Charmonium production in Pb-Pb collisions with the ALICE Central Barrel -status and plans-

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22/08/2019, Bergen

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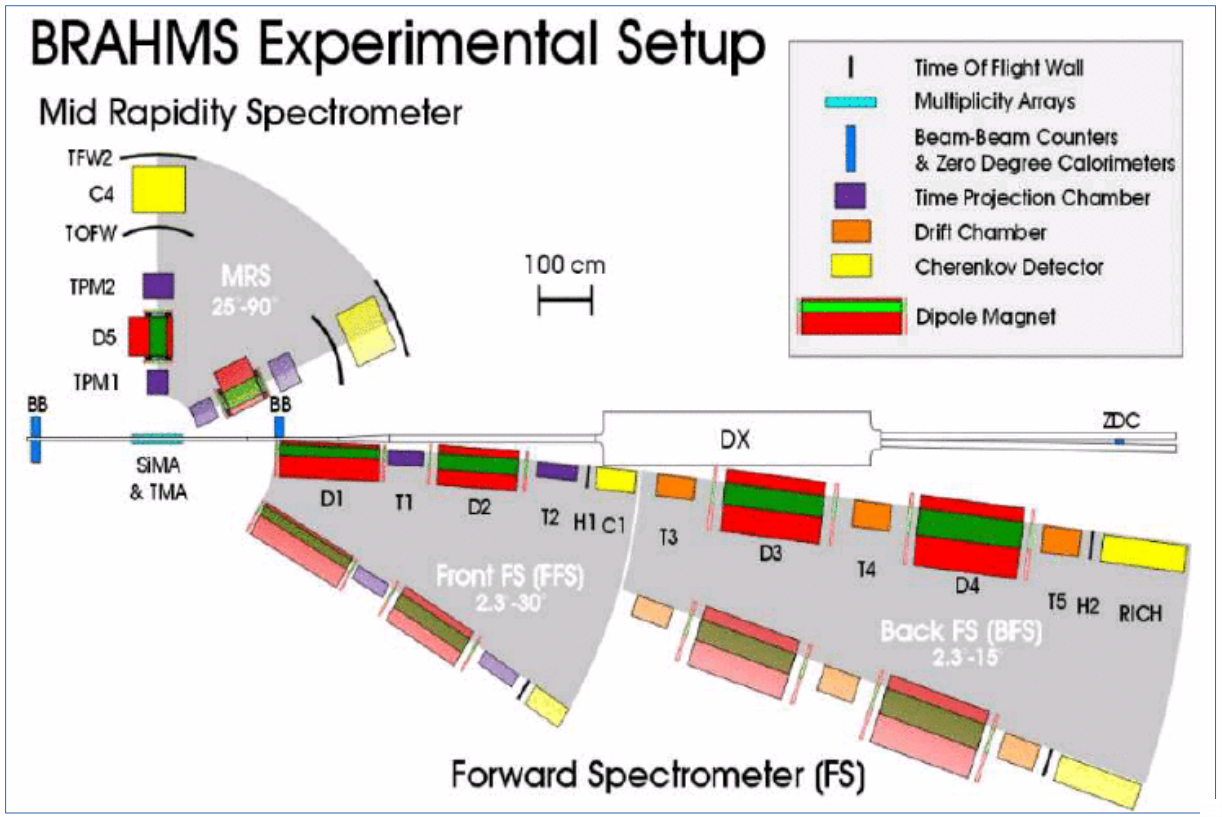
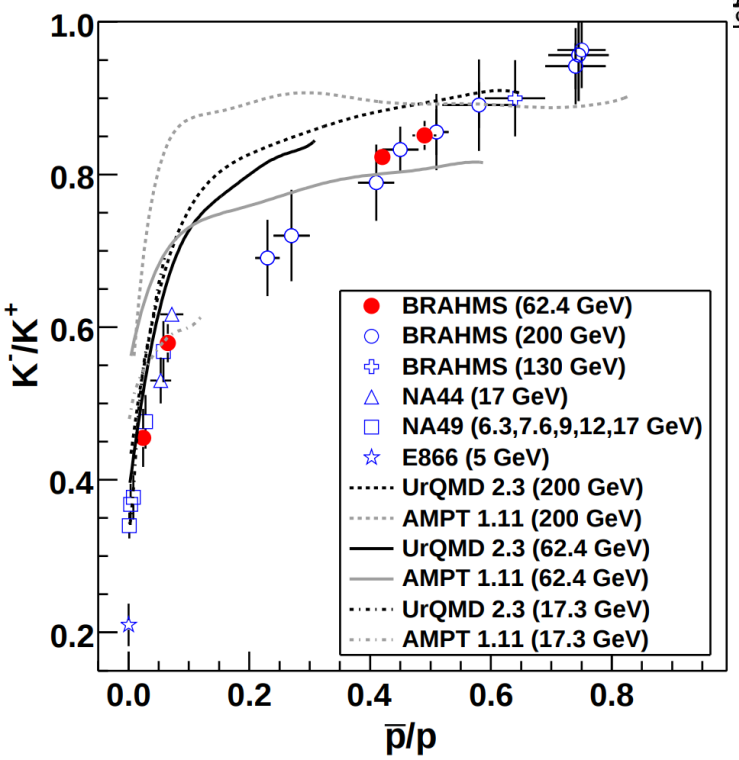
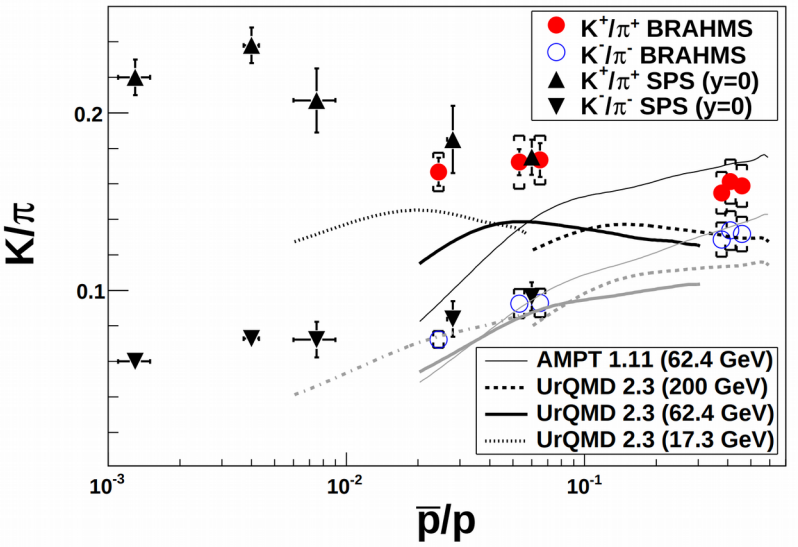
BRAHMS

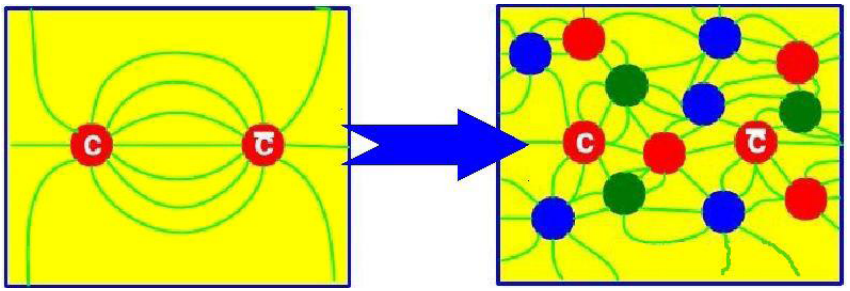

BRAHMS Experimental Setup
Mid Rapidity Spectrometer
Time Of Flight Wall
Multiplicity Arrays
Beam-Beam Counters
& Zero Degree Calorimeters
Time Projection Chamber
Drift Chamber
Cherenkov Detector
Dipole Magnet
TFW2
C4
TOFW
TPM2
D5
TPM1
MRS
25°-90°
100 cm
BB
BB
SiMA
& TMA
ZDC
DX
D1
T1
D2
T2
H1
C1
T3
D3
T4
D4
T5
H2
RICH
Front FS (FFS)
2.3 -30°
Back FS (BFS)
2.3 -15°
Forward Spectrometer (FS)


K⁻/K⁺
p̄/p
BRAHMS (62.4 GeV)
BRAHMS (200 GeV)
BRAHMS (130 GeV)
NA44 (17 GeV)
NA49 (6.3,7.6,9,12,17 GeV)
E866 (5 GeV)
UrQMD 2.3 (200 GeV)
AMPT 1.11 (200 GeV)
UrQMD 2.3 (62.4 GeV)
AMPT 1.11 (62.4 GeV)
UrQMD 2.3 (17.3 GeV)
AMPT 1.11 (17.3 GeV)


K/π
p̄/p
K⁺/π⁺ BRAHMS
K⁻/π⁻ BRAHMS
K⁺/π⁺ SPS (y=0)
K⁻/π⁻ SPS (y=0)
AMPT 1.11 (62.4 GeV)
UrQMD 2.3 (200 GeV)
UrQMD 2.3 (62.4 GeV)
UrQMD 2.3 (17.3 GeV)

Heavy quarkonia in the QGP

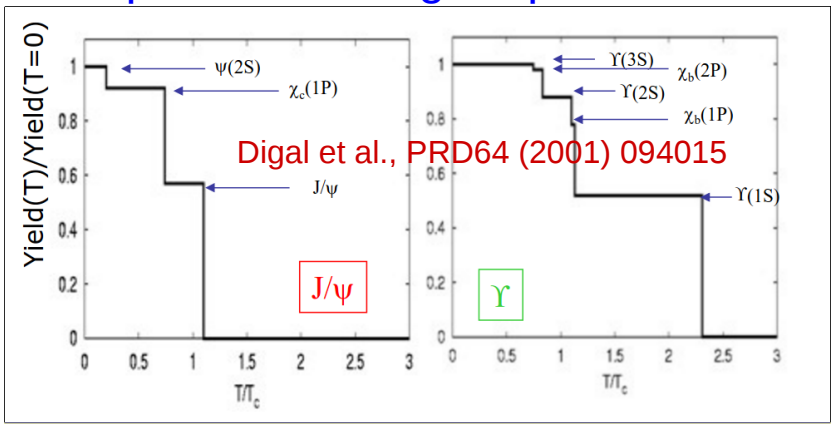
- Vacuum potential: $V_{total} = (-q)\frac{q}{4\pi r} + kr$

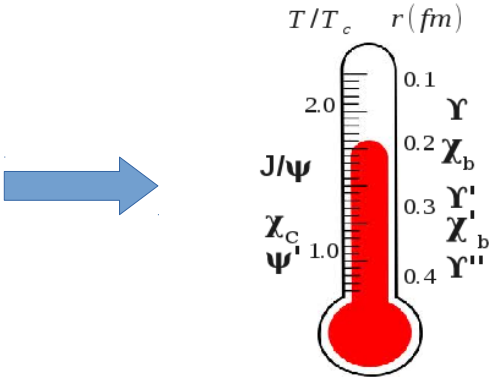


- In a deconfined medium
  - string tension disappears
  - Coulomb potential is screened (Debye)
- The quark-antiquark potential becomes a Yukawa-like short range potential

$$V_{medium}(\boldsymbol{r}) = \frac{q}{4\pi}\frac{e^{-r/\lambda_D}}{r} \qquad \lambda_D \simeq \frac{1}{T}$$ - Debye screening length

- Quarkonium states will be melted if $r > \lambda_D$: *Matsui and Satz, PLB178 (1986) 416*
  - Sequential melting of quarkonium states → thermometer of the QGP





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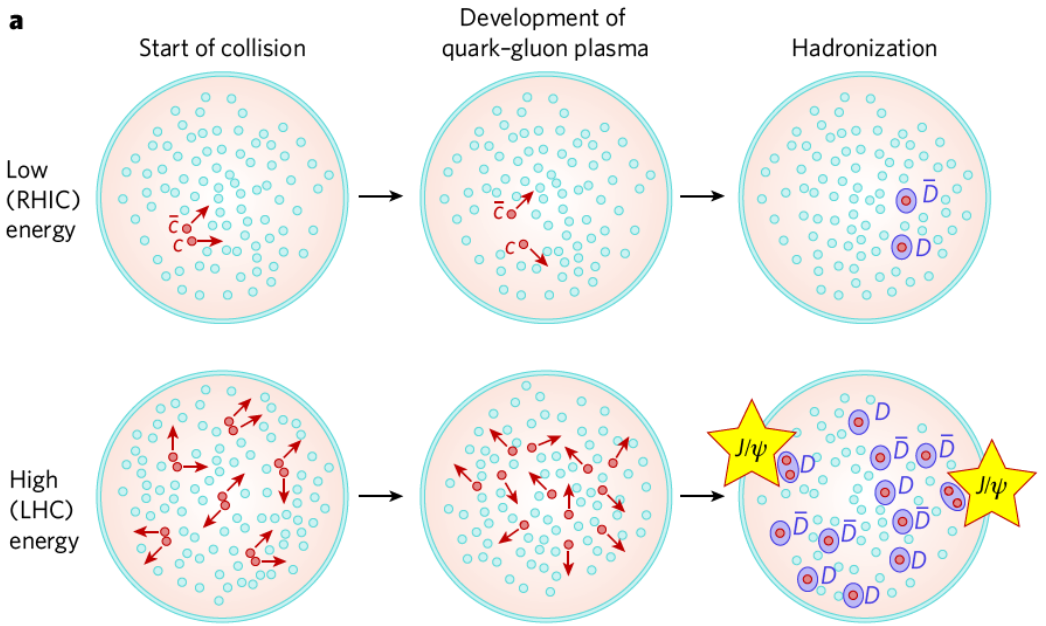
Statistical hadronization

P.Braun-Munzinger, J.Stachel, PLB490 (2000) 196



$$N_{c\bar{c}}^{direct} = \frac{1}{2} g_c V \left(\sum_i n_{D_i}^{therm} + n_{\Lambda_i}^{therm}\right) + g_c^2 V \left(\sum_i n_{\psi_i}^{therm}\right) + \ldots.$$

- At the LHC energies, large amounts of $c\bar{c}$ pairs are created
- Possible to create charmonium on a statistical basis
  - Assuming charm-quark thermalization and knowing the total $c\bar{c}$ cross-section, all charmed particle yields can be predicted

Microscopic transport models

- Microscopic models developed for the transport of charmonium in QGP
  - CNM effects taken into account to estimate primordial total $c\bar{c}$ cross-section (EPS09 NLO)
  - Cronin effect → broadening of the pt spectra
  - Ideal hydrodynamics for the fireball evolution
    - QGP phase: ideal gluon gas
    - Hadronic phase: ideal hadron gas
    - Initialization tuned to match charge multiplicities see in Pb-Pb at LHC
  - Boltzmann-type equation for charmonia (J/ψ, χ_c and ψ(2S)) with gain and loss terms

Texas model: X.Zhao, R.Rapp NPA859 (2011) 114
Tsingua model: Y.Liu, P.Zhuang et al. PLB678 (2009) 72

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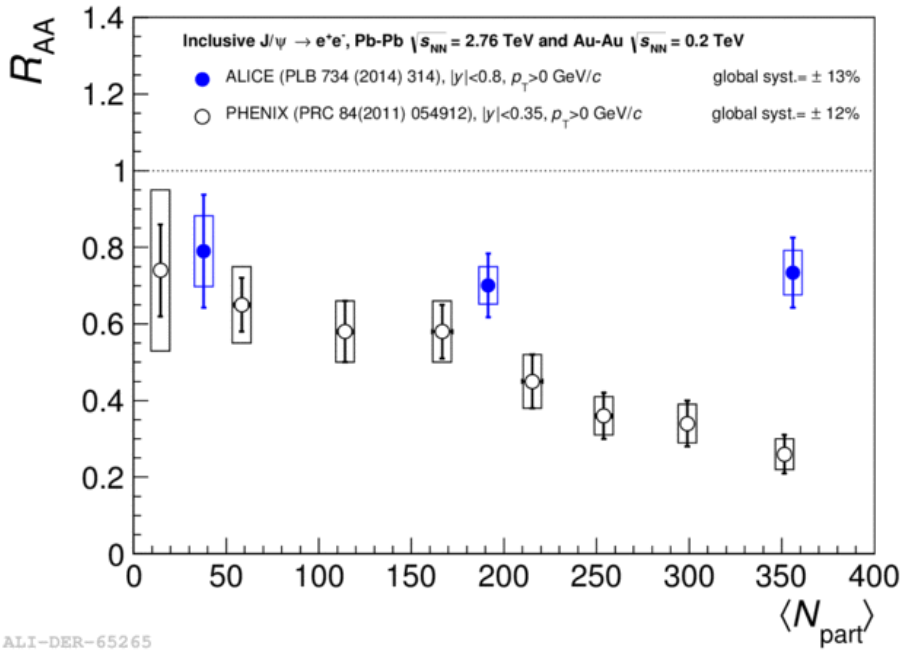
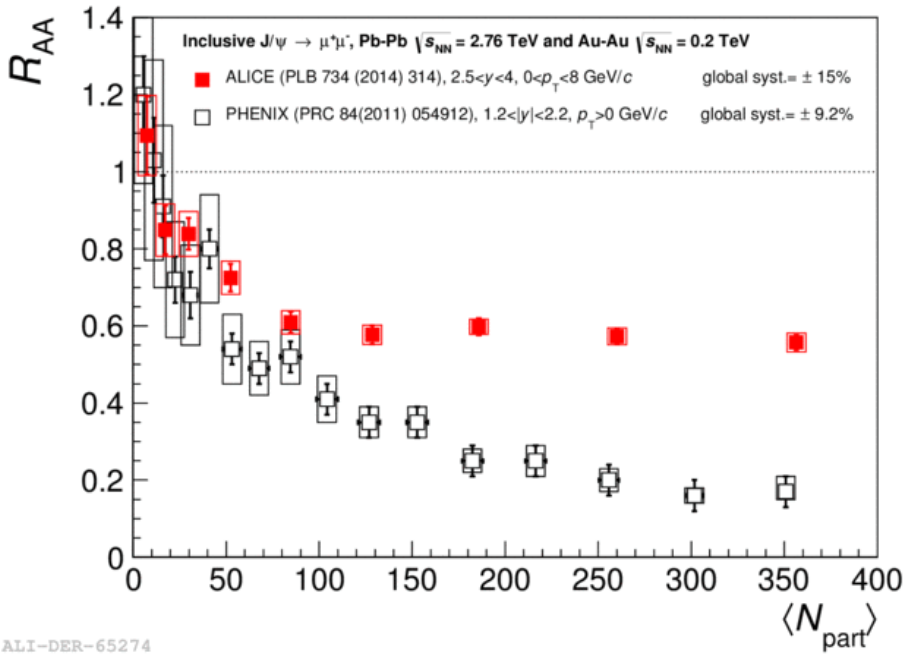
J/ψ suppression vs centrality (2.76 TeV)

ALICE, PLB734 (2014) 314

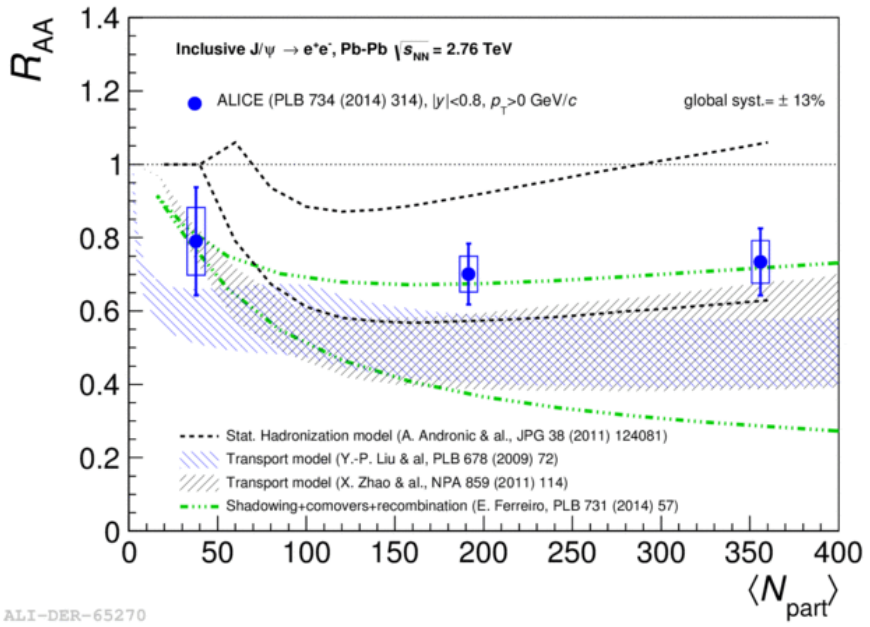


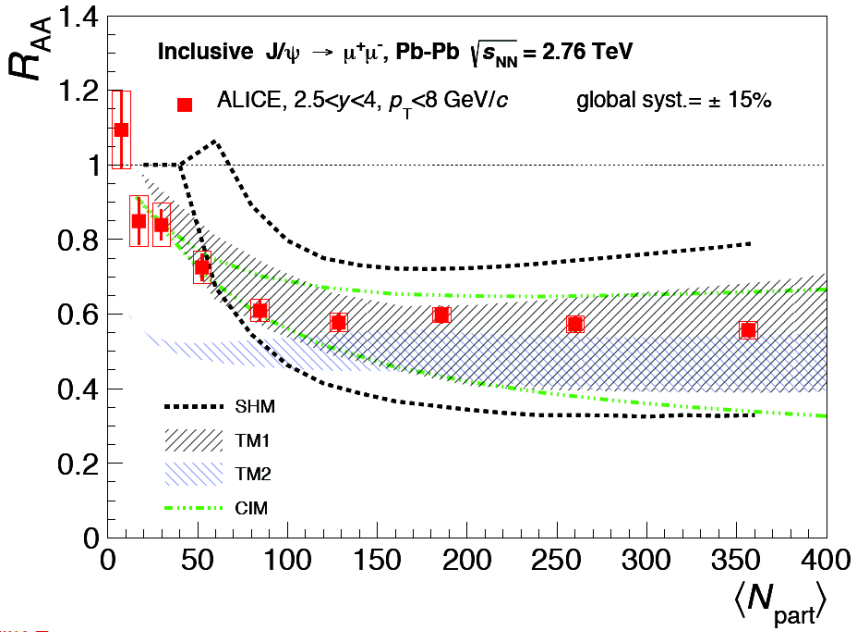


- Much less suppression in central and semi-central collisions wrt to the lower energy measurements
- Indication of a lower suppression at mid-rapidity compared to forward rapidity

J/ψ suppression vs centrality (2.76 TeV)

ALICE, PLB734 (2014) 314



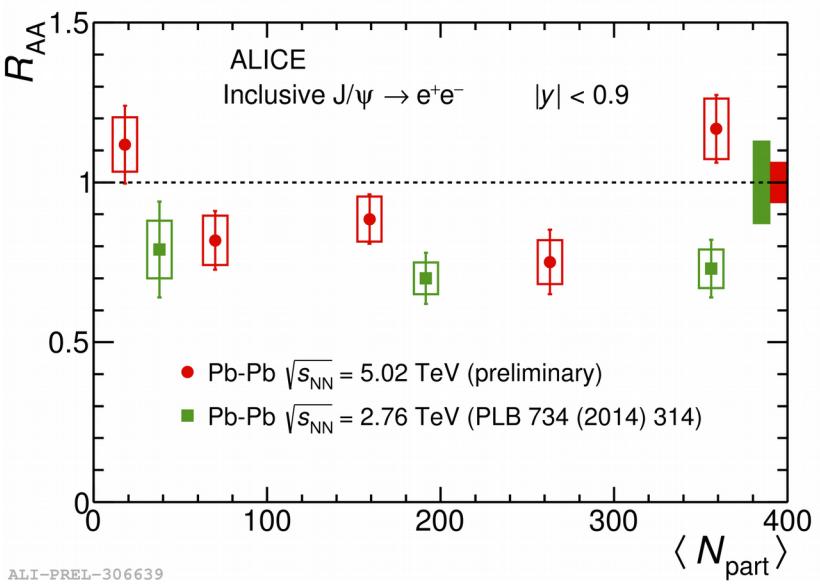


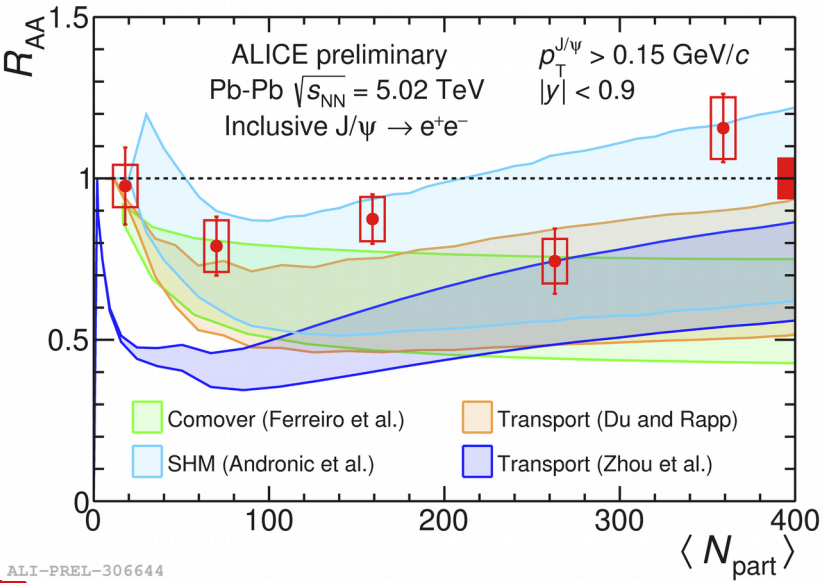
- Models which implement a regeneration component are in agreement with data
- Model uncertainties are dominated by the poor knowledge of the total $c\bar{c}$ cross-section / CNM effects

SHM: A.Andronic et al., JPG38 (2011)12408
TM1: X.Zhao et al.,NPA859 (2011) 114
TM2: Y.-P.Liu et al., PLB578 (2009) 72
CIM: E.Ferreiro, PLB731 (2014) 57

J/ψ R_{AA} in Pb-Pb collisions at 5.02 TeV

ALICE, paper draft in preparation

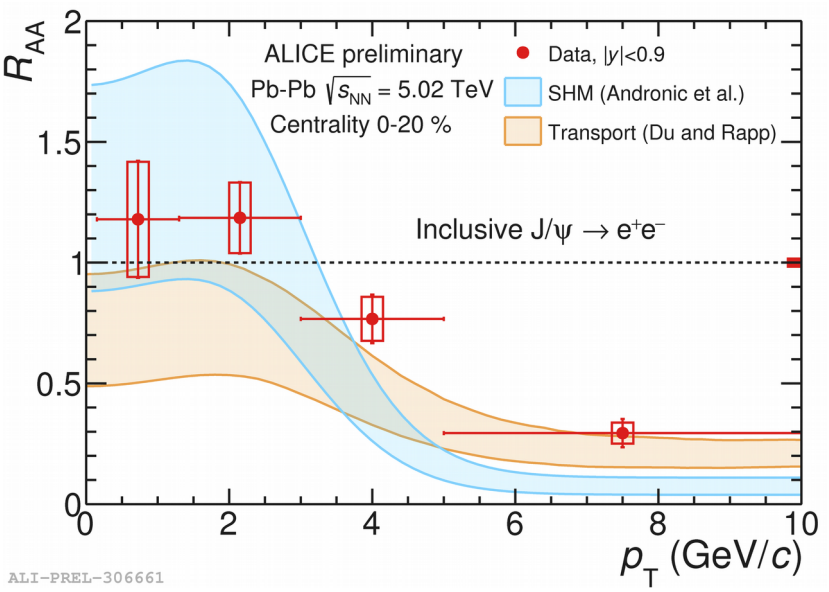


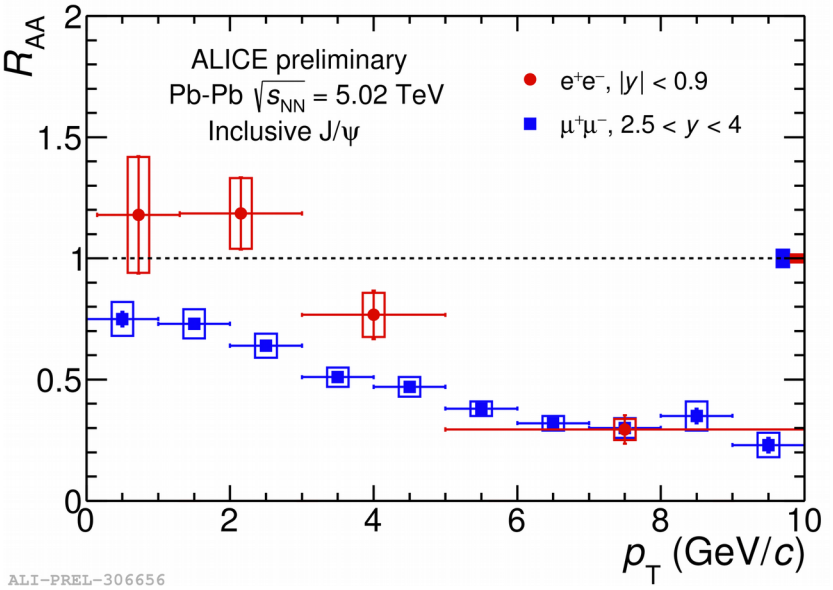


- Analysis done using the 2015 dataset
- Reduced syst uncertainties from the pp reference → measured reference at 5 TeV
- With the current uncertainties, no clear variation of the suppression factor
- Large model uncertainties
- Besides the SHM calculations, all models show tensions with the data

J/ψ R_{AA} in Pb-Pb collisions at 5.02 TeV

ALICE, paper draft in preparation

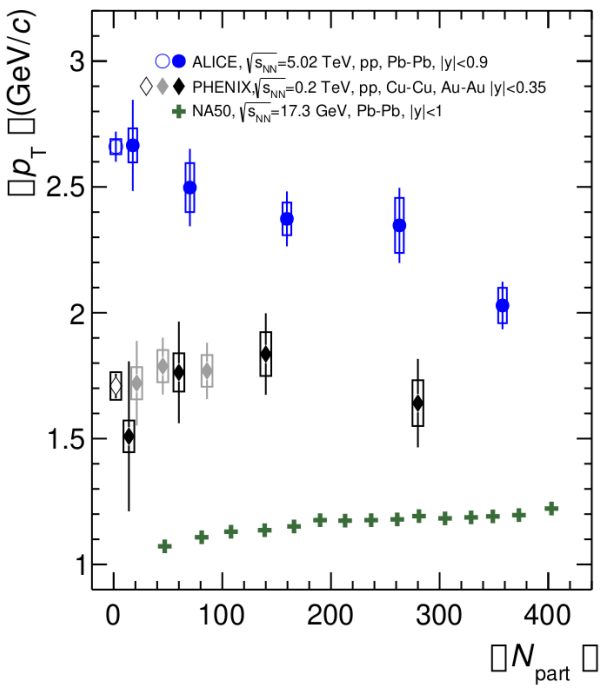


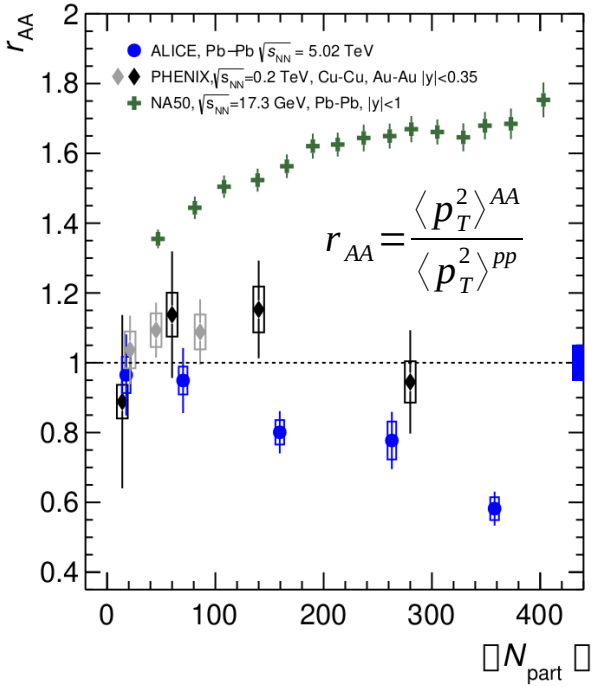


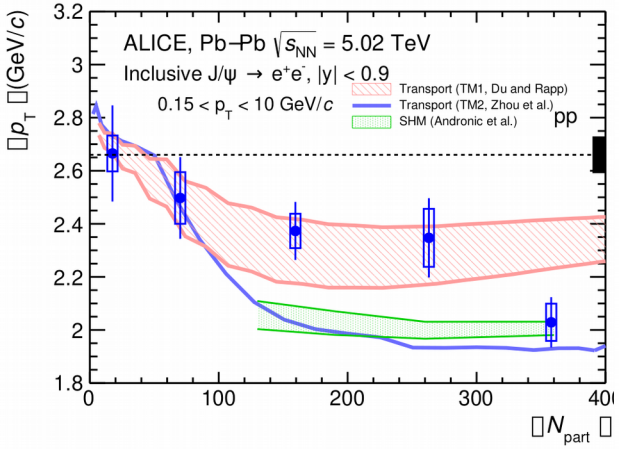
- p_T dependence of the suppression reproduced only qualitatively by models
- SHM uses a blast-wave parameterization of the freeze-out hyper-surface to obtain a p_T spectrum
- Comparison with forward-y results suggests stronger (re)combination effects at mid-y, as expected due to larger σ_{cc}

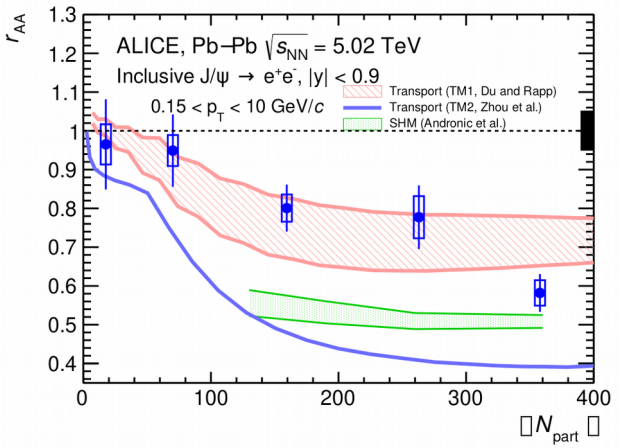
J/ψ <p_T> in Pb-Pb collisions at 5.02 TeV

ALICE, paper draft in preparation







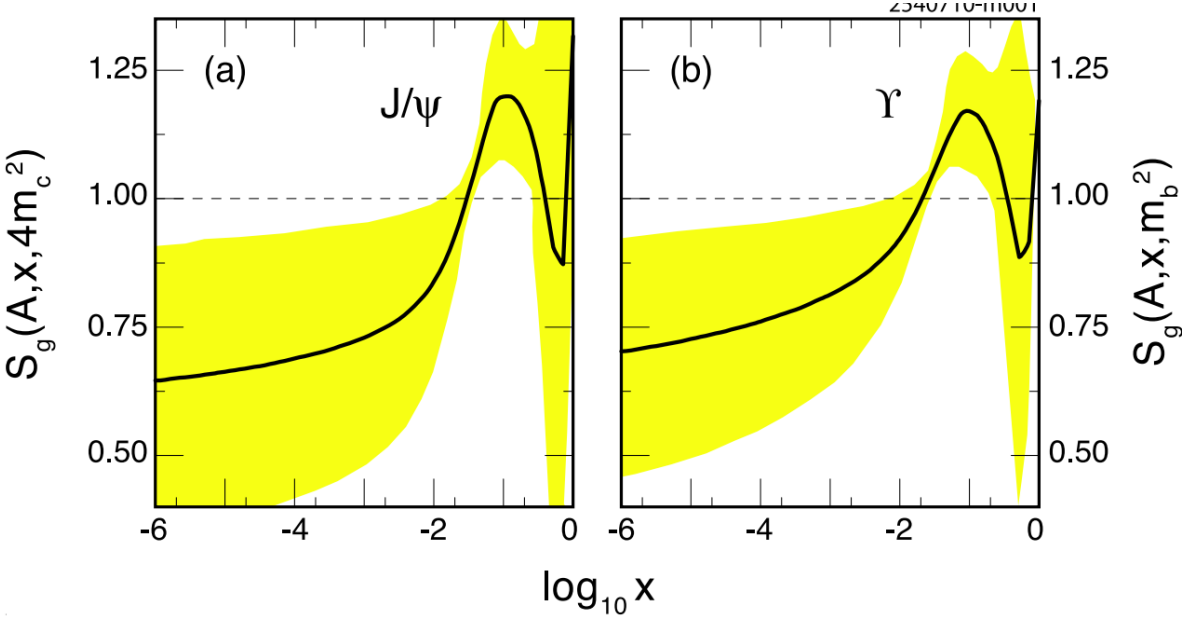


- Very different behaviour of <p_T> and <p_T^2> between SPS, RHIC and LHC
- SPS: Cronin-like increase with centrality
- RHIC: Nearly flat behaviour
- LHC: Drop of both <p_T> and <p_T^2> with centrality
- Drop explained by models via recombination

Cold nuclear matter (CNM) effects

- Modification of the parton PDF in nuclear matter: shadowing and Color Glass Condensate (CGC)

EPS'09



- Other possible CNM effects: coherent energy loss, Cronin, comover interaction
- CNM effects studied using proton-nucleus collisions

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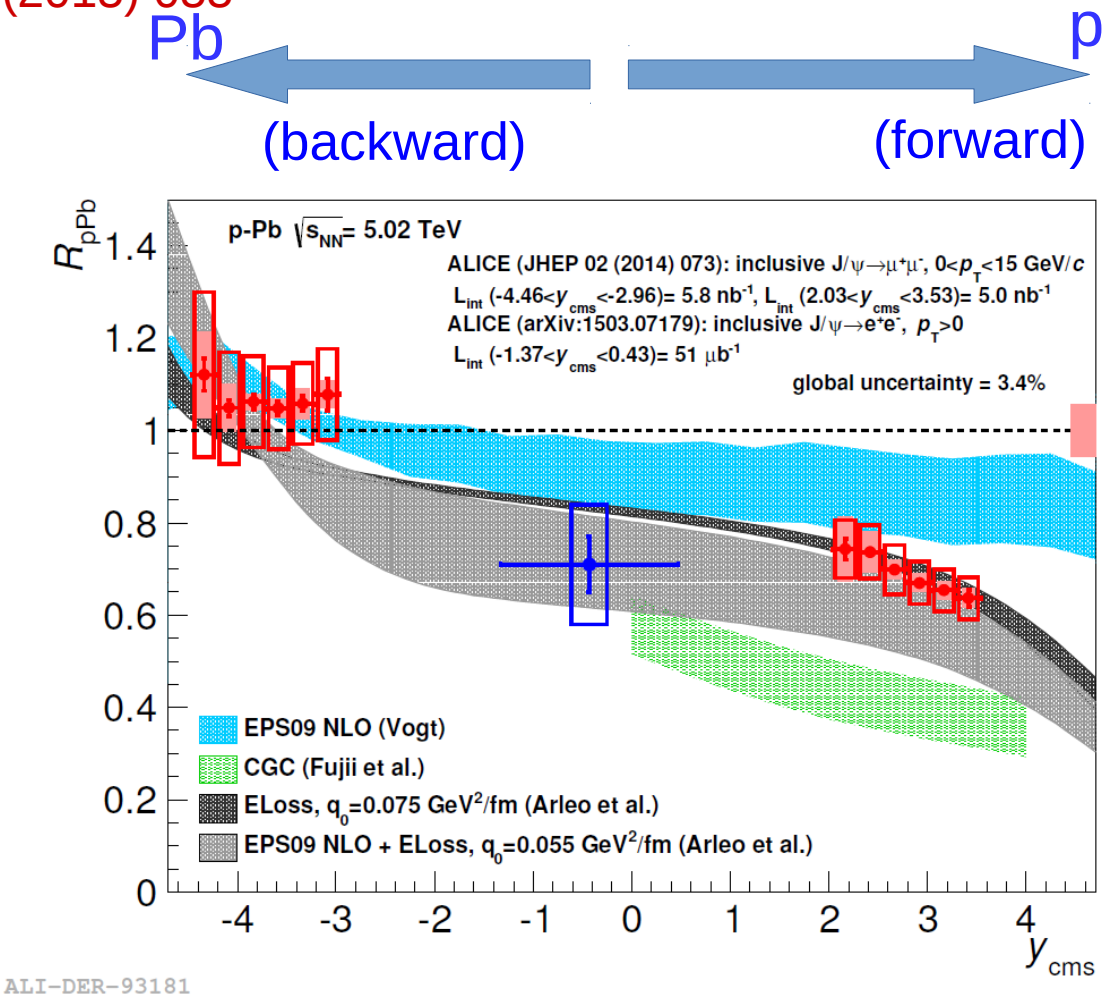
Inclusive J/ψ in p-Pb collisions (Run-1 data)

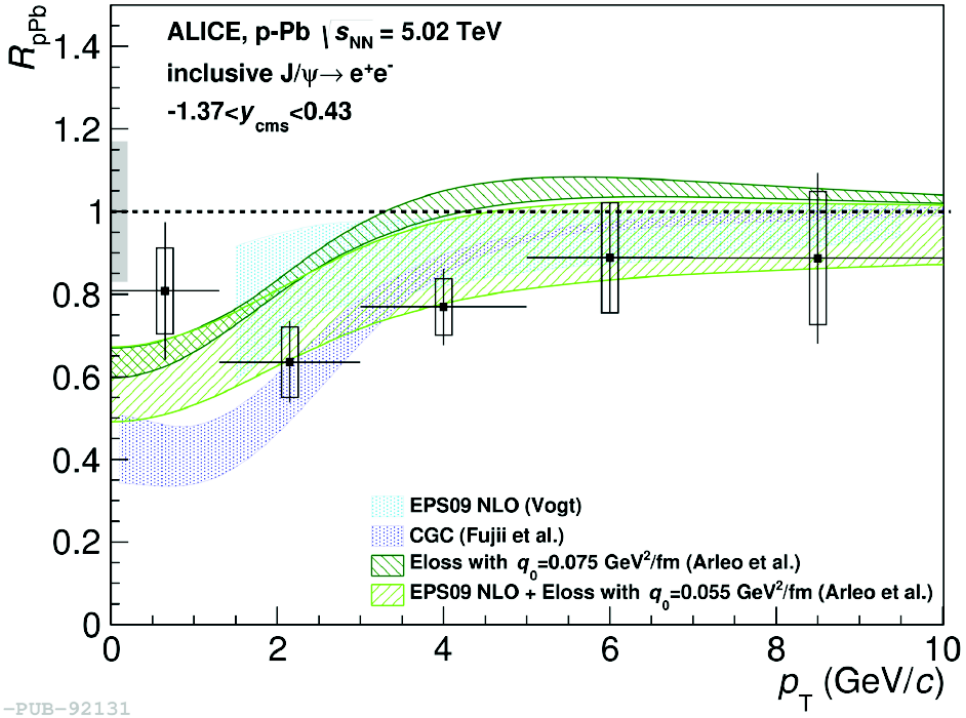
ALICE, JHEP06 (2015) 055

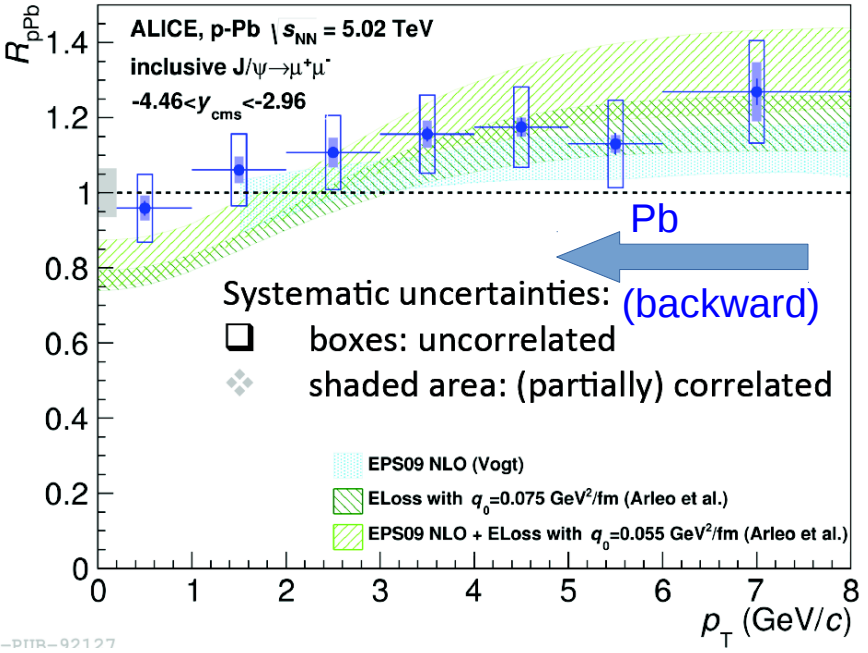


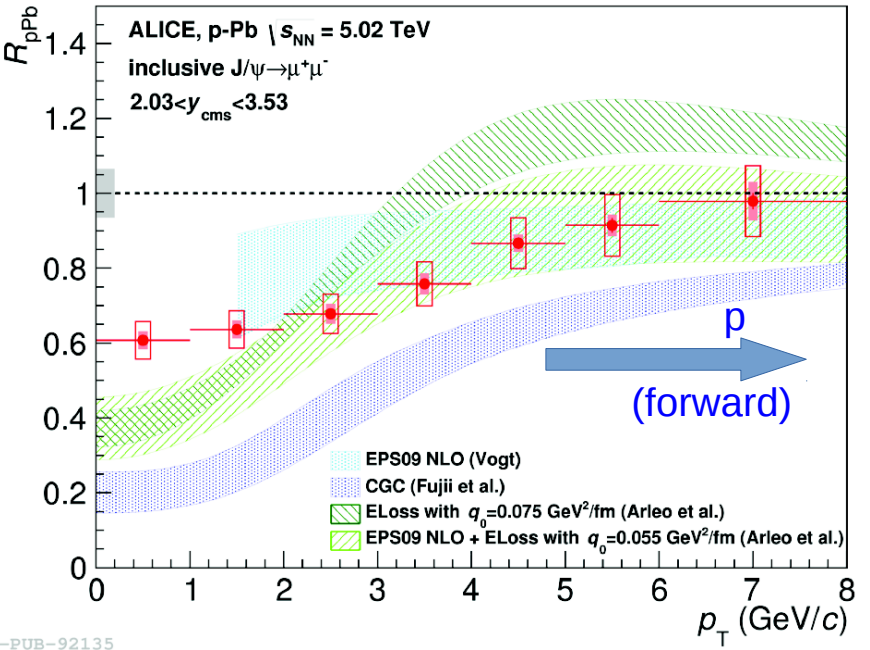
- Mid- and fwd-y:
  - Suppression beyond expectations from pure shadowing
  - Coherent energy loss models in good agreement to the data

Inclusive J/ψ in p-Pb collisions (Run-1 data)

ALICE, JHEP06 (2015) 055





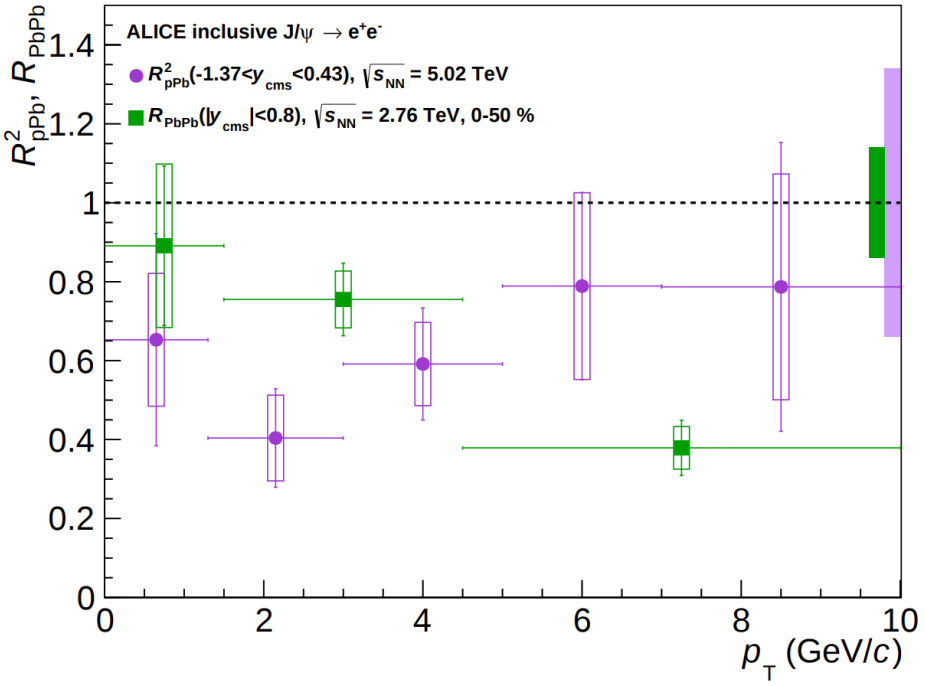


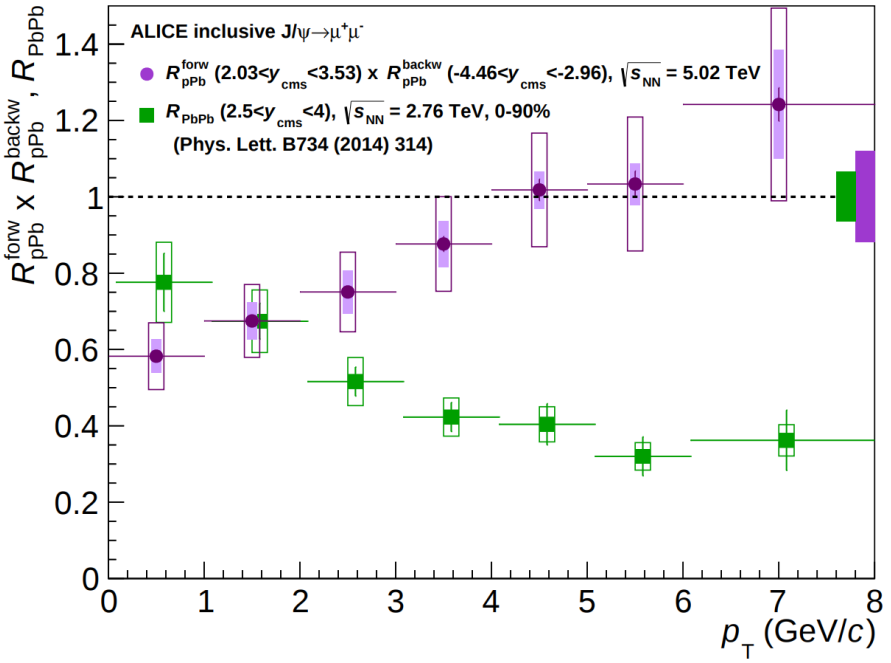
- J/ψ is suppressed at mid- and forward rapidity, except for the highest-p_T region

- Run-2 data + improved pp reference expected to largely improve the mid-y results

J/ψ R_{pA} in p-Pb collisions at 5.02 TeV

ALICE, JHEP06 (2015) 55





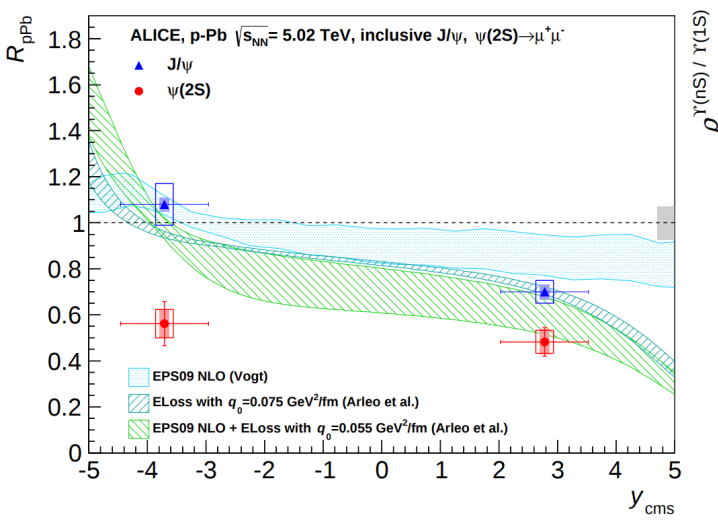
- Crude estimation of CNM effects on R_{AA} assuming
  - Only shadowing
  - Simplified 2→ 1 production kinematics

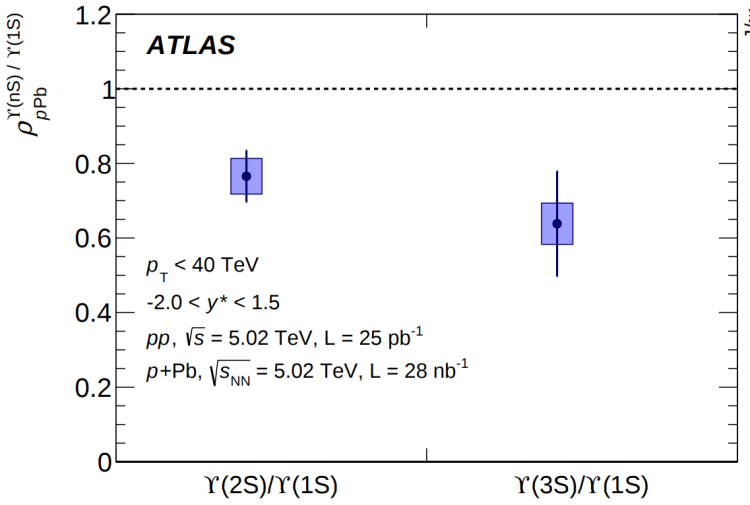
Outlook

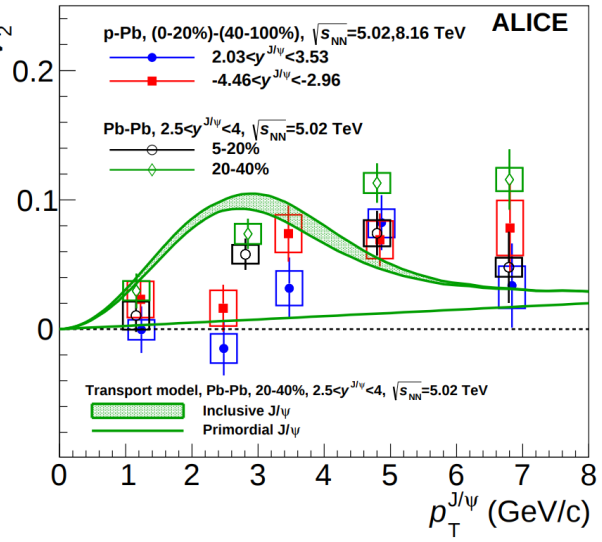
Initial state for quarkonium observables

- Initial state / CNM effects tipically derived from p-Pb collisions, however:

ALICE, JHEP12 (2014) 073





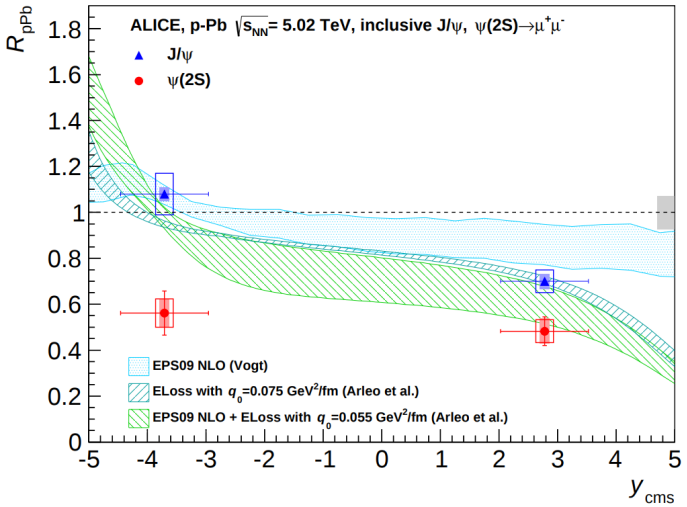


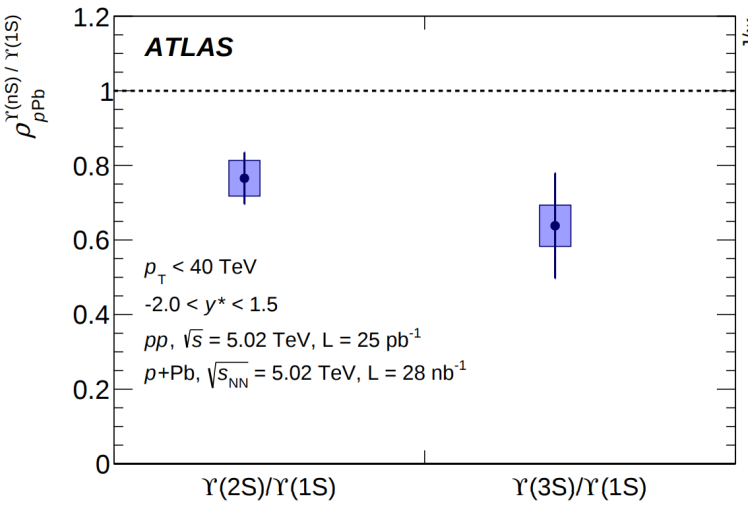
- Higher suppression observed for quarkonium excited states wrt ground states in p-Pb collisions
  - Not expected from nPDF modification or initial state Eloss models
- Long range J/ψ – hadron correlations: hint of collective effects on heavy quarks
- Strong indication that final state effects are present in p-Pb: comovers, QGP droplet?
  - The p-Pb collisions might not be an ideal cold system reference for Pb-Pb observations...

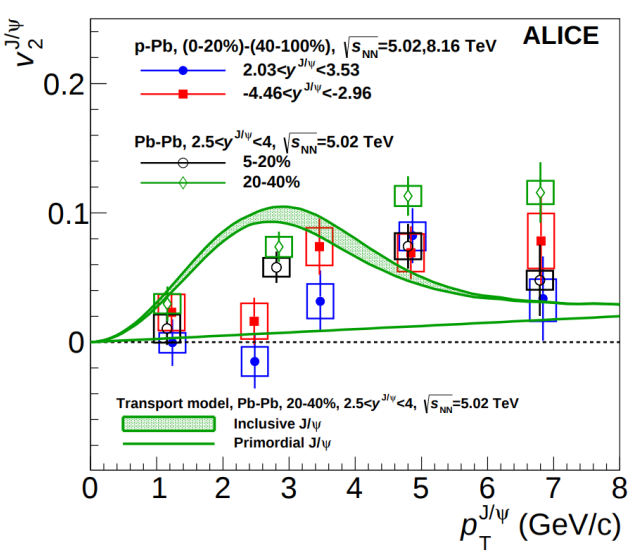
Initial state for quarkonium observables

- Initial state / CNM effects tipically derived from p-Pb collisions, however:

ALICE, JHEP12 (2014) 073







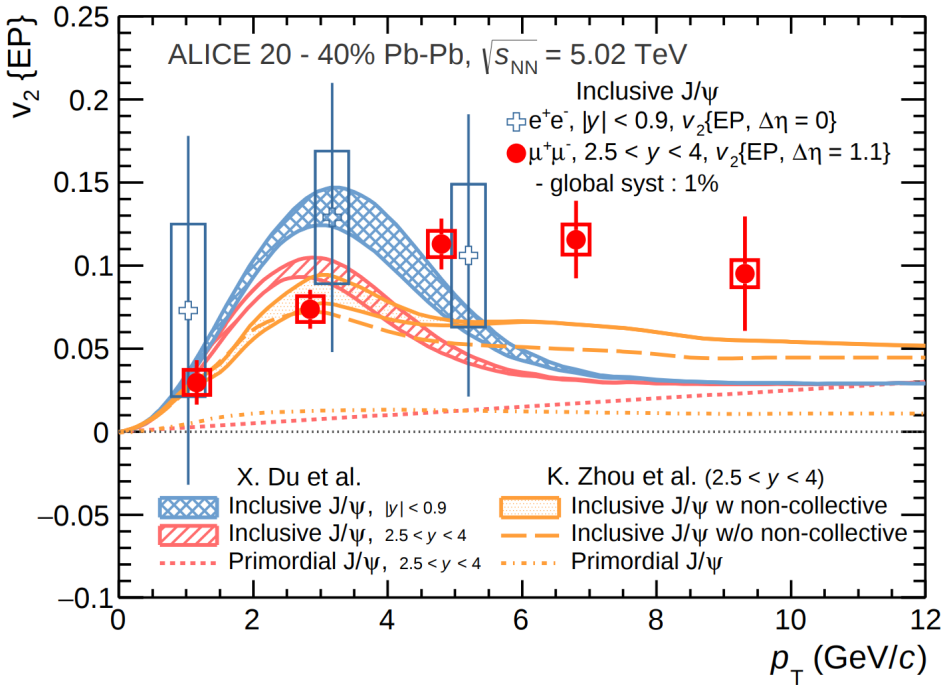
- An alternative method is the measurement of total $c\bar{c}$ and $b\bar{b}$ cross-sections in Pb-Pb via
  - open-charm hadrons down to zero p_T (D mesons but also charm baryons)
  - non-prompt J/ψ,
  - low mass di-leptons, heavy flavor leptons

Hot medium effects

- Higher precision on “standard” measurements like the p_T spectra, elliptic flow v_2
- Prompt and non-prompt J/ψ measurements
- Measurement of v_2 as a function of the event shape (ESE)
- Higher flow harmonics
- Excited charmonia: ψ(2S), χ_c

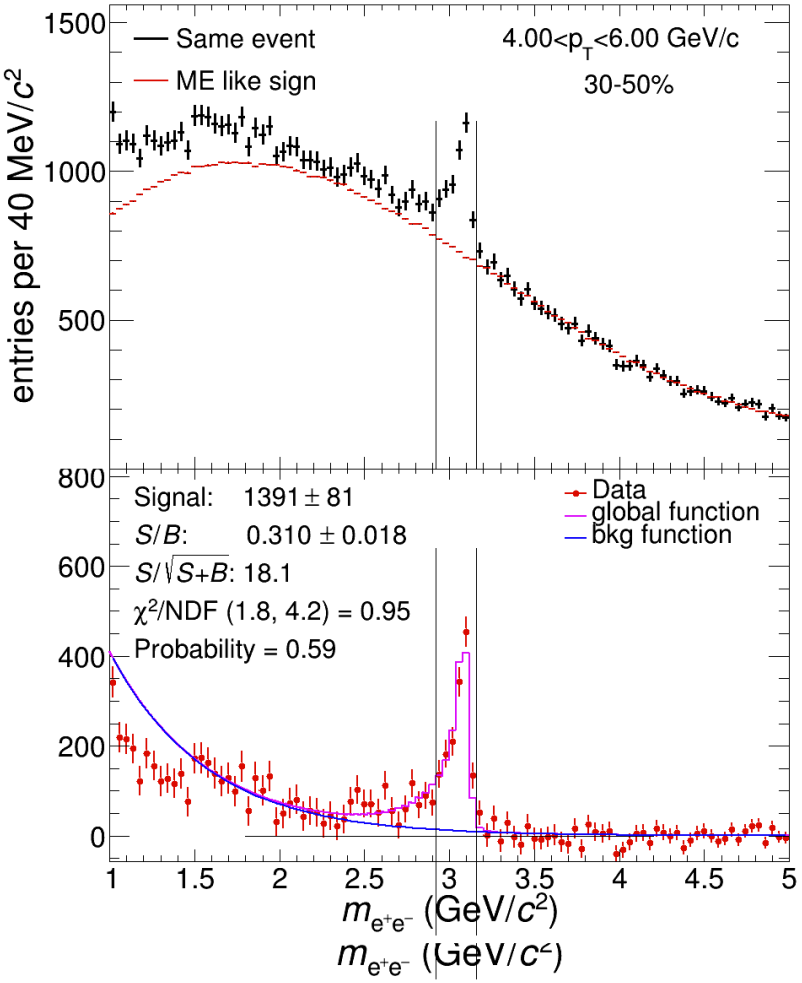
J/ψ elliptic flow in semi-central Pb-Pb collisions

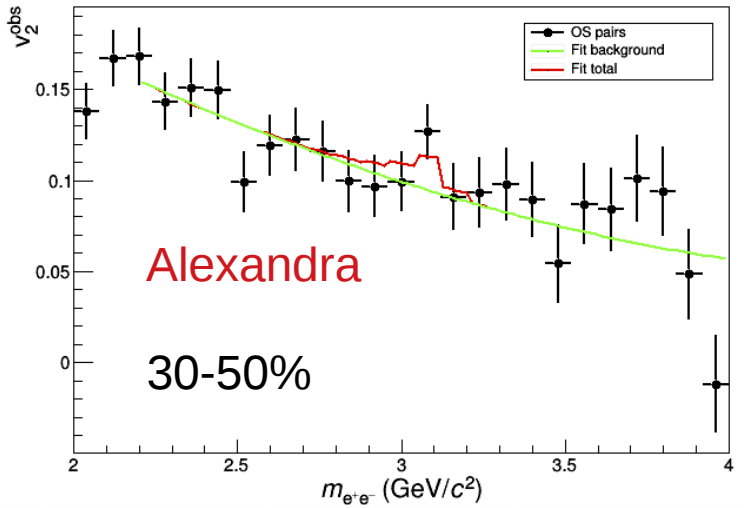
ALICE, PRL119 (2017) 242301

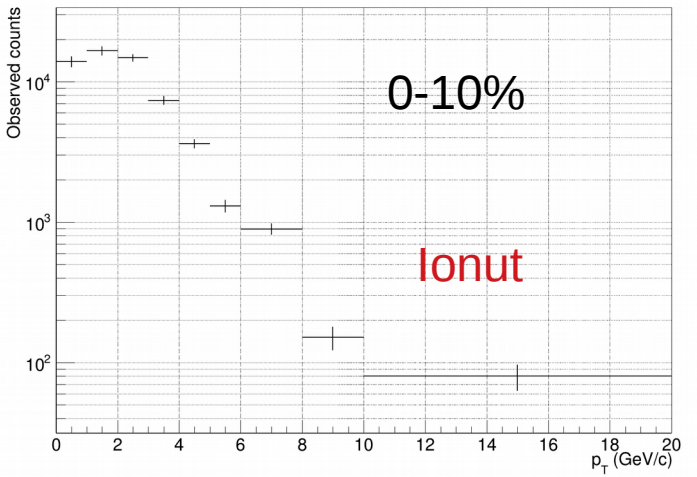


- Significant J/ψ elliptic flow observed at forward rapidity using the MUON arm
- Large v_2 even at high p_T, not described in transport models!
- Insufficient statistics for a similar measurement at mid-y with 2015 data

Run2(2018): J/ψ elliptic flow in semi-central Pb-Pb collisions



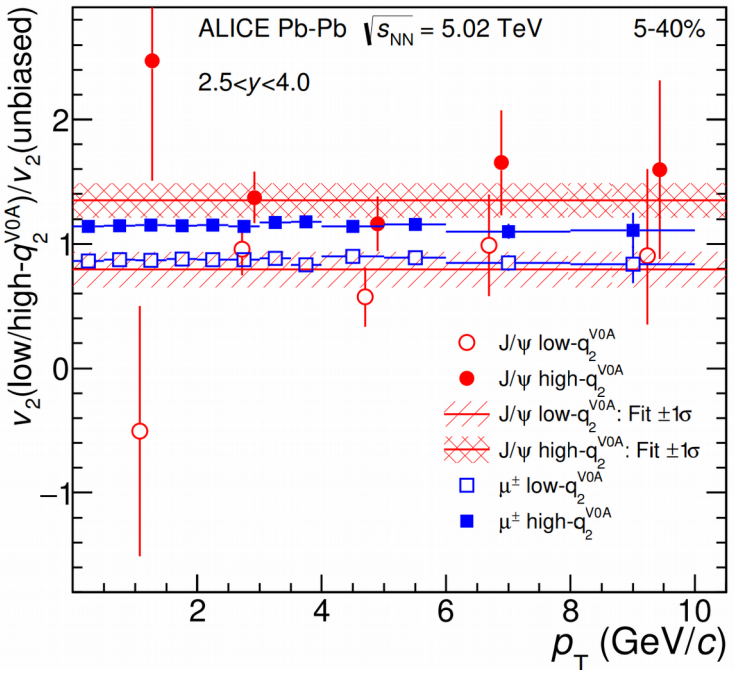




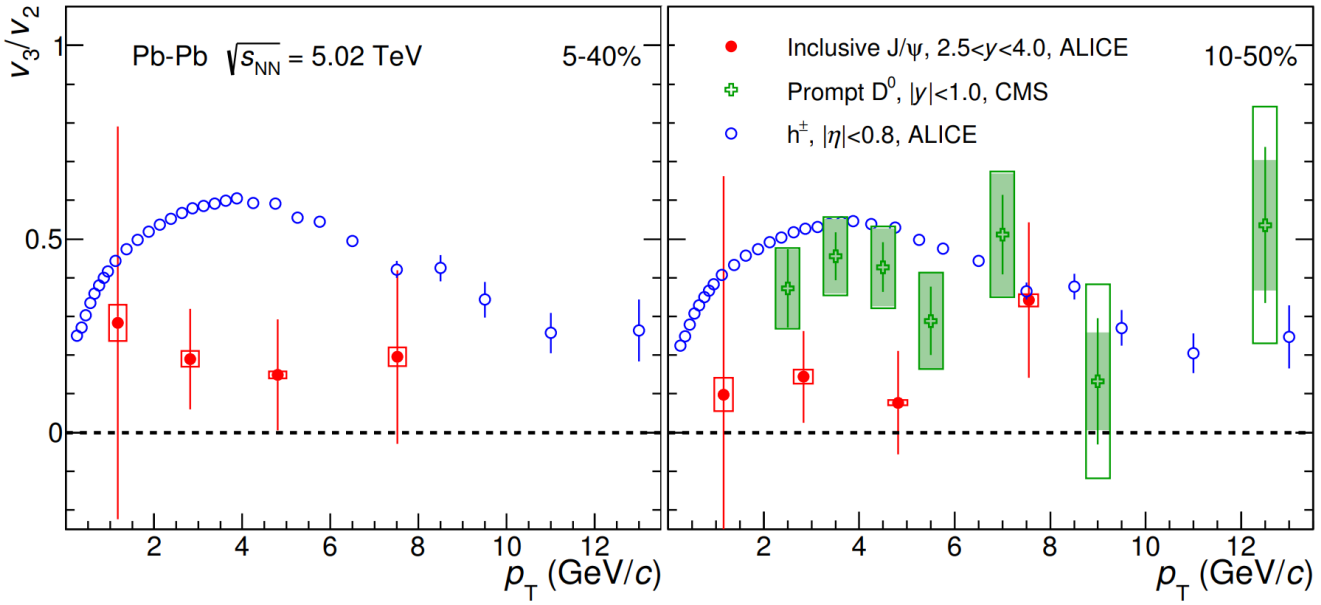
- The 2018 Pb-Pb dataset provides an ~9x increase in statistics for central collisions and ~4x for semi-central collisions
  - Precise R_{AA} vs p_T in central collisions
  - Elliptic flow measurement in semi-central collisions

Run3+4: J/ψ triangular flow and event shape engineering

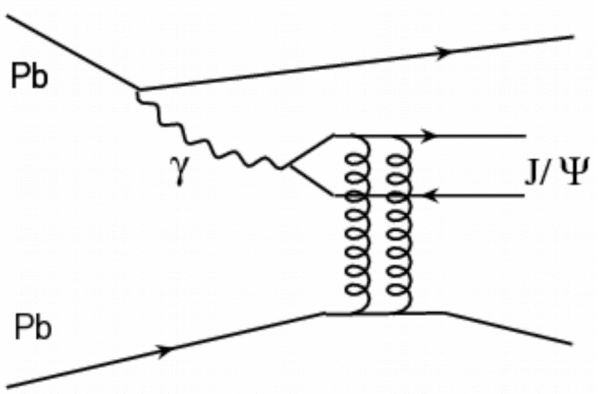
ALICE, arXiv: 1811.12727



- J/ψ v_2 as a function of event shape
  - Indication that heavy quarks flow together with the bulk
- Triangular flow
  - Provide information on the dynamics of the charm hadron production

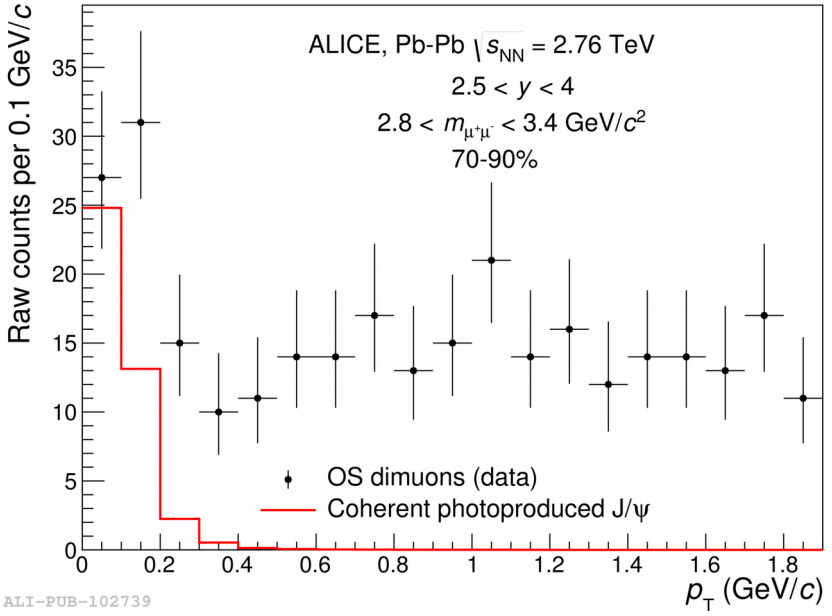


J/ψ photo-production in Pb-Pb collisions with b<2R



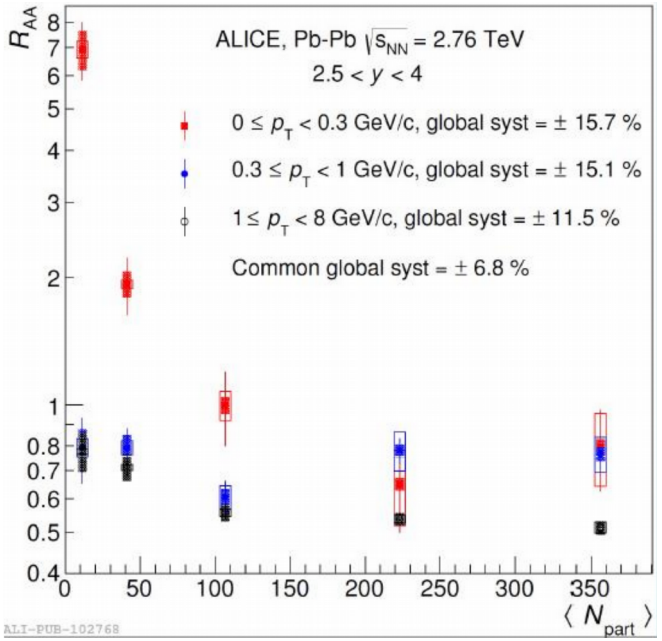
$$\frac{d\sigma}{dy} = k_1 \times \frac{dn}{dk_1} \times \sigma_{\gamma+A_2 \to J/\psi+A_2} + k_2 \times \frac{dn}{dk_2} \times \sigma_{\gamma+A_1 \to J/\psi+A_1}$$

ALICE, PRL116 (2016)222301



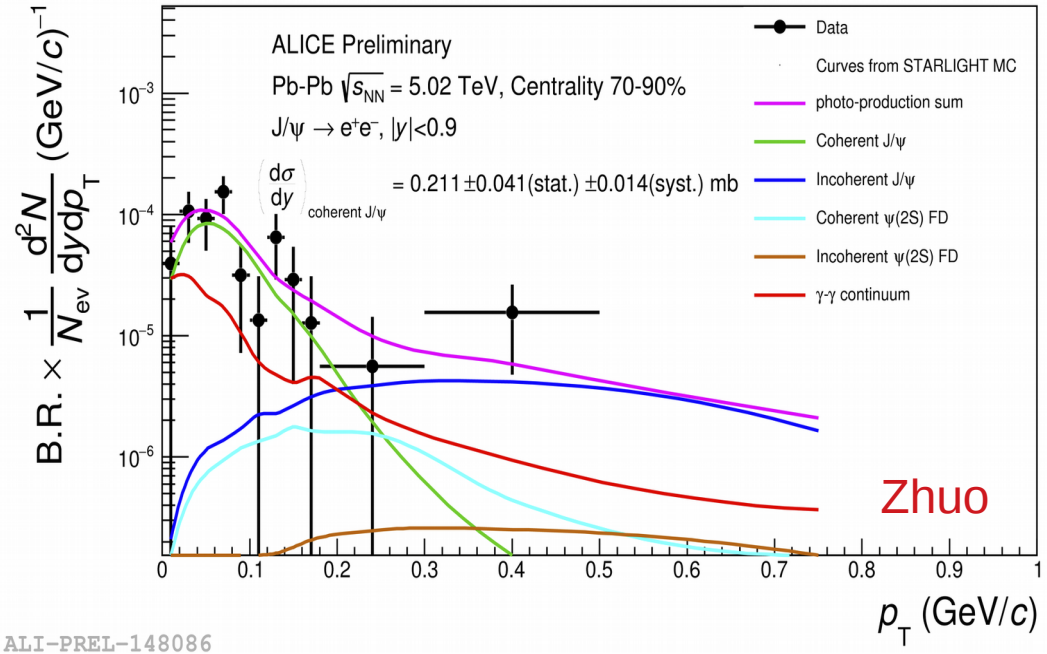
- J/ψ excess observed at very low-p_T (pT<300 MeV) at forward rapidity in peripheral Pb-Pb collisions at 2.76 TeV

- Likely origin: coherent photo-production



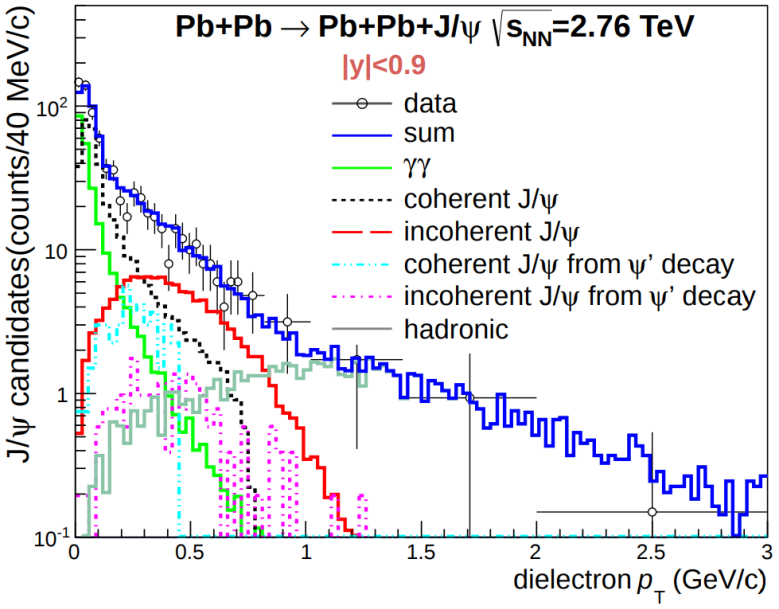
J/ψ photo-production in Pb-Pb collisions with b<2R

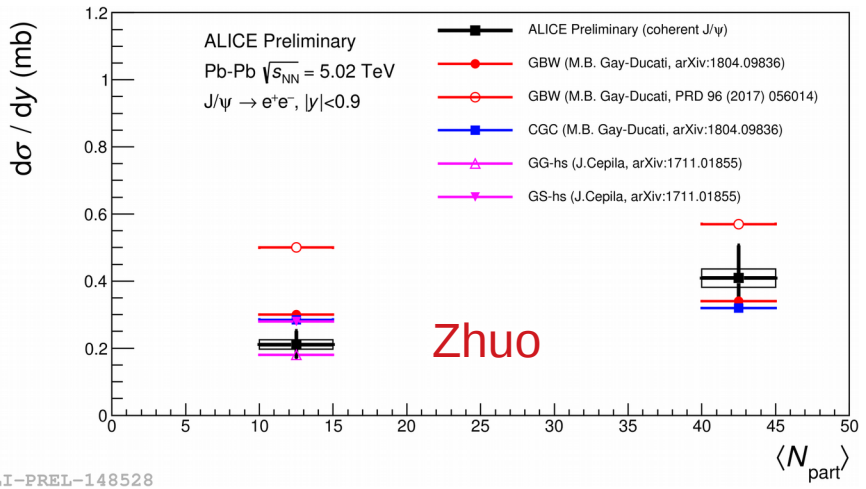
Mid-y (70-90%)



ALI-PREL-148086

(ultra-peripheral)





ALI-PREL-148528

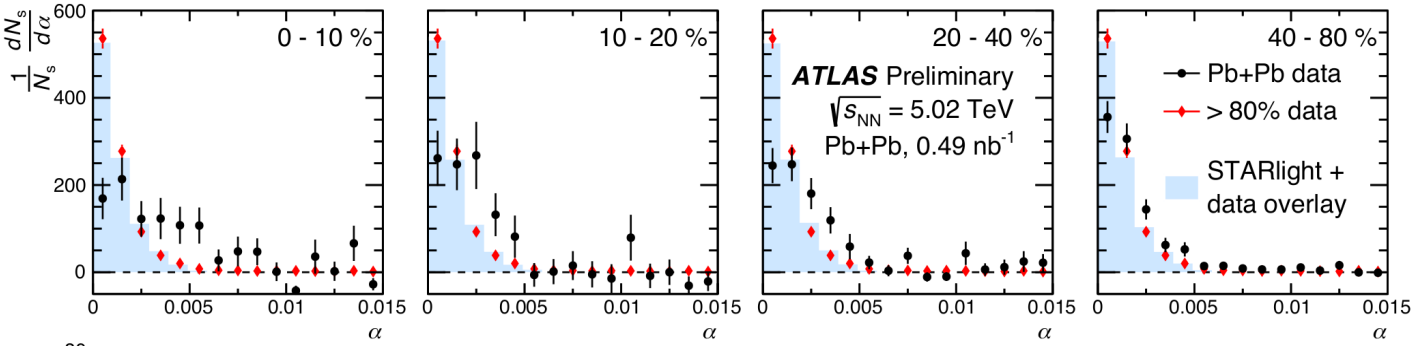
- Excess present also at mid-y using Pb-Pb data (2015) at 5.02 TeV
- Characteristic p_T spectrum for photo-production, as also observed in ultra-peripheral collisions (UPC)
- Plan to improve these results with 2018 and Run-3+4 data

Vector meson production in electromagnetic interactions

- Unique opportunity for photo-nuclear physics:
  - reaction plane dependent measurements
  - Impact parameter dependence

  W. Zha, S.Klein et al., PRC97 (2018) 044910

- Hadronic physics: novel “probe” of the fireball?



- Sensitivity to nuclear PDFs ?
  - LO: Ryskin 1993,
  - *NLO: S.P.Jones et al., J.Phys.G43 (2016) 035002*

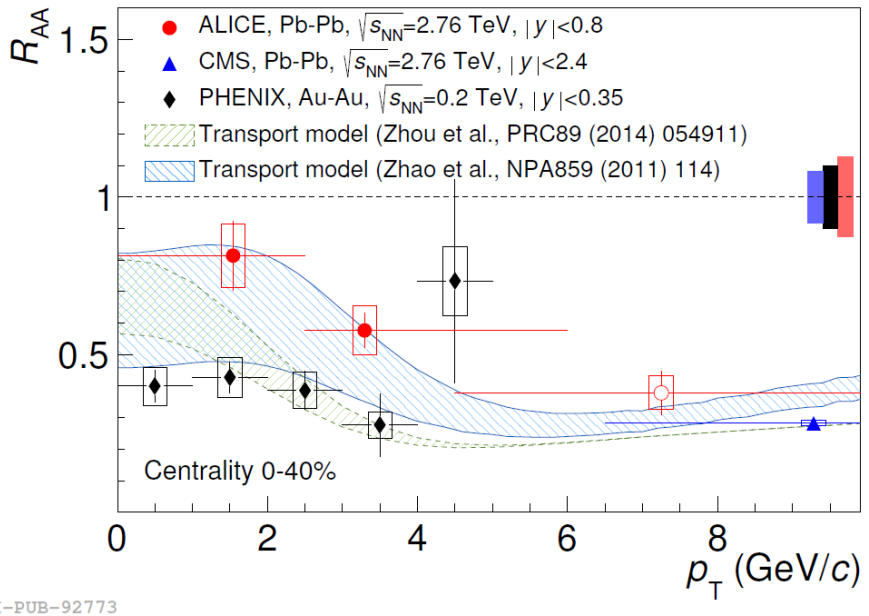
Overview of contributions

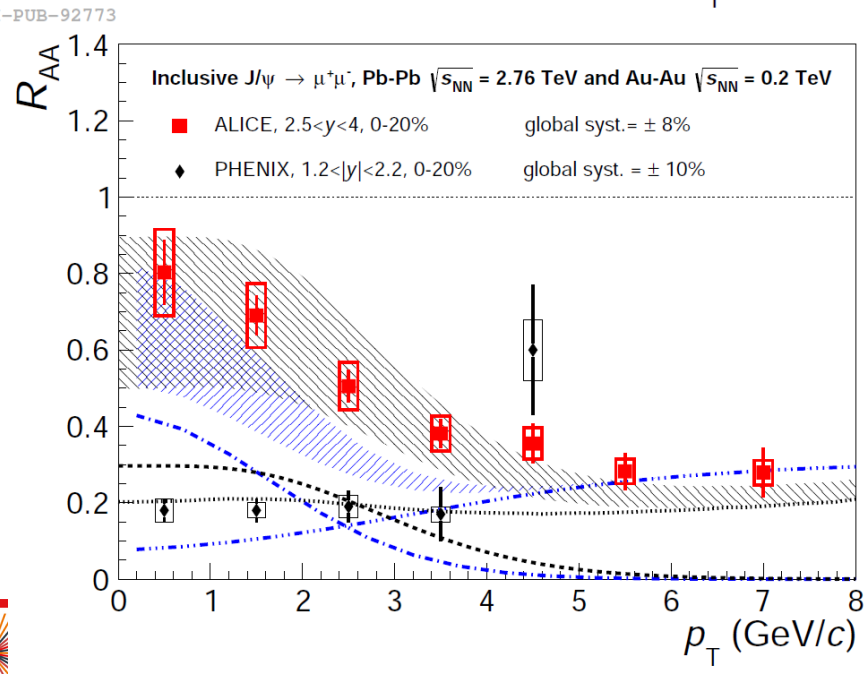
- Run-1 (published analyses)
  - Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV
    - Inclusive, prompt and non-prompt J/ψ R_{AA}
    - Elliptic flow of φ-meson
    - Kaon femtoscopy
  - p-Pb at $\sqrt{s_{NN}}$=5.02 TeV
    - Rapidity, p_T and centrality dependence of inclusive J/ψ R_{pA}
- Run-2
  - Pb-Pb at $\sqrt{s_{NN}}$=5.02 TeV
    - Inclusive J/ψ R_{AA} (2015 dataset); paper in preparation (aim to publish before QM'19)
    - Coherent photo-production of J/ψ in peripheral collisions; paper to be proposed after QM'19
    - Inclusive J/ψ R_{AA} (2018 dataset); analysis ongoing
    - J/ψ elliptic flow in semi-central Pb-Pb collisions; analysis ongoing
  - Xe-Xe at $\sqrt{s_{NN}}$=5.44 TeV
    - Inclusive J/ψ R_{AA}; preliminary results approved

Backup

J/ψ suppression vs p_T

ALICE, JHEP07 (2015) 051

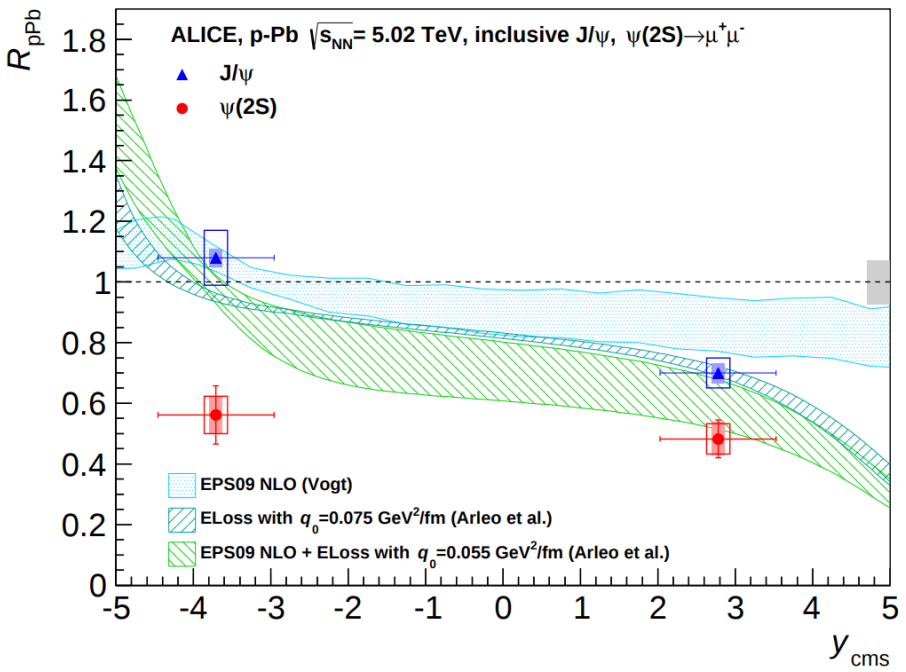




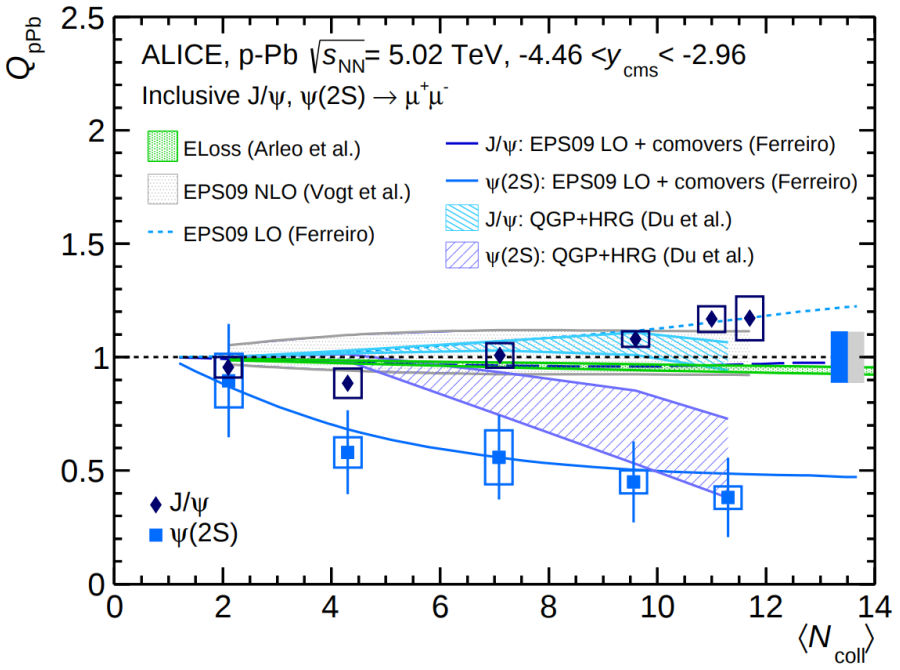
- Low p_T : striking difference between LHC and RHIC
- Quite clear support for (re)generation hypothesis
- Transport model calculations using regeneration describe qualitatively the data

ψ(2S) production in p-Pb collisions

ALICE, JHEP12 (2014) 073



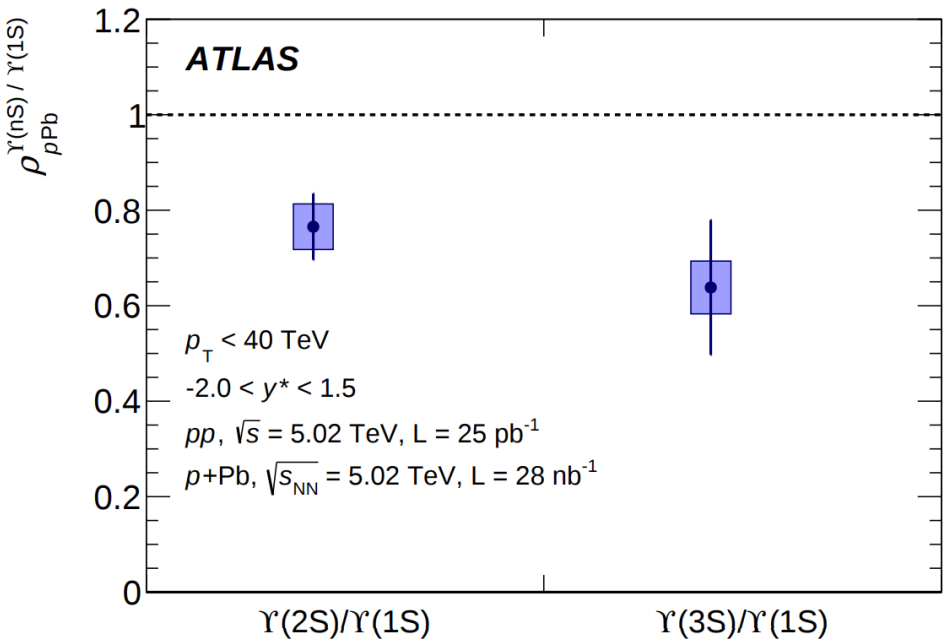
ALICE, JHEP06 (2016) 50

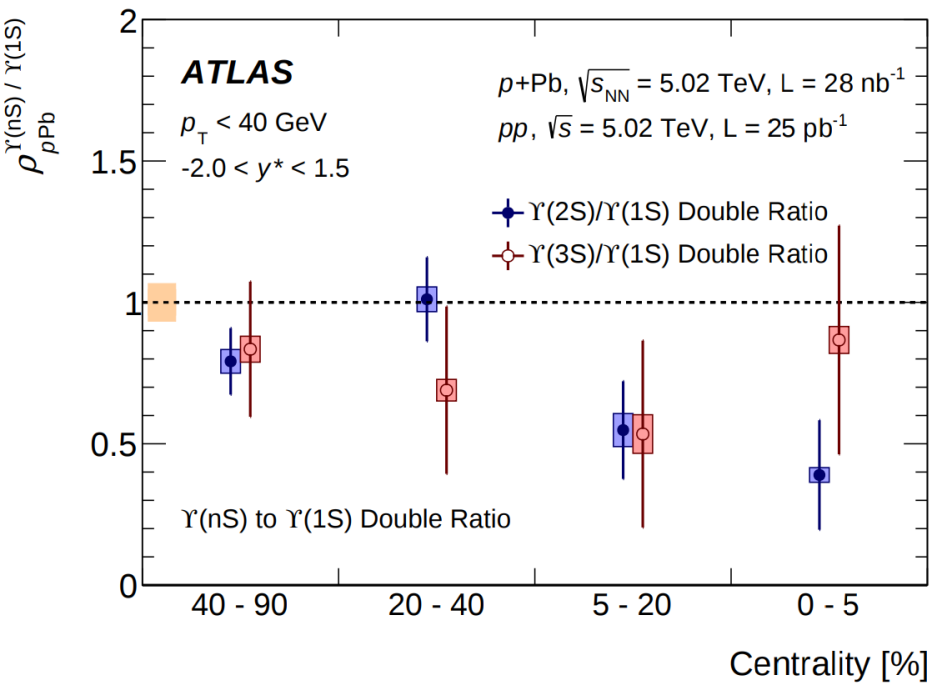


- Higher suppression for ψ(2S) wrt J/ψ in p-Pb collisions
  - Not expected from nPDF modification or initial state Eloss models
- Strong indication that final state effects are present in p-Pb
  - Comover interaction, QGP

Y(2S) and Y(3S) production in p-Pb collisions

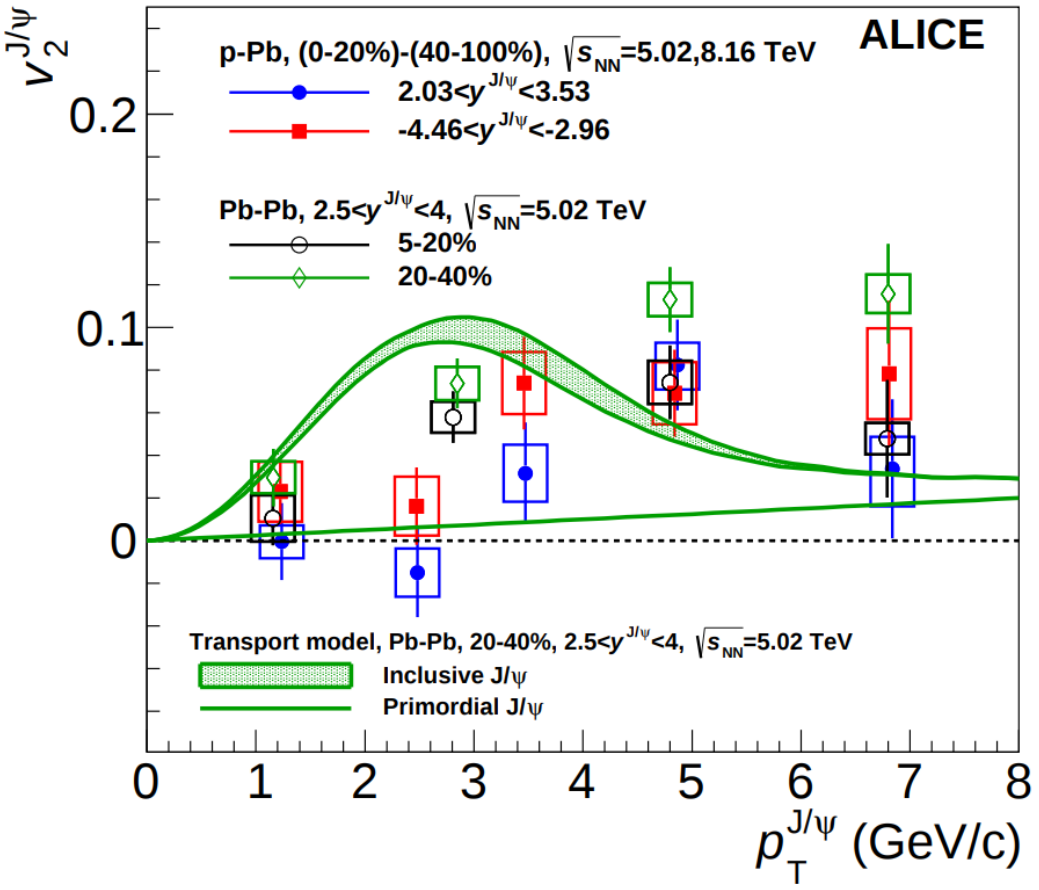
ATLAS, EPJC78 (2018) 171





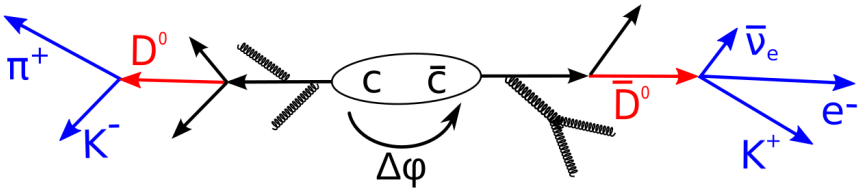
- Excited Y states are also more suppressed wrt ground state
- *Nota bene*: Y(2S) binding energy is similar to J/ψ

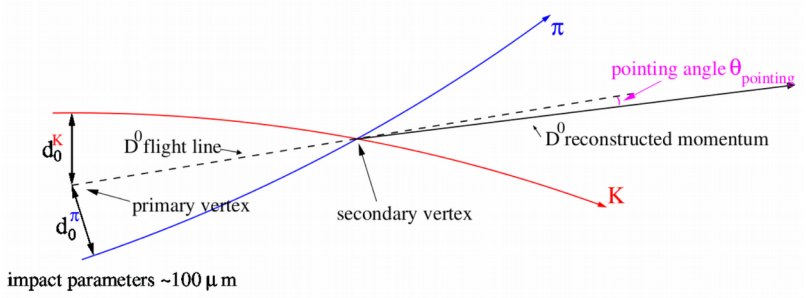
J/ψ elliptic flow in p-Pb collisions at fwd-y

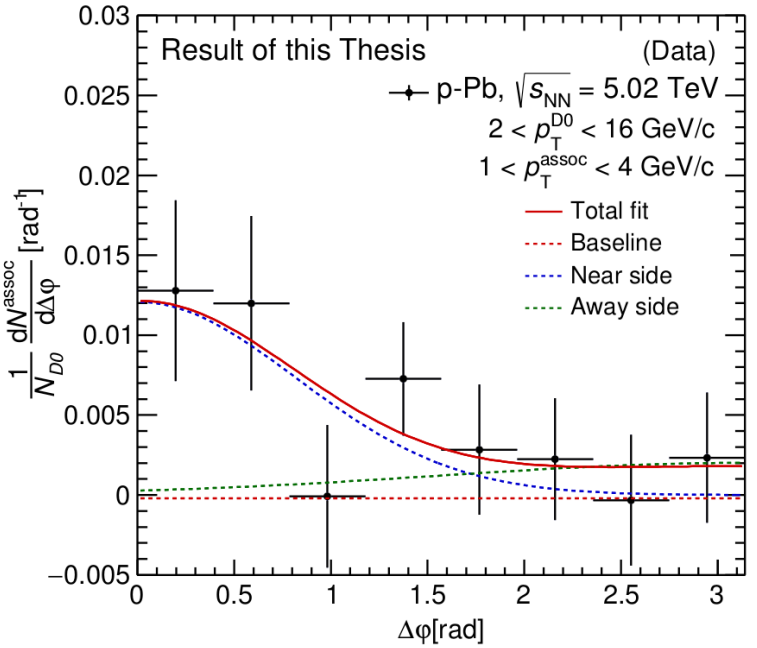


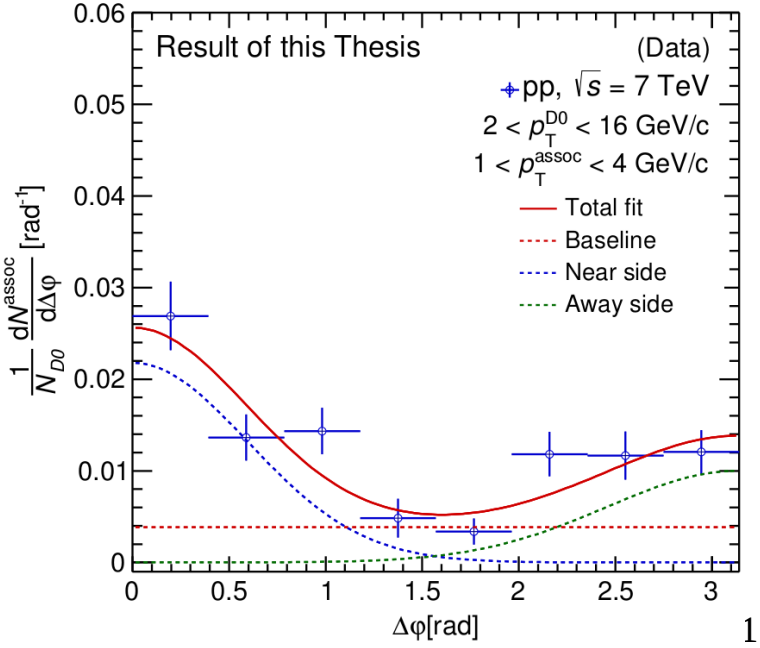
- Non-zero elliptic flow suggest collective effects

D⁰-e correlations in p-Pb and pp collisions





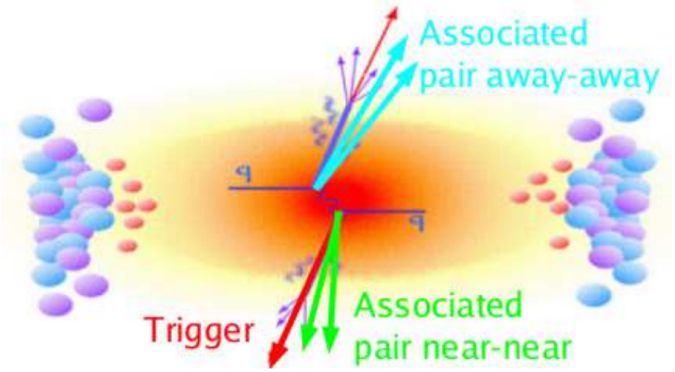


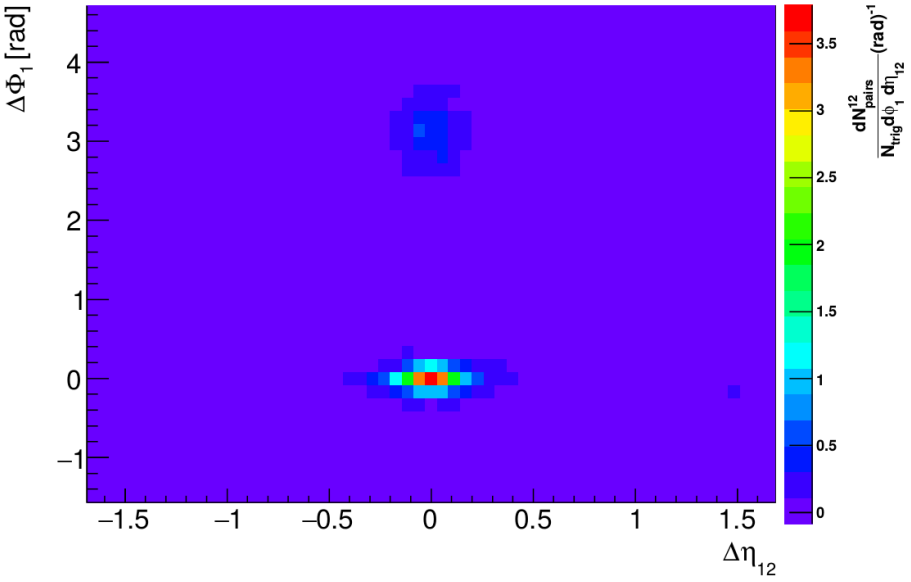


- D⁰-e correlations employed to constrain heavy quark production and fragmentation models
- D⁰ reconstructed employing the measurement of the secondary decay vertex
- Results using Run-1 data affected by large statistical uncertainties

Per-Ivar Lonne

3-particle correlations in Pb-Pb and pp collisions



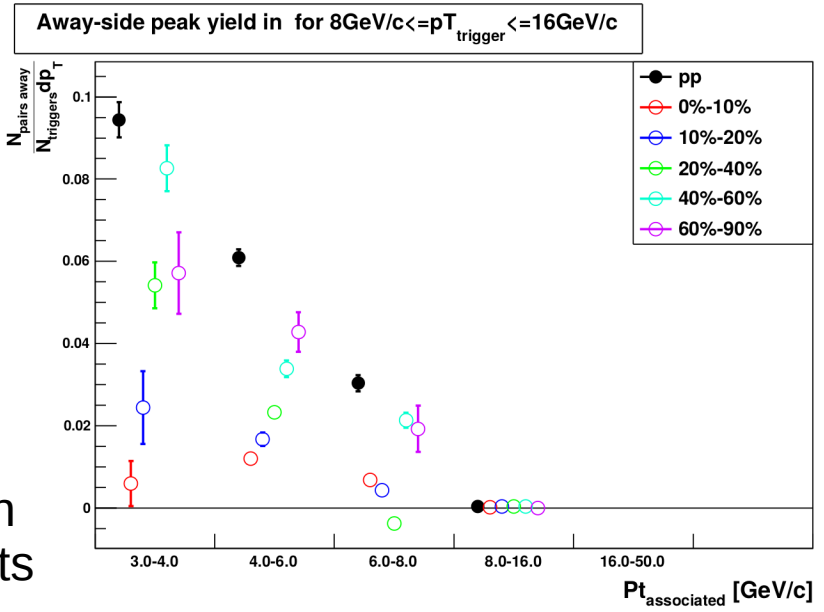


$$\Delta\phi_1 = \phi_{trigger} - \phi_{assoc,1}$$

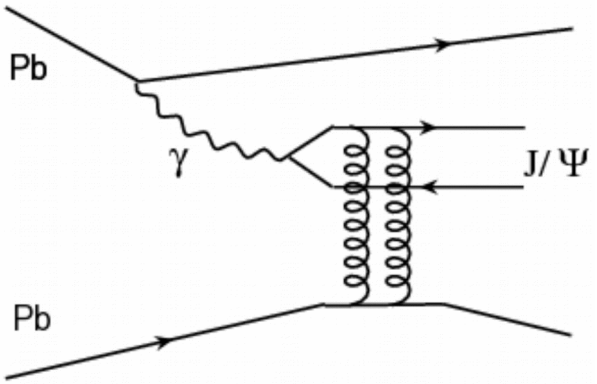
$$\Delta\phi_2 = \phi_{trigger} - \phi_{assoc,2}$$

$$\Delta\eta_{12} = \eta_{assoc,1} - \eta_{assoc,2}$$

- Study in-medium jet fragmentation using 3-particle correlations between
  - leading particle (trigger)
  - 2 associated particles
- Method allows for a good isolation of the away side peak
- Results consistent with the 2-particle correlation results and observations for fully reconstructed jets



Vector meson production in electromagnetic interactions



$$\frac{d\sigma}{dy} = k_1 \times \frac{dn}{dk_1} \times \sigma_{\gamma+A_2 \to J/\psi+A_2} + k_2 \times \frac{dn}{dk_2} \times \sigma_{\gamma+A_1 \to J/\psi+A_1}$$

$$\frac{d\sigma}{dt}\Big|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 \left[xg\left(x, \frac{M_V^2}{4}\right)\right]^2$$

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  W. Zha, S.Klein et al., PRC97 (2018) 044910

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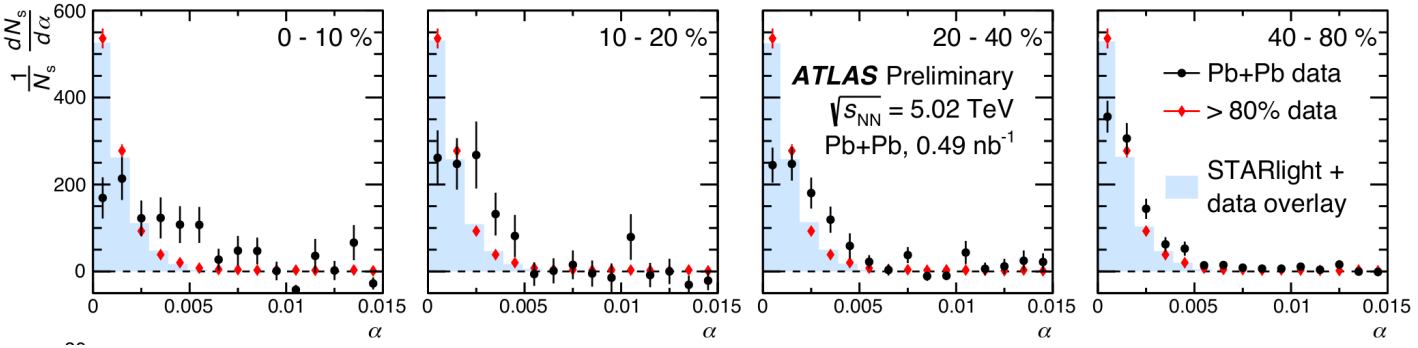

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ALICE