Quarkonium results from pp and p–Pb collisions with ALICE at the LHC

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On behalf of the ALICE collaboration

Discovery Physics at the LHC - Kruger 2018
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Quarkonia as QCD probe

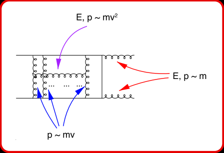
[EPJC71 (2011) 1534] [JHEP12 (2015) 101]

Quarkonium: bound states formed by a pair of heavy quark + anti-quark

Benefit from $m_Q \gg \Lambda_{QCD}$: long lived and non-relativistic system ($v \ll 1$)

Key feature: intrinsic separation of scales

- the mass m (hard scale);
- the relative momentum $p \sim mv$ (soft scale);
- the binding energy $\Delta E \sim mv^2$ (ultrasoft scale).



Quarkonium annihilation diagram

Well described below Λ_{QCD} threshold and at $T = 0$ with the Cornell potential and direct lattice QCD studies:

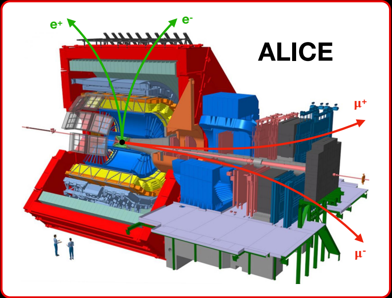
$$V(r) = -\frac{\alpha_s(r)}{r} + Kr$$

States	J/ψ(1S)	χ_c(1P)	ψ(2S)	ϒ(1S)	χ_b(1P)	ϒ(2S)	χ_b(2P)	ϒ(3S)
m_{PDG} (GeV)	3.09	3.49	3.69	9.46	9.89	10.02	10.25	10.36
r_0 (fm)	0.56	0.81	1.15	0.29	0.48	0.59	0.77	0.86
ΔE (GeV)	0.64	0.23	0.06	1.1	0.63	0.54	0.29	0.21

Quarkonum is an ideal probe of the confined region of QCD and its interplay with perturbative QCD

[Eur. Phys. J. C 77 (2017) 392], [Eur. Phys. J. C 74 (2014) no.8, 2974]

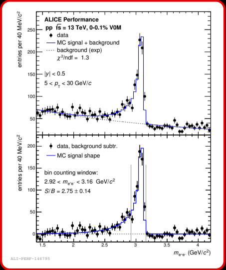
Quarkonium yields are extracted **down to zero p_{T}** by fitting the dilepton invariant mass distribution or by the bin counting technique



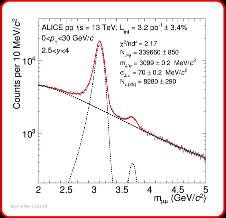
Data samples

pp	$\sqrt{s}$	$= 0.9,\ 2.76,\ 5,\ 7,\ 8,\ 13$ TeV
p–Pb	$\sqrt{s_{\mathrm{NN}}}$	$= 5.02,\ 8.16$ TeV

$|y| < 0.9$ - dielectrons



$2.5 < y < 4$ - dimuons



Quarkonium measurements with ALICE

[Eur. Phys. J. C 77 (2017) 392], [Eur. Phys. J. C 74 (2014) no.8, 2974]

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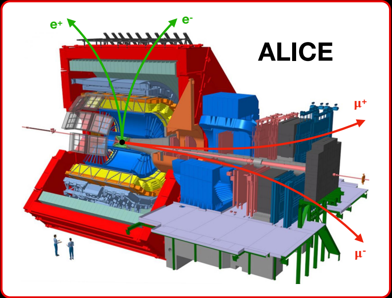

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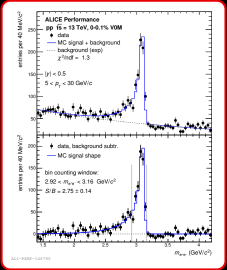

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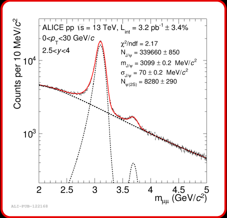

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p–Pb	$\sqrt{s_{\mathrm{NN}}}$	$= 5.02,\ 8.16$ TeV
Pb–Pb	$\sqrt{s_{\mathrm{NN}}}$	$= 2.76,\ 5.02$ TeV

→ See G. Luparello's talk on Friday

pp collisions

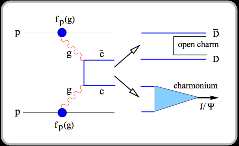
pp collisions: small energy density $\longrightarrow$ no QGP expected $\longrightarrow$ test bench for QCD ($\sim$ vacuum)

Two distinct steps for production process (factorization of scales):

- Heavy quarks produced in hard-scattering process (pQCD)

$$\mathrm{d}\sigma^{\mathrm{pp}\to \mathrm{Q}\bar{\mathrm{Q}}+X} = \sum_{i,j} f_i^{\mathrm{p}}(x_1, Q^2) \otimes f_j^{\mathrm{p}}(x_2, Q^2) \otimes \mathrm{d}\sigma^{i,j\to \mathrm{Q}\bar{\mathrm{Q}}+X}$$

PDF (non-perturbative)



$\sim$ 90% open charm
$\sim$ 10% charmonia

- Non-perturbative evolution into color neutral bound states
  Three approaches for $\mathrm{Q}\bar{\mathrm{Q}} \to$ Onium:
  - Color Evaporation Model (CEM) [Phys. Rev. D 12 (1975) 2007]
  - Color Singlet Model (CSM) [Phys. Lett. B 67 (1977) 217]
  - Non-Relativistic QCD (NRQCD) [Phys. Rev. D 51 (1995) 1125]

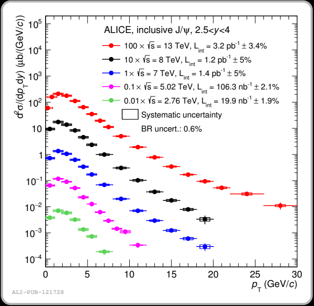
$$\mathrm{d}\sigma^{\mathrm{pp}\to \mathrm{J}/\psi+X} = \mathrm{d}\sigma^{\mathrm{pp}\to \mathrm{Q}\bar{\mathrm{Q}}+X} \otimes (\kappa_1 \langle O|\mathcal{O}_8(^1S_O)|O\rangle + \kappa_2 \langle O|\mathcal{O}_8(^1P_O)|O\rangle + \ldots)$$

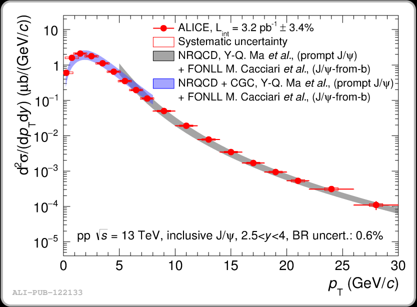
non-perturbative matrix elements

Quarkonium measurements in pp collisions as QCD laboratory and baseline to quantify the nuclear matter effects

However, the ideal reference is the total charm cross section in AA collisions
(nuclear medium could modify the fraction of produced $c\bar{c}$ pairs going into charmonium)
$\rightarrow$ Run-3: ALICE will measure the open charm component down to zero p_{T}

[Eur. Phys. J. C 77 (2017) 392]





- **J/ψ production has been measured at all available LHC energies**
- Spectra become harder with increasing energy (onset of non-prompt J/ψ)
- Slope changes at high p_T

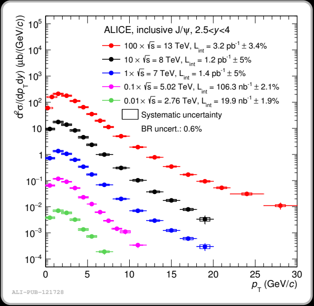
Sum of the prompt (NRQCD) and the non-prompt (FONLL) contributions assuming fully uncorrelated uncertainties.

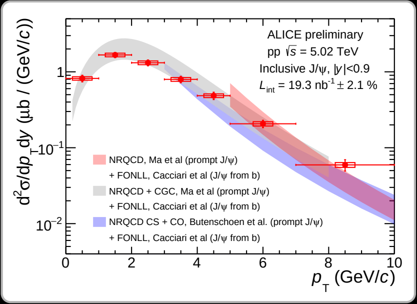
NRQCD:	[PRL, 106 (2011) 042002]
NRQCD+CGC:	[PRL, 113 (2014) 192301]
FONLL:	[JHEP, 1210 (2012) 137]

Charmonium cross sections well described by QCD-based models over the full p_T range

Inclusive J/ψ production cross sections

[Eur. Phys. J. C 77 (2017) 392]





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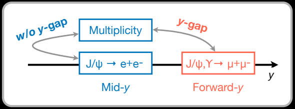
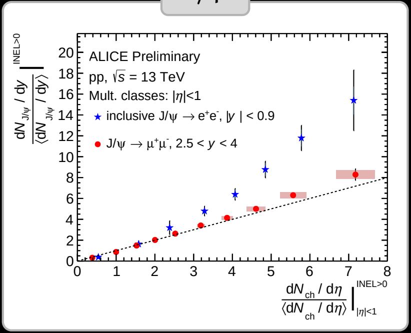
Charmonium cross sections well described by QCD-based models over the full p_{T} range

Charged-particle multiplicity dependence to study:

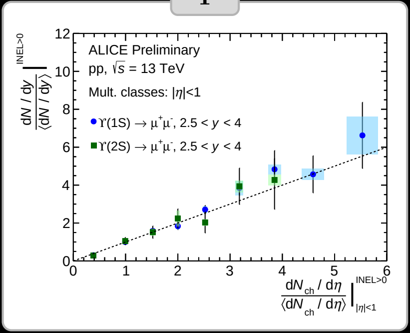
- Multiple parton interactions
- Interplay between soft and hard scales



J/ψ



ϒ



Forward rapidity (with *y*-gap): linear increase for J/ψ, ϒ(1S) and ϒ(2S)

Mid-rapidity (without *y*-gap): Stronger than linear increase for J/ψ

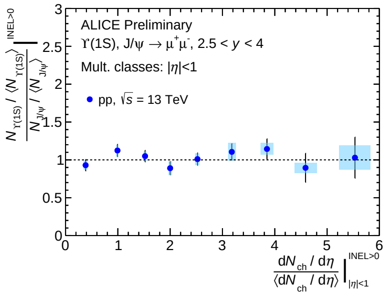
→ Strong rapidity dependence

Inclusive J/ψ and Υ production *vs* multiplicity

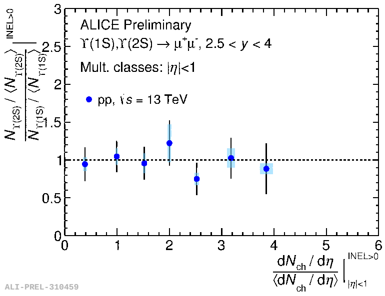
Double ratio of charged-particle multiplicity dependence to study:

- Relative production in terms of mass and flavor content
- Excited to ground state production

Υ(1S) / J/ψ



Υ(2S) / Υ(1S)



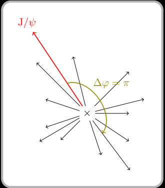
Measurements performed at forward rapidity, *i.e.* with *y*-gap

Left: No dependence on mass and quark content

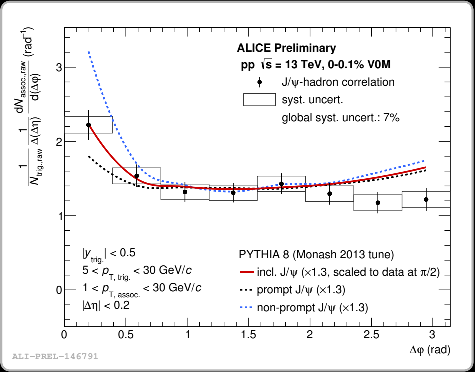
Right: Υ(2S)/Υ(1S) ratio is compatible with unity within uncertainties but also consistent with a drop with multiplicity as measured by CMS

J/ψ – hadron correlations to quantify hadronic activity w.r.t. to J/ψ direction

- Near-side correlation expected for
  - non-prompt J/ψ from additional decay products
  - prompt J/ψ depending on its production mechanism
- Away-side correlation expected from back-to-back jets



High multiplicity triggered events



Sharp $\Delta\eta$ cut to enhance near-side, suppresses possible away-side correlation

Significant near-side peak for associated hadrons with $p_{\mathrm{T}} > 1$ GeV/c

→ Qualitative agreement with Pythia 8: near-side dominated by non-prompt contributions

Inclusive J/ψ polarization at forward rapidity

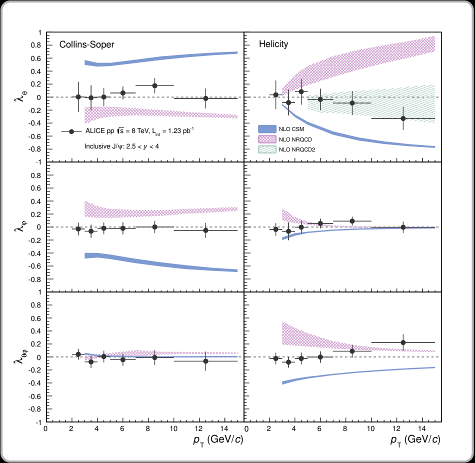
[arXiv:1805.04374]

Polarization determined from angular distribution of muons in both Collins-Soper and Helicity frames:

$$W(\cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}\,[1+\lambda_\theta\cos^2\theta + \lambda_\varphi \sin^2\theta\cos(2\varphi) + \lambda_{\theta\varphi}\sin(2\theta)\cos\varphi]$$

No polarization of inclusive J/ψ within uncertainties

Tension between models and experimental results



NLO CSM: [PRL, 108 (2012) 172002]
NLO NRQCD: [PRL, 108 (2012) 172002]
NLO NRQCD2: [PRL, 108 (2012) 242004]

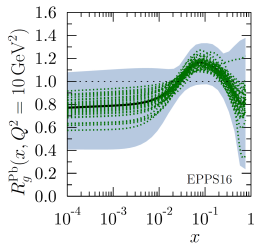
p–Pb collisions

pA collisions: Model and quantify the **cold nuclear matter effects**

- Shadowing → [EPJ C77 (2017) 163]
  Saturation (CGC) [Nucl. Phys. 1924 (2014)]
- Energy loss (initial/final state, or coherent) [PRL 109 (2012) 122301]
- Nuclear absorption (negligible at LHC) [Nucl. Phys. A 700 (2002) 539]
- Comovers absorption [PLB 749 (2015) 98]

$$\mathrm{d}\sigma^{\mathrm{pA}\to\mathrm{Q\bar{Q}}+X} = \sum_{i,j} f_i^{\mathrm{p}}(x_1, Q^2) \otimes f_j^{\mathrm{A}}(x_2, Q^2) \otimes \mathrm{d}\sigma^{i,j\to\mathrm{Q\bar{Q}}+X}$$

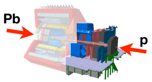
↓



Open question: has the energy density become large enough yet for QGP formation?

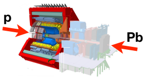
Data collected at $\sqrt{s_{\mathrm{NN}}}$ = **5.02 and 8.16 TeV** with **two beam configurations**:
p–Pb and Pb–p with $\Delta y_{\mathrm{cms}} = 0.465$ in the p-going direction

Backward



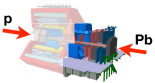
$-4.46 < y_{\mathrm{cms}} < -2.96$

Mid



$-1.37 < y_{\mathrm{cms}} < 0.43$

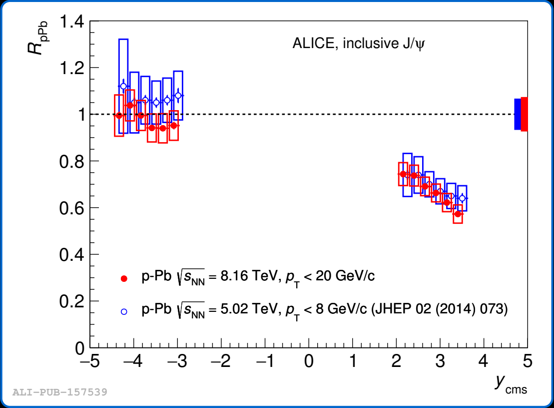
Forward



$2.03 < y_{\mathrm{cms}} < 3.53$

Inclusive J/ψ R_{pPb} *vs* rapidity

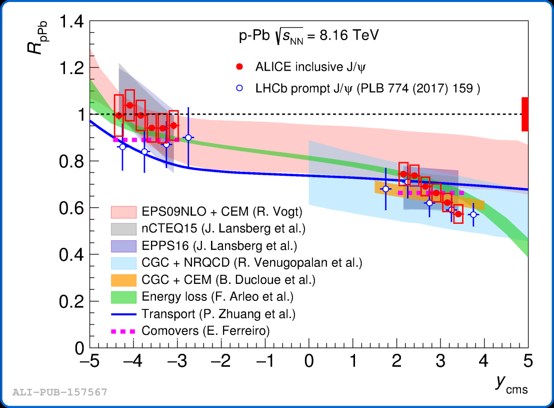
[JHEP 1807 (2018) 160]



- **J/ψ suppression at forward rapidity**
- Same magnitude within uncertainties at $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 8.16 TeV

Inclusive J/ψ R_{pPb} vs rapidity

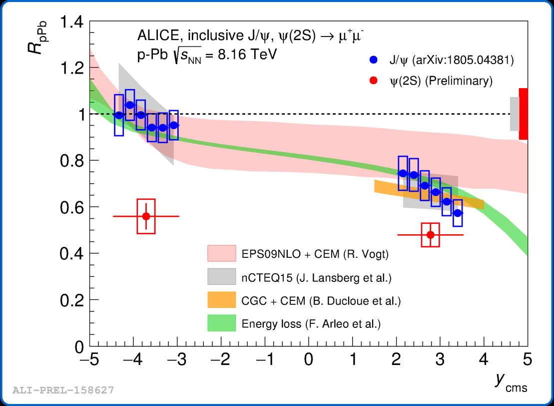
[JHEP 1807 (2018) 160]



- **J/ψ suppression at forward rapidity**
- Same magnitude within uncertainties at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV
- Same magnitude within uncertainties as prompt J/ψ from LHCb
- All the models fairly describe the J/ψ data

Inclusive J/ψ and ψ(2S) R_{pPb} vs rapidity

[JHEP 1807 (2018) 160]



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- **Stronger ψ(2S) suppression than the J/ψ one**, especially at backward rapidity (Pb-going)

- Models based on different shadowing/CGC implementations and energy loss cannot describe the ψ(2S) data

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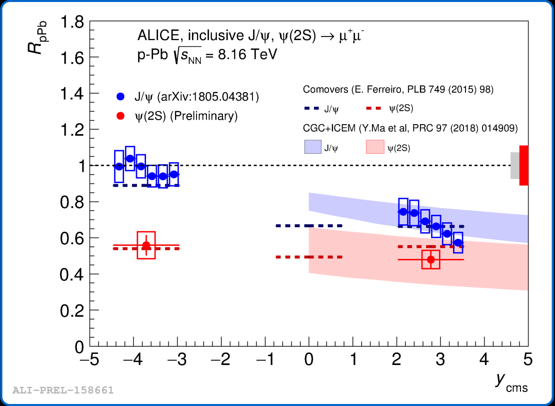

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- **Stronger ψ(2S) suppression than the J/ψ one**, especially at backward rapidity (Pb-going)

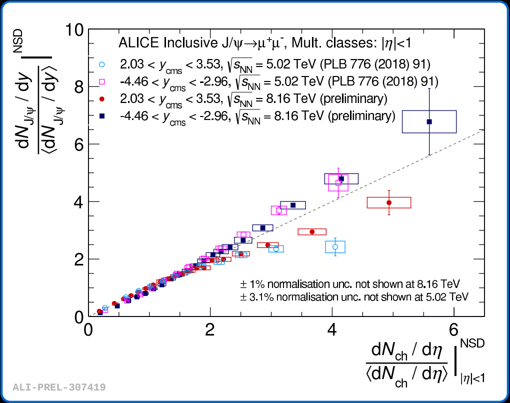
- Models based on different shadowing/CGC implementations and energy loss cannot describe the ψ(2S) data
- **Models including partonic or hadronic interactions with comovers (final-state effects) reproduce both J/ψ and ψ(2S) data**

Final-state effects needed to explain the ψ(2S) behaviour

Inclusive J/ψ production *vs* multiplicity

[PLB 776 (2018) 91]

Charged-particle multiplicity dependence has also been measured in p–Pb collisions



- Low multiplicity:

  Both backward and forward results show an increase of J/ψ production

- High multiplicity, *i.e.* $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ / $\langle \mathrm{dN_{ch}}/\mathrm{d}\eta \rangle > 2$:
  - Forward: J/ψ production shows slower than linear increase (saturation?)
  - Backward: J/ψ production keeps increasing within uncertainties

J/ψ production *vs* multiplicity shows a rapidity dependence while no energy-dependence is observed

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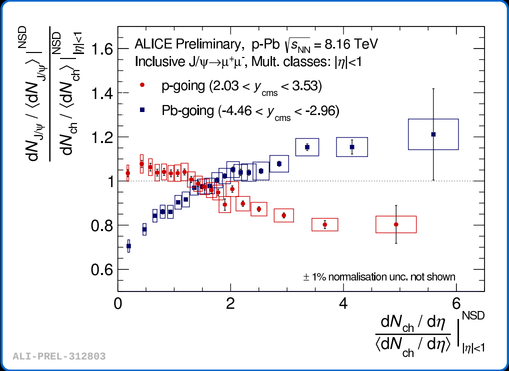

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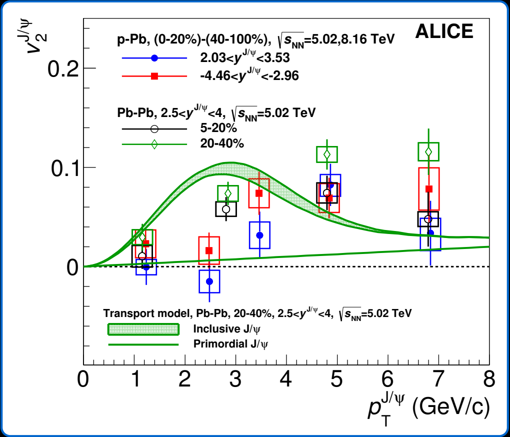
[PLB 780 (2018) 2]



Anisotropy is quantified by the 2nd order coefficient v_2 of the Fourier expansion of the J/ψ – hadron azimuthal correlation

- Low p_T: **v_2 compatible with zero**
- High p_T: **positive v_2**

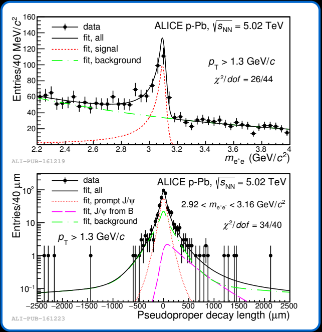
  → similar to the Pb–Pb data!!
  Not understood

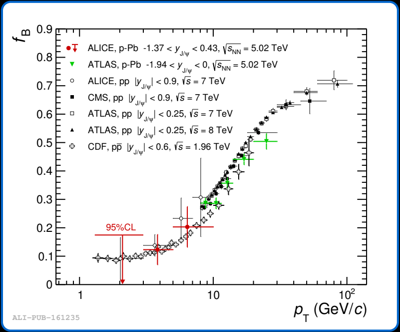
Very challenging result

Current theoretical models do not reproduce the measured v_2 in p–Pb collisions

Prompt/non-prompt J/ψ at mid-rapidity

[EPJC 78 (2018) 466]



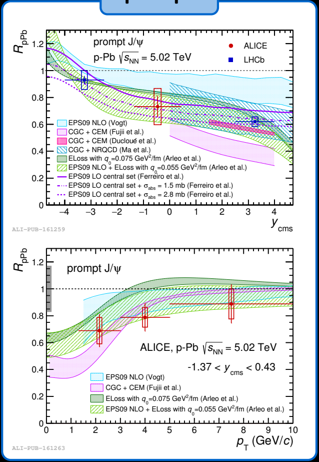


- Prompt/non-prompt separation via a combined fit to dielectron invariant mass and pseudoproper decay length
- Fraction of J/ψ originating from B-hadron decays is compatible with pp measurement: f_B ($p_T > 1.3$ GeV/c, $-1.37 < y < 0.43$) $= \mathbf{0.105} \pm 0.038$ (stat) ± 0.012 (syst)

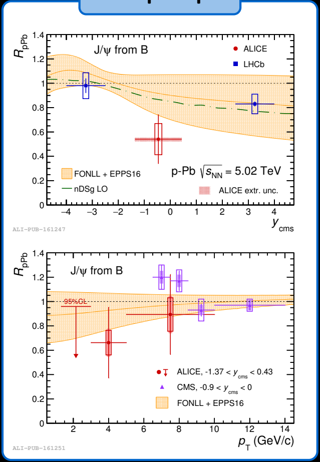
Prompt/non-prompt J/ψ at mid-rapidity

[EPJC 78 (2018) 466]

prompt



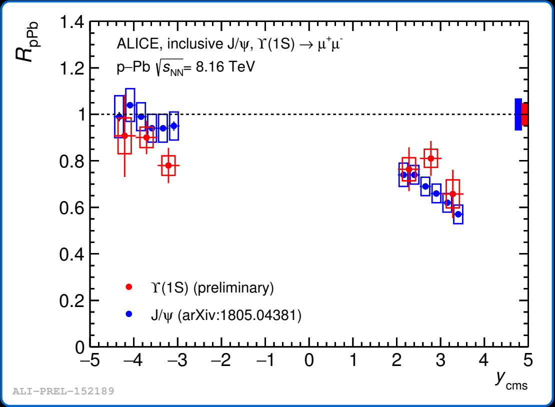
non-prompt



- Prompt J/ψ R_{pPb} shows the same trend as the inclusive R_{pPb}: suppression at mid-rapidity with a hint for a low-p_{T} effect
- R_{pPb} of non-prompt J/ψ from B-hadron decays show compatible degrees of suppression than the prompt J/ψ production

$\Upsilon(1S)$ R_{pPb} *vs* rapidity

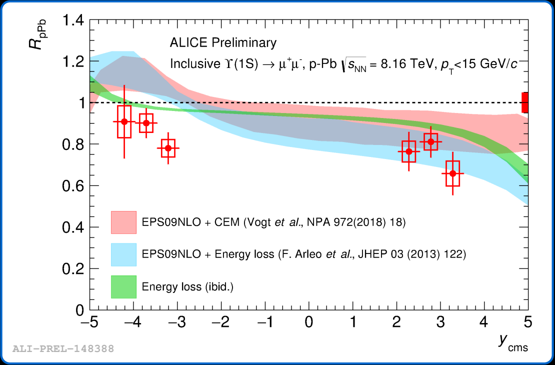
[ALICE-PUBLIC-2018-008]



- Similar **$\Upsilon(1S)$ suppression** within uncertainties **at forward and backward rapidity**
- Similar magnitude of $\Upsilon(1S)$ and J/ψ R_{pPb} within uncertainties

$\Upsilon(1S)$ R_{pPb} *vs* rapidity

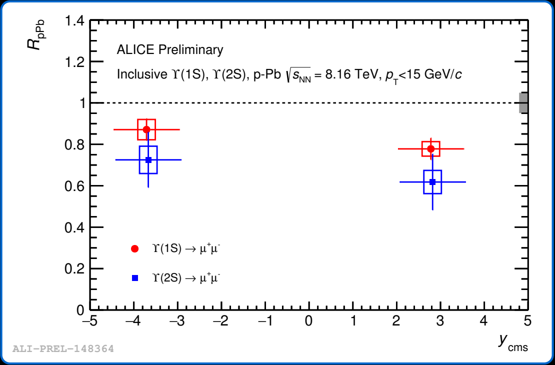
[ALICE-PUBLIC-2018-008]



- Similar **Υ(1S) suppression** within uncertainties **at forward and backward rapidity**
- Similar magnitude of Υ(1S) and J/ψ R_{pPb} within uncertainties
- Models based on shadowing and/or energy loss reproduce the forward rapidity data but slightly overestimate the backward rapidity data

$\Upsilon(2S)$ R_{pPb} *vs* rapidity

[ALICE-PUBLIC-2018-008]



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- Similar magnitude of $\Upsilon(1S)$ and J/ψ R_{pPb} within uncertainties
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- **$\Upsilon(2S)$ R_{pPb} consistent with the $\Upsilon(1S)$ one** within uncertainties with a **hint for a stronger suppression of $\Upsilon(2S)$** (as observed by CMS and ATLAS at mid-y)

Similar CNM effects within uncertainties for Υ at backward and forward rapidity

Summary

- ALICE has measured J/ψ, $\psi(2S)$, $\Upsilon(1S)$ and $\Upsilon(2S)$ productions in pp and p–Pb collisions
- Run-2 results increased significantly the precision of the measurements
- Models face difficulties in describing consistently all the results

After more than 30 years, the quarkonium field is still very rich and more investigations are needed to understand quarkonium production from first principles

Results to follow up:

- Multiplicity dependence of quarkonium production. Continuity from pp to pA to AA?
- J/ψ – hadron correlations (prompt/non-prompt separation)
- Excited to ground state ratio in pA
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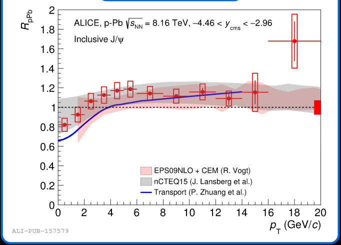
- At long term → ALICE upgrades for Run-3: continuous readout, new Muon Forward Tracker detector (separation of prompt/non-prompt J/ψ at forward rapidity)
  F. Ronchetti's talk: LHC phase one ALICE upgrades

Backup

Inclusive J/ψ R_{pPb} vs p_{T}

[JHEP 1807 (2018) 160], [ALICE-PUBLIC-2018-007]

Backward



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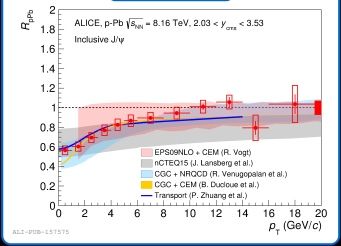
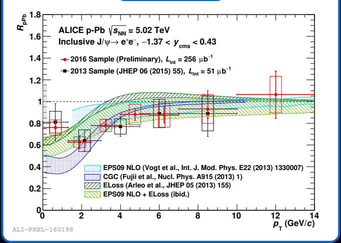


Mid-*y*

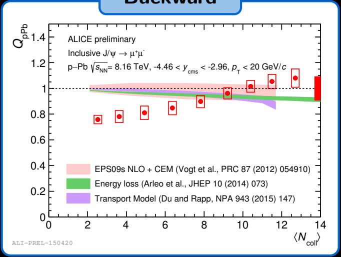


- higher p_{T} reached with Run-2 datasets
- **p_{T}-dependence:** R_{pPb} increasing from low to high p_{T}
- J/ψ suppression at mid and forward rapidity is **a low-p_{T} effect**
- Various models based on different theoretical approaches describe the data

Inclusive J/ψ Q_{pPb} vs N_{coll}

[ALICE-PUBLIC-2018-007]

Backward



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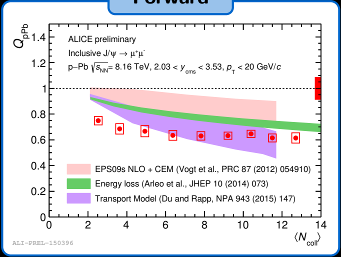
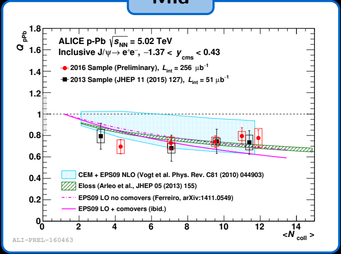


Mid

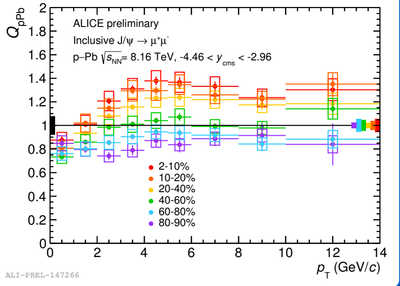


- Q_{pPb} increases at backward rapidity from peripheral to central collisions
- Q_{pPb} is constant at mid-rapidity and slightly decreases at forward rapidity from peripheral to central collisions
- Models do not reproduce the slope of the data at backward rapidity

Inclusive J/ψ Q_{pPb} *vs* p_{T} for different centralities

Preliminary

Backward



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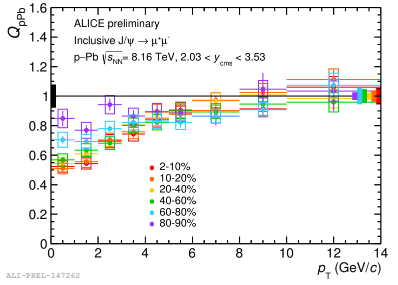
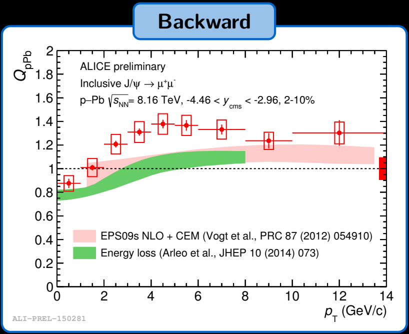
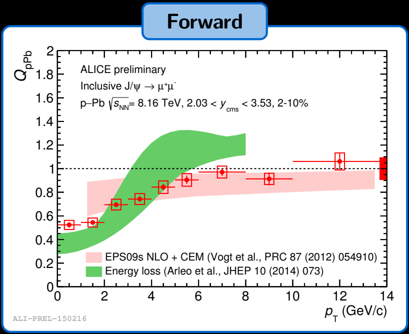


- Clear evolution of Q_{pPb} *vs* p_{T} in different centrality classes
- Backward: enhancement in most central collisions for $p_{\mathrm{T}} > 3$ GeV/c
- Forward: stronger suppression at low p_{T} in most central collisions

J/ψ Q_{pPb} *vs* p_{T} for 2–10% centrality

Preliminary

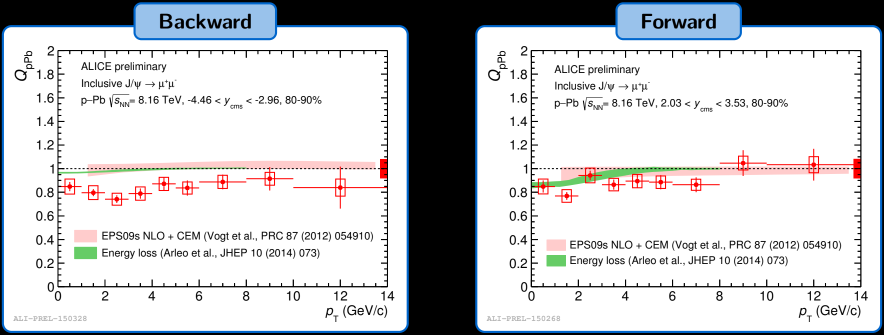




- Clear evolution of Q_{pPb} *vs* p_{T} in different centrality classes
- Backward: enhancement in most central collisions for $p_{\mathrm{T}} > 3$ GeV/c
- Forward: stronger suppression at low-p_{T} in most central collisions
- Tension between models and data for most central collisions

J/ψ Q_{pPb} *vs* p_{T} for 80–90% centrality

Preliminary



- Clear evolution of Q_{pPb} *vs* p_{T} in different centrality classes
- Backward: enhancement in most central collisions for $p_{\mathrm{T}} > 3$ GeV/c
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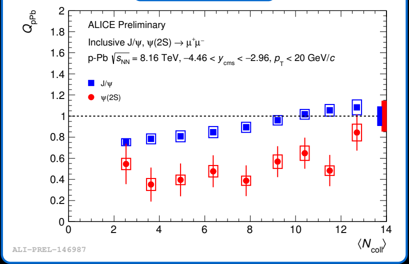
ψ(2S) Q_{pPb} vs N_{coll}

Preliminary

Backward



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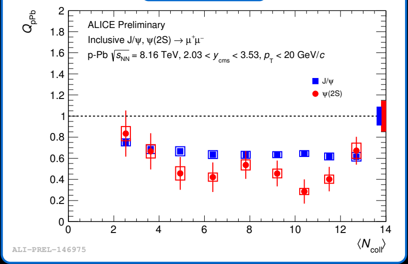
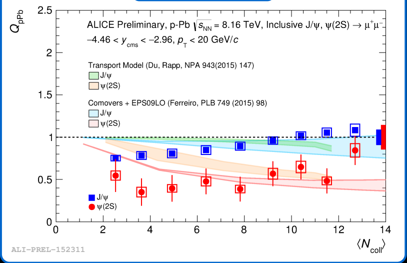


- **ψ(2S) suppression** both at forward and backward rapidity
- Stronger suppression than the J/ψ one, especially at backward rapidity

$\psi(2S)$ Q_{pPb} vs N_{coll}

Preliminary

Backward



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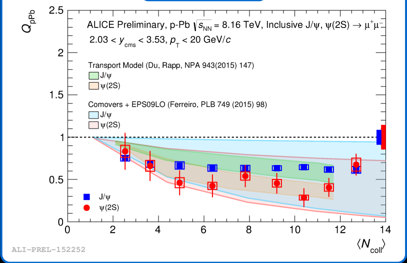
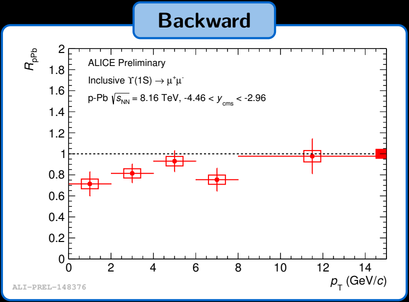
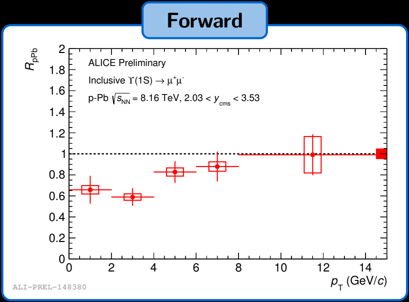


- **$\psi(2S)$ suppression** both at forward and backward rapidity
- Stronger suppression than the J/ψ one, especially at backward rapidity
- $\psi(2S)$ suppression fairly **reproduced by models including final-state effects**
- Tension between models and data at backward rapidity for peripheral collisions

$\Upsilon(1S)$ R_{pPb} vs p_T

[ALICE-PUBLIC-2018-008]



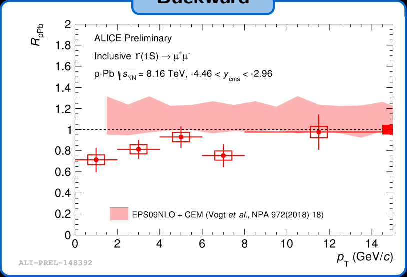


- Similar behavior at both backward and forward rapidity with a **hint for a stronger suppression at low p_T**

$\Upsilon(1S)$ R_{pPb} vs p_T

[ALICE-PUBLIC-2018-008]

Backward



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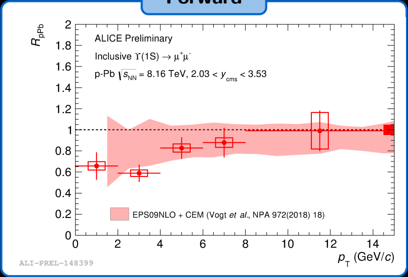
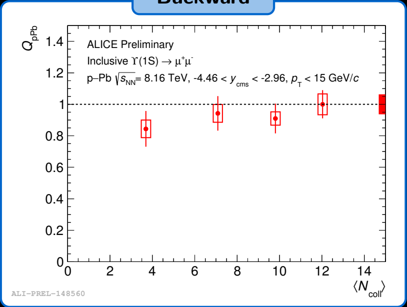


- Similar behavior at both backward and forward rapidity with a **hint for a stronger suppression at low p_T**
- Model based on shadowing describes the forward rapidity results but slightly overestimates the backward rapidity ones

$\Upsilon(1S)$ Q_{pPb} vs N_{coll}

[ALICE-PUBLIC-2018-008]

Backward



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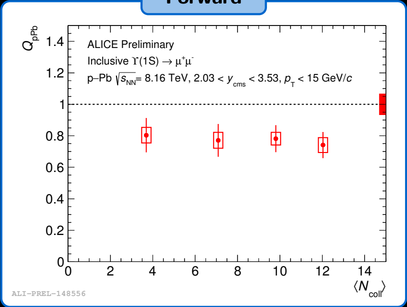

- **Almost no centrality dependence** of Q_{pPb} both at forward and backward rapidity
- Hint for a stronger suppression at forward rapidity