Heavy-Ion Meeting (HIM 2012-12)
Chonnam National University, Gwangju, Korea, 7-8 December, 2012

Recent Heavy-Ion Results from CMS

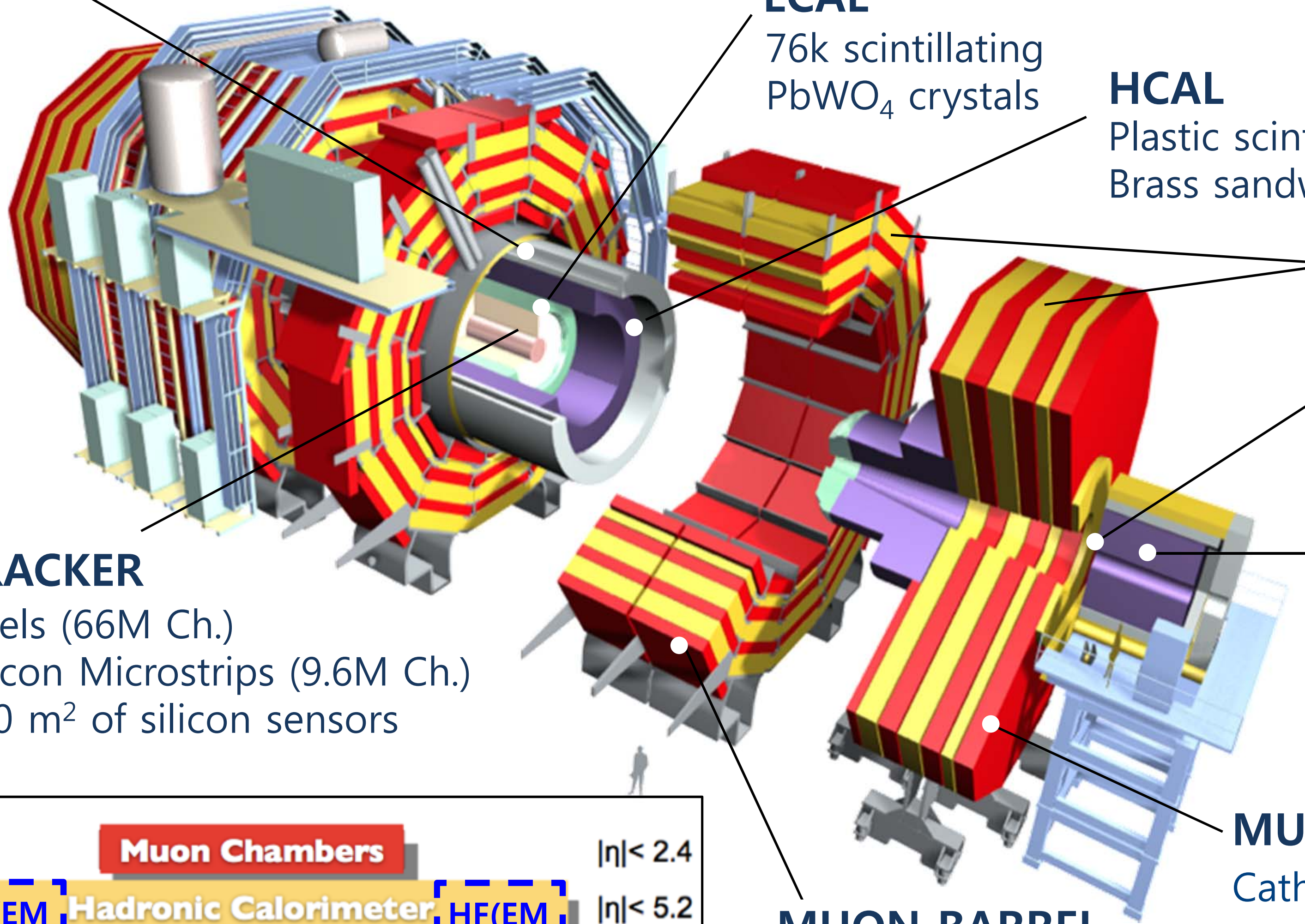
Byungsik Hong
(Korea University)

For the CMS Collaboration

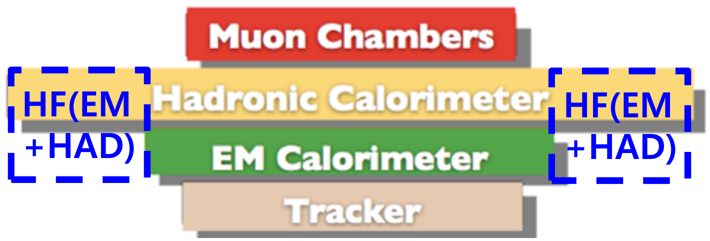
Outline

1. Introduction
   - CMS detector
   - Heavy-ion runs at LHC
2. Experimental data
   - Two-particle correlations
     - High-p_T dihadron correlation and dijet behavior
   - Dijet production
     - Angular Correlation and momentum imbalance
     - Modification of jet fragmentation and shapes
   - Quarkonium production
     - Prompt J/ψ, Non-prompt J/ψ, and $\psi(2S)$
     - $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$
3. Summary

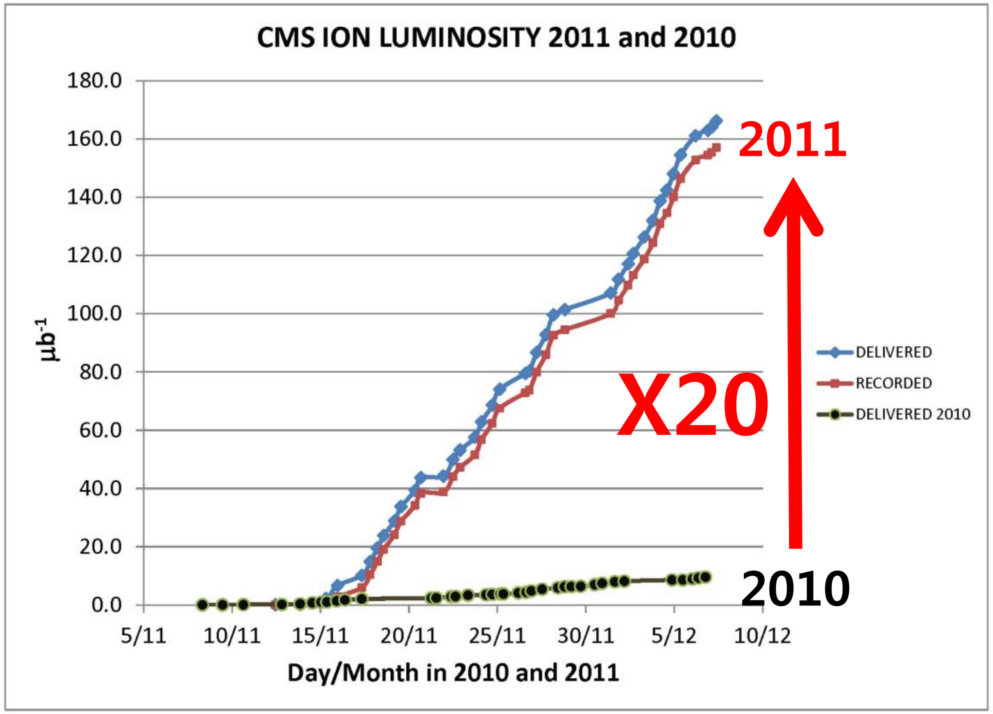
Compact Muon Solenoid (CMS)

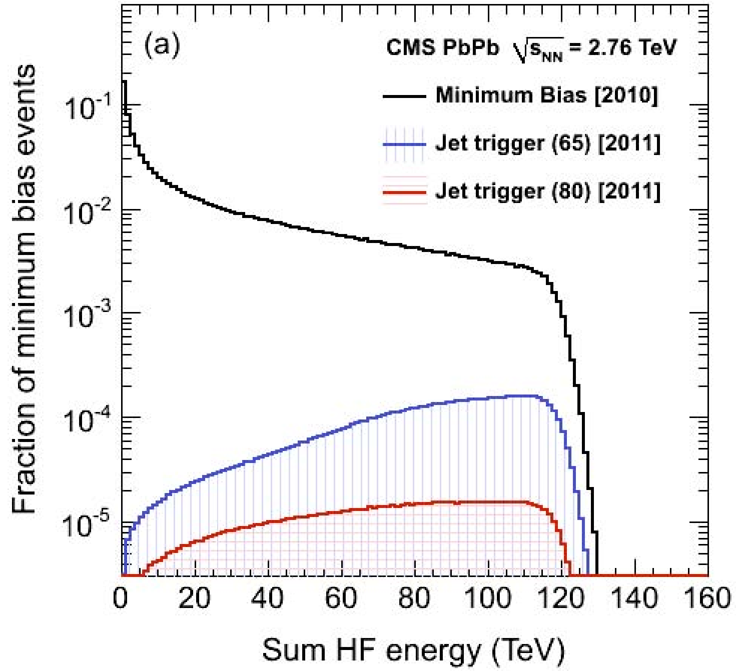


Weight: 12,500 tons
Diameter: 15 m
Length: 22 m



Heavy-Ion Runs in LHC & CMS

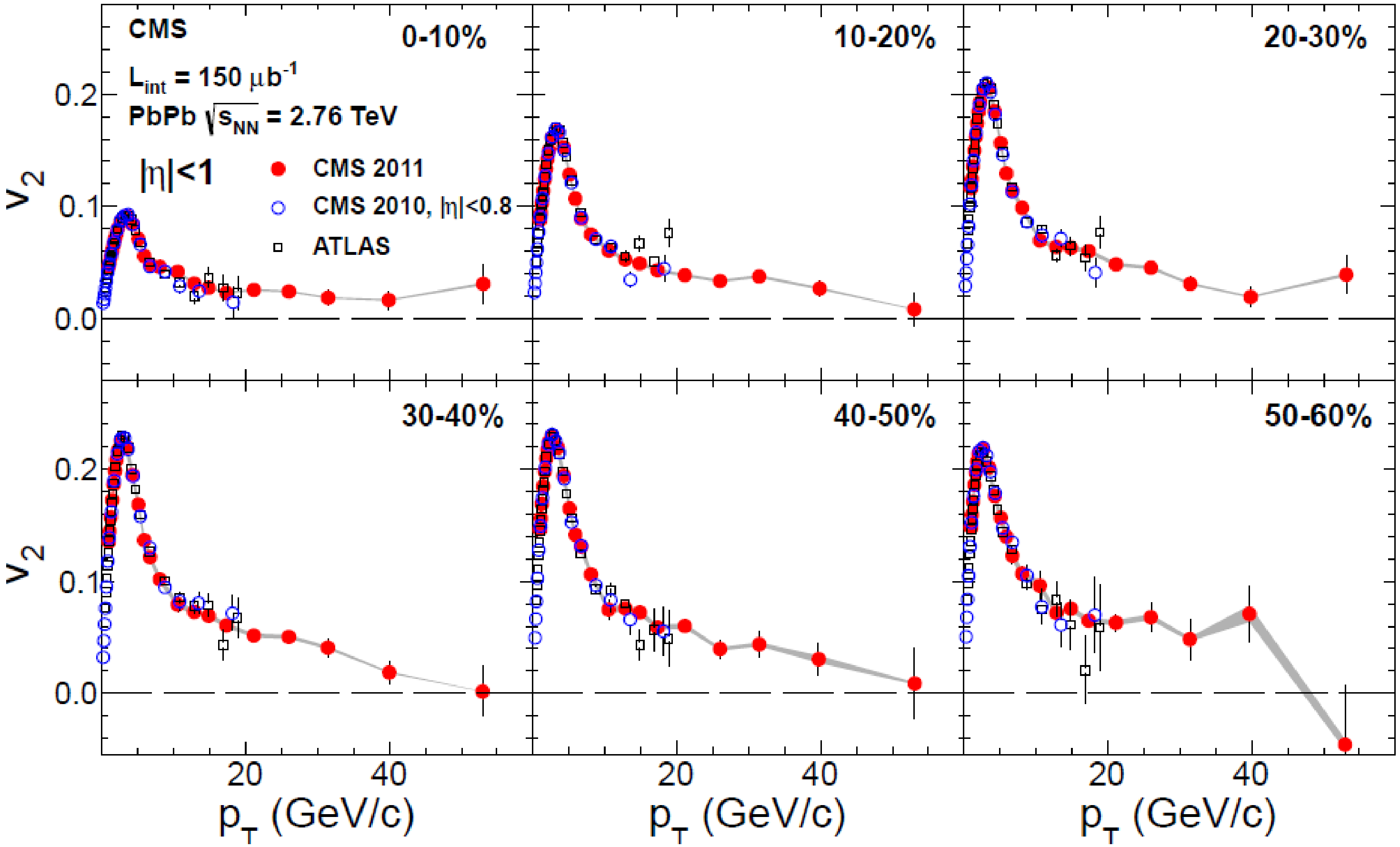




1. MinBias trigger: Coincidence of BSC and HF signals ($\varepsilon = 97 \pm 3$ %)
2. Dimuon trigger: Two tracks in muon detector
3. Jet trigger: Uncorrected jet E_T > 35, 50 GeV
4. High-p_T trigger: p_T > 12 GeV
5. Photon trigger: Uncorrected photon E_T > 15 GeV

High-p_T Dihadron Correlation

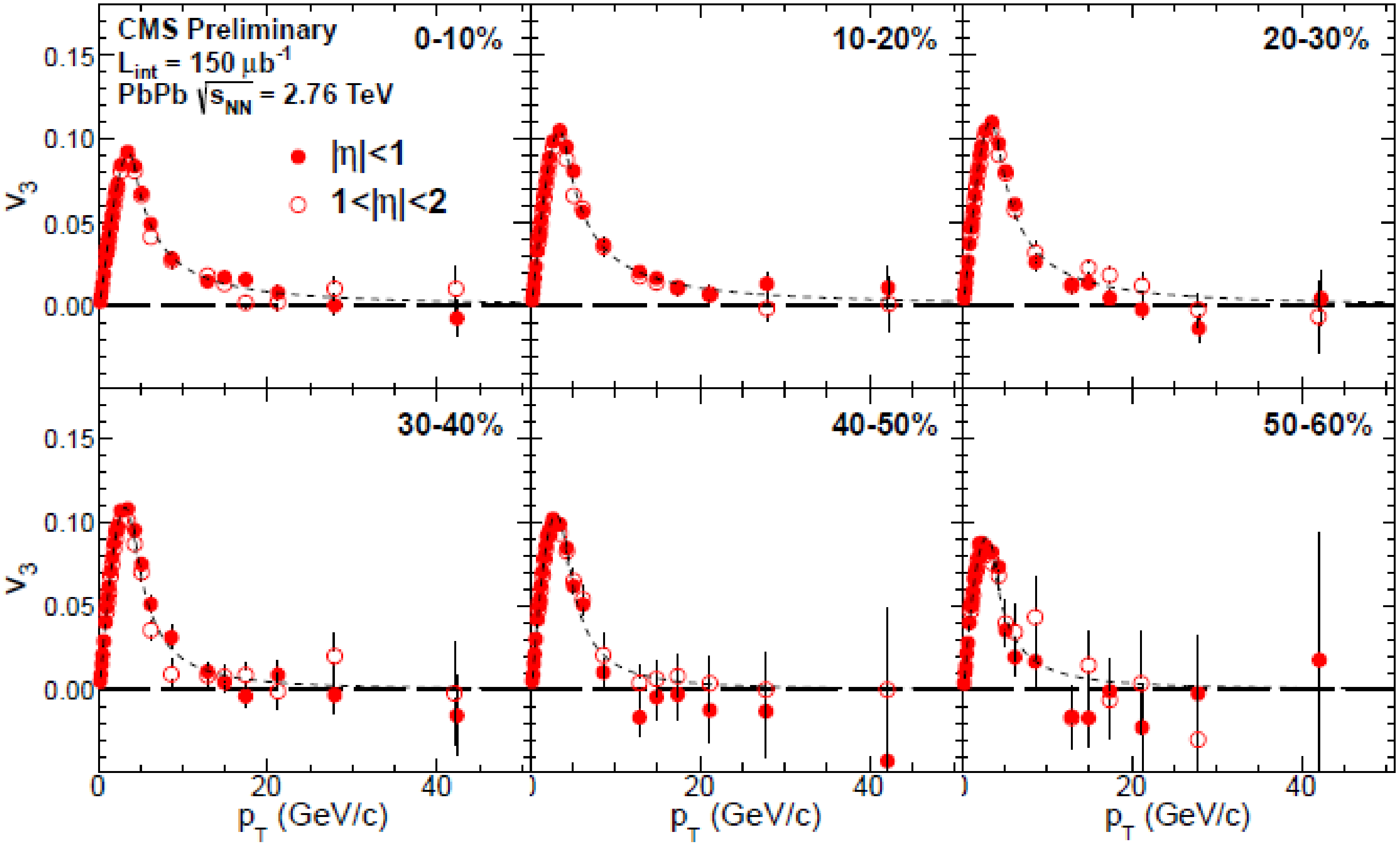
PRL 109, 022301 (2012)



- v_2 persists to p_T > 40 GeV/c

High-p_T Dihadron Correlation

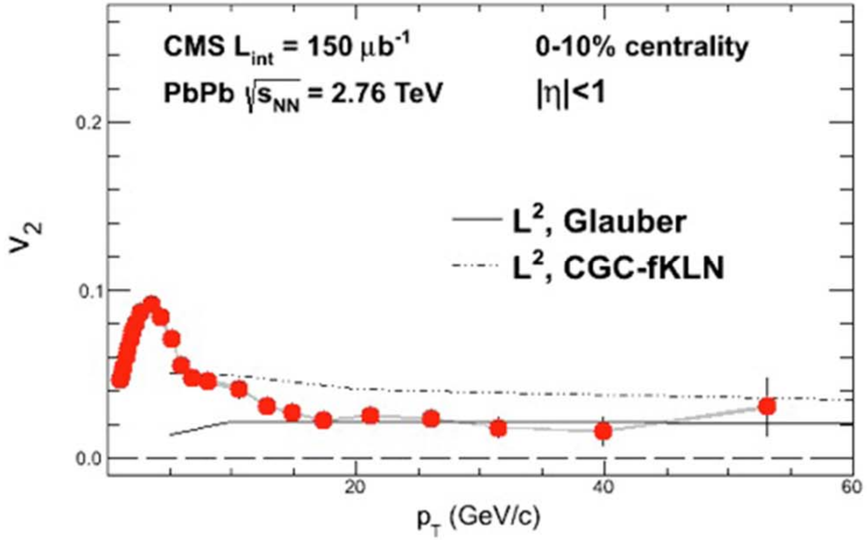
CMS PAS HIN-12-010

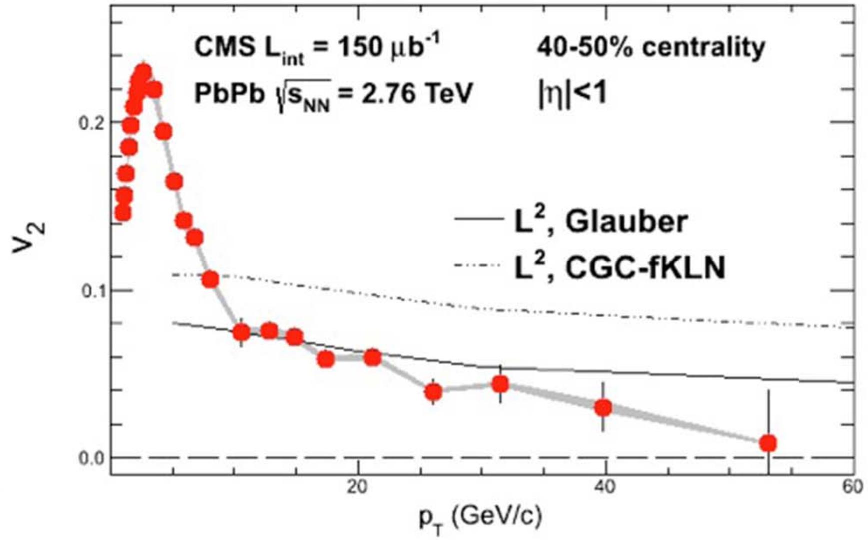


- v_3 (and also v_4) vanishes for p_T > 20 GeV/c
- Weaker correlations of path length and Ψ_3 (and Ψ_4) plane

High-p_T Dihadron Correlation

Theory: B. Betz, M. Gyulassy, arXiv:1201.0281





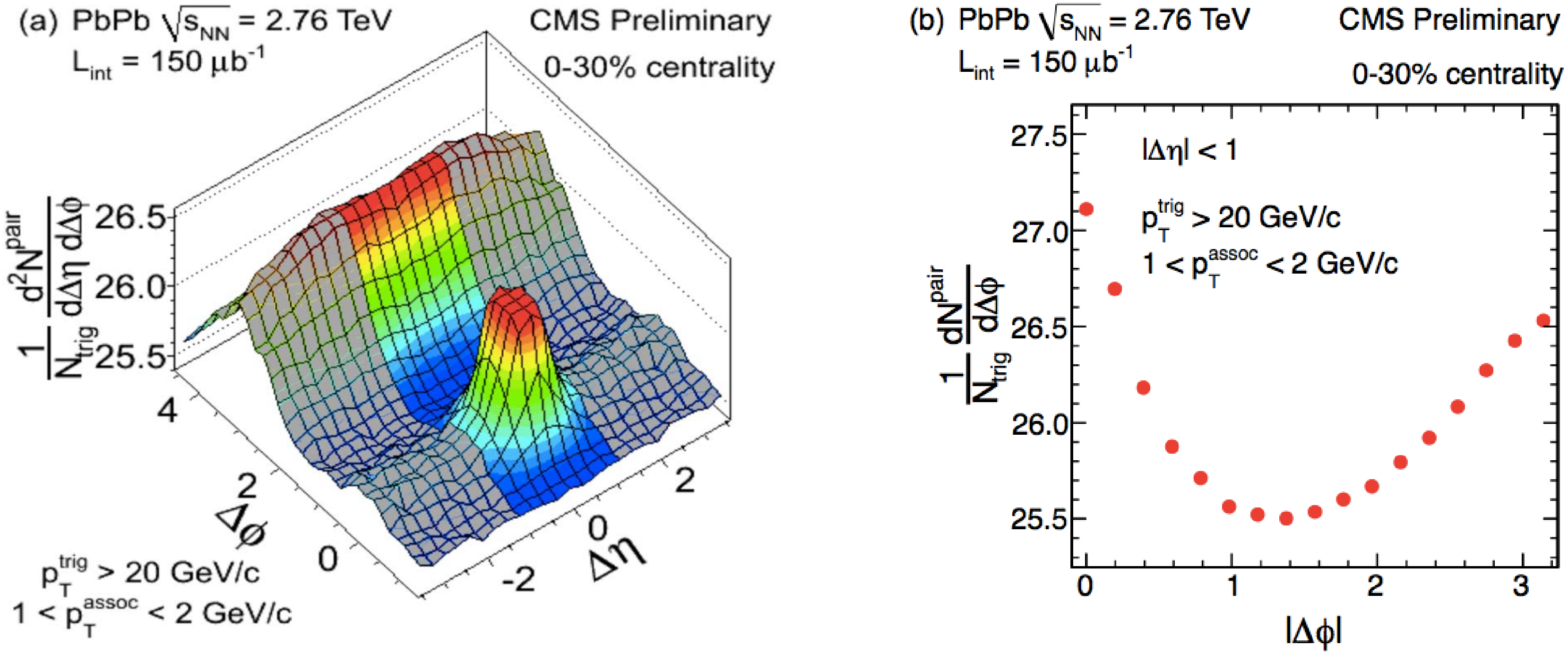
- Data can constrain the path-length dependence of the energy loss and different initial conditions (Glauber vs. CGC)

$\Delta E \sim L^{\alpha}$
α=1 for pQCD, collisional
α=2 for pQCD, radiative
α=3 for AdS/CFT

High-p_T Dihadron Correlation

CMS PAS HIN-12-010

$|\Delta\eta|<1$



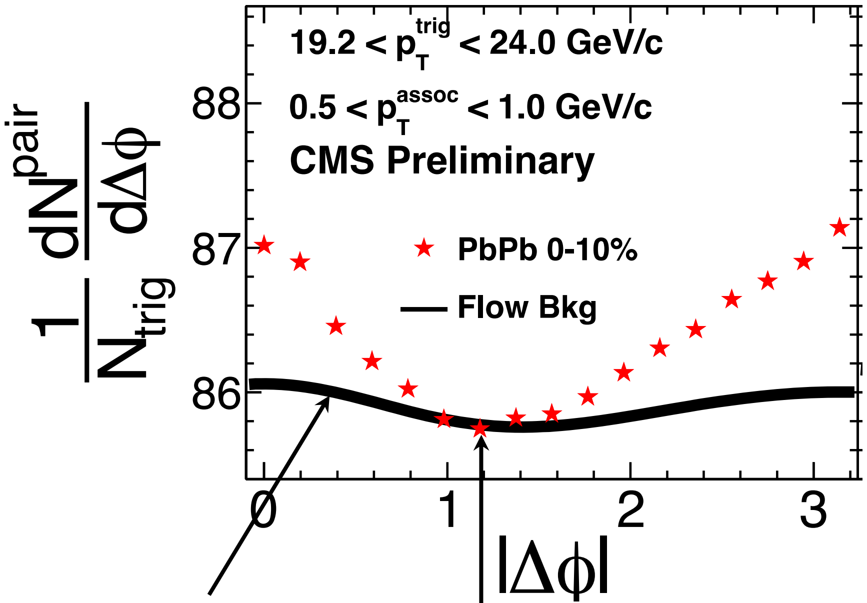
- Azimuthal correlation at high p_T near the jet components
  - Reflects the path-length dependence of parton energy loss
  - Quantitative constraint on various jet quenching models
  - Flow (v_2-v_4) from LR correlation needs to be subtracted for jet

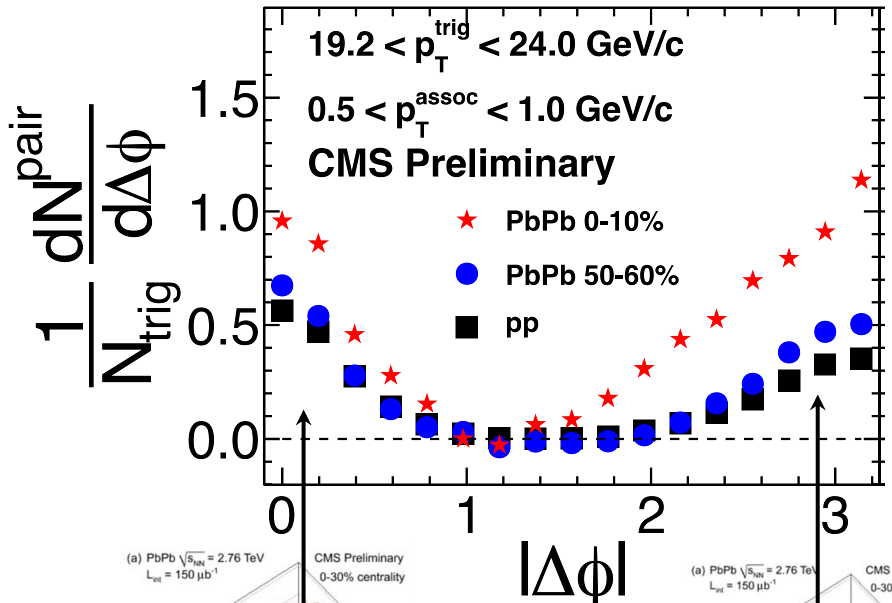
Dijet Behavior from High-p_T Correlation

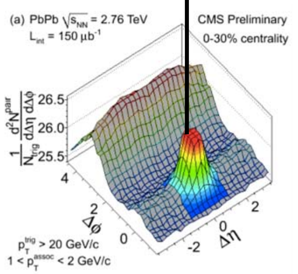
- Need to subtract event-plane related correlations (v_2-v_4) from dihadron correlation

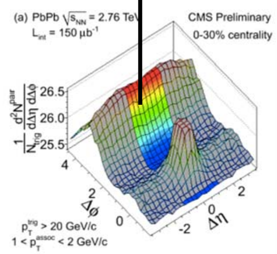
CMS PAS HIN-12-010

Before ZYAM Subtraction ⟹ After ZYAM Subtraction









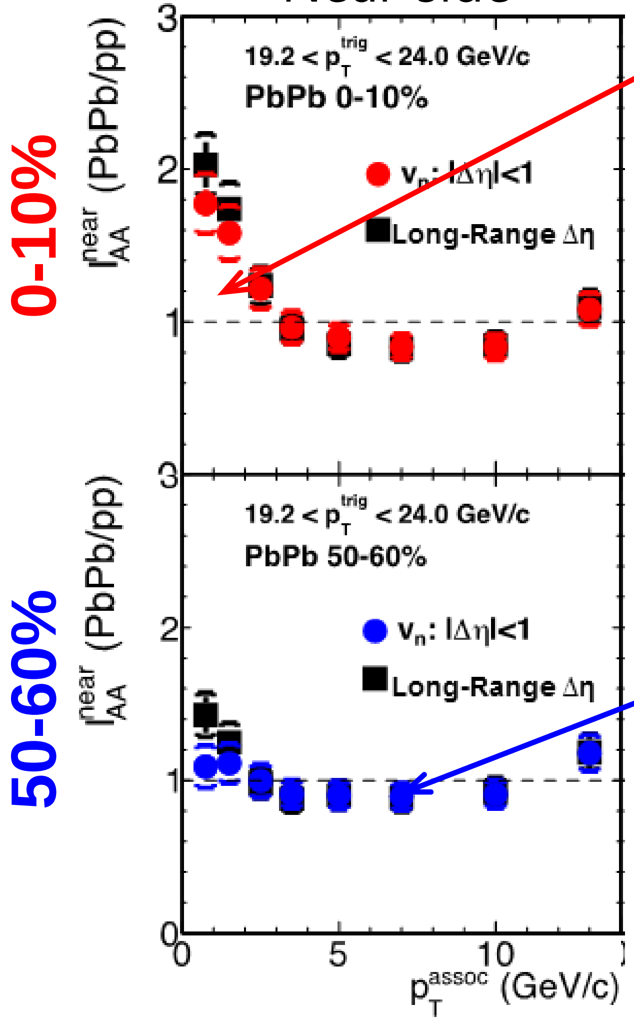
Flow Background

"Zero Yield At Minimum"

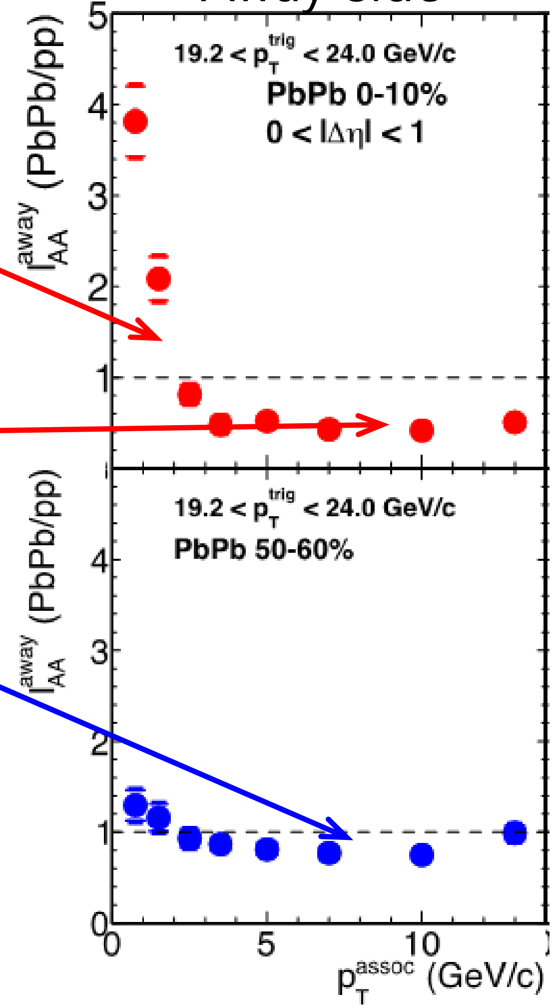
Dijet Behavior from High-p_T Correlation

CMS PAS HIN-12-010

Near side



Away side



Some enhancement at low p_T

Significant enhancement (X4) at low p_T

Significant deficit (X0.5) at high p_T

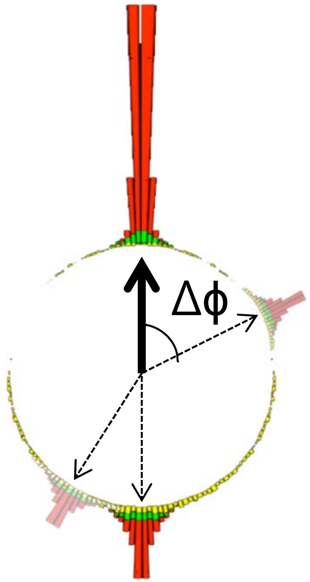
No significant modification in perpheral events

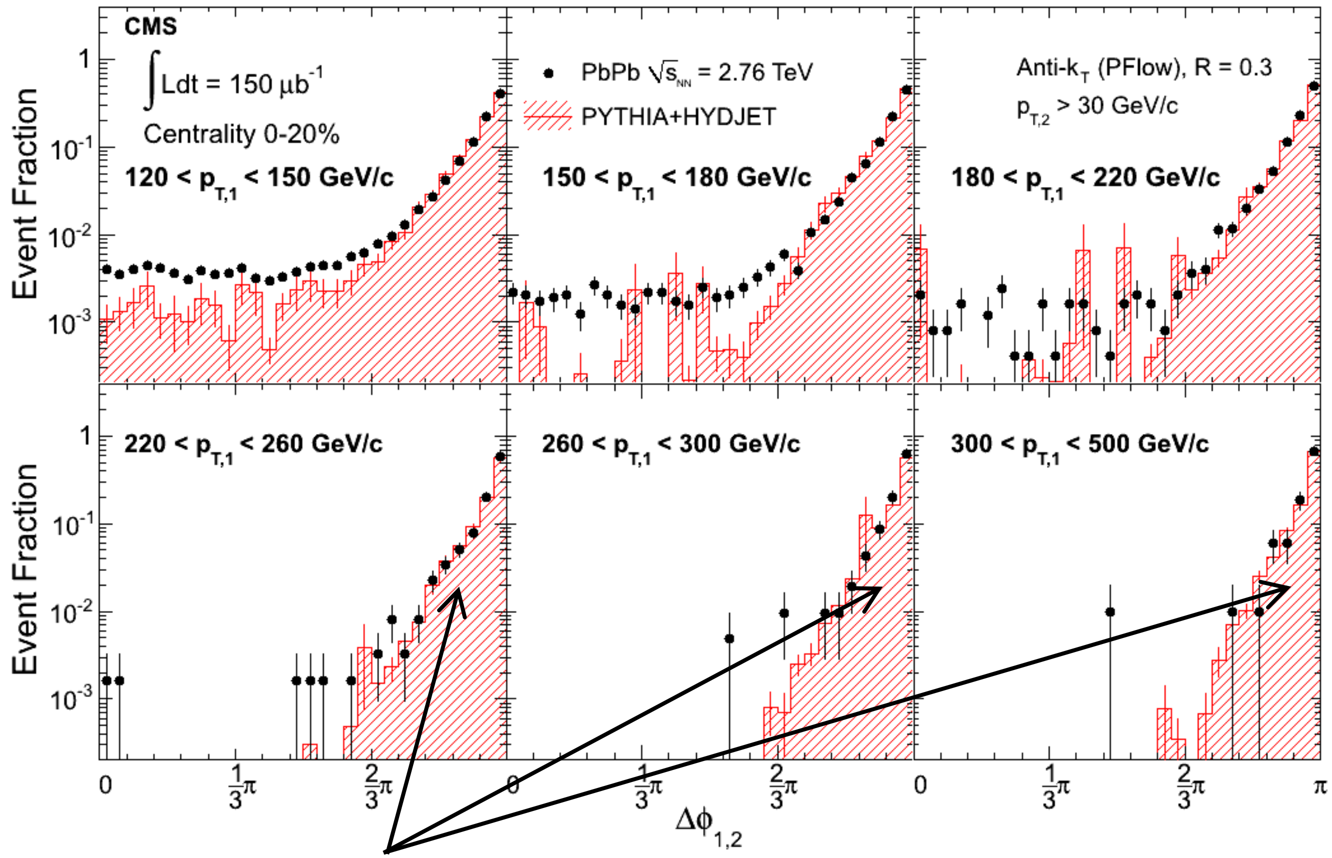
$$I_{AA}^{near(away)} = \frac{Y_{PbPb}^{near(away)}}{Y_{pp}^{near(away)}}$$

Dijet Angular Correlation

Now turn to the full jet reconstruction!

PLB 712, 176 (2012)

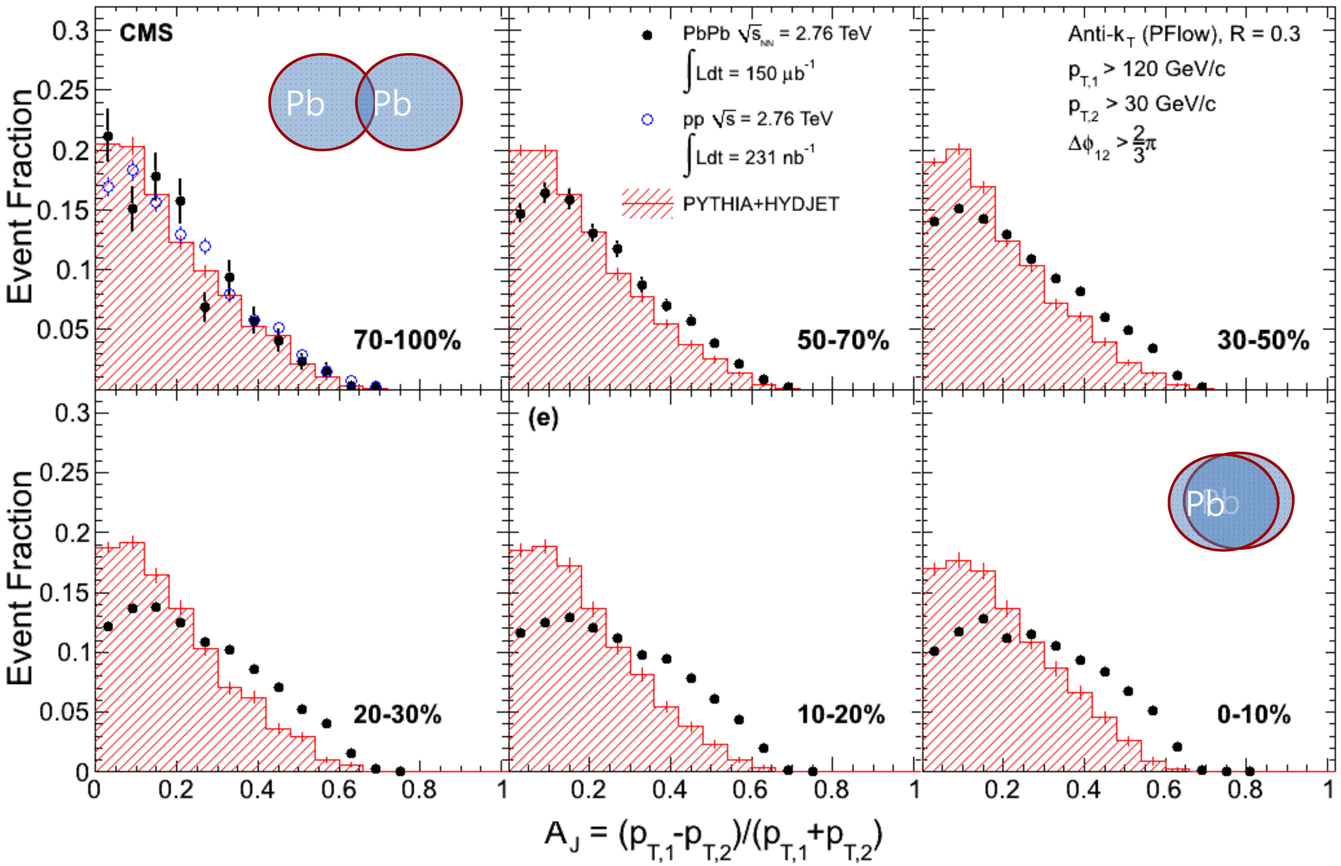


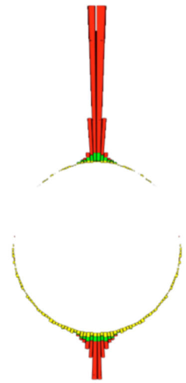


- Correlation peak in the data are reproduced by PYTHIA for all p_T ranges

Dijet Momentum Imbalance

PLB 712, 176 (2012)

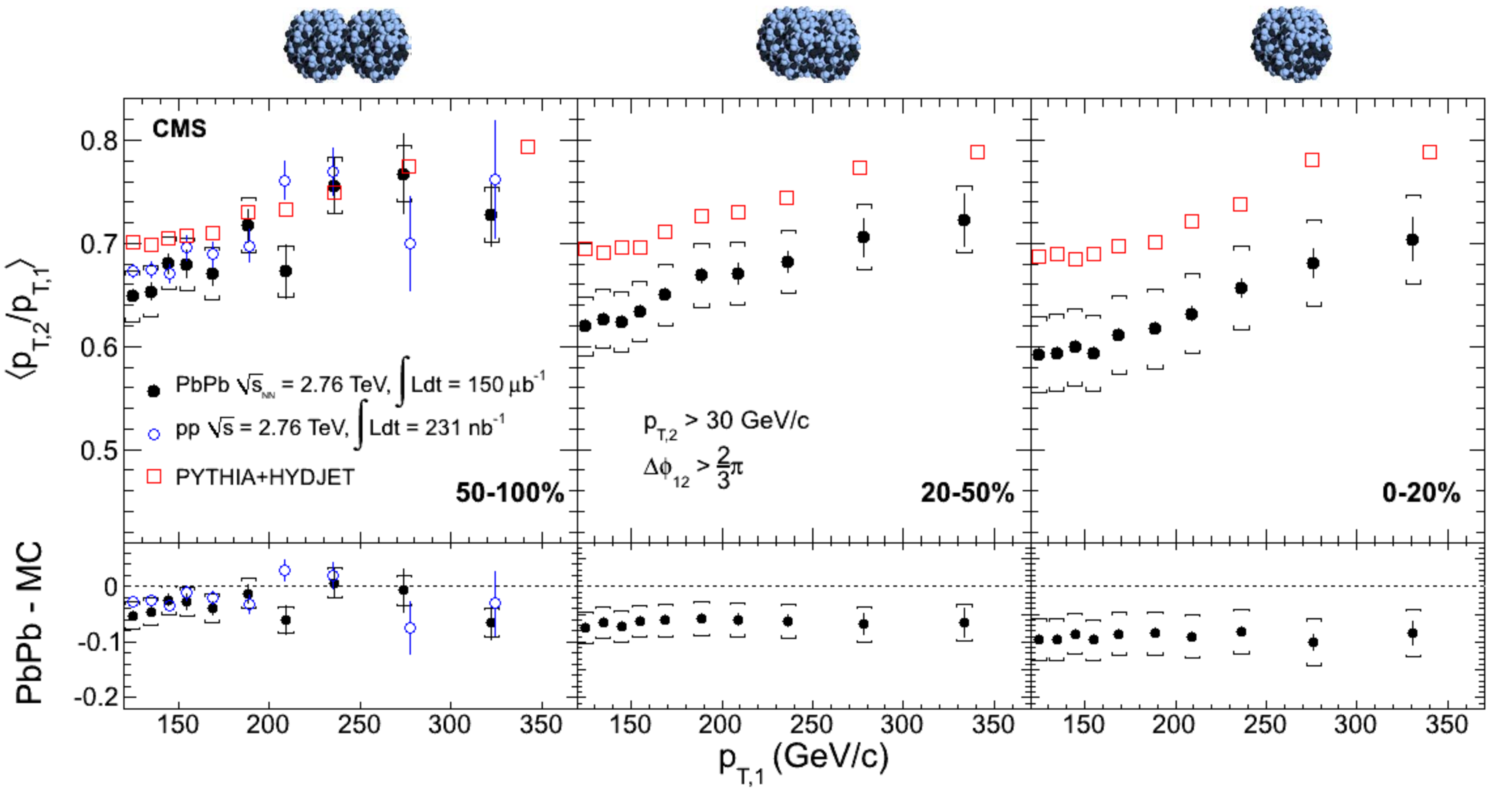




- Dijets in PbPb are more imbalanced than PYTHIA except the most peripheral events

p_T-Dependence of Dijet Imbalance

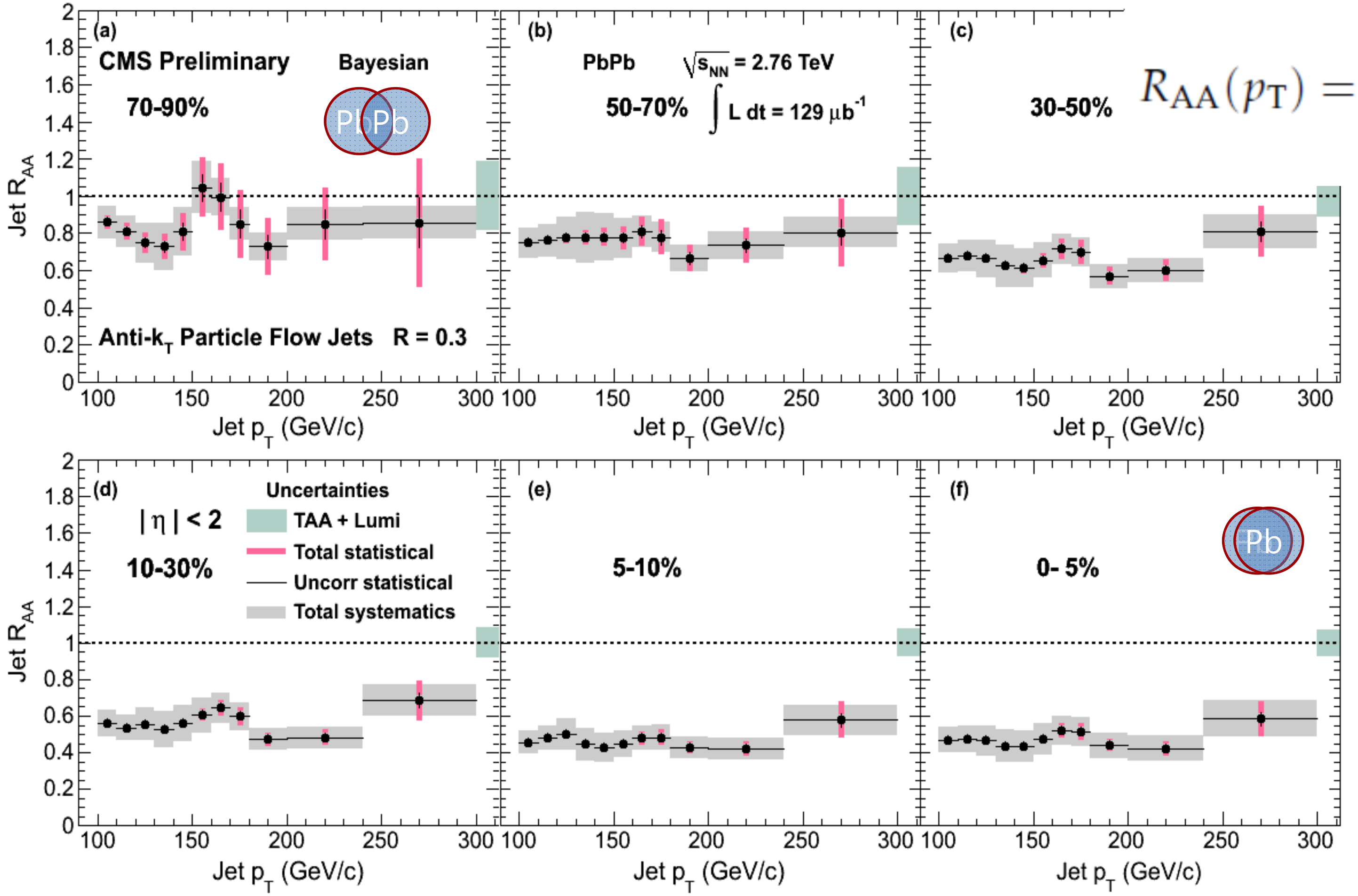
PLB 712, 176 (2012)



- Energy loss is apparent except the most peripheral events
- Energy loss is larger for more central collisions
- No significant dependence on jet p_T

Nuclear Modification of Jets

CMS PAS HIN-12-004

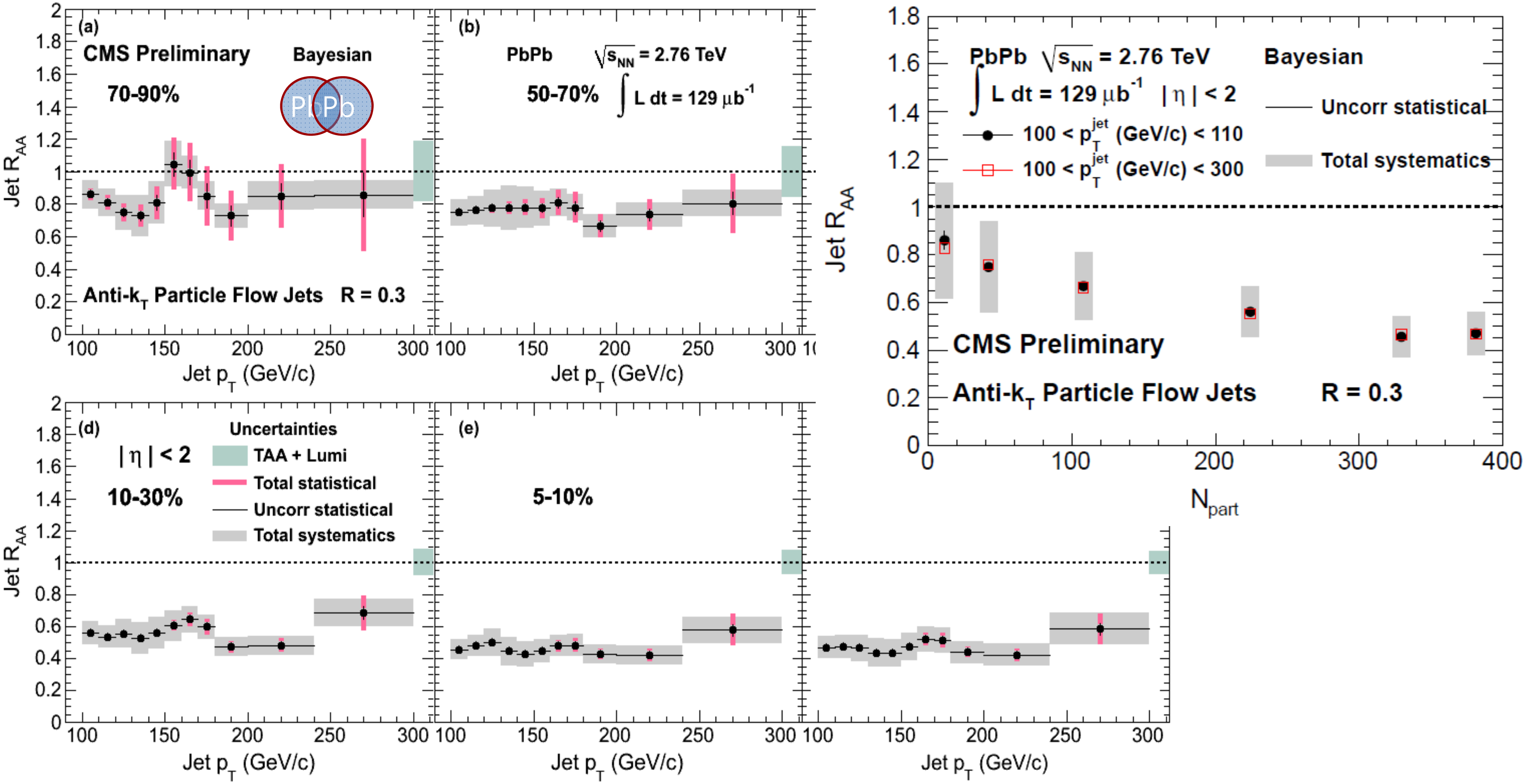


$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{\langle T_{AA}\rangle\, d^2\sigma^{NN}/dp_T d\eta}$$

- No significant p_T (as well as cone size) dependence

Nuclear Modification of Jets

CMS PAS HIN-12-004

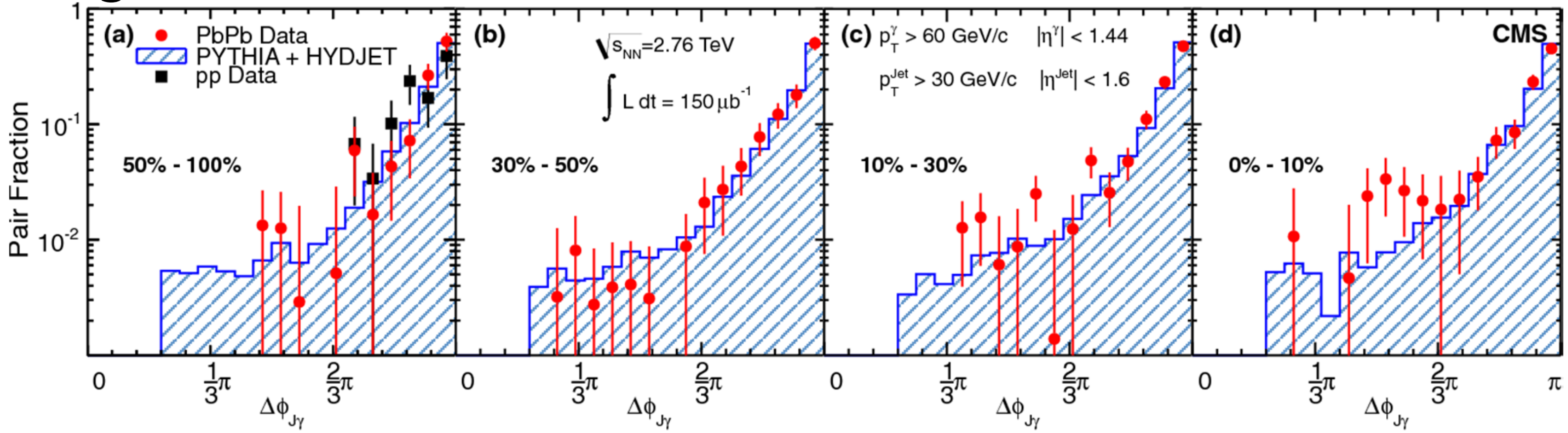


- No significant p_T (as well as cone size) dependence

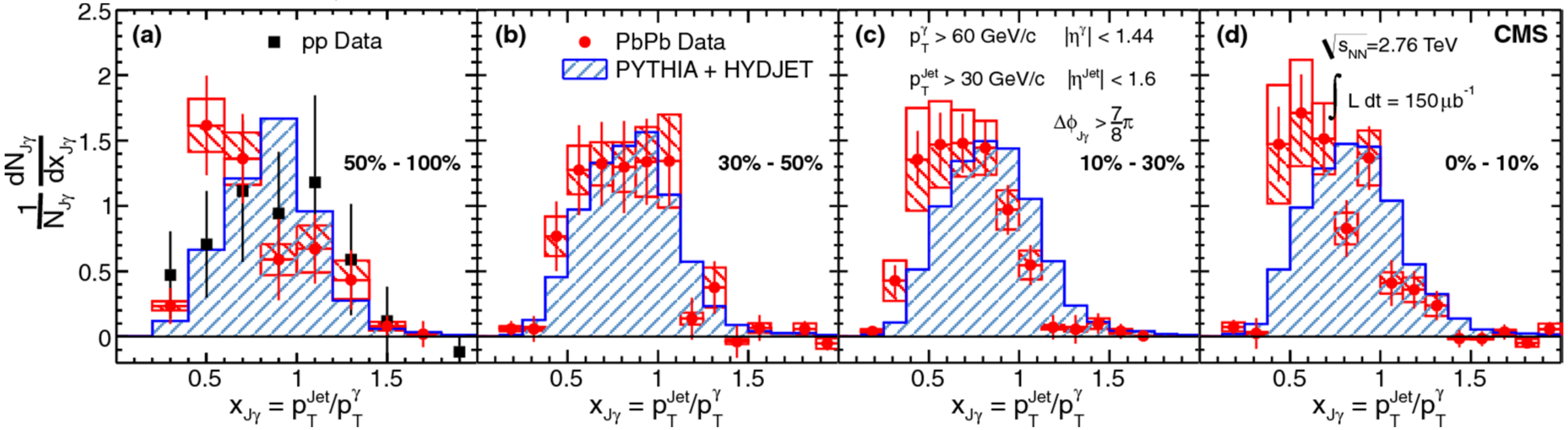
Jet Energy Loss in γ-Jet Correlation

- Angular correlation

arXiv:1205.0206



- Photons serve as an unmodified energy tag for the jet partner
  - Ratio $x_{J\gamma}=p_T^{jet}/p_T^{\gamma}$: direct measure of the jet energy loss

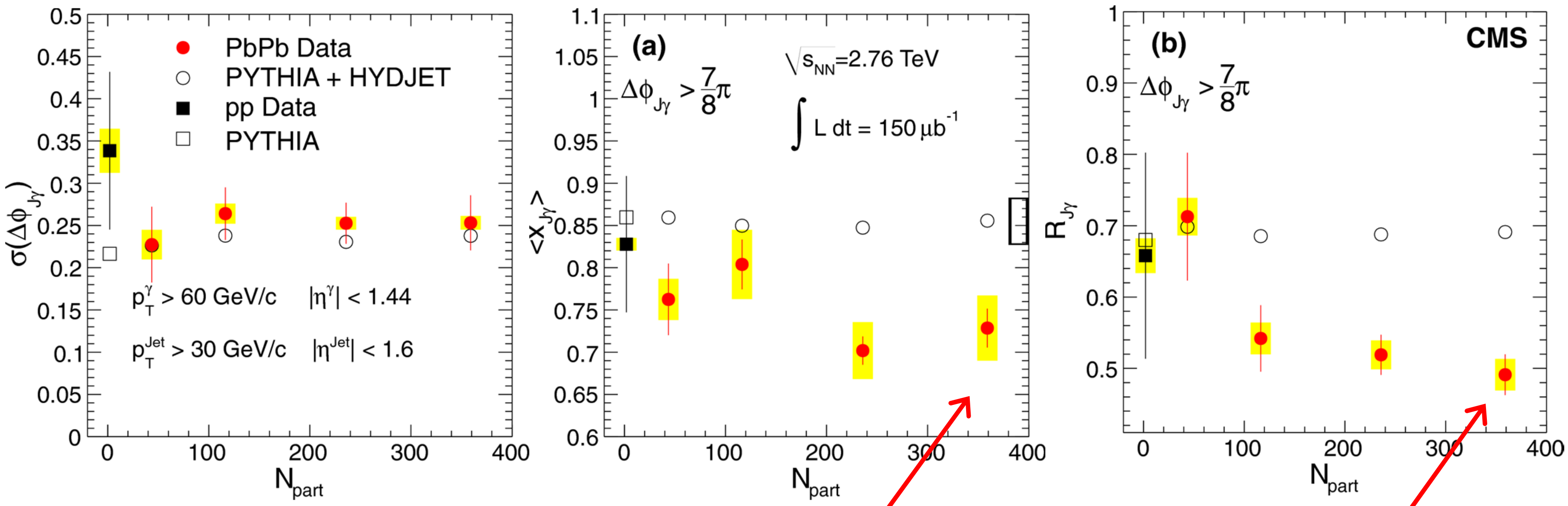


Jet Energy Loss in γ-Jet Correlation

arXiv:1205.0206

$x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$

$R_{J\gamma}$ = Fraction of photons with jet partner >30 GeV/c



No particular ϕ decorrelation

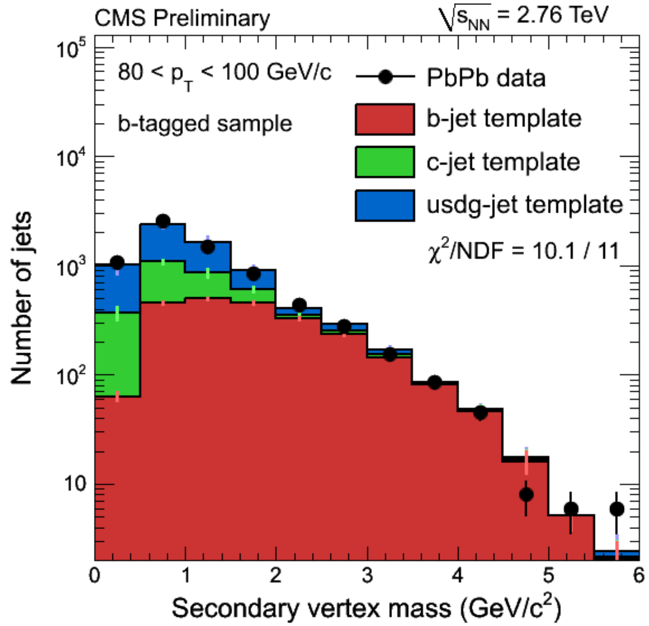
Increasing p_T imbalance in central collisions
(Jets lose ~14% of their initial energy)

Less jet partners above threshold
(~20% of photons lose their jet partner)

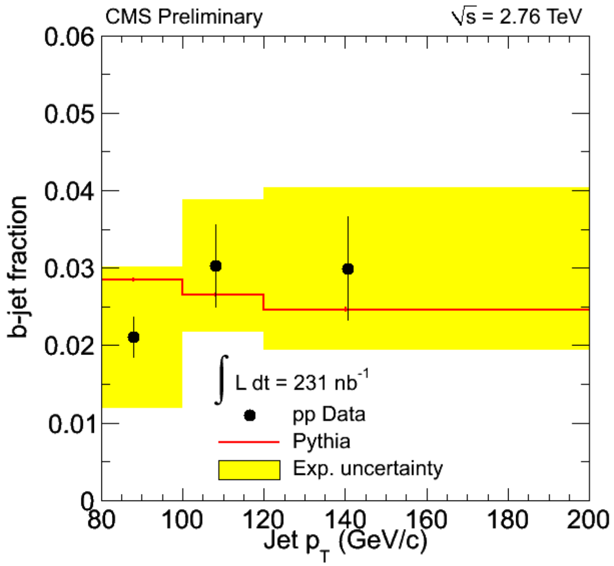
Are heavy-quark jets quenched, too?

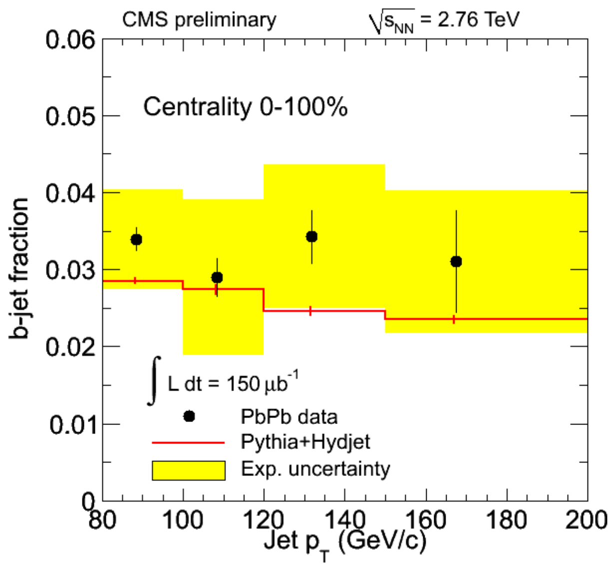
CMS PAS HIN-12-003

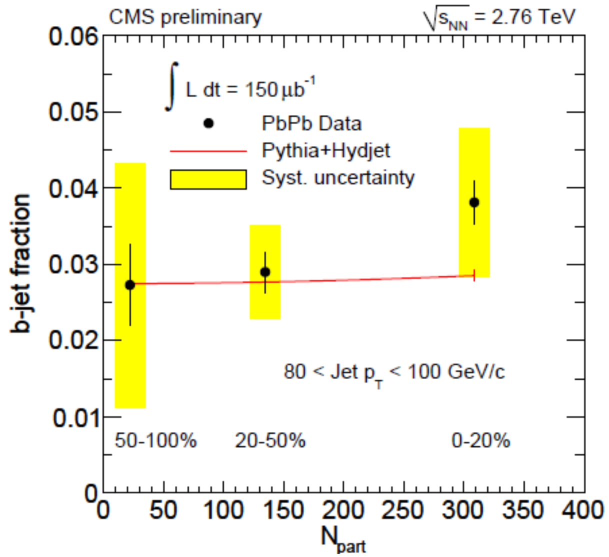
- Secondary vertex tagged using flight distance significance
- Purity from template fits to (tagged) secondary vertex mass distributions



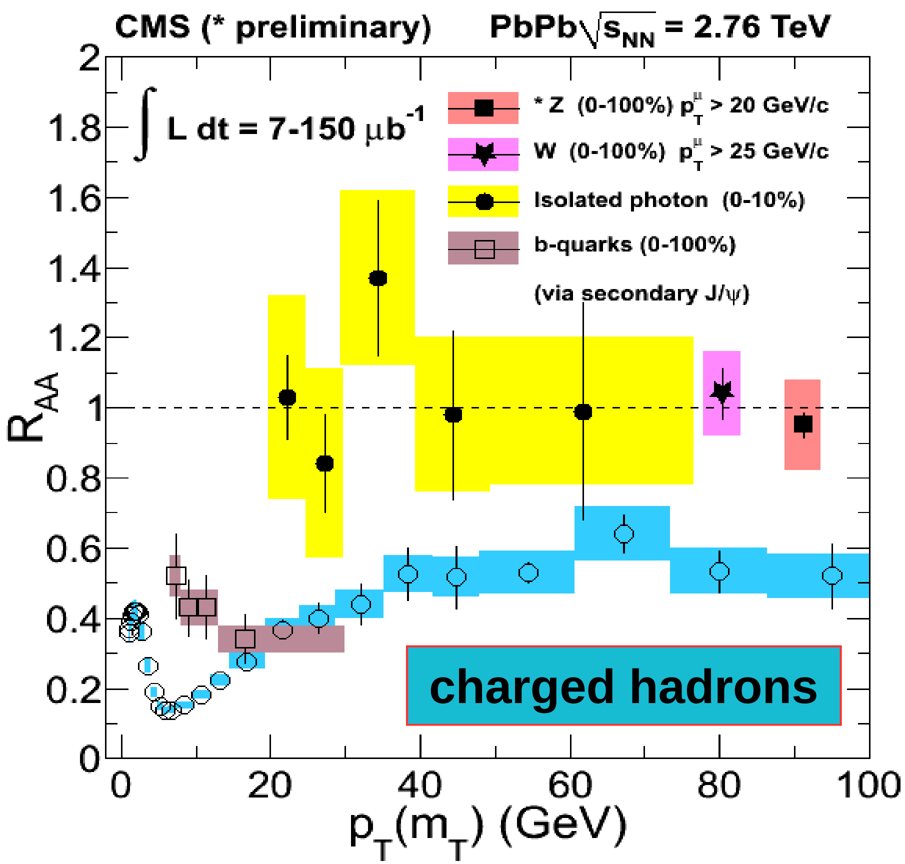
- b-jet fraction: similar in pp and PbPb → b-jet quenching is comparable to light-jet quenching (R_{AA}≈0.5) within present systematics



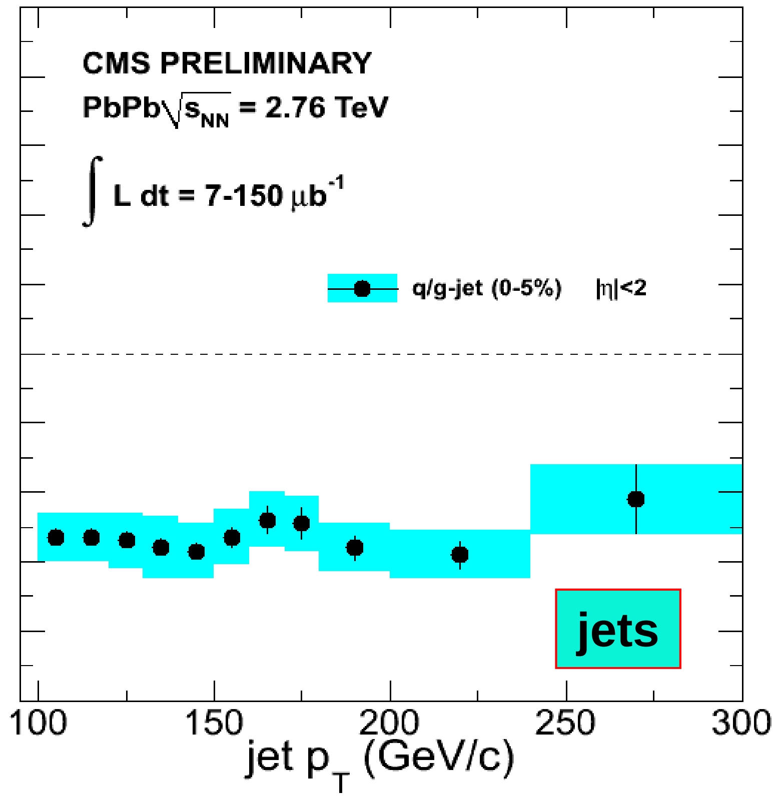




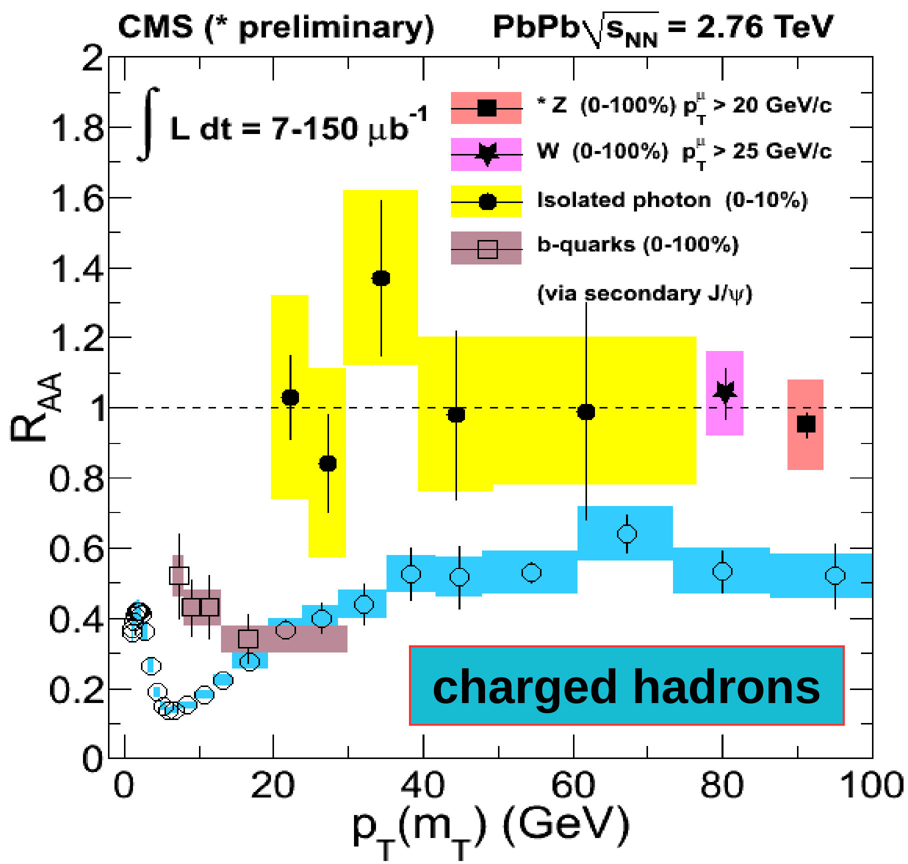
Comparison of R_{AA}



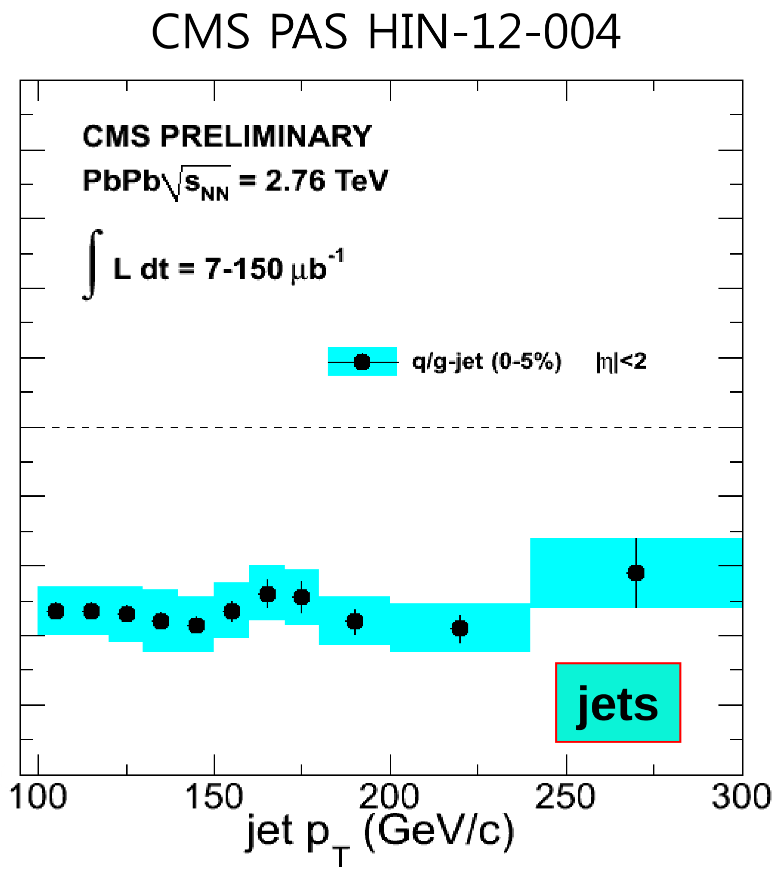
CMS PAS HIN-12-004



Comparison of R_{AA}



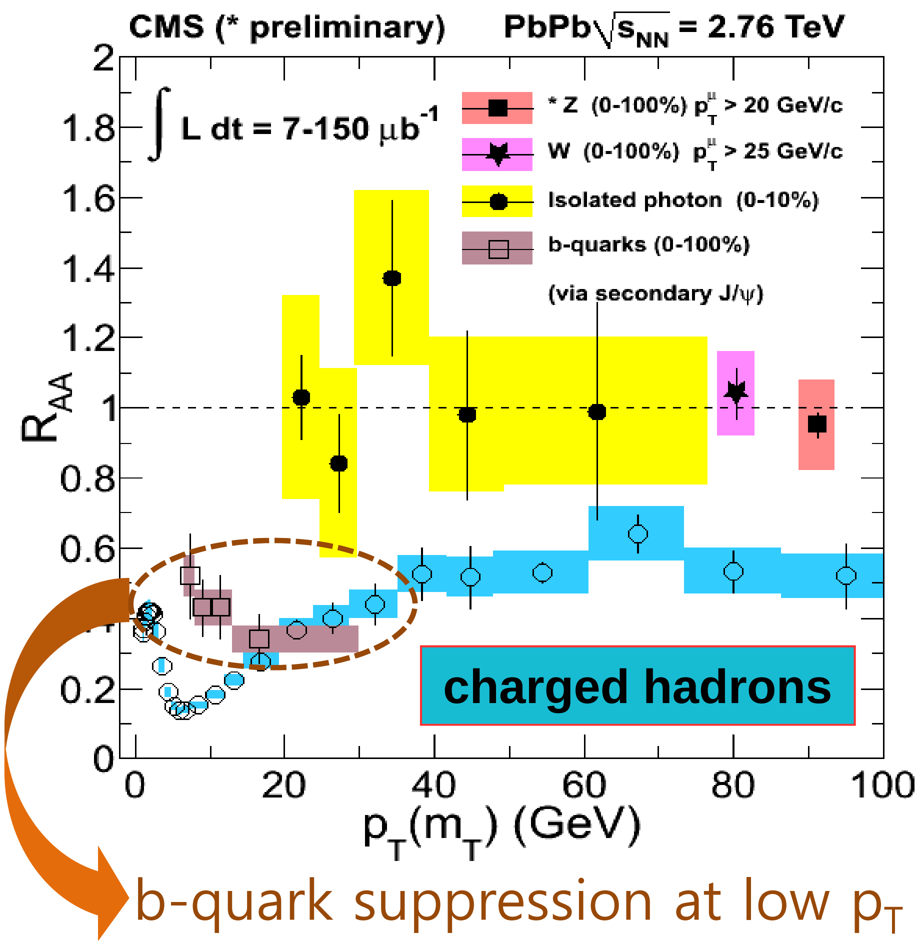
CMS PAS HIN-12-004



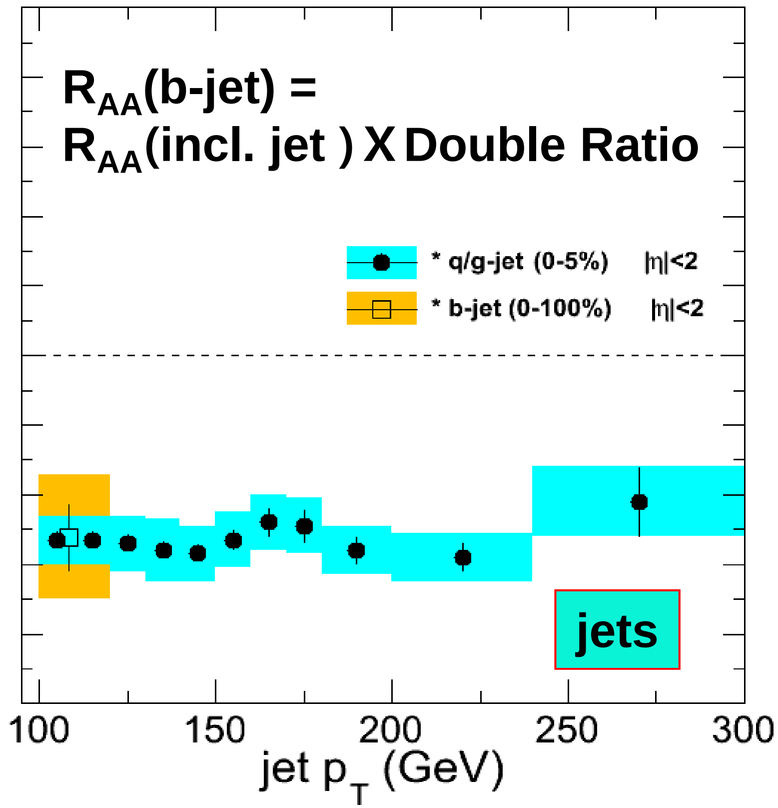
z ~ 0.5 for
p_T=20~100 GeV/c

Sampling the ~same parton p_T range

b-Jet Quenching



CMS PAS HIN-12-003



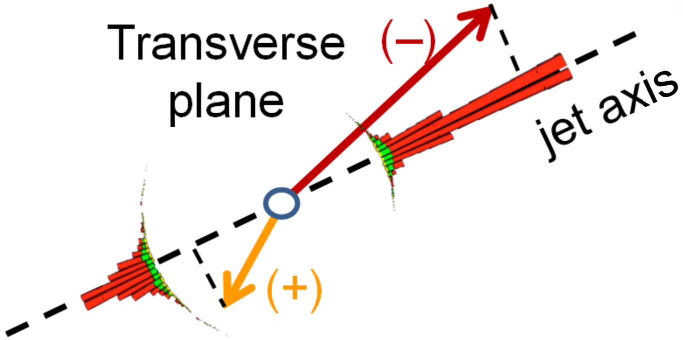
b-quark suppression at low p_T by the secondary J/ψ analysis (see later)

First observation of b-jet suppression at high p_T

Where did missing energy go?

Definition of missing $p_T^{||}$

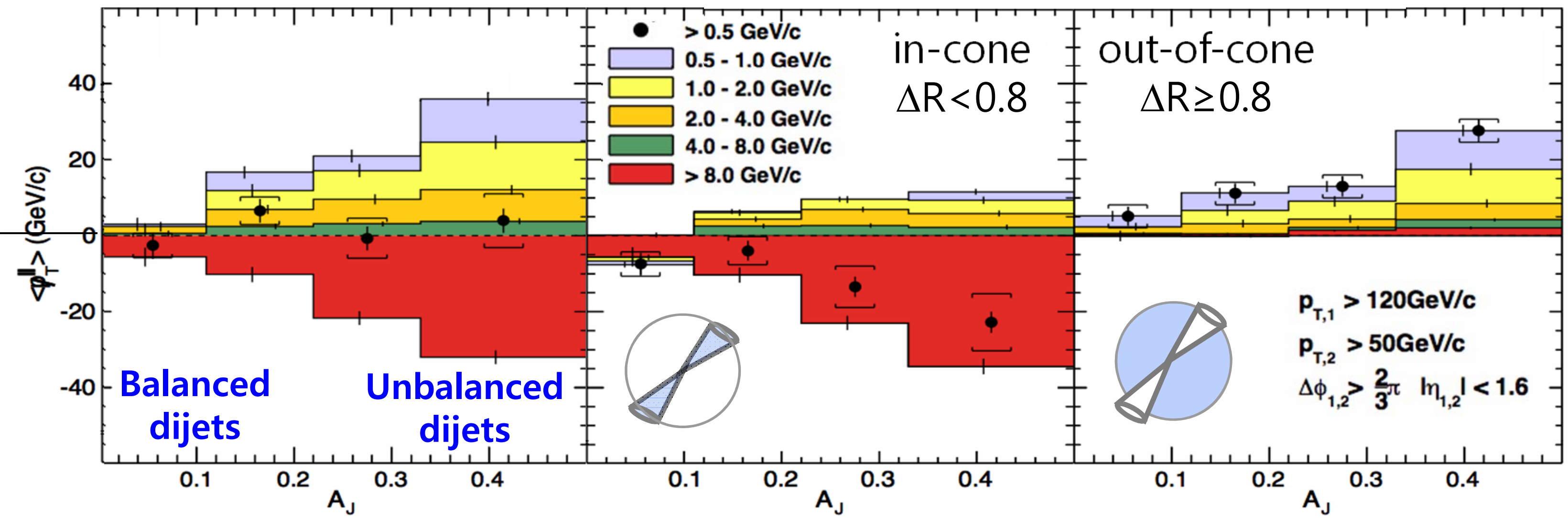
$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$



PRC 84, 024906 (2011)
PbPb 0-30%, L_{int} = 6.7 μb^{-1}

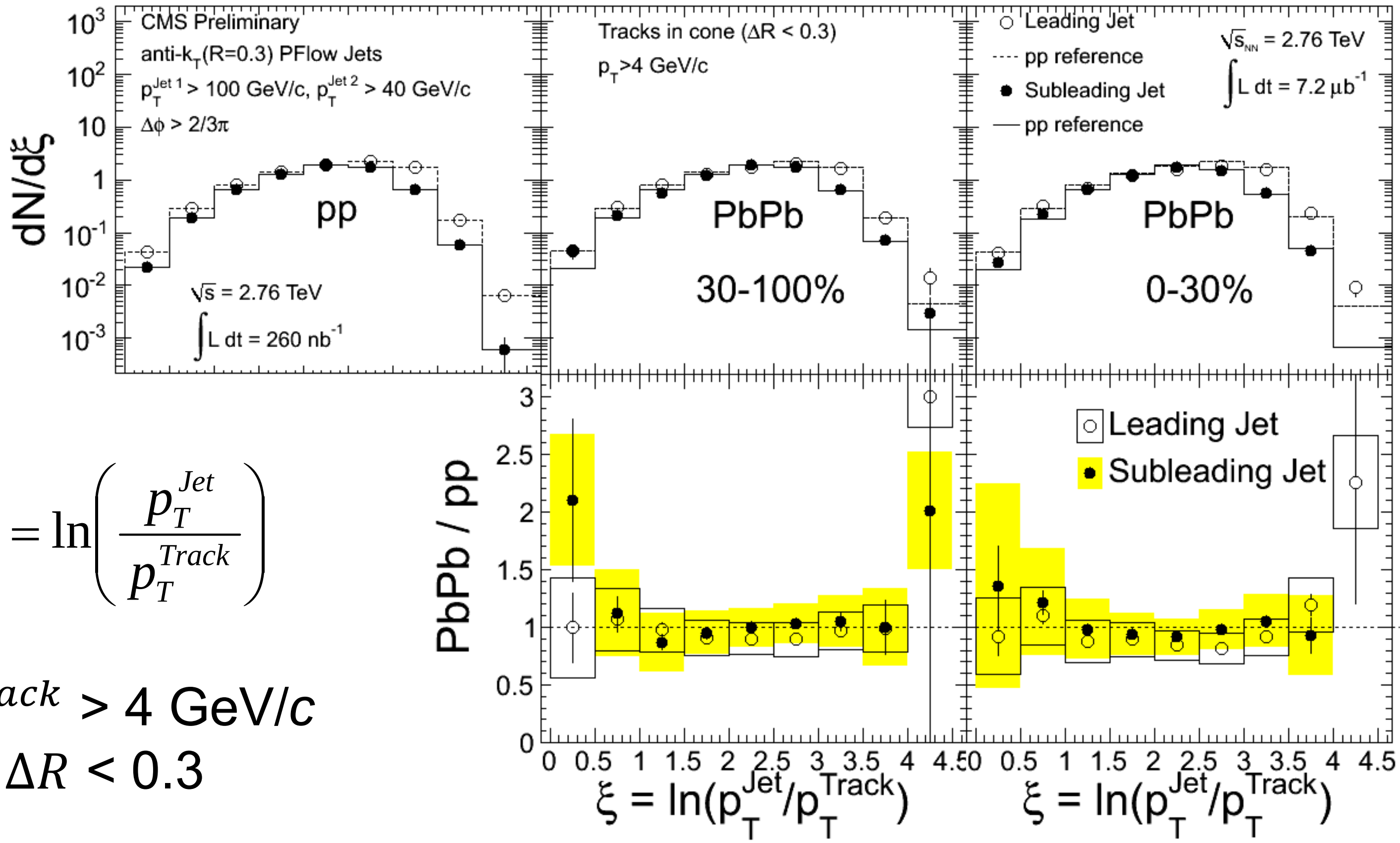
Excess away from leading jet

Excess towards leading jet



- The momentum difference in the dijet is balanced by low-p_T particles at large angles relative to the away side jet axis.

Modification of Jet Fragmentation?



JHEP 10, 087 (2012)

$$\xi = \ln\left(\frac{p_T^{Jet}}{p_T^{Track}}\right)$$

p_T^{Track} > 4 GeV/c

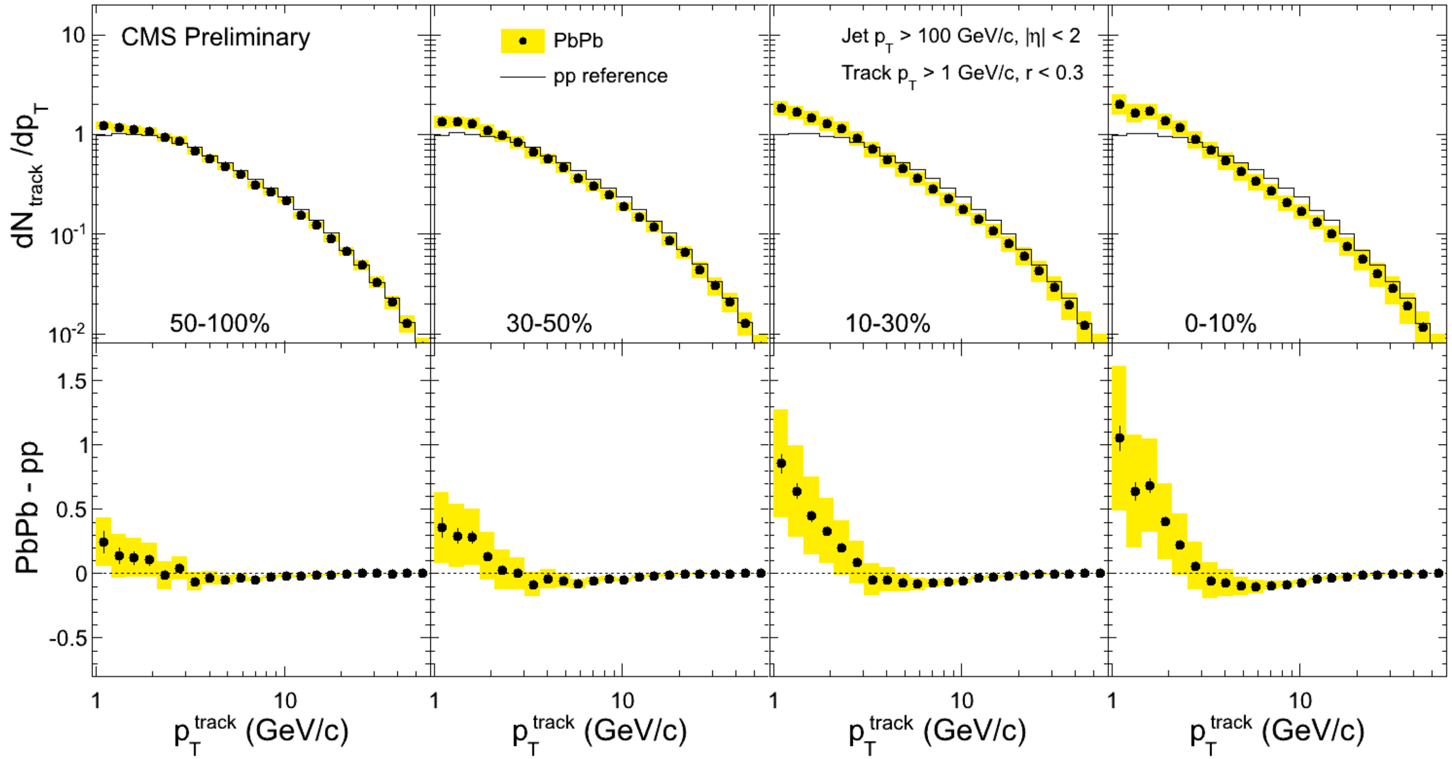
ΔR < 0.3

- The jet fragmentation functions of leading and subleading (quenched) jet in PbPb are essentially unmodified within systematic errors for p_T > 4 GeV/c.

⇒ *This statement was based on 6.7* μb^{-1} !

Modification of Jet Fragmentation?

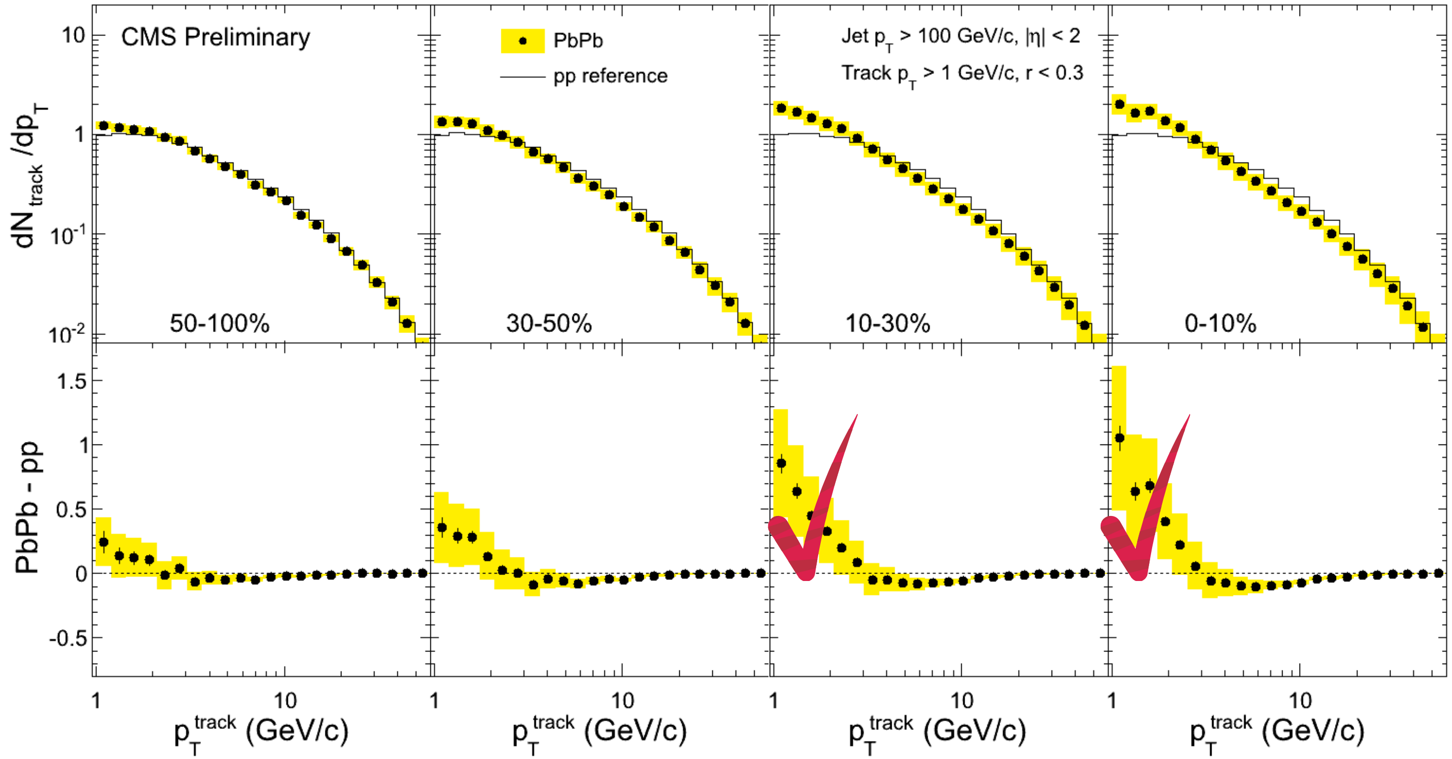
- Changes from 2010 to 2011 data analysis
  - ~20 times more statistics
  - Simplified jet selection: inclusive jet with p_T > 100 GeV/c
  - Lower p_T tracks down to 1 GeV/c



CMS PAS HIN-12-013

Modification of Jet Fragmentation?

- Changes from 2010 to 2011 data analysis
  - ~20 times more statistics
  - Simplified jet selection: inclusive jet with p_T > 100 GeV/c
  - Lower p_T tracks down to 1 GeV/c

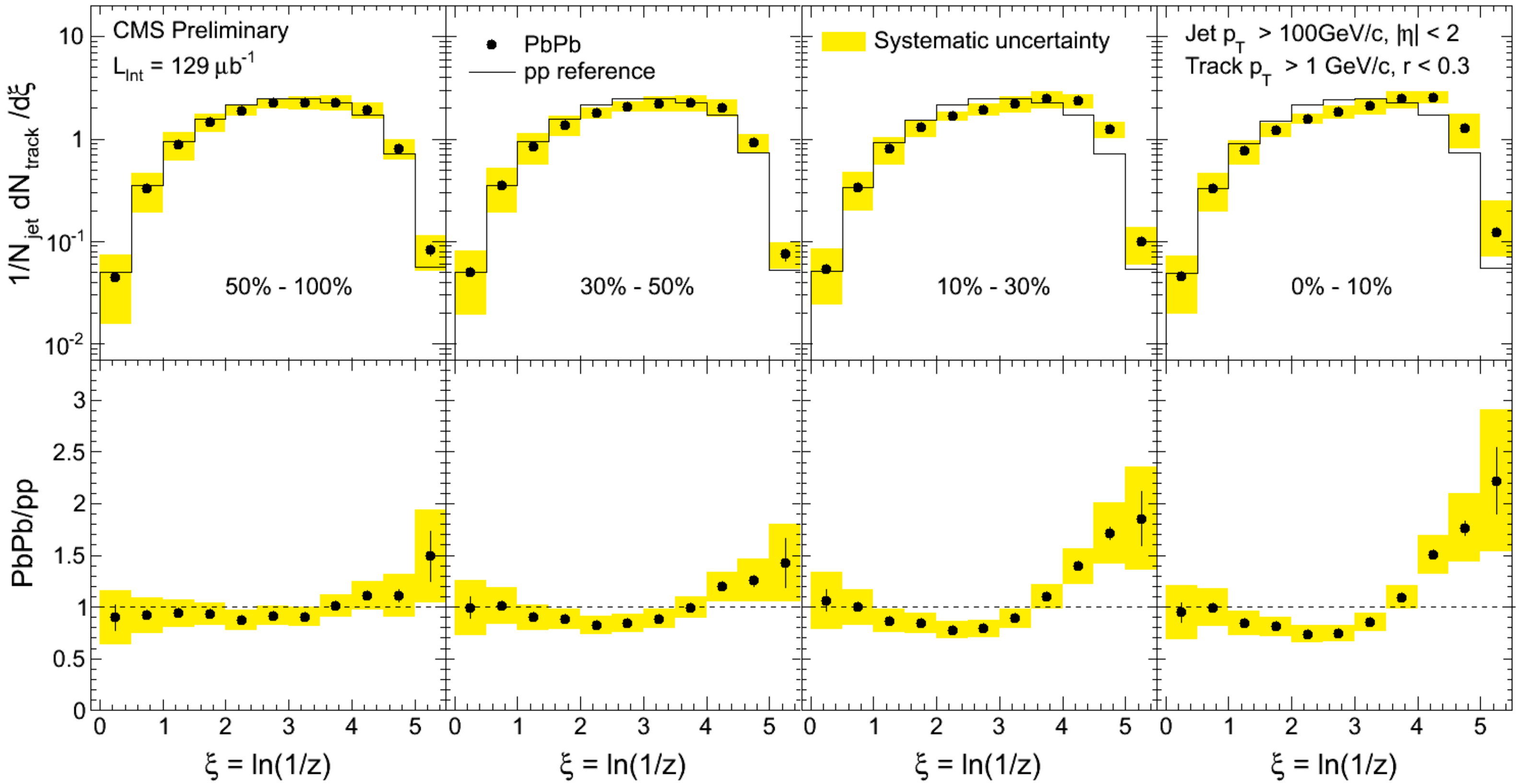


CMS PAS HIN-12-013

- Clear excess at low p_T compared to pp for central events!

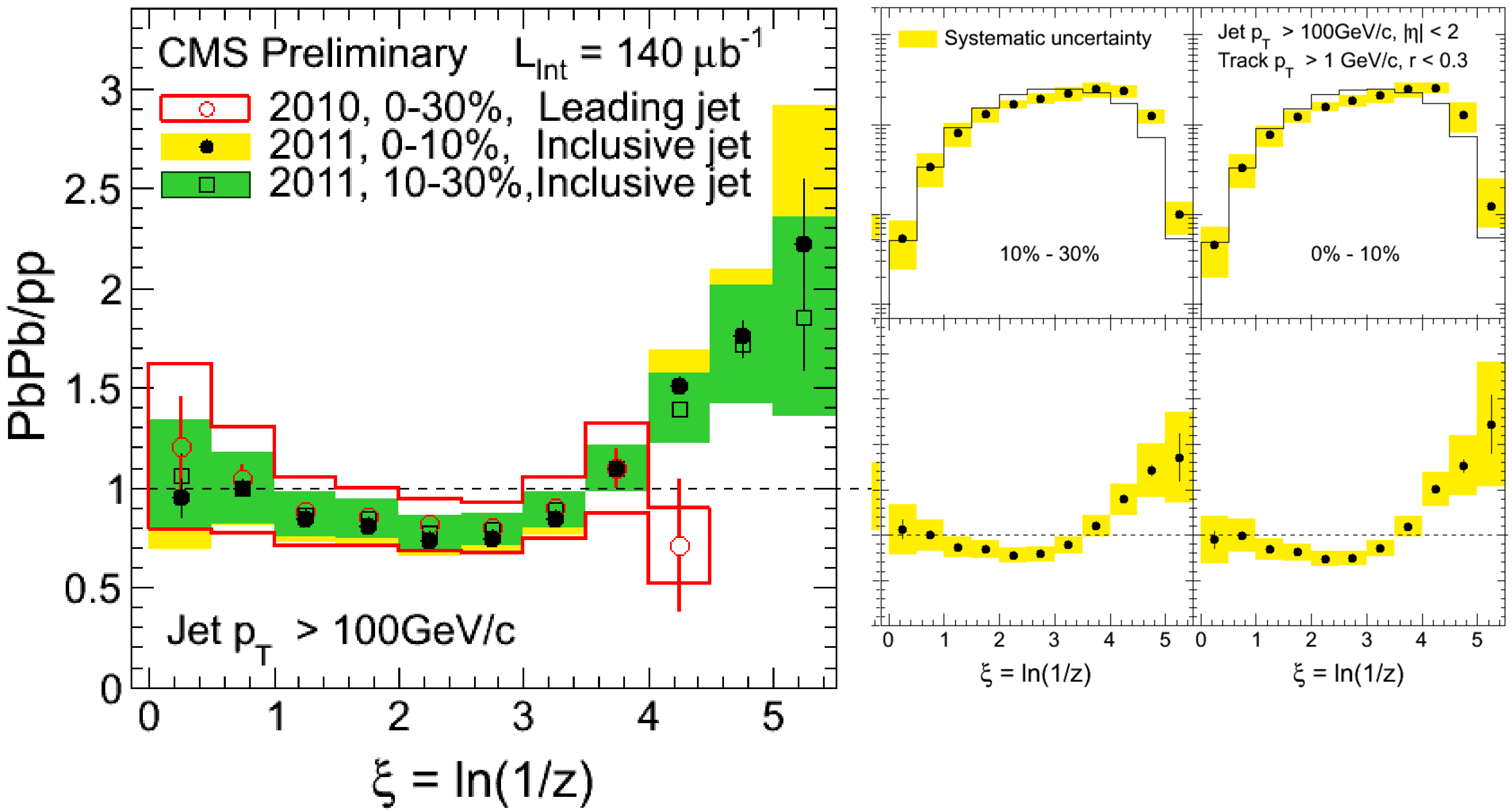
Modification of Jet Fragmentation?

CMS PAS HIN-12-013



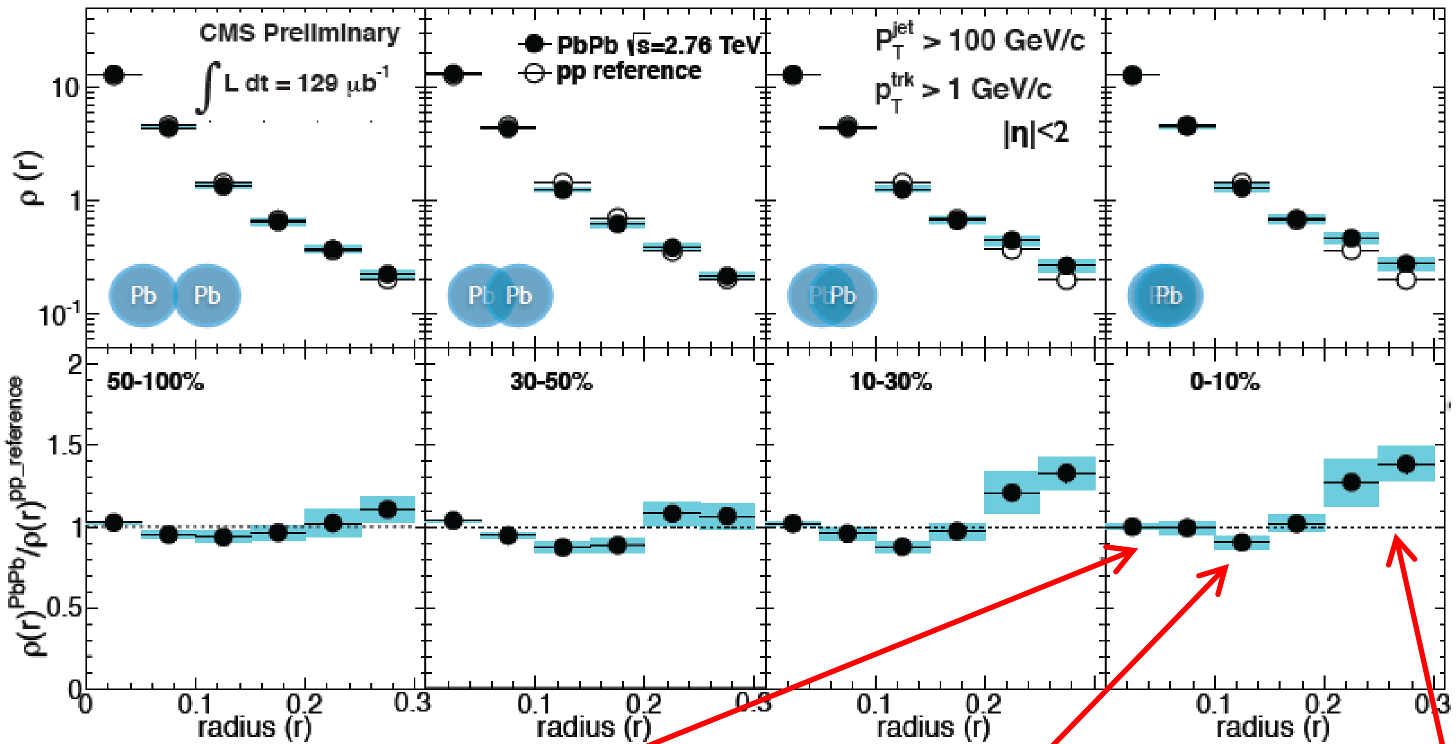
Modification of Jet Fragmentation?

CMS PAS HIN-12-013

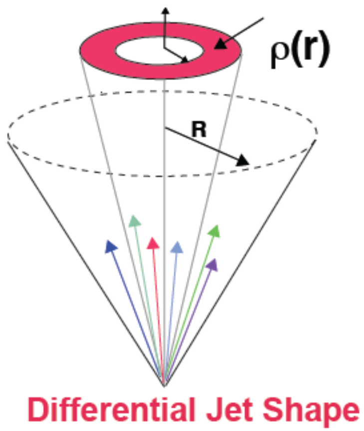


Modification in Jet Shapes

CMS PAS HIN-12-013



ρ(r): average fraction of jet p_T in an annulus in the η-ϕ plane



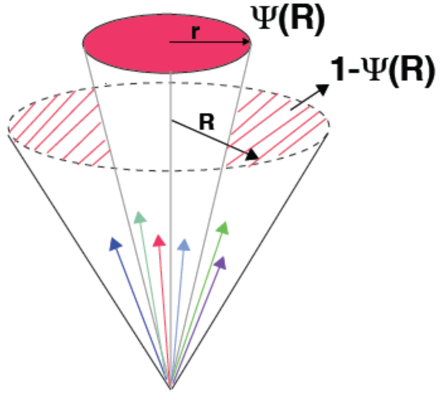
Same as pp close to the jet axis

A bit narrowing in between

Ratio > 1 in tail ⇒ Broadening in larger radii

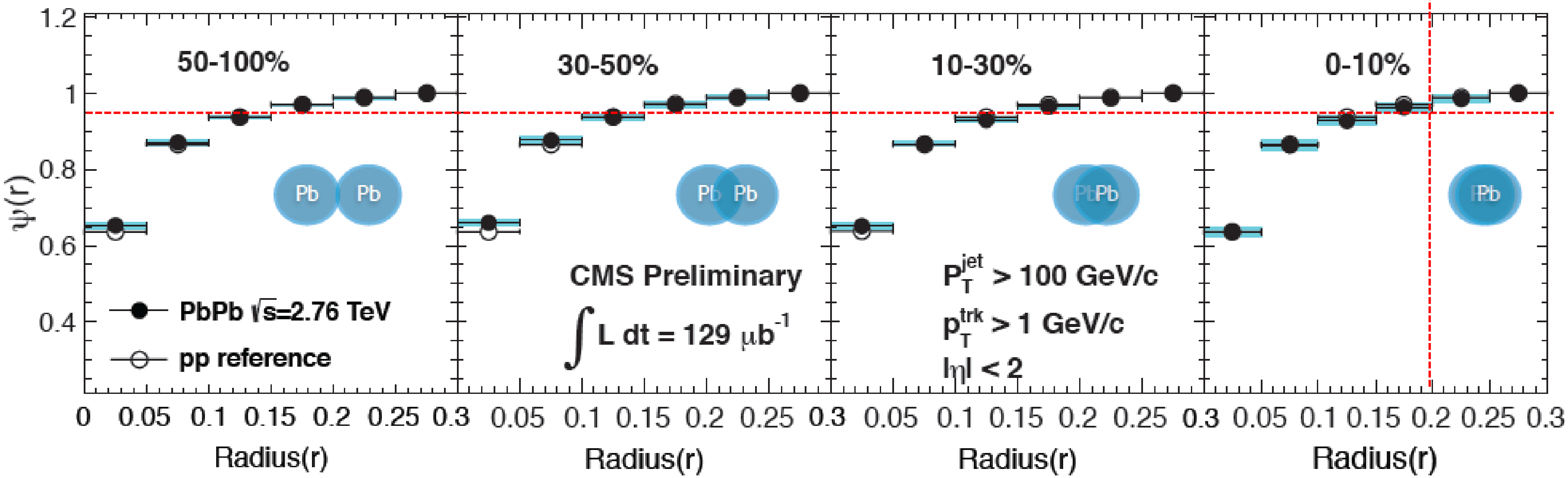
Modification in Jet Shapes

CMS PAS HIN-12-013



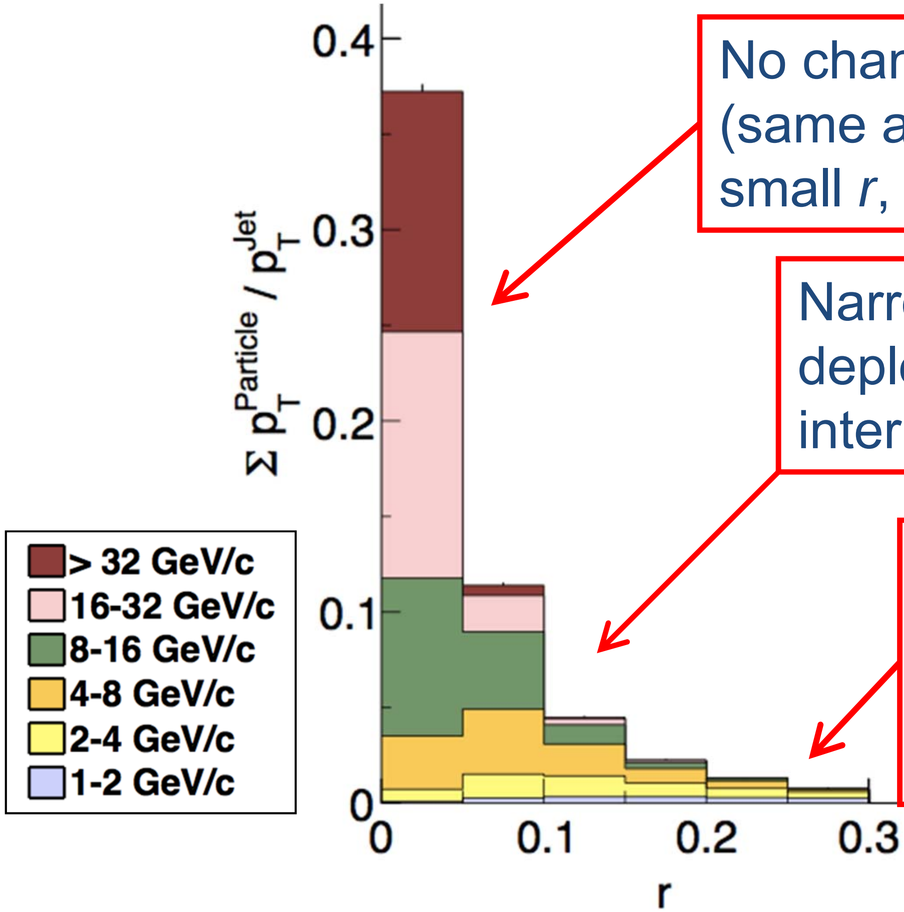
$\Psi(r)$: average fraction of jet p_T inside the cone of radius r

More than 95% of the jet energy deposited in r < 0.2



Anatomy of a Jet in PbPb

PYTHIA 100 GeV inclusive jet
Anti-k_T R=0.3 jet
Charged particle energy fraction

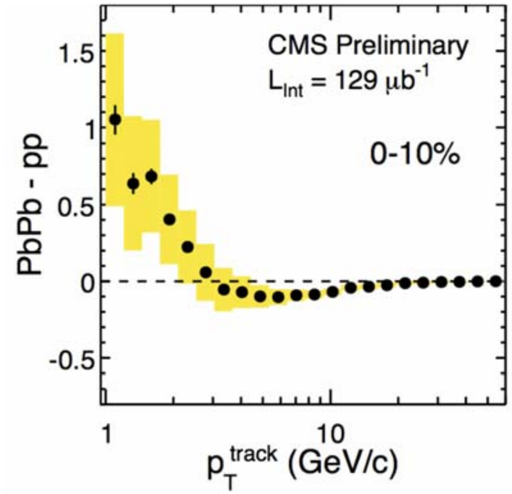


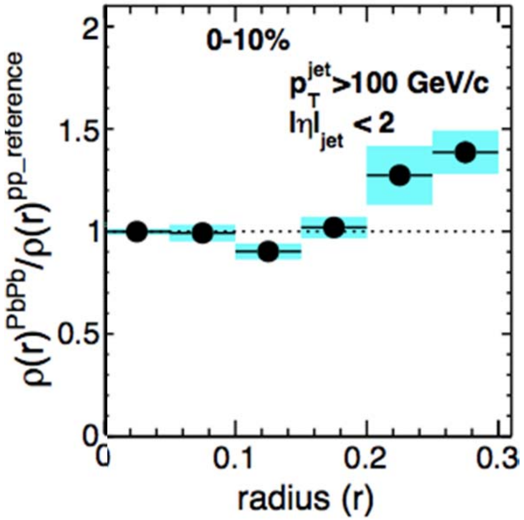
No change (same as pp) at small *r*, high p_T

Narrowing/ depletion at intermediate *r*, p_T

Broadening/ excess at large *r*, low p_T

(~2% of jet energy)

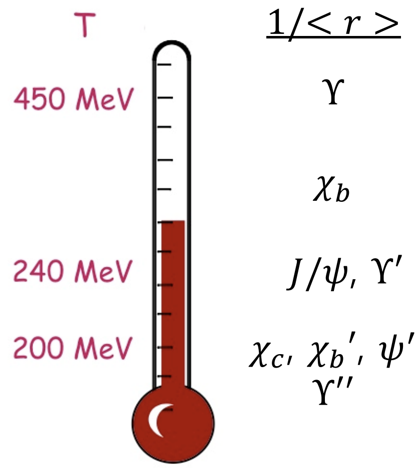




Quarkonium in Heavy Ions

- Powerful tool to probe QGP
  - Large mass: a large momentum transfer needed in hard gg scattering at early stage
  - Color screening: various quarkonium states melt at different temperatures
  - Important signature of the QGP formation

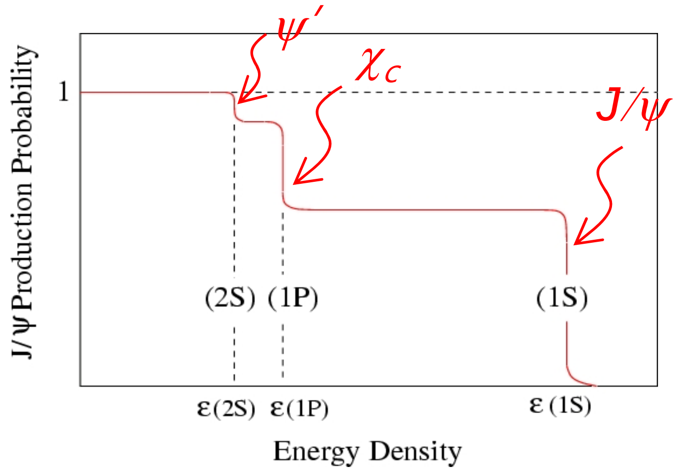
  [Matsui & Satz, PLB 178, 416 (1986)]



A. Mocsy, EPJC 61, 705 (2009)

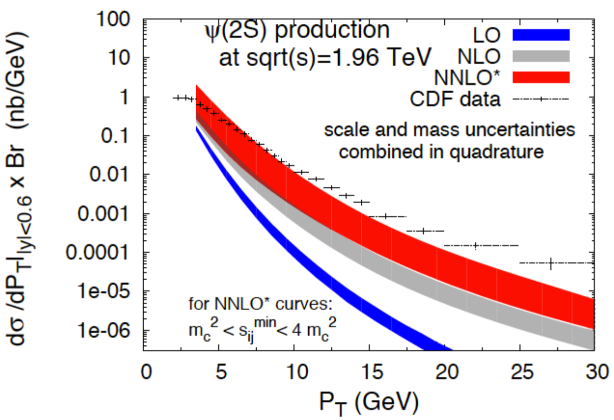
State	J/ψ (1S)	χ_c (1P)	ψ' (2S)
m (GeV/c^2)	3.10	3.53	3.68
r_0 (fm)	0.50	0.72	0.90

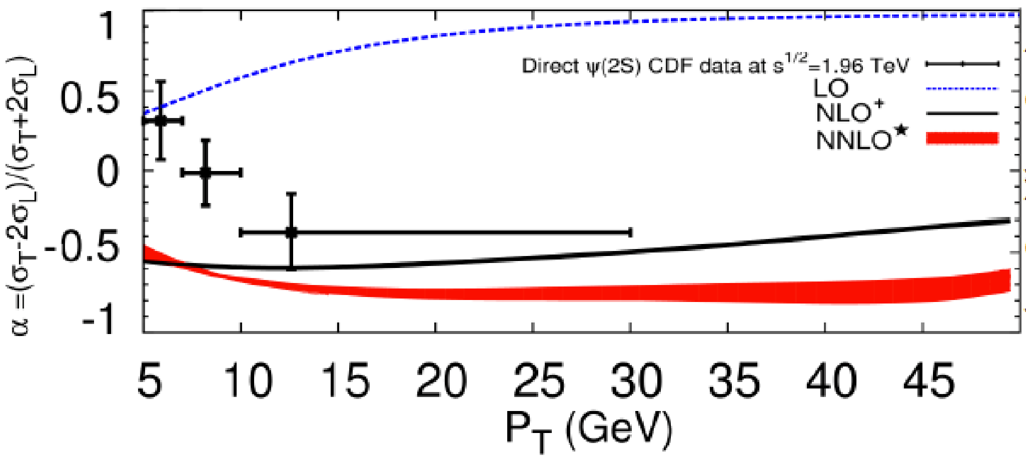
Υ (1S)	χ_b (1P)	Υ' (2S)	χ_b' (2P)	Υ'' (3S)
9.46	9.99	10.02	10.26	10.36
0.28	0.44	0.56	0.68	0.78



Complication in pp & pA

- Nonperturbative hadronization process not well understood
  - CEM, CSM, NRQCD or COM, etc.
  - No satisfactory model to explain the cross section and the polarization simultaneously in pp





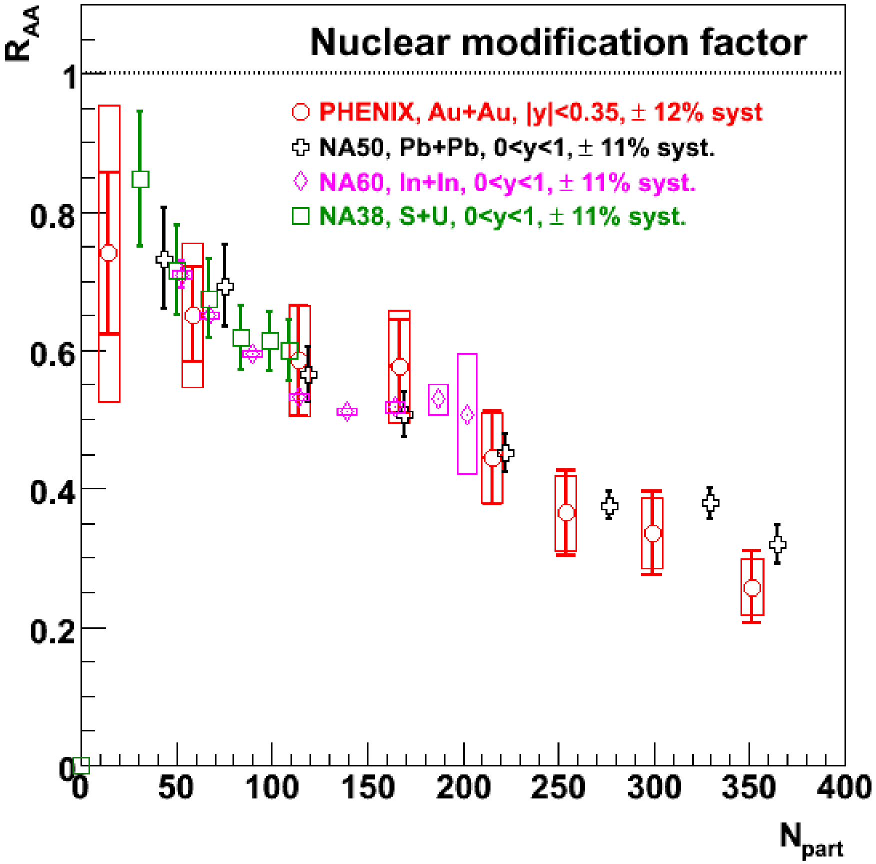
CSM calculations by J.P. Lansberg (QM11)

- Cold nuclear matter (CNM) effects
  - Can be studied in pA (or dA) collisions
  - Essential to understand hot, dense nuclear matter effect
  - Errors are still very large, e.g., $\sigma_{Breakup} = 2.8^{+1.7}_{-1.4}$ mb by the EKS model fit to PHENIX $R_{dAu}(J/\psi)$ [PRC 77, 024912 (2008)]

J/ψ at Lower Energies

- Two puzzles
  1) At midrapidity, similar suppression at RHIC & SPS, while density must be higher at RHIC

$$R_{AA}(p_T) = \frac{d^2N_{AA}/dp_T d\eta}{< T_{AA} > d^2\sigma_{NN}/dp_T d\eta}$$



J/ψ at Lower Energies

- Two puzzles
  1) At midrapidity, similar suppression at RHIC & SPS, while density must be higher at RHIC
  2) More suppression at forward rapidity, while density must be lower

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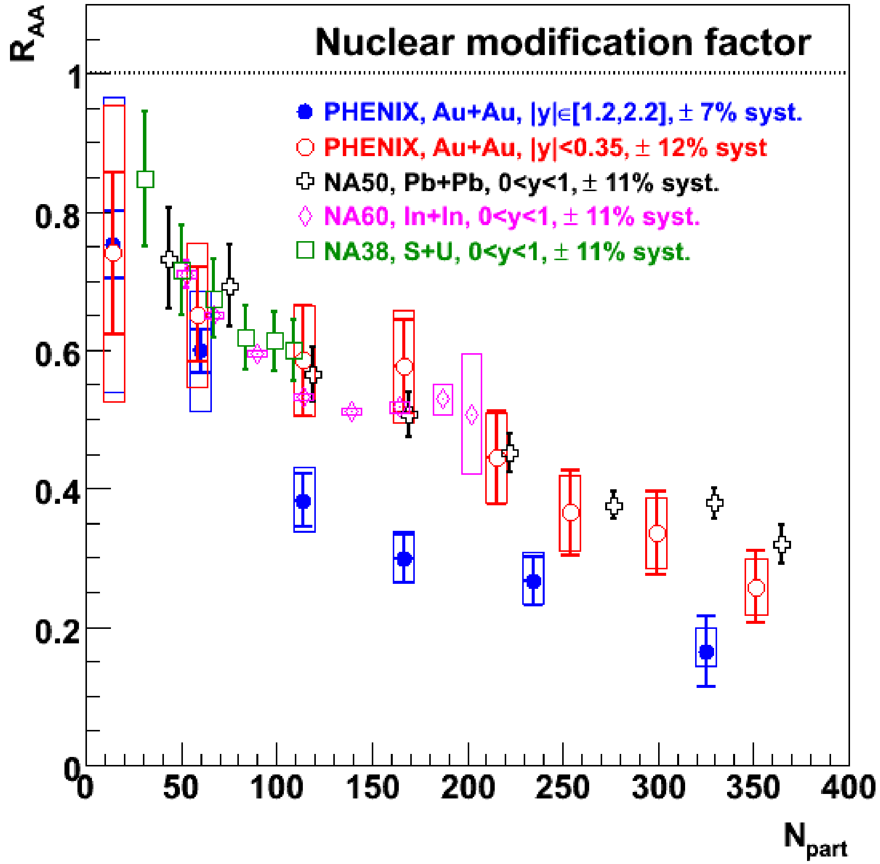
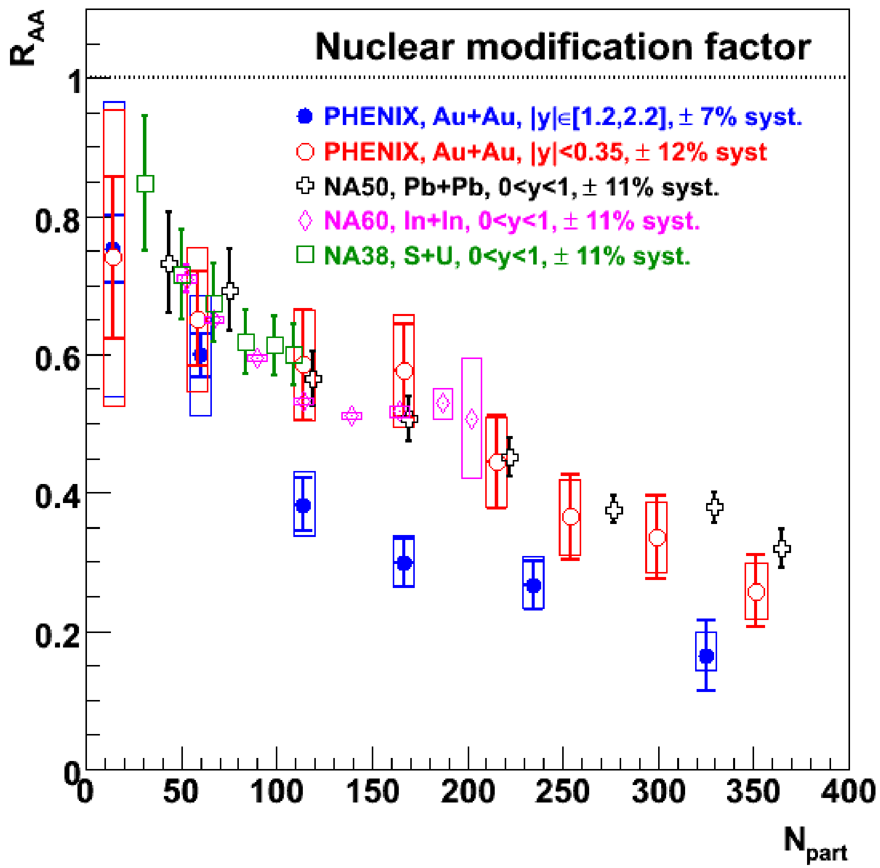


J/ψ at Lower Energies

- Two puzzles
  1) At midrapidity, similar suppression at RHIC & SPS, while density must be higher at RHIC
  2) More suppression at forward rapidity, while density must be lower
- Two possibilities
  1) Cold: shadowing, saturation brings the forward yield down
  2) Hot: recombination of uncorrelated $c\bar{c}$ brings the midrapidity yield up

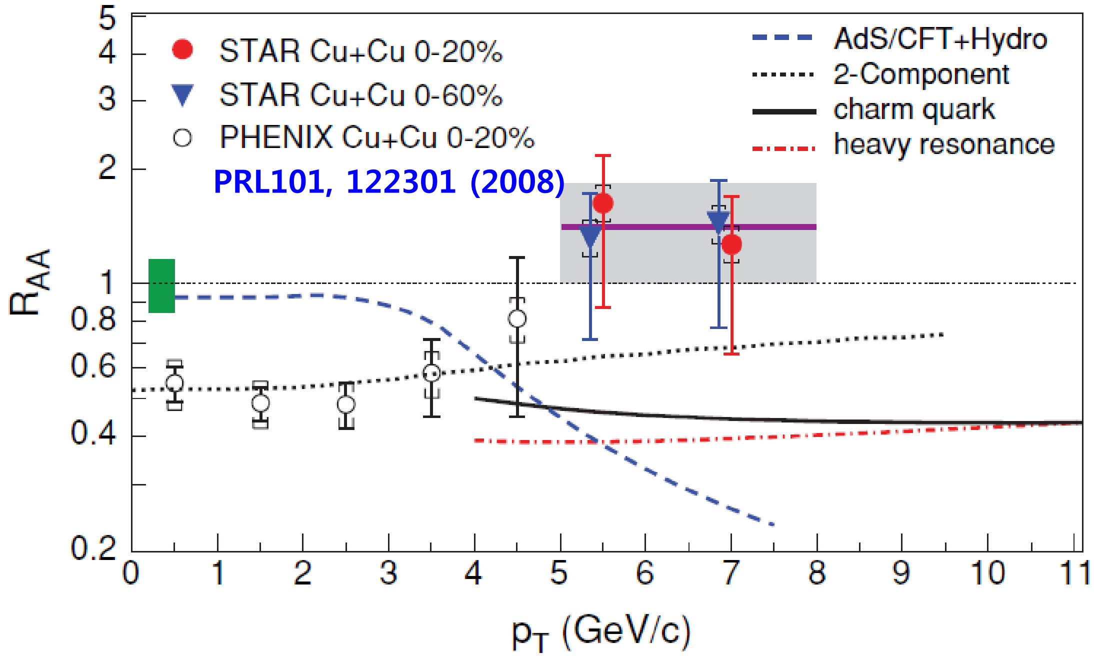
$$R_{AA}(p_T) = \frac{d^2N_{AA}/dp_T d\eta}{< T_{AA} > d^2\sigma_{NN}/dp_T d\eta}$$



J/ψ at Lower Energies

J/ψ suppression can not be satisfactorily explained by models.

STAR, PRC 80, 041902 (2009)



Diverse theoretical results

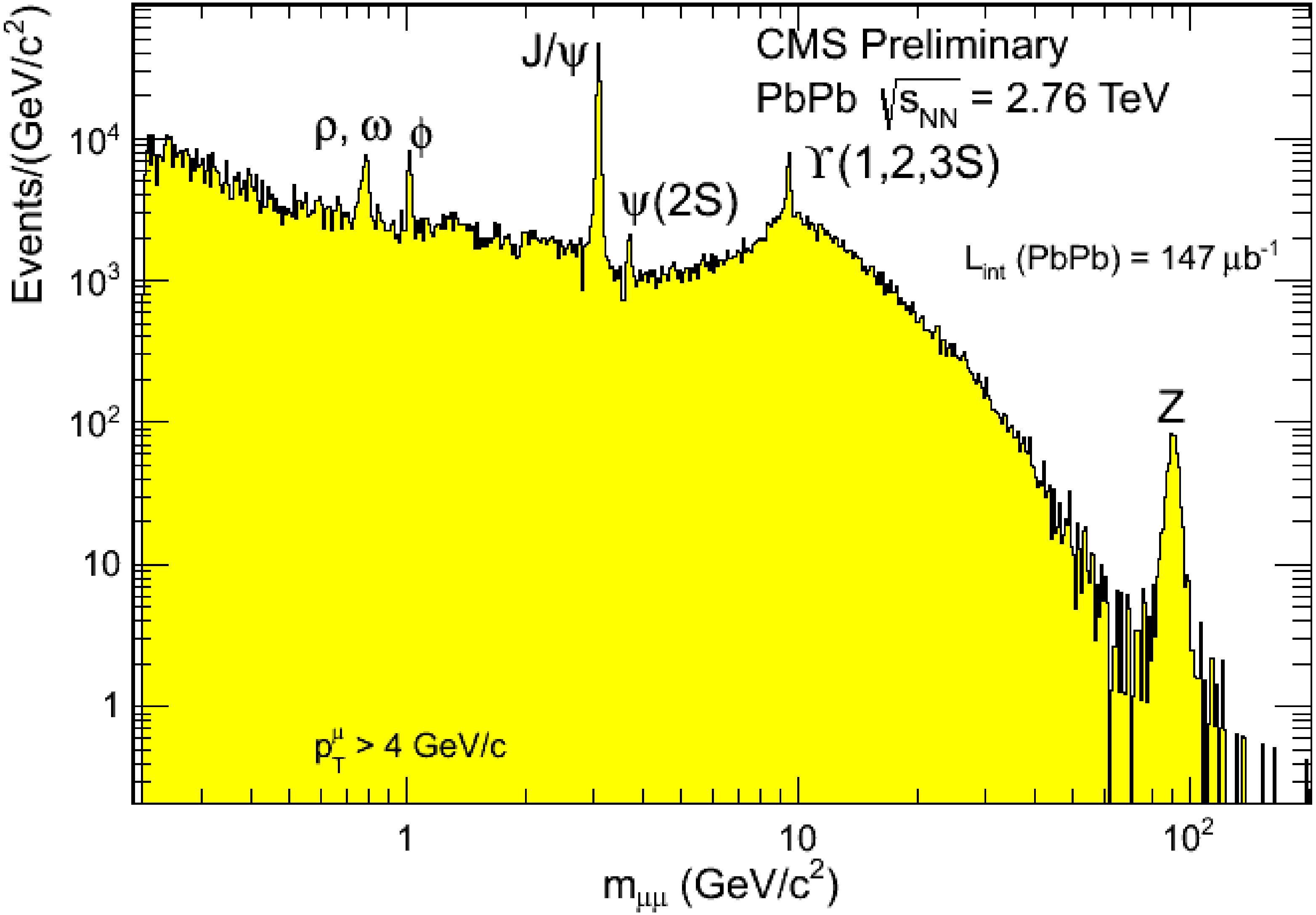
QGP+recombination+…

Calculations for open charm

AdS/CFT

- LHC data with higher temperature and density will help to resolve the J/ψ puzzles.

$\mu^+\mu^-$ Invariant Spectrum

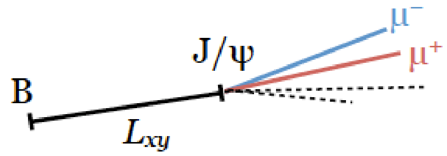


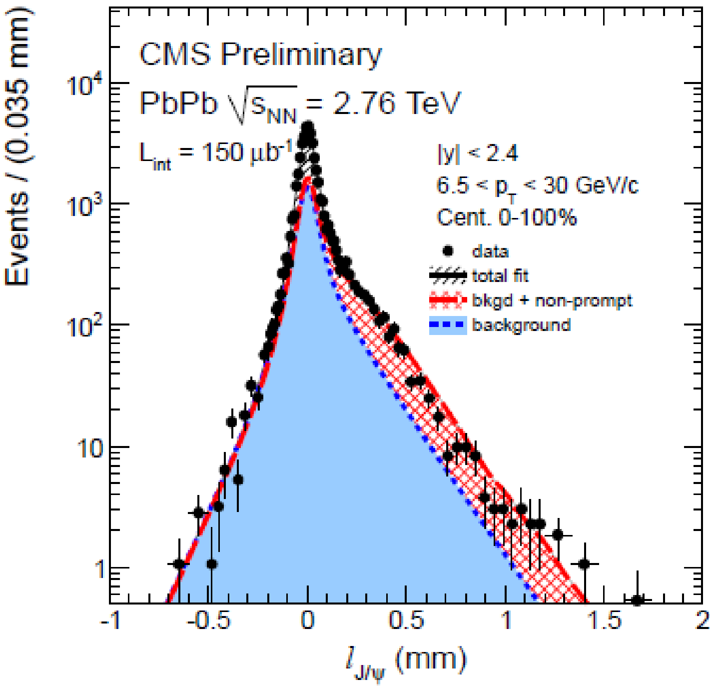
J/ψ Analysis

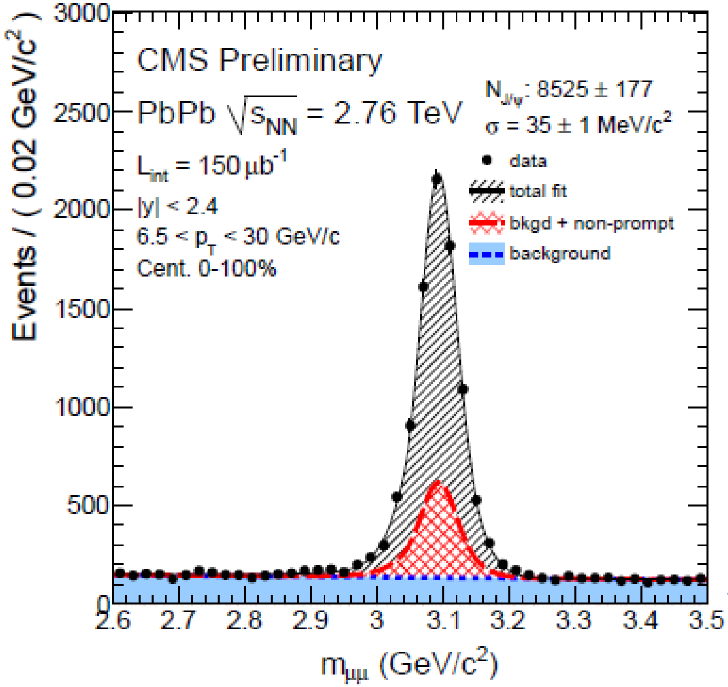
Inclusive J/ψ
- **Prompt J/ψ**
  - **Direct J/ψ**
  - **Feed-down from ψ' and χ_c**
- **Non-prompt J/ψ from B-decays**

- Simultaneous fit
  - $\mu^+\mu^-$ invariant mass
  - Pseudo-proper decay length

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





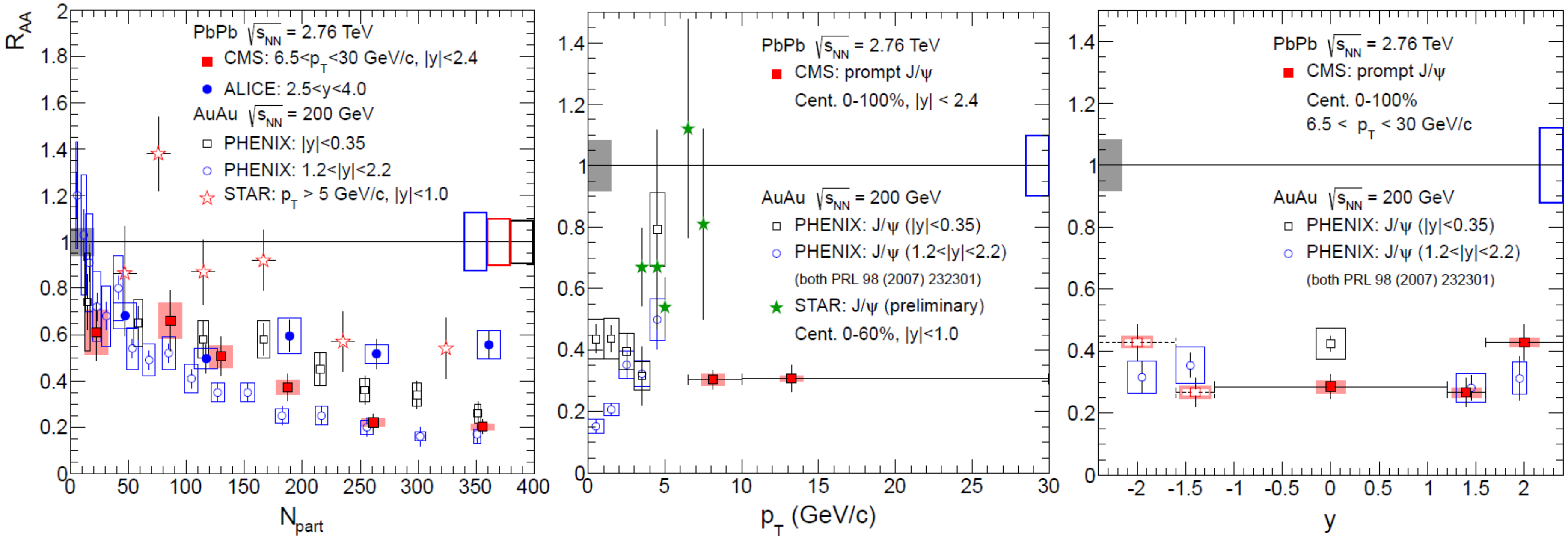


σ_m = 35 MeV comparable to pp

CMS PAS HIN-12-014

Prompt J/ψ

JHEP 1205, 063 (2012), L_{int} = 7.28 μb^{-1}

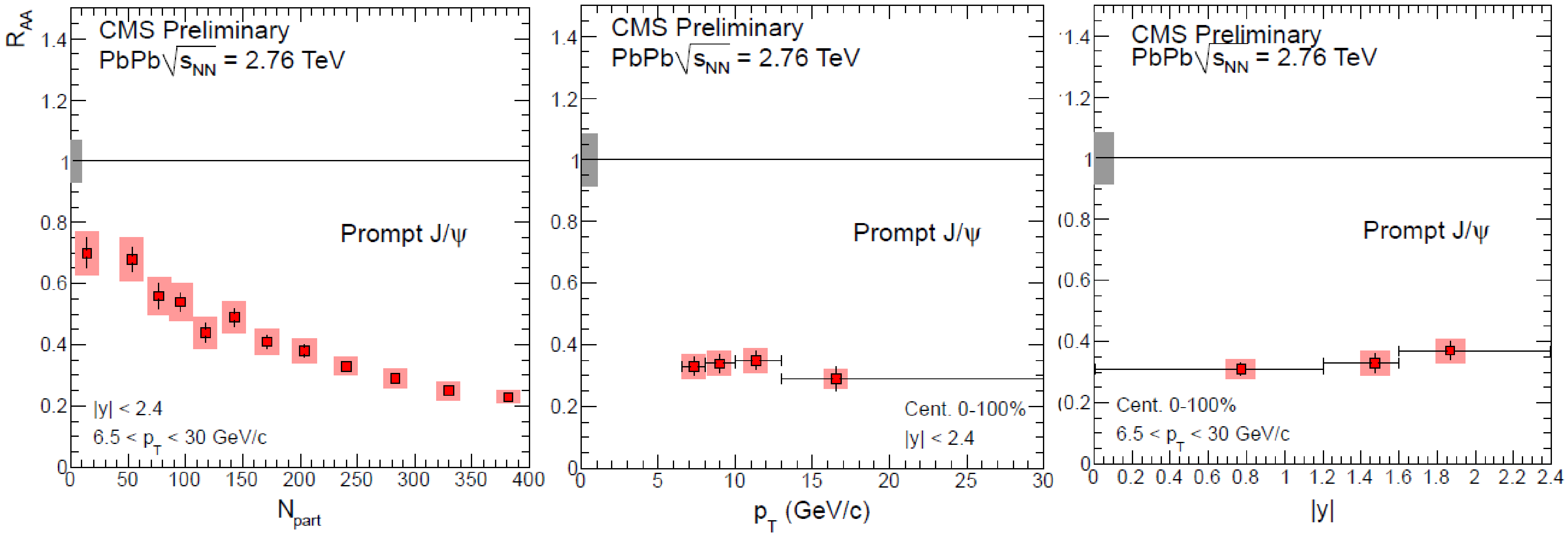


- CMS measures J/ψ at high p_T > 6.5 GeV/c
  - Factor 5 suppression for the most central 10%

- CMS, ALICE, PHENIX and STAR measure different phase space
  - Require more systematic study for definite conclusions

Prompt J/ψ

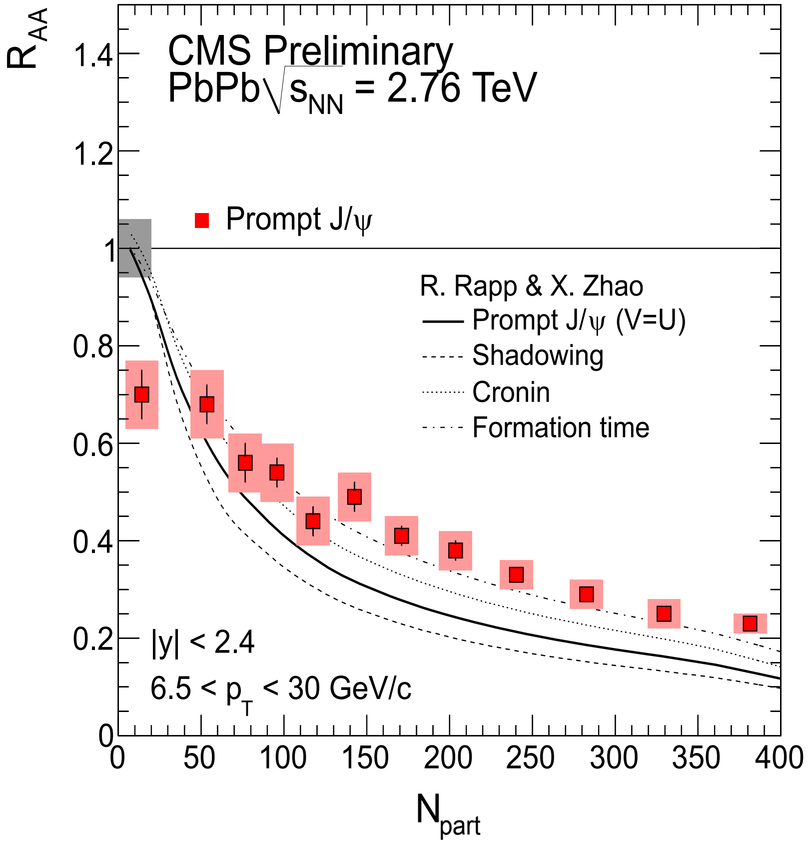
CMS PAS HIN-12-014, L_{int} = 150 μb^{-1}



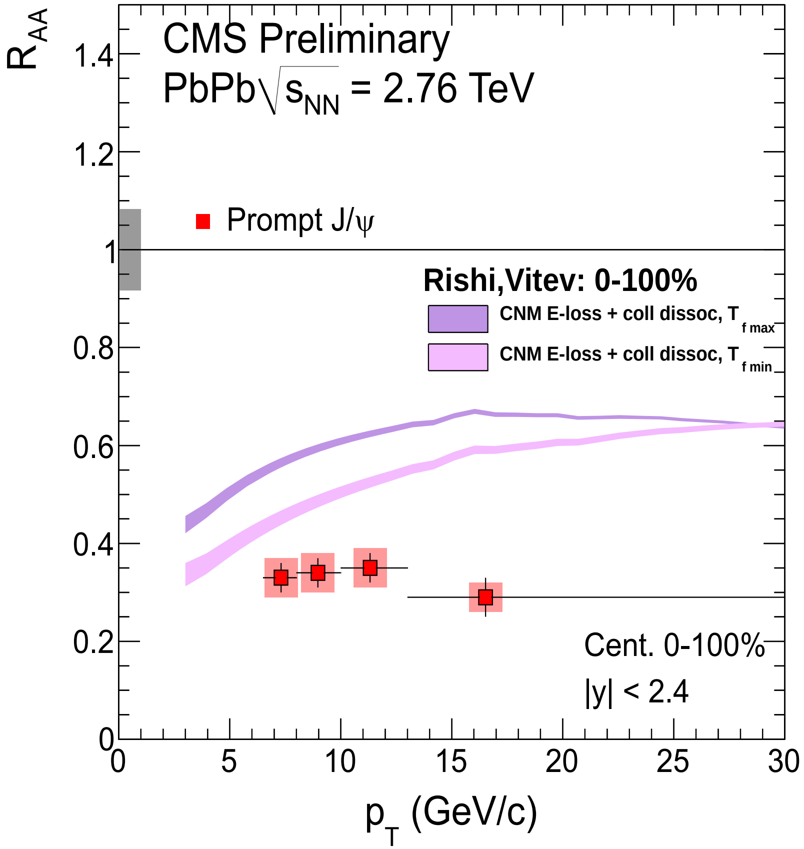
- CMS measures J/ψ at high p_T > 6.5 GeV/c
  - Factor 5 suppression for the most central 10%

Model Comparison

NPA 859, 114 (2011)+priv. comm.



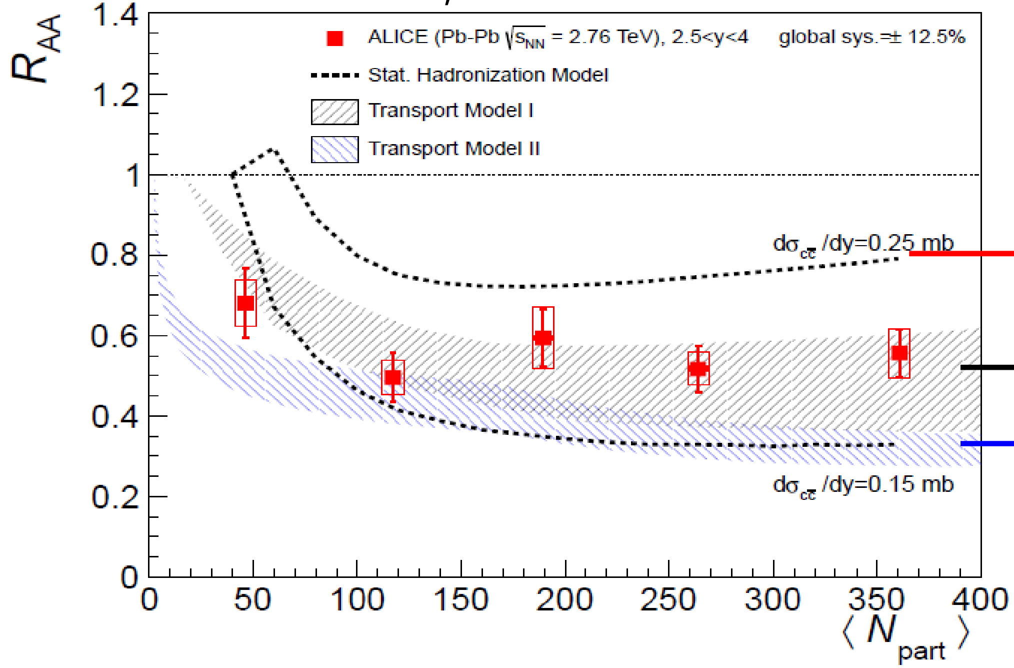
arXiv:1203.0329+priv. comm.



- No need for the regeneration component at high p_T
- Treatment of quarkonia energy loss similarly as open flavor energy loss, without color-octet included, is not supported by data

More on Recombination

ALICE, arXiv:1202.1383



Statistical Hadronization
Andronic et al.,
arXiv:1106.6321

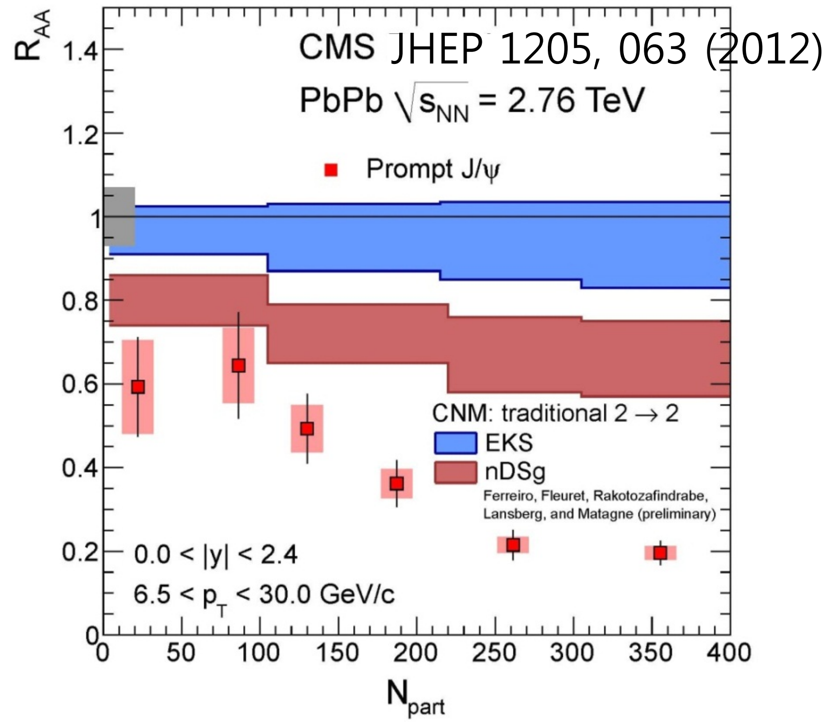
Transport Model I
Zhao & Rapp
NPA 859, 114 (2011)

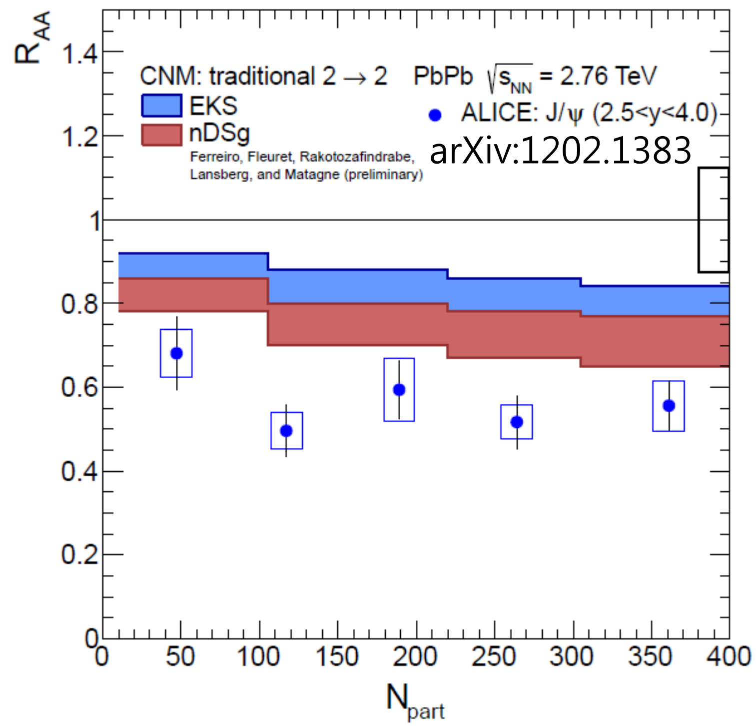
Transport Model II
Liu et al.,
PLB 678, 72 (2009)
- Upper limit: no shadowing
- Lower limit: with shadowing (artificially lower $d\sigma_{c\bar{c}}/dy$)

- Models are sensitive to $d\sigma_{c\bar{c}}/dy$
- The transport models are sensitive to the rate equation controlling the J/ψ dissociation and regeneration
  - For the most central collisions, recombination component is ~50%

Cold Nuclear Matter Effects

Preliminary theoretical calculations:
Ferreiro et al., BNL and EMMI Workshops in 2011

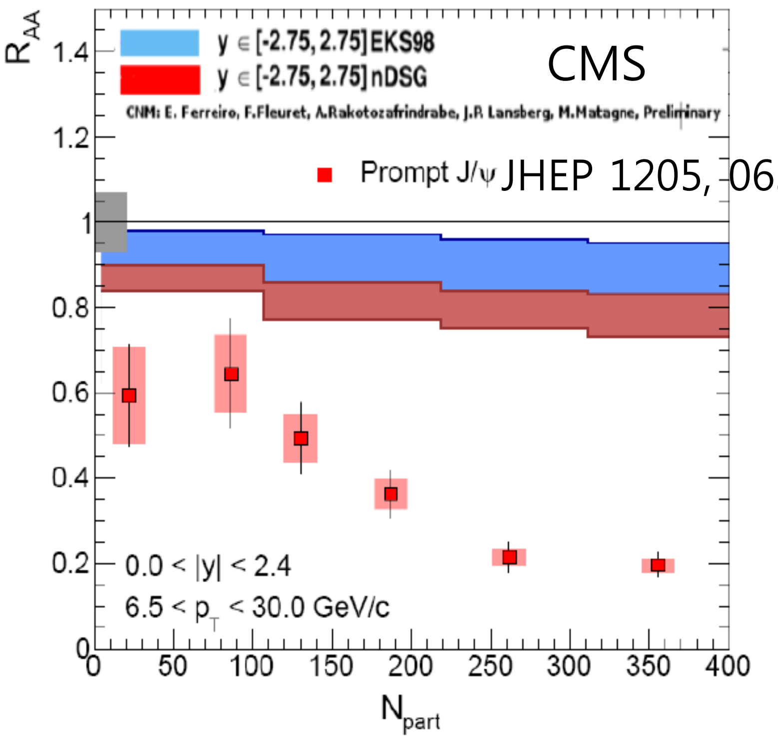


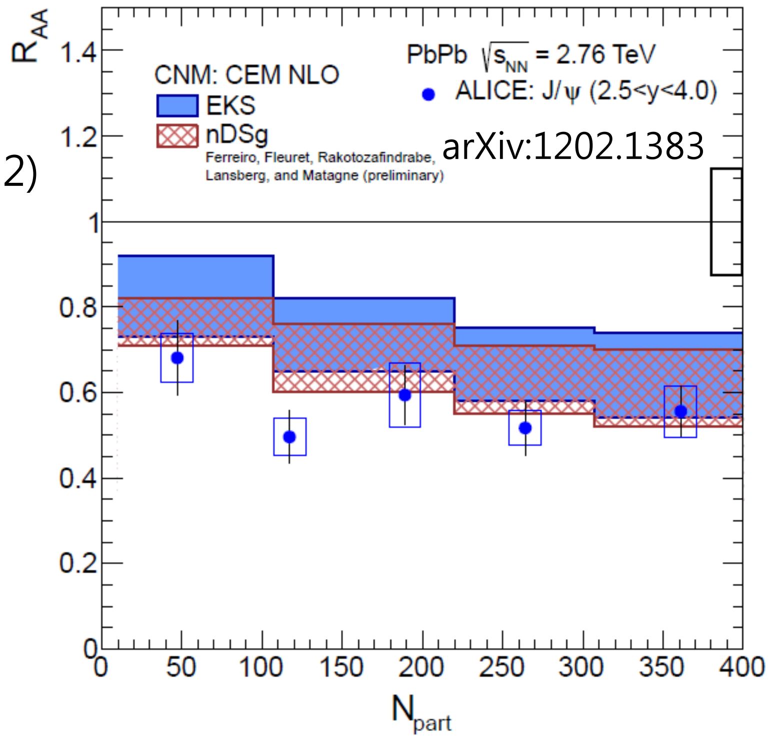


- CNM for traditional 2 → 2 ($gg \to J/\psi + g$)
  - Different parametrizations of nPDF (EKS and nDSg)

Cold Nuclear Matter Effects

Preliminary theoretical calculations:
Ferreiro et al., BNL and EMMI Workshops in 2011

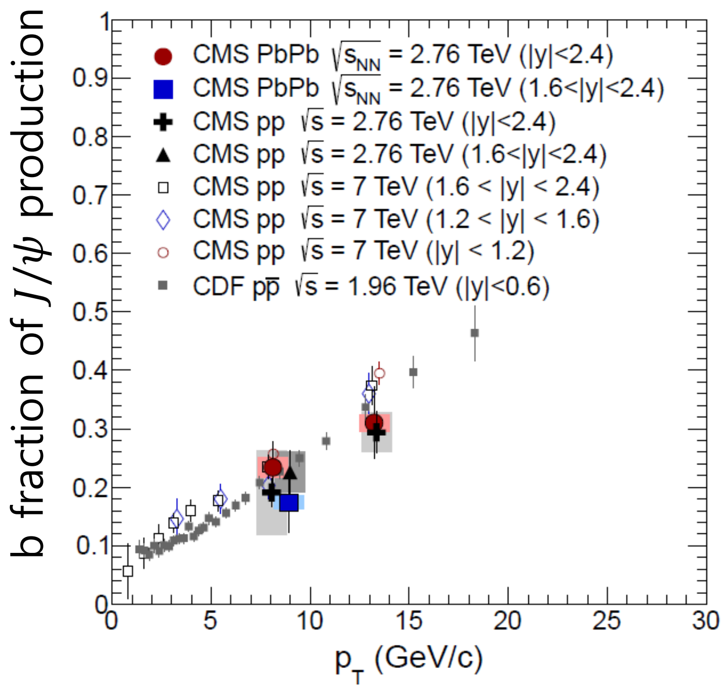


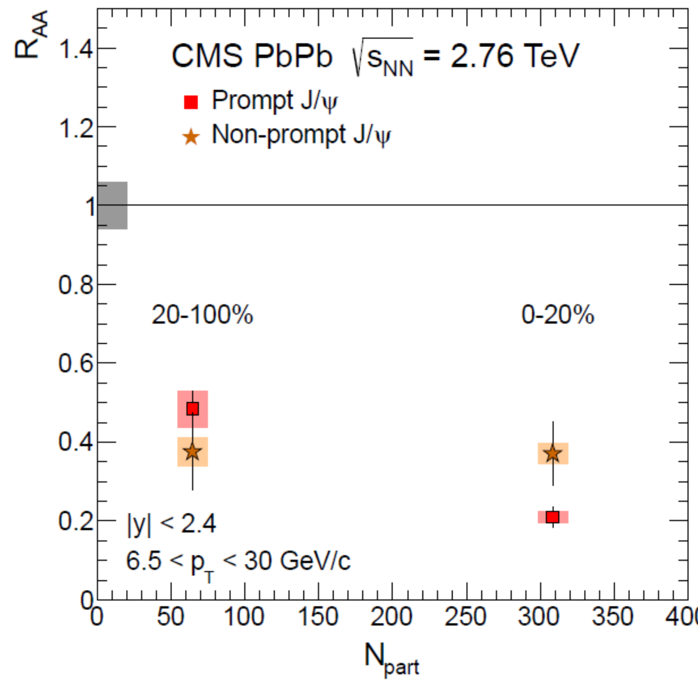


- CNM effect from CEM NLO before k_T smearing
  - Different parametrizations of nPDF (nDSg and EKS)
- pPb run next year will help to understand the CNM effect

Non-prompt J/ψ

JHEP 1205, 063 (2012), L_{int} = 7.28 μb^{-1}

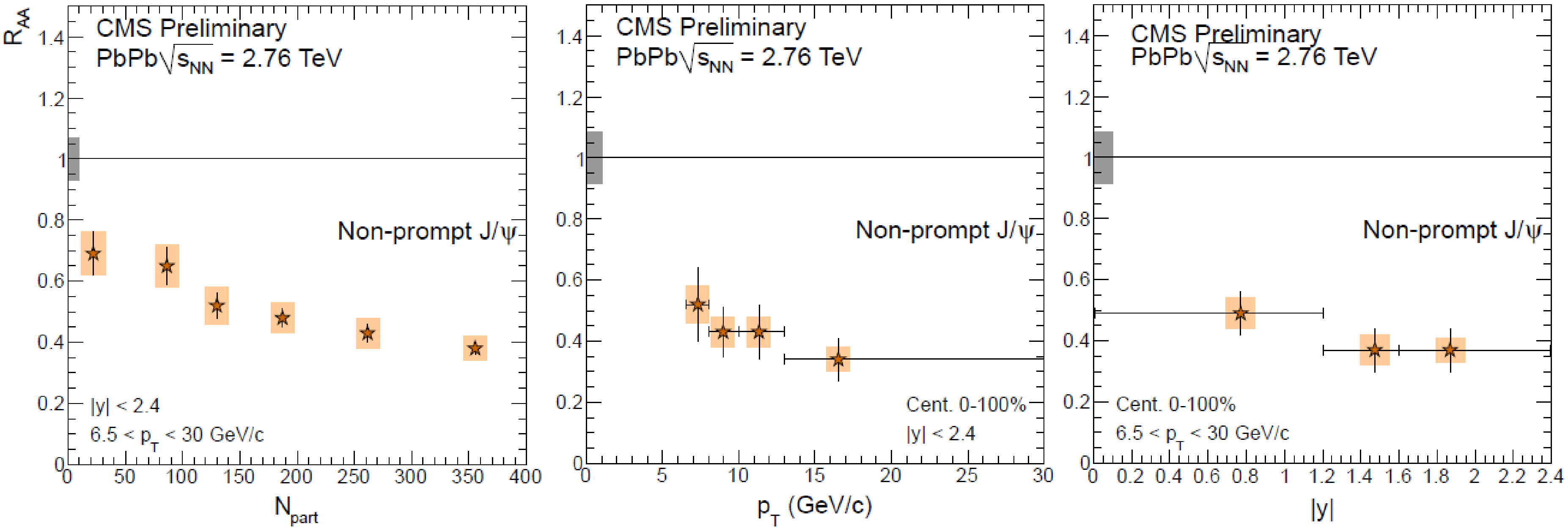




- Secondary J/ψ from B decay suppressed strongly
  - Factor ~3 suppression for the most central collisions
- b-quark energy loss in medium at low p_T

Non-prompt J/ψ

CMS PAS HIN-12-014, L_{int} = 150 μb^{-1}



- Secondary J/ψ from B decay suppressed strongly
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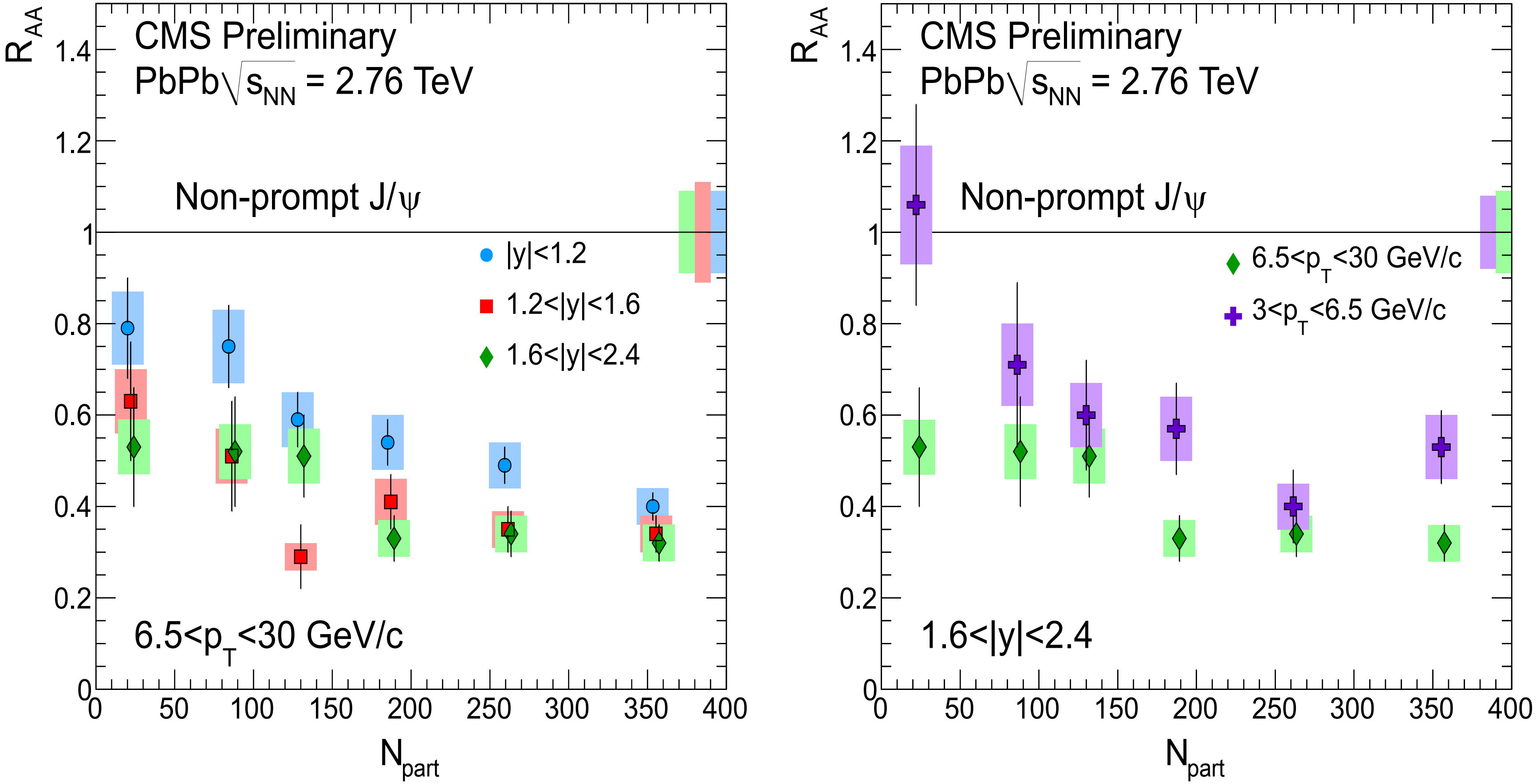
Non-prompt J/ψ

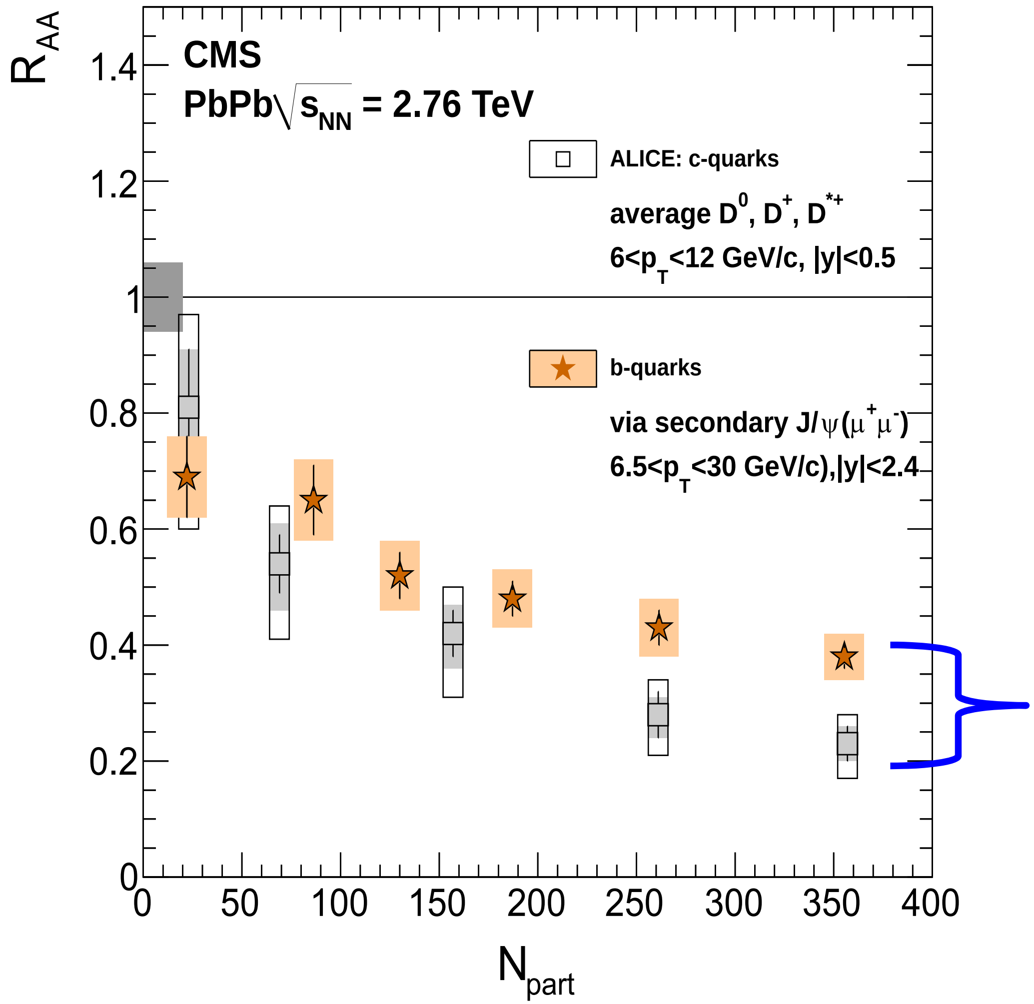
CMS PAS HIN-12-014



- In forward region, non-prompt J/ψ has a strong centrality dependence and less suppressed at low p_T than high p_T.

Non-prompt J/ψ

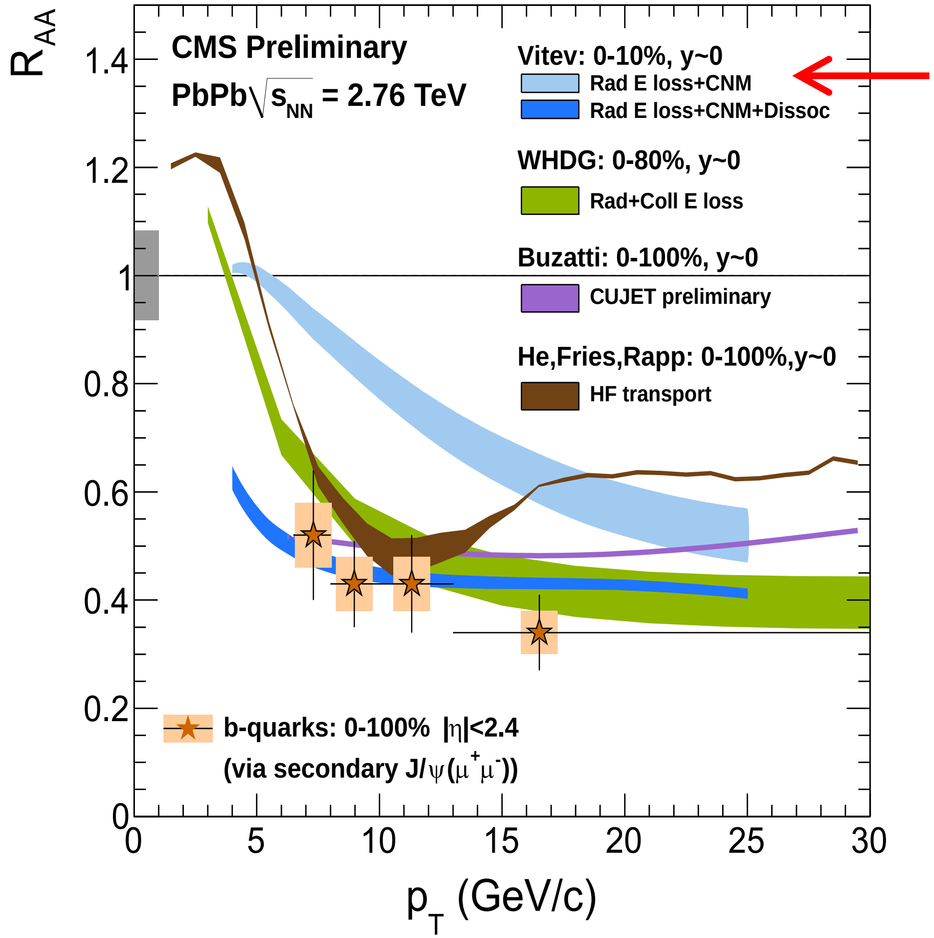
CMS PAS HIN-12-014



In central collisions,

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

Model Comparison

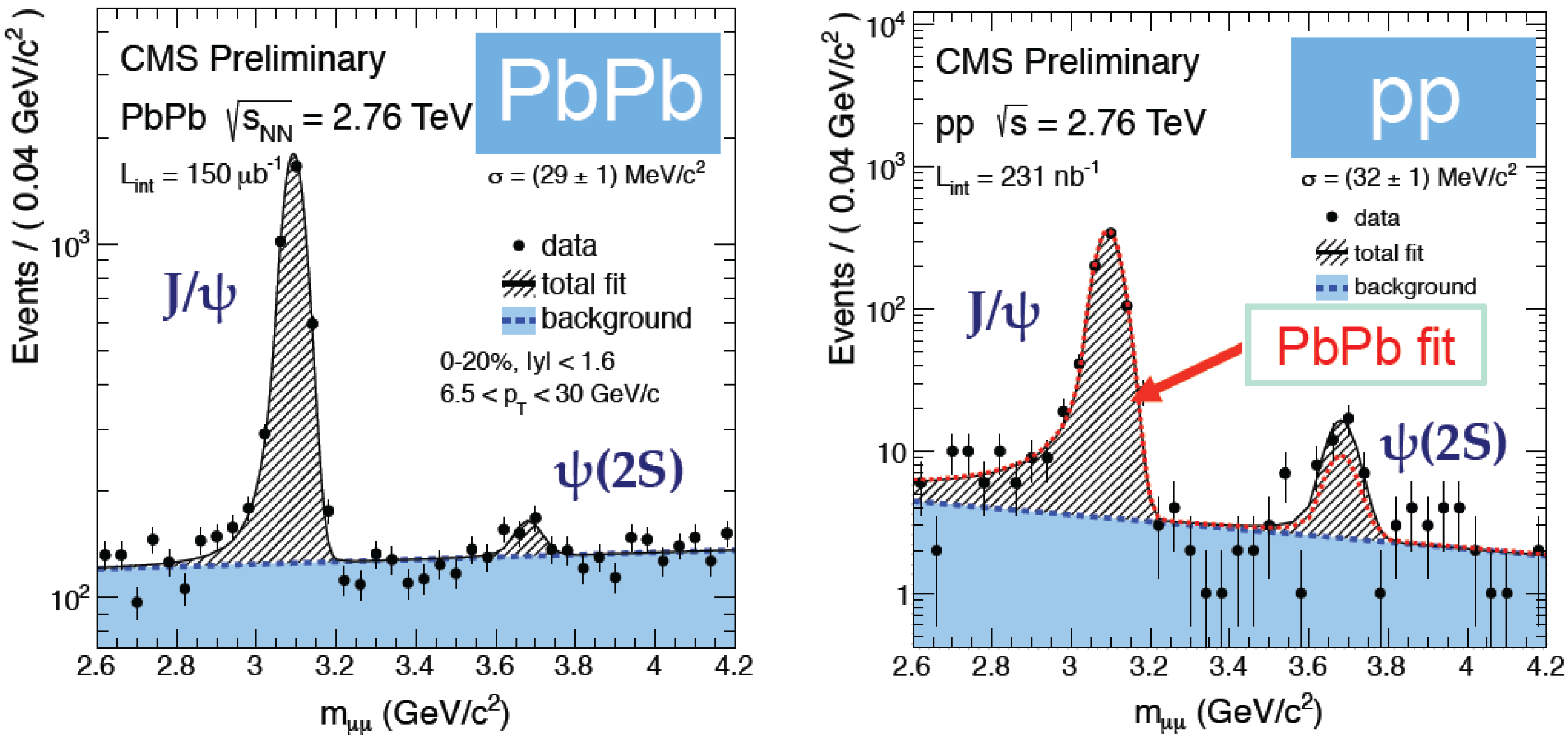


Model with only radiative energy loss and CNM fails to describe the data.

- Vitev: J. Phys.G35, 104011 (2008) + private communication
- Horowitz: arXiv:1108.5876 + private communication
- Buzzatti & Gyulassy: arXiv: 1207.6020 + private communication
- He, Fries, Rapp: PRC 86, 014903 (2012) + private communication

ψ(2S)

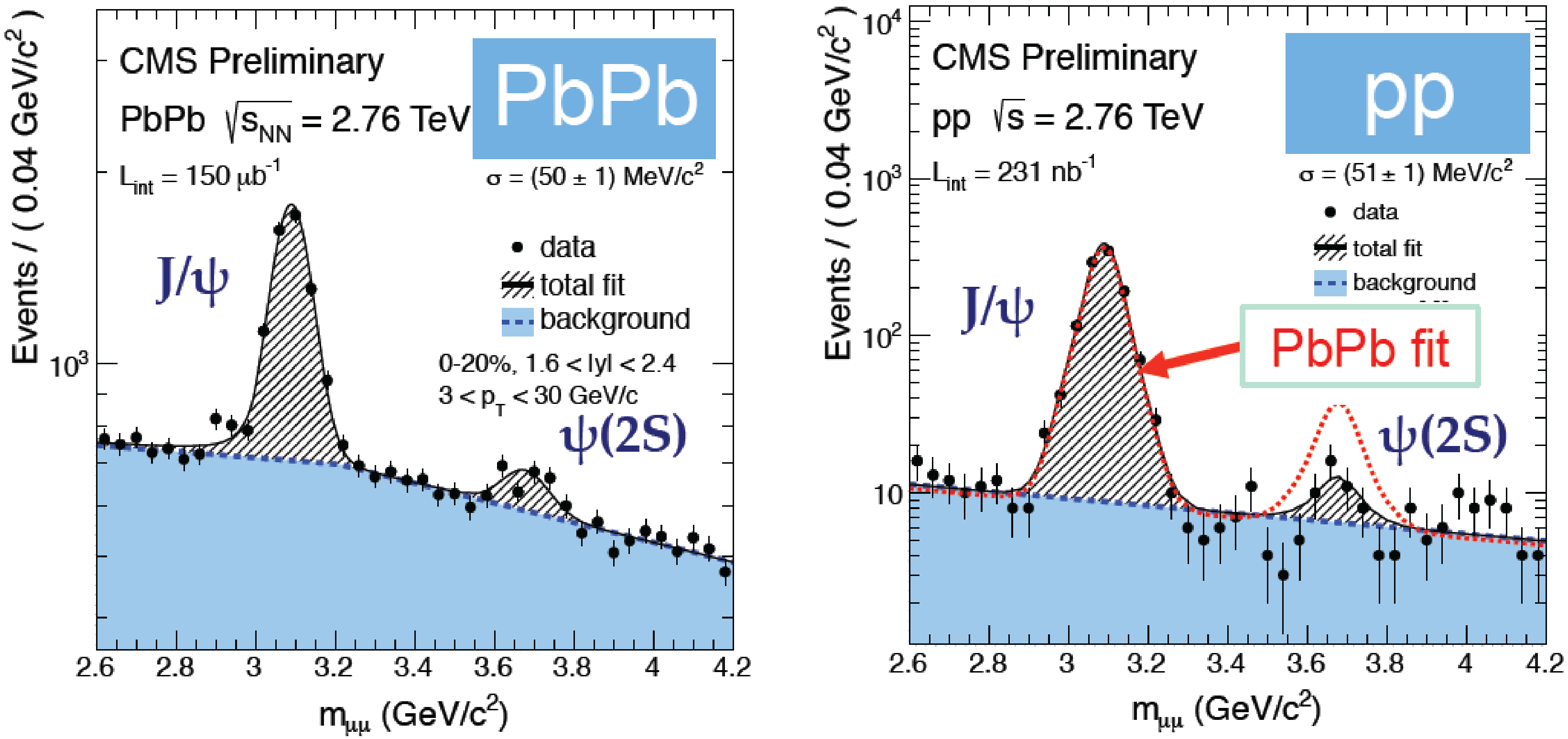
CMS PAS HIN-12-007



- $R_{\psi(2S)}$: raw yield ratio of ψ(2S) / J/ψ
- For 6.5 < p_T < 30 GeV/c and $|y|$ < 1.6
  $R_{\psi(2S)}$ in 0–20% PbPb ~ 2 times smaller than in pp

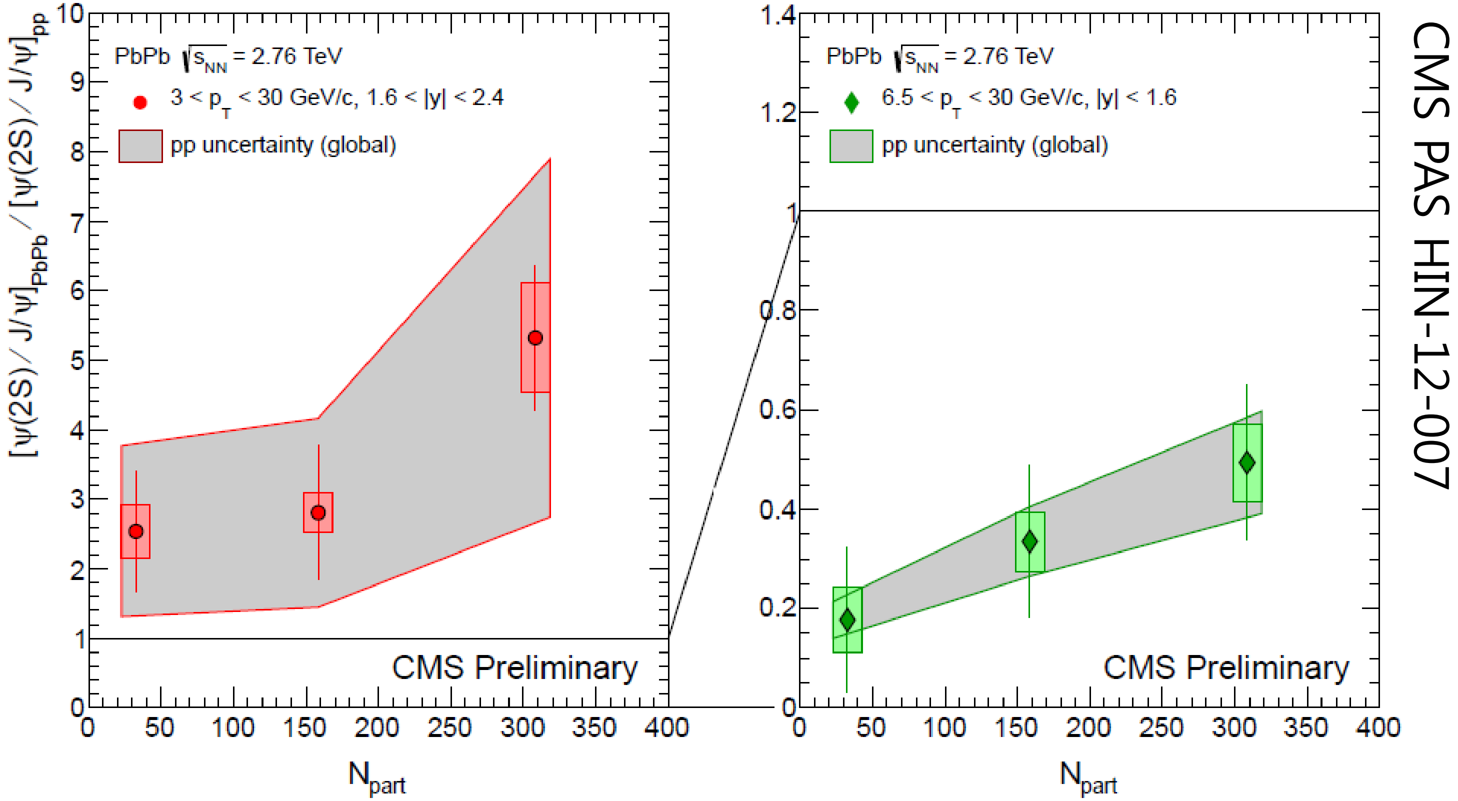
Ψ(2S)

CMS PAS HIN-12-007



- For $3 < p_T < 30$ GeV/c and $1.6 < |y| < 2.4$
  $R_{\psi(2S)}$ in 0–20% PbPb ~ 5 times larger than in pp with LARGE systematic errors

Ψ(2S) / J/Ψ Double Ratio



- For $p_T > 3$ GeV/c and $1.6 < |y| < 2.4$

  Indication of ψ(2S) being less suppressed than J/ψ (<2σ effect)

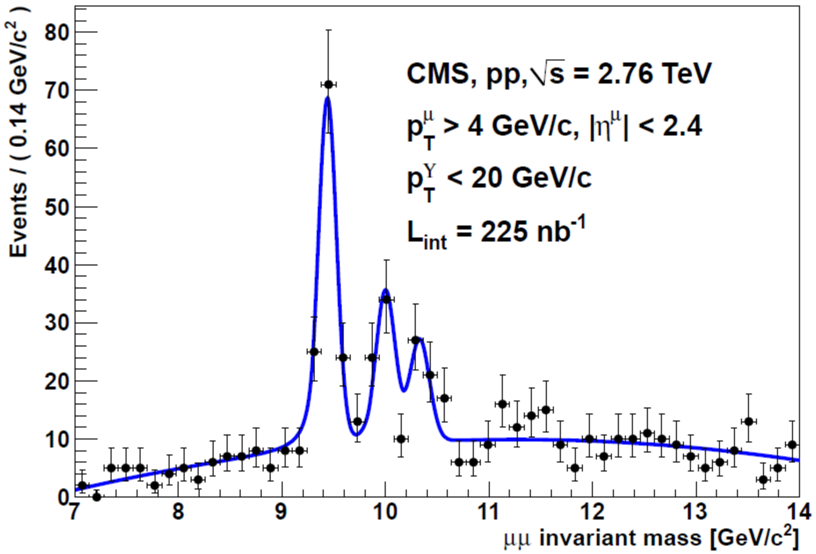
  Limited by pp statistics!

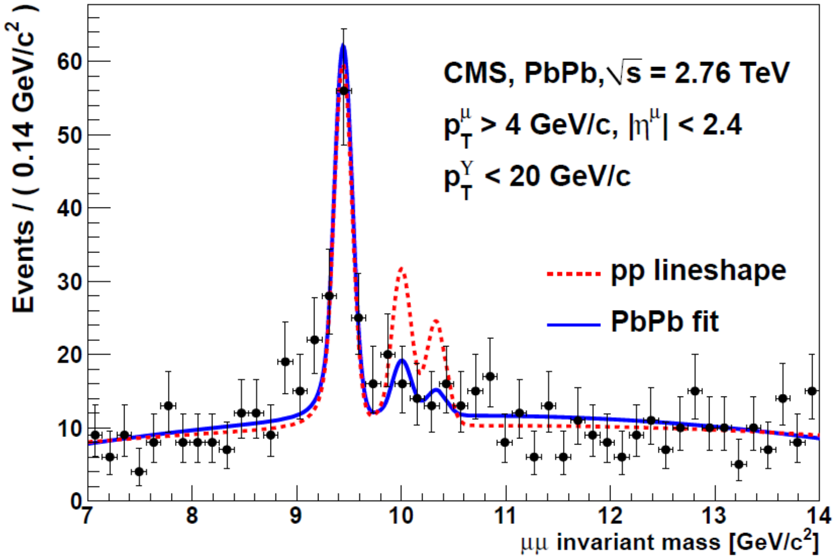
- For $p_T > 6.5$ GeV/c and $|y| < 1.6$

  ψ(2S) are more suppressed than J/ψ

Υ(2S+3S)

PRL 107, 052302 (2011), PbPb MinBias, L_{int} = 7.28 μb^{-1}



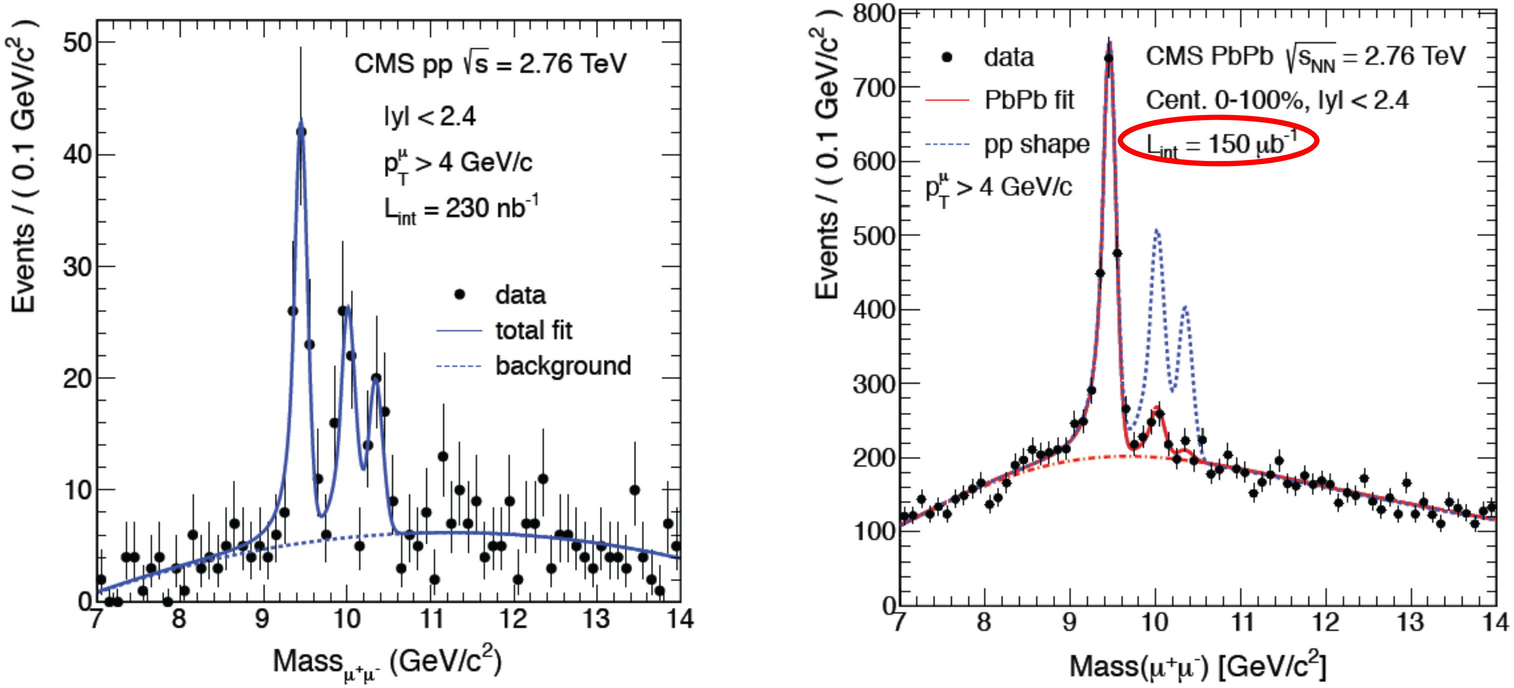


$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Probability to obtain the measured value, or lower, from the background fluctuation is 0.9% (2.4σ effect)

Υ(2S) and Υ(3S)

arXiv:1208.2826

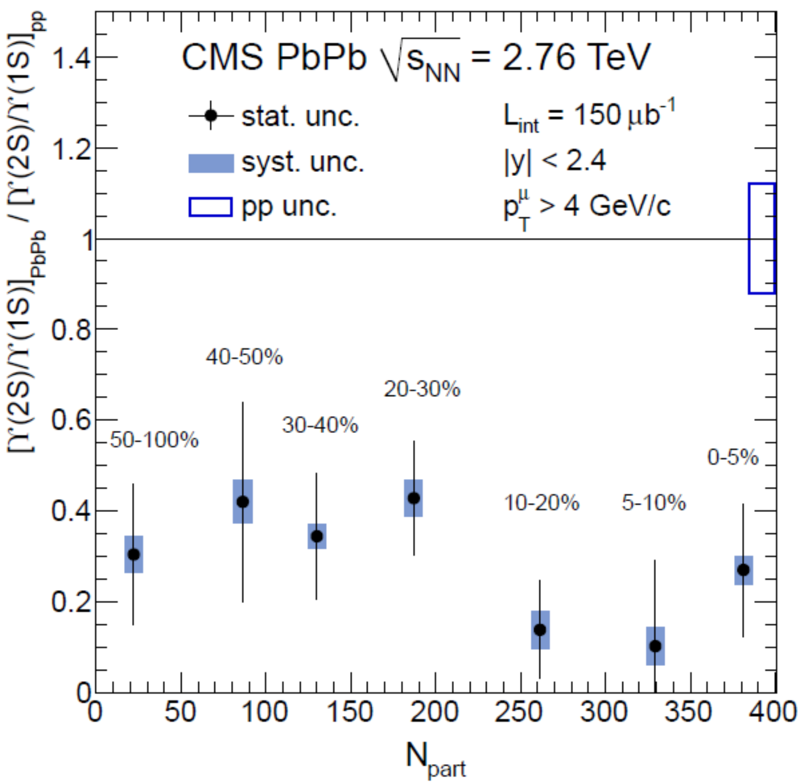


$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.15 \pm 0.05 \pm 0.03$$

- Observation of Υ(2S+3S) relative suppression (>5σ effect)

Υ(2S) and Υ(3S)

arXiv:1208.2826



- Centrality integrated

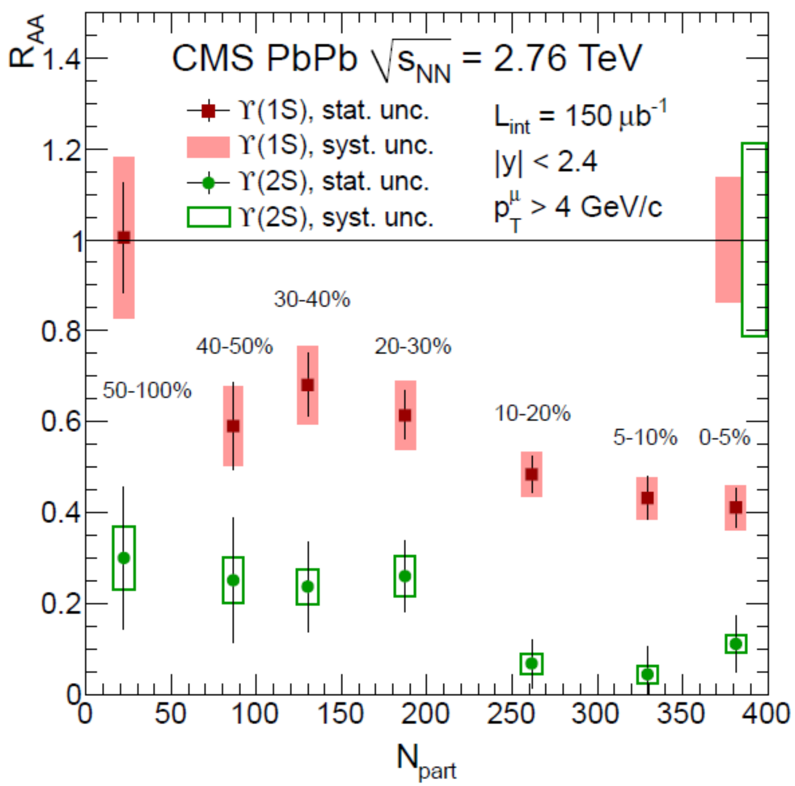
$$\frac{\Upsilon(2S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S)/\Upsilon(1S)|_{pp}} = 0.21 \pm 0.07 \pm 0.02$$

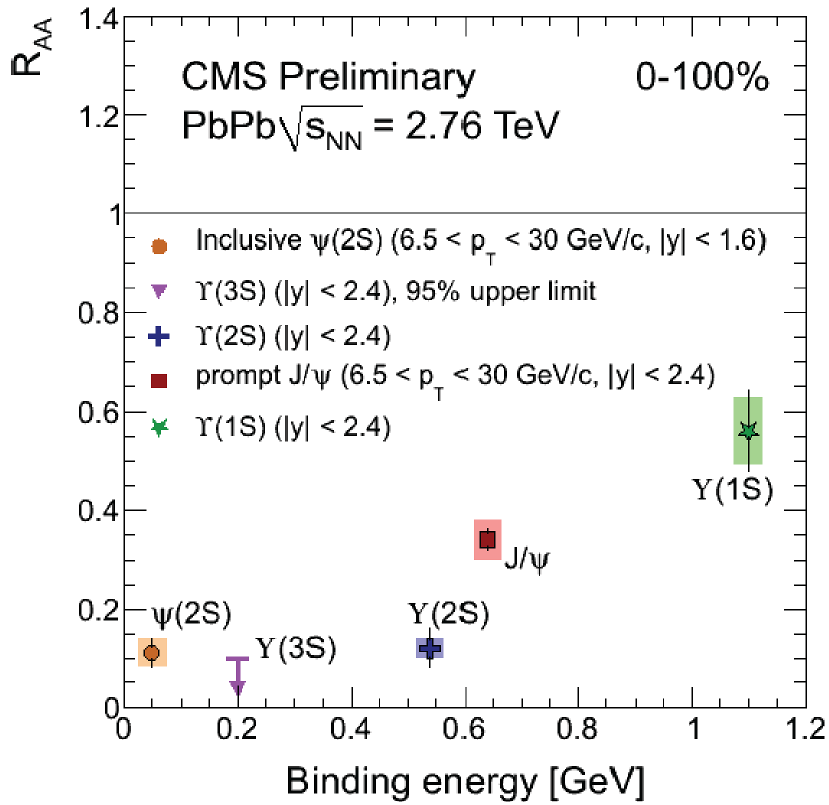
$$\frac{\Upsilon(3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(3S)/\Upsilon(1S)|_{pp}} = 0.06 \pm 0.06 \pm 0.06 < 0.17\ (95\%\ \mathrm{CL})$$

- Υ states are suppressed sequentially
  $R_{AA}[\Upsilon(3S)] < R_{AA}[\Upsilon(2S)] < R_{AA}[\Upsilon(1S)]$
- $\Upsilon(2S)$ is suppressed even in the most peripheral bin.

Υ(1S) and Υ(2S)

arXiv:1208.2826

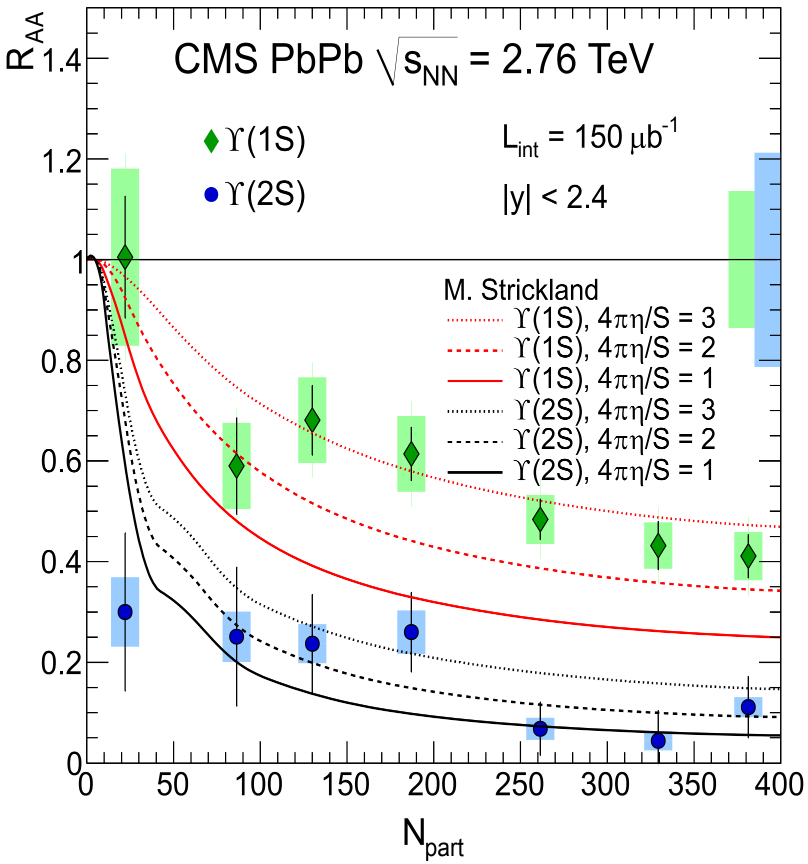




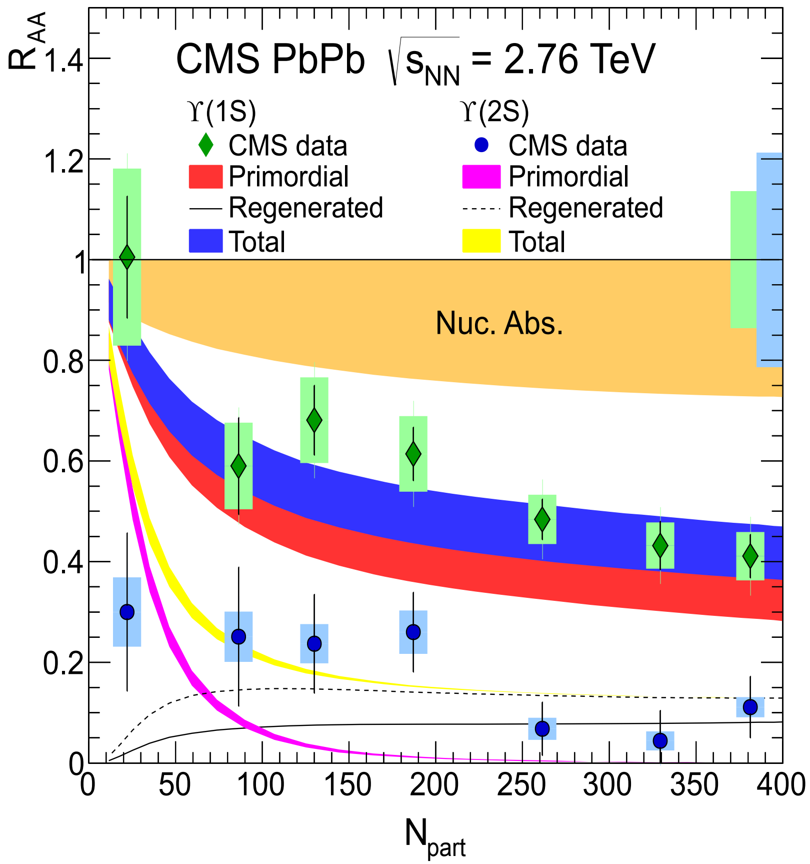
- If the feed-down contribution from χ_b, $\Upsilon(2S)$, and $\Upsilon(3S)$ is ~50%, R_{AA} of inclusive $\Upsilon(1S)$ is consistent with the suppression of excited states only.

Model Comparison

arXiv:1207.2827



EPJA 48, 72 (2012)



- Centrality dependence of the $\Upsilon(1S)$ and $\Upsilon(2S)$ yields can be reproduced by the models.

Summary

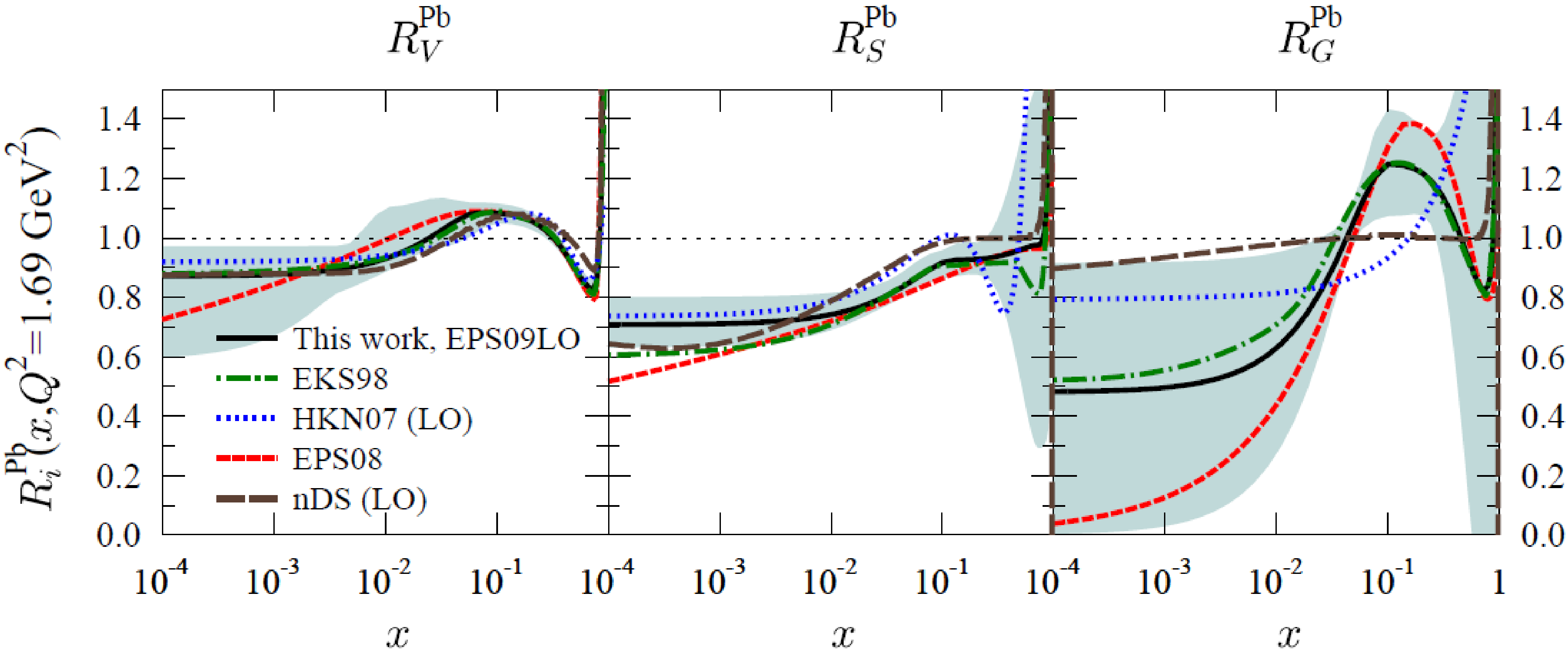
1. Long-range dihadron correlation and dijet behavior
   - Jet enhancement at low p_T and deficit at high p_T
   - The effect is larger on the away side
2. Dijet correlations
   - Dijet energy is largely unbalanced, *which is compensated by low-p_T particles over large angles.*
   - Jet fragmentation and shape is modified at large r and low p_T.
3. Quarkonium production
   - Prompt and non-prompt J/ψ are suppressed.
   - $\psi(2S)$ are more (less) suppressed than J/ψ at high (low) p_T.
   - $\Upsilon(2S)/\Upsilon(1S)$ in PbPb is suppressed by about a factor of five.
   - Upper limit on $\Upsilon(3S)$ double ratio is measured.

➢ More results in our web page
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

Backups

nPDF

Eskola et al., hep-ph/0902.4154v1



Kinematic Coverage