J/ψ production in pp, p-Pb and Pb-Pb collisions with ALICE

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on behalf of the ALICE collaboration

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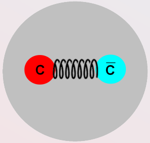
The 9th international conference on Quarks and Nuclear Physics - QNP 2022
Florida State University - 5-10th September 2022

J/ψ as a tool for studying small systems



The J/ψ meson :

- Ground state of spin 1 charmonia.
- Heavy quarks **produced at the initial stage of the collision** and described by perturbative QCD.
- **Hadronization** into a "colourless" bound state through a non-perturbative process.

pp collisions :

- Allow to understand better the quarkonium **production mechanisms**.
- Give a **reference** for Pb-Pb and p-Pb collisions.

p-Pb collisions :

- Information on **cold nuclear matter** effects.

High multiplicity events :

- Give insight on **multiparton interactions** (MPI).
- Insights on **collectivity** via for instance elliptic flow measurements.

J/ψ as a probe of the QGP in Pb-Pb collisions

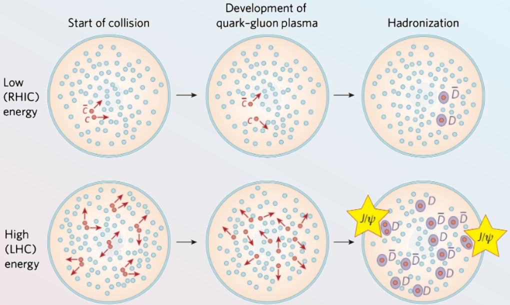
ALICE

Pb-Pb collisions

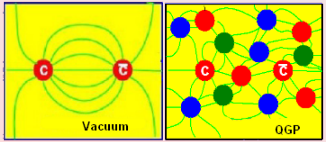
- Quark Gluon Plasma (QGP) is a deconfined state of nuclear matter produced in heavy ions collisions.
- Quarkonia **suppressed** by color screening due to free color charges in the QGP or by dissociation.

  T. Matsui and H. Satz, PLB 178 (1986) 416, A Rothkopf, Phys. Rept. 858 (2020) 1-117
- **Recombination** happening at the LHC energies due to the large $c\bar{c}$ production cross section.

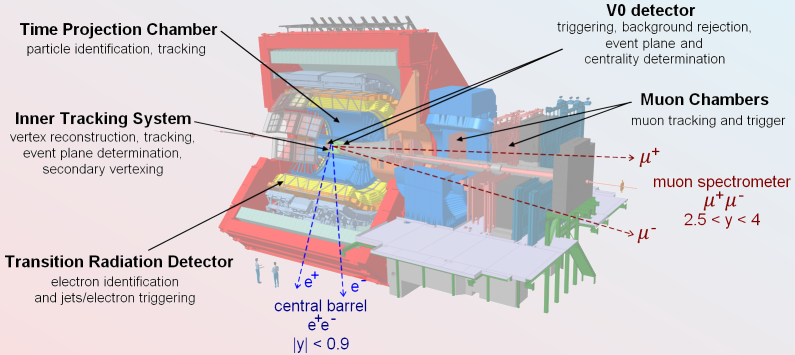
  P. Braun-Muzinger, J. Stachel, PLB 490 (2000) 196, R. Thews et al, Phys. Rev. C 63 (2001) 054905)
- Non-prompt J/ψ, originating from beauty hadron decays, allow to access beauty quark energy loss inside the QGP.



P Braun-Munzinger and J Stachel, *Nature volume 448, pages 302–309 (2007)*



A Large Ion Collider Experiment (ALICE)



- Central barrel : inclusive J/ψ down to zero p_T and prompt/non-prompt J/ψ down to low p_T.
- Muon spectrometer : inclusive quarkonia down to zero p_T.

J/ψ production for different energies at forward rapidity

Cross section :

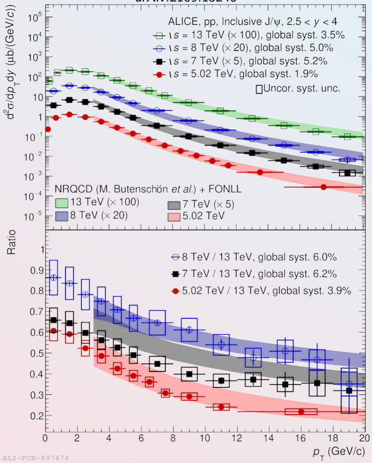
- **Increasing values and hardness** of the p_T spectra **with the energy** of the collision.
- Data in agreement with NRQCD + FONLL model.
- Same result for ICEM + FONLL model (Back-up).

Cheung et al., Phys. Rev. D 98, 114029 (2018)

Ratio :

- For the ratio, part of the theoretical and experimental uncertainties cancel → more constraints on models.
- Data reproduced by NRQCD + FONLL within uncertainties, 7-to-13 TeV ratio at the lower edge of model predictions.
- Separating prompt and non-prompt production at forward-y could help to constrain further separately the models.

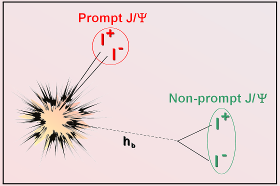
arXiv:2109.15240



NRQCD, Butenschön et al. : arXiv:1009.5662

FONLL, Cacciari et al. : arXiv:1205.6344

Prompt and non-prompt J/ψ production at midrapidity



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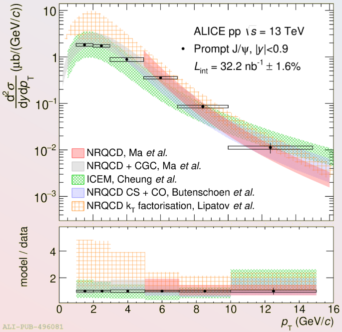
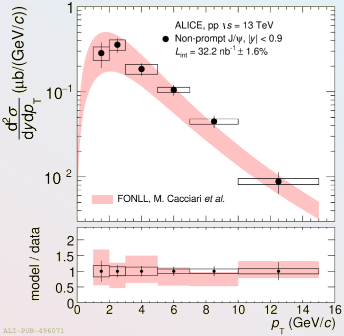




NRQCD, Butenschoen : arXiv:1009.5662

NRQCD+CGC, Ma et al. : arXiv:1408.4075

ICEM, Cheung et al. : arXiv:1808.02909

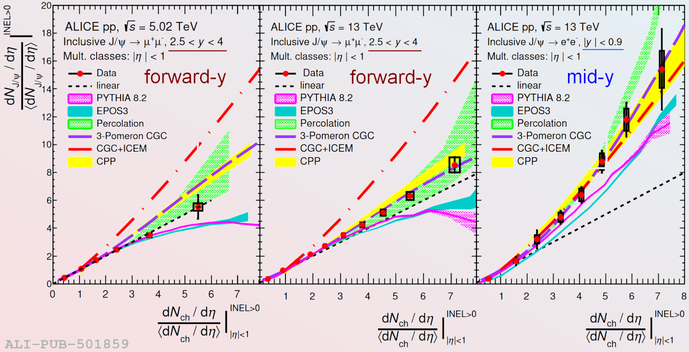
FONLL, Cacciari et al. : arXiv:9803400

NRQCD, Lipatov et al. : Phys. Rev. D 100, 114021

- For prompt J/ψ, most of the models are in **good agreement** with the data. k_T factorisation model slightly overestimates the production at low p_T.
- Non-prompt J/ψ in agreement with FONLL model.

J/ψ production as a function of multiplicity

JHEP 06 (2022) 015



CPP, Kopeliovich et al. : arXiv:1910.09682

ICEM + CGC, Ma et al. : arXiv:1803.11093

3-Pomeron CGC, Siddikov et al. : arXiv:1910.13579

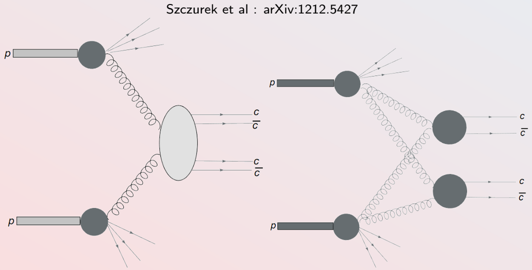
Percolation, Ferreiro et al. : arXiv:1203.5936

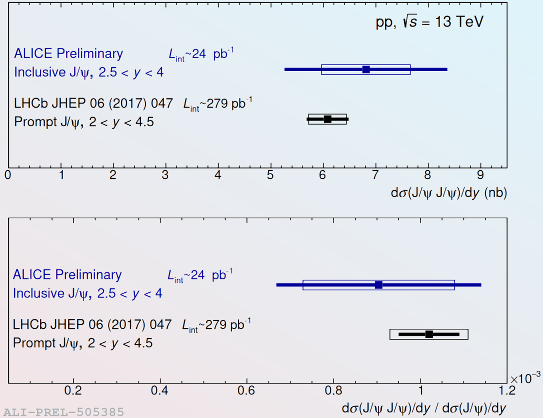
EPOS3, Werner et al. : arXiv:1312.1233

PYTHIAS 8.2, Sjöstrand et al. : arXiv:1410.3012

- Self-normalized J/ψ yield measured at forward rapidity shows a **linear trend** as a function of midrapidity multiplicity.
- **Stronger than linear** increase for the J/ψ self-normalised yield at midrapidity.
- Models can reproduce qualitatively the trends observed at both rapidities within uncertainties.

Double J/ψ production



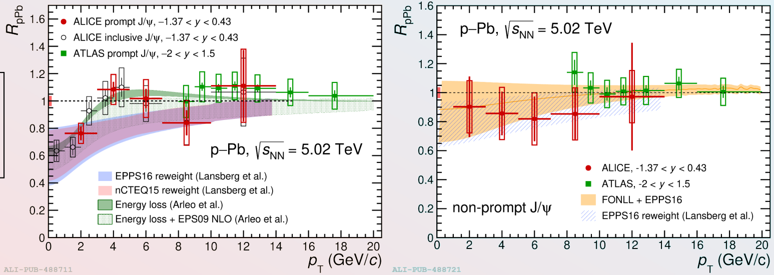


- **Good agreement between ALICE and LHCb** for both double J/ψ production cross section and its ratio to single J/ψ production cross section.

Prompt and non-prompt J/ψ nuclear modification factor

$$R_{pA} = \frac{1}{\langle N_{coll} \rangle} \frac{\frac{d^2 N_{pA}}{dy dp_t}}{\frac{d^2 N_{pp}}{dy dp_t}}$$

JHEP 06 (2022) 011



ALICE Collaboration: JHEP 06 (2022) 011

ATLAS Collaboration: Eur. Phys. J. C 78 (2018) 171

nCTEQ15 EPPS16 reweight, Lansberg et al: Phys.Rev.Lett.121,052004

FONLL : JHEP 9805:007,1998

Arleo et al. : Phys.Rev.Lett. 88 (2002) 232303

EPS09, Eskola et al. : JHEP 0904:065,2009

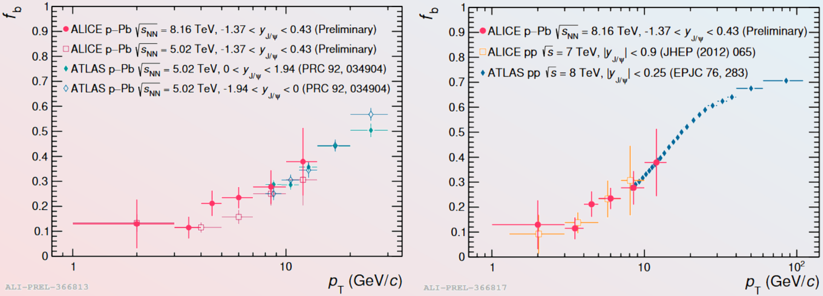
EPPS16, Eskola et al. : Eur. Phys. J. C 77, 163 (2017)

- Inclusive and prompt J/ψ **suppressed at low** p_T by about 40%; smaller suppression for non-prompt J/ψ with no significant p_T dependence.
- Data compatible with ATLAS in the common p_T range.
- For inclusive and prompt J/ψ R_{pPb}, models implementing initial state effects (nPDF modification and/or coherent energy loss) agree with data.
- EPPS16 reweighted nPDFs or FONLL coupled to EPPS16 nPDFs describe well non-prompt J/ψ data.

Non-prompt J/ψ fraction

$$f_b = \frac{\frac{d^2N_{np}}{dydp_t}}{\frac{d^2N_{inc}}{dydp_t}}$$

JHEP (2012) 065



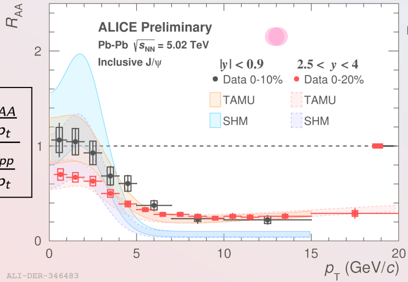
ATLAS Collaboration: PRC 92, 034904

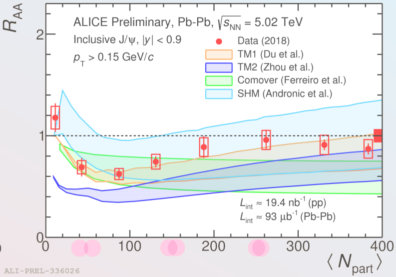
ATLAS Collaboration: EPJC 76, 283

- TRD triggered data used at $\sqrt{s_{NN}} = 8.16$ TeV.
- **No visible CNM effect** within the large experimental uncertainties.
- Good agreement between ALICE and ATLAS in the common p_T range.

Inclusive J/ψ production in Pb-Pb collisions

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{\frac{d^2 N_{AA}}{dy dp_t}}{\frac{d^2 N_{pp}}{dy dp_t}}$$





TM1, TAMU: Du X. and Rapp R., NPA 943 (2015) 147-158

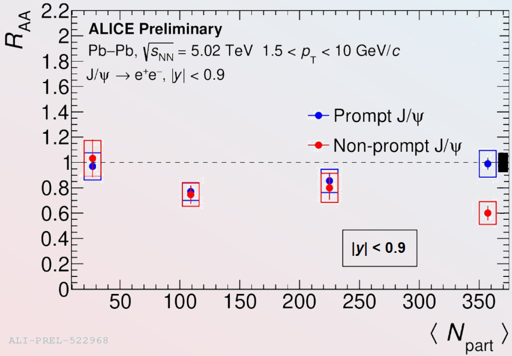
TM2: Zhou et al., PRC 89, 054911 (21 May 2014)

SHM: Andronic A. et al., PLB 797 (2019) 134836

Comover: Ferreiro E. et al., PLB 731 (2014) 57

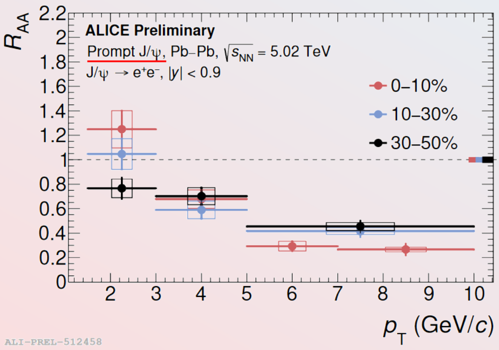
- Forward rapidity R_{AA} **smaller** compared to midrapidity at low p_T.
- R_{AA} is showing the **effect of regeneration** (low-p_T, mid-y and central collisions).
- R_{AA} shows also **suppression/dissociation** (high-p_T central events and semi-central collisions).
- Good agreement with models including regeneration at low p_T and in central events.

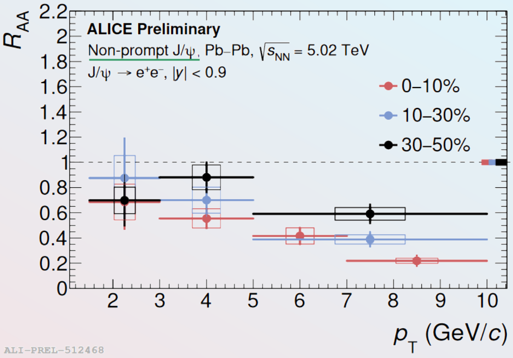
(Non-)Prompt J/ψ R_{AA} vs centrality



- Similar values of prompt and non-prompt R_{AA}, except for most central collisions → hint at regeneration for prompt J/ψ.

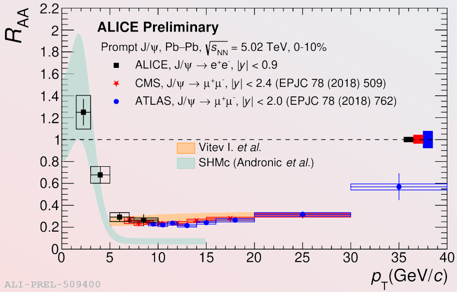
(Non-)Prompt J/ψ R_{AA} vs p_T in centrality intervals

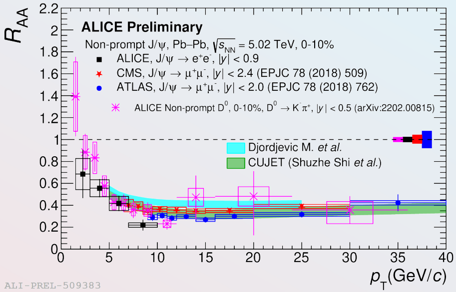




- **Prompt J/ψ R_{AA} increases at low p_T** especially in central collisions → consistent with the regeneration scenario.
- **Strong suppression at large p_T** for both prompt and non-prompt J/ψ.

(Non-)Prompt J/ψ R_{AA} vs p_T: comparison with models





CMS collaboration: EPJC 78 (2018) 509

ATLAS collaboration: EPJC 78 (2018) 762

Vitev et al. : arXiv:1709.02372

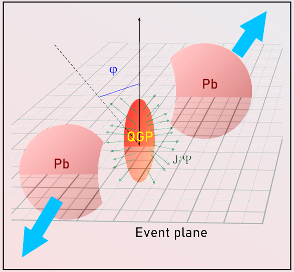
SHMc, Andronic et al. : JHEP07 (2021) 035

Djordjevic et al. : Phys. Rev. C 105, L021901 (2022)

CUJET, Shuzhe Shi et al. : Chin.Phys.C 43 (2019) 4, 044101

- Agreement between ALICE, ATLAS and CMS results in the overlapping p_T range; ALICE extends measurements down to $p_T = 1.5$ GeV/c.
- SHMc model which includes regeneration agrees with prompt J/ψ R_{AA} measurement at low p_T, while model by Vitev et al. which includes quarkonium dissociation can reproduce data at high p_T.
- Both Djordjevic and CUJET models, including collisional and radiative energy loss processes, agree with measured non-prompt J/ψ R_{AA}.

Elliptic flow measurements in Pb-Pb collisions



$$v_2 = \langle \cos\left[2\left(\phi - \Psi_{EP}\right)\right]\rangle$$

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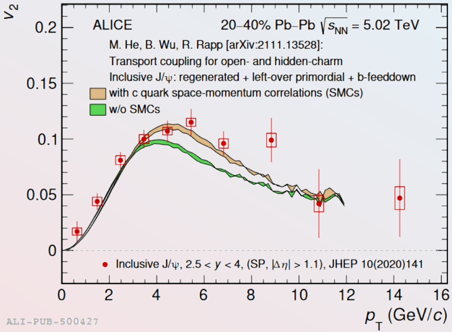
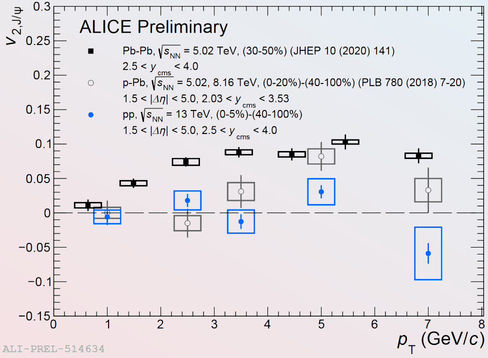


TAMU SMC, He et al. : arXiv:2111.13528

- **Non-zero** v_2, vanishing towards zero p_T.
- Increasing trend at low p_T; decrease at high p_T approaching a non-zero asymptotic value.
- Transport model with c-quark SMCs explains better the trend observed for the data at intermediate p_T.

Elliptic flow measurements: comparison among collisions systems



- **No collective behavior** observed for the J/ψ **in pp collisions** with ALICE.
- Hierarchy of flow amplitude with system size : $v_2(pp) < v_2(pPb) < v_2(PbPb)$

Summary and outlook

pp collisions :

- Prompt J/ψ production at midrapidity described by NRQCD and ICEM models, non-prompt J/ψ by FONLL. Inclusive J/ψ described by NRQCD+FONLL and ICEM+FONLL at forward y.
- First di-J/ψ and J/ψ v_2 measurements in pp collisions. No evidence for J/ψ flow in pp.
- Production vs multiplicity qualitatively described by models for both midrapidity and forward rapidity J/ψ.

p-Pb collisions :

- Good agreement with theoretical models including initial state effects.

Pb-Pb collisions:

- Theoretical models including regeneration agree with prompt and inclusive J/ψ R_{AA} measurements.
- v_2 results in Pb-Pb agree with transport models calculations.

Coming soon with Run 3:

- Smaller statistical uncertainties thanks to the increased statistics (J/ψ vs mult, double J/ψ...).
- Separation of prompt/non-prompt J/ψ at forward rapidity thanks to the new MFT detector.
- Improved spatial resolution at midrapidity thanks to the ITS upgrade.

Thanks

Thank you for your attention !

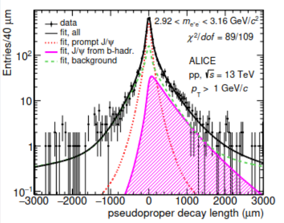
Prompt and non-prompt J/ψ separation

- The pseudo proper decay length x is better designed for central rapidity :

$$x = \frac{\vec{L}.\vec{p}_T M_{J/\psi}}{|\vec{p}_T|}$$

where $\vec{L}$ is the vector from the PV to the SV.

- Prompt : Dirac function / Non-prompt : Exponential. Both are convoluted with a triple-Gaussian function.

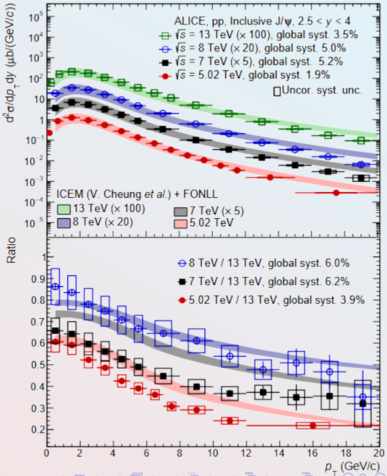


J/ψ production at forward rapidity in pp collisions (ICEM model)

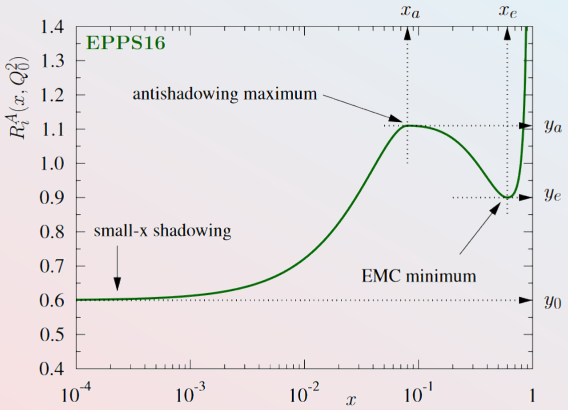
ALICE

- In agreement with the ICEM + FONLL model.
- Ratio theoretical values qualitatively reproduce the data, slightly overestimating it.

ICEM : arXiv:1808.02909

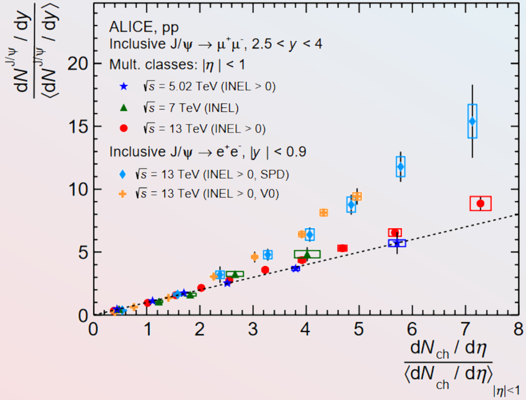


Scale-dependent nuclear modification factor for gluons



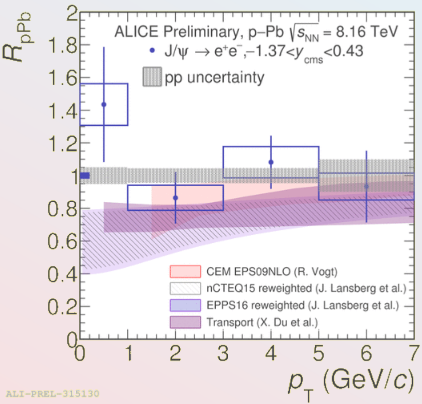
- Shadowing explains suppress in prompt J/ψ R_{pPb} at low p_T.

Self-Normalized J/ψ yield vs multiplicity



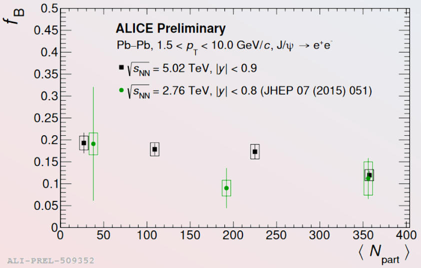
- Agreement between SPD and V0 excludes self-correlation bias.

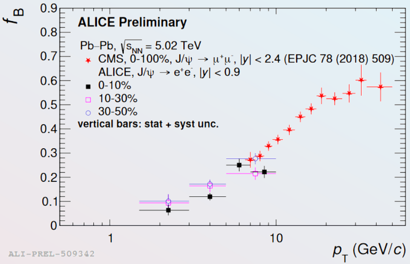
Comparison of nuclear modification factor vs p_T with models



- First data using TRD trigger at $\sqrt{s_{NN}} = 8.16$ TeV.

Non-prompt ratio in Pb-Pb collisions





- No strong centrality dependence. Small reduction of f_B in central events due to the regeneration of prompt J/ψ.
- Increase of non-prompt production with p_T, consistent with CMS measurement in the common p_T interval.

Elliptic flow definition

$$v_n SP = \left\langle \frac{\mathbf{u}_n \mathbf{Q}_n^{A*}}{\sqrt{\frac{\langle Q_n^A Q_n^{B*} \rangle \langle Q_n^A Q_n^{C*} \rangle}{\langle Q_n^B Q_n^{C*} \rangle}}} \right\rangle_{ll}$$

- $u_n = e^{in\phi}$ is the unit flow vector for a given harmonic n, of the particle of interest and Q_n^{A*} the complex conjugate of the event flow vector in a subdetector A.
- Q_n^B and Q_n^C are the n-th harmonic event flow vectors measured in two additional subdetectors, B and C.
- The star ($*$) represents the complex conjugate and the bracket $<...>_{ll}$ indicates the average over dileptons from all events in a given p_T range, dilepton invariant mass (m_{ll}), and centrality interval.
- No path-length dependence with this method as compared to the geometrical methode.

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