Thermodynamics of strongly interacting matter

K. Redlich Uni. Wroclaw, Poland

- Equation of state of QCD hadronic phase

  From S-matrix Hadron Resonance Gas

  <=> LQCD EoS

- QCD Eqs and hadron production yields in HIC
  - light quark hadron yields in AA collisions
- Charm hadron production: probing QCD phase boundary
  - emergence of new systematics for open charm production in high energy pp, pA and AA collisions

P. Braun-Munzinger, N. Sharma, J. Stachel &K.R., *JHEP* 04 (2025) 058

N. Sharma, Pok Man Lo, & K.R. Phys. Rev. C107 (2023)

P. Braun-Munzinger, B. Friman, A. Rustamov, J. Stachel & K.R. Nucl. Phys. A 1008 (2021)

A. Andronic, P. Braun-Munzinger, M. K. Köhler, A. Mazeliauskas, K. R., J. Stachel & V. Vislaviciusg, JHEP 07 (2021) 035

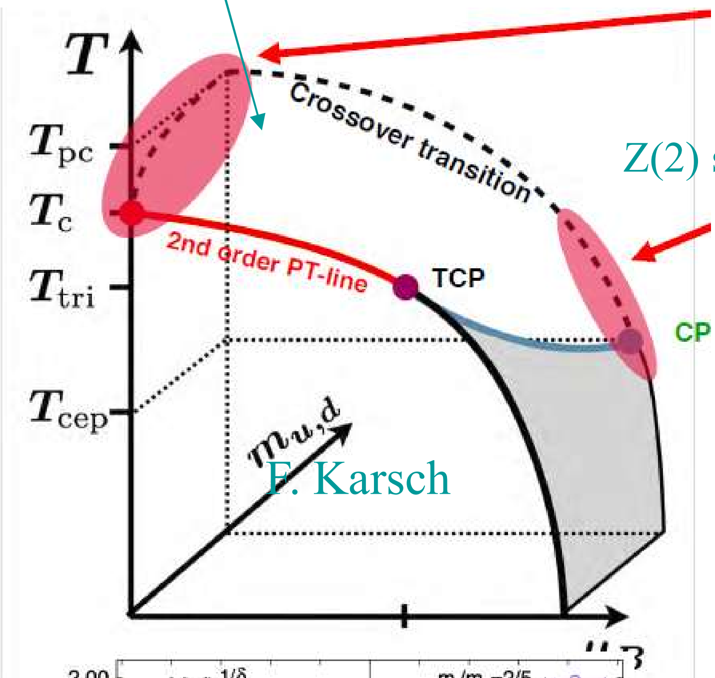
J. Cleymans, Pok Man Lo, N. Sharma & K.R. Phys. Rev. C103 (2021)

A. Andronic, P. Braun-Munzinger, Pok Man Lo, B. Friman, J. Stachel & K.R Phys. Lett. B 792 (2019)

A. Andronic, P. Braun-Munzinger, J. Stachel & K.R., Nature 561, 302 (2018)

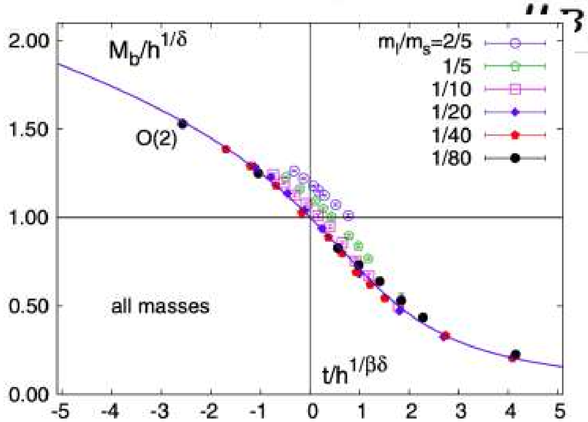
Linking LHC AA yields data with LQCD

HIC LHC



Z(2) scaling

F. Karsch



S. Ejiri *et al.*, PRD 80, 094505 (2009)

- Due to expected O(4) scaling of QCD free energy

$$F = F_R(T,\mu_q,\mu_I) + b^{-1} F_S(b^{(2-\alpha)^{-1}} t(\mu), b^{\beta\delta/\nu} h)$$

- Fluctuations and correlations of conserved charges an excellent probe of QCD criticality and EQS in different sectors of quantum numbers

$$\chi_B^{(n)} = \frac{\partial^n (F/T^4)}{\partial(\mu_B/T)^n} = \frac{1}{VT^3}\kappa_B^{(n)} = \chi_R^{(n)} + \chi_S^{(n)}$$

$$\chi_s^{(n)}\big|_{\mu\neq 0} \approx h^{(2-\alpha-n)/\beta\delta}$$

At $\mu = 0$, $\chi_B^{(n\geq 6)}$ are singular at $h \to 0$

At $\mu \neq 0$, $\chi_B^{(n\geq 3)}$ are singular at $h \to 0$

M. A. Stephanov, K. Rajagopal, E. V. Shuryak
Phys.Rev.Lett. 81 (1998) 4816, Phys.Rev.D 60 (1999) 114028

- **CP: 2nd order point - critical fluctuations of net protons.**
  (Hatta, Stephanov PRL 91, 102003 (2003))

- **Crossover: exhibits critical fluctuations in scaling regime**
  (Ejiri, Karsch, Redlich, PLB 633, 275 (2006))

H.-T. Ding et al. Phys.Rev.D 109 (2024) 1

Modelling QCD thermodynamic potential in hadronic phase

Pressure of an interacting, a+b ⇔ a+b, hadron gas in equilibrium

$$P(T) \approx P_a^{id} + P_b^{id} + P_{ab}^{\text{int}}$$

The leading order interactions, determined by the two-body scattering phase shift, which is equivalent to the second virial coefficient

$$P^{\text{int}} = \sum_{I,j} \int_{m_{th}}^{\infty} dM \; B_j^I(M) P^{id}(T,M)$$

$$B_j^I(M) = \frac{1}{\pi}\frac{d}{dM}\delta_j^I(M)$$

↓ *Effective weight function* ↓ *Scattering phase shift*

R. Dashen, S. K. Ma and H. J. Bernstein, Phys. Rev. 187, 345 (1969)
R.Venugopalan, and M. Prakash, Nucl. Phys. A 546 (1992) 718.
W. Weinhold,, and B. Friman, Phys. Lett. B 433, 236 (1998).
Pok Man Lo, Eur. Phys.J. C77 (2017) no.8, 533

- Interactions driven by narrow resonance of mass M_R

  $B(M) = \delta(M^2 - M_R^2) \quad \Rightarrow \quad P^{\text{int}} = P^{id}(T, M_R) \Rightarrow HRG$

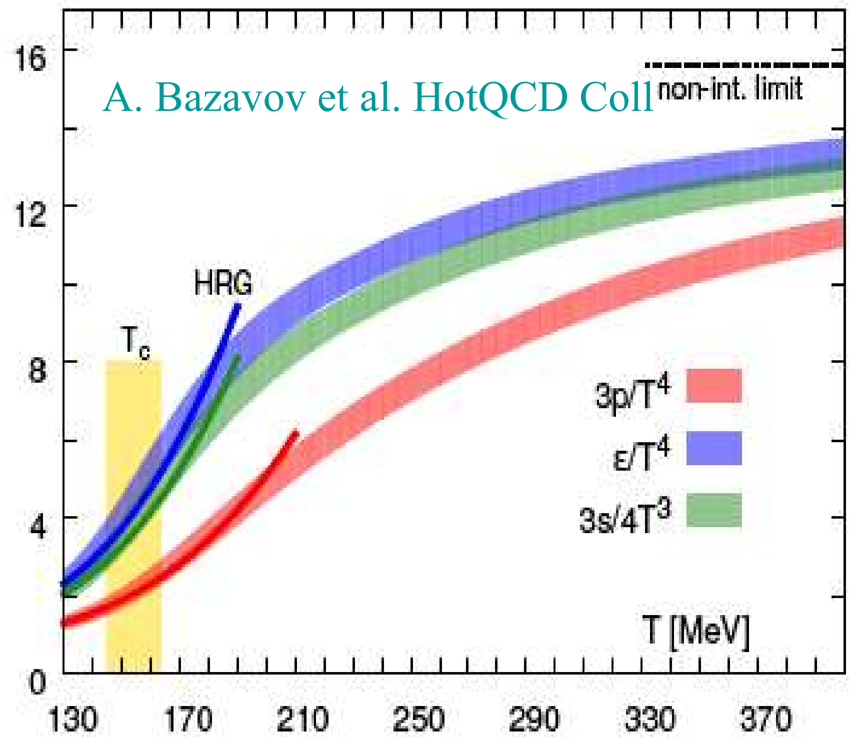
  For finite and small width of resonance, B(M) => Breit-Wigner form
- For non-resonance interactions or for broad resonances $P_{ab}^{\text{int}}(T)$ should be linked to the phase shifts

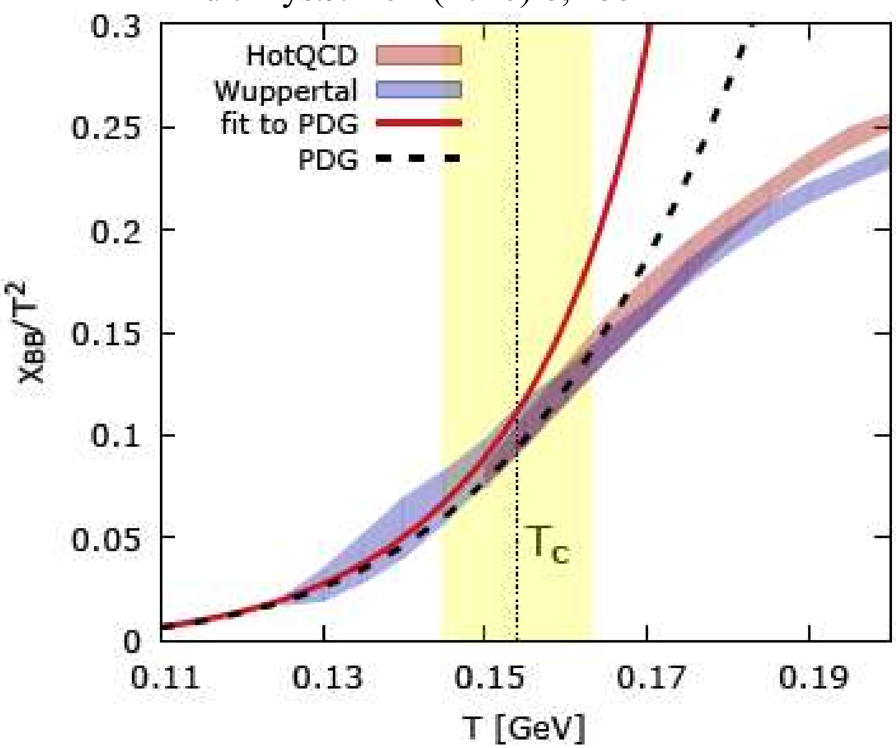
Quark-Hadron duality near the QCD phase boundary

$$P(T,\vec{\mu}) \approx \sum_H P_H^{id} + \sum_R P_R^i$$

$$P_R^i = \pm \frac{Tg_i}{2\pi^2} \int p^2 dp \int dM \ln(1 \pm e^{-\beta(E_i - \vec{q}_i \vec{\mu}_i)}) F_R^{BW}(M)$$

J. Goswami, et al., 2011.02812 [hep-lat]
R. Bellwied, et al. Phys.Rev.D 104 (2021) 7
S. Borsányi, et. al Phys.Rev.D 110 (2024)]
Pok Man Lo, M. Marczenko et. al. Eur.Phys.J.A 52 (2016) 8, 235

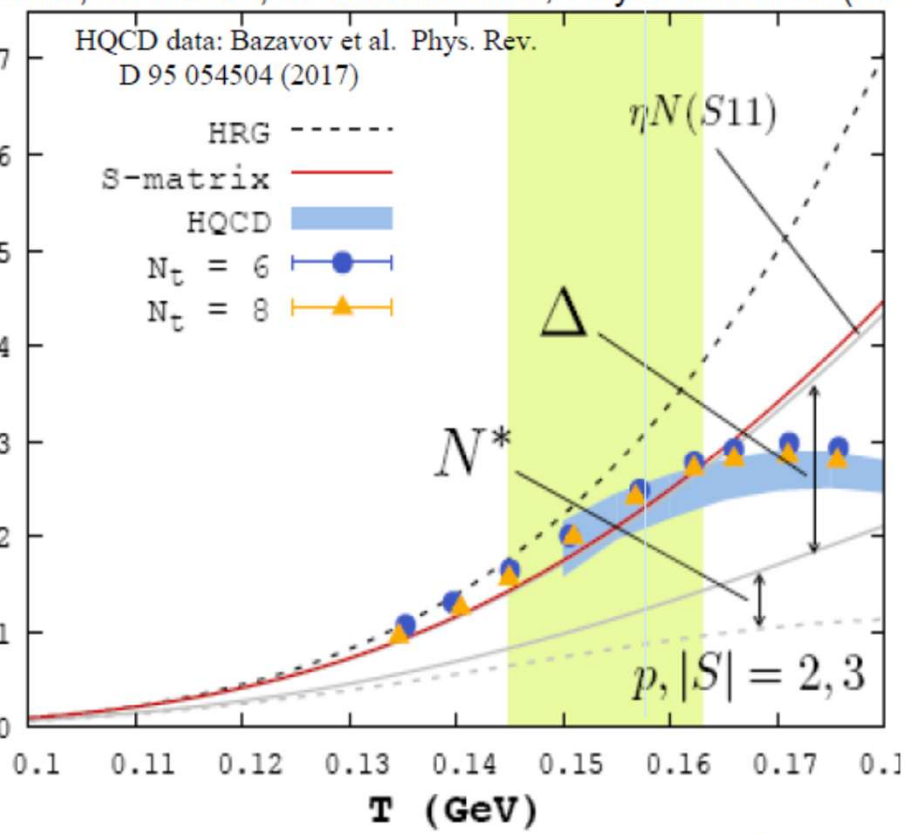




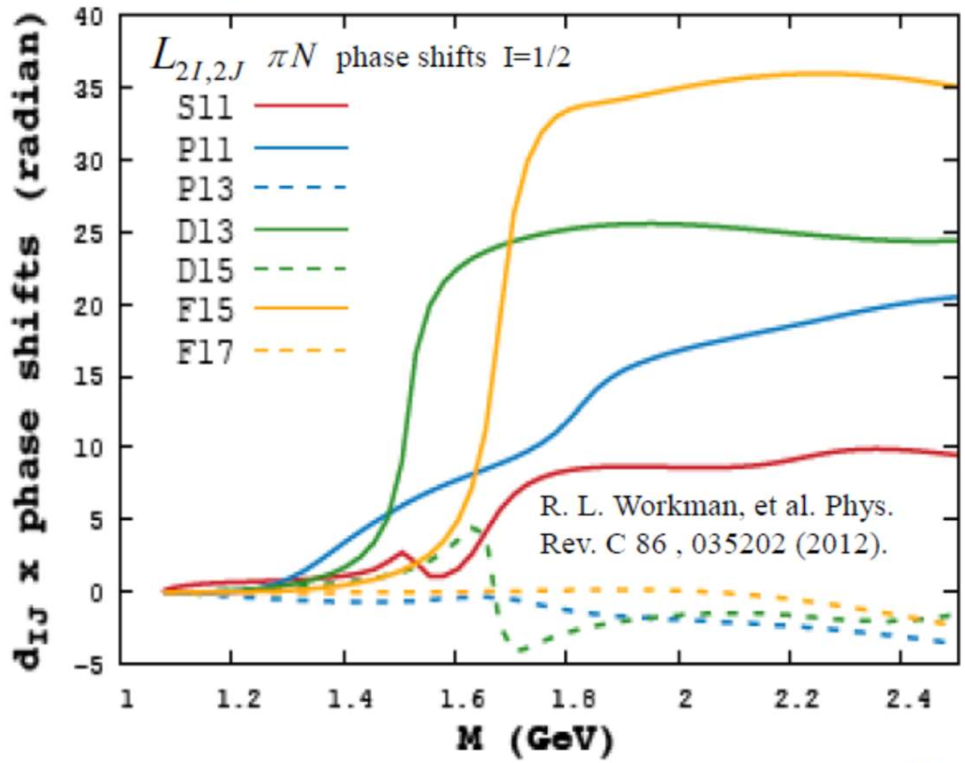
- SM Hadron Resonance Gas thermodynamic potential provides good approximation of the QCD equation of states in confined phase
- Good description of net- baryon number fluctuations and in further sectors of hadronic quantum number on correlations and fluctuations

robing non-strange baryon sector in πN- system

an Lo, B. Friman, C. Sasaki & K.R., Phys.Lett. B778 (2018)



$\chi_{BQ} = (\chi_{BB} - |\chi_{BS}|)/2$

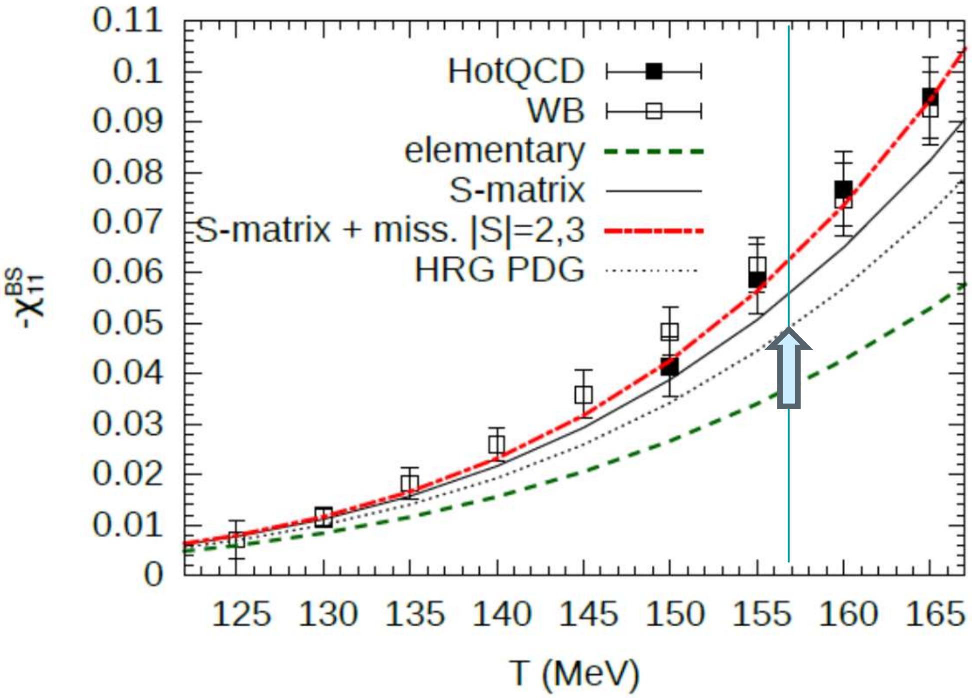


$$\Delta\chi_{BQ} \approx \sum_{I_z, j, B} d_j BQ \int dM \int d^3p \frac{1}{T} \frac{d\delta_j^I}{dM} \times e^{-\beta\sqrt{p^2+M^2}} (1+e^{-\beta\sqrt{p^2+M^2}})^{-2}$$

- Considering contributions of all πN $\delta_j^{I=(1/2),\ (3/2)}$ (N^*, Δ^* resonances) to χ_{BQ} within S-matrix approach, reduces the HRG predictions towards the LQCD in the chiral crossover $0.15 < T < 0.16\ GeV$

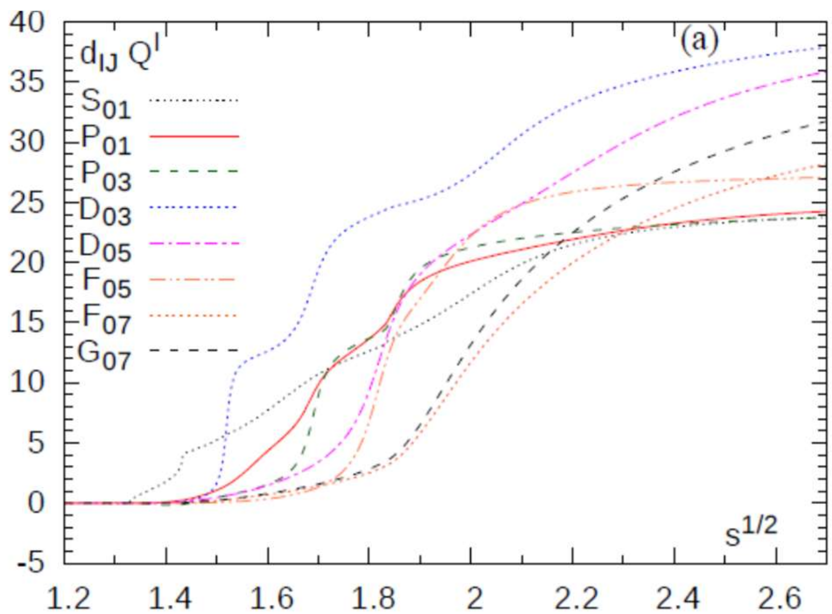
S-matrix HRG in strange baryon channel and LQCD

Cesar Fernandez-Ramırez, Pok Man Lo, and Peter Petreczky PRC 98 (2018)



Joint Physics Analysis Center

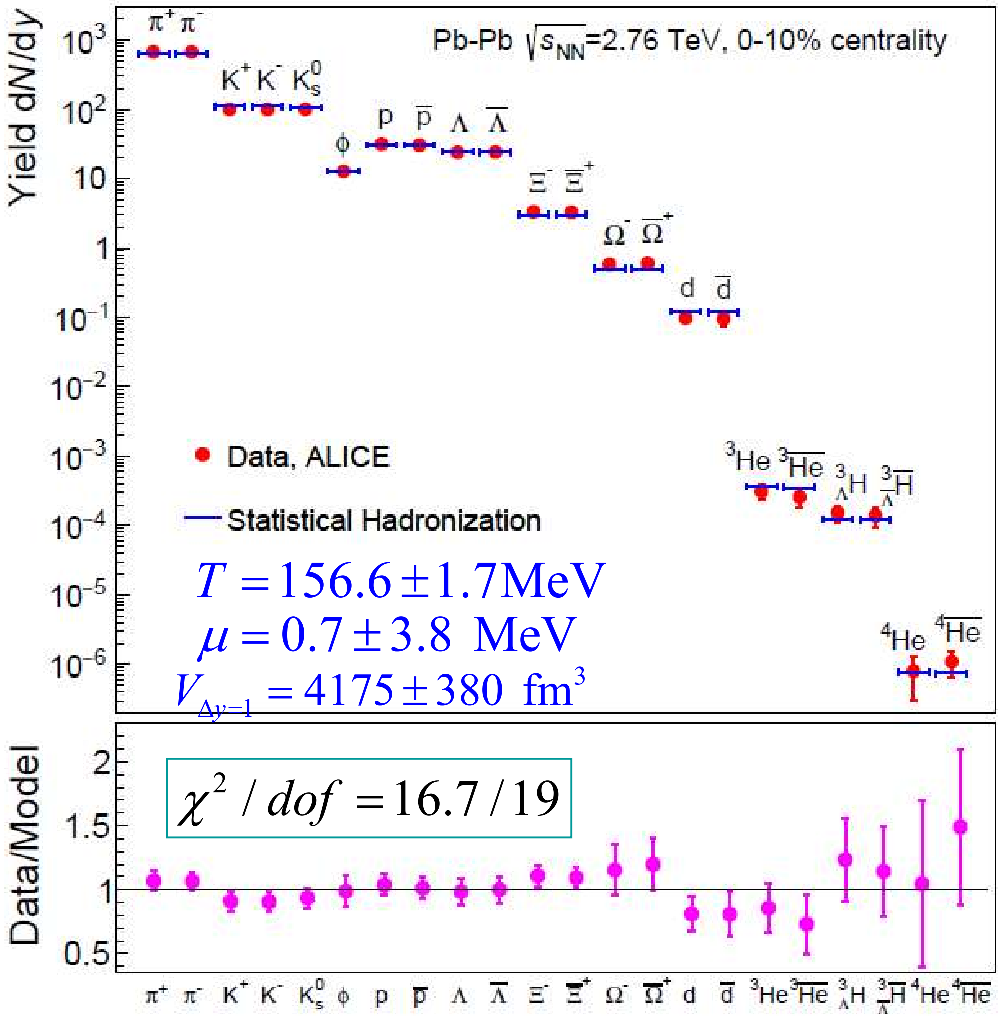
C. Fernandez-Ramırez,I. V. Danilkin, D. M. Manley, V. Mathieu, and A. P. Szczepaniak1 (2018)



- Employing the coupled-channel study involving $\overline{K}N,\ \overline{K^*}N,\ \pi\Lambda,\ \pi\Sigma,$ interactions in the S = −1 sector.
- Improvements of model description of LQCD results

S-matrix HRG and particle yields in Pb-Pb collisions at the LHC

Measured yields reproduced at $T \approx T_c$



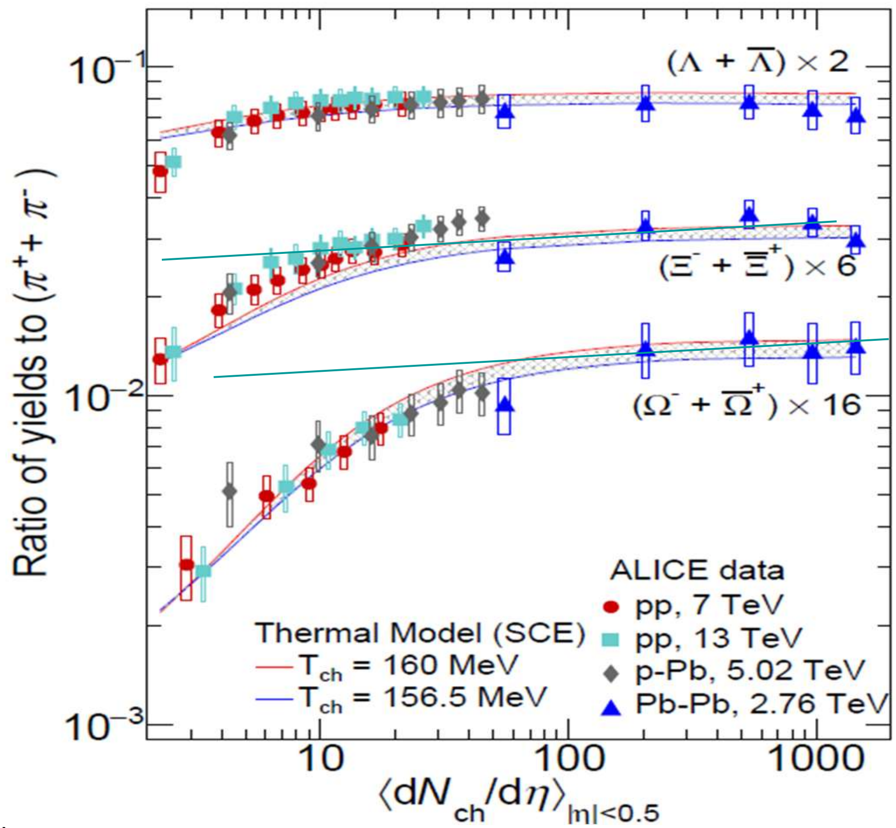
A. Andronic, P. Braun-Munzinger, Pok Man Lo, B. Friman, J. Stachel & K.R Phys. Lett. B 792, 304 (2019)

A. Andronic, P. Braun-Munzinger, J. Stachel & K.R., Nature 561, 302 (2018)

The observed scaling with requires exact strangeness conservation

$$n_s^C(T,V_c) \approx n^{GC}(T) \cdot \frac{I_s(2V_C n^{th}_{s=1}(T))}{I_0(2V_C n^{th}_{s=1}(T))}$$

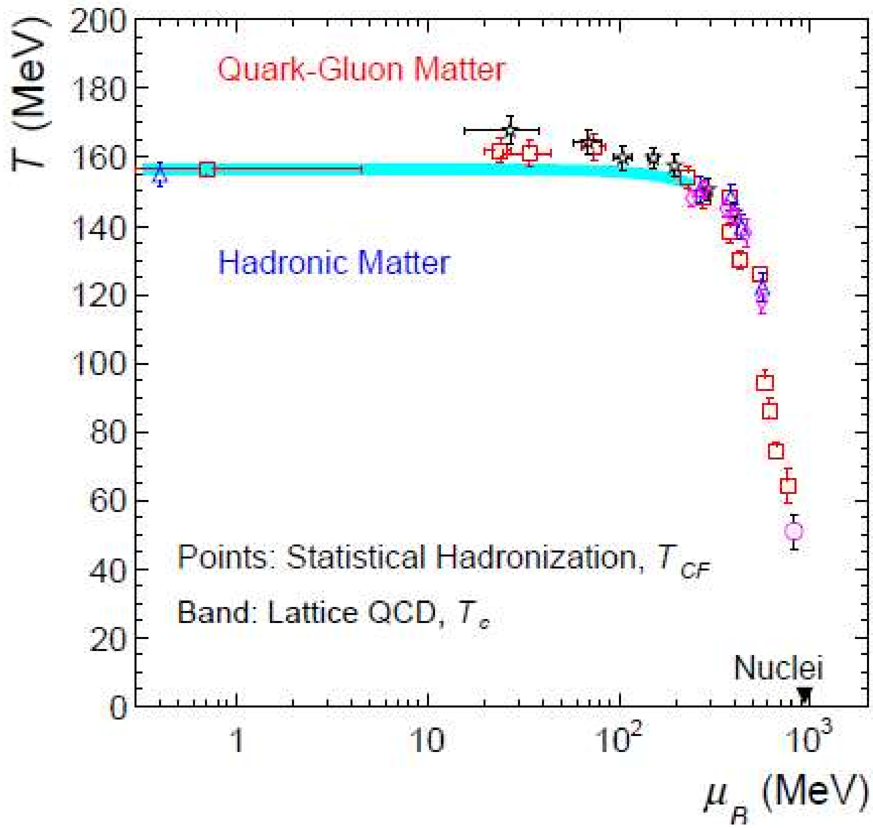
$$V_C = V_C(dN_{ch}/d\eta)$$

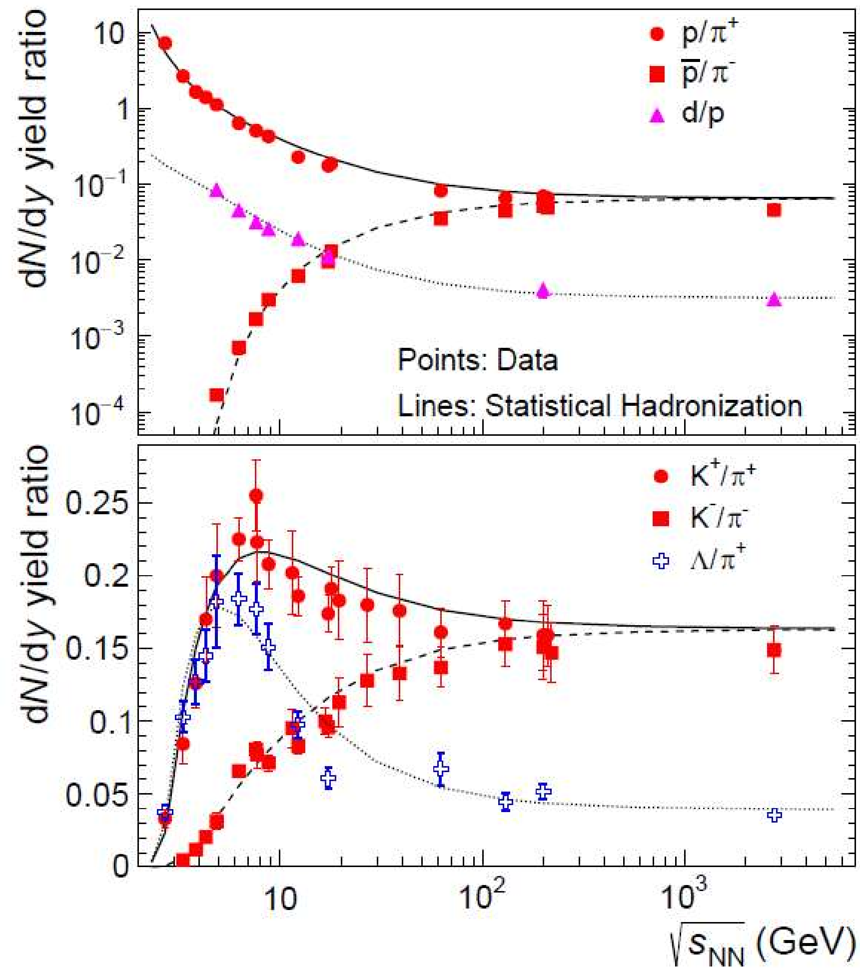


A fireball in central Pb-Pb collisions is the matter created near the QCD phase boundary

Thermal origin of light flavors in HIC: Beam Energy dependence

A. Andronic, P. Braun-Munzinger, J. Stachel, K.R.
Nature 561 (2018) (720 citations)

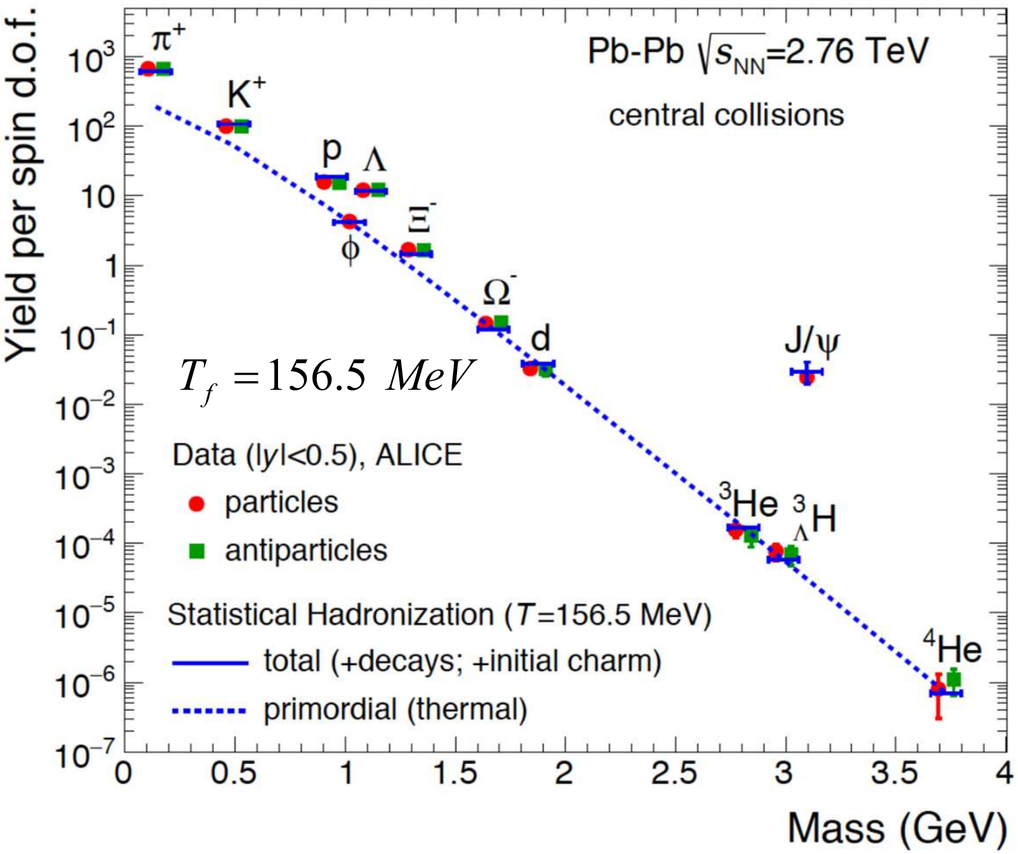




- Hadron yields in heavy-ion collisions from SIS to LHC are consistent with the SHM in C-ensemble. Particle produced at QCD phase-boundary from hadronizing QGP!
- A. Andronic, P. Braun-Munzinger and J. Stachel Nucl. Phys. A772 (2006) 167
- A. Andronic, P. Braun-Munzinger and J. Stachel Phys. Lett. B673 (2009) 142

The thermal model and Charm particle production

A. Andronic, P. Braun-Munzinger,
J. Stachel & K.R, Nature (2018)



The yield of J/Psi differs by a huge factor 900 from model expectation:

There are too few charm quark pairs in equilibrium QGP at Tc!

The way out: Statistical Hadronization Model of Charm (SHMc) introduced by:

Peter Braun-Minzinger & Johanna Stachel
Phys. Lett. B490 (2000) 196.

See also:
A. Andronic, P. Braun-Munzinger, J. Stachel & K.R, NPA 789 (2007) 334, *Phys.Lett.B* 652 (2007) 259

- Light quark hadrons produced at the QCD phase boundary during hadronization of QGP and their yields are consistent with QCD EQS

SHMc charm statistical hadronization:
Yields and Spectra of Open Charmed Hadrons

Intial $c\bar{c}$ production in partons scattering $\Rightarrow$ Thermalization of cc pairs in QGP $\Rightarrow$ Hadronization of cc quarks at the QCD phase boundary

Formation of cc pairs in hard initial scattering on time scale $t_c \approx 1/2m_c$ with $m_c = 1.3$ GeV $\rightarrow$ t = 0.1 fm: comparable to QGP formation and much shorter than charmed hadron production at few fm/c

Charm quarks as external source in QGP: annihilation and production of charm quarks in QGP negligible

Charm quarks thermalize inside the QGP: strong evidence through observed elliptic flow and energy loss

$\Rightarrow$ Justifying application of charm statistical hadronization

- The final number of charm-anticharm quark pairs bound in the produced hadrons is the same as in the initial state

SHMc: linking initial with final state

- The charm balance equation to preserve Ncc quark pairs

$$2N_{cc} = g_c V \sum_{h^i_{oc,1}} n_i^{th} + g_c^2 V \sum_{h^i_{oc,2}} n_i^{th} + g_c^2 V \sum_{h^i_{hc}} n_i^{th} \quad \text{with} \quad n_i^{th} \simeq d_{i,J} m_i^2 T K_2(m_i / T)$$

obtained from measured open charm cross section or from QCD+Glauber

thermal charm hadrons

- In general for small N one needs to include canonical suppression

$$2N_{cc} \simeq \sum_{\alpha=1,2} N_{oc,\alpha} \frac{I_\alpha(N_{oc,1})}{I_0(N_{oc,1})} + N_{hc}$$

defining:

$$N_{oc,1} = V g_c \sum_{h^i_{oc,1}} n_i^{th} \qquad N_{hc} = V g_c^2 \sum_{h^i_{hc}} n_i^{th}$$

$$N_{oc,2} = V g_c^2 \sum_{h^i_{oc,2}} n_i^{th}$$

- For a given Ncc and knowing T, V from thermal analysis of light hadron yields:

⇨ solve the above balance equation to get g_c, consequently

Heavy flavor particle yields in SHMc

- The rapidity density of open and hidden charm hadrons in SHMc:

$$\frac{dN_{i,\alpha=1,2}}{dy} = g_c^{\alpha} V n_i^{th} \frac{I_\alpha(2Vg_c\sqrt{n_{c=1}^{tot} n_{c=-1}^{tot}})}{I_0(2Vg_c\sqrt{n_{c=1}^{tot} n_{c=-1}^{tot}})}$$

Total thermal density of $c = \pm 1$

$$n_{c=\pm 1}^{tot} = \sum_k n_{k,c=\pm 1}^{th}$$

$$\frac{dN_{i,hc}}{dy} = g_c^2 V n_i^{th}$$

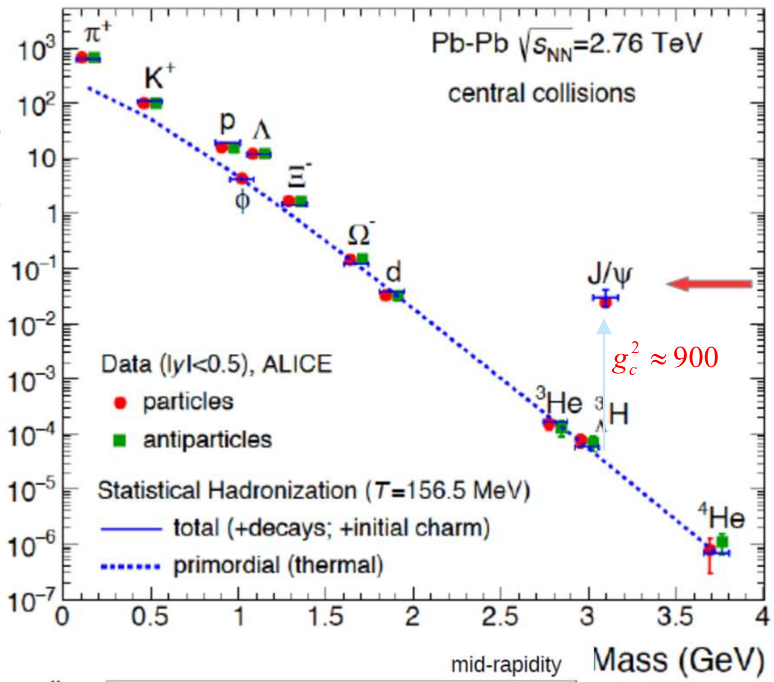
contribution of resonances:

$$n_i^{th} = n_i^{prompt} + \sum_j Br(j \to i) n_j^r$$

- The essential difference with light particle thermal yields is due to the fugacity factor $g_c = g_c(N_{cc}, V, T, \vec{\mu})$ which guarantees conservation of N_{cc} pairs from the initial partonic to the final hadronic state.

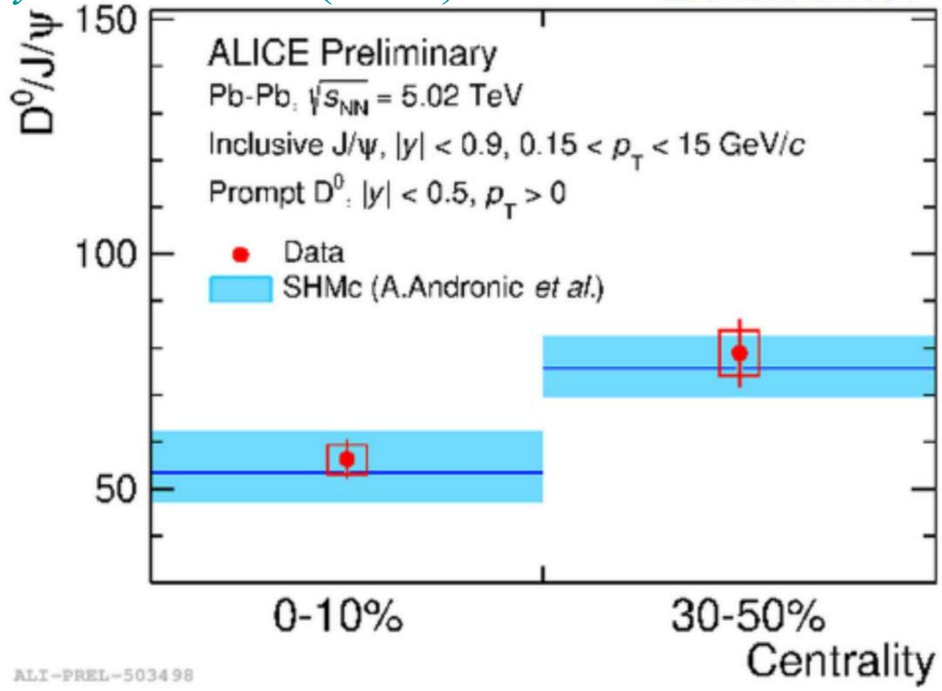
Model comparison with ALICE data

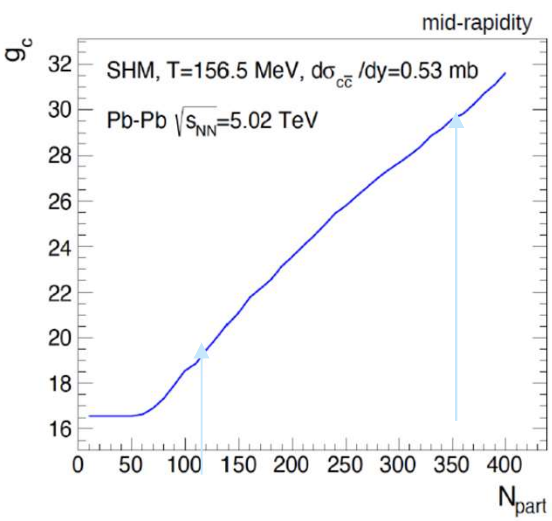
A.Andronic et al., PLB 797 (2019) 134836



Phys.Lett.B 849 (2024) 138451

arXiv:2303.13361

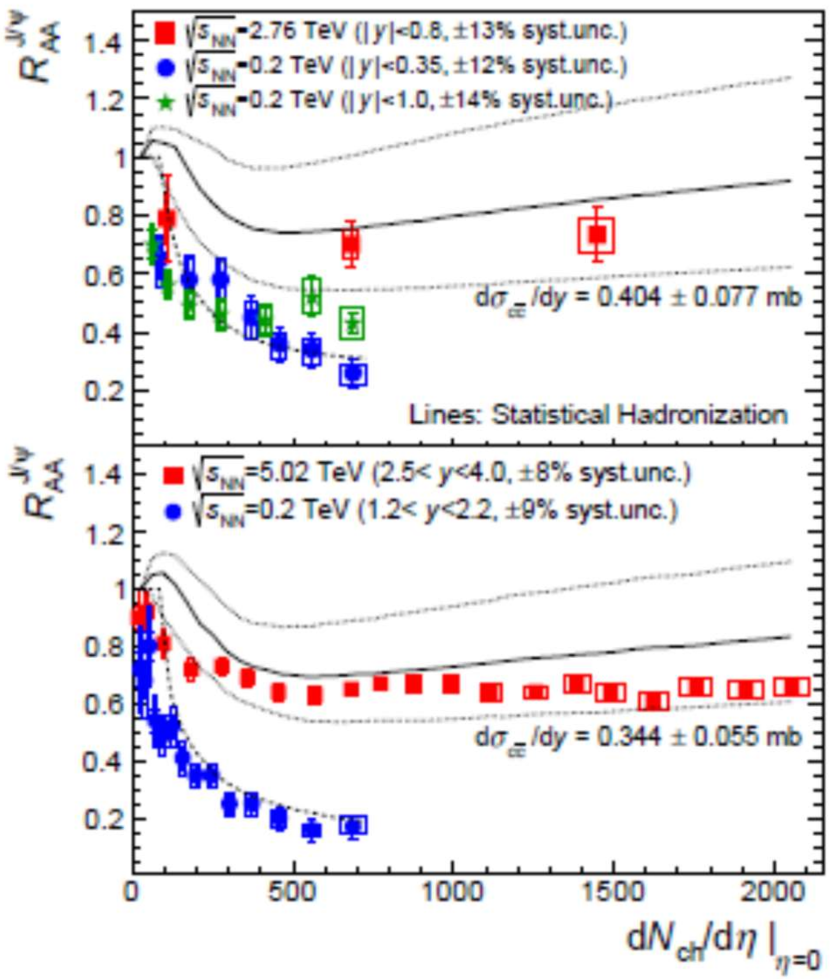




- Strong increase of J/Psi yields due to off chemical equilibrium facto $g_c^2 \approx 900$ in central collisions
- First data on $D^0/(J/\psi)$ and centrality dependence well described by SHMc. Increasing ratio towards non central collisions due to decreasing g_c since:

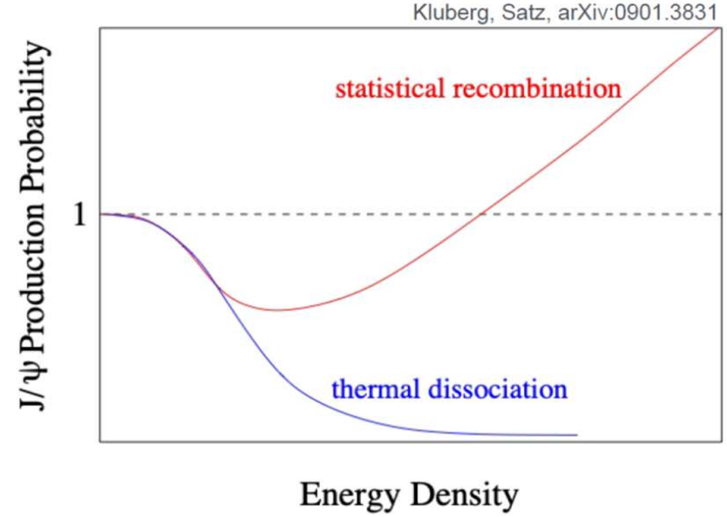
$$D^0/(J/\psi) \sim f(T)(I_1/I_0)g_c^{-1}$$

Essential predictions of SHMc: J/Psi suppression



Predictions successfully applied to quantify SPS, RHIC and LHC data: Regeneration of J/Psi at the QCD phase boundary and increasing number of Ncc with energy imply that the J/Psi suppression observed at SPS decreases with increasing energy towards LHC

Kluberg, Satz, arXiv:0901.3831



Melting scenario at the LHC not observed

Emergence of New Systematics of Open Charm production at High Energy Collisions

- Consider SHMc balance equation and its approximation:

$$2N_{cc} \simeq Vg_c n_{oc,1}^{tot} \frac{I_1(N_{oc,1}(g_c,V)}{I_0(N_{oc,1})} + N_{oc,2} \frac{I_2(N_{oc,1}(g_c,V))}{I_0(N_{oc,1})} + N_{hc}$$

However, contributions of $c = \pm 2$ and hidden charm hadrons less than 3% thus can be neglected to extract g_c

- Consequently:

$$Vg_c \frac{I_1(N_{oc,1})}{I_0(N_{oc,1})} \approx \frac{2N_{cc}}{n_{oc,1}^{tot}}$$

and since

$$\frac{dN_{i,c=\pm 1}}{dy} = Vg_c \frac{I_1(N_{oc,1})}{I_0(N_{oc,1})} n_i^{th}$$

- the open charm hadron rapidity density with $c = \pm 1$,

$$\frac{dN_{i,c=\pm 1}}{dy} \simeq 2 \frac{n_i^{th}(T)}{n_{oc,1}^{tot}(T)} N_{cc}$$

$$n_i^{th} = n_i^{prompt} + \sum_j Br(j \to i) n_j^r$$

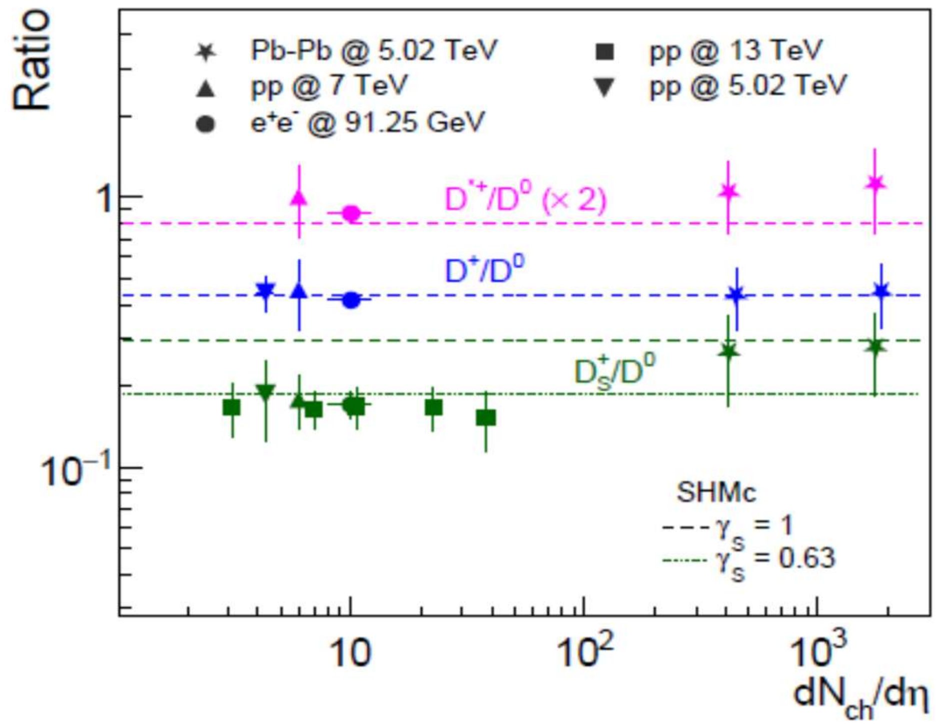
$$n_{c=\pm 1}^{tot} = \sum_k n_{k,c=\pm 1}^{th}$$

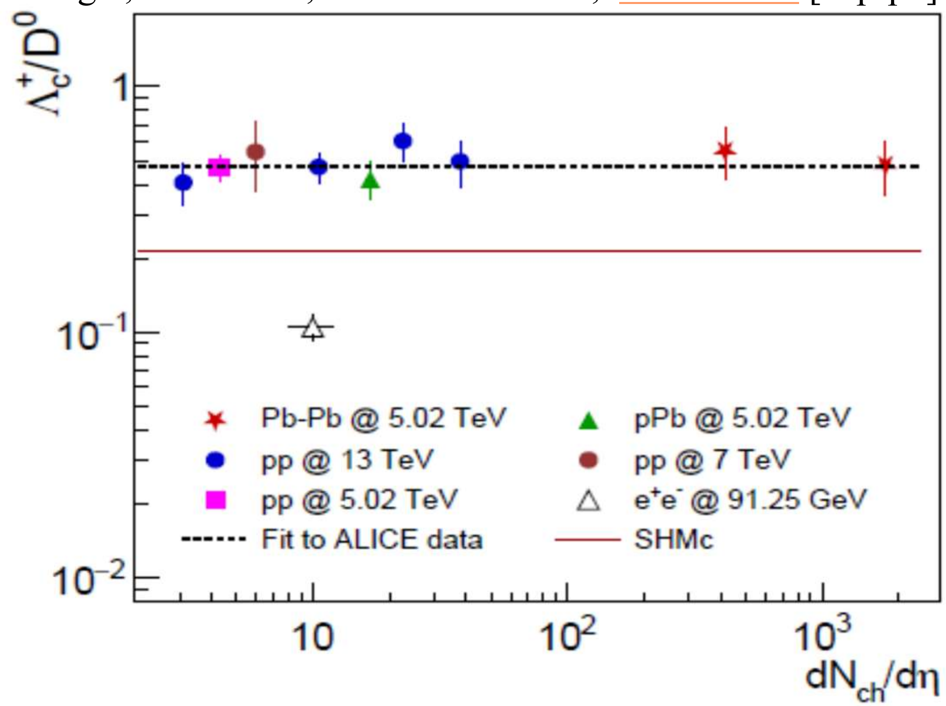
is fully determined by Ncc (from experiment or model) and the temperature, which at high energy collisions $T = T_c = 156.5$ MeV. Yield is independent of the colliding systems i.e. pp, pA and AA and collision centrality.

Basic properties for different open charm yield ratios

$N_{i,c=\pm1} / N_{k,c=\pm1} = n_i^{th}(T) / n_k^{th}(T)$ Ratios entirely determined by T

P. Braun-Munzinger, N. Sharma, J. Stachel &K.R., 2408.07496 [hep-ph]





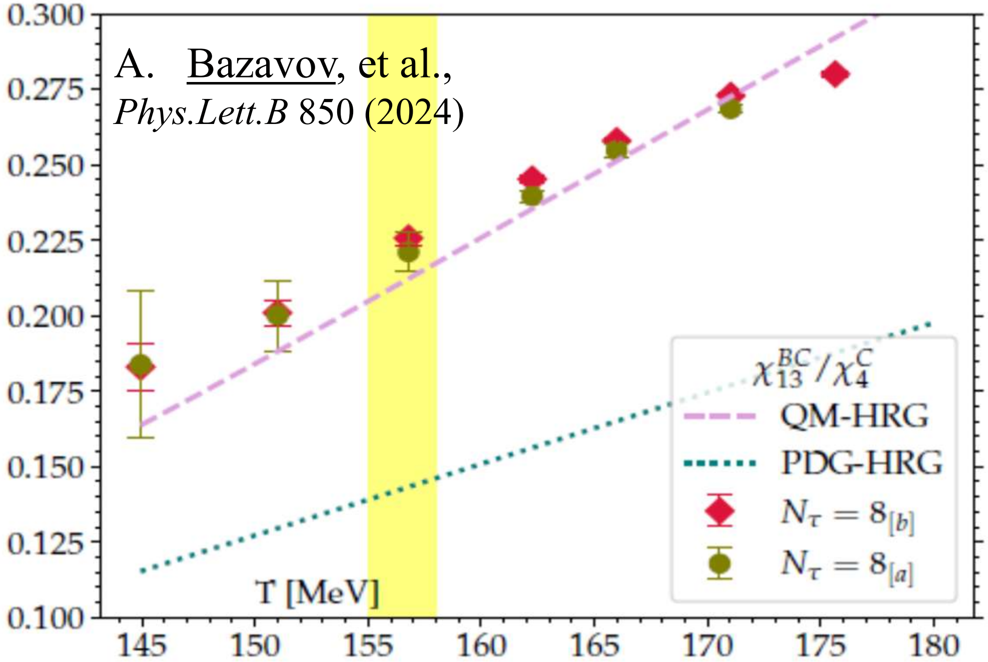
Ratios in pp, pA and AA collisions are within uncertainties the same and independent of associated charged particle pseudo-rapidity density, as expected in SHM.

An increase of D_s^+ / D^0 from pp to AA is possible and needs more data.

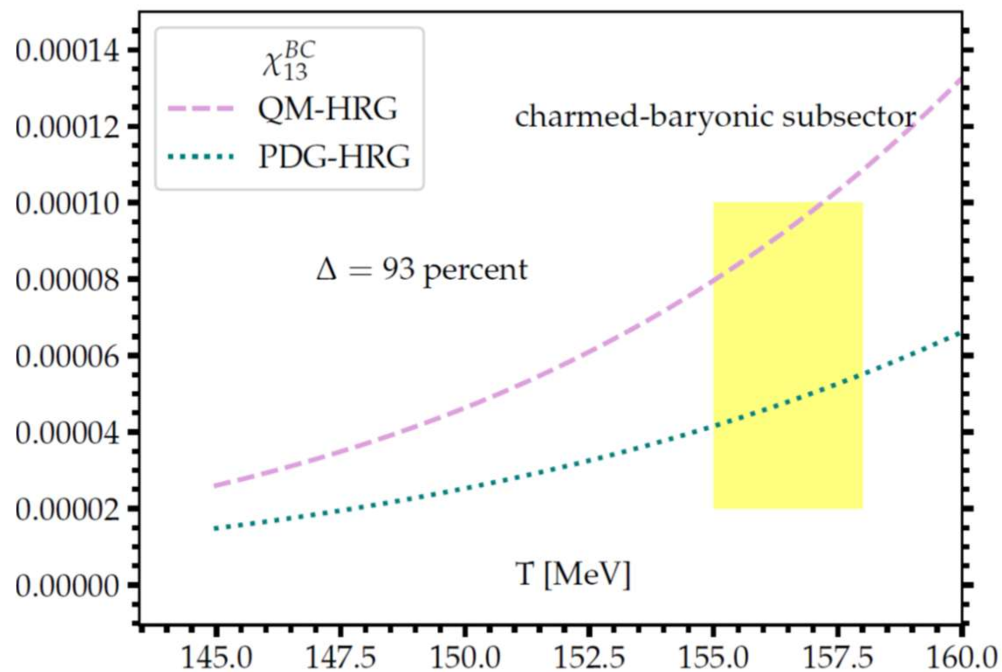
Quantitative agreement of $D^{*+}$and D^+ to D^0 ratios with SHMc, however suppression of D_s^+ / D^0 from AA to pp. Λ_c / D^0 Larger by a factor 2.2 ± 0.15 than SHMc =>

Missing baryonic resonanses in charm sector

Charm fluctuations calculated in the framework of Lattice QCD receive enhanced contributions relative to PDG due the existence of not-yet-discovered open-charm states



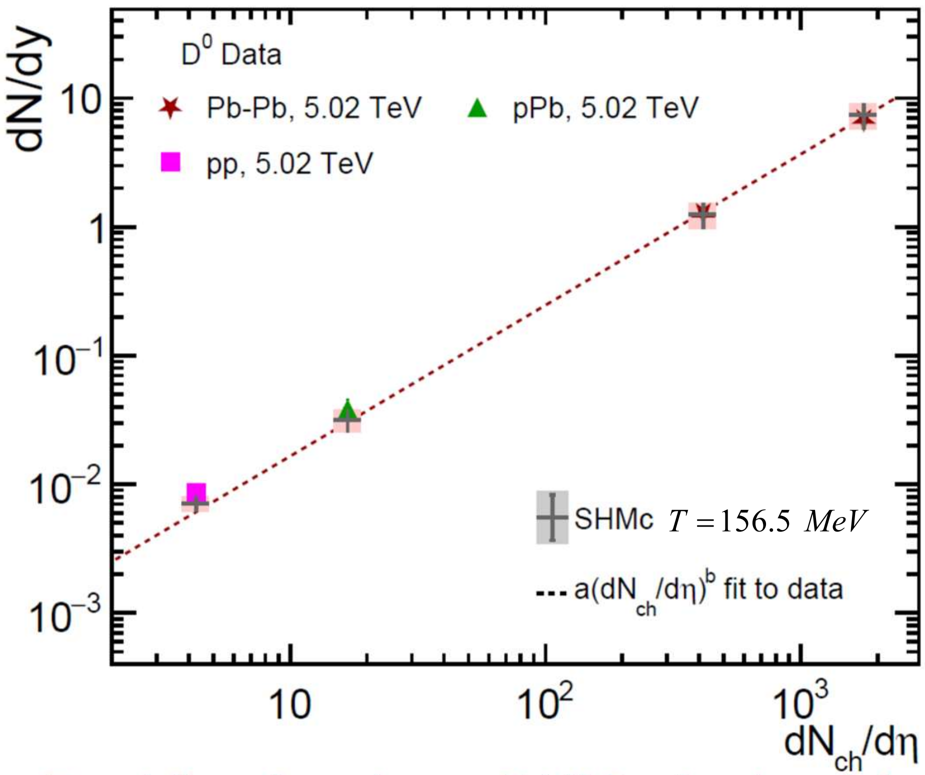
Sipaz Sharma, F. Karsch, P. Petreczky J.Sub. Part.Cos. 3 (2025)



Charm baryon susceptibilities are better described by the quark model of hadrons which indicates an increase of charm baryonic resonances relative to PDG at Tc by a factor >1.9. We include this missing states by rescaling Λ_c density by 2.2.

Quantifying rapidity densities of open charm hadrons

P. Braun-Munzinger, N. Sharma, J. Stachel &K.R., 2408.07496 [hep-ph]



$$\frac{dN_{i,c=\pm1}}{dy} \simeq 2\frac{n_i^{th}(T)}{n_{oc,1}^{tot}(T)} N_{cc}$$

$$N_{cc} = \begin{cases} \sigma_{cc}^{pp} / \sigma_{inel}^{pp} & \text{in pp} \\ \sigma_{cc}^{pA} / \sigma_{inel}^{pA} & \text{in pA} \\ \alpha_A \sigma_{cc}^{pp} T_{AA} & \text{in AA} \end{cases}$$

Cross sections from data: T=156.5 MeV

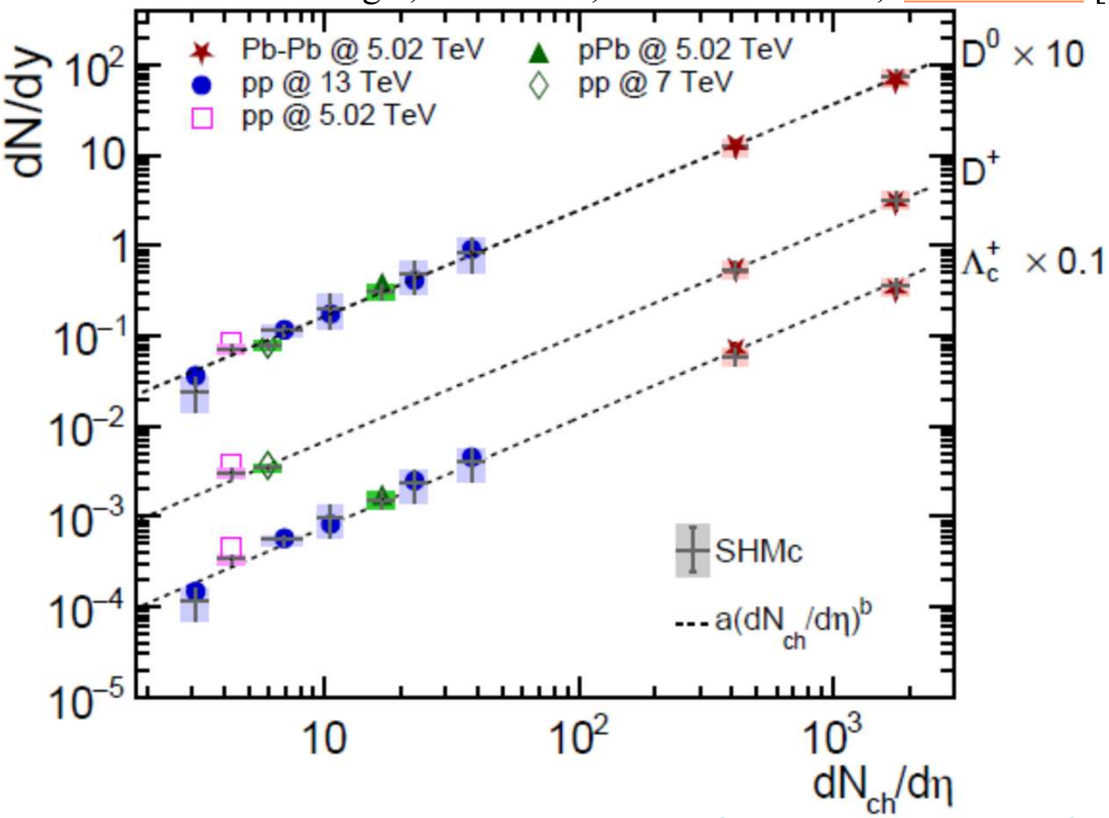
Thickness function from Glauber model.

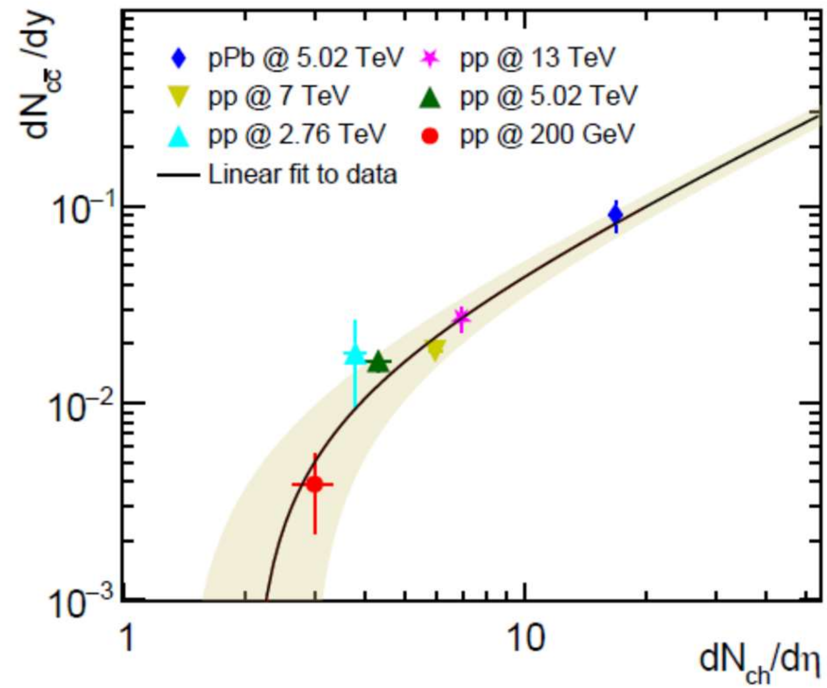
Factor α_A accounts for nuclear modification effects such as shadowing, energy loss or saturation.

- Rapidity density at RHIC obtained from the fit to p_t with Tsallis function
- SHMc provides consistent description of data from pp, pA and AA
- Data at LHC exhibit power law scaling: $dN/dy = a(dN_{ch}/d\eta)^b$ with $b = 1.2 \pm 0.02$ and $a = (1.1 \pm 0.1) \times 10^{-3}$ At RHIC data consistent $b \approx 1.2$ and $a = 3.8 \times 10^{-4}$.

Including predictions for pp at different N_{ch}

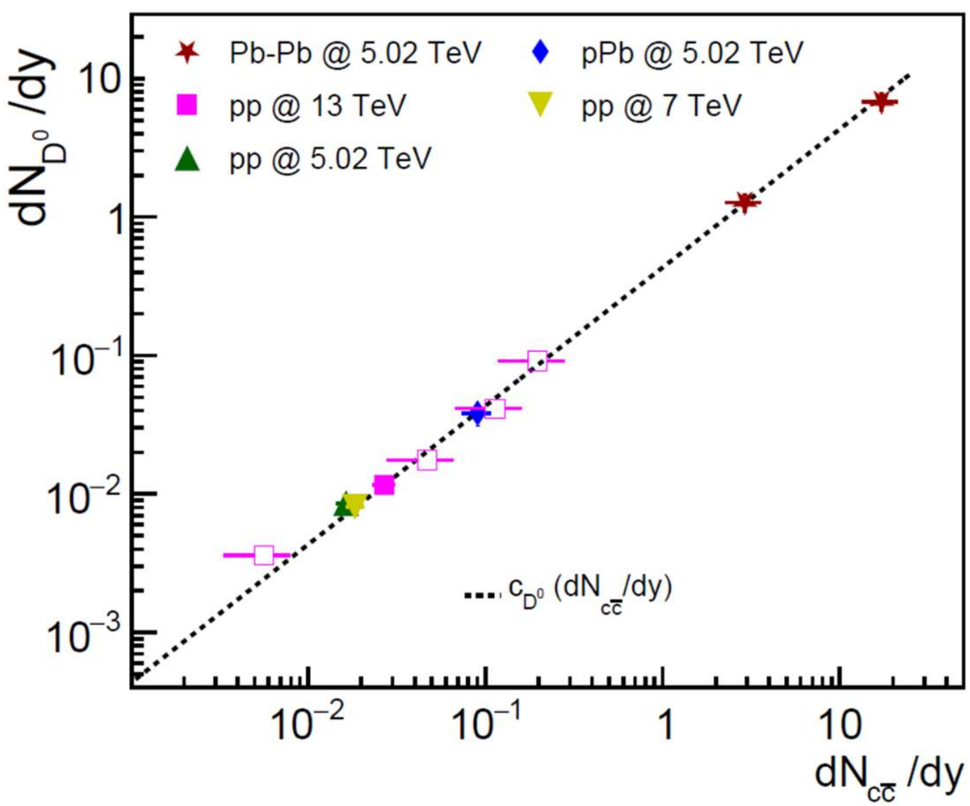
P. Braun-Munzinger, N. Sharma, J. Stachel &K.R., 2408.07496 [hep-ph]

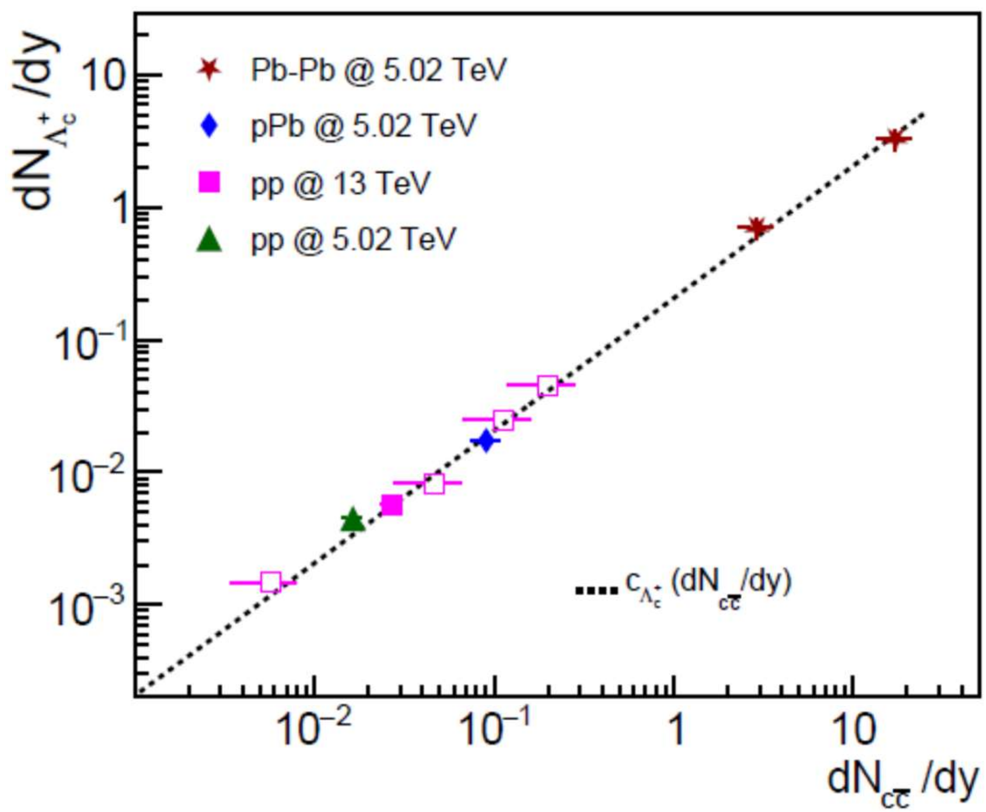




- In a narrow rapidity window Ncc fitted with a linear function of N_{ch}. This allows to extract experimentally unknown values of N_{cc} at $N_{ch} = 3.1,\ 10.5,\ 22.6,\ 37.8$ where D^0 and Λ_c were measured in pp collisions at $\sqrt{s_{NN}} = 13$ TeV .
- All data follow the observed power law scaling with N_{ch}. The yields are also well quantified by the SHMc.

Charm quarks fragmentation/hadronization in the SHMc





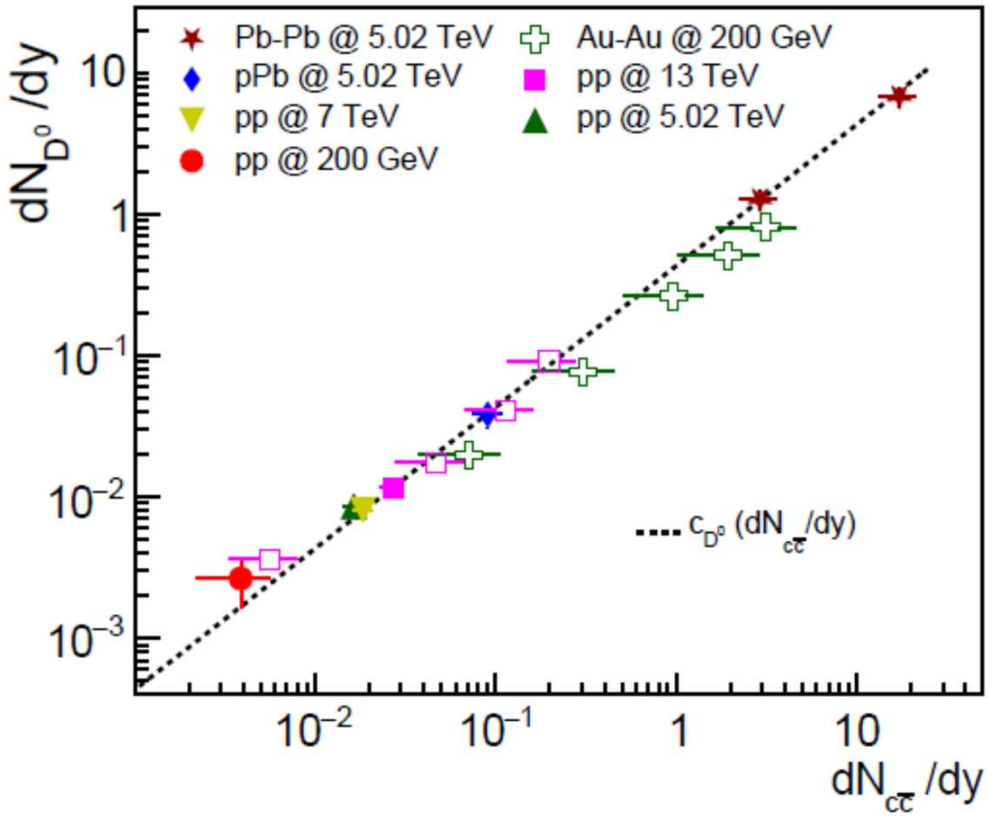
- In SHMc the rapidity density of open charm hadrons in high energy pp, pA and AA collisions should closely follow the proportional scaling with rapidity density of the number of cc pairs:

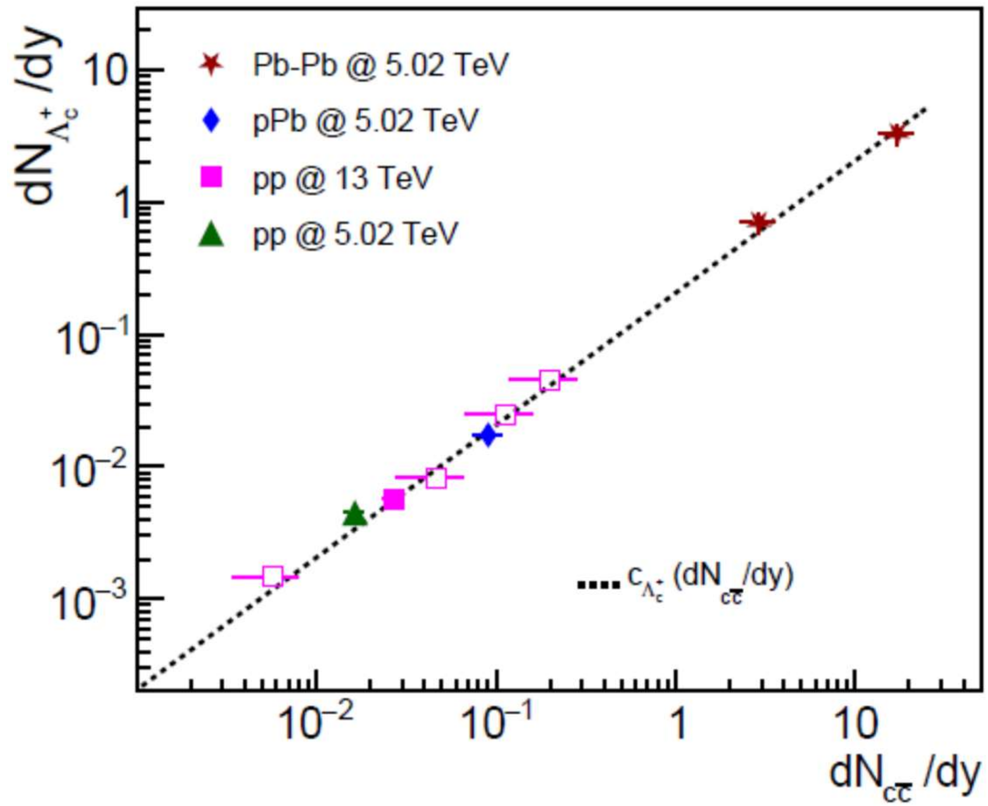
$$\frac{dN_{i,c=\pm1}}{dy} \simeq 2\frac{n_i^{th}(T)}{n_{oc,1}^{tot}(T)} N_{cc} \rightarrow T = 156.5 MeV \rightarrow \frac{dN_{i,c=\pm1}}{dy} = \begin{cases} 0.43 \times N_{cc} & for \quad D^0 \\ 0.21 \times N_{cc} & for \quad \Lambda_c^+ \end{cases}$$

- Data follow SHMc model expectations indicating that it provides a good description of charm fragmentation/hadronization in high energy collisions.

Charm quarks fragmentation/hadronization in the SHMc

P. Braun-Munzinger, N. Sharma, J. Stachel &K.R., 2408.07496 [hep-ph]





- In SHMc the rapidity density of open charm hadrons in high energy pp, pA and AA collisions should closely follow the proportional scaling with rapididy density of the number of cc pairs:

$$\frac{dN_{i,c=\pm1}}{dy} \simeq 2\,\frac{n_i^{th}(T)}{n_{oc,1}^{tot}(T)} N_{cc} \rightarrow T = 156.5 MeV \rightarrow \frac{dN_{i,c=\pm1}}{dy} = \begin{cases} 0.43\times N_{cc} \quad for \quad D^0 \\ 0.21\times N_{cc} \quad for \quad \Lambda_c^+ \end{cases}$$

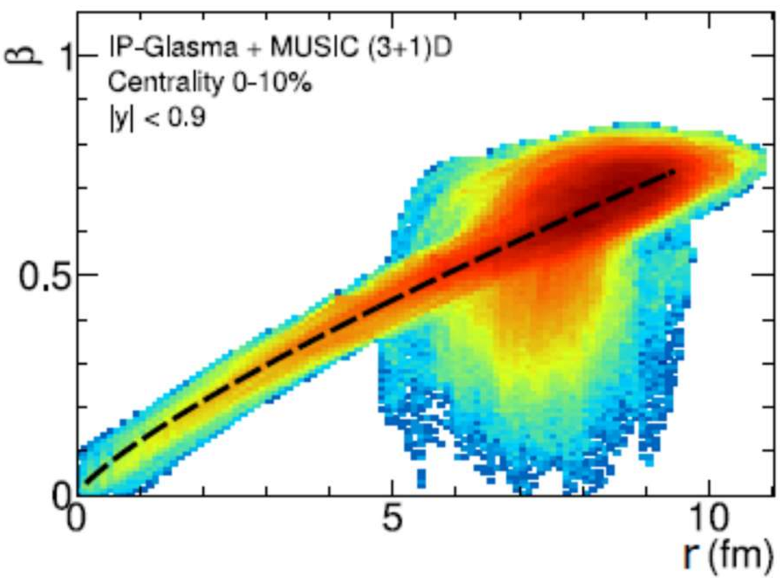
- Data follow SHMc model expectations indicating that it provides a good description of charm fragmentation/hadronization in high energy collisions.

Spectra of charm hadrons established at QCD phase boundary

- Charm quarks in QGP follow collective flow and are hadronized at Tc=156.5 MeV
- Use blast-wave parametrization of particle spectra with the input from 3+1 dim hydrodynamics

A. Andronic, P. Braun-Munzinger, M. Koehler, A. Mazeliauskas, K. Redlich J. Stachel, V. Vislavicius, JHEP 07 (2021) 035

A. Andronic, P. Braun-Munzinger, M. Koehler, K. Redlich J. Stachel, PLB 797 (2019) 134836



Radial velocity profile on the freezeout surface of central Pb-Pb coll.

$$\frac{d^2N}{2\pi p_T dp_T dy} = \frac{2J+1}{(2\pi)^3}\int d\sigma_\mu p^\mu f(p)$$

For boost-inv. and azimuthally sym. freezeout surface

$$= \frac{2J+1}{(2\pi)^3}\int_0^{r_{\max}} dr\ \tau(r) r \left[K_1^{eq}(p_T, u^r) - \frac{\partial\tau}{\partial r}K_2^{eq}(p_T, u^r)\right]$$

the freezeout kernels: $K_1^{eq}(p_T, u^r) = 4\pi m_T I_0\left(\frac{p_T u^r}{T}\right) K_1\left(\frac{m_T u^\tau}{T}\right)$

$$K_2^{eq}(p_T, u^r) = 4\pi p_T I_1\left(\frac{p_T u^r}{T}\right) K_0\left(\frac{m_T u^\tau}{T}\right).$$

with freezeout hypersurface $\tau(r) = r_{\max} + \frac{r\beta(r)}{n+1}$

velocity $u^r = \beta(r)/\sqrt{1-\beta^2(r)}$

$r_{\max}$: fixed to reproduce extracted volume at freezeout

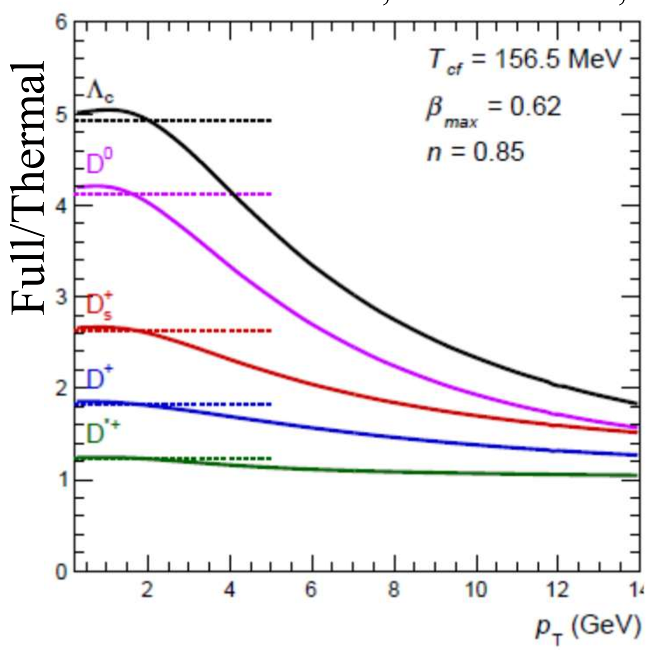
$$\beta(r) = \beta_{\max}(r/r_{\max})^n$$

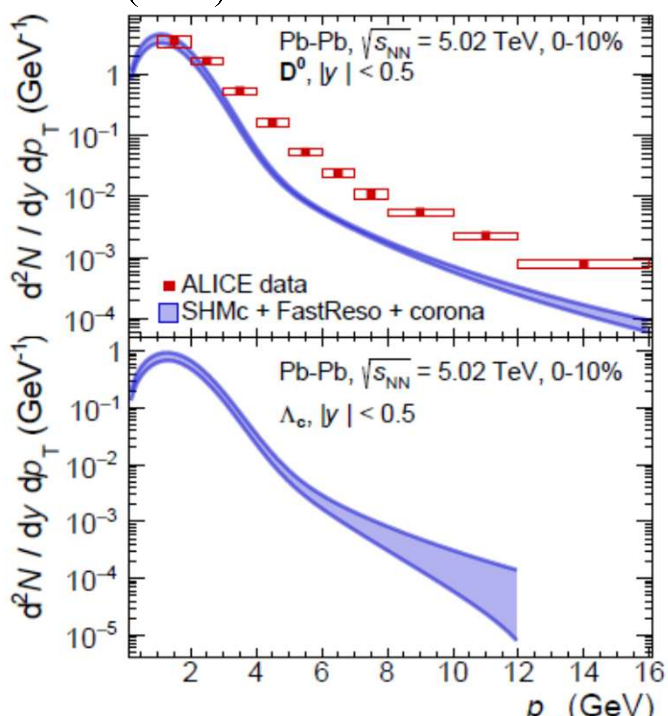
Use hydro velocity profile at Tc from MUSIC (3+1) D to fit: $\beta_{\max} = 0.62,\quad n = 0.85$ for central coll.

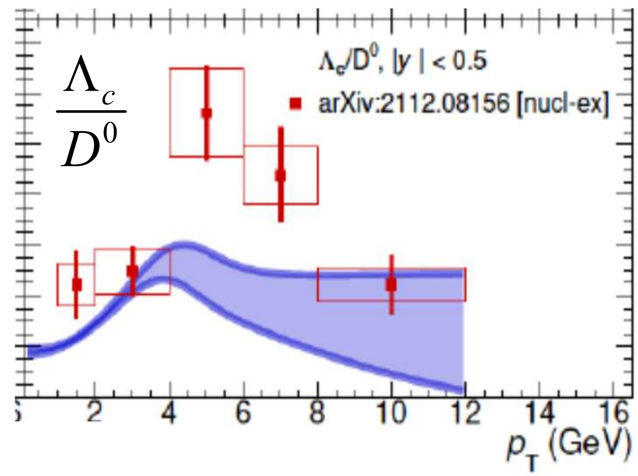
Spectra of open charm mesons and baryons

- The final spectra of open charm hadrons required proper determination of resonance contributions
- Including all known charm hadron resonances summarized in PDG the decay spectra for D0 and Lambda_c were computed with an efficient FastReso algorithm accounting of 76 2-body and 10 3-body decays based on A. Mazeliauskas, S. Floerchinger, E. Grossi, EPJ C79 (2019) 284

A. Andronic, P. Braun-Munzinger, M. Koehler, A. Mazeliauskas,
K. Redlich J. Stachel, V. Vislavicius, JHEP 07 (2021) 035



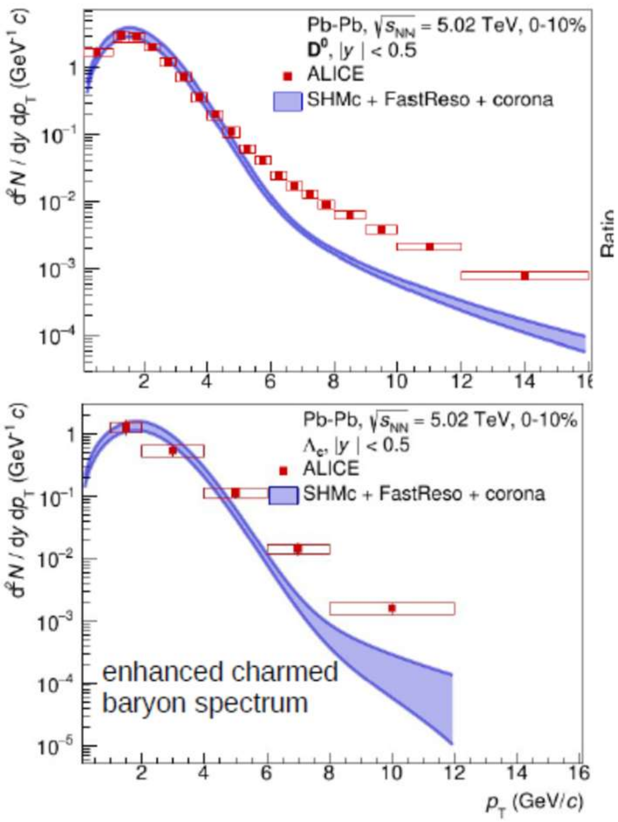


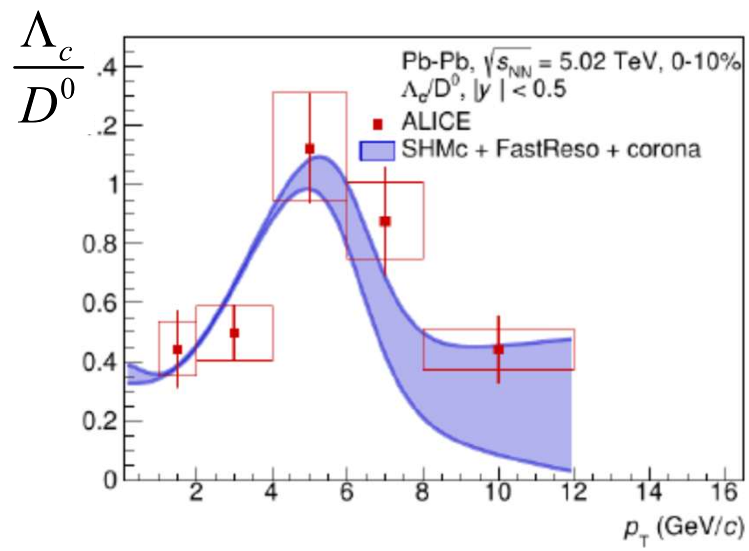


- Very good description of soft part of D0 spectra in SHMc+hydro+FastReso decay within PDG
- Too low strength for Lambda_c: However missing baryon resonances not yet included

Open charm spectra: with more complete description of freezeout conditions from 3D hydro

A. Andronic, P. Braun-Munzinger, J. Brunßen, J. Crkovska, J. Stachel, V. Vislavicius, M. Völkl, arXiv: 2308.14821, HEP (2024)



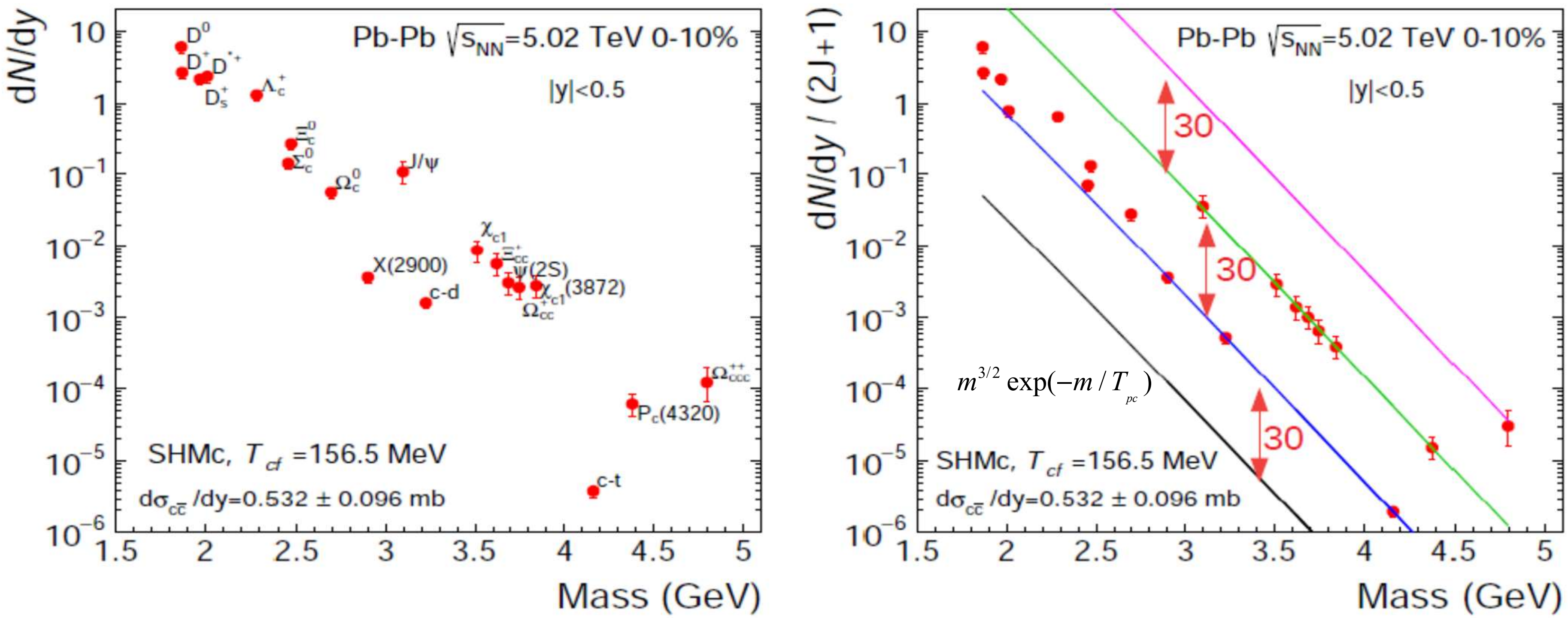


- Maximum in ratio appears due to transverse expansion and mass difference between particles

- With optimally matched blast wave parameters to MUSIC hydro and including contributions of missing baryonic resonances in charm sector a very good description of low and intermediate p_t spectra is reached.

SHMc predictions for different charm states

A. Andronic, P. Braun-Munzinger, M. Koehler, A. Mazeliauskas, K. Redlich J. Stachel, V. Vislavicius, JHEP 07 (2021) 035



- Within SHMc model we can also make predictions for yet unmeasured charm and multi-charm hadron species and exotic states like e.g. X-state.
- There are also interesting systematics of particle yields and hierarchy, not only with a mass but also with the charm quark content of hadron due to the g_c =30 fugacity factor.

CONCLUSIONS:

- S-matrix (Hadron Resonance Gas) thermodynamic potential provides good approximation of LQCD equation of states and 2^{nd} order fluctuations and correlations
- The QCD thermodynamic potential is encoded in nuclear collisions
- LHC hadron yields data originating from thermal source at T_c=156 MeV and their yields are consistent with LQCD Eqs.
- Strong experimental evidence for charm thermalization in Pb-Pb and parameter free description of charmonium and open charm yields (SHMc) and spectra with the only input of total charm cross section
  - New scaling of open charm data with N_ch and N_cc in pp, pA and AA col. for all energies and centralities predicted by SHMc

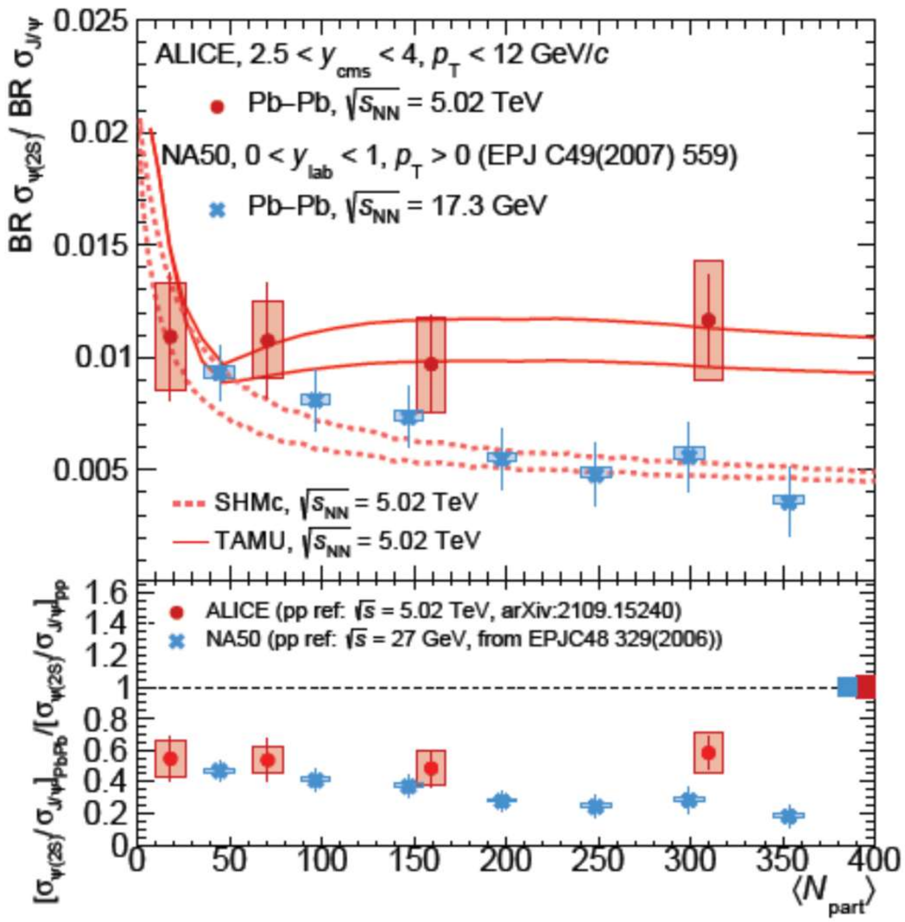
Puzzling and interesting results requiring more data:

- Enhanced production of D_s/D_0 in AA relative to pp collisions
- Psi(2s)/Psi(1s) in central AA at LHC larger than at SPS
- Missing charm-baryon resonances

Answer may come with much increased luminosity in ALICE Run 3 and 4

Unexpected result in the SHMc:

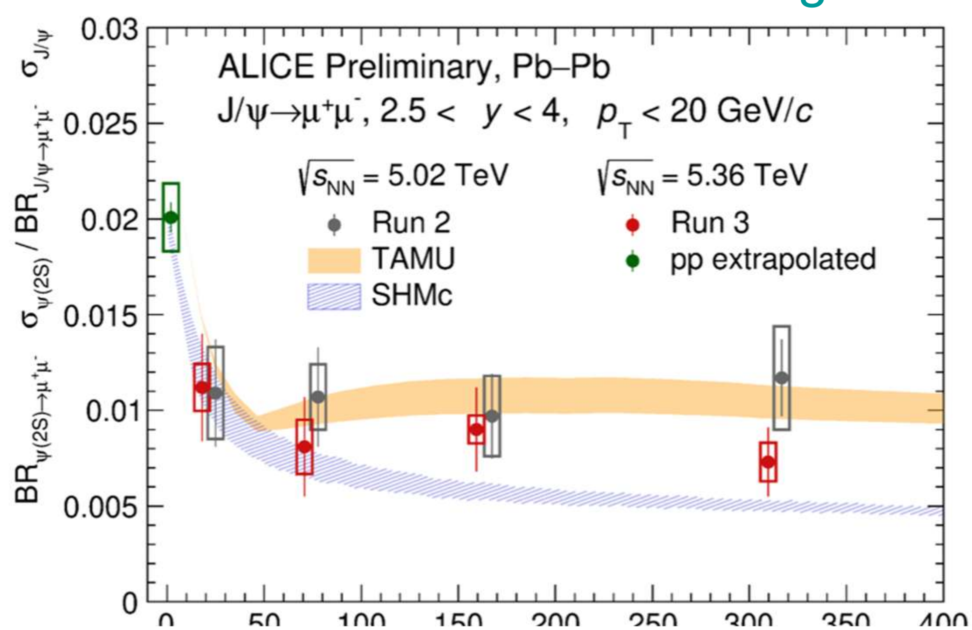
ALICE: Phys.Rev.Lett. 132 (2024) 4, 042301



- Within SHMc and in central collisions the ratio depends only on temperature,

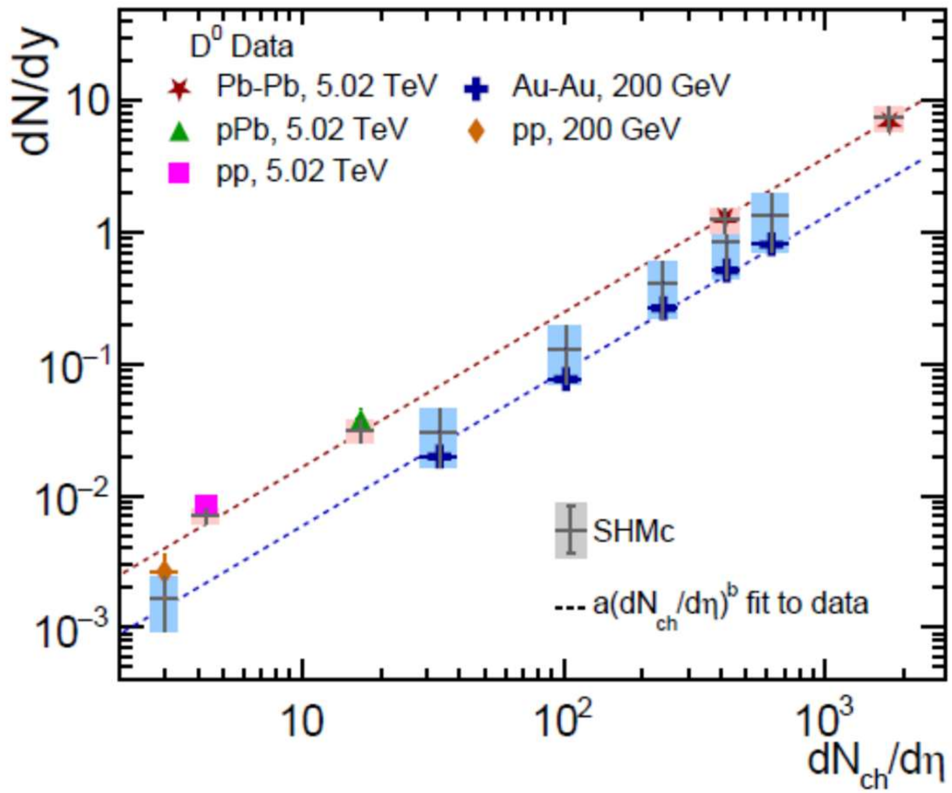
$$\frac{\psi(2s)}{J/\psi} = \frac{n_{\psi(2s)}(T)}{n_{J/\psi}(T)}$$

consequently since freezeout temperature at SPS is similar as in LHC, the ratio should coincide at these energies



Quantifying rapidity densities of open charm hadrons

P. Braun-Munzinger, N. Sharma, J. Stachel &K.R., 2408.07496 [hep-ph]



$$\frac{dN_{i,c=\pm1}}{dy} \simeq 2\frac{n_i^{th}(T)}{n_{oc,1}^{tot}(T)} N_{cc}$$

$$N_{cc} = \begin{cases} \sigma_{cc}^{pp} / \sigma_{inel}^{pp} & \text{in pp} \\ \sigma_{cc}^{pA} / \sigma_{inel}^{pA} & \text{in pA} \\ \alpha_A \sigma_{cc}^{pp} T_{AA} & \text{in AA} \end{cases}$$

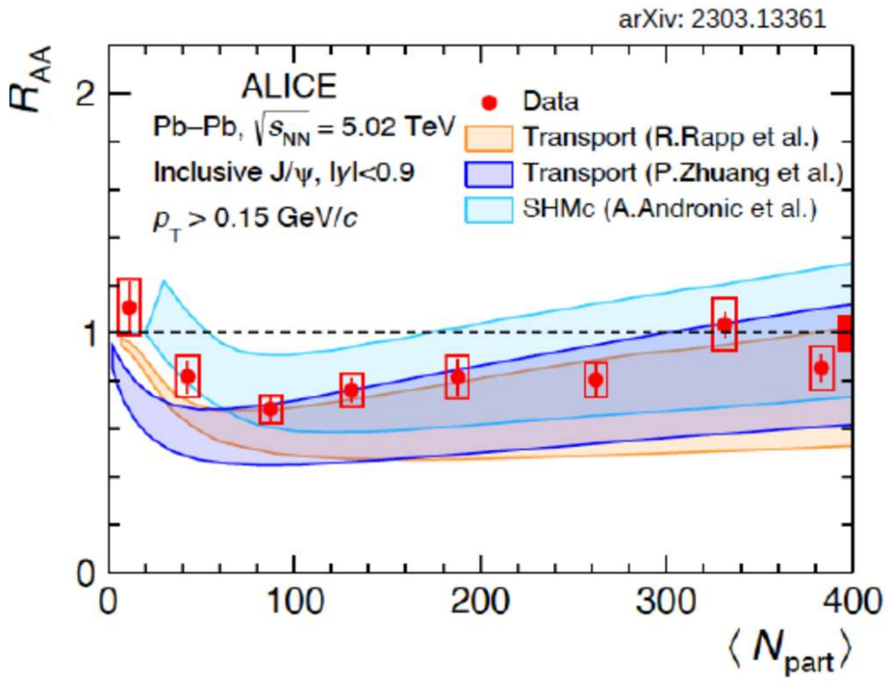
Cross sections from data: T=156.5 MeV

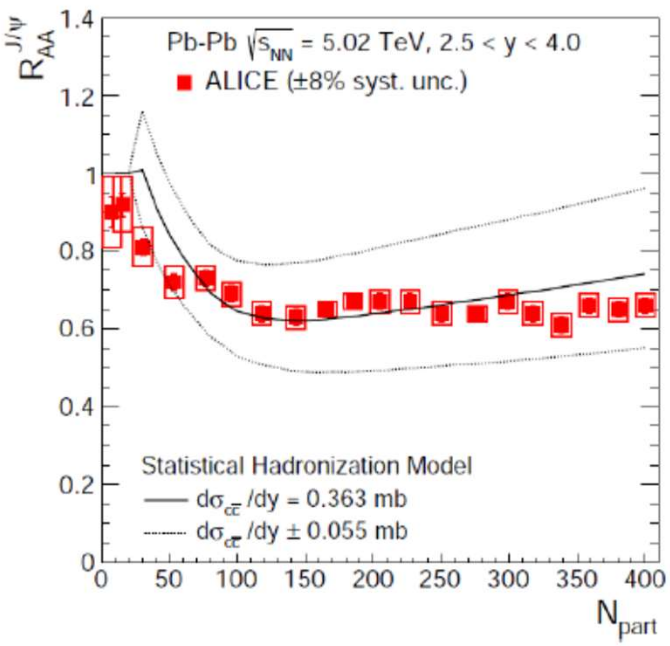
Thickness function from Glauber model.

Factor α_A accounts for nuclear modification effects such as shadowing, energy loss or saturation.

- Rapidity density at RHIC obtained from the fit to p_t with Tsallis function
- SHMc provides consistent description of data from pp, pA and AA
- Data at LHC exhibit power law scaling: $dN/dy = a(dN_{ch}/d\eta)^b$ with $b = 1.2 \pm 0.02$ and $a = (1.1 \pm 0.1)\times 10^{-3}$. At RHIC data consistent $b \approx 1.2$ and $a = 3.8 \times 10^{-4}$.

Model comparison with ALICE data: R_{AA}

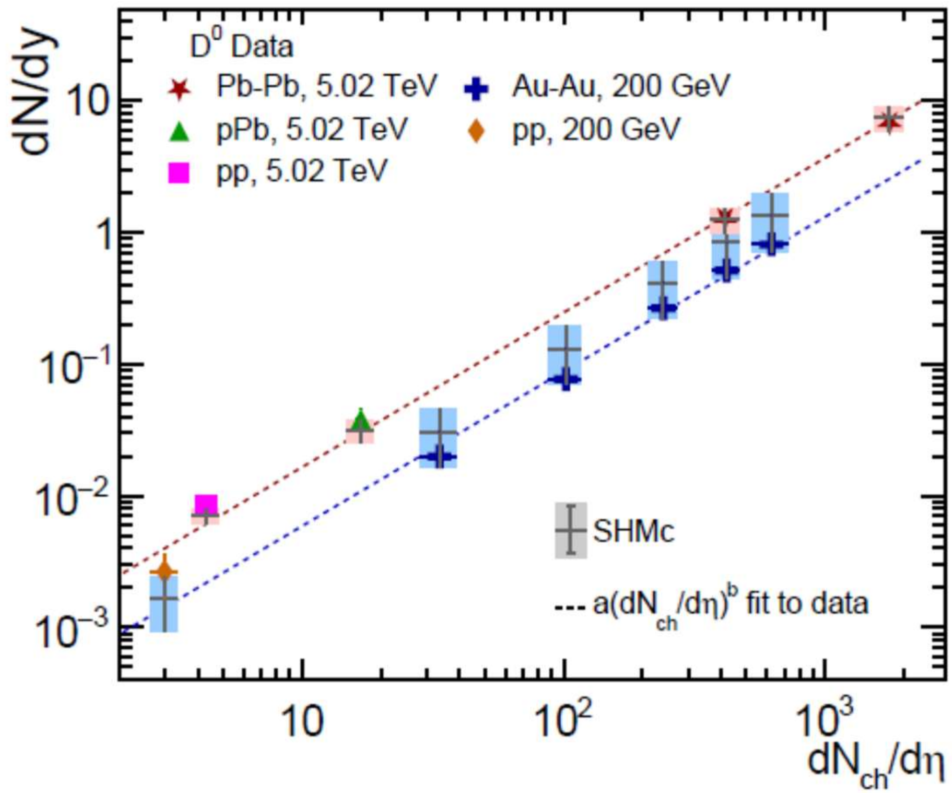




- Production in Pb-Pb collisions consistent with deconfinement in QGP and subsequent hadronization at the phase boundary. The main uncertainty of the model prediction due to open charm cross-section.

Quantifying rapidity densities of open charm hadrons

P. Braun-Munzinger, N. Sharma, J. Stachel &K.R., 2408.07496 [hep-ph]



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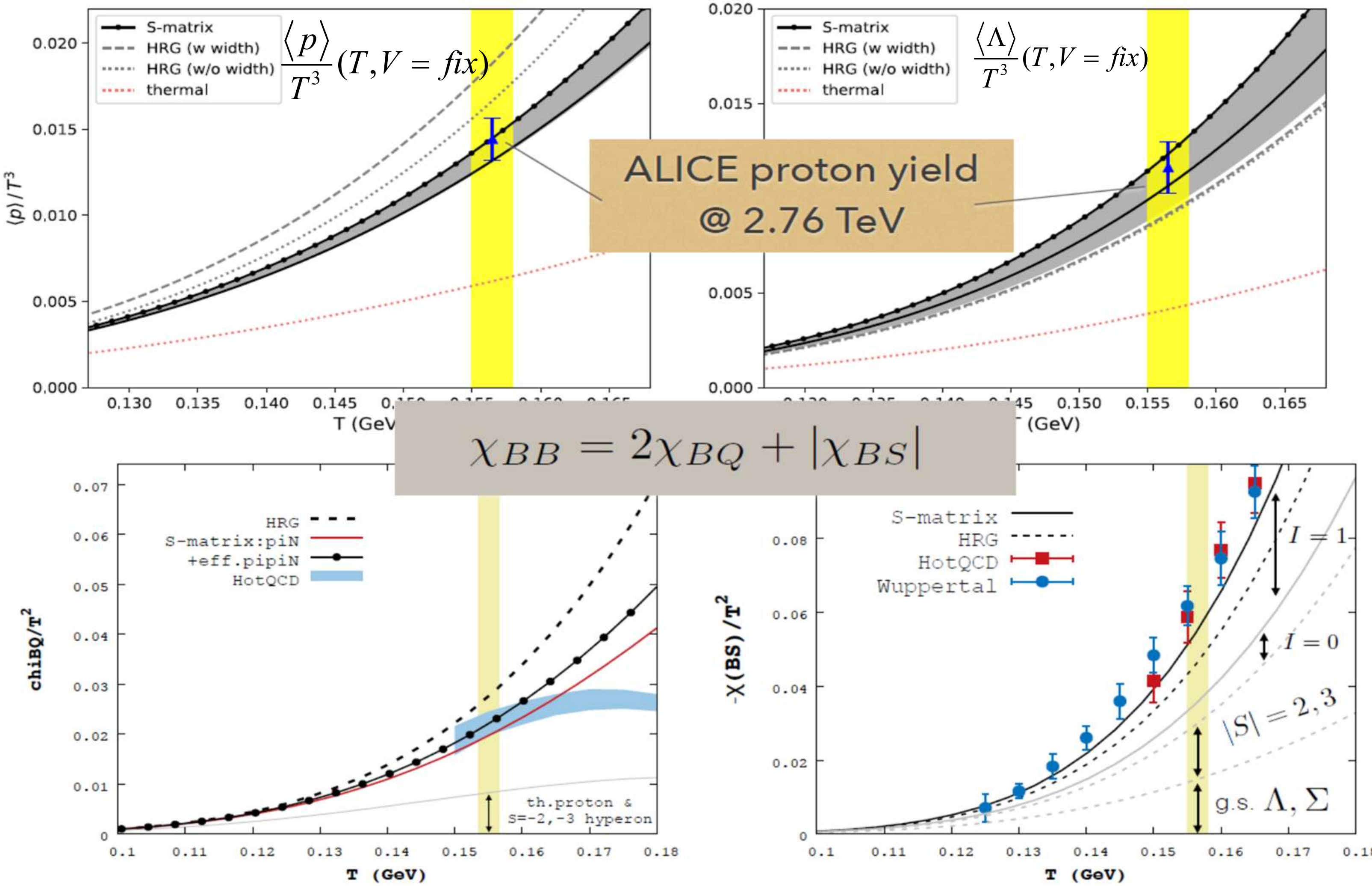
Synergy between LQCD ⇨ S-matrix HRG ⇨ ALICE data

J. Cleymans, Pok Man Lo, N. Sharma & K.R. Phys. Rev. C103 (2021)



S-matrix corrections in thermal model: needed to describe LQCD fluctuations at Tc and simultaneously proton and Lambda yields in central Pb-Pb collisions.