Prospects of Heavy Ion Physics at LHC

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Plan of the talk

- **Introduction**
- **Observables in Heavy Ion collisions**
- **Selected measurements at LHC**

  How they have improved, extended our understandings from RHIC
- **Future directions**

A Note on Heavy Ion Physics ?

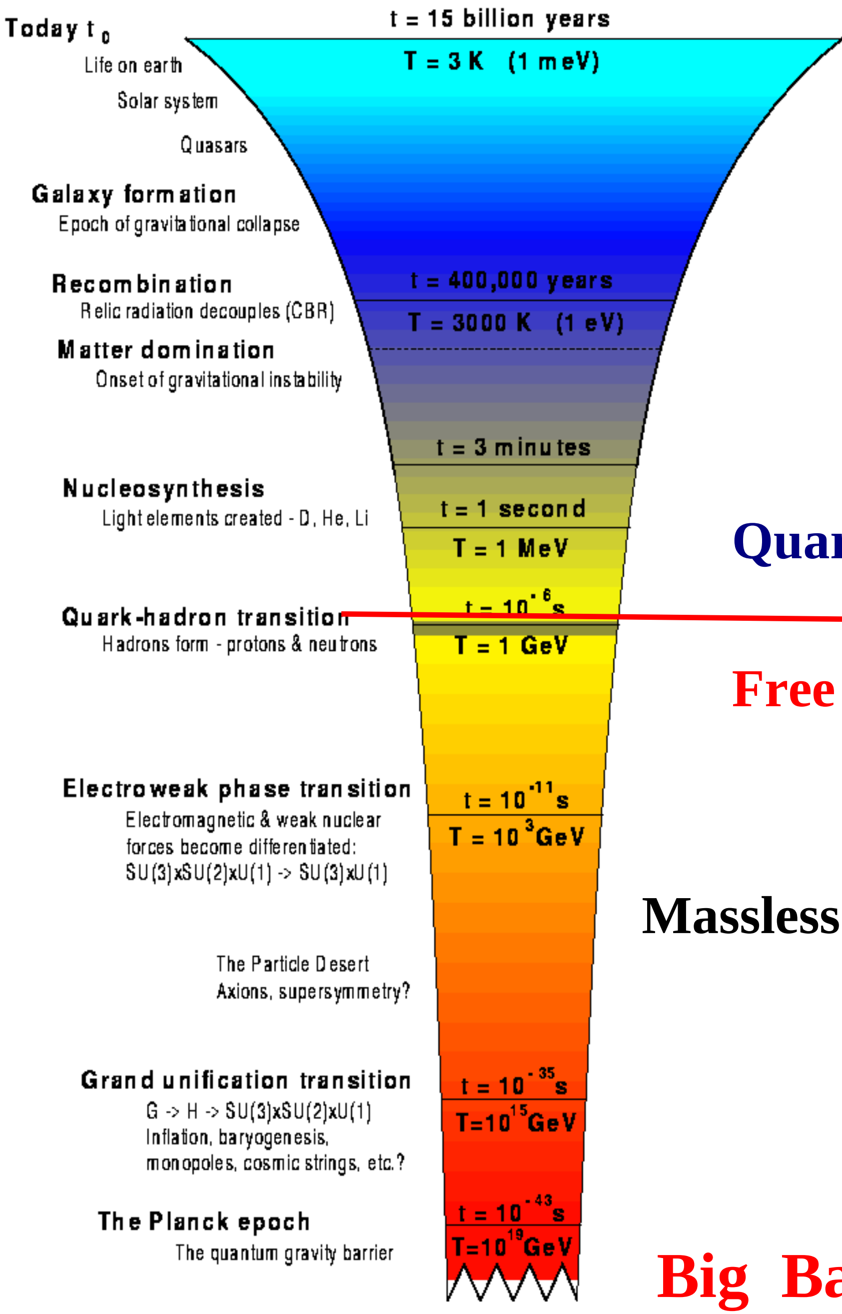
- **The aim of colliding two heavy nuclei at high energies is to create a matter where colour degrees of freedom (quarks, gluons, ..) are dominant over a finite volume- a state known as Quark Gluon Plasma (QGP).**

- **The heavy ion collisions basically revolve arround creating and detecting the signals of QGP. But in general one can call this field of physics as the study of behaviour of strongly interacting matter in bulk.**

- **Learning from RHIC**
  Perfect liquid
  sQGP (Strongly interacting)

- **LHC**
  Precision machine for QGP studies

Early universe phase transitions



Reachable Today

RHIC ~ 300-350 MeV

LHC ~ 500-600 MeV

Quarks, Gluons confined

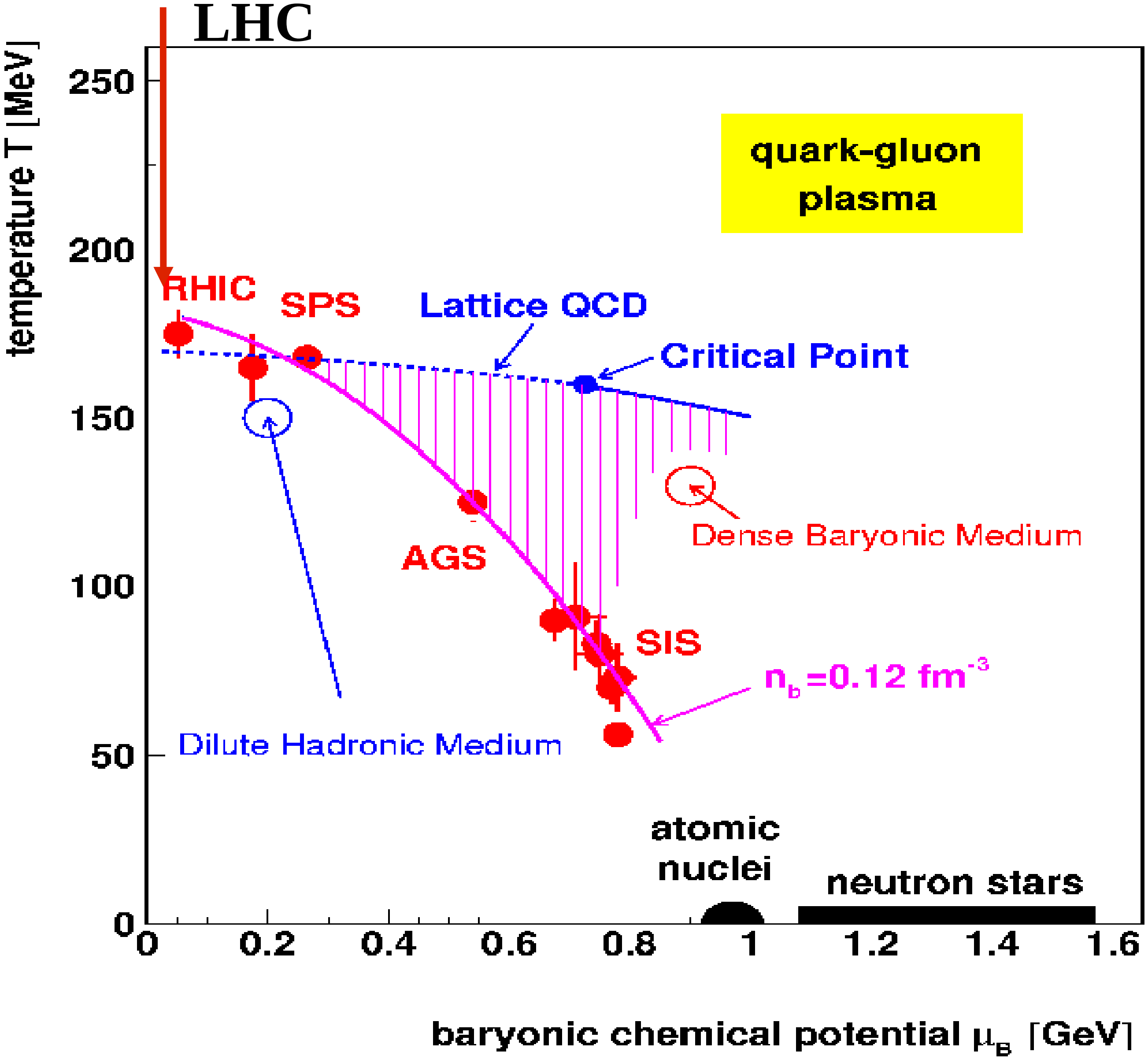
Free quarks and gluons

Massless standard model

LHC pp collisions searches rare events

Big Bang

Quark-hadron phase diagram



RHIC (130 GeV)

pbar/p ~ 0.65

PRL86, 4778 (2001)

RHIC (200 GeV)

pbar/p ~ 0.77

NPA734 , 13 (2004)

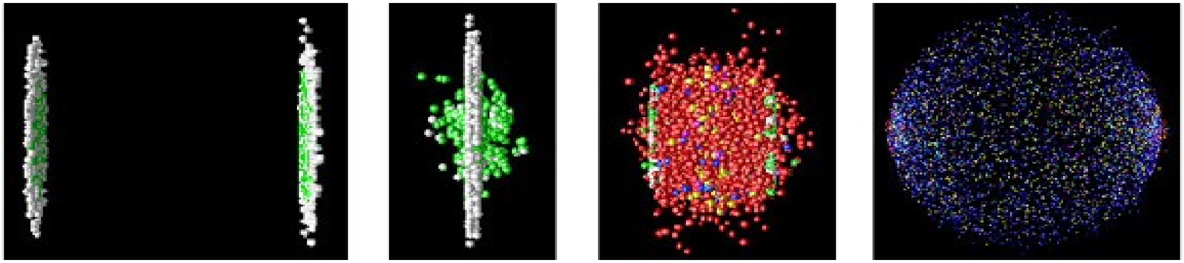
LHC

pbar/p ~ 1

ALICE Arxiv:1303.0737

Colliding Heavy Ions in Lab

The heavy ion collision experiments run parallel to usual particle physics experiments which like to collide electrons or protons.



Experiments:

CERN SPS (1986 ...)

pp, Pb+Pb @ $\sqrt{s_{NN}} \sim$ 3 to 20 GeV

RHIC (2001 to present):

pp, dAu and Au+Au @ $\sqrt{s_{NN}} \sim$ 7.7 GeV to 200 GeV.

LHC (2010 to present):

Run1 PbPb @ $\sqrt{s_{NN}}$ = 2.76 TeV

Run2 PbPb and pp @ $\sqrt{s_{NN}}$ = 2.76 TeV 150 μb^{-1}

Run3 pPb @ $\sqrt{s_{NN}}$ = 5.02 TeV, pp @ $\sqrt{s_{NN}}$ = 2.76 TeV

Future --> 5.5 TeV PbPb

Observables in Heavy Ion collisions

- **Soft probes: Properties derivable from measured particles of low (<2 GeV) and intermediate p_T (<4-5 GeV)**

Total multiplicity, Transverse Energy --> energy density
Interferrometry --> System Size, Life Time
Hadron yields and spectra --> Freezeout conditions, Thermalization
Hydrodynamic flow, v_n --> η/S
E by E Fluctuations --> Sucseptibilities
Electromagnetic probes at low p_T --> Temperature

- **Hard probes:**

Penetrating probes: Carry system properties.
Produced in short time scale, early in the collisions.
Produced in Hard collisions (high momentum transfer events) and their production can be treated in perturbative QCD.
--> Colour screening, Plasma opacity

Observables: Hard Probes (Advantage LHC)

1. Quarkonia (ccbar, bbar bound states)
   Colour screening properties of QGP hot matter.

2. Open heavy flavours (c and b) measured through D and B mesons
   Interact and loose energy in hot matter.

3. High p_T hadrons
   Interact and loose energy in hot matter.

4. Jets, Dijets
   Photon tagged jets or Z tagged jets.

Major advances in these areas have been achieved due to much larger cross section (compared to RHIC), coupled with excellent capabilities of LHC detectors.

At 5.5 TeV with increased luminosity it will be possible to carry out a detailed map of the system using these probes.

Nuclear modification factor of hard probes

- Nuclear modification factor (for hard probes R_{AA} = 1: no modifications)
  - compare measurement in heavy ion collision with pp reference (at the same √s, needs interpolation between Tevatron and LHC)

$$R_{AA}(x) = \frac{dN_{AA}/dx}{\langle T_{AA}\rangle \, d\sigma_{pp}/dx} = \frac{dN_{AA}/dx}{\langle N_{\mathrm{coll}}\rangle \, dN_{pp}/dx}$$

with x being the observable, e.g. centrality, p_T, y…

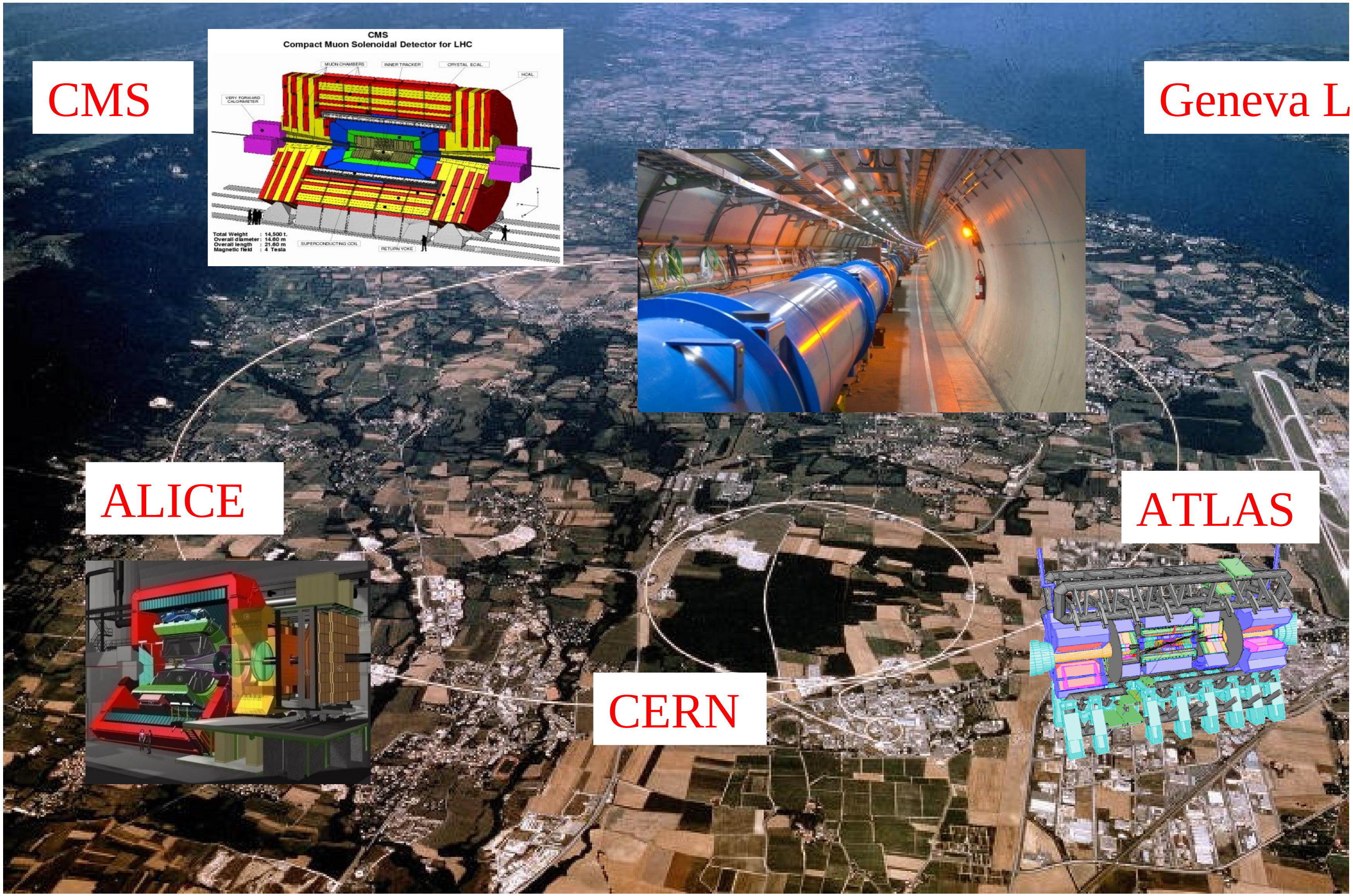
T_{AA}: nuclear overlap function
N_{coll}: number of binary collisions

  - compare measurement in central heavy ion collision to peripheral ("pp like") collisions

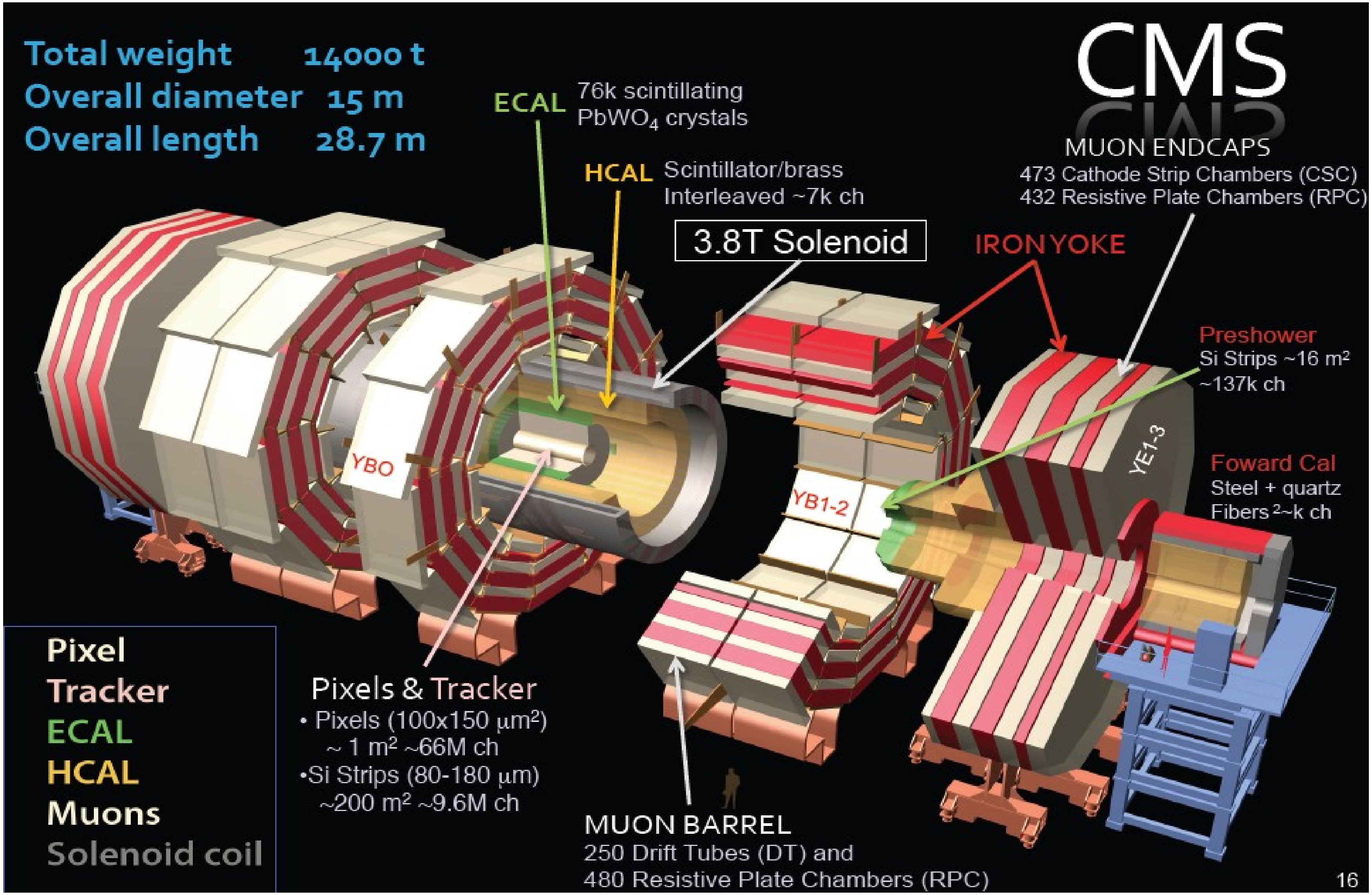
$$R_{CP}(x) = \frac{\langle N_{\mathrm{coll}}^{\mathrm{peripheral}}\rangle \, dN_{\mathrm{AA}}^{\mathrm{central}}/dx}{\langle N_{\mathrm{coll}}^{\mathrm{central}}\rangle \, dN_{\mathrm{AA}}^{\mathrm{peripheral}}/dx}$$

advantage: many efficiencies and systematics cancel in the ratio

LHC at CERN
Experiments for Heavy Ions

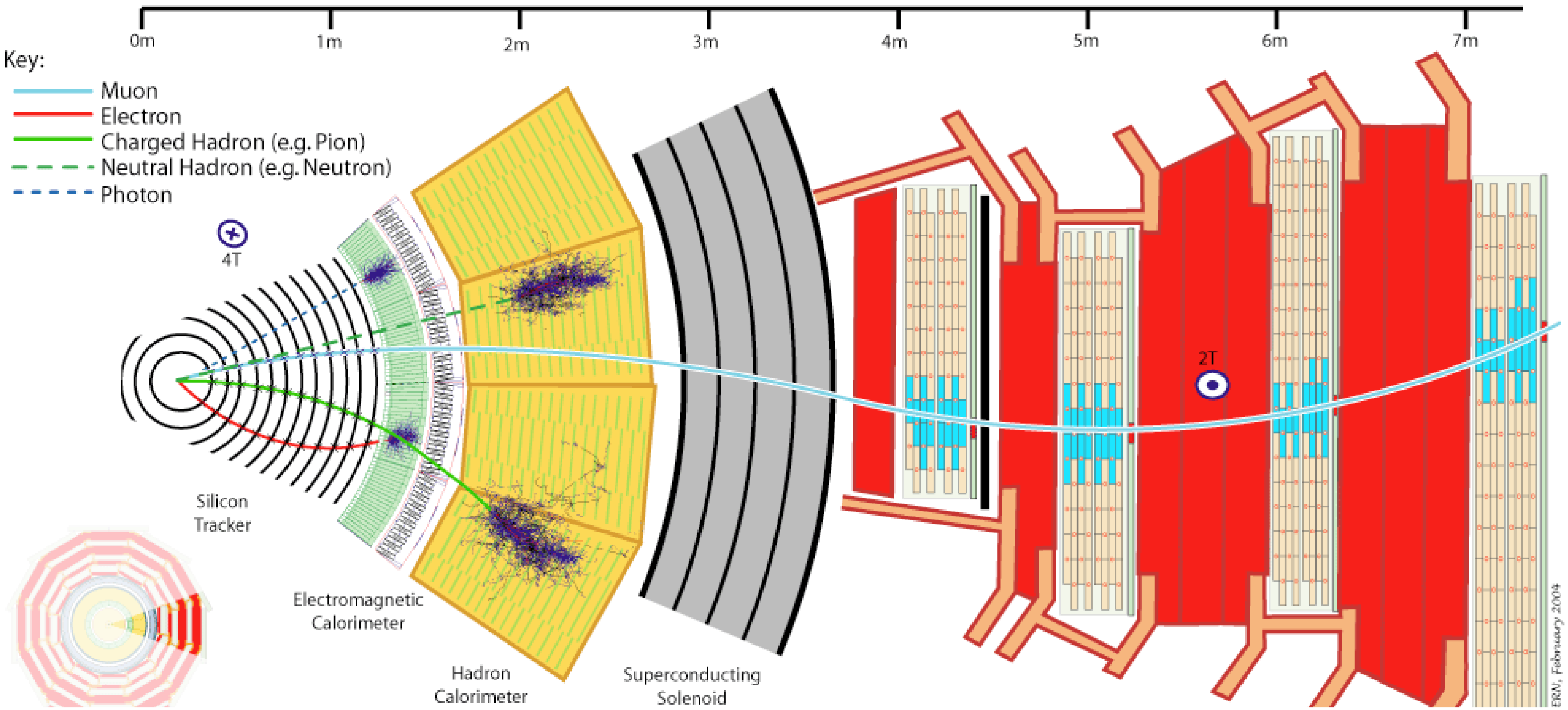


The CMS Experiment



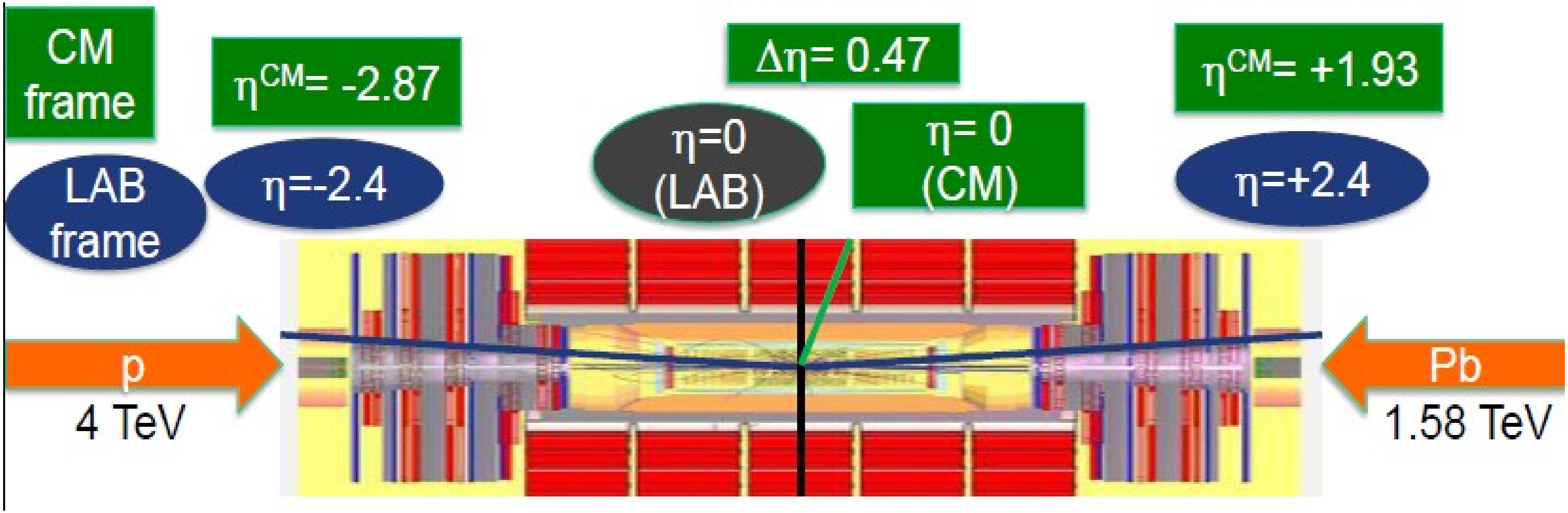
- **Large coverage for muons, Caloriemetry: An excellent detector for Hard probes.**

Cross sectional view of CMS



- **Muons : silicon tracker + muon stations.**
- **Good track momentum resolution and muon ID lead to excellent resolution of quarkonium states.**
- **Displaced vertex for heavy-flavour decay measurements .**
- **Full jet reconstruction upto p_T ~ 2 TeV using EMCal and HCAL**

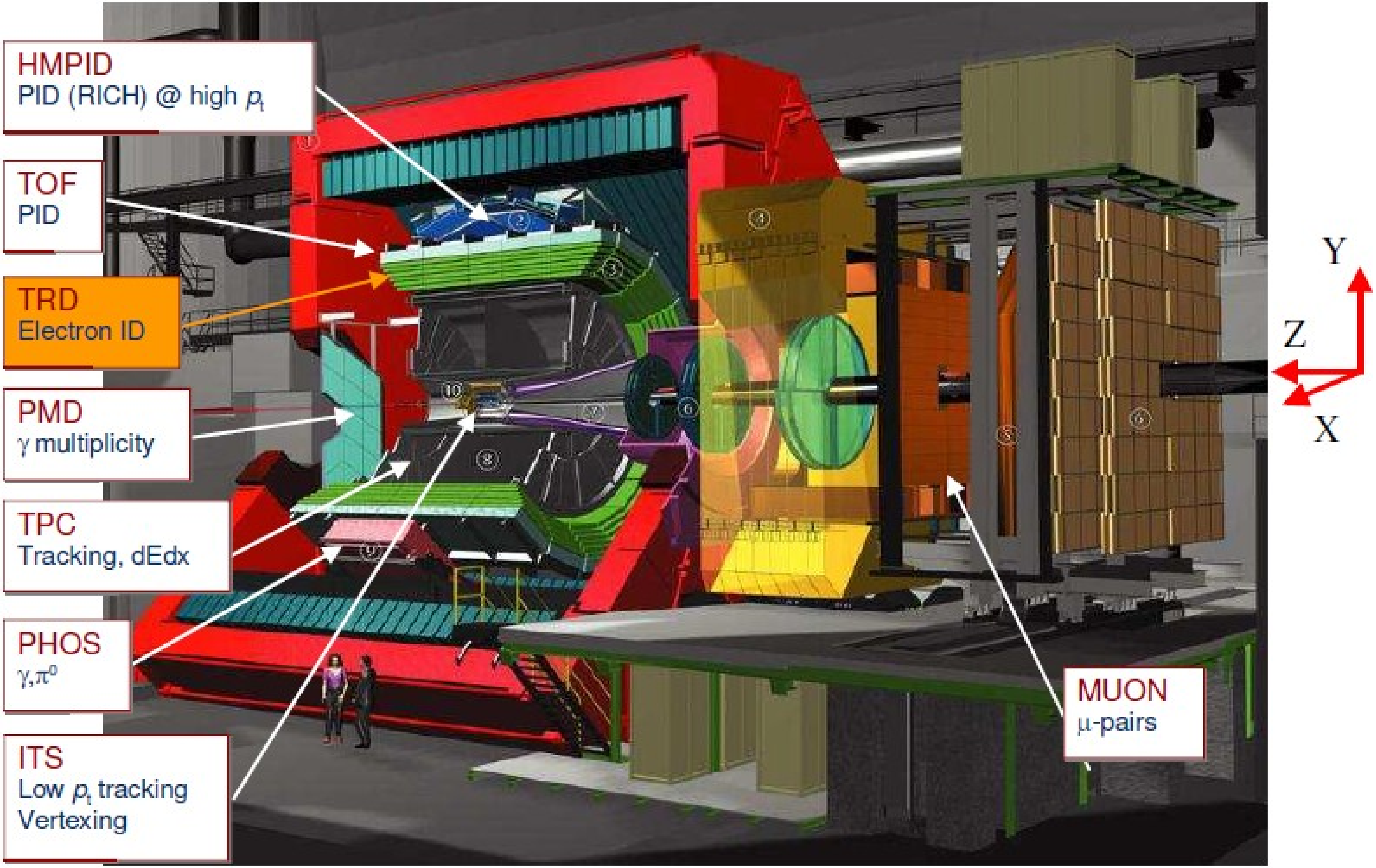
The pPb and Pbp runs



Integrated Luminosity Pb+p 18.4 nb^{-1}, p+Pb 12 nb^{-1}

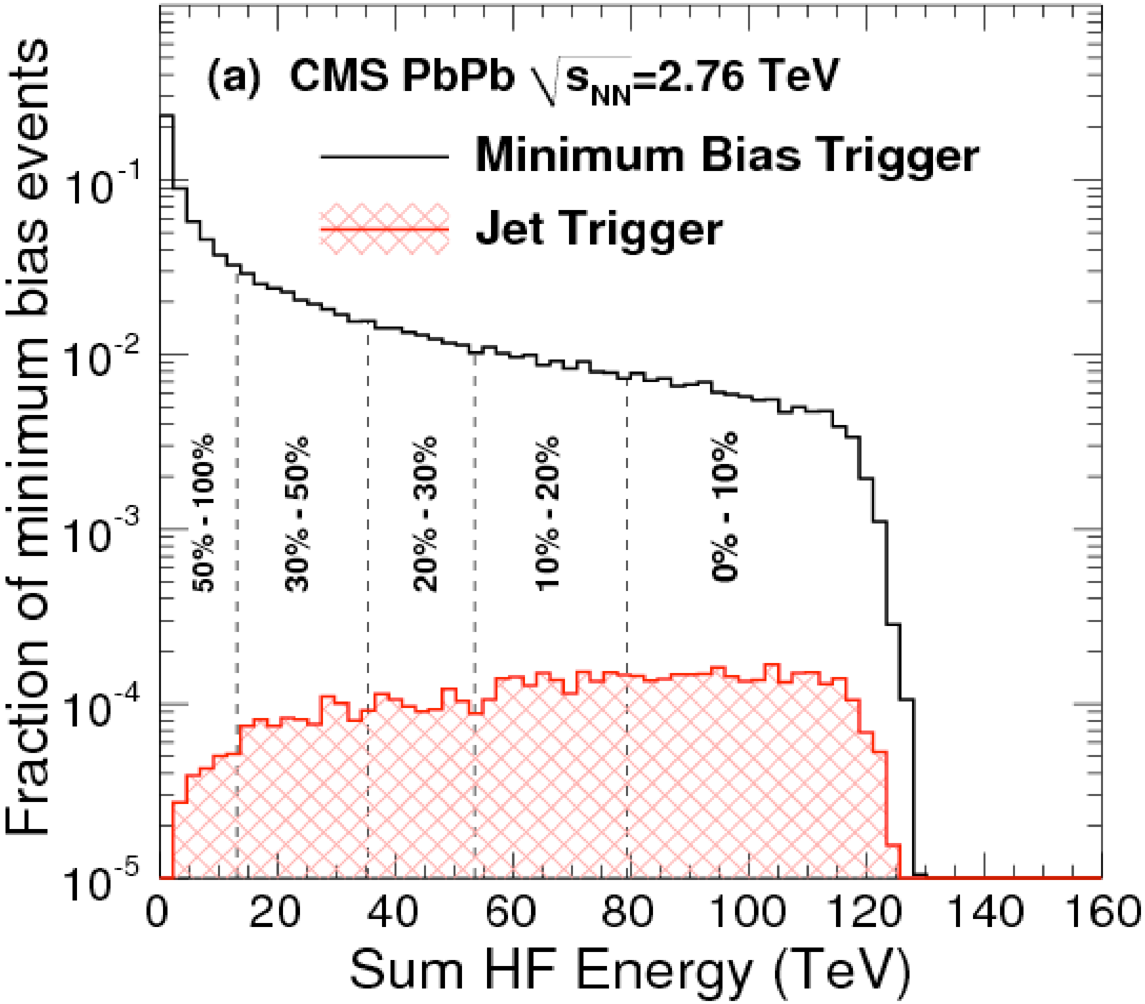
- **Rapidity shift 0.47**
- **Energy of p = 4 TeV, Energy of Pb = 4*82/208 = 1.58 ATeV.**
- **$\sqrt{s_{NN}} = \sqrt{(4 * E_p * E_{Pb})}$ = 5.02 TeV/ nucleon.**

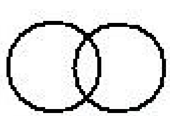
ALICE at LHC

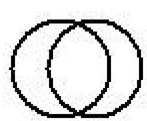


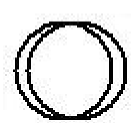
- **Excellent for soft probes, PID spectra.**

Centrality and how it is determined (in CMS)







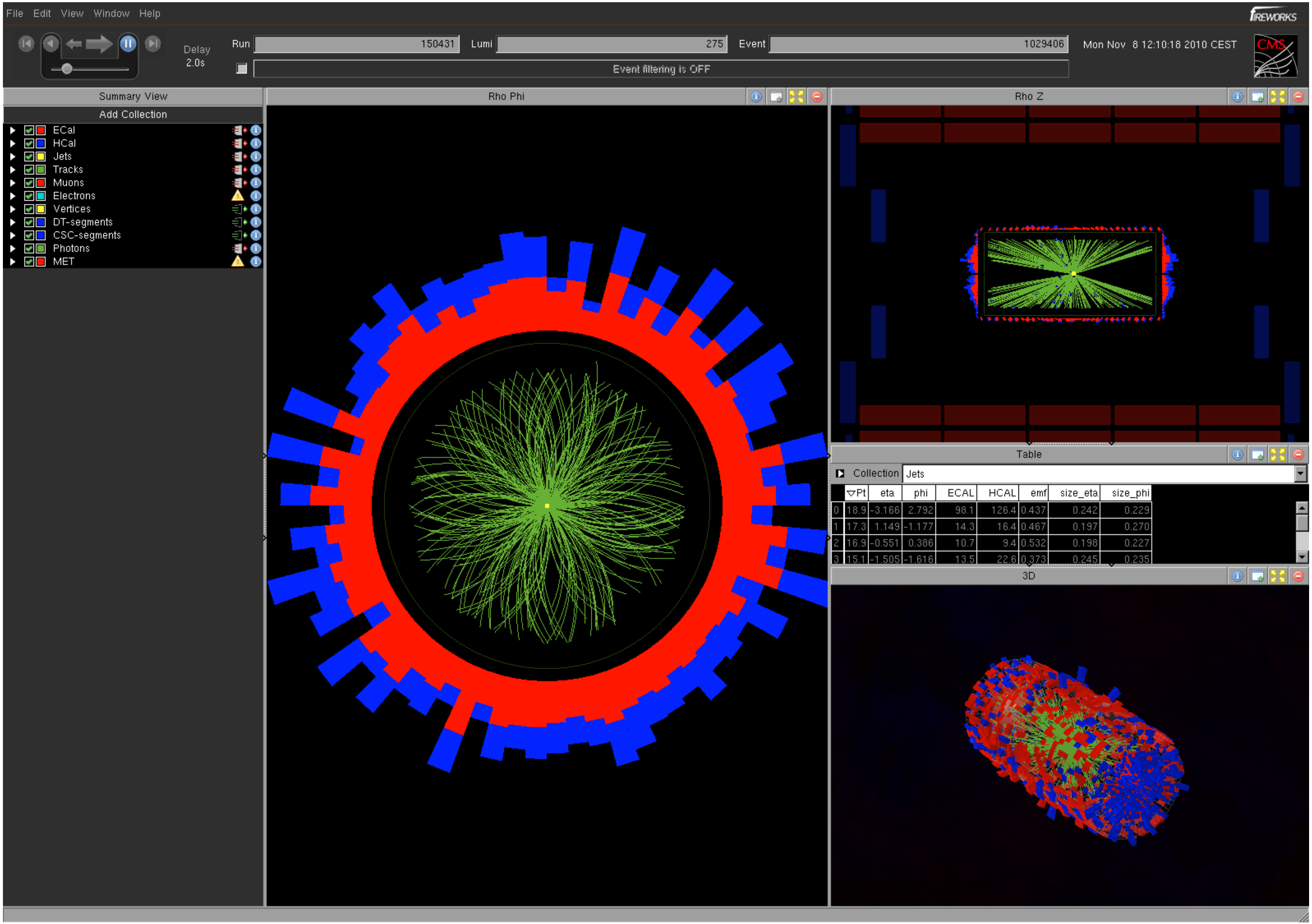


- **Collision centrality is determined by energy deposit in Hadron Forward calroriemeter.**

- **The centrality in % is mapped to N_{part} and N_{coll} by Glauber model.**

Or one can study signals as function of Ntraks or Calo Energy in an event.

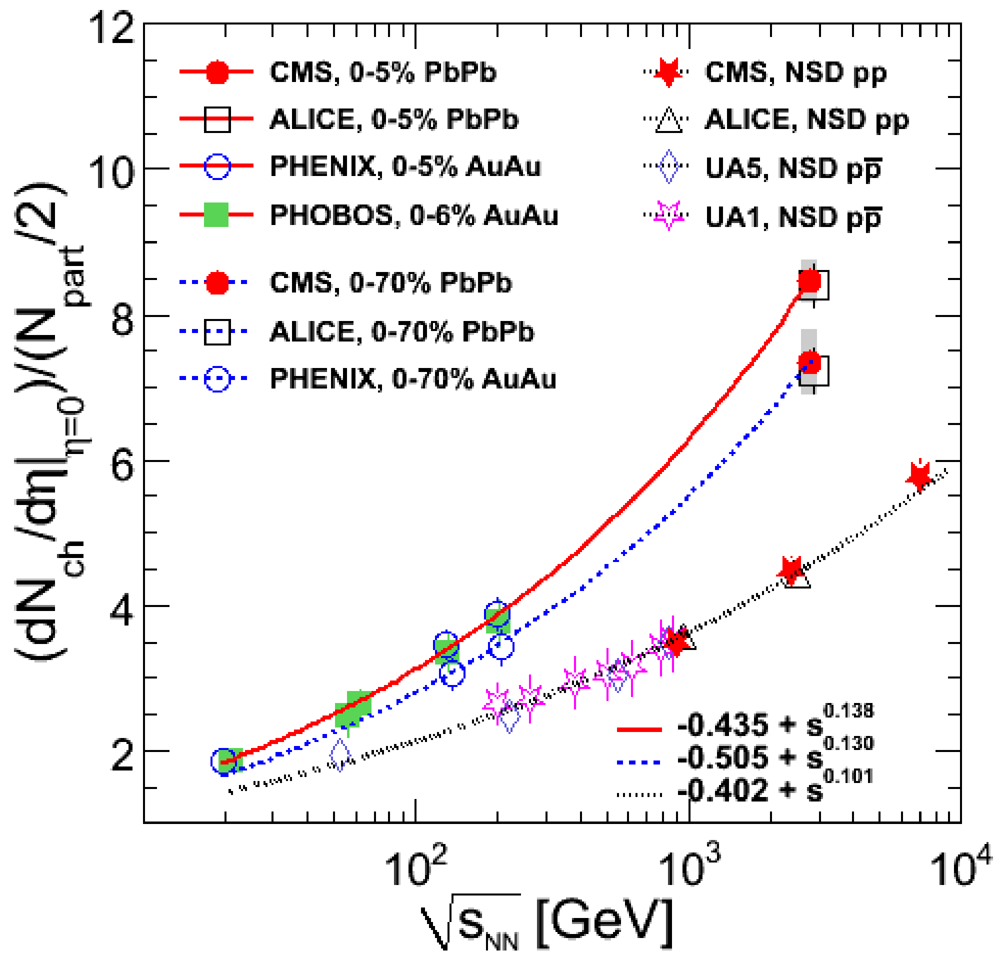
A typical PbPb central event

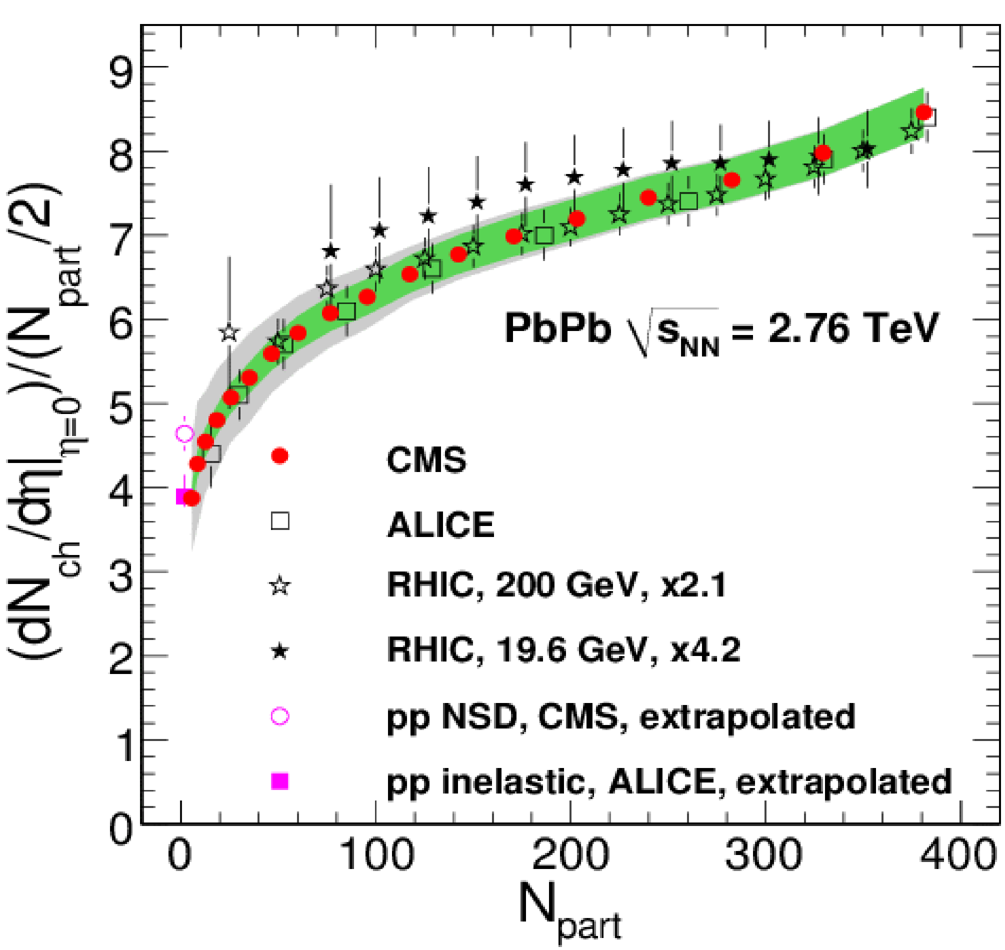


Global and collective features

Charged particle multiplicity at LHC

Multiplicity per participant grows logarithmicly with collision energy

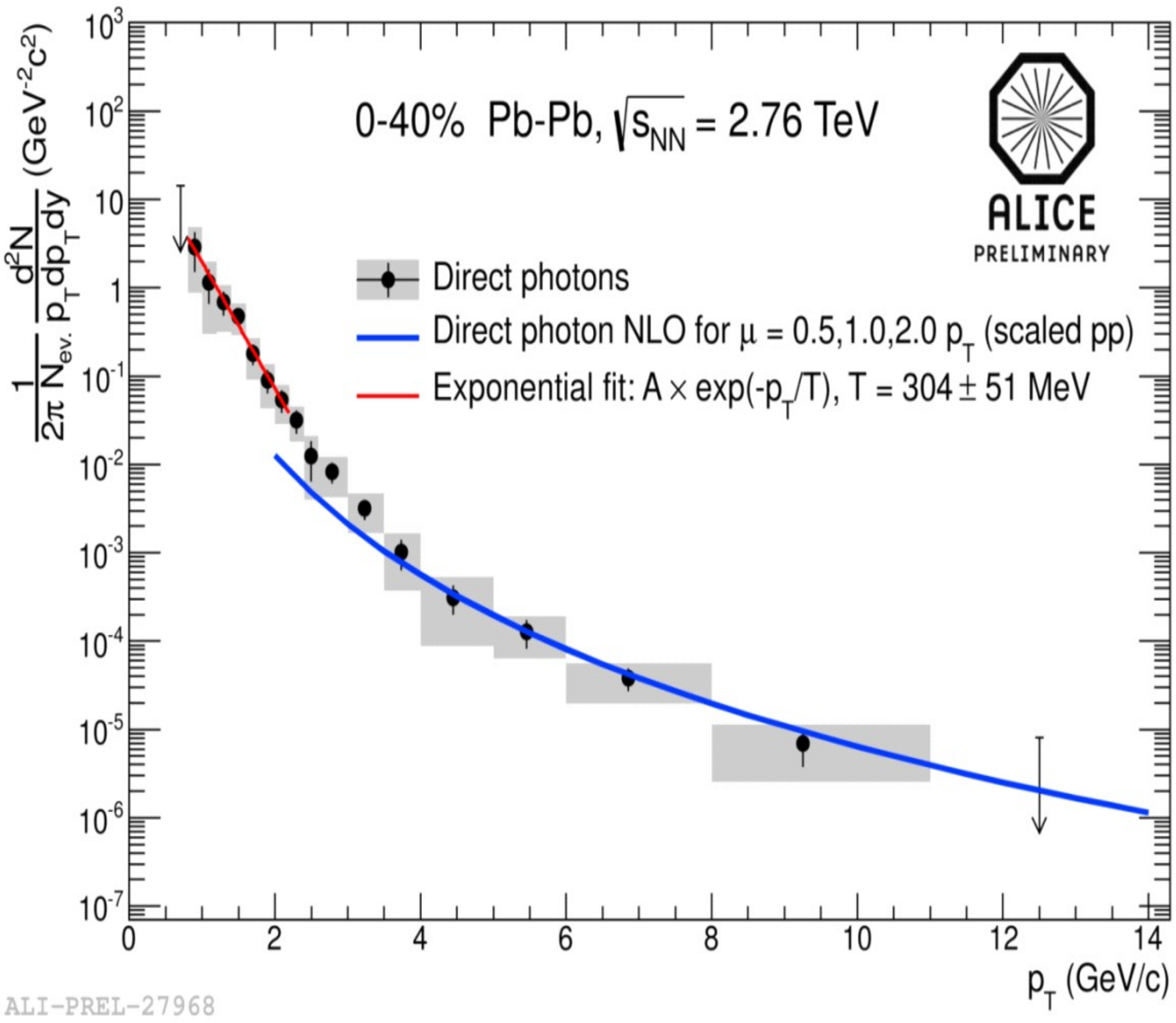




Multiplicity: > 2 x RHIC
Energy Density: 3 x RHIC

CMS, JHEP 08, 141 (2011)

LHC hotter than RHIC



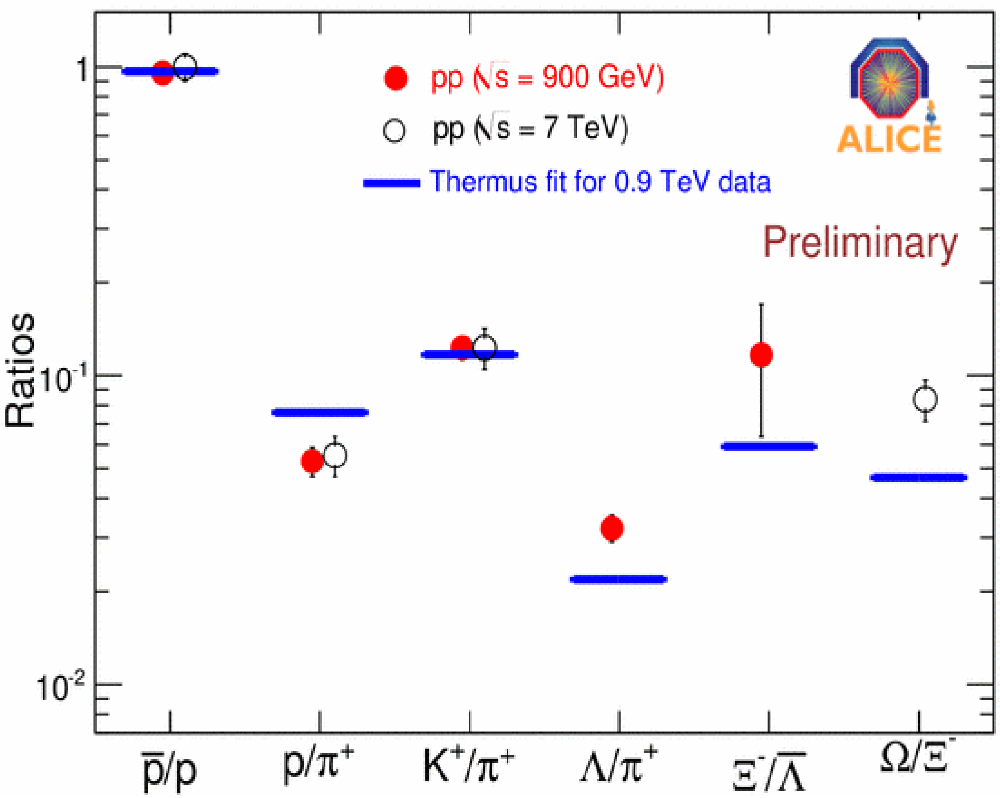
ALICE 0-40 % PbPb
Exp fit for p_T < 2.2 GeV/c
Inverse slope
T = 304 ± 51 MeV

PHENIX 0-20 % AuAu
T = 221 ± 19 ± 19 MeV

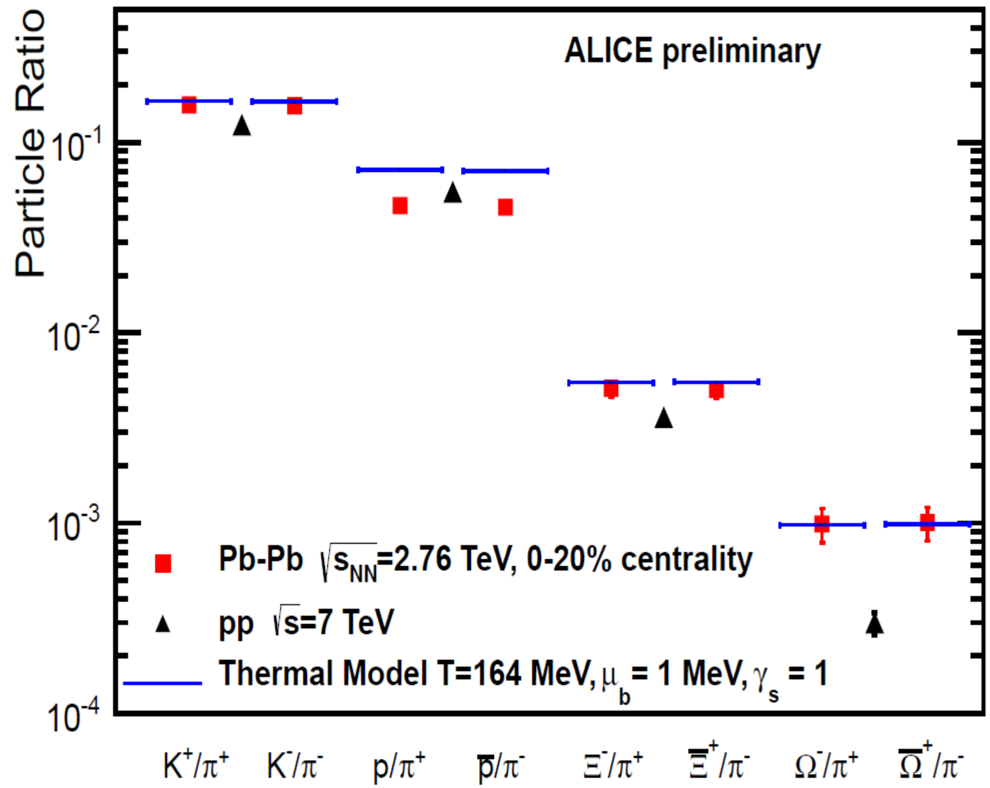
The initial temperature is 50 % higher than these values.

Hadron yield ratios
Statistical model

pp



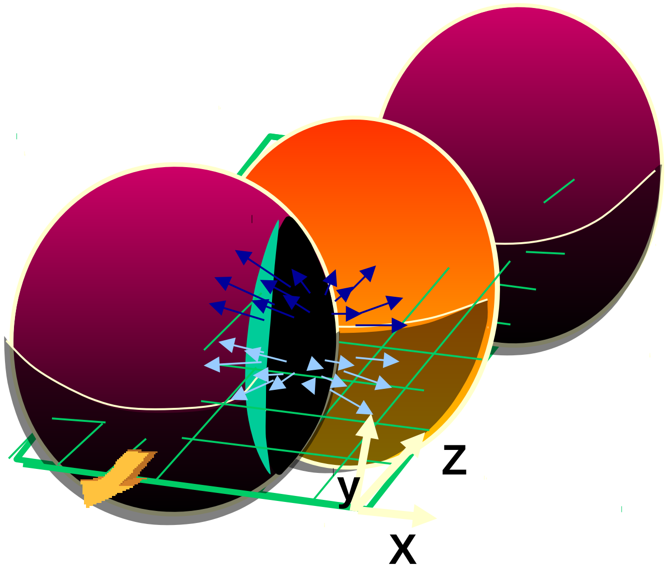
PbPb



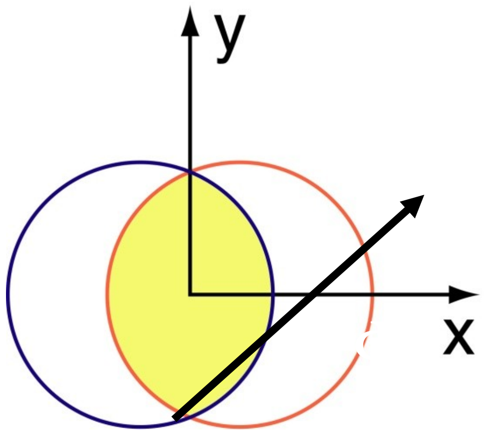
Statistical model does not describe p/π ratio:
Possible explainations
- Sequential freezeout
- Dominance of hard processes at LHC energies

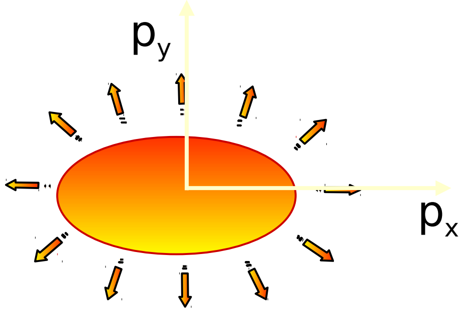
ALICE Arxiv:1303.0737

The anisotropic flow



Anisotropic Flow





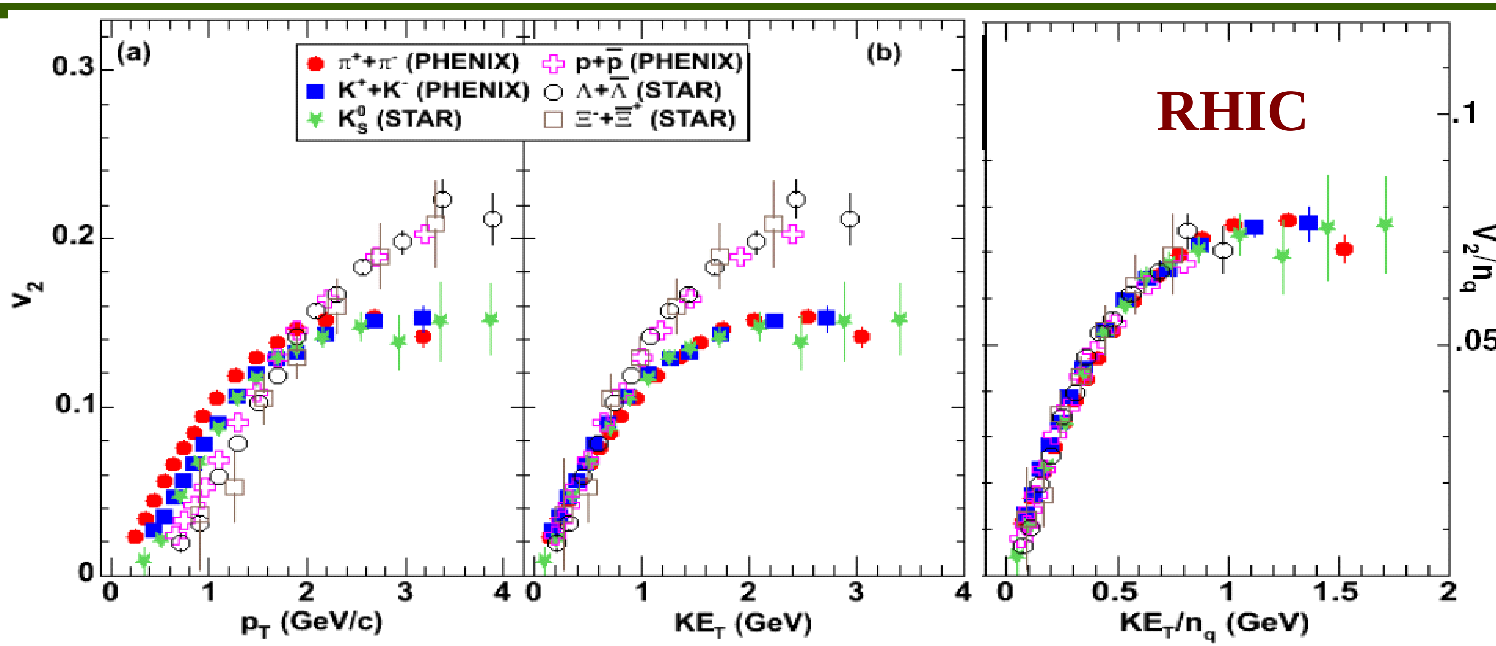
$$dN/d\phi = 1 + 2\, v1 \cos(\phi) + 2\, v2 \cos(2\phi) + 2\, v3 \cos(3\phi) + \ldots$$

$$\phi = \text{atan}\,(py/px)$$

v_2 gives pressure transfer from y to x direction

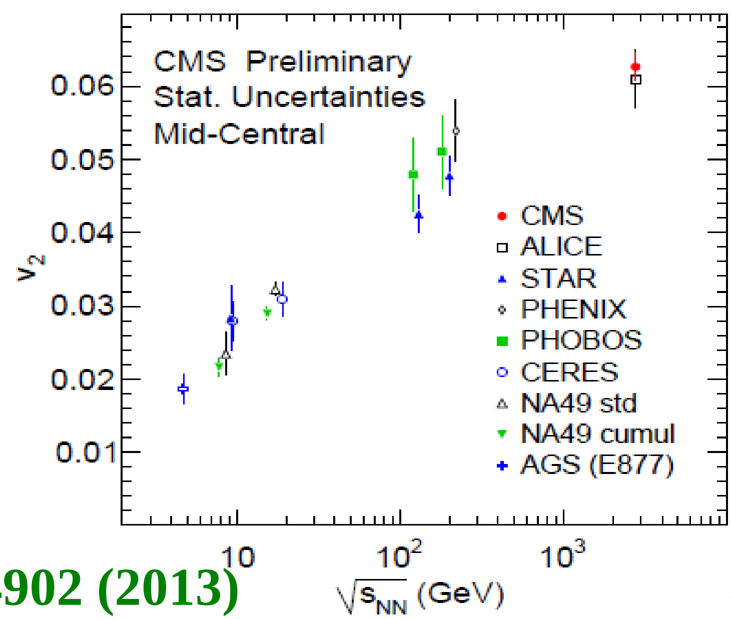
The anisotropoc flow v2

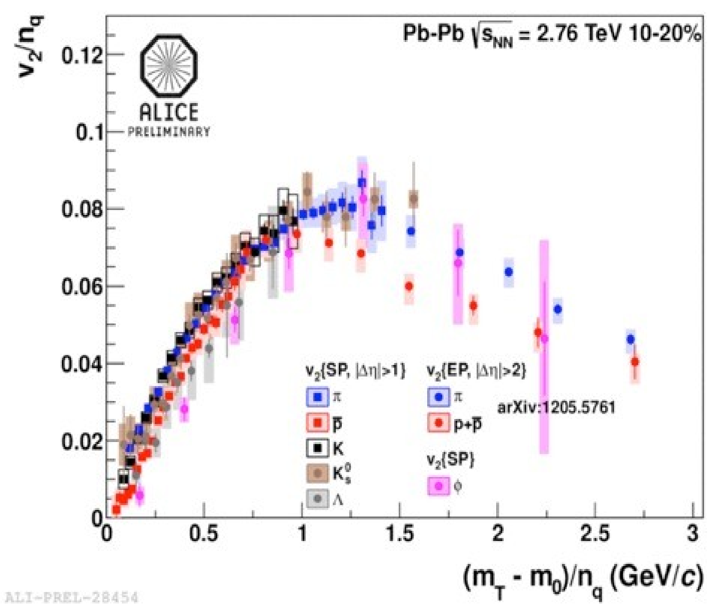
v2 scales with number of constituent quarks at RHIC



v_2 is 30 % higher at LHC <p_T> is also higher

Quark scaling is not good.





CMS, PRC87, 014902 (2013)

ALICE Arxiv:1309.3237

η/S at LHC

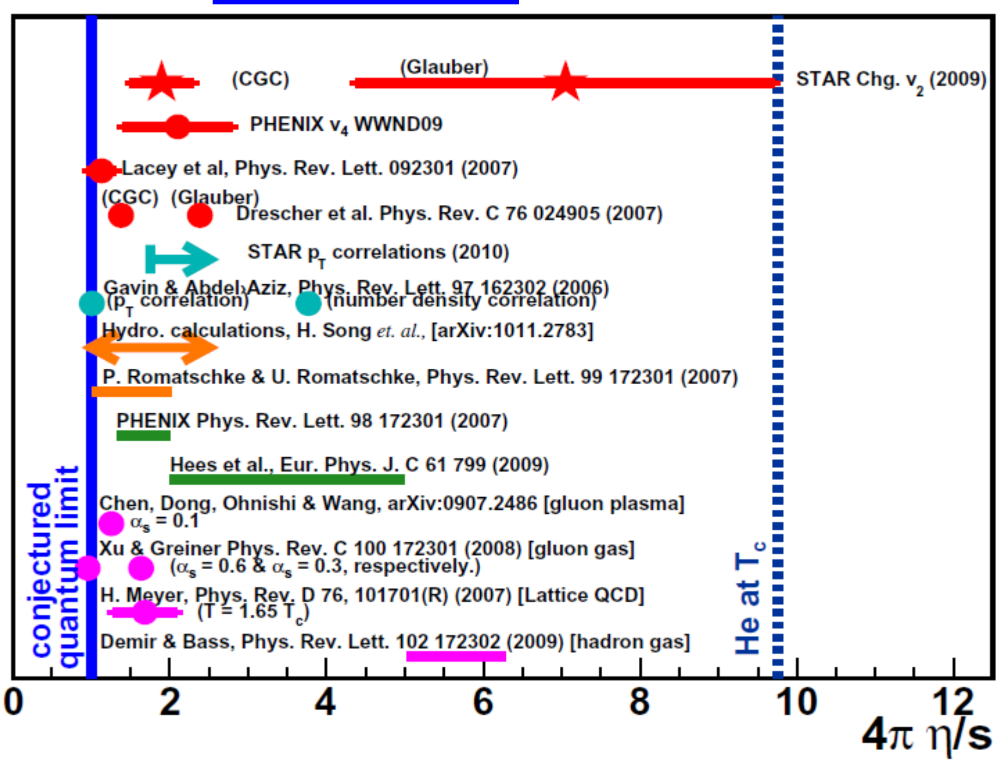
Measurements of higher harmonic flows at LHC + Better Hydro codes

-> improved precision of η/S

$$\eta = \frac{\sqrt{2mkT}}{\sigma}$$

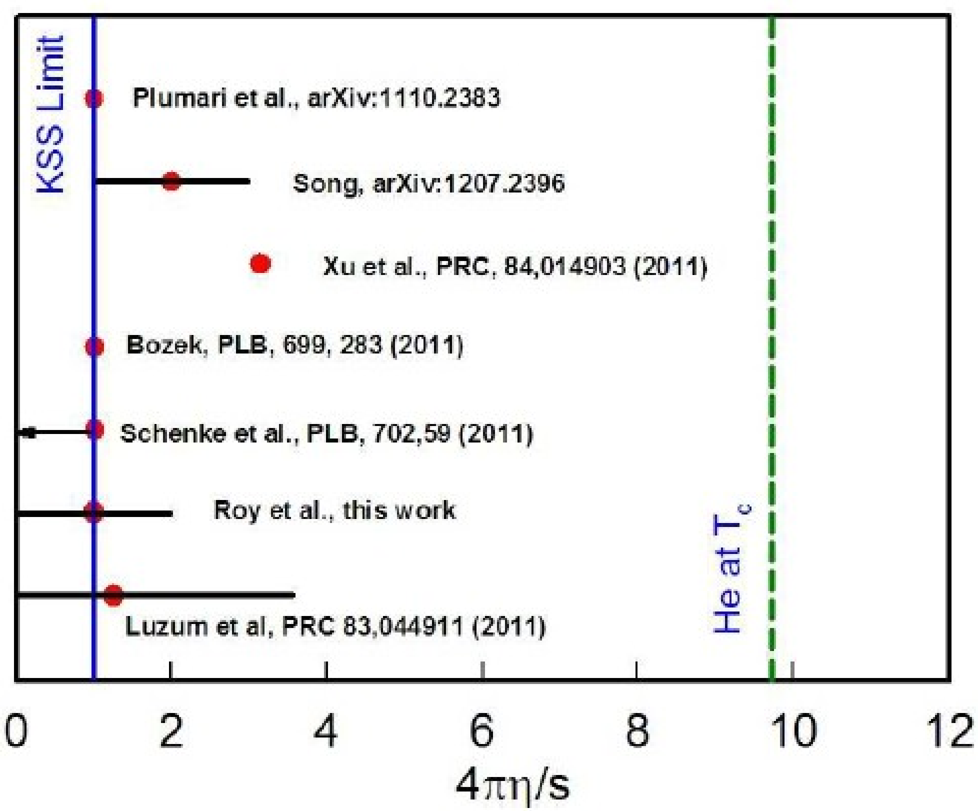
RHIC

4πη/S < 3-6



LHC

4πη/S < 2-3



Quarkonia and colour screening

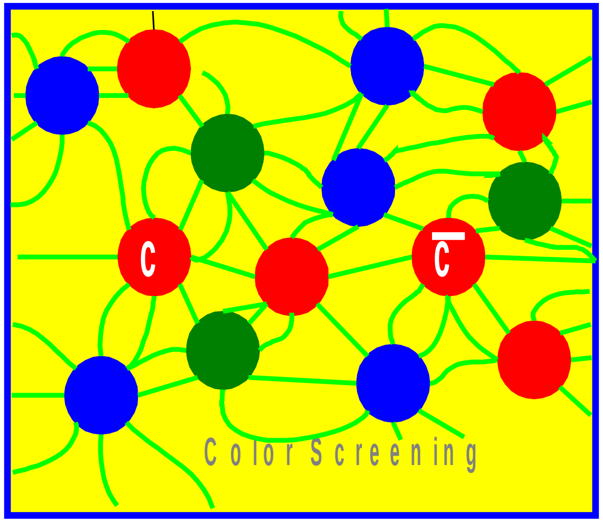
Quarkonia as probes of QGP

Particles with hidden Charm and beauty produced in initial collisions:

1. **J/Ψ (~3.1 GeV) - bound state of (c cbar)**
2. **Υ - Upsilon (~9.5 GeV) - bound state of (b bbar)**

Quarkonia as probes of strongly interacting matter

Debye screening in QGP leads to sequential melting as per the binding energy of quarkonia states.

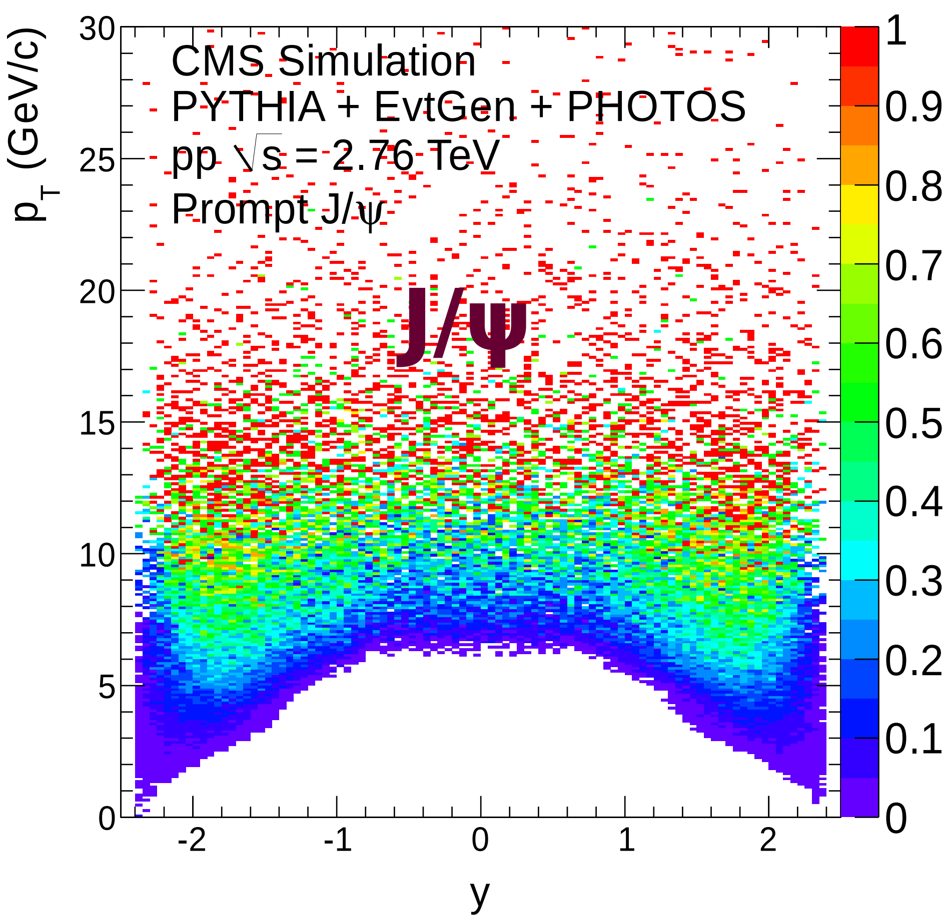


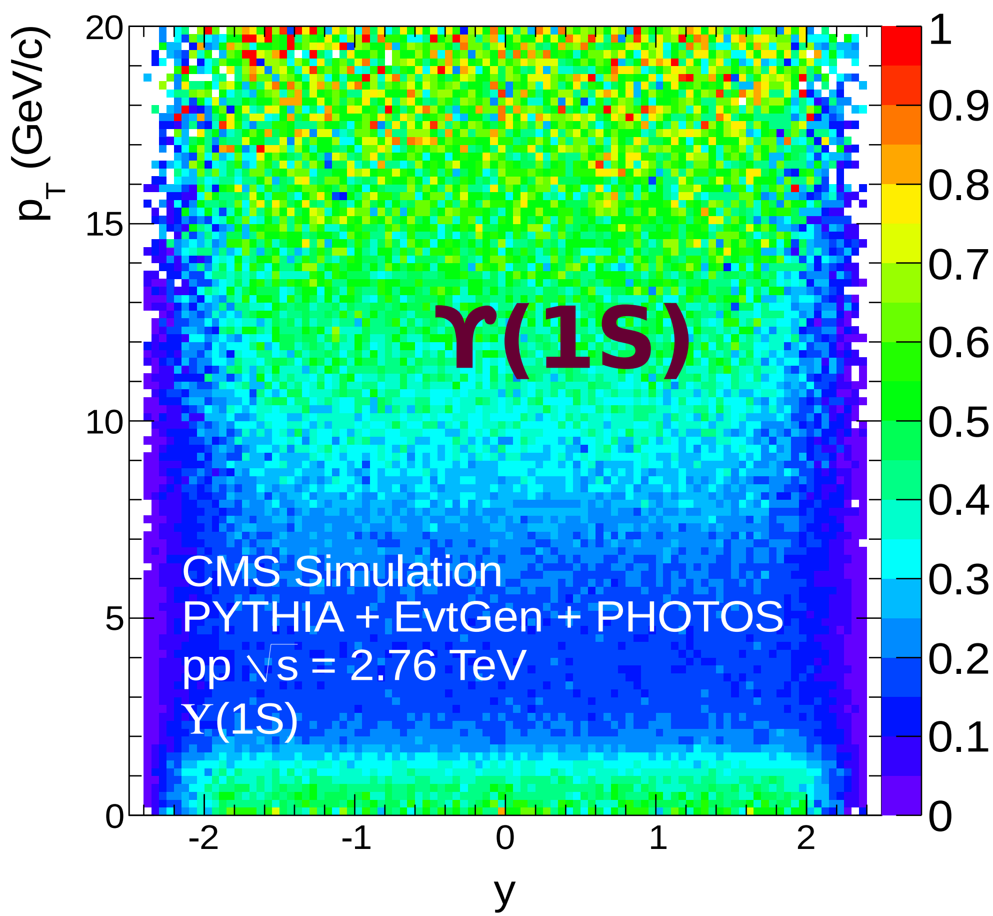
Nuclear & Comover suppression

Shadowing

Regeneration

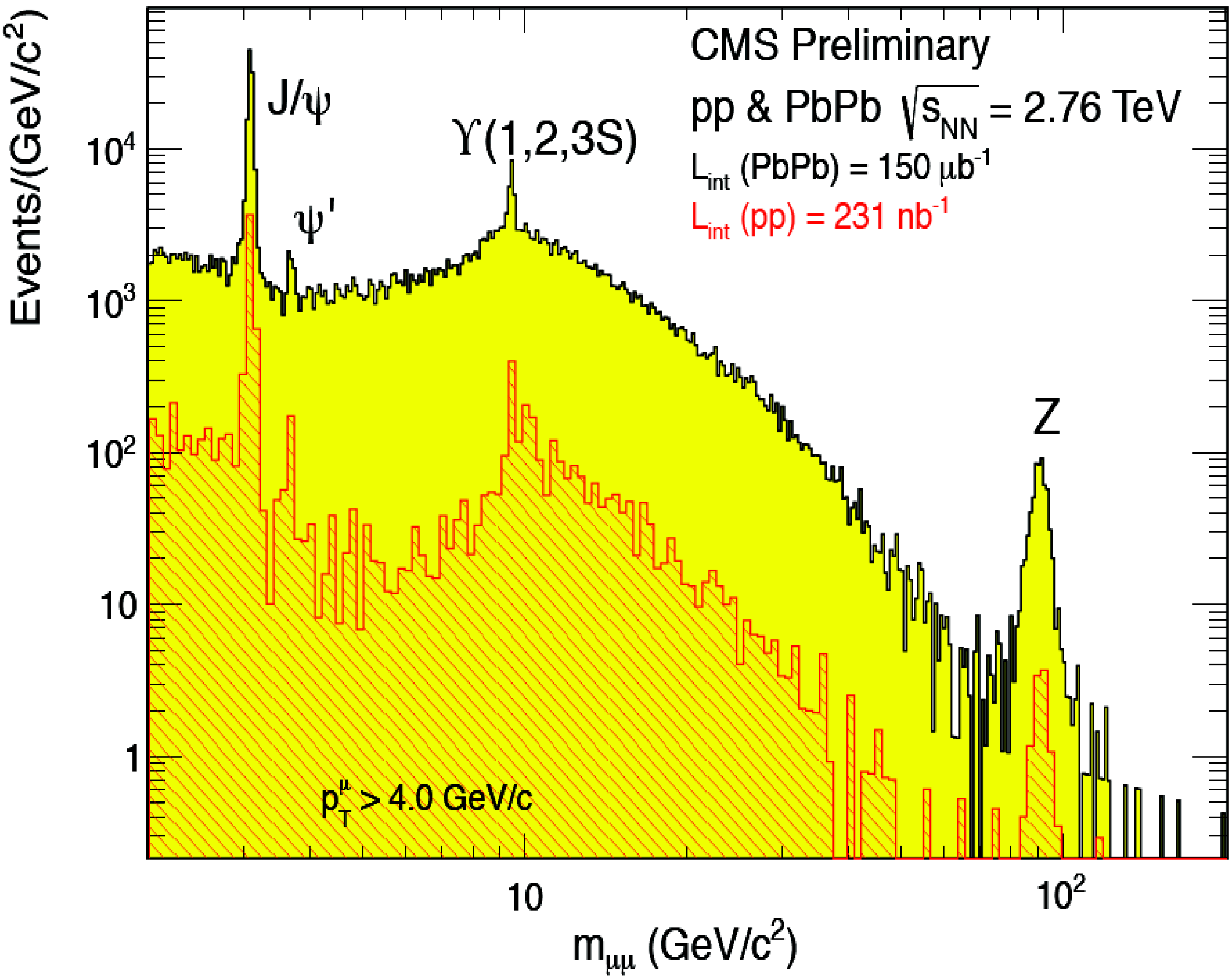
Quarkonia acceptance of CMS





- **Single muons: p_{min} ~ 3-5 GeV/c for muon stations**
  - **J/ψ: p_{Tmin} ~ 3 GeV/c for |y| > 1.6**
  - **ϒ: p_{Tmin} = 0 GeV/c for |y| < 2.4**

Dimuons with 2011 Pb+Pb data at LHC



In 2013 we had

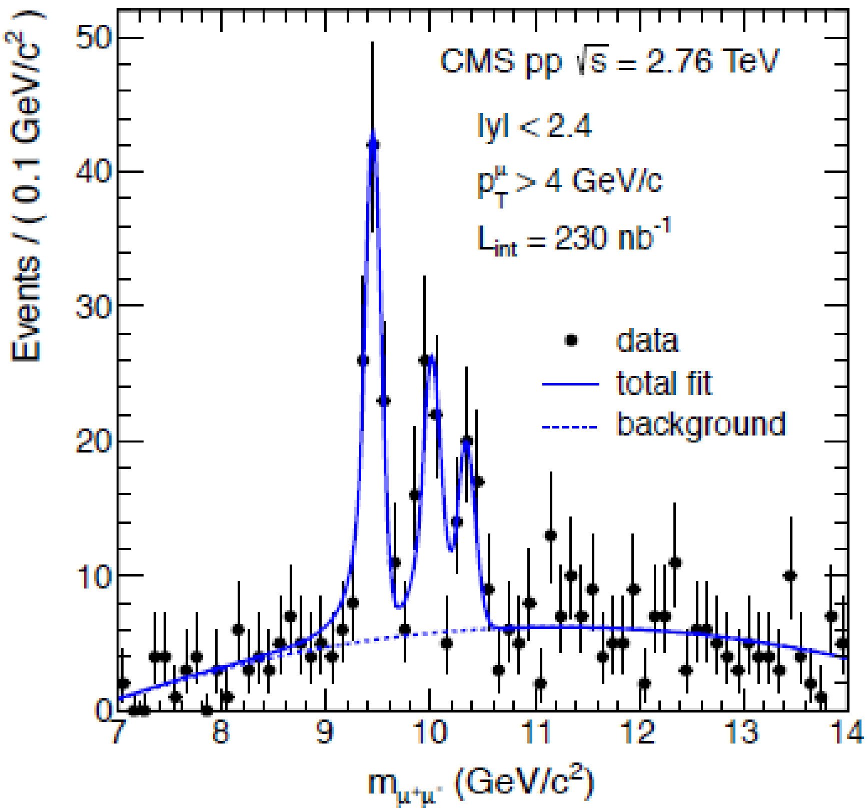
pPb@ $\sqrt{s_{NN}}$ = 5.02 TeV, 31.7 /nb

pp @ $\sqrt{s_{NN}}$ = 2.76 TeV 5.4 /pb

Bottomonia measurements

Υ states and their ratios

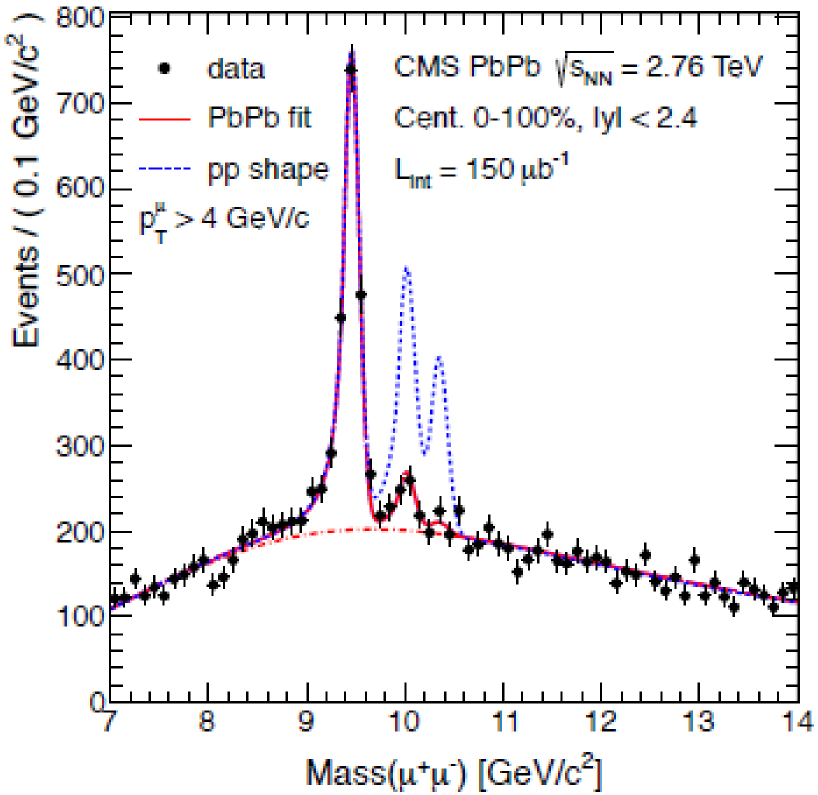
pp



$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.02$$

$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.41 \pm 0.11 \pm 0.04$$

PbPb

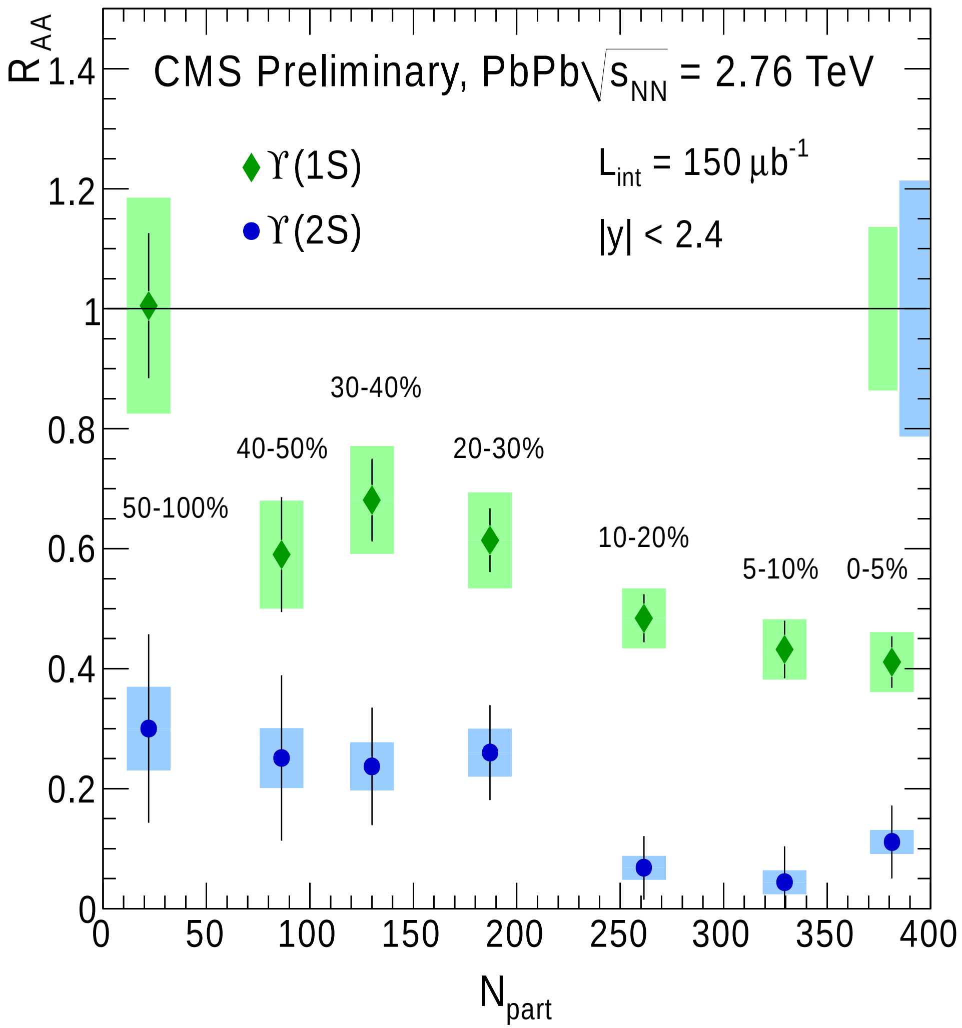


$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.02$$

$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

Phys. Rev. Lett. 109, 222301 (2012)
CMS HIN-11-011,

Centrality dependence of suppression of Y states



Clear suppression of Y(2S)

Suppression of Y(1S)

(includes feed down from higher states)

Centrality integrated:

$$R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08\,(\text{stat.}) \pm 0.07\,(\text{syst.})$$

$$R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04\,(\text{stat.}) \pm 0.02\,(\text{syst.})$$

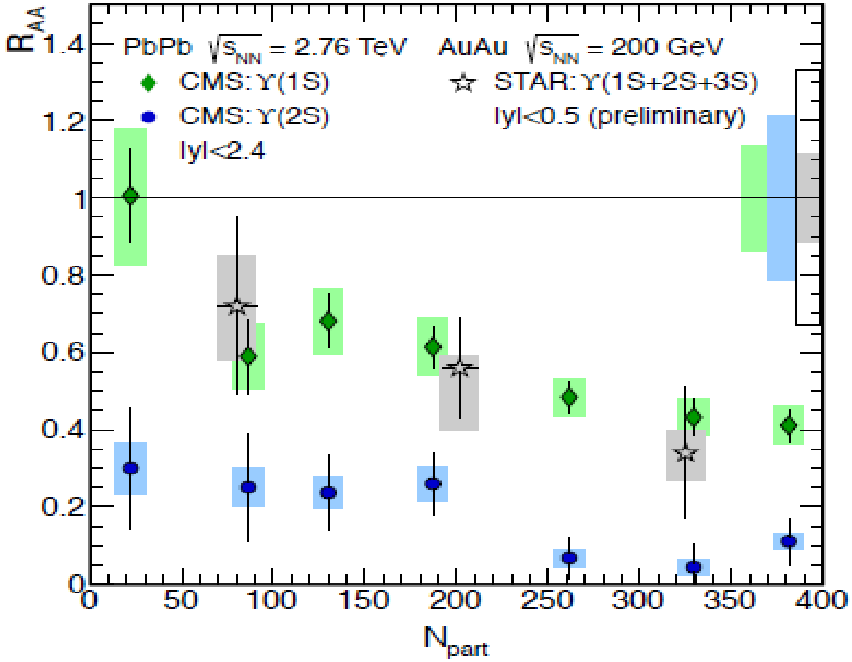
$$R_{AA}(\Upsilon(3S)) < 0.1\ \ (\text{at } 95\%\ \text{C.L.})$$

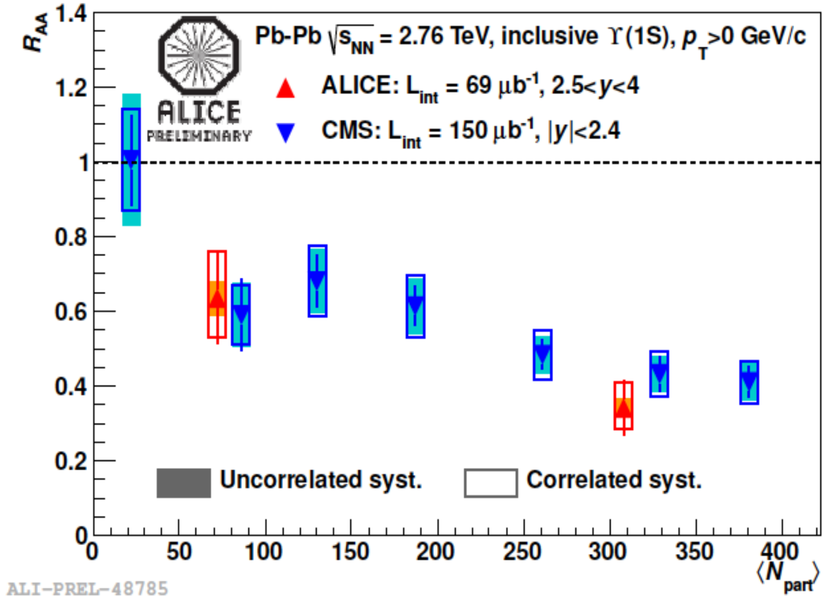
Sequential suppression of the three states in order of their binding energies

The new pp measurements will allow R_{AA} of Y(2S) Vs p_T and y and will improve R_{AA} of Y(1S) vs p_T and y.

Phys. Rev. Lett. 109, 222301 (2012)
CMS HIN-11-011,

Upsilon- R_{AA} : Are Different experiments Consistent ?





STAR (arXiv:1109.3891)
Centrality integrated R_{AA} of Y(1S) +Y(2S)+Y(3S)

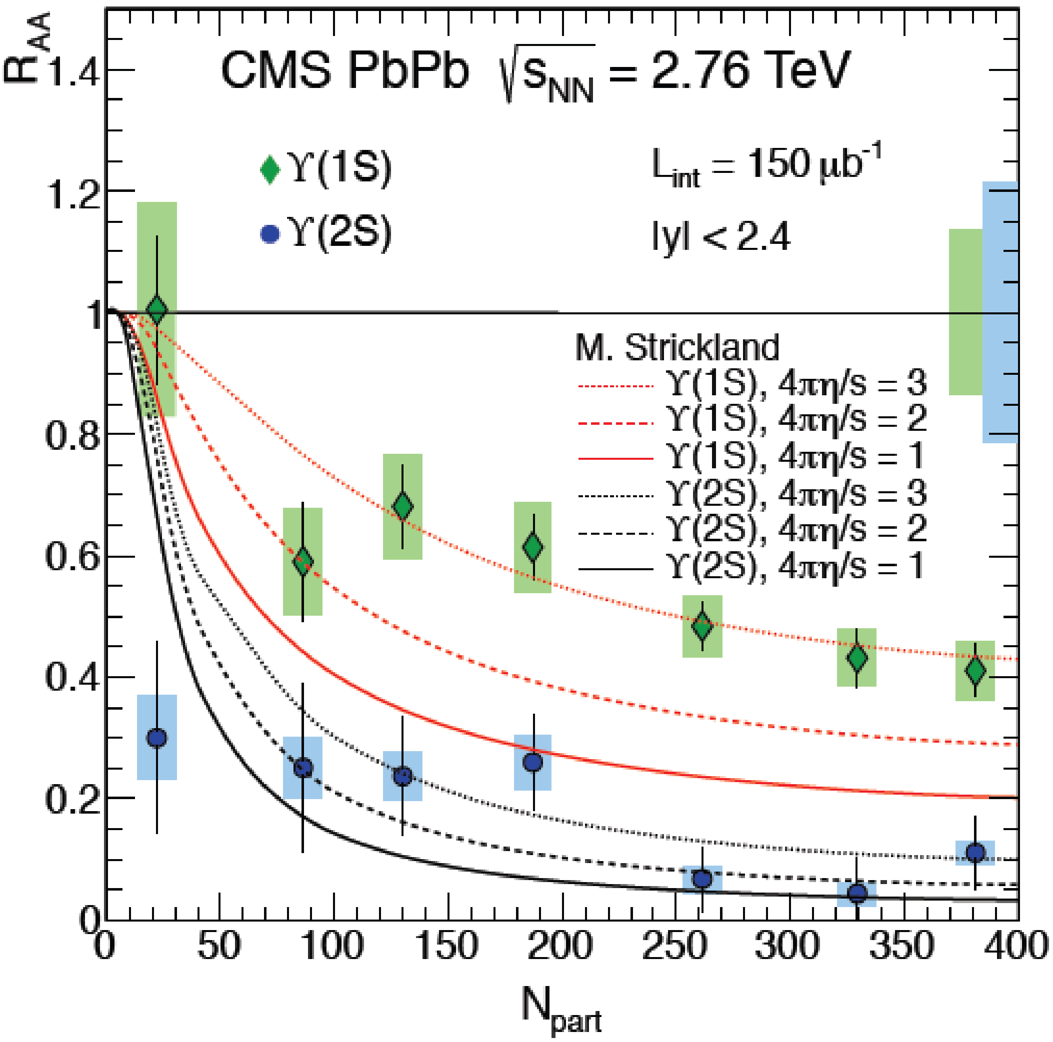
$$R_{AA}(\Upsilon(1S+2S+3S)) = 0.56 \pm 0.21^{+0.08}_{-0.16}$$

CMS: Centrality integrated R_{AA}

$$R_{AA}(\Upsilon(1S+2S+3S))$$
$$= R_{AA}(\Upsilon(1S)) \times \frac{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{PbPb}}}{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{pp}}}$$
$$= 0.56 \times \frac{1+0.14}{1+0.97} \approx 0.32$$

ALICE and CMS consistent
More suppression at LHC as compared to RHIC

Υ suppression: QGP models



- Starts with lattice-based potentials
- Calculates thermal widths of quarkonia as a function of temp.
- Dynamical expansion with initial conditions (for fixed dNch/dy)

  552 MeV < T0 < 580 MeV

  1 < 4pi η/S < 3
- Includes feed down corrections
- Tau0 = 0.3 fm/c

Requires different η/S values for explaining Υ(2S) and Υ(3S) suppressions. Also the shape of p_T distribution of Υ(1S) not reproduced

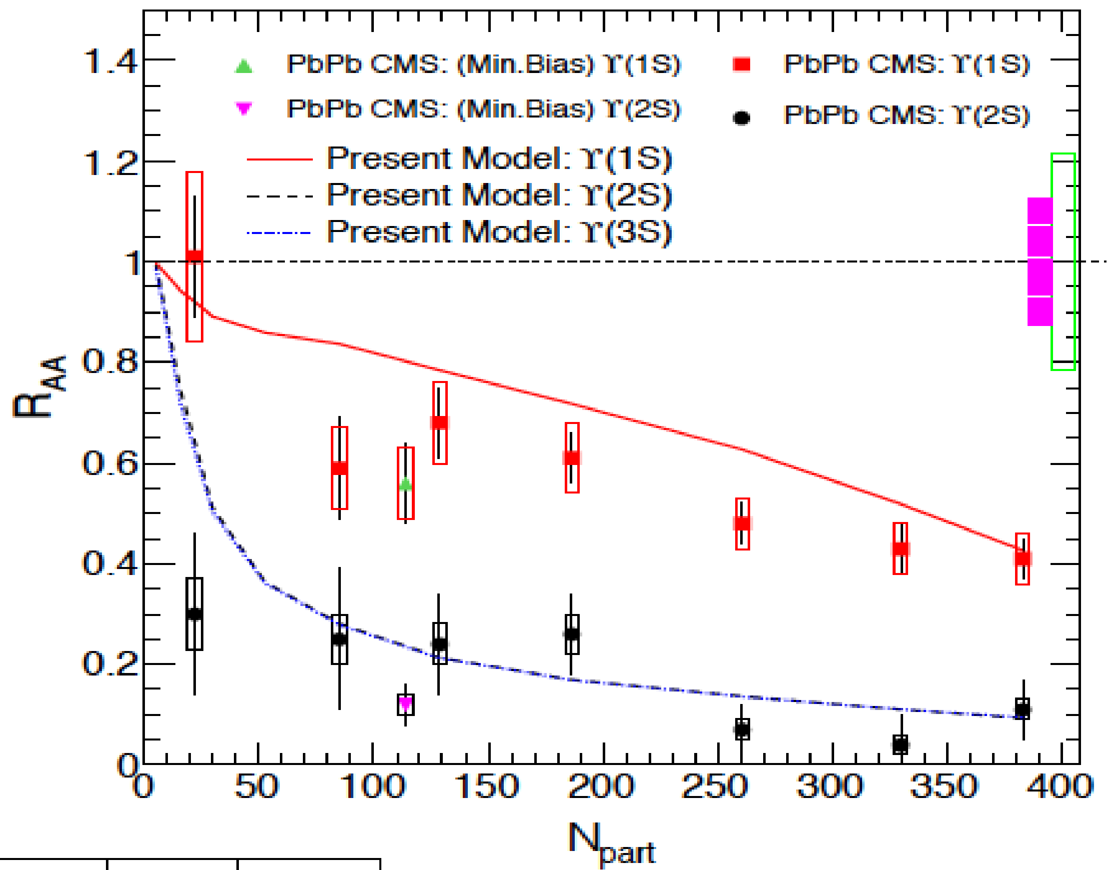
M. Strickland and D. Bazow, NPA 879, 25 (2012)

M. Strickland, PRL 107, 132301 (2011)

Υ suppression: Colour screening

- **The bottomonia properties: formation time and dissociation temperature are obtained using potential models.**

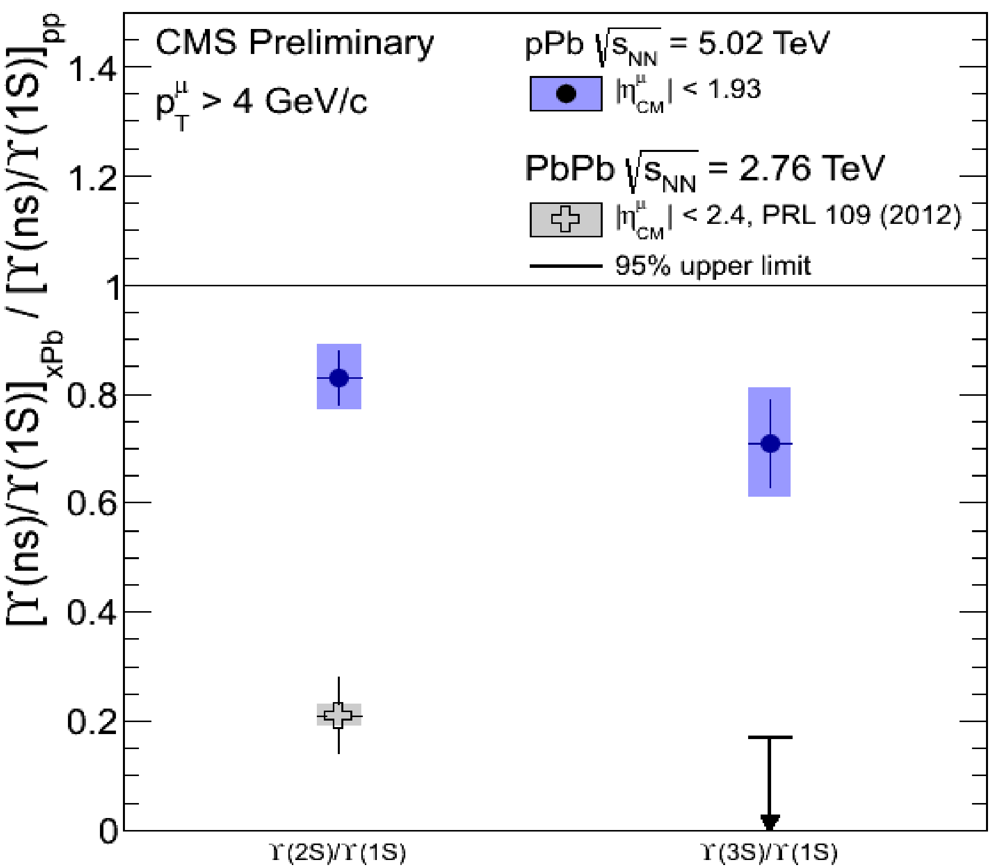
- **Feed down corrections are accounted**

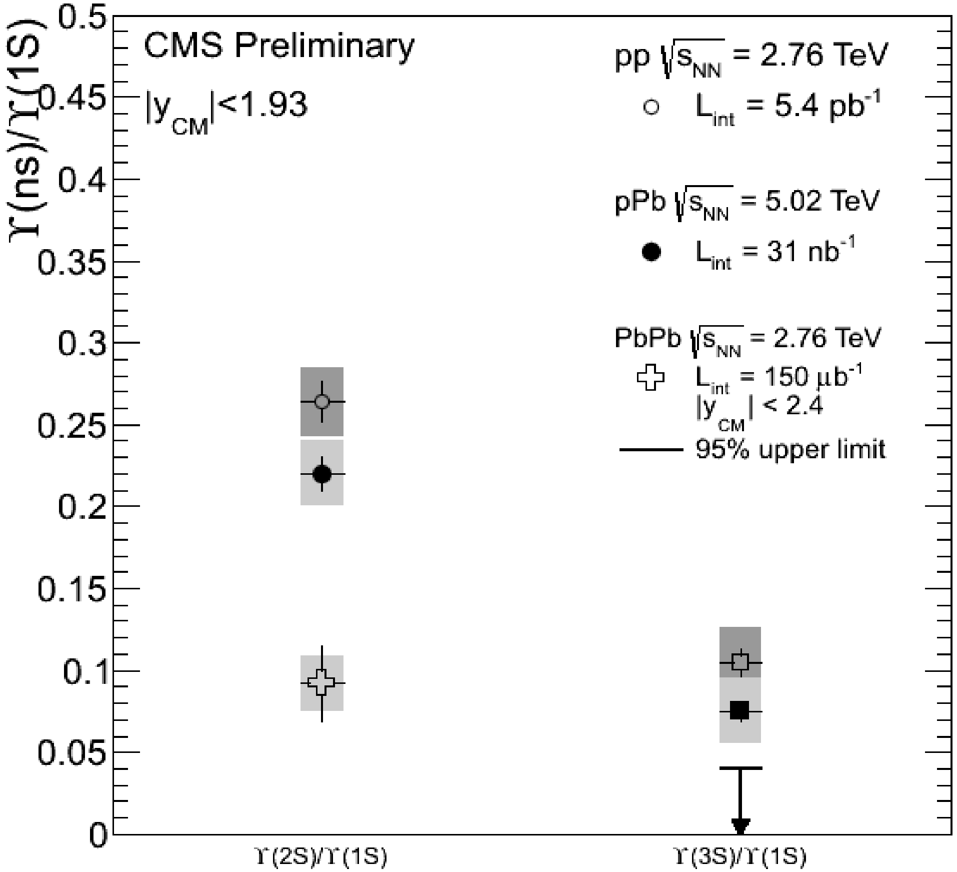


Bottonium properties	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\chi_b(2P)$
T_D [GeV] upper limit [18] **PRL 99, 211602 (2007).**	$2\ T_C$	$1.3\ T_C$	$1.2\ T_C$	$1\ T_C$	
T_D [GeV] used in the present work	$1.8\ T_C$	$1.15\ T_C$	$1.1\ T_C$	$0.9\ T_C$	

A. Abdulsalam and P Shukla
IJMPA28, 1350105 (2013)

Y Suppression in pPb at LHC

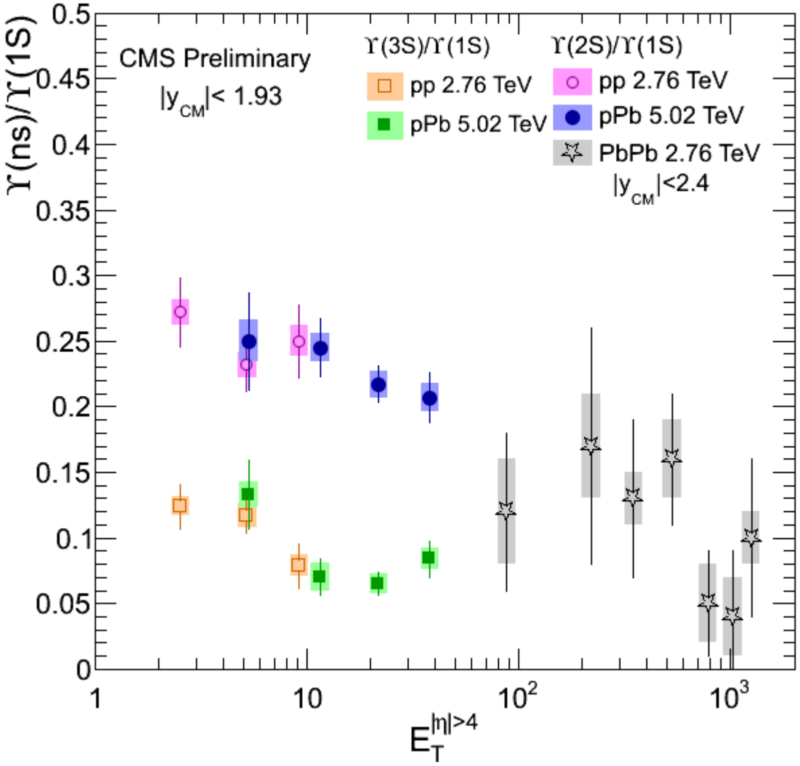


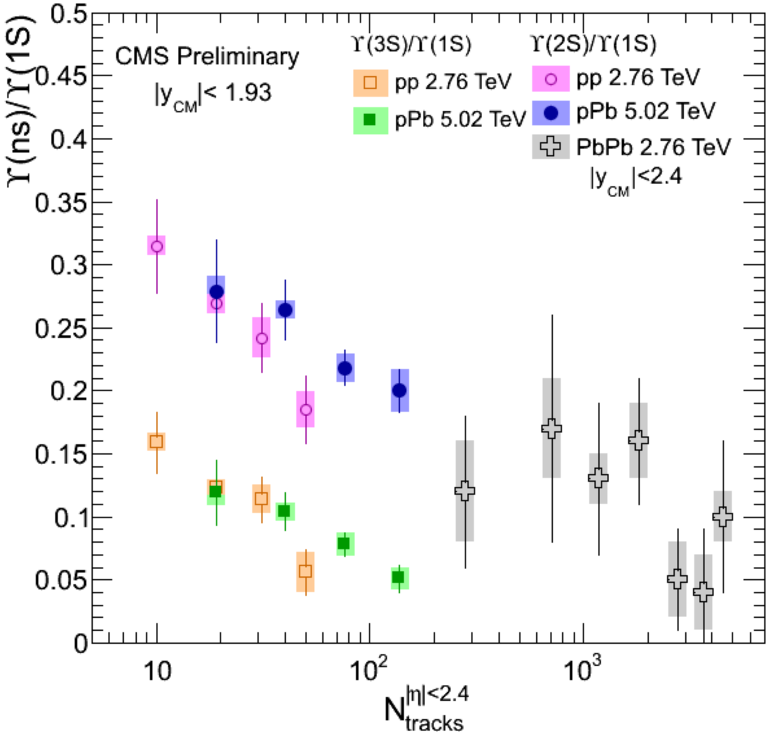


- **In Double Ratio (DR) initial state effects cancel to first approximation.**
- **DR suggest presence of effects in pPb collisions compared to pp collisions.**
- **Affect ground state and excited states differently.**

arXiv:1312.6300 [nucl-ex]

Υ ratios in different systems



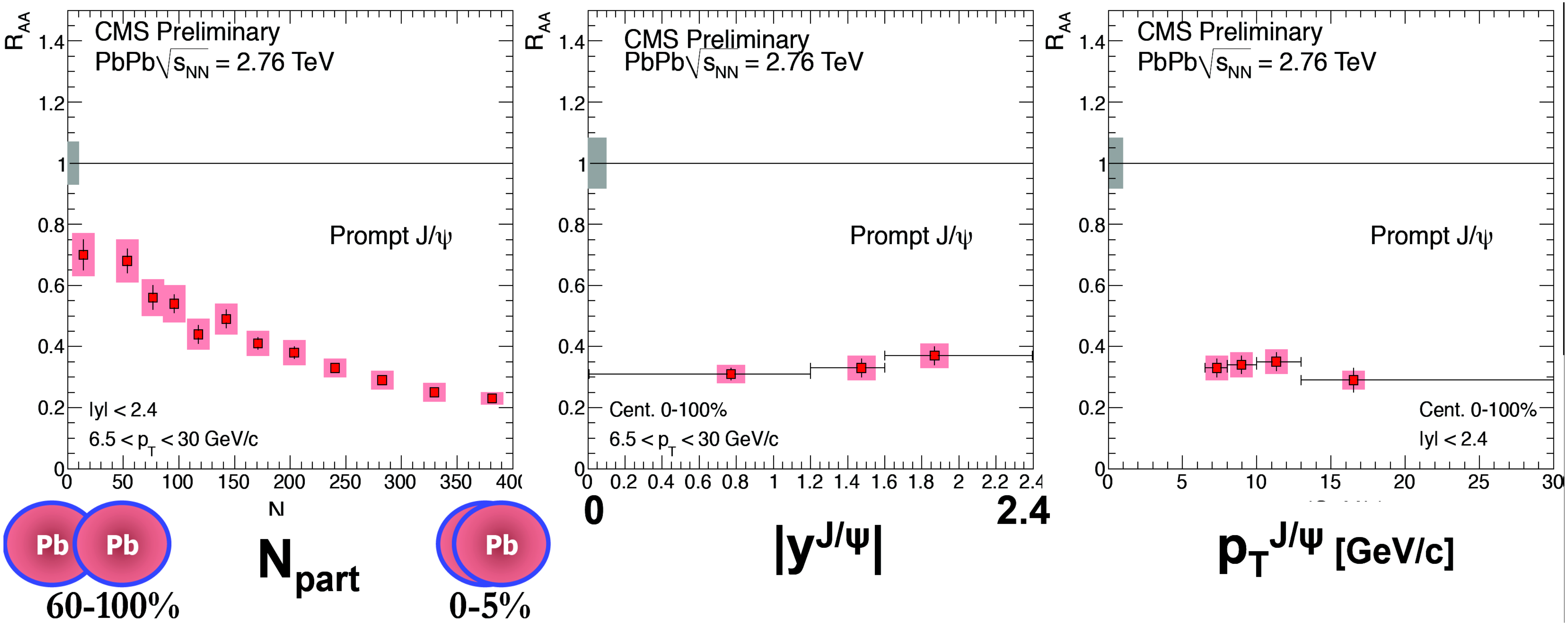


- ❑ **Single Ratios are compared for all three collision systems.**
- ❑ **All pp and pPb ratios are far above the PbPb activity-integrated ratios.**
- ❑ **Ratio seems to be constantly decreasing with increasing mid rapidity multiplicity.**
- ➢ **More PbPb data are needed to investigate the dependence in three systems and their possible relation.**

arXiv:1312.6300 [nucl-ex]

Charmonia measurements

R_{AA} prompt J/Ψ

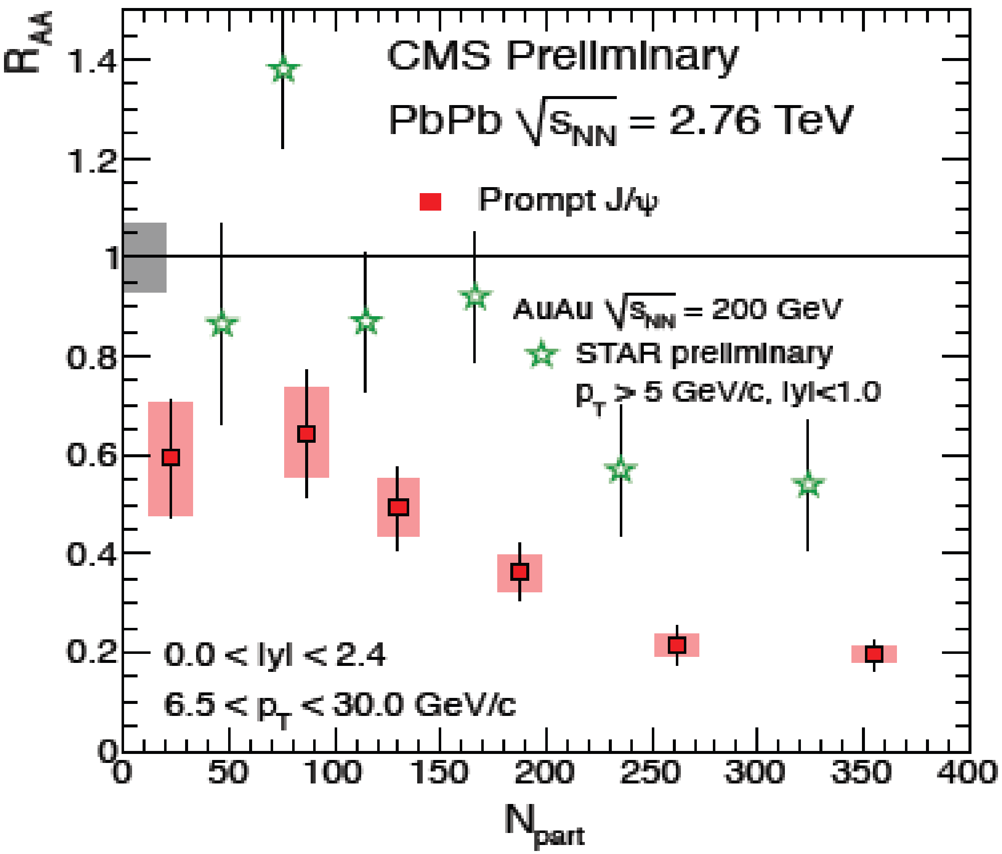


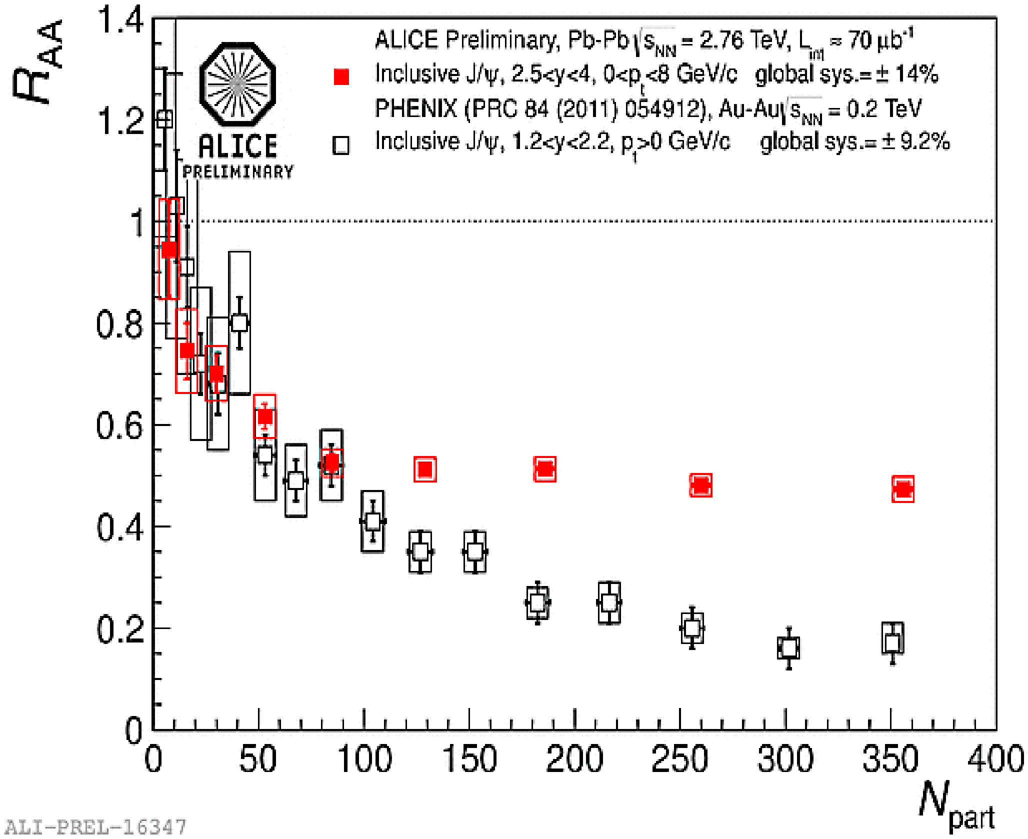
Centrality, p_T and rapidity:

- **0-5%(most central)** **factor ~5 suppression**
- **60-100% (most peripheral)** **factor ~1.4 suppression**
- **Weak p_T dependence (High p_T)**
- **Weak rapidity dependence**
- **With the new pp run expect finer binnings of p_T and y**

CMS-PAS-12-014

J/ψ: RHIC vs LHC

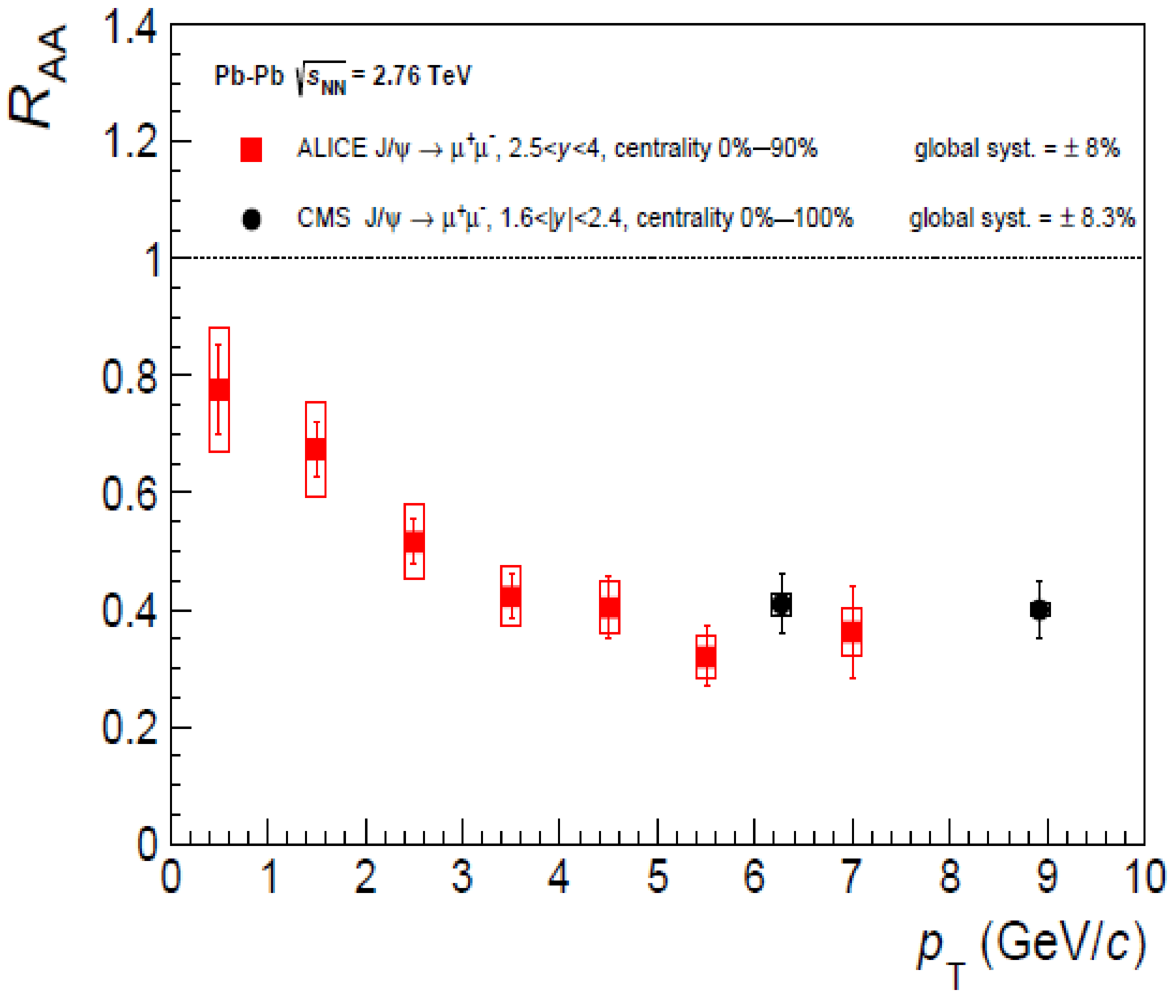




At high-p_T: J/ψ more suppressed at LHC → More screening

But at low-p_T: J/ψ less suppressed at LHC → Regeneration

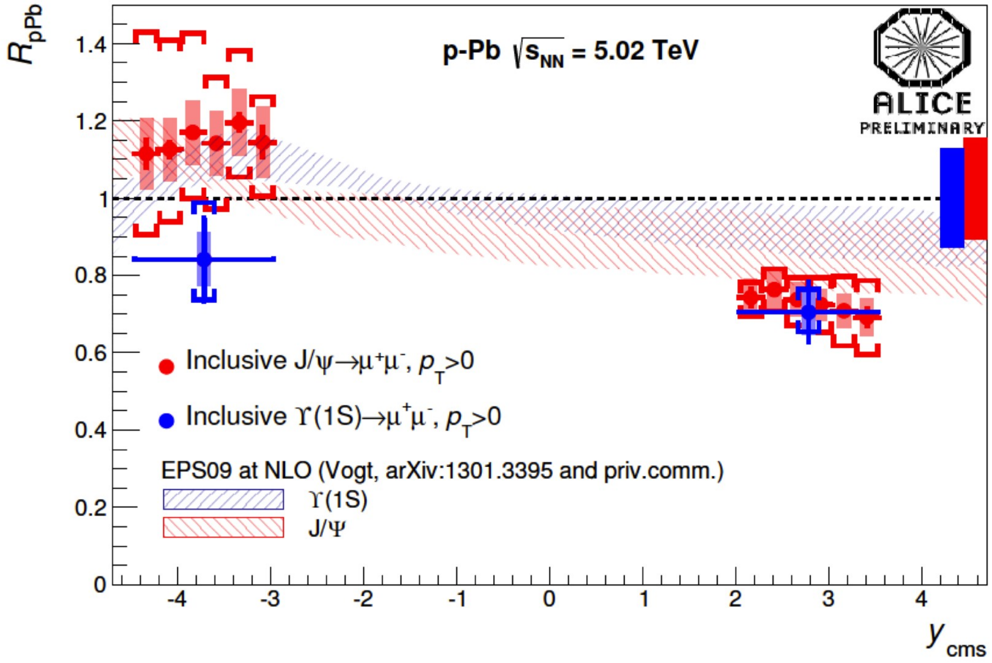
J/ψ R_{AA}: ALICE vs CMS



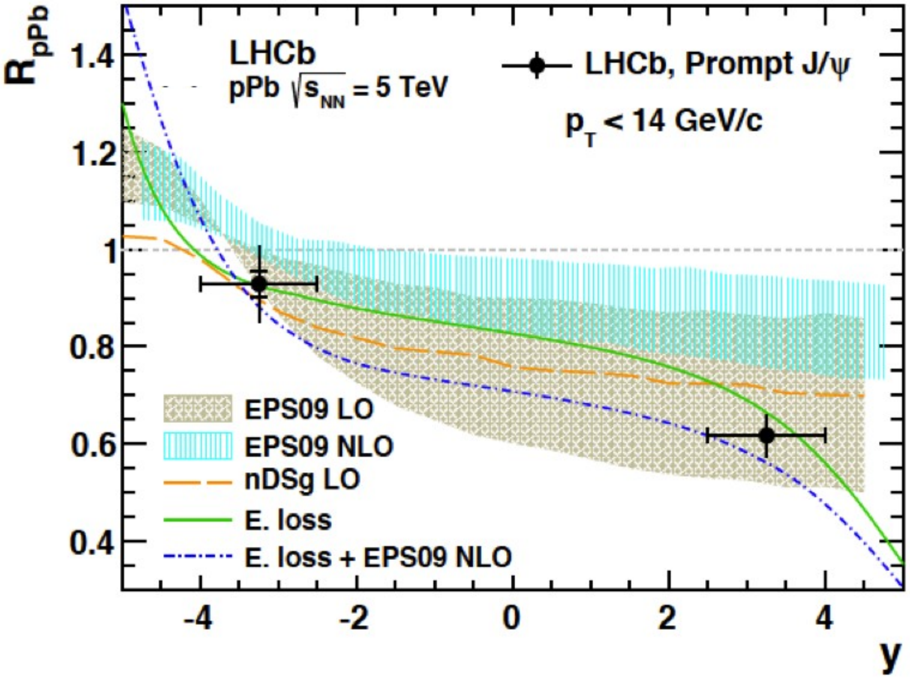
- At high p_T ALICE and CMS are consistent.
- Regeneration may causes the low p_T bump

ALICE: arxiv 1311.0214
CMS:JHEP 1205 (2012) 063

Quarkonia: p+Pb collisions at LHC: Rapidity Dependence



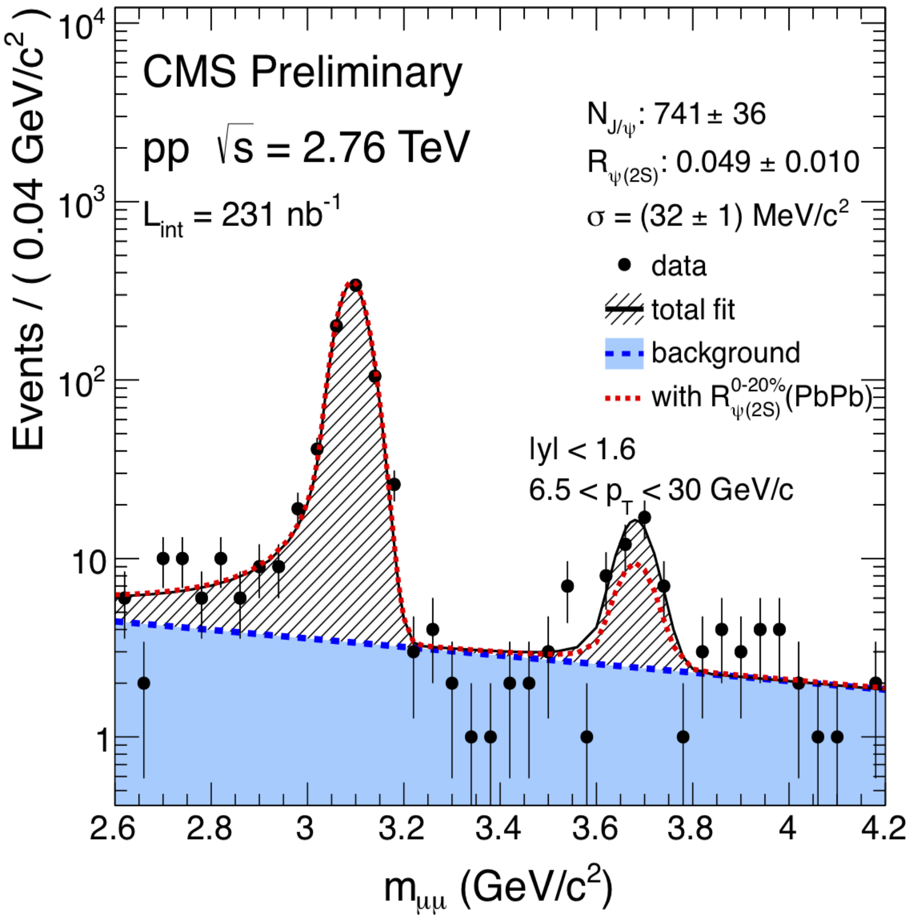
ALICE Collaboration hep-ex:1308.6726

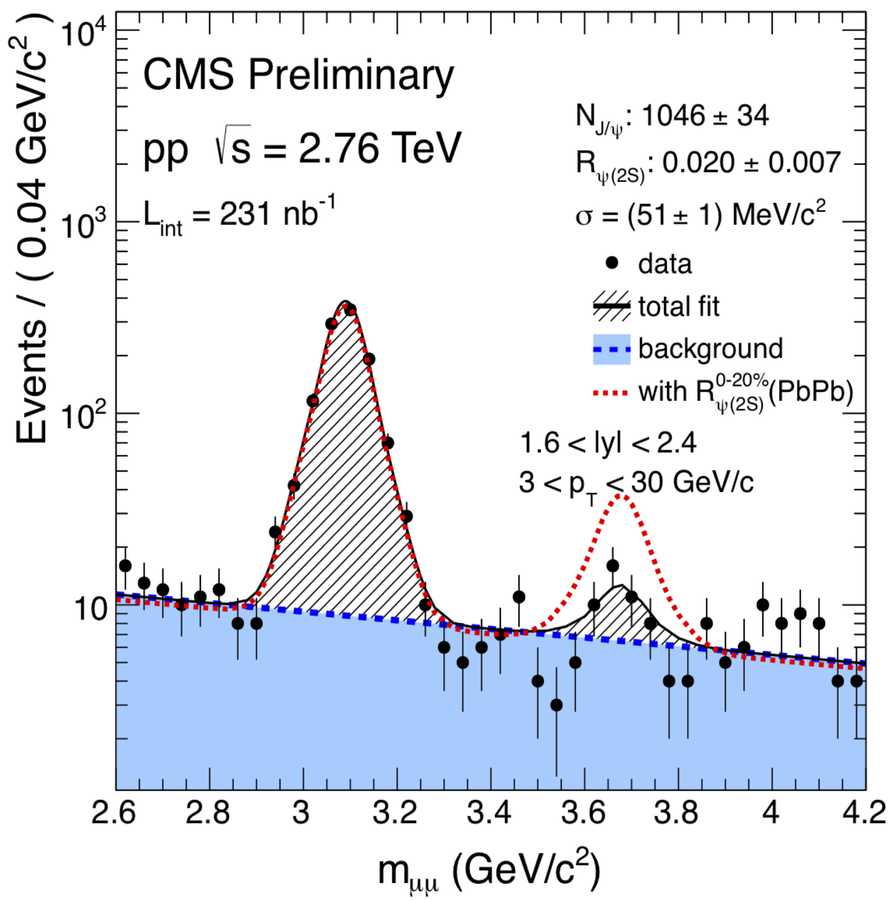


LHCb Collaboration hep-ex:1308.6729

- **ALICE measured inclusive J/ψ and ϒ in forward and backward rapidity regions.**
- **LHCb measure prompt J/ψ.**
- **J/ψ production decreases with respect to pp collisions from backward to forward rapidity.**
- **Only shadowing is not sufficient to reproduce data.**

Ratio of Ψ(2S) and J/Ψ



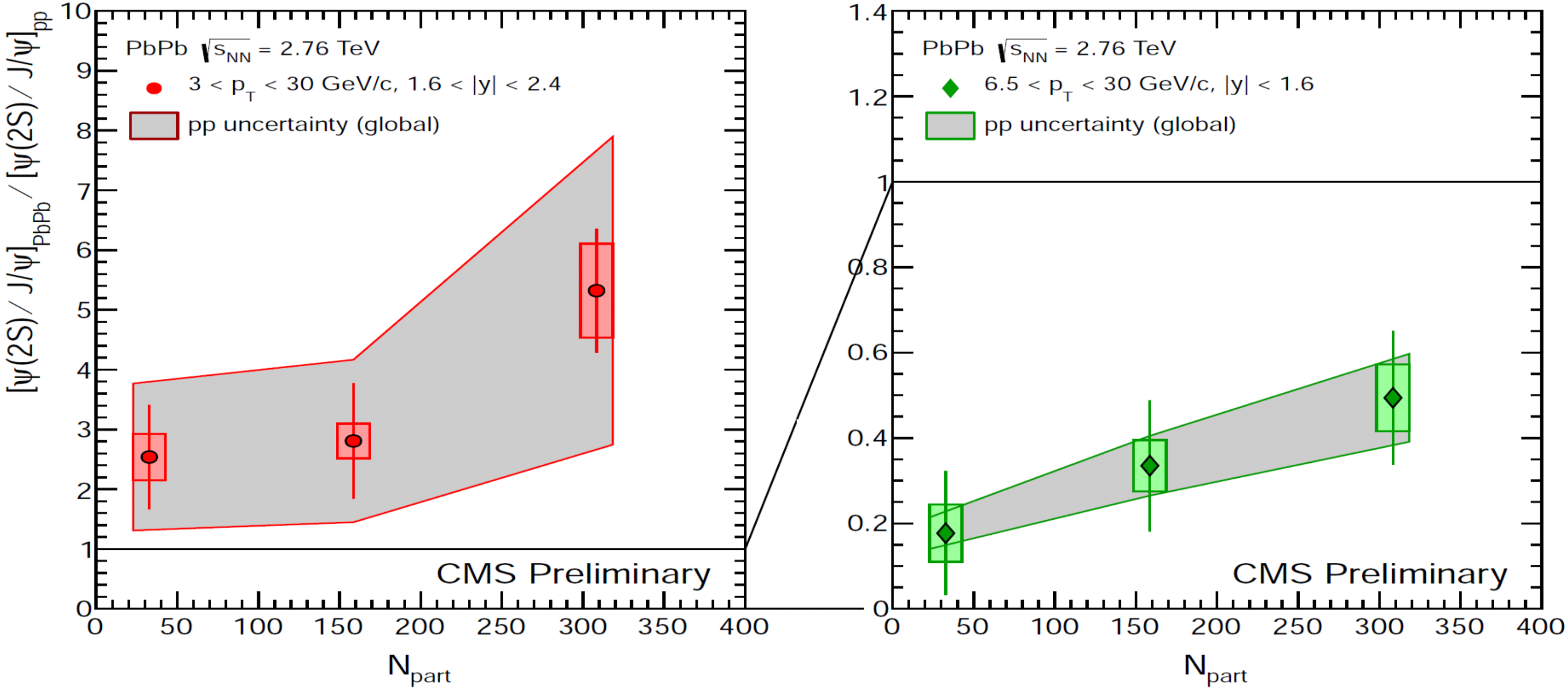


Hight p_T Ratio (Ψ(2S) / J/Ψ) in PbPb is ~2 times smaller than that in pp.

Low p_T Ratio (Ψ(2S) / J/Ψ) in PbPb is ~5 times larger than that in pp.

CMS-PAS HIN-12-007

Ratio of Ψ(2S) and J/Ψ



- p_T > 3 GeV/c and 1.6 < |y| < 2.4: **Indication that Ψ(2S) less suppressed than J/Ψ with large pp uncertainties preventing to draw a strong conclusion.**

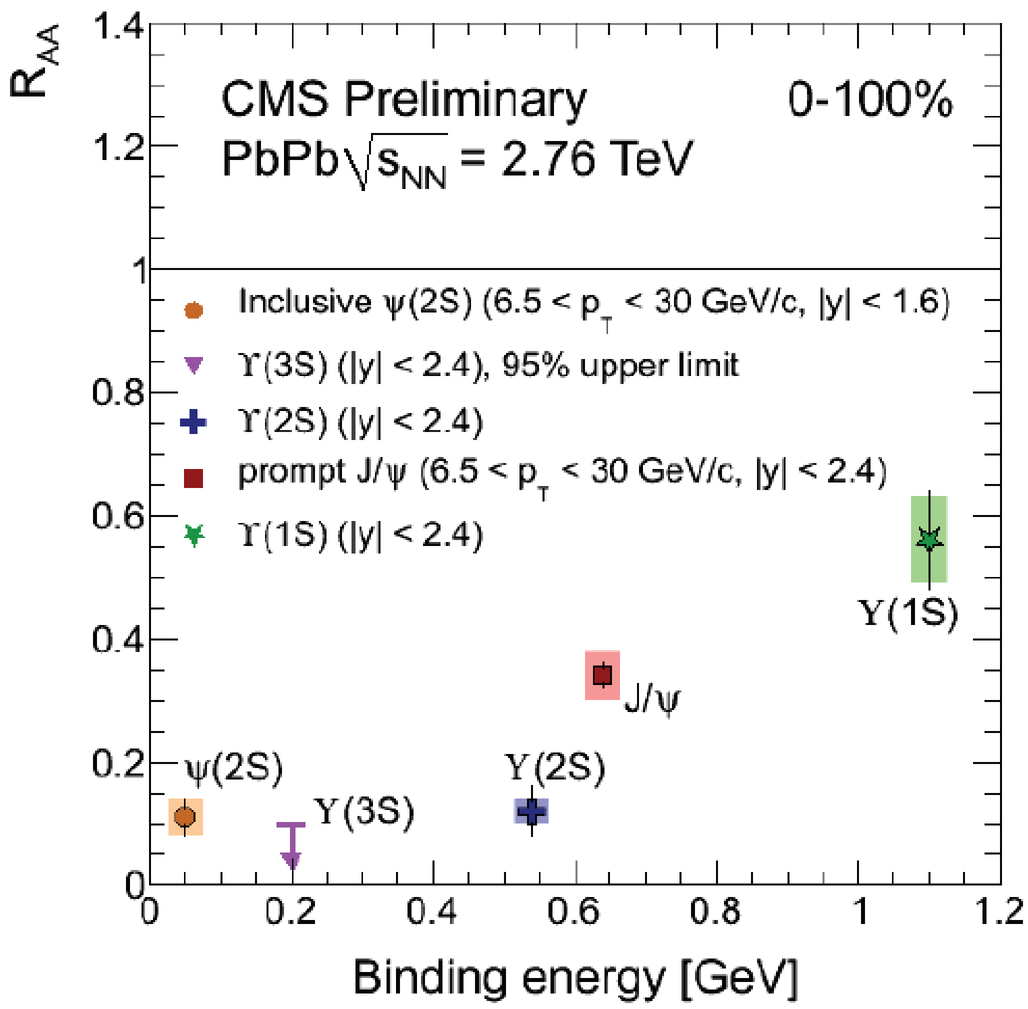
- p_T > 6.5 GeV/c and |y| < 1.6: **Ψ (2S) are more suppressed than J/Ψ at mid-rapidity and high p_T**

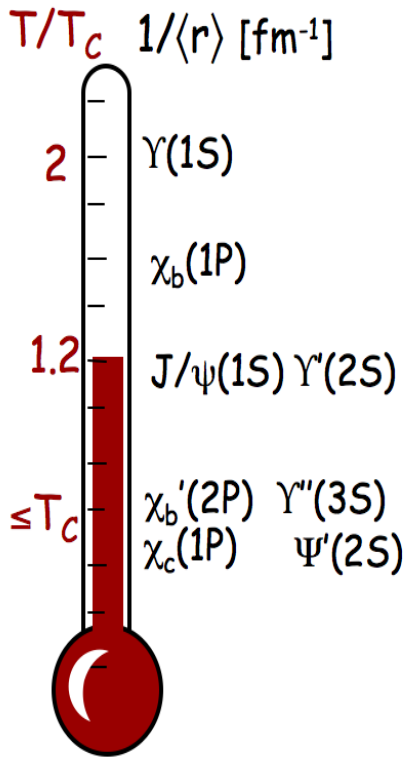
- **The low p_T results will be improved by new pp measurements**

CMS-PAS HIN-12-007

Quarkonia Summary

- The suppression of different quarkonia states consistent with their binding energy → CMS Quarkonia thermometer





PRL 109, 222301 (2012)

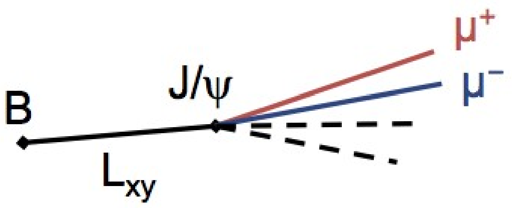
CMS-PAS HIN-12-007

CMS-PAS HIN-12-014

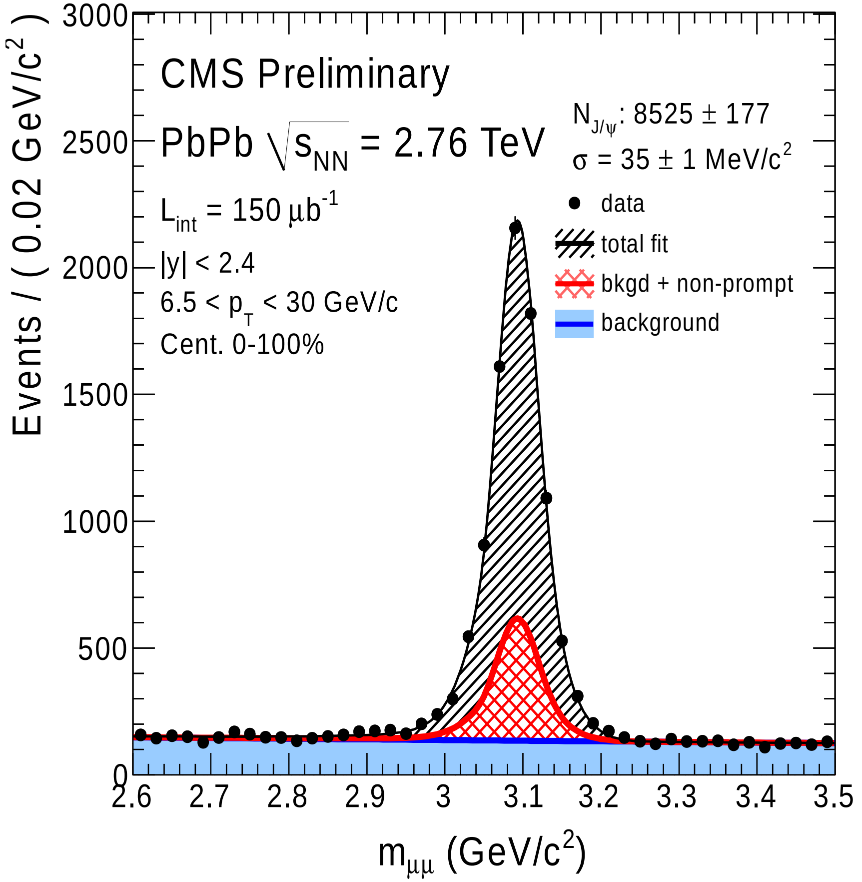
Non prompt J/Ψ or B--> J/ψ measurements

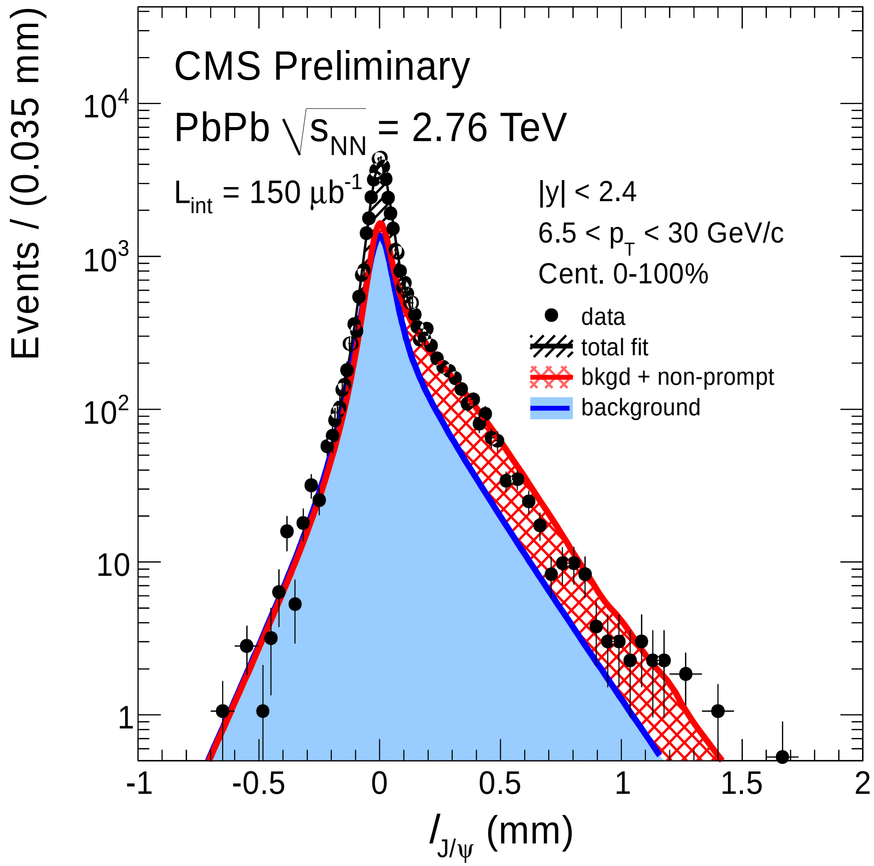
Non prompt J/Ψ reconstruction

Fit mass and lifetime simultaneously



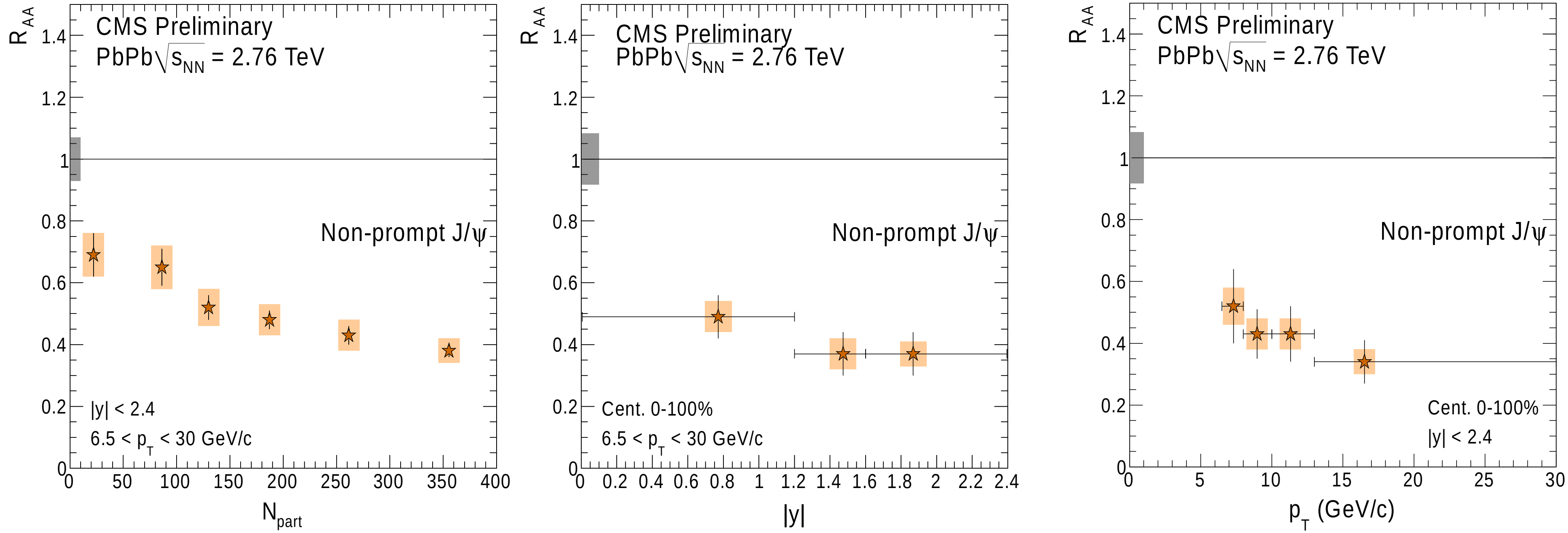
$$\ell_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}$$





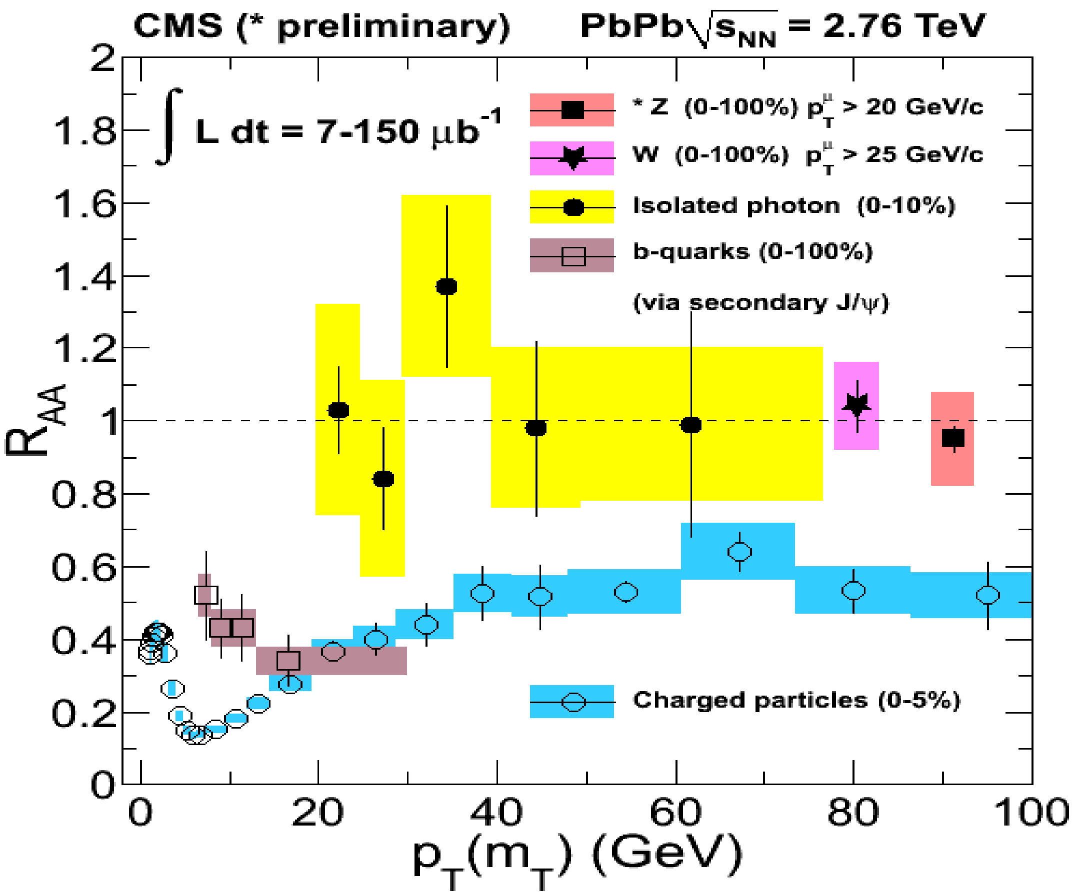
CMS-PAS-12-014

R_{AA}: Non prompt J/ψ from B->J/ψ



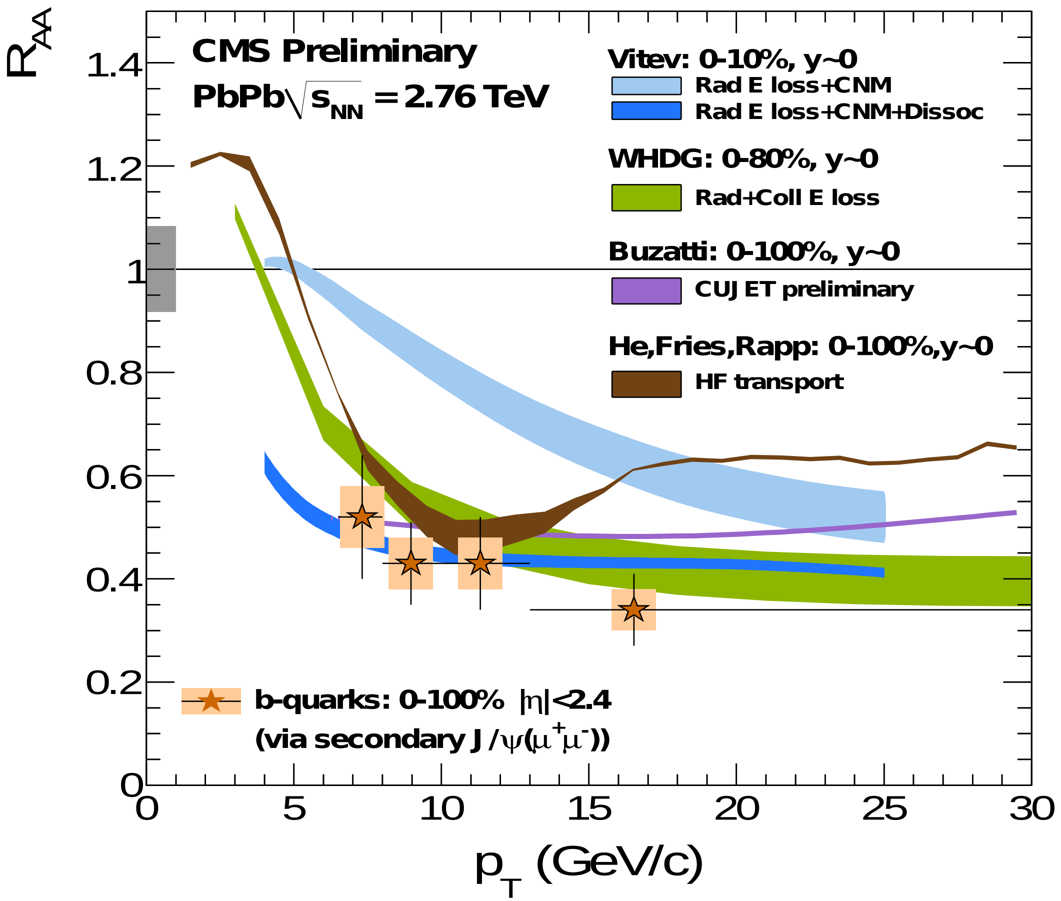
- **Centrality (p_T, y integrated): slow decrease of R_{AA}**
  - **50-100%: factor ~1.4**
  - **0-5%: factor ~2.5**
- **y (p_T, centrality integrated): hints of increasing suppression at forward rapidity**
- **p_T(y, centrality integrated): hints of increasing suppression at high-p_T**
- **The new pp measurements will allow finer binings of p_T and y dependence**

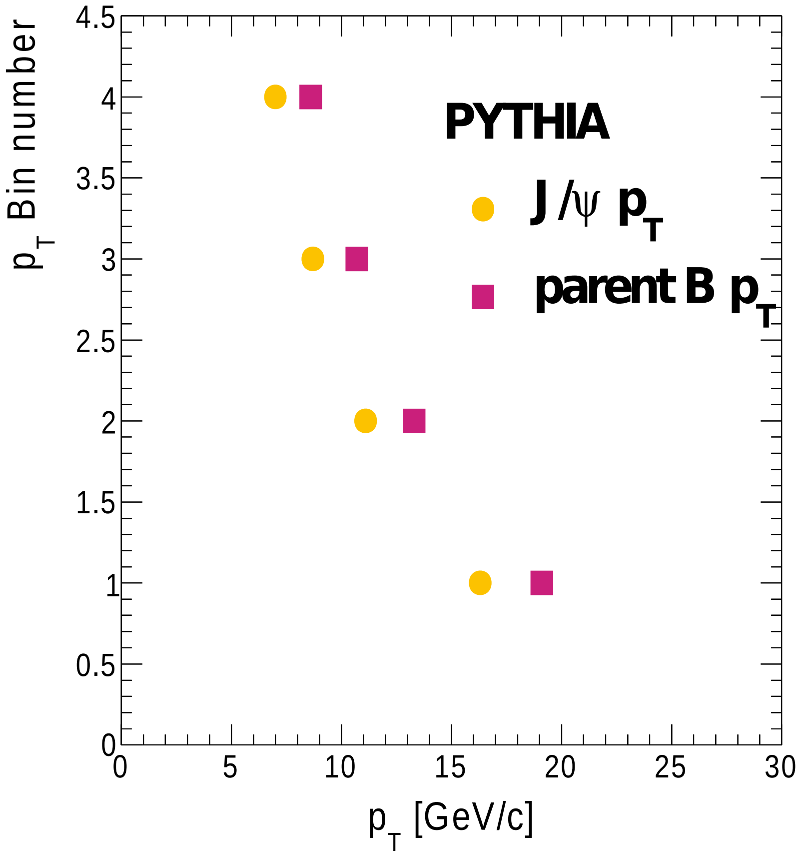
R_{AA}: Non prompt J/Ψ compared with light hadrons



- **At low-p_T: Different suppression pattern from light hadrons**
- **At high-p_T: Similar suppression as light hadrons**

R_{AA}: Non prompt J/ψ Vs theory





Vitev: J. Phys.G35 (2008) 104011 + privat

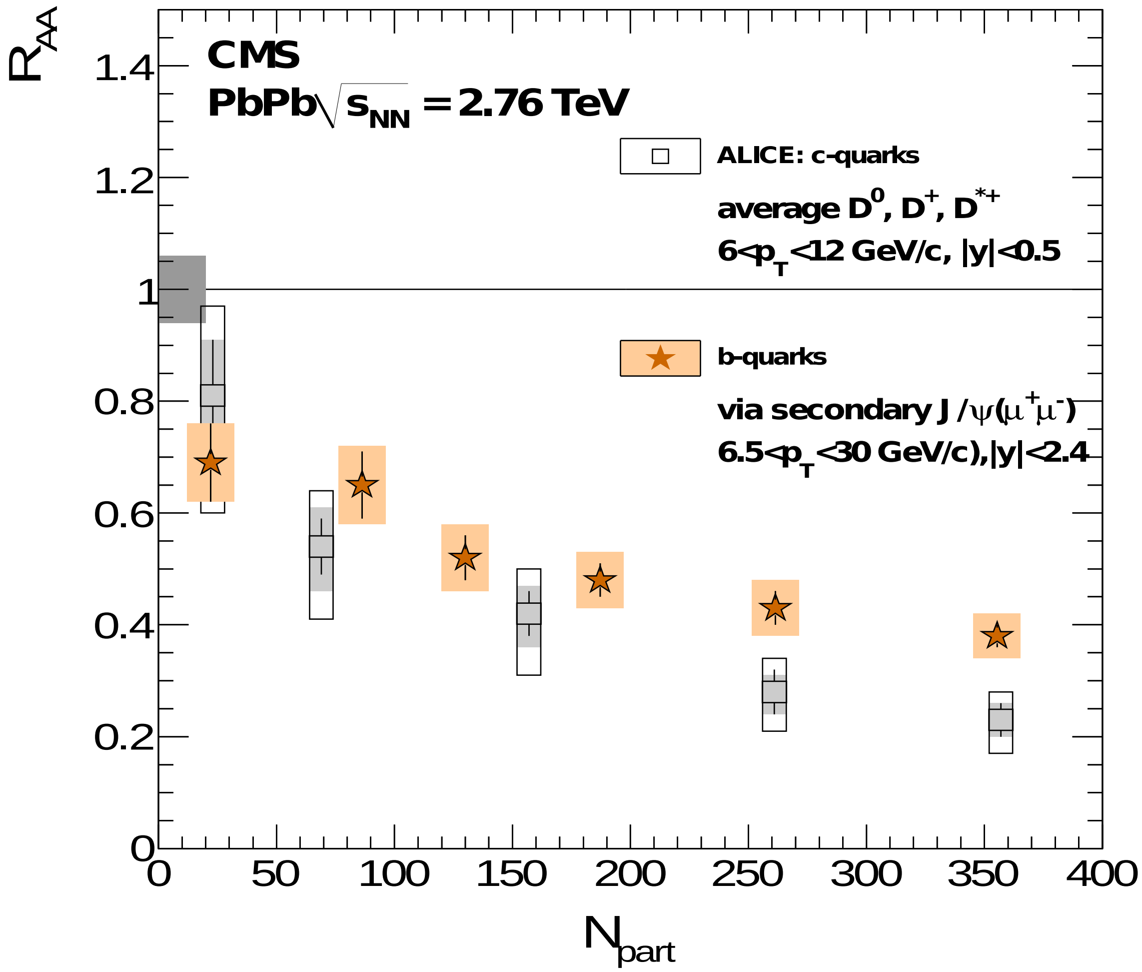
Horowitz: arXiv:1108.5876 + private

Buzzatti, Gyulassy: arXiv: 1207.6020+ private

He, Fries, Rapp: PRC86(2012)014903+ private communications

- **Radiative energy loss not enough to describe data**

R_{AA}: Non prompt J/ψ Vs ALICE D mesons

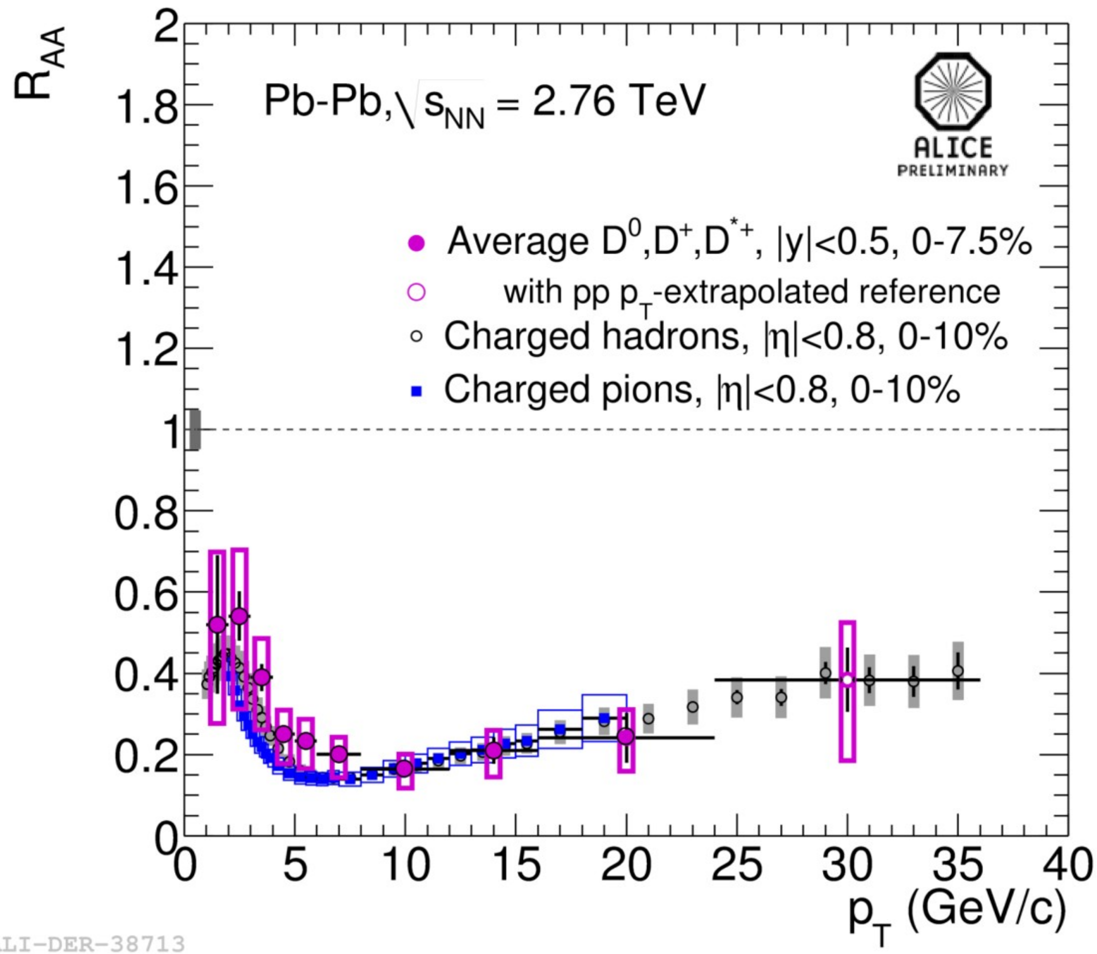


ALICE : arXiv:1203.2160
CMS : CMS-PAS HIN-12-014

- **In central collisions, at p_T > 6 GeV, R_{AA} hierarchy**

$R_{AA}^{charm} < R_{AA}^{bottom}$

R_{AA}: D mesons Vs light charged hadrons at LHC



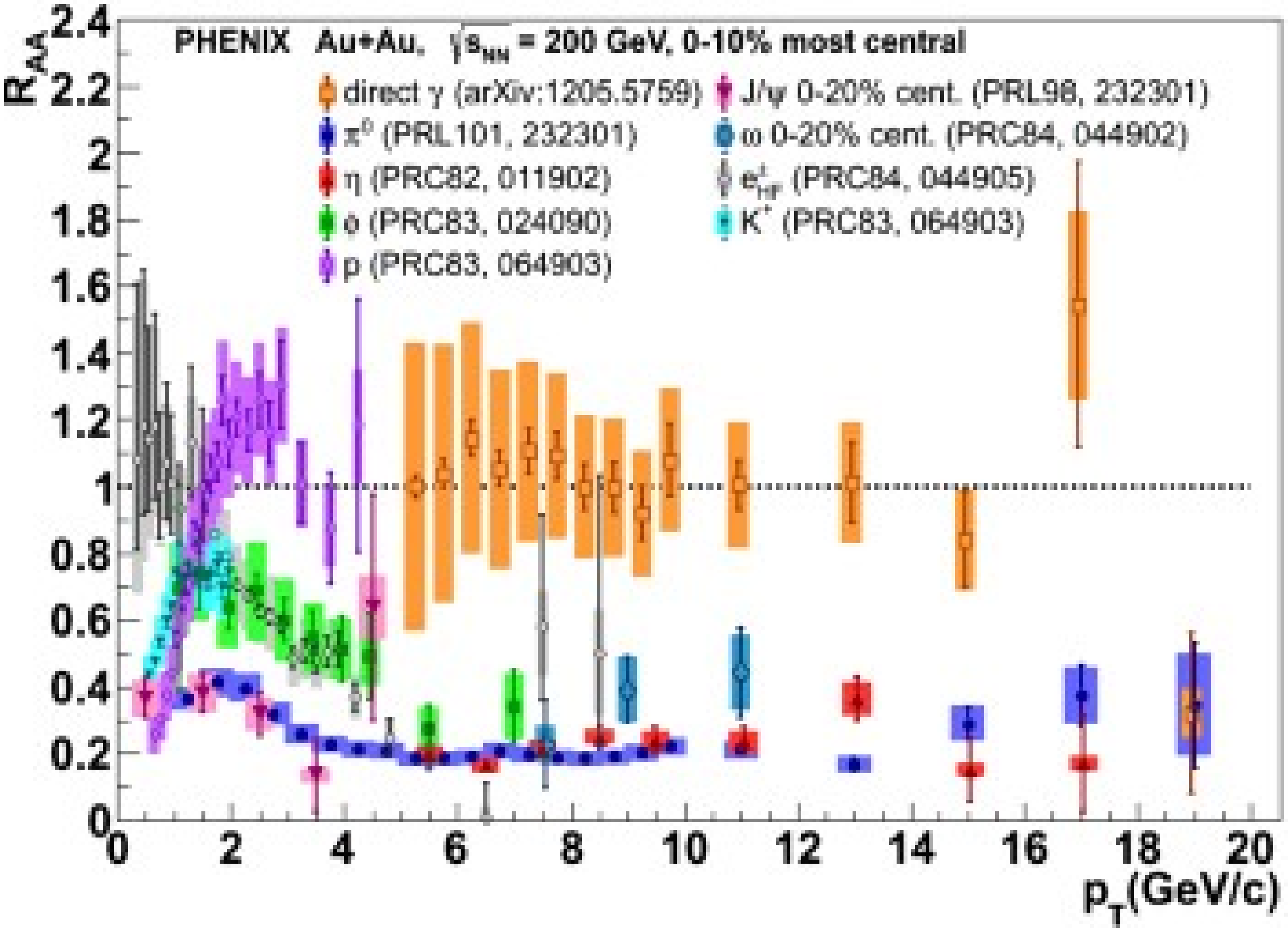
pT < 8 GeV/c:
- hint of less suppression than for π ?

pT > 8 GeV/c
- same suppression as for π…

Jets and high p_T hadrons

R_{AA} of different particles at RHIC

$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T\, d\eta}{T_{AA}\, d^2 \sigma^{NN} / dp_T\, d\eta}$$



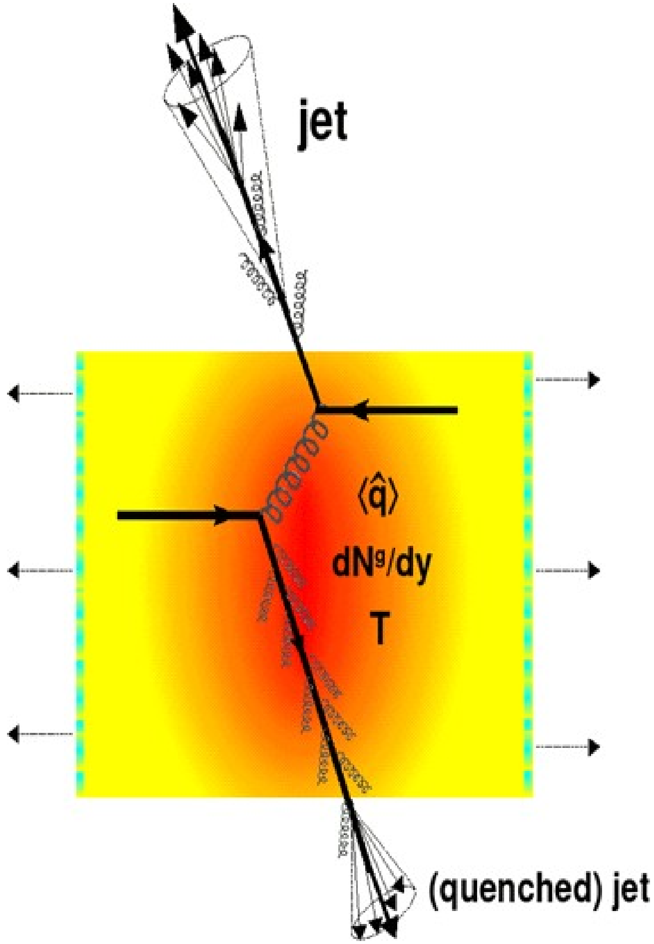
PHENIX – RHIC

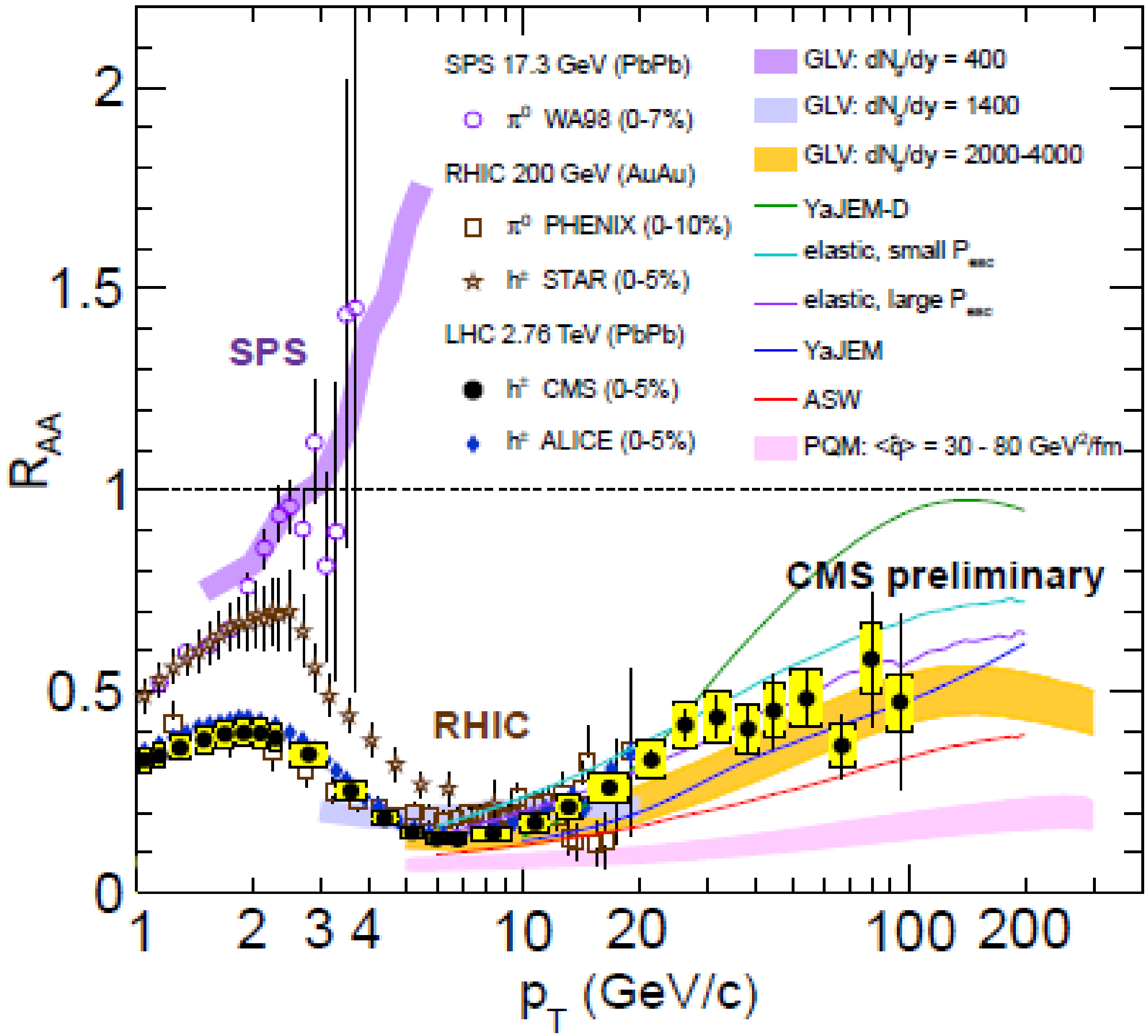
photons not suppressed but

hadrons suppressed at high p_T.

arXiv:1212.6722 [nucl-ex]

R_{AA} light hadrons: LHC reach



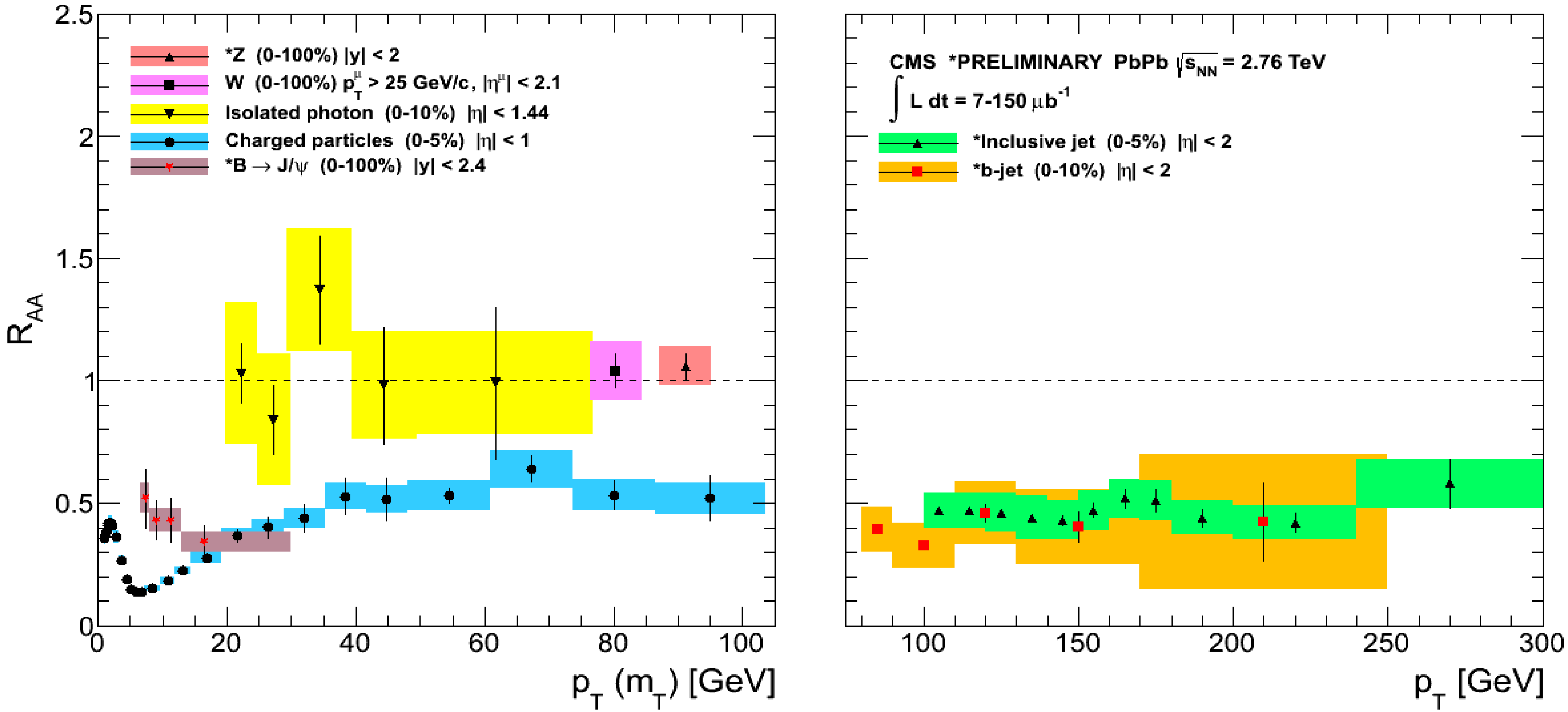


More suppression than at RHIC

upto $p_T < 8$ GeV/c.

→ LHC medium more opaque than RHIC

Jet R_{AA} at LHC

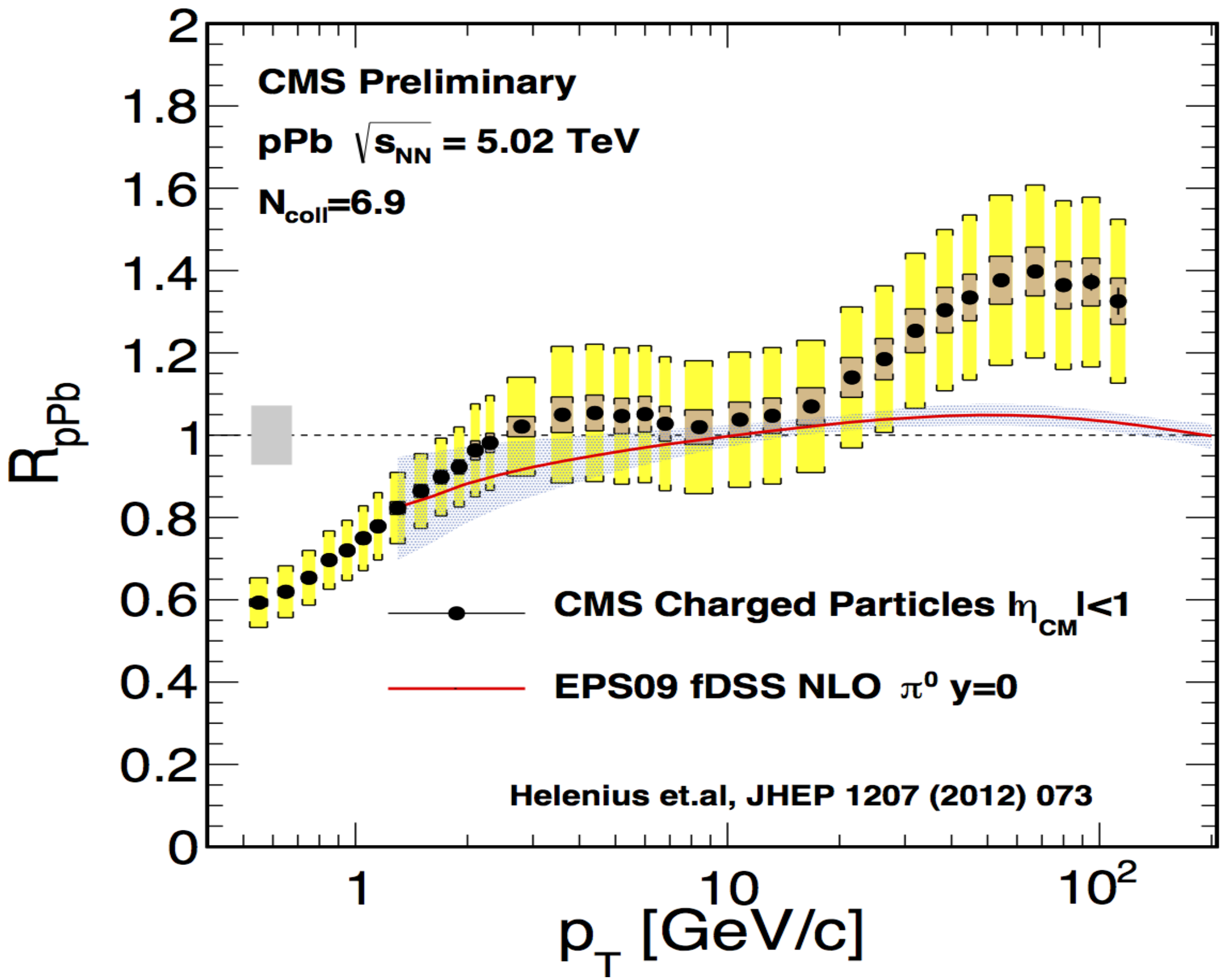


Jet R_{AA} upto p_T of 300 GeV/c.

Jet suppression stays same after p_T 30 GeV.

R_{AA} b-jets consistent with inclusive jets, requires more statistics

R_{AA}: light particles in pPb

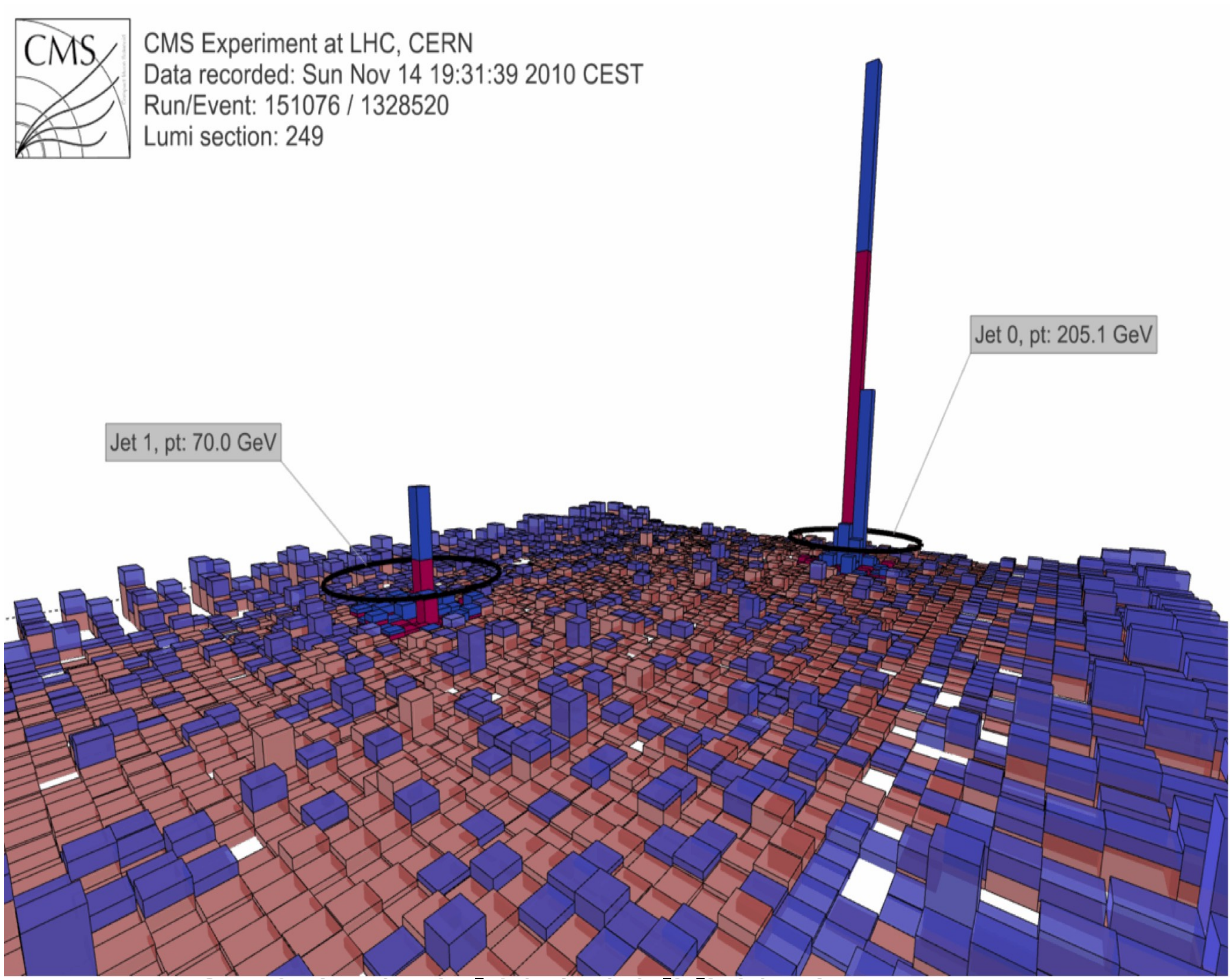


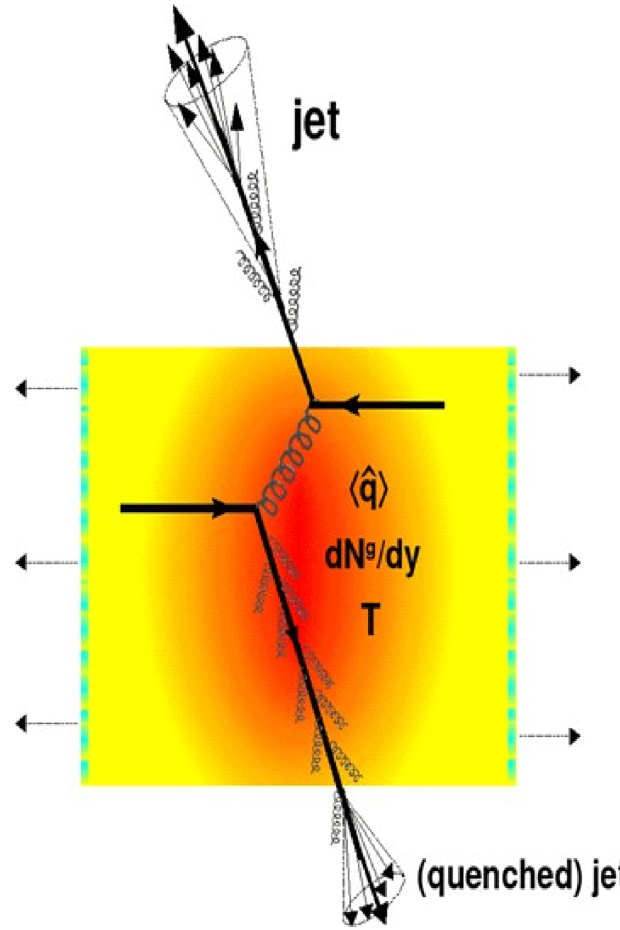
R_{AA} consistent with 1 from 2< p_T < 30 GeV/c

Above 30 GeV/c shadowing does not explain the data.

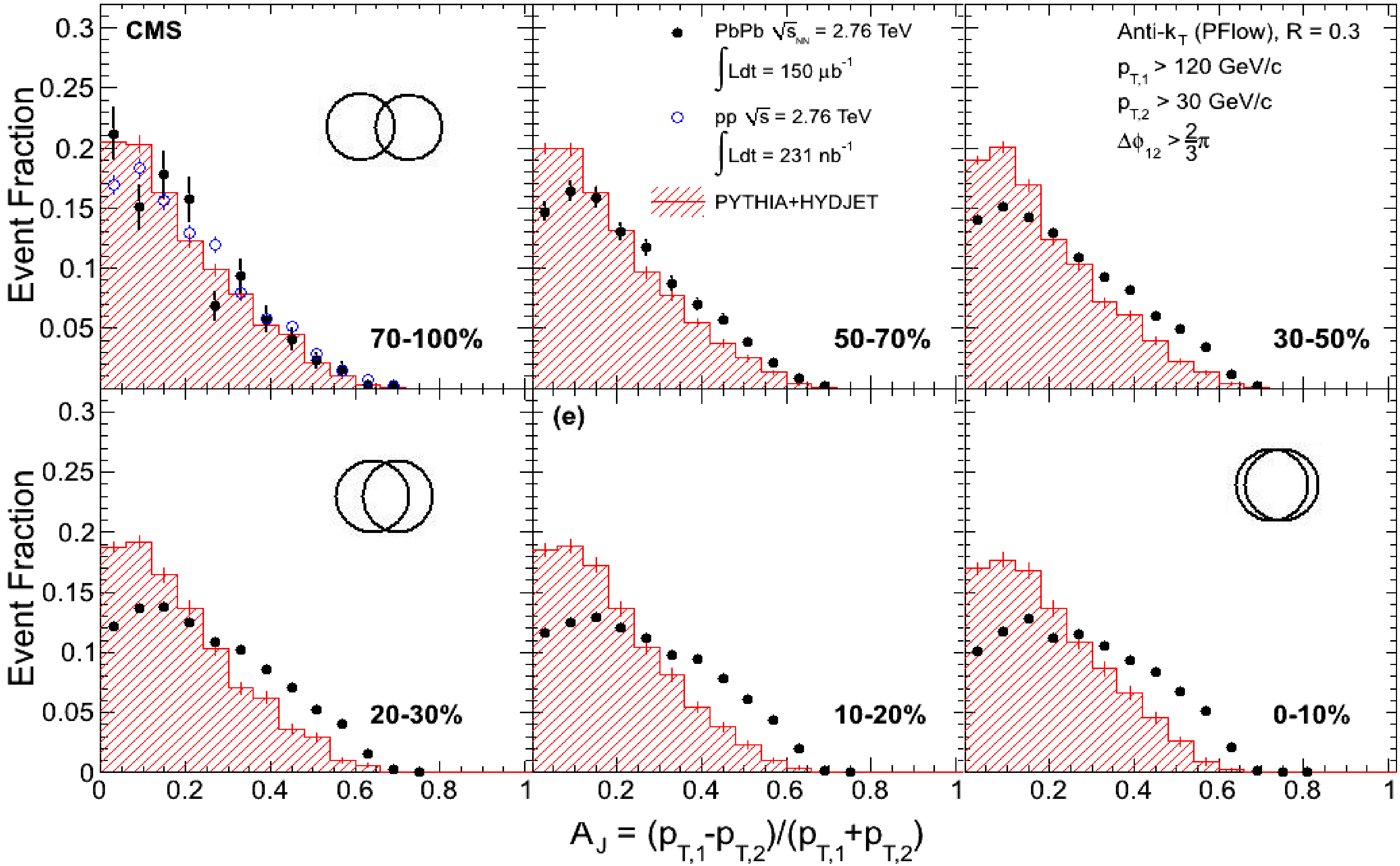
CMS-HIN-12-017

Dijet Asymmetry





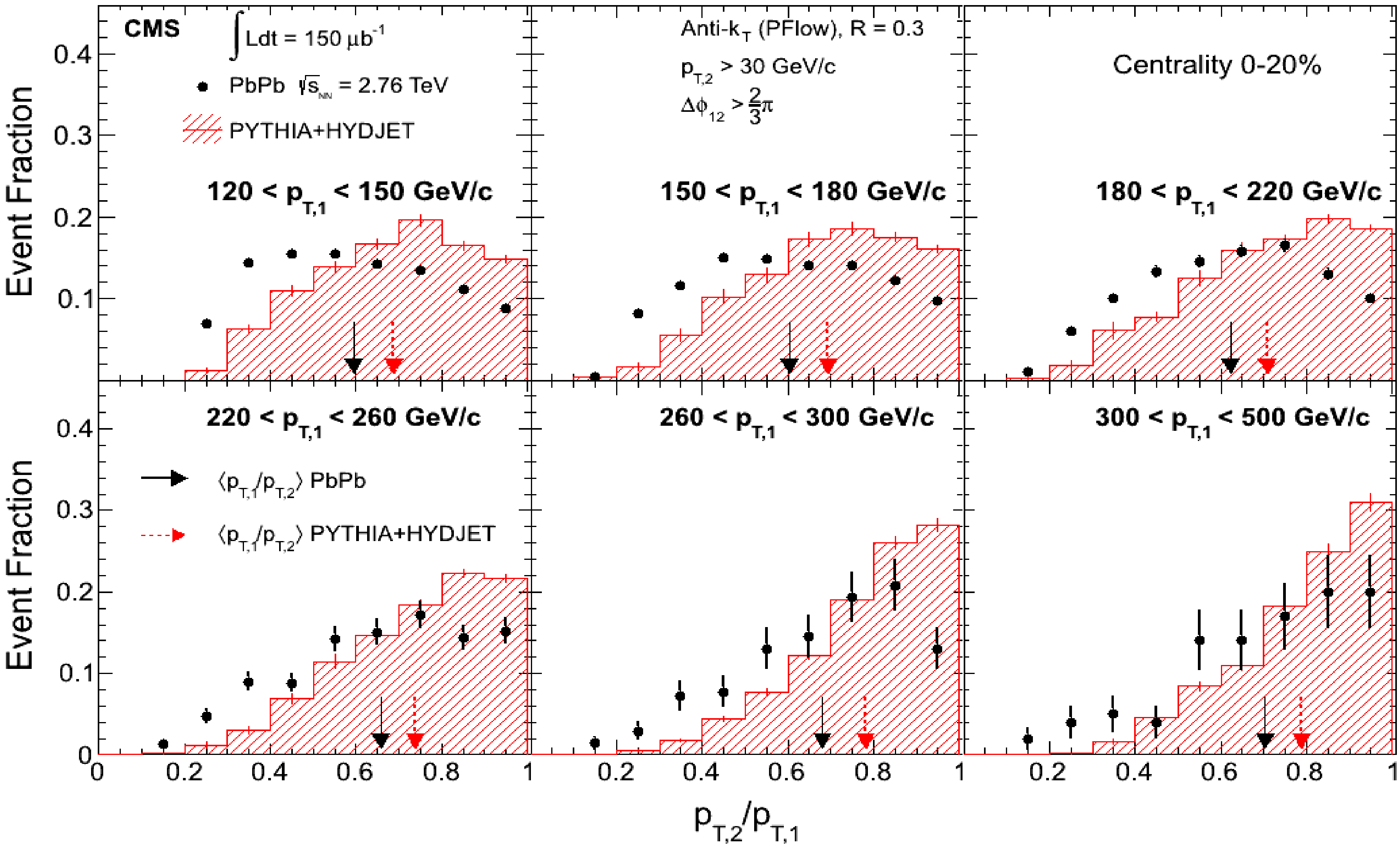
Dijet Asymmetry: Quantitative



Jet loosing energy in more central collisions

CMS, PLB 712 (2012) 176

Dijet Asymmetry: Ratios of 2 jets p_T

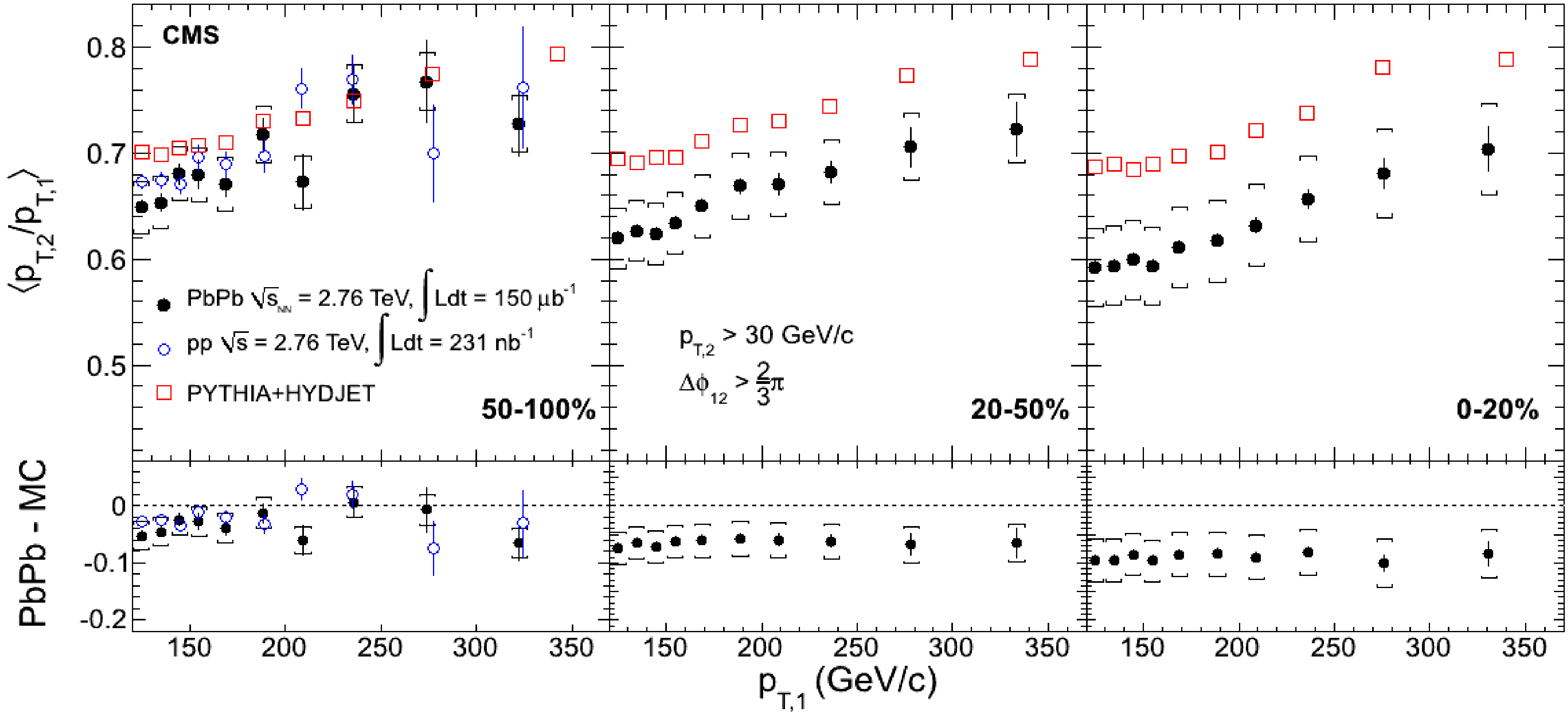


Jets loose energy even at Trigger jet p_T ~ 300 GeV/c

Consistent with Jet R_{AA}

CMS, PLB 712 (2012) 176

Dijet Asymmetry: Quantitative

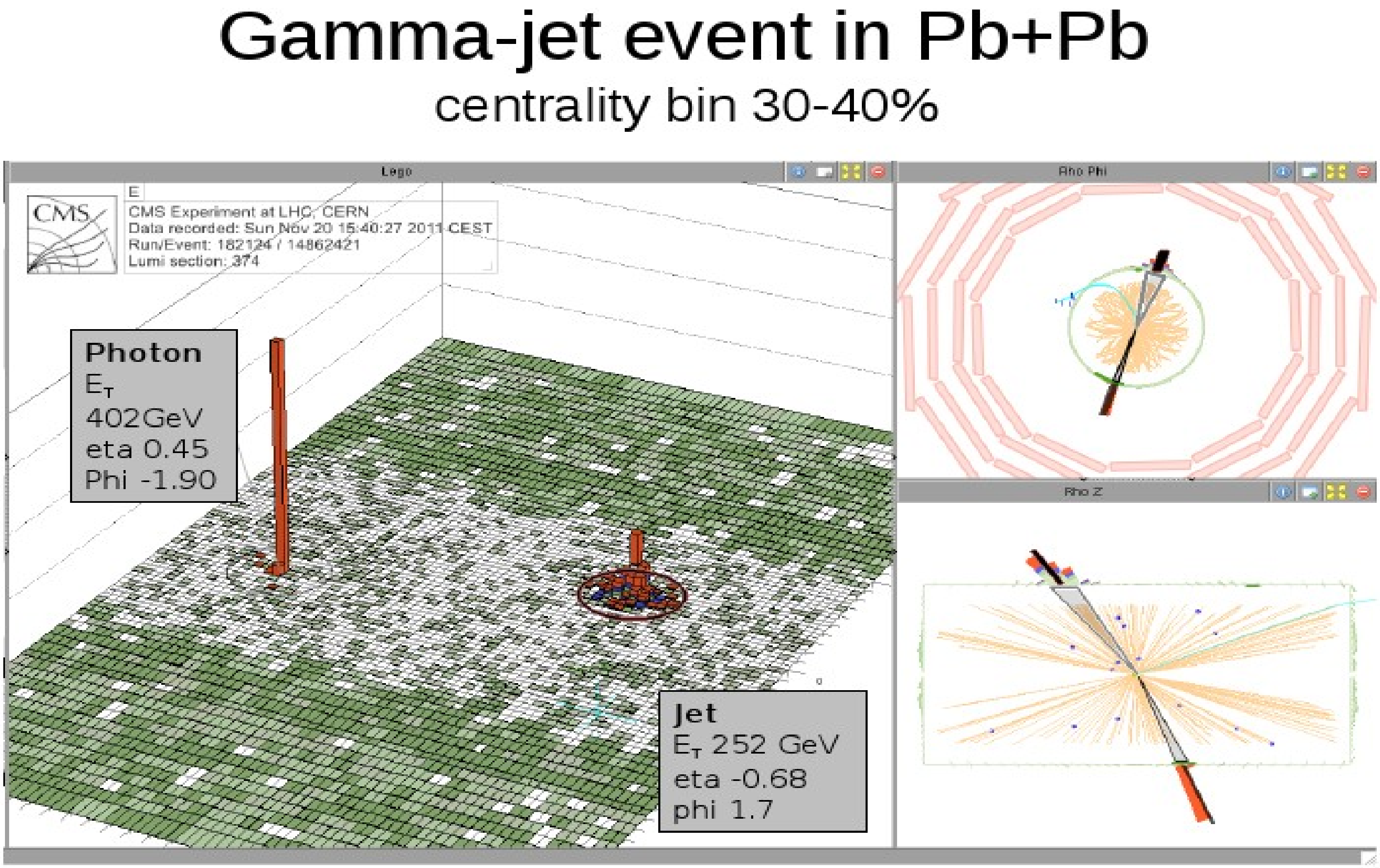


Jets energy loss independent of Trigger jet p_T

Consistent with Jet R_{AA}

CMS, PLB 712 (2012) 176

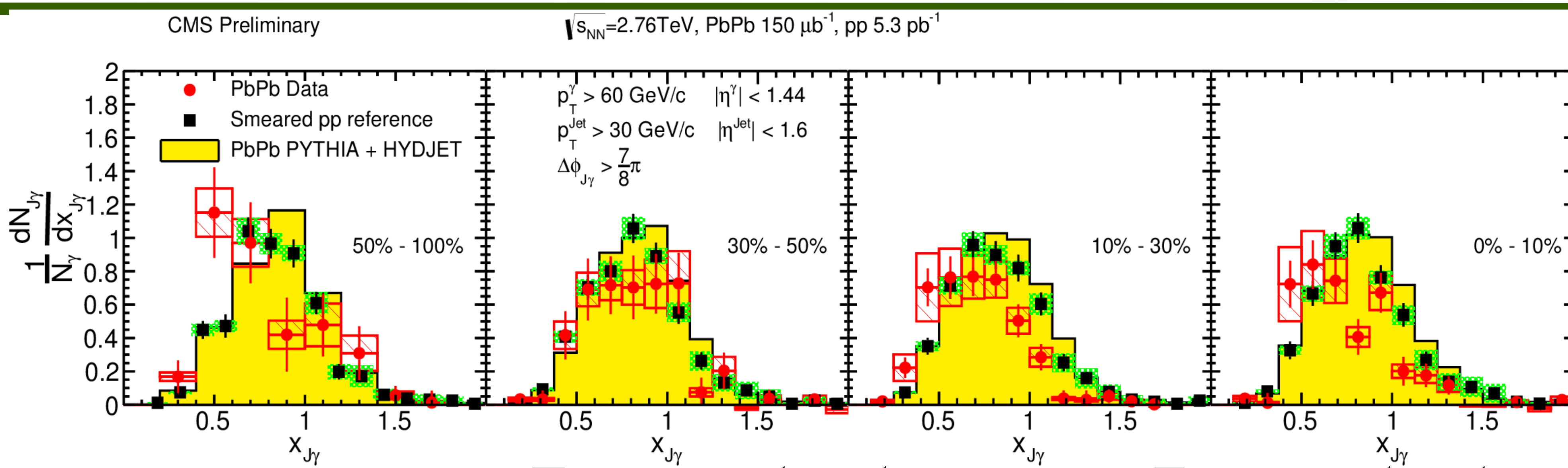
Gamma-jet assymetry in PbPb



Better probe as photon does not lose energy.

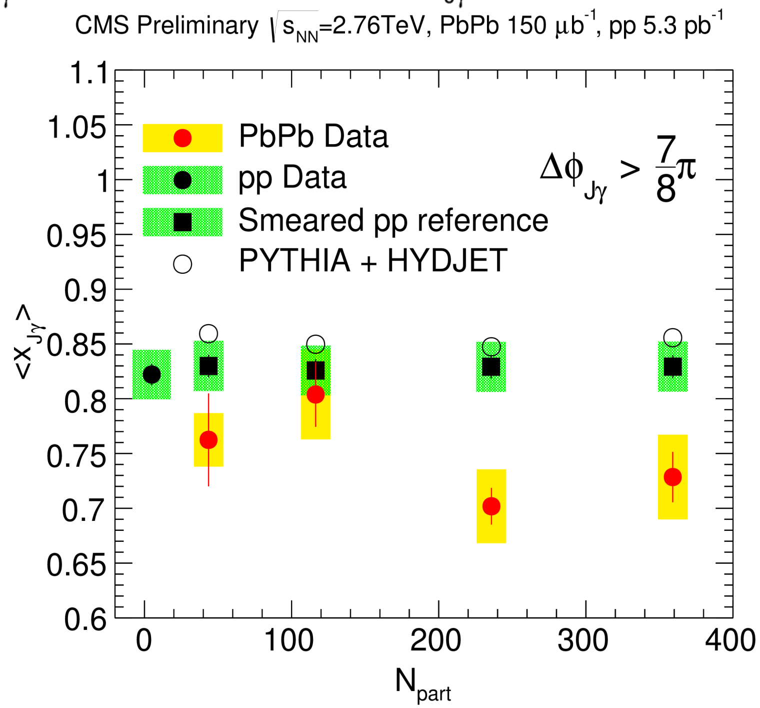
Jet loose energy but it is almost back to back with photon

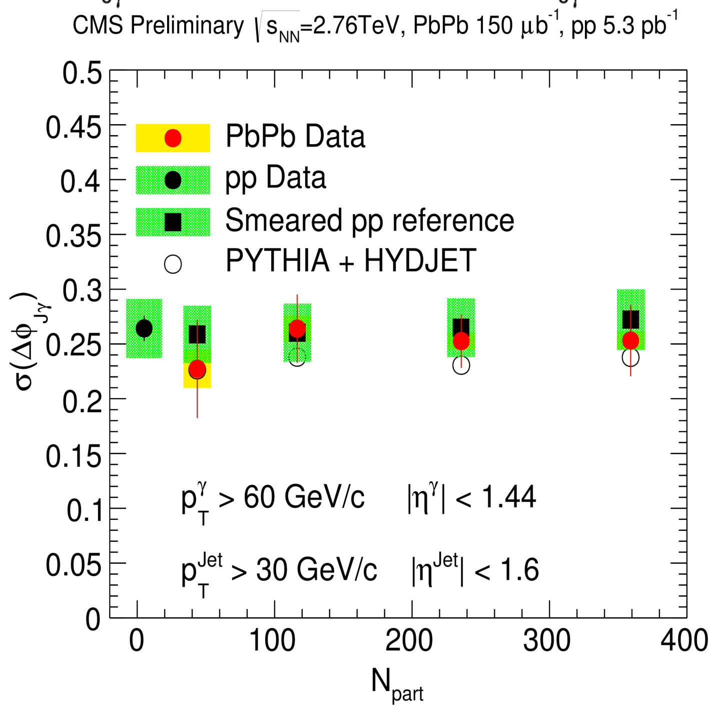
Gamma-jet assymetry in PbPb: Quantitative



The ratio of jet p_T with gamma p_T. Shifts.

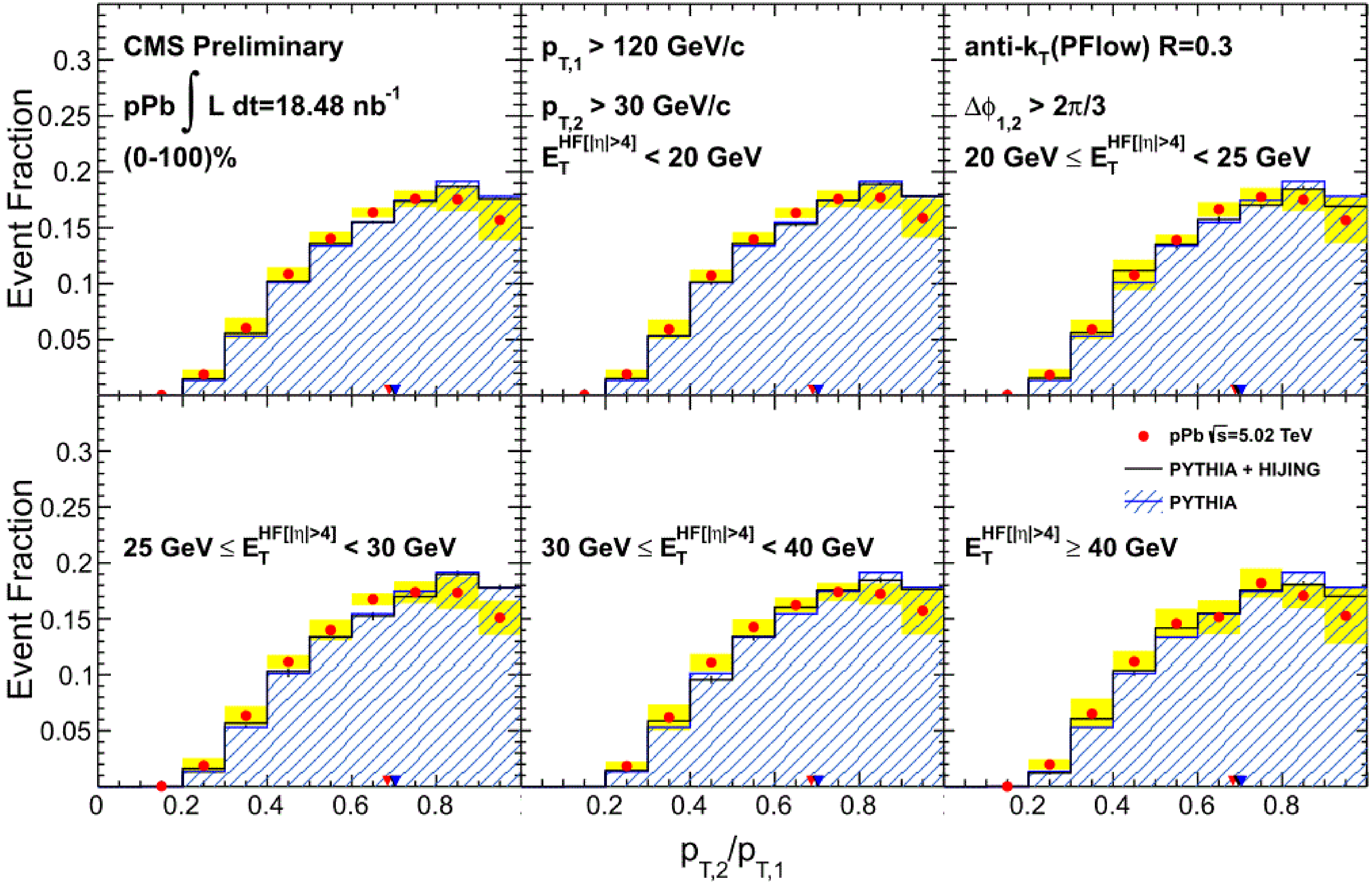
Jet loose energy but it is almost back to back with photon





CMS PLB 718 (2013) 773 and CMS-HIN-13-006

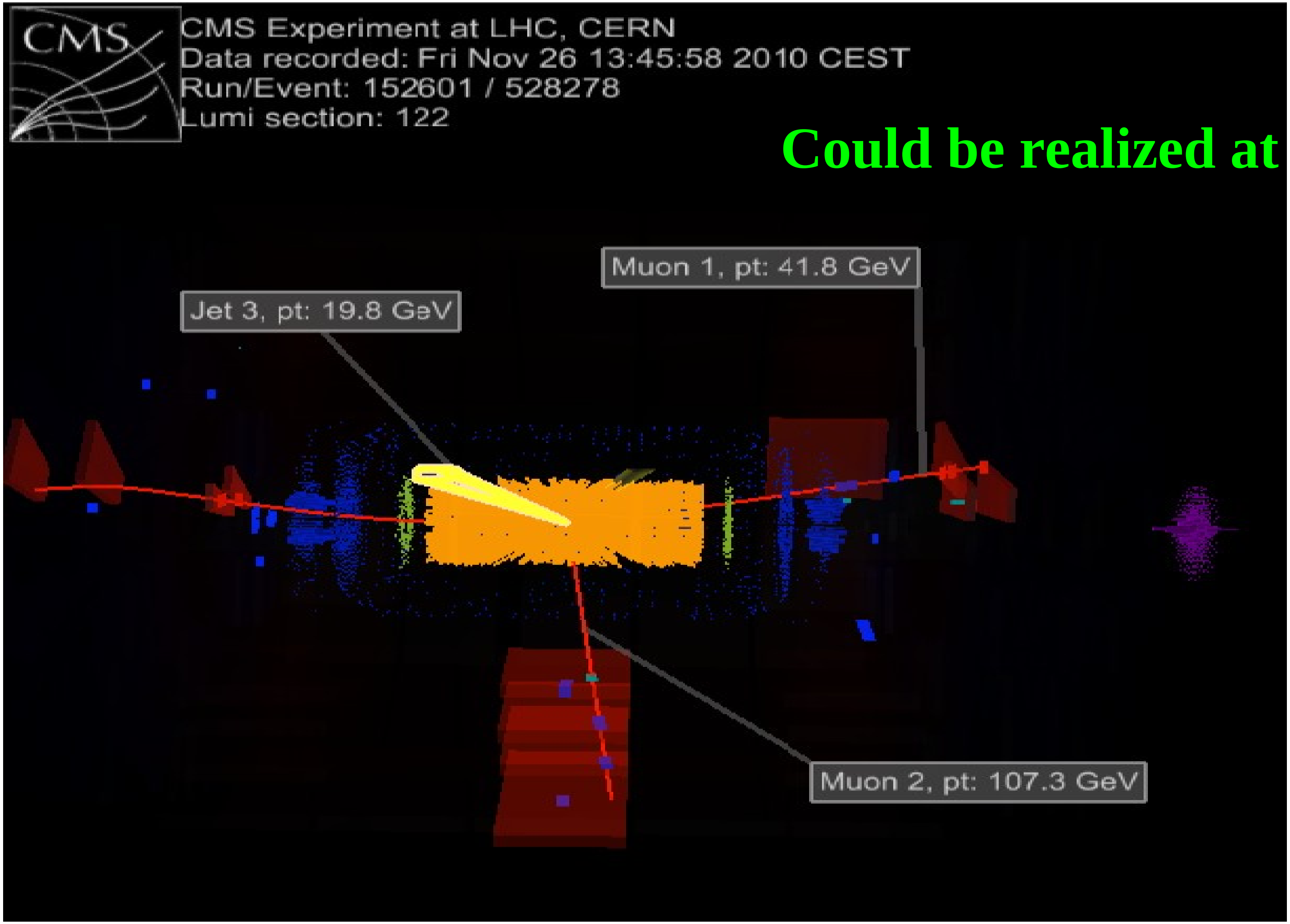
No di-jet assymetry in pPb



Jet R_{AA} in pPb (TBD)

CMS-HIN-13-001

Z-Jet study



Could be realized at 5.5 TeV

Summary and future outlook (General)

• **There has already been a wealth of wonderful measurements in PbPb at LHC although limited by ststistics. The future 5.5 TeV run will improve the precision tremendously.**

• **PbPb collisions at LHC create a system with higher temperature, larger size as compared to RHIC**

• **Better precision of properties of matter at LHC eta/S is smaller at LHC as compared to RHIC. More perfect liquid.**

• **LHC collisions have shown some difference with collisions at RHIC e.g. as low proton/pion ratios or quark number scaling of v2. To be understood.**

• **Last 3 years we witnessed a hard probe revolution at LHC due to larger cross sections, new generation detectors.**

Summary and future outlook (Colour screening)

- **Colour screening at LHC (Υ states)**
  Sequential suppression first time observed.
  More suppression as compared to RHIC.
  Final state effects in pPb.
  More PbPb data are needed to understand system size dependence.

Colour screening at LHC (J/ψ)

High p_T J/ψ more suppressed as compared to RHIC

Low p_T J/ψ less suppressed → hints of Regeneration

Charmonia ratios → Hint of regeneration

An overall understanding from RHIC and LHC measurements is emerging. More statistics at 5.5 TeV, a better p_T and y dependence of quarkonia will help settle the issues of colour screening and regeneration.

Summary and future outlook (Energy loss)

- **Energy loss of heavy quarks**

Mass hierarchy vissible at p_T < 8 GeV/c

Above 8 GeV charm and lights are consistent.

Better precision and larger p_T reach required for bottom measurements.

- **Jets quenching more at LHC as compared to RHIC → More interacting medium.**

LHC fecilitating quantitative analysis of energy loss transport coefficient of the medium.

B-jets studies require more statistics.

Newer cleaner probes Z-jet studies at 5.5 TeV.

Summary and future outlook (pPb)

- **pPb results need to be studied in totally:**

Hints of collectivity in pPb (Ridge story)
Suppression of higher Υ states.
Shadowing calculations not producing R_{AA} J/psi and R_{AA} of charged particles.
Jet R_{AA} at high p_T required to be done to understand high p_T behaviour.
PbPb peripheral to be studied in detail

- **PbPb at 5.5 TeV, Better statistics of hard probes**

Must settle issue of colour screening, regeneration.
Energy loss of quarks as a function of mass.

- **Reference pp runs at 5.5 TeV will also be needed.**

Summary and future outlook

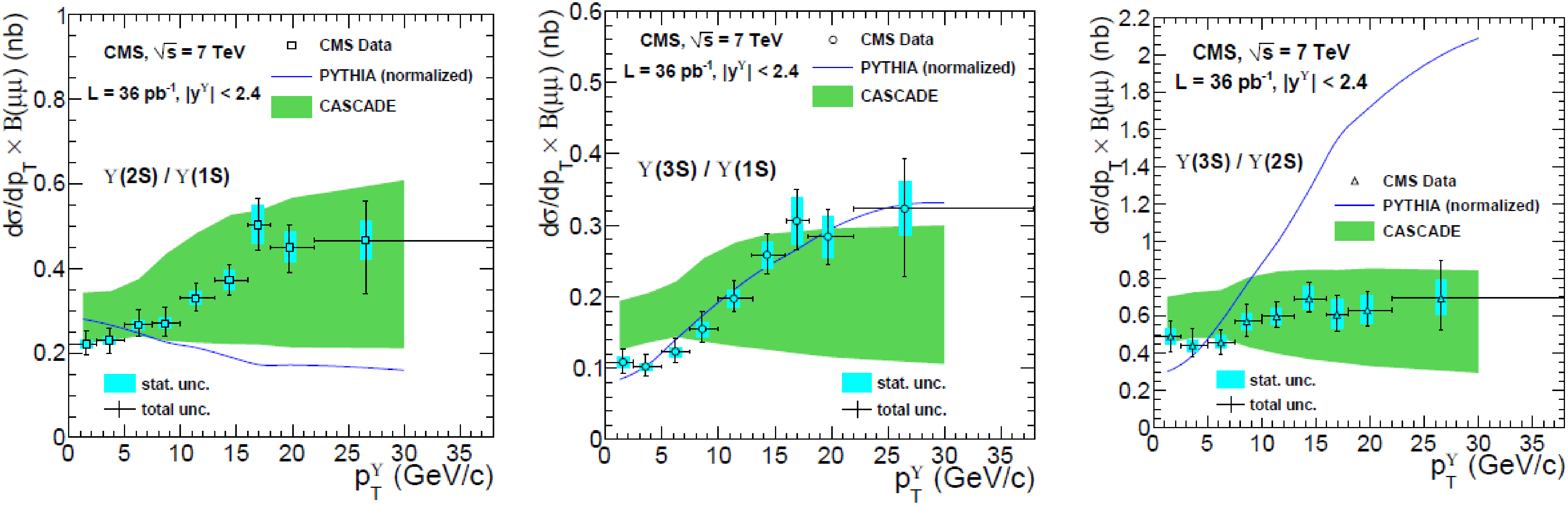
- 5.2/5.5 TeV collisions, 10 times more integrated luminosity in next 4 years.
- Upgrades: Tracking, Caloriemetry, Particle ID → Better precision.
- New signals, Z-jet I mentioned already, More ideas ?
- Surprises !

Backup

Reconstruction of Jets

- Jets are accompanied by the large "thermal background" or "underlying event" that depends on the overall event multiplicity
  - Use background subtraction procedures
- CMS uses several jet finding algorithms
  - Iterative Cone
  - Anti-k_T (M. Cacciari, G. P. Salam, G. Soyez, JHEP 0804:063,2008.)
- Jets are found using different sets of detectors
  - Calorimetric Jets: use ECAL and HCAL
  - Particle Flow Jets: use Tracker and Calorimeters
- Jet cone size can vary
  - We use R = 0.5
- CMS HI "workhorse"
  - IC5 CaloJets with iterative background subtraction (O. Kodolova et al., EPJC (2007))

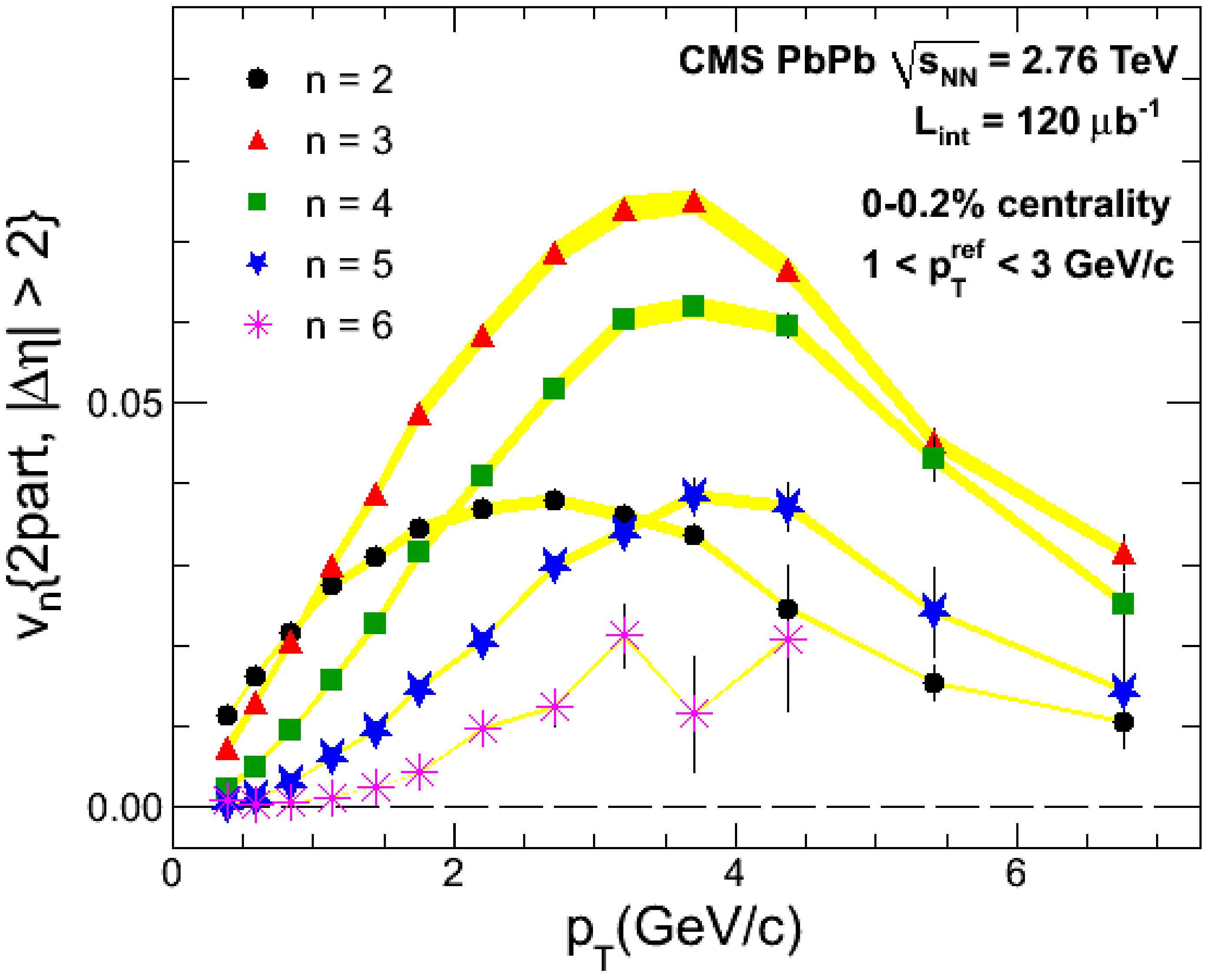
Υ ratios at 7 TeV



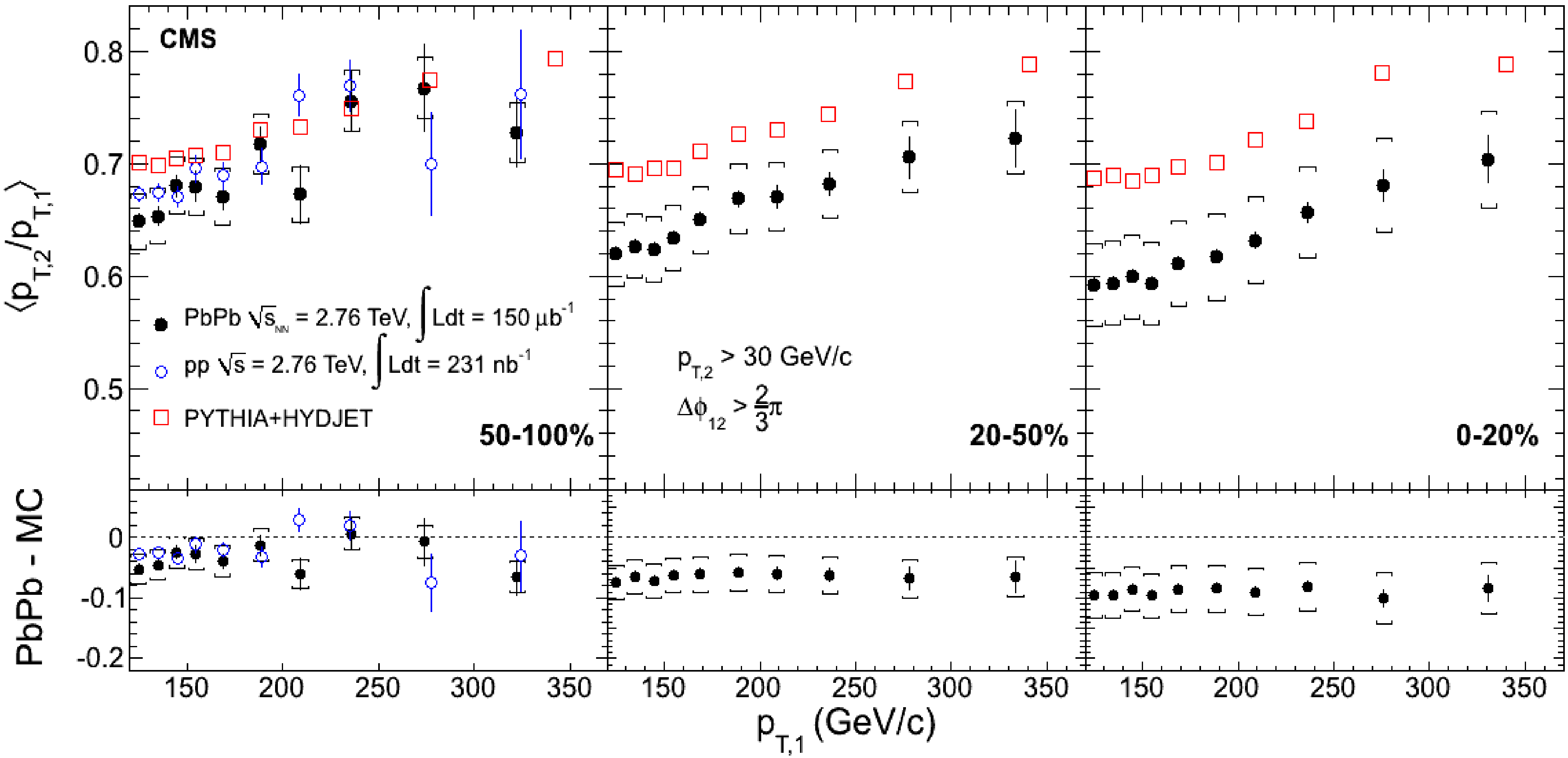
$$\sigma(pp \to \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = (3.06 \pm 0.02\,^{+0.20}_{-0.18} \pm 0.12)\,\text{nb},$$
$$\sigma(pp \to \Upsilon(2S)X) \cdot \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = (0.910 \pm 0.011\,^{+0.055}_{-0.046} \pm 0.036)\,\text{nb},$$
$$\sigma(pp \to \Upsilon(3S)X) \cdot \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = (0.490 \pm 0.010\,^{+0.029}_{-0.029} \pm 0.020)\,\text{nb},$$

arXiv 1303.5900, submitted to PLB

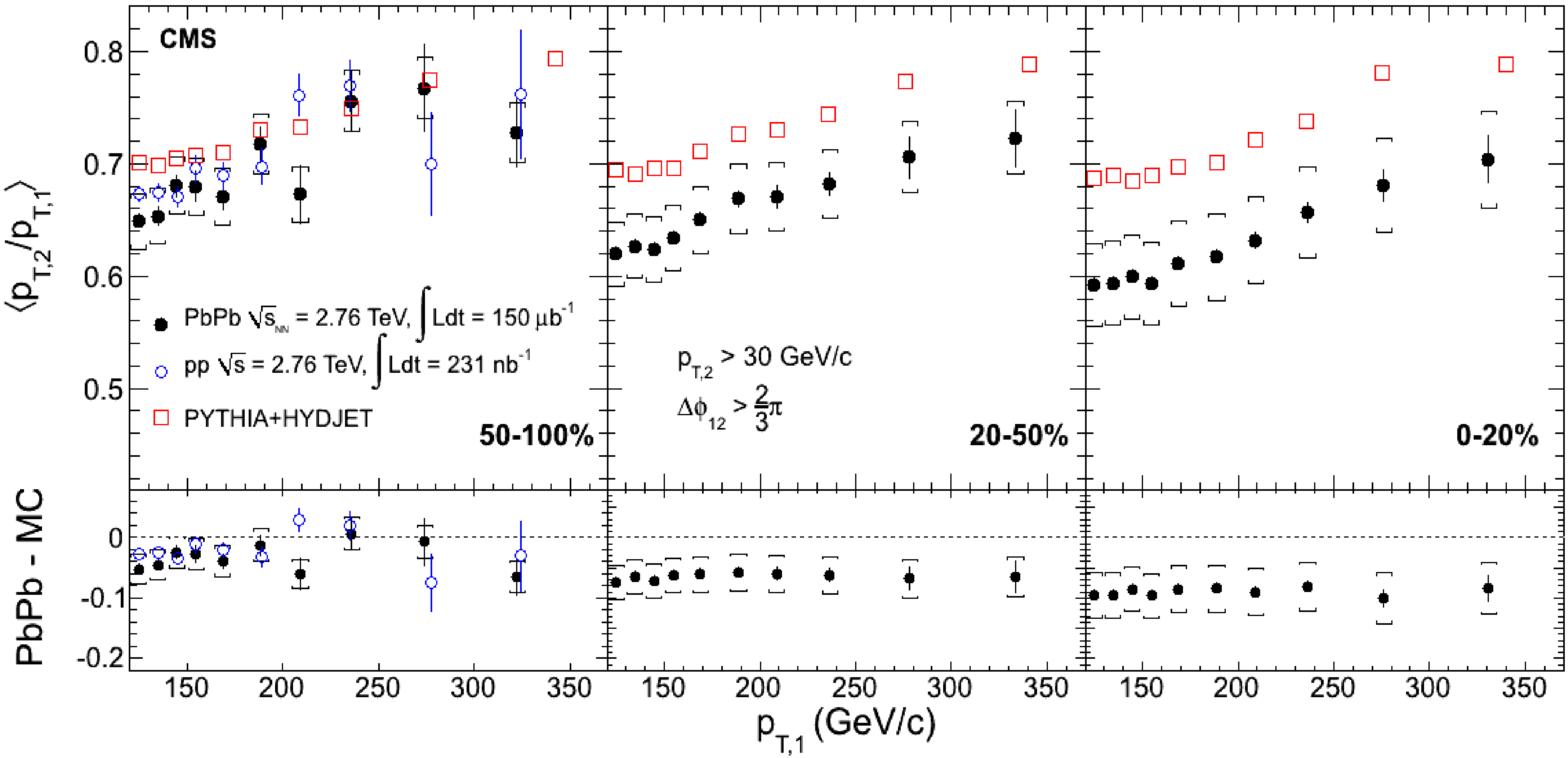
Higher harmonic flow



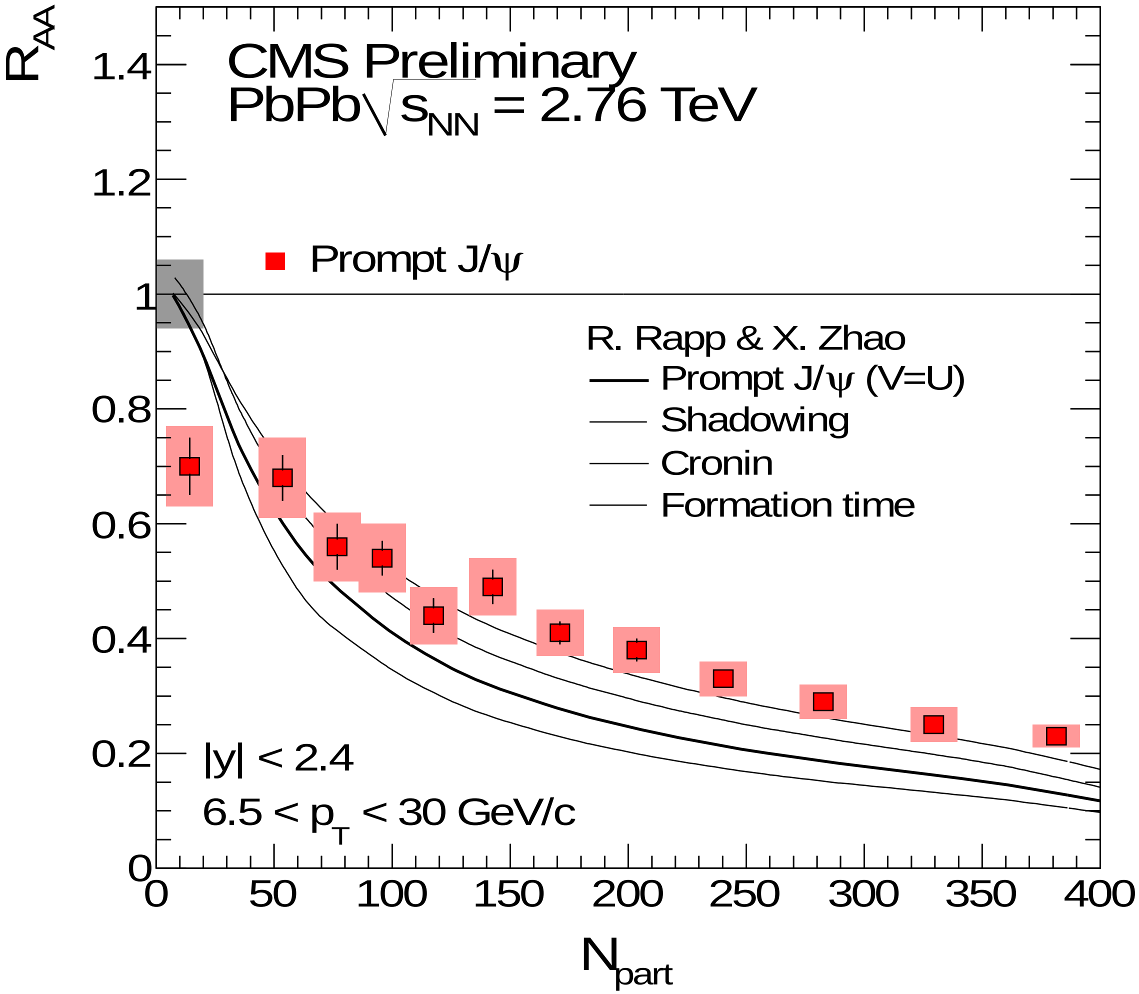
Dijet Asymmetry: Quantitative



Dijet Asymmetry: Quantitative



R_{AA} prompt J/ψ vs theory



High-p_T J/ψ: no need for regeneration to describe data

CMS-PAS-12-014