Results on resonance production in heavy-ion collisions from the ATLAS experiment at the LHC

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Introduction

- Focus on final states with quarkonia ($c\bar{c}$, $b\bar{b}$) and charmed D mesons which allow to study the behaviour of heavy quarks in nuclear collisions.
- In nucleus-nucleus collisions, heavy quarks are produced at early stages and experience the full evolution of the hot and dense quark-gluon plasma.
- In proton-nucleus collisions, their production is sensitive to cold nuclear matter effects such as initial parton energy loss or nuclear modifications to PDFs.

- Presentation of results from:
  - J/Ψ and $\Psi(2S)$ production in Pb+Pb at $\sqrt{s_{NN}} = 5.02$ TeV: arXiv:1805.04077, submitted to EPJC (pp reference measured in $\sqrt{s} = 5.02$ TeV data)
  - J/Ψ flow in Pb+Pb at $\sqrt{s_{NN}} = 5.02$ TeV: ATLAS-CONF-2018-013
  - D^0/D^* production and D^* flow in p+Pb at $\sqrt{s_{NN}} = 8.16$ TeV: ATLAS-CONF-2017-073

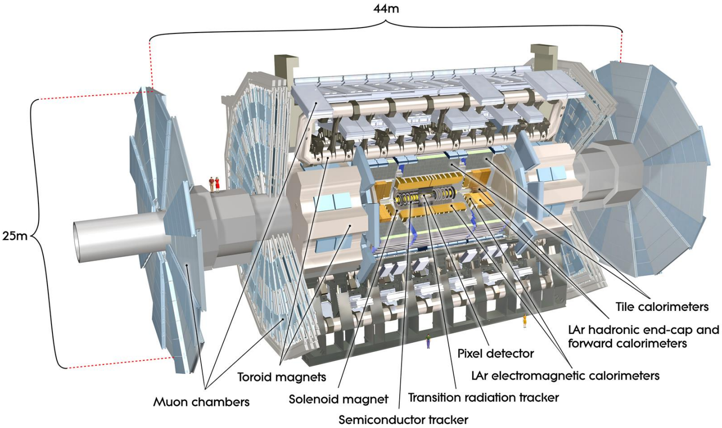
Run 2

  - J/Ψ and $\Psi(2S)$ production in p+Pb at $\sqrt{s_{NN}} = 5.02$ TeV: Eur. Phys. J. C 78 (2018) 171 (pp reference measured in Run 2 $\sqrt{s} = 5.02$ TeV data)
  - Υ(nS) production in p+Pb at $\sqrt{s_{NN}} = 5.02$ TeV: Eur. Phys. J. C 78 (2018) 171 (pp reference measured in Run 2 $\sqrt{s} = 5.02$ TeV data)

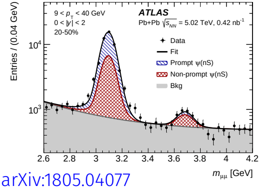
Run 1

ATLAS detector

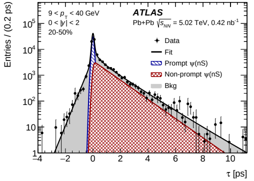
- Charged particle tracking in $|\eta| < 2.5$ provided by Inner Detector.
- Forward calorimeters (FCal, $3.1 < |\eta| < 4.9$) used for centrality determination and event plane estimation.
- Muon reconstruction in $|\eta| < 2.4$, combining measurements in Muon Spectrometer and Inner Detector.

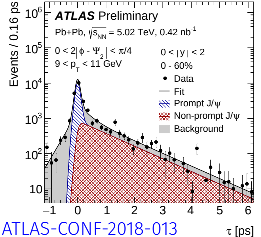


Charmonia in Pb+Pb: Measurement strategy



arXiv:1805.04077



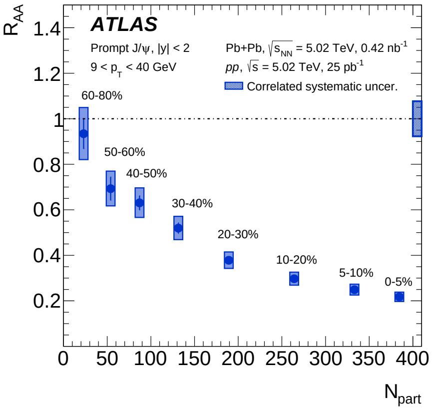


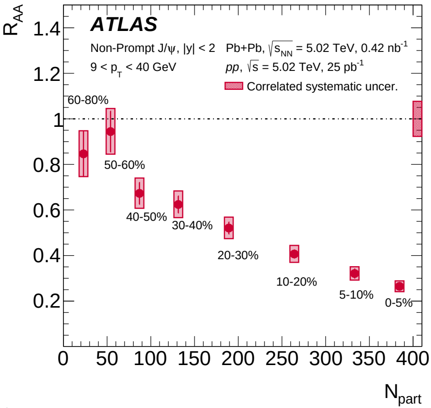
ATLAS-CONF-2018-013

- Di-muon decay channels considered for J/Ψ and $\Psi(2S)$.
- Events collected with di-muon trigger.
- Di-muon mass range: $2.6 < m_{\mu\mu} < 4.2$ GeV
- Kinematic range: $9 < p_{\mathrm{T}}^{\mu\mu} < 40$ GeV, $|y_{\mu\mu}| < 2$
- Di-muon 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 $\tau = \frac{L_{xy} m_{\mu\mu}}{p_{\mathrm{T}}^{\mu\mu}}$.
- Separated yields from two types of production mechanisms:
  - prompt - direct production and feed-down
  - non-prompt - from B-hadron decays
- Fits are repeated separately for each considered centrality, $p_{\mathrm{T}}^{\mu\mu}$ or $y_{\mu\mu}$ interval.
- For the J/Ψ flow measurement, also intervals of the di-muon azimuthal angle $|\phi - \Psi_2|$ measured with respect to the event plane are considered.

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

arXiv:1805.04077

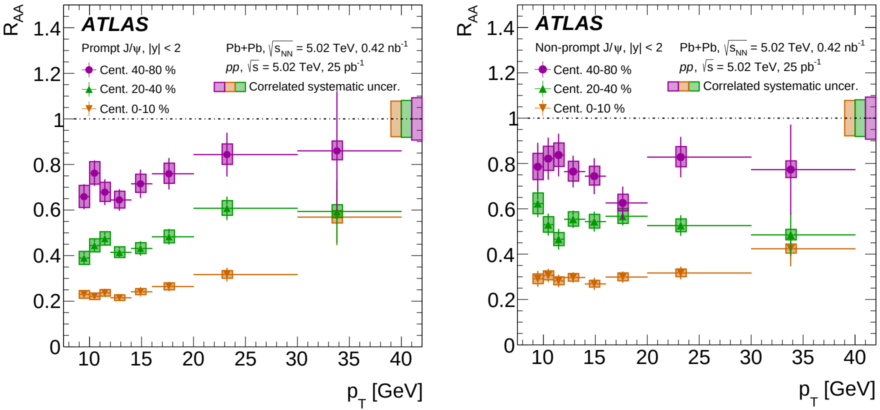




- Nuclear modification factor $R_{AA} = \frac{N^{AA}}{\langle T_{AA} \rangle \times \sigma^{pp}}$
- Suppression of J/Ψ production increases strongly with centrality.
- Similar magnitude and trend of nuclear modification is observed for both prompt and non-prompt J/Ψ production.

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

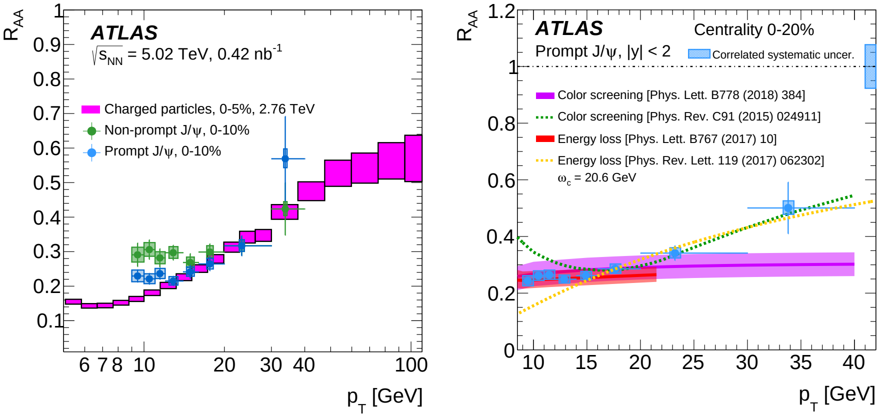
arXiv:1805.04077



- Prompt J/Ψ R_{AA} is increasing slightly with p_T, while the suppression magnitude for non-prompt J/Ψ is constant.
- Similar magnitude of nuclear modification suggests that B-hadrons producing non-prompt charmonia are suppressed in a similar way to prompt charmonia.

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

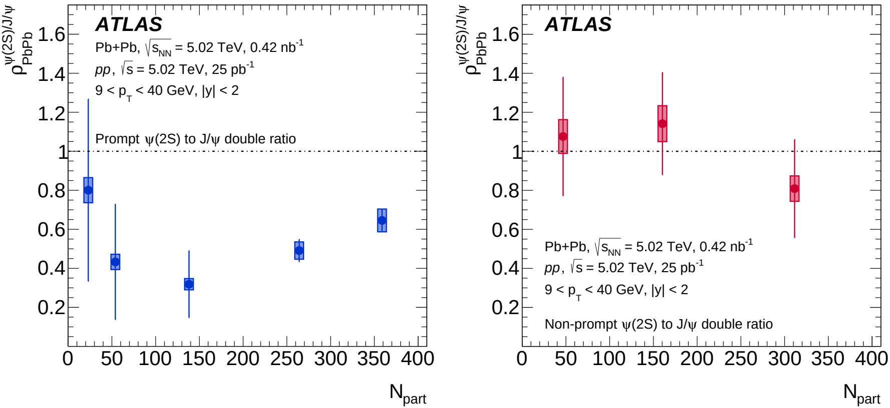
arXiv:1805.04077



- The measured nuclear modification of prompt J/Ψ production follows the general trend for charged particles above $p_T > 12$ GeV.
- Observed modification is consistent with both energy loss models and the colour screening picture.

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

arXiv:1805.04077



- Prompt $\Psi(2S)$ production is suppressed more strongly than J/Ψ production which is related to the difference in binding energies.
- For non-prompt charmonia, the ratio of nuclear modification factors is consistent with unity - as 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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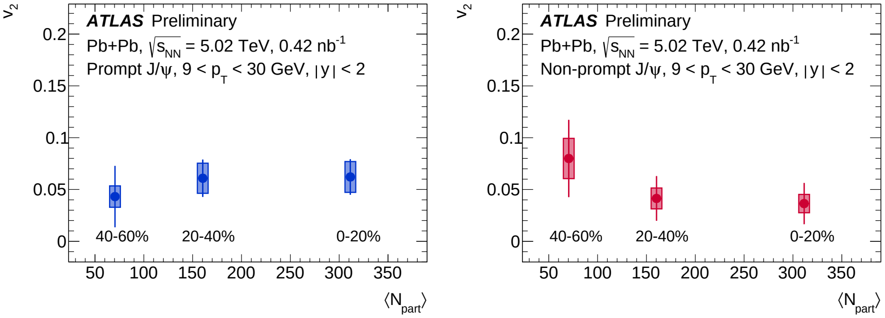
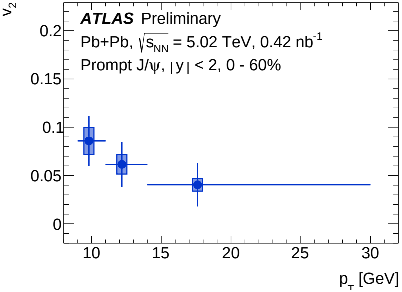
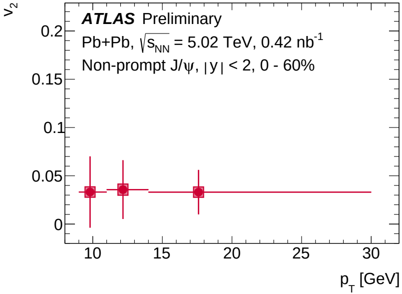


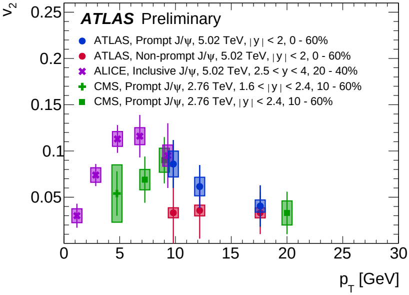
- Elliptic flow coefficients v_2 are evaluated from Fourier fits to azimuthal distributions of J/Ψ yields, measured relative to the event plane angle.
- The event plane angle is estimated via its second order harmonic Ψ_2 using the azimuthal distributions of transverse energy deposits in the forward calorimeters.
- Fits are performed simultaneously for the prompt and non-prompt components.
- Measurement favours non-zero v_2 values for both prompt and non-prompt J/Ψ, and no significant centrality dependence is observed.

Charmonia in Pb+Pb: J/Ψ flow vs. p_T

ATLAS-CONF-2018-013







- Different trends with p_T for prompt and non-prompt J/Ψ.
- Reasonable agreements with results from ALICE and CMS measurements, despite different kinematic ranges.

Quarkonia in p+Pb: Measurement strategy

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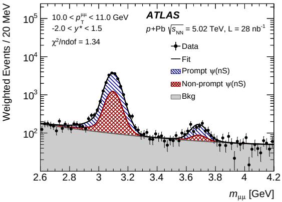

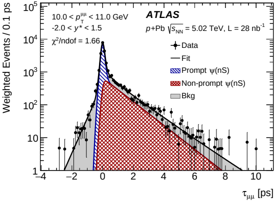

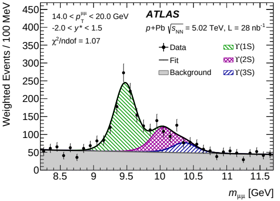

Charmonia measurements (similar strategy to Pb+Pb):

- Di-muon mass range: $2.6 < m_{\mu\mu} < 4.2$ GeV
- Kinematic range: $8 < p_T^{\mu\mu} < 40$ GeV, $-2 < y^*_{\mu\mu} < 1.5$
- Di-muon 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:

- Di-muon decay channels considered for $\Upsilon(nS)$.
- Events collected with di-muon trigger.
- Di-muon mass range: $8.2 < m_{\mu\mu} < 11.7$ GeV
- Kinematic range: $p_T^{\mu\mu} < 40$ GeV, $-2 < y^*_{\mu\mu} < 1.5$
- Di-muon 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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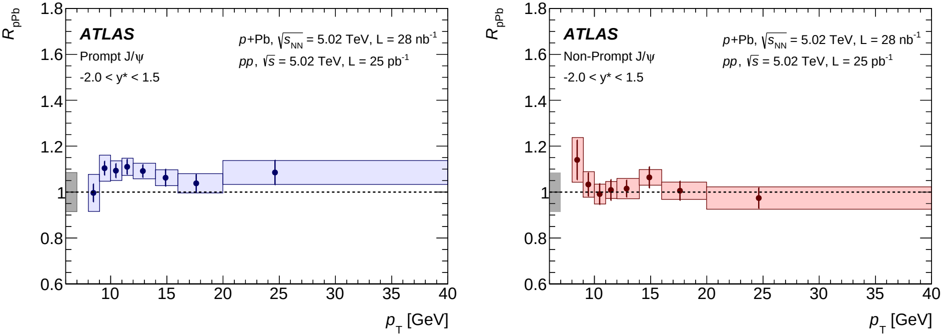

- Nuclear modification factor $R_{pPb} = \frac{1}{A^{Pb}} \frac{d^2\sigma_\Psi^{p+Pb}/dy^*dp_T}{d^2\sigma_\Psi^{pp}/dy^*dp_T}$
- Within uncertainties, both the prompt and non-prompt J/Ψ production exhibit an R_{pPb} factor consistent with unity.
- No significant trend in p_T is observed.

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

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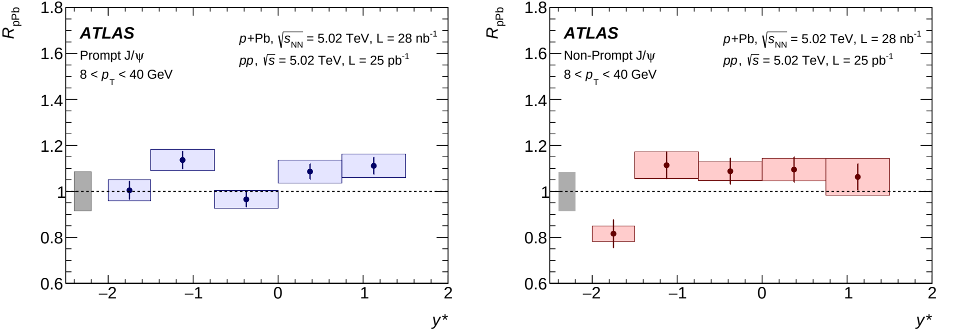

- Measurements for prompt and non-prompt component show no significant dependence on rapidity.

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

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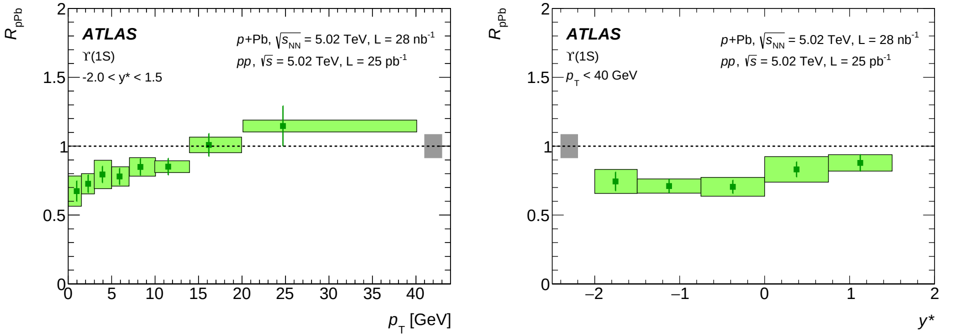

- The Υ(1S) production in p+Pb is found to be suppressed with respect to pp collisions for $p_\mathrm{T} < 15$ GeV and increases with p_T.
- The observation of suppressed Υ(1S) production at low p_T might be explained by stronger nPDF shadowing in this kinematic range.
- A constant suppression at the level of 0.8 is measured as a function of rapidity.

Quarkonia in p+Pb: R_{pPb} ratios

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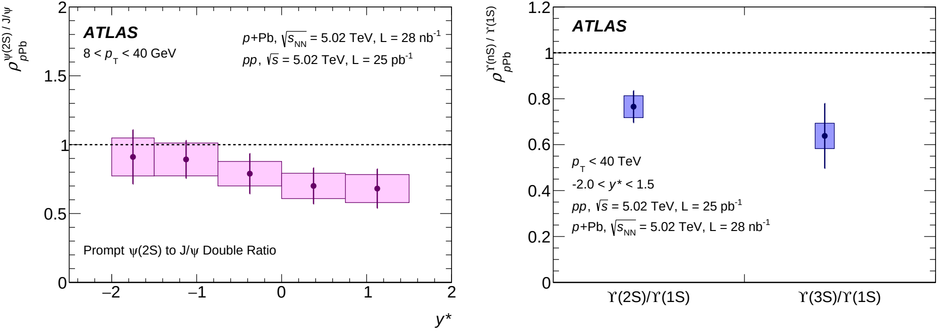
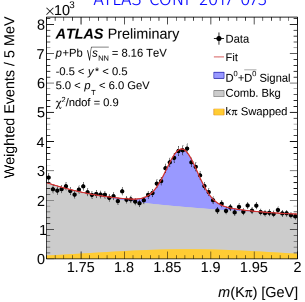
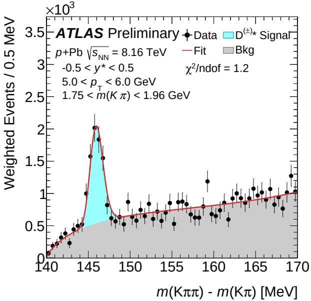


- Measurements indicate a slightly increased suppression of prompt $\Psi(2S)$ production relative to J/Ψ production in the forward direction.
- For both $\Upsilon(2S)$ and $\Upsilon(3S)$, the ratios of integrated R_{pPb} factors to the $\Upsilon(1S)$ modification factor are below unity.

D mesons in p+Pb: Measurement strategy

ATLAS-CONF-2017-073

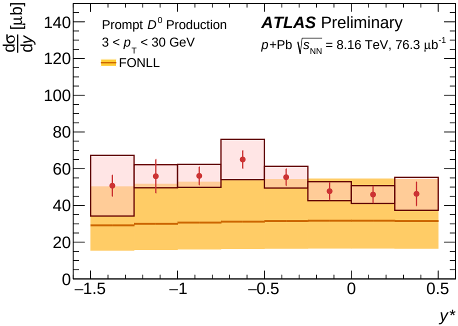


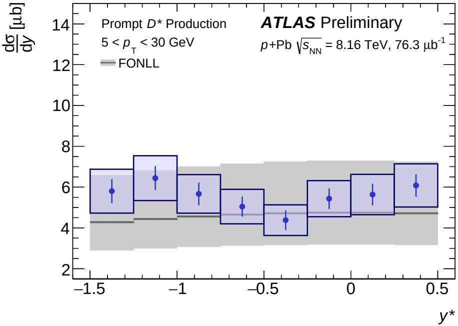


- Reconstructed decay channels: $D^0 \to K\pi$ and $D^* \to D^0\pi$
- Events collected with minimum bias and high multiplicity track triggers.
- D^0 candidates are constructed from opposite-sign pairs of charged particle tracks with $p_T > 1$ GeV each.
- Both combinations of kaon and pion masses are 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: Cross-sections vs. y^*

ATLAS-CONF-2017-073

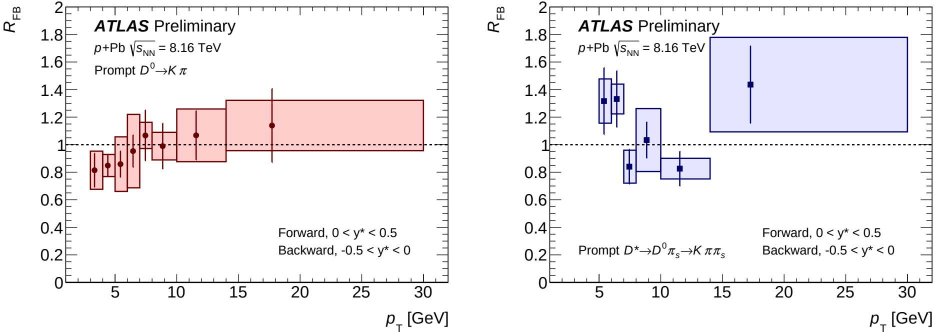




- Non-prompt component of D^0 and D^* meson production is subtracted based on FONLL calculation of $b \to D$ cross-section.
- FONLL predictions for pp collisions are extrapolated from $\sqrt{s} = 8$ TeV to $\sqrt{s} = 8.16$ TeV and scaled by the Pb nucleus mass number ($A^{\mathrm{Pb}} = 208$).
- Predictions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

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

ATLAS-CONF-2017-073



- Forward-backward ratios R_{FB} measured for D meson production cross-sections in the proton-going (forward) and Pb-going (backward) directions.
- 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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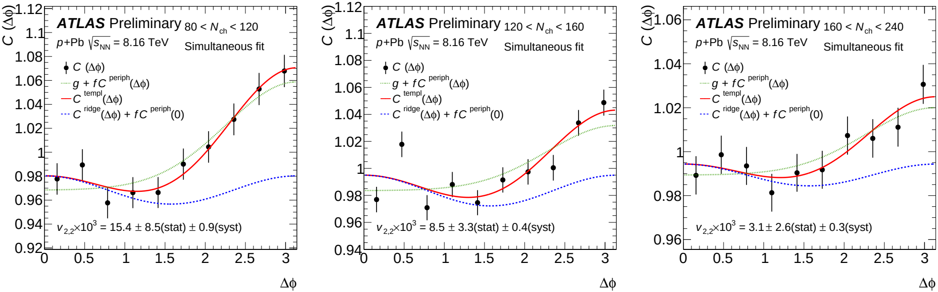


- D^*-hadron correlations are studied using the two-particle correlation function $C(\Delta\phi)$ defined between pairs of D^* candidates and charged particle tracks, separated in pseudorapidity by $\Delta\eta > 1$.
- Harmonic coefficients $v_{2,2}$ associated with the long-range ridge correlation are 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:
  - Measured strong suppression of charmonia production, increasing with centrality.
  - Similar suppression observed for prompt and non-prompt charmonia, despite different production mechanisms.
  - Measurement favours a non-zero J/Ψ elliptic flow for both the prompt and non-prompt production.
- p+Pb collisions:
  - Charmonia nuclear modifications do not deviate significantly from unity, suggesting the absence of cold nuclear matter effects.
  - The $\Upsilon(1S)$ 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 studied multiplicity classes.

Additional slides

Charmonia fit model

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

- 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)

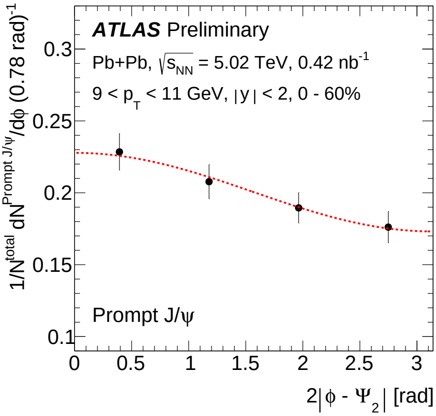
i	Type	Source	$f_i(m_{\mu\mu})$	$h_i(\tau_{\mu\mu})$
1	J/ψ	Prompt	$\omega_1 CB_1(m_{\mu\mu}) + (1-\omega_1)G_1(m_{\mu\mu})$	$\delta(\tau_{\mu\mu})$
2	J/ψ	Non-prompt	$\omega_1 CB_1(m_{\mu\mu}) + (1-\omega_1)G_1(m_{\mu\mu})$	$E_1(\tau_{\mu\mu})$
3	$\psi(2S)$	Prompt	$\omega_2 CB_2(m_{\mu\mu}) + (1-\omega_2)G_2(m_{\mu\mu})$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

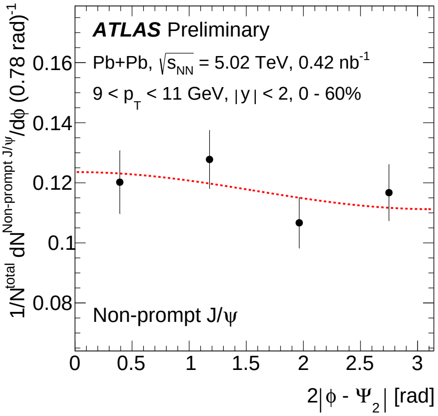
- CB: Crystal Ball function
- G: Gaussian
- E: exponential
- δ: delta function

Summary of Pb+Pb systematic uncertainties

	J/ψ yield		$R_{\mathrm{AA}}^{J/\psi}$		$\rho_{\mathrm{PbPb}}^{\psi(2\mathrm{S})/J/\psi}$
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

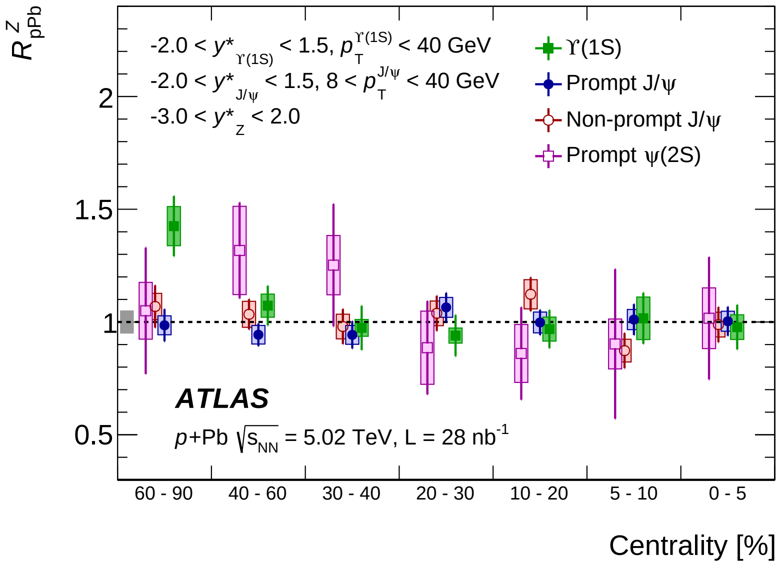




Summary of p+Pb systematic uncertainties

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



Quarkonia in p+Pb: self-normalised yields