Measurements of quarkonia and open heavy-flavour production in heavy-ion collisions with the ATLAS detector

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Introduction

- Goal: study the behaviour of **heavy quarks in nuclear collisions** by using as probes **quarkonia** ($c\bar{c}$, $b\bar{b}$), D **mesons** and **muons from heavy-flavour decays**.
- In **nucleus-nucleus** collisions, **heavy quarks are produced in hard processes** before the quark-gluon plasma (QGP) is formed, and are sensitive to **final-state effects** like energy loss in the QGP.
- In **proton-nucleus** collisions, they can provide insight on **initial-state effects** such as energy loss of the incoming parton or nuclear modifications to PDFs.
- Measurements reported in this presentation:
  - J/ψ and $\psi(2S)$ production in Pb+Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV: Eur. Phys. J. C 78 (2018) 762 (pp reference measured in $\sqrt{s} = 5.02$ TeV data)
  - J/ψ flow in Pb+Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV: Eur. Phys. J. C 78 (2018) 784
  - D^0/D^* production and D^* flow in p+Pb at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV: ATLAS-CONF-2017-073

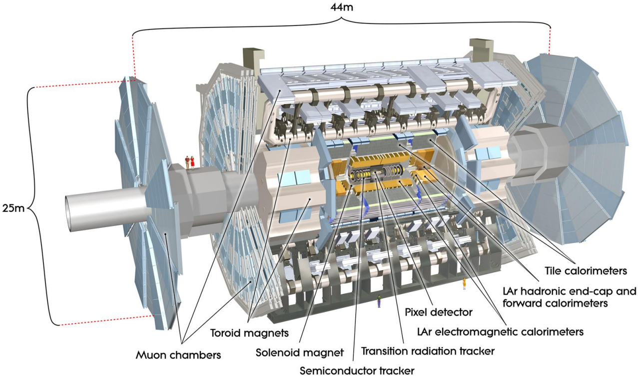
  Run 2

  - Muons from heavy-flavour decays in Pb+Pb at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV: arXiv:1805.05220 (pp reference measured in $\sqrt{s} = 2.76$ TeV data)
  - J/ψ, $\psi(2S)$, $\Upsilon(nS)$ production in p+Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV: Eur. Phys. J. C 78 (2018) 171 (pp reference measured in Run 2 $\sqrt{s} = 5.02$ TeV data)

  Run 1

ATLAS detector / Datasets

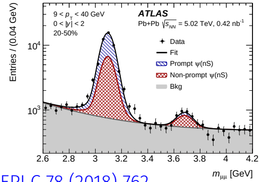
- **Charged particle tracking** in $|\eta| < 2.5 \rightarrow$ muons, charged hadrons
- **Forward calorimeters** in $3.1 < |\eta| < 4.9 \rightarrow$ centrality, event plane estimation
- **Muon reconstruction** in $|\eta| < 2.4$ (muon spectrometer + inner detector)



Datasets:

- Pb+Pb at $\sqrt{s_{\rm NN}} = 2.76$ TeV: 0.14 nb^{-1} (2011)
- Pb+Pb at $\sqrt{s_{\rm NN}} = 5.02$ TeV: 0.42 nb^{-1} (2015)
- p+Pb at $\sqrt{s_{\rm NN}} = 5.02$ TeV: 28 nb^{-1} (2013)
- p+Pb at $\sqrt{s_{\rm NN}} = 8.16$ TeV: 76.3 μb^{-1} (2016)
- pp at $\sqrt{s} = 2.76$ TeV: 570 nb^{-1} (2013)
- pp at $\sqrt{s} = 5.02$ TeV: 25 pb^{-1} (2015)

Charmonia in Pb+Pb: Measurement strategy



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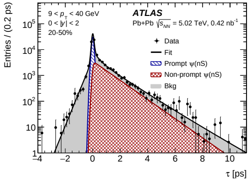

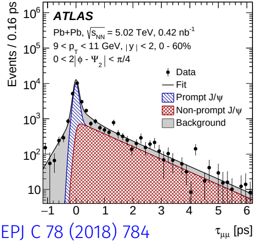

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- **Dimuon decay channels** considered for J/ψ and $\psi(2S)$.
- Events collected with dimuon trigger.
- Dimuon mass range: $2.6 < m_{\mu\mu} < 4.2$ GeV
- Kinematic range: $9 < p_T^{\mu\mu} < 40$ GeV, $|y_{\mu\mu}| < 2$
- Dimuon candidates are corrected for trigger efficiency, reconstruction efficiency and detector acceptance.
- Yields from **two-dimensional** unbinned maximum likelihood **fits in $m_{\mu\mu}$ and pseudo-proper decay time $\tau = \frac{L_{xy} m_{\mu\mu}}{p_T^{\mu\mu}}$**.
- **Separate yields** from two types of production mechanisms:
  - **prompt** - direct and feed-down from higher-mass states
  - **non-prompt** - from b-hadron decays (outside of QGP)
- Fits performed for each considered centrality, $p_T^{\mu\mu}$, $y_{\mu\mu}$ bin.
- For the J/ψ flow measurement, fits are made additionally in bins of $|\phi - \Psi_2|$, where ϕ is the dimuon azimuthal angle and Ψ_2 is the second harmonic of the event plane angle.

Charmonia in Pb+Pb: R_{AA} vs. p_T and centrality

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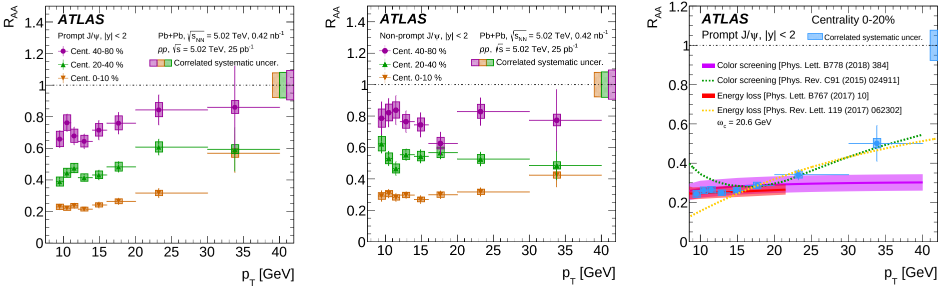

- Study modification of production using **nuclear modification factor** $R_{AA} = \frac{N^{AA}/N^{evt}}{\langle T_{AA}\rangle \times \sigma^{pp}}$.
- Prompt J/ψ R_{AA} increases slowly with p_T, while it is constant for non-prompt J/ψ.
- The magnitude of **suppression increases** strongly **with centrality**.
- **Similar level of modification for prompt and non-prompt J/ψ production** indicates that b quarks might be suppressed in a similar way to c quarks.
- Observed **modification** is **consistent with colour screening models and energy loss models**, but no considered model describes the suppression over the full p_T range.

Charmonia in Pb+Pb: R_{AA} ratio vs. centrality

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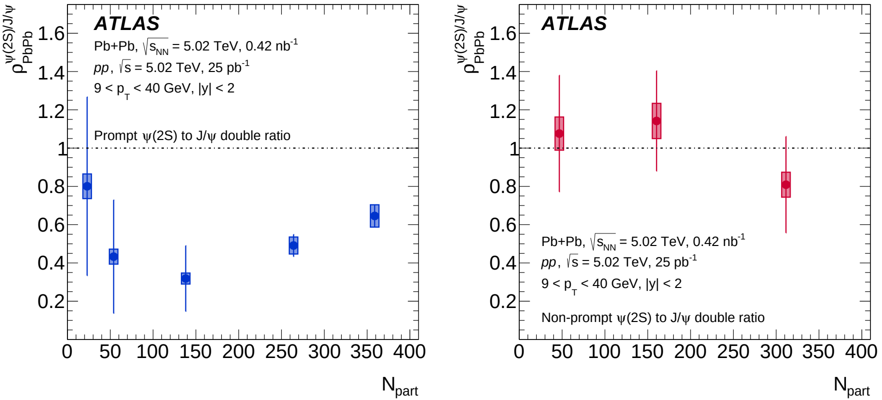

- Study relative modification of production using **ratio** $\rho_{\mathrm{PbPb}}^{\psi(2S)/J/\psi} = \frac{R_{AA}^{\psi(2S)}}{R_{AA}^{J/\psi}}$.
- **Prompt production**: $\psi(2S)$ suppressed more than J/ψ → due to different binding energies?
- **Non-prompt production**: modification similar for J/ψ and $\psi(2S)$ → expected from production in B-hadron decays outside the dense nuclear medium

Charmonia in Pb+Pb: J/ψ flow vs. centrality

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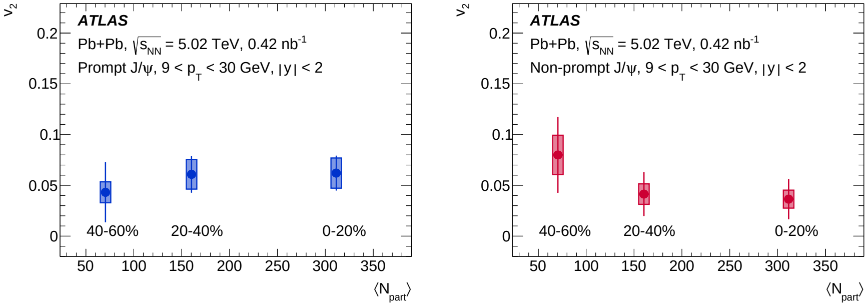


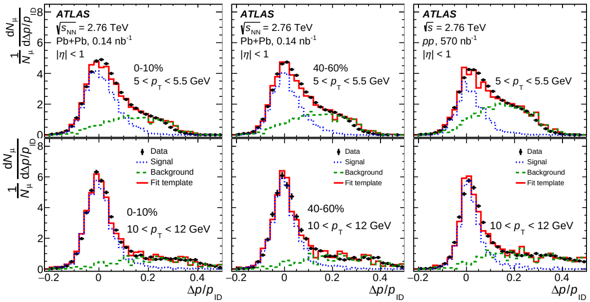
- **Elliptic flow coefficients v_2** are defined using the Fourier expansion of particle yields N in the azimuthal angle, measured relative to the event plane angle:

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n\left(\phi - \Psi_n\right)\right]$$

- The **event plane angle** is estimated via its **second order harmonic Ψ_2** using the azimuthal distributions of transverse energy deposits in the **forward calorimeters**.
- Simultaneous fits to azimuthal distributions of prompt and non-prompt J/ψ yields.
- Observed v_2 values are **non-zero by 1-2σ** (no significant centrality dependence).

Heavy-flavour muons in Pb+Pb: Measurement strategy

arXiv:1805.05220



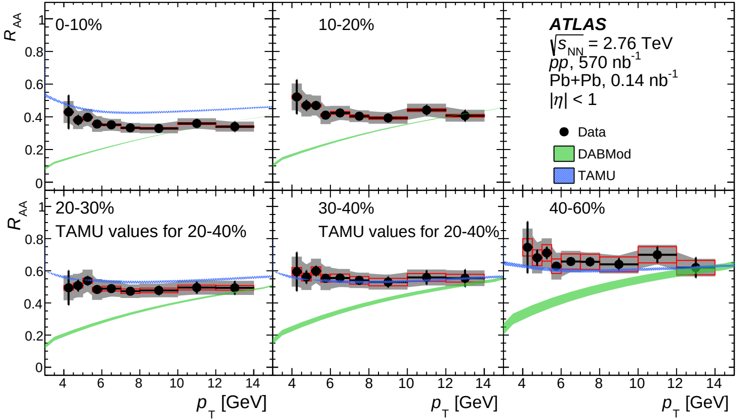
- Focus on **muons from semileptonic decays of *c*- and *b*-quark mesons**.
- Events collected with single-muon trigger ($p_T = 4$ GeV threshold).
- Muons required to pass reconstruction quality selection and match trigger.

- Kinematic selections: $4 < p_T^\mu < 14$ GeV, $|\eta_\mu| < 1$ (production measurement) or $|\eta_\mu| < 2$ (flow measurement)
- **Signal and backgrounds** differ in **momentum imbalance** $\frac{\Delta p}{p_{ID}} = \frac{p_{ID} - p_{MS} - p_{calo}}{p_{ID}}$.
- Separation using **fits of $\frac{\Delta p}{p_{ID}}$ templates** obtained from simulation to data.
- Corrections applied for reconstruction and trigger efficiencies.

Heavy-flavour muons in Pb+Pb: R_{AA} vs. p_T and centrality

arXiv:1805.05220

DABMod: Phys. Rev. C 96 (2017) 064903, TAMU: Phys. Lett. B 735 (2014) 445

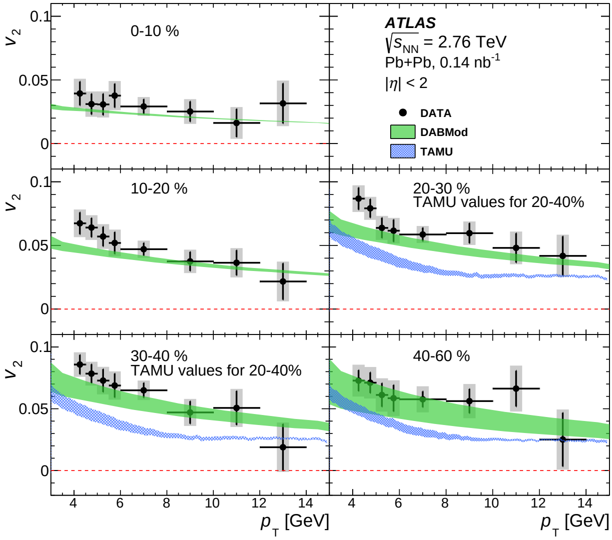


- Measured heavy-flavour muon R_{AA} **does not depend on the muon p_T** and shows **increasing suppression with centrality**.
- Comparison to theoretical models:
  - **Transport model (TAMU)** describes data well except for most central collisions.
  - **Energy loss model (DABMod)** fails to reproduce data at low p_T.

Heavy-flavour muons in Pb+Pb: flow vs. p_T and centrality

arXiv:1805.05220

DABMod: Phys. Rev. C 96 (2017) 064903, TAMU: Phys. Lett. B 735 (2014) 445



- **Elliptic flow coefficients v_2** extracted from fits to azimuthal yield distributions.
- **Non-zero flow** measured up to $p_T = 12$ GeV for all centralities.
- v_2 coefficients **decrease with p_T** except for 0-10% and 40-60% centralities.
- Comparison to theoretical models:
  - **Transport model (TAMU)** underestimates measured flow.
  - **Energy loss model (DABMod)** describes data quite well.

Quarkonia in p+Pb: Measurement strategy

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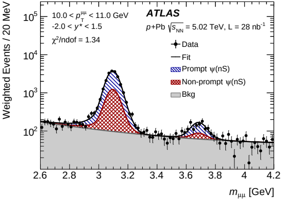

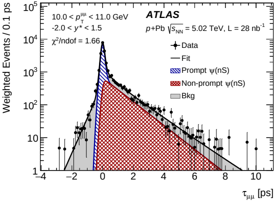

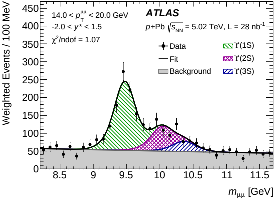

Charmonia measurements (**similar strategy to Pb+Pb**):

- Dimuon mass range: $2.6 < m_{\mu\mu} < 4.2$ GeV
- Kinematic range: $8 < p_T^{\mu\mu} < 40$ GeV, $-2 < y^*_{\mu\mu} < 1.5$
- Dimuon candidates are corrected for trigger efficiency, reconstruction efficiency and detector acceptance.
- Yields from **simultaneous fits in $m_{\mu\mu}$ and τ**, separately for each considered centrality, $p_T^{\mu\mu}$ or $y^*_{\mu\mu}$ interval.

Bottomonia measurements:

- **Dimuon decay channels** considered for $\Upsilon(nS)$.
- Events collected with dimuon trigger.
- Dimuon mass range: $8.2 < m_{\mu\mu} < 11.7$ GeV
- Kinematic range: $p_T^{\mu\mu} < 40$ GeV, $-2 < y^*_{\mu\mu} < 1.5$
- Dimuon candidates are corrected for trigger efficiency, reconstruction efficiency and detector acceptance.
- Yields from maximum likelihood **fits in $m_{\mu\mu}$**, separately for each considered centrality, $p_T^{\mu\mu}$ or $y^*_{\mu\mu}$ interval.

Charmonia in p+Pb: R_{pPb} vs. p_T

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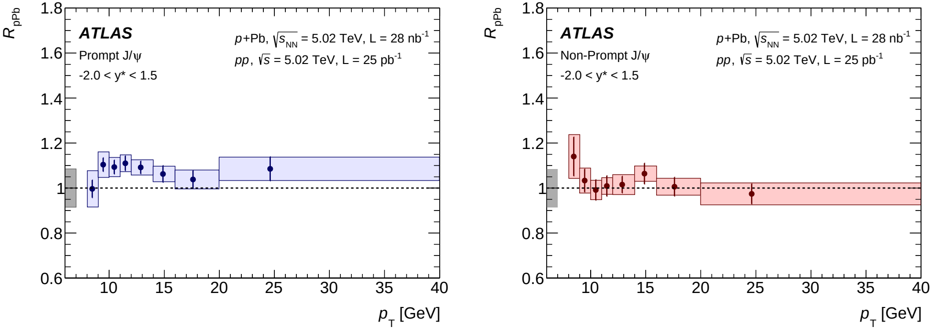

- **Nuclear modification factor** defined as $R_{pPb} = \frac{1}{A_{Pb}} \frac{\sigma^{p+Pb}}{\sigma^{pp}}$ ($A_{Pb} = 208$).
- Both the **prompt and non-prompt** J/ψ R_{pPb} factors are **consistent with unity**.
- No significant trend in p_T is observed.

Bottomonia in p+Pb: R_{pPb} vs. y^*

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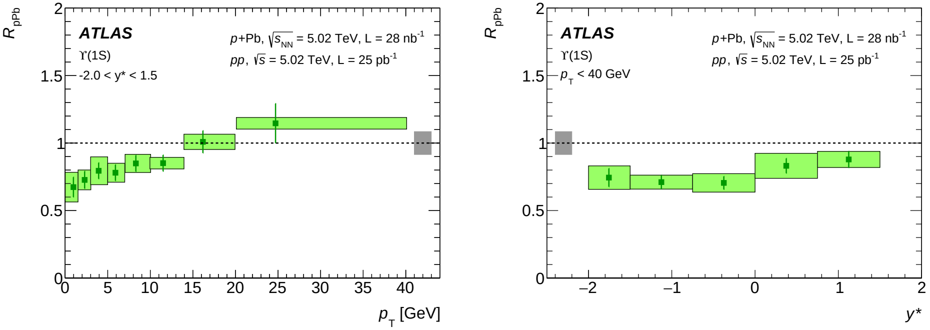

- **Suppression of Υ(1S)** production observed **for $p_T < 15$ GeV** (rising trend).
- A **constant suppression** at the level of 0.8 is measured **as a function of rapidity**.
- The suppressed Υ(1S) production at low p_T might be explained by **nuclear shadowing of PDFs** in the low-x region.

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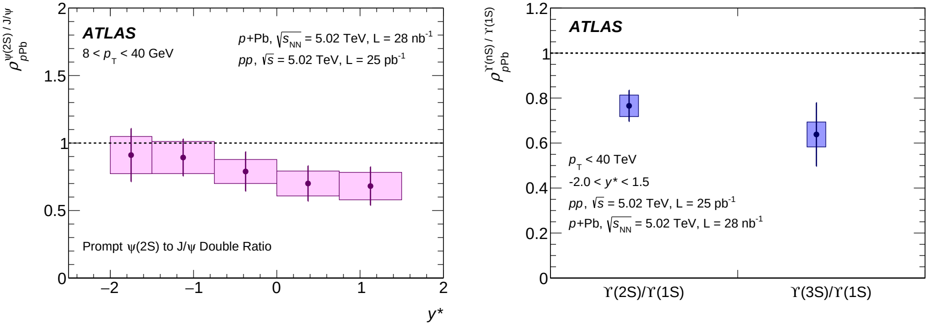

- Study relative modification of production using **ratios of R_{pPb} factors measured for excited states and ground states**.
- **Prompt $\psi(2S)$ production at forward rapidity** (proton-going direction) is slightly **suppressed** relative to J/ψ production.
- **For both $\Upsilon(2S)$ and $\Upsilon(3S)$**, the **ratios** of integrated R_{pPb} factors to the $\Upsilon(1S)$ modification factor are **below unity**.

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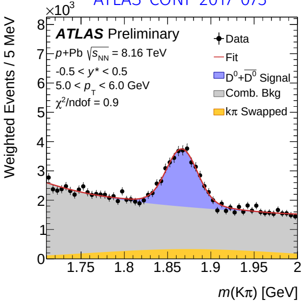

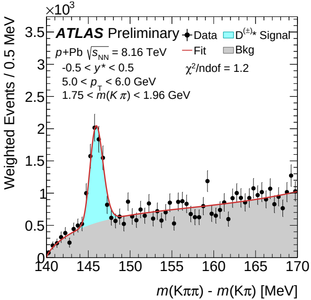

- Reconstructed **decay channels:** $D^0 \rightarrow K\pi$ and $D^* \rightarrow D^0\pi$
- Events collected with minimum bias and high multiplicity track triggers.
- **D^0 candidates** are constructed from **opposite-sign pairs** of charged particle **tracks** with $p_T > 1$ GeV each.
- Both combinations of kaon and pion masses are considered for the tracks, since **no particle identification** is applied.
- Track pair mass range: $1.75 < m(K\pi) < 1.96$ GeV
- Additional topological requirements are applied to improve the signal to background significance.
- **D^* candidates** are built by **adding a soft pion track** with $p_T > 250$ MeV (flow measurement) or $p_T > 400$ MeV (yield measurement) **to D^0 candidates**.
- *D* meson candidates are corrected for topological selection efficiency, reconstruction efficiency and detector acceptance.
- Yields extracted from maximum likelihood **fits to $m(K\pi)$ or $m(K\pi\pi) - m(K\pi)$ distributions**.

D mesons in p+Pb: Forward-backward ratios vs. p_T

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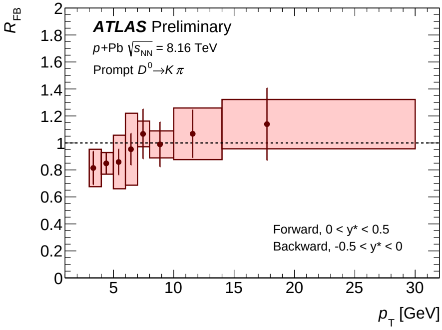

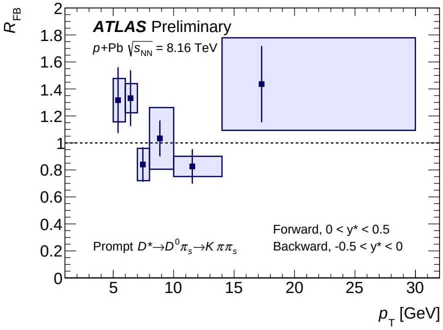

- Study modification of production using **forward-backward ratio of** differential production **cross-sections** $d^2\sigma/dp_T dy^*$:

$$R_{FB} = \frac{d^2\sigma/dp_T dy^*\ (0 < y^* < 0.5)}{d^2\sigma/dp_T dy^*\ (-0.5 < y^* < 0)}$$

- **Non-prompt D-meson subtraction** using a FONLL calculation of $b \to D$ cross-sections.
- In the central rapidity range, **no significant deviation of R_{FB} from unity** is observed.

D mesons in *p*+Pb: *D**-hadron correlations

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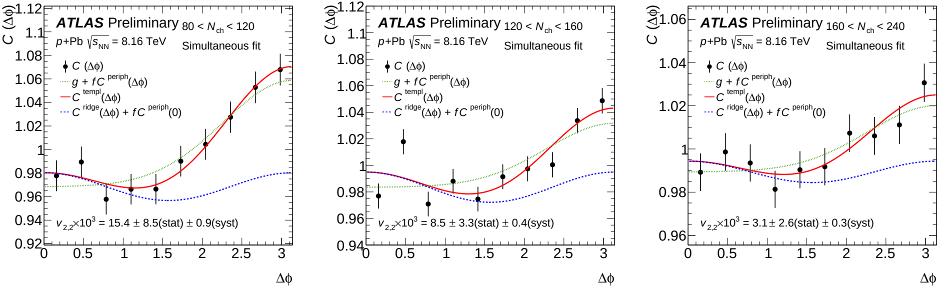

- ***D**-hadron correlations** are studied using the **two-particle correlation function $C(\Delta\phi)$** defined between pairs of D^* candidates and charged particle tracks, separated in pseudorapidity by $\Delta\eta > 1$.
- **Harmonic coefficients $v_{2,2}$** associated with the long-range ridge correlation are **extracted via template fits** with a separate contribution from the correlation function measured in low-multiplicity ($10 < N_{ch} < 80$) events.
- Measurements favour **non-zero $v_{2,2}$ coefficients** for all multiplicity classes.

Summary

- Pb+Pb collisions:
  - **Strong suppression of charmonia production**, increasing with centrality.
  - **Similar suppression** observed for **prompt and non-prompt charmonia**, despite different production mechanisms.
  - **Hints of non-zero J/ψ elliptic flow** for both the prompt and non-prompt production.
  - **Suppression of muons from heavy-flavour decays** increases with centrality, and is independent of p_{T}.
  - Measurement shows a **significant elliptic flow of heavy-flavour muons**.
- p+Pb collisions:
  - **Charmonia nuclear modifications do not deviate significantly from unity**, suggesting the absence of cold nuclear matter effects.
  - The **Υ(1S) production is modified** significantly **at low p_{T}**, which might be explained by **nuclear shadowing** at low x.
  - Measured **harmonic coefficients for D^* mesons** tend to be **non-zero** for all considered multiplicity classes.
- We look forward to taking 3-4 times more Pb+Pb data next month!

Additional slides

Charmonia fit model

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$$\text{PDF}(m,\tau) = \sum_{i=1}^{7} \kappa_i f_i(m) \cdot h_i(\tau) \otimes g(\tau)$$

- κ_i: normalization factor for each component
- $f_i(m)$: distribution function for mass m
- $h_i(\tau)$: distribution function for pseudo-proper decay time τ
- $g(\tau)$: time resolution function (double Gaussian)

i	Type	Source	$f_i(m_{\mu\mu})$	$h_i(\tau_{\mu\mu})$
1	J/ψ	Prompt	$\omega_1 CB_1(m_{\mu\mu}) + (1-\omega_1)G_1(m_{\mu\mu})$	$\delta(\tau_{\mu\mu})$
2	J/ψ	Non-prompt	$\omega_1 CB_1(m_{\mu\mu}) + (1-\omega_1)G_1(m_{\mu\mu})$	$E_1(\tau_{\mu\mu})$
3	$\psi(2S)$	Prompt	$\omega_2 CB_2(m_{\mu\mu}) + (1-\omega_2)G_2(m_{\mu\mu})$	$\delta(\tau_{\mu\mu})$
4	$\psi(2S)$	Non-prompt	$\omega_2 CB_2(m_{\mu\mu}) + (1-\omega_2)G_2(m_{\mu\mu})$	$E_2(\tau_{\mu\mu})$
5	Background	Prompt	F	$\delta(\tau_{\mu\mu})$
6	Background	Non-prompt	$E_3(m_{\mu\mu})$	$E_4(\tau_{\mu\mu})$
7	Background	Non-prompt	$E_5(m_{\mu\mu})$	$E_6(\lvert\tau_{\mu\mu}\rvert)$

- CB: Crystal Ball function
- G: Gaussian
- E: exponential
- δ: delta function

Charmonia in Pb+Pb: R_{AA} vs. centrality

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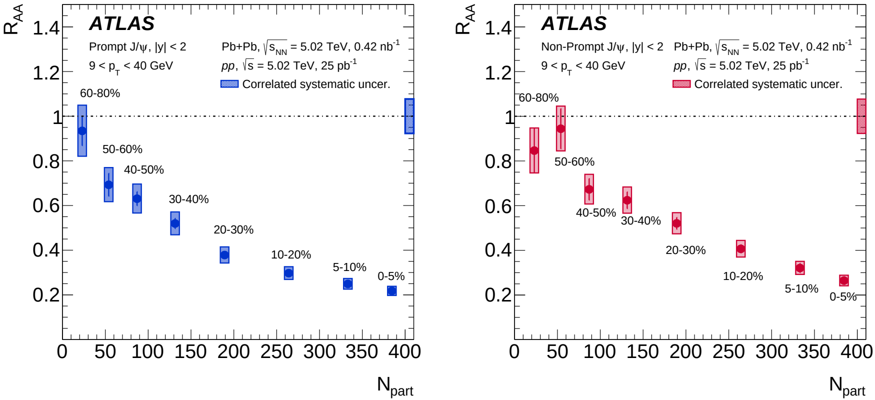

- Suppression of J/ψ production increases strongly with centrality.
- Similar magnitude and trend of nuclear modification is observed for both prompt and non-prompt J/ψ production.

Summary of Pb+Pb systematic uncertainties

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	J/ψ yield		$R_{AA}^{J/\psi}$		$\rho_{PbPb}^{\psi(2S)/J/\psi}$
Source	Uncorr.	Corr.	Uncorr.	Corr.	Uncorr.
Trigger	2 - 4%	3%	5 - 6%	5%	< 1%
Reconstruction	4 - 5%	2%	6 - 7%	2%	< 1%
Fitting	1 - 2%	1%	1 - 2%	1%	8 - 9%
T_{AA}	–	1 - 8%	–	1 - 8%	–
Luminosity	–	–	–	5.4%	–

Examples of J/ψ v_2 fits

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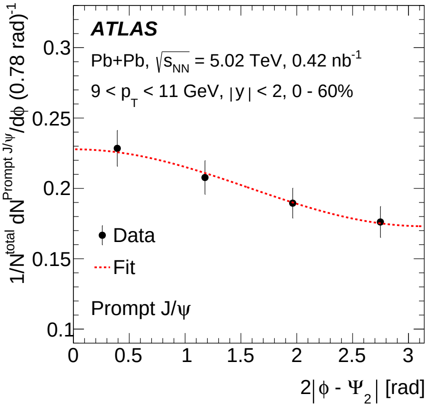

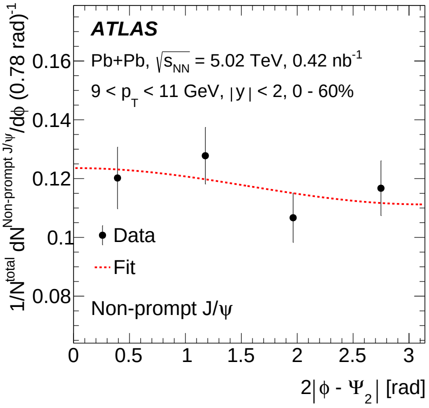

Charmonia in Pb+Pb: J/ψ flow vs. p_T

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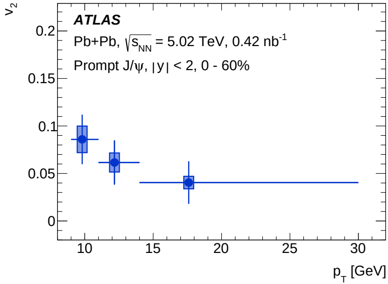

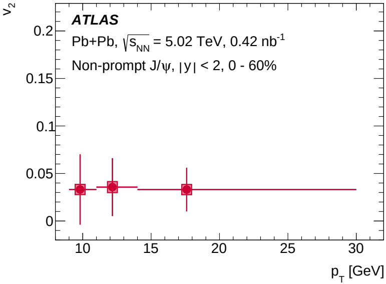

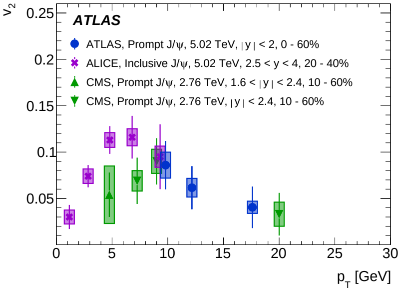

- Hint of **different trends** with p_T for **prompt and non-prompt** J/ψ.
- **Good agreement with ALICE and CMS** results in the overlapping p_T region, despite different rapidity and centrality ranges.

Summary of p+Pb systematic uncertainties

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Collision type	Sources	Ground-state yield [%]	Excited-state yield [%]	Ratio [%]
p+Pb collisions	Luminosity	2.7	2.7	–
	Acceptance	1–4	1–4	–
	Muon reco.	1–2	1–2	< 1
	Muon trigger	4–5	4–5	< 1
	Charmonium fit	2–5	4–10	7–15
	Bottomonium fit	2–15	2–15	5–12
pp collisions	Luminosity	5.4	5.4	–
	Acceptance	1–4	1–4	–
	Muon reco.	1–5	1–5	< 1
	Muon trigger	5–7	5–7	< 1
	Charmonium fit	2–7	4–10	7–11
	Bottomonium fit	1–15	2–15	5–12

Charmonia in p+Pb: comparison to Z bosons

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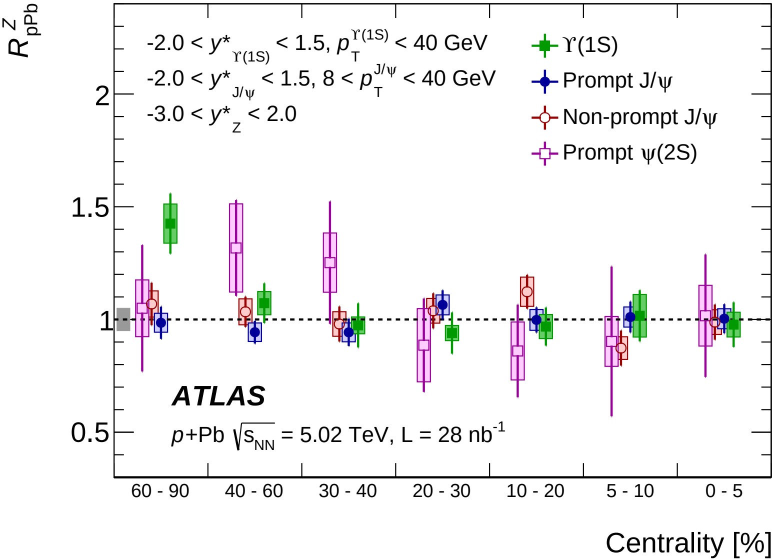

Quarkonia in p+Pb: self-normalised yields

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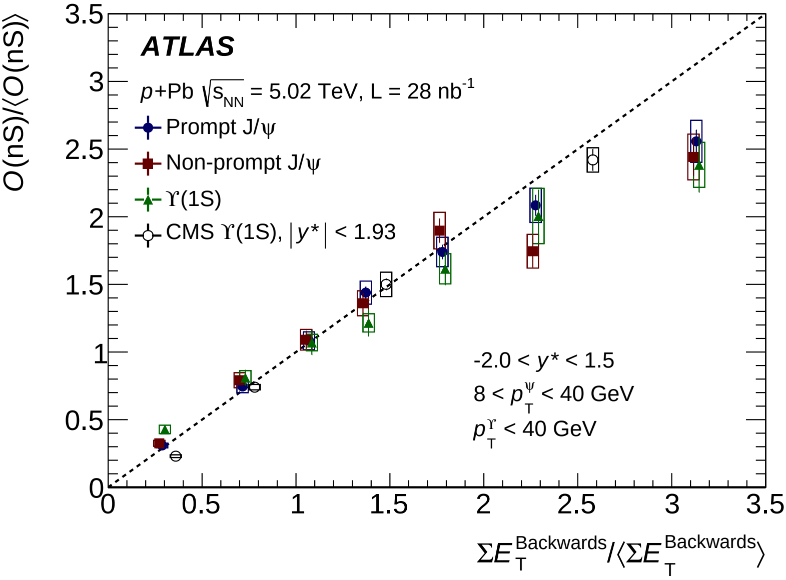

Charmonia in p+Pb: R_{pPb} vs. y^*

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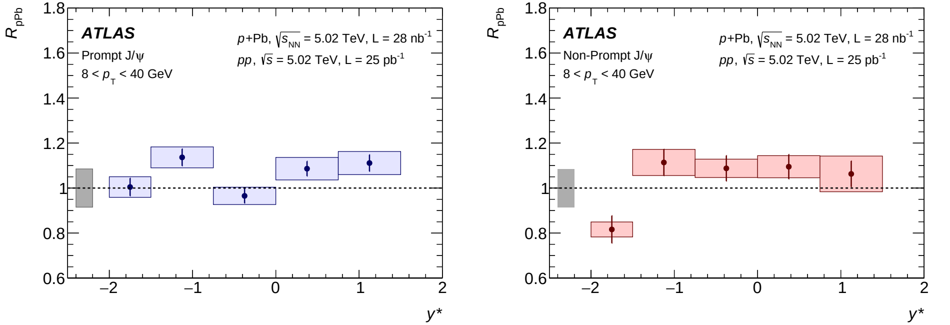
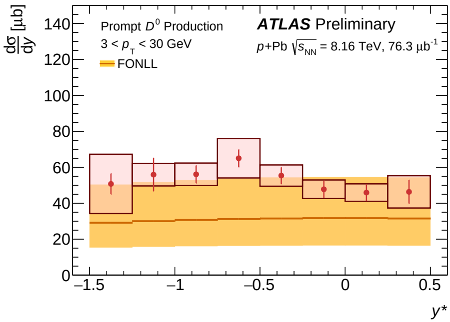
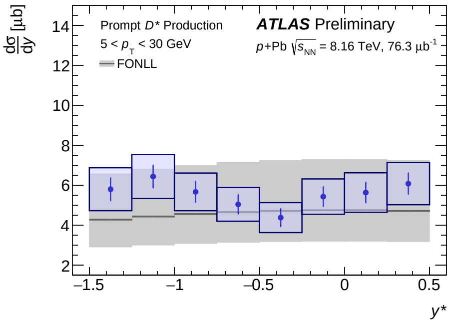


- Measurements for prompt and non-prompt component show no significant dependence on rapidity.

D mesons in p+Pb: Cross-sections vs. y^*

ATLAS-CONF-2017-073





- Non-prompt component of D^0 and D^* meson production is subtracted based on FONLL calculation of $b \to D$ cross-section.
- FONLL predictions for pp collisions are extrapolated from $\sqrt{s} = 8$ TeV to $\sqrt{s} = 8.16$ TeV and scaled by the Pb nucleus mass number ($A^{\mathrm{Pb}} = 208$).
- Predictions are compatible with measured cross-sections within uncertainties for both D^0 and D^* mesons.