XXIII DAE-BRNS HIGH ENERGY PHYSICS SYMPOSIUM 2018

December 10 - 14, 2018

Quarkonium and heavy-flavour measurements with ALICE at the LHC

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Motivation

- Nuclear matter at extreme energy density forms a Quark-Gluon Plasma
- Heavy quarks are produced at the first instant of collisions
- Interact with the hot and dense QCD medium
- Quarkonium
  - Suppression due to colour screening
  - (Re)generation during the QGP evolution or at the phase boundary
  - Elliptic flow
- Heavy-Flavour
  - Collisional and radiative energy loss
  - Energy loss dependence on a) medium density, b) colour charge and c) quark mass
- Cold Nuclear Matter effects
  - Nuclear parton shadowing/gluon saturation
  - Parton energy loss
  - Nuclear break-up

Andronic et al., EPJ C 76 (2016) 107

Matsui and Satz, PLB 178 (1986) 416

Thews, Schroedter , Rafelski, PRC 63 (2001) 054905, Braun-Munzinger, and Stachel PLB 490 (2000) 196

Poskanzer and Volosin, PRC 58 (1998) 1671

Dokshitzer et al., PLB 519 (2001) 199, Armesto et al., PRD 69 (2004) 114003

Djordjevic et al., NPA 783 (2007) 493

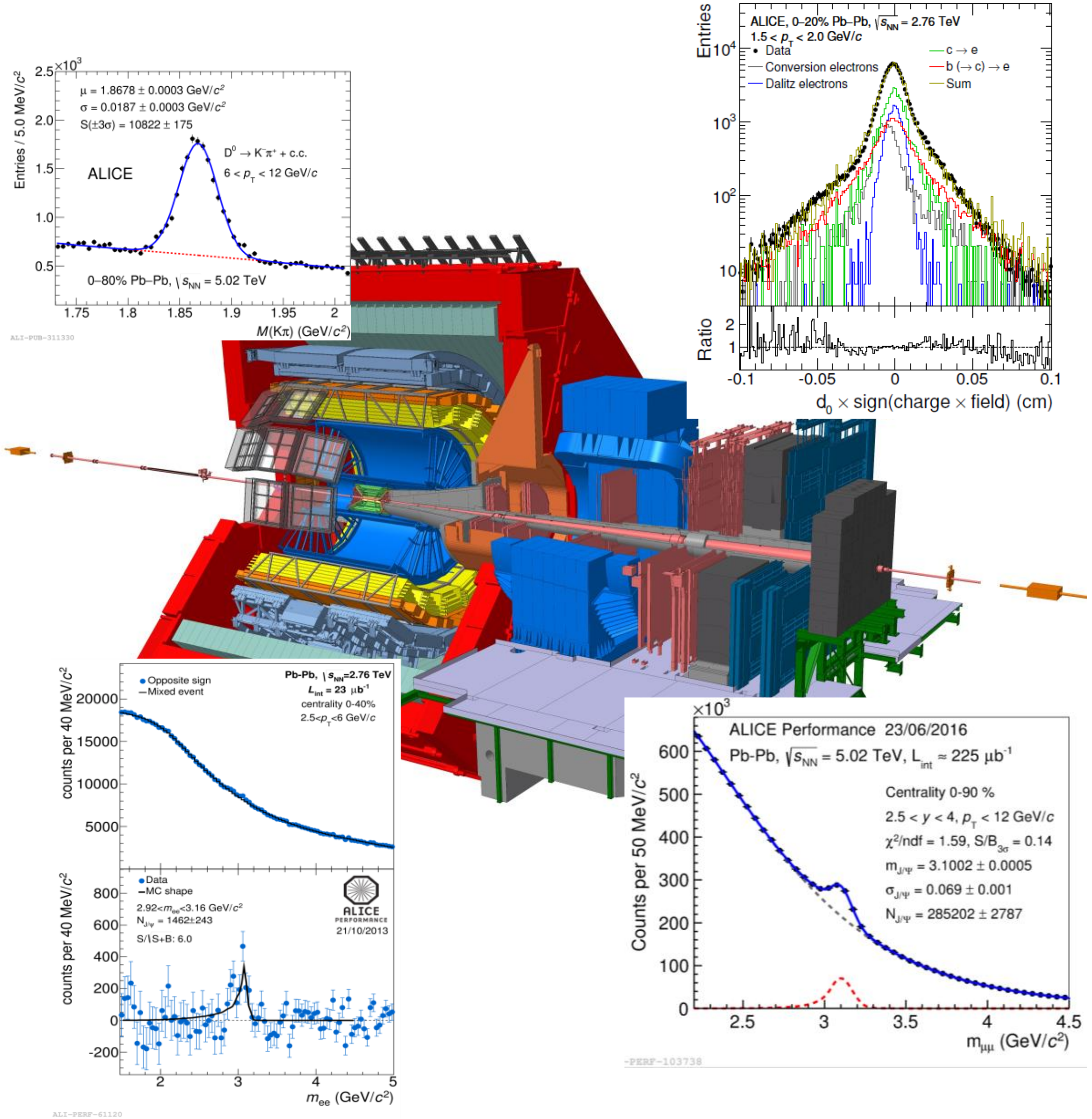
Heavy-Flavour :
- Ashik Ikbal Sheikh
- Bharati Naik
- Renu Bala
- Samrangy Sadhu
- Sudhir Pandurang Rode

Quarkonia :
- Anisa Khatun
- Dhananjaya Thakur
- Hushnud
- Wadut Shaikh

A Large Ion Collider Experiment

System	Year	$\sqrt{s_{NN}}$ (TeV)	$\mathcal{L}_{int}$ (*)
pp	2009-13	0.9, 2.76, 7, 8	200 μb^{-1}, 100 nb^{-1} 1.5 pb^{-1}, 2.5 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 nb^{-1}, 25 nb^{-1}
Xe-Xe	2017	5.44	0.3 μb^{-1}
Pb-Pb	2010,11	2.76	75 μb^{-1}
	2015	5.02	250 μb^{-1}
	2018	5.02	536 μb^{-1}

* Approximate value of luminosity recorded in ALICE

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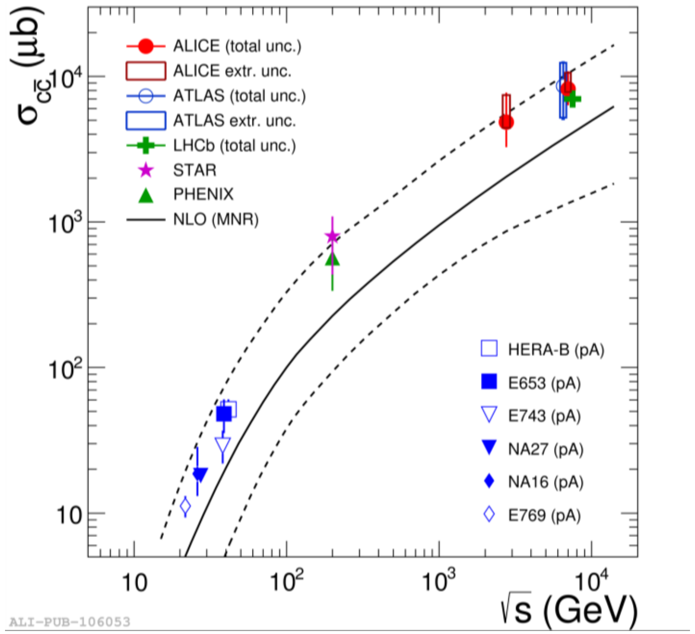
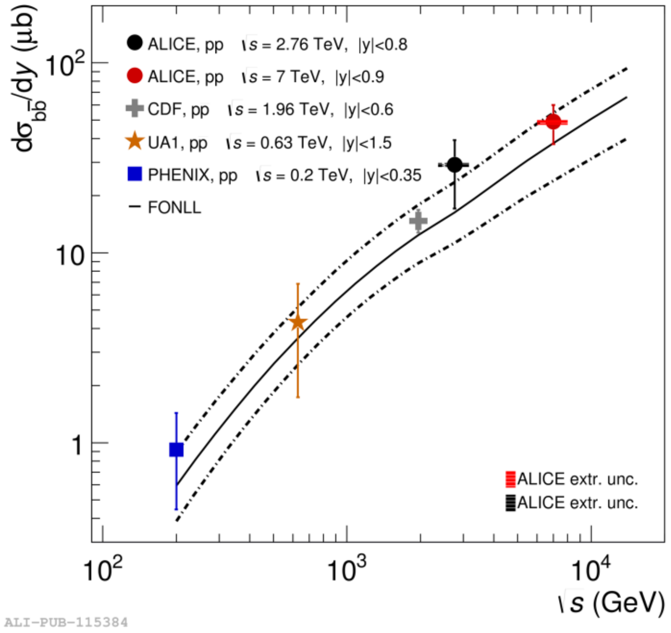
p

Heavy-flavour production in pp collisions

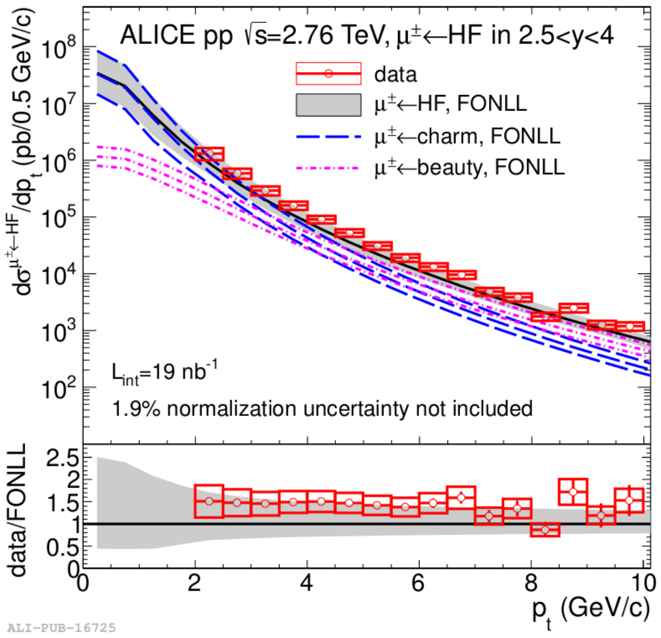
PRC 94 (2016) 054908



PLB 763 (2016) 507



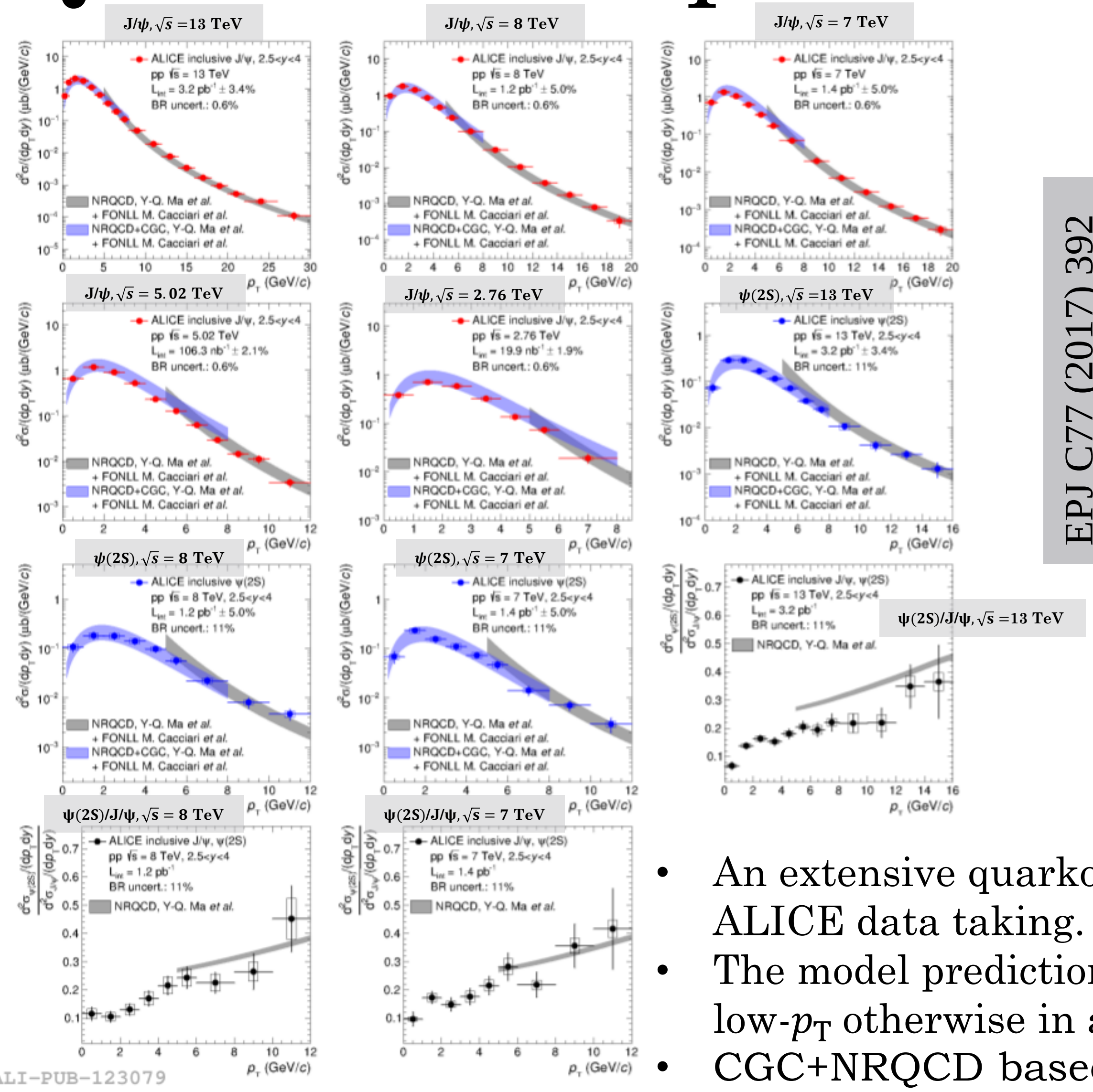
PRL 109 (2012) 112301



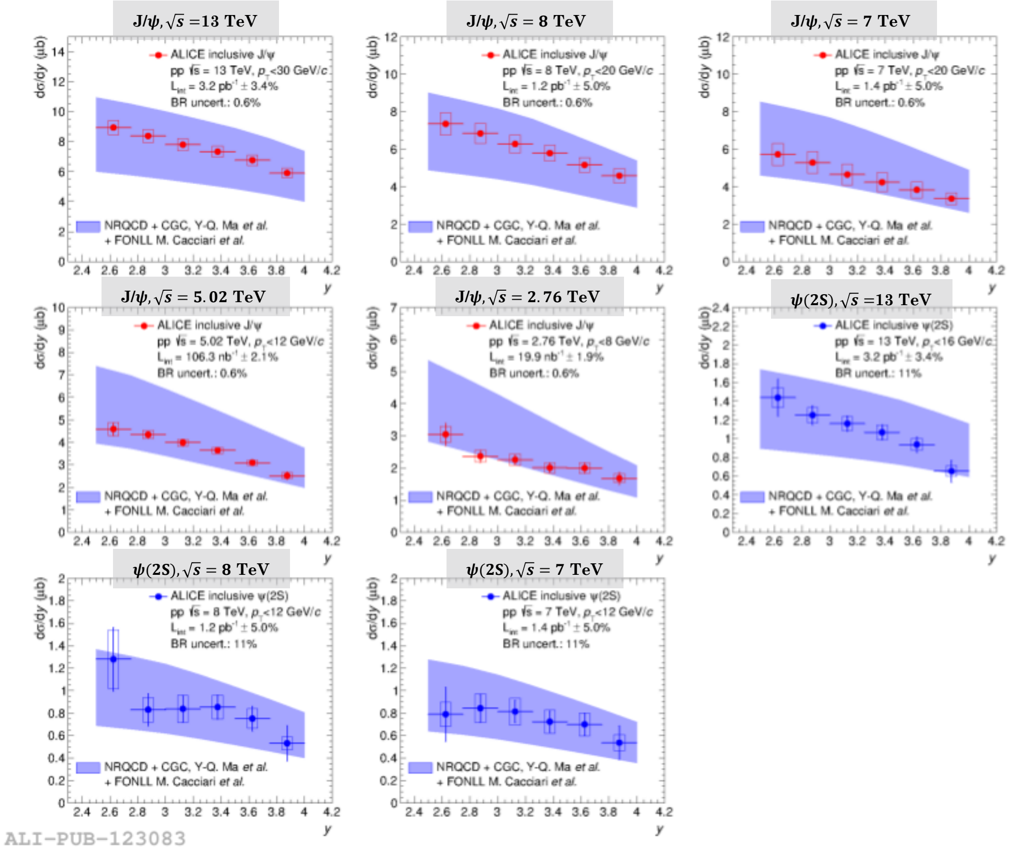
- The production cross section of heavy quarks as measured in ALICE agrees with the world data.
- The heavy quark cross section increases as a function of $\sqrt{s}$ in agreement with the theory calculation.
- The differential production cross section of heavy-flavour also agrees with theory calculations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

Quarkonium production in pp collisions

ALICE



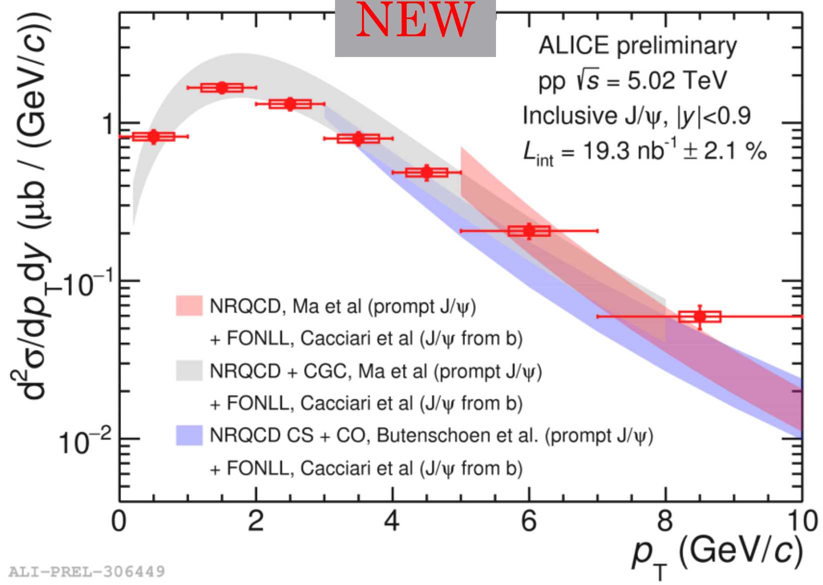
EPJ C77 (2017) 392



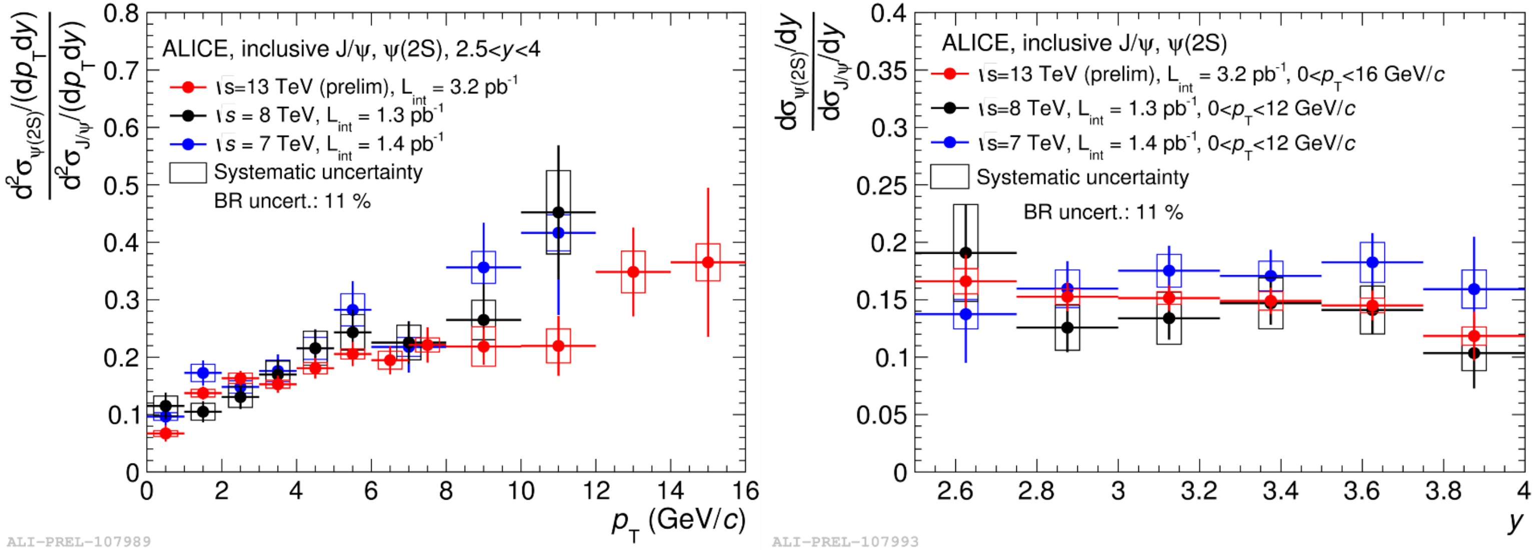
- An extensive quarkonium study at various energies, thanks to LHC and stable ALICE data taking.
- The model prediction for the ψ(2S)/J/ψ cross section slope does not cover the low-p_{T} otherwise in agreement with data.
- CGC+NRQCD based model is now able to properly describe the low p_{T} region.

Quarkonium production in pp collisions

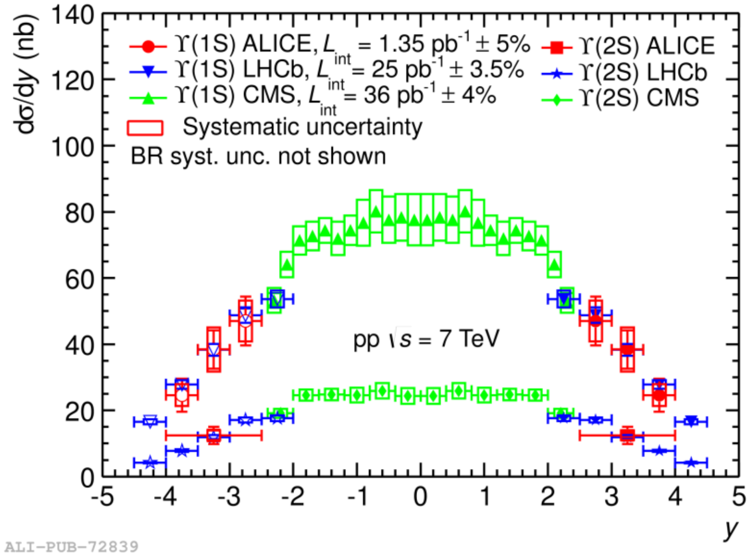
NEW



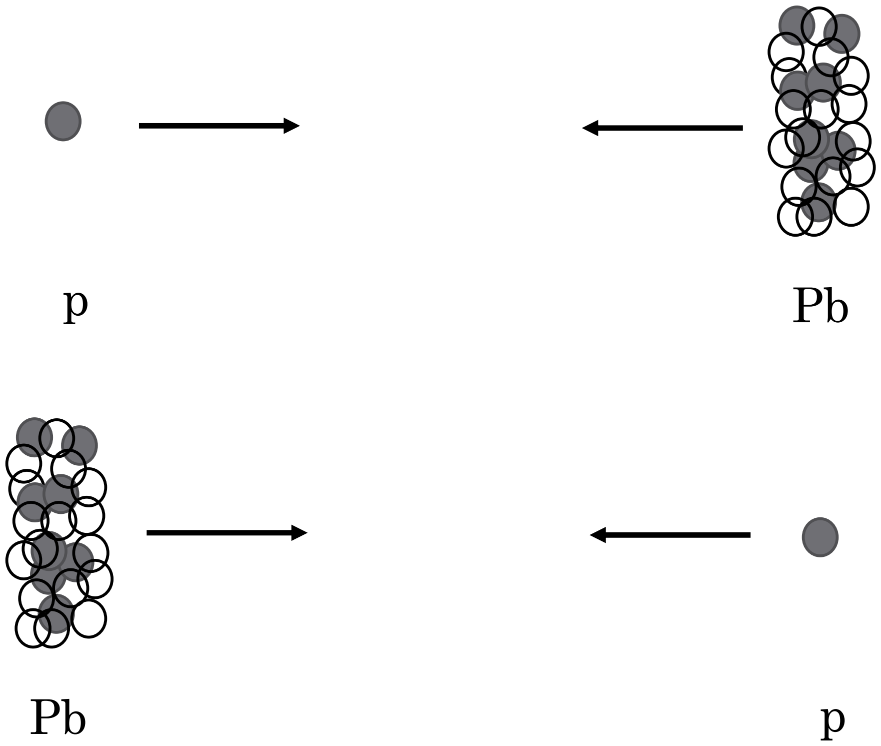
EPJ C77 (2017) 392



EPJ C74 (2014) 2974



- CGC+NRQCD based model is now able to properly describe the low p_T region.
- The cross section ratio for ψ(2S)/J/ψ 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.
- ALICE results are in agreement with other LHC experiments (shown only for Υ production).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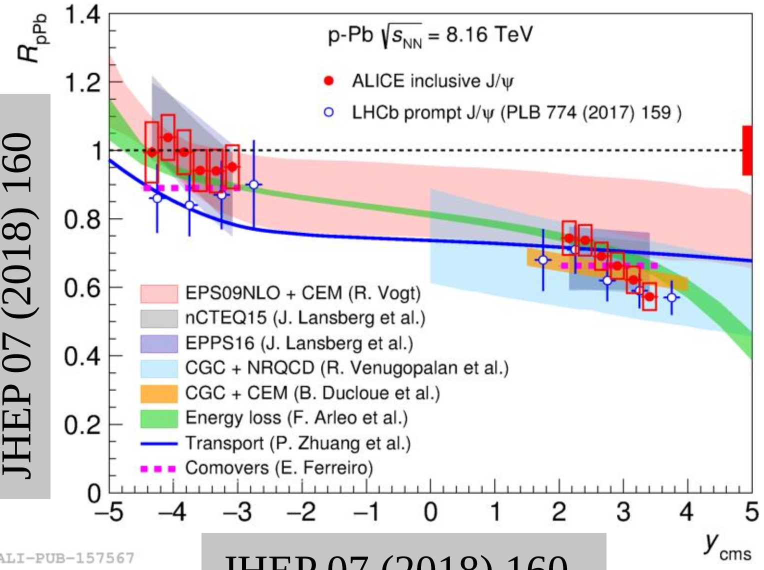
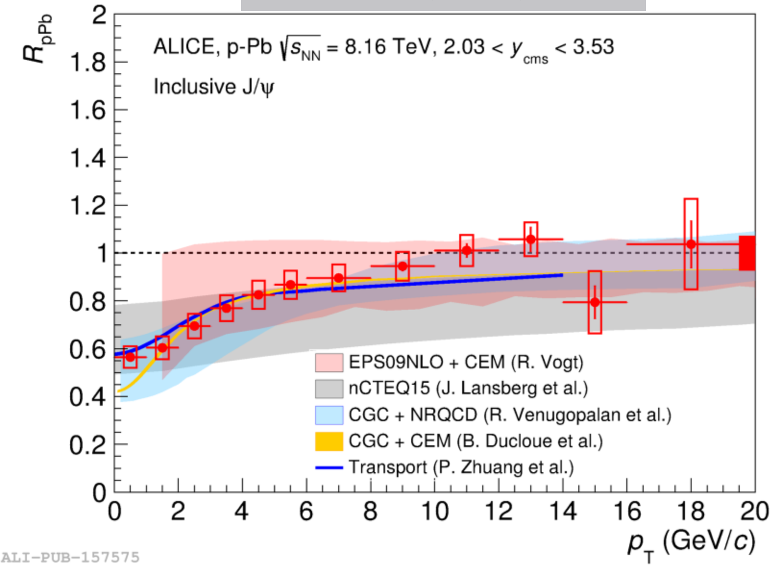
Quarkonium production in p-Pb

JHEP 07 (2018) 160

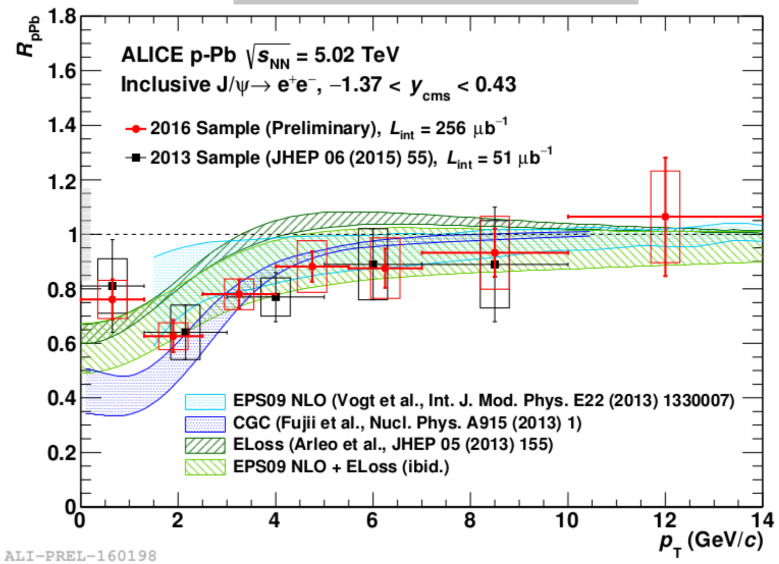


- Stronger suppression of J/ψ is observed at forward rapidity, while R_{pPb} is compatible with unity at backward rapidity.
- ALICE and LHCb results are in agreement.
- Models based on different shadowing implementations, CGC, energy loss, transport models and comovers fairly describe the data.
- The p_{T} dependence of R_{pPb} shows an increase from low to high p_{T} at both forward, mid and backward rapidity.

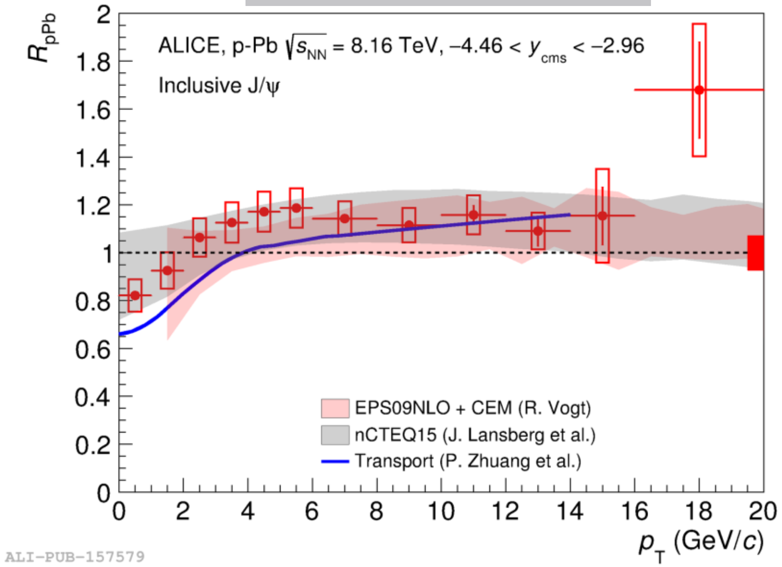
JHEP 07 (2018) 160



QM-2018 : Biswarup

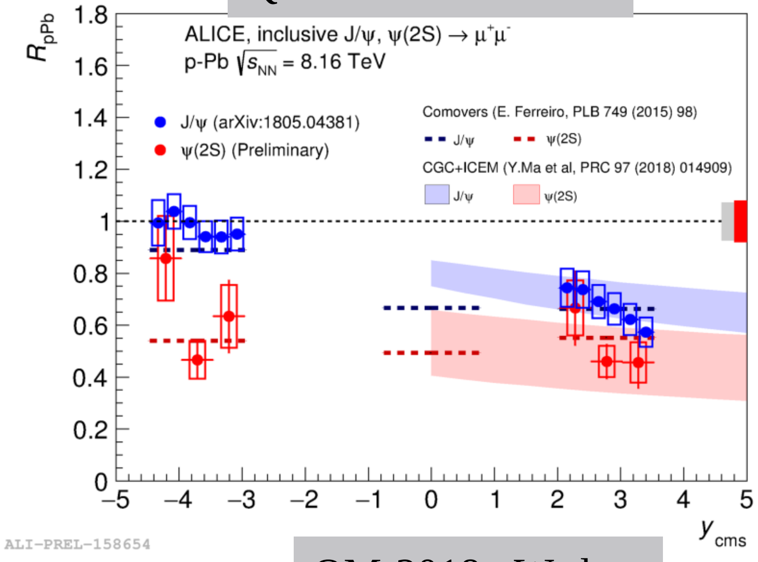


JHEP 07 (2018) 160



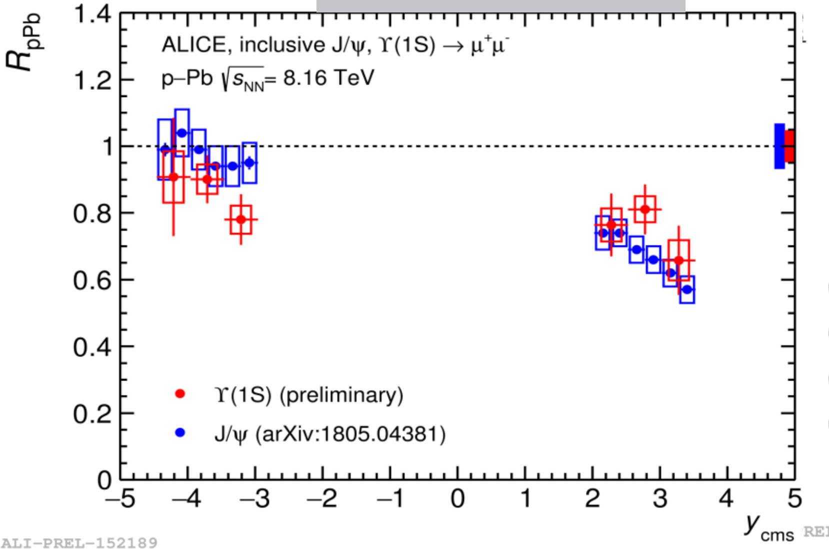
Quarkonium production in p-Pb

QM-2018 : Jhuma

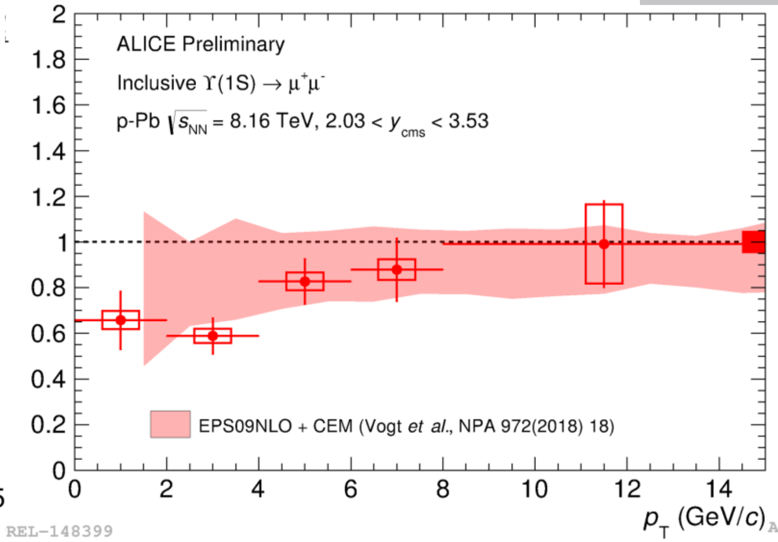


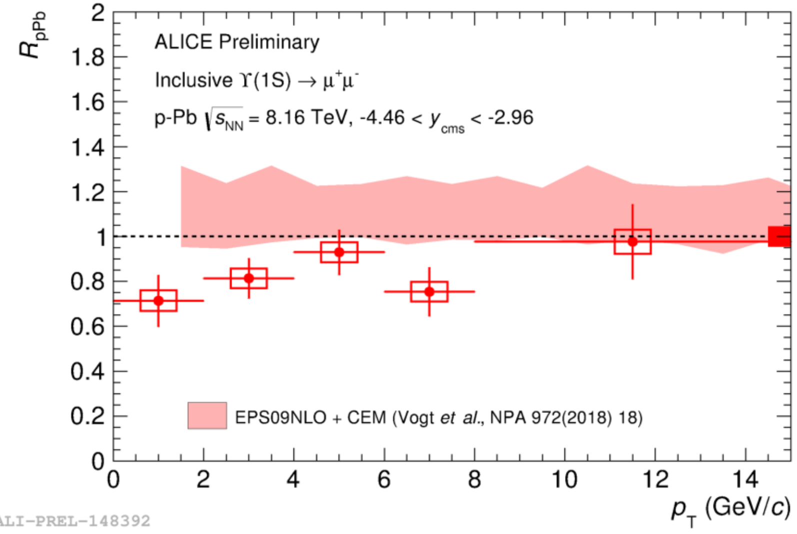
- A similar suppression as for J/ψ is observed at forward rapidity for ψ(2S) and Υ(1S). The J/ψ and Υ(1S) R_{pPb} are compatible with no modification at backward rapidity.
- At backward rapidity, final-state effects needed to explain the ψ(2S) behaviour.
- The p_{T} dependence of Υ R_{pPb} shows an increase from low to high p_{T} at both forward and backward rapidity, where the model prediction suggests flat distribution.

QM-2018 : Wadut

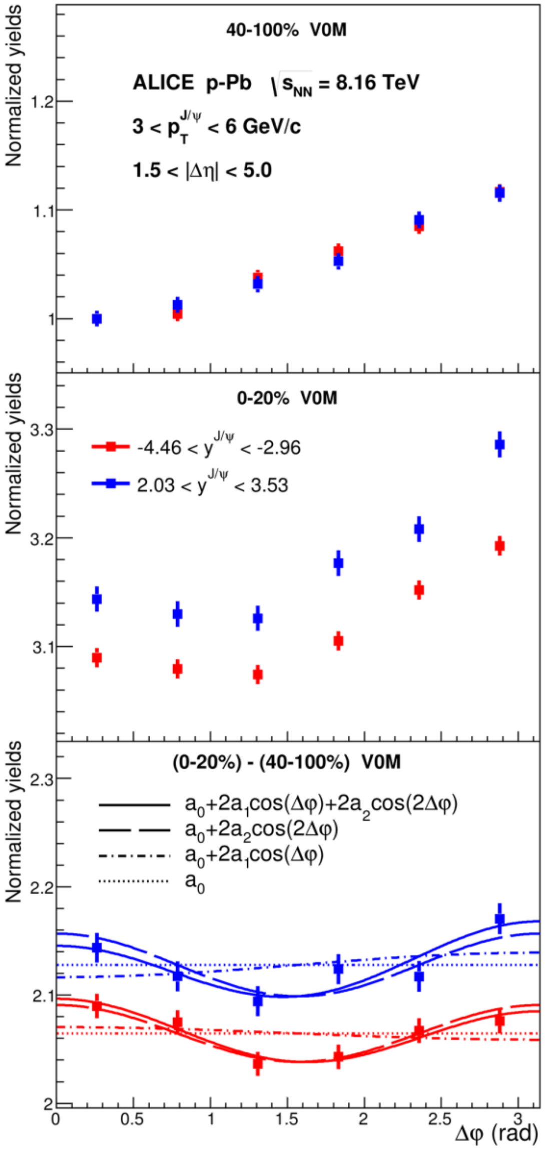


QM-2018 : Wadut

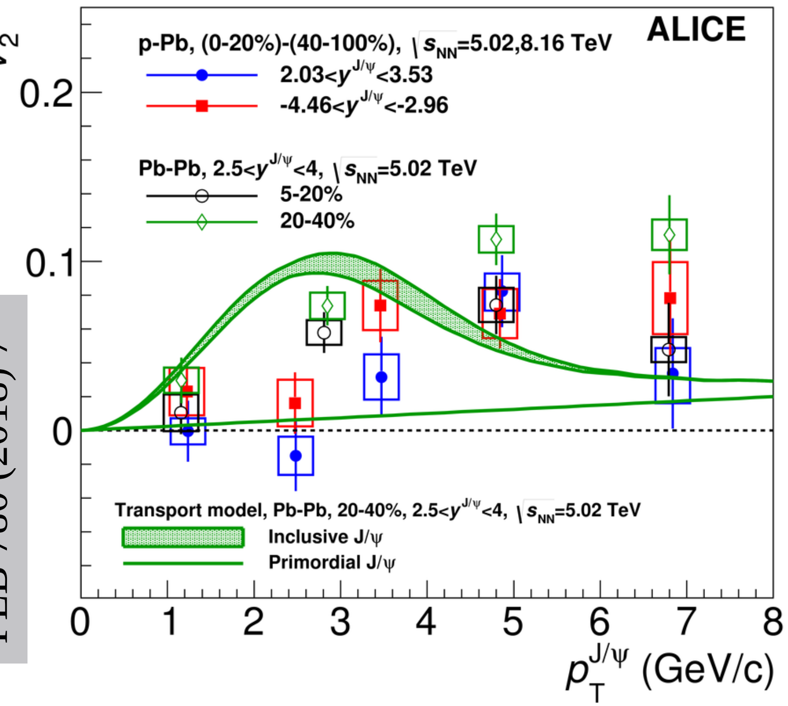


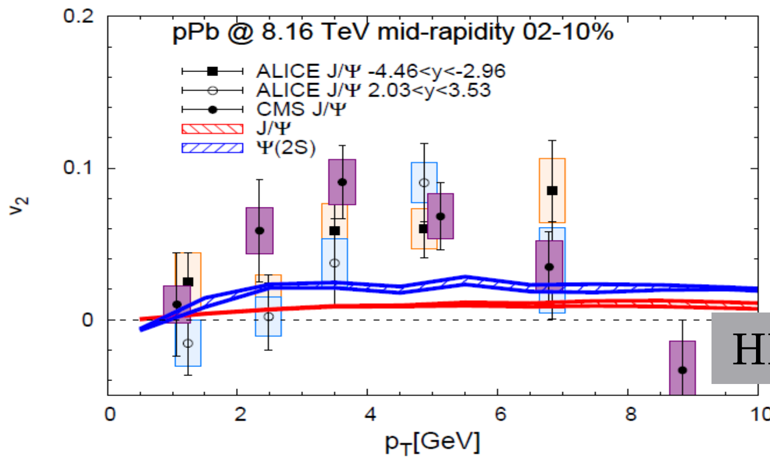


Quarkonium flow in p-Pb



PLB 780 (2018) 7



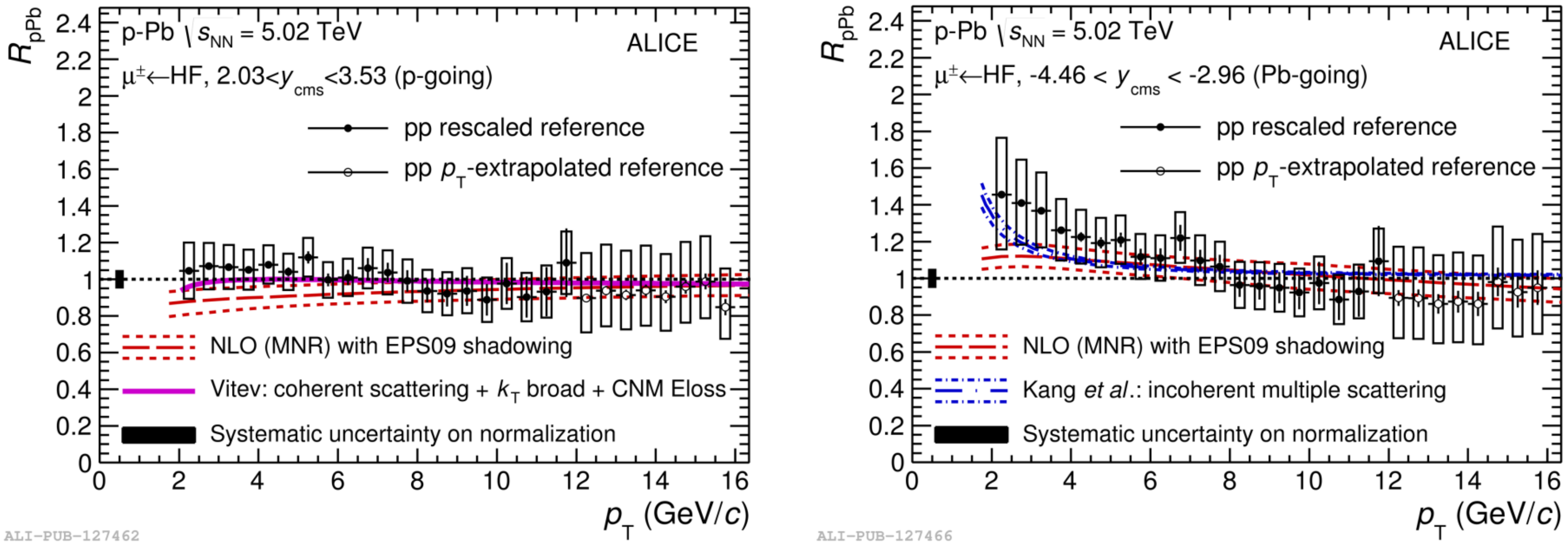


HP2018 : R. Rapp

- 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 although the underlying mechanism is not known to be also same or different.
- The transport model calculations give very small v_2 over the full p_T range.

Heavy-flavour production in p-Pb

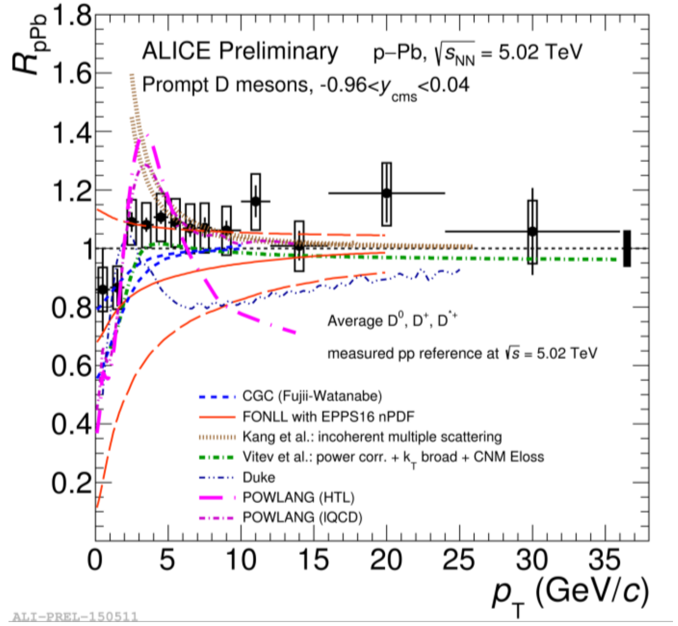
PLB 770 (2017) 459



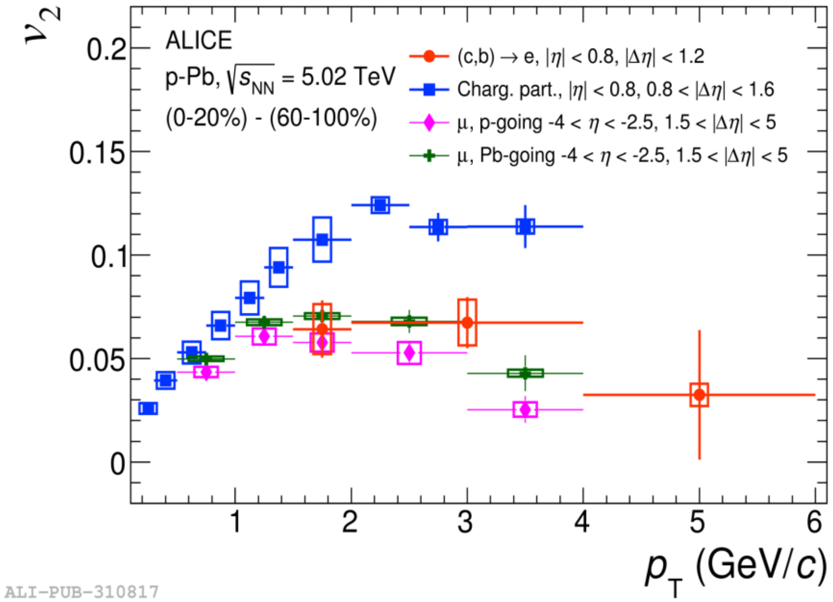
- The nuclear modification factor is compatible with unity at forward rapidity.
- The R_{pPb} of heavy-flavor decay muons at high p_T is also compatible with unity at backward rapidity, but above unity by more than 2σ in $2.5 < p_{\mathrm{T}} < 3.5$ GeV/c.
- The NLO calculation with shadowing can reproduce 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

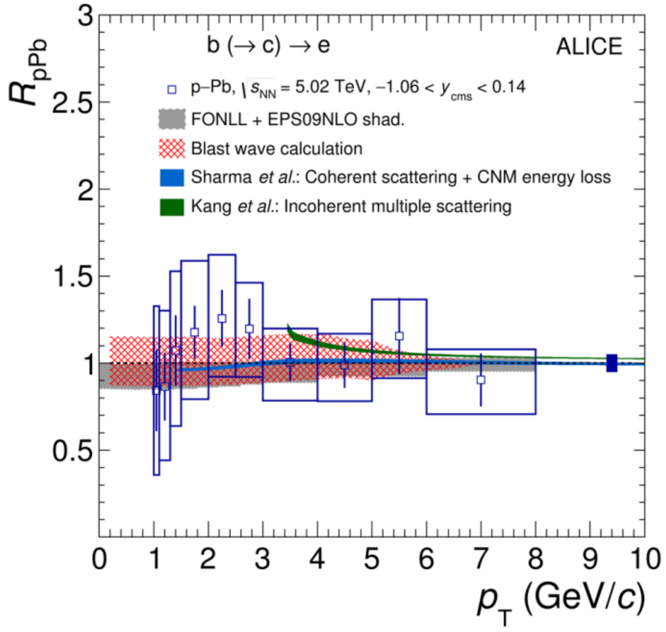
PRL 113 (2014) 232301



arXiv : 1805.04367

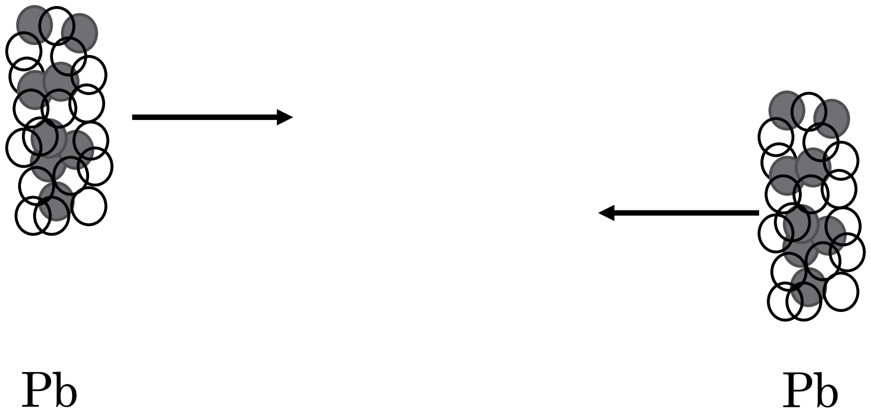


JHEP 7 (2017) 52



- 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 $1 < p_{\mathrm{T}} < 8$ GeV/c.

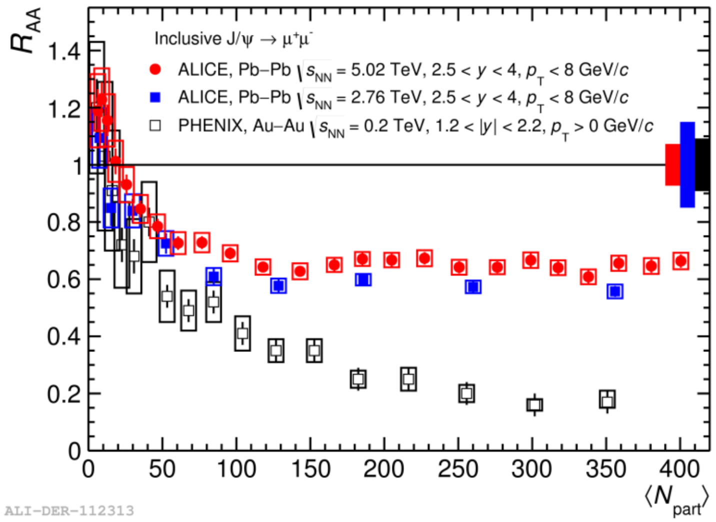
Further : oral presentation by Bharti and Renu and poster presentation by Ashik



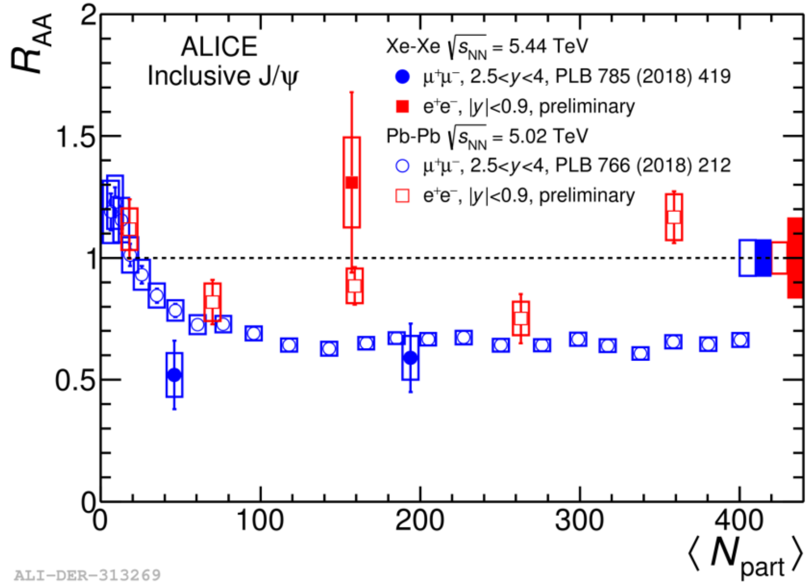
Pb
Pb

Quarkonium in Pb-Pb and Xe-Xe

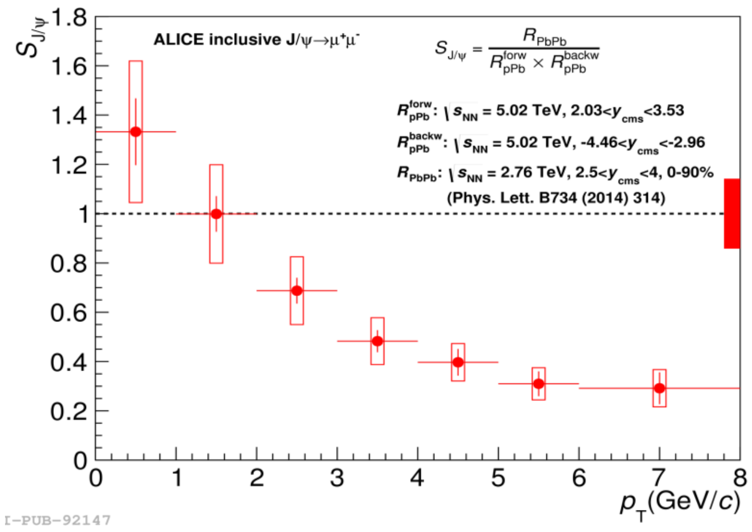
PLB 766 (2017) 212



NEW



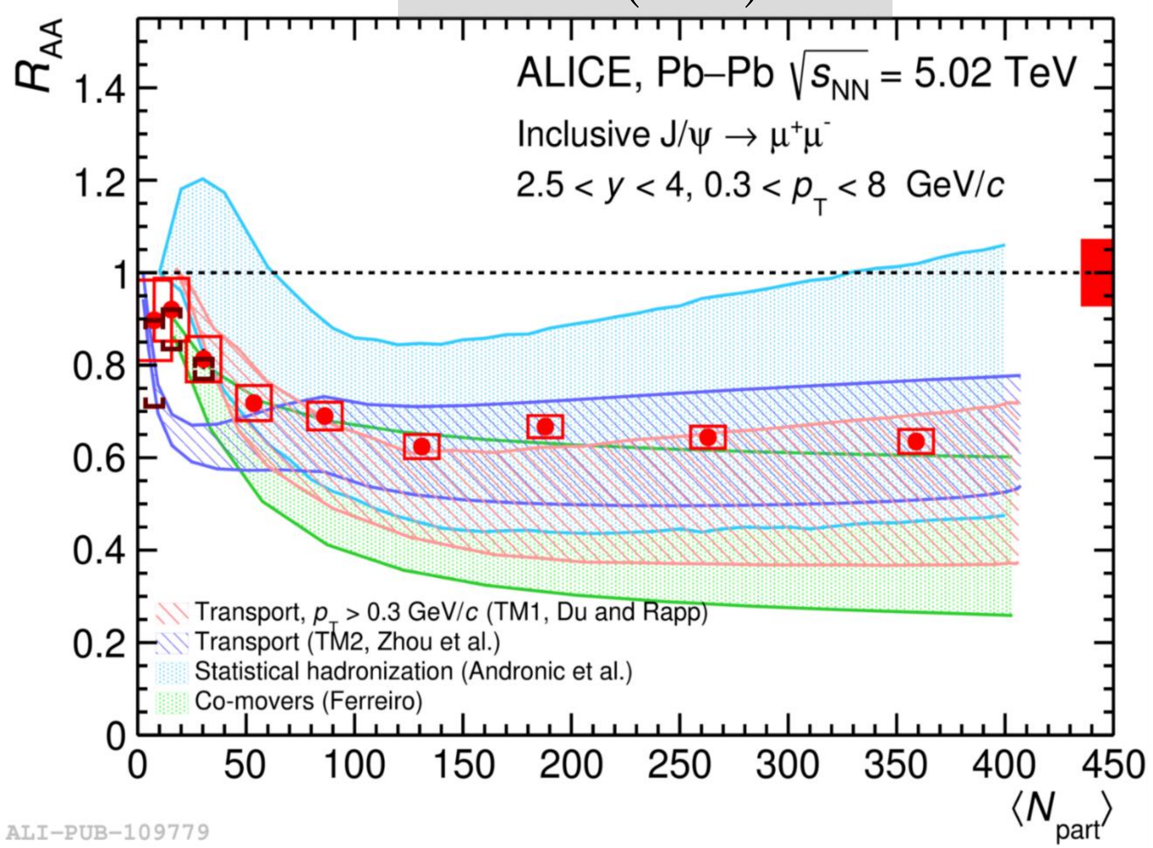
JHEP 06 (2015) 55



- 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/ψ R_{AA} is found to be of similar magnitude for Pb-Pb and Xe-Xe collisions at forward rapidity, however no suppression is observed at mid-rapidity for Xe-Xe.
- A stronger suppression factor $\left(= \frac{R_{PbPb}}{R_{pPb} \times R_{Pbp}}\right)$ is found at high-p_T by combining the J/ψ p-Pb and Pb-Pb forward rapidity results.

Quarkonium predictions in Pb-Pb

PLB 766 (2017) 212



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

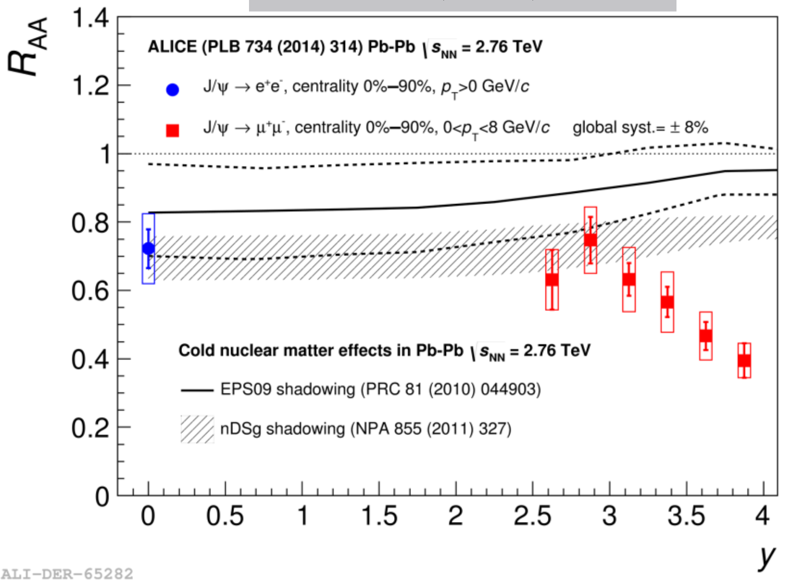
Transport model (TM2) : [slant blue lines]
Zhou et al., Phys. Rev C 89 no.5, 459 (2014) 054911

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

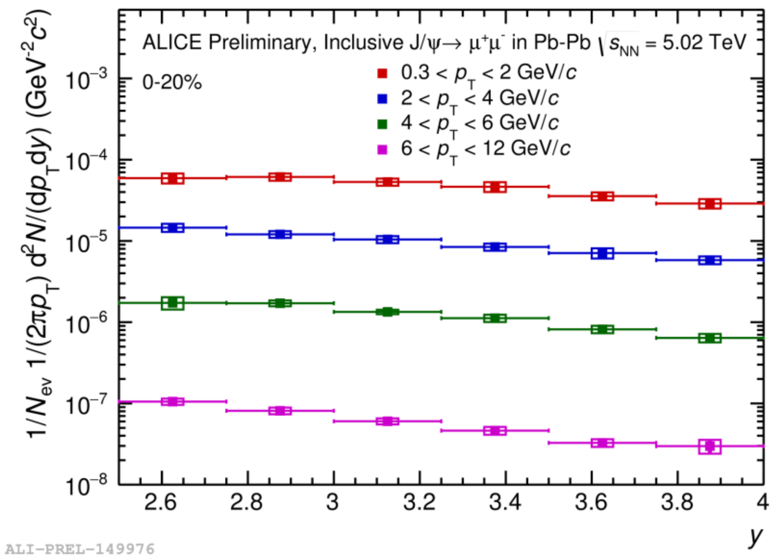
❑ All models can describe the data but with larger uncertainties.

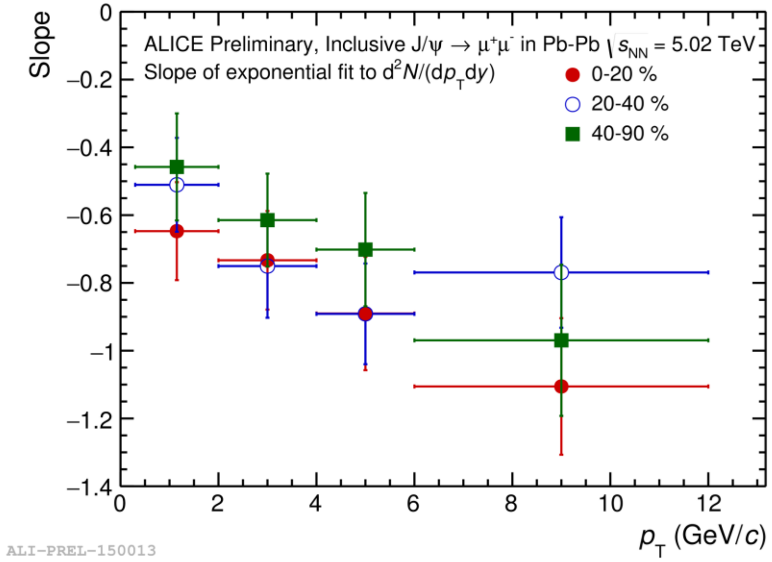
Quarkonium in Pb-Pb

PLB 734 (2014) 314



QM-2018 : Hushnud

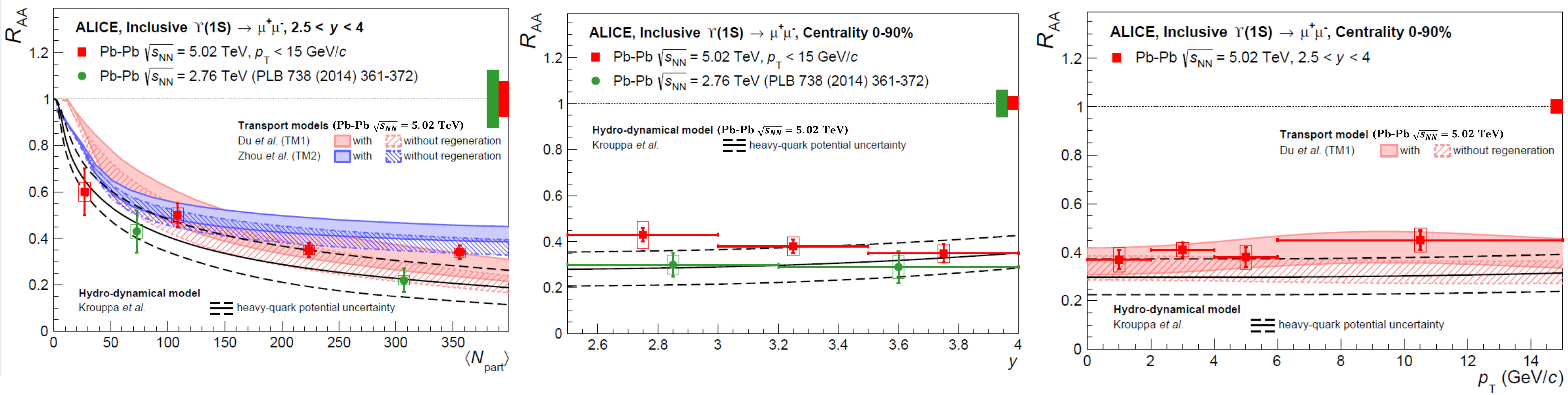




- A strong rapidity dependence is measured for J/ψ R_{AA} which shows a trend opposite to that of shadowing predictions.
- The multi-differential measurement of J/ψ R_{AA} as a function of centrality, p_T, and rapidity is ongoing and will provide more insight into the interplay between suppression and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

Quarkonium in Pb-Pb

arXiv : 1805.04387

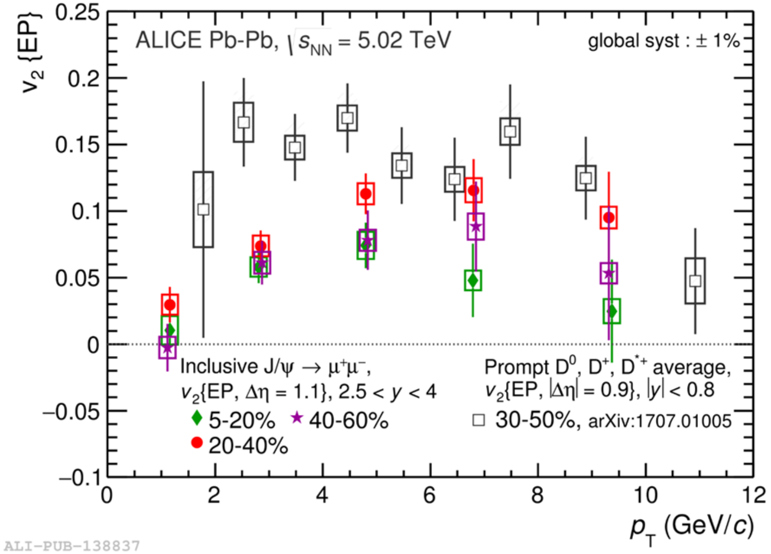


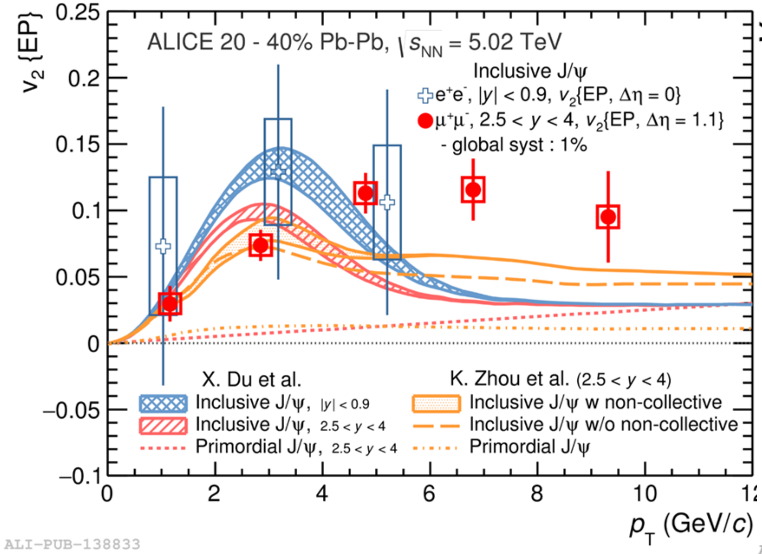
- Transport models by Zhou et al. (TM2) and Rapp et al. (TM1) and the anisotropic hydrodynamic model by Strickland et al qualitatively reproduce the centrality dependence.
- The anisotropic hydrodynamic model by Strickland et al. can describe the rapidity dependence of R_{AA}, but hint of different trend is observed.
- The p_T dependence of ϒ(1S) R_{AA} in Pb-Pb collisions is described by the transport model and anisotropic hydrodynamics model.
- Transport model, with or without (re)generation effect can describe the data.
- The ratio of R_{AA} for ϒ(2S) to ϒ(1S) is 0.28±0.12 (stat.)±0.06 (sys.) → sequential suppression.

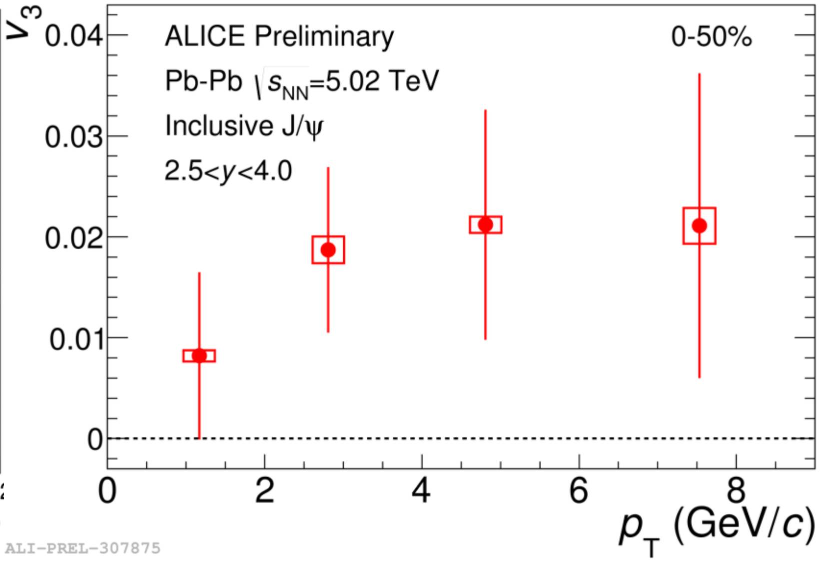
Quarkonium flow in Pb-Pb

PRL 119(2017) 242301

arXiv : 1811.12727







- 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.
- A non-zero v_3 of J/ψ (3.7σ significance) has been measured for the first time.

Heavy-flavour production in Pb-Pb

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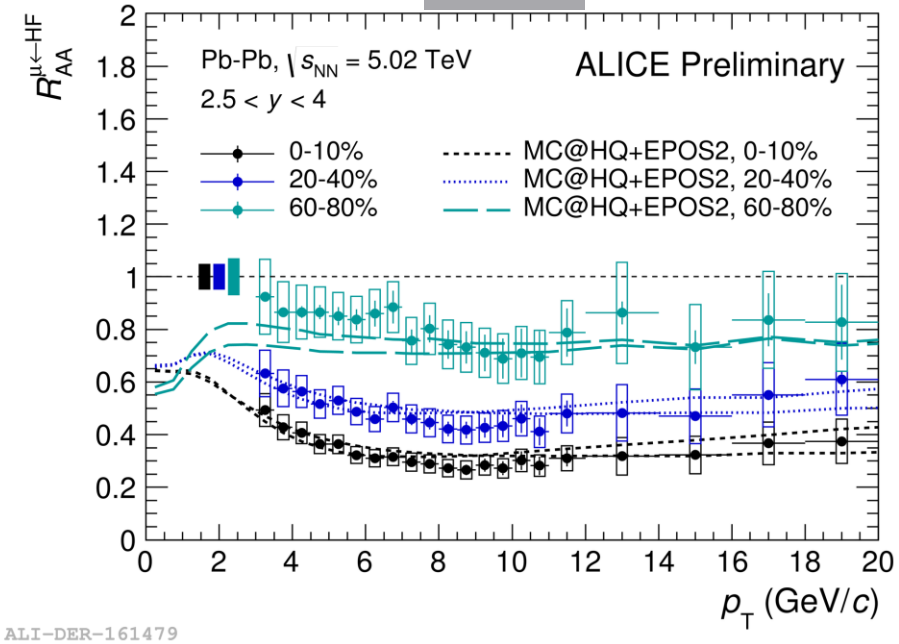
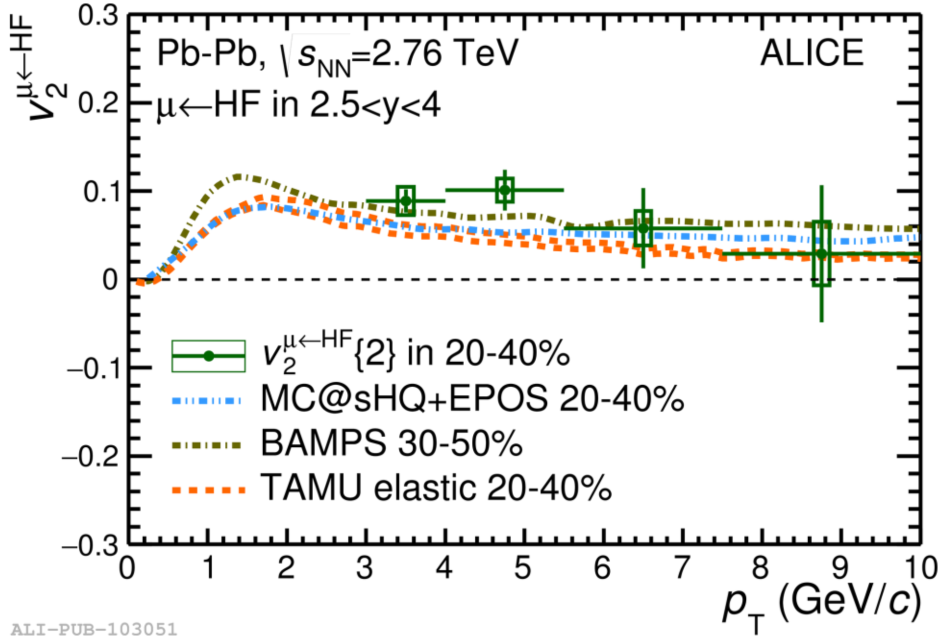


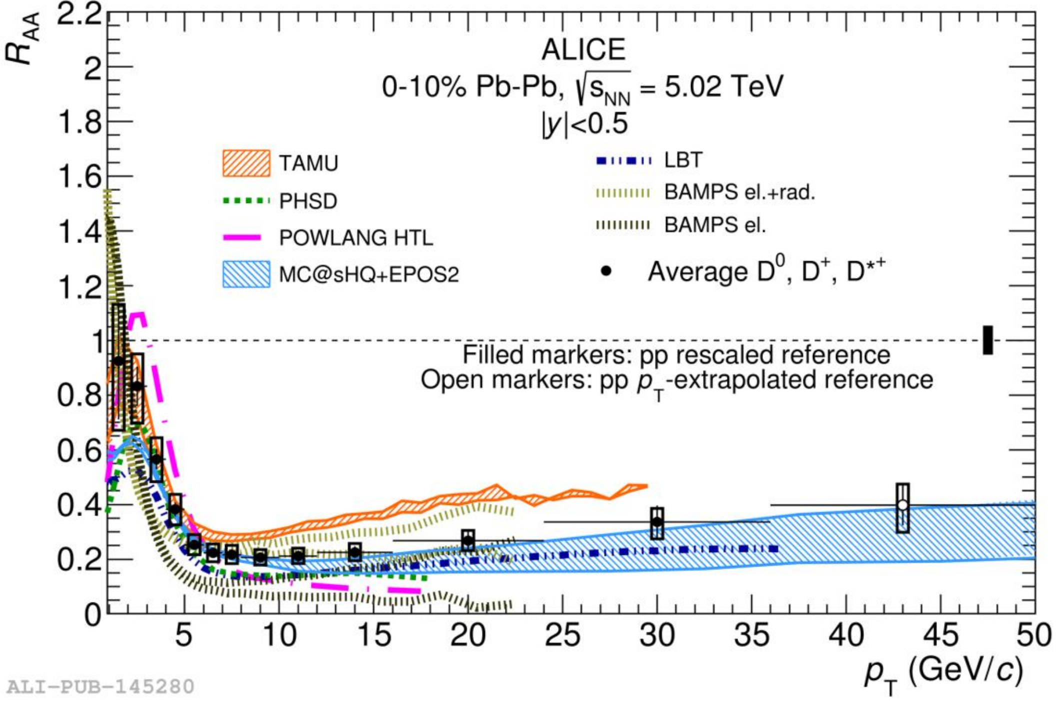
PLB 753 (2016) 41

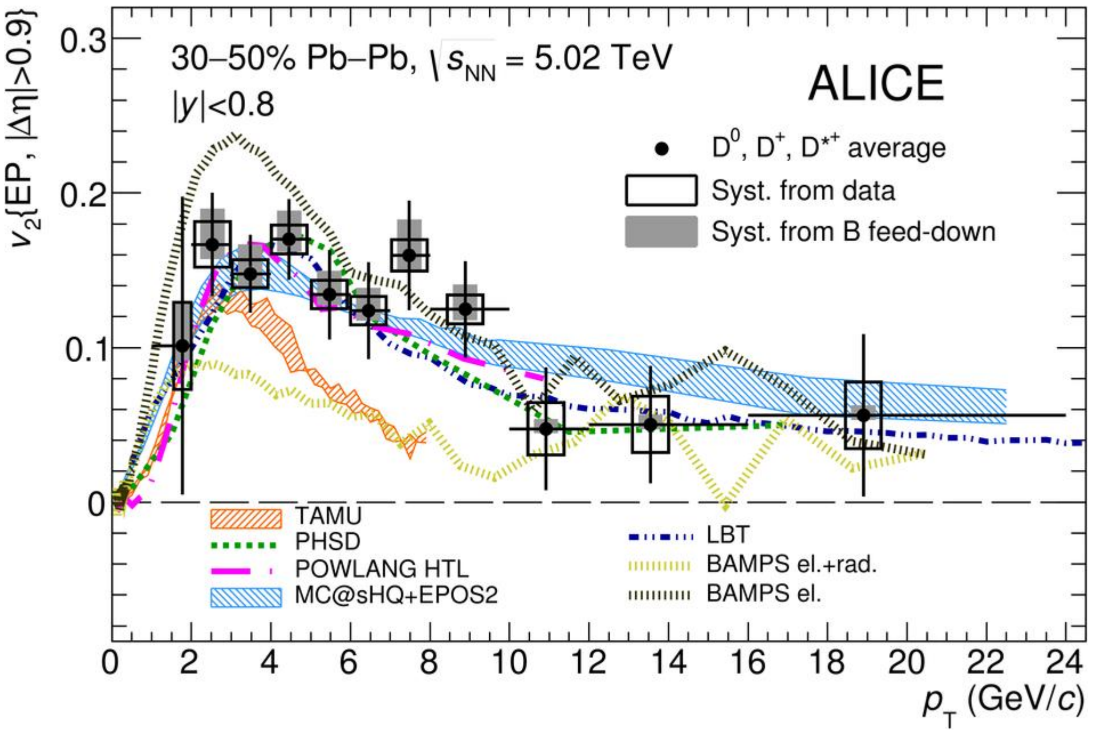


- A strong suppression is observed for the heavy-flavour muon R_{AA} for central collisions.
- A positive heavy-flavour v_2 is measured using scalar product and two particle Q cumulants in semi-central collisions with more than 3σ significance for $3 < p_T < 5$ GeV/c.
- The model predictions based on 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

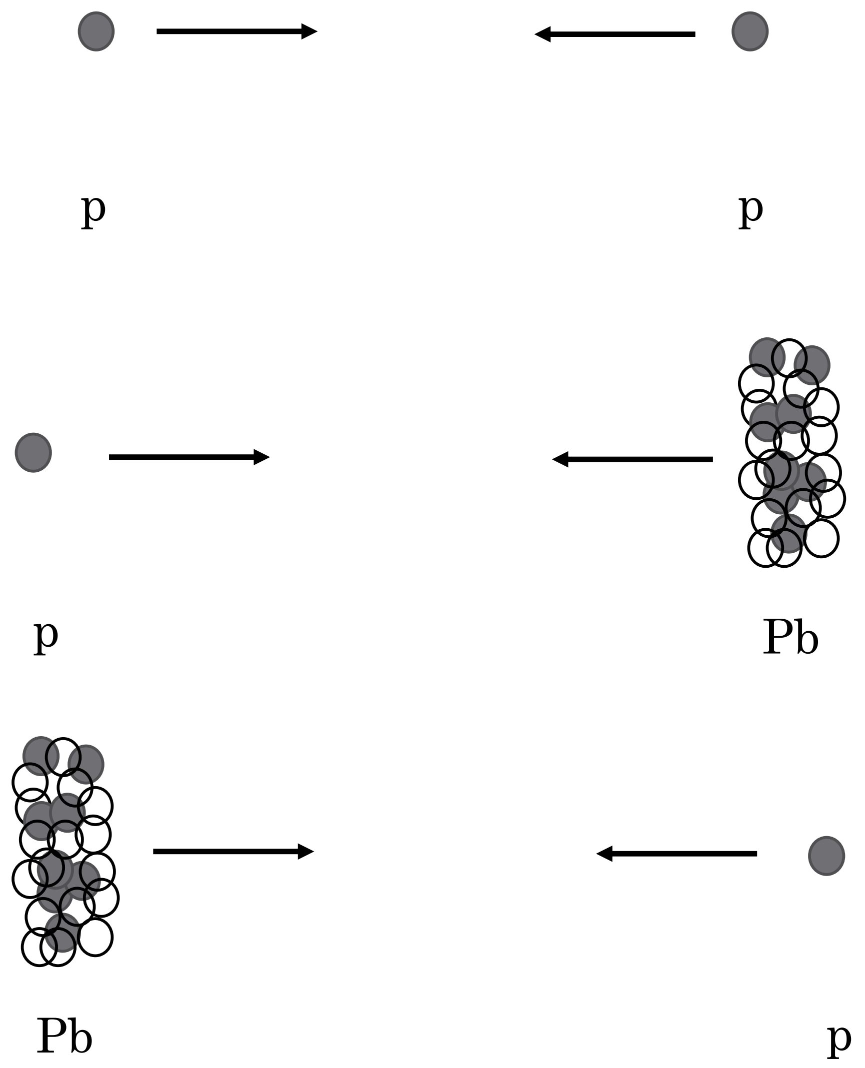
arXiv:1804.09083





- 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.

Further : poster presentation by Sudhir and Samrangy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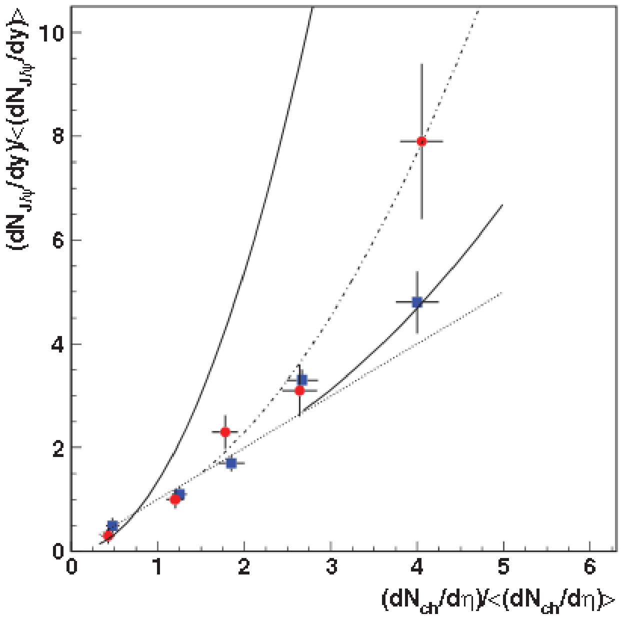
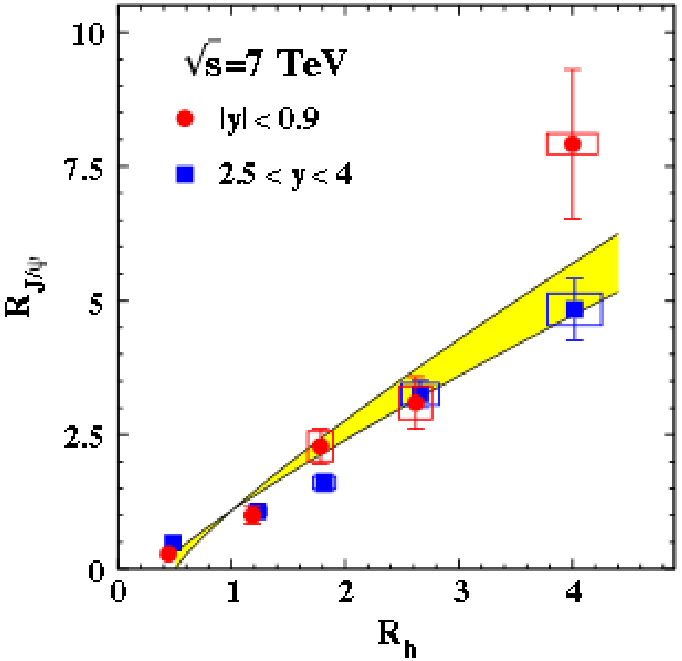
Quarkonium as a function of multiplicity in pp

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



PLB 712 (2012) 165.



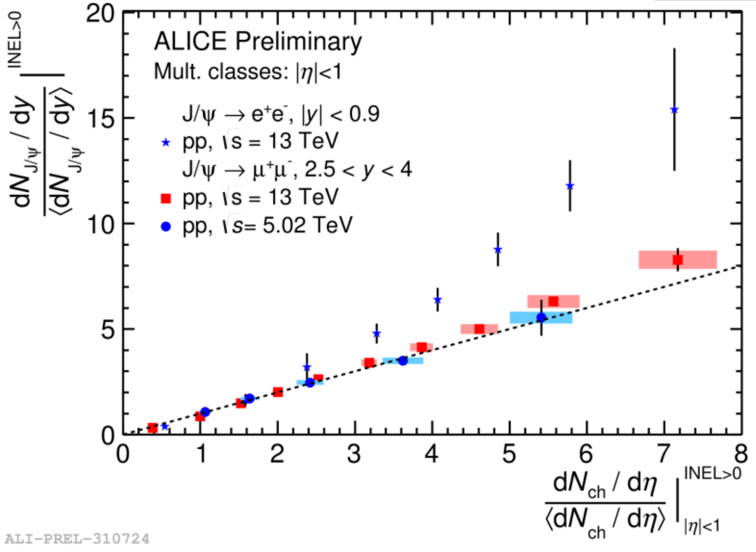
B.Z.Kopeliovich et. al., PRD 88 (2013) 116002

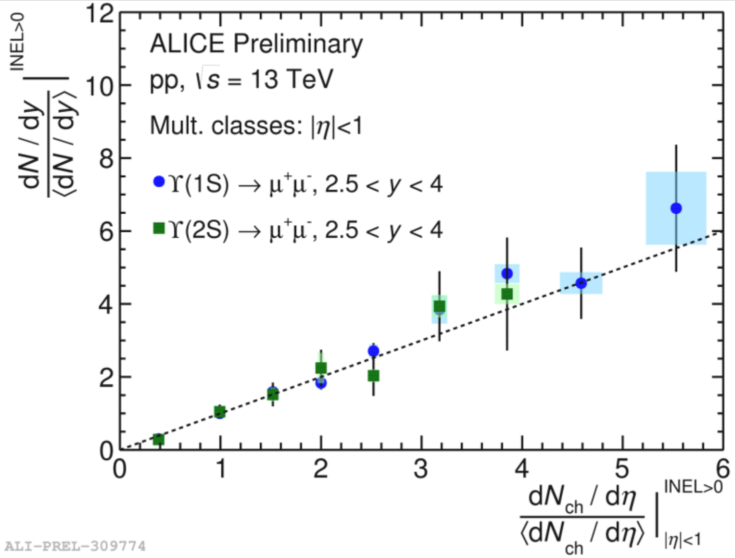
- Finite spatial extension (non-zero impact parameter) for elementary parton-parton interactions.
- Formation of colour ropes or flux tubes—strings.
- $N^{collisions}_{parton-parton} \propto N_{strings}$.
- Strings can overlap in transverse direction resulting in a reduction of soft-particle production,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

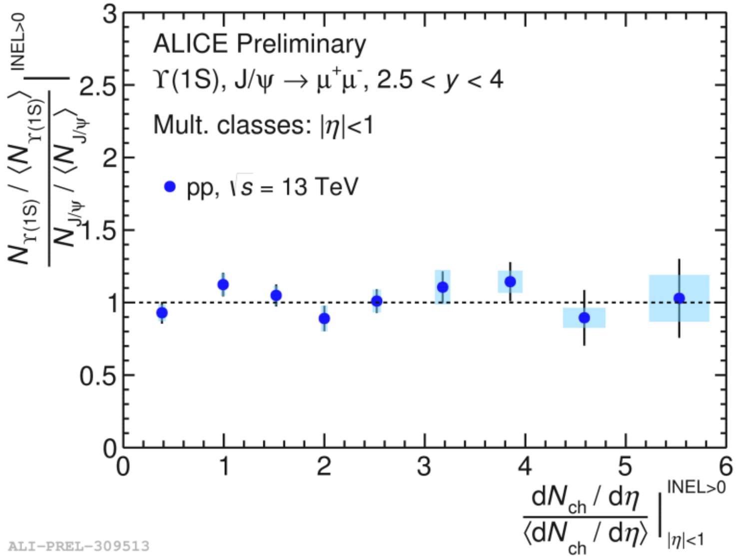
- The high multiplicity pp events are similar to pA.
- NA3 and E866 collaboration results used for :
$$R^{pA}_{J/\psi} = N_{coll} A^{\alpha-1} \; [\alpha = 0.95 \text{ from E866}]$$
- Compilation of various hadron-nuclear results [NPA395(1983)482] :
$$R^{pA}_{h} = 1 + \beta(N_{coll} - 1) \text{ with } [0.5 < \beta < 0.65]$$
- Finally using, $N_{coll} \approx \frac{\sigma^{pp}_{in}}{\pi r_0^2} A^{1/3}$ for pA collisions, the dependency is extracted for $R^{pA}_{J/\psi} \propto R^{pA}_{h}$ and applied for pp collisions

Quarkonium as a function of multiplicity in pp

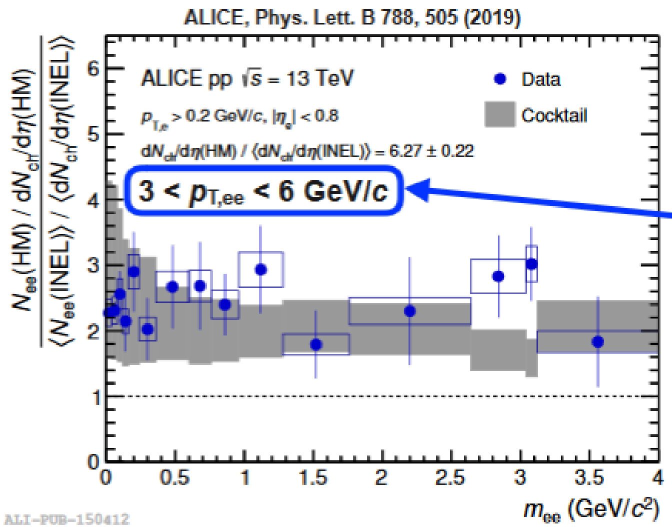
QM2018 : Anisa, Dhananjaya, Tasnuva, Yanchun

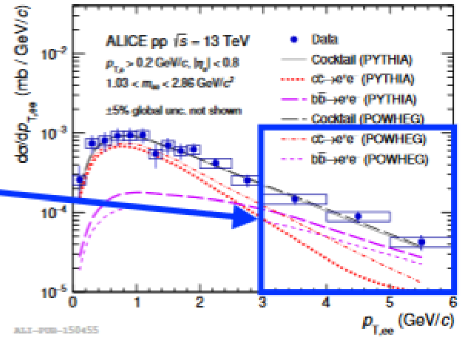






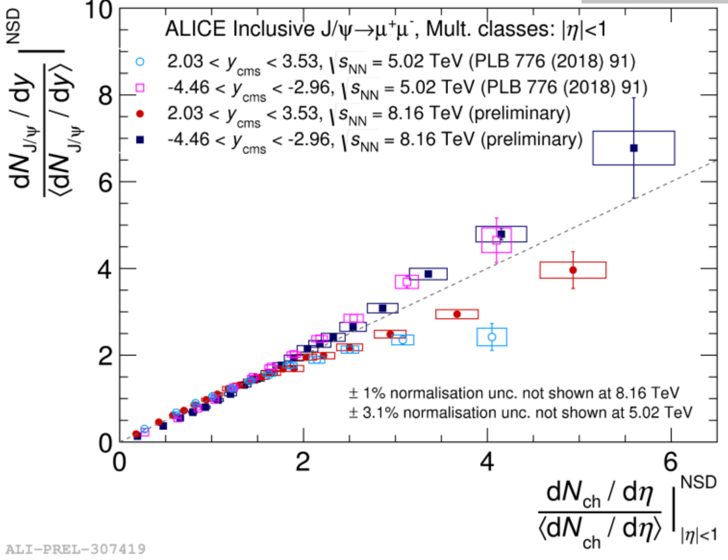
- A detailed study has been performed to explore the rapidity dependence at various energies for different colliding systems and different resonances.
- A linear increase has been observed for forward rapidity J/ψ vs mid-rapidity multiplicity compared to the faster than linear increase of midrapidity 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.

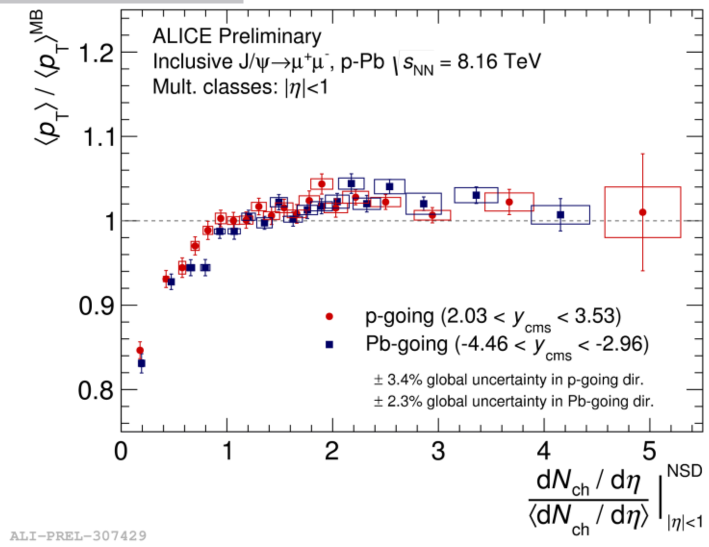




Heavy-quark as a function of multiplicity in p-Pb

EPS2017 : Jana





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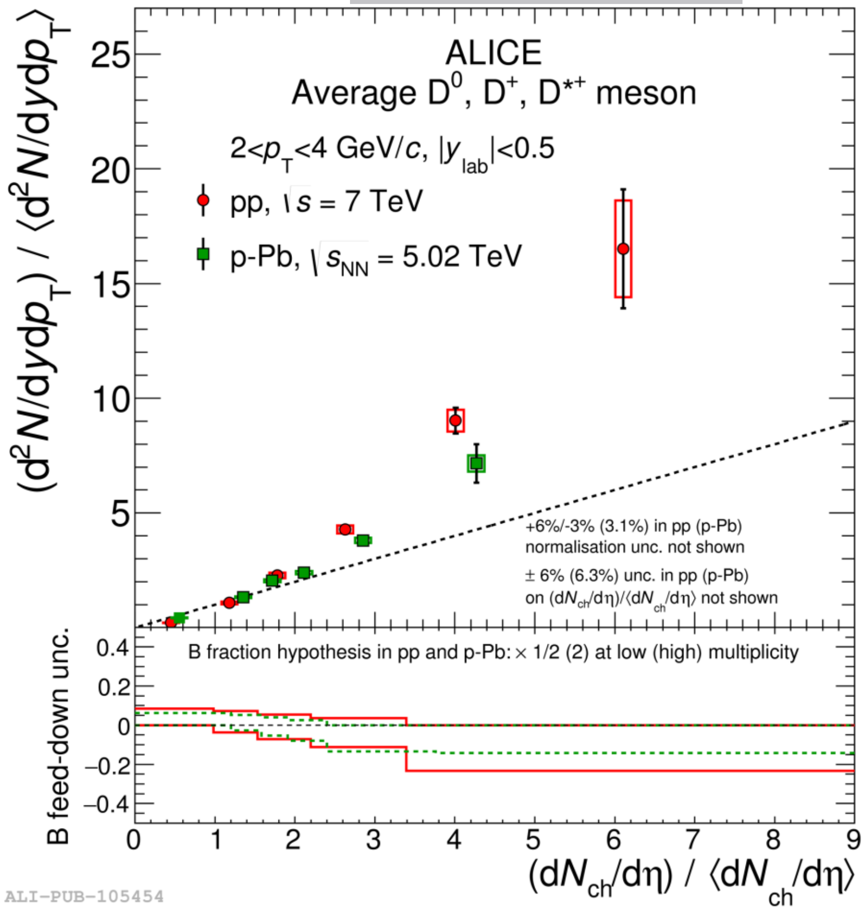


- An increase of J/ψ yield with normalized $\frac{dN_{ch}}{d\eta}$ is observed at backward rapidity, however in forward rapidity a hint of saturation is observed.
- The normalized J/ψ $< p_T >$ increases at low charged-particle multiplicity and saturates at high multiplicity events.
- A similar increase for heavy-flavour production has been measured as a function of charged-particle multiplicity.

Summary

ALICE

- pp collisions
  - ALICE results are in agreement with the other LHC experiments and world data.
  - Theoretical calculations start to describe data over all p_{T} but polarisation is still a puzzle.
- p-Pb collisions
  - The nuclear modification factor can be explained by Cold Nuclear Matter effects.
  - A long-range correlation is observed : J/ψ v_2 in central p-Pb collisions.
- Heavy-ion collisions
  - Interplay of two main mechanisms : suppression and (re)generation for charmonium, whereas for bottomonium suppression plays dominant role with negligible (re)generation.
  - Observation of non-zero v_2 with higher precision and first look at non-zero v_3 for J/ψ.
  - A strong energy loss of open heavy flavours in central collisions.
  - The elliptic flow measurement of heavy-flavour together with R_{AA} set stringent constraints for modes.
- 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.
  - An increase of bottom quark production compared to charm is observed in dielectron spectra for $p_T > 3$ GeV/c.
  - The production of D mesons shows a similar increase with charged-particle multiplicity.

ALICE upgrade

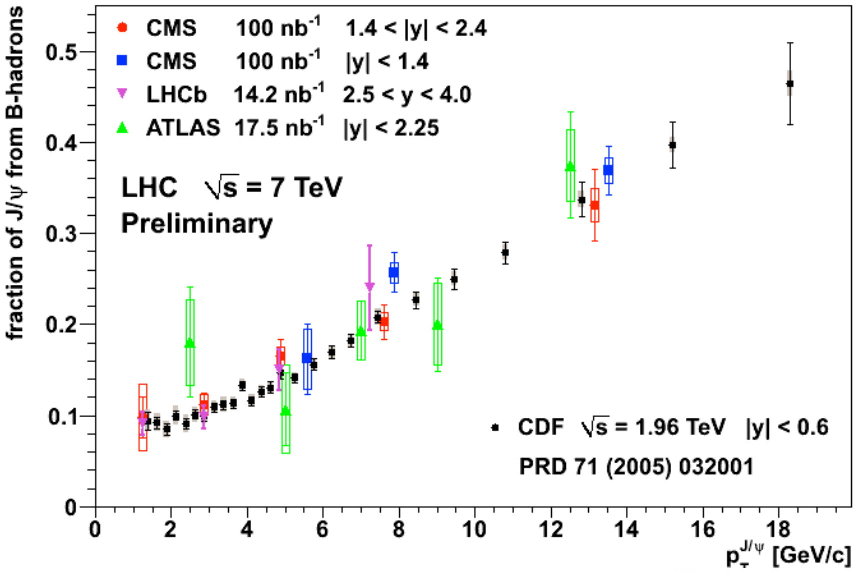
- ALICE is entering LS2 upgrade.
- ALICE will be able to collect pp and p-Pb data at 200 kHz and Pb-Pb 50 kHz in Run3 of LHC.
- ALICE plans to collect 10 nb^{-1} of Pb-Pb data for a detailed understanding of QGP.

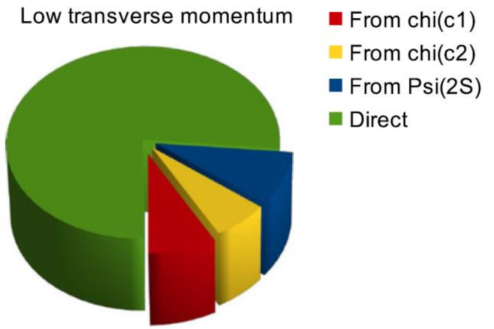
Thank you

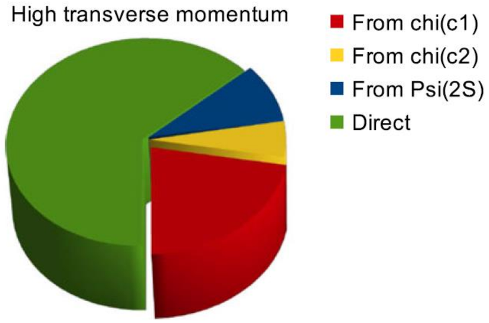
Prompt, non-prompt and feed-down

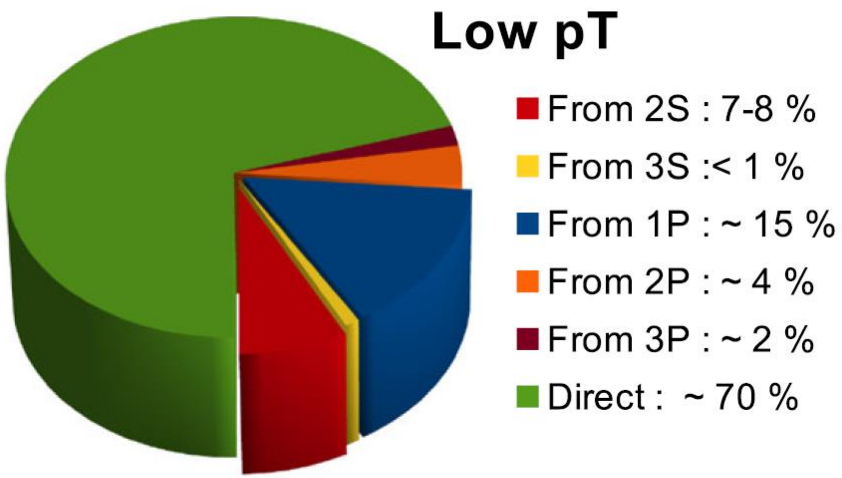
Charmonium [A. Andronic et al., EPJC 76 (2016) 107] **Bottomonium**

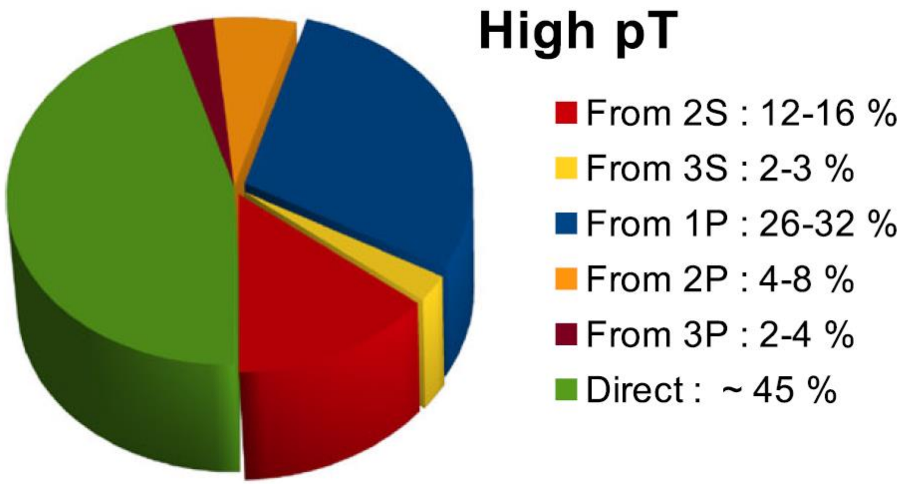
In addition to (10-30)% B-decay production





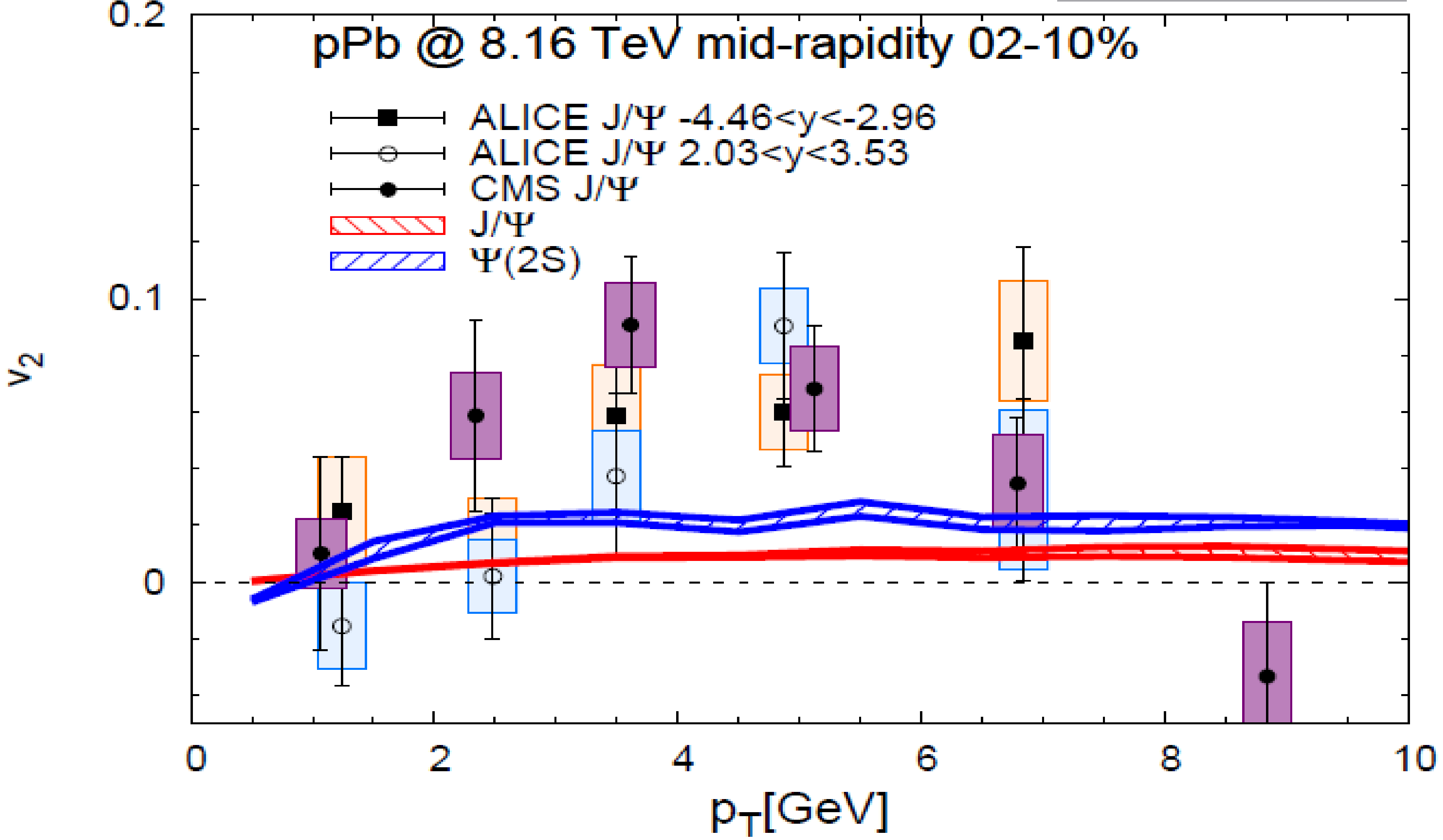






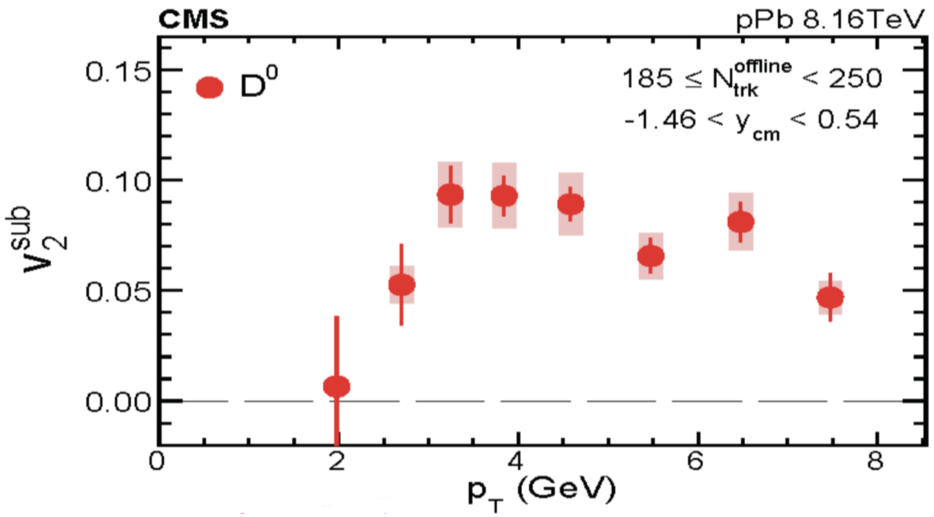
Prdictions for charmonium v_2 in p-Pb

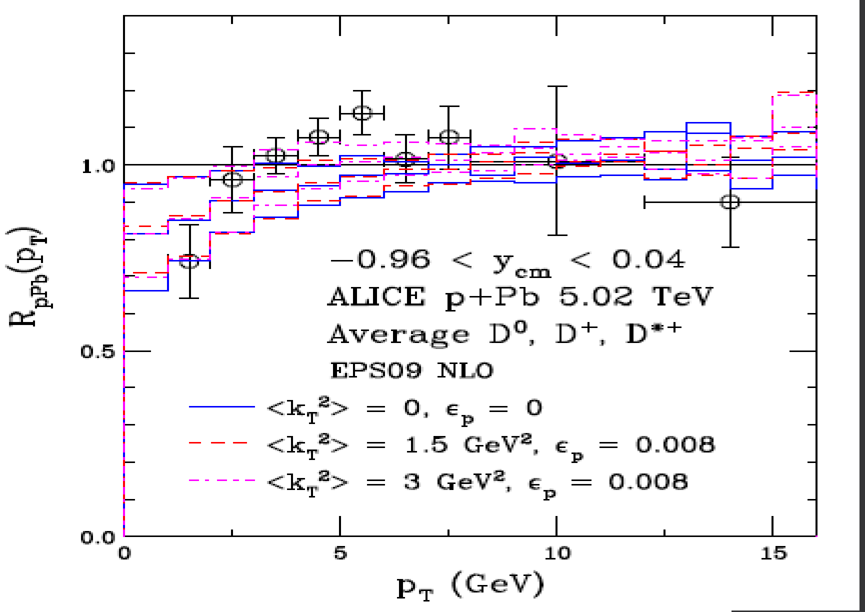
HP2018 : R. Rapp



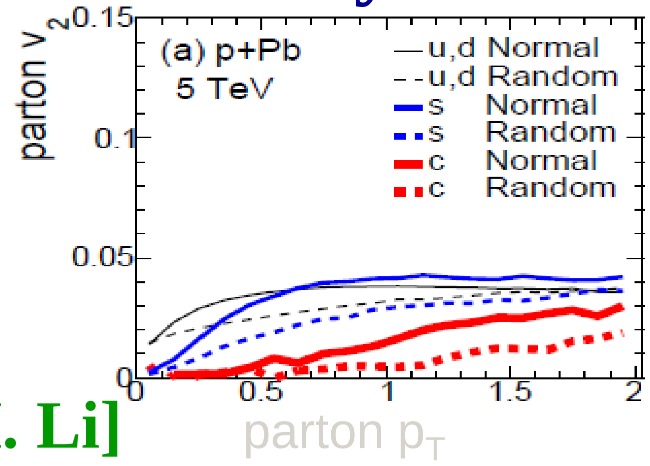
6.) Charm in pA Collisions:

- R_{pA} data consistent with shadowing **[R. Vogt]**
  - But: large v_2



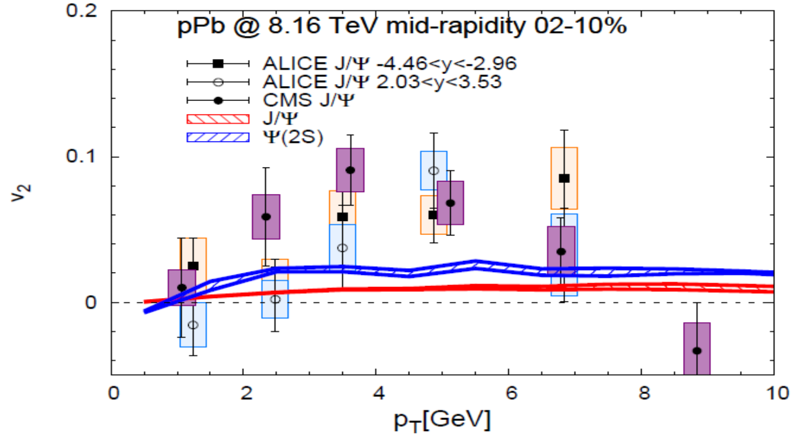


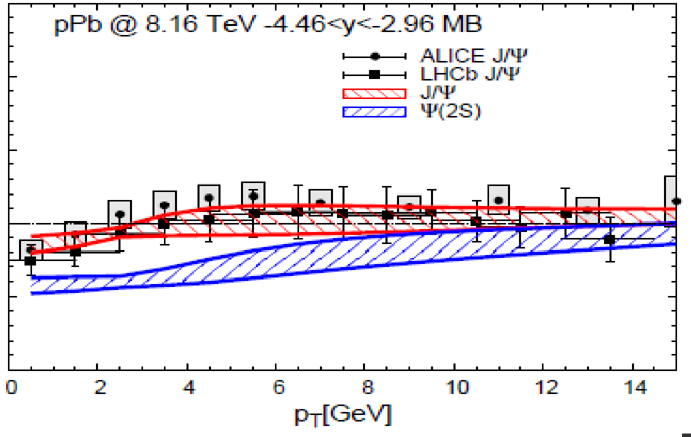
- **Collectivity?**



[H. Li]

- small c-quark v_2





- very similar for charmonia **[Du+RR'18]**