Charmonium production within the statistical hadronisation model

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in collaboration with

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arXiv:1807.01236 [nucl-th]

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From QCD matter to hadrons

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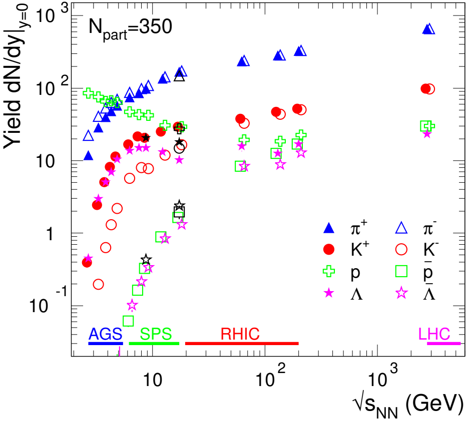
EMMI

ISOQUANT SFB1225

Statistical hadronisation in heavy-ion collisions

- Copious production of newly created particles in relativistic heavy-ion collisions ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y \sim 10^3$ at LHC energies)

- Mass hierarchy in particle production
- Thermal/statistical approach to describe particle production



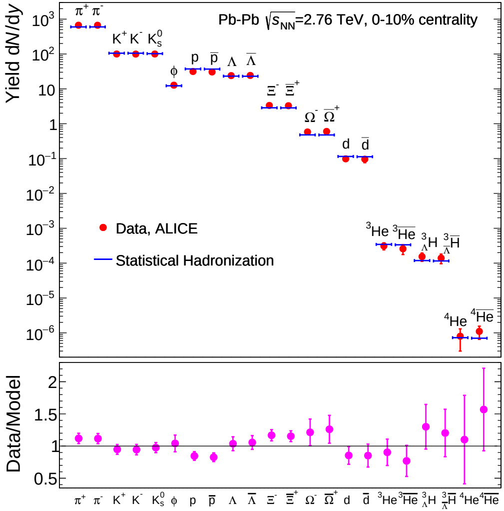
[Andronic, Int.J.Mod.Phys. A29 (2014) 1430047]

Statistical hadronisation in heavy-ion collisions

[Andronic *et al.*, Nature 561 (2018) 321]

- Mass hierarchy in particle 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}, μ_b, and V
  $T_{CF} = 156.5 \pm 1.5$ MeV, $\mu_b = 0.7 \pm 3.8$ MeV

$\rightarrow$ see Pok Man Lo's talk for a recent update

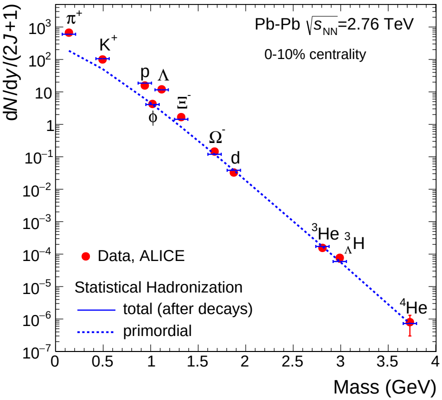


Statistical hadronisation in heavy-ion collisions

- Mass hierarchy in particle production
- For $m \gg T_{CF}$, the yield dN/dy scales with

$$m^{3/2} \exp(-m/T_{CF})$$

[Andronic *et al.*, Nature 561 (2018) 321]



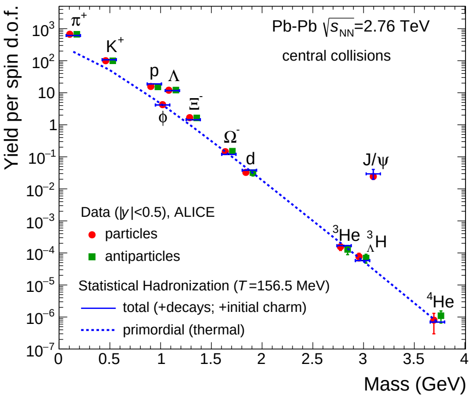
Statistical hadronisation in heavy-ion collisions

- Mass hierarchy in particle production
- For $m \gg T_{\mathrm{CF}}$, the yield $\mathrm{d}N/\mathrm{d}y$ scales with

$$m^{3/2} \exp(-m/T_{\mathrm{CF}})$$

- Significantly different behaviour between charmonium state J/ψ and hyper-triton which has (approximately) the same mass

[Andronic *et al.*, in preparation]



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_CF
- Charmonium is formed at phase boundary (together with other hadrons)
- Thermal model input ($T_\mathrm{CF}, \mu_\mathrm{b} \to n_X^\mathrm{th}$)

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

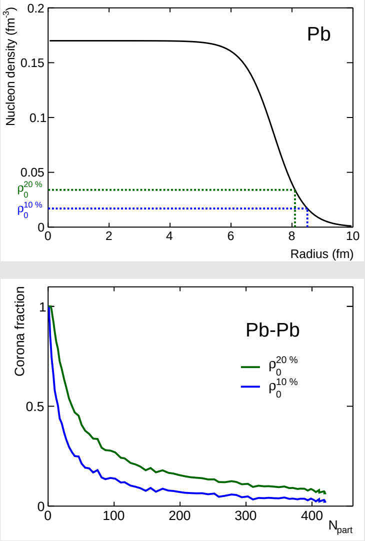
- Canonical correction $N_{c\bar{c}}^\mathrm{dir} = \frac{1}{2} g_c N_\mathrm{oc}^\mathrm{th} \frac{I_1}{I_0}(g_c N_\mathrm{oc}^\mathrm{th}) + g_c^2 N_{c\bar{c}}^\mathrm{th} \to g_c$
- Outcome $N_{\mathrm{J}/\psi} = g_c^2 n_{\mathrm{J}/\psi}^\mathrm{th} V, N_D = g_c n_D^\mathrm{th} V \frac{I_1}{I_0},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

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

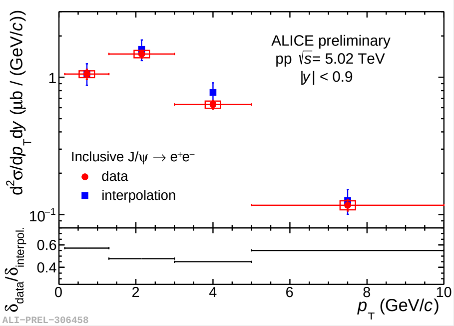
Corona pp distributions scaled by N_{coll}



New ALICE results at mid-rapidity

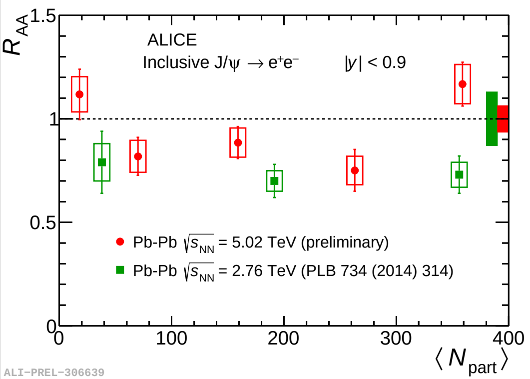
Cross-section measurement in pp collisions at 5 TeV

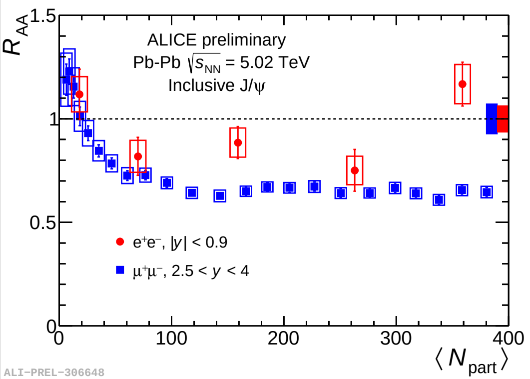
- The reference is a crucial ingredient for the precision of the R_{AA} results
- Previously an interpolated cross section was used
- New measurement with significantly increased statistics from 2017
- Increase precision by factor $\gtrsim 2$



New ALICE results at mid-rapidity

Comparisons of results in Pb-Pb collisions

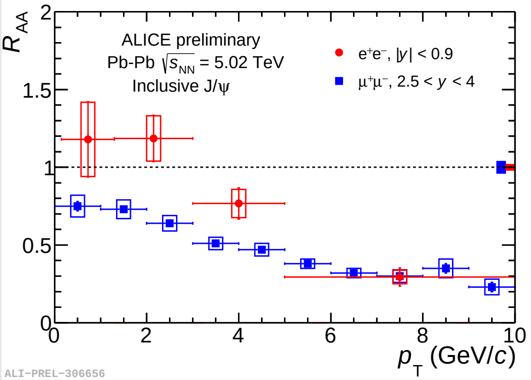




- ‘Enhancement’ at mid-rapidity towards central collisions compared to lower collision energy and forward rapidity

Transverse momentum dependence

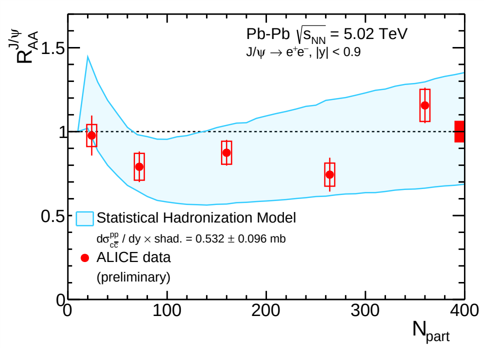
Finalisation of the analysis of the Pb-Pb data from 2015



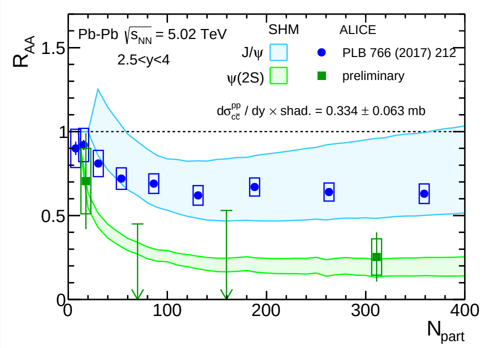
- 'Enhancement' at mid-rapidity concentrated at low p_T
- Transverse momentum can be used to discriminate between different production mechanisms

Comparison of the model with data vs centrality at 5.02 TeV

Mid-rapidity



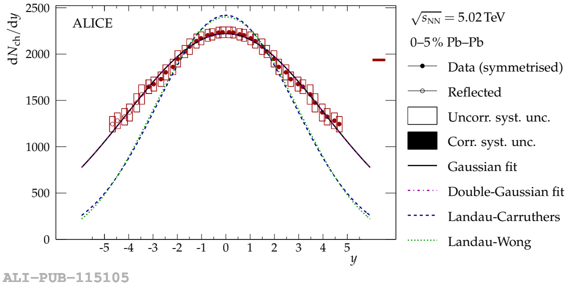
Forward rapidity

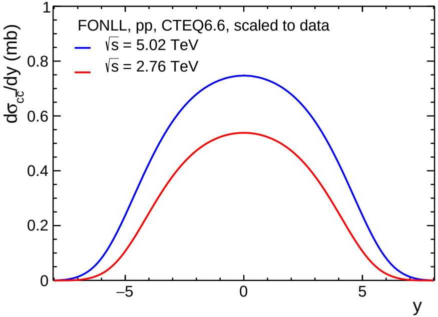


- $d\sigma_{c\bar{c}}/dy$ from measurements in pp collisions in appropriate rapidity region and shadowing coming from open charm and J/ψ production in p–Pb collisions is applied
- Simultaneous description at mid- and forward rapidity of different charmonium states

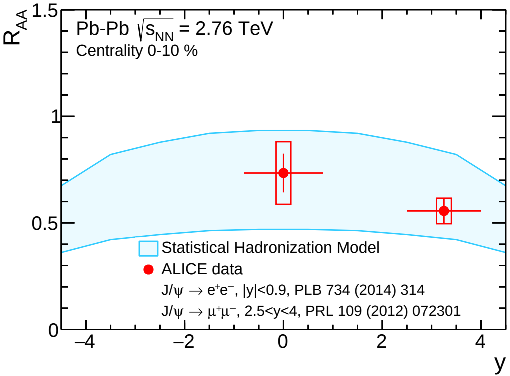
Rapidity dependence of J/ψ production

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





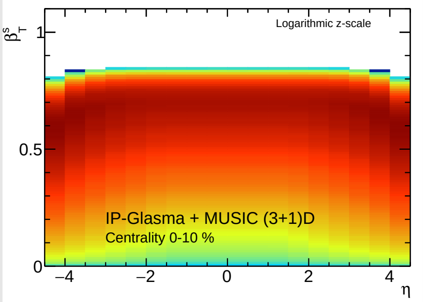
Comparison with data

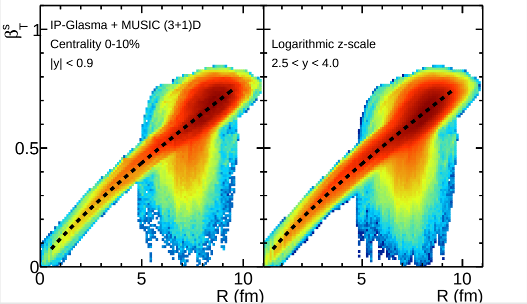


- Good description of data by the model as a function of J/ψ rapidity
- Fall-off towards large rapidities is significant (and would be in contrast to screening-dominated descriptions)

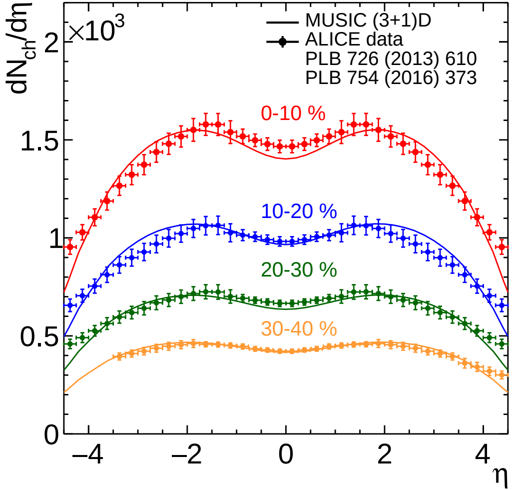
Transverse momentum spectra

- The underlying idea of thermalised 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.*, NPA 979 (2018) 251], and IP-Glasma for initial conditions [Schenke, Tribedy & Venugopalan, PRL 108 (2012) 252301] at $T = T_{CF}$





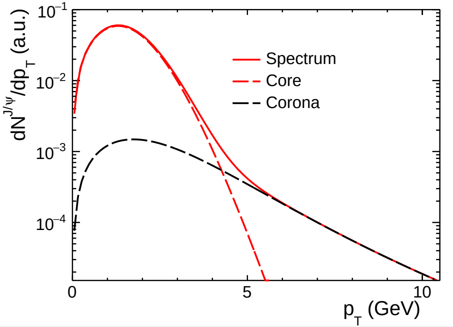
Comparison of particle distribution



- MUSIC(3+1)D needs input for η 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 procedure afterwards
  [Cooper & Frye, PRD 10 (1974) 186]
  [Cooper, Frye & Schonberg, PRD 11 (1975) 192]
- Turns ‘massless’ fluid into massive particles (with subsequent resonance decays)
- Good agreement between hydro simulation and data for $|\eta| \lesssim 4$

Transverse momentum parametrisation

- A rapidity dependent blast wave function for boost-invariant expansion and Hubble flow following the earlier work from Schnedermann, Heinz and Florkowski is used to compute spectral shape using the collective velocity
- The corona part is added to the thermal part



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

Blast-wave function with Hubble-type expansion

- Follows [Florkowski, Phenomenology Of Ultra-Relativistic Heavy-Ion Collisions]

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

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

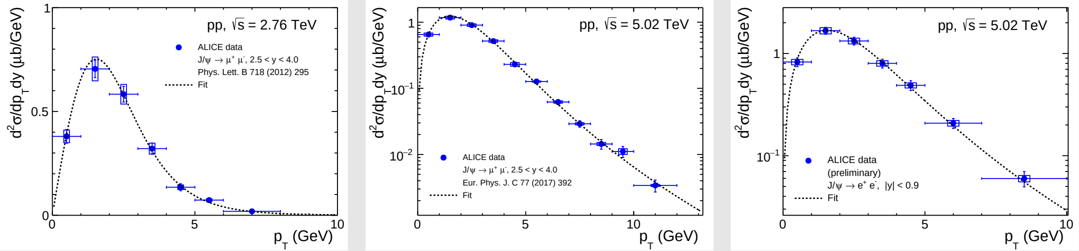
$$\rho = \tanh^{-1}\left\{ \beta_\mathrm{T}^\mathrm{s} \left(\frac{r}{R}\right)^n \right\},$$

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

- For J/ψ mass, function reliable for $p_\mathrm{T} \lesssim 5$ GeV

Constraints on corona shape

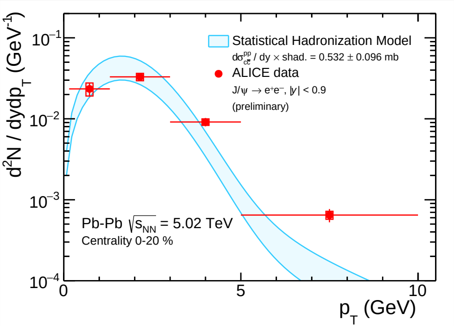
- Corona shape modeled by measured p_T spectra in pp collisions
- Available data fitted by $f(p_T) = C\frac{p_T}{\{1+(p_T/p_0)^2\}^n}$



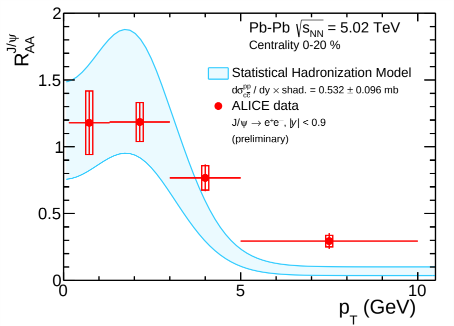
Comparison of the model with data

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

p_T spectrum



R_{AA} versus p_T

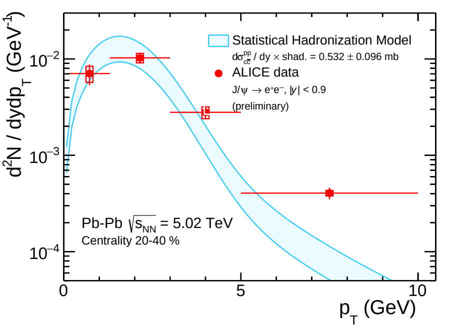


- Very good agreement between data and predictions without free parameters

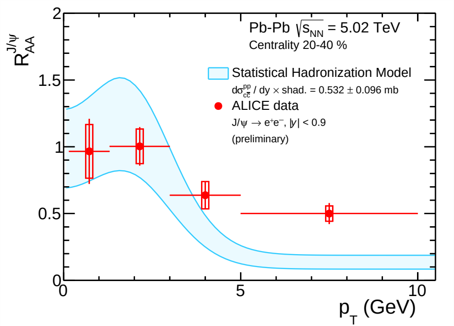
Comparison of the model with data

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

p_T spectrum



R_{AA} versus p_T

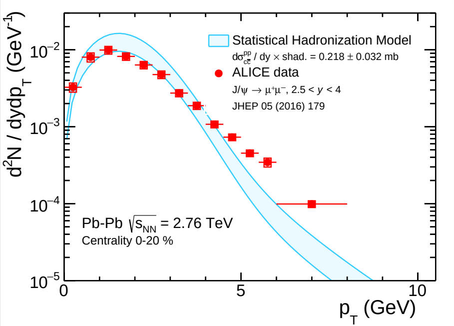


- Very good agreement between data and predictions without free parameters

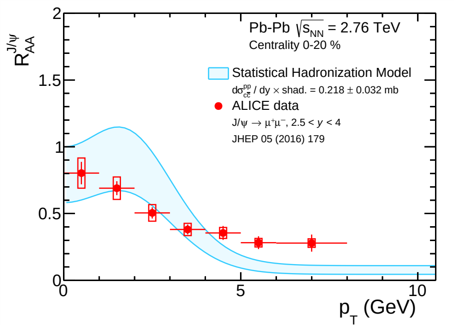
Comparison of the model with data

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

p_T spectrum



R_{AA} versus p_T

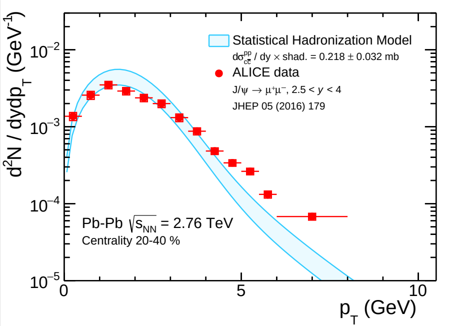


- Very good agreement between data and predictions without free parameters at low p_T

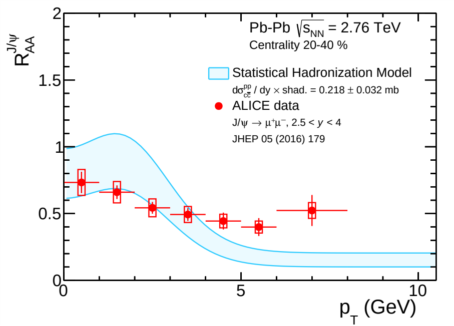
Comparison of the model with data

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

p_T spectrum



R_{AA} versus p_T

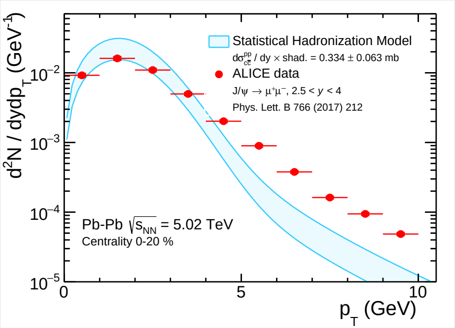


- Very good agreement between data and predictions without free parameters at low p_T

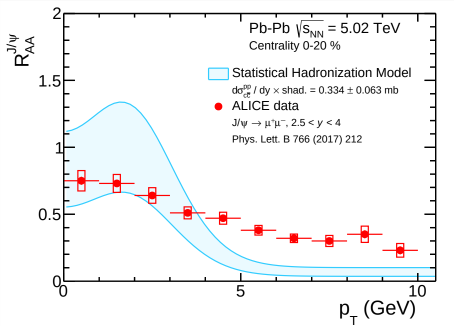
Comparison of the model with data

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

p_T spectrum



R_{AA} versus p_T

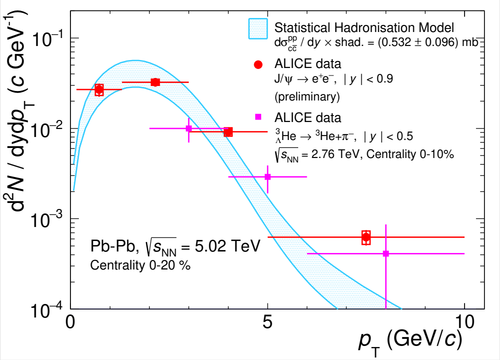


- Very good agreement between data and predictions without free parameters at low p_T

Comparing hyper-triton with J/ψ

[Braun-Munzinger & Dönigus, arXiv:1809.04681 [nucl-ex]]

- Thermal nature of loosely bound objects like (anti-)(hyper-)nuclei?
- Surprising flow pattern
- Consistent with multi-quark states formed at the phase boundary developing later into hadronic wave functions [Andronic *et al.*, Nature 561 (2018) 321]

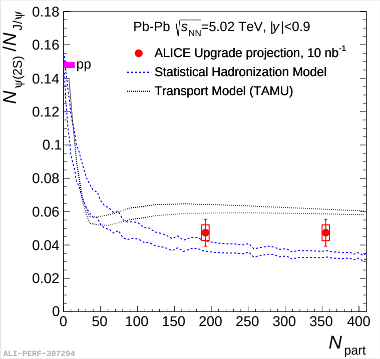


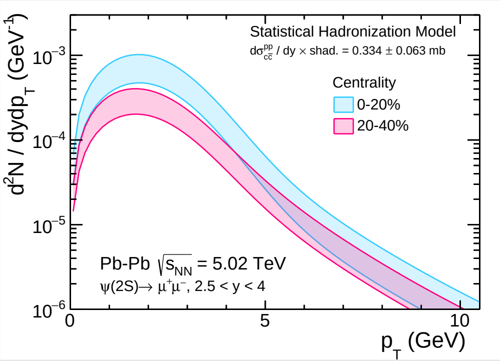
- J/ψ and (scaled) hyper-triton can be described by the same flow parameters
- Need the precision on hyper-triton p_T spectra as will be available in LHC Run3
- Comparison of loosely bound and compact objects allow for a test of the hypothesis

Looking towards ALICE high-rate PbPb run

Yellow Report, arXiv:1812.06772 [hep-ph]

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

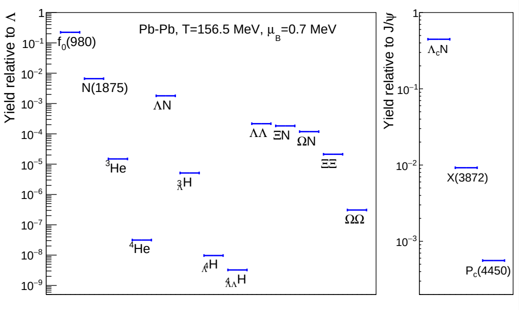




Looking towards 2030 and beyond

Yellow Report, arXiv:1812.06772 [hep-ph]

- Predictions for exotic strange and charmed particles
- Key particles to understand parton and hadron dynamics

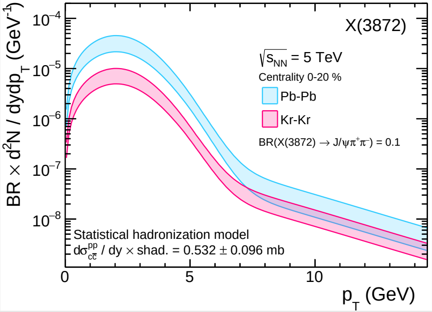


- Particular interest in X(3872)
- Invariant mass close to $D^0\bar{D}^{*0}$ production threshold
- Potential tetra-quark state and charmed meson molecule

X(3872) transverse momentum spectra

Yellow Report, arXiv:1812.06772 [hep-ph]

- Predictions for exotic strange and charmed particles
- Key particles to understand parton and hadron dynamics



- If compact and loosely bound objects are produced at the phase boundary
- Likely that future colliders will run with smaller nuclei (higher luminosity) $\rightarrow$ ^{84}Kr would lead to a decrease of the yield on the order of 4 – 5 for low p_T

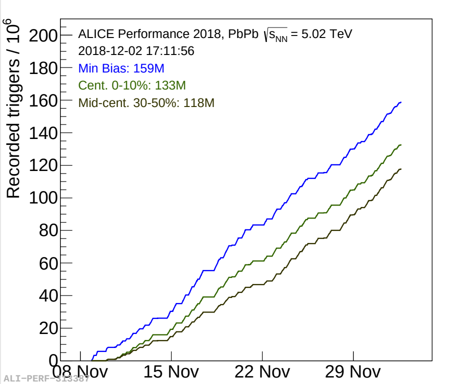
What to expect in the near future from the data side

Pb-Pb data taking in 2018

- Focus on centrality triggers
- Approximate increase in statistics compared with Pb-Pb statistics from 2015

  at mid-rapidity
  $\rightarrow 1\times$ minimum bias
  $\rightarrow 4\times$ $30-50\%$
  $\rightarrow 9\times$ $0-10\%$

  at forward rapidity
  $\rightarrow 1\times$ di-muon channel



- Significant increase in precision especially in central collisions

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_T provides strong support for the picture that charmonia are formed from deconfined thermalised charm quarks flowing with the QGP

Outlook

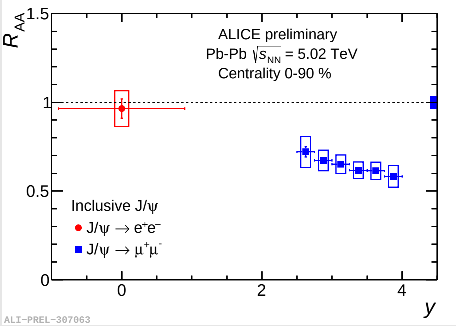
- With the increase of coming data, the more precise measurement of the charm cross section will help to discriminate between models
  $\rightarrow$ crucial to understand whether colour-less bound states exit for $T > T_{CF}$
- In a long term perspective exotic charmonia can help to sharpen our understanding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

Backup

What to expect in the near future from the data side

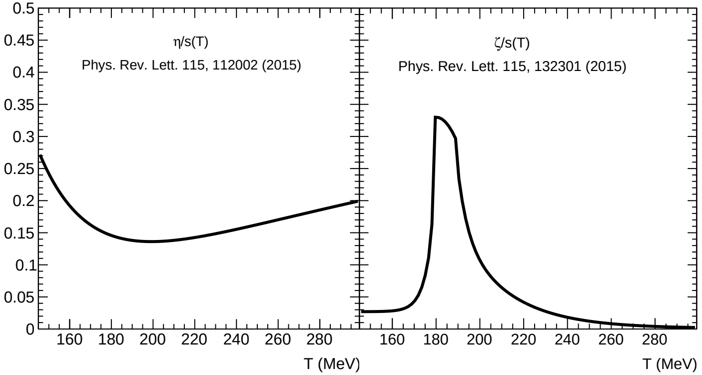
Finalisation of the analysis of the Pb-Pb data from 2015

- Including the new reference
- Significant improvement of the systematic uncertainty on the reference



QCD inspired parameters as MUSIC input

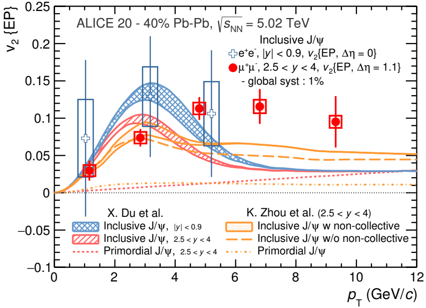
[Dubla *et al.*, NPA 979 (2018) 251]

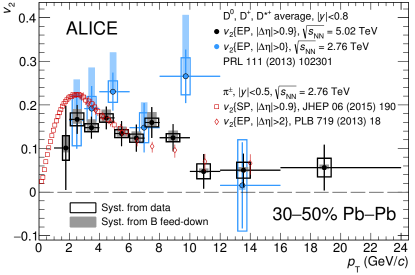


- $\eta/s(T)$ computed with a QCD based approach used as input parameter for MUSIC simulations

Thermalisation of charm quarks

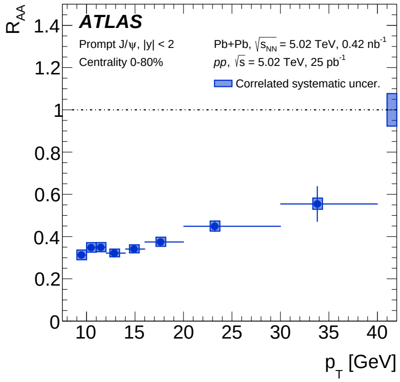
- J/ψ [ALICE, PRL 119 (2017) 242301] and D-mesons [ALICE, PRL 120 (2018) 102301] flow
- Strong support for recombination of thermalised charm quarks at low p_T
- Path-length dependence of suppression towards higher p_T



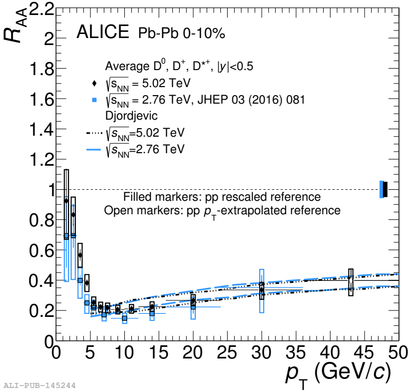


R_{AA} of charmonia and charmed mesons

[ATLAS Coll., arXiv:1805.04077]



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



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

Previously used pp interpolation at mid-rapidity

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

Procedure

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

- Available p_T spectra at mid-rapidity down to zero p_T is used to estimate the cross section and the $\langle p_T \rangle$

  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 $\langle p_T \rangle / p_T$ to interpolate to the aimed collision energy