Features of the crossover region in the QCD phase diagram from rare particle production and multiplicity fluctuations

R. Bellwied (University of Houston)

Thanks: Livio Bianchi, *Fernando Flor*, Anders Knospe, *Nalinda Kulathunga*, *Jake Martinez, Corey Myers, Paolo Parotto,* Claudia Ratti, Jihye Song, Cristina Terrevoli, *Ejiro Umaka*

The QCD Phase Transition – where do we stand ?

Discovery of the deconfined phase (SPS/RHIC results) by 2005

Signatures: jet quenching (partonic energy loss), quark scaling of large anisotropic flow (hydrodynamics, viscosity limit), photon temperature, J/ψ melting, strangeness enhancement,……..

Characterization measurements (GSI/SPS/RHIC/LHC results) still ongoing.

Two avenues

Characterization of the phase:
(phase identified)
- -transport coefficients
- -viscosity, conductivity, etc.
- -vorticity, chiral magnetic effects
- -……

Characterization of the transition:
(particle identified)
- -hadronization
- -chiral symmetry
- -confinement
- -degrees of freedom
- -critical point
- -……

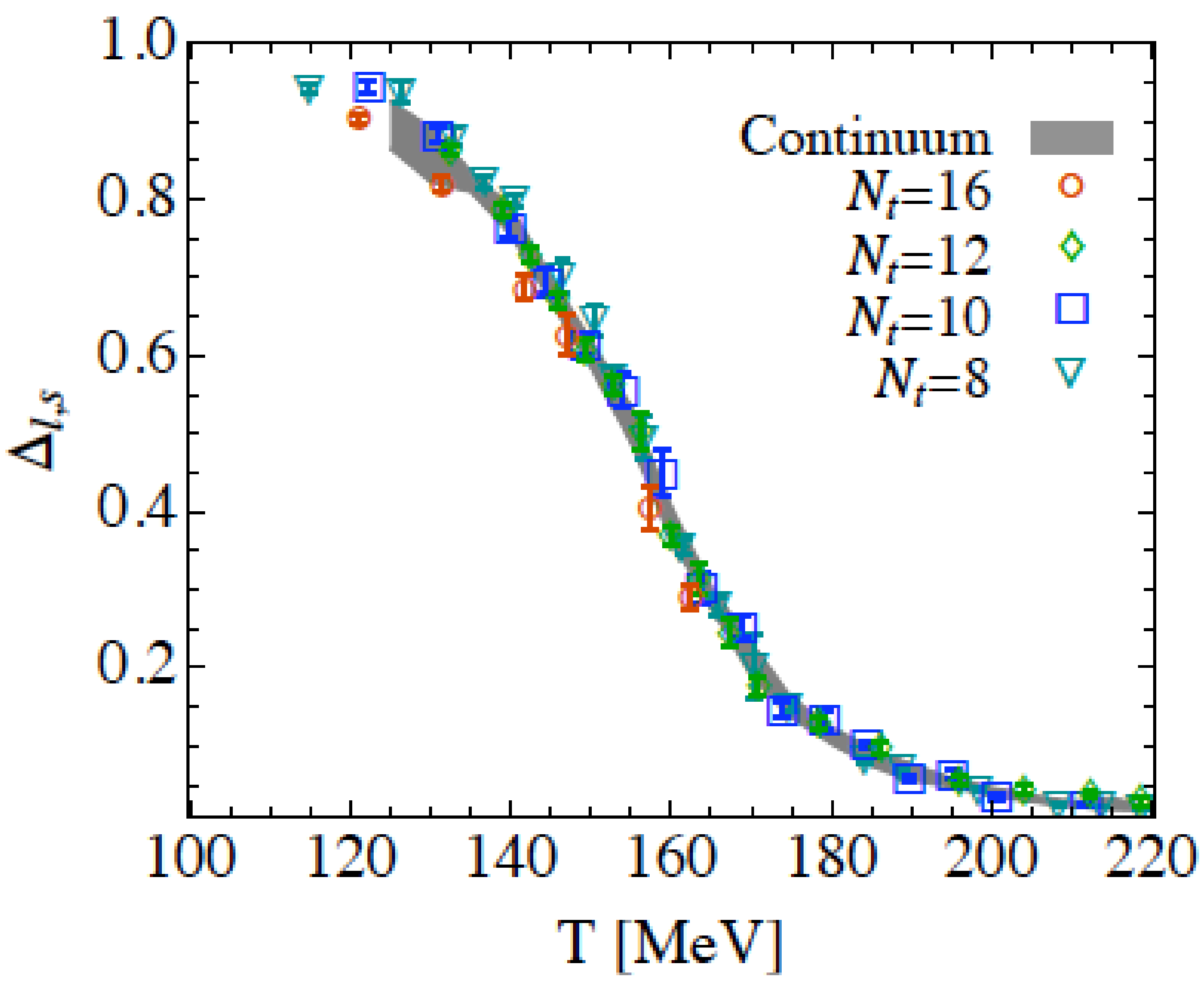
The characterization of the transition Topics to be addressed

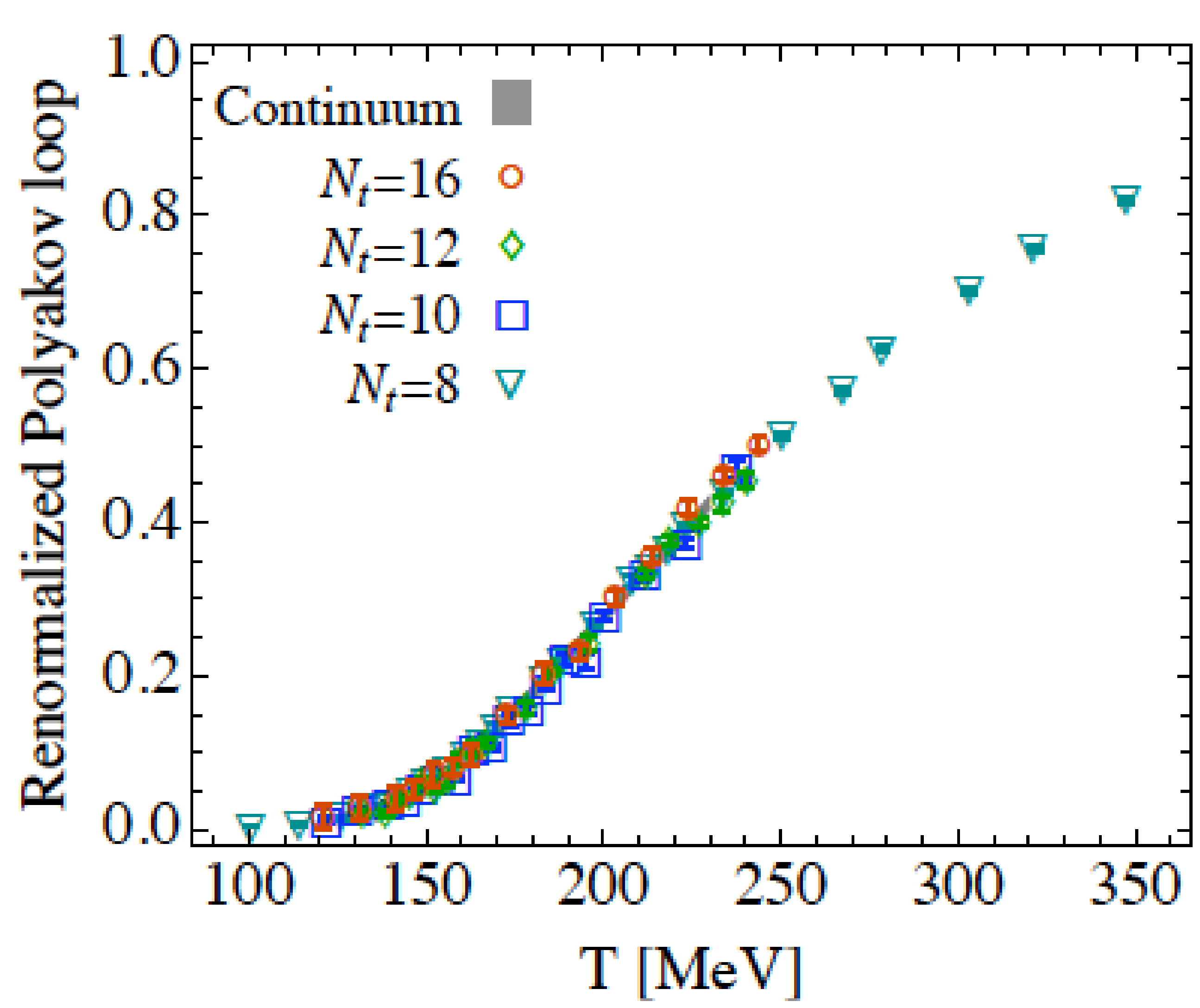
- Flavor hierarchy in the hadronization during crossover
- Strangeness enhancement vs. canonical suppression
- Chiral restoration through parity doubling
- Light nuclei and hypernuclei production
- Quantum entanglement
- Multi-quark states
- EOS with and without strangeness clustering

The order parameters of the QCD phase diagram

Chiral restoration vs. Deconfinement, ‘good’ or ‘bad’ ?

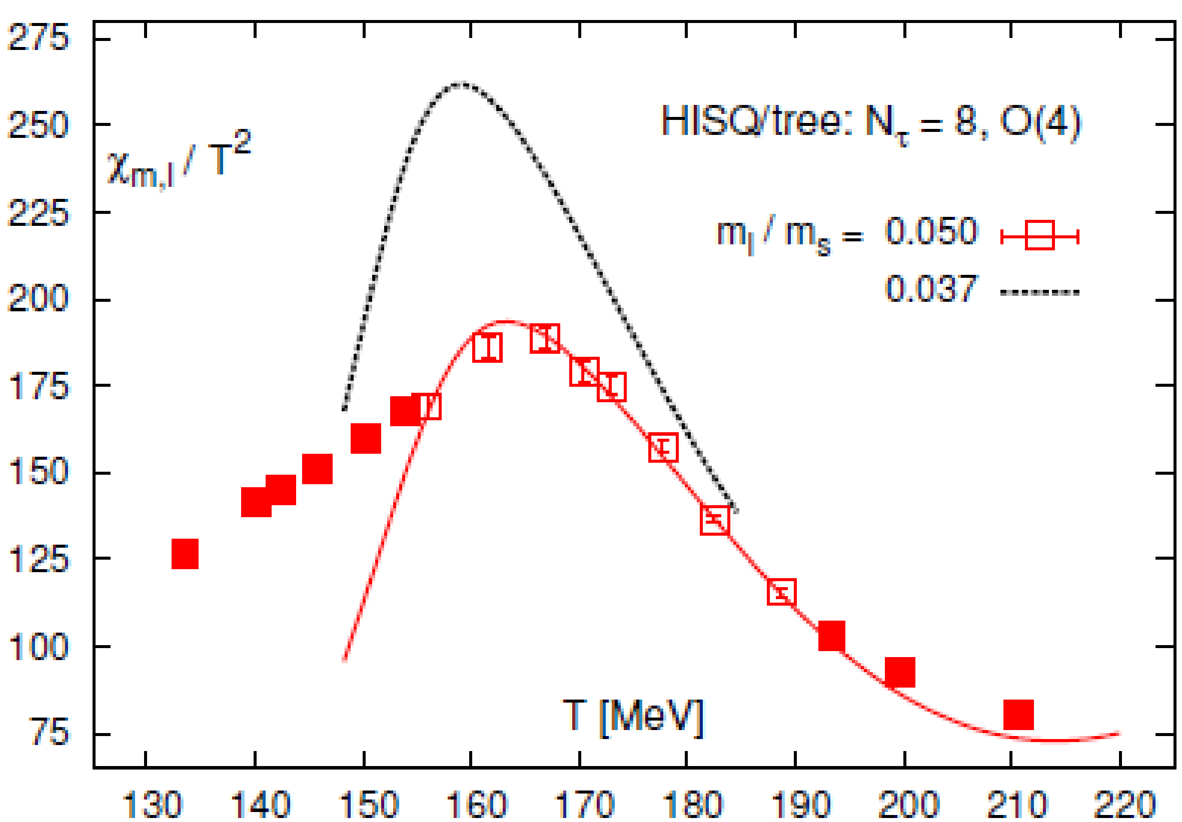
All of them show analytic crossover

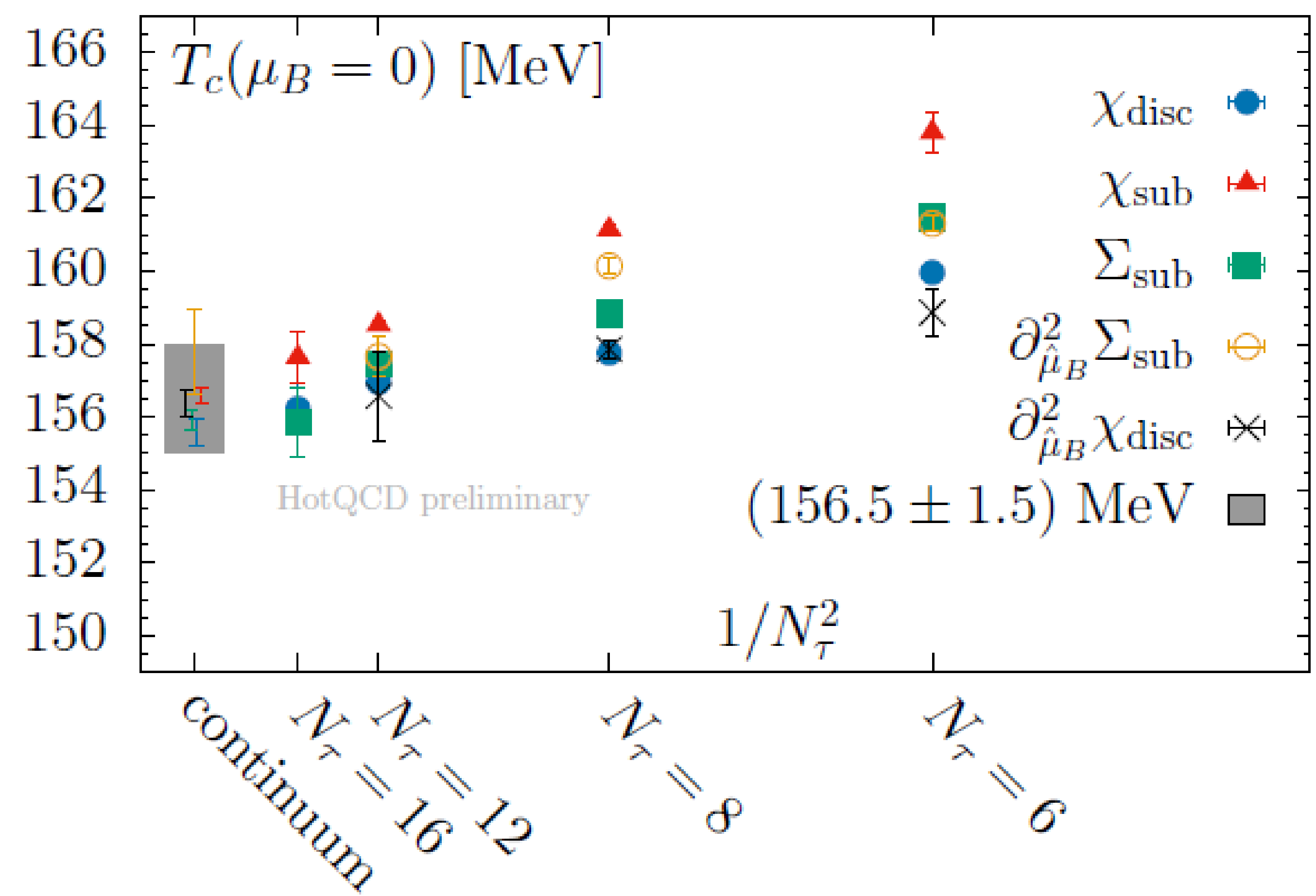




The order parameters of the QCD phase diagram

The chiral transition defines the pseudo-critical T

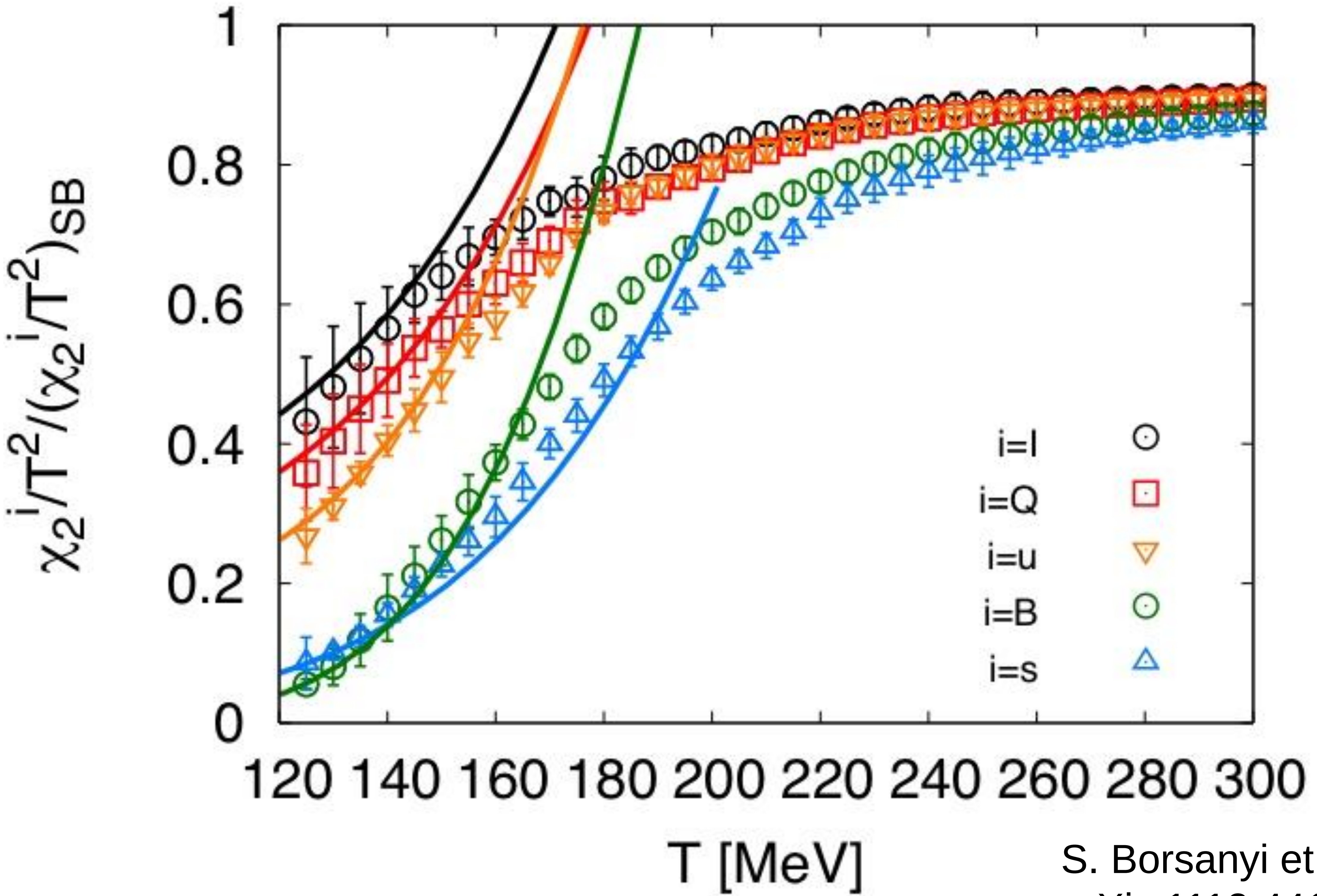




HotQCD (1504.05274)
T_{pc}: 154+- 9 MeV

HotQCD (1807.05607)
T_{pc}: 156.5+- 1.5 MeV

The relevance of conserved charges as order parameters for the phase transition – Understanding hadronization microscopically



S. Borsanyi et al., arXiv:1112.4416

What is the physical meaning of a ‘pseudo-critical temperature T_{pc} = 154 MeV’ ?

ECT* 2018: There is none. Its relation to the chemical freeze-out temperature from statistical hadronization models (GSI-Heidelberg 156 +- 2 MeV) is fascinating, but any simple explanation defies logic to some extent.

Decoding the phase structure of QCD via particle production at high energy

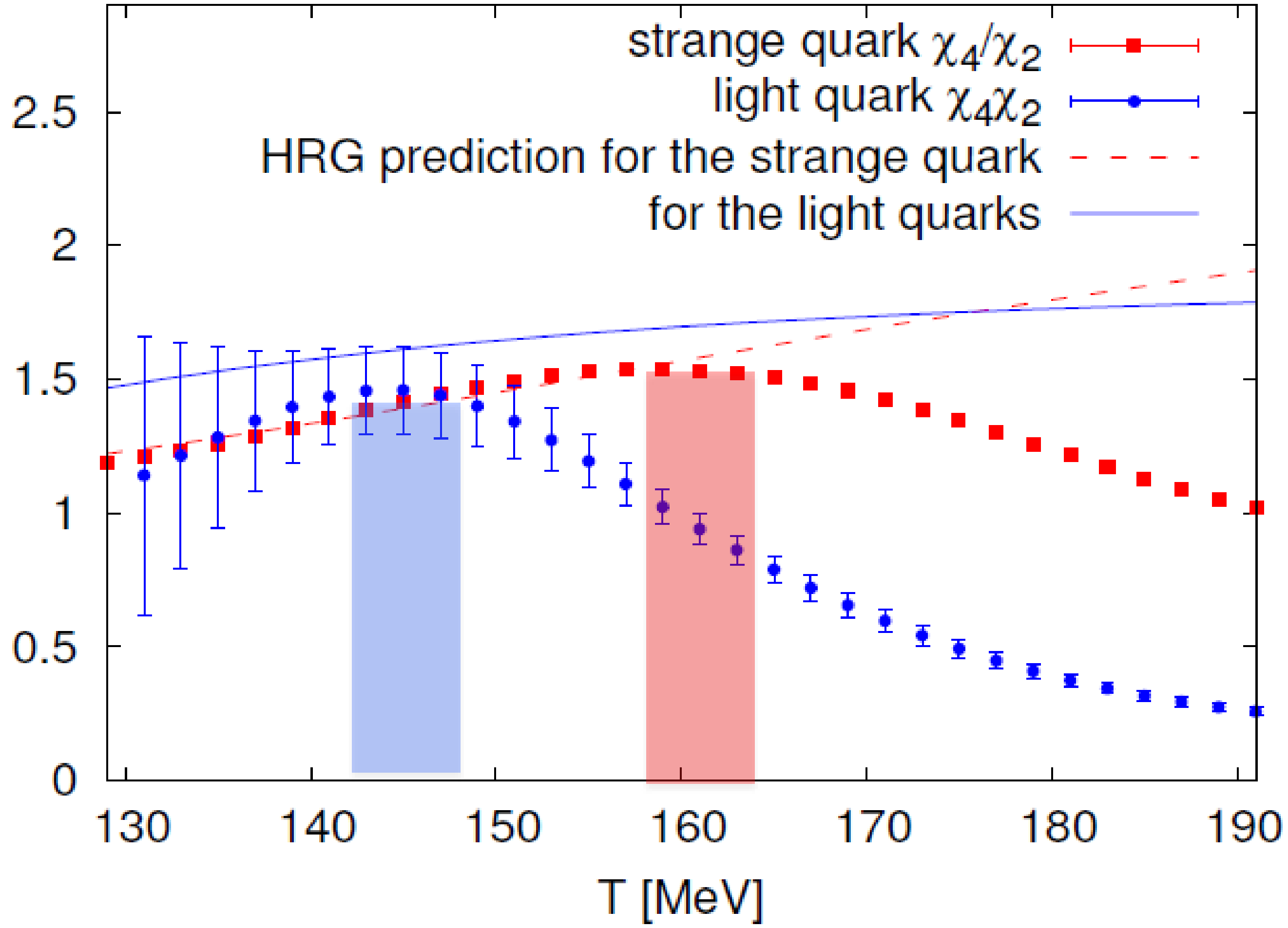
A. Andronic, P. Braun-Munzinger, K. Redlich. J. Stachel

Nature *volume 561*, 321–330 (2018)

Direct determination of freeze-out parameters from first principles (lattice QCD)

$$\kappa_B \sigma_B^2 \equiv \frac{\chi^B_{4,\mu}}{\chi^B_{2,\mu}} = \frac{\chi^B_4(T)}{\chi^B_2(T)} \left[\frac{1 + \frac{1}{2}\frac{\chi^B_6(T)}{\chi^B_4(T)}(\mu_B/T)^2 + \ldots}{1 + \frac{1}{2}\frac{\chi^B_4(T)}{\chi^B_2(T)}(\mu_B/T)^2 + \ldots} \right]$$

Susceptibility ratios are a model independent measure of the chemical freeze-out temperature near μ=0. (Karsch, arXiv:1202.4173)



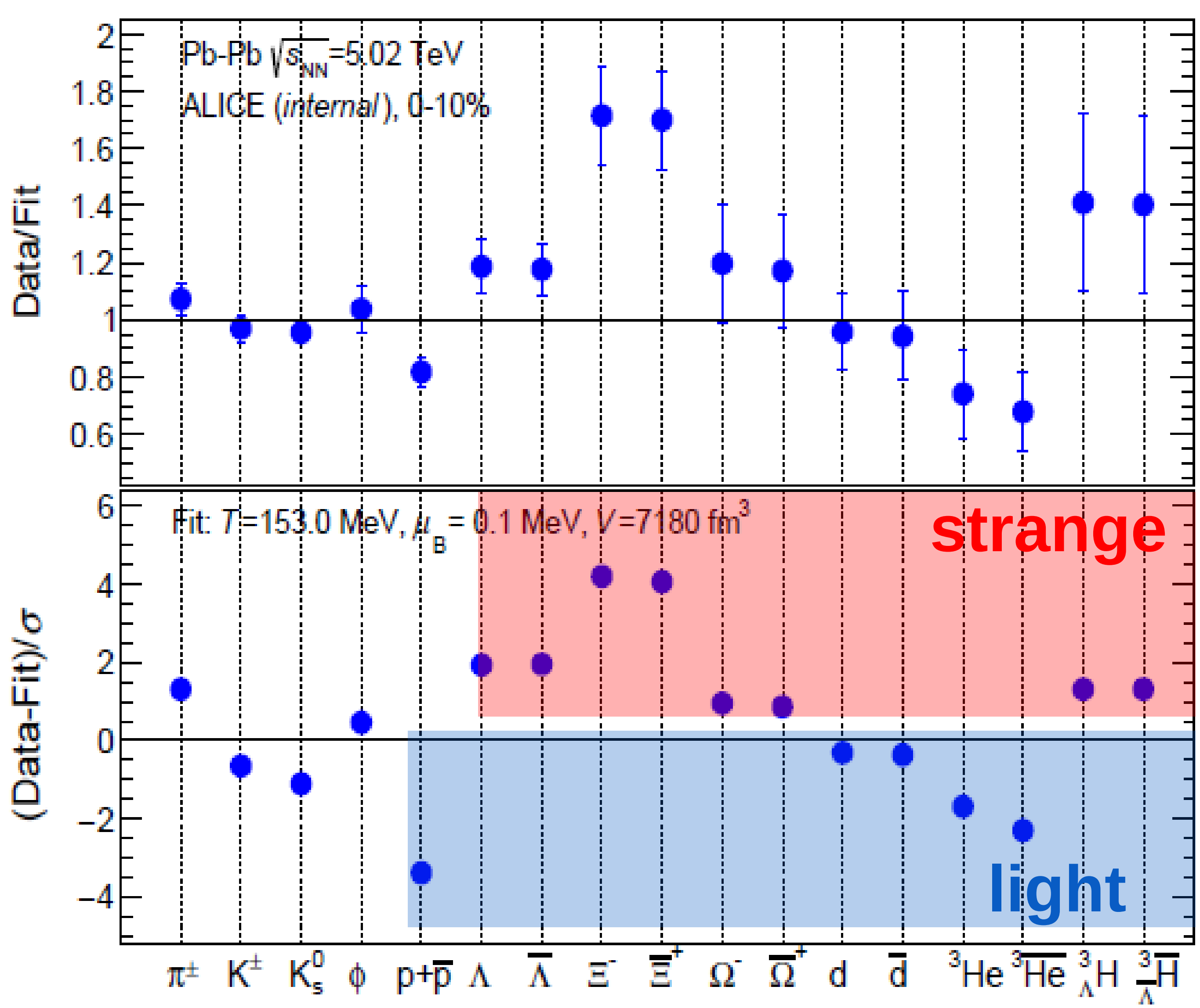
R. Bellwied & WB Collab., PRL (2013), arXiv:1305.6297

<u>Indication of sequential hadronization</u>

<u>Either based on the peak position in the lattice QCD calculation or on the point of deviation from the hadron resonance gas (HRG)</u>

<u>Needs experimental verification</u>

Experimental evidence: HRG (PDG 2010) model comparison based on yields



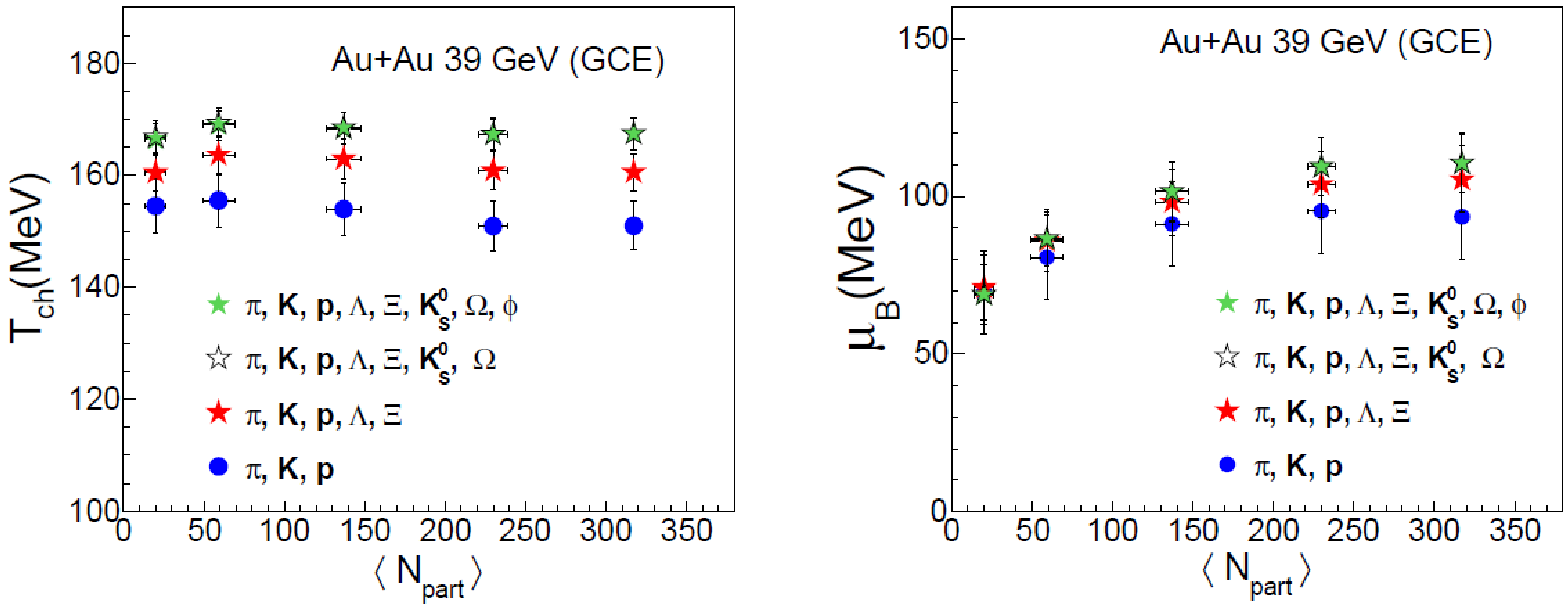
The new 5.02 TeV show a more pronounced and more precise tension between strange and non-strange particles in the baryonic sector (-3σ effect in protons vs. +5σ effect in Ξ baryons)

Data: ALICE (preliminary)
Fit: GSI-Heidelberg (preliminary)

Overall there seems to be a light vs. strange particle trend

Experimental evidence from varying the input particles into the chemical fit

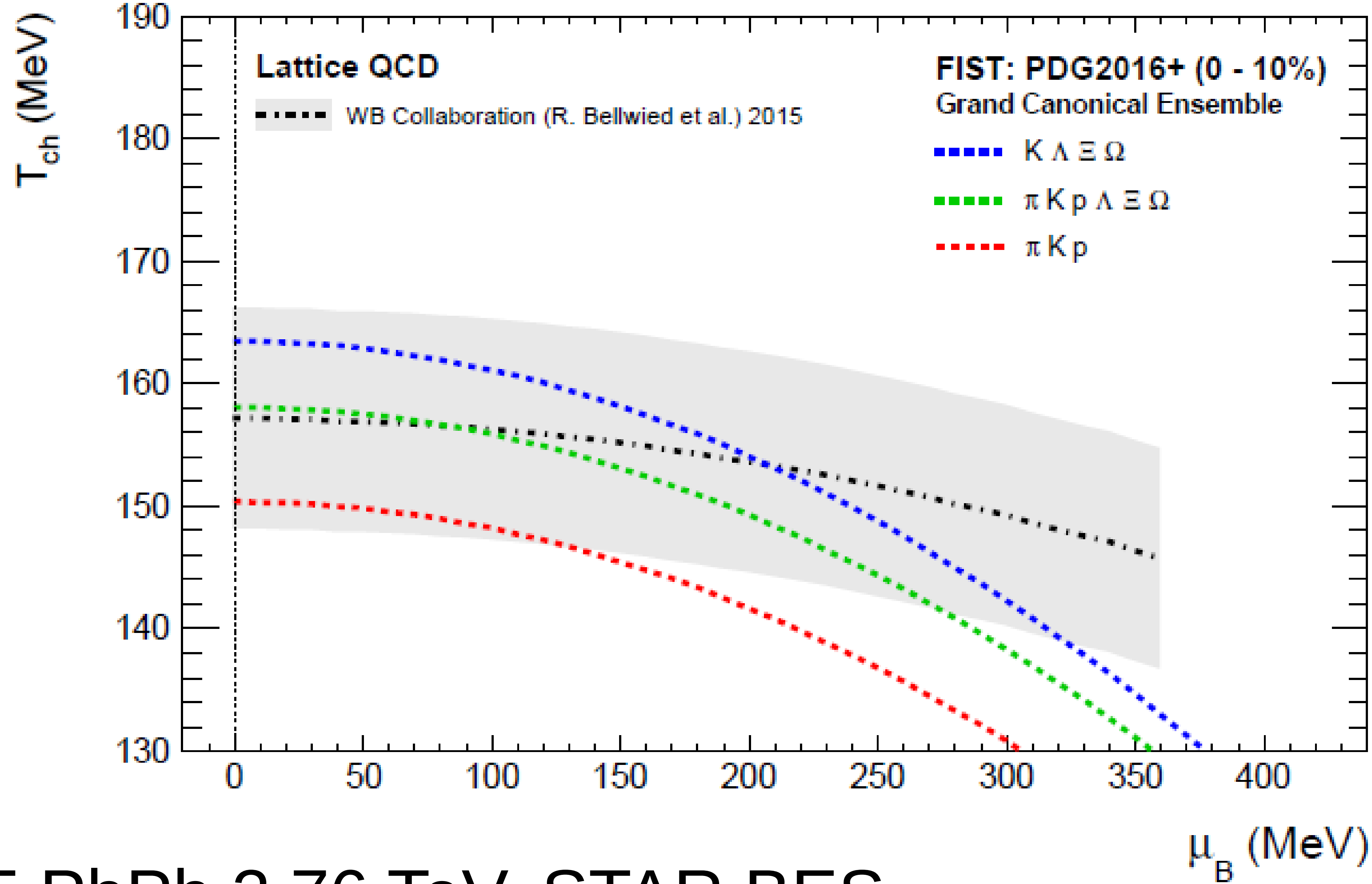
Latest example: Beam Energy Scan data from STAR (arXiv:1701.07065)



This is a long known fact in SHM, always argued as 'the more states the better', but all additional states (to π,k,p) are strange states

Latest internal study using FIST
(F. Flor, G. Olinger for ALICE week)

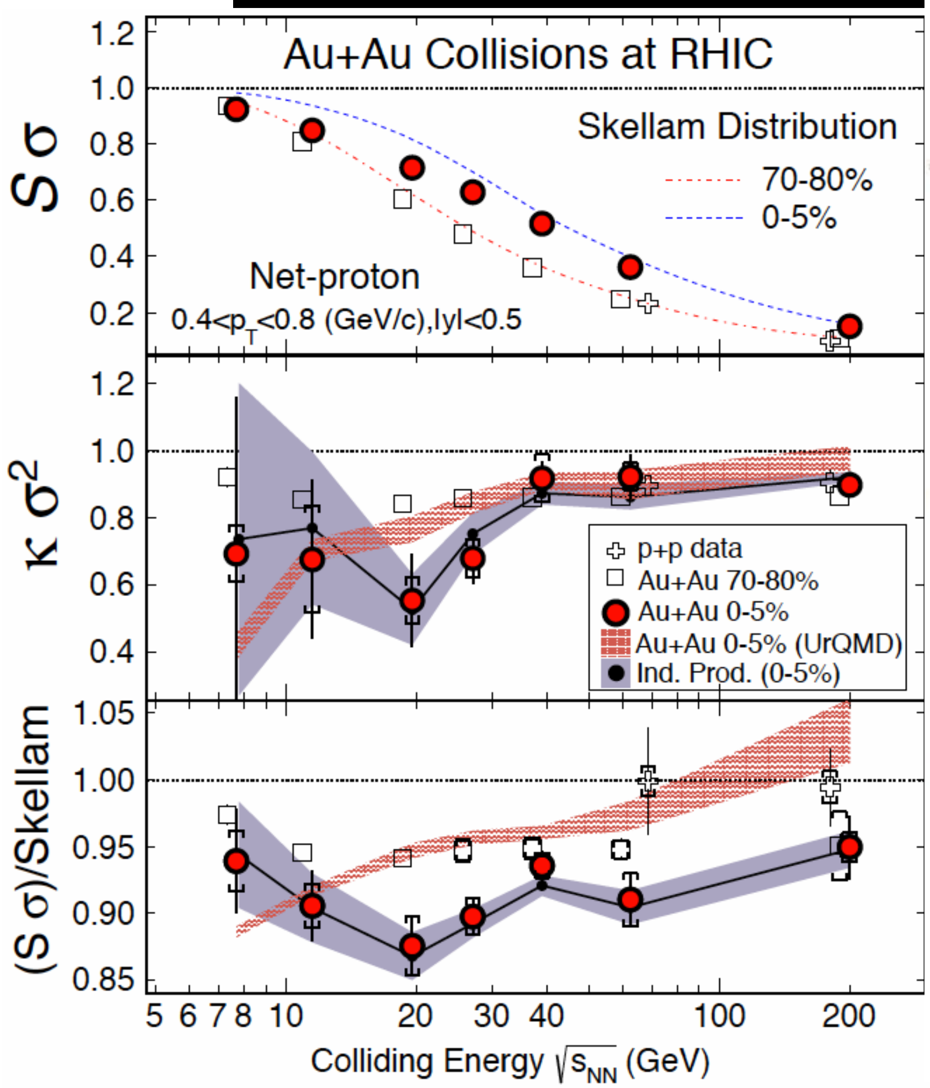
FIST Fits and Curve Extrapolations



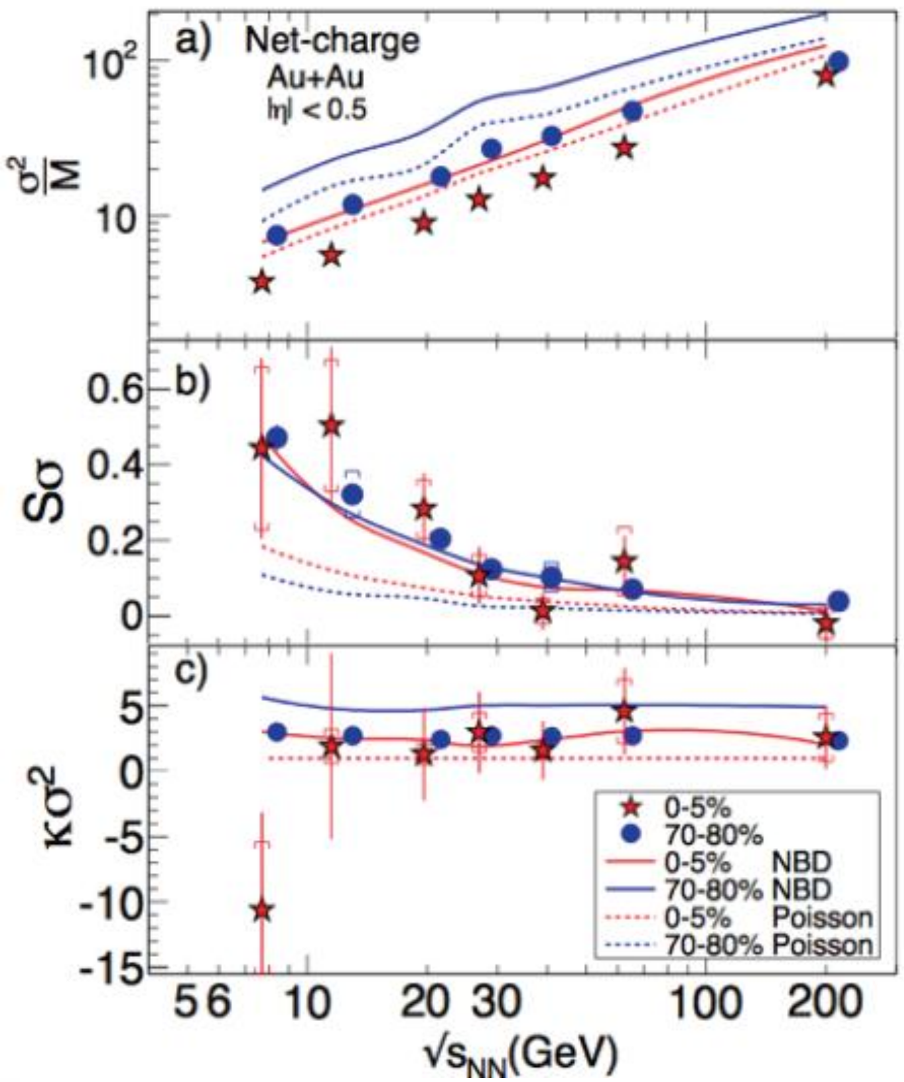
Data: ALICE PbPb 2.76 TeV, STAR BES

Higher moment ratios for net-charge and net-proton, net-charge and net-Kaon distributions from STAR

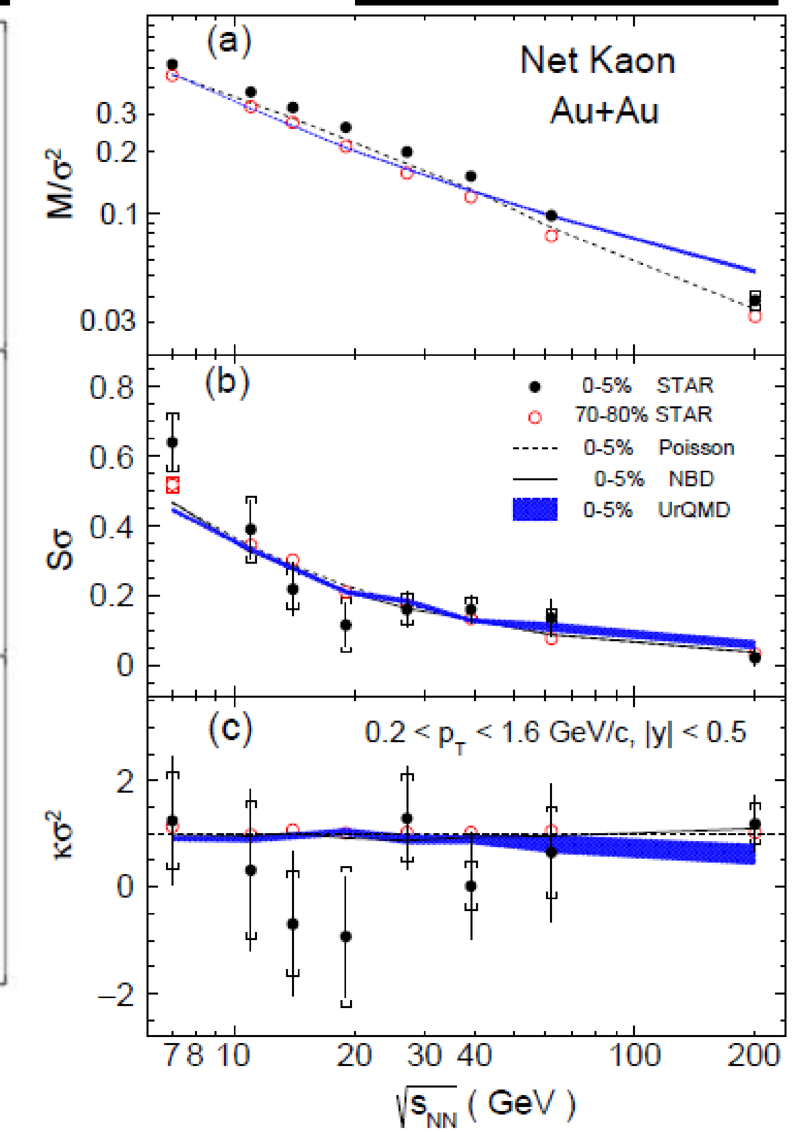
Phys. Rev. Lett. 112 (2014) 32302



arXiv:1402.1558

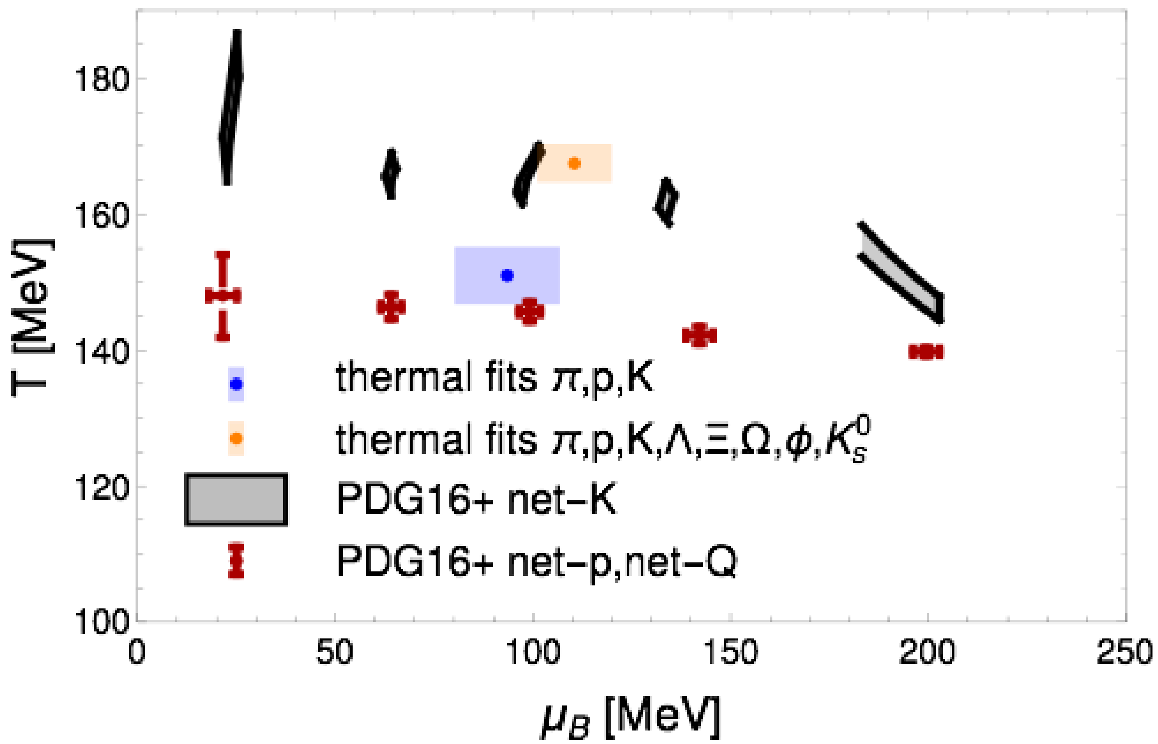


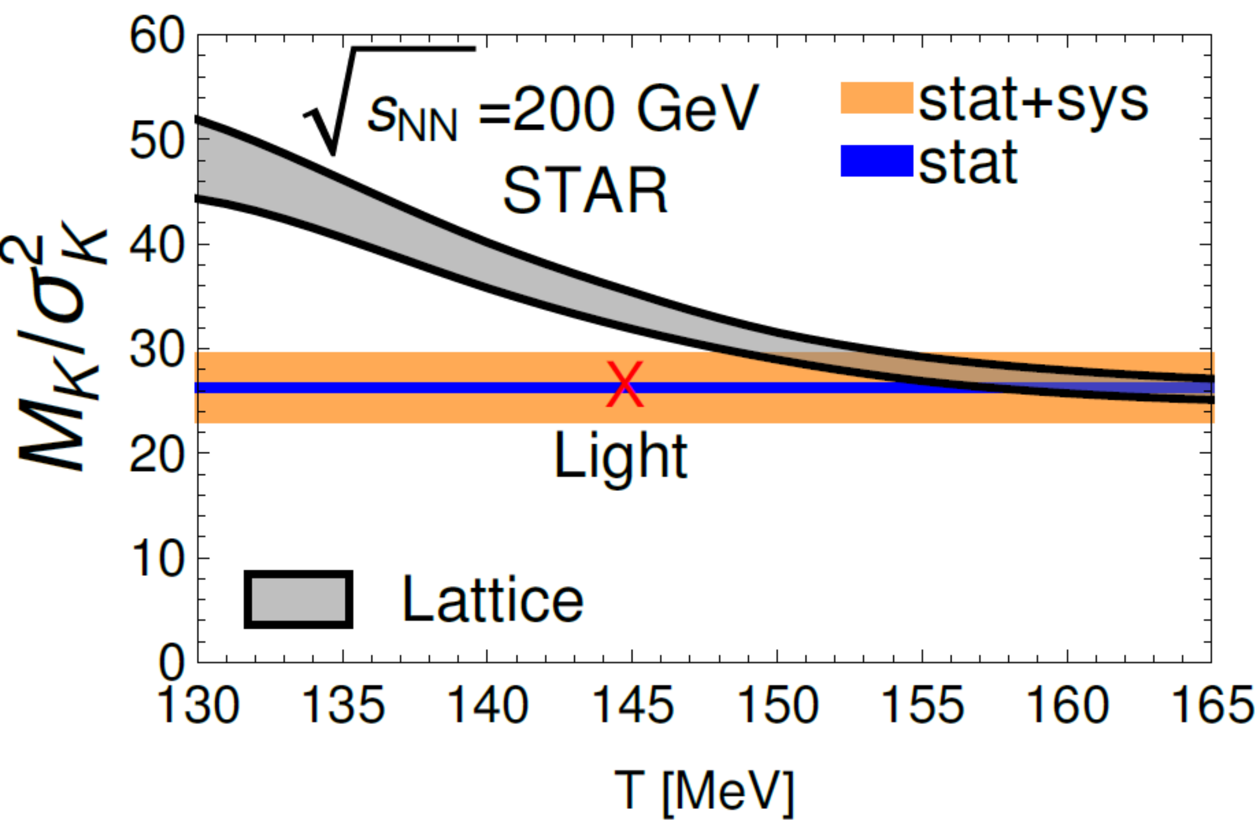
arXiv:1611.07132

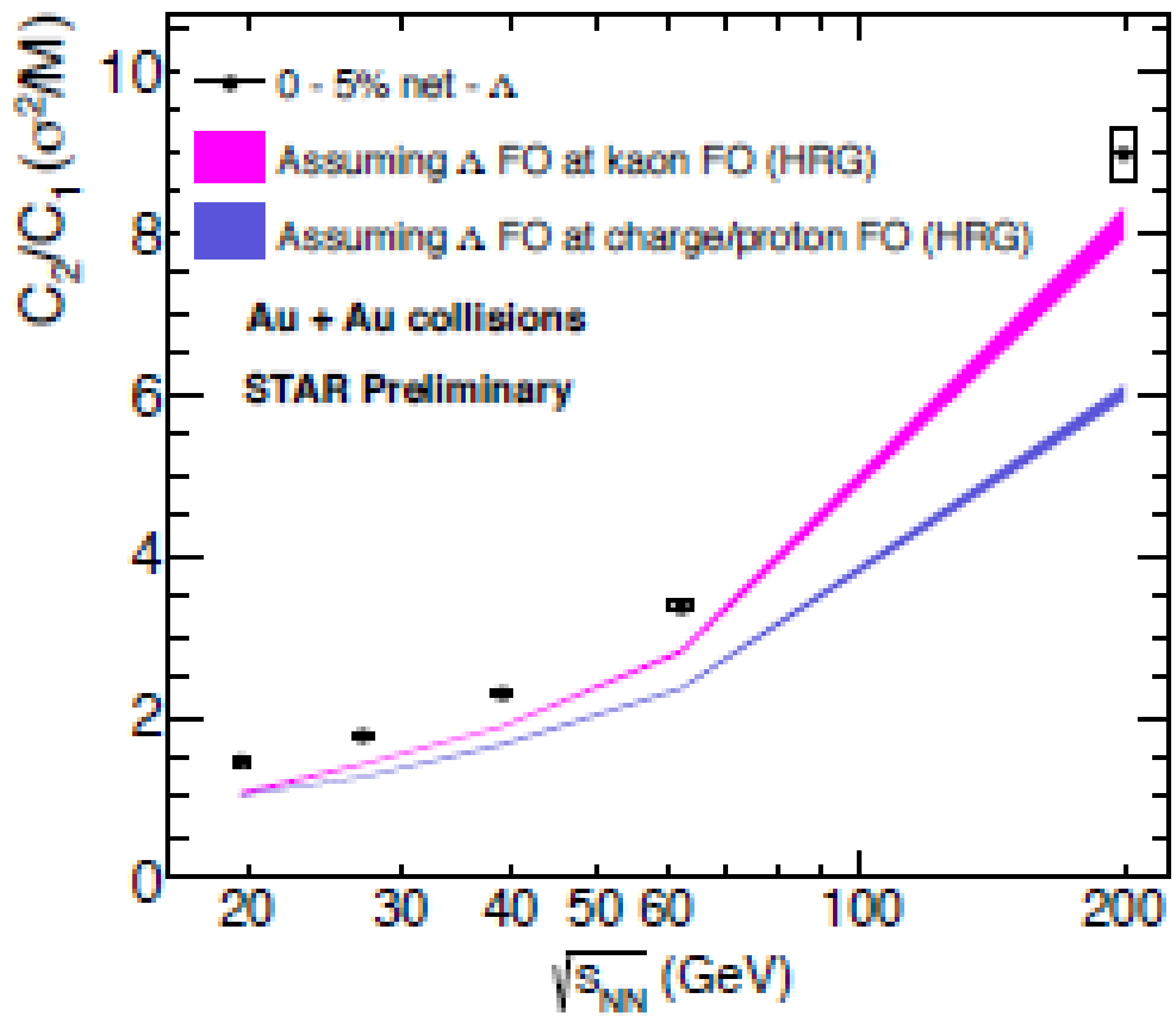


Fluctuations are more sensitive to chemical freeze-out as simple yields. They can be directly compared to susceptibilities on the lattice (P.Alba et al., PRC, (arXiv:1504.03262))

HRG fits to σ^2/M for net-protons, net-charge, net-kaons and net-Lambda STAR data







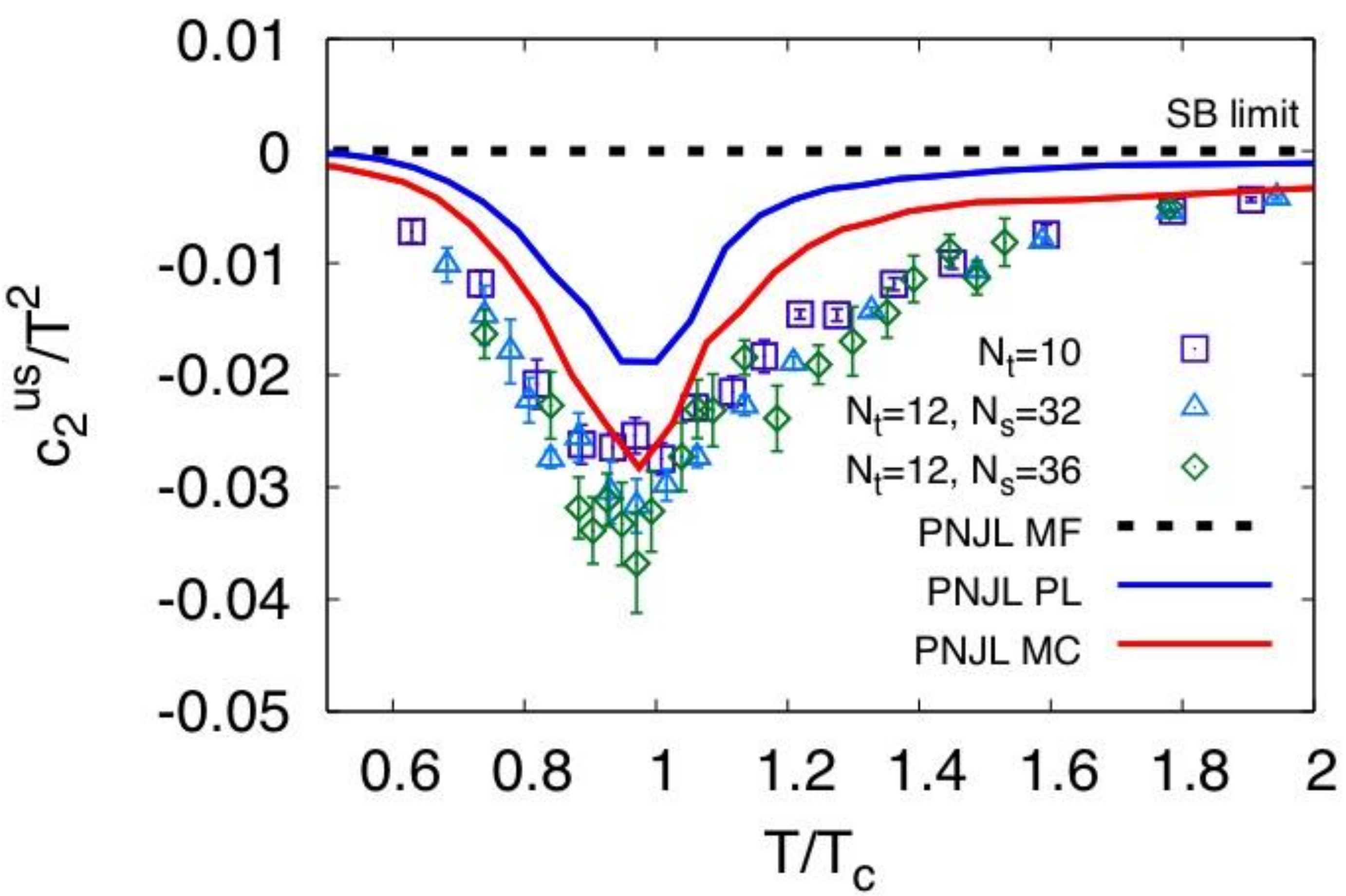
Net-Λ follow the net-kaon freeze-out (N.Kulathunga, STAR/UH, Ph.D. thesis)

Net-Λ fluctuations studied in ALICE at UH

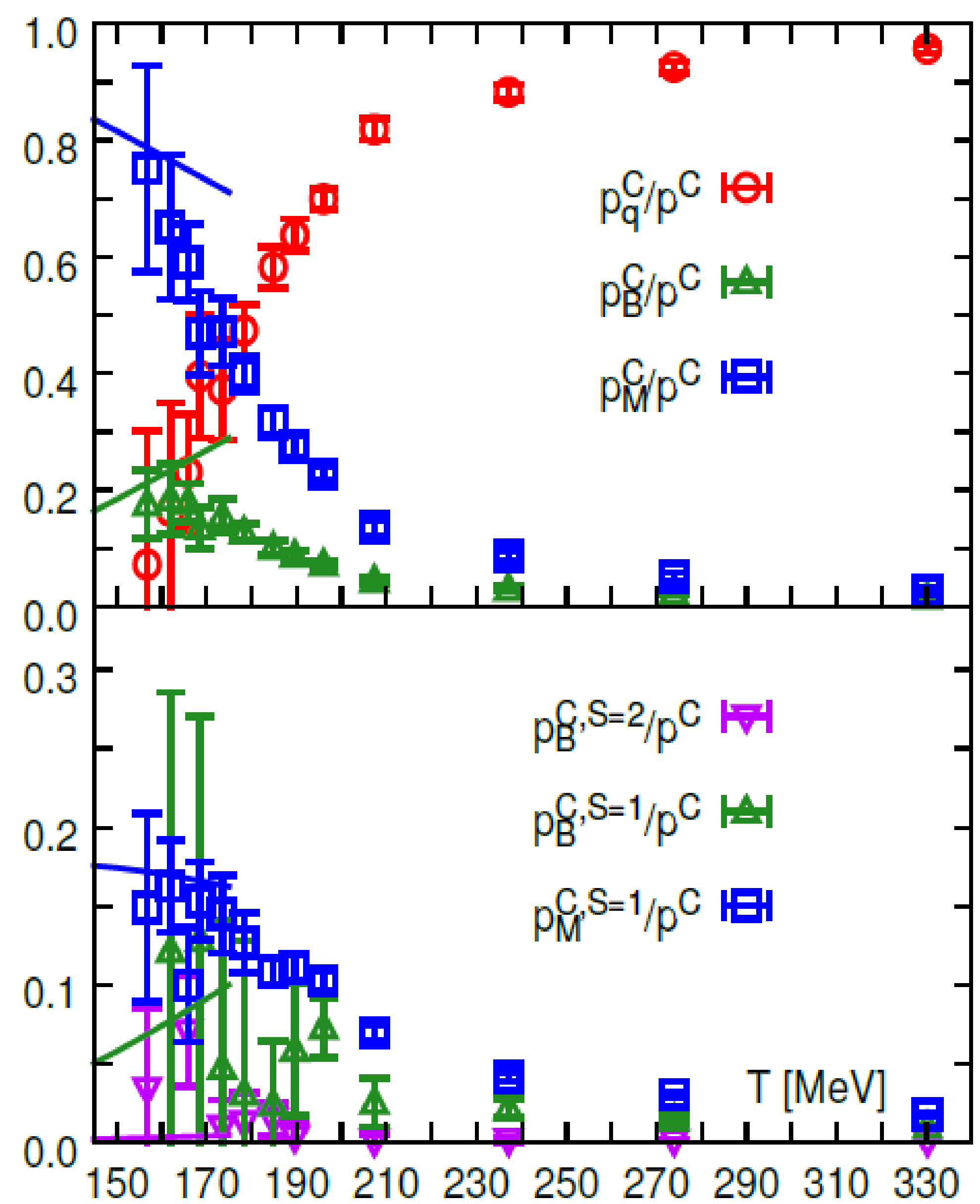
JNH, Ratti et al., arXiv:1607.02527 and Bellwied et al. arXiv: 1805.00888

Is there evidence from other lattice studies for a flavor dependence ?

Bound states in the strange sector
(C. Ratti et al., PRD 85 (2012))
through BS Correlator



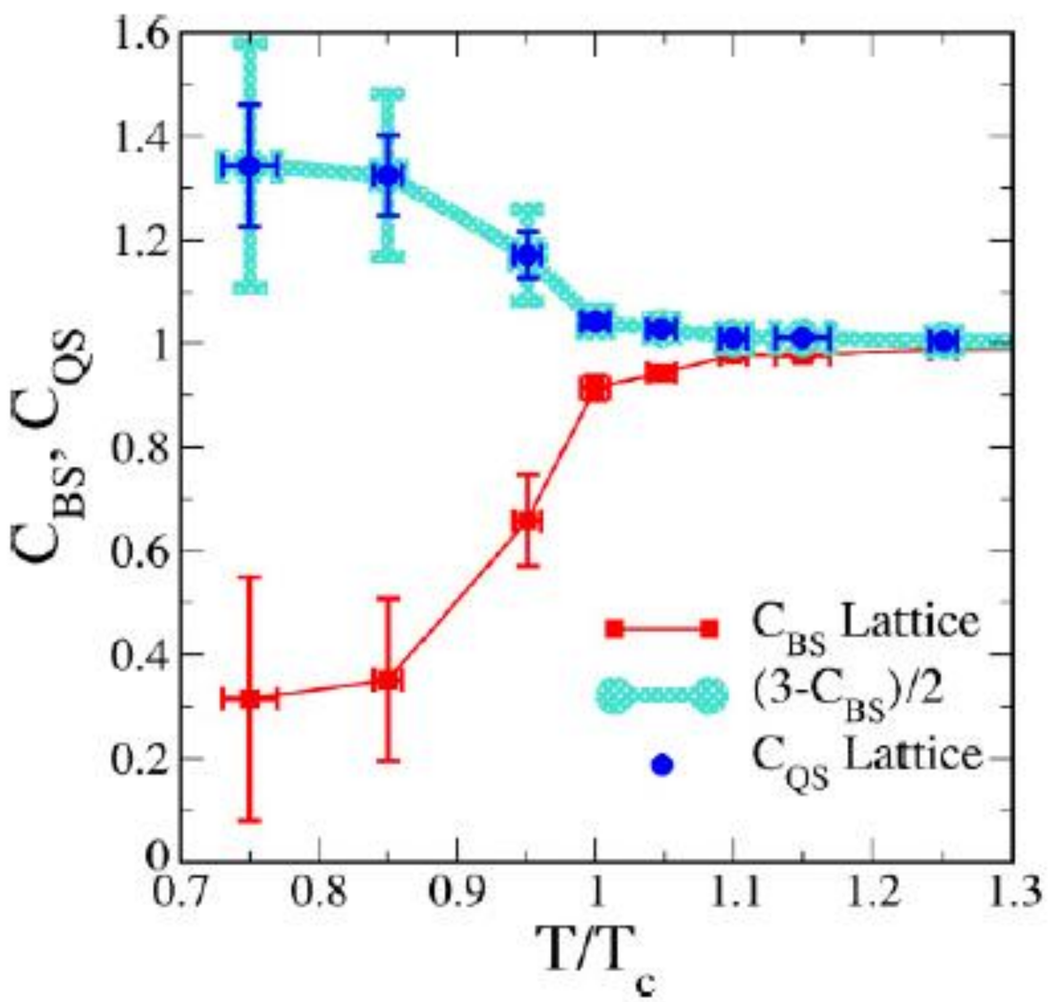
Bound states in the charm sector
(S. Mukherjee et al., PRD 93 (2016))



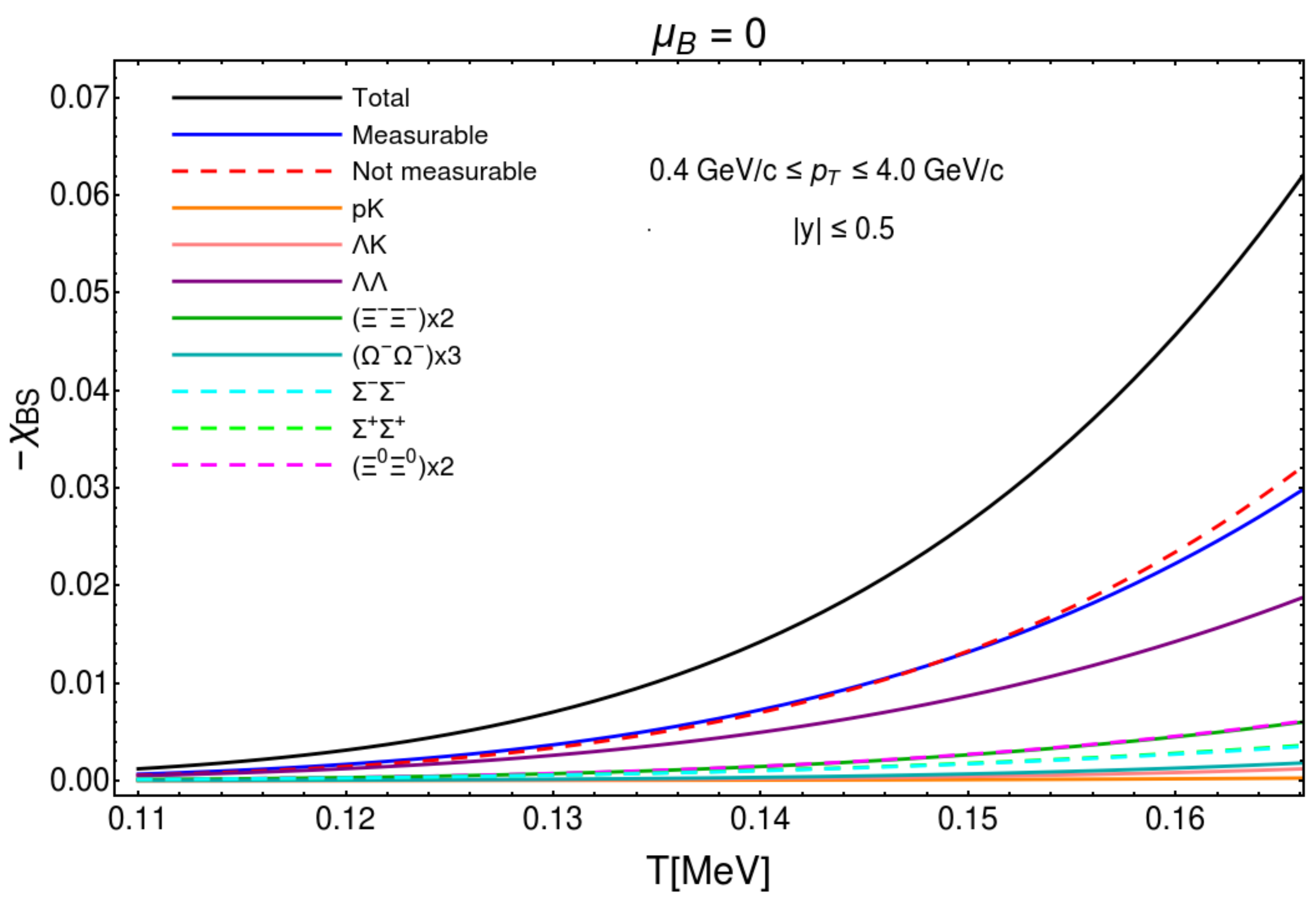
What can we learn from cross-correlators (specifically BS-correlator)?

Determined by the ratio of off-diagonal to diagonal cumulants: $\kappa^{1,1}_{B,S}/\kappa^2_S$

The related susceptibility ratio: $C_{B,S} = -3\chi^{1,1}_{B,S}/\chi^2_S$
(-3 is just a normalization factor so that the asymptotic value = +1)



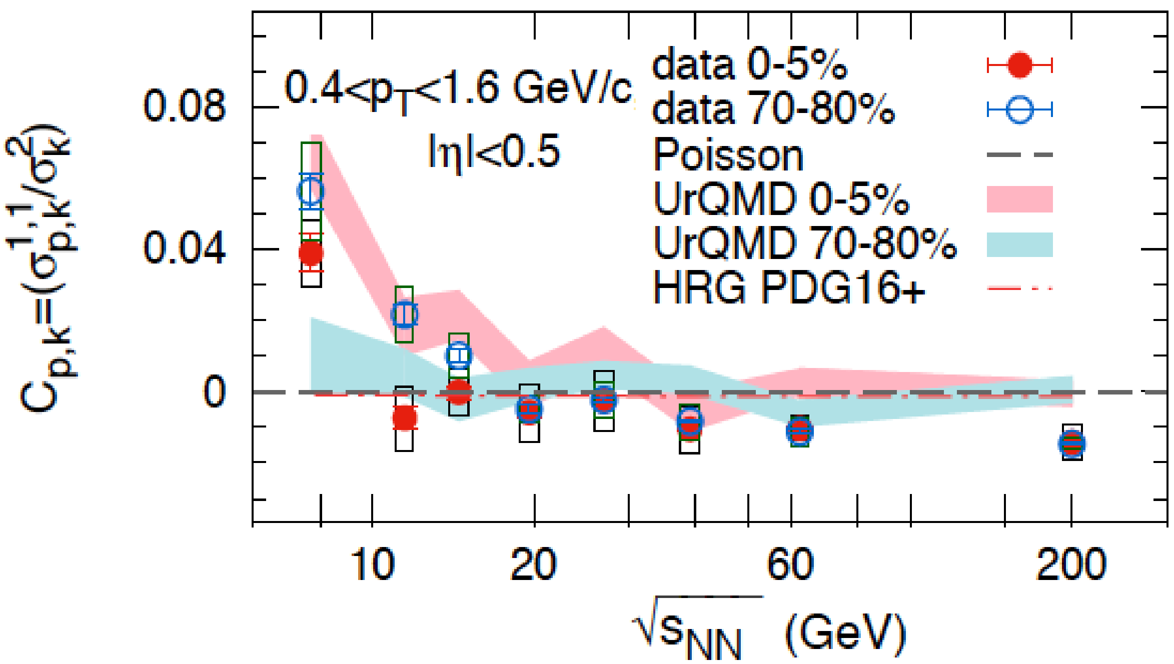
Koch, Majumder, Randrup (2005), Mueller, Majumder (2006)



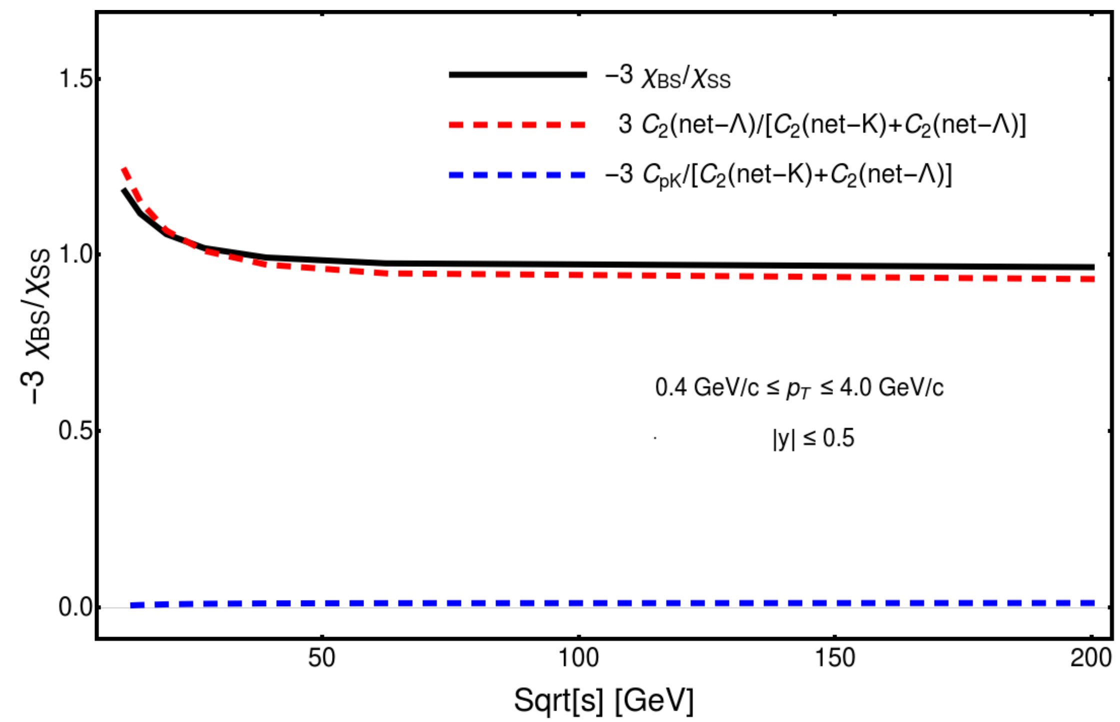
Parotto, Ratti, Stafford (SQM 2019)

Contributions to the 2nd-order off-diagonal BS cumulant

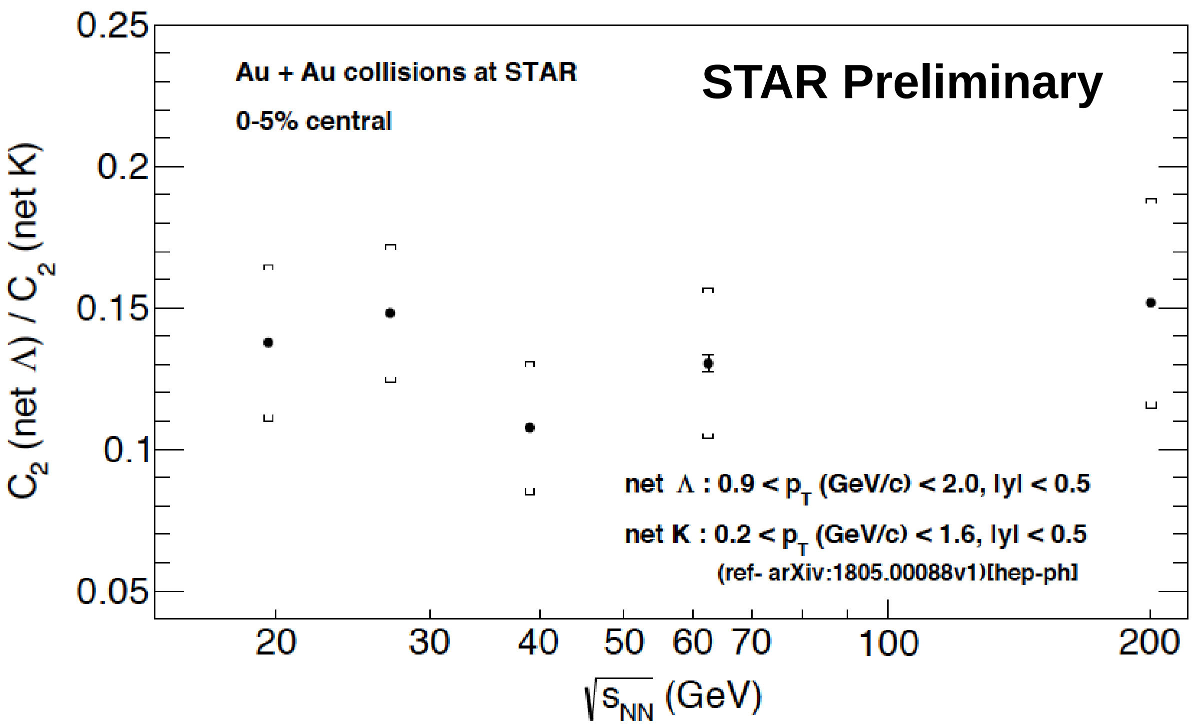
STAR measurements:
pK contribution, arXiv:1903.05370

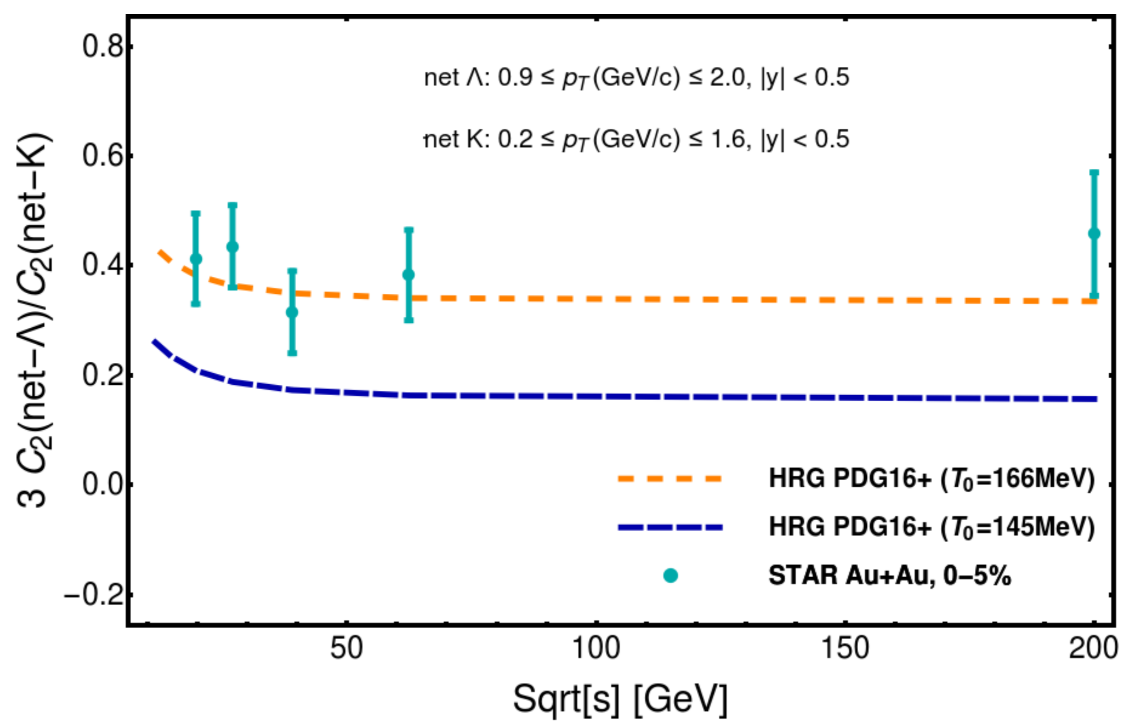


HRG predictions:
Parotto, Ratti, Stafford, SQM 2019



Λ contribution, R. Bellwied (SQM 2019)





Freeze-out is driven by flavor not baryon number ?

The thermal charm opportunities / challenges

Ultimately the question of hadronization in an analytic crossover region can be reduced to:

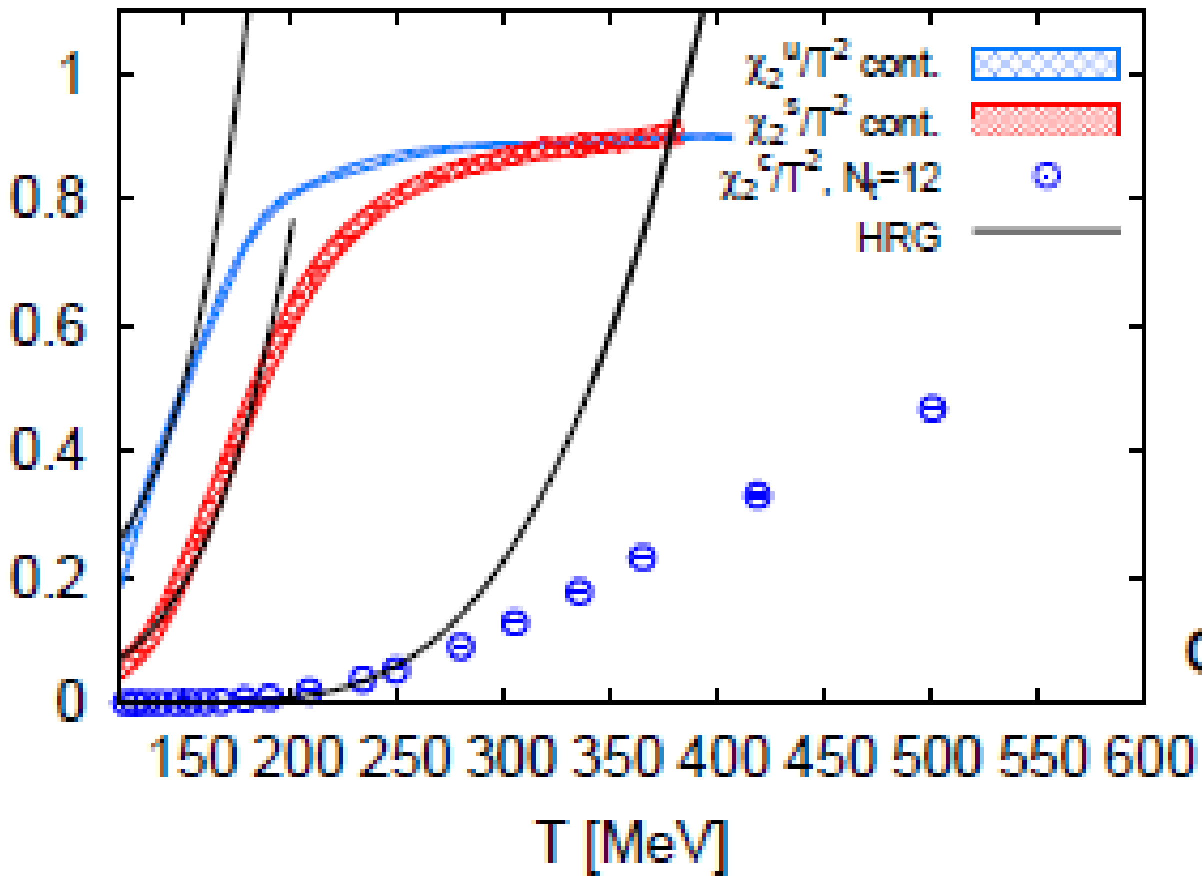
- Is there a flavor (quark mass) or other quantum number dependence when looking at lattice results from the QGP side (WB et al.)?
- Is there a hadron mass dependence when looking at HRG results from the hadronic side (Vovchenko et al.)?

At high collision energies charm can be thermally produced (C.M. Ko et al.) and/or equilibrate during the cooling of the deconfined phase.

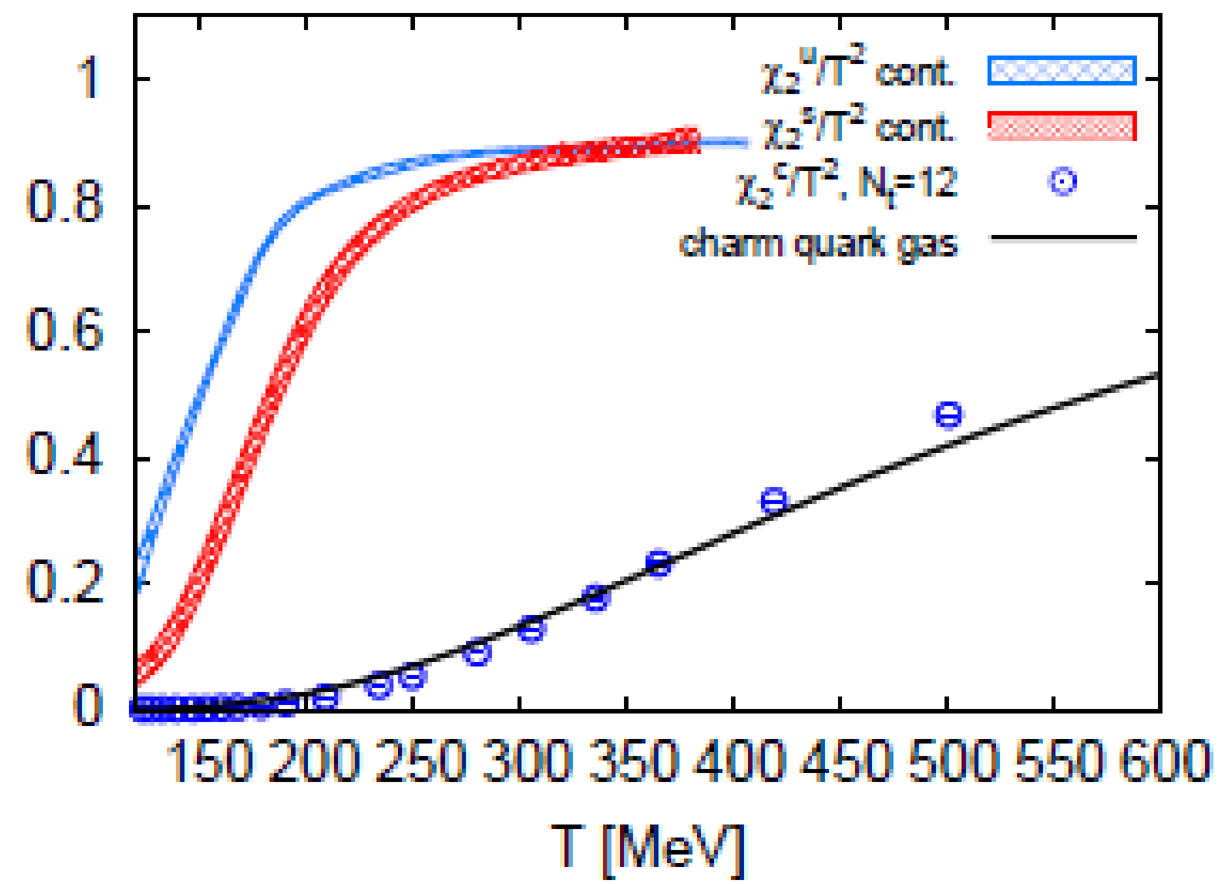
Charm fluctuation measurements could be used to explore a flavor dependent decoupling temperature for produced particles (Graf et al. (1802.07908)).

What does lattice have to say about a flavor/quark mass dependence of the freeze-out based on open charm ?

Lattice QCD: WB results (1507.04627)



or



- survival of open charm hadrons up to $T \simeq 2T_c$?
- HRG results agree with the lattice up to the inflection point in the data

- thermal excitation of charm quarks takes place at larger temperatures
- ideal gas of charm quarks agrees with lattice

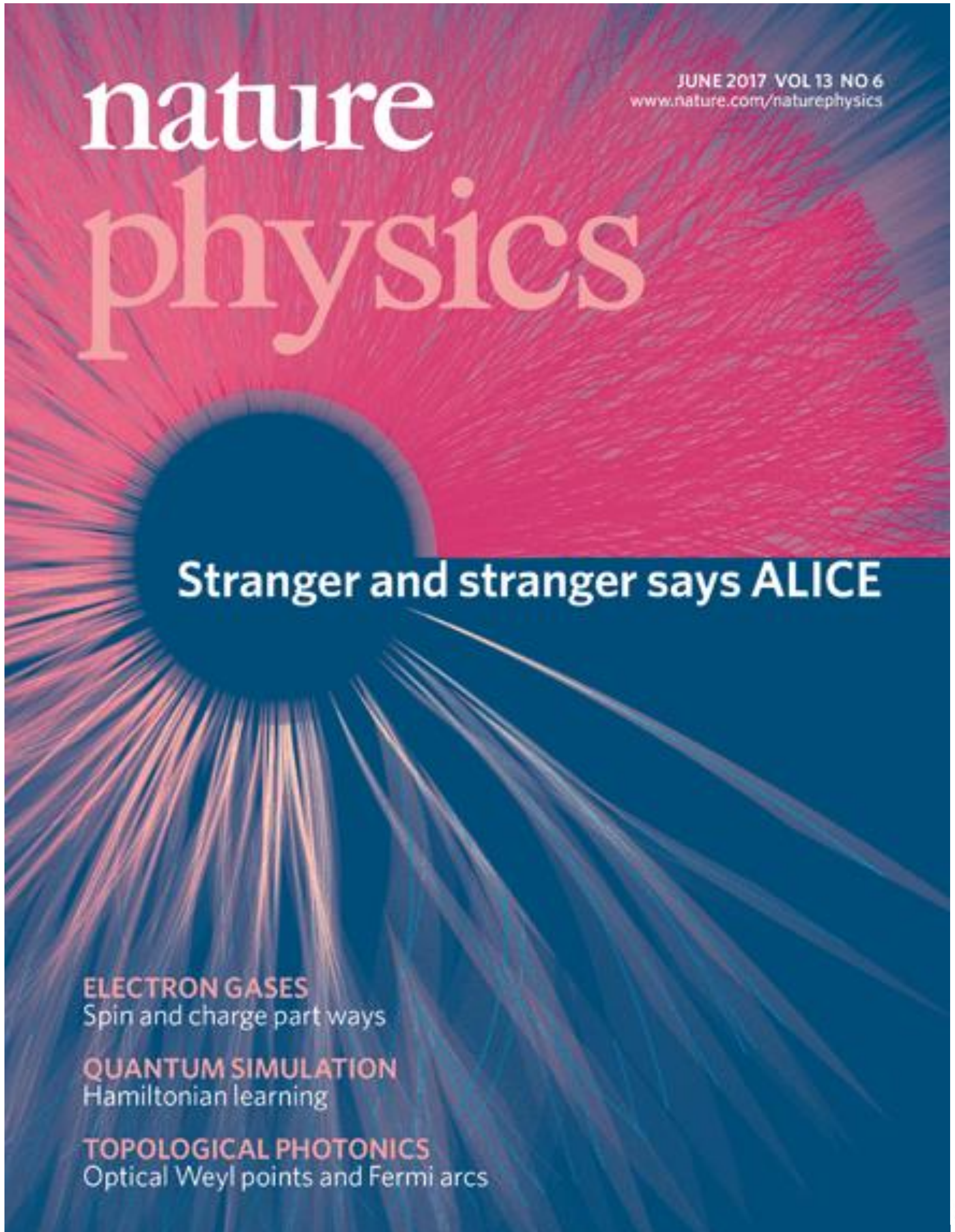
need for non-diagonal quark number susceptibilities

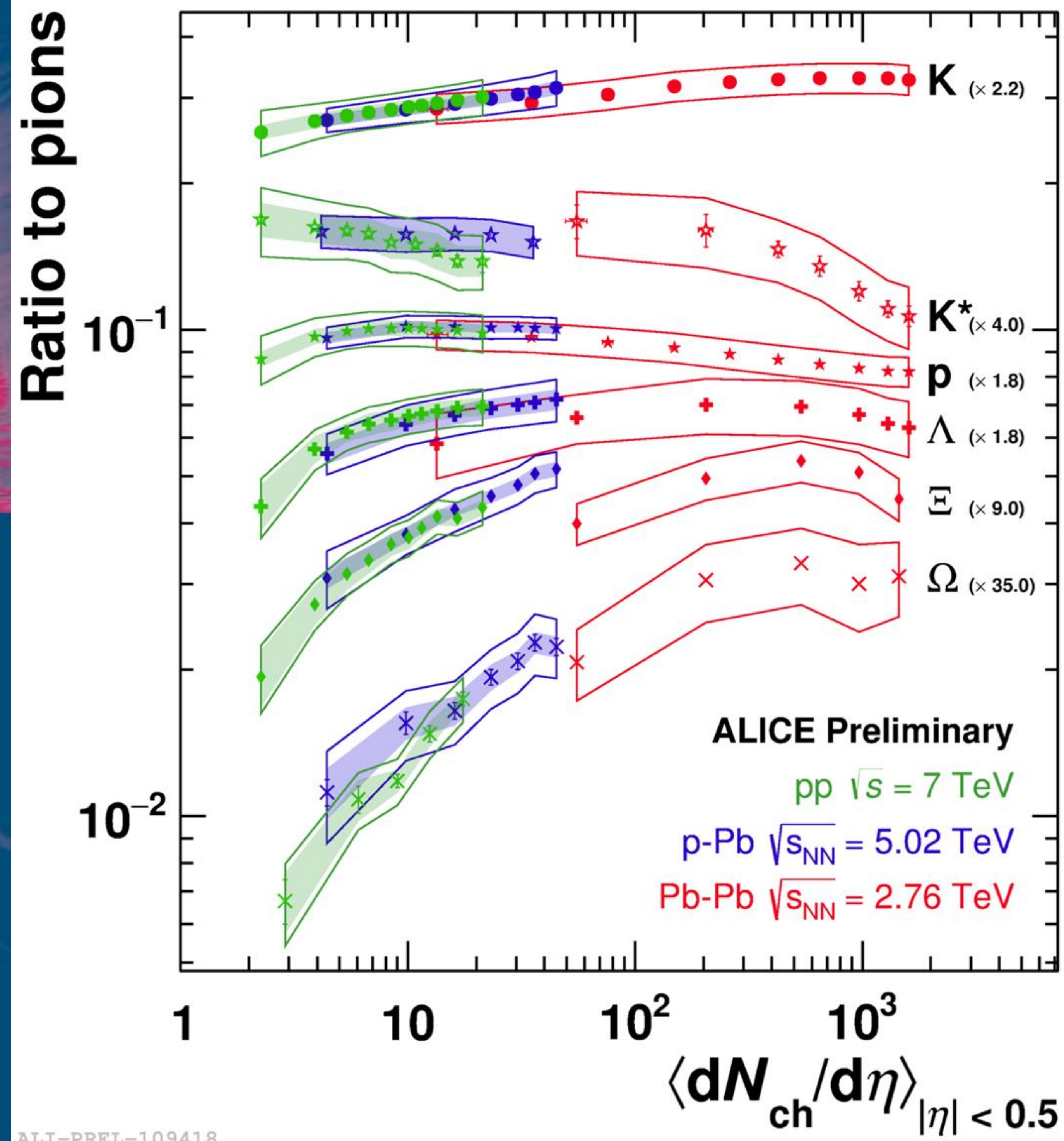
So let’s assume there is a separate freeze-out hypersurface for strangeness – do we care ?

Strange matter creation ?:

1.) strangeness enhancement vs. suppression
2.) chiral restoration at different T ?
3.) exotica

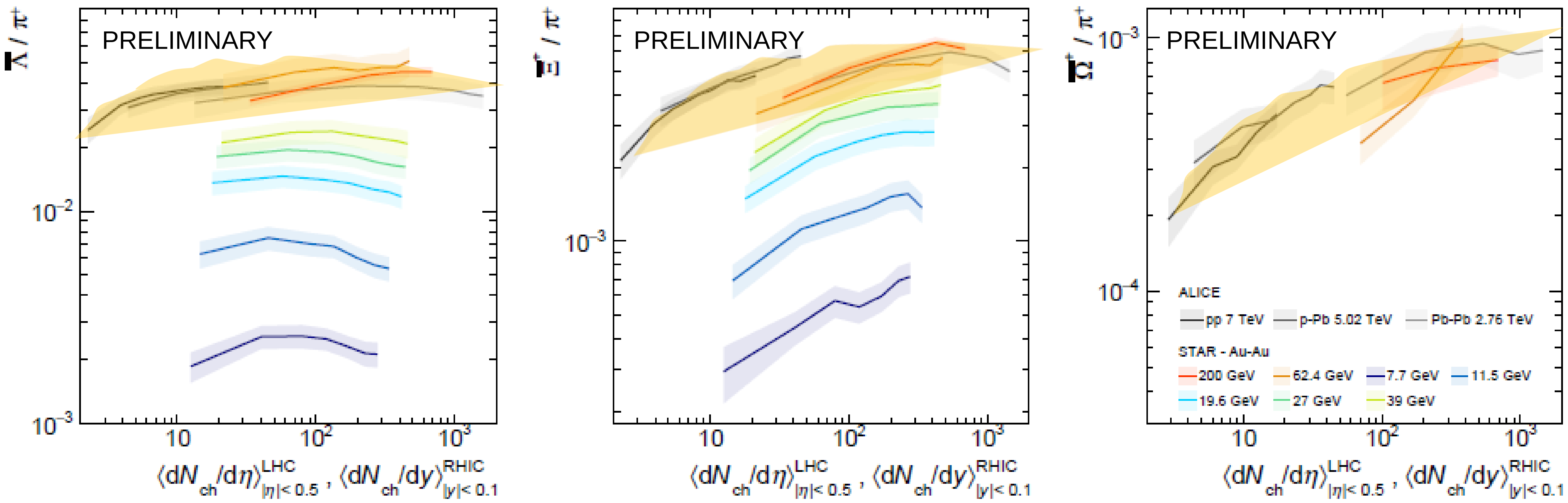
Stranger and stranger from small to large systems (ALICE, arXiv:1606.07424)





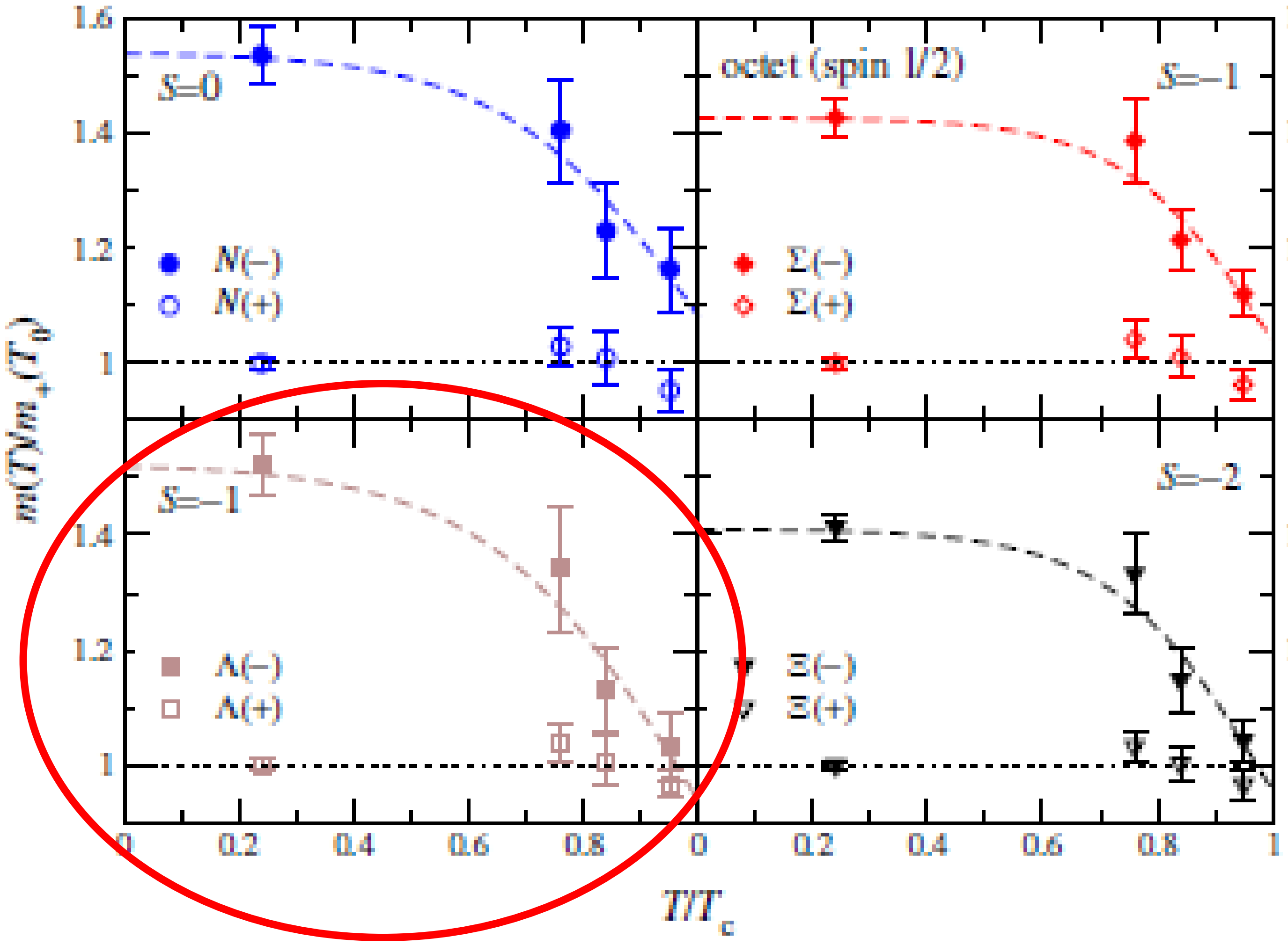
Is it time to re-evaluate strangeness suppression/enhancement ?

Canonical suppression reduces as a function of energy and as a function of system size (Tounsi, Redlich (2001)). Is suppression over at LHC energies ? Do we only see enhancement ? Can we distinguish ?



Above 39 GeV the curves seem to fall together, no more energy dependence. The volume dependence is still there (γ_s dependence ?). A higher T freeze-out surface in PbPb will lead to actual strangeness enhancement

Effects studied in STAR (arXiv.1906.03732) and ALICE



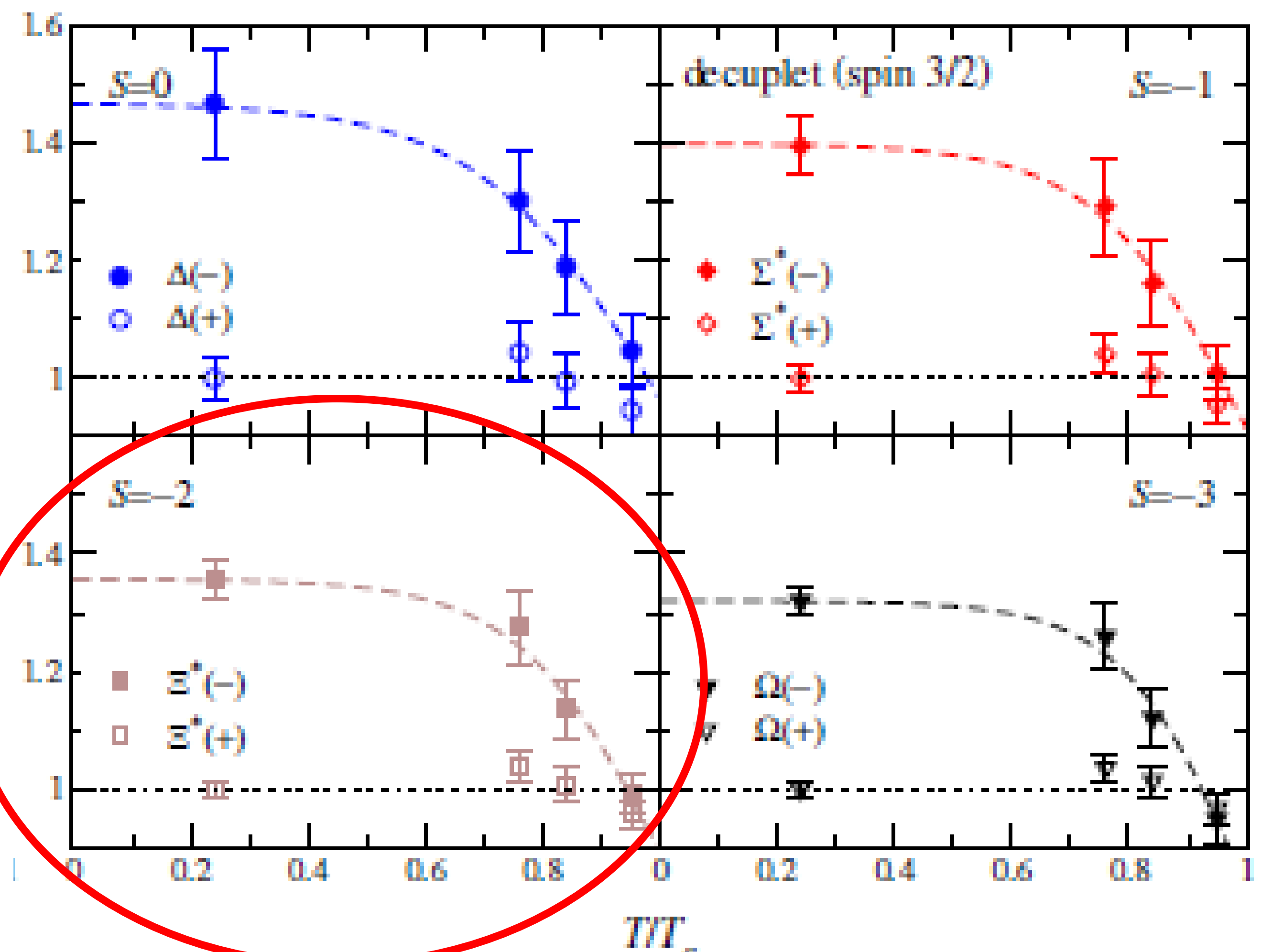
Chiral restoration in the strange baryonic resonance sector

FASTSUM Collaboration:

Baryon spectral functions

JHEP 06 (2017) 034

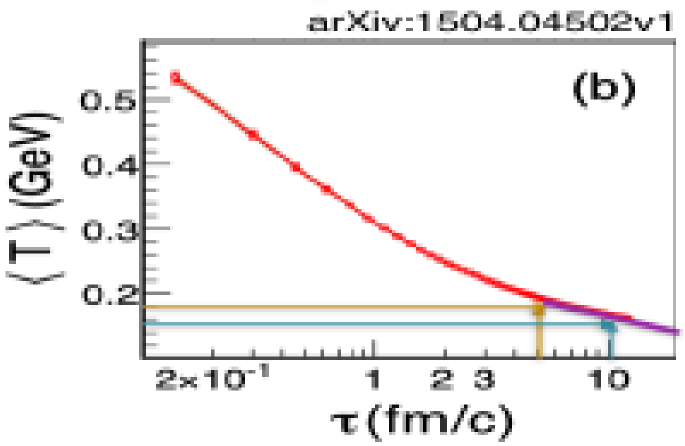
(arXiv:1703.09246)



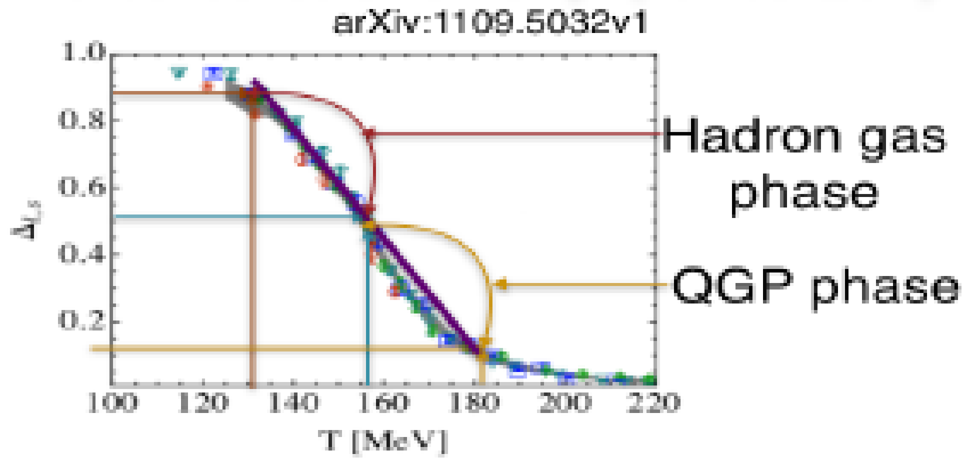
- Emerging degeneracy around T_c for chiral partners
- Positive parity masses nearly temperature independent
- Negative parity masses drop as temperature increases
- Experiment: find appropriate chiral partners.

Width broadening estimation

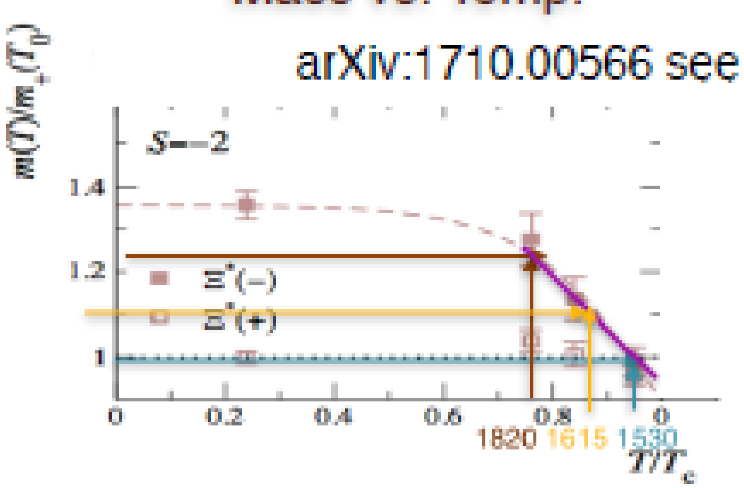
Temp. Vs. Time



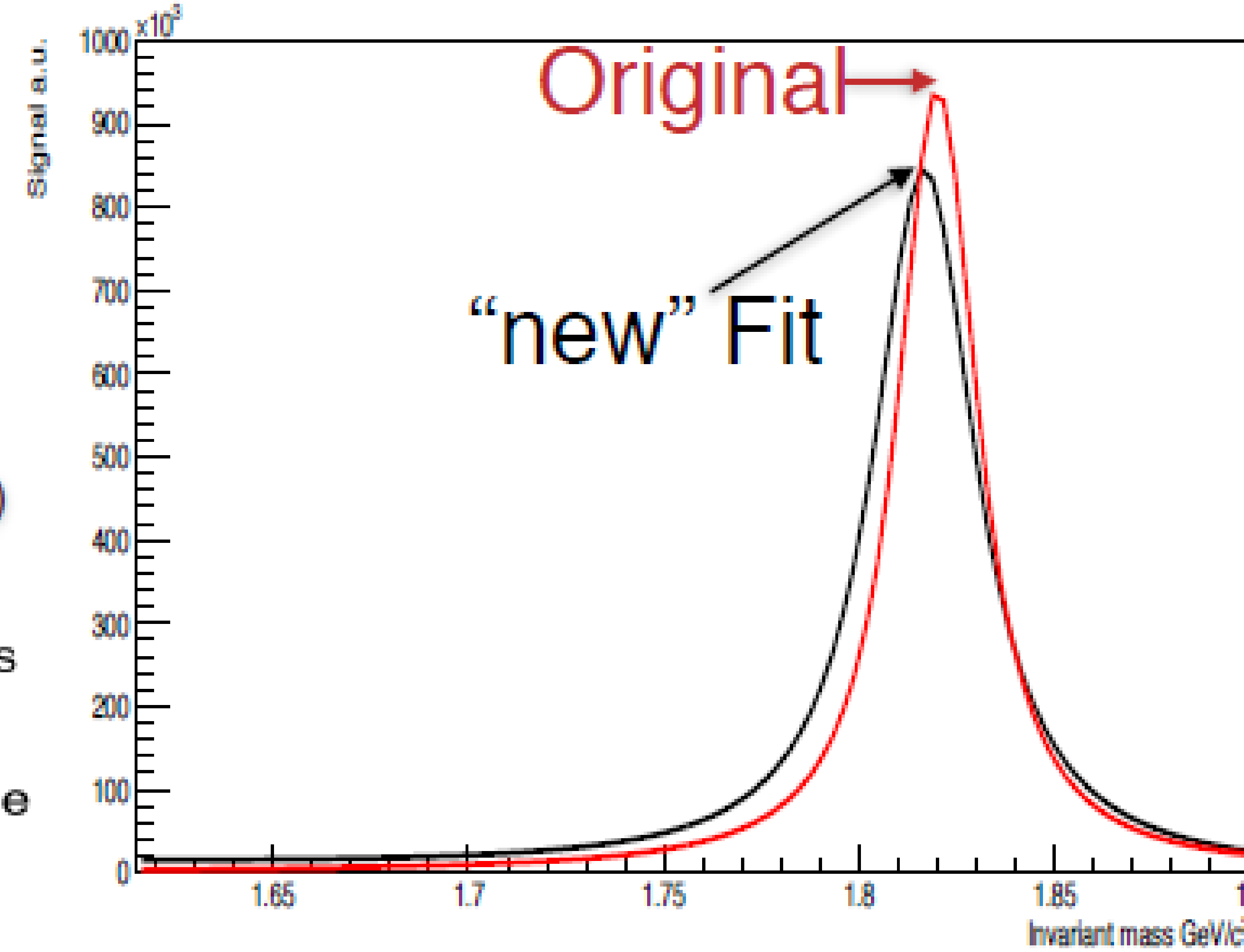
Chiral condensate vs. Temp. (Lattice QCD)



Mass vs. Temp.



Width Broadened Invariant mass plots for Ξ(1820)



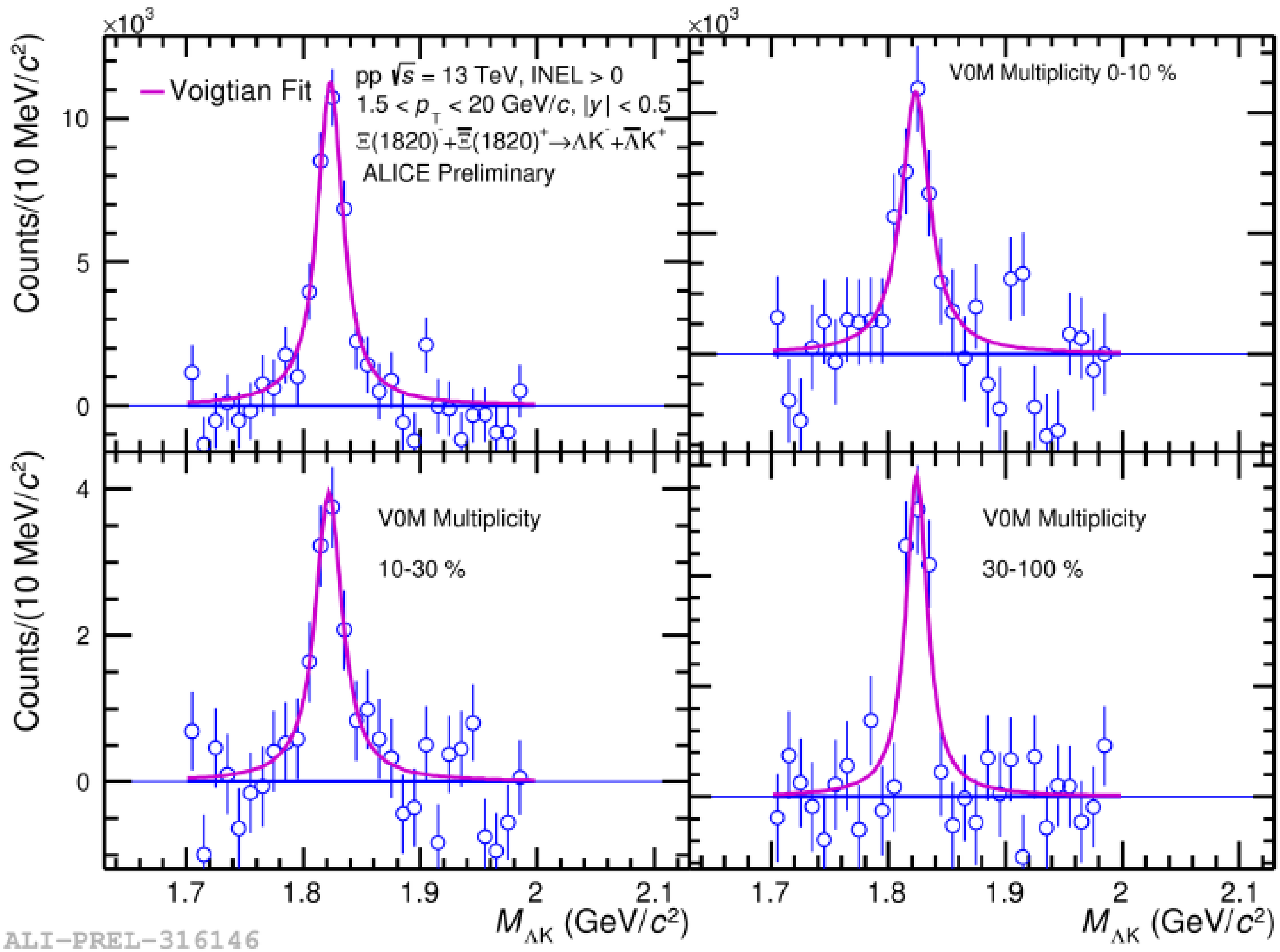
- ~14%(~17%) of forming inside(outside) QGP and decaying before chirality is completely broken.
- ~20% are decaying in the mass range we can detect.
- Expected change in mass: 1.820→1.817 GeV/c^2
- Expected change in width: 0.024→0.031 GeV/c^2

ALICE

April 15, 2019

APS Meeting

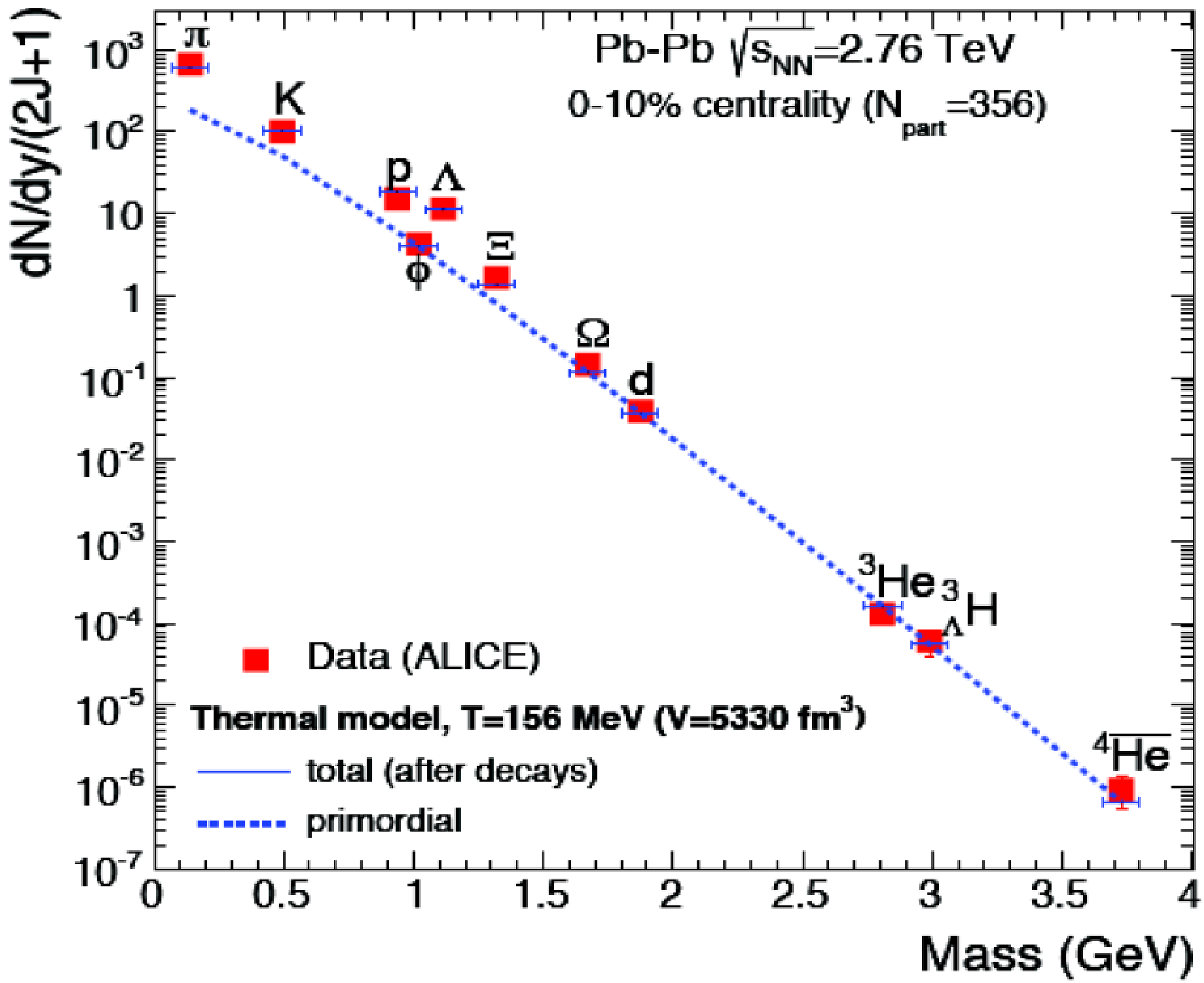
Parity doubling studied at UH
First measurement of Ξ(1820) in 30 years



C. J. Myers for ALICE Coll. (SQM 2019)

Not conclusive in pp, move on to pPb and PbPb

Thermal model for light nuclei 'works' remarkably well



How can loosely bound objects 'survive' the fireball heat bath ?

- Artoisenet & Braaten: The size of loosely bound objects (constituents are often separated by more than the range, e.g. deuteron (2.2 MeV BE, 3.1 fm rms separation) or hypertriton (130 KeV separation energy (a factor 1000 less than the chemical freeze-out temperature of the fireball), deuteron-lambda structure, 10.3 fm rms separation, extreme halo state)
- PBM & Stachel et al.: The 'snowball in hell' approach. (J.Phys.G21(1995) L17 and PLB 697 (2011) 203). Successful description of composite objects with SHM implies no entropy production after chemical freeze-out
- Siemens & Kapusta: Cluster formation probability is determined by the entropy of the fireball in its compressed state, i.e. E/B is constant (PRL 43 (1979) 1486)

This seems to be true, but why and how on the parton level ?

The Quantum Mechanics of partons: entanglement

<u>Groundbeaking paper (experimental):</u>

A.M. Kaufman et al., (Harvard), arXiv:1603.04409

Quantum thermalization through entanglement in isolated many-body system

<u>Initial state evolution for relativistic particle collisions (pp, e^+e^-)</u>

D. Kharzeev, E. Levin, arXiv:1702.03489

O. K. Baker, D. Kharzeev, arXiv:1712.04558

Thermal radiation and entanglement in proton-proton collisions at the LHC

J. Berges, S.Floerchinger, R.Venugopalan, arXiv:1707.05338

J. Berges, S.Floerchinger, R.Venugopalan, arXiv:1712.09362

Thermal excitation spectrum from entanglement in an expanding quantum string

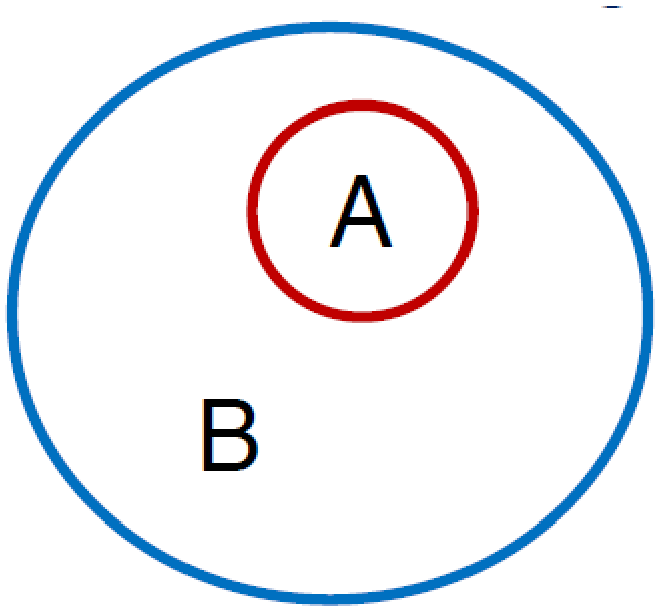
R. Bellwied, arXiv:1807.04589

Composite particle production in relativistic particle collisions through quantum entanglement

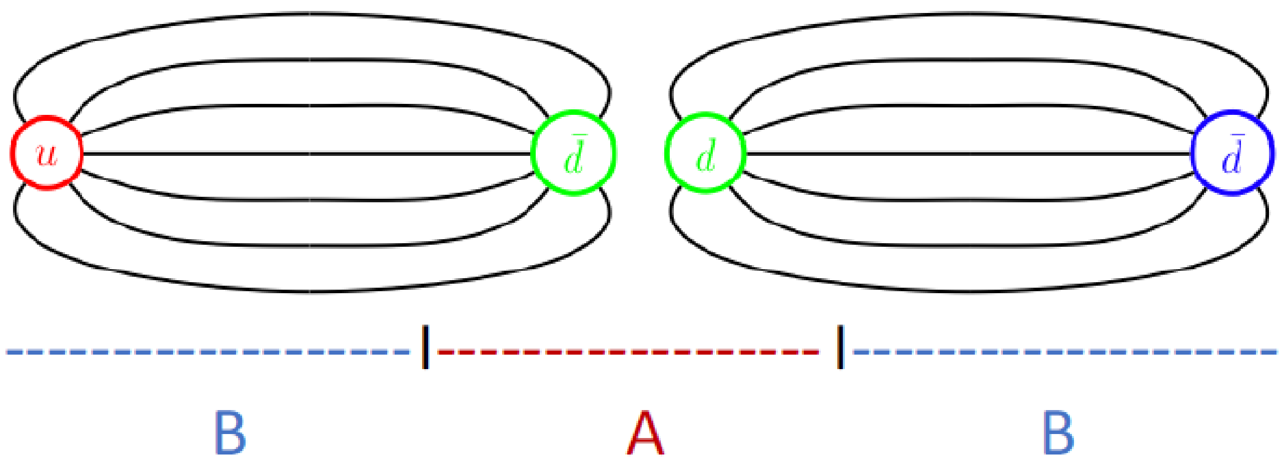
Quantum entanglement in transverse and longitudinal direction

Transverse:
DIS probes only part of the proton's wave function (region a), but we sum over all hadronic final states, which, in QM, corresponds
to the density matrix of a mixed state: $\hat{\rho}_A = \mathrm{tr}_{\mathrm{B}} \hat{\rho}$

with a non-zero entanglement entropy: $S_A = -\mathrm{tr}\left[\hat{\rho}_{\mathrm{A}} \ln \hat{\rho}_{\mathrm{A}}\right]$



Longitudinal:
Particle production in QCD strings:



Example: PYTHIA
Different regions in a string are entangled. Again A is described by a mixed state reduced density matrix.
Could this lead to thermal-like behavior in the final state particles ?

Conclusion: Entanglement entropy is an extensive quantity (depends on volume

Extension to heavy ion collisions

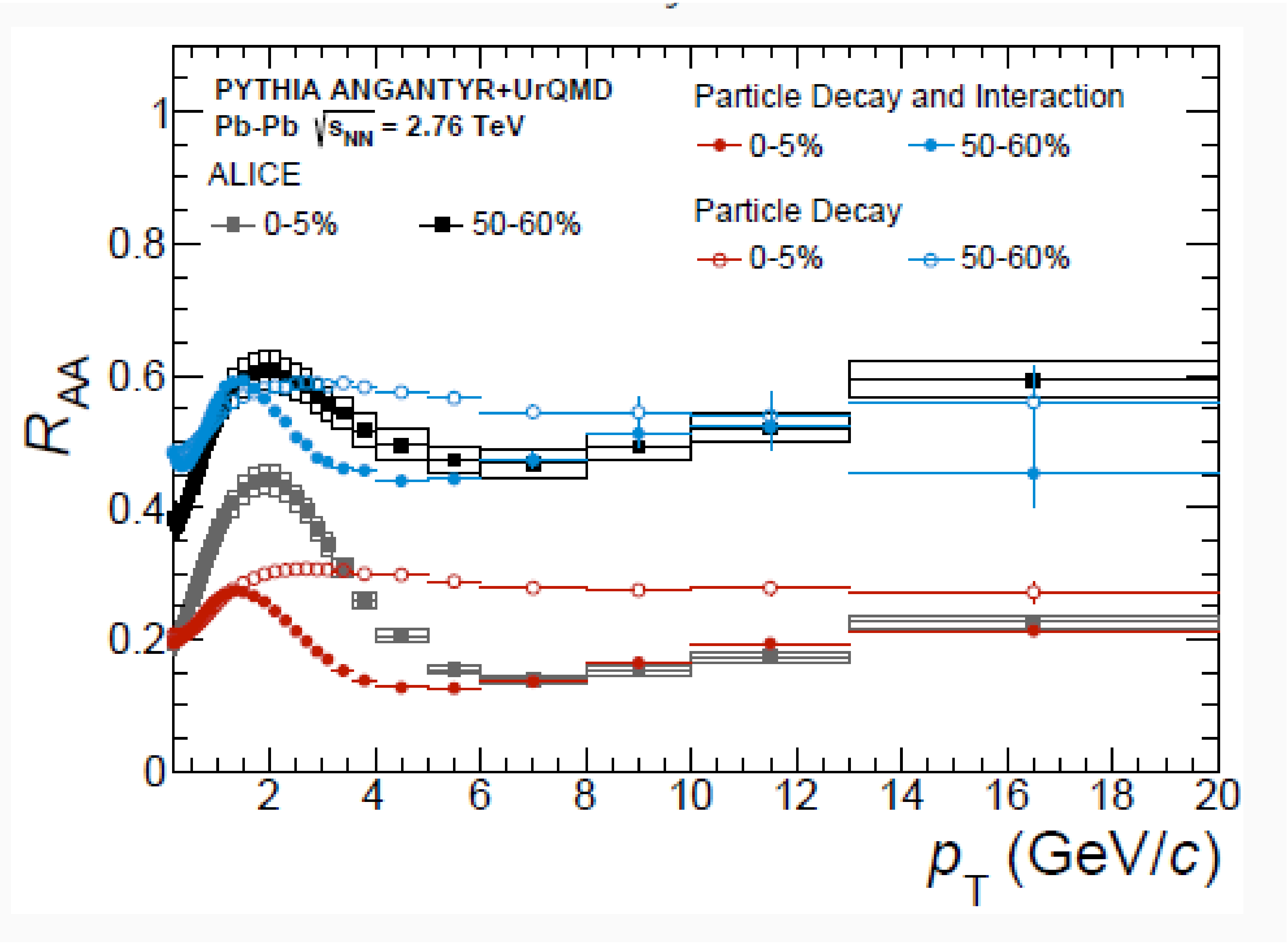
• If the system looks 'thermal' due to entanglement, but actually never thermalizes through interactions, then there is no decoherence effect and hadronic re-interaction effects are negligible.

•If entanglement entropy follows the 2nd law of thermodynamics then the initial entropy is reflected in the final entropy, which is approximately constant during the strong coupling phase (parton-hadron duality).

•All light quark hadron yields, including composite hadronic objects are formed from a single multi-quark QCD string and are frozen in during the initial state at a common 'temperature'.

•Entanglement entropy is calculated over extended volume at QCD crossover. Temperature should be related to Hagedorn temperature but needs to be quantitatively established. (see e.g. Pajares et al., arXiv:1805.12444)

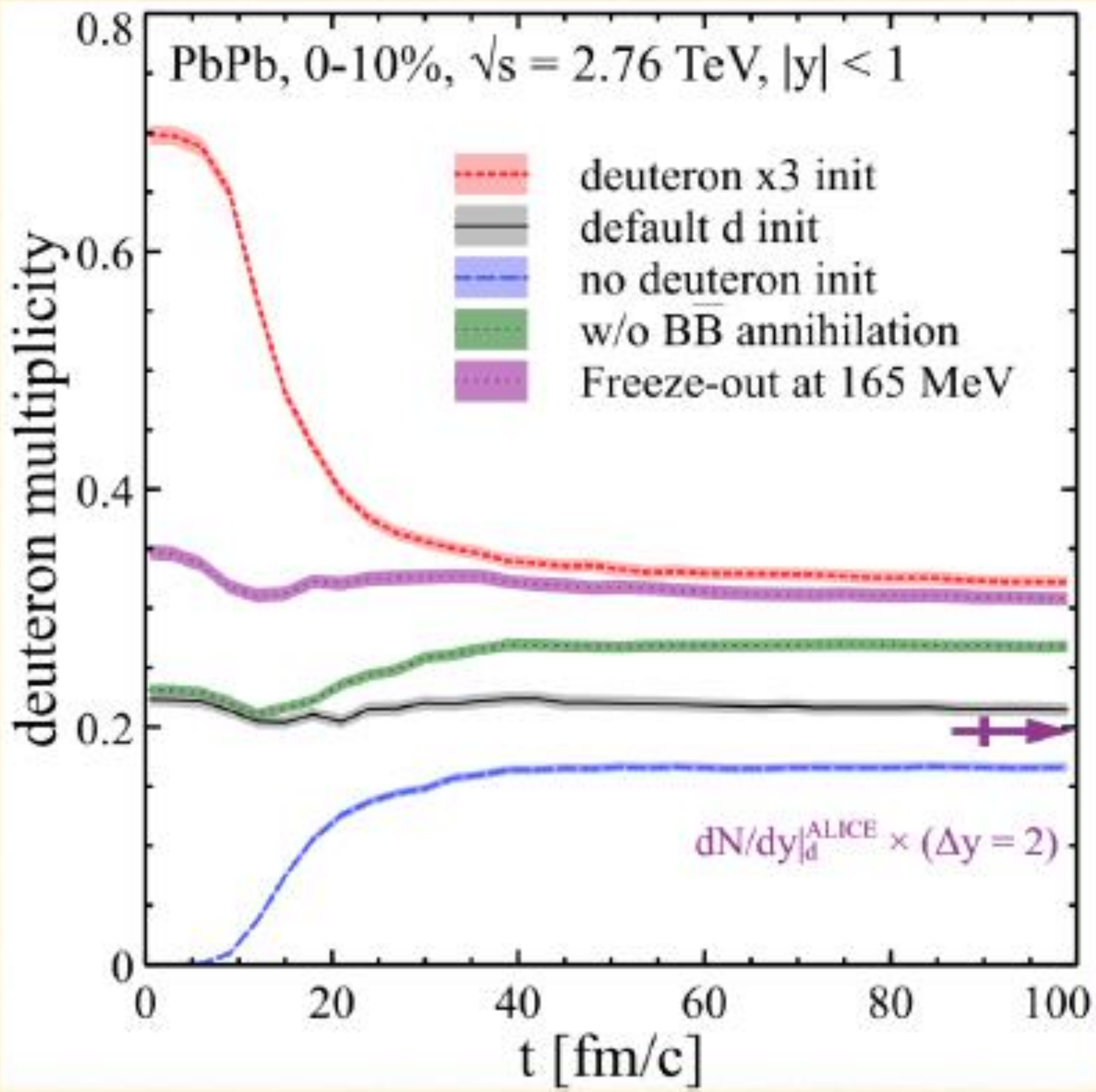
Jet quenching without a partonic hydro phase ?



<u>SQM 2019, Bierlich et al.: PYTHIA+URQMD</u>

Color reconnection from the initial state (a form of quantum entanglement ?) plus hadronic final state interactions. <u>No QGP necessary</u> ? Much debated. Also works (partially) for particle yields

Detailed balance through multi-hadron interactions



Hydrodynamics does well, but finer points regarding initial production

$2 \leftrightarrow 3$ reactions in SMASH!

$$\pi d \leftrightarrow \pi np$$
$$Nd \leftrightarrow Nnp$$

Oliinychenko Phys. Rev. C 99, 044907 (2019)

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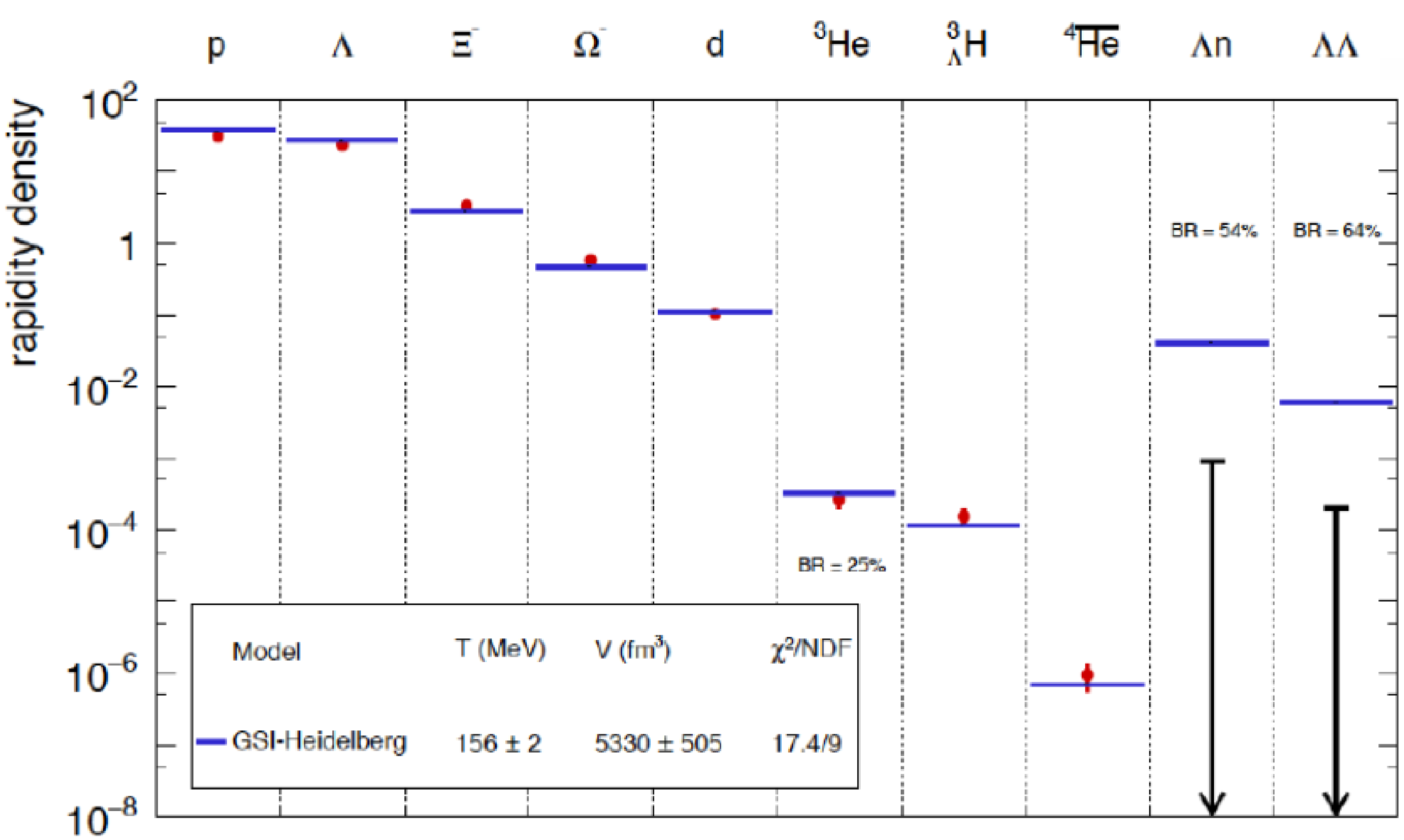
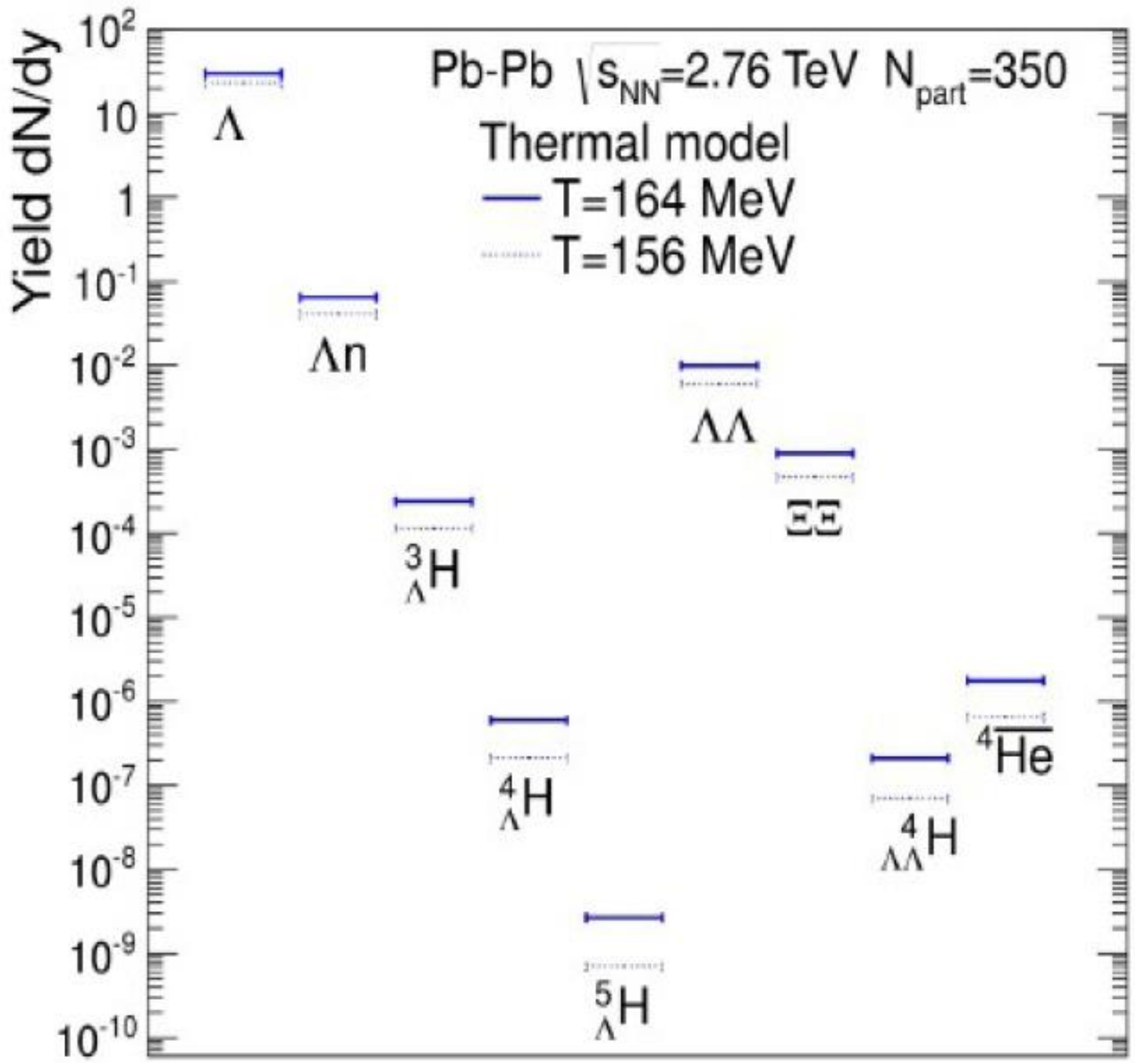
from last week’s SQM 2019 conference

Experimental conclusions and outlook

- Hadron multiplicity fluctuations in elementary collisions show already intriguing patterns that point at entanglement. Similar studies in heavy ion collisions are underway.

- If thermal models can reliably predict exotic and rare multi quark clusters then we can make estimates for more exotic states.





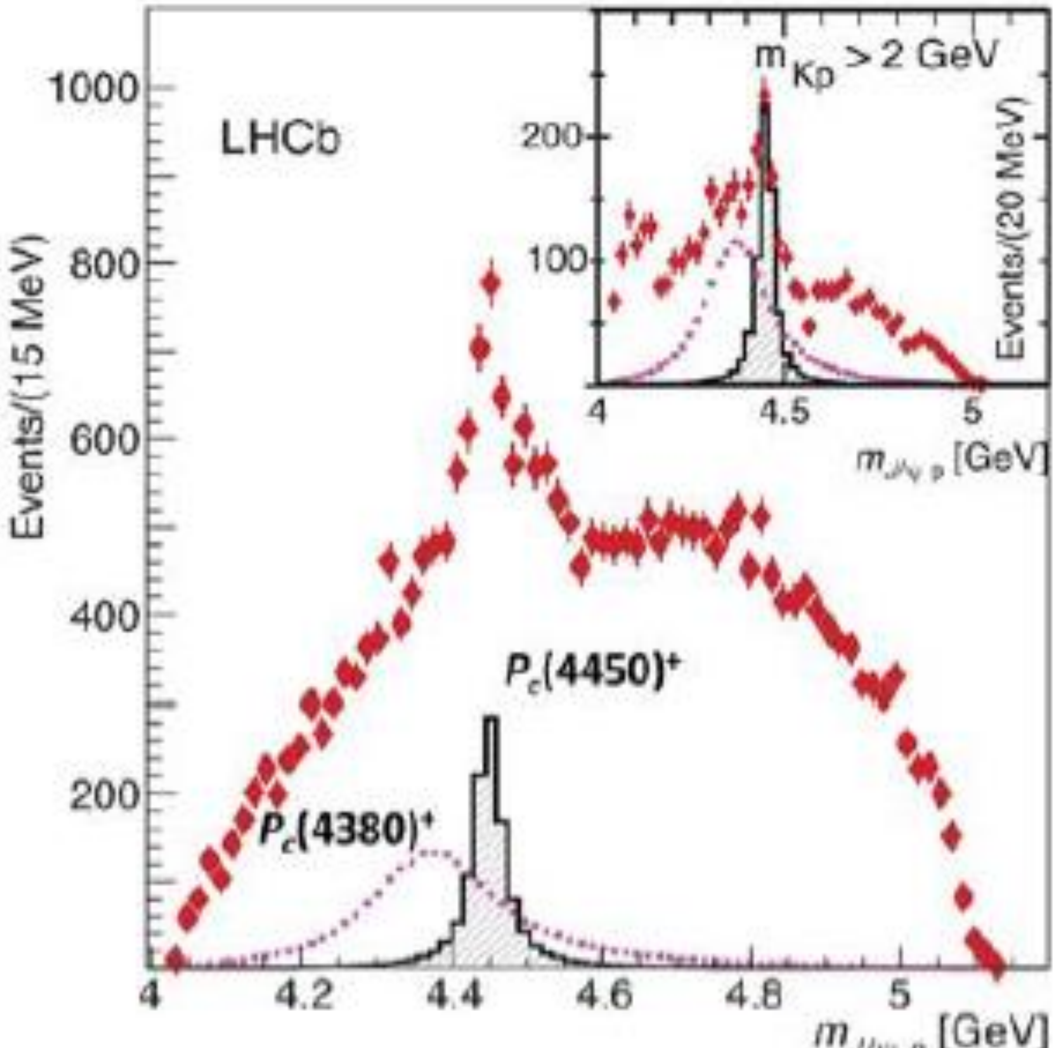
Exotica:

Penta- and Tetra-quarks from LHCb

Penta-quark in 2015, 9σ evidence by 2016

In the charm sector: J/ψ p resonance

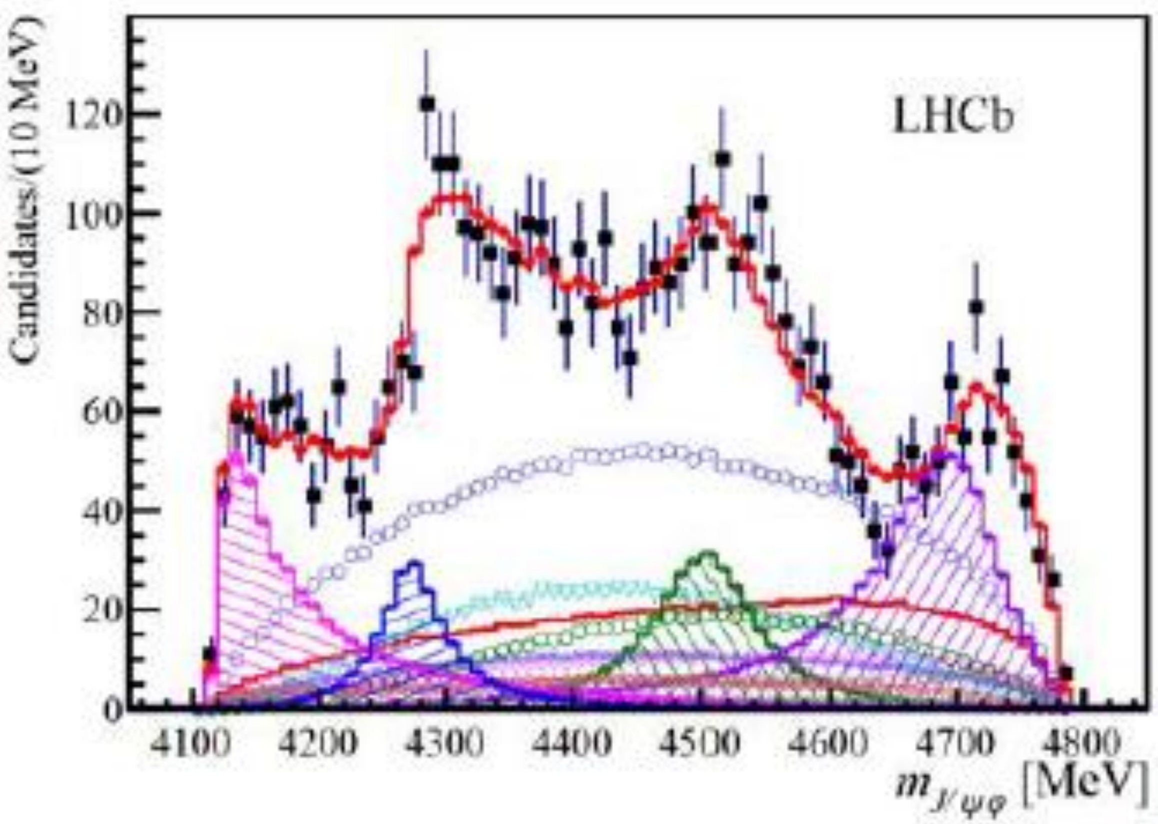
In Λ_b decays to J/ψ p K^-



Tetra-quarks in 2016

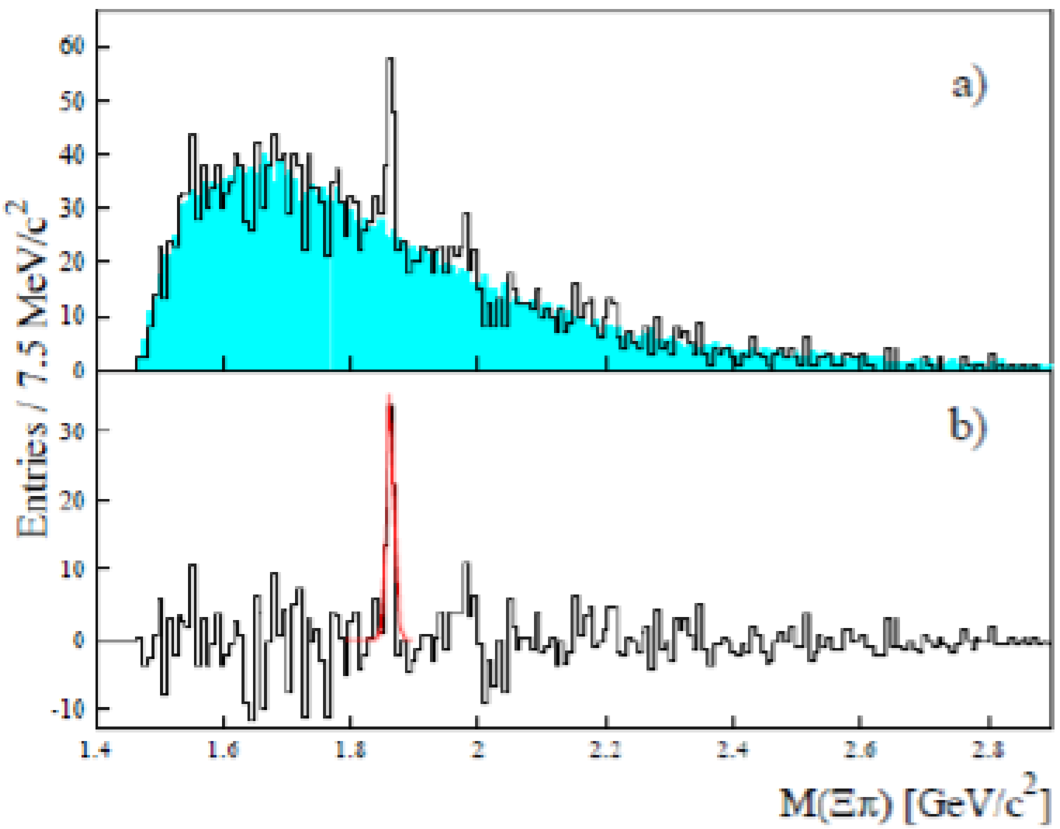
In the charm sector: J/ψ ϕ resonance

In B^+ decays to J/ψ ϕ K^+

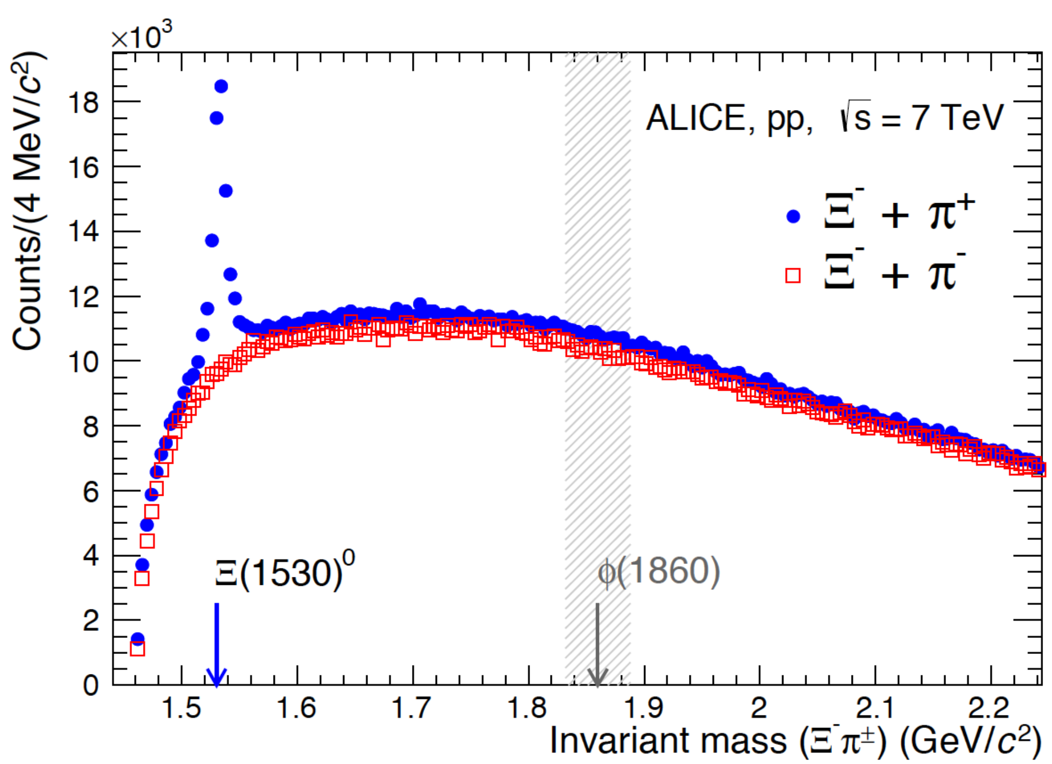


Why nothing in the strange sector ?

Exotica in strange sector ?



Famous pentaquark candidate from NA49 (2008) in Ξπ channels (ϕ(1860)) (dsdsubar)
Never retracted, never confirmed



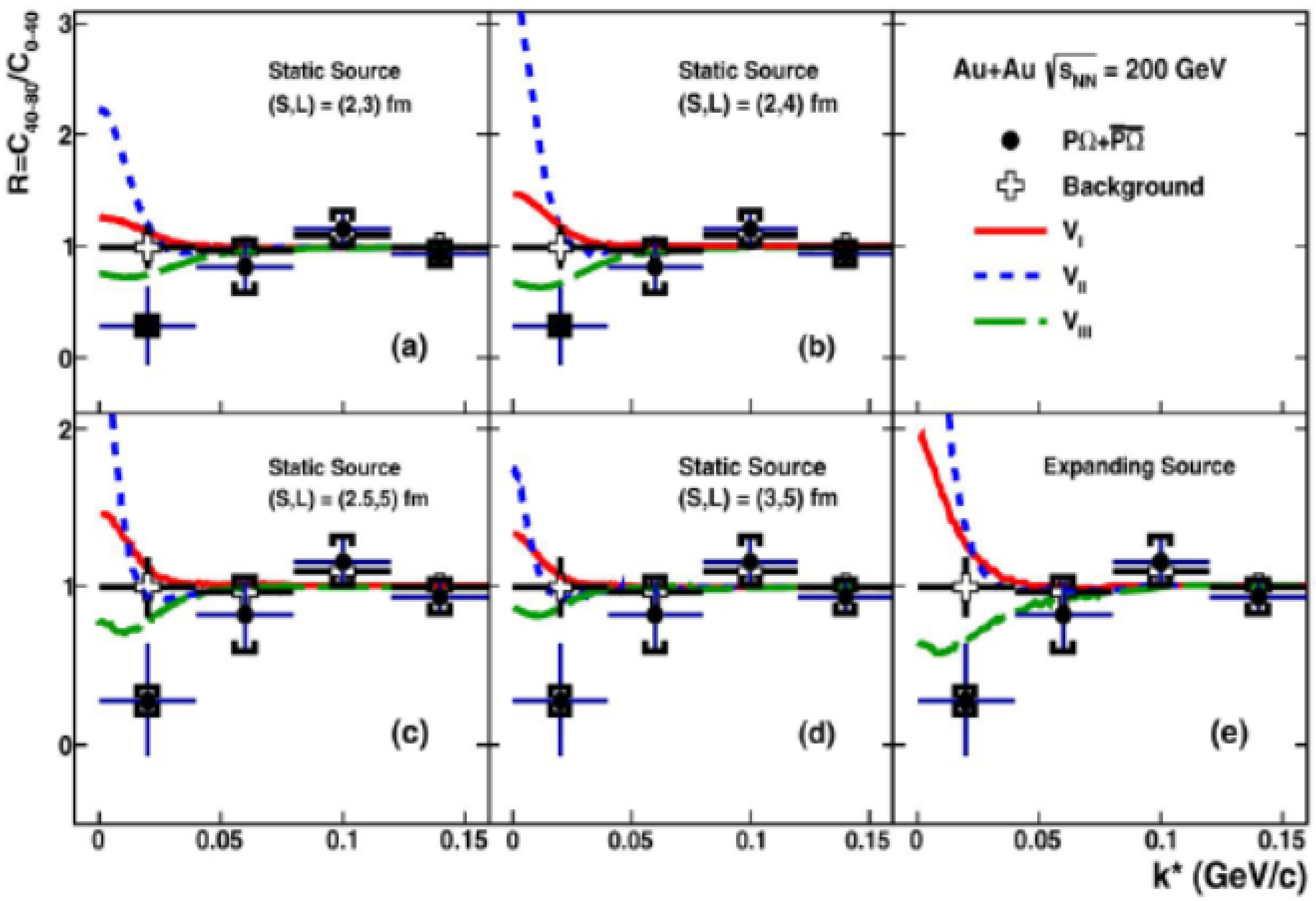
No evidence for H-dibaryon or ϕ(1860) in ALICE data.

Maybe we are looking in the wrong channels. In the charm sector all tetra- and penta-quarks seem to require closed charm components.

Keep looking !!

Another avenue: Femtoscopic studies of di-baryon strong interactions (STAR & ALICE)

- Study of the p-Ω^- correlation function in Au-Au collisions at $\sqrt{s_{NN}}$ = 200GeV STAR Collaboration. Phys. Lett. B790 (2019) 490-497
- Observable: ratio of the correlation function peripheral/central collisions.
- Comparison with Lattice QCD calculations (with large masses)



- Test different fits to Lattice QCD data (delivering **three different binding energies of the NΩ**):

Binding energy ($\mathbf{E_b}$), scattering length ($\mathbf{a_0}$) and effective range ($\mathbf{r_{eff}}$) for the Spin-2 proton–Ω potentials [24].

Spin-2 pΩ potentials	V_I	V_{II}	V_{III}
$\mathbf{E_b}$ (MeV)	–	6.3	26.9
$\mathbf{a_0}$ (fm)	−1.12	5.79	1.29
$\mathbf{r_{eff}}$ (fm)	1.16	0.96	0.65

[24] K. Morita, A. Ohnishi, F. Etminan, T. Hatsuda, Phys. Rev. C 94 (2016), 031901

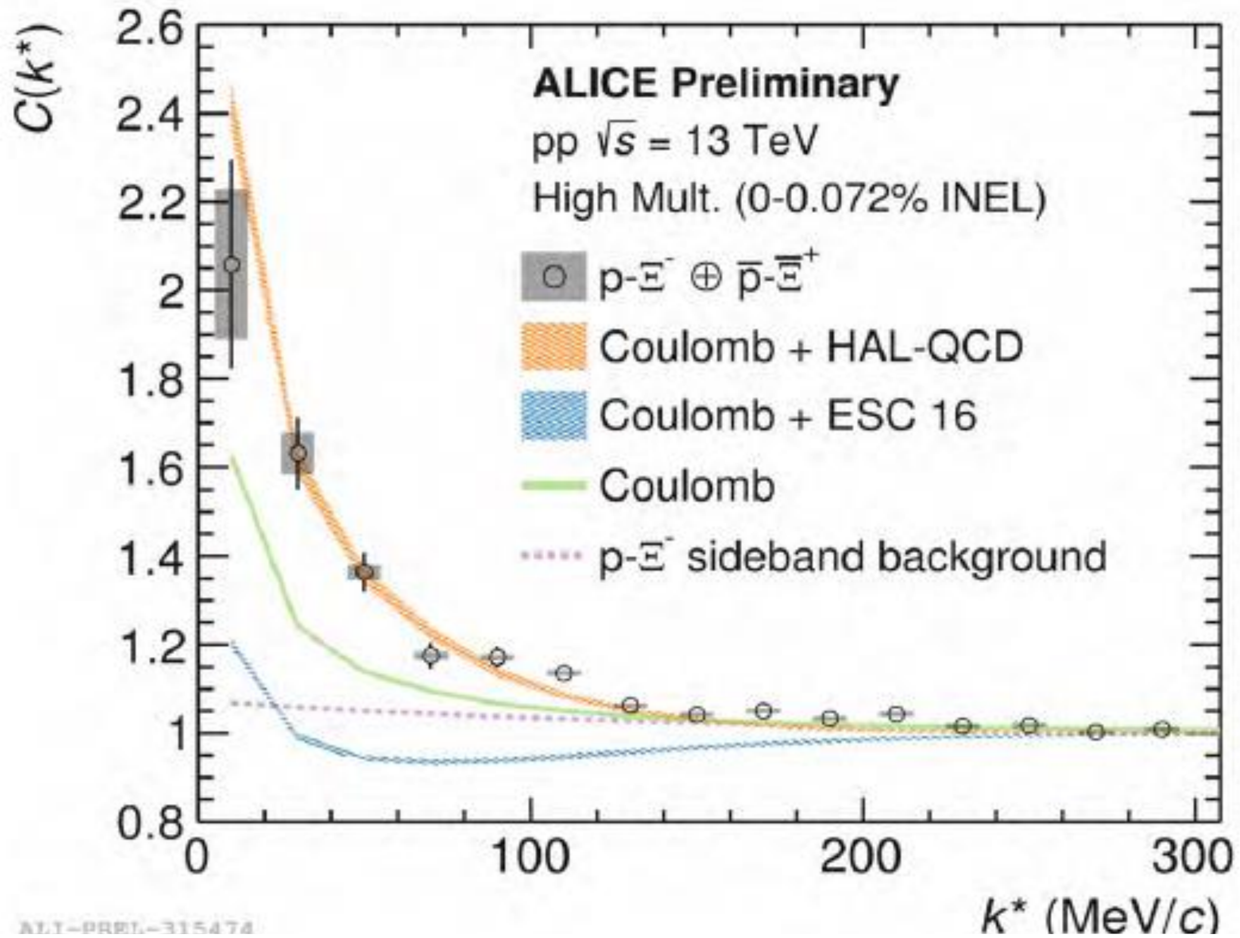
STAR data favor V_{III}, with $\mathbf{E_b}$ **= 27 MeV**

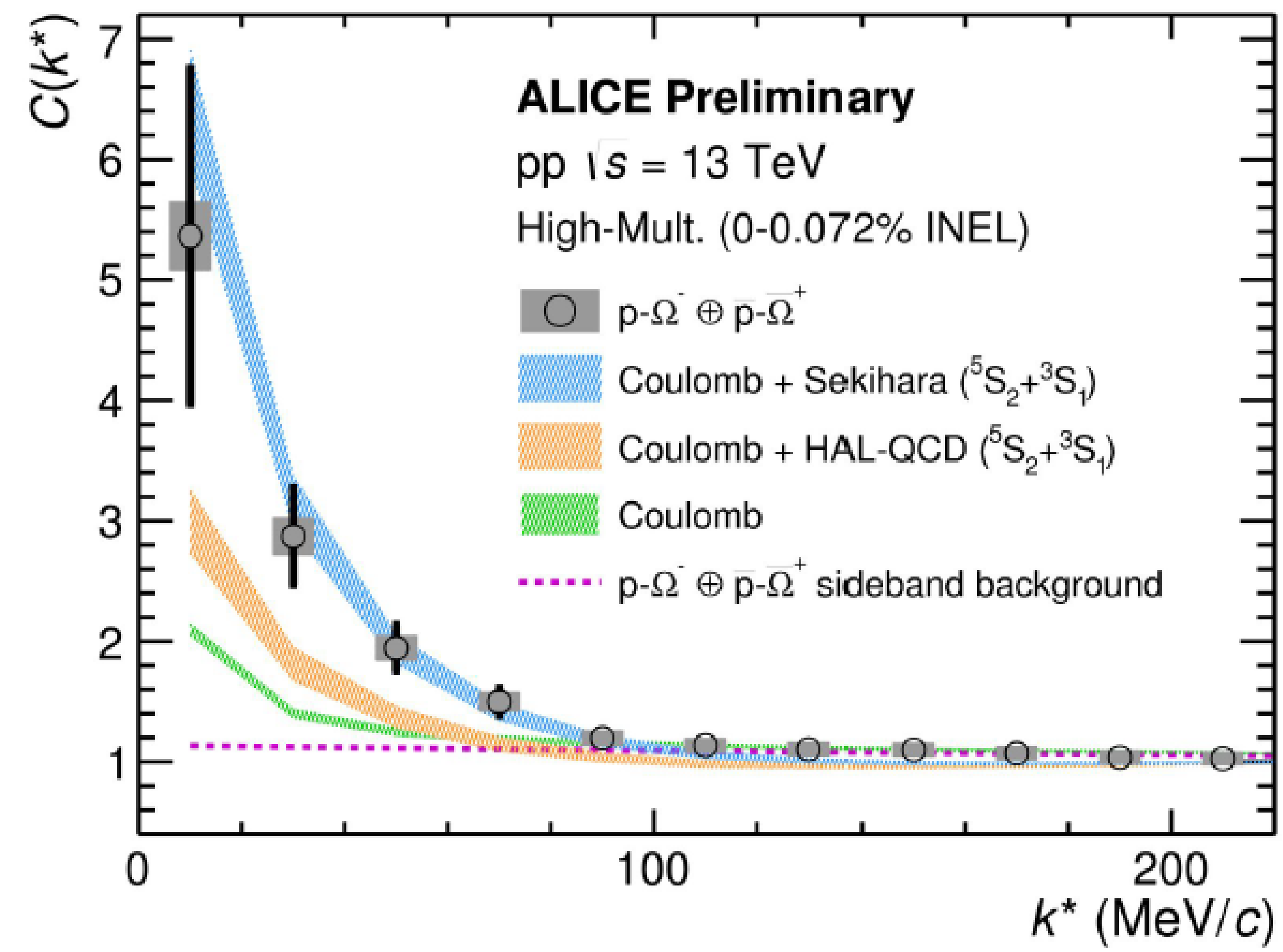
3

STAR concluded attractive potential and large binding energy For a di-baryon state (based on comparison to lattice QCD (with wrong hadron masses).

Another avenue: Femtoscopic studies of di-baryon strong interactions (STAR & ALICE)

ALICE, High multiplicity pp collisions, pΞ and pΩ correlations





ALICE concluded attractive potential and but very small binding energy for a di-baryon state (based on comparison to lattice QCD (with correct hadron masses) and meson exchange model.

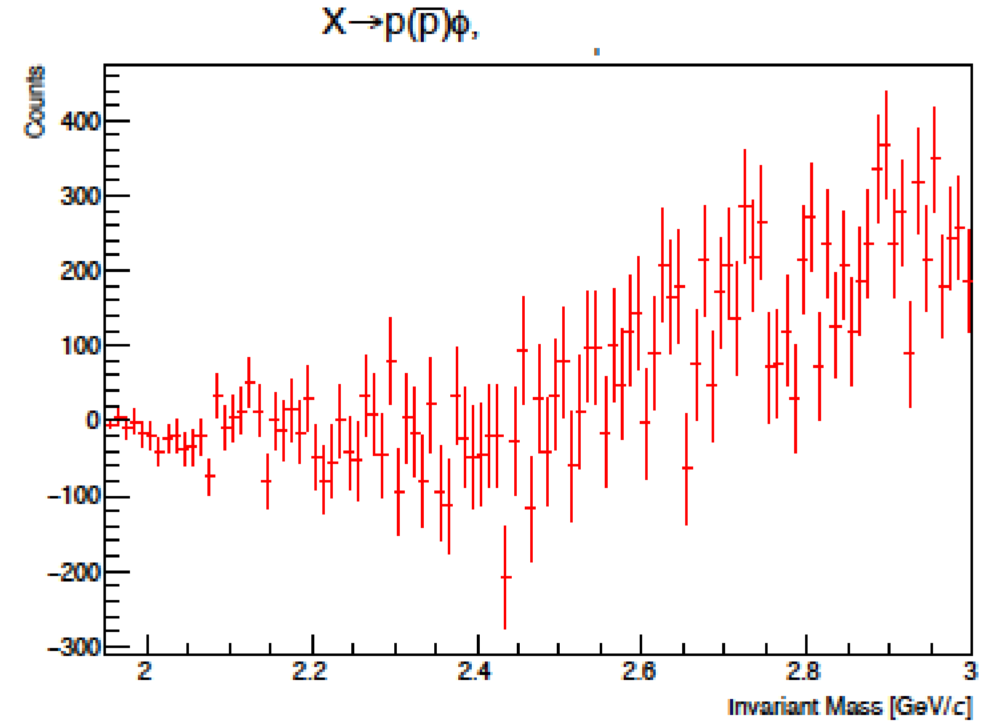
We are looking !
Strange multi-quark states

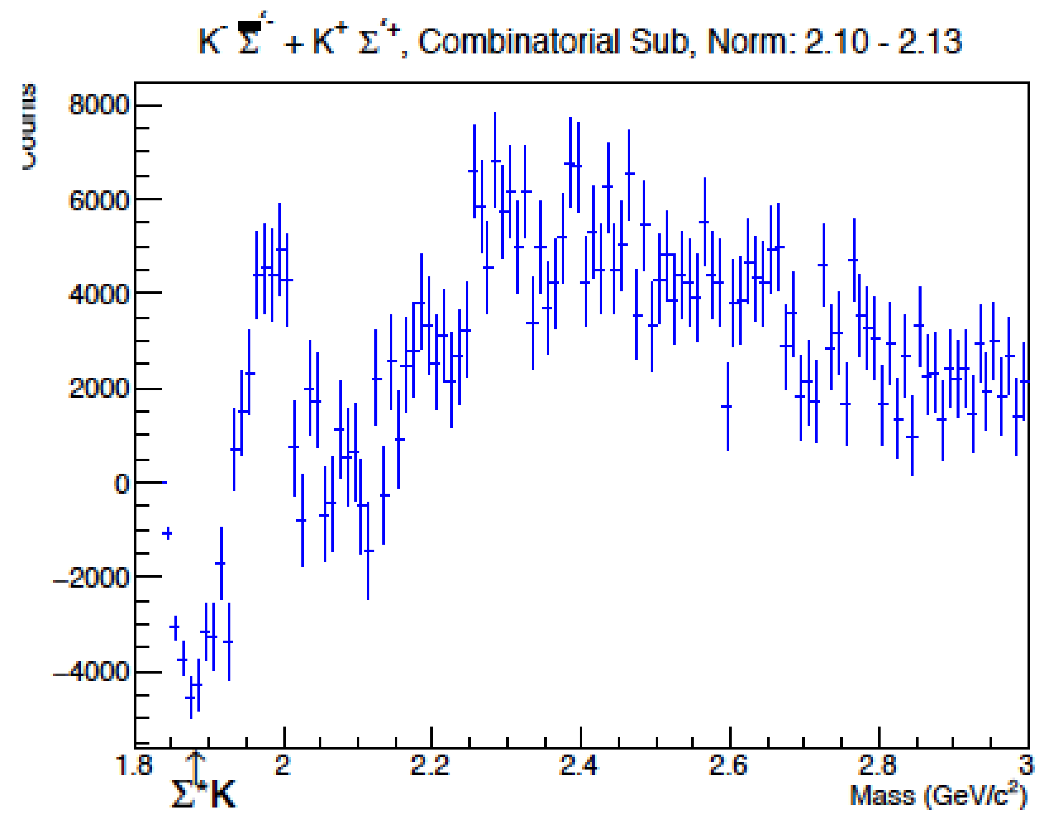
- There is a likelihood that the closed charm stabilizes the charmed multi-quark states Let's look for closed strangeness: ϕp, $\phi\Lambda$, ϕK, $\phi\pi$-states

- Another proposed pentaquark channel: KΣ* (something in the doubly charged channel !?, unlikely !), arXiv:1803.05267 (also ΛK*)

- Started di-baryon searches other than the H-Dibaryon. Most promising: pΞ and pΩ Most exciting: $\Omega\Omega$ (not enough stats, yet…)

- We keep looking !! Tens of channels proposed by ExHIC collaboration, arXiv:1702.00486





Conclusions / Outlook

- High precision (continuum limit) lattice QCD susceptibility ratios indicate *flavor separation in the crossover from the partonic to the hadronic matter.*
- There are hints, when comparing to hadron resonance gas and PNJL calculations, that this could lead to a short phase during the crossover in which strange particle formation is dominant.

- If the abundance of strange quarks is sufficiently high (LHC) this could lead to *enhancements in the strange hadron yields (evidence from ALICE)* and it could lead to *strangeness clustering (exotic states: dibaryons, strangelets)* or *higher mass strange Hagedorn states* (as predicted by Quark Models).
- Dynamic quantities that evolve during the deconfined phase will be affected as long as the hadronization temperature plays a significant role, i.e. quark phase is shortened for heavier flavors, which could explain flavor effects in R_{AA} if energy loss builds up near Tc.

- Ongoing project (BEST Collaboration): The phases can be linked in a hydrodynamic calculation by using a mixed EOS from lattice and HRG with varying flavor-dependent switching temperatures.

Some speculation, conclusions

- We are starting to learn about the intricate hadronization mechanism in the QCD crossover region.

- There are plenty of ideas of the dynamic system ranging from quark clustering into Hagedorn states (Greiner, Noronha-Hostler) over interacting hadron states (Vovchenko, Stoecker) to colored and color neutral quasiparticles (Bratkovskaya, Cassing) to constituent quarks embedded in gluon clouds (Stock).

- Lattice seems to indicate quantum number dependencies in the crossover region. Flavor (thus quark mass) seems to play more of a role than baryon number or charge.

- By studying identified particle production features in terms of quantum number fluctuations we can learn detailed features of the hadronization process not only from following the flavor dependencies (up to charm), but also the charge, isospin and baryon number dependencies.