

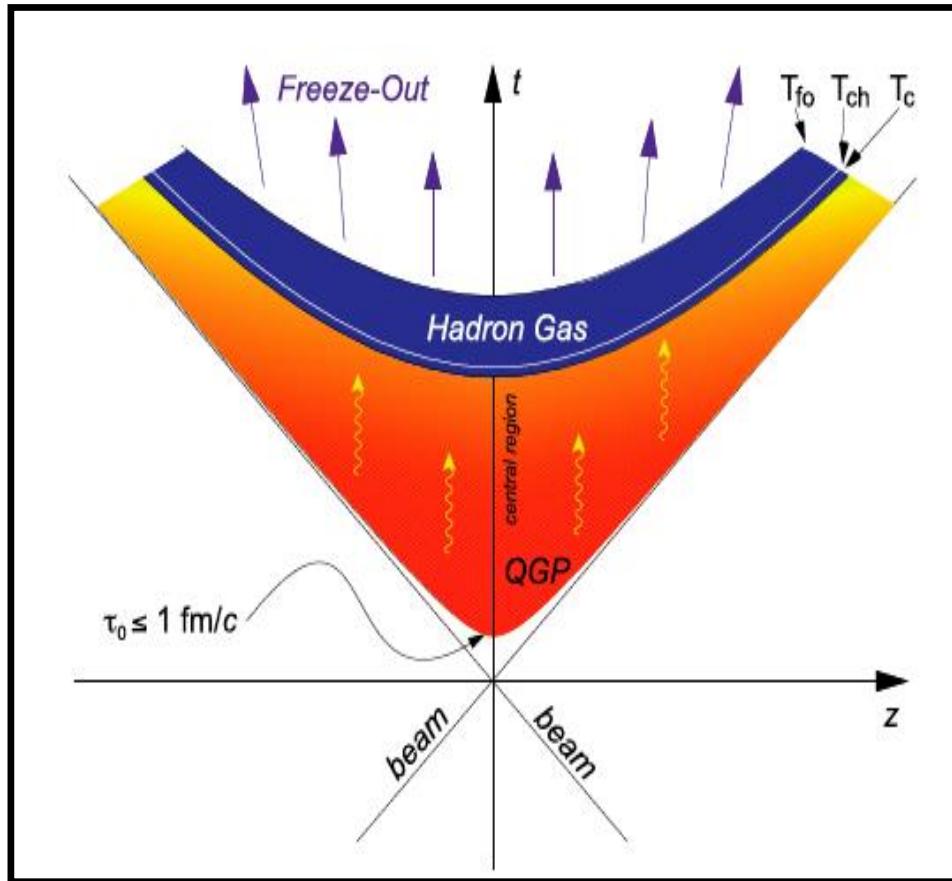
Quarkonium measurements at the LHC

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3rd Heavy Flavour Meet, IIT Indore
18th March, 2019

Quark Gluon Plasma



- **collision time**
 $\sim 2R/\gamma = 0.005 \text{ fm}/c$
 $\approx 2 \cdot 10^{-26} \text{ s}$
- **thermalization time**
 $\sim 0.5 \text{ fm}/c \approx 2 \cdot 10^{-24} \text{ s}$
- **QGP life time**
 $\sim 10 \text{ fm}/c \approx 3 \cdot 10^{-23} \text{ s}$
- **formation time**
(e.g. charm quark):
 $\sim 1/2m_c = 0.08 \text{ fm}/c \approx 3 \cdot 10^{-25} \text{ s}$

M. Kleiment et. al.,
DOI 10.1007/978-3-642-02286-9_2

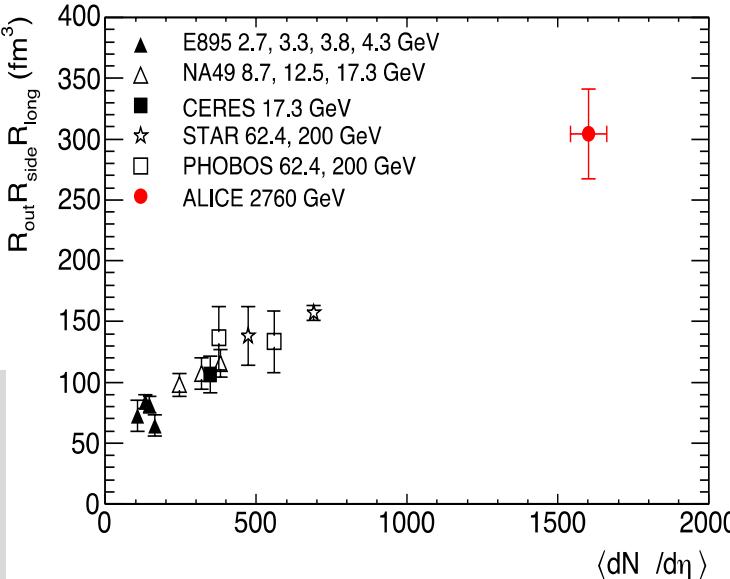
T_c : Phase transition temperature

T_{ch} : Chemical freeze-out temperature, relative abundances of hadrons are fixed ($\sim 160 \text{ MeV}$)

T_{fo} : Kinetic freeze-out temperature, end of hadronic interactions ($\sim 90 \text{ MeV}$)

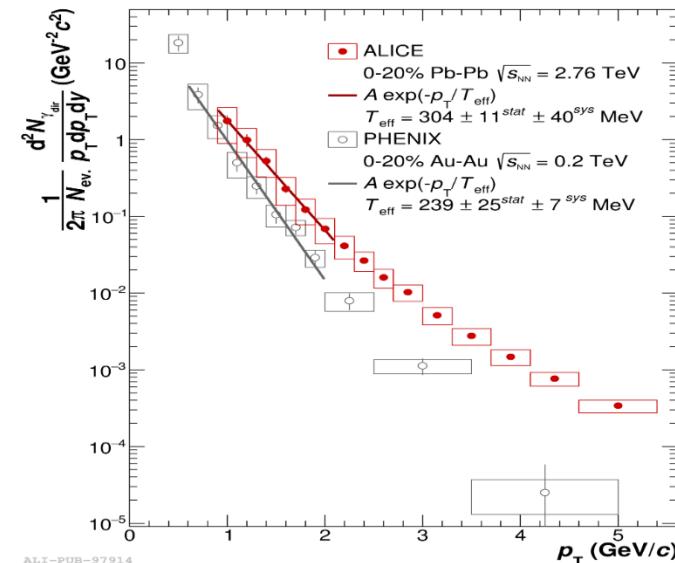
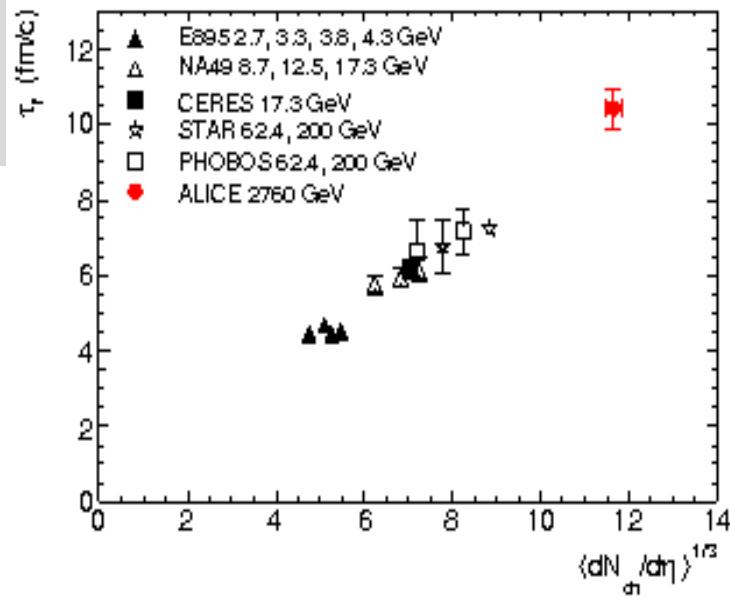
Medium at the LHC

PLB 696 (2011) 328

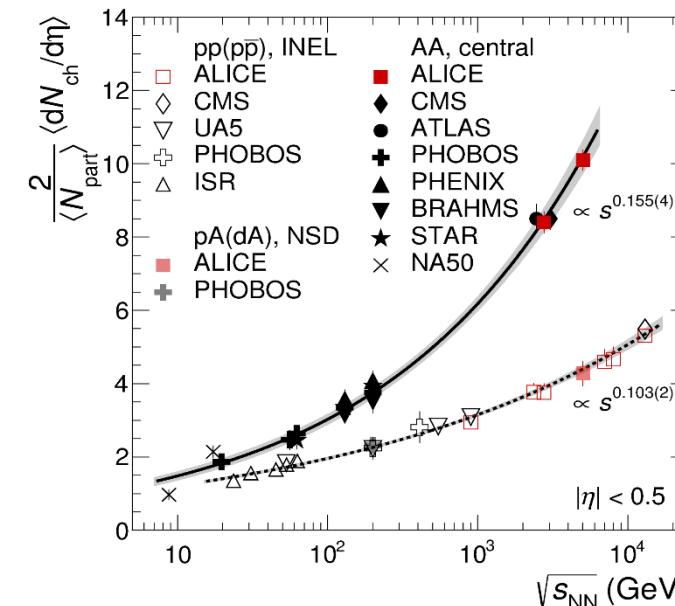


Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$

- Freeze-out volume
 - $304.28 \pm 39.96 \text{ fm}^3$
- Thermal photon (blueshifted) temperature
 - $304 \pm 41 \text{ MeV}$
- Lifetime of the fireball till freeze-out
 - $10.42 \pm 0.53 \text{ fm/c}$
- Charged-particle Multiplicity = 1584 ± 76
 $\rightarrow \epsilon \cdot \tau \sim 12.5 \text{ GeV/fm}^2 c$

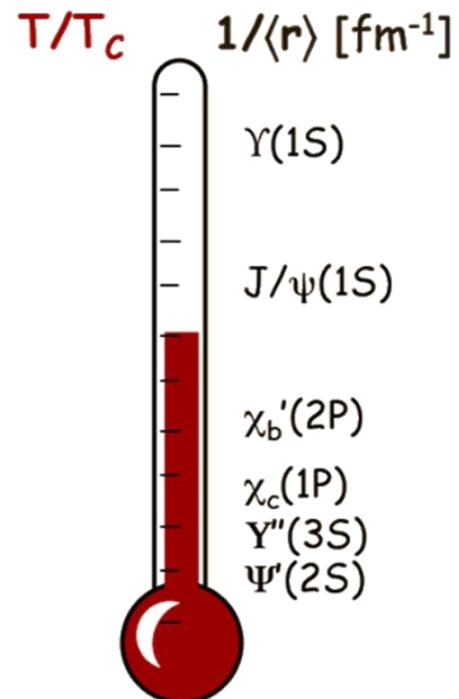
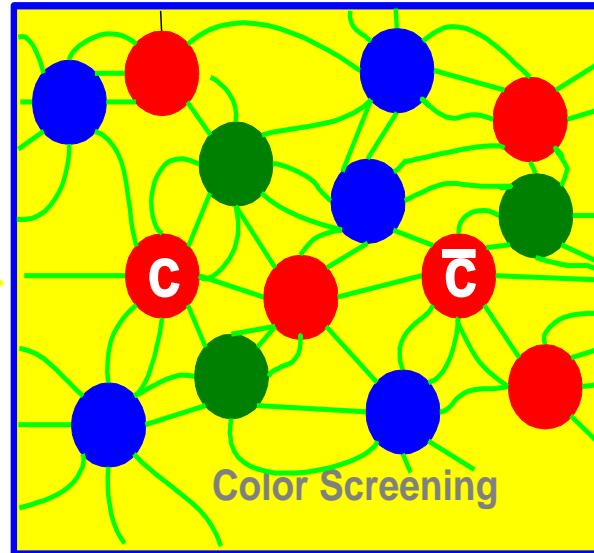
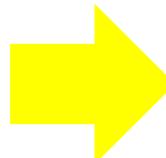
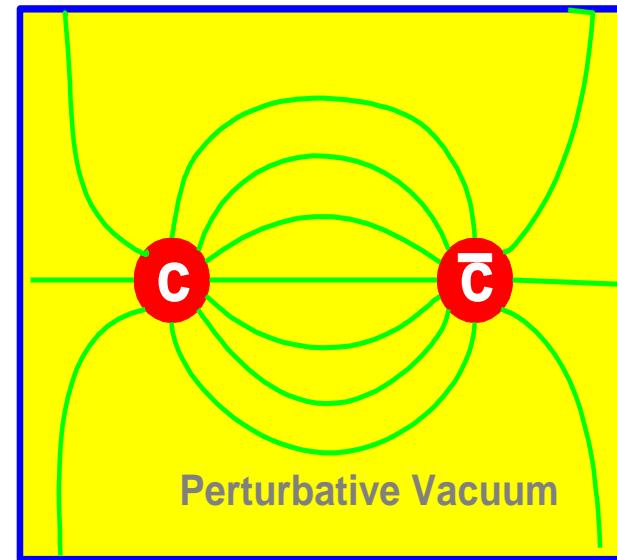


PLB 754 (2016) 235



PRL 116 (2016) 222302

QGP Probe : Quarkonium Suppression



T. Matsui and H. Satz, PLB 178 (1986) 416

Suppression

- Screening effect is stronger at high T
- $\lambda_D \rightarrow$ maximum size of a bound state in a QGP at a temperature T, decreases when T increases (Debye length)
- Higher states (less bound) are more easily dissociated \rightarrow Sequential suppression

PRC 91 (2001) 024913

M. Strickland, PRC 92 (2015) 061901

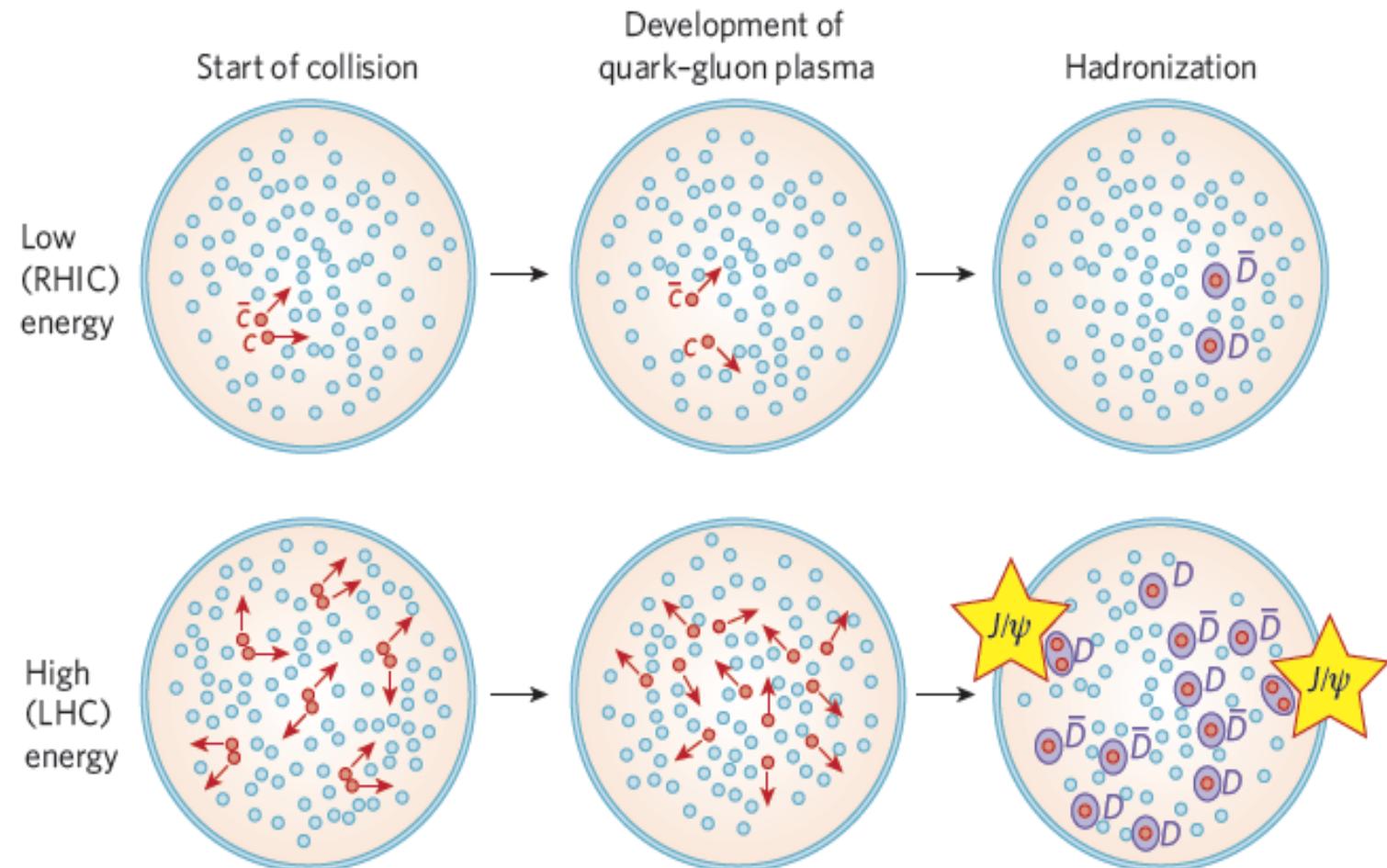
- Large binding energy \rightarrow short formation time
- Most of the resonances are created at the anisotropic phase of the plasma
- In addition when T increases, particle lifetime decreases ($< 1 \text{ fm}/c$ for $T \sim 300 \text{ MeV}$)

QGP Probe : Quarkonium Regeneration

P. Braun-Muzinger and J Stachel, PLB 490 (2000) 196;
R. Thews et. al. PRC 63 (2001) 054905

Regeneration

- The number of $Q\bar{Q}$ pairs increases strongly with colliding beam energy
- A (re)combination of $Q\bar{Q}$ pairs to produce quarkonia may take place during the QGP stage or at the phase boundary.
- A small (if any) fraction of (re)combination is expected for Υ states than for charmonia, because the number of pairs is much smaller for b quarks.



Sources of charmonium

- Charmonium production can proceed:
 - directly in the interaction of the initial partons
 - via the decay of heavier hadrons (feed-down)
- For J/ψ the contributing mechanisms are:

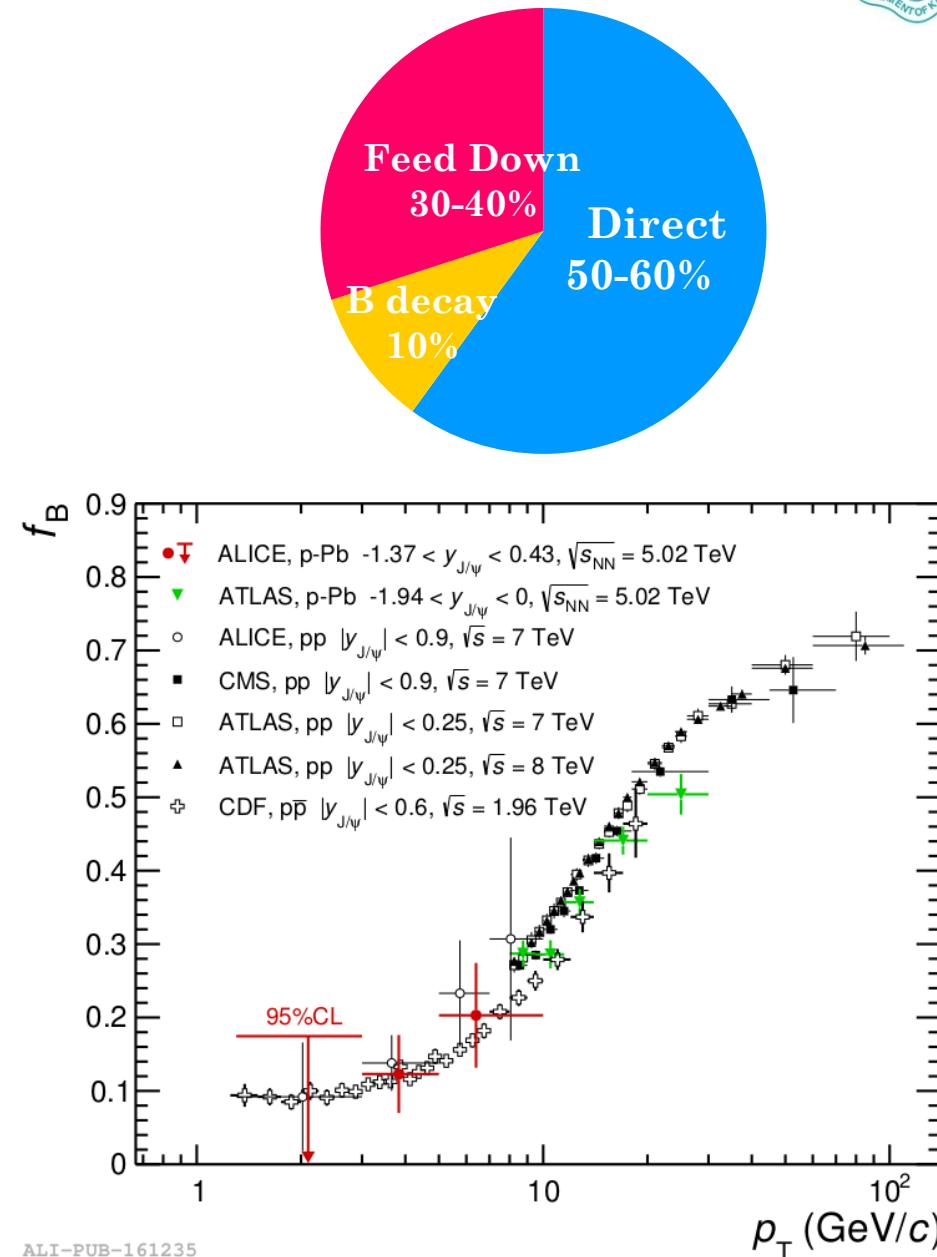
Prompt

- Direct production
- Feed-down from higher charmonium states:
 $\sim 8\%$ from $\psi(2S)$,
 $\sim 20\text{-}30\%$ from χ_c

Non-prompt

- B decay
 contribution is p_T dependent
 $\sim 10\%$ at $p_T \sim 1.5 \text{ GeV}/c$

B-decay component “easier” to separate
 → displaced production



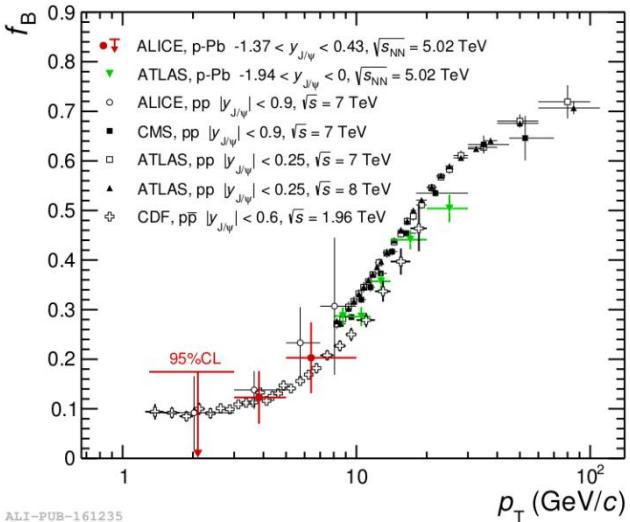
Prompt, non-prompt and feed-down

Charmonium

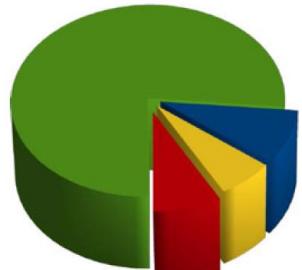
A. Andronic et. al., EPJC 76 (2016) 107

Bottomonium

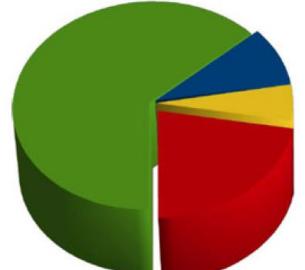
In addition to (10-30)% B-decay production



Low transverse momentum



High transverse momentum



Low pT

- From 2S : 7-8 %
- From 3S : < 1 %
- From 1P : ~ 15 %
- From 2P : ~ 4 %
- From 3P : ~ 2 %
- Direct : ~ 70 %

High pT

- From 2S : 12-16 %
- From 3S : 2-3 %
- From 1P : 26-32 %
- From 2P : 4-8 %
- From 3P : 2-4 %
- Direct : ~ 45 %

low- p_T Υ feed-down fractions are obtained by extrapolating the high- p_T results.

Different sources of medium effects

- Nuclear modification factor R_{AA} :

Ratio of the quarkonium yield in AA (Y_{AA}) with respect to the pp one, scaled by the overlap factor T_{AA} (from Glauber model)

$$R_{AA} = \frac{Y_{AA}}{\langle T_{AA} \rangle \sigma_{pp}}$$

If yield scales with the number of binary collisions

$$\rightarrow R_{AA} = 1$$

and if,

$$\rightarrow R_{AA} \neq 1$$

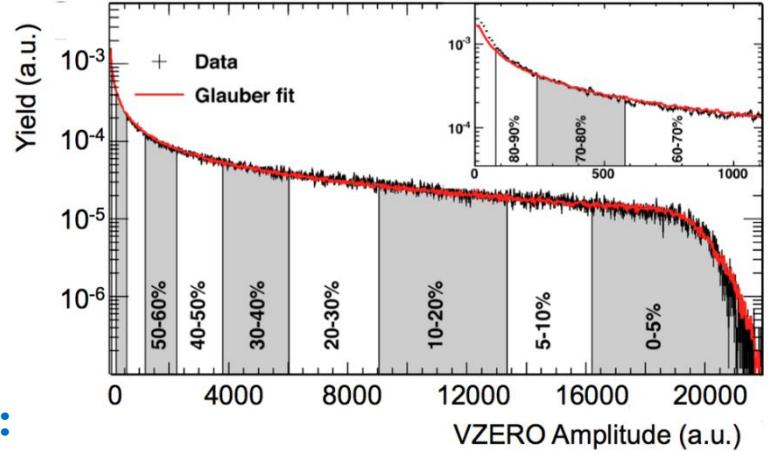
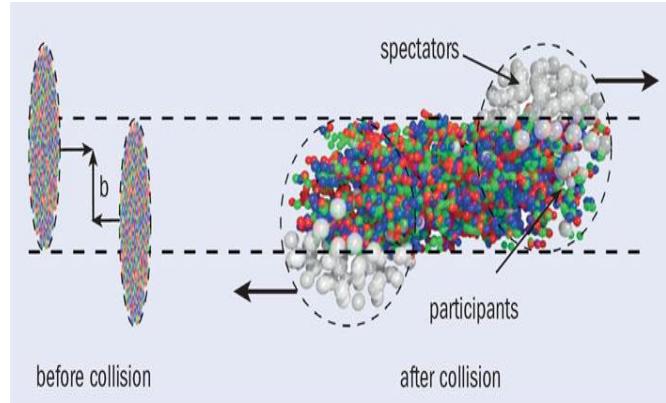
there are medium effects

Hot Medium effects:

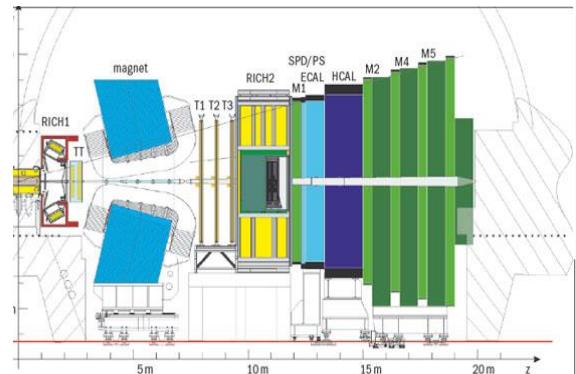
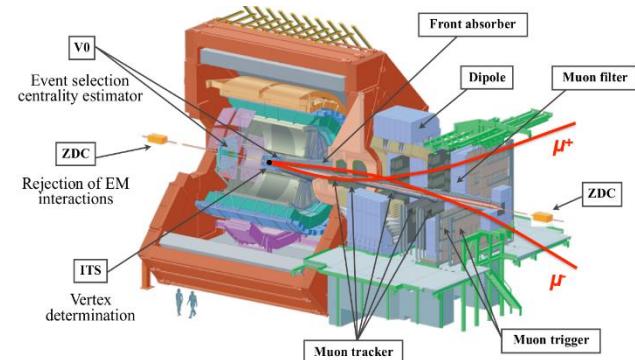
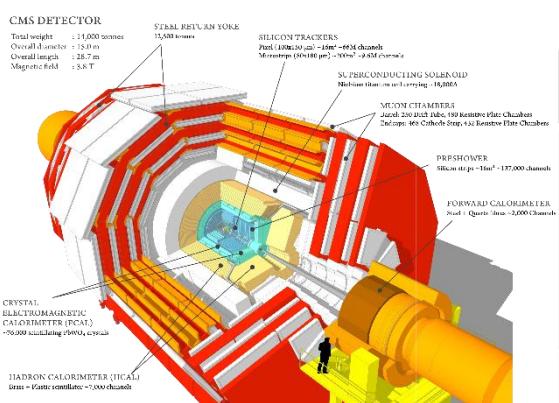
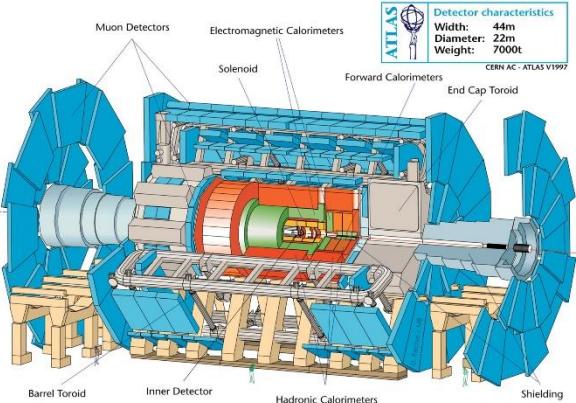
- Quarkonium suppression
- Enhancement due to recombination

Cold Nuclear Matter effects (CNM):

- Nuclear parton shadowing/gluon saturation
- Parton energy loss
- $c\bar{c}$ in medium break-up



LHC Experiments

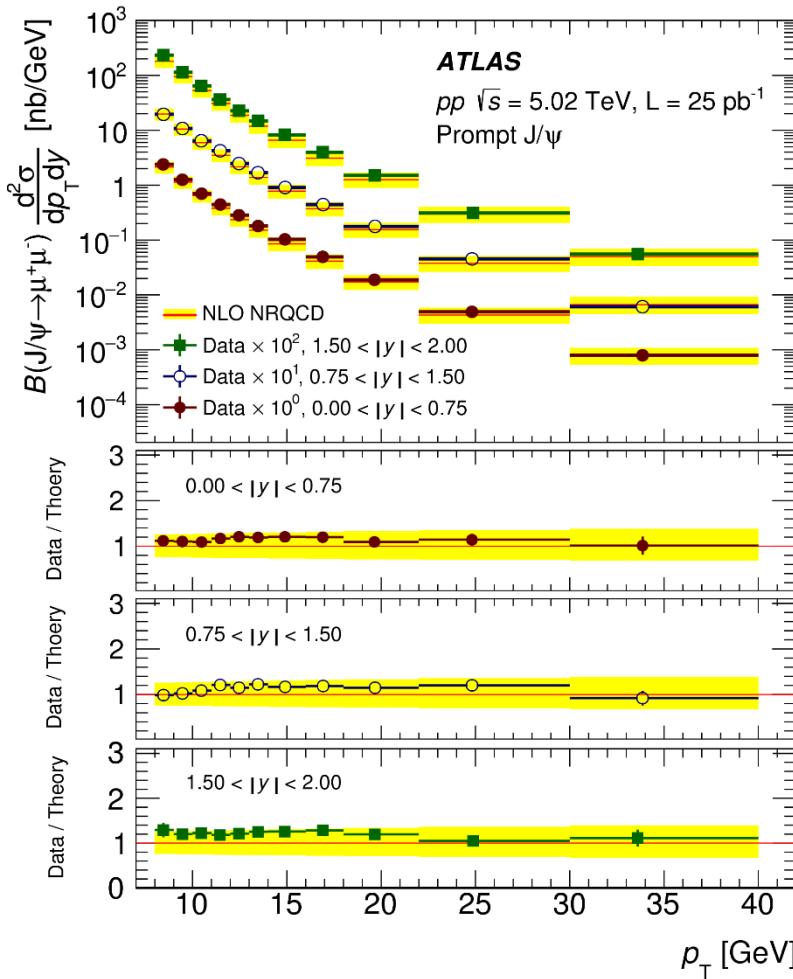


Experiment	Charmonium	Bottomonium
ALICE	$ \eta < 1.0$: prompt+ $p_T \sim 0$ $2.5 < \eta < 4.0$: inclusive+ $p_T \sim 0$	$2.5 < \eta < 4.0$: $p_T \sim 0$
ATLAS	$ \eta < 2.0$: prompt+ $p_T > 9$	$ \eta < 2.0$: $p_T \sim 0$
CMS	$ \eta < 2.4$: prompt+ $p_T > 6.5$	$ \eta < 2.4$: $p_T \sim 0$
LHCb	$2.0 < \eta < 4.5$: prompt+ $p_T \sim 0$	$2.0 < \eta < 4.5$: $p_T \sim 0$

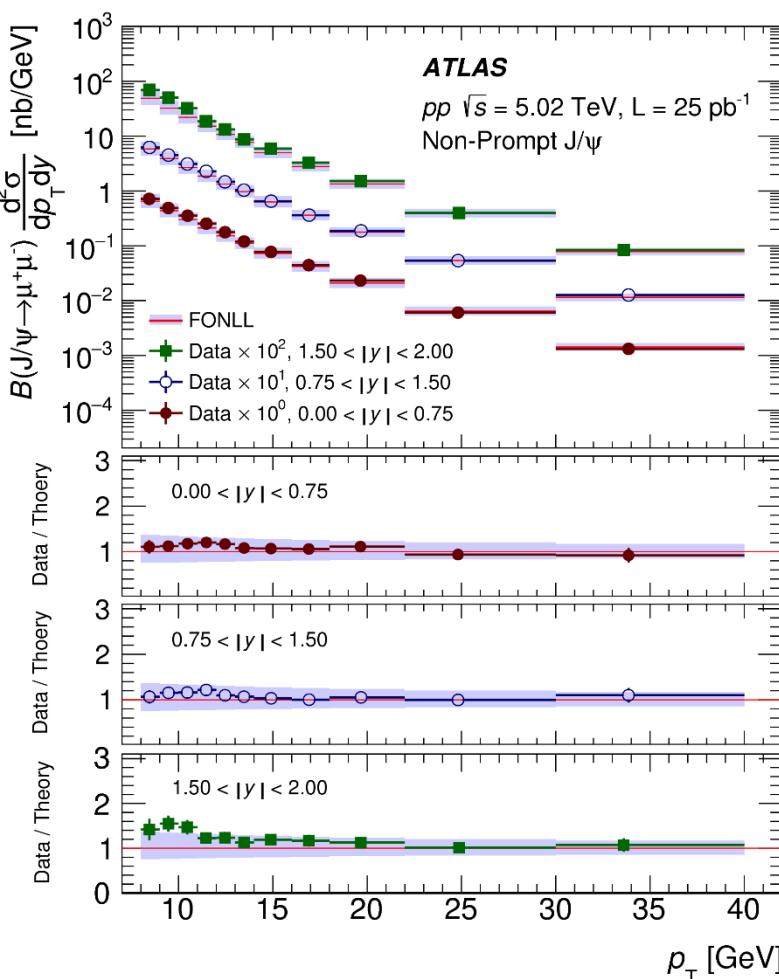
p_T in GeV/c



Charmonium production in pp collisions



EPJC 78 (2018) 171



Good agreement between data and predictions

NLO NRQCD

M. Cacciari et. al., JHEP 1210 (2012) 137

and

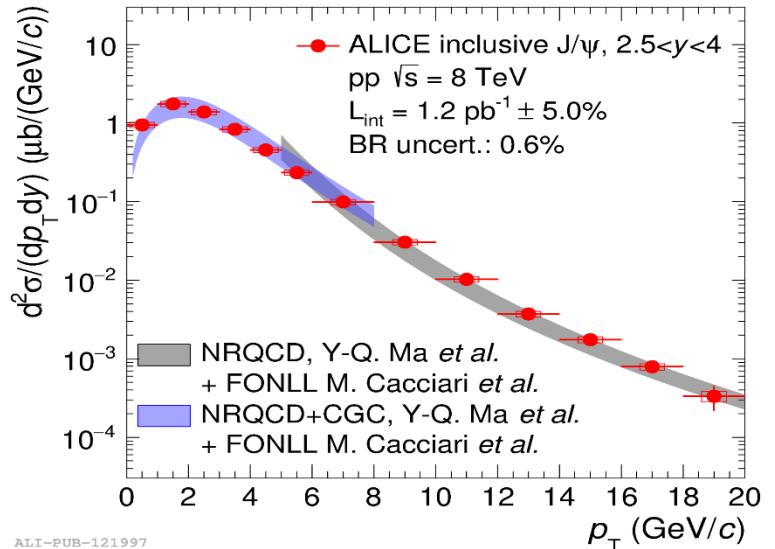
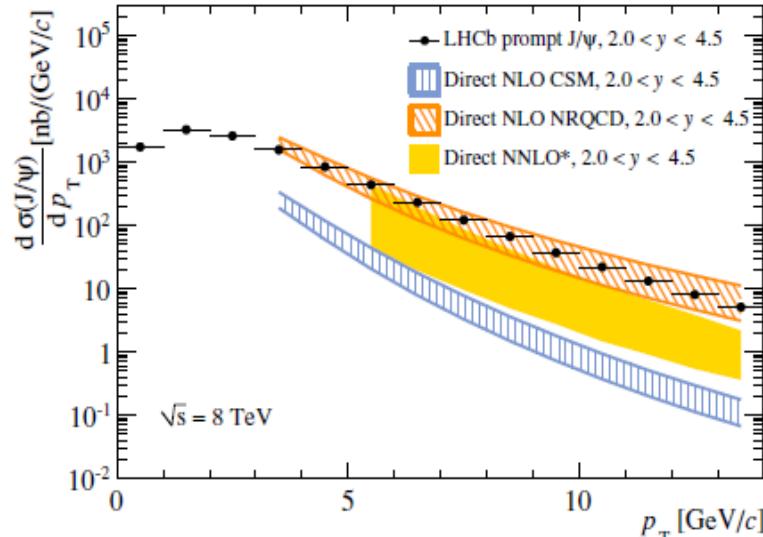
FONLL

Y. Ma et. al., PRL 106 (2011) 042002

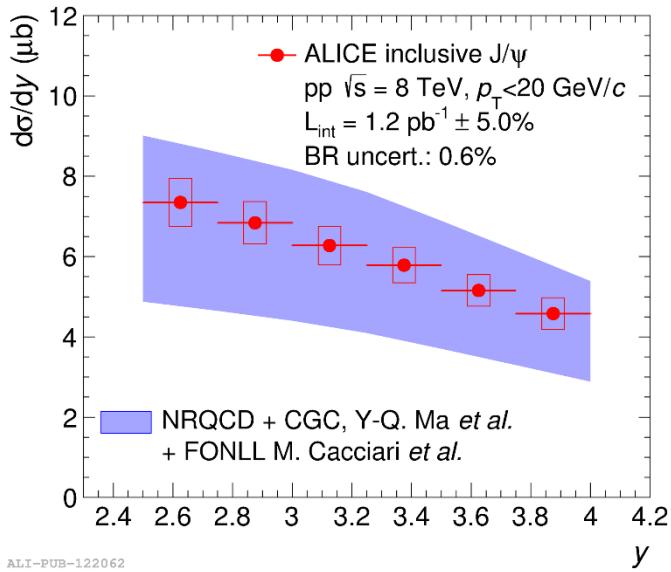
Charmonium production in pp collisions

EPJ C77 (2017) 392

JHEP 06 (2013) 064

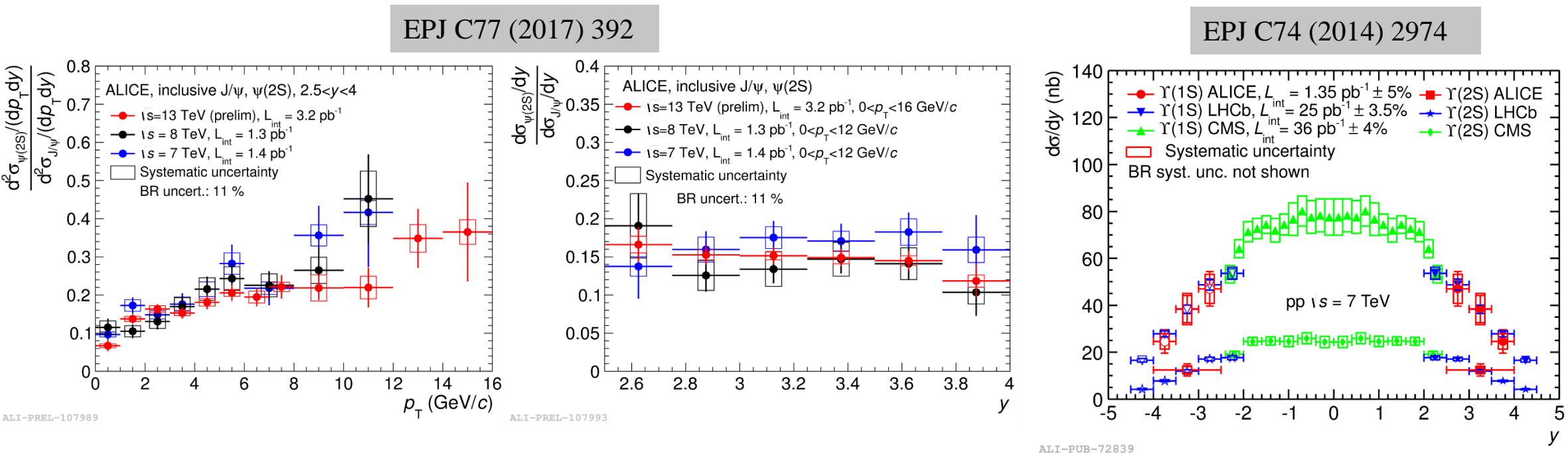


EPJ C77 (2017) 392

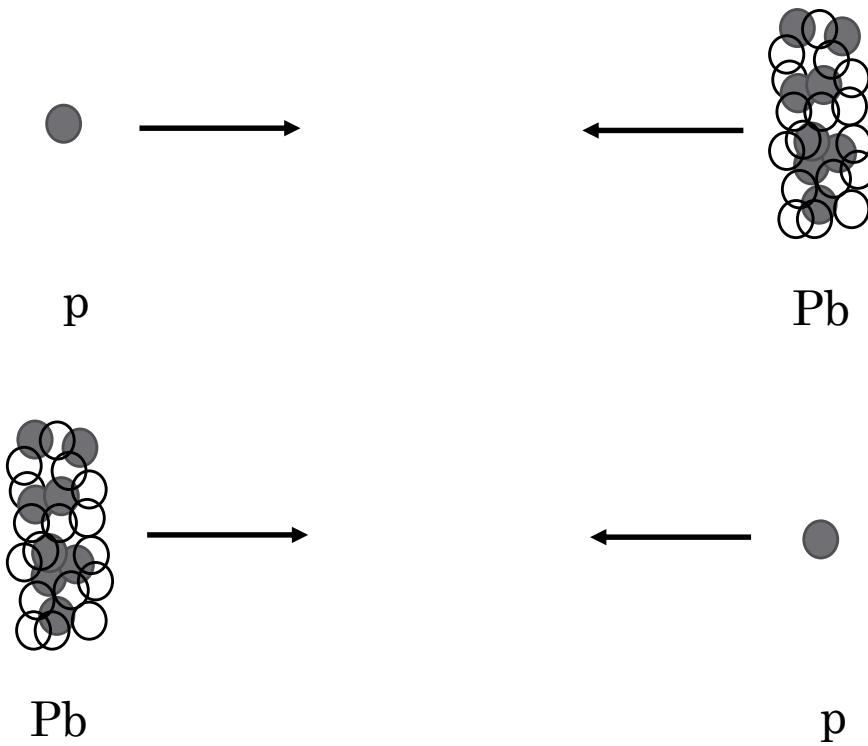


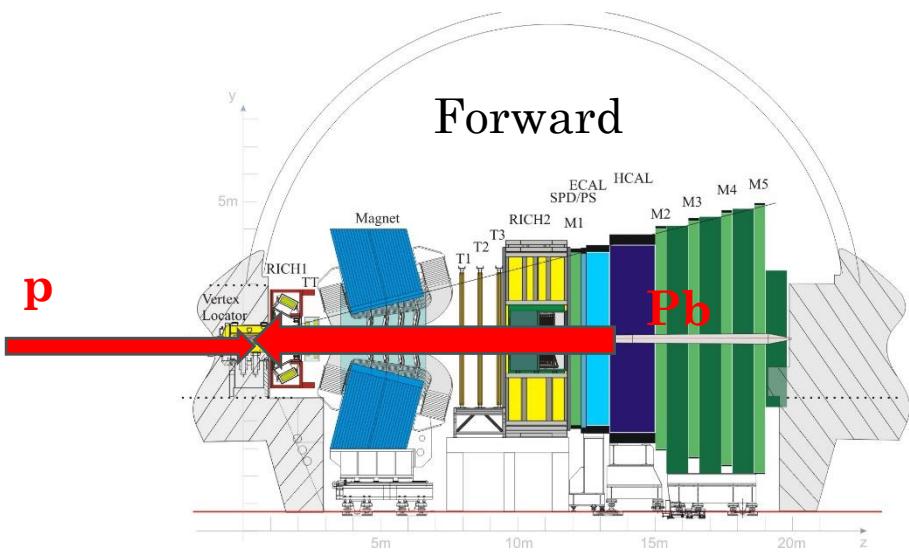
- Initially the theory prediction could not describe the region $p_T < 4 \text{ GeV}/c$.
- CGC+NRQCD based model is now able to properly describe the low p_T region.
- The theory uncertainty of CGC based model is still large when plotted as a function of dimuon rapidity.

Quarkonium production in pp collisions



- The cross section ratio for $\psi(2S)/J/\psi$ is found to be independent of colliding energy as a function of p_T and rapidity.
- The 2S/1S cross section ratio shows a increasing trend with p_T and no rapidity dependence.
- Results are in agreement among LHC experiments (shown only for Υ production).





Rapidity shift in pA collision

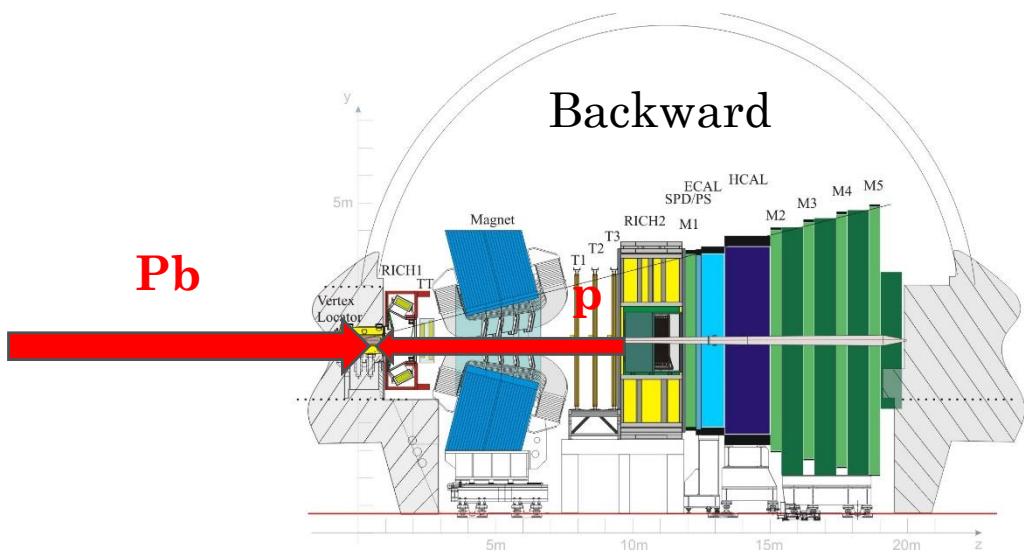
$$\Delta y = 0.5 \cdot \ln \frac{z_1 A_2}{z_2 A_1} = 0.465 \quad [\text{Pb: } z = 82, A = 208]$$

- Forward:

$$y_{\text{cms}} = y_{\text{lab}} - 0.465$$

- Backward:

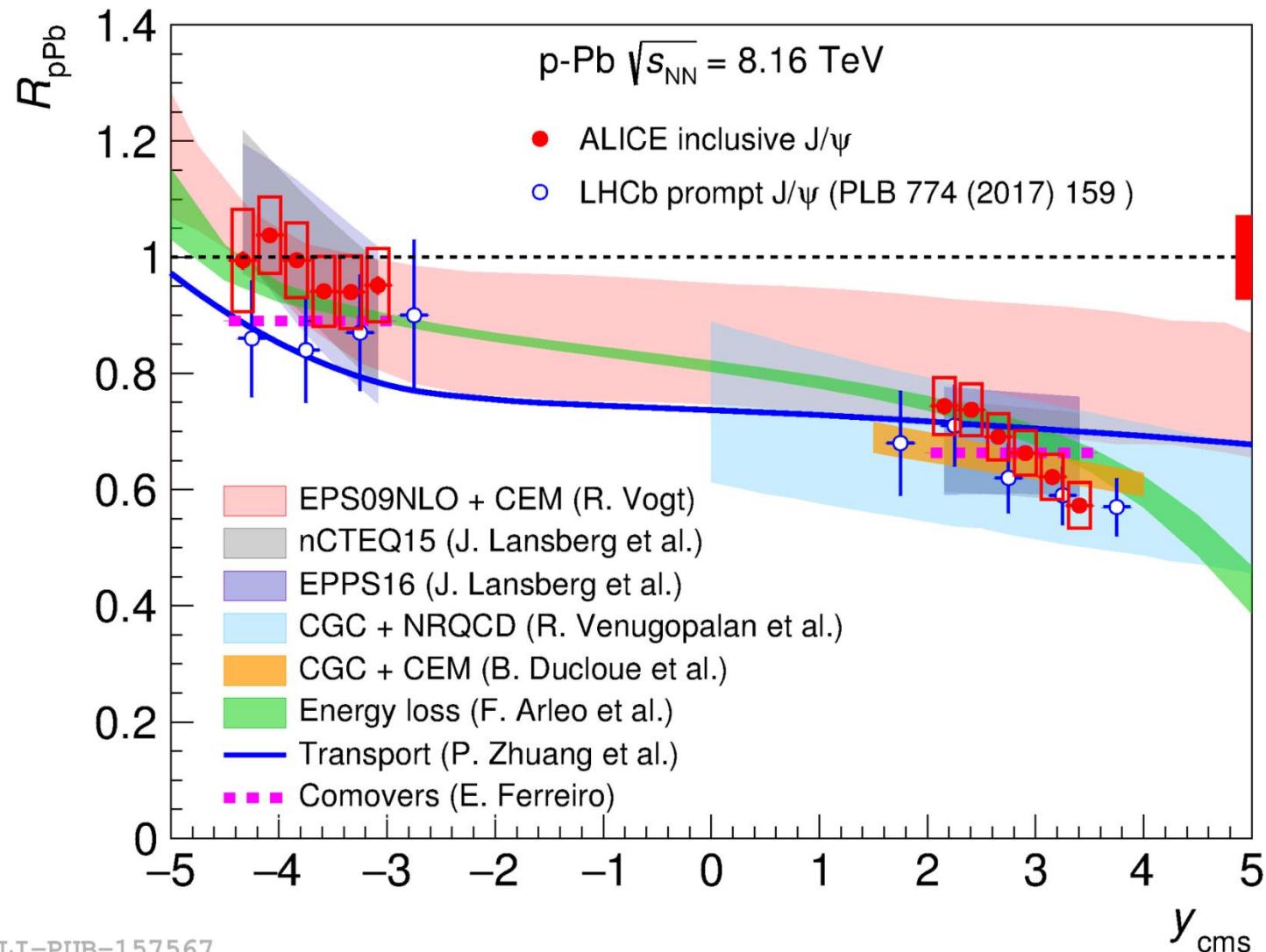
$$y_{\text{cms}} = -(y_{\text{lab}} + 0.465)$$



J/ ψ production in p-Pb

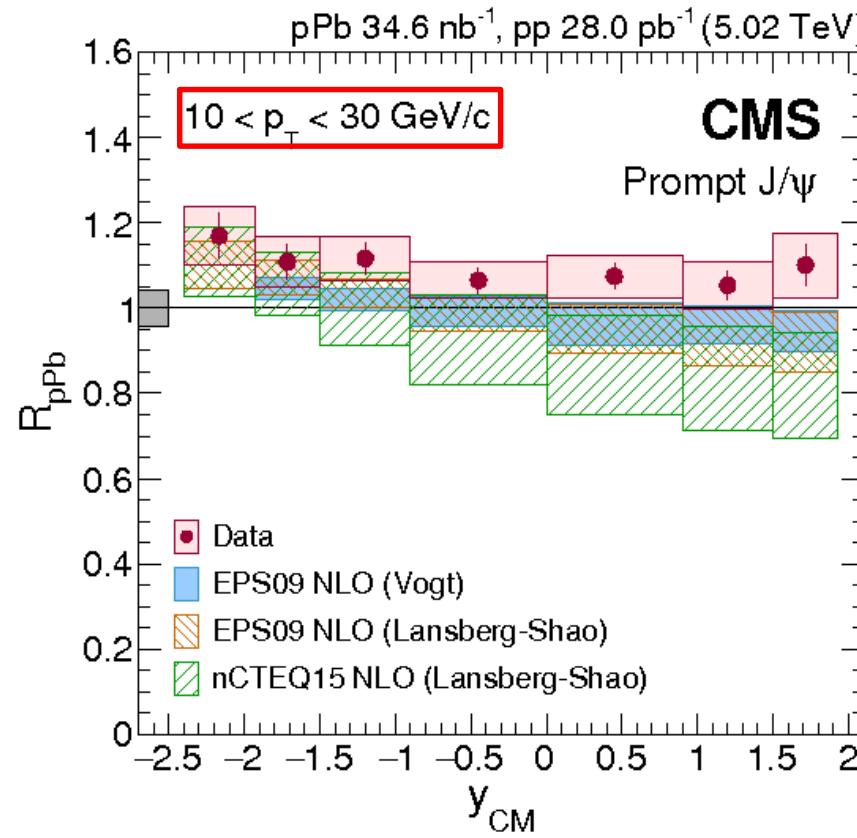
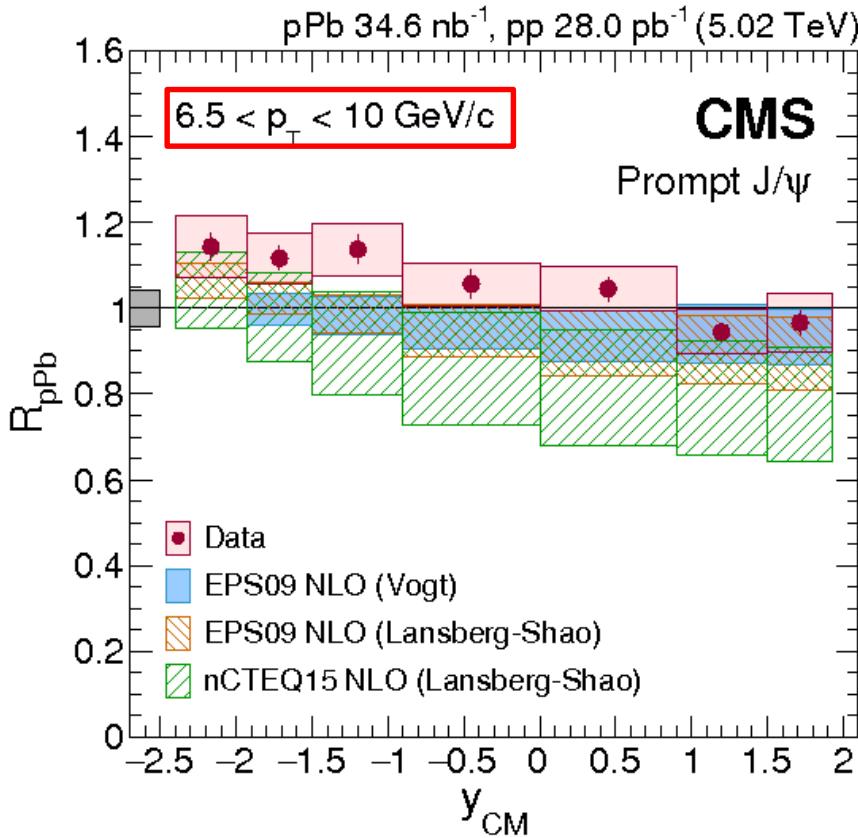
March 18 2019

Quarkonium and measurements at the LHC, 3rd Heavy Flavour Meet 2019, I.Das



- Stronger suppression of J/ ψ is observed at forward rapidity, while $R_{p\text{Pb}}$ is compatible with unity at backward rapidity.
- ALICE and LHCb results are in agreement.
- Models based on different shadowing implementations, CGC, energy loss, transport models and comovers fairly describe the data.

High- p_T J/ ψ production in p-Pb

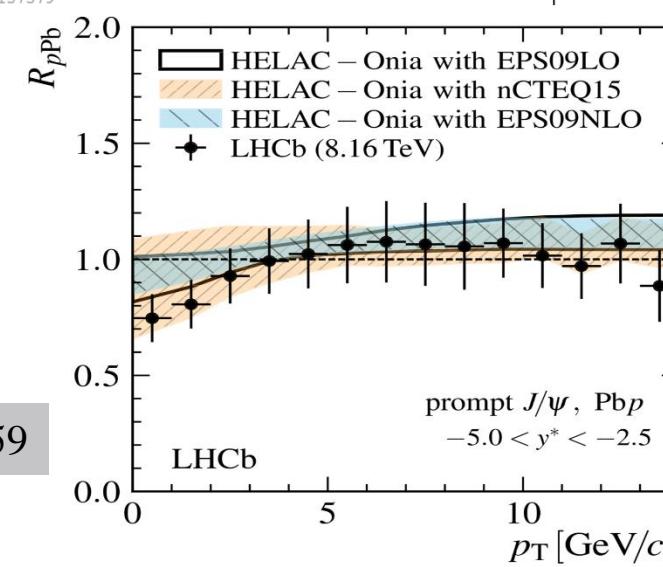
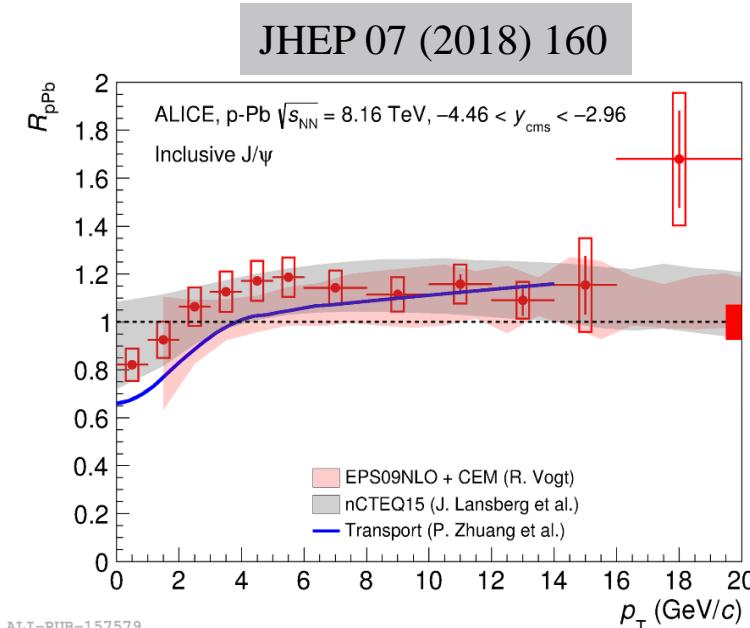
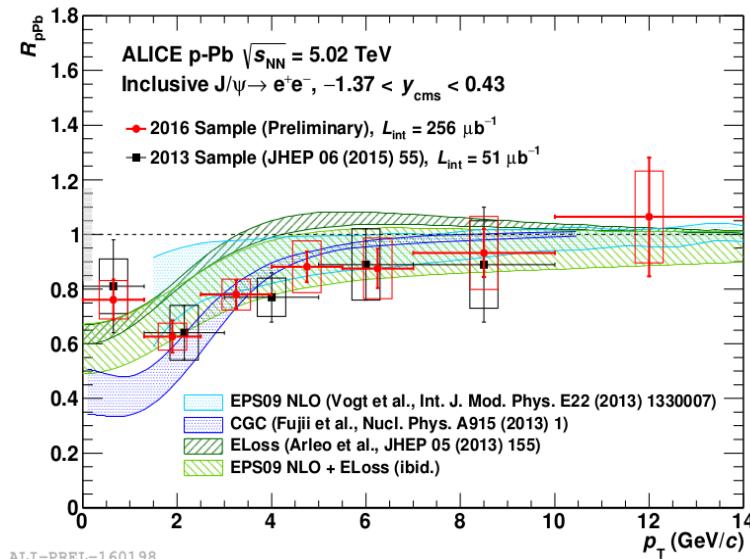
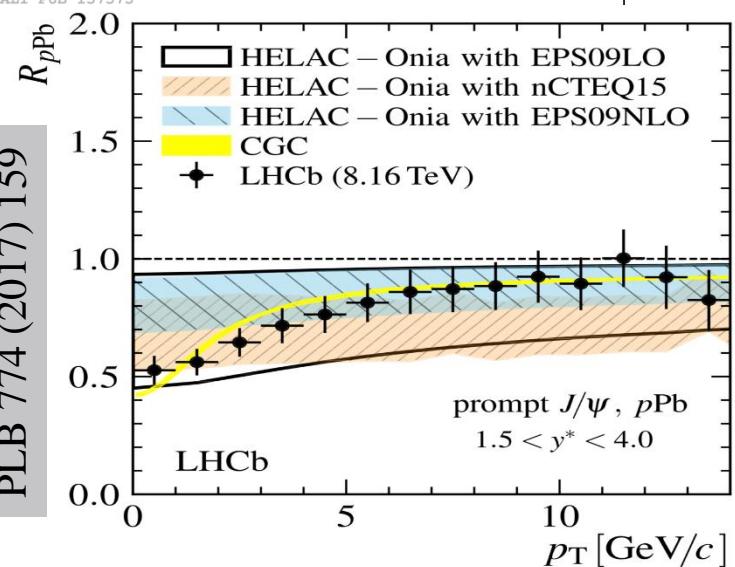
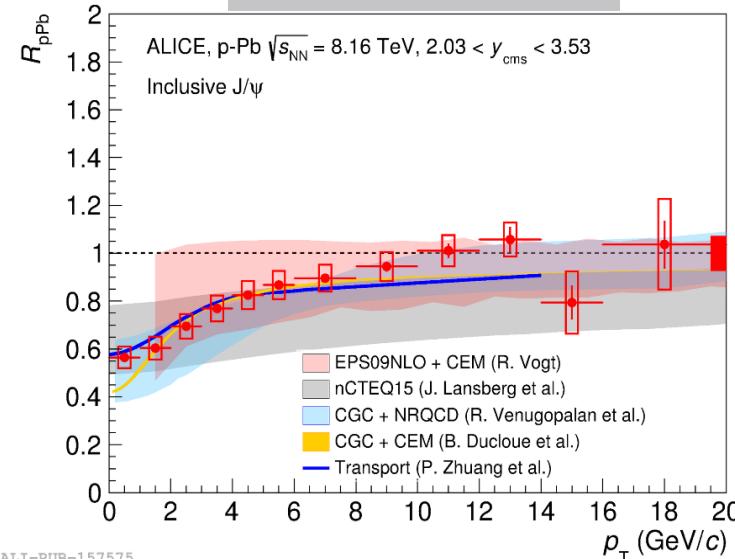


EPJ C77 (2017) 269

- Decreasing of R_{pPb} for increasing y_{CM}
- R_{pPb} above unity for the whole y_{CM}
- Models predict lower R_{pPb} , but describe the y_{CM} trend

J/ ψ production in p-Pb

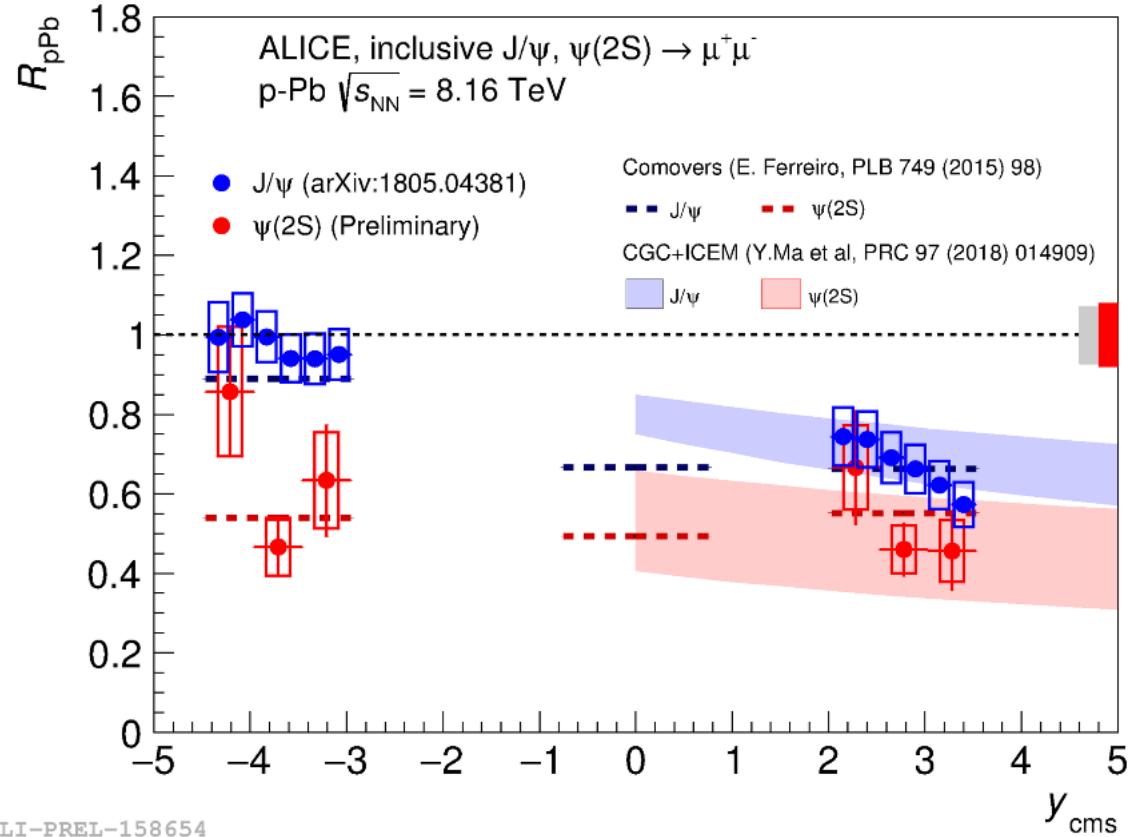
JHEP 07 (2018) 160



- The p_T dependence of R_{pPb} shows an increase from low to high p_T at forward, mid and backward rapidity.

$\psi(2S)$ production in p-Pb

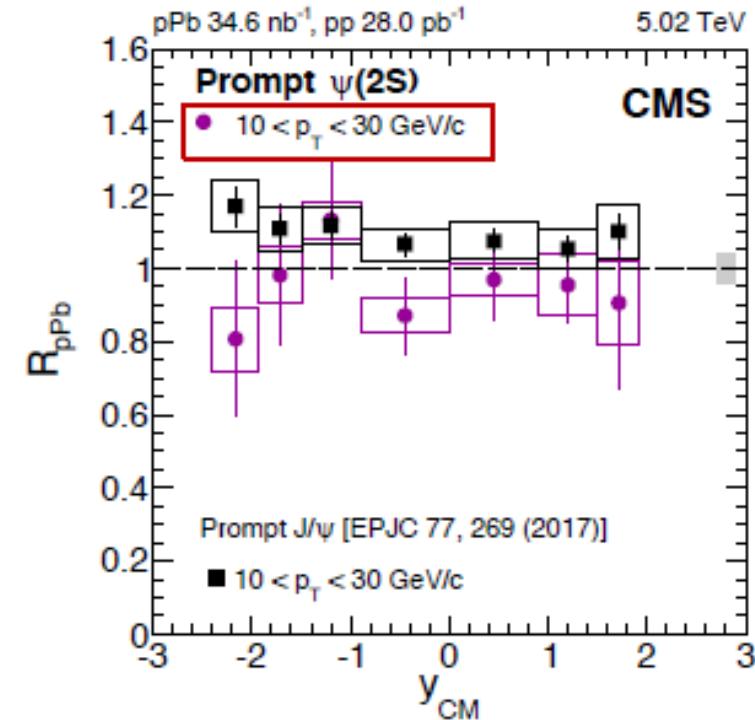
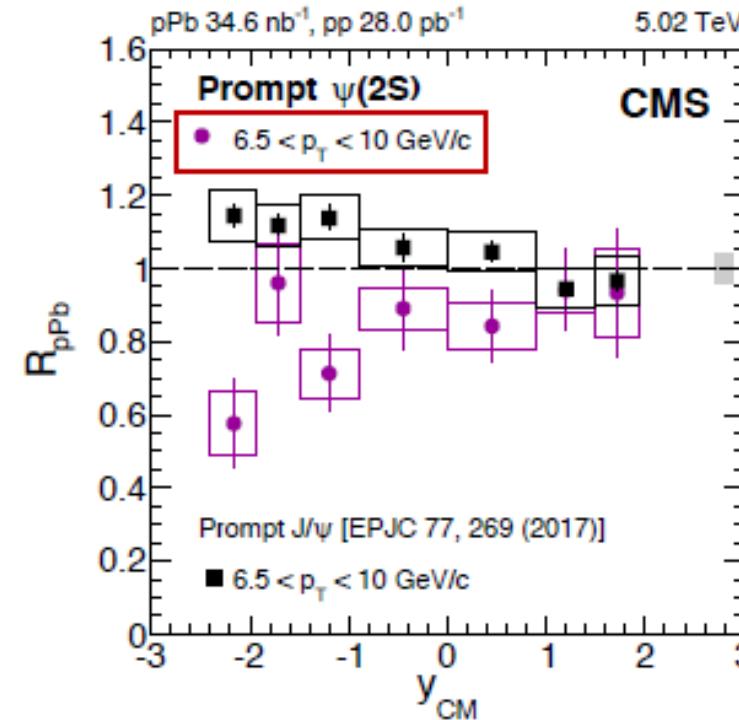
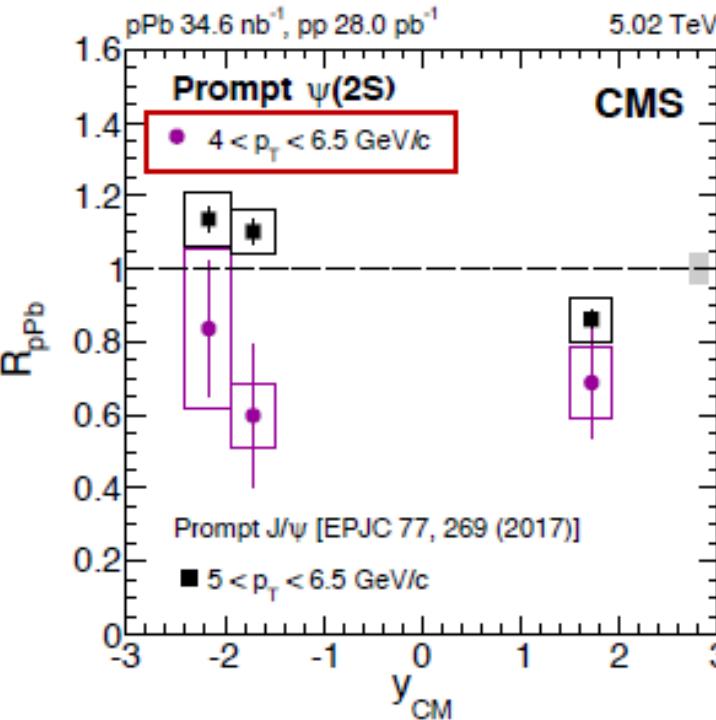
HFM-2019 (Wed 20/3) : Jhuma



- A similar suppression as for J/ψ is observed at forward rapidity for $\psi(2S)$ but found different for backward rapidity.
- At backward rapidity, final-state effects needed to explain the $\psi(2S)$ behaviour..

$\psi(2S)$ production in p-Pb

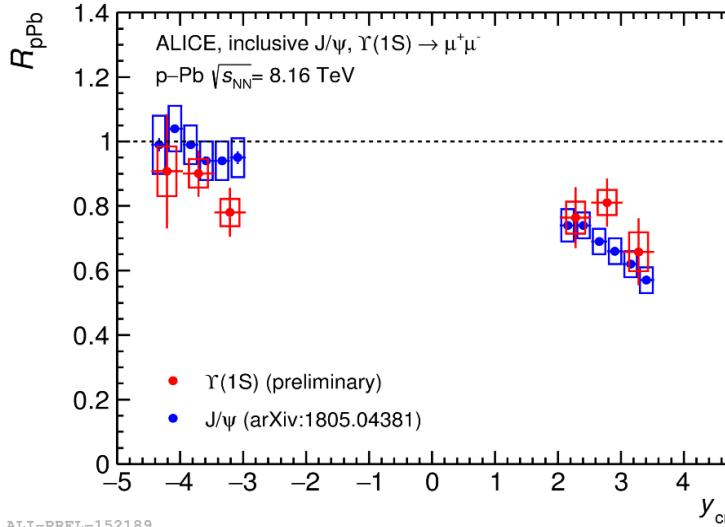
PLB 790 (2019) 509



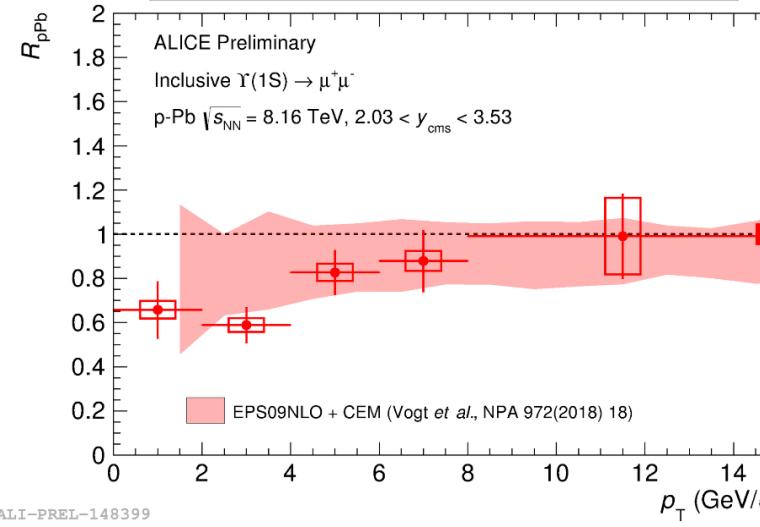
- $R_{p\text{Pb}}(2\text{S})/R_{p\text{Pb}}(1\text{S}) < 1$ in all measured bins
- $\psi(2\text{S})$ is suppressed strongly
- Suppression of excited states continues in higher p_T

Indication of final state effect : suppression by interaction with co-movers ?

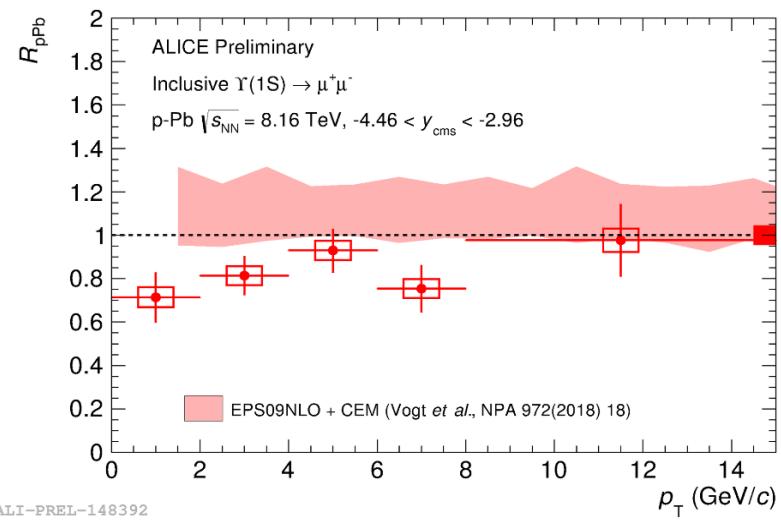
Υ production in p-Pb



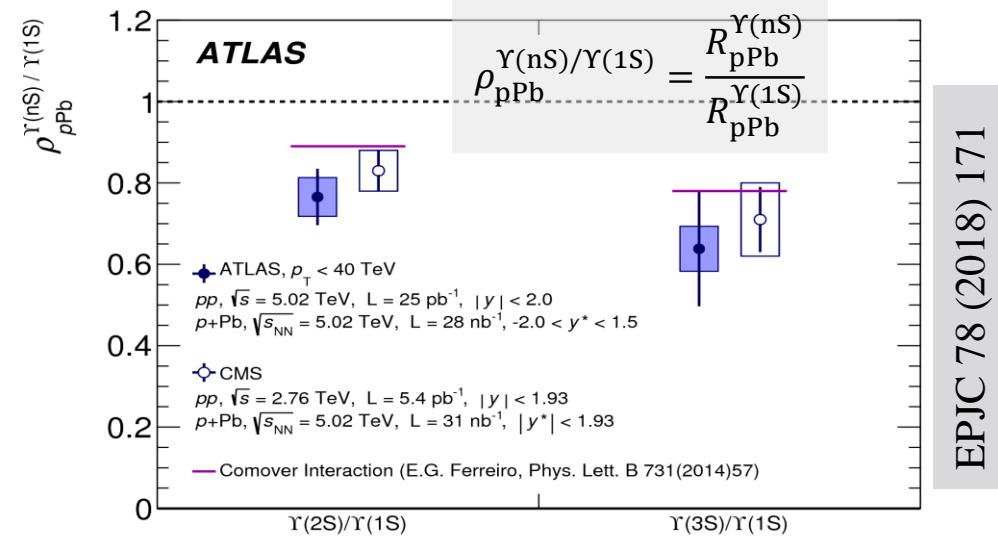
ALI-PREL-152189



ALI-PREL-148399



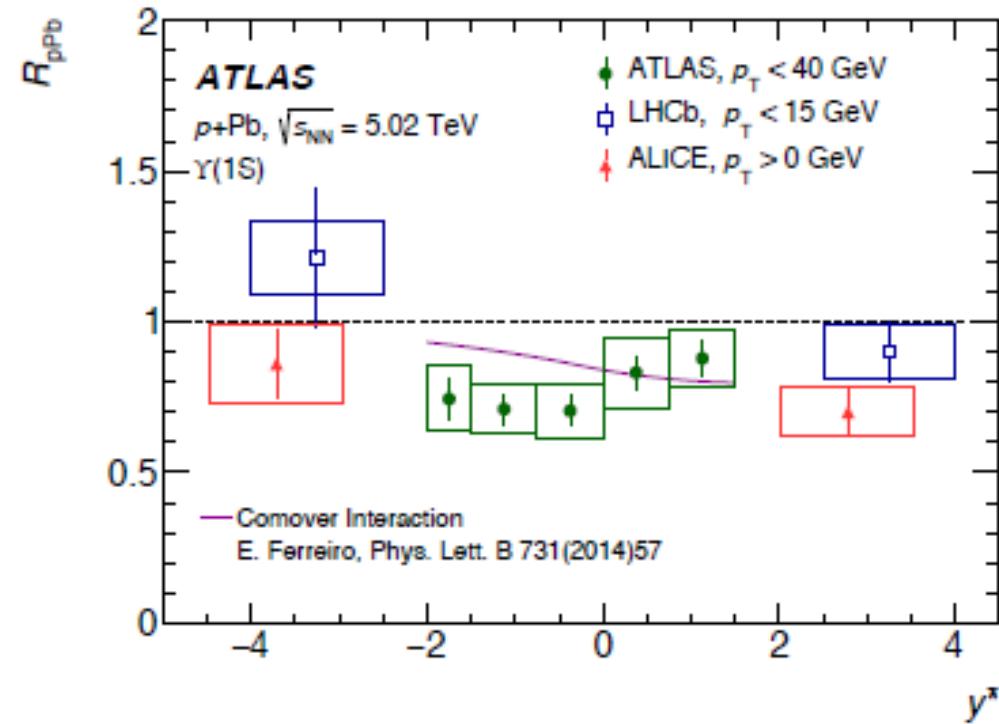
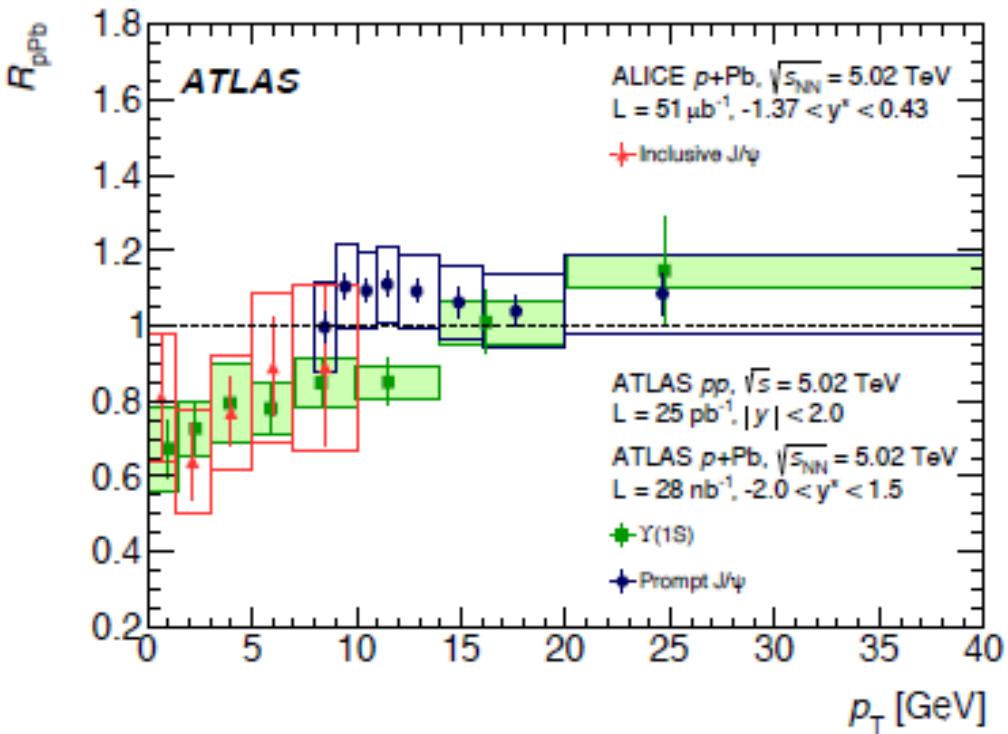
ALI-PREL-148392



- A similar suppression as for J/ψ is observed at forward rapidity for $\Upsilon(1S)$. The J/ψ and $\Upsilon(1S)$ $R_{p\text{Pb}}$ are compatible with no modification at backward rapidity.
- The p_T dependence of Υ $R_{p\text{Pb}}$ shows an increase from low to high p_T at both forward and backward rapidity, where the model prediction suggests flat distribution.
- The $\Upsilon(2S)$ is strongly suppressed than $\Upsilon(1S)$, analogous to what is observed for charmonia.



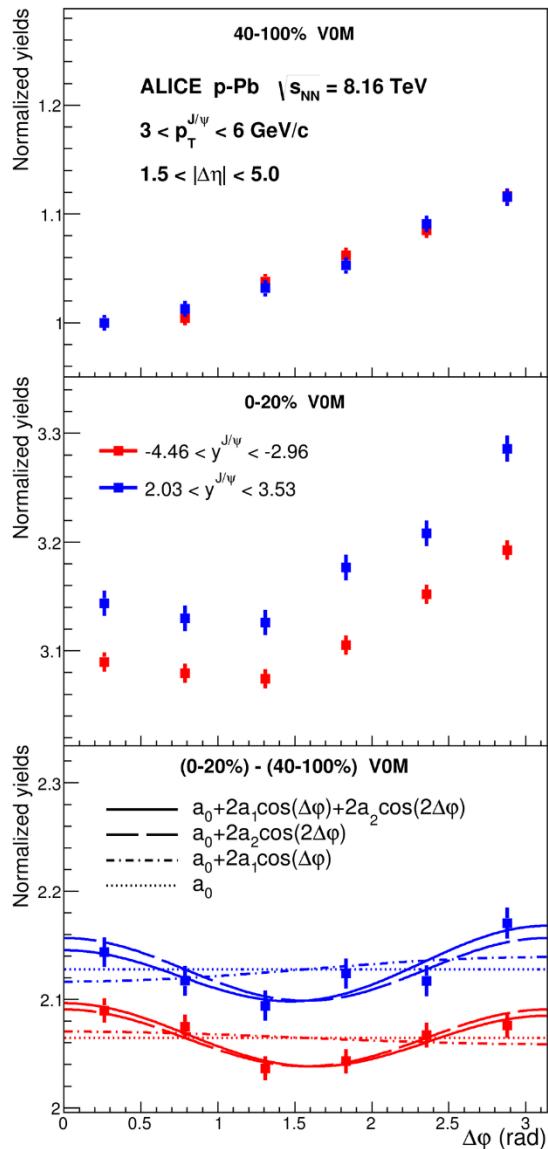
J/ ψ and $\Upsilon(1S)$ production in p-Pb



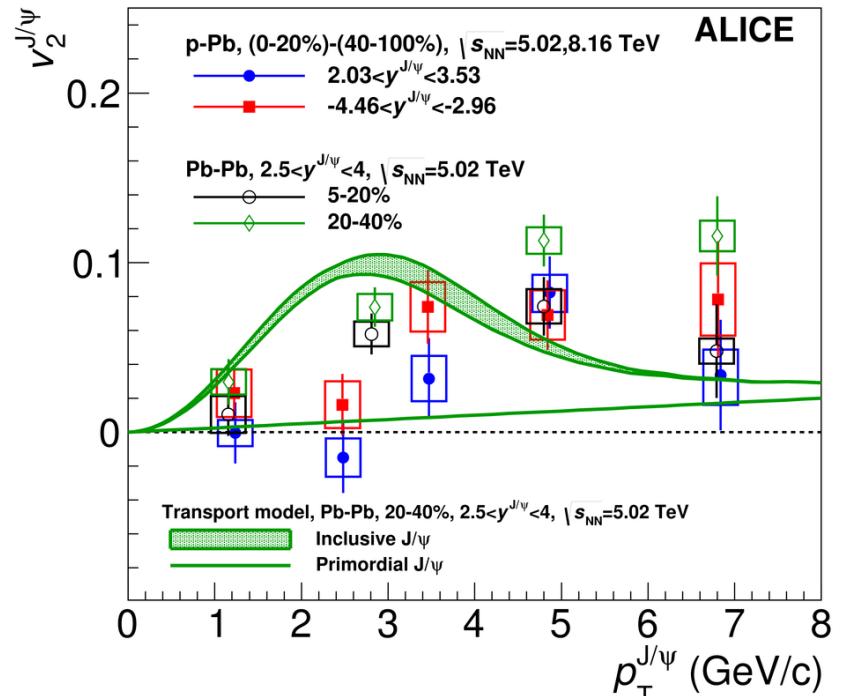
EPJ C78 (2018) 171

- R_{pPb} is consistent with unity from $p_{\text{T}} > 9 \text{ GeV}/c$
 - Supports the idea of a clean window for the studies of hot matter effects at high p_{T} .

J/ψ flow in p-Pb



PLB 780 (2018) 7

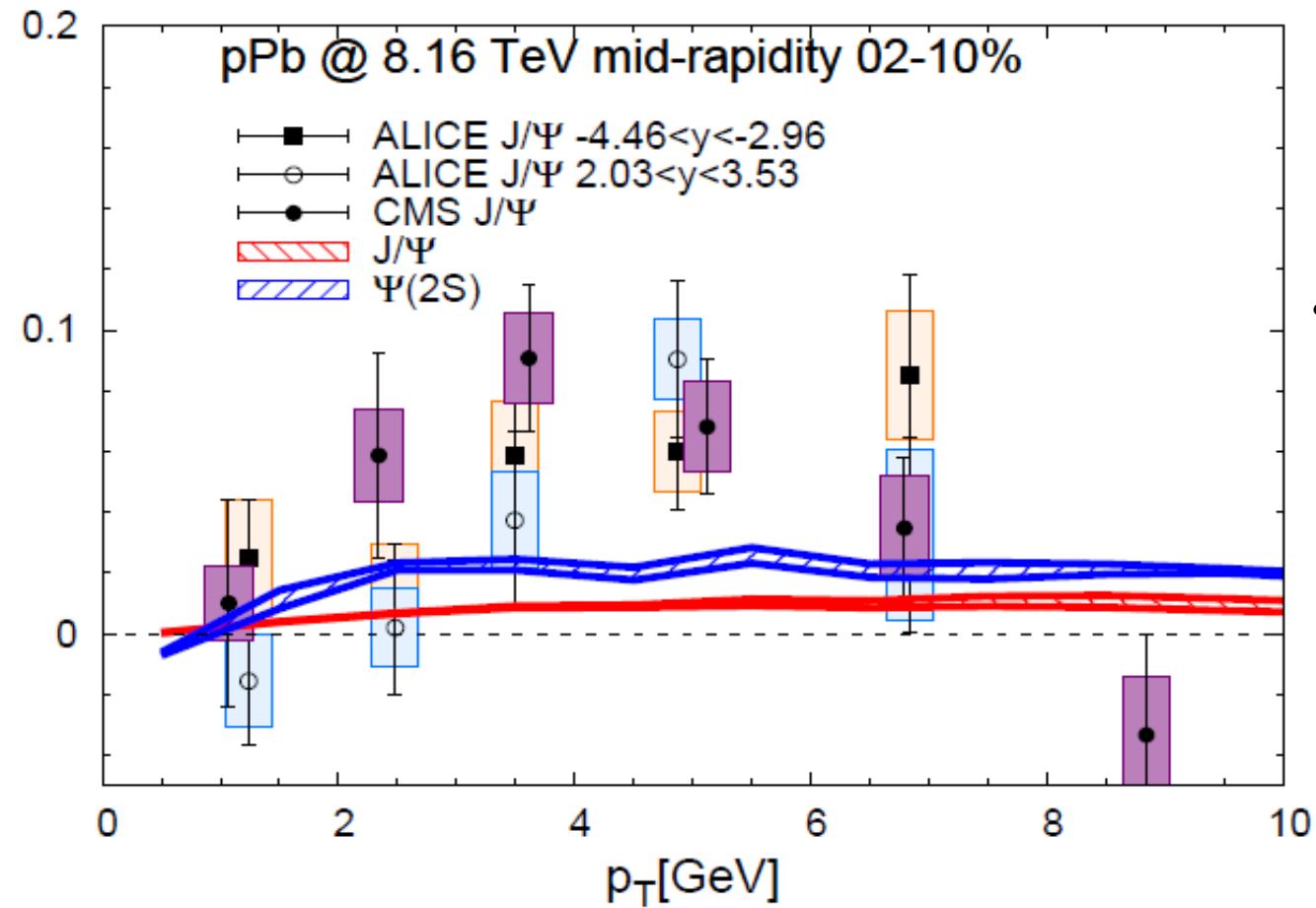


PLB 719 (2013) 29

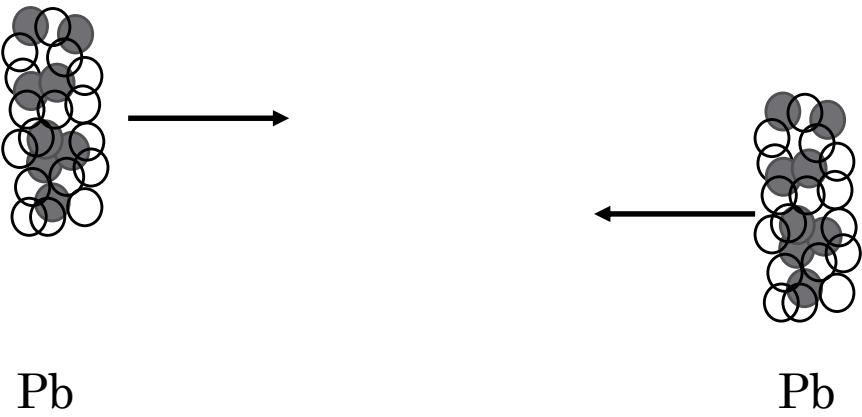
- Angular correlations between forward and backward J/ψ and charged hadrons separated by rapidity gap of at least 1.5.
- Similar long range correlation as observed for double ridge structure at $\Delta\phi = 0$ and $\Delta\phi = \pi$. PLB 719 (2013) 29
- A significance of 5σ reported for the v_2 measured between 3 and 6 GeV/c .
- The J/ψ v_2 measured for p-Pb is comparable to that in Pb-Pb ($p_T > 3 \text{ GeV}/c$) although the underlying mechanism is not known to be same or different.

J/ψ flow in p-Pb

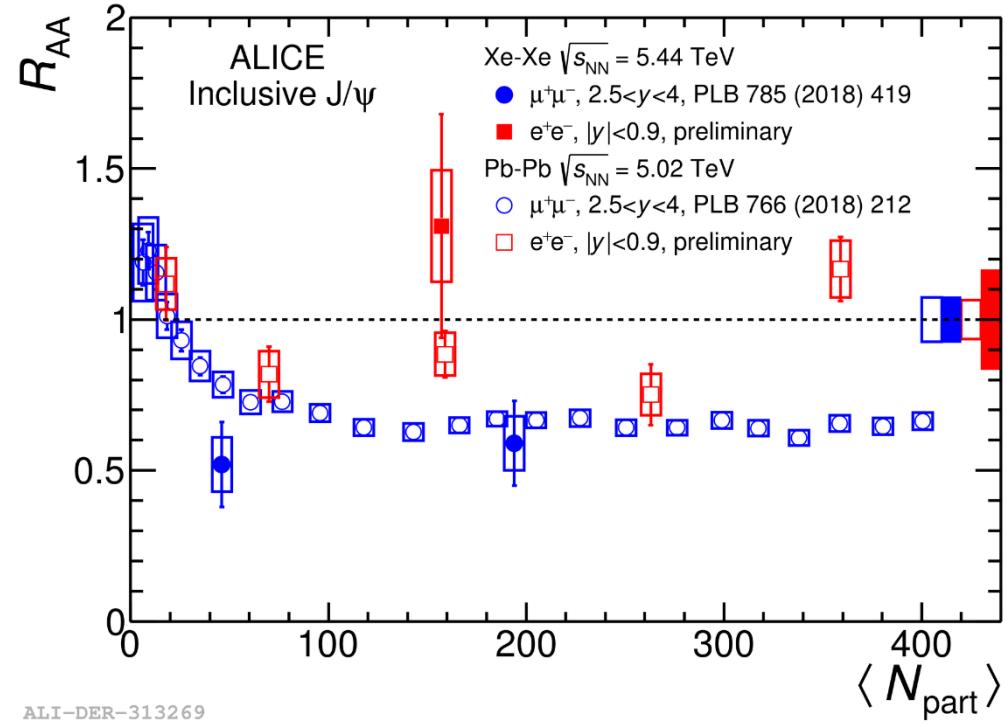
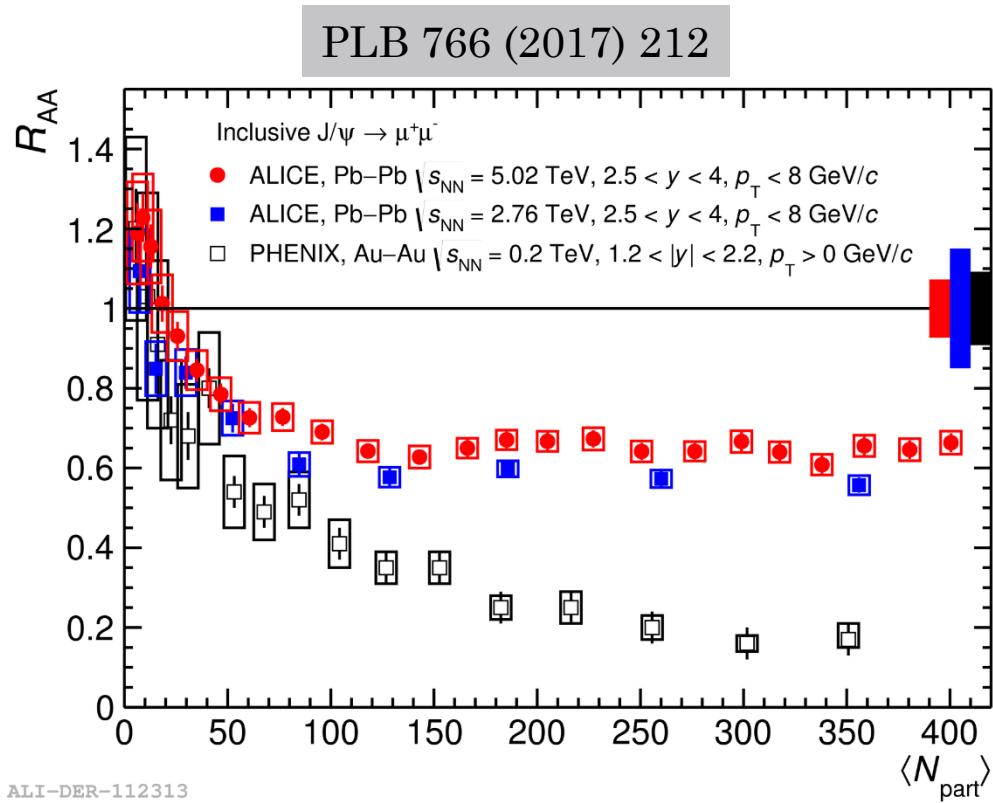
JHEP 1903 (2019) 015



- The transport model calculations give very small v_2 over the full p_T range.

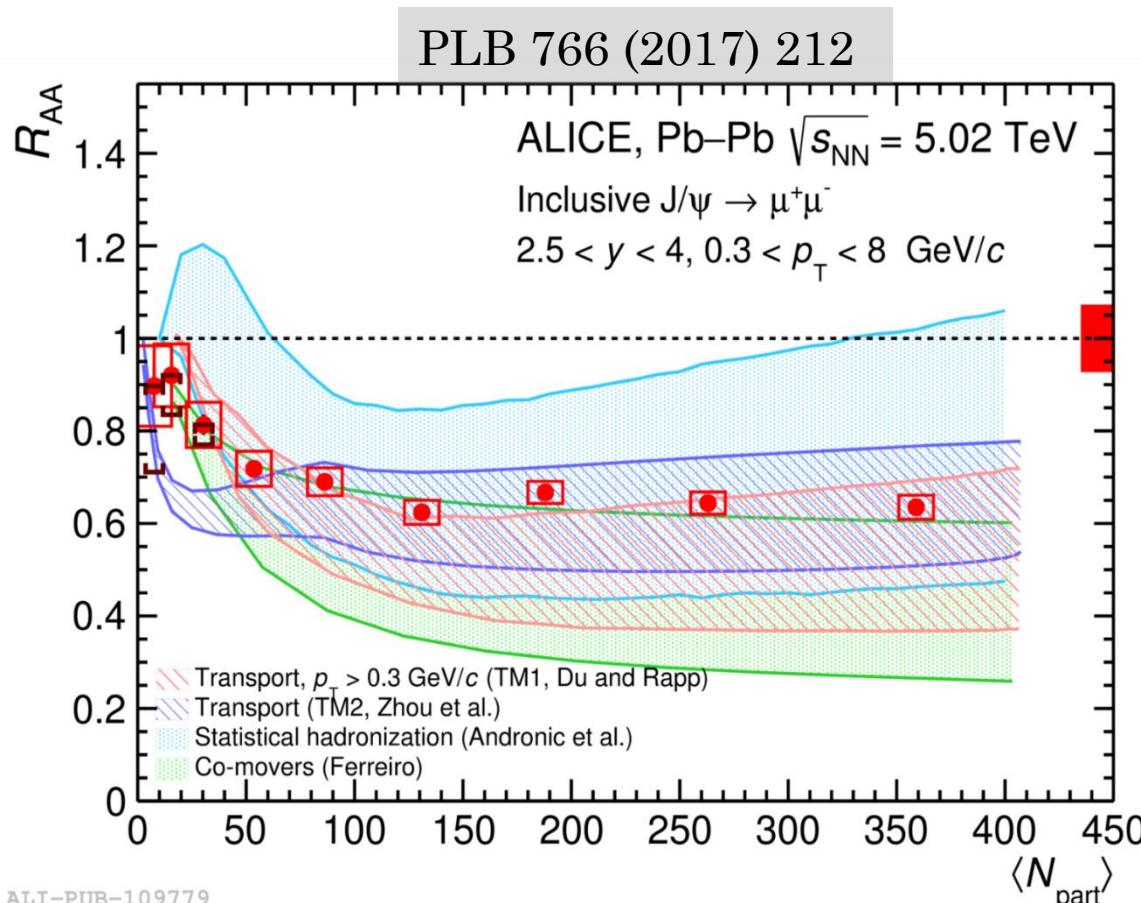


Charmonium in Pb-Pb and Xe-Xe



- J/ψ suppression is visible at RHIC whereas at the LHC there is an interplay of suppression and (re)generation.
- Most precise result in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and similar to that at $\sqrt{s_{NN}} = 2.76$ TeV.
- The $J/\psi R_{AA}$ is found to be of similar magnitude for Pb-Pb and Xe-Xe collisions.

Charmonium predictions in Pb-Pb



- $p_T > 0.3$ GeV/c to suppress the contribution from photo-production. The brackets represent the remaining photo-production contribution.

Statistical Hadronization : [continuous blue shade]
Andronic et al., Nucl. Phys. A 904-905 (2013) 535c

Co-movers interaction model : [continuous green shade]
Ferreiro, Phys. Lett. B 731 (2014) 57

Transport model (TM1) : [slant red lines]
Du and Rapp, Nucl. Phys. A 859 (2011) 114-125

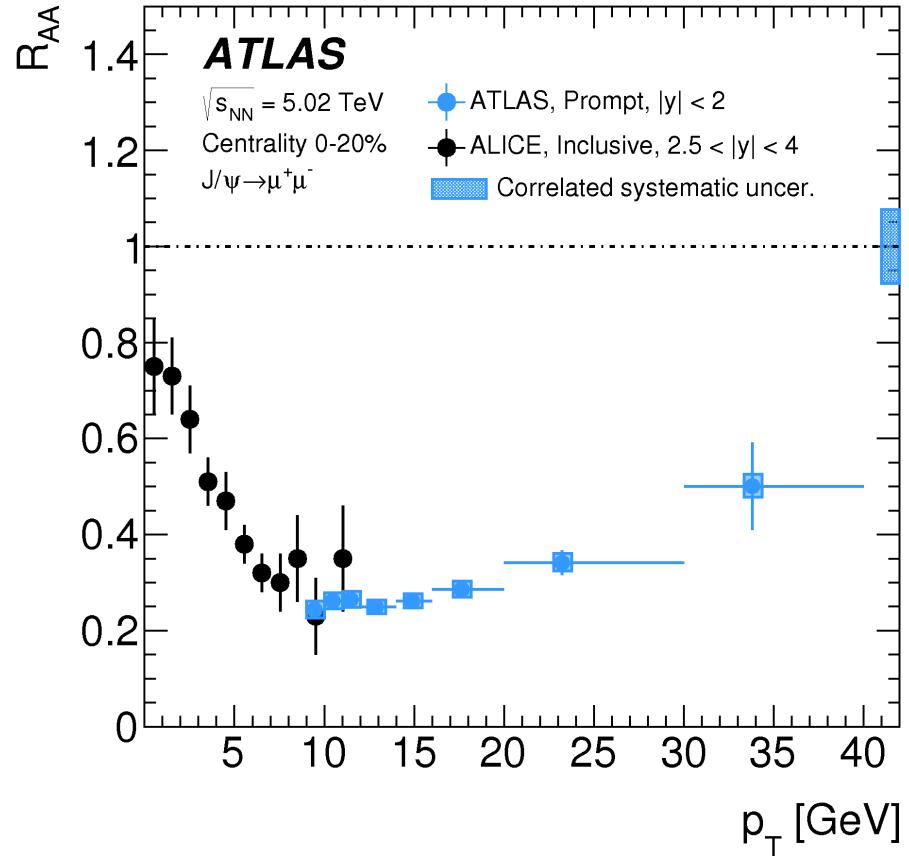
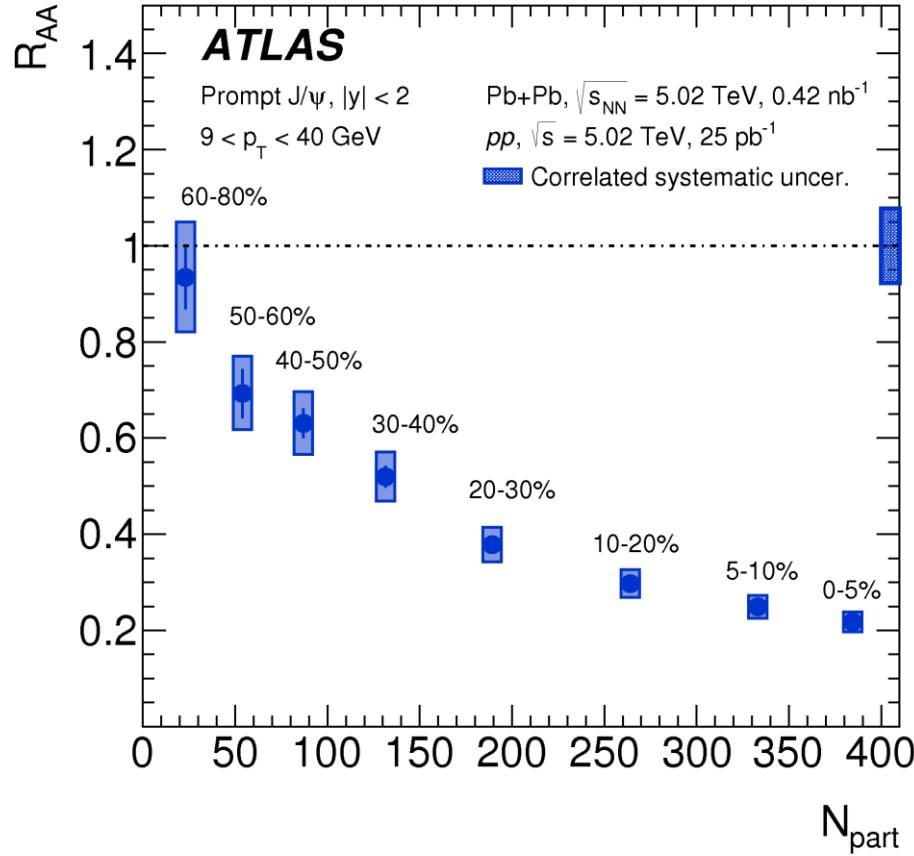
Transport model (TM2) : [slant blue lines]
Zhou et al., Phys. Rev C 89 no.5, 459 (2014) 054911

- All models can describe the data but with large uncertainties.

The dominant uncertainty on the models is the uncertainty on the total charm cross section

Charmonium in Pb-Pb

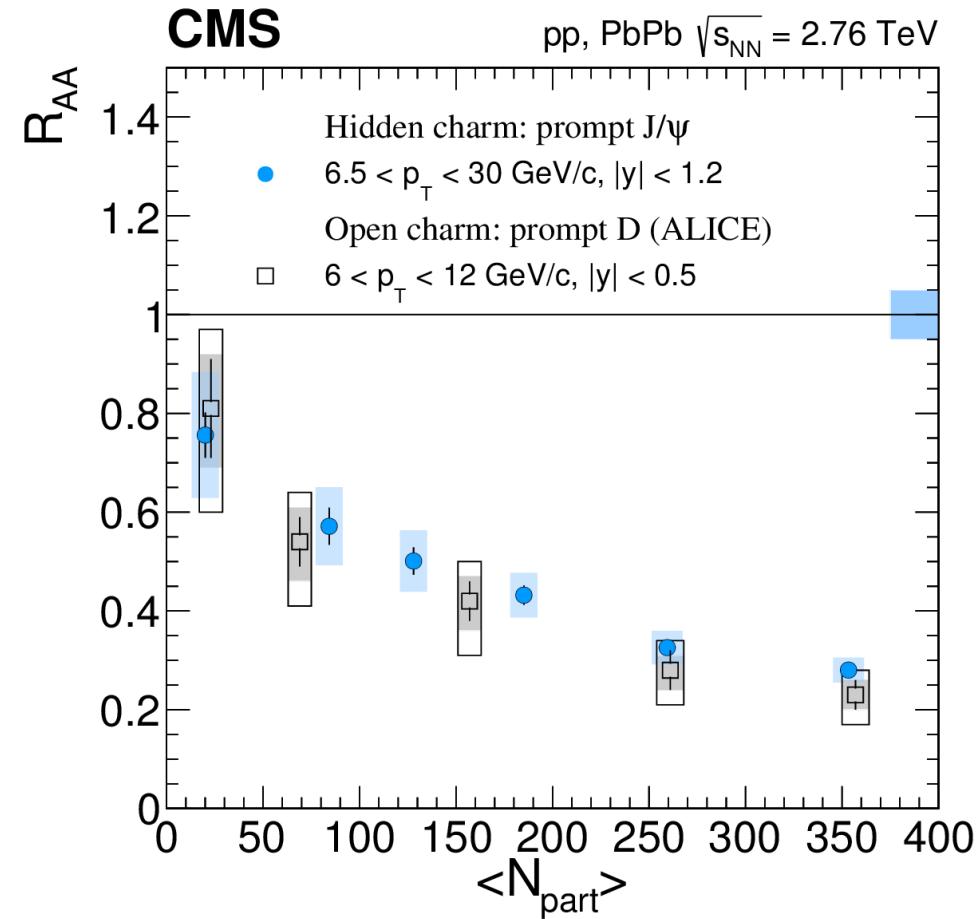
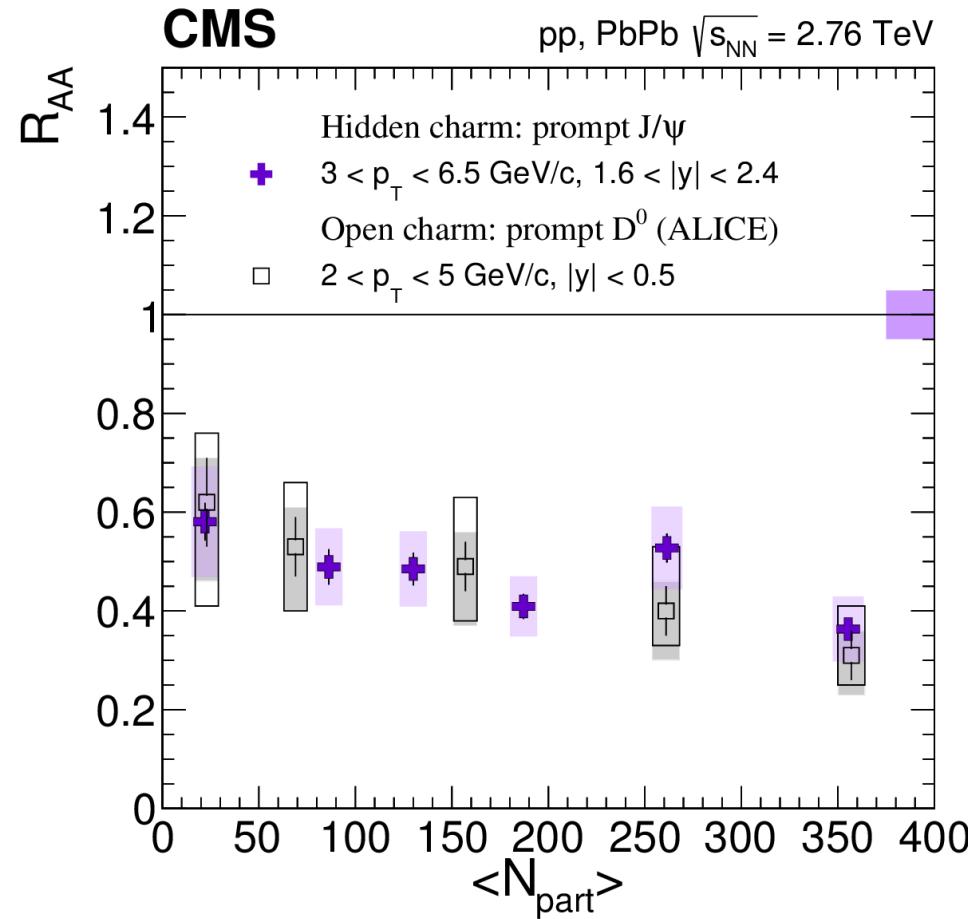
EPJ C78 (2018) 762



- Strong centrality dependence for prompt and high- p_T J/ ψ ($p_T > 9$ GeV/c).
- The results shows agreement between different LHC experiments, although covering different rapidity range.

Hidden and open charm

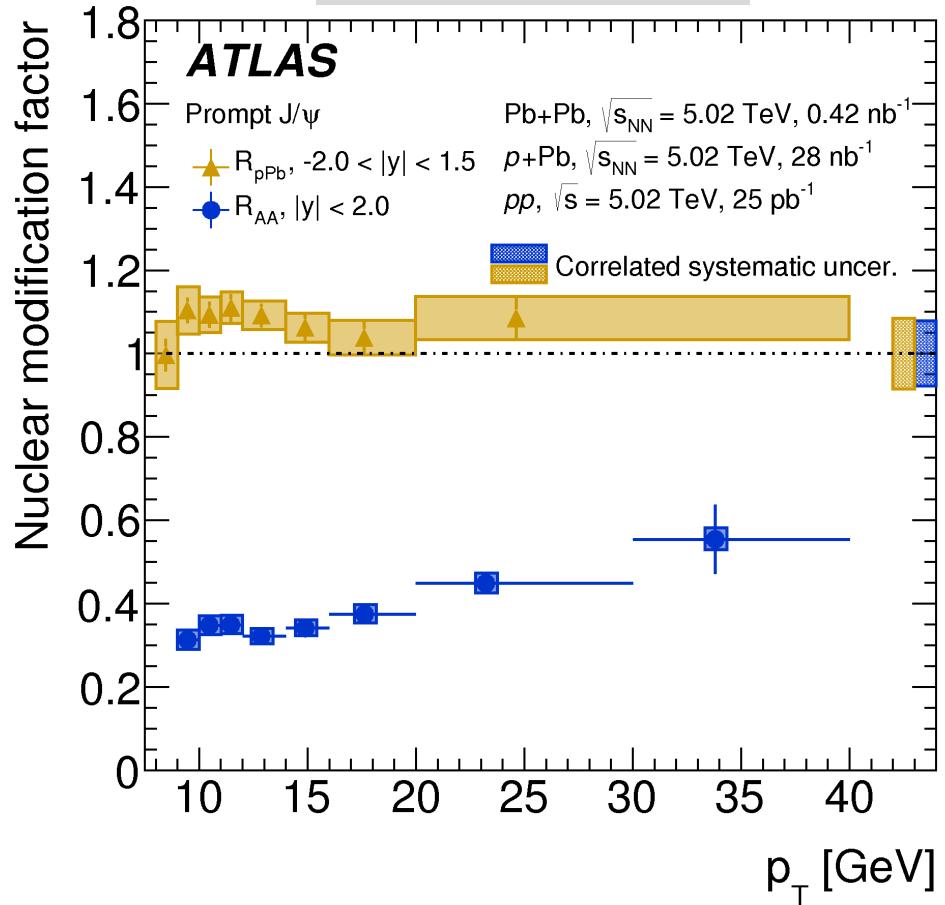
EPJ C77 (2017) 252



Similar suppression observed for prompt J/ψ and D -meson measured by CMS and ALICE, respectively.

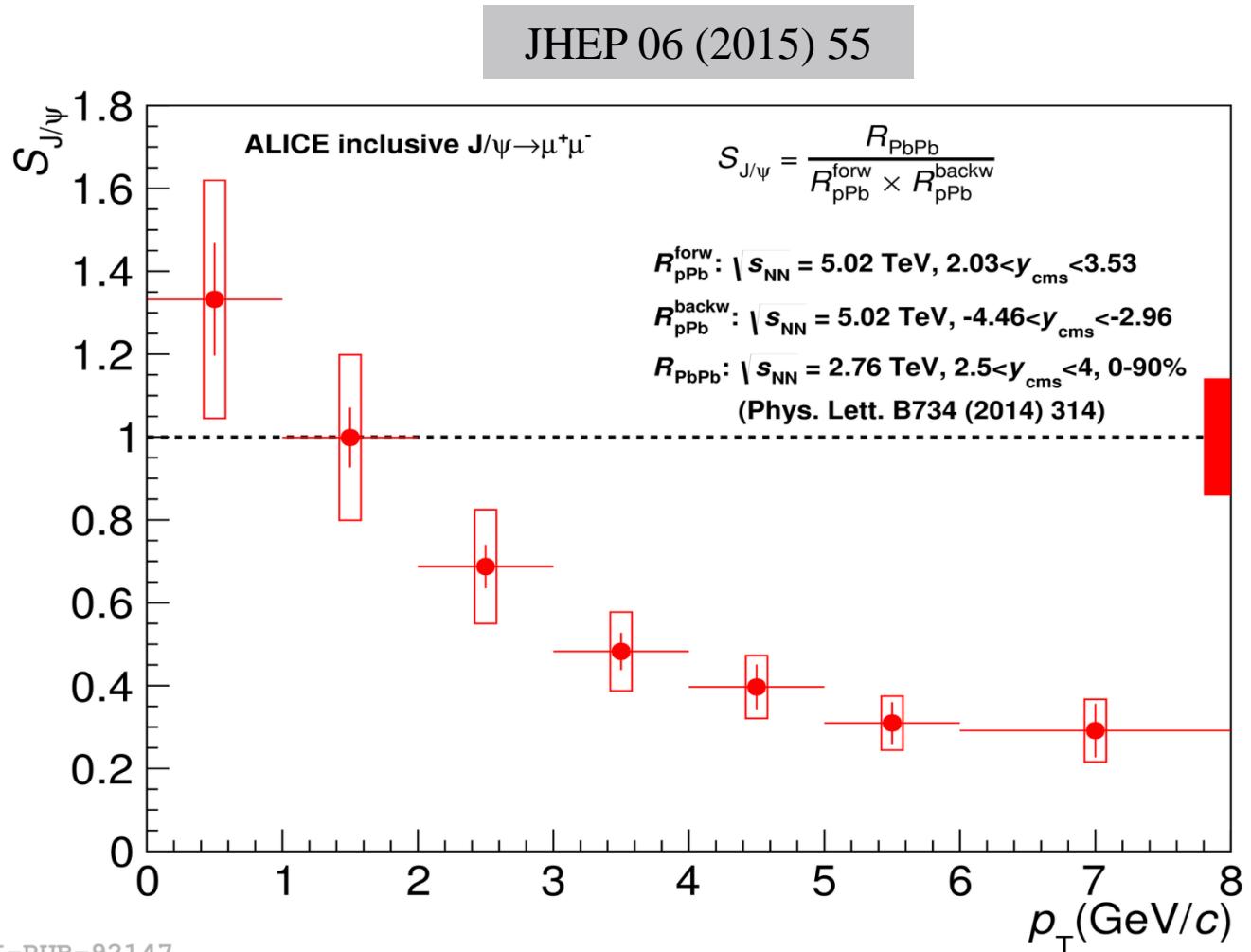
Charmonium in Pb-Pb

EPJ C78 (2018) 762



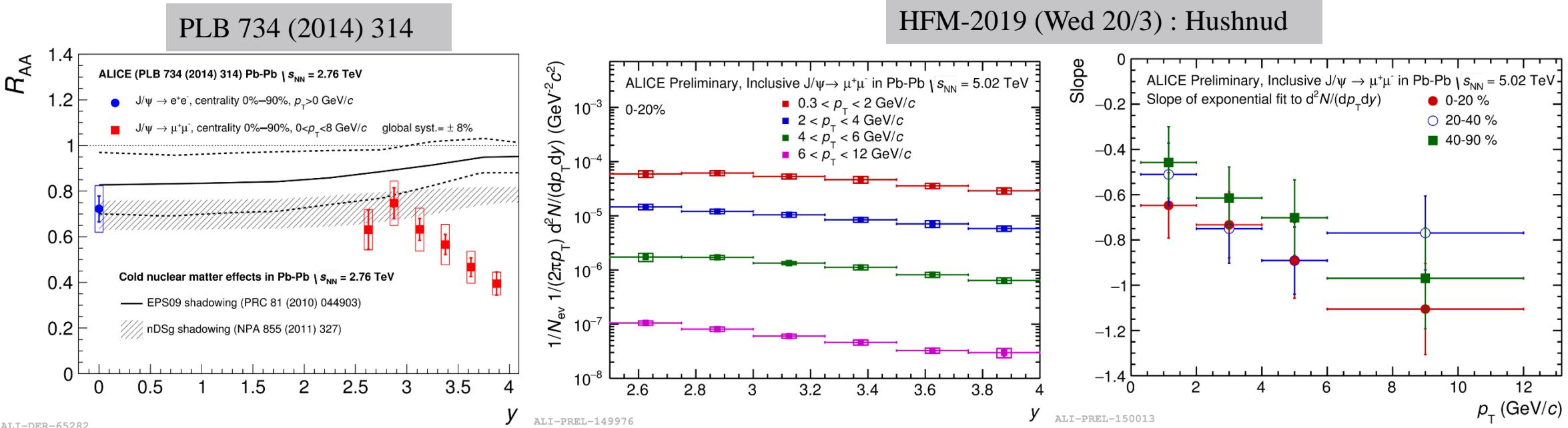
- In p-Pb : $R_{p\text{Pb}}$ is consistent with unity \rightarrow clean window for hot matter studies under these kinematics.
- In Pb-Pb : Suppression (R_{AA}) is mainly coming from QGP effects.

Charmonium in Pb-Pb and p-Pb



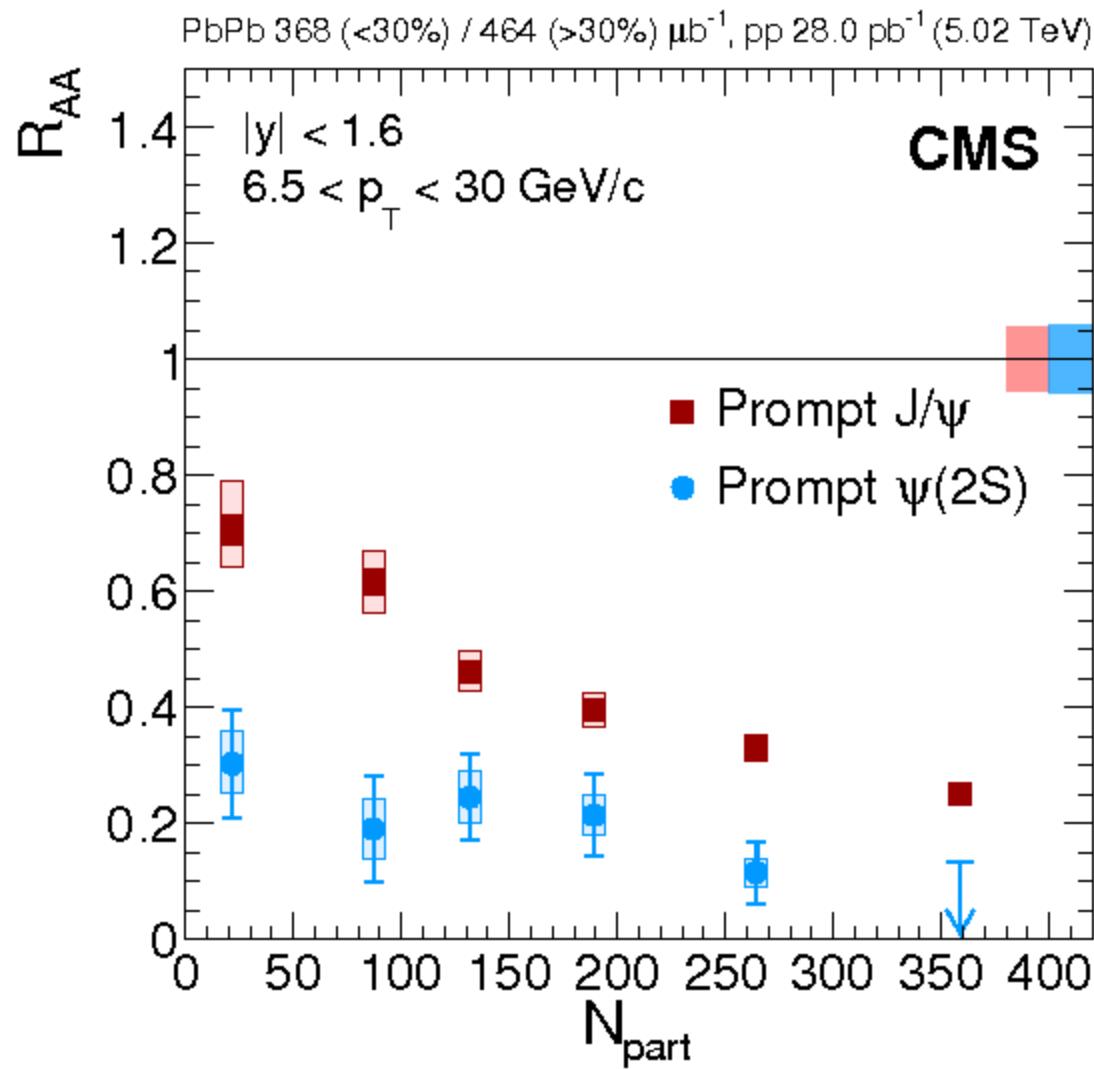
- A stronger suppression factor $\left(= \frac{R_{\text{PbPb}}}{R_{\text{pPb}} \times R_{\text{pPb}}} \right)$ is found at high- p_{T} by combining the J/ψ p-Pb and Pb-Pb forward rapidity results.

J/ ψ multi-differential studies in Pb-Pb



- A strong rapidity dependence is measured for J/ ψ R_{AA} which shows a trend opposite to that of shadowing predictions.
- The multi-differential measurement of J/ ψ R_{AA} as a function of centrality, p_T , and rapidity is ongoing and will provide more insight into the interplay between suppression and (re)generation in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Charmonium in Pb-Pb



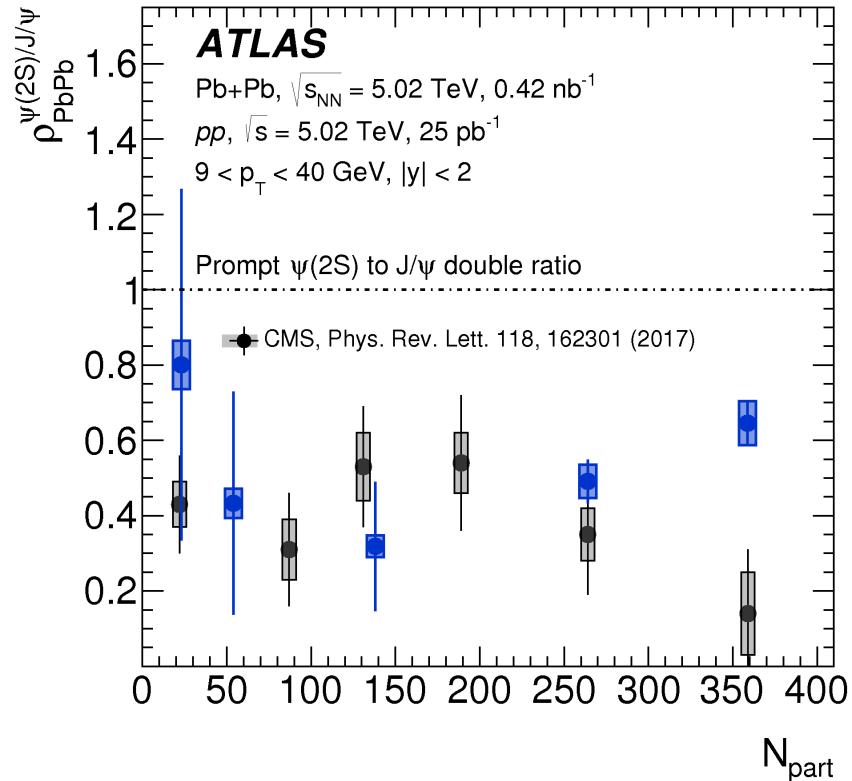
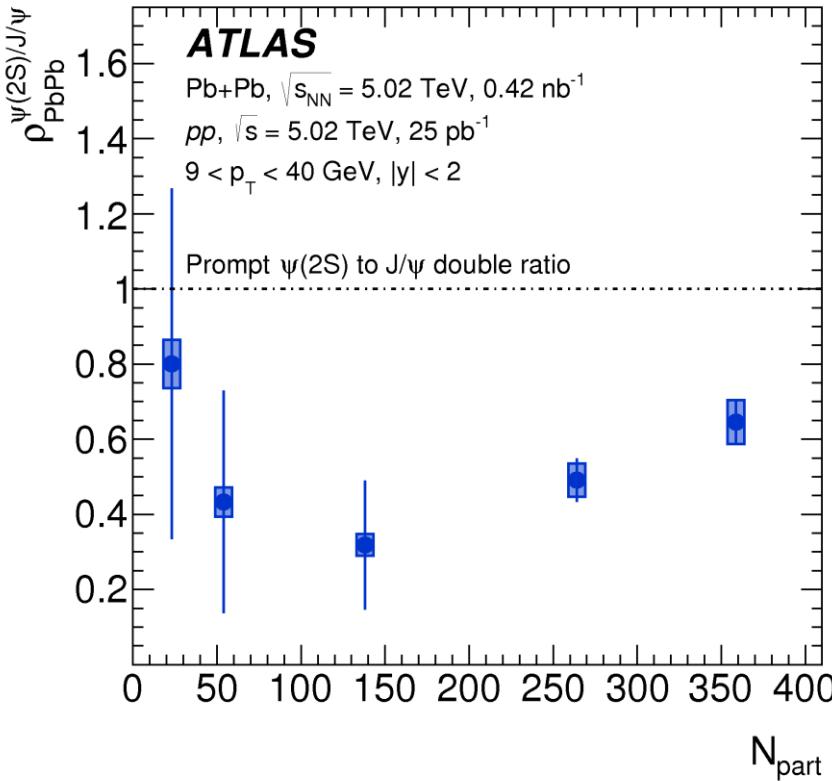
EPJ C78 (2018) 509

- $R_{AA}^{\psi(2S)} < R_{AA}^{J/\psi}$
- Since the $\psi(2S)$ production is reduced in peripheral collisions, the feed-down to 1S state is also reduced which might lead to a suppressed $R_{AA}^{J/\psi}$ even for most peripheral events (70-100%).
- Enhanced suppression for increasing centrality.

What causes the suppression ?
QGP effect, but also p-Pb effects.

Charmonium in Pb-Pb

EPJ C78 (2018) 762

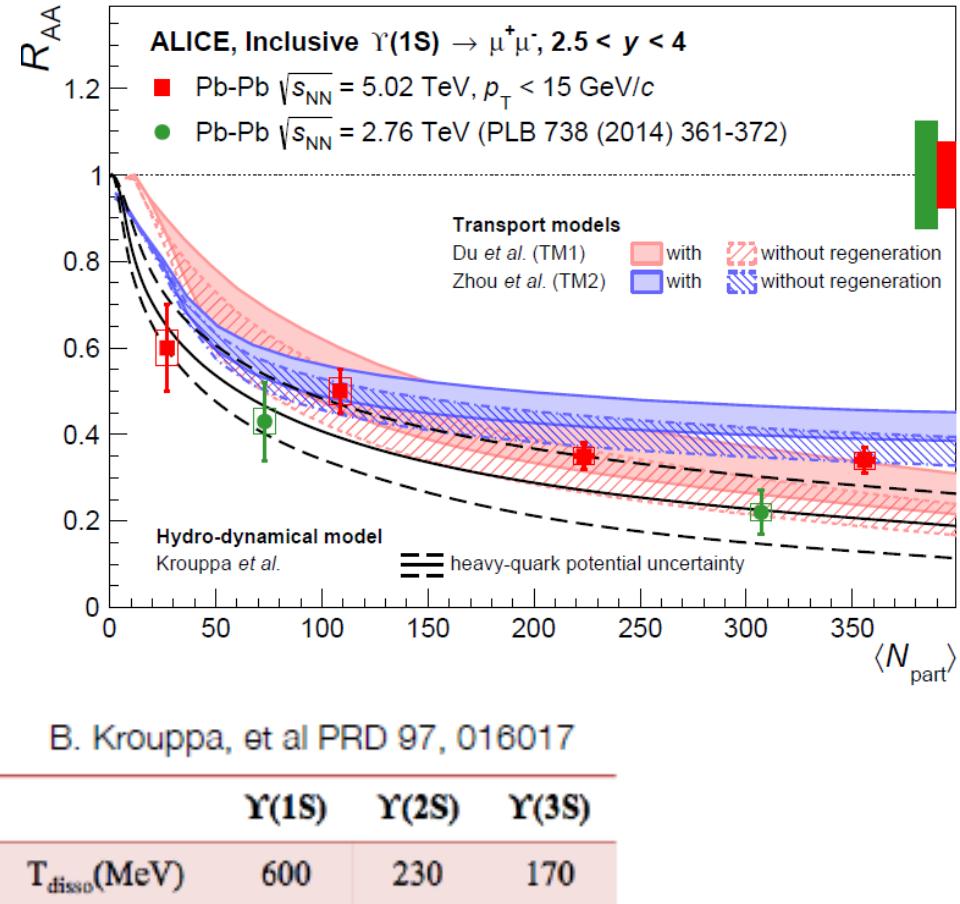
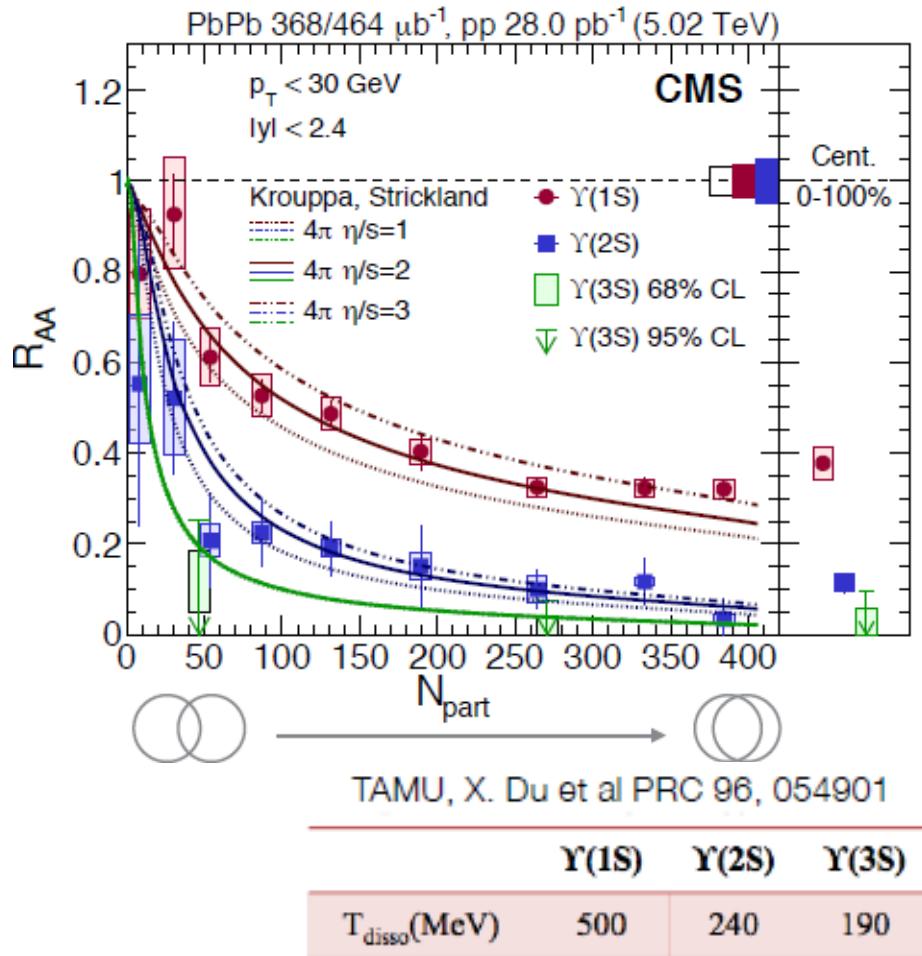


$$\rho_{\text{PbPb}}^{\psi(2S)/J/\psi} = R_{\text{AA}}^{\psi(2S)} / R_{\text{AA}}^{J/\psi}$$

- Non-trivial behavior for prompt J/ψ :
 - Good test for the sensitivity of QGP effects and difference of binding energy.
 - Sequential melting $R_{\text{AA}}^{\psi(2S)} < R_{\text{AA}}^{J/\psi}$.
- The results of different experiment are yet to be understood for most central collision.

Bottomonium in Pb-Pb

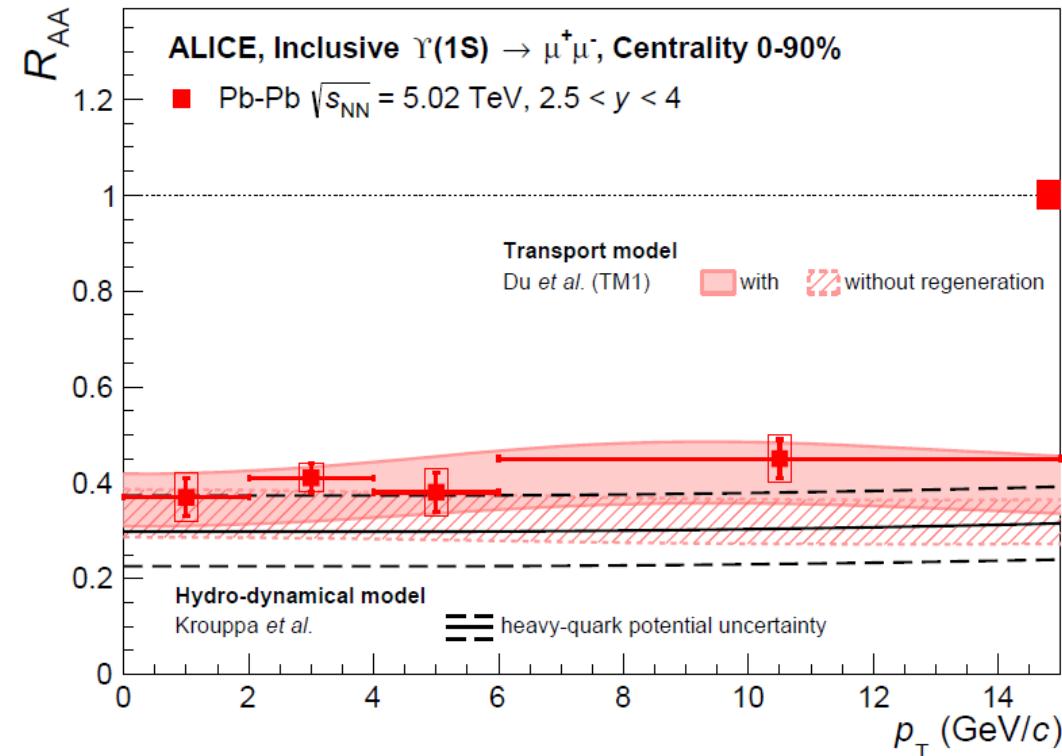
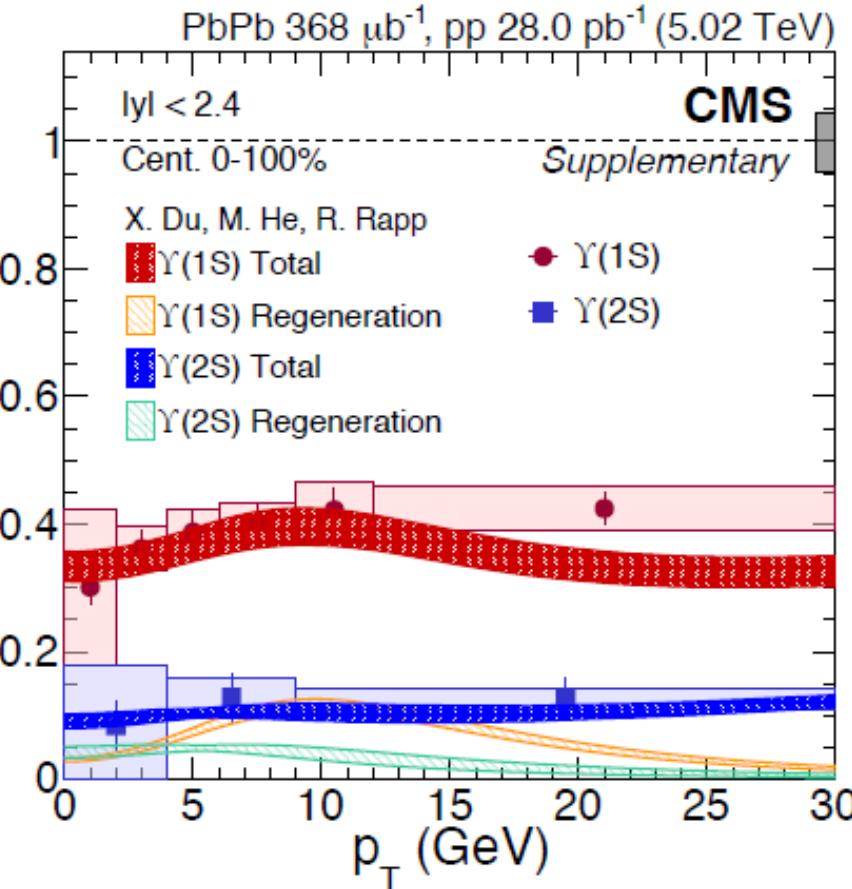
PLB 790 (2019) 270



PLB 790 (2019) 89

- Transport models by Du et al. (TM1) and Zhou et al. (TM2) and the anisotropic hydrodynamic model by Krouppa et al qualitatively reproduce the centrality dependence.
- The ratio of R_{AA} for $\Upsilon(2S)$ to $\Upsilon(1S)$ is $0.28 \pm 0.12 \text{ (stat.)} \pm 0.06 \text{ (sys.)} \rightarrow$ sequential suppression.

Bottomonium in Pb-Pb

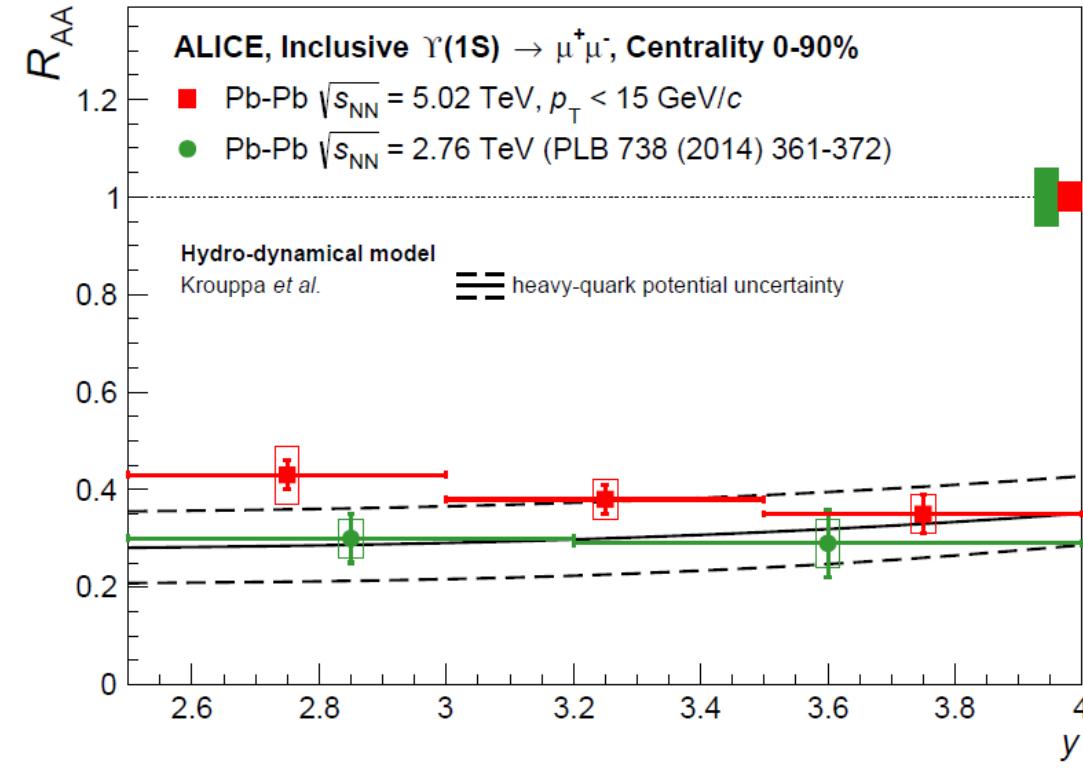
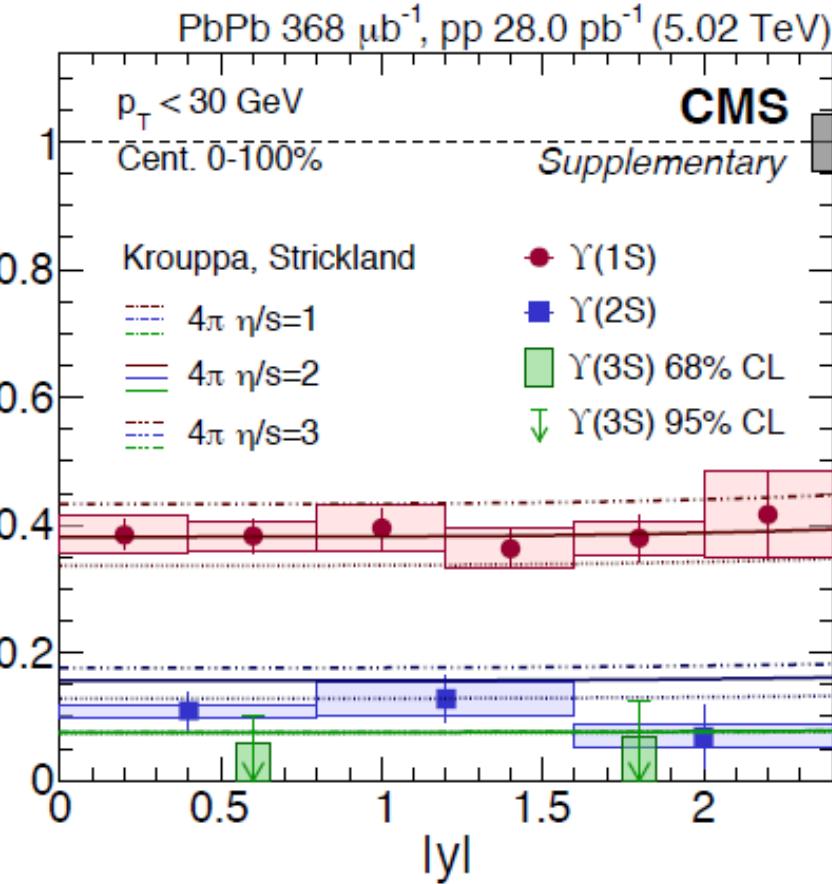


PLB 790 (2019) 89

- The (re)generation contribution to $R_{AA} \sim 0.1$
- A (re)generation bump is expected for the p_T dependence of $\Upsilon(1S) R_{AA}$, however monotonic increase for $\Upsilon(2S) R_{AA}$ is predicted by the transport model.
- The p_T dependence of $\Upsilon(1S) R_{AA}$ in Pb-Pb collisions is described by the transport model and anisotropic hydrodynamics model.

Bottomonium in Pb-Pb

PLB 790 (2019) 270

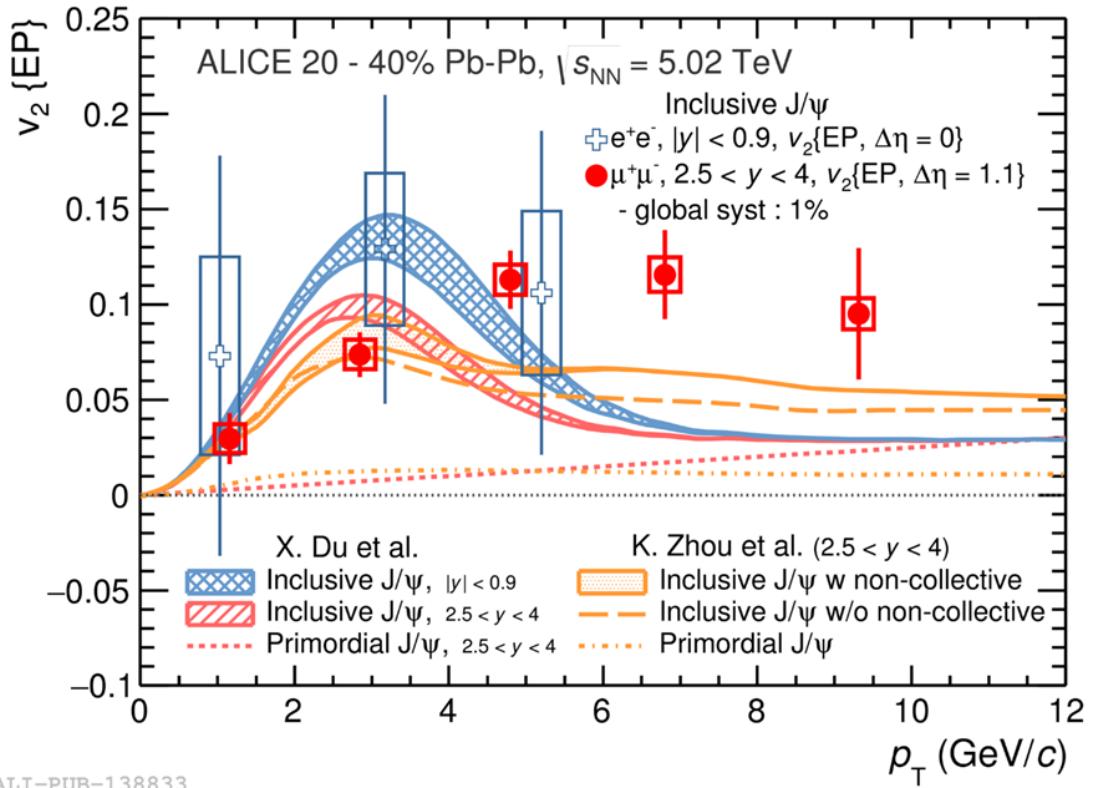
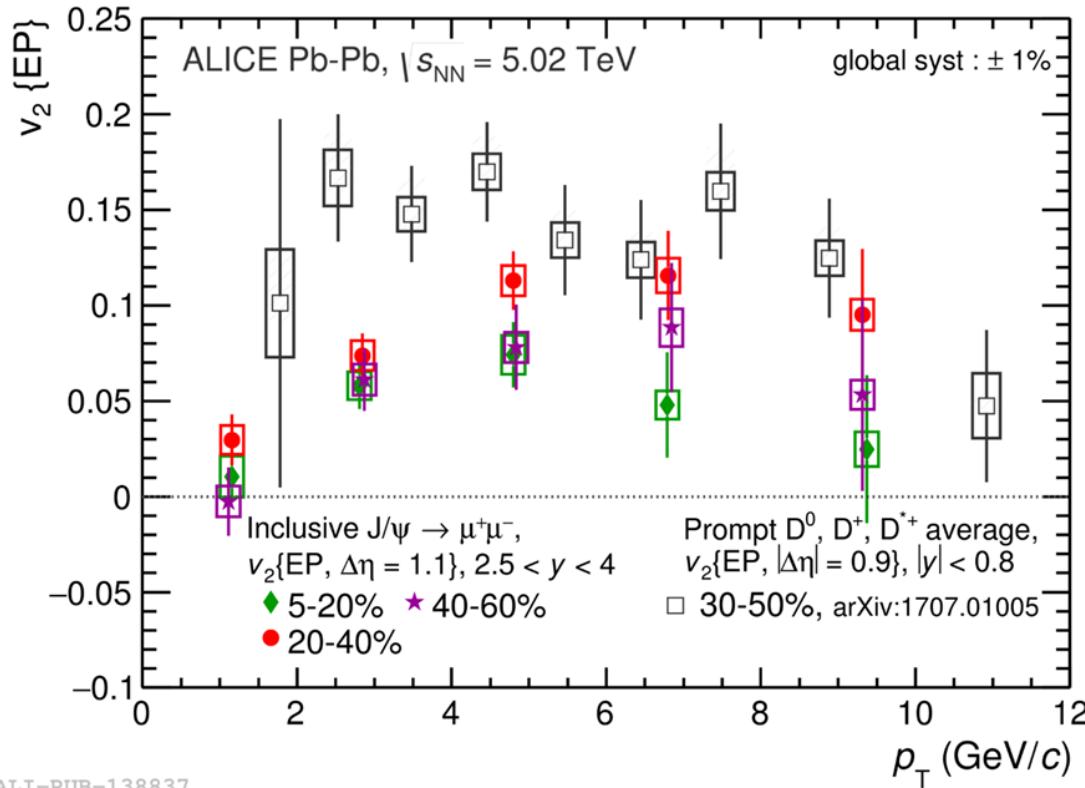


PLB 790 (2019) 89

- The anisotropic hydrodynamic model by Krouppa et al. can describe the rapidity dependence of R_{AA} , but hint of different trend is observed.

$J/\psi \nu_2$ in Pb-Pb

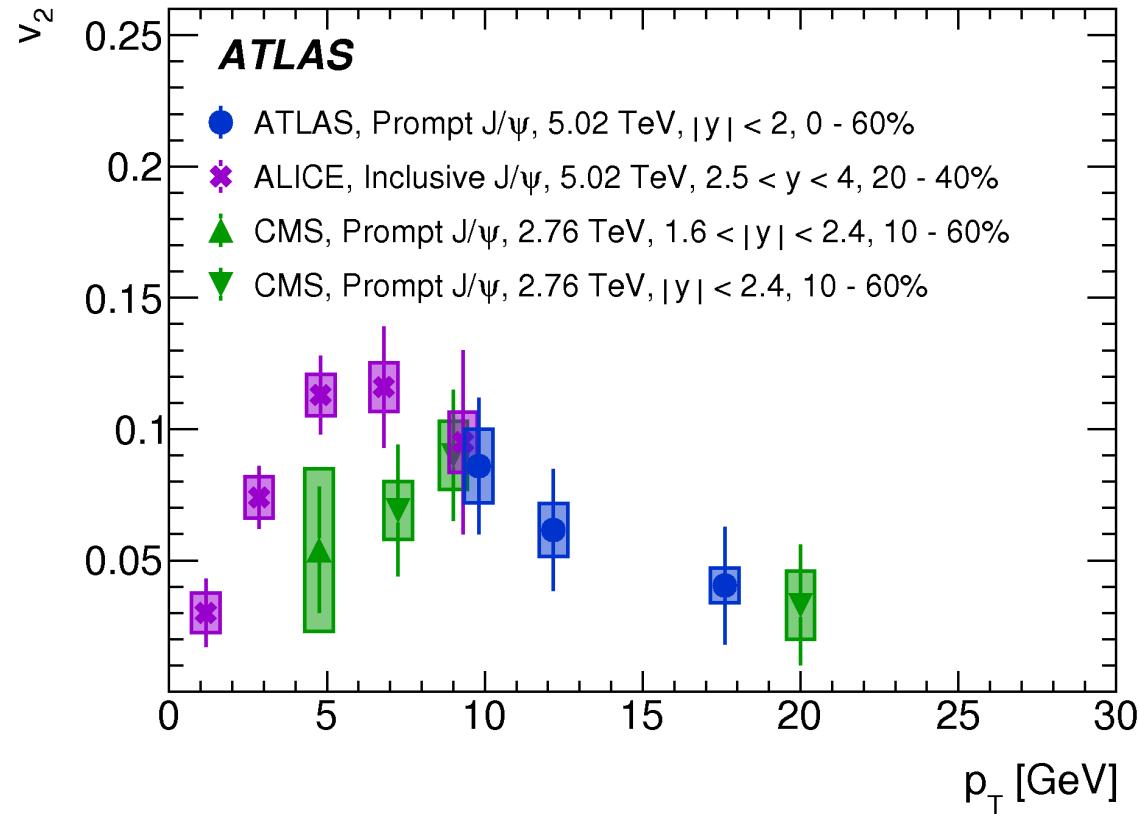
PRL 119(2017) 242301



- Both the bound state charmonium and prompt open-charm mesons show non-zero elliptic flow.
- The transport model predictions are not able to describe the data in the high p_T region.

$J/\psi \nu_2$ in Pb-Pb

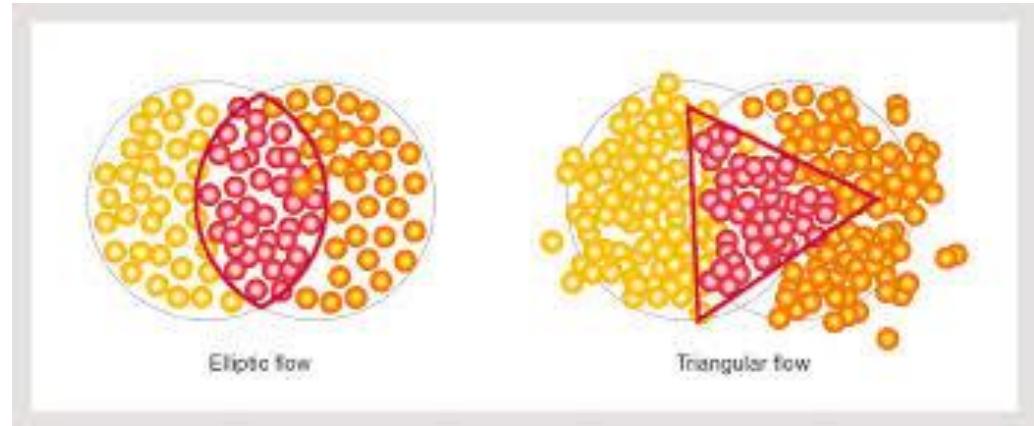
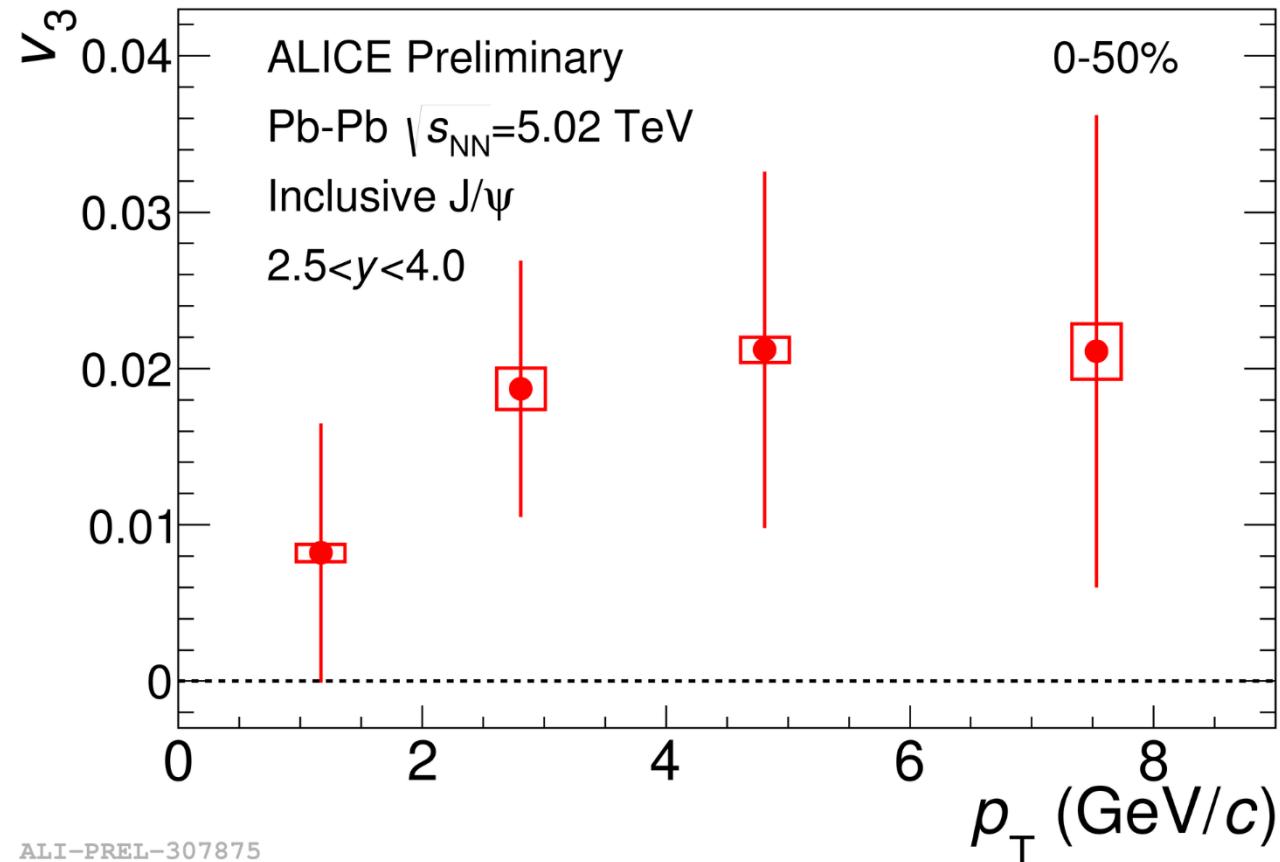
EPJC 78 (2018) 784



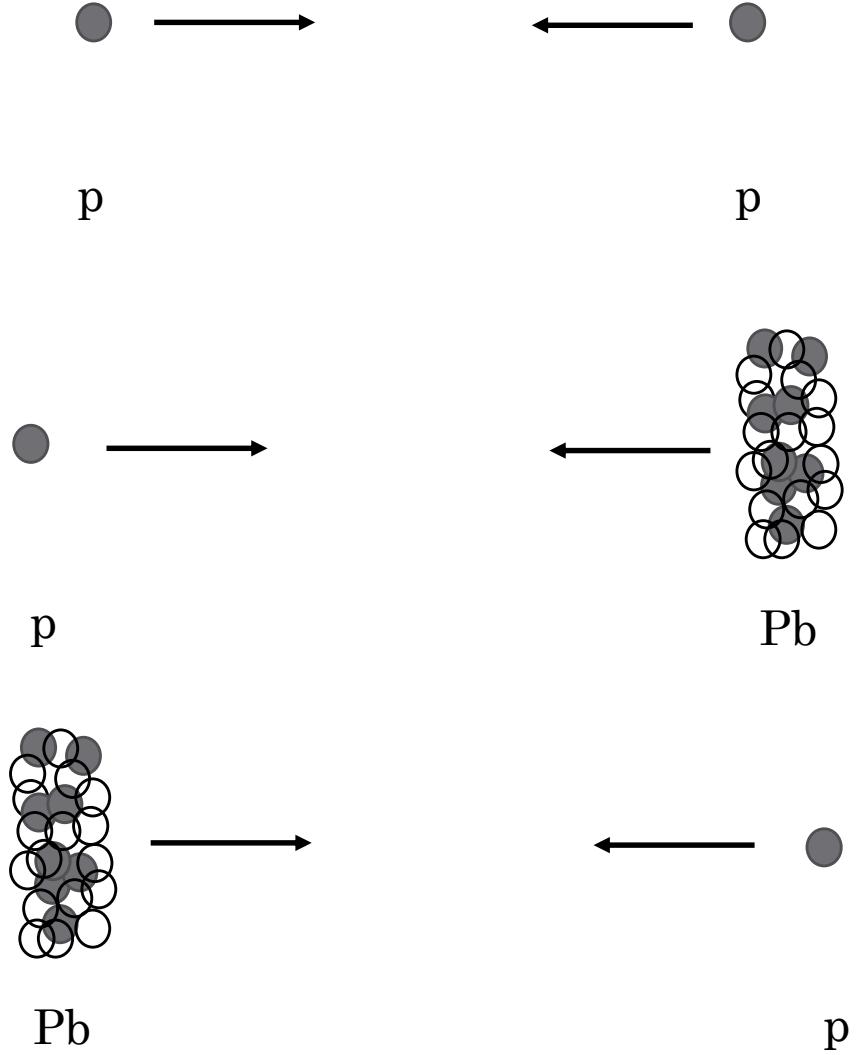
- Non-prompt fraction at low- p_T is very small allowing to compare inclusive and prompt J/ψ production.
- Good agreement at $p_T \sim 9$ GeV/c between ATLAS, CMS and ALICE.

$J/\psi \nu_3$ in Pb-Pb

JHEP 1902 (2019) 012

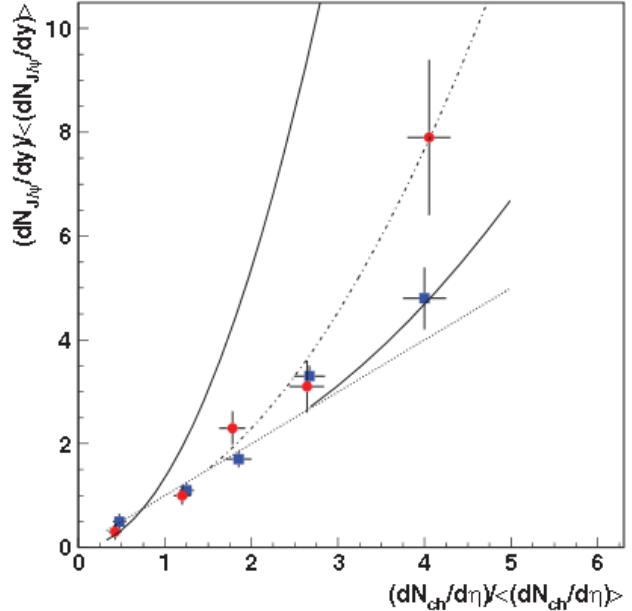


- A non-zero ν_3 of J/ψ (3.7σ significance) has been measured for the first time.

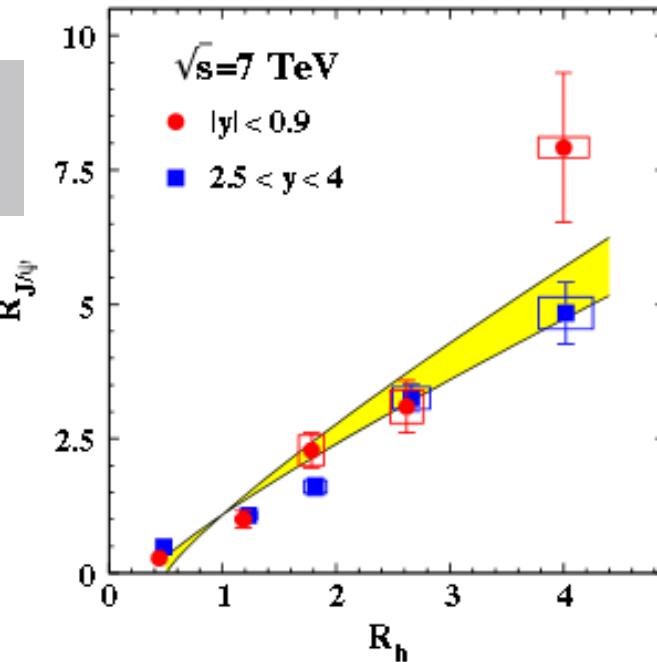


Charmonium as a function of multiplicity in pp

E.G.Ferreiro et. al., PRC 86 (2012) 034903



ALICE Data
PLB 712 (2012)
165



B.Z.Kopeliovich et. al., PRD 88 (2013) 116002

- Finite spatial extension (non-zero impact parameter) for elementary parton-parton interactions.
- Formation of colour ropes or flux tubes—strings.
- $N_{\text{parton-parton}}^{\text{collisions}} \propto N_{\text{strings}}$.
- Strings can overlap in transverse direction resulting in a reduction of soft-particle production, $\frac{dN_{ch}}{d\eta} \sim \sqrt{N_{\text{strings}}}$.
- Hard particle production,

$$N_{J/\psi} \propto N^{\text{coll}} \propto N_{\text{strings}}$$
.

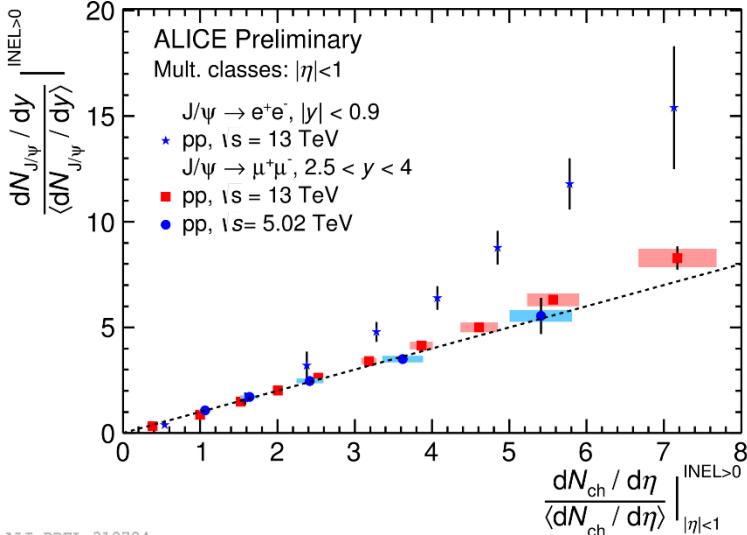
- The high multiplicity pp events are similar to pA.
- NA3 and E866 collaboration results used for :

$$R_{J/\psi}^{pA} = N_{\text{coll}} A^{\alpha-1} \quad [\alpha = 0.95 \text{ from E866}]$$
- Compilation of various hadron-nuclear results [NPA395(1983)482] :

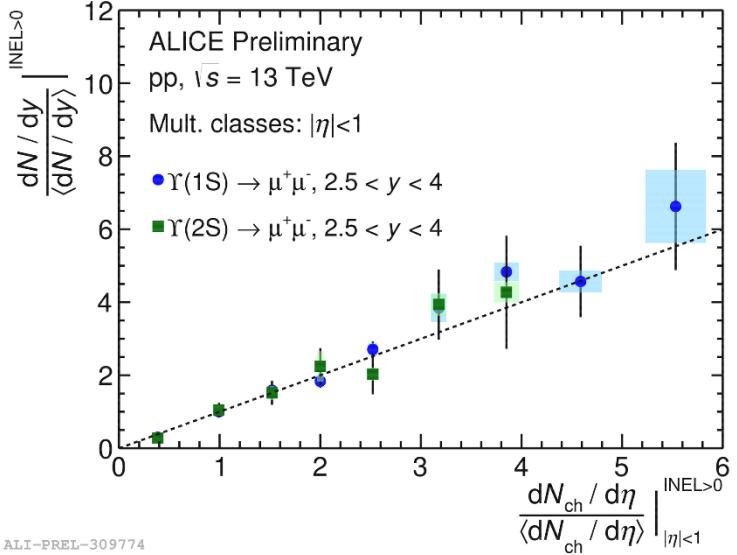
$$R_h^{pA} = 1 + \beta(N_{\text{coll}} - 1) \quad \text{with } [0.5 < \beta < 0.65]$$
- Finally using, $N_{\text{coll}} \approx \frac{\sigma_{in}^{pp}}{\pi r_0^2} A^{1/3}$ for pA collisions, the dependency is extracted for $R_{J/\psi}^{pA} \propto R_h^{pA}$ and applied for pp collisions

Quarkonium as a function of multiplicity in pp

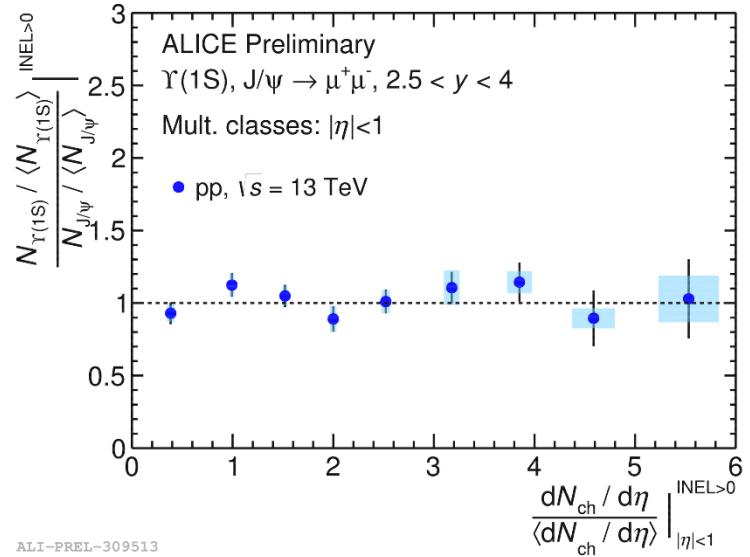
HFM-2019 (Wed 20/3) : Anisa, Dhananjaya



ALI-PREL-310724

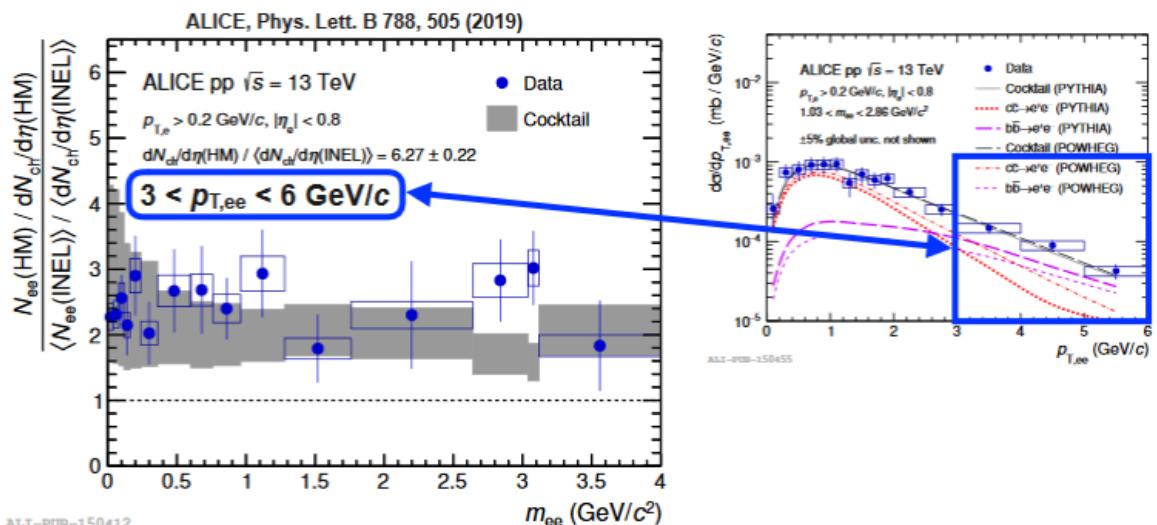


ALI-PREL-309774

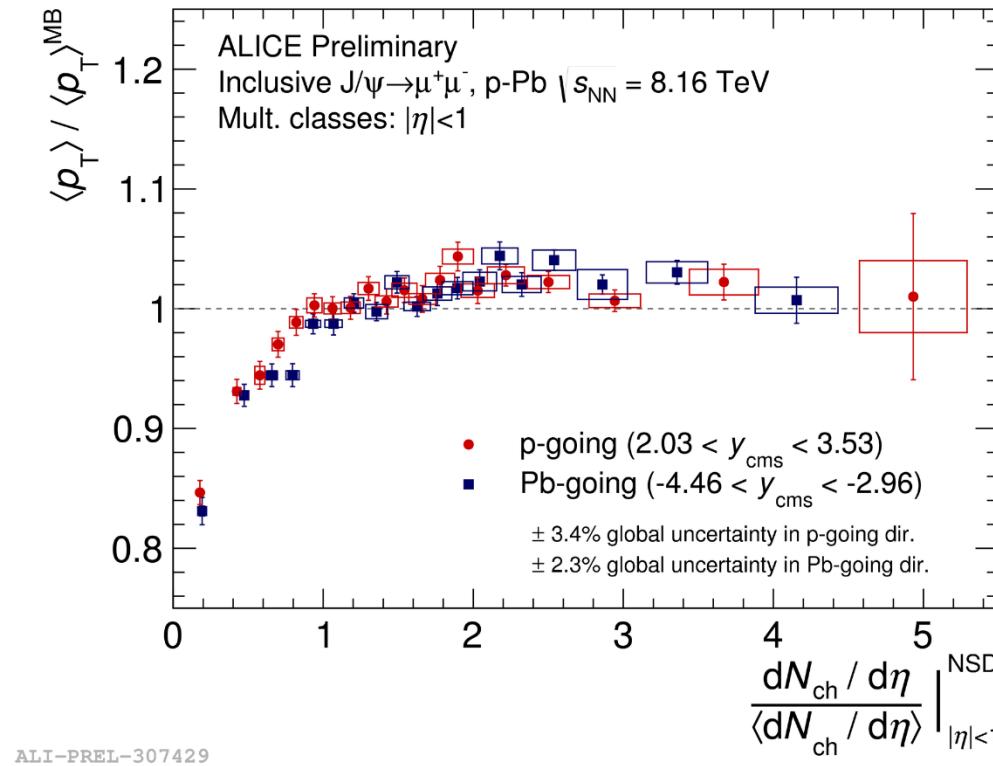
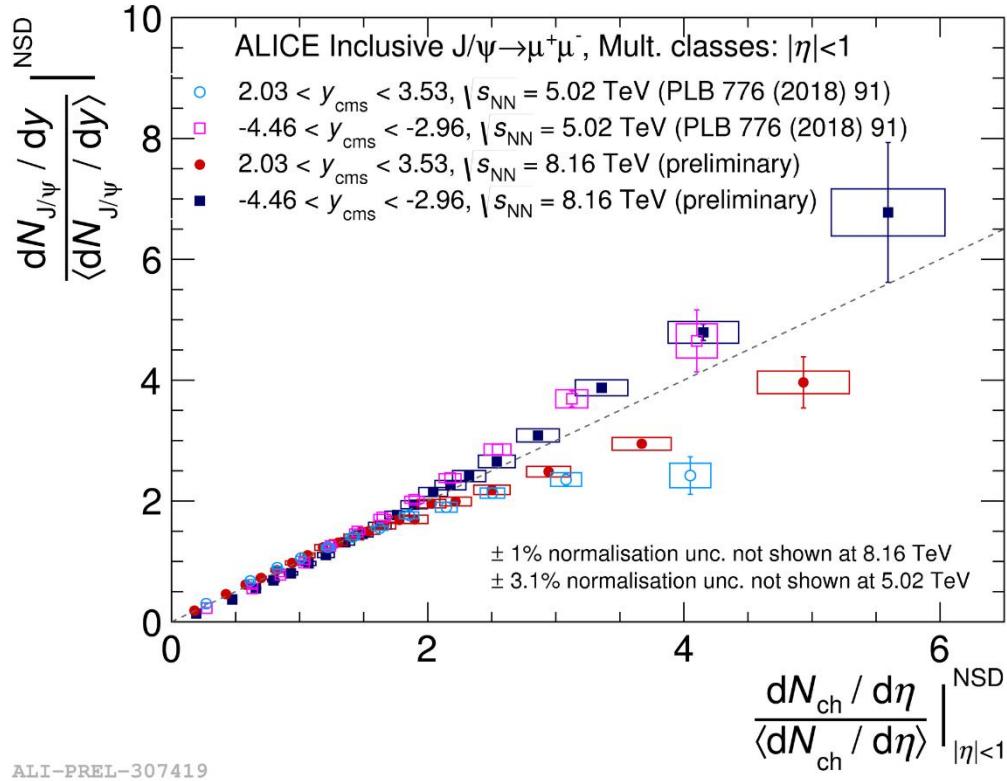


ALI-PREL-309513

- A detailed study has been performed to explore the rapidity dependence at various energies for different colliding systems and different resonances.
- A linear increase has been observed for forward rapidity J/ψ vs mid-rapidity multiplicity compared to the faster than linear increase of midrapidity J/ψ with multiplicity in mid-rapidity.
- The increase of the bottom production as function of charged particle multiplicity is found to be similar to that observed for charm production. Similar observation in di-electron spectra for open heavy flavour.

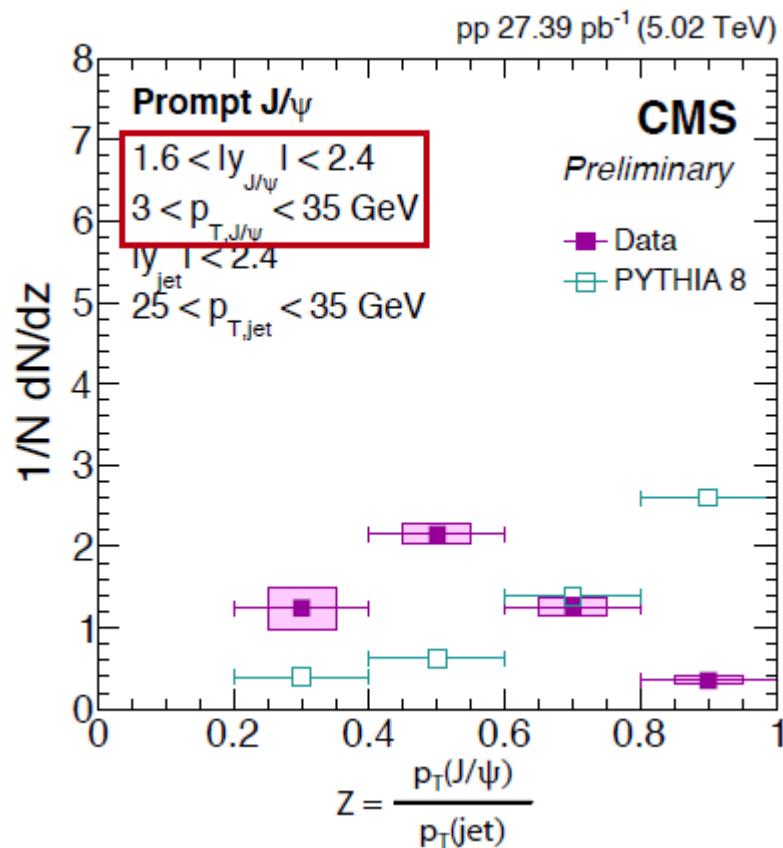
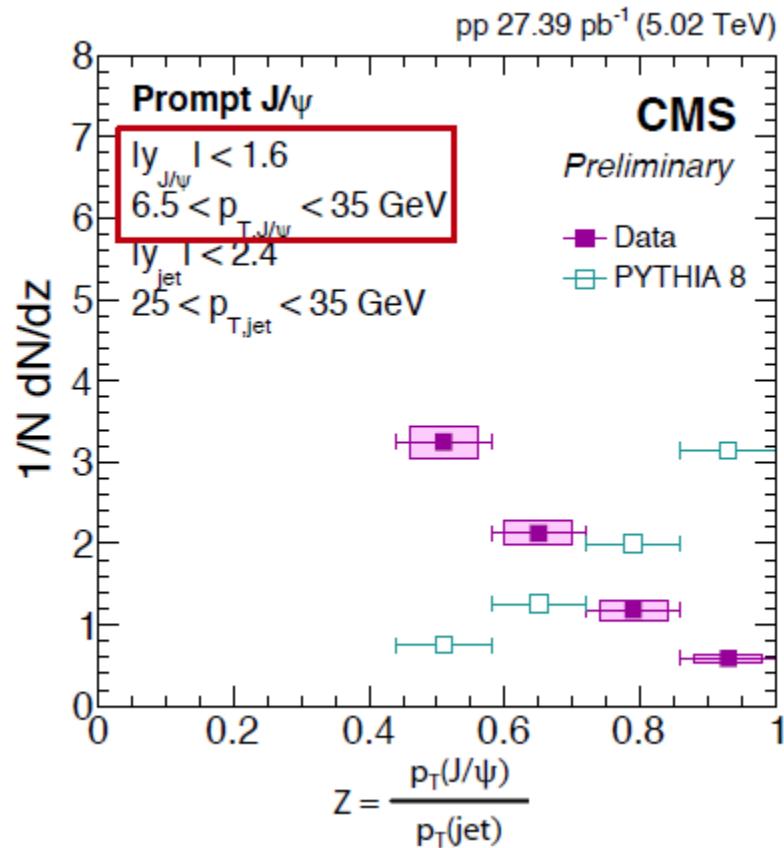


Charmonium as a function of multiplicity in p-Pb



- An increase of J/ψ yield with normalized $\frac{dN_{\text{ch}}}{d\eta}$ is observed at backward rapidity, however in forward rapidity a hint of saturation is observed.
- The normalized $J/\psi \langle p_T \rangle$ increases at low charged-particle multiplicity and saturates at high multiplicity events.

J/ ψ in Jets



- Influence of initial state in J/ ψ production.
- How much it is isolated in terms of fragmatation parameter, $z = \frac{p_T(J/\psi)}{p_T(\text{jet})}$
- PYTHIA8 does not describe the prompt J/ ψ production in pp
- J/ ψ are much less isolated in data than in MC.



Summary

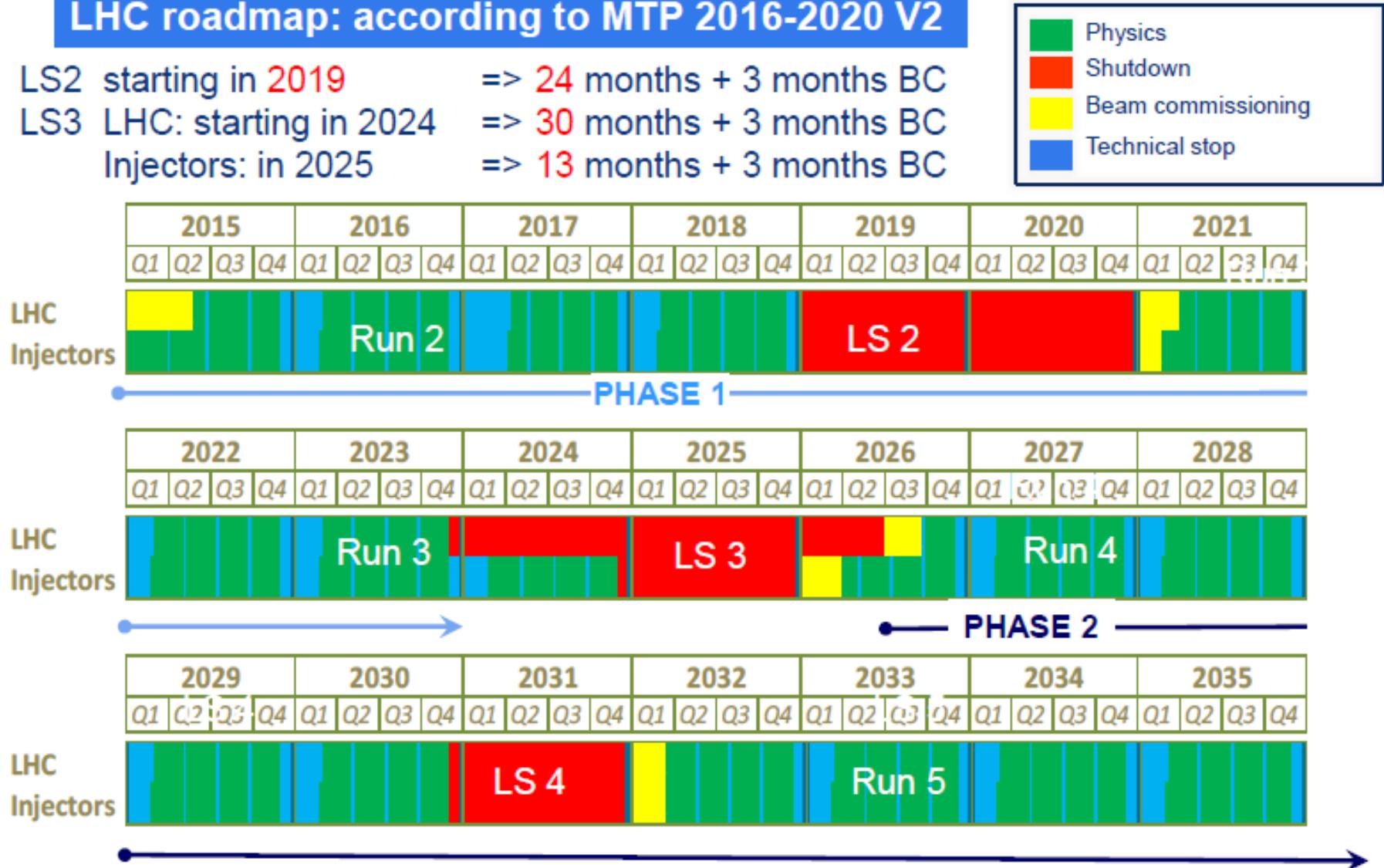
- General : LHC results are in agreement among the four ALICE, ATLAS, CMS and LHCb experiments except very few data points.
- pp collisions
 - Theoretical calculations start to describe data over all p_T .
- p-Pb collisions
 - The nuclear modification factor of J/ψ and $\Upsilon(1S)$ can be explained by Cold Nuclear Matter effects.
 - The final state effect is needed to explain the R_{pPb} of $\psi(2S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$.
 - A long-range correlation is observed : $J/\psi \nu_2$ in central p-Pb collisions.
- Heavy-ion collisions
 - At Low p_T the interplay of two main mechanisms : suppression and (re)generation for charmonium, whereas for bottomonium suppression plays dominant role with negligible (re)generation.
 - At high p_T the suppression effects is dominant.
 - Observation of non-zero ν_2 with higher precision and first look at non-zero ν_3 for J/ψ .
- Heavy-quark as a function of multiplicity
 - The increase of quarkonium production as a function of charged-particle multiplicity exhibits no strong \sqrt{s} dependence and also found to be similar for charmonium and bottomonium.
 - Via dielectron continuum: Bottom quark production scales with multiplicity just like open charm.



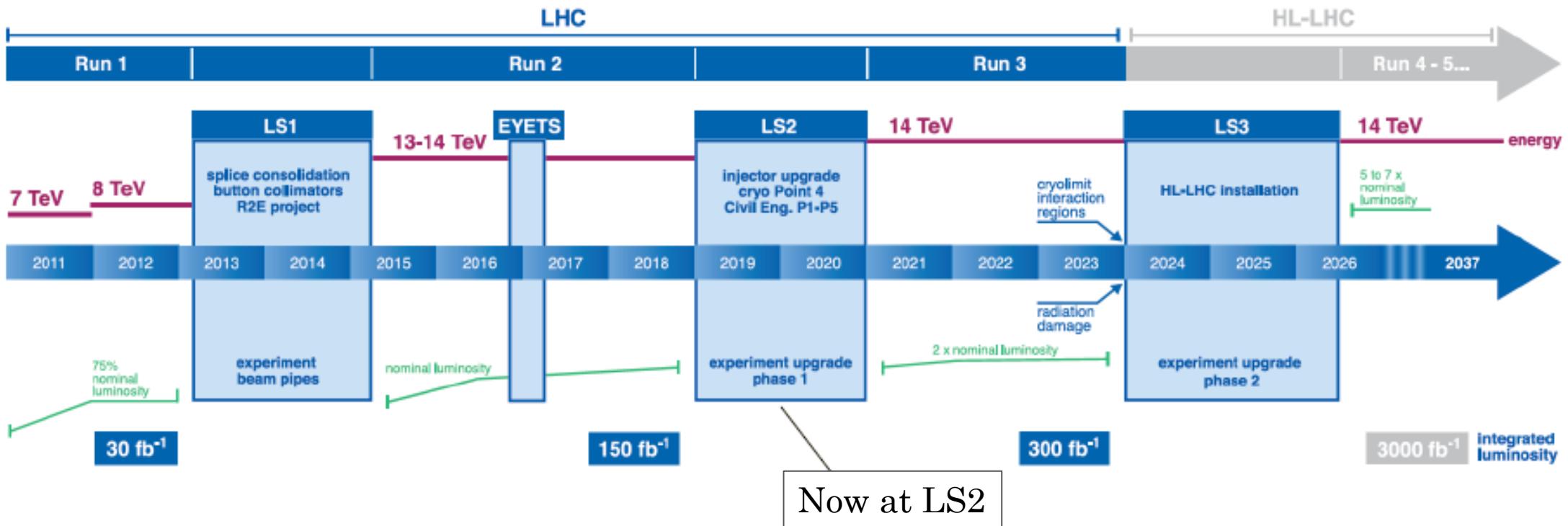
LHC plan

LHC roadmap: according to MTP 2016-2020 V2

LS2 starting in 2019	=> 24 months + 3 months BC
LS3 LHC: starting in 2024	=> 30 months + 3 months BC
Injectors: in 2025	=> 13 months + 3 months BC



LHC plan

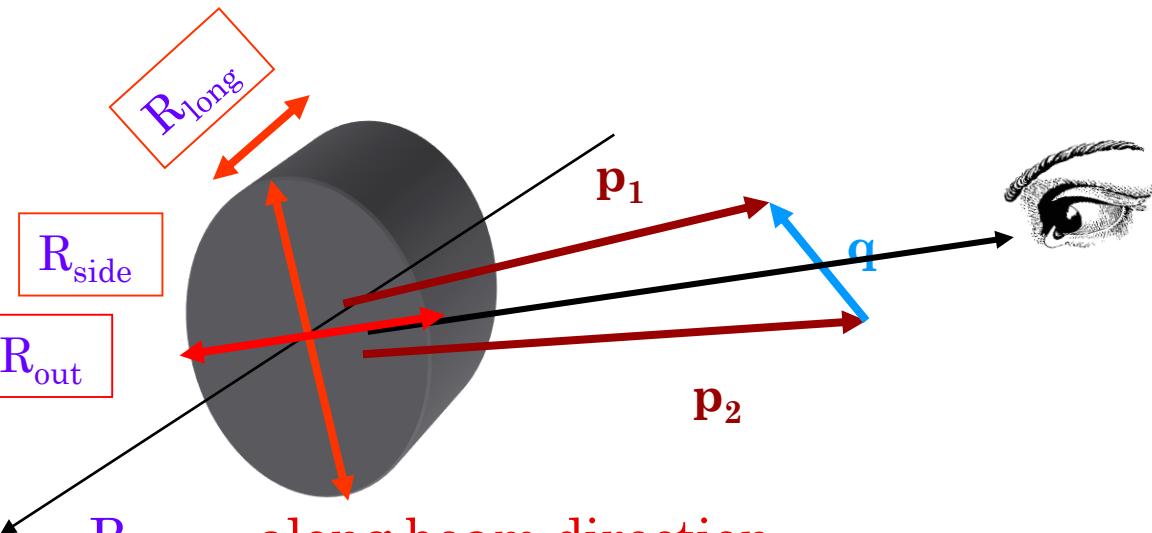




Thank You

Size and Lifetime of Fireball

ALICE Phys. Lett. B696 (2011)328



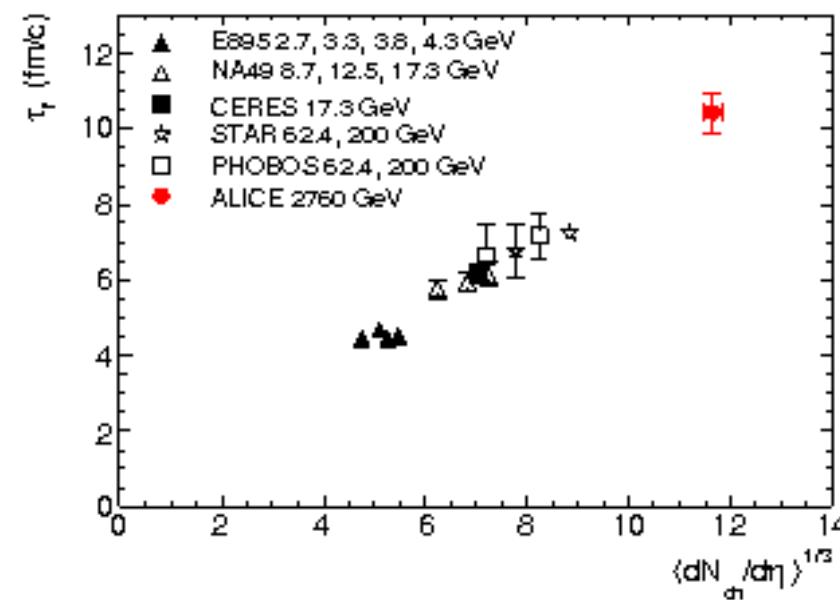
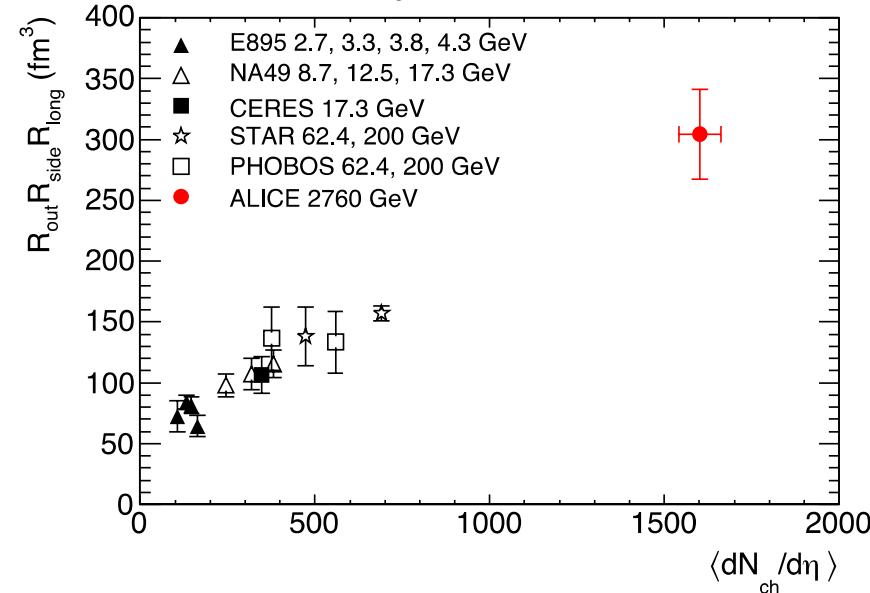
R_{long} – along beam direction

R_{out} – along “line of sight”

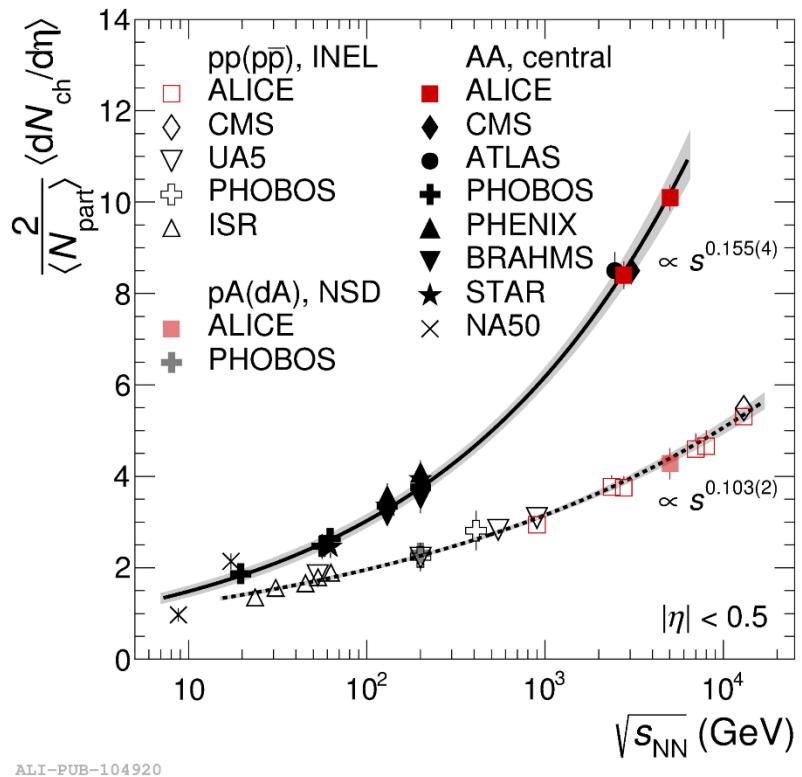
R_{side} – \perp “line of sight”

$$\frac{R_{\text{OUT}}}{R_{\text{SIDE}}} \leftrightarrow \tau$$

Volume: 2 x larger than RHIC
Lifetime: 20% larger than RHIC



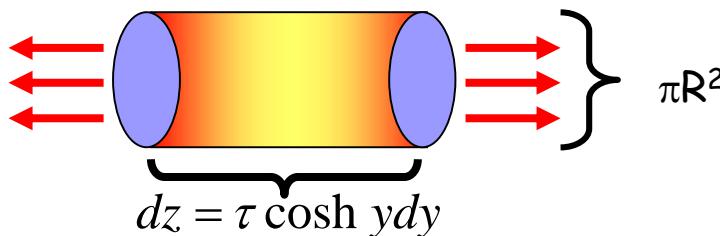
Multiplicity and Energy Density



ALICE, PRL 116 (2016) 222302

At LHC:

- Multiplicity: $> 2 \times \text{RHIC}$
- Energy Density: $2 \times \text{RHIC}$



J.D.Bjorken, Phys.Rev. D 27 (1983) 140

$$\epsilon_{Bj} = \frac{1}{\pi R^2 \tau} \frac{dE_T}{dy} \Big|_{y=0}$$

$\epsilon \cdot \tau \sim 12.5 \text{ GeV/fm}^2 c$

$$R \sim 0.5 \times (R_{\text{out}} + R_{\text{side}})$$

$$dE_T/dy = \langle m_T \rangle dN/dy$$

$$dN_{\text{ch}}/dy \sim 0.66 dN/dy \text{ (for pions)}$$

$$R \sim 6.08 \text{ fm} \quad [\text{ALICE, Phys. Lett. B} 696 (2011) 328]$$

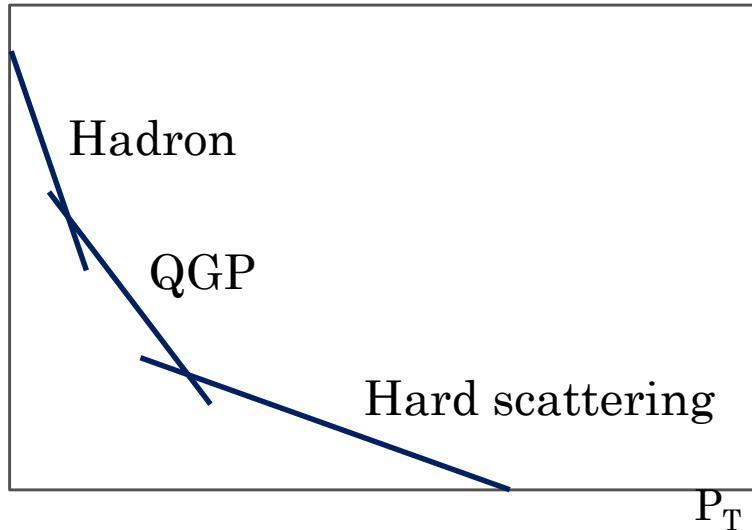
$$\langle m_T \rangle \sim 0.6 \text{ GeV} \quad [\text{Phenix, Nucl. Phys A} 757 (2005) 184]$$

$$dN_{\text{ch}}/dy \sim 1600 \quad [\text{ALICE, PRL 105 (2010) 252301}]$$

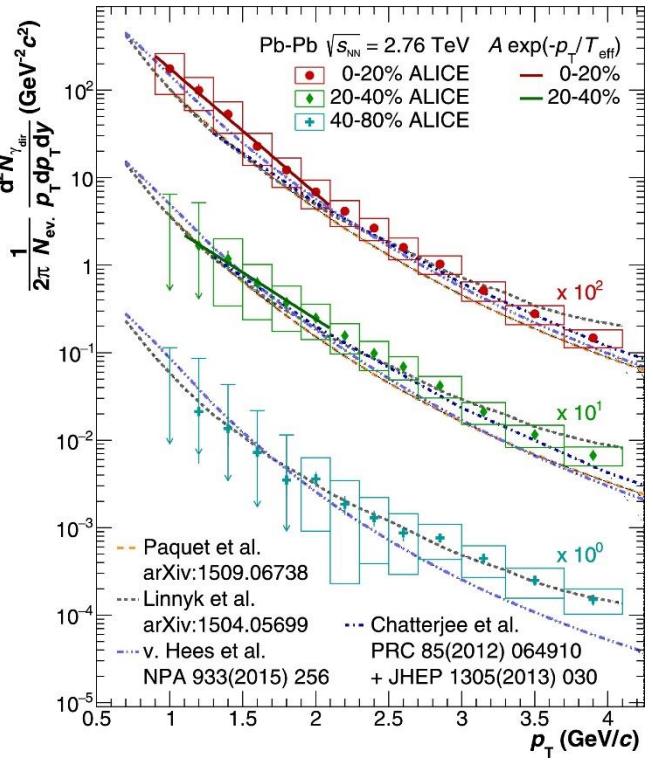
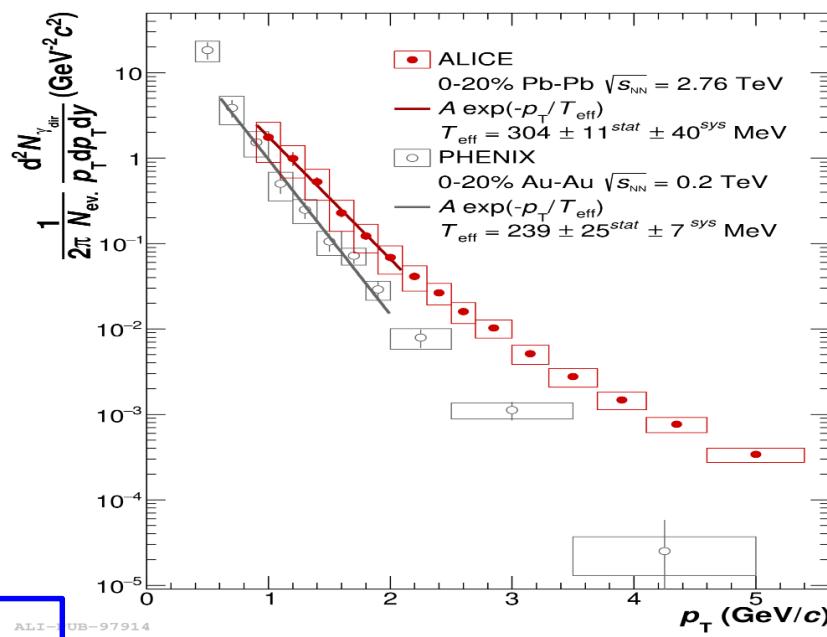
Rapidity $y = \frac{1}{2} \ln \frac{t+z}{t-z}$ $z = \tau \sinh y$ $E = m_T \cosh y$
--

Direct Photon Spectra

Entries



- Exponential fit for $p_T < 2.2 \text{ GeV}/c$
inv. slope $T = 304 \pm 11 \pm 40 \text{ MeV}$
for 0–20% Pb–Pb at $\sqrt{s} = 2.76 \text{ TeV}$
- PHENIX: $T = 239 \pm 25 \pm 7 \text{ MeV}$
for 0–20% Au–Au at $\sqrt{s} = 200 \text{ GeV}$



Temp at LHC $\sim 1.3 \times$ RHIC

[ALICE, Phys. Lett. B 754 (2016) 235]

with π - ρ - ω channels recently described in Ref. [67]. The space-time evolution starts at $\tau_0 = 0.2 \text{ fm}/c$ with temperatures $T_0 = 682, 641, 461 \text{ MeV}$ for the 0–20%, 20–40%, and 40–80% classes, respec-

Sequential suppression

The various quarkonium states are characterized by different, binding energy and radius

state	J/ ψ	$\psi(2S)$
Mass(GeV)	3.10	3.69
)		
ΔE (GeV)	0.64	0.05
r_o (fm)	0.25	0.45

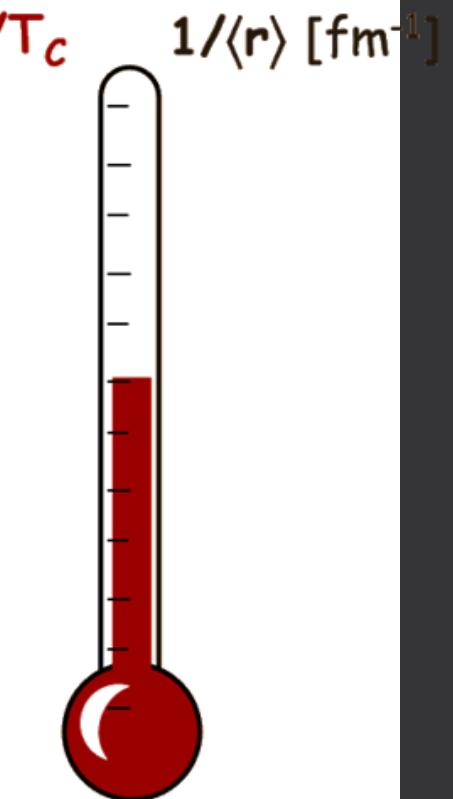
state	Y(1S)	Y(2S)	Y(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_o (fm)	0.28	0.56	0.78

More bound states \rightarrow smaller size

Sequential suppression of the resonances



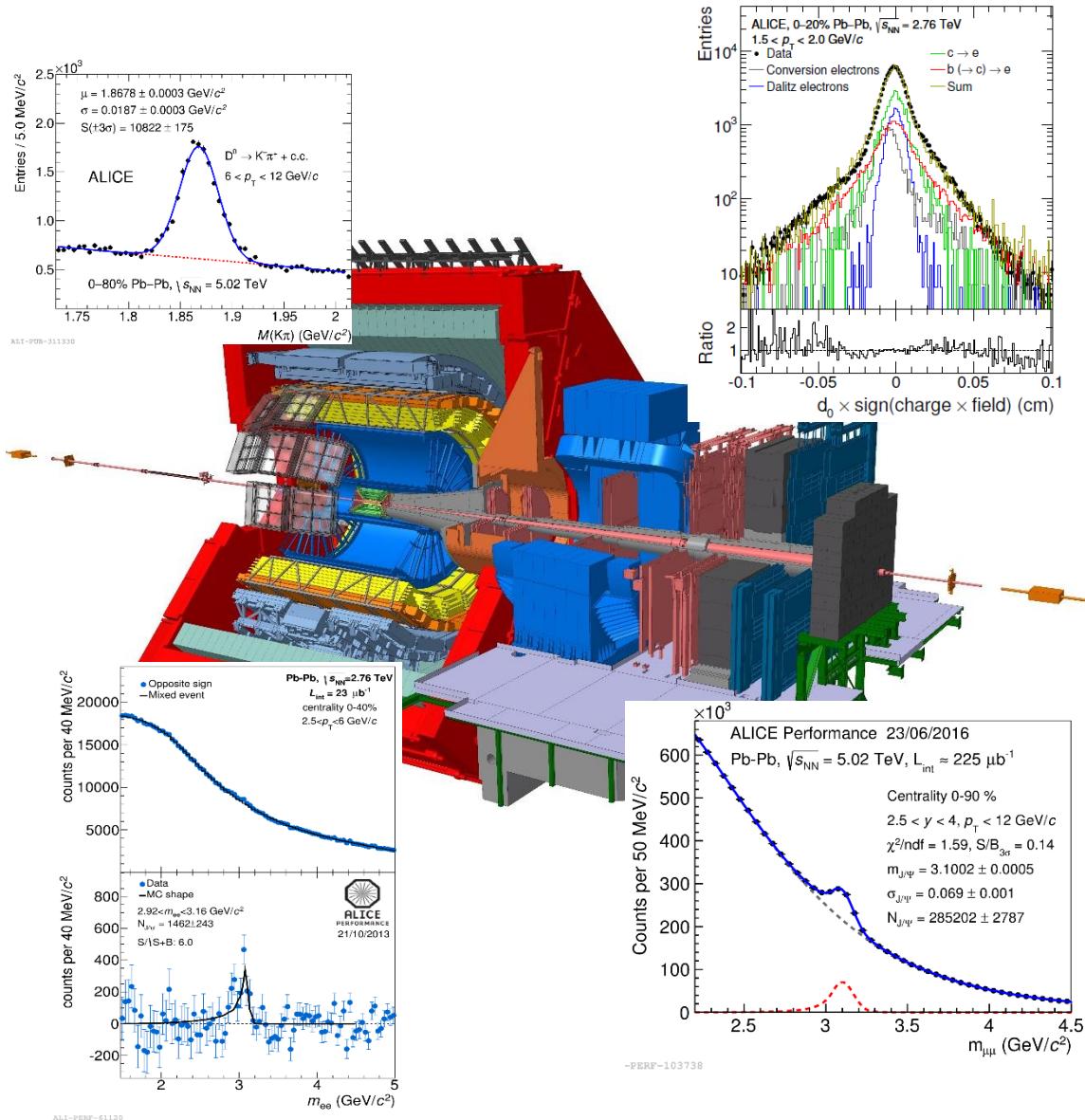
Thermometer of the QGP !



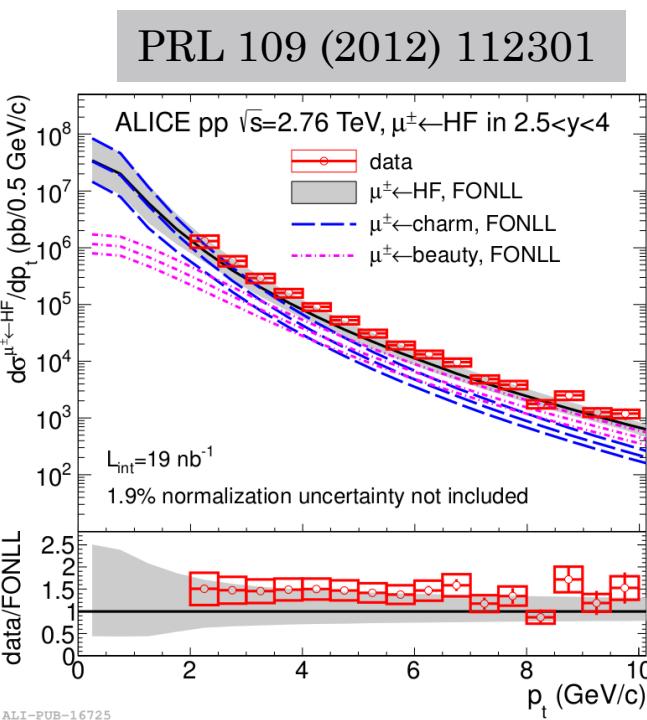
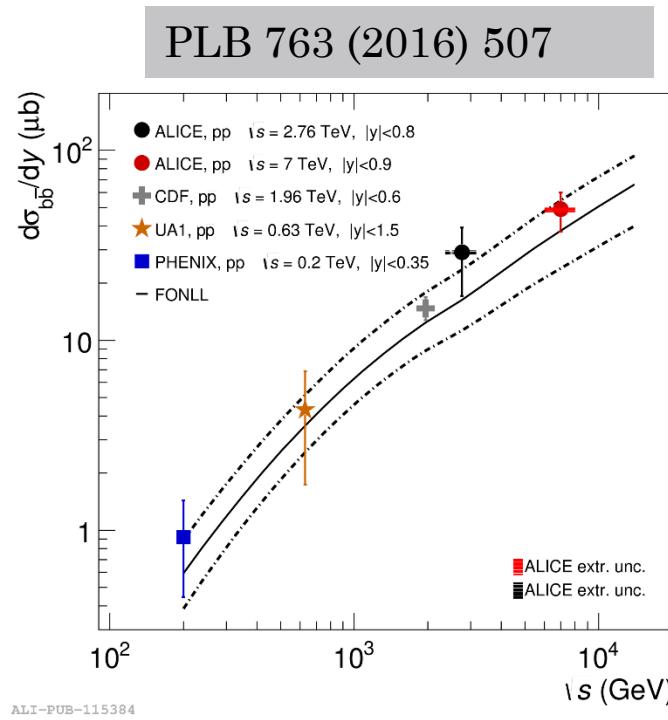
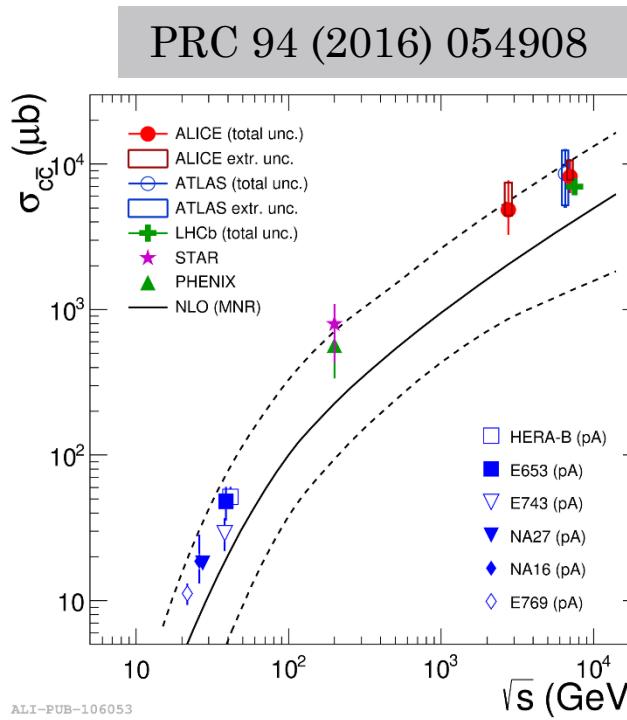
A Large Ion Collider Experiment

System	Year	$\sqrt{s_{NN}}$ (TeV)	\mathcal{L}_{int} (*)
pp	2009-13	0.9, 2.76, 7, 8	$200 \mu\text{b}^{-1}, 100 \text{ nb}^{-1}$ $1.5 \text{ pb}^{-1}, 2.5 \text{ pb}^{-1}$
	2015,17	5.02	1.3 pb^{-1}
	2015-18	13	35 pb^{-1}
p-Pb	2013	5.02	15 nb^{-1}
	2016	5.02, 8.16	$3 \text{ nb}^{-1}, 25 \text{ nb}^{-1}$
Xe-Xe	2017	5.44	$0.3 \mu\text{b}^{-1}$
Pb-Pb	2010,11	2.76	$75 \mu\text{b}^{-1}$
	2015	5.02	$250 \mu\text{b}^{-1}$
	2018	5.02	$536 \mu\text{b}^{-1}$

* Approximate value of luminosity recorded in ALICE

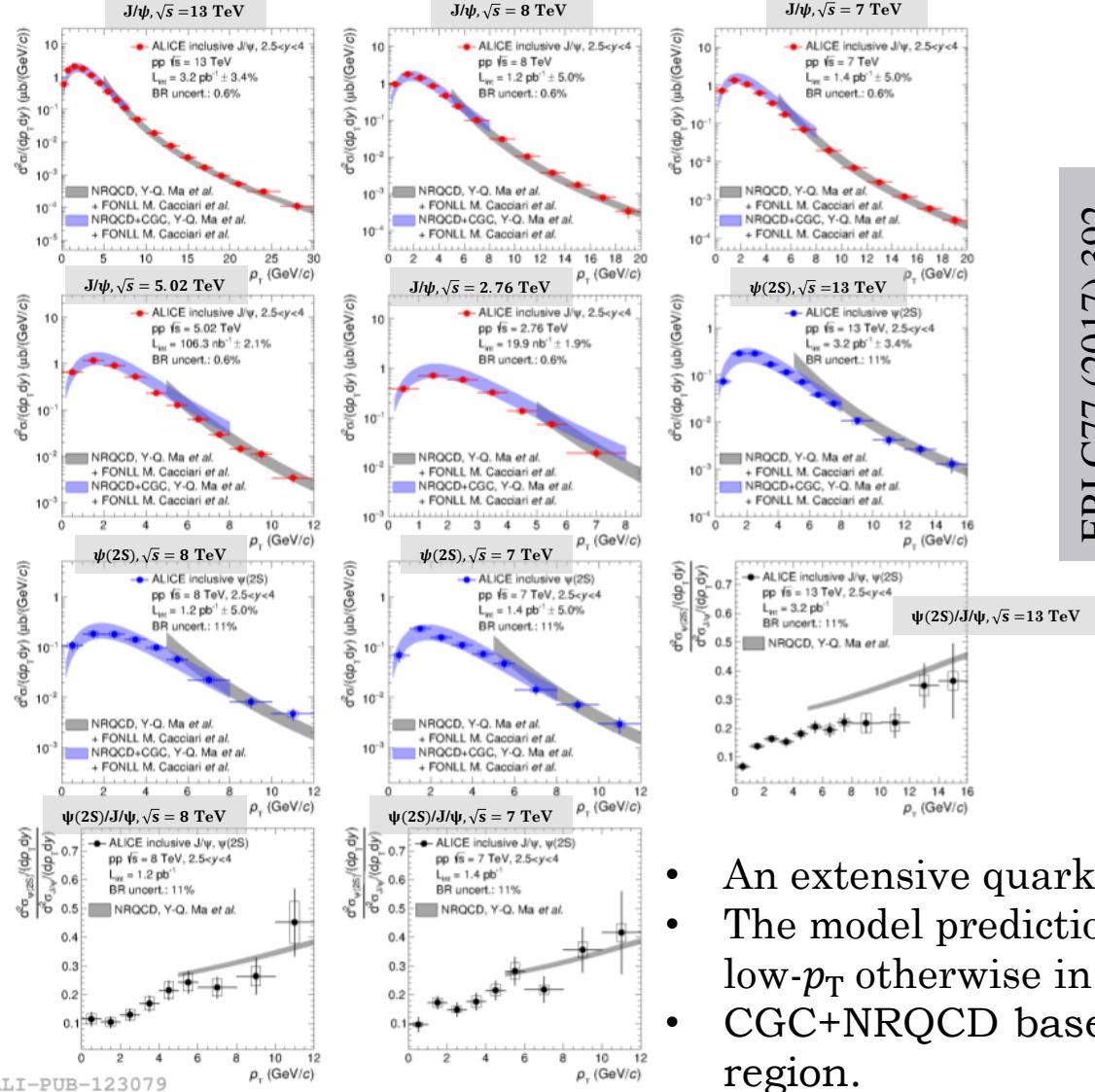


Heavy-flavour production in pp collisions

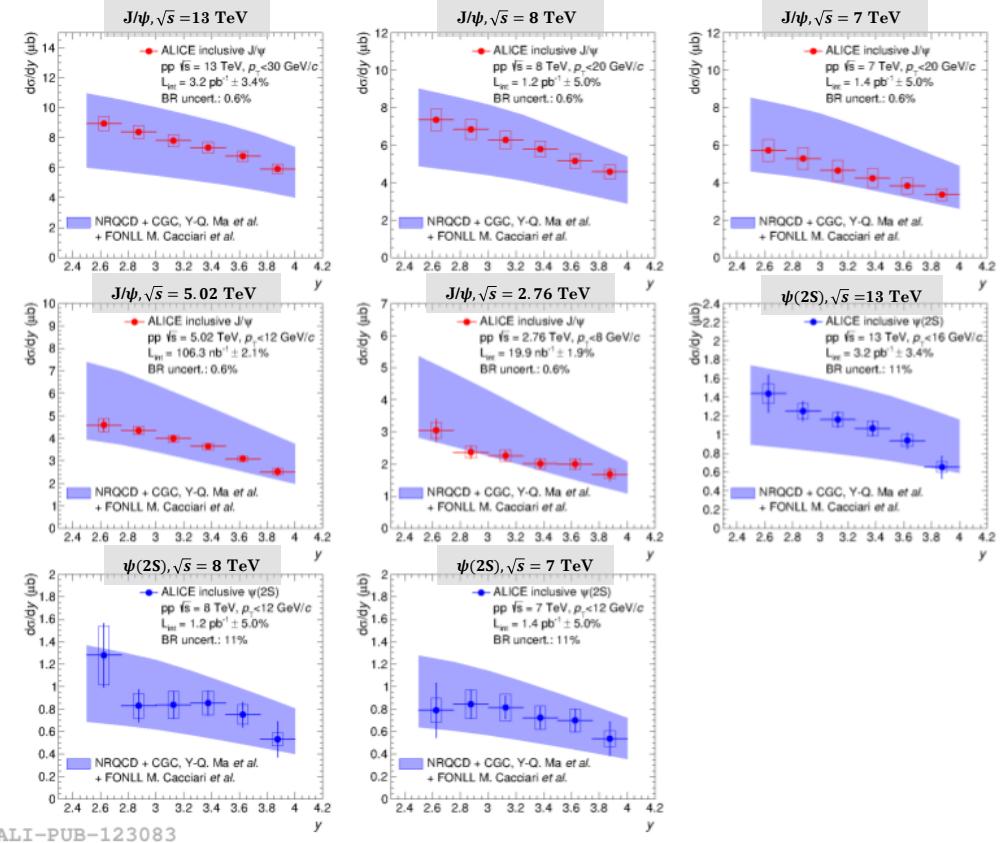


- The production cross section of heavy quarks as measured in LHC agrees with the world data.
- The heavy quark cross section increases as a function of \sqrt{s} in agreement with the theory calculation.
- The differential production cross section of heavy-flavour also agrees with theory calculations within uncertainties.

Quarkonium production in pp collisions



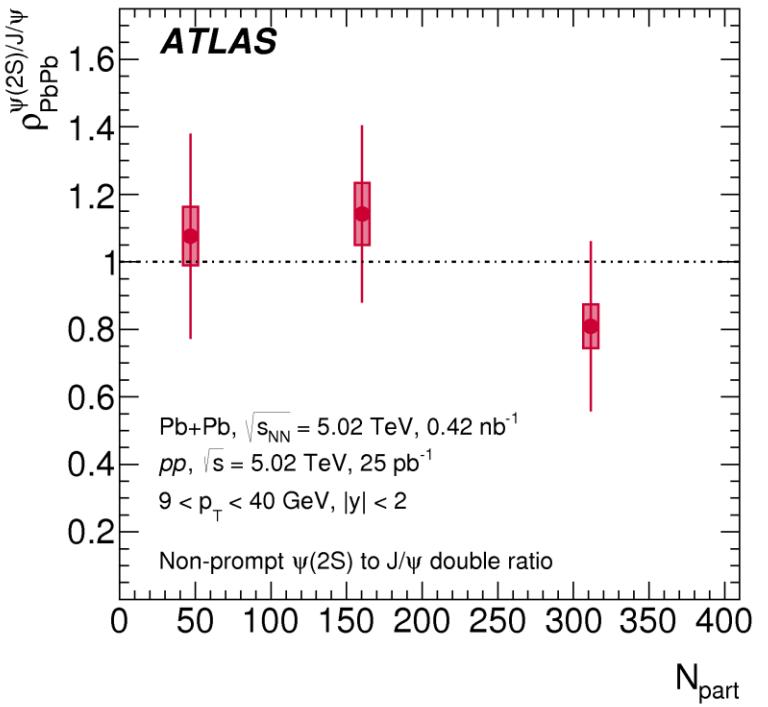
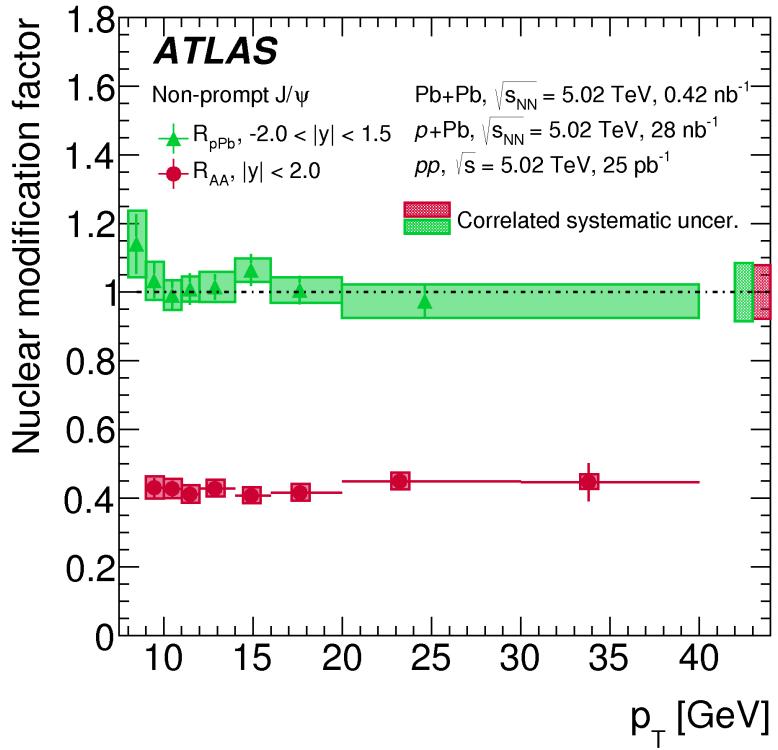
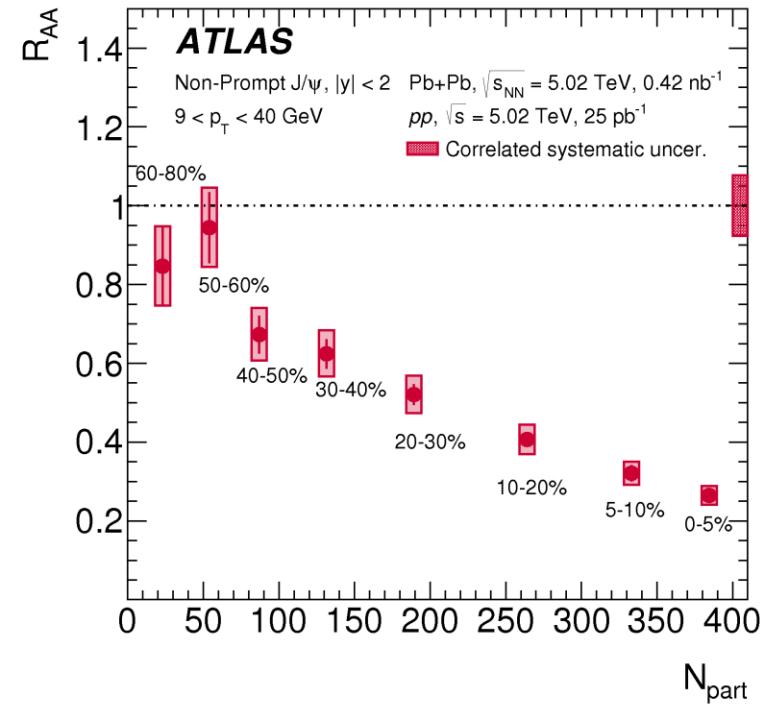
EPJ C77 (2017) 392



- An extensive quarkonium study at various energies.
- The model prediction for the $\psi(2S)/J/\psi$ cross section slope does not cover the low- p_T otherwise in agreement with data.
- CGC+NRQCD based model is now able to properly describe the low p_T region.

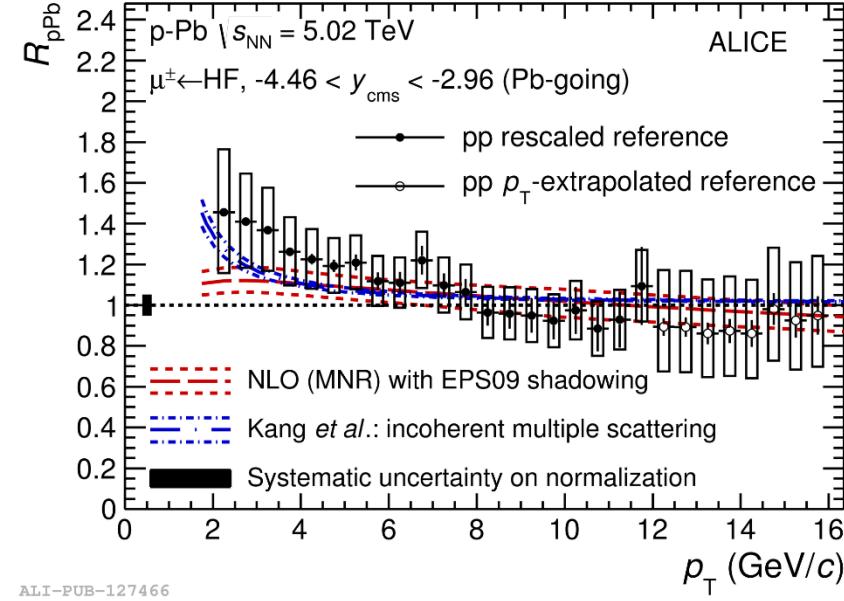
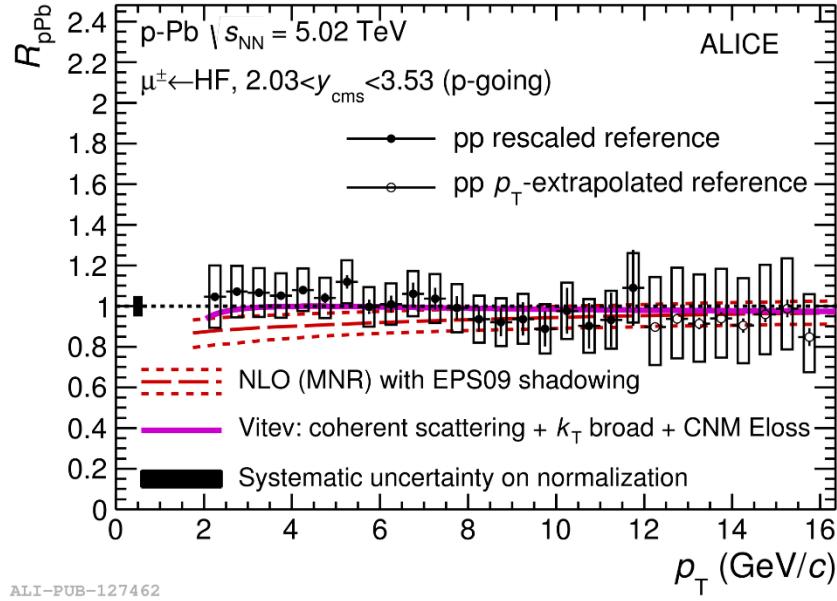
Non-prompt J/ ψ

March 18, 2019



Heavy-flavour production in p-Pb

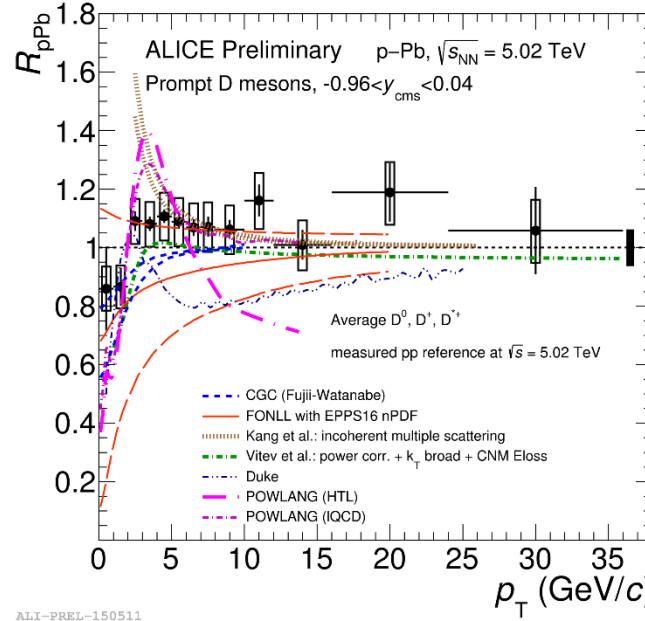
PLB 770 (2017) 459



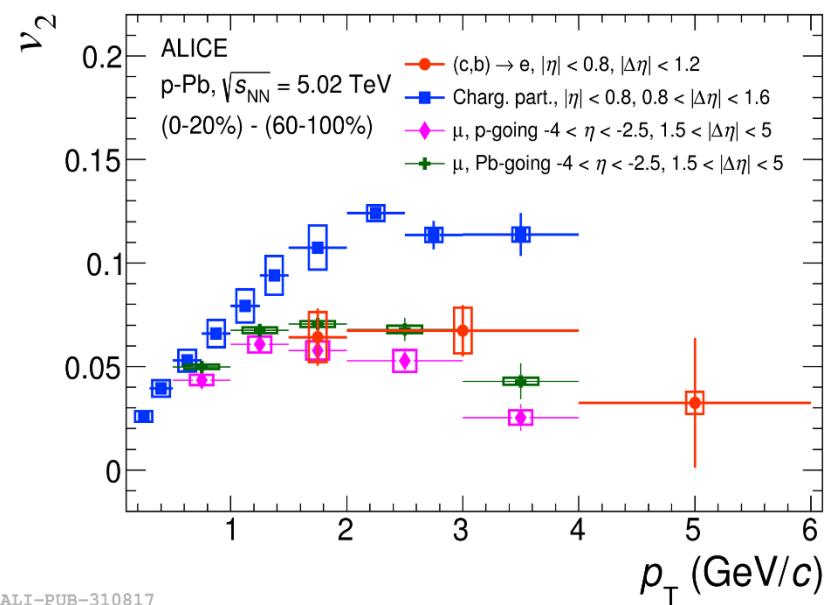
- The nuclear modification factor is compatible with unity at forward rapidity.
- The R_{pPb} of heavy-flavor decay muons at high p_T is also compatible with unity at backward rapidity, but above unity by more than 2σ in $2.5 < p_T < 3.5$ GeV/c.
- The NLO calculation with shadowing can reproduce the data at both forward and backward rapidity.
- The coherent scattering model based on CNM energy loss and k_T broadening can explain the forward rapidity R_{pPb} , while for backward rapidity incoherent multiple scattering models can reproduce the data.

Heavy-flavour production in p-Pb

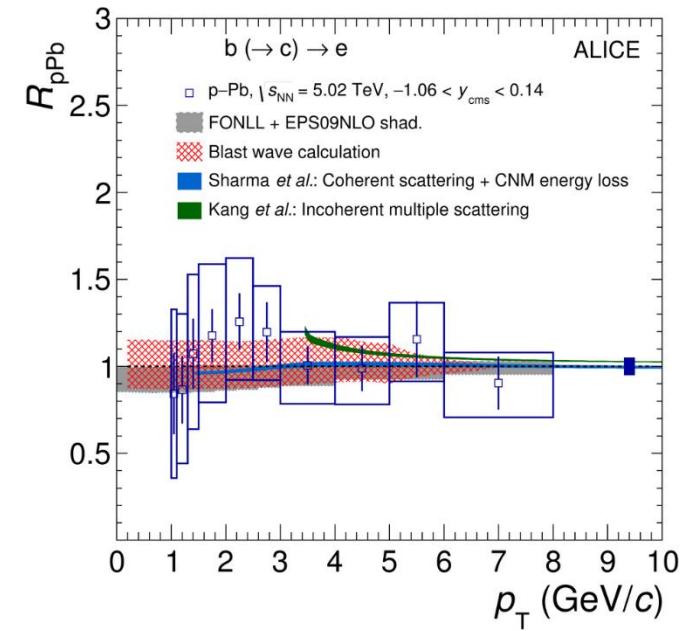
PRL 113 (2014) 232301



arXiv : 1805.04367

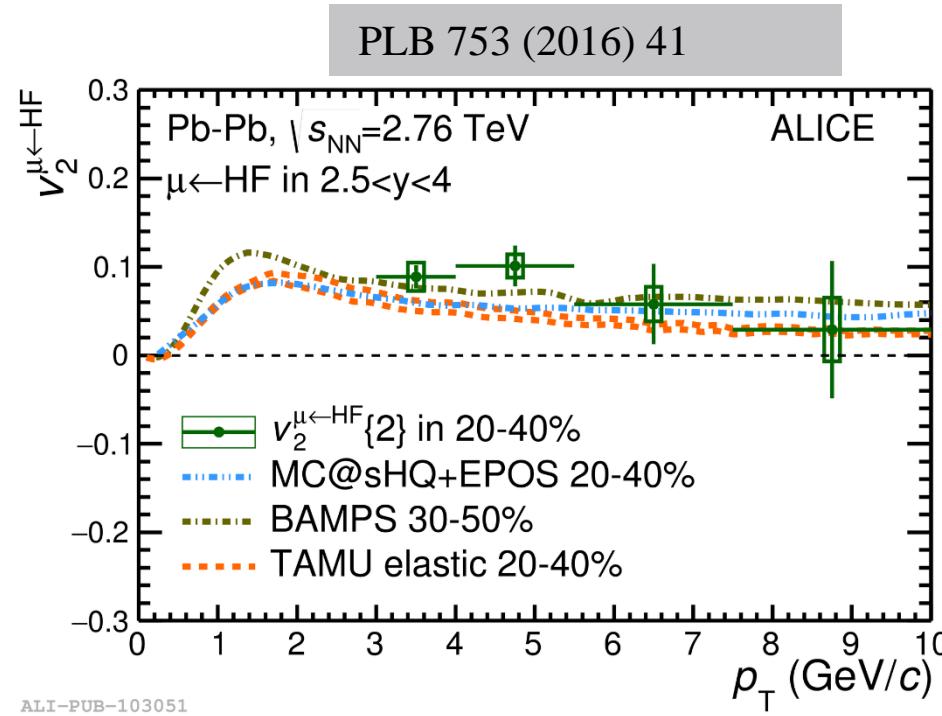
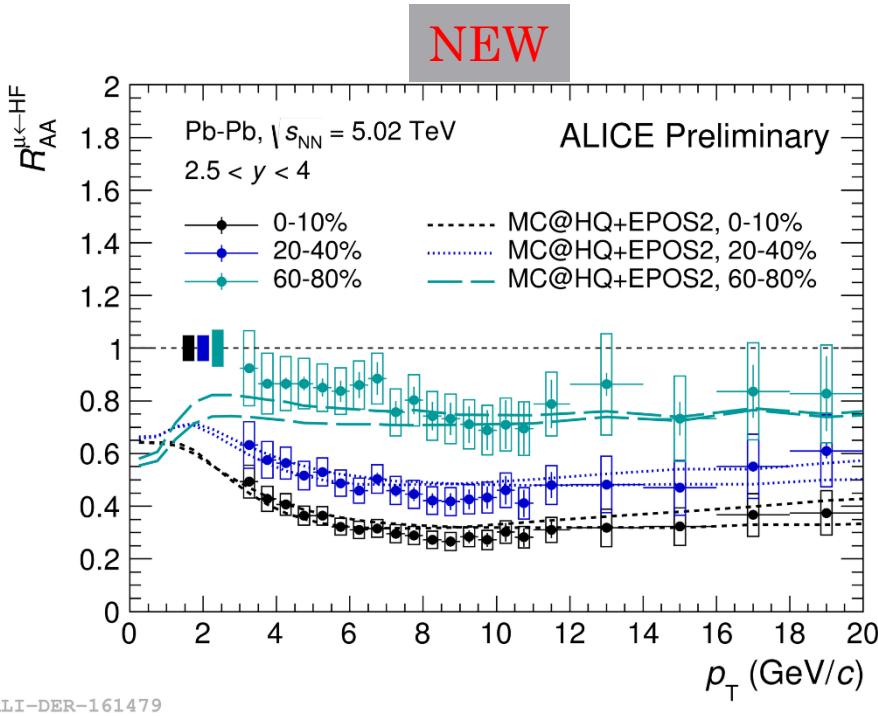


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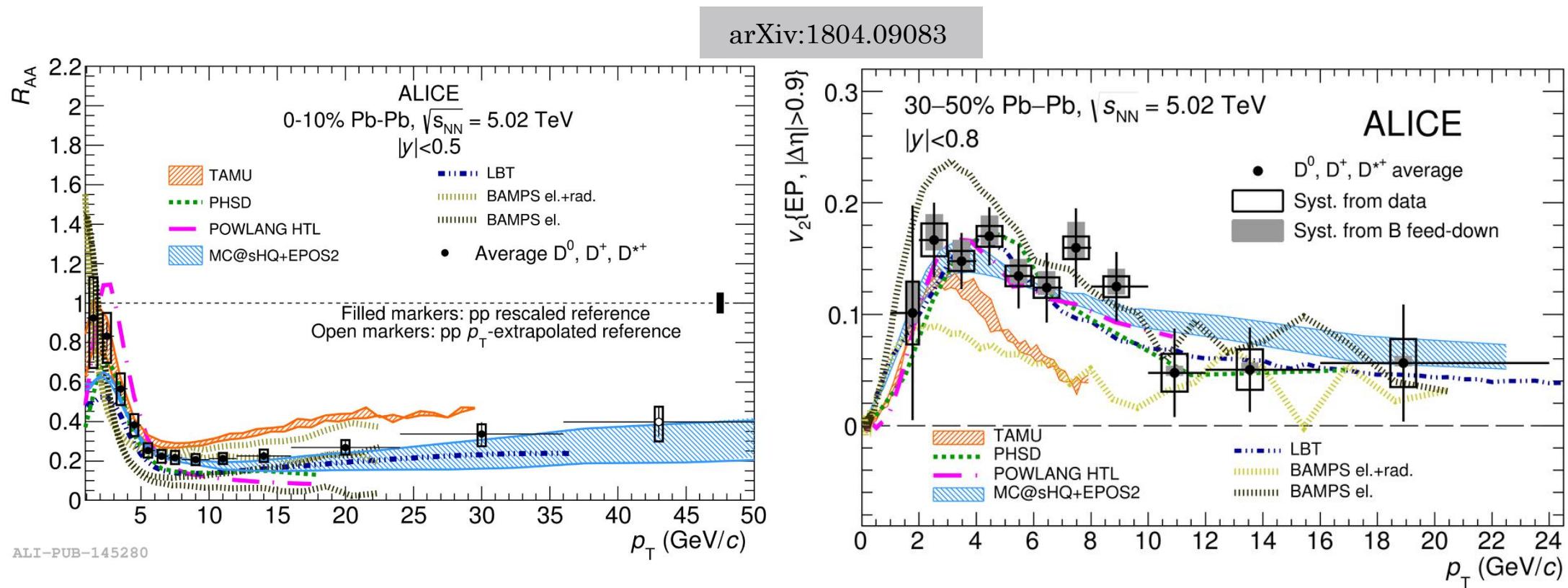
- The average R_{pPb} of prompt D^0, D^+ and D^{*+} mesons is compatible with unity and can be explained by the theoretical calculations that include initial-state effects.
- The v_2 of heavy-flavour decay electrons in high-multiplicity events are above 5σ significance and found similar to those of forward rapidity heavy-flavour decay muons.
- The R_{pPb} of beauty-hadron decay to electron is compatible with unity for $1 < p_T < 8$ GeV/c.

Heavy-flavour production in Pb-Pb



- A strong suppression is observed for the heavy-flavour muon R_{AA} for central collisions.
- A positive heavy-flavour v_2 is measured using scalar product and two particle Q cumulants in semi-central collisions with more than 3σ significance for $3 < p_T < 5 \text{ GeV}/c$.
- The model predictions based on Boltzmann (BAMPS) and Langevin (TAMU) transport equations consider collisional energy loss, they can explain the elliptic flow measurements.
- Both results can be also explained by MC@sHQ+EPOS which considers collisional and radiative energy loss.

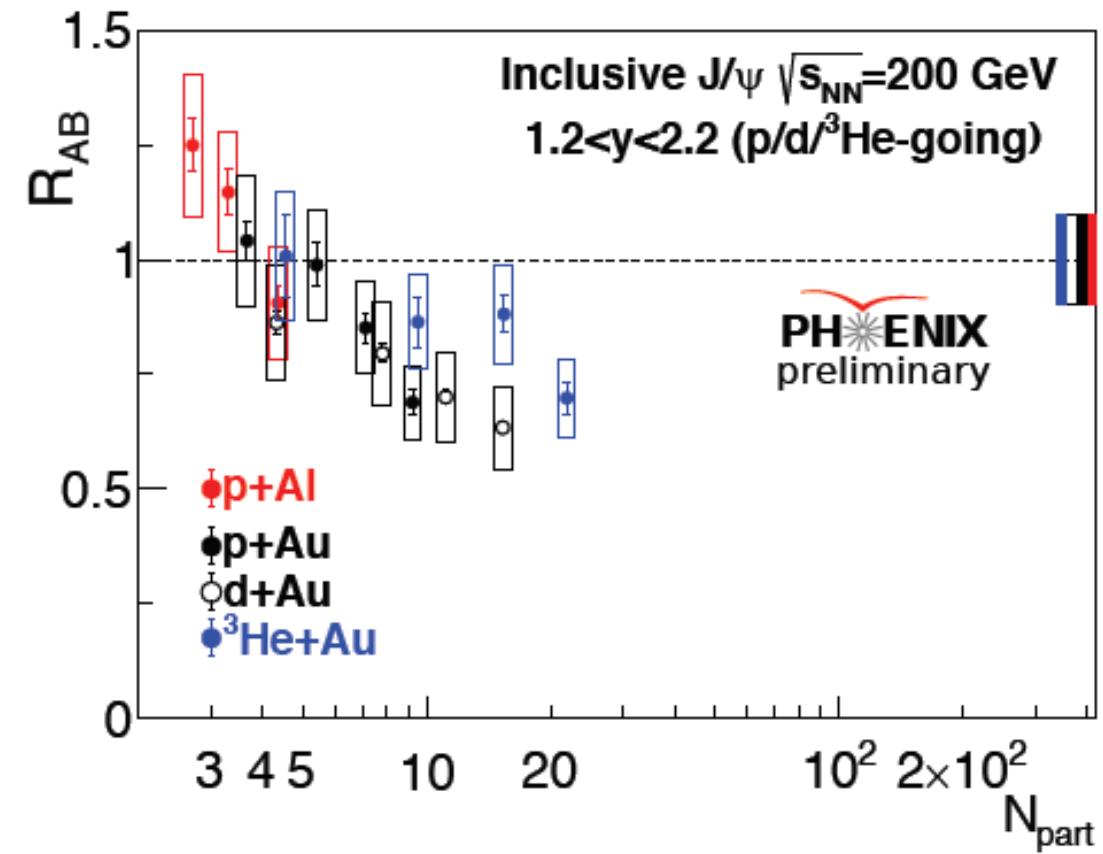
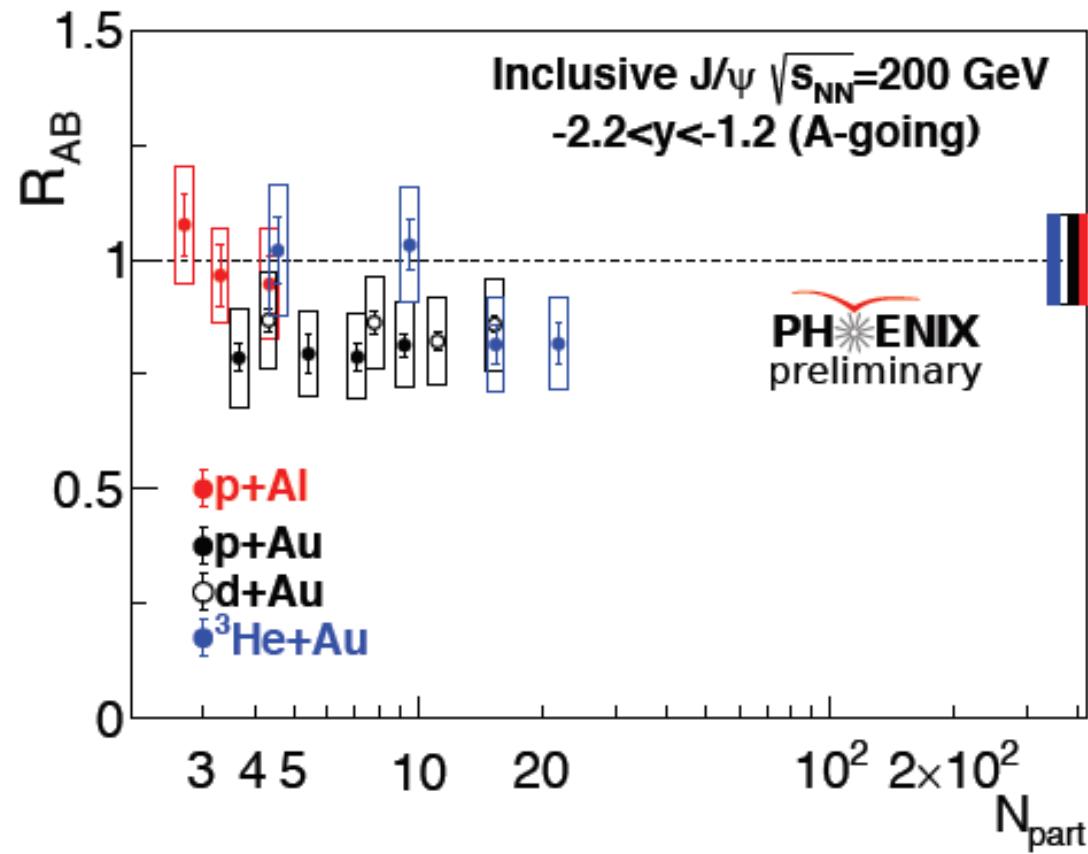
Heavy-flavour in Pb-Pb



- A strong suppression is observed for the D-meson R_{AA} for central collisions and $p_T > 3$ GeV/c.
- The elliptic flow is stronger in the interval $2 < p_T < 4$ GeV/c.
- The R_{AA} and v_2 observables together set stringent constraints to model calculations and charm diffusion coefficient.

Quarkonium in AA

QM-2018



Quarkonium in AA

QM-2018

