# Charmonium production within the Statistical Hadronisation Model

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in collaboration with

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MIAPP Munich Institute for Astro- and Particle Physics
Exploring the Perfect Liquid

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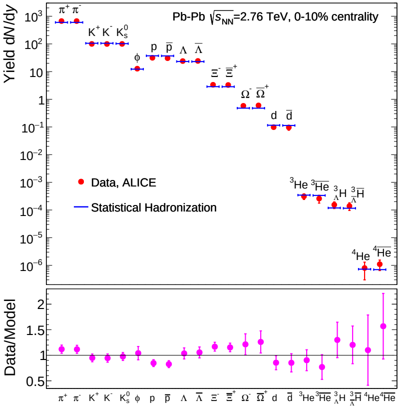
# Statistical Hadronisation in heavy-ion collisions

- Copious production of newly created particles in relativistic heavy-ion collisions

- Mass hierarchy in production
- Thermal/statistical approach to describe particle production
- Grand-canonical partition function
- Conserve the quantum numbers $B$, $I_3$, and $S$ on average
- Assume rapid chemical freeze-out at $T_{CF}$
- Outcome: $T_{CF}$, $\mu_b$, and $V$

[Andronic *et al.*, 1710.09425]



# Extending the model with charm

[Braun-Munzinger and Stachel, PLB 490 (2000) 196]
[Andronic, Braun-Munzinger and Stachel, NPA 789 (2007) 334]

- Charm quarks are produced in initial hard scatterings ($m_{c\bar{c}} \gg T_\mathrm{c}$) and production can be described by pQCD ($m_{c\bar{c}} \gg \Lambda_\mathrm{QCD}$)
- Charm quarks survive and *thermalise* in the QGP
- Full screening before $T_\mathrm{CF}$
- Charmonium is formed at phase boundary (together with other hadrons)
- Thermal model input ($T_\mathrm{CF}, \mu_\mathrm{b} \rightarrow n_X^\mathrm{th}$)

$$N_{c\bar{c}}^\mathrm{dir} = \underbrace{\frac{1}{2} g_c V \left( \sum_i n_{D_i}^\mathrm{th} + n_{\Lambda_i}^\mathrm{th} + \cdots \right)}_{\text{Open charm}} + \underbrace{g_c^2 V \left( \sum_i n_{\psi_i}^\mathrm{th} + n_{\chi_i}^\mathrm{th} + \cdots \right)}_{\text{Charmonia}}$$

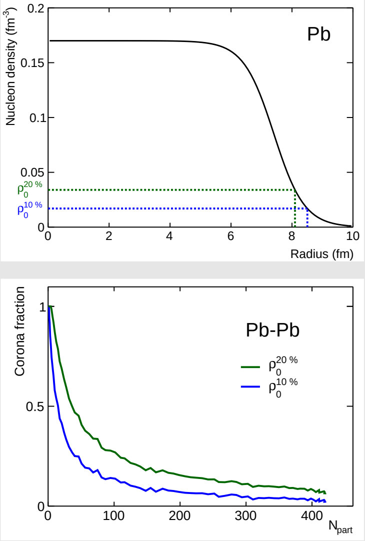
- Canonical correction $N_{c\bar{c}}^\mathrm{dir} = \frac{1}{2} g_c N_\mathrm{oc}^\mathrm{th} \frac{I_1}{I_0}(g_c N_\mathrm{oc}^\mathrm{th}) + g_c^2 N_{c\bar{c}}^\mathrm{th} \rightarrow g_c$
- Outcome $N_{\mathrm{J}/\psi} = g_c^2 n_{\mathrm{J}/\psi}^\mathrm{th} V, N_D = g_c n_D^\mathrm{th} V \frac{I_1}{I_0}, \ldots$

# Core and Corona

- Collision geometry determines which nucleons participate in the fireball
- Surface nucleons do not contribute to the QGP formation

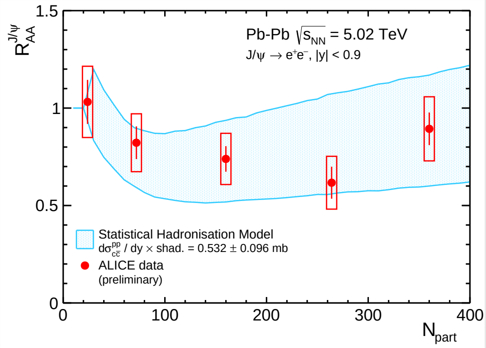
**Core** Thermal contribution from statistical hadronisation model

**Corona** pp distributions scaled by $N_{coll}$

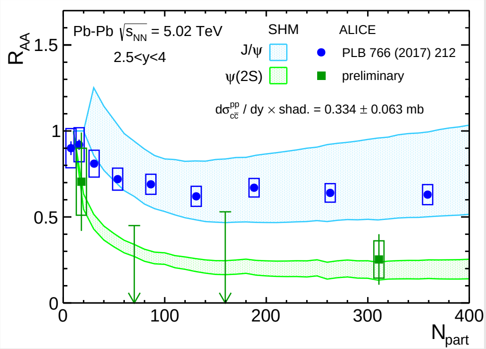


# Comparison of the model with data vs centrality at 5.02 TeV

## Mid-rapidity



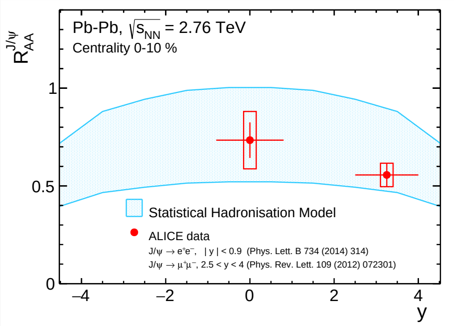

## Forward rapidity



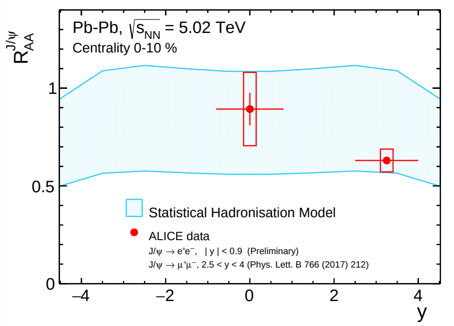

- $d\sigma_{c\bar{c}}/dy$ from measurements in pp collisions in appropriate rapidity region and shadowing coming from open charm and $J/\psi$ production in p–Pb collisions is applied
- Simultaneous description at mid- and forward rapidity of different charmonium states

# Comparison with data

## 2.76 TeV



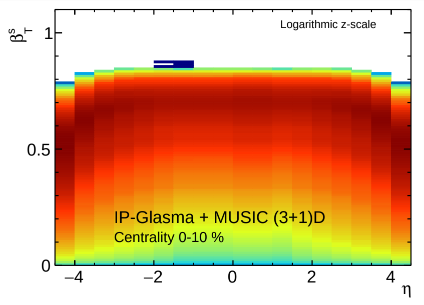

## 5.02 TeV

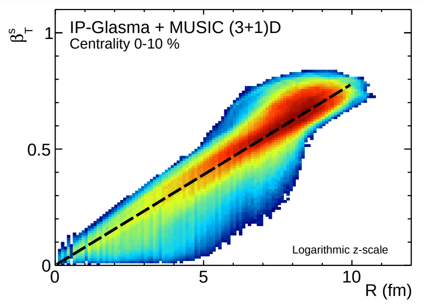



- Good description of data by the model as a function of $J/\psi$ rapidity
- Fall-off towards large rapidities is significant (and would be in contrast to screening-dominated descriptions)

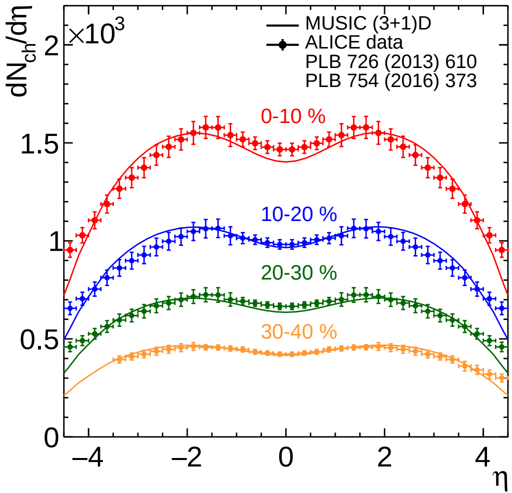
# Transverse momentum spectra

- The underlying idea of thermalized charm quarks forming charmonia at the hadronisation of the fireball can be extented to compute spectra
- Charm quarks follow collective expansion of the QGP fireball, as modeled well by state of the art viscous hydrodynamics codes used to describe light flavor hadron observables
- Use collective expansion velocity from MUSIC(3+1)D [Schenke, Jeon & Gale, PRC82 (2010) 014903] with QCD inspired parameters [Dubla *et al.*, arXiv:1805.02985], and IP-Glasma for initial conditions [Schenke, Tribedy & Venugopalan, PRL 108 (2012) 252301] at $T = T_{CF}$



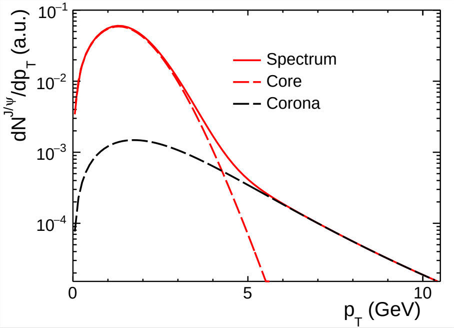
# Comparison of particle distribution




- MUSIC(3+1)D needs input for $\eta$ dependence $\rightarrow$ need to compare with data
- For the comparison of the simulation with data, there is also the possibility to run the Cooper-Frye equation afterwards
  [Cooper & Frye, PRD 10 (1974) 186]
  [Cooper, Frye & Schonberg, PRD 11 (1975) 192]
- Turns 'massless' fluid into massive particles (with subsequent resonance decays)
- Fair agreement between hydro simulation and data for $|\eta| \lesssim 4$

# Transverse momentum parametrisation

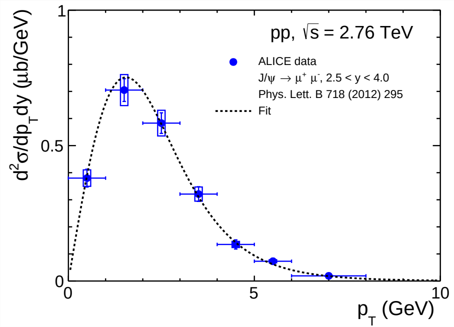
- A rapidity dependent blast-wave function [Florkowski, Pheno. of URHIC] is used to compute spectral shape using the collective velocity
- In addition to this thermal part, the corona fraction has to be added which is normalised as described above

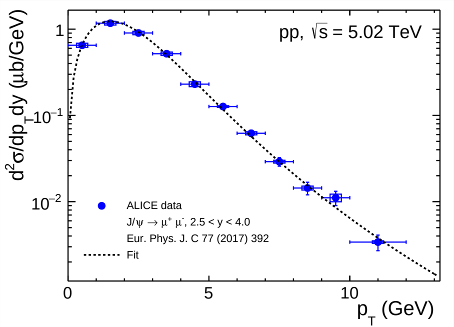



- The approach is sensitive to the degree of thermalisation of charm quarks in the fireball
- If the $p_T$ distribution of the J/$\psi$ can be described within this picture <u>for low $p_T$</u>, this provides strong support for charm quark thermalisation

# Constrains on corona part

- Corona shape modeled by published or interpolated $p_T$ spectra in pp collisions
- Normalisation fixed by Statistical Hadronisation Model
- Data fitted by $f(p_T) = C \frac{p_T}{\{1+(p_T/p_0)^2\}^n}$

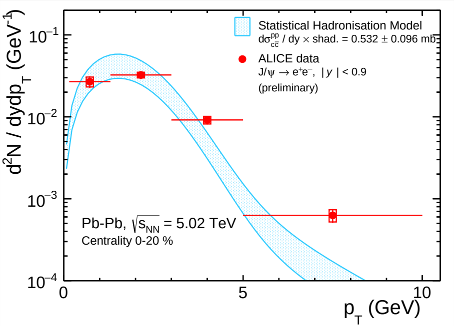


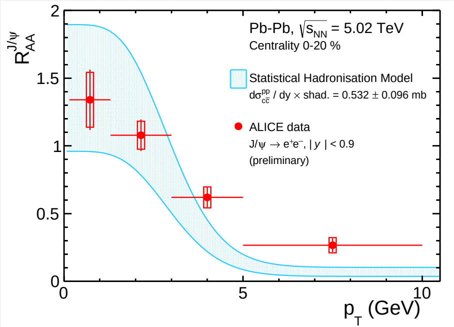
# Comparison of the model with data

**$\sqrt{s_{NN}} = 5.02$ TeV, mid-rapidity, 0-20 %**

## $p_T$ spectrum




## $R_{AA}$ versus $p_T$

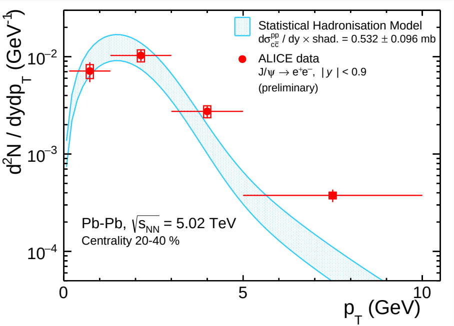



- Very good agreement between data and predictions without free parameters

# Comparison of the model with data

$\sqrt{s_{NN}} = 5.02$ **TeV, mid-rapidity, 20-40 %**

## $p_T$ spectrum

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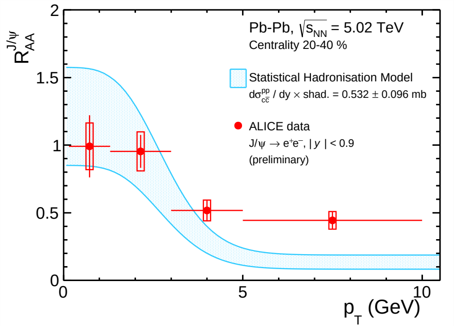


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# Comparison of the model with data

$\sqrt{s_{NN}} = 2.76$ TeV, forward rapidity, 0-20 %

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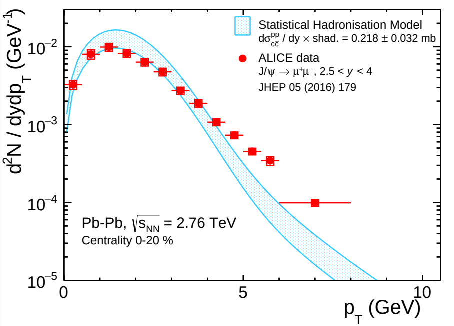
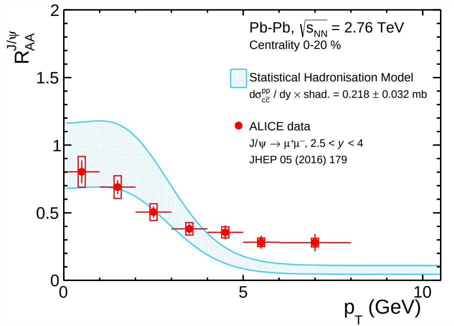



## $R_{AA}$ versus $p_T$

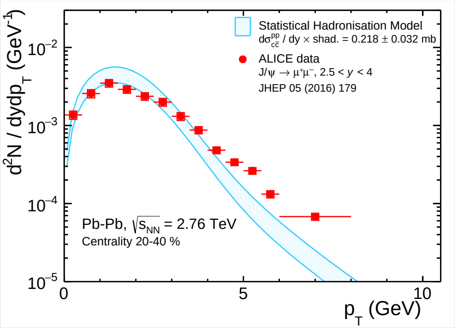



- Very good agreement between data and predictions without free parameters at low $p_T$

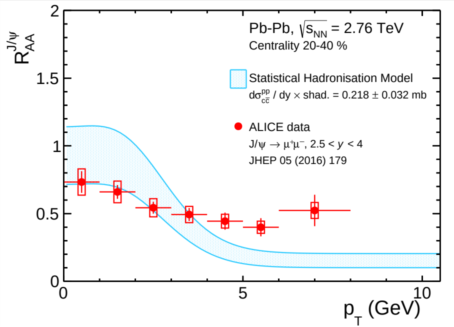
# Comparison of the model with data

$\sqrt{s_{\mathrm{NN}}} = 2.76$ **TeV, forward rapidity, 20-40 %**

## $p_T$ spectrum




## $R_{AA}$ versus $p_T$

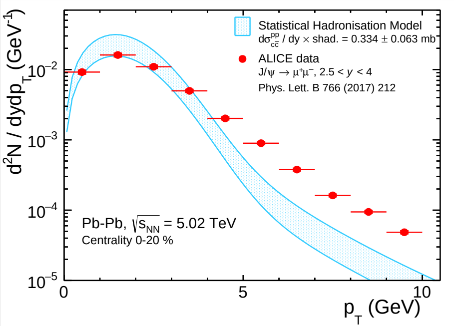



- Very good agreement between data and predictions without free parameters at low $p_T$

# Comparison of the model with data

$\sqrt{s_{NN}} = 5.02$ TeV, forward rapidity, 0-20 %

## $p_T$ spectrum

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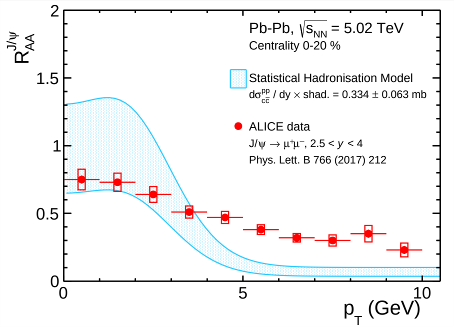
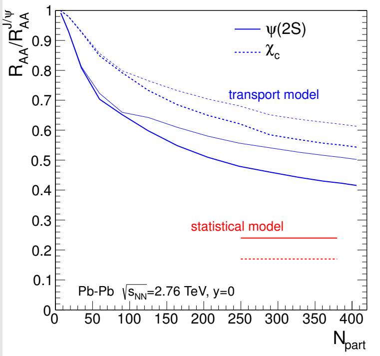
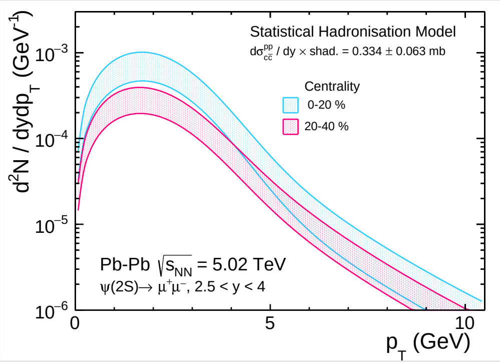



- Very good agreement between data and predictions without free parameters at low $p_T$

# Looking towards ALICE high-rate PbPb run

- Charmonium ratio's (e.g. $\psi(2S)$ or in particular $\chi_c$) are a crucial probe to understand whether colour-less bound state exist above $T_{CF}$

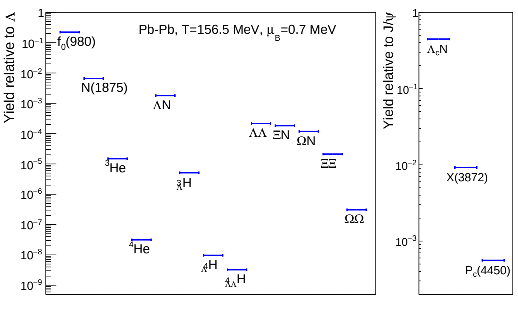


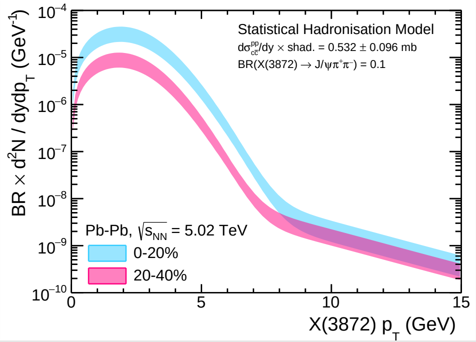



# Looking towards 2030 and beyond

[Andronic, Braun-Munzinger, mkk, Redlich & Stachel, in preparation]

- Predictions for exotic strange and charmed particles
- Key particles to understand parton and hadron dynamics
- Still a rich charmonium program in the long term future



# Summary

- We presented current developments on charmonium production within the SHM
- The SHM describes charmonium yields as a function of centrality, rapidity and transverse momentum
- The agreement at low and moderate $p_{\mathrm{T}}$ provides strong support for the picture that charmonia are formed from deconfined thermalised charm quarks flowing with the QGP

## Outlook

- A more precise measurement of the charm cross section will help to discriminate between models $\rightarrow$ crucial to understand whether colour-less bound states exit for $T > T_{\mathrm{CF}}$
- In a long term perspective exotic charmonia can help to sharpen our understanding of underlying parton production and dynamics

# Backup

# Blast-wave model with Hubble expansion

Adapted from [Florkowski, Phenomenology of URHIC]

$$\frac{\mathrm{d}^2 N}{p_\mathrm{T}\mathrm{d}p_\mathrm{T}\mathrm{d}y} \propto \int_0^R r\mathrm{d}r \left\{ m_\mathrm{T}\cosh\rho\, K_1\left(\frac{m_\mathrm{T}\cosh\rho}{T}\right) I_0\left(\frac{p_\mathrm{T}\sinh\rho}{T}\right) - p_\mathrm{T}\sinh\rho\, K_0\left(\frac{m_\mathrm{T}\cosh\rho}{T}\right) I_1\left(\frac{p_\mathrm{T}\sinh\rho}{T}\right) \right\},$$

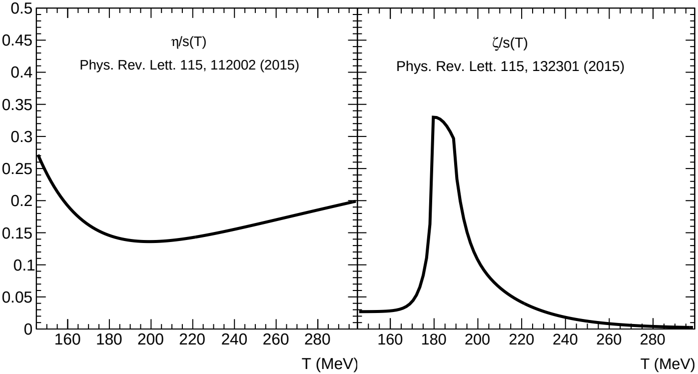
where $I_i$ and $K_i$ with $i = \{1, 2\}$ are modified Bessel functions, $T$ is the temperature, and $\rho$ is given by

$$\rho = \tanh^{-1}\left\{ \beta_\mathrm{T}^\mathrm{s} \left(\frac{r}{R}\right)^n \right\},$$

with $\beta_\mathrm{T}^\mathrm{s}$ being the transverse surface velocity.

# QCD inspired parameters as MUSIC input

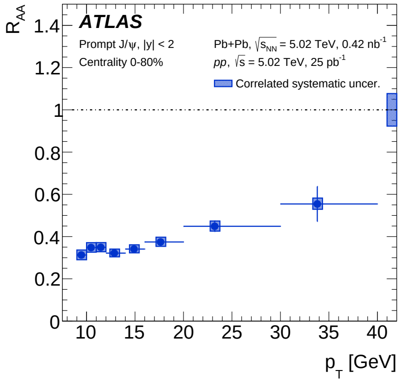
[Dubla *et al.*, arXiv:1805.02985]



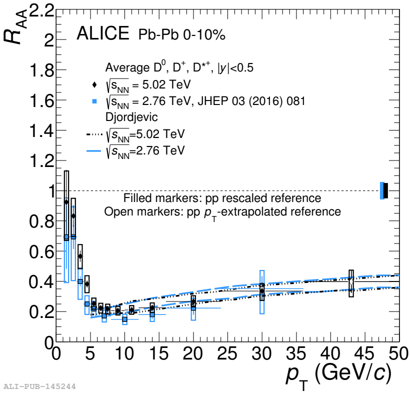

- $\eta/s(T)$ computed with a QCD based approach used as input parameter for MUSIC simulations

# $R_{AA}$ of charmonia and charmed mesons

[ATLAS Coll., arXiv:1805.04077]




[ALICE Coll., arXiv:1804.09083 [nucl-ex]]




- Data suggests an increase of the $J/\psi$ $R_{AA}$ with increasing $p_T$ remiscent of the behaviour of $D$ mesons

# pp interpolation at mid-rapidity

- No data available for an inclusive J/$\psi$ cross section in pp collisions at $\sqrt{s} = 5$ TeV down to zero $p_{\mathrm{T}}$
- To estimate the spectrum, an interpolation procedure is used

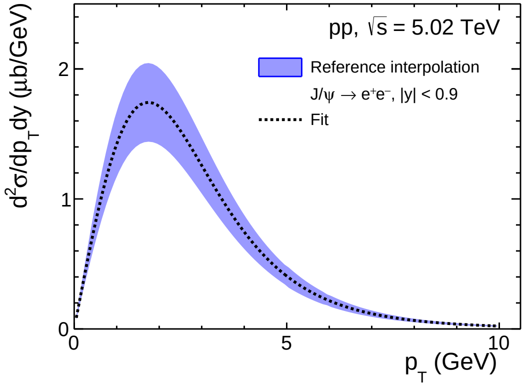
## Procedure

See also [Bossu *et al.*, arXiv:1103.2394]

- Available $p_{\mathrm{T}}$ spectra at mid-rapidity down to zero $p_{\mathrm{T}}$ is used to estimate the cross section and the $\langle p_{\mathrm{T}} \rangle$

  1) PHENIX, PRD85 (2012) 092004
  2) CDF, PRD71, (2005) 032001
  3) ALICE, PLB718 (2012) 295
  4) ALICE, PLB704 (2011) 442

- Use a one-parameter fit function as a function of $\langle p_{\mathrm{T}} \rangle / p_{\mathrm{T}}$ to interpolate to the aimed collision energy



# Rapidity dependence of $\mathrm{J}/\psi$ production

- Rapidity dependence of $\mathrm{J}/\psi$ production in statistical hadronisation picture is determined by rapidity dependence of charm cross section
- $T_{\mathrm{CF}}, \mu_{\mathrm{b}}$ from thermal fits, $V(y) = \frac{\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y}{n_{\mathrm{ch}}^{\mathrm{SHM}}}$, where $\begin{cases} \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y & \text{[ALICE, PLB 726 (2013) 610] [ALICE, PLB 772 (2017) 567]} \\ n_{\mathrm{ch}}^{\mathrm{SHM}} & \hat{=} \text{ particle density from SHM} \end{cases}$
- Rapidity dependence $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ from FONLL [Cacciari *et al.*, JHEP (2012) 2012:137] anchored to pp measurements from ALICE and LHCb