Universität
Heidelberg

Summary of Hard Probes 2012

“Heavy Particles”

MinJung Kweon
University of Heidelberg
July 16 2012, Group meeting

Why heavy quarks are interesting?

Silvia

Heavy flavours are produced
in hard scattering processes
in the early phase of the collisions

- Present from the early times
- In the highest density phase
- Travel and interact in the medium, experience the full collision history

provide underlying energy loss mechanism of heavy quarks and medium properties

Parton energy loss by:

- Medium-induced gluon radiation
- Collisions with medium partons

Depends on

- Colour charge (Casimir factor, $\Delta E_g > \Delta E_{u,d,s}$)
- Parton mass (dead cone effect, $\Delta E_b < \Delta E_c <$ ..)

$\Delta E_g > \Delta E_c > \Delta E_b$
"suppression": π > D > B

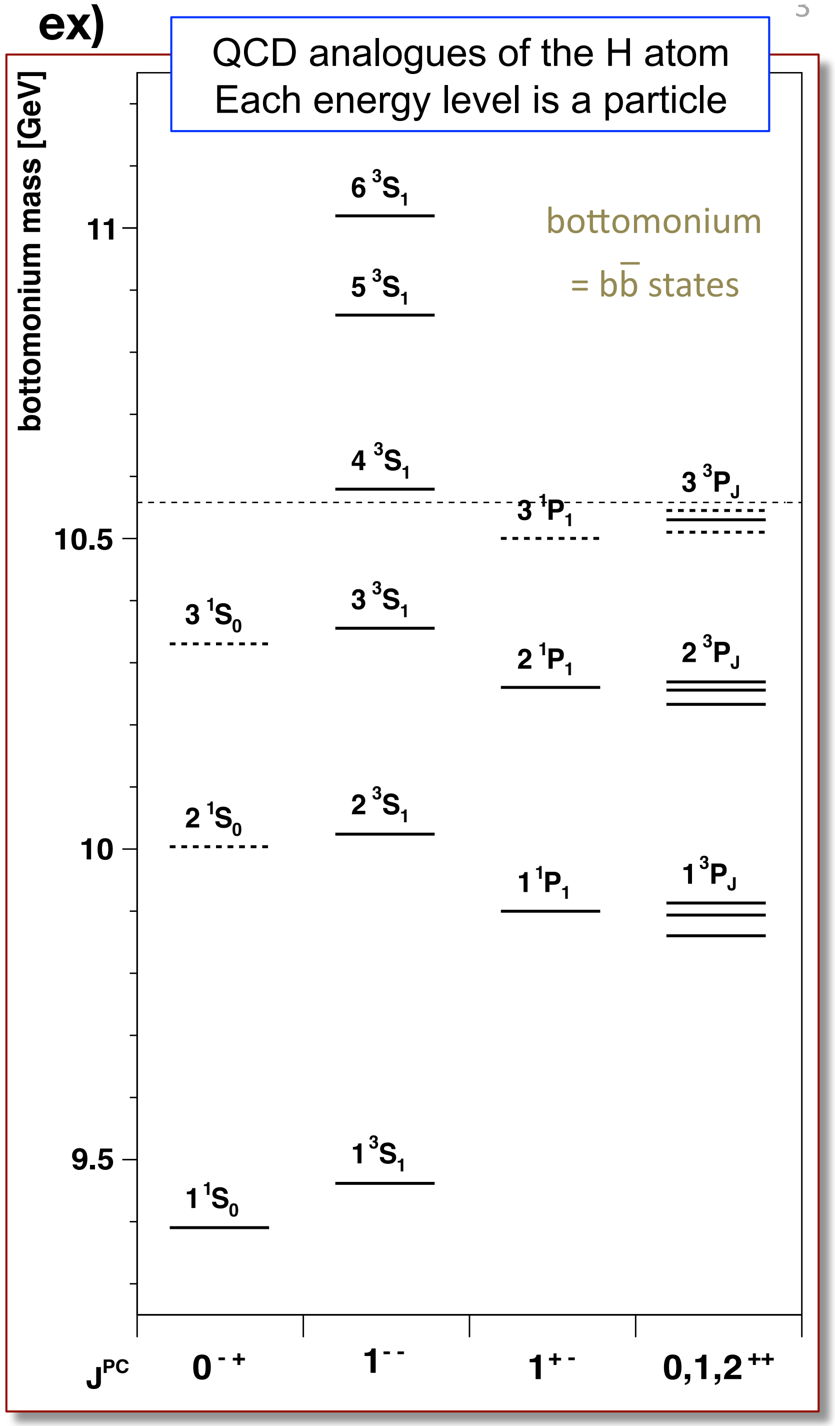
Elliptic flow of heavy flavours

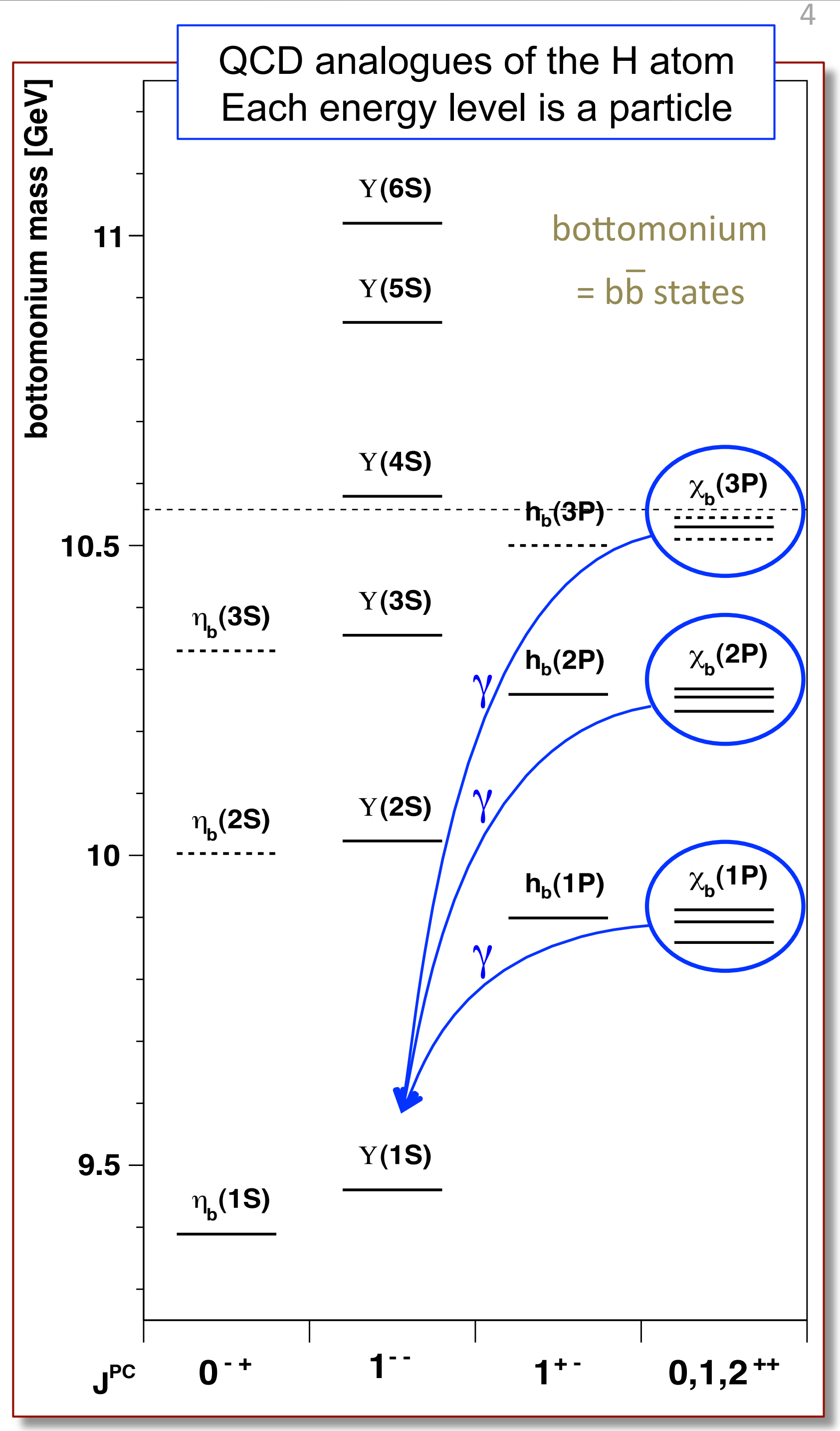
→ information on medium transport properties: thermalization in QGP (low p_t) and path length dependence of the parton energy loss (high p_t)

Why Quarkonia?

Carlos Lourenço (CERN)
Torsten Dahms LLR – École Polytechnique

ex)

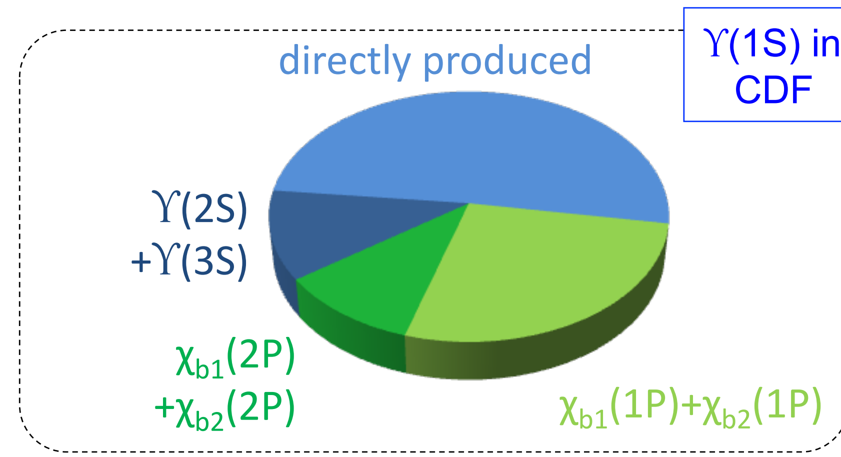




Quarkonia:
bound states of *heavy* quark-antiquark pairs, studied with non-relativistic QCD

An important goal for CMS: **in pp**

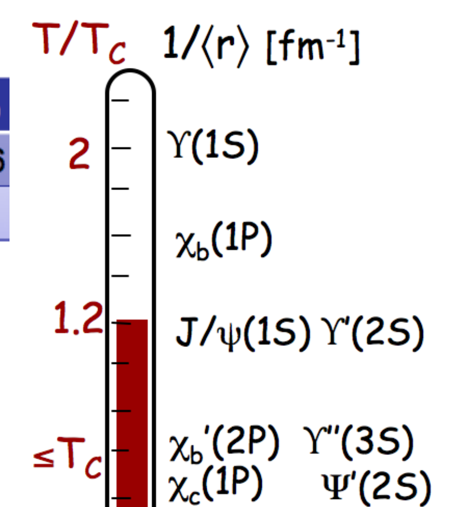
Cross section and polarization measurements of S and P states in high-energy pp collisions



in PbPb

ex)

state	Υ(1S)	Υ(2S)	Υ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20



A. Mocsy Eur.Phys.J.C61, 2009

Debye screening in QGP leads to melting of quarkonia

Different binding energy of bound states lead to sequential melting of the states with increasing temperature

EWK Bosons in HI Collisions

- In HI collisions, electroweak bosons (γ, W, Z) are not expected to interact with hot and dense strongly interacting medium.
- Photons already studied at previous experiments, and LHC conditions (energy, luminosity) have made Z & W bosons available.
- Establish a reference for other particles whose properties change in the bulk or provide normalization to other processes.
- Profit from leptonic decays of W, Z bosons as they suffer negligible energy loss in the medium

In this talk...

Focus on PbPb results, select some of pp results

Tried to put together results of same observable from different experiments

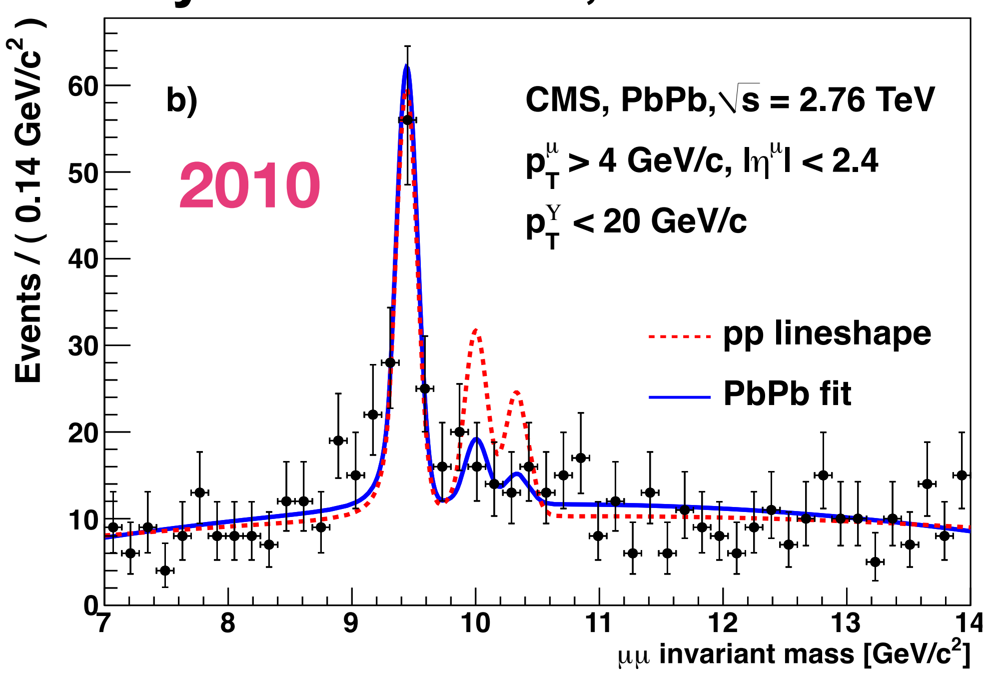
- $\Upsilon(nS)$ in pp, PbPb
- χ_c in pp
- J/ψ, J/ψ from beauty hadrons in pp, PbPb
- ψ(2S) in pp, PbPb
- D mesons, muons, electrons from heavy flavour decays in pp
- Single muon and D mesons R_{AA}
- Elliptic flow of D mesons
- Elliptic flow of J/ψ
- Photon, W, Z R_{AA}
- Elliptic flow of Z boson

Only experimental sides are shown

Υ(nS) yields

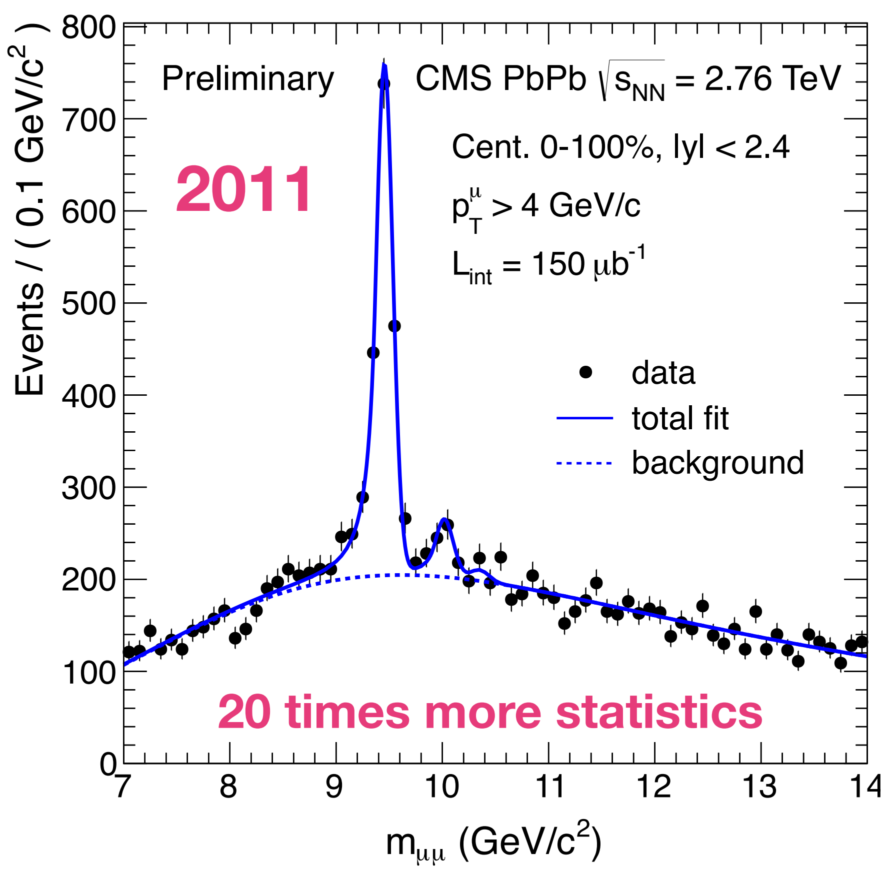
CMS

Phys.Rev.Lett.107, 2011



- 2010: PbPb@2.76TeV
  - 7.28 μb⁻¹
  - **86 ± 12 Υ(1S)**
- 2011: pp@2.76TeV
  - 231 nb⁻¹
  - **101 ± 12 Υ(1S)**

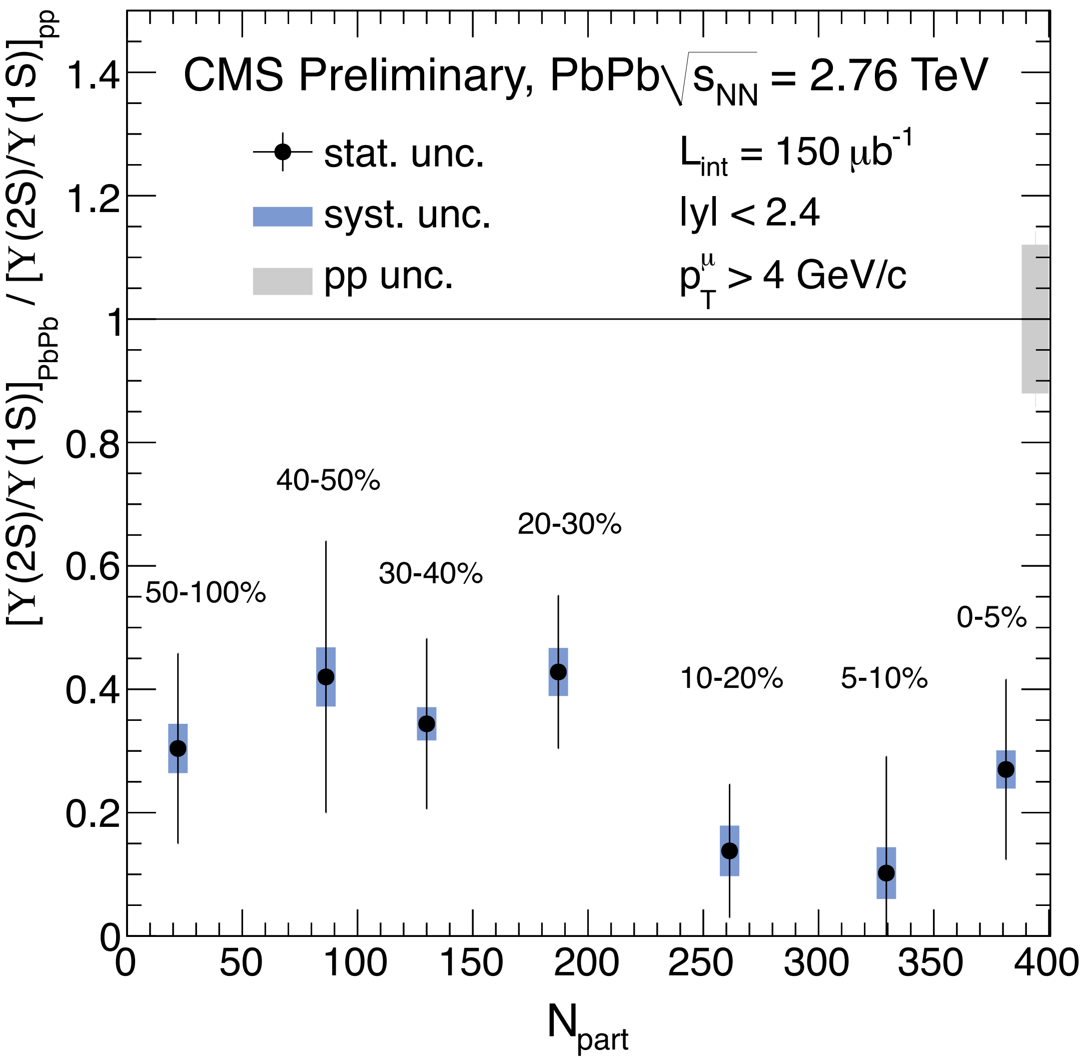
$$\frac{N_{\Upsilon(2S+3S)}/N_{\Upsilon(1S)}|_{\mathrm{PbPb}}}{N_{\Upsilon(2S+3S)}/N_{\Upsilon(1S)}|_{\mathrm{pp}}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

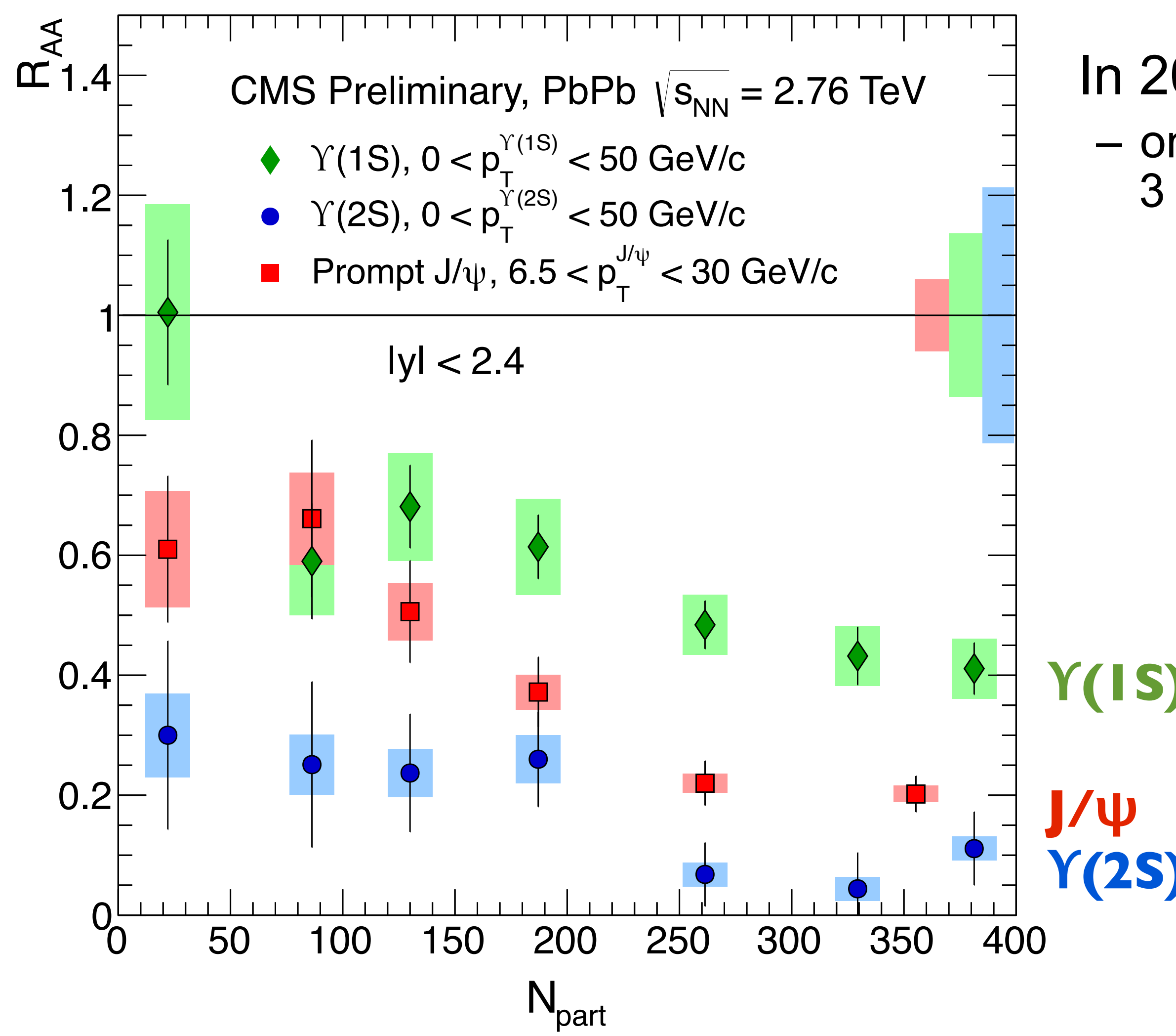


Why relative yields?

- The relative yields analysis of the 3 states
  - ➡ cancels cold nuclear matter effects
    - nPDFs (shadowing, etc)
    - initial parton energy loss
    - final state nuclear absorption (if negligible at LHC energies)
  - ➡ carries only effects related to final (hot) medium
    - *different binding energies* → color screening occurs at different temperatures → sequential melting → **thermometer of the final state medium**

$[\Upsilon(nS)/\Upsilon(1S)]_{PbPb}$ / $[\Upsilon(nS)/\Upsilon(1S)]_{pp}$ and Nuclear Modification Factor





In 2010 (7.28μb^{-1})
- only $\Upsilon(1S)$ R_{AA} in 3 centrality bins

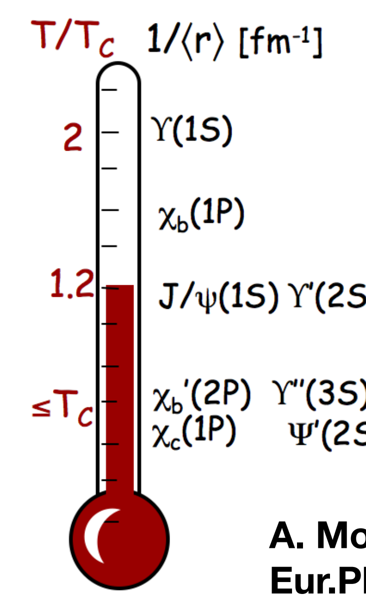
0-100%:

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

$$\frac{[\Upsilon(3S)/\Upsilon(1S)]|_{PbPb}}{[\Upsilon(3S)/\Upsilon(1S)]|_{pp}} < 0.1\ (95\% C.L.)$$

no strong centrality dependence
measured upper limit on ϒ(3S)

- $\Upsilon(1S)$ R_{AA} in 7 centrality bins
- first results on $\Upsilon(2S)$ R_{AA}
- clear suppression of $\Upsilon(2S)$
- $\Upsilon(1S)$ suppression consistent with excited state suppression (~50% feed down)



A. Mocsy
Eur.Phys.J.C61,2009

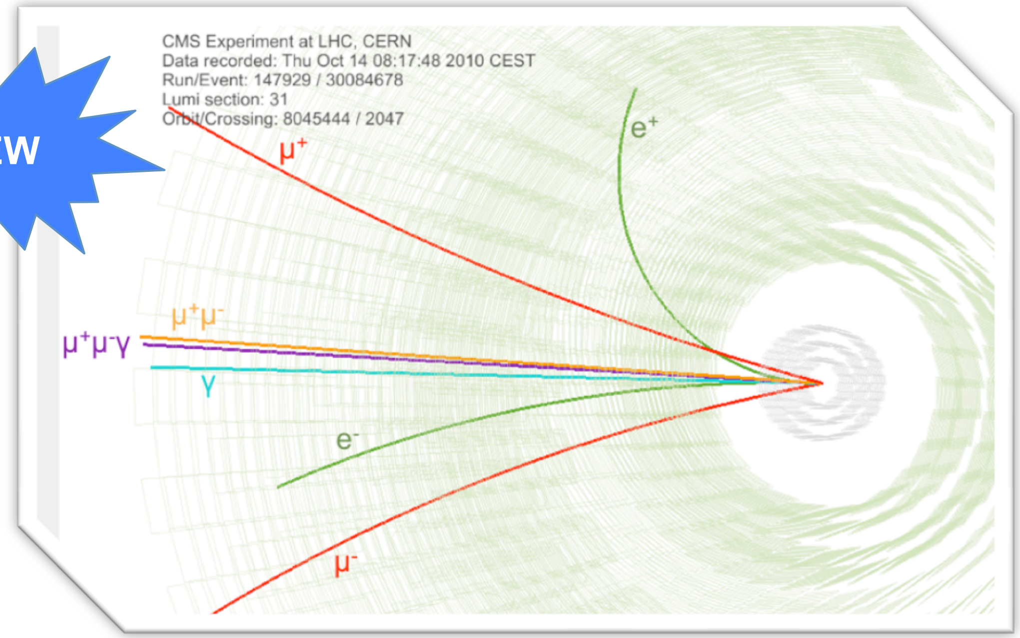
Suppression pattern in most central collisions, as expected from sequential melting

Surfing the P waves

Carlos Lourenço (CERN)

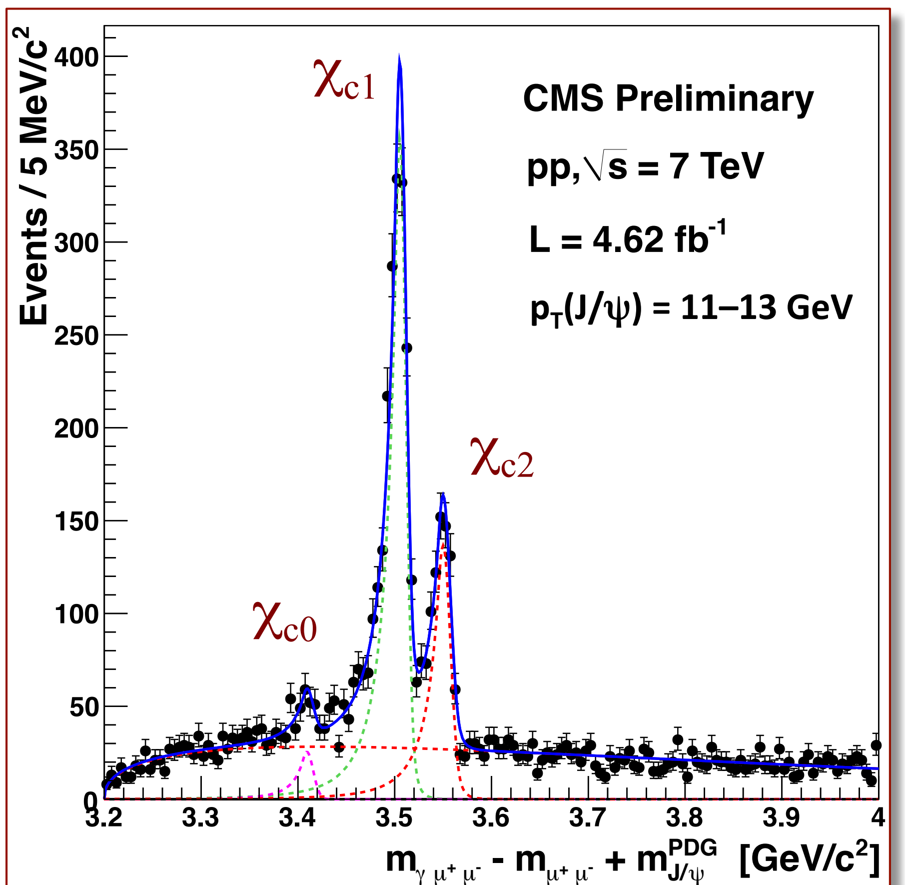
Production of χ_c mesons studied via $\chi_c \to J/\psi + \gamma$ radiative decays, with tracker-seeded γ conversions to e^+e^-

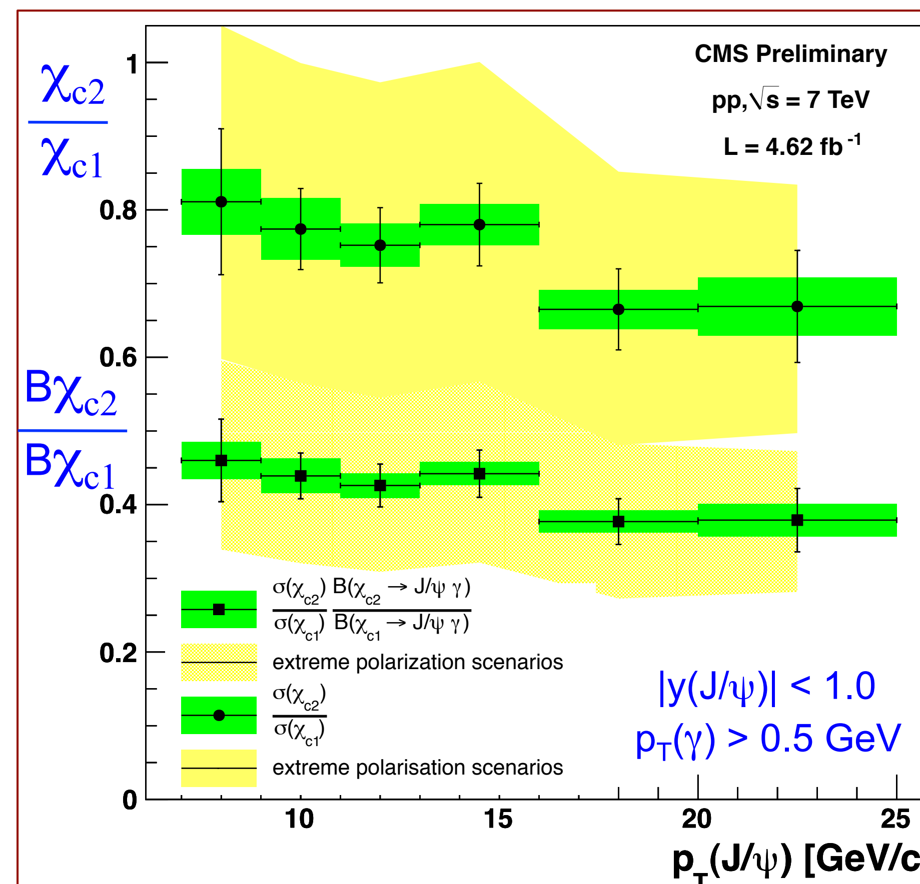
NEW



$n^{2S+1}L_J$	$I^G(J^{PC})$		
1^3P_0	$0^+(0^{++})$	$\chi_{c0}(1P)$	3,414.75 ±0.31
1^3P_1	$0^+(1^{++})$	$\chi_{c1}(1P)$	3,510.66 ±0.07
1^3P_2	$0^+(2^{++})$	$\chi_{c2}(1P)$	3,556.20 ±0.09

dimuon $|y| < 1.0$; $p_T(\gamma) > 0.5$ GeV





CMS PAS-BPH-11-010

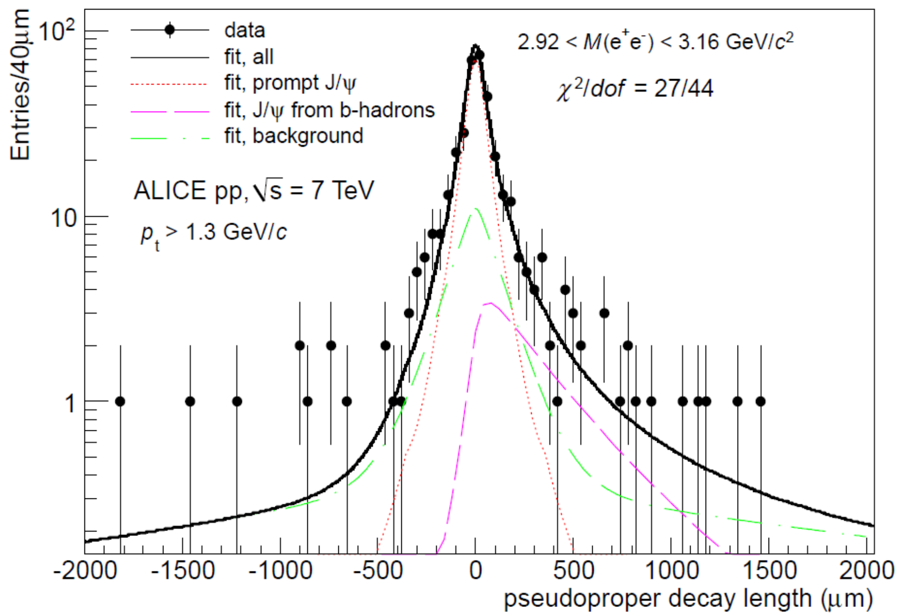
The χ_{c2} / χ_{c1} cross-section ratio has been measured vs. p_T

To compare with theory calculations, much care is needed regarding the polarizations (which can change the results by up to around ±25%)

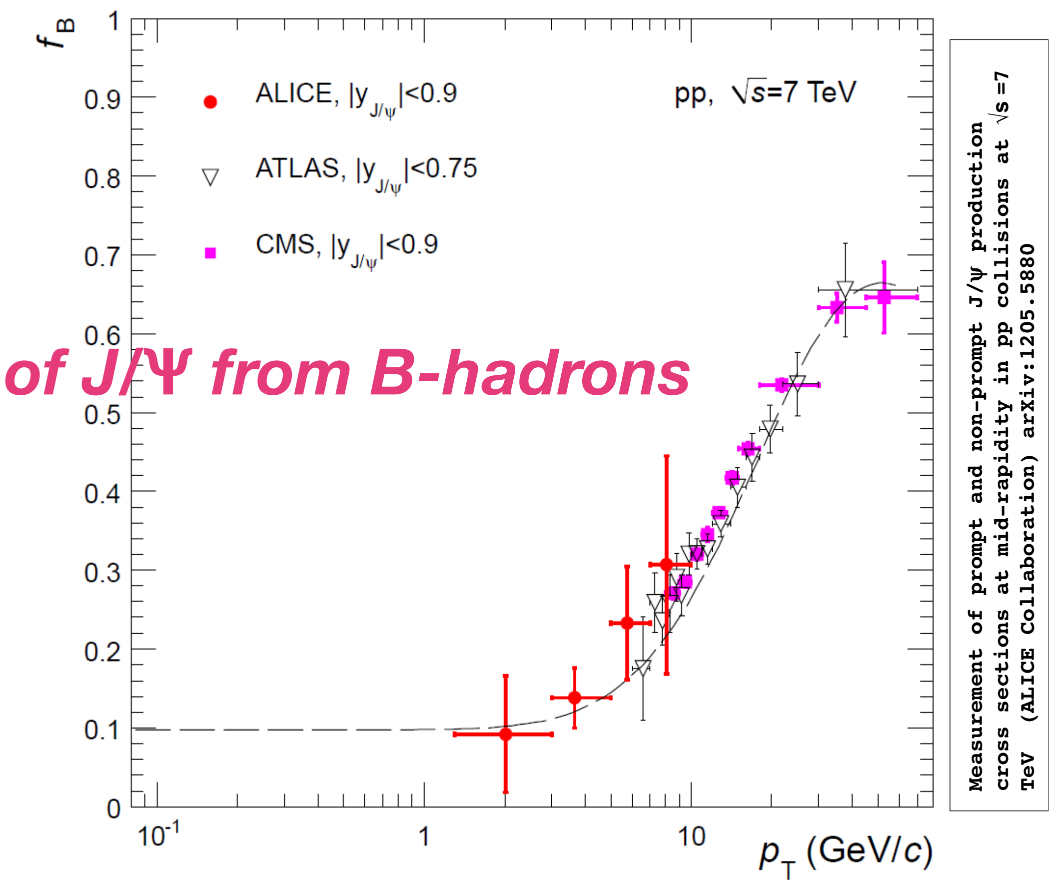
Christophe Suire
Carlos Lourenço (CERN)

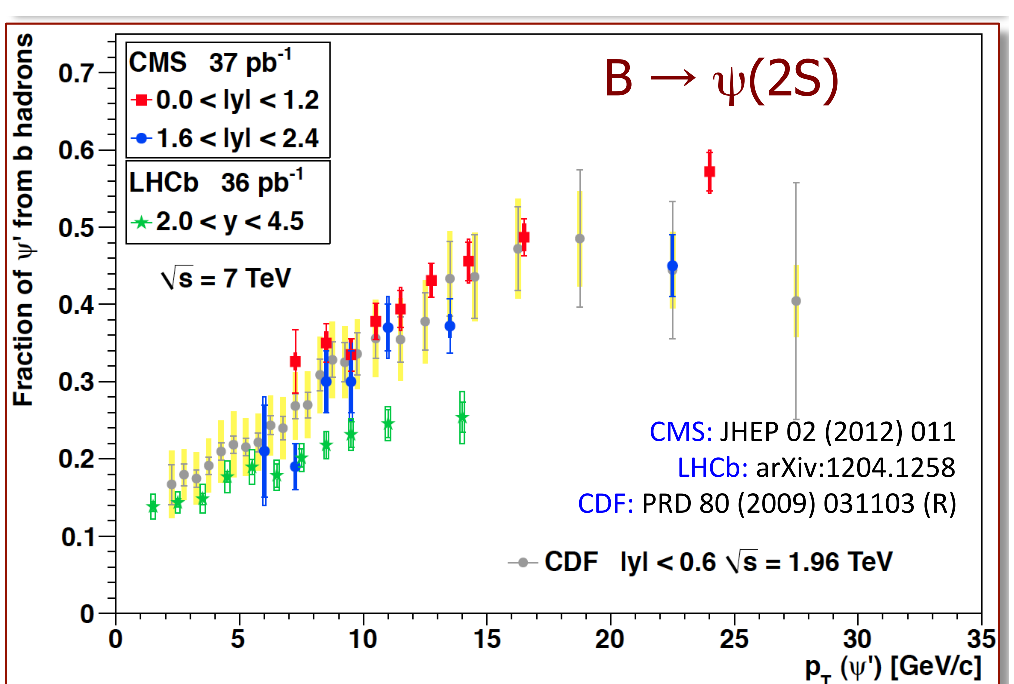
J/Ψ from B-hadrons decay in pp collisions

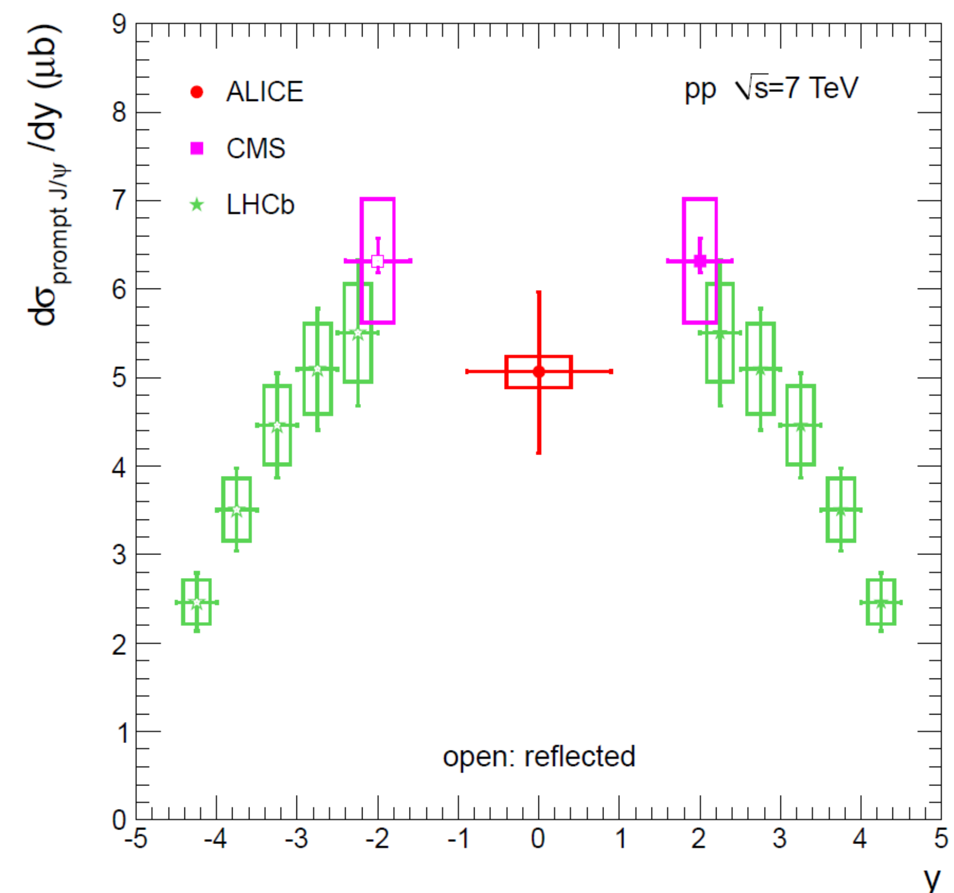
Impact parameter resolution: $\sigma_{r\varphi}$ < 75 μm
for p_t>1 GeV/c, at mid-rapidity
→ contributions from B decays estimated from the pseudo-proper decay length



fraction of J/Ψ from B-hadrons



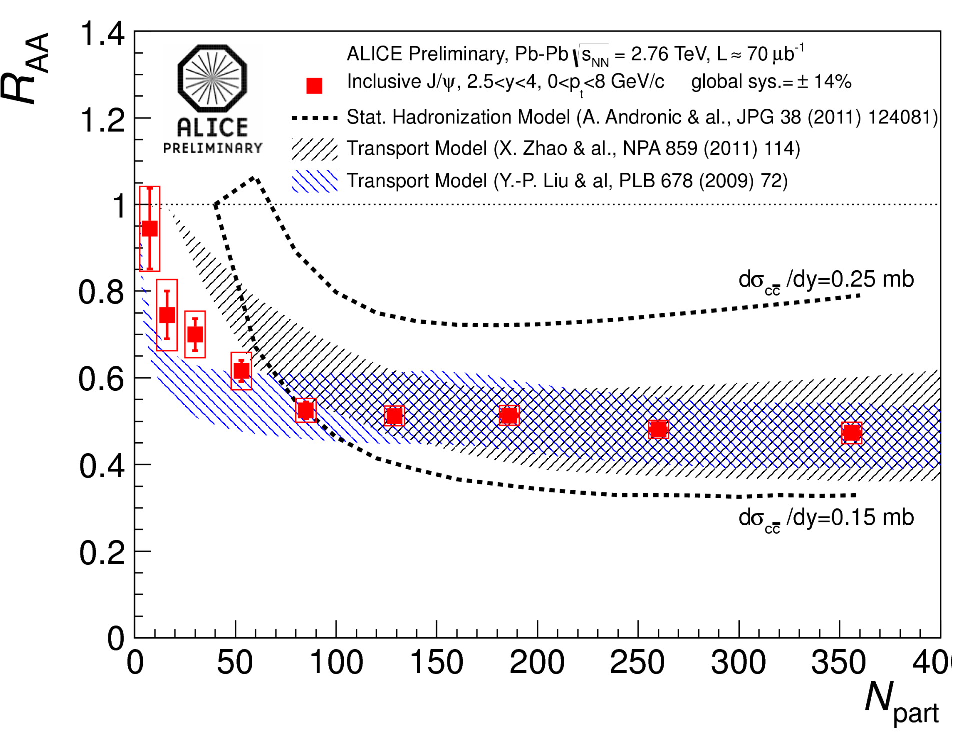


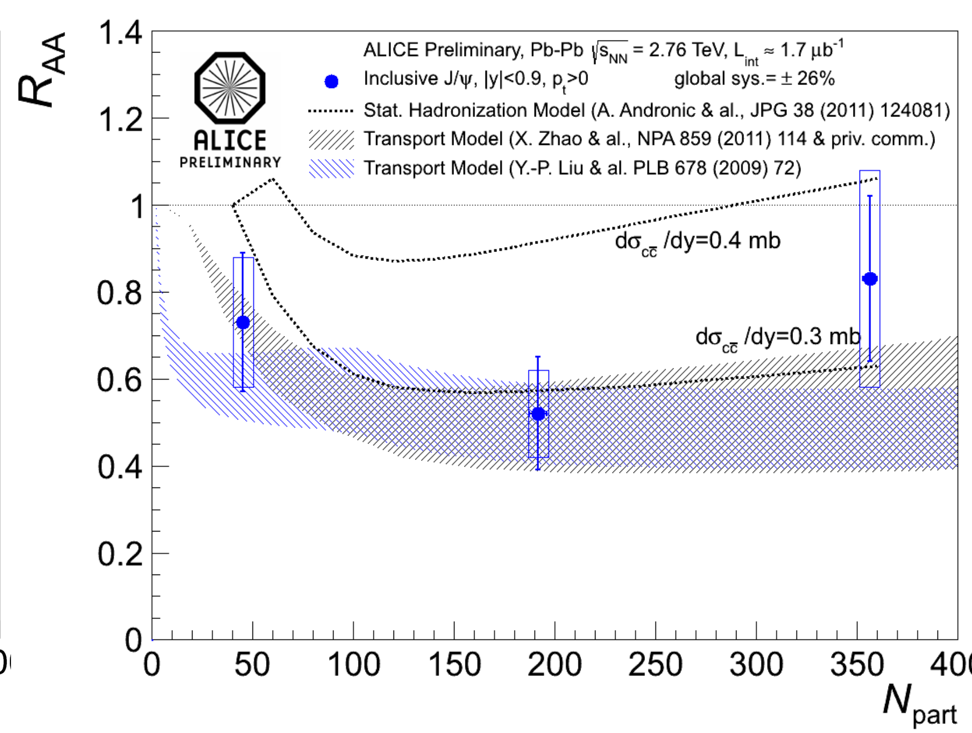


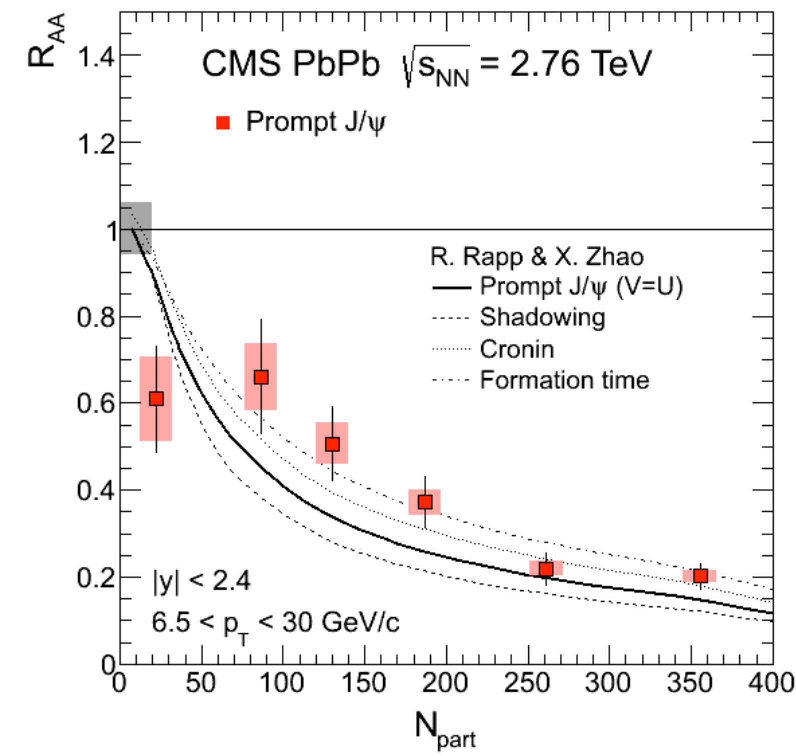
Above p_T ~ 20 GeV, more than half of the J/ψ and ψ(2S) mesons are from B decays

R_{AA} of Inclusive and Prompt J/ψ

ALICE inclusive (low p_t), CMS prompt (high p_t)







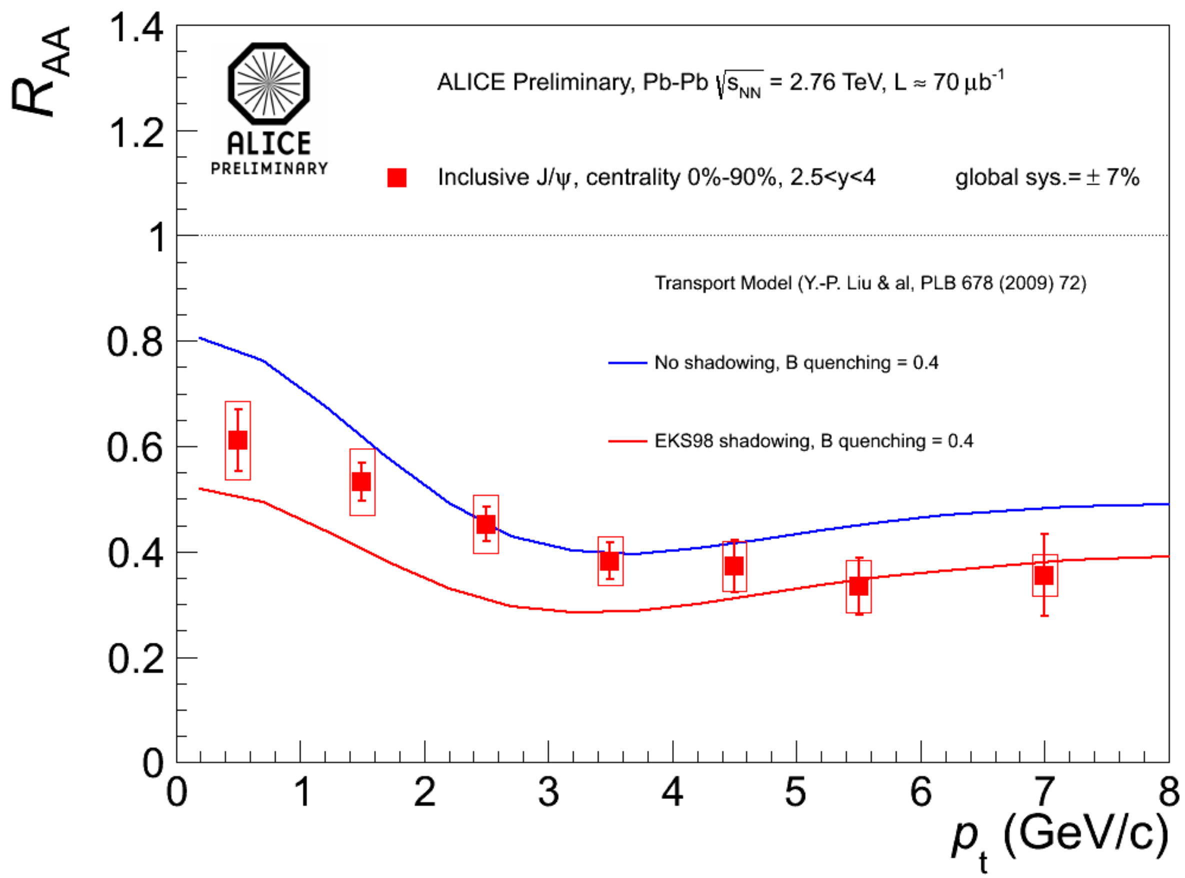
Zhao & Rapp, NPA 859 (2011) 114
+ private communication

Clear J/Ψ suppression at forward rapidity.
→ almost no centrality dependence above N_{part} ~ 100.
At mid rapidity, similar pattern but but large uncertainties prevent a firm conclusion.

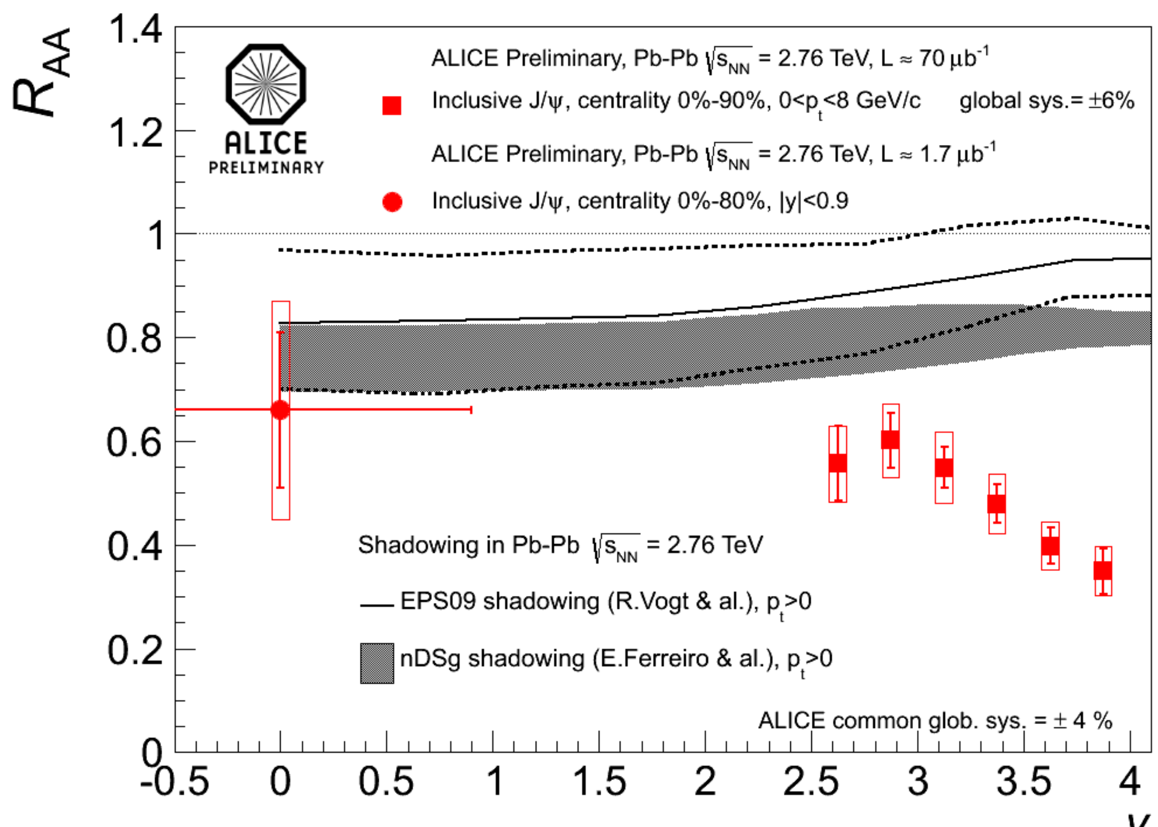
- Prompt J/ψ
  - p_T > 6.5 GeV/c & |y|<2.4
  - in 0–10% centrality: suppressed by factor 5
  - in 50–100%: suppressed by factor ~1.6
- Recombination effects:
  - expected to be small at high p_T

In both transport models, the amount of J/ψ produced from regeneration is ≥ 50% in the most central collisions.
In SH model, all J/ψ are formed at hadronization.

R_{AA} of Inclusive and Prompt J/ψ



Both models correctly reproduce our measurement
In both models, a large fraction of regenerated J/Ψ have p_t < 3-4 GeV/c



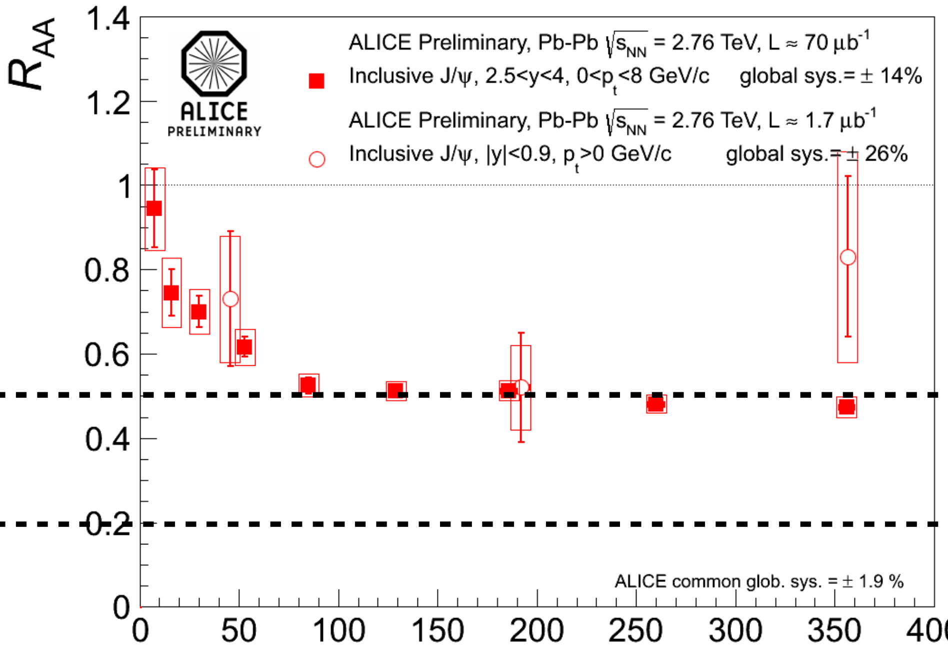
◀ Inclusive J/ψ measured in ALICE at both mid and forward rapidity.
R_{AA} decrease of 40% from y=2.5 to y=4.
Possible flat dependence toward mid rapidity.

◀ Suppression beyond the current estimate of shadowing at forward rapidity.

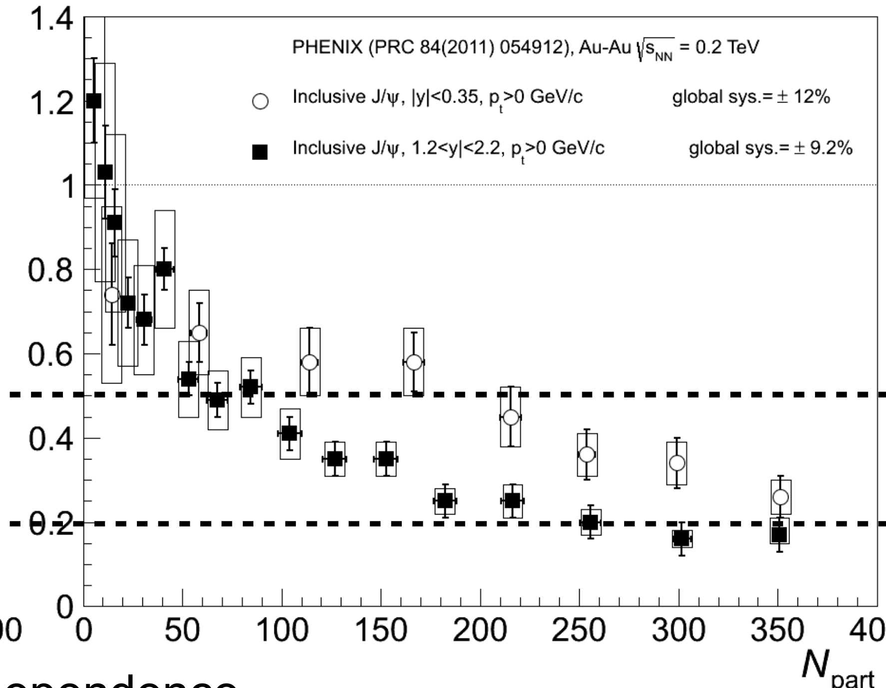
→ importance to measure cold nuclear matter effects.

Comparisons

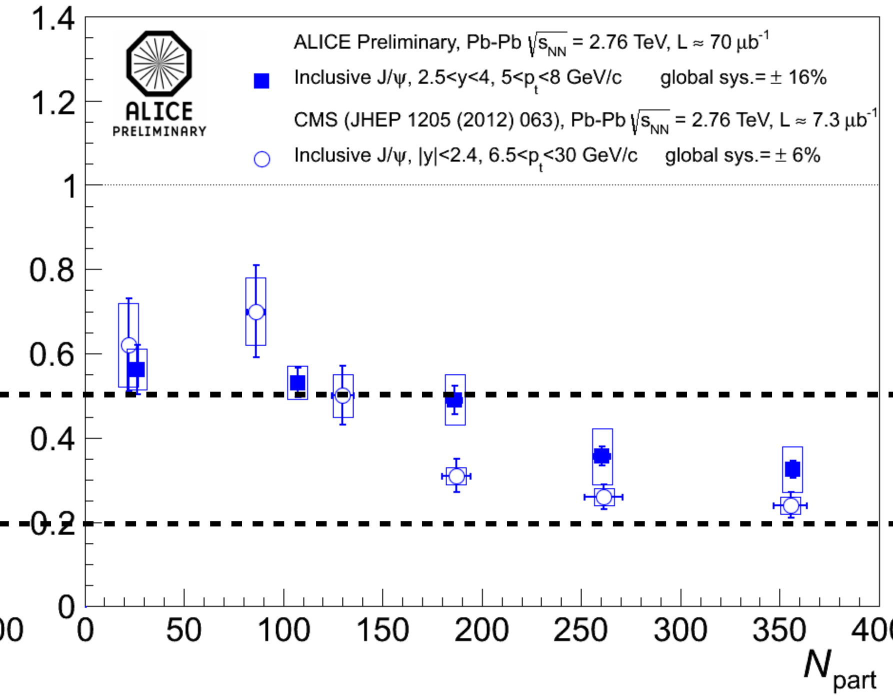
ALICE $p_t > 0$



PHENIX $p_t > 0$



ALICE/CMS high p_t

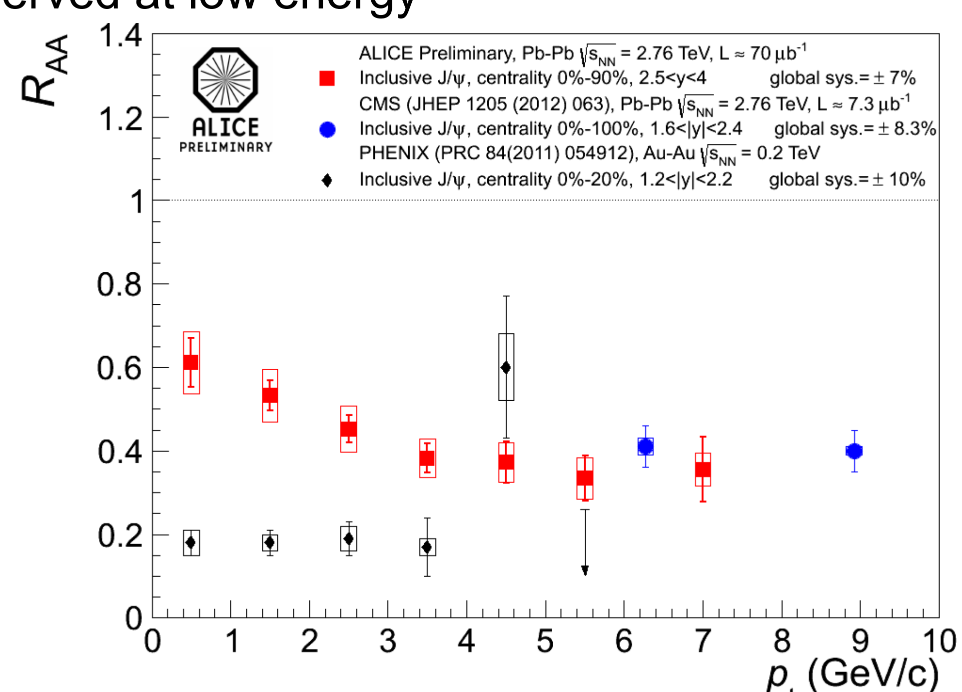


At low-pt, ALICE $R_{AA} \geq 0.5$, no centrality dependence

→ behavior clearly different to the one observed in PHENIX where a larger suppression and a strong centrality dependence is seen

At high-p_t, larger suppression seen both by ALICE and CMS

→ behavior is similar to the one observed at low energy



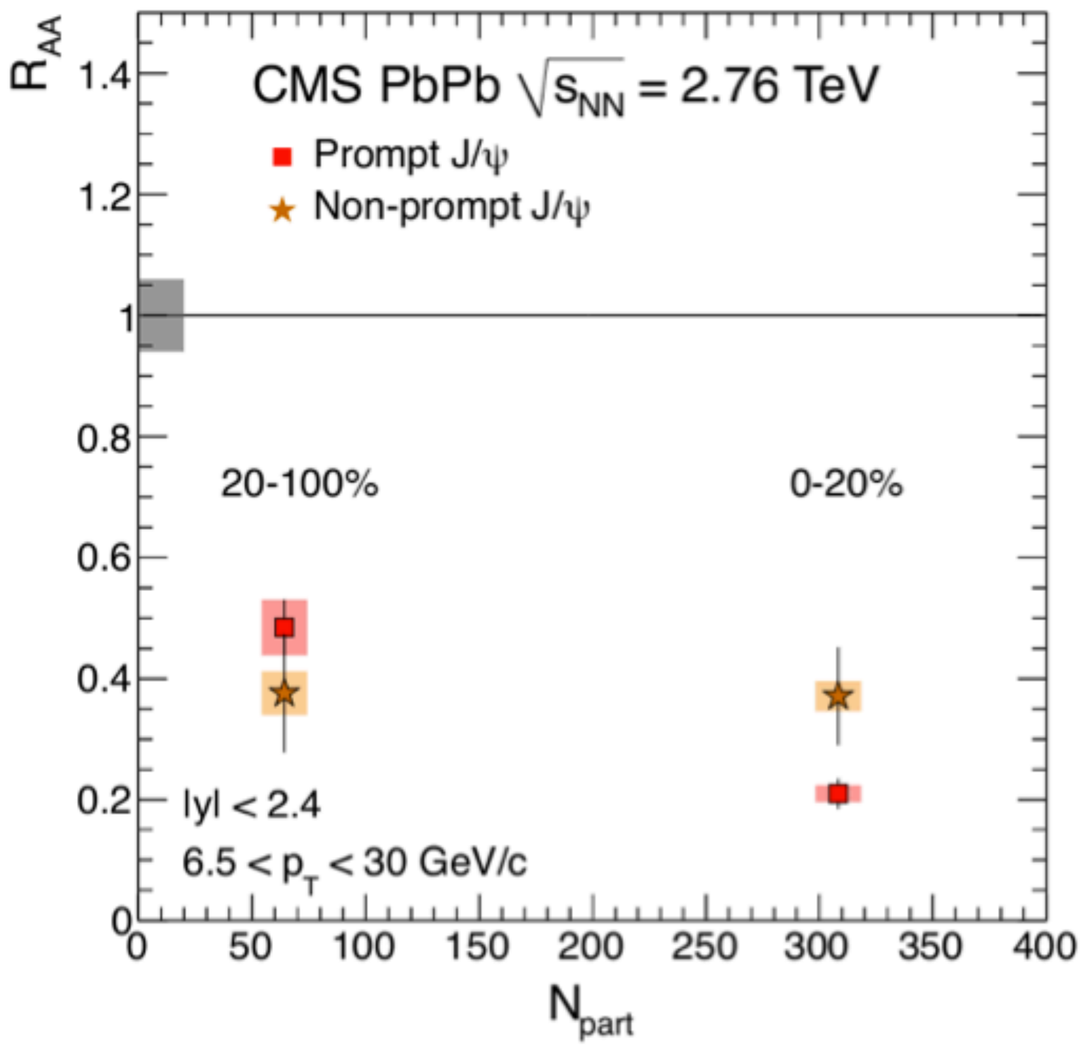
◀ ALICE inclusive J/ψ → μ+μ- at forward rapidity. R_{AA} ~ 0.6 at low-pt down to R_{AA} ~ 0.35 at high-p_t. Suppression increases with increasing p_t.

◀ Agreement with CMS data at high-p_t (1.6<|y|<2.4) .

◀ PHENIX measured larger suppression at low-p_t (0-20% central, 1.2<|y|<2.2)

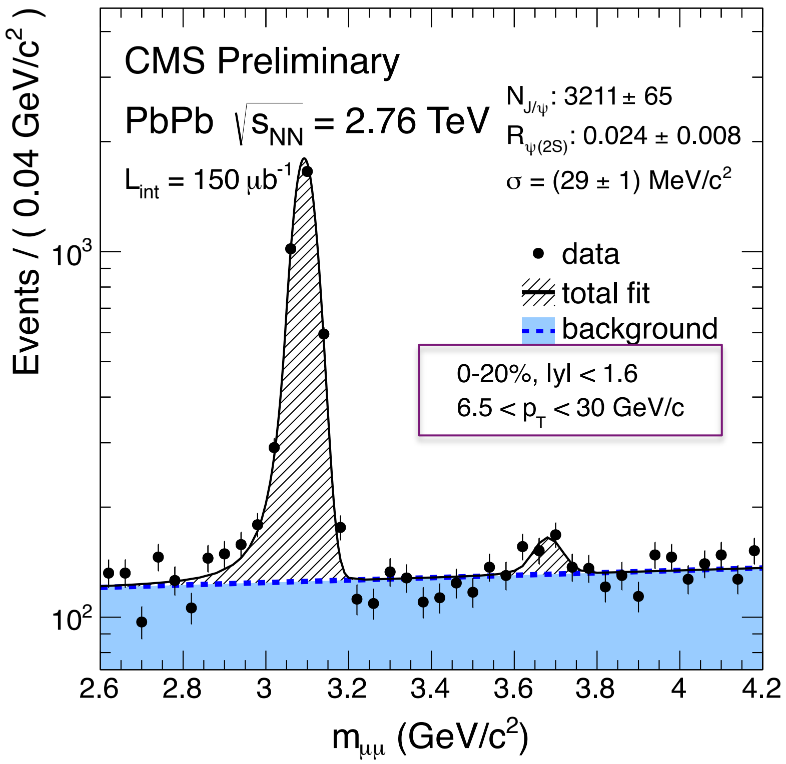
R_{AA} of Prompt(B→) J/ψ vs N_{part}

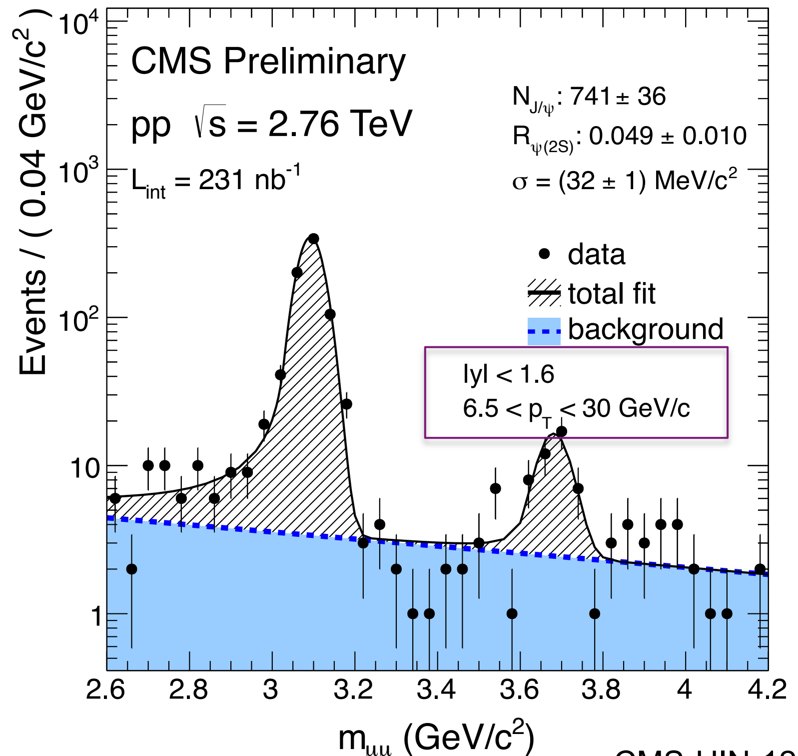
JHEP 1205 (2012) 063



Not quite different from last QM results
CMS has a plan to show finer binned results for both p_t and N_{part} for coming QM

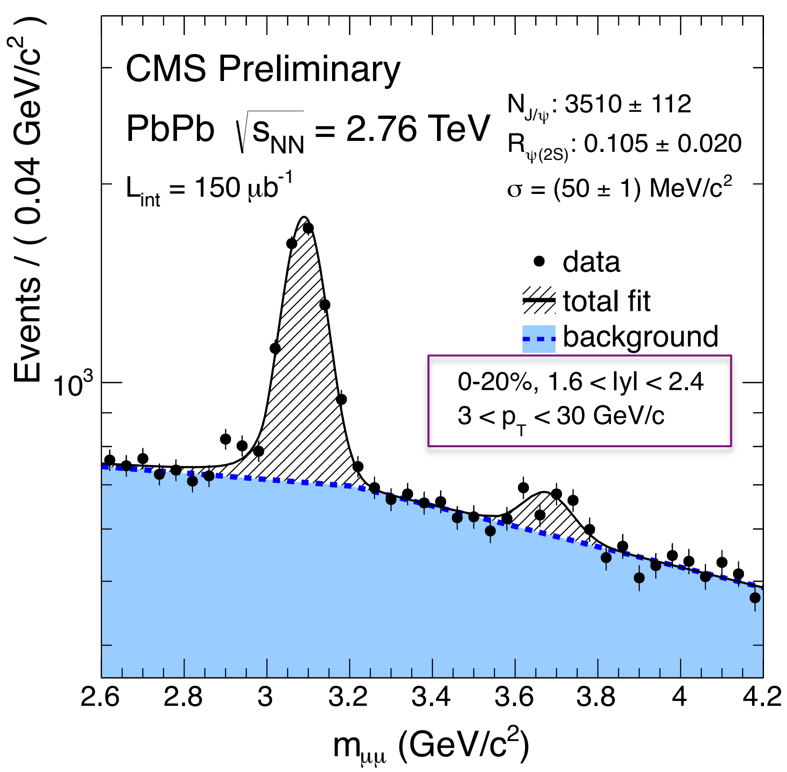
ψ(2S) in pp & PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

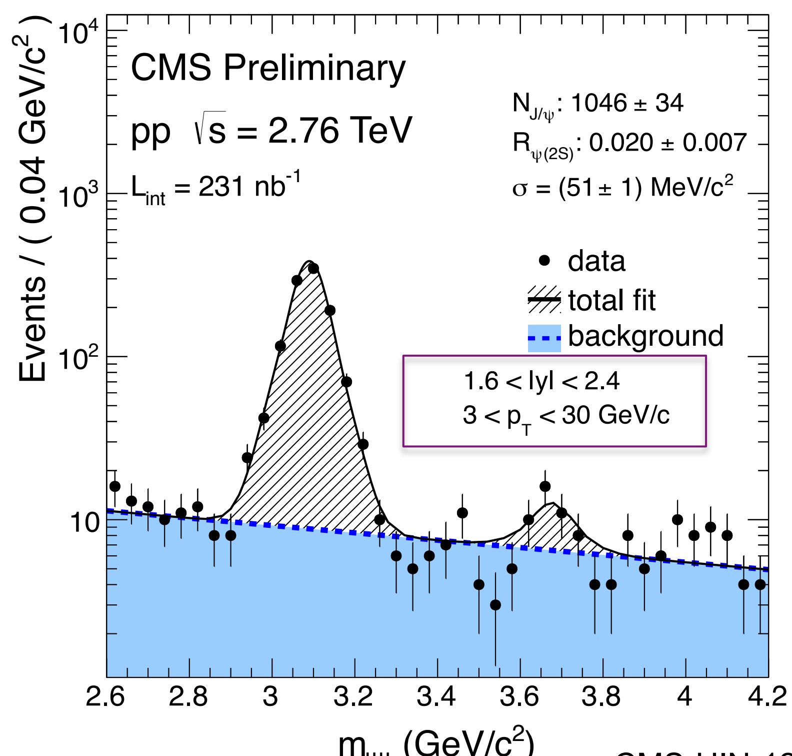




CMS-HIN-12-007

|y| < 1.6 and 6.5 < p_T < 30 GeV/c



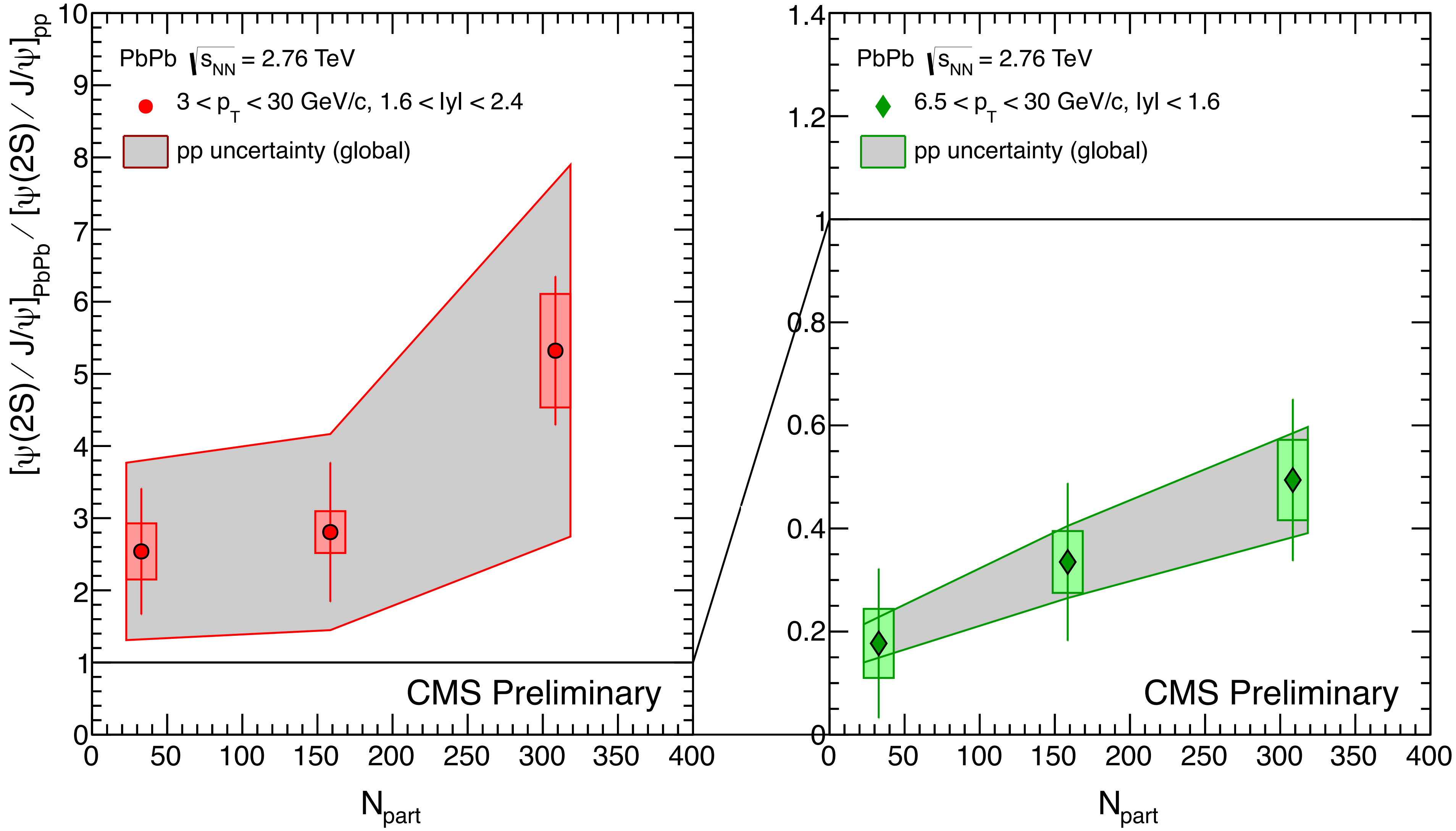


CMS-HIN-12-007

1.6 < |y| < 2.4 and 3 < p_T < 30 GeV/c

ψ(2S) / J/ψ Double Ratio

Double ratio of $[\psi(2S) / J/\psi]_{PbPb} / [\psi(2S) / J/\psi]_{pp}$

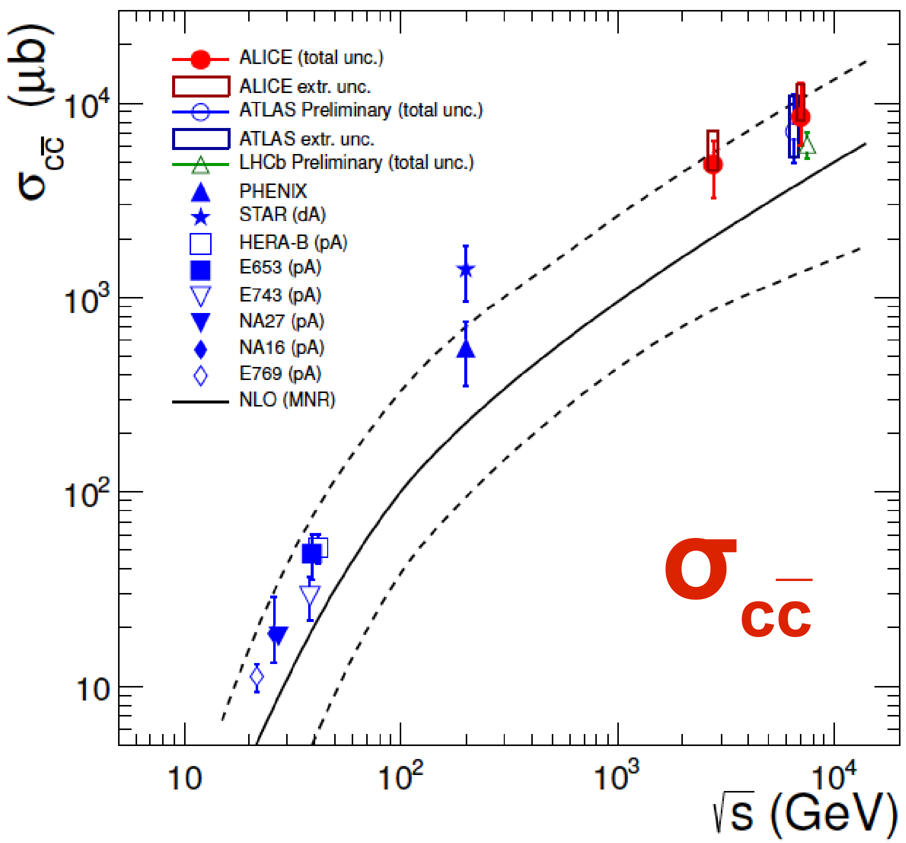


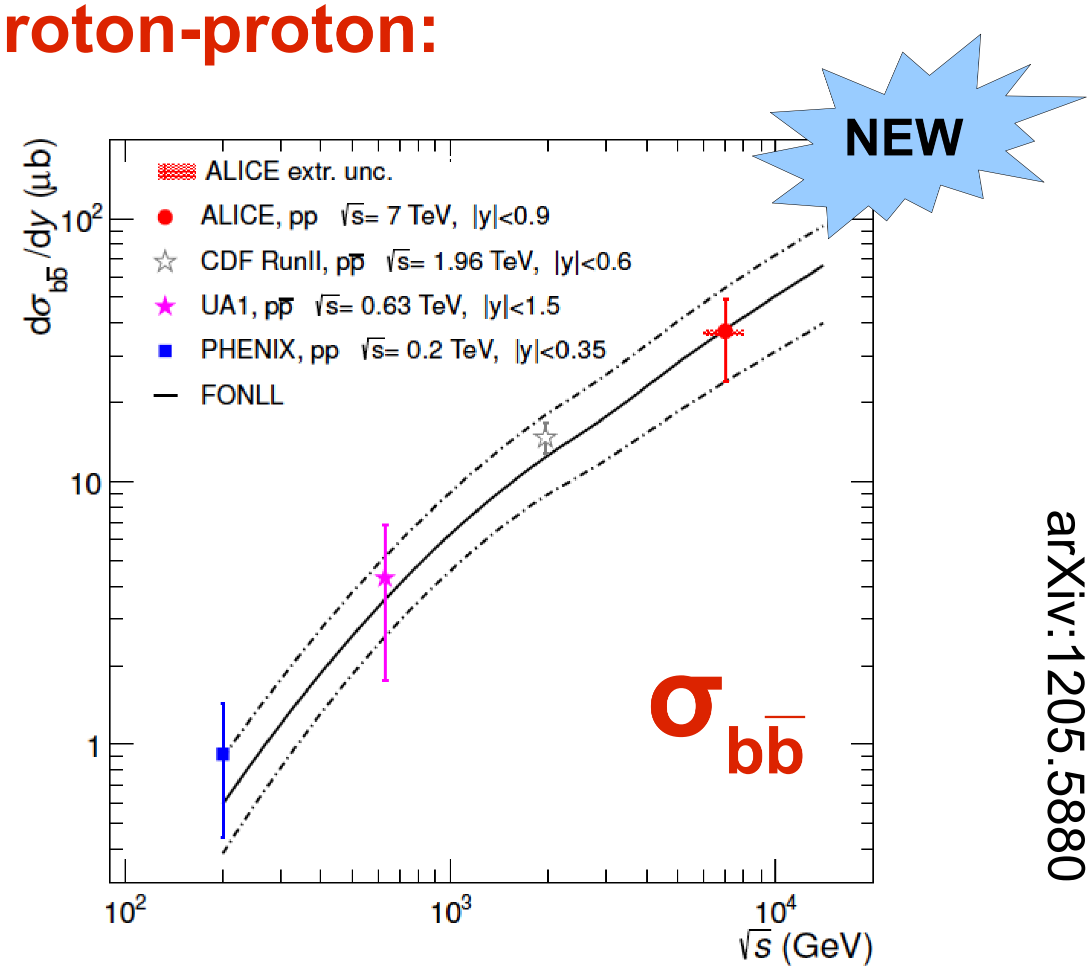
- For p_T>3 GeV/c and 1.6<|y|<2.4: large uncertainties on pp
  Indication of ψ(2S) being less suppressed than J/ψ, but need more statistics (in particular pp)!
- For p_T>6.5 GeV/c and |y|<1.6: ψ(2S) are more suppressed than J/ψ

Energy dependence of HF cross sections

Measured in proton-proton:

arXiv:1205.4007



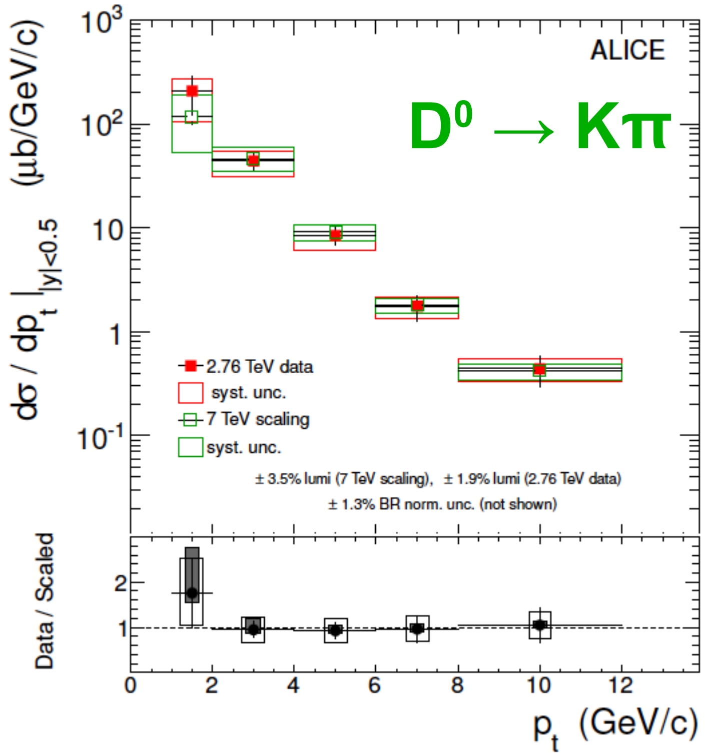


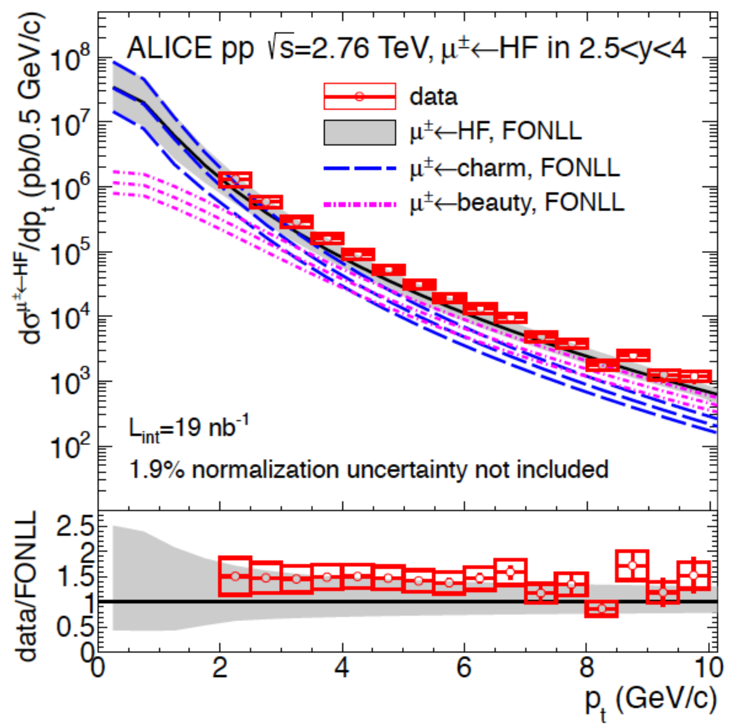
arXiv:1205.5880

pp at $\sqrt{s}$ = 2.76, 7 TeV: D mesons, muons, electrons

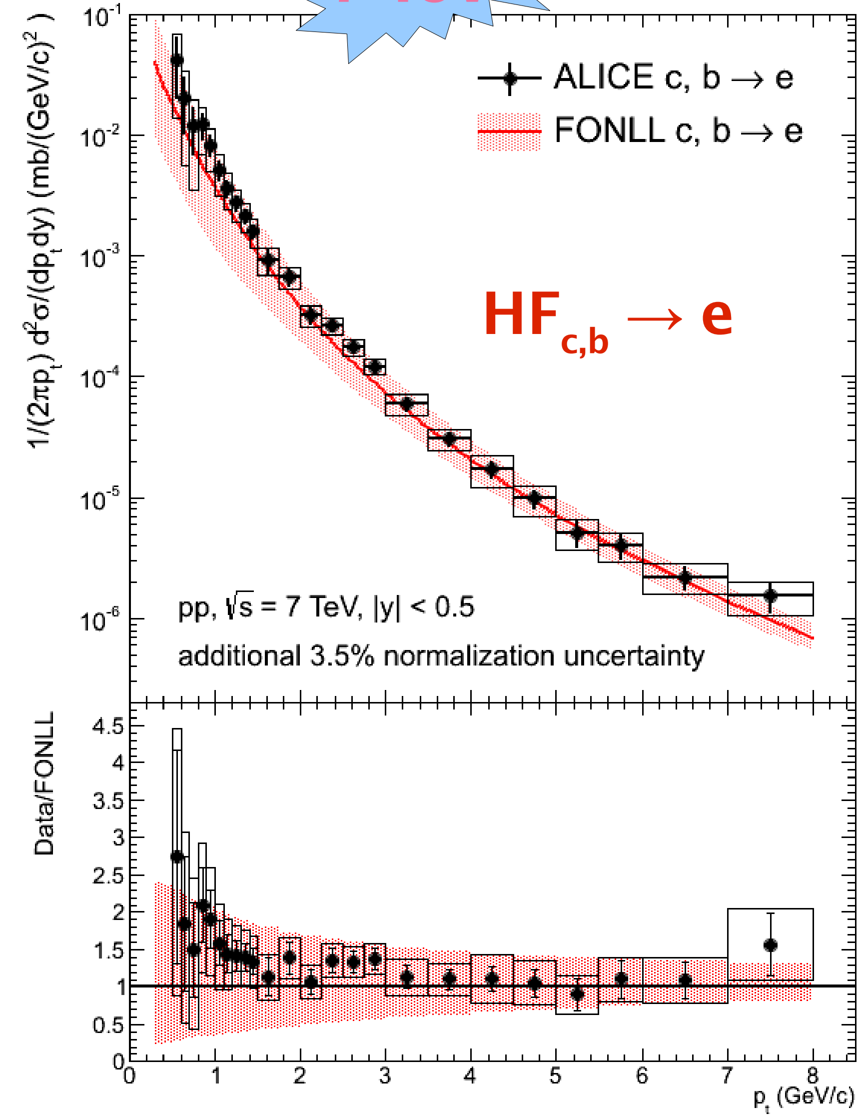
2.76 TeV

Also:
$D^+ \to K\pi\pi$
$D^* \to D^0\pi$

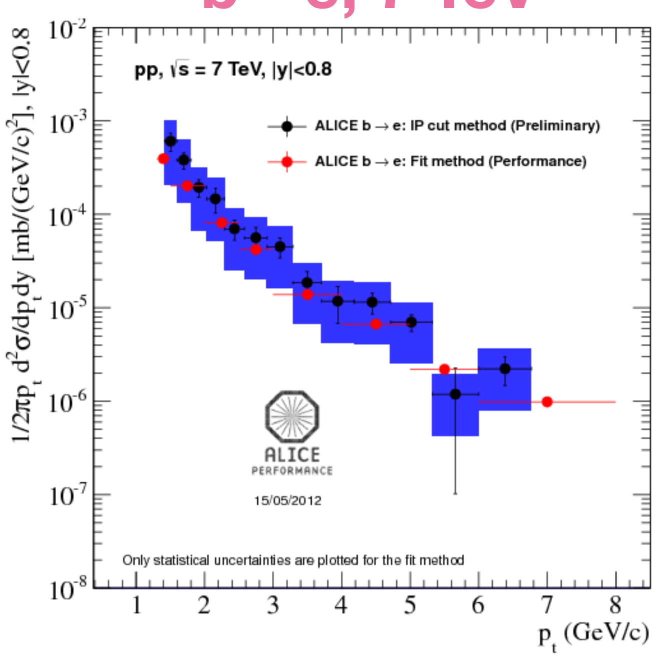




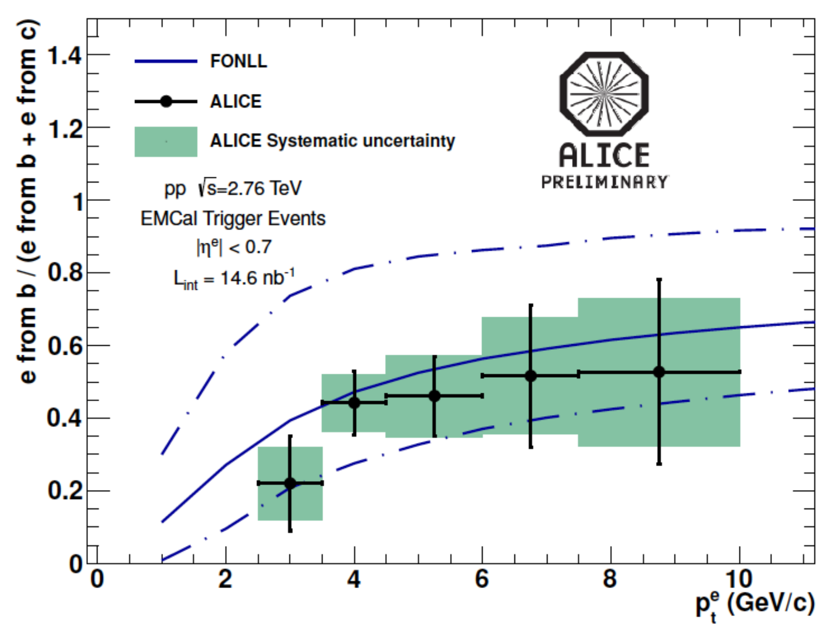
7 TeV



b→e, 7 TeV



2.76 TeV

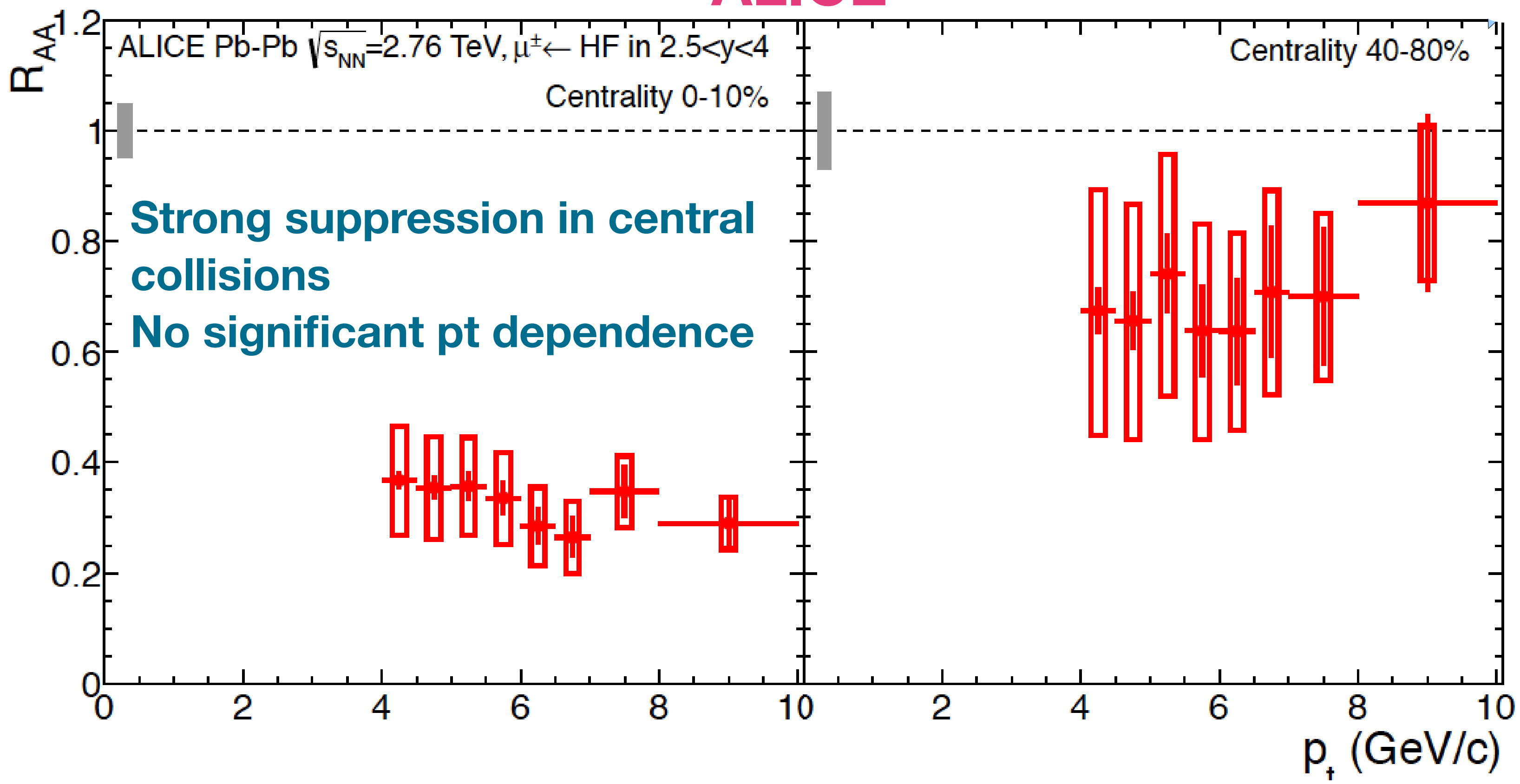


Data are well described by pQCD predictions (FONLL, GM-VFNS) within uncertainties

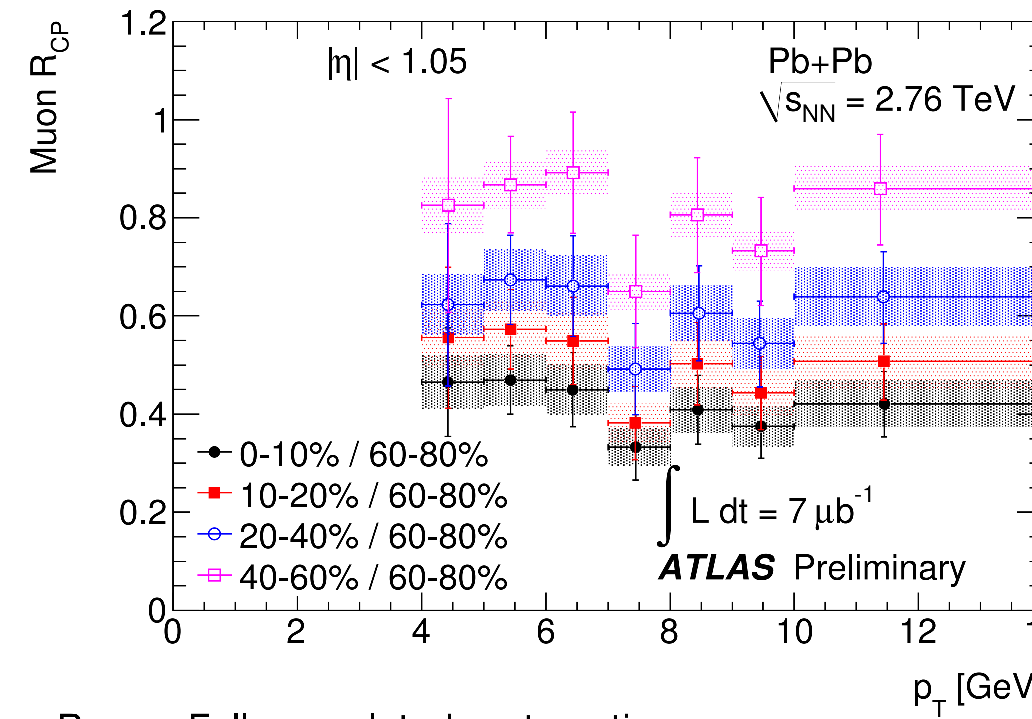
Important test of pQCD

Single muon and D meson (|y|<0.5) R_{AA}

ALICE

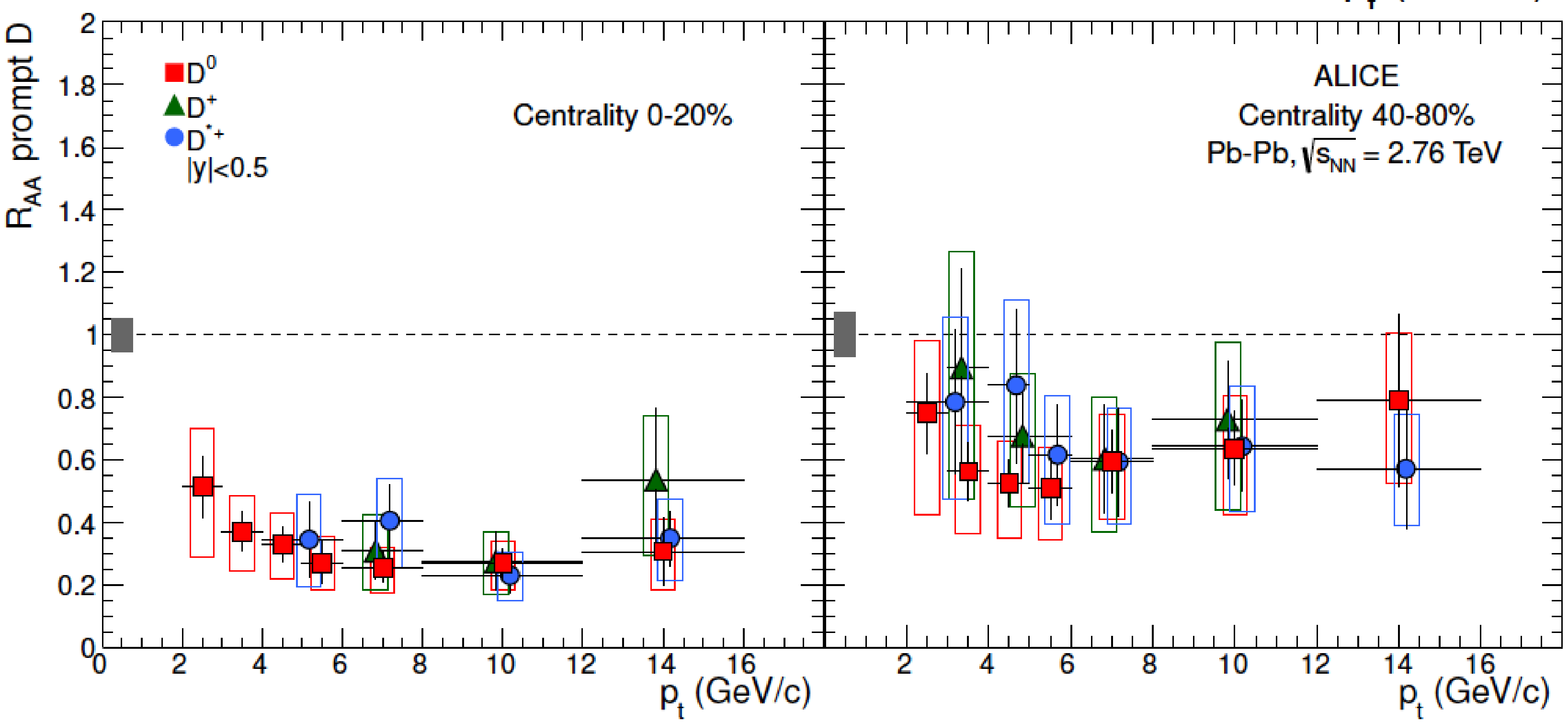


ATLAS



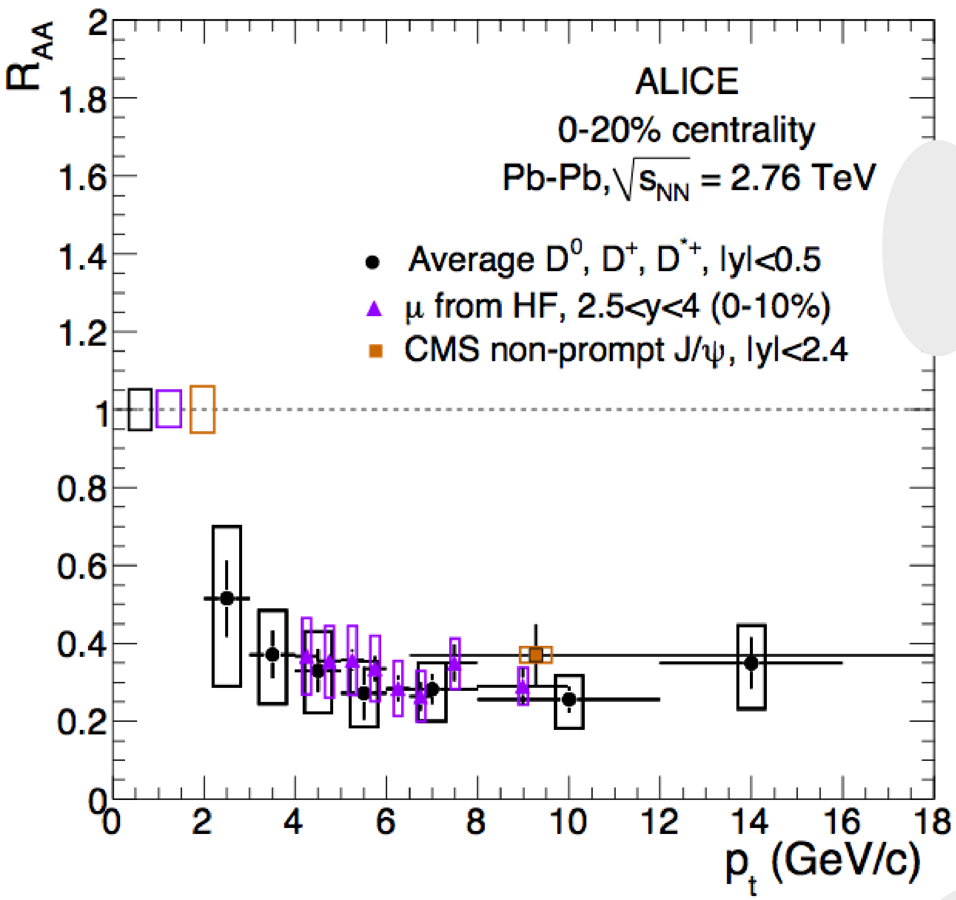
Boxes: Fully correlated systematics
Error bars: uncorrelated combined statistical+systematic

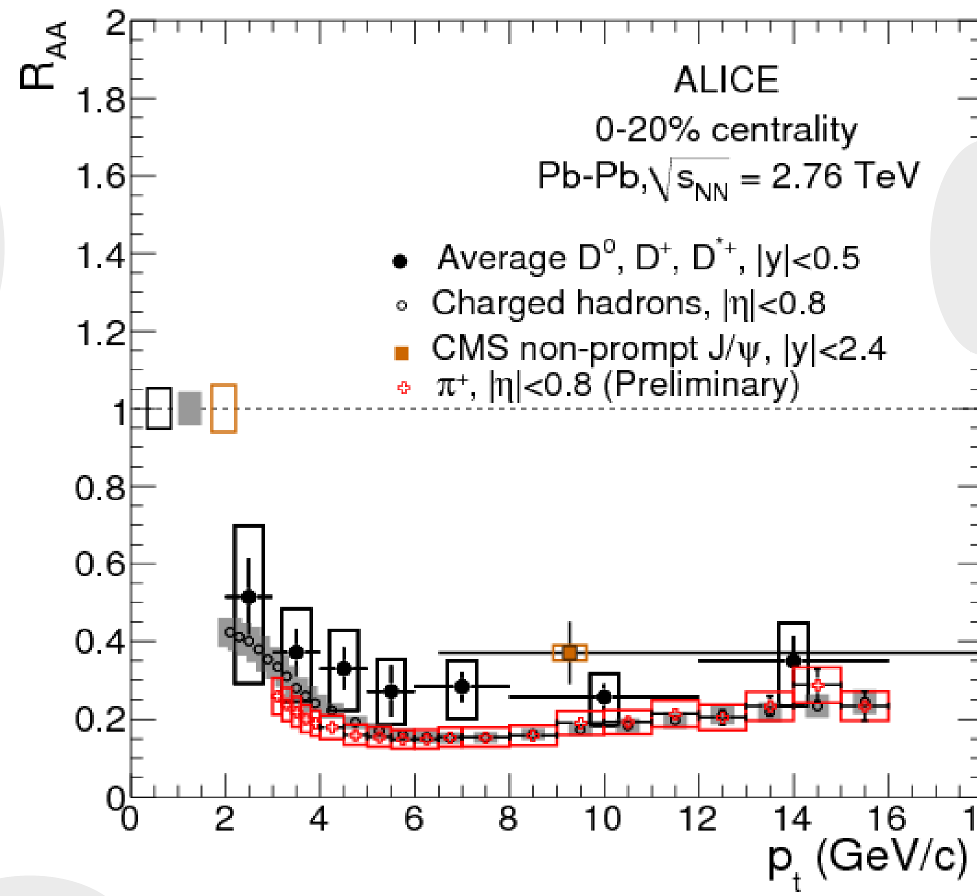
Generally flat with p_t (used R_{pc} to check flatness)



D^0, D^+, D^* compatible
Strong suppression in central collisions

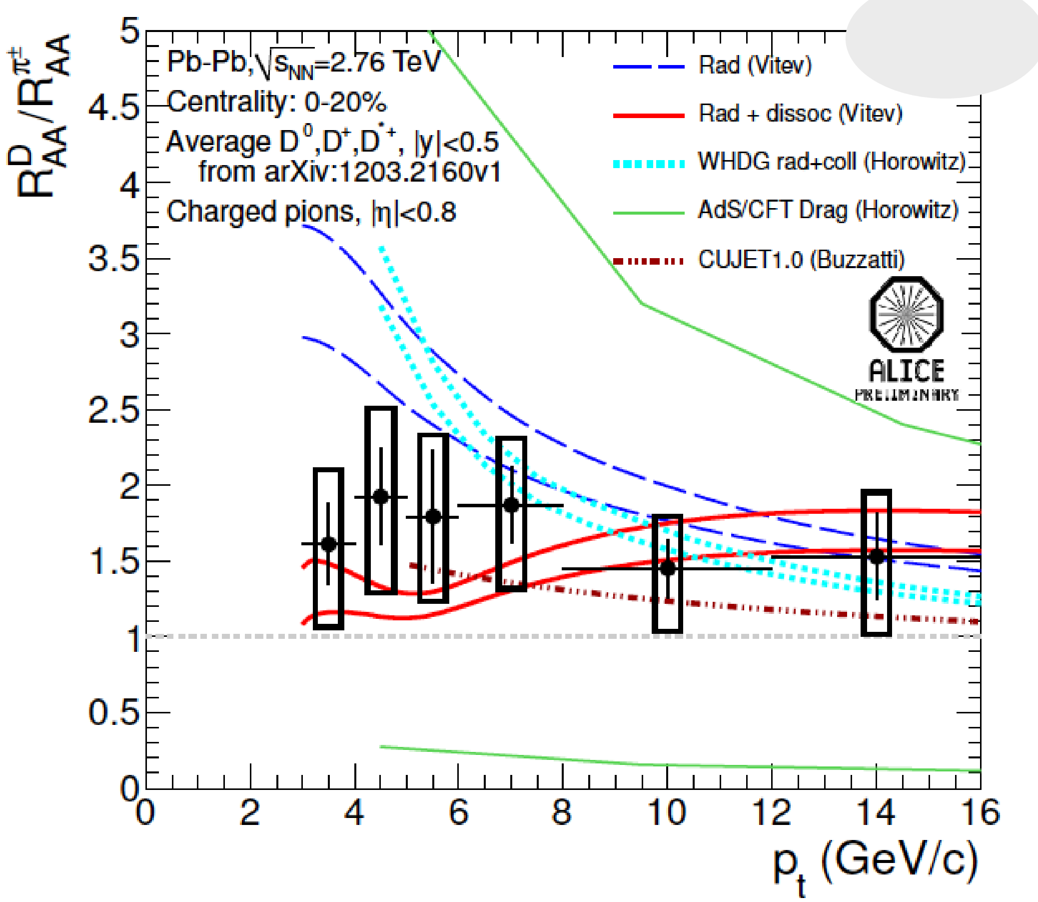
R_{AA} compilation





Charm and beauty: no evidence of mass effects yet (dead cone, ….)

Pions, charm and beauty RAA: similar. Hint of a hierarchy?



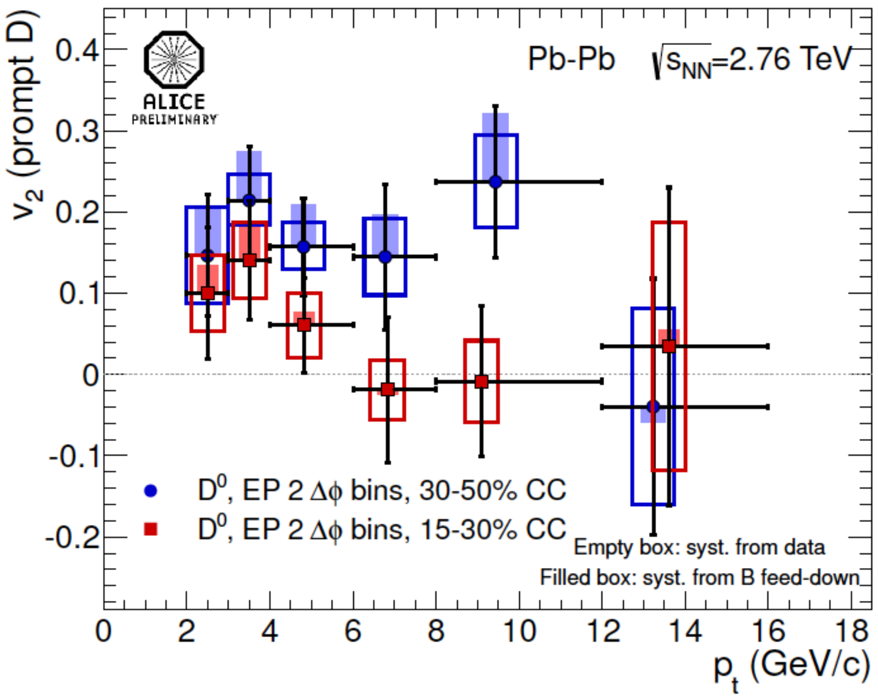
To compare charm mesons and pions → ratio of R_{AA}'s

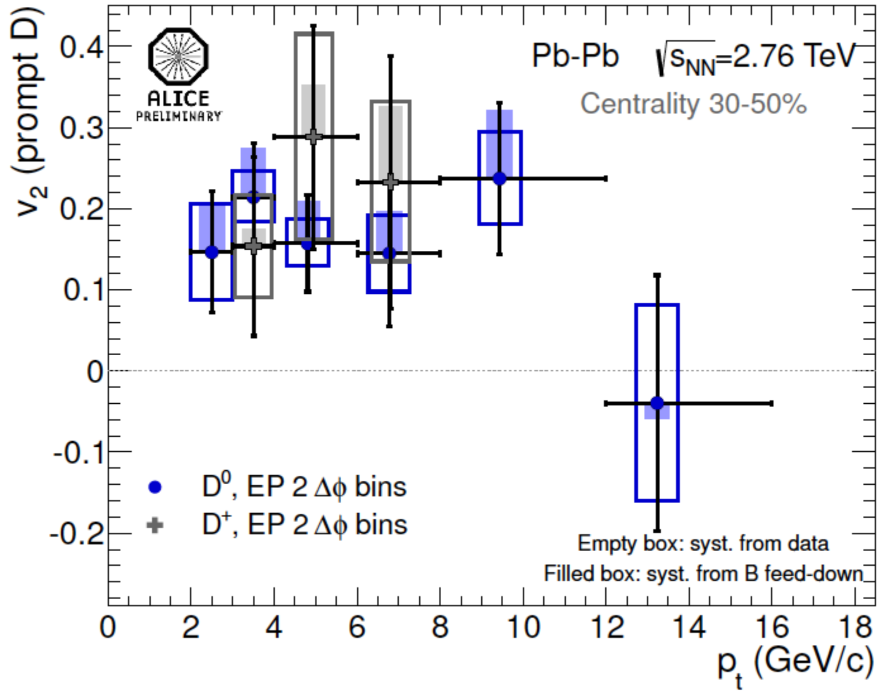
With the current uncertainties:

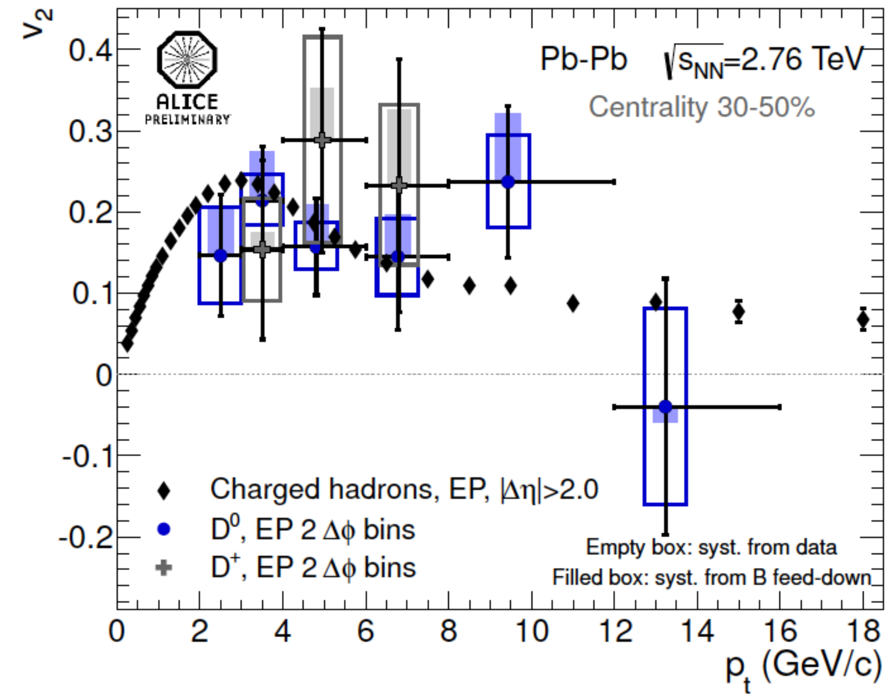
- Hint of R > 1
- Color charge effect?

Measurements are not yet conclusive → in reach for ALICE ! More precision !

Elliptic flow of D

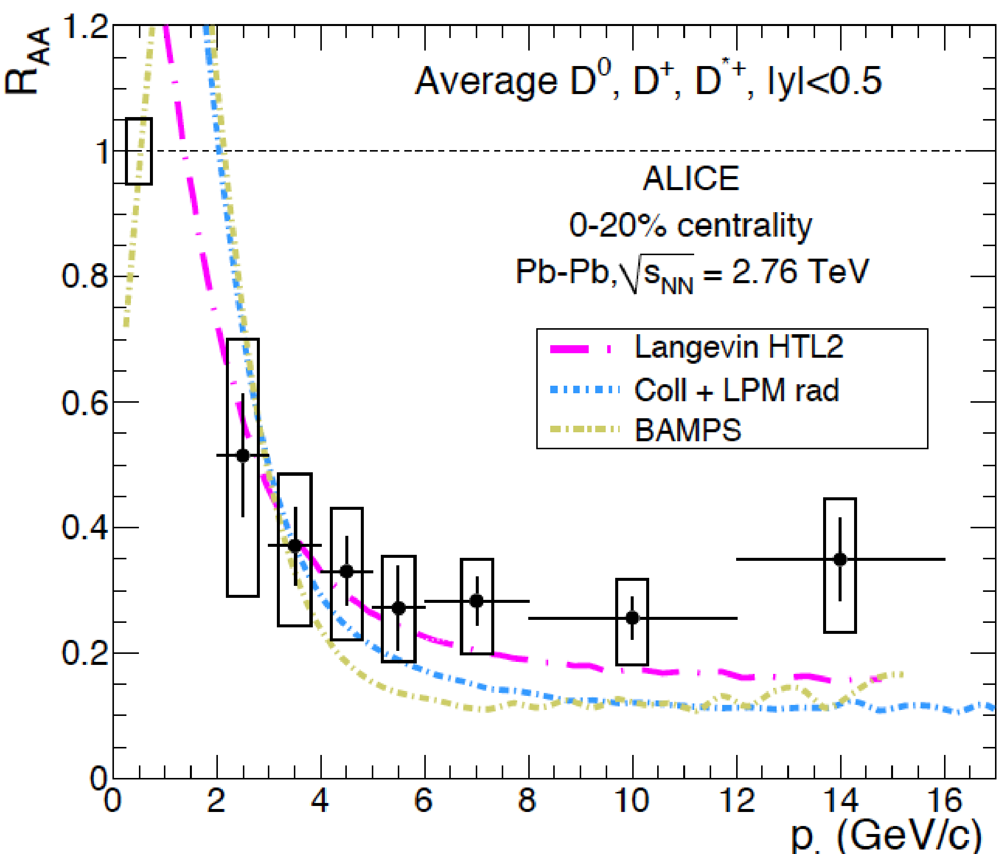


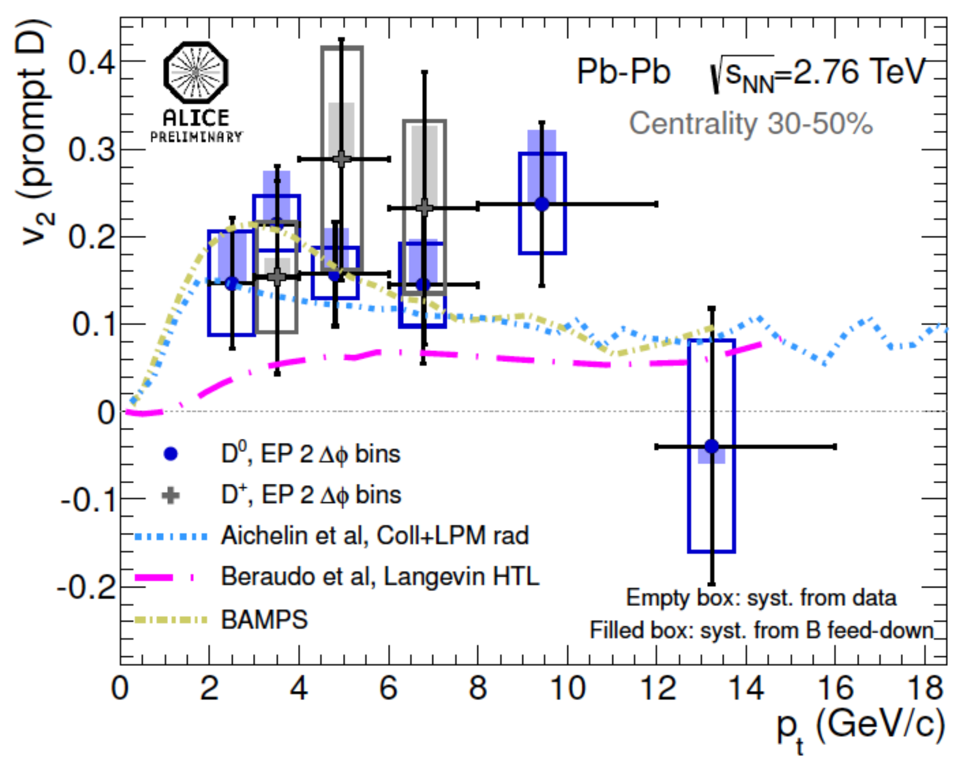




Hint of centrality dependence: D^0 v_2 flow larger in less central collisions

Comparable with charged hadrons elliptic flow





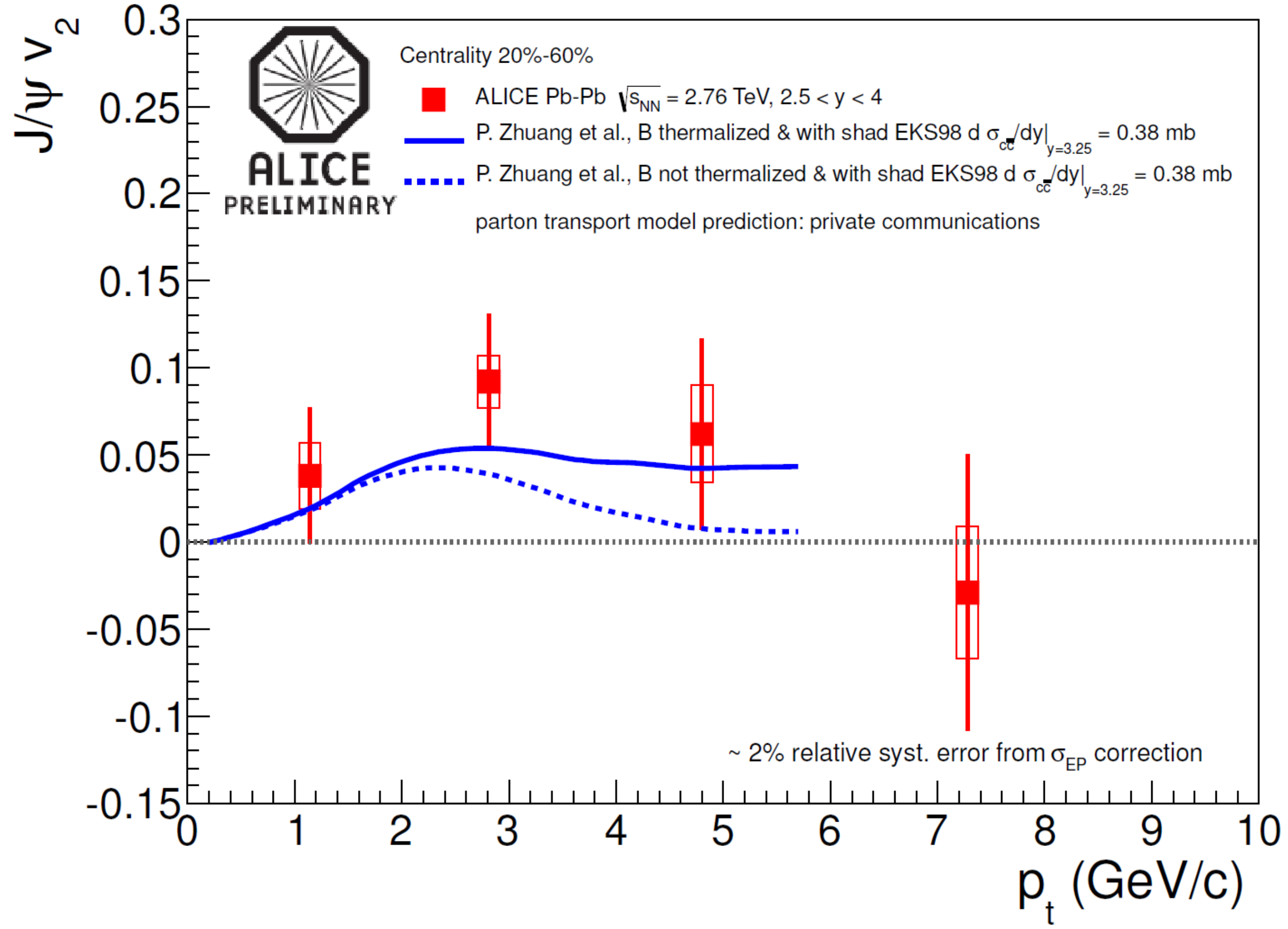
Challenge for the models: Describe both R_{AA} and v_2

J/ψ elliptic flow

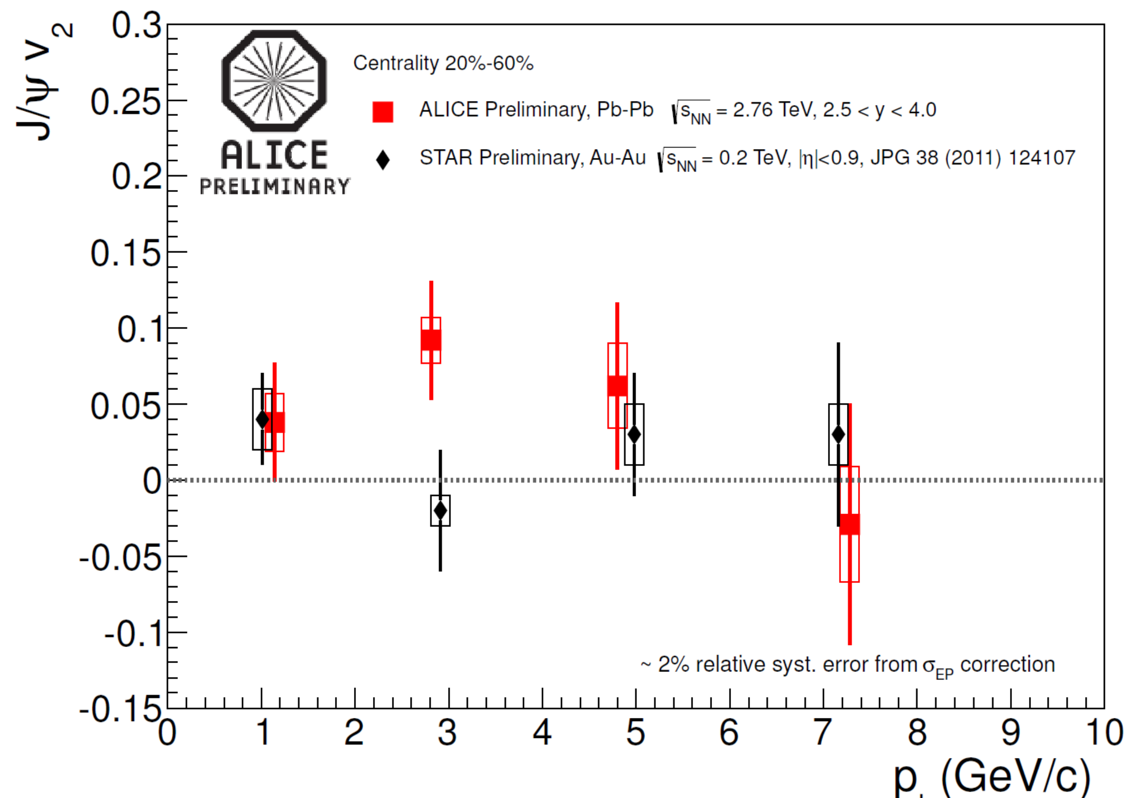
J/Ψ v_2 as a function pt for 20%-60% most central Pb-Pb collisions

Clear hint of non-zero J/Ψ v_2 at intermediate p_t (2-4 GeV/c): significance = 2.2 σ

Model prediction for v_2 shown here succeeds well at reproducing J/ψ R_{AA}.

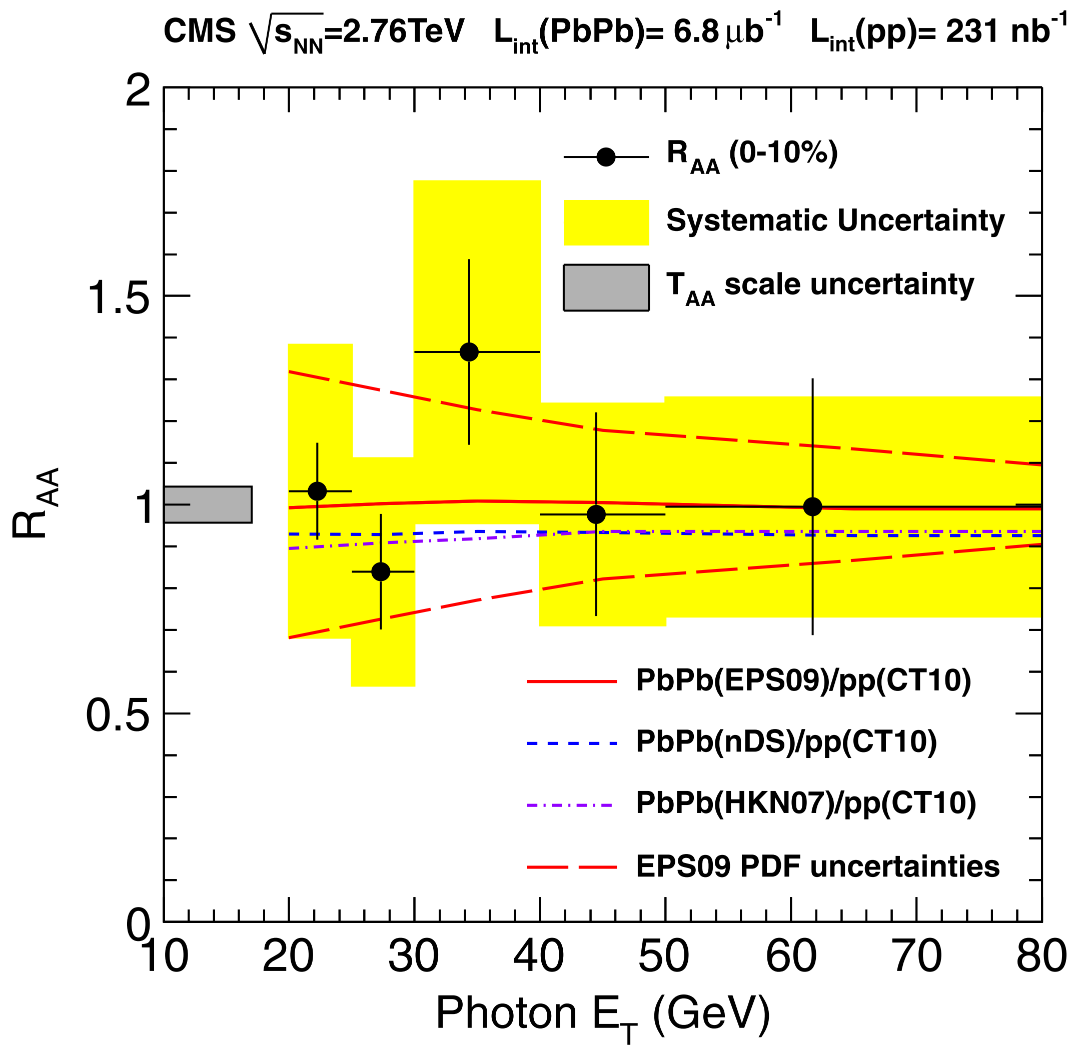


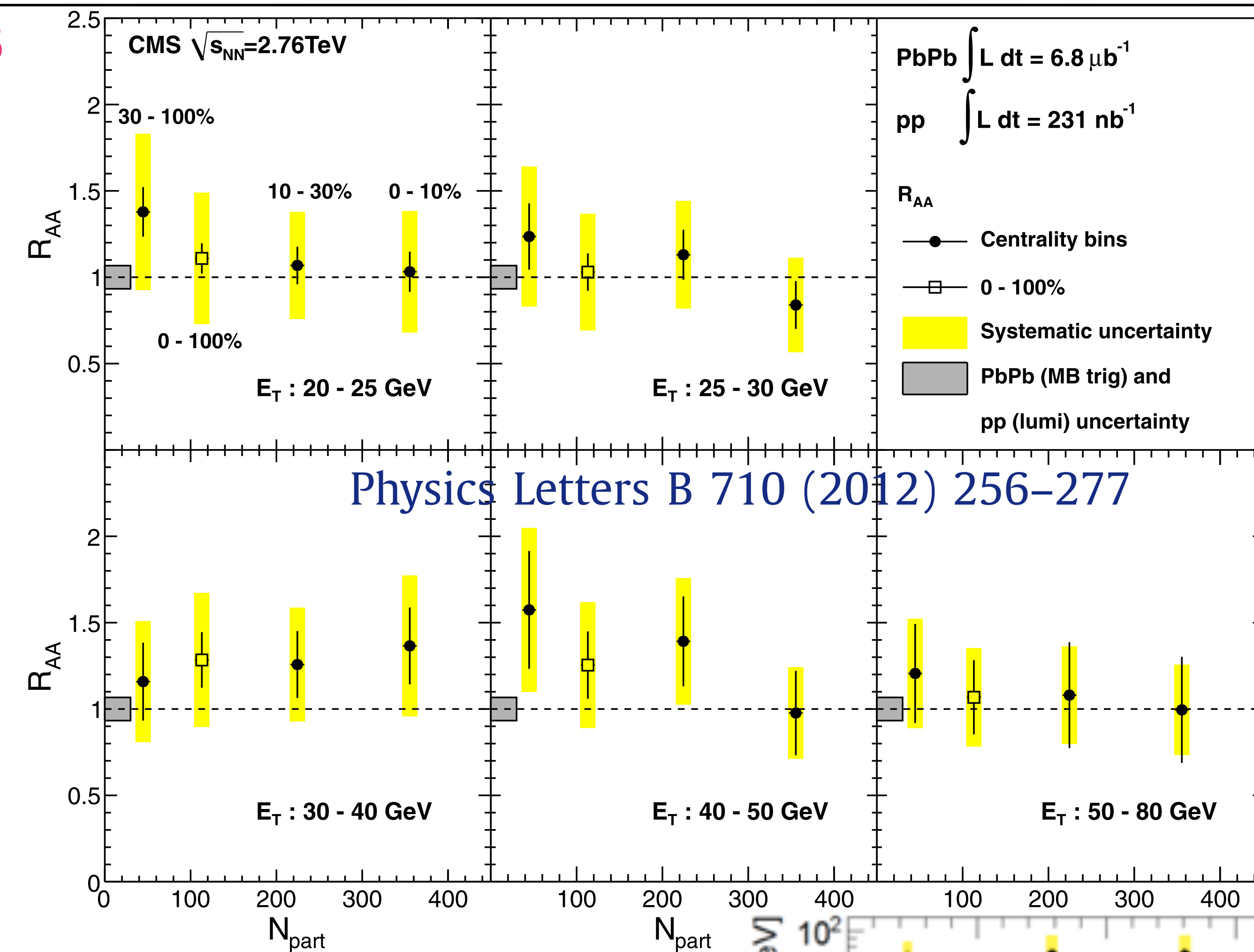
- Sensitive to transport properties, and production mechanisms
  - Primordial/Initial
    - pQCD: isotropic in phi.
  - Coalescence/Regeneration
    - Thermalized, flowing charm: large v2
      - Can light quarks move heavy quarks?



Measurement of isolated photon production in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV ☆

CMS



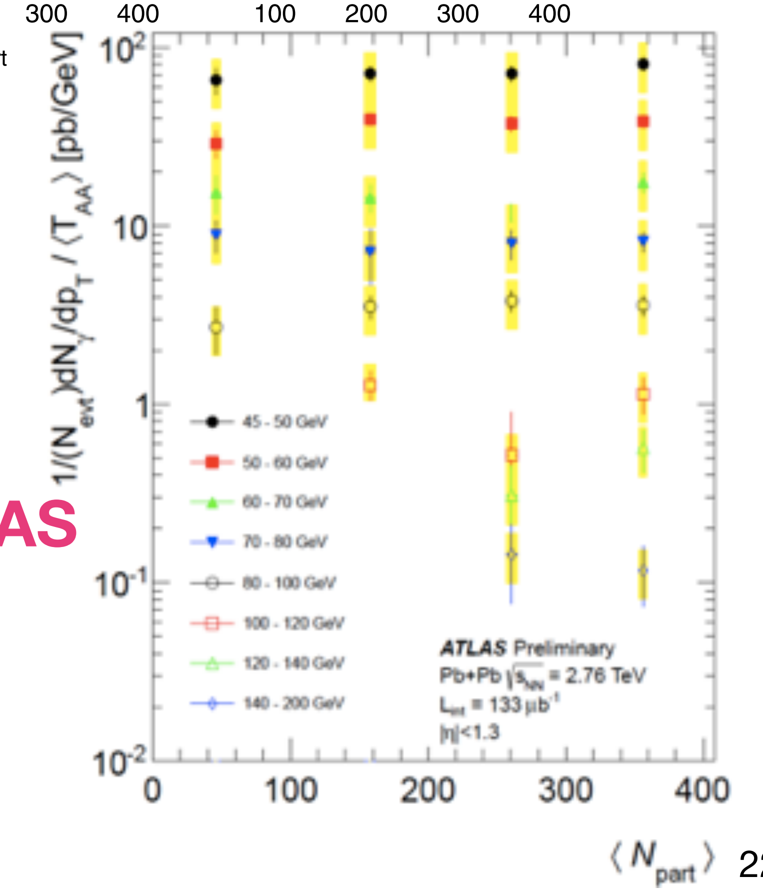


Physics Letters B 710 (2012) 256–277

Photons are unmodified

- 20-30% uncertainty in PbPb (background modeling + energy scale)
- 15% uncertainty in pp (same sources)

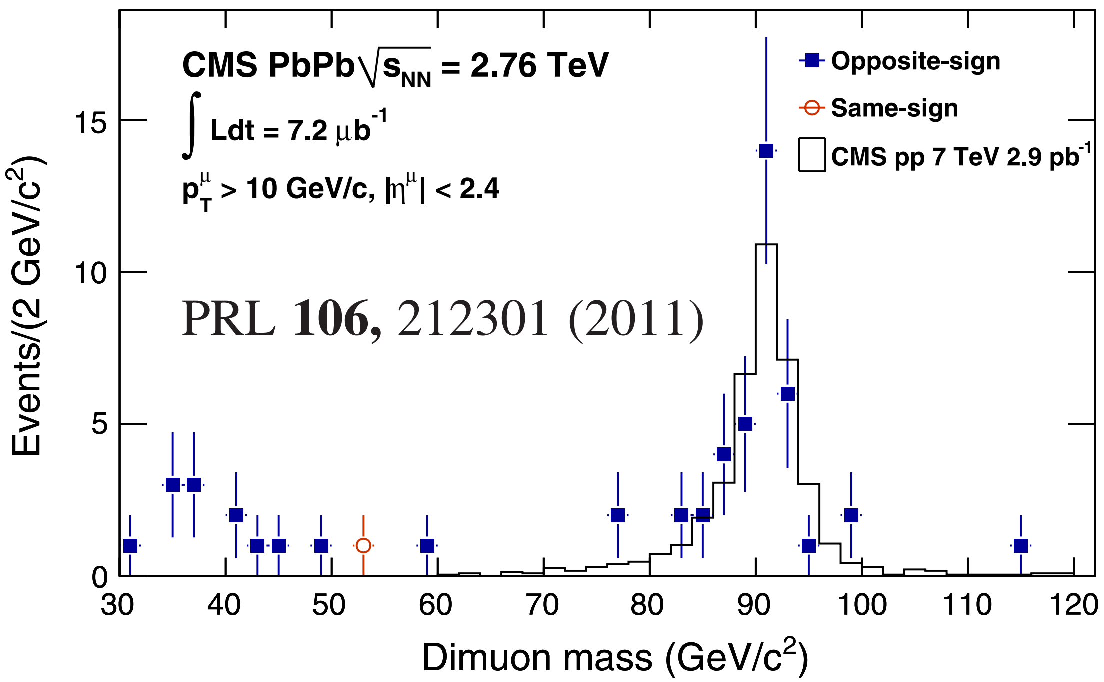
ATLAS



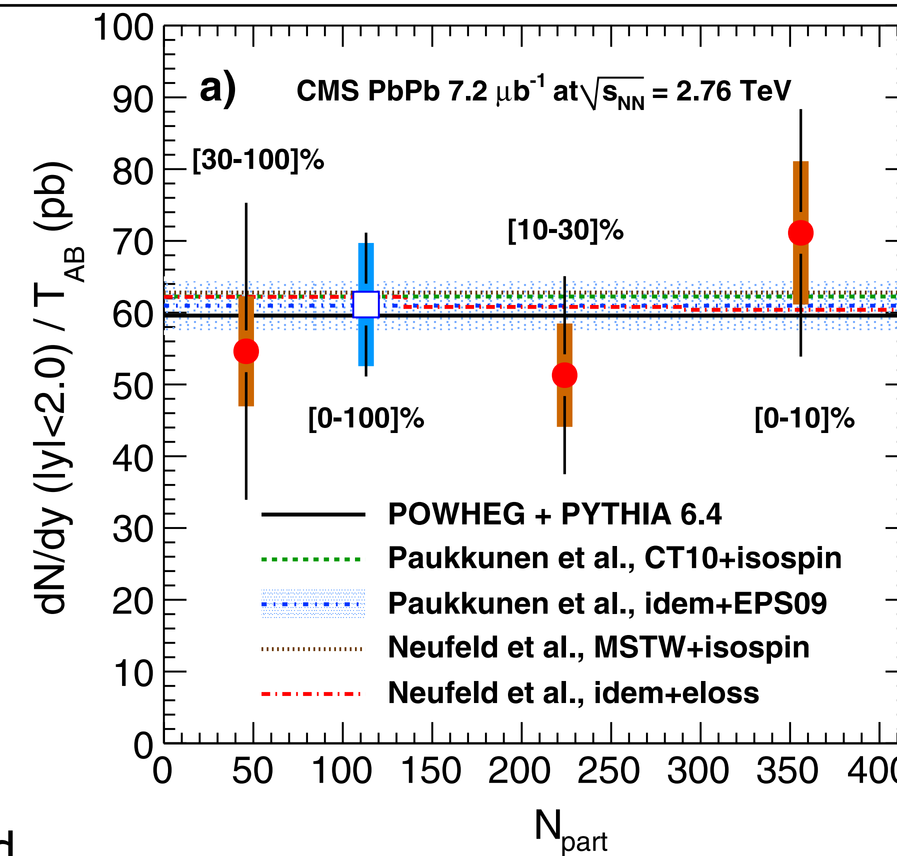
❖ But also for as a function of centrality (Npart) in photon E_T bins

Establish a baseline for further analyses with isolated photons

Study of Z Boson Production in PbPb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV



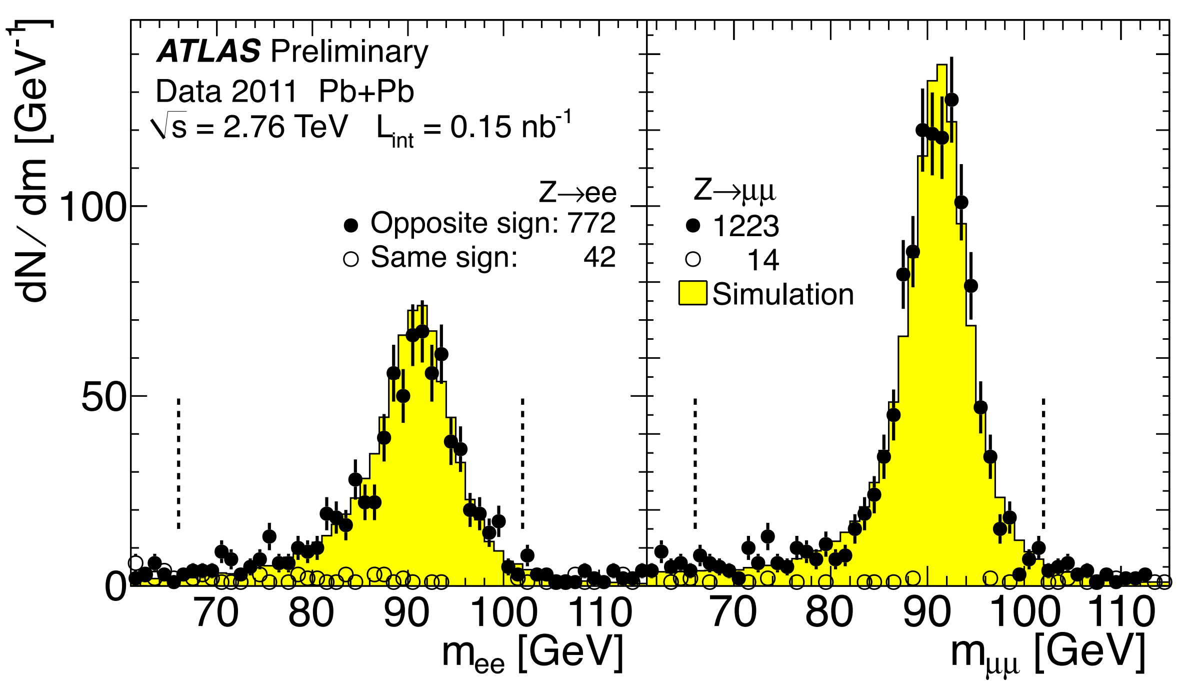
CMS



No dependence with centrality observed.

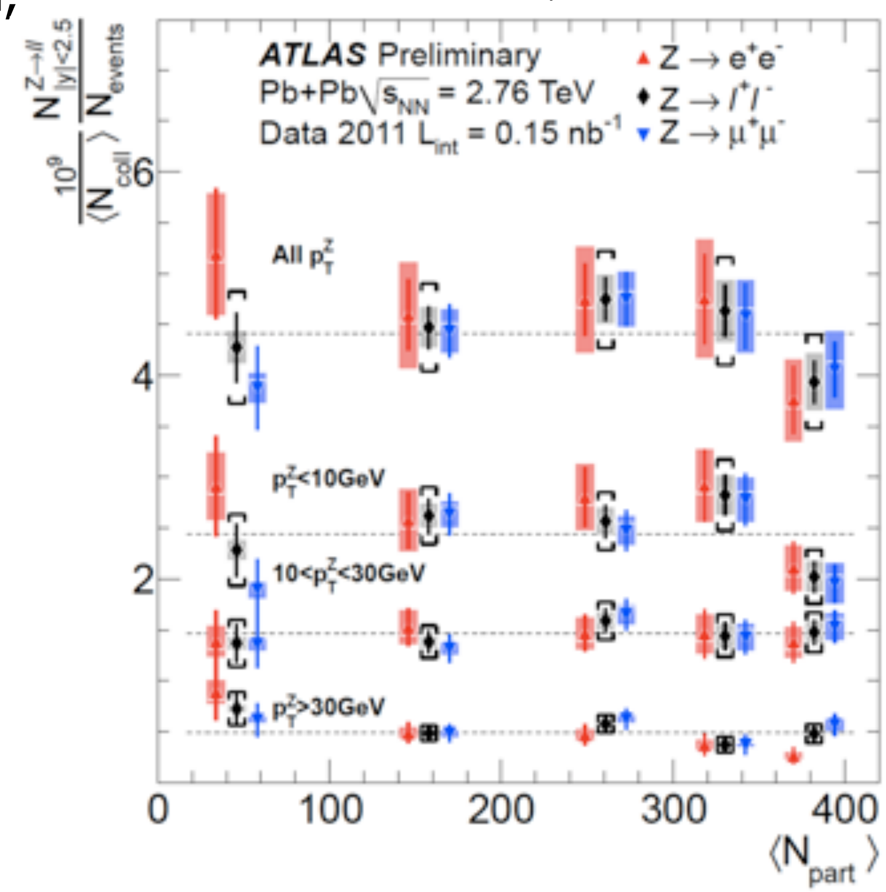
Within uncertainties, no violation of binary NN collision scaling is observed,

➡ R_{AA}=1.00±0.16±0.14 referred to pp from Powheg.



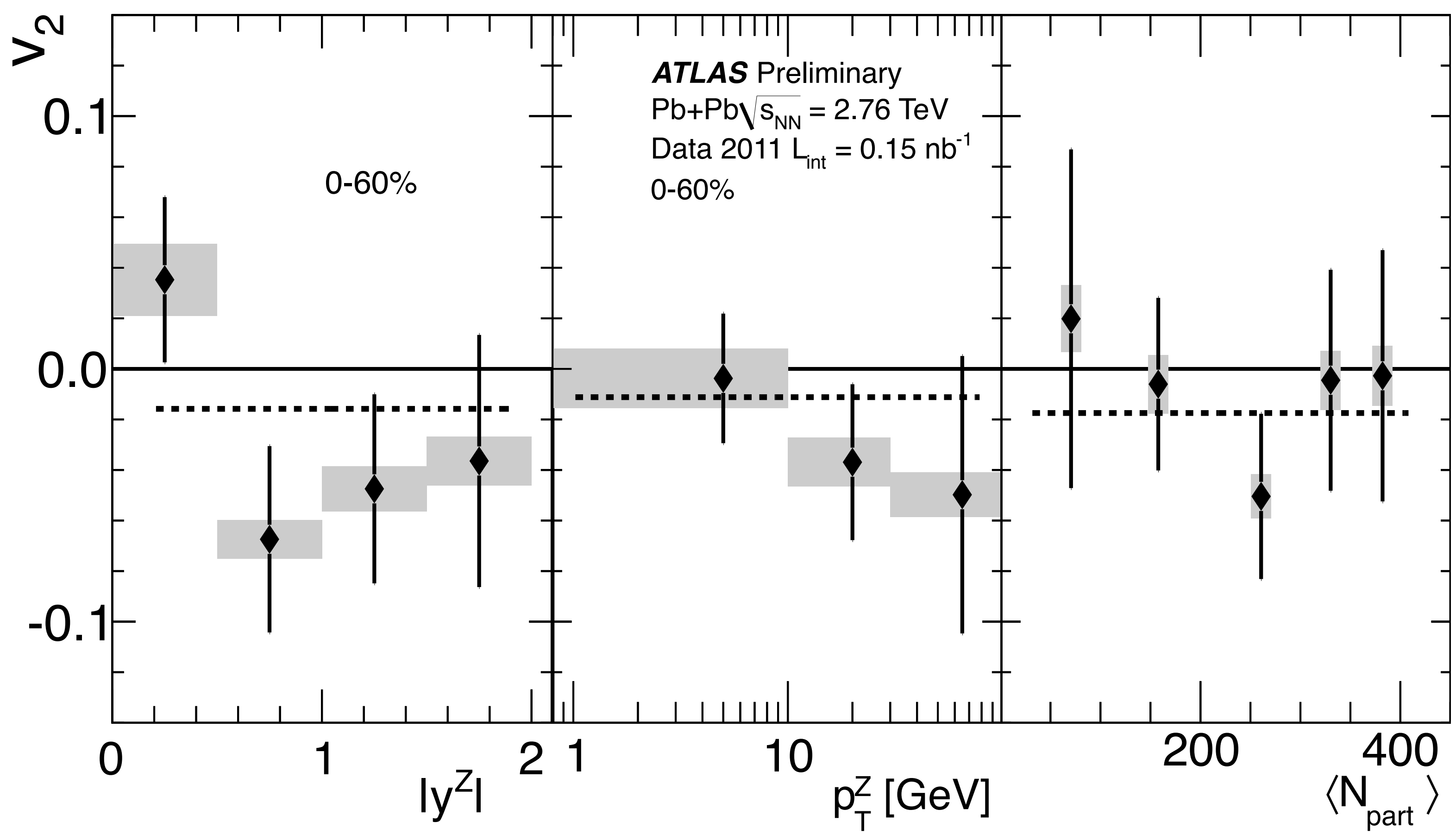
ATLAS-CONF-2012-052

ATLAS



Consistent with unity for all measured points

Elliptic flow of Z



v_2 = −0.011 ± 0.018(stat.) ± 0.014(sys.)

Z elliptic flow is consistent with zero

$W^{\pm} \to \mu^{\pm} \nu$

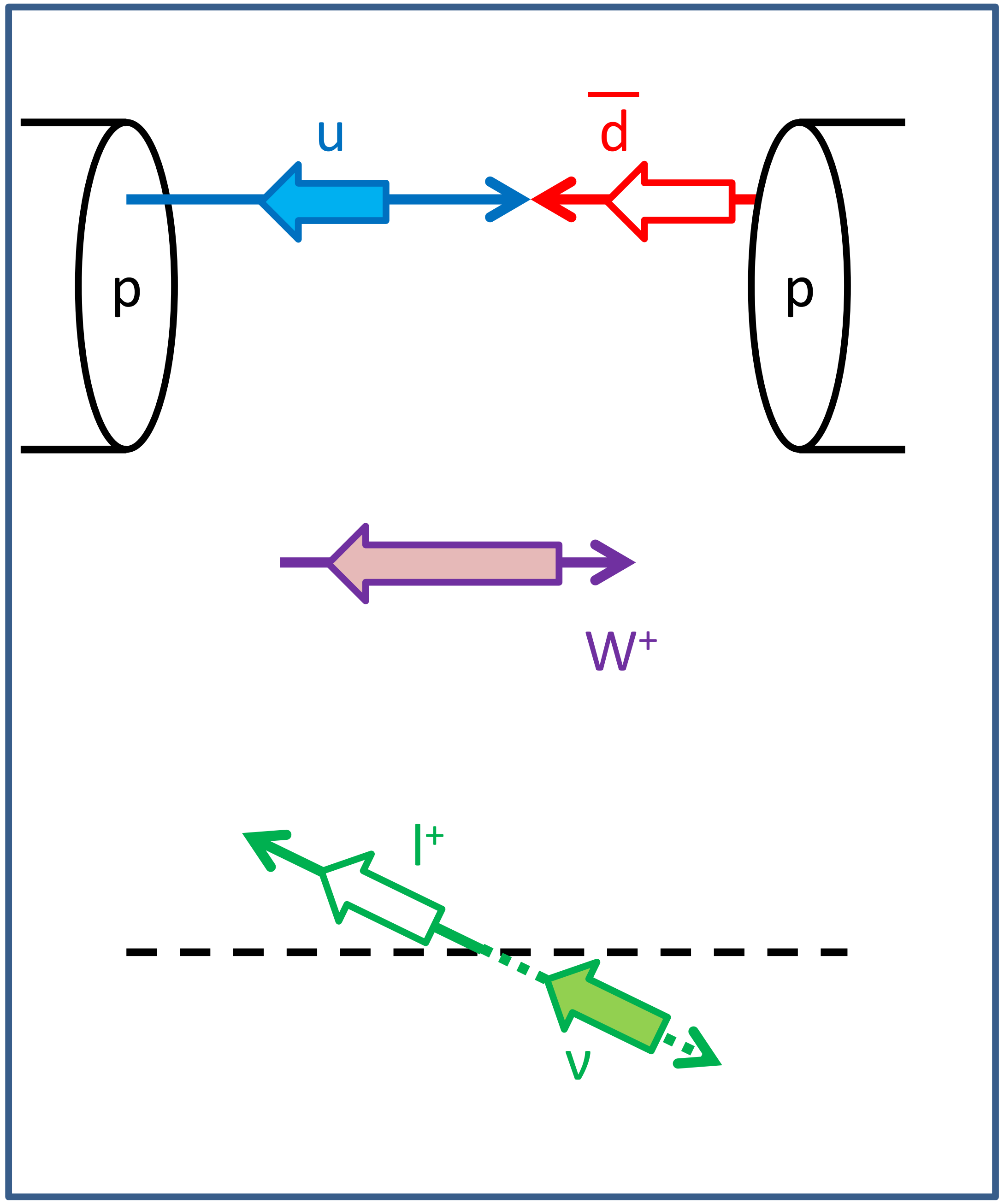
Different yields expected for $W^{+} \to \mu^{+} \nu$ and $W^{-} \to \mu^{-} \nu$

- W production: At LO, W bosons are produced by fusion of a valence quark and an antiquark from the sea: $u\bar{d} \to W^{+}$ and $\bar{u}d \to W^{-}$
  ➔ W is boosted in valence quark direction

➔ Different phase space (rapidity) for W^{+} and W^{-}

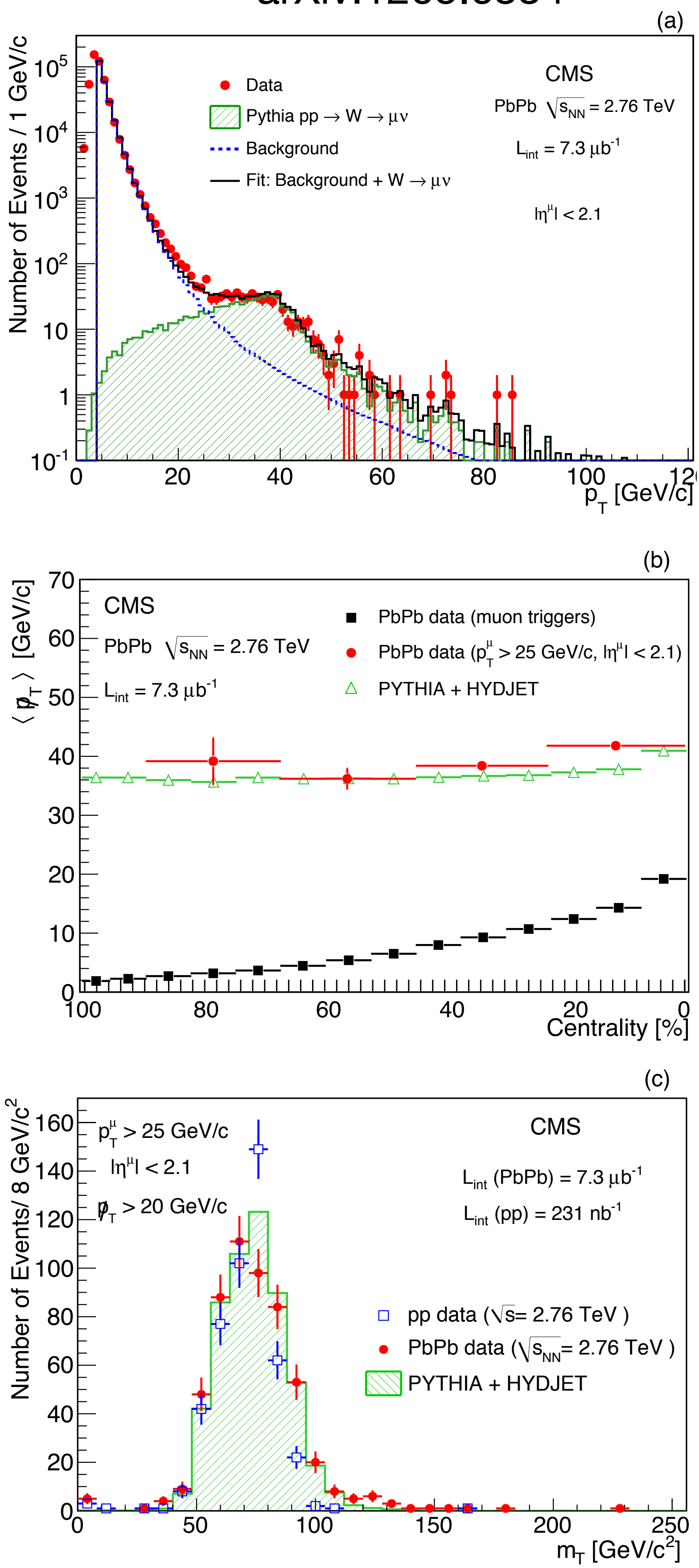
- $W^{\pm}$ decay into lepton+neutrino is not charge symmetric, due to V-A EWK coupling (ν lefthanded)
  ➔ different angular distributions for decay μ^{+} and μ^{-}

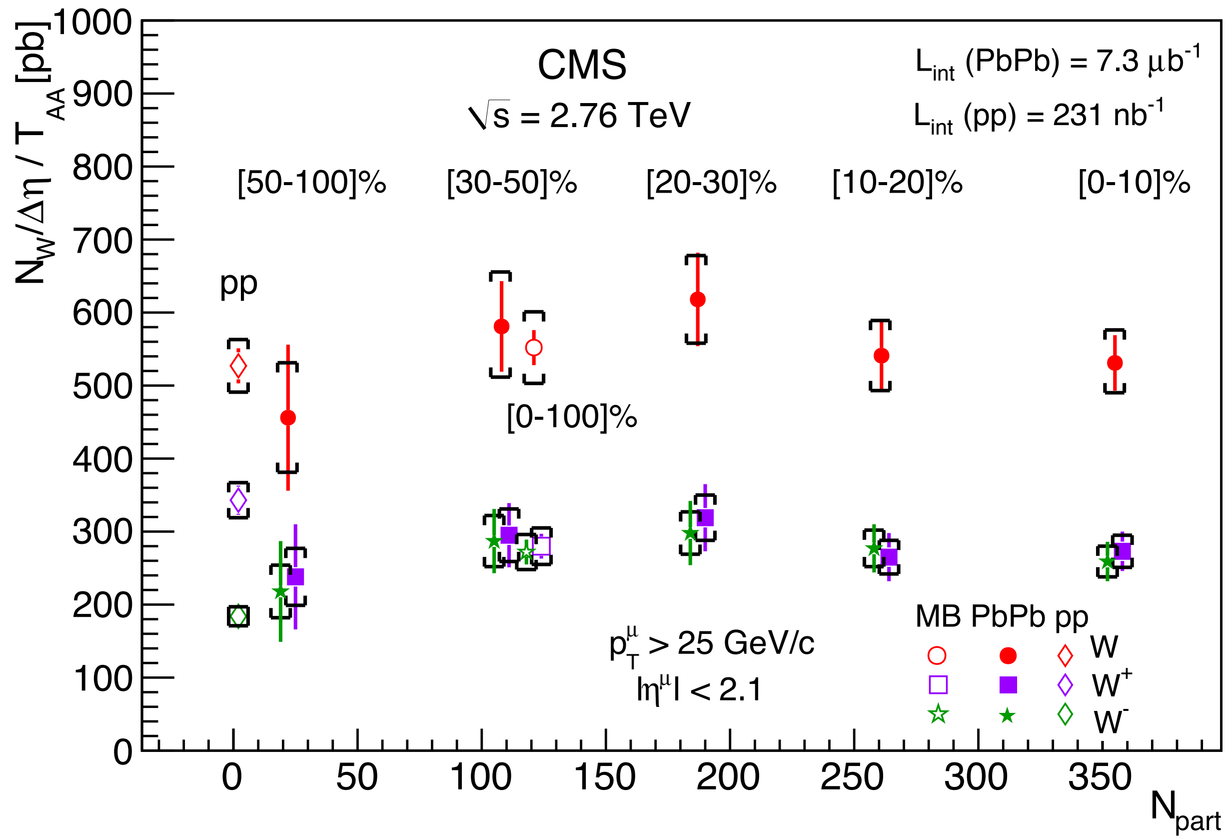
- Strong isospin effect since Pb has higher d/u than proton
  - Cancels for W^{+} + W^{-}

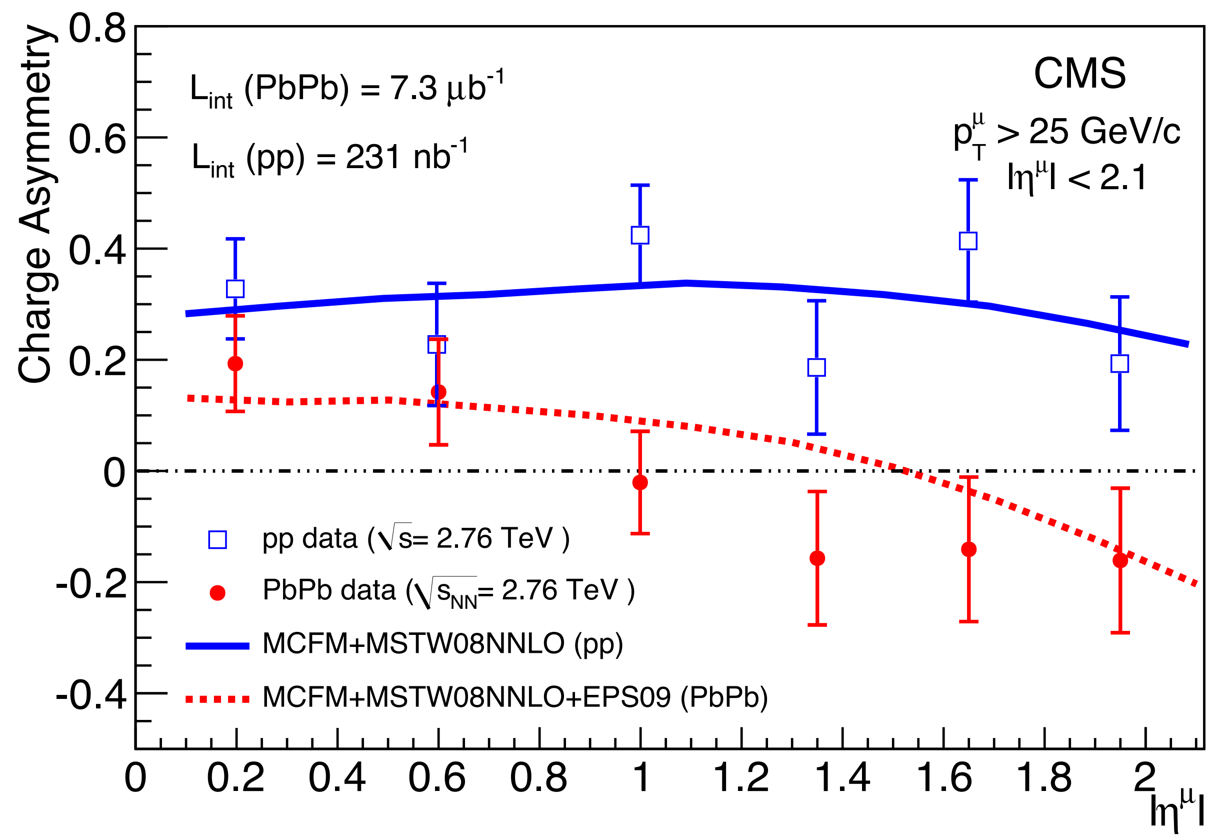


$W^{\pm} \rightarrow \mu^{\pm}\nu$

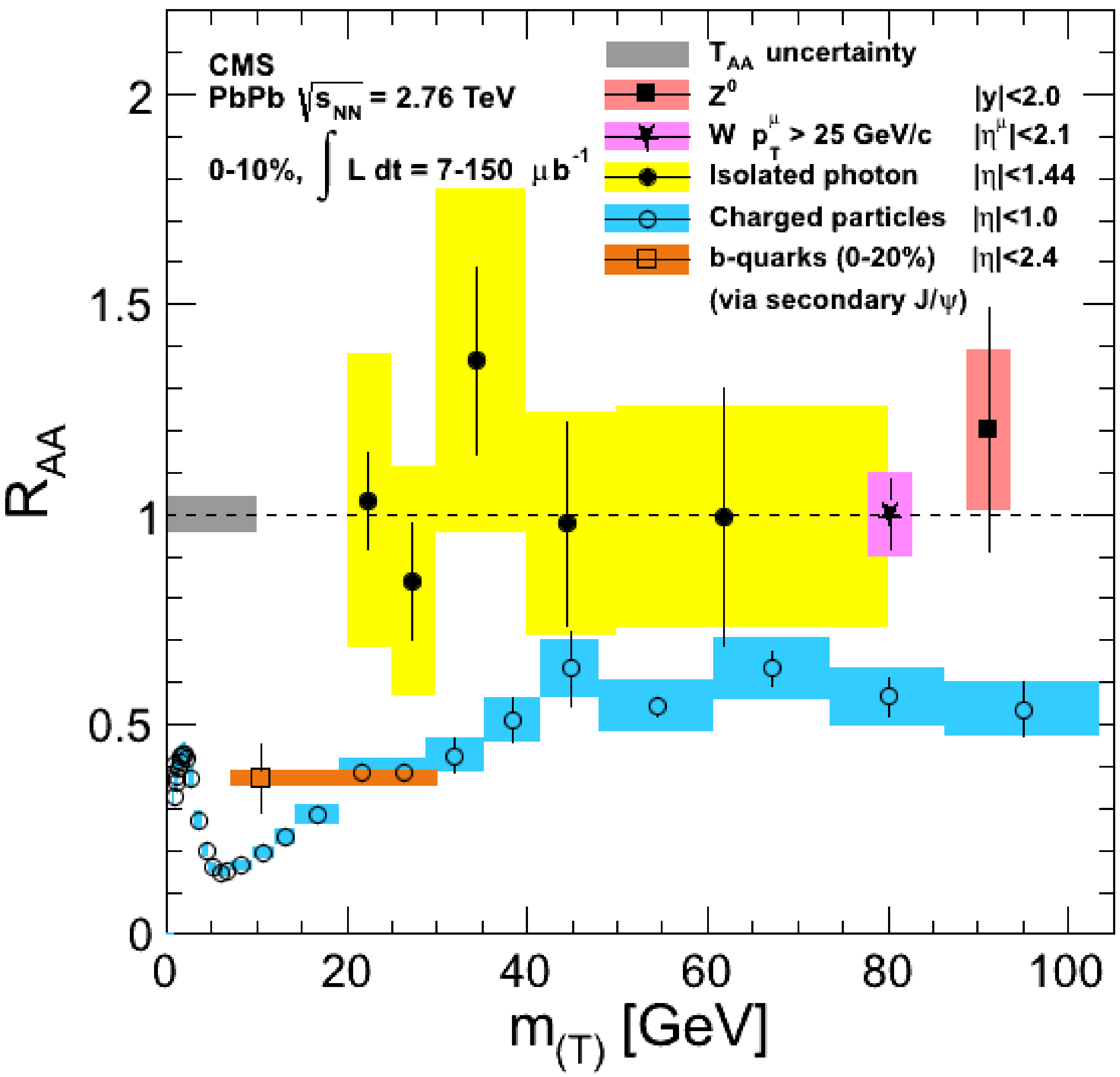
arXiv:1205.6334







Photon, W, Z R_{AA}



Production of Photon, W and Z bosons in PbPb collisions, scale with the number of binary NN interactions.

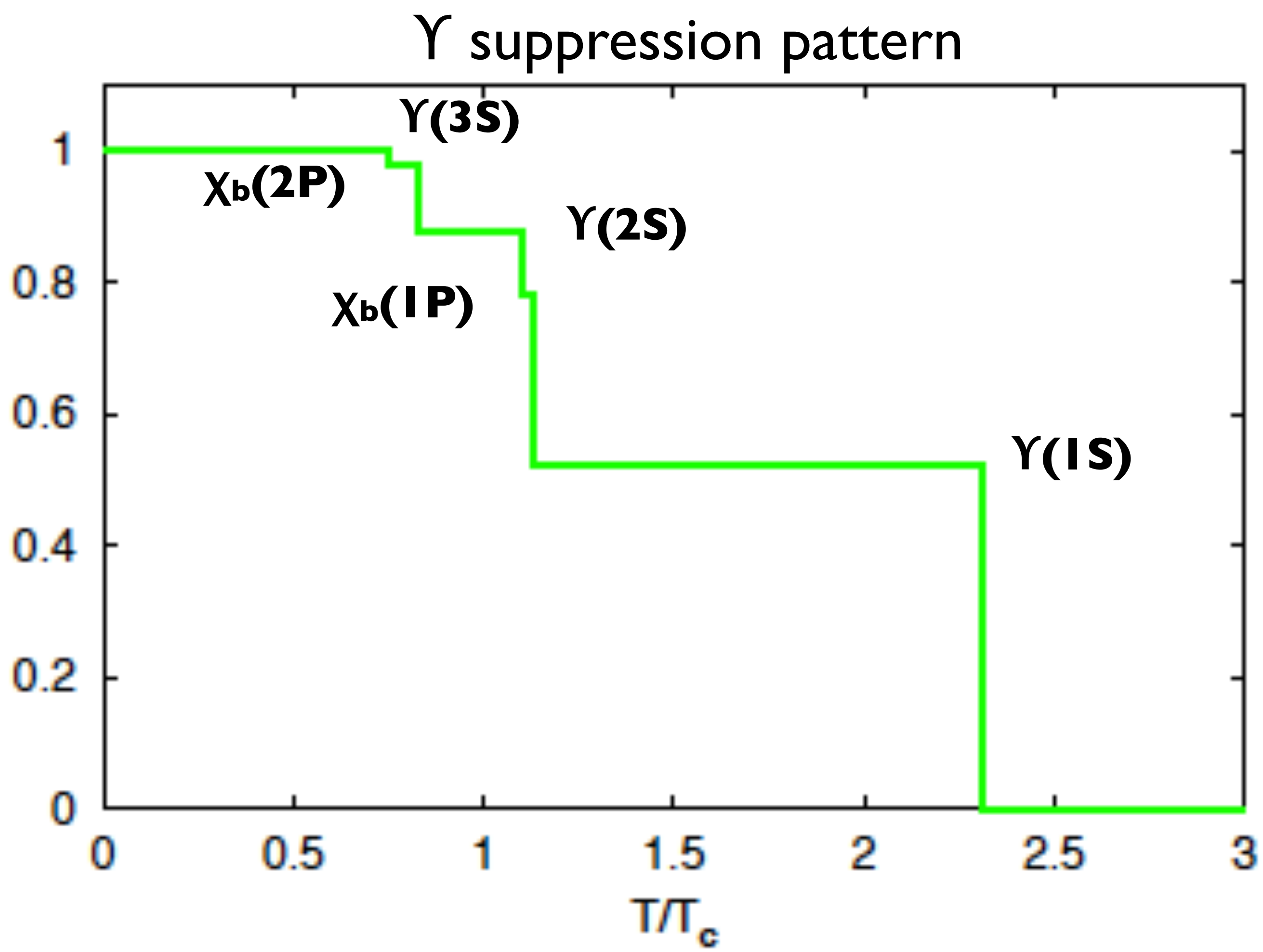
$R_{AA} \approx 1$ (10-20% uncertainty)

Carriers of the electromagnetic and the weak force, their production and propagation in the medium results unaltered, for the region of mass/p_T ~100 GeV/c …..

….. unlike other particles (strongly interacting hadrons and mesons) whose production in PbPb is strongly suppressed relative to pp.

Backup Slides

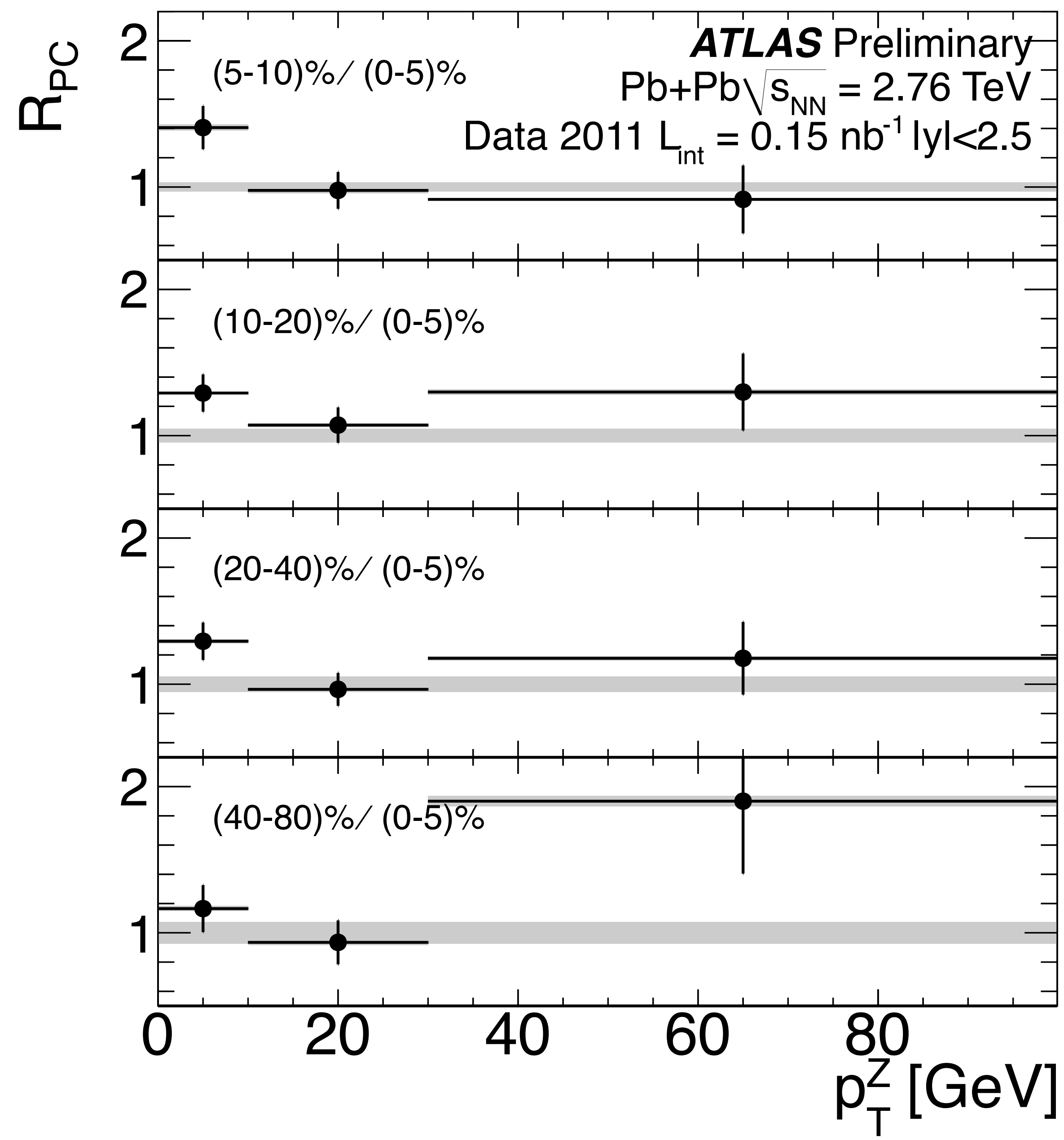
Feed-down fraction from the excited states



state	$f_i(p\bar{p})$ [%]
$\Upsilon(1S)$	52 ± 9
$\chi_b(1P)$	26 ± 7
$\Upsilon(2S)$	10 ± 3
$\chi_b(2P)$	10 ± 7
$\Upsilon(3S)$	2 ± 0.5

feed-down fraction from excited states

S.Digal et al
PRD 64, 2001

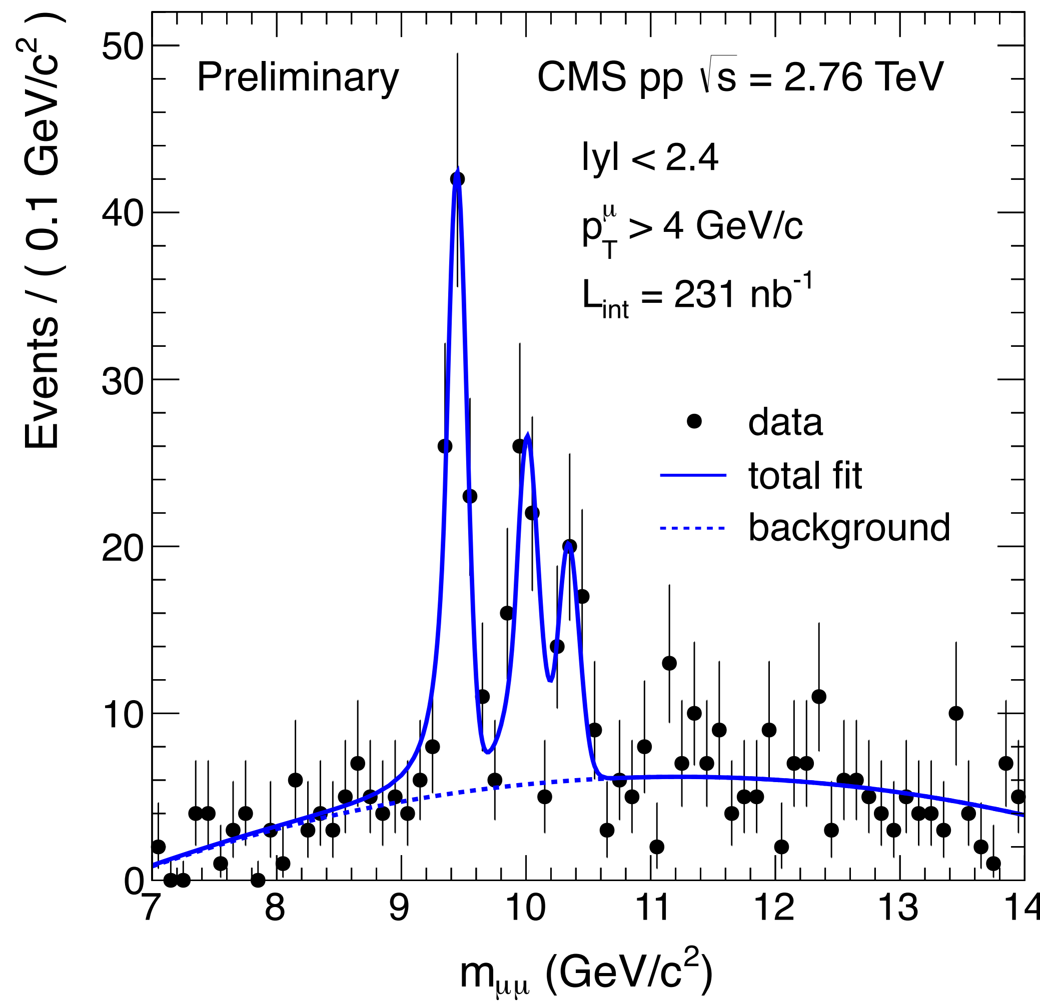

ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
Data 2011 L_{int} = 0.15 nb^{-1} |y|<2.5
R_{PC}
(5-10)%/ (0-5)%
(10-20)%/ (0-5)%
(20-40)%/ (0-5)%
(40-80)%/ (0-5)%
p_T^Z [GeV]

Υ(nS) yield extraction: pp

- **Unbinned max likelihood fit**
- **Signal**
  - ➡ 3 Crystal-ball: Gaussian core & power law tail

$$f_{CB}(m) = \begin{cases} \frac{N}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(m-m_0)^2}{2\sigma^2}\right), & \text{for } \frac{m-m_0}{\sigma} > -\alpha; \\ \frac{N}{\sqrt{2\pi}\sigma} \left(\frac{n}{|\alpha|}\right)^n \exp\left(-\frac{|\alpha|^2}{2}\right) \left(\frac{n}{|\alpha|} - |\alpha| - \frac{m-m_0}{\sigma}\right)^{-n}, & \text{for } \frac{m-m_0}{\sigma} \leq -\alpha. \end{cases}$$

  - ➡ Free parameters:
    - yield, resolution and mass for Υ(1S)
    - yield ratios: Υ(2S+3S)/Υ(1S), Υ(2S)/Υ(1S)
    - tail parameter, α (transition Gaussian→power-law)
  - ➡ Fixed parameters:
    - n (MC), exponent for tail description
    - resolution forced to scale with PDG mass ratios
- **Background**
  - ➡ 2nd order polynomial
    - Free parameters: all



<u>Raw ratios</u>
<u>(no acceptance or efficiency corrected)</u>

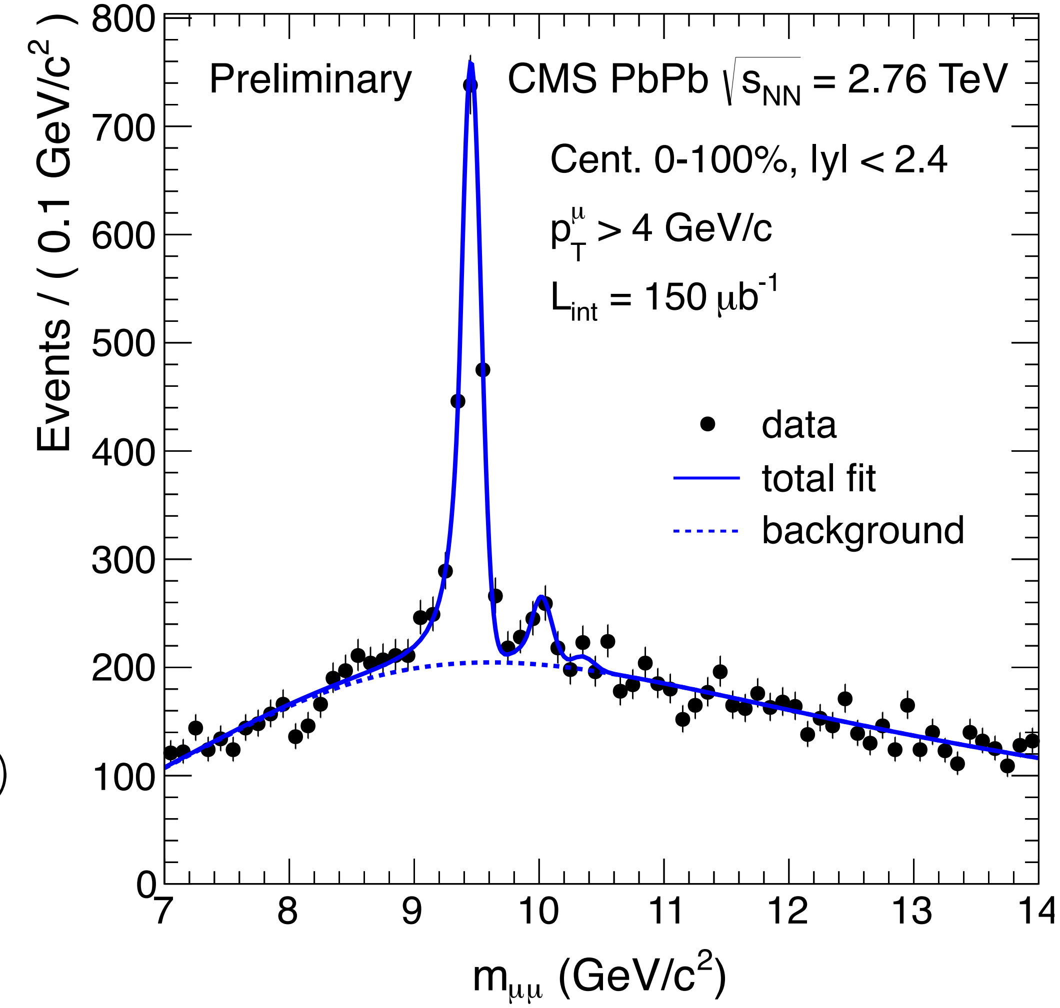
$$\frac{\Upsilon(2S)}{\Upsilon(1S)}\Big|_{pp} = 0.56 \pm 0.13 \pm 0.01$$

$$\frac{\Upsilon(3S)}{\Upsilon(1S)}\Big|_{pp} = 0.41 \pm 0.11 \pm 0.02$$

Υ(nS) yield extraction: PbPb

- Unbinned max likelihood fit
- **Signal (same as for pp)**
  - 3 Crystal-ball: Gaussian core & power law tail
  - Free parameters:
    - yield, resolution and mass for Υ(1S)
    - yield ratios: Υ(2S+3S)/Υ(1S), Υ(2S)/Υ(1S)
    - tail parameter, α (transition Gaussian→power-law)
  - Fixed parameters:
    - n (MC), exponent for tail description
    - resolution forced to scale with PDG mass ratios
- **Background** ('shoulder'-like structure)
  - exponential x error function
  - Free parameters: all
    - exponential decay constant
    - error fct shoulder mean and width

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}\, dt$$



<u>Raw ratios (0-100%)</u>
<u>(no acceptance or efficiency corrected)</u>

$$\frac{\Upsilon(2S)}{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$$

$$\frac{\Upsilon(3S)}{\Upsilon(1S)}|_{PbPb} < 0.07\ (95\% C.L.)$$