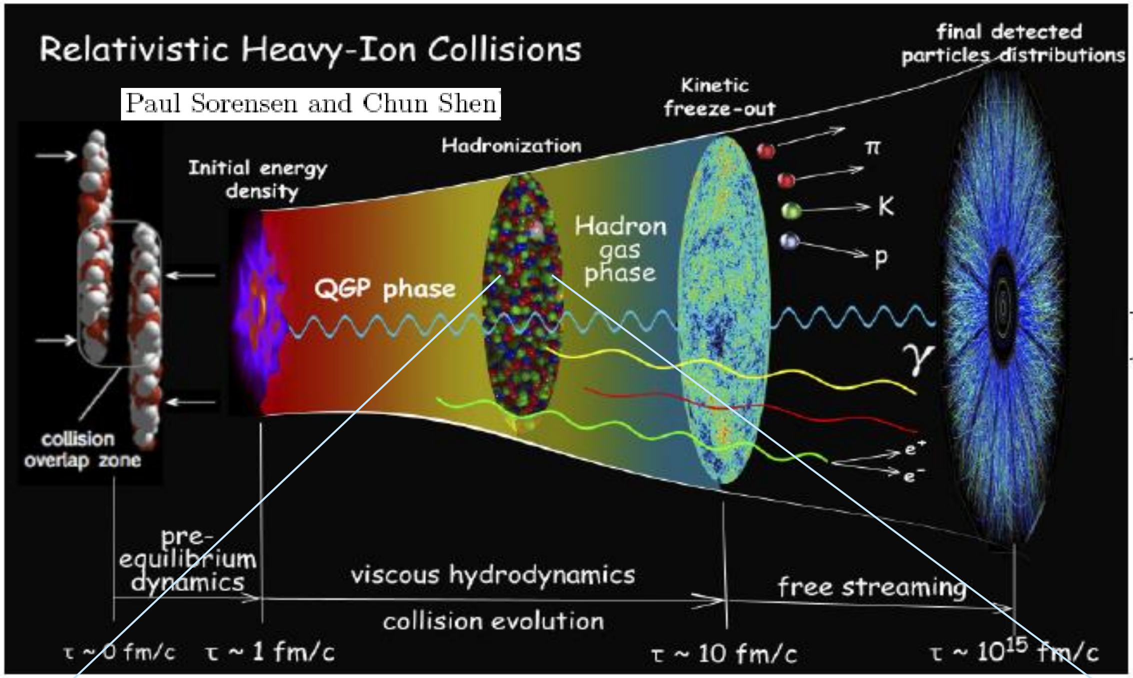
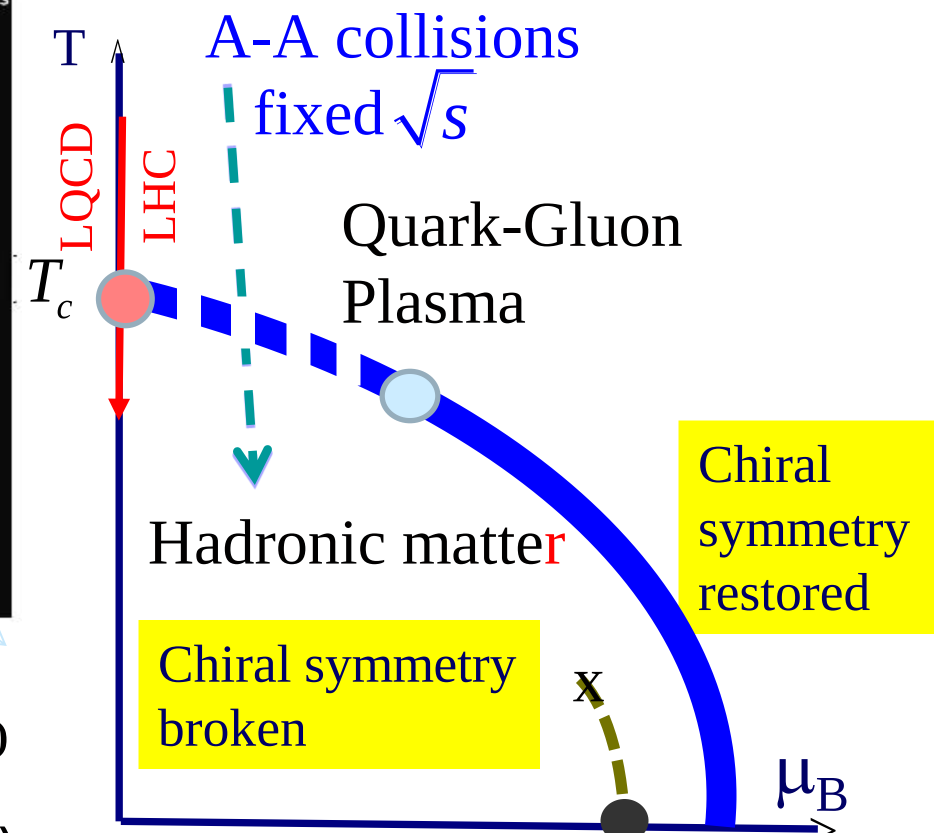
Heavy flavour and light nuclei production at QCD phase boundary





A. Andronic, P. Braun-Munzinger, J. Stachel & K.R., **Nature 561, 302-309 (2018)**

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

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

A. Andronic, P. Braun-Munzinger, M. K. Köhler J. Stachel & K.R, **arXiv:1901.09200**

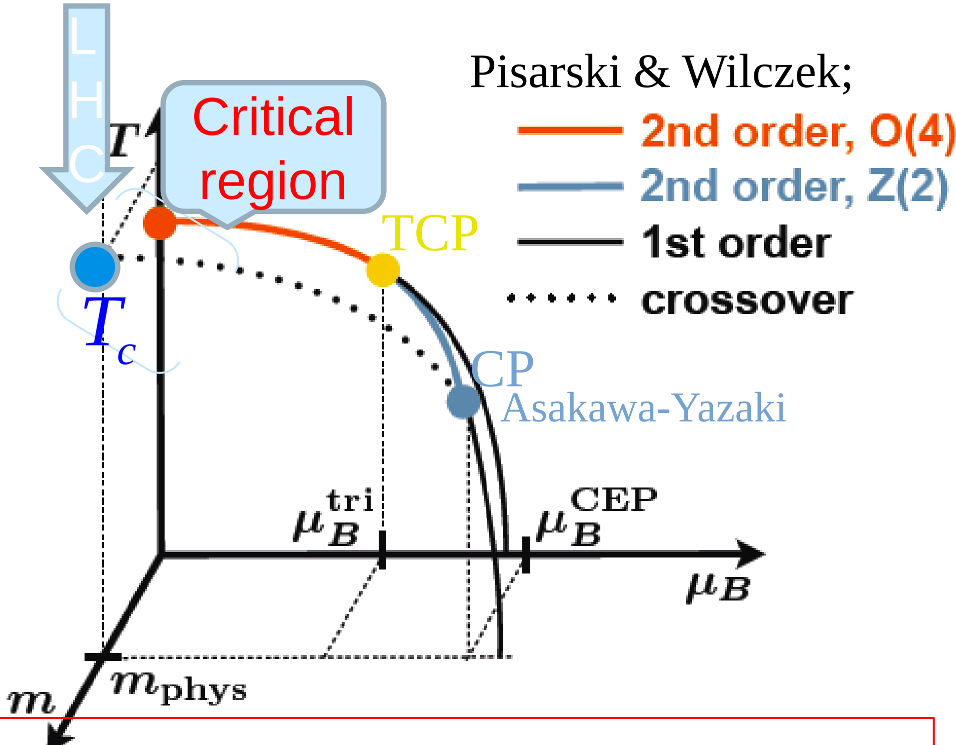
1st principle calculations:

$\mu, T << \Lambda_{QCD}$: χ – perturbation theory

$\mu, T >> \Lambda_{QCD}$: pQCD >

$\mu_q < T$: LGT

Deconfinement and chiral symmetry restoration in LQCD



QCD chiral crossover appears in the critical region of the O(4) universality class

Deconfinement of quarks sets in at the chiral crossover

- The QCD chiral transition is crossover Y.Aoki, et al Nature (2006)
- The chiral transition temperature

$$T_c = 156.5 \pm 1.5 \text{ MeV}$$

P. Steinbrecher et.al. (2018) for HotQCD Coll. 1807.05607 [hep-lat]

- Shift of T_c with chemical potential

A. Lahiri, et al. (2018) for HotQCD Coll

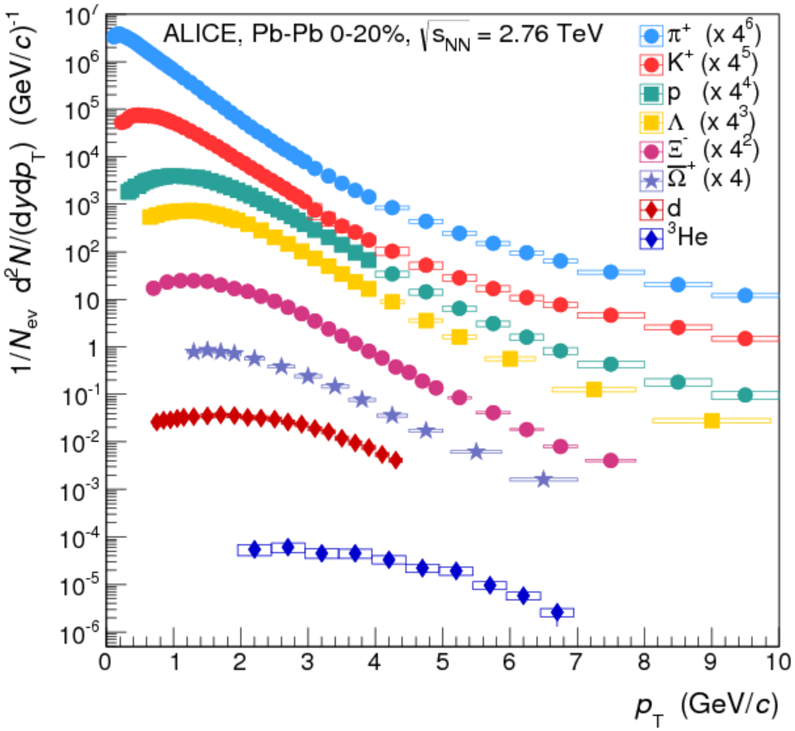
$$T_c(\mu_B) = T_c(0)[1 - \kappa_2 \cdot (\mu_B / T_c)^2 - \kappa_4 \cdot (\mu_B / T_c)^4]$$

$$\kappa_2 = 0.0123 \pm 0.003 \ , \ \ \kappa_4 = 0.00131 \pm 0.004$$

A direct comparison of LHC data and lattice QCD

Can the thermal nature and composition
of the collision fireball in HIC be verified ?

HIC ⟷ **Lattice QCD**



Excellent data of LHC experiments on p_T-distributions and particle pseudo-rapidity densities

- The strategy:

Compare directly measured fluctuations and correlations of conserved charges, (B,Q,S) în HIC at LHC and LQCD results

$$\chi_{ijk}^{BQS} = \frac{\partial^{(i+j+k)}(P)}{\partial \mu_B^i \partial \mu_Q^j \partial \mu_S^k}\Big|_{\vec{\mu}=0} \sim < B^i Q^j S^k > + ..$$

F. Karsch and K. R, Phys. Lett. B 695, 136 (2011) A. Bazavov et al., Phys. Rev. Lett. 109, 192302 (2012):

P. Braun-Munzinger, et al. Nucl.Phys. A956, 805 (2016)

Consider 2nd order fluctuations and correlations of conserved charges to be compared with LQCD

Excellent probe of:

- QCD χ-criticality

A. Asakawa at. al.

S. Ejiri et al.,…

M. Stephanov et al.,

K. Rajagopal,

E. Schuryak

B. Frimann et al.

- EQS in HIC

F. Karsch &

S. Mukherjee et al.,

C. Ratti et al.

P. Braun-Munzinger et al.

- They are quantified by susceptibilities:

If $P(T, \mu_B, \mu_Q, \mu_S)$ denotes pressure, then

$$\frac{\chi_N}{T^2} = \frac{\partial^2(P)}{\partial(\mu_N)^2} \qquad \frac{\chi_{NM}}{T^2} = \frac{\partial^2(P)}{\partial\mu_N \partial\mu_M}$$

$$N = N_q - N_{-q}, \quad N, M = (B, S, Q), \quad \mu = \mu / T, \quad P = P / T^4$$

- Susceptibility is connected with variance

$$\frac{\chi_N}{T^2} = \frac{1}{VT^3}(< N^2 > - < N >^2)$$

- If $\mathrm{P}(N)$ probability distribution of N then

$$< N^n > = \sum_N N^n \mathrm{P}(N)$$

In experiment χ_N are measured from the event by event net charge distributions

Consider 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

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

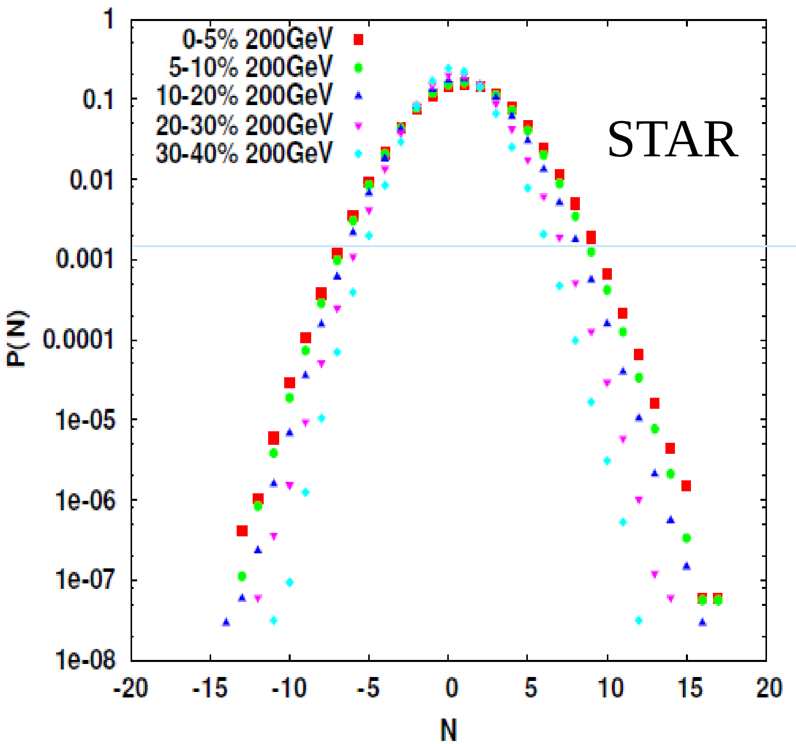
- Then, the susceptibility

$$\frac{\chi_N}{T^2} = \frac{1}{VT^3}(< N_q > + < N_{-q} >)$$

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

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

Variance in AA central coll. at LHC and RHIC

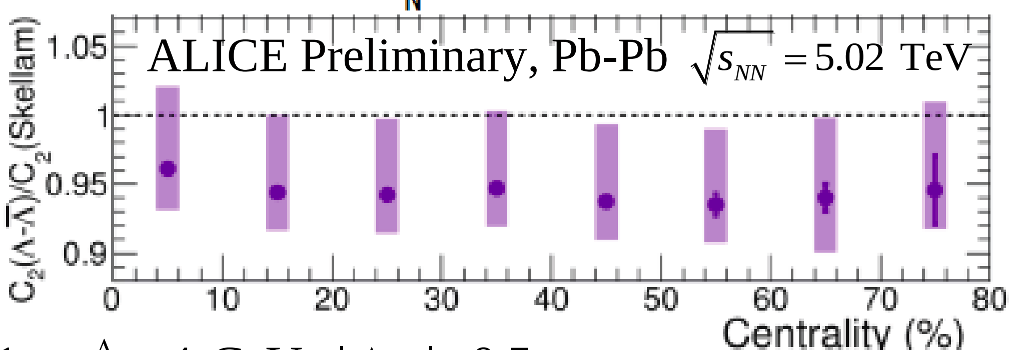


STAR $\chi_{\Delta p}$ data in central coll. 200 GeV

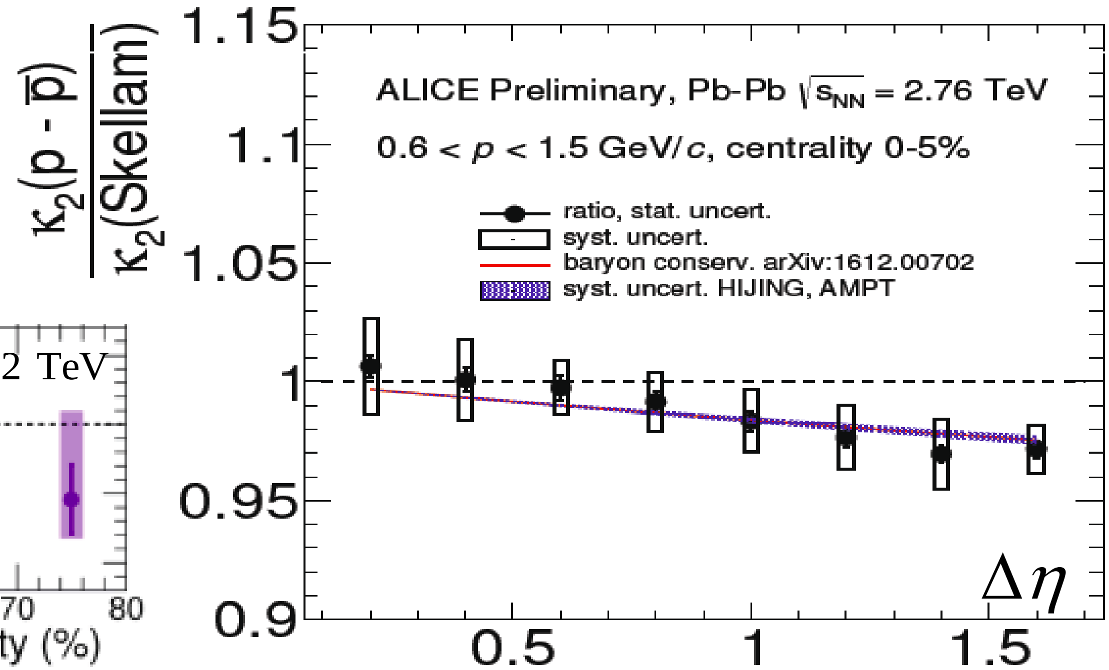
- Consistent with Skellam distribution

$$\frac{<p>+<\overline{p}>}{\chi^2_{\Delta p}} = 1.022 \pm 0.016 \qquad \frac{\chi^1_{\Delta p}}{\chi^3_{\Delta p}} = 1.076 \pm 0.035$$

- ALICE χ_{MN} data consistent with Skellam $|\Delta\eta| < 0.5$



$1 < p_T^{\Lambda} < 4$ GeV $|\Delta\eta| < 0.5$

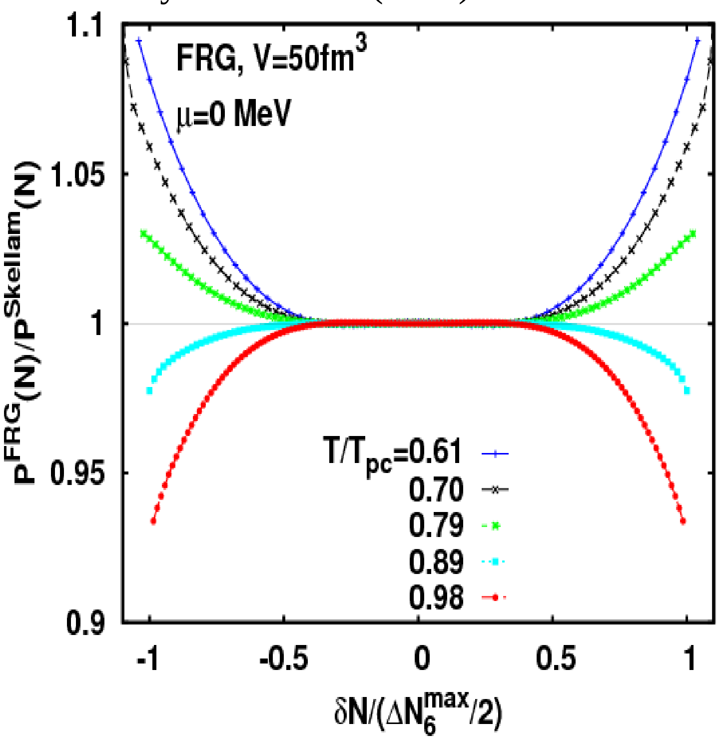


P. Braun-Munzinger, A. Rustamov,

The influence of baryon number conservation: J. Stachel. Nucl Phys. A960 (2017) 114

Variance in AA central coll. at LHC and RHIC

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

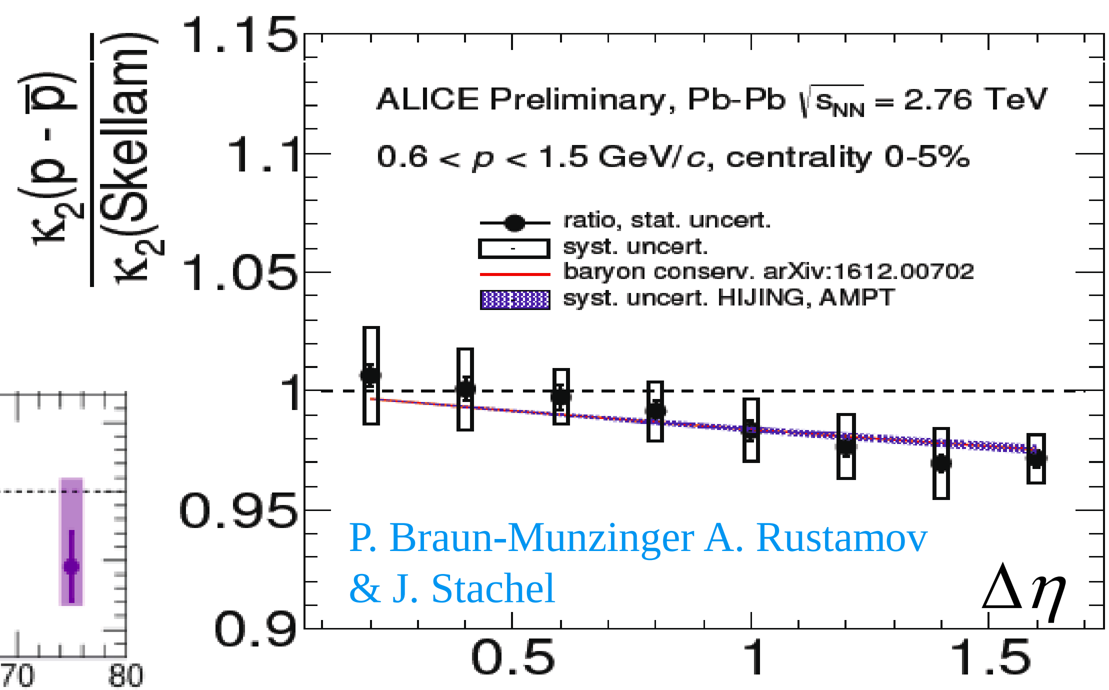


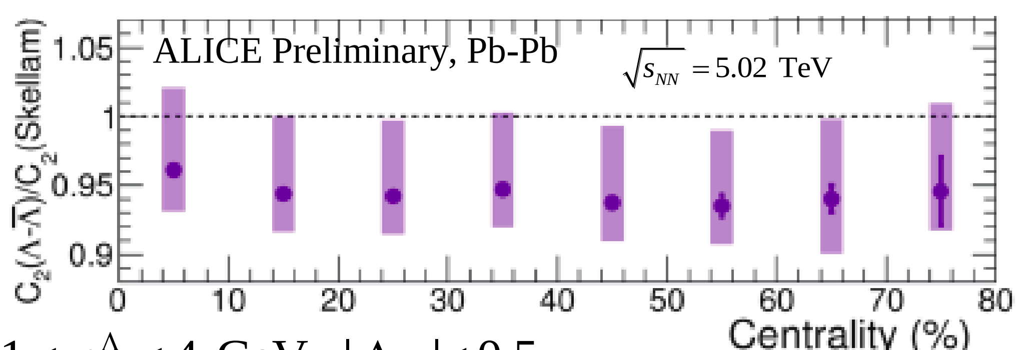
STAR $\chi_{\Delta p}$ data in central coll. 200 GeV

- Consistent with Skellam distribution

$$\frac{<p>+<\bar{p}>}{\chi^2_{\Delta p}} = 1.022 \pm 0.016 \qquad \frac{\chi^1_{\Delta p}}{\chi^3_{\Delta p}} = 1.076 \pm 0.035$$

- ALICE χ_{MN} data consistent with Skellam $|\Delta\eta| < 0.5$



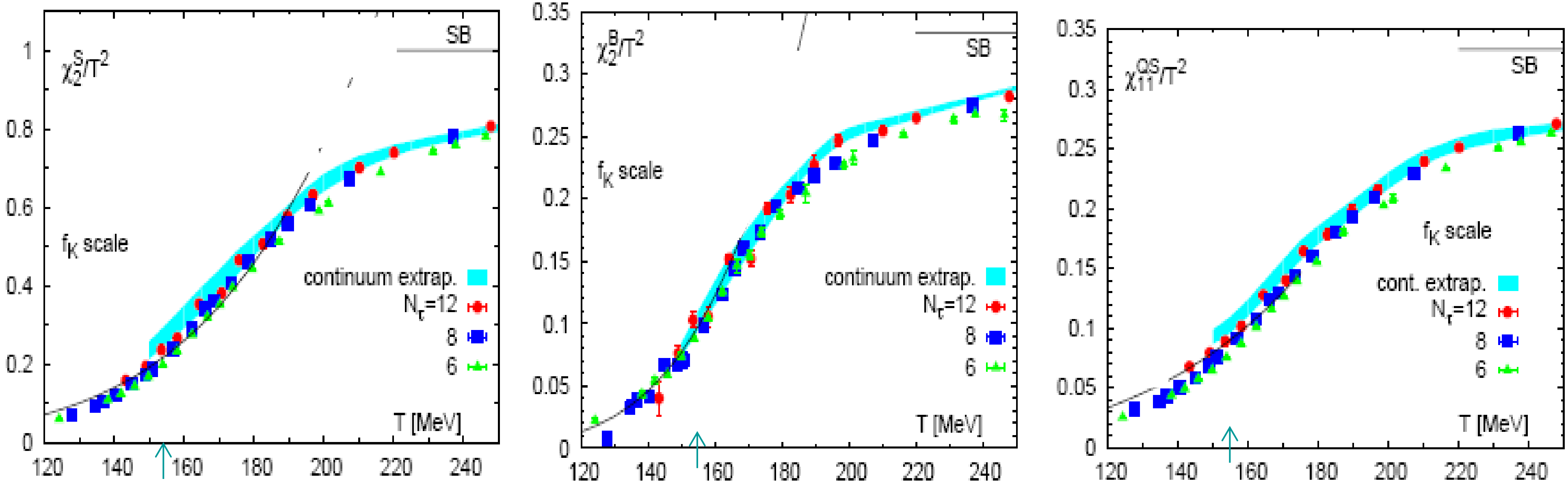


$1 < p_T^{\Lambda} < 4$ GeV $\quad |\Delta\eta| < 0.5$

2nd order fluctuations in LQCD

- 2nd order cumulants of strangeness and net-baryon number fluctuations and charge-strangeness correlation calculated on the lattice and extrapolated to the continuum limit.

A. Bazavov, et al. HotQCD Coll (2014).



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

$$\frac{\chi_N}{T^2} = \frac{1}{VT^3}(< N_q > + < N_{-q} >)$$

Direct comparisons of Heavy ion data at LHC with LQCD

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

$$\frac{\chi_B}{T^2} \approx \frac{1}{VT^3}(\langle p\rangle + \langle N\rangle + \langle \Lambda + \Sigma_0\rangle + \langle \Sigma^+\rangle + \langle \Sigma^-\rangle + \langle \Xi^-\rangle + \langle \Xi^0\rangle + \langle \Omega^-\rangle + \overline{par}\ )$$

LQCD From ALICE DATA

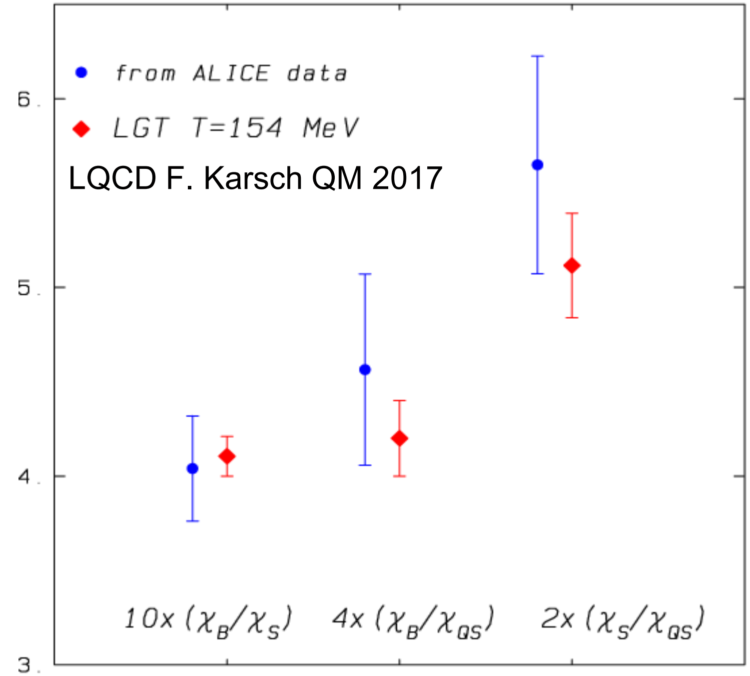
$$\frac{\chi_B}{T^2} = \frac{1}{VT^3}(203.7 \pm 11.4)$$

$$\frac{\chi_S}{T^2} = \frac{1}{VT^3}(504.2 \pm 16.8)$$

$$\frac{\chi_{QS}}{T^2} = \frac{1}{VT^3}(191.1 \pm 12)$$

- 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

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

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

Modelling QCD thermodynamic potential in hadronic phase

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

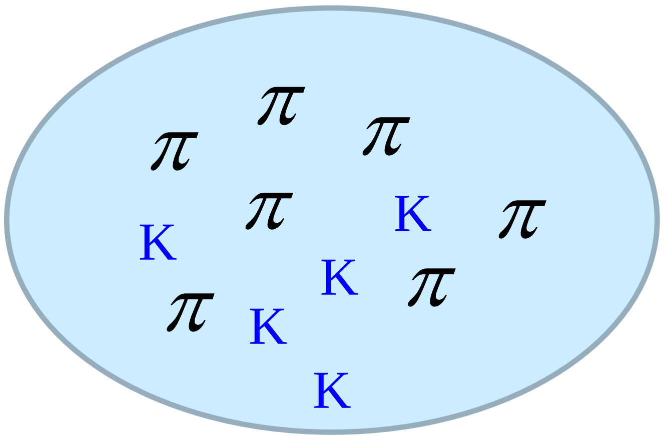
- Interactions driven by narrow resonance of mass M_R

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

- For non-resonance interactions or for broad resonances $P_{ab}^{\text{int}}(T)$ should be linked to the phase shifts

S-MATRIX APPROACH

Thermal system at fixed T



- Consider interacting pions and kaons gas in thermal equilibrium at temperature T
- Due to *K*π scattering resonances are formed

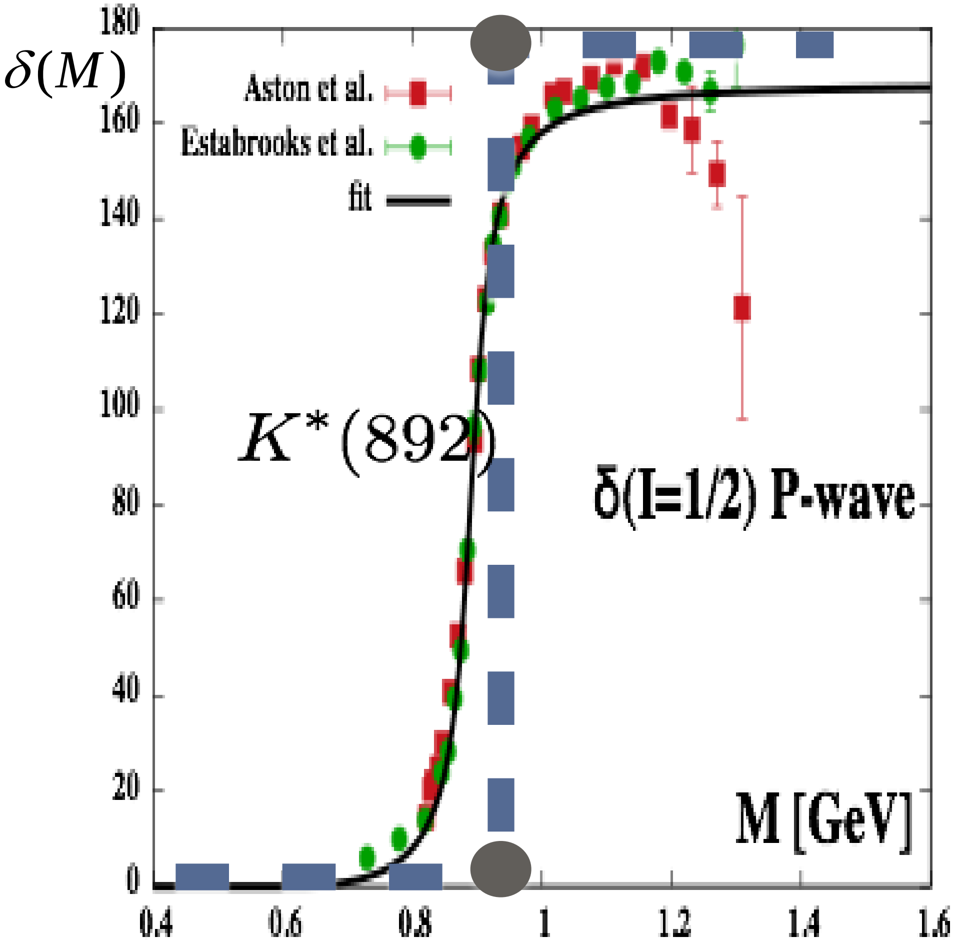
  I =1/2, s -wave : κ(800), K0*(1430) [*JP* = 0+]

  I =1/2, p -wave : *K**(892), *K**(1410), *K**(1680) [*JP* =1−]

  I =3/2 purely repulsive interactions
- In the S-matrix approach the thermodynamic pressure in the low density approximation

$$P(T) \approx P_{\pi}^{id} + P_{K}^{id} + P_{\pi K}^{\text{int}}$$

Experimental phase shift in the P-wave channel



B. Friman, P. M. Lo, M. Marczenko, K. Redlich and C. Sasaki, Phys. Rev. D 92, no. 7, 074003 (2015)

For narrow resonance

$$B(M) = 2\frac{d}{dM}\delta(M)$$

very well described by the Breit-Wigner form

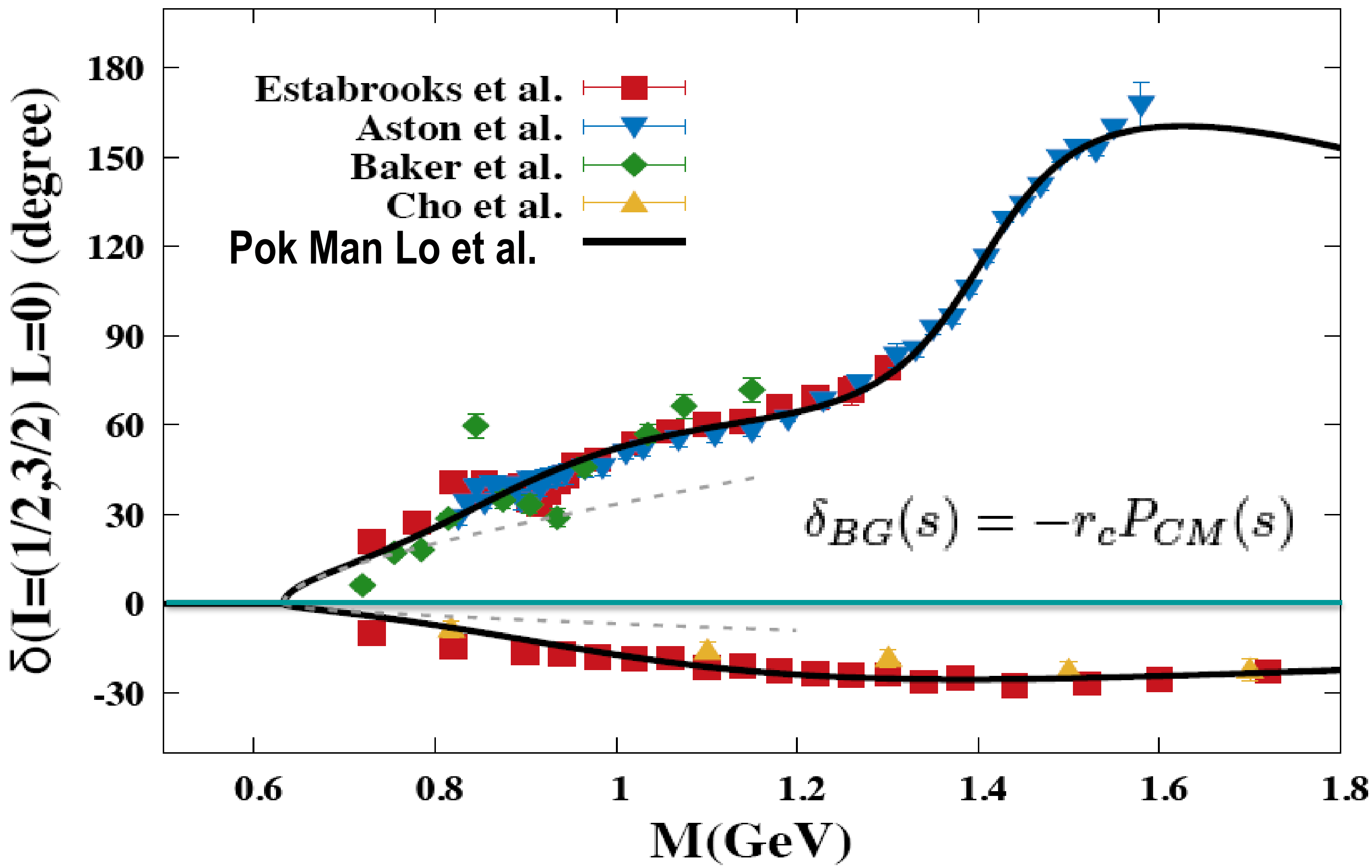
$$B(M) \approx M\frac{2M\gamma_{\mathrm{BW}}}{(M^2 - M_0^2)^2 + M^2\gamma_{\mathrm{BW}}^2}$$

for $\gamma_{BW} \to 0$

$$B(M) = \delta(M^2 - M_0^2)$$ **and**

$$P_{\pi K}^{\mathrm{int}}(T) \approx P_{K^*}^{id}(T)$$

Non-resonance contribution- negative phase shift in S-wave channel



$$\delta_0^{1/2} = \delta_\kappa + \delta_{K_0^*} + \delta_{BG}.$$

$$B(M) = 2\frac{d}{dM}\delta(M)$$

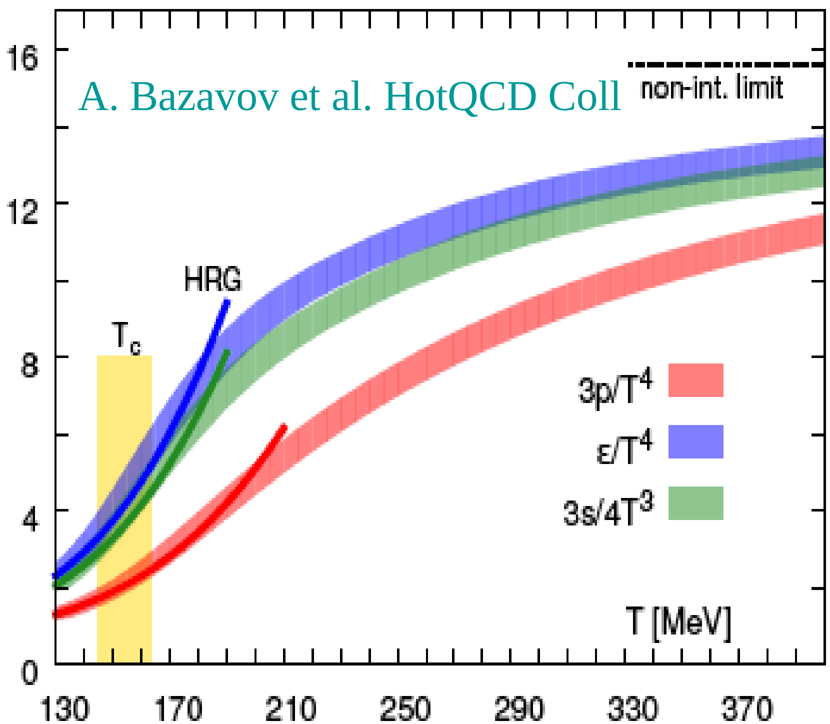
$$P_{\pi K}^{\text{int}}(T)$$

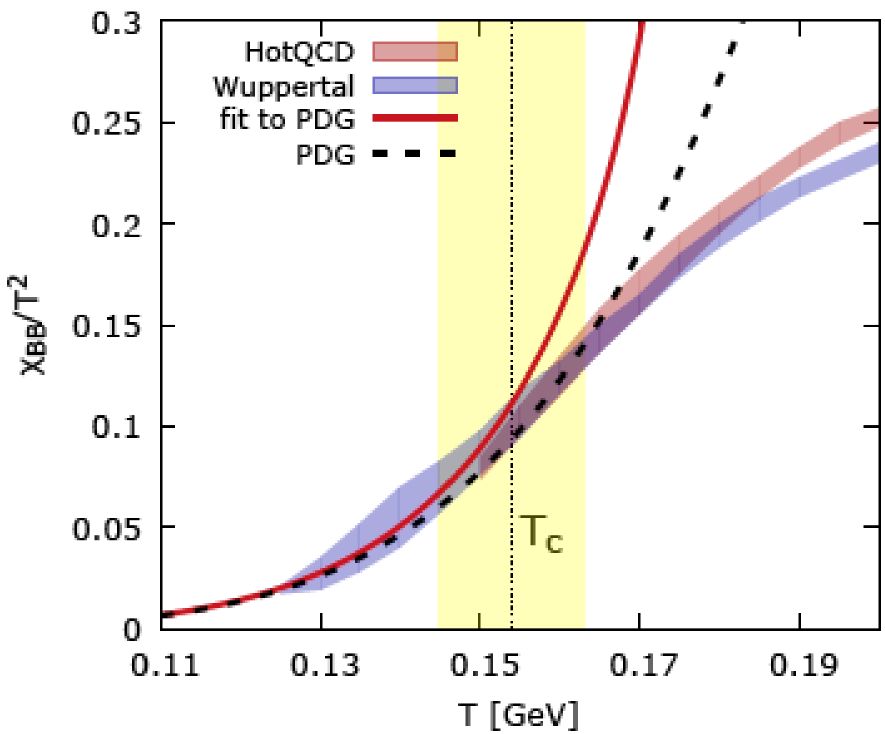
Quark-Hadron duality near the QCD phase boundary

The HRG is a 1st order approximation of the QCD EQS in confined phase

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

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





- Hadron Resonace Gas thermodynamic potential provides an excellent 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

Charm and strangeness deconfinement in LQCD

Ratios of cumulants

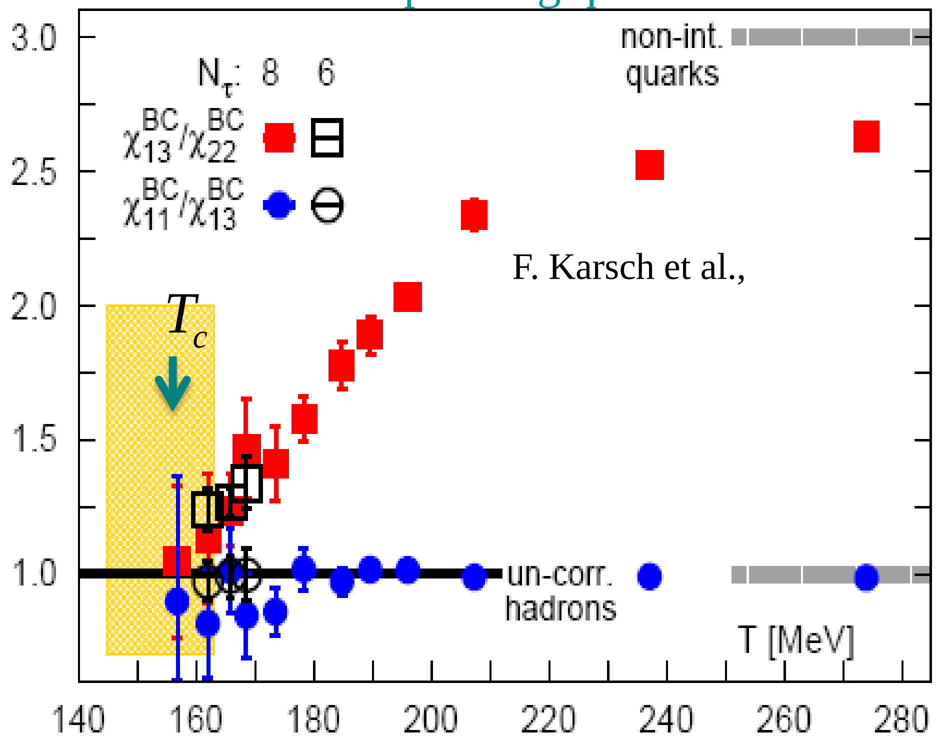
$$\chi_{n,m}^{B,C} = \frac{1}{T^4} \frac{\partial^{(n+m)} P(\mu_B, \mu_C)}{\partial \mu_B^n \partial \mu_C^m} |_{\mu=0}$$

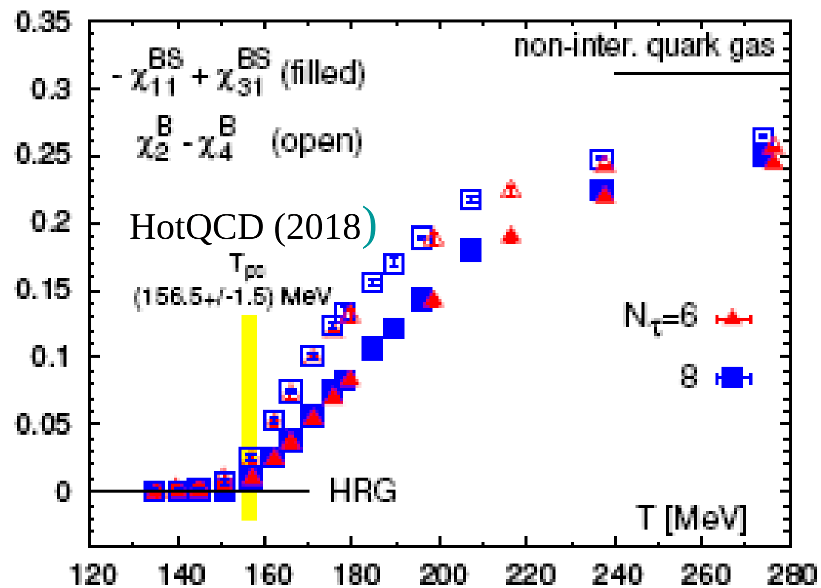
are sensitive to the degrees of freedom that are carriers of the corresponding quantum numbers

Factorized pressure in HRG and QGP

$$P(T, \vec{\mu}) \simeq F(m/T) \cdot \cosh(B\mu_B + C\mu_C + S\mu_S)$$

$$\frac{\chi_{1,3}^{B,C}}{\chi_{2,2}^{B,C}} \approx \frac{C}{B} = \begin{cases} 1 & T < T_c \\ 3 & T \gg T_c \end{cases}$$





- Deconfinement of open charm and strange hadrons sets in just at the chiral crossover transition. Common hadronization T for all flavour hadrons.

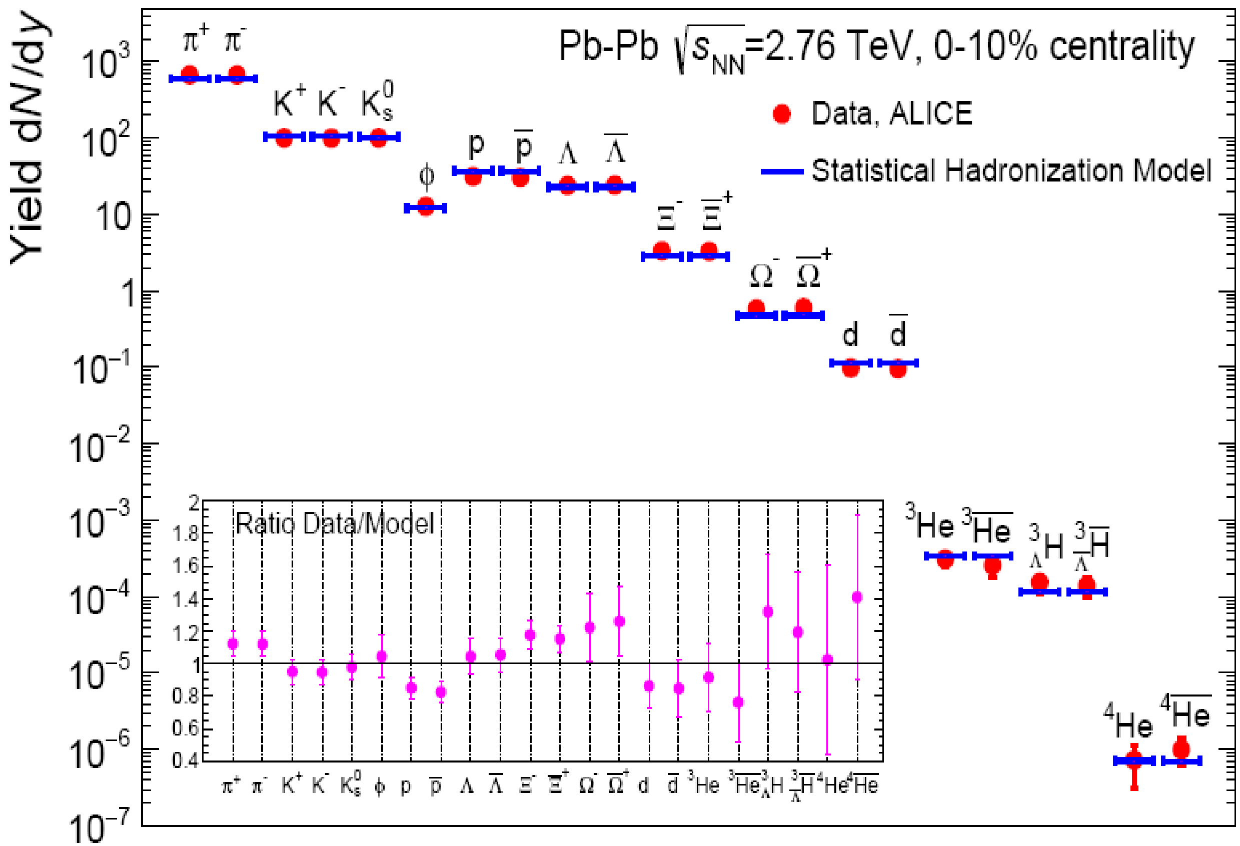
Thermal origin of particle yields and production at T_c

Apply the Hadron Resonance Gas (HRG) partition function as an excellent approximation of QCD statistical operator in the hadronic phase,

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

$$\frac{<N_i>}{V} = n_i^{th}(T,\vec{\mu}) + \sum_K \Gamma_{K\to i} n_i^{Res.}(T,\vec{\mu})$$

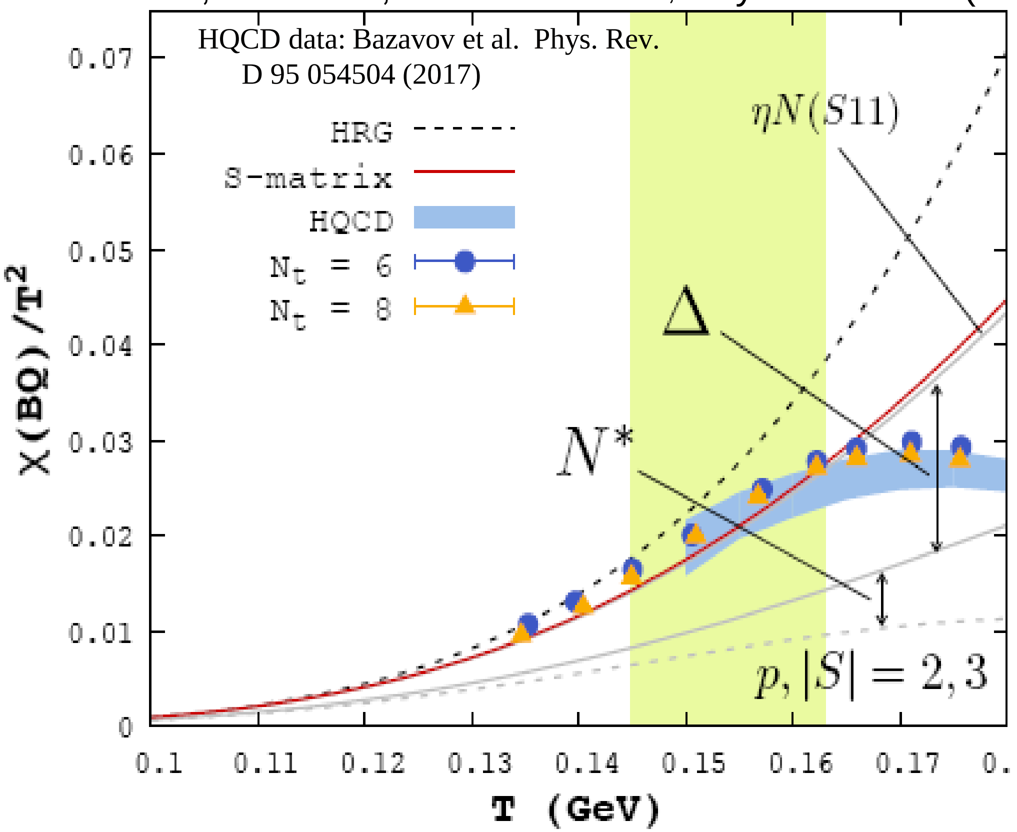
A. Andronic, P. Braun-Munzinger, J. Stachel & K.R., Nature 561 (2018)



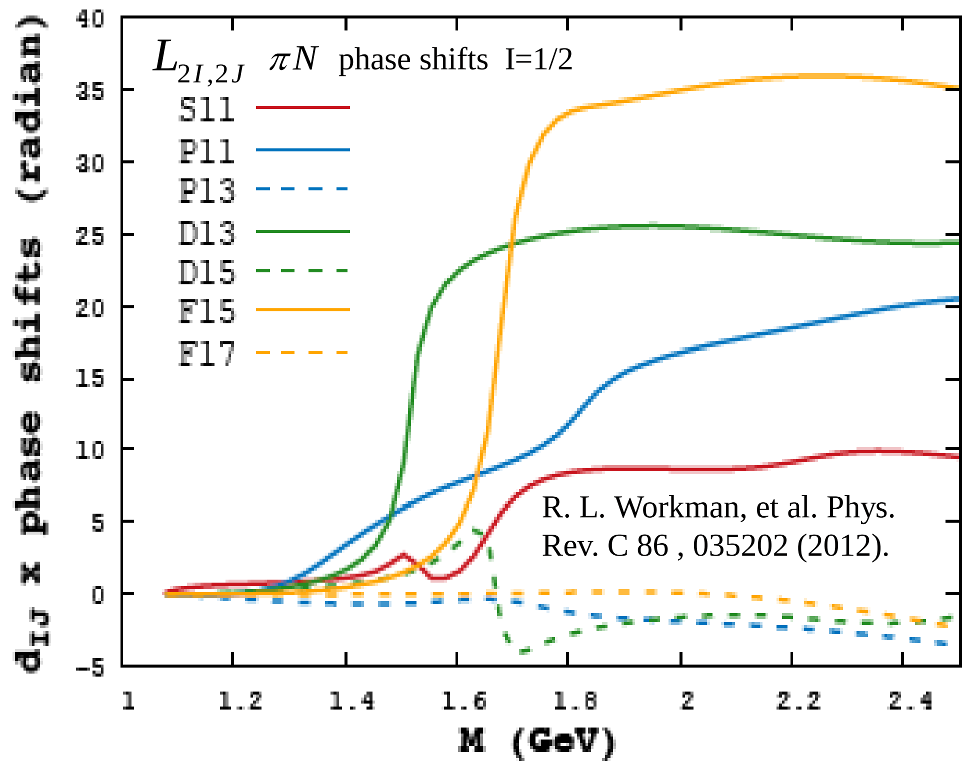
- Measured yields are well reproduced at
  $T \approx 156\ MeV$
  $\mu_B = 0.7 \pm 3.8$ MeV
  $\chi^2/\text{dof} = 19.7/19$
- The fireball created in central A-A collisions is QCD matter in equilibrium
  Hadrons are produced at QCD phase boundary

Probing non-strange baryon sector in πN- system

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



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

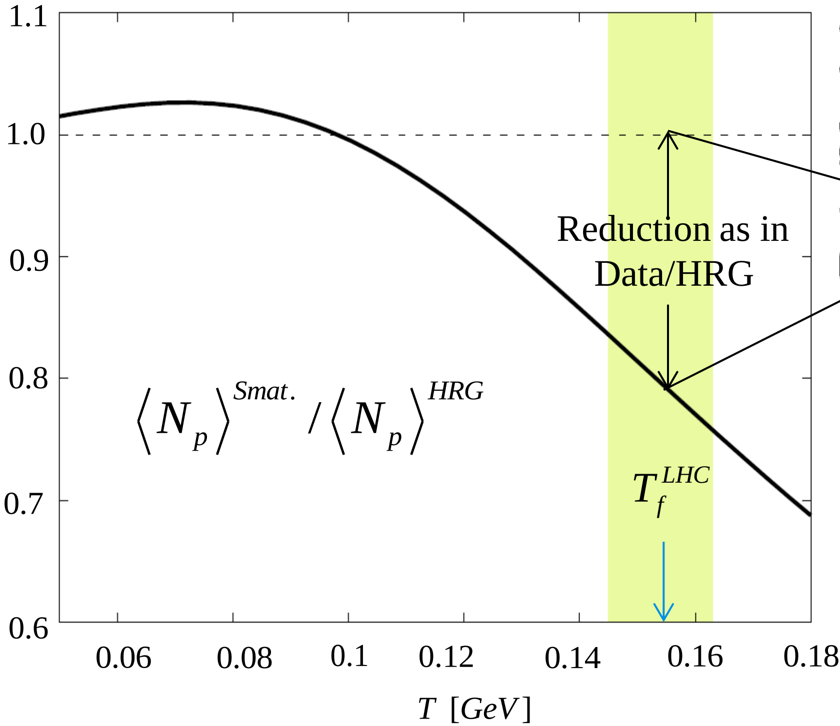


$$\Delta\chi_{BQ} \approx \sum_{I_z,j,B} d_j BQ \int dM \int d^3p \frac{1}{T}\frac{d\delta_j^I}{dM} \times e^{-\beta\sqrt{p^2+M^2}} (1+e^{-\beta\sqrt{p^2+M^2}})^{-2}$$

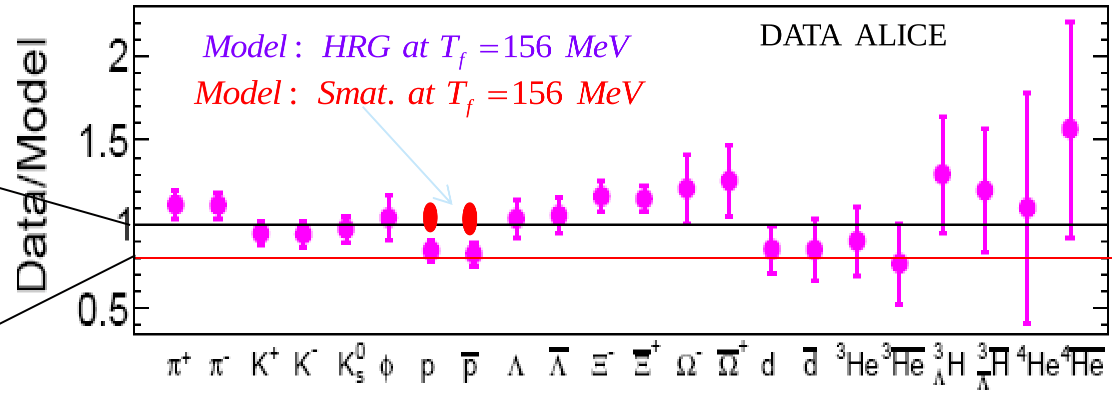
- Considering contributions of all πN $\delta_j^{I=(1/2),\ (3/2)}$ $(N^*, \Delta^*$resonances) to χ_{BQ} within S-matrix approach, reduces the HRG predictions towards the LQCD in the chiral crossover $0.15 < T < 0.16\ GeV$

S-matrix Phenomenological consequences: proton production

see: A. Andronic, P. Braun-Munzinger, B. Friman, Pok Man Lo, J. Stachel & K.R. **Phys.Lett. B792 (2019) 304**

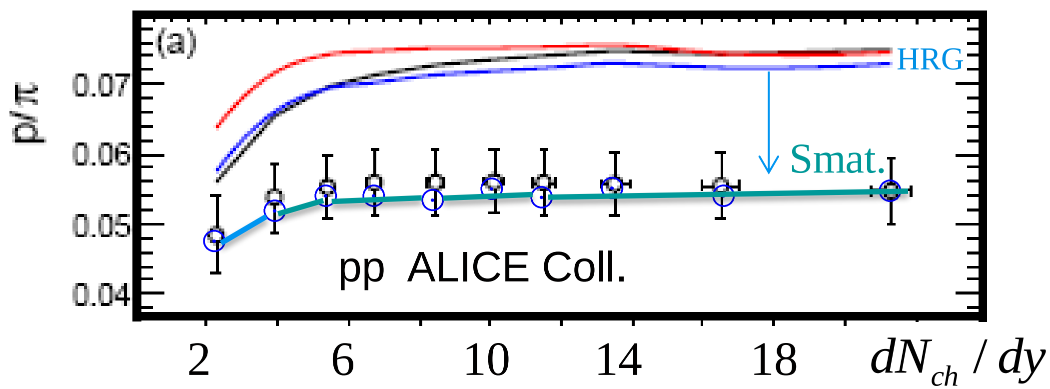


- Yields of protons in the S-matrix is suppressed relative to HRG



- Yields of protons in AA collisions at LHC is consistent with S-matrix result within 1σ

HRG: N. Sharma, J. Cleymans, B. Hippolite, arXiv: 1803.05409



For further consequences of smat. See also: P. Huovinen, P. Petreczky Phys. Lett. B77 (2018)

- S-matrix results well consistent with pp data

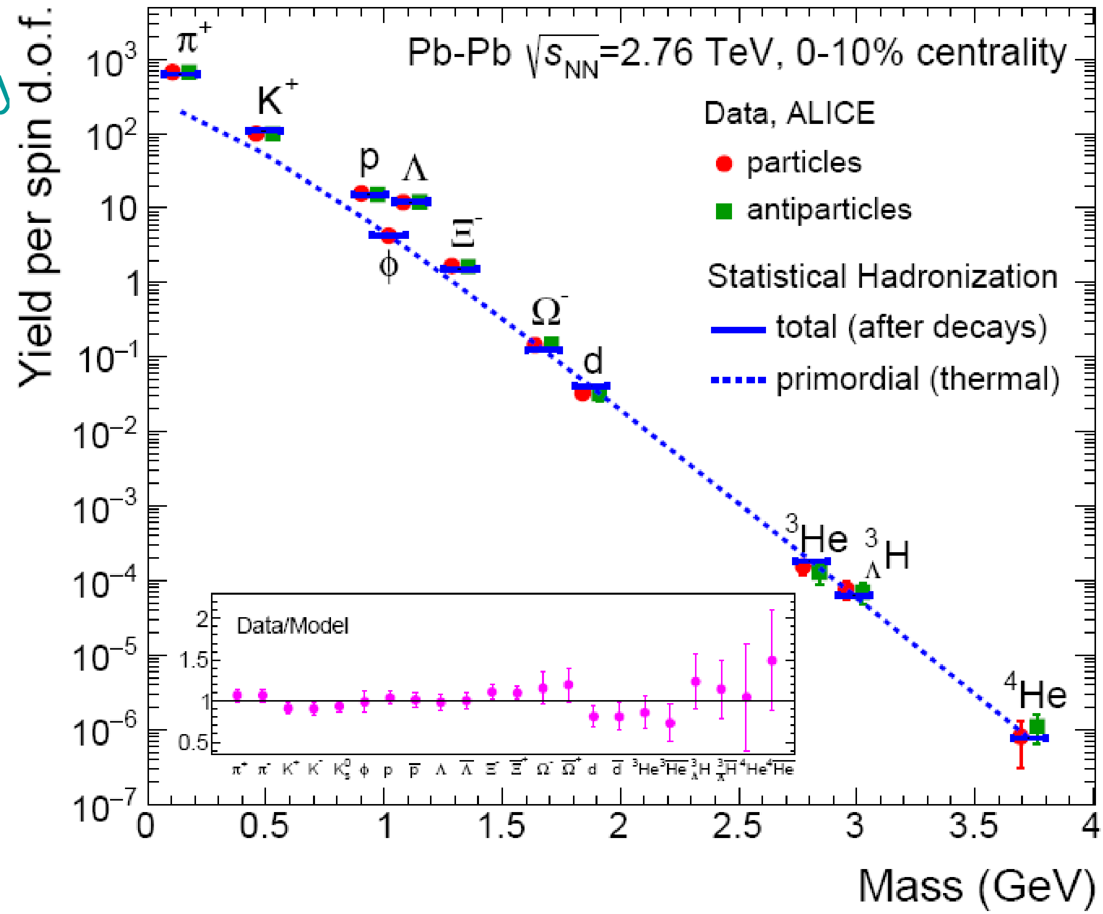
Systematics of prompt hadron production

A. Andronic, et al. Nature 561 (2018)

Particle yields with no resonance decay contributions scale with their mass

$$\frac{1}{2j+1}\frac{dN}{dy} \approx V(m/T)^{3/2}\exp(-m/T)$$

- How can the loosely-bound states like deuteron or hyper-triton survive at such high T ?



$$T = 156.5 \pm 1.5 \text{ MeV}$$

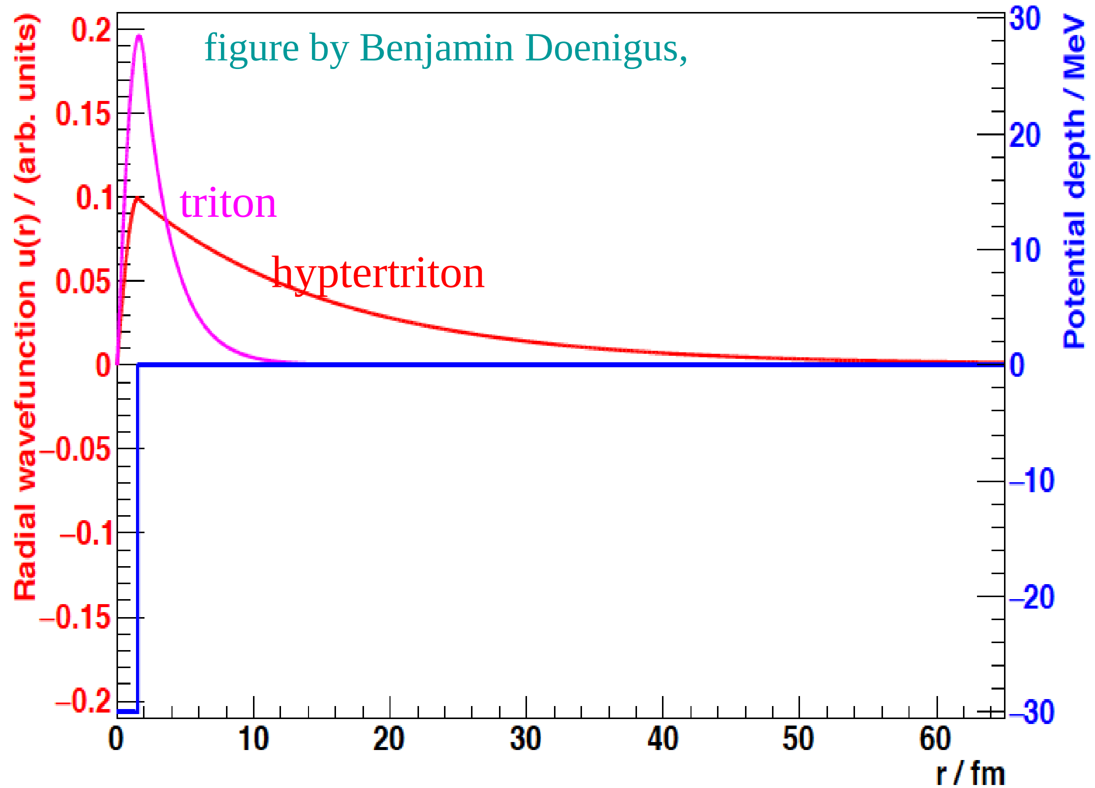
(a)Hyper-triton yields fixed at the QCD phase boundary

- Mass = 2990 MeV, Binding energy = 2.3 MeV
- Λseparation energy = 0.13 MeV
- Molecular structure: (p+n) + Λ
- rms radius =rms separation between d and Λ = 10.6 fm
- hypertriton = pnΛ= d Λ is the ultimate halo state

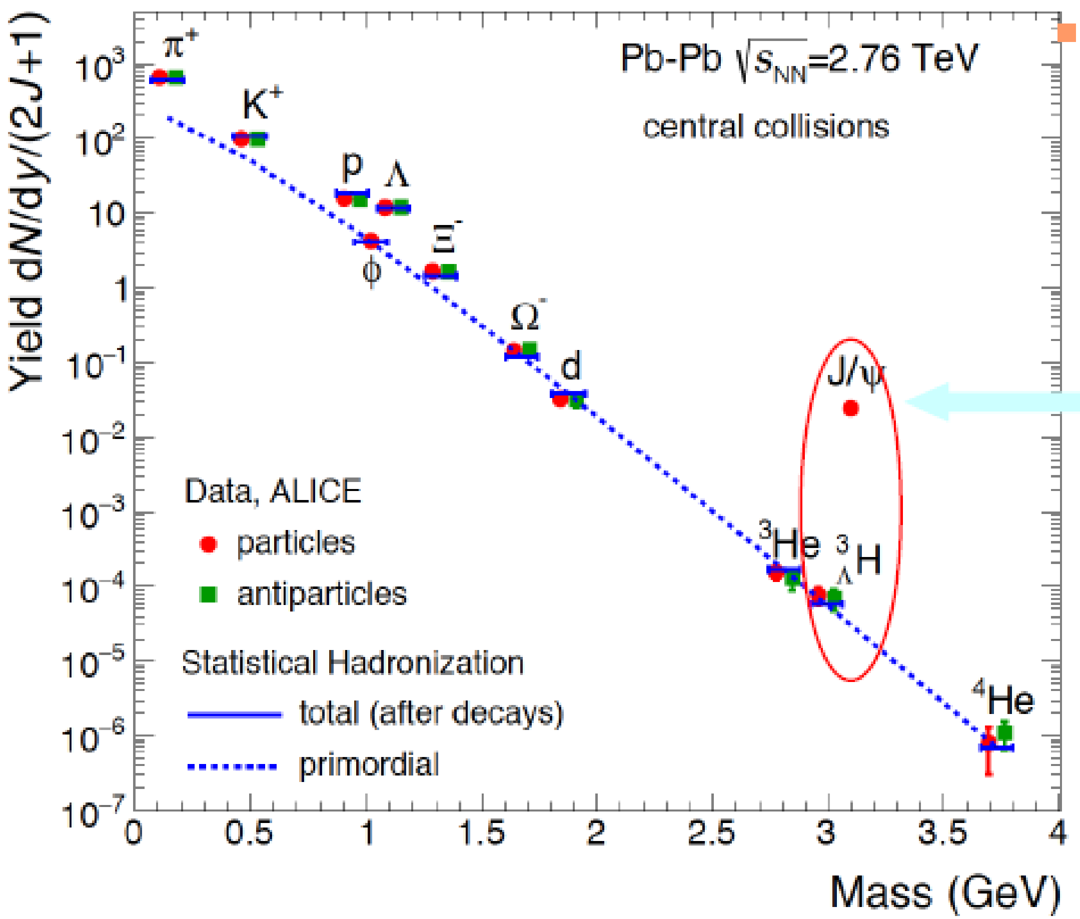
Yet production yield is fixed at 156 MeV temperature (about 1000 x separation energy.)

Hypothesis: all nuclei and hyper-nuclei are formed as compact multi-quark states at the phase boundary. Then slow time evolution into hadronic representation.

Andronic, Braun-Munzinger, Stachel, K.R. Nature 561 (2018)



Quarkonium and the QCD phase boundary

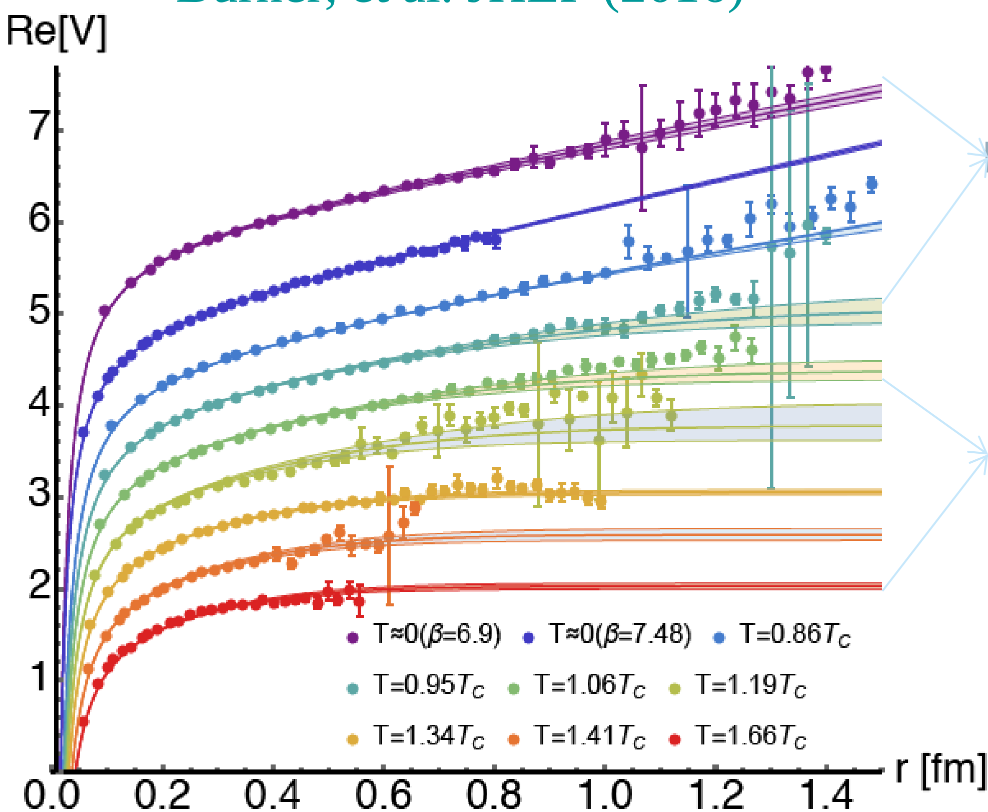


- J/psi mass close to hypertriton and yet its yield does not follow the light hadron production systematics at the QCD phase boundary

Where does the 3 orders of magnitude enhancement come from?

Heavy Quark potential and screening in QGP

Burner, et al. JHEP (2016)



Heavy quark $Q\bar{Q}$ potential V(r)

at $T < T_c$ confined potential

$$V(r) = -\alpha / r + \sigma r$$

at $T > T_c$ color screening

$$V(r) = \frac{-\alpha}{r} e^{-r m_D(T)}$$

T. Matsui & H. Satz: color screening prevents $Q\bar{Q}$ binding in QGP.

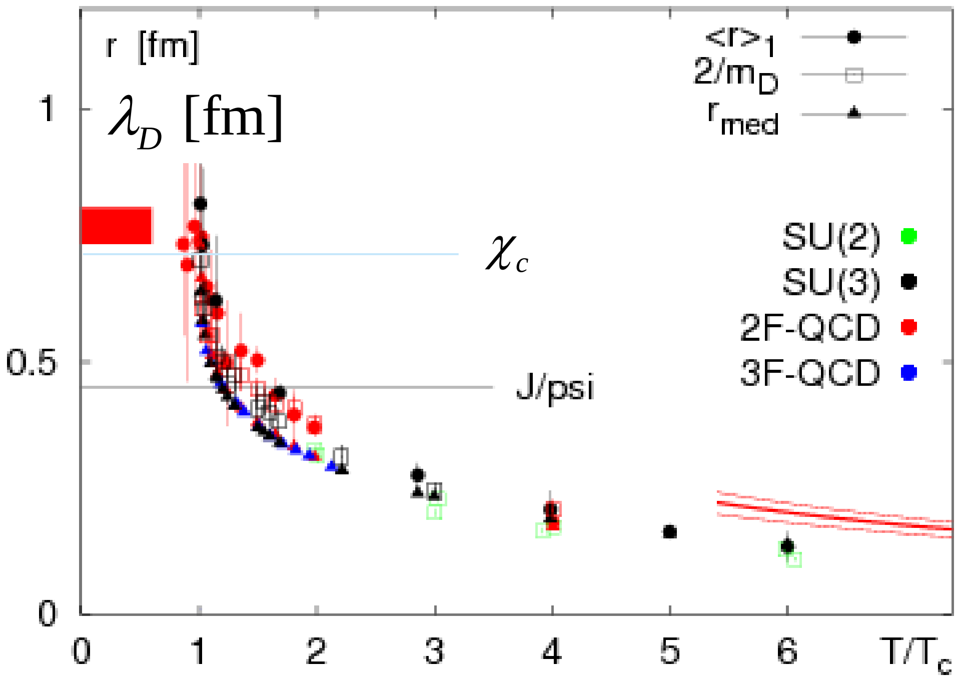
Phys.Lett. B178 (1986) Predicted suppression of quarkonium in nuclear collisions as a signature of deconfined medium

Debye screening and Quarkonium in QGP

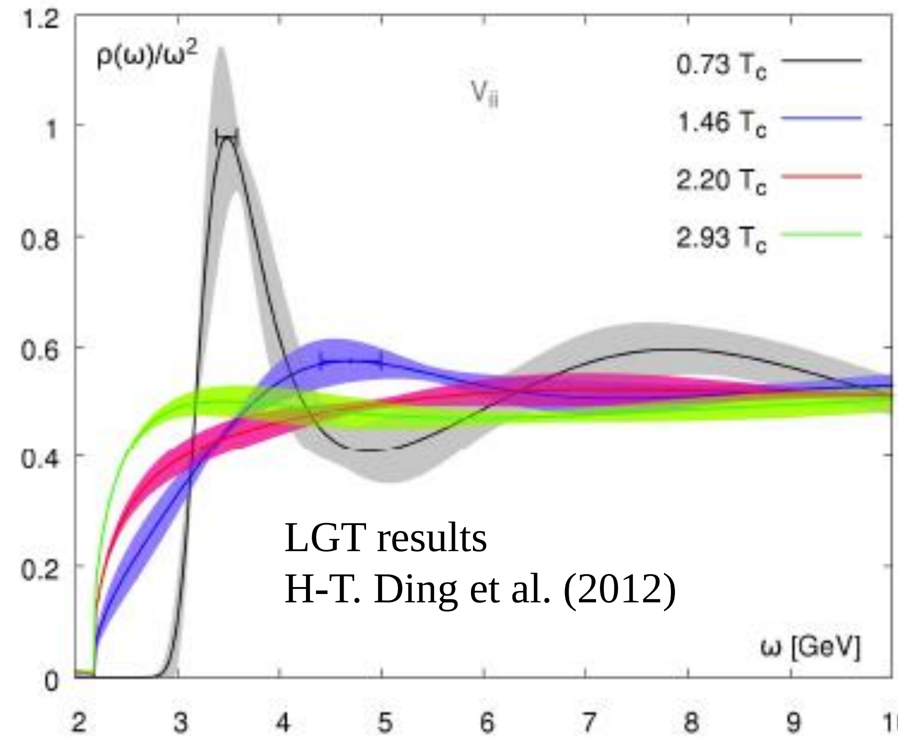
Debye screening: Quarkonium dissociation if Debye length $\lambda_D < r^{rms}_{J/\psi}$ where $\lambda_D(T) \approx 1/m_D$

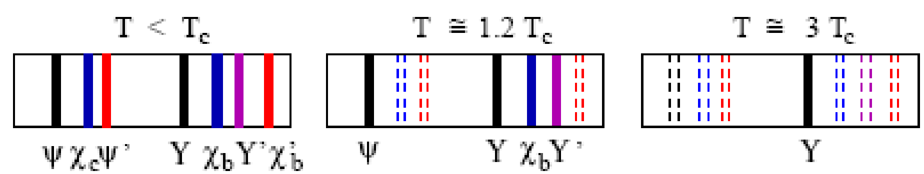
In QGP Sequential melting of Quarkonia

$$r^{rms}_{\psi'} \approx 1.1\,fm \quad r^{rms}_{\chi_c} \approx 0.8\,fm \quad r^{rms}_{J/\psi} \approx 0.5\,fm$$



Spectral function of $c\bar{c}$ in vector channel





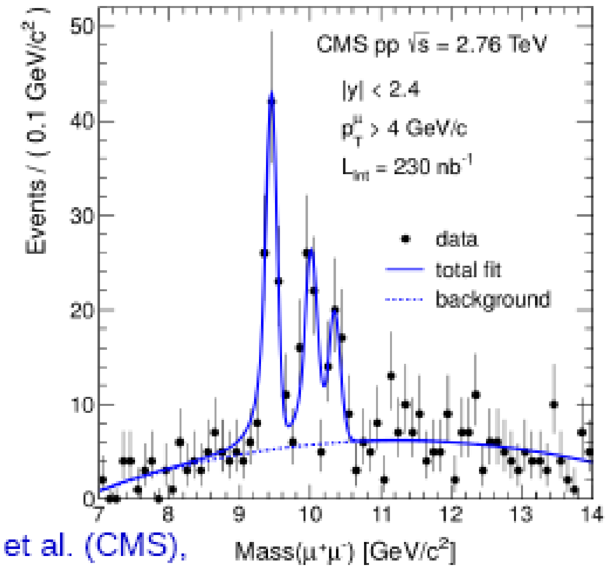
1st observation of J/ψ suppression in Pb-Pb collisions at 158 A GeV by NA50 Collaboration:

Thermal botomonium melting in CMS data?

bottomonium melting

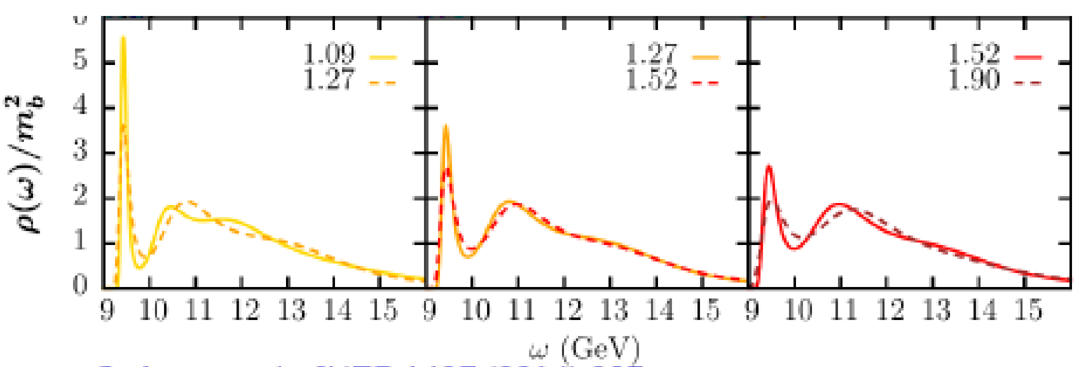
states	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$
$T_{\rm melt}^{\Gamma=E_{\rm bind}}/T_C$	$2.66^{+0.49}_{-0.14}$	$1.25^{+0.17}_{-0.05}$	$1.01^{+0.03}_{-0.03}$	< 0.95

Y. Burnier, O. Kaczmarek, A. Rothkopf, JHEP 1512 (2015) 101

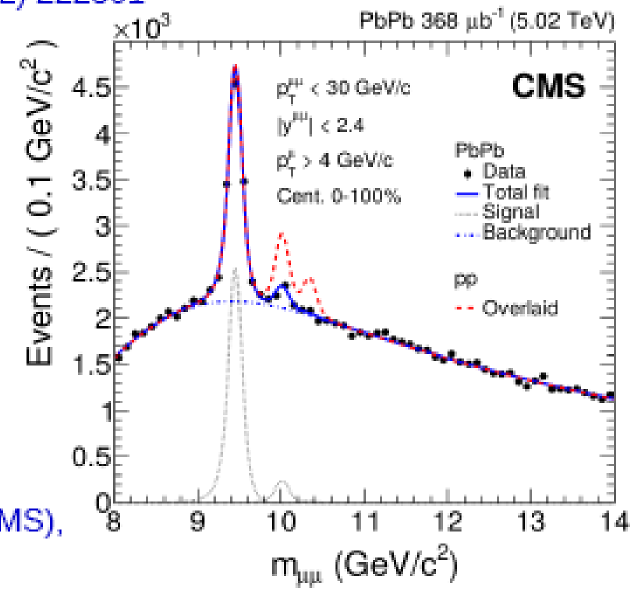


S. Chatrchyan et al. (CMS), PRL 109 (2012) 222301

Lattice QCD spectral functions



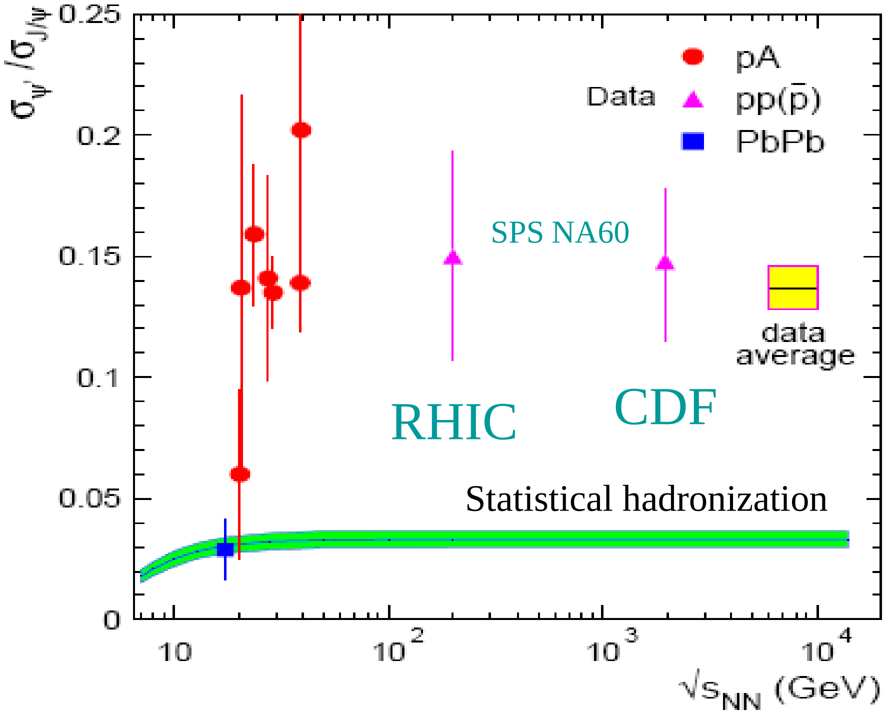
G. Aarts et al., JHEP 1407 (2014) 097



A.M. Sirunyan et al. (CMS), arXiv:1706.05984

Quarkonium produced at the phase boundary

- Drop of the $\psi(2s)/\psi(1s)$ from elementary to AA collisions at SPS indicates their different production dynamics



At SPS heavy ion data consistent with the statistical production of ψ at the same temperature as all other hadrons

$$\frac{\psi(2s)}{\psi(1s)} \approx \frac{d_2}{d_1}\left(\frac{m_2}{m_1}\right)^2 \frac{K_2(m_2/T)}{K_2(m_1/T)}$$

- The concept of charmonium regeneration at the QCD phase boundary was first proposed by P. Braun-Munzinger & J. Stachel (2000).

Thermal charm regeneration at the phase boundary

P. Braun-Munzinger, J. Stachel, Phys. Lett. B 490, 196 (2000)

- Charm quarks are produced in initial hard scattering, their number $N_{c\bar{c}}^{in}$ obtained from total charm cross section
- Quarks thermalize in QGP and hadronize at the phase boundary
- The number of initial quark pairs after hadronization at T_c is preserved which is imposed by the balance equation with fugacity $g_c(T_c, N_{c\bar{c}}^{in})$

$$N_{c\bar{c}}^{in} = V g_c (n_D^{th}(T) + n_\Lambda^{th}(T) + ..) + g_c^{\,2} (n_{\psi(1s)}^{th}(T) + n_{\psi(2s)}^{th}(T) + ..) N_{J/\psi}^{th}$$

where $n_k^{th}(T) = (d/2\pi^2) m_k^{\,2} T K_c(m_k/T)$, corrected by canonical suppression if needed

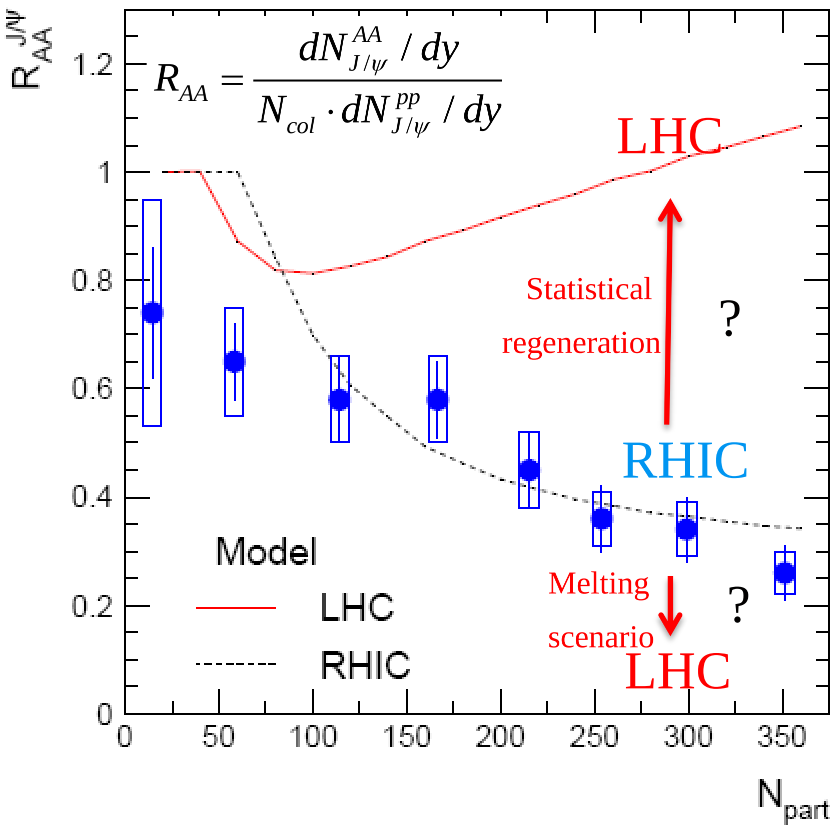
- The yield of charmonia $\psi = J/\psi,\ \psi^{'}, ..$ at T_c is obtained as

$$N_\psi = V g_c^{\,2}(T, N_{c\bar{c}}^{in})\, n_\psi^{th}(T, m_\psi)$$

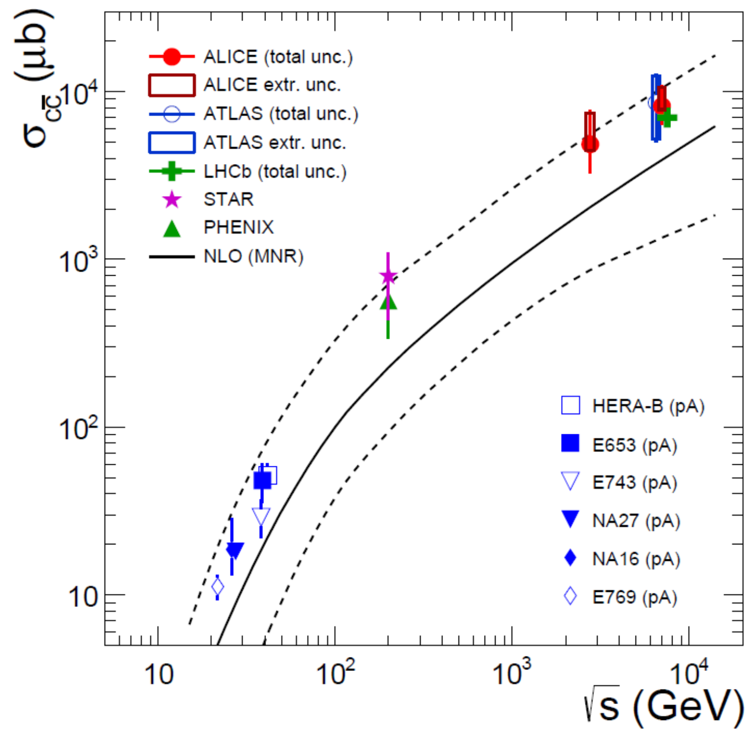
production probability of ψ at T_c from thermalized charm quarks scales with $(N_{c\bar{c}}^{in})^2$ from initial hard partons scattering

J/psi production at RHIC & statistical regeneration

A.Andronic, P. Braun-Munzinger, J. Stachel et al., Nucl. Phys. (2007)



Results of the total $c\bar{c}$ cross section in pp collisions at the LHC

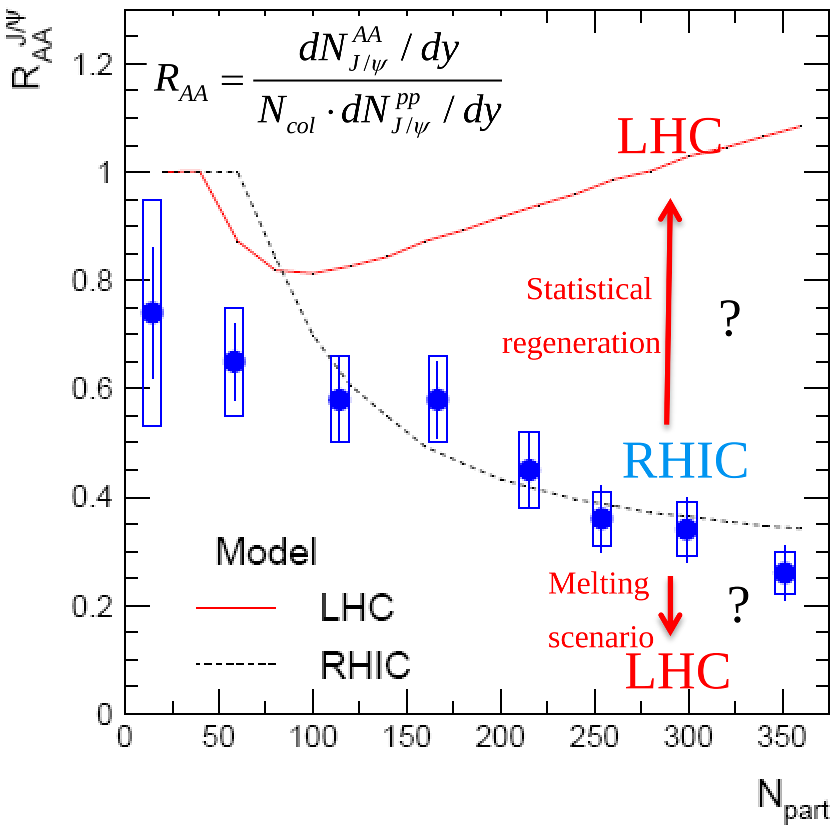


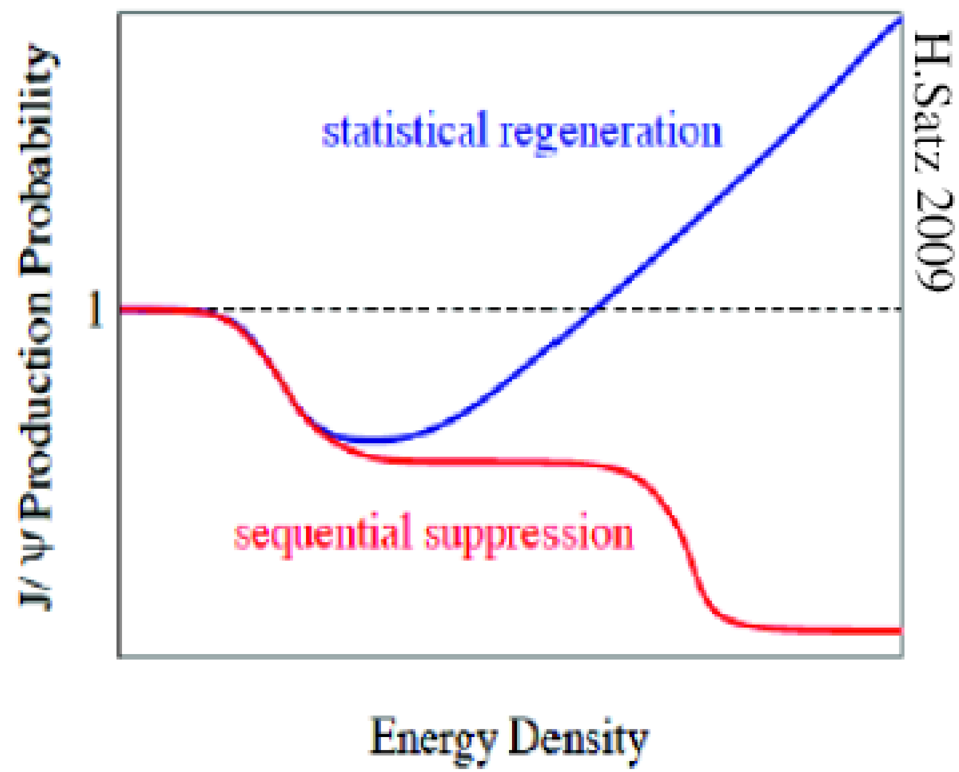
- At LHC expected increase of $R_{AA}^{J/\psi}$ due to regeneration at the phase boundary
  expected suppression of $R_{AA}^{J/\psi}$ in melting scenario

Increase of $R_{AA}^{J/\psi}$ at the LHC was also a generic prediction of kinetic recombination models:
R.L. Thews, M. Mangano, J Rafelski et al. (05,06); Y. Liu at al. (09); X. Zhao & R. Rap (11, 2017); C.M. Ko ..

J/psi production at RHIC & statistical regeneration

A.Andronic, P. Braun-Munzinger, J. Stachel et al., Nucl. Phys. (2007)

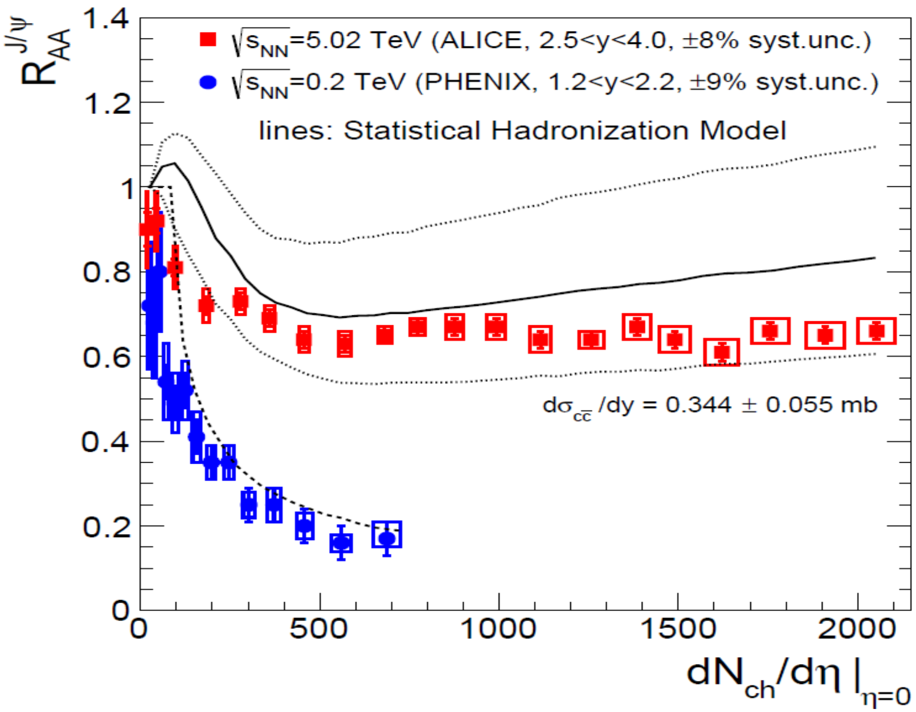


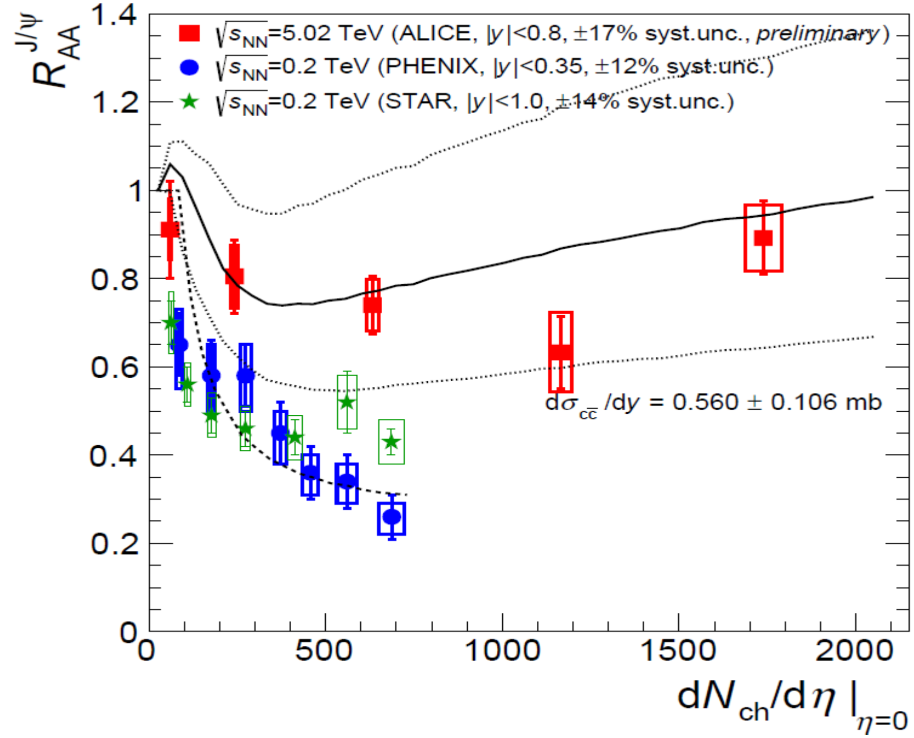


- At LHC expected increase of $R_{AA}^{J/\psi}$ due to thermal production at the phase boundary
  expected suppression of $R_{AA}^{J/\psi}$ in melting scenario

Increase of $R_{AA}^{J/\psi}$ at the LHC was also a generic prediction of kinetic recombination models:
R.L. Thews, M. Mangano, J Rafelski et al. (05,06); Y. Liu at al. (09); X. Zhao & R. Rap (11, 2017); C.M. Ko ..

J/ψ and statistical hadronization at LHC



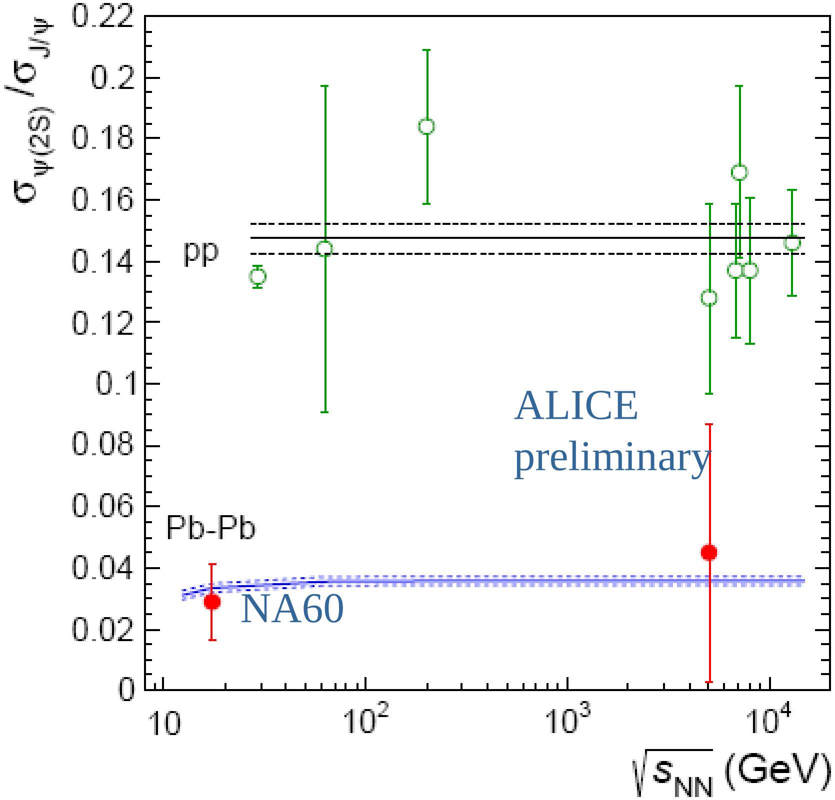


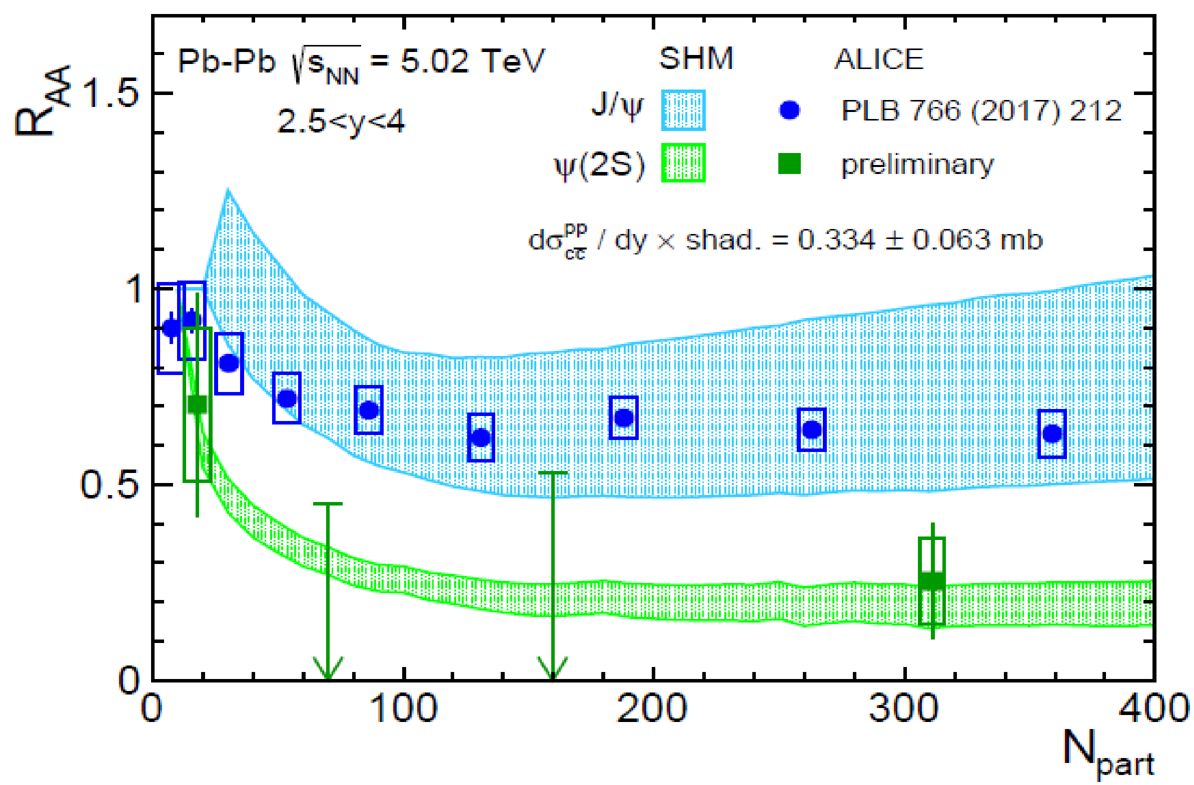
- J/psi production in PbPb collisions at LHC consistent with statistical hadronization at the phase boudary, within present uncertainties. main uncertainties: open charm cross section, shadowing in Pb
- Sequential melting scenario not observed but rather: enhancement with increasing energy density and charam production cross section!

  (from RHIC to LHC and from forward to mid-rapidity)

Production $\psi(2s)$ in line of hadronization at T_c

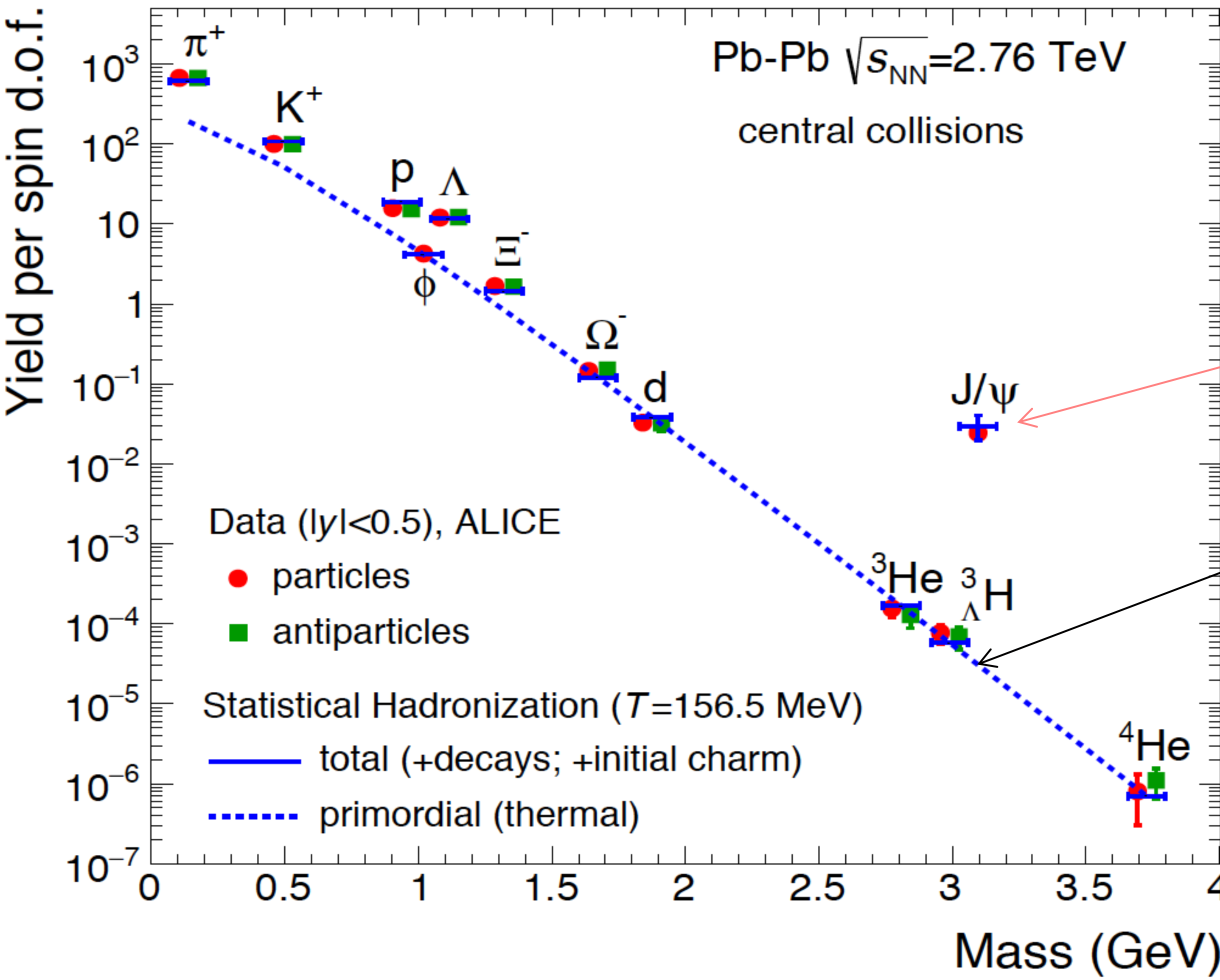
M. Köhler, A. Andronic, P. Braun-Munzinger, J. Stachel arXiv:1807.01236





- $\psi(2s)$ excited state completely in line with the concept of its production at T_c.
- Suppressed $R_{AA}^{\psi(2s)}$ relative to $R_{AA}^{\psi(1s)}$ due to Boltzmann factor and $m_{\psi(2s)} > m_{\psi(1s)}$
- Ratio $\sigma(2s)/\sigma(1s)$ consistent with SHM prediction, allbeit still within large error.

Charmonium production systematics at T_c

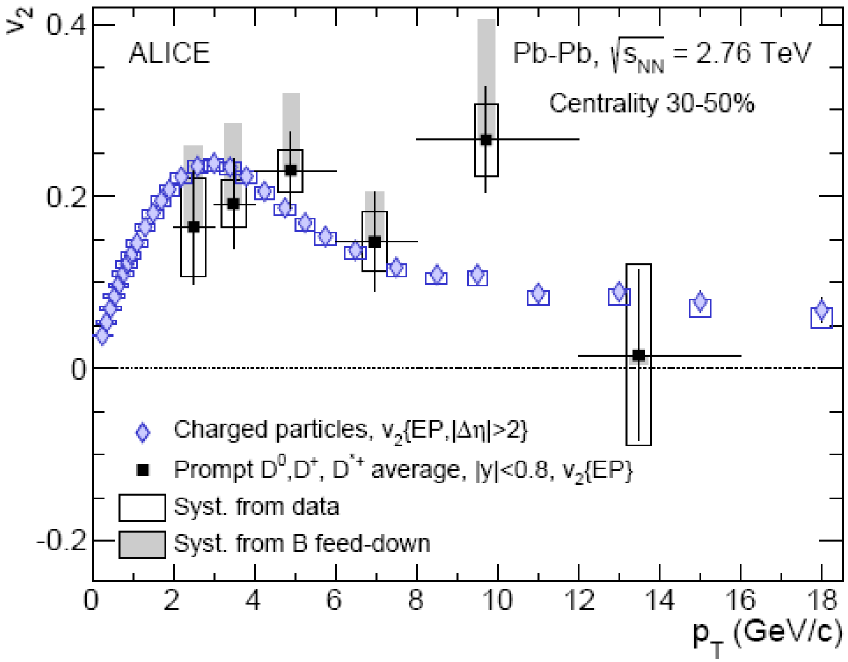


$$N_{J/\psi} = g_c^2 \underbrace{V n_Y^{th}(T, m_{J/\psi})}$$

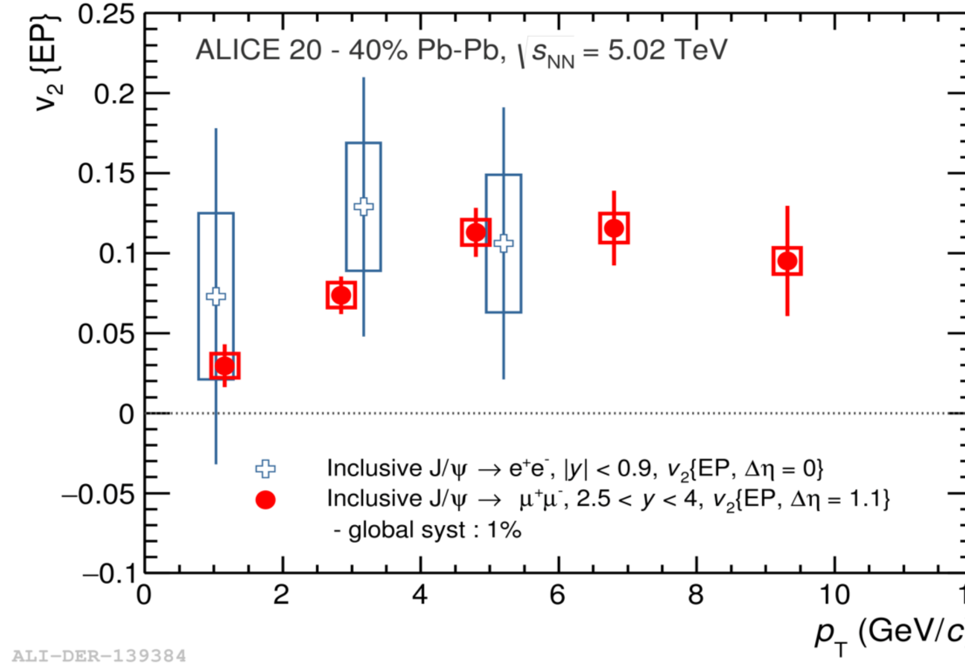
J/ψ yield exactly reproduced with statistical hadronization of deconfined and thermalized c-quarks from initial hard scattering with fugacity $g_c \approx 30$ preserving total number of quark pairs.

LHC data indicate that charm quarks thermalize in QGP

- Elliptic flow of open charm mesons as large as for charged particles



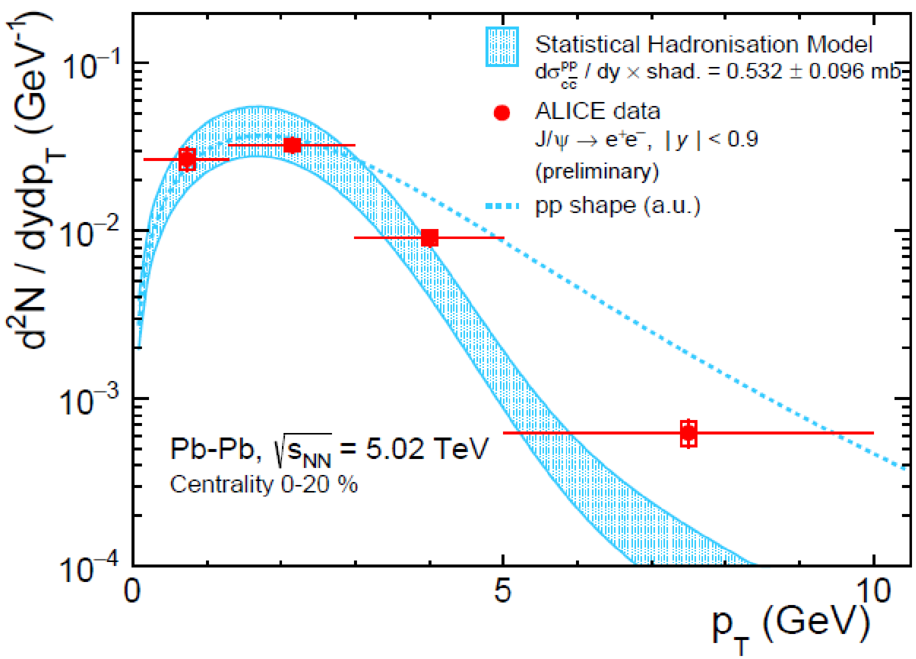
- First observation of J/ψ v_2 consistent with expectation of statistical hadronization

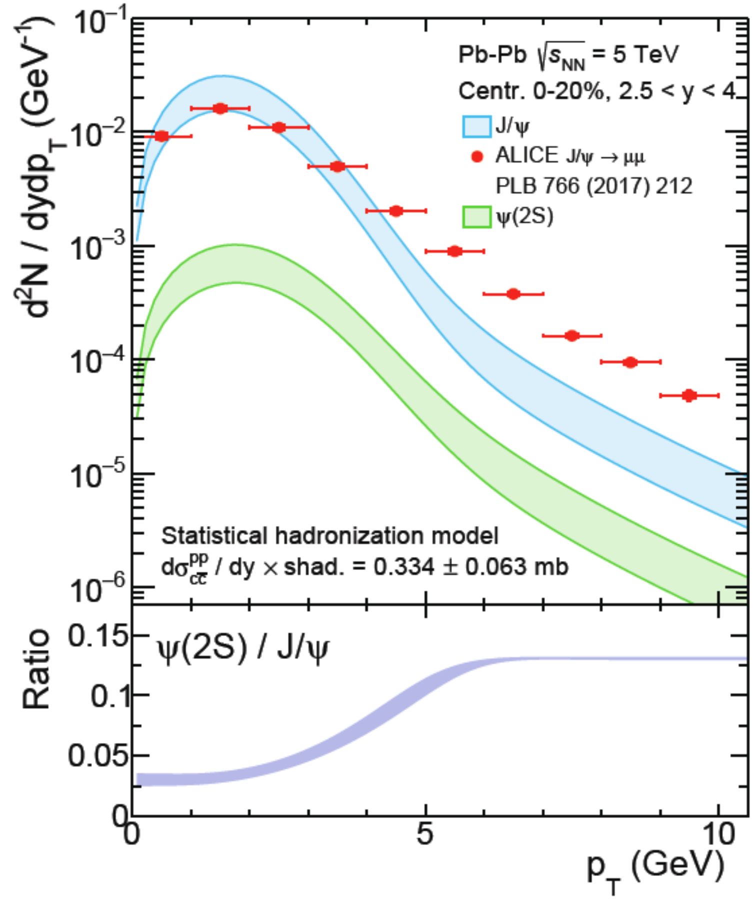


- The observed thermalization of charm quarks in a QGP and increase of $R_{AA}^{J/\psi}$ in AA collisions at the LHC relative to RHIC, strongly supports the concept of the Statistical Hadronization of Charmonium at the phase boundary

Transverse momentum distribution of J/ψ is fixed at T_c

- J/ψ is formed at QGP hadronization at T_c, thus is subject to transverse flow with velocity developed in the hydrodynamic expansion of QGP at T_c

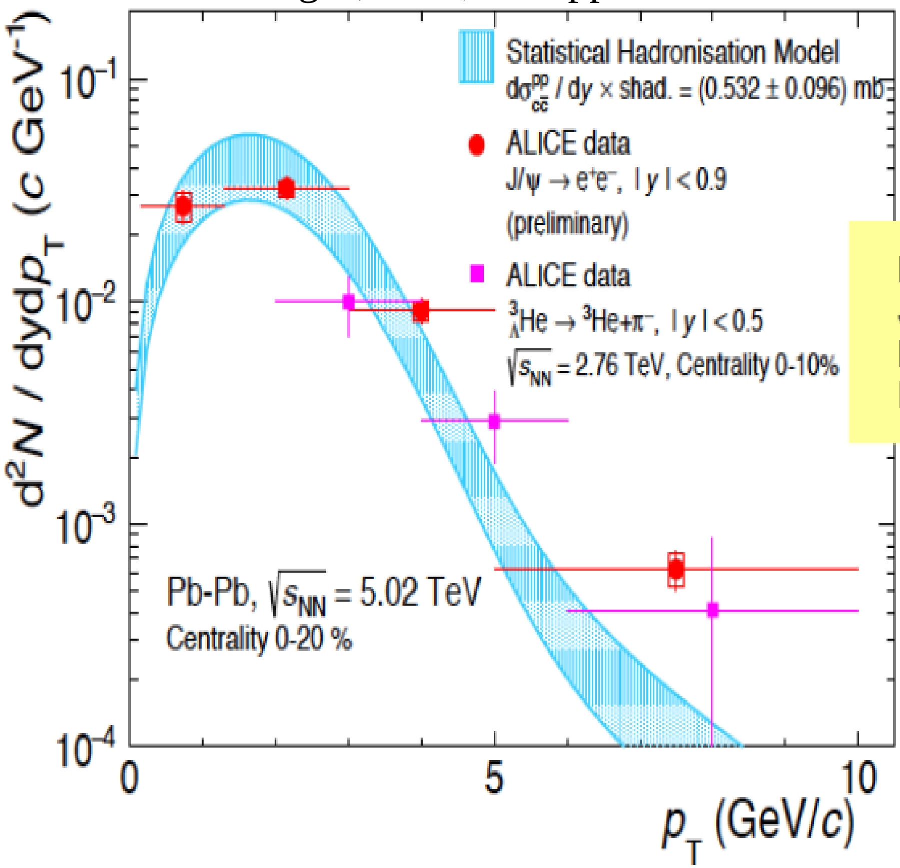




- Indeed, taking the flow velocity profile $\beta(r)$at T_c from hydro, MUSIC(3+1), implemented in the Cooper-Frye prescription one gets consistent description of transverse momentum spectra with no free parameters, however still within large errors

Hyper-triton momentum distribution consistent with J/ψ

B. Doenigus, et al., too appear



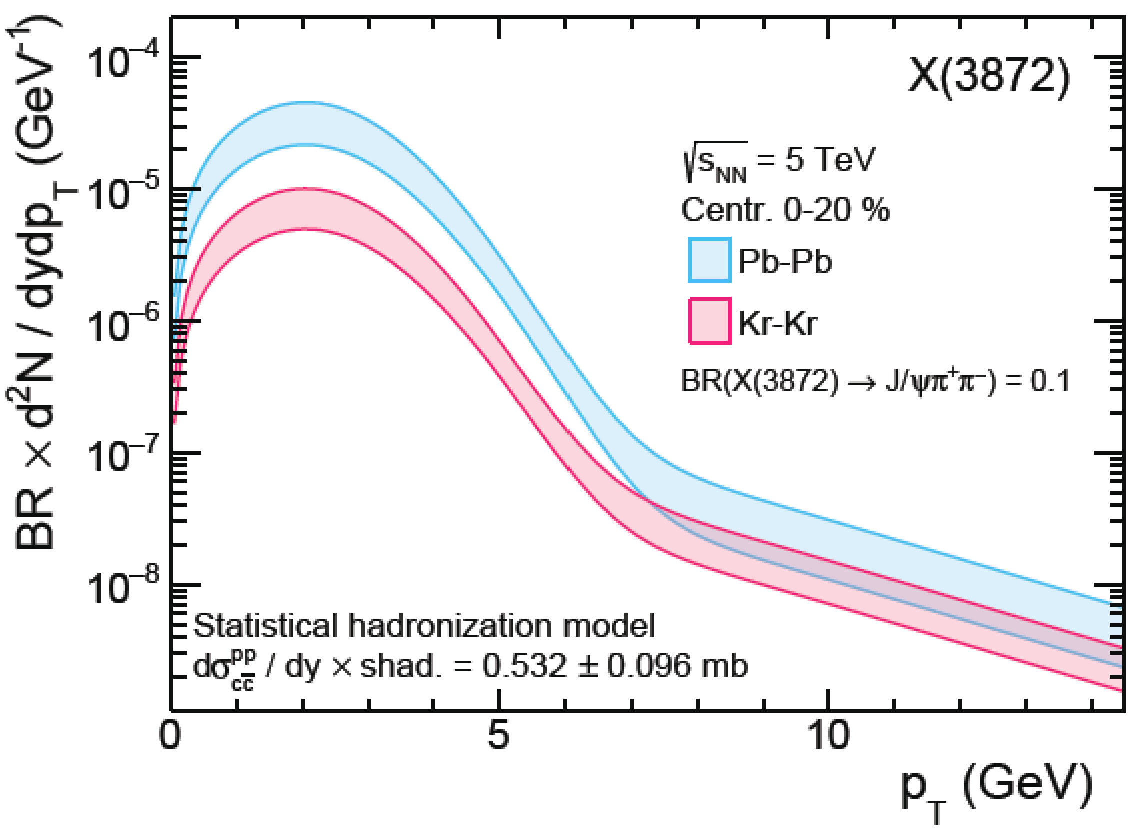
binding energies:
J/psi 600 MeV
hypertriton 2.2 MeV
Lambda S.E. 0.2 MeV

- Hyper-triton and J/ψ are produced at the phase boundary, and due their similar masses experience the same transverse momentum distribution. This property is seen in data, albeit still with large errors.

- Doorway state hypothesis: Not only nuclei and hyper-nuclei, but also penta-quarks and X,Y,Z states are formed in AA collisions as virtual, compact multi-quark states at the phase boundary, then slow time evolution into hadronic representation (PBM)

arXiv:1710.09425, Nature 561 (2018) no.7723, 321-330

Predictions for X(3872) tetraquark charmonium state

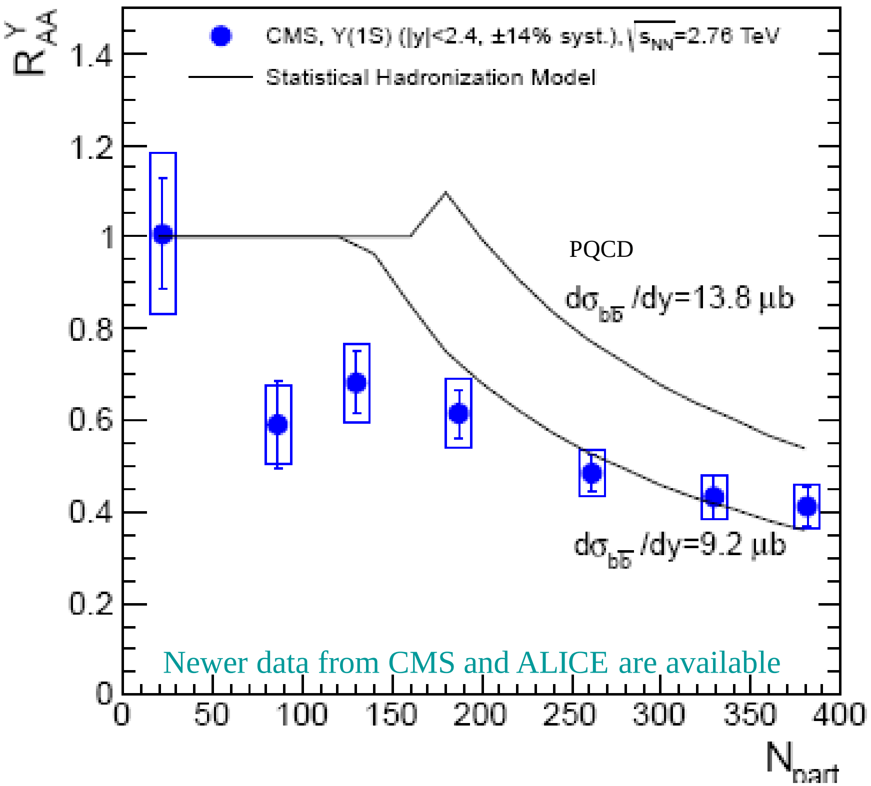


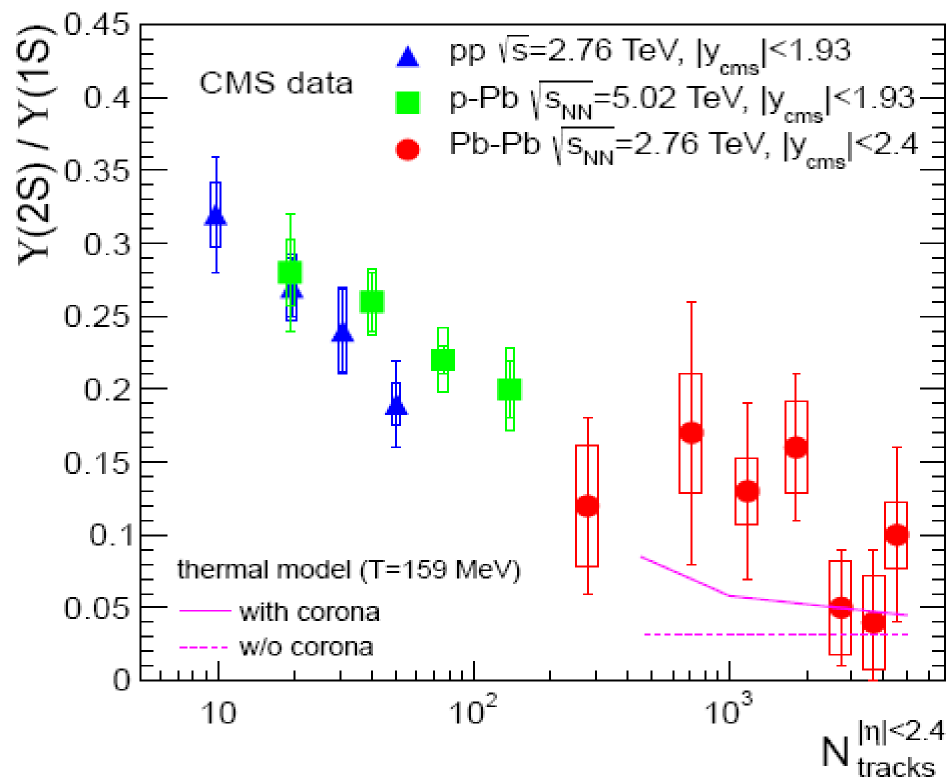
- Prediction for X production at the phase boundary, with the same hydro profile as all other hadrons
- X(3872) Belle coll. And confirmed by the CDF, D0, BaBar and LHCb which determined the quantum numbers $J^{PC} = 1^{++}$

Do Bottomonium States Hadronize at the phase boundary?

- Yield ratios, excellent test of thermal regeneration at the QCD phase boundary due to deconfinement

A. Andronic, et al. Nature (2018)





- In most central collisions, the yield ratio is approximately consistent with thermal value at deconfinement temperature. Further needs for high statistic data and precise value of $b\bar{b}$ cross section to verify bottomonium thermalization.

Conclusion:

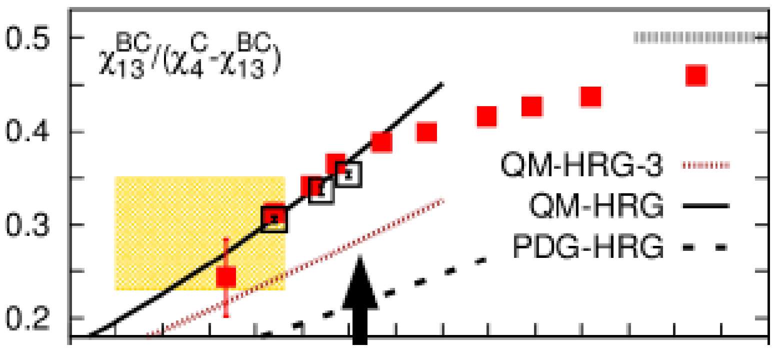
The 2nd Heavy Ion Run at the LHC, experiments brought new insides and novel results to physics of Quark Gluon Plasma and its hadronization , which allow to conclude that:

- **QCD thermodynamic potential is encoded in nuclear collision data: hadrons are produced at the phase boundary with yields and their 2nd order fluctuations consistent with LQCD equation of state at** $T_c \approx 156.5 \pm 1.5$ MeV
- **Novel observation of decreased suppression of J/Psi production at LHC relative to RHIC, its dependence on rapidity,** <dN^{ch}/dy> **and transverse momentum, is consistent with predicted scenario (PBM & J. Stachel) of charmonium deconfinement and subsequent statistical hadronization at the phase boundary**
- **charm quarks produced in the initial hard parton scatterings thermalize in QGP and follow its collective expansion dynamics resulting in novel observation of open charm and J/Psi elliptic flow and energy loss**
- **Light (a)nuclei, (a)hyper-nuclei are produced at the QCD phase boundary, and within present accuracy, follow the flow systematics of other hadrons**

Evidence for many charmed baryons in QCD thermodynamics

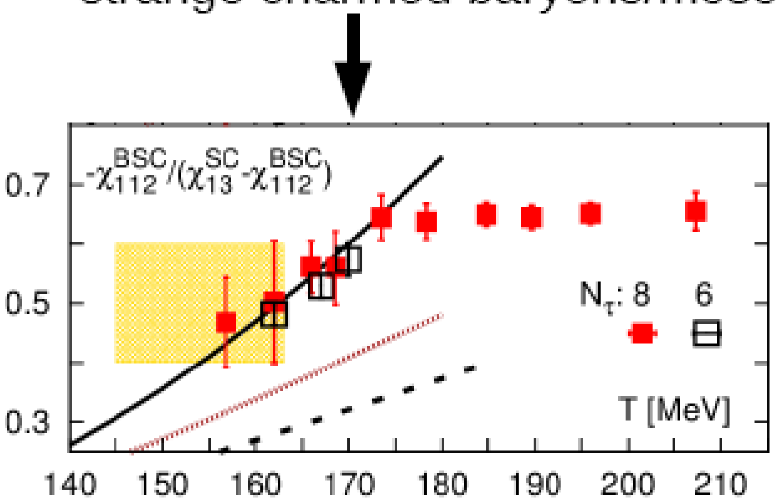
close to Tc charmed baryon fluctuations are about 50% larger than expected in a HRG based on known charmed baryon resonances (PDG-HRG); missing states of QCD

F. Karsch, for HotQCD



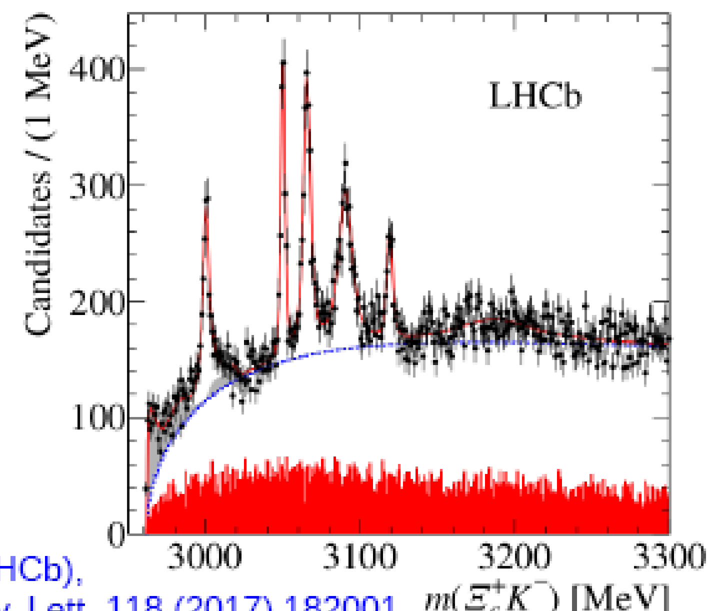
all charmed baryons/mesons

strange charmed baryons/mesons



A. Bazavov et al., Phys.Lett. B737 (2014) 210

observation of
5 new charmed baryons
by LHCb
arXiv:1703.04639



R. Aaij (LHCb),
Phys. Rev. Lett. 118 (2017) 182001