Quarkonia measurements in 5 TeV heavy-ion collisions with the ATLAS detector

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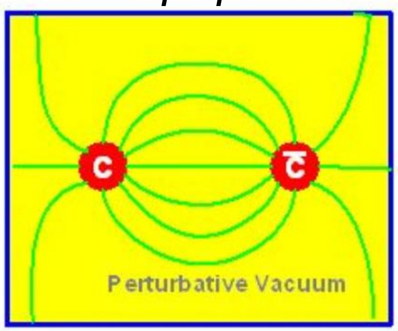
Why study quarkonia?

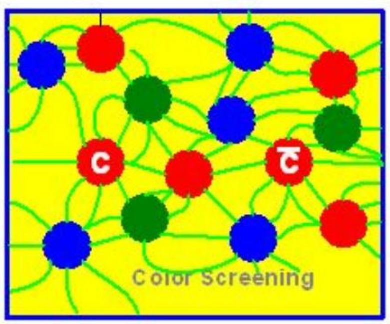
- Quarkonia
  - Bound states of quark and anti-quark (*c*,*b*)
  - Strong interaction with matter
  - Sensitive to hot and cold matter effects
  - Two different production mechanisms

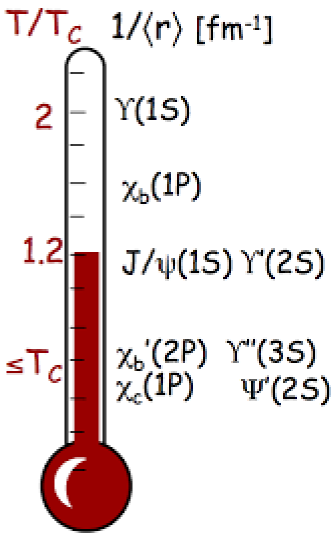
p+p



Quark-gluon plasma formation →

Pb+Pb

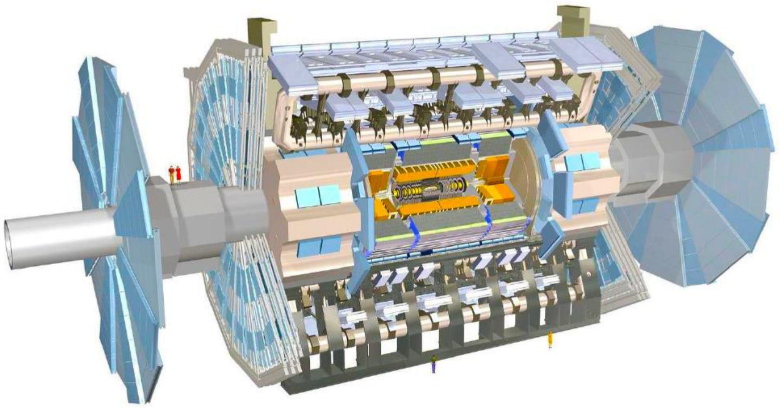


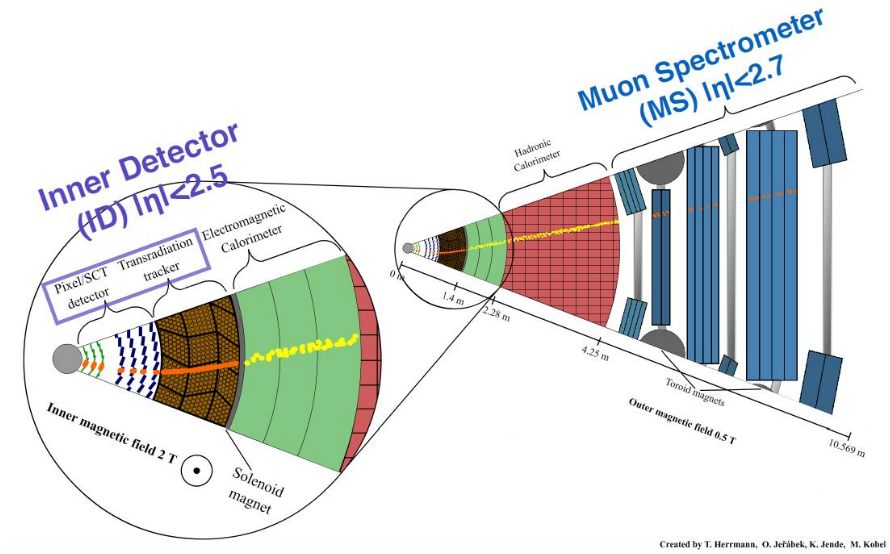


Hot Nuclear Matter (*Pb+Pb*)
• Colour screening • Regeneration • Probing b-quark energy loss

Cold Nuclear Matter (*p+Pb*)
• Modification to nuclear PDFs • Nuclear absorption • Parton energy loss • Gluon saturation

ATLAS detector





- Muon reconstruction is done using muons spectrometer, inner detector and trigger system ($|\eta| < 2.4$)
- Forward calorimeters (FCal, $3.1 < |\eta| < 4.9$) are used in centrality determination

Used heavy-ion data:

- 2013 *p*+*Pb* $5.02\ \mathrm{TeV},\ 28\ \mathrm{nb}^{-1}$
- 2015 *Pb*+*Pb* $5.02\ \mathrm{TeV},\ 0.49\ \mathrm{nb}^{-1}$
- 2015 *p*+*p* $5.02\ \mathrm{TeV},\ 25\ \mathrm{pb}^{-1}$

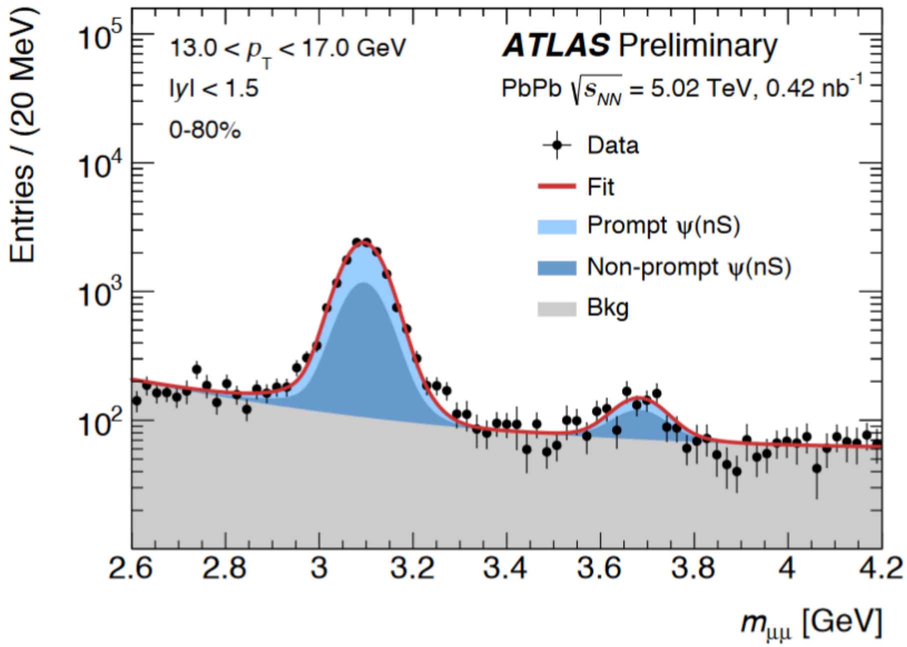
ATLAS quarkonia measurements

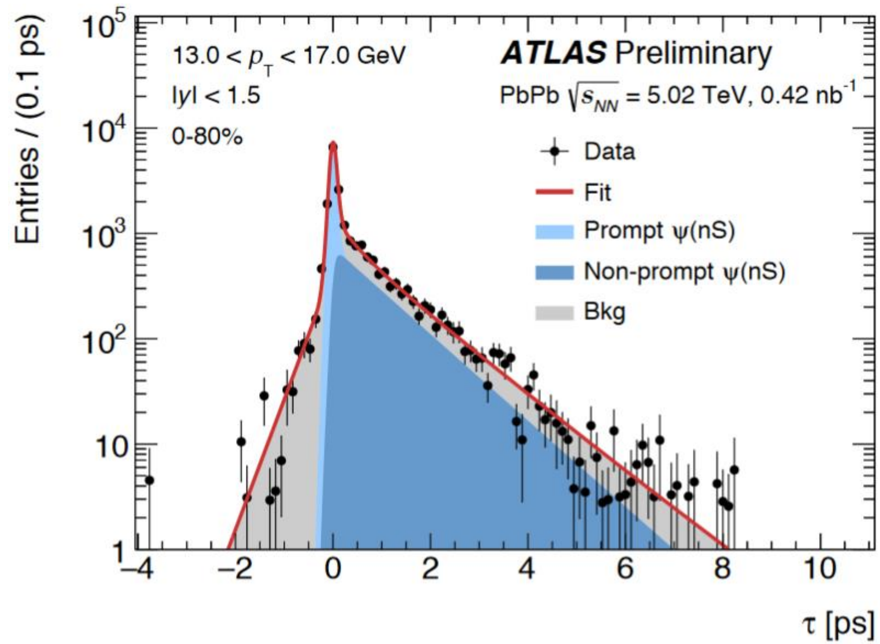
Two major quarkonia results

- September 2016 J/ψ and $\psi(2S)$ ATLAS-CONF-2016-109
  - 2015 *Pb+Pb* $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$ and 2015 *p+p* $\sqrt{s} = 5.02\ \mathrm{TeV}$
- September 2017 J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ arXiv:1709.03089 (ATLAS paper pre-print)
  - 2013 *p+Pb* $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$ and 2015 *p+p* $\sqrt{s} = 5.02\ \mathrm{TeV}$

Charmonium in Pb+Pb

Simultaneous 2D fit





i	Type	Source	$f_i(m)$	$h_i(\tau)$
1	J/ψ	P	$\omega_i \mathrm{CB}_1(m) + (1-\omega_i)\mathrm{G}_1(m)$	$\delta(\tau)$
2	J/ψ	NP	$\omega_i \mathrm{CB}_1(m) + (1-\omega_i)\mathrm{G}_1(m)$	$\mathrm{E}_1(\tau)$
3	$\psi(2S)$	P	$\omega_i \mathrm{CB}_2(m) + (1-\omega_i)\mathrm{G}_2(m)$	$\delta(\tau)$
4	$\psi(2S)$	NP	$\omega_i \mathrm{CB}_2(m) + (1-\omega_i)\mathrm{G}_2(m)$	$\mathrm{E}_2(\tau)$
5	Bkg	P	flat	$\delta(\tau)$
6	Bkg	NP	$\mathrm{E}_3(m)$	$\mathrm{E}_4(\tau)$
7	Bkg	NP	$\mathrm{E}_5(m)$	$\mathrm{E}_6(\lvert\tau\rvert)$

Mass pdf — Time resolution model

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

Time pdf

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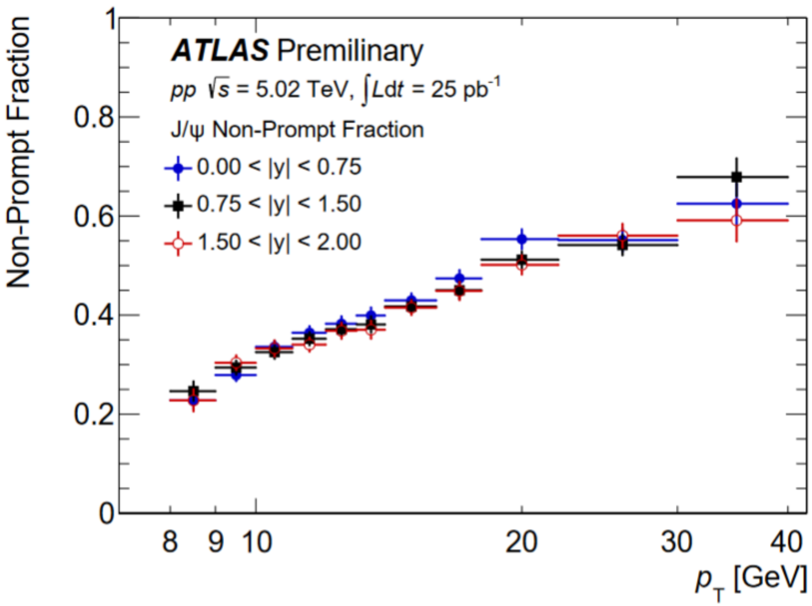
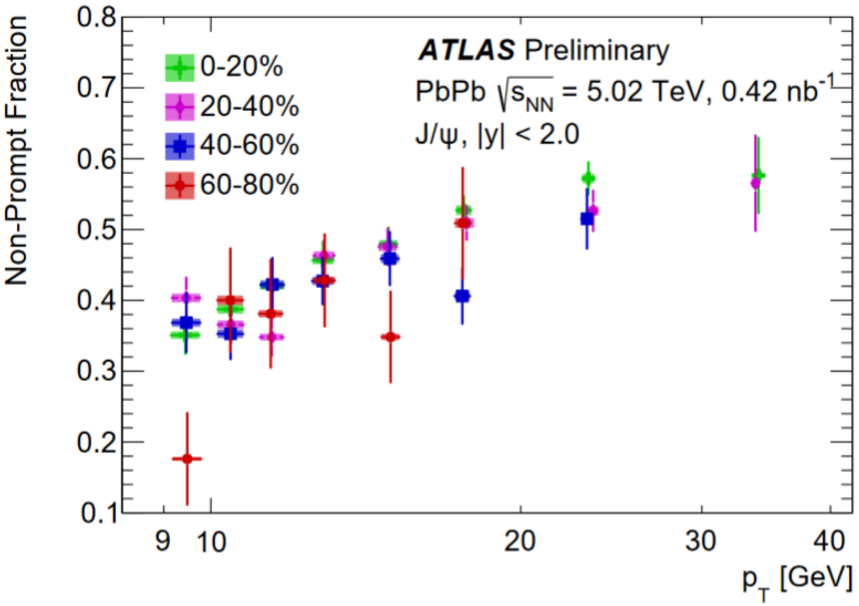
Non-prompt J/ψ fraction





- The fraction of non-prompt J/ψ is similar in trend and magnitude for both *p+p* and *Pb+Pb* collisions
- No significant centrality dependence in *Pb+Pb* measurements

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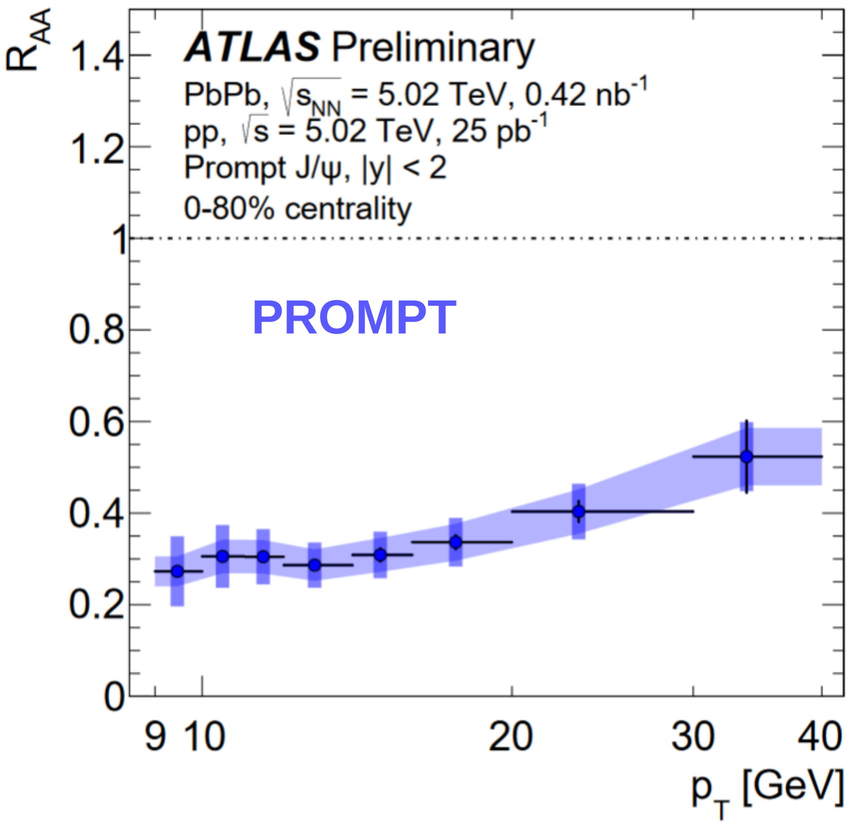
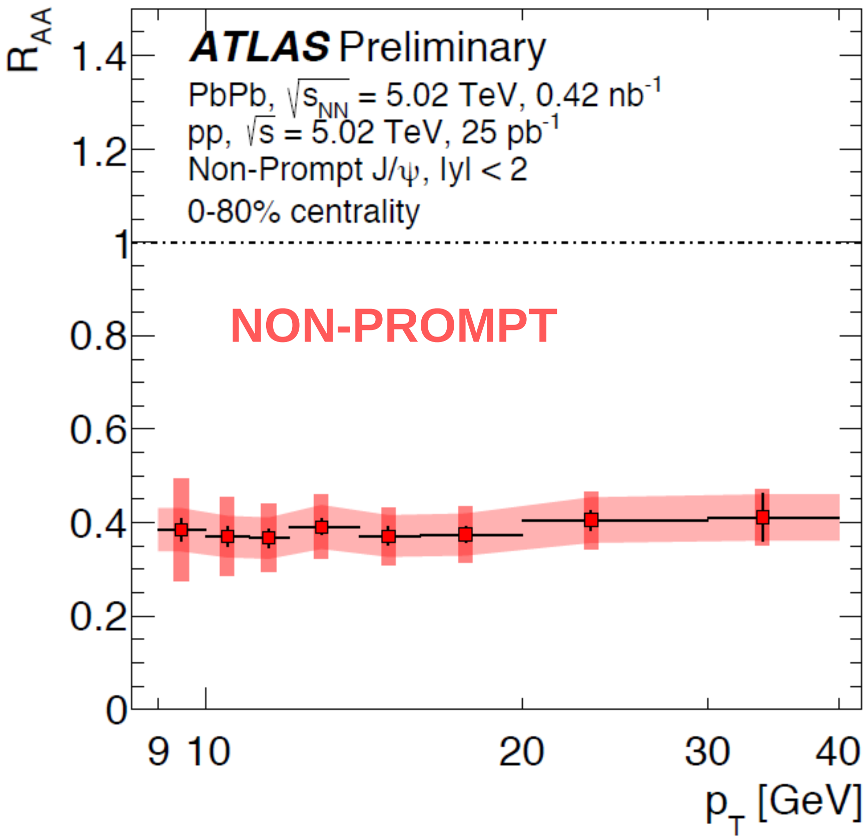
$J/\psi\ R_{AA}$ vs. p_T

$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma^{pp}}$$





- R_{AA} is increasing at high p_T
- Flat in measured p_T range

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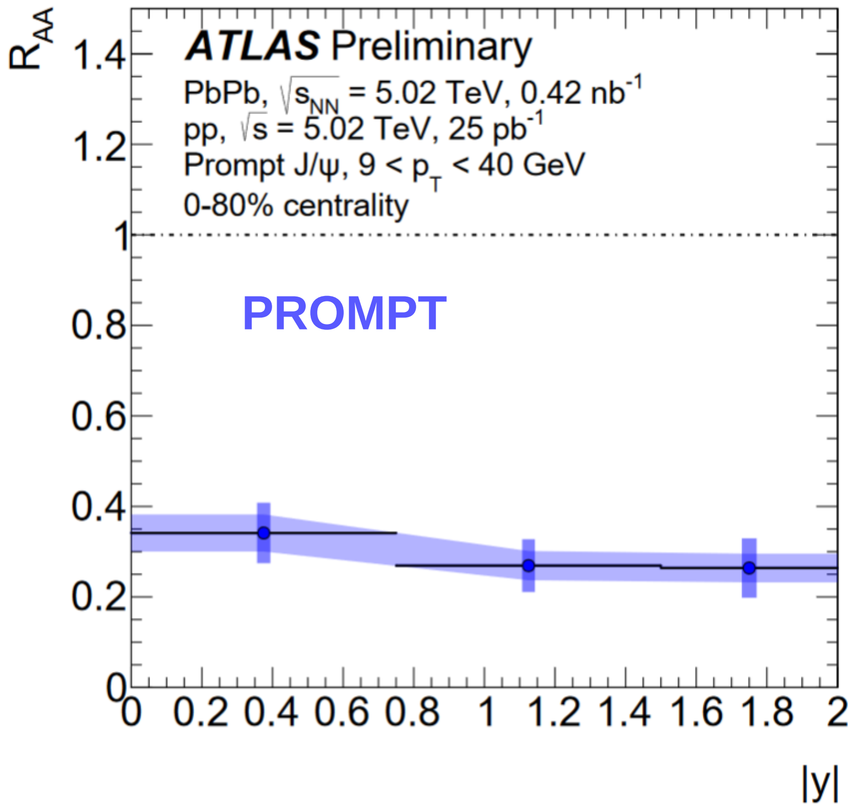
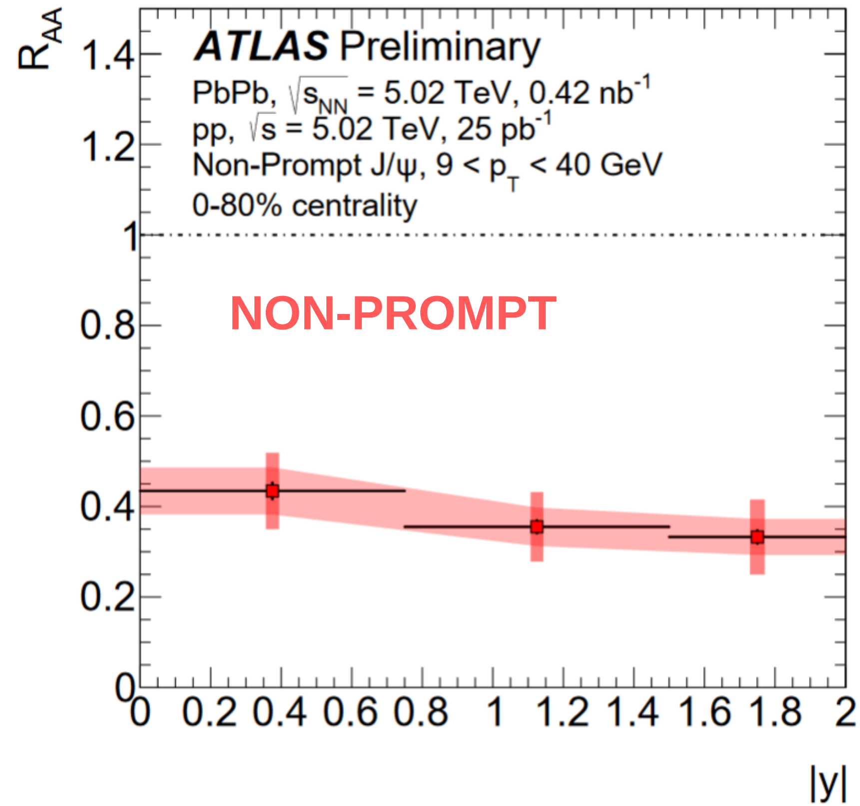
$J/\psi\ R_{AA}$ vs. y

$$R_{AA} = \frac{N_{AA}}{\langle T_{AA}\rangle \times \sigma^{pp}}$$





- No significant dependence from y

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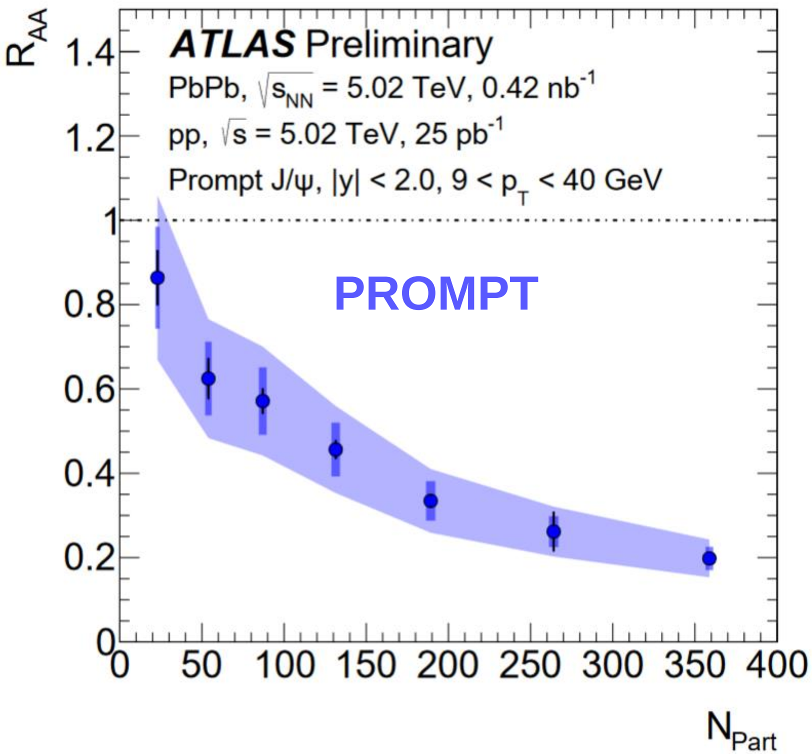
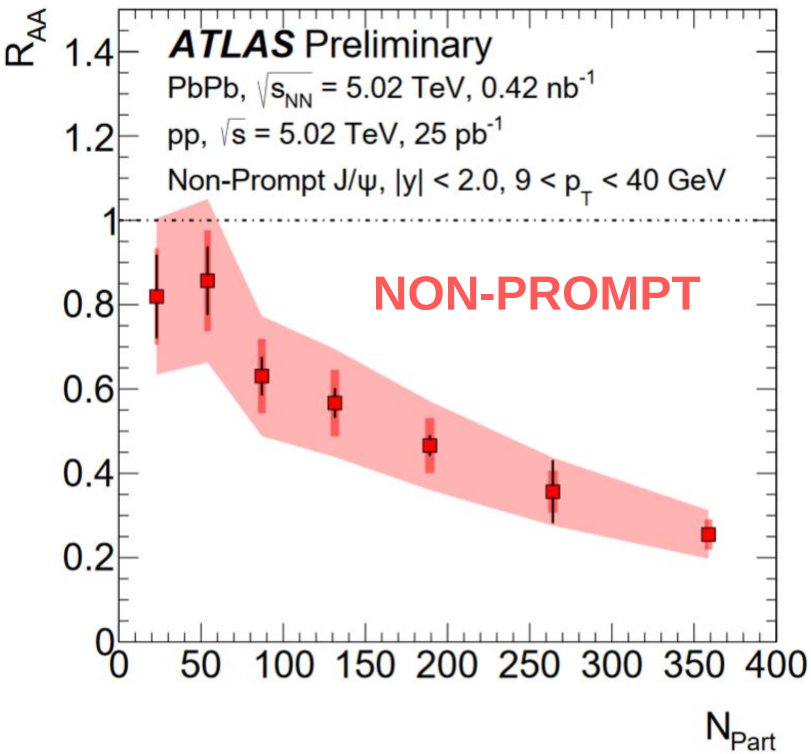
$J/\psi\ R_{AA}$ vs. N_{part}

$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma^{pp}}$$





- Similar degree of suppression is observed for both prompt and non-prompt production
- Strong suppression in most central collisions

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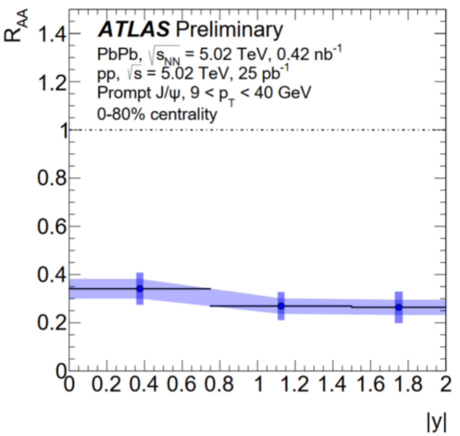
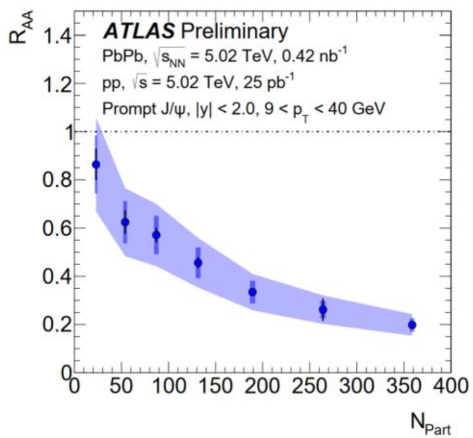
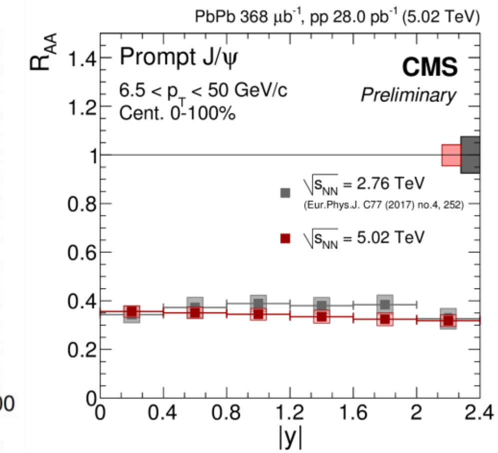
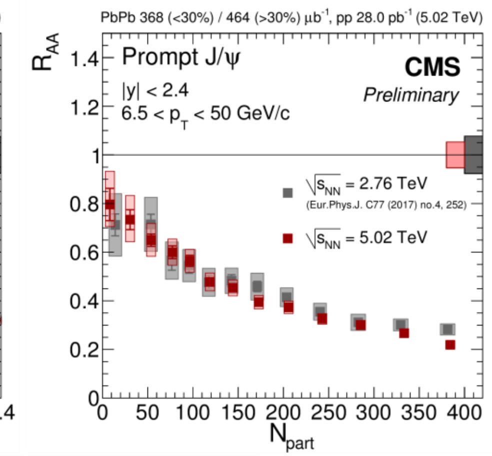
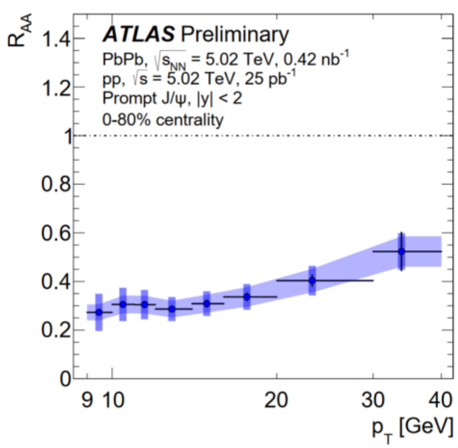
ATLAS and CMS results

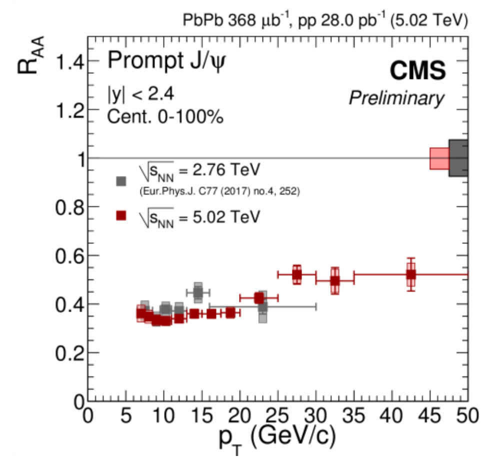












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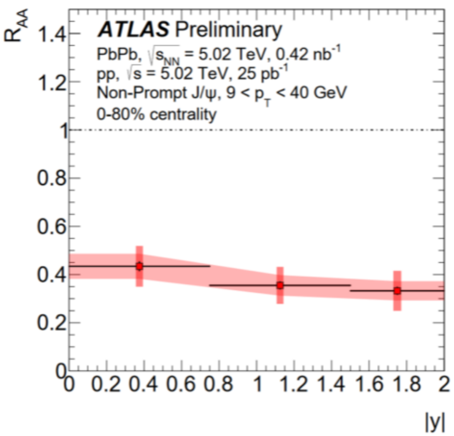
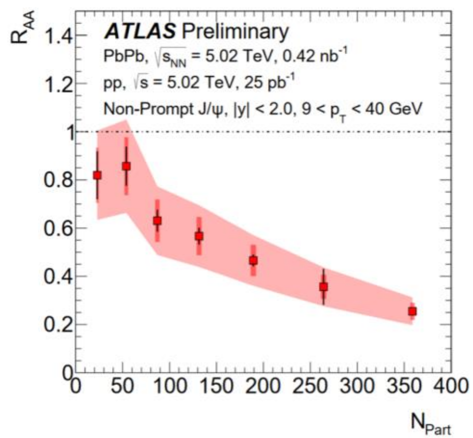
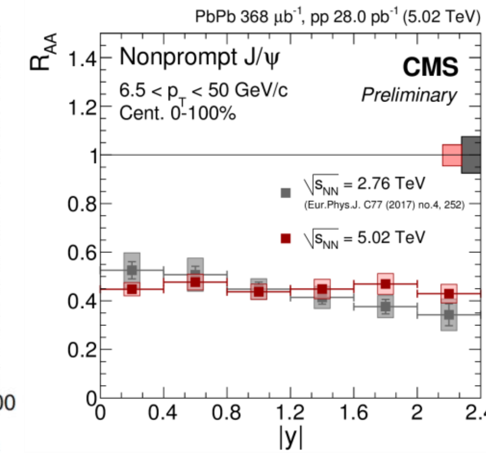
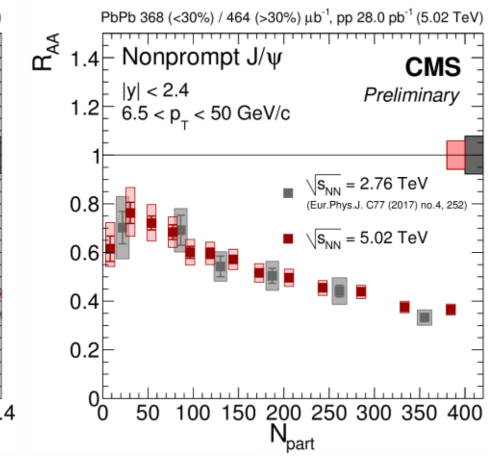
CMS-PAS-HIN-16-025

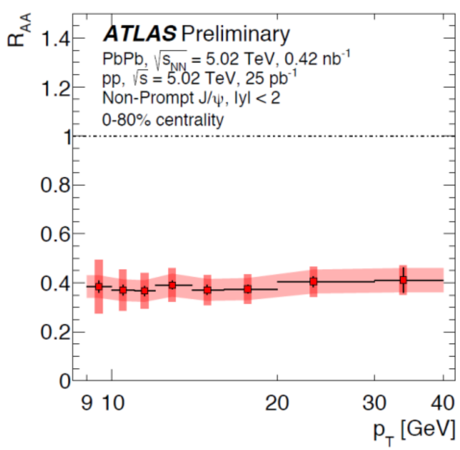
ATLAS and CMS results

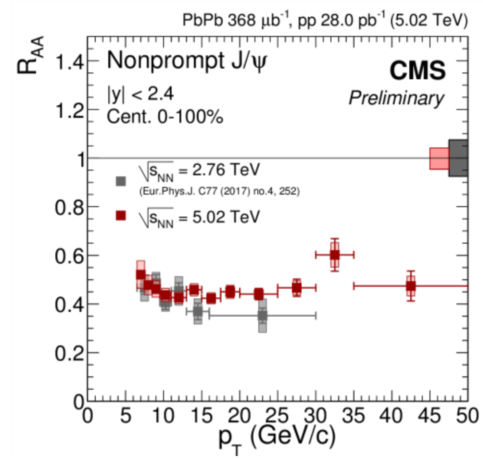












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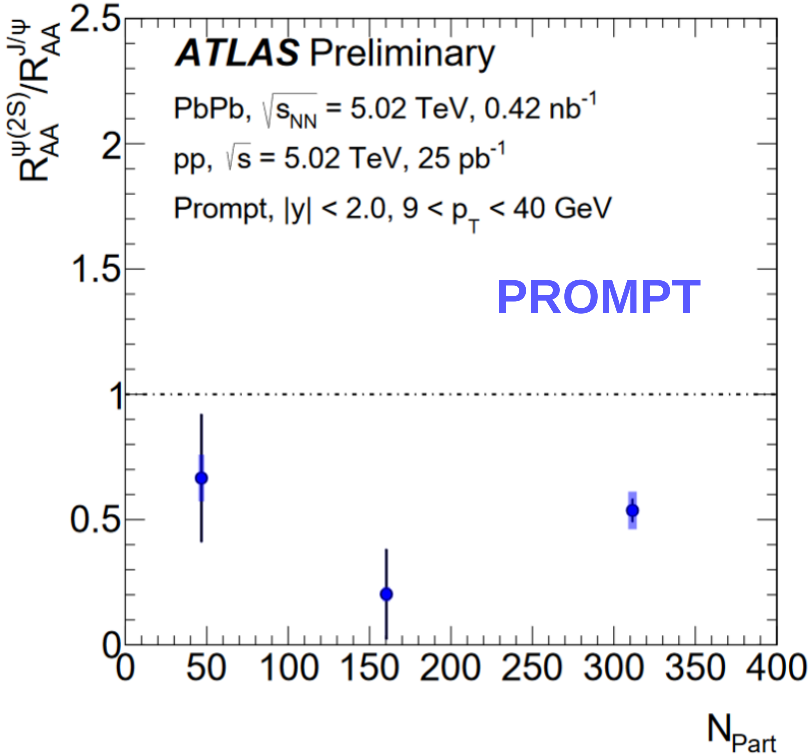
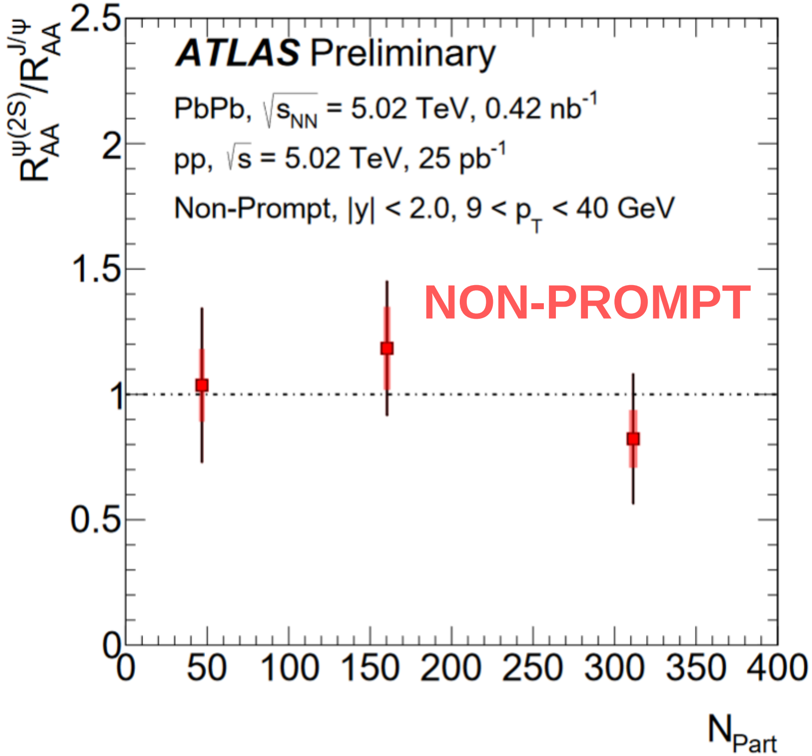
$\psi(2S)$ to J/ψ double ratio





- $\psi(2S)$ is suppressed stronger than J/ψ as expected
- $\psi(2S)$ has lower binding energy → easier to suppress

- Consistent with unity
- Production from B-hadron decays outside of hot medium → no color screening

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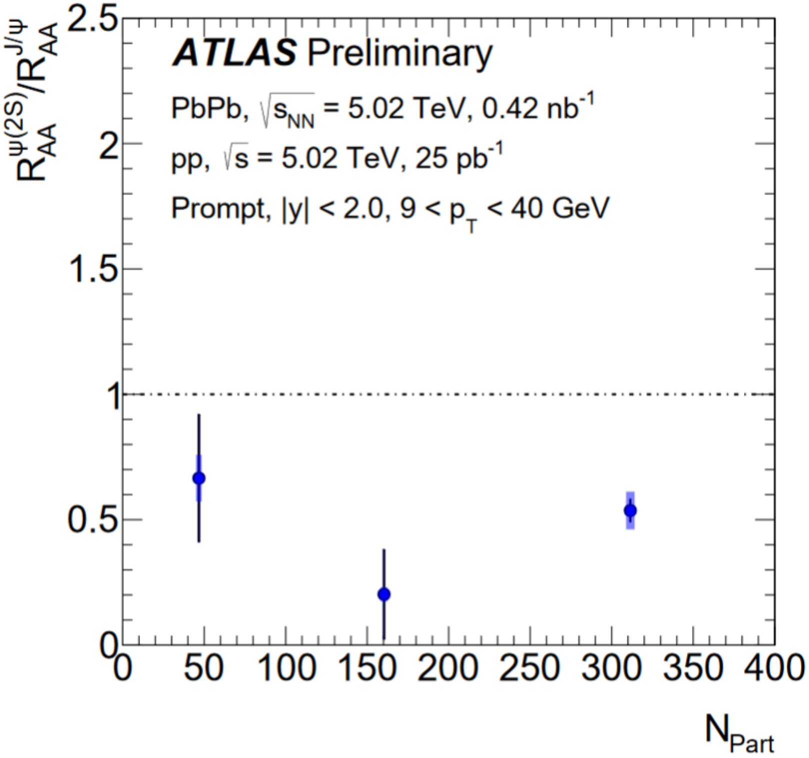
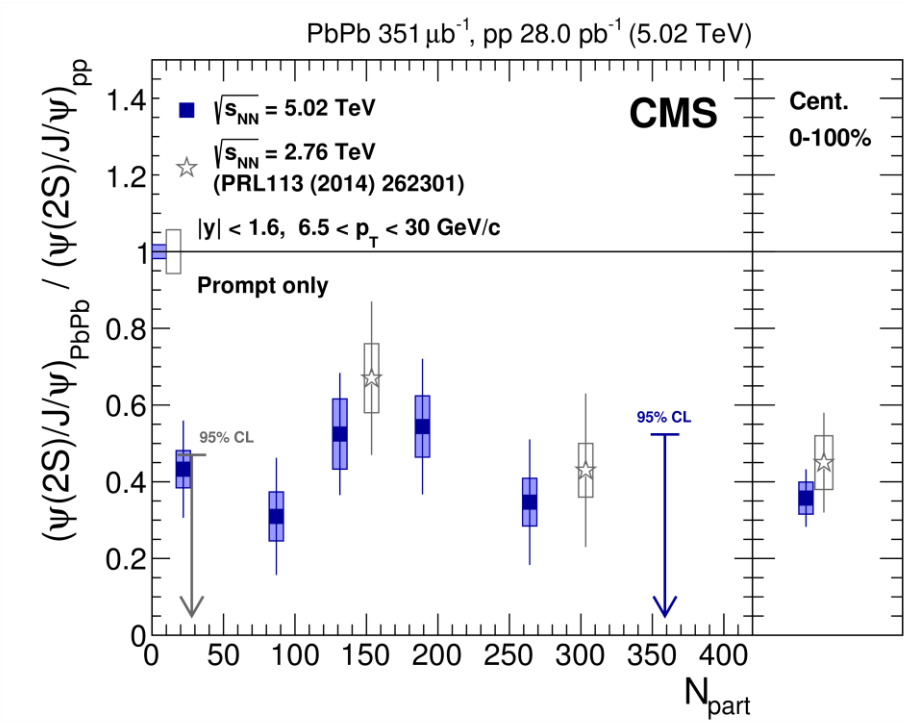
ATLAS and CMS results





- Both experiments are showing consistent with each other results for ratio of excited to ground charmonium states

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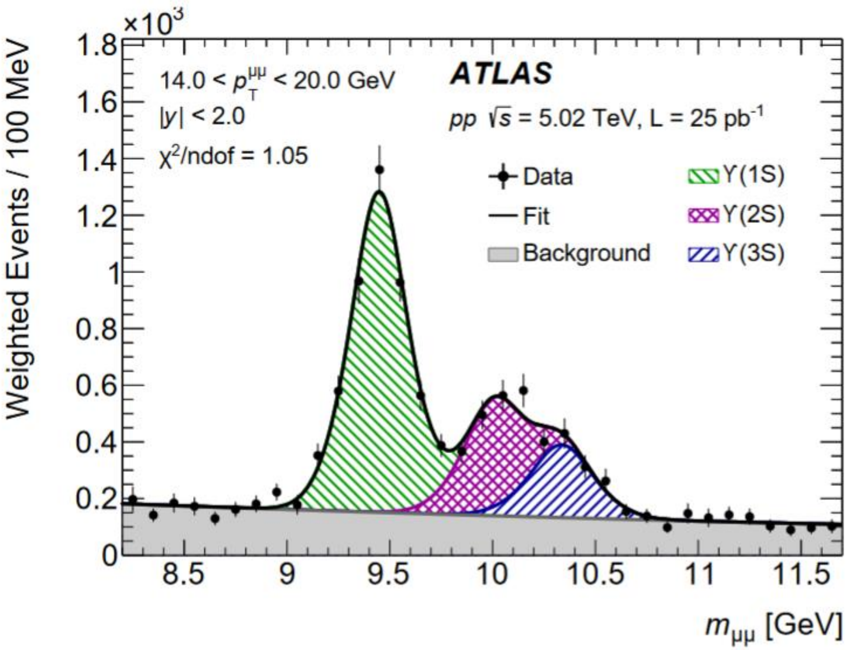
Phys. Rev. Lett. 118 (2017) 162301

Quarkonium in p+Pb

Fitting model ($\Upsilon(nS)$)



arXiv:1709.03089

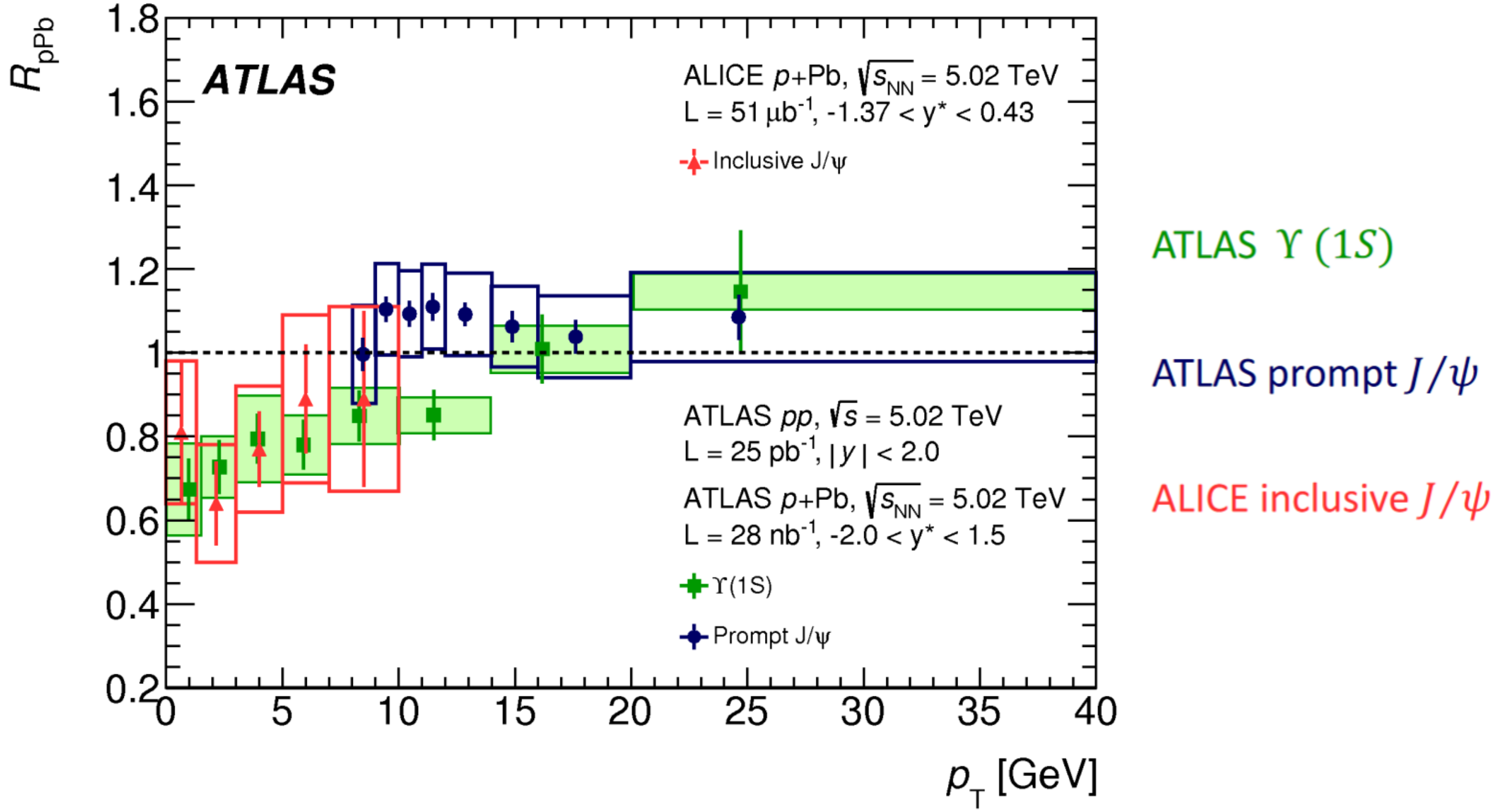
- Weighted yields are obtained by performing unbinned maximum likelihood fits of invariant mass distribution

Signal	$\omega \cdot G(m) + (1-\omega) \cdot CB(m)$	
Background	Low p_T	$erf(m) \times E(m)$
	High p_T	$P(m)$

$$\mathrm{PDF}(m) = N_{\Upsilon(1S)} f_{\Upsilon(1S)}(m) + N_{\Upsilon(2S)} f_{\Upsilon(2S)}(m) + N_{\Upsilon(3S)} f_{\Upsilon(3S)}(m) + N_{\mathrm{bkg}} f_{\mathrm{bkg}}(m),$$

Quarkonia R_{pPb}

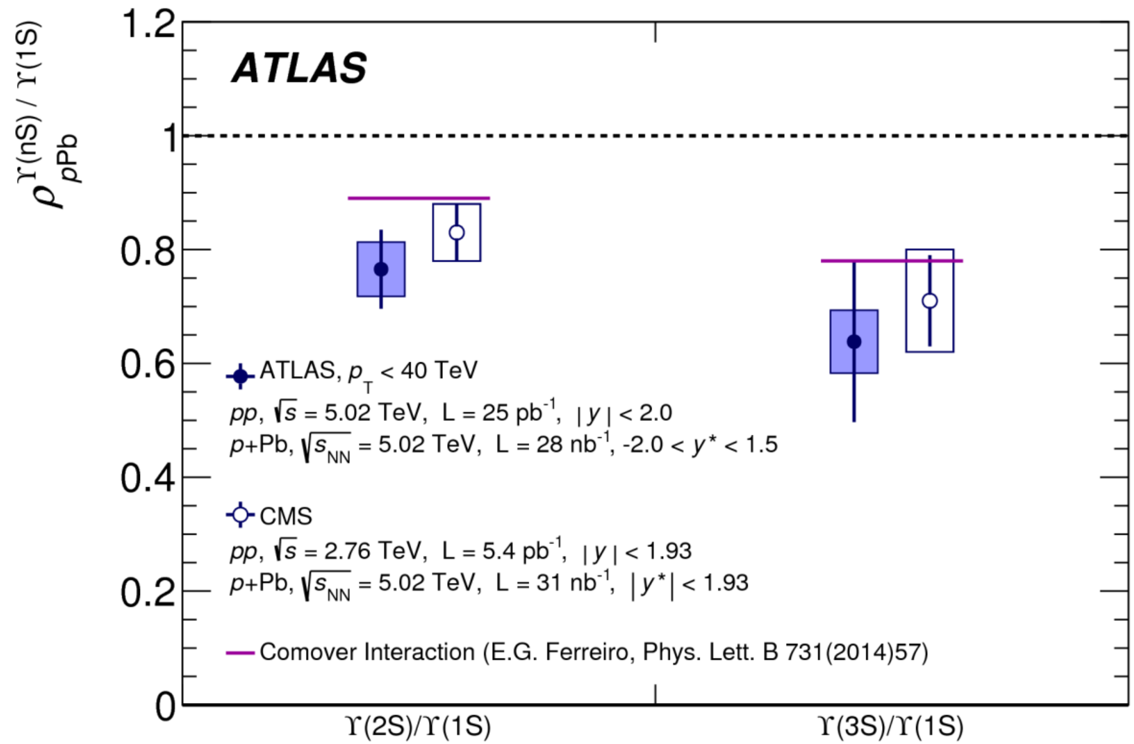
$$R_{pPb} = \frac{1}{208}\frac{\sigma^{pPb}}{\sigma^{pp}}$$



- R_{pPb} of J/ψ is consistent with unity across measured p_T range
- At lower p_T ALICE (inclusive J/ψ) and ATLAS ($\Upsilon(1S)$) are showing light suppression becoming comparable to *p*+*p* collisions at higher p_T

arXiv:1709.03089

Double ratio of excited states ($\Upsilon(nS)$)



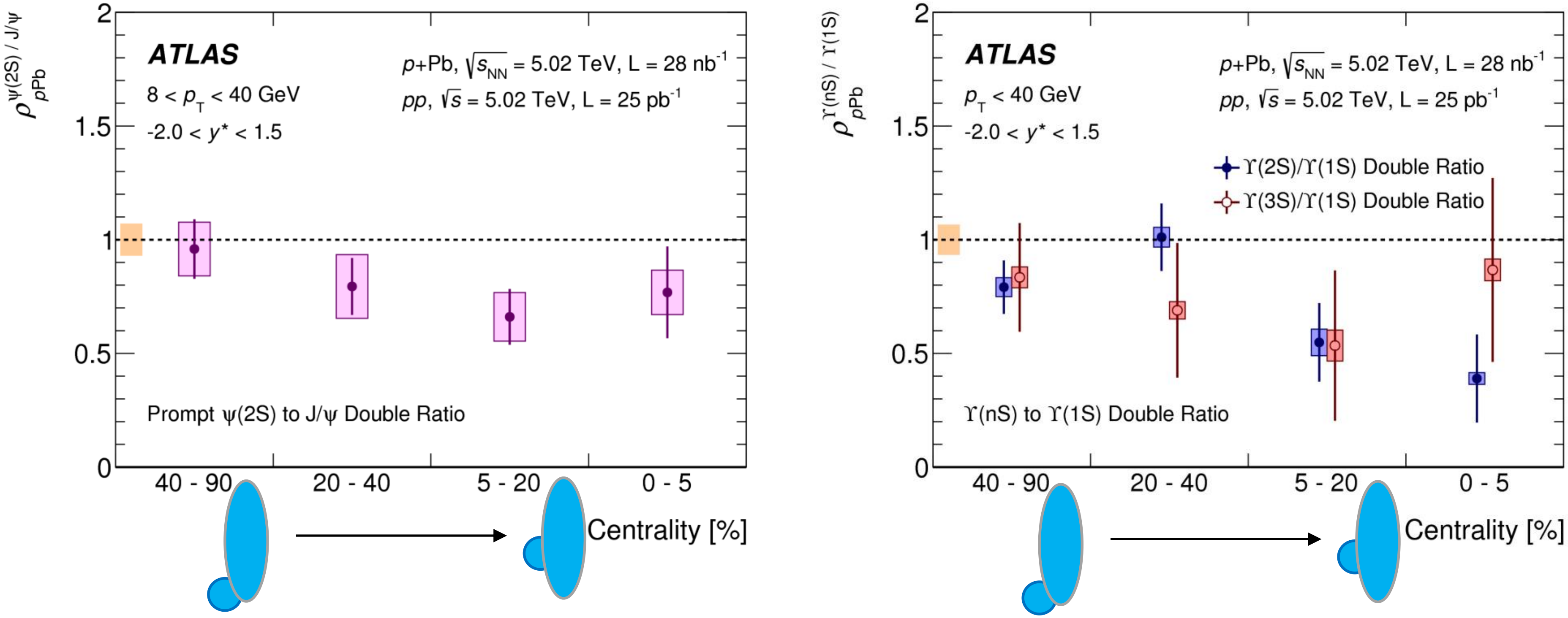
Double ratio

$$\rho_{pPb}^{O(nS)/O(1S)} = \frac{R_{pPb}^{O(nS)}}{R_{pPb}^{O(1S)}}$$

- Double ratio of bottomonium shows stronger suppression of excited states in *p+Pb* compared to *p+p* collisions
- Measurements are consistent with CMS results and theoretical prediction

arXiv:1709.03089

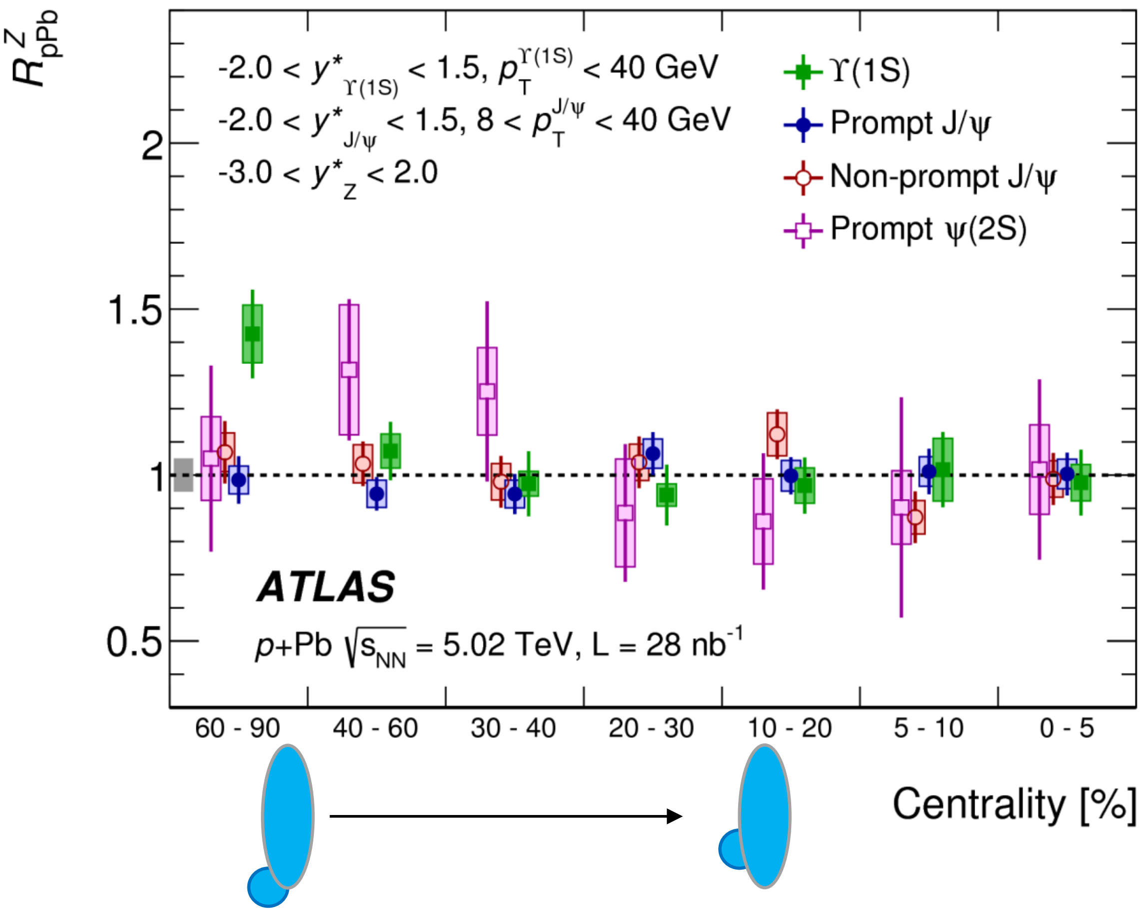
Double ratio of excited states



- Double ratios of excited states are showing growing suppression of excited states with centrality
- $\Upsilon(3S)$ is inconclusive due to statistical uncertainty

arXiv:1709.03089

Comparison to Z boson



$$R^{Z}_{pPb}(O(nS)) = \frac{N^{cent}_{O(nS)}/N^{cent}_{Z}}{N^{0-90\%}_{O(nS)}/N^{0-90\%}_{Z}}$$

- Ratios of the yields of Z and quarkonia ground states are consistent with unity except for the most peripheral for $\Upsilon(1S)$

arXiv:1709.03089

Summary

- Measurements of quarkonia production in Pb+Pb and p+Pb collisions are presented
- *Pb+Pb* collisions:
  - Prompt and non-prompt charmonia production show different R_{AA} trends as function of p_T
  - Both prompt and non-prompt J/ψ components show similar suppression pattern with collision centrality
  - Prompt $\psi(2S)$ is strongly suppressed with respect to J/ψ, while non-prompt production do not result in such behavior
- *p+Pb* collisions:
  - Suppression of J/ψ do not show obvious dependence from p_T and consistent with unity
  - Suppression of $\Upsilon(1S)$ is observed at low p_T range
  - Double ratios show suppression of excited states with respect to ground state and show slight centrality dependence
  - Ratios of quarkonia ground states to Z boson are independent on event activity and scale with the number of binary-collisions
- ATLAS HI public results

ADDITIONAL SLIDES

Analysis methods

- Trigger:
  - p+Pb: 2 muons with $p_T > 2$ GeV, at least one muon at L1 ($p_T > 0$ GeV)
  - Pb+Pb: 2 muons with $p_T > 4$ GeV, at least one muon at L1 ($p_T > 4$ GeV)
- Kinematic range:
  - p+Pb: $8.5 < p_T^{\mu\mu} < 30$ GeV, $-2 < y^* < 1.5$
  - p+Pb ($\Upsilon(nS)$): $0 < p_T^{\mu\mu} < 30$ GeV, $-2 < y^* < 1.5$
  - Pb+Pb: $9 < p_T^{\mu\mu} < 40$ GeV, $|y| < 2$
- Weighted yields from two-dimensional unbinned maximum likelihood fits in $m_{\mu\mu}$ and pseudo-proper decay time $\tau = \frac{L_{xy} m_{\mu\mu}}{p_T^{\mu\mu}}$
- Weighted unbinned 1D maximum likelihood fit for bottomonium
- Separate yields from two production mechanisms:
  - Prompt – direct production and feed-down
  - Non-prompt – from B-hadrons decays

Definition of y*

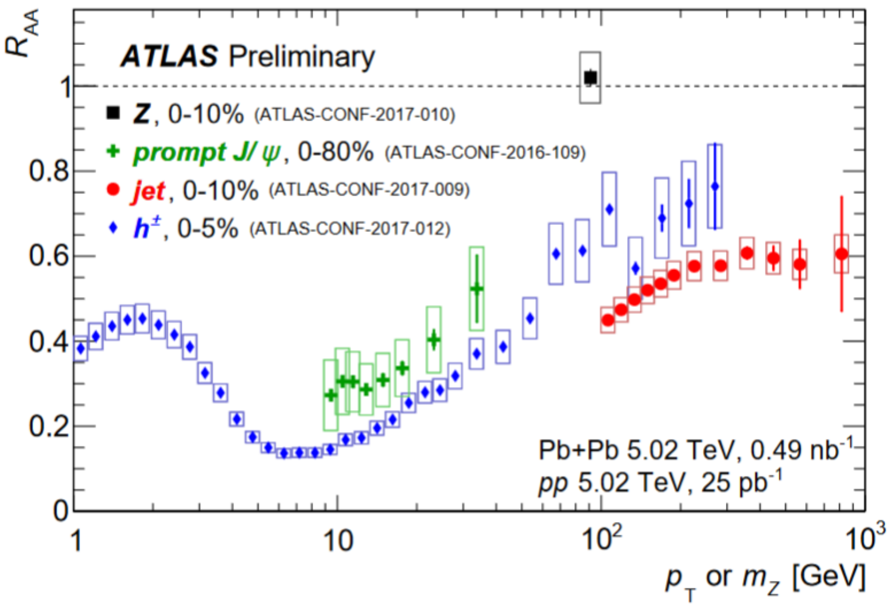
p+Pb

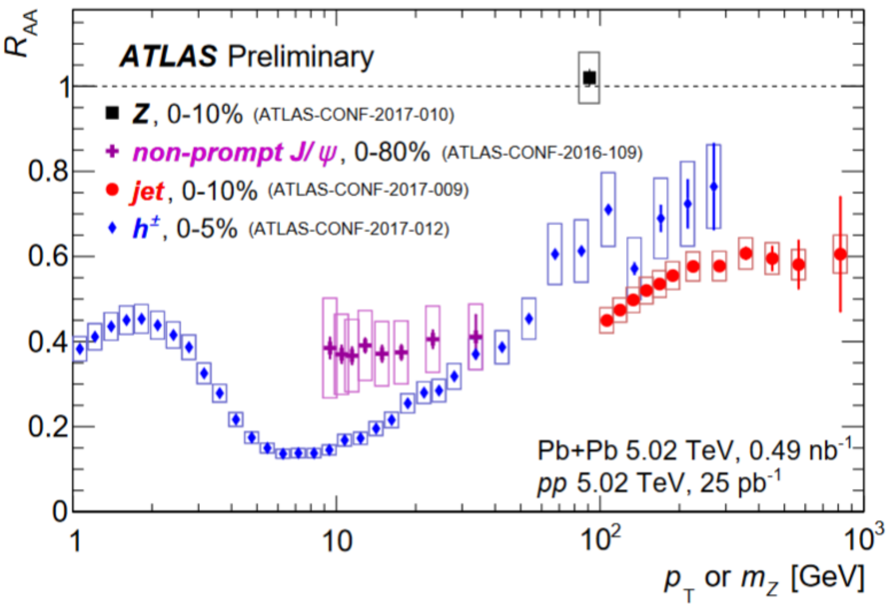
$y^* = -(y_{lab} + 0.465)$ Run period A

$y^* = y_{lab} - 0.465$ Run period B

y* defined as positive in the proton beam direction

Nuclear modification of different probes





Pb+Pb systematic uncertainties summary

Source	J/ψ Pb+Pb yield	J/ψ pp cross section	$R_{AA}^{J/\psi}$	$R_{AA}^{\psi(2S)}/R_{AA}^{\psi}$
Trigger	11 - 18 %	5 %	12 - 19 %	3 %
Reconstruction	13 - 27 %	6 %	14 - 28 %	6 %
Migration	< 2 %	–	< 2 %	–
Fitting	2 %	1 %	2 %	8 %

Table 3: Systematic uncertainties of the J/ψ yield determination and $\psi(2S)/J/\psi$ ratio measured in Pb+Pb collisions.

Centrality in Pb+Pb

Centrality [%]	$\langle T_{AA} \rangle$ [mb^{-1}]	$\langle N_{part} \rangle$
0-10	23.35 ± 0.20	358.8 ± 2.2
10-20	14.33 ± 0.17	264.0 ± 2.8
20-30	8.63 ± 0.17	189.1 ± 2.7
30-40	4.94 ± 0.15	131.4 ± 2.5
40-50	2.63 ± 0.11	86.9 ± 2.3
50-60	1.27 ± 0.07	53.9 ± 1.9
60-70	0.56 ± 0.04	30.5 ± 1.5
70-80	0.22 ± 0.02	15.3 ± 1.0

Table 1: The $\langle T_{AA} \rangle$ and $\langle N_{part} \rangle$ values and their uncertainties in each centrality bin.

Centrality

Glauber model

1) Generate two colliding nuclei

with 3D nucleon positions chosen

from measured density

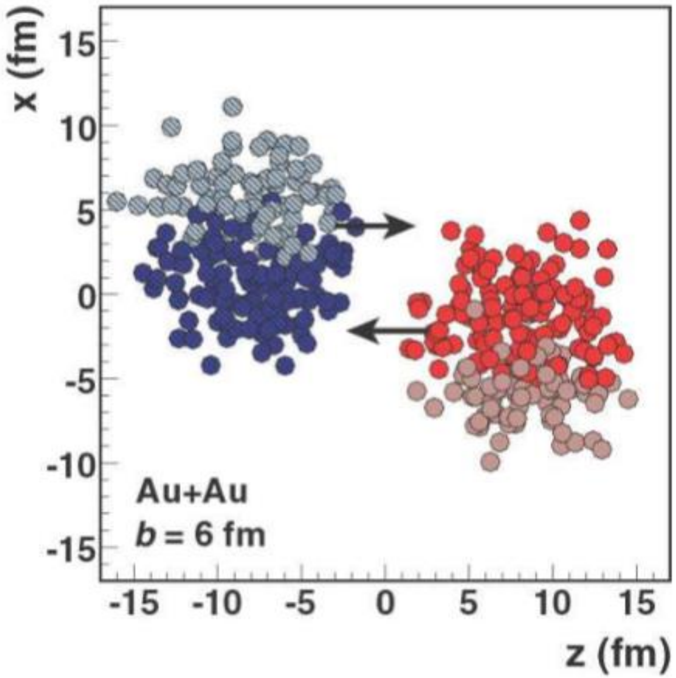
distributions (e^- scattering)

$$\rho(r) = \frac{\rho_0}{1 + \exp([r - R]/a)}$$

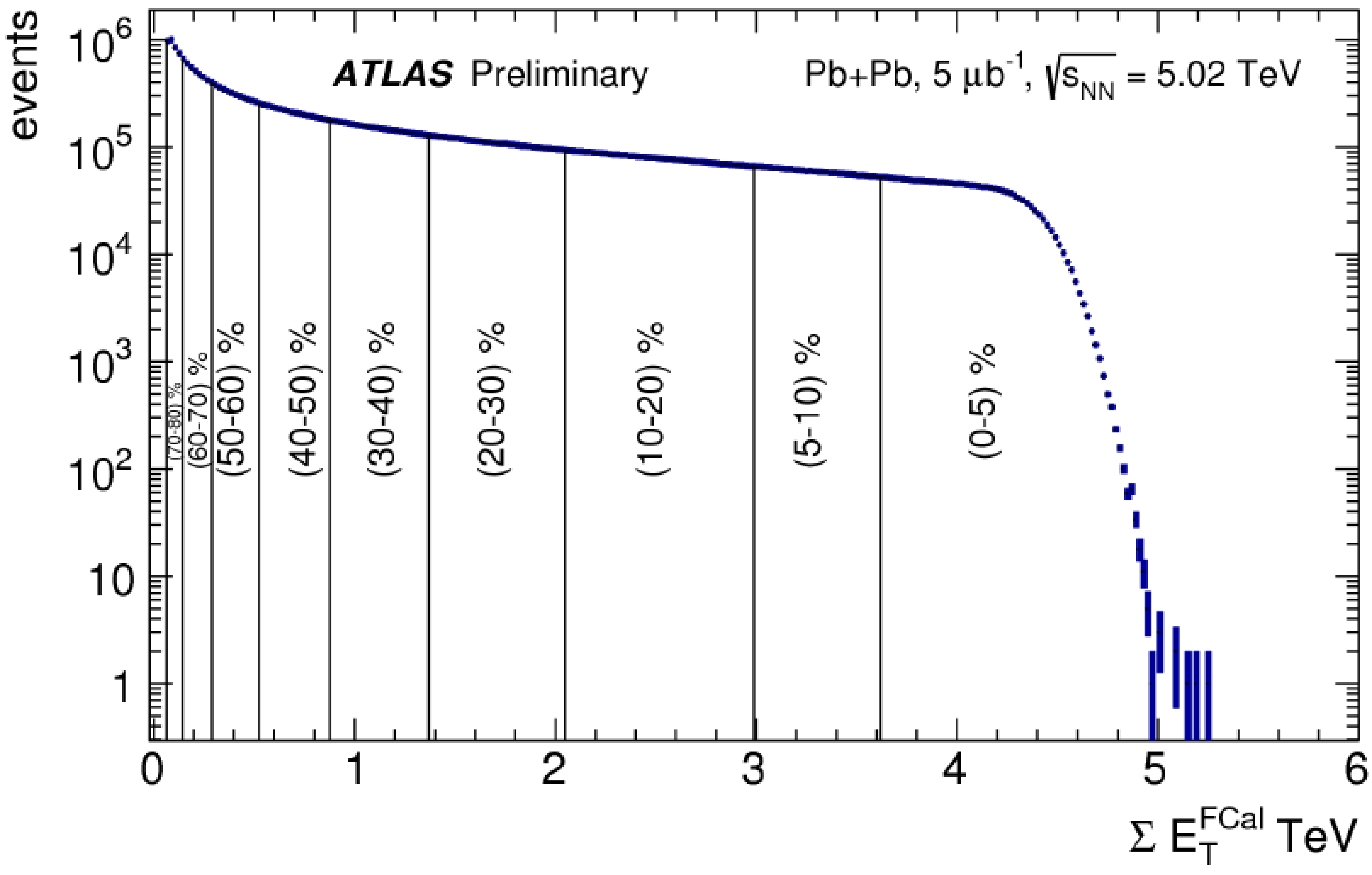
2) Nucleons interact when transverse distance satisfies

$$d < \sqrt{\sigma_{NN} / \pi}$$

typically using he inelastic pp cross section for NN



Centrality



events
ATLAS Preliminary
Pb+Pb, 5 μb⁻¹, √s_NN = 5.02 TeV
(70-80) %
(60-70) %
(50-60) %
(40-50) %
(30-40) %
(20-30) %
(10-20) %
(5-10) %
(0-5) %
Σ E_T^FCal TeV

Non-prompt fraction
(p+Pb)