Thermal origin of hadron production in ALICE experiment at LHC

K. Redlich Uni. Wroclaw, Poland

- Modelling equation of state of hadronic phase

  From S-matrix Hadron Resonance Gas

  => LQCD EoS $\Leftrightarrow$ Particle Yields at LHC

- Exact strangeness conservation and hadron production scaling with $dN_{ch}/d\eta$ linked to ALICE data
- Charm hadron production probing QCD phase boundary (SHMc)
- Emergence of New Systematics for Open Charm Production in High Energy Collisions

Joint work with: A. Andronic, P. Braun-Munzinger, N. Sharma, J. Stachel, et. al.

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

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

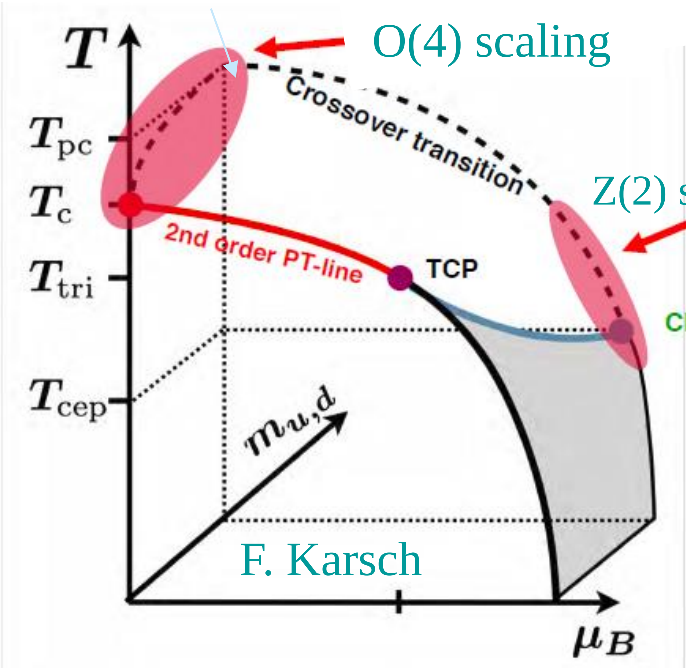
P. Braun-Munzinger, B. Friman, A. Rustamov, J. Stachel & K.R. Nucl. Phys. A 1008 (2021)

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

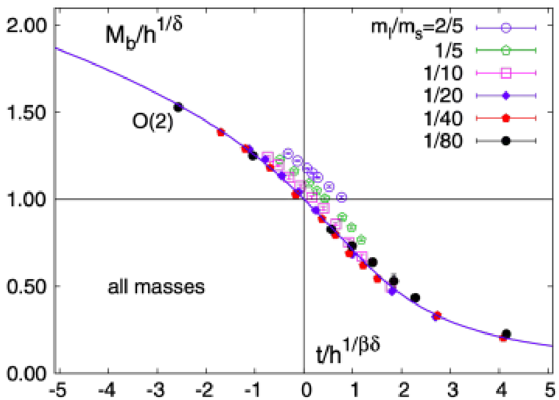
A. Andronic, P. Braun-Munzinger, Pok Man Lo, B. Friman, J. Stachel & K.R Phys. Lett. B 792 (2019)

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

Linking LHC AA yields data with LQCD



F. Karsch



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

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

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

- Direct delineation of chiral symmetry restoration via higher order cumulants

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

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

$$\chi_S^{(n)}\big|_{\mu\neq0} \approx h^{(2-\alpha-n)/\beta\delta}$$

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))

M. Asakawa, K. Yazaki Nucl.Phys.A 504 (1989) 668

Modelling $P^{s-gular}(T,\mu_B)$ in the O(4)/Z(2) universality class

Gabor Almasi, Bengt Friman & K.R., Phys. Rev. D96 (2017) no.1, 014027

$$\mathcal{L} = \bar{q}\left(i\gamma^\mu D_\mu - g(\sigma + i\gamma_5\vec{\tau}\vec{\pi}) - g_\omega\gamma^\mu\omega_\mu\right)q + \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\vec{\pi})^2 - U_m(\sigma,\vec{\pi}) - \mathcal{U}(\Phi,\bar{\Phi};T) - \frac{1}{2}m_\omega^2\omega^2 + \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Effective potential is obtained by solving *the exact flow equation* (Wetterich eq.) with the approximations resulting in the O(4)/Z(2) critical exponents

$$\partial_k\Omega_k(\sigma) = \frac{Vk^4}{12\pi^2}\left[\sum_{i=\pi,\sigma}\frac{d_i}{E_{i,k}}[1+2n_B(E_{i,k})] - \frac{2\nu_q}{E_{q,k}}[1-n_F(E^+_{q,k})-n_F(E^-_{q,k})]\right]$$

Full propagators with k < q < □

$$E_{\pi,k} = \sqrt{k^2+\Omega'_k}$$

$$E_{\sigma,k} = \sqrt{k^2+\Omega'_k+2\rho\Omega''_k}$$

$$E_{q,k} = \sqrt{k^2+2g^2\rho}$$

$$\Omega'_k \equiv \frac{\partial\Omega_k}{\partial(\sigma^2/2)}$$

□□□S classical

Integrating from k=□ to k=□ gives full quantum effective potential

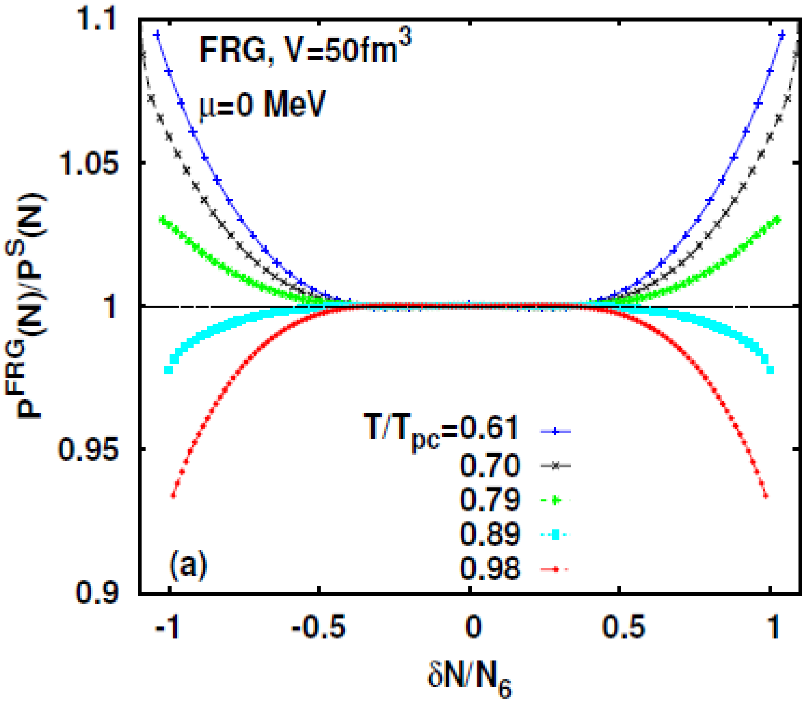
B. Friman & K. Morita, K.R., *Phys.Lett.B* 741 (2015) 178

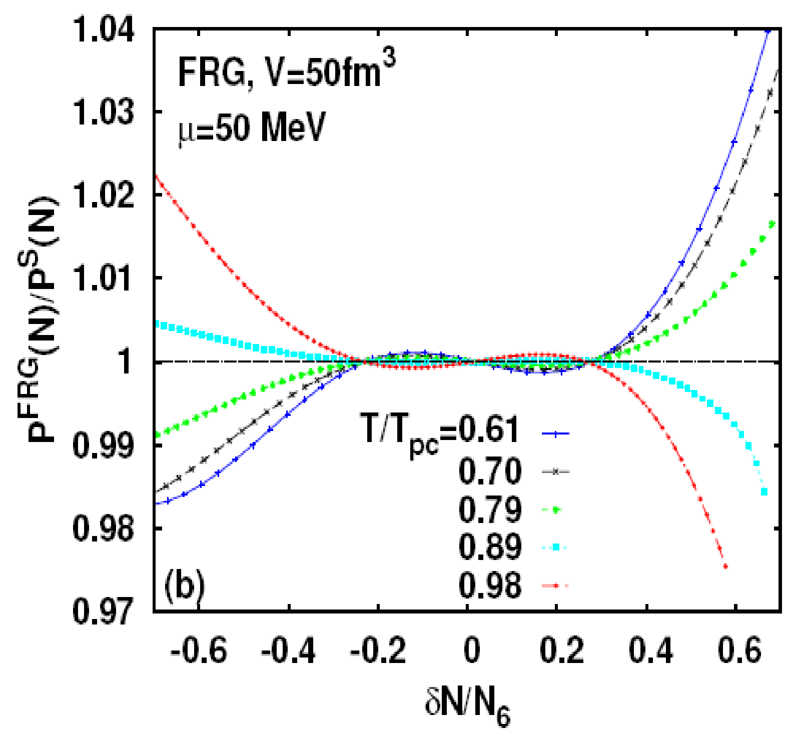
Probability distribution of the net-baryon number near chiral crossover normalized to Skellam function

K. Morita, B. Friman and K.R.
Phys.Lett. B741 (2015) 178

- Probability distribution of net charge N

$$P(N) = \frac{Z^C(T,V,N)e^{\mu N/T}}{Z^{GC}(T,V,\mu)}$$





Skellam distribution provides good approximation of P(N) to reproduce variance of the net-baryon number fluctuations. This is however not the case for higher order cumulants which are sensitive to O(4) criticality.

Special case: the Skellam distribution

- Charge $\mathrm{P}(N_q)$ and anti-charge $\mathrm{P}(N_{\bar{q}})$ Poisson distributed, then for $N = N_q - N_{\bar{q}}$
- $\mathrm{P}(N)$ is the Skellam distribution

$$\mathrm{P}(N) = \left(\frac{< N_q >}{< N_{-q} >} \right)^{N/2} I_N(2\sqrt{< N_q >< N_{-q} >}) \exp[-(< N_q > + < N_{-q} >)]$$

- Then, the susceptibility $\chi_N = \frac{1}{VT^3} \sigma_N^2$

$$\chi_N = \frac{1}{VT^3} (< N_q > + < N_{-q} >)$$

$$\chi_N = \frac{\partial^2 (P)}{\partial (\mu_N)^2}$$

expressed by yields of particles and antiparticles carrying the conserved charge $q = \pm 1$

$$< N_q > = \sum_i < N_q^i > \qquad < N_{\bar{q}} > = \sum_i < N_{\bar{q}}^i >$$

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

Skellam distribution provides reasonable Description of measured 2nd order cumulants of net-proton fluctuations in HIC at LHC and the top RHIC energies

Constructing net charge fluctuations and correlation from ALICE data

$$\chi_Q^{lQCD} \approx \frac{1}{VT^3}\left(\langle N_q\rangle + \langle N_{-q}\rangle\right)^{\exp}$$

P. Braun-Munzinger, A. Kalweit, J. Stachel, & K.R. Phys. Lett. B747, 292 (2015) with update.

- Net baryon number susceptibility

$$\chi_B \approx \frac{1}{VT^3}\left(\langle p\rangle + \langle N\rangle + \langle \Lambda + \Sigma_0\rangle + \langle \Sigma^+\rangle + \langle \Sigma^-\rangle + \langle \Xi^-\rangle + \langle \Xi^0\rangle + \langle \Omega^-\rangle + \overline{par}\ \right)$$

- Net strangeness

$$\chi_S \approx \frac{1}{VT^3}\Big(\langle K^+\rangle + \langle K_S^0\rangle + \langle \Lambda + \Sigma_0\rangle + \langle \Sigma^+\rangle + \langle \Sigma^-\rangle + 4\langle \Xi^-\rangle + 4\langle \Xi^0\rangle + 9\langle \Omega^-\rangle + \overline{par}$$

$$-(\Gamma_{\varphi\to K^+} + \Gamma_{\varphi\to K^-} + \Gamma_{\varphi\to K_S^0} + \Gamma_{\varphi\to K_L^0})\langle \varphi\rangle\ \Big)$$

- Charge-strangeness correlation

$$\chi_{QS} \approx \frac{1}{VT^3}\Big(\langle K^+\rangle + 2\langle \Xi^-\rangle + 3\langle \Omega^-\rangle + \overline{par}$$

$$-(\Gamma_{\varphi\to K^+} + \Gamma_{\varphi\to K^-})\langle \varphi\rangle - (\Gamma_{K_0^*\to K^+} + \Gamma_{K_0^*\to K^-})\langle K_0^*\rangle\ \Big)$$

Direct comparison of Heavy ion data at LHC with LQCD

χ_{NM} with $N,M=\{B,Q,S\}$ are expressed by particle yields:

- Is there a common temperature where all 2nd order cumulants constructed from ALICE data agree with LQCD result?

LQCD From ALICE DATA

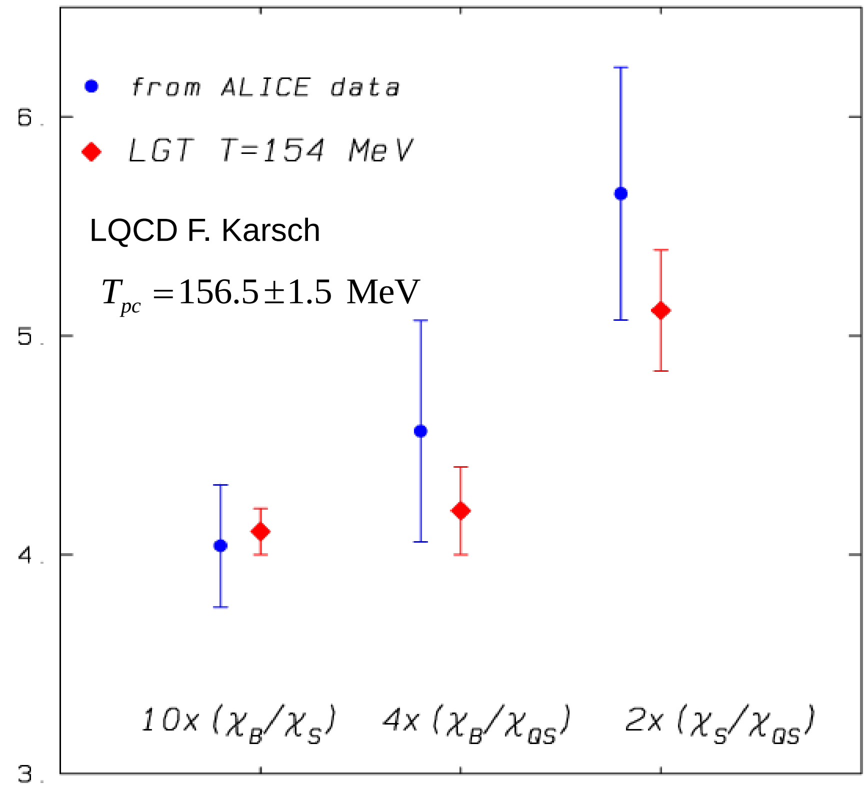
$$\chi_B = \frac{1}{VT^3}(203.7 \pm 11.4)$$

$$\chi_S = \frac{1}{VT^3}(504.2 \pm 16.8)$$

$$\chi_{QS} = \frac{1}{VT^3}(191.1 \pm 12)$$

- The Volume at $T \approx 154\ MeV$

$$V_{T_f} = 3800 \pm 500\ \ fm^3$$



The 2nd cumulant ratios extracted from ALICE data are consistent with LQCD results at

$$T_f = 154 \pm 6\ \text{MeV}$$

Evidence for thermalization and saturation of the 2nd order fluctuations near the QCD phase boundary

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

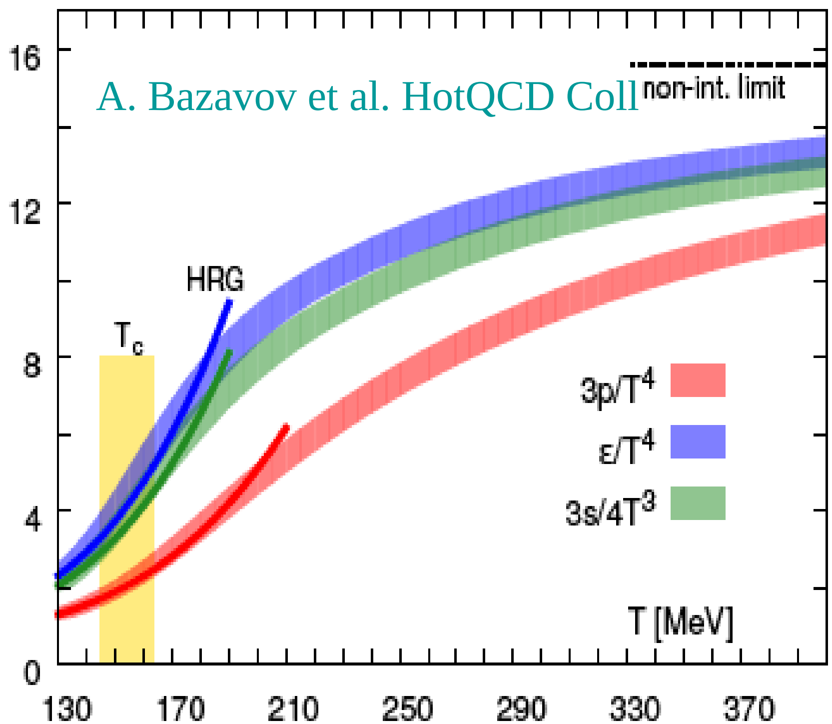
Quark-Hadron duality near the QCD phase boundary

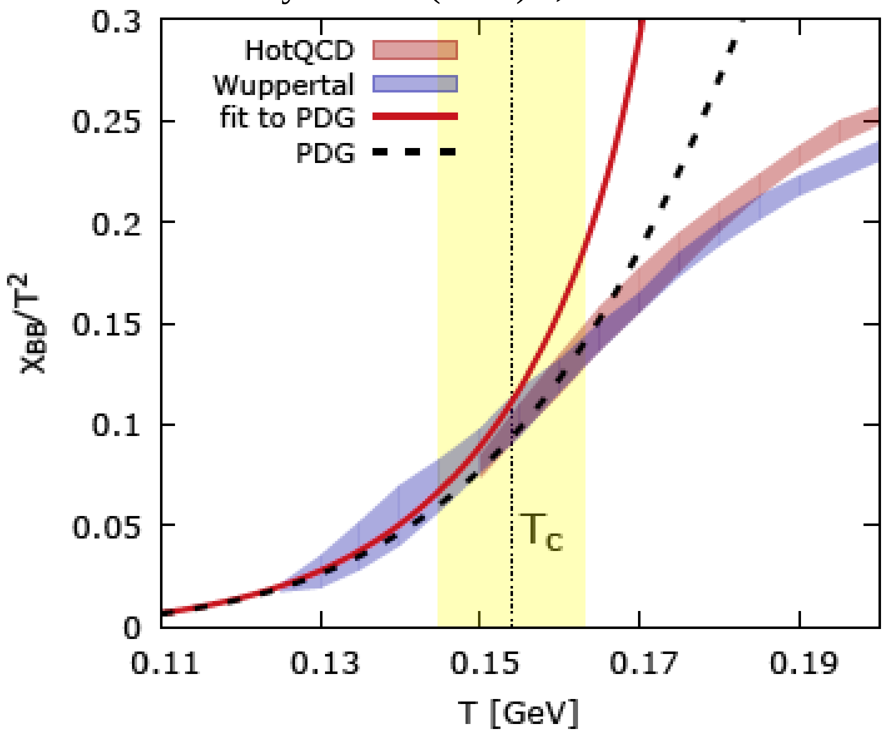
$$P(T,\vec{\mu}) \approx \sum_H P_H^{id} + \sum_R P_R^i$$

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

J. Goswami, et al., 2011.02812 [hep-lat]
R. Bellwied, et al. 2102.06625 [hep-lat]
S. Borsányi, et. al 2102.06660 [hep-lat]

Pok Man Lo, M. Marczenko et. al.
Eur.Phys.J.A 52 (2016) 8, 235

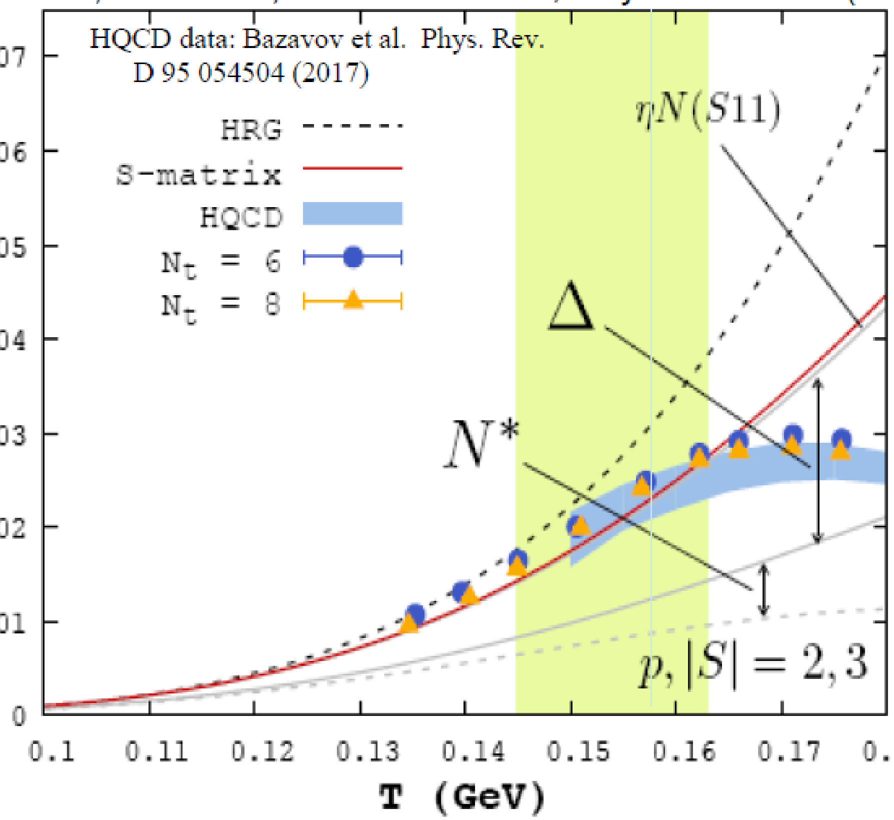




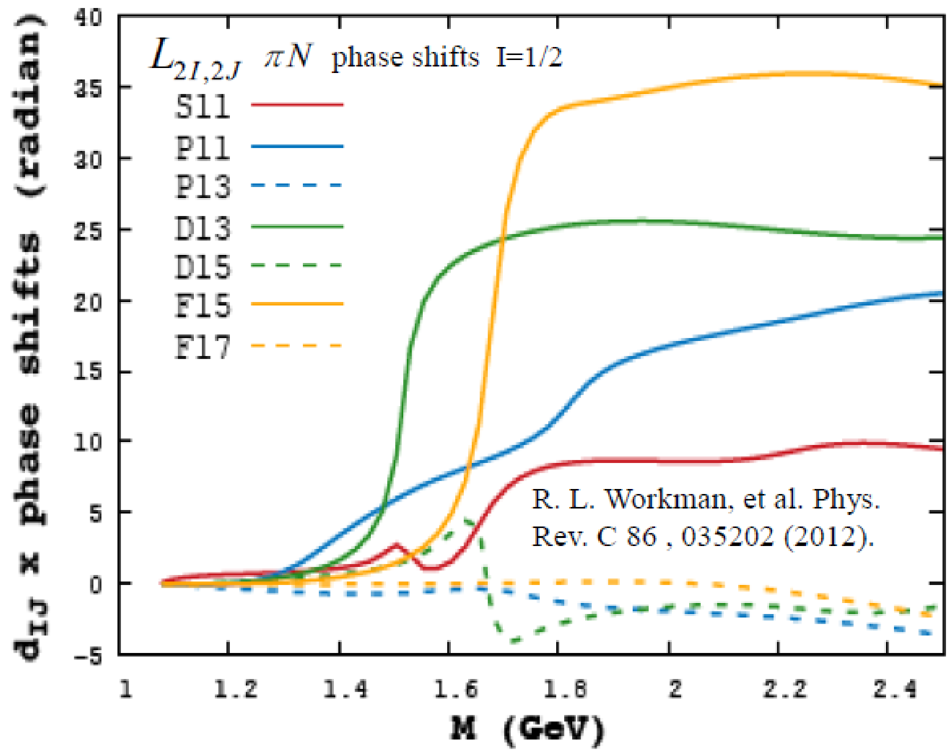
- SM Hadron Resonance Gas thermodynamic potential provides good approximation of the QCD equation of states in confined phase
- Good description of net- baryon number fluctuations and in further sectors of hadronic quantum number on correlations and fluctuations

robing non-strange baryon sector in πN- system

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



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

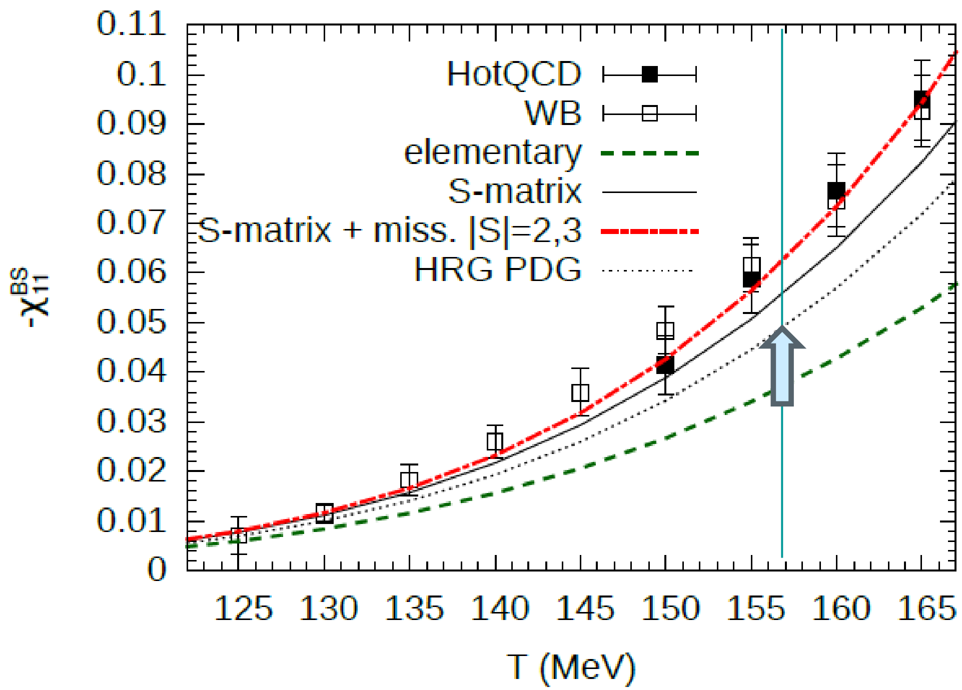


$$\Delta\chi_{BQ} \approx \sum_{I_z, j, B} d_j BQ \int dM \int d^3p \frac{1}{T} \frac{d\delta_j^I}{dM} \times e^{-\beta\sqrt{p^2+M^2}} (1 + e^{-\beta\sqrt{p^2+M^2}})^{-2}$$

- 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 $0.15 < T < 0.16\ GeV$

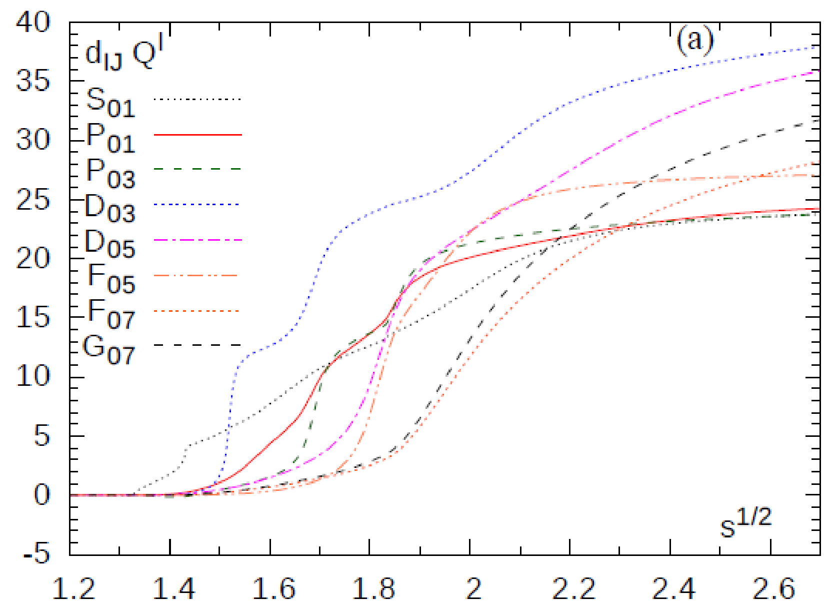
S-matrix HRG in strange baryon channel and LQCD

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



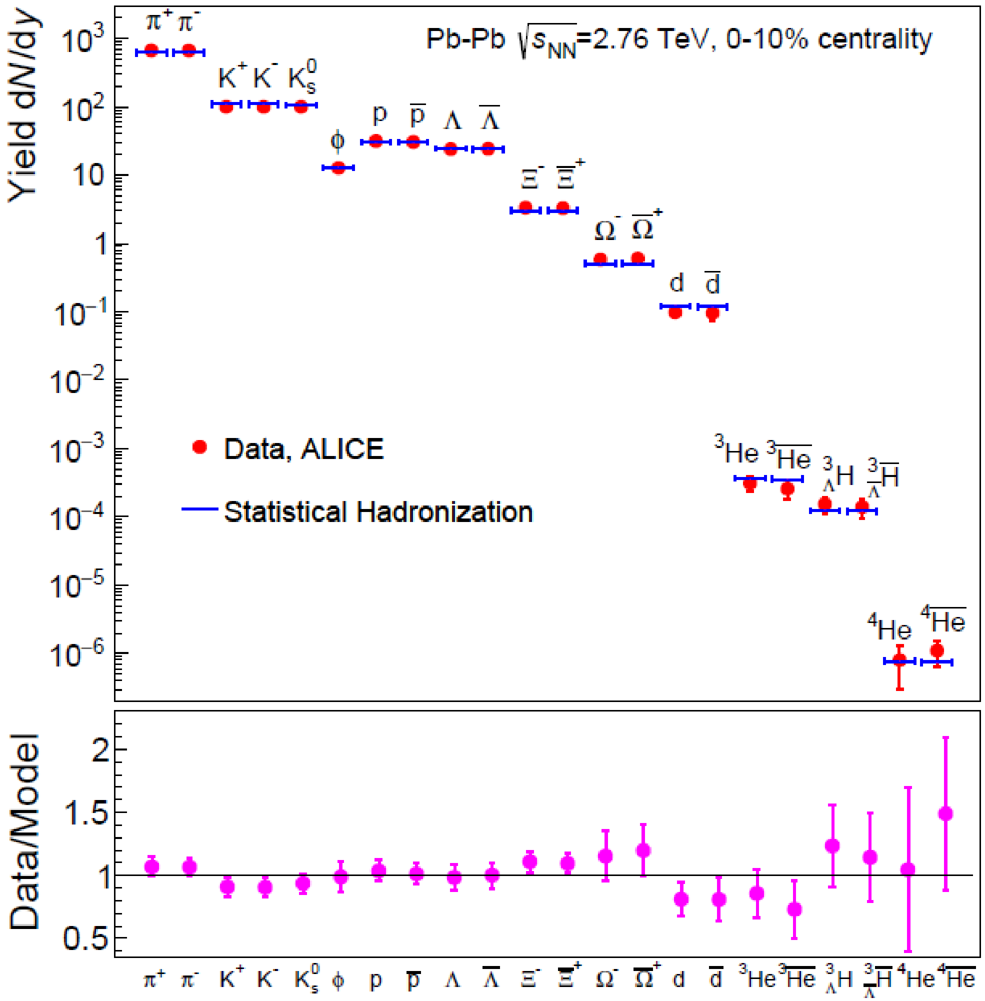
Joint Physics Analysis Center

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



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

The S-matrix HRG model formulated in GC ensemble that incudes empirical information on pion-nucleon interactions provides a very good description of LHC yields data

- Measured yields reproduced at

$$T = 156.6 \pm 1.7 \text{MeV}$$

$$\mu = 0.7 \pm 3.8 \text{ MeV}$$

$$V_{\Delta y=1} = 4175 \pm 380 \text{ fm}^3$$

$$\chi^2 / dof = 16.7/19$$

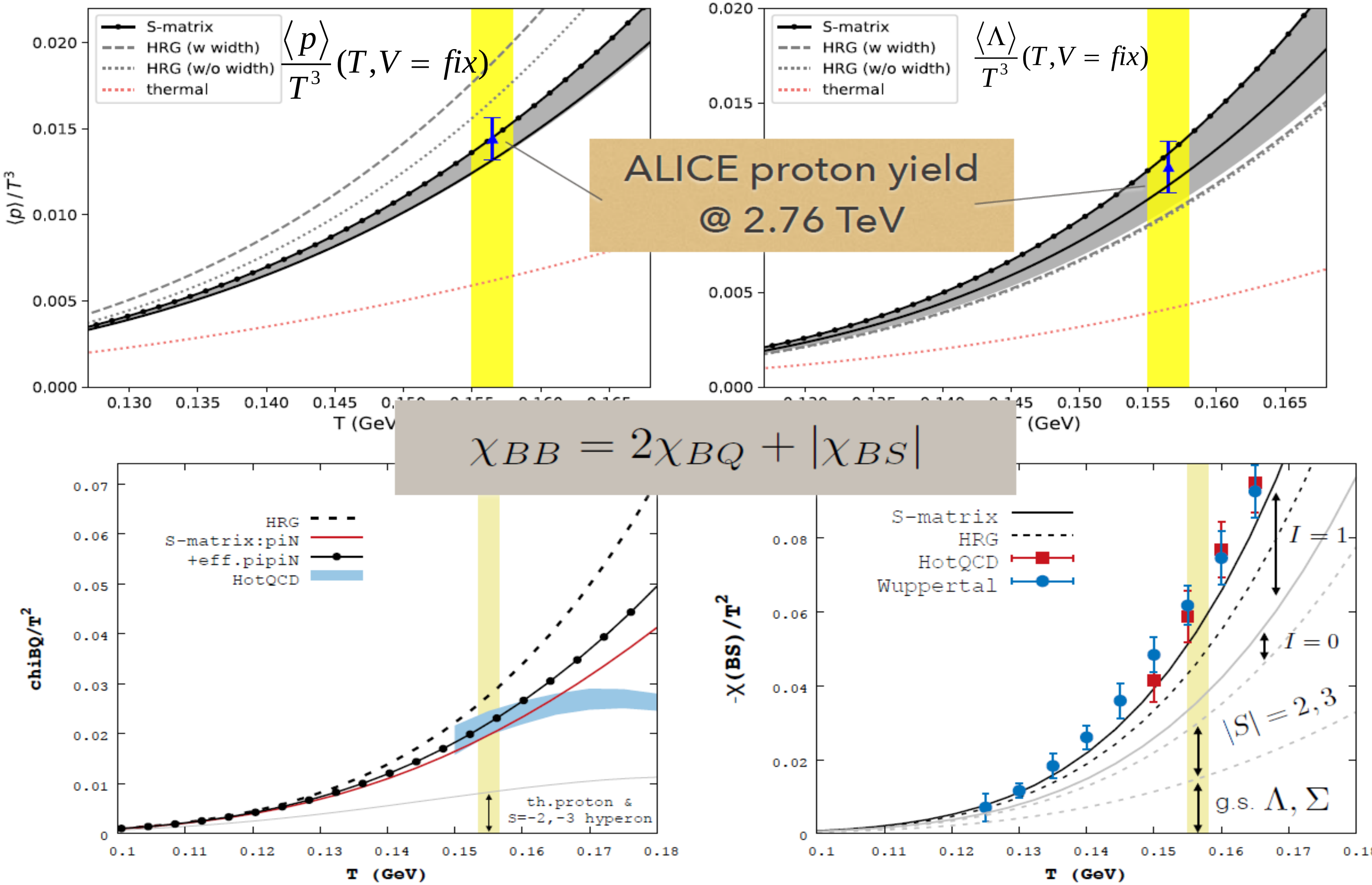
- A fireball in central Pb-Pb collisions is the matter created near the QCD phase boundary

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)

Synergy between LQCD → S-matrix HRG → ALICE data

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



$$\chi_{BB} = 2\chi_{BQ} + |\chi_{BS}|$$

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

Particle yields linked to $dN_{ch}/d\eta$:   from pp, pA to AA

- Suppression of strangeness production per pion yield with decreasing multiplicity as well as,

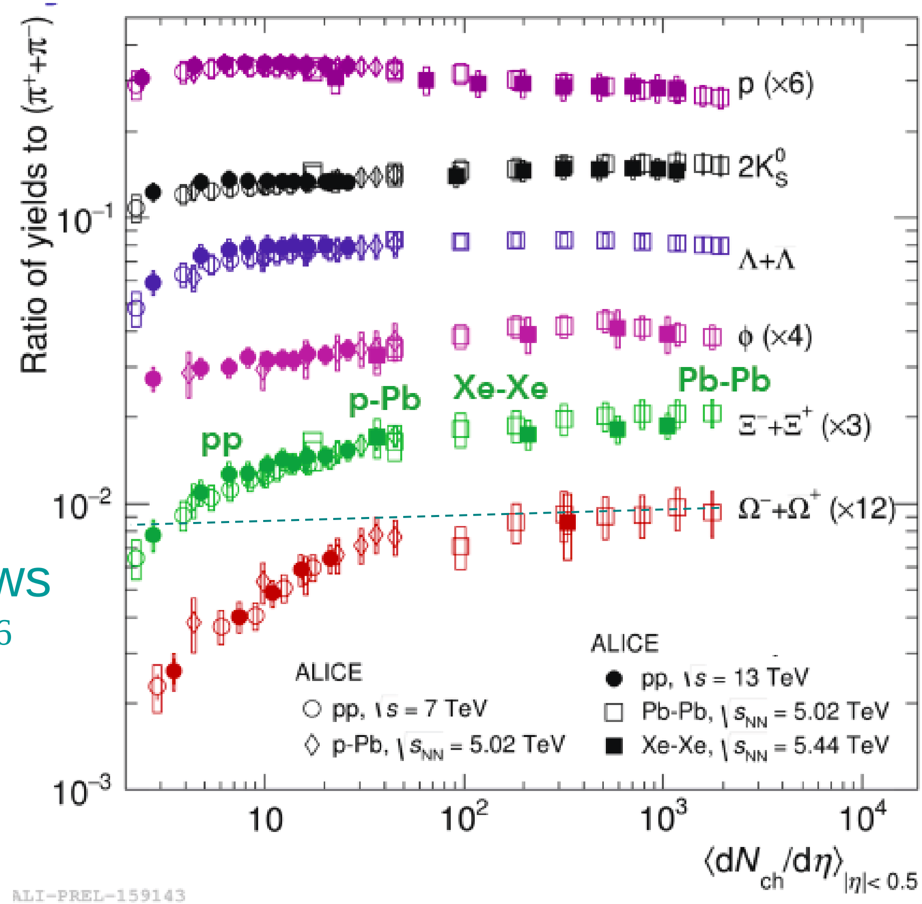
  its dependence on strange quantum number of hadrons can be

  linked to "canonical suppression effect"

  i.e. being due to

  constraints imposed on thermal particle yields by the exact strangeness conservation. This requires canonical ensemble formulation of conservation laws

Smooth evolution of particle yields as function of charged particle multiplicity, and strangeness suppression



J. Cleymans, E. Suhonen & K.R. Z.Phys.C 51 (1991) 137Z.Phys.C 76 (1997) 269

S. Hamieh, A. Tounsi & K.R. Phys. Lett. B486 (2000), Eur.Phys.J. C24 (2002) ,

J. Cleymans, H. Oeschler & K.R. Phys. Rev. C59 (1999) 1663

Strangeness canonical suppression with yields of charged particles

- Strangeness conservation must be exact

J. Cleymans, Pok Man Lo, N. Sharma & K.R.
Phys. Rev. C103 014904 (2021)

$$Z^{GC}(\mu) = Tr[e^{-\beta(H-\mu S)}] \Rightarrow Z_S^C = Tr[e^{-\beta H}\delta_S]$$

$$Z^{GC}(\lambda) = \sum_{S=-\infty}^{\infty} \lambda^S Z_S^C \quad \Rightarrow Z_S^C \simeq \int_{-\pi}^{\pi} d\varphi e^{i\phi S} e^{\ln(Z^{GC}(\mu \to i\varphi))}$$

$$\ln Z^{GC}(\mu, T, V) = \sum_{s=-3}^{3} z_s e^{s\mu/T}$$

Interactions in z_s included: S-matrix

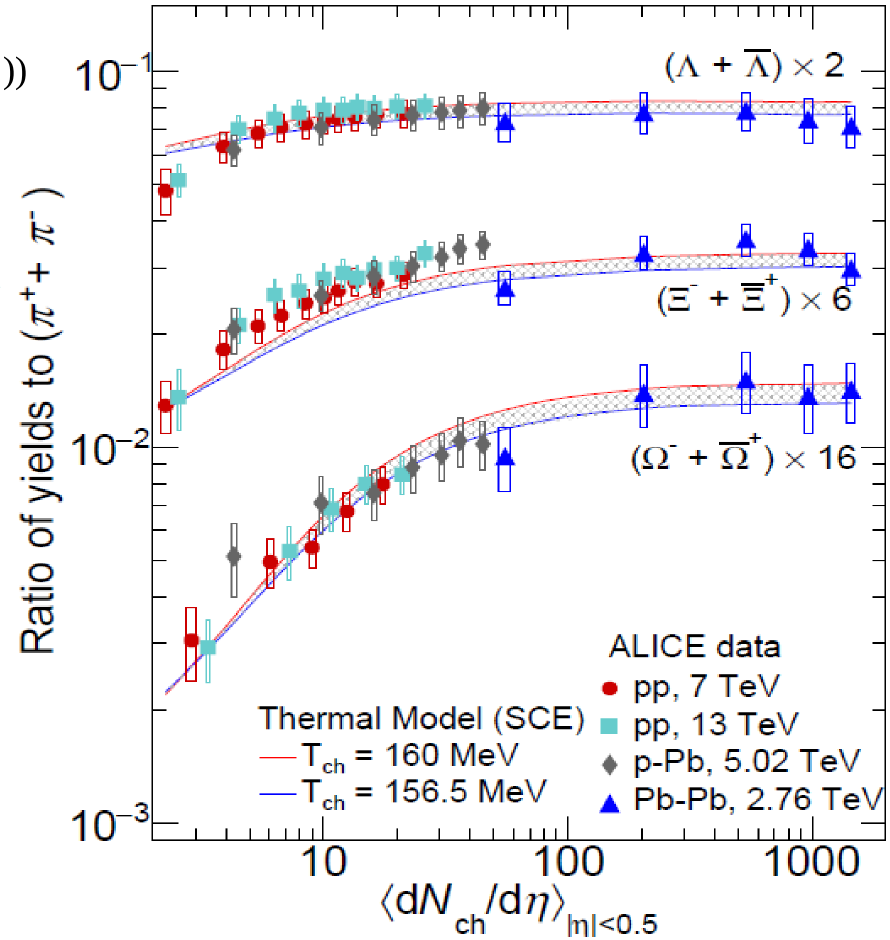
- This implies strangeness suppression effect

$$< N_s >_A^C \approx V_A n_s^{GC} \bullet \frac{I_s(2V_C n_{s=1}^{th}(T))}{I_0(2V_C n_{s=1}^{th}(T))}$$

where volume parameters $V_{A(C)} \sim dN_{ch} / d\eta$

V_C - full phase-space volume where S is exactly conserved

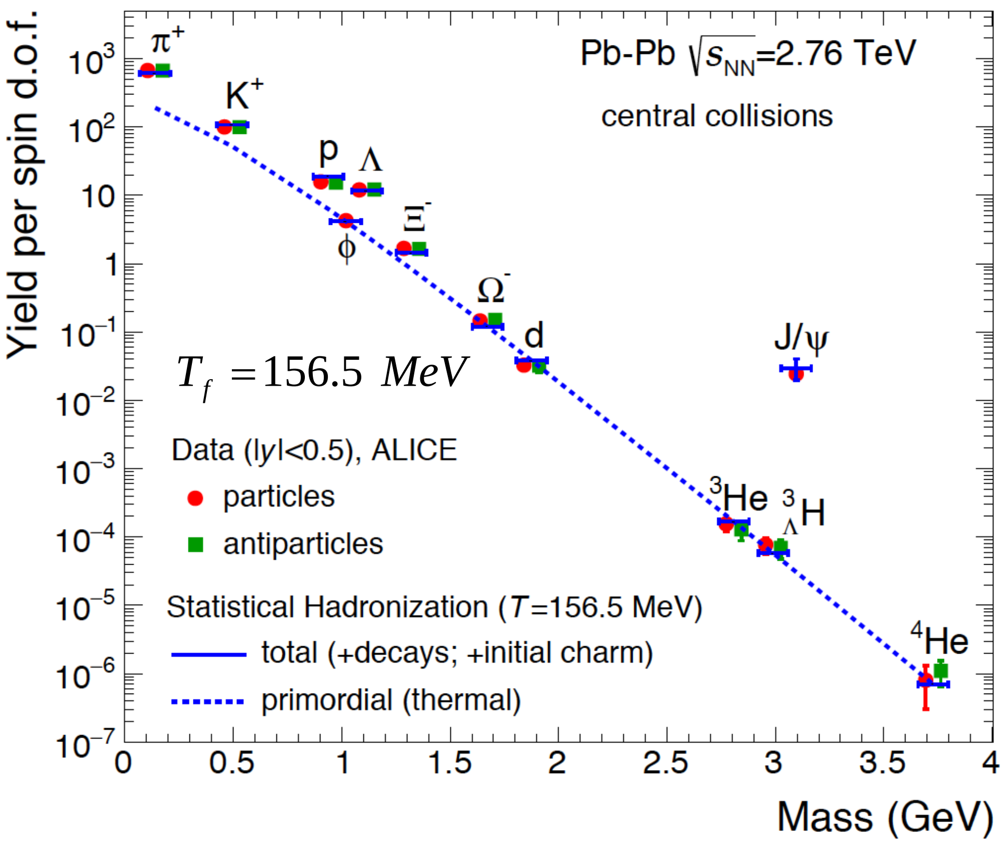
V_A - effective fireball volume in the acceptance



The suppression factor $I_S(x) / I_0(x) \leq 1$ decreases with decreasing x, and increasing strange s-quantum number of hadron.

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:

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

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

Also applies to b-quark hadrons and bottomonia

See also:

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

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

Intial $\bar{c}c$ 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 within R_{AA}

⇨ 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 $c = \pm 1$

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

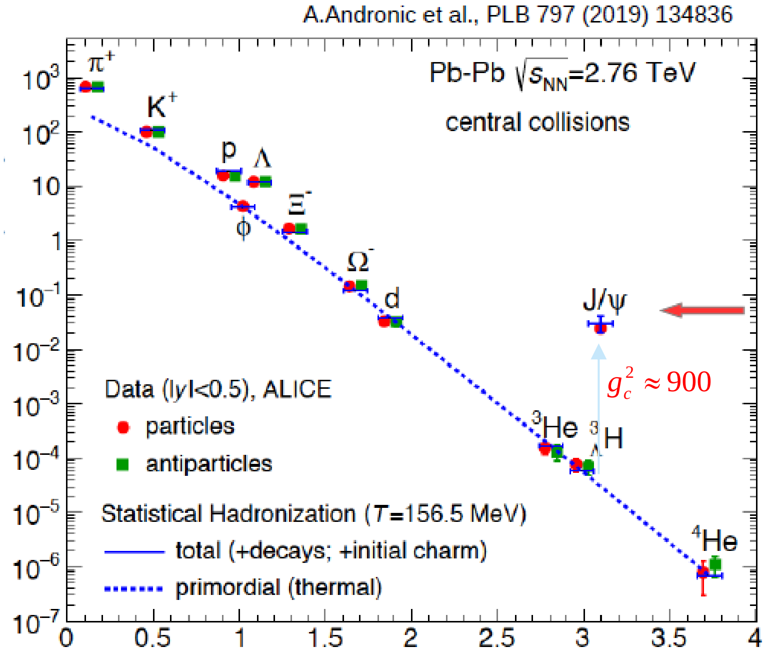
$$\frac{dN_{i,hc}}{dy} = g_c^2 V n_i^{th}$$

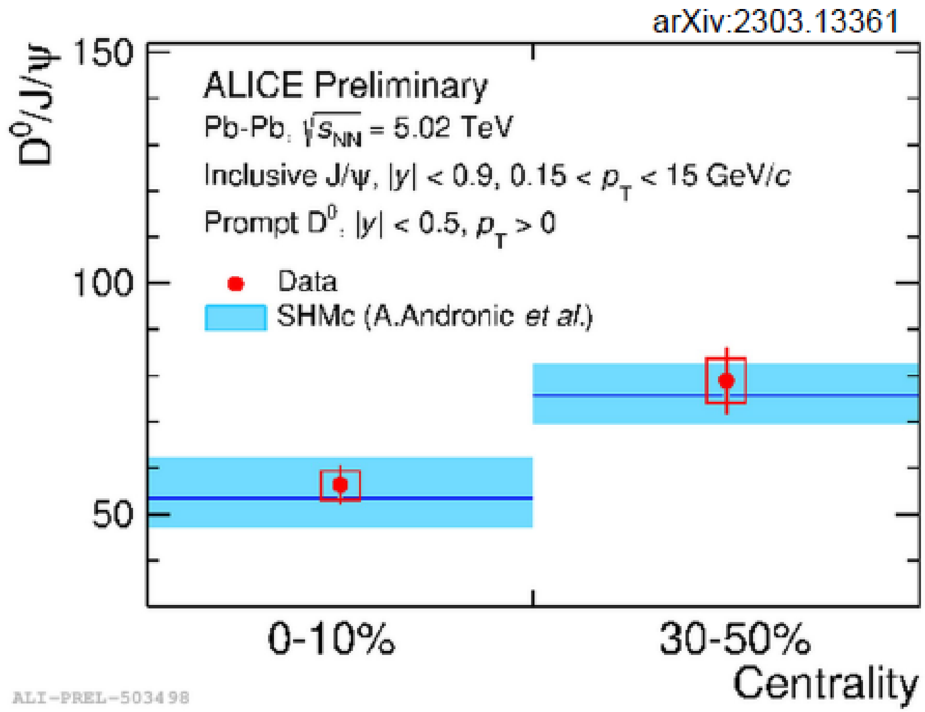
contribution of resonances:

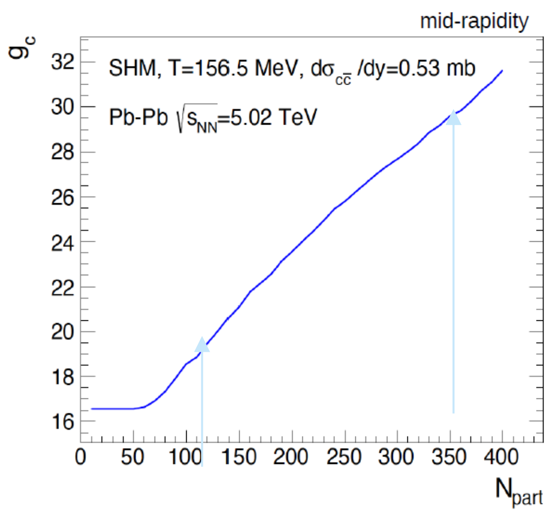
$$n_i^{th} = n_i^{prompt} + \sum_j Br(j \to i) n_j^r$$

- 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



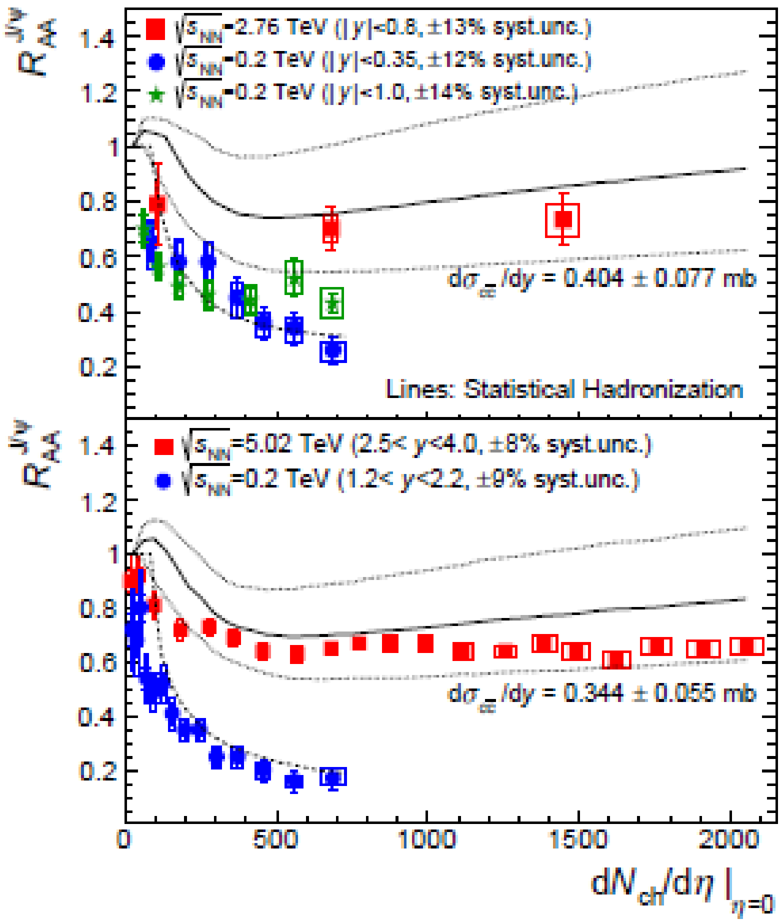




- Strong increase of J/Psi yields due to off chemical equilibrium facto $g_c^2 \approx 900$ in central collisions
- First data on $D^0/(J/\psi)$ and centrality dependence well described by SHMc. Increasing ratio towards non central collisions due to decreasing g_c since:

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

Essential predictions of SHMc: J/Psi suppression

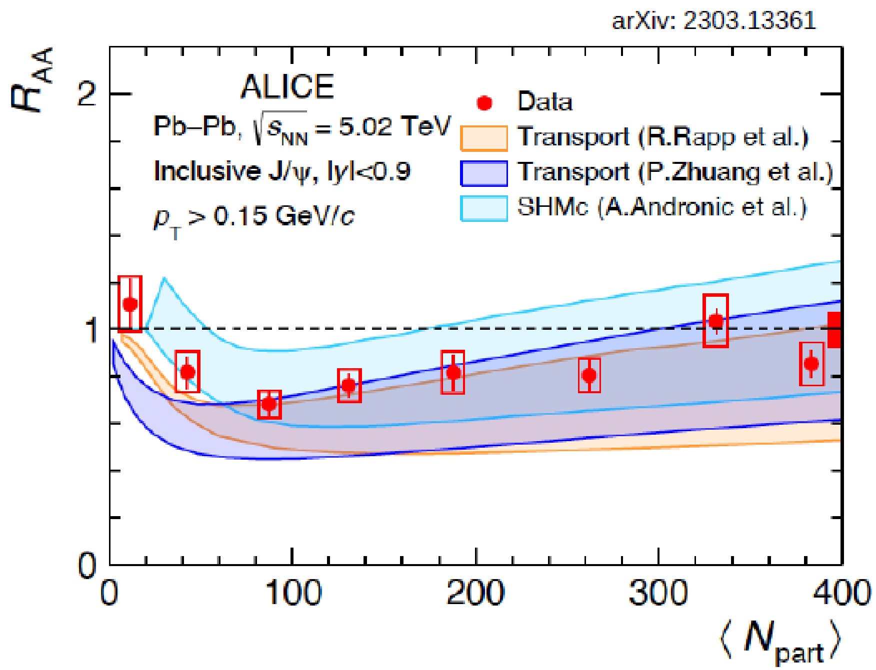


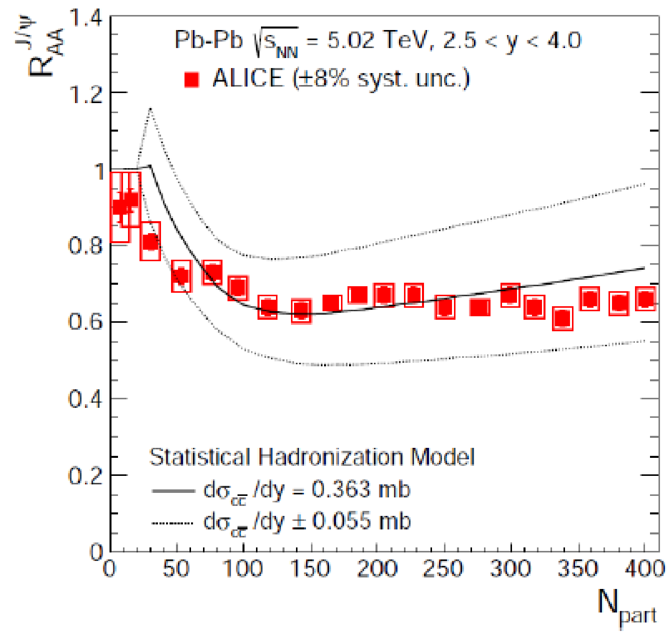
Model predictions successfully applied to quantify SPS, RHIC and LHC data: in particular due to SHMc thermal regeneration of J/Psi at the QCD phase boundary and increasing number of Ncc the J/Psi suppression observed at SPS decreases with increasing energy towards LHC contrary to the expectation of the sequential suppression concept due to Debay screening.

Melting scenario not observed but rather enhancement with increasing energy density from RHIC to LHC

due to statistical/thermal hadronization of charm quarks at the QCD phase boundary described by SHMc

Model comparison with ALICE data: R_{AA}

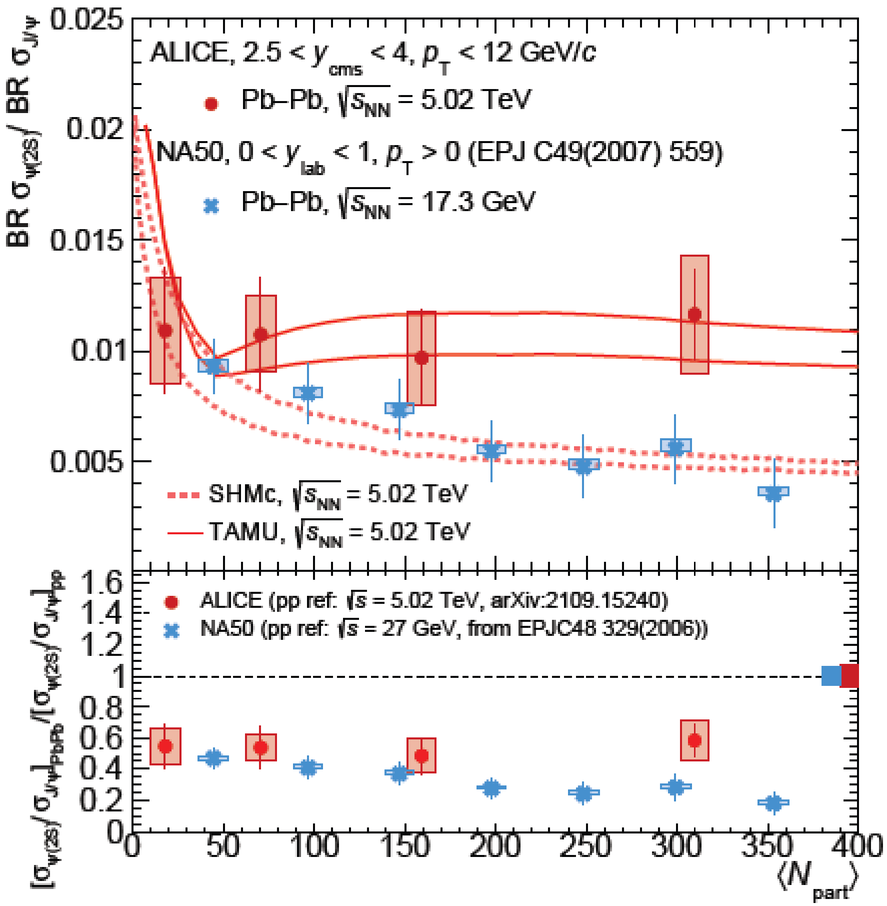




- Production in Pb-Pb collisions consistent with deconfinement in QGP and subsequent hadronization at the phase boundary. The main uncertainty of the model prediction due to open charm cross-section.

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
- The observed deviation by 1.8 σ at LHC from SHMc in central collisions is unexpected and there is little room to be accommodated in likely physical scenario
- The only space could be due to unknown contributions from b-hadrons or exotic baryons decay

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 $c = \pm 1$, reads

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

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

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

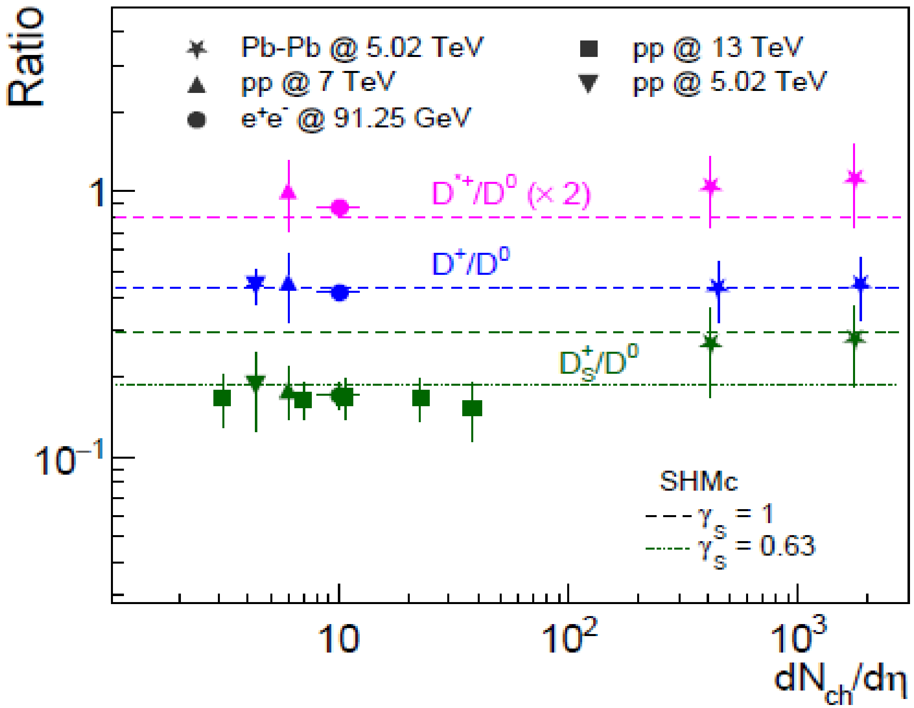
is fully determined by Ncc (from experiment or model) and the temperature, which at high energy collisions $T = T_c = 156.5$ MeV. Yield is independent of the volume i.e. system size and canonical suppression factor.

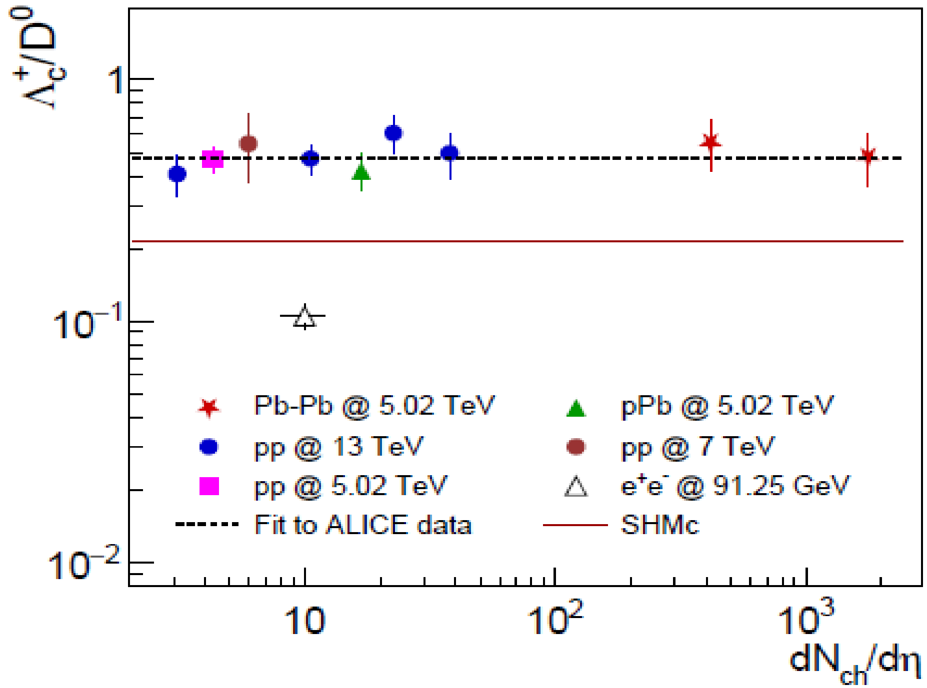
Basic properties for different open charm yield ratios

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

Ratios entirely determined by T

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





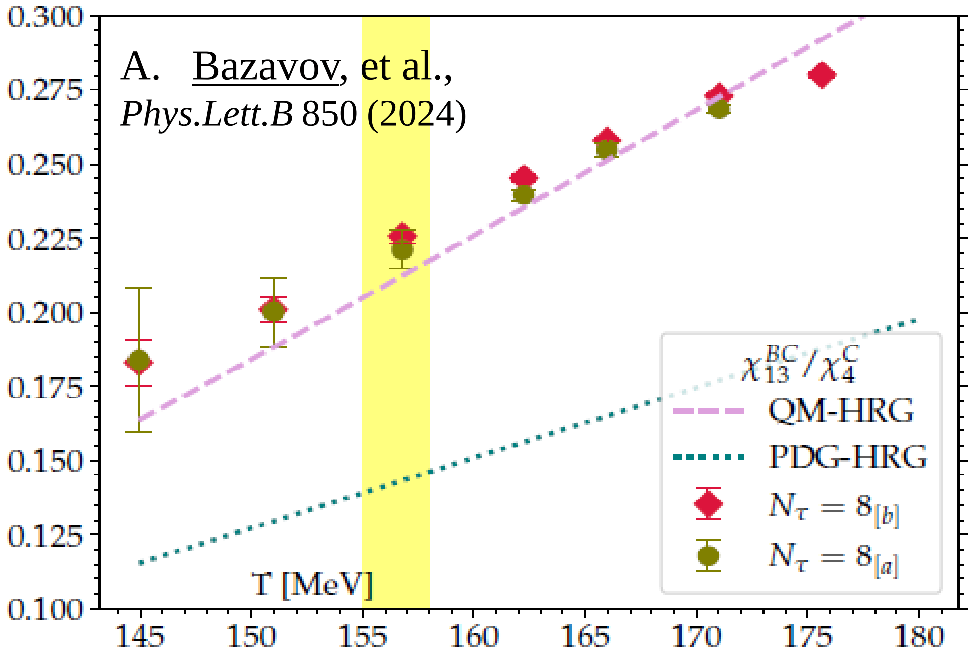
Ratios in pp, pA and AA collisions are within uncertainties the same and independent of associated charged particle pseudo-rapidity density, as expected in SHM.

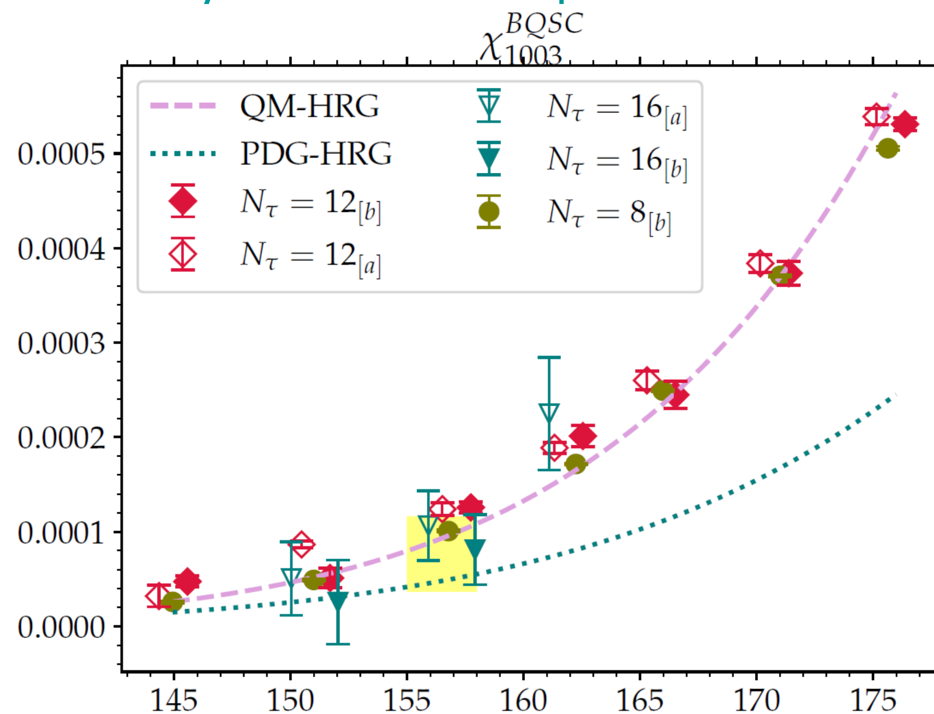
An increase of D_s^+ / D^0 from pp to AA is possible and needs more data.

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

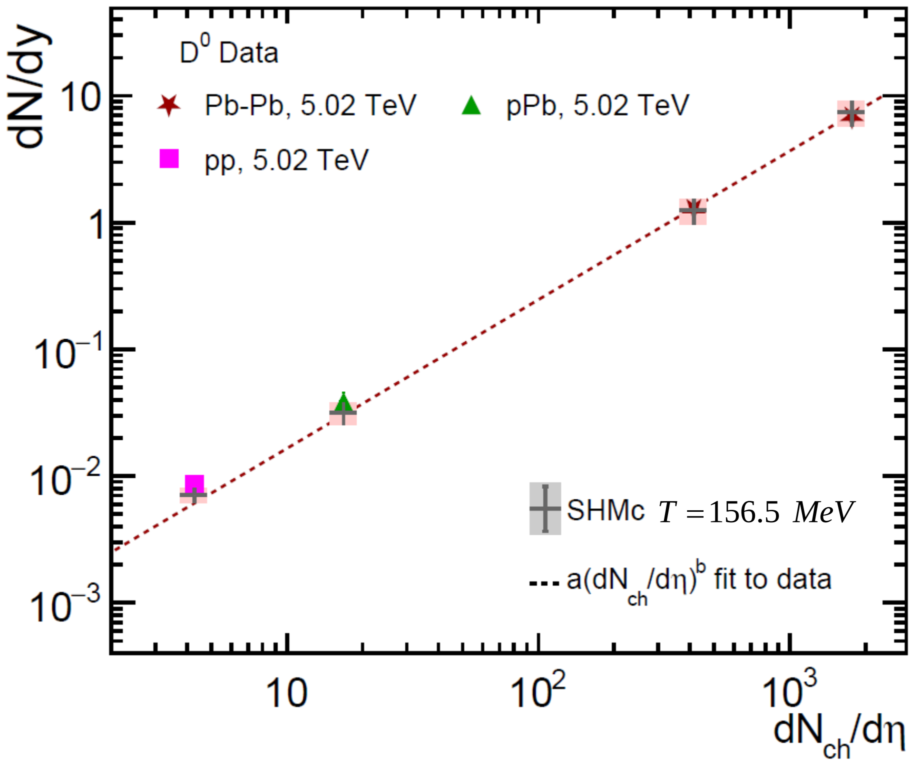




Charm baryon susceptibilities are better described by the quark model of hadrons which indicates an increase of charm baryonic resonances relative to PDG at Tc by a factor 1.9. We include this missing states by rescaling Λ_c density by 2.2.

Quantifying rapidity densities of open charm hadrons

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



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

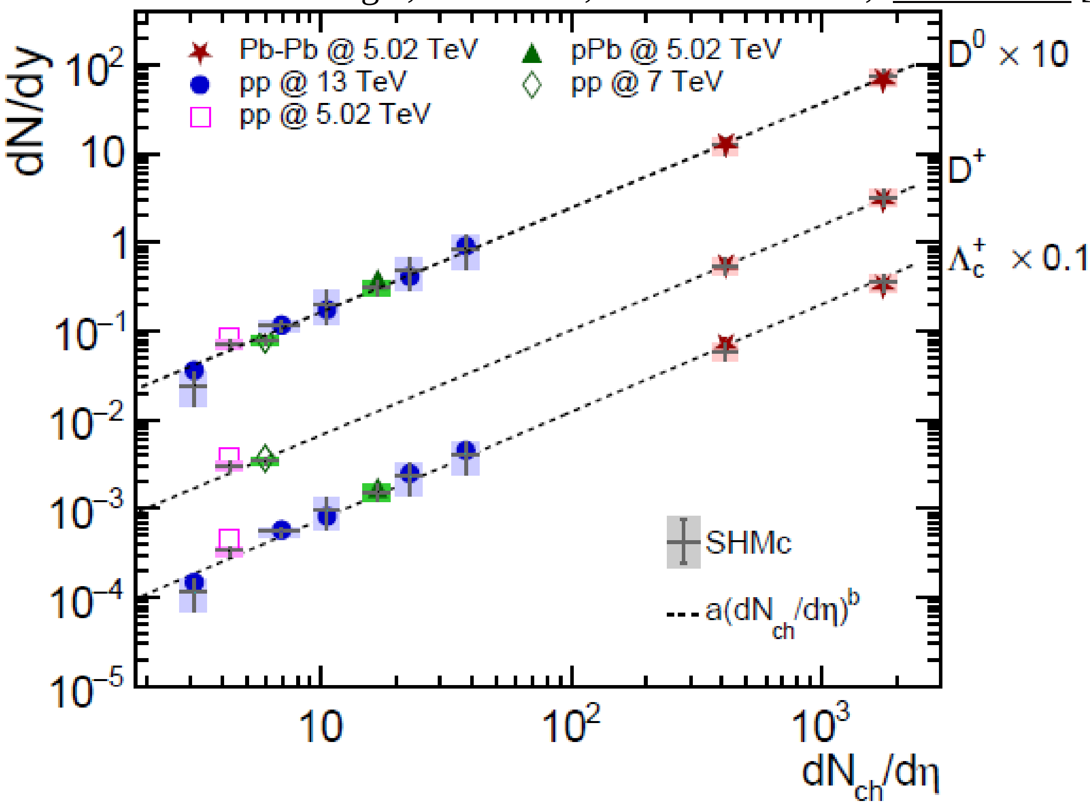
$$N_{cc} = \begin{cases} \sigma_{cc}^{pp} / \sigma_{inel}^{pp} & \text{in pp} \\ \sigma_{cc}^{pA} / \sigma_{inel}^{pA} & \text{in pA} \\ \alpha_A \sigma_{cc}^{pp} T_{AA} & \text{in AA} \end{cases}$$

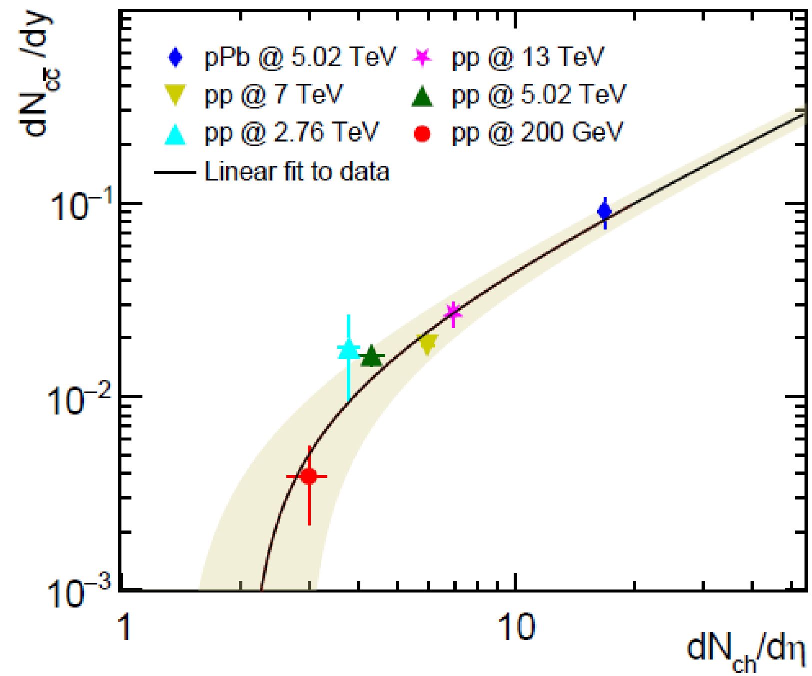
Cross sections from data: T=156.5 MeV
Thickness function from Glauber model.
Factor α_A accounts for nuclear modification effects such as shadowing, energy loss or saturation.

- 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}

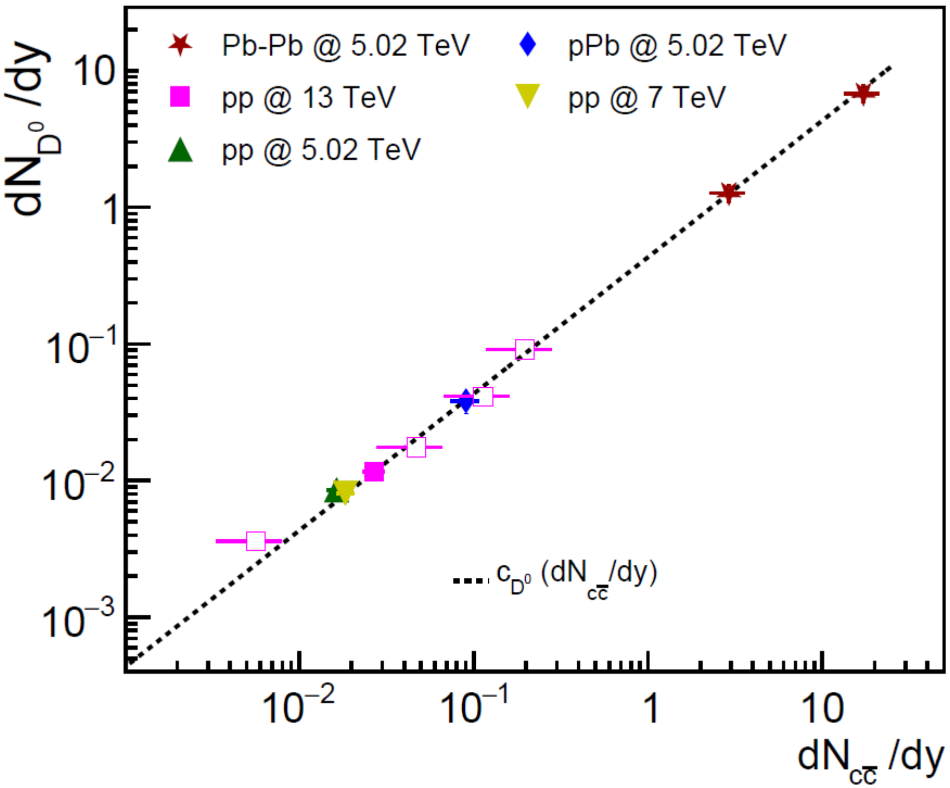
P. Braun-Munzinger, N. Sharma, J. Stachel &K.R., 2408.07496 [hep-ph]

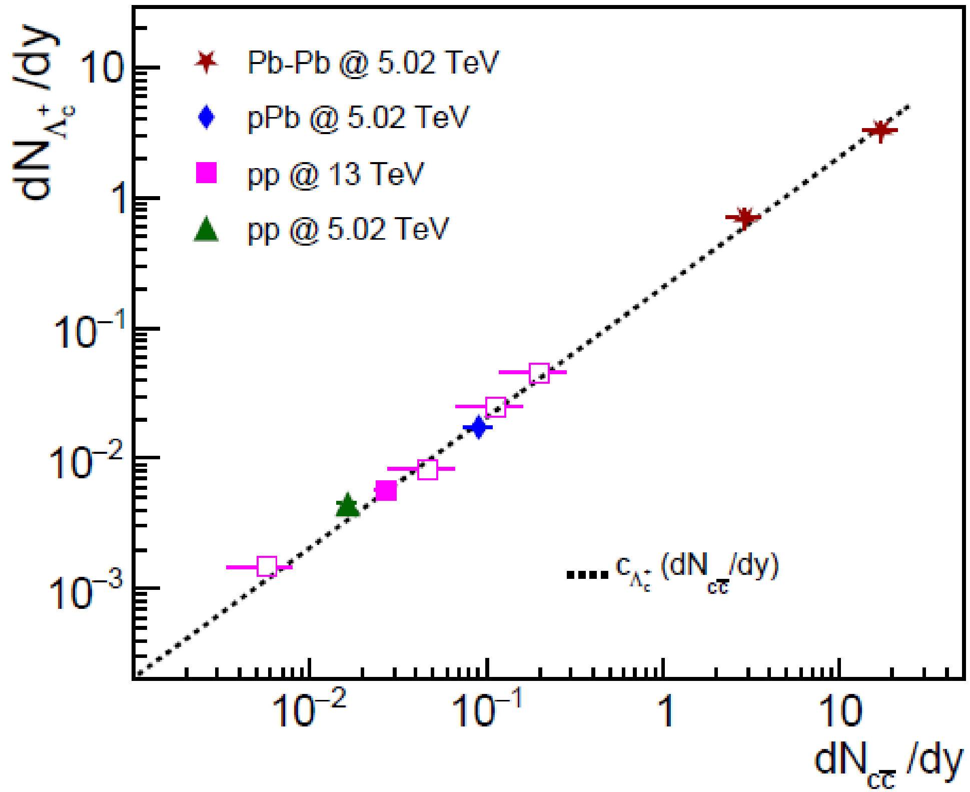




- In a narrow rapidity window Ncc fitted with a linear function of N_{ch}. This allows to extract experimentally unknown values of N_{cc} at $N_{ch} = 3.1,\ 10.5,\ 22.6,\ 37.8$ where D^0 and Λ_c were measured in pp collisions at $\sqrt{s_{NN}} = 13$ TeV .
- All data follow the observed power law scaling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

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

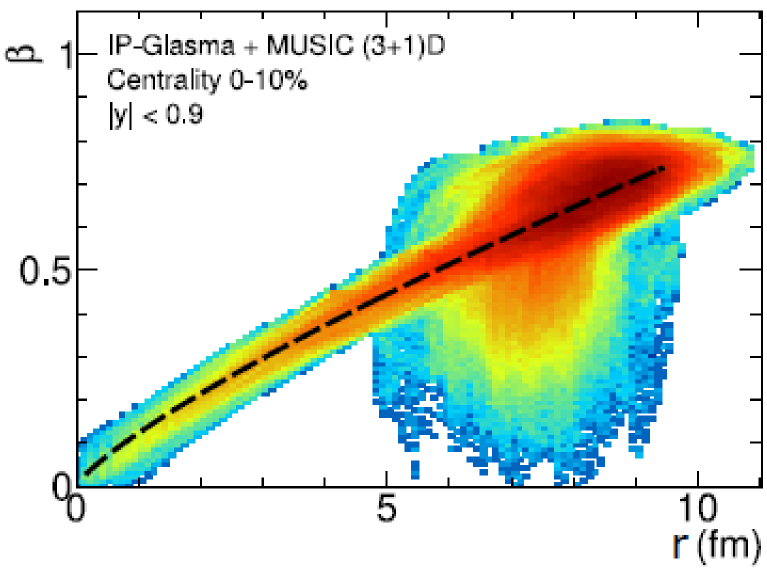
- Data follow SHMc model expectations indicating that it provides a good description of charm fragmentation/hadronization in high energy collisions.

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

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

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

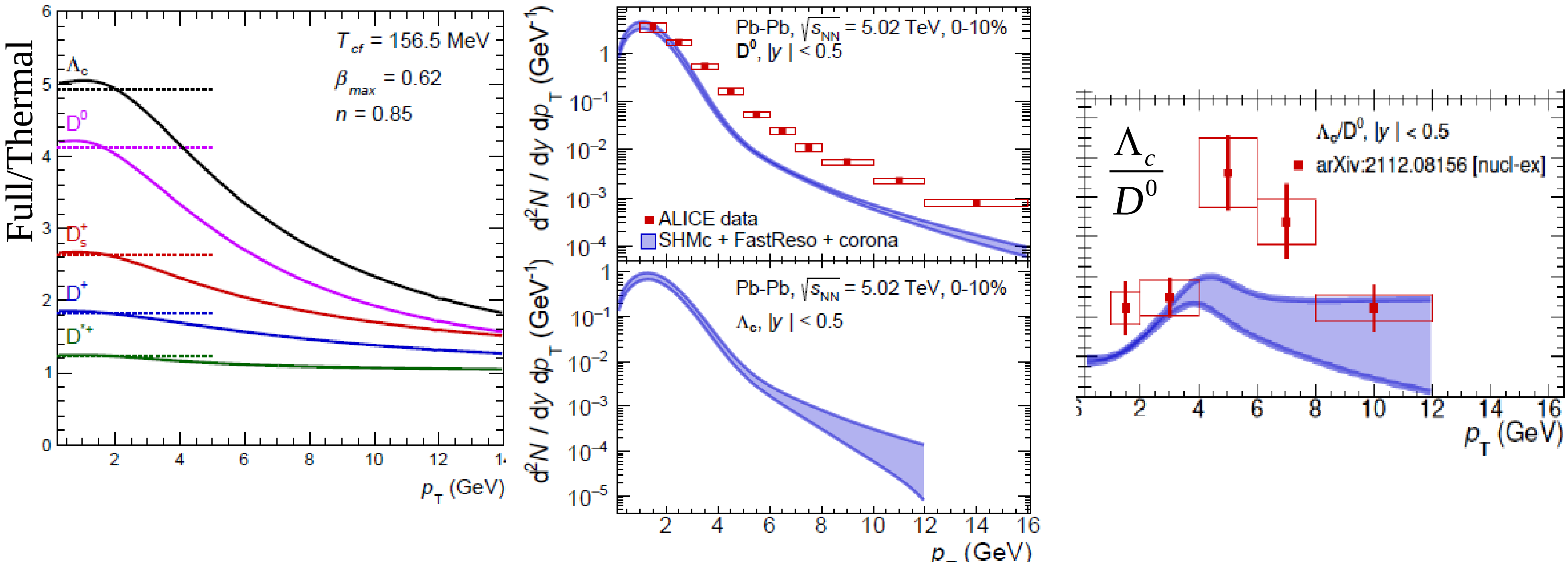
$$\beta(r) = \beta_{\max}(r/r_{\max})^n$$

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

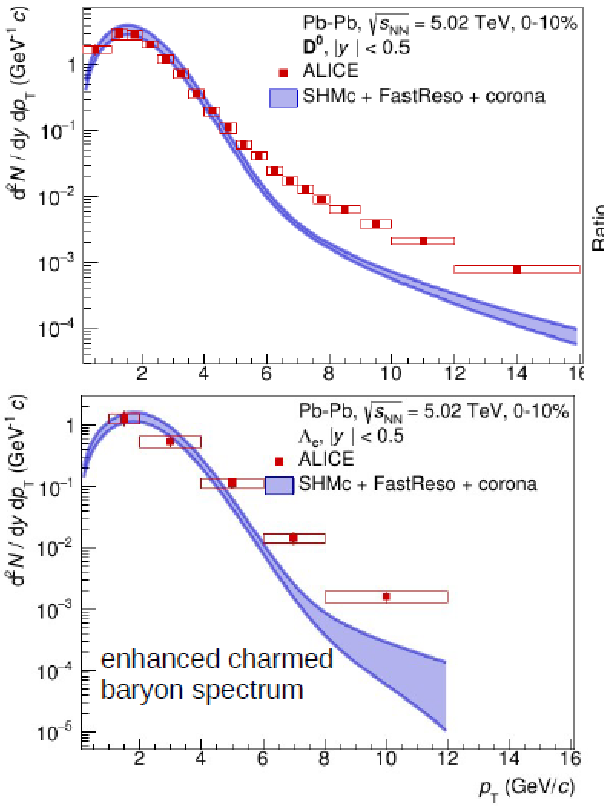
A. Andronic, P. Braun-Munzinger, M. Koehler, A. Mazeliauskas, K. Redlich J. Stachel, V. Vislavicius, JHEP 07 (2021) 035

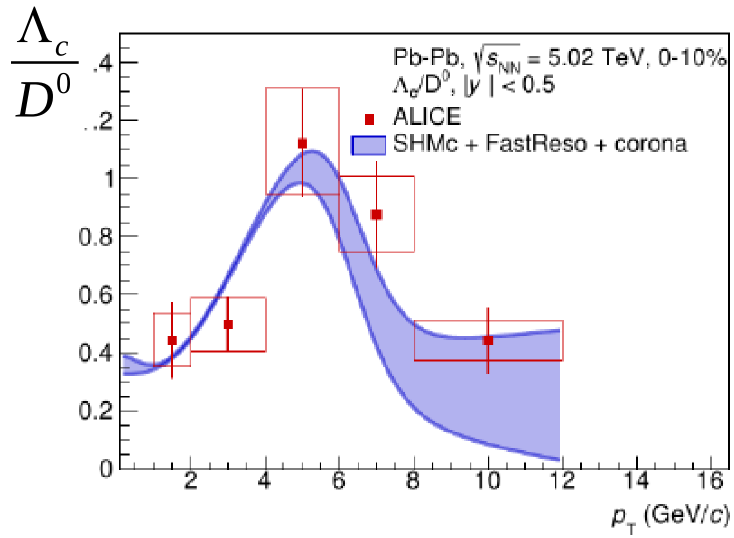


- Very good description of soft part of D0 spectra in SHMc+hydro+FastReso decay within PDG
- Too low strength for Lambda_c: However missing baryon resonances not yet included

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



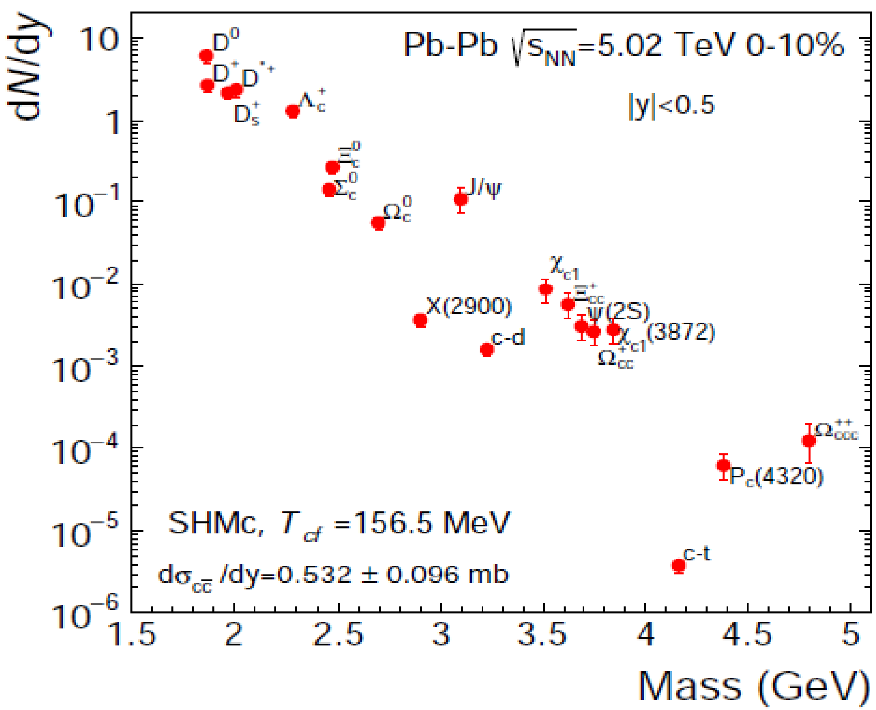


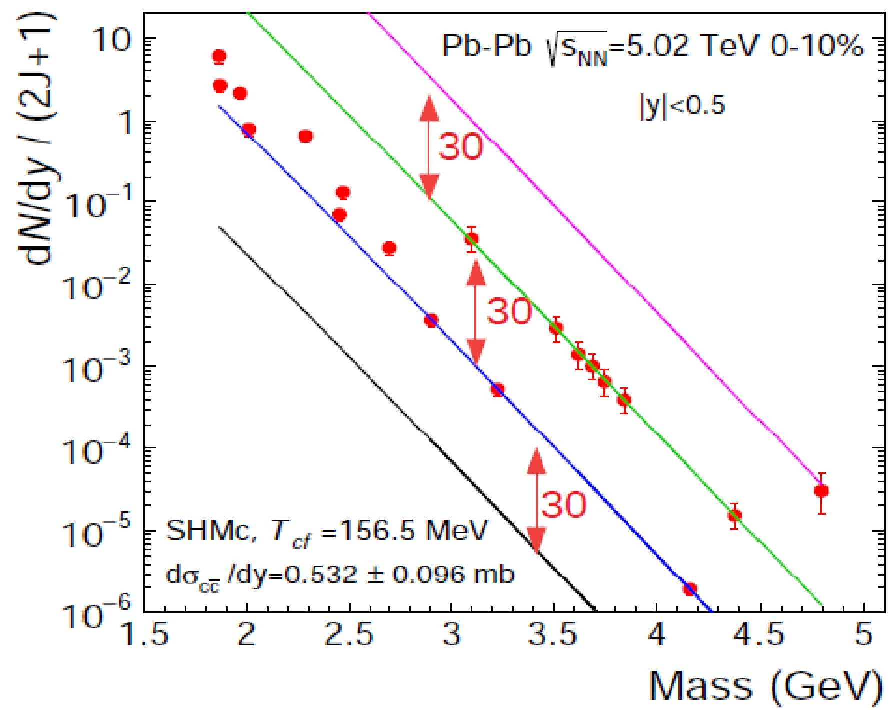
- Maximum in ratio appears due to transverse expansion and mass difference between particles

- 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

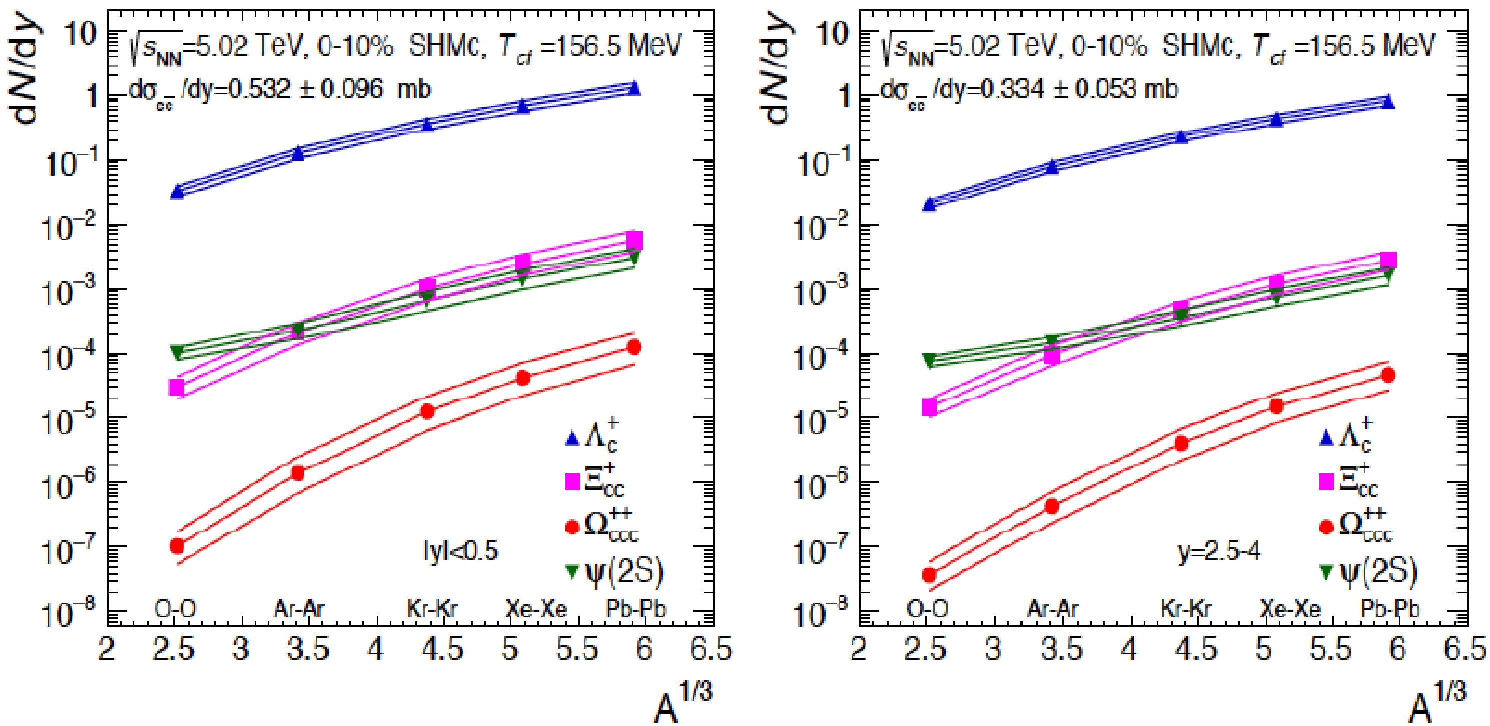




- Within SHMc model we can also make predictions for yet unmeasured charm and multi-charm hadron species and exotic states like e.g. X-state.
- There are also interesting systematics of particle yields and hierarchy, not only with a mass but also with the charm quark content of hadron due to the g_c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

System size dependence of multi-charm hadrons

A. Andronic, et. Al, , JHEP 07 (2021) 035



- Similar suppression pattern for multicharm states as in strangeness sector due to exact conservation of charm and resulting canonical effect. This implies that measuring multicharm states in light collision systems is not favored.

CONCLUSIONS:

- lQCD thermodynamic potential is encoded in nuclear collisions
- S-matrix (Hadron Resonance Gas) thermodynamic potential provides an excellent approximation of LQCD equation of states, 2nd order fluctuations and correlations, and ALICE hadron yields data originating from thermal source at T_c=156 MeV.
- The exact conservation of net-strange and -baryon numbers is essential to quantify particle yields and their observed scaling with N-ch
- 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
    - Interesting scaling of open charm data with N_ch and N_cc in pp and AA for all energies and centralities

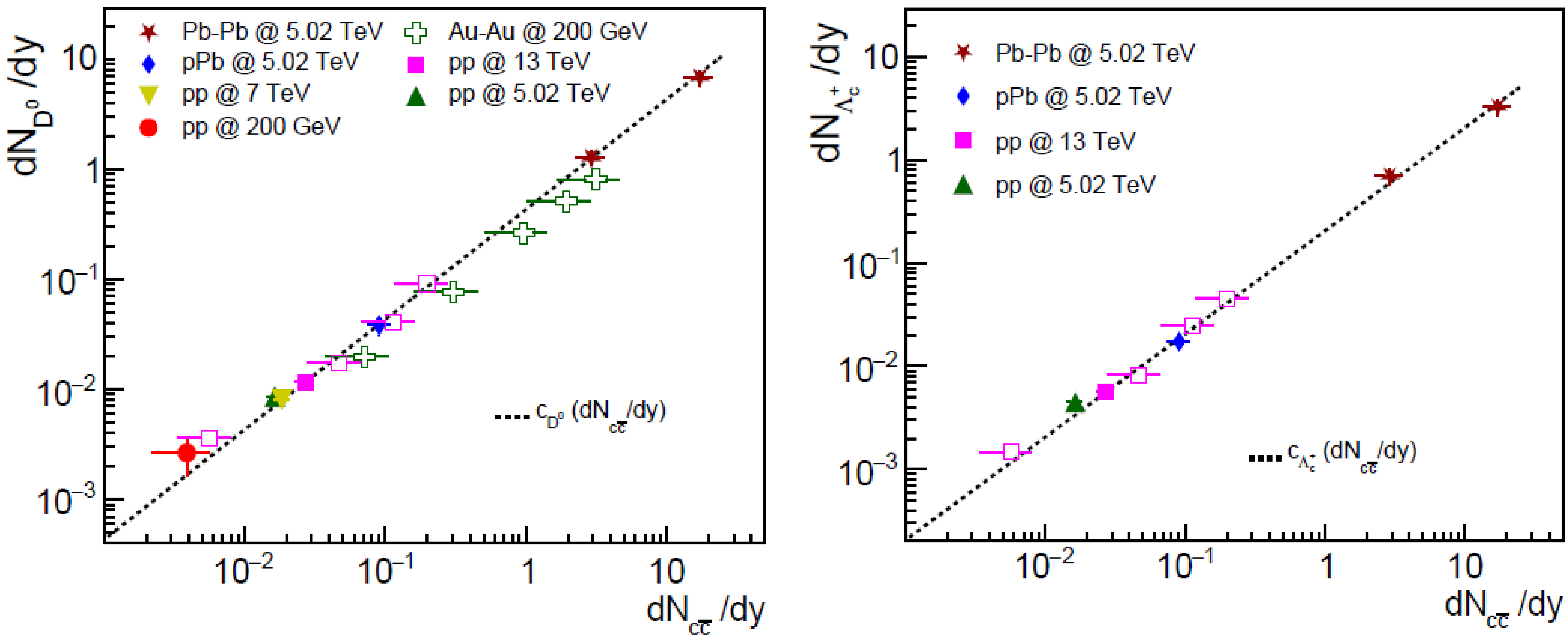
Puzzling and interesting results requiring more data:

- 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

Charm quarks fragmentation/hadronization in the SHMc

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



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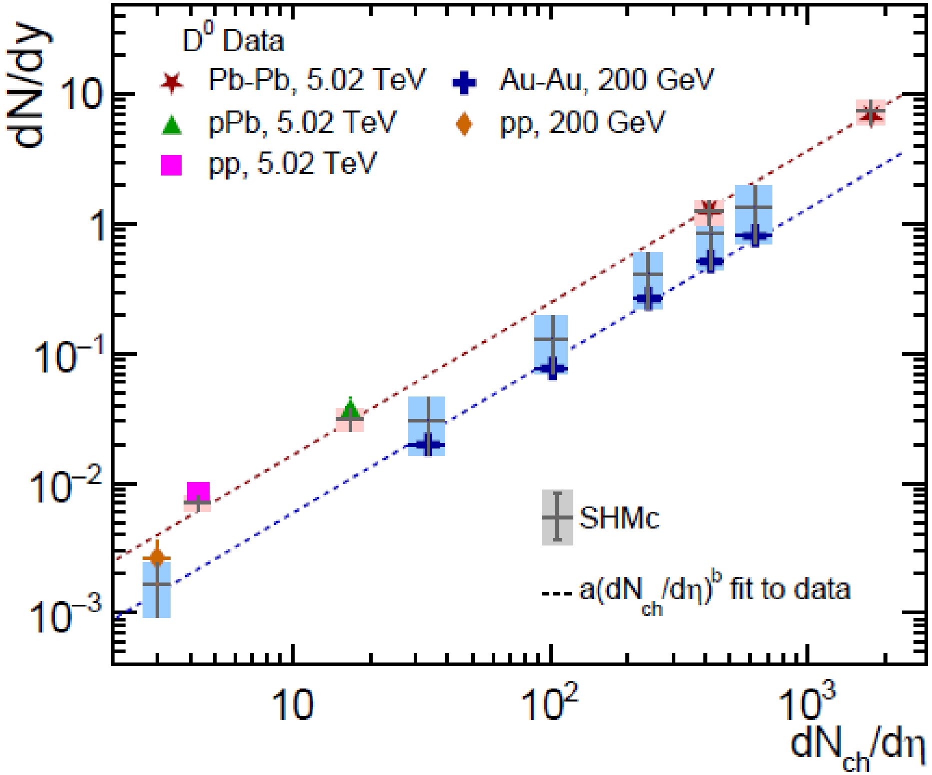

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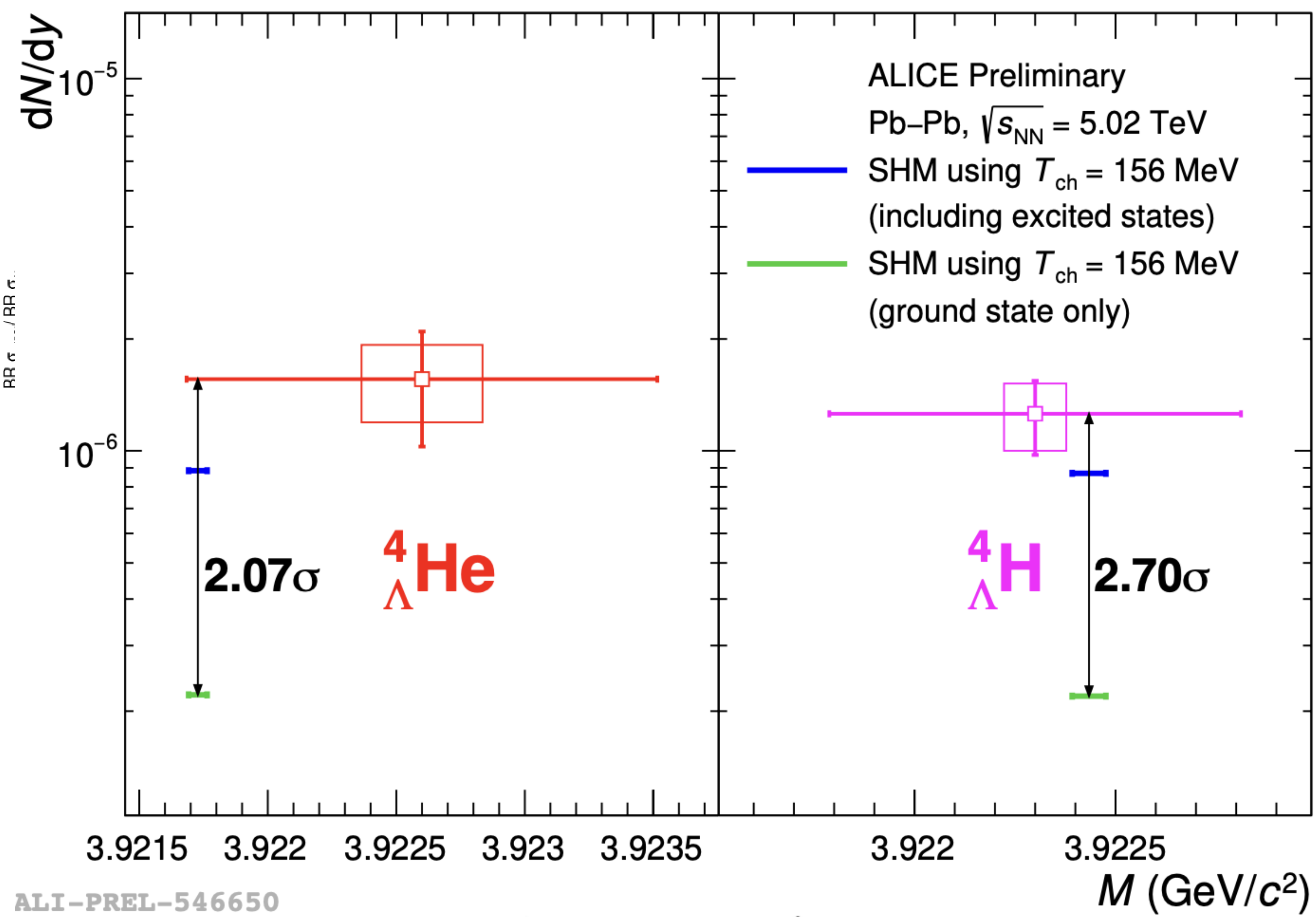


dN/dy
10⁻⁵
10⁻⁶
ALICE Preliminary
Pb–Pb, √sNN = 5.02 TeV
SHM using Tch = 156 MeV
(including excited states)
SHM using Tch = 156 MeV
(ground state only)
2.07σ
4ΛHe
4ΛH
2.70σ
3.9215
3.922
3.9225
3.923
3.9235
3.922
3.9225
M (GeV/c²)
ALI-PREL-546650

Canonical suppression in baryonic sector in pp and pA collisions

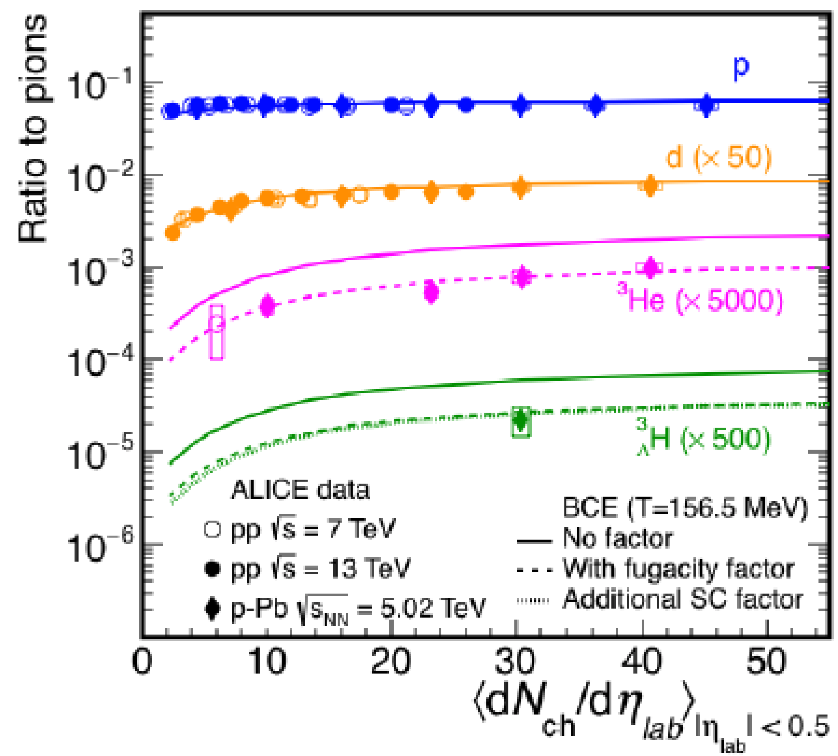
- Baryon canonical suppression effect

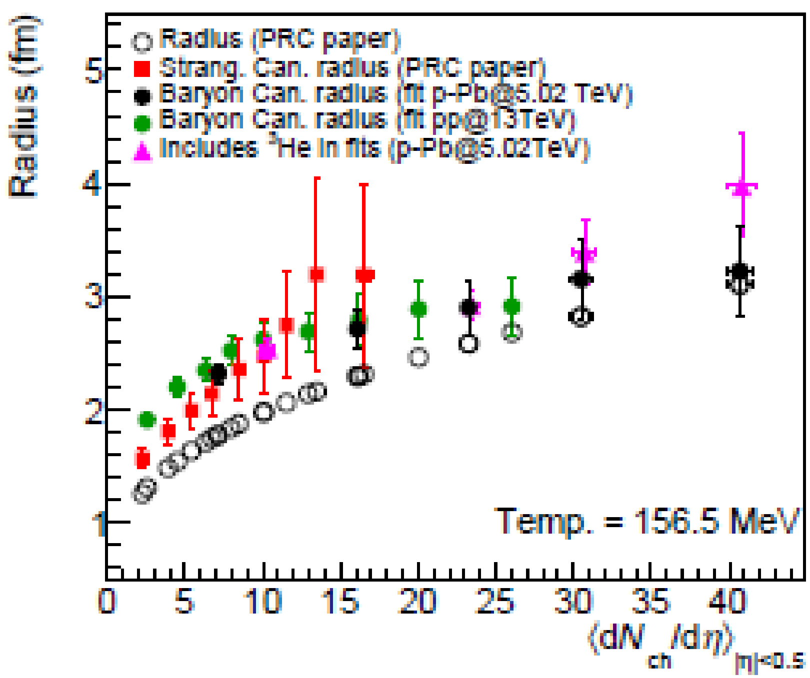
$$<N_b>^C_A = V_A n^{GC} \bullet \frac{I_b(2V_C^B n^{th}_{b=1}(T))}{I_0(2V_C^B n^{th}_{b=1}(T))} \times \lambda_B$$

Where T, and V_A known parameters.

The only fitted parameter is: $V_C^B = 4/3\pi R^3$

N. Sharma, Lokesh Kumar, Pok Man Lo, & K.R.
PRC (2023)

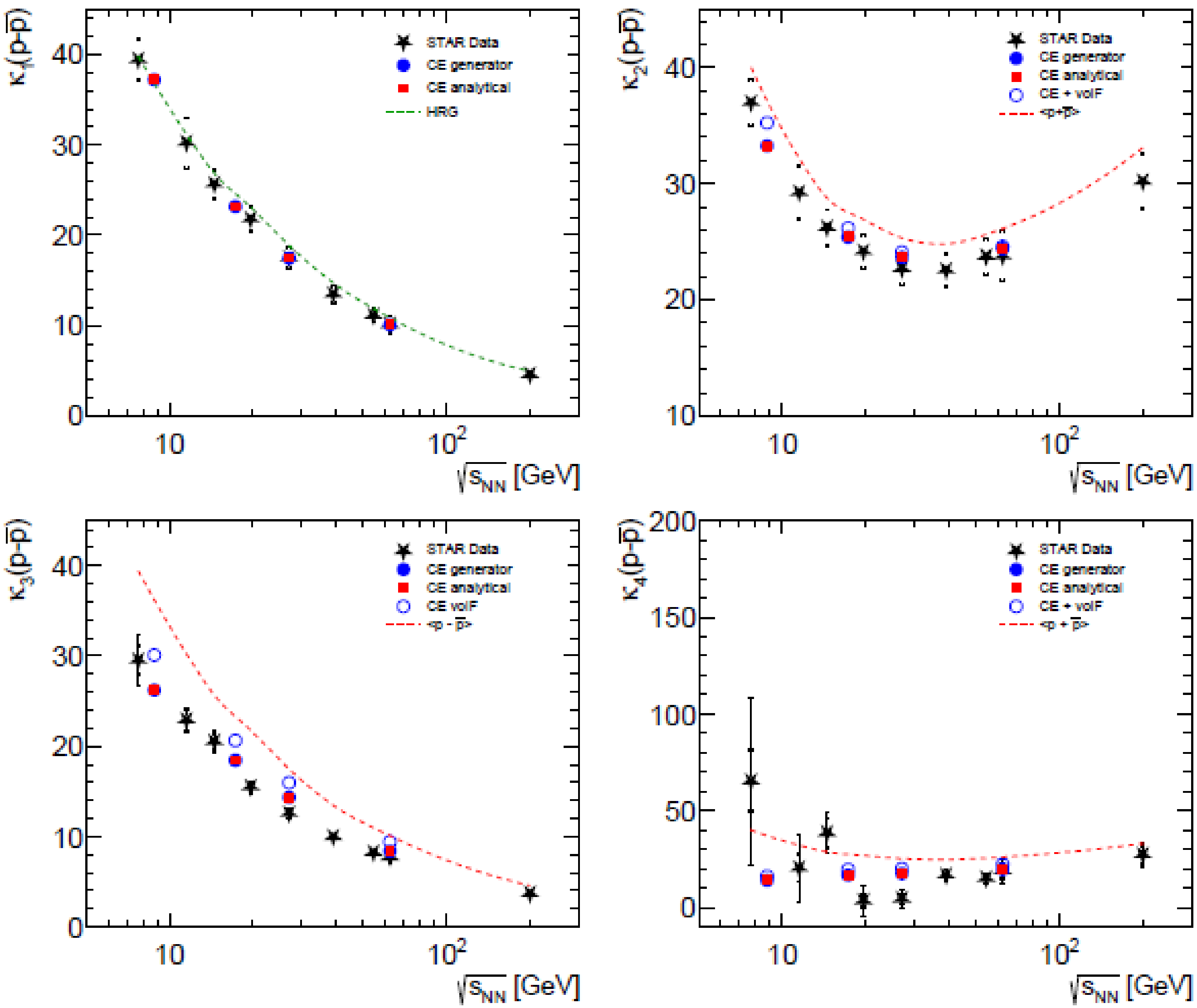




Proton and deuteron yields very well described by thermal model with exact baryon conservation. The shape of ^3He and $^3_\Lambda He$ also well described by canonical suppression. However, yields are off -chemical equilibrium by $\lambda_B \approx 0.45$

Comparison with STAR data

Adam *et al.* arXiv 2001.02852v2



- Broken lines calculated from Skellam distribution, and are consistent with S-matrix HRG results calculated along the chemical freezeout line extracted from HIC HIC data
- Open circle include volume fluctuations

P. Braun-Munzinger, A. Rustamov and J. Stachel, Nucl. Phys. A960, 114 (2017).

V. Skokov, B. Friman and K. Redlich, Phys. Rev. C88, 034911 (2013)