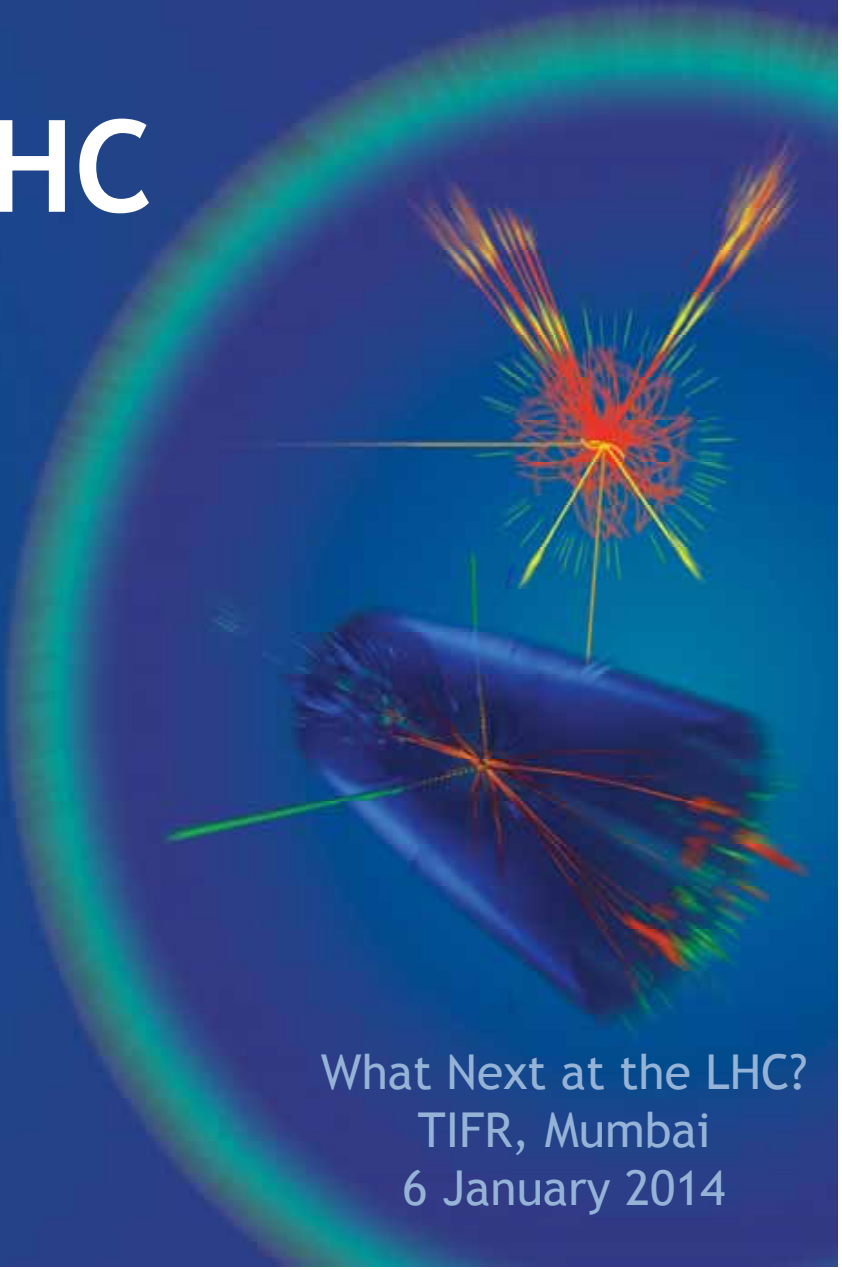
Physics at the LHC

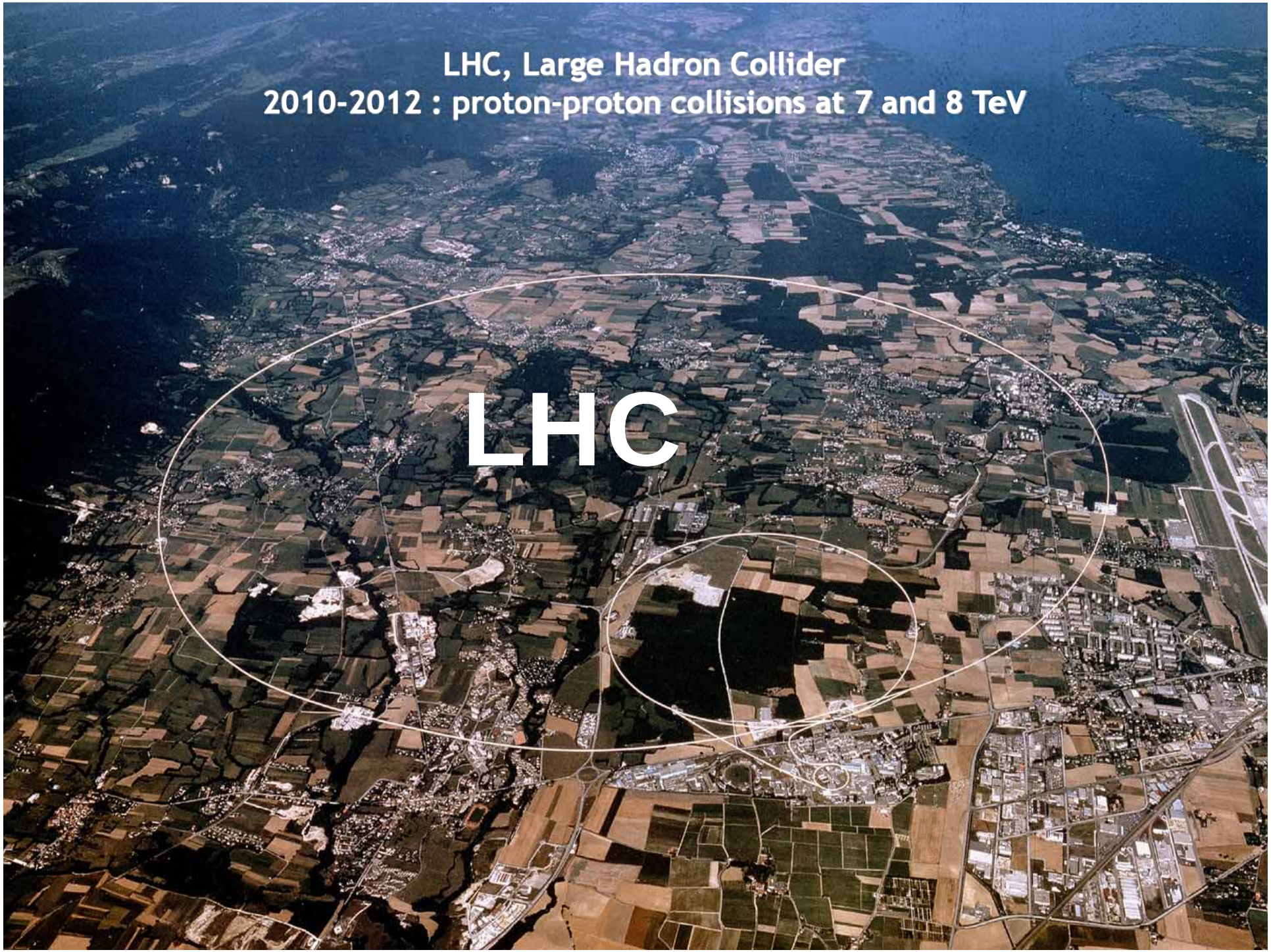
Gautier Hamel de Monchenault

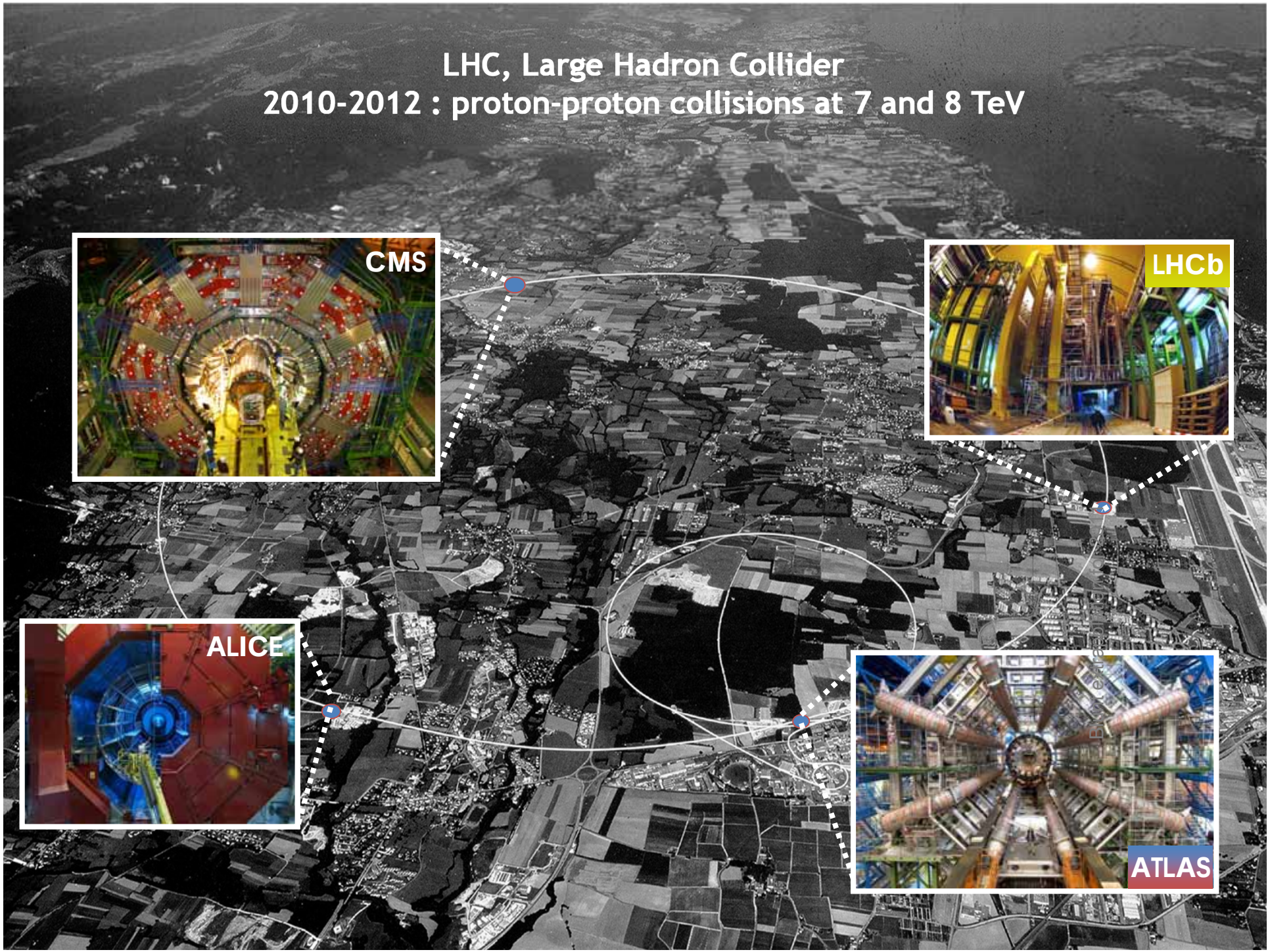
CEA-Saclay Irfu

on behalf of the ATLAS and CMS Collaborations



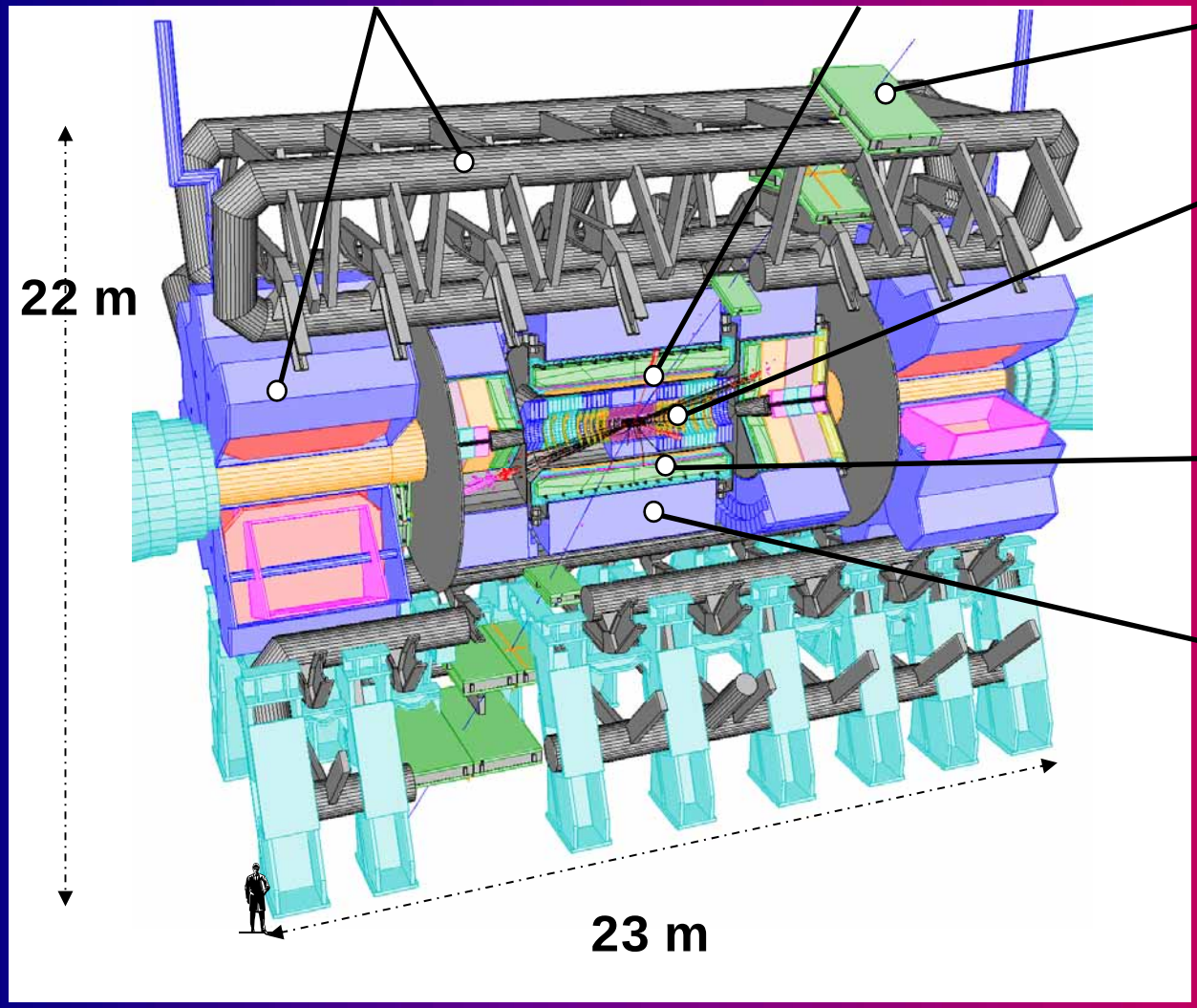
What Next at the LHC?
TIFR, Mumbai
6 January 2014


LHC, Large Hadron Collider
2010-2012 : proton-proton collisions at 7 and 8 TeV
LHC


LHC, Large Hadron Collider
2010-2012 : proton-proton collisions at 7 and 8 TeV
CMS
LHCb
ALICE
ATLAS

ATLAS

Weight: 7000 t
Diameter: 25 m
Length: 44 m
Solenoid 2 Tesla, Toroid: 3-8 T.m



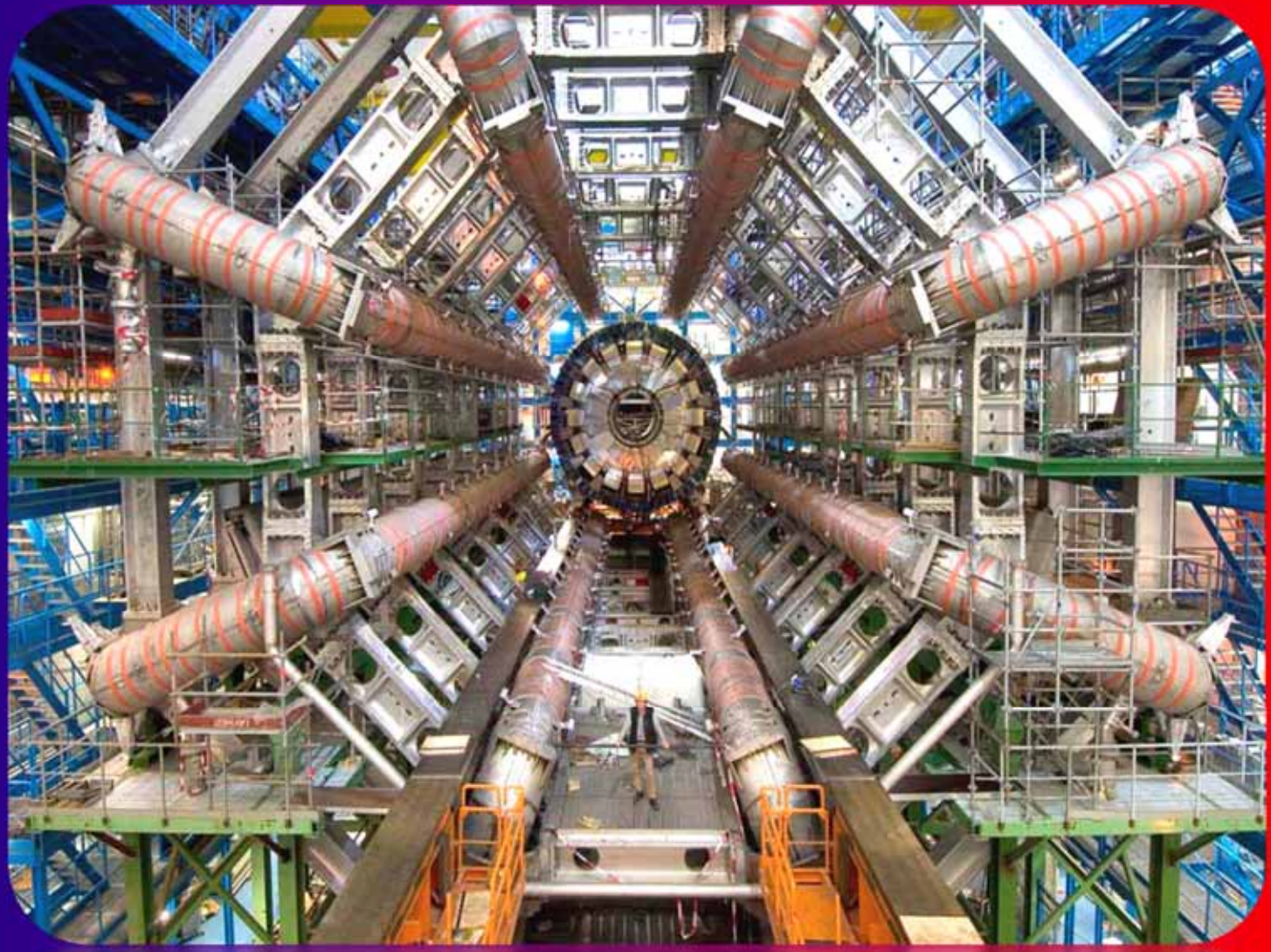
Muon detectors

Silicon Tracker
pixels & micro-strips
TRT

EM Calorimeter
Pb + Liquid Argon

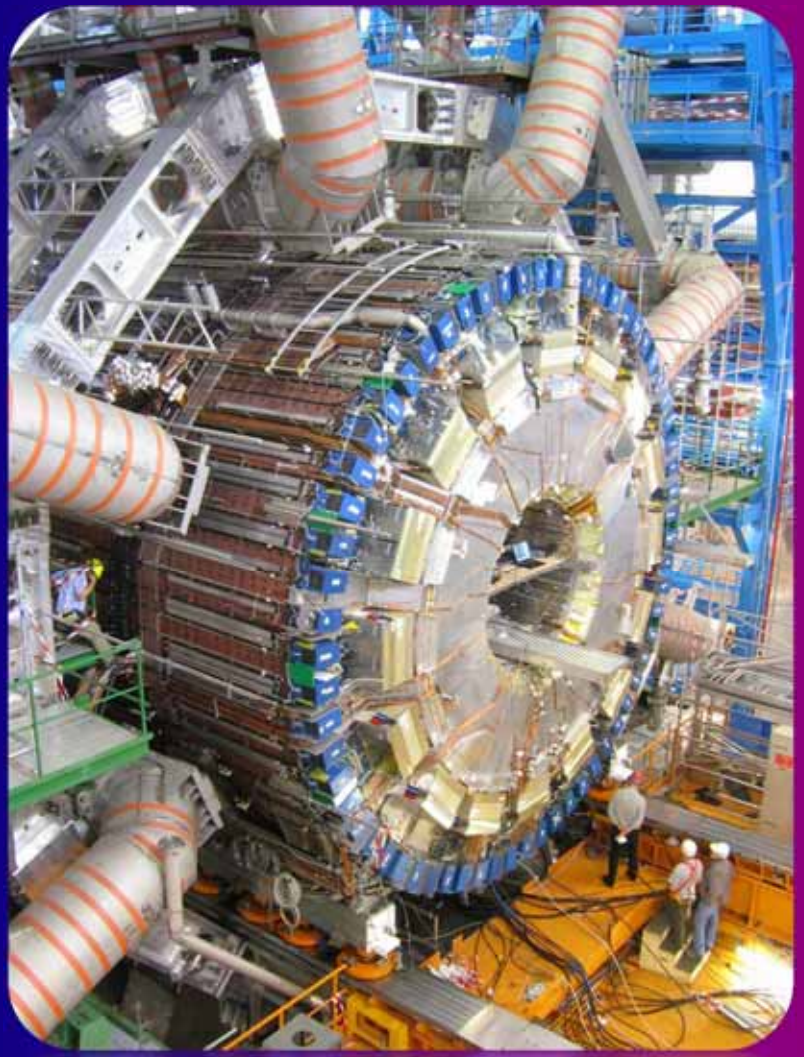
HAD Calorimeters
Cu + Liquid Argon
Fe + scintillators

ATLAS



ATLAS

Barrel Toroids & Endcap Calorimeters



Liquid Argon Calorimeter

Central detector

Pixel detector

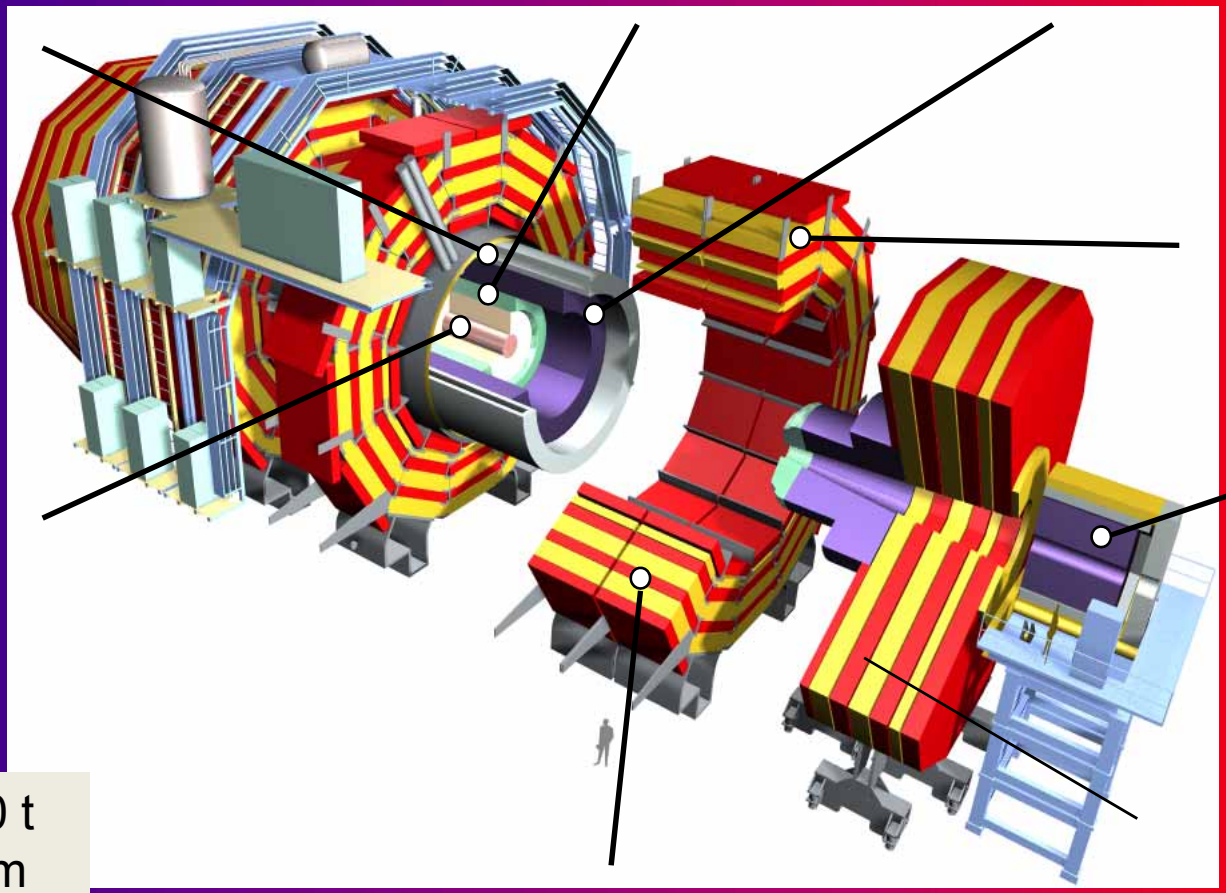
CMS

Calorimeters

ECAL
$PbWO_4$ Crystals

HCAL
Cu + plastic scintillators

SC
Solenoid



Flux
return

HF
Calorimeter

Silicon
Tracker
pixels &
micro strips

Muon system

Weight: 12500 t
Diameter: 15 m
Length: 20 m
B Field: 3.8 Tesla

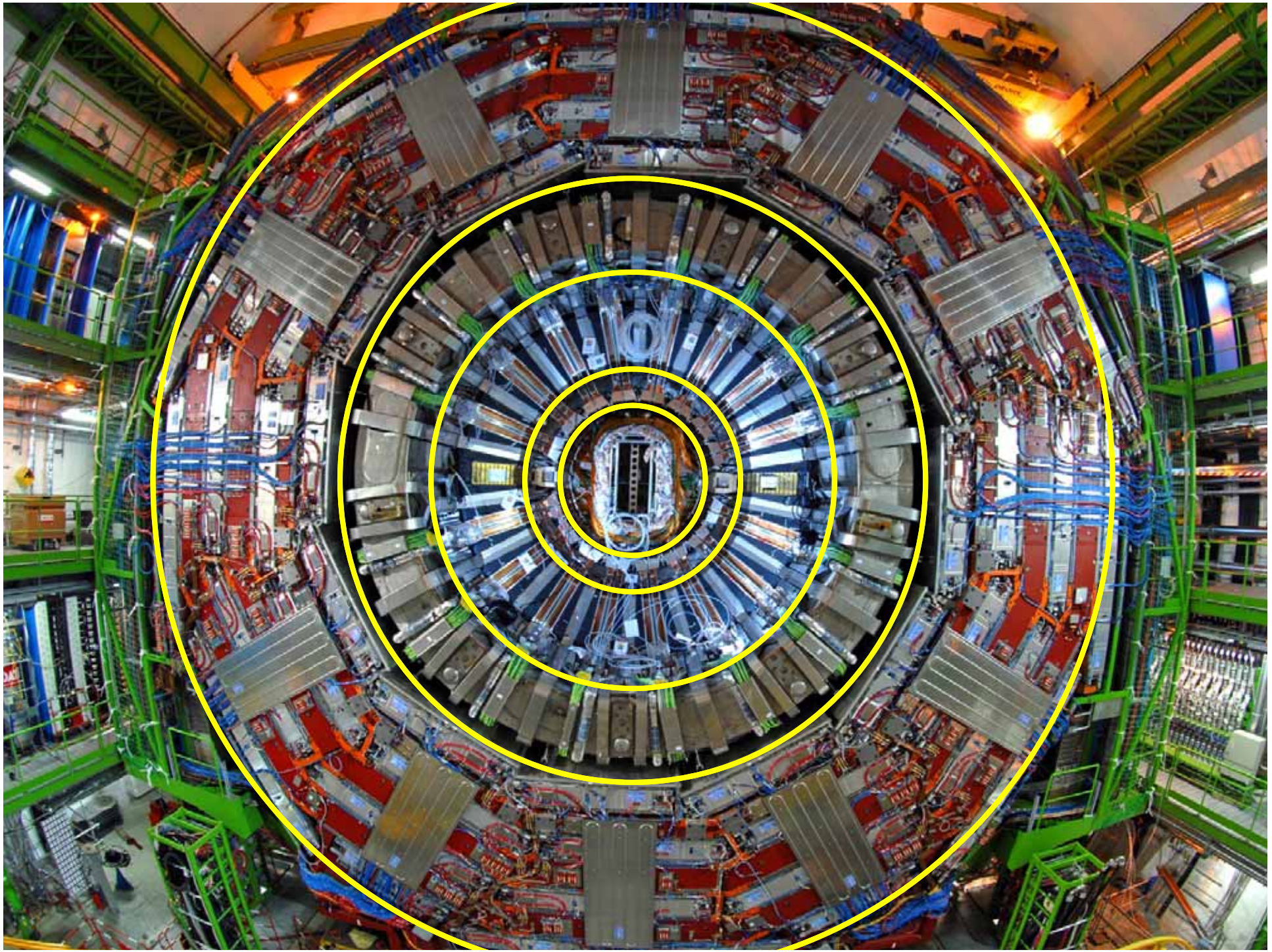
CMS

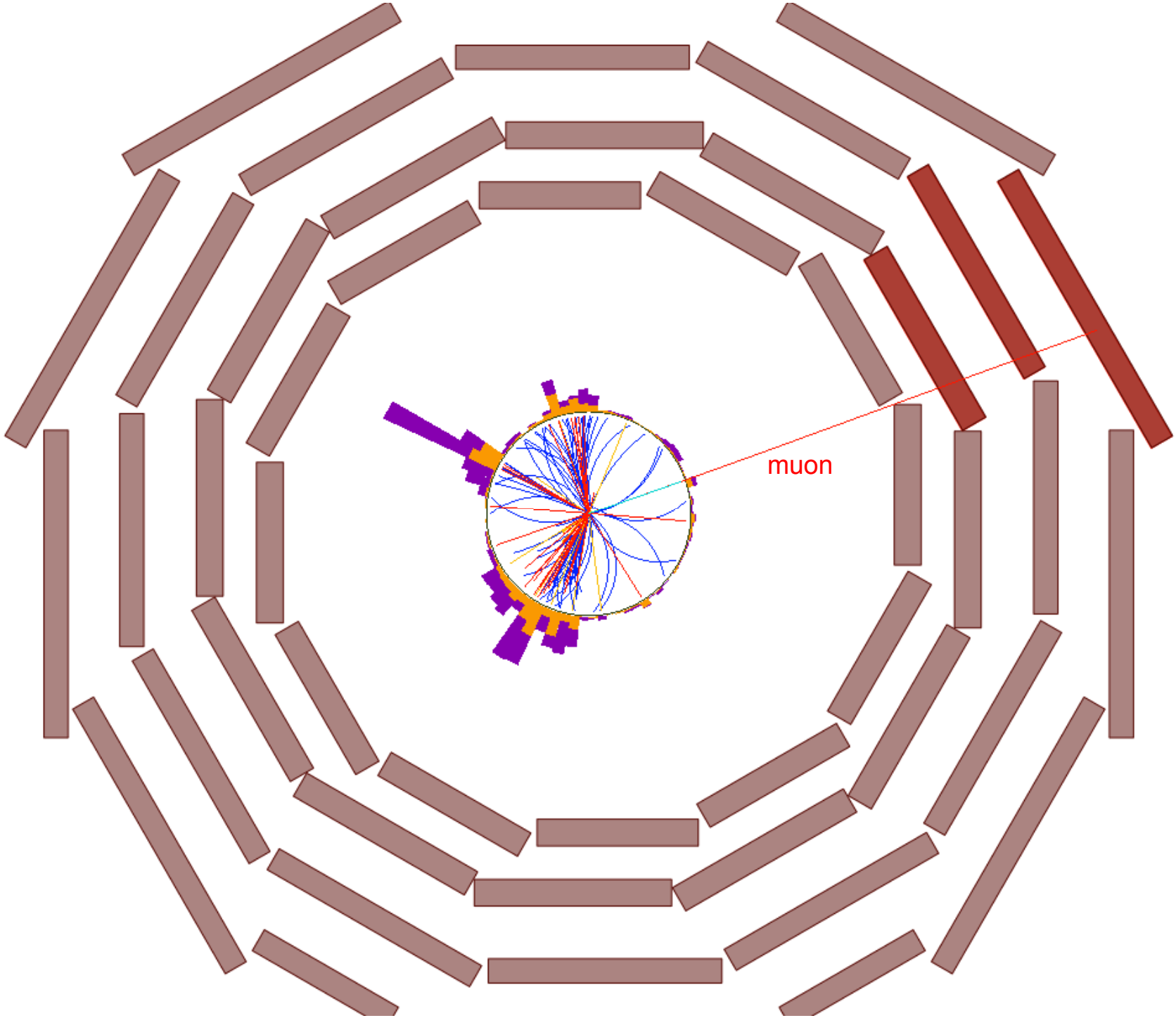
Solenoid 3,8 Tesla

Electromagnetic Calorimeter

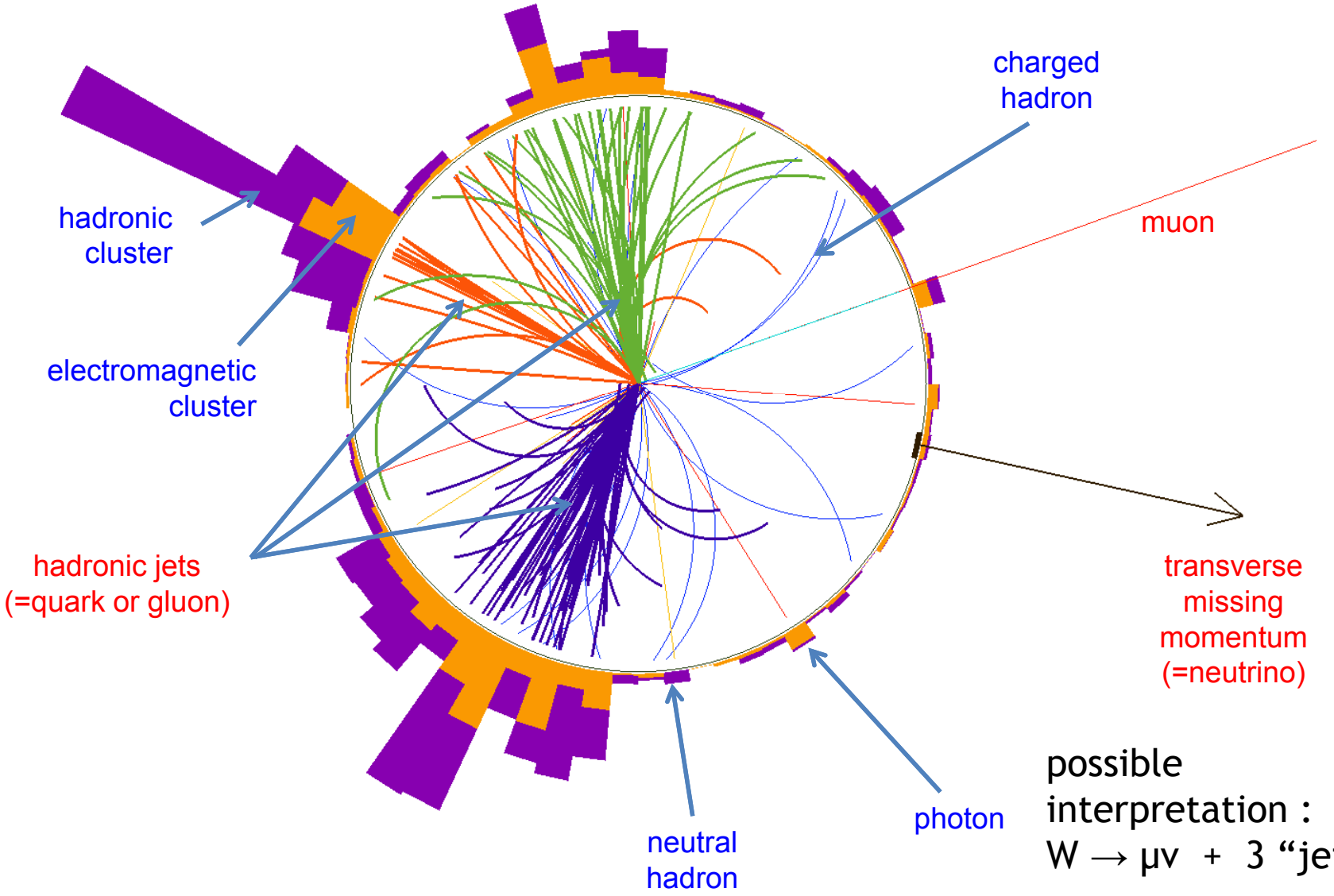
Muon system

Silcon tracker




muon

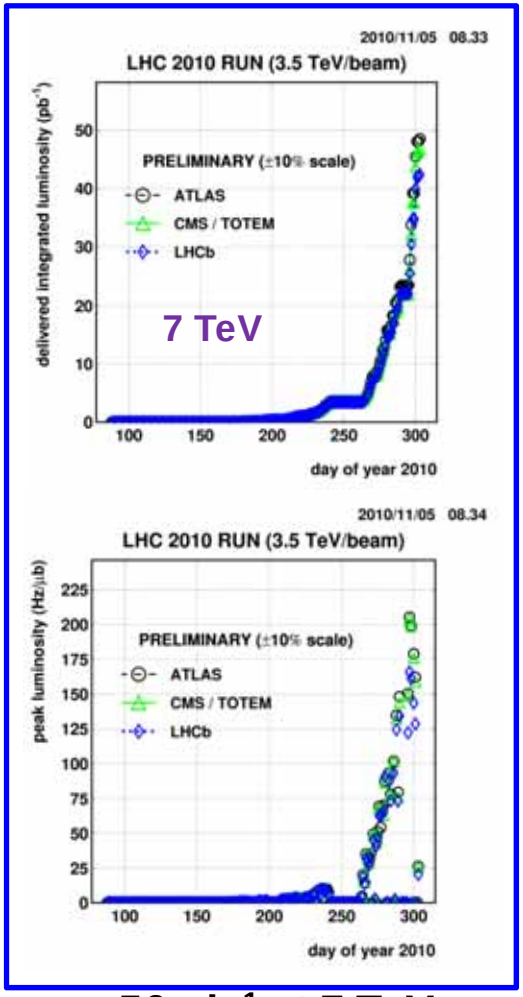
Object Reconstruction, Particle Flow



possible
interpretation :
$W \rightarrow \mu\nu$ + 3 “jets”

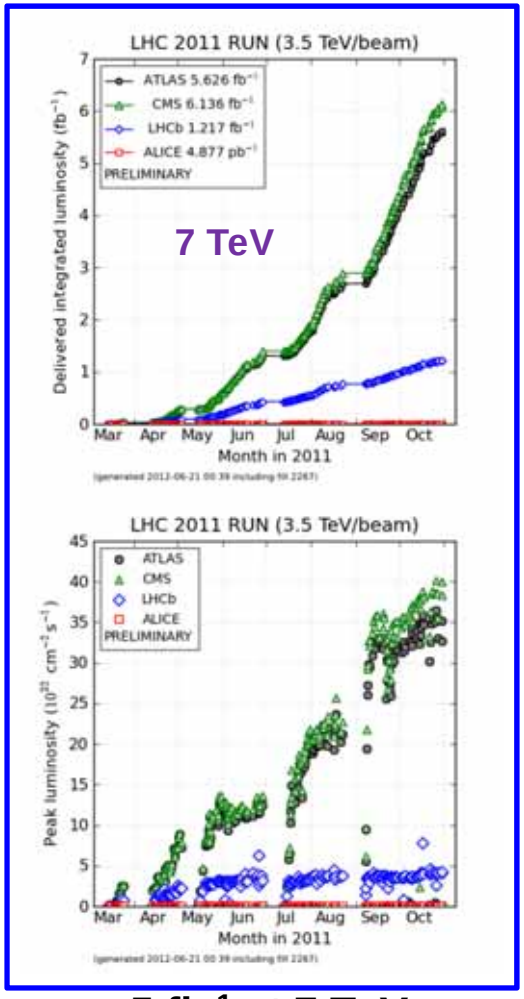
LHC Running

2010



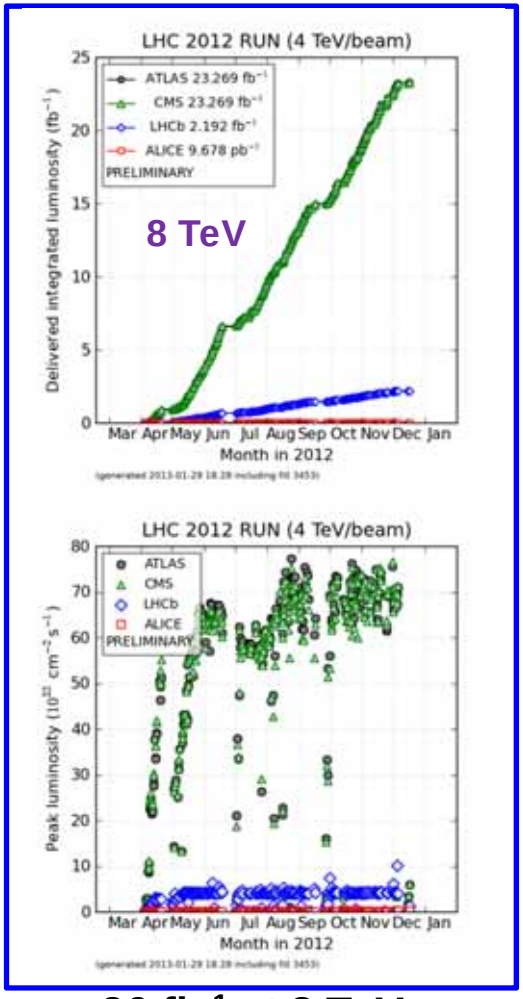
50 pb^{-1} at 7 TeV

2011



5 fb^{-1} at 7 TeV

2012



20 fb^{-1} at 8 TeV

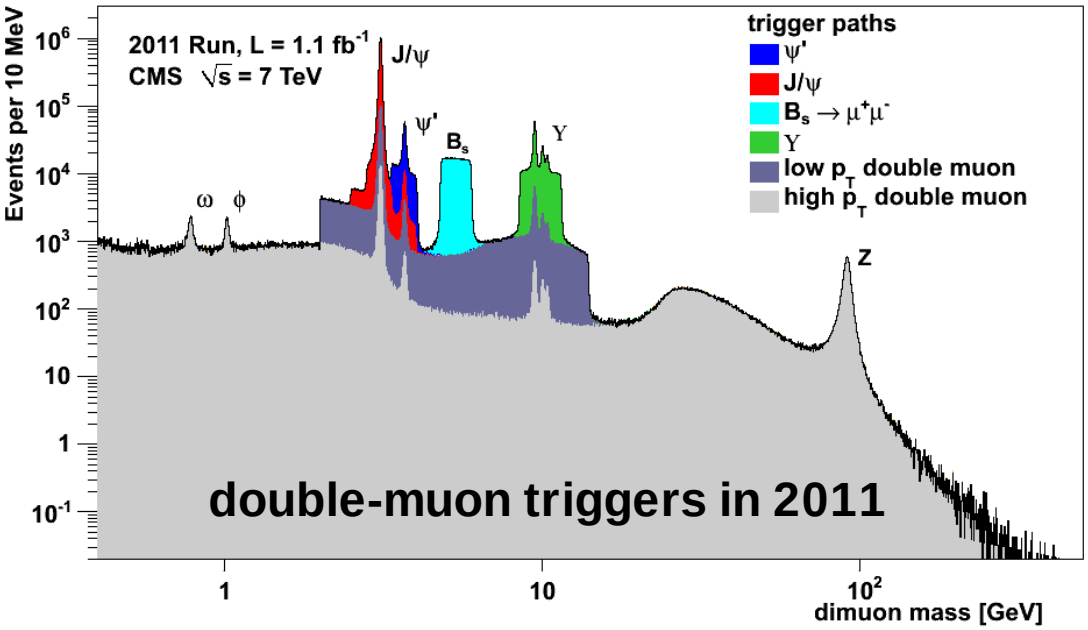
http://lpc.web.cern.ch/lpc/

instantaneous luminosity unit
10^{33} cm^{-2} s^{-1} = 1 Hz/nb

Triggers! Pile-up !

talk by Andrea Bocci

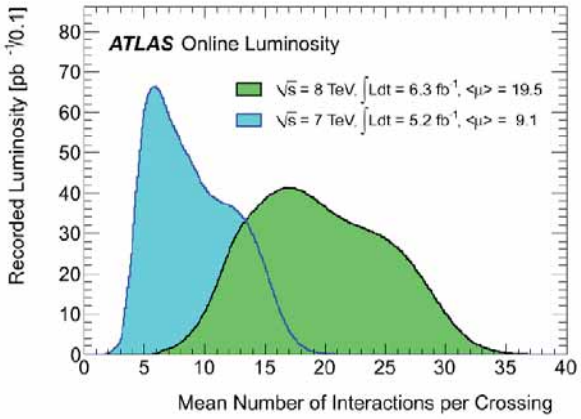
First and most important steps of the physics at the LHC

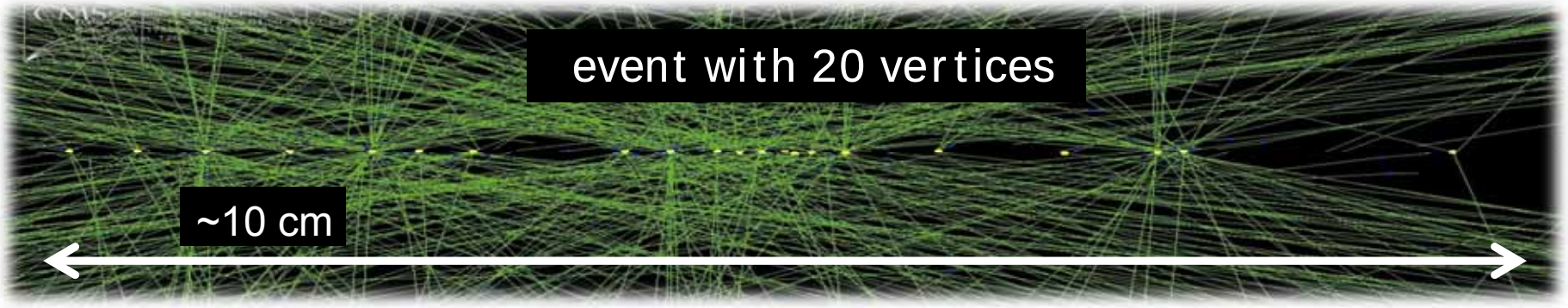


One bunch crossing every 50 ns

The trigger systems select less than 0.01% of the events!

In each event, many inelastic interactions (pileup)





Physics at the LHC - Highlights

see talks by

Standard Model Physics

- QCD, hadron physics and parton densities — Maxime Gouzevitch
- tests of the electroweak gauge structure — Michael Schmitt
- precision studies of the top quark and W boson — Alessandro Vicini

Electroweak symmetry breaking and the origin of mass

- discovery and characterization of the Higgs boson — Jim Olsen
- search for additional Higgs bosons — **Daniel Froidevaux (ATLAS)**

New phenomena at the high-energy frontier

- search for supersymmetric partners — Sunil Somalwar
- search for Dark Matter candidates — N. Nayeemuddin
- search for new gauge interactions at high energy
- search for extra dimensions of space, micro black holes, etc.

Flavor physics

- CP violation in the B and charm sectors; tests of CKM
- search for New Physics in b to s transitions
- measurements of GIM-suppressed B decays into lepton pairs

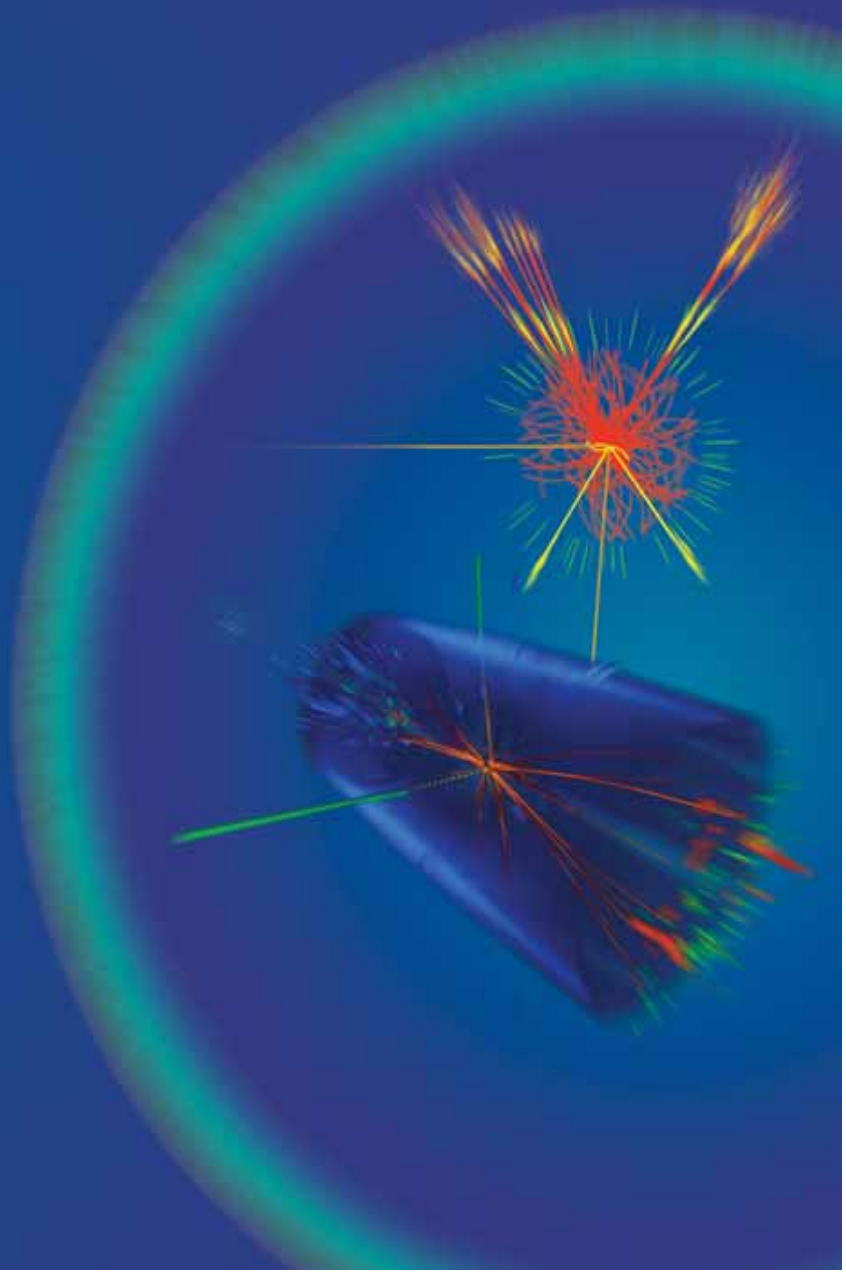
Quark-gluon plasma

- study deconfined nuclear matter using various probes — Bedangdas Mahanty
- suppression and regeneration of quarkonia in QGP evolution

Outline

- Standard Model Physics
- Higgs Boson Physics
- B Physics and CP Violation
- Supersymmetry and Exotica

- What Next?



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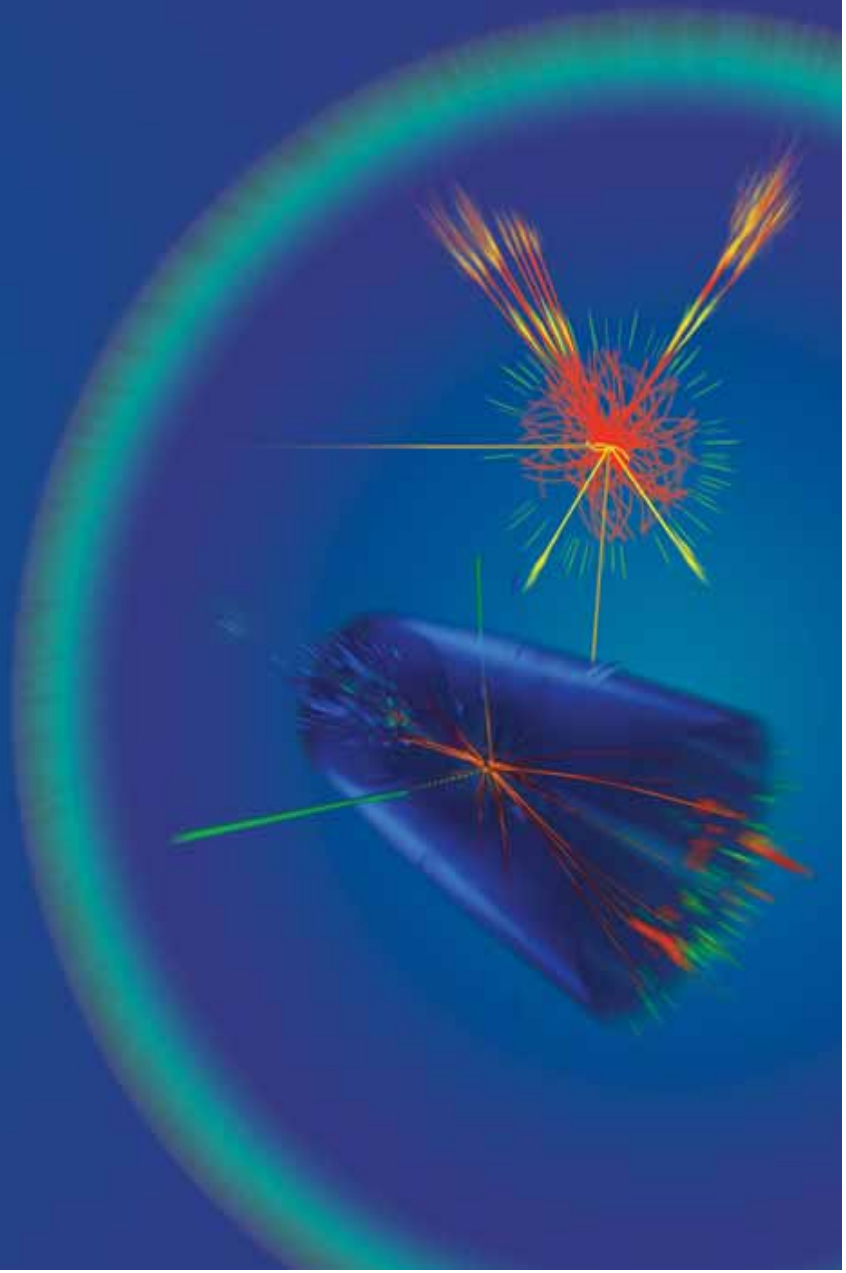
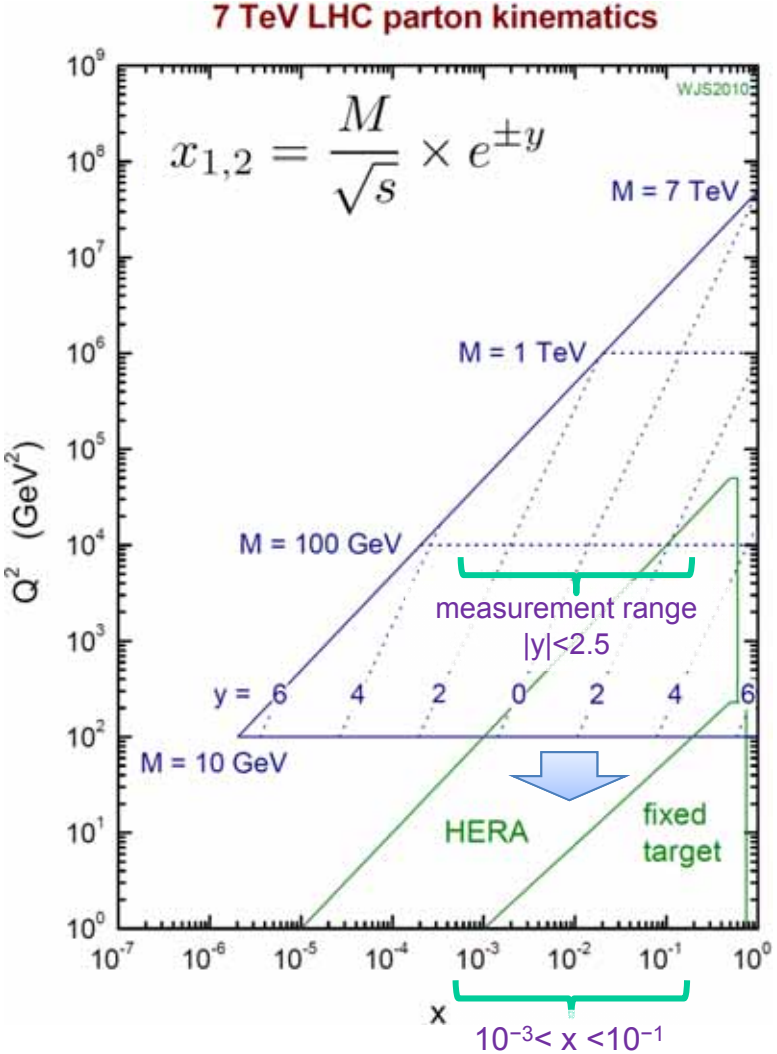
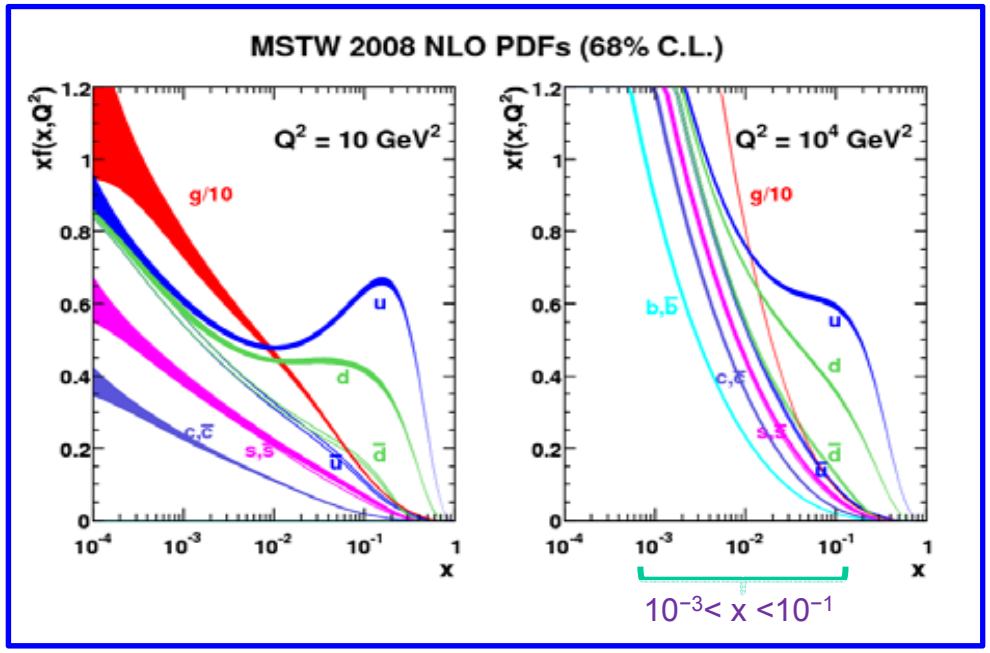


Parton Kinematics



rapidity $y = \frac{1}{2} \ln \frac{x_1}{x_2}$

the parton structure of the proton is encoded in the parton density functions (PDFs)



valence $u_V = u - \bar{u}$, $d_V = d - \bar{d}$

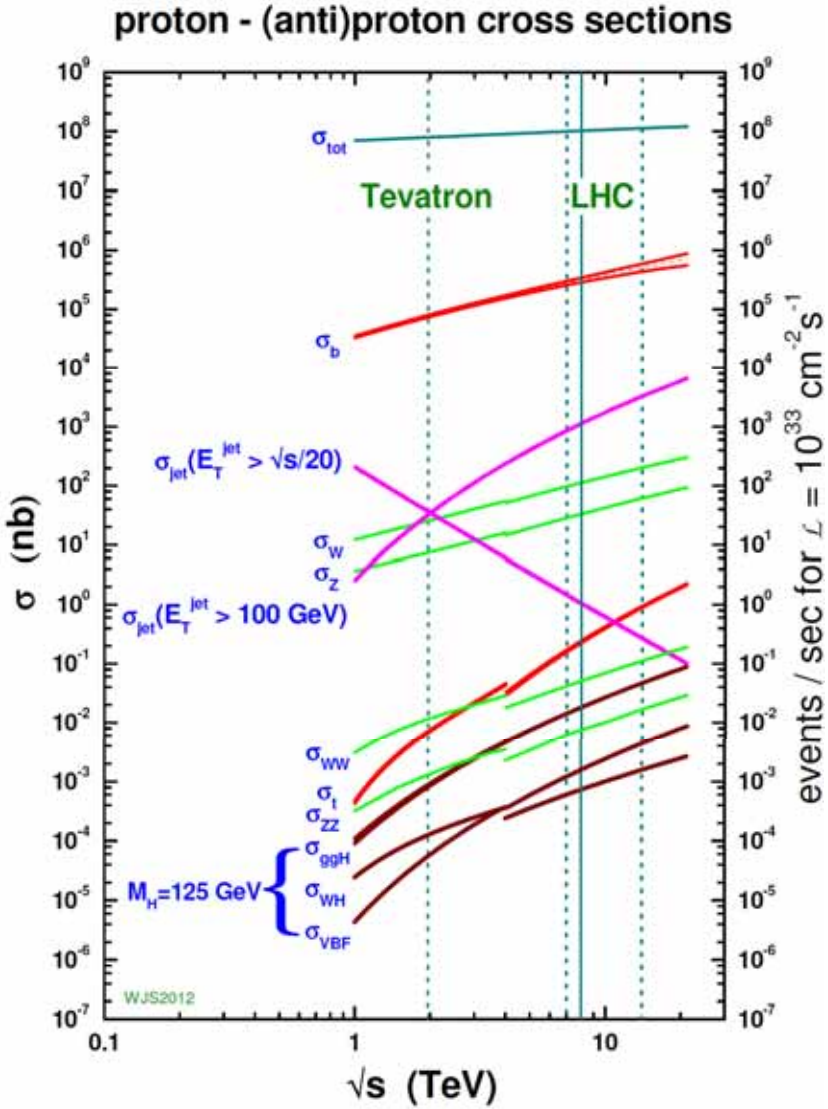
sea $2 \times (\bar{u} + \bar{d} + \bar{s})$, $\bar{d} - \bar{u}$

strangeness $s + \bar{s}$

low Q^2 data (HERA) dominate the PDF estimation

heavy quarks (c,b) are treated perturbatively

Cross Sections at Colliders



Cross sections in pp collisions at 7 TeV

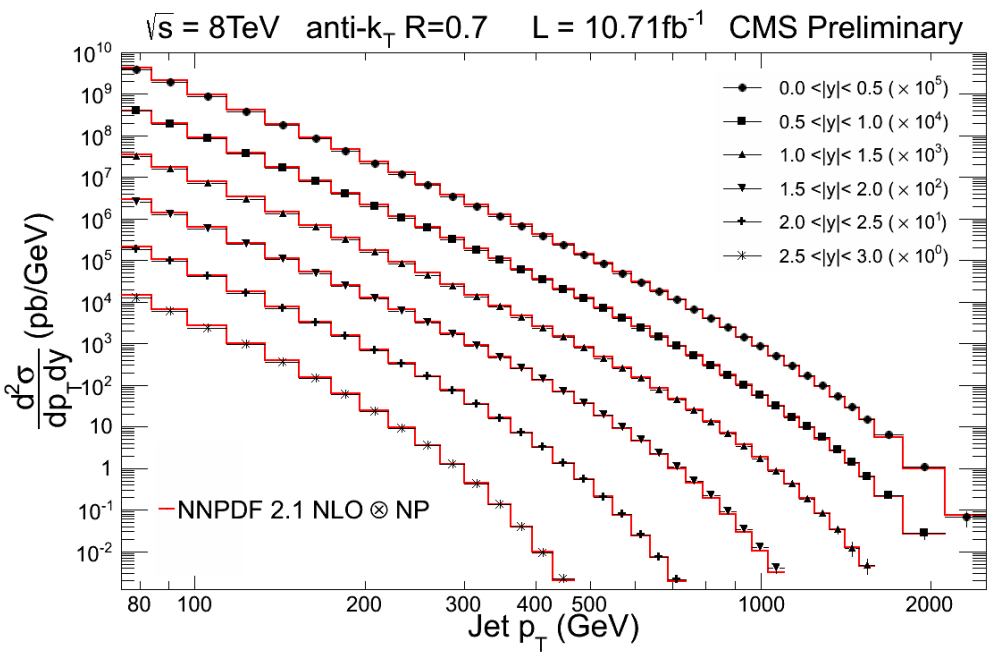
- total: 110 mb
  - elastic: 40 mb
  - inelastic: 60 mb
  - diffractive: 12 mb
- b-quark pair: 0.4 mb
- W and Z: 100 nb and 30 nb
  (3 times larger than at Tevatron)
- top quark pair: 160 pb
  (20 times larger than at Tevatron)
- 125-GeV Higgs boson: 20 pb

- W & Z cross sections in leptonic mode
  expect
  $\sigma(W) \times B(W \to l\nu) \sim 10$ nb
  and
  $\sigma(Z) \times B(Z \to ll) \sim 1$ nb

with acceptances of ~0.5 (W) or ~0.4 (Z)
5 000 000 W per lepton channel per fb^{-1}
500 000 Z per lepton channel per fb^{-1}

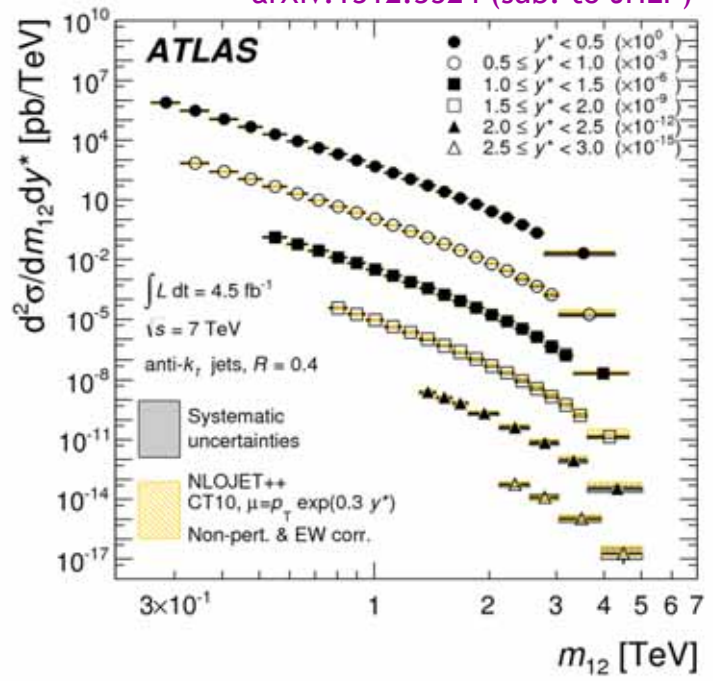
Jet Physics: Cross Sections

CMS-PAS-SMP-12-012



CMS 8 TeV
double differential (PT, y)
cross sections

arXiv:1312.3524 (sub. to JHEP)



ATLAS 7 TeV
double differential (m12, y)
cross sections

See talk by Deepak Kar

Jet Physics: Constraints on PDFs and α_S

Inclusive jet cross sections are compared to predictions of perturbative QCD at NLO using various sets of PDFs

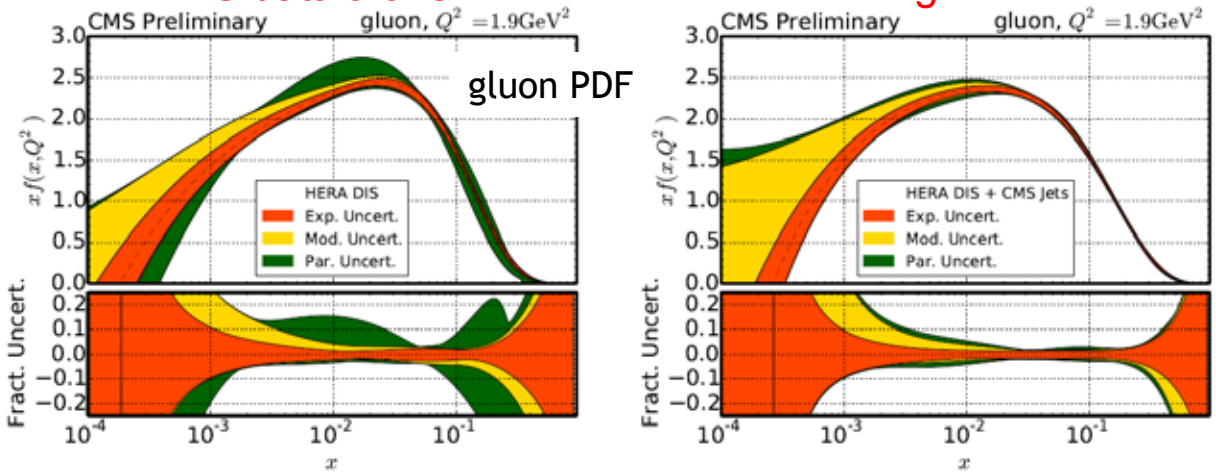
Constraints on PDFs

Strong coupling at high momentum scales

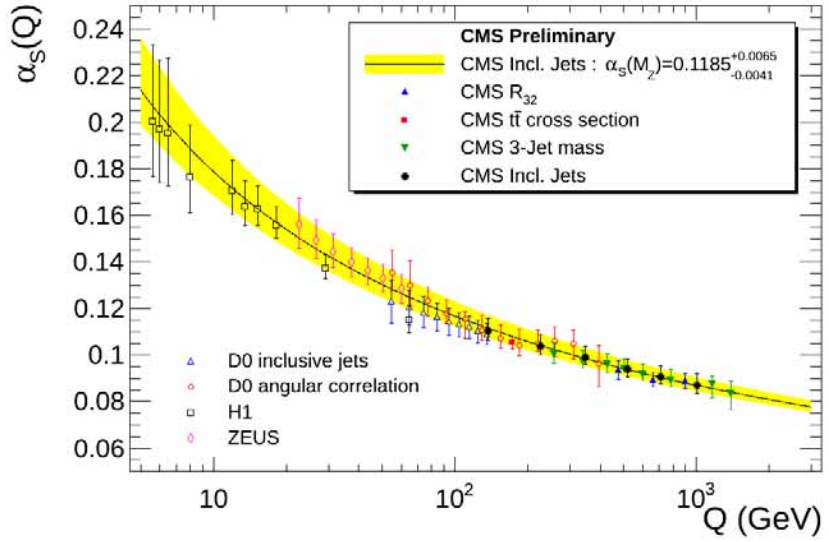
DIS data alone

Including CMS data

gluon PDF



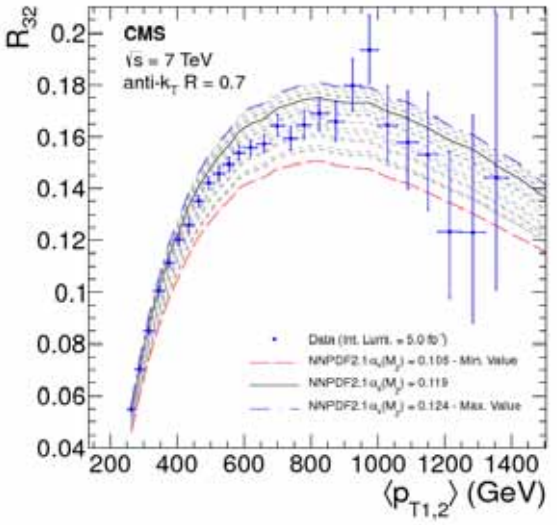
CMS-PAS-SMP-12-028



Multijets: extract aS with similar precision

3-jet/2-jet ratio and 3-jet mass measured vs Q

EPJC 73 (2013) 2604



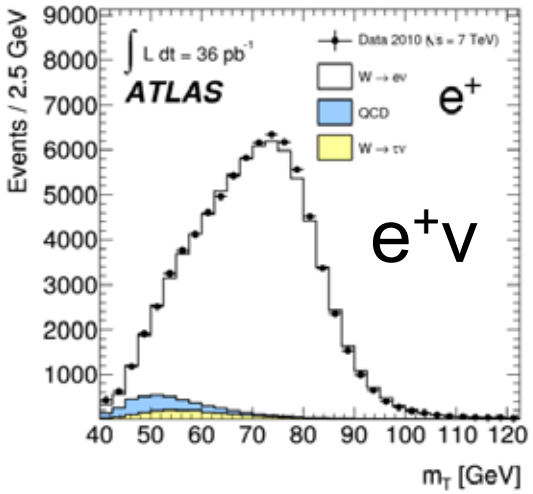
W and Z Signals

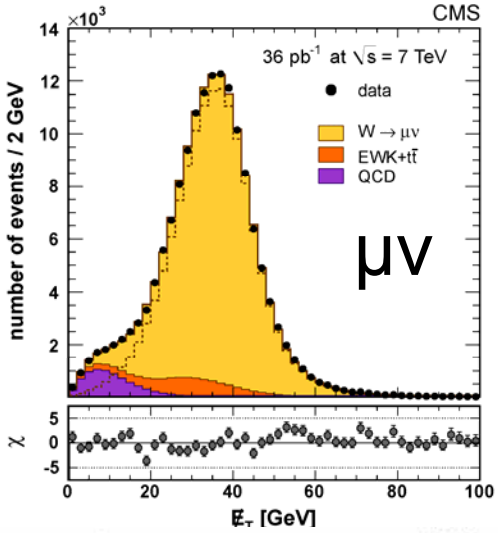
ATLAS

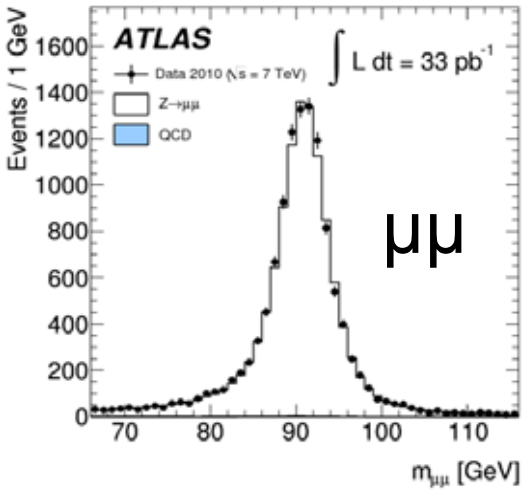
CMS

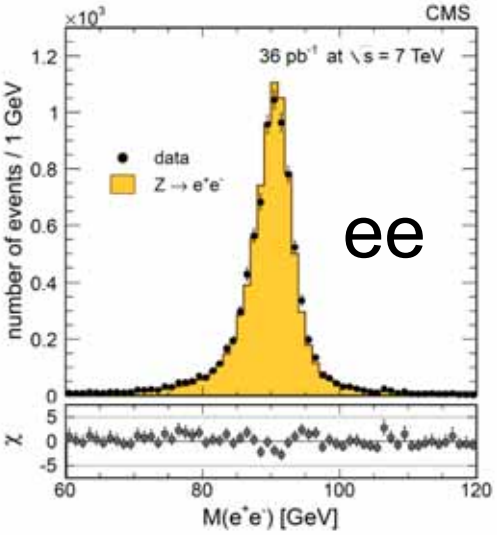
W

Z



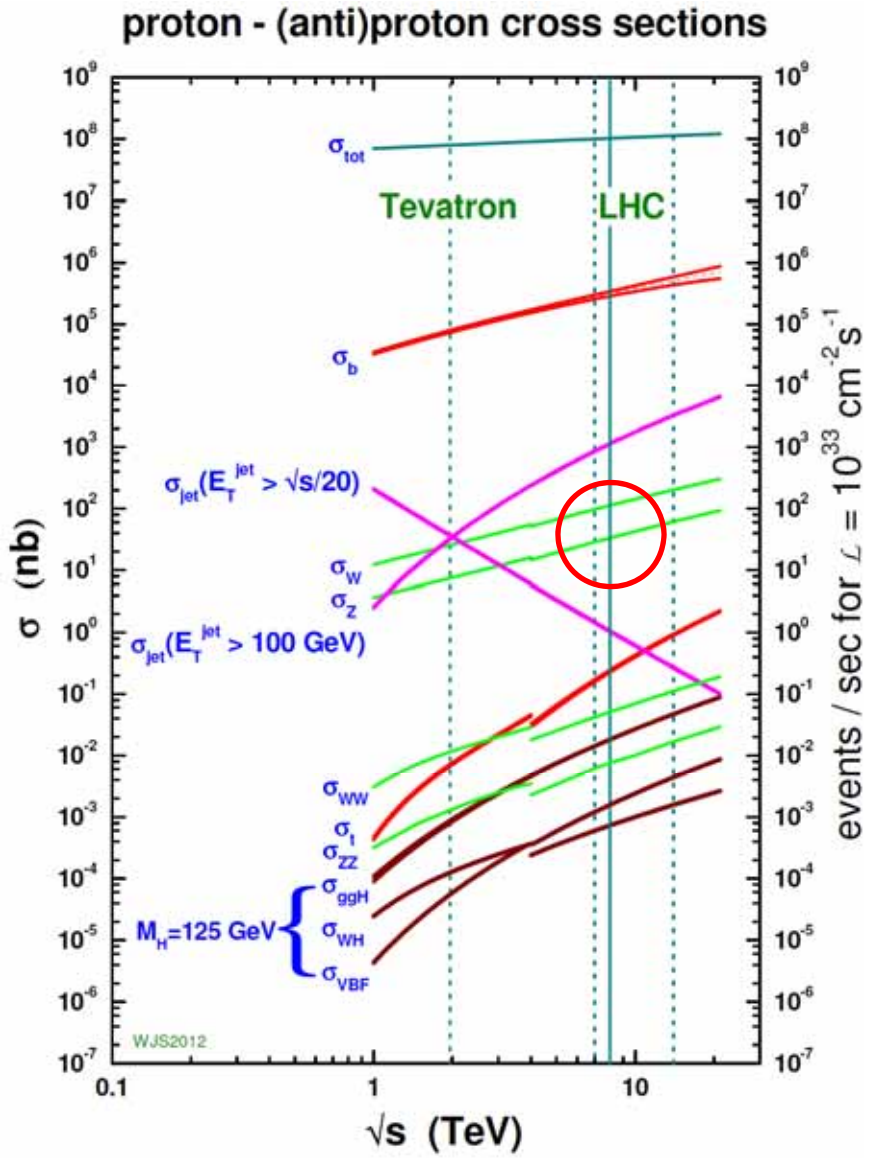




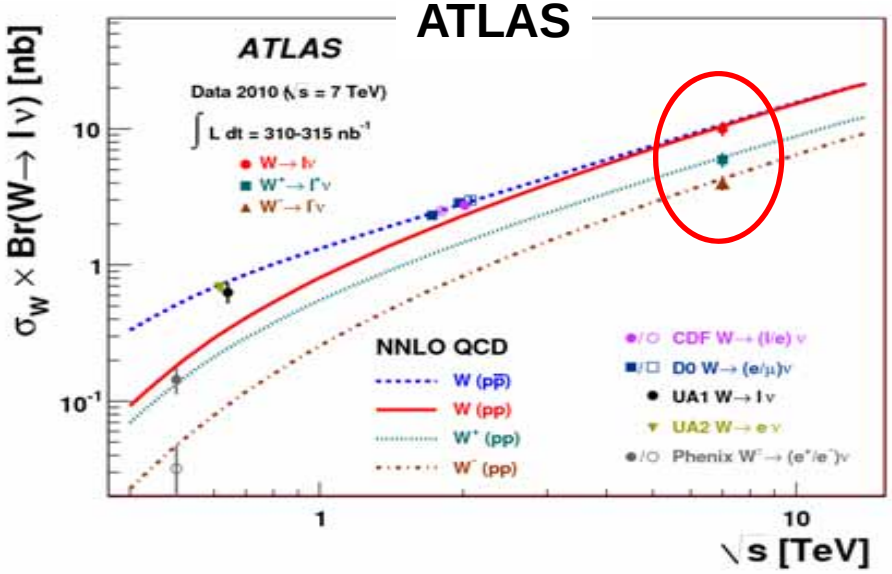


2010 data

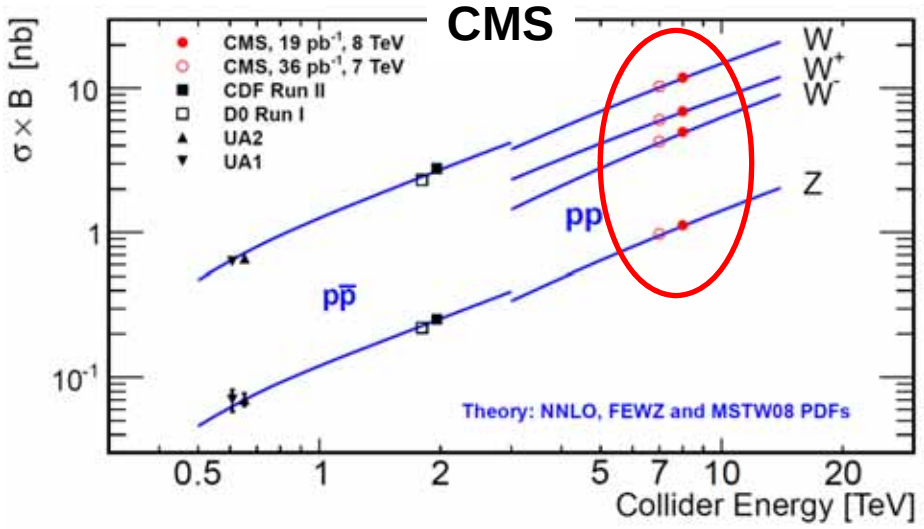
W & Z Inclusive Cross Sections



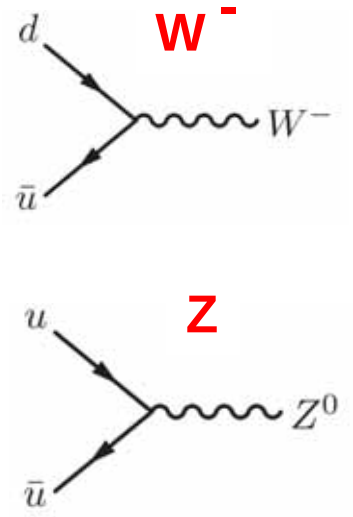
ATLAS

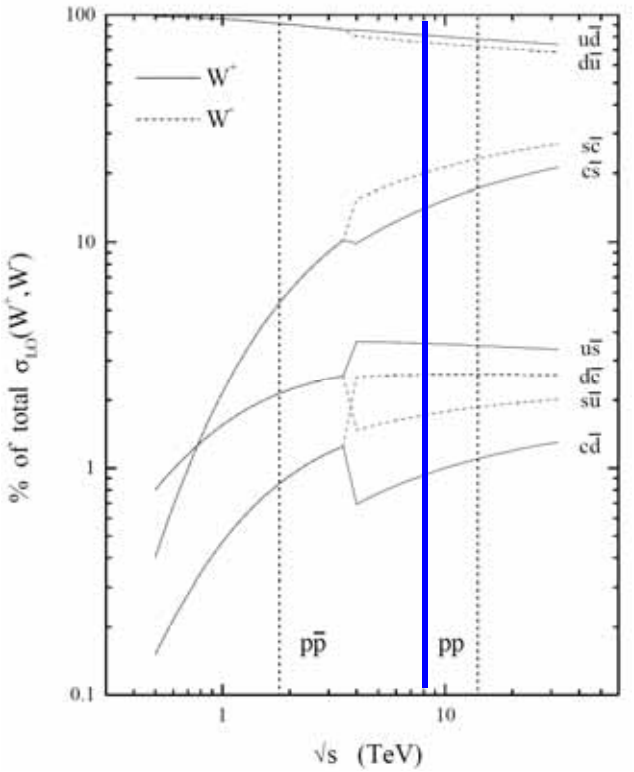


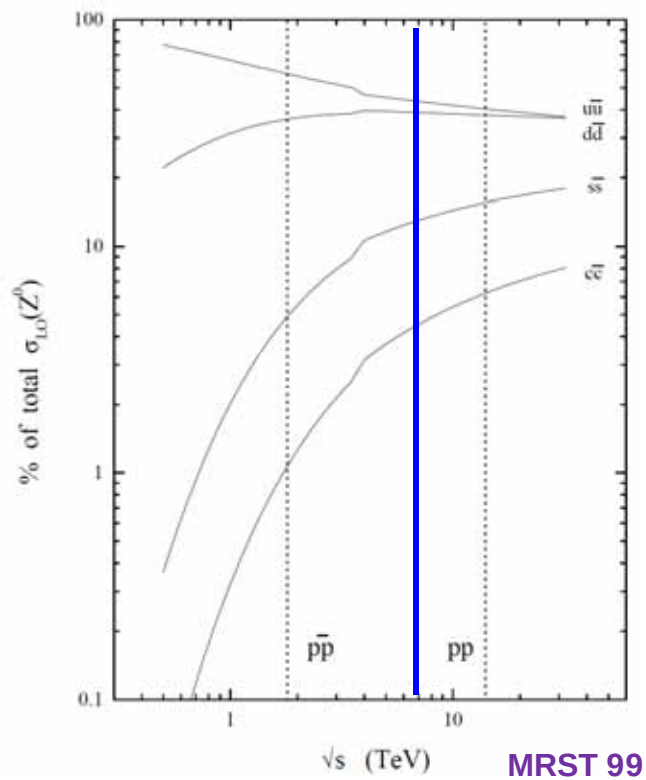
CMS



Flavor in W and Z Production







MRST 99

At the LHC
W production is
charge asymmetric ; naively
$\sigma(W^+)/\sigma(W^-) \sim 2$
if only valence quark + sea antiquark

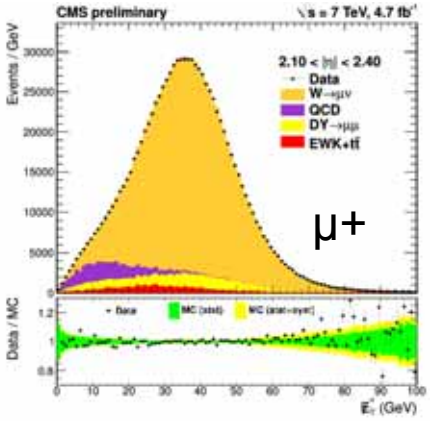
but because involved parton fractions are low
($10^{-3} < x < 10^{-1}$)
annihilation of a sea quark and a sea anti-quark
is significant:
$\sigma(W^+)/\sigma(W^-) \sim 1.4$

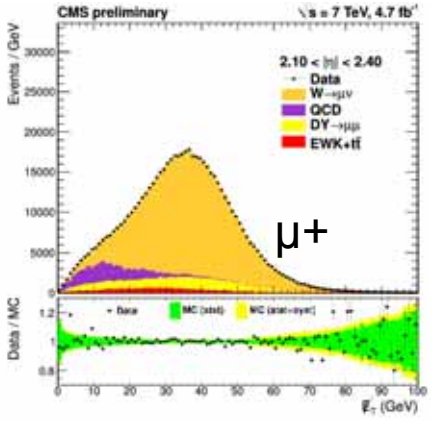
charge asymmetry
depends on rapidity

the strange density as an impact
on both W and Z production rates (10-20%)

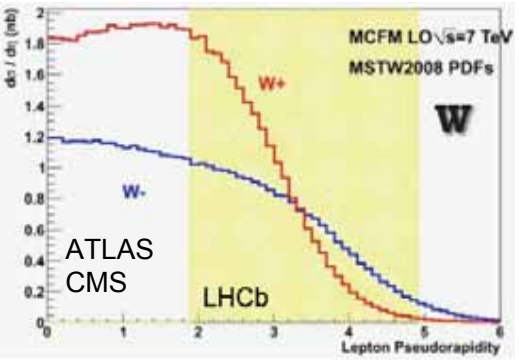
LHC W and Z data can improve PDFs
- constraints on u, d sea (anti)quarks
- constraints on strangeness
- constraints on heavy quark content

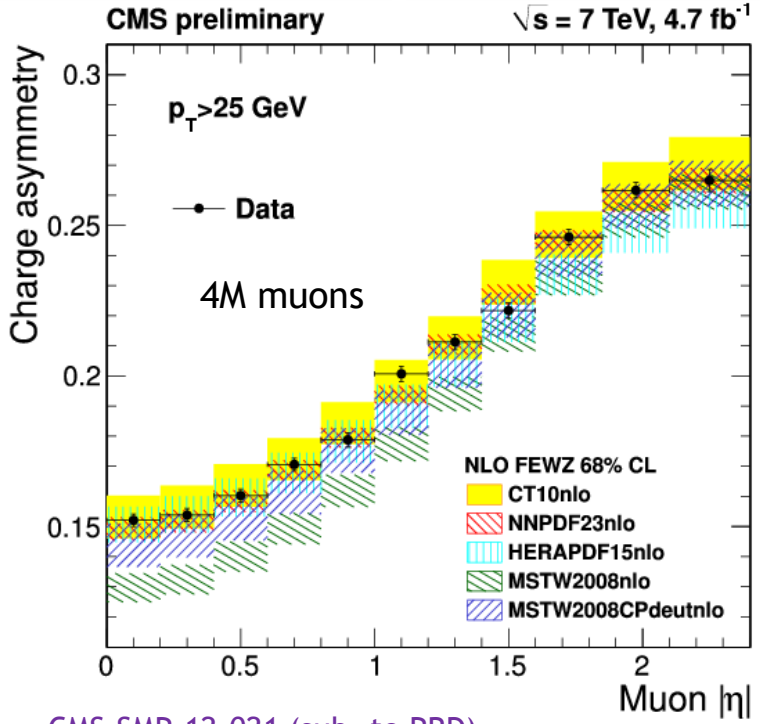
Lepton Charge Asymmetry



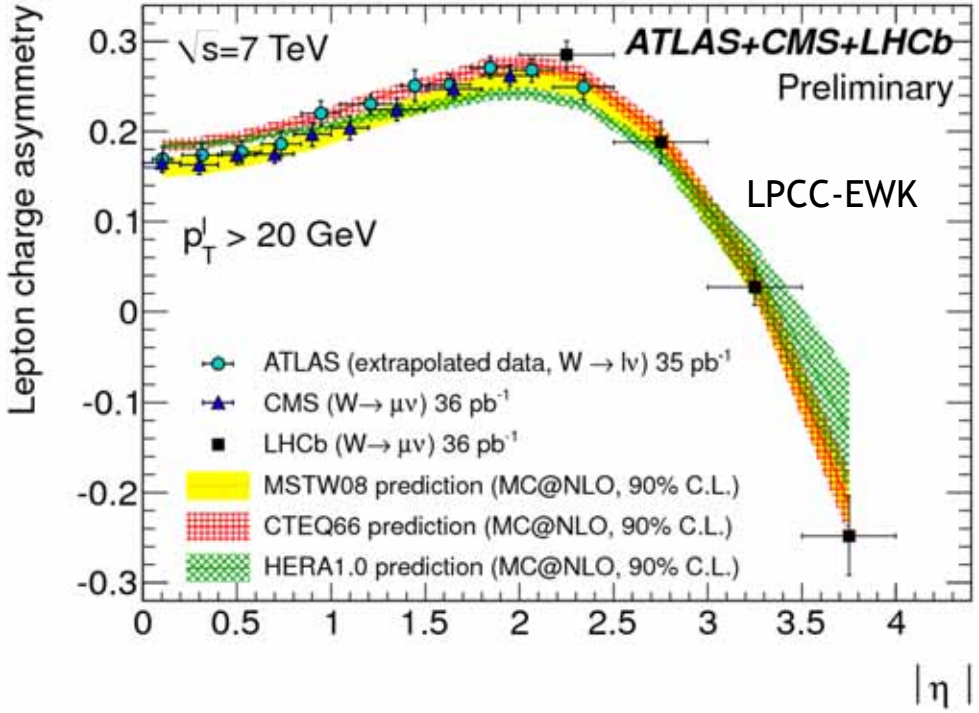


the lepton charge asymmetry is an interplay of u_V, d_V, sea quarks and the V±A structure of the W interactions with quarks and leptons





CMS-SMP-12-021 (sub. to PRD)



Drell Yan Mass Spectrum

$$q + \overline{q} \rightarrow Z^0/\gamma^* \rightarrow \ell^+\ell^-$$

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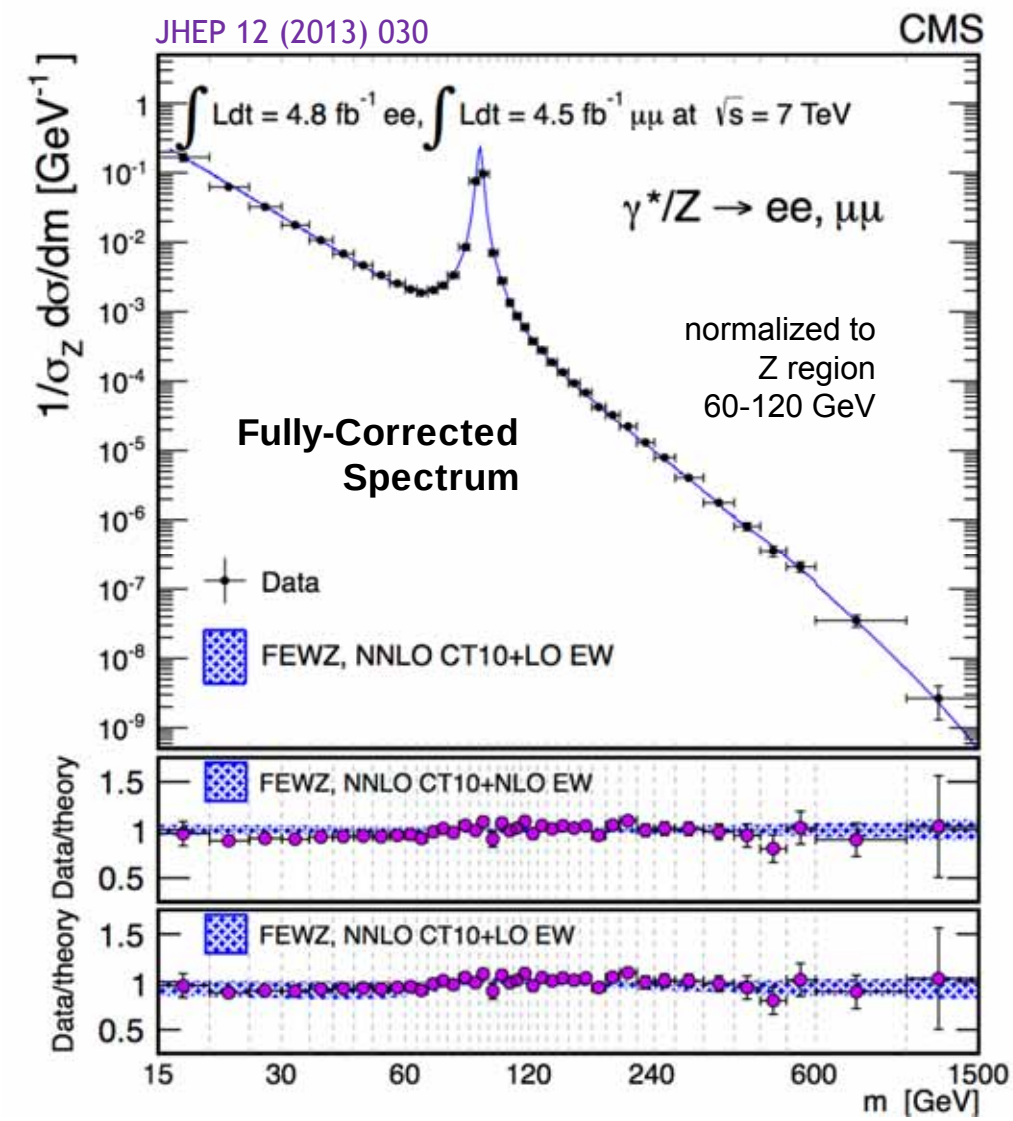
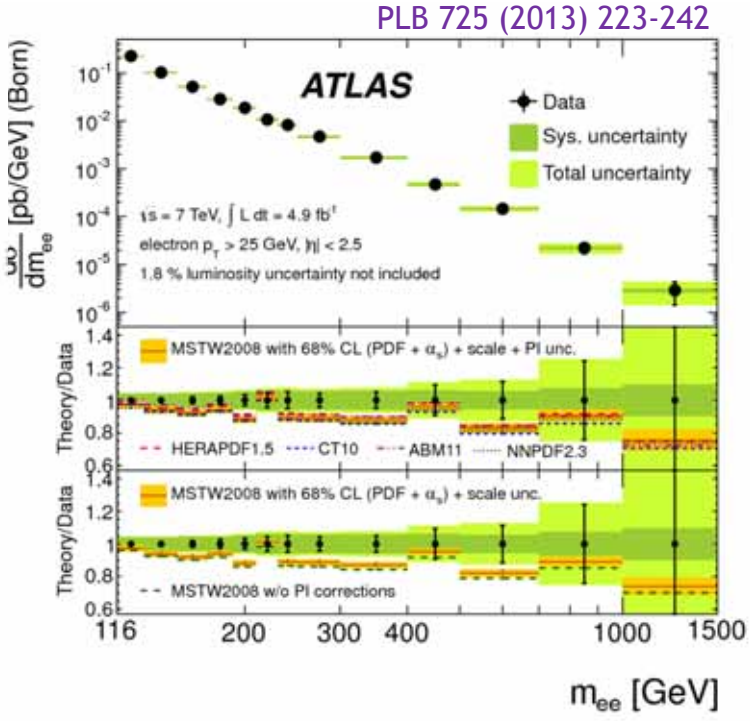
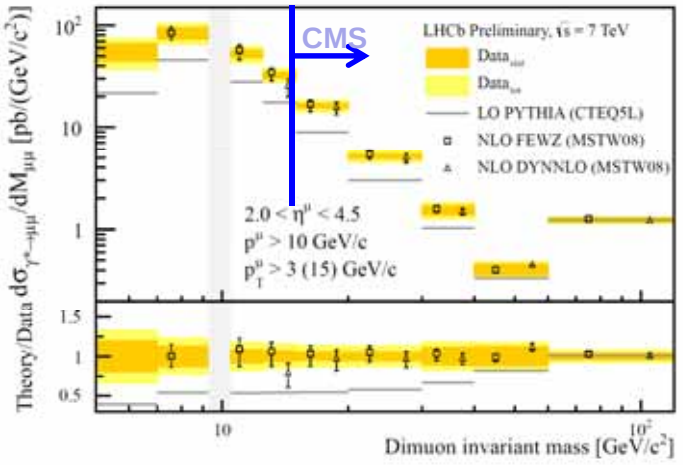


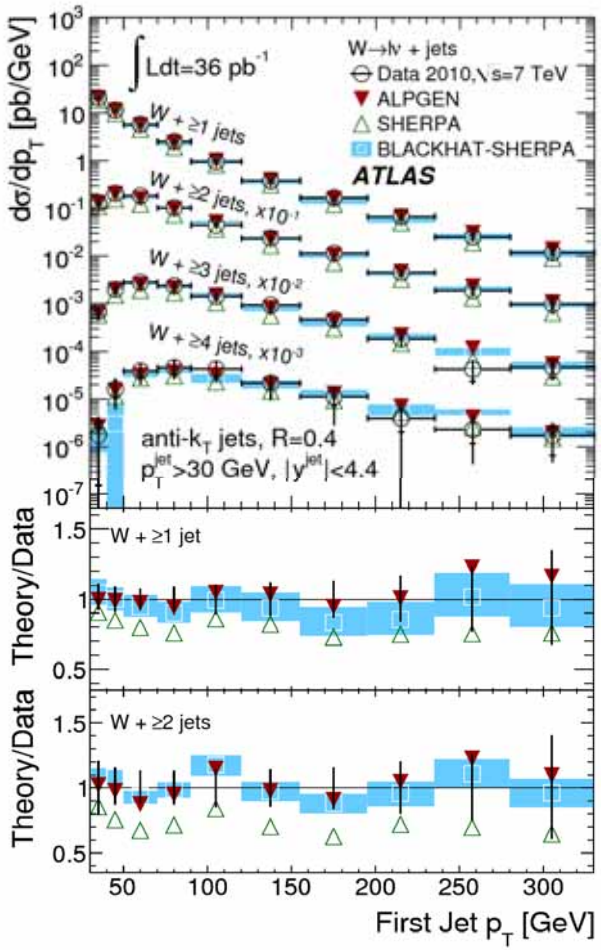
PLB 725 (2013) 223-242





W & Z Bosons + Jets

W+jets: p_T 1st jet



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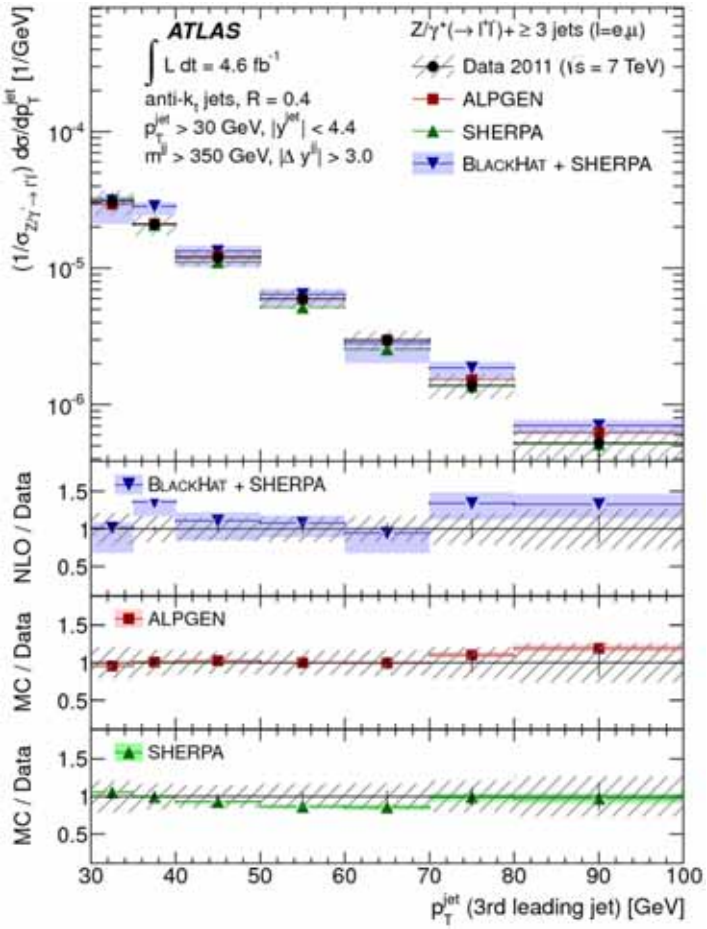
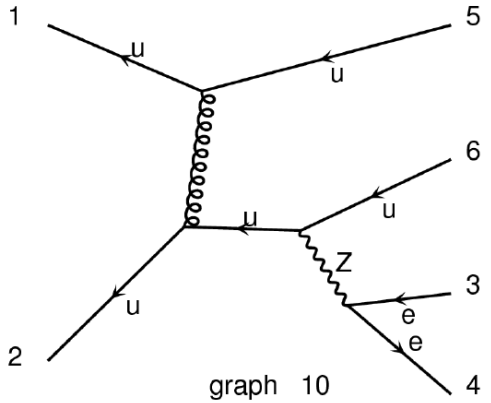
Z+3-jets: p_T jet 3



JHEP 07 (2013) 032



Good agreement with calculations

MC event generators

- NLO + parton shower (MC@NLO, POWHEG.)
- LO (many legs) + parton shower (ALPGEN, MadGraph, SHERPA)

Parton level codes at NLO

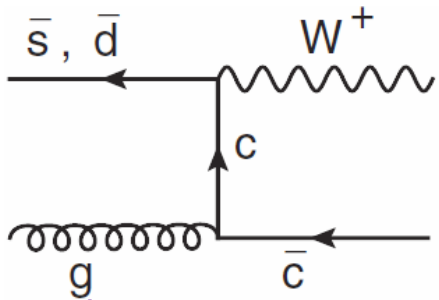
- BlackHat, Rocket...

See talk by Deepak Kar

W+charm

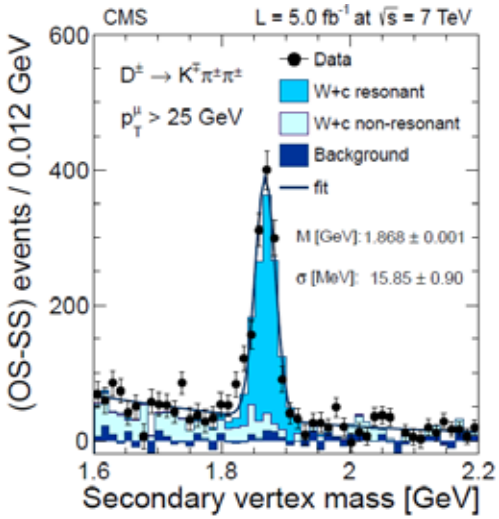
W+c directly probes strange quark PDF

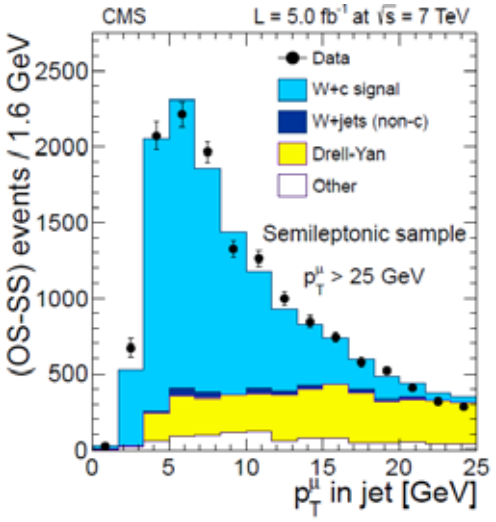
leading order



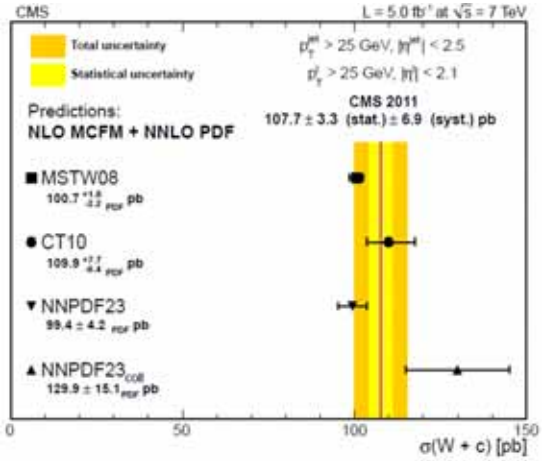
W and c are opposite sign

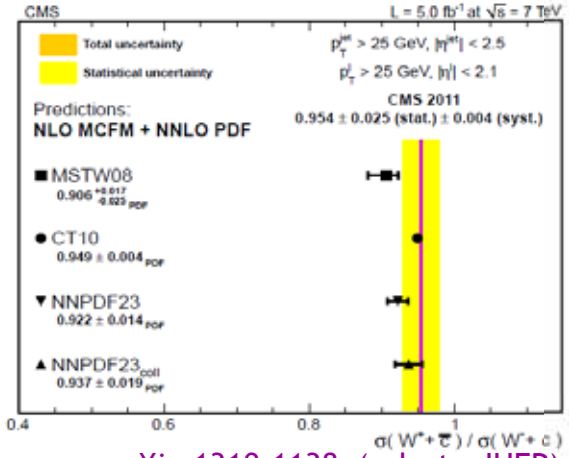
(semi-)exclusive charm hadron reconstruction



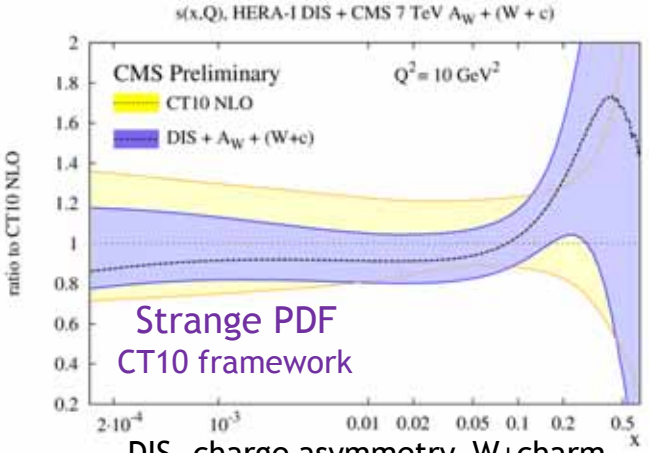


Strange and anti-strange probed independently by W+, W-





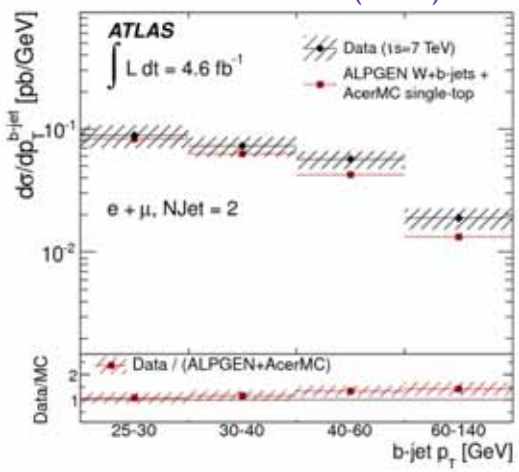
arXiv:1310.1138 (sub. to JHEP)

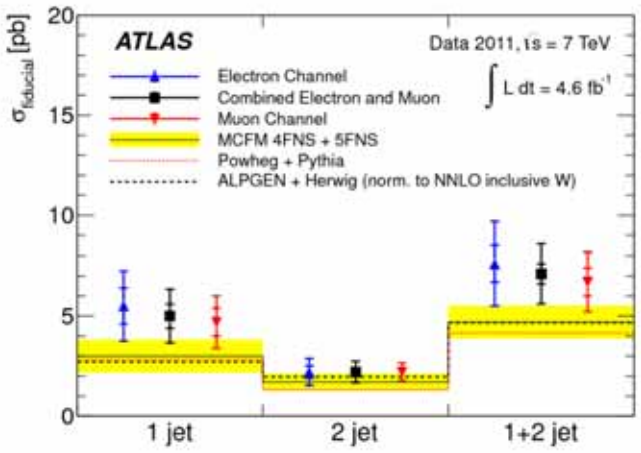


DIS, charge asymmetry, W+charm

V+b-jets Cross-Sections

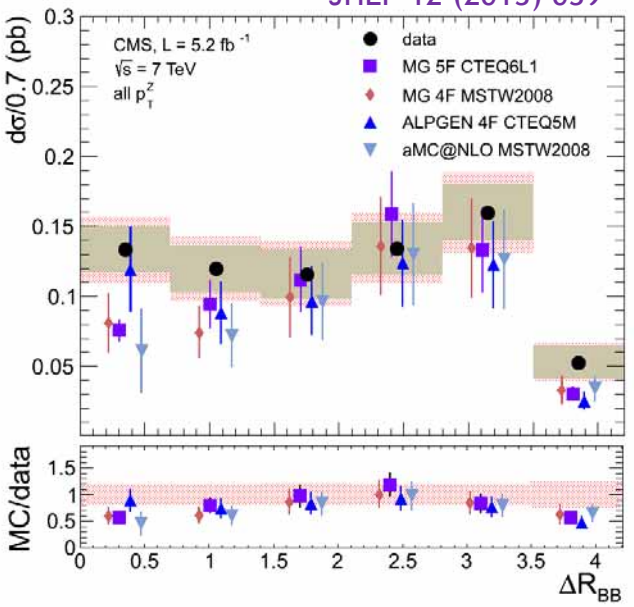
JHEP 06 (2013) 084

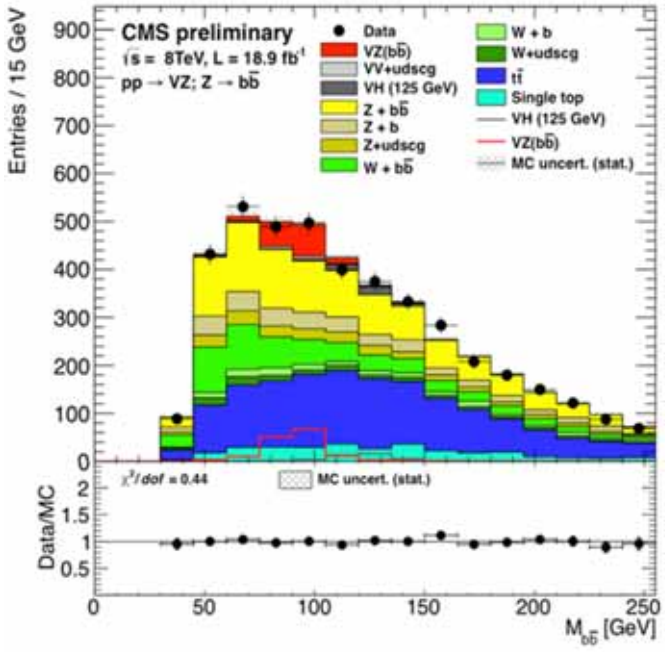




Using a tracker-driven inclusive vertex reconstruction technique

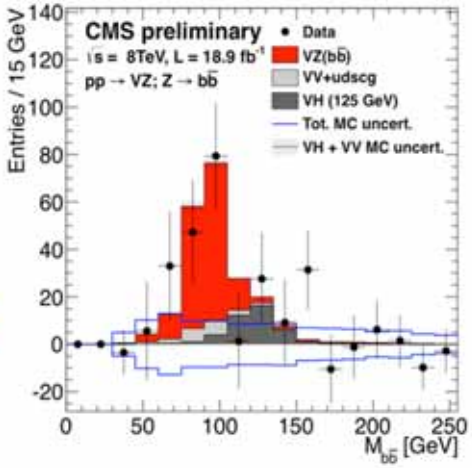
JHEP 12 (2013) 039





CMS-SMP-12-026 (sub. to PLB)

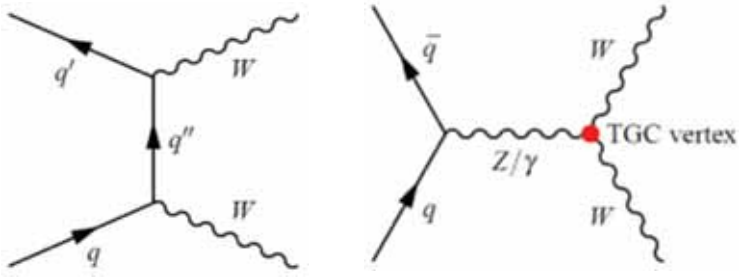
CMS-PAS-SMP-13-011



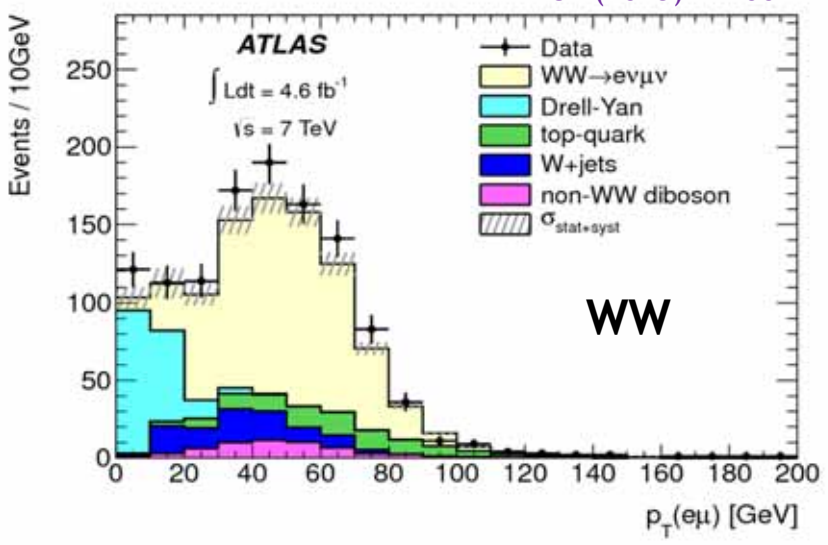
WZ: 6σ significance

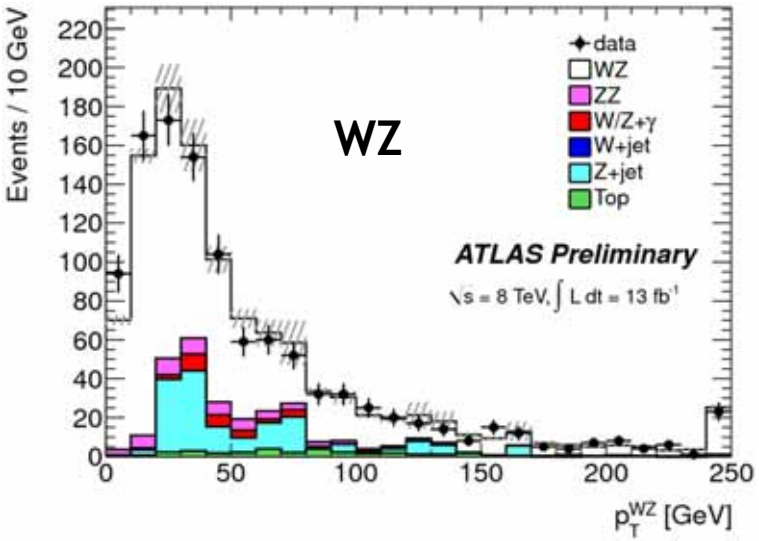
Probing the Triple Gauge Couplings

Diboson production: γγ, Wγ, Zγ, WW, WZ, ZZ

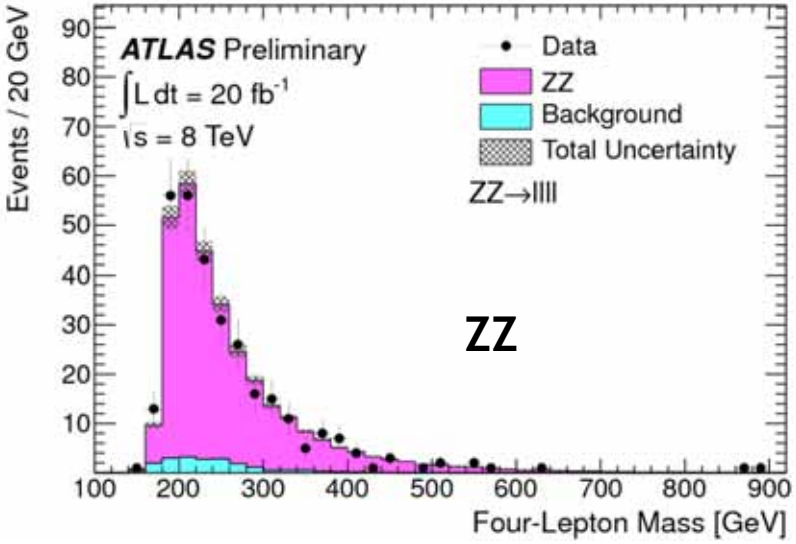


PRD 87 (2013) 112001



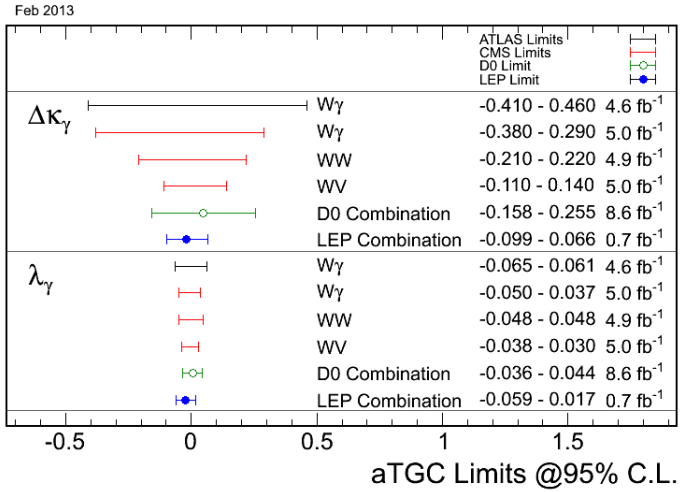


ATLAS-CONF-2013-020

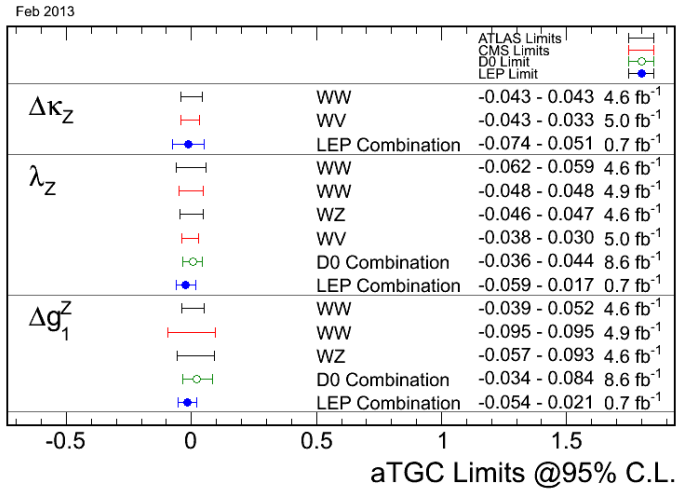


Limits on Anomalous TGC

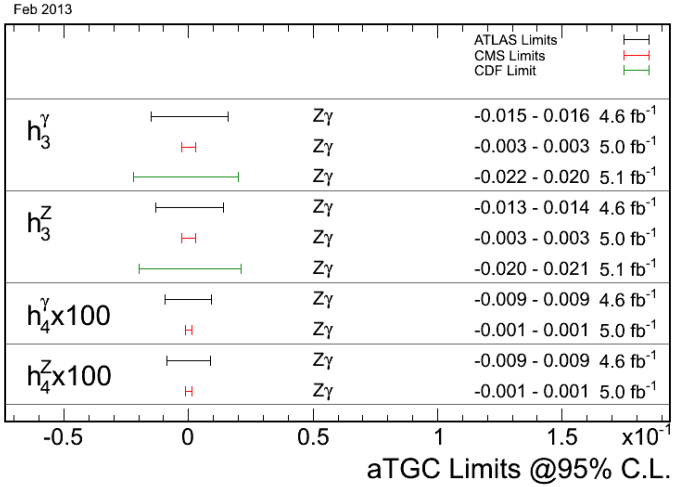
WWγ



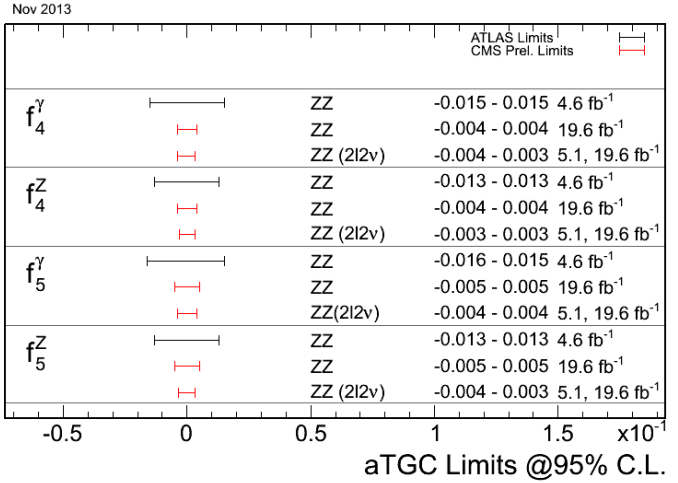
WWZ



Zγγ
ZZγ



ZZγ
ZZZ

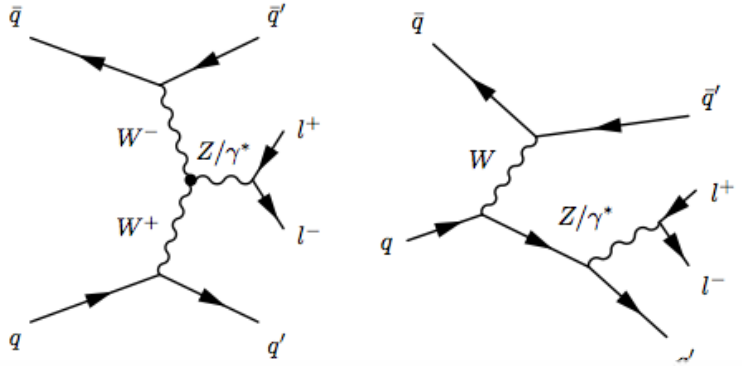


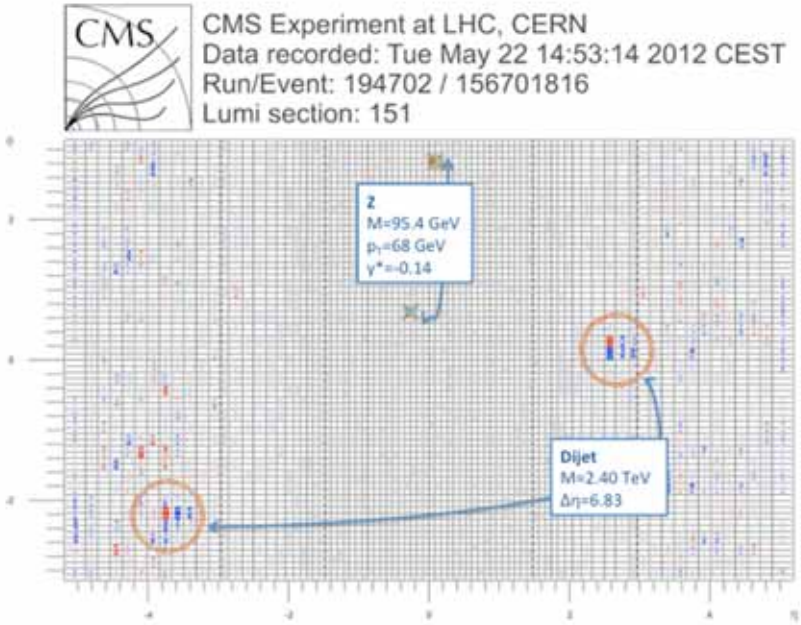
ATLAS 7TeV Vγ: PRD 87 (2013) 112003
ATLAS 7TeV WW: PRD 87 (2013) 112001
ATLAS 7TeV WZ: EPJC 72 (2012) 2173
ATLAS 7TeV ZZ: JHEP 03 (2013) 128

CMS 7TeV Zγ: JHEP 10 (2013) 164
CMS 7TeV Vγ: CMS-EWK-11-009 sub. to PRD
CMS 7TeV WW: EPJC 73 (2013) 2610
CMS 7TeV VW: EPJC 73 (2013) 2283
CMS 7TeV ZZ: CMS-PAS-SMP-13-005
CMS 8TeV ZZ: CMS-PAS-SMP-13-016

Electroweak Z Boson Production

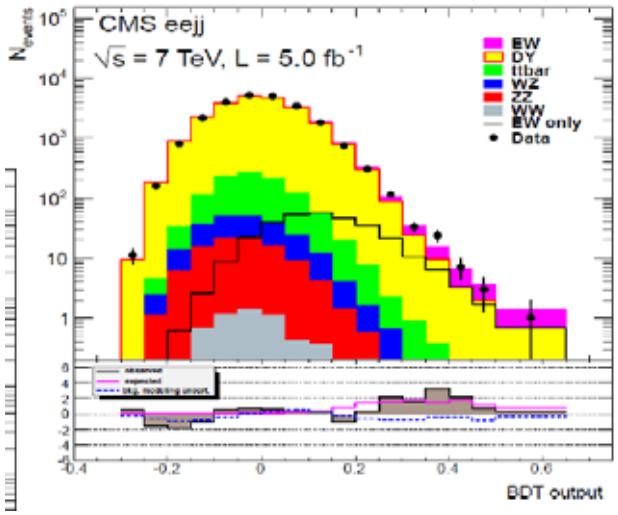
Important foundation for a study of VBF production process

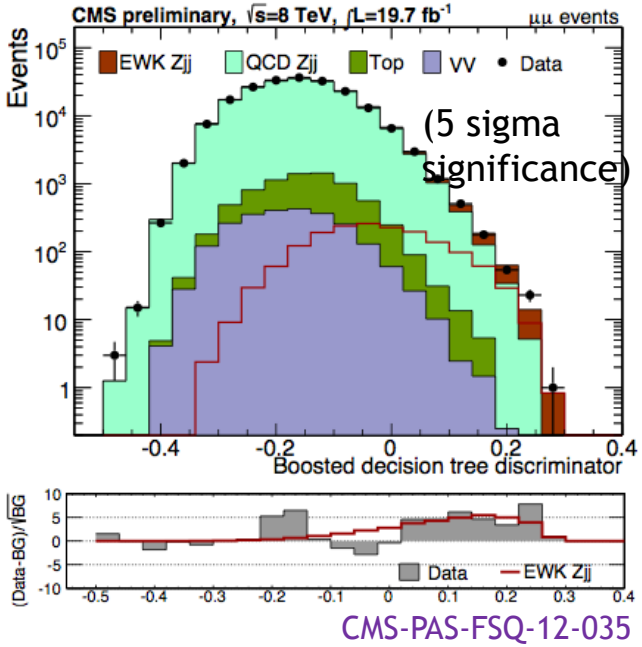




Measurement agrees with SM prediction (240 fb)
(5σ significance)

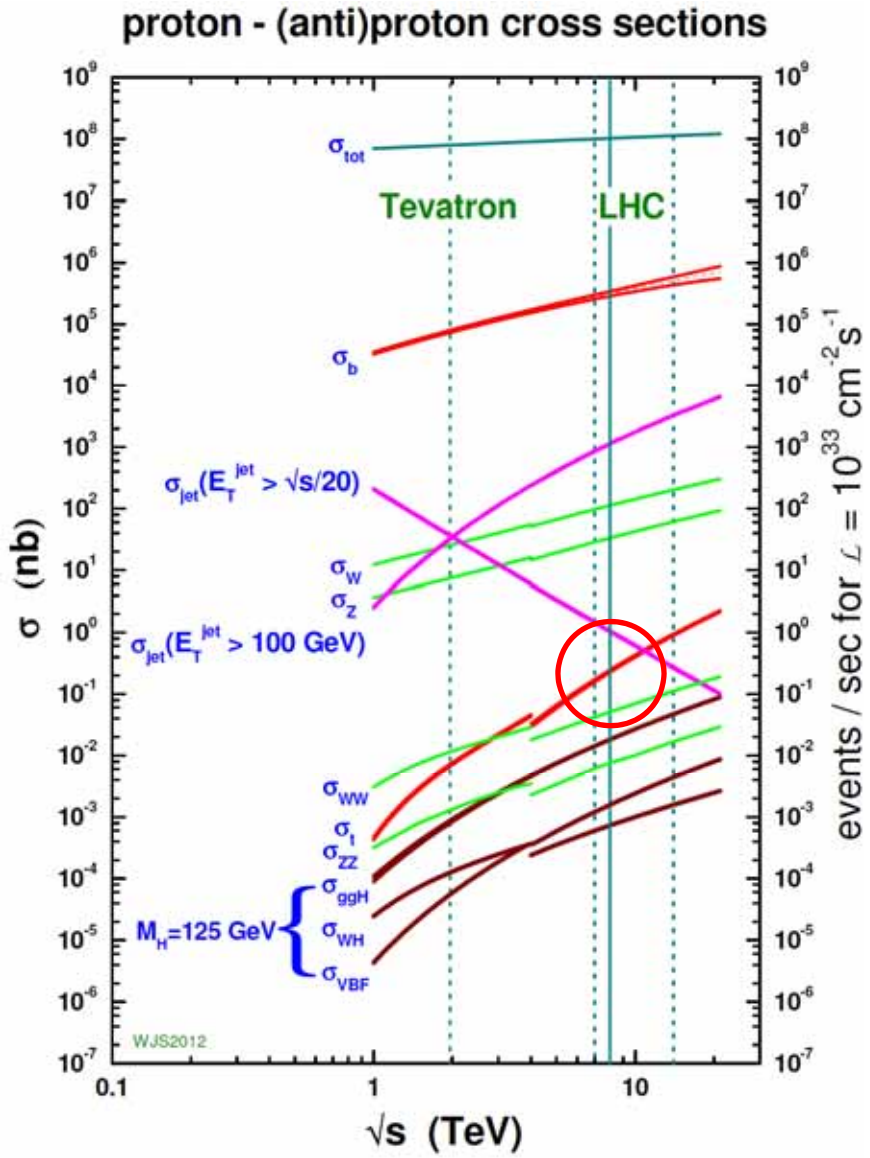
JHEP 1310 (2013) 101



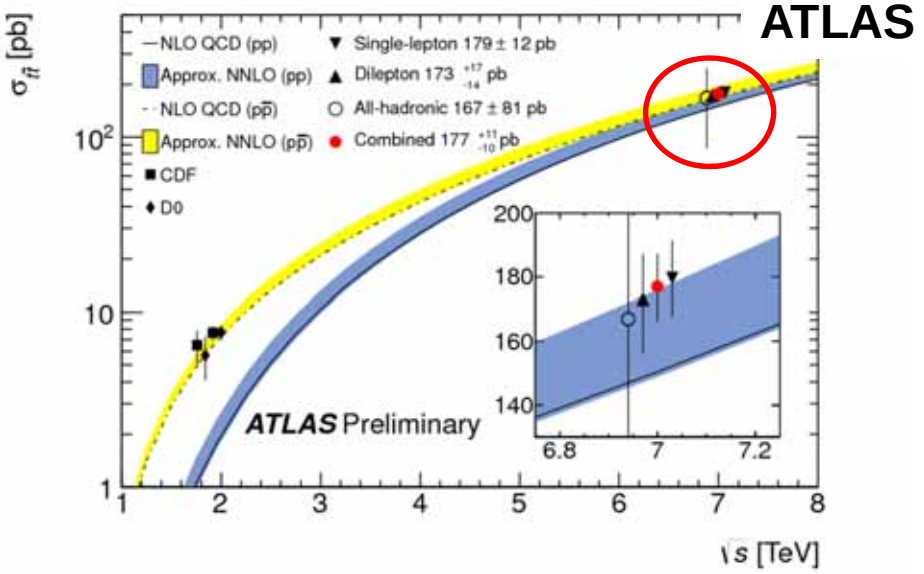


CMS-PAS-FSQ-12-035

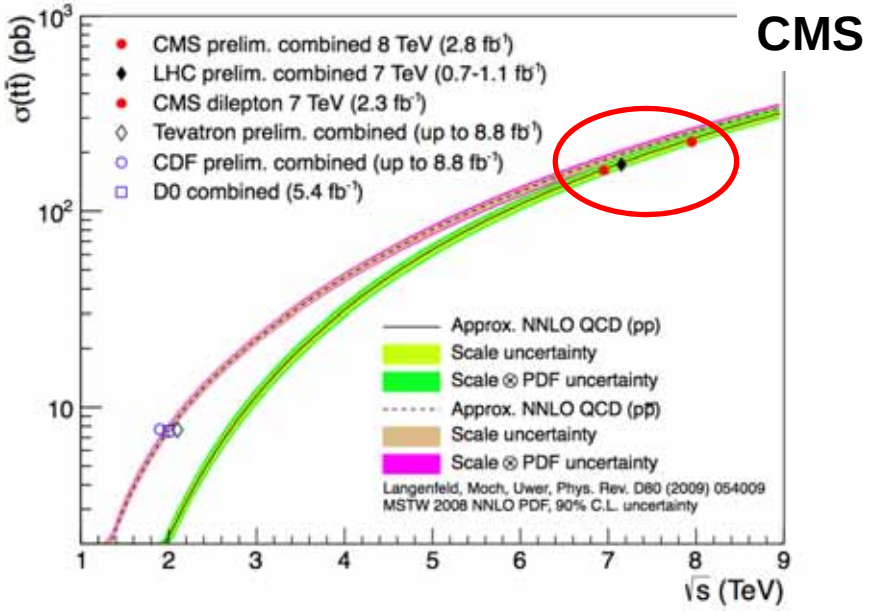
Top Inclusive Cross Sections



ATLAS

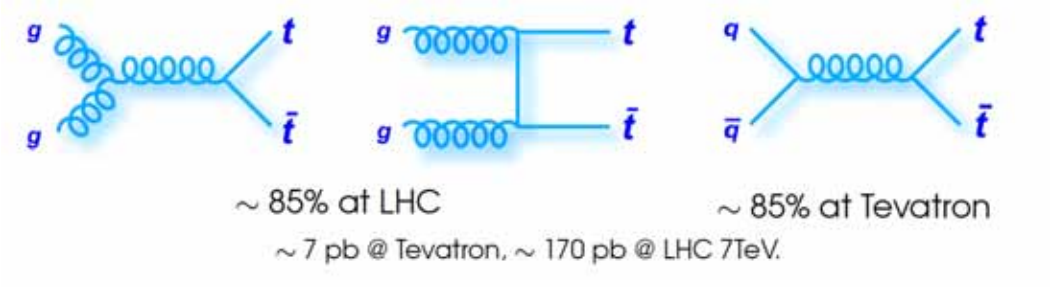


CMS



Top Polarization and Spin Correlations

Production of the top quark pairs via strong interactions

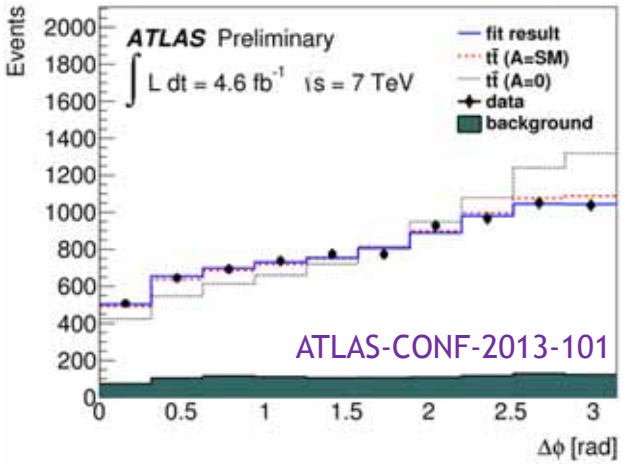


Top quark spins are correlated

Tevatron: near threshold in a $^3S_1$ state
parallel spins, 100% correlation

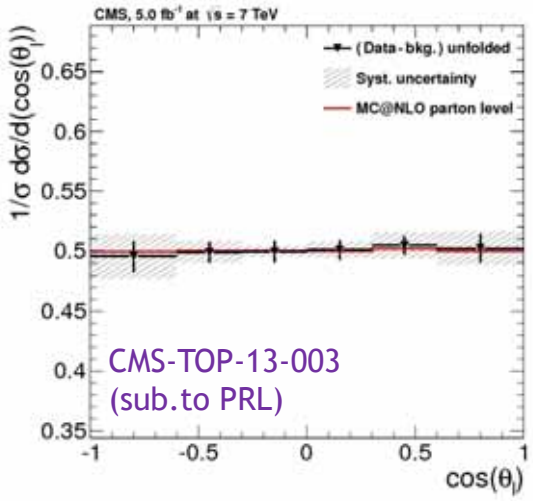
LHC: in a $^1S_0$ state, not close from threshold
same helicities, not 100% correlated

Spin correlation



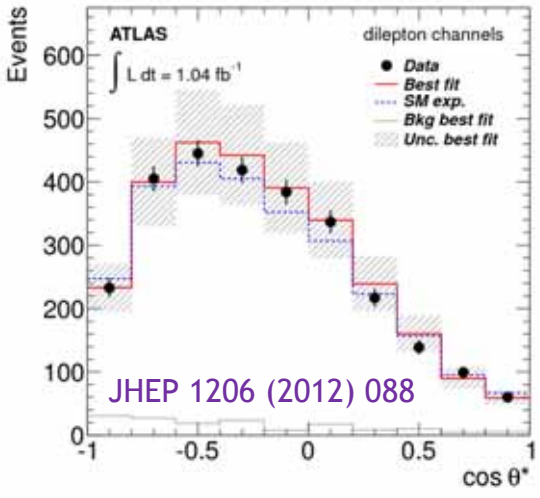
observation of spin correlations
from angular correlation
of the decay products

Top Polarization



top quark polarization
consistent with zero

W Polarization

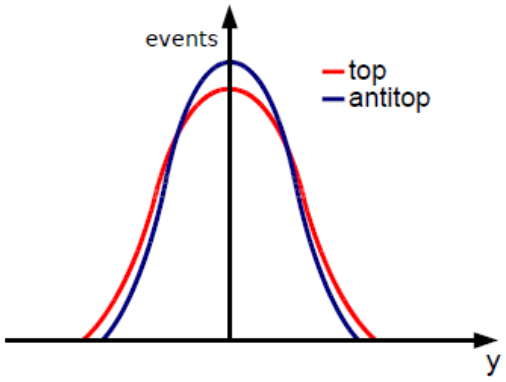


V-A nature of the
top coupling to the W

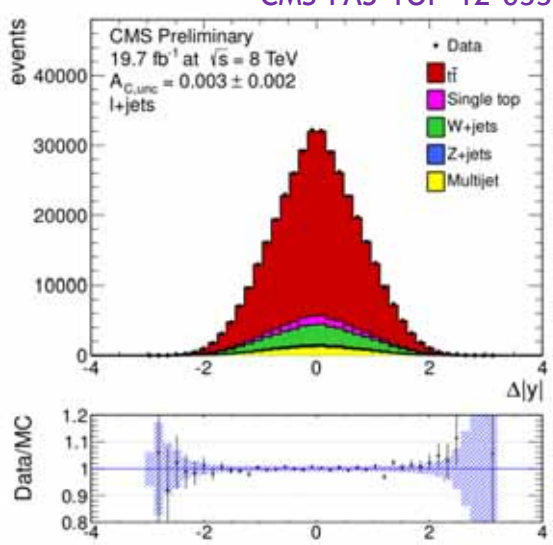
Charge Asymmetry

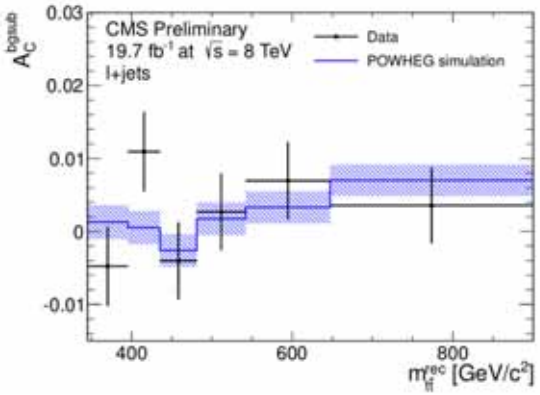
At the Tevatron, claim of non zero forward-backward asymmetry by CDF and DØ

At the LHC, study the charge asymmetry $\Delta|y|$

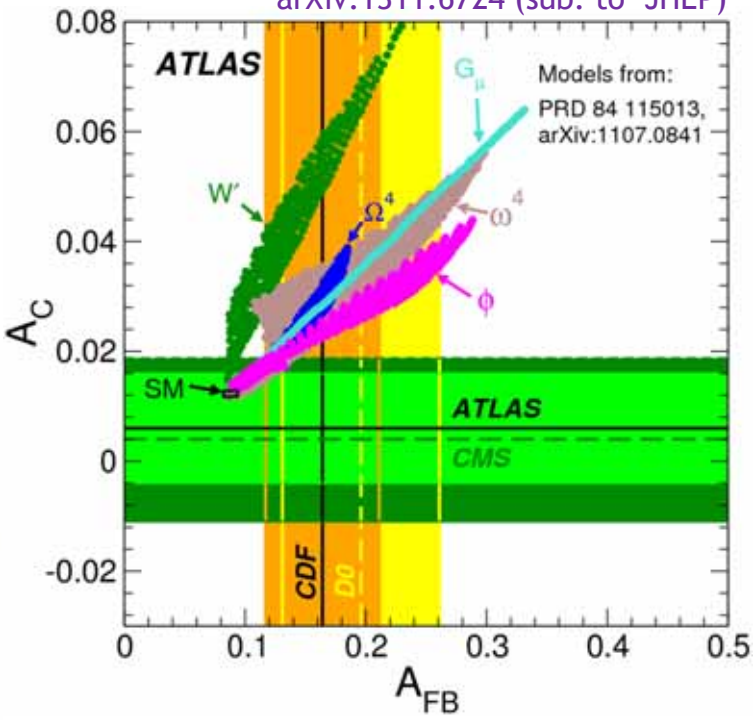


CMS-PAS-TOP-12-033





arXiv:1311.6724 (sub. to JHEP)



agreement with NLO QCD predictions, even at large mass

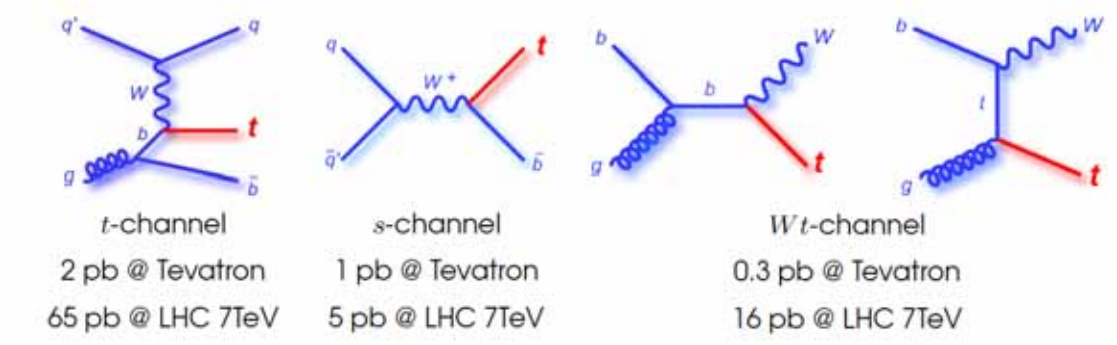
Charge asymmetry from New Physics by exchange of new heavy particles:

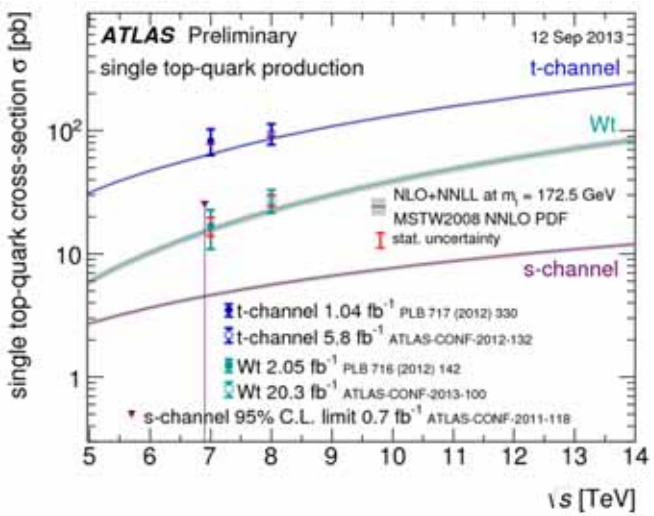
- Z'-bosons
- W' bosons with right-handed couplings
- axigluons
- Kaluza-Klein excitations of gluons

LHC data tend to disfavor most of the models proposed to explain Tevatron observation

Single Top Production

Production of the top quark via electroweak interactions

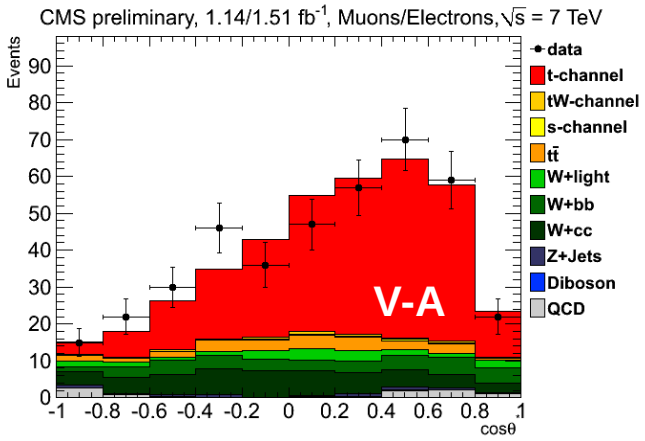




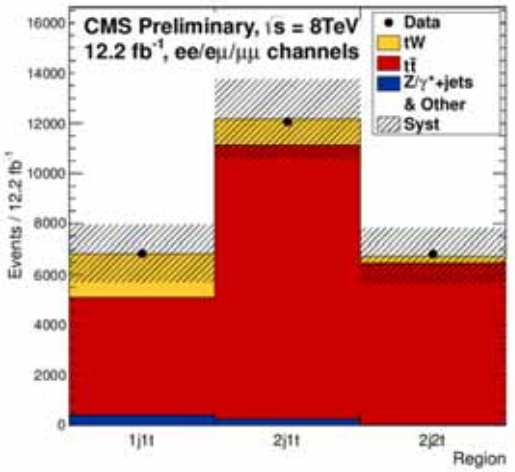
t-channel

Wt channel

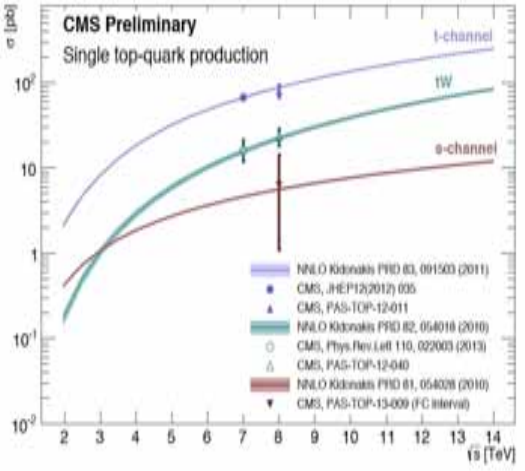
cos θ* in the $|\eta^{\text{light-jet}}|$ > 2.8 region



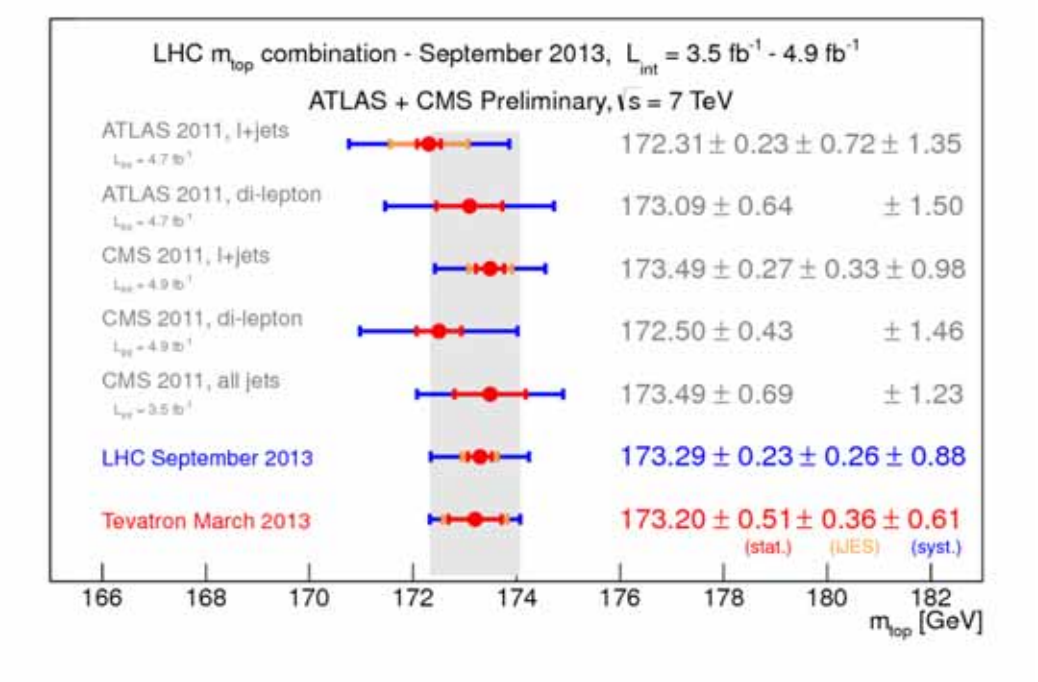
JHEP 12 (2012) 035



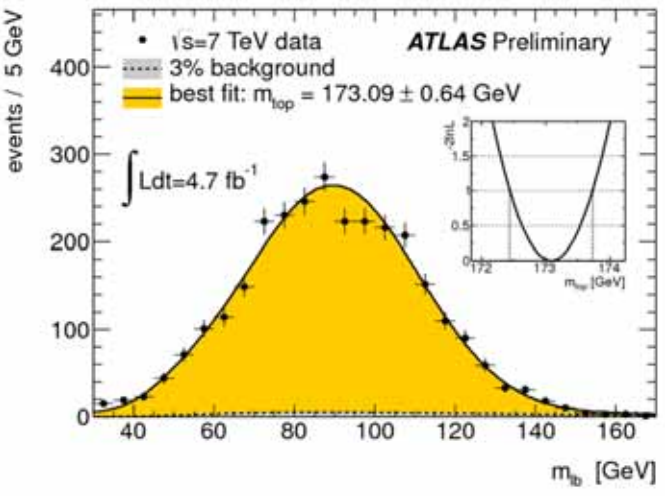
CMS-PAS-TOP-12-040

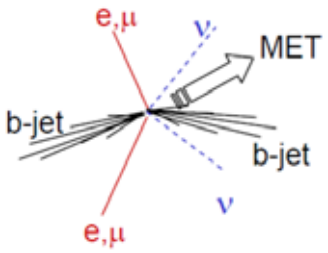


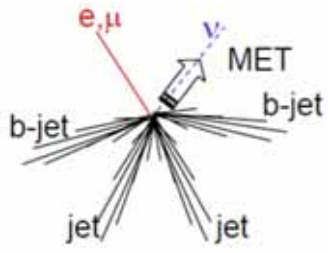
Top Quark Mass

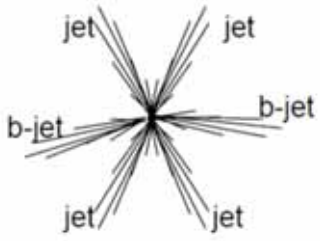


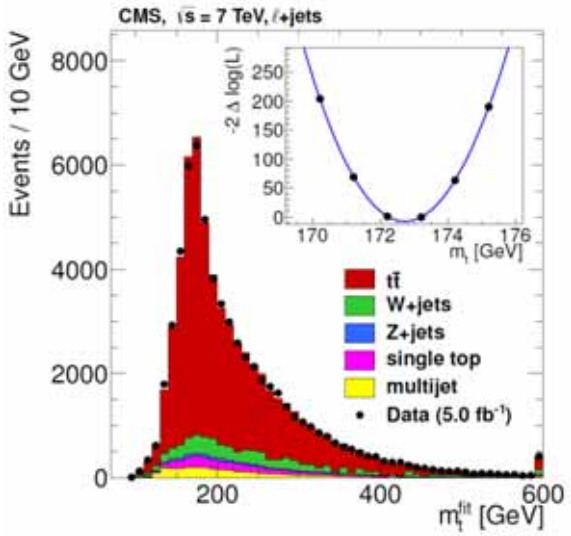
ATLAS-CONF-2013-077











Dilepton

- ee, μμ, eμ
- BR=4.7%

Lepton+Jets

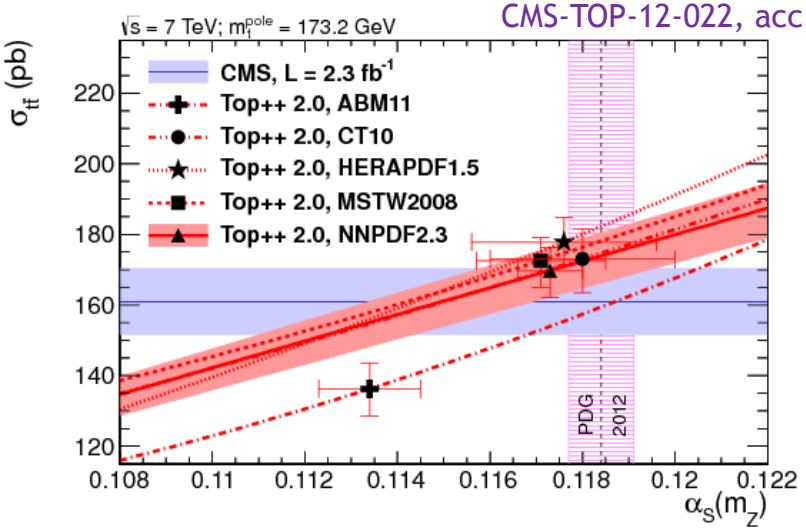
- e+jets, μ+jets
- BR=29.2%

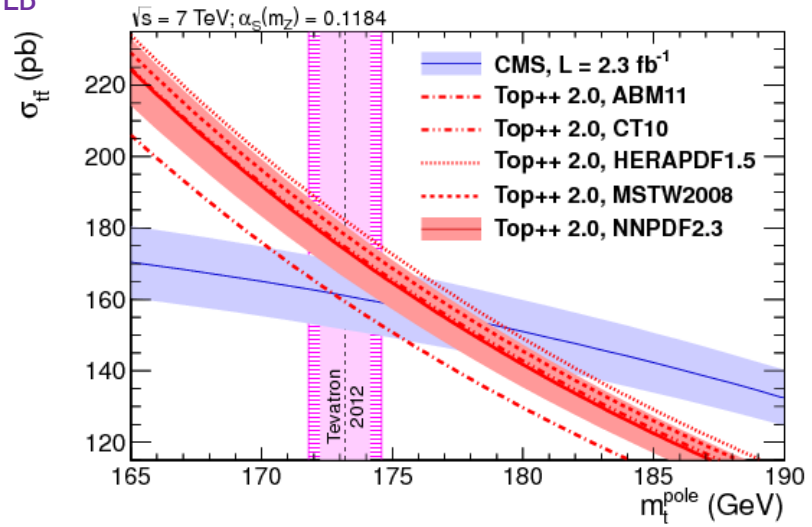
All Hadronic

- BR=45.7%

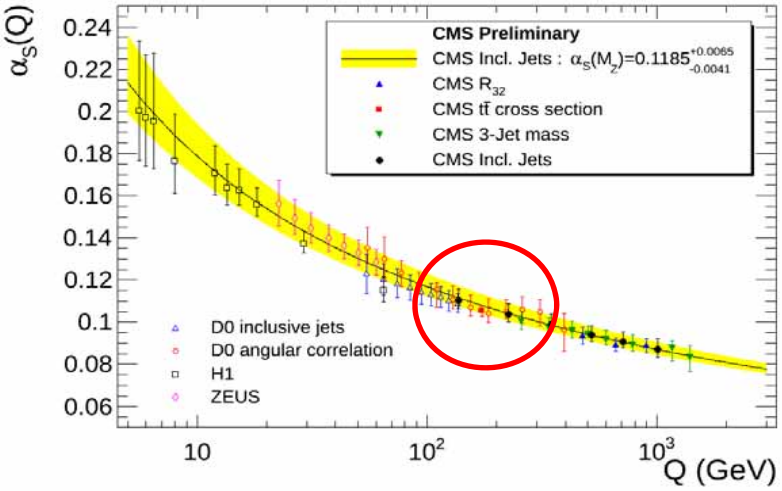
Top Quark Pole Mass, PDFs and α_s

CMS-TOP-12-022, acc. by PLB

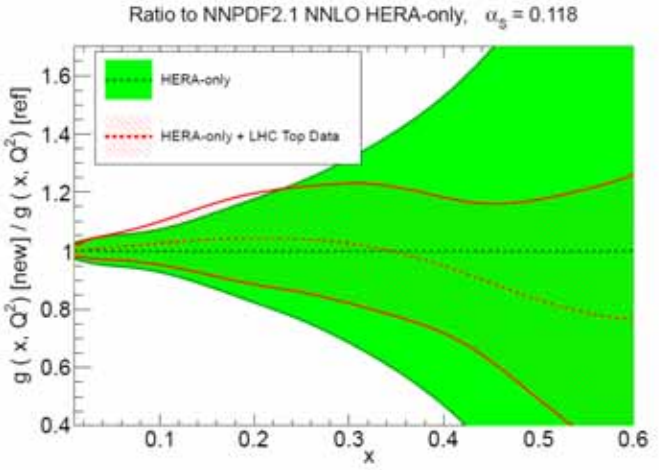




Most precise constraint on αs from LHC

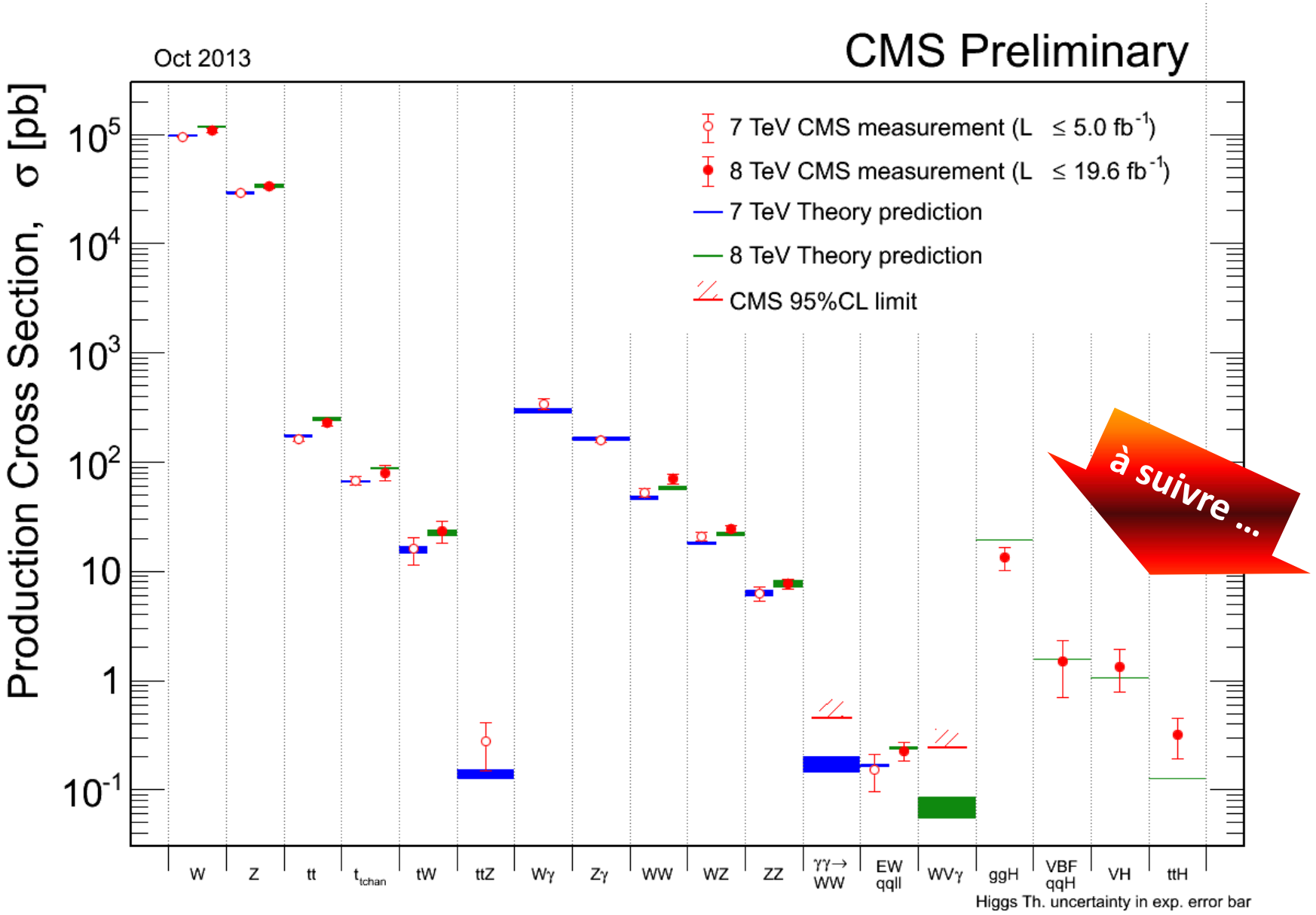


Improvements on gluon PDF at high-x



arXiv:1303.7215
Czakon, Mangano, Mitov, Rojo

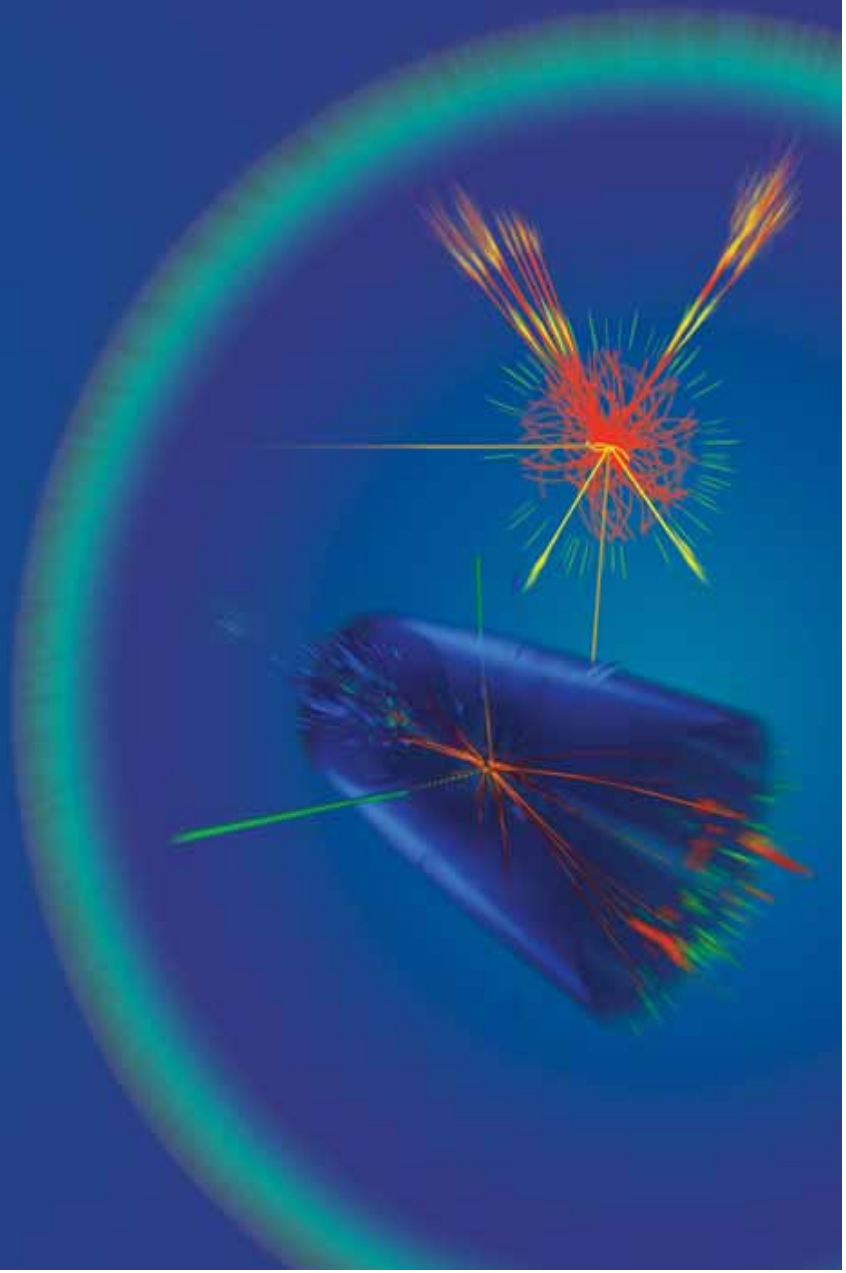
Summary of Inclusive Cross Sections



Outline

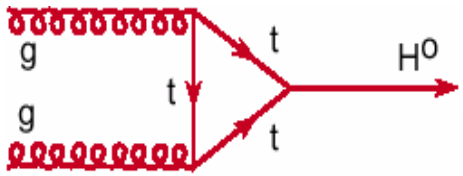
- Standard Model Physics
- Higgs Boson Physics
- B Physics and CP Violation
- Supersymmetry and Exotica

- What Next?



How to Produce the Higgs Boson ?

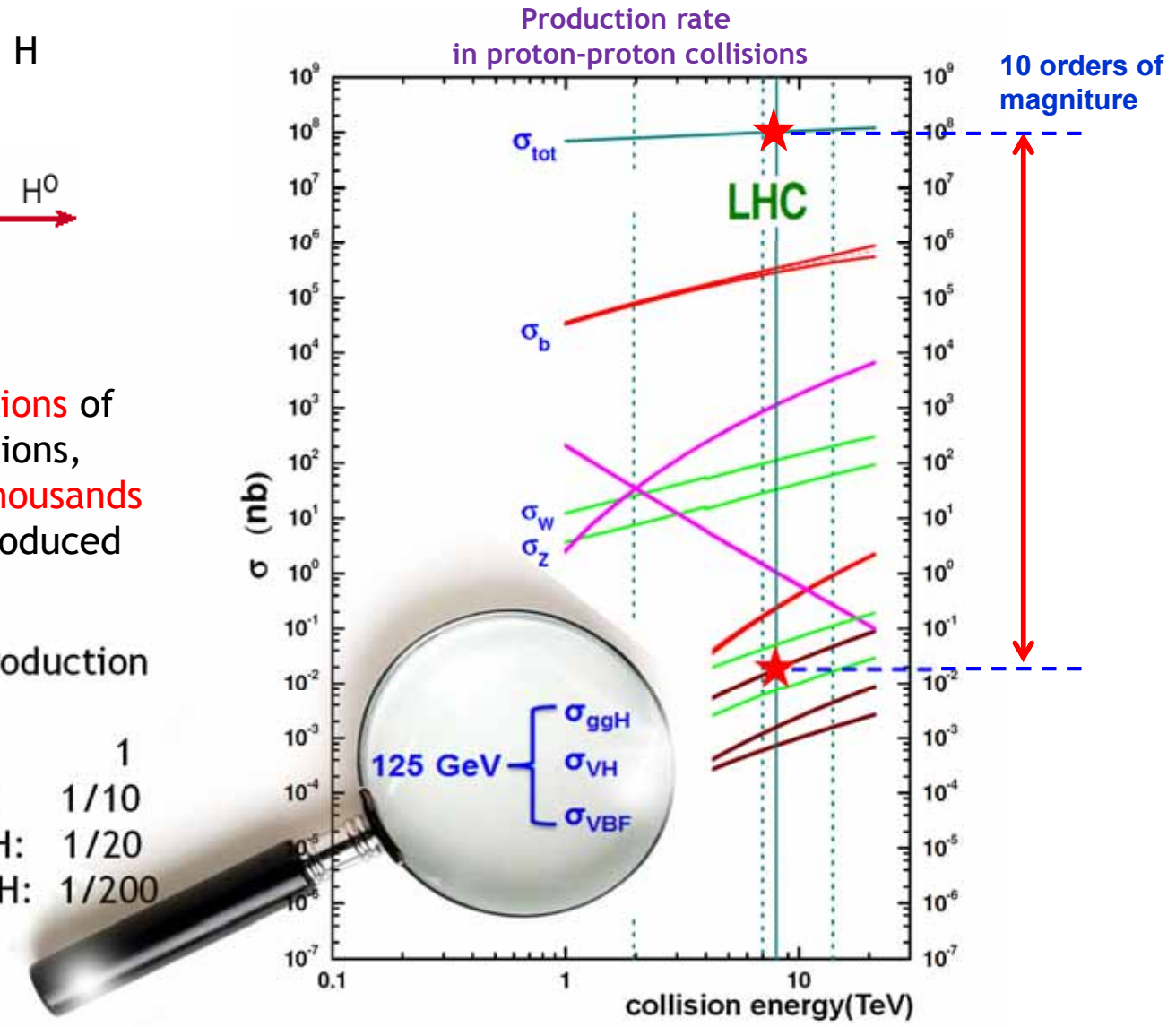
Gluon fusion : g + g → H



Among millions of billions of proton-proton collisions, only few hundreds of thousands of Higgs bosons are produced

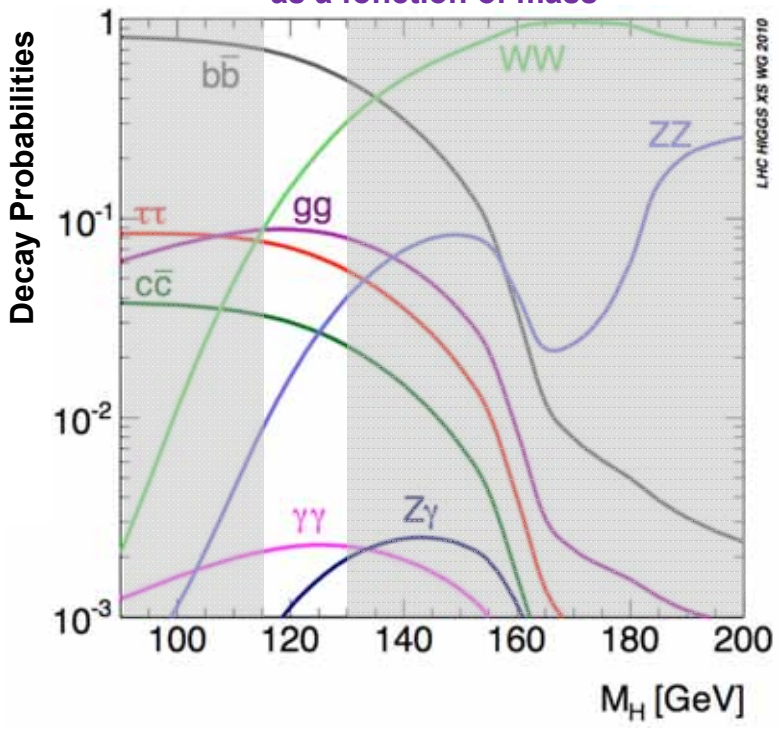
125-GeV SM Higgs boson production at the LHC

- gluon fusion: 1
- vector boson fusion VBF: 1/10
- associated production VH: 1/20
- associated production ttH: 1/200



How to Detect the Higgs Boson ?

Decay probabilities of the Higgs boson as a fonction of mass



Decay Probabilities as predicted for a 125 GeV Higgs boson mass

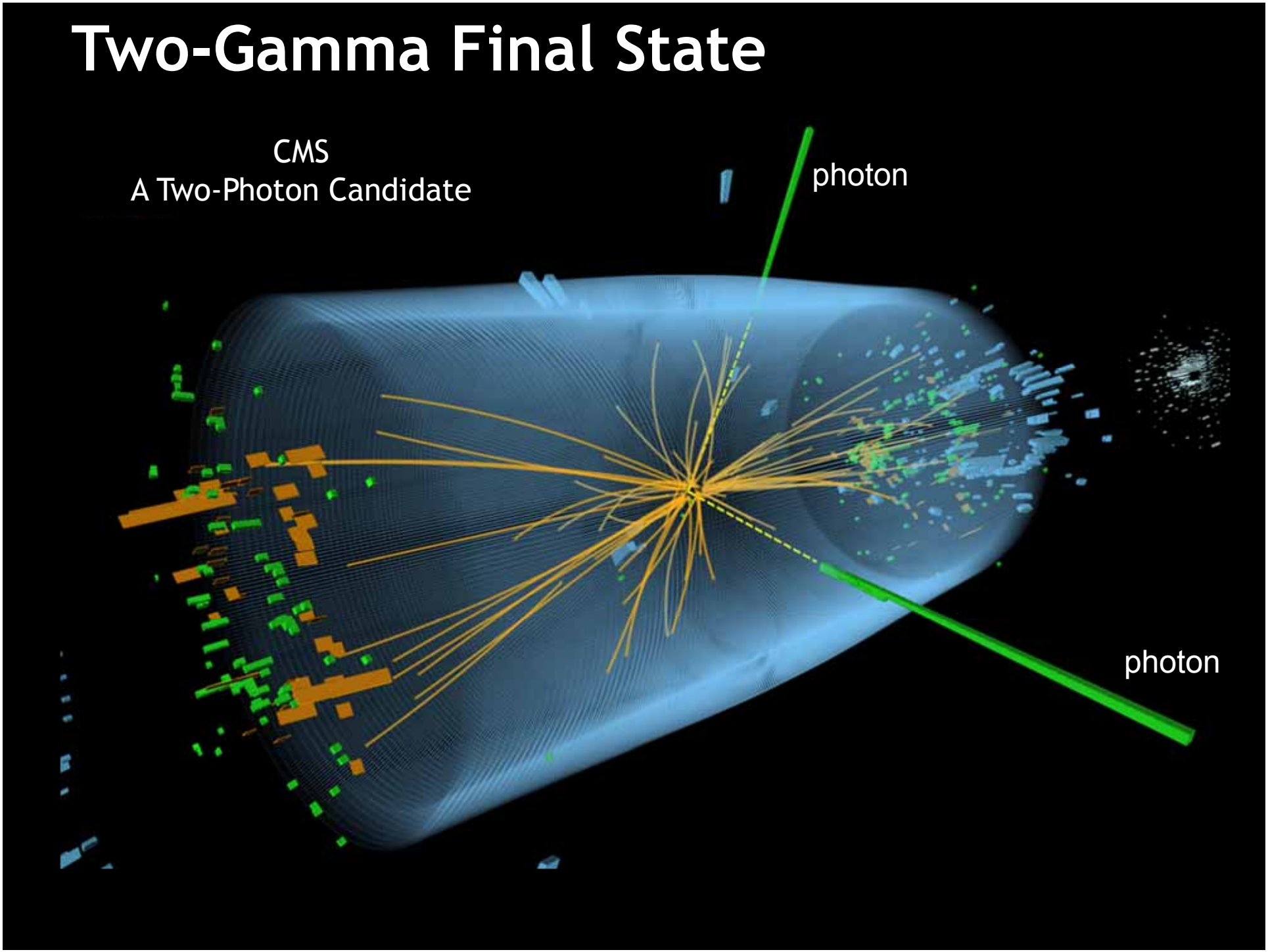
H → bb	58%
H → WW*	21%
H → τ+τ-	6.4%
H → ZZ*	2.7%
H → γγ	0.2%

One can expect:

- few hundreds decays into two photons
- about 30 decays into ZZ* in the four lepton final state

CERN, 4th of July 2012 : the Discovery

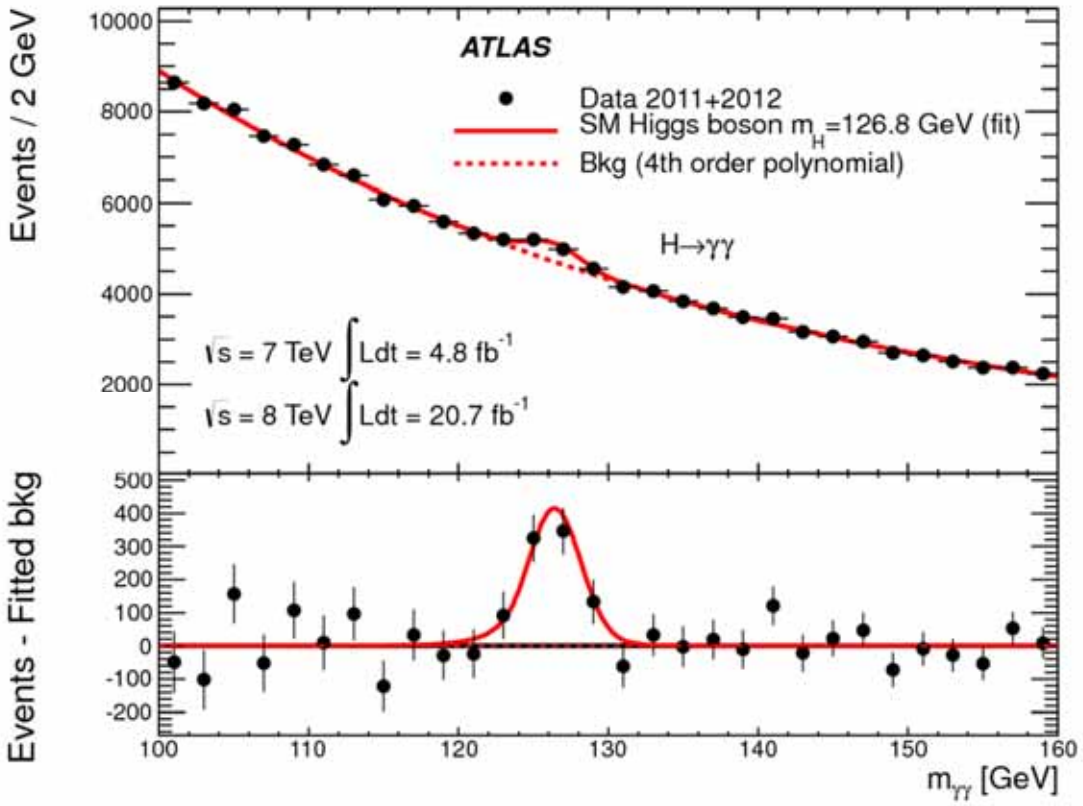
Two-Gamma Final State



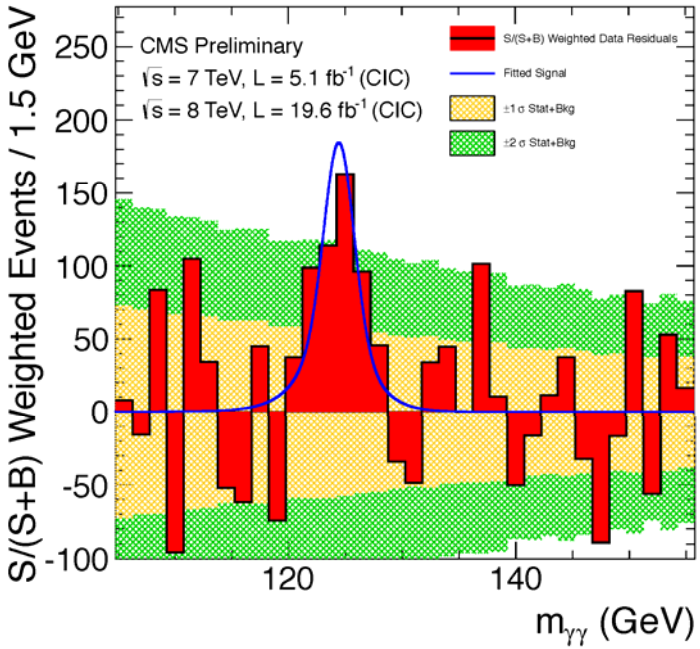
Two-Gamma Final State

Updates with full data sets: 5 fb^{-1} at 7 TeV and 20 fb^{-1} at 8 TeV

PLB 726 (2013) 88-119



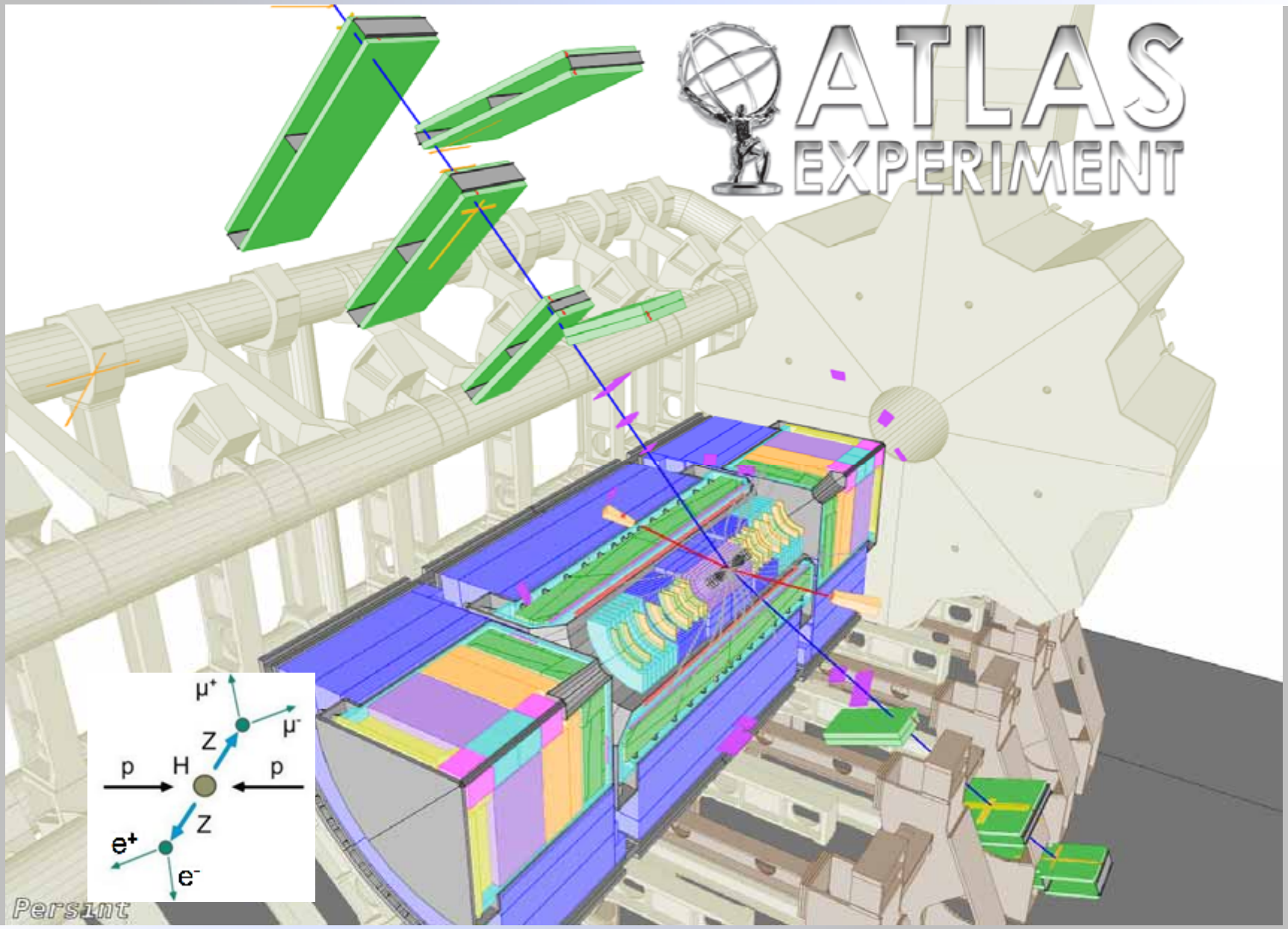
CMS-PAS-HIG-13-001



Significance (m_H = 126.5 GeV)
- observed : **7.4 σ**
- expected: 4.1σ

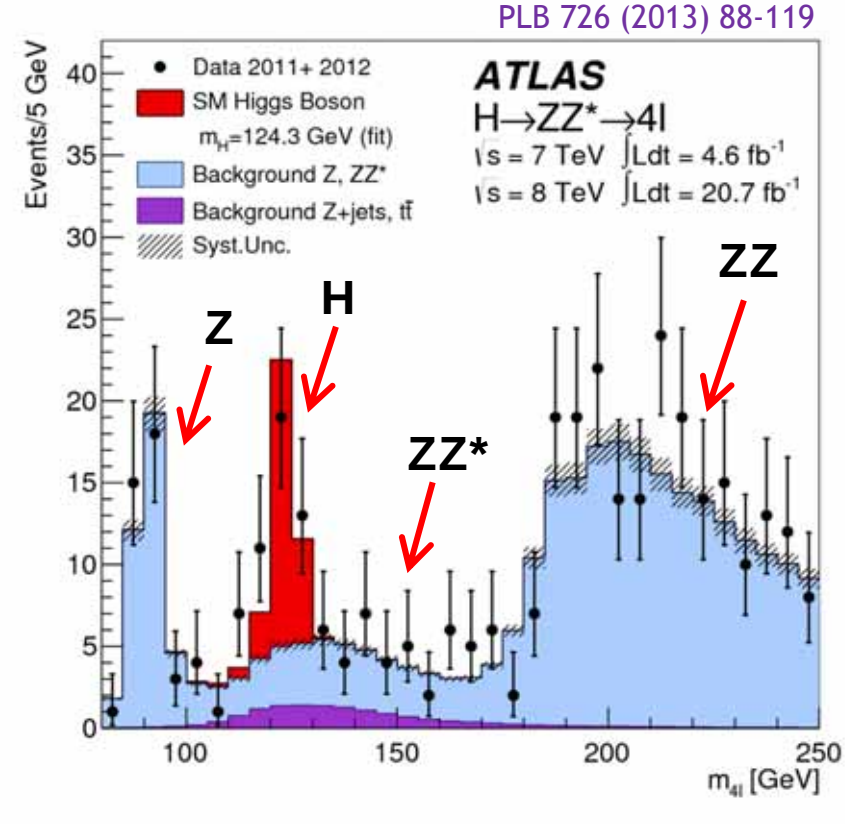
Significance (m_H = 125.7 GeV)
- observed : **3.9σ**
- expected: 4.2σ

ZZ* Final State

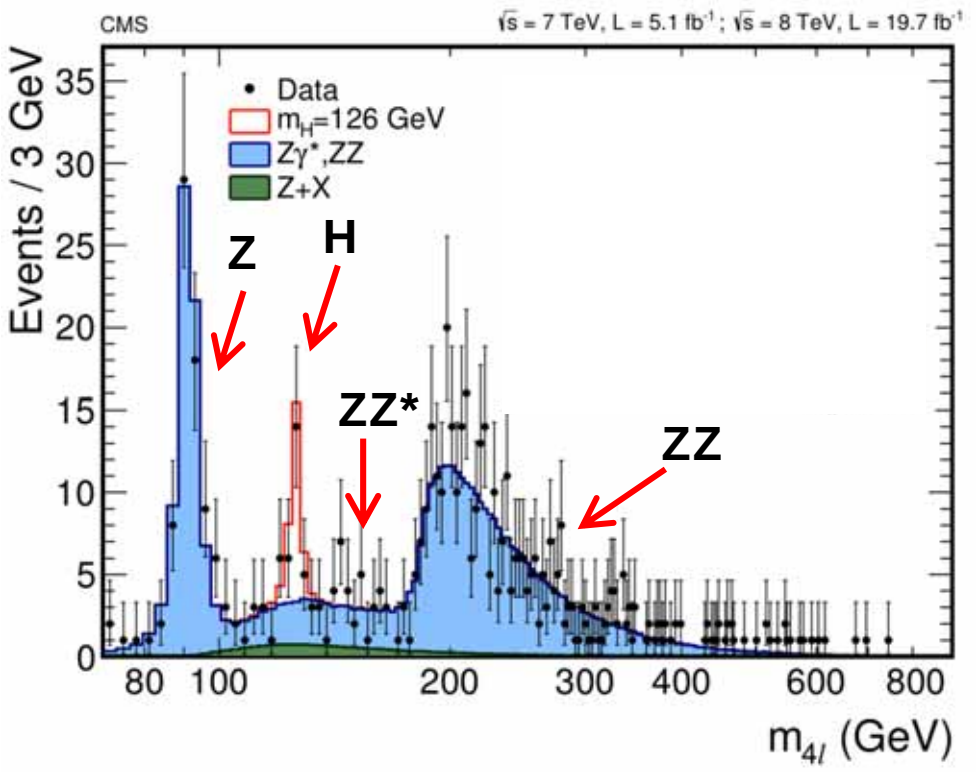


ZZ* Final State

PLB 726 (2013) 88-119



CMS-HIG-13-002 (sub. to JHEP)

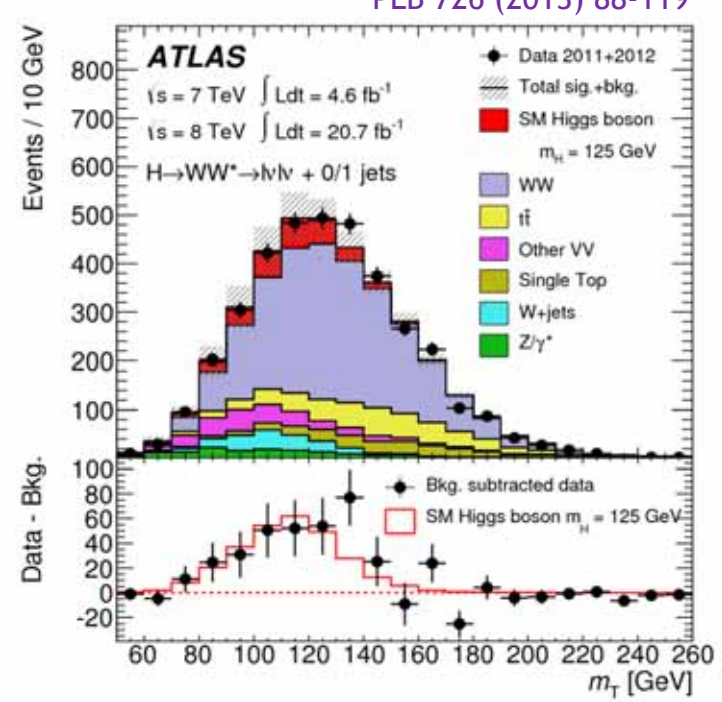


Significance (m_H = 124.3 GeV)
- observed : **6.6σ**
- expected: 4.4σ

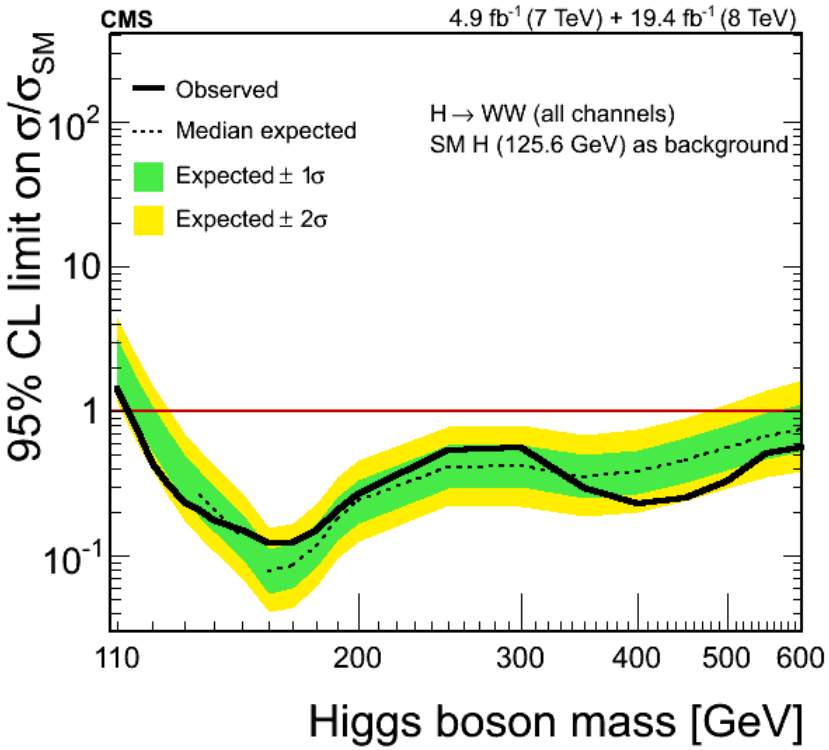
Significance (m_H = 125.7 GeV)
- observed : **6.7σ**
- expected: 7.1σ

WW Final State

PLB 726 (2013) 88-119



CMS-HIG-13-023 (acc. by JHEP)

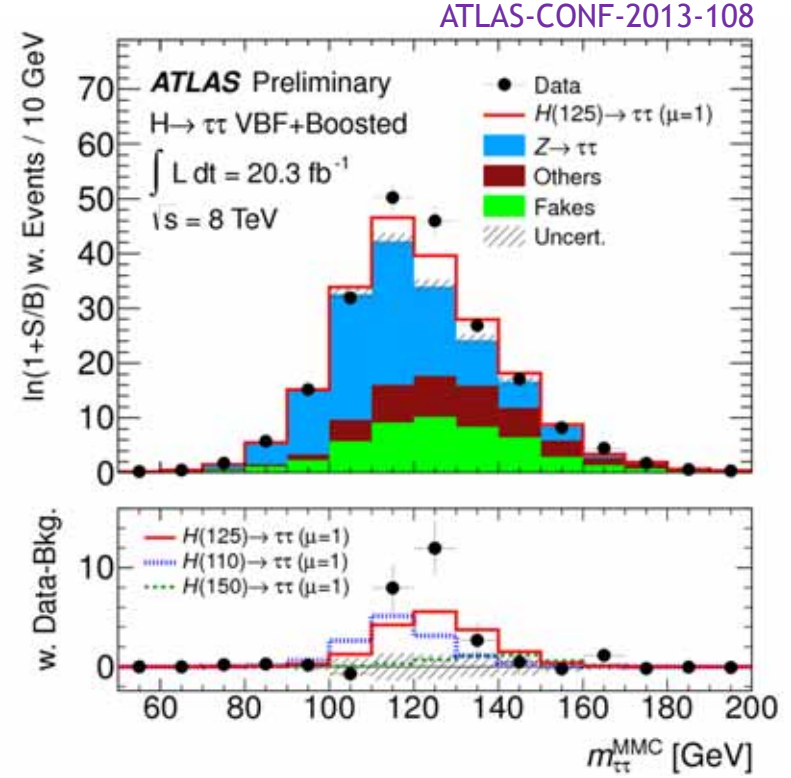


Significance (m_H = 125.5 GeV)
- observed : **3.8σ**
- expected: 3.8σ

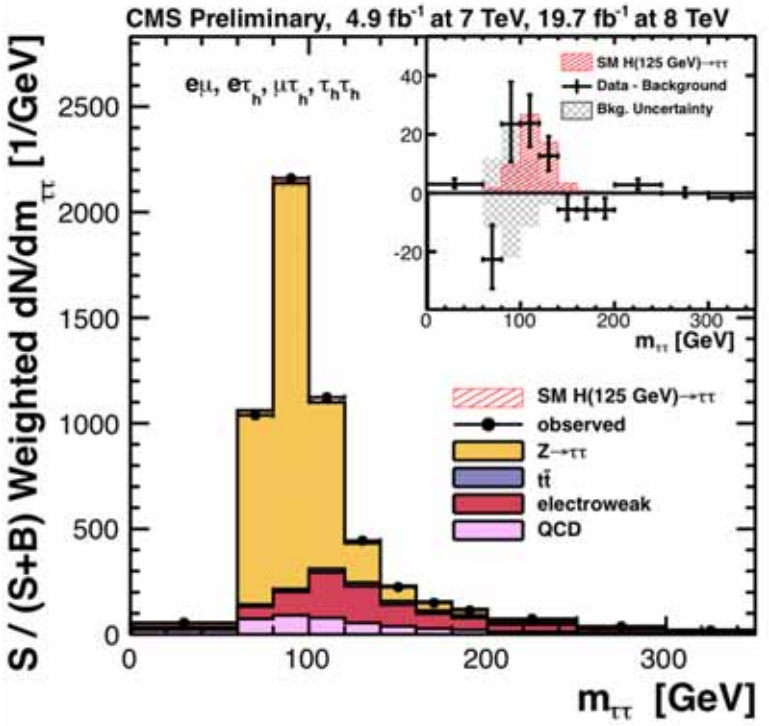
Significance (m_H = 125.7 GeV)
- observed : **3.9σ**
- expected: 5.6σ

Evidence for Decay in Two τ Leptons

ATLAS-CONF-2013-108



CMS-PAS-HIG-13-004

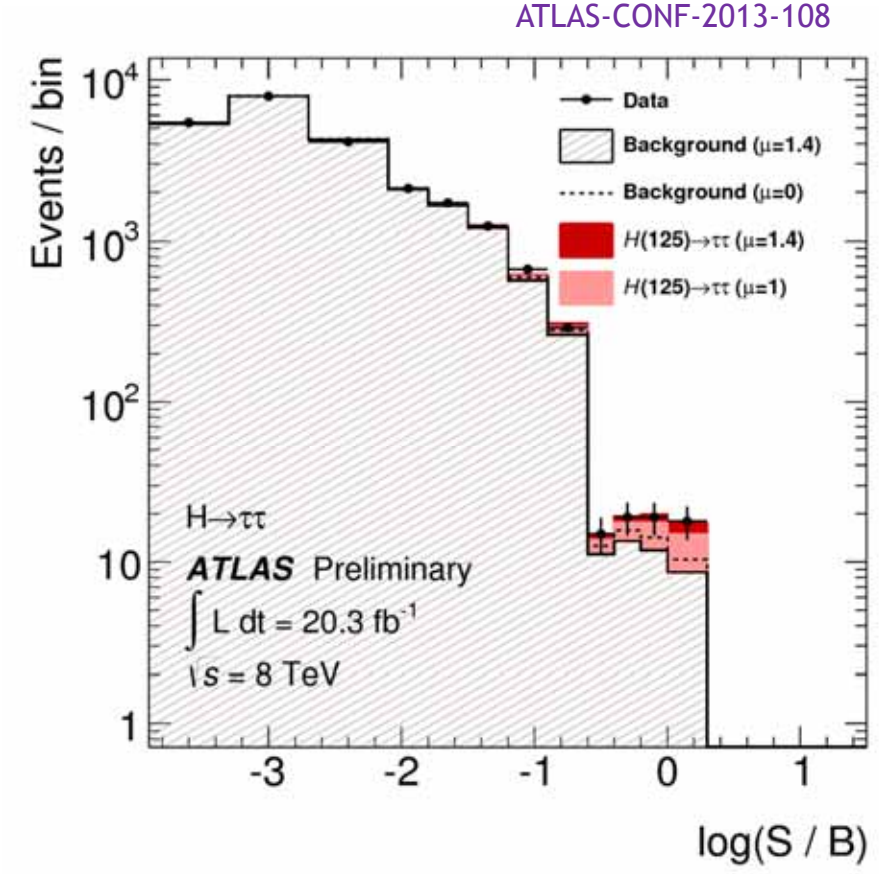


Significance (m_H = 125 GeV)
- observed : **4.1σ**
- expected: 3.2σ

Significance (m_H = 125 GeV)
- observed : **3.4σ**
- expected: 3.6σ

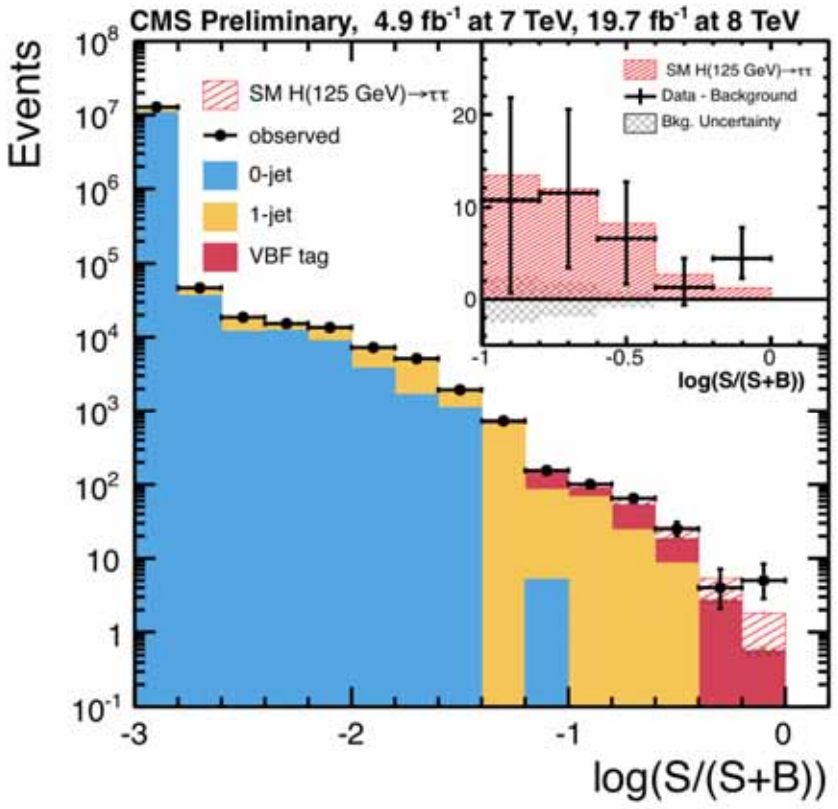
Evidence for Decay in Two τ Leptons

ATLAS-CONF-2013-108



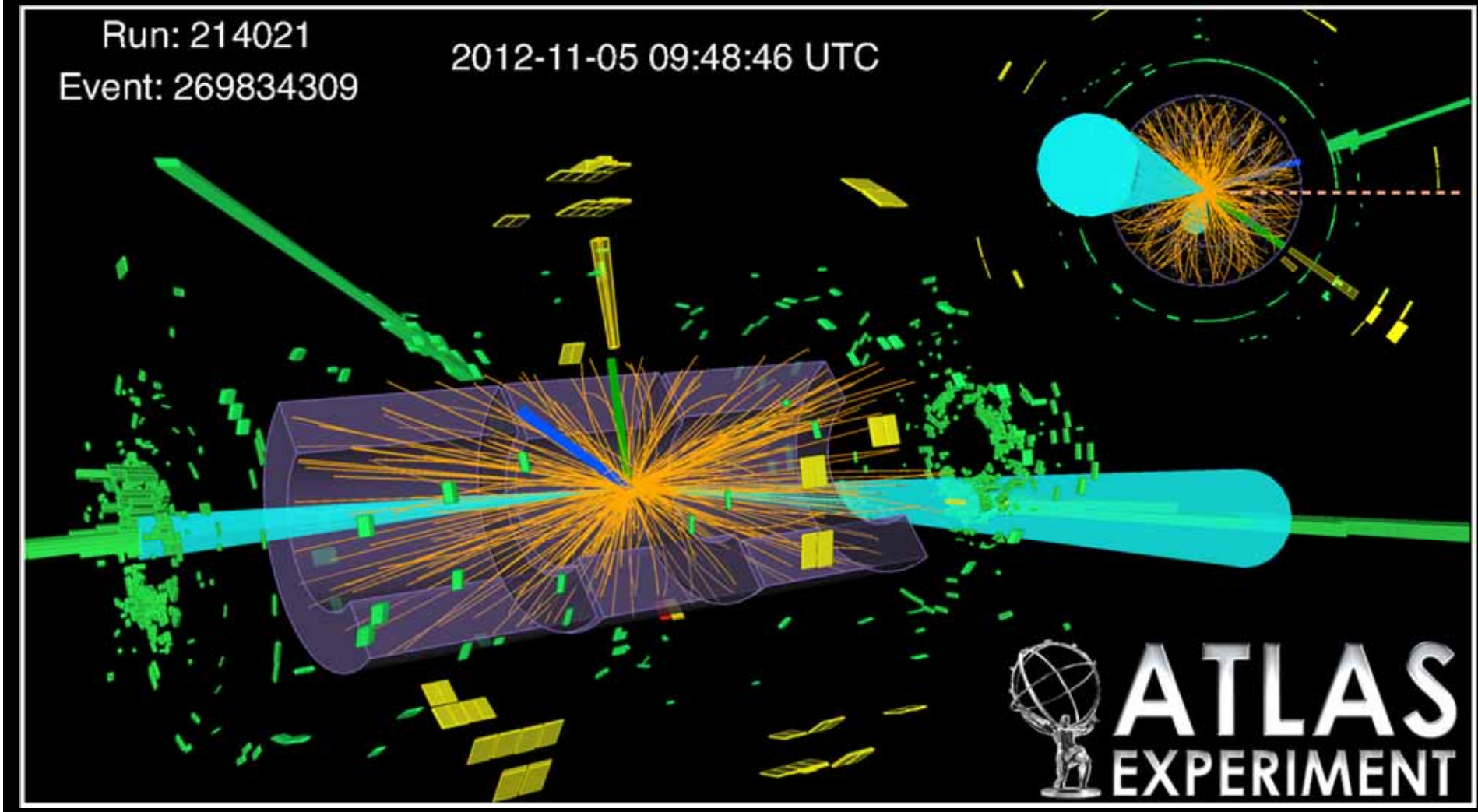
Significance (m_H = 125 GeV)
- observed : **4.1σ**
- expected: 3.2σ

CMS-PAS-HIG-13-004



Significance (m_H = 125 GeV)
- observed : **3.4σ**
- expected: 3.6σ

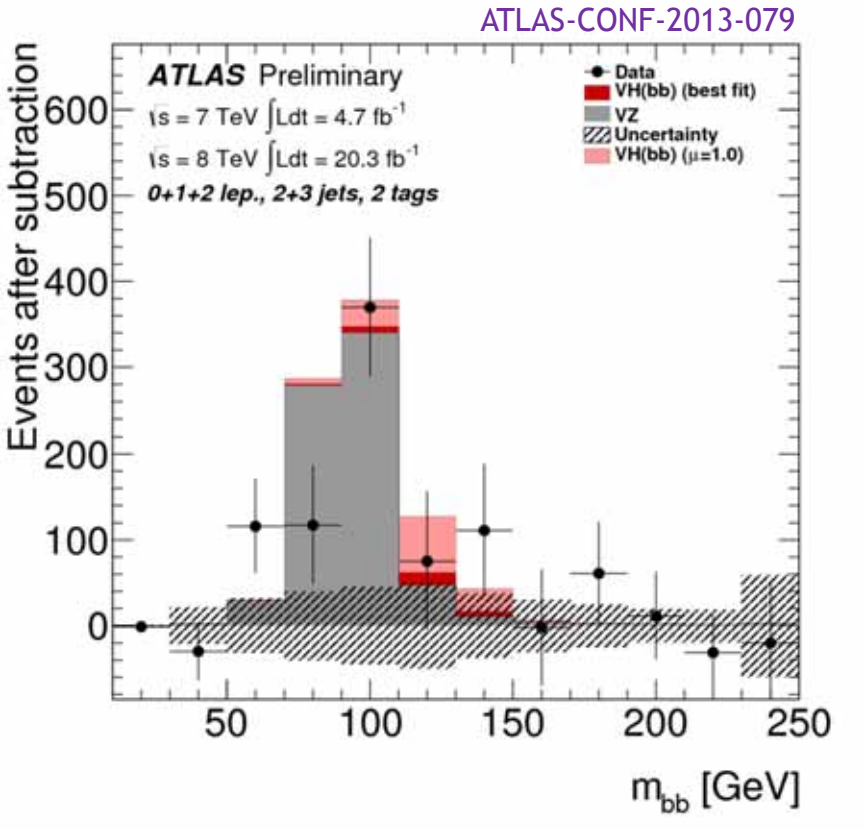
Evidence for Decay in Two τ Leptons



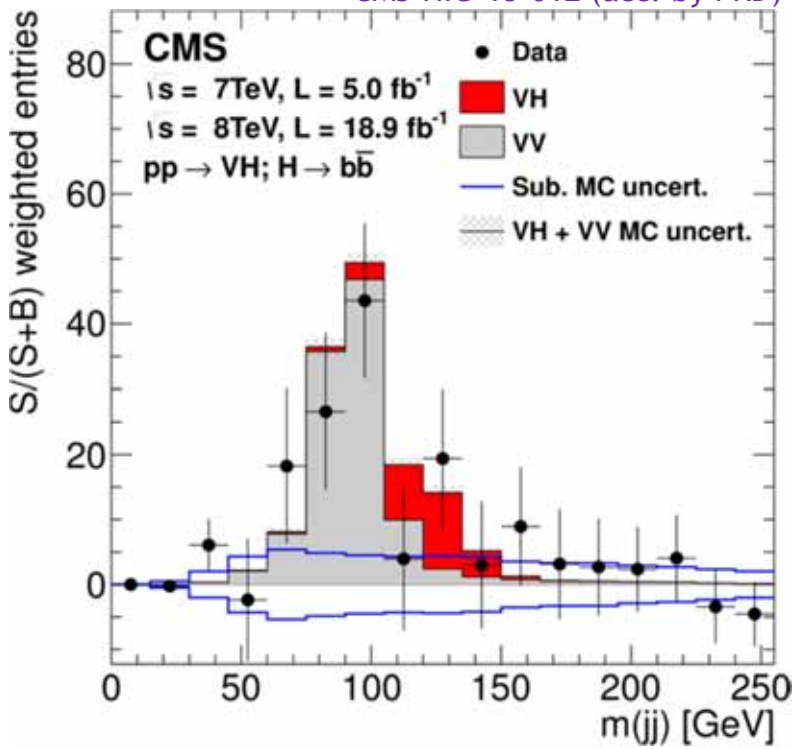
Event in the electron-jet VBF category with BDT=0.99 (S/B=1.0)

Search for Decay in Two b Quarks

ATLAS-CONF-2013-079



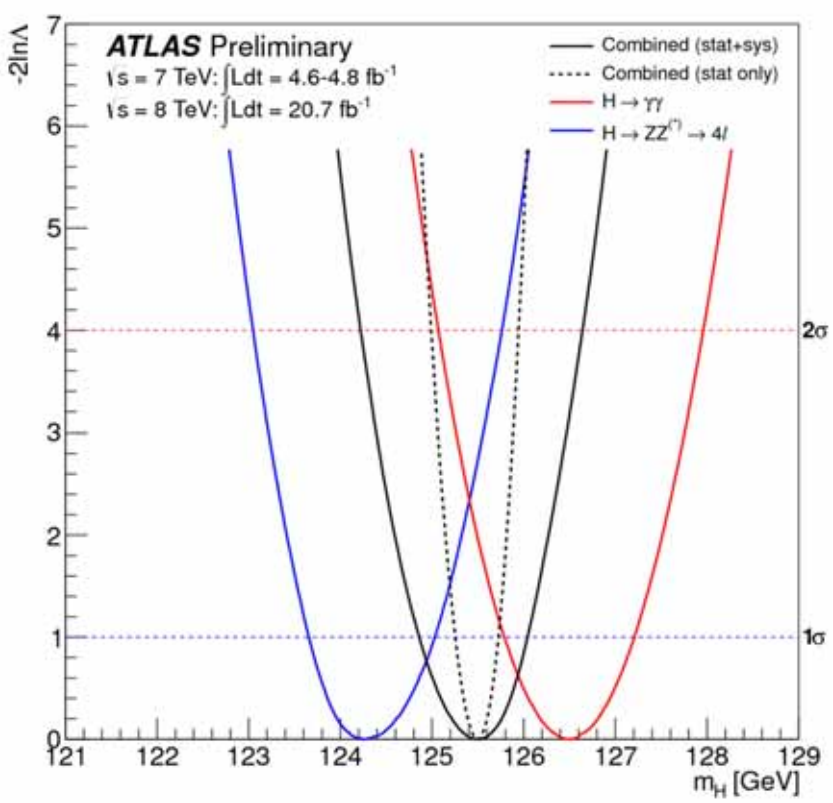
CMS-HIG-13-012 (acc. by PRD)

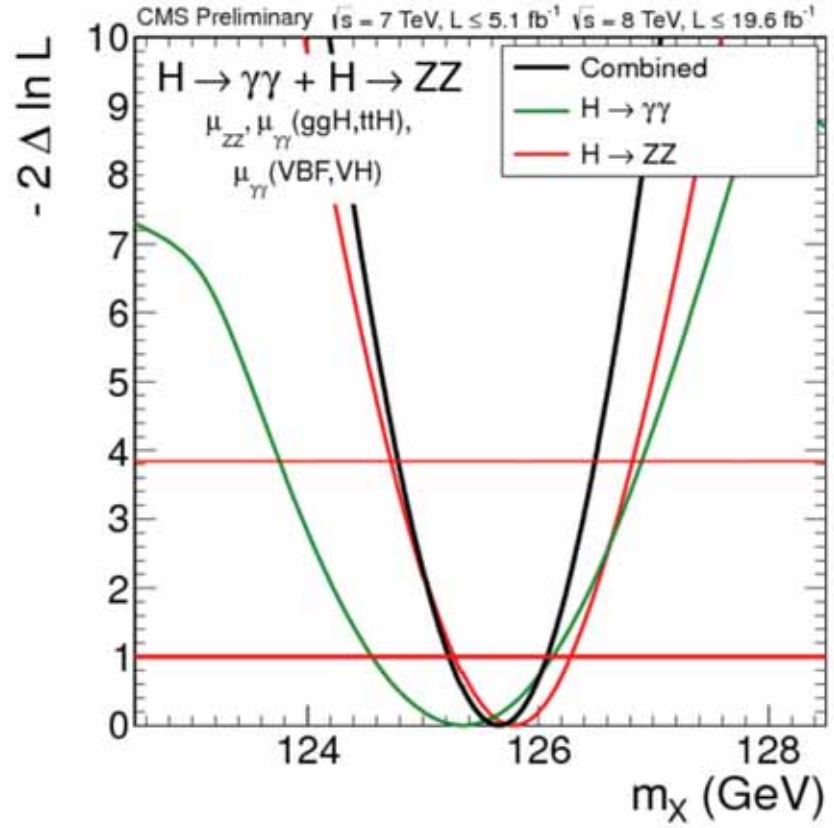


95% limit (m_H = 125 GeV)
- observed : **1.4xSM**
- expected: 1.3xSM

Significance (m_H = 125 GeV)
- observed : **2.1σ**
- expected: 2.1σ

Higgs Boson Mass



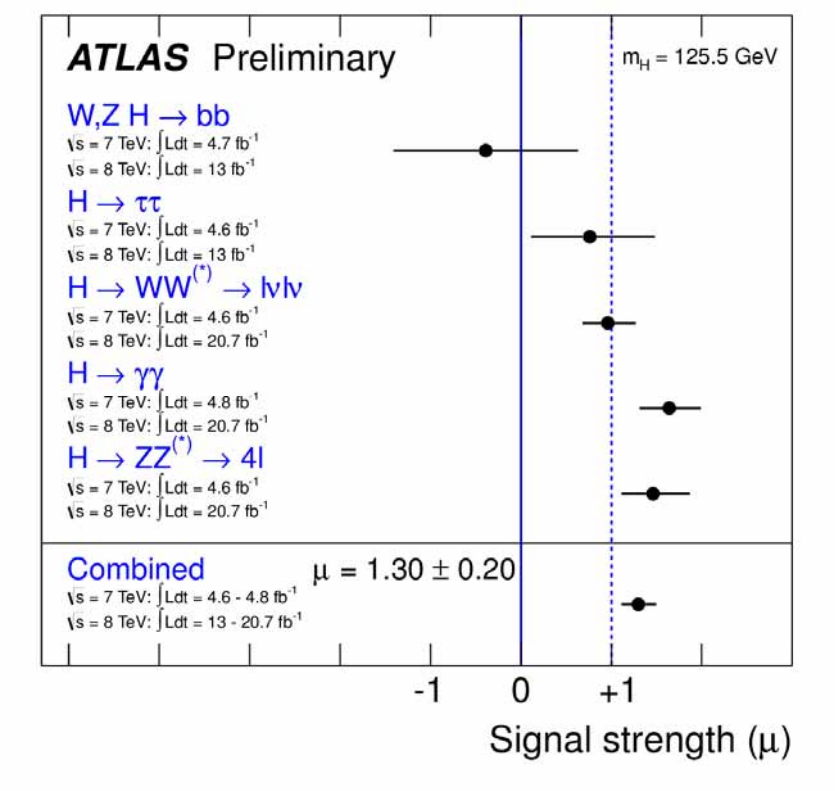


$m_H = 125.5 \pm 0.2\ (stat.)\ ^{+0.5}_{-0.6}\ (syst.)$ GeV

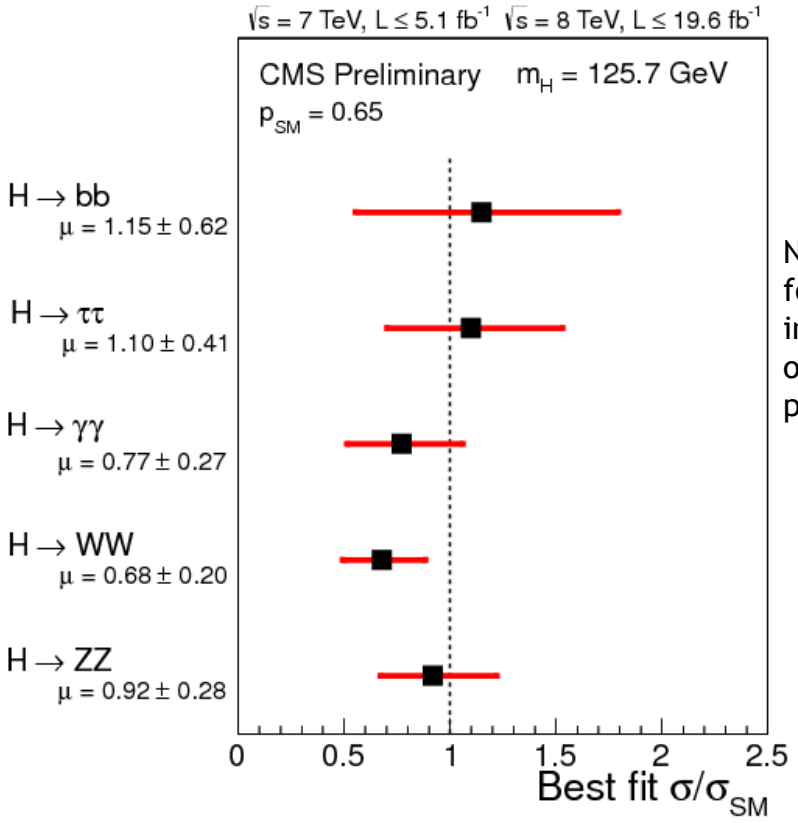
$m_H = 125.7 \pm 0.3\ (stat.) \pm 0.3\ (syst.)$ GeV

naïve average: $m_H = 125.6 \pm 0.4$ GeV

Higgs Boson Couplings



μ = 1.30 ±0.20



μ = 0.80 ±0.14

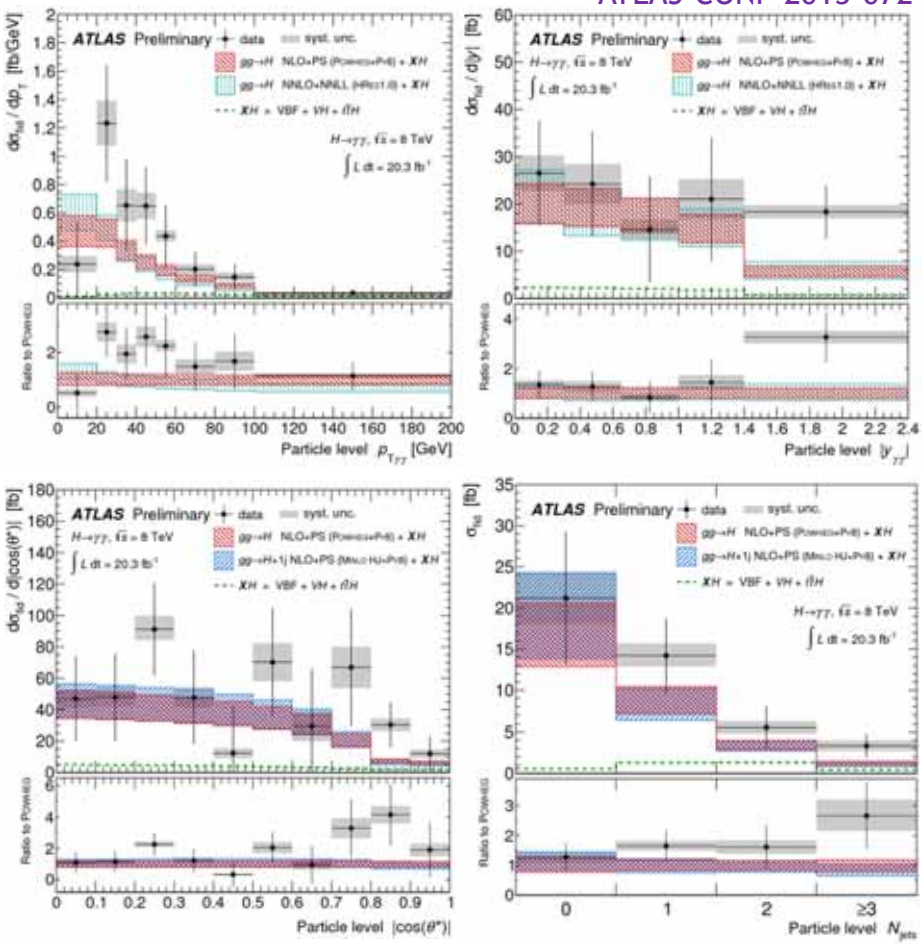
No evidence for decays into muon or electron pairs

naïve average: μ = 0.98 ±0.11

Spin and Parity

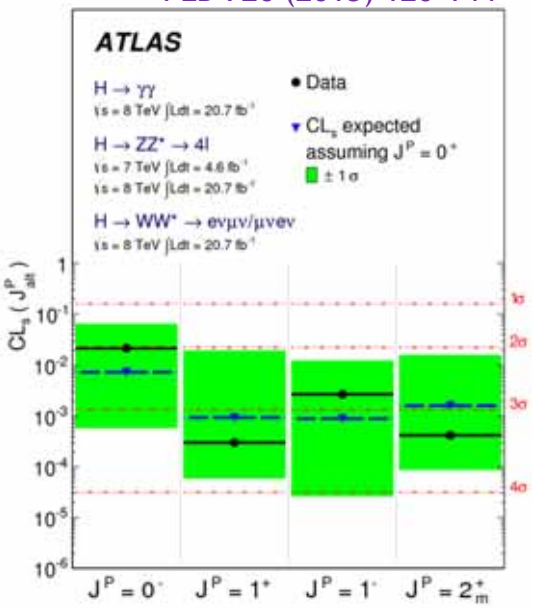
Study angular distributions in diphoton and ZZ* modes

ATLAS-CONF-2013-072

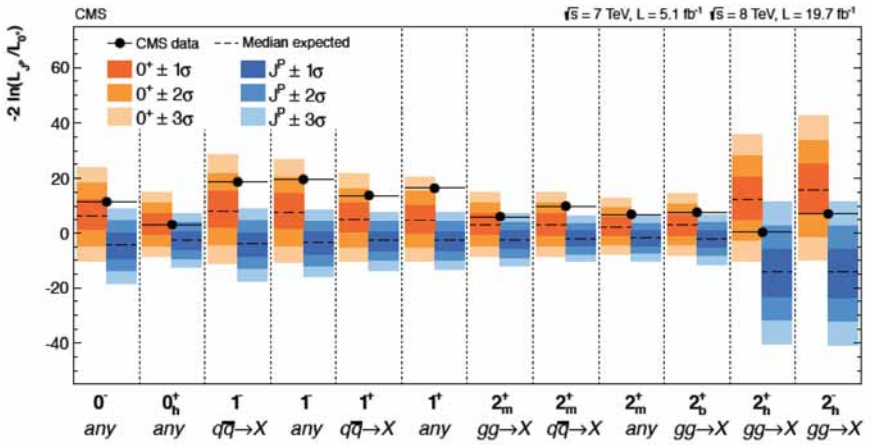


non-standard 0+ spin-parity hypothesis is already strongly disfavored

PLB 726 (2013) 120-144



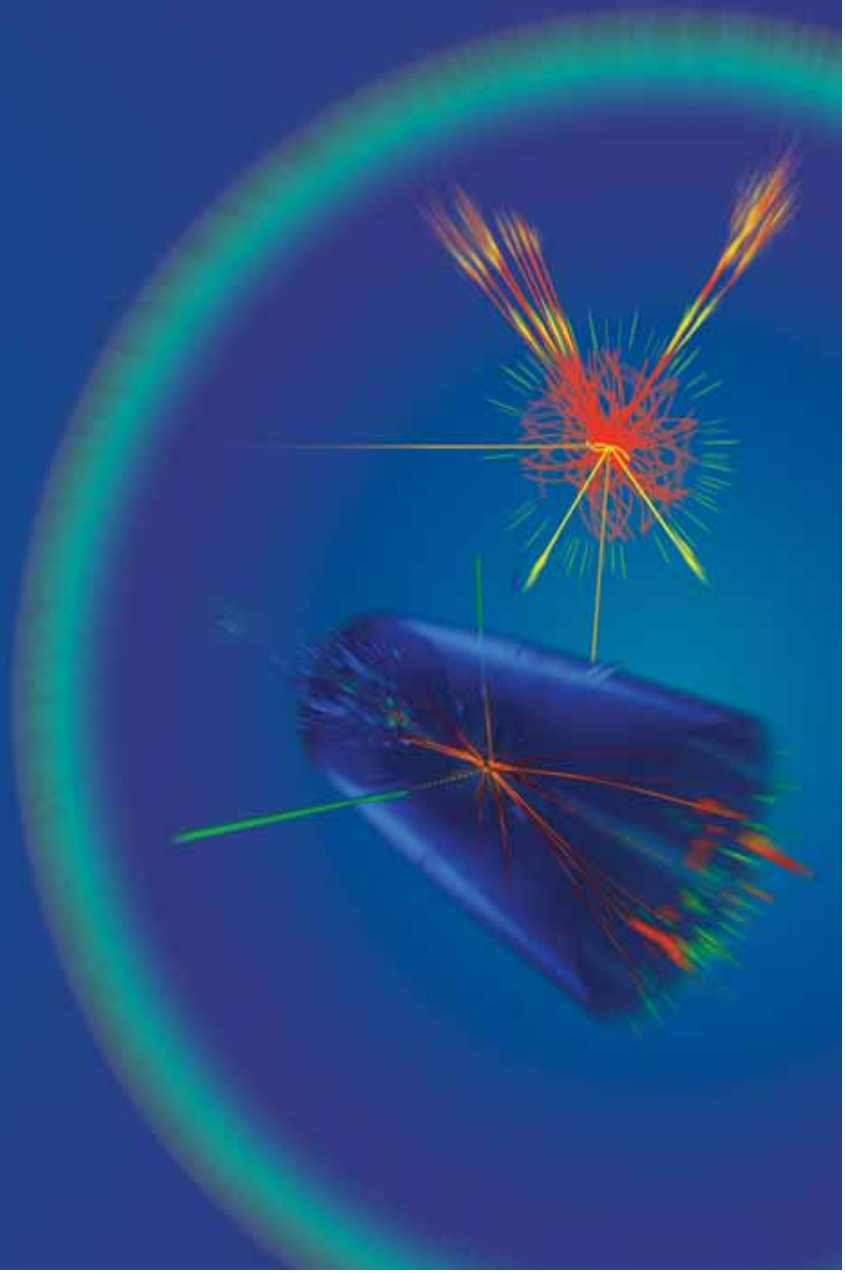
CMS-HIG-13-002 (sub. to JHEP)



Outline

- Standard Model Physics
- Higgs Boson Physics
- B Physics and CP Violation
- Supersymmetry and Exotica

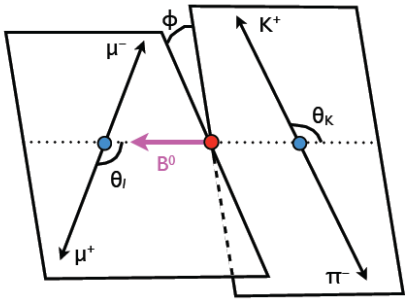
- What Next?



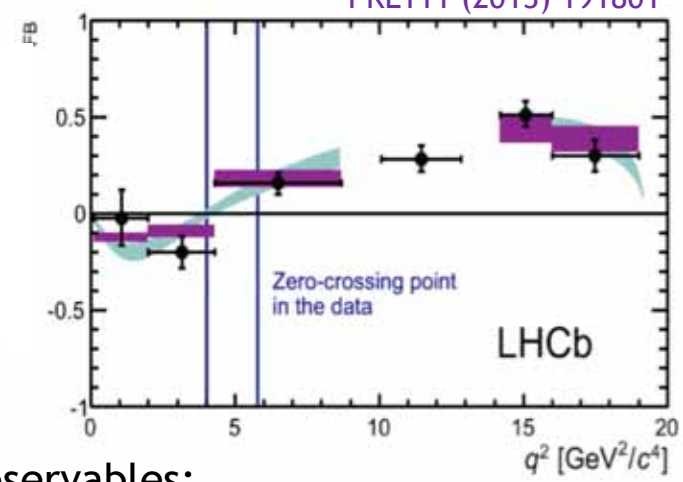
The B to K*ll Decay to Probe New Physics

Traditional observables: excellent agreement with SM predictions

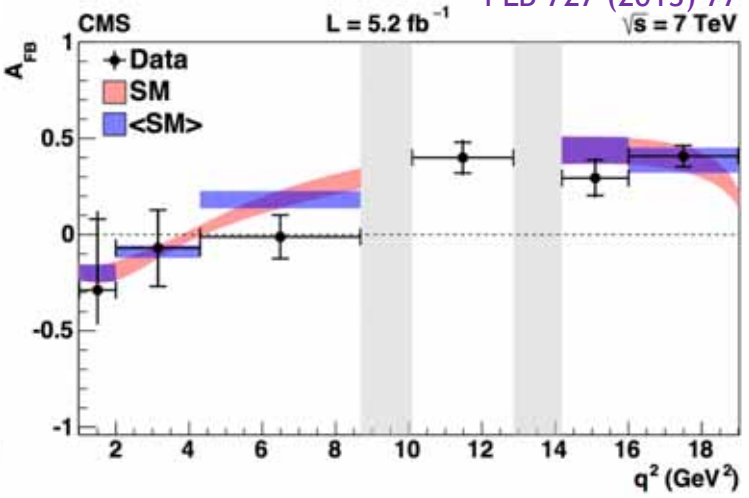
measurement of the AFB zero-crossing point



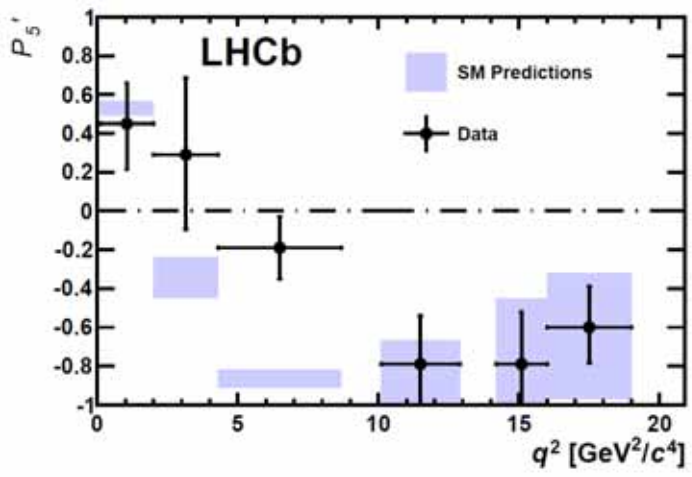
PRL111 (2013) 191801



PLB 727 (2013) 77



Four new angular observables:

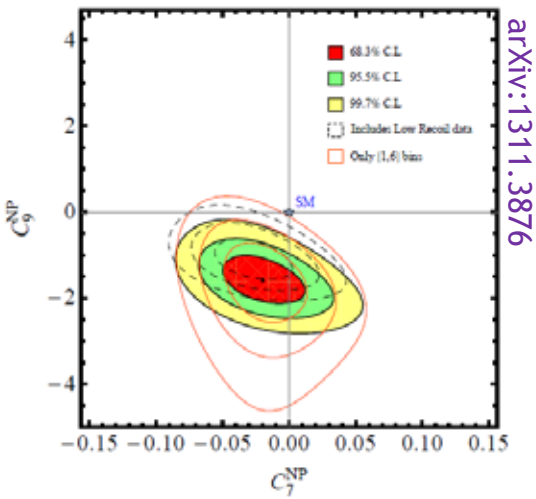


Agreement with SM for 23 out of 24 measurements

Local discrepancy: 3.7σ

Suggests smaller than expected C_9 Wilson coefficient

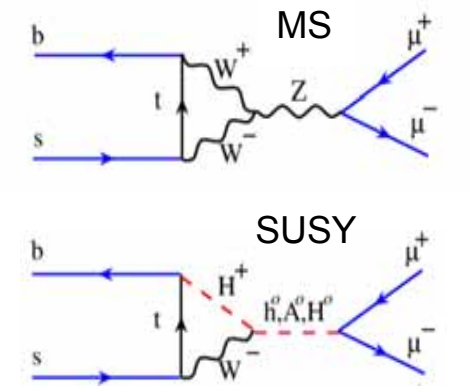
complications with form factors, charm quark loops, scales, etc.



arXiv:1311.3876

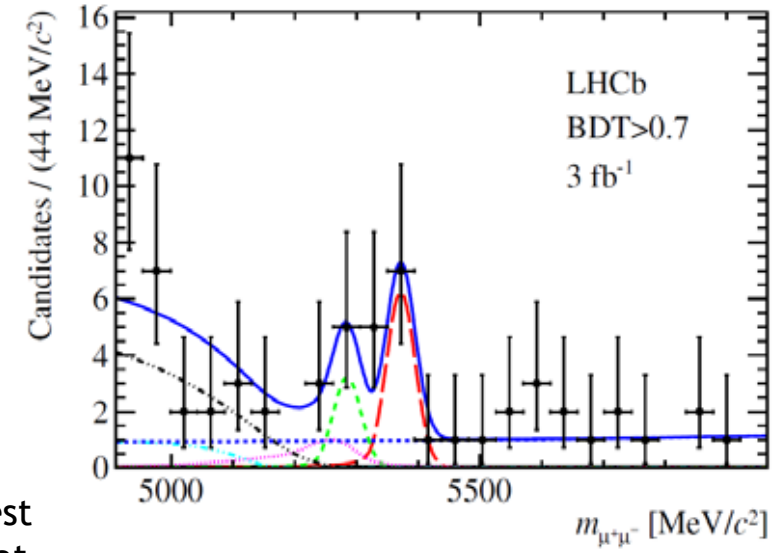
Observation of B_s to mumu

This decay is GIM, CKM and helicity suppressed in the MS

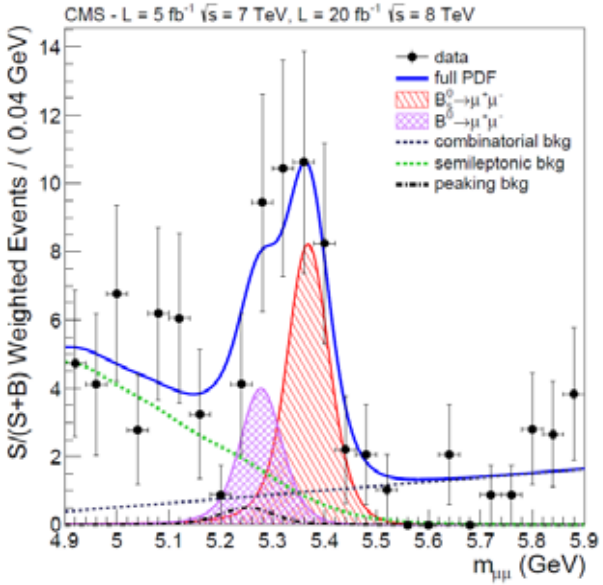


Large sensitivity to the exchange of NP charged and neutral scalars

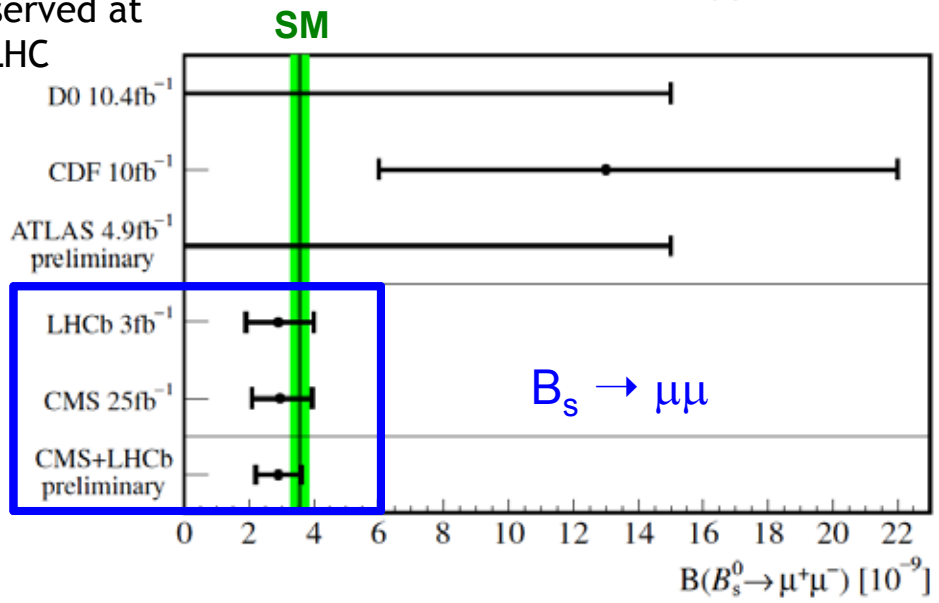
PRL 111 (2013) 101805



PRL 111 (2013) 101804

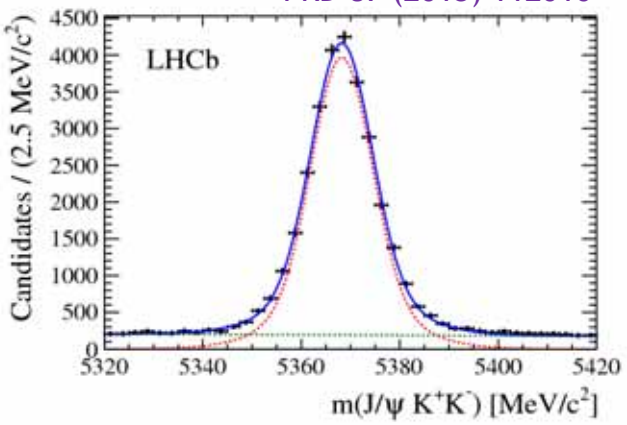


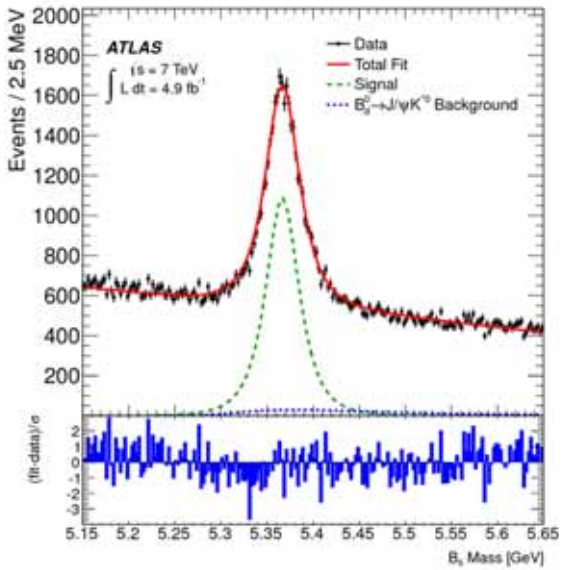
One of the smallest signals observed at the LHC



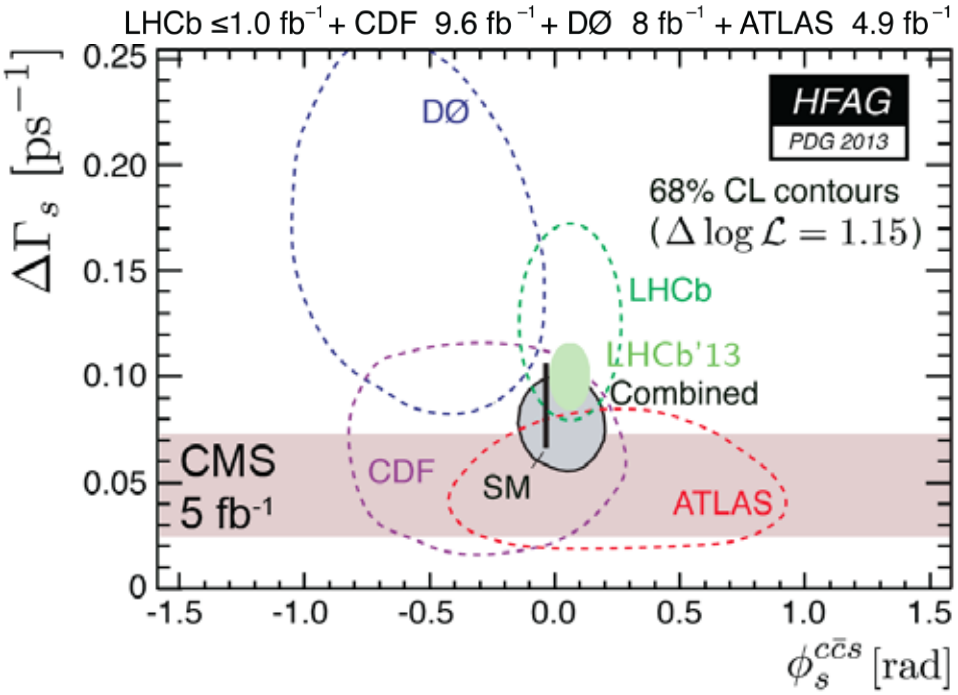
CP Violation in the B_s to J/ψϕ Decay

PRD 87 (2013) 112010





JHEP 1212 (2012) 072



The Unitarity Triangle in the Bs system provides test of BSM physics owing to precise prediction of (tiny) *CP* phase

Most precise measurement from LHCb

The **non-zero decay width difference** between Bs mass eigenstates is established at around 9%

The indication of large CP violation from the Tevatron is not confirmed

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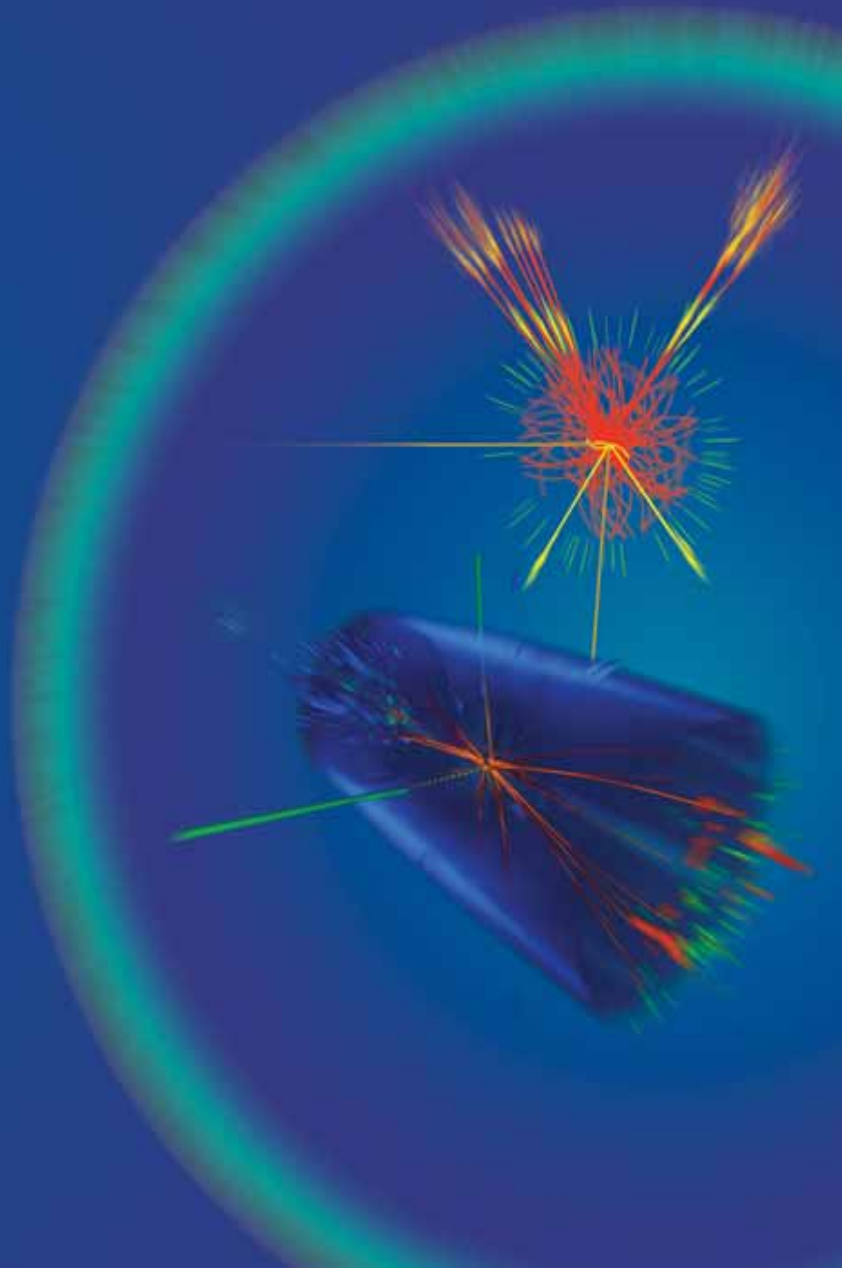
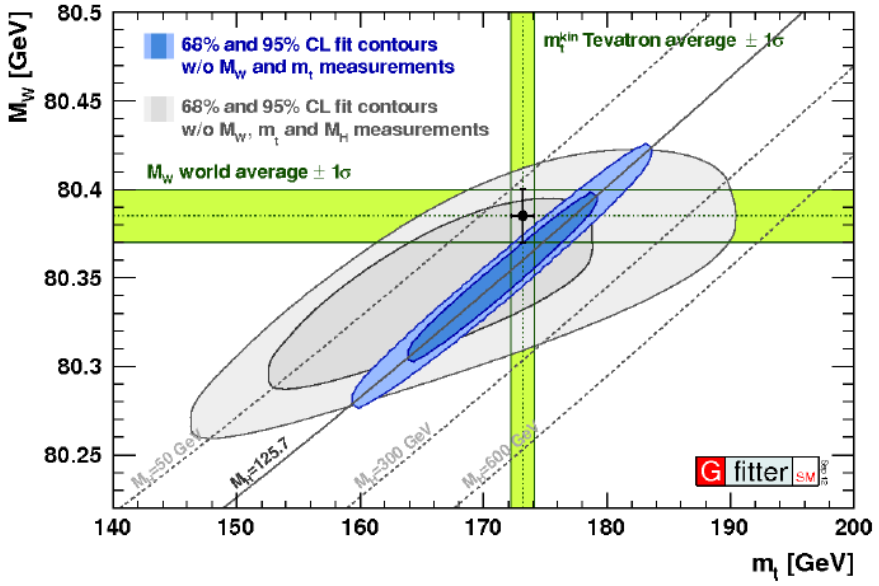


Why Look for New Physics ?

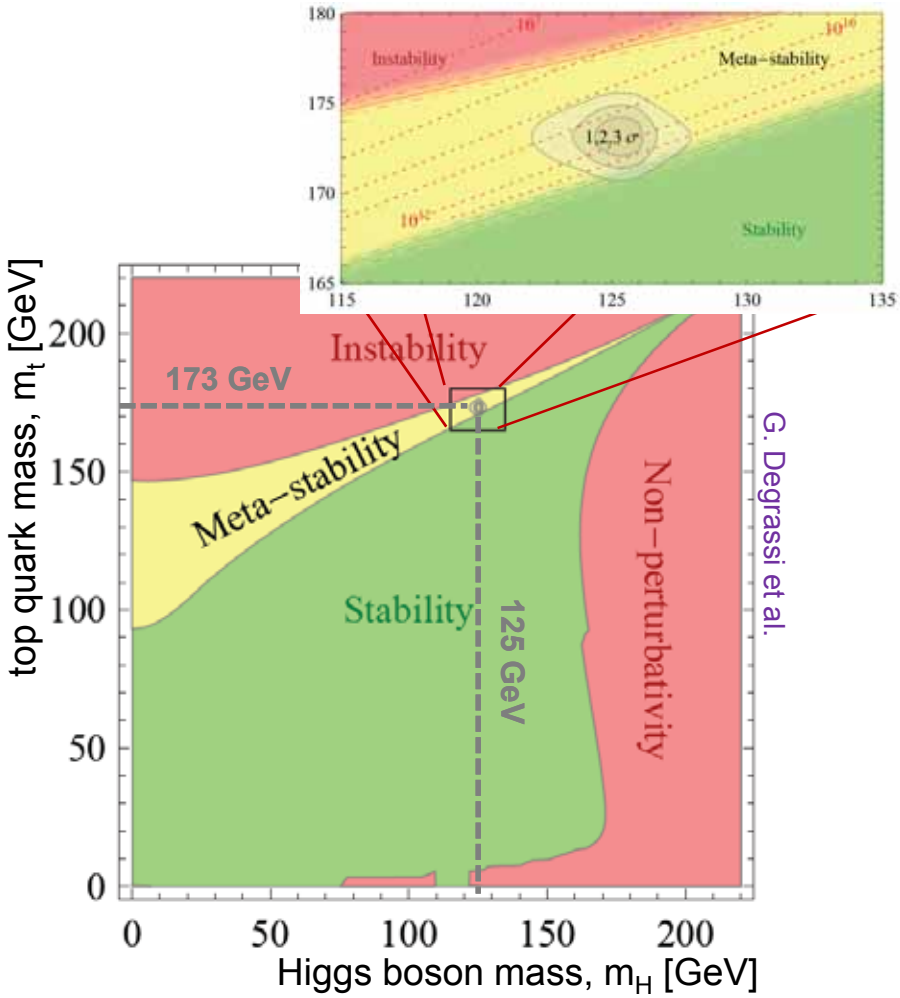
Success of the Electroweak Theory



The Standard Model cannot be the final theory

- **Hierarchy and Naturalness**
  Relative strength of the gravitation and EM?
  Some symmetry must "protect" the mass of the Higgs boson against growth due to quantum corrections
- **Metastability of the EW vacuum**
- **Unification of fundamental forces** (GUT)
- **Dark Matter!**
- **Neutrino masses?**
- **Gravitation, dark energy**

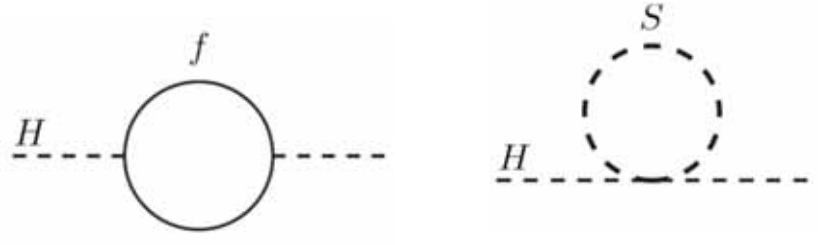
Stability of the EW vacuum up to extremely high energy scales



Super-Symmetry

Supersymmetry (SUSY) is a family of weakly-coupled theories that give solutions to the Naturalness problem, realize unification at the GUT scale and, in certain cases, provide candidates of Dark Matter

fundamental space-time symmetry between fermions and bosons that regularizes the Higgs boson mass

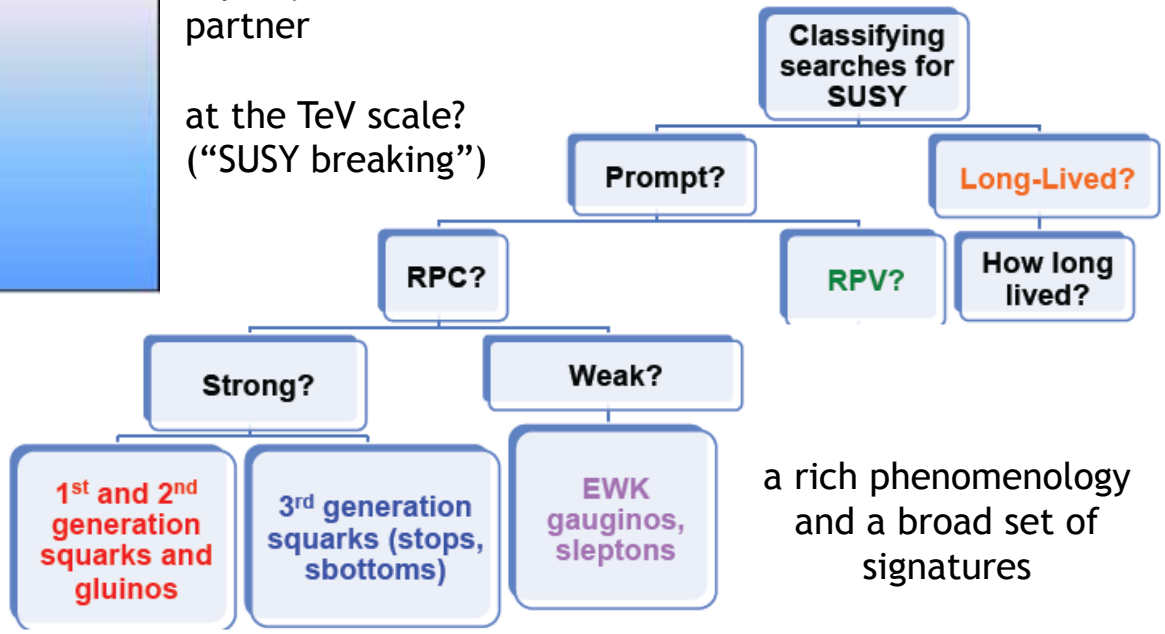


Spin 0	Spin 1/2	Spin 1	Spin 3/2	Spin 2
sleptons	leptons		gravitino	graviton
squarks	quarks			
Higgs	Higgsino			
	photino	photon		
	Zino	Z		
	Winos	W+ W-		
	gluinos	gluons		

Each SM particle has a supersymmetric partner

at the TeV scale? ("SUSY breaking")

Search for SUSY partners



a rich phenomenology and a broad set of signatures

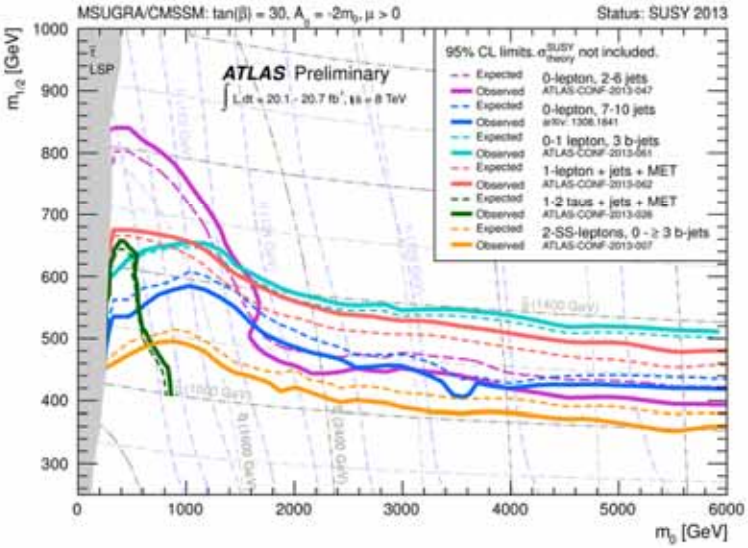
And an extended Higgs sector

For instance in 2HDM like MSSM

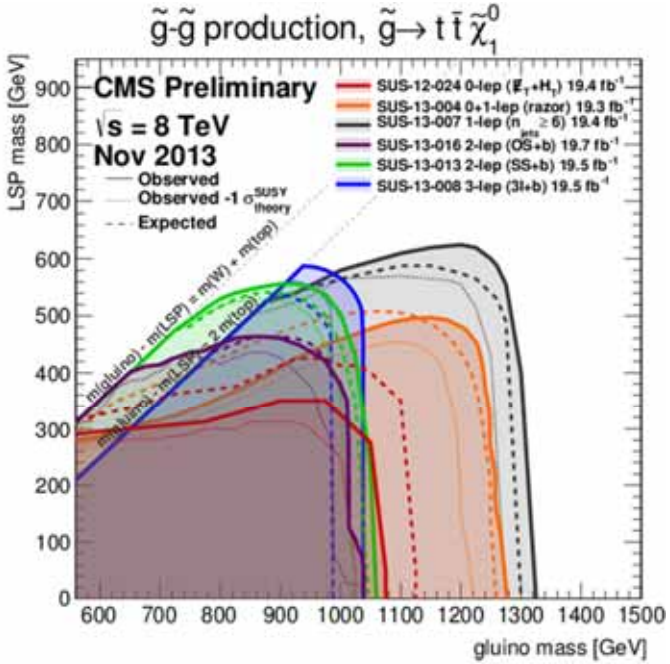
- CP-even: h and H
- CP-odd: A
- Charged: H+ and H-

Squarks, Gluinos, Charginos, Neutralinos

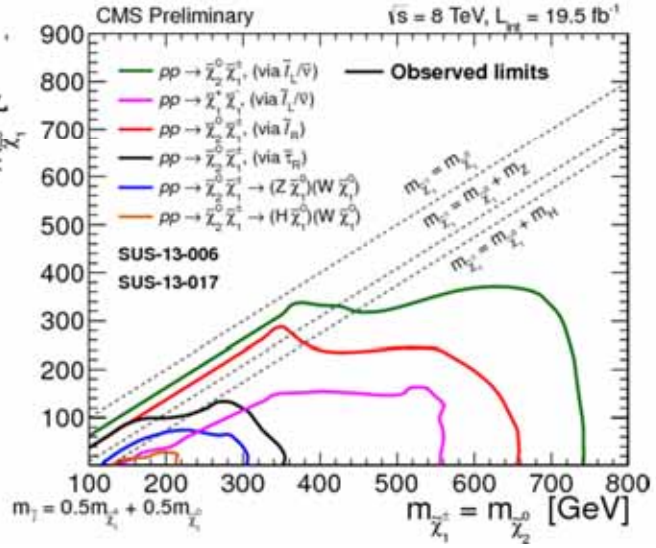
Search for strong production of SUSY in multi-jet events with large MET



Search for gluino 3-body decay top anti-top neutralino

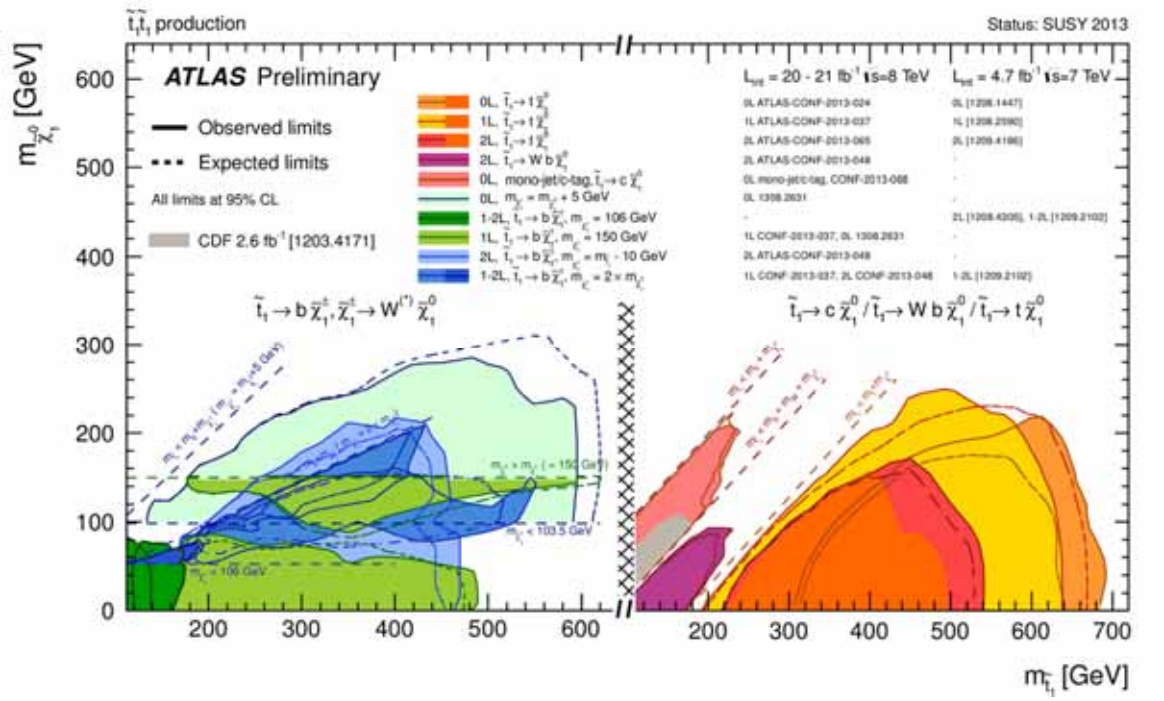


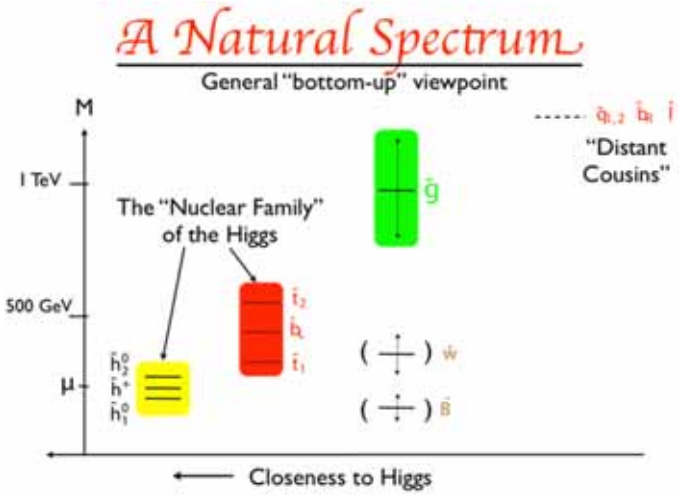
Search for direct electroweak production of SUSY particles in multileptons events

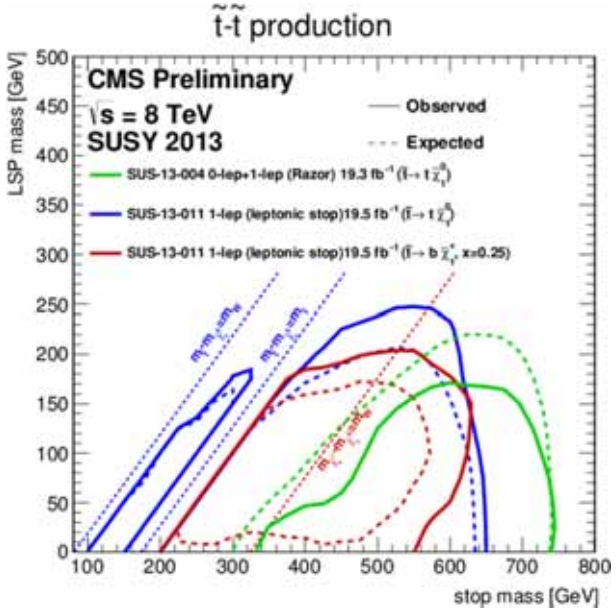


Search for the Lightest Top Squark

Natural SUSY:
the top squark (or stop) superpartner of the top quark is expected to be not too much heavier than the top quark

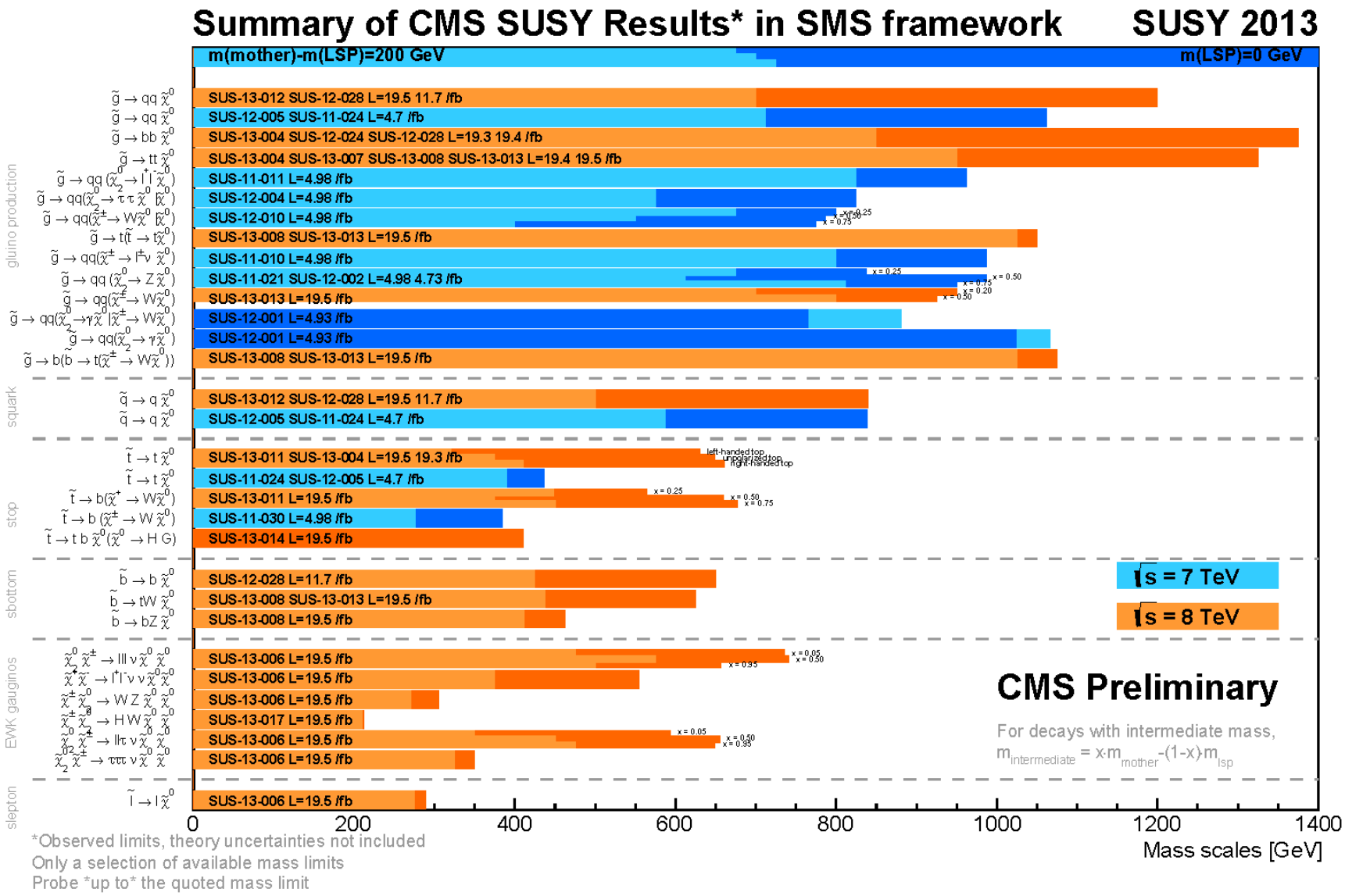






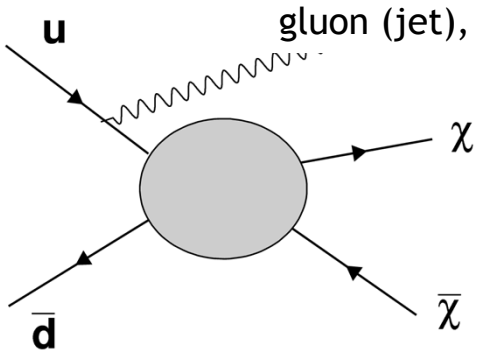
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Summary of SUSY Analyses in CMS



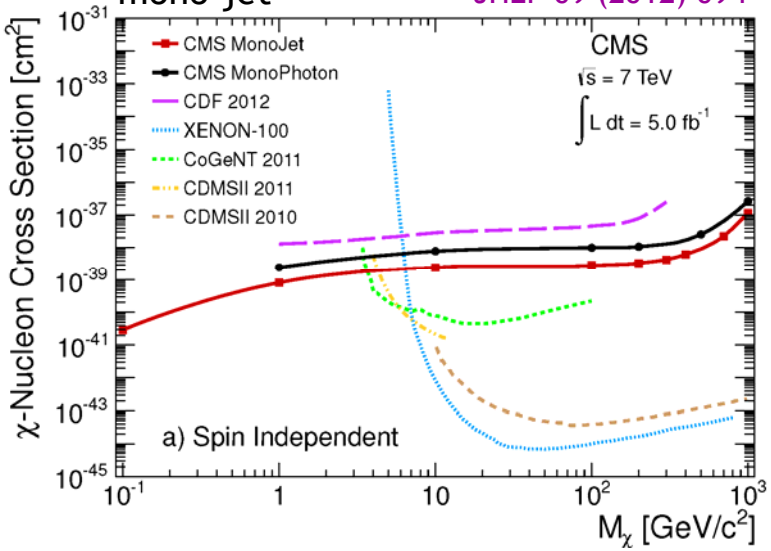
Search for Dark Matter

Exploit initial state radiation (ISR)

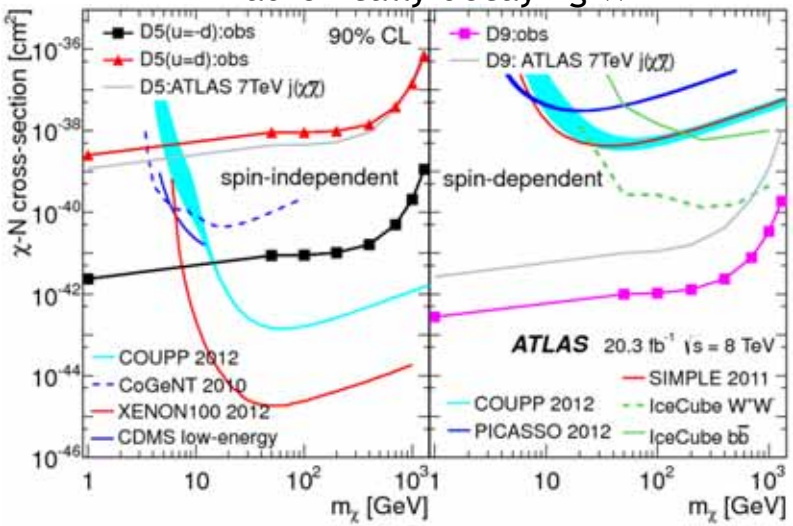


Search for events with one energetic (jet/photon/W) and an imbalance in transverse momentum

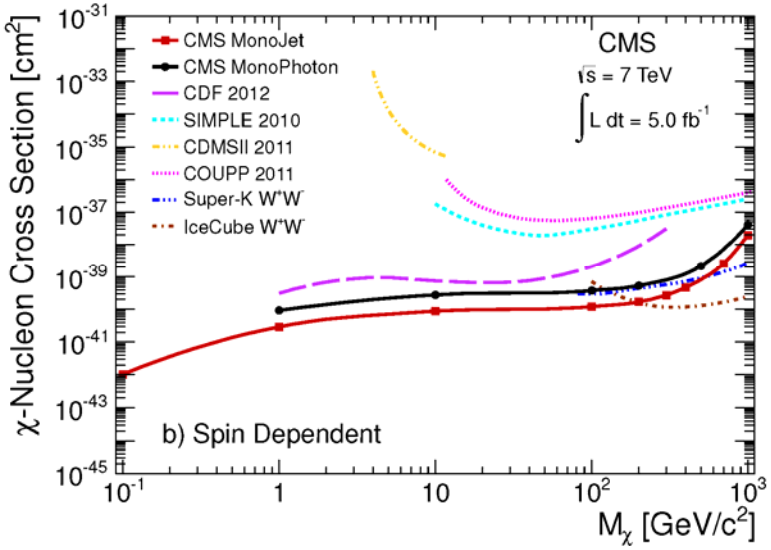
mono-jet JHEP 09 (2012) 094



hadronically decaying W



aXiv:1309.4017 (sub. to PRL)



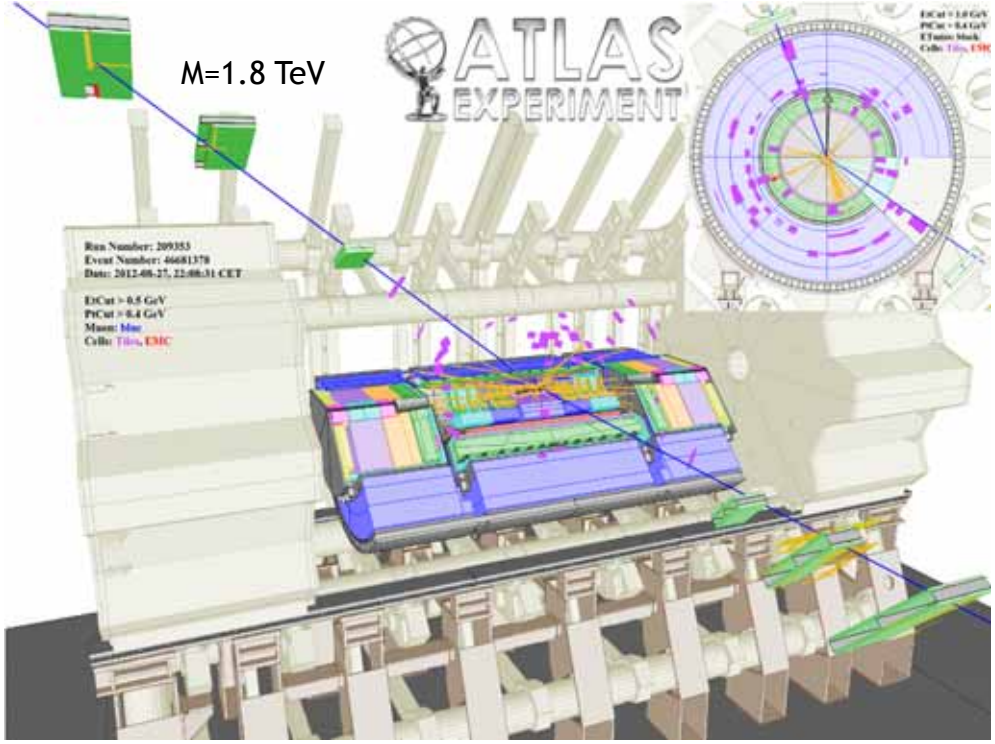
see talk by M.Tripathi

Search for Heavy Resonances

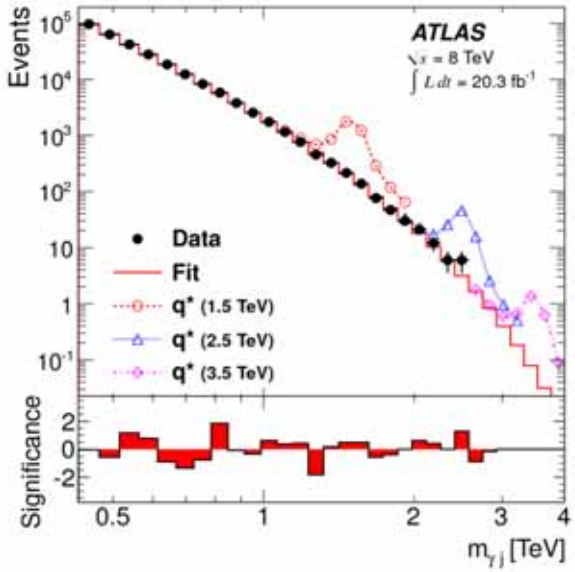
Explore the TeV scale

Signatures
- jet-jet, jet-γ, jet-MET
- ee, μμ, eν, μν, ττ
- γγ, WW, WZ
- t-tbar, td, tb
- etc.

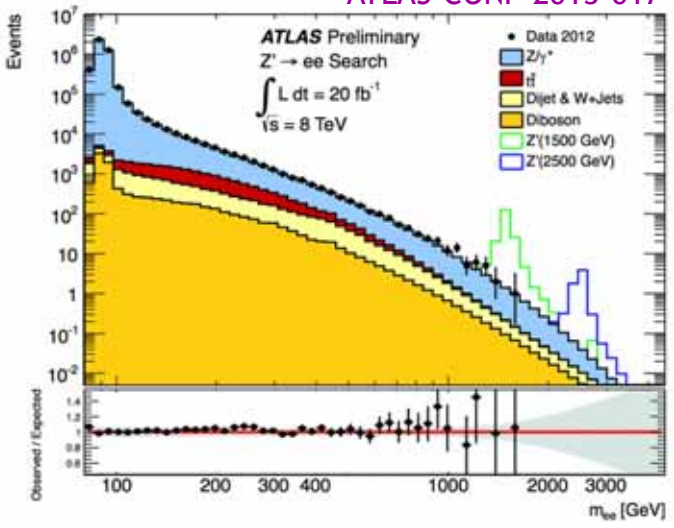
Interpretation:
- new gauge bosons
- excited quarks
- Kaluza-Klein excitations
- etc.



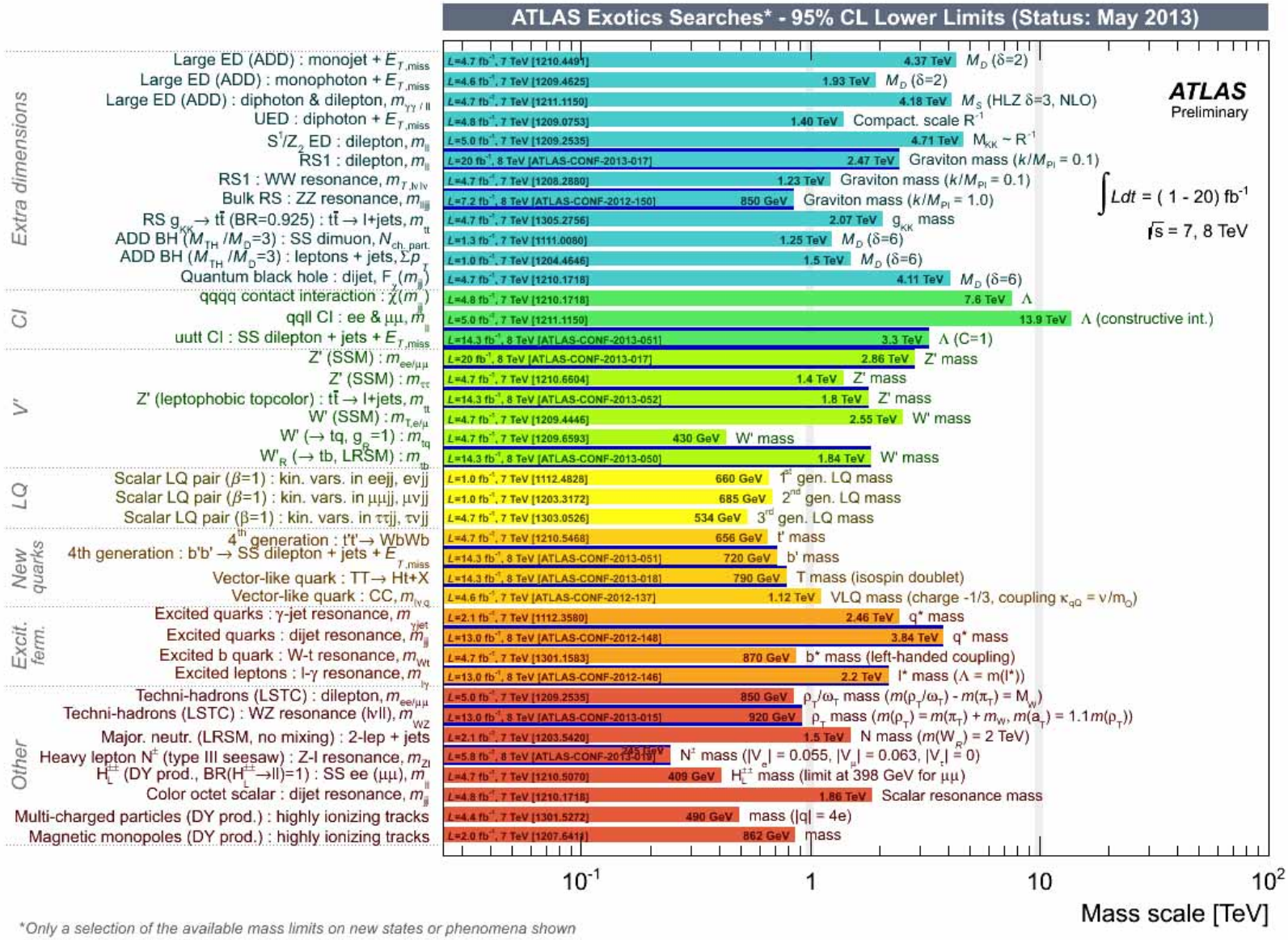
ATLAS-CONF-2013-059



ATLAS-CONF-2013-017



Summary of BSM Analyses in ATLAS

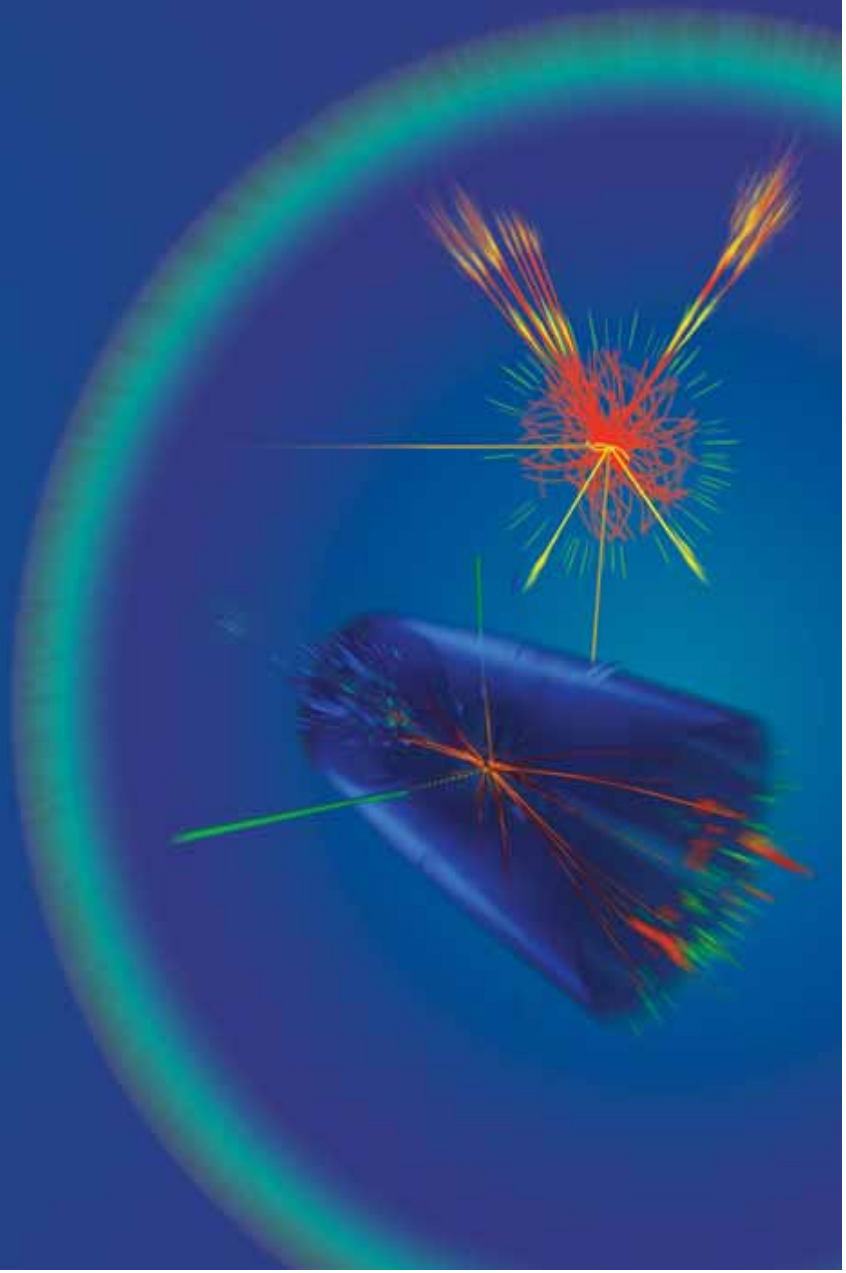


*Only a selection of the available mass limits on new states or phenomena shown

Outline

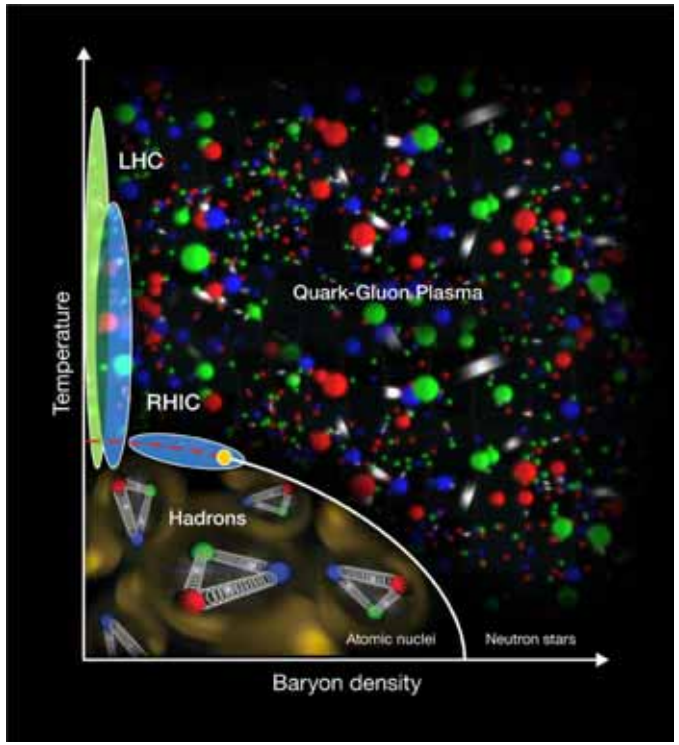
- Standard Model Physics
- Higgs Boson Physics
- B Physics and CP Violation
- Supersymmetry and Exotica
- Hot QCD Matter

- What Next?



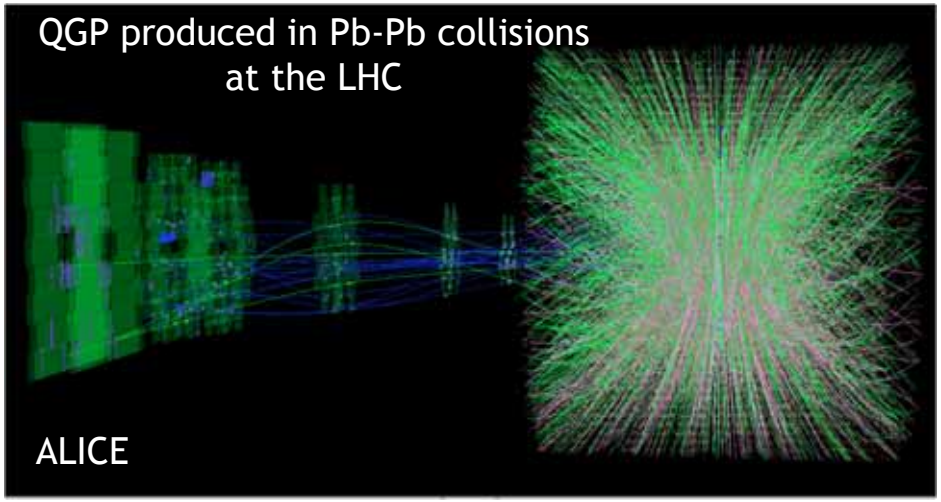
The Quark Gluon Plasma

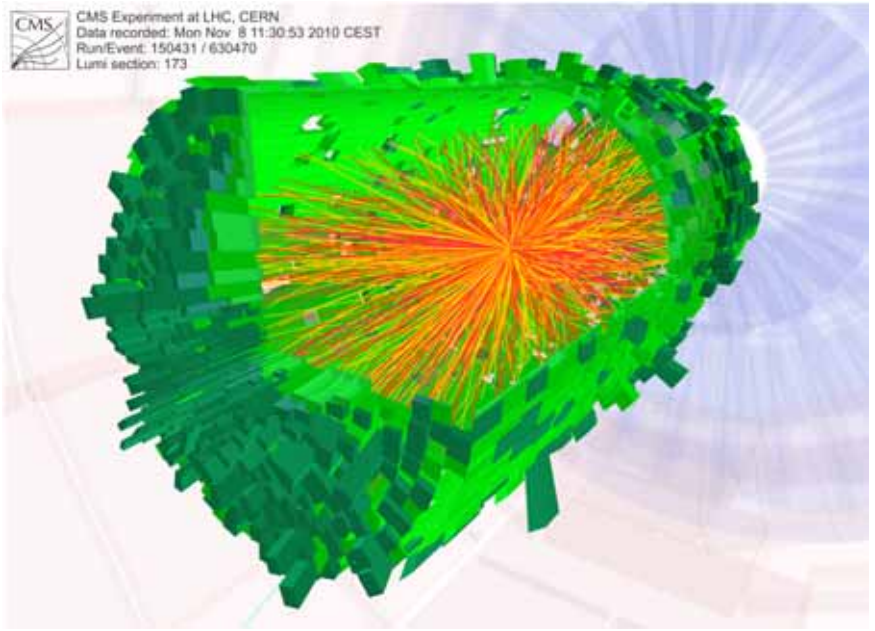
Quark-Gluon Plasma (QGP) :
New state of nuclear matter – deconfined –



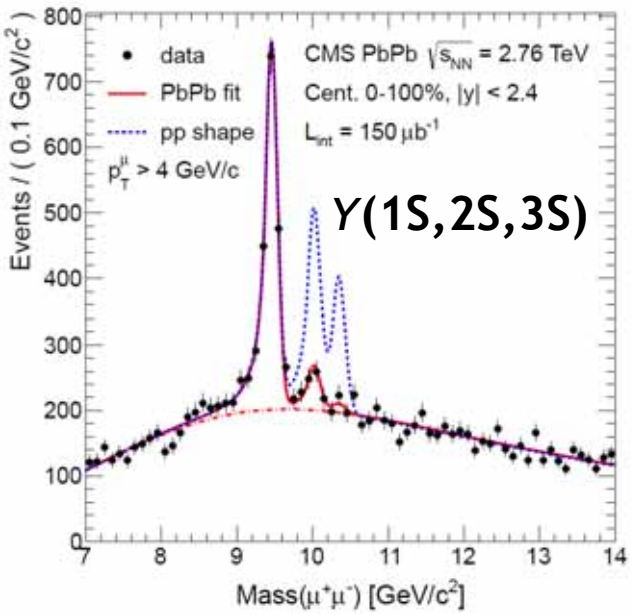
Heating / Compression

$T > T_c \sim 170$ MeV
$\varepsilon > \varepsilon_c \sim 0.7$–$1$ GeV/fm^3

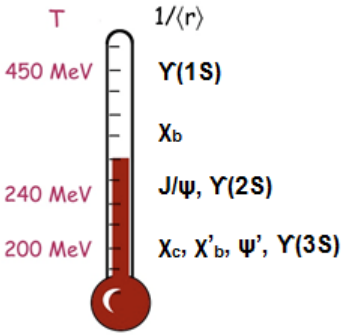




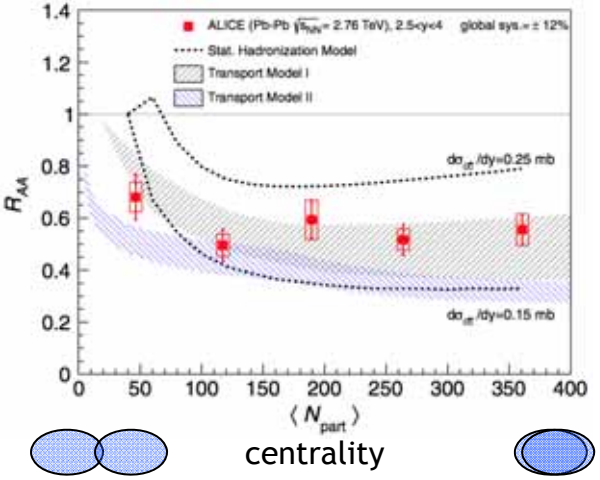
Probing the QGP



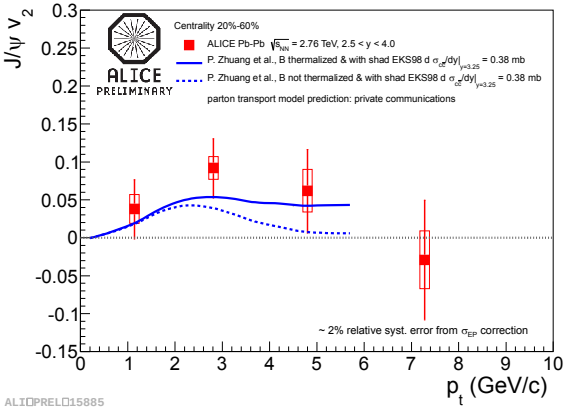
The sequential suppression of quarkonia by color screening depends on the QGP temperature



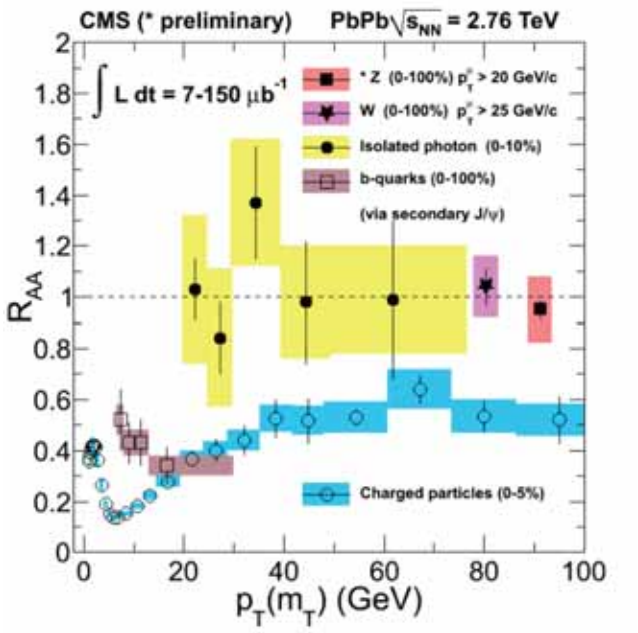
R_{AA} : production ratio Pb-Pb versus p-p



centrality



anisotropy w.r.t. reaction plane



R_{AA} smaller for strongly interacting probes

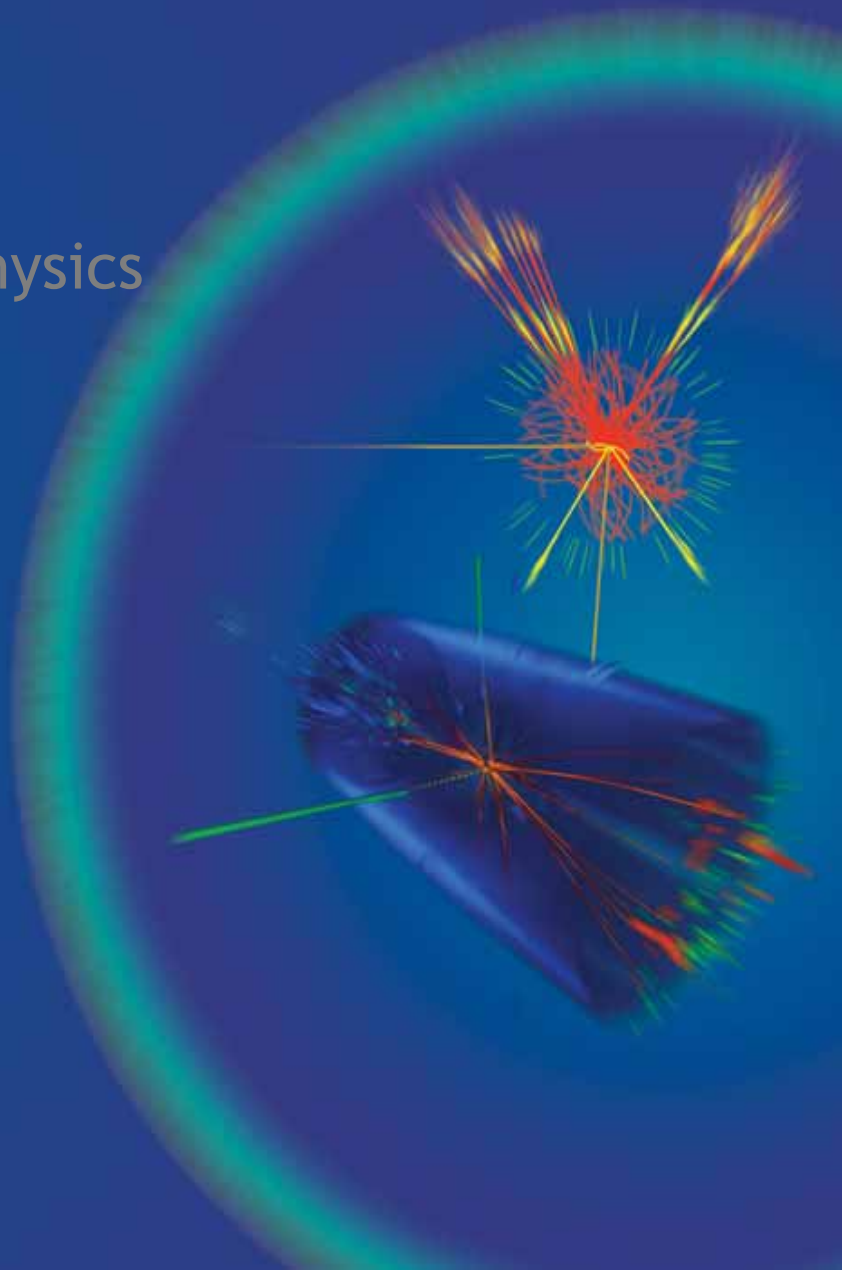
Electroweak probes

- do not seem to see the dense medium
- independently of centrality
- can be used to determined initial jet energy

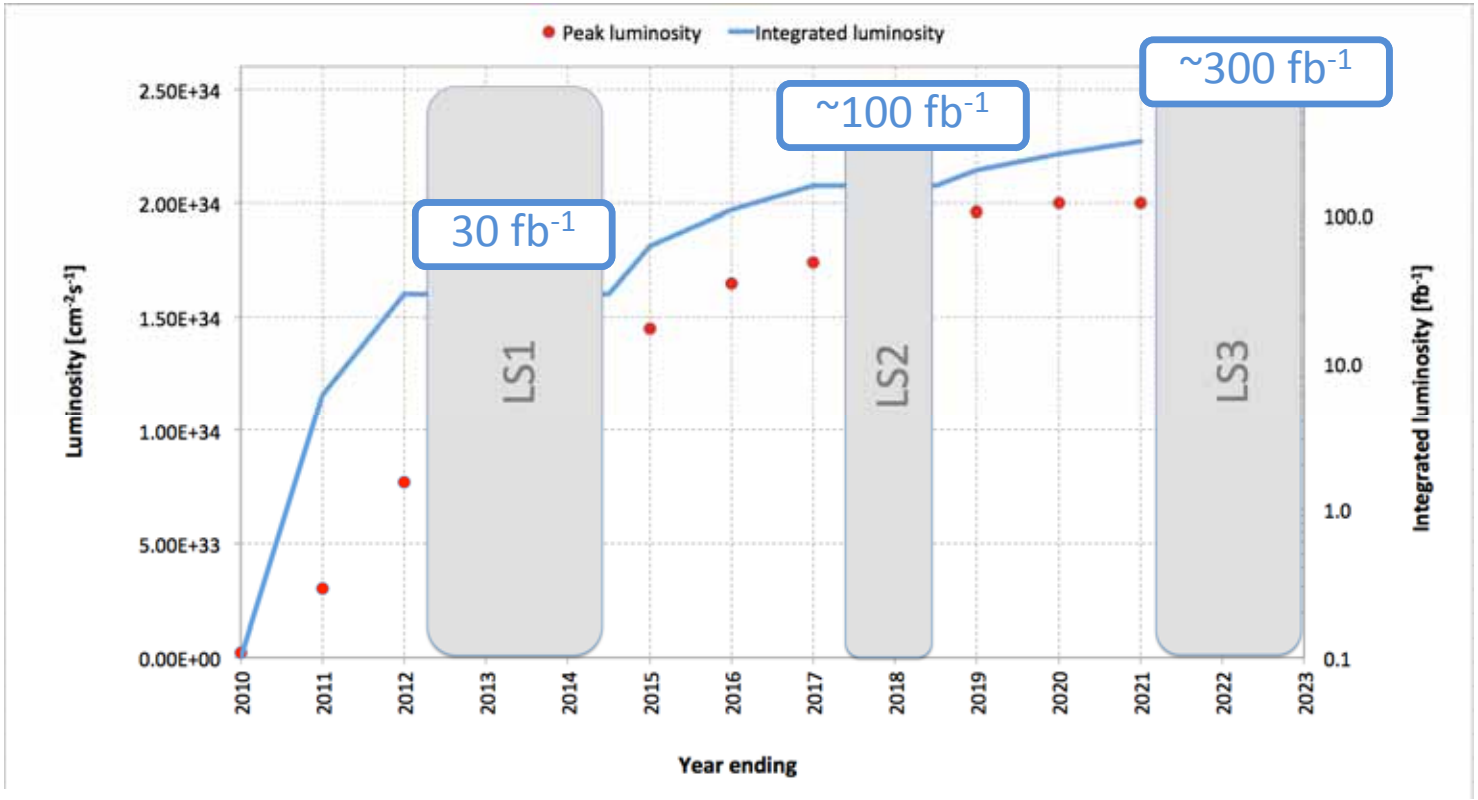
Outline

- Electroweak and Top Quark Physics
- Higgs Boson Physics
- B Physics and CP Violation
- Supersymmetry and Exotica

- What Next?



The LHC in the Next Ten Years



LS1 (2013-2014)
Shutdown to repear interconnections and prepare the 13 TeV energy run

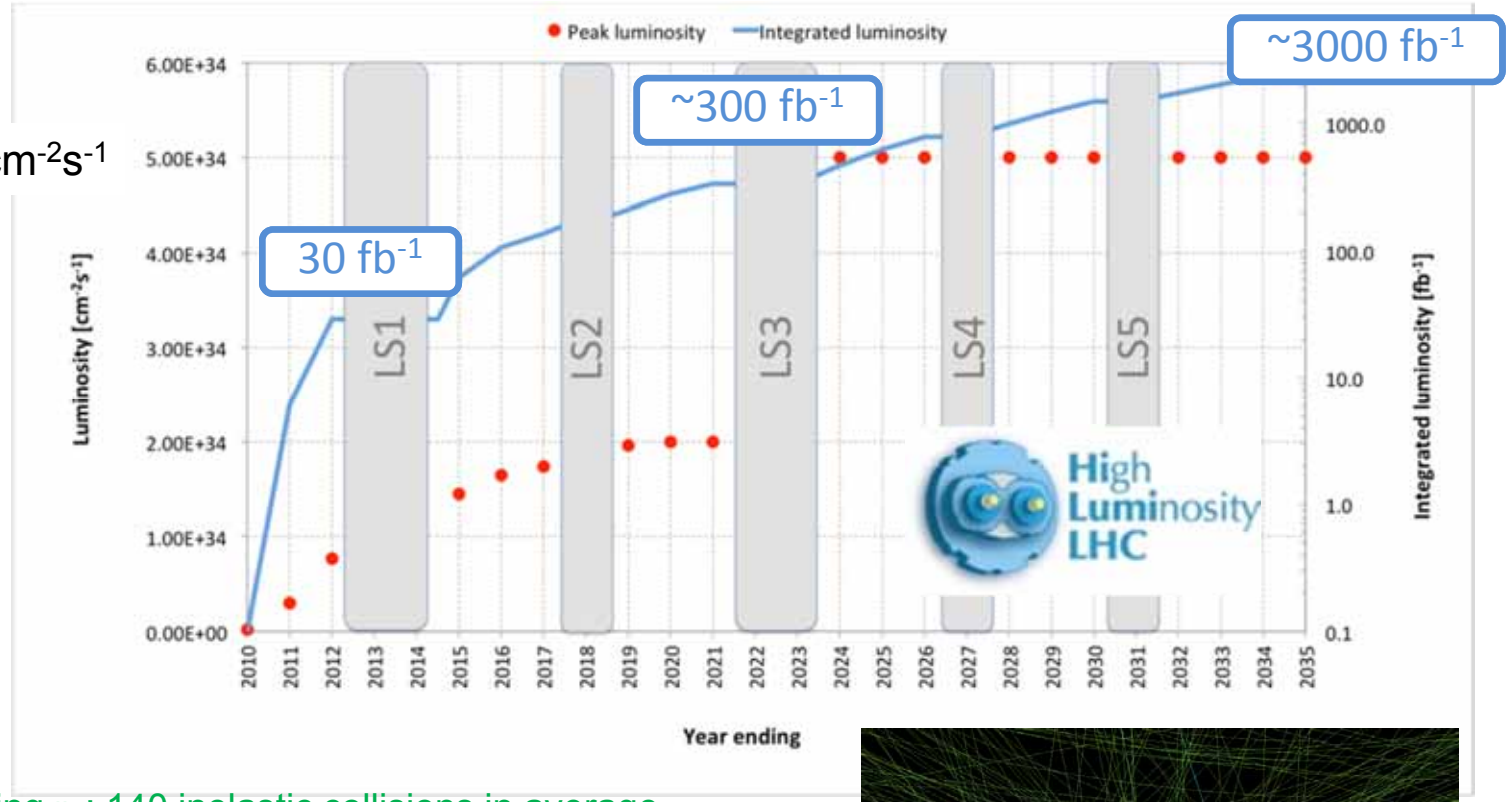
LS2 (2018)
Shutdown to prepare the luminosity improvement to 2×10^{34} $cm^{-2}s^{-1}$

LS3 (2022-2023)
with LS3 improvement and consolidations, the goal is to reach 3000 fb^{-1} in ten years

Problem : around 2022, some magnets of the machine, most exposed to radiation (triplets), will have to be replaced

High luminosity LHC (phase-II)

5×10^{34} cm^{-2}s^{-1}



see talks by

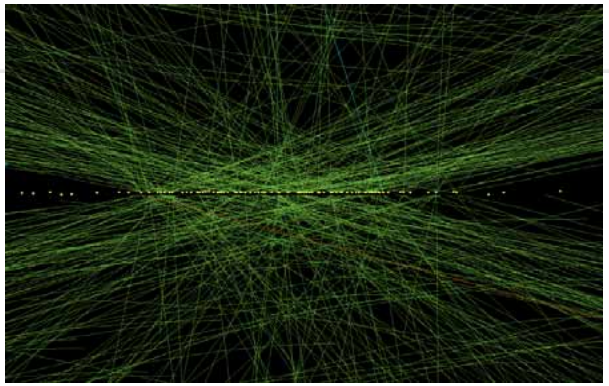
E. Todesco

D.Contardo

« Levelling » : 140 inelastic collisions in average per bunch crossing (≈ 1 vertex per mm)

3 to 4 fb^{-1} per experiment and per day

250 to 300 fb^{-1} per experiment and per year



EW Symmetry Breaking at HL-LHC

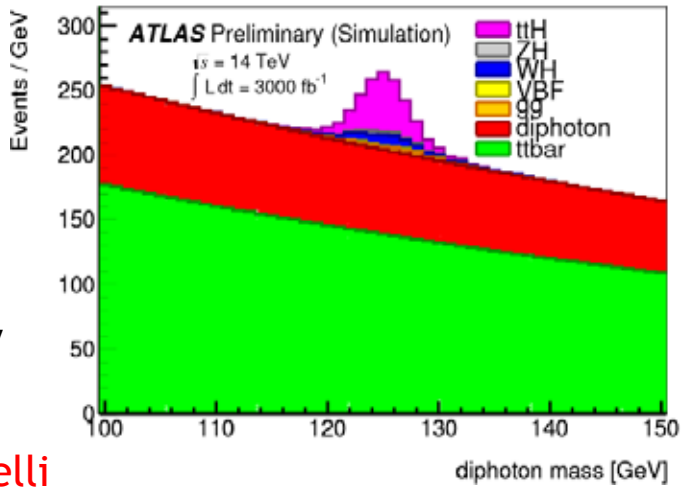
see talks by

S. Dasu

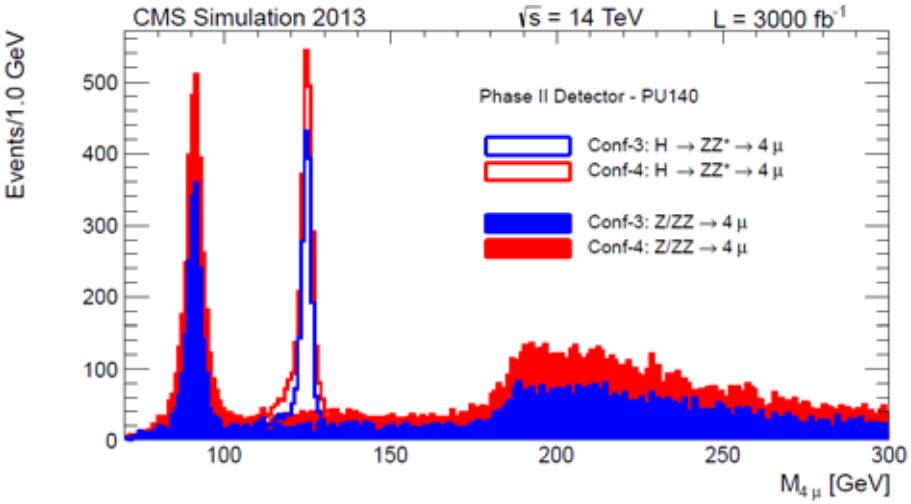
P. Giacomelli

S. Pahdi

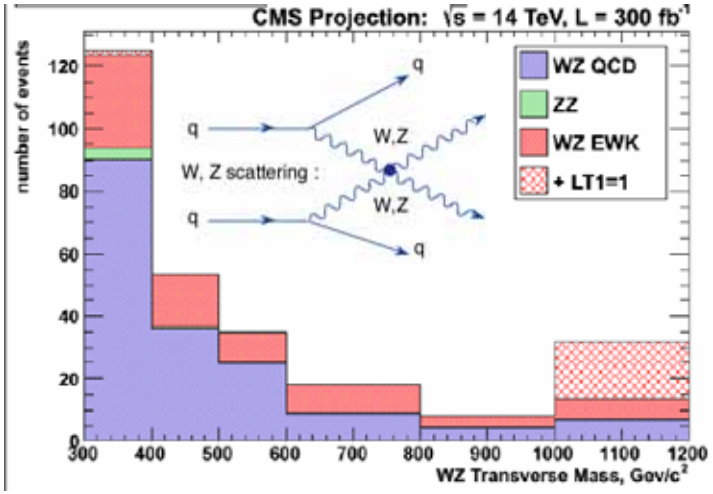
Direct coupling to the top quark



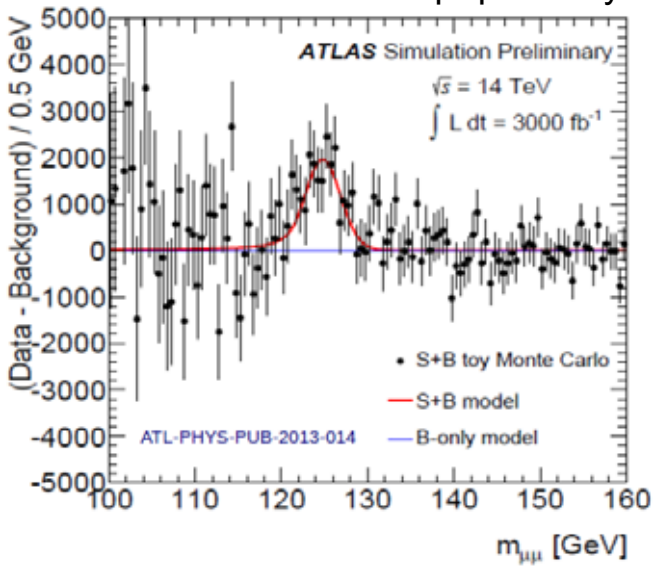
Detailed kinematics in the four lepton channel



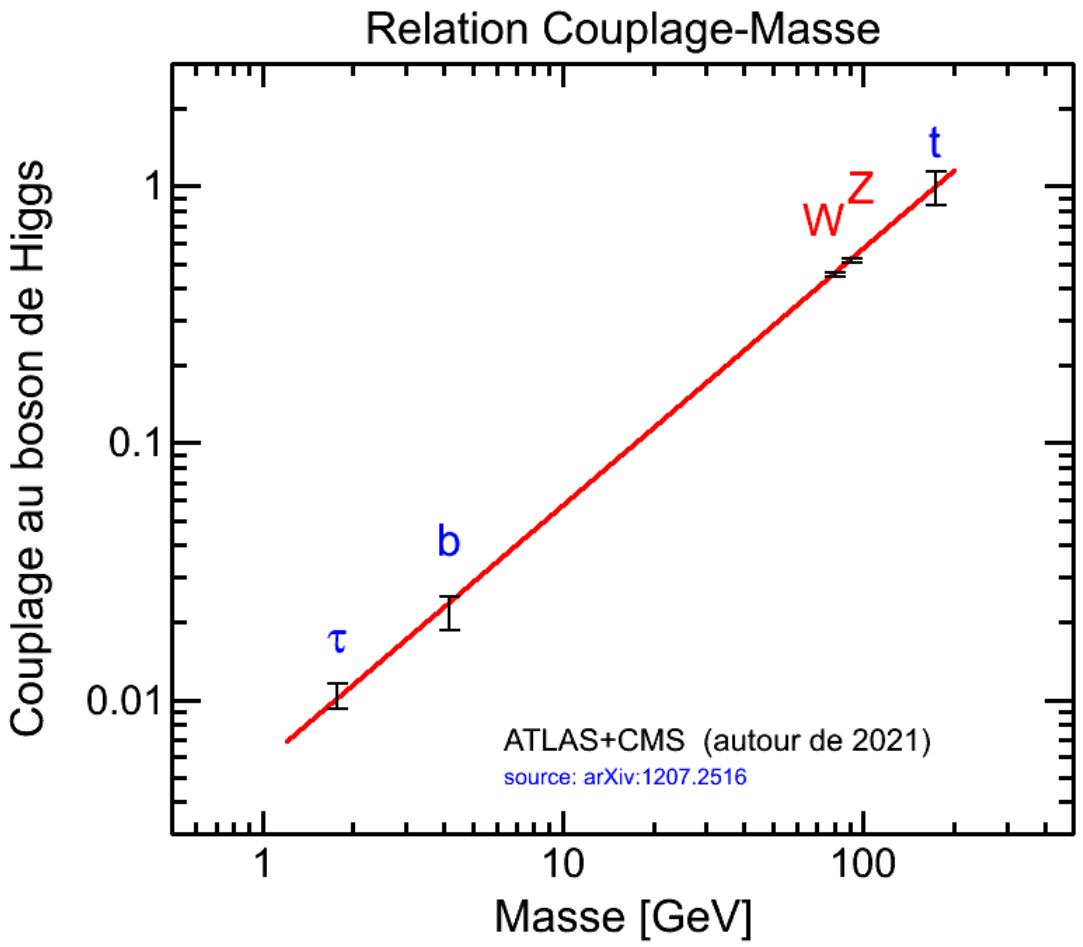
Probing the anomalous quartic gauge couplings



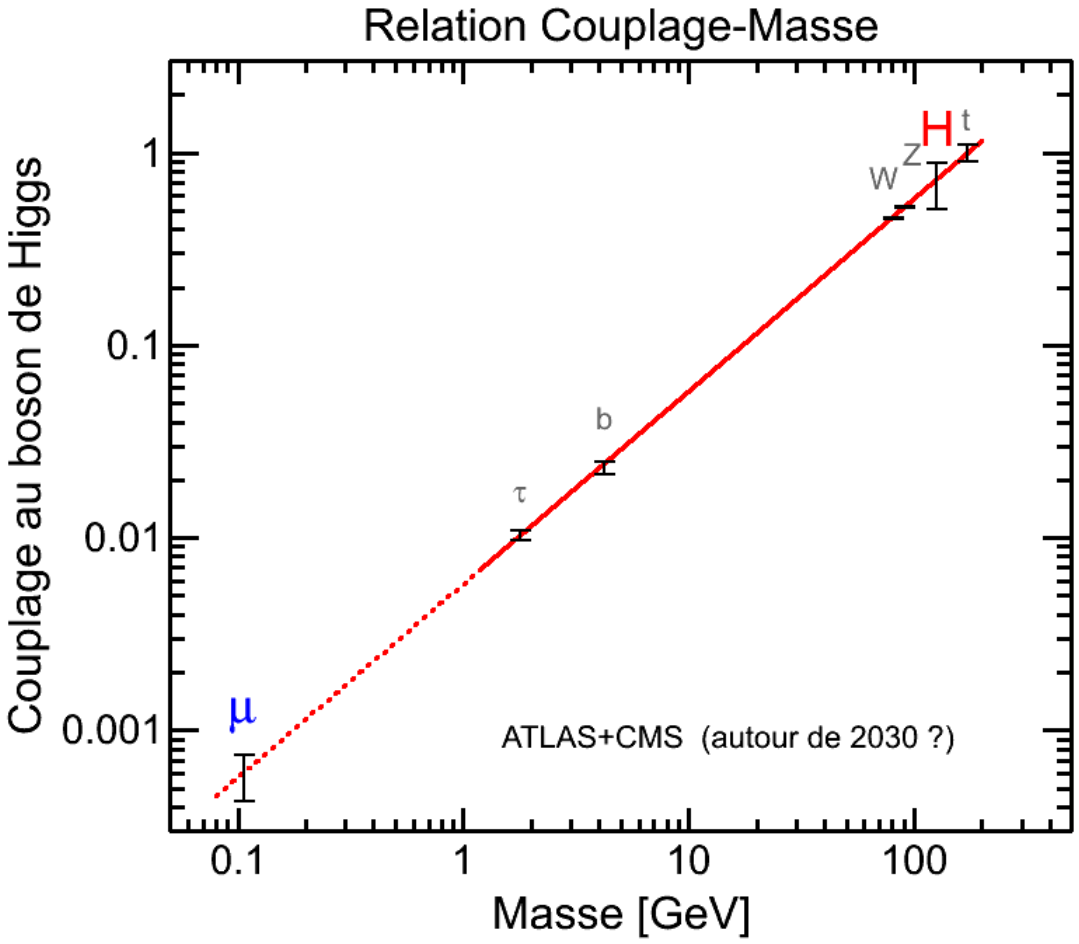
Observation of the μ+μ- decay

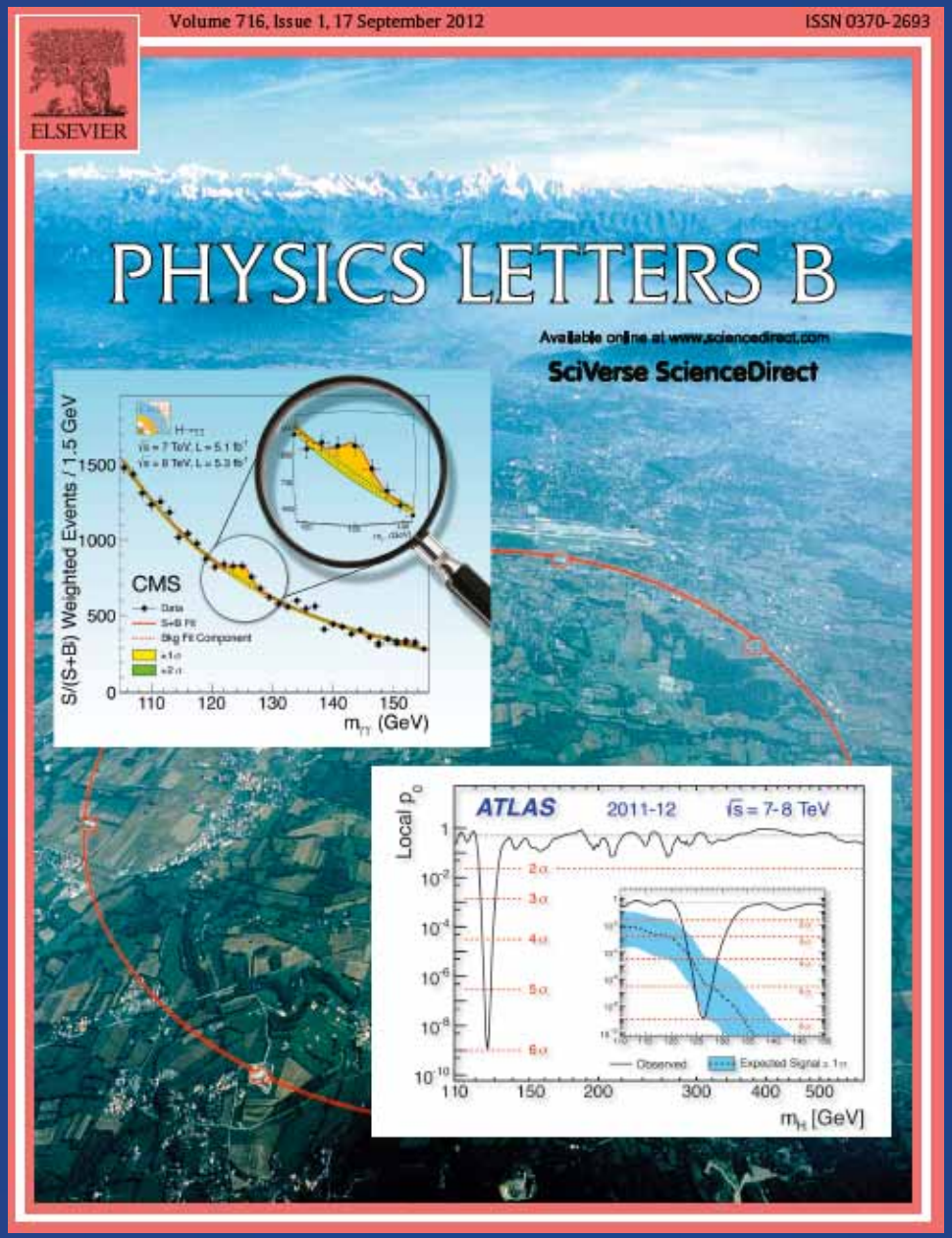


Higgs Boson Signature



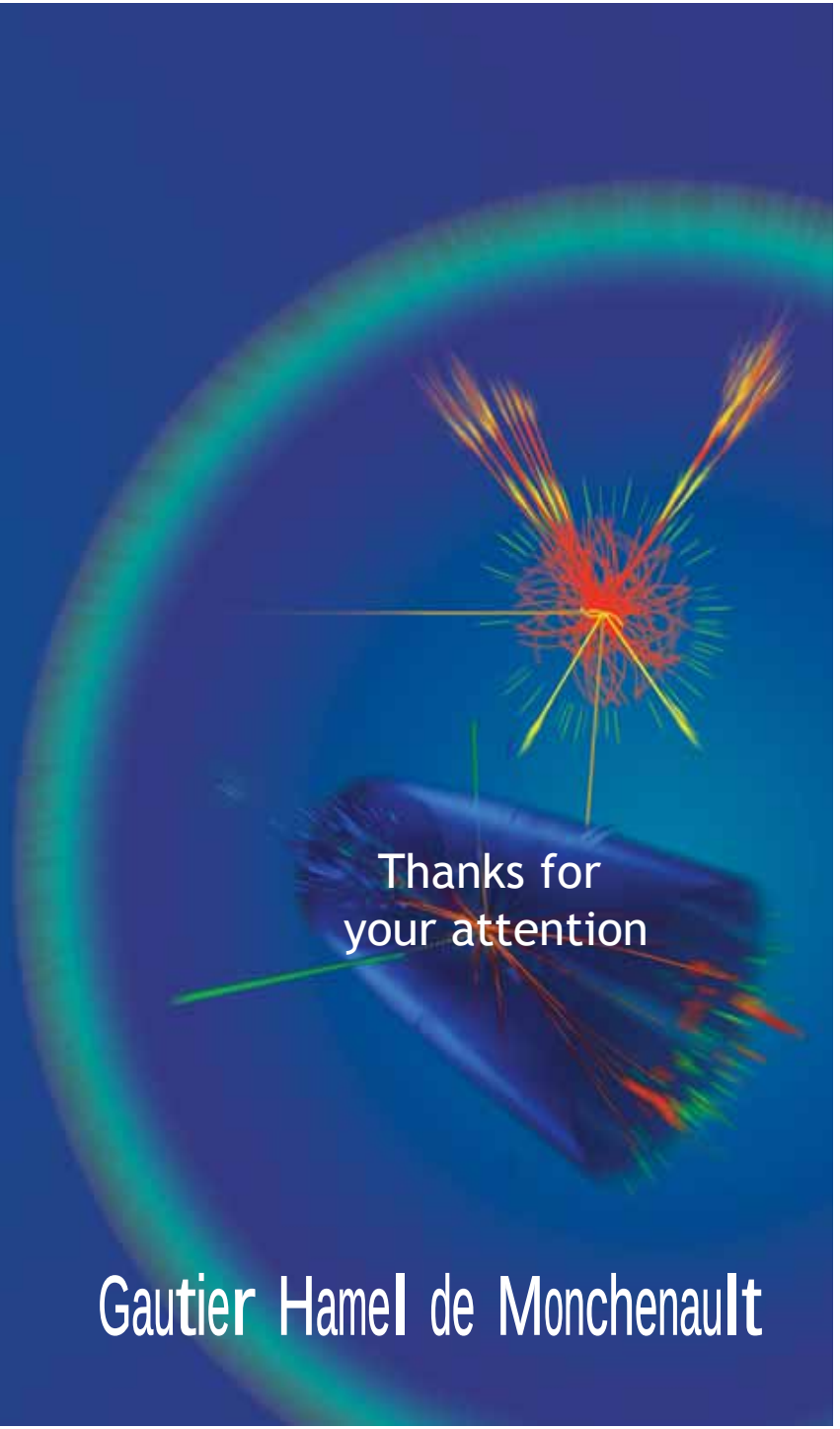
Higgs Boson Signature





Thanks for
your attention

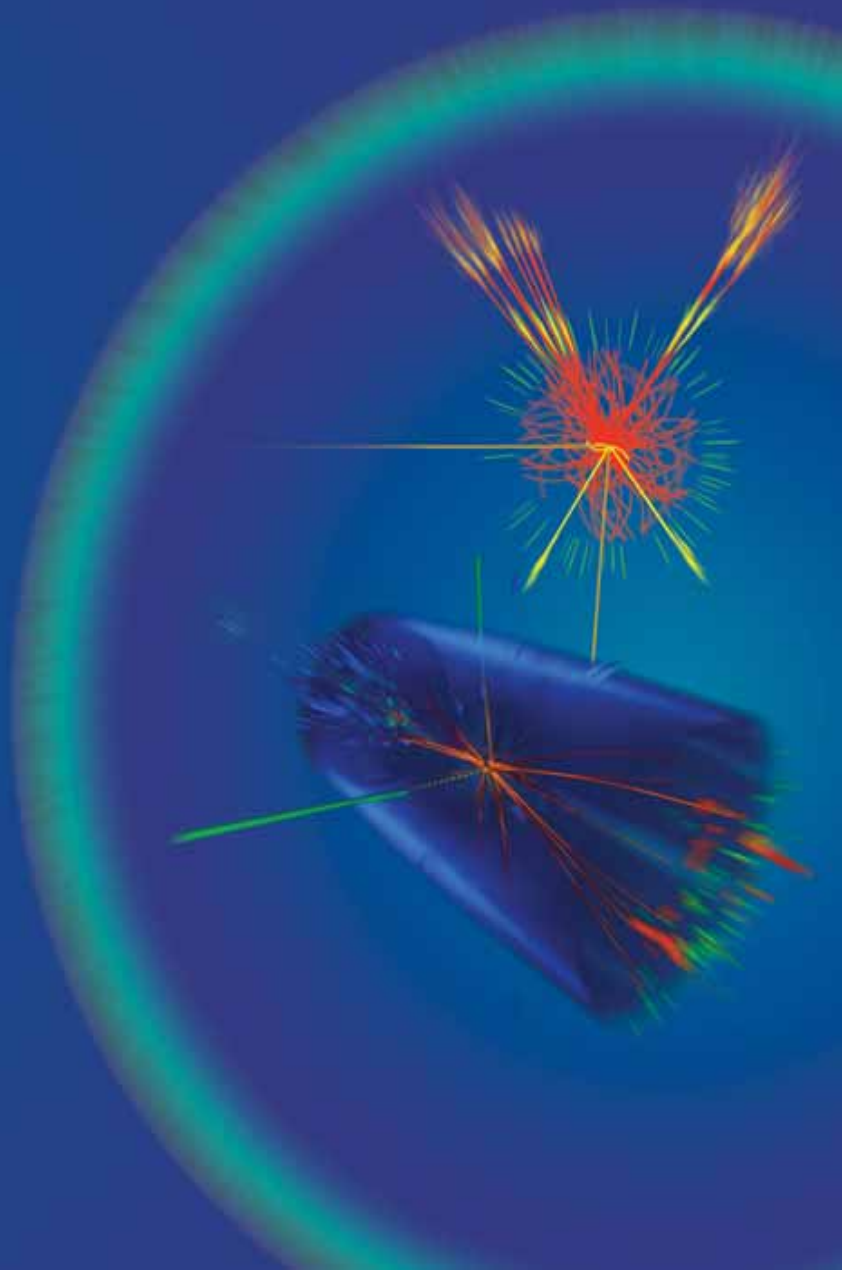
Gautier Hamel de Monchenault



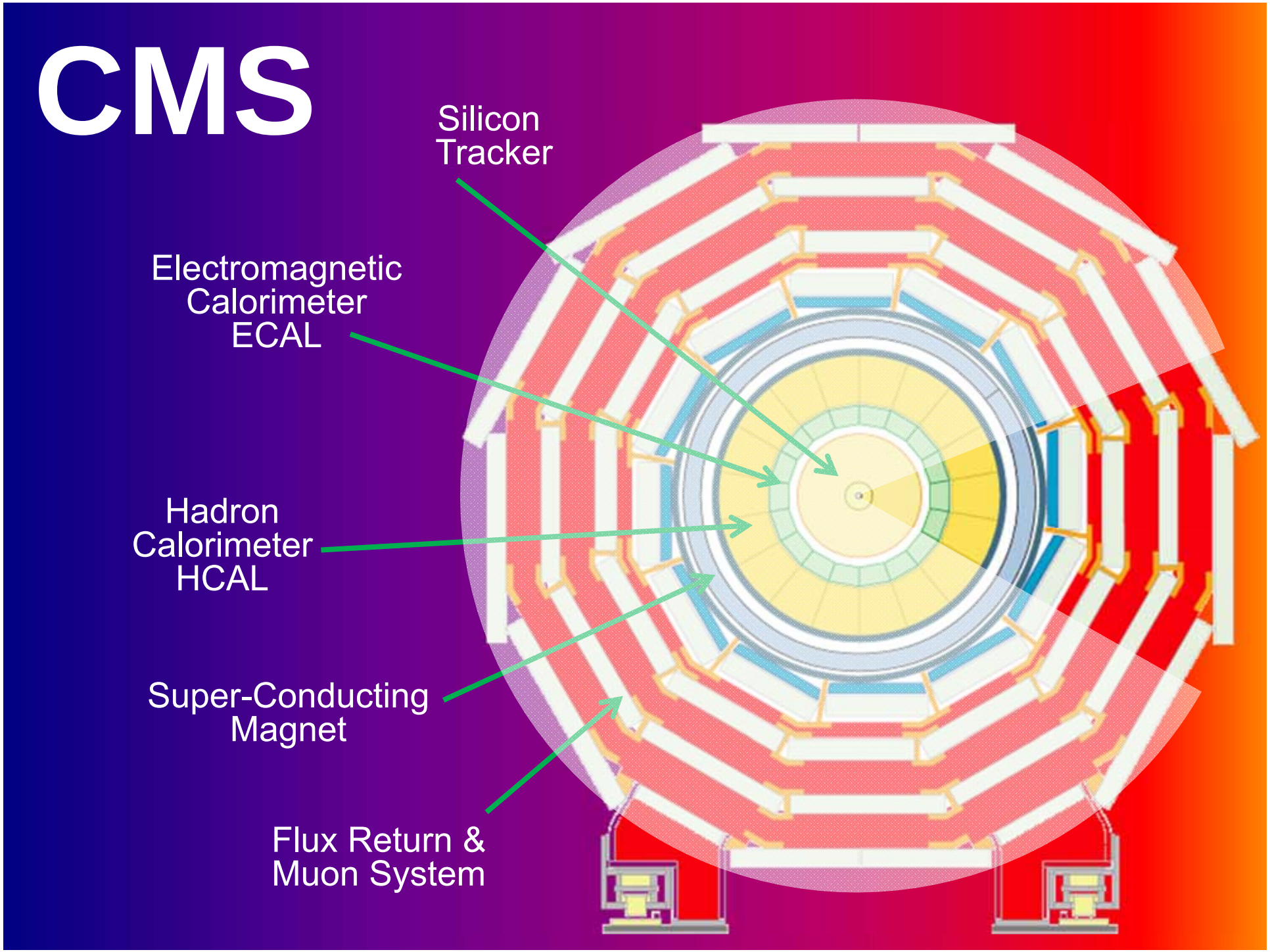
Thanks for
your attention

Gautier Hamel de Monchenault

Additional Slides



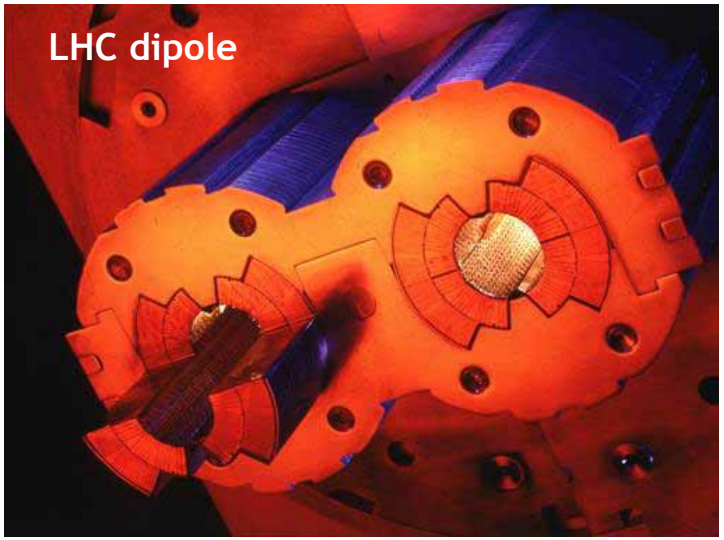
CMS


Silicon Tracker
Electromagnetic Calorimeter ECAL
Hadron Calorimeter HCAL
Super-Conducting Magnet
Flux Return & Muon System

The LHC

The LHC

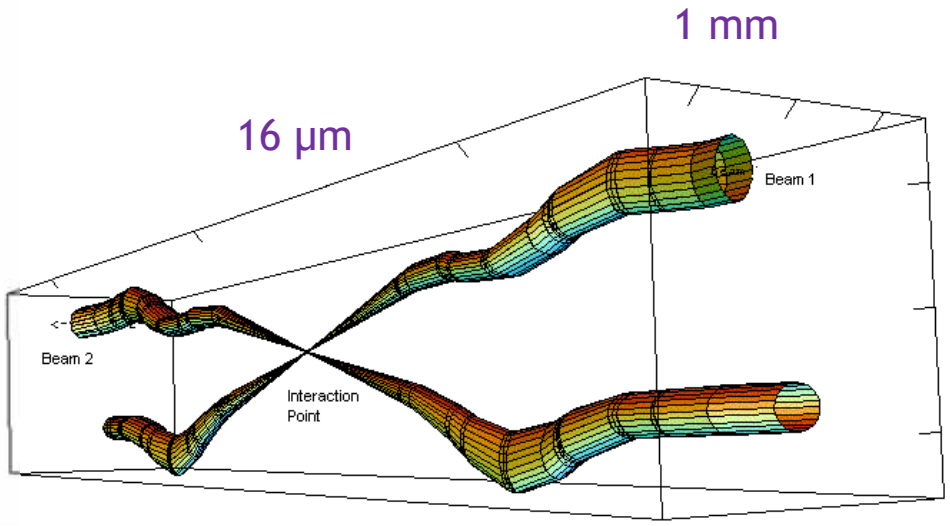
- 1232 superconducting dipoles of 15 m (8 T)
- 10000 superconducting magnets
- 150 tons of superfluid liquid at 1.9 K
  to cool down 37000 tons of material
- Cryogenic ultra-vacuum (10^{-13} atm)



- Magnetic energy stored
  in the magnets : 4 GJ
- Cryogenic cooling power : 240 MW

Beams and Collisions

Stephen Hawking in front of
focalization quadrupole magnets at IP1(ATLAS)



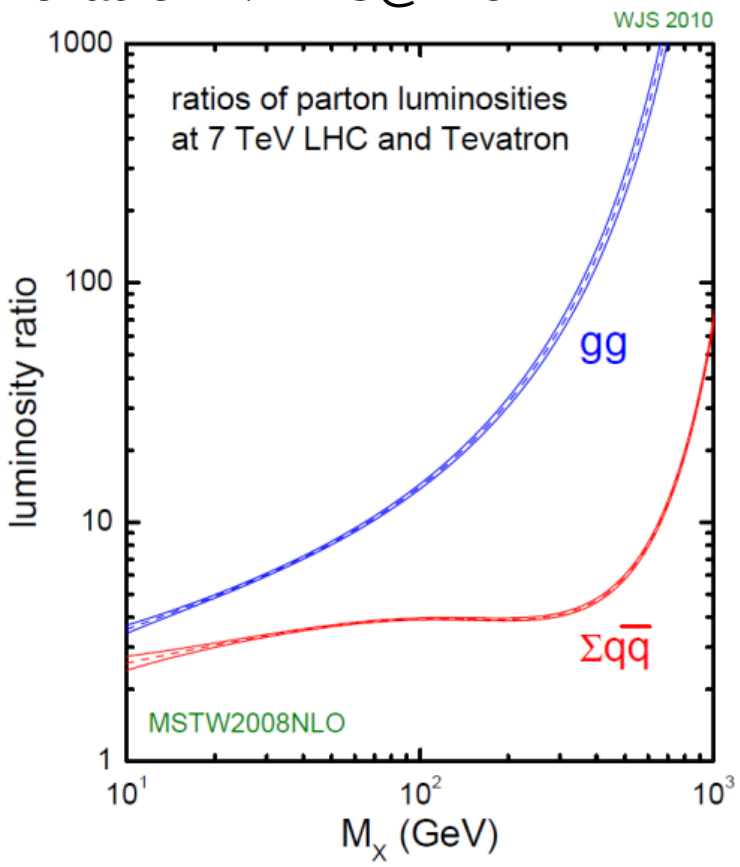
relative beam size
around the IP1 interaction point (ATLAS)

In 2012 : protons at 4 TeV

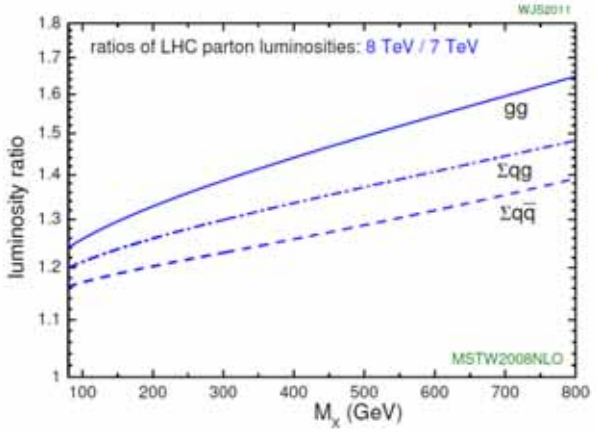
- 11100 revolutions per second at 99,999997% of the speed of light
- 2x1900 bunches of 10^{11} protons (0,5 ng of H^+) every 50 ns (=14 m)
  energy stored in beams : 180 MJ
- interaction region : 16 µm (transverse), few cm (longitudinal)
- around twenty inelastic proton-proton collisions per bunch crossing
- beam lifetime : around 10 hours

Parton Luminosity

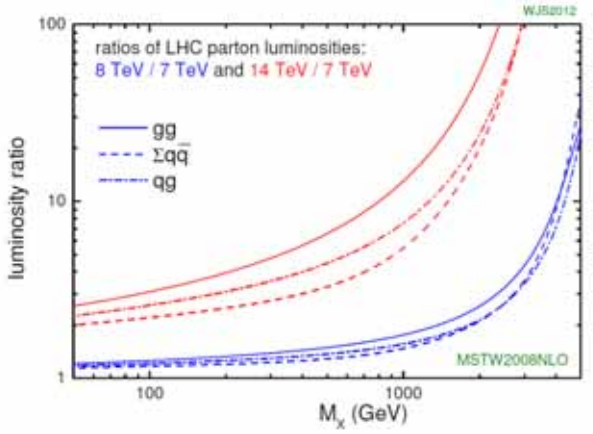
Tevatron → LHC@7TeV



LHC@7TeV → LHC@8TeV



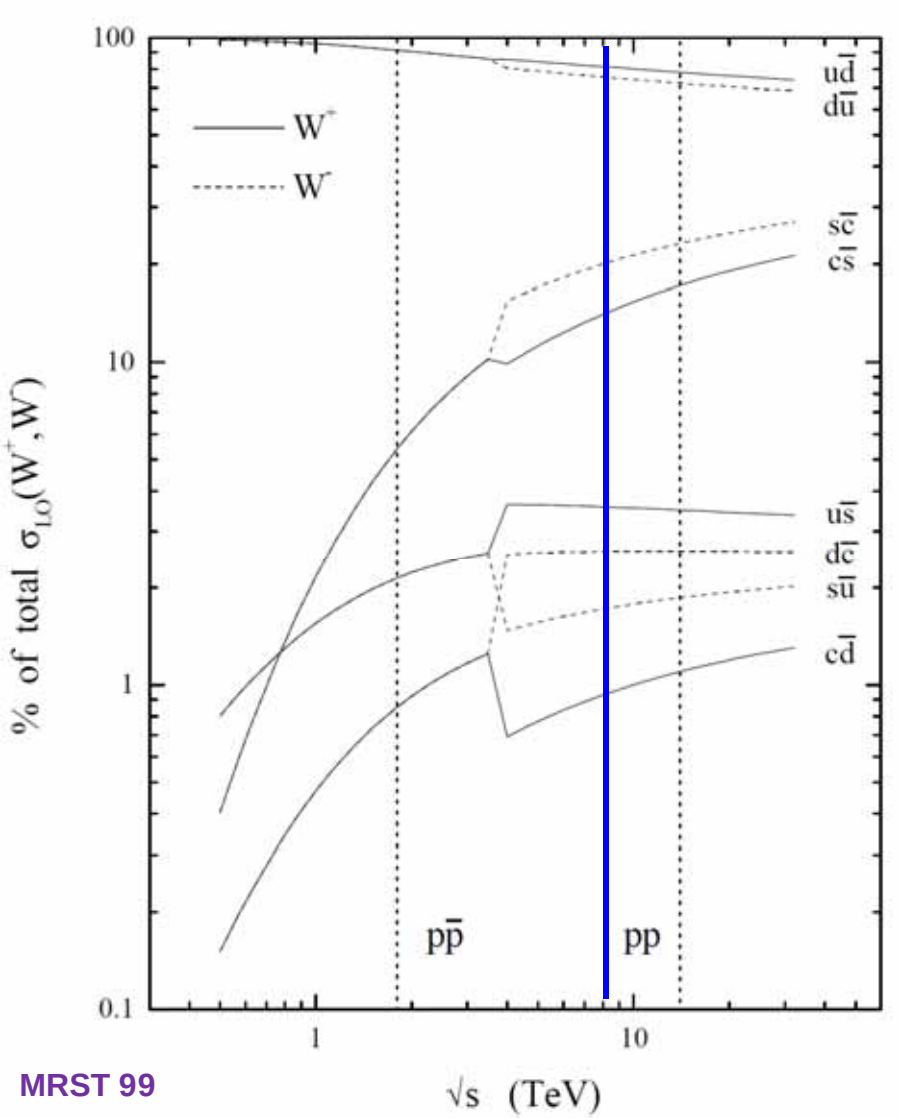
LHC@7TeV → LHC@14TeV



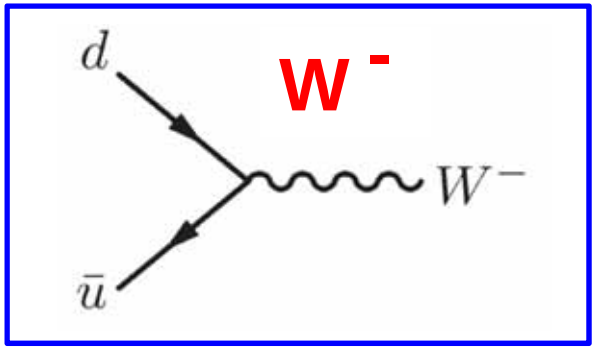
The gluon-gluon luminosity increases much more that the quark luminosity

- top quark pair production and Higgs production by gluon fusion are dominant at the LHC

Flavor in W Production



MRST 99



At the LHC

W production is charge asymmetric

expect

$\sigma(W^+)/\sigma(W^-) \sim 2$

if only valence quark + sea antiquark

but

involved parton fractions are low

$(10^{-3} < x < 10^{-1})$

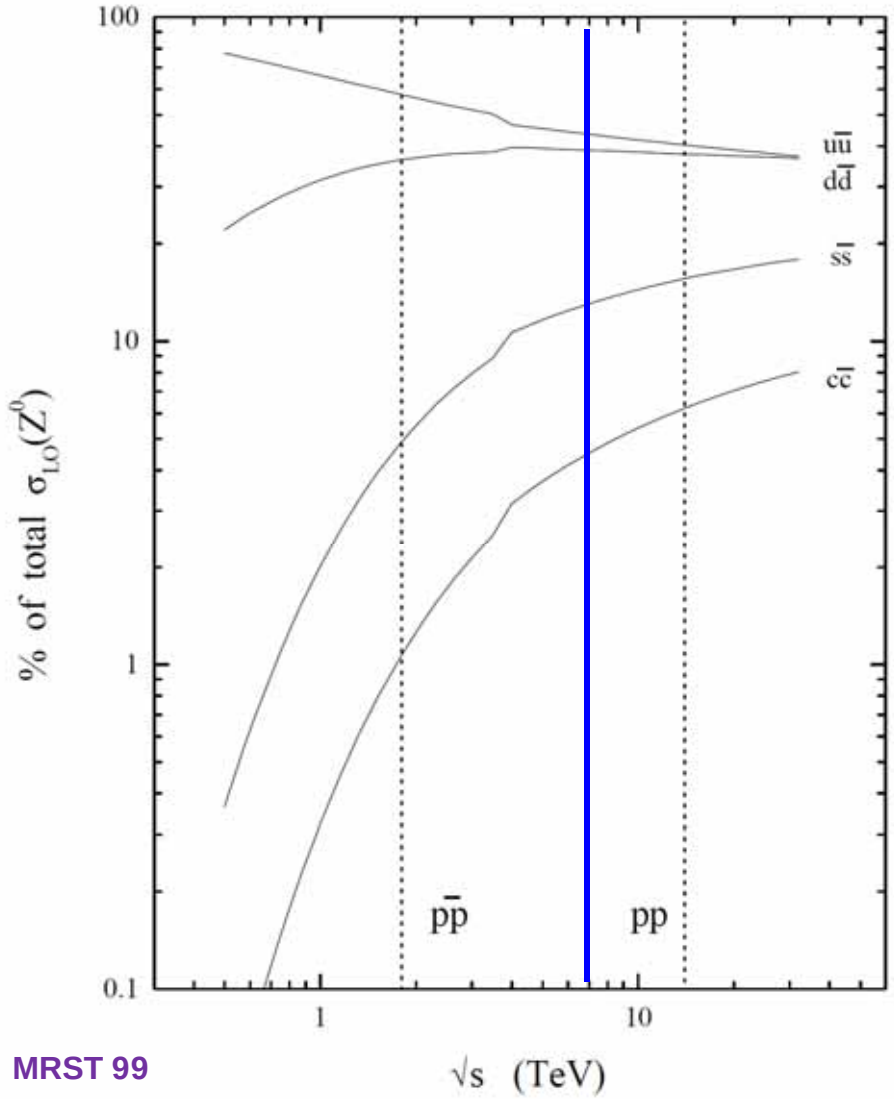
annihilation of a sea quark

and a sea anti-quark is significant:

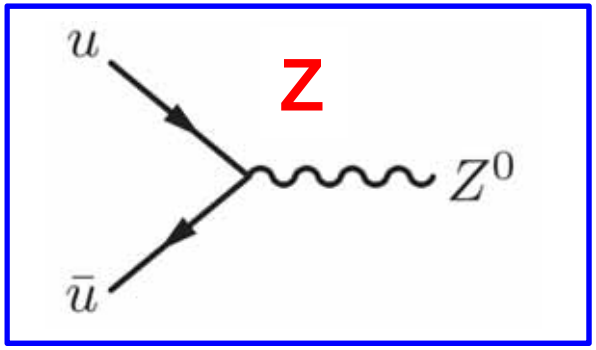
$\sigma(W^+)/\sigma(W^-) \sim 1.4$

charge asymmetry
depends on rapidity

Flavor in Z Production



MRST 99

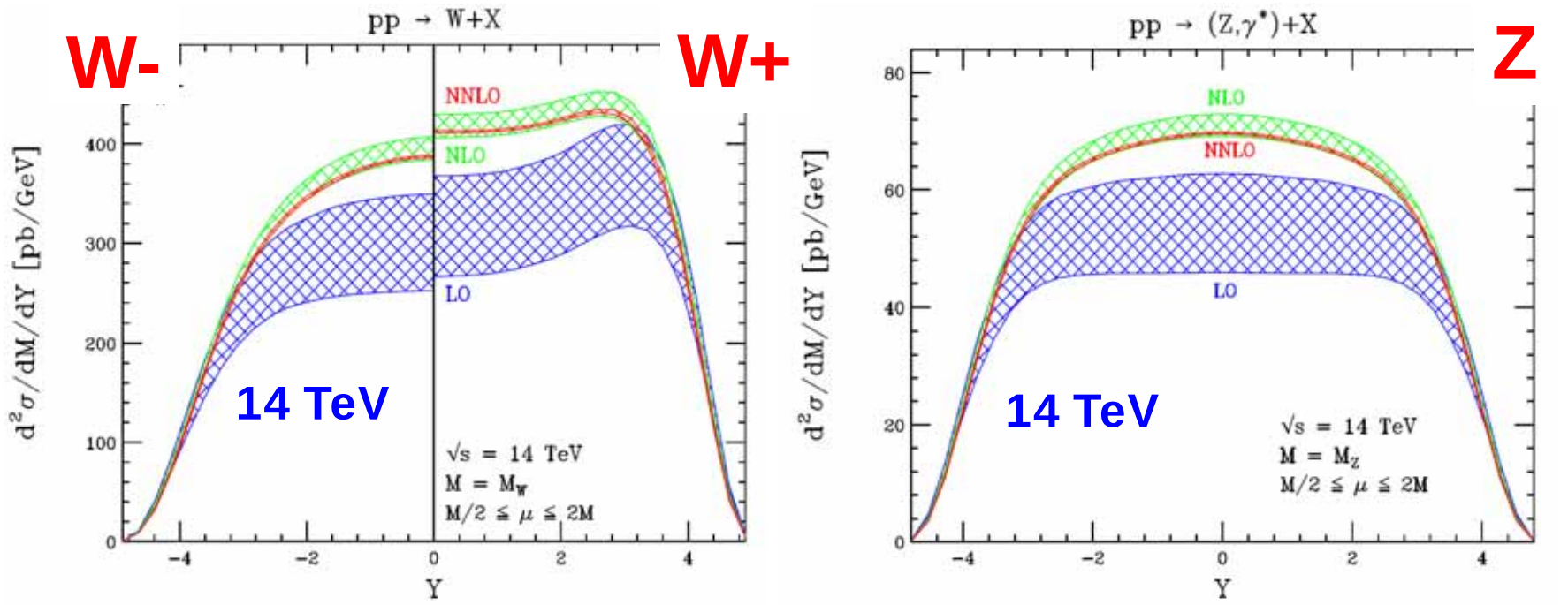


the strange density as an impact
on both W and Z production rates (10-20%)
but proton strangeness is poorly known

LHC W and Z data can improve PDFs

- constraints on u, d sea (anti)quarks
- constraints on strangeness
- constraints on heavy quark content
- crucial for reducing PDF uncertainties in searches

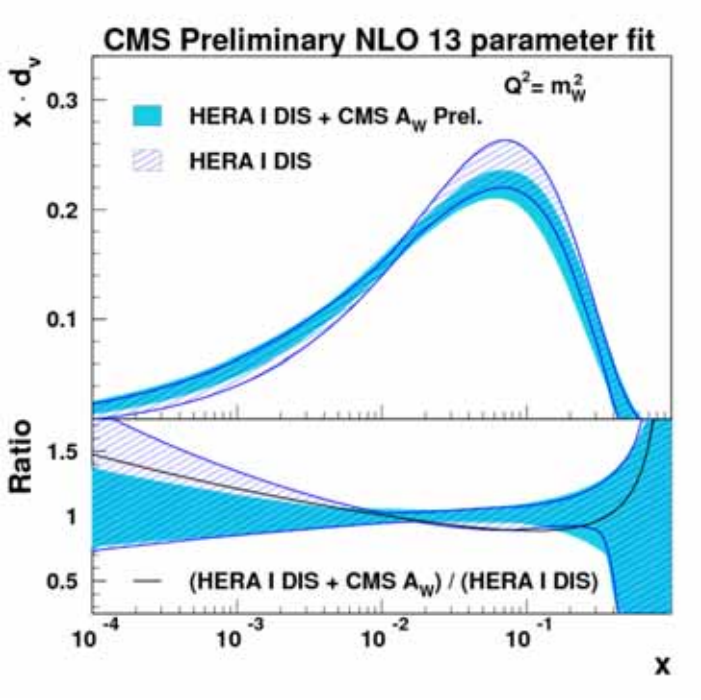
Theory Predictions



- Accurate theoretical NLO+ tools
  - QCD MC generators (LO: PYTHIA, HERWIG,… NLO: POWHEG, MC@NLO,…)
  - (N)LO-matched multi-jet generators (ALPGEN, MADGRAPH, SHERPA,…)
  - (N)NLO QCD cross-section calculations (MCFM, RESBOS, FEWZ, DYNNLO,…)
  - QED & electroweak corrections (HORACE,…)
- Parton density functions (PDF) (MSTW, CTEQ, HERAPDF, NNPDF,…)

W Production: Constraints on PDFs

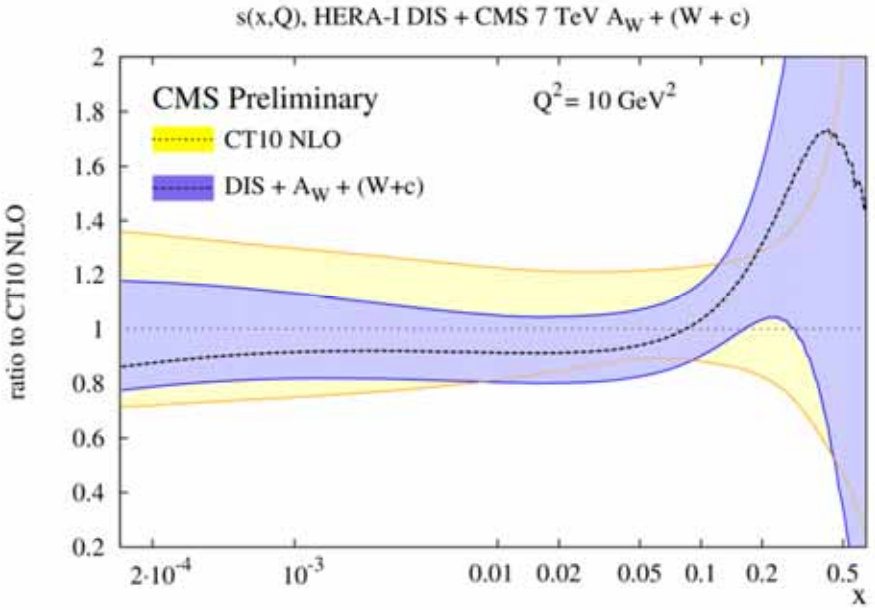
Valence PDF



HERA fitter framework

Using DIS, CMS lepton-charge asymmetry

Strange PDF



CT10 framework

… and W+charm

Effective Theory of Anomalous Couplings

Effective Lagrangian WWV (V=γ, Z)

$$\begin{aligned}\mathcal{L}/g_{WWV} &= ig_1^V[W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}] + i\kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} \\ &+\frac{i\lambda^V}{M_W^2}W^\dagger_{\lambda\mu}W^\mu{}_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) \\ &+g_5^V\varepsilon^{\mu\nu\rho\sigma}(W^\dagger_\mu\partial_\rho W_\nu - (\partial_\rho W^\dagger_\mu)W^\nu)V_\sigma \\ &+i\tilde{\kappa}^V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}^V}{M_W^2}W^\dagger_{\lambda\mu}W^\mu{}_\nu\tilde{V}^{\nu\lambda}\end{aligned}$$

anomalous

WWV: 10 anomalous couplings
assume QED, C and P invariance, and additional (LEP) relations
→ 3 anomalous couplings
$\Delta\kappa^\gamma$, Δg_1^Z, $\lambda = \lambda_\gamma = \lambda_Z$

SM: all zero

Effective Lagrangian ZVγ (V=γ,Z)

$$\begin{aligned}\mathcal{L}_{VV'V''}\frac{M_Z^2}{e} &= -[f_4^\gamma(\partial_\mu F^{\mu\beta}) + f_4^Z(\partial_\mu Z^{\mu\beta})]Z_\alpha(\partial^\alpha Z_\beta) \\ &+[f_5^\gamma(\partial^\sigma F_{\sigma\mu}) + f_5^Z(\partial^\sigma Z_{\sigma\mu})]\tilde{Z}^{\mu\beta}Z_\beta \\ &-[h_1^\gamma(\partial^\sigma F_{\sigma\mu}) + h_1^Z(\partial^\sigma Z_{\sigma\mu})]Z_\beta F^{\mu\beta} \\ &-[h_3^\gamma(\partial_\sigma F^{\sigma\rho}) + h_3^Z(\partial_\sigma Z^{\sigma\rho})]Z^\alpha\tilde{F}_{\rho\alpha} + \text{dim 8}\end{aligned}$$

anomalous

ZVγ: 12 anomalous couplings
assume CP invariance and dim<8
→ 4 anomalous couplings
h_3^γ, h_1^Z, f_4^γ, f_5^Z

- anomalous couplings result in violation of partial wave unitarity at large energy

Parton Kinematics

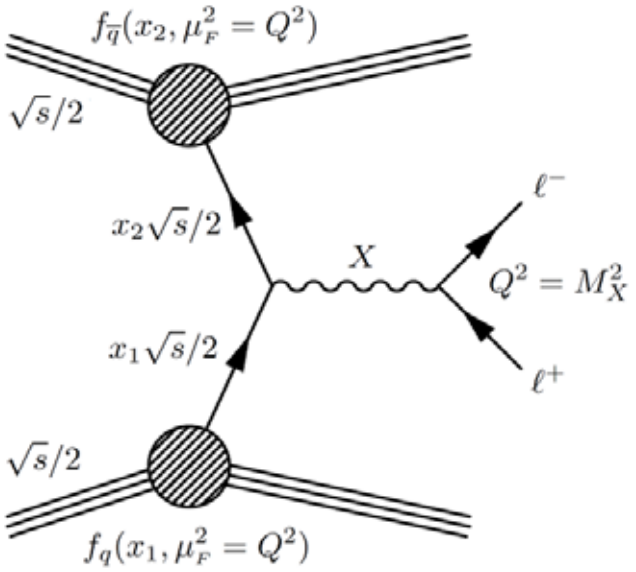
Rapidity of 4-vector $P(E, p_X, p_Y, p_Z)$

$$y \equiv \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

kinematic variable such that

$$\mathrm{d}y/\mathrm{d}p_z = 1/E$$

(differences in rapidity are invariant under longitudinal Lorentz boosts)



Hard scattering seen as interaction between two partons

$$a(x_1) + b\,(x_2) \rightarrow X$$

√s = center of mass energy

Parton system (at leading order) in lab frame

$$E = (x_1 + x_2)\sqrt{s}/2$$
$$p_z = (x_1 - x_2)\sqrt{s}/2$$

one gets $Q^2 = E^2 - p_z^2 = x_1 x_2 s$

and $$y = \frac{1}{2} \ln \frac{x_1}{x_2}$$

x Bjorken: fraction of the longitudinal momentum carried out by the parton

Simple case of a boson of mass M produced in the s channel

$$x_{1,2} = \frac{M}{\sqrt{s}} \times e^{\pm y}$$

for a given mass *M*, the rapidity *y* relates *M* to the Bjorken *x* values of the quark (x_1) and the anti-quark (x_2)

Drell-Yan, Angular Analysis

$$\frac{\mathrm{d}\sigma_q}{\mathrm{d}\cos\theta}(s) = \frac{3\pi\alpha_{\mathrm{QED}}^2}{2s} Q_q^2 \left(1+\cos^2\theta\right) \quad \gamma^* \text{ exchange}$$

$$- \frac{3\alpha_{\mathrm{QED}} G_F M_Z^2}{2\sqrt{2}\Gamma_Z^2} \frac{s-M_Z^2}{s} \mathrm{BW}(s)\, Q_q g_{Vq} g_{V\ell} \left[\left(1+\cos^2\theta\right) + 2\frac{g_{Aq} g_{A\ell}}{g_{Vq} g_{V\ell}} \cos\theta\right] \quad Z/\gamma^* \text{ interference}$$

$$+ \frac{3G_F^2 M_Z^4}{16\pi\Gamma_Z^2} \mathrm{BW}(s) \left({g_{Vq}}^2 + {g_{Aq}}^2\right)\left({g_{V\ell}}^2 + {g_{A\ell}}^2\right) \left[\left(1+\cos^2\theta\right) + \frac{8}{3} A_{\mathrm{FB}}^q \cos\theta\right] \quad Z \text{ exchange}$$

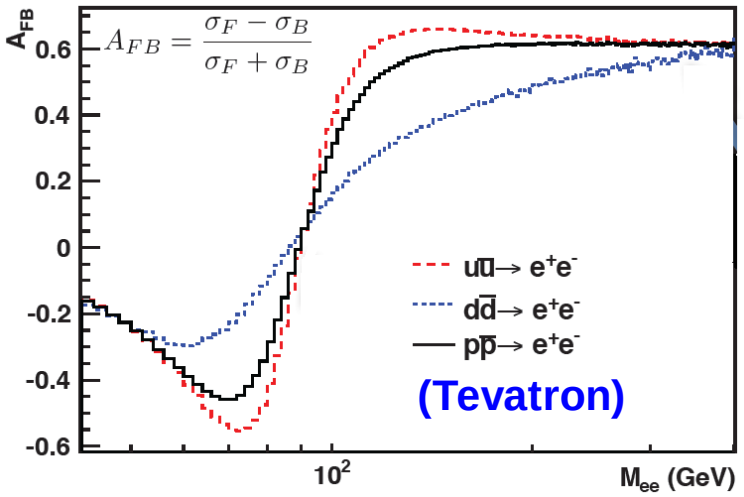
$$\text{with} \quad \mathrm{BW}(s) = \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} \quad \text{and} \quad A_{\mathrm{FB}}^q \equiv \frac{3}{4}\mathcal{A}_q\mathcal{A}_\ell.$$

The forward-backward asymmetry A_{FB} results from an average over all flavor of quarks

$$\frac{\mathrm{d}\sigma\left(Z^0/\gamma^* \to \ell^+\ell^-\right)}{\mathrm{d}\cos\theta^*} = \frac{3}{8}\left(1+\cos^2\theta^*\right) + A_{\mathrm{FB}}\cos\theta^*$$

At the LHC: the initial state is symmetric

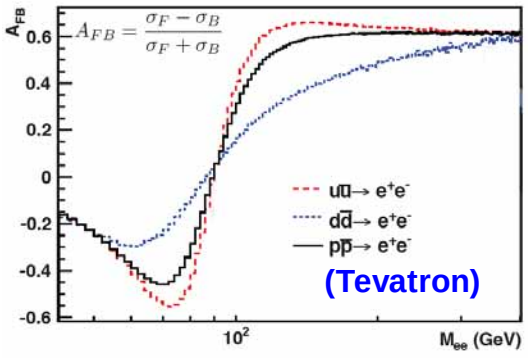
- at large rapidity, the longitudinal boost of the Z boson indicates more likely the direction of the parent (valence) quark



Drell-Yan, Forward-Backward Asymmetry

The forward-backward asymmetry A_{FB} results from an average over all flavor of quarks

sensitivity on $\sin^2\theta_W$



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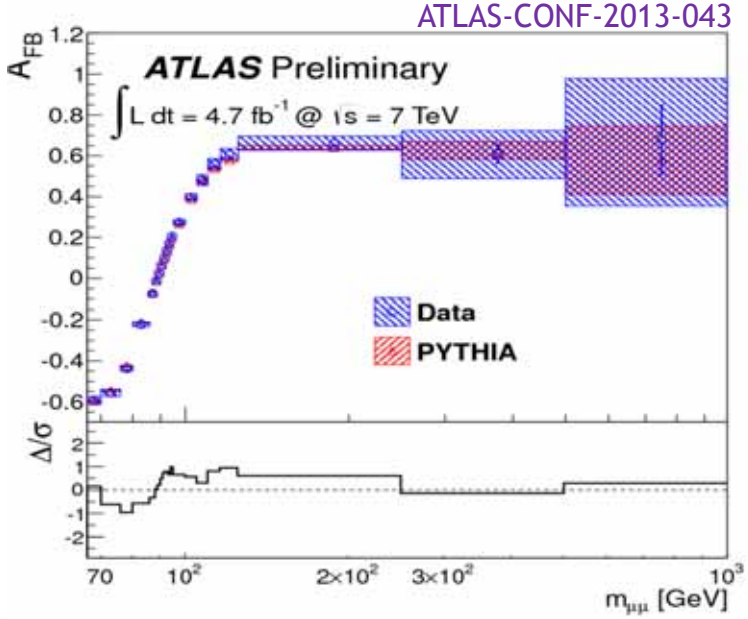
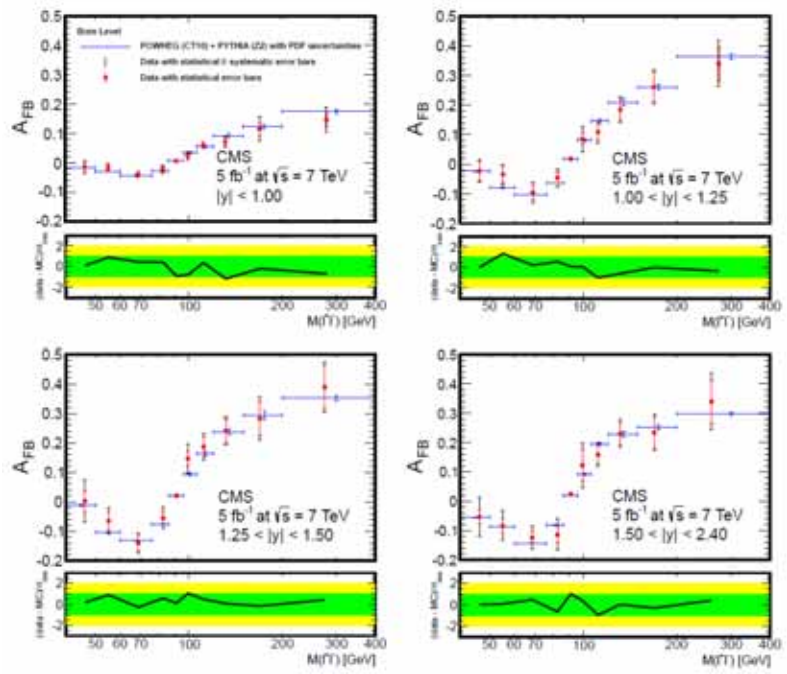
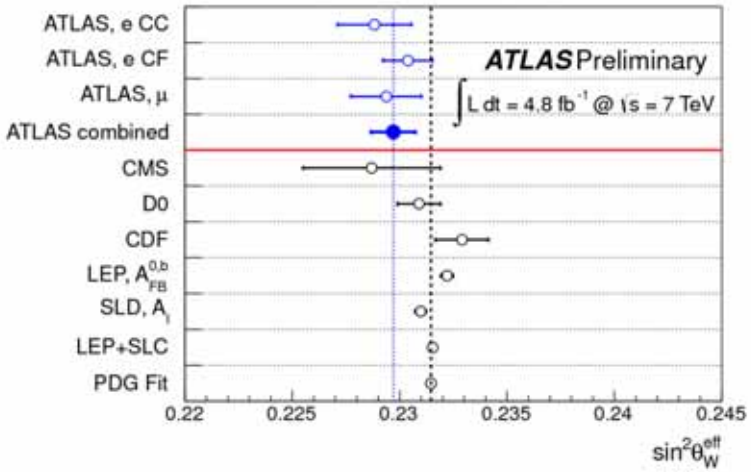


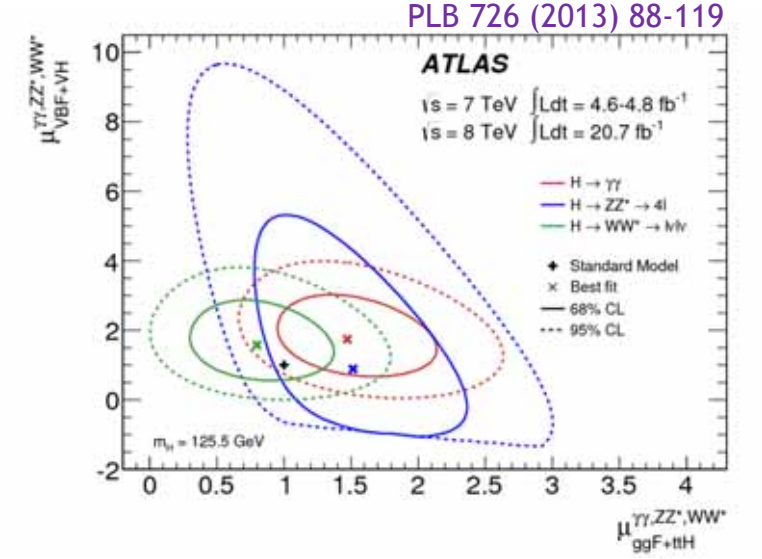


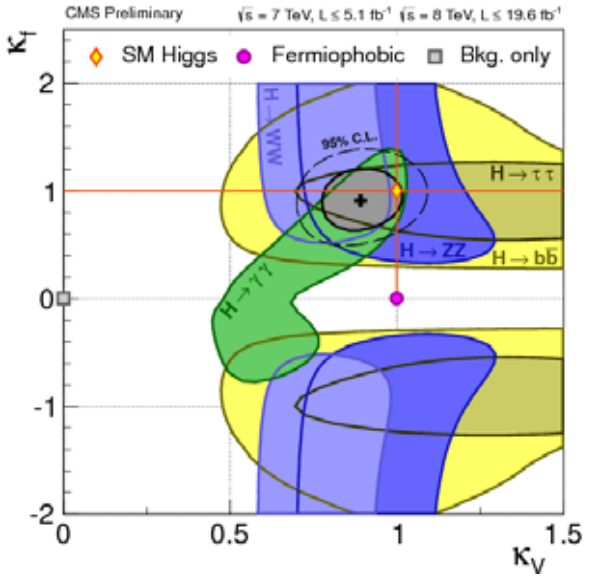
AFB distributions unfolded to Born-level

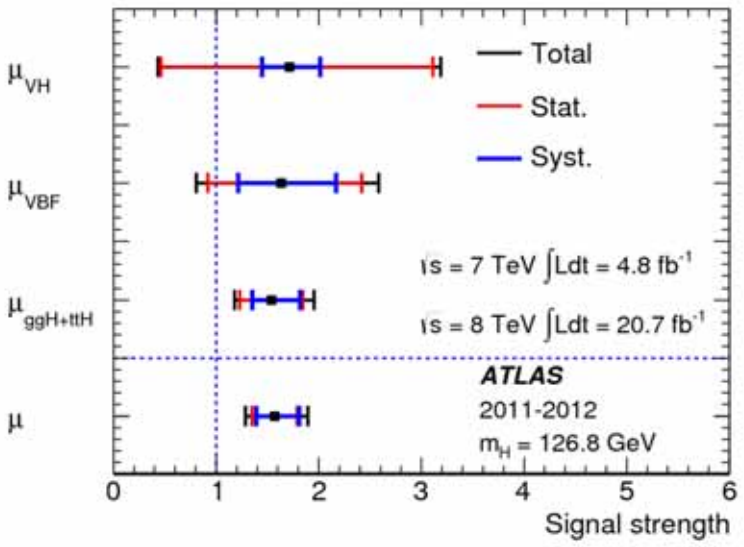


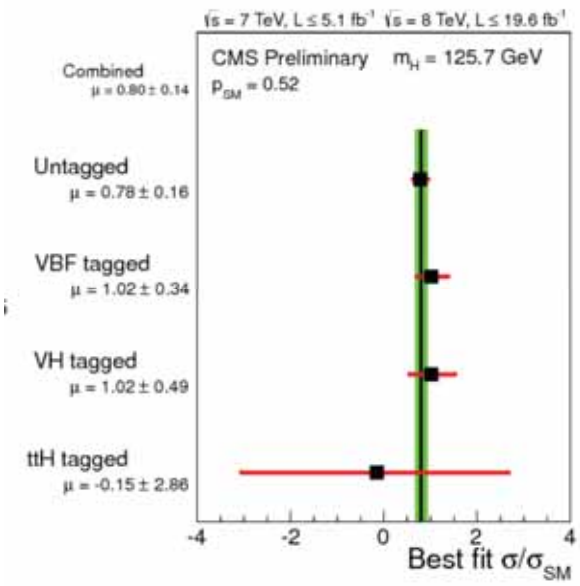
Higgs Boson Properties

PLB 726 (2013) 88-119



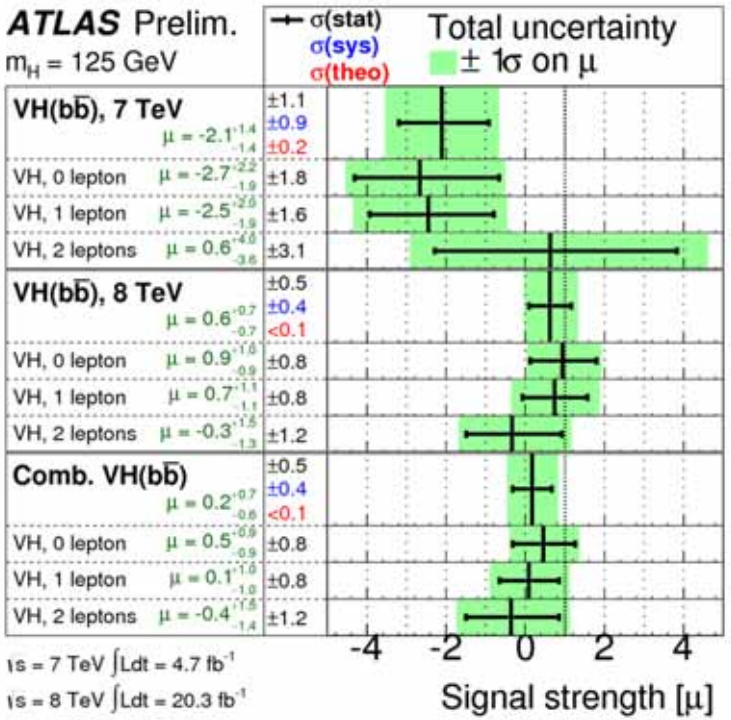




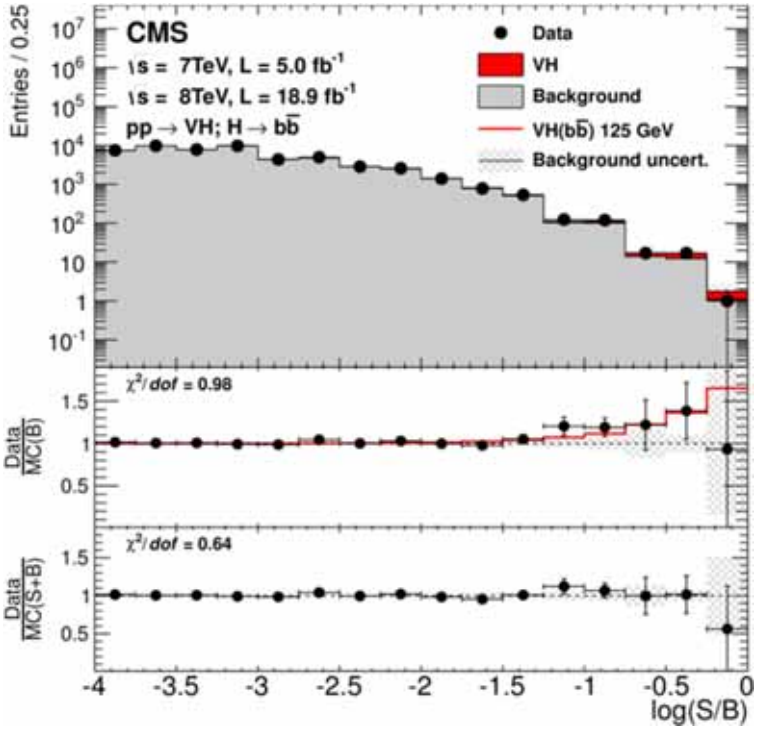


Search for Decay in Two b Quarks

ATLAS-CONF-2013-079



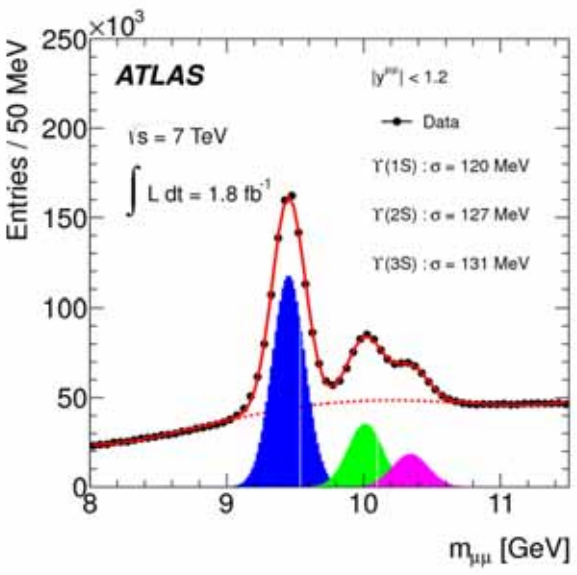
CMS-HIG-13-012 (acc. by PRD)



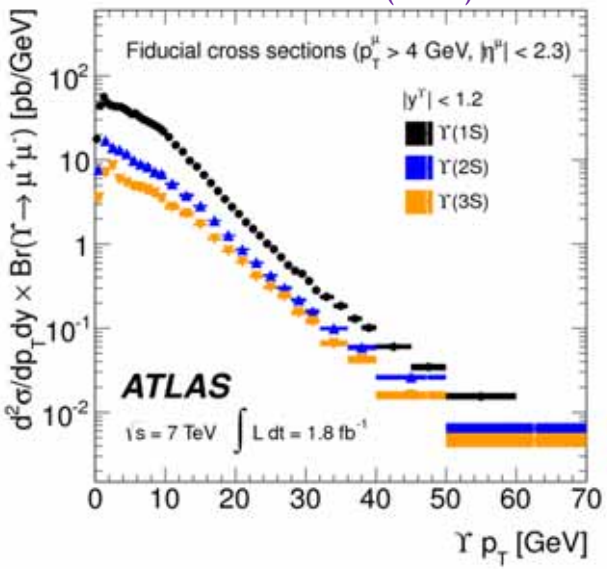
95% limit (m_H = 125 GeV)
- observed : **1.4xSM**
- expected: 1.3xSM

Significance (m_H = 125 GeV)
- observed : **2.1σ**
- expected: 2.1σ

Bottomium Physics

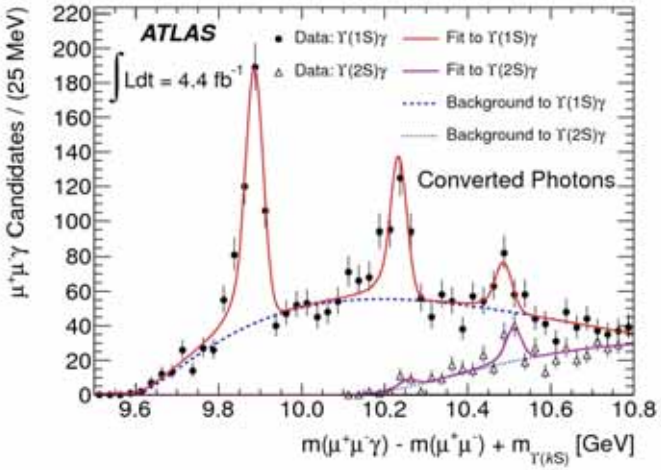


PRD 87 (2013) 052004

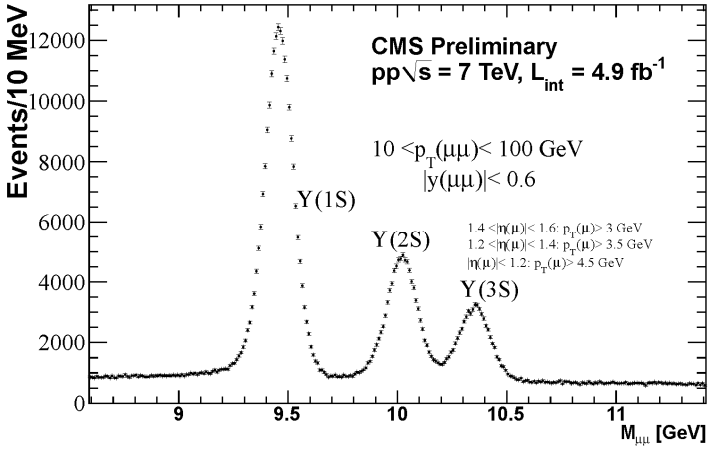


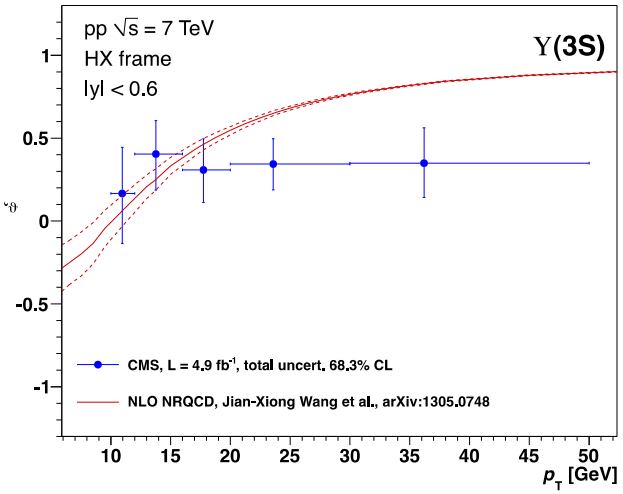
Observation of a new state

Phys. Rev. Lett. 108 (2012)



CMS-PAS-BPH-12-006



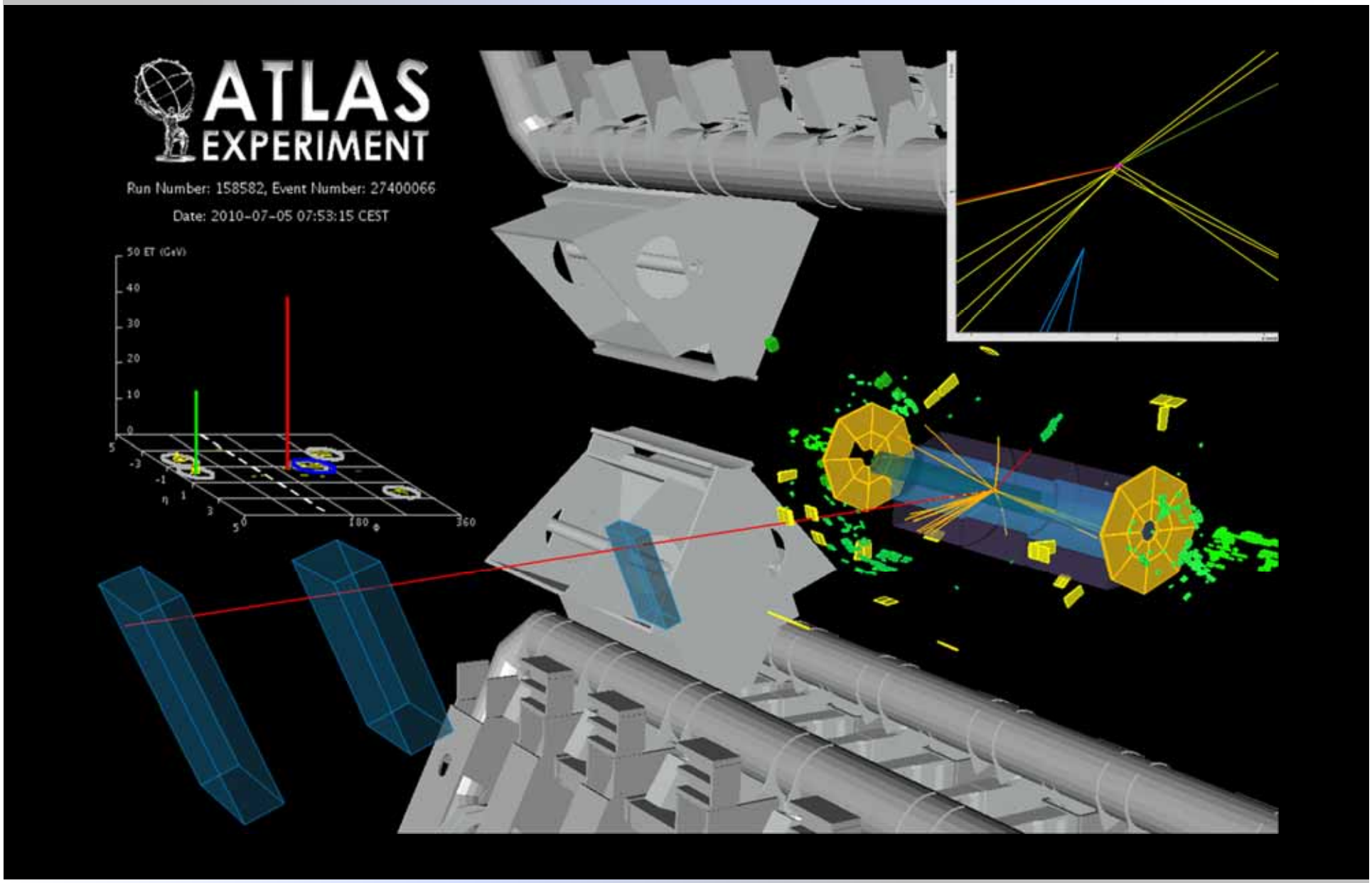


Polarizations measured from angular decay distributions

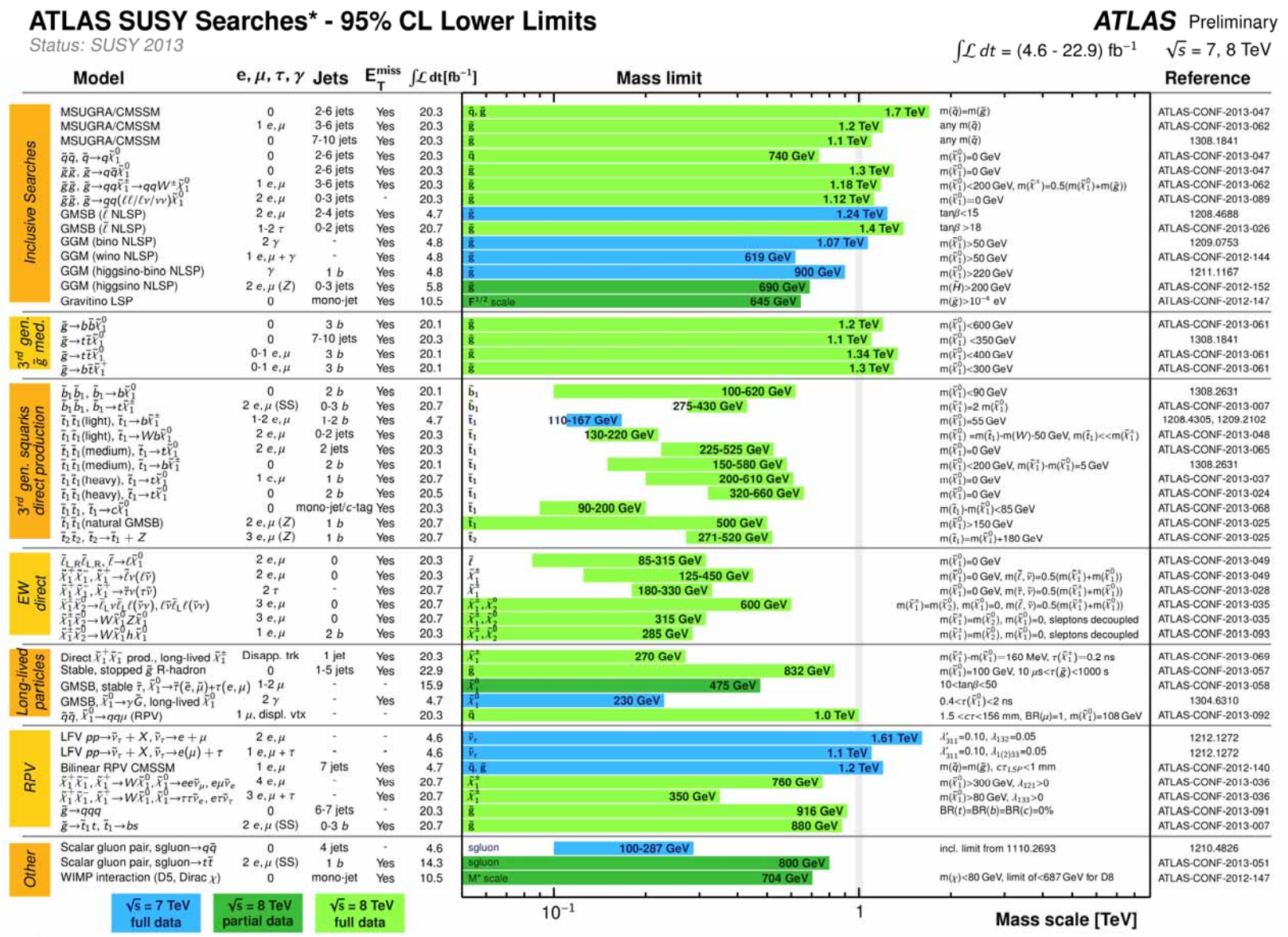
The CMS result disagree with NLO NRQCD

one of the largest discrepancies with SM expectations so far

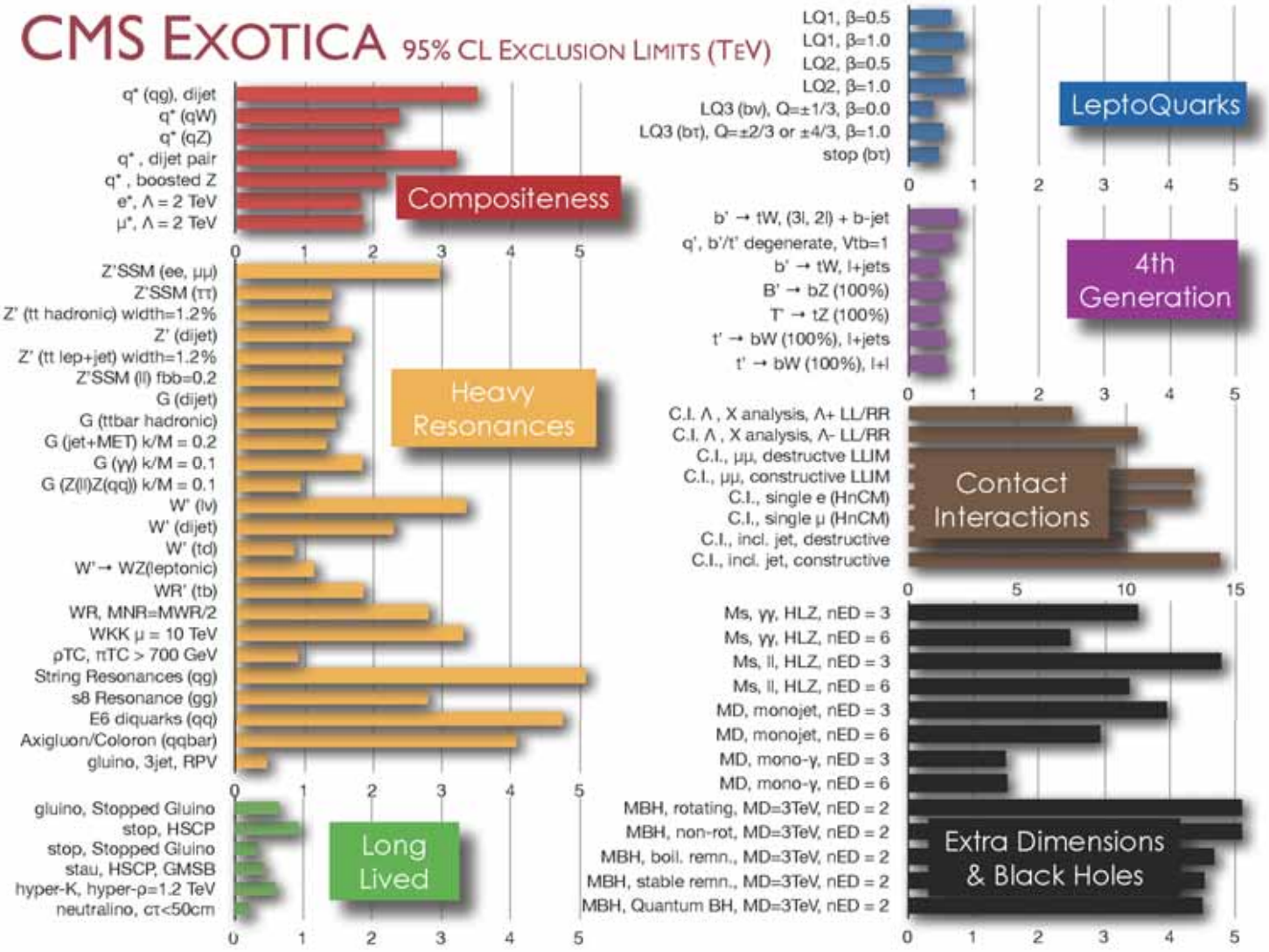
Top Candidate in the Dilepton Channel



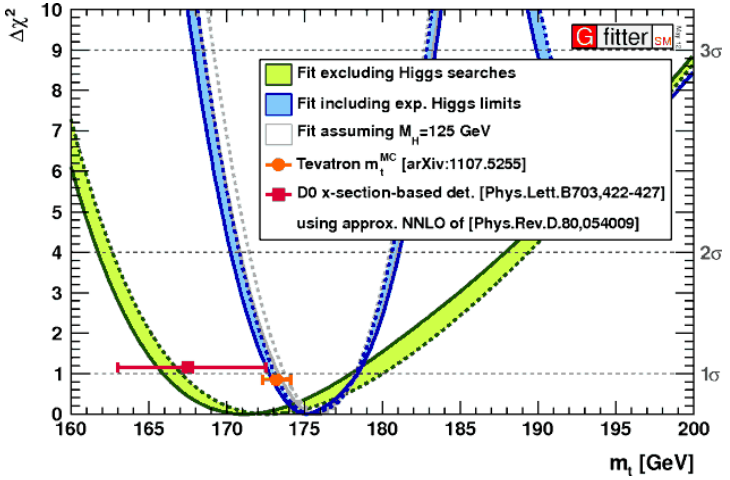
Summary of SUSY Analyses in ATLAS

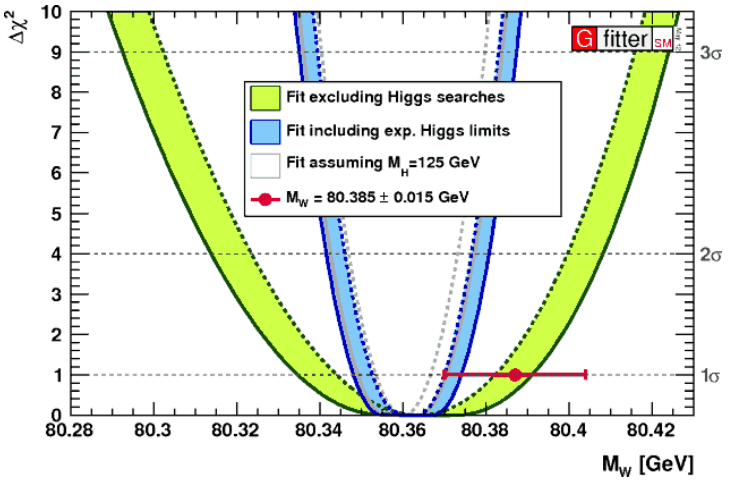


Summary of BSM Analyses in CMS

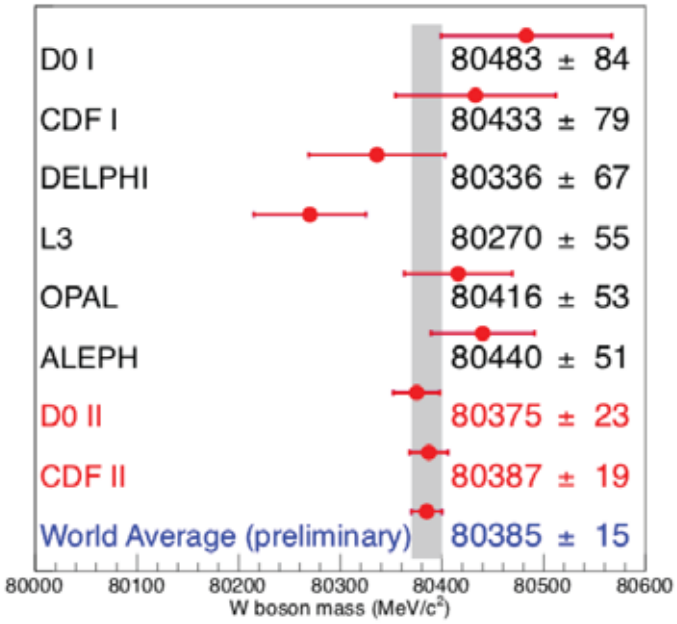


Electroweak Fits and W Mass





$$\Delta m_t = 0.9\ \text{GeV} \quad \leftrightarrow \quad \Delta m_W \approx 5\ \text{MeV}$$



Current precision: 15 MeV

Goal at LHC? 5 MeV!

Experimental challenges

- control lepton energy scale at <0.1%
- energy resolution to ~1%
- p_T dependence of the efficiency to 1%