Quarkonium production in pp, p-Pb and ultra-peripheral collisions with the ALICE detector at the LHC

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The fifth installment on the physics of the initial stages of high energy nuclear collisions

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Quarkonium production at LHC

- Quarkonium production in pp collisions at LHC

Heavy-quark pair production (perturbative) + **Evolution into colorless state (Non-perturbative)**

- ➢ **Sensitive to gluon PDF**
- ➢ Production mechanism still not fully understood
  - ✓ Color Singlet Model *PLB102 364 (1981)*
  - ✓ Color Evaporation Model *PRD 12 2007 (1975)*
  - ✓ Non-relativistic Model (NRQCD) *PRD 51 1125 (1995)*

- Cold nuclear matter (CNM) effects
  - ✓ Modification of gluon distribution (nPDF): **Shadowing, saturation**
  - ✓ Multiple scattering of incident partons
  - ✓ Coherent energy loss
  - ✓ Break up with co-moving particles

- Ultra-peripheral collisions (p-Pb/Pb-Pb)
  - ✓ Give access to the investigation of gluon PDF in proton/lead

Introduction

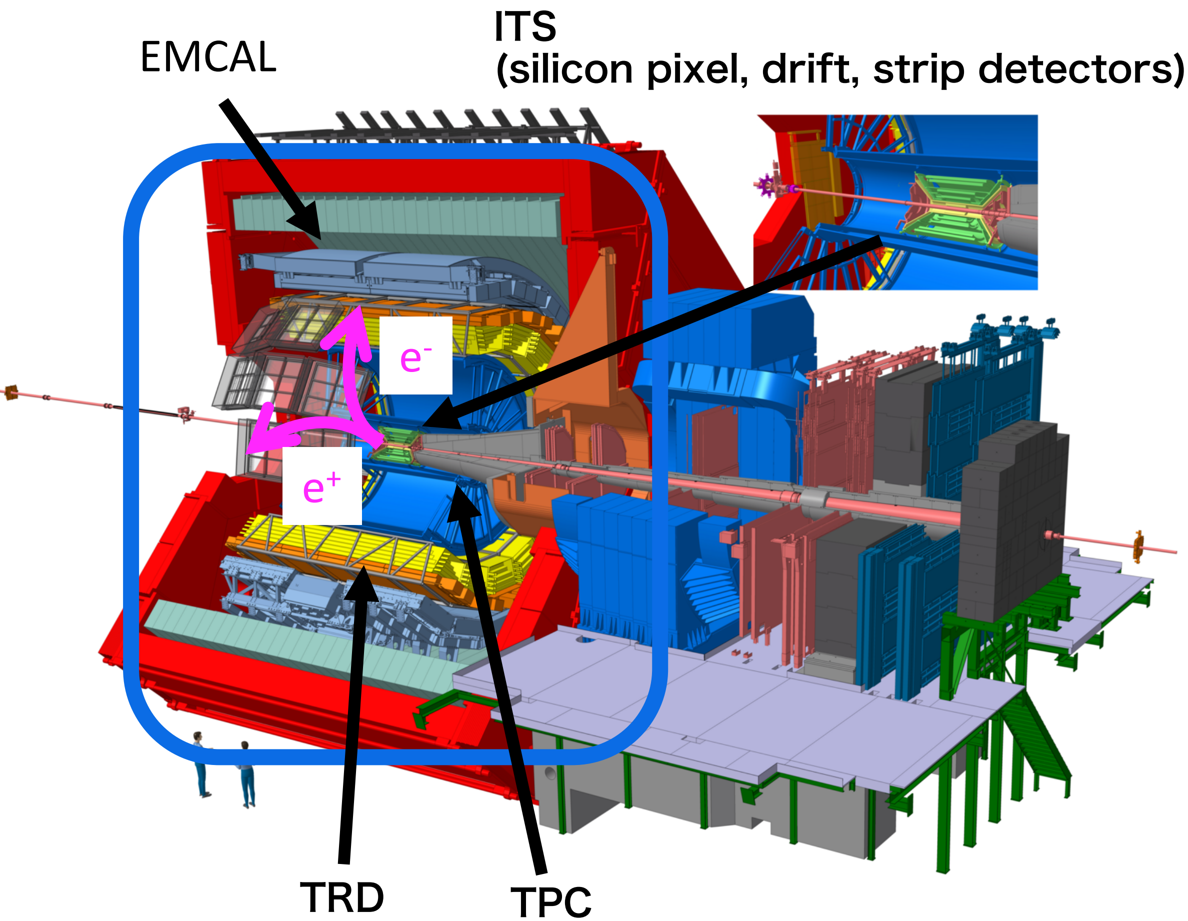
- Multiplicity dependence of quarkonium production
  - ➢ Underlying physics:
    - ✓ Multi-parton interaction (MPI)
    - ✓ Color reconnection

  High multiplicity pp and p-Pb collisions show collectivity similar to that in Pb-Pb collisions
    - ➢ **Flow of quarkonium in small systems**

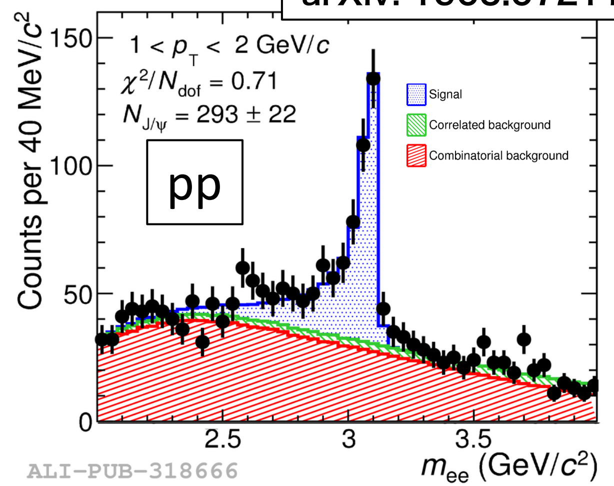
Quarkonium measurements in ALICE

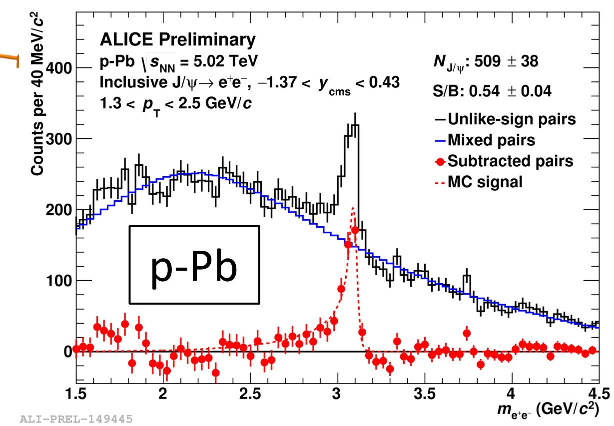
- Dilepton decay measurements
  - ✓ Wide rapidity coverage
  - ✓ Down to zero p_T

➢ Dielectron channel ($|y| < 0.9$)
- ✓ Charged-particle tracking
- ✓ Electron identification (TPC)



arXiv: 1905.07211

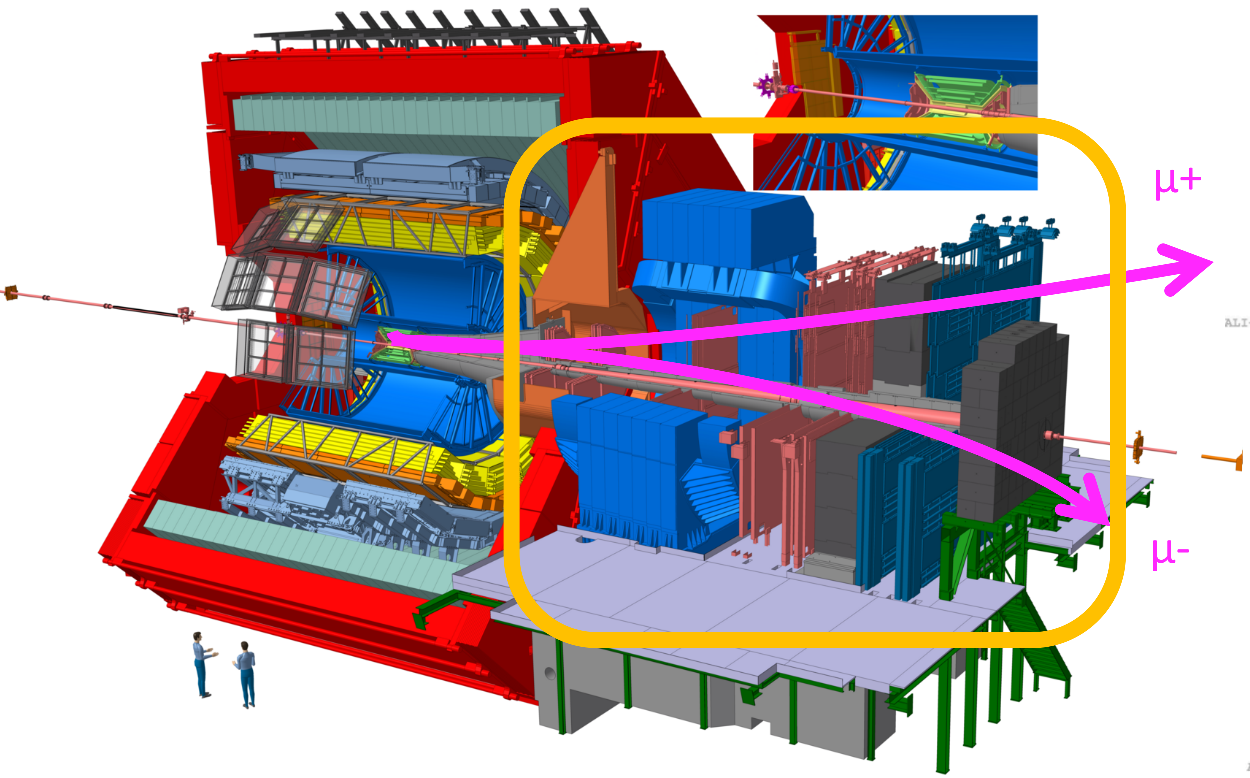


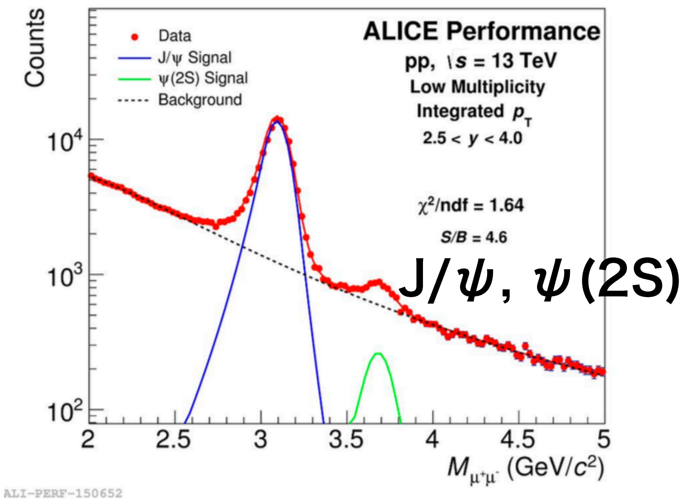


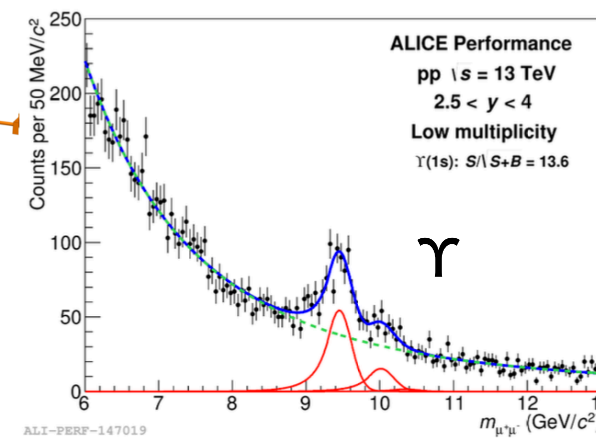
Quarkonium measurements in ALICE

- **Dilepton decay measurements**
  - ✓ Wide rapidity coverage
  - ✓ Down to zero p_T

➢ **Dimuon channel ($2.5 < y < 4$)**
  - ✓ Muon triggered data





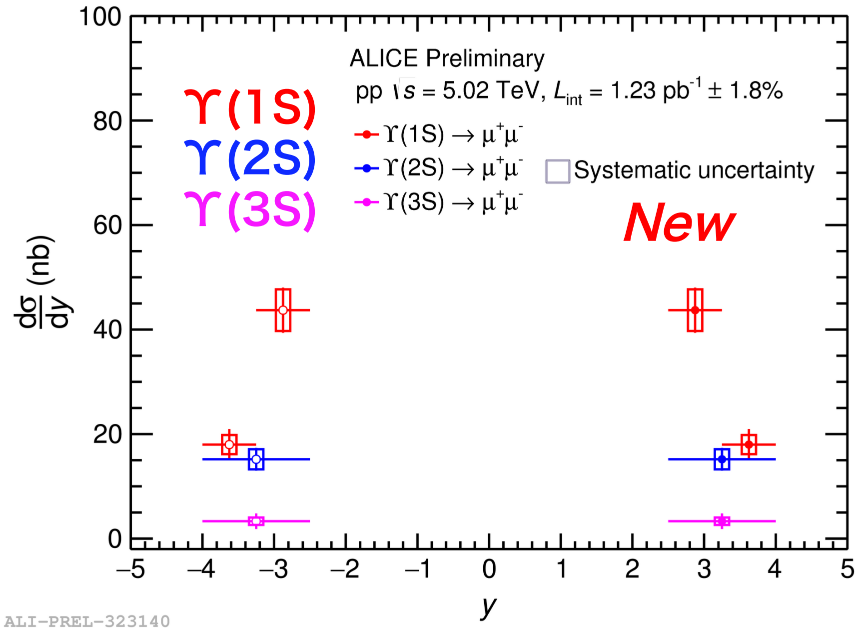


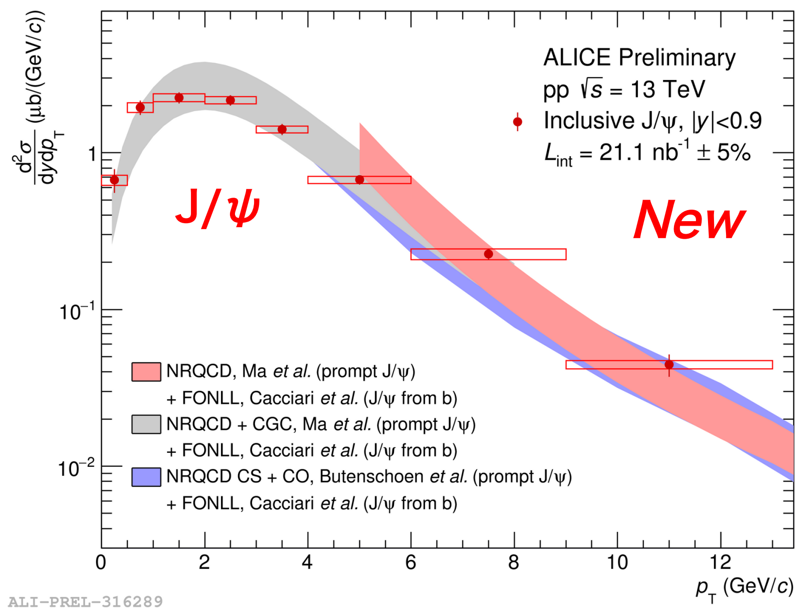
Quarkonium production cross section in pp collisions

- Υ cross section at $\sqrt{s}$ = 5.02 TeV with 2017 data set
  - ➢ Luminosity increases by a factor 10 w.r.t the previous data set
    - ✓ Benefit in calculation of the nuclear modification factor

- Inclusive J/ψ cross section at mid-rapidity at $\sqrt{s}$ = 13 TeV
  - ➢ NRQCD including CGC + FONLL (B→J/ψ) describes the data down to zero p_T
    - ➢ Same conclusion reached at forward rapidity

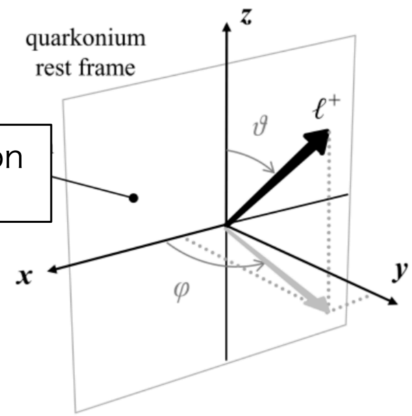
EPJC 77 392 (2017)





J/ψ polarization in pp collisions

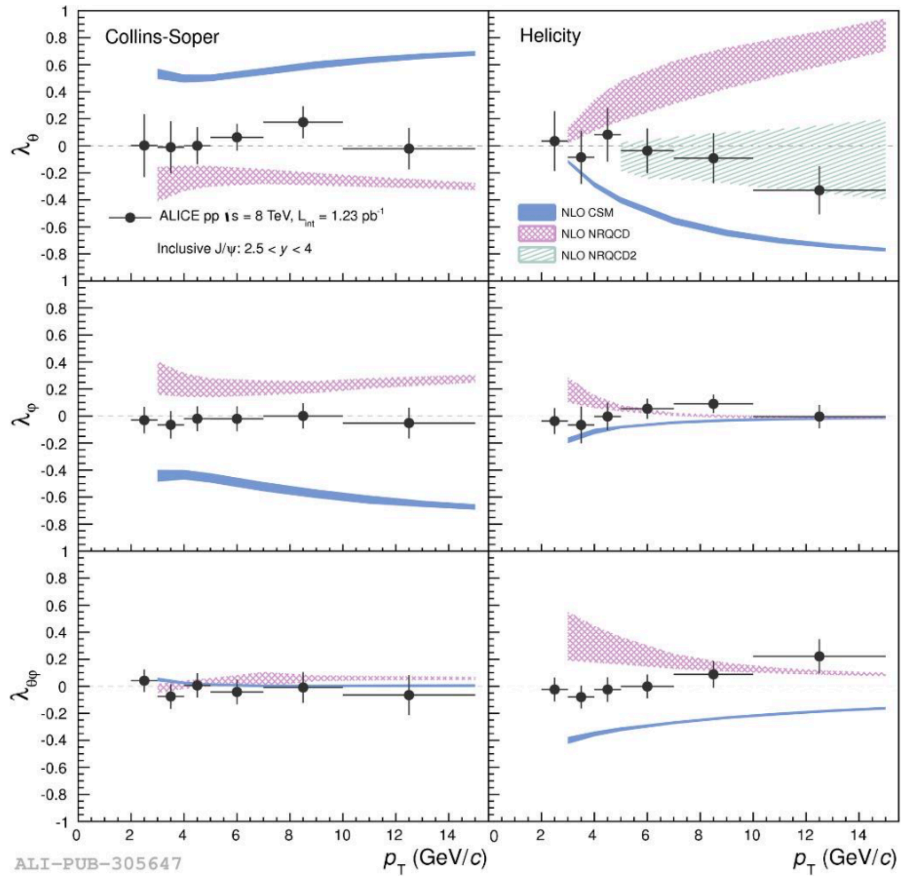
EPJC 78 562 (2018)



$$\frac{d^2N}{d\cos\theta d\varphi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\varphi}\sin 2\theta\cos\varphi + \lambda_\varphi \sin^2\theta\cos 2\varphi$$

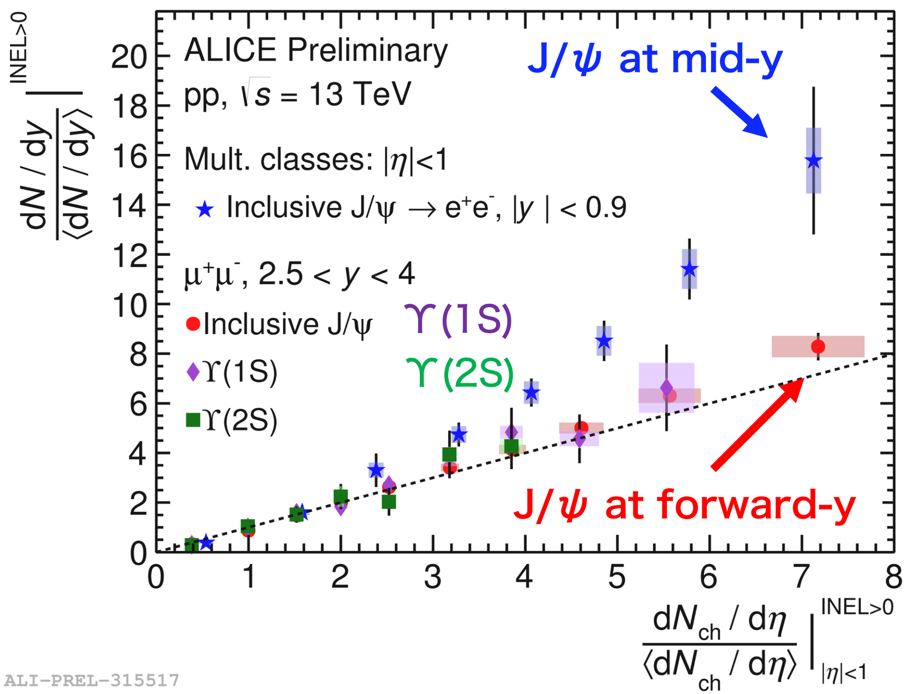
Z-axis:

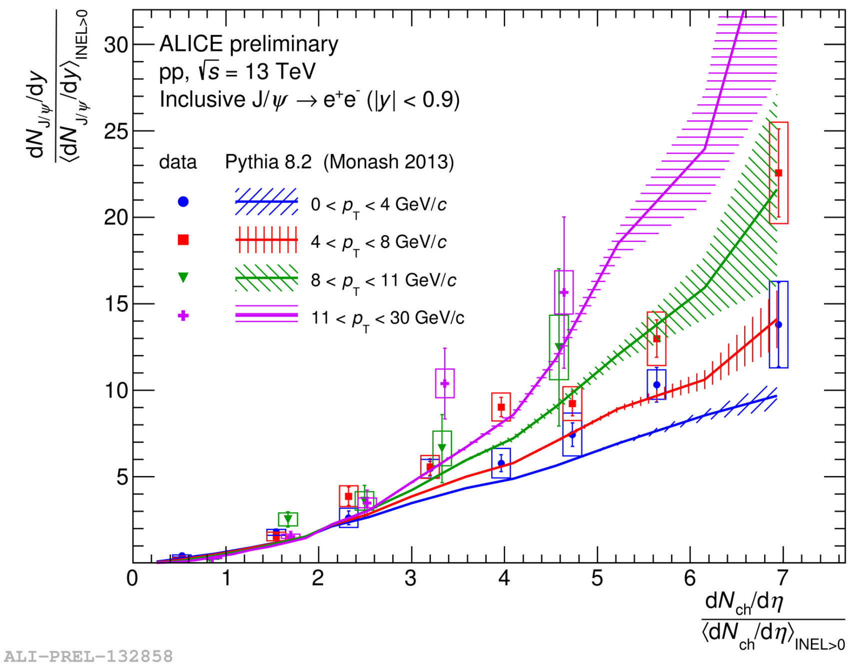
- ✓ Collins-Soper:
  Direction of the relative velocity of the colliding beams in the J/ψ rest-frame
- ✓ Helicity:
  Direction of J/ψ in the Lab-frame



- No significant J/ψ polarization measured
  - ➢ CSM and NRQCD cannot describe all polarization parameters

Multiplicity dependence of quarkonium production in pp collisions

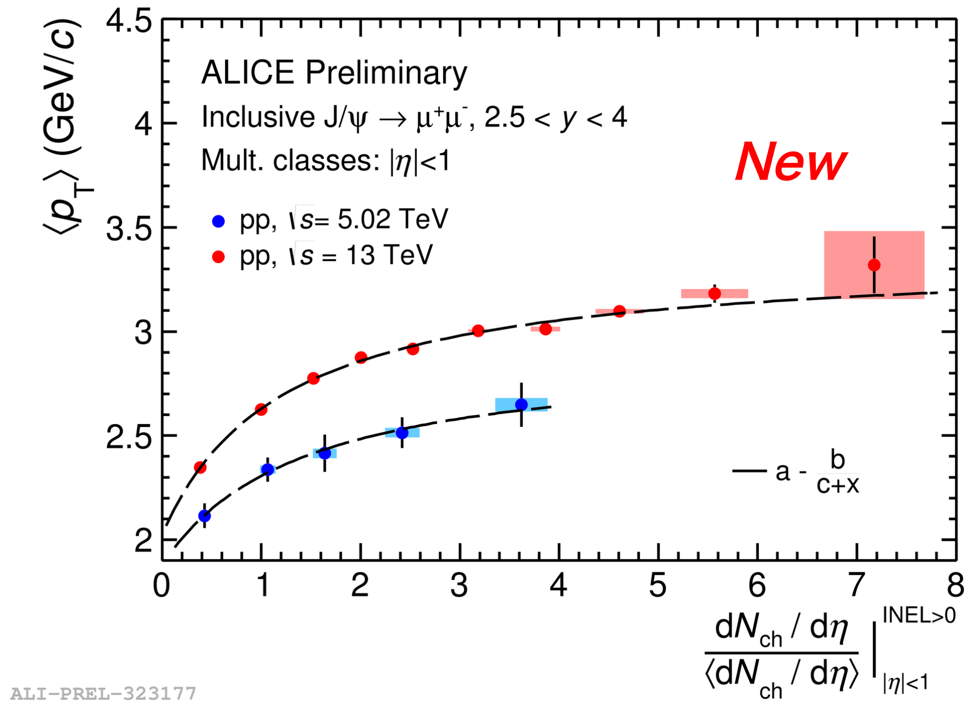




- Linear increase at forward rapidity: J/ψ, ϒ(1S), ϒ(2S)
  - ➢ Uncertainties large enough to be consistent with the CMS results
    - ✓ ϒ(nS)/ϒ(1S) decreases with multiplicity at mid-rapidity *JHEP04 103 (2014)*
- Stronger than linear (steeper at high p_T) increase at mid-rapidity (in same η range) : Auto-correlation
  - ➢ Qualitative agreement with model calculations including MPI (Pythia8 Monash 2013)

J/ψ ⟨p_T⟩ vs multiplicity in pp collisions

- No strong collision energy dependence
  - ✓ Increase of ⟨p_T⟩ at low multiplicity
  - ✓ A little saturation trend towards higher multiplicity



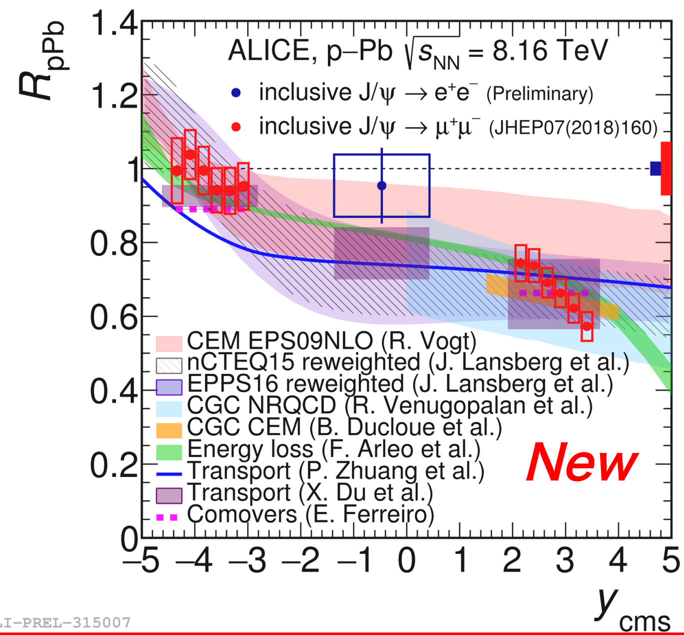
√s = 5.02 TeV

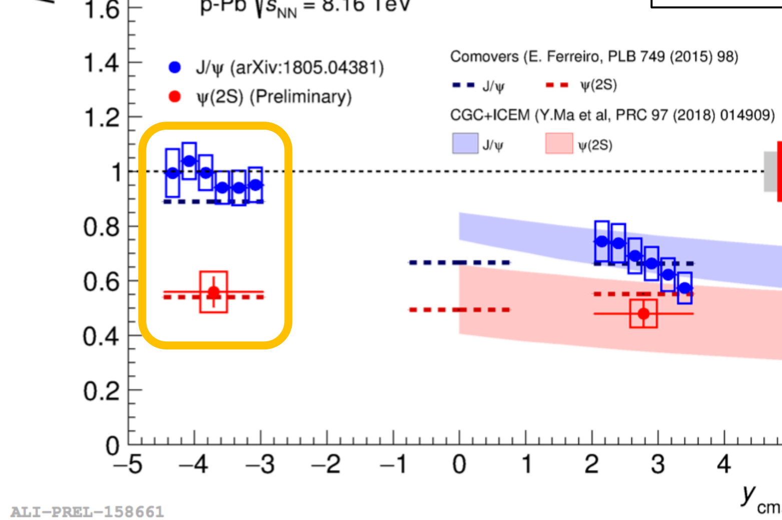
√s = 13 TeV

Charmonium production in p-Pb collisions

- Suppression of J/ψ production at forward rapidity
  - ➢ Generally described by initial state effects (including shadowing/saturation)
    - ✓ nPDF: EPS09NLO, nCTEQ15, EPPS16, CGC
    - ✓ Coherent energy loss
    - ✓ Transport model: nPDF + Cronin effect + fireball evolution+ feeddown
- Stronger suppression of ψ(2S), in particular at backward rapidity
  - ➢ Models including shadowing and interaction with co-moving particles describe the data

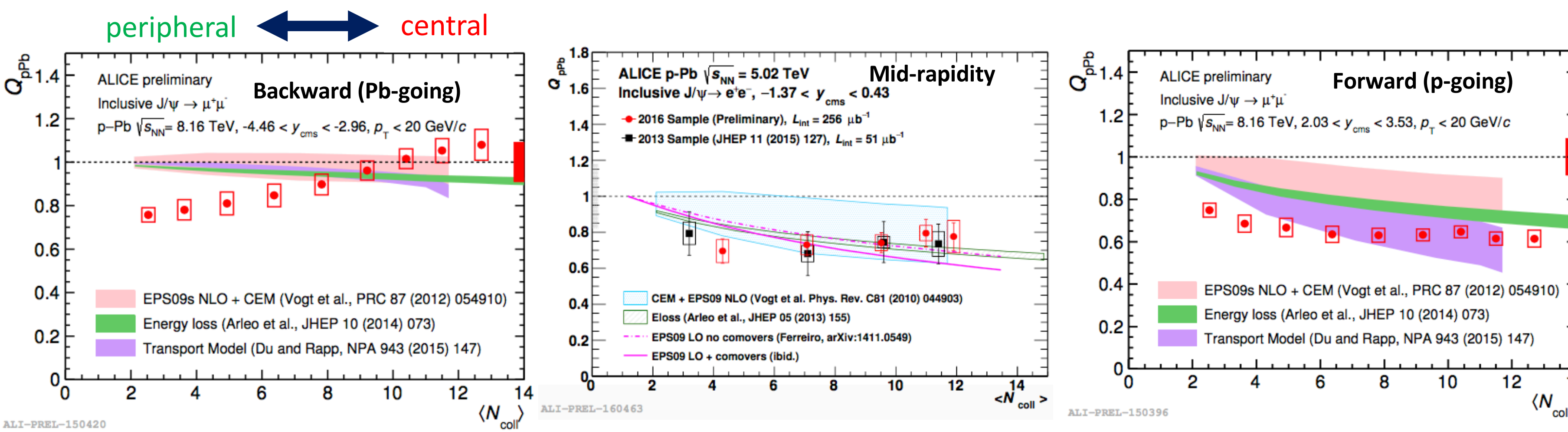
$$R_{\mathrm{pPb}} = \frac{\sigma^{Q\bar{Q}}_{\mathrm{pPb}}}{A\sigma^{Q\bar{Q}}_{\mathrm{pp}}}$$





Centrality dependence of J/ψ production in p-Pb collisions

- Centrality estimation using ZDC (112.5m away from IP)
  - ✓ Smallest biases from multiplicity fluctuation, Jet contribution, etc

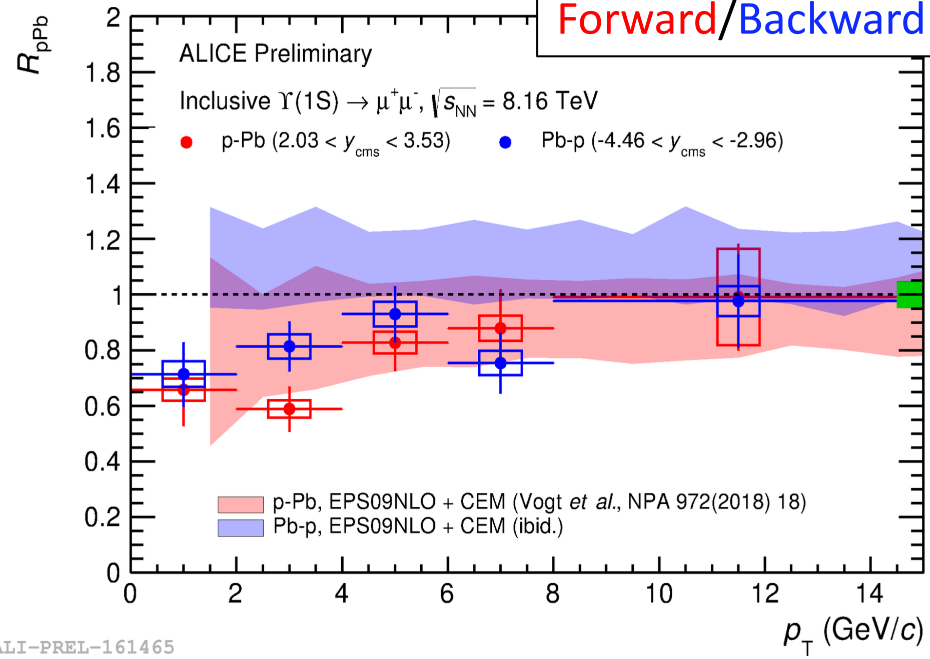


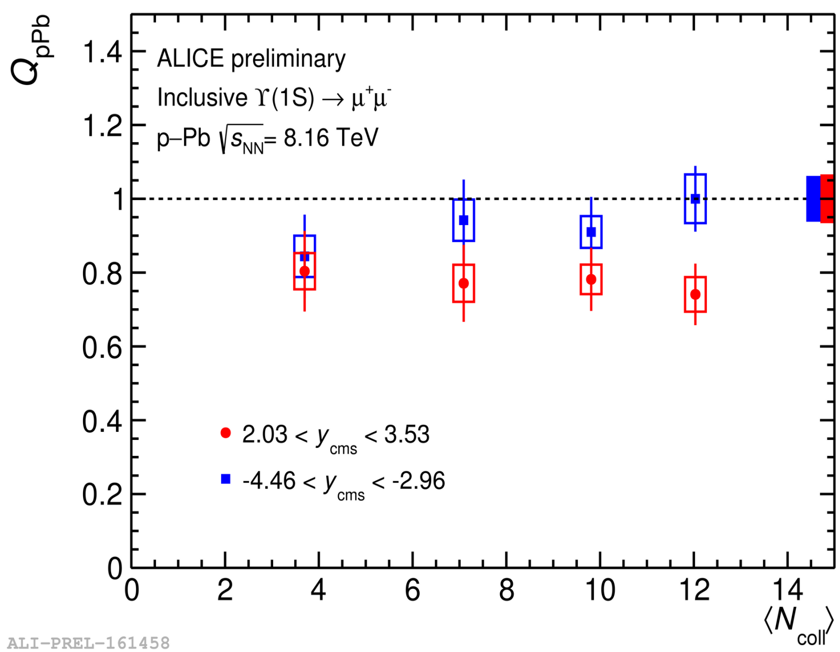
- ✓ Mid- and forward rapidity: Little centrality dependence
  - ➢ Reasonable agreement with model calculations within current model uncertainties
- ✓ Backward rapidity: Increasing Q_{pPb} for more central collisions
  - ➢ Discrepancy between the data and model calculations

Υ(1S) production in p-Pb collisions

- Suppression of Υ(1S) both at forward and backward rapidity
  - ➢ A model including the shadowing effect (EPS09NLO)
    - ✓ Reasonable agreement at forward rapidity
    - ✓ Overestimate the data at backward rapidity
  - ➢ No strong centrality dependence observed

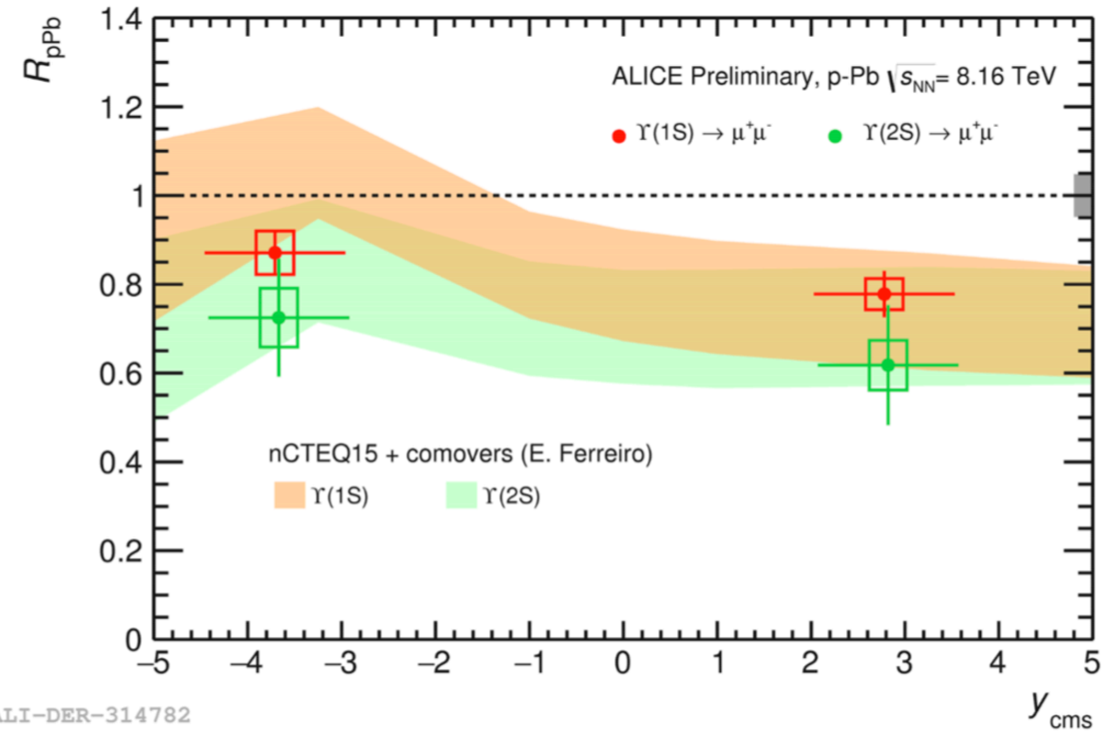
Forward/Backward





Υ(1S) and Υ(2S) production in p-Pb collisions

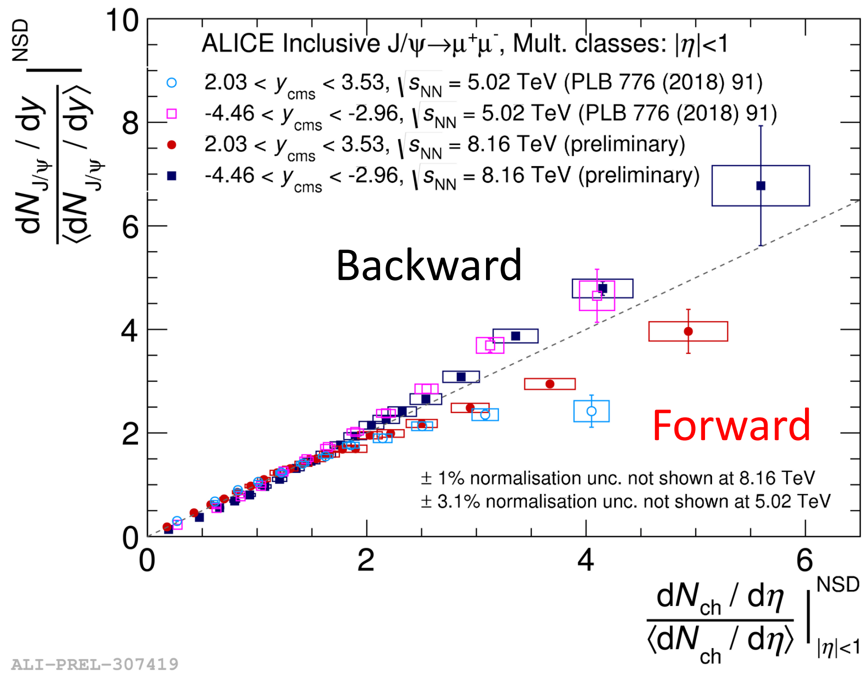
- Suppression for Υ(1S) and Υ(2S) at both forward and backward rapidity
  - ➢ Υ(2S) shows slightly stronger suppression compared to Υ(1S)
  - ➢ Models including shadowing and interaction with co-moving particles describe the data

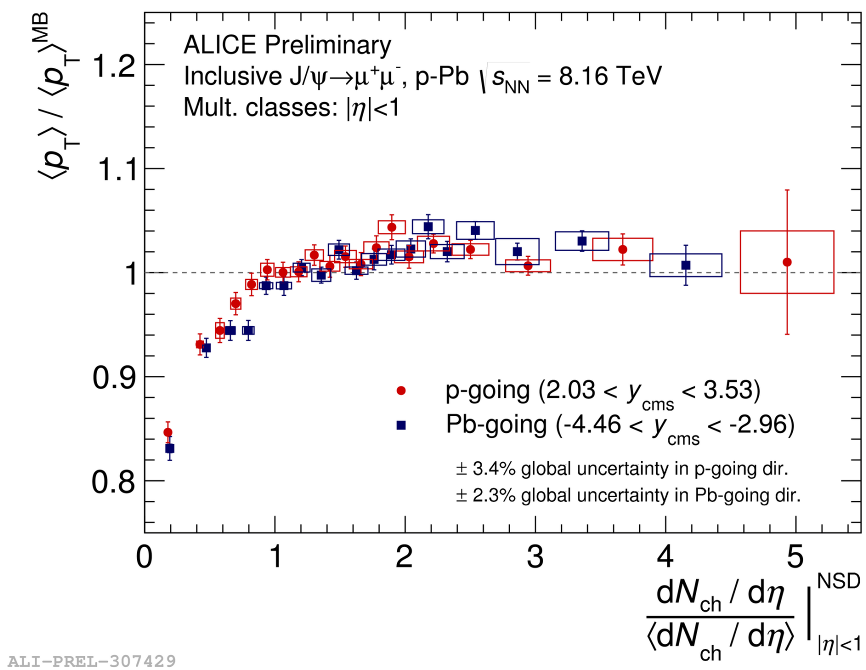


Multiplicity dependence of J/ψ production in p-Pb collisions

- Rapidity dependence seen
  - Linear increase at backward rapidity: similar behavior as in pp
  - Slower than linear increase at forward rapidity
- Strong saturation trend of $\langle p_T \rangle$ at high multiplicity
  - Saturated $\langle p_T \rangle$: Compatible with $\langle p_T \rangle_{MB}$
  - Monotonic increase for charged particles at same charged-particle density

PLB 727 371 (2013)

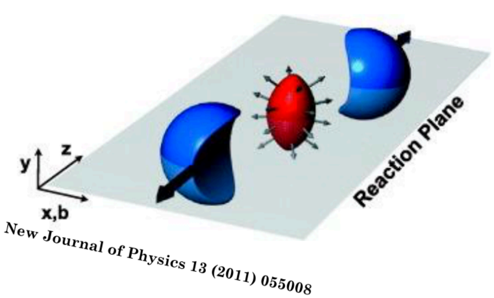




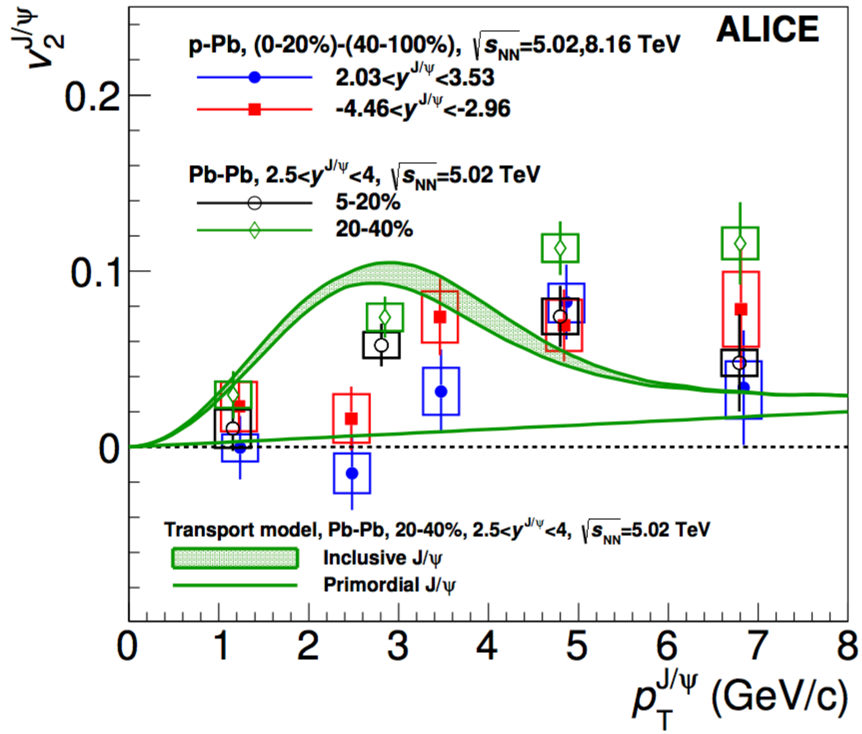
J/ψ v_2 in high multiplicity p-Pb collisions

Elliptic flow: $v_2 = \langle \cos n(\varphi_{particle} - \Psi_{EP,2}) \rangle$

- ✓ 2nd order Fourier coefficient of azimuthal angle correlation



PLB 780 7 (2018)



- High-multiplicity p-Pb events
  - ✓ Consistent with zero v_2 at low p_T
  - ✓ Large v_2 at p_T > 3 GeV/c
    - ➢ Similar magnitude of J/ψ v_2 in p-Pb and Pb-Pb collisions

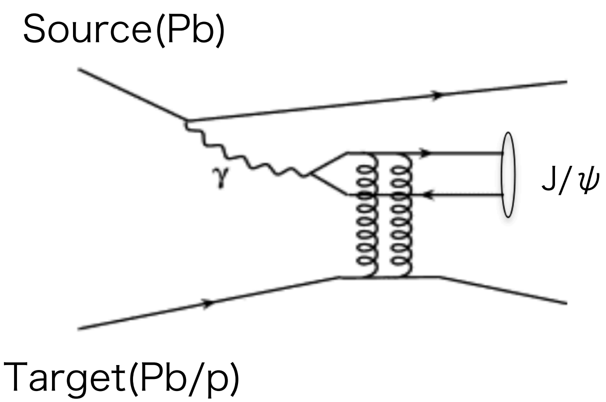
The origin of positive v_2 is not understood yet.

A transport model, which describes a large v_2 at low p_T in Pb-Pb, cannot describe the data in p-Pb *arXiv:1808.10014*

Ultra-peripheral collisions

- Ultra-peripheral collisions (UPC)
  - ✓ Impact parameter larger than sum of nuclear radii
    - ➢ Hadronic interaction suppressed
    - ➢ The electromagnetic field of ions can be viewed as an equivalent flux of photons($\propto Z^2$)

- Exclusive charmonium production
  - ✓ 2 gluons exchange process at leading order

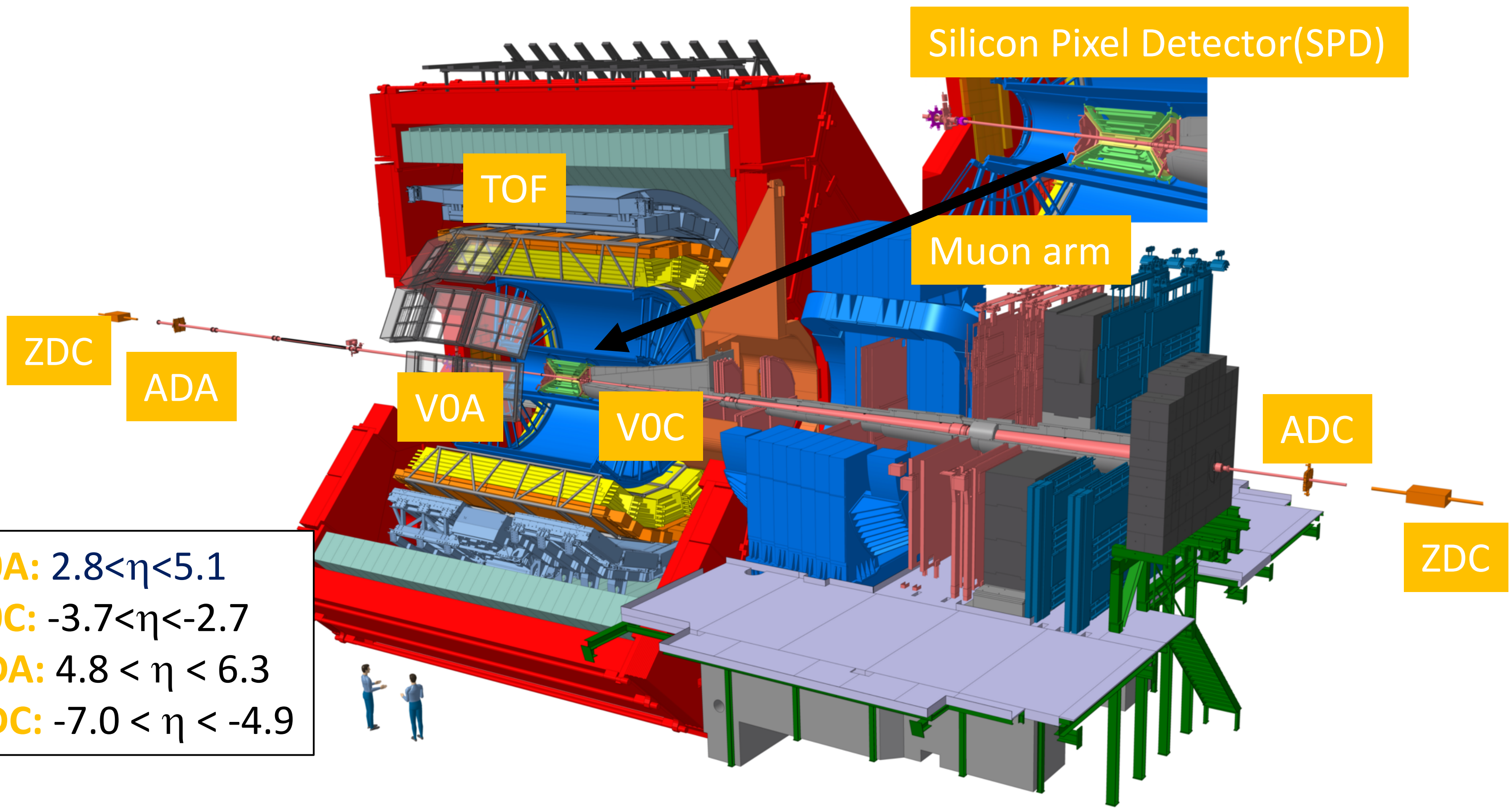


- Cross section is proportional to the gluon PDF squared
- Hard scale of J/ψ production
  - ✓ $Q^2 \sim (M_{J/\psi}{}^2/4) \sim 2.5$ GeV^2
  - ✓ $x \sim 10^{-5} - 10^{-2}$

<u>Investigation of gluon PDF at low *x* in the target</u>

ALICE UPC triggers

- ✓ Central trigger: $\overline{\text{V0A}}\cdot\overline{\text{V0C}}\cdot\overline{\text{ADA}}\cdot\overline{\text{ADC}}\cdot\text{SPD}\cdot\text{TOF}$(2≦hits≦6, back-to-back)
- ✓ Forward trigger: $\overline{\text{V0A}}\cdot\overline{\text{ADA}}\cdot\overline{\text{ADC}}\cdot$di-muon

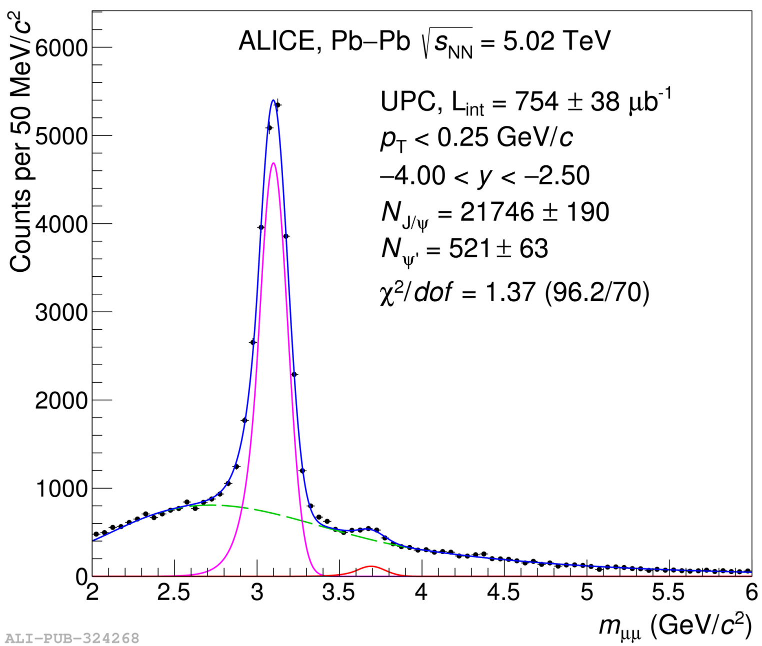


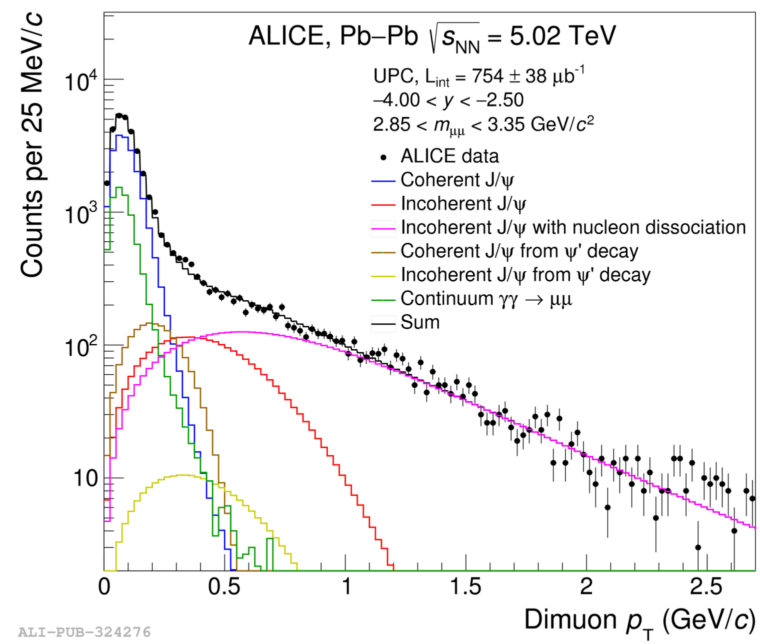
V0A: $2.8<\eta<5.1$
V0C: $-3.7<\eta<-2.7$
ADA: $4.8 < \eta < 6.3$
ADC: $-7.0 < \eta < -4.9$

ALICE UPC triggers

- ✓ Central trigger: $\overline{\text{V0A}}\cdot\overline{\text{V0C}}\cdot\overline{\text{ADA}}\cdot\overline{\text{ADC}}\cdot\text{SPD}\cdot\text{TOF}(2\leqq\text{hits}\leqq 6\text{, back-to-back})$
- ✓ Forward trigger: $\overline{\text{V0A}}\cdot\overline{\text{ADA}}\cdot\overline{\text{ADC}}\cdot\text{di-muon}$

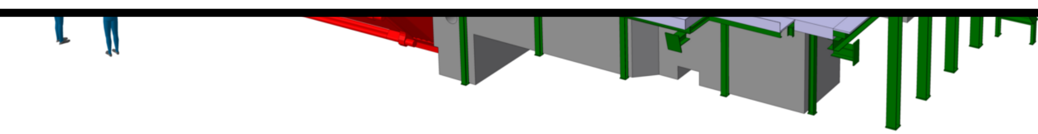
arXiv:1904.06272





STARLIGHT template fits for p_T
- ✓ Estimate coherent/incoherent contributions

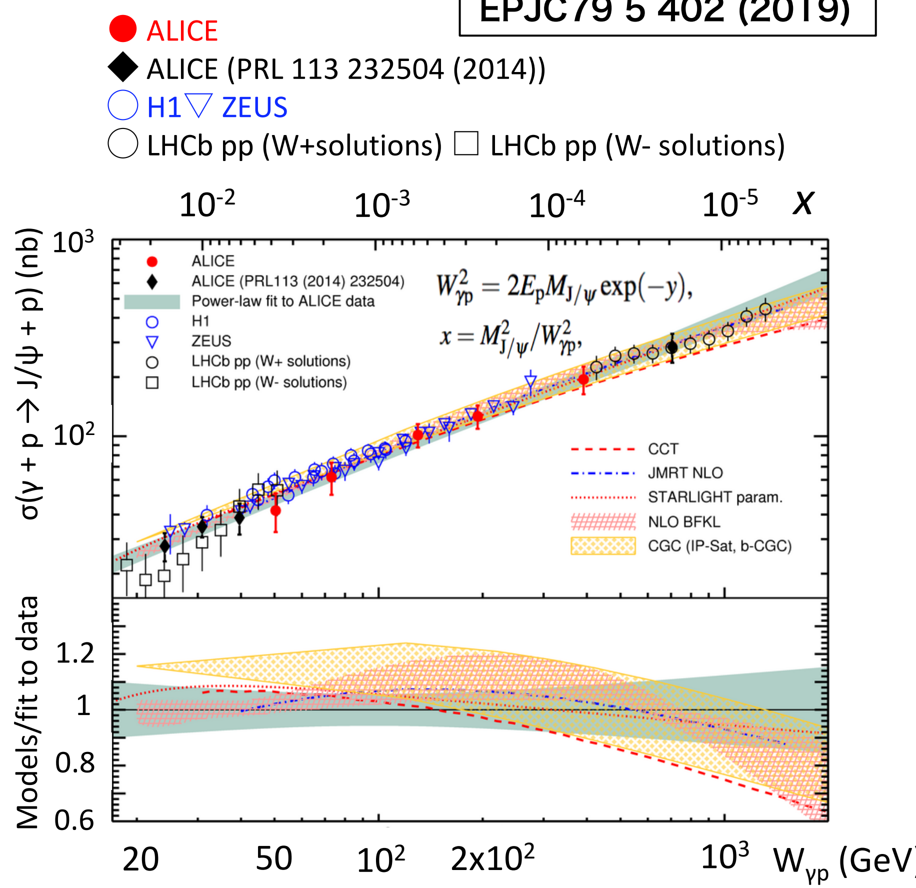
ADC: $-7.0 < \eta < -4.9$



Exclusive J/ψ production in ultra-peripheral p-Pb collisions

- The energy in the photon-target proton system can be determined with J/ψ rapidity
  - ✓ x~2×10^{-5}-2×10^{-2}
- $\sqrt{s_{NN}}$ = 5.02 TeV data shown
  - ➢ Consistent with the HERA data

EPJC79 5 402 (2019)



- ✓ CCT: Saturation in an energy dependent hot spot model
- ✓ JMRT NLO: DGLAP including the expected main NLO contributions
- ✓ CGC: Color dipole model
- ✓ NLO BFKL: Proton impact factor from HERA
- ✓ STARLIGHT: Parameterized by fixed target data

Power low parameter	
H1	δ=0.67±0.03
ZEUS	δ=0.69±0.02
ALICE	δ=0.70±0.05

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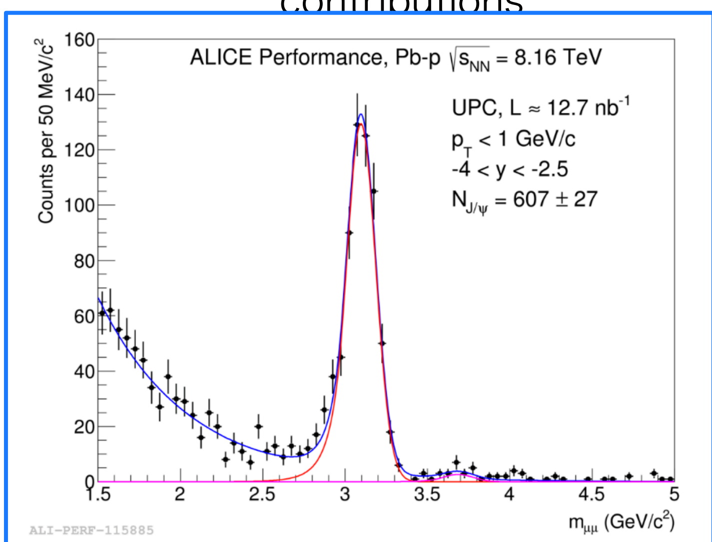
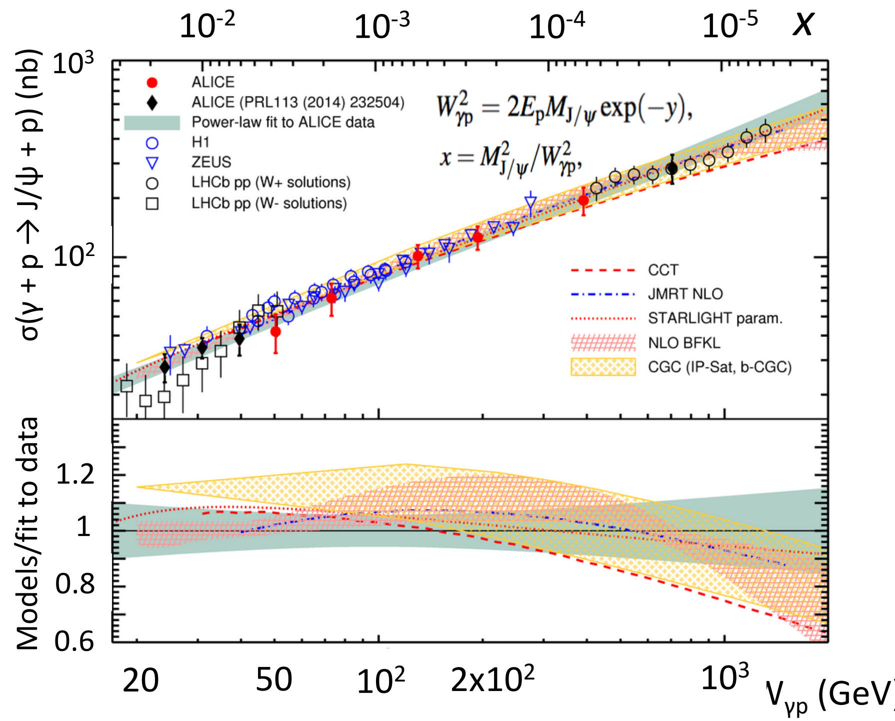


EPJC79 5 402 (2019)

● ALICE
◆ ALICE (PRL 113 232504 (2014))
○ H1 ▽ ZEUS
○ LHCb pp (W+solutions) □ LHCb pp (W- solutions)



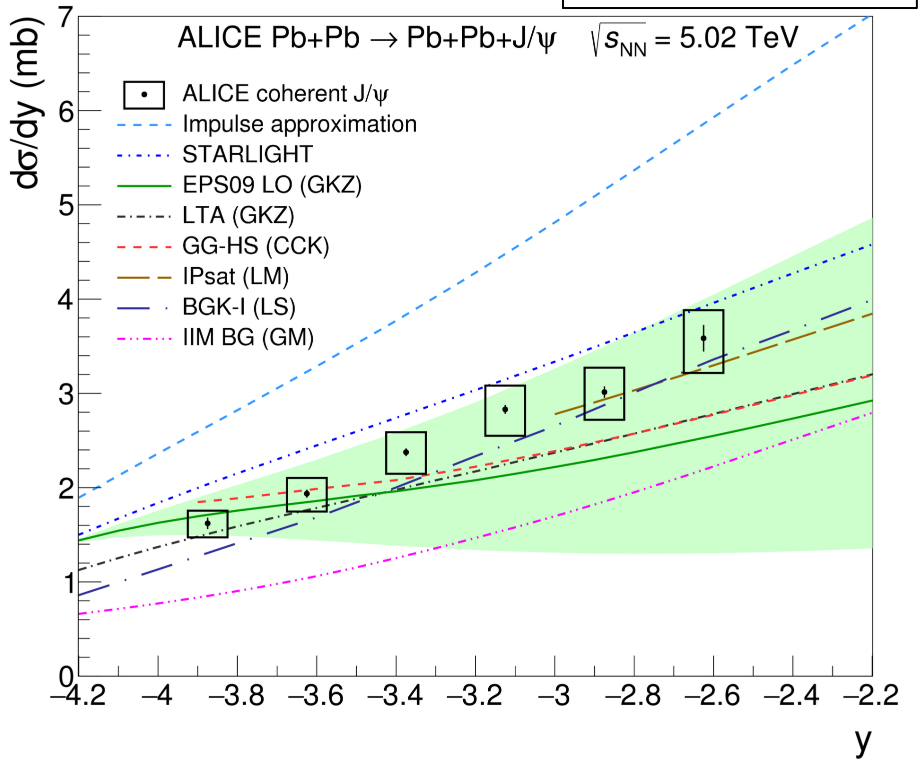
- $\sqrt{s_{NN}}$ = 8.16 TeV data analysis ongoing
  - ➢ Extend $w_{\gamma p}$ to 1.4 TeV

    Looking for saturation effects in proton

Coherent J/ψ production at forward rapidity in Pb-Pb collisions

arXiv:1904.06272

- Combined 2015+2018 data
  - ✓ L_{int}: 750 μb^{-1}
  - ✓ Over 20000J/ψs available



- ✓ No nuclear effects: Impulse approximation
- ✓ STARLIGHT: VDM + Glauber
- ✓ EPS09 LO: EPS09 shadowing
- ✓ LTA: Leading twist approximation
- ✓ GM, LM, LS: Color dipole model (CGC)

Measurement consistent with moderate shadowing model
- ✓ Same conclusion reached in the previous mid-rapidity measurement

EPJC73, 2617(2013)

- Run-2(2015, 2018) mid-rapidity analysis is ongoing
  - ✓ Higher statistics and cross sections than the previous data
    - 95 μb^{-1} (2015) + 250 μb^{-1} (2018) for 5.02 TeV ← 23 μb^{-1} for 2.76 TeV

Summary and outlook

- pp collisions
  - ✓ J/ψ and Υ cross section down to zero p_T and J/ψ polarization
    - Production mechanism still open question
  - ✓ Increase of the yields as a function of charged-particle density
    - No particle species dependence: J/ψ, Υ(1S), Υ(2S)
    - Qualitatively described by the model including MPI

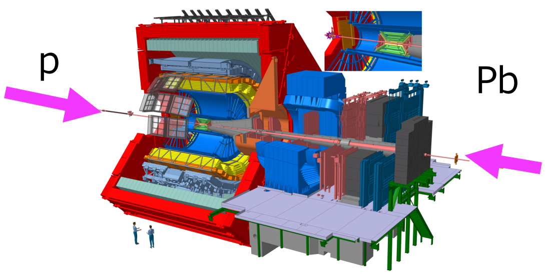
- p-Pb collisions
  - ✓ Described by CNM model calculations except for backward rapidity
  - ✓ Non-zero v_2 and saturation trend of $\langle p_T \rangle$ for J/ψ in high multiplicity events

- Ultra-peripheral collisions
  - ✓ Precise forward rapidity dependence in Pb-Pb collisions
    - Agreement with moderate shadowing models
  - ✓ Run2 data (high statistics and collision energy) analysis is ongoing
    - Mid-rapidity in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
    - p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV

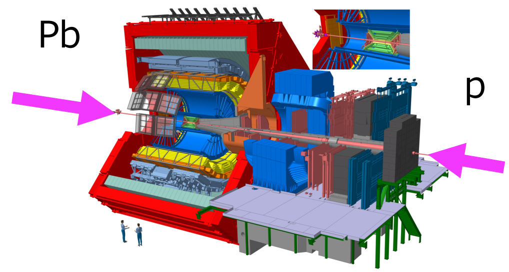
Backup

- p-Pb measurements

p-Pb (p-going)



Pb-p (Pb-going)



$\Delta y = 0.465$ in p-going direction

Forward (p-going):

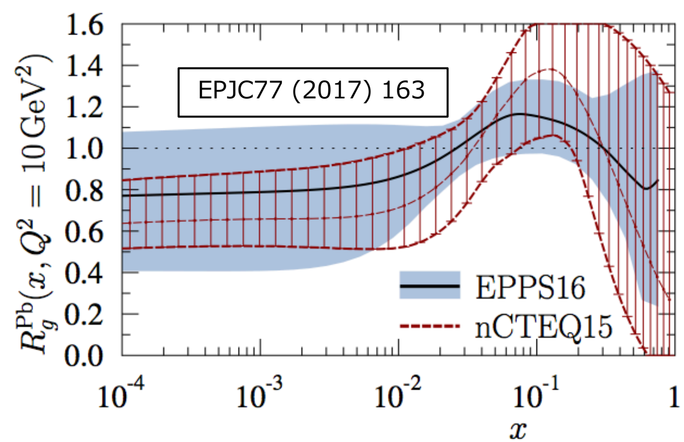
Probing low-x in Pb: 10^{-5} – 10^{-4}

Backward (Pb-going):

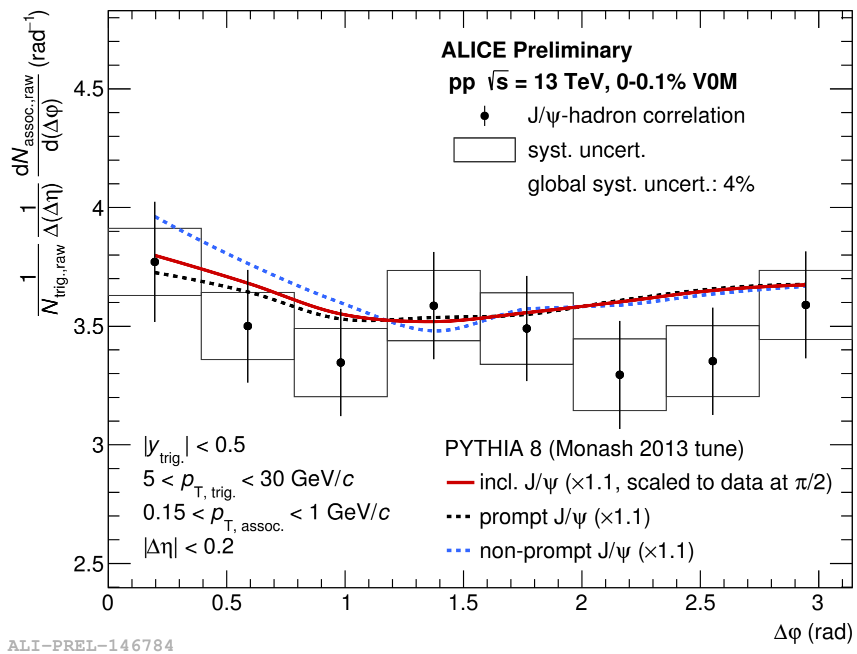
Probing large-x in Pb: 10^{-2} - 10^{-1}

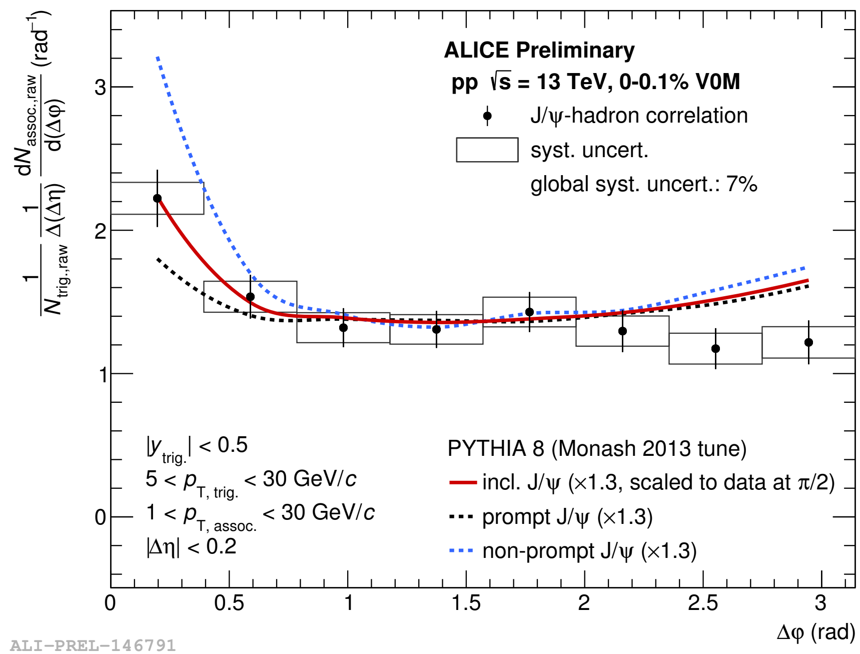
Mid-rapidity:

Probing x in Pb : 10^{-4} - 10^{-3}



J/ψ-hadron correlation in pp collisions

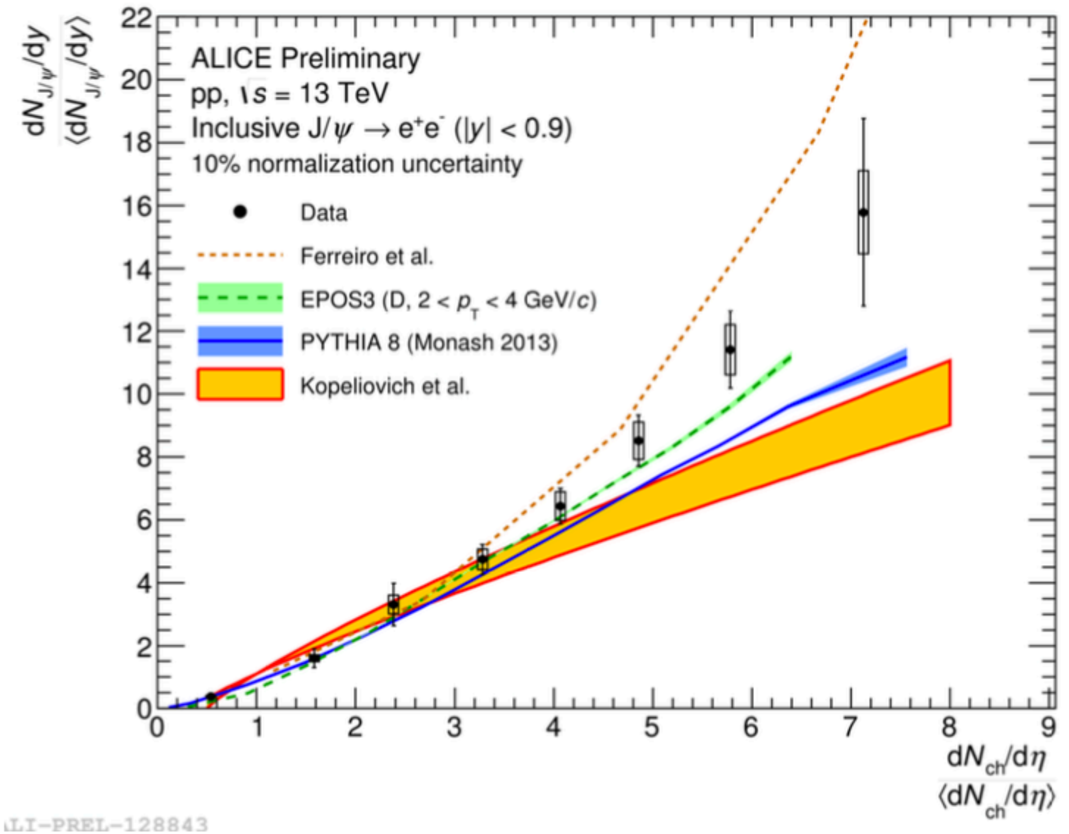




- High multiplicity selection: 0-0.1% highest multiplicity in V0
- Clear near-side peak observed in the correlation of J/ψ (p_T > 5 GeV/c) and hadrons with p_T > 1 GeV/c
  - ➢ Pythia 8 (Monash 2013 tune) describes the data

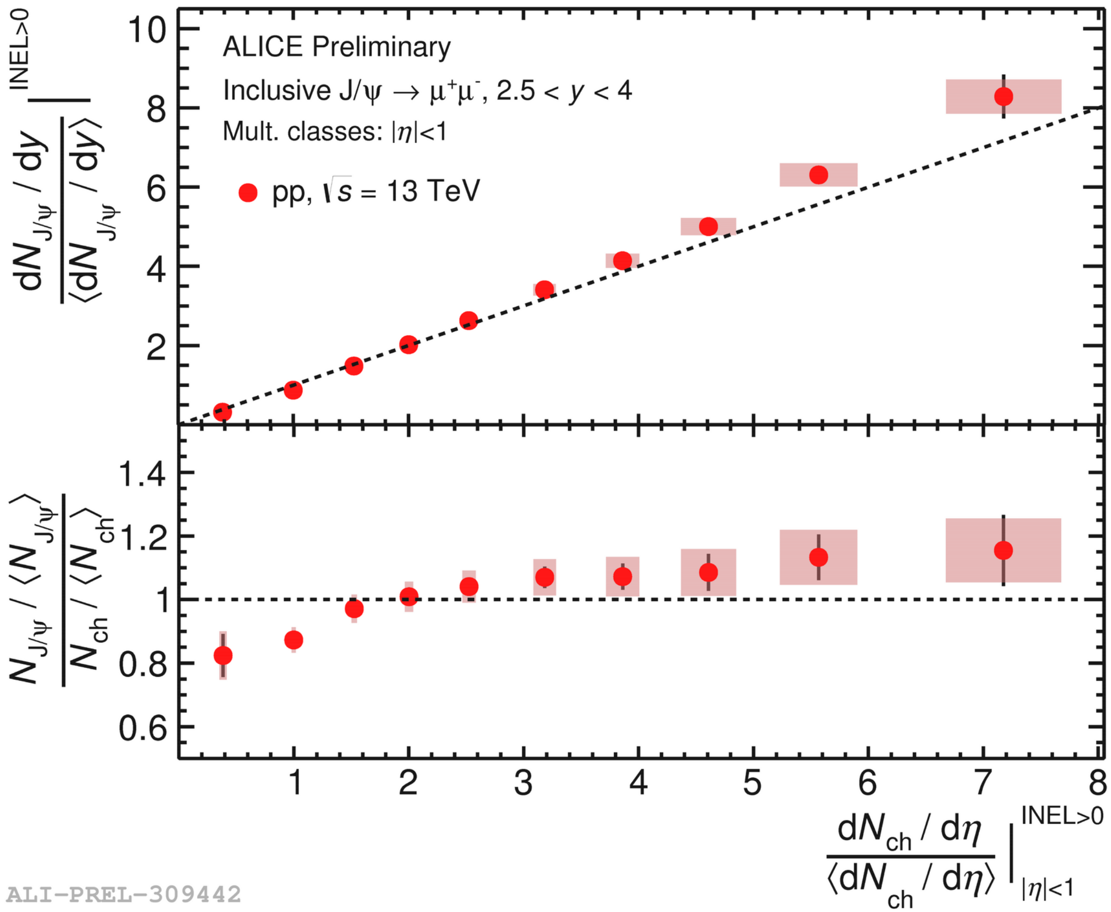
    Suggest the large contribution from non-prompt (B-feeddown) J/ψ for the near-side peak

Multiplicity dependence of J/ψ production at mid-rapidity in pp collisions

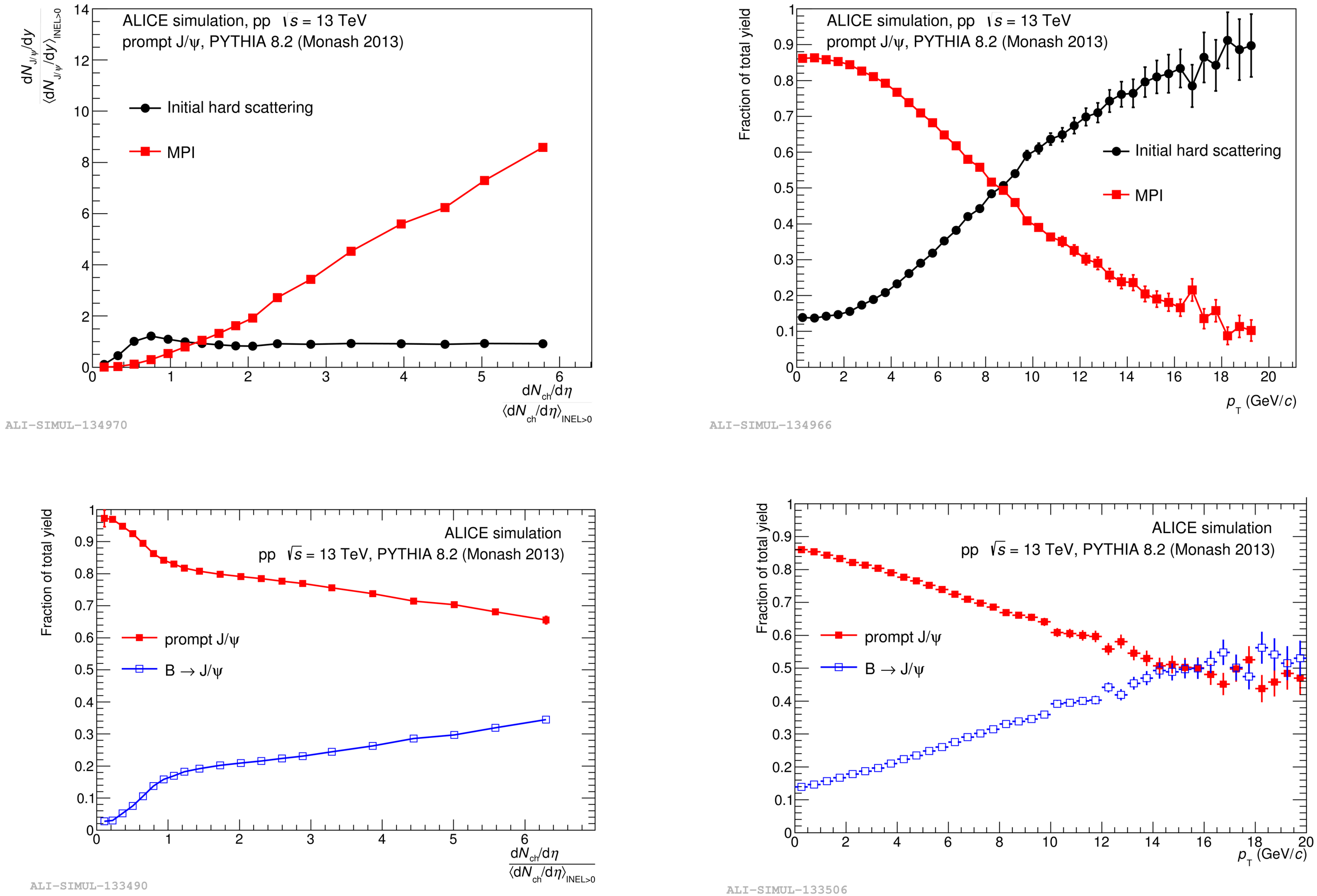


- ✓ String percolation Ferreiro *PRC86 (2012) 034903*
- ✓ Hydro dynamical evolu.on (EPOS3) *Phys. Rept.350 (2001) 93*
- ✓ Multi parton interaction (PYTHIA8)
- ✓ Contribu.ons of higher Fock states *Kopeliovich PRD88 (2013) 116002*

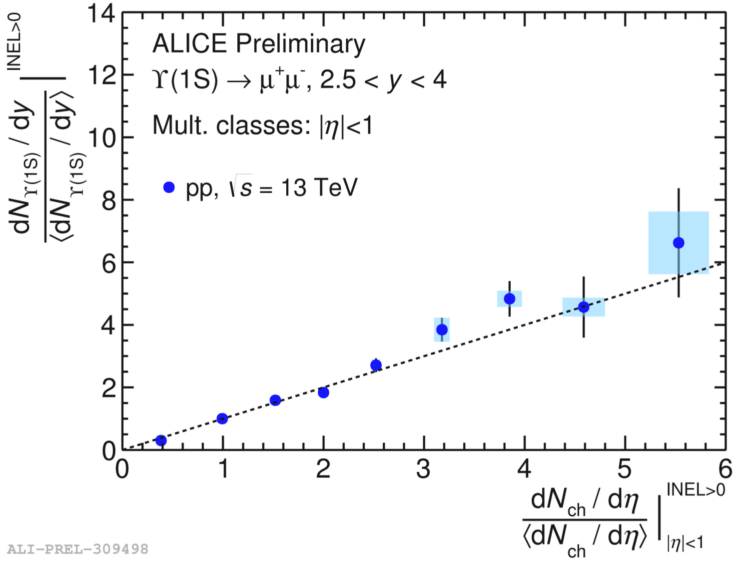
Multiplicity dependence of J/ψ production at forward rapidity in pp collisions

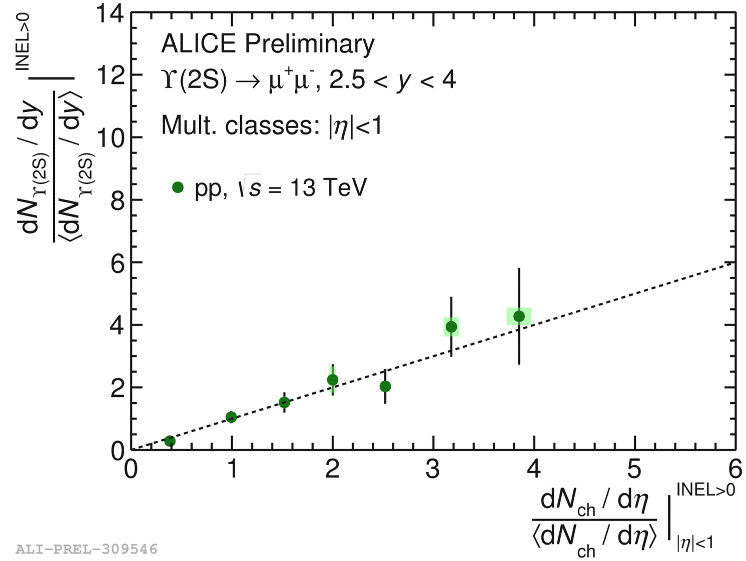


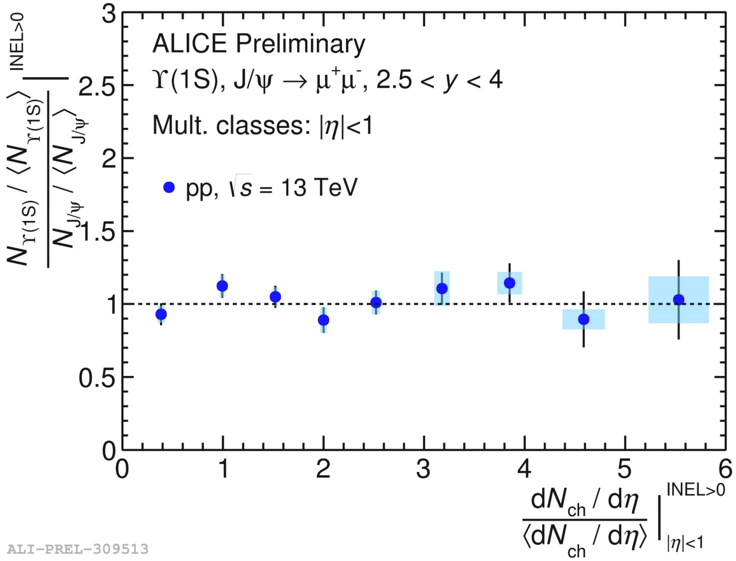
Pythia8 Monash 2013 production

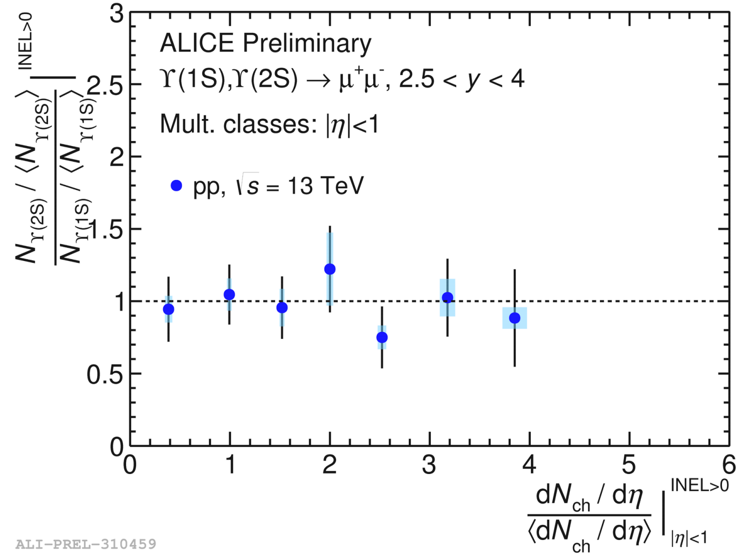


Multiplicity dependence of Υ production

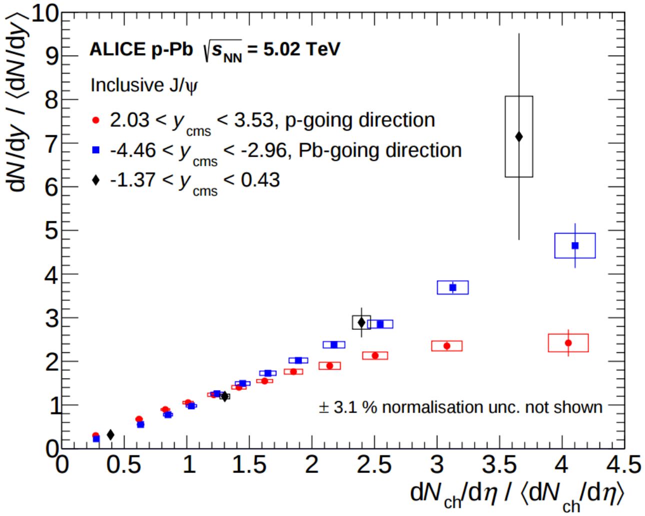


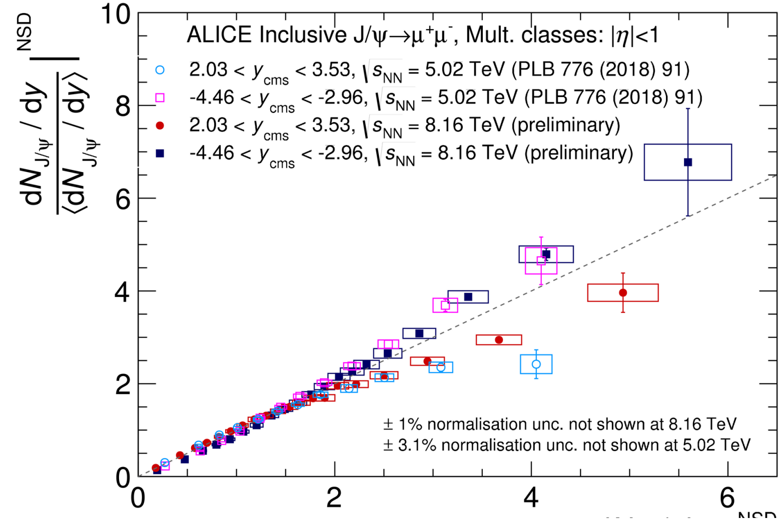


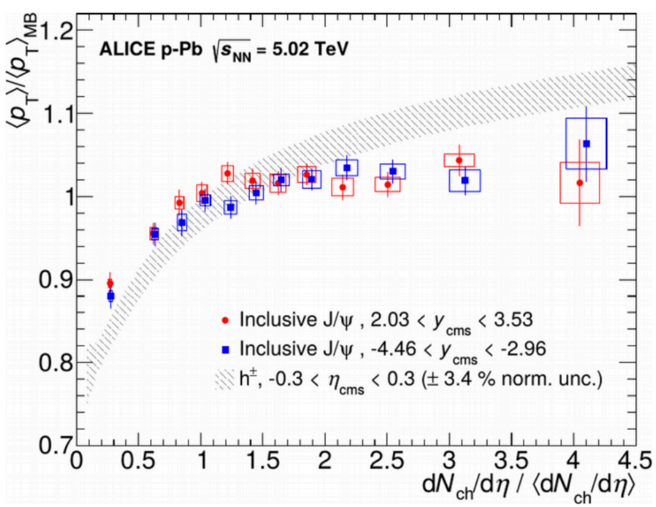


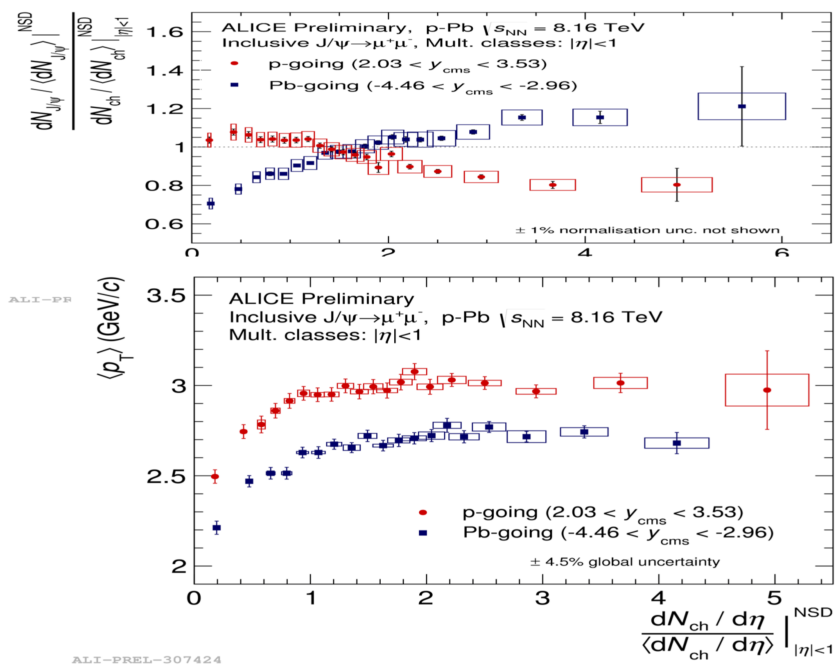


Multiplicity dependence in p-Pb

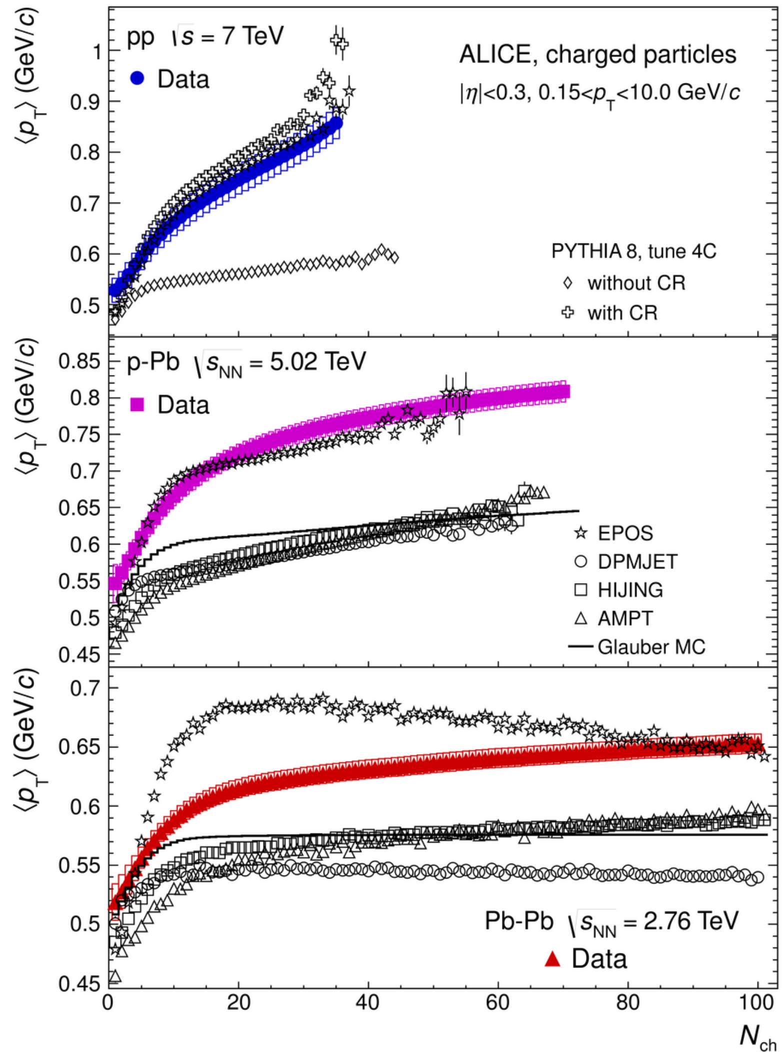








$\langle p_T \rangle$ for charged particles



Multiplicity dependence of ϒ production at CMS

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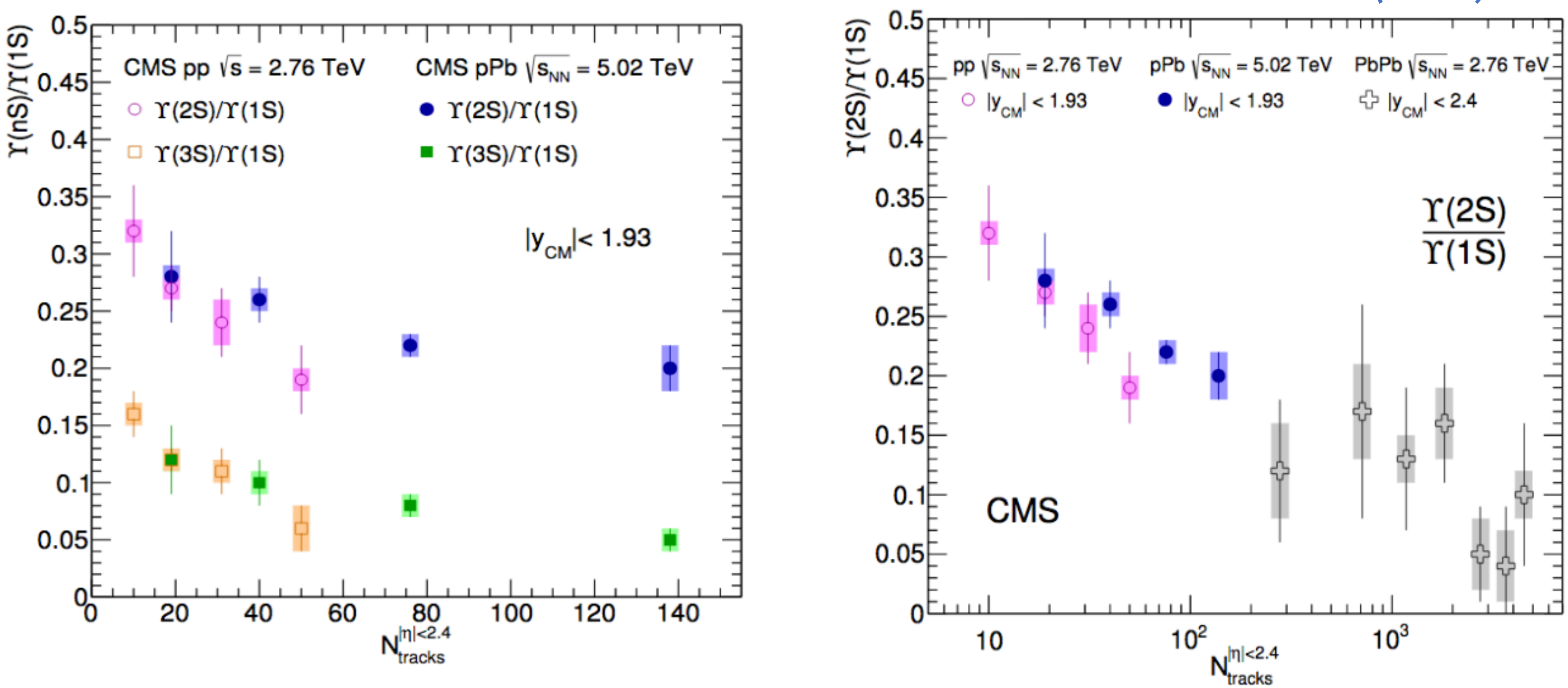

J/ψ R_{pPb} vs p_T at $\sqrt{s_{NN}}$ = 5.02 TeV

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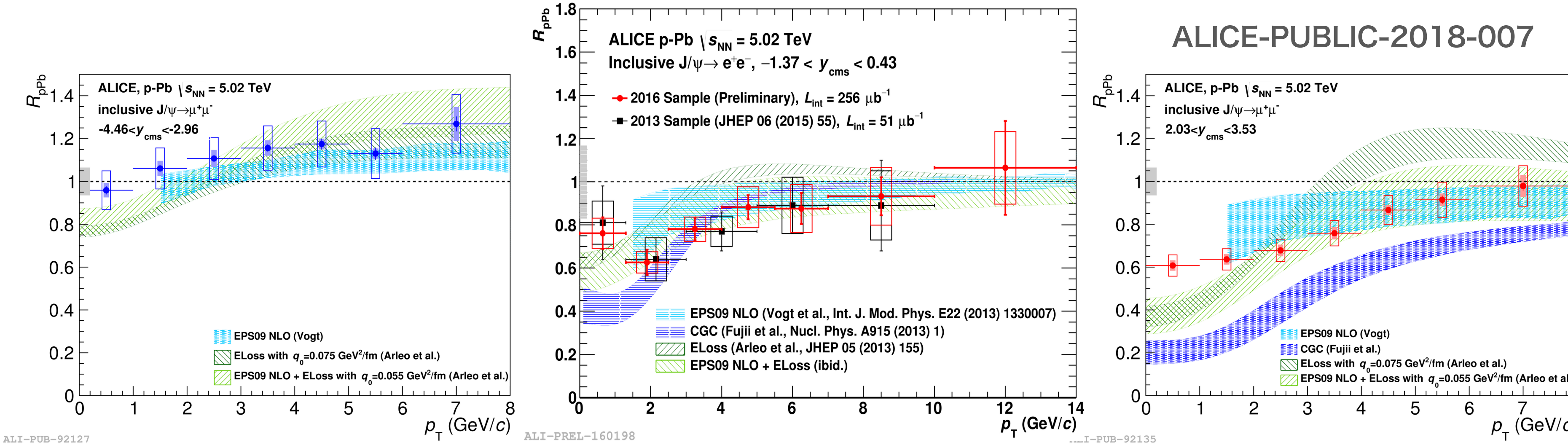

✓ Suppression at low p_T
✓ Small enhancement at backward rapidity

Consistent with nPDF trends

Model calculations describe the data within the uncertainties.

✓ nPDF: EPS09NLO, nCTEQ15, CGC
✓ Coherent energy loss
✓ Transport model: nPDF(EPS09NLO) + Cronin effect + fireball evolution+ feeddown

J/ψ R_{pPb} vs p_T at $\sqrt{s_{NN}}$ = 8.16 TeV

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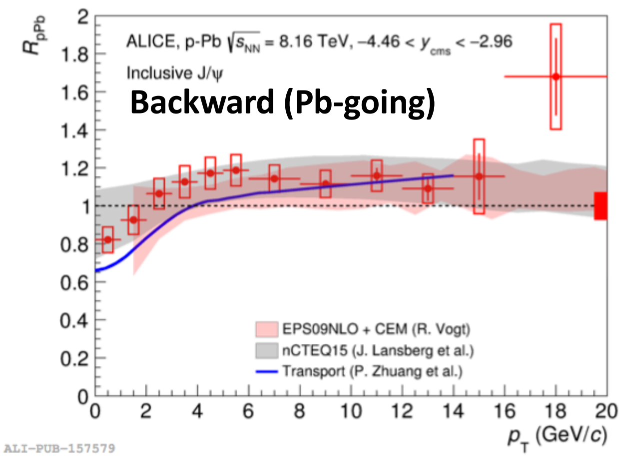
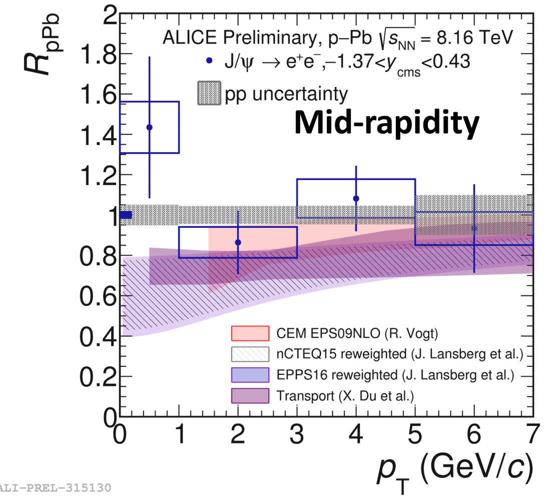
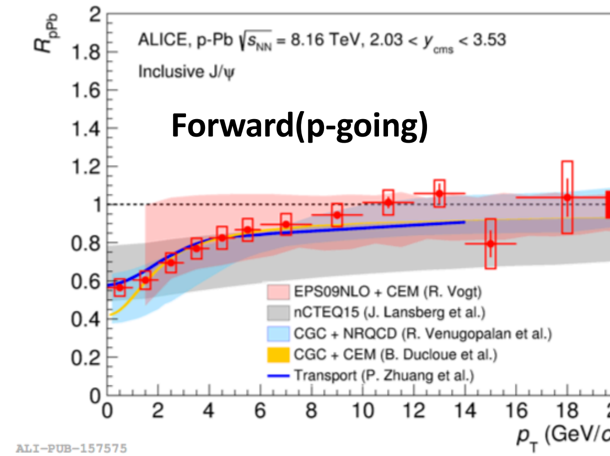
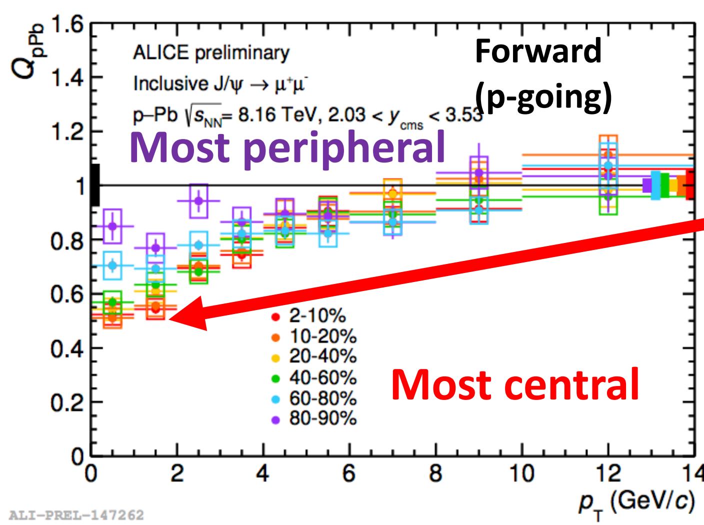
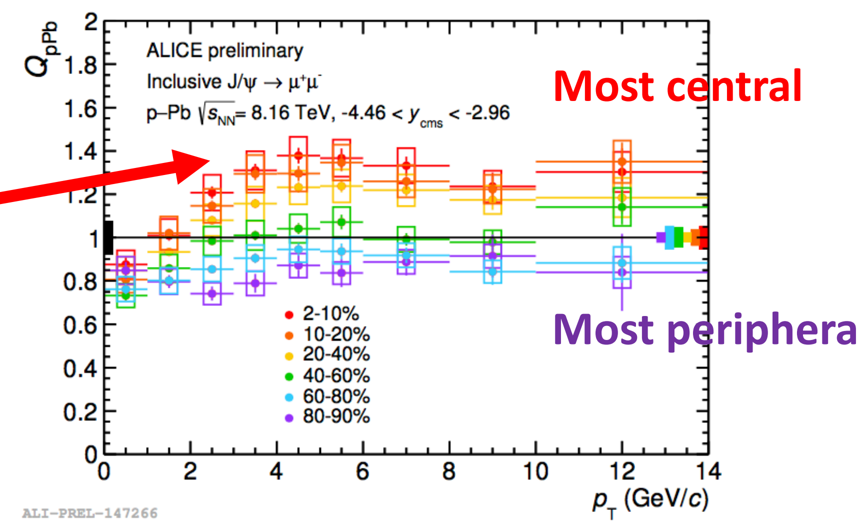
$$R_{pPb}(Q_{pPb}) = \frac{dN^{J/\psi\,(cent)}_{pPb}/dp_T}{\langle T_{pPb}\rangle_{(cent)} \times d\sigma^{J/\psi}_{pp}/dp_T}$$



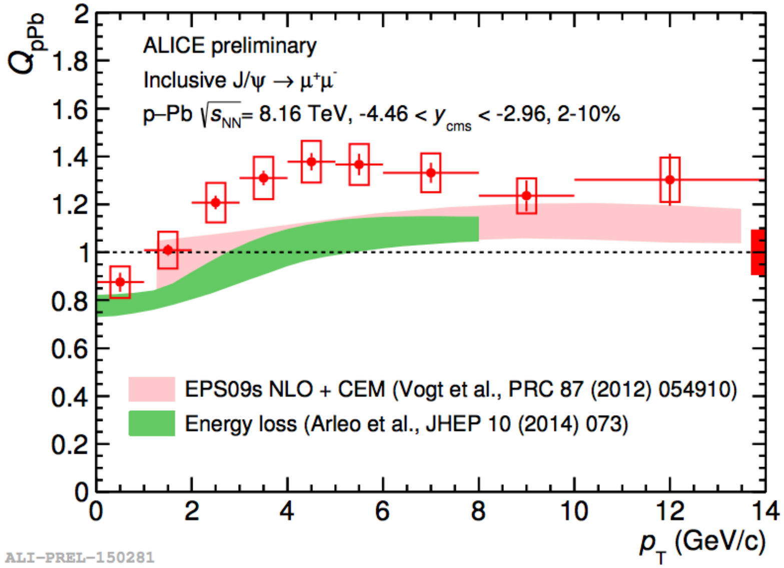


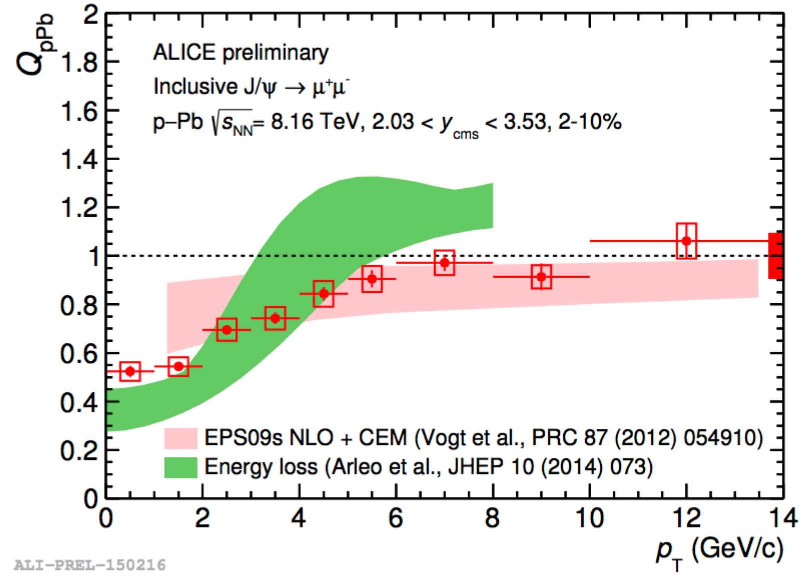


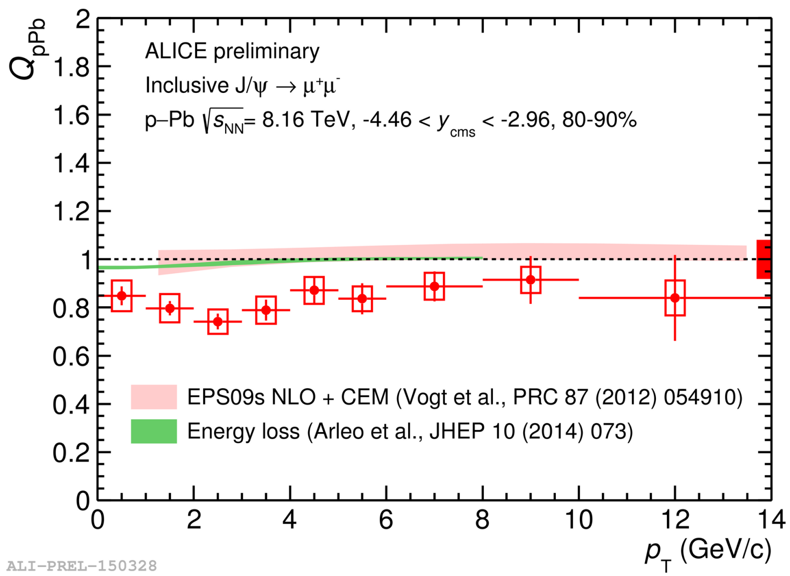


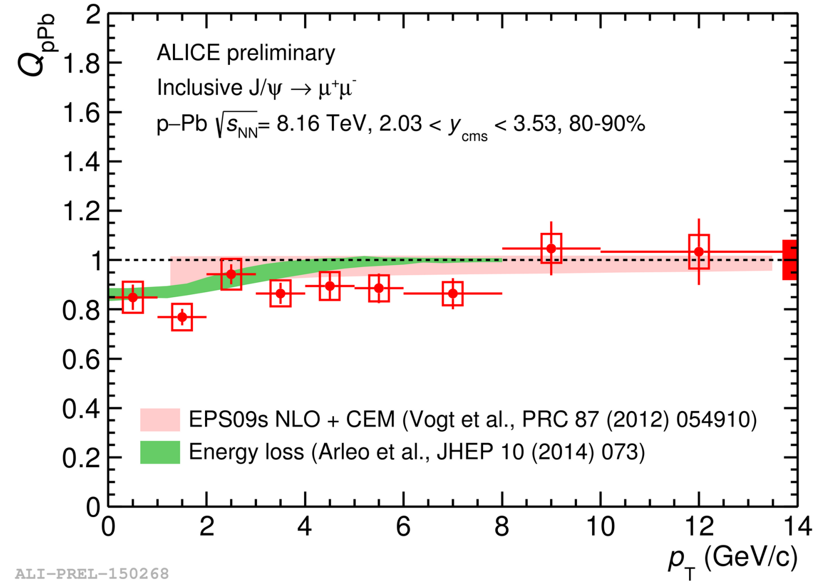


J/ψ Q_{pPb} vs p_{T}

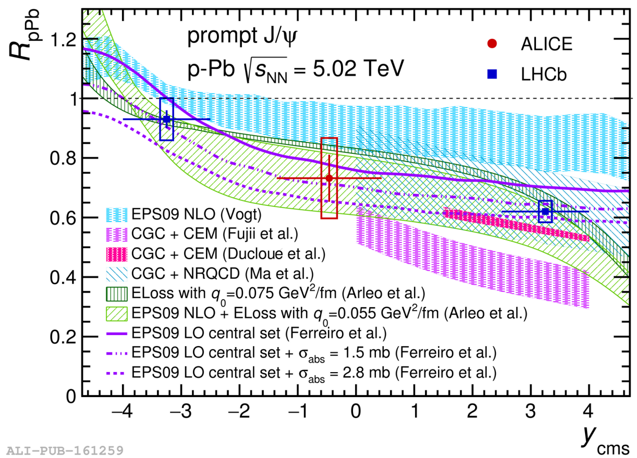


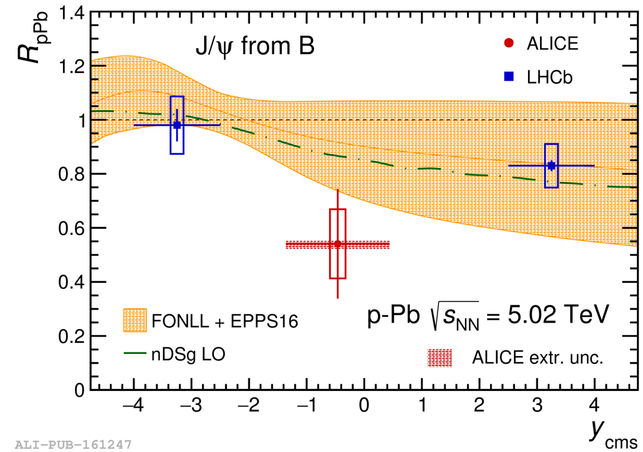


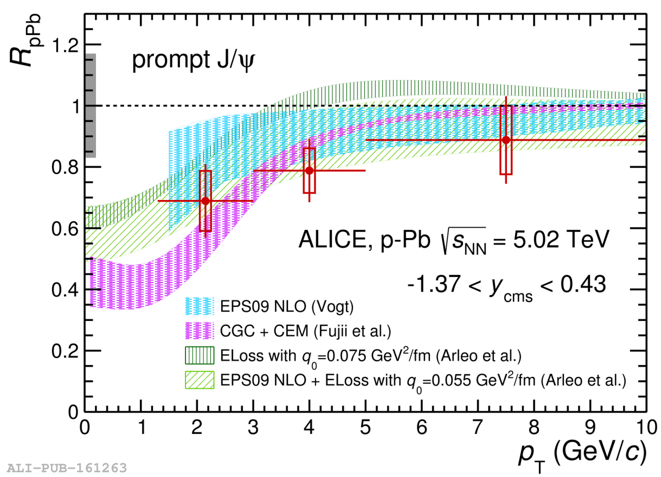


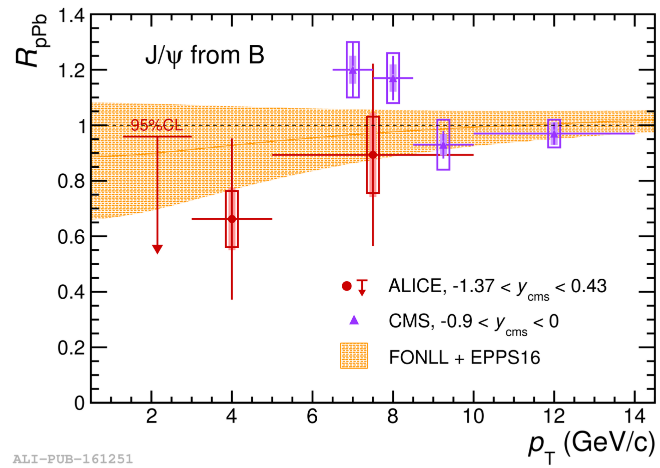


Prompt/Non-prompt J/ψ in p-Pb collisions



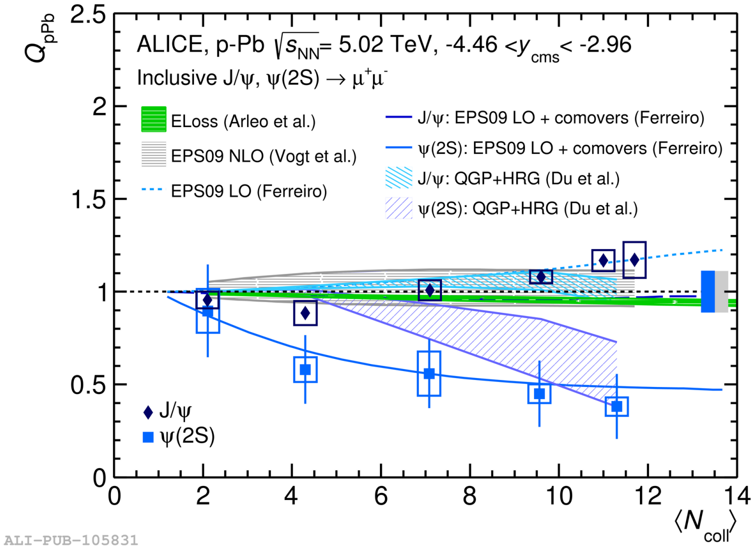


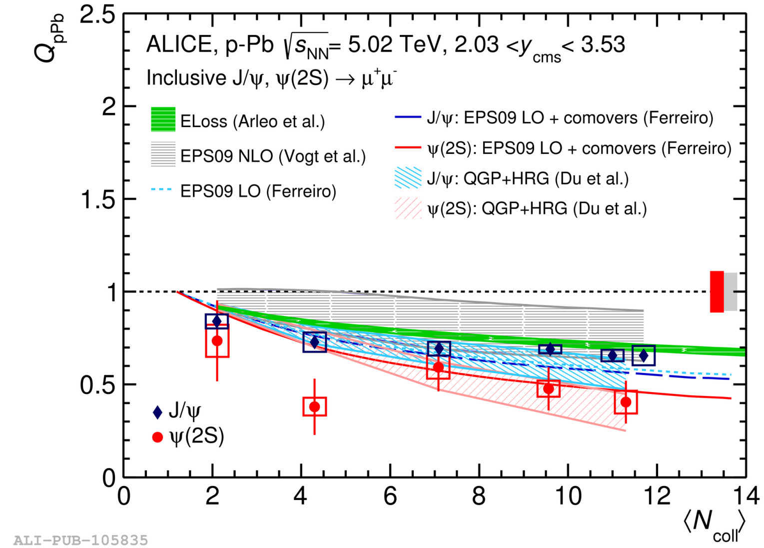


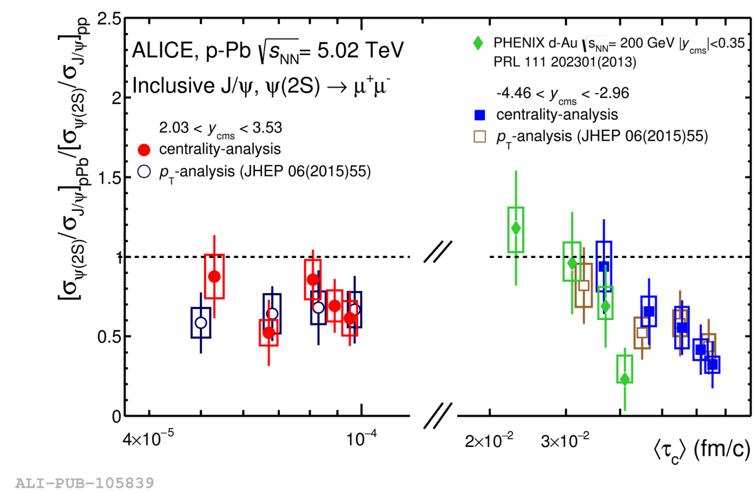


ψ(2S) in p-Pb collisions

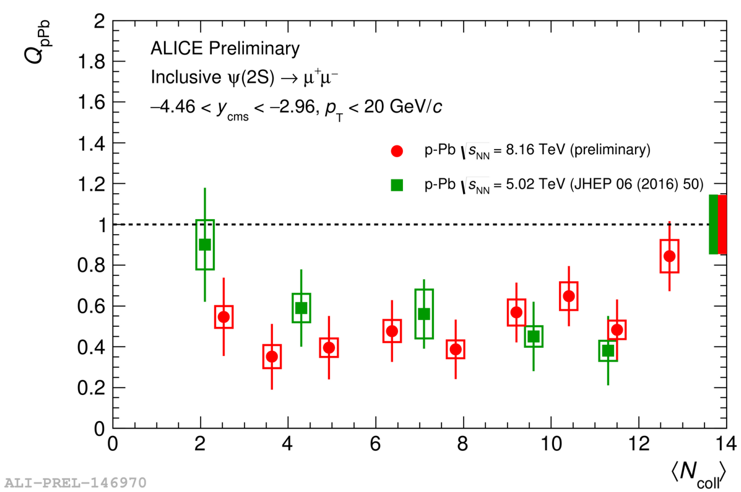
-

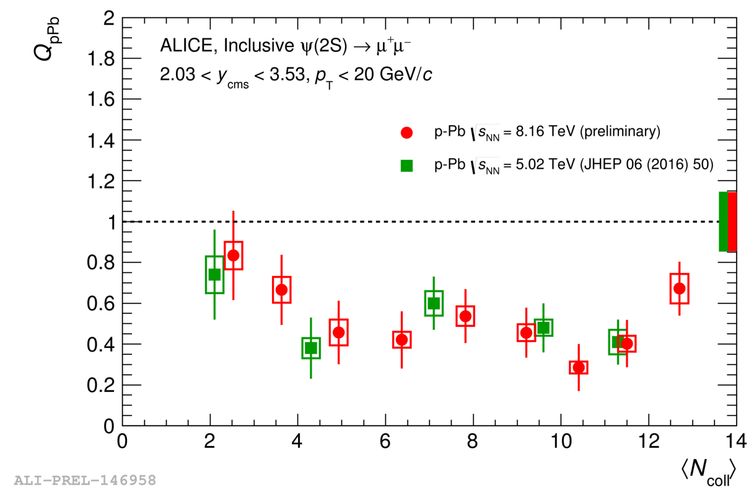


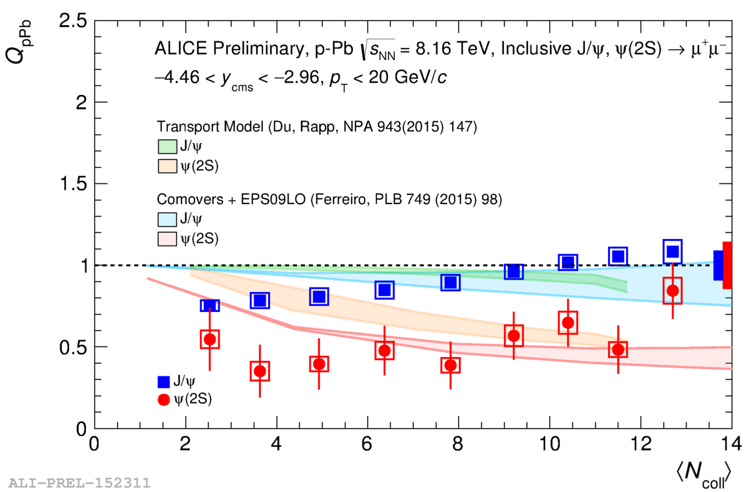


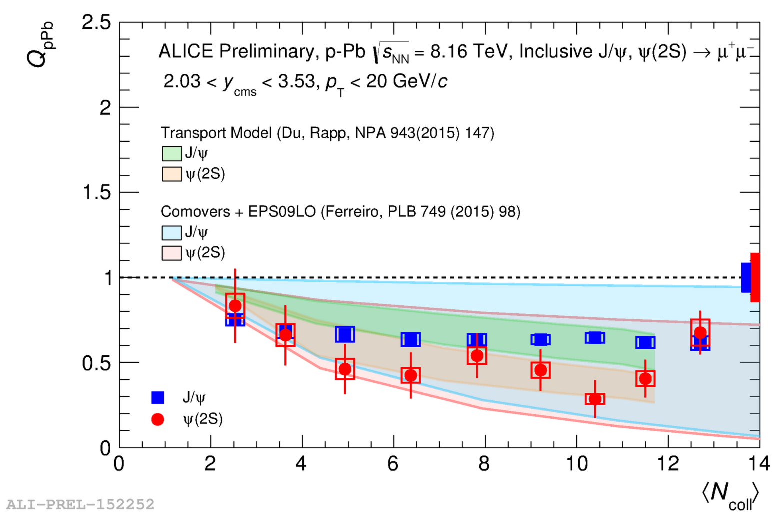


ψ(2S) in p-Pb collisions





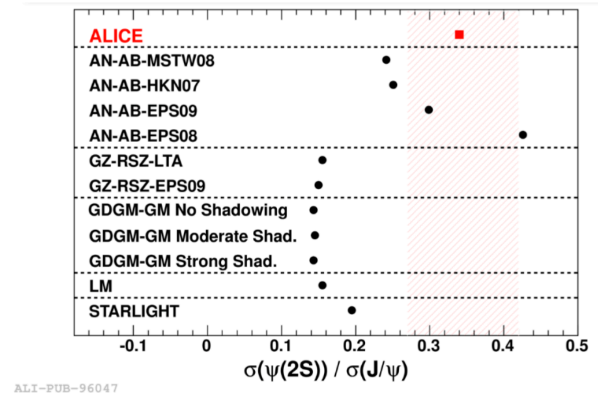




Coherent charmonium production at mid-rapidity in Pb-Pb collisions in Run1

- J/ψ measurement consistent with moderate shadowing
- ψ(2S) data disfavor models using impulse approximation (no nuclear effects) and strong nuclear shadowing
  - ✓ Difficult to give an preference between gluon shadowing and Glauber nuclear effects only (as STARLIGHT)
  - ✓ Need to understand γ+p → ψ(2S) + p baseline

$R(\sigma(\psi(2S)/\sigma(J/\psi))) = 0.34^{+0.08}_{-0.07}$



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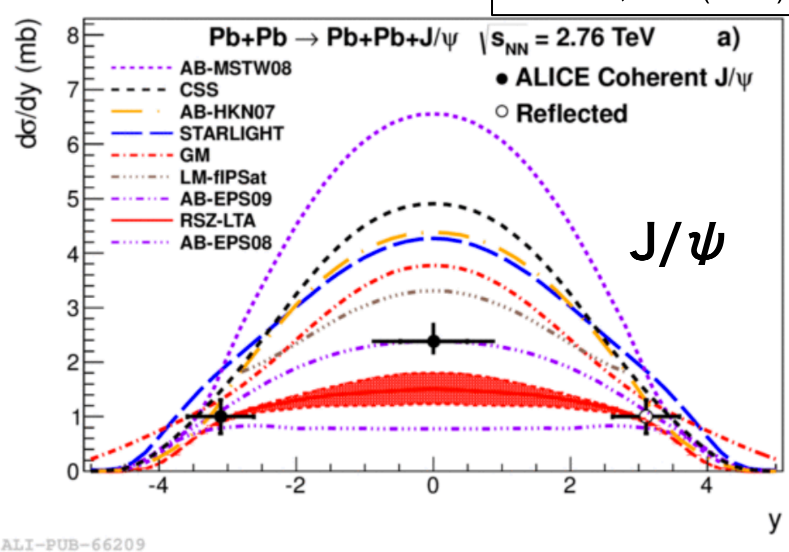

Phys. Lett. B 751,358-370(2015)