J/ψ production measurements in pp, p-Pb and Pb-Pb collisions at mid-rapidity using the ALICE detector at the LHC

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The 18th International Conference on Strangeness in Quark Matter
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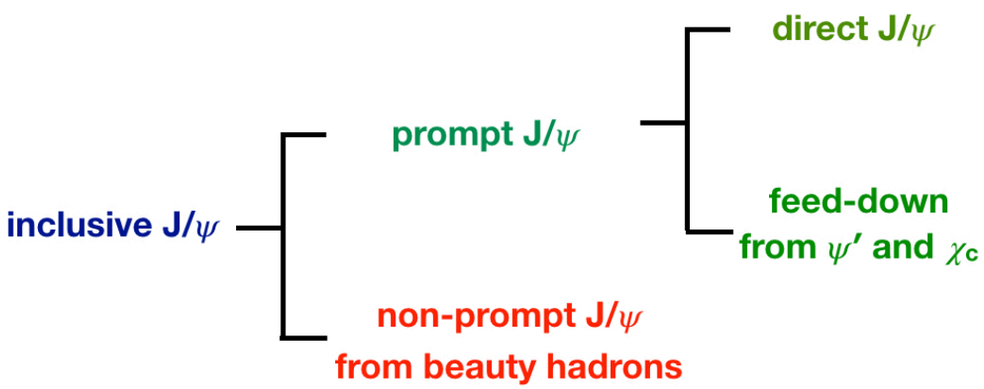
J/ψ production in heavy-ion collisions

- **Heavy quarks (charm and beauty):**
  Large mass → produced in the early stages of the HI collision with short formation time
  ➡ natural probe of the hot and dense medium created in HI collisions

- **Measurement of J/ψ production:**
  - Initial idea: suppression of J/ψ production due to colour screening and sequential melting of quarkonia
    → charmonium as thermometer of QGP
    Matsui and Satz, PLB 178 (1986) 416
    Karsch et al., PLB 637 (2006) 75
  - At LHC energies : with larger $c\bar{c}$ cross section, (re)generation of charmonium and charmed hadron production take place at the phase boundary or in QGP?
    → direct probe of charm quark thermalisation in QGP
    P. Braun-Muzinger, J. Stachel, PLB 490(2000)196
    R. L. Thews, M. Schroedter, J. Rafelski, PRC 63 (2001) 054905

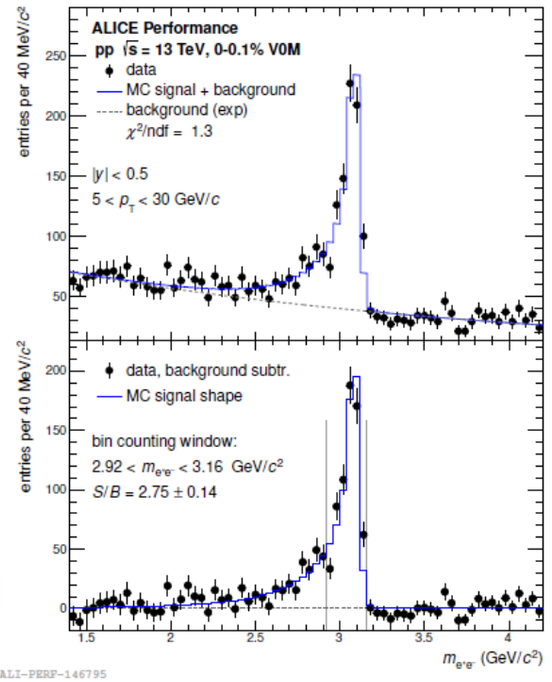
- **Separation of prompt and non-prompt J/ψ production:**

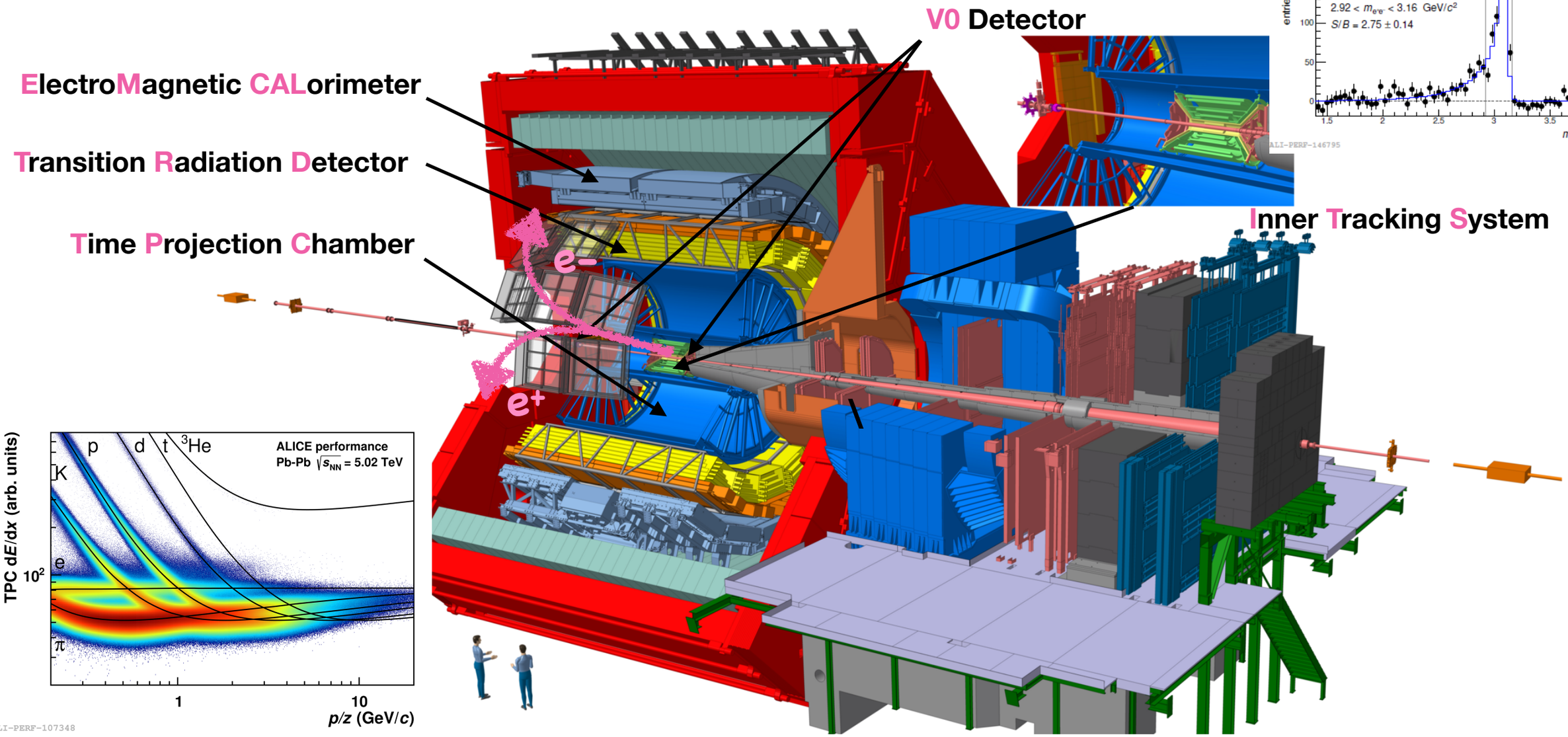


- Beauty quark production down to low p_T
- Allows direct comparison with models that describe prompt J/ψ production

J/ψ measurements at mid-rapidity in ALICE

- J/$\psi \rightarrow e^+e^-$, $|y| < 0.9$
- $\Delta m/m$ ~ 1 %
- Unique kinematic coverage at the LHC:
  - J/ψ measurements down to $p_T = 0$
  - Non-prompt J/ψ separation down to 1 GeV/c

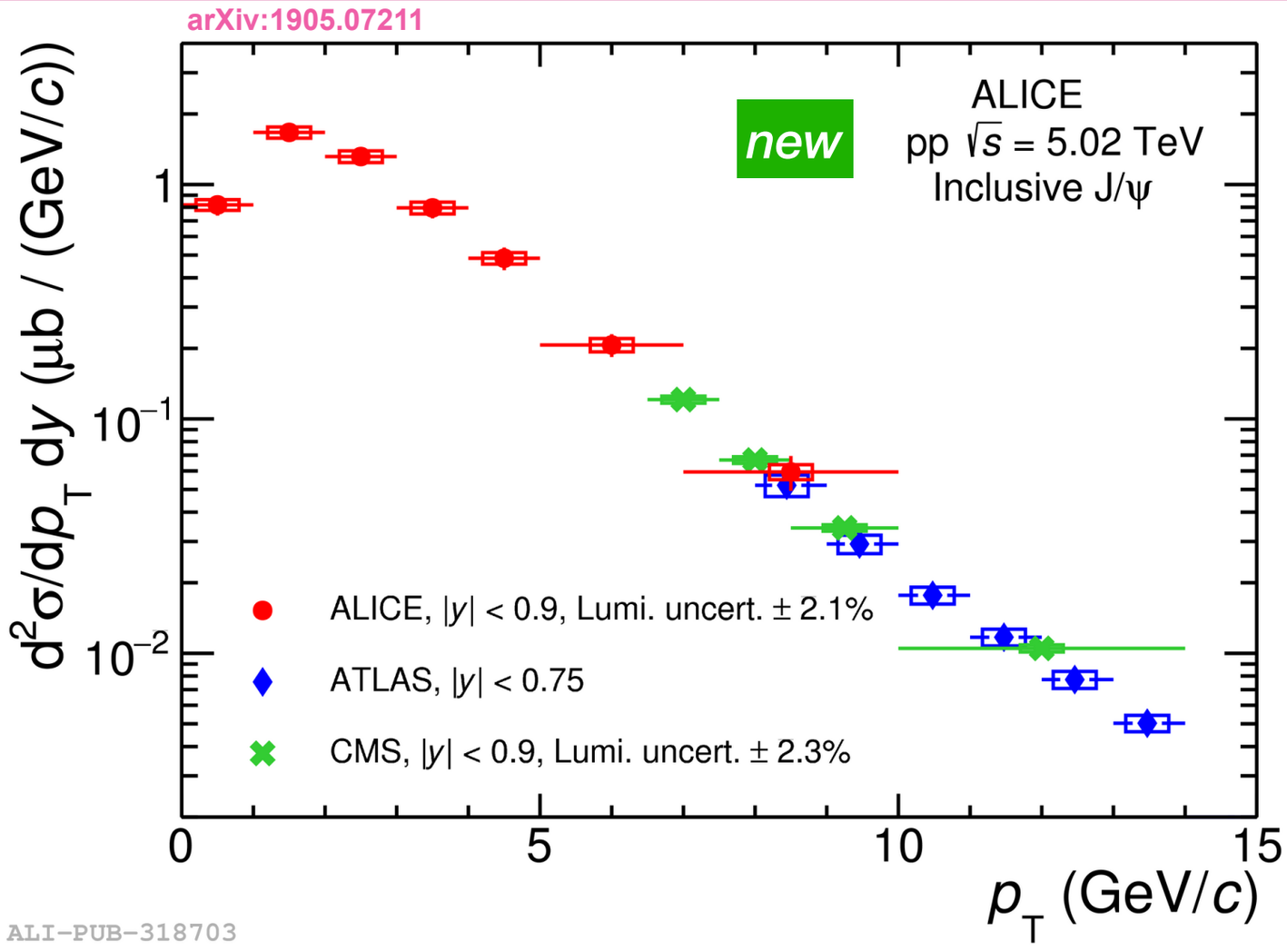




J/ψ production measurements in pp collisions

- Reference for p-Pb and Pb-Pb measurements to quantify nuclear matter effects
- Test for quarkonium production mechanisms:
  - ✓ Color Evaporation Model (CEM) H.Fritzsch, PLB 67 (1977) 217
  - ✓ Color Singlet Model (CSM) R. Baier and R. Rückl, PLB 102 (1981) 364–370
  - ✓ Non-Relativistic QCD (NRQCD) G. T. Bodwin, E. Braaten, and G. P. Lepage, PRD 51 (1995) 112

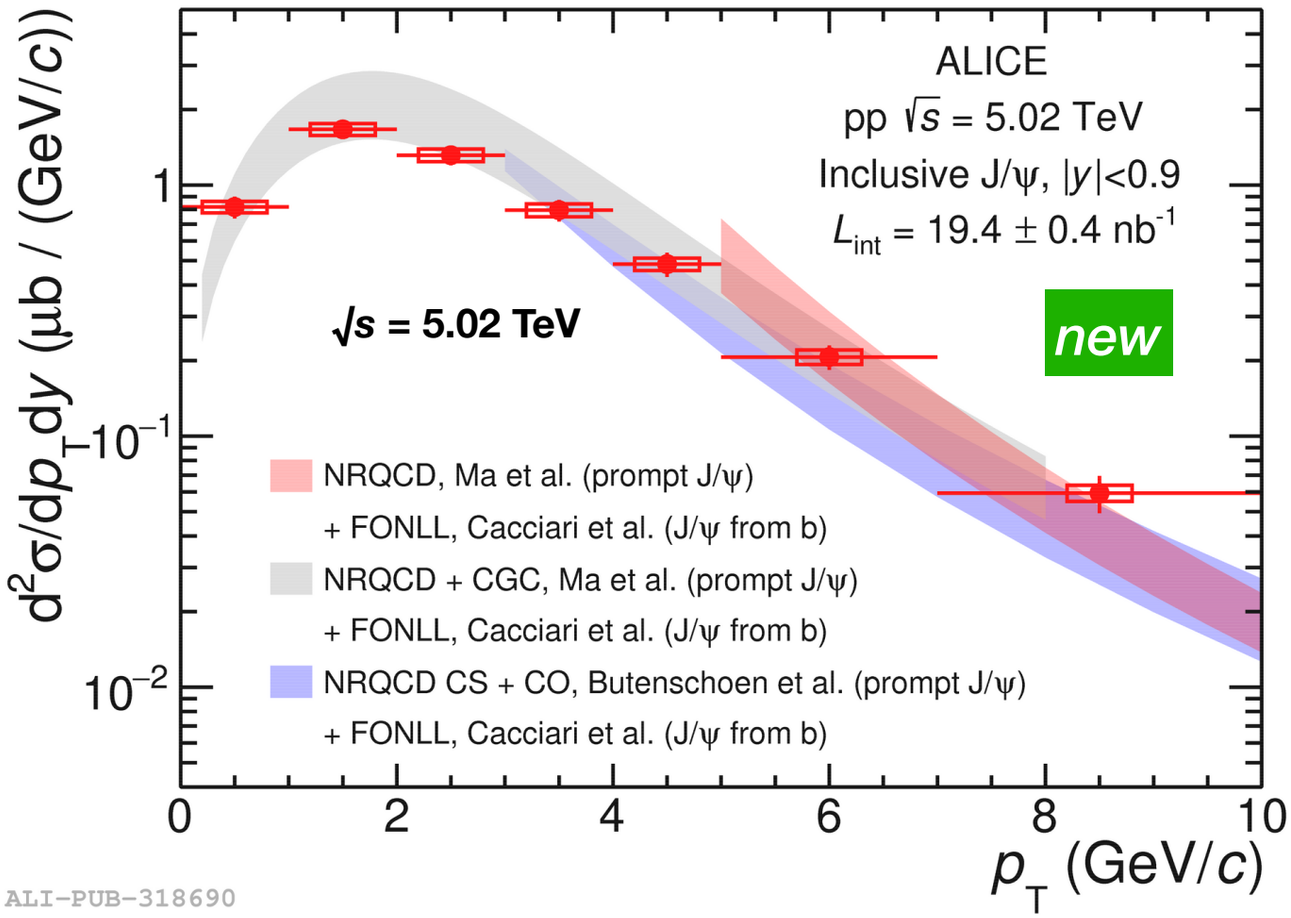
J/ψ production cross section in pp collisions



- J/ψ p_T-differential production cross section measured at mid-rapidity at $\sqrt{s}$ = 5.02 TeV down to p_T = 0 → unique kinematic coverage at the LHC
- Very good agreement with ATLAS and CMS in overlap region
- Reference for p-Pb and Pb-Pb measurements at same $\sqrt{s_{NN}}$

J/ψ production cross section in pp collisions

arXiv:1905.07211



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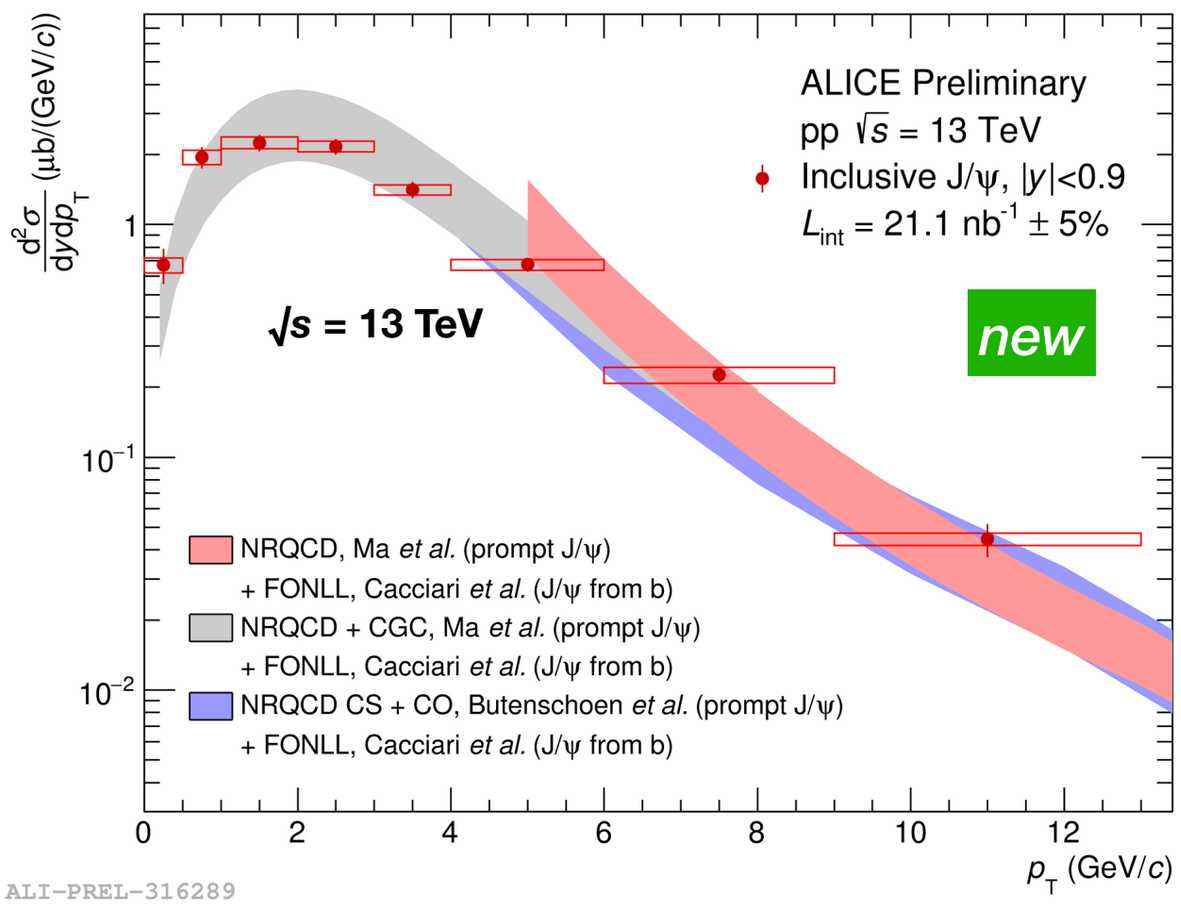

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- J/ψ p_T-differential cross sections measured at mid-rapidity at $\sqrt{s}$ = 5.02 TeV and $\sqrt{s}$ = 13 TeV

- NRQCD including CGC (prompt J/ψ) + FONLL (B→J/ψ) describes the data down to p_T = 0

  → small experimental uncertainties compared to theoretical uncertainties

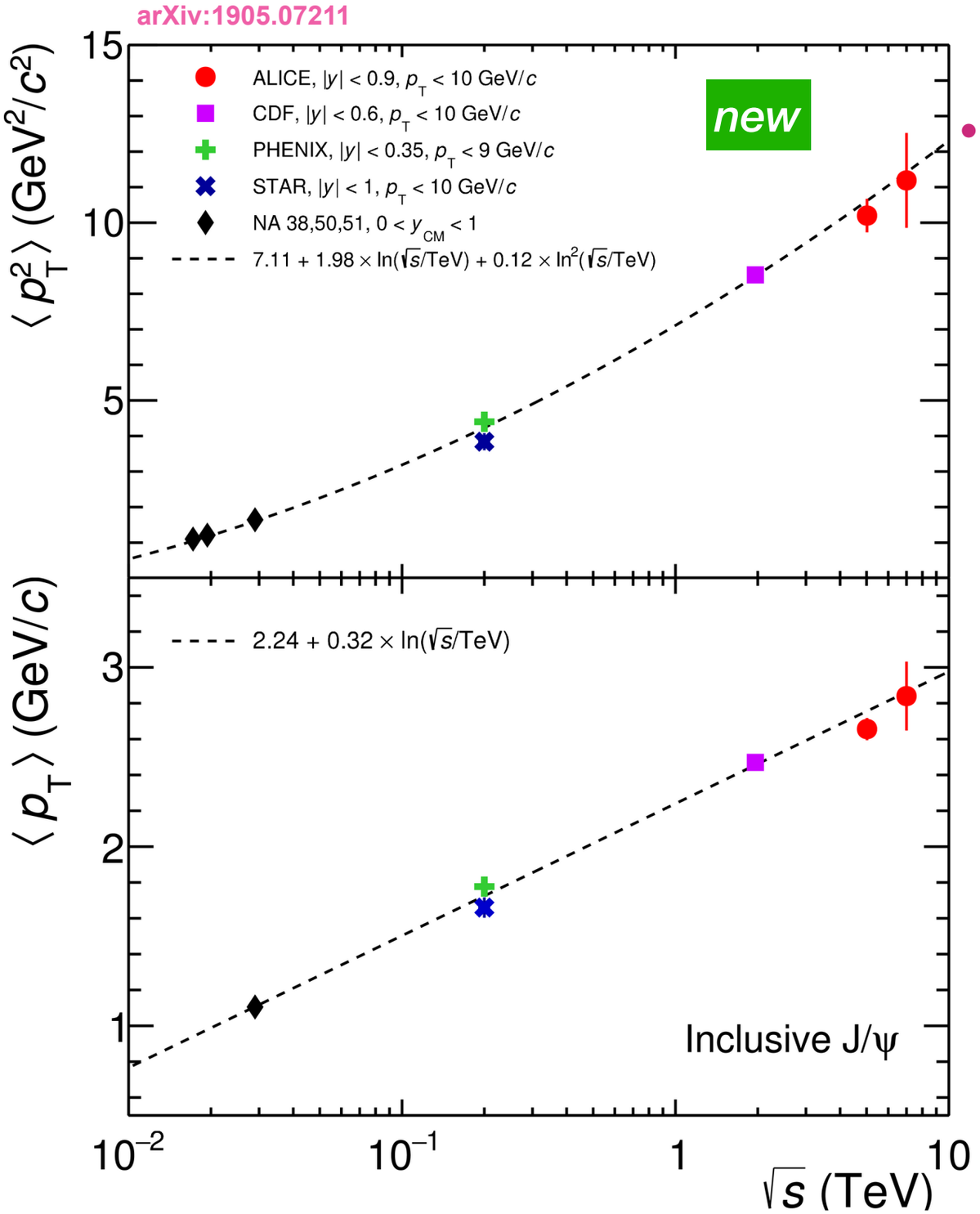
  Y.-Q. Ma and R. Venugopalan, PRL 113 (2014) 192301

- Same conclusion reached at forward rapidity

  ALICE Collaboration, EPJC 77 (2017) 392

W. Sheikh's talk
13.06. 15:20

$\langle p_T \rangle$ and $\langle p_T^2 \rangle$ in pp collisions



- Steady increase of $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ with $\sqrt{s}$
  → for fixed Bjorken-x, Q^2 grows with $\sqrt{s}$ ($x \propto Q^2/\sqrt{s}$)
- ➡ hardening of the J/ψ p_T spectrum

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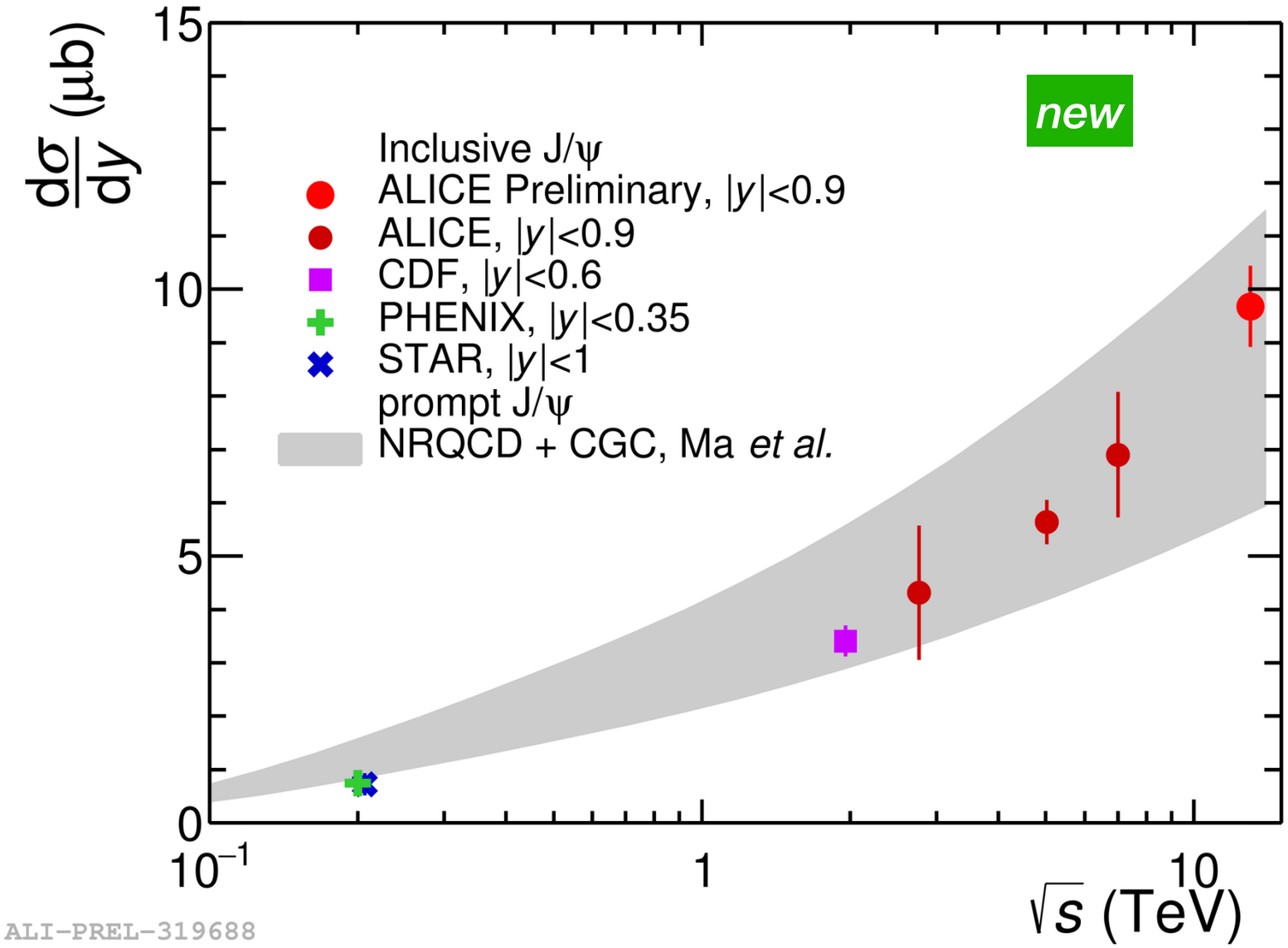
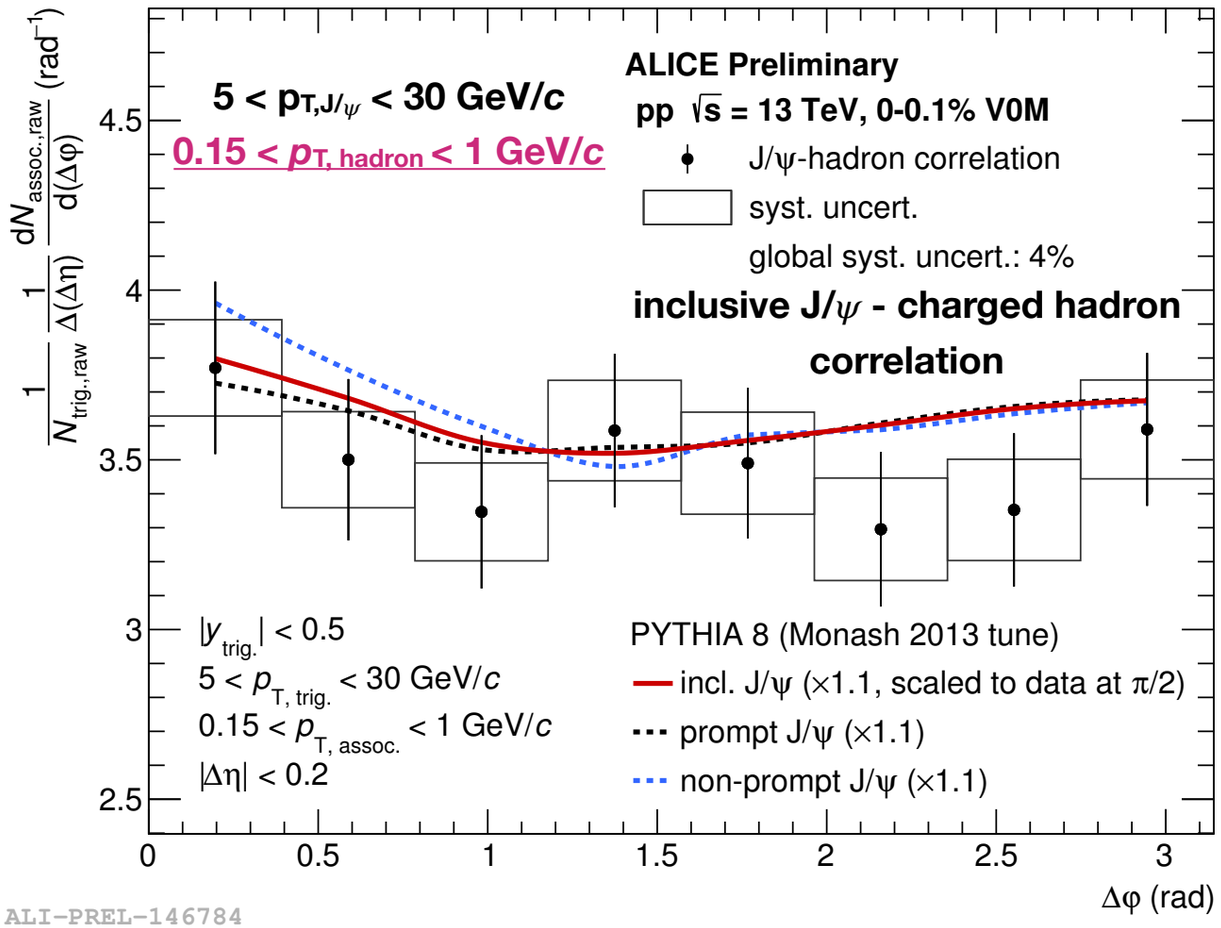
J/ψ production cross section vs. $\sqrt{s}$ in pp collisions



- Cross section increases approximately logarithmically with $\sqrt{s}$
- Cross section measurements at different $\sqrt{s}$ described by NRQCD + CGC (within significant model uncertainties)

Y.-Q. Ma and R. Venugopalan, PRL 113 (2014) 192301

J/ψ-hadron correlations in pp collisions



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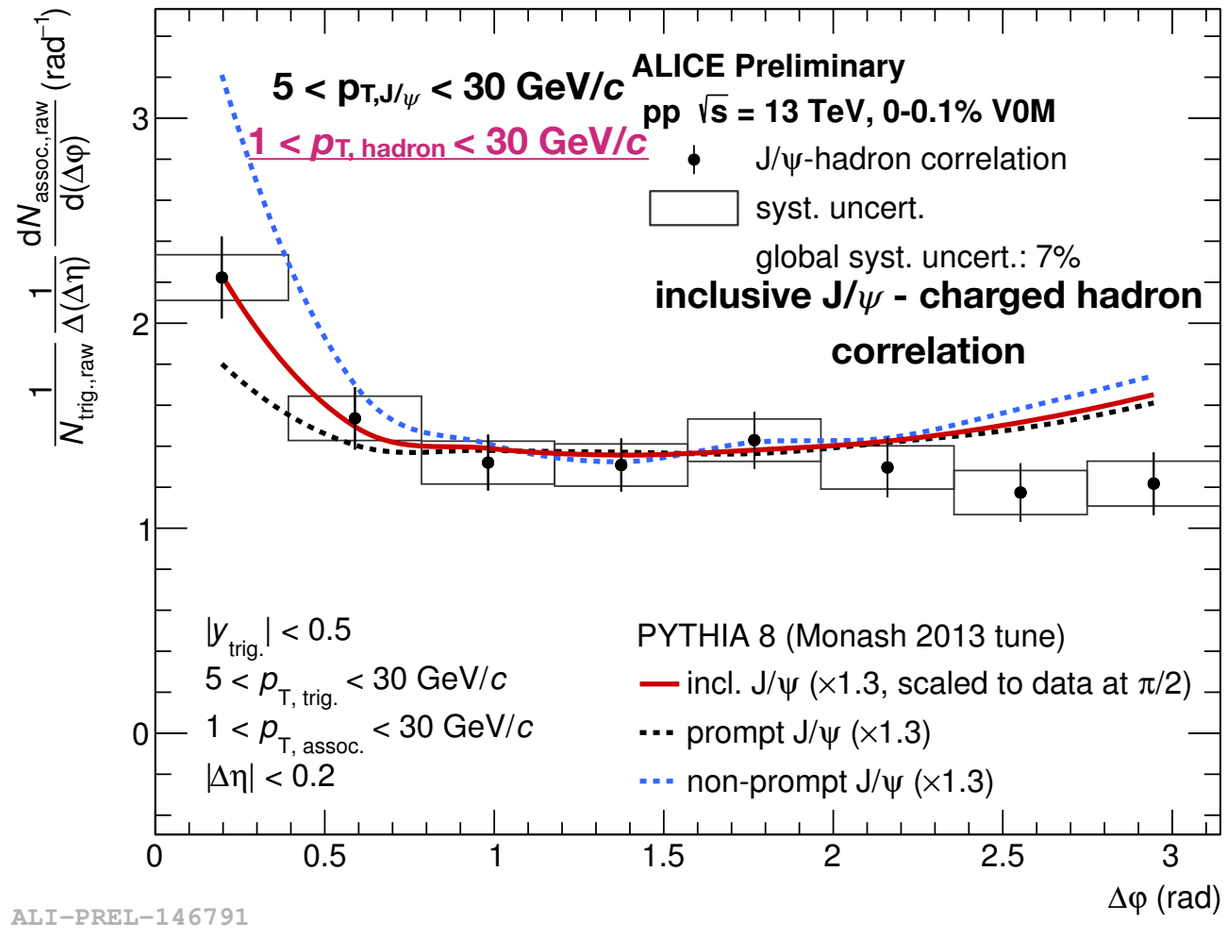

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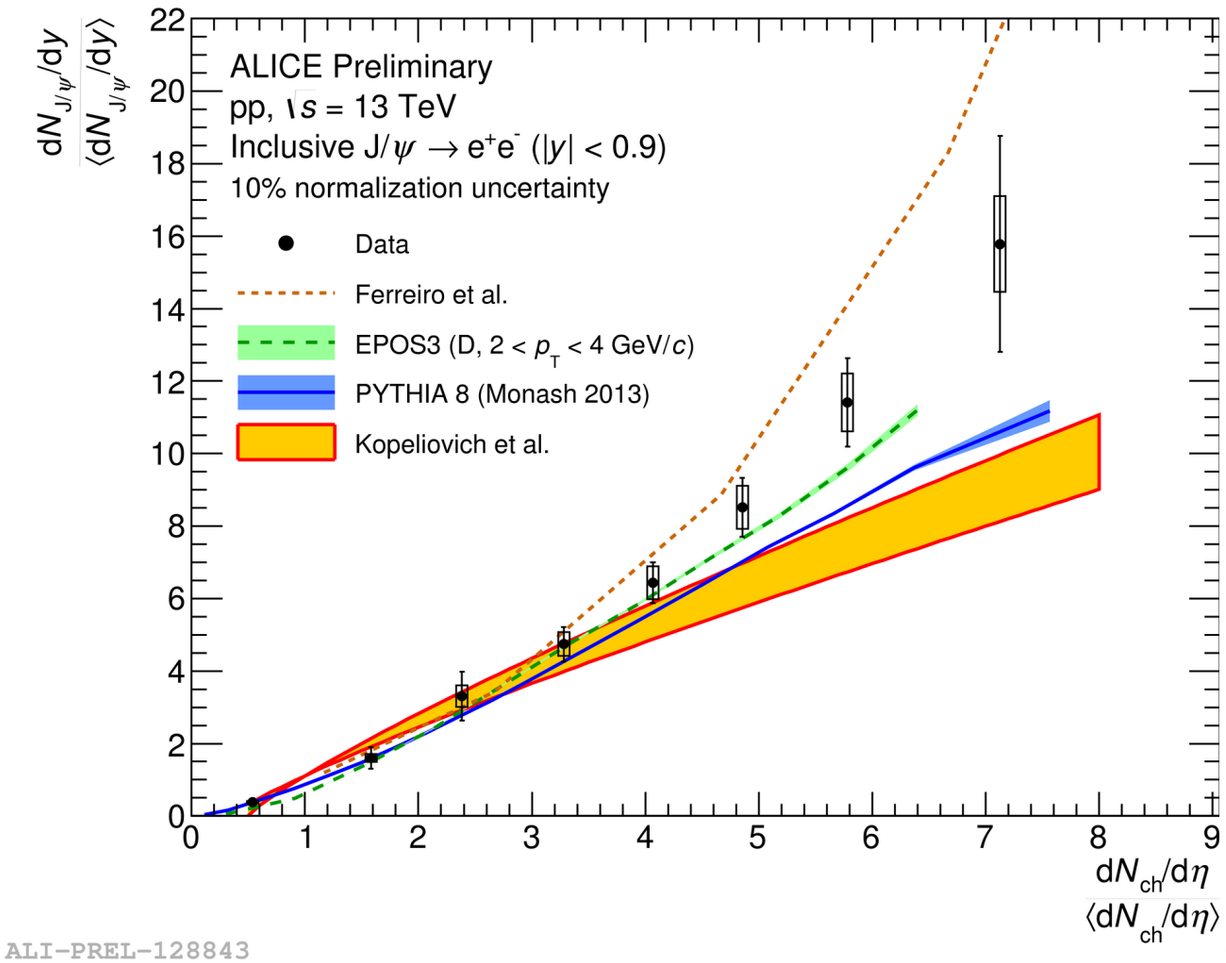
- J/ψ-hadron correlations quantify hadronic activity relative to J/ψ direction
- Clear near side peak observed by correlating high-p_T J/ψ (p_T > 5 GeV/c) and hadrons with p_T > 1 GeV/c
- PYTHIA 8 qualitatively describes the data
  → large contribution from non-prompt J/ψ for near side peak
- Full Run 2 data sample will improve measurement precision

Multiplicity dependent J/ψ production in pp collisions



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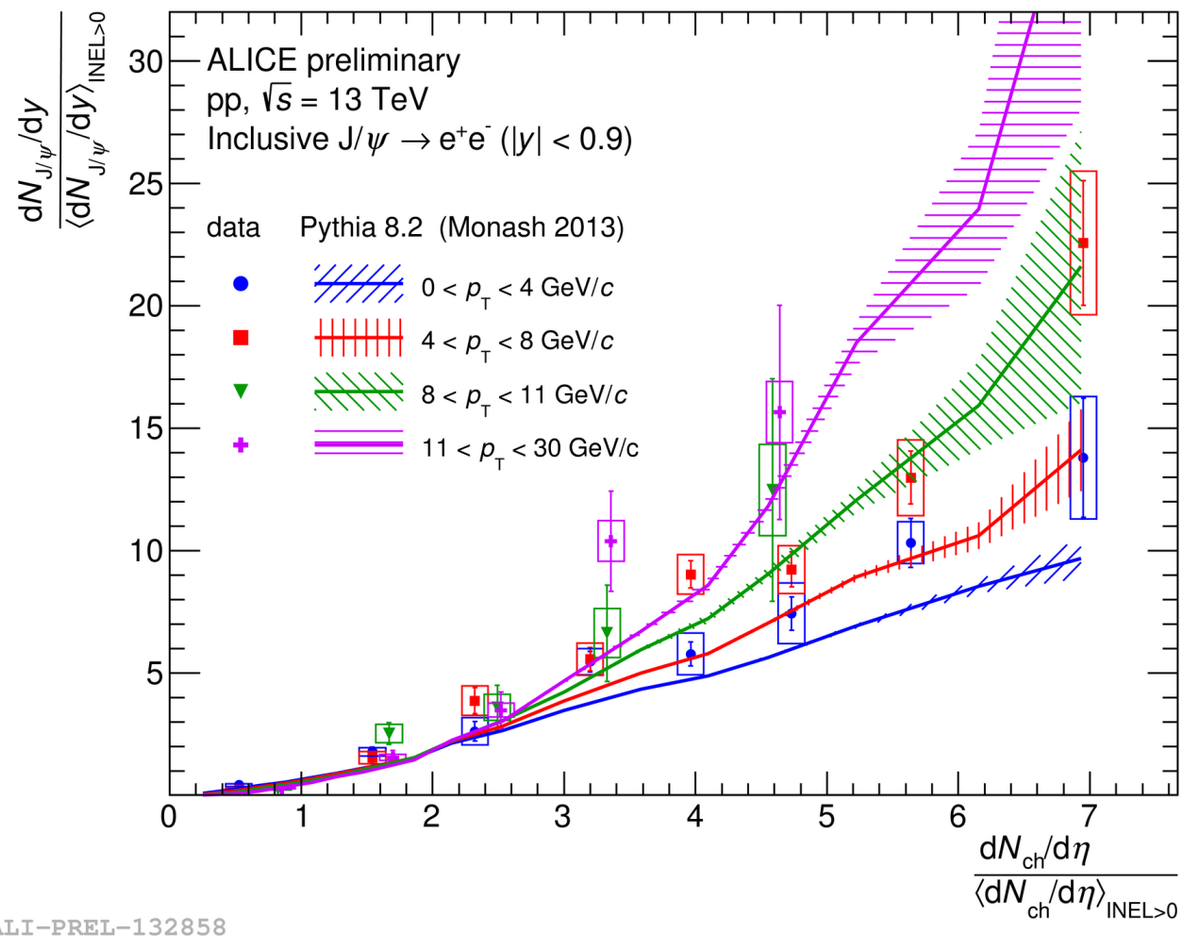

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- Stronger than linear increase of J/ψ production with multiplicity (in same η range)
- Qualitative agreement with various model predictions including production of heavy-quarks in Multi-Parton Interactions (PYTHIA8 Monash 2013, EPOS3, …)

  Percolation - Ferreiro, Pajares, PRC 86 (2012) 034903, EPOS3 - Werner et al., Phys.Rept. 350 (2001) 93

  PYTHIA8 - Sjostrand et al., Comput.Phys.Comm.178(2008), higher Fock states - Kopeliovich et al., PRD 88 (2013) 116002
- Stronger increase for higher p_T, possibly points to auto-correlations (e.g. J/ψ in jets)

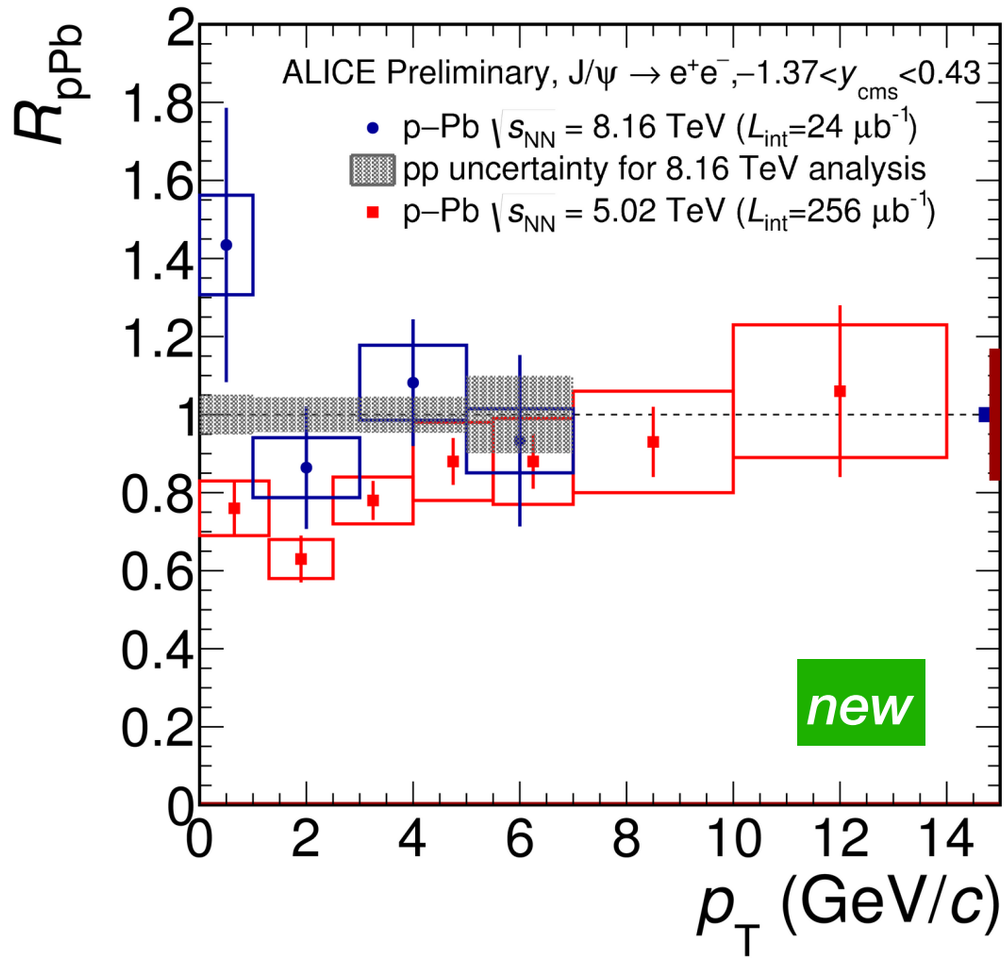
  S.G. Weber, A. Dubla, A. Andronic, A. Morsch, EPJC 79 (2019) 37

J/ψ production measurements in p-Pb collisions

- Address possible cold nuclear matter effects:
  - ✓ nuclear modification of parton distribution function EPPS16K. J. Eskola, et al., EPJC 77 (2017) 163
  - ✓ saturation in the colour Glass Condensate (CGC) approach H. Fuji & K. Watanabe, NPA 915(2013) 1
  - ✓ multiple scattering and energy loss dipole model - B.Kopeliovich, et al., PRC 83 (2011) 014912; coherent energy loss - Arleo et al., JHEP 1303 (2013)
  - ✓ Breakup by comovers E. G. Ferreiro, PLB 749 (2015) 98

Nuclear modification factor R_{pPb}

$$R_{\mathrm{pA}} = \frac{\sigma_{\mathrm{pA}}}{A\sigma_{\mathrm{pp}}}$$



- R_{pPb} of inclusive J/ψ at mid-rapidity at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV and at $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV consistent with each other within uncertainties

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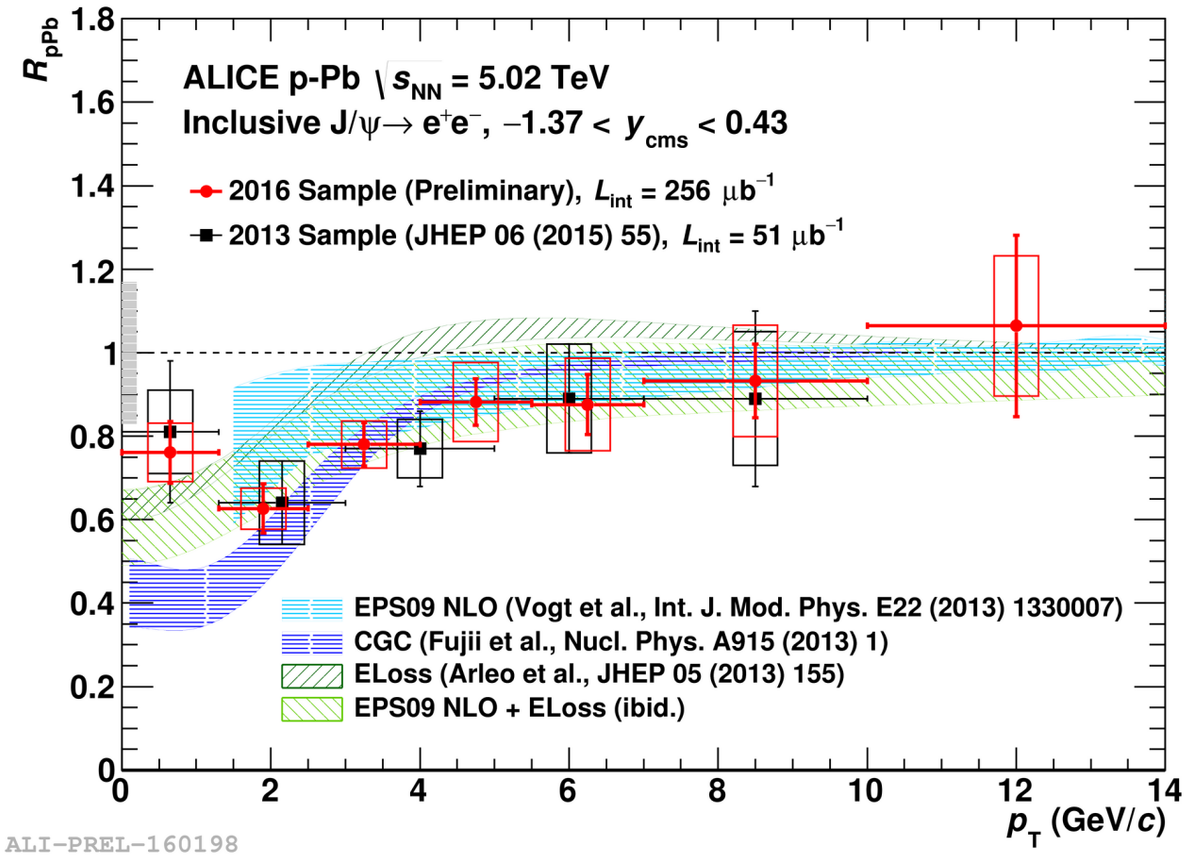
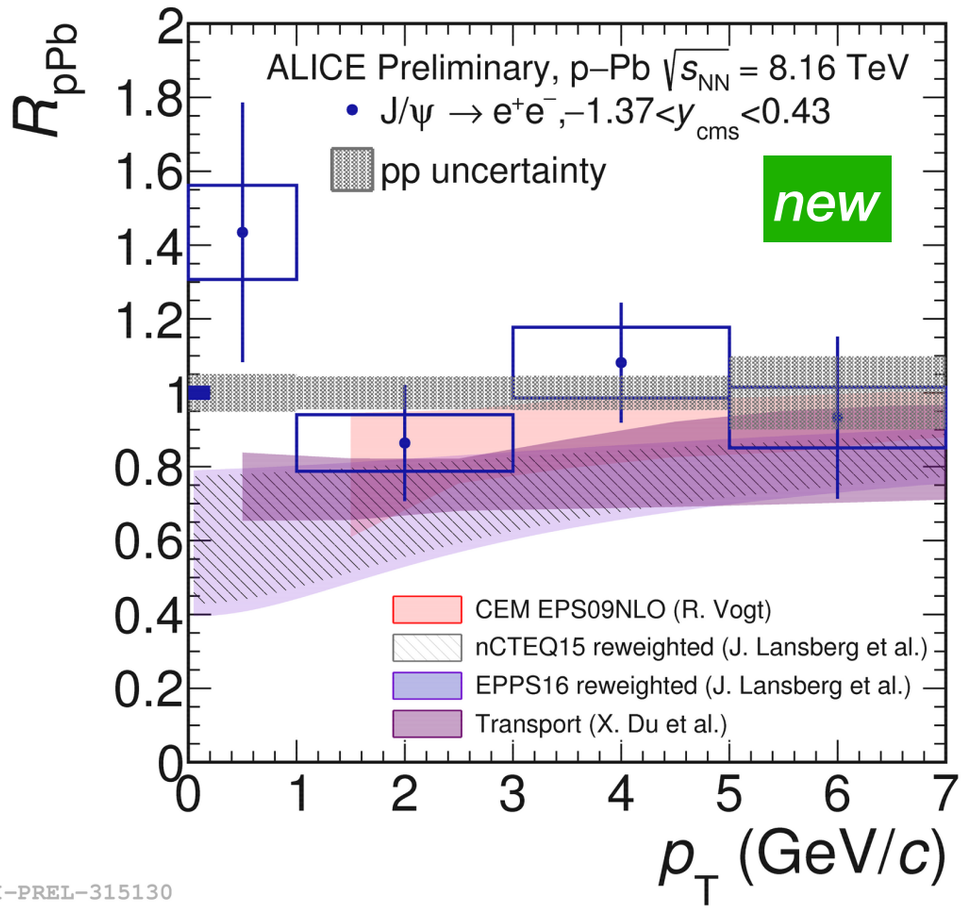
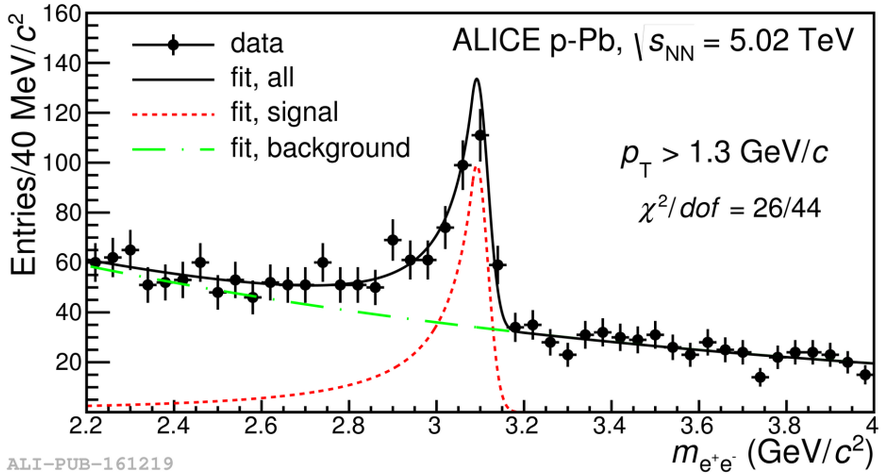


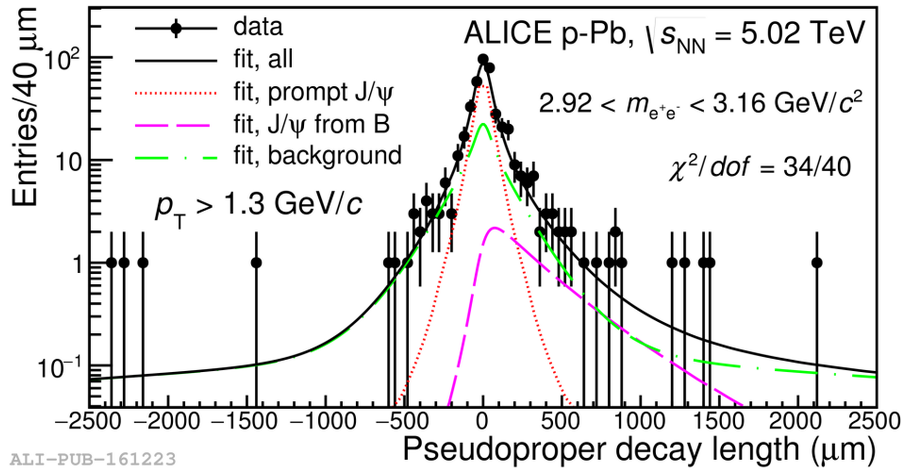


- R_{pPb} of inclusive J/ψ at mid-rapidity at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV and at $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV consistent with each other within uncertainties
- Models generally describe the p_{T} dependence of R_{pPb}
  → suppression due to shadowing and/or energy loss
- Additional data sample from TRD triggered data for $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV
  → will extend the mid-rapidity measurement to higher p_{T}

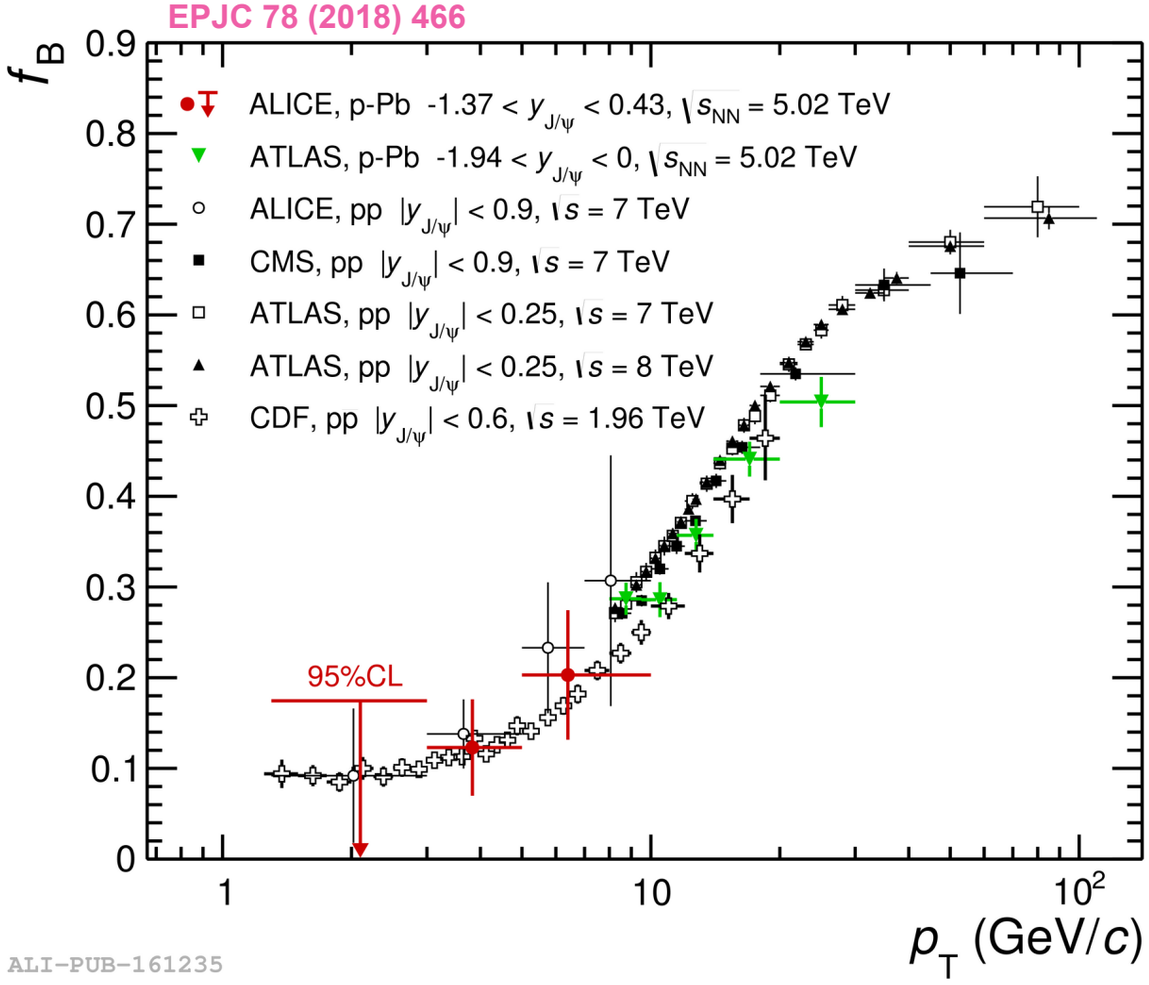
Prompt/Non-prompt J/ψ separation in p-Pb collisions

EPJC 78 (2018) 466





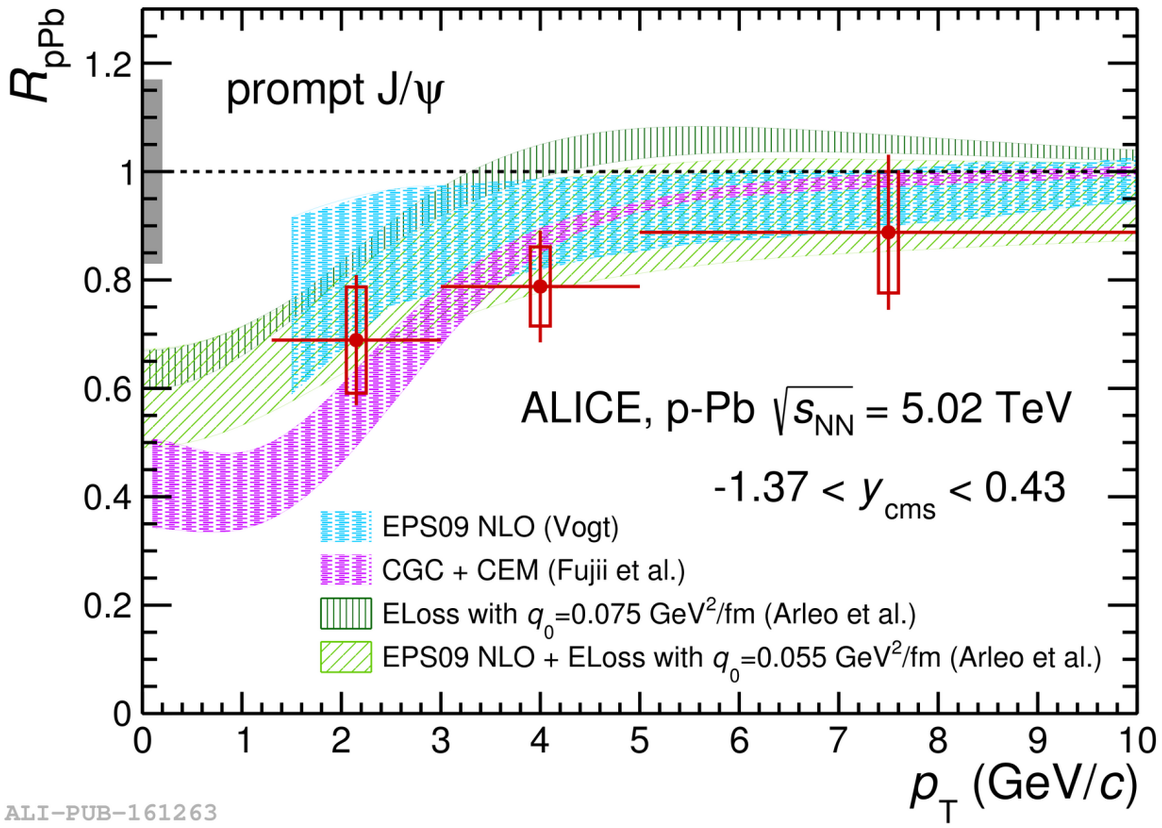
EPJC 78 (2018) 466



- Prompt/Non-prompt J/ψ separation based on displaced secondary vertex
  → use distribution of pseudo-proper decay-length to determine the fraction of non-prompt J/ψ (f_B)
- Non-prompt J/ψ fraction in p-Pb collisions has similar p_T dependence as in pp collisions

Prompt/Non-prompt J/ψ separation in p-Pb collisions

EPJC 78 (2018) 466



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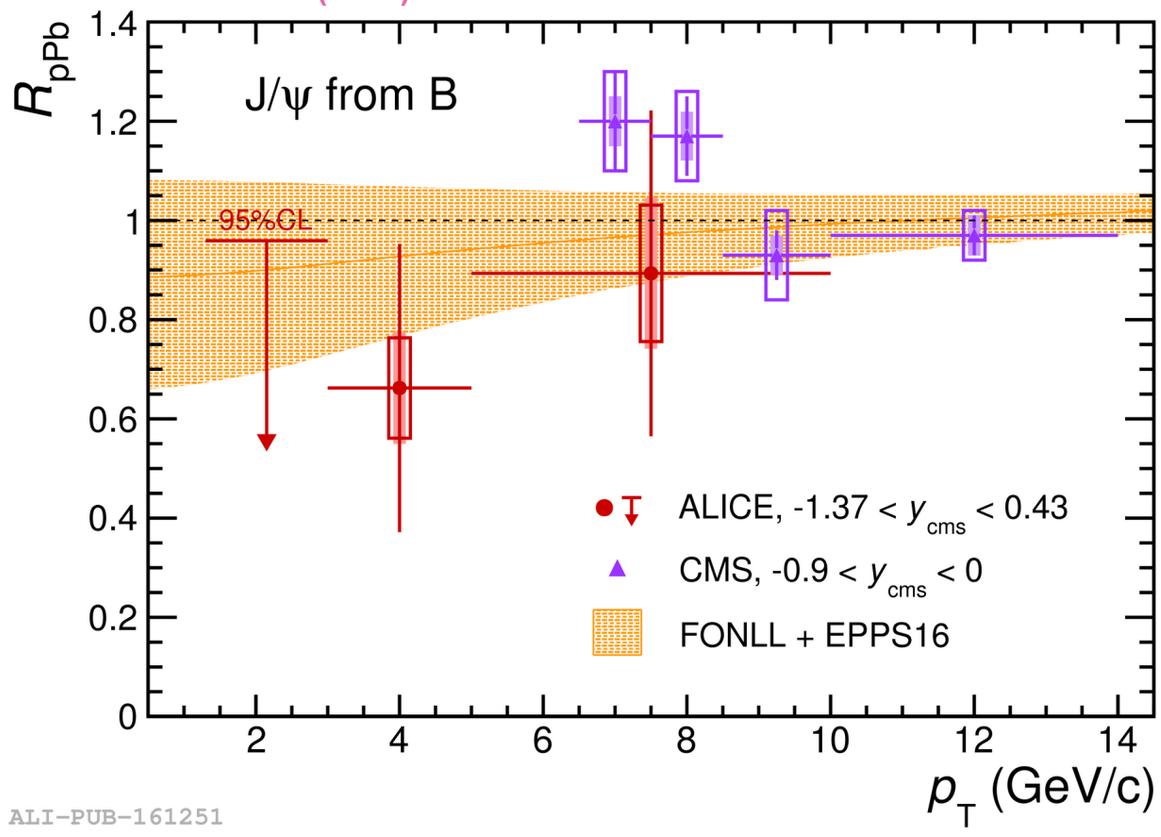
EPJC 78 (2018) 466



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- Prompt J/ψ R_{pPb} and non-prompt J/ψ R_{pPb} described by model predictions within the current experimental and theoretical uncertainties
  → sign of shadowing and/or energy loss for prompt J/ψ

- ~ x6 increased Run 2 data sample & newly measured pp reference will improve measurement precision

G. Trombetta's poster 11.06. 18:45

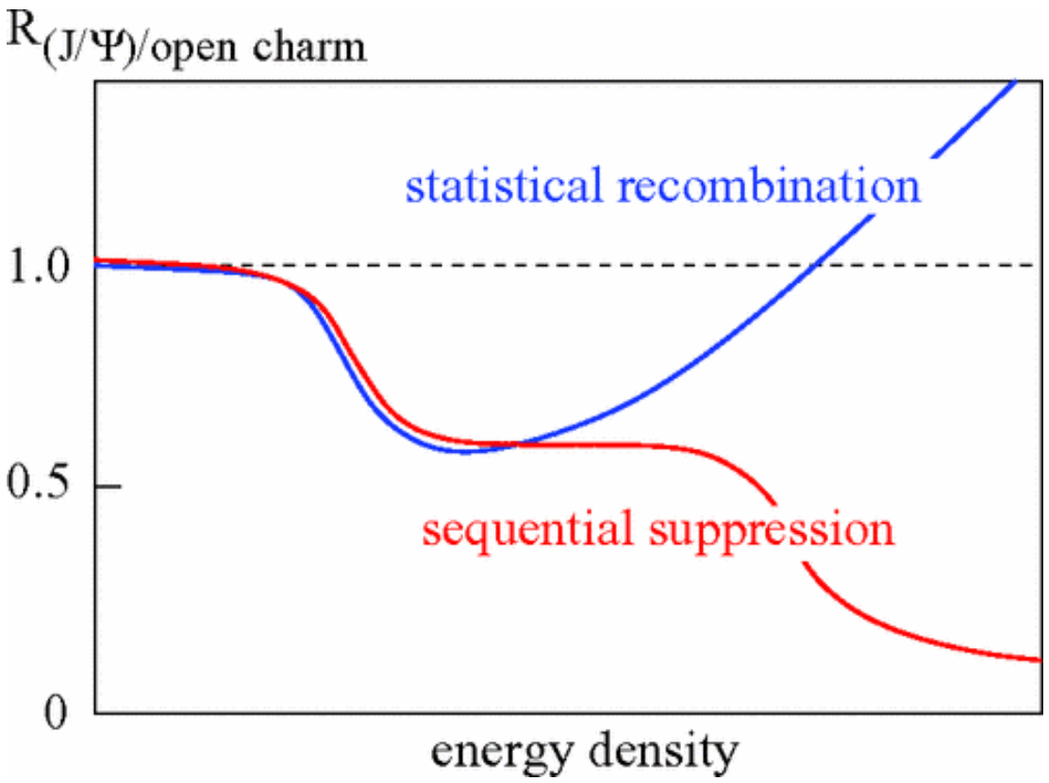
J/ψ production measurements in Pb-Pb collisions

- Quarkonium production in heavy-ion collisions at LHC energies:
  formation of J/ψ from statistical recombination
  → direct probe of charm quark thermalisation in QGP

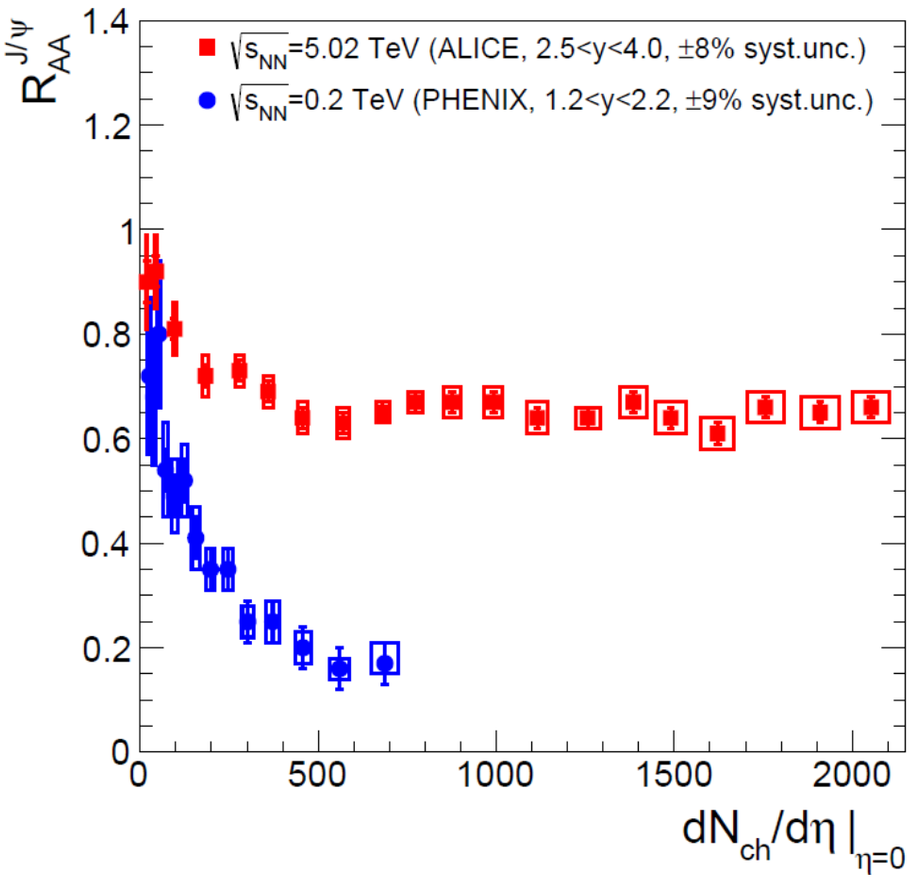
P. Braun-Muzinger, J. Stachel, PLB 490 (2000) 196

R. L. Thews, M. Schroedter, J. Rafelski, Phys.Rev. C63 (2001) 054905

S. Digal, H. Satz, and R. Vogt, PRC 85 (2012) 034906



A. Andronic, P. Braun-Muzinger, K.Redlich and J. Stachel, nature 561 (2018) 321

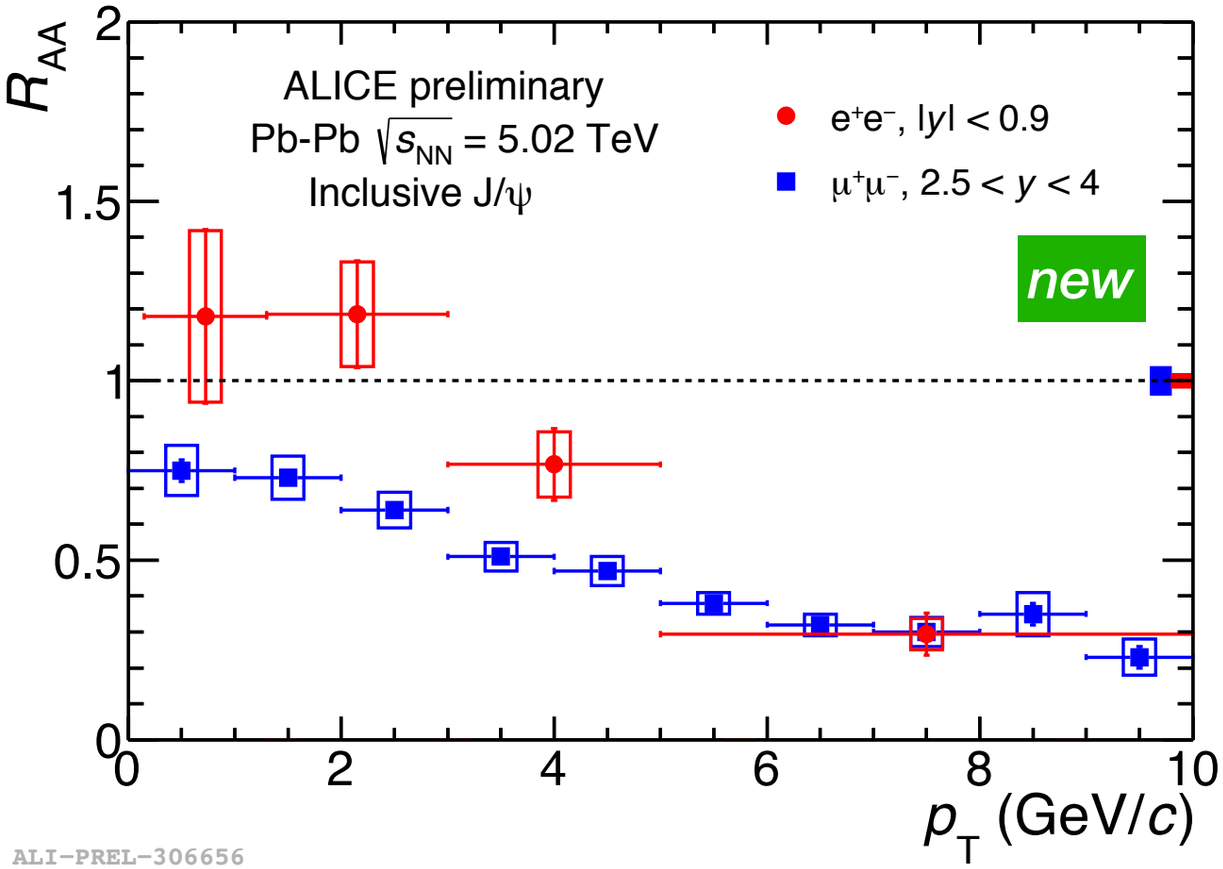


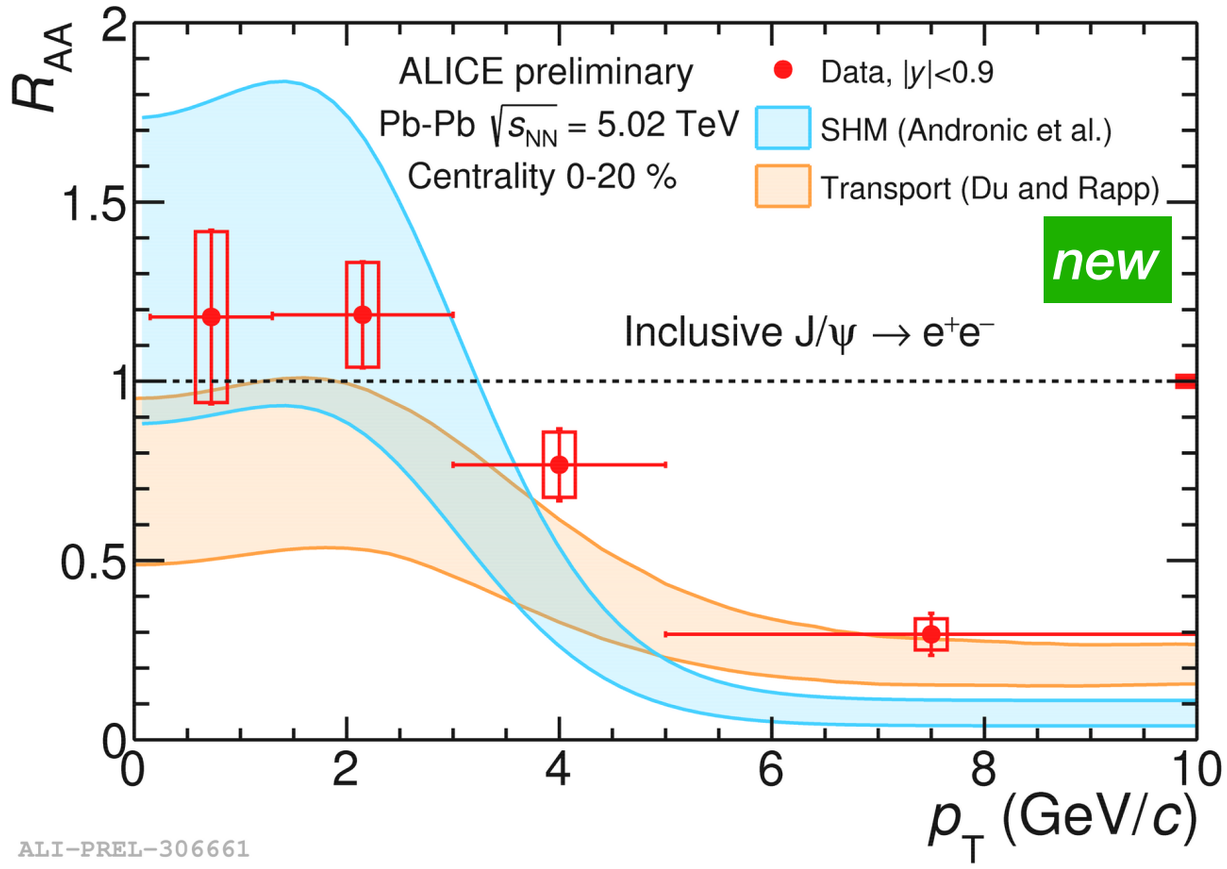
ALICE Collaboration, PLB 766 (2017) 212

PHENIX Collaboration, PRC 84 (2011) 054912

Nuclear modification factor R_{AA}

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \times dN_{pp}/dp_T}$$

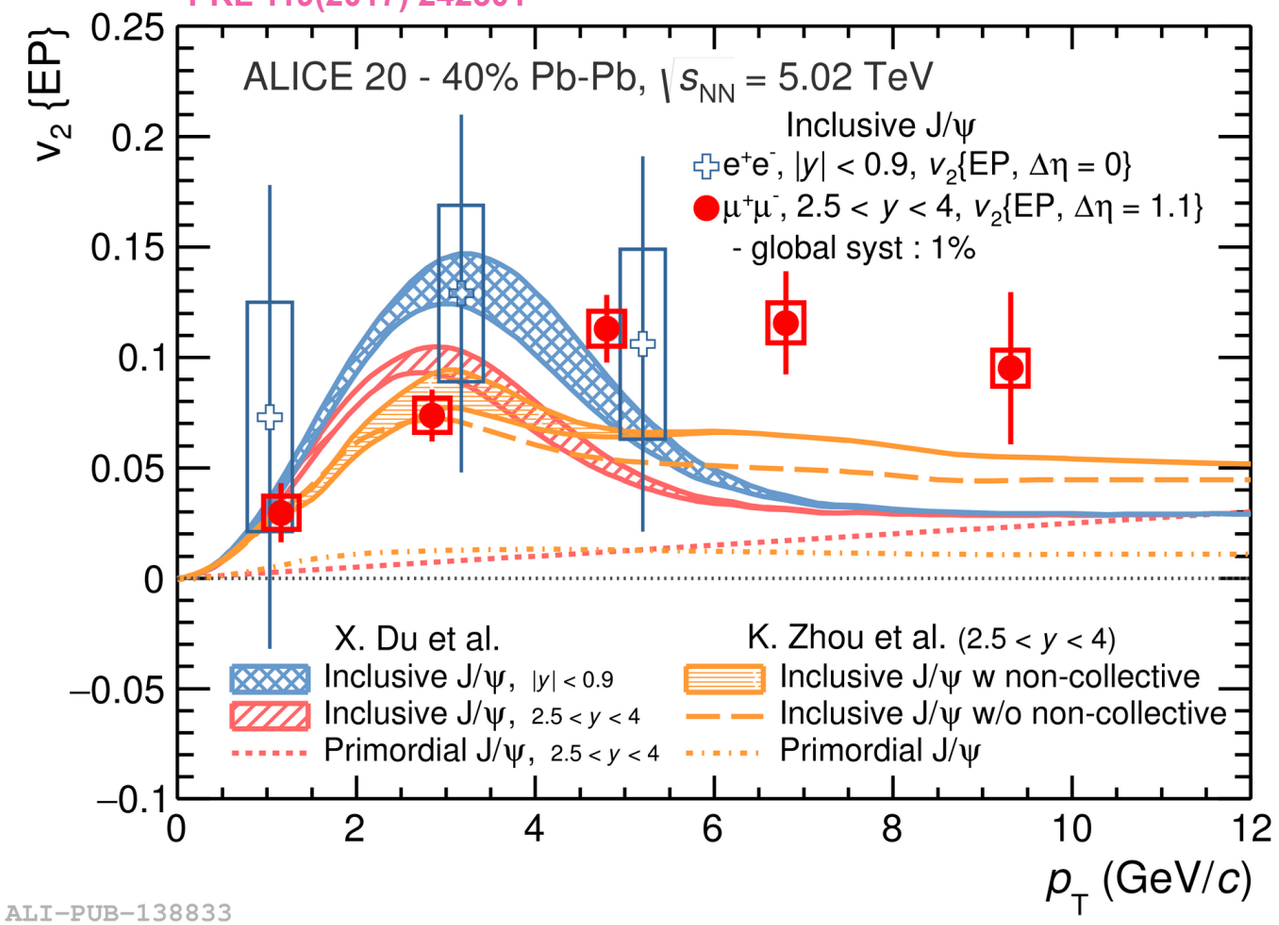




- Mid-rapidity and forward rapidity results exhibit comparable suppression at high p_T
- Stronger R_{AA} increase towards lower p_T for mid-rapidity
  → (re)generated J/ψ concentrated at low p_T at mid-rapidity
- Trend described by transport and statistical hadronization model within the current experimental and theoretical uncertainties
  → full Run 2 data sample will reduce statistical uncertainties

J/ψ elliptic flow in Pb-Pb collisions

PRL 119(2017) 242301



- Positive J/ψ v_2 is measured at mid- and forward rapidity

- Transport models including (re)generation component describe low p_T well
  → J/ψ inherit elliptic flow from deconfined (thermalised) charm quarks

- Sizeable v_2 at high p_T not described by transport models
  → path-length dependence of energy loss and/or dissociation

Summary & Outlook

- Thanks to excellent tracking, vertexing and particle-identification capabilities provided by ALICE, J/ψ production is studied at mid-rapidity in pp, p-Pb and Pb-Pb collisions with various observables

  - pp collisions: precise differential cross sections, down to $p_T = 0$
    → valuable reference for p-Pb, Pb-Pb measurements & constraint for theoretical development

  - p-Pb collisions: suppression of inclusive and prompt J/ψ at low p_T possibly due to nPDF and/or energy loss effects

  - Pb-Pb collisions:

    ✓ stronger R_{AA} increase towards lower p_T for mid-rapidity → (re)generated J/ψ concentrated at low p_T

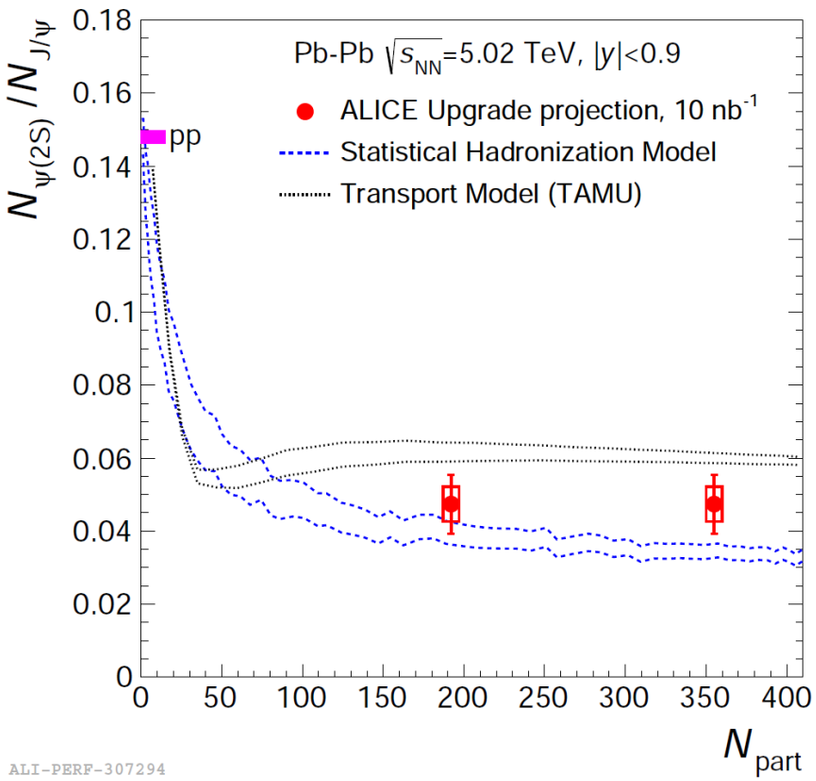
    ✓ positive J/ψ v_2 measured at low & intermediate p_T consistent with J/ψ formation from locally thermalised charm quarks

- Analyses with full Run2 data sample actively ongoing
  → results with better precision expected

Summary & Outlook

- Run 3 scheduled in 2021 - 2023
  - continuous read-out of 50 kHz Pb-Pb collisions, sample 10 nb^{-1}, 10 - 100 times larger data sample for charmonia with **TPC readout upgrade** and new **combined Online-Offline system** for calibration and data compression
  - improved tracking and vertexing precision at mid-rapidity via **ITS upgrade**
  - ➡ much larger data sample for current observables and new observables (i.e. ψ(2S), prompt/non-prompt J/ψ v_2, …)

Citron, Z. et al. , CERN-LPCC-2018-07

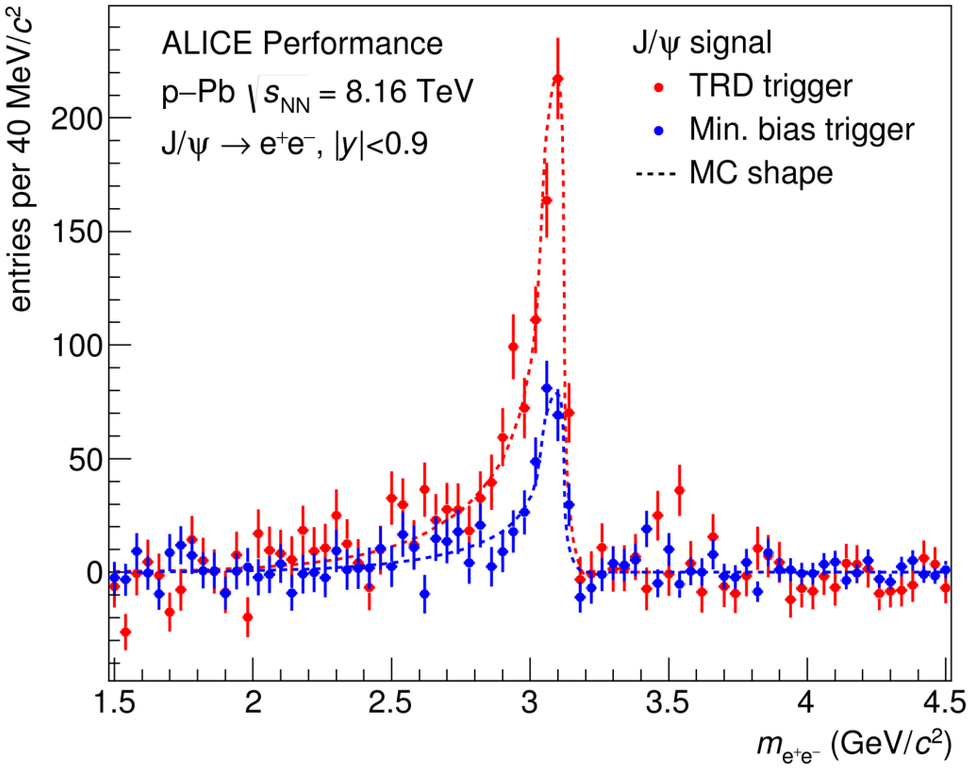


D. Colella's talk 13.06. 14:40

A. Uras's poster 11.06. 18:45

Backup

TRD triggered events in p-Pb at 8 TeV



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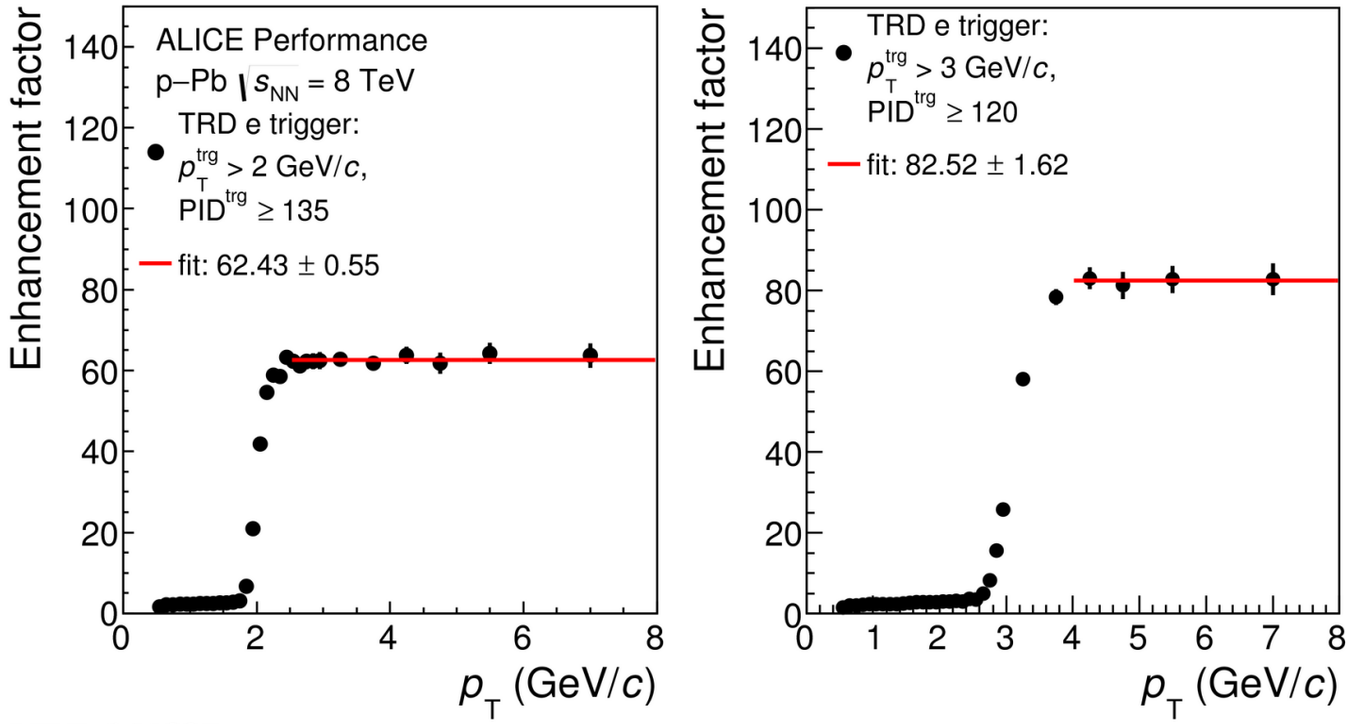

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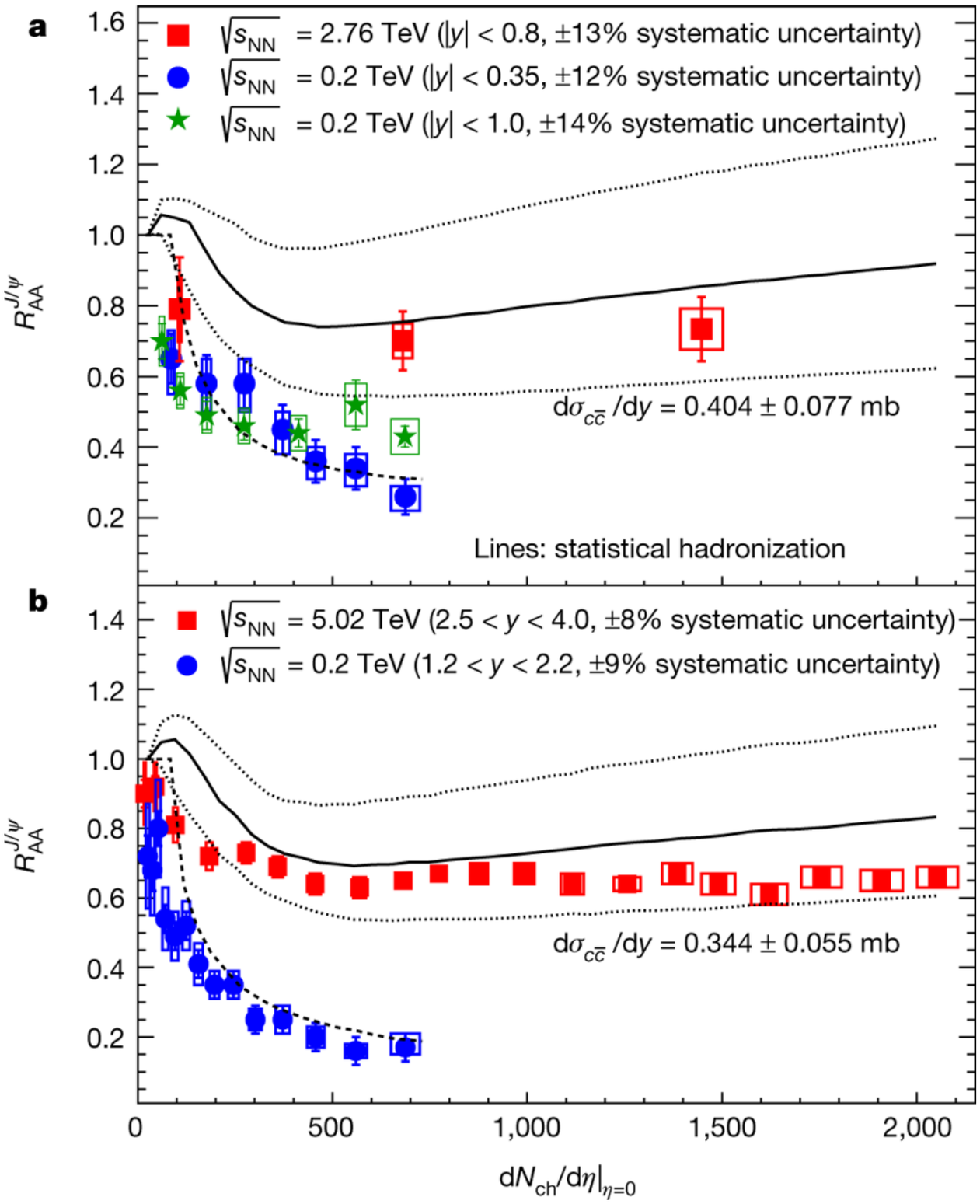
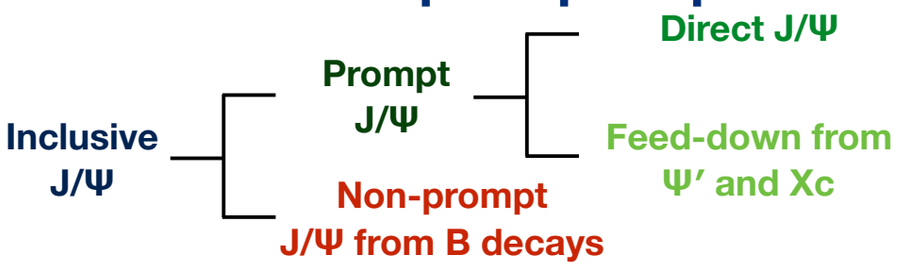
R_{AA} vs. dN/dη



PHENIX Collaboration, *Phys. Rev. Lett.* **98**, 232301 (2007)
PHENIX Collaboration, *Phys. Rev. C* **84**, 054912 (2011)
STAR Collaboration, *Phys. Rev. C* **90**, 024906 (2014)
ALICE Collaboration, *Phys. Lett. B* **743**, 314–327 (2014)
ALICE Collaboration, *Phys. Lett. B* **766**, 212–224 (2017)

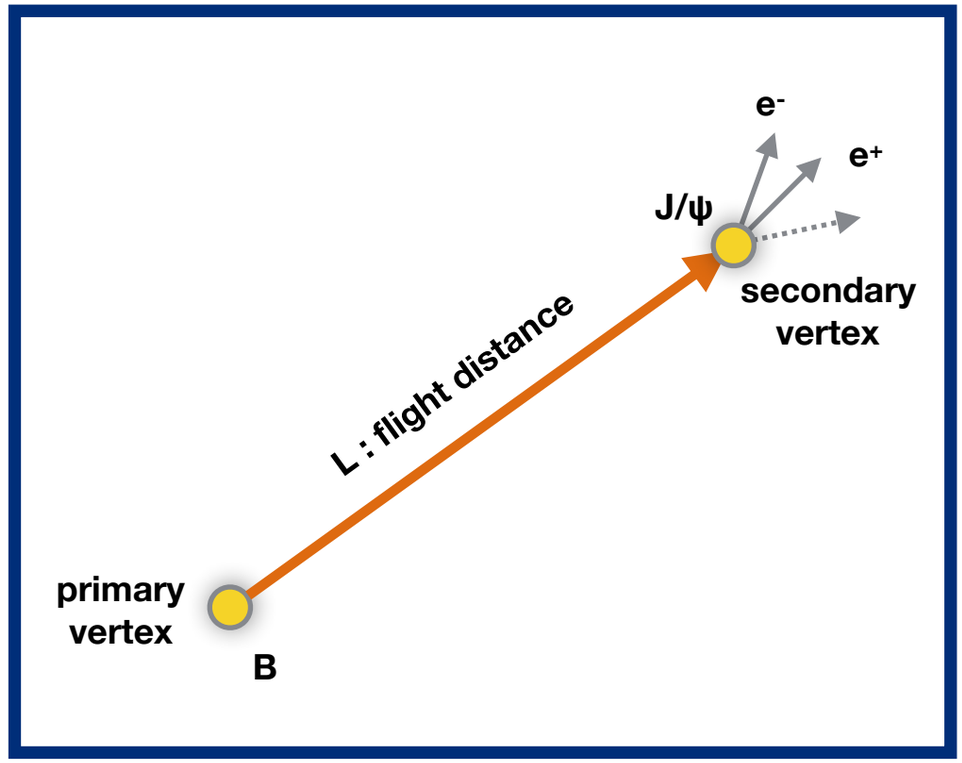
Non-prompt j/psi separation

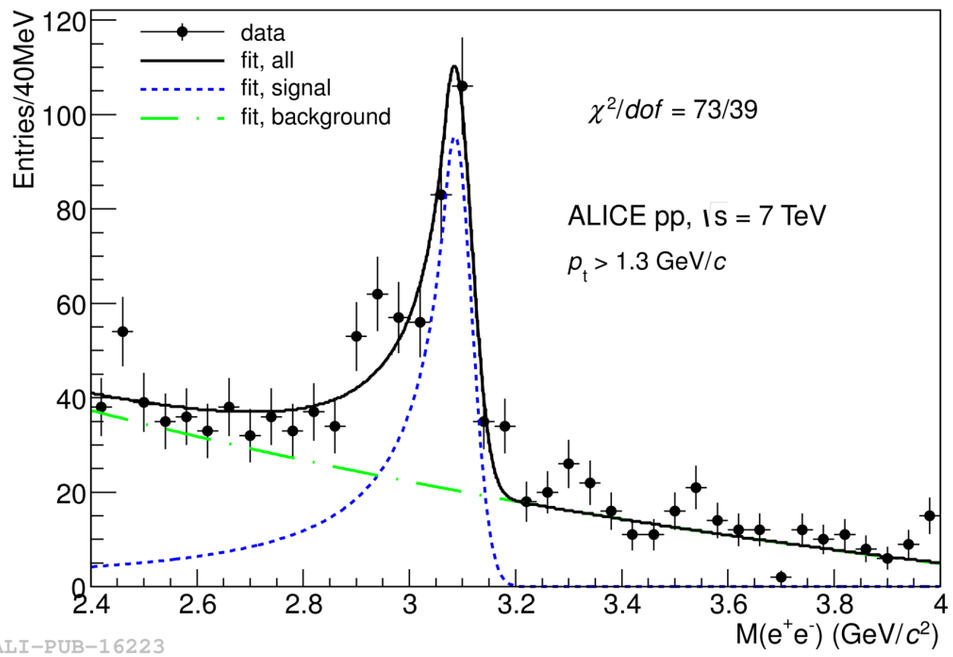
- **Measurement of non-prompt J/ψ :**

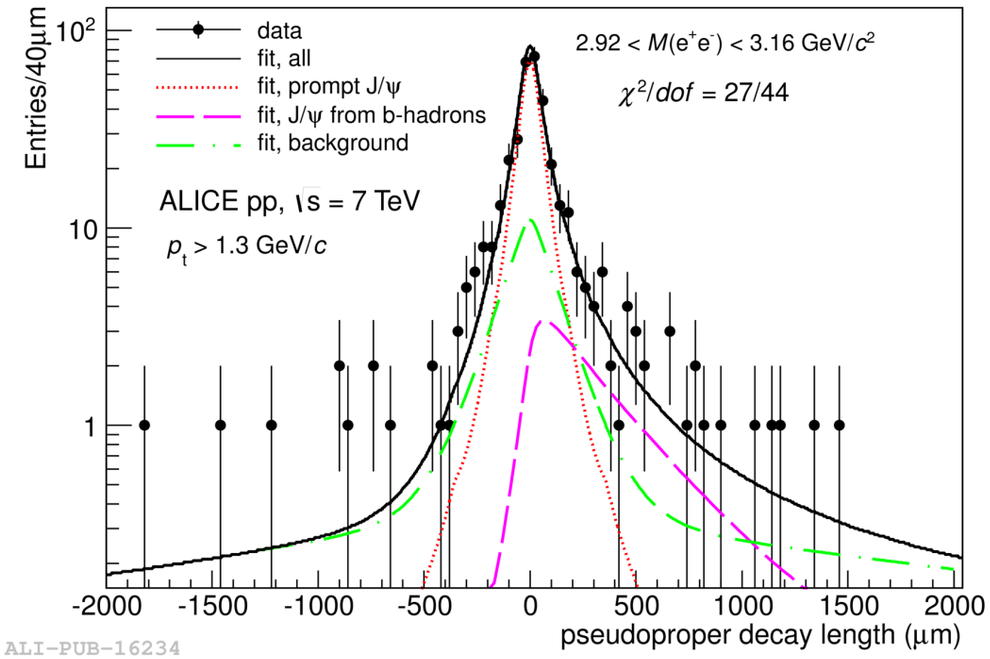


Long lifetime of B hadrons (cτ ~ 500μm) leads to larger flight distance of electrons coming non-prompt J/ψ

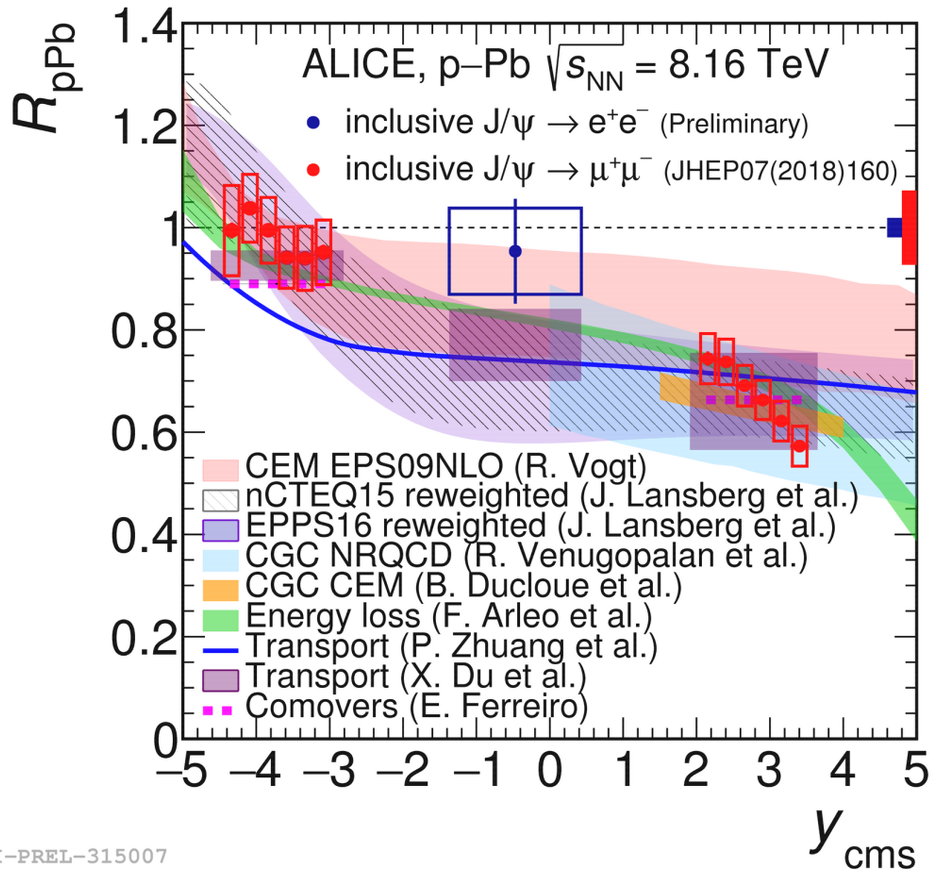
- **Analysis strategy**
  - 2-dimensional simultaneous fit for M_{ee} and pseudo-proper decay length x
  - $x = c \cdot L_{xy} \cdot m_{J/\psi} / p_T^{J/\psi}$
  - L_{xy} : projection of the flight distance onto its transverse momentum vector







more in p-Pb



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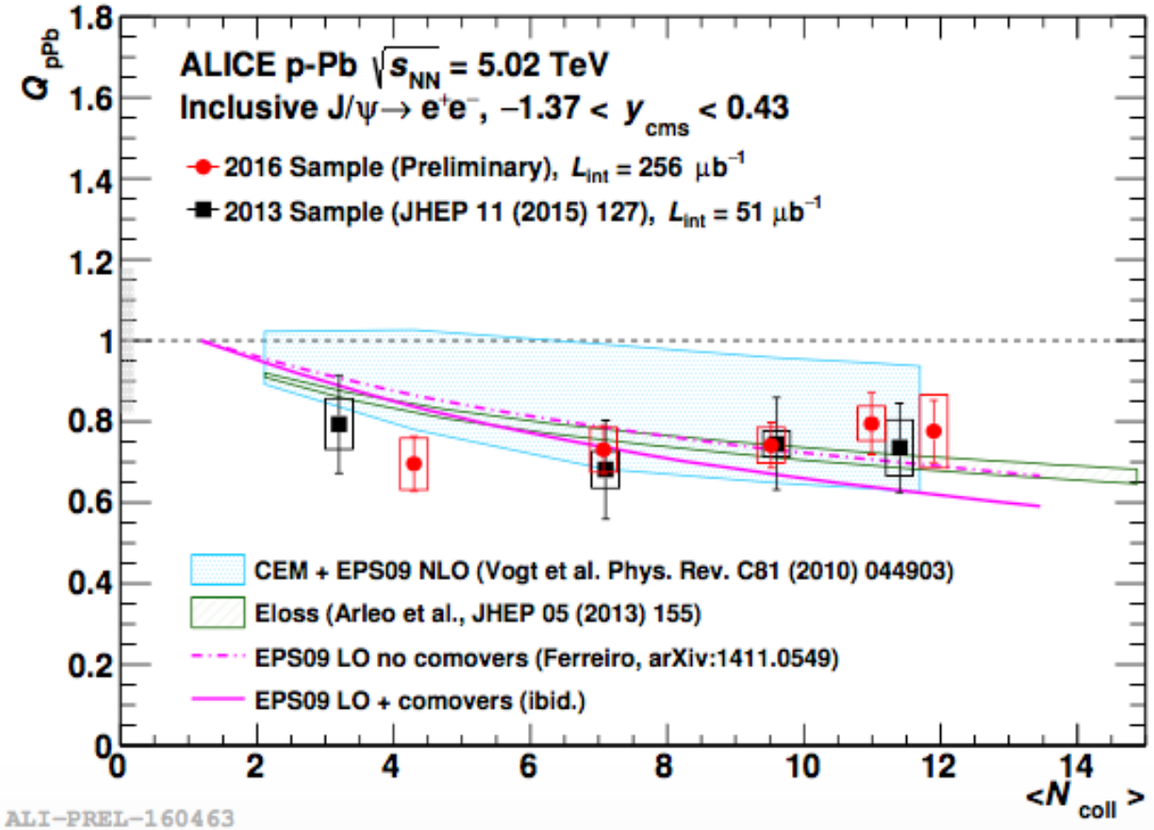

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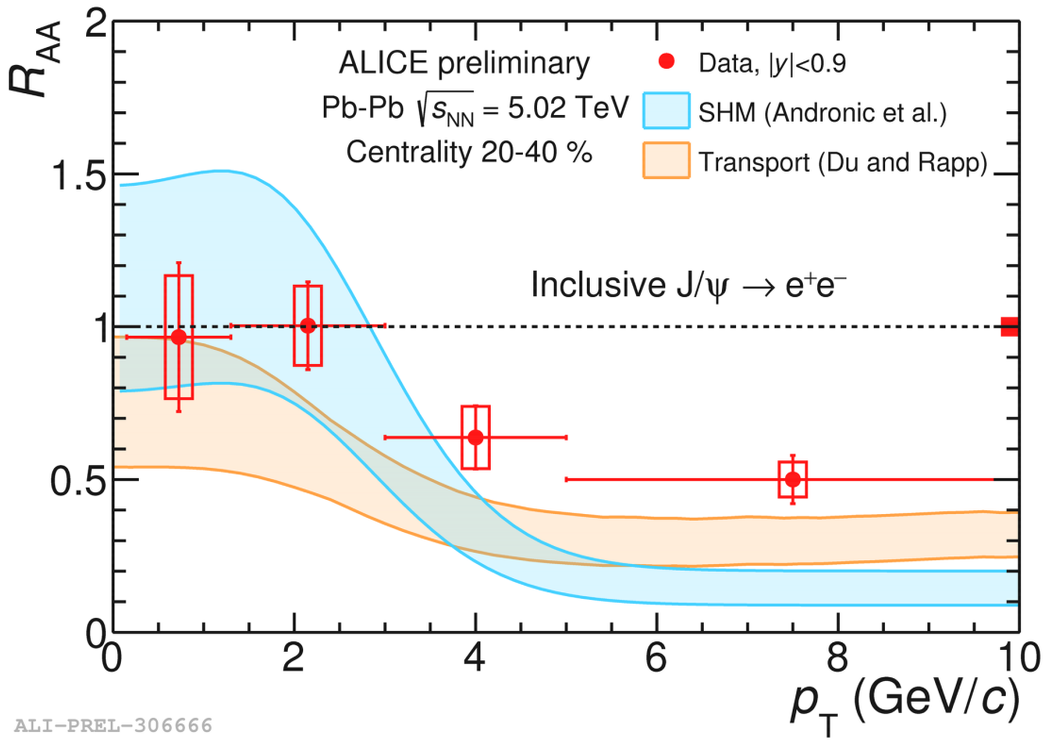
R_{AA} at 5.02 TeV



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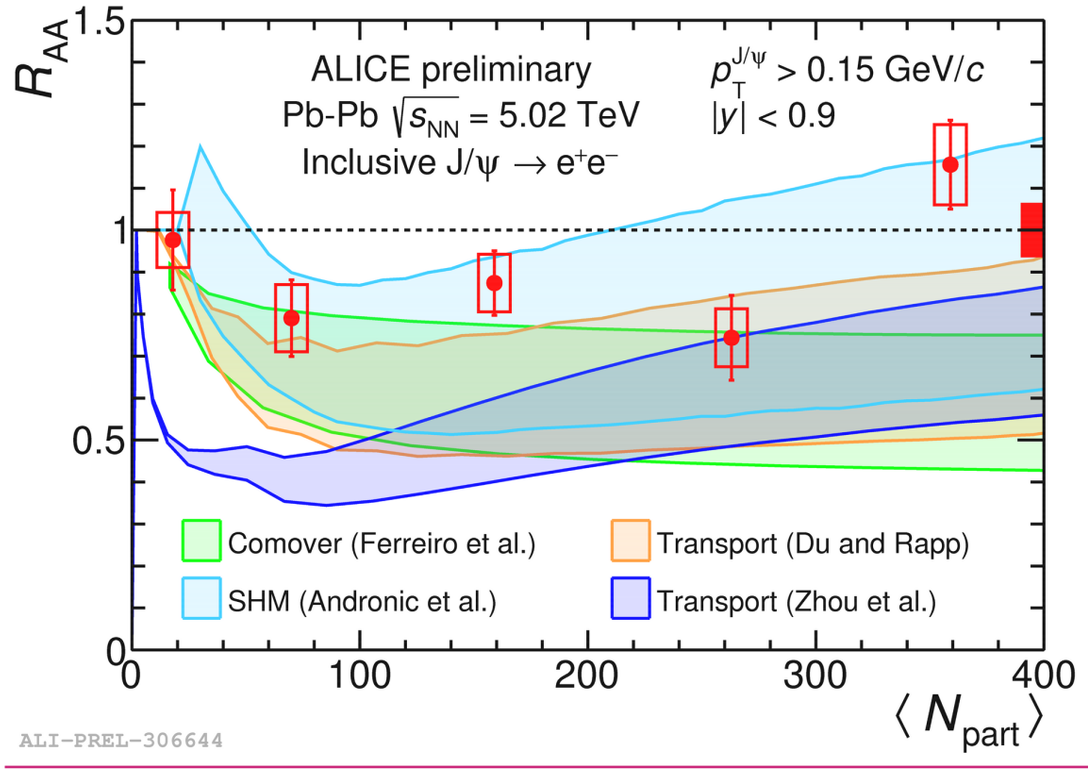
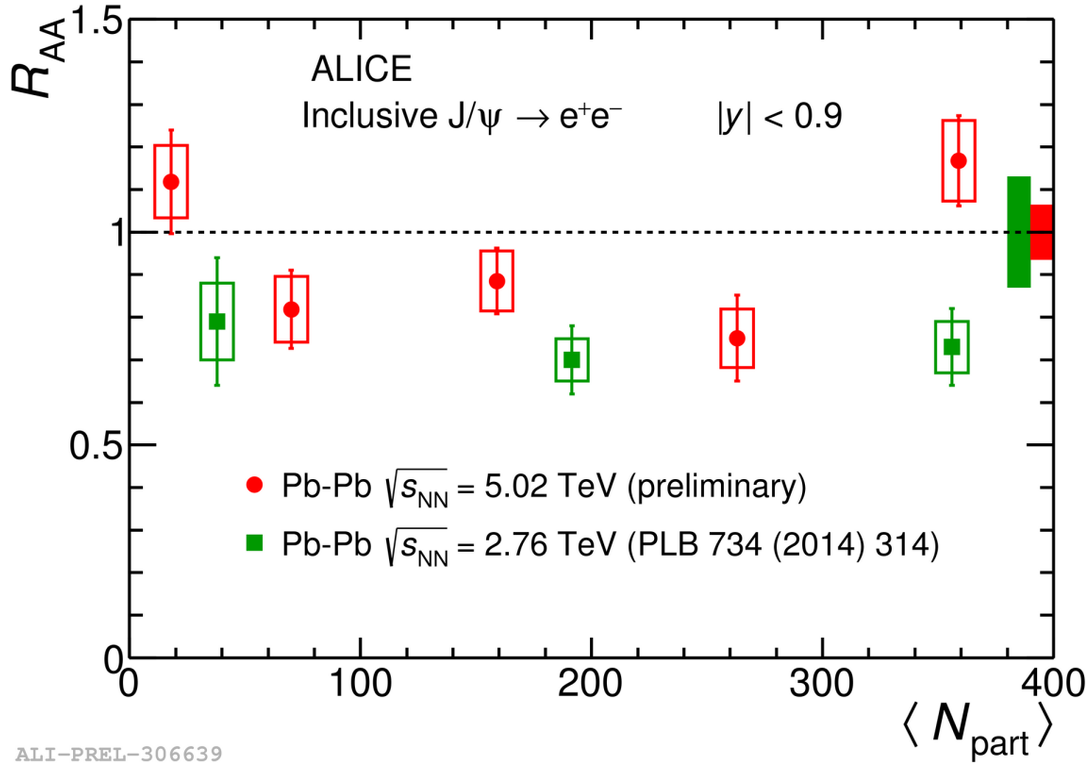


ALI-PREL-306644



ALI-PREL-306639

Statistical Hadronisation Model

Andronic et al., NPA 789 (2007) 334

- Full screening before T_c
- Rapid hadronisation of (light or heavy) quarks at phase boundary

Transport Models

Zhao and Rapp, NPA 859 (2011) 114; Zhou et al., PRC89 (2014) 054911

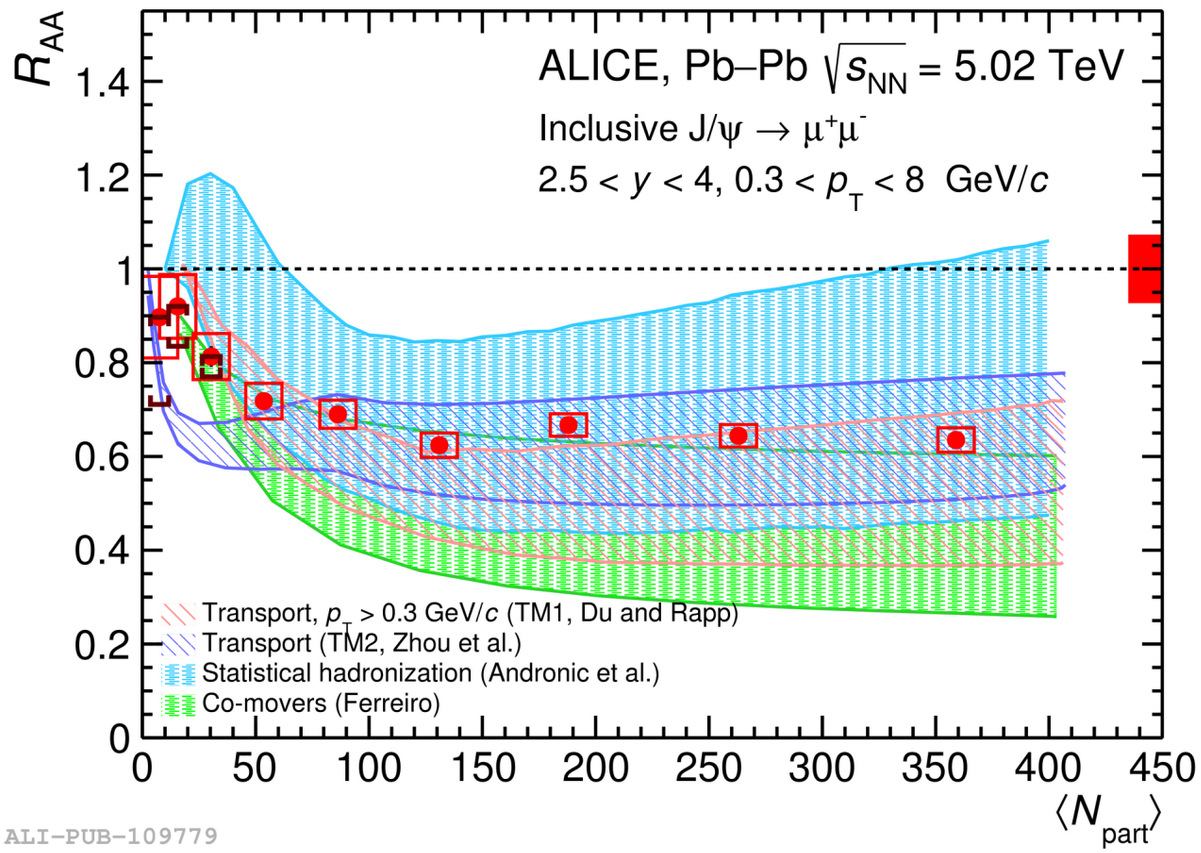
- Kinetic rate-equation approach in an evolving QGP
- Continous production and dissociation of Ψ already before T_c

Co-Mover Model

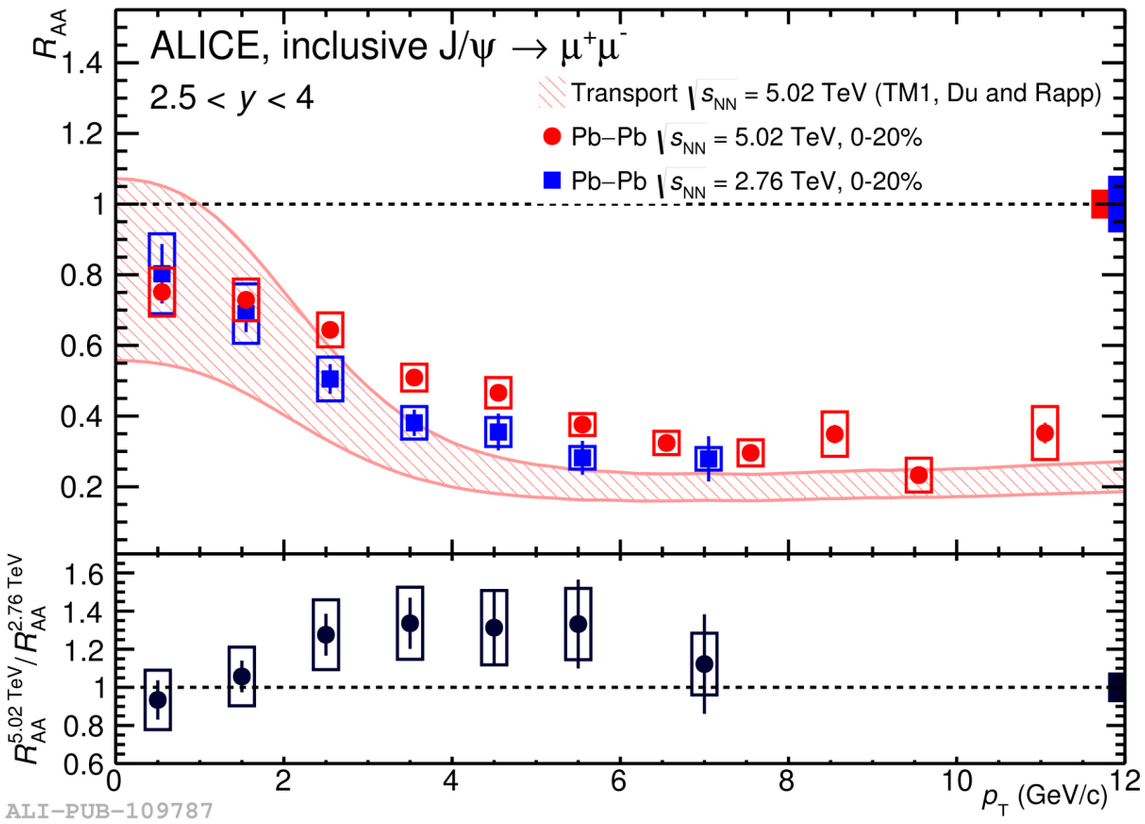
Ferreiro, PLB 731 (2014) 57

- Does not assume thermal equilibrium
- Interaction with comoving (hadronic or partonic) particles

R_{AA} at 5.02 TeV



ALI-PUB-109779

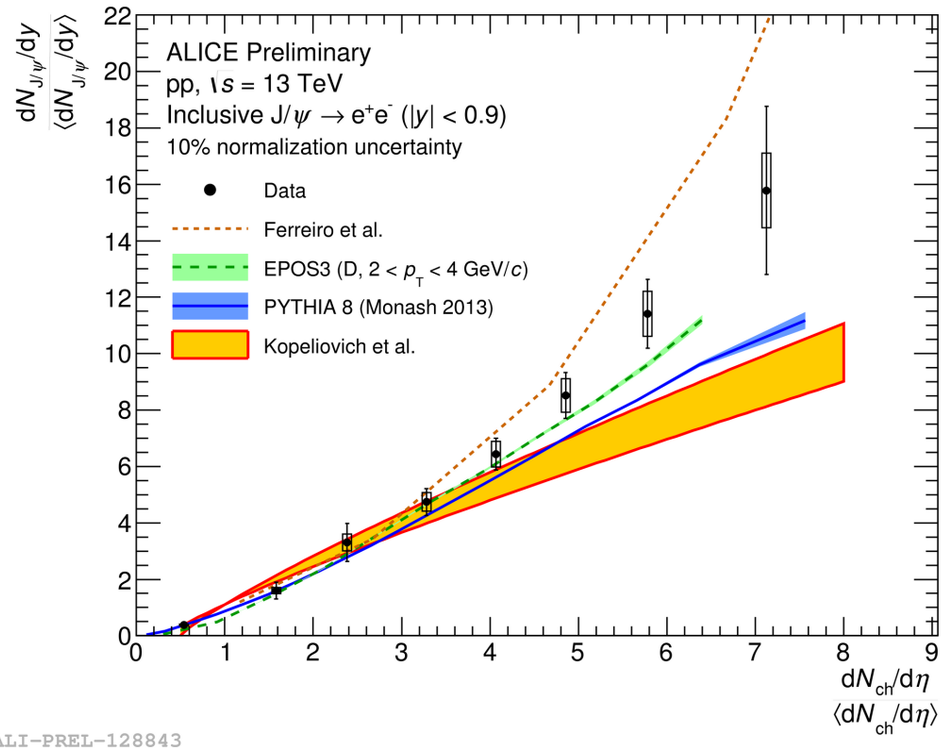


ALI-PUB-109787

Run2 luminosities used ($\mathscr{L}_{2\mu}|\mathscr{L}_{MB}$)

Coll. system	$\sqrt{s_{(NN)}}$ (TeV) 5.02	5.44
pp	106|19 nb^{-1}	-
Pb-Pb	225|14 μb^{-1}	-|

Models for J/psi vs. multiplicity

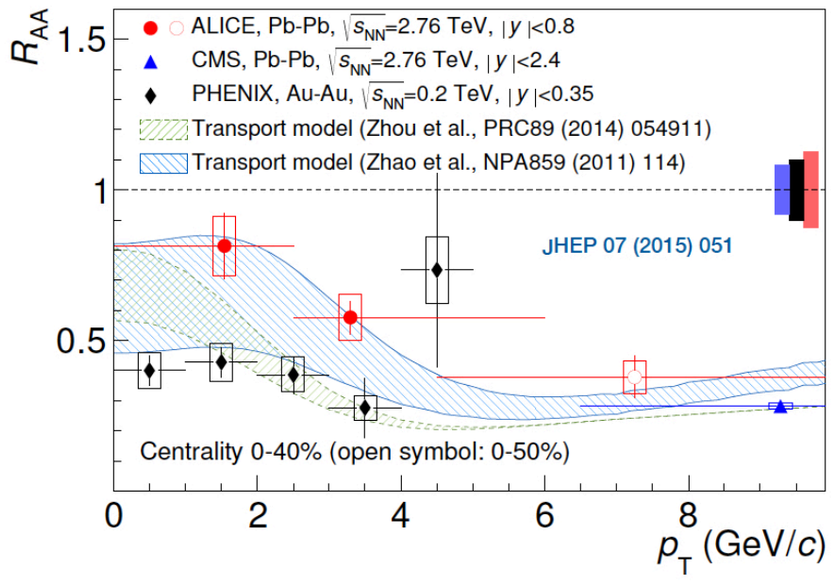


Stronger than linear increase attributed to soft particle saturation due to

- String overlapping (Ferreiro)
- Higher Fock states (Kopeliovich)
- Hydrodynamic expansion (EPOS3)
- CGC saturation effects

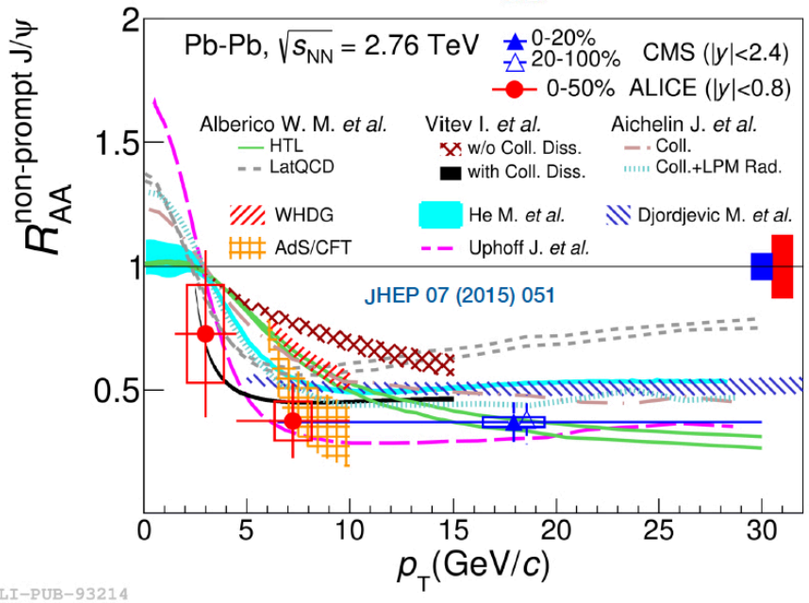
Run1 results

inclusive J/ψ,
0 - 40 % Pb-Pb, $\sqrt{s_{NN}}$= 2.76 TeV
mid-rapidity (|y| < 0.8)



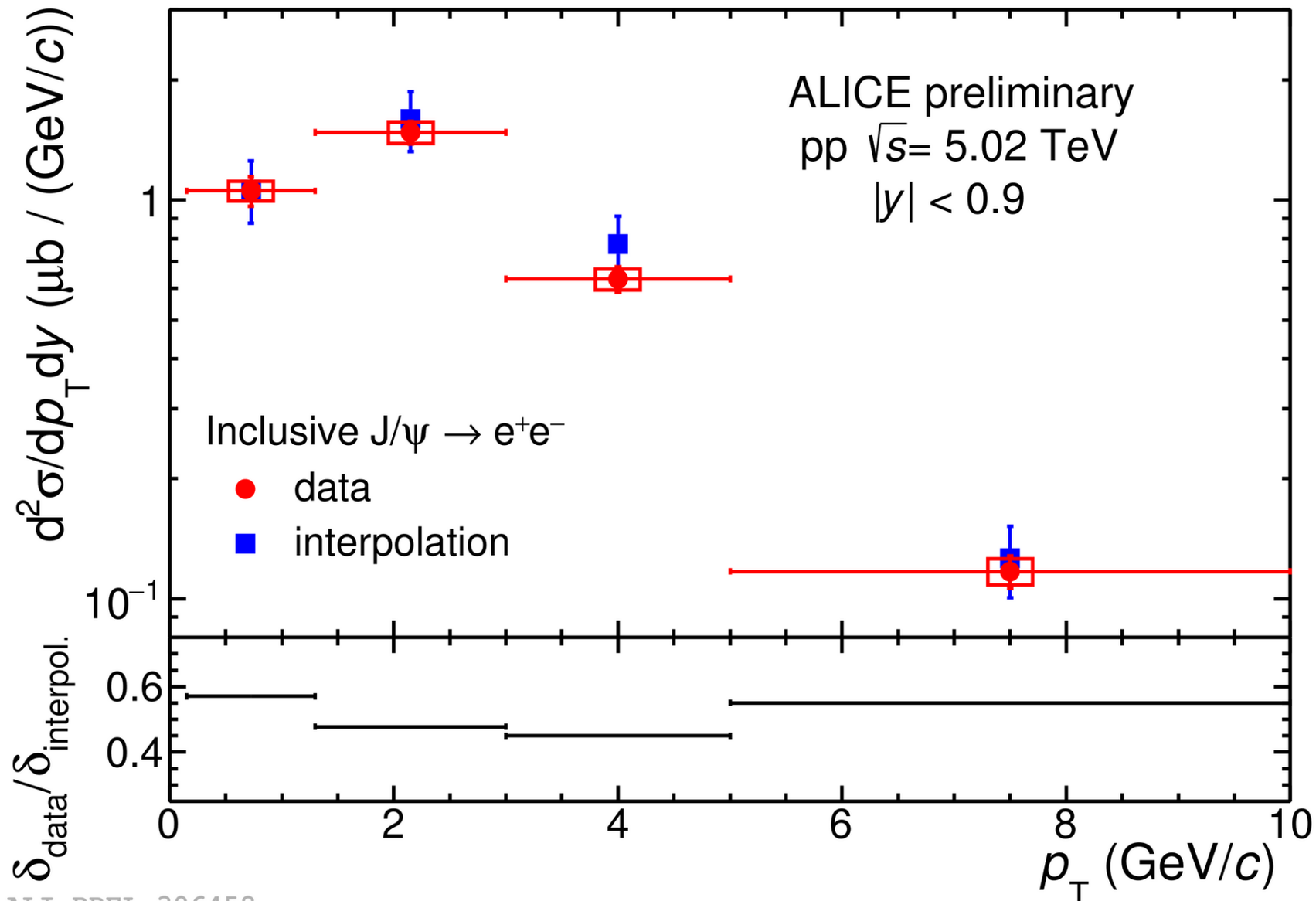
non-prompt J/ψ
0 - 50 % Pb-Pb, $\sqrt{s_{NN}}$= 2.76 TeV
mid-rapidity (|y| < 0.8)

$$R_{AA}^{\text{non-prompt J}/\psi} = \frac{f_B^{\text{Pb-Pb}}}{f_B^{\text{pp}}} R_{AA}^{\text{incl. J}/\psi}$$



ALI-PUB-93214

pp reference for R_{AA}

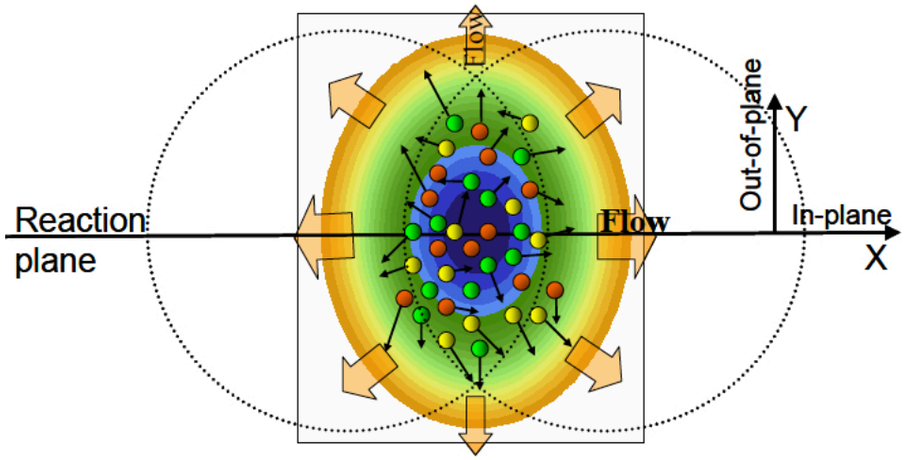


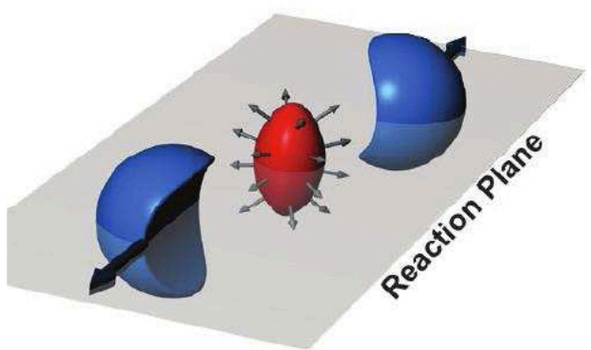
Elliptic flow

Initial spatial anisotropy $\xrightarrow[\text{in the medium}]{\text{via re-scatterings}}$ momentum anisotropy of particle emission

The anisotropy is quantified via a Fourier expansion in azimuthal angle ( ) with respect to the reaction plane (Ψ_{RP})

$$\frac{dN}{} = \frac{N_0}{}(1 + 2v_1\cos(\varphi - \Psi_{RP}) + 2v_2\cos[2(\varphi - \Psi_{RP})] + \ldots)$$





- Due to their large mass, c and b quarks should take longer time (= more re-scatterings) to be influenced by the collective expansion of the medium
  - $v_2(b) < v_2(c)$
- Uniqueness of heavy quarks: cannot be destroyed and/or created in the medium
  - Transported through the full system evolution