ALICE results on quarkonium hadroproduction

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IPN Orsay

on behalf of the ALICE Collaboration

Heavy Ion Forum
CERN June 3rd 2013

ALICE results on quarkonium hadroproduction

- Probing the Quark-Gluon Plasma with quarkonia
- Detection of quarkonium states with the ALICE experiment
- pp measurements (reference): J/Ψ, Ψ’ and Υ
- Pb-Pb measurements: J/Ψ, Ψ’ and Υ
- p-Pb measurements (cold nuclear matter effect): J/Ψ

Probing the QGP with quarkonia: from suppression...

Properties of quarkonium states

- produced in the initial hard partonic collisions ($\tau \simeq 1/ m_Q \simeq 0.05$-$0.15$ fm/c)
- stable and tightly bound: $M_{ccbar} < 2\ M_D$ and $M_{bbbar} < 2\ M_B$

spectroscopy in non-relativistic potential theory

Satz JoP G32(2006)

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

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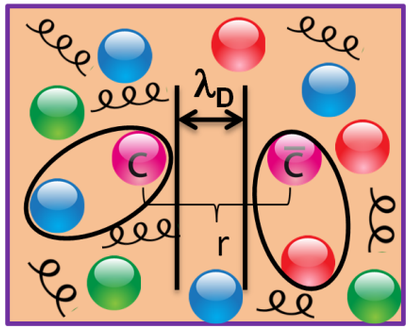
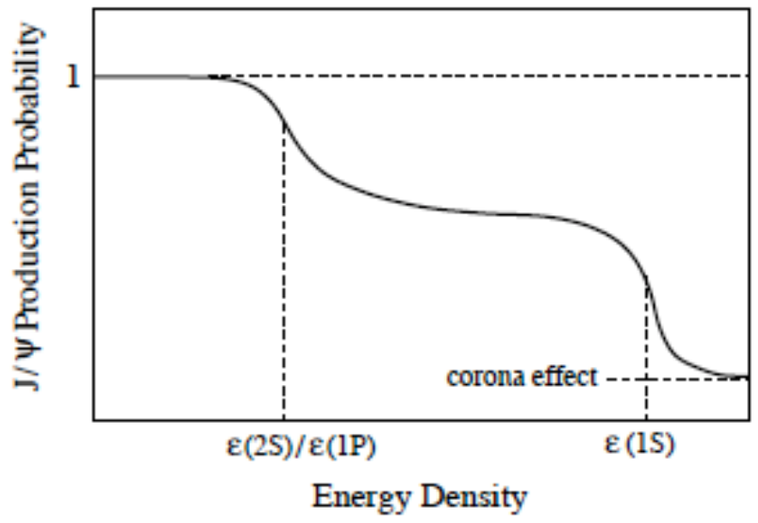
In ultra-relativistic heavy ion collisions, at T >> 0 , Debye screening induced by the high density of colour charges of the medium

- melting of quarkonia at high $T=T_D$ for a Debye screening radius $\lambda_D <$ quarkonium radius r *Matsui, Satz PLB178(1986)*
- as binding energy different → sequential suppression of quarkonium states *Digal et al. PRD64(2001)*



prompt J/Ψ ≃ 60% direct J/Ψ + 30% χ_C + 10% Ψ(2S)



... to regeneration

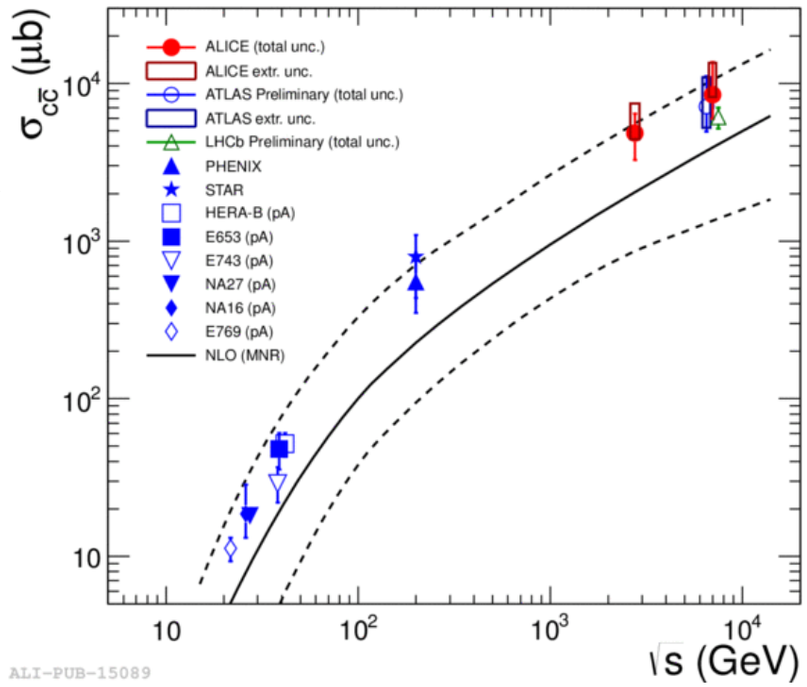
Regeneration of charmonia

- total charm cross-section increases with energy
- c and cbar combination in the QGP phase → regeneration of charmonia *Braun-Munzinger, Stachel PLB490(2000)* *Thews et al. PRC62(2000)*
- no regeneration expected for bottomonia

$$\frac{N_{q\bar{q}}}{event} = \frac{\sigma^{pp}_{q\bar{q}}}{\sigma^{pp}_{inel}} \times N_{coll}$$

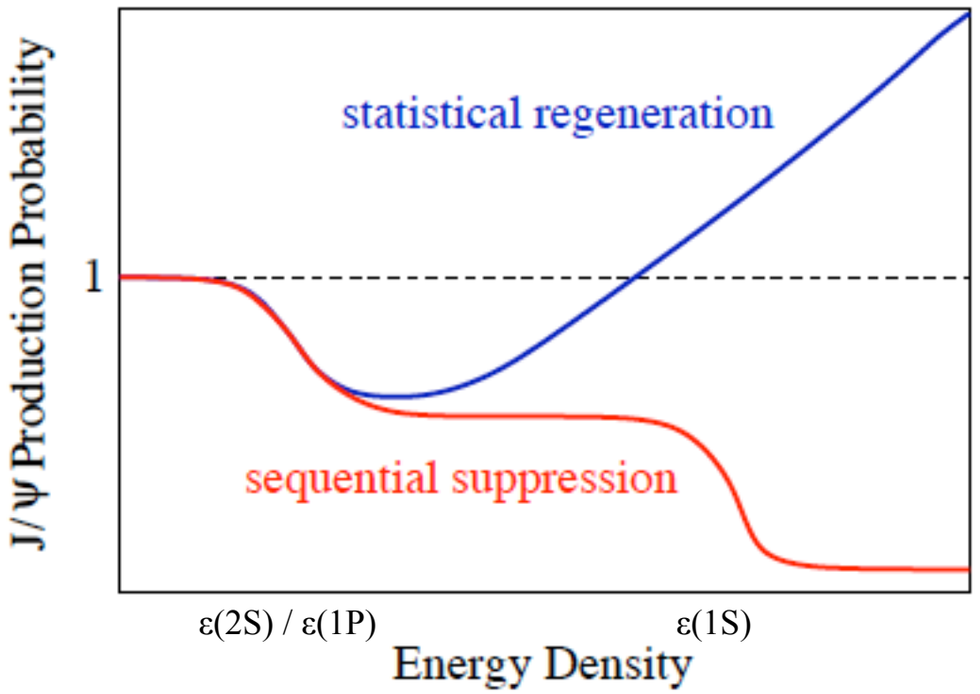
In most central collisions [0-10%]	RHIC 200 GeV	LHC 2.76 TeV
N_{ccbar}/event	13	115
N_{bbbar}/event	0.1	3

ALICE Coll. JHEP 1207 (2012) 191



Implication of regeneration

- enhancement of J/ψ
- charmonium states not anymore a QGP thermometer from sequential suppression
- evidence of thermalization of charm quarks
- J/ψ inherit of charm elliptic flow



Observables

Nuclear modification factor

$$R_{AA} = \frac{dN^{AA}/dp_T dy}{\langle N_{coll} \rangle \, dN^{pp}/dp_T dy}$$

Hard processes: scale with N_{coll}

- $R_{AA} > 1$: enhancement
- $R_{AA} < 1$: suppression

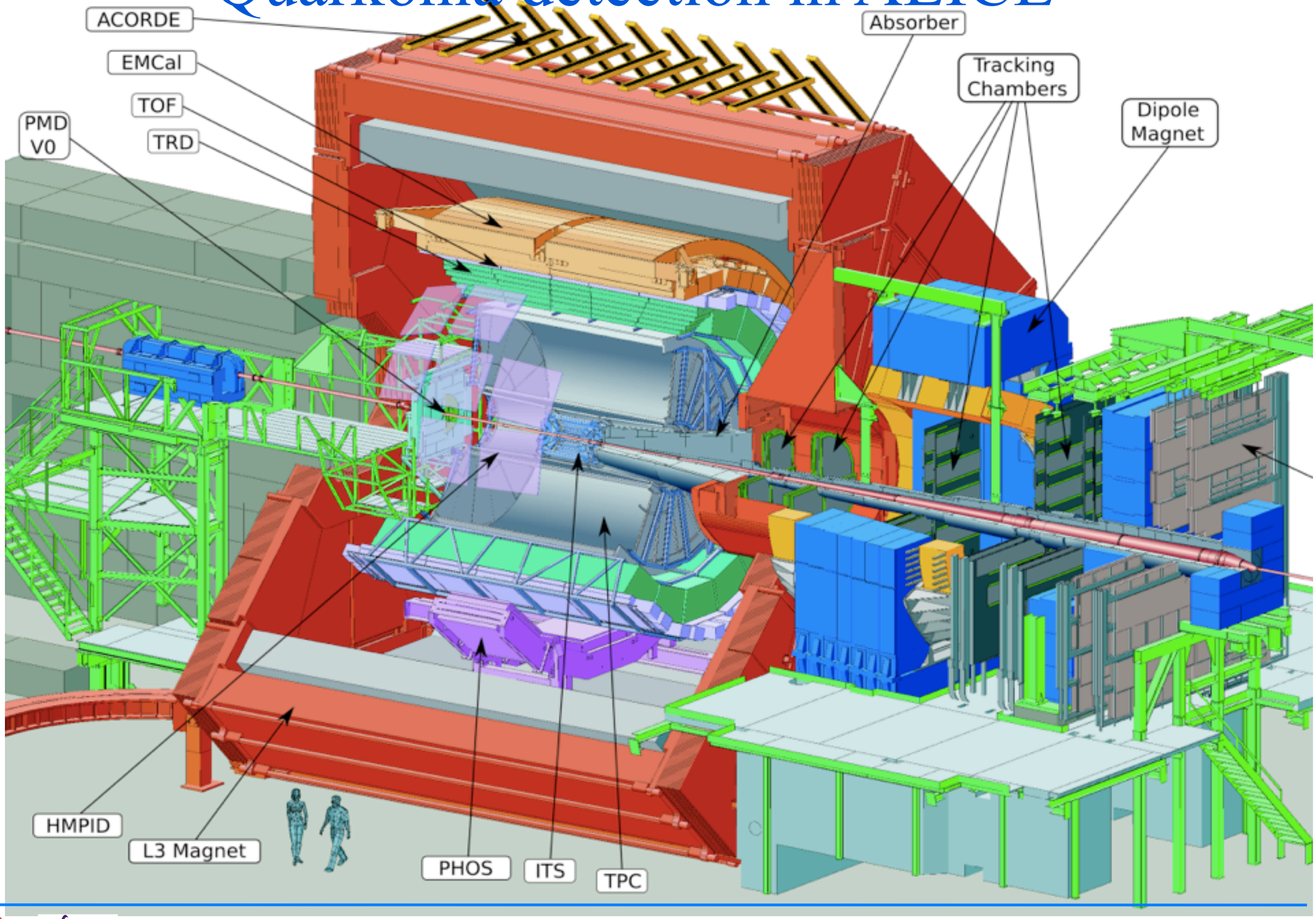
Reference

- Production in pp at the same energy (whenever possible): reference for R_{AA}
- Production in p-A at the same energy (whenever possible): cold nuclear matter determination

Cold nuclear matter (CNM)

- Initial state effects: nuclear shadowing (npdf) -or gluon saturation in the nucleus-, parton energy loss, multiple elastic scatterings of partons (Cronin effect), ...
- Final state effects: breakup of precursor quarkonia by collisions with nucleons (nuclear absorption), energy loss, ...

Quarkonia detection in ALICE



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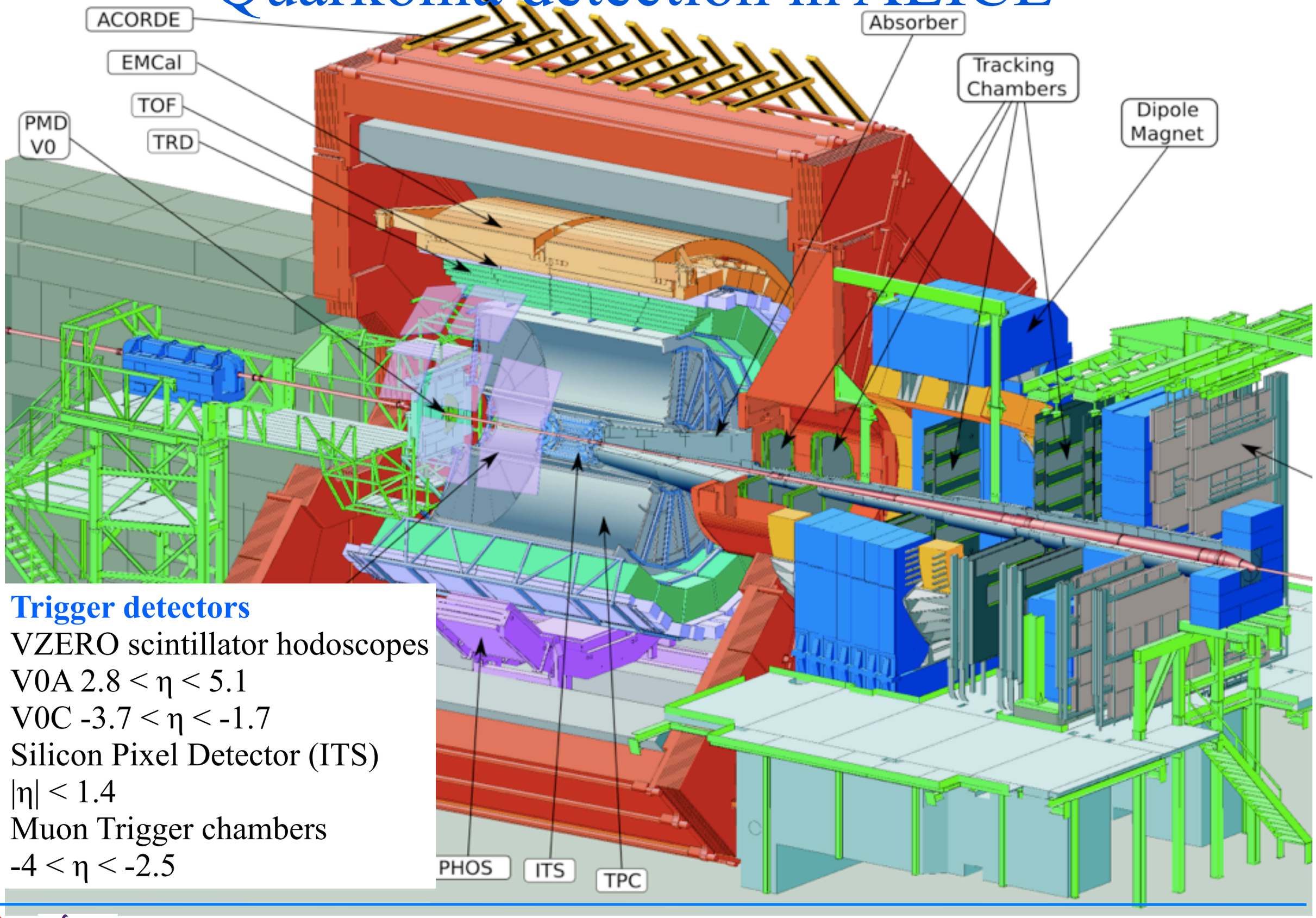


Trigger detectors

VZERO scintillator hodoscopes

V0A $2.8 < \eta < 5.1$

V0C $-3.7 < \eta < -1.7$

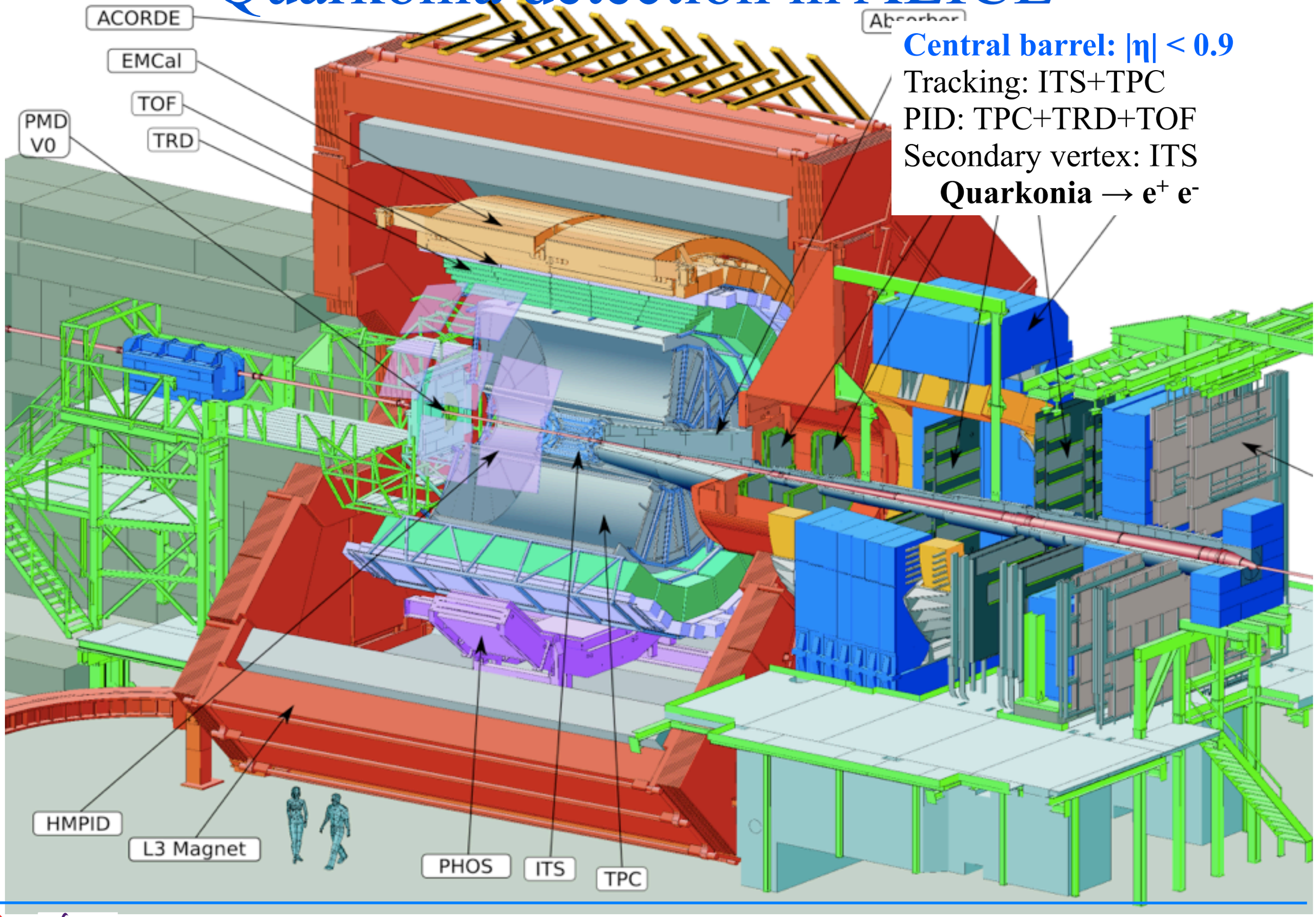
Silicon Pixel Detector (ITS)

$|\eta| < 1.4$

Muon Trigger chambers

$-4 < \eta < -2.5$

Quarkonia detection in ALICE



Central barrel: $|\eta| < 0.9$

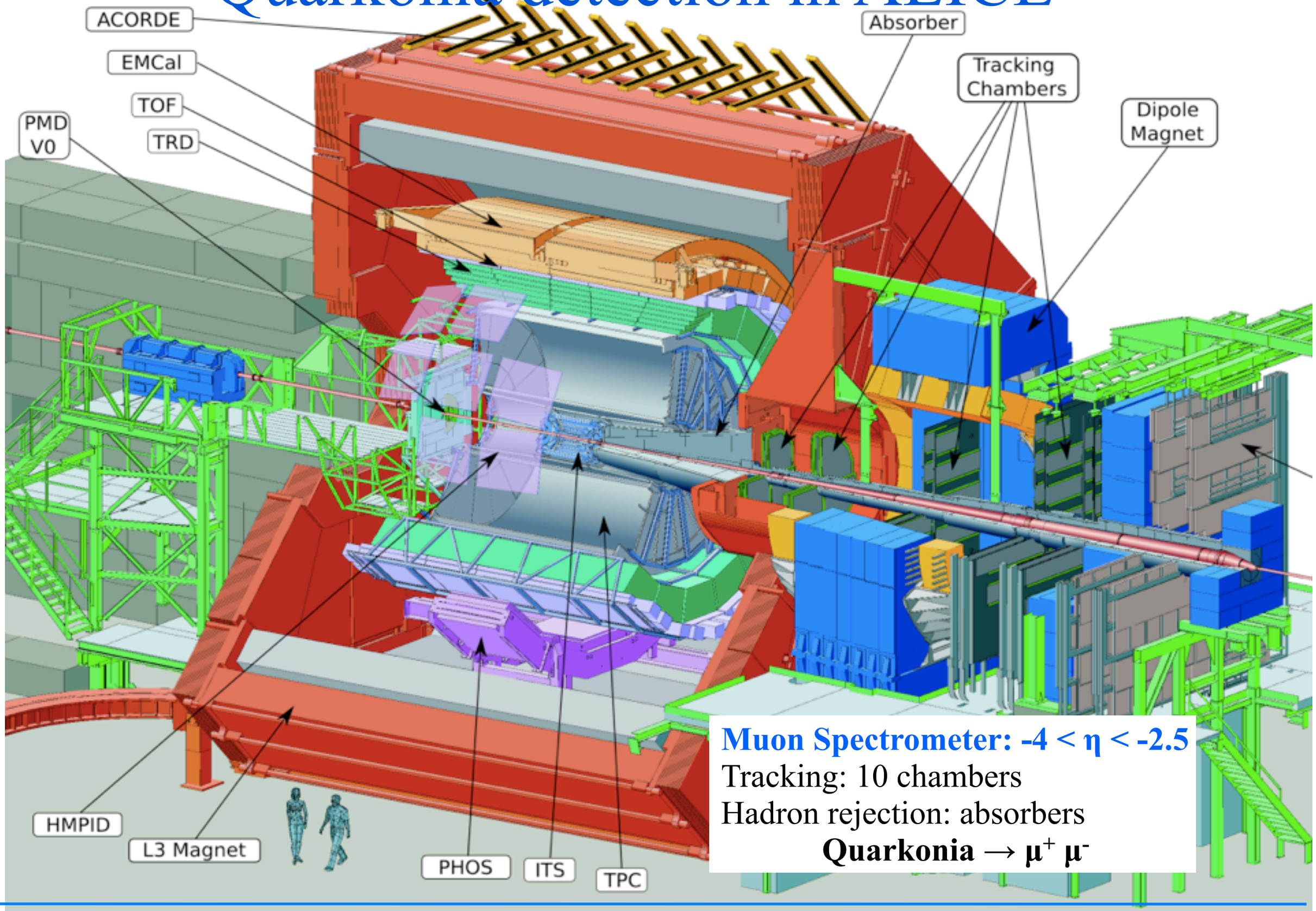
Tracking: ITS+TPC

PID: TPC+TRD+TOF

Secondary vertex: ITS

Quarkonia → $e^+ e^-$

Quarkonia detection in ALICE



Muon Spectrometer: $-4 < \eta < -2.5$

Tracking: 10 chambers

Hadron rejection: absorbers

Quarkonia → $\mu^+ \mu^-$

pp measurements

Inclusive J/Ψ cross-sections at 7 TeV and 2.76 TeV at mid- and forward rapidity

ALICE Coll. PLB704(2011)442 *ALICE Coll. PLB718(2012)295*

Prompt and non-prompt J/Ψ (B→ J/Ψ) at mid-rapidity at 7 TeV *ALICE Coll. JHEP1211(2012)065*

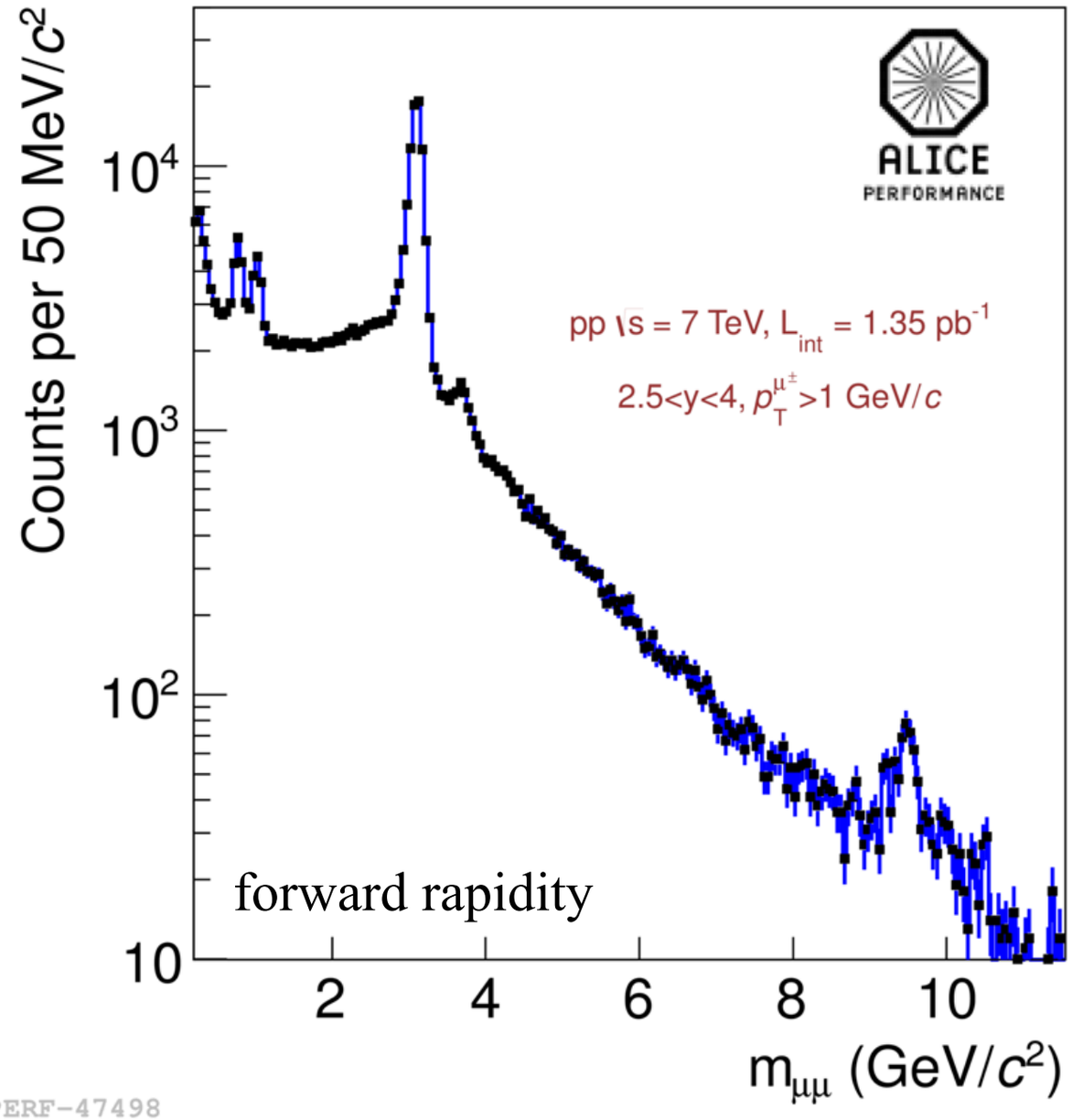
Inclusive J/Ψ polarization at forward rapidity at 7 TeV *ALICE Coll. PRL108(2012)082001*

Multiplicity dependence of inclusive J/Ψ relative yield at mid- and forward rapidity at 7 TeV

ALICE Coll. PLB712(2012)165

Multiplicity dependence of prompt and non-prompt J/Ψ relative yield at mid-rapidity at 7 TeV - **New!**

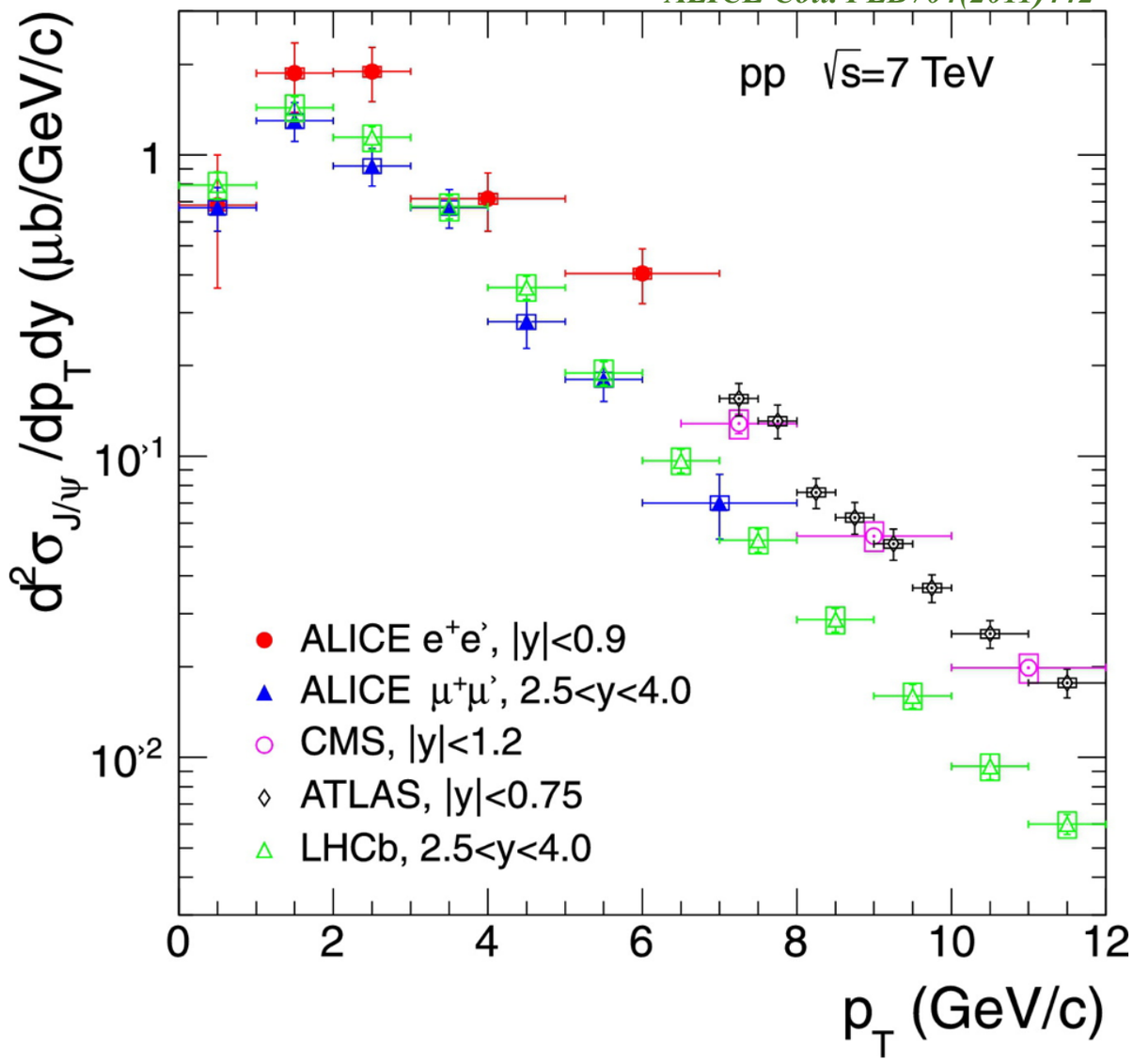
Inclusive Υ(1S), Υ(2S) cross-sections at 7 TeV at forward rapidity - **New!**



ALI-PERF-47498

Inclusive J/Ψ production in pp

ALICE Coll. PLB704(2011)442



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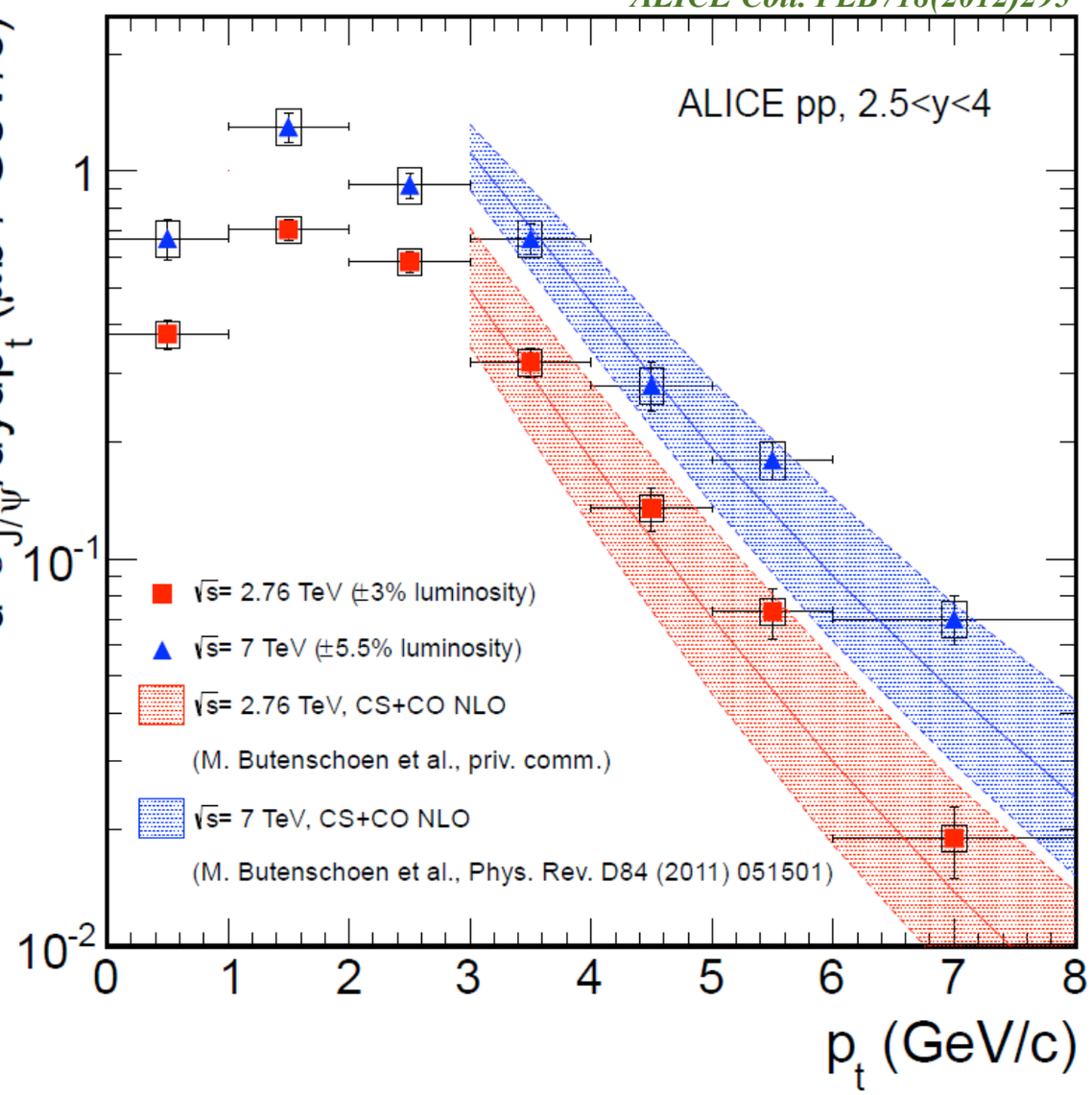


Good agreement with LHCb for inclusive J/Ψ production at $2.5 < y < 4$

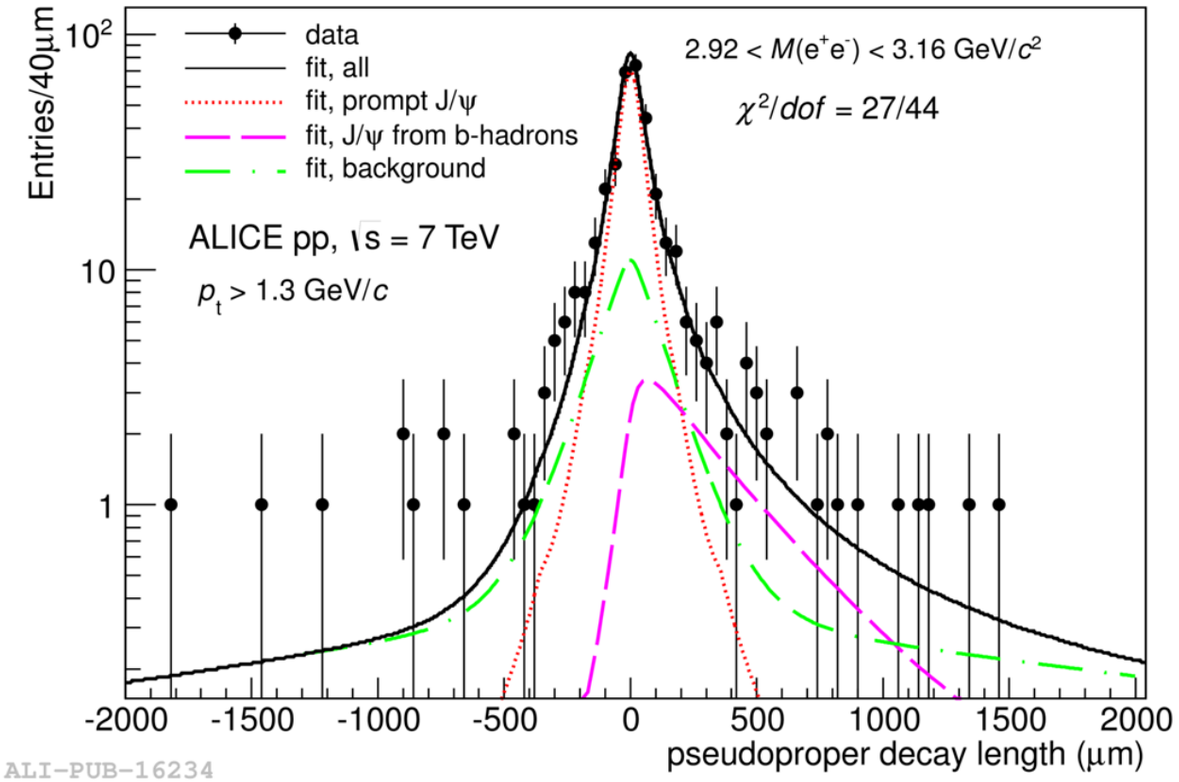
At mid-rapidity, ALICE covers the low p_T region

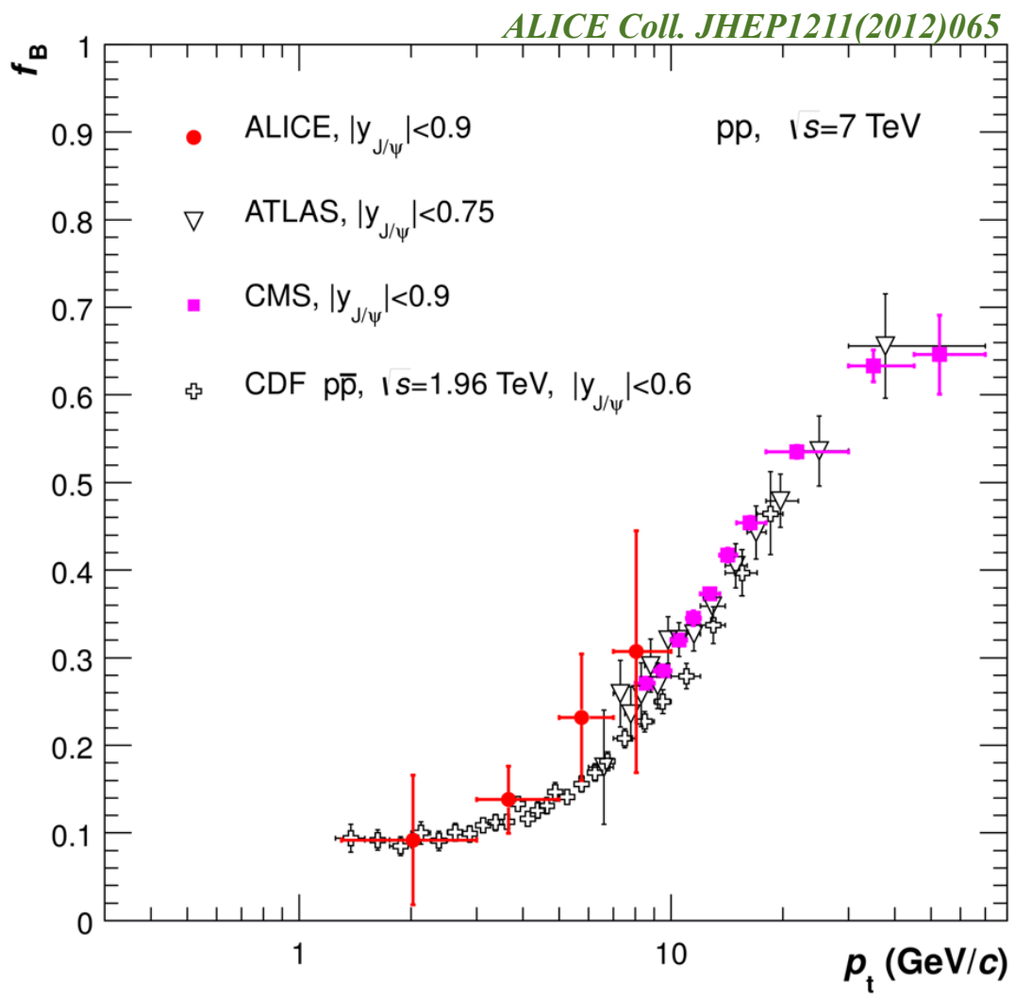
→ ALICE has a broad rapidity coverage for inclusive J/Ψ measurement for $p_T > 0$

2.76 TeV data at forward rapidity are used as a reference for Pb-Pb measurement

Data at 2.76 and 7 TeV are well described by NLO NRQCD calculations

J/Ψ from B-hadrons decay at mid-rapidity





Thanks to the good resolution on the impact parameter (rφ < 75 μm), pseudo-proper decay length is used to extract prompt and non-prompt (from b) J/Ψ

At low p_T the contribution of non-prompt J/Ψ is ~10% at mid- and forward rapidity

J/Ψ polarization in pp at forward rapidity

Polarization is a critical observable to test the hadroproduction mechanisms

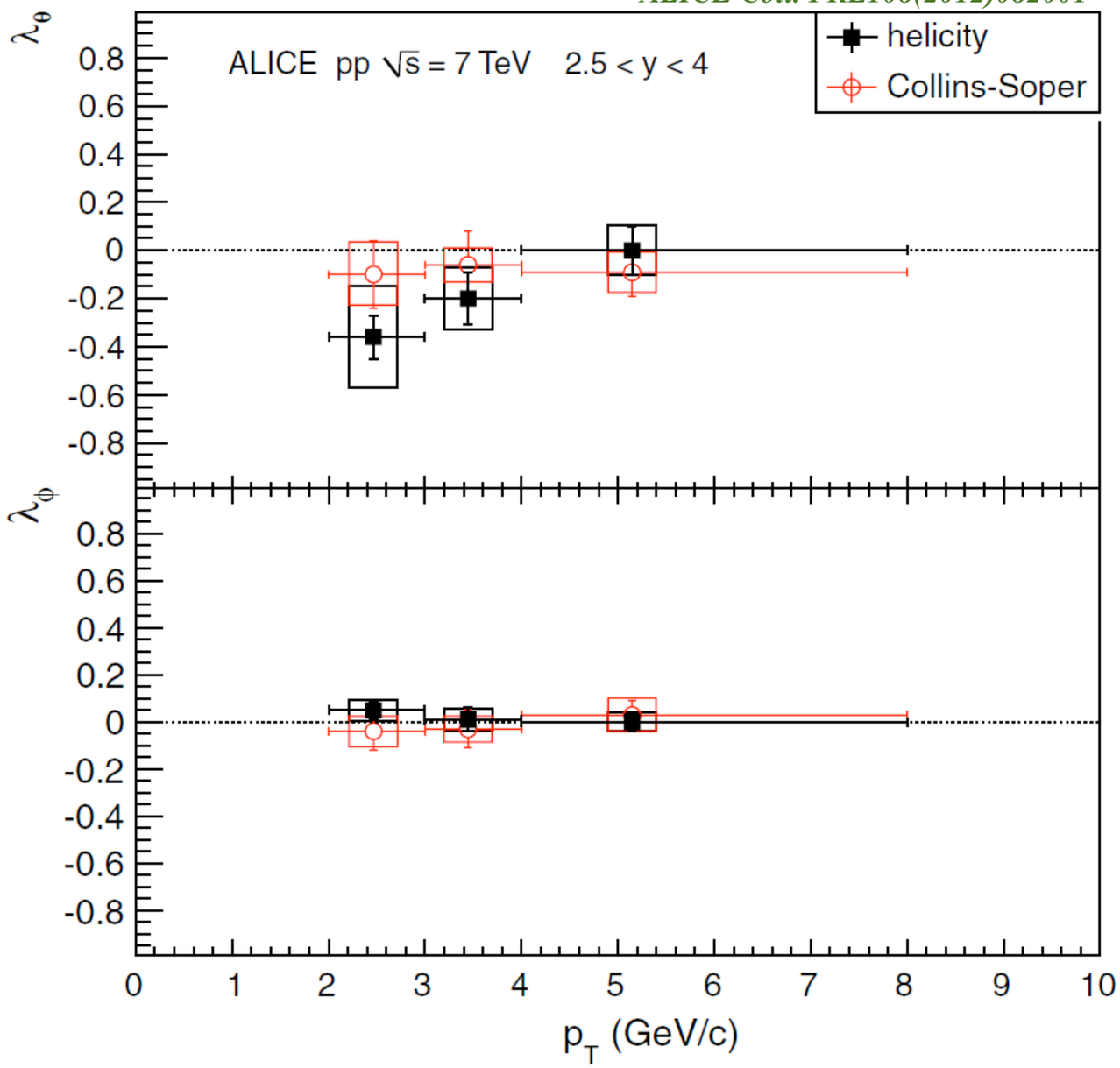
Unknown polarization results in large uncertainty on acceptance correction

First measurement at LHC:

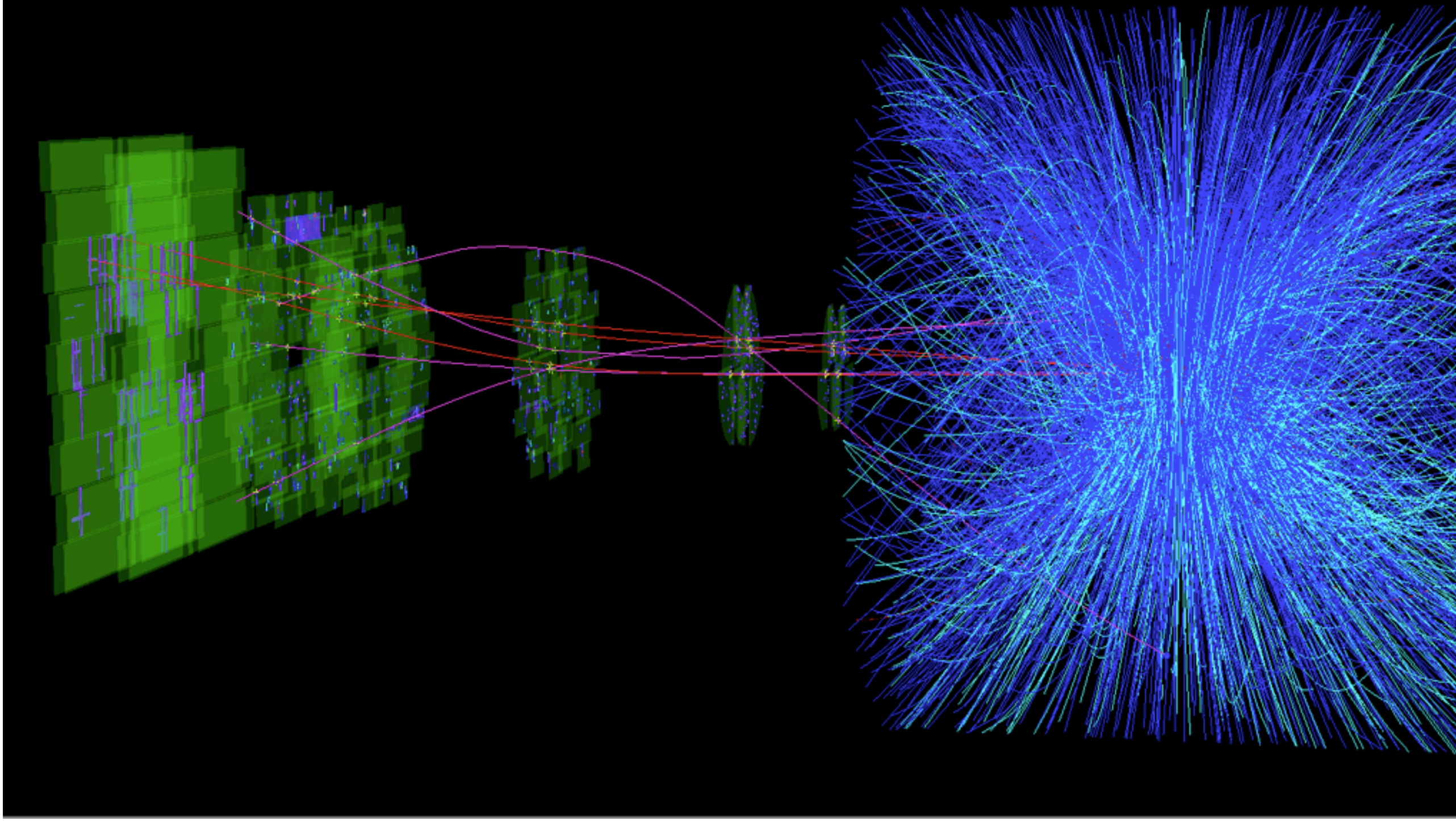
- small longitudinal polarization that vanishes when increasing p_T
- azimuthal component compatible with zero

In the following analysis (Pb-Pb and p-Pb), the polarisation of the quarkonia is assumed to be zero

ALICE Coll. PRL108(2012)082001



Pb-Pb measurements at $\sqrt{s_{NN}} = 2.76$ TeV



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J/Ψ R_{AA} at mid- and forward rapidity:

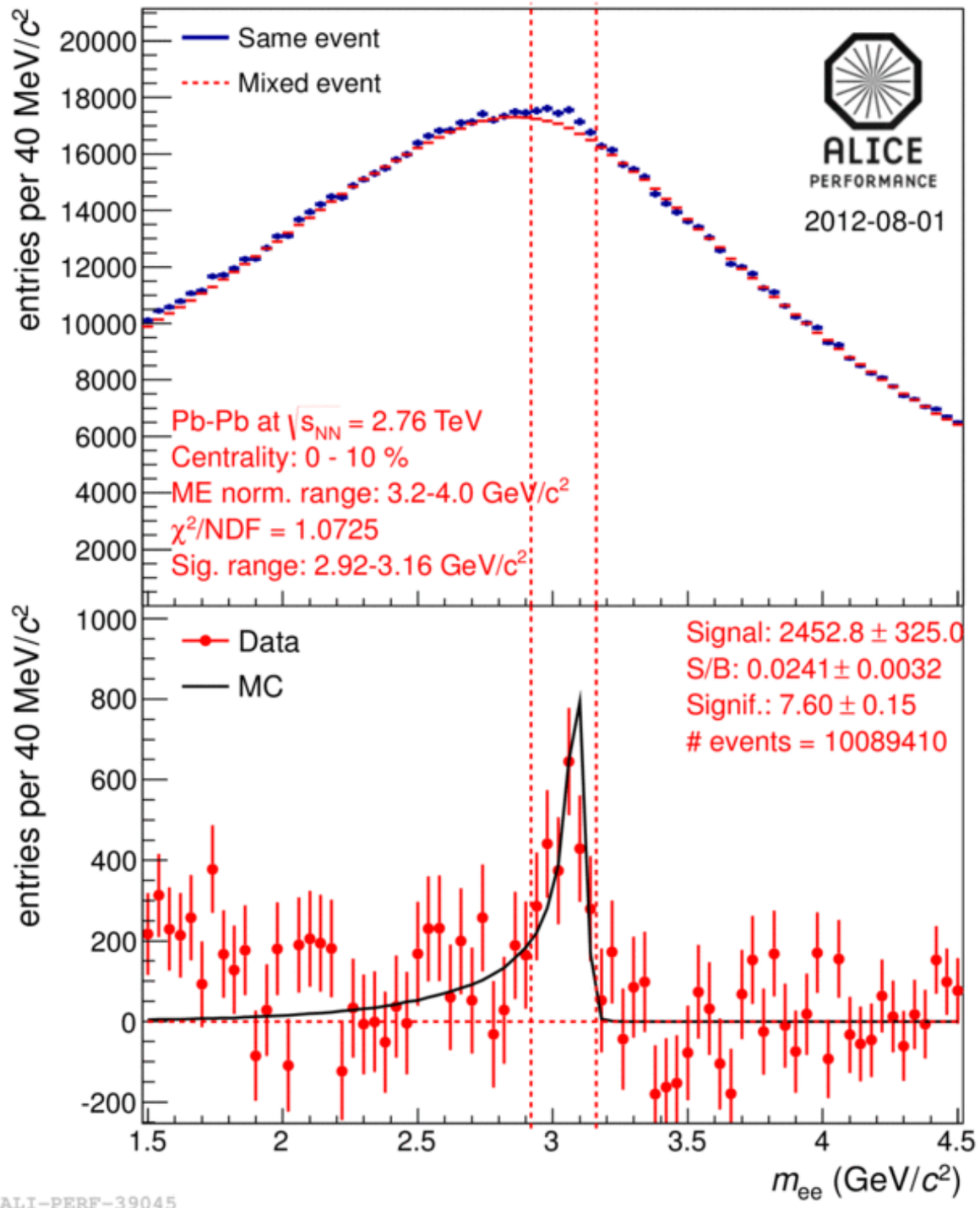
- **as a function of the collision centrality**
  ALICE Coll. PRL109(2012)072301
- **differential in y, p_T at forward rapidity**
  Hard Probes 2012 Quark Matter 2012

J/Ψ $\langle p_t \rangle$ at forward rapidity
Quark Matter 2012

J/Ψ elliptic flow at forward rapidity
ALICE Coll. arXiv:1303:5880

$[\Psi(2S) / J/\Psi]_{AA} / [\Psi(2S) / J/\Psi]_{pp}$ at forward rapidity
Quark Matter 2012

Y R_{AA} at forward rapidity - New!
LHCP 2013



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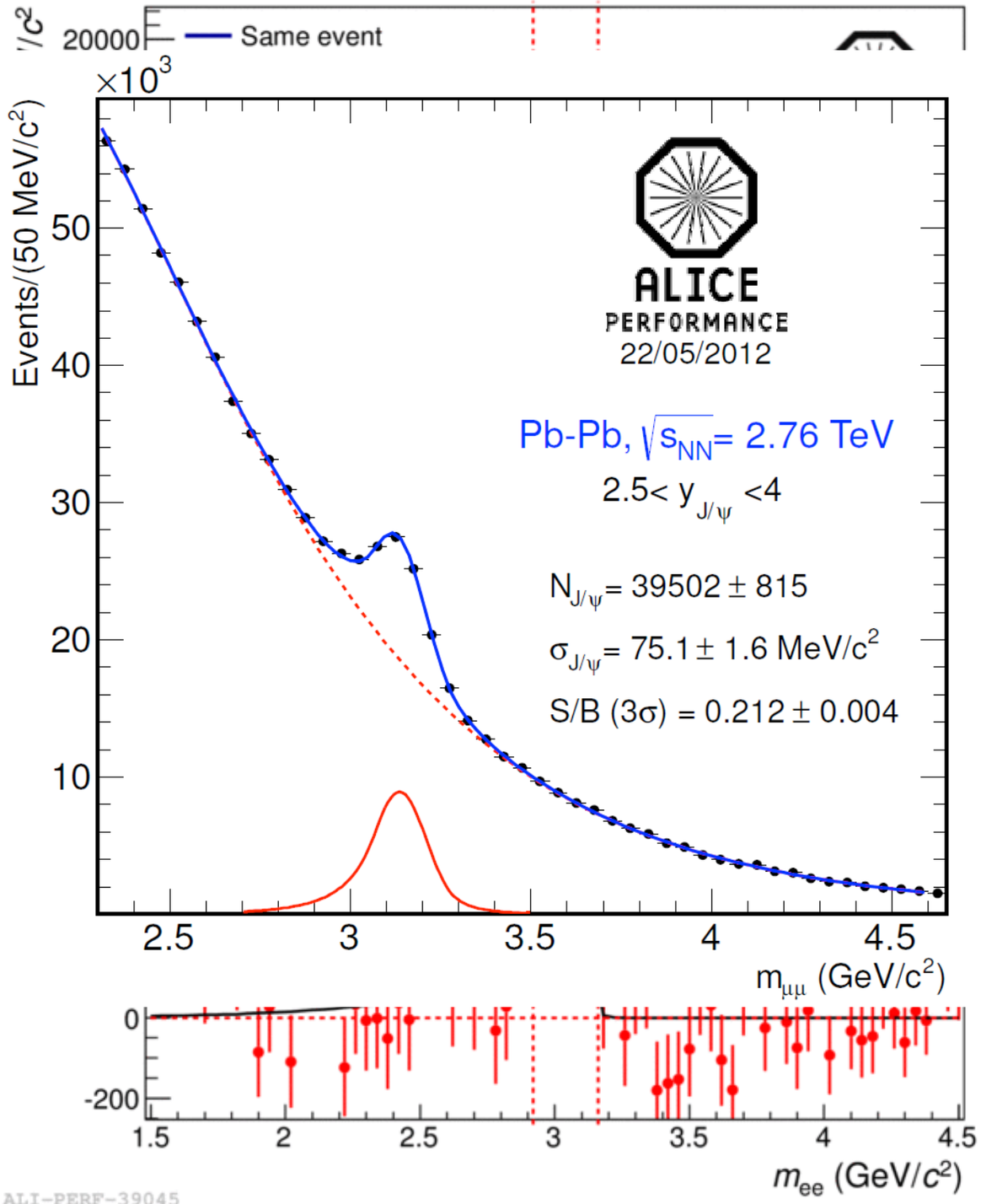

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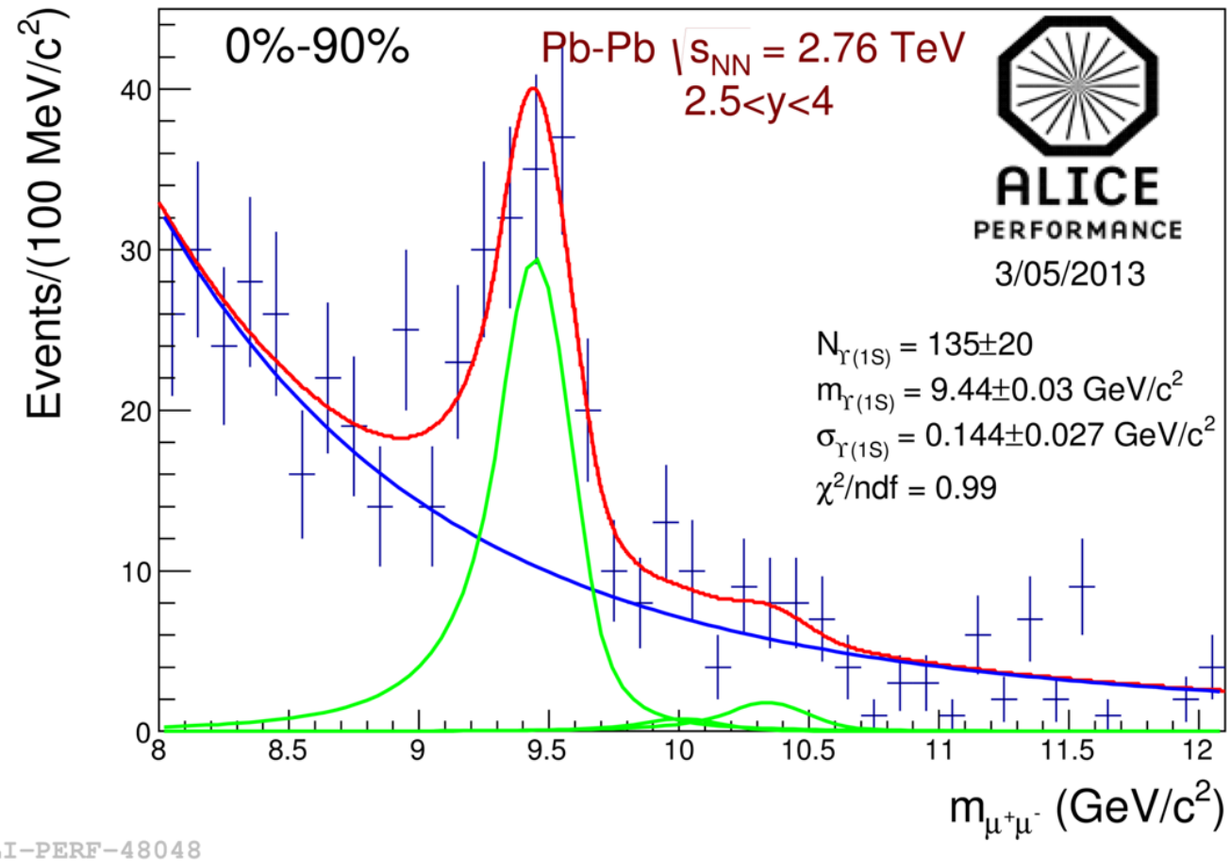
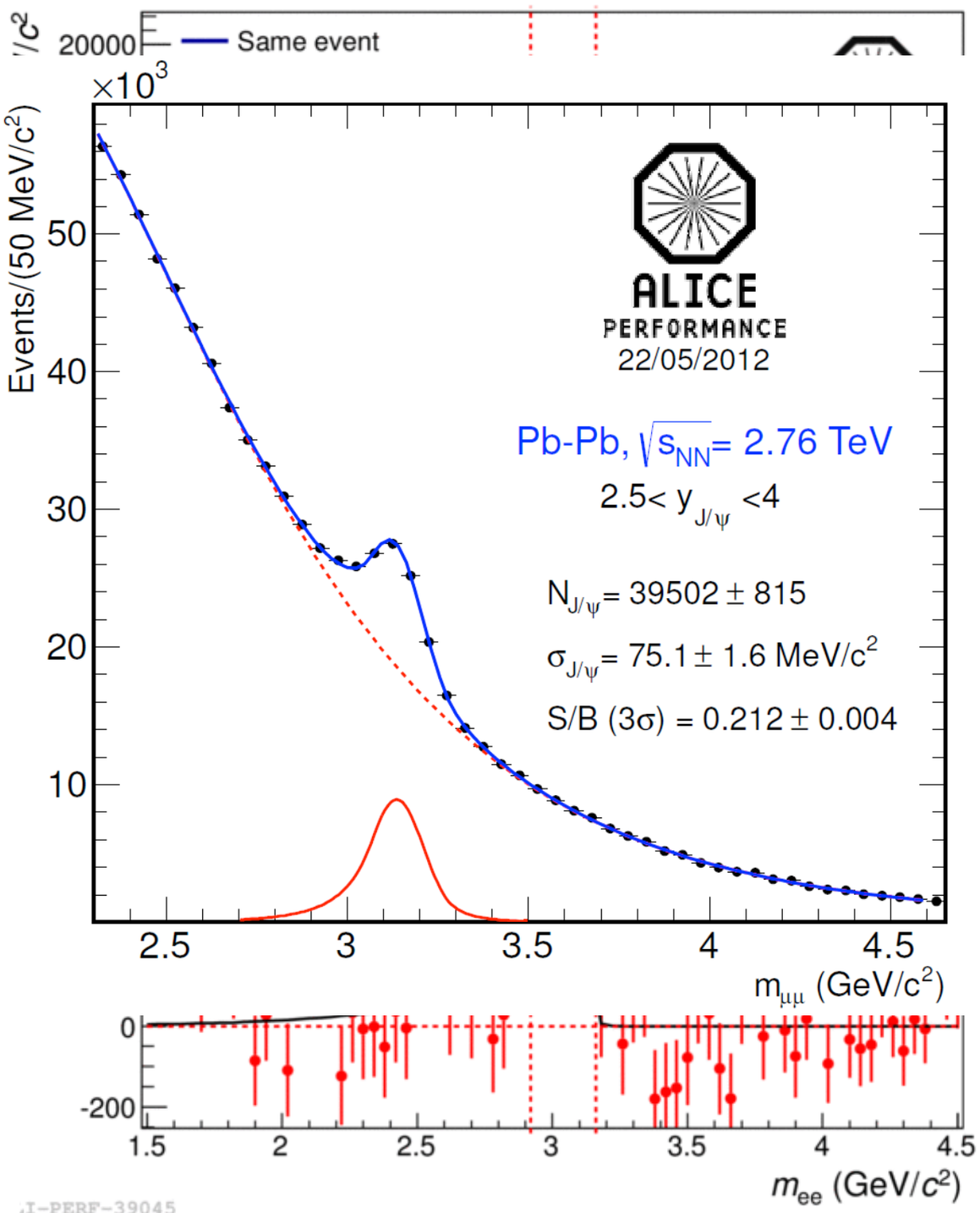
Quark Matter 2012

Υ R_{AA} at forward rapidity - New!
LHCP 2013





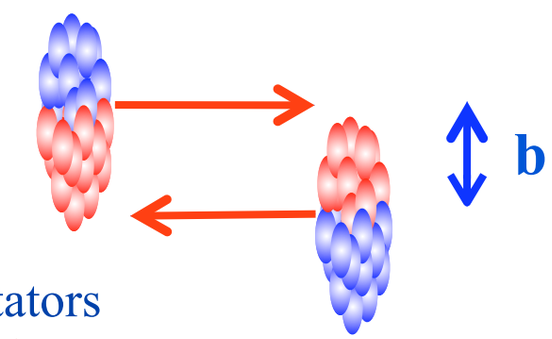
ALI-PERF-48048

ALI-PERF-39045

Centrality of the collision in Pb-Pb

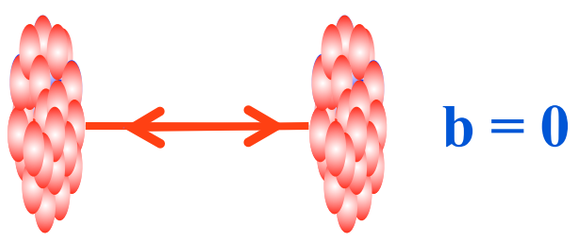
Centrality of the collisions

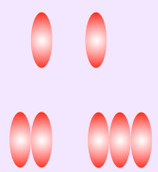
semi-central collision



Spectators
Participants
b impact parameter

central collision





	$N_{part} = 2$	$N_{coll} = 1$
	$N_{part} = 5$	$N_{coll} = 6$
Pb-Pb cent.	$N_{part} = 360$	$N_{coll} = 1500$
p-Pb cent.	$N_{part} = 16$	$N_{coll} = 15$

→ Glauber model used to determine the geometry of the collision

Centrality of the collision in Pb-Pb

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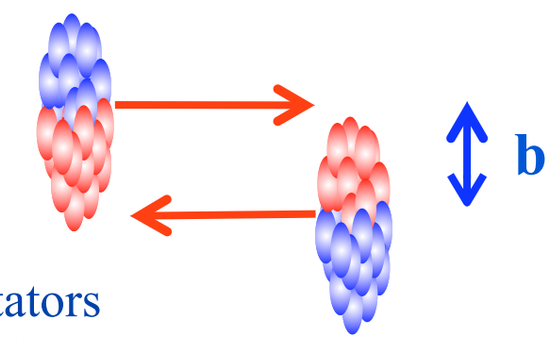

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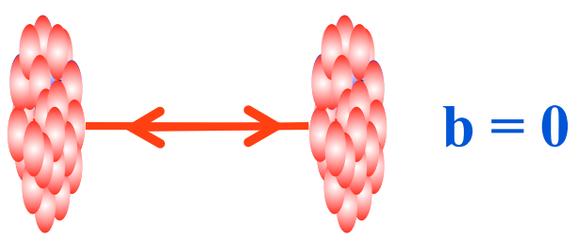

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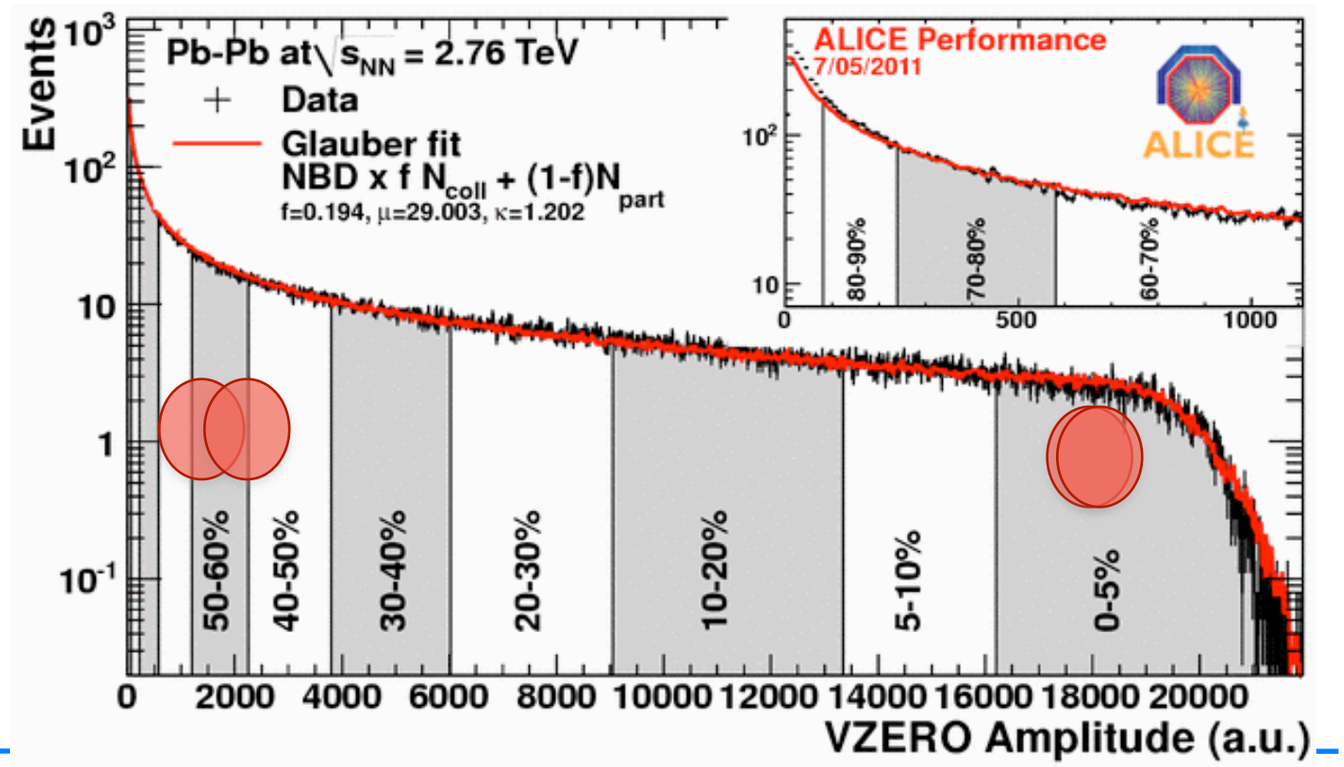
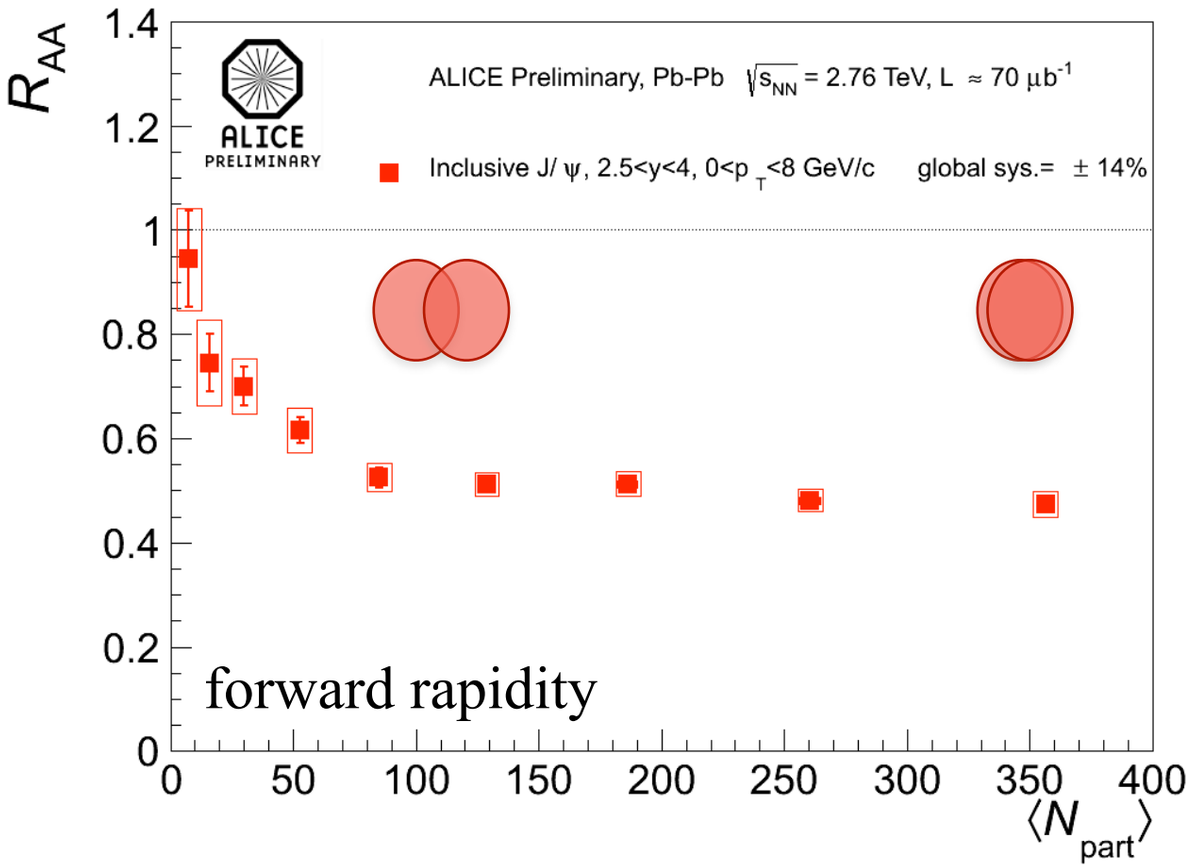
Centrality determination

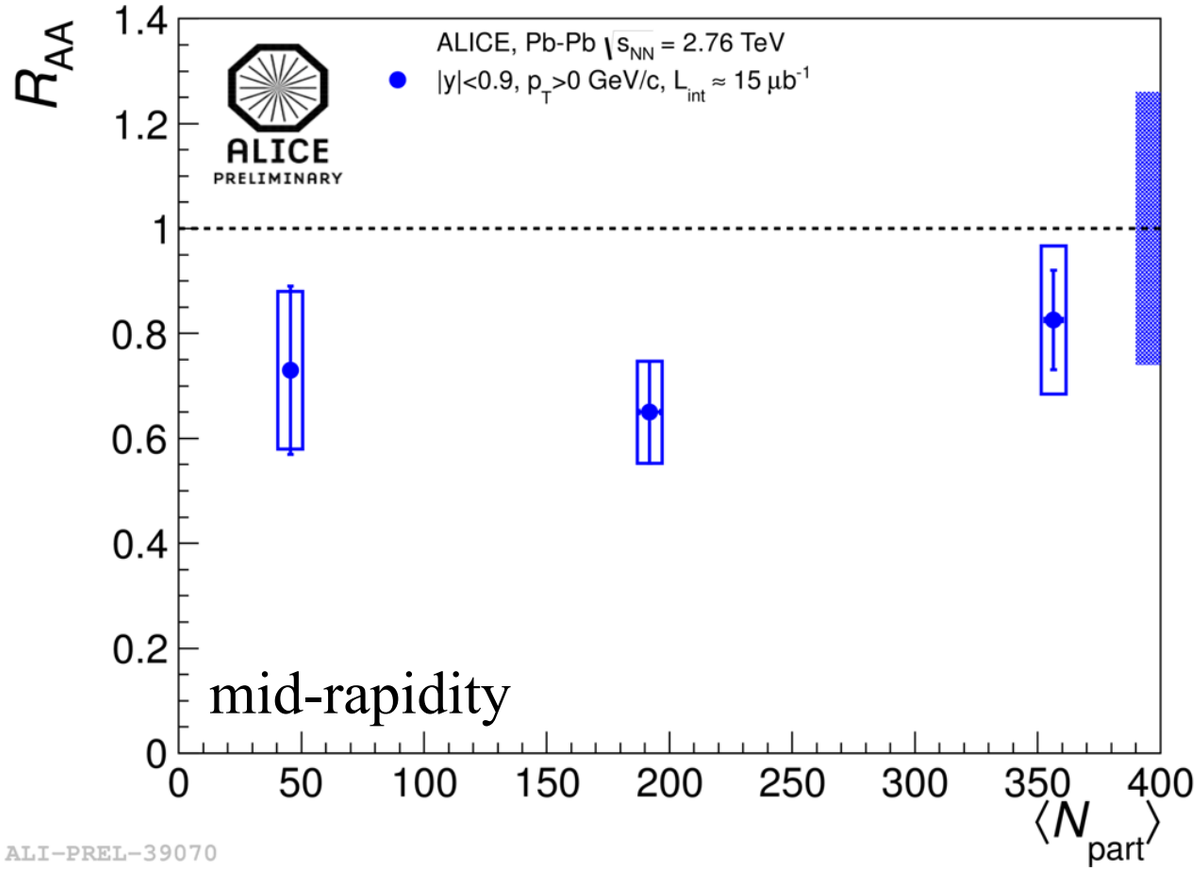
Multiplicity measurements with forward or central detectors

Relate the measured multiplicity in A-A collisions to N_{part} and N_{coll}



J/Ψ R_{AA} vs centrality

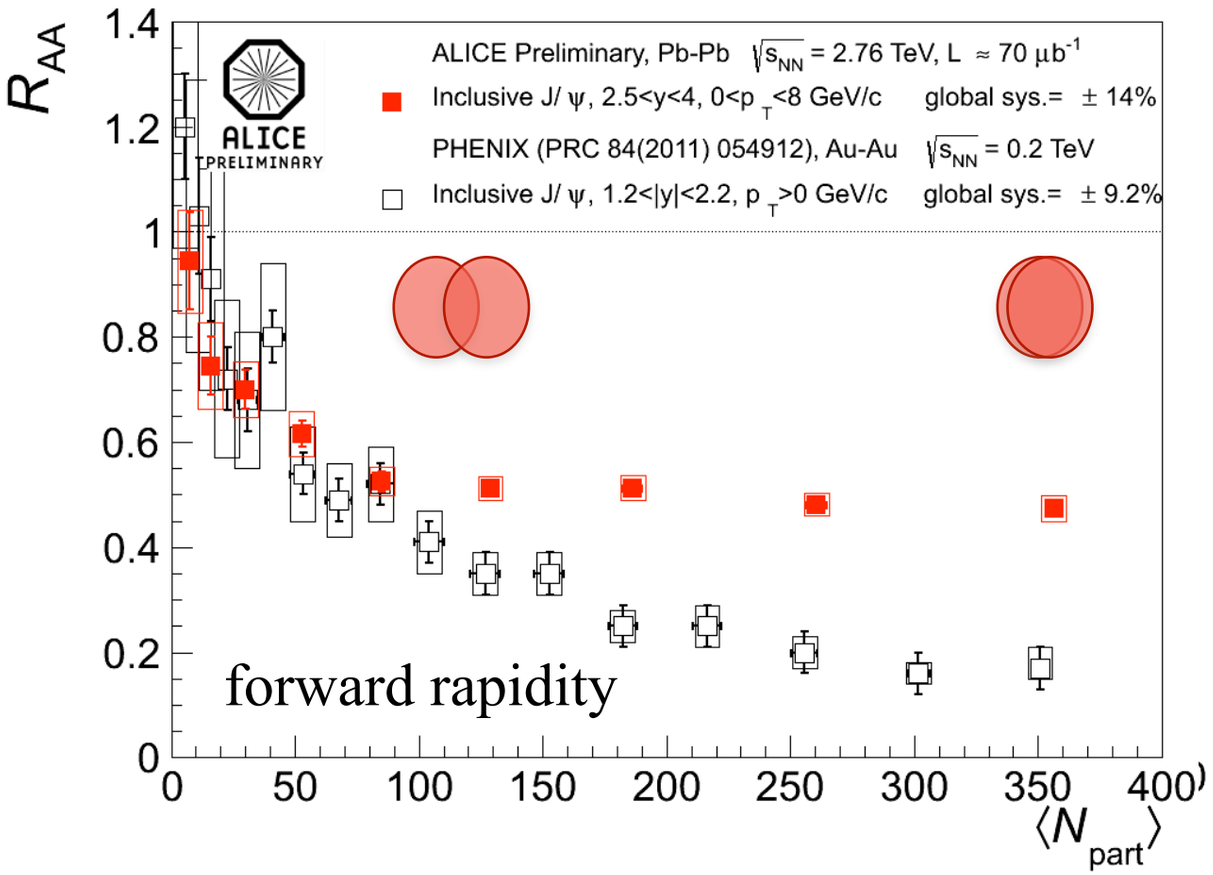


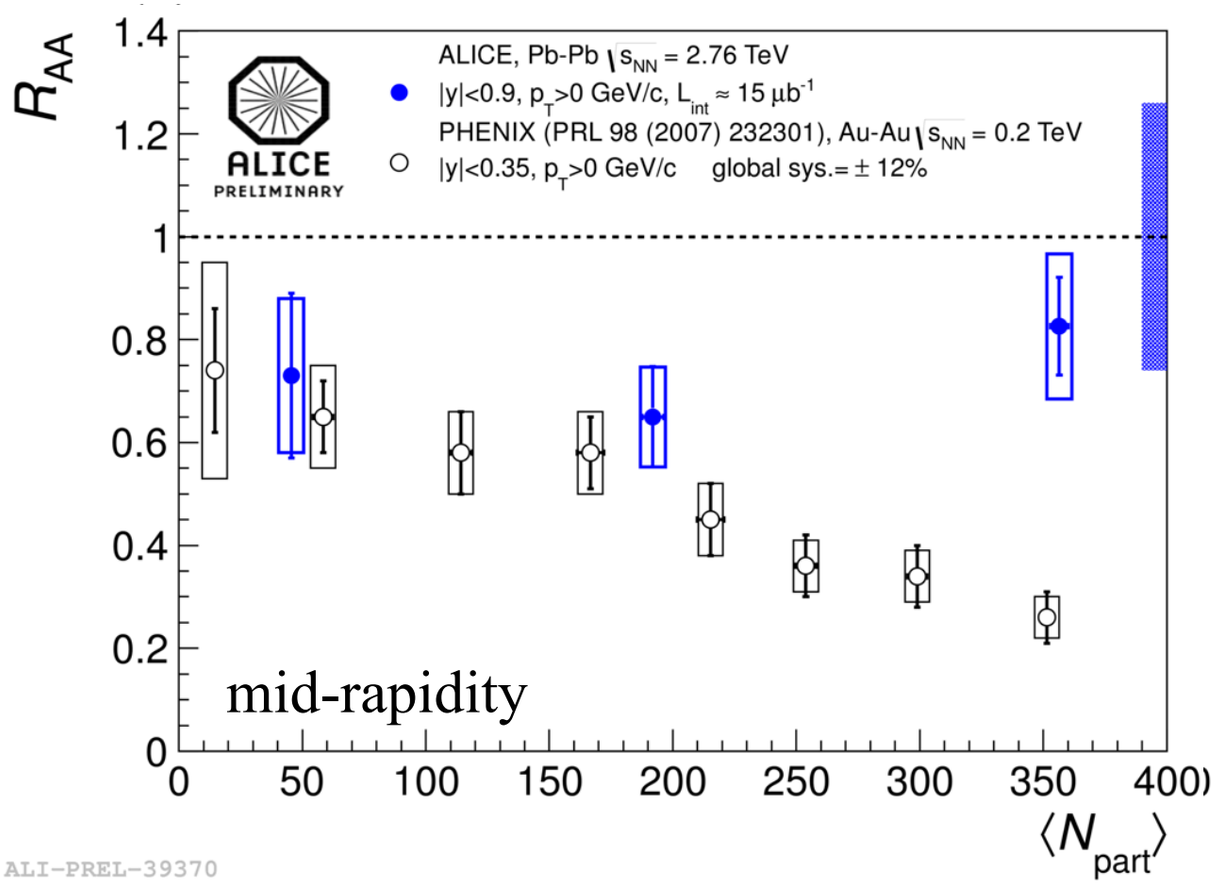


ALI-PREL-39070

Forward rapidity: clear J/Ψ suppression with almost no dependence for $N_{part} > 100$
Mid-rapidity: no significant dependence with centrality but large uncertainty
Feed-down from B: negligible effect on R_{AA} integrated over p_T

J/Ψ R_{AA} vs centrality



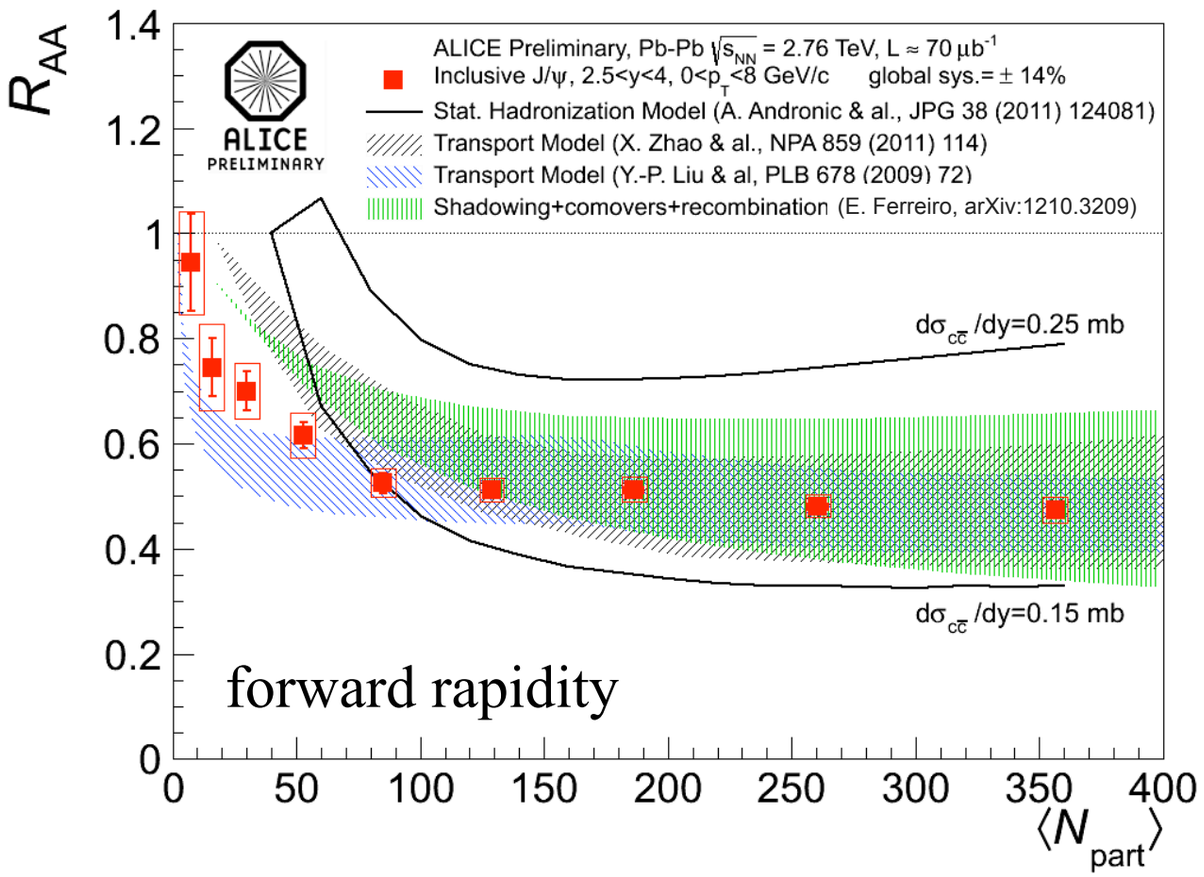


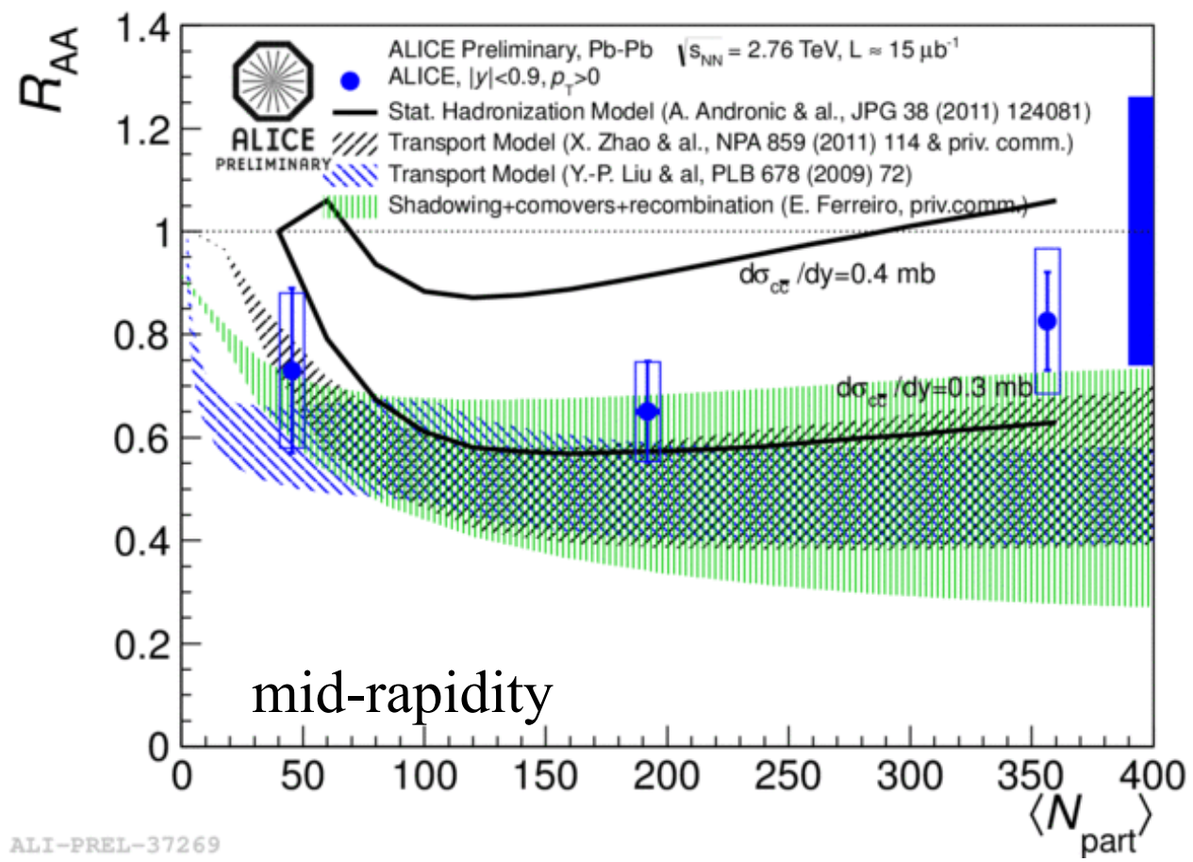
ALI-PREL-39370

Forward rapidity: clear J/Ψ suppression with almost no dependence for $N_{part} > 100$
Mid-rapidity: no significant dependence with centrality but large uncertainty
Feed-down from B: negligible effect on R_{AA} integrated over p_T

Comparison to RHIC:
- Different centrality dependence at LHC
- R_{AA} larger at LHC than at RHIC at mid- and forward rapidity for most central collisions

J/Ψ R_{AA} vs centrality





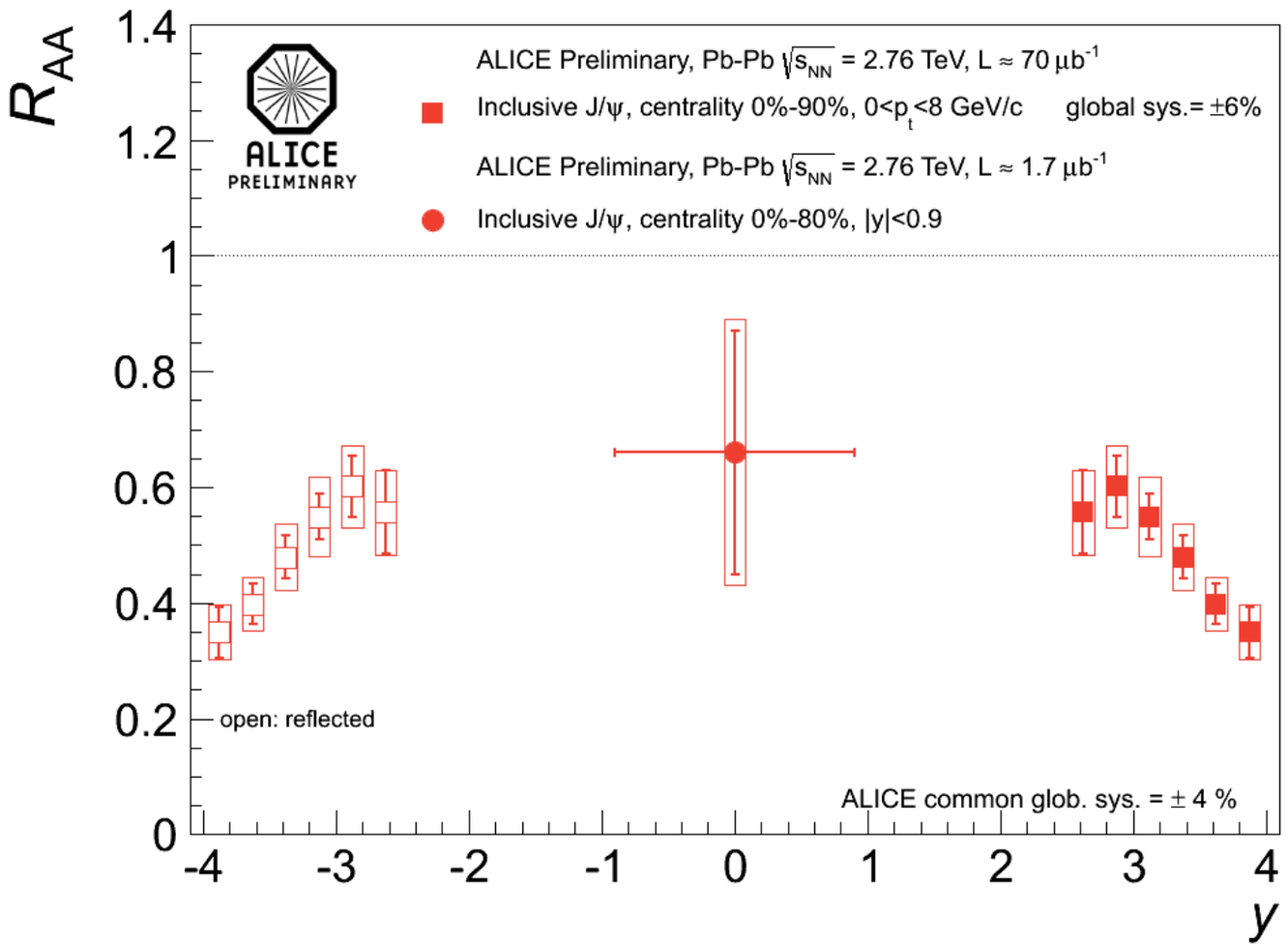
ALI-PREL-37269

Models:

- Statistical model (Andronic et al.): thermal model, all J/Ψ formed at hadronization, different σ_{ccbar} hypothesis
- Transport (Zhao et al./ Liu et al.) and comovers+recombination (Ferreiro) models: suppression and more than 50% of J/Ψ from regeneration for most central events, different σ_{ccbar} and/or shadowing hypothesis

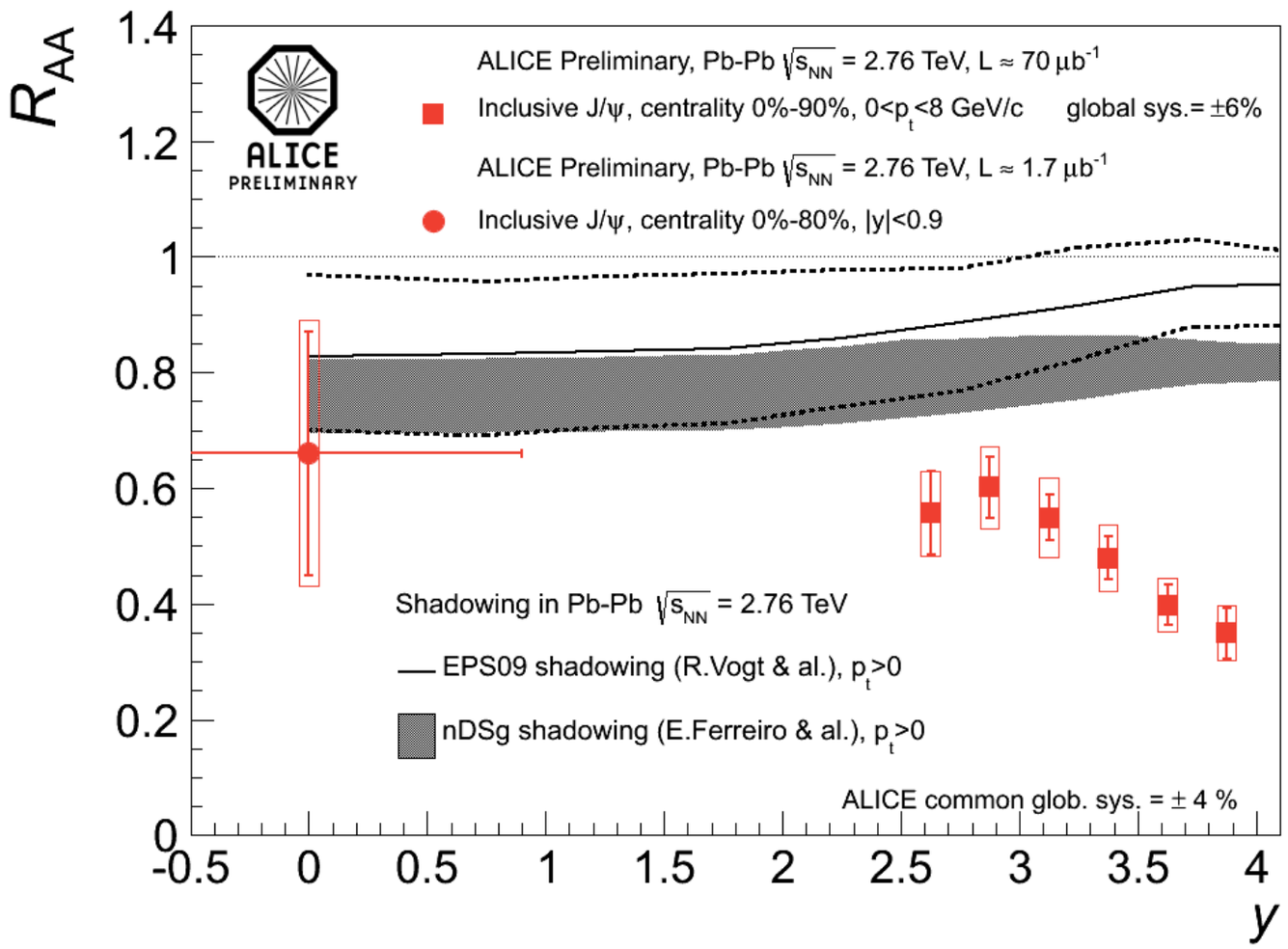
These models that include regeneration mechanism describe well the data at semi-central and central collisions

J/Ψ R_{AA} vs y



Suppression more important at forward rapidity

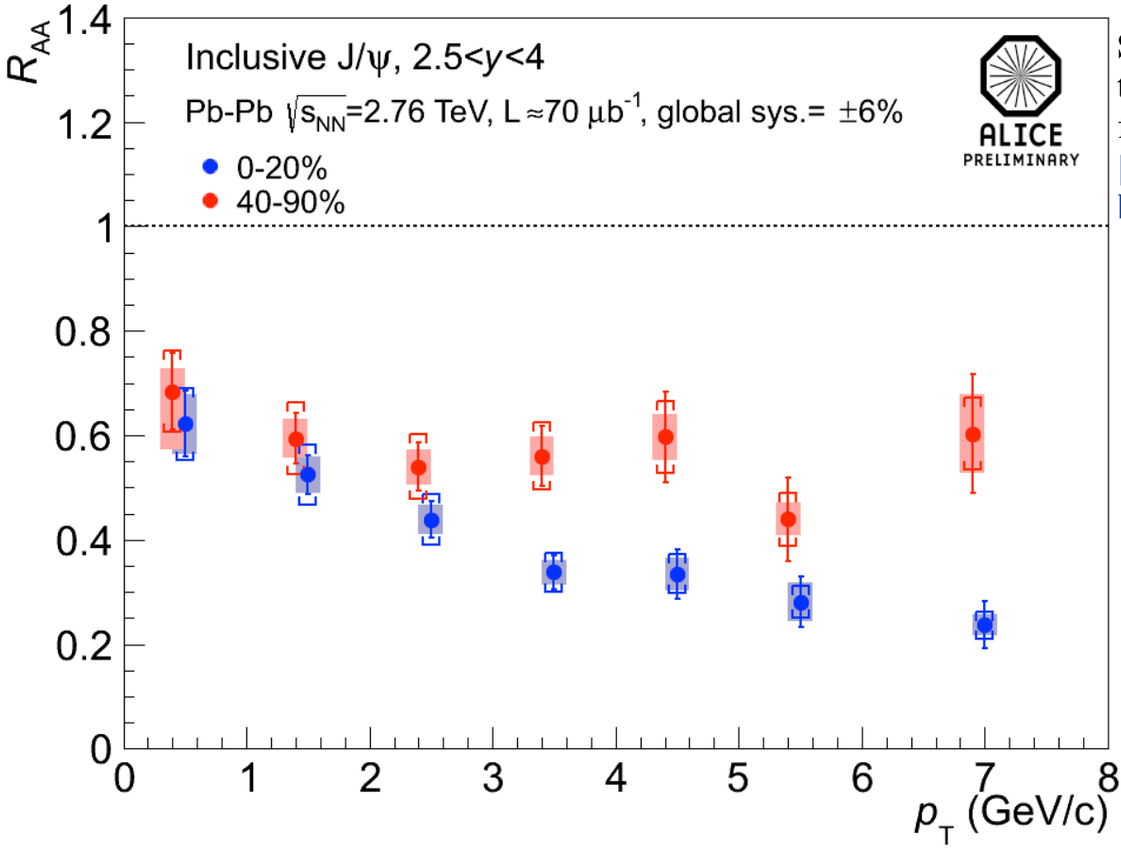
J/Ψ R_{AA} vs y



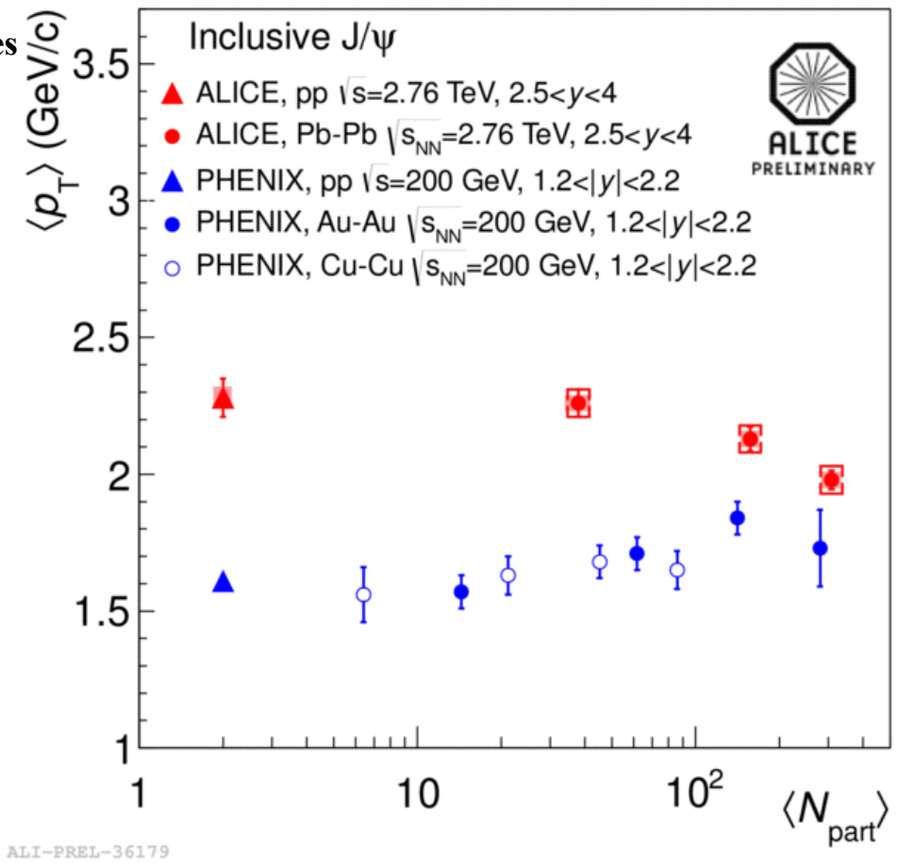
Suppression more important at forward rapidity

Shadowing models do not account for this rapidity decrease of R_{AA}

J/Ψ R_{AA} vs p_T and $\langle p_T \rangle$ at forward rapidity



Systematic uncertainties
text inbetween data sets
fully correlated
[] partially correlated
box uncorrelated



J/Ψ less suppressed at low p_T than high p_T for most central collisions
→ $\langle p_T \rangle$ different pattern at LHC vs the collision centrality as compared to RHIC

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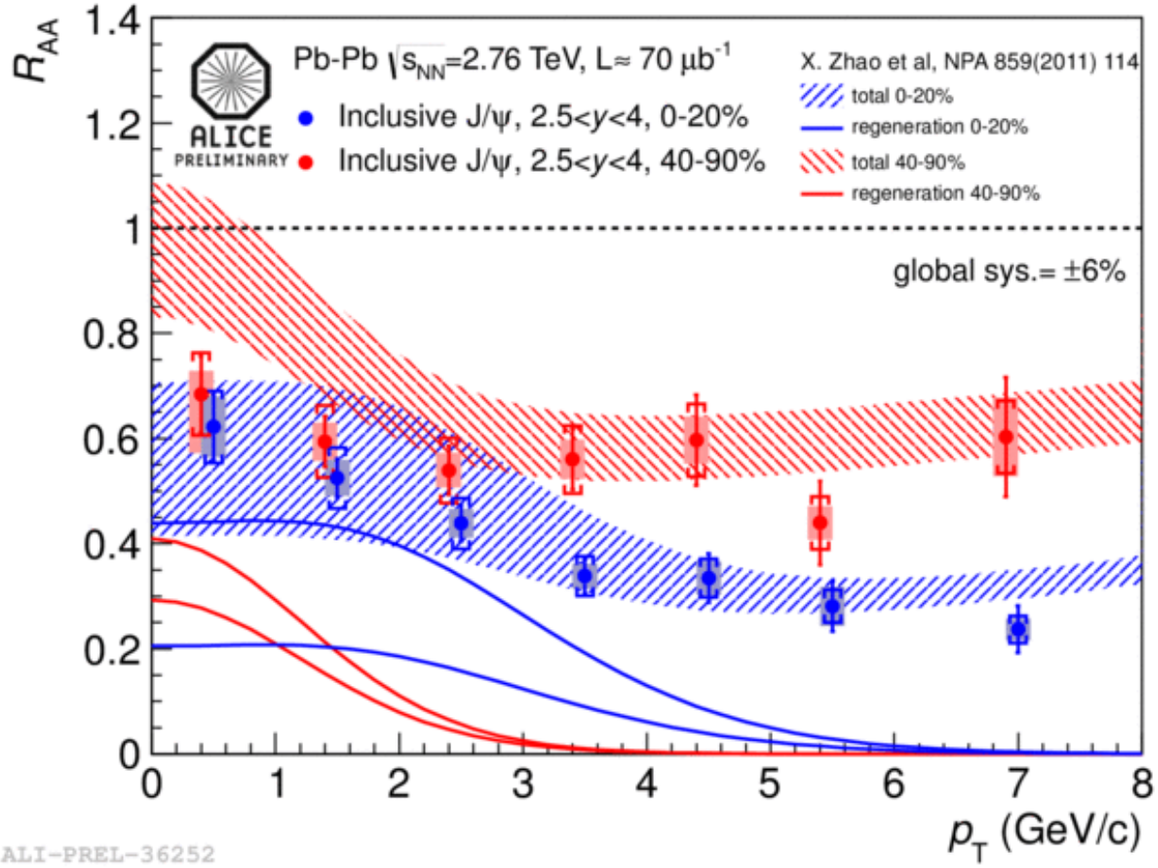

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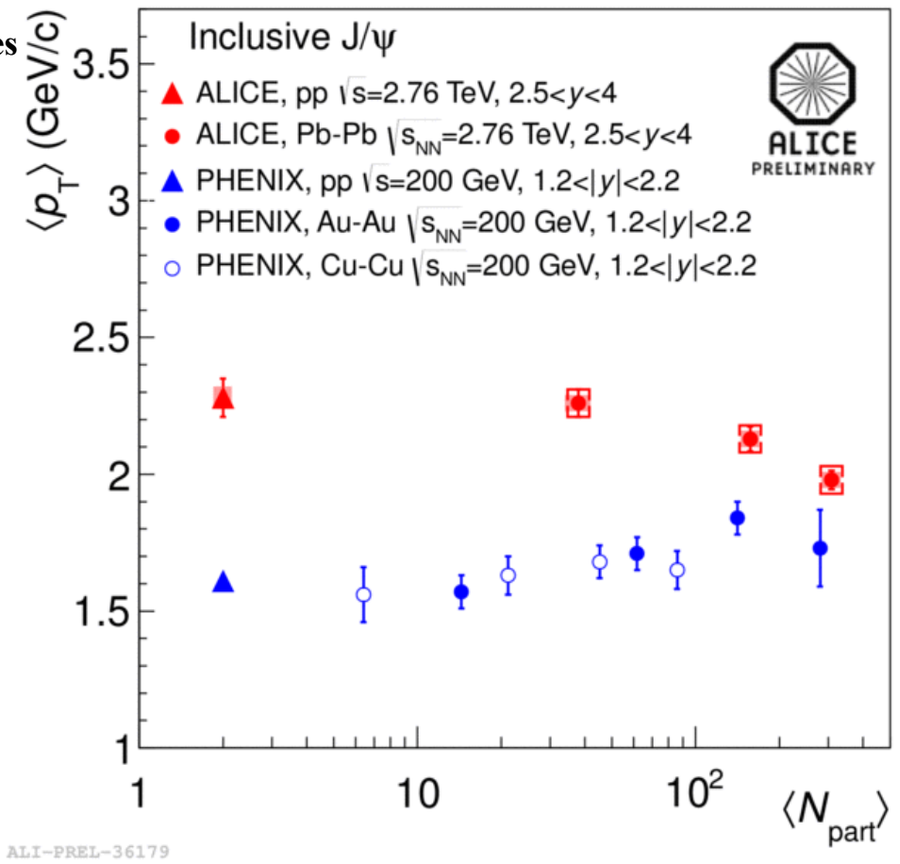
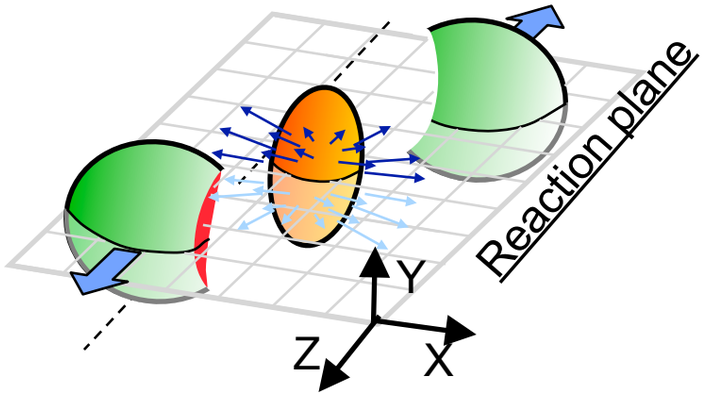


J/Ψ less suppressed at low p_T than high p_T for most central collisions
→ $\langle p_T \rangle$ different pattern at LHC vs the collision centrality as compared to RHIC

Transport models (Zhao et al./Liu et al.): regeneration contribution important for p_T < 3 GeV/c and negligible at large p_T

J/Ψ elliptic flow

At finite impact parameter:

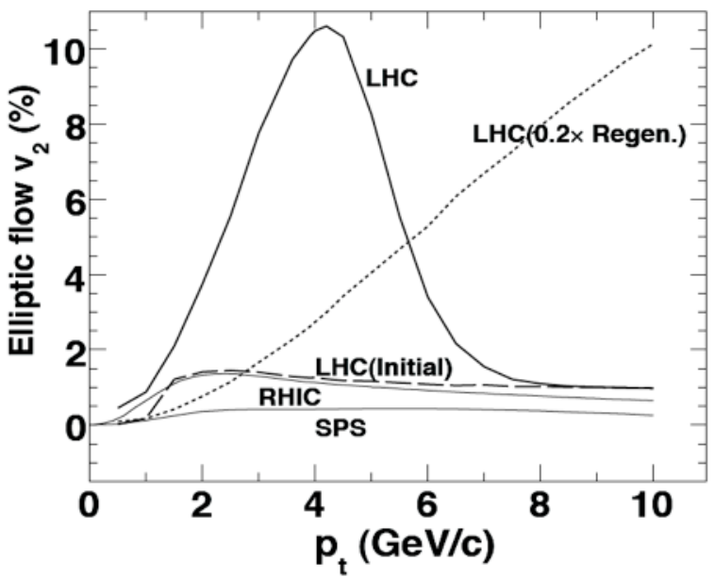


→ anisotropy of the geometrical overlap region

→ for interacting matter (via multiple collisions): density, pressure gradient convert spatial anisotropy into momentum space

Azimuthal dependence of the particle yield

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos[n(\phi-\Psi_R)]\right)$$



Elliptic flow n=2

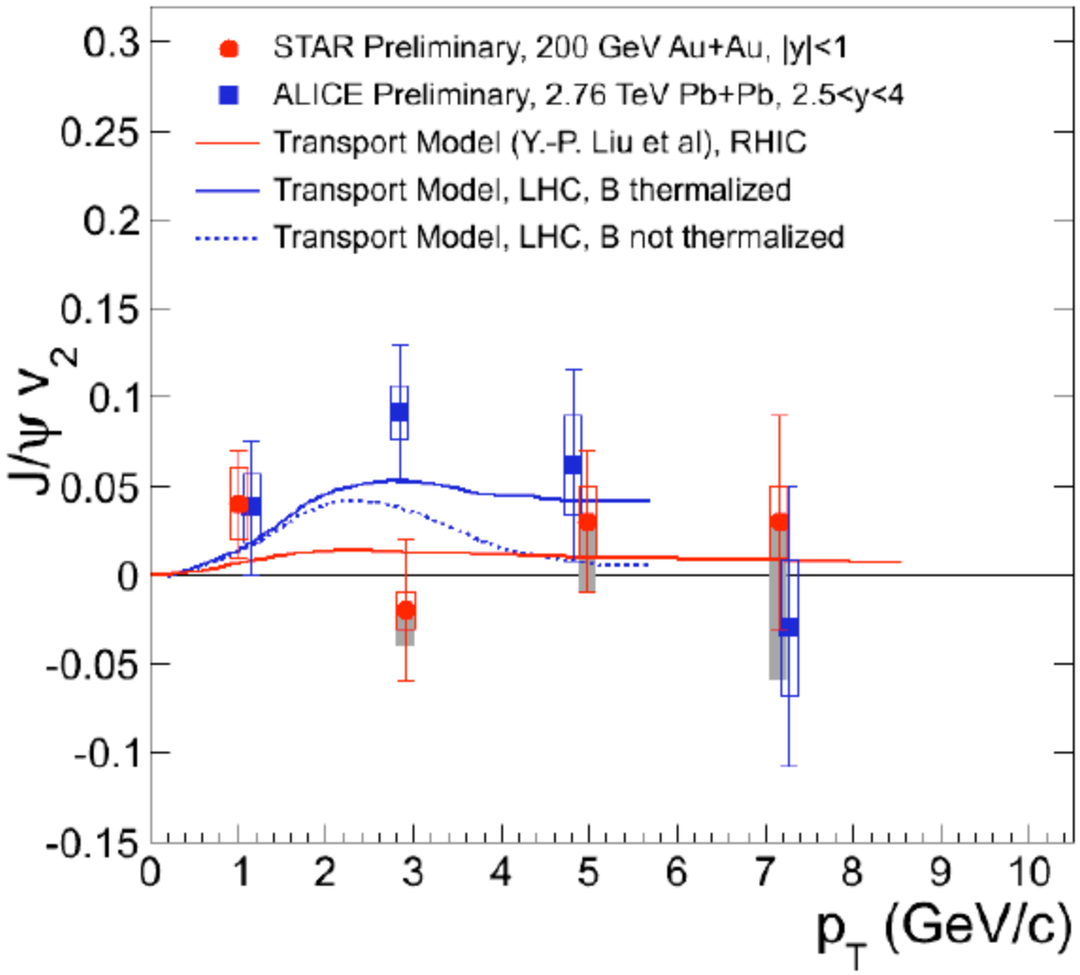
$v_2(p_T) = \langle\cos[2(\varphi-\Psi_R)]\rangle(p_T)$

If c quarks participate to the collective motion of the QGP, then they will acquire some elliptic flow and regenerated J/ψ will inherit their elliptic flow.

→ prediction for large flow at LHC for mid-p_T range from regeneration model

J/Ψ elliptic flow at forward rapidity

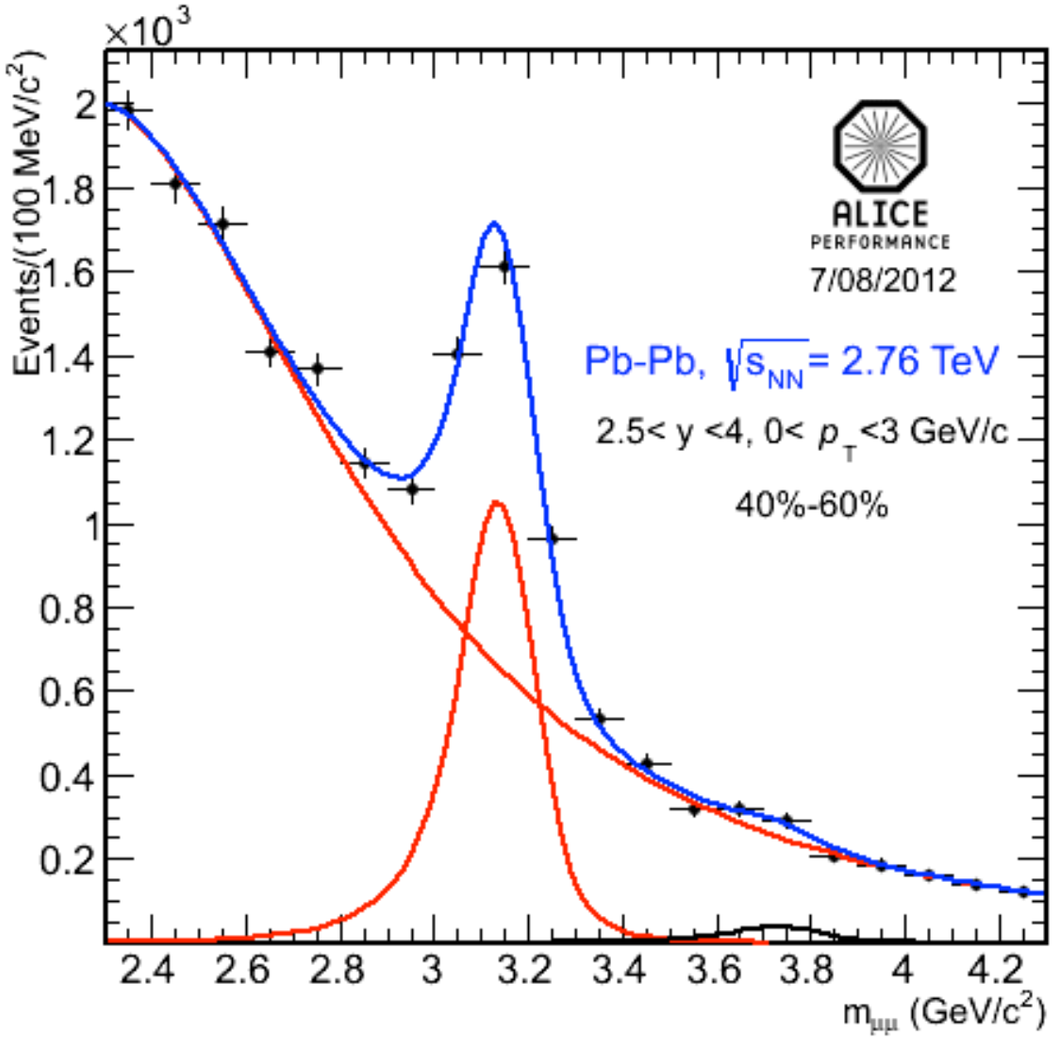
ALICE Coll. arXiv:1303:5880

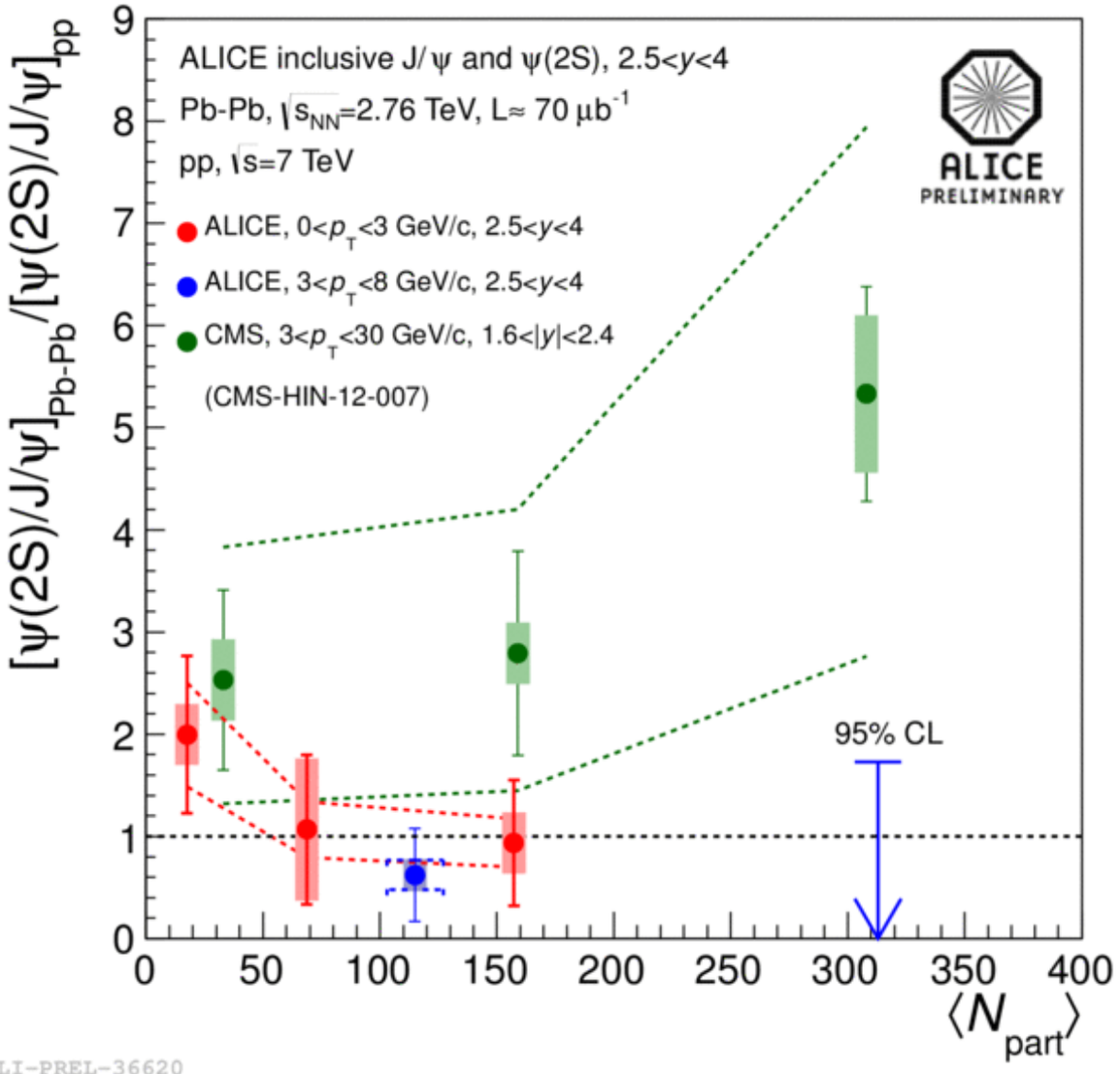


Non-zero J/Ψ v_2 observed at intermediate p_T for semi-central collisions at LHC (consistent with zero at RHIC)

v_2 complements R_{AA}: both are qualitatively well described by transport models including regeneration

Ψ(2S) measurements at forward rapidity

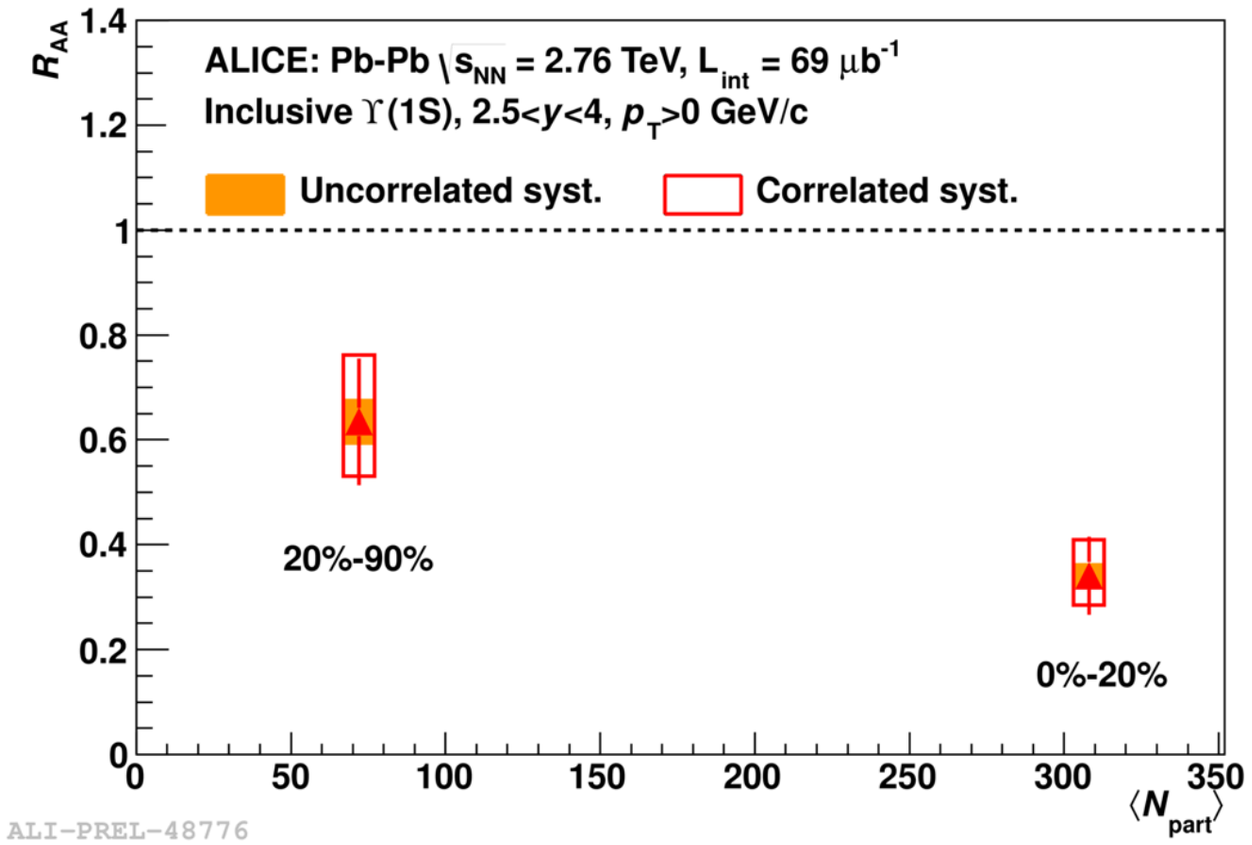




Double ratio measurement: Ψ(2S)/ J/Ψ in Pb-Pb over pp
pp reference from 7 TeV data but ratio is not expected to vary much with energy (dashed line uncertainty)

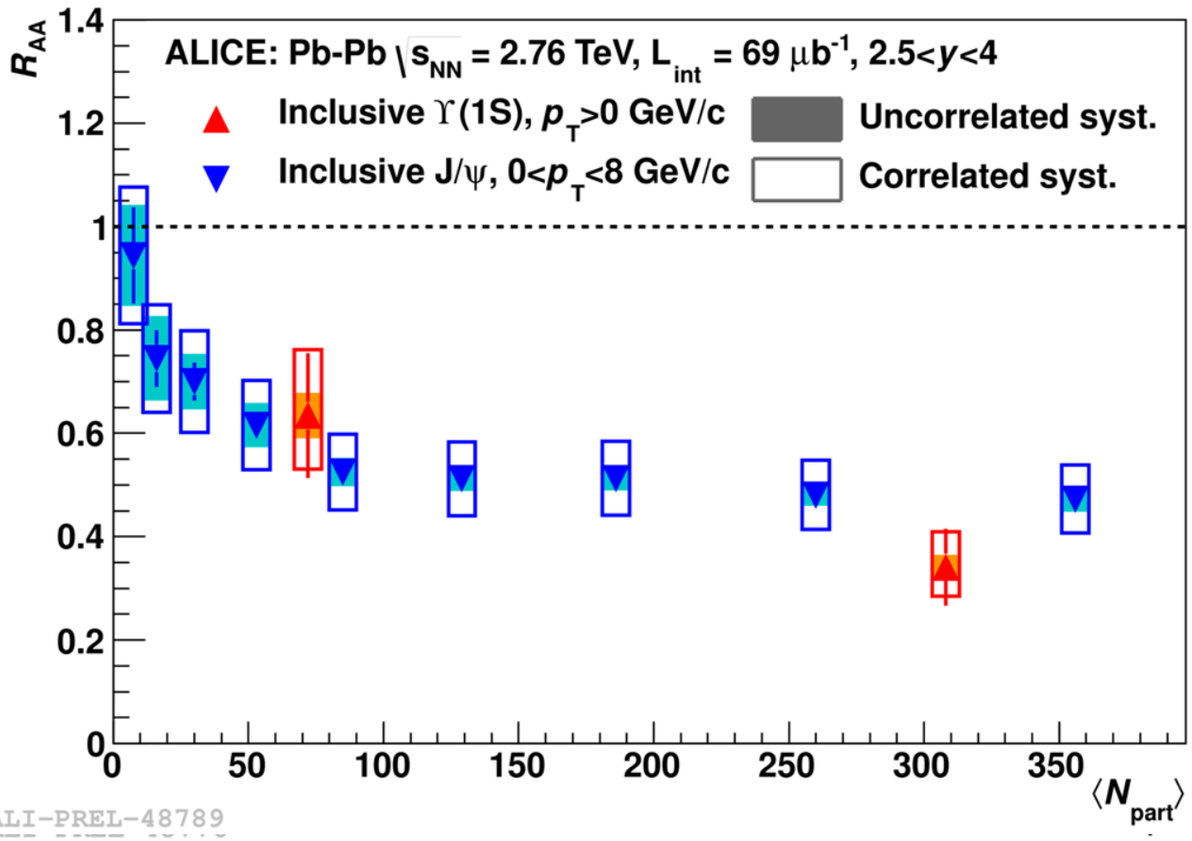
ALICE measurements has large uncertainties but there is not indication of a large Ψ(2S) enhancement in most central collisions

Y(1S) measurements at forward rapidity



Suppression increases for most central collisions

Y(1S) measurements at forward rapidity



Suppression increases for most central collisions

More suppressed than J/Ψ (but compatible within uncertainty) for most central collisions

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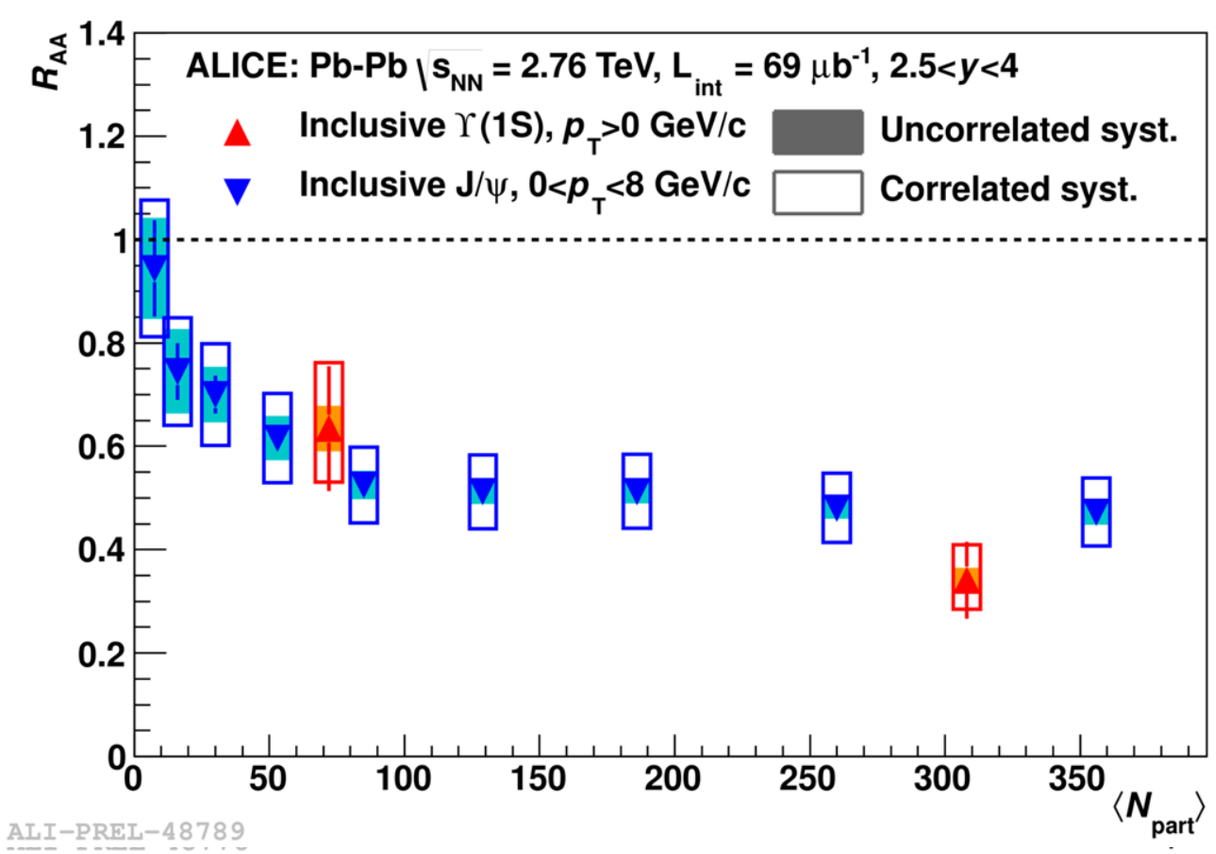
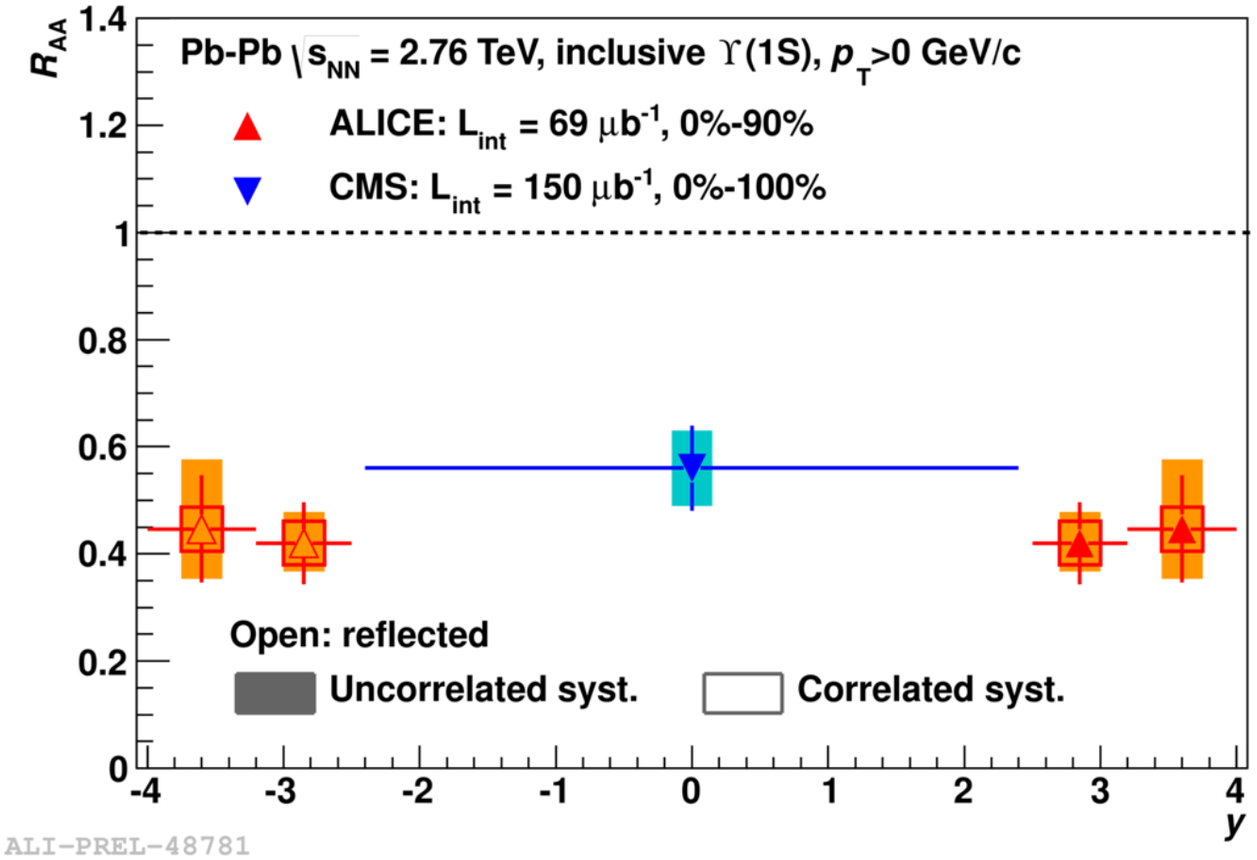


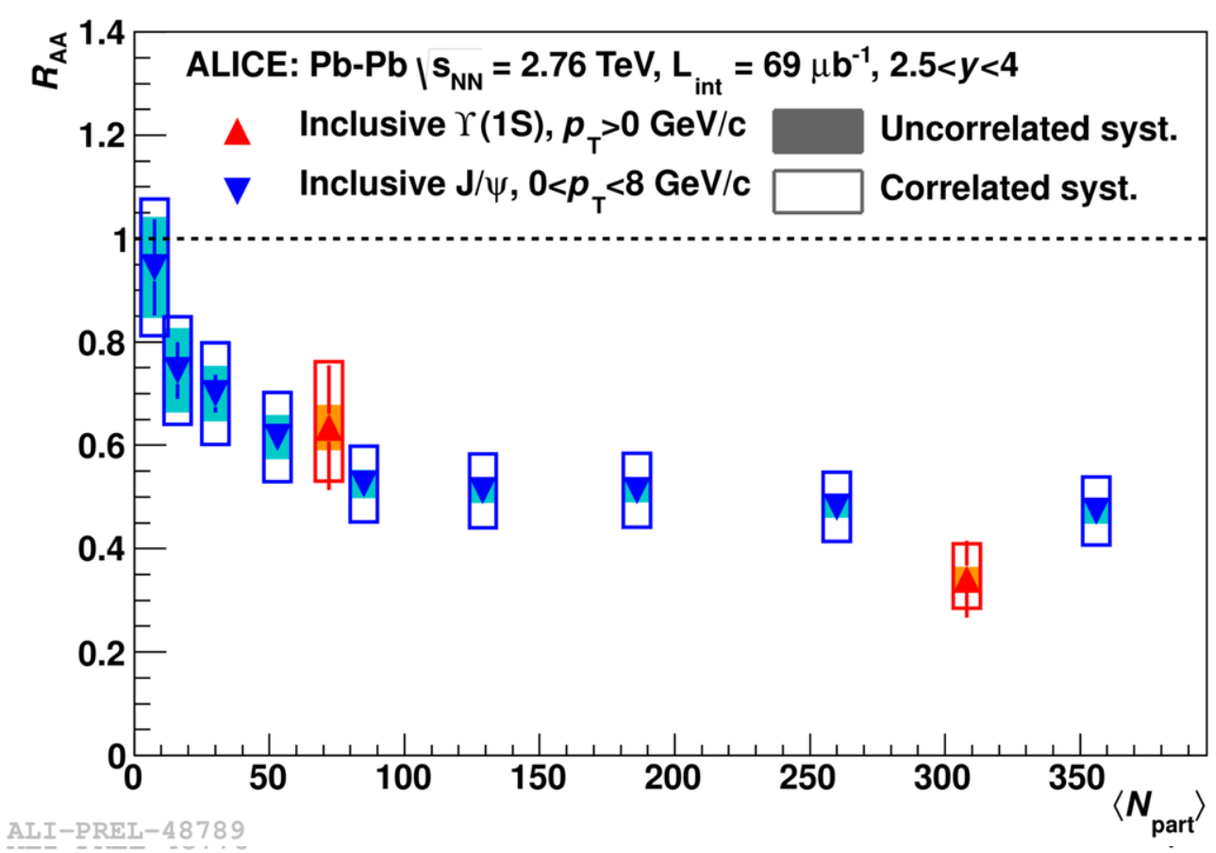


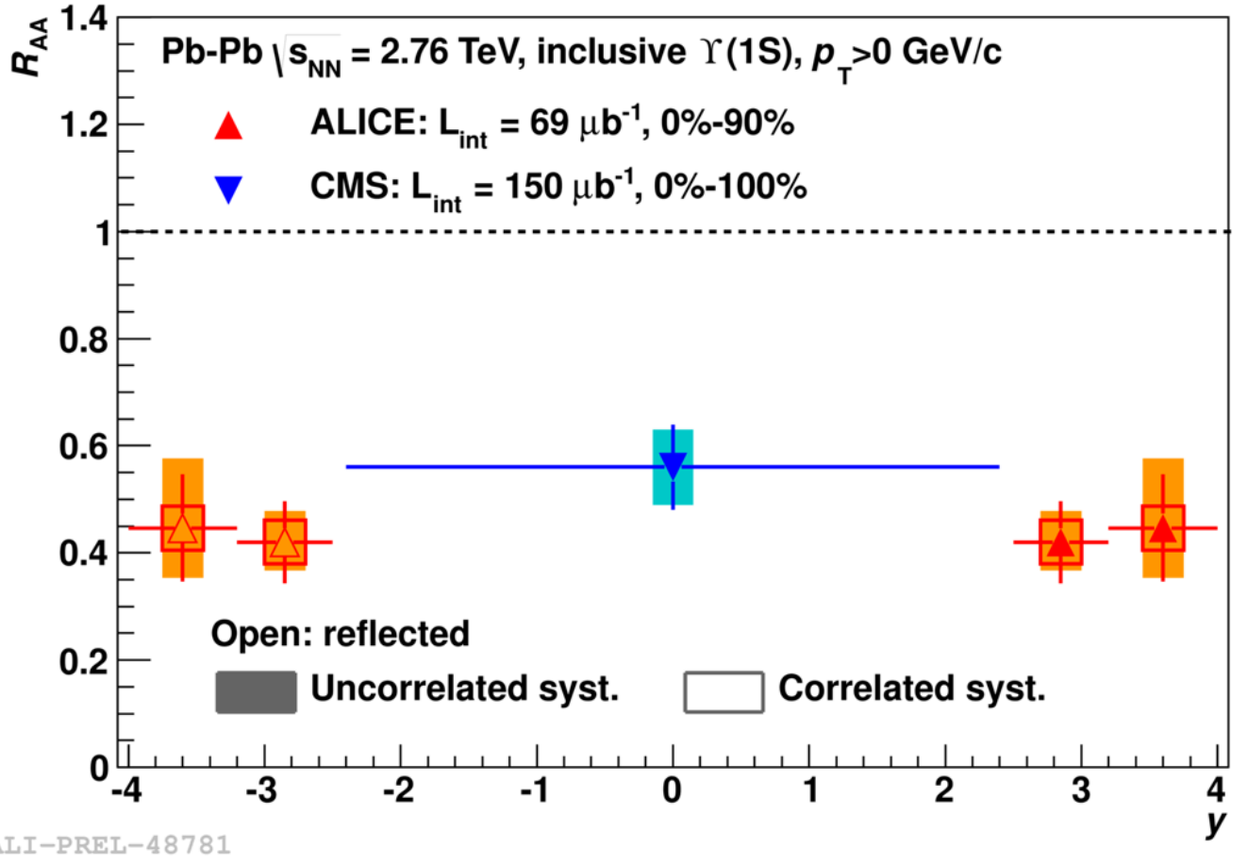
Suppression increases for most central collisions

More suppressed than J/Ψ (but compatible within uncertainty) for most central collisions

Small rapidity dependence as compared with CMS

Y(1S) measurements at forward rapidity





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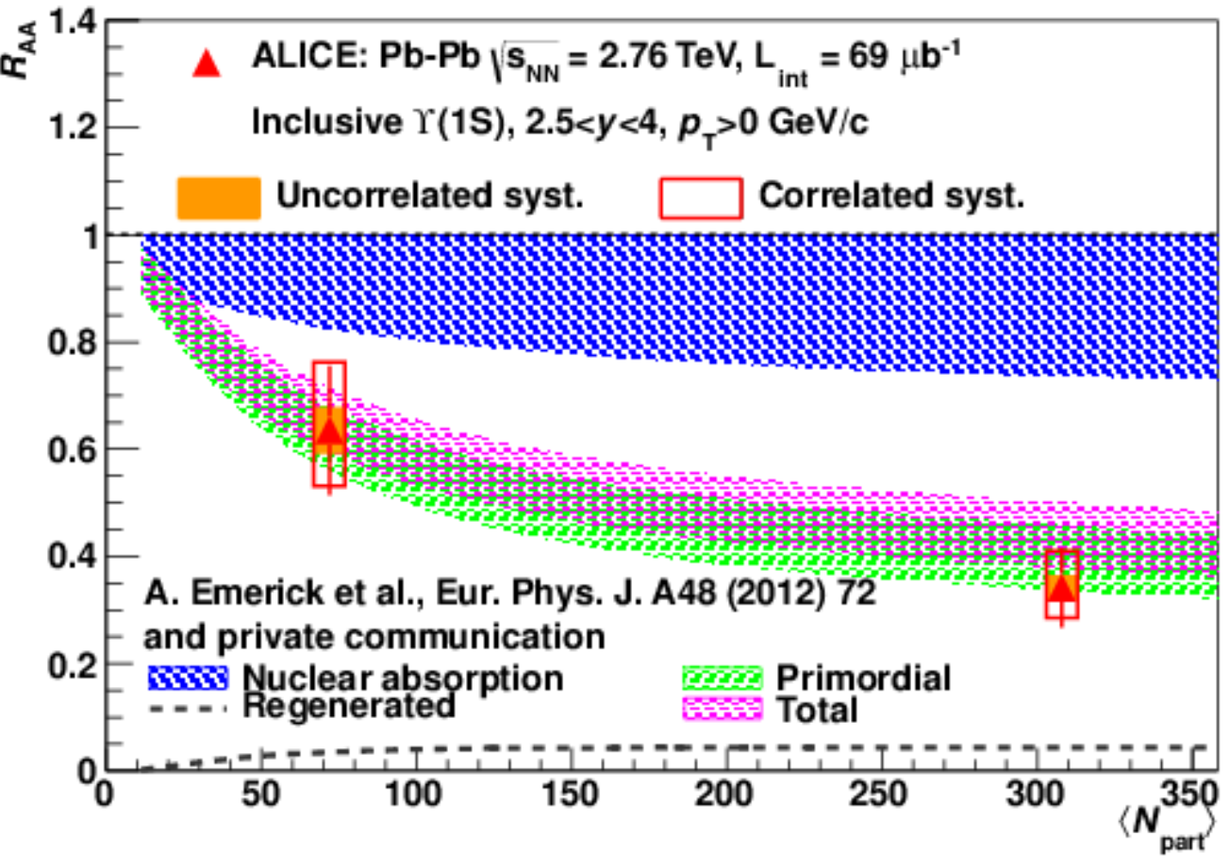
Y(1S) suppression compatible with feed-down suppression

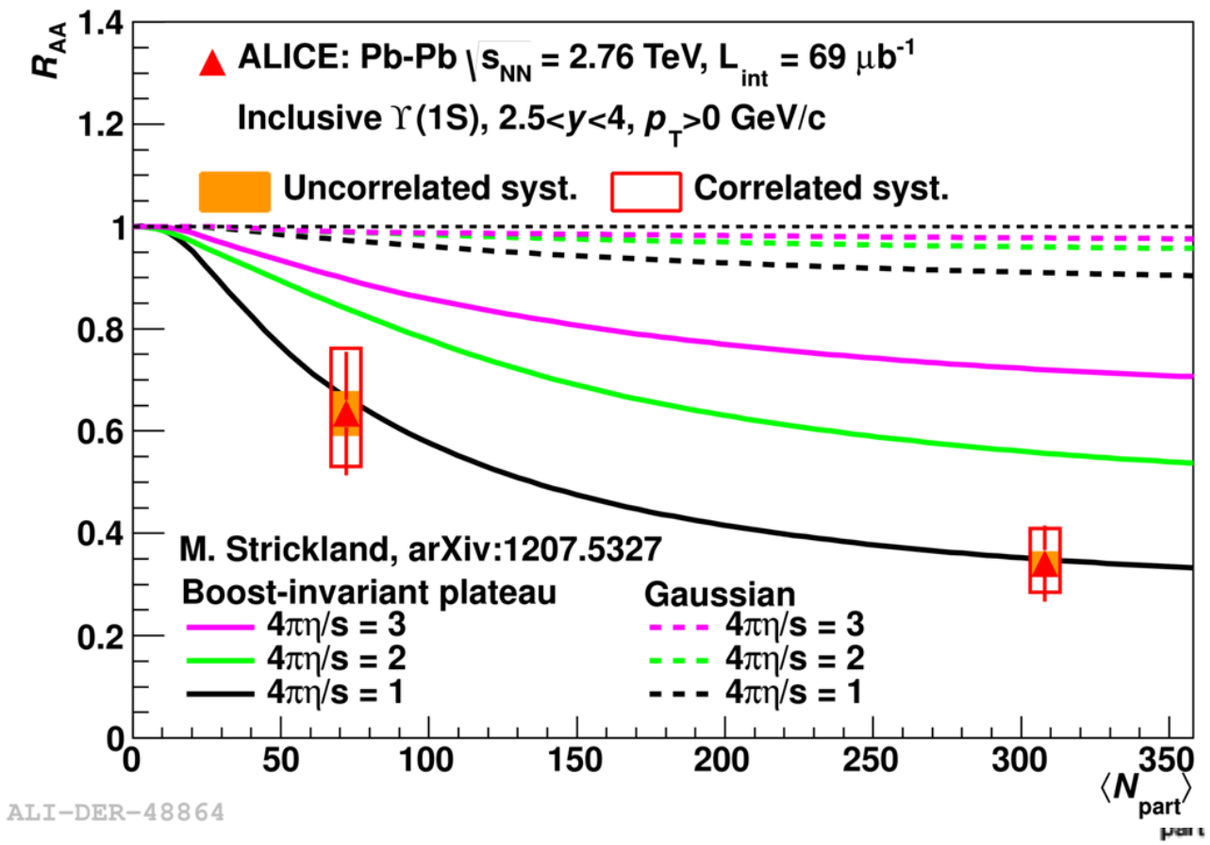
Y(1S) measurements at forward rapidity

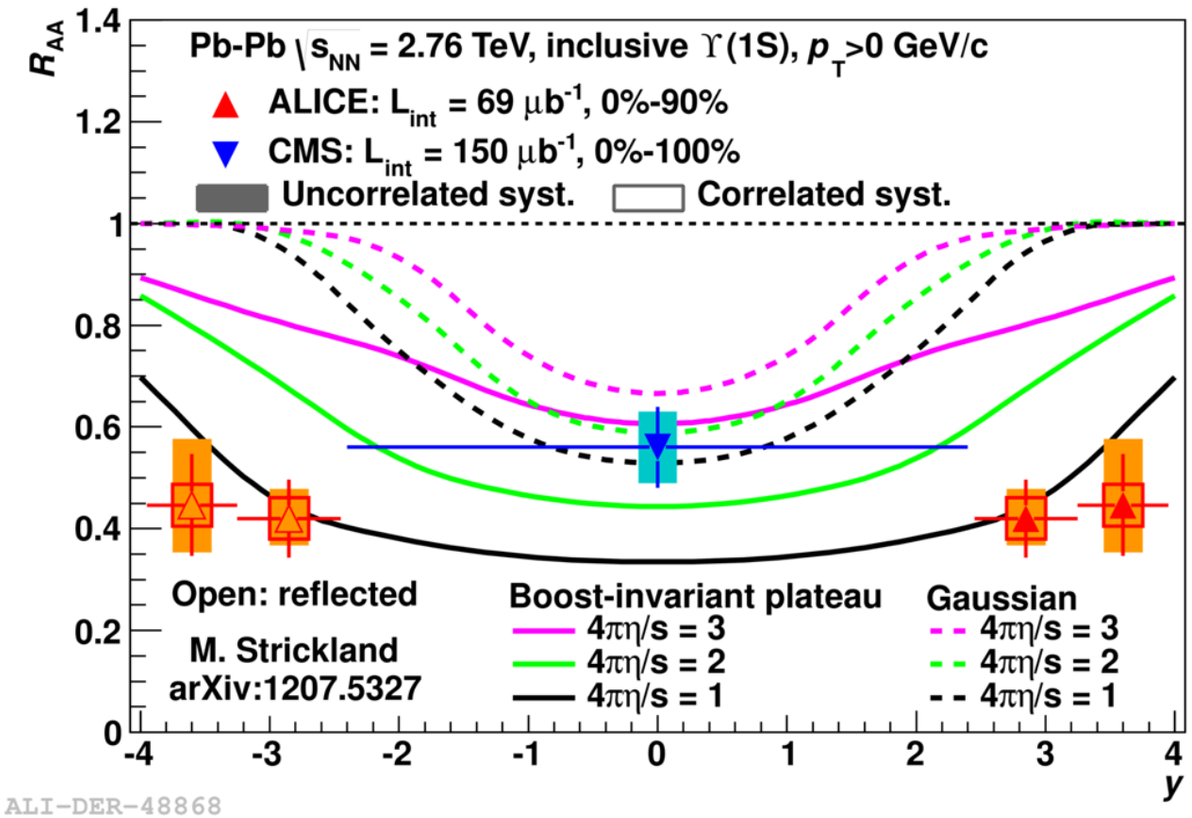


Models:

- Rate equation approach (Emerick et al.): suppression from dissociation and Y(1S) regeneration (small contribution), different absorption cross-sections (0 and 2 mb)
- Hydrodynamic model (Strickland): thermal dissociation and dynamic model, different hypothesis for the initial temperature profile suppression and the shear viscosity, no initial or final state cold nuclear effect

Y(1S) measurements at forward rapidity





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- Hydrodynamic model (Strickland): thermal dissociation and dynamic model, different hypothesis for the initial temperature profile suppression and the shear viscosity, no initial or final state cold nuclear effect

While equation rate model is in good agreement with data, the hydro model can not reproduce both ALICE and CMS data

p-Pb measurements at $\sqrt{s_{NN}} = 5.02$ TeV

Crucial measurements to determine the cold nuclear matter effects in heavy-ion collisions

2013 Jan.-Feb. data taking running conditions:
- 2 beam configurations: p-Pb and Pb-p
- Shift in rapidity in the proton beam direction
  $\Delta y = 0.465$

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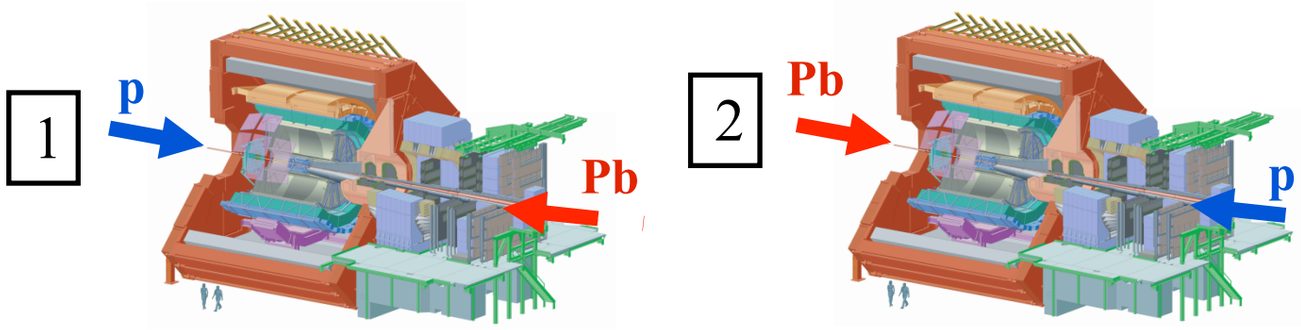
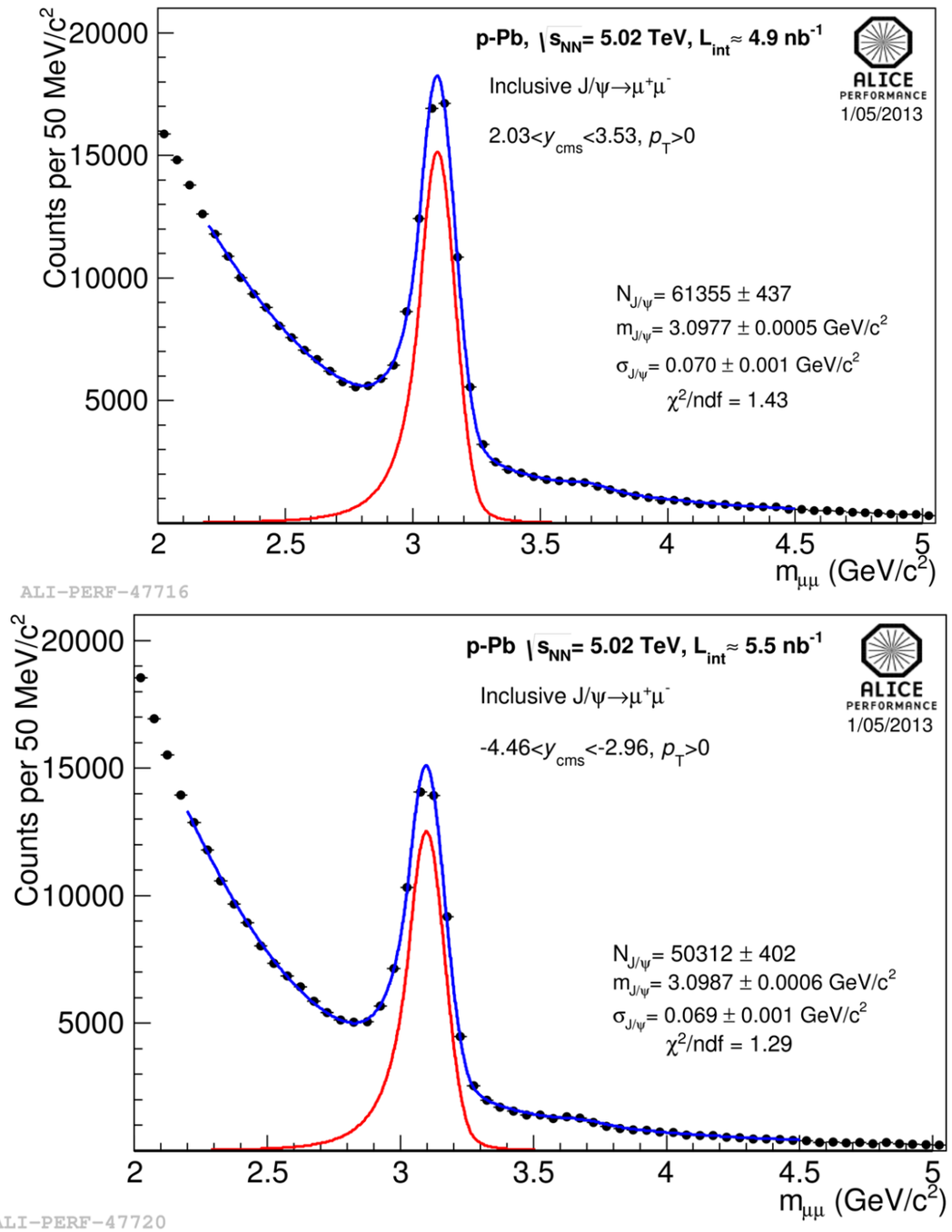
  → two rapidity ranges with the ALICE Muon Spectrometer



1	p-Pb	$2.5 < y_{lab} < 4$	$2.03 < y_{cms} < 3.53$
2	Pb-p	$-4 < y_{lab} < -2.5$	$-4.46 < y_{cms} < -2.96$

p-Pb measurements at $\sqrt{s_{NN}} = 5.02$ TeV



J/Ψ R_{pA} at forward rapidity

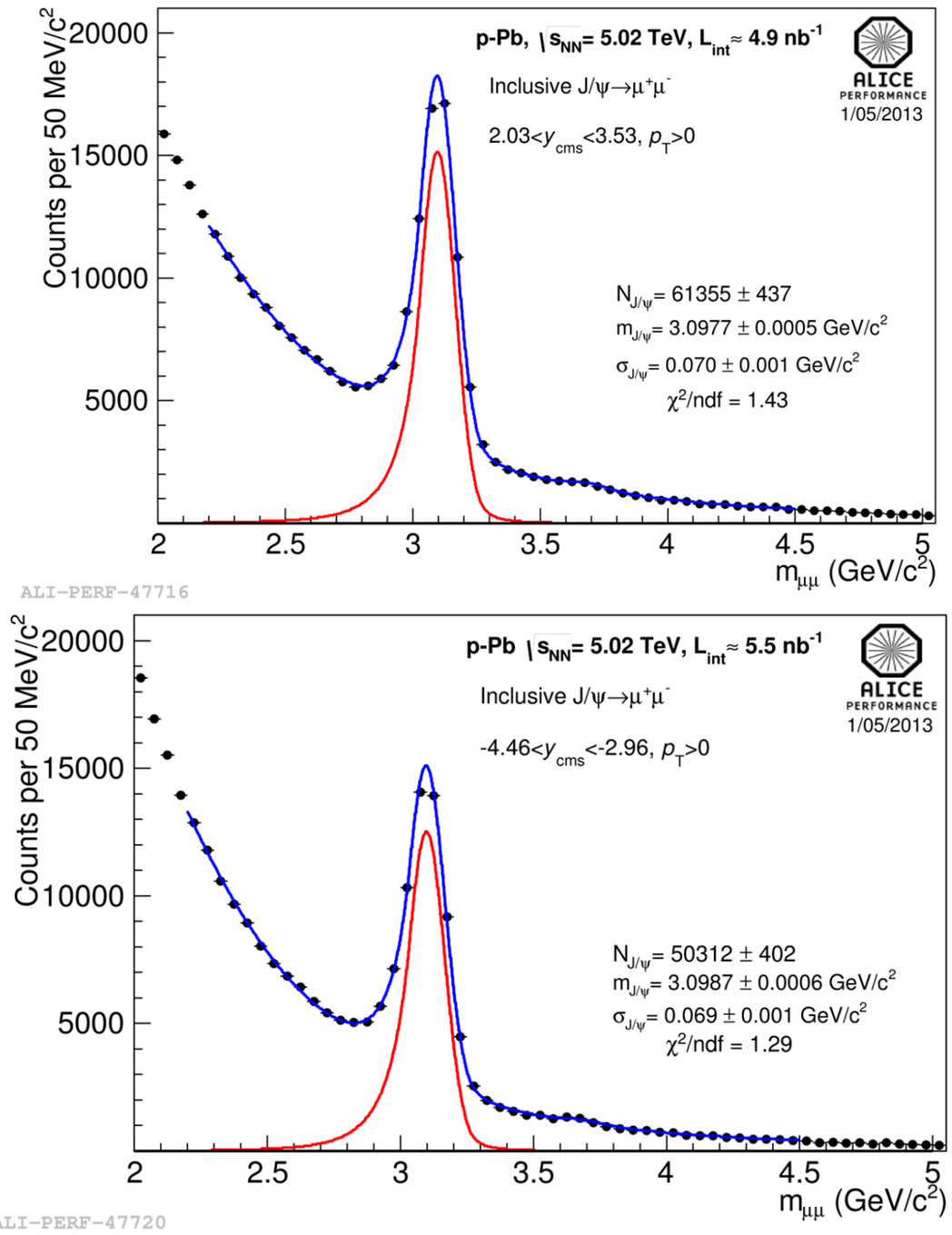
$$R_{pPb} = \frac{Y_{J/\psi\to\mu\mu}}{\langle T_{pPb}\rangle\, \sigma^{pp}_{J/\psi\to\mu\mu}}$$

$$Y_{J/\psi\to\mu\mu} = \frac{N_{J/\psi\to\mu\mu}}{N_{MB}\, A\, \epsilon}$$

No pp reference at 5.02 TeV

→ interpolation of world data

p-Pb measurements at $\sqrt{s_{NN}} = 5.02$ TeV



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J/Ψ R_{FB} evaluated at y_{cms}

$$R_{FB}(|y_{cms}|) = \frac{R_{pPb}(y_{cms})}{R_{pPb}(-y_{cms})} = \frac{Y_{pPb}(y_{cms})}{Y_{pPb}(-y_{cms})}$$

pp reference cancels out

but rapidity range restrained to the common range:

$2.96<|y_{cms}|<3.53$

$R_{p\text{-}Pb}$ vs y_{cms}: pp cross-section interpolation

Two steps procedure using phenomenological parametrization ***F. Bossu et al. arXiv:1103.2394***

Energy interpolation at mid-rapidity

Data set: RHIC @ 200 GeV, CDF @ 1.96 TeV, ALICE @ 2.76, 7 TeV

Parametrization: power-law

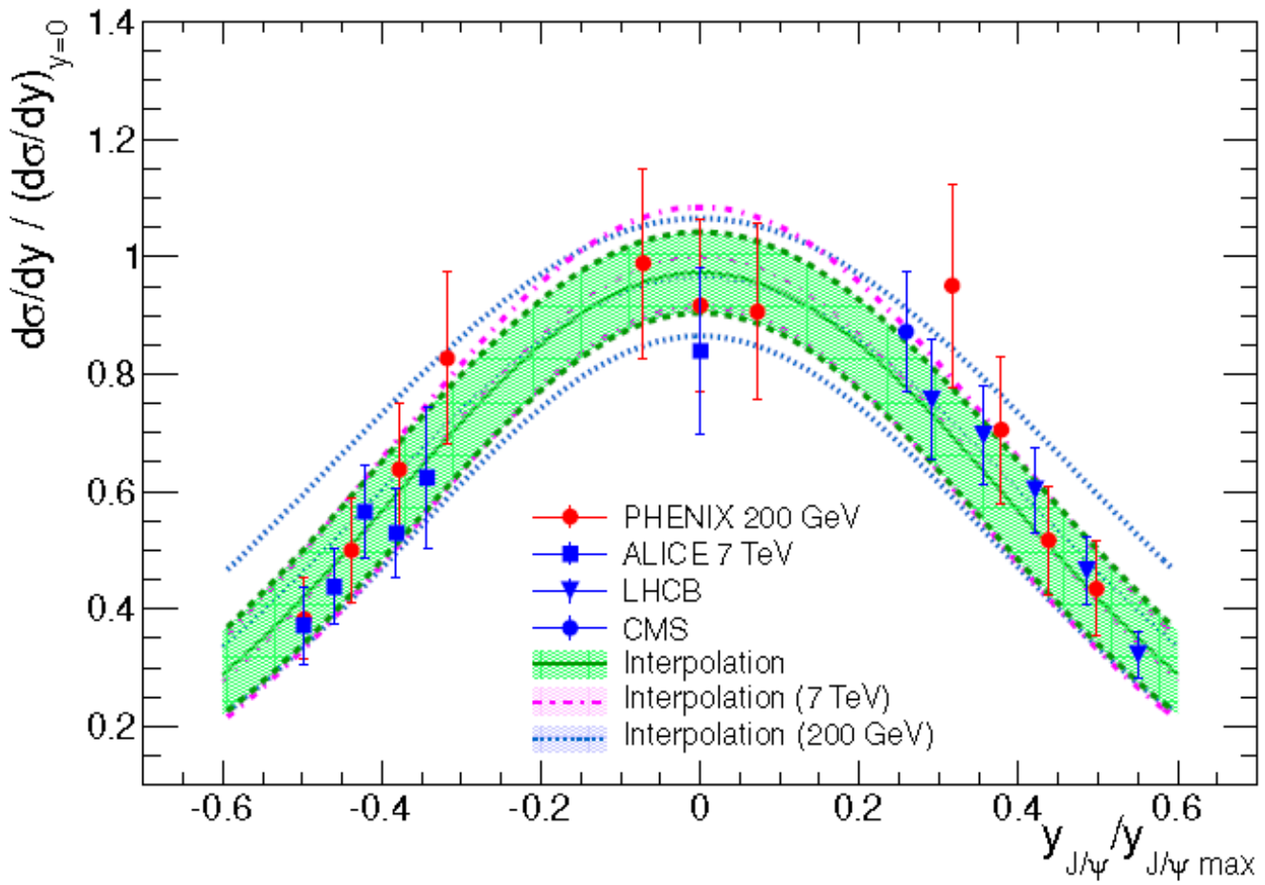
BR $d\sigma_{pp}/dy|_{y=0}$ (5.02 TeV) = 362 ± 6 (stat)+ 55 (syst)- 37(syst) nb

Rapidity interpolation (integrated over p_t)

Data set: RHIC @ 200 GeV, ALICE + LHCb @ 7 TeV

Observation: if scaling variable Y= y / y_{max} is used, no dependence in energy of $d\sigma/dY$ / $(d\sigma/dY)_{Y=0}$

Parametrization: gaussian



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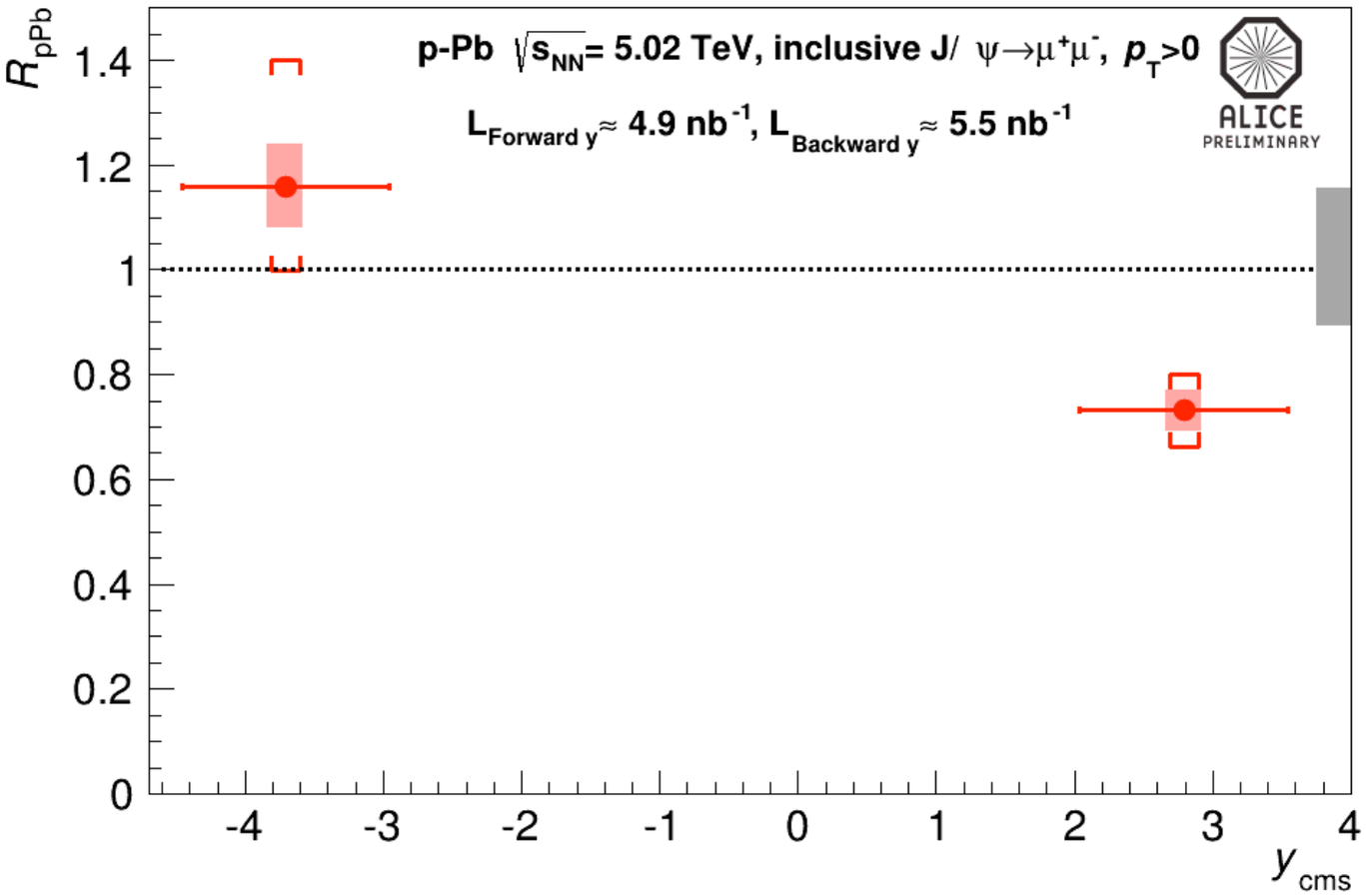


Systematic uncertainties
grey box forward to backward fully correlated
[] partially correlated
red box uncorrelated

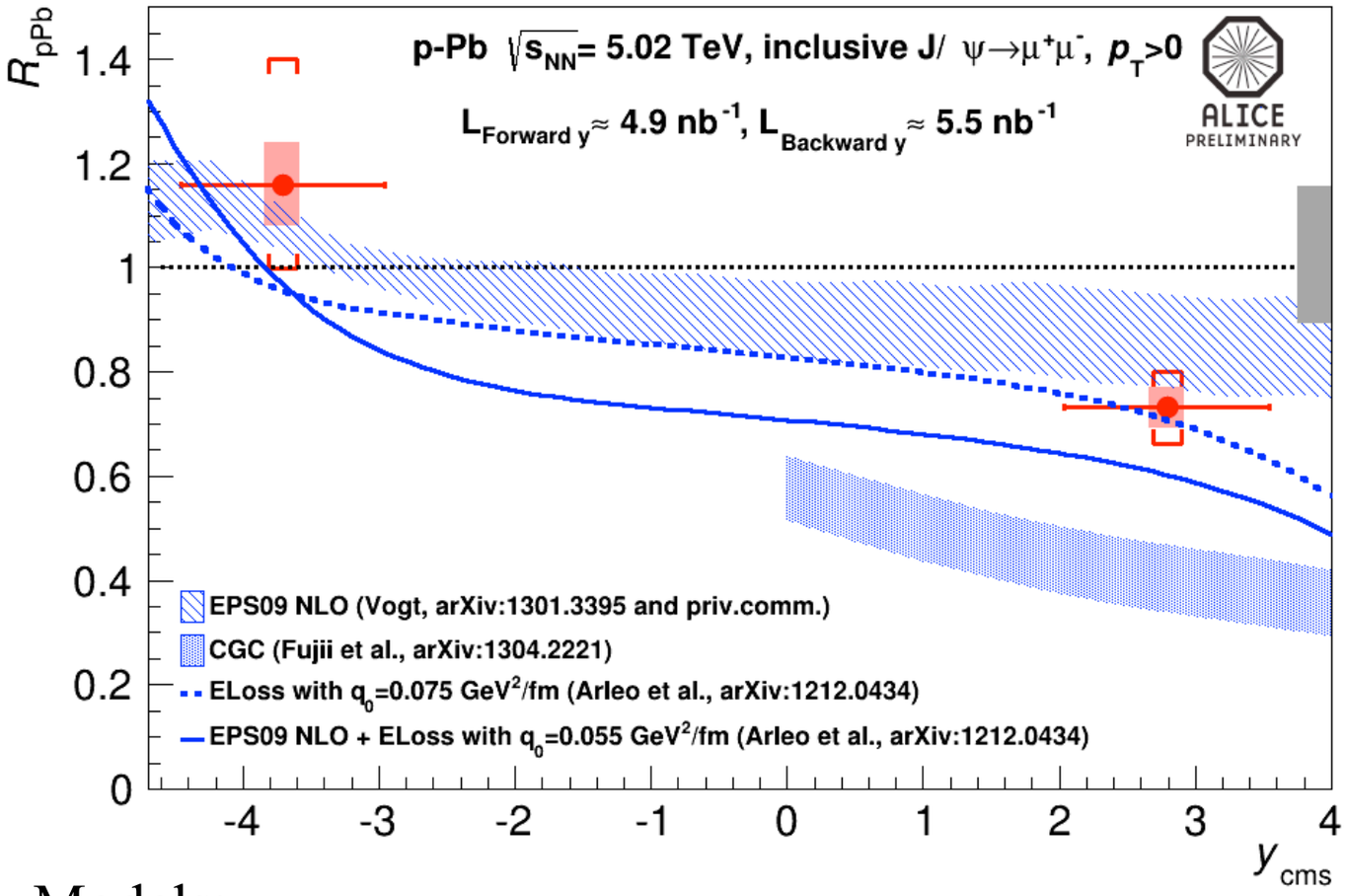
Uncertainties dominated by the pp interpolation

J/Ψ suppressed at forward rapidity

LHCb measurement of non-prompt to prompt J/Ψ ratio: f_B does not differ much in pp, p-Pb forward and backward: inclusive R_{pPb} ~ prompt R_{pPb}

Trento2013 LHCb-CONF-2013-008

$R_{p\text{-}Pb}$ vs y_{cms}



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Models:

- Shadowing model EPS09NLO (Vogt)
- Coherent energy loss (Arleo et al.): interference between gluon emission amplitudes before (inital state energy loss) and after (final state energy loss) the hard process
- Gluon saturation (Fuji et al.): Color Glass Condensate framework, saturation scale $Q^2_{s,A}(x=0.01)$= 0.7-1.2 GeV/c²

Shadowing: y-dependence well reproduced, lower band in better agreement (strong shadowing at forward rapidity)
Coherent energy loss: y-dependence well reproduced, maybe too steep at backward rapidity
CGC calculations underestimate the data by a factor two
→ No much room for other cold nuclear effect as final state nuclear absorption

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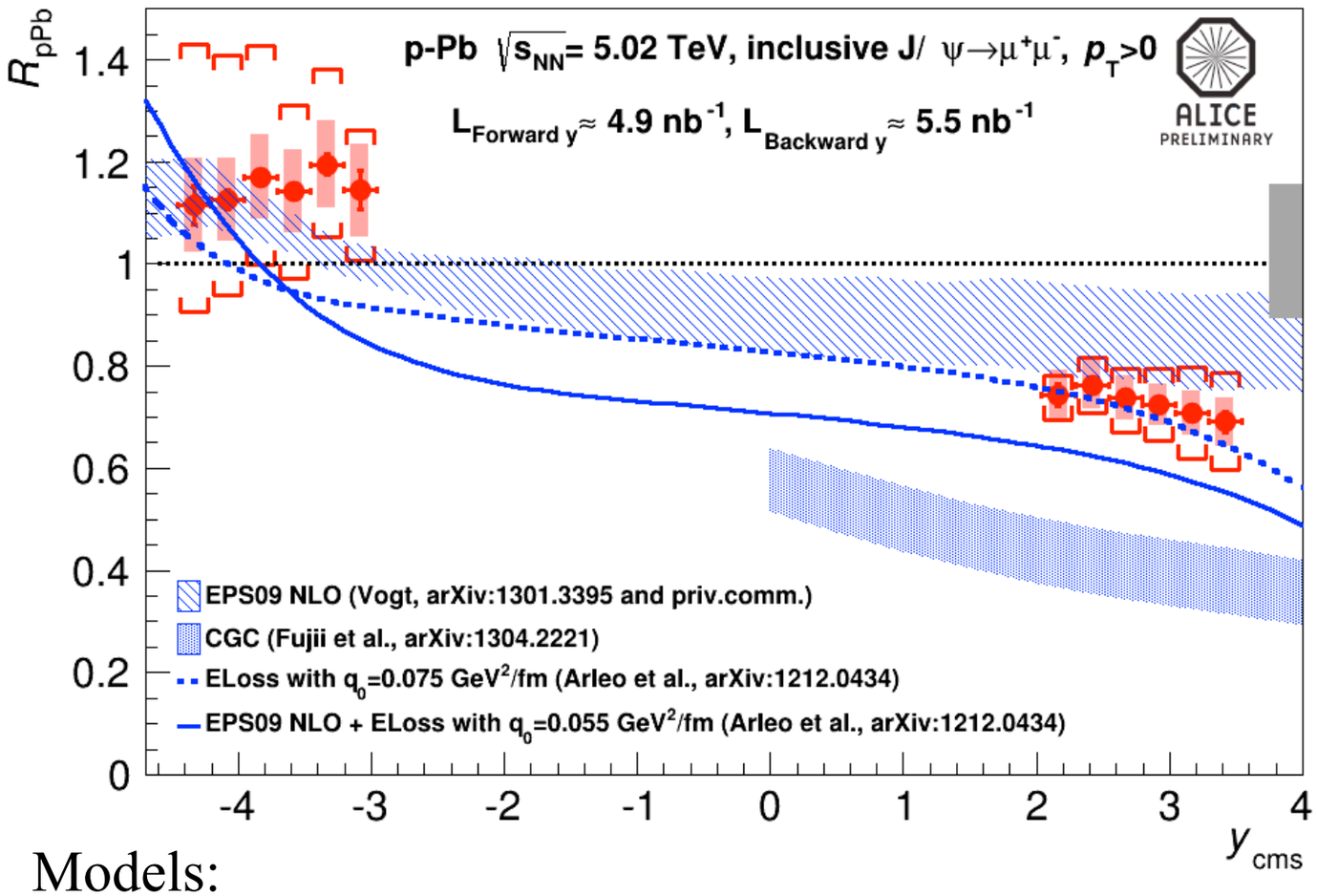

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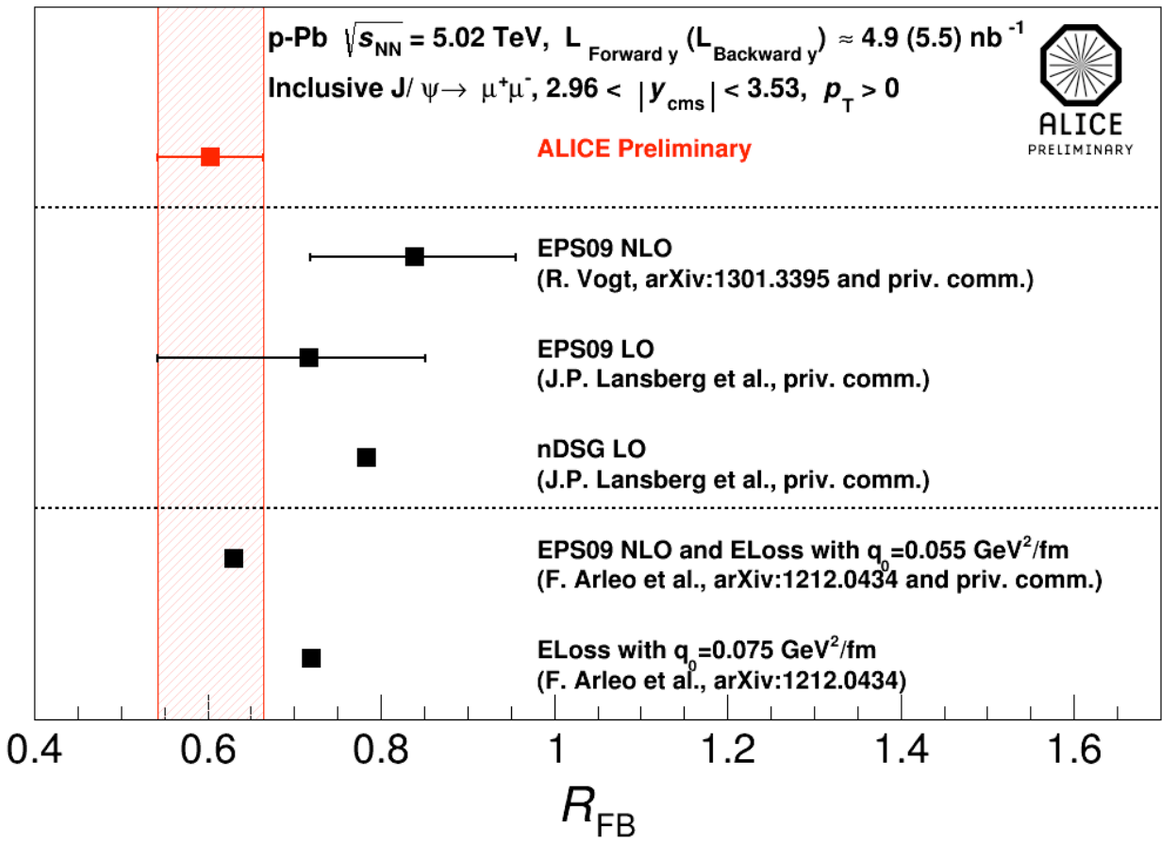
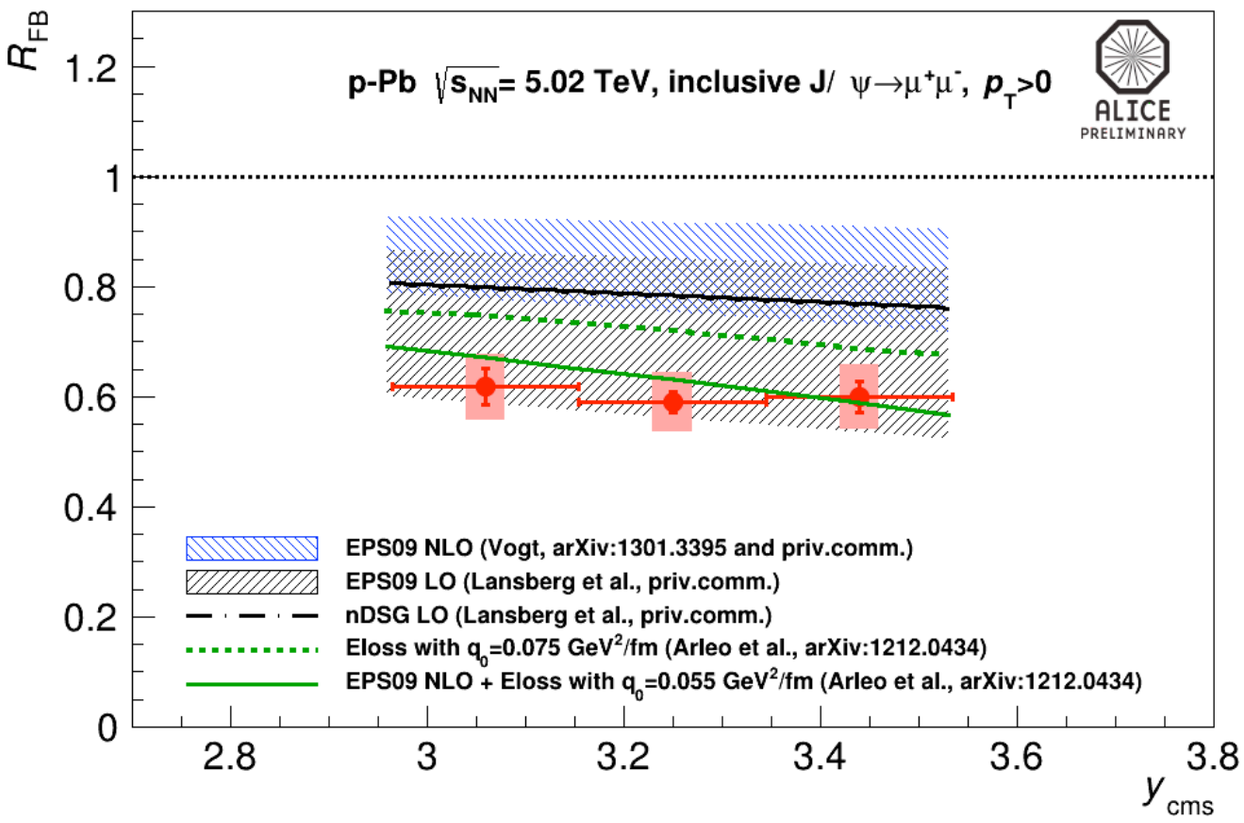
Forward to Backward Yield Ratio: R_{FB}





Uncertainties dominated by the systematics

No strong rapidity dependence within $2.96 < |y_{cms}| < 3.53$

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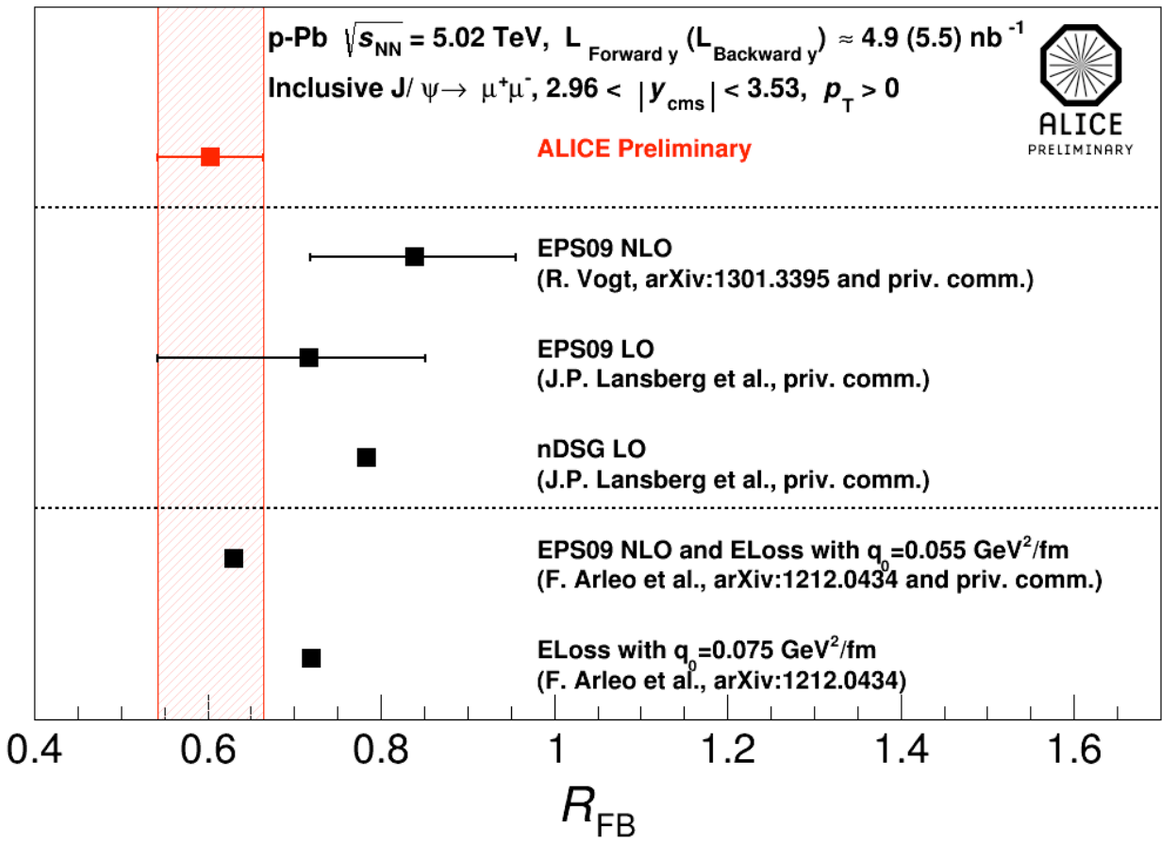

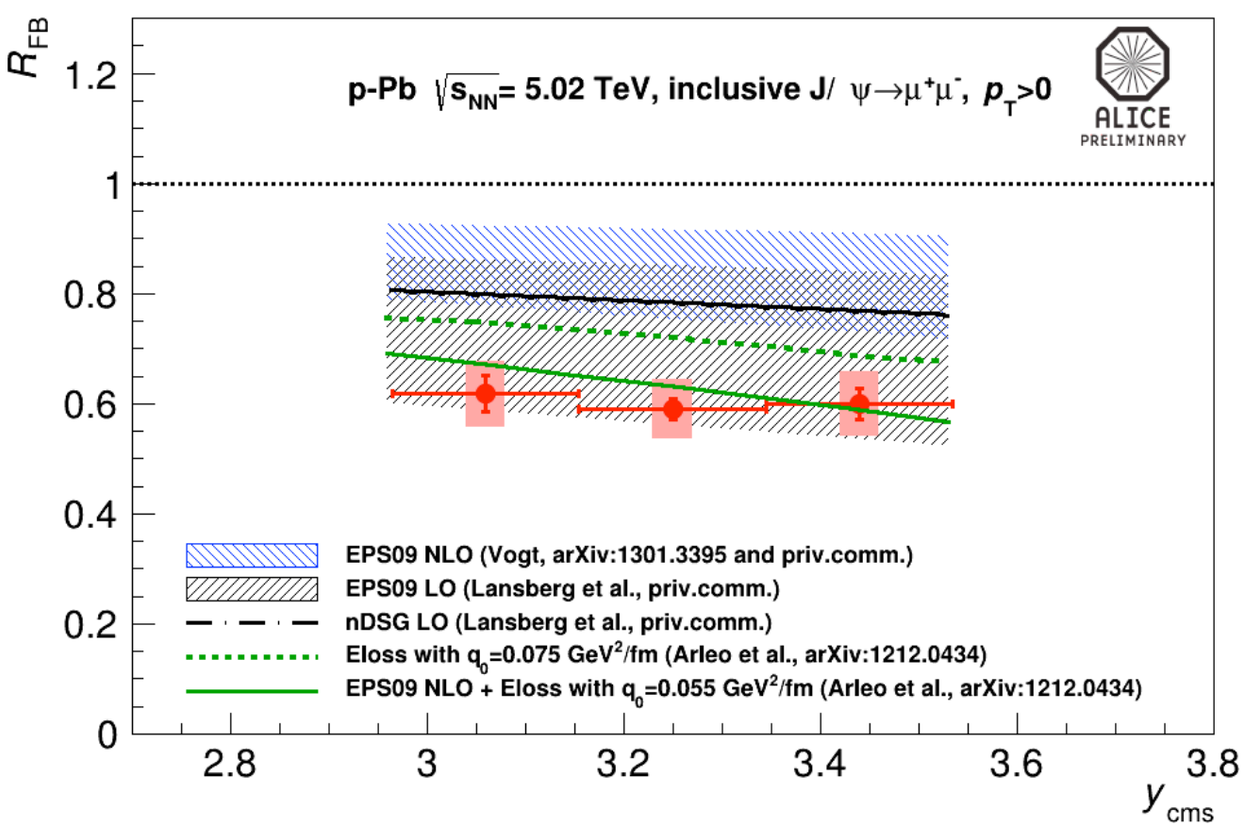

Uncertainties dominated by the systematics

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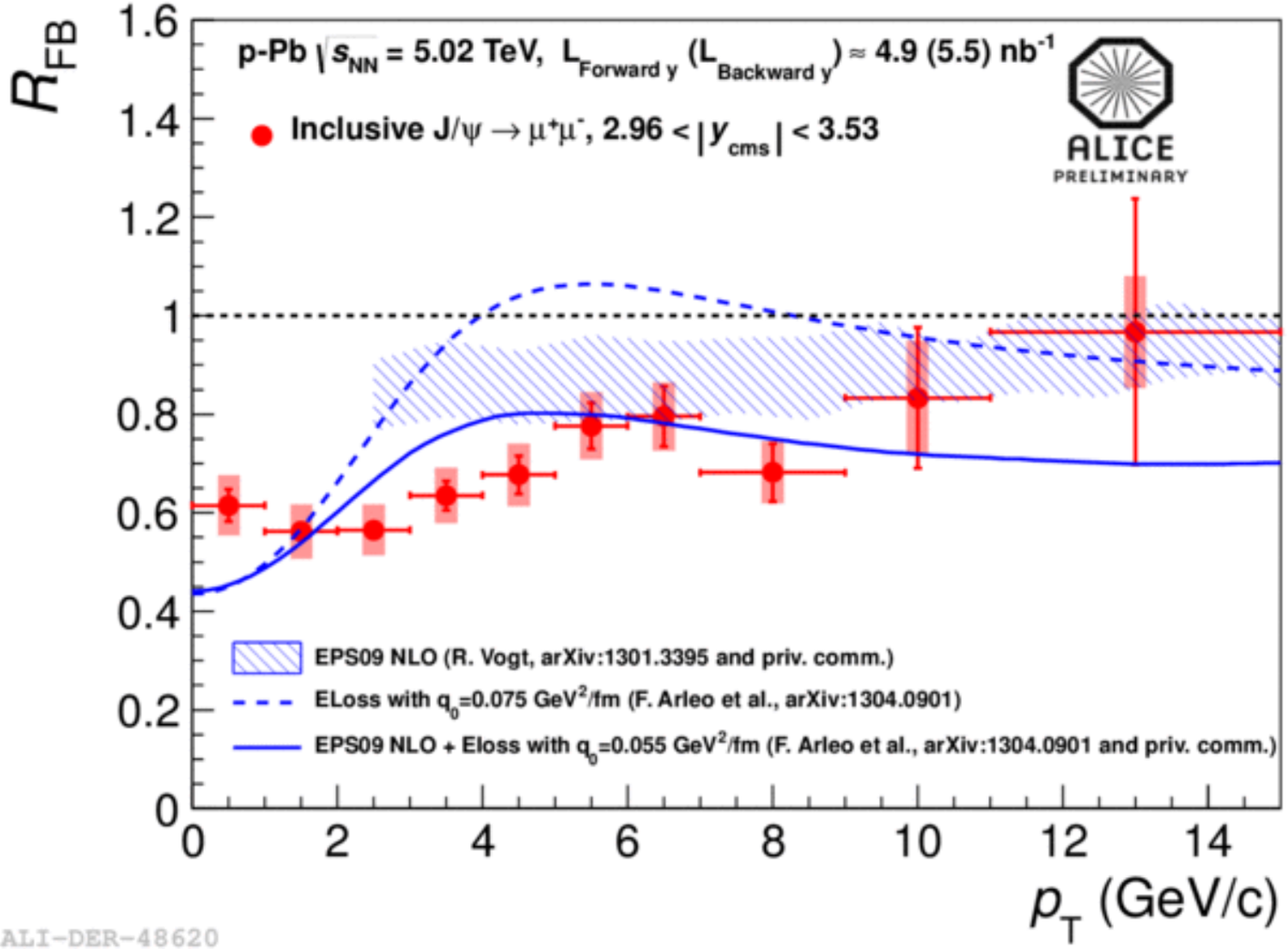
Models:

- Shadowing model EPS09NLO (Vogt) and nDSG LO (Lansberg et al.): overestimate the data by ~30%
- Shadowing model EPS09LO (Lansberg et al.): lower value and larger uncertainty than EPS09NLO, in agreement with the data
- Coherent energy loss (Arleo et al.): in better agreement with the data if shadowing is included

R_{FB} vs p_T

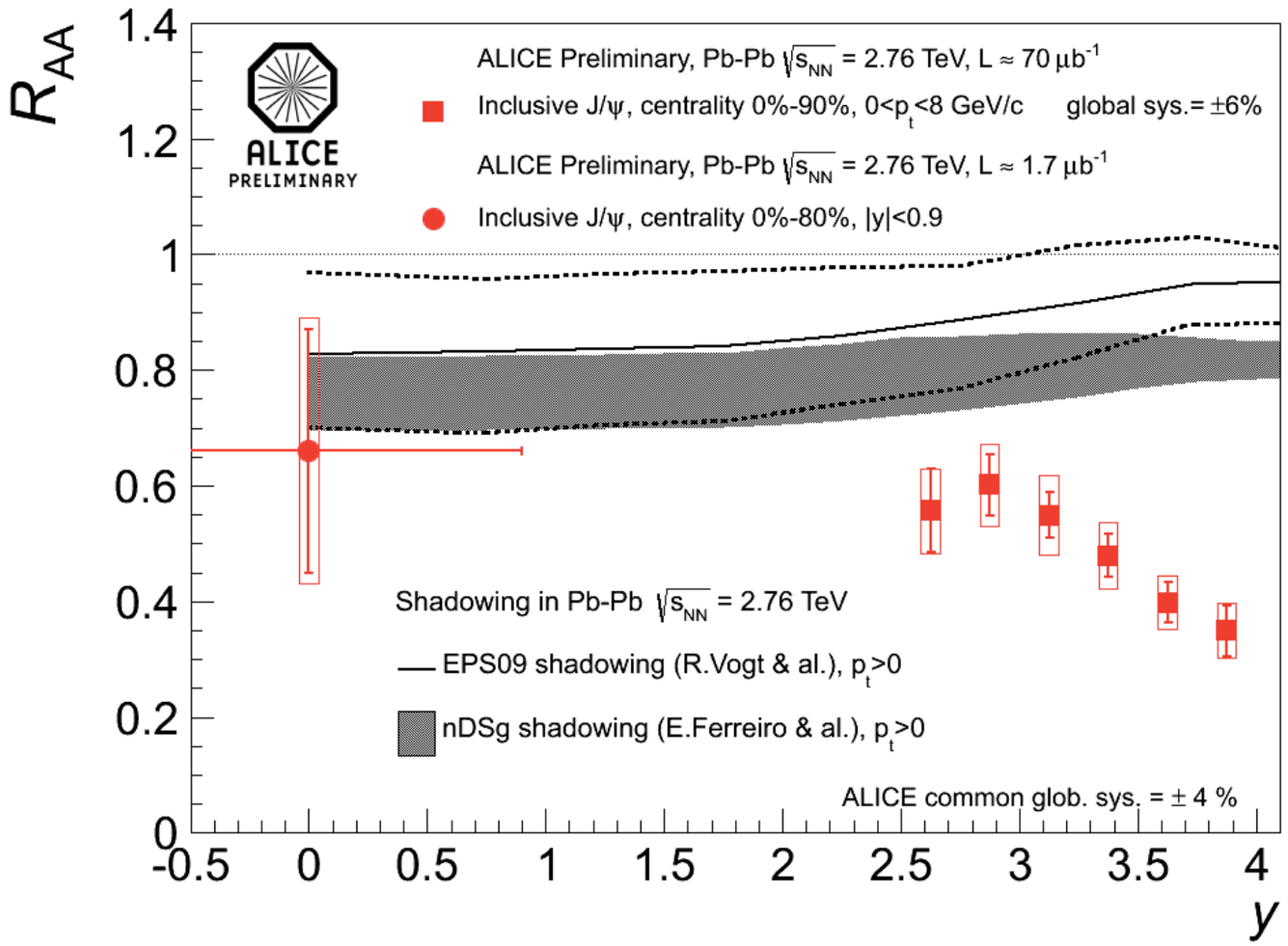


R_{FB} increases toward unity with increasing p_T : the forward/backward asymmetry is larger at low p_T

Models:

- Shadowing model EPS09NLO (Vogt): does not reproduce the p_T shape
- Coherent energy loss (Arleo et al.): stronger p_T dependence at low p_T than the data

Let's go back to J/Ψ R_{AA} vs y



If we believe the lower uncertainty band of the EPS09 NLO shadowing gives a reasonable description of cold nuclear matter effect in p-Pb then the effective measured suppression in Pb-Pb would be smaller and the decrease vs rapidity slightly stronger

Conclusion

- Quarkonium production is used as a probe of the hot (QGP) and cold nuclear matter effects

- pp: important measurements that allow us to constrain the quarkonium production mechanism and serve as reference for Pb-Pb (cross-section, non-prompt contribution, polarization, ...)

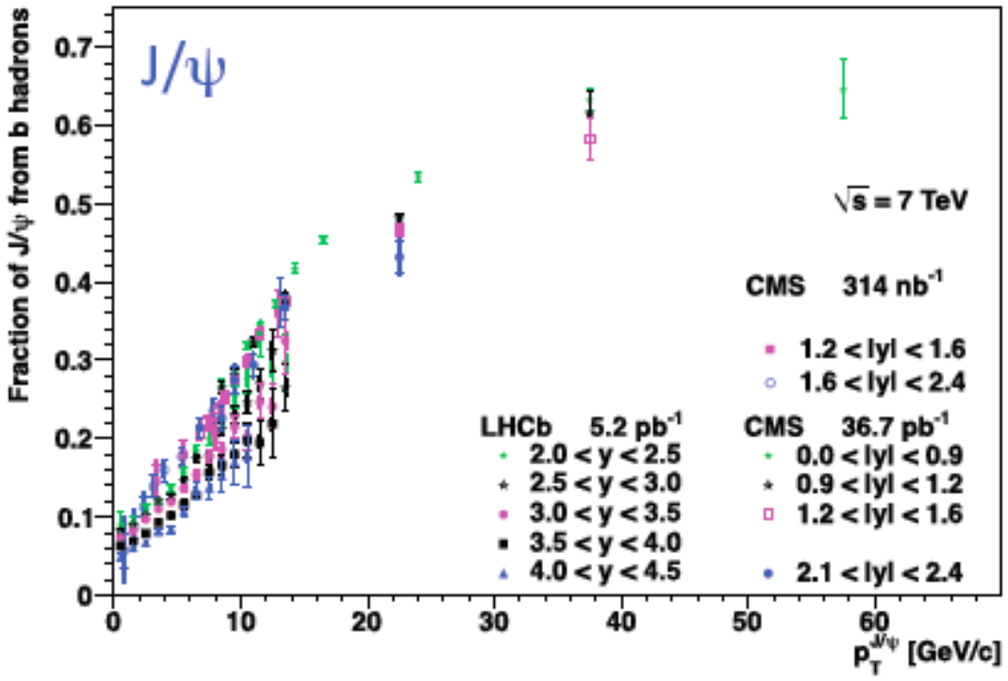
- Pb-Pb measurements:
  - J/Ψ : R_{AA} measurements show a different behaviour wrt lower energy measurements. Models including J/Ψ production from deconfined charm quarks in the QGP phase reproduce well the R_{AA}. The hint of a non zero v_2 is also in agreement with regeneration models expectaction.
  - first $\Upsilon(1S)$ R_{AA} at forward rapidity: small rapidity dependence as compared to CMS

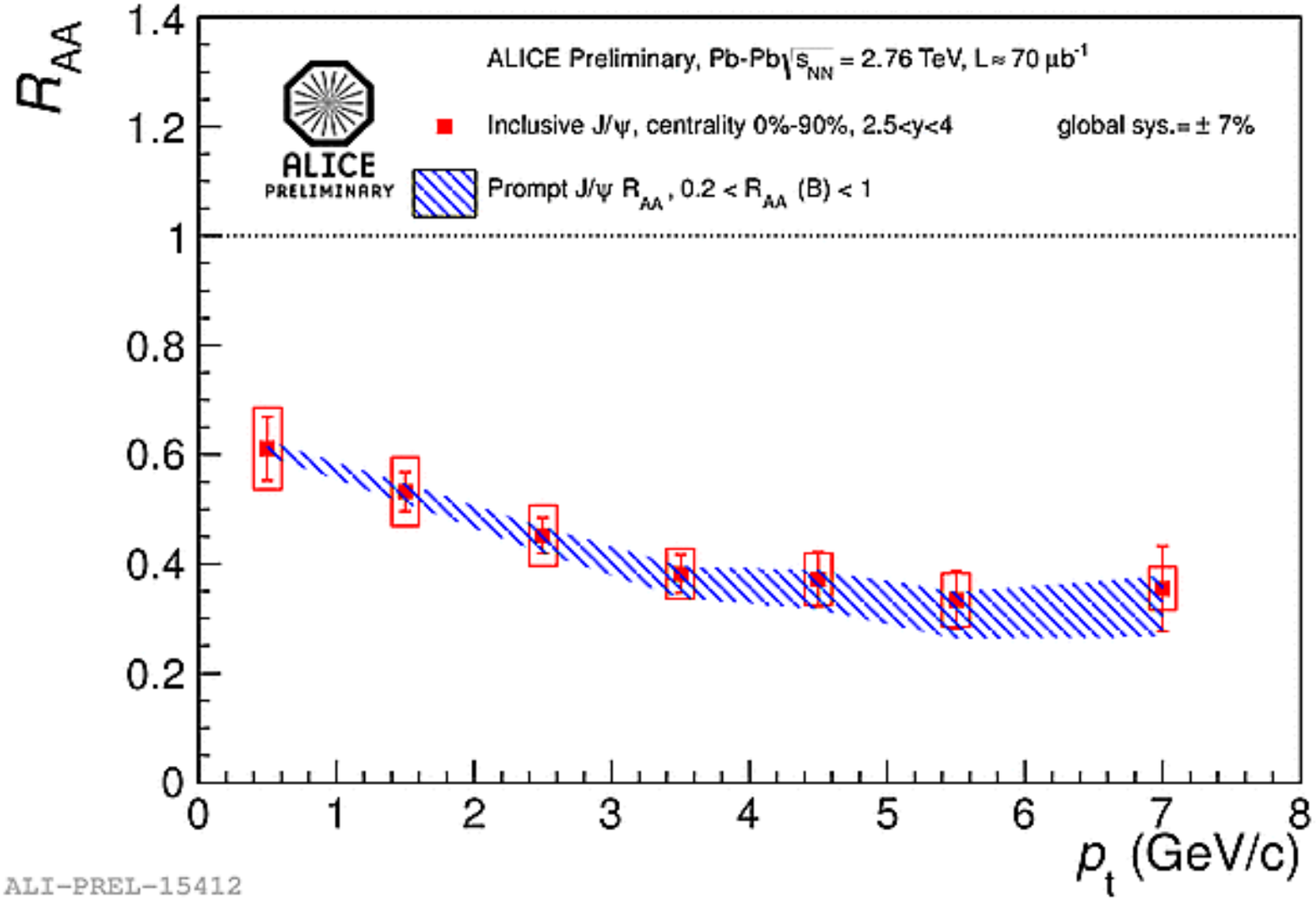
- p-Pb measurements: first J/Ψ measurements support the coherent energy loss model and/ or a strong shadowing at forward rapidity

More measurements to come, stay tuned!

back-up slides

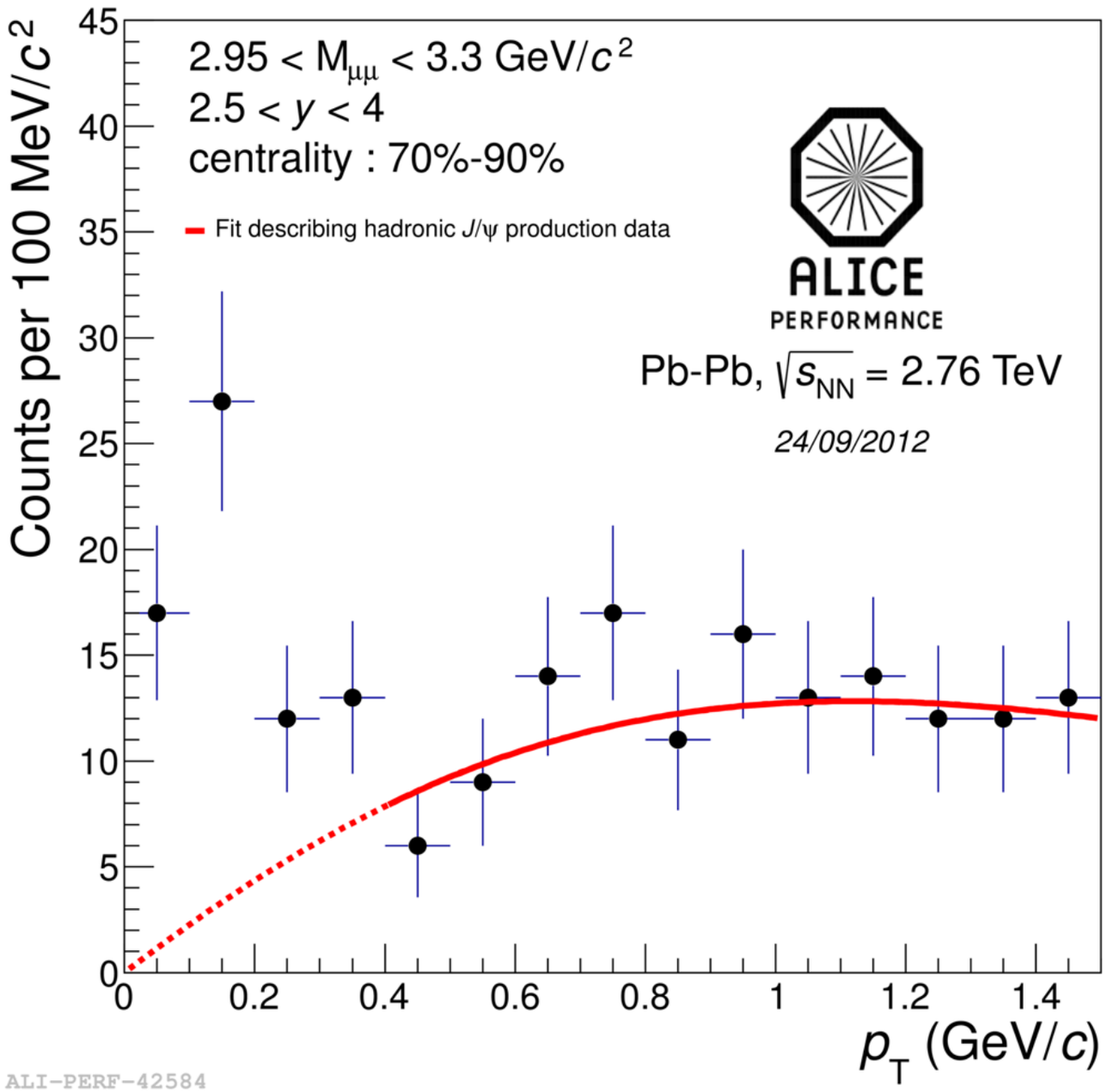
From inclusive to prompt J/Ψ R_{AA}

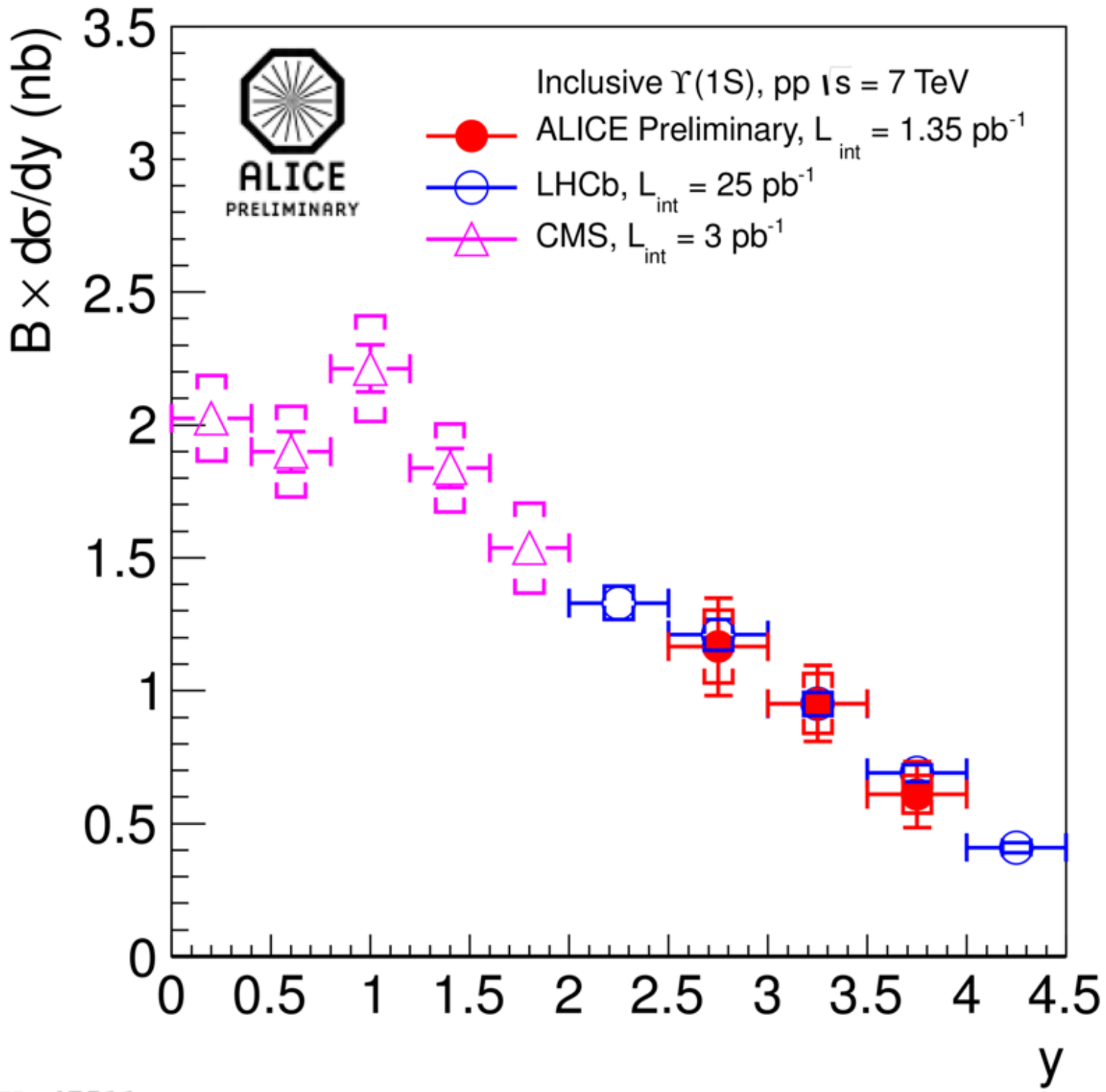




ALI-PREL-15412

Low p_T dimuon at J/Ψ mass for peripheral collisions



Hint of photo-production J/Ψ production

Inclusive Y production in pp