Statistical hadronisation model

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ZUKUNFT SEIT 1386

Suppression and (re)generation of quarkonium in heavy-ion collisions at the LHC

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GSI Helmholtzzentrum für Schwerionenforschung GmbH

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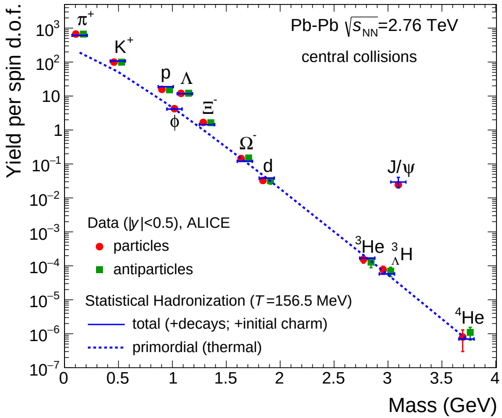
Statistical hadronisation in heavy-ion collisions

- 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



Extending the model with charm

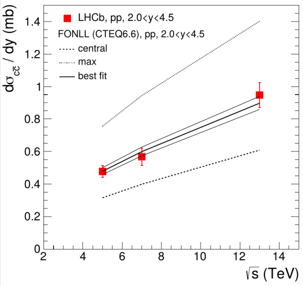
- Charm quarks are produced in initial hard scatterings ($m_{c\bar{c}} \gg T_{\mathrm{c}}$) and production can be described by pQCD ($m_{c\bar{c}} \gg \Lambda_{\mathrm{QCD}}$)
- Charm quarks survive and *thermalise* in the QGP
- Full screening before T_{CF}
- Charmonium is formed at phase boundary (together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

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

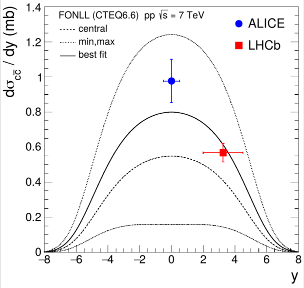
- Charm conservation is fulfilled exactly through $\sigma_{c\bar{c}} \rightarrow N_{c\bar{c}}^{\mathrm{dir}}$
- Canonical correction $N_{c\bar{c}}^{\mathrm{dir}} = \frac{1}{2} g_c N_{\mathrm{oc}}^{\mathrm{th}} \frac{I_1}{I_0}(g_c N_{\mathrm{oc}}^{\mathrm{th}}) + g_c^2 N_{c\bar{c}}^{\mathrm{th}} \rightarrow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

Calculation of $d\sigma^{pp}_{c\bar{c}}/dy$

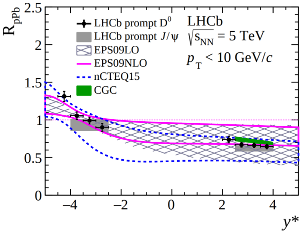
$\sqrt{s}$ dependence



Rapidity dependence



Shadowing



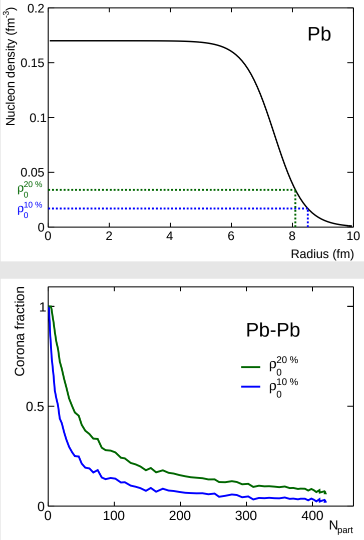
- Cross section including shadowing only uncertainty of the model
- Scale available measurements of $d\sigma^{pp}_{c\bar{c}}/dy$ to the corresponding rapidity and collision energy using FONLL
- Shadowing based on R_{pPb} measurements of D^0 from LHCb. Interpolation, if necessary, based nPDF calculations

Core and Corona

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

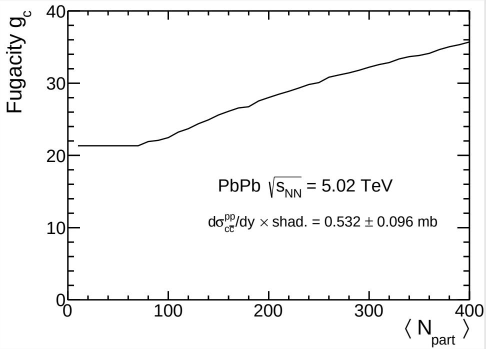
Core Thermal contribution from statistical hadronisation model

Corona pp distributions scaled by N_{coll}

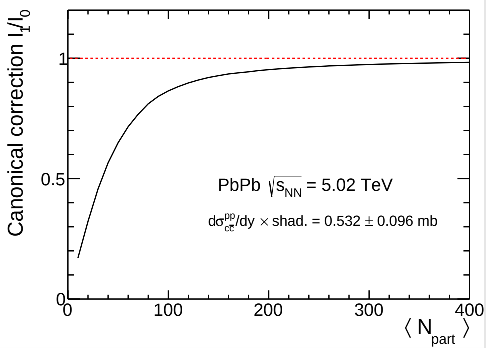


Derived quantities

Fugacity

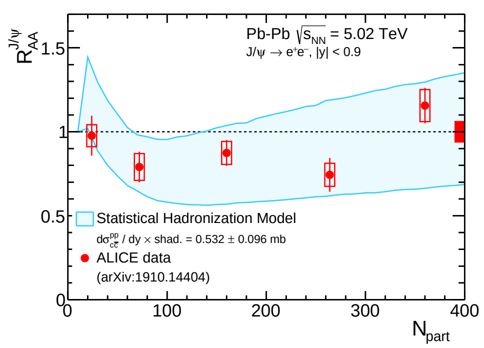


Canonical correction

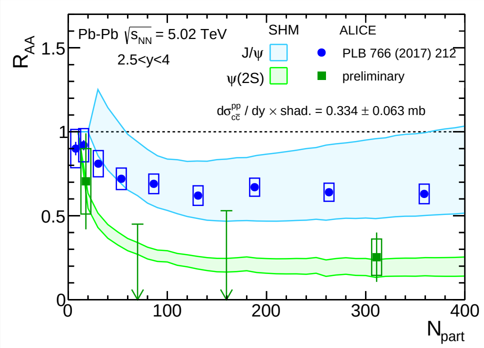


Comparison of the model with data vs centrality at 5.02 TeV

Mid-rapidity



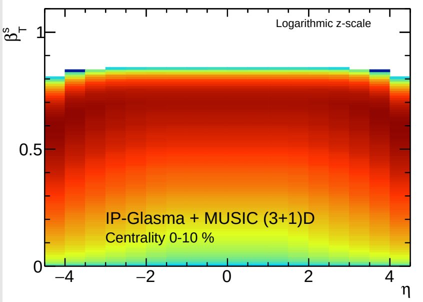
Forward rapidity

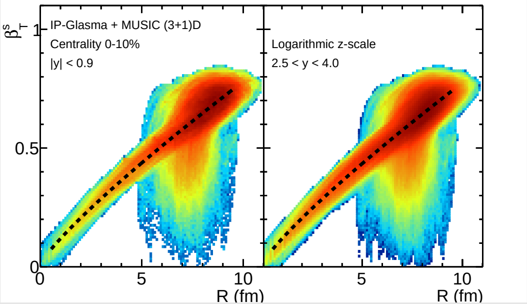


- Simultaneous description at mid- and forward rapidity of different charmonium states

Transverse momentum spectra

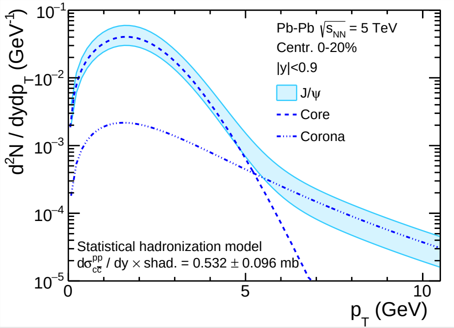
- The underlying idea of thermalised charm quarks forming charmonia at the hadronisation of the fireball can be extented to compute spectra
- Charm quarks follow collective expansion of the QGP fireball, as modeled well by state of the art viscous hydrodynamics codes used to describe light flavour hadron 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 $T = T_{CF}$





Transverse momentum parametrisation

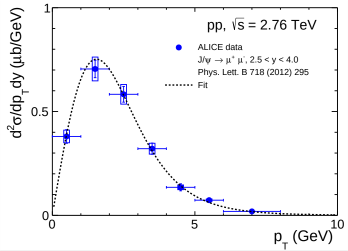
- A rapidity dependent blast wave function for boost-invariant expansion and Hubble flow following the earlier work from Schnedermann, Heinz and Florkowski is used to compute spectral shape using the collective velocity
- The corona part is added to the thermal part

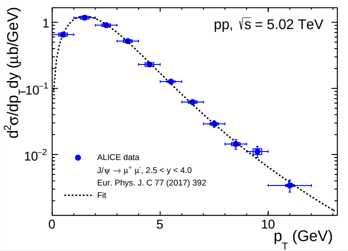


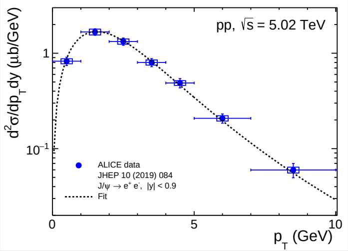
- The approach is sensitive to the degree of thermalisation of charm quarks in the fireball
- If the p_T distribution of the J/ψ can be described within this picture for low p_T, this provides strong support for charm quark thermalisation

Constraints on corona shape

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







$C = 8.25e-01 \pm 8.38e-02$
$p_0 = 4.44e+00 \pm 7.11e-01$
$n = 4.63e+00 \pm 9.19e-01$

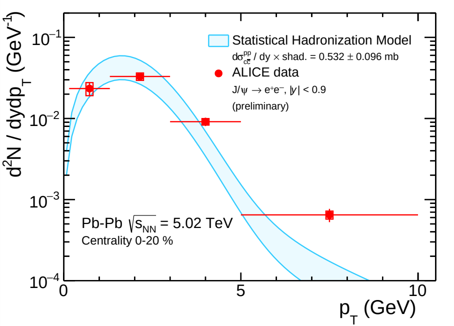
$C = 1.40e+00 \pm 7.61e-02$
$p_0 = 3.81e+00 \pm 1.87e-01$
$n = 3.72e+00 \pm 1.74e-01$

$C = 1.87e+00 \pm 1.96e-01$
$p_0 = 3.35e+00 \pm 4.17e-01$
$n = 2.82e+00 \pm 3.35e-01$

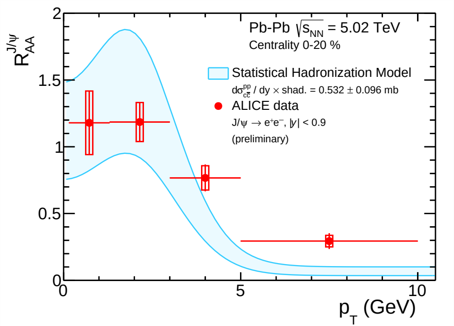
Comparison of the model with data

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

p_T spectrum



R_{AA} versus p_T

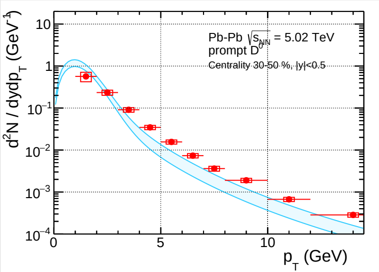


- Very good agreement between data and predictions without free parameters

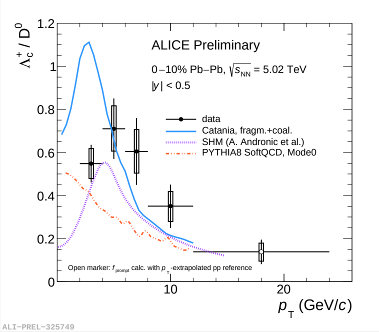
Approach can be extended to open charm hadrons as well

D^0 p_T-spectrum

[ALICE, JHEP 1810 (2018) 174]



Λ_c^+/D^0 versus p_T



- Good description of p_T dependence of D^0 yield and the ratio of Λ_c/D^0

Summary

- The SHM describes charmonium yields as a function of centrality, rapidity and transverse momentum
- The agreement at low p_T provides strong support for the picture that charmonia are formed from deconfined fully thermalised charm quarks flowing with the QGP
- The approach also describes open charmed hadrons and the charmed baryon-over-meson ratio

Outlook

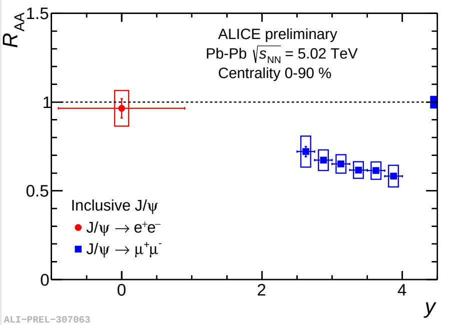
- The more precise measurements of the charm cross section in future will help to decrease uncertainties of models
  $\rightarrow$ crucial to understand whether color-less bound states exit for $T > T_{CF}$
- Extend studies to describe elliptic flow of charmonium states

Backup

What to expect in the near future from the data side

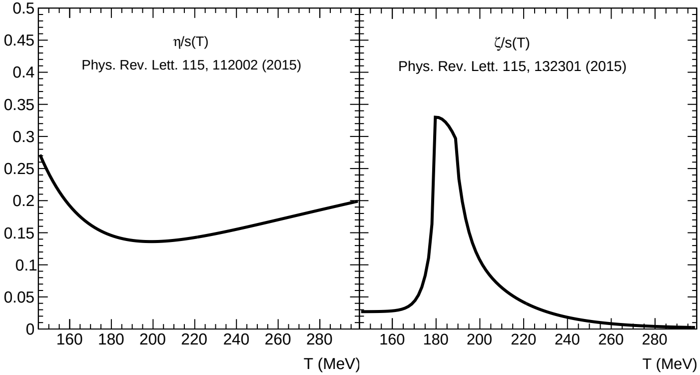
Finalisation of the analysis of the Pb-Pb data from 2015

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



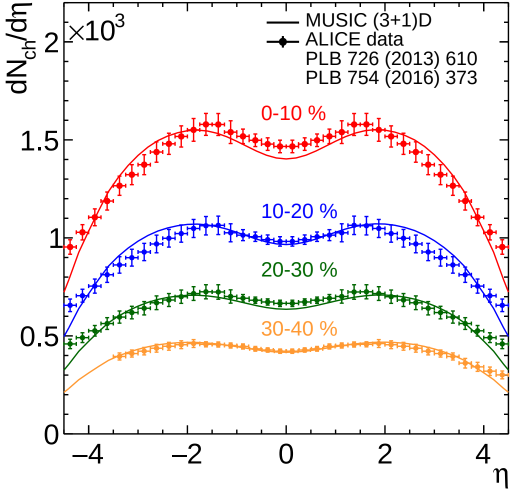
QCD inspired parameters as MUSIC input

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



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

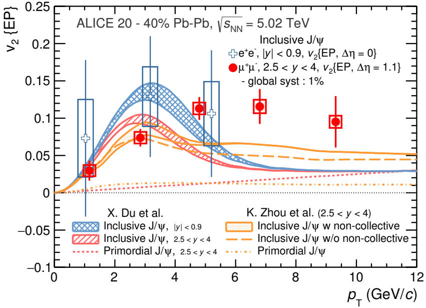
Comparison of particle distribution

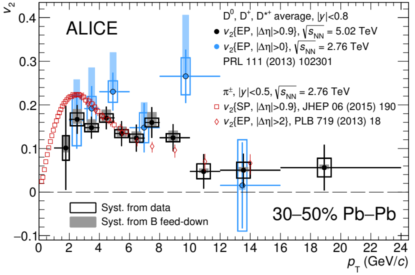


- MUSIC(3+1)D needs input for η dependence $\rightarrow$ need to compare with data
- For the comparison of the simulation with data, there is also the possibility to run the Cooper-Frye procedure afterwards
  [Cooper & Frye, PRD 10 (1974) 186]
  [Cooper, Frye & Schonberg, PRD 11 (1975) 192]
- Turns 'massless'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

Thermalisation of charm quarks

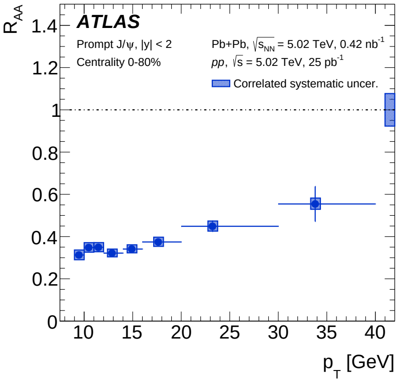
- J/ψ [ALICE, PRL 119 (2017) 242301] and D-mesons [ALICE, PRL 120 (2018) 102301] flow
- Strong support for recombination of thermalised charm quarks at low p_T
- Path-length dependence of suppression towards higher p_T



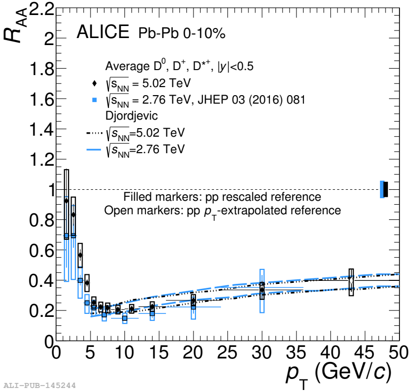


R_{AA} of charmonia and charmed mesons

[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

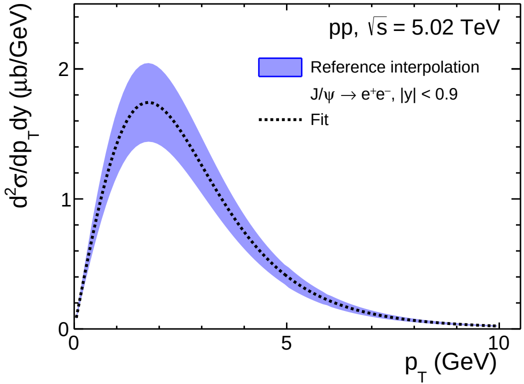
Procedure

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



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

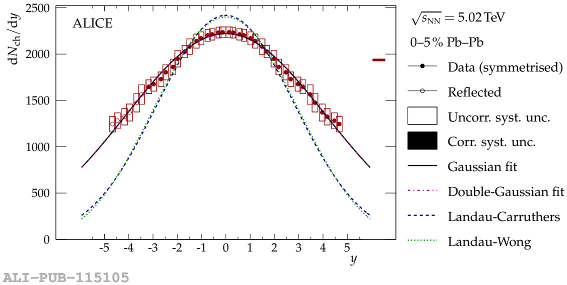
$$\rho = \tanh^{-1}\left\{ \beta_\mathrm{T}^\mathrm{s} \left(\frac{r}{R}\right)^n \right\},$$

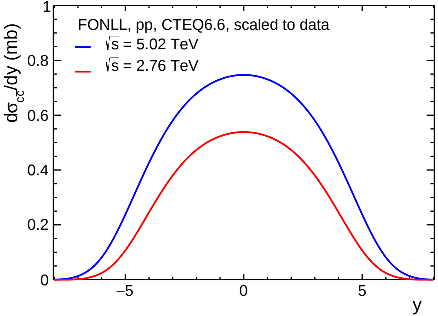
with $\beta_\mathrm{T}^\mathrm{s}$ being the transverse surface velocity.

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

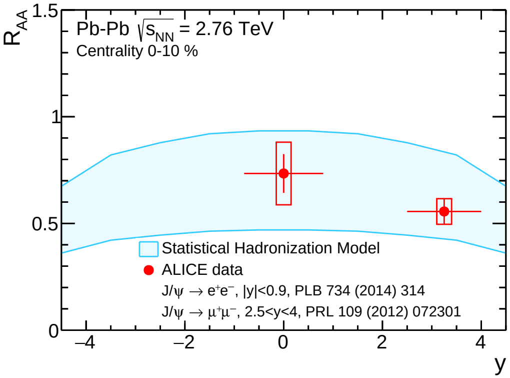
Rapidity dependence of J/ψ production

- 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 $\begin{cases} dN_{ch}/dy \\ n_{ch}^{SHM} \end{cases}$ [ALICE, PLB 726 (2013) 610] [ALICE, PLB 772 (2017) 567] $\hat{=}$ particle density from SHM
- 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

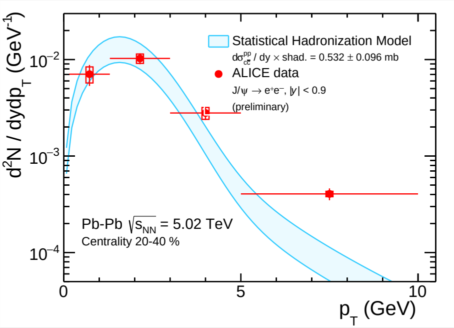


- Good description of data by the model as a function of J/ψ rapidity
- Fall-off towards large rapidities is significant (and would be in contrast to screening-dominated descriptions)

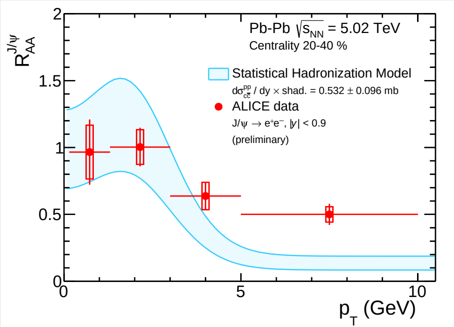
Comparison of the model with data

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

p_T spectrum



R_{AA} versus p_T

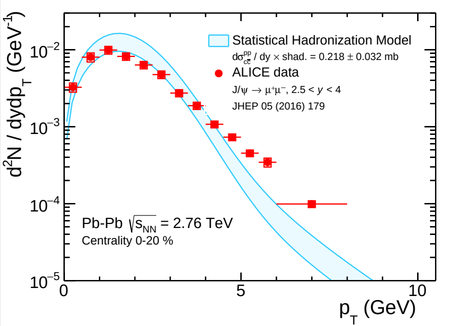


- Very good agreement between data and predictions without free parameters

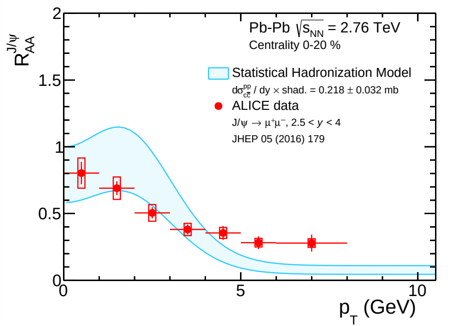
Comparison of the model with data

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

p_T spectrum



R_{AA} versus p_T

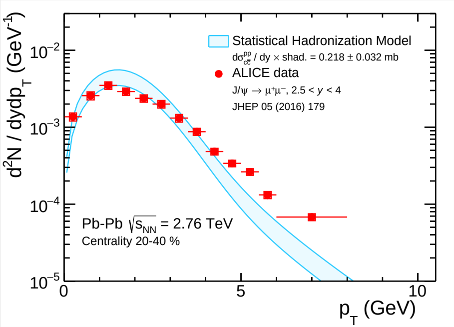


- Very good agreement between data and predictions without free parameters at low p_T

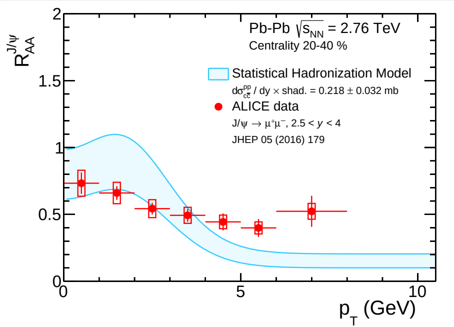
Comparison of the model with data

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

p_T spectrum



R_{AA} versus p_T



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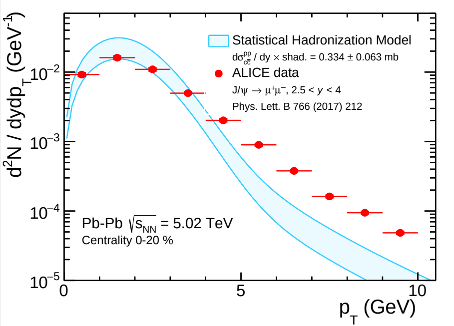
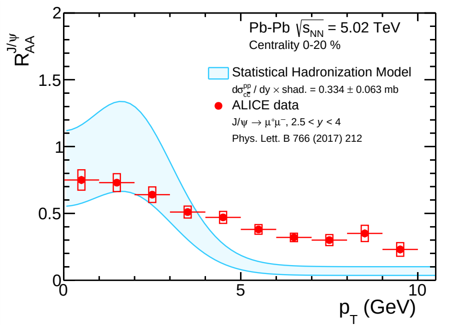


R_{AA} versus p_T

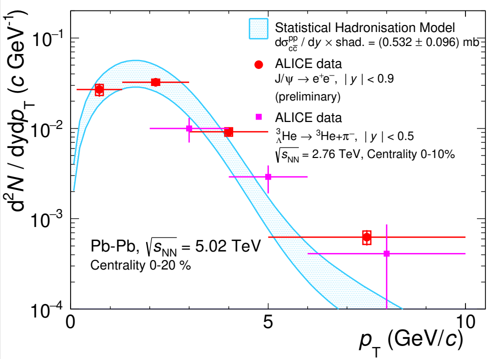


- Very good agreement between data and predictions without free parameters at low p_T

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]

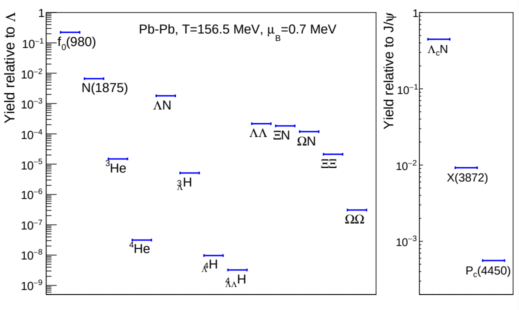


- J/ψ and (scaled) hyper-triton can be described by the same flow parameters
- Need the precision on hyper-triton p_T spectra as will be available in LHC Run3
- Comparison of loosely bound and compact objects allow for a test of the hypothesis

Looking towards 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

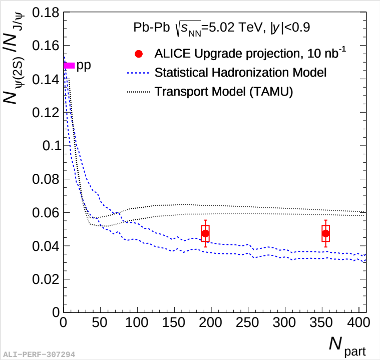


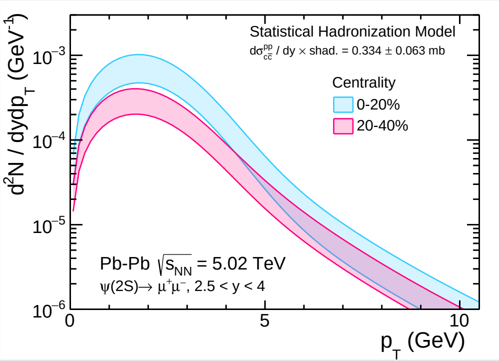
- Particular interest in X(3872)
- Invariant mass close to $D^0\bar{D}^{*0}$ production threshold
- Potential tetra-quark state and charmed meson molecule

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}

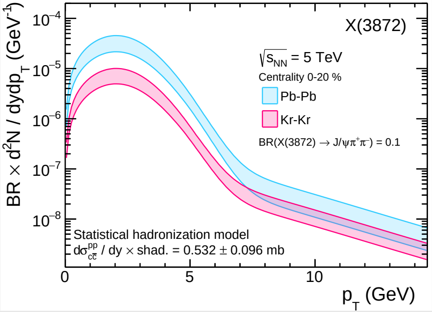




X(3872) transverse momentum spectra

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