

Golden period of particle physics

- 4π acceptance
- Trace a charged particle with good efficiency
- Calculate momentum
- Identify particle, $e/\pi/\mu/p/n$
- Separate them out, spatial resolution ($\sim 8\mu\text{m}$) with particle multiplicity up to 150
- Mass identification, identify mother
- Secondary vertex



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momentum

@Santiniketan (1994)

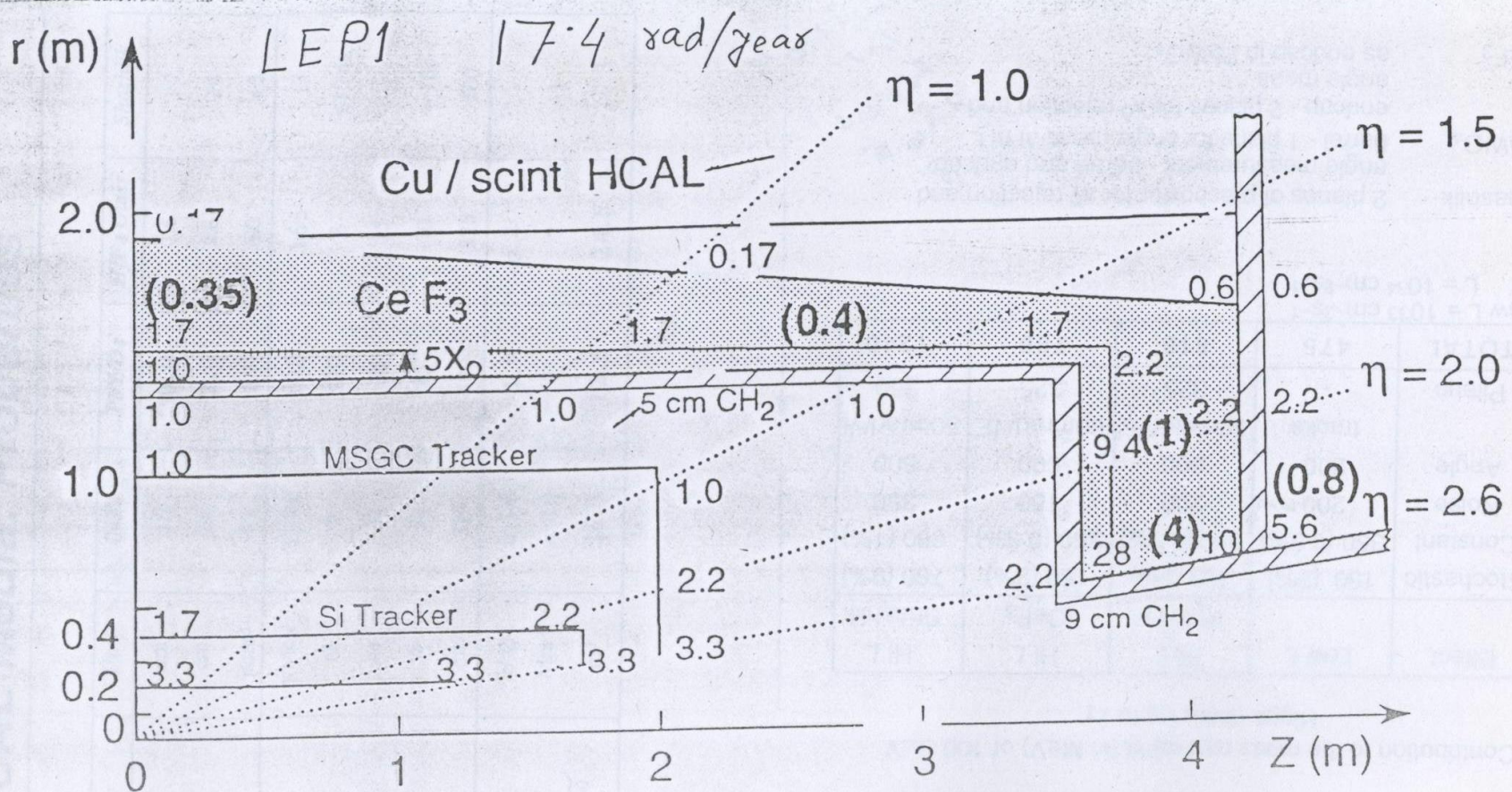


Fig. 1.4 : Neutron fluence and dose in CMS. The numbers in the figure are the fluence in units of 10^{13} n/cm². Numbers in bold are the dose in Mrads. These numbers are given for an integrated luminosity of $L = 10^{42}$ cm⁻², corresponding to 10 years of running at design luminosity.

LHC
0.04 rad/s

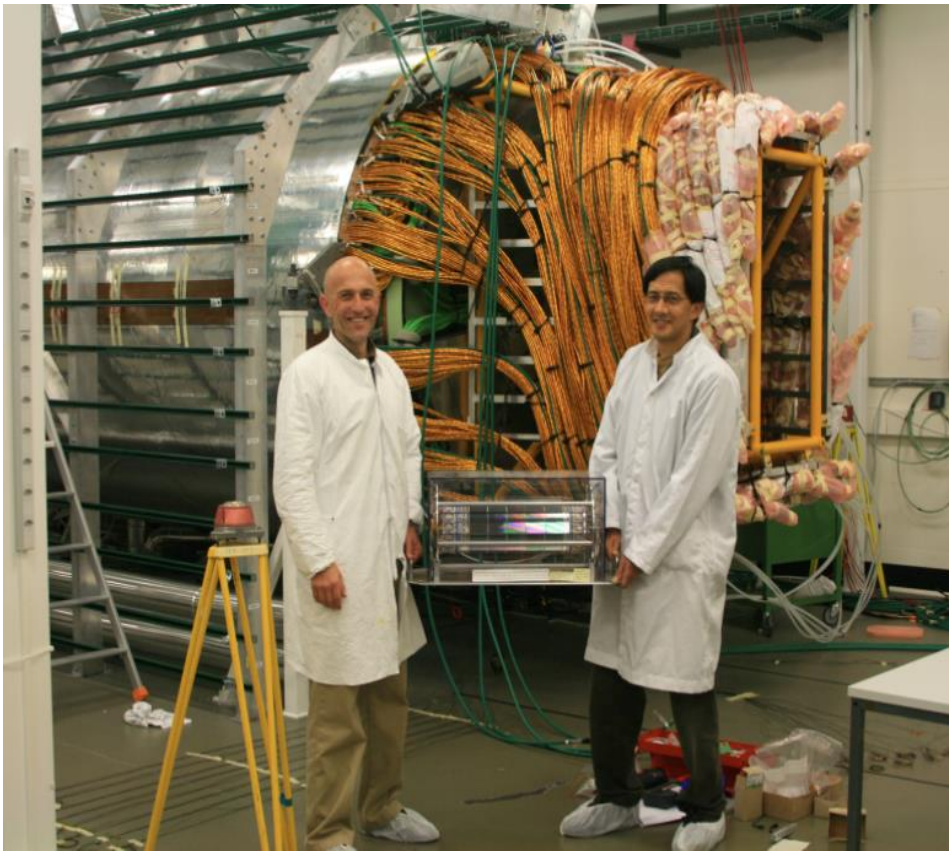
γ -source
~ 56 rad/s

1.17 &
1.32 MeV

} 10^6

MSGC → Silicon strip
CeF₃ → PbWO₄

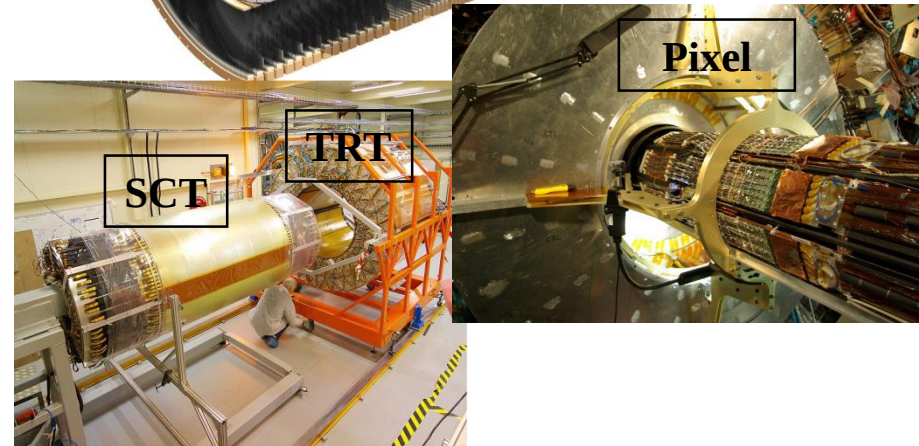
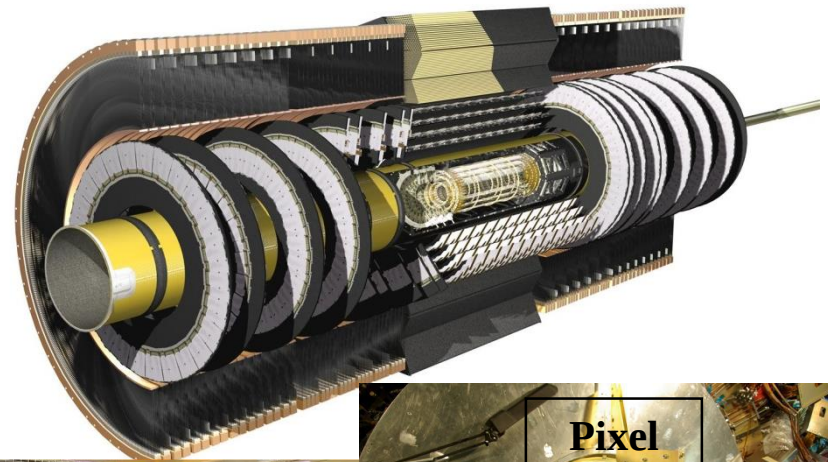
CMS and ATLAS Tracking Detector



**CMS members hold the OPAL Vertex Detector
in front of the CMS Silicon Strip Detector**

L3 tracker had 74**K** channels, whereas CMS is
having 76**M** channels (increases by three order)

Bunch spacing : LEP to LHC : 23μs to 25ns



Silicon pixels (**Pixel**): 80×10^6 channels

Silicon strips (**SCT**): 6×10^6 channels

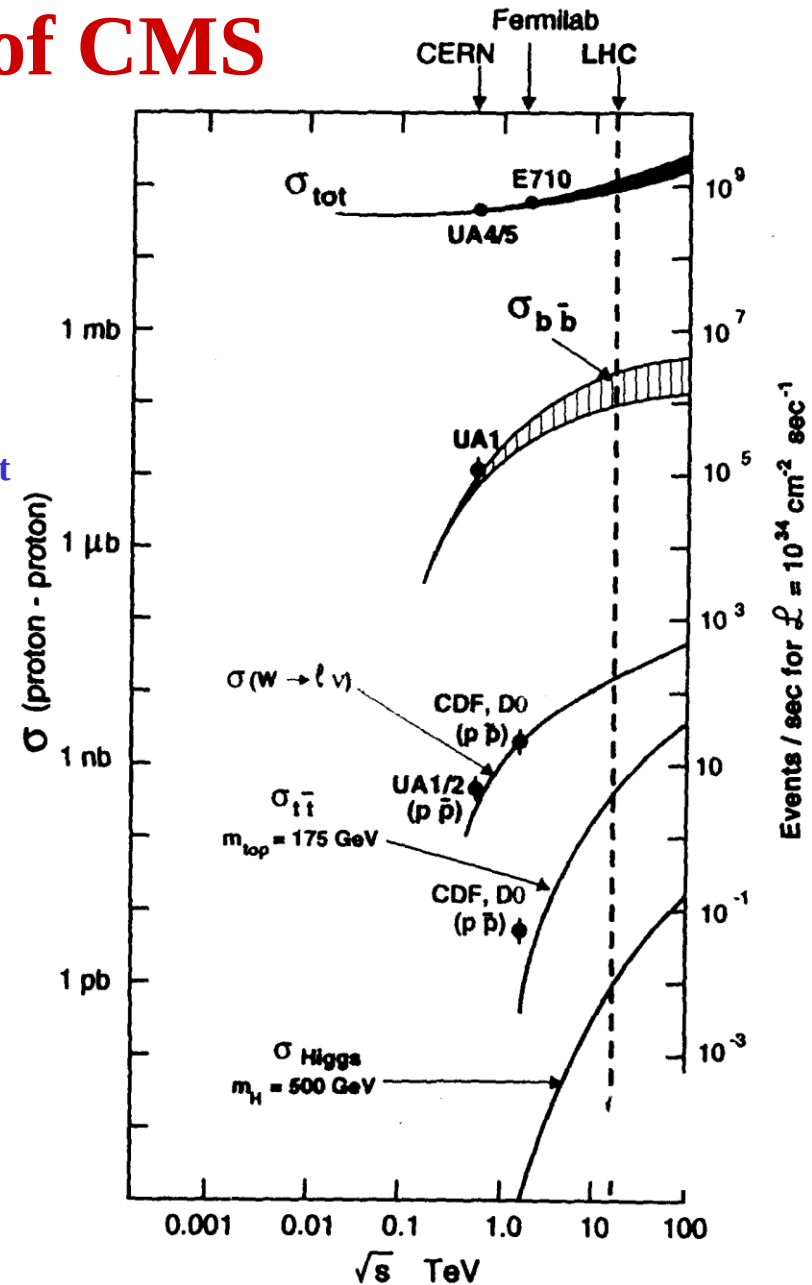
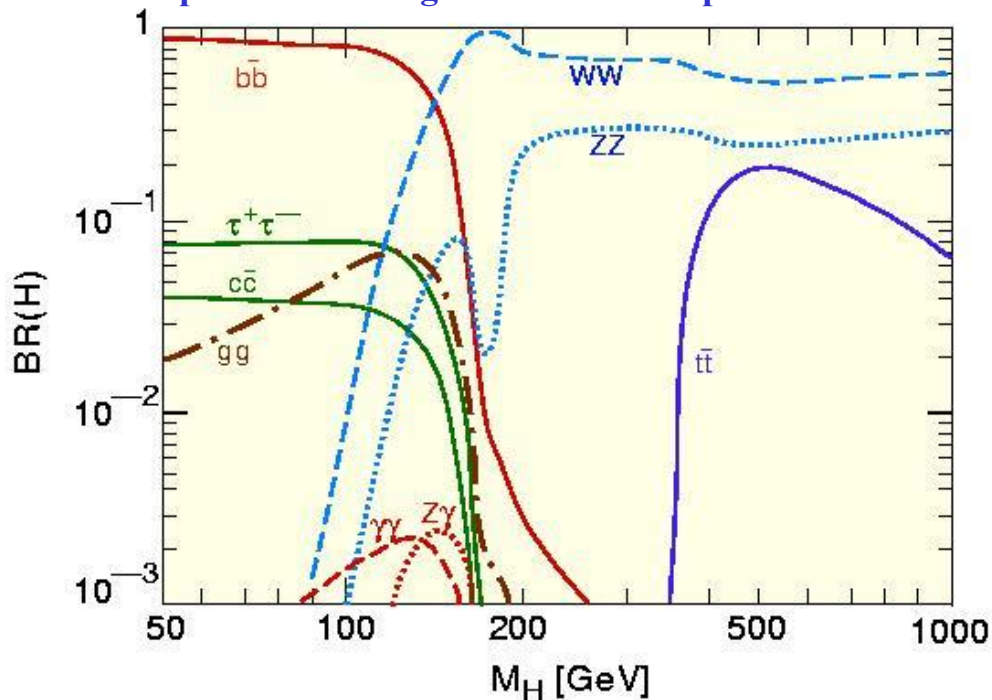
Transition Radiation Tracker (**TRT**):
straw tubes (Xe), 4×10^5 channels e/π
separation

$$\sigma/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$$

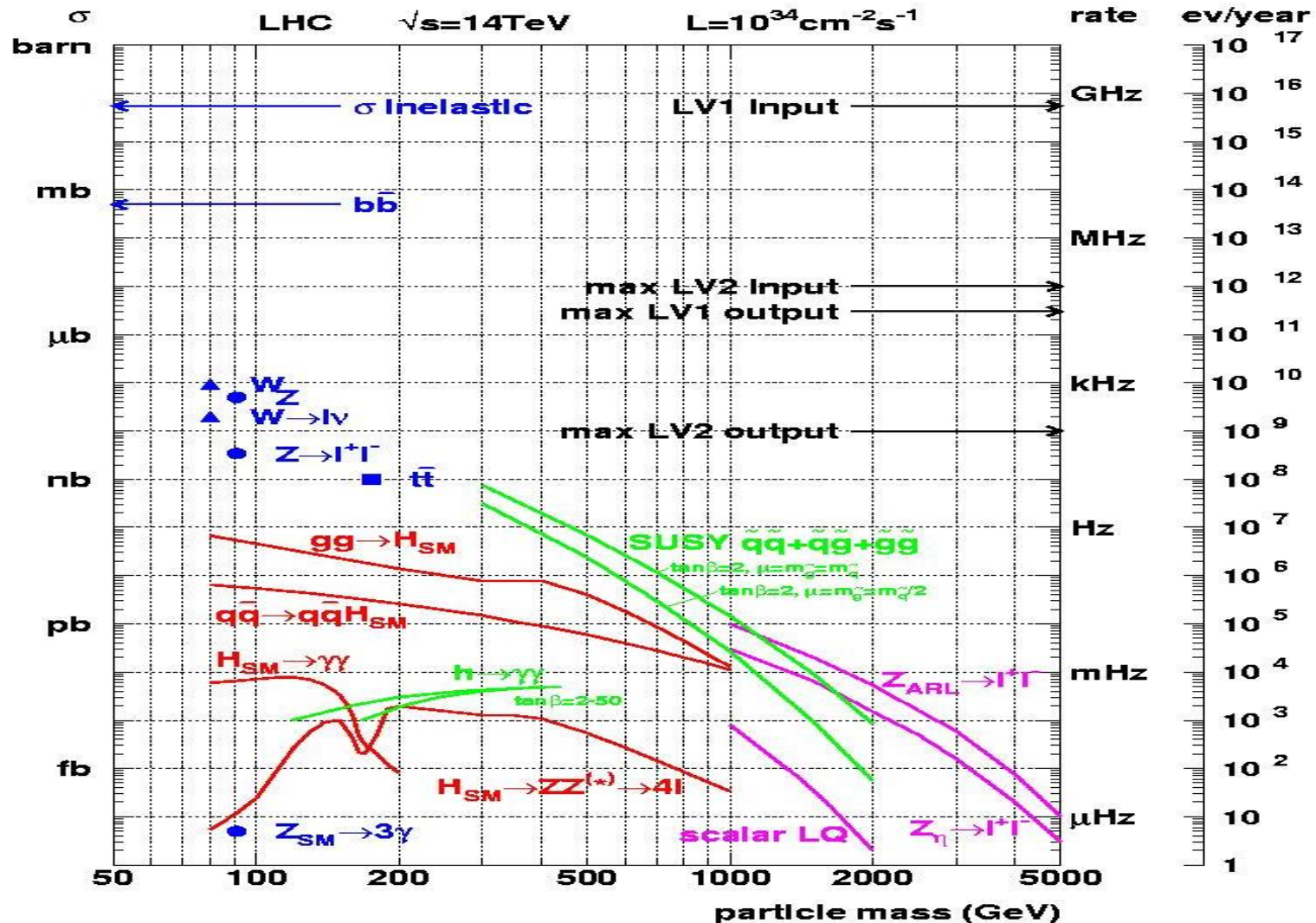
Same is true for KGF → INO

Physics goal of CMS

- Don't know what will we find at the LHC!
- ATLAS and CMS are “general purpose” detectors – they need to be designed to be able to detect anything!
- We believe that the Higgs boson, and/or Supersymmetric (SUSY) particles exist, and the LHC will provide collisions energetic enough to create them
 - But we cannot see Higgs/SUSY particles directly as they either decay to lighter (stable) particles or cannot be seen with any known detector
 - We have to design our detector to look for the stable particles and signs of “invisible” particles.....

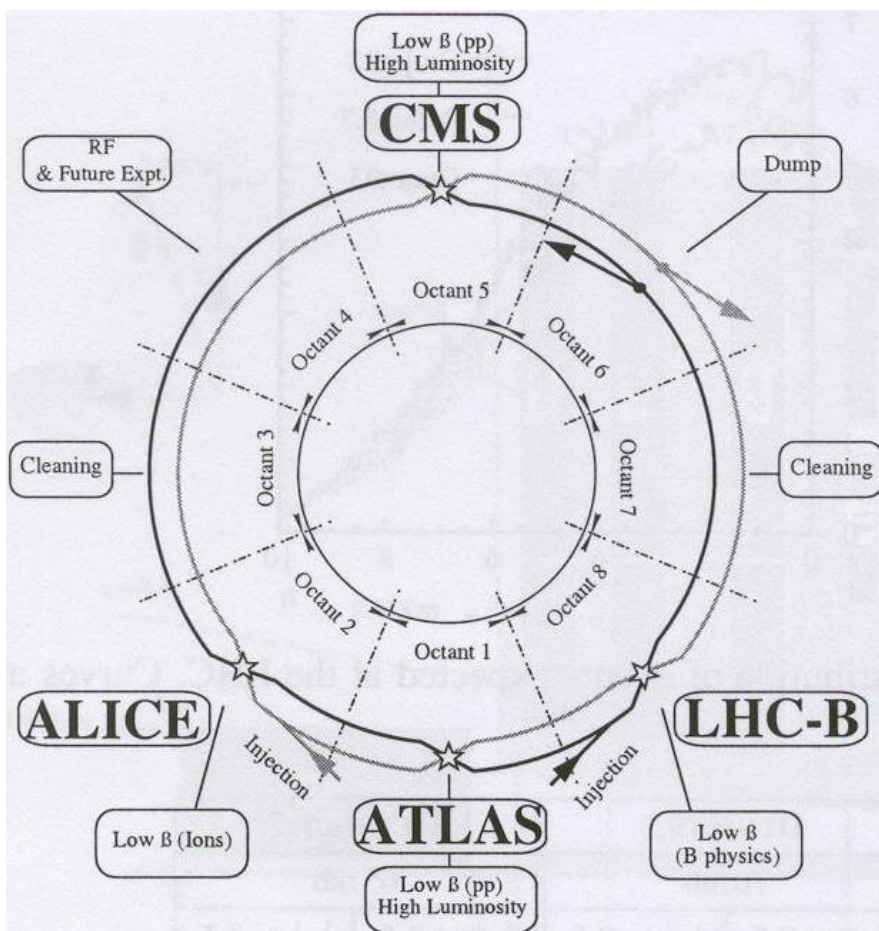
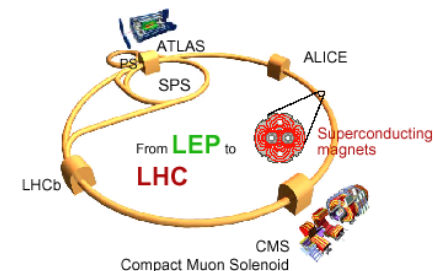


Physics processes at LHC



Interesting physics processes are 10^{-10} - 10^{-9} times smaller than inelastic pp interaction rate → Searching for a needle in a hay stack

LHC machine



Beam Energy

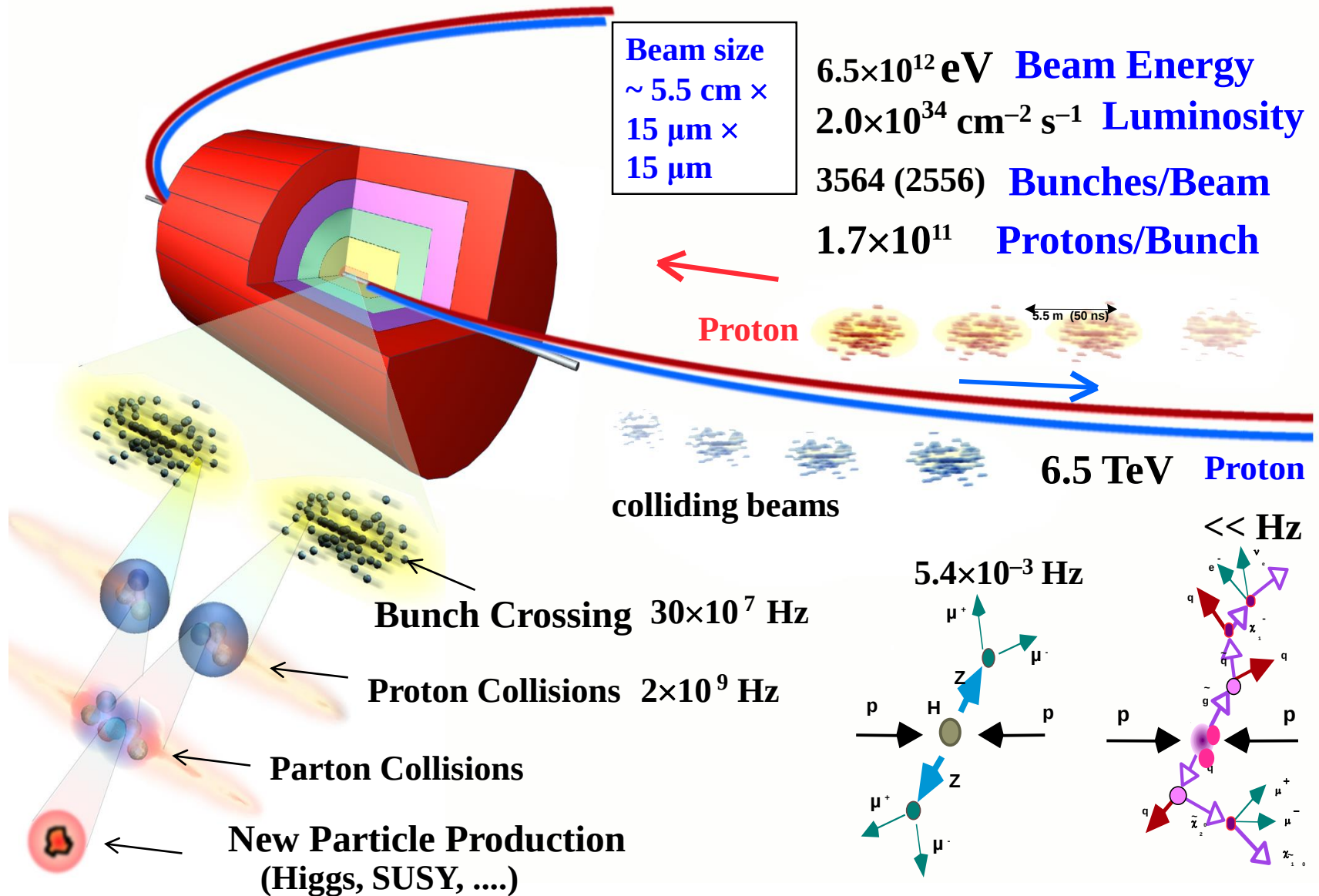
Beams	Energy GeV	Luminosity
LEP e+ e-	200	$10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
LHC p p	14000	10^{34}
	Pb Pb	1,312,000
		10^{27}

Peak Luminosity ($\mathcal{L}$)	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
$\sigma_{pp} \text{ ND (+ D)}^\dagger$	70 mb (+ 10 mb)
ND events at peak $\mathcal{L}$	$7 \times 10^8 \text{ s}^{-1}$
Protons / beam at start of fill	3×10^{14}
Fills per day $\times$ duration †	$1 \times 20 \text{ h}$ or $2 \times 8 \text{ h}$
Operation days per year (pp) †	3×60
$\mathcal{L}$ (24h average) †	$5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
$\int \mathcal{L} dt$ (per year) †	$0.75 \times 10^5 \text{ pb}^{-1}$
ND events (24h average) †	$3.5 \times 10^8 \text{ s}^{-1}$
Number of ND events per year †	5.5×10^{15}
$\mathcal{L}$ (years 1–4 in % of max.) †	10, 33, 67, 100
Protons lost in experiments / beam †	$3 \times 10^{13} / \text{day}$
Protons lost in scrapers / beam †	$9 \times 10^{13} / \text{day}$
Protons lost around ring / beam †	$2 \times 10^{13} / \text{day}$
Protons dumped / beam per day $^\dagger \ddagger$	$46 \times 10^{13}, 18 \times 10^{13}$

† Preliminary assumption.

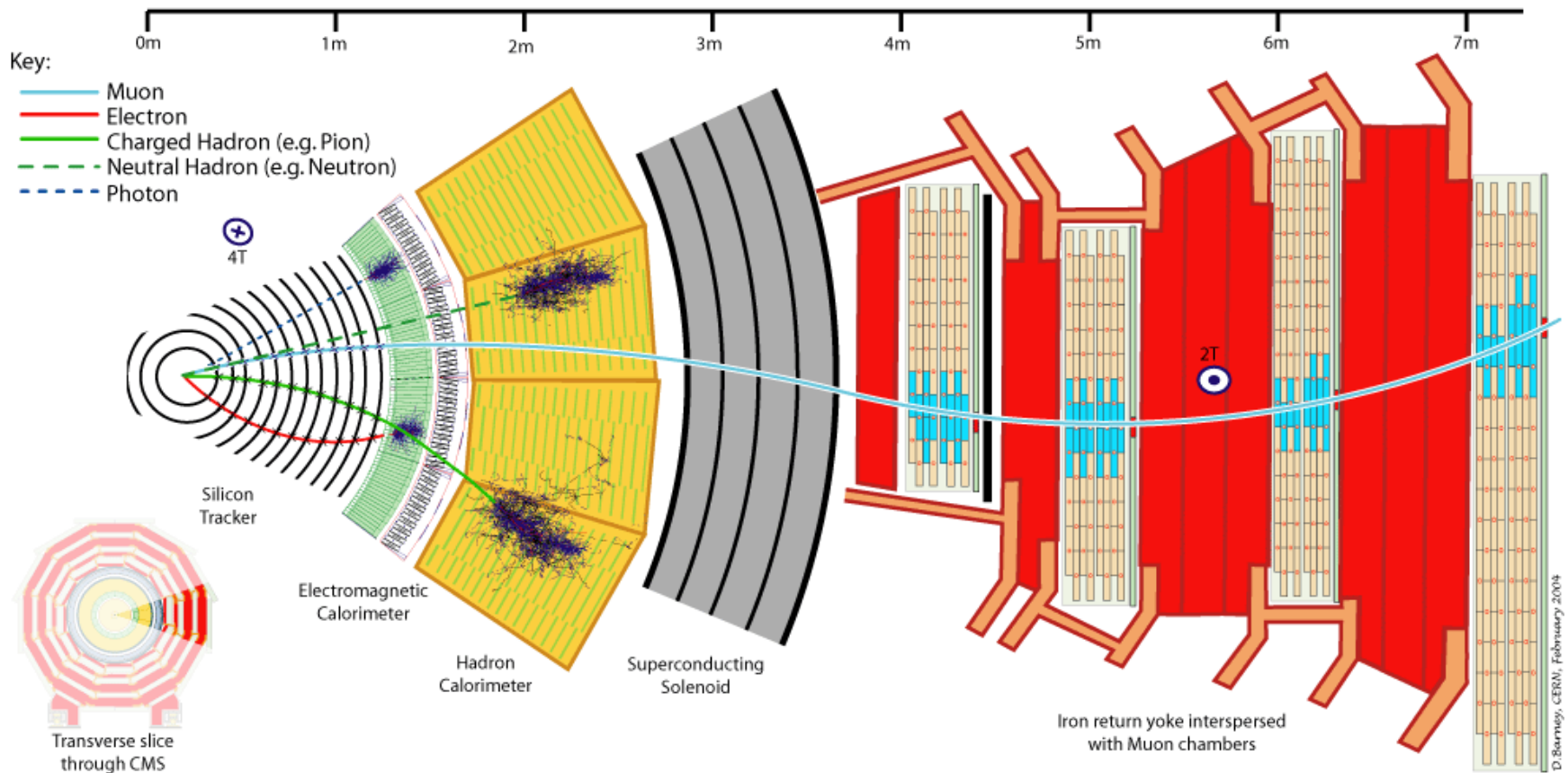
‡ For 8h and 20h fills.

Collisions at the Large Hadron Collider



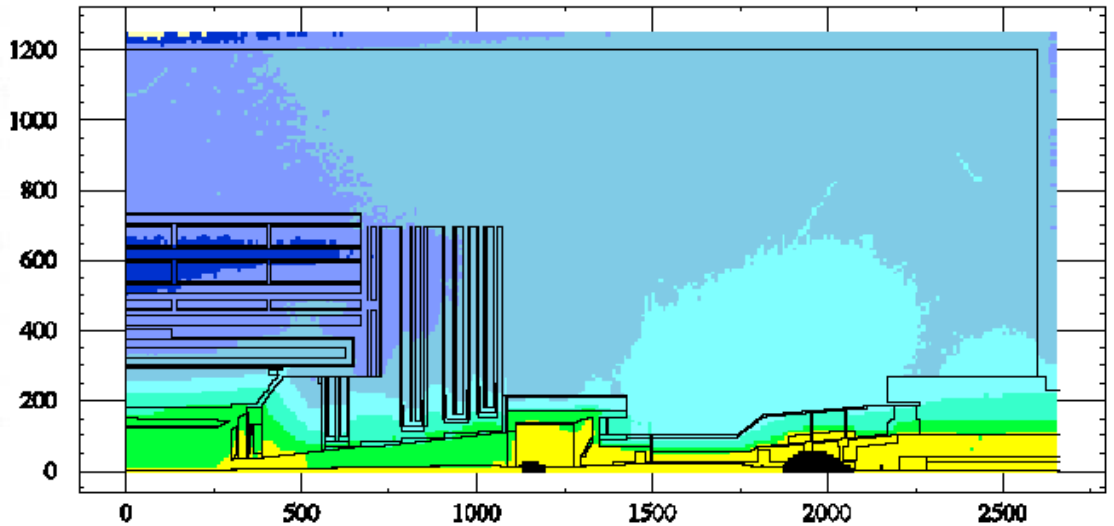
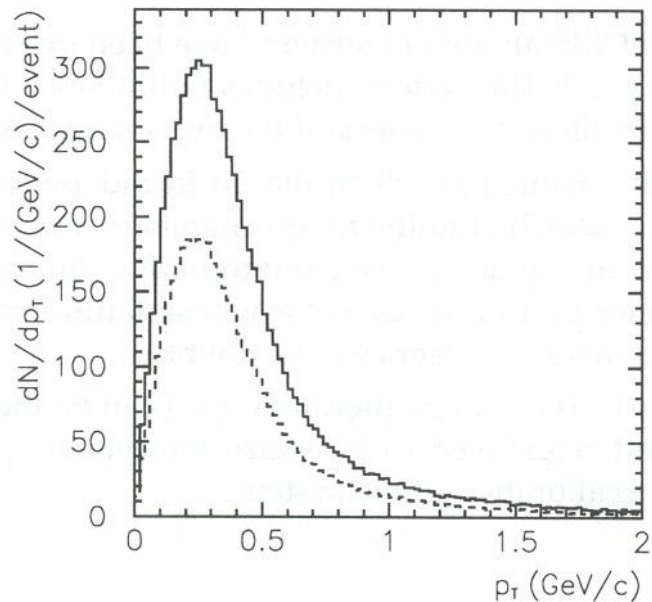
Basic concepts of HEP detector

- Heavy particles decay to low mass particles
- Stable particles are detected in the detector
- Stable particles : $e^\pm$, γ , p , $p\text{-bar}$, $K^\pm$, $\pi^\pm$, K_L^0 , n , $n\text{-bar}$, $\mu^\pm$, ν , $\nu\text{-bar}$
- Design detector which can detect all these stable particles
- Layers of subdetectors to detect different particle in different detector layer
- Most interacting particles are detected in the innermost layer and less interacting one in the

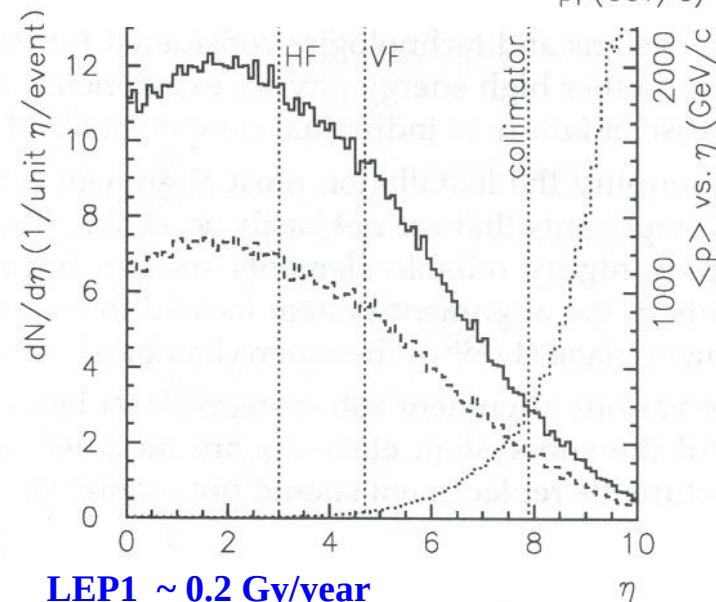
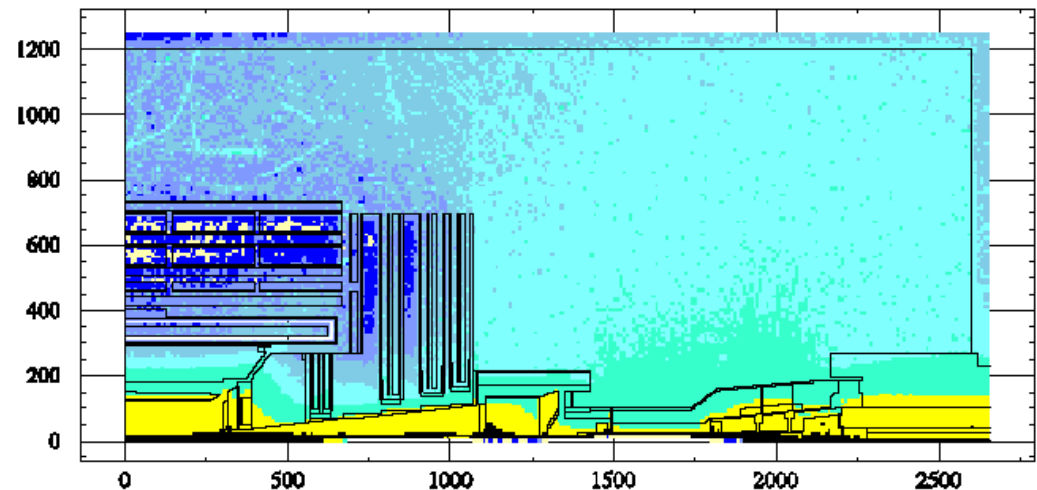


Particle flux in LHC experiments

n fluence in CMS for an integrated luminosity of $5 \cdot 10^5 \text{ pb}^{-1}$ (~ 10 years)



Dose in CMS for an integrated luminosity of $5 \cdot 10^5 \text{ pb}^{-1}$ (~ 10 years) Gy



LEP1 ~ 0.2 Gy/year

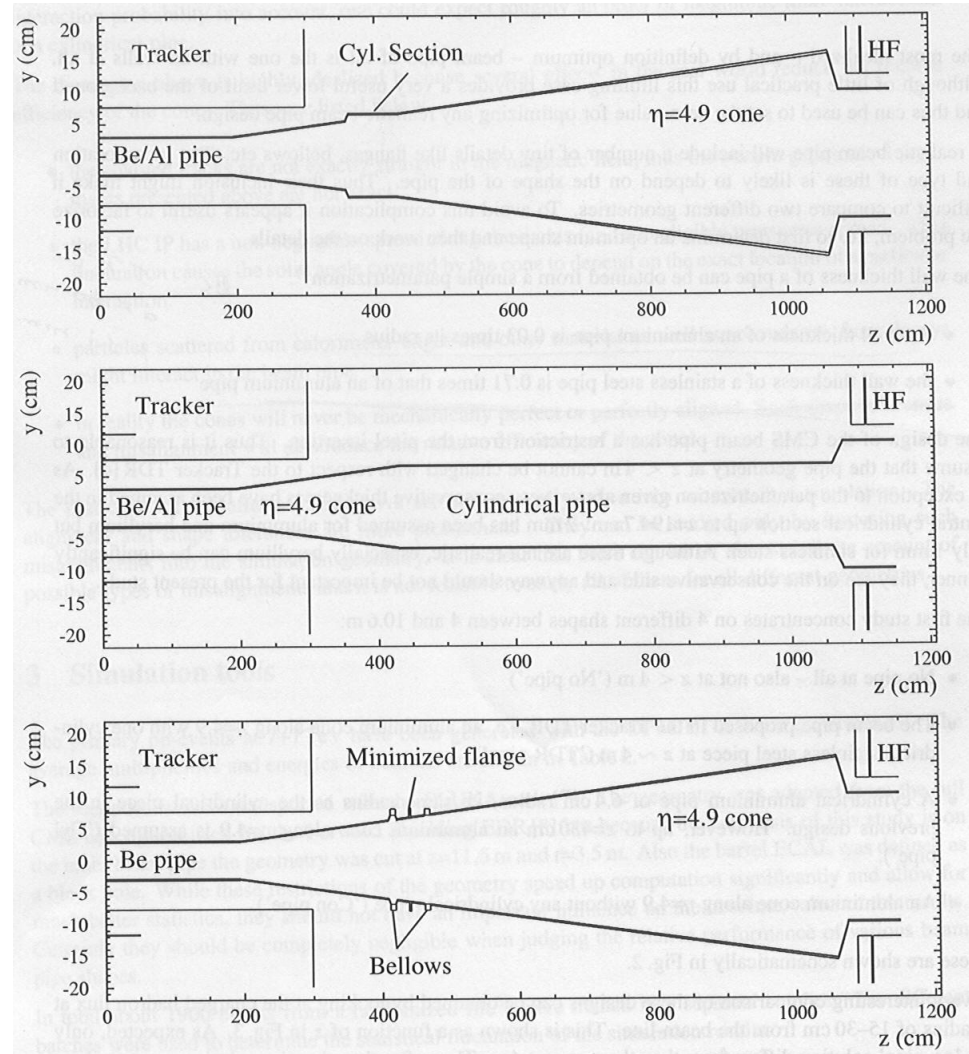
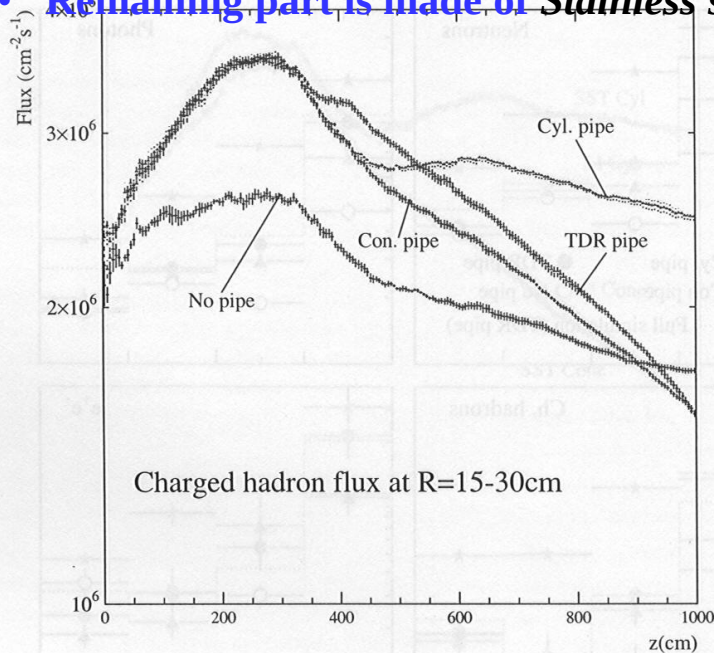
4% : detector, 31% : collimator and shielding; 65% : behind collimator

Beam pipe design

- Track length in beam pipe

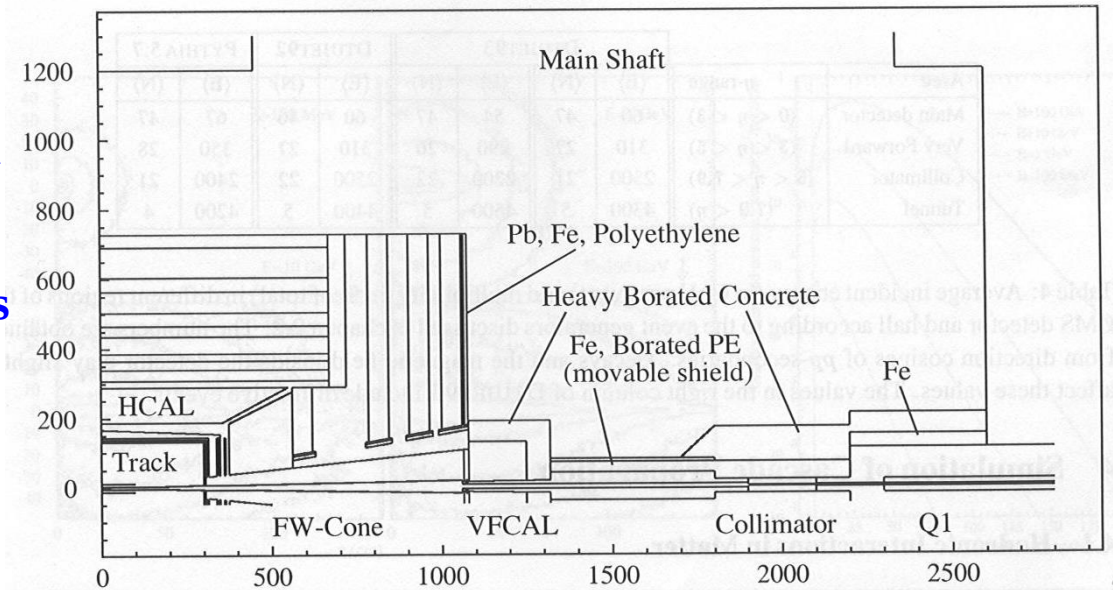
$$\ell = \frac{t}{\sin(2 \arctan e^{-\eta})} \approx \frac{t}{2e^{-\eta}}$$

- For $\eta=5.3$ and $t=2\text{mm} \Rightarrow \ell=20\text{cm}$
- High cost, handling problem and toxicity reduced **Be** beam pipe upto $\sim \pm 75\text{cm}$
- Beyond $\eta=2.5$, there are no strong constraints from CMS performance
- Al** has problem with welding, NEG-coating (upto $\pm 1.98\text{ m}$)
- Remaining part is made of **Stainless steel**



Shielding of hadronic beam background

- Low energy neutron shielding using hydrogenous material
- $E > 10$ MeV, cross section is small ($1/v$), heavier material provide better shielding but inelastic interaction with several neutrons in the final state, good choice is medium mass nuclei, good materials are cadmium $[(A(n,n)A^*)]$ and boron $[(n,\alpha)]$
 - At high energies boron has inelastic interaction, which increase the neutron flux
 - Cadmium produces numerous energetic capture gammas



The general solution to shield radiation in accelerator environments:

To reduce the flux of high energy particle with dense but medium A material, e.g. iron, placed close to the source. Then to slow down neutrons with hydrogenated materials and to capture them either in the hydrogen or with boron or cadmium. Finally the photons can be suppressed with a layer of lead

Detecting signature of the Higgs/SUSY particles

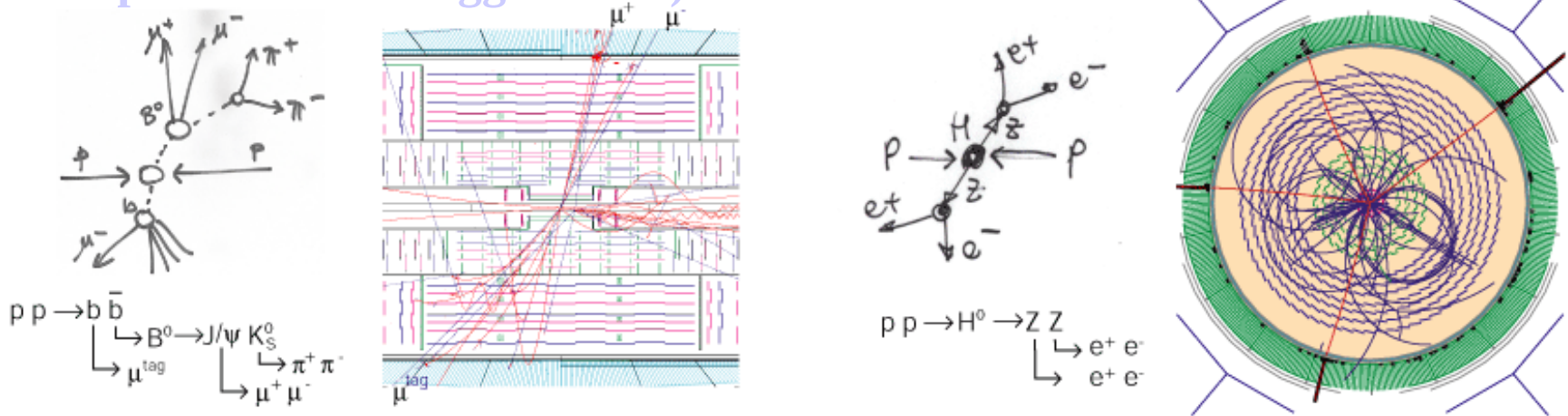
- If Higgs mass is around 115-130 GeV, the easiest way to detect it is via its decay to two photons
 - Need an excellent electromagnetic calorimeter - **ECAL** (for 4-moneta of photons)
 - Need excellent **tracker** to identify the primary interaction vertex
- If the Higgs is heavier, it may be seen via its decay to electrons and/or muons
 - Need an excellent **ECAL**, Need excellent **muon chambers** (for muon identification and momentum measurement) and **central tracking** (for momentum measurement)
- Many SUSY particles decay to hadronic jets (many charged and neutral particles in a tight bunch)
 - Need good calorimeters – hadronic (**HCAL**) and **ECAL**
- SUSY decays also lead to the production of the “lightest supersymmetric particle” (LSP), which is invisible in any known detector
 - Need excellent **calorimetry coverage** in order to detect “missing” energy

Requirements :

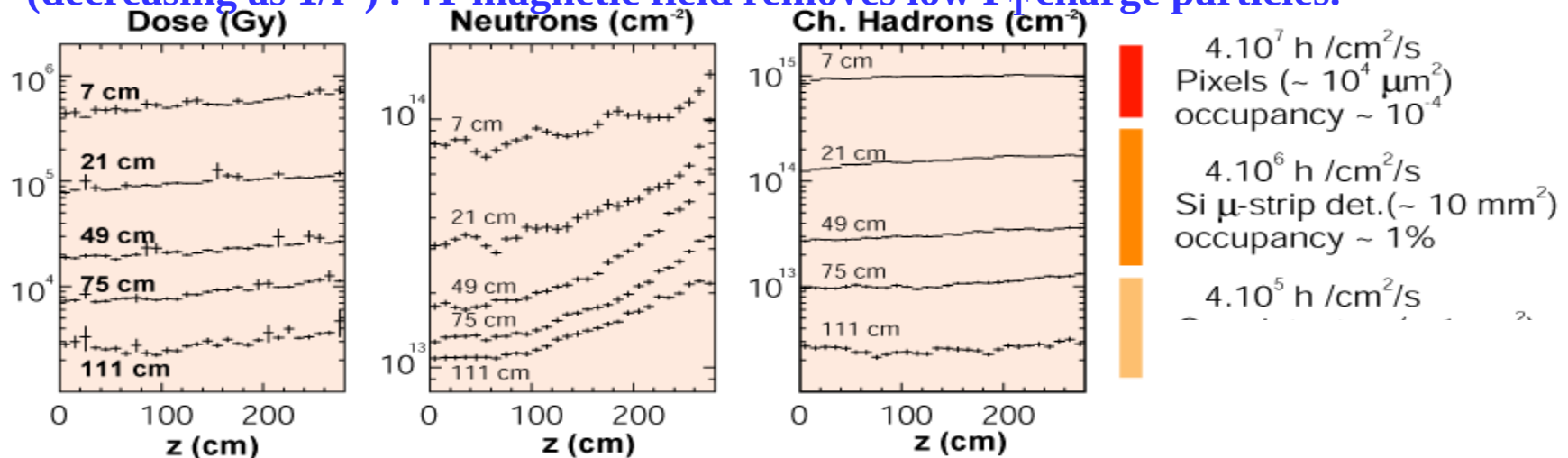
- A good and redundant *muon system*
- The best possible *electromagnetic calorimeter*
- A high quality *central tracking*
- A *hadronic calorimeter* that has good energy resolution and that is as hermetic as possible
- **Affordable!** (~500 MCHF)

CMS tracker

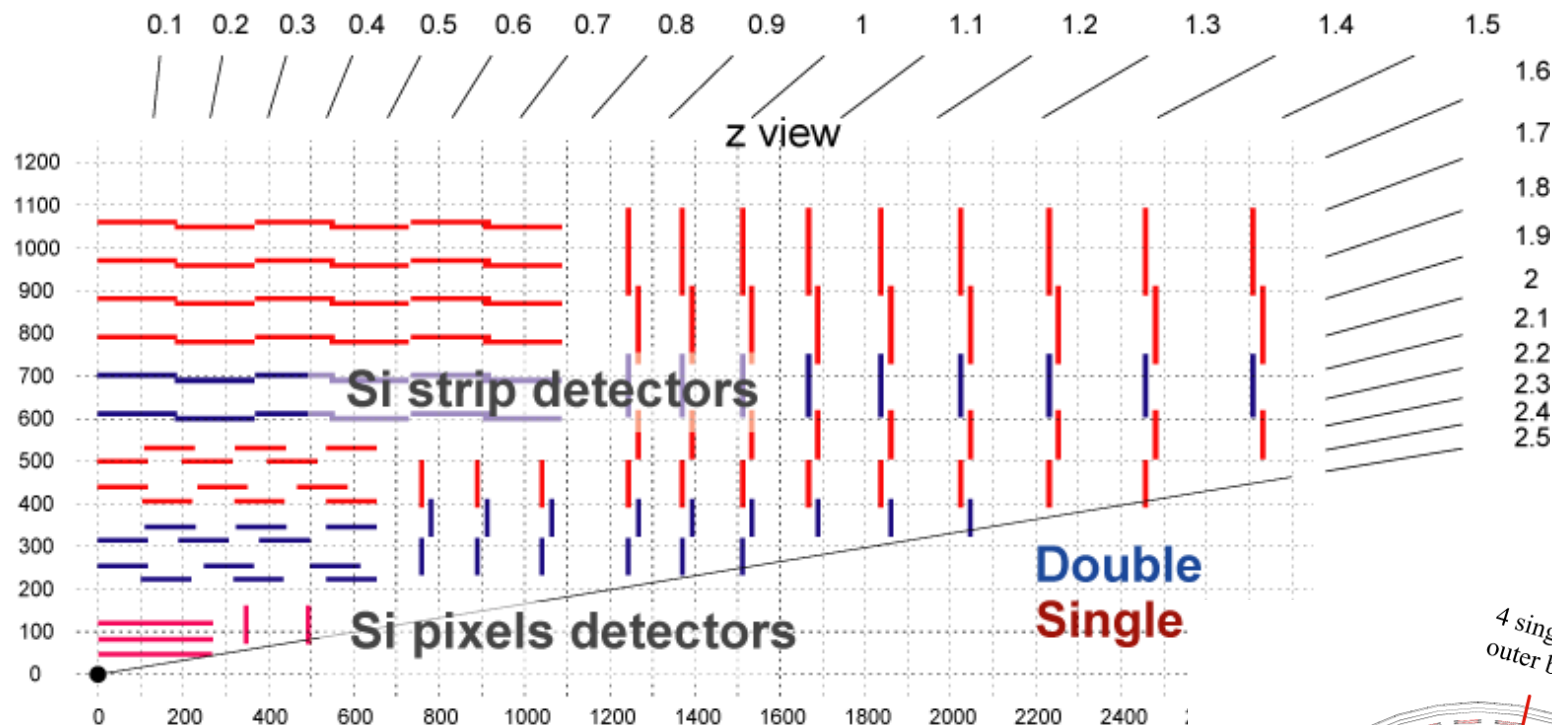
- Design to reconstruct high P_T muons, isolated electrons and hadrons with high momentum resolution and an efficiency better than 98% in the range $|\eta| < 2.5$ along with the identification of detached vertex (efficiency to detect two photons from Higgs $\sim 50\%$).



- Precise position measurement, robustness in high density of particle flux/rate (decreasing as $1/r^2$). 4T magnetic field removes low P_T charge particles.



CMS tracker



The layout of the CMS inner tracker

Type inversion due to high radiation dose $\Rightarrow$ *p-substrate*

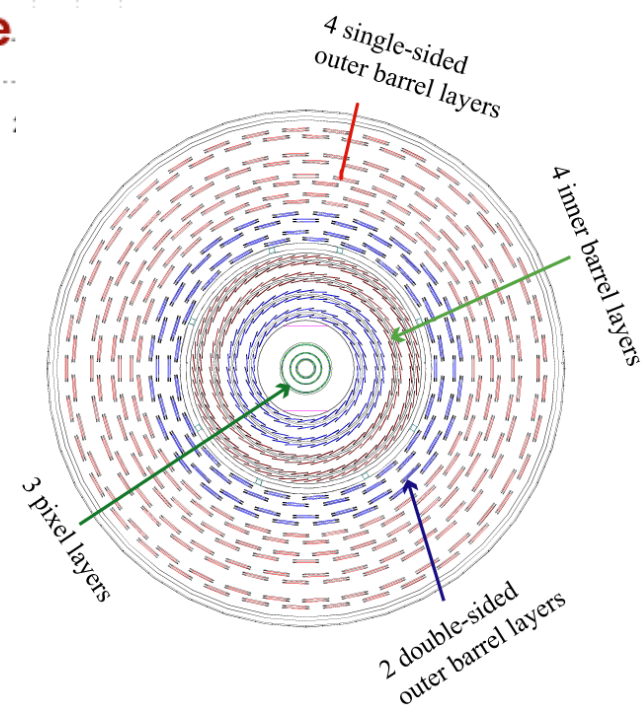
Pixels : $150 \mu\text{m} \times 150 \mu\text{m}$

Strip pitch : 80 to $205 \mu\text{m}$

Outer region : higher noise due to “long” strip is compensated by larger signal in thick ($500 \mu\text{m}$) sensor

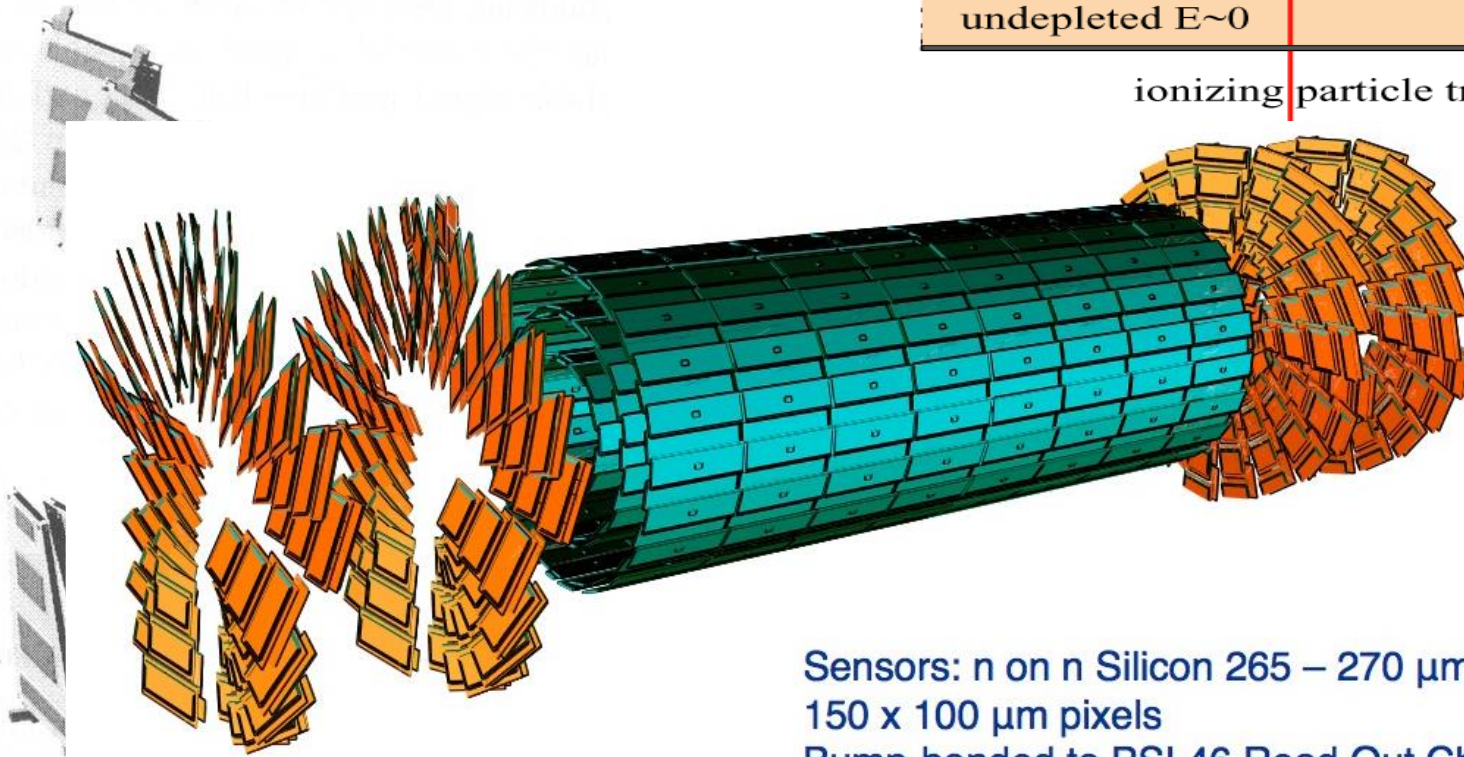
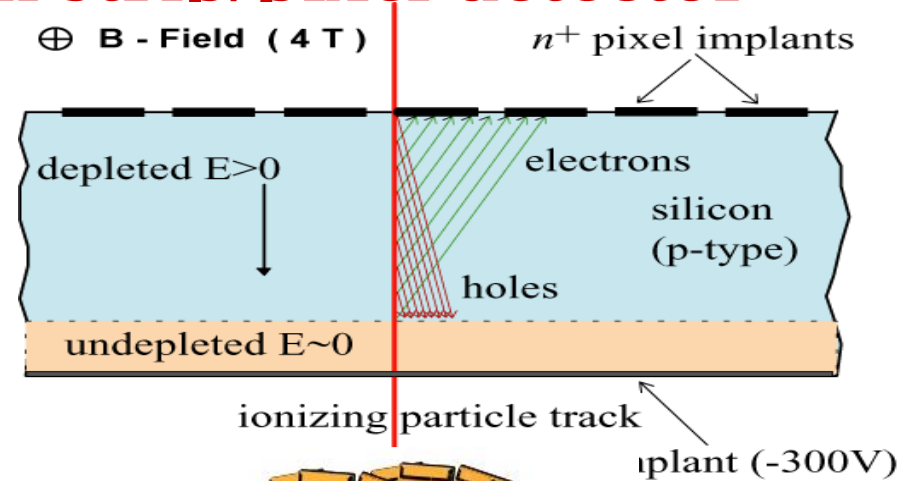
Total readout channel : 9.6 M

Operating at -10°C



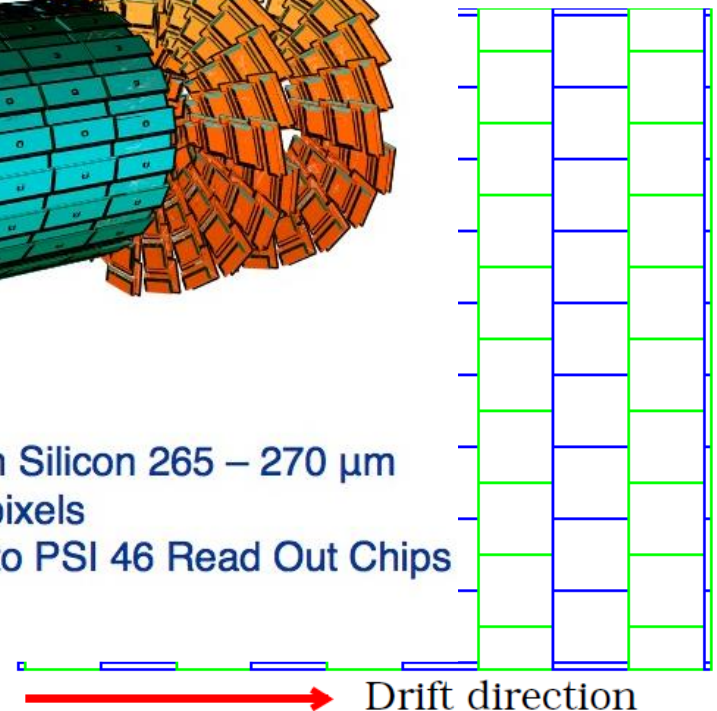
Design of CMS silicon strip/pixel detector

- Barrel detector uses the principle of Lorentz angle to improve resolution
- Endcap detector are put a paddle/blade shape disk to have a



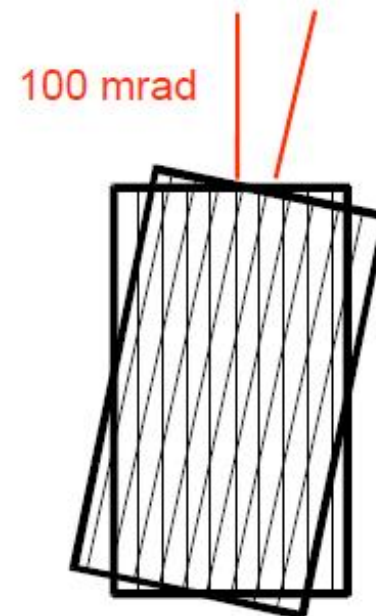
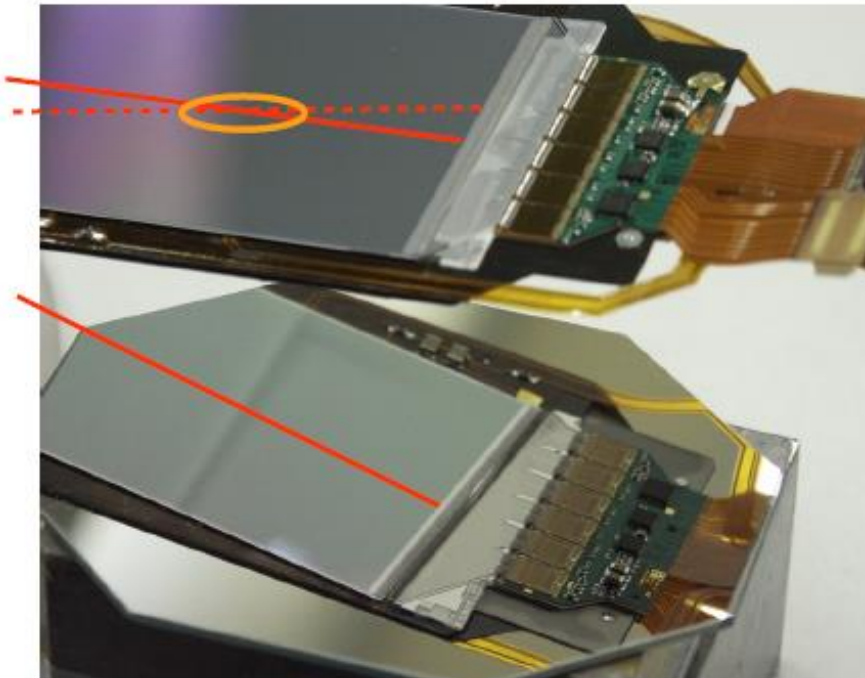
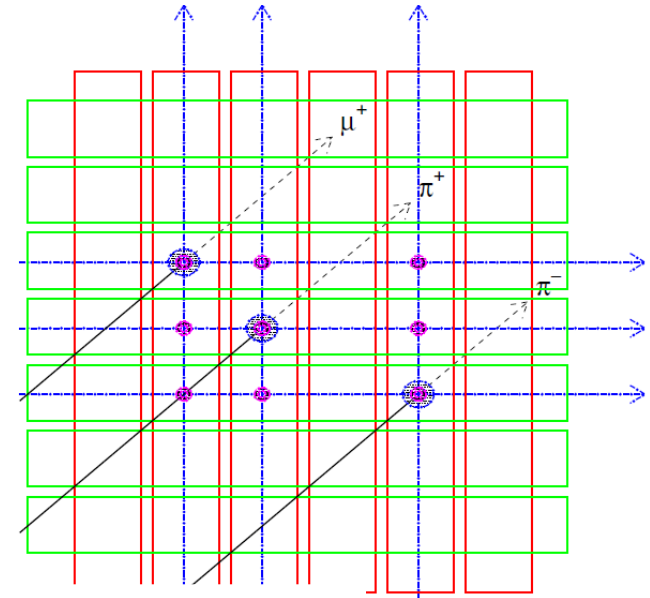
Total Area: 0.78+0.28 m²
66 Million Pixels

Sensors: n on n Silicon 265 – 270 μm
150 x 100 μm pixels
Bump-bonded to PSI 46 Read Out Chips



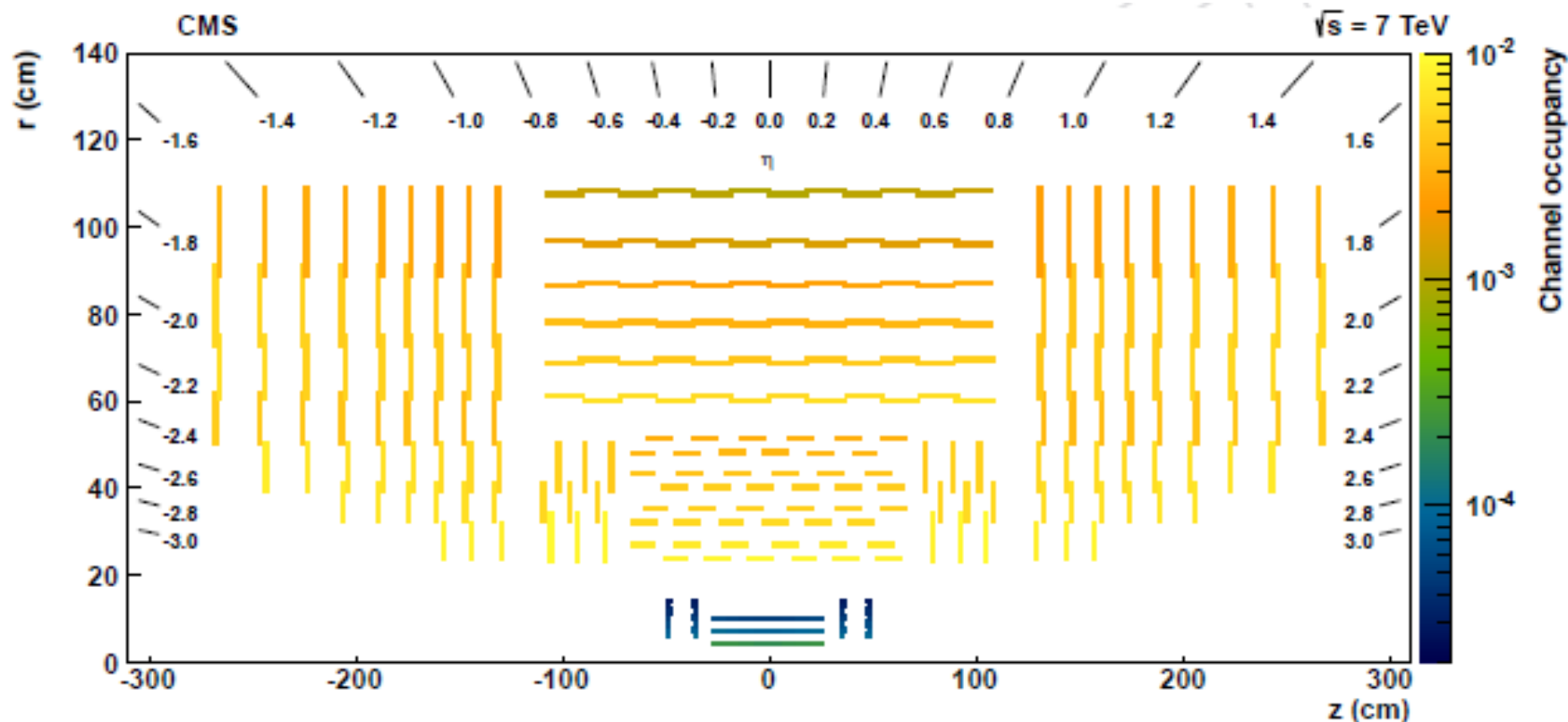
Double sided (DS) module

- DS modules are two single sided modules literally glued back-to-back
- DS modules eventually provide 2D hit information.
- Large angle has more ghost hit, whereas small angle has poorer position information.



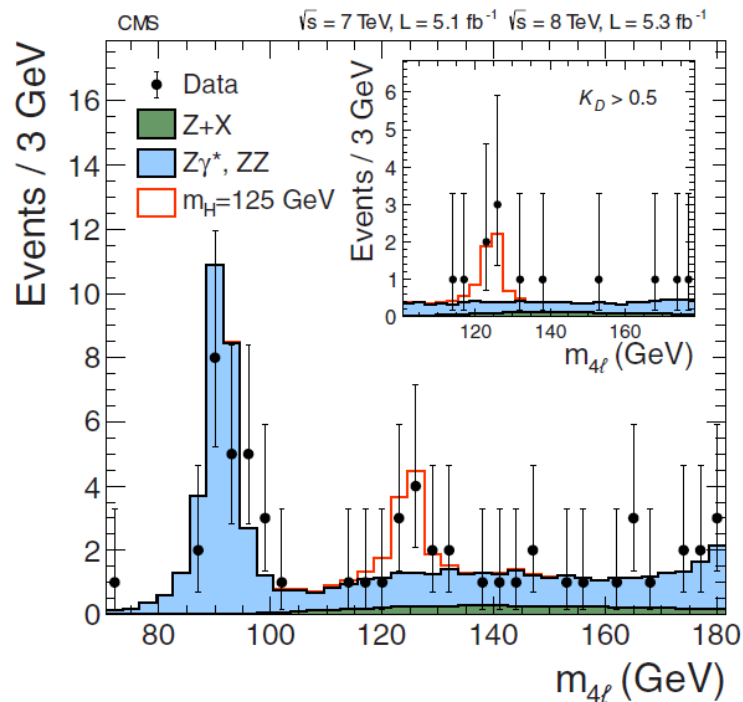
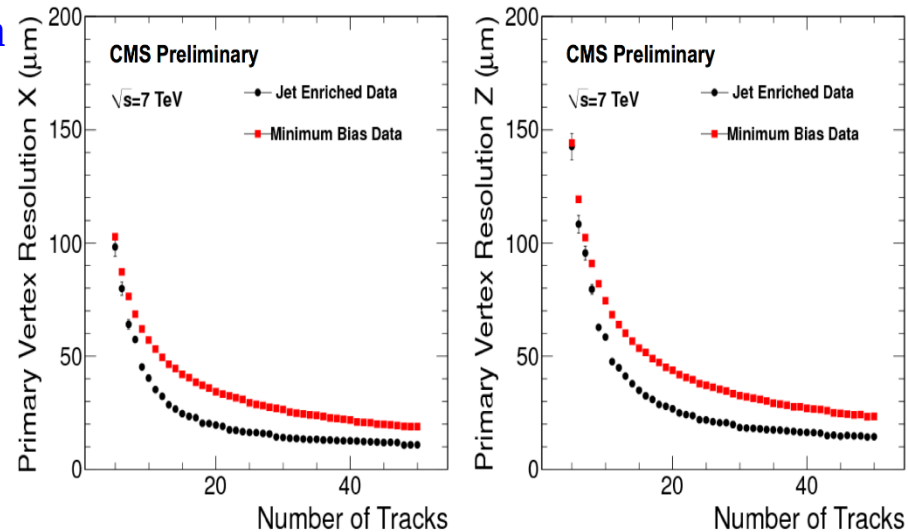
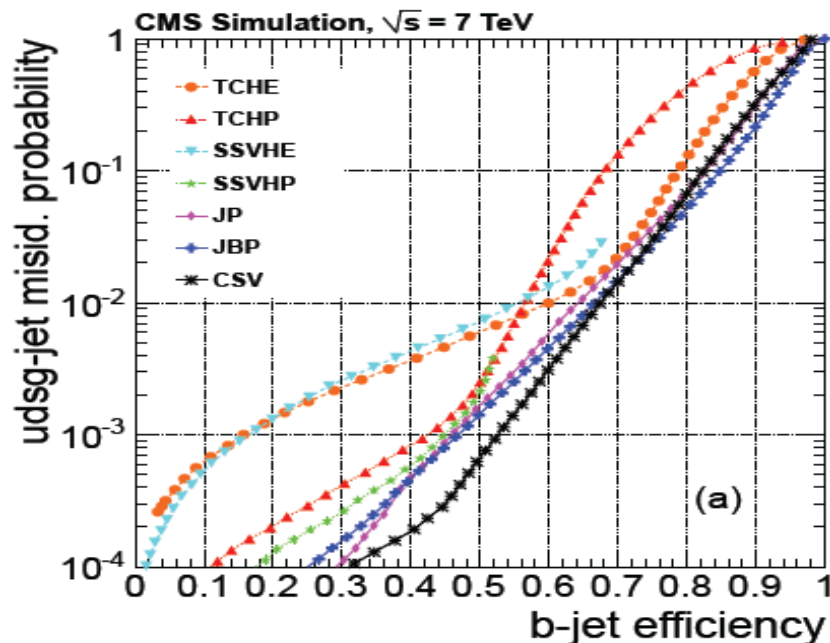
Occupancy/granularity

- Despite the position, the channel occupancy in the pixel detector is typically an order-of-magnitude smaller than in the strip detector. Occupancy decreases stronger than area/r^2 (magnetic field confines softer particles inside)
 - single pixel area = $100\mu\text{m} \times 150\mu\text{m} = 1.5 \times 10^{-2} \text{mm}^2$
 - typical strip area = $10\text{cm} \times 100\mu\text{m} = 10\text{mm}^2$
- This plot explains why CMS tracking is heavily pixel driven (seeding).



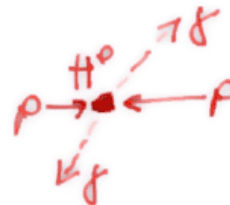
Performances of CMS tracker system

- $\delta P_T/P_T \approx (1.5P_T + 0.5)\%$ with P_T in TeV, in the central region $|\eta| < 1.6$ and gradually degrading to $\delta P_T/P_T \approx (60P_T + 0.5)\%$ as $|\eta|$ approaches 2.5.
- Combining with muon chamber, P_T resolution is better than 10% for P_T upto 4 TeV
- Efficiency $>95\%$ for hadronic track with $P_T > 10$ GeV and $>98\%$ for muon and $>90\%$ for electron
- Secondary vertex reconstruction :

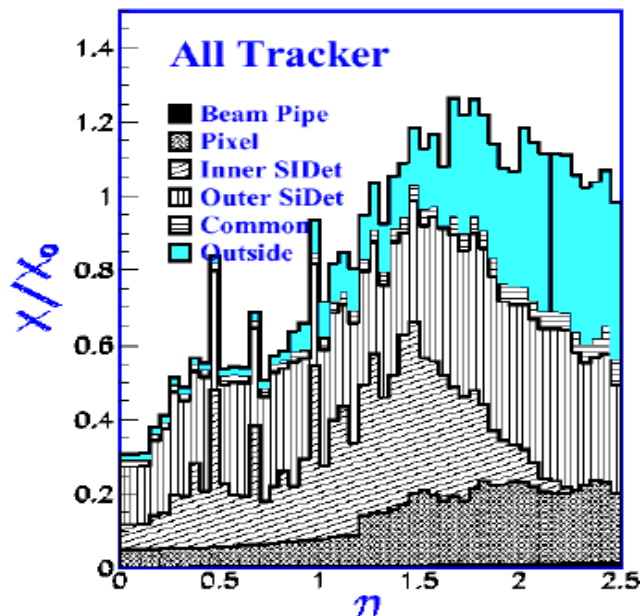
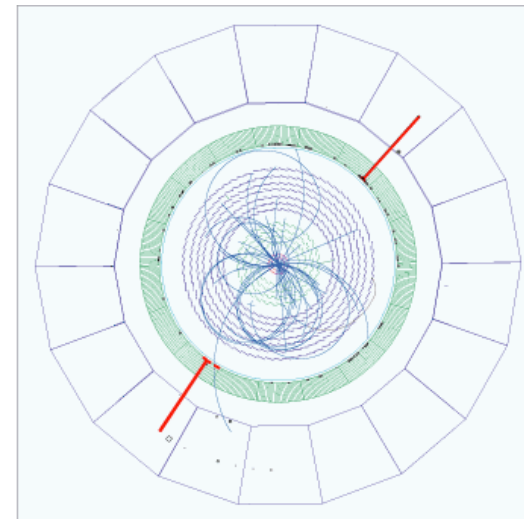


CMS electromagnetic calorimeter

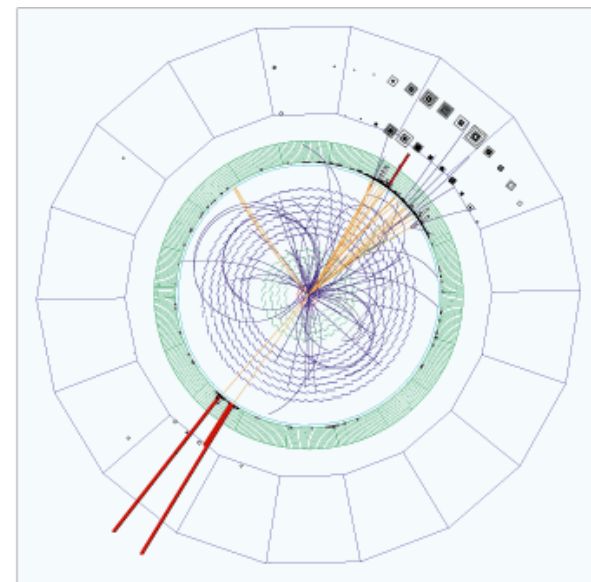
- **Design goal** : Two photon mass resolution depends on the energy resolution and the angle between two photons.
- Measure 4-momentum of electron and photon with great accuracy
- Good two shower separation capability to reject a sufficient number of π^0 carrying moderate energy (20-40 GeV)
- Average spread of the interaction vertices an additional 1.5 GeV contribution to diphoton mass resolution



$$p p \rightarrow H^0 \rightarrow \gamma \gamma$$

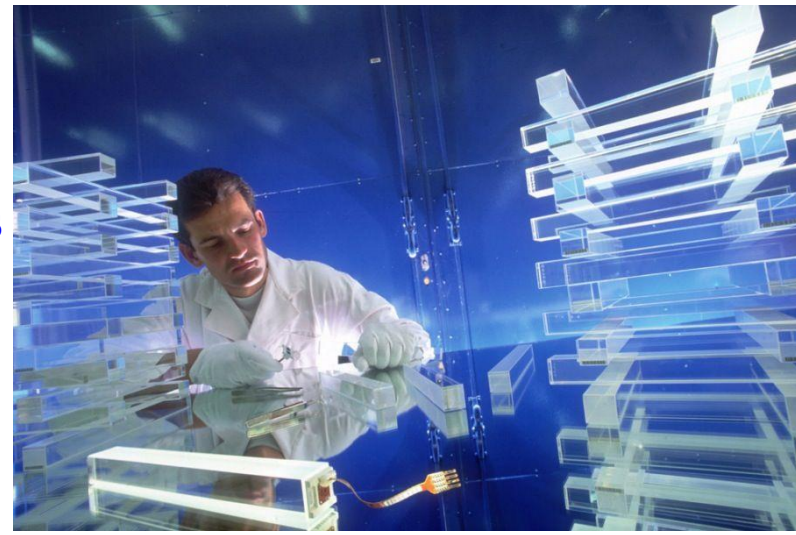


$$p p \rightarrow H^0 \rightarrow Z Z \rightarrow \text{jet jet } e^+ e^-$$

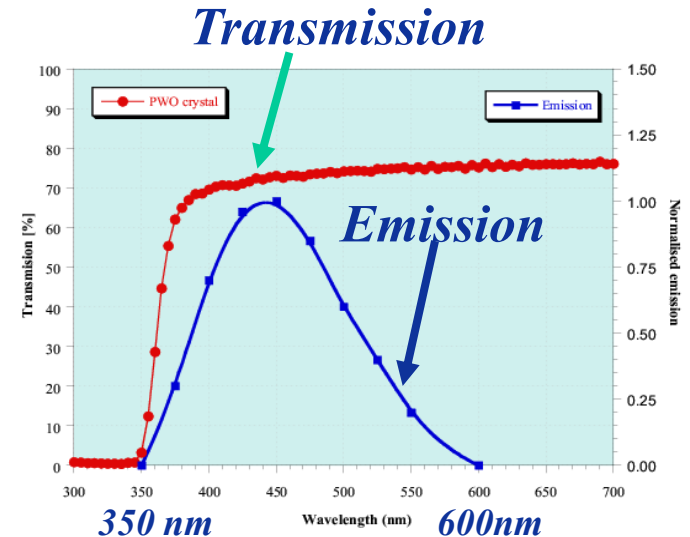
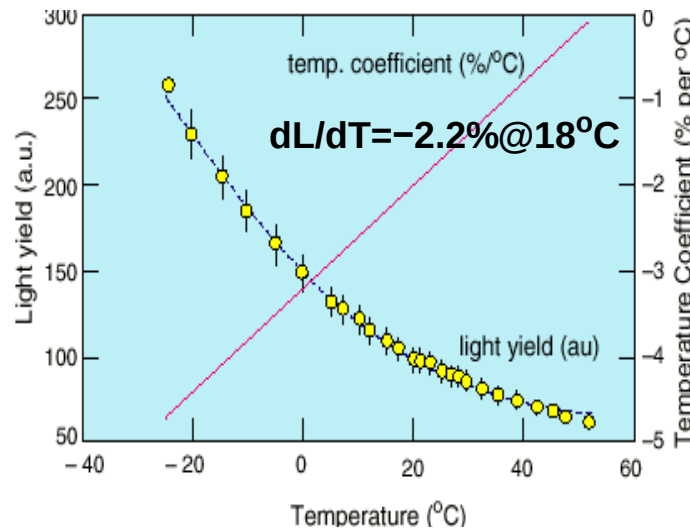
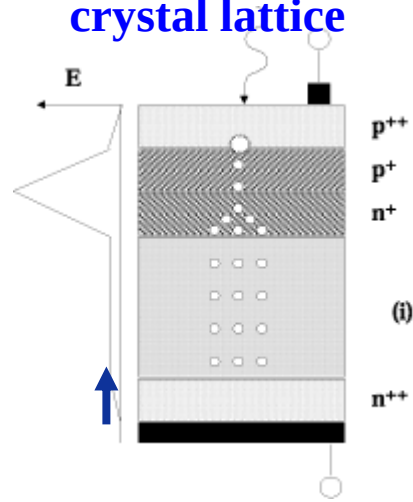


PbWO₄ crystal calorimeter

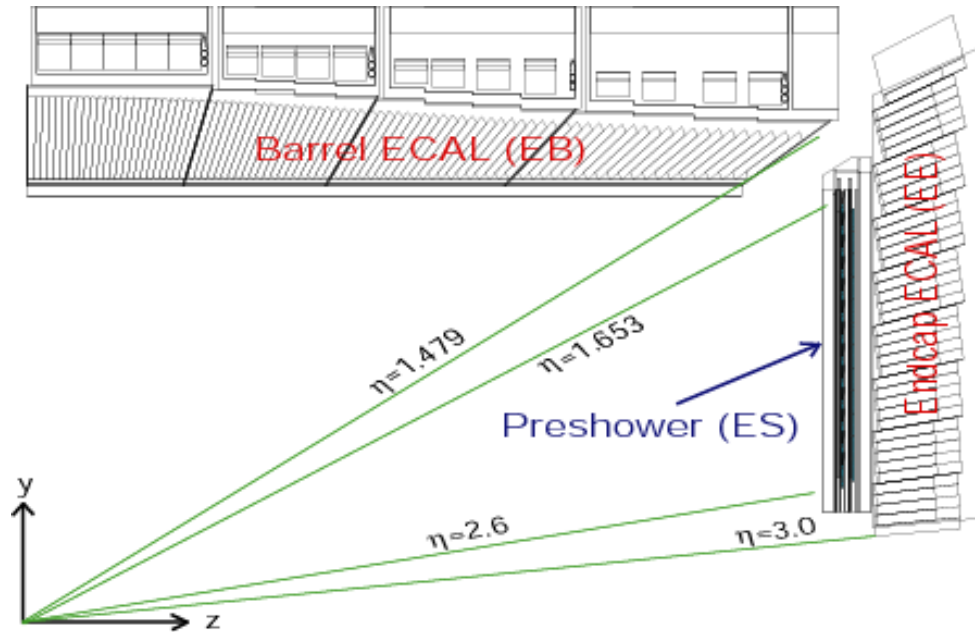
- Over 80K lead tungstate crystal equipped with avalanche photon diodes and associated electronics operating at 4T magnetic field, a time of 25 ns bunch crossing and a radiation dose
 - 10^{13} neutrons/cm² and 1 kGy at $\eta = 0$ to 2×10^{14} neutrons/cm² and 50 kGy for $\eta = 2.6$.
- PbWO₄ calorimeter : short radiation length and Molière radius, fast scintillation.
- Radiation does not have any affect scintillation and uniformity. But, affects the transparency of the crystals through the formation of colour centres due to crystal defects such as oxygen vacancies in the crystal lattice



Linearity of ECAL crystal : One can not get very long crystal, problem with manufacturing as well as nonlinearity due to self absorption, reflections on surfaces.



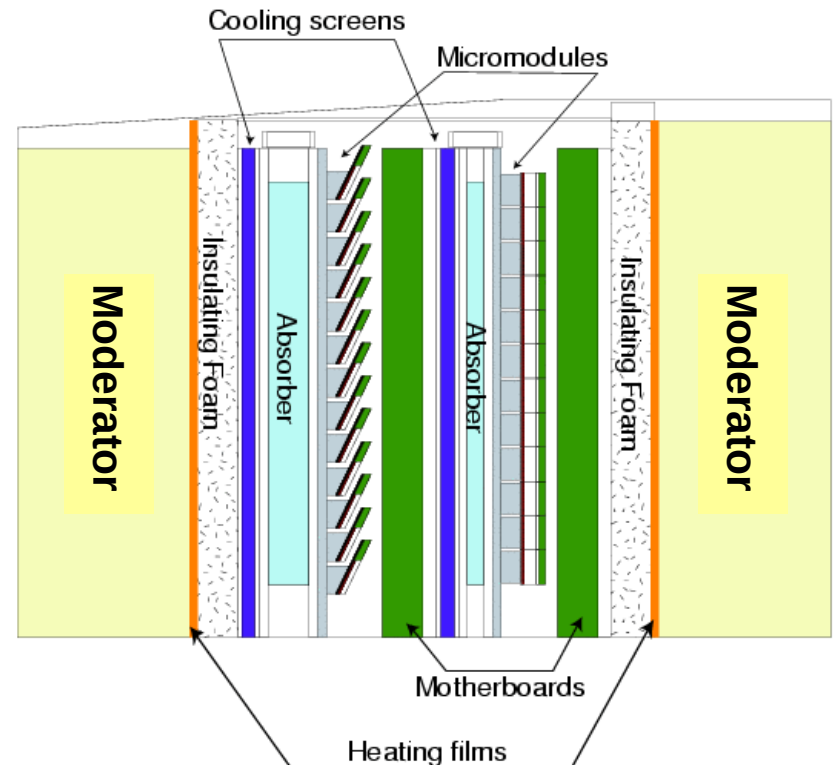
CMS electromagnetic calorimeter



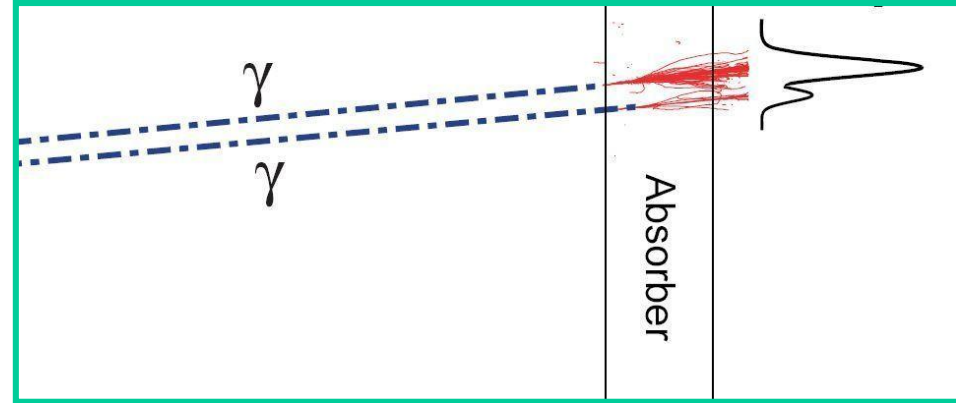
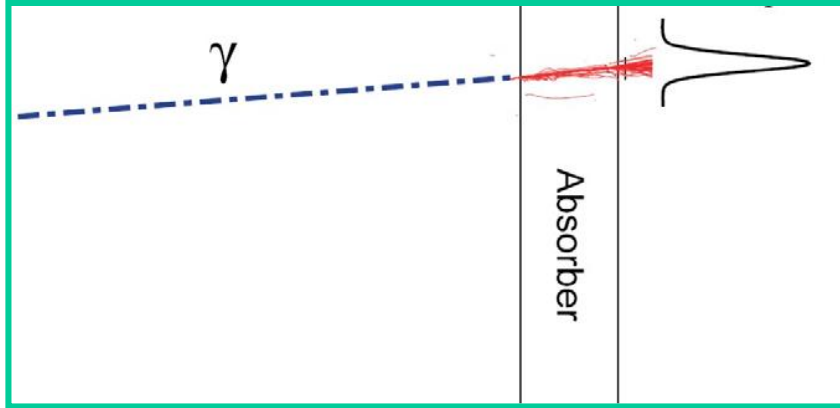
Two lead blocks to start electromagnetic shower at endcap

1.9mm silicon strip pitch allows to determine impact position ($\sim 300 \mu\text{m}$ at 50 GeV), $\Rightarrow$ direction and as well as separation of single shower (γ) and overlaps of two close showers (π^0)

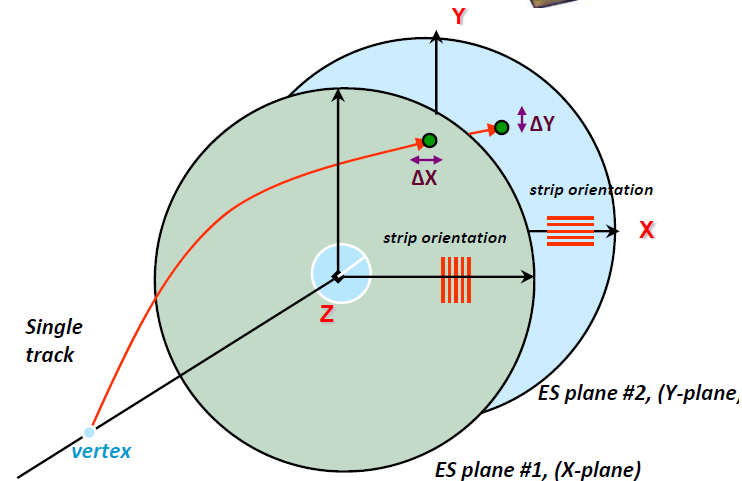
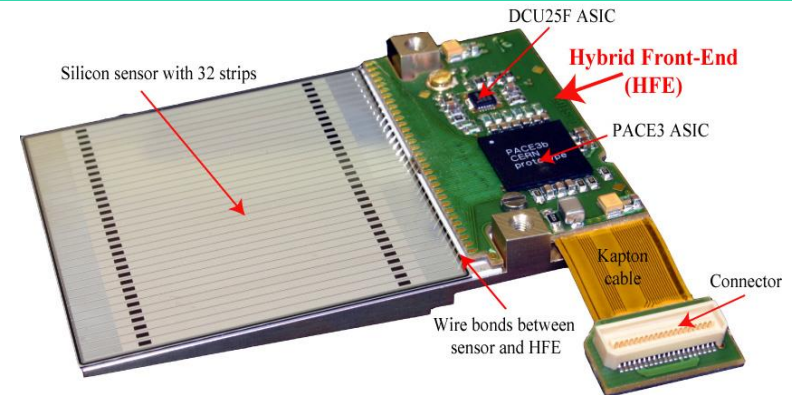
Parameter	Barrel	Endcaps
Coverage	$ \eta < 1.48$	$1.48 < \eta < 3.0$
$\Delta\phi \times \Delta\eta$	0.0175×0.0175	0.0175×0.0175 to 0.05×0.05
Depth in X_0	25.8	24.7
# of crystals	61200	14648
Volume	8.14m^3	2.7m^3
Xtal mass (t)	67.4	22.0



Preshower



- Opening angle of two photon in a decay of 100 GeV π^0 : $\sim 2.7\text{mrad}$, for 3m gap, separation of two photon $\sim 8.1\text{mm}$, whereas Moliere radius is 22mm (for PbWO_4)
- Preshower silicon strip detector will be used for π^0/γ rejection in the ECAL, CMS
- Strips of 1.80 mm width with a pitch of 1.9 mm (whereas crystal size $2.5\text{cm} \times 2.5\text{cm}$ and Moliere radius = 2.2cm)
- Area - $63\text{mm} \times 63\text{mm}$

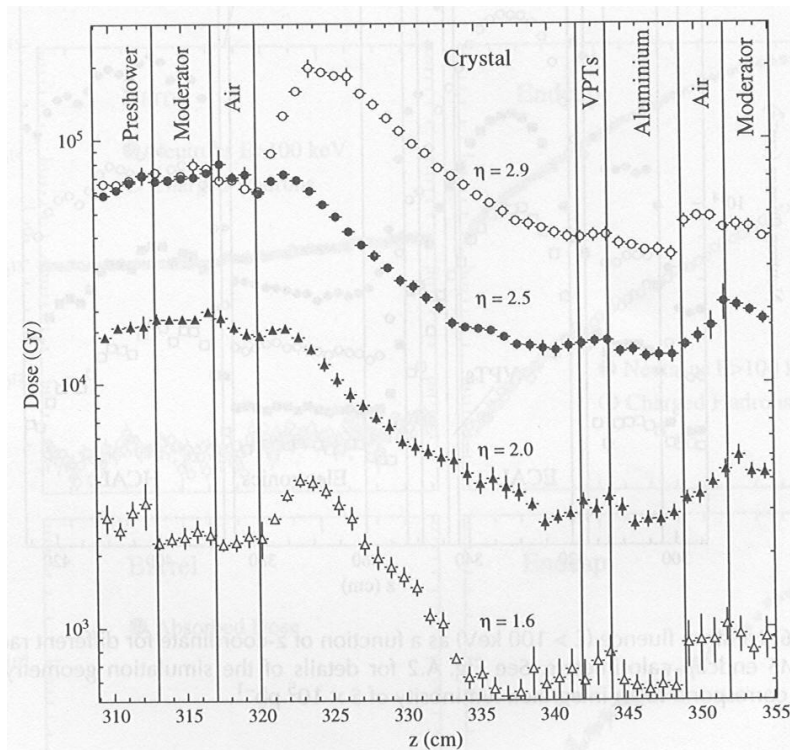


Preshower

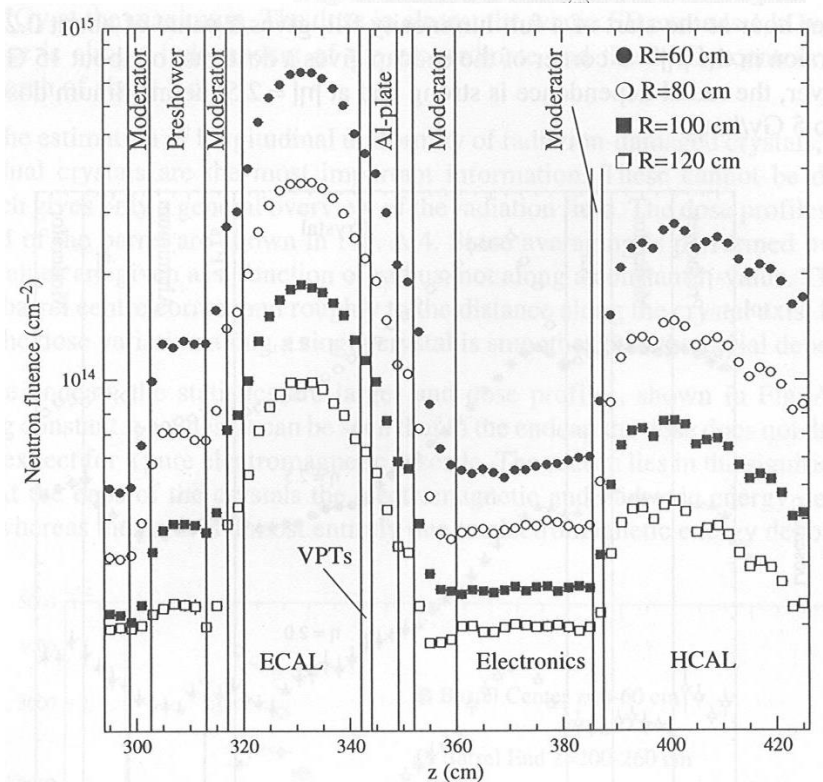
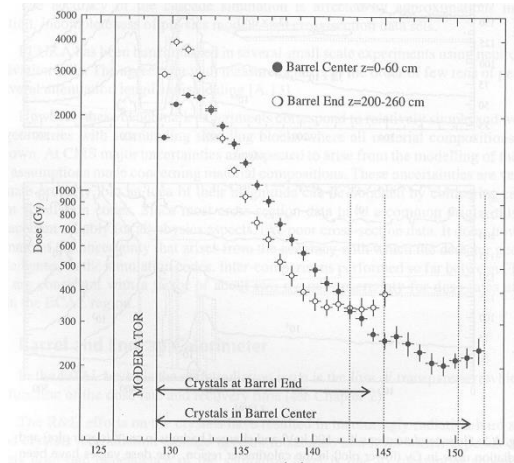
- The preshower acts as a sampling calorimeter
 - Lead Absorber : initiate em showers
 - Silicon sensors : act as energy sampling
- Sampling calorimeter $\Rightarrow$ Poor energy resolution
- High momentum π^0 in forward direction $\rightarrow$ smaller opening angle + Cost $\rightarrow$ Preshower only in endcap region
- An energetic photon, accompanied by a nearby charged hadron/muon in a jet, may be misinterpreted as an electron.
- Can be distinguished in first $1-2X_0$ of calorimeter (Preshower).
 - Three layer in upstream of ECAL
 - **Single gamma** : NO signal in first, several MIPs in next two
 - **A $\pi^0 \rightarrow \gamma\gamma$** : No signal in first, two multiple MIP clusters in next
 - **An electron** : MIP in 1st, and multi-MIP in next
 - **A pion** : MIP in all three layer
- Other than distinguishing electron/photon/pion/ π^0 ,
 - **Angular measurements for photons**
 - **Clean-up of electron sample, by identifying $e + \gamma$ events**

Radiation due to EM shower and reduction of albedo

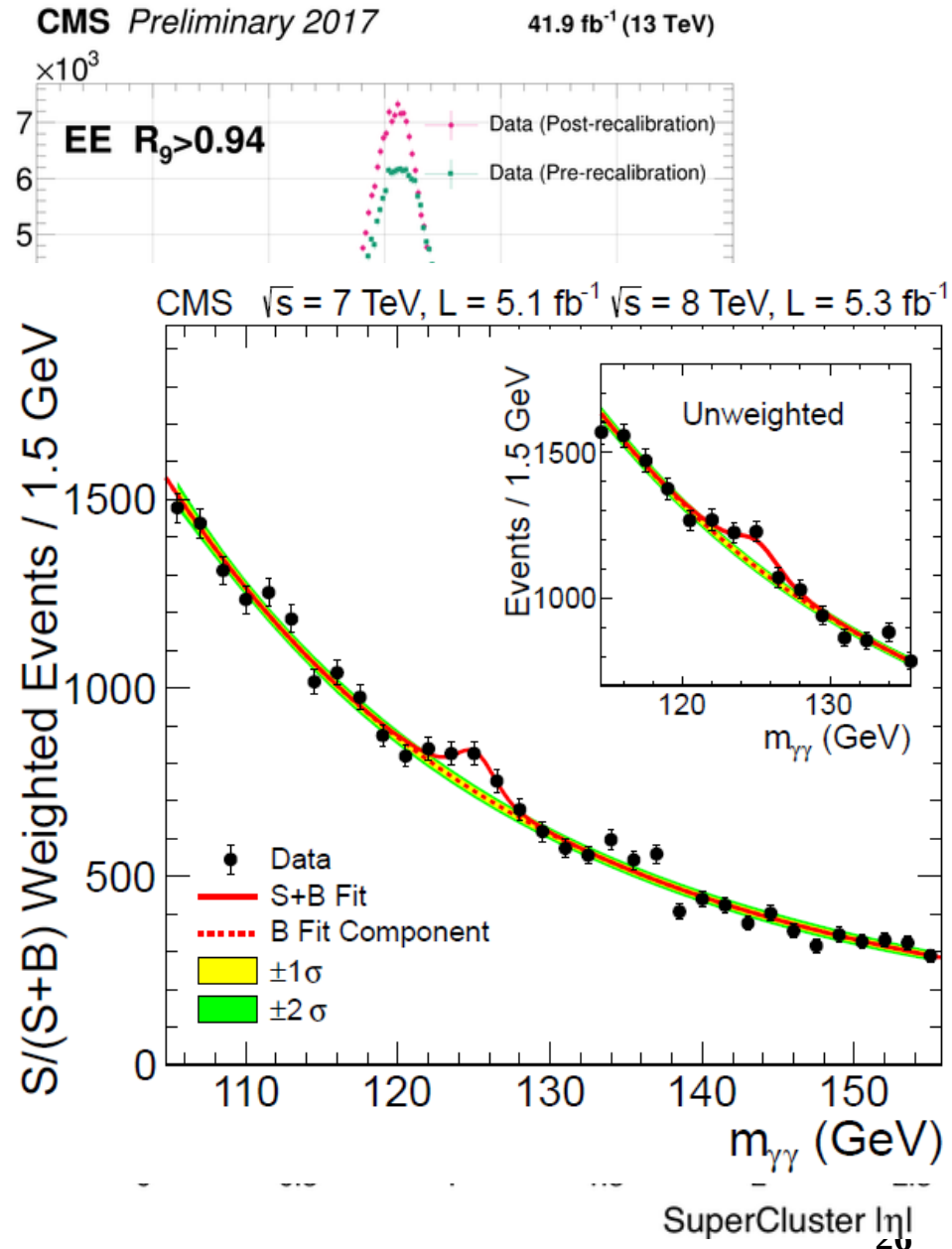
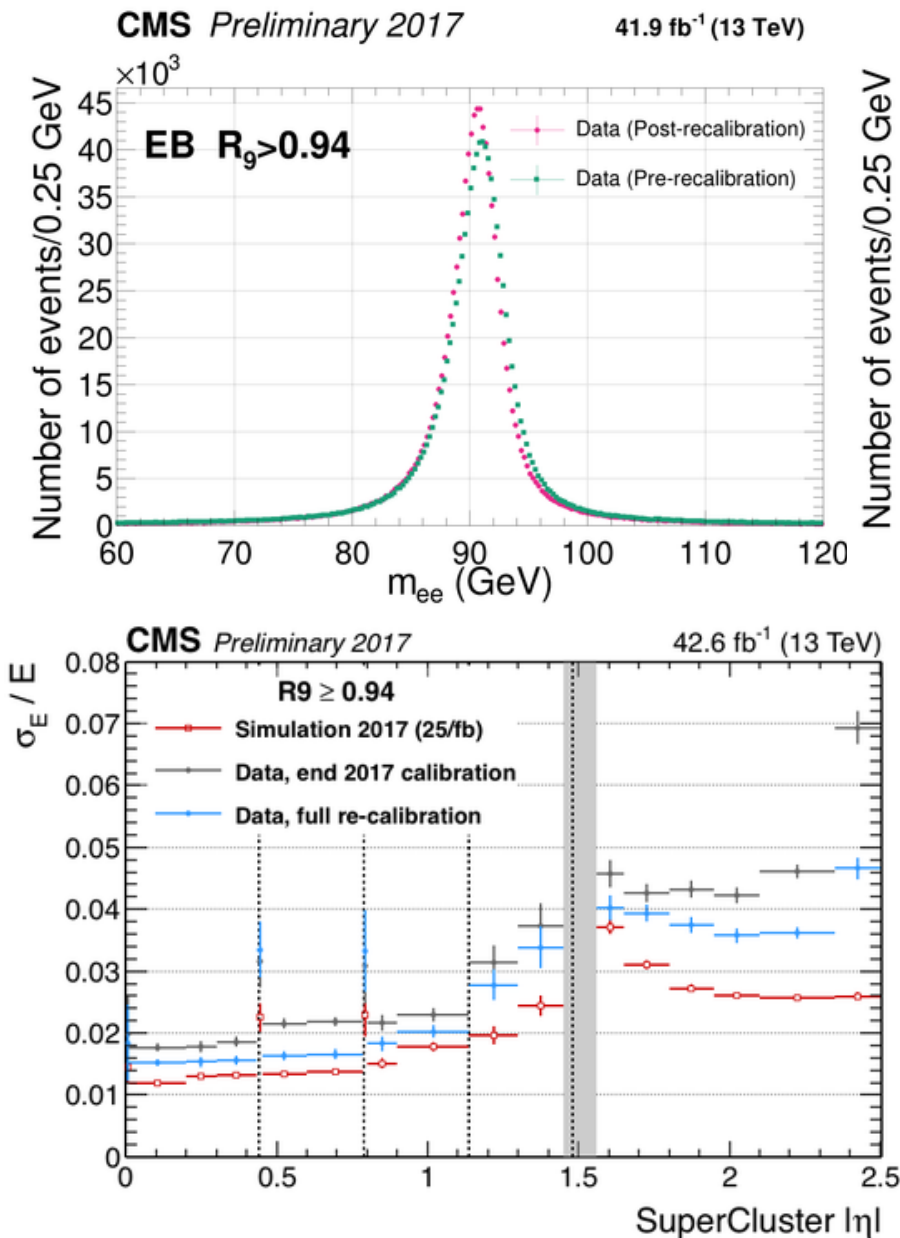
- Radiation/neutron flux due to EM shower can damage silicon preshower/APD and can also produce large damage in tracking chamber
- Use polyethylene moderator to remove neutrino albedo from this EM shower



Vacuum fine-mesh phototriode (VPT)



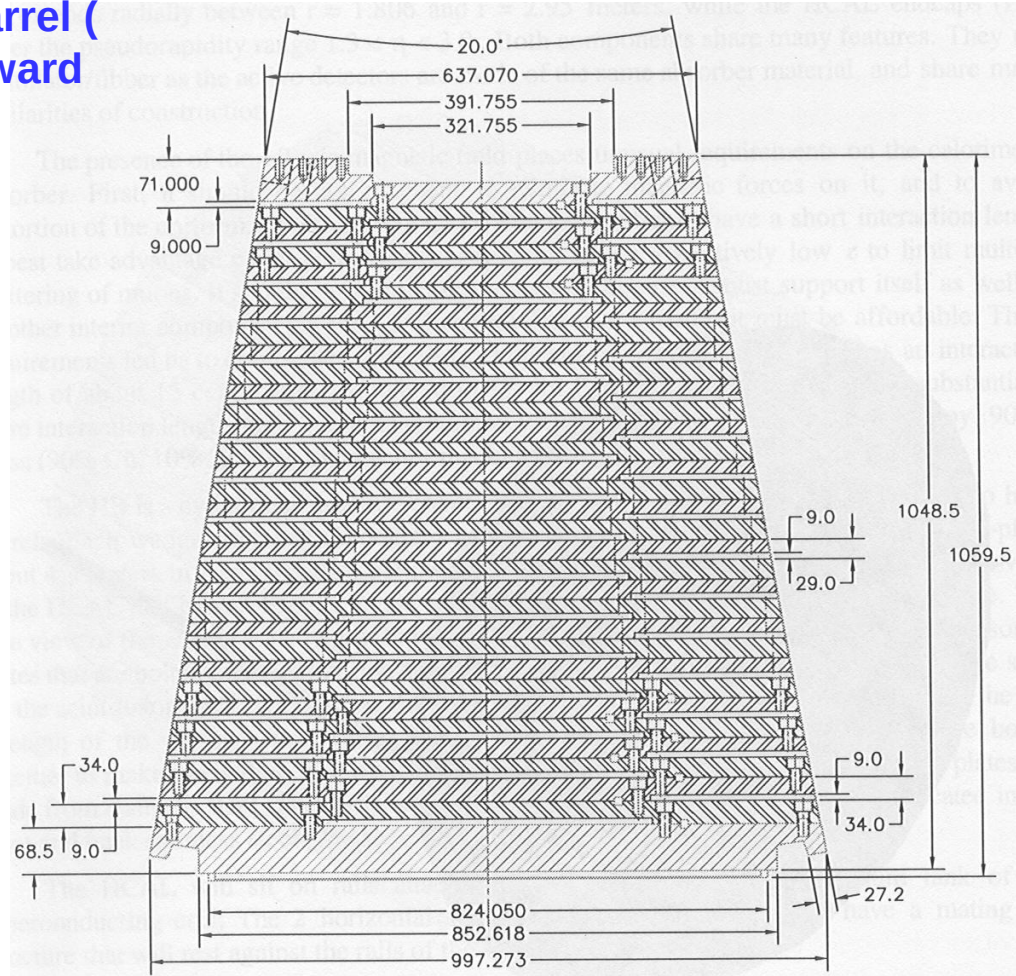
Performances of CMS ECAL



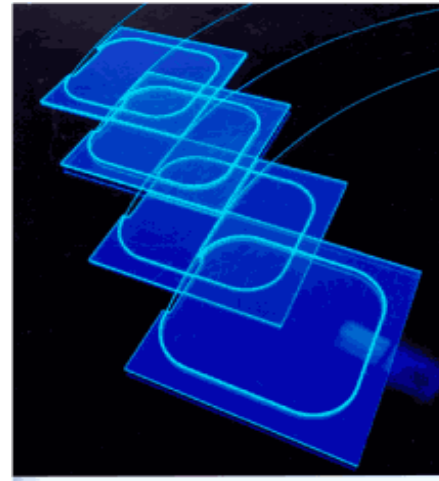
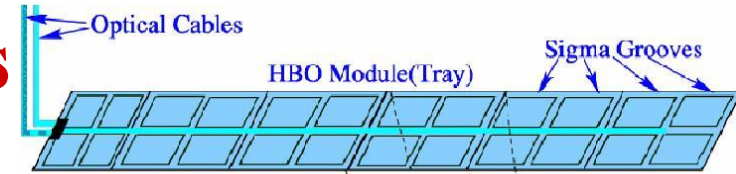
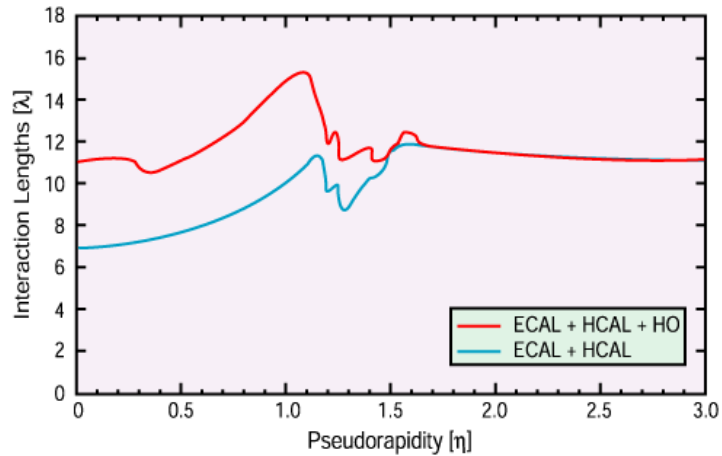
Hadron calorimeter

- Requirement : Identification and measurement of quarks, gluons and neutrinos by measuring the energy and direction of jets and missing transverse energy flow of the events.
 - Good missing energy a hermetic calorimetry coverage to $|\eta| < 5$ is required
- CMS HCAL is constructed in 3 parts: Barrel ($|\eta| < 1.5$), Endcaps ($1.5 < |\eta| < 3.0$) and forward ($3.0 < |\eta| < 5.0$) (~10000 channels in total)

- Barrel HCAL (HB) + Endcap HCAL (HE) 17-18 Brass (laiton) plates (5.0cm thick) interleaved with plastic scintillator (4mm thick) embedded with wavelength-shifting optical fibres.
- Additional scintillation layers (HOB) are placed just outside the magnetic coil $\Rightarrow$ total depth $\sim 11\lambda_{\text{int}}$
- Scintillation light emission $\lambda \sim 410$ -425 nm
- Wave length shifter, peak at $\lambda = 490$
- Megatiles are subdivided into size, $\Delta\eta \times \Delta\Phi = 0.087 \times 0.087$



Reading outs of tower tiles with WLS fibres and HPD's



HCAL Tower

ECAL

Tracker

Layer to Tower Decoding Fiber

HPD in RBX

HPD

RBX

Optical cable

Optical Connector

Clear Fiber

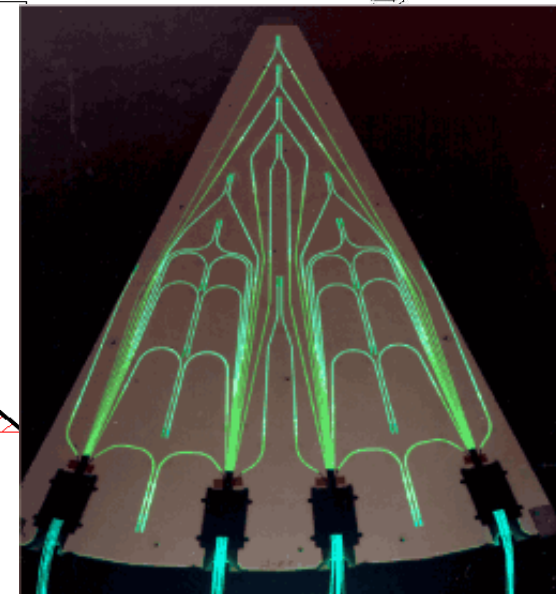
Splice

Mirror

WLS fiber

Tile

4 Tesla Magnetic Field

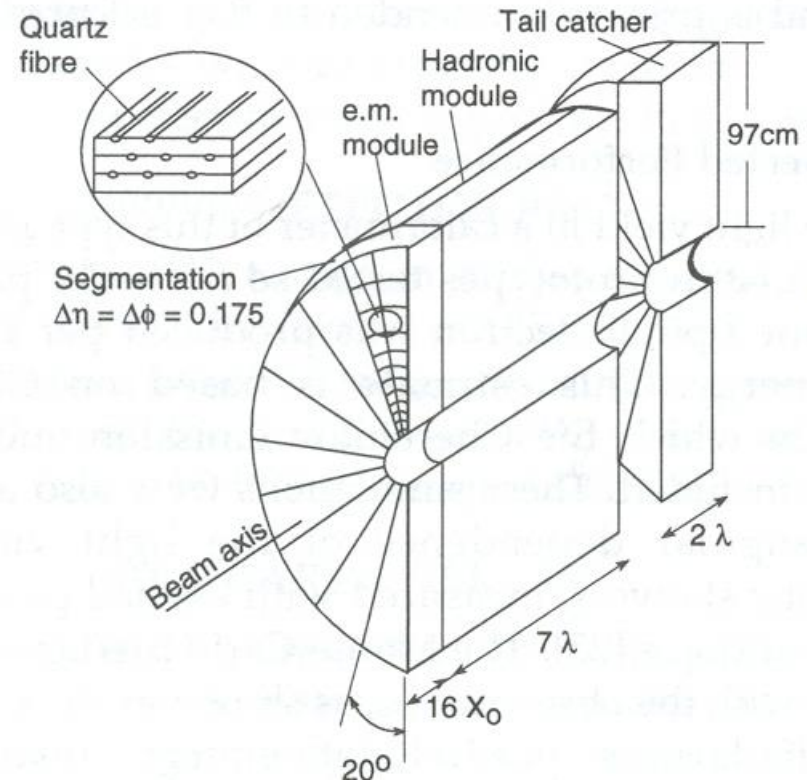


HCAL in construction phase



Forward hadron calorimeter (HF)

- **Passive material** : Steel instead of Cu, because of less activation under irradiation
- **Active material** : radiation resistant quartz fibre ($d=300\mu\text{m}$). Jet energy is measure by the Cherenkov light produced as charged particles passed through the quartz fibre, which is mainly electromagnetic component of showers, consequently good directional information. (~ 100 Mrad at $\eta=5$; 2% loss in 30 Mrad)
- **Signals to PMT, located in radiation shielded zones**
- **Segmentation**
 $\Delta\eta \times \Delta\Phi = 0.175 \times 0.175$



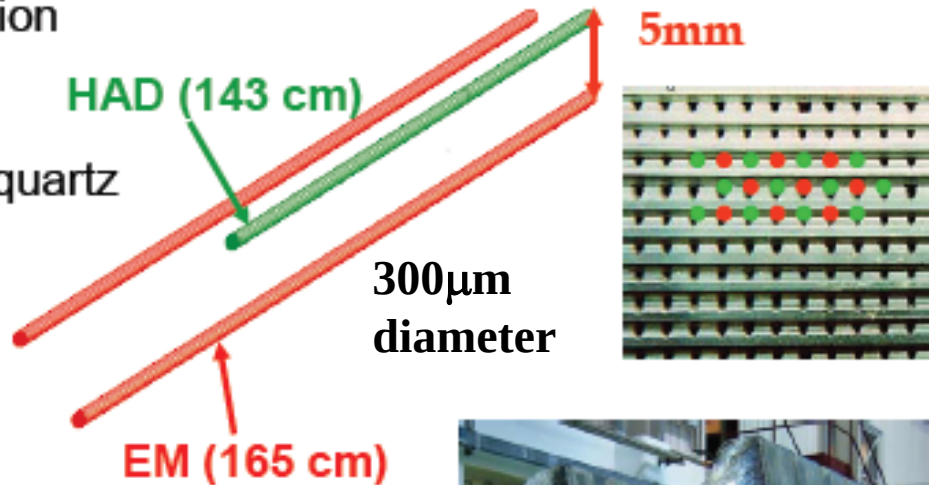
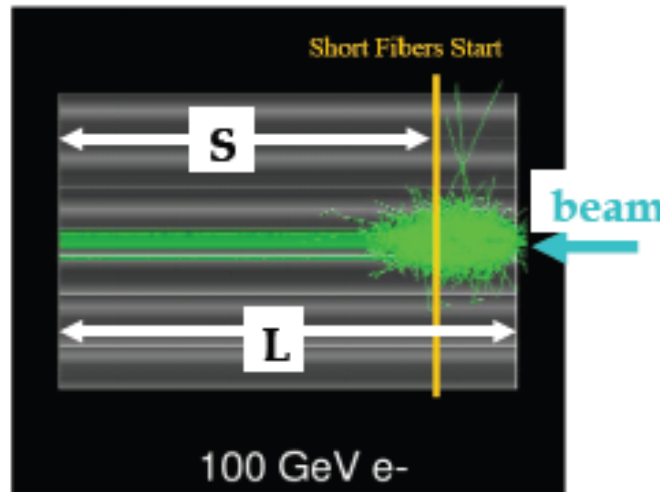
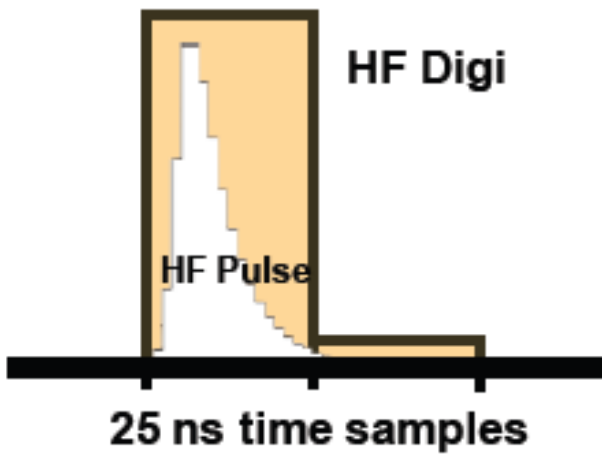
CMS forward calorimeter : Same readout for EM/HAD

HF is located about 11 m from the interaction point, covers $3 < |\eta| < 5$ with depth $10 \lambda_{\text{int}}$

Consists of iron absorber embedded with quartz fibers parallel to the beam direction in a 5x5 mm matrix

Charged particles from showers produce Cherenkov light

HF signal generation and collection is very fast ~ 10 ns

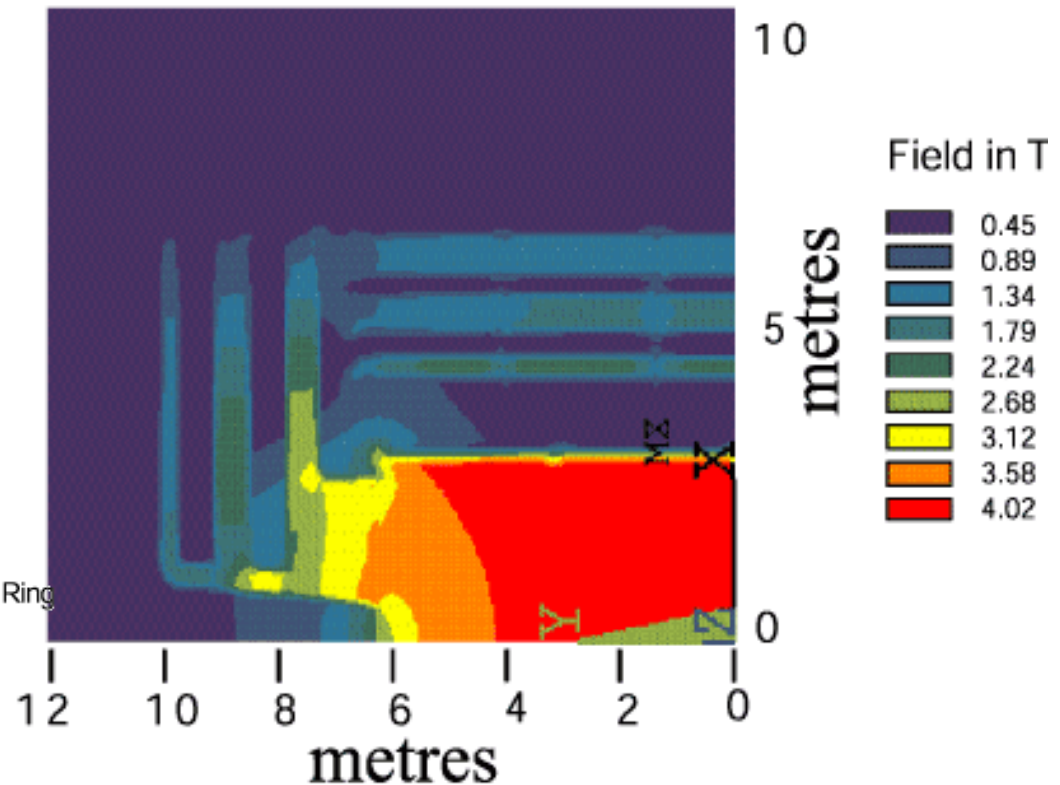
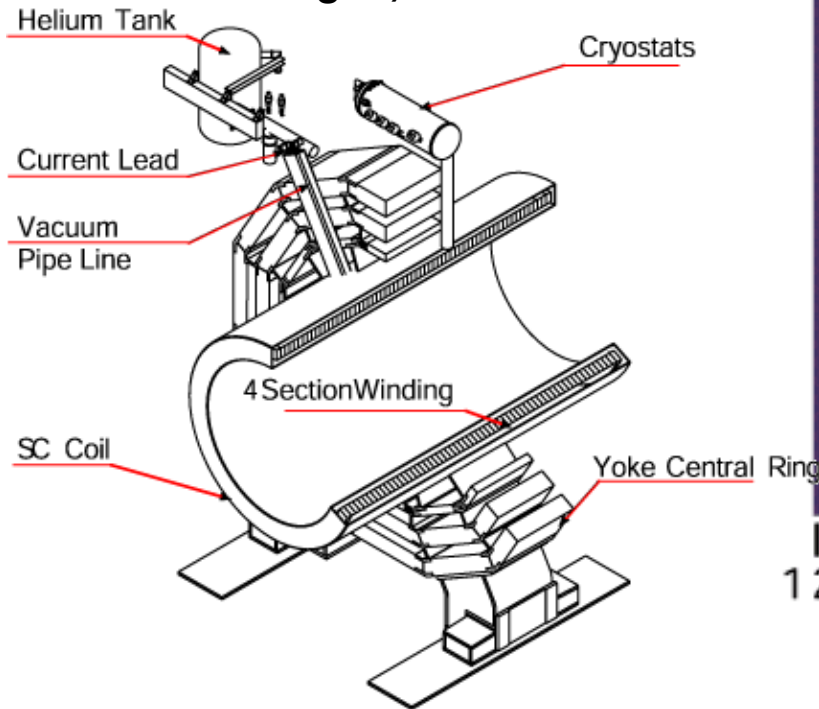


Steel instead of Cu, because of less activation under irradiation (100Mrad in LHC)

Magnet system

- Field : 3.8 Tesla, Diameter : 14m (13m), length : 21.6m (5.9m), weight:12000 tone, stored energy : 2.52 GJ

200 m³ of pressurise
He gas, 5000 lt of LHe



For a similar bending power, the overall size of a solenoid system is smaller than that of a toroidal

4T → 3T ⇒ Occupancy in the inner tracker increases by ~40%, outermost part of the barrel region by ~25%, in contrast it decreases by ~20% in the innermost areas.
4T field deduces particle flux in ECAL

CMS muon chambers

Muon chamber consists of four muon stations interleaved with the iron return yoke plates are placed behind the calorimeters .

The thickness of the absorber between the stations (30 to 75 cm) also prevents station-to-station correlations due to high energy muon radiation.

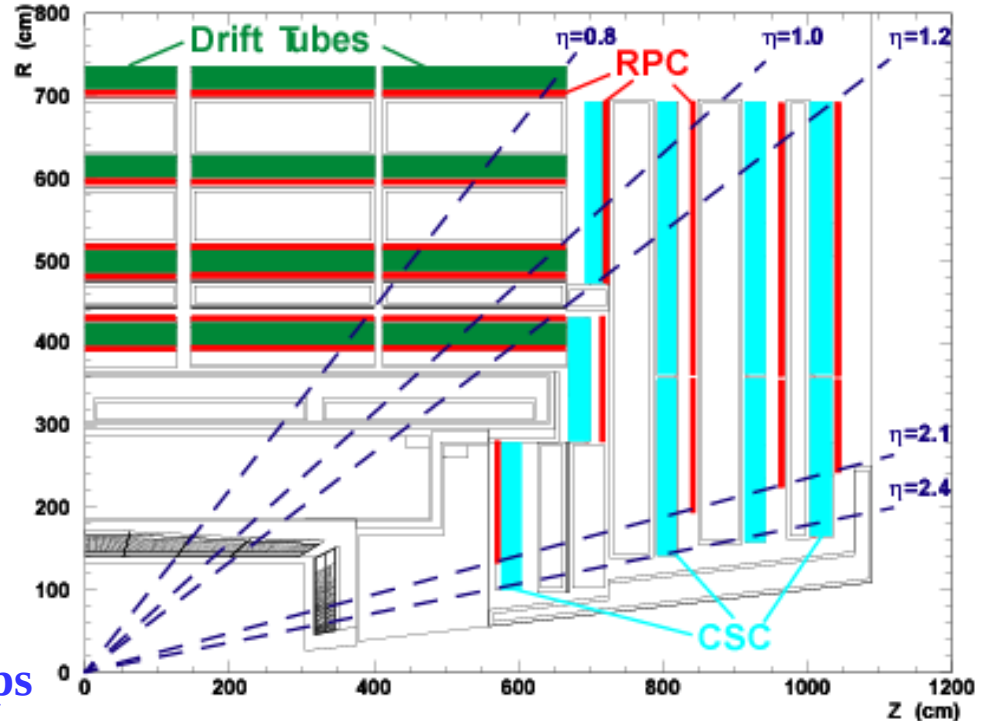
Position measurement:

Drift Tubes (DT) in barrel

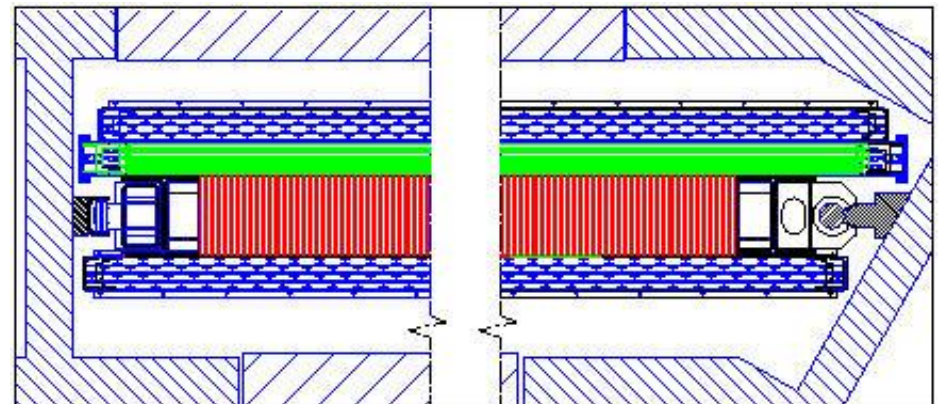
Cathode Strip Chambers (CSC) in endcaps

Trigger:

Resistive Plate Chambers (RPCs) in barrel and endcaps



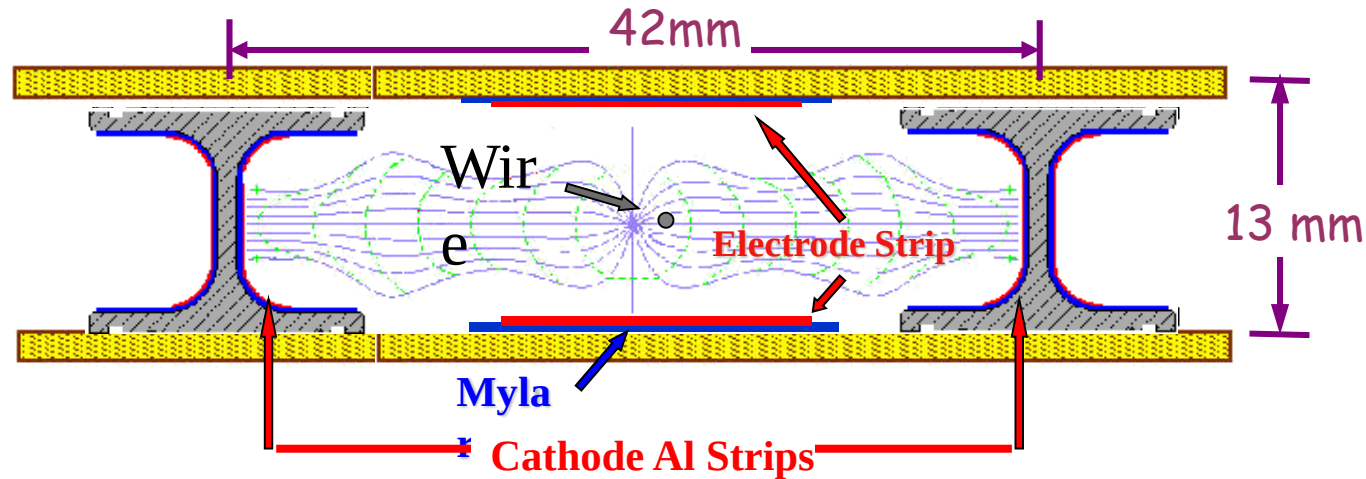
Drift Tube



195000 DT channels
210816 CSC channels
162282 RPC channels

4 Φ SL
4 η SL
Honeycomb
4 Φ SL

Characteristics of drift chamber



GAS: Ar/CO₂ (85/15)
HV: Wires 3600 V
 Strips 1800 V
 I-beams -1800 V

Tmax: < 400 ns
Drift Velocity : ~ 5.25cm/μs
Single Wire
Resolution : < 300 μm

100μm Φ
 150μm θ

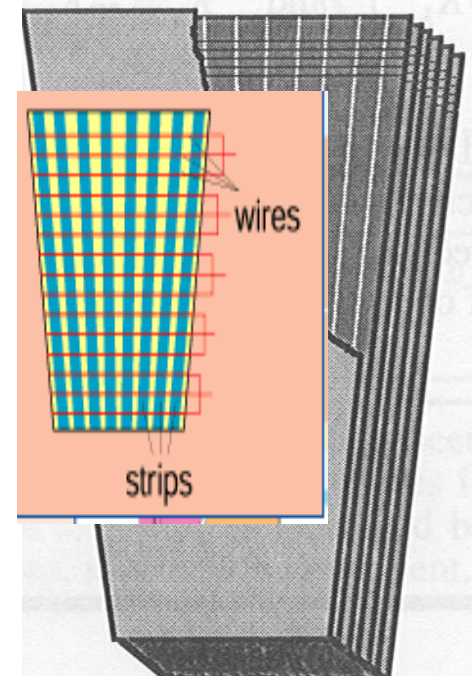
long drift time tubes are cheaper than MWPC, but more sensitive to magnetic field, delta rays and e.m.showers

use of cool gas (Ar/CO₂), accurate field shaping (4 electrodes), many staggered layers
 redundancy generates robustness against neutron and e.m. background

and allow prompt measurement of time , position and angle of passage of a track for MU trigger

Cathode strip chambers

- Magnetic field is very intense (up to several tesla) and very inhomogeneous.
- Two co-ordinates are available by the simultaneous and independent detection of the signal induced by the same track on the wires and on the strips (six plane chamber).
- Strip width = 3 - 16 mm, anode wire gap = 3.12 mm, chamber gap 9.5mm, 50 μm Au-tungsten with tension 350g, Gas mixing : Ar-CO₂-CF₄ (30 % - 50 % - 20%)



468 CSCs

140K Anode channels

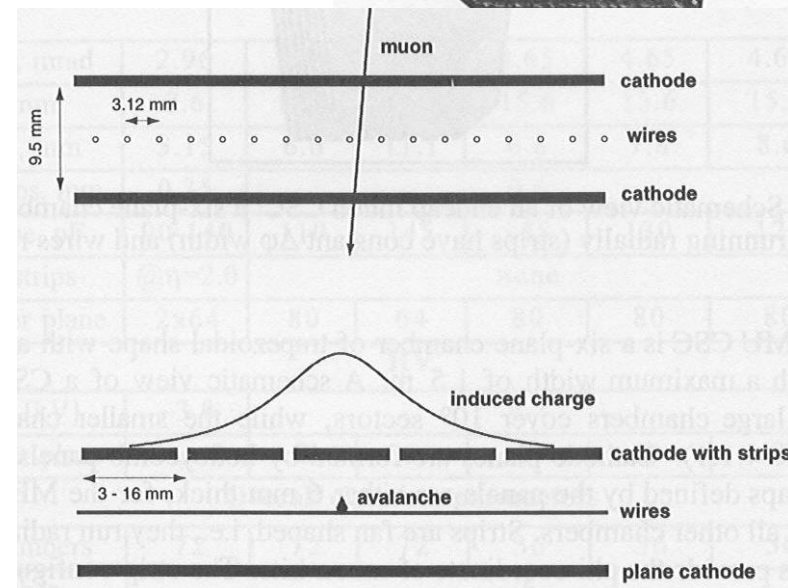
170K Cathode channels

360 10⁰ CSCs

- 3/2 : 144 Large CSCs (3.4x1.5 m²):
- 1/2/3 : 216 Small CSCs (1.8x1.1 m²):
- **108** (1/2/3) : 20⁰ CSCs (1.9x1.5 m²):
- Frontend Electronics:

~2,000,000 wires

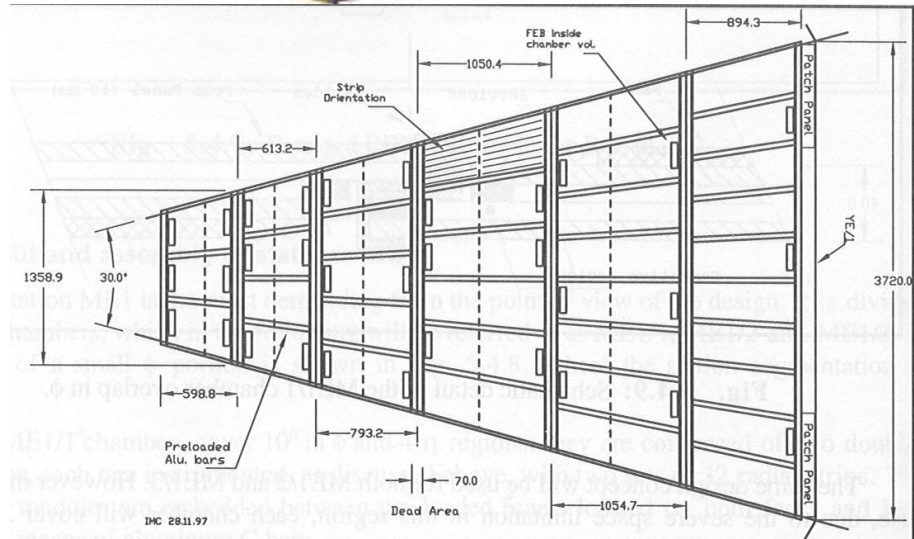
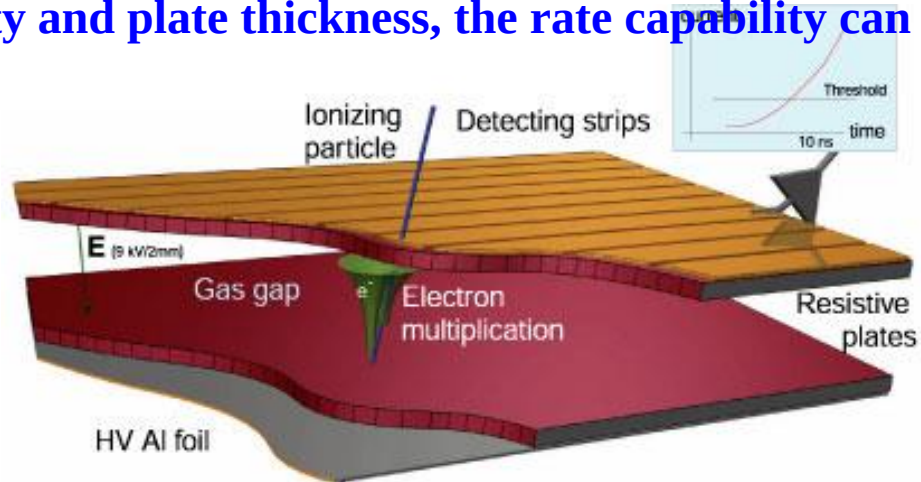
~6,000 m² sensitive area



precision(trigger) $\delta r_\phi \sim 1 \text{ mm}$, $\delta r \sim 1 \text{ cm}$, $\delta t \sim 4 \text{ ns}$, (offline) $\delta r_\phi \sim 100 \mu\text{m}$

Resistive plate chamber

- High gas gain without developing streamer/spark
- The strips are oriented parallel to the tubes in the barrel (one RPC layer in station 3 and 4 and two in 1 and 2) and to the radial strips in endcap CSCs. The pattern of hit strips gives a measure of muon momentum $\Rightarrow$ trigger.
- With proper choice of the resistivity and plate thickness, the rate capability can reach several thousand Hz/cm².
- C₂H₂F₄ – i-C₄H₁₀ (95.5% - 4.5%)
- Efficiency ~100% at 8.5 kV
- Timing resolution = 1.7 ns
- $6\eta \times (36 - 120) \Phi$ (endcap)
- $5/16$ degrees in Φ (barrel)

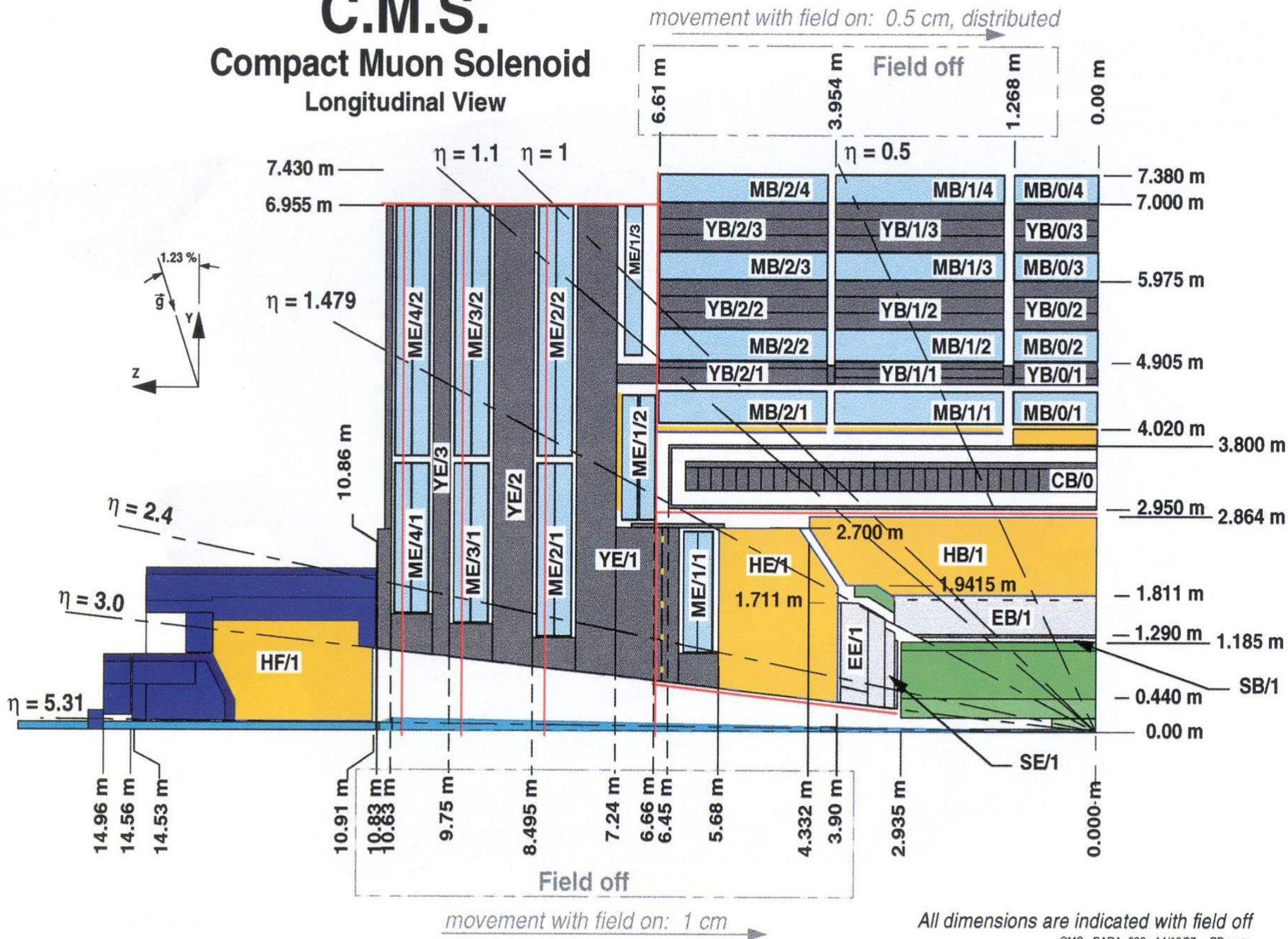


Rejection of backgrounds, which arise from hadronic punch through, debris from muon interactions with matter, thermal neutrons, beam halo in the forward direction, noise in the electronics etc

C.M.S.

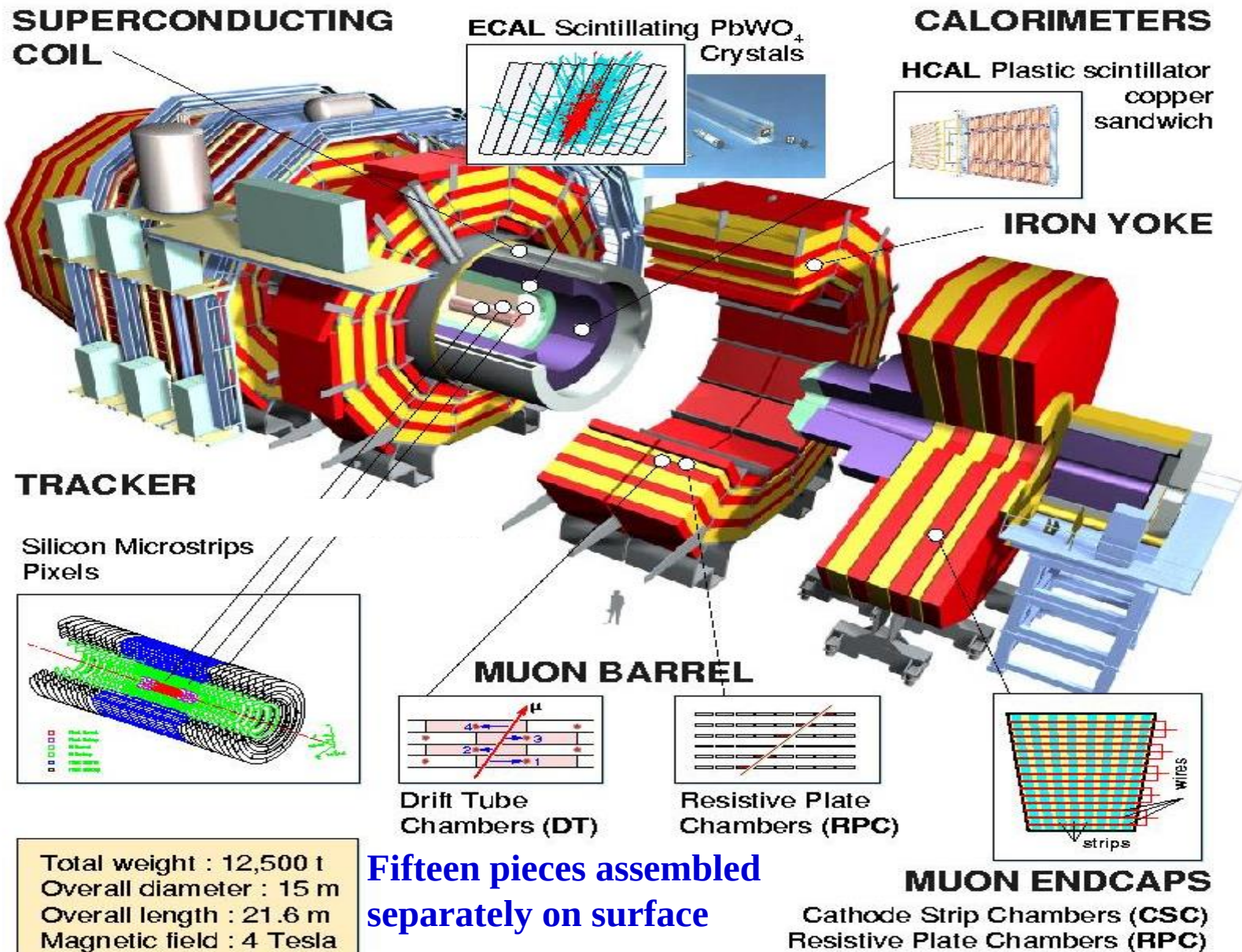
Compact Muon Solenoid

Longitudinal View

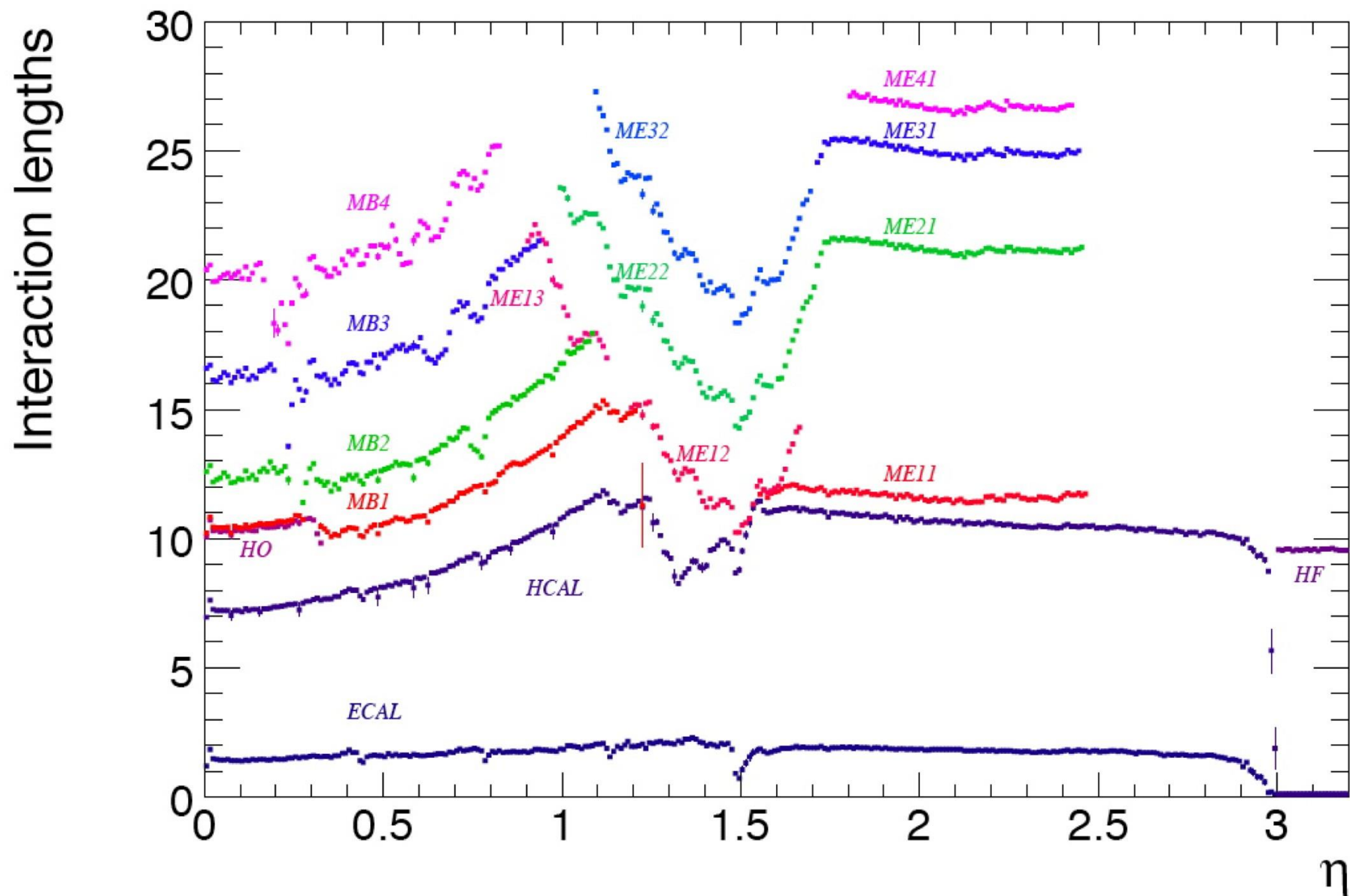


All dimensions are indicated with field off

CMS, a large complicated detector



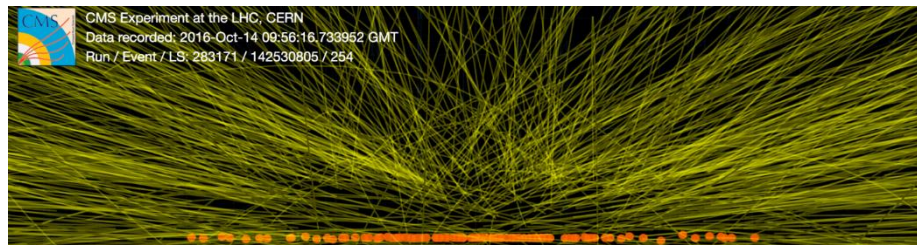
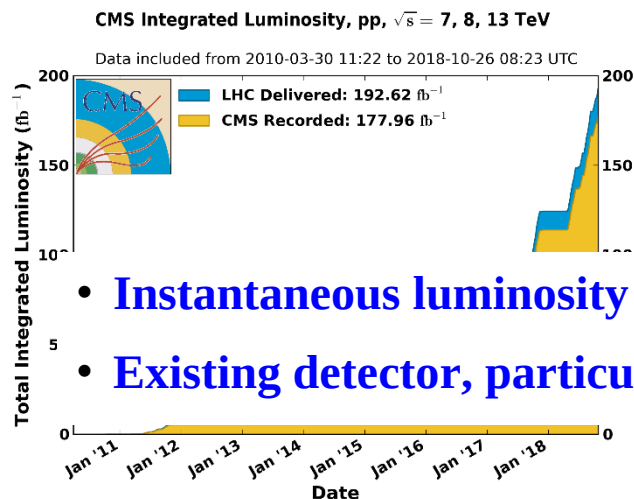
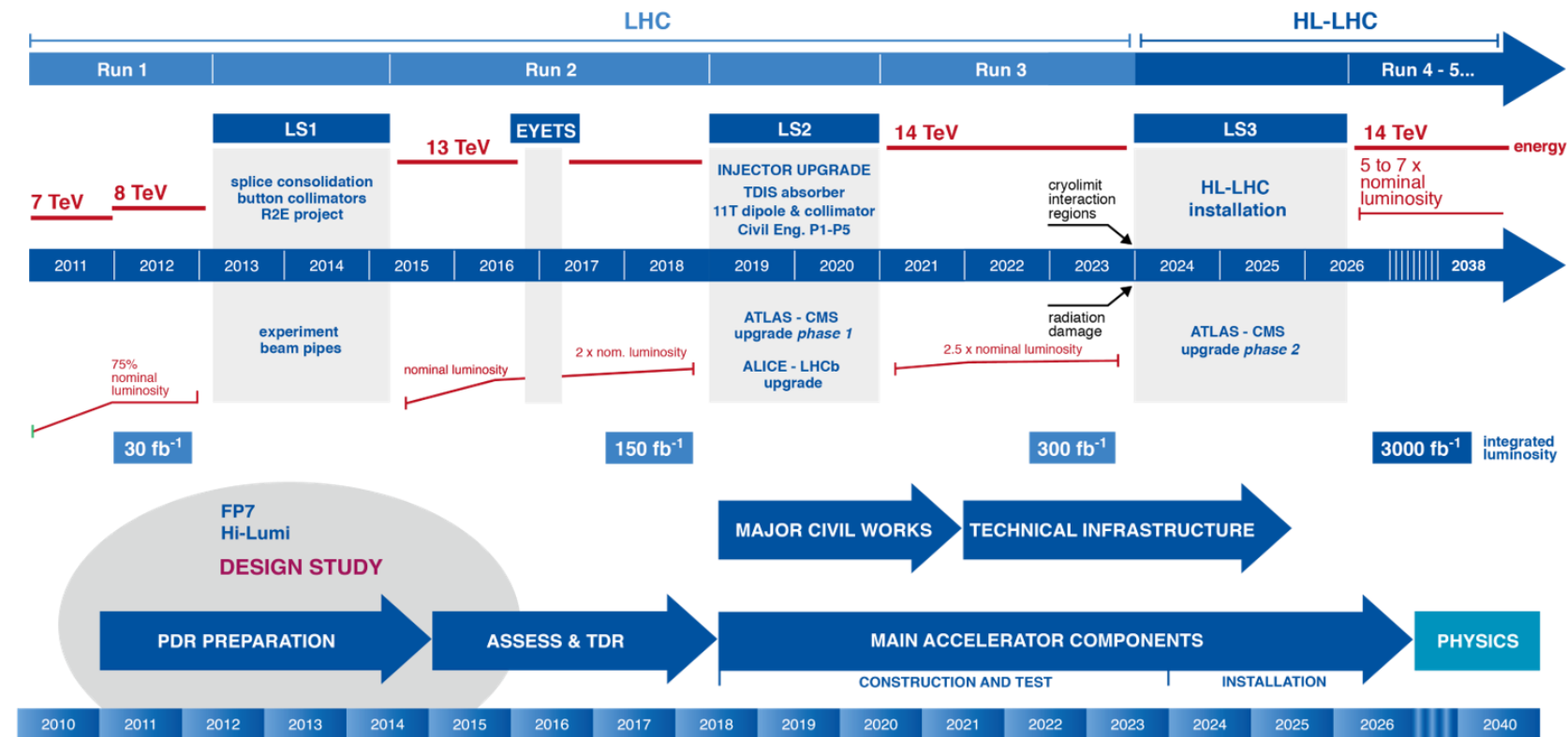
CMS design to reality



Chronological steps towards Large Hadron Collider

- 1983 : $Z^0/W^\pm$ discovered at SPPS proton-antiproton collider. - S. Myers and W. Schnell proposed twin-ring pp collider in LEP tunnel
- 1984 : Workshop in Lausanne on installing a Large Hadron Collider (LHC) in the LEP tunnel
- 1987 : CERN's long-range planning committee chaired by Carlo Rubbia recommended LHC as the right choice for lab's future
- 1989 : ECFA Study Week on instrumentation technology for a high-luminosity hadron collider; Barcelona; LEP starts operation, injection 14th July, collision 13th Aug
- 1990 : ECFA LHC workshop, Aachen
- 1992 : General meeting on LHC physics and detectors, Evian-les-Bains
- 1993 : Letters of intent for LHC detectors submitted : SSC termination
- 1994 : Technical proposals for ATLAS and CMS approved
- 1998 : Construction begins
- 2000 : CMS assembly begins above ground; LEP collider closes
- 2003 : ATLAS underground cavern completed and assembly started
- 2004 : CMS cavern completed
- 2007 : Experiments ready for beam
- 2008 : First proton beam in LHC tunnel
- 2009 : First proton-proton collisions
- 2010 : First physics results
- 2011- : Exploring Higgs- BSM....
- 2012 : Discovery of Higgs

LHC/HL-LHC Plan

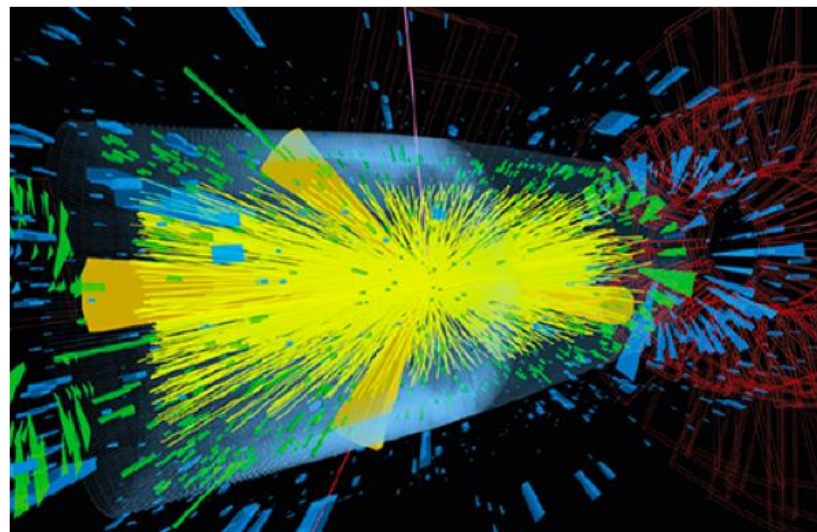
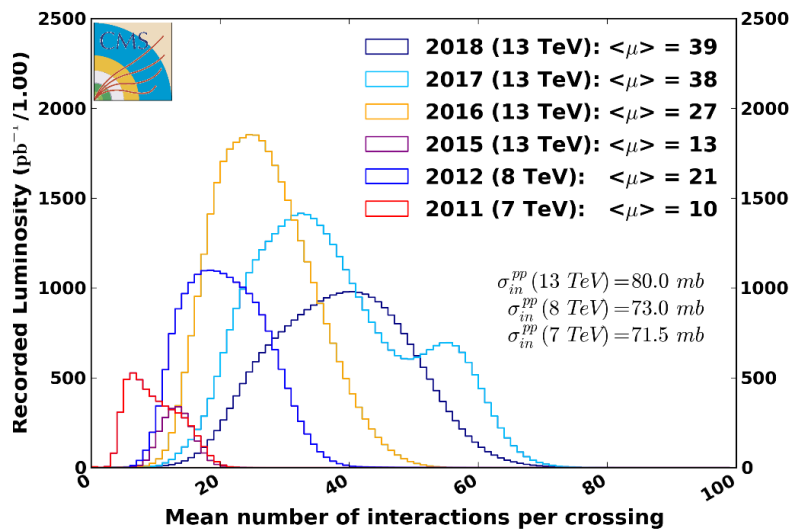


- Instantaneous luminosity will go up to $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, Pileup up to 140
- Existing detector, particularly endcap part is not able to cope with this high PU

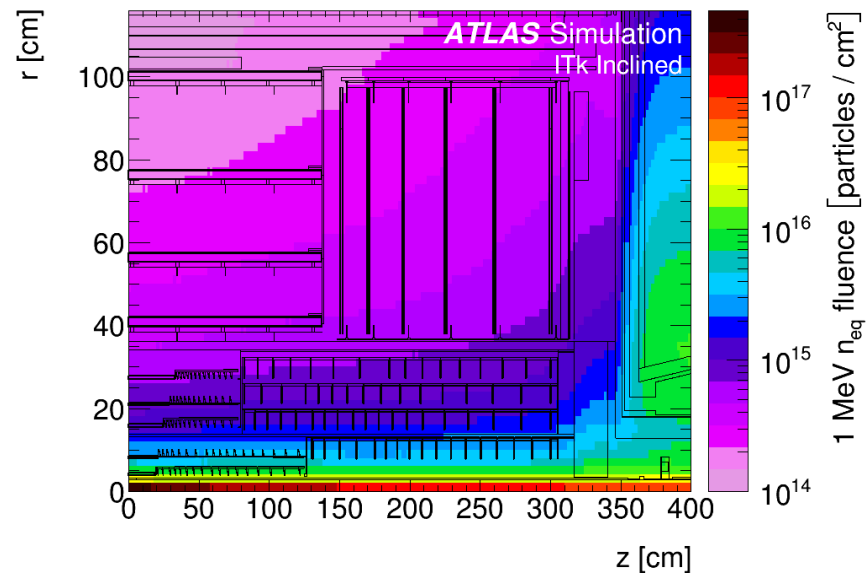
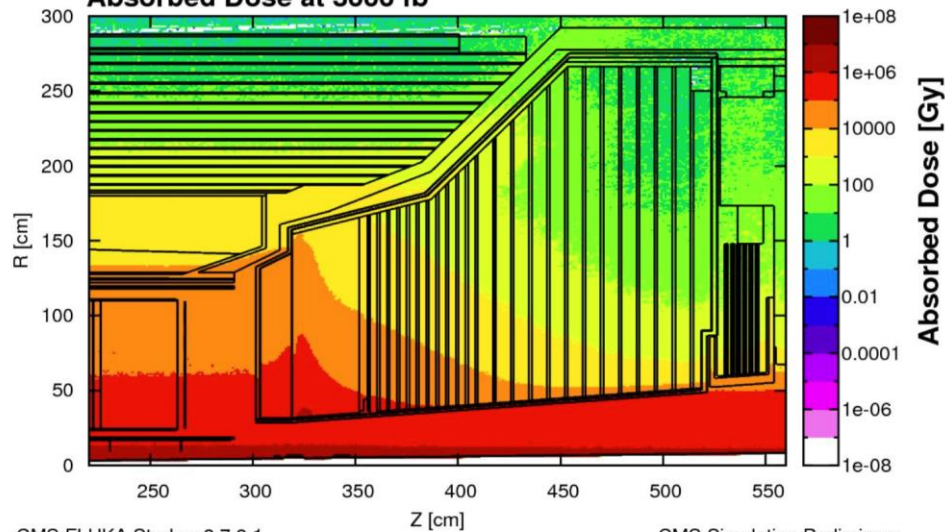


Pileup and radiation dose

CMS Average Pileup



CMS p-p collisions at 7 TeV per beam
Absorbed Dose at 3000 fb^{-1}



CMS Upgrade Program

LS1 consolidation: Complete detector & consolidate operation for nominal LHC beam conditions $\sim 13 \text{ TeV}$, $1 \times \text{Hz/cm}^2$, $\langle \text{PU} \rangle \sim 25$

- Complete Muon system (4th endcap station), improve RO of CSC ME1/1 & DTs
- Replace HCAL HF and HO photo-detectors and HF backend electronics
- Tracker operation at -20°C
- Prepare and install slices of Phase 1 upgrades

Phase 1 upgrades: Prepare detector for $1.6 \times 10^{34} \text{ Hz/cm}^2$, $\langle \text{PU} \rangle \sim 40$, and up to 200 fb^{-1} by LS2, and $2.5 \times 10^{34} \text{ Hz/cm}^2$, $\langle \text{PU} \rangle \sim 60$, up to 500 fb^{-1} by LS3

- New L1-trigger systems (Calorimeter - Muons - Global)
- New Pixel detector (ready for installation in 2016/17 Year End Technical Stop)
- HCAL upgrade: photodetectors and electronics (HF 2015/16 YETS, HB/HE LS2)

Phase 2 upgrades: $\gtrsim 5 \times 10^{34} \text{ Hz/cm}^2$ luminosity leveled, $\langle \text{PU} \rangle \sim 128$ (simulate 140), reach total of 3000 fb^{-1} in ~ 10 yrs operation

- Replace detector systems whose performance is significantly degrading due to radiation damage
- Maintain physics performance at this very high PU

LS1
2013-14

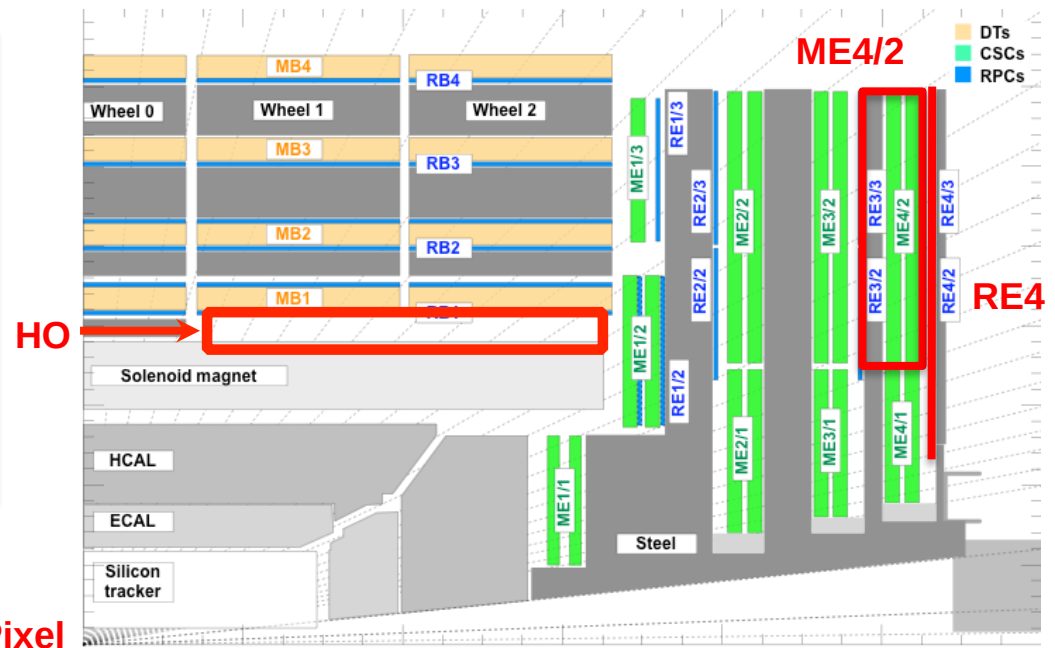
LS2
2018

LS3
2022-23

CMS upgrade program

LS1 Projects

- Complete Muon coverage (ME,RE4)
- Improve muon operation, DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD→SiPMs)
- DAQ1→DAQ2



Phase 1 Upgrades

- New Pixel detector, HCAL electronics and L1-Trigger upgrade
- GEMs for forward muon det. under review
- Preparatory work during LS1
 - New beam pipe for pixel upgrade
 - Install test slices of pixel, HCAL, L1-trigger
 - Install ECAL optical splitters for L1-trigger

Phase 2: being defined now

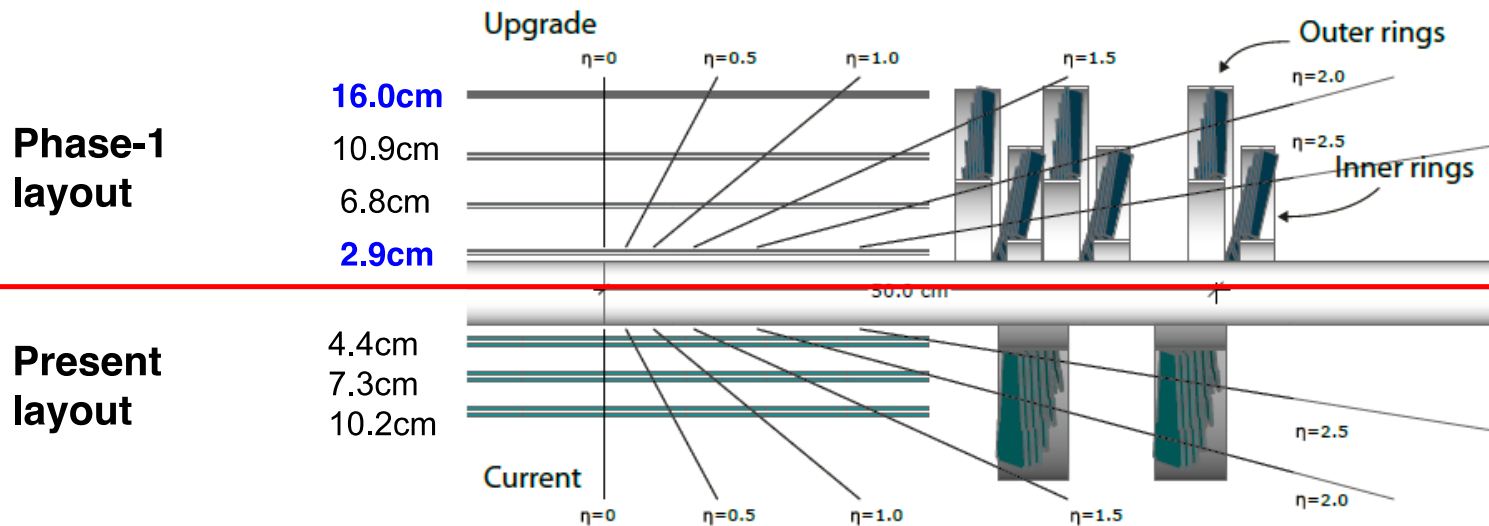
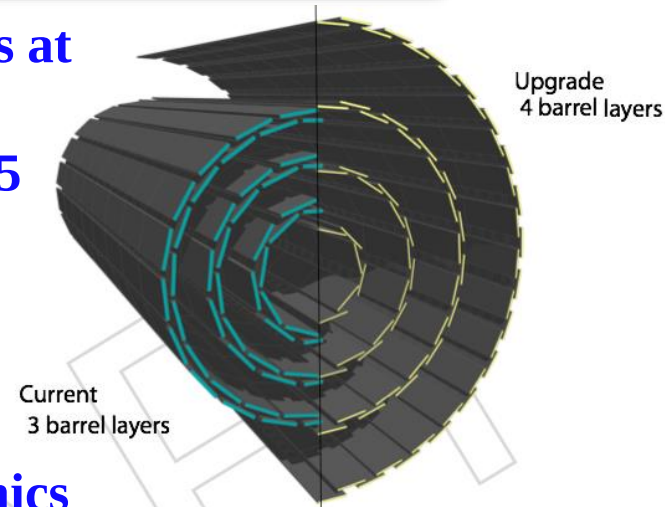
- Tracker replacement, L1 Track-Trigger
- Forward: calorimetry, muons and tracking
- High precision timing for PU mitigation
- Further Trigger upgrade
- Further DAQ upgrade

Medium term (LS1 to LS2): pixel

Install in YET 2016-17

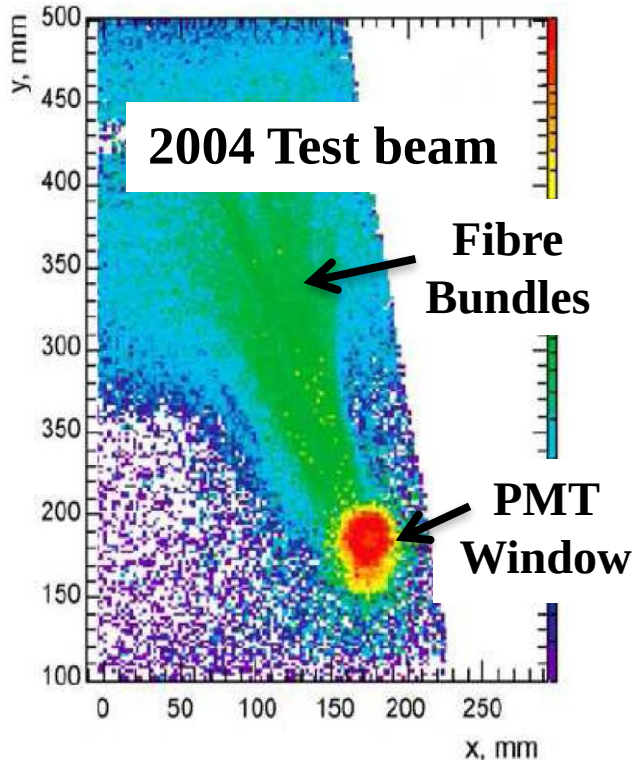
Features of New Design

- Robust design: 4 barrel layers and 3 endcap disks at each end (124M channel from 66M)
- Four hit coverage in whole tracking range, $|\eta| < 2.5$
- Smaller inner radius (44mm $\rightarrow$ 29mm) (new beampipe), large outer
- New readout chip with expanded buffers, embedded digitization and high speed data link
- Reduced mass with 2-phase CO₂ cooling, electronics moved to high eta, DC-DC converters



Upgrade of CMS Forward HCAL

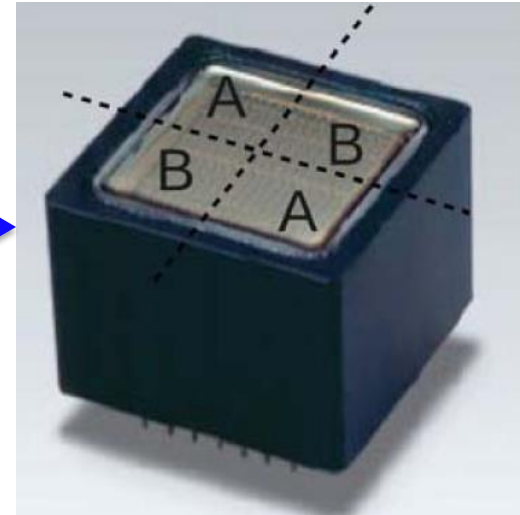
HCAL: HF



- Appear in one channel
- In time with collisions
- Caused by C^ν light by particles going through PMT glass

LS1 : Single anode PMT to multi-anode PMT

- Thins glass window (effect of Cherenkov light is 25%)
- Metal envelope (remove Cherenkov from side)
- Increase in Quantum efficiency

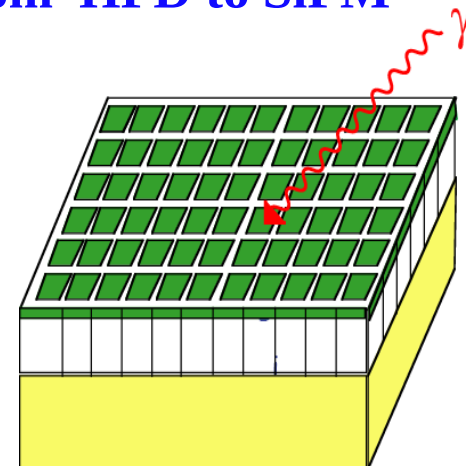
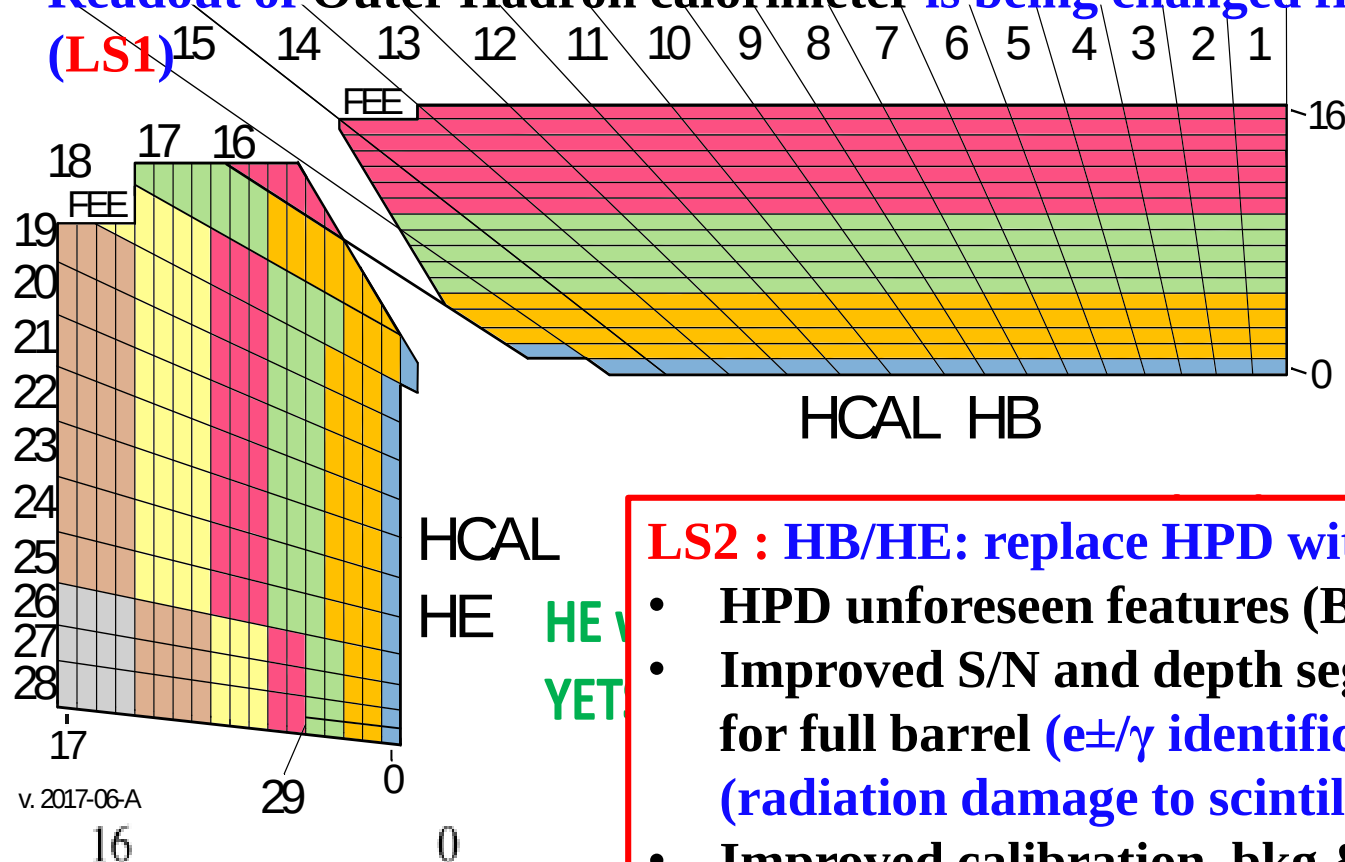


New Back-Ends (microTCA etc)

Near future upgrade plan of CMS central HCAL

Readout of Outer Hadron calorimeter is being changed from HPD to SiPM

(LS1)



LS2 : HB/HE: replace HPD with SiPMs

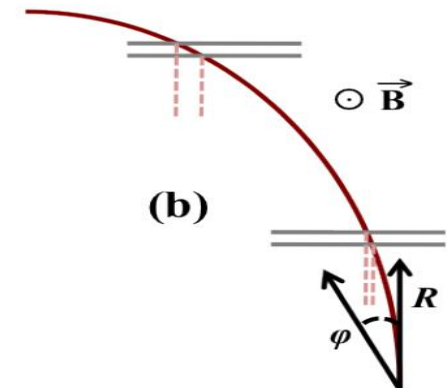
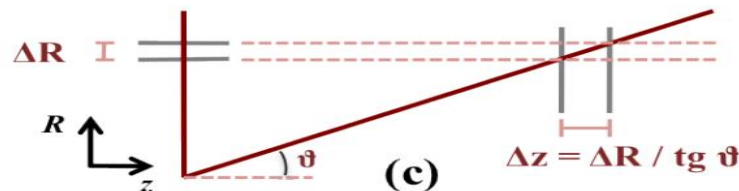
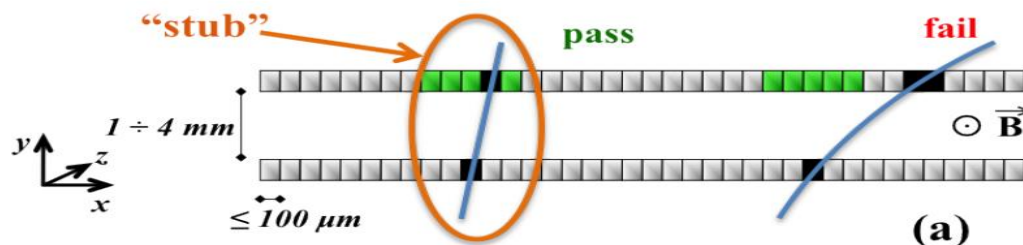
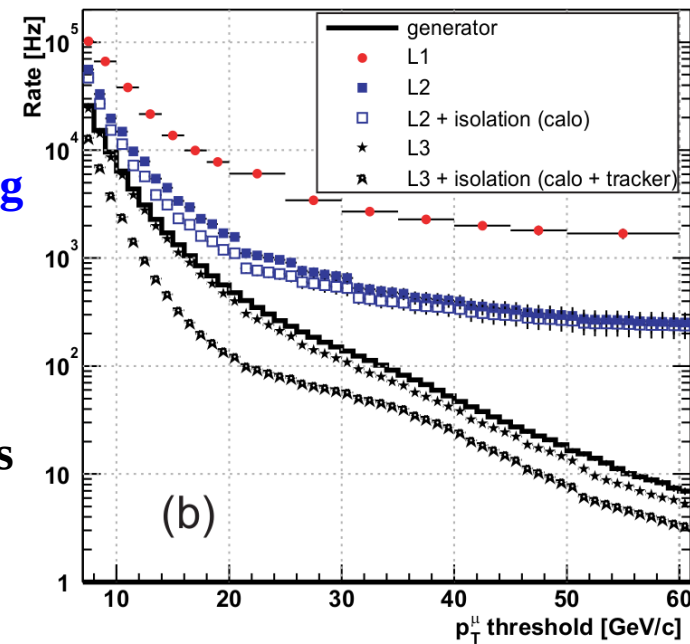
- HPD unforeseen features (B-field, gain drifts)
- Improved S/N and depth segmentation added for full barrel ($e^\pm/\gamma$ identification) / endcap (radiation damage to scintillator)
- Improved calibration, bkg & PU suppression, EM isolation (analysis and trigger)
- New electronics with broader dynamic range, TDC capability (identifying anomalous signal in HF and isolation in HB/HE)

Install front-end and back-end electronics

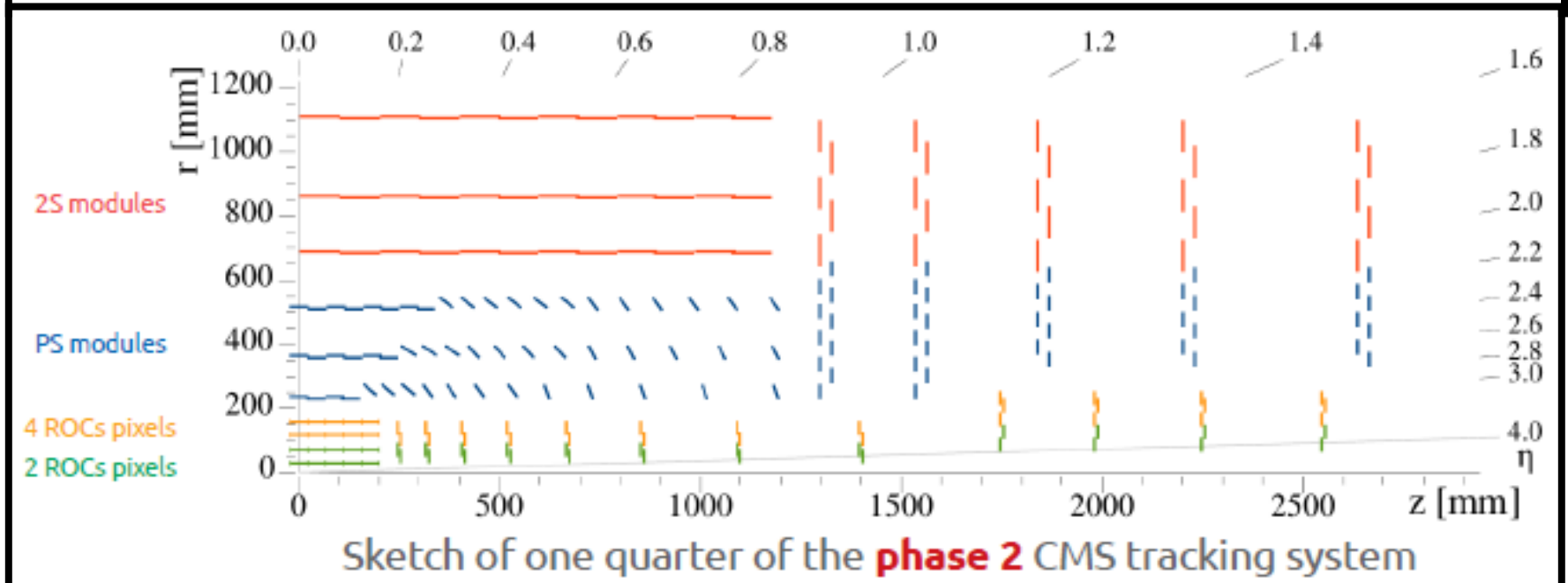
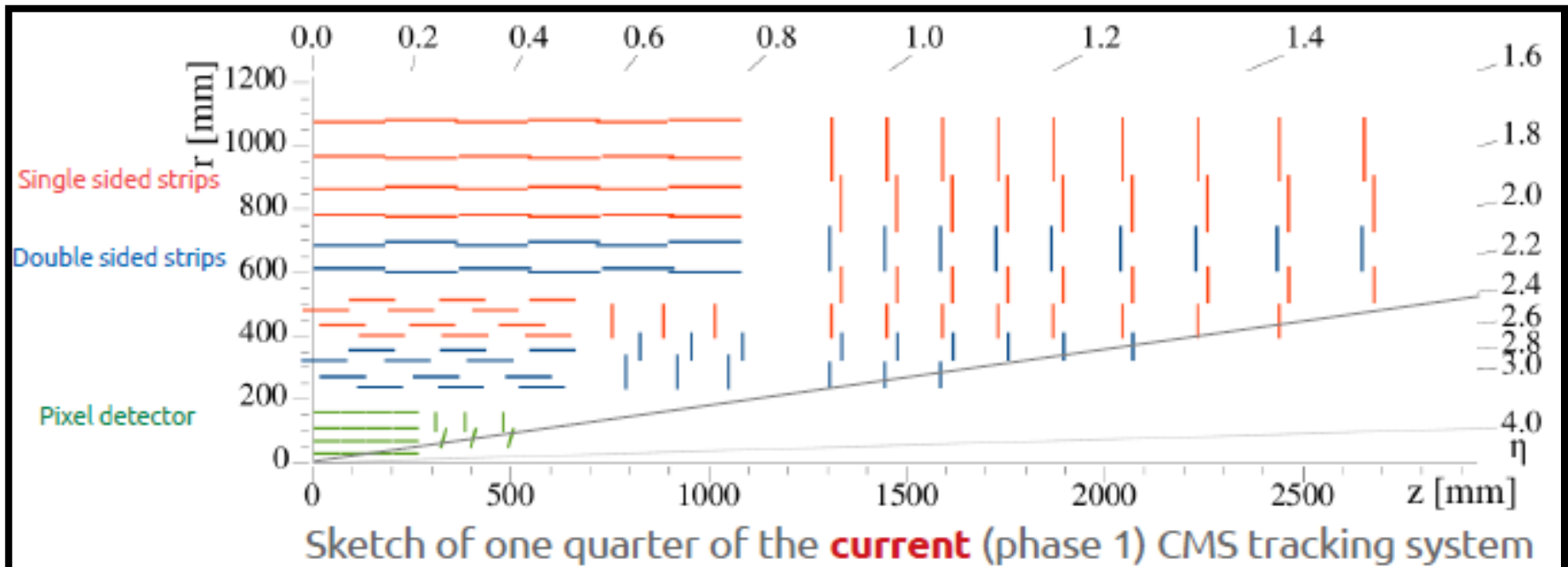
Paramount to maintain efficient Particle flow approach in high pileup environment

Phase 2 : Tracker in Level-1 Trigger

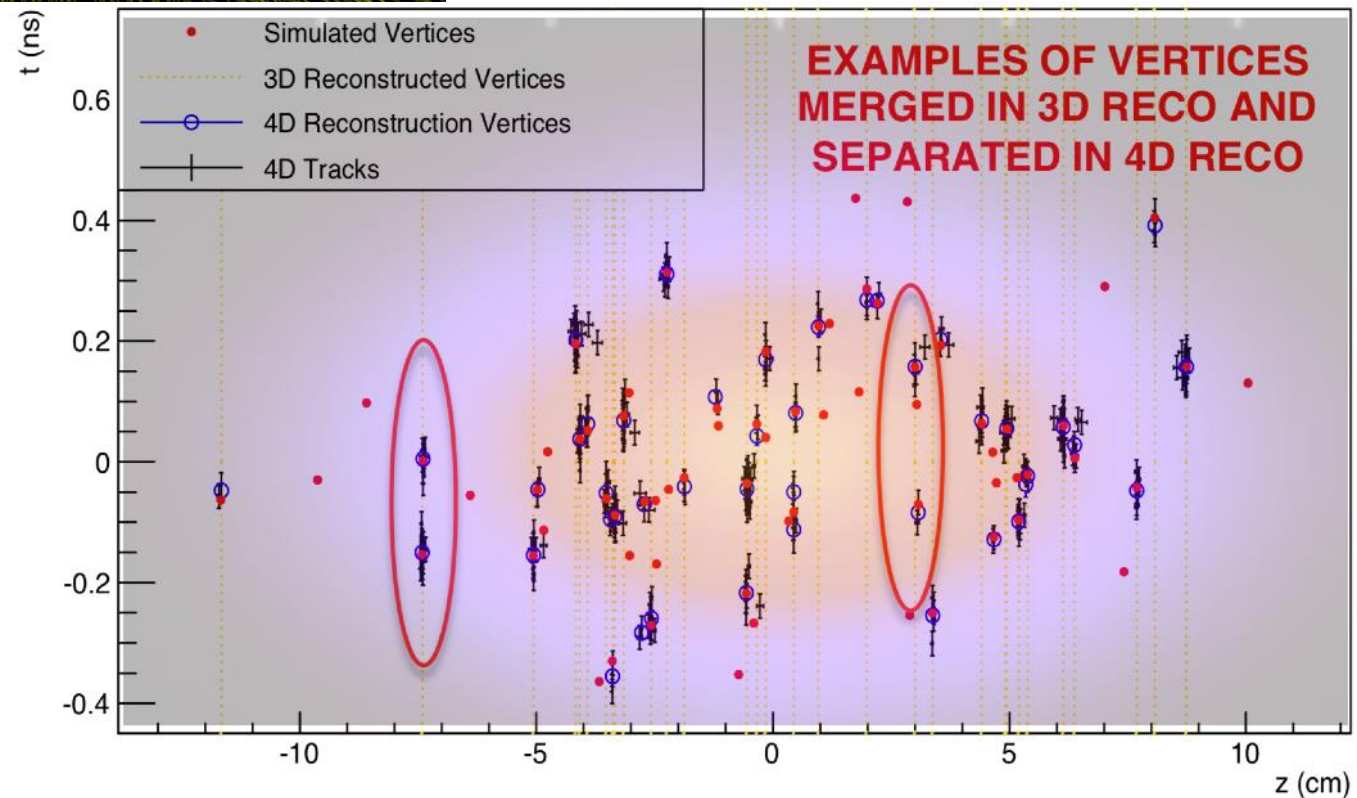
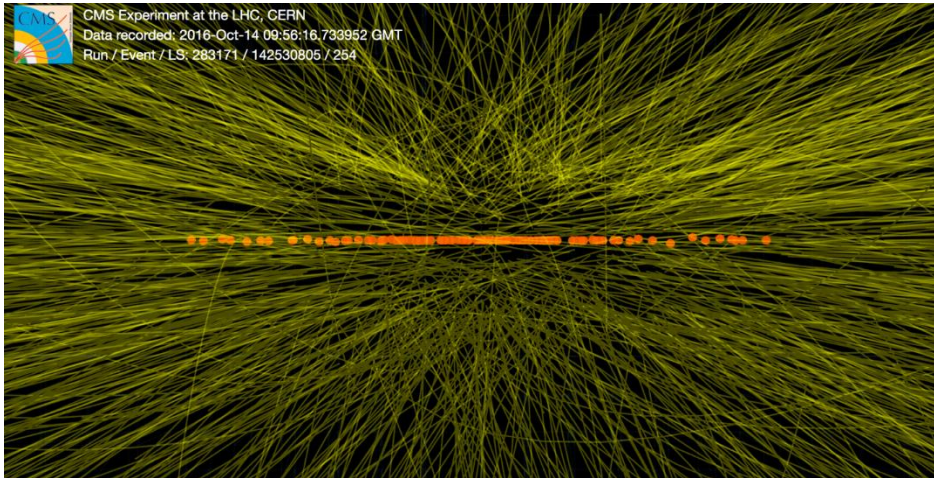
- Higher radiation resistance, higher readout granularity
- Without tracker input muon triggering becomes saturated
- A trigger-capable tracker could take advantage of strong CMS magnetic field
 - Send only selected hits for Level-1 Trigger (Pt threshold of 1GeV or more)
 - (L1 tracks using stubs and) refine trigger primitives from calorimeters and muon, electron trigger rate reduce by a factor of 10)
 - Binary readout for the strip tracker



CMS Tracker Upgrade for the HL-LHC

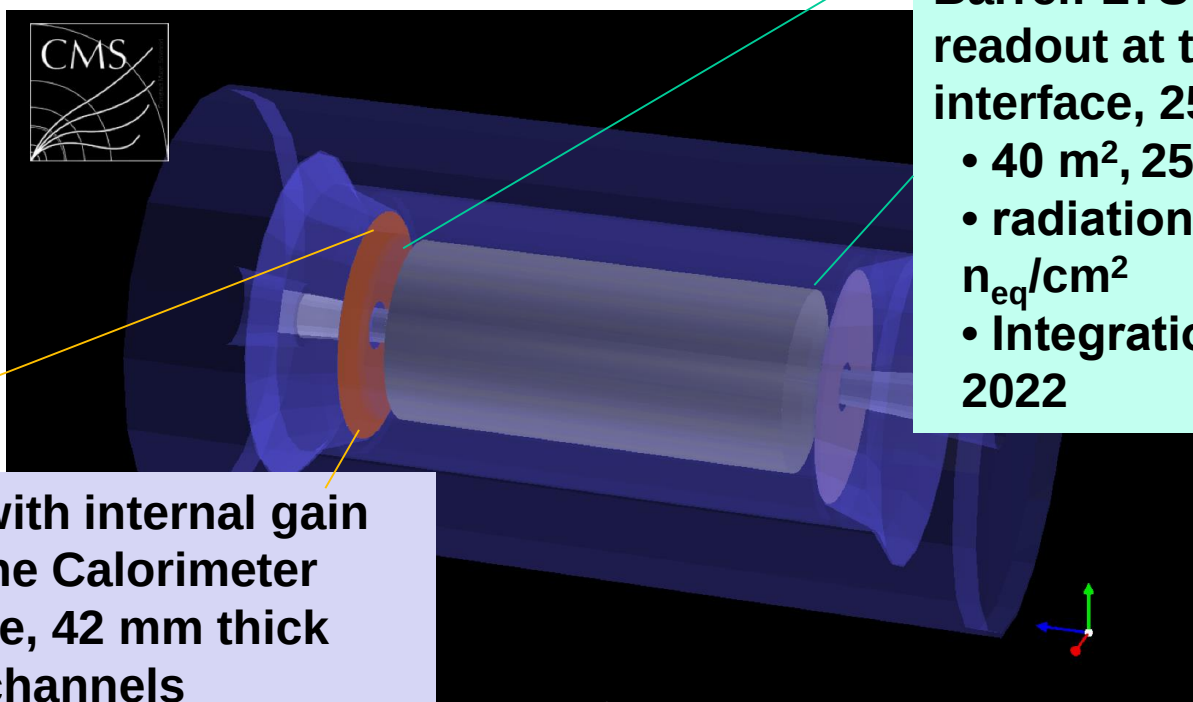


Timing information to remove Pileup track



Timing layers at CMS

- Thin layer between tracker and calorimeters
- ~ 30 ps resolution for charged tracks (above 0.7 GeV)
- Hermetic coverage for $|\eta| < 3.0$



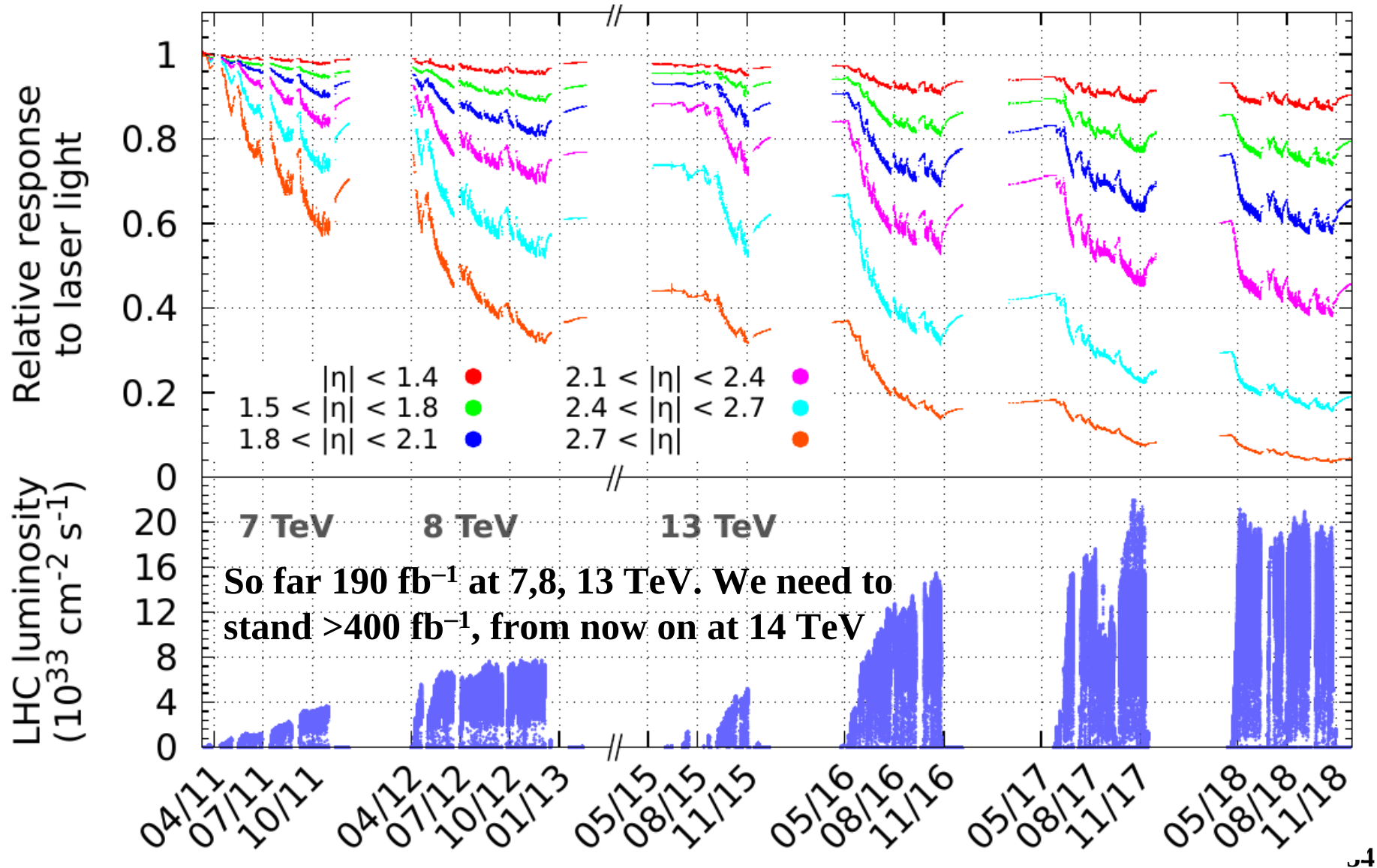
Barrel: LYSO tiles + SiPM readout at tracker-ECAL interface, 25 mm thick

- 40 m², 250k channels
- radiation (4/ab): 2×10^{14} n_{eq}/cm²
- Integration with tracker in 2022

Endcap: Si with internal gain (LGAD) on the Calorimeter Endcap nose, 42 mm thick

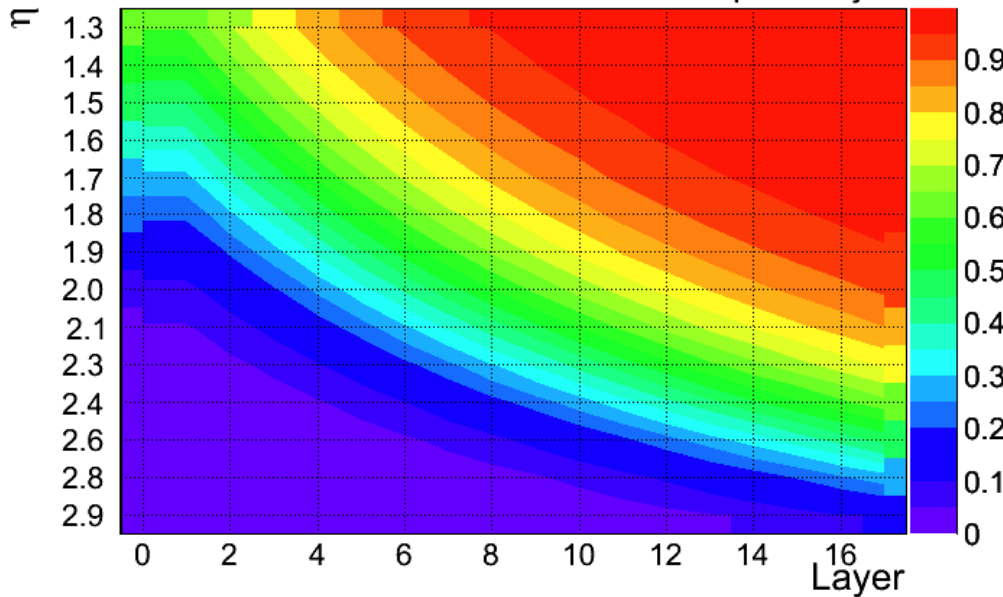
- 12 m², 4M channels
- radiation (4/ab): $\sim 10^{15}$ n_{eq}/cm²
- Integration with tracker in 2024

CMS ECAL history of laser transparency measurement subdivided by eta regions

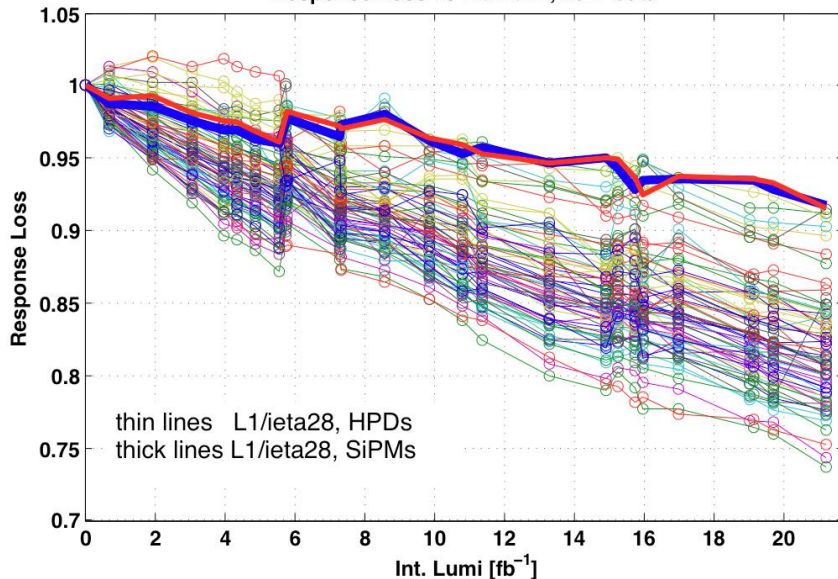


Response of HE scintillator and upgrade plan

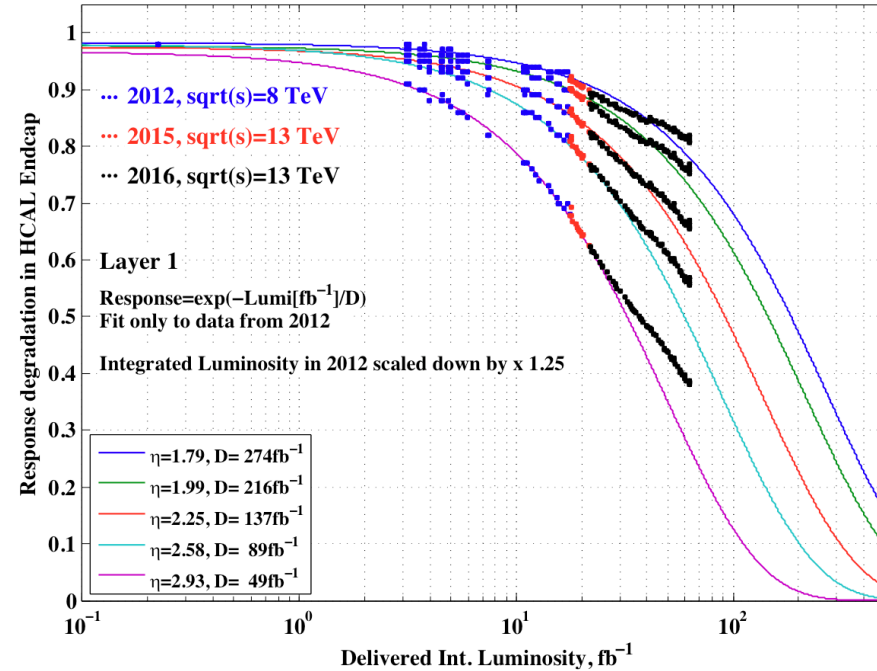
Response degradation in HE after 500 fb⁻¹ @ 13 TeV collisions
CMS preliminary



Response Loss vs int. Lumi, 2017 data



CMS preliminary

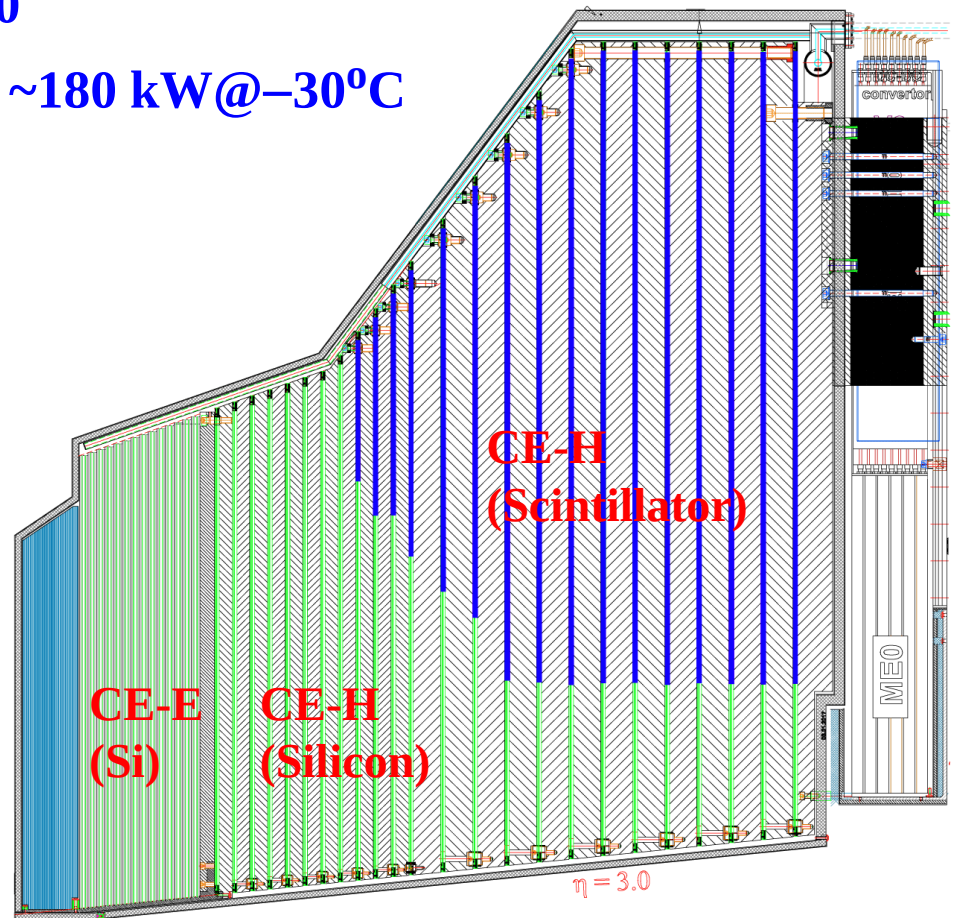


- Initial estimation of damage is larger than observation
- Damage is more in HPD, rather than in the scintillator
- Continue to use same scintillator till LS3 and then also use scintillator at larger radius

CMS HGCal upgrade plan

- Silicon/Scintillator detector in the high/low radiation region
- 28 layers in the ECAL (CE-E) + 24 layers in HCAL (CE-H)
- Trigger and reading data of >6M channels at 40MHz
- Endcap coverage : $1.5 < |\eta| < 3.0$
- Total power at end of HL-LHC $\sim 180 \text{ kW} @ -30^\circ\text{C}$

Total	Silicon sensors	Scintillators
Area (m ²)	600	500
# of modules	27000	4000
Cell size (cm ²)	0.5 - 1	4 - 30
# of channels	6M	0.4M



High-Granularity Calorimeter (HGCAL)

Initial design :

Number is varying : So this is not final number

ECAL: ~33 cm, 25 X_0 , 1 λ , 31 layers:

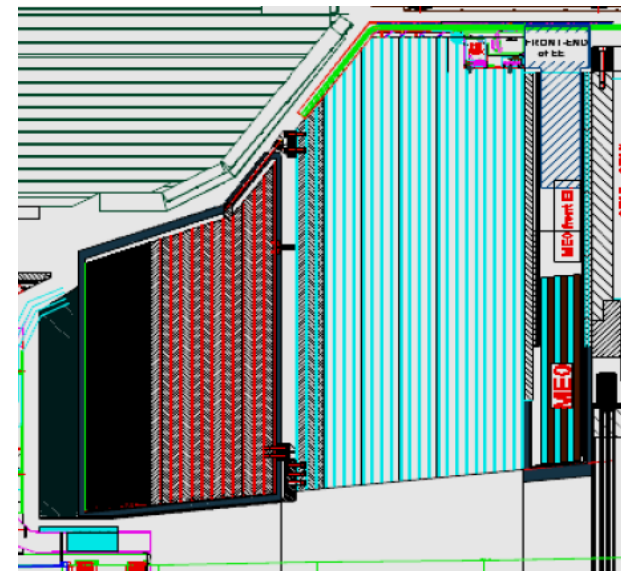
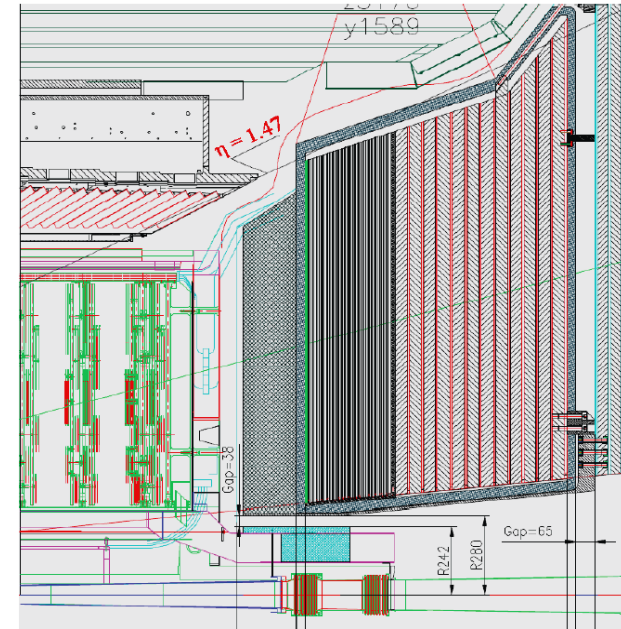
- 10 planes of Si separated by 0.5 X_0 of lead/Cu
- 10 planes of Si separated by 0.8 X_0 of lead/Cu
- 10 planes of Si separated by 1.2 X_0 of lead/Cu

HCAL: ~66 cm, 3.5 λ :

- 12 planes of Si separated by ~0.3l of absorber
- Fine grain pads 0.5~1cm²
- ~10M channels and 700m² of Silicon

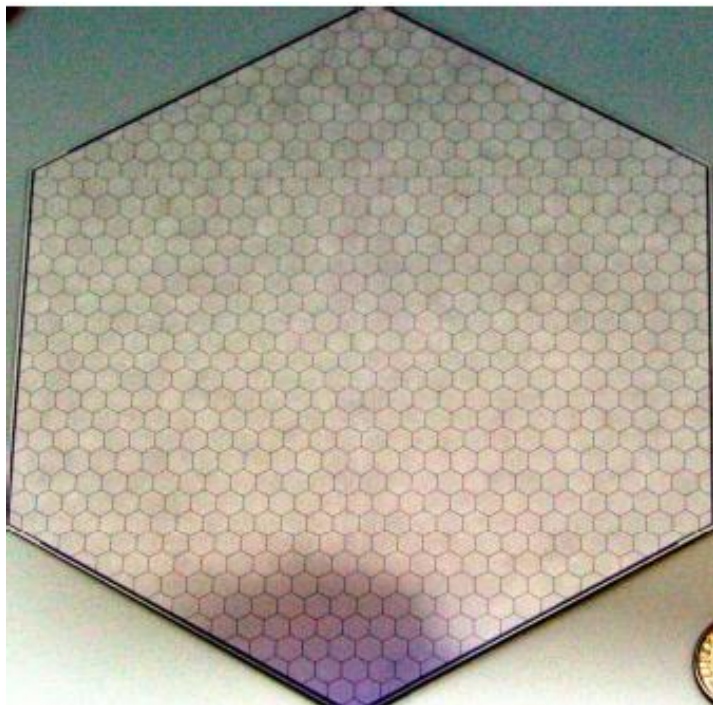
Back HCAL as HE re-build 5 λ

- With increased granularity
 - $\Delta E/E \sim 20\%/\sqrt{E}$; 3D shower reconstruction
- => Use detailed shower topology to mitigate PU effect



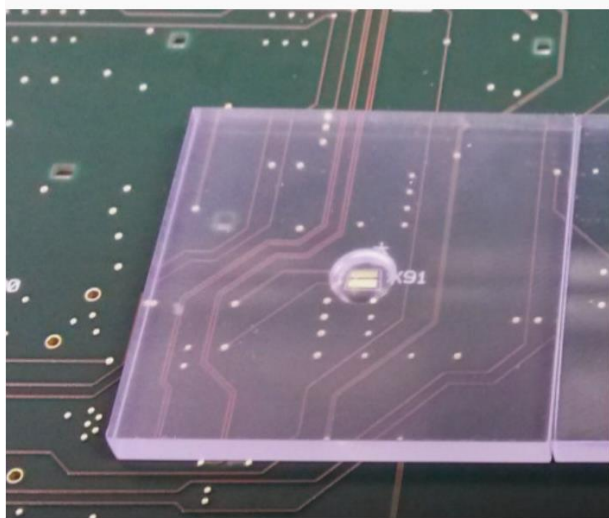
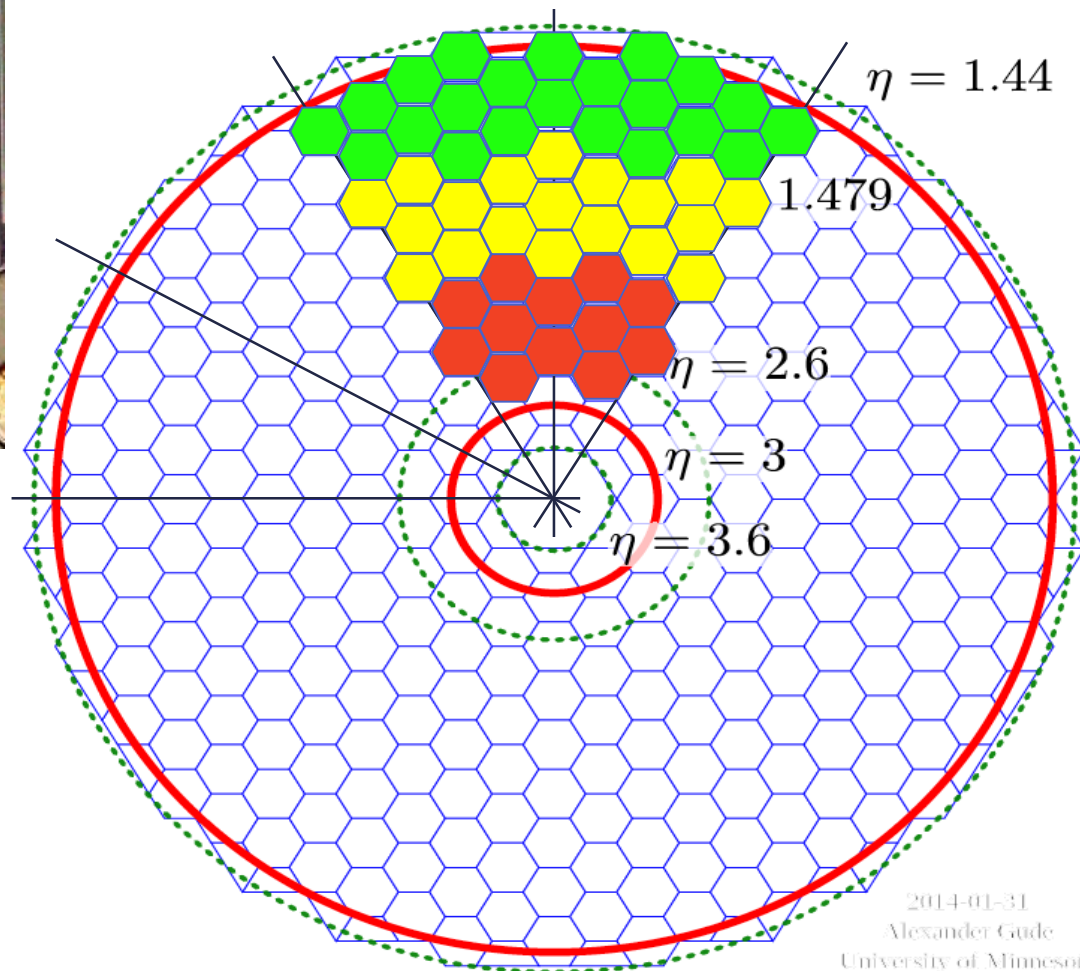
Area of Silicon(m2)	ECAL	HCAL	Total
Channels	10.0M	3M	13M
Detector module	18.2k	10.5k	28.7k
Weight(one endcap (tones)	18	81	99

Module type distribution EE-HGC (initial design)



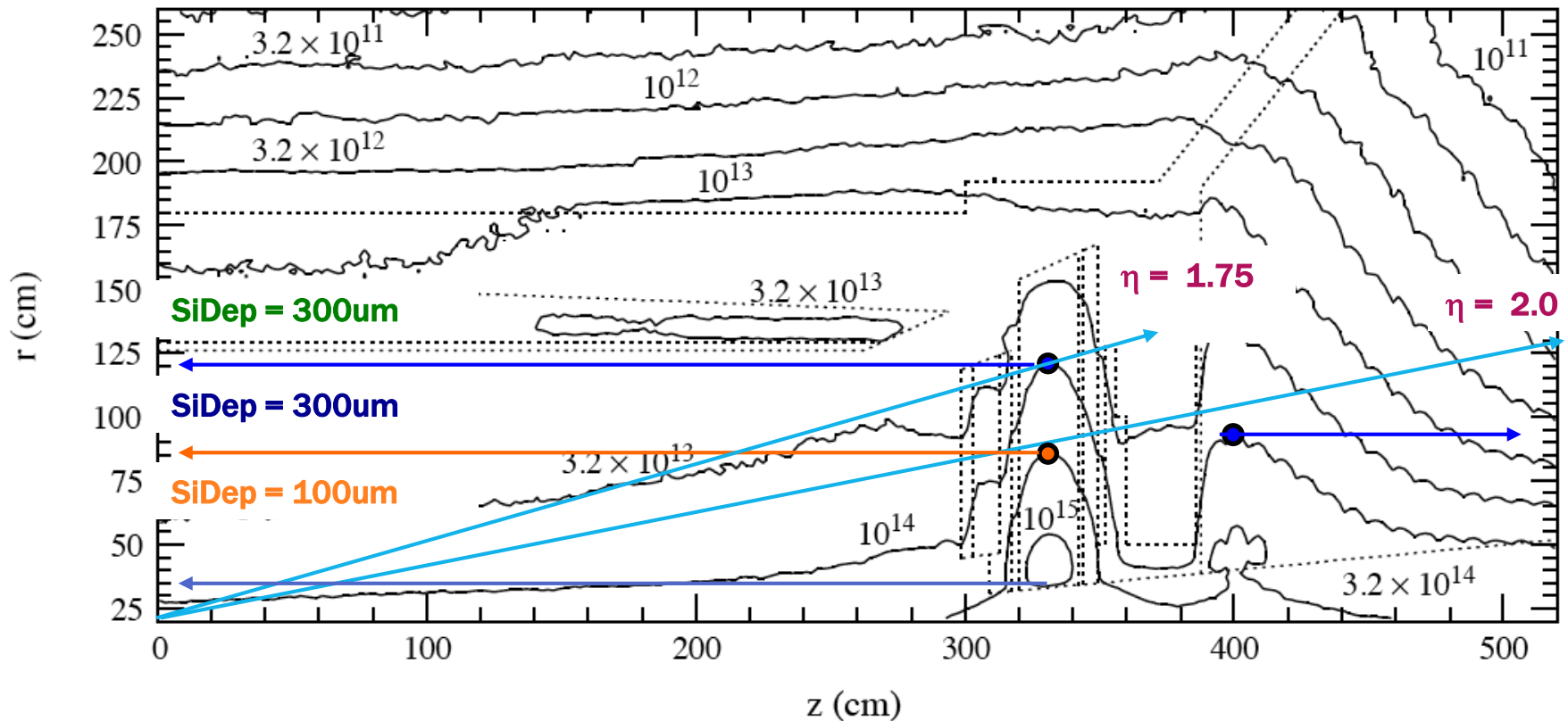
	Sensor Surface cm ²	
	Square	Hexagonal
6" wafers	~ 100	~ 130
8" wafers	~ 180	~ 230

300um / 256 ch
200um / 256 ch
100um / 512 ch

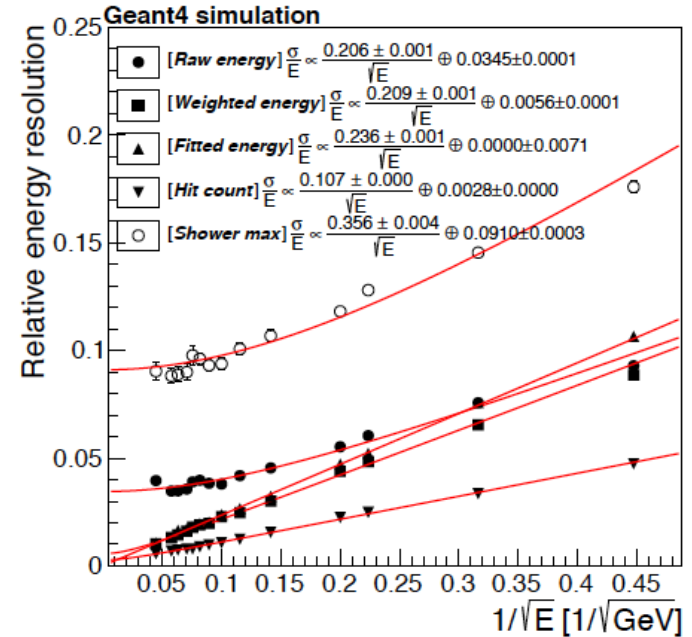
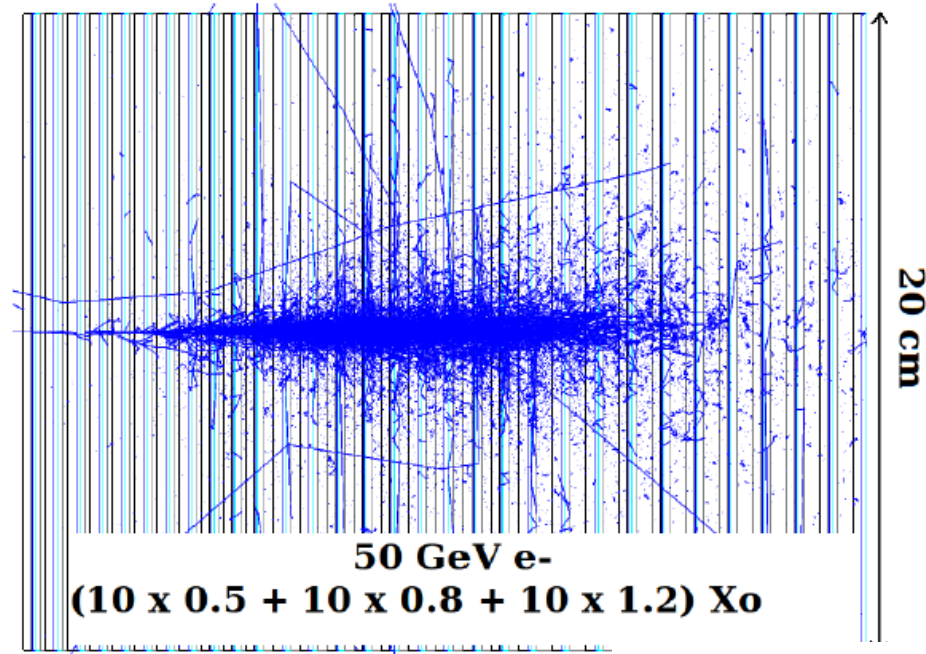


Possible Sensor Parameters

Si Thick	300	200	100	um
Max Fluence	6.4×10^{14}	2.5×10^{15}	1×10^{16}	n/cm ²
HGC EE Area	220	120	140	m2
Vbias	600~900	600~900	600~900	V
Signal	15,000	7,500	6,000	e ⁻
Ileak Power/Module	0.5~0.7	1.4~2.1	2.7~4.1	W/module
Ileak Power	5~7	7~11	16~25	kW

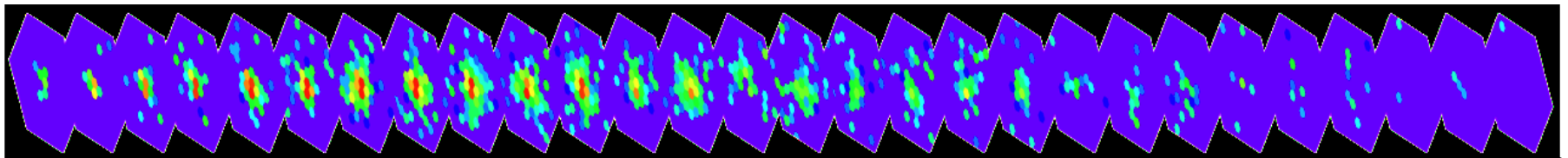


Simulations

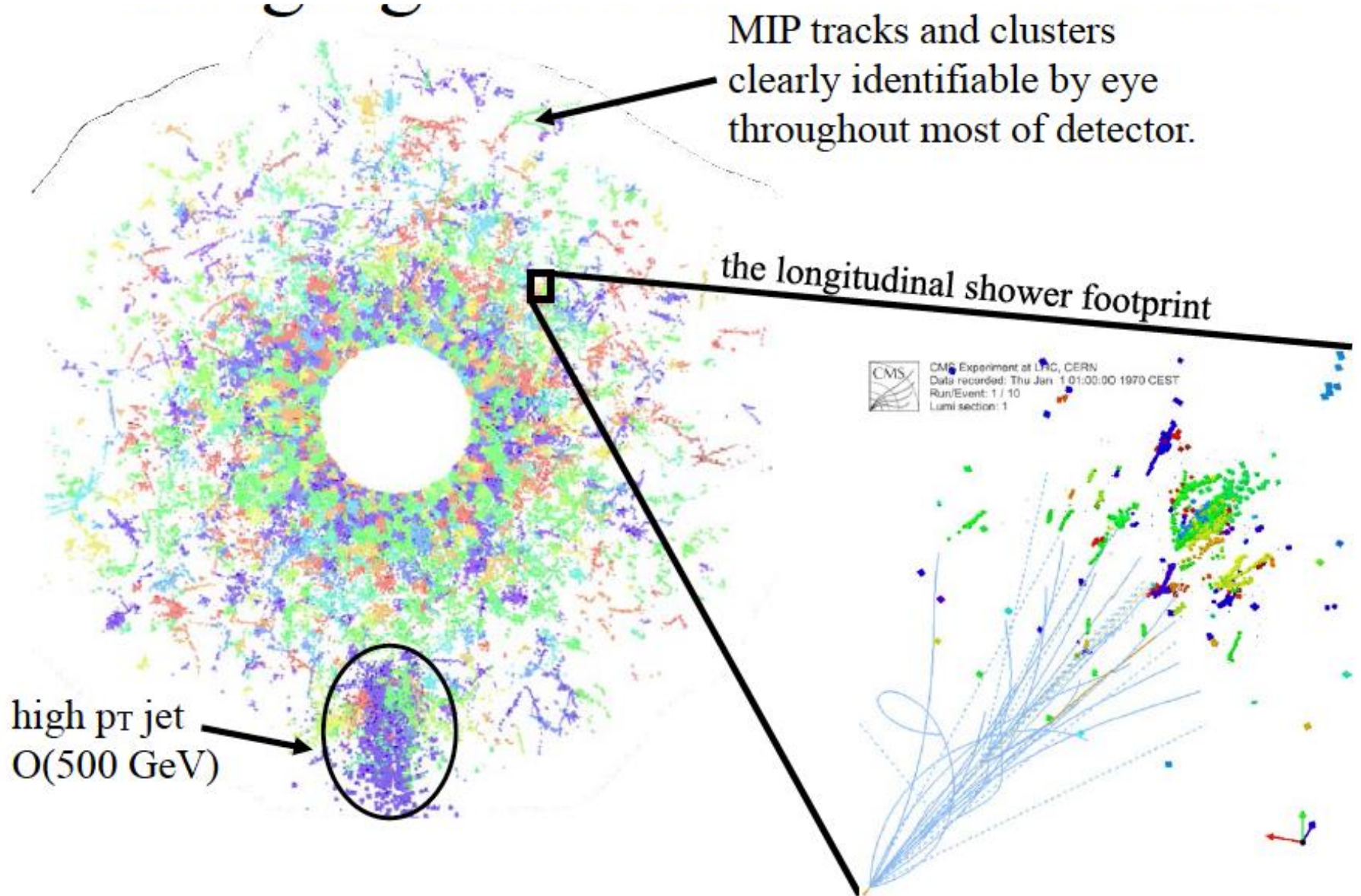


ρ (mm)	$\left(\frac{\sigma_E}{E}\right)_{\text{stoch}}$	$\left(\frac{\sigma_E}{E}\right)_{\text{cte}}$
∞	0.209 ± 0.001	0.0056 ± 0.0001
2.5	0.280 ± 0.001	0.0130 ± 0.0001
7	0.237 ± 0.001	0.0090 ± 0.0001
25	0.216 ± 0.001	0.0069 ± 0.0001
dynamical	0.228 ± 0.001	0.0128 ± 0.0001

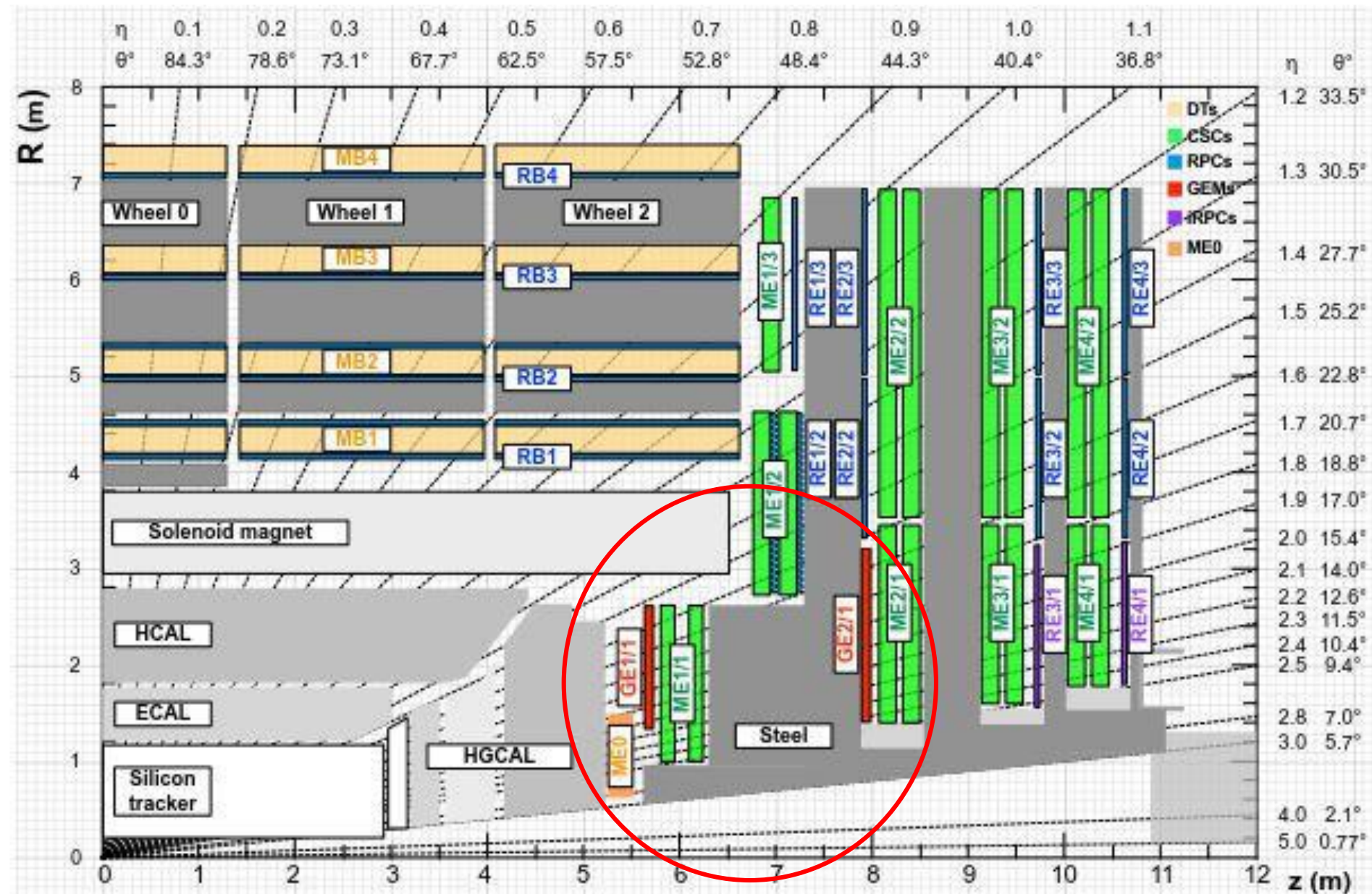
CERN beam test in
2016-2018 for the
validation



Imaging Showers with the HGCAL

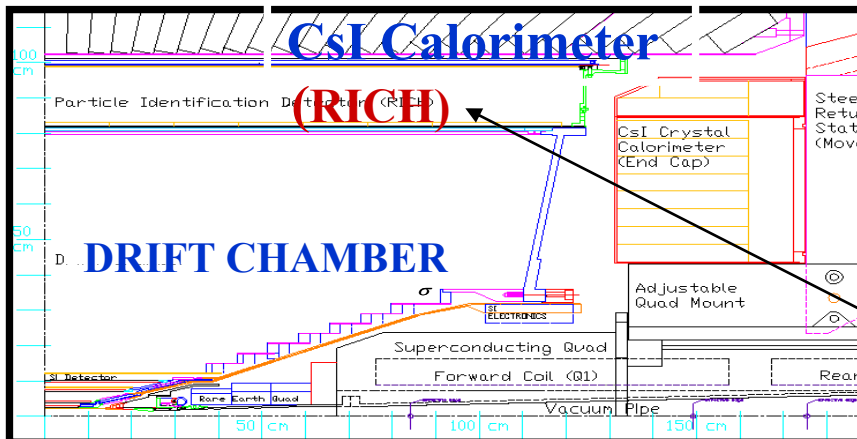
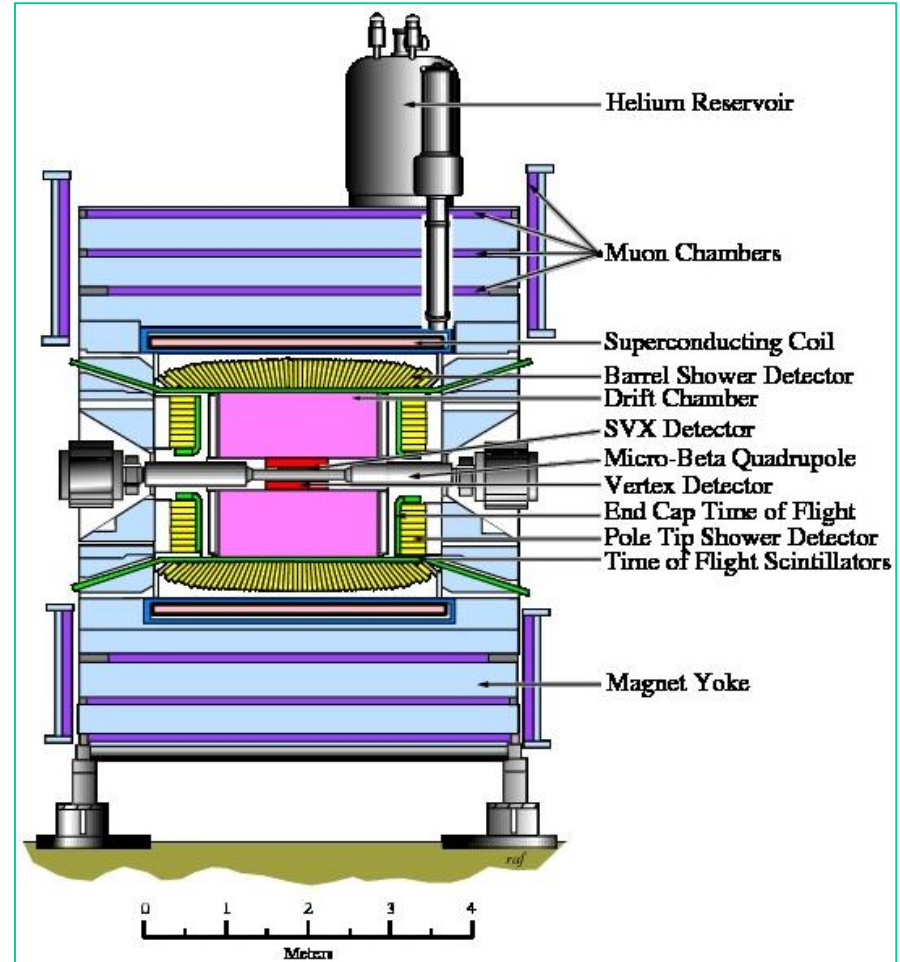
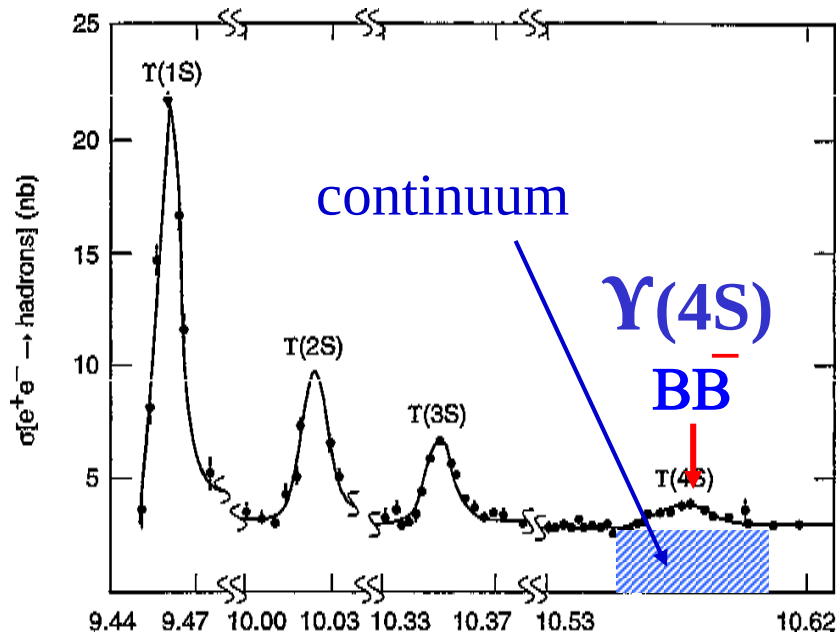


Forward muon detector upgrade : GEM



B-physics at e^+e^- machine : CLEO-II-III

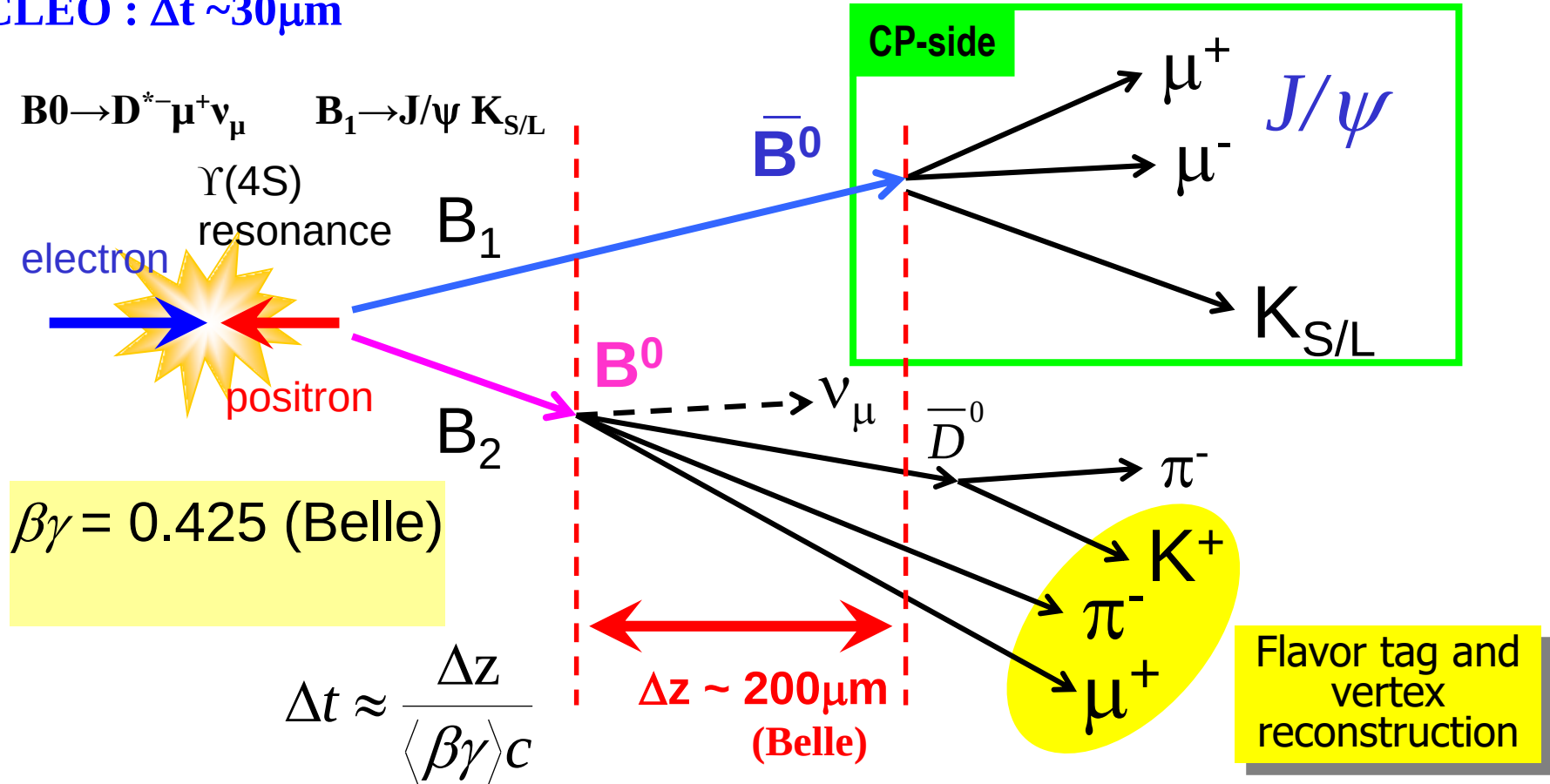
Started with ARGUS and continued long time with CLEO



Ring Imaging Cherenkov (RICH) counter was necessary to identify K/π mainly for the CP-violation study

Principle of time dependent CPV measurement

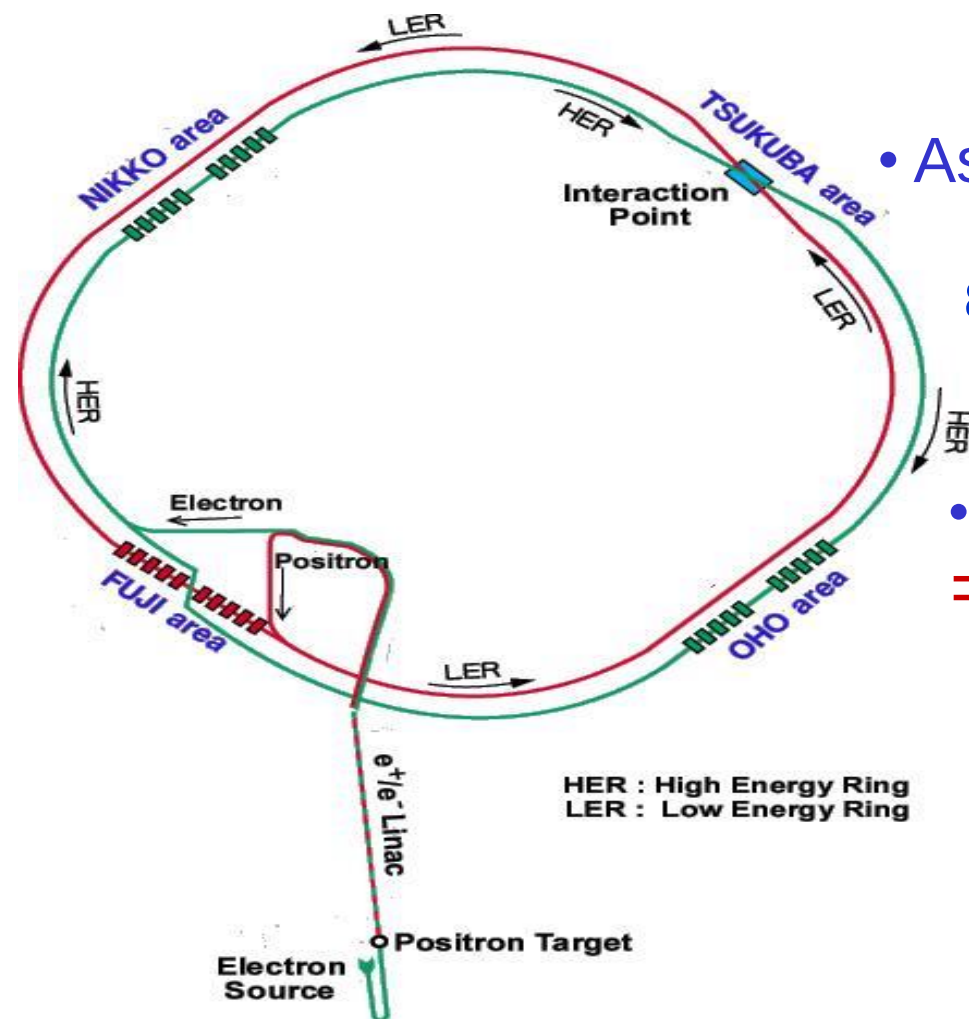
CLEO : $\Delta t \sim 30 \mu\text{m}$



1. Fully reconstruct one B-meson which decays to CP eigenstate
2. Tag-side determines its flavor (effective efficiency, $\epsilon D^2 = 30\%$)
3. **Proper time (Δt)** is measured from **decay-vertex difference (Δz)**

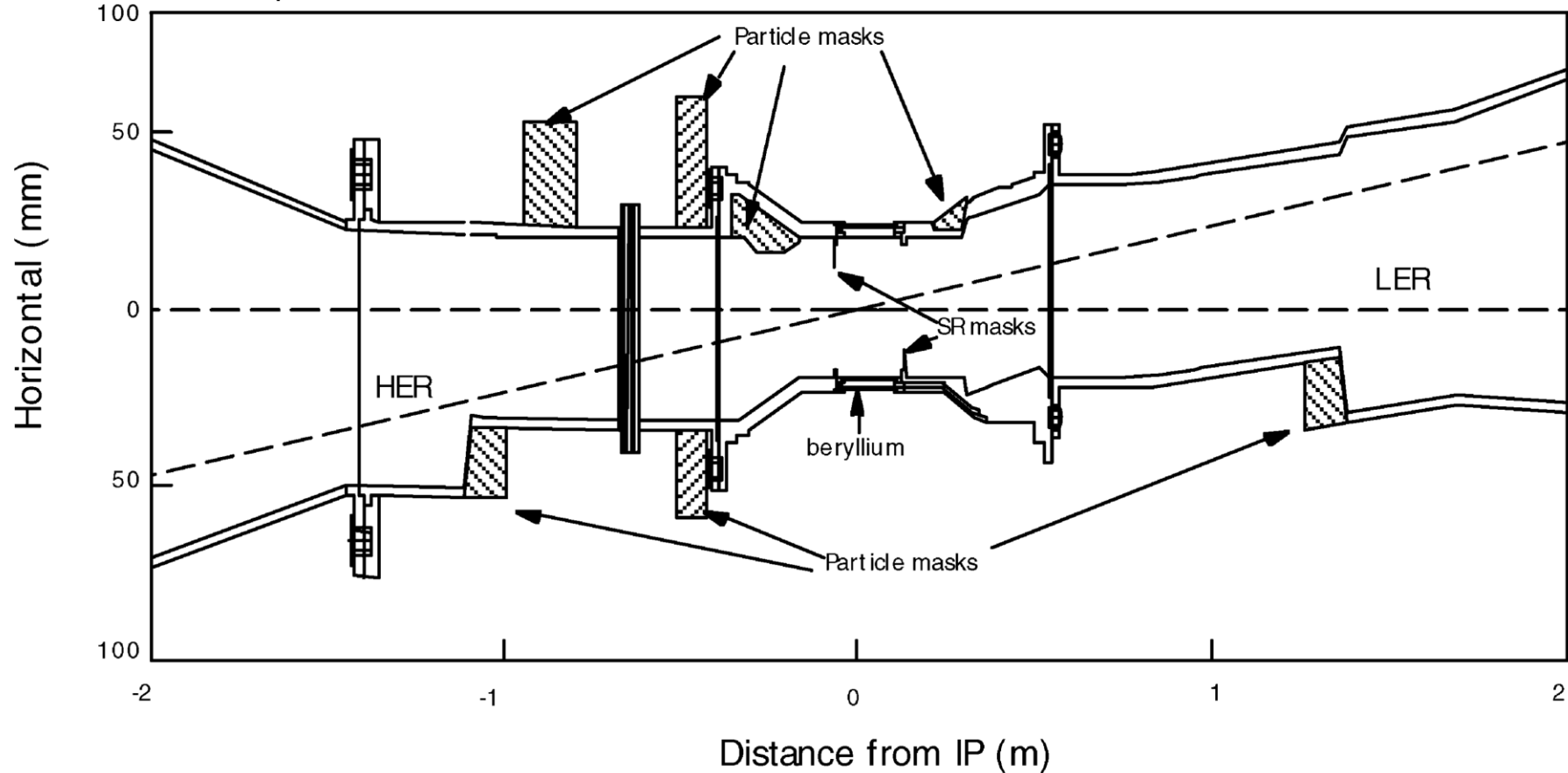
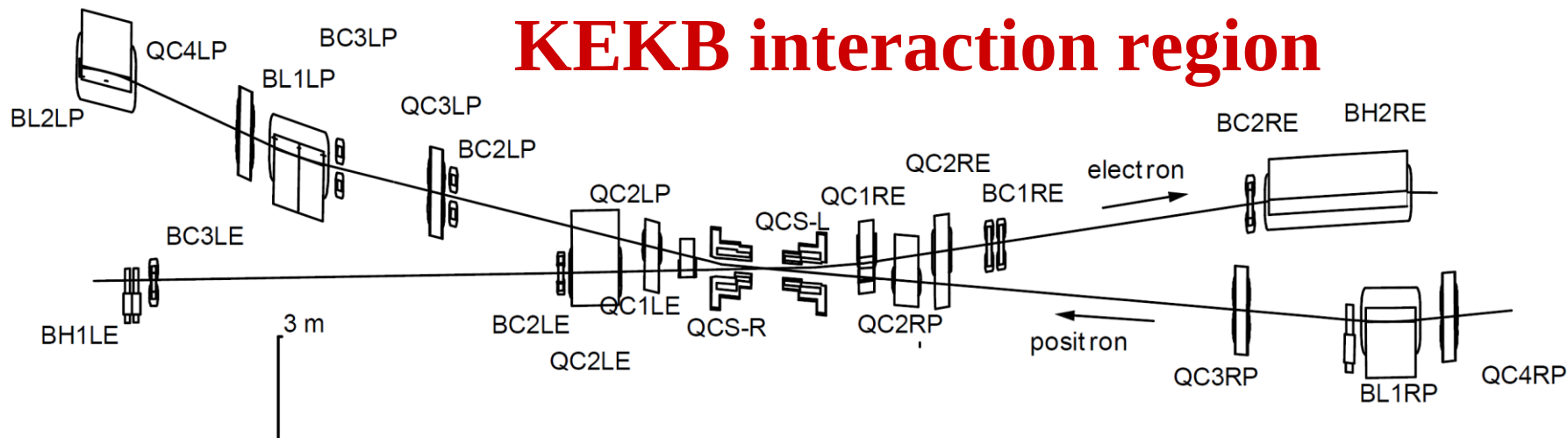
1. Low momentum π
2. High momentum π/K
3. Charge of lepton
4. **Same side tag (B^{*+})**

KEK-B Collider

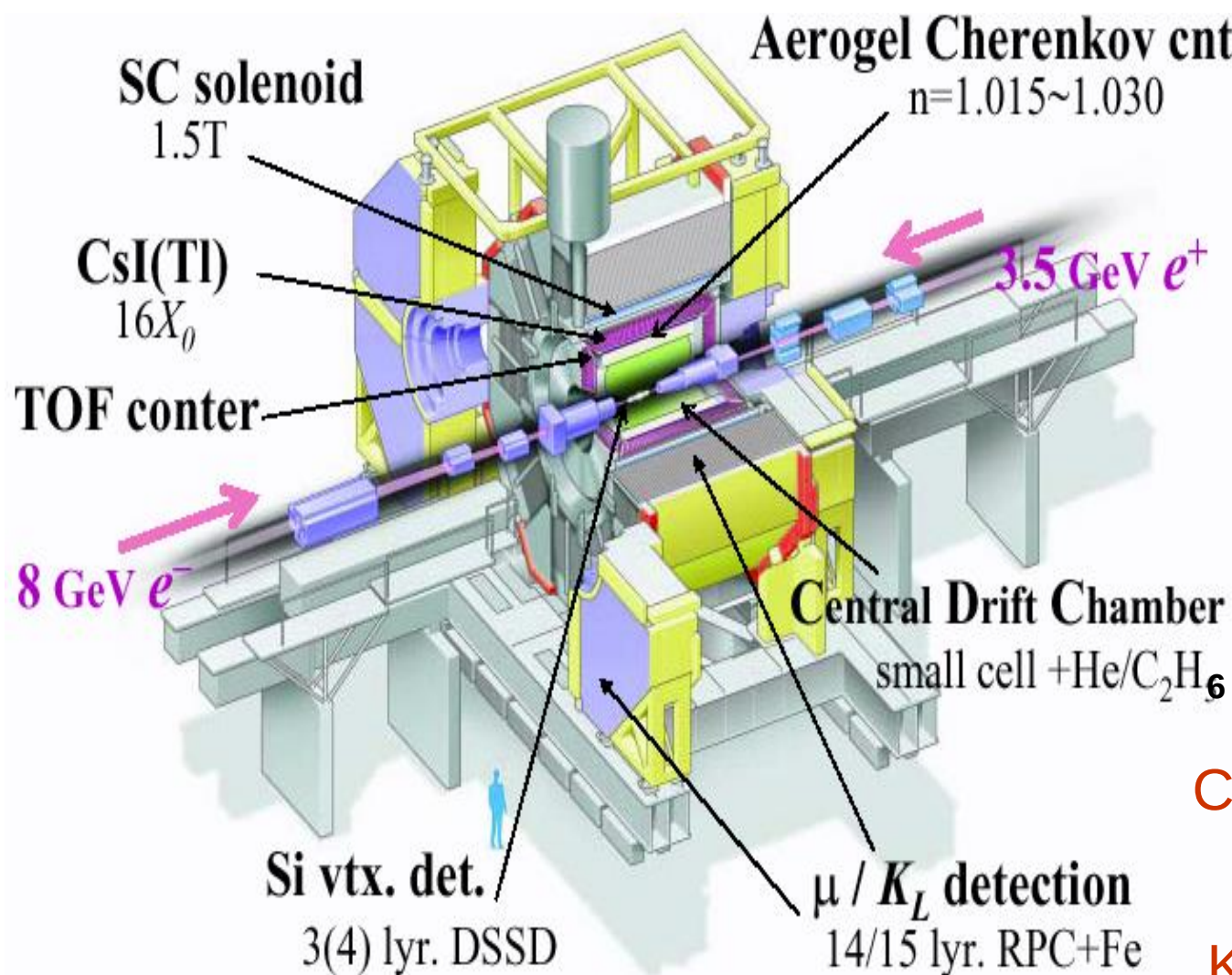


- Asymmetric $e^- e^+$ collider
(3 Km in circumference)
 $8 \text{ GeV } e^- (\text{HER}) \times 3.5 \text{ GeV } e^+ (\text{LER})$
 $\sqrt{s} = 10.58 \text{ GeV} \Leftrightarrow \Upsilon(4S)$
- Beam crossing angle:
 $\pm 11 \text{ mrad}$
- Continuous injection
 $\rightarrow > 1.2 \text{ fb}^{-1}/\text{day}$
- Luminosity
 $L_{\text{max}} = 1.71 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
 $\int L dt > 1000 \text{ fb}^{-1}$

KEKB interaction region



Belle Detector



SVD: 3/4 DSSD
lyr $\sigma \sim 55 \mu\text{m}$

CDC: 50 layers

$\sigma_p/p \sim 0.35 \%$

$\sigma_\pi(dE/dx) \sim 7 \%$

TOF: $\sigma \sim 95 \text{ ps}$

Aerogel
($n=1.01\sim 1.03$)

$K/\pi \sim 3.5$

GeV/c

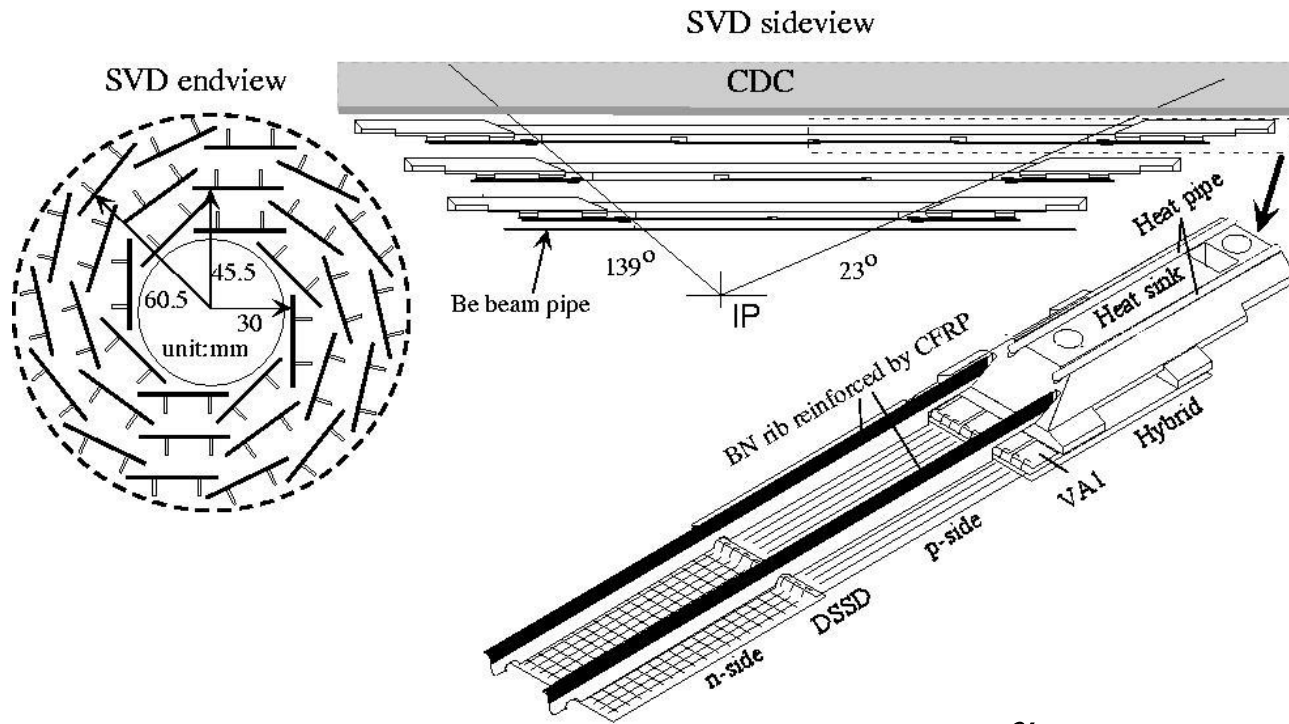
Csl: $\sigma_{E\gamma}/E\gamma \sim 1.8 \%$
(@ 1 GeV)

KLM: RPC 14 lyr

Chronological steps towards BELLE

- 1973 : Third generation to accommodate CP violation
- 1977 : Discovery of $b\bar{b}$ bound state
- 1980 : Possibility of larger CP violation in neutral B decays Carter and Sanda
- 1981 : Evidence of $\Upsilon(4S) \rightarrow B\bar{B}$ (CLEO)
- 1983 : Observation of long B life time (MAC, MARK-II)
- 1987 : Large mixing in the neutral B meson system (ARGUS, UA1)
- 1991 : Concept of asymmetric B factory
- 1994 : Letter of Intent
- 1995 : BELLE Technical Design Report
- 1999 : First asymmetric e^+e^- interactions in KEKB
- 2003 : $>100\text{M}$ $B\bar{B}$ events
- 2008 : Nobel Prize for Makoto Kobayashi and Toshihide Maskawa
- 2011 : $> 1 \text{ ab}^{-1}$ of data

Belle silicon detector : DSSD

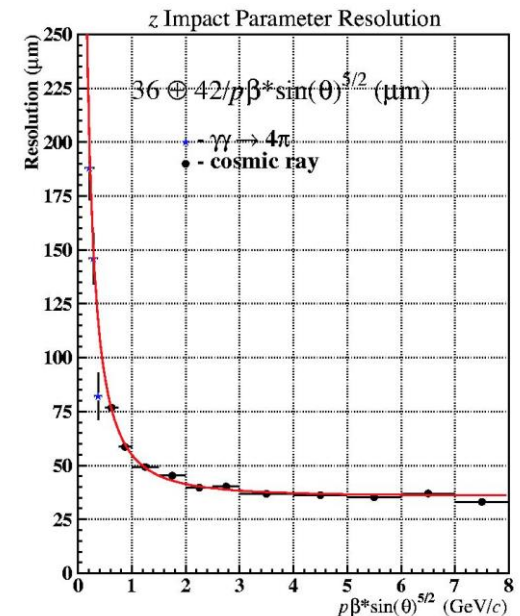
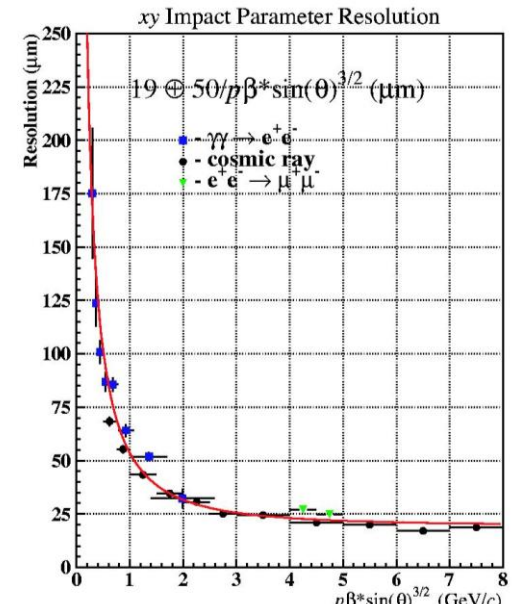


A p-stop structure is used to isolate strips on ohmic side (n-side)

102 DSSD : size = 57.5×33.5 mm² :
total channel =81920; S/B ~ 19

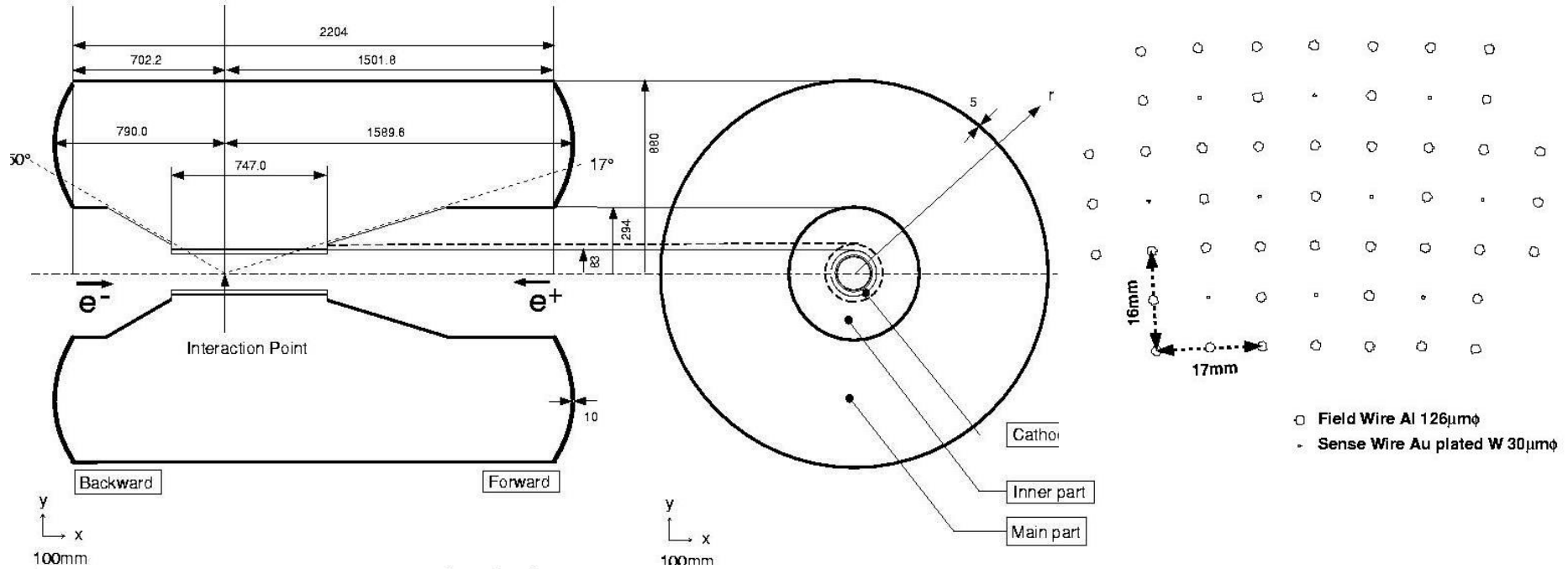
$$\sigma_{IP_{R\varphi}} = \frac{\alpha_{MS}}{P \sin^{3/2} \theta} \oplus \sigma_{0,R\varphi}$$

$$\sigma_{IP_{Rz}} = \frac{\alpha_{MS}}{P \sin^{5/2} \theta} \oplus \sigma_{0,Rz}$$

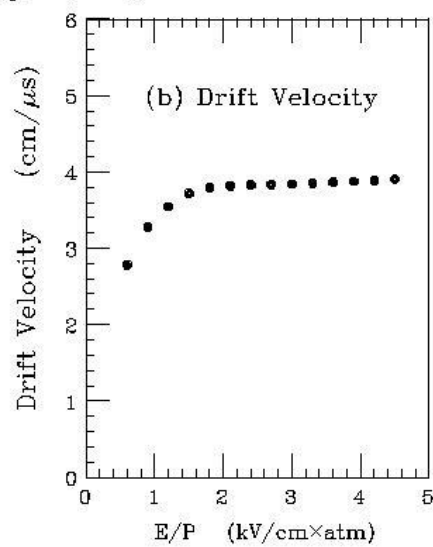
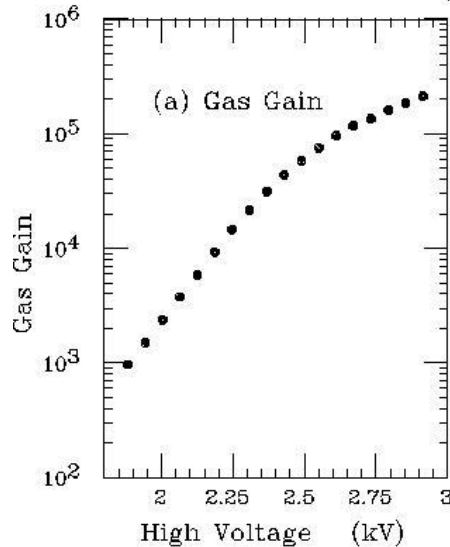


	size	pitch	width
Z-strip(n)	53.5×32.0 mm ²	42μm	14 μm
Φ-strip (p)	54.5×32.0 mm ²	25μm	12 μm

Central Drift Chamber (CDC) @ Belle

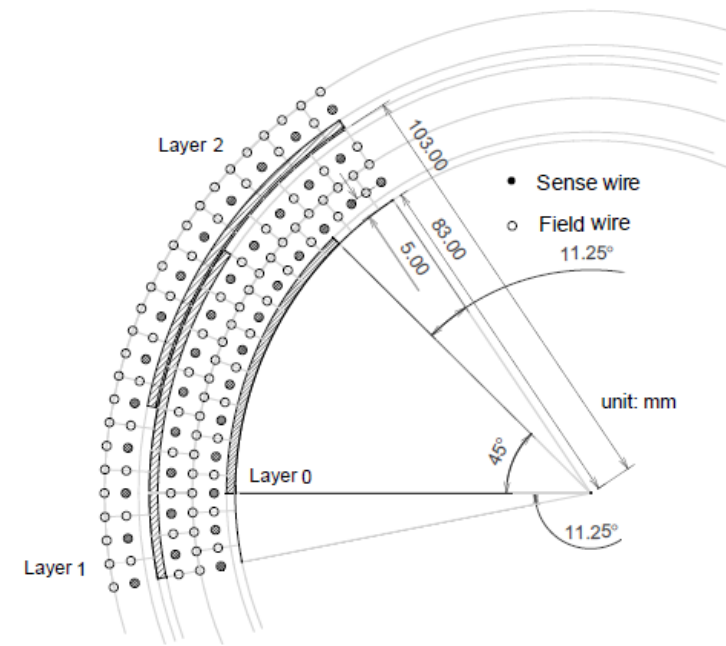


He-C₂H₆(50/50)



- 50 layer of anode wire, 8400 drift cell
- Concave shape to balance wire tension
- Less multiple Coulomb scattering but reasonable dE/dx for PID He-C₂H₆
- Nearly constant drift velocity

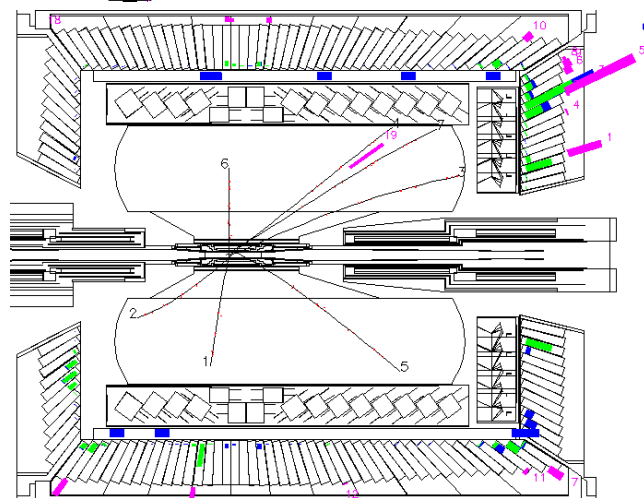
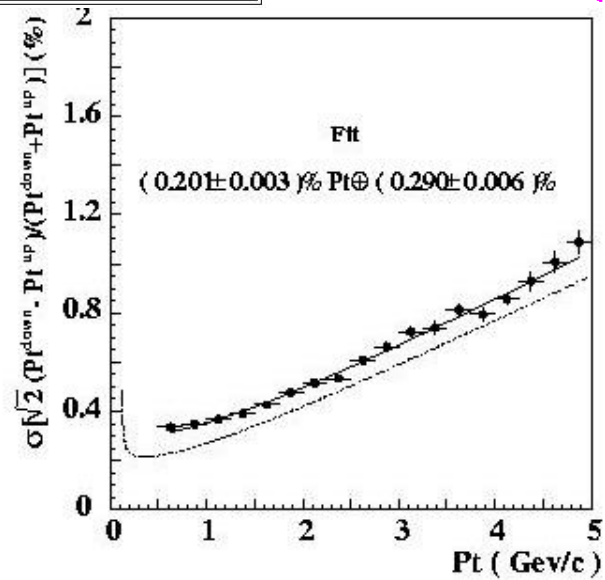
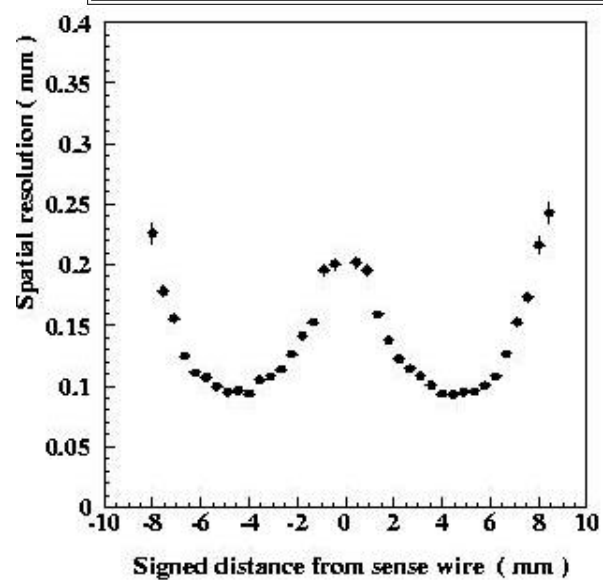
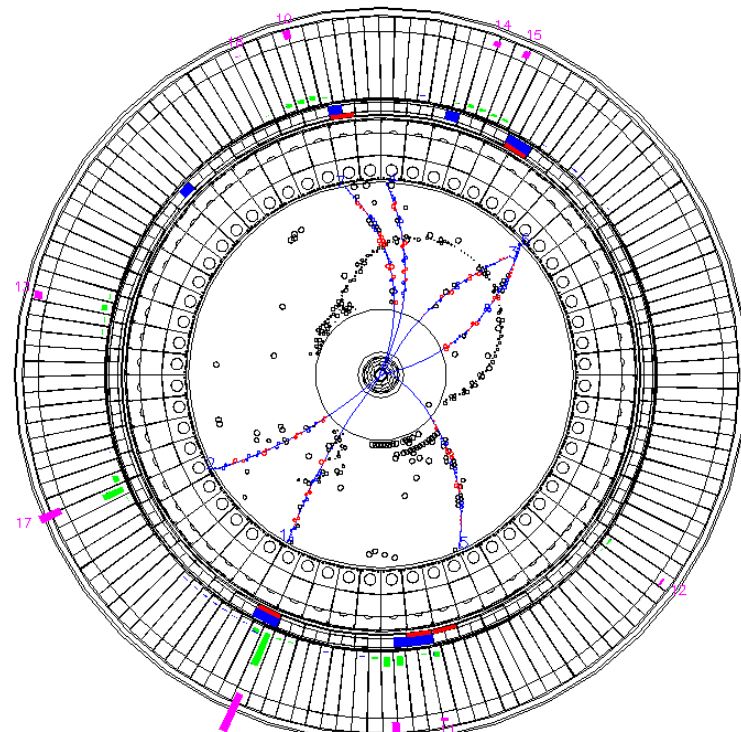
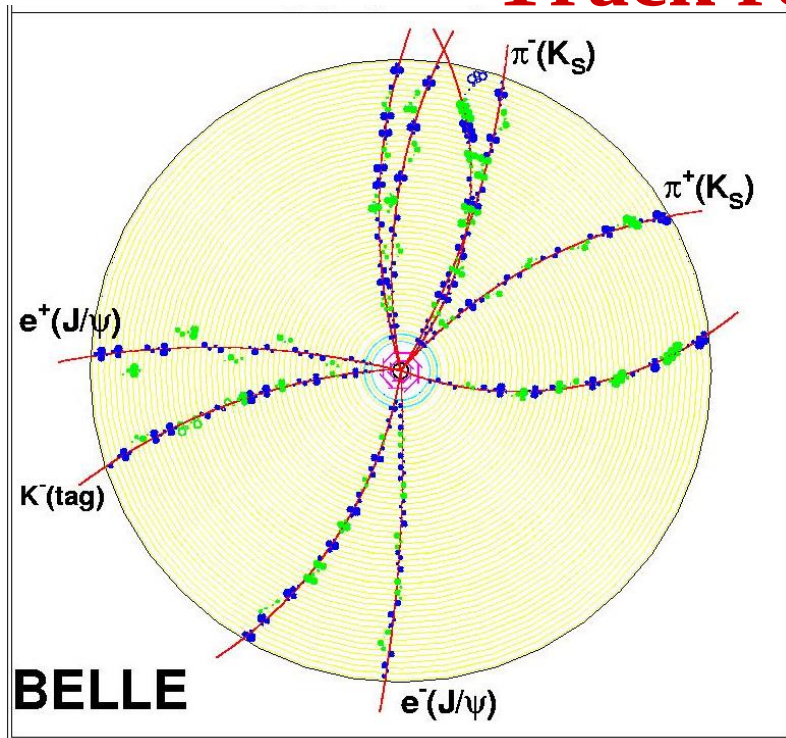
Details in wire configurations



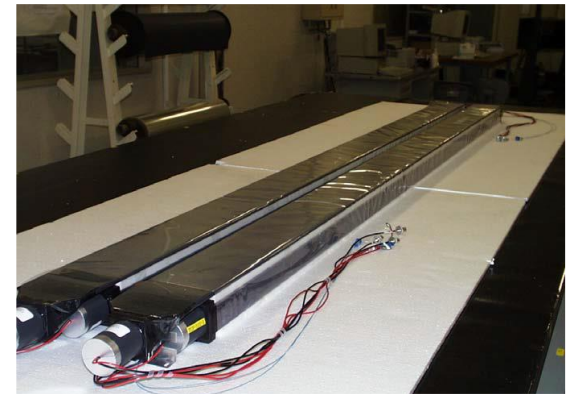
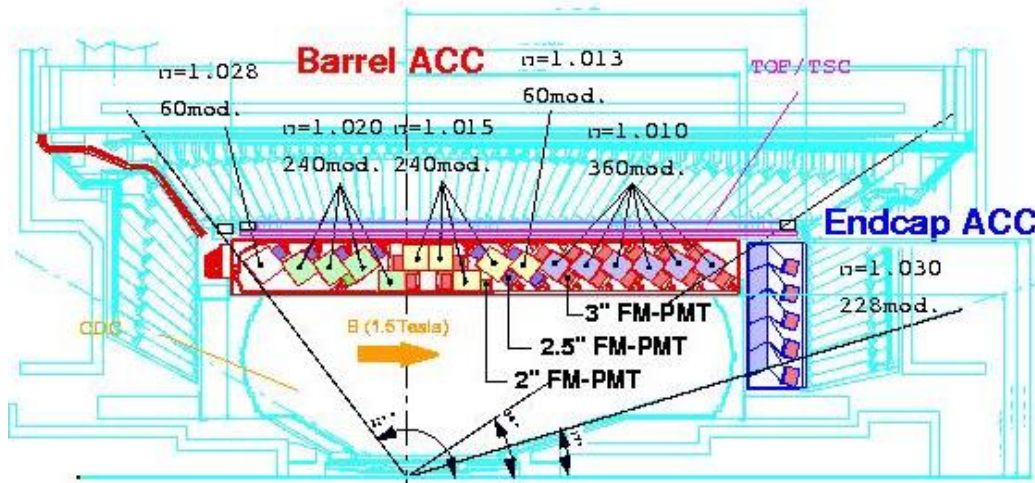
Configurations of the CDC sense wires and cathode strips

Superlayer type and no.	No. of layers	Signal channels per layer	Radius (mm)	Stereo angle (mrad) and strip pitch (mm)
Cathode	1	$64(z) \times 8(\phi)$	83.0	(8.2)
Axial 1	2	64	88.0–98.0	0.
Cathode	1	$80(z) \times 8(\phi)$	103.0	(8.2)
Cathode	1	$80(z) \times 8(\phi)$	103.5	(8.2)
Axial 1	4	64	108.5–159.5	0.
Stereo 2	3	80	178.5–209.5	71.46–73.75
Axial 3	6	96	224.5–304.0	0.
Stereo 4	3	128	322.5–353.5	–42.28–45.80
Axial 5	5	144	368.5–431.5	0.
Stereo 6	4	160	450.5–497.5	45.11–49.36
Axial 7	5	192	512.5–575.5	0.
Stereo 8	4	208	594.5–641.5	–52.68–57.01
Axial 9	5	240	656.5–719.5	0.
Stereo 10	4	256	738.5–785.5	62.10–67.09
Axial 11	5	288	800.5–863.0	0.

Track reconstruction

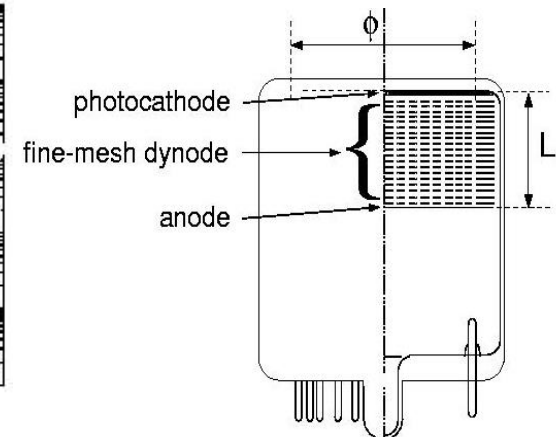
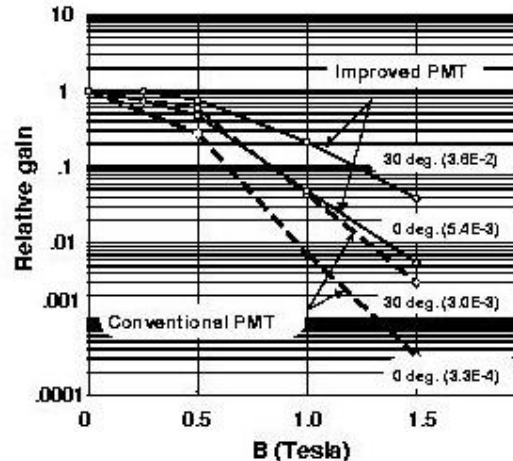
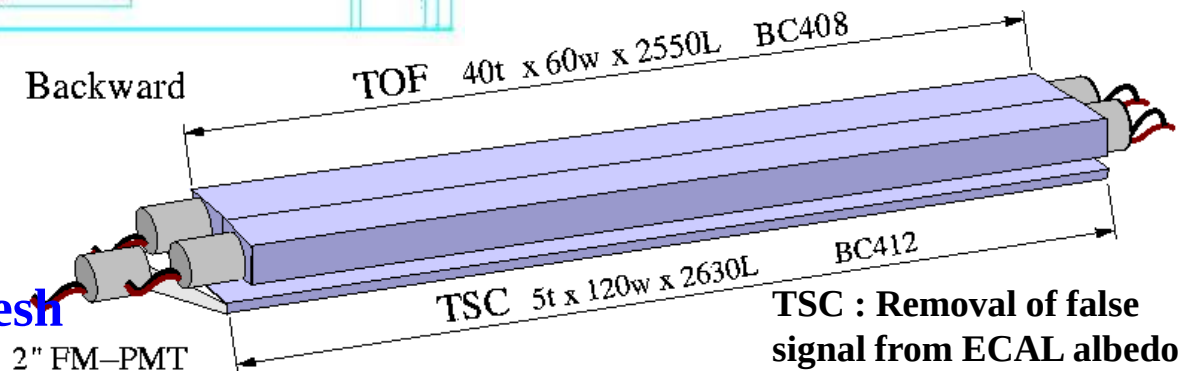


BELLE TOF detector

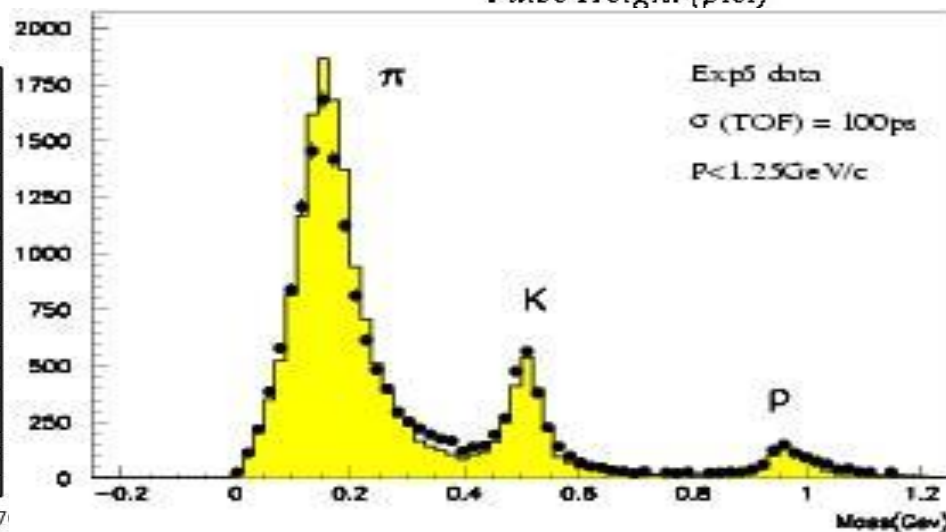
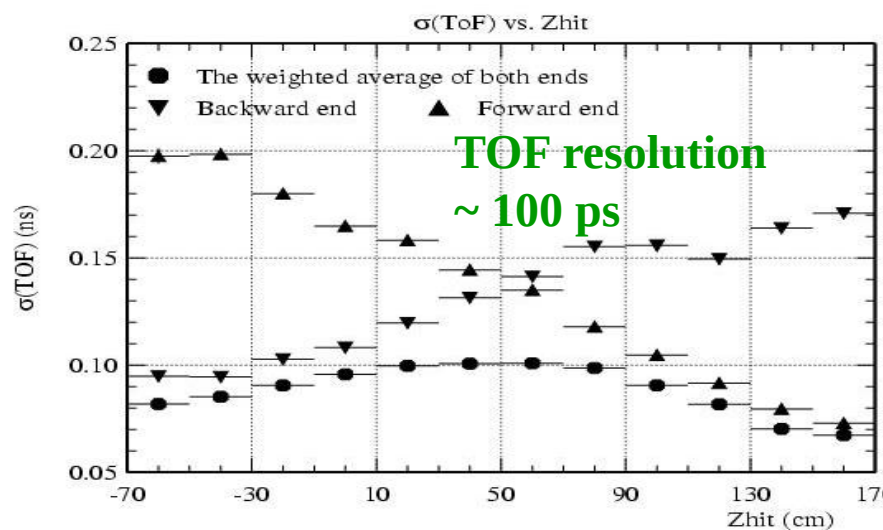
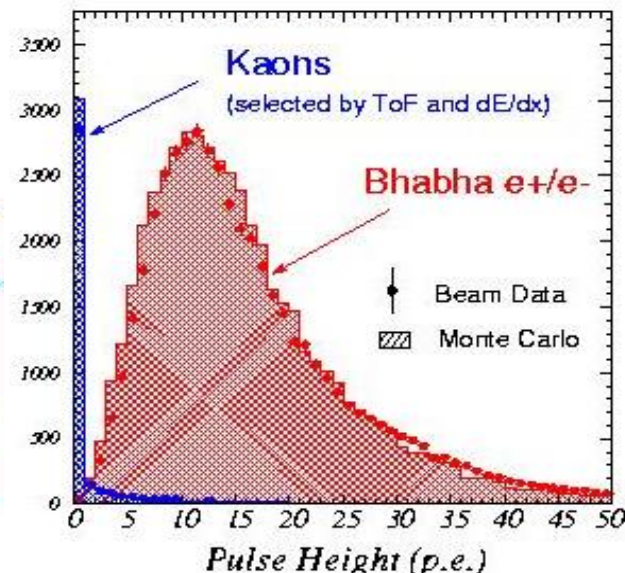
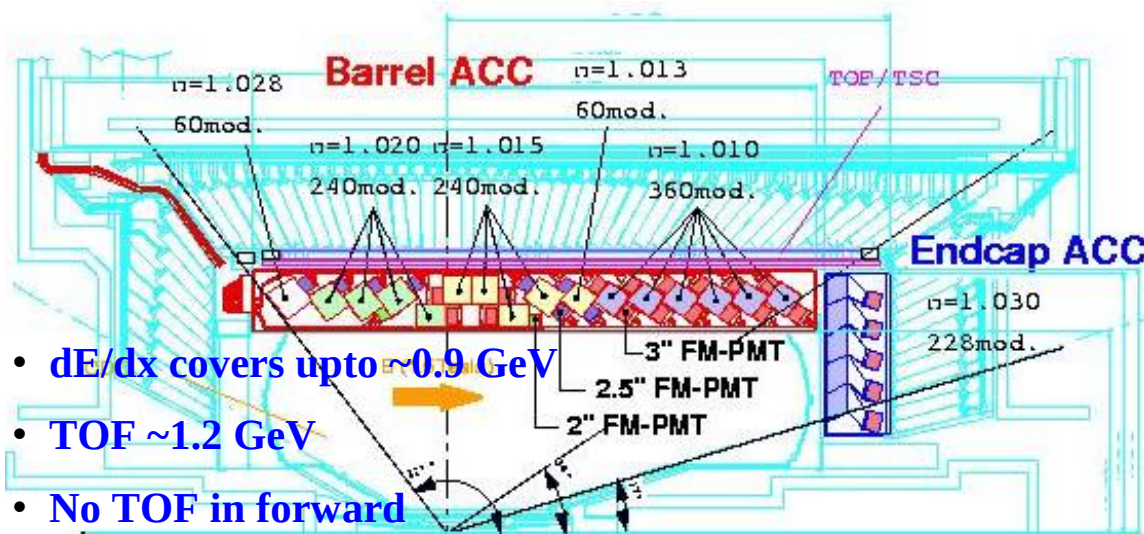


Forward

- **High B-field Operation**
- **HamamatsuR6680 Fine Mesh PMTs**
 - 24 stages
 - 2000 mesh/in.
 - $G > 3 \times 10^6$ in 1.5T field
- **TSC radius = 118 cm**
- **TOF radius = 120 cm**

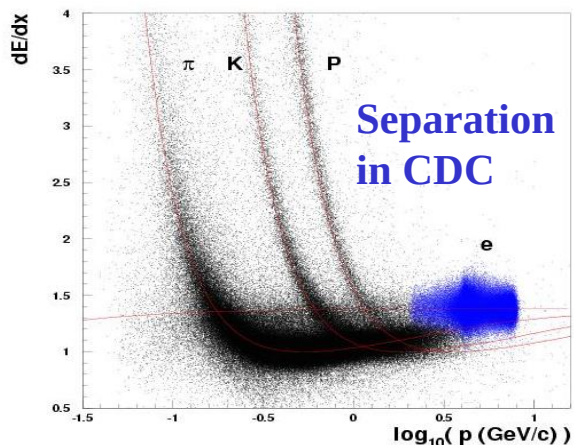


Particle identification at BELLE (K, π, p)



TOF reconstructed mass

Particle identification (K)

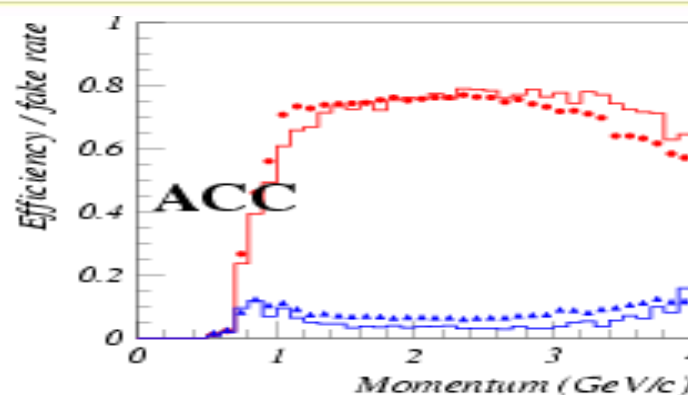
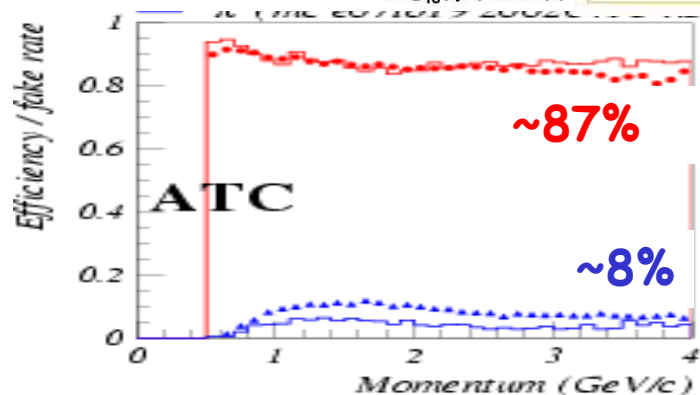
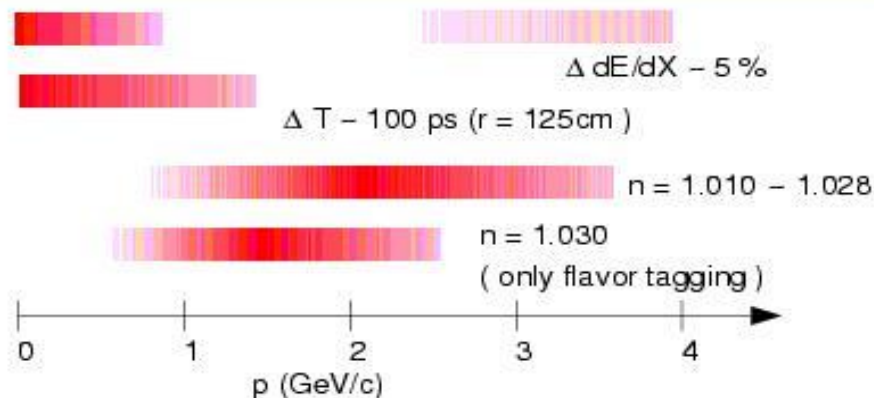


dE/dx (CDC)

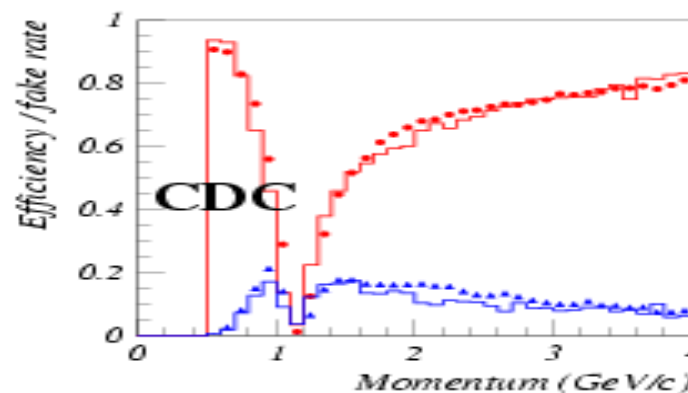
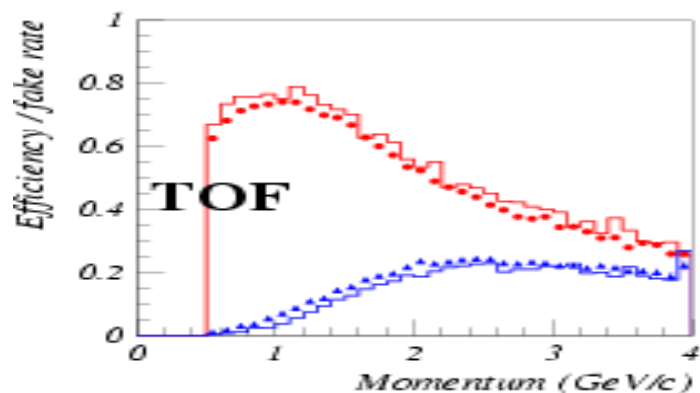
TOF (only Barrel)

Barrel ACC

Endcap ACC

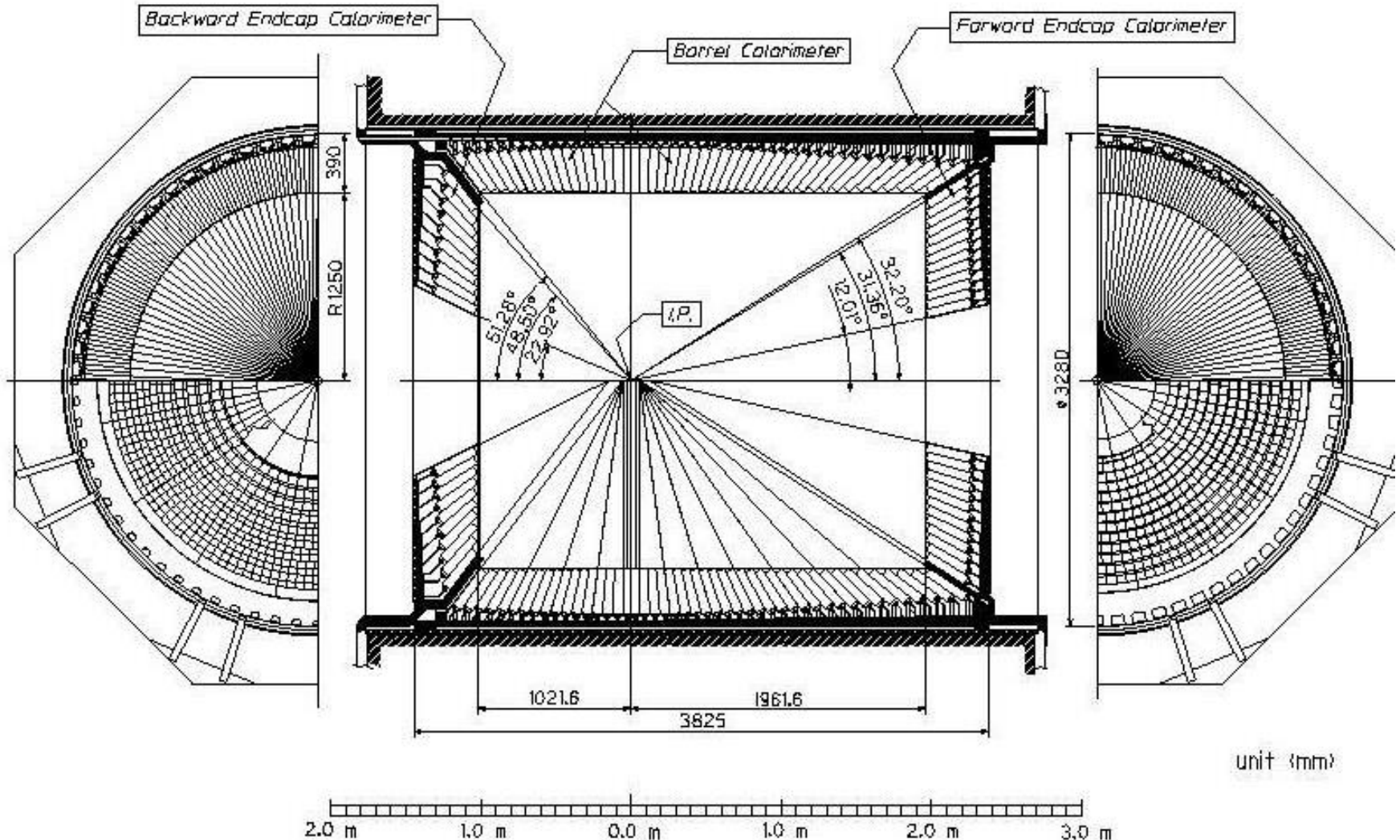


Momentum dependent identification criteria



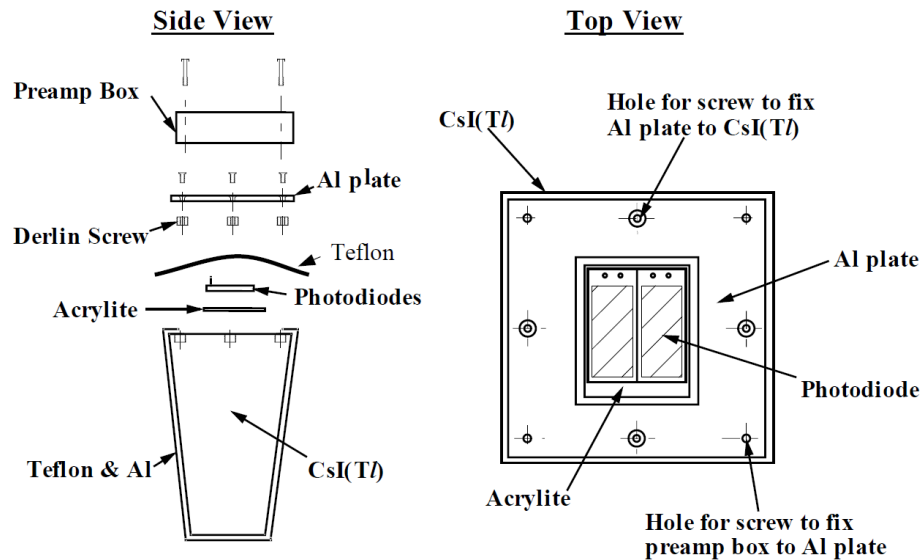
Efficiency(ϵ) = 81-93% with background 5-10 %

BELLE electromagnetic calorimeter



Total # of crystal = 1152 + 6624 + 960 of dimensions 5.5cm×5.5cm (6.5cm×6.5cm)×30cm in barrel and in endcaps, front face =4.45cm to 7.08cm and backend = 5.4cm to 8.2cm with length of 30cm(16.2X₀)

Performance of ECL



Calibration :

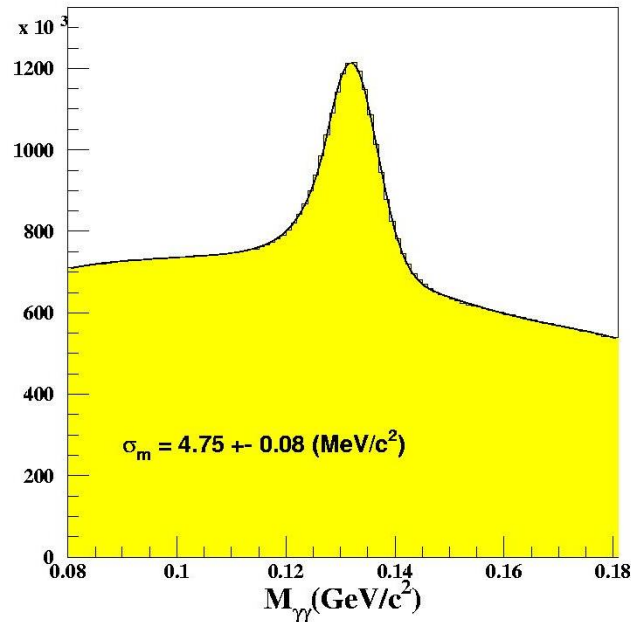
$\pi/\eta \rightarrow \gamma\gamma$,

$D^* \rightarrow D\gamma$

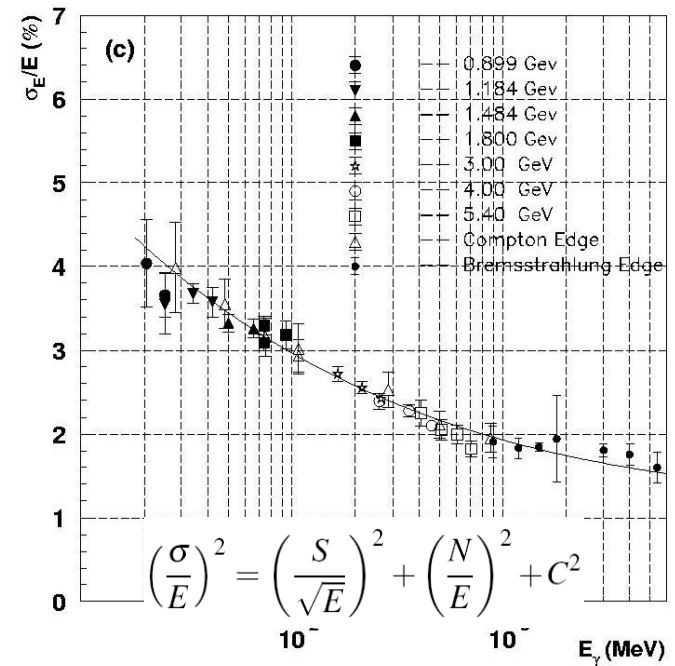
E (Calorimeter)

/P(tracker)

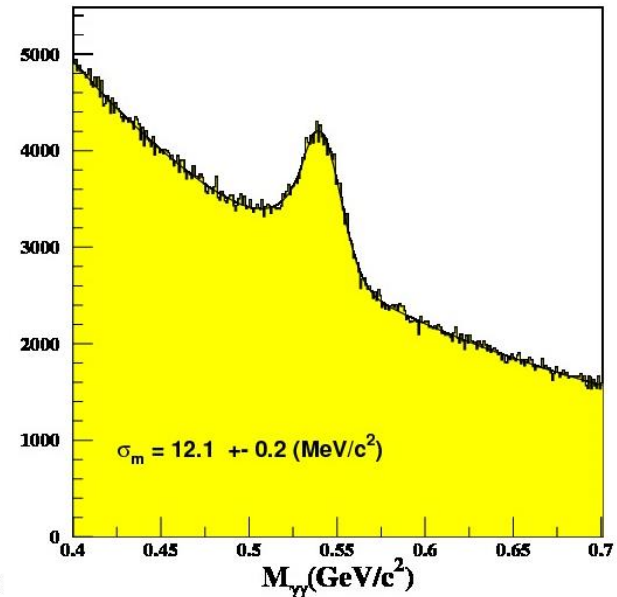
$\pi^0 \rightarrow \gamma\gamma$ in hadronic events



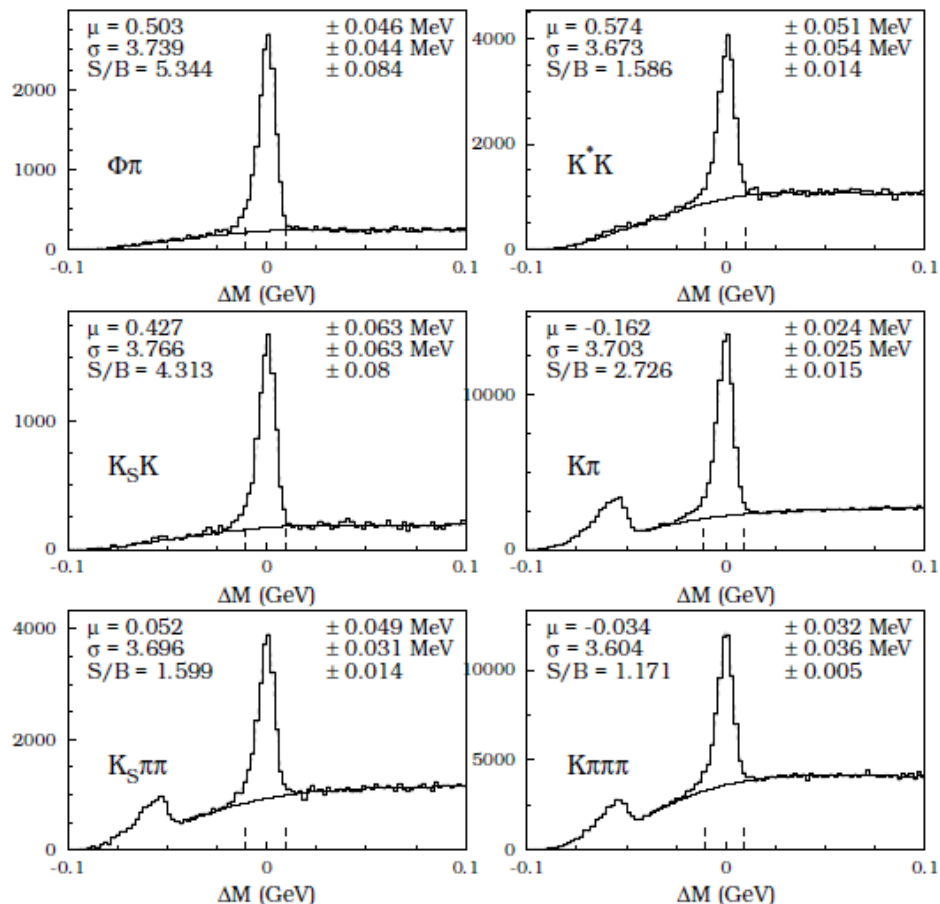
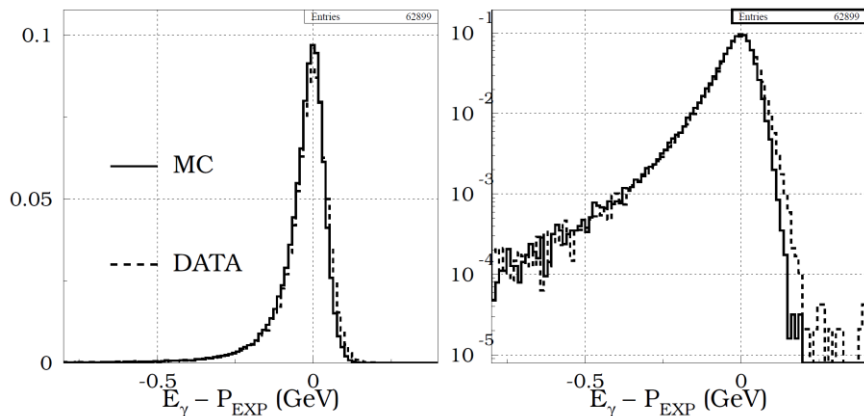
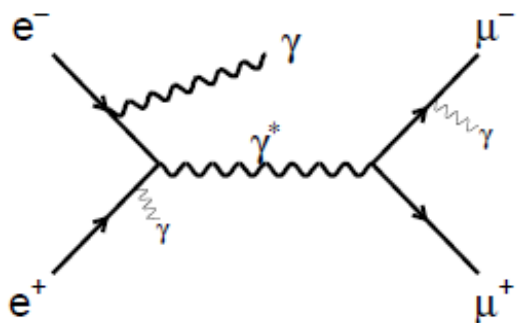
3 x 3 matrix with 0.5 MeV threshold



$\eta \rightarrow \gamma\gamma$ in hadronic events

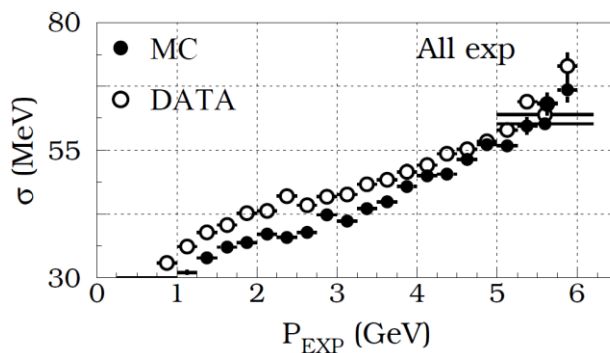
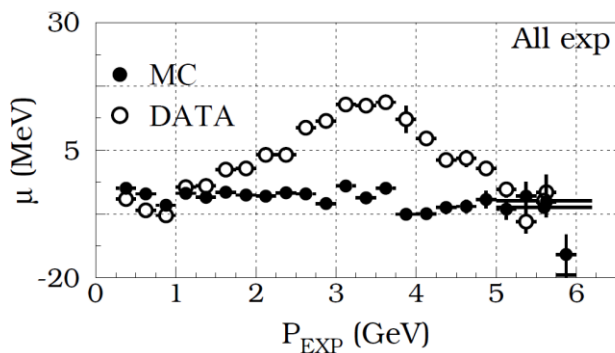


ECL calibration with data



- Data was corrected using these two calibrations

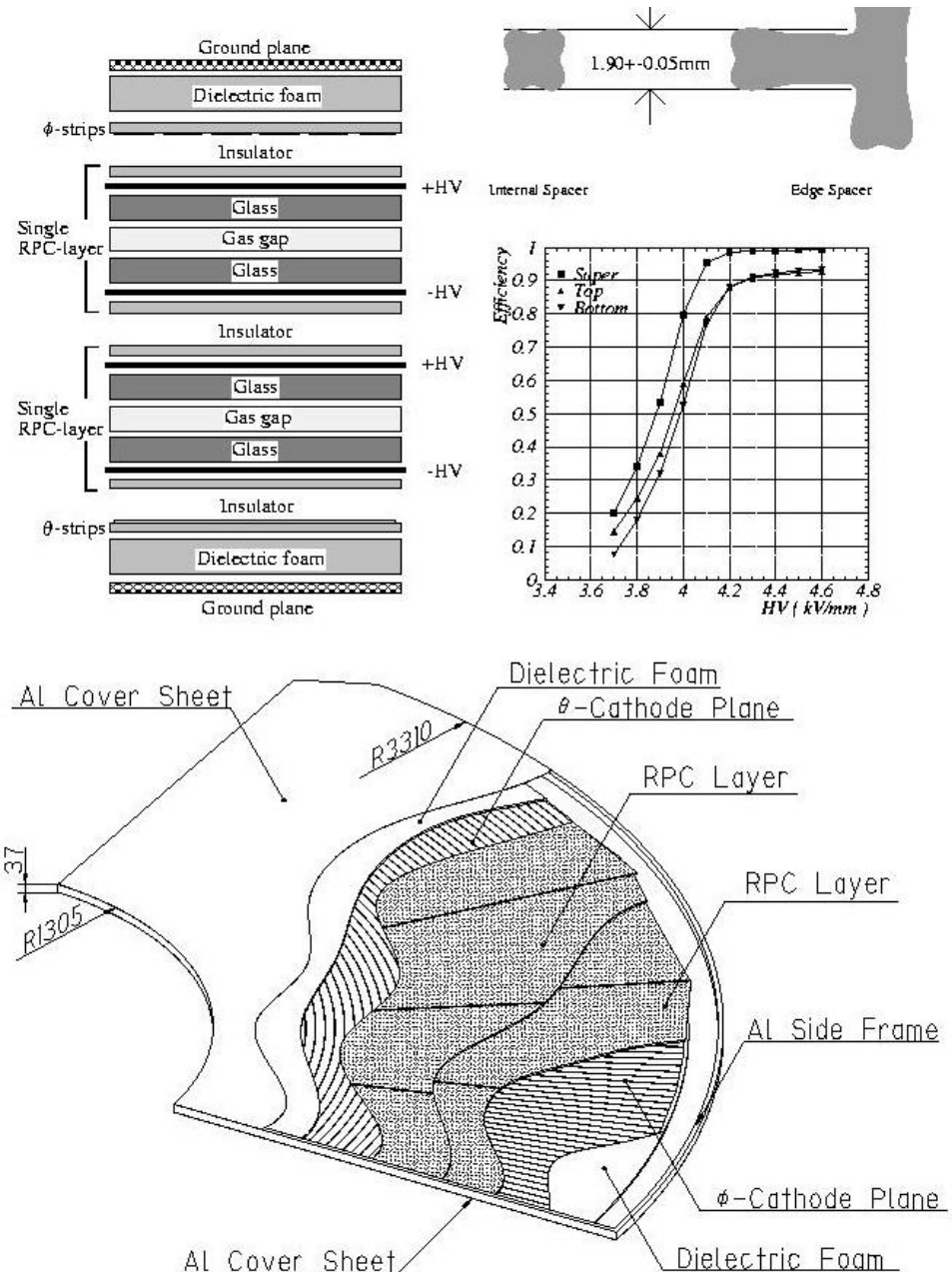
- Belle note # 583 & 718



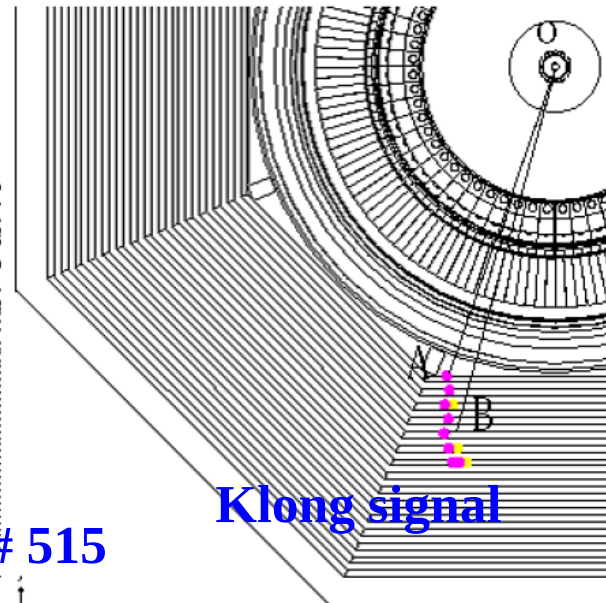
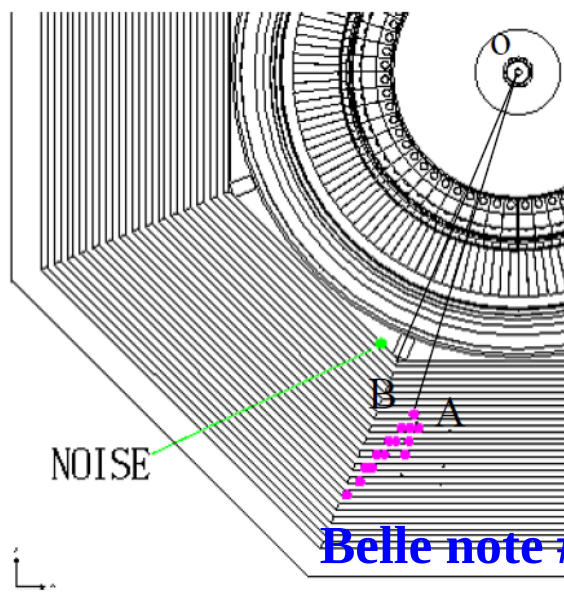
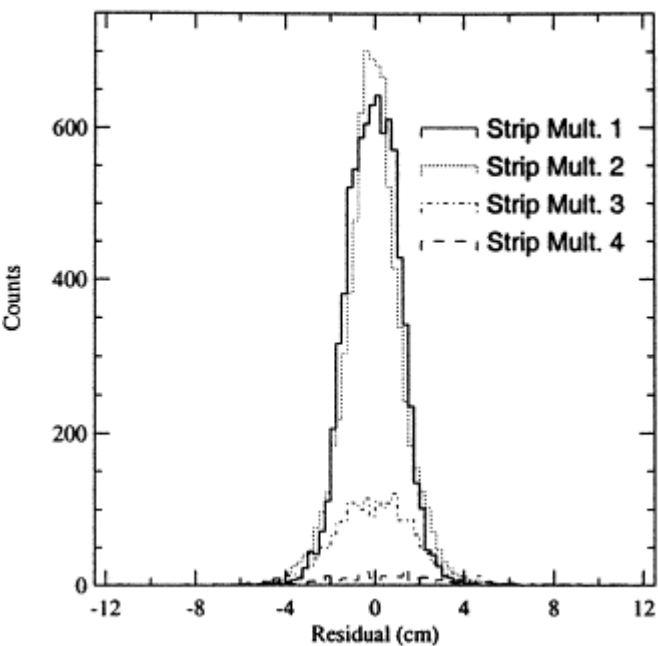
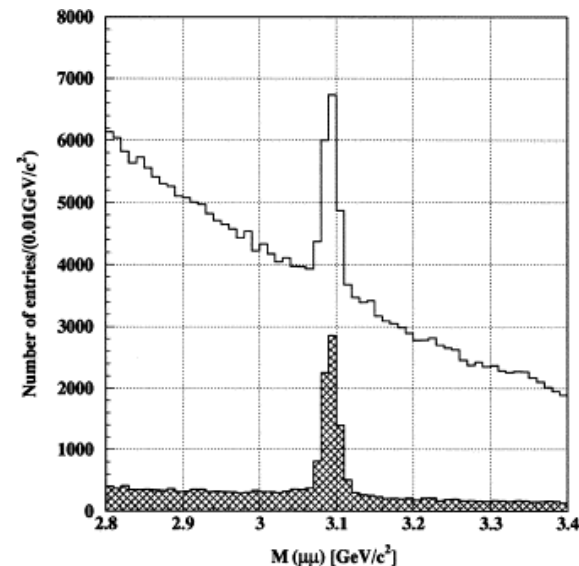
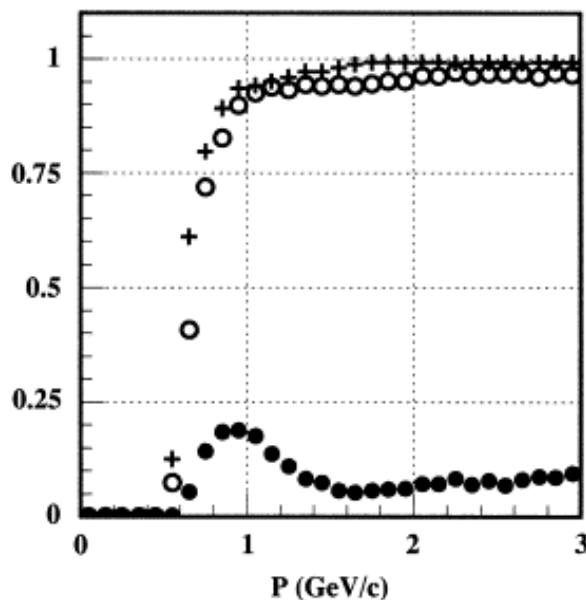
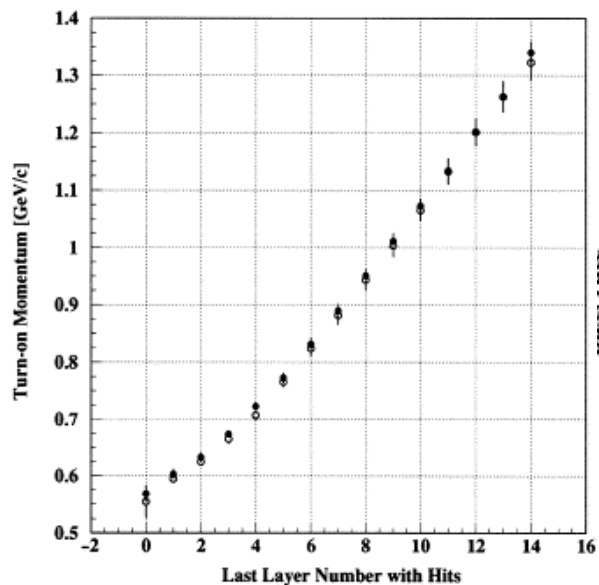
for $D^0 \rightarrow k^- D^*(s) \rightarrow D(s) \gamma$
 $\tau \rightarrow K_s^+ K^-$ for photon energy greater than 300 MeV.
 data : EXP07-EXP19.

KLM

- **Two parallel electrodes with high bulk resistivity**
 - $\sim 2 \times 10^{12} \Omega\text{-cm}$: glass,
 - $\sim 10^{10} \Omega\text{-cm}$: bakelite)
 - $\sim 10^4 \Omega\text{-cm}$: undepleted silicon
 - $1.68 \times 10^{-6} \Omega\text{-cm}$: Cu
 - $7.5 \times 10^{19} \Omega\text{-cm}$: Quartz
- **A local discharge of the plates due to initiation of streamer by an ionising particle**
- **Gain $\sim 10^6$ (avalanche mode) and 10^8 (streamer mode)**
- **Discharge limited by high resistivity and quenching characteristics of the gas**
- **Induced signal on external pickup strips**
- **Position and timing information**
 - Strip size 19mm(47mm) $\times$ 2m (5m)
 - Applied H.V. 8kV/1.9 mm
 - Timing resolution : few ns
 - Rate $< 0.2\text{Hz/cm}^2$

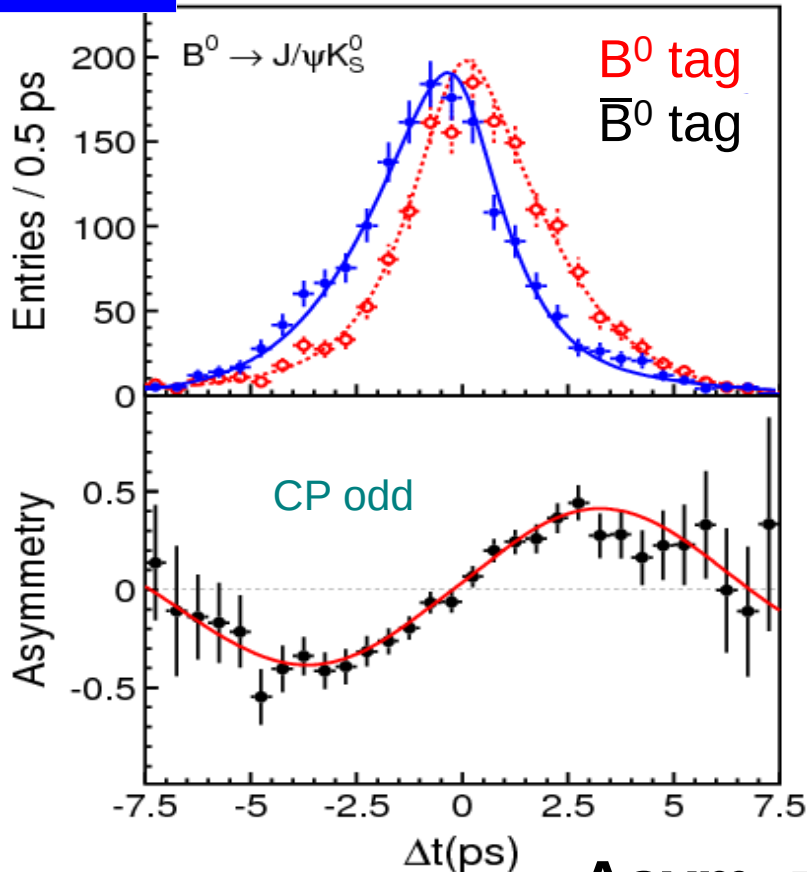


Performance of KLM





$$B^0 \rightarrow J/\psi K_S^0$$

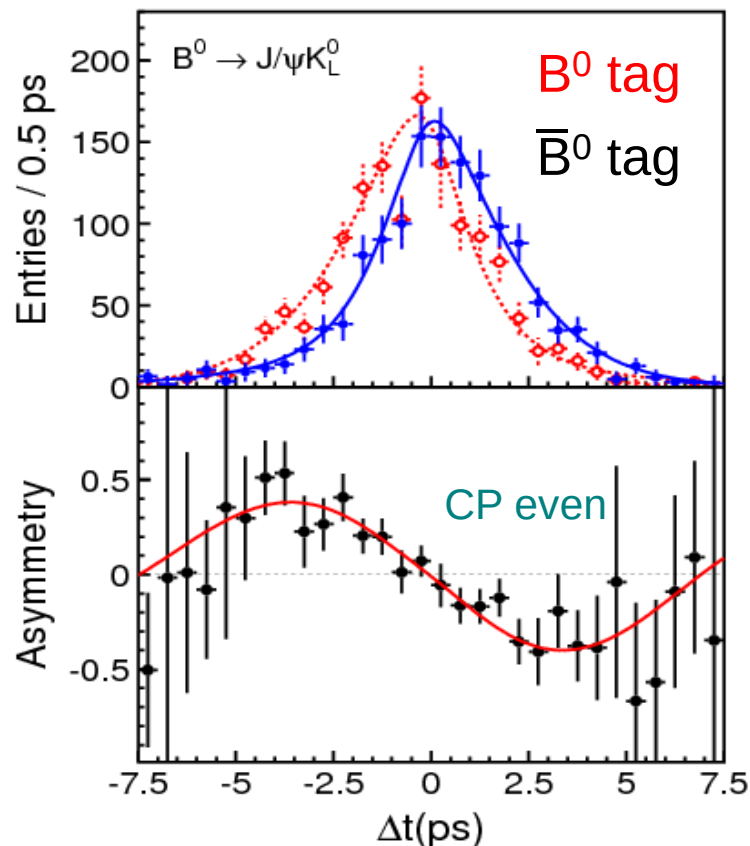


$$\text{Asym.} = -\xi_{CP} \sin 2\phi_1 \sin \Delta m \Delta t$$

$$\sin 2\phi_1 = +0.643 \pm 0.038$$

$$A = -0.001 \pm 0.028$$

$$B^0 \rightarrow J/\psi K_L^0$$

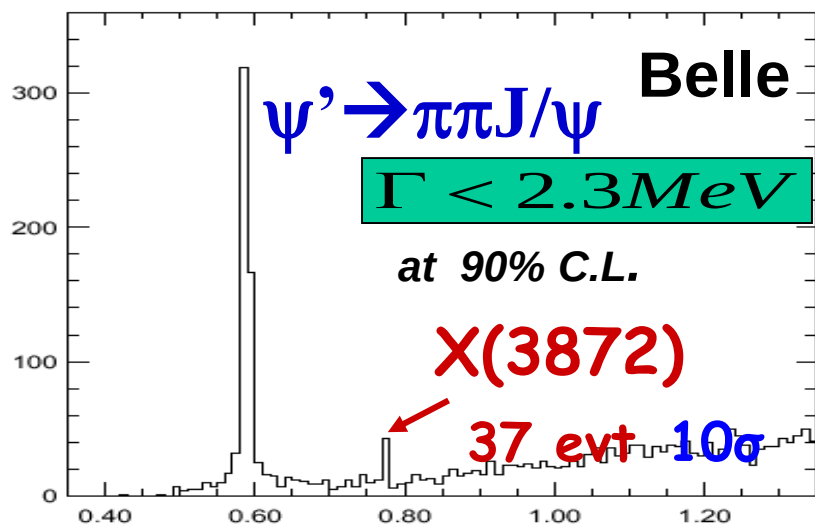


$$\sin 2\phi_1 = +0.641 \pm 0.057$$

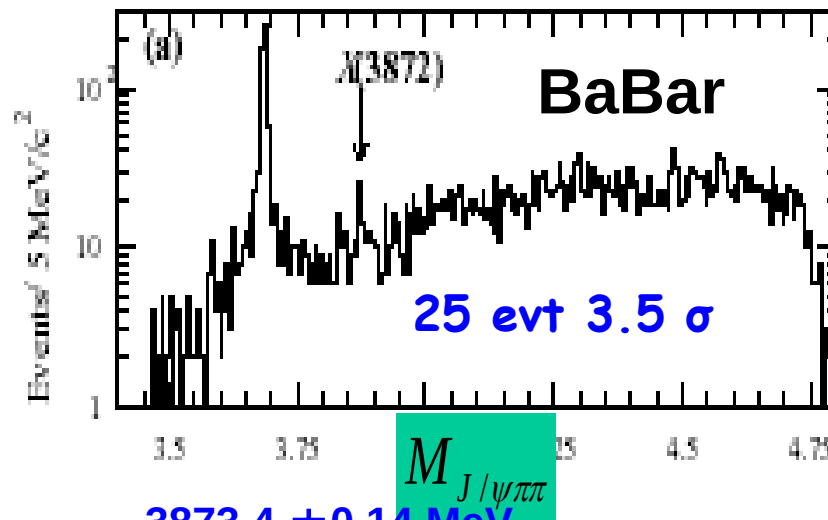
$$A = +0.045 \pm 0.033$$

All results of $b \rightarrow ccs$ and $b \rightarrow ccd$ are consistent with each other

Observation of $(J/\psi\pi^+\pi^-)$ peak in $B \rightarrow J/\psi\pi^+\pi^-K$ signal

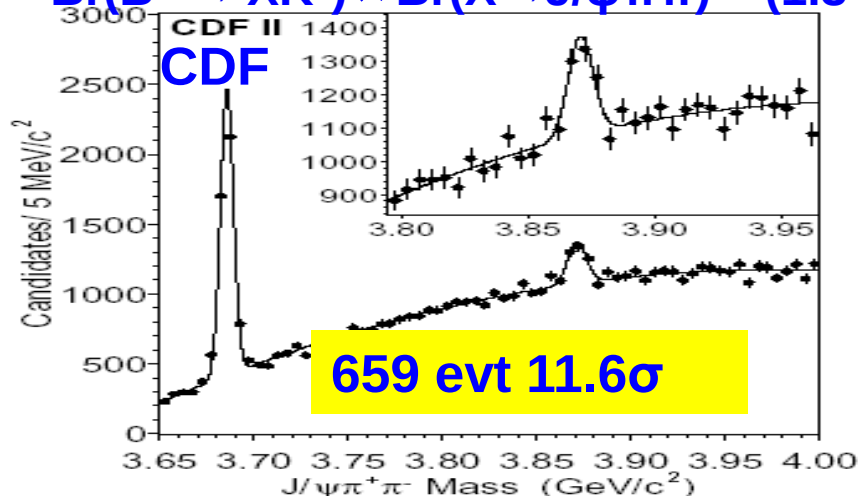


$$M_X = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV}$$

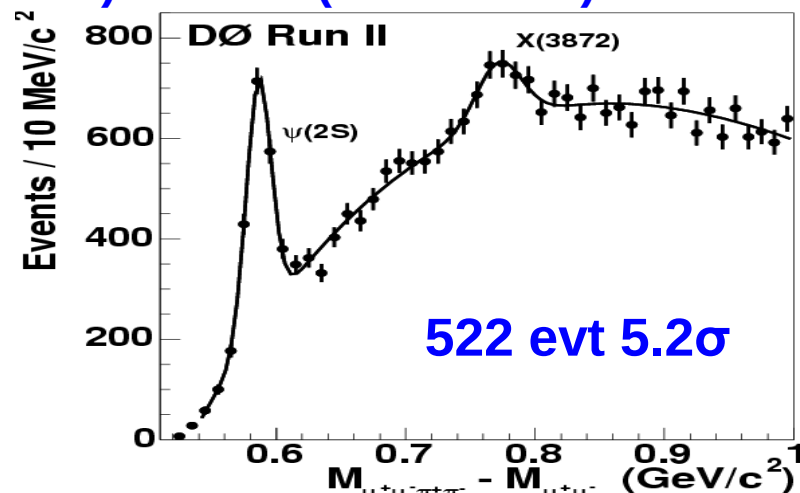


$$3873.4 \pm 0.14 \text{ MeV}$$

$$\text{Br}(B^- \rightarrow XK^-) \times \text{Br}(X \rightarrow J/\psi\pi\pi) = (1.3 \pm 0.3) 10^{-5} \quad (1.28 \pm 0.41) 10^{-5}$$



$$M_X = 3871.3 \pm 0.7 \pm 0.4 \text{ MeV}$$

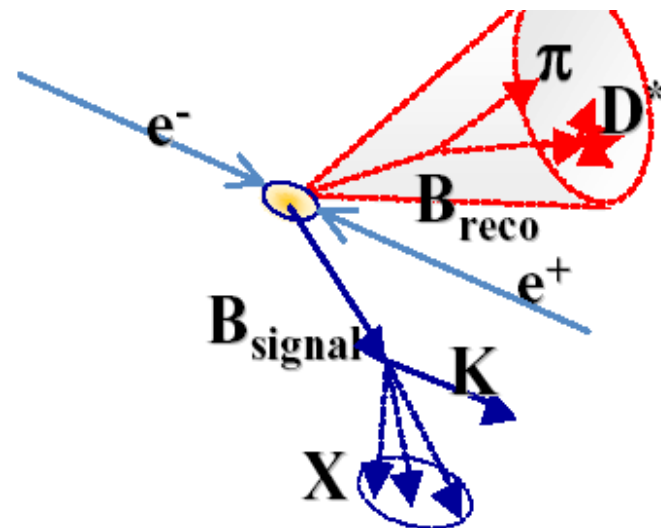
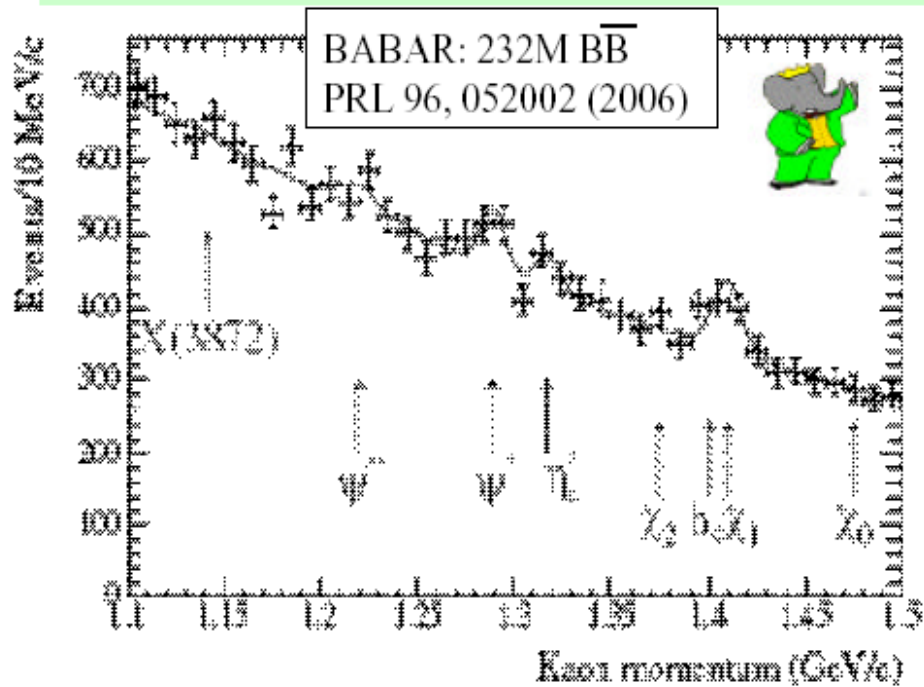


$$M_{J/\psi\pi\pi} - M_{J/\psi} = 774.9 \pm 3.1 \pm 3.0$$

$$3871.77$$

Inclusive $B \rightarrow XK$ from BaBar

- Fully reconstruct one B
- Measure $p(K)$ in the other B frame
- Calculate $m(X)$ based on $p(K)$



$BF(B^\pm \rightarrow K^\pm c\bar{c})$ are consistent with PDG values for known charmonia

Efficiency $\sim 0.5\%$

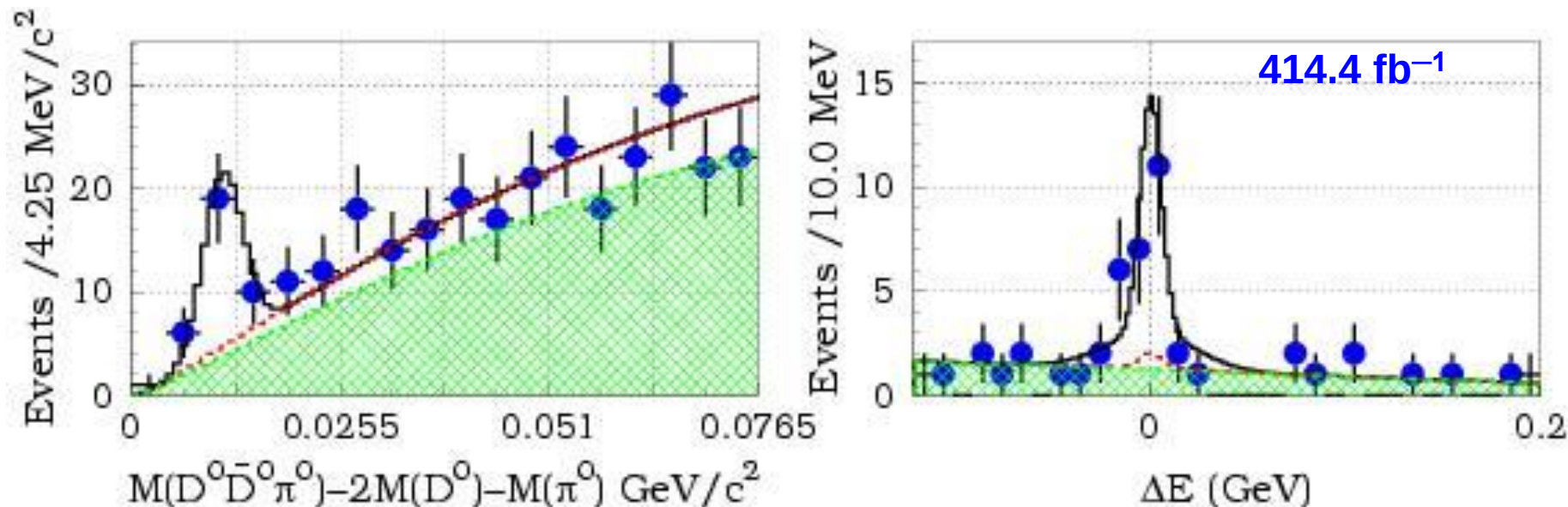
Determined lower/upper limits on **absolute BF's**

$B(B^\pm \rightarrow K^\pm X(3872)) < 3.2 \times 10^{-4} @ 90\% \text{ CL}$

$B(X(3872) \rightarrow \pi^+ \pi^- J/\psi) > 4.2\% @ 90\% \text{ CL}$

Observation $D^0\bar{D}^0\pi^0$ threshold peak in $B \rightarrow D^0\bar{D}^0\pi^0 K$ signal

D^0 reconstruction : $K^-\pi^+$, $K^-\pi^+\pi^0\pi^+$, $K_S\pi^+\pi^-$ and K^+K^-



Signal	$\epsilon\mathcal{B} \times 10^4$	N_{obs}	sig, σ	$\mathcal{B} \times 10^4$
$B \rightarrow D^0\bar{D}^0\pi^0 K$	2.12 ± 0.10	24.1 ± 6.1	6.4	$1.27 \pm 0.31^{+0.22}_{-0.39}$
$B^+ \rightarrow D^0\bar{D}^0\pi^0 K^+$	3.62 ± 0.14	17.4 ± 5.2	5.0	$1.07 \pm 0.31^{+0.19}_{-0.33}$
$B^0 \rightarrow D^0\bar{D}^0\pi^0 K^0$	0.84 ± 0.04	6.5 ± 2.6	4.6	$1.73 \pm 0.70^{+0.31}_{-0.53}$

Fitted peak, $M = 3875.4 \pm 0.7^{+0.7}_{-1.7} \pm 0.8$ MeV

$$\frac{\text{Br}(X \rightarrow D^0\bar{D}^0\pi^0)}{\text{Br}(X \rightarrow \pi^+\pi^- J/\psi)} = 9 \pm 4$$

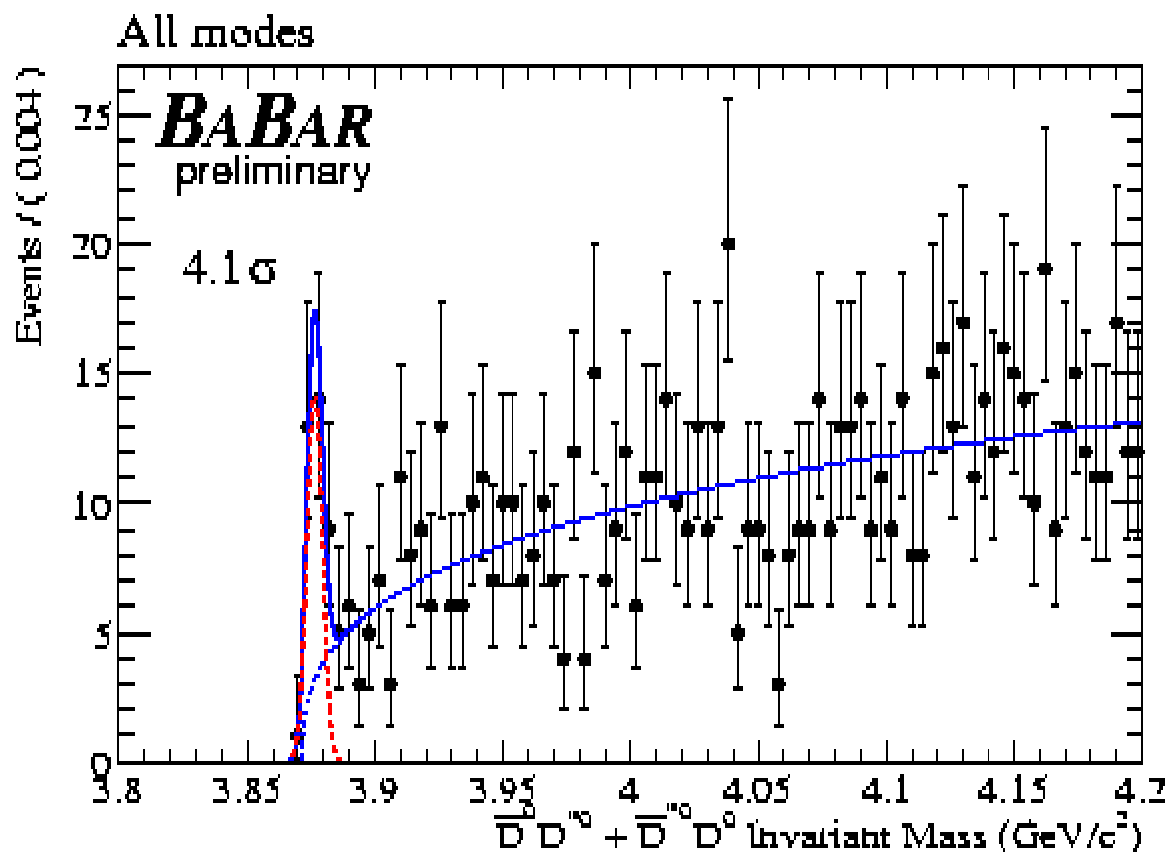
Threshold enhancement in $B \rightarrow (D^0 \bar{D}^{*0}) K$

BaBar
@Moriond
2007

$B \rightarrow D^{*0} \bar{D}^0 K$
(all four mode)

With

$D^{*0} \rightarrow D^0 \gamma$ & $D^0 \pi^0$



The mass is also 2.5σ above the nominal X(3872) mass

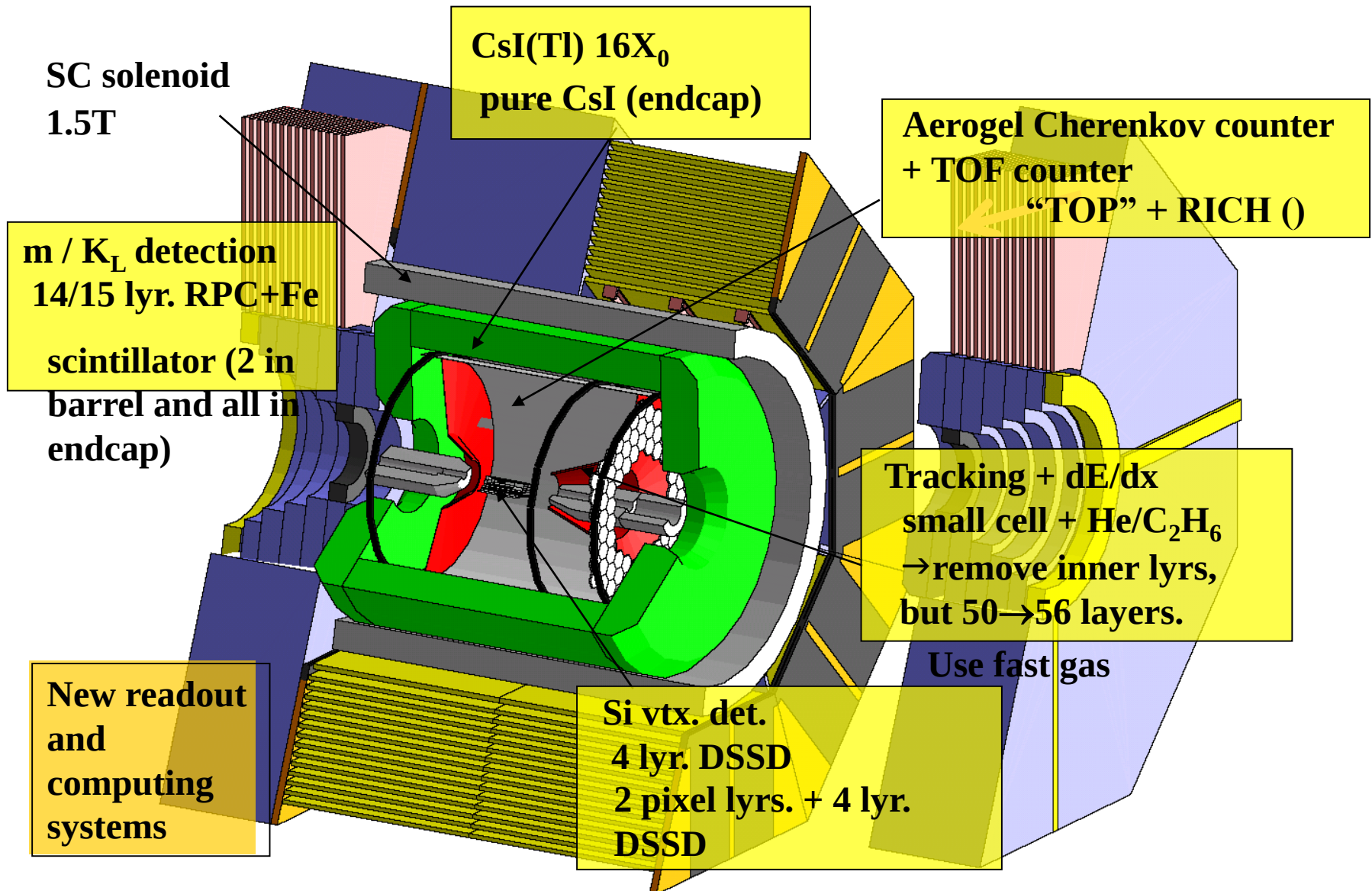
~~X(3872)~~

Signals in $J/\psi \pi \pi$ and $D^0 \bar{D}^0 \pi^0$ are due to same or different particle ?

Motivation for BELLE2 experiment

- Measurements of rare decay modes (e.g., $B \rightarrow \tau \nu$, $D \tau \nu$);
- Observation of new charmonium-like and bottomonium-like hadronic states;
- $b \rightarrow s$ transitions: probe for new sources of CPV and constraints from the $b \rightarrow s \gamma$ branching fraction;
- Forward-backward asymmetry (AFB) in $b \rightarrow s l^+ l^-$ has become a powerful tool to search for physics beyond SM;
- Observation of DD mixing;
- Search for lepton flavour violation in τ decays;
- Study of the hadronic τ decays;
- Precise measurement of the hadronic cross sections in $\gamma\gamma$ and e^+e^- (γ ISR) processes

Belle-II



KEKB : Beam Energy 3.5/8.0 to 4.0/7.0 GeV, $L (10^{34})$: 2.11 to 80

Belle/II upgrade – side view

Physics Requirements

Flavor Tagging

$B \rightarrow \pi \pi$

$B \rightarrow DK$

Detector Line-up

dE/dx (CDC)

$\Delta dE/dX \sim 5\%$

TOF (only Barrel)

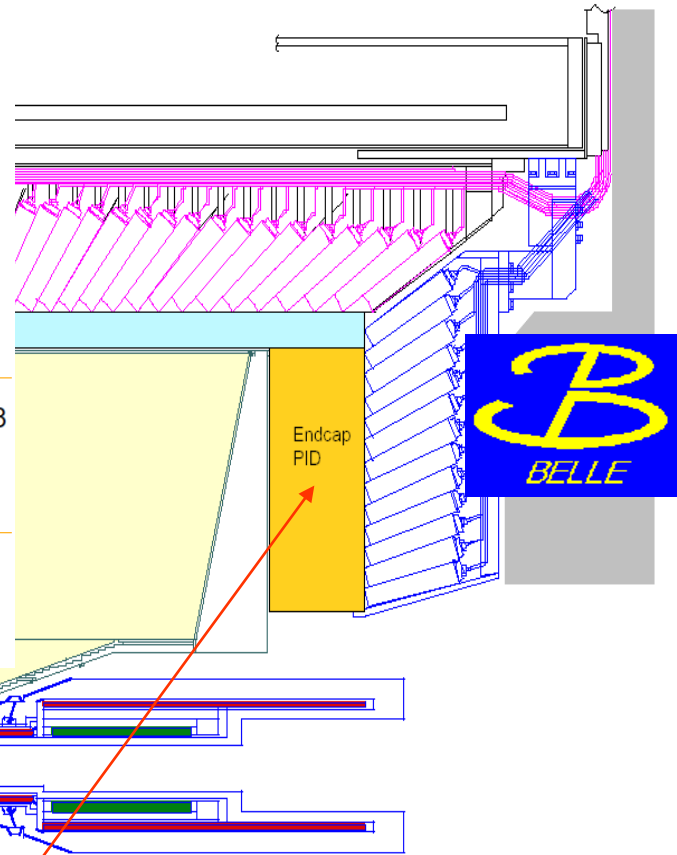
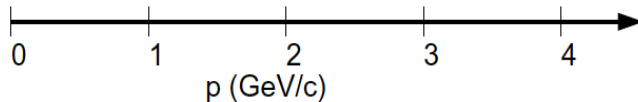
$\Delta T \sim 100 \text{ ps}$ ($r = 125 \text{ cm}$)

Barrel ACC

$n = 1.010 \sim 1.028$

Endcap ACC

$n = 1.030$
(only flavor tagging)



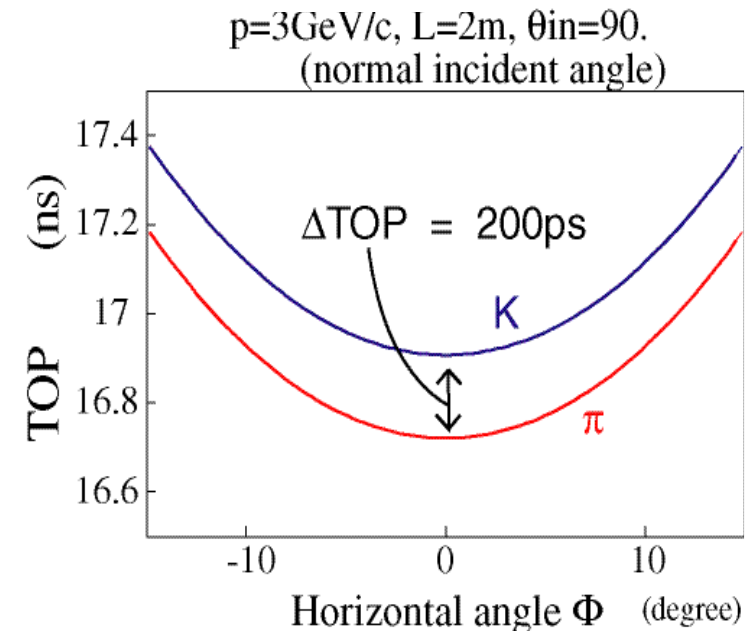
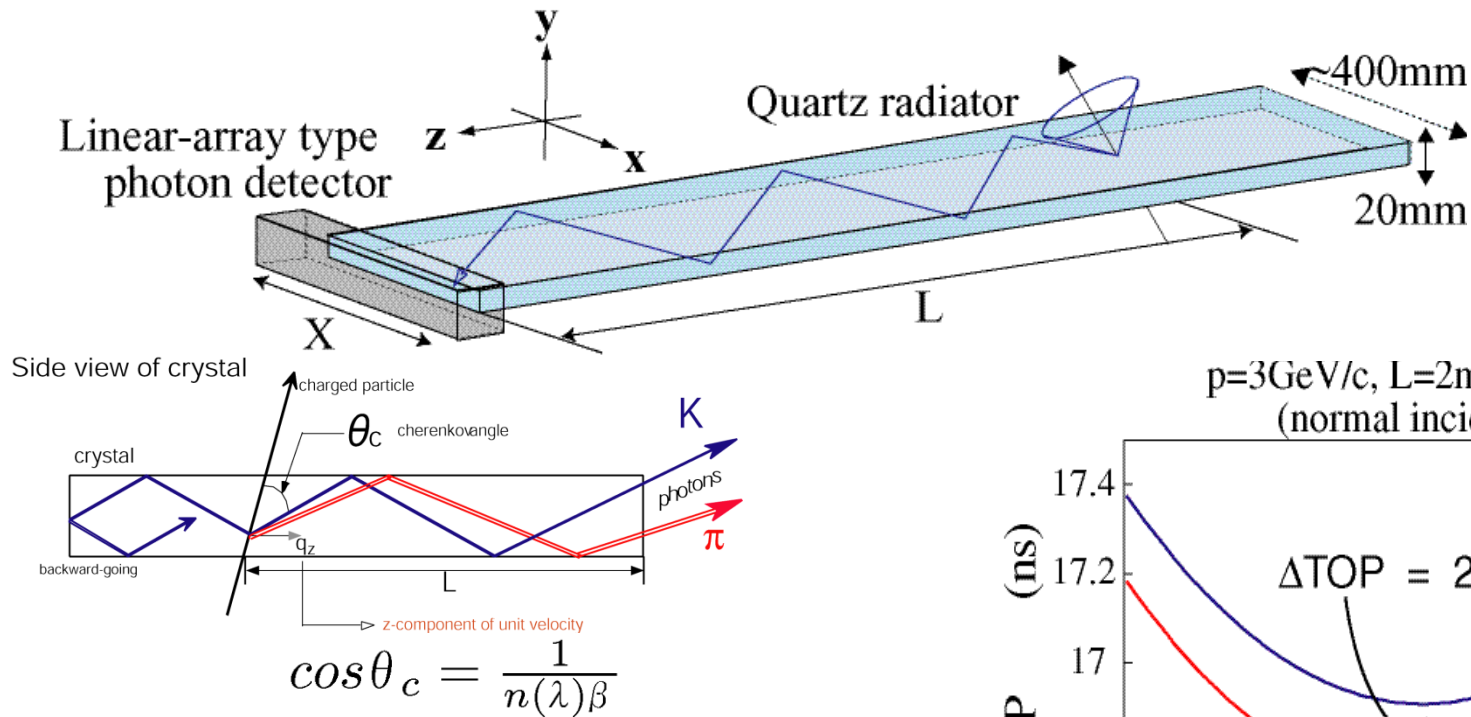
Two new particle ID devices, both RICHes:

Barrel: **Time-Of-Propagation (TOP)** or **focusing DIRC**

Endcap: **proximity focusing RICH**

Belle-II: TOP counter

Cherenkov ring imaging is used as timing information



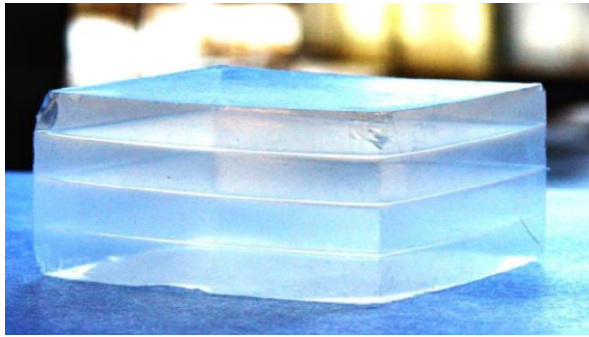
Difference of path length

→ Difference of **time of propagation** (TOP)
(+ TOF from IP)

With precise time resolution ($\sigma \sim 40\text{ps}$)

Particle-id with Aerogel RICH

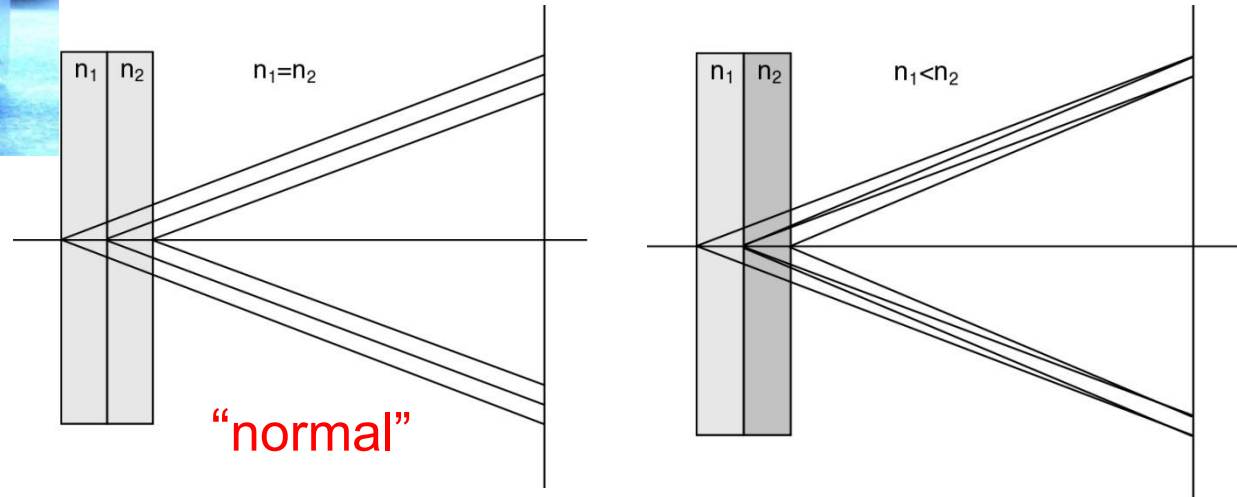
Multi layer Aerogel from



developed and
proposed for
Super-Belle
endcap region
to improve π/K

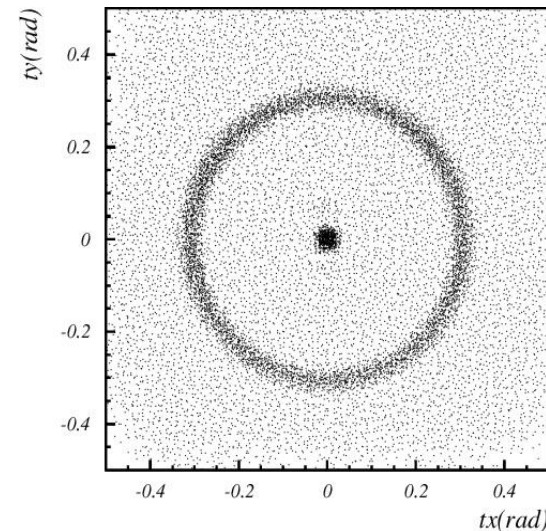
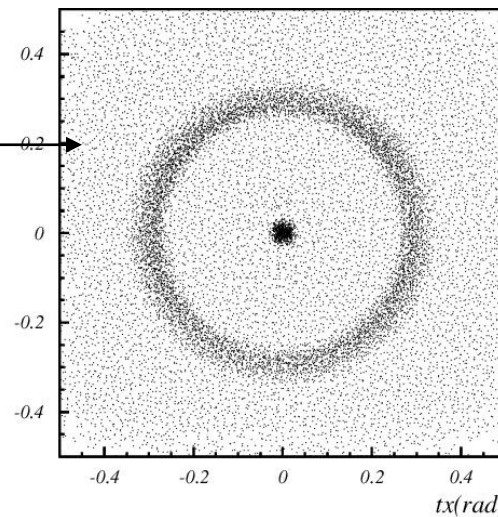
NIM A548 (2005) 383

stack two tiles with different refractive indices:
“focusing” configuration

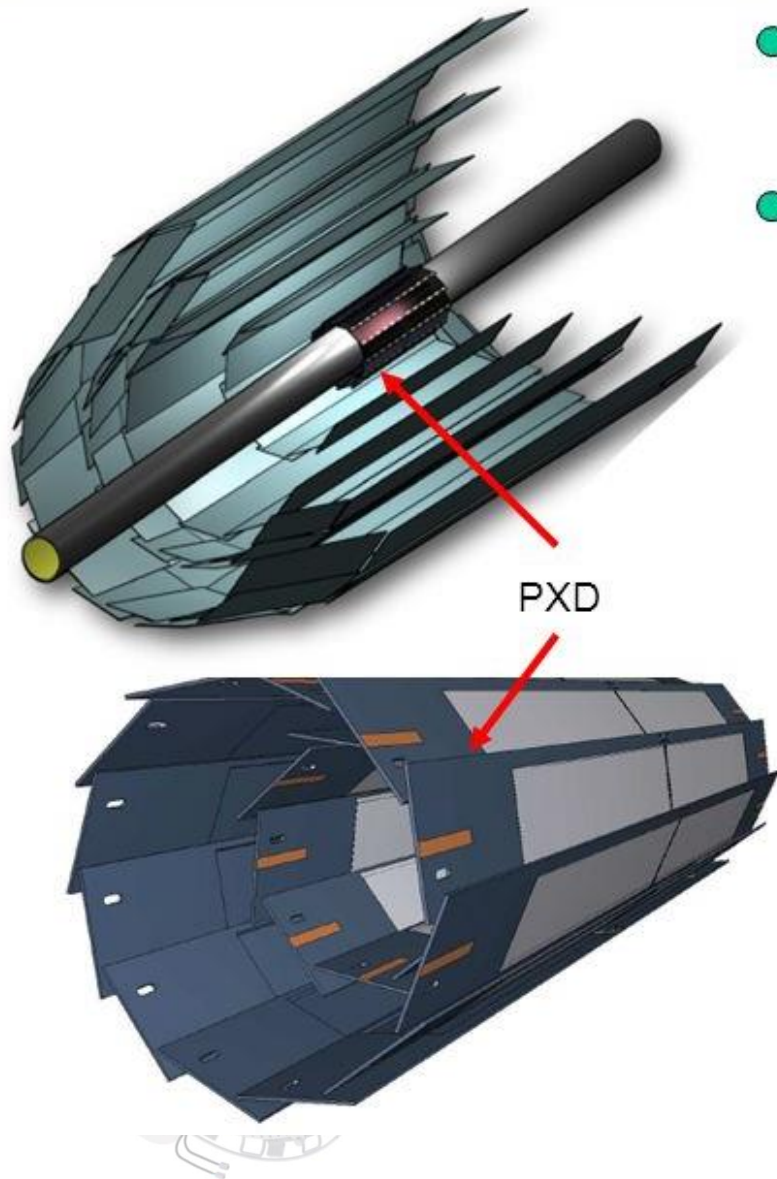


▲ Test beam results:

5.5 σ π/K separation
at 4 GeV with 9 pe
and
promise of ToF

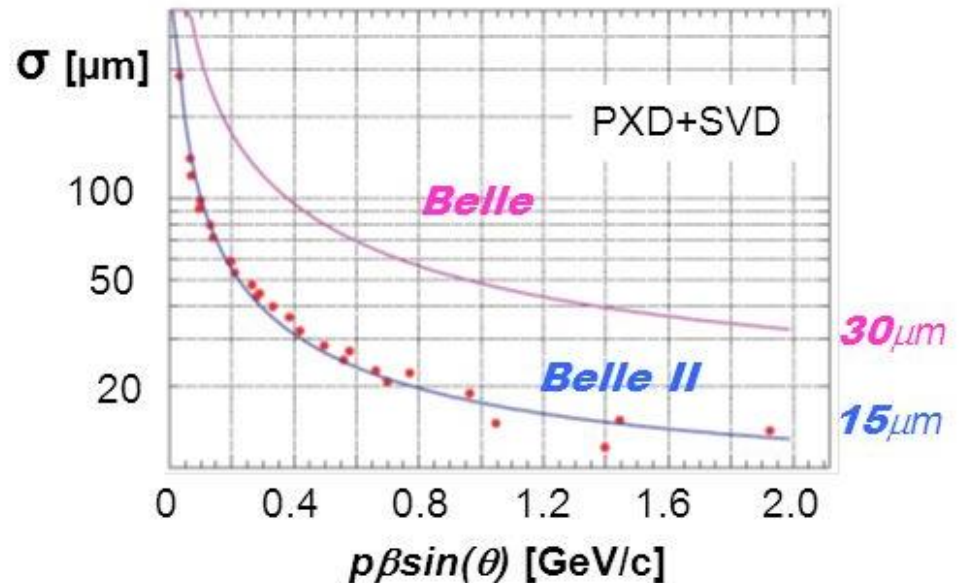


Upgraded vertex detector



- SVD: 4 layer Si strip detector (DSSD)
($R = 3.8, 8.0, 11.5, 14.0$ cm)
- PXD: 2 layer Si pixel detector (DEPFET technology)
($R = 1.4, 2.2$ cm)
monolithic sensor
thickness $75\text{ }\mu\text{m}$ (I),
pixel size $50 \times 55\text{ }\mu\text{m}^2$ to $50 \times 85\text{ }\mu\text{m}^2$ (depending on layer and z)

Significant improvement in z -vertex resolution



LHCb detector

Horizontal : $\pm 300\text{mrad}$
Vertical : $\pm 250\text{mrad}$

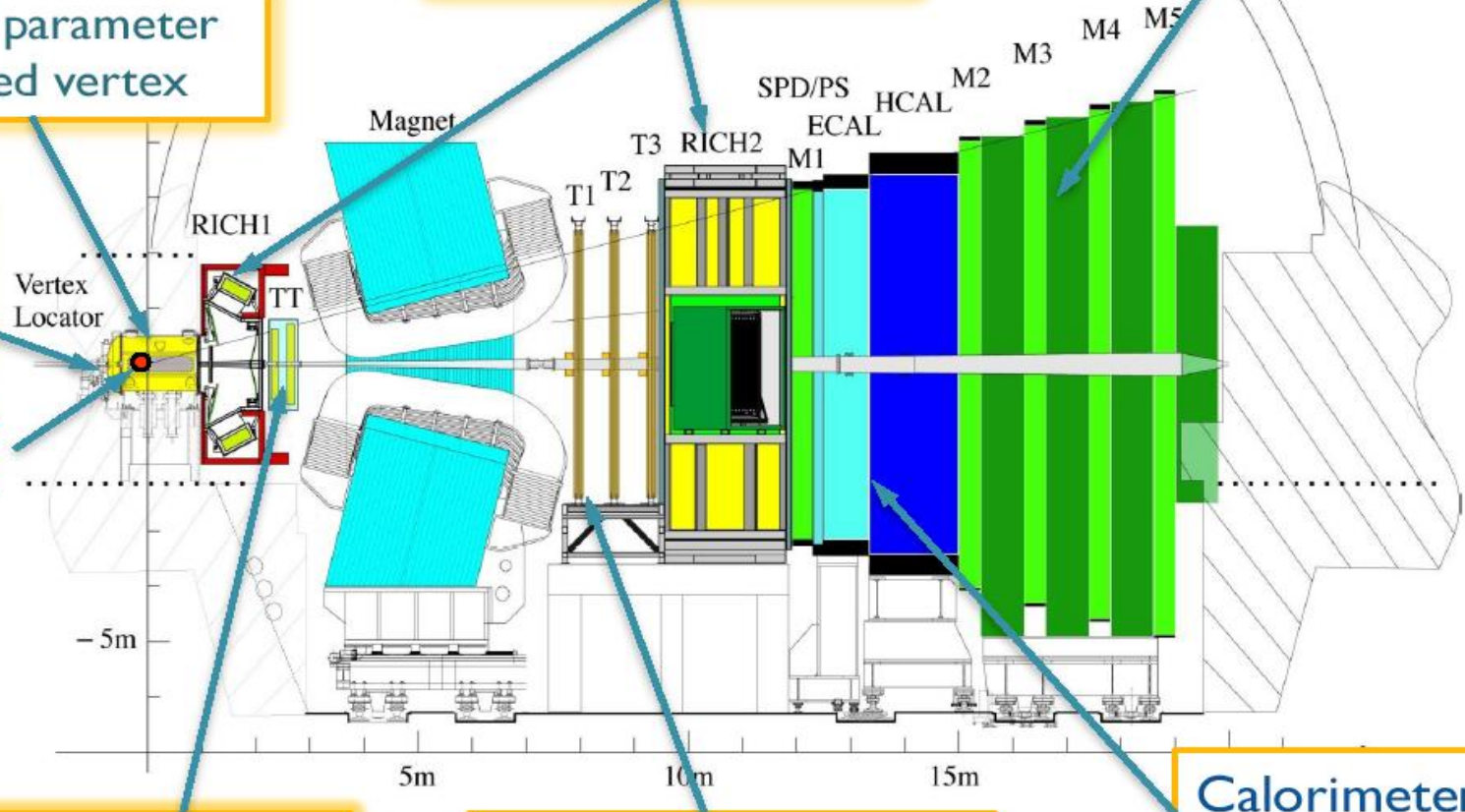
Muon System

VELO:
primary vertex
impact parameter
displaced vertex

RICHES:
PID: K, π separation

PileUp
System

Interaction
region



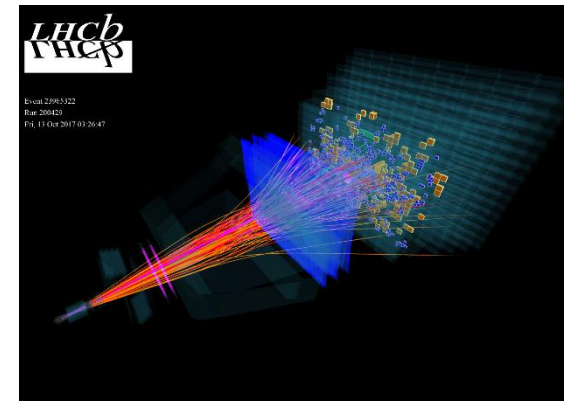
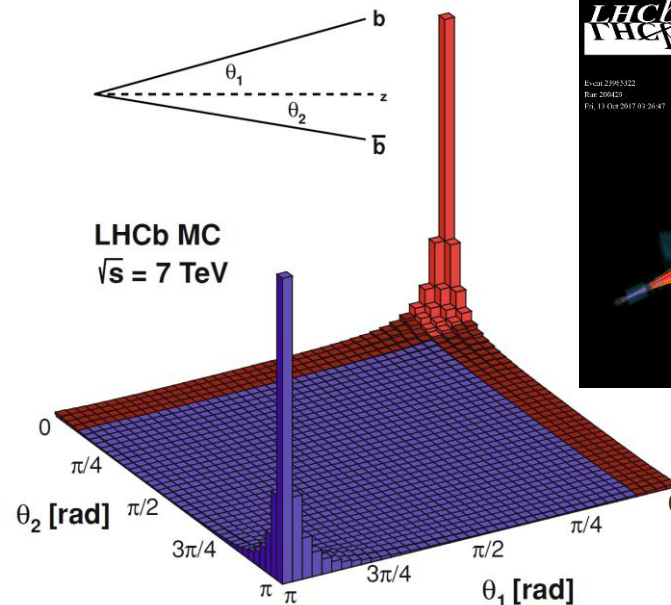
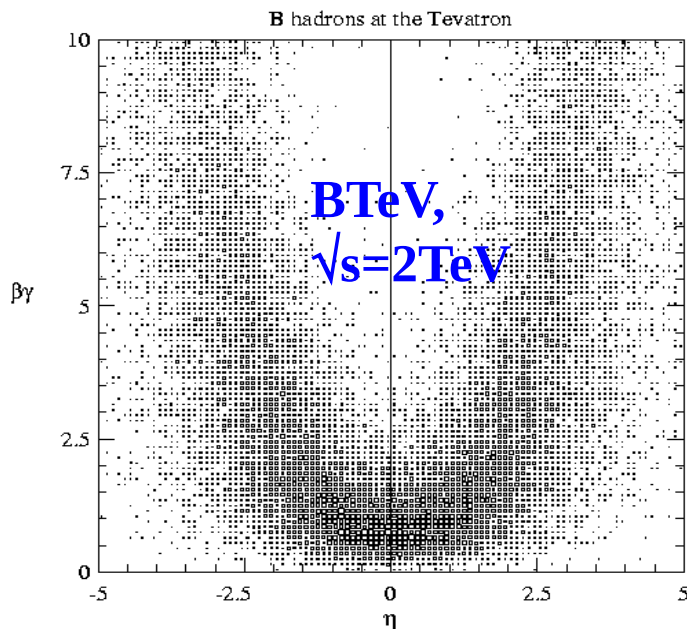
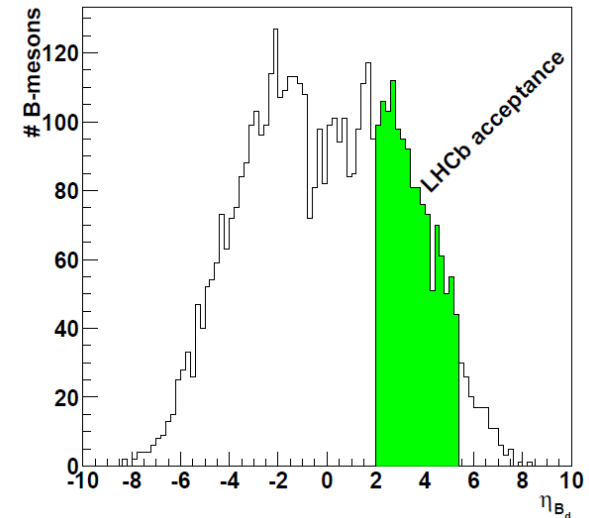
Trigger Tracker: p for
trigger and K_s reco

Tracking Stations:
 p of charged particles

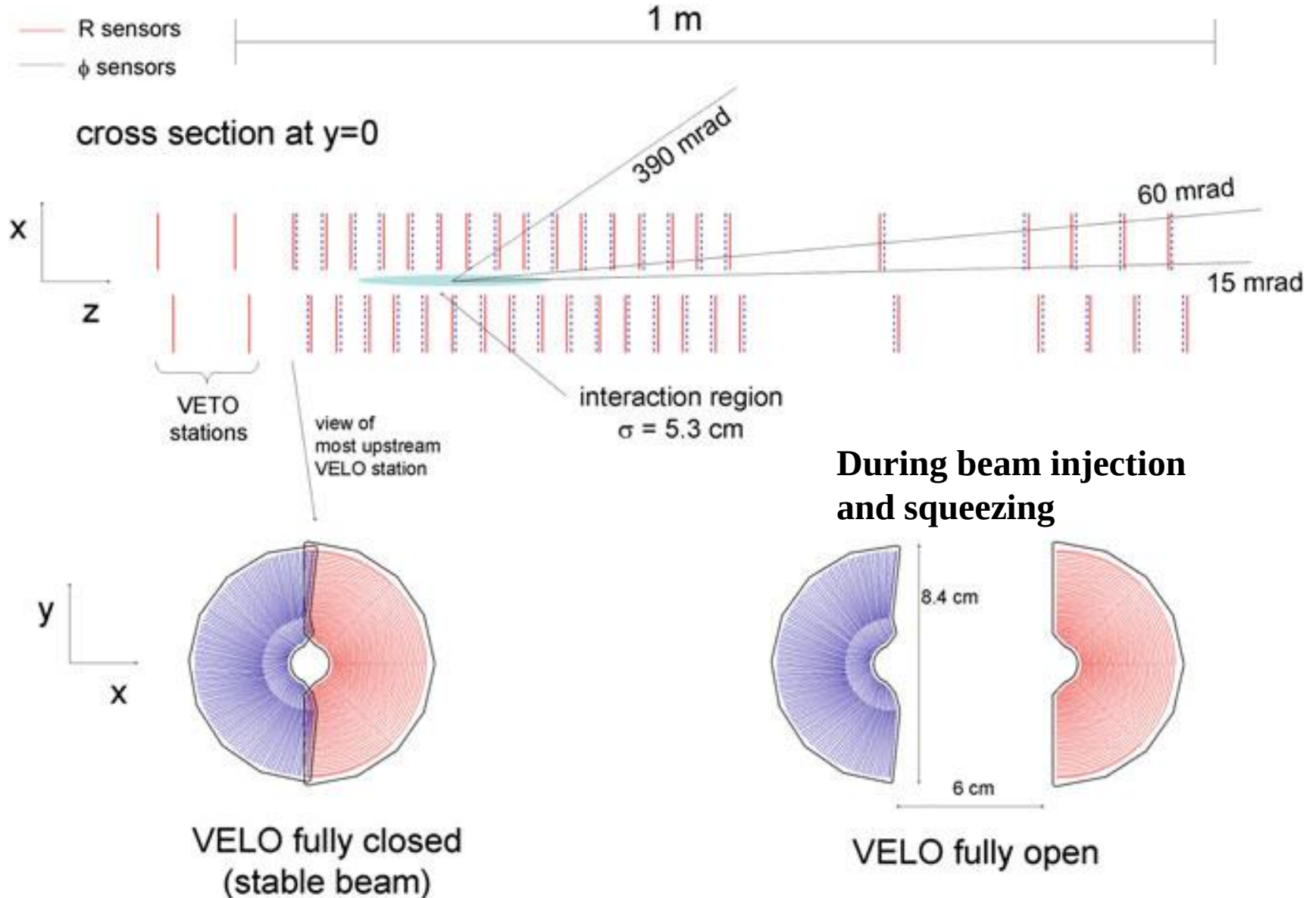
Calorimeters:
PID: e, γ, π^0

Characteristics of hadronic b production in hadron collider

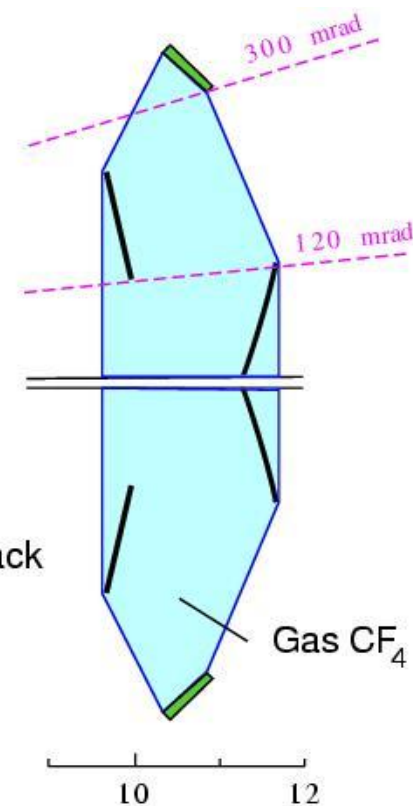
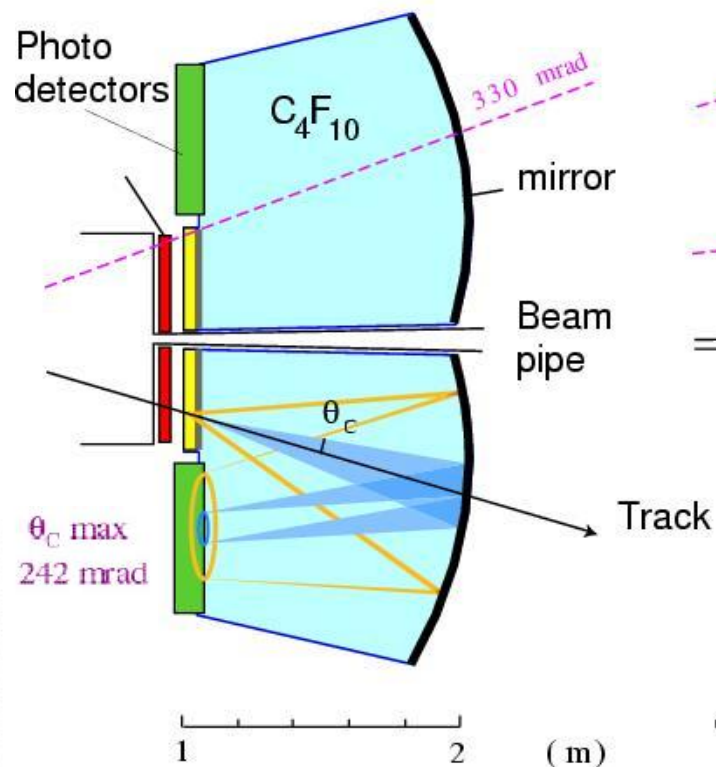
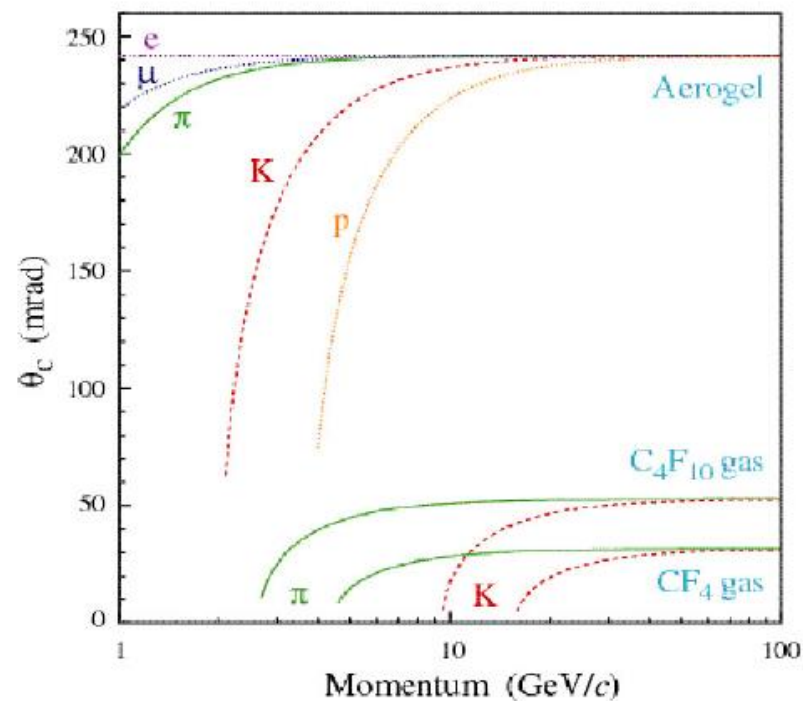
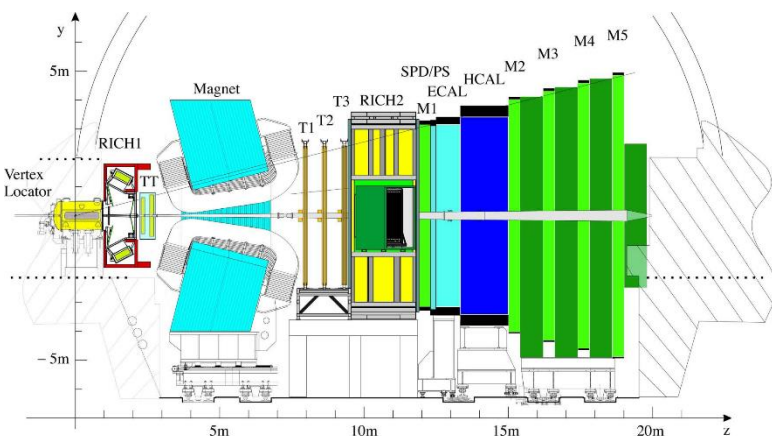
- B_s & Λ_b and other b-flavored hadrons are accessible at hadron collider.
- The higher momentum b's are at larger η 's
- b production peaks at large angles with large bb correlation



LHCB VELO detector



LHC-B RICH system



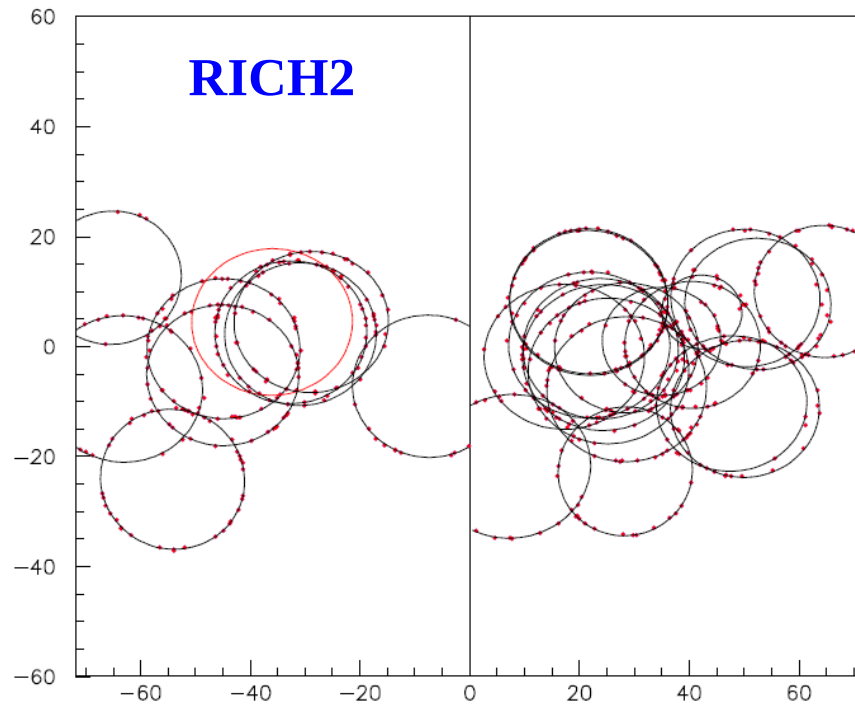
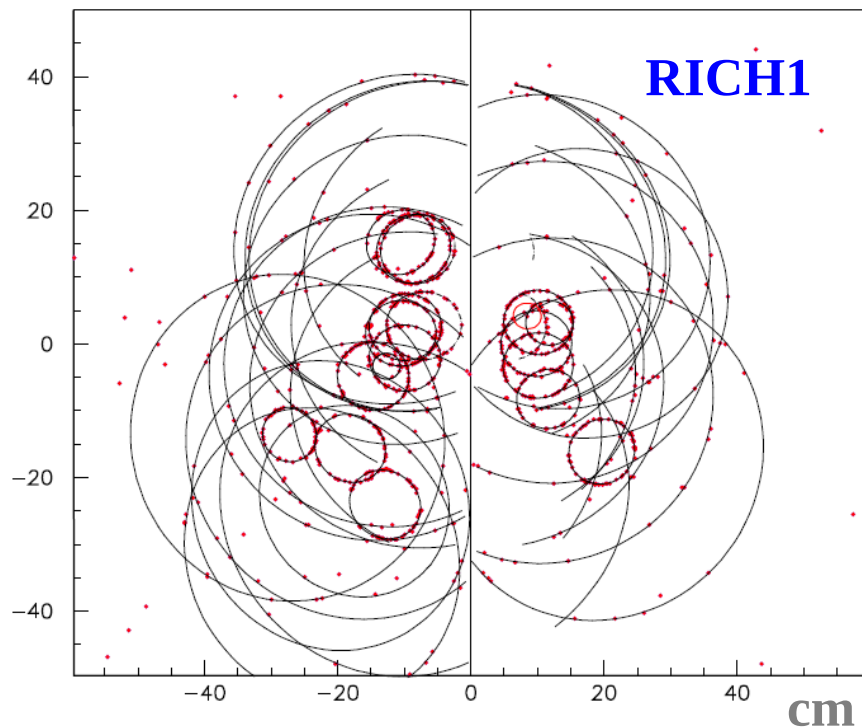
**Mean Number of hits
per isolated saturated
track ($\beta \sim 1$).**

Aerogel	: 5.3
C_4F_{10}	: 24.0
CF_4	: 18.4

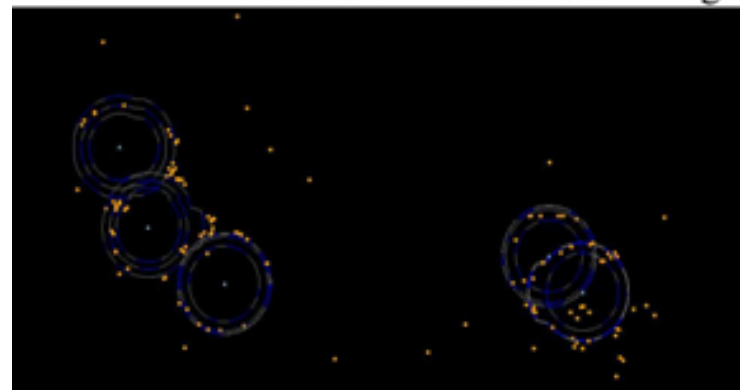
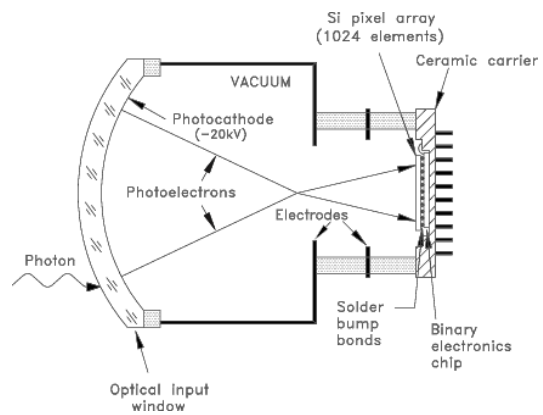
**Two RICH detectors covering the
particle momentum range 1 to 100
GeV/c using aerogel, C_4F_{10} and CF_4 gas**

RICH signals in LHCb

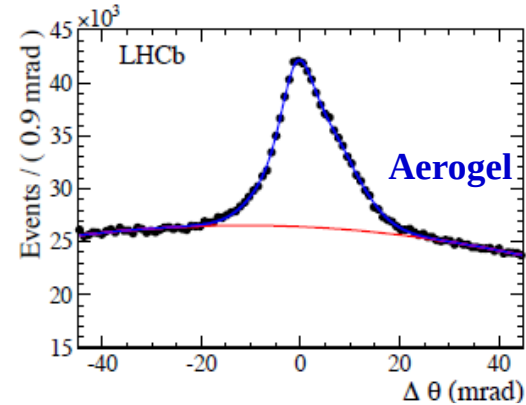
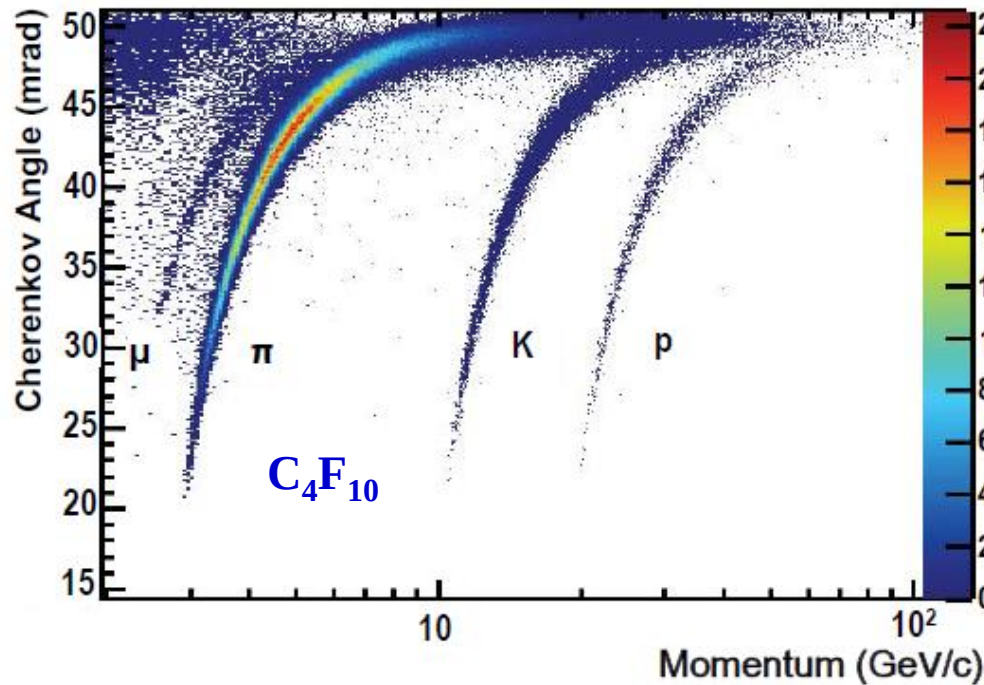
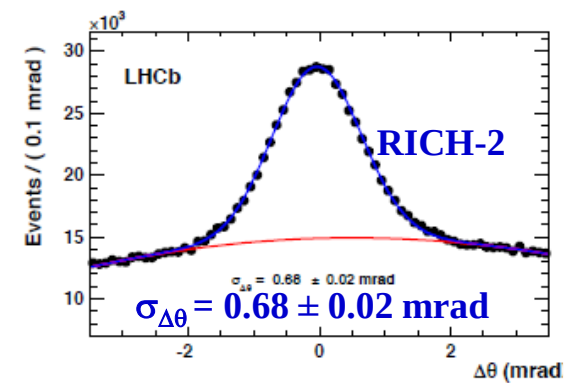
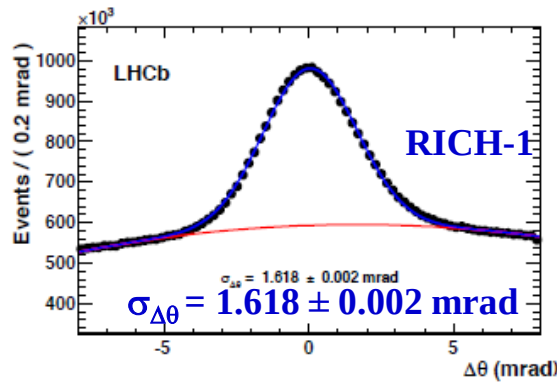
- $B \rightarrow \pi^+ \pi^-$ signal at LHCb simulation



RICH2 HPD Panels with Pixels and CK Rings



Performances of LHBb RICH



Radiator	N_{pe} from data		N_{pe} from simulation
	$D^0 \rightarrow K^- \pi^+$	$pp \rightarrow pp \mu^+ \mu^-$	$D^0 \rightarrow K^- \pi^+$
Aerogel	5.0 ± 3.0	4.3 ± 0.9	8.0 ± 0.6
C_4F_{10}	20.4 ± 0.1	24.5 ± 0.3	28.3 ± 0.6
CF_4	15.8 ± 0.1	17.6 ± 0.2	22.7 ± 0.6

Surface quality in aerogel

QE of photo-cathode

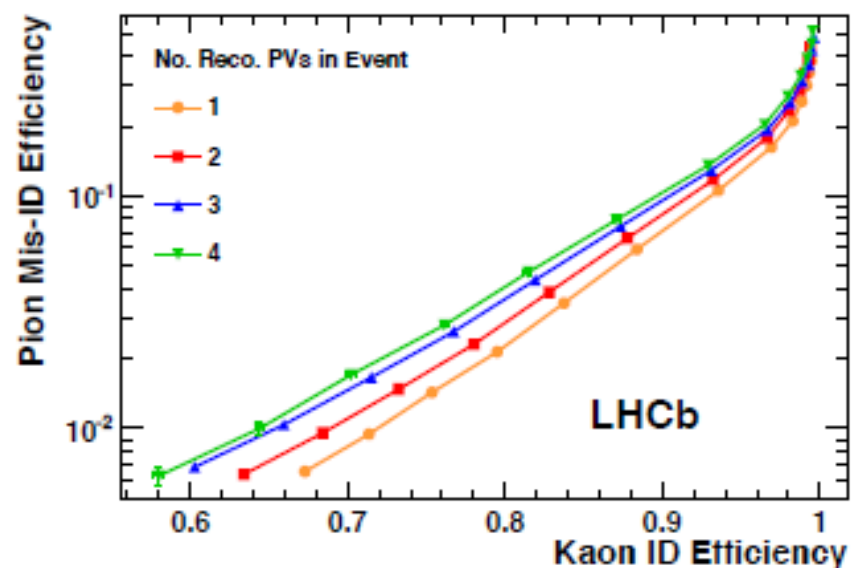
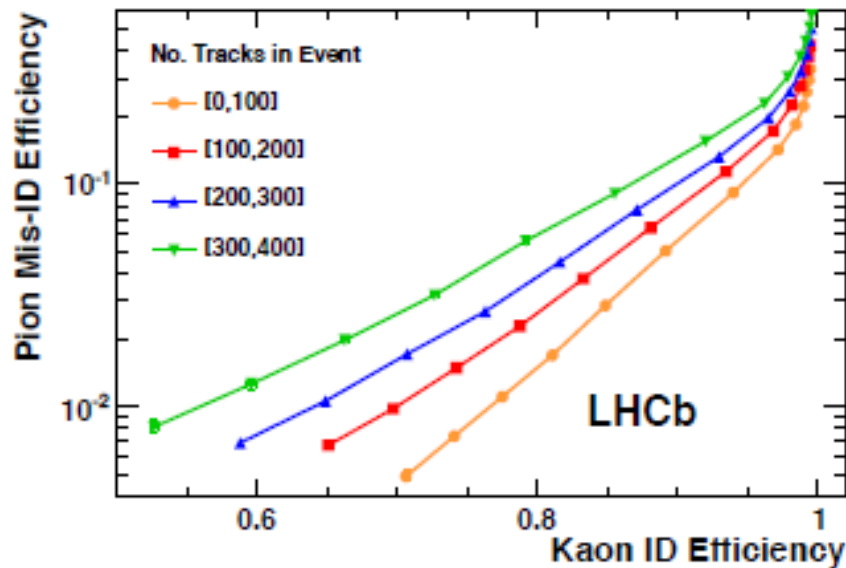
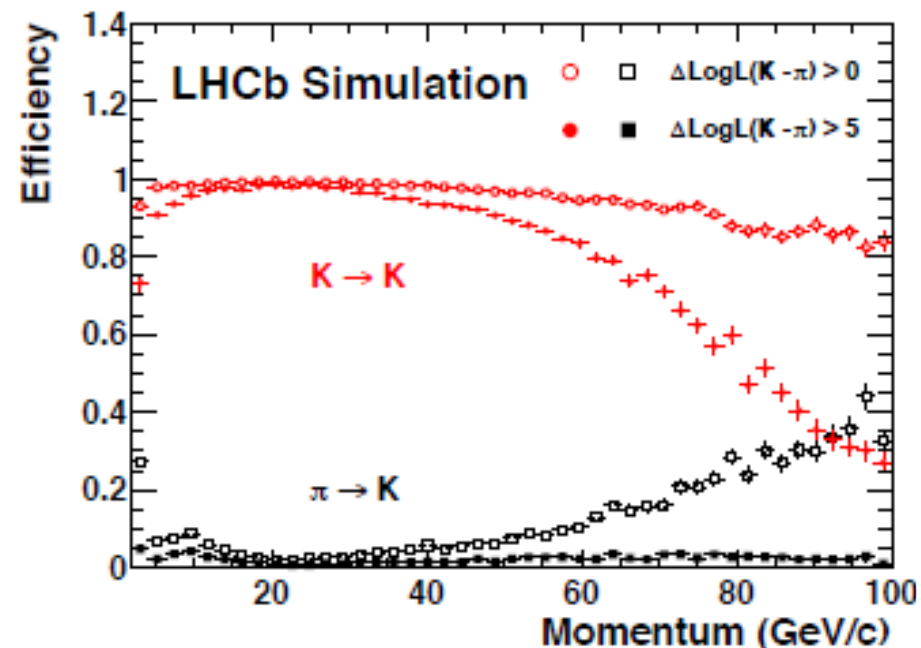
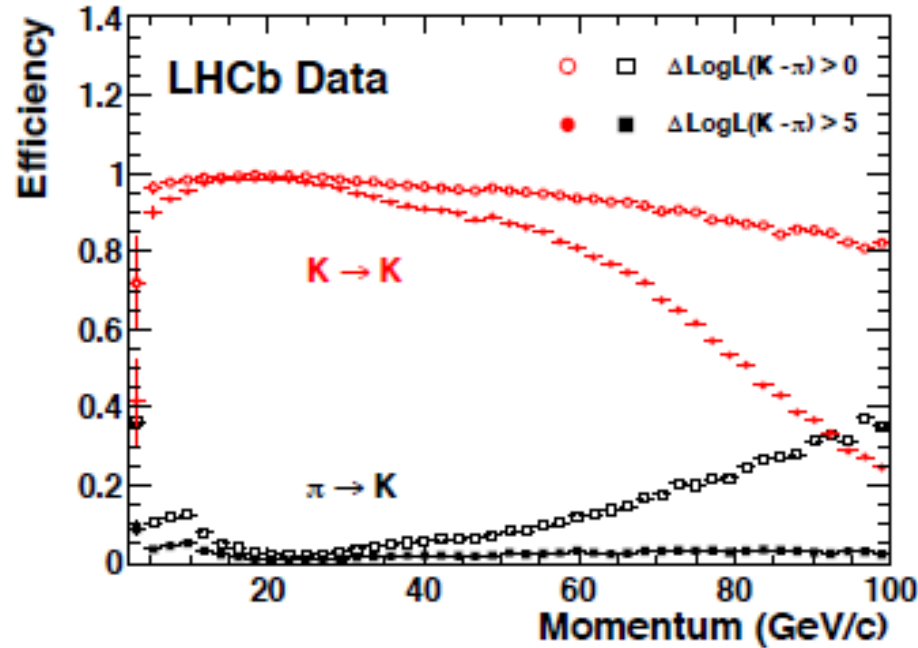
Resolutions in LHC-b RICH detector

Single Photon Cherenkov Angle Resolutions in mrad.

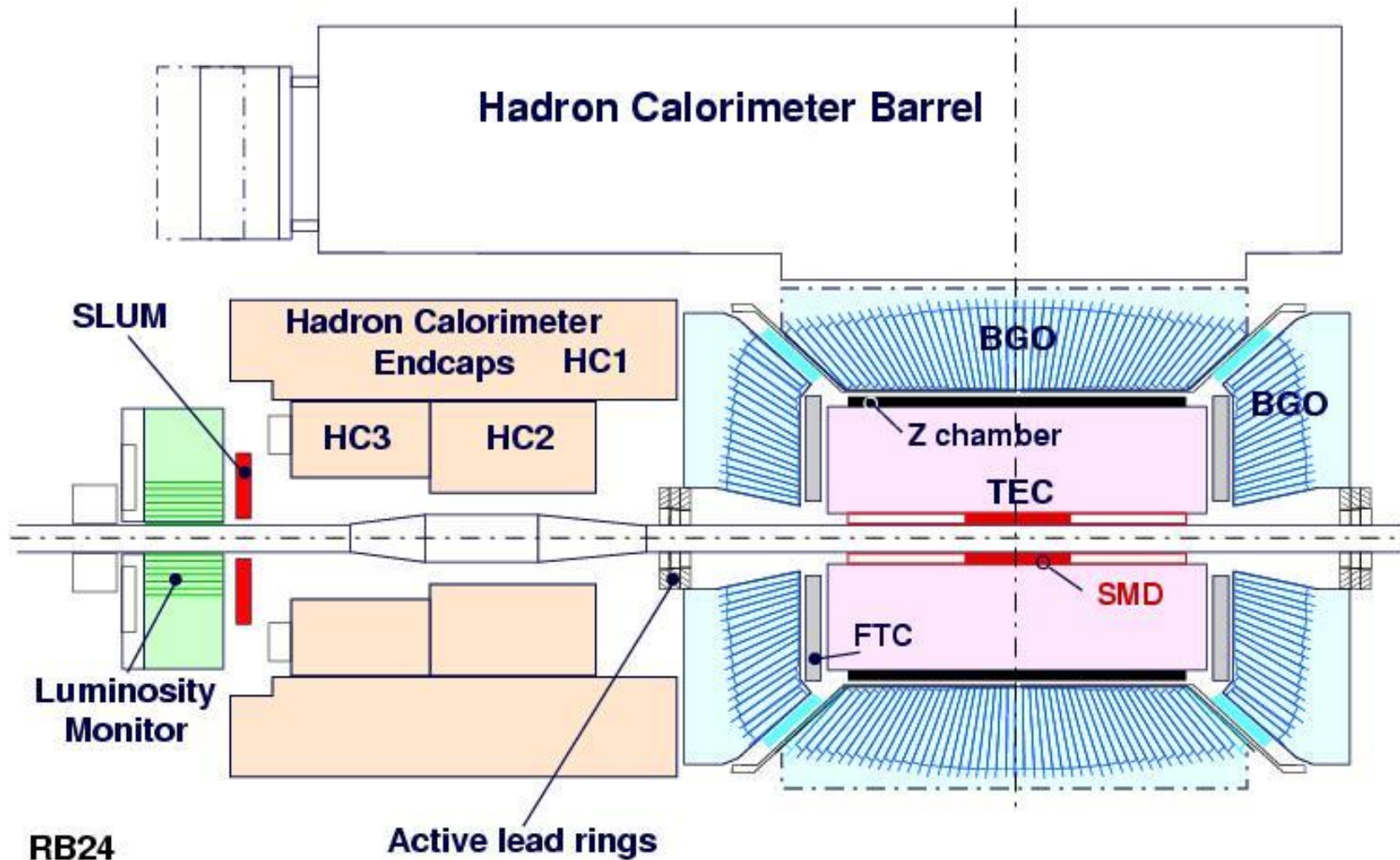
- **Chromatic:** From the variation in refractive index.
- **Emission Point:** Essentially from the tilt of the mirrors.
- **Pixel Size:** From the granularity of the Silicon detector pixels in HPD
- **PSF (Point Spread Function):**From the spread of the Photoelectron direction as it travels inside the HPD,(from the cross focusing in the electron optics)

Component and overall (mrad)	Aerogel	C ₄ F ₁₀	CF ₄
Chromatic	2.36	0.90	0.46
Emission point	0.38	0.82	0.36
Pixel size	0.52	0.52	0.17
PSF	0.54	0.53	0.17
Overall RICH	2.53	1.44	0.66
Overall RICH + Tracks	2.60	1.60	0.70
Average number of photon	5.3	24.0	18.4

Performances of LHCb RICH

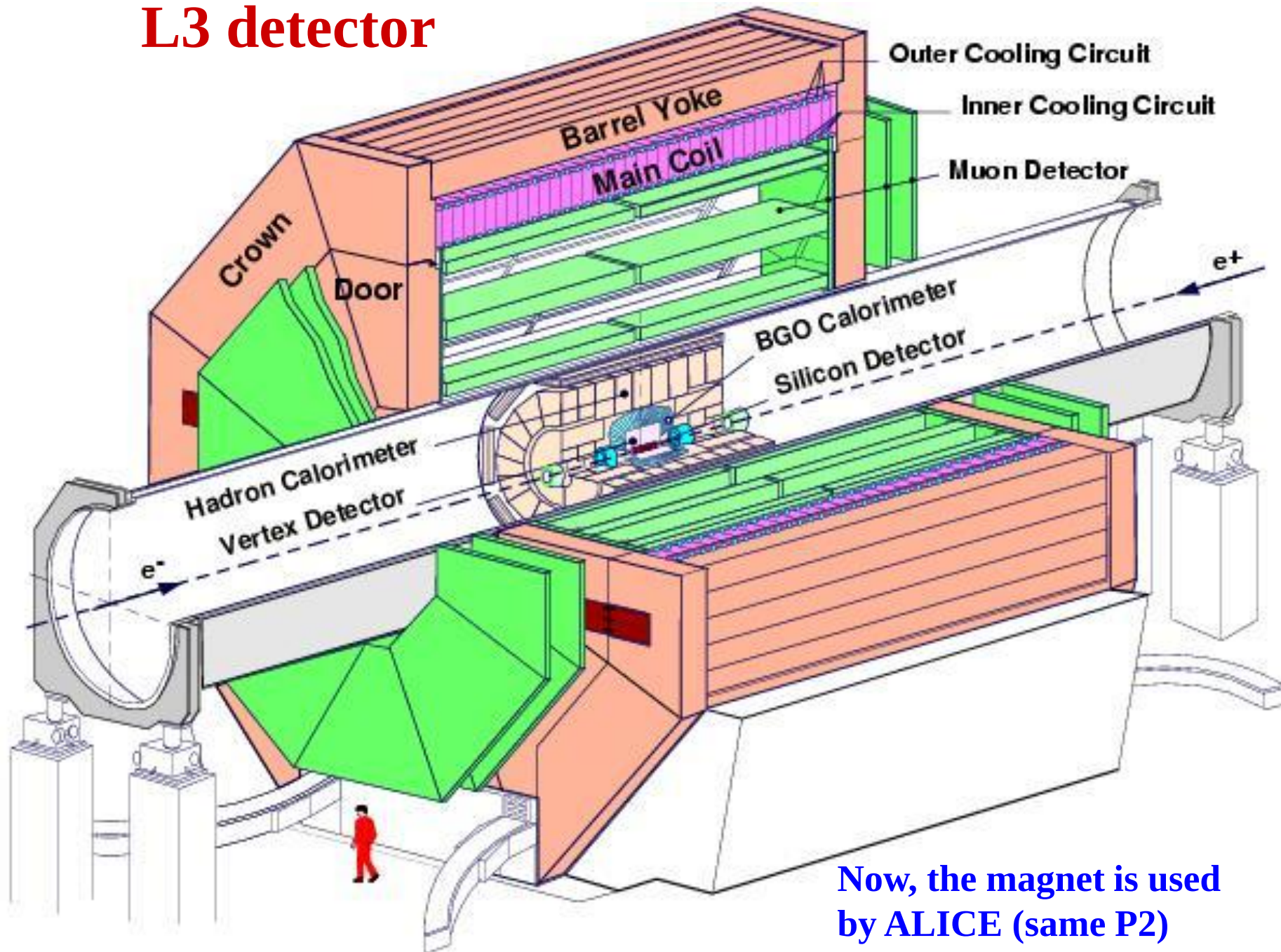


History : A detector for toponium !



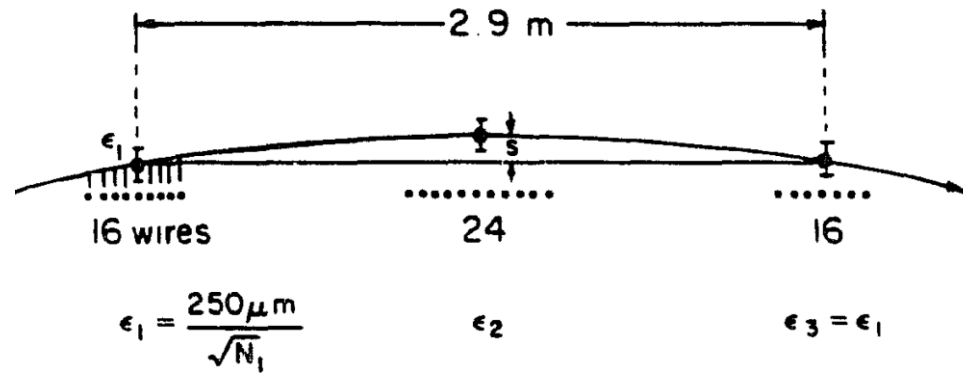
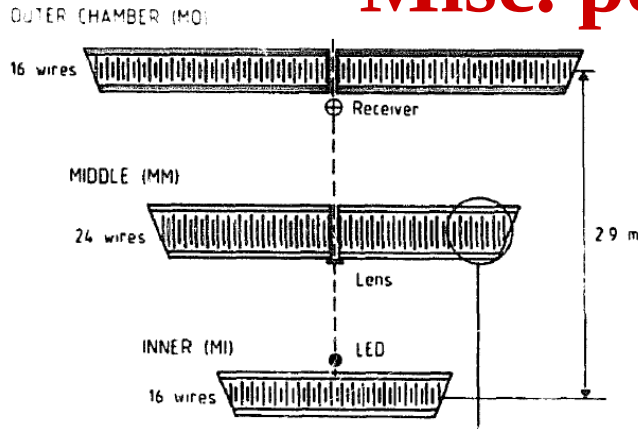
- The best ECAL at that time
- But, to reduce cost, size of tracker became very small; TEC (80% CO_2 + 20% iC_4H_{10}), +1atm to reduce drift velocity by an order ($6\mu\text{m/ns}$)

L3 detector



Now, the magnet is used
by ALICE (same P2)

Misc. point on L3 experiment



Detector	Mixture	Detector volume [m ³]	Operating pressure [bar gauge]	Fresh gas flow [m ³ /h]	Recirculation flow [m ³ /h]	Number of parallel circuits	Special requirements [Relative stability]
Time expansion chamber	CO ₂ + 20% i-butane	0.75	1	discontinuous	0.2	1	O ₂ < 1 ppm Δ drift v. < ± 0.1%
Central Z chambers	AR + 20% CO ₂	0.05	0.005	0.02	0	2 × 2	
Muon filter	AR + 20% CO ₂	3	0.005	0.24	0	16 × 10	
LM forward chambers	AR + 20% CO ₂	< 0.01	0.005	< 0.02	0	2 × 2	
Hadron calorimeter end caps	AR + 20% CO ₂	1	0.01–0.05	0.06	0	4 × 7	Δ density
Hadron calorimeter barrel	AR + 20% CO ₂	16	0.01–0.05	0.8	0	16 × 9 × 6	< ± 0.05%
Muon p chambers	AR + 38.5% ethane	250	0.001	2.5	50	16 × 5	Δ mix. < ± 0.1%
Muon Z chambers	AR + 8.5% methane	50	0.001	0.5	10	16 × 3	

- i-butane in calorimeter was not allowed due to safety reason
- Though no material inbetween muon chamber, multiple scattering of muon in calorimeter deteriorate the performance of momentum measurement, ALEPH has better performance as well as B-tagging

LHC Heavy Ion Program

Machine

Energy:

$$\star E_{\text{beam}} = 7 \times Z/A \text{ [TeV]} \Rightarrow \sqrt{s} = 5.5 \text{ TeV}/A \text{ or } 1.14 \text{ PeV} \quad (\text{Pb-Pb})$$

Beams:

$\star$ possible combinations: pp, pA, AA (constant beam rigidity)

heavy ion running:

$\star \sim 4 \text{ weeks/year}$ (10^6 s effective); typically after pp running (like at SPS)

luminosity:

$\star 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ (Pb) to $>10^{30}$ (light ions), $\Rightarrow$ 8000 minimum bias collision per second $\rightarrow$ rate 10 kHz to several 100 kHz

$\star$ integrated luminosity $0.5 \text{ nb}^{-1}/\text{year}$ (Pb-Pb)

Detector(s)

one single dedicated 'general purpose' HI expt at LHC: ALICE

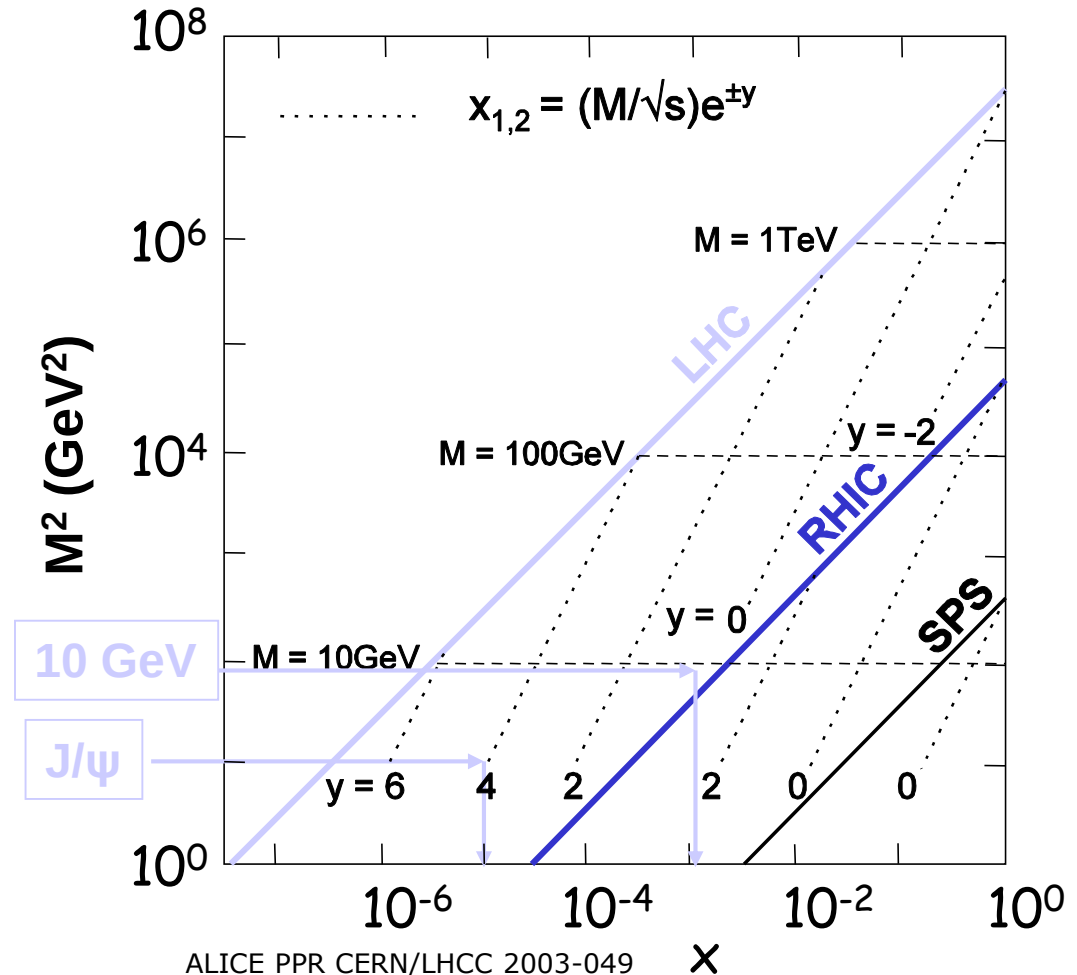
$\star$ AGS/SPS: several (6-8) 'special purpose expts'

$\star$ RHIC: 2 large multipurpose + 2 small special purpose expts

Comparison with previous experiments

Qualitatively new regime

- **Probe initial partonic state in a novel Bjorken-x range ($10^{-3} - 10^{-5}$):**
 - nuclear shadowing,
 - high-density saturated gluon distribution (CGC)
 - effectively moves RHIC forward region to mid-rapidity at LHC
- **Larger saturation scale ($Q_s = 0.2A^{1/6}\sqrt{s}^\delta = 2.7 \text{ GeV}$) particle production dominated by the saturation region**



Comparison with previous experiments

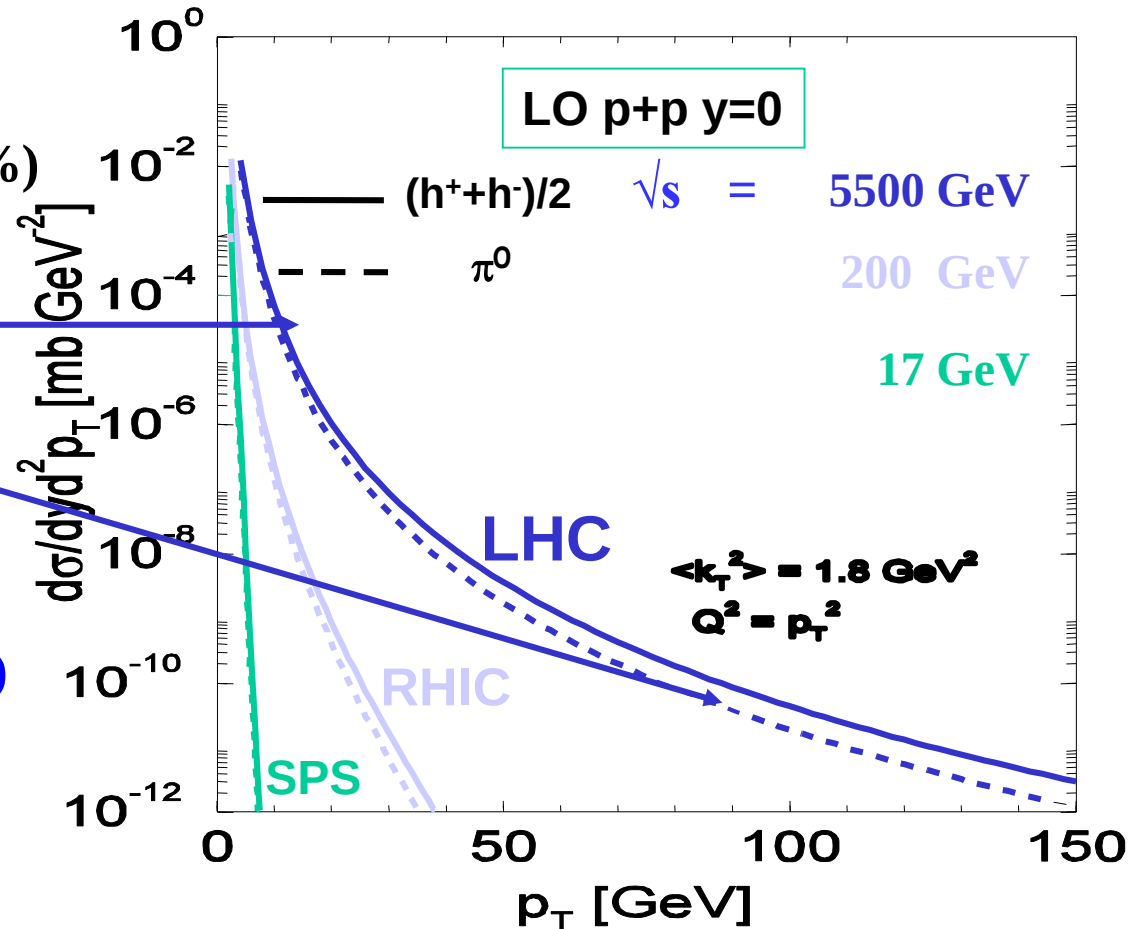
Qualitatively new regime

- **Hard processes contribute significantly to the total AA cross-section ($\sigma^{\text{hard}}/\sigma^{\text{tot}} = 98\%$)**

- Bulk properties dominated by hard processes

- Very hard probes are abundantly produced

- **Weakly interacting probes become accessible (γ , Z^0 , $W^\pm$)**



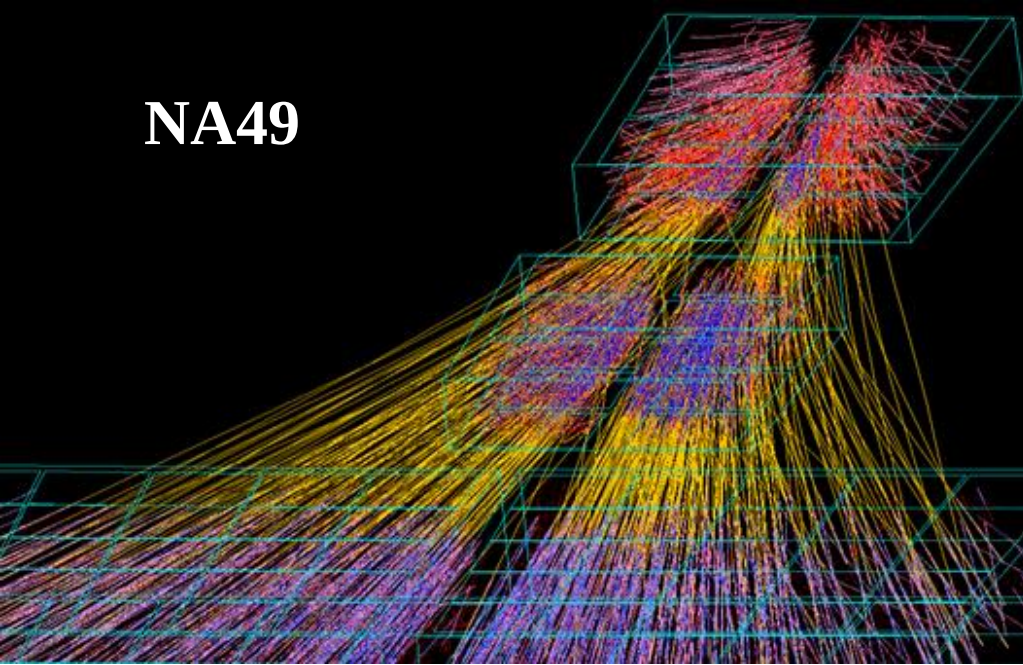
Observables in ALICE detector

- Particle multiplicities (number)
- Particle spectrum (momentum)
- Particle Correlations
- Jets
- Direct photons
- Di-leptons
- Heavy quark and quarkonia
- Cosmic ray muon

Need large detector in terms of size, granularity, complexity

ALICE Tracking Challenge

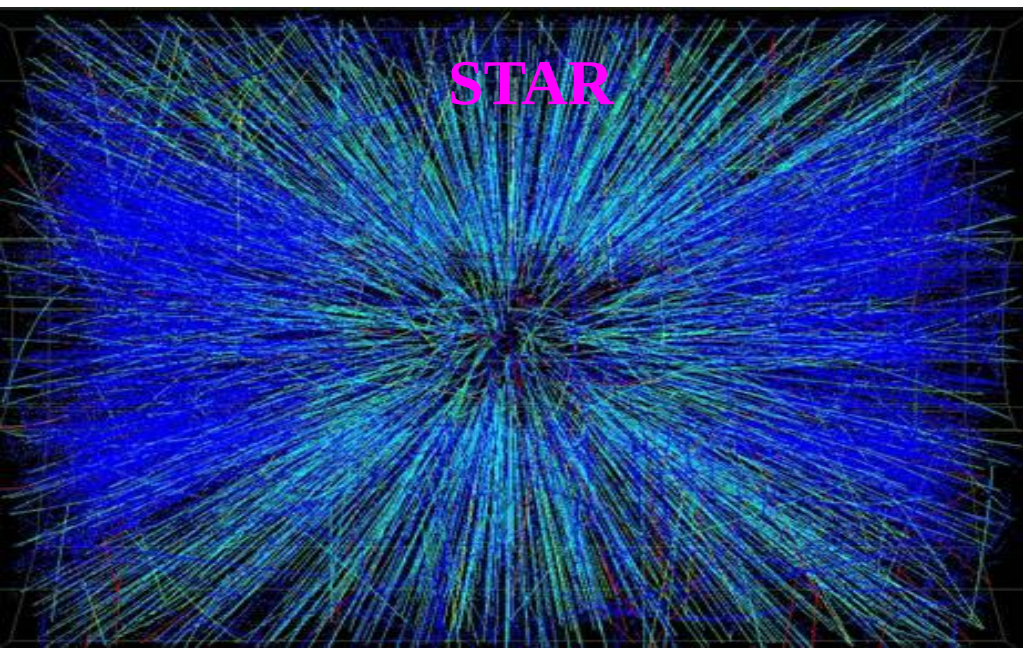
NA49



STAR : 500 particles in fiducial volume

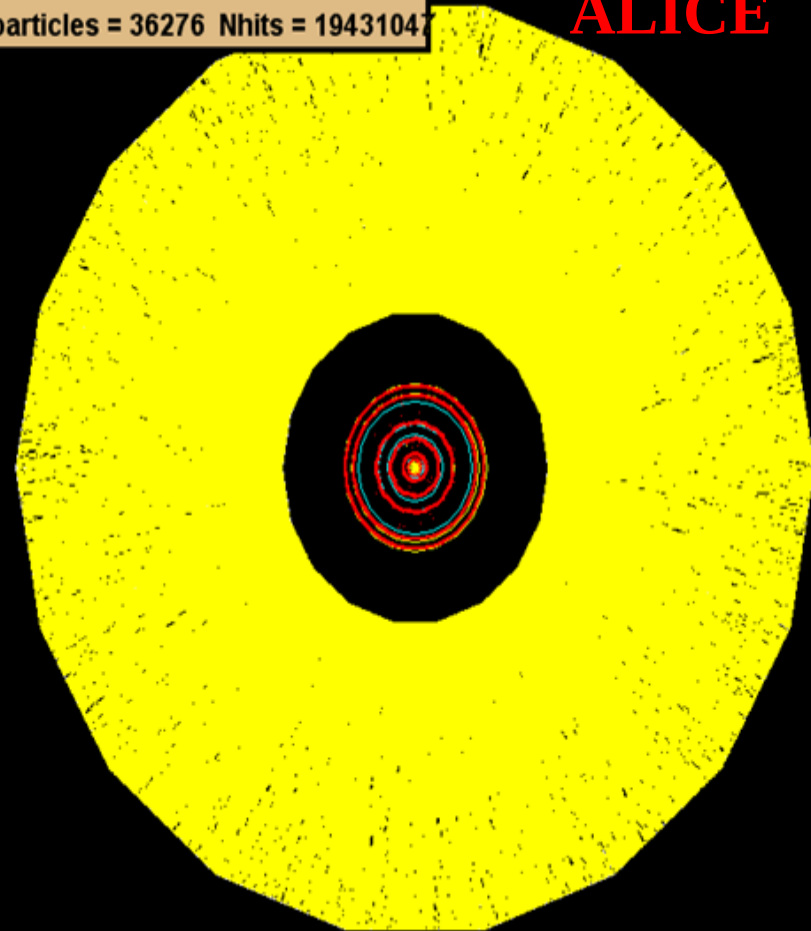
ALICE : $dN/d\eta = 8000$

STAR

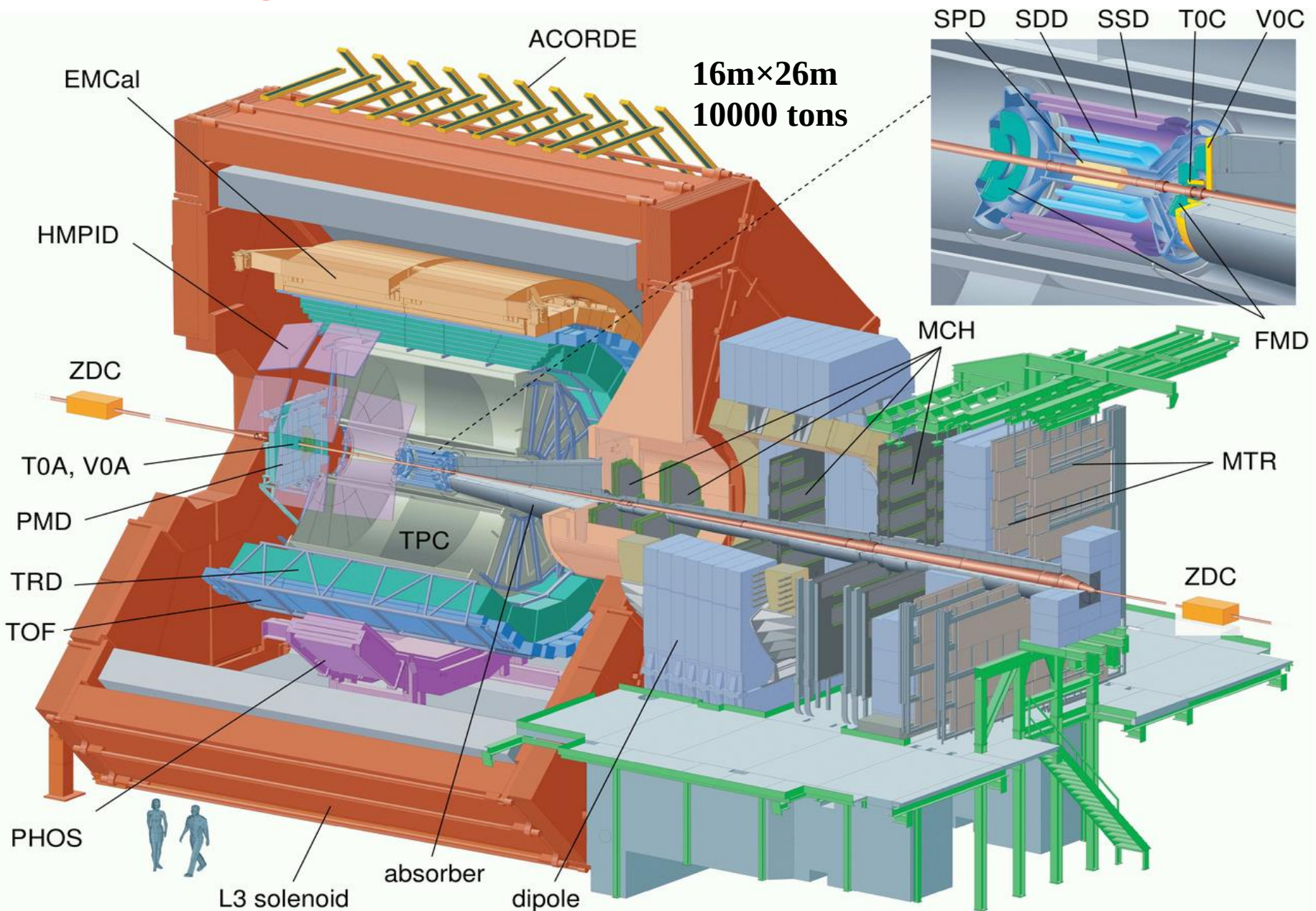


Alice event: 0, Run:0
Nparticles = 36276 Nhits = 1943104

ALICE



A Large Ion Collider Experiment (ALICE)



ALICE Acceptance

central barrel $-0.9 < \eta < 0.9$

2 π tracking, PID

single arm RICH (HMPID)

single arm em. calo (PHOS)

jet calorimeter (proposed)

forward muon arm $2.4 < \eta < 4$

absorber, 3 Tm dipole magnet

10 tracking + 4 trigger chambers

multiplicity $-5.4 < \eta < 3$

including photon counting in

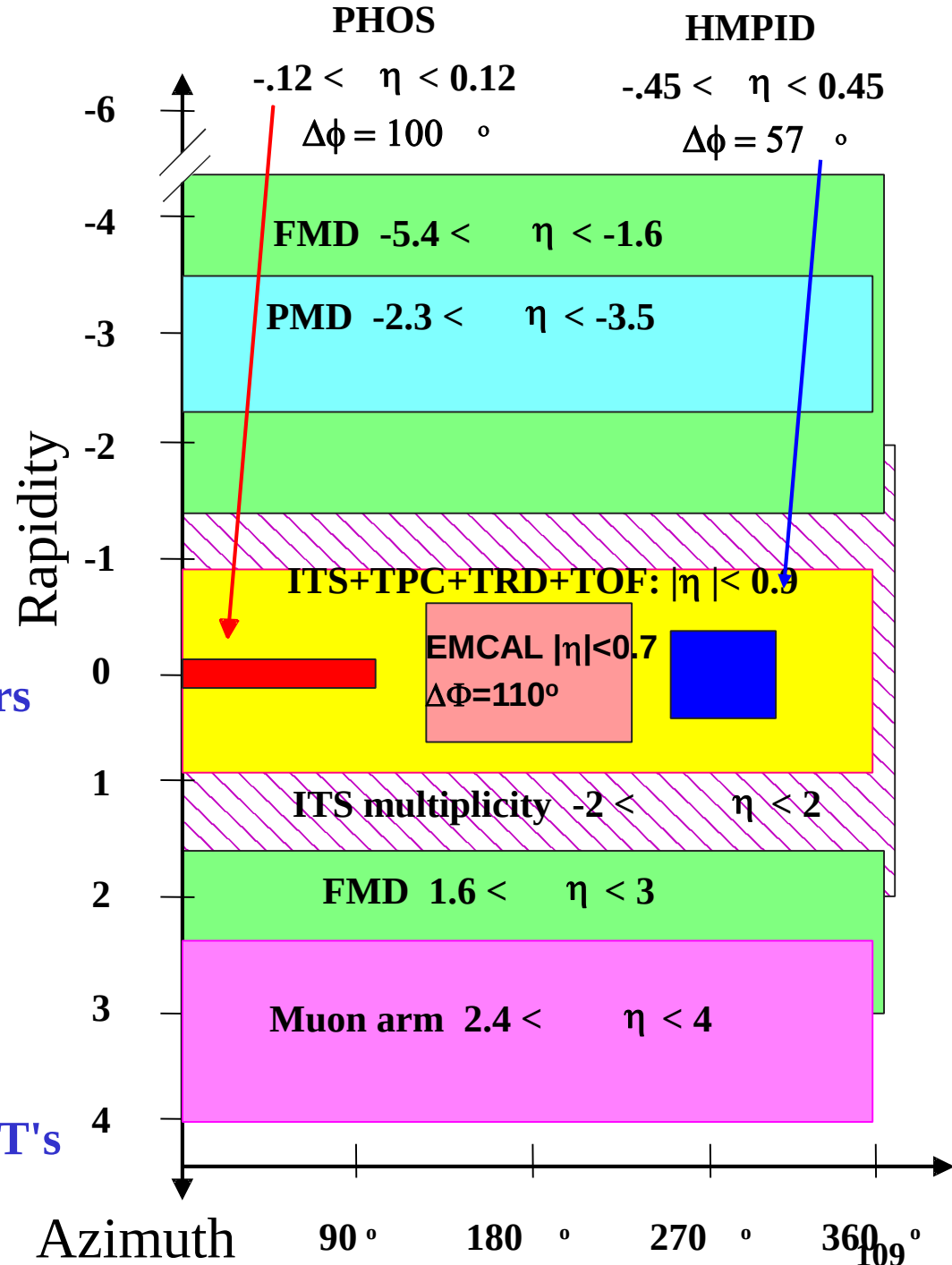
PMD

trigger & timing dets

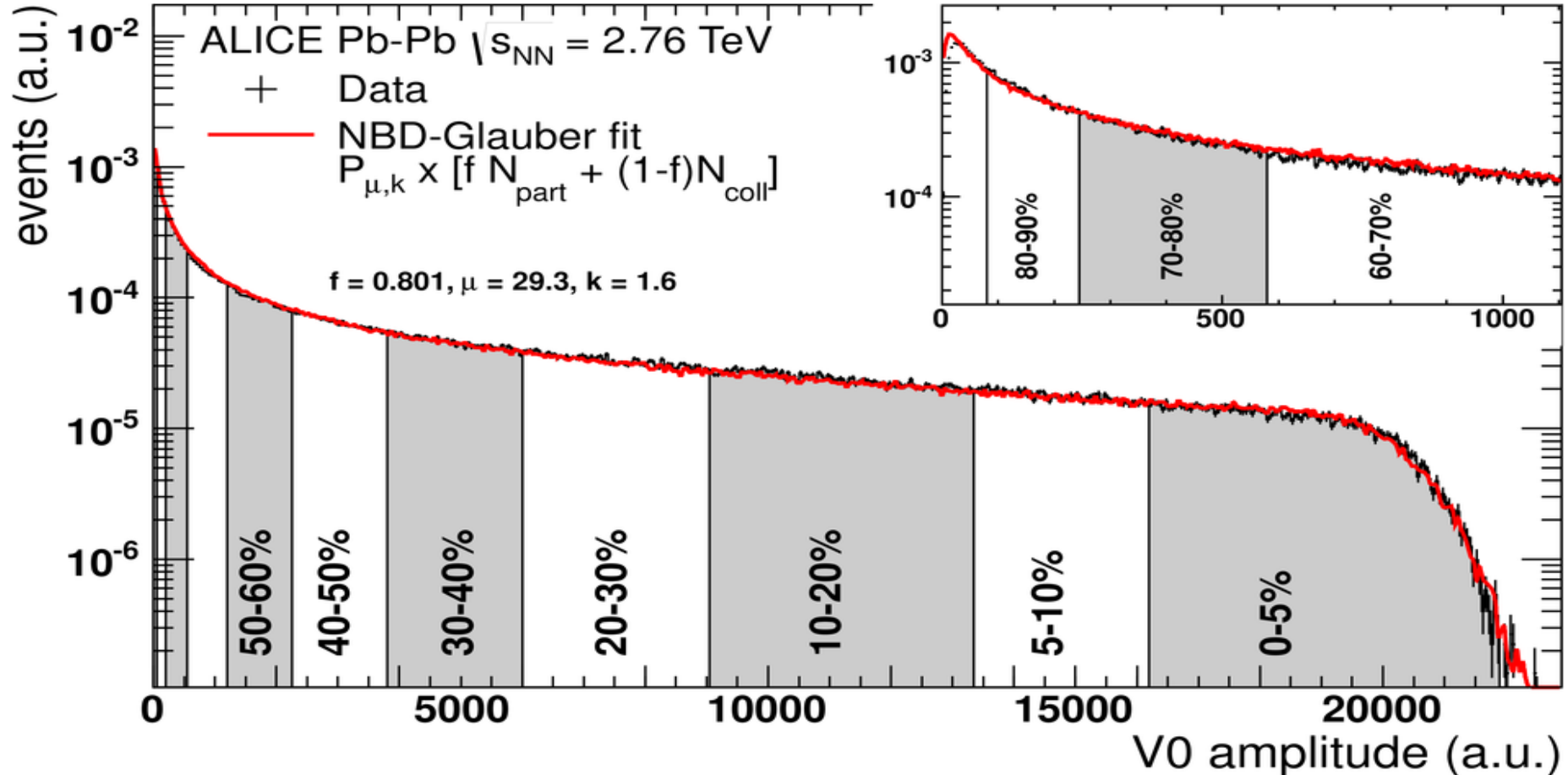
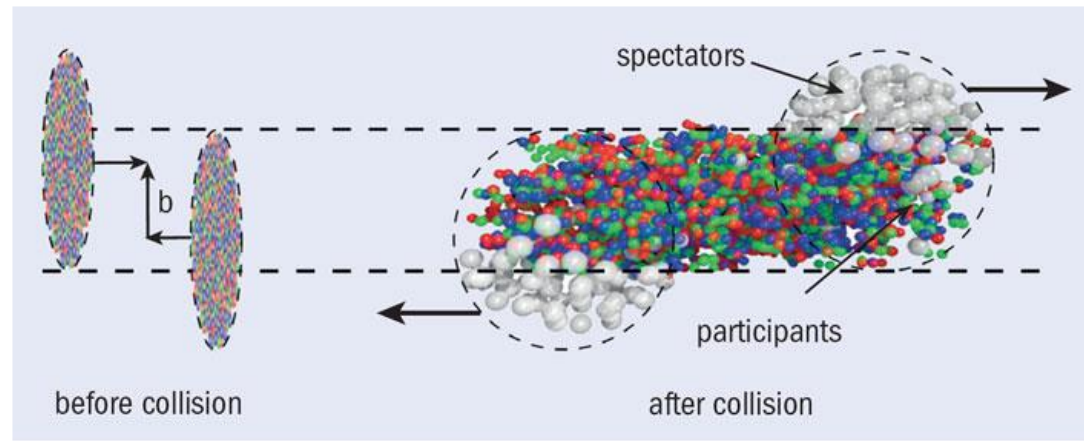
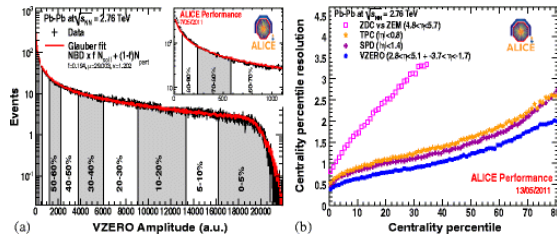
6 Zero Degree Calorimeters

T0: ring of quartz window PMT's

V0: ring of scint. Paddles



Centrality at ALICE



Physics goals for ALICE upgrade

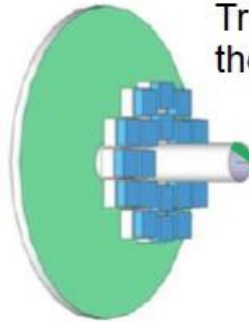
Charm/beauty meson and baryon production in a wide momentum range, down to very low p_T

- Probe the quark-medium interaction (in-medium energy loss) and the QGP transport coefficients
- Study degree of charm thermalization and possible hadronization via coalescence
- J/ψ , ψ' states and prompt/non-prompt J/ψ separation down to lowest p_T in wide rapidity range
 - Charmonium dissociation and regeneration pattern as a probe of color deconfinement and medium temperature
- Measurement of low-mass and low- p_T di-leptons (vector mesons, thermal virtual photon)
 - Initial temperature, space-time evolution and equation of state of the QGP
 - Chiral-symmetry restoration $\rightarrow$ modification of ρ spectral function
- Jet quenching and fragmentation: PID of jet particle content, heavy flavour tagging
- Light nuclei and hyper-nuclei
 - Study their production mechanisms and degree of collectivity
- For most of these observables S/B is very low, so it is not possible to implement dedicated triggers.

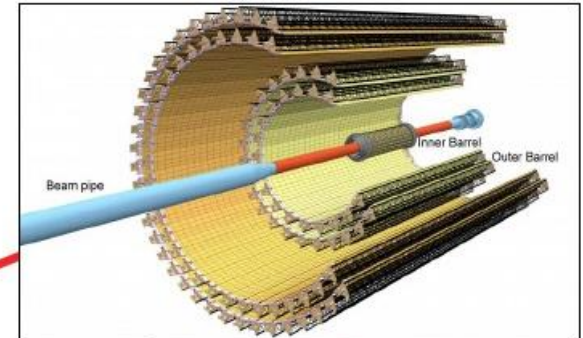
ALICE detector upgrade

ALICE

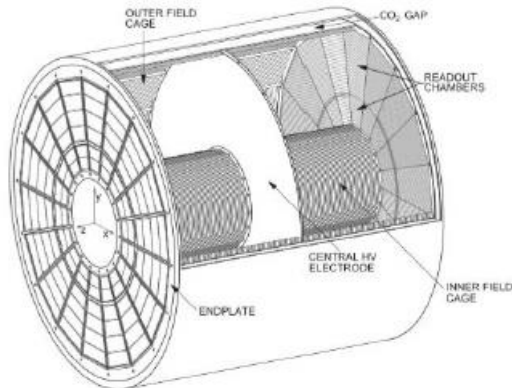
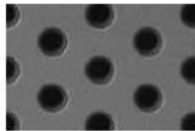
New Forward Interaction Trigger (FIT) to replace the V0 and T0 detectors



New Inner Tracking System (ITS)



TPC with GEM based readout



Both based on Monolithic Active Pixel Sensors (MAPS)

Muon Forward Tracker (MFT)



- + improved readout for TOF, ZDC, TRD, MUON ARM
- + new Central Trigger Processor
- + new DAQ/Offline architecture

Tracking in ALICE

Robust, redundant tracking from 100 MeV to 100 GeV

- modest solenoidal field (0.5 T) => easy pattern recognition
- long lever arm => good momentum resolution (BL^2 : Alice ~ CMS > Atlas !)
- small material budget: $< 10\% X_0$ vertex $\rightarrow$ end of TPC
 - Beryllium beam pipe of outer radius 2.98cm and thickness 0.8mm 3.5m (RB24 and copper) and 0.4m (RB26 and stainless steel)
- Inner Tracking System (ITS) : Design considerations :
 - Primary vertex resolution $< 100 \mu\text{m}$
 - Reconstruct secondary vertices of B,D mesons
 - Stand along tracking at low p_T and provide dE/dx measurements for low momentum track
- **Constraints** : Space ($4 \text{ cm} < r < 44 \text{ cm}$), integrated radiation doses 2.2kGy and $10^{12} \text{ n cm}^{-2}$ and particle flux 80/cm² in innermost layer and 1/cm² in outermost layer

Silicon vertex detector (ITS)

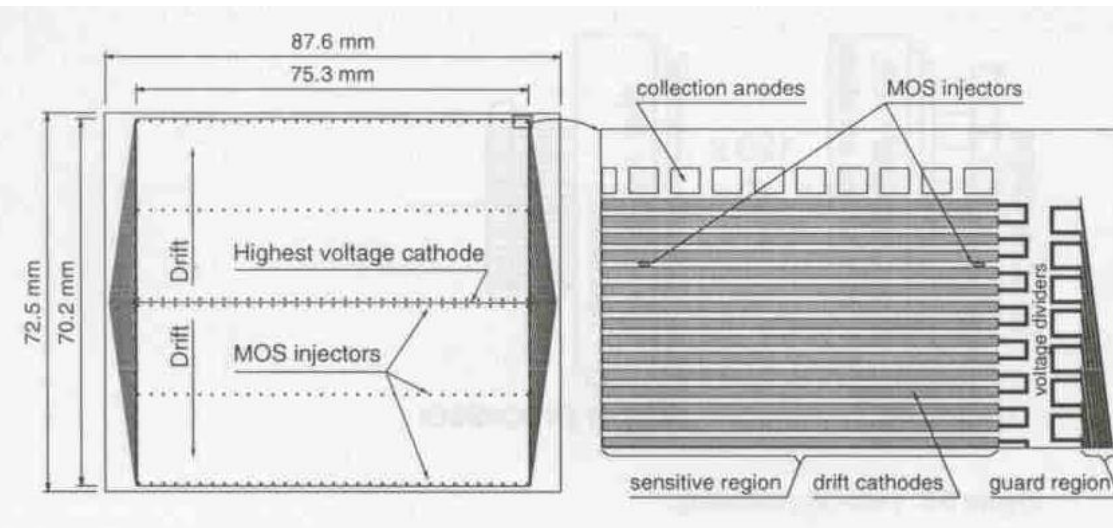
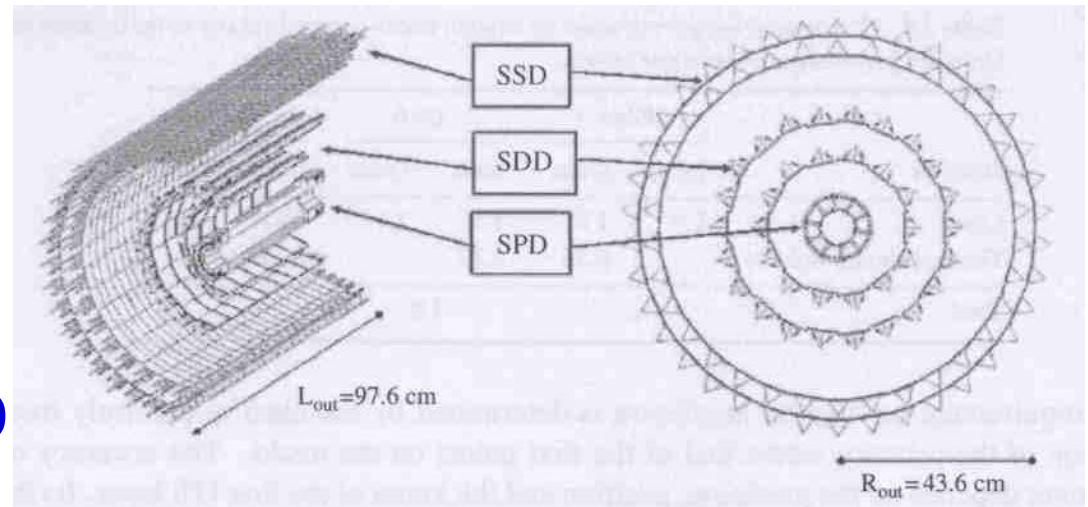
–Three different types of silicon detectors (at $r=3.9, 7.6, 14.0, 23.9, 37.8/38.4, 42.8/43.4\text{cm}$)

–Two silicon pixel layers ($\sigma_{r-\phi}=12\mu\text{m}$ and $\sigma_z=100\mu\text{m}$)

–Two silicon drift layers ($\sigma_{r-\phi}=38\mu\text{m}$ and $\sigma_z=28\mu\text{m}$)

–Two double sided silicon strip layers with angle stereo angle 7.5 mrad and 27.5 mrad ($\sigma_{r-\phi}=20\mu\text{m}$ and $\sigma_z=830\mu\text{m}$)

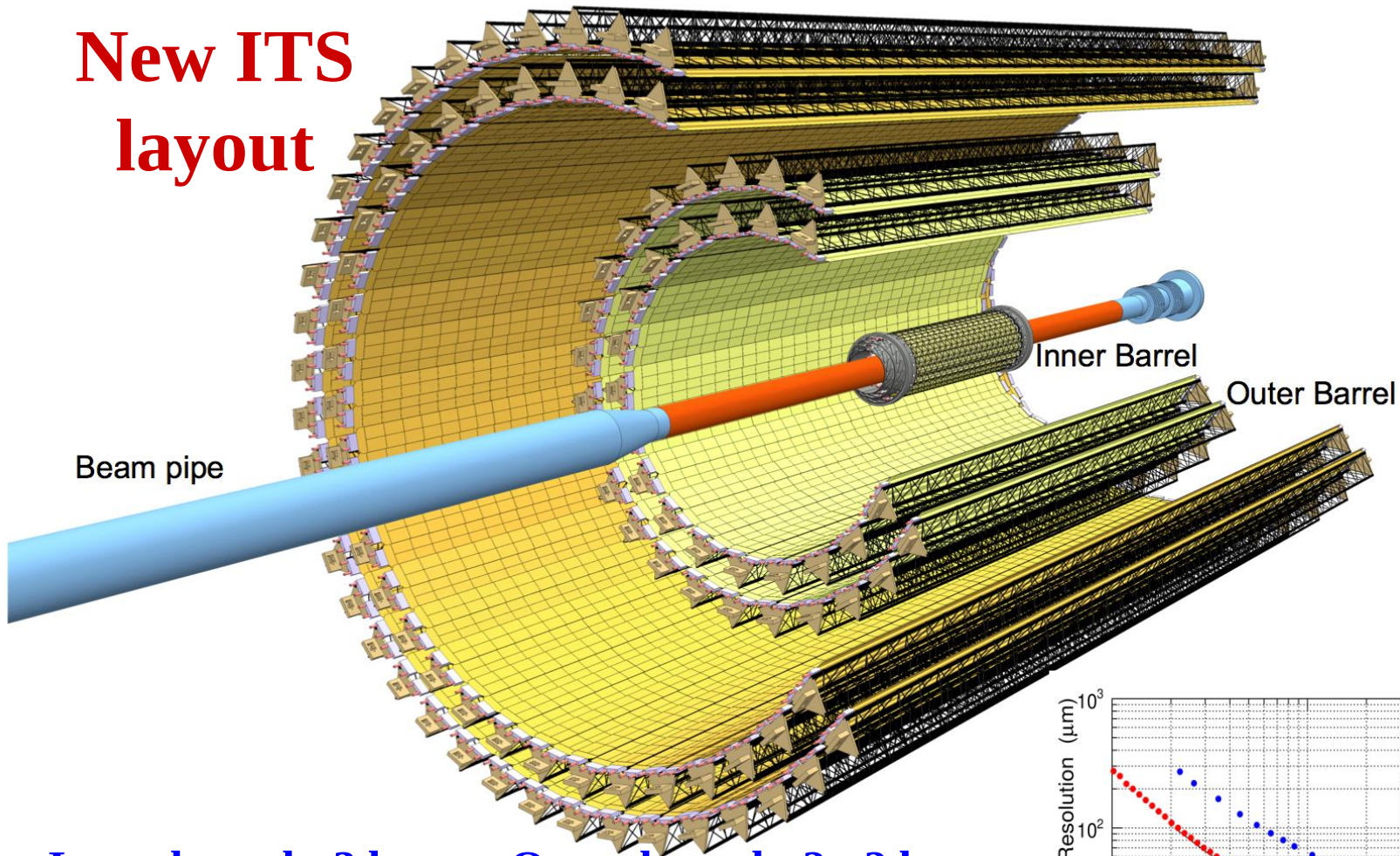
–Total readout channels >12M (mainly pixel readout)



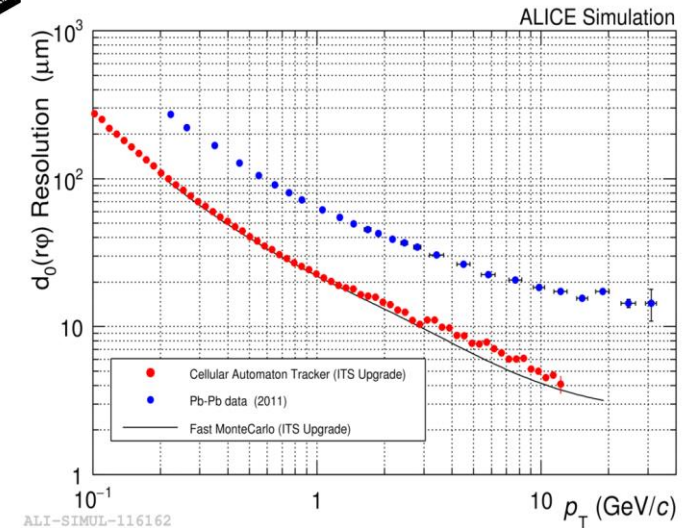
ITS upgrade objectives

- **Improve track DCA resolution, in particular at low P_T ($\sim 3(5)$ in $r\phi$ (z) @PT=500 MeV/c)**
- **Improve tracking efficiency and P_T resolution at low P_T**
- **Increase read-out rate : 1 kHz $\rightarrow$ 50 kHz in Pb-Pb, 200 kHz in pp**
- **Withstand radiation load (10 years operation) :**
 - **TID ~ 270 krad, NIEL : $\sim 1.7 \times 10^{12}$ 1MeV neq/cm²**
- **Easier maintenance**
- **Implementation :**
 - **7-layer barrel geometry of Monolithic Active Pixel Sensors (MAPS)**
 - **First layer closer to IP ($r_0 = 39\text{mm} \rightarrow 22\text{mm}$)**
 - **Smaller beam pipe : $29\text{mm} \rightarrow 18.2\text{mm}$**
 - **Reduced material budget, in particular for the 3 innermost layers**
 - **$X/X_0 = 1.14\% \rightarrow 0.3\%$ for the first layers**
 - **Silicon thickness : $50\text{ }\mu\text{m}$**
 - **Smaller pixel size : $50 \times 425\text{ }\mu\text{m}^2 \rightarrow 25 \times 25\text{ }\mu\text{m}^2$**
 - **Increase number of layers $6 \rightarrow 7$**

New ITS layout

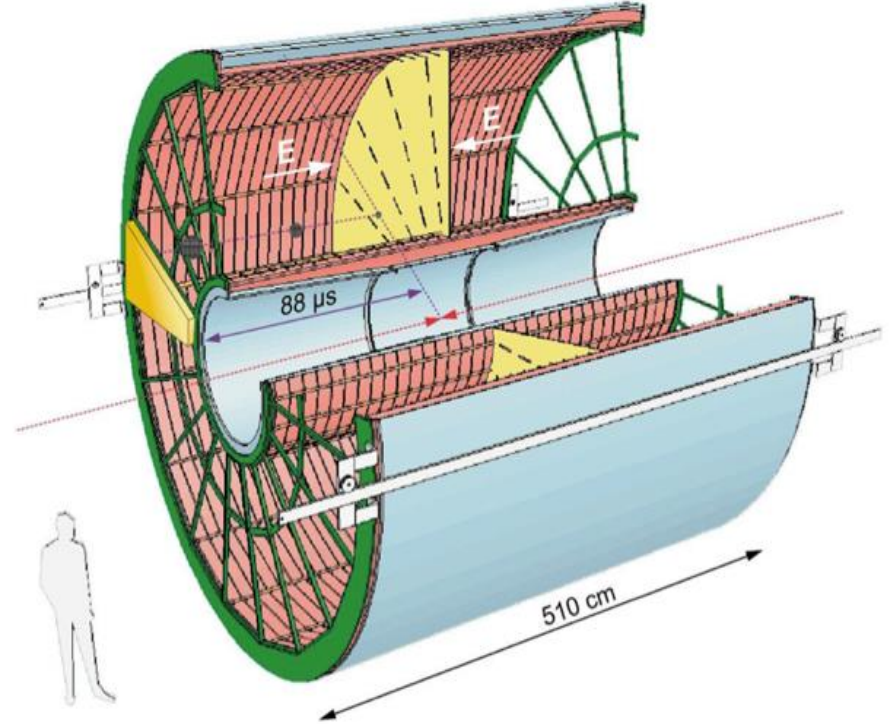


- Inner barrel : 3 layers, Outer barrel : 2 +2 layers
- $|\eta| \leq 1.3$ for track from 90% most luminous region, R coverage : 23 - 400mm
- 24000 pixel chips, 12.5 G pixel, Area : $\sim 10\text{m}^2$, spatial resolution : $5\mu\text{m}$

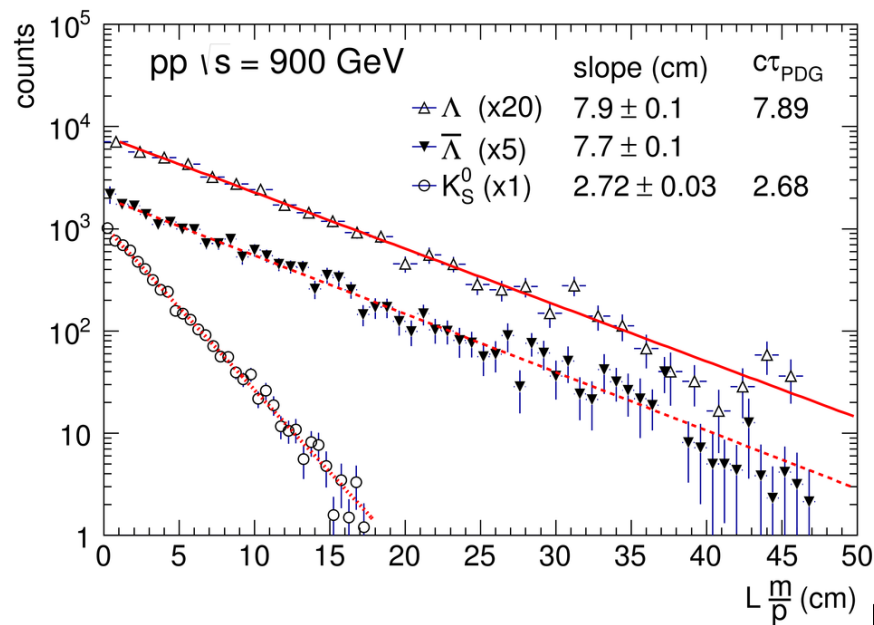
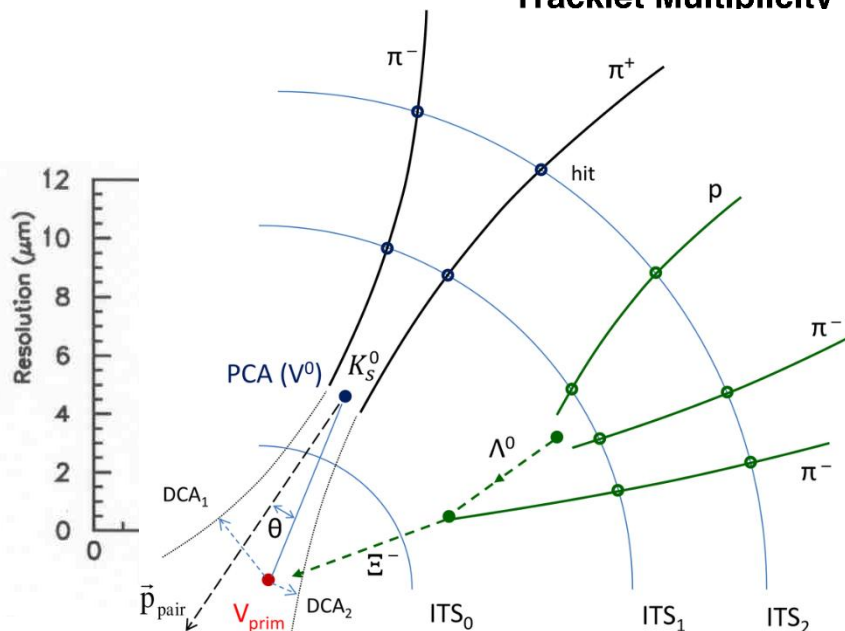
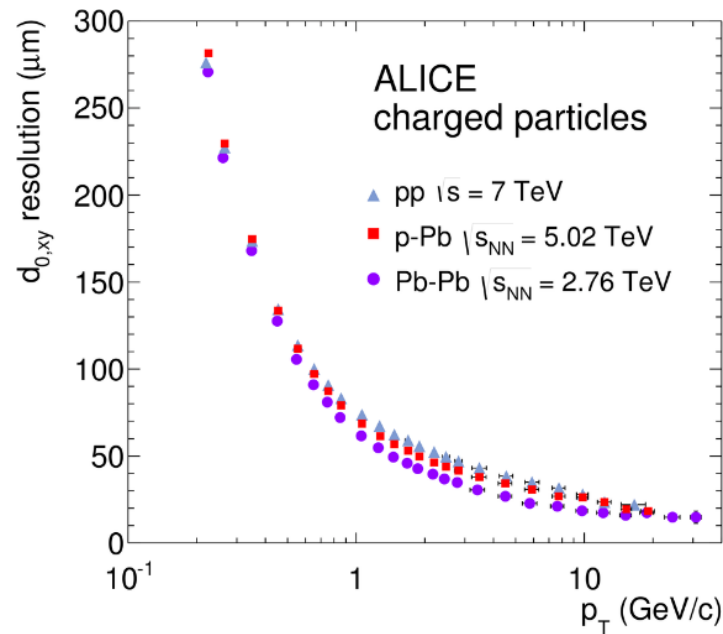
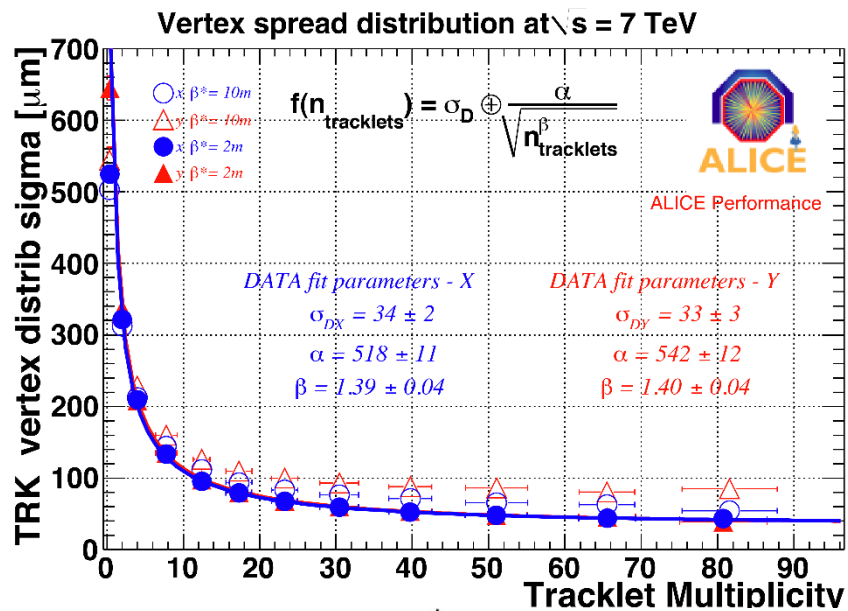


Time Projection Chamber (TPC)

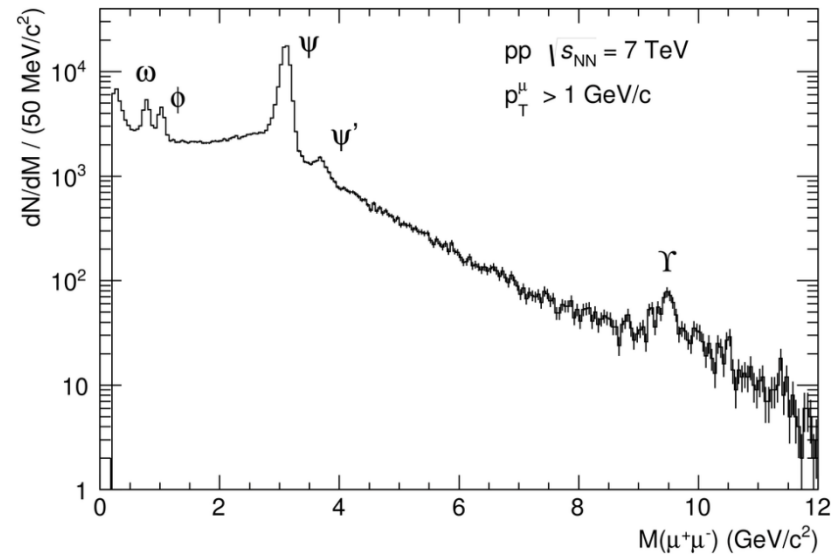
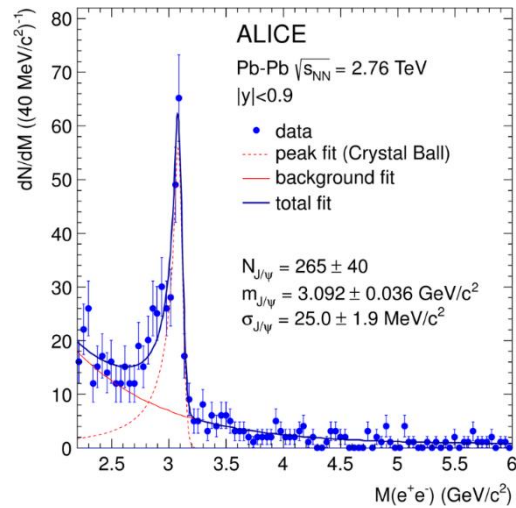
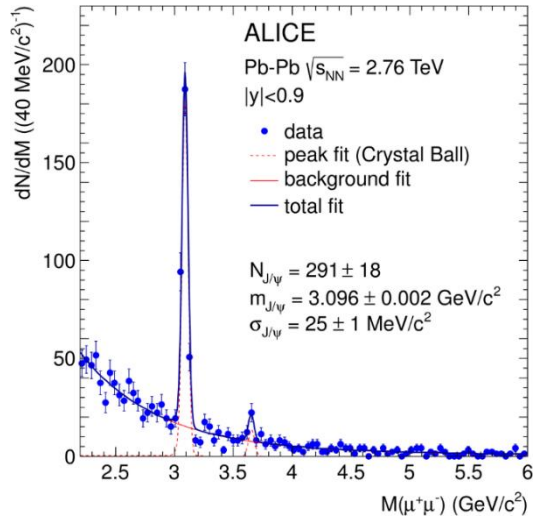
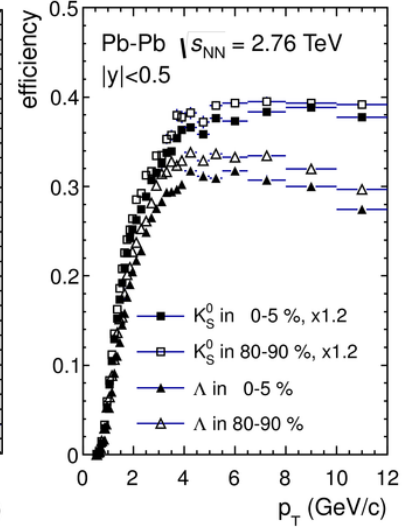
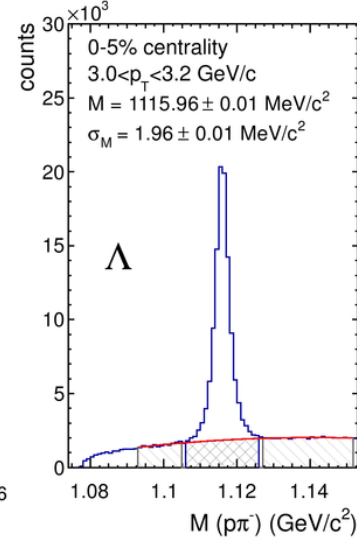
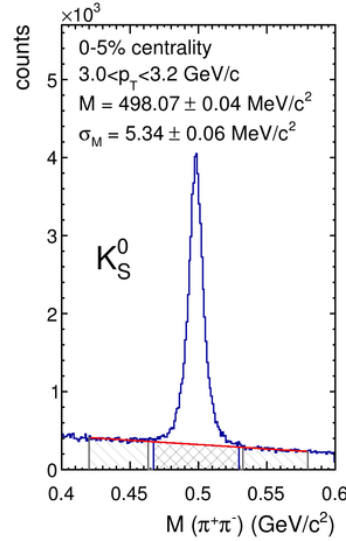
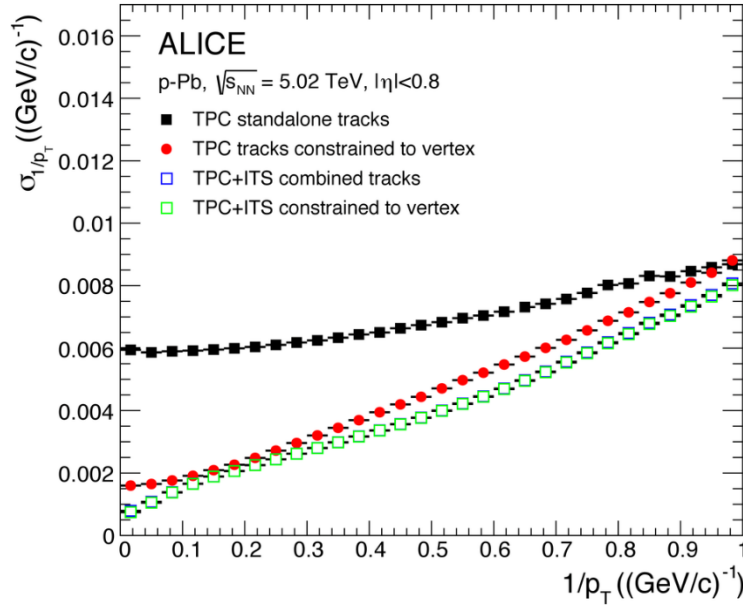
- $|\eta| < 0.9$ (~ 1.5 with reduced track length poorer resolution)
- 88 m³ of Ne/CO₂ (90%/10%), minimum diffusion for better positioning
- Material is less than 3.5% for normal incident
- Rate capability is restricted due maximum drift time 90 μ s at 100kV (field 400 V/cm)
- MWPC with cathode pad readout : In total 560K pads with size (4 $\times$ 7.5 mm² for inner segment, 84.1cm<2<132.1cm and 6 $\times$ 10mm² & 6 $\times$ 15mm² for outer segment, 134.2cm<r<246.4cm)
- Expected pad occupancy 40-15% (inner/outer radius)
- dE/dx resolution : 5.5/6.9% for isolated (dN/dy=8000) track
- Momentum resolution : 1-2% for track 100 MeV to 1 GeV and 10% for $p_T=100$ GeV



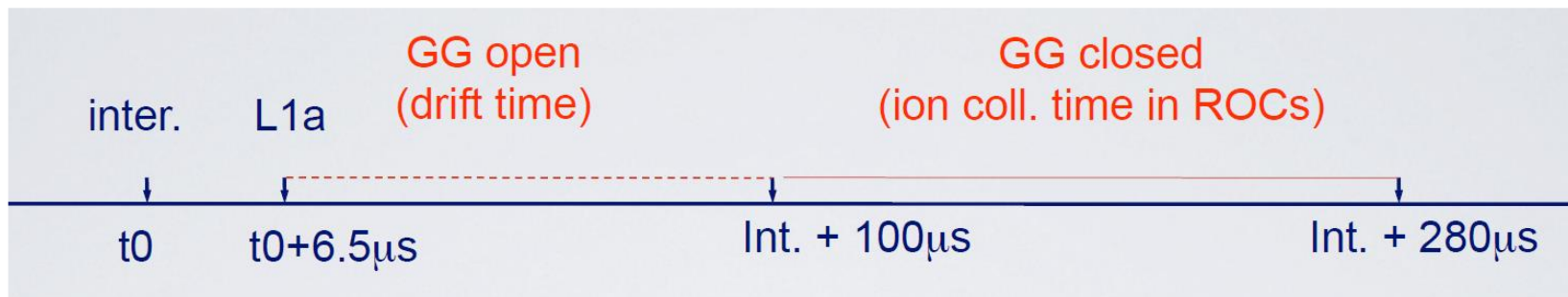
Vertex and Impact parameter



Momentum resolution of track and invariant mass



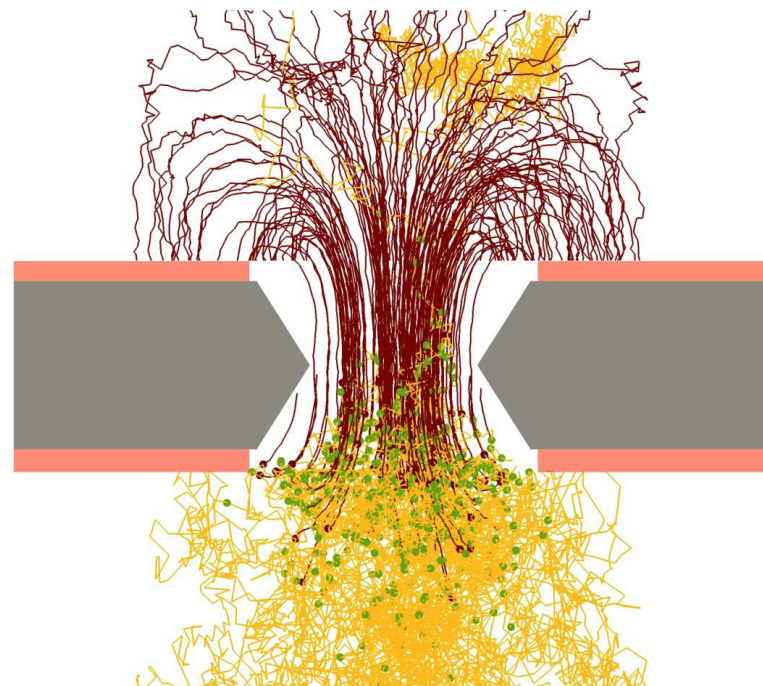
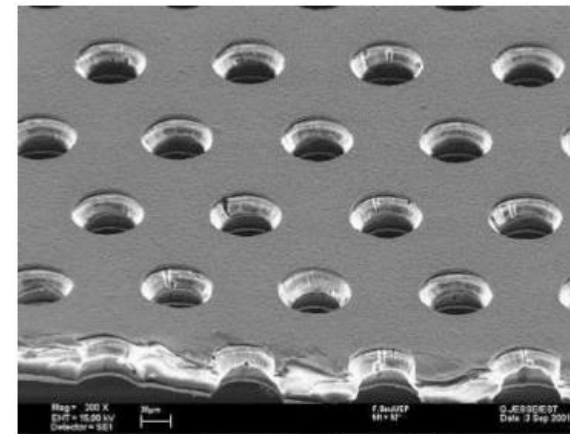
Existing TPC : Rate Limitation



- **Gating grid**
 - Open during drift time to allow electron into MWPC
 - Closed afterwards to prevent ion back-flow
 - Limits readout rate 3.5kHz
- **Opening GG permanently not possible**
 - Ion back flow creates large space charge
 - Space point distortion up to 1m – not tolerable

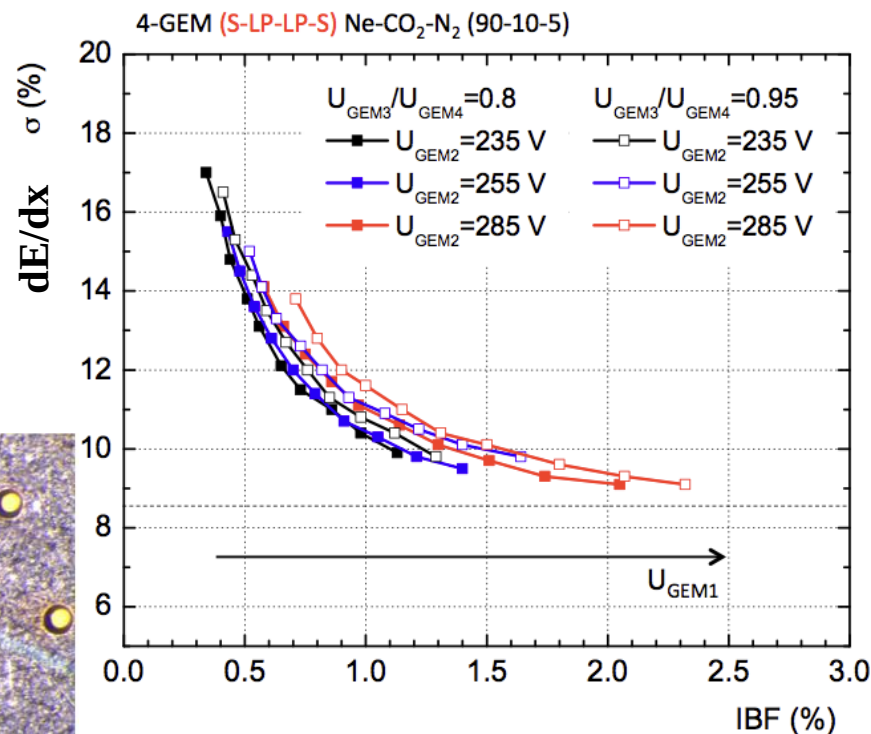
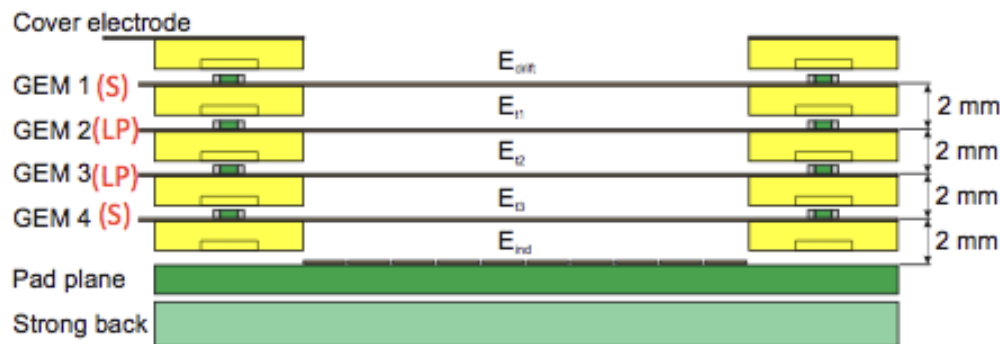
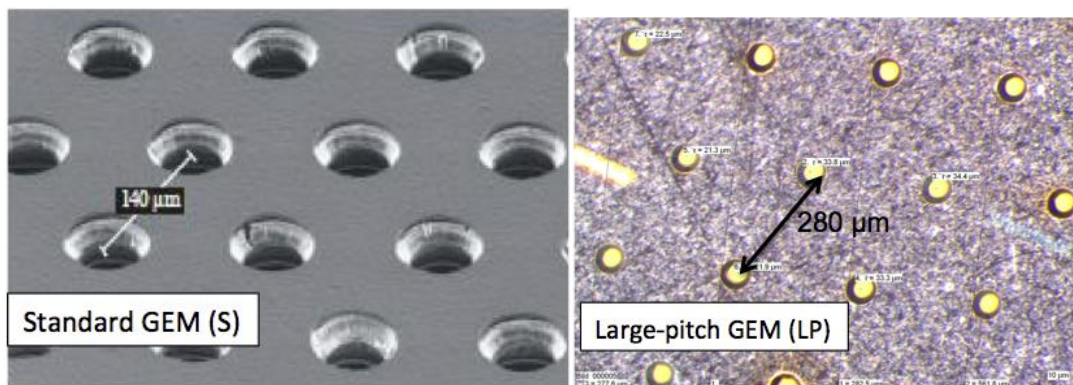
TPC upgrade objectives

- **Main objective: Retain physics performance in high rate operation**
 - continuous read-out of Pb-Pb events at 50 kHz collision rate
- **Operation of MWPC without gating grid would lead to massive space-charge distortions due to back-drifting ions**
- **Instead: Continuous read-out with micropattern gaseous detectors**
- **Advantages:**
 - reduced ion backflow (IBF)
 - high rate capability
 - no long ion tail
- **Requirements for read-out system:**
 - $\text{IBF} < 1\%$ at gain 2000
 - dE/dx resolution $< 12\%$ for ^{55}Fe
 - Stable operation under LHC conditions



GEM setup with S and LP foils

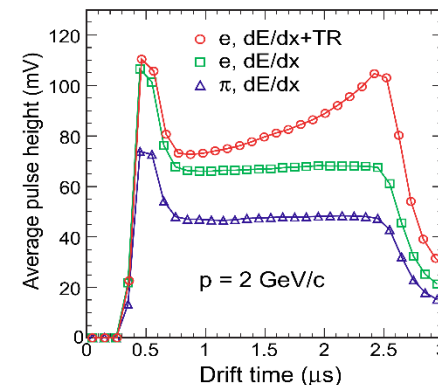
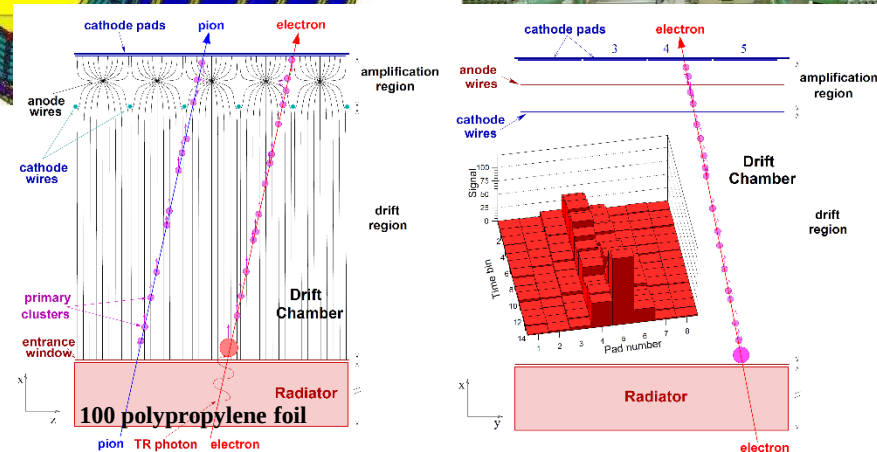
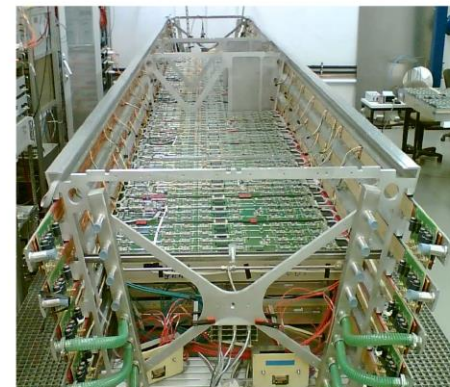
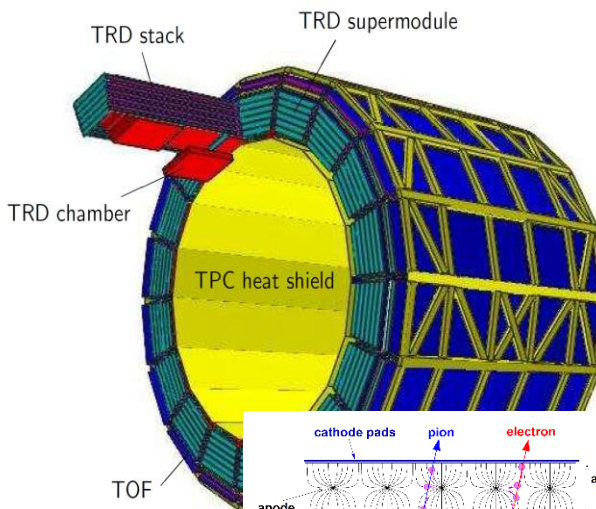
- IBF and energy resolution studies for baseline solution (4GEM stack)
- Different foil configuration, V_{GEM} , E_T (transfer fields)



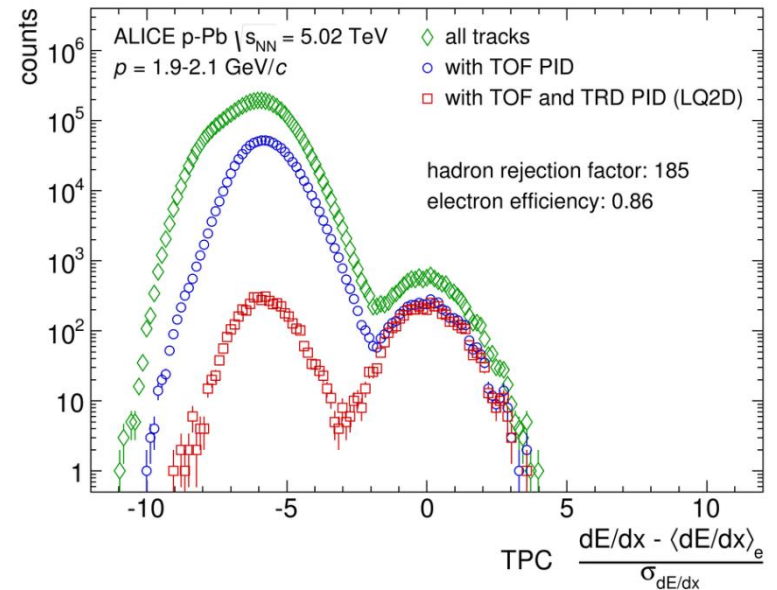
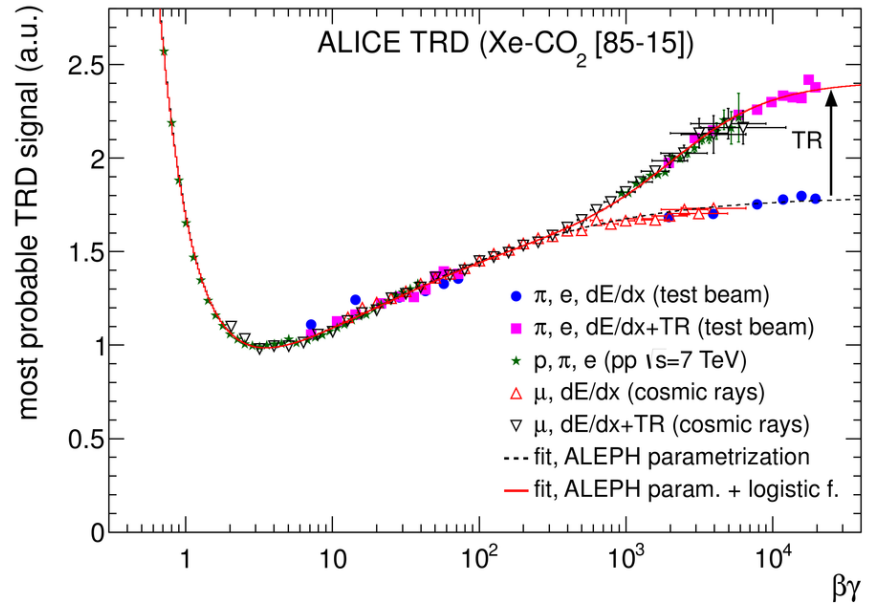
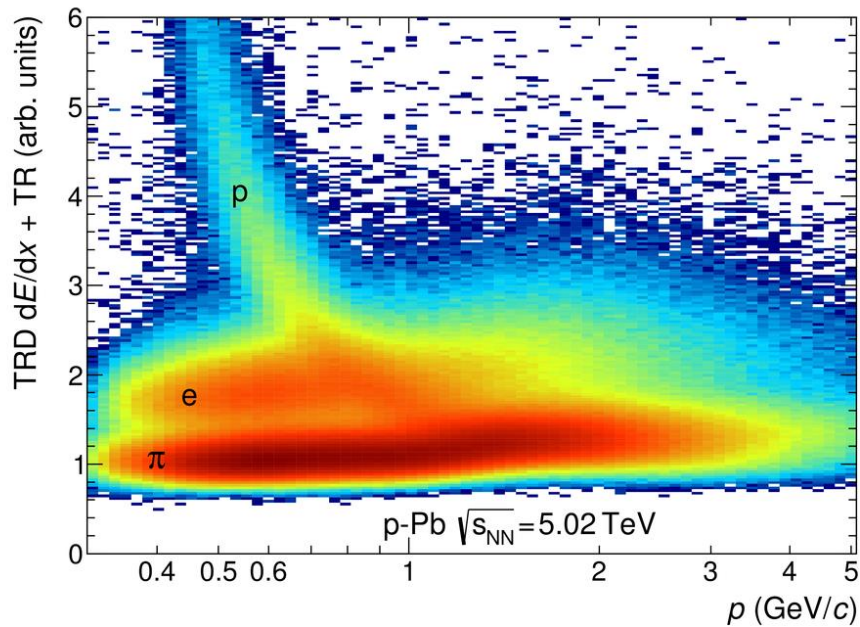
- IBF optimised settings : High E_{T1} & E_{T2} , low E_{T3} , $V_{\text{GEM1}} \approx V_{\text{GEM2}} \approx V_{\text{GEM3}} \ll V_{\text{GEM4}}$
- Achieved performance : 0.6 – 0.8 % IBF at (5.9 keV) ~ 12%

Transition radiation detector (TRD)

- **Electron identification in the central barrel for momenta greater than 1 GeV**
- **Five layers of 4.8cm thick radiator (Fibres/foam sandwich) and MWPC readout chamber (Xe :CO₂ = 85%:15%) with $2.9\text{m} < r < 3.7\text{m}$**
- **Pad occupancy $\sim 34\%$**
- **Position resolution $\sim 600\mu\text{m}$ and 2cm in (r- ϕ and z measurement)**
- **Total readout channel 1.16M**
- **Momentum resolution $\delta p/p = 2.5\% \oplus 0.8 \times p\%$**
- **Radial detector thickness $15X_0$**
- **Due to properties of fast tracker, it can be used as an efficient trigger for high transverse momentum electron**

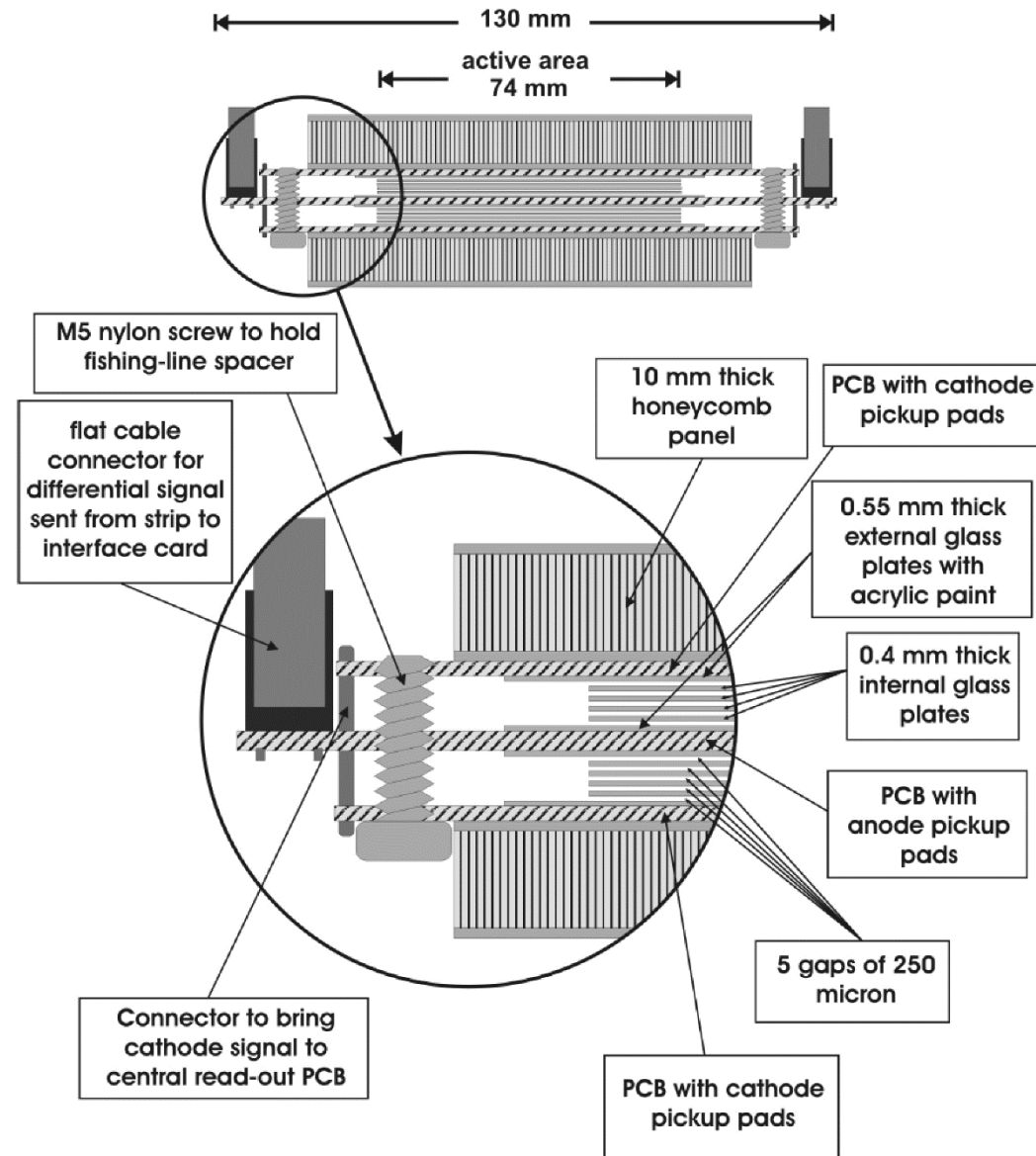


Electron identification



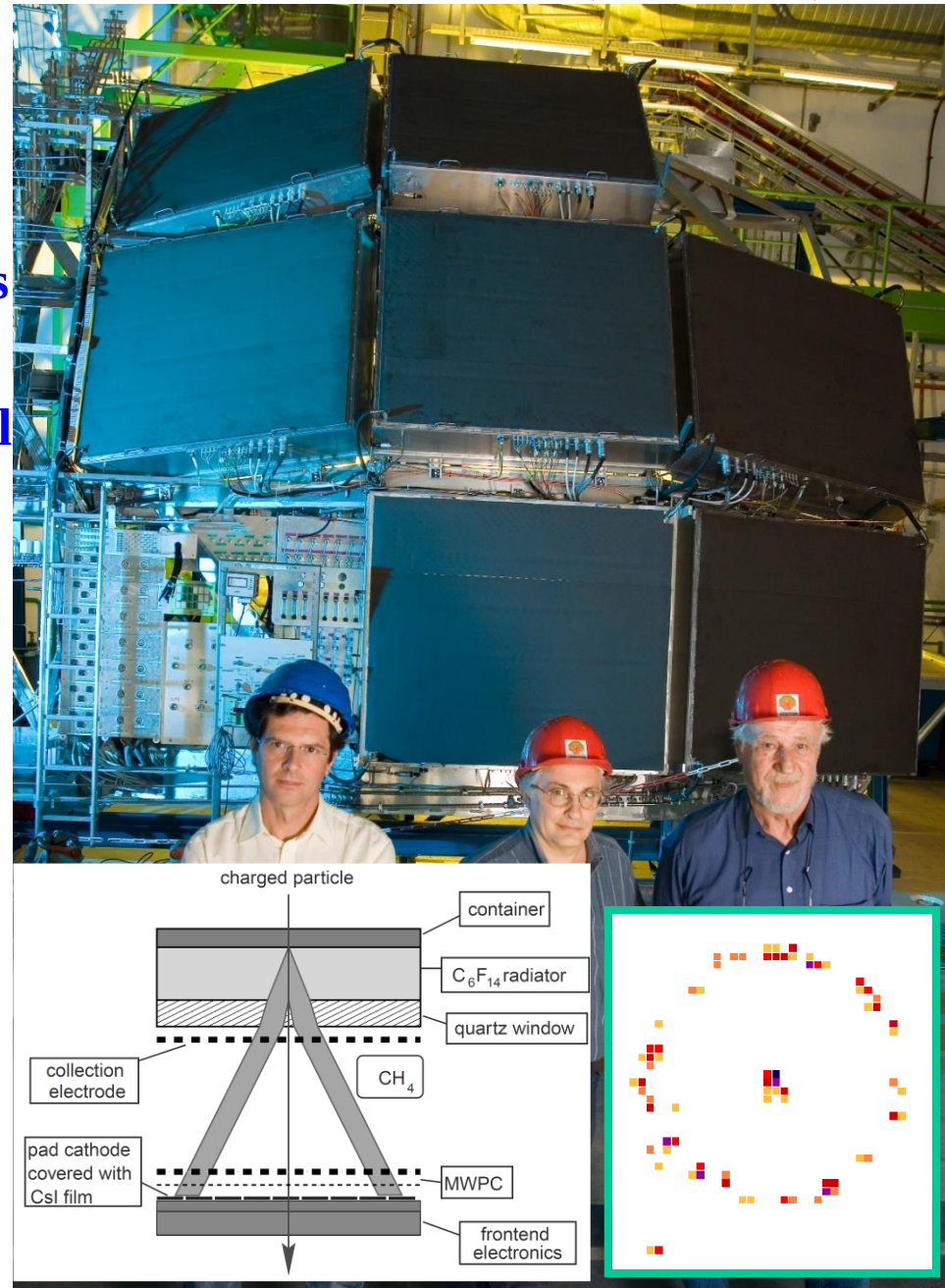
Time-Of-Flight (TOF)

- **Particle identification (PID) in the intermediate momentum range (from 0.2 GeV to 2.5 GeV)**
- **Constraints : Not exceeding occupancy 10-15%**
- **A group of Multi-gap Resistive Plate Chamber (15 in the central, 19 in the intermediate and 1 the external modules), radial distance from 3.7m to 3.99m**
- **Radial thickness $0.18X_0$**
- **Gas composition : $C_2H_2F_4$ (90%), $i-C_4F_{10}$ (5%), SF_6 (5%)**
- **Typical size : 122cm long and 13cm width, subdivided in pad size $35mm \times 25mm^2$**
- **Readout channel : 157K**
- **Expected timing resolution $\sim 40ps$**

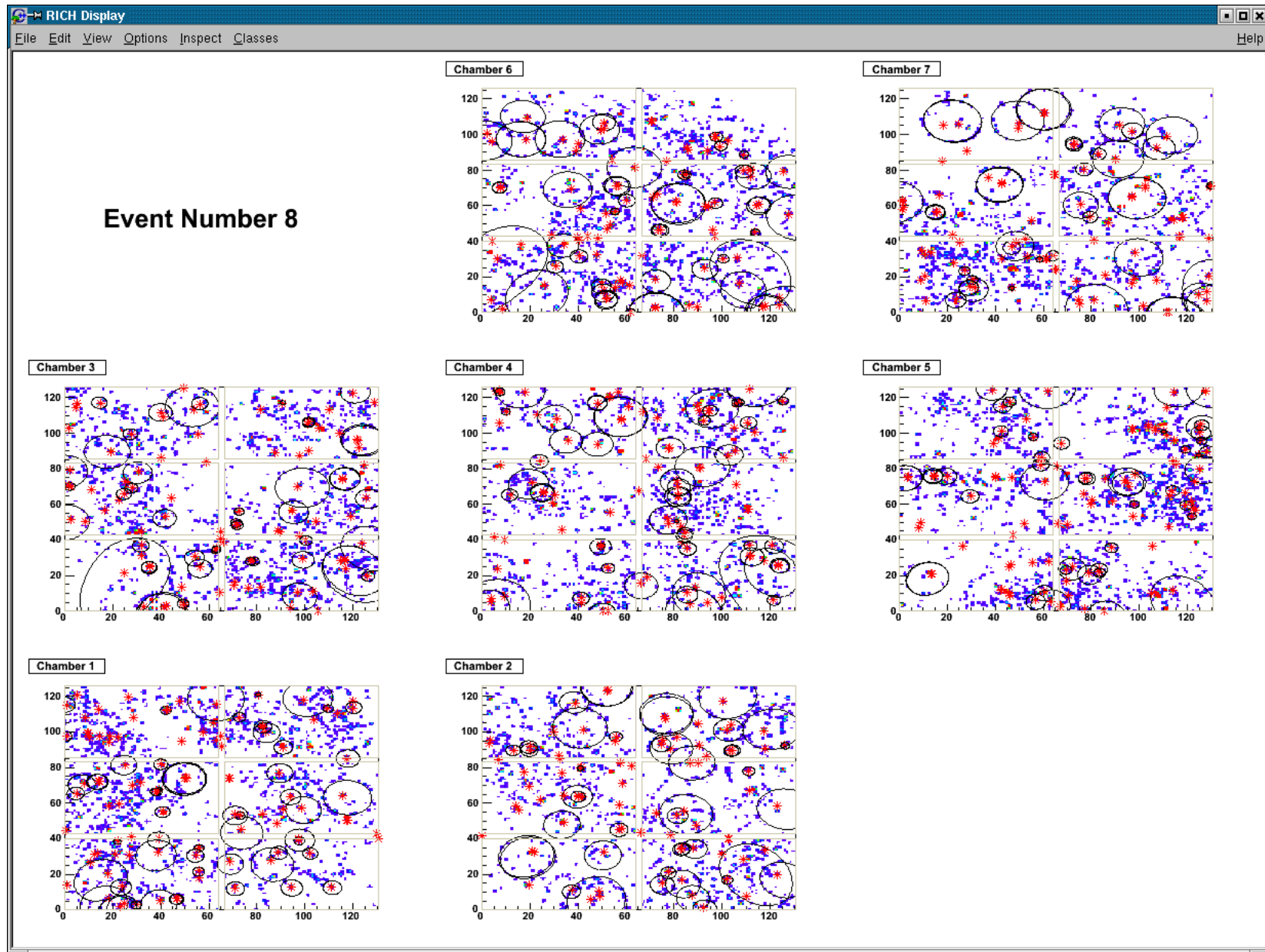


High Momentum Particle Identification Detector (HMPID)

- Extend PID up to 3 and 5 GeV π/K and K/p discrimination
- Seven Proximity Focusing Ring Imaging CHerenkov (RICH) counters of size $\sim 1.5\text{m} \times 1.5\text{m}$
- Coverage : $-0.6 < \eta < 0.6$ & Azimuthal coverage 57.61°
- $n=1.2989$ at $\lambda=175\text{nm} \Rightarrow \beta_{\min} = 0.77$ ($p_{\text{th}} = 1.21\text{m}$)
- Photo-electron conversion through 6 independent CsI photocathode (QE=25%) board, $64 \times 40\text{cm}^2$, segmented into pads $8 \times 8.4\text{mm}^2$
- Amplification : $20\mu\text{m}\Phi$ W-Re anode wires separated from cathode and collection wire plane (100 μm gold plated Cu/Be) by 2mm
- Material budget $0.18 X_0$



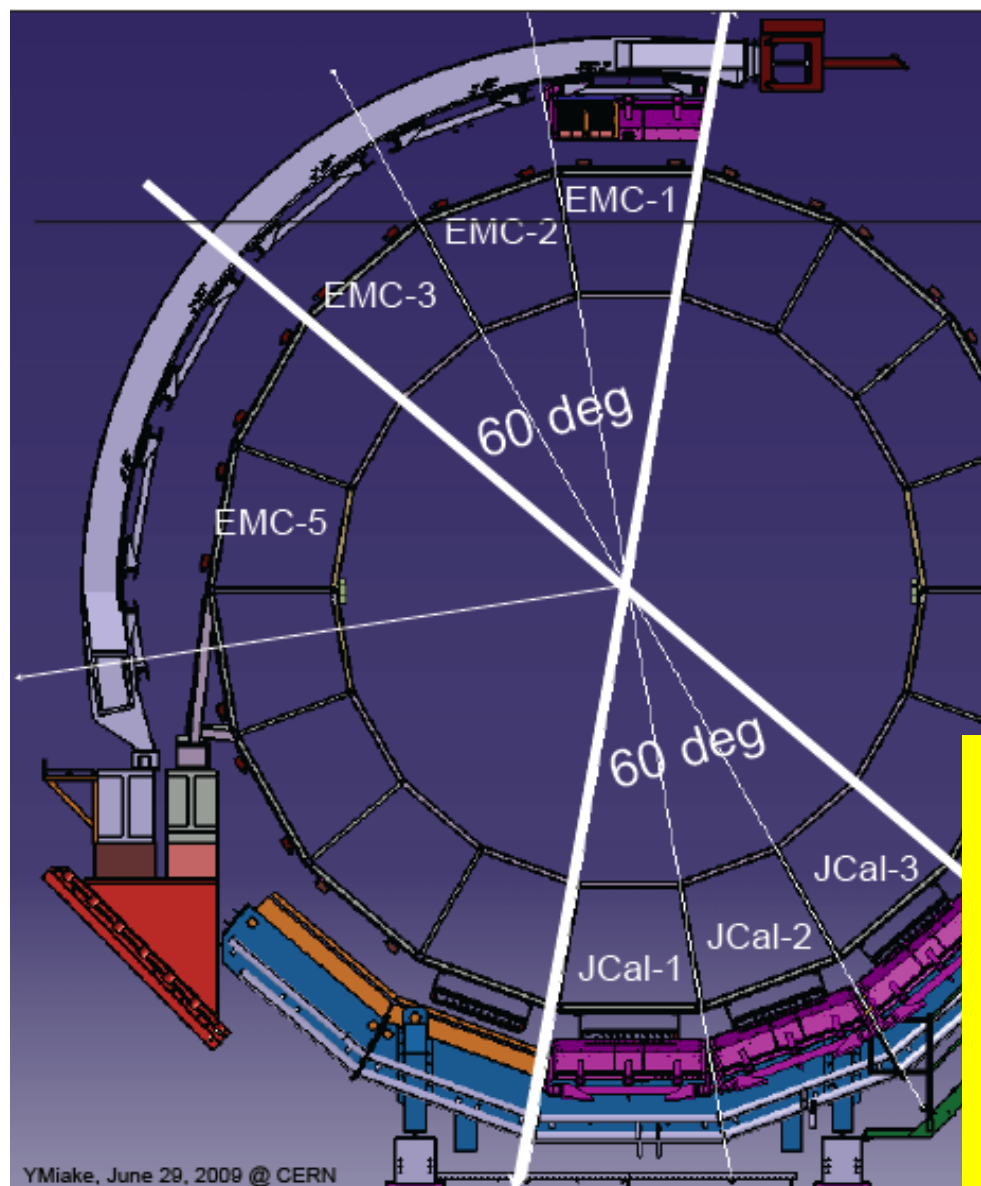
ALICE HMPID



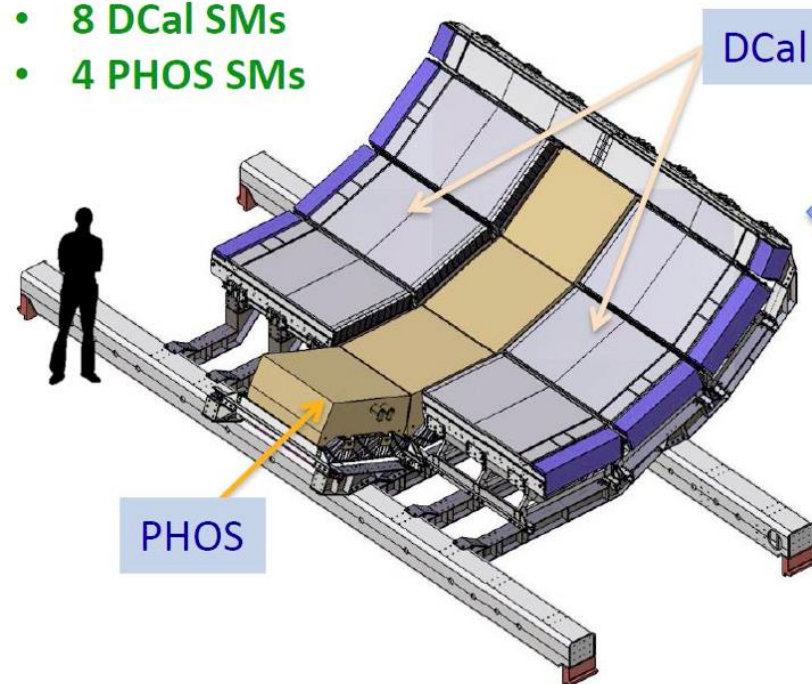
PHOton Spectrometer (PHOS)

- Detected electromagnetic particles in a limited acceptance domain at central rapidity and identification of photon as well as π^0 , η through two photon decay
- Requirements : Identification, high resolution, (energy & spatial) with large dynamical range (100 GeV with least count 5-10 MeV)
- Coverage : $-0.12 < \eta < 0.12$ & $\Delta\Phi = 100^\circ$
- Photon detector : An array of 56 rows and 64 columns PbWO_4 crystal of size $22 \times 22 \times 180 \text{ mm}^3$ (Moliere radius = 22mm and $X_0 = 8.9\text{mm}$) operated at -25°C with precision 0.3°C ($dN/dT = -2\%$)
 - $5 \times 5 \text{ cm}^2$ Avalanche Photodiode (APD) readout
- Charge particle veto detector : 14mm active volume of proportional chamber filled with 80%Ar/20%CO₂. 256 anode wires, 30 μm in Φ stretched 7mm above cathode of pitch 5.65mm. Cathode planes are segmented into 7168 of $22 \times 10.5 \text{ mm}^2$.
- Its charge particle identification is better than 99% with material budget $0.05X_0$ and sensitive area $\sim 1.8\text{m}^2$.
- $6 \times 6 \times 24.6 \text{ cm}^3$ for EMCAL : 77 layer of 1.44mmPb/1.76mm scintillator, $X_0 = 12.3\text{mm}$, $R_M = 3.2\text{cm}$, # of r.l. = 20,

LS1 : EMCal Extension/Upgrade

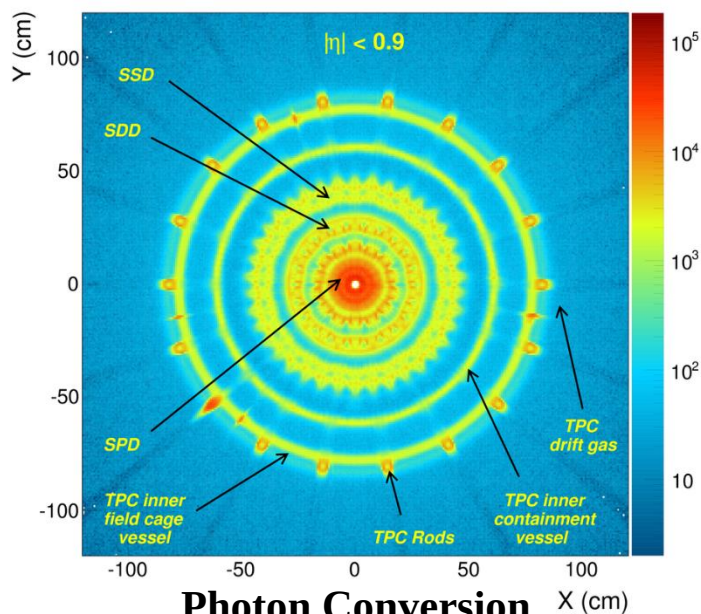


- 8 DCal SMs
- 4 PHOS SMs



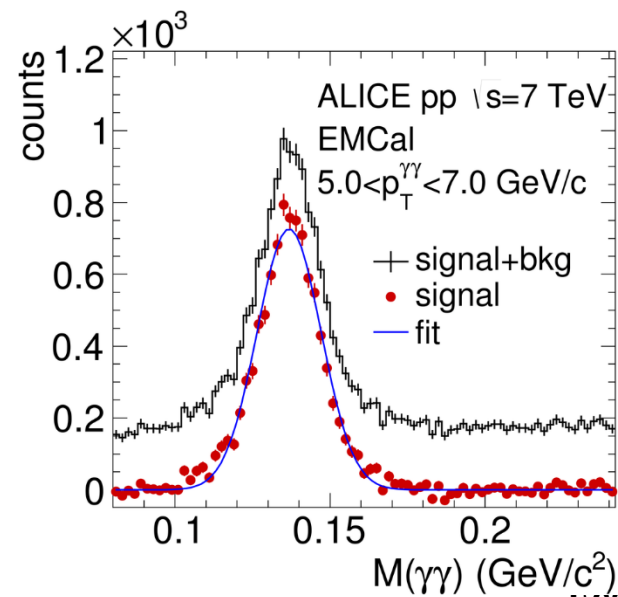
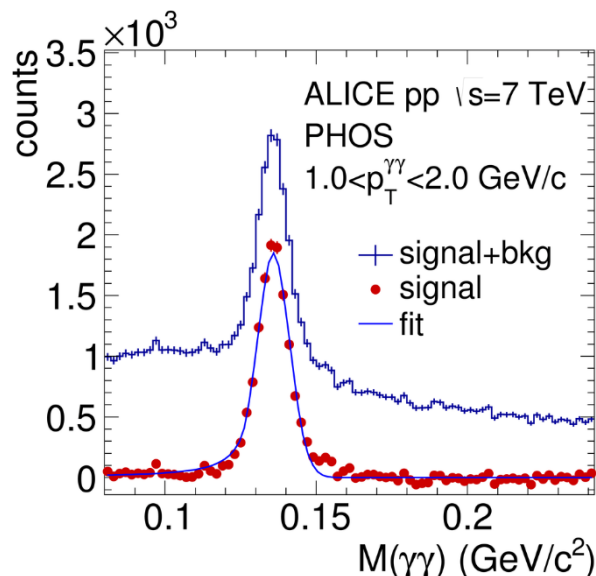
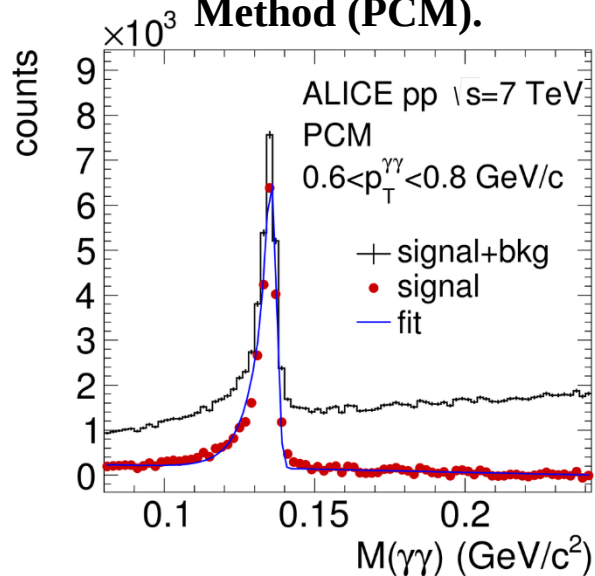
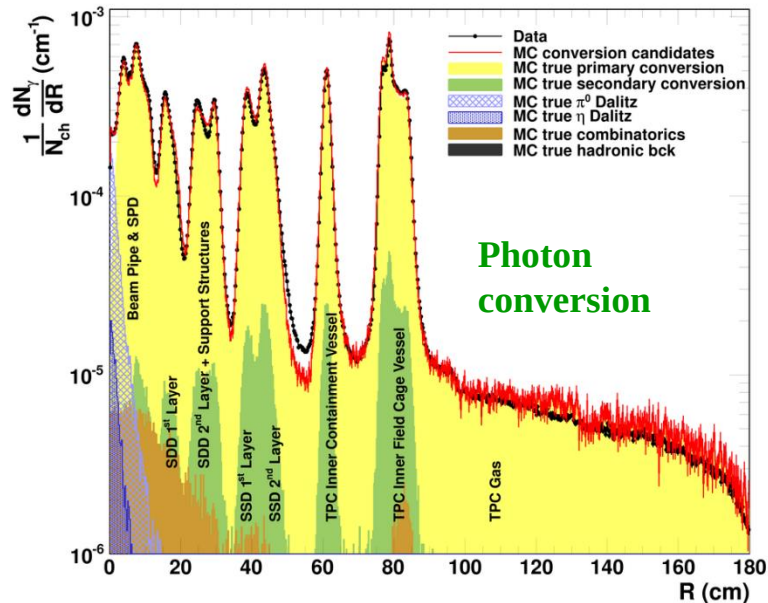
- **DCal (Di-jet Calorimeter) :**
- **Same modules as the EMCAL**
- **Shorter SuperModules in η**
- **Including PHOS, acceptance is $\Delta\eta=1.4$, $\Delta\phi=67^\circ$**
- **Enhance di-jet yield (w/ jet trigger)**

Reconstruction of γ and π^0



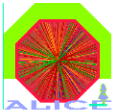
Photon Conversion

Method (PCM).





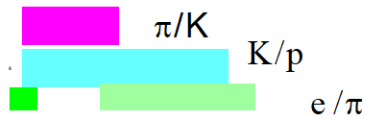
Particle Identification



- stable hadrons (π , K, p): $100 \text{ MeV} < p < 50 \text{ GeV}$
 - dE/dx in silicon (ITS) and gas (TPC) + Time-of-Flight (TOF) + Cerenkov (RICH)
 - dE/dx relativistic rise $\Rightarrow$ extend PID to several 10 GeV
- decay topology (K^0 , K^+ , K^- , Λ , D^+ , ...)
 - K and Λ decays up to $> 10 \text{ GeV}$
- leptons (e, μ), photons, η , π^0

Alice uses ~ all known techniques!

TPC + ITS
(dE/dx)



electrons in TRD: $p > 1 \text{ GeV}$

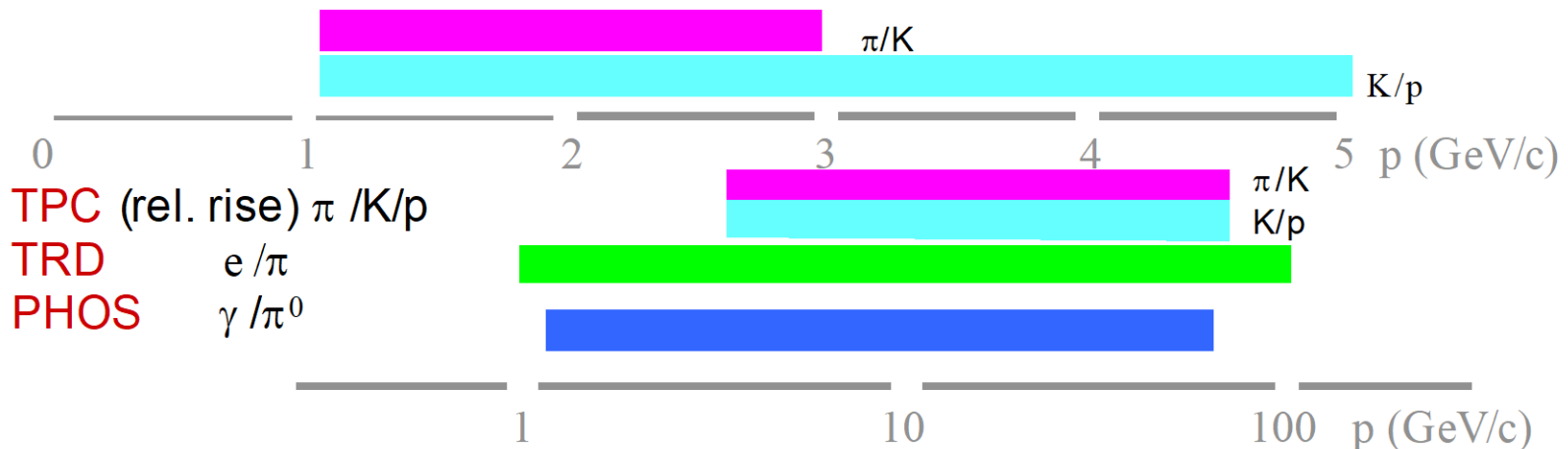
muons: $p > 5 \text{ GeV}$

π^0 in PHOS: $1 < p < 80 \text{ GeV}$

TOF



HMPID
(RICH)



TPC (rel. rise) π /K/p

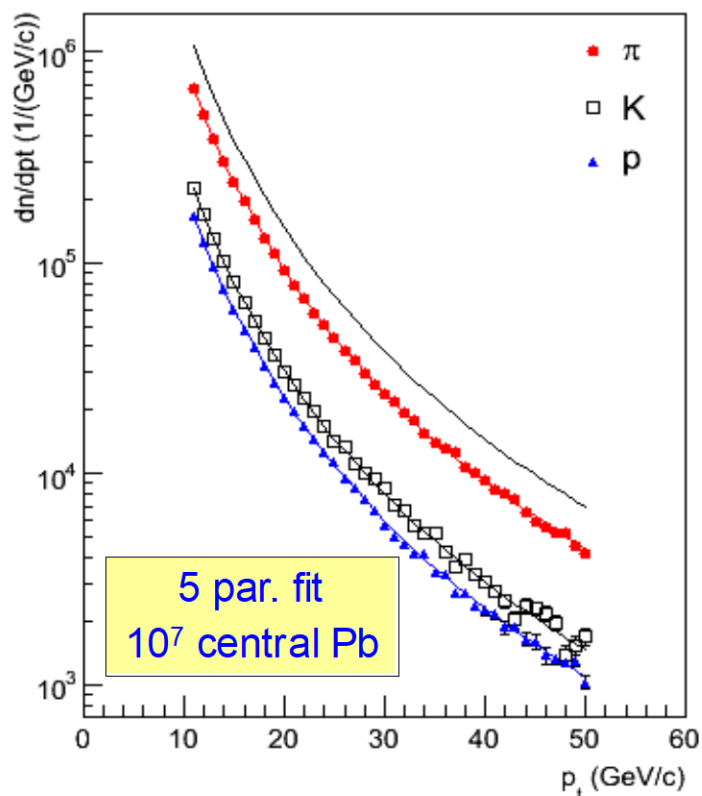
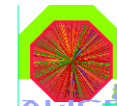
TRD e / π

PHOS γ / π^0

1 10 100 p (GeV/c)



PID at High Momentum



TPC dE/dx

5.5% (pp) $\rightarrow$ 6.5% (central Pb)

$\pi/K/p$ spectra up to ~ 50 GeV

limited by statistics

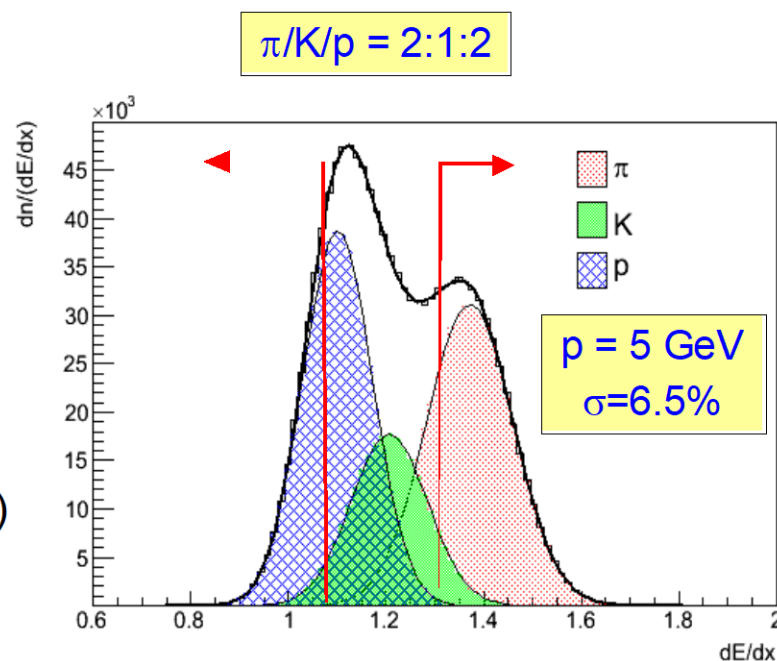
requires good systematics (calibrate with data)

π/p PID to ~ 50 GeV

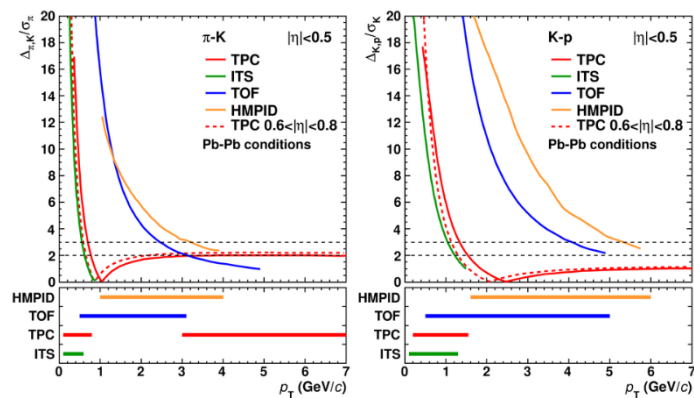
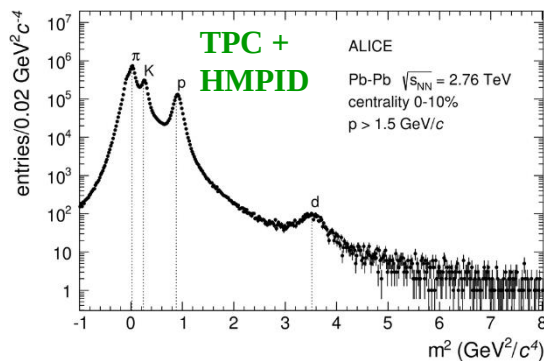
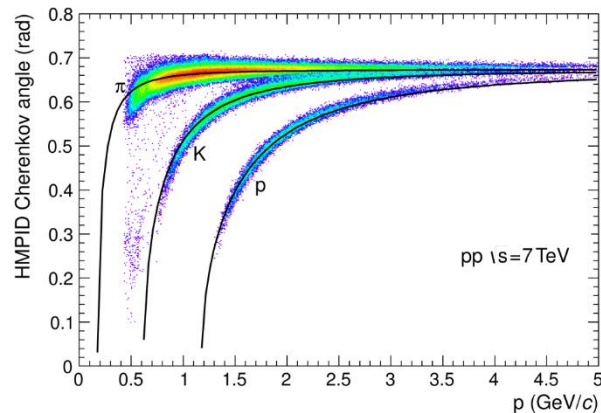
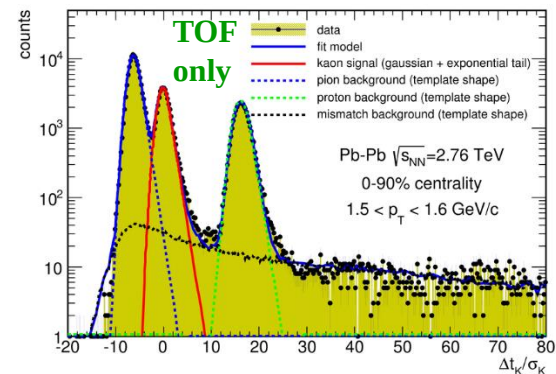
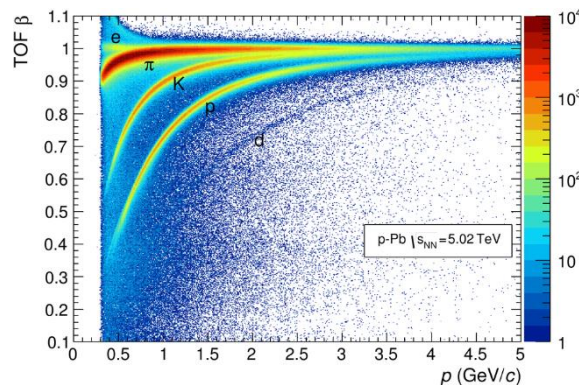
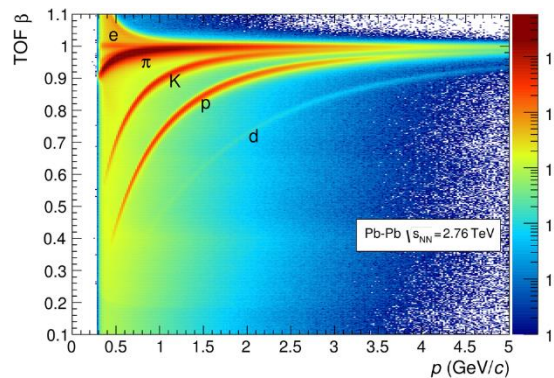
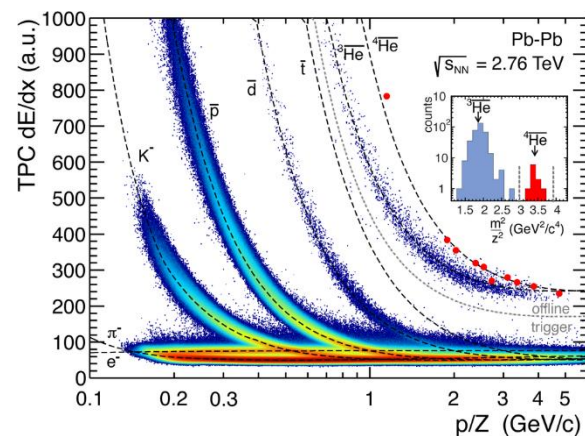
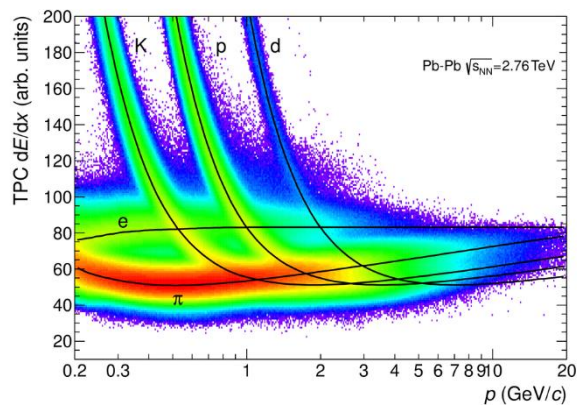
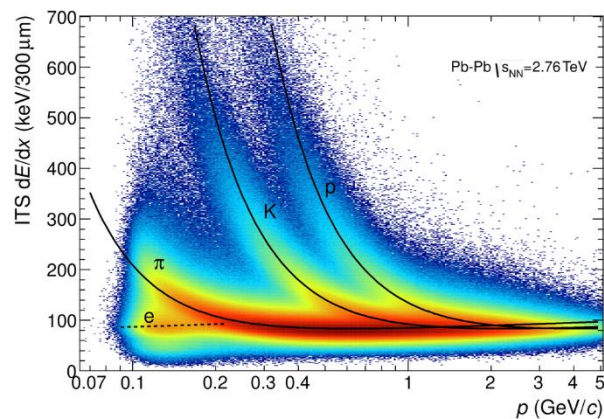
purity $> 80\%$

reasonable efficiency

40% (p at 50 GeV) $\rightarrow$ 90% (π at 5 GeV)

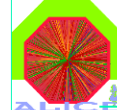


PID at ALICE



3X₀ Pb sandwiched in two
honeycomb gas detectors

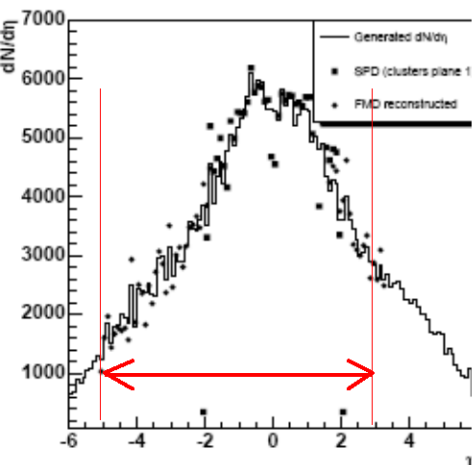
Forward Detectors



PMD Pre-shower detector $2.3 < \eta < 3.5$, N_{charged} and N_{photons} (**DCC's**)

V0 $1.6 < |\eta| < 3.9$ **Interaction** trigger (beam-gas rejection), centrality trigger and beam-gas rejection. Two arrays of 64 **scintillator tiles** readout via fibers

T0_L

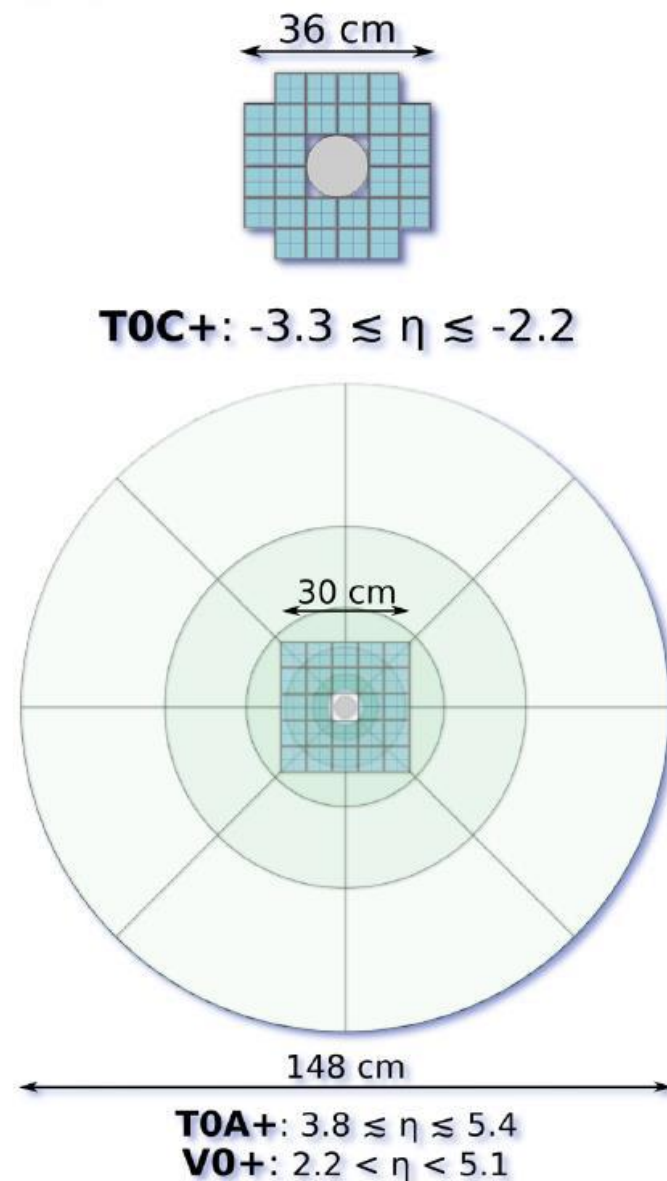


FMD: Multiplicity and η dist. $1.6 < \eta < 3$, $-5.4 < \eta < -1.6$ **Silicon strip** disks, 12k analog channels

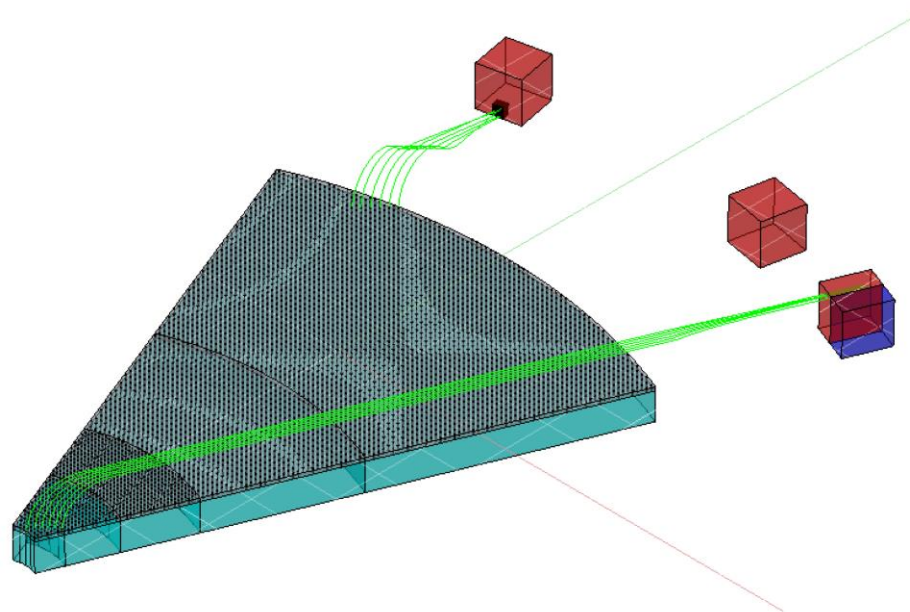
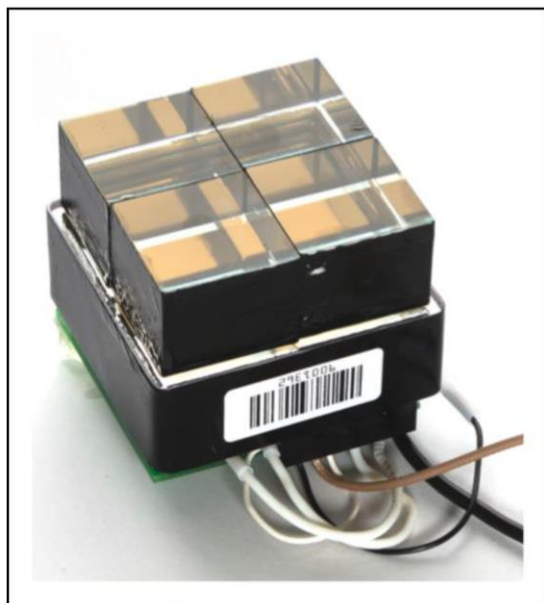
T0_R: $2.6 < |\eta| < 3.3$ **Time** (T_0) for the TOF (~ 50 ps time res.) Two arrays of **12 quartz counters**. Also backup to V0

New Fast Interaction Trigger detector

- To replace V0 and T0 detectors
- Requirements:
 - Preserve resolution
 - Increase acceptance
 - Integrate detectors
- Good Time resolution < 30 ps Time zero for PID
- Large acceptance
- Trigger efficiency, centrality, beam gas background reduction, for *pp* and *Pb-Pb*, veto forward hadronic activity for the detection of ultra-peripheral *Pb-Pb* collision
- •Finer segmentation
- Reaction plane determination



FIT = T0+ and V0+



T0+ modules

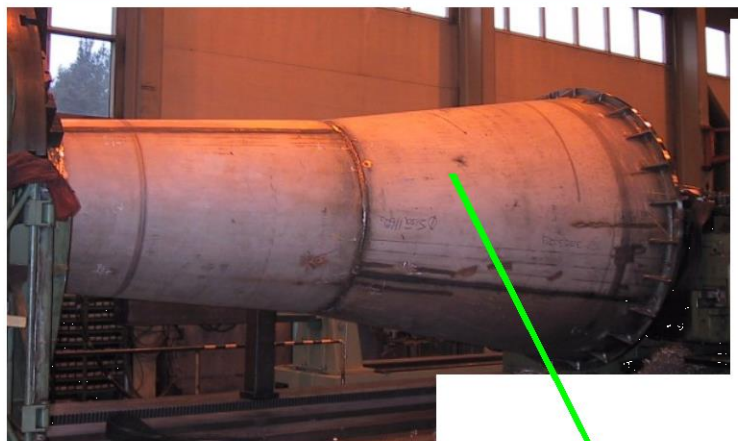
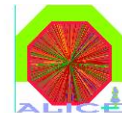
- Improved T0
- Rectangular quartz radiators
- New sensors MCP-PMT
- Larger acceptance
- More channels
- Upgraded electronics and readout

V0+ sectors

- Improved V0
- Faster plastic scintillator
- Monolithic structure
- Reduced fibre length
- New sensor (SiPM or MCP-PMT)
- New electronics and readout



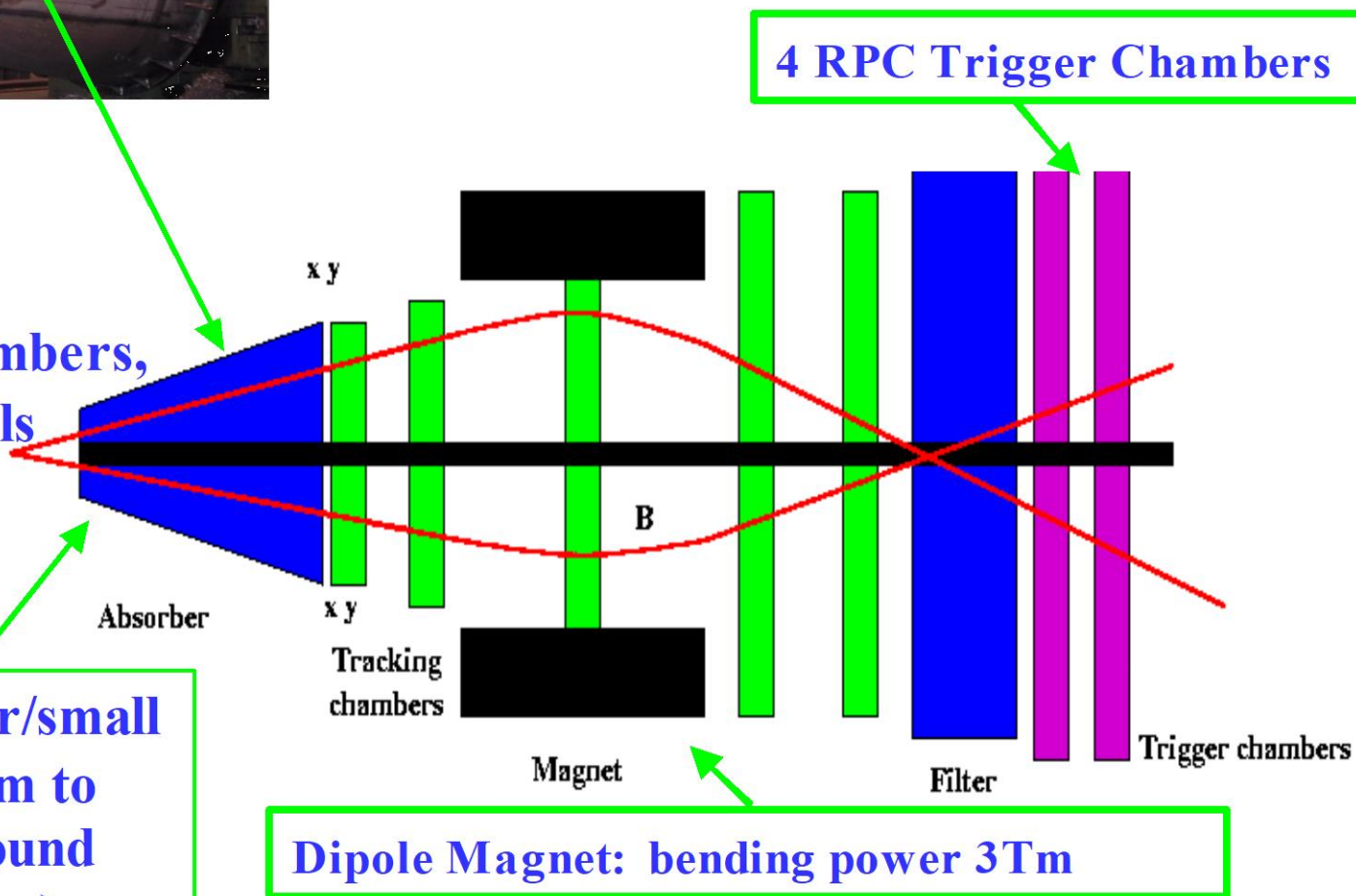
Dimuon Spectrometer



10 planes of high granularity pad tracking chambers, over 800k channels

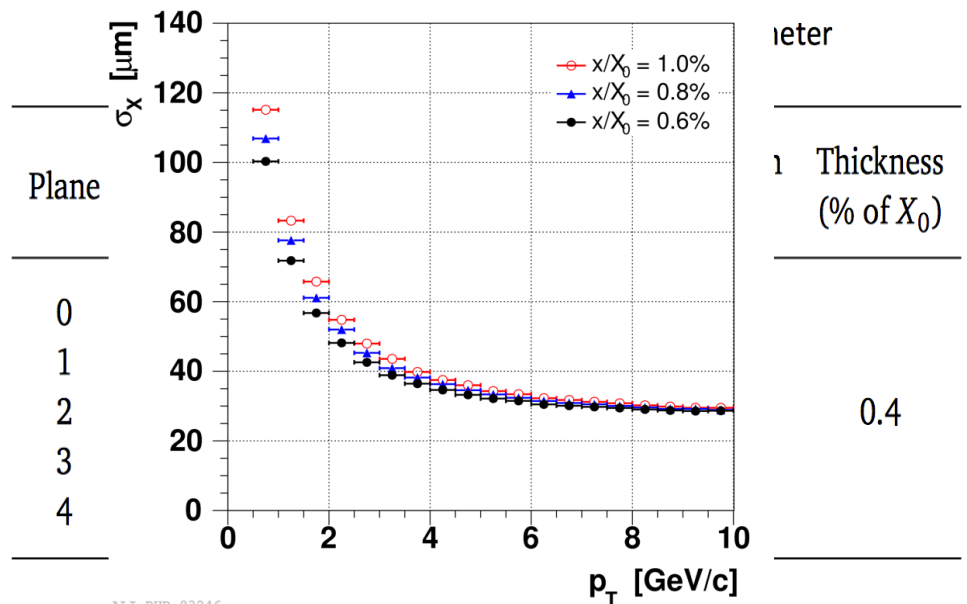
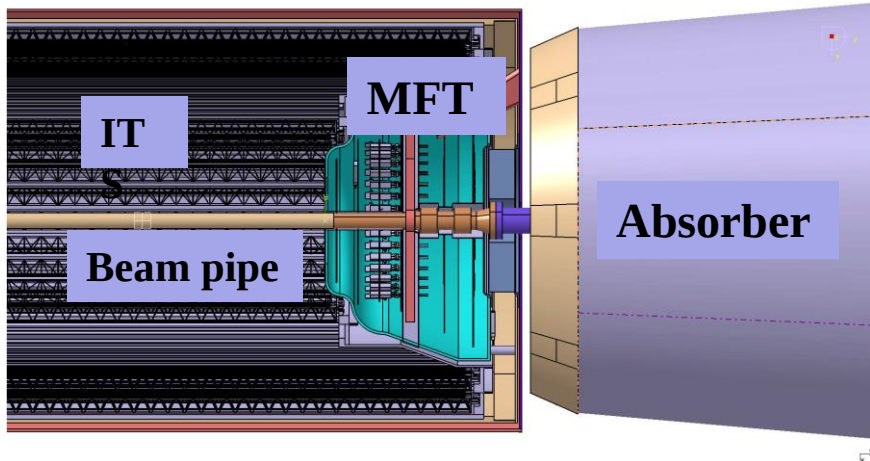
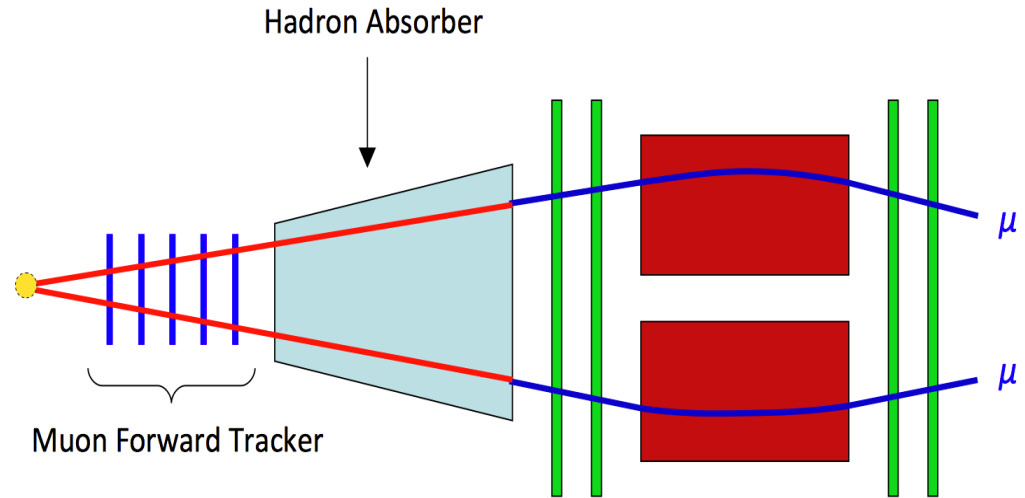
Complex absorber/small angle shield system to minimize background (90 cm from vertex)

- Study the production of the J/ψ , ψ' , $\psi(2S)$, $\psi(3S)$, $\psi(4S)$ decaying in 2 muons, $2.4 < \eta < 4$
- Resolution 70 MeV at the J/ψ , 100 MeV at the ψ'



Muon Forward Tracker (MFT)

- **ALICE muon arm** : detect muons in forward range $-4.0 < \eta < -2.5$
- **MFT design objectives** : Increase pointing accuracy for the muon tracks, in particular at low P_T
- **Implementation** : 5-plane silicon telescope in front of the hadron absorber

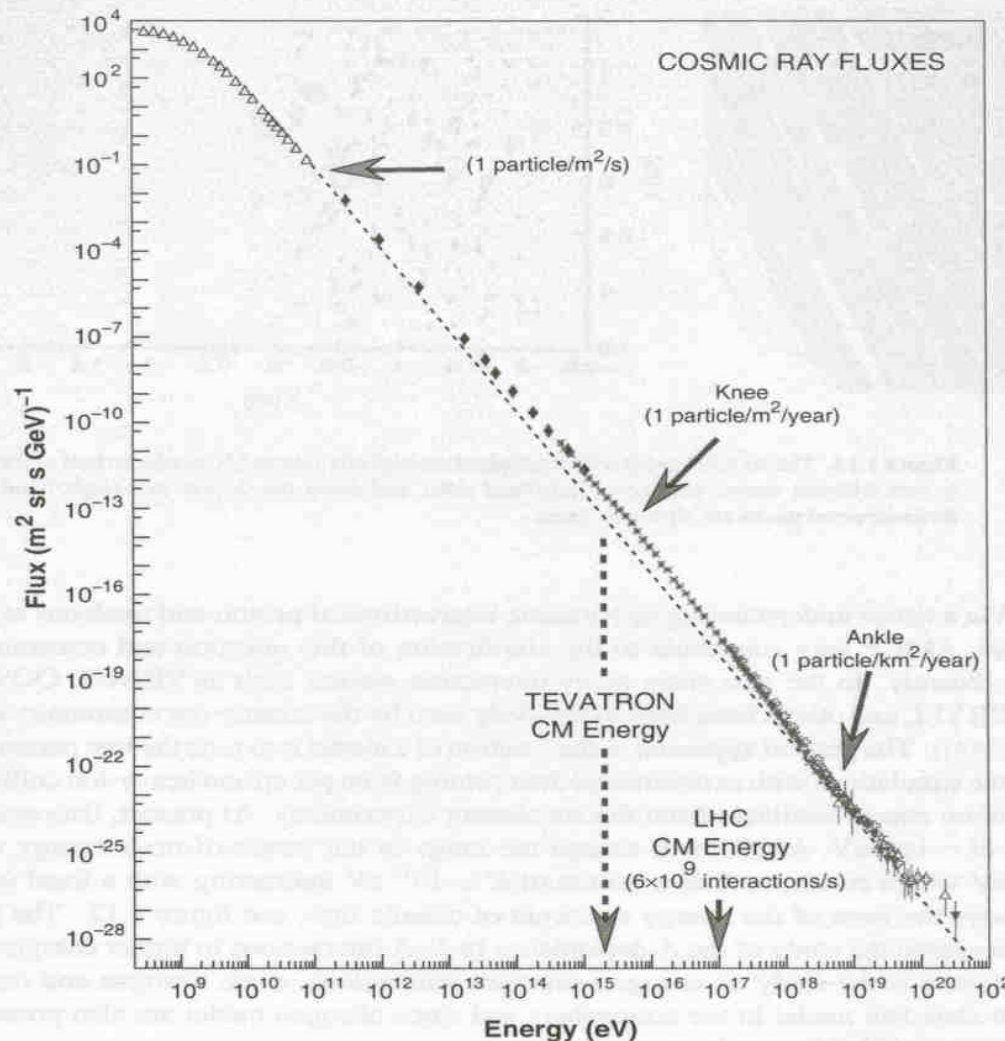


ALI-PUB-93246

Expectation & performance of ALICE detector

Parameter	Expected	Achieved
<i>Event vertex resolution with ITS–TPC tracks</i>		
vertex resolution at $dN_{\text{ch}}/d\eta = 5$, transverse	85 μm	97 μm
vertex resolution at $dN_{\text{ch}}/d\eta = 25$, transverse	35 μm	32 μm
<i>DCA resolution of ITS–TPC tracks in central Pb–Pb collisions</i>		
transverse DCA resolution at $p_{\text{T}} = 0.3 \text{ GeV}/c$	200 μm	200 μm
transverse DCA resolution at $p_{\text{T}} = 3 \text{ GeV}/c$	30 μm	30 μm
transverse DCA resolution at $p_{\text{T}} = 20 \text{ GeV}/c$	15 μm	15 μm
<i>DCA resolution of ITS–TPC tracks in pp collisions (including vertex resolution)</i>		
transverse DCA resolution at $p_{\text{T}} = 0.2 \text{ GeV}/c$	300 μm	300 μm
transverse DCA resolution at $p_{\text{T}} = 3 \text{ GeV}/c$	50 μm	45 μm
transverse DCA resolution at $p_{\text{T}} = 30 \text{ GeV}/c$	25 μm	20 μm
<i>Barrel tracking efficiency in central Pb–Pb collisions</i>		
TPC track finding efficiency at $p_{\text{T}} > 0.2 \text{ GeV}/c$	$> 78\%$ ^a	$> 70\%$
TPC track finding efficiency at $p_{\text{T}} > 1.0 \text{ GeV}/c$	$> 90\%$ ^a	$> 78\%$
ITS matching efficiency at $p_{\text{T}} > 0.2 \text{ GeV}/c$	$> 95\%$	$> 92\%$
<i>Barrel p_{T} resolution</i>		
$\Delta p_{\text{T}}/p_{\text{T}}$ of TPC tracks at $p_{\text{T}} = 10 \text{ GeV}/c$	4–6%	6%
$\Delta p_{\text{T}}/p_{\text{T}}$ of TPC tracks at $p_{\text{T}} = 30 \text{ GeV}/c$	10–15%	18%
$\Delta p_{\text{T}}/p_{\text{T}}$ of ITS–TPC tracks at $p_{\text{T}} = 10 \text{ GeV}/c$	1–2%	1.5%
$\Delta p_{\text{T}}/p_{\text{T}}$ of ITS–TPC tracks at $p_{\text{T}} = 30 \text{ GeV}/c$	2–3%	2.5%
<i>Barrel particle identification</i>		
TPC dE/dx resolution in pp	5.4%	5.2%
TPC dE/dx resolution in central Pb–Pb	6.8%	6.5%
TOF resolution	60–110 ps	80 ps
T0 resolution	15–50 ps	21 ps
<i>Muon spectrometer</i>		
MUON track finding efficiency	95%	85–87%
invariant mass resolution at J/ψ peak in central Pb–Pb	70–74 MeV/c^2	73 MeV/c^2
invariant mass resolution at Υ peak in central Pb–Pb	99–115 MeV/c^2	147 (27) MeV/c^2

A Cosmic Ray Detector for ALICE (ACORDE)



- 20 scintillator modules ($1.88 \times 0.2 \text{ m}^2$) arranged in a doublet configuration are covering the central part of the top face
- Efficiency $> 90\%$

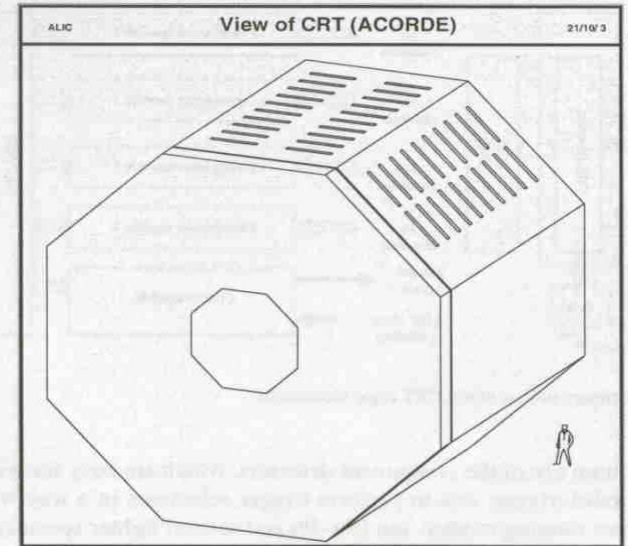


Figure 3.41. CRT scintillator array on top of the ALICE magnet.

