Particle formation in the early universe: The fascinating features of the crossover region in the QCD phase transition

R. Bellwied (University of Houston)

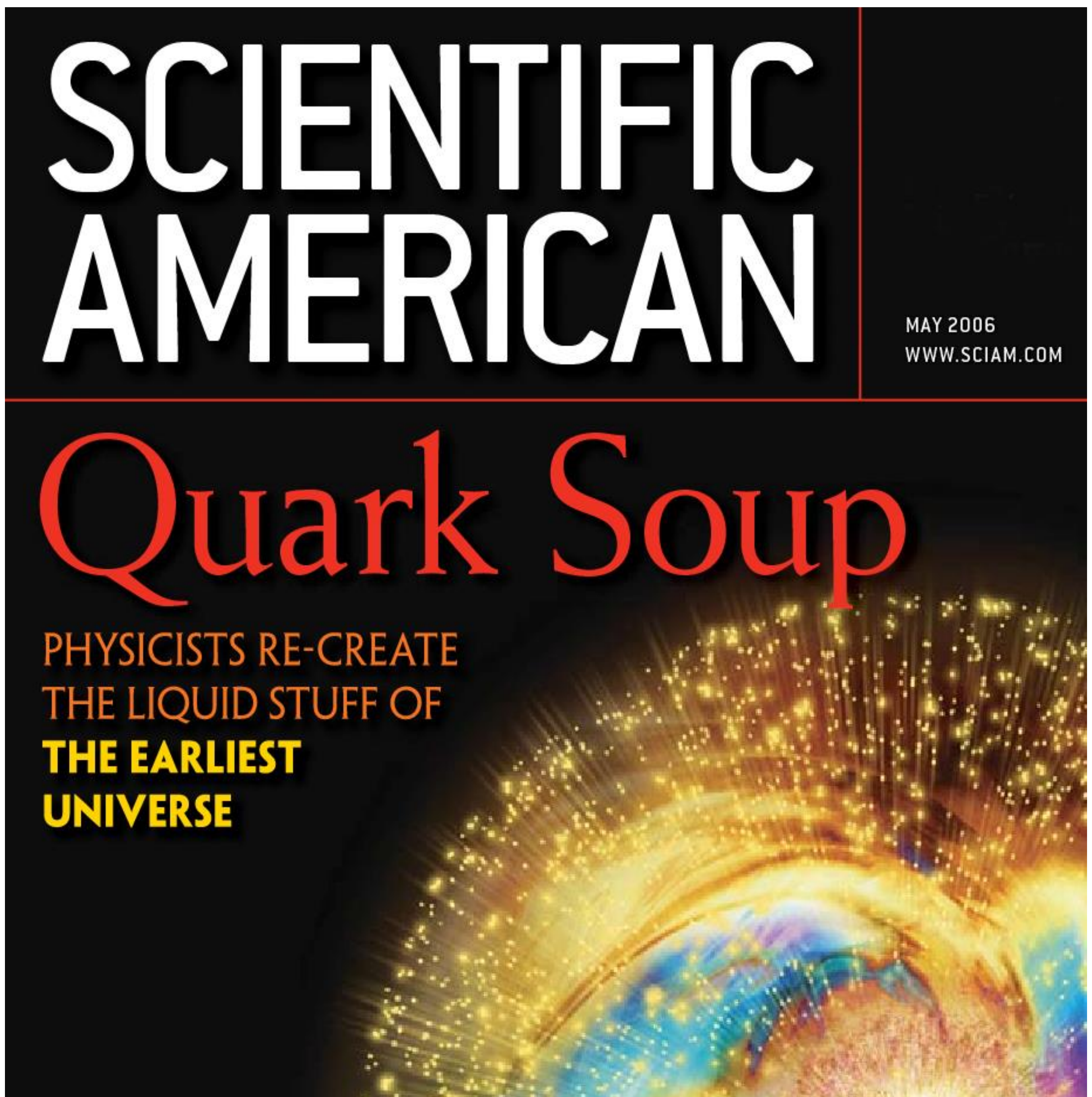
Thanks to: Paolo Alba, Livio Bianchi, Szabolcs Borsanyi, Zoltan Fodor, Anders Knospe, Valentina Mantovani-Sarti, Jackie Noronha-Hostler, Paolo Parotto, Attila Pasztor, Claudia Ratti

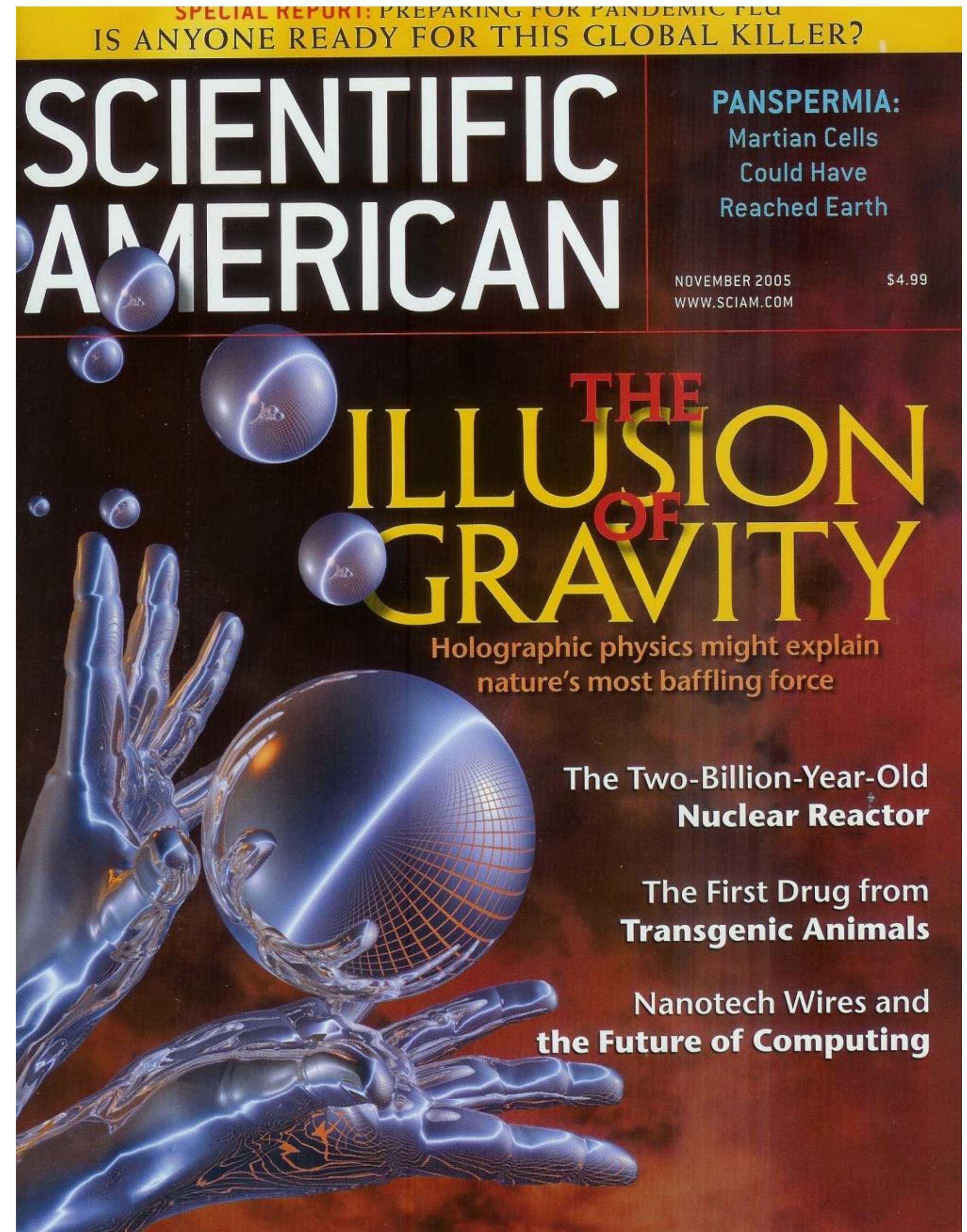
U.S. DEPARTMENT OF ENERGY
Office of Science

ITP/IKF Colloquium
Frankfurt, Dec.20th, 2018

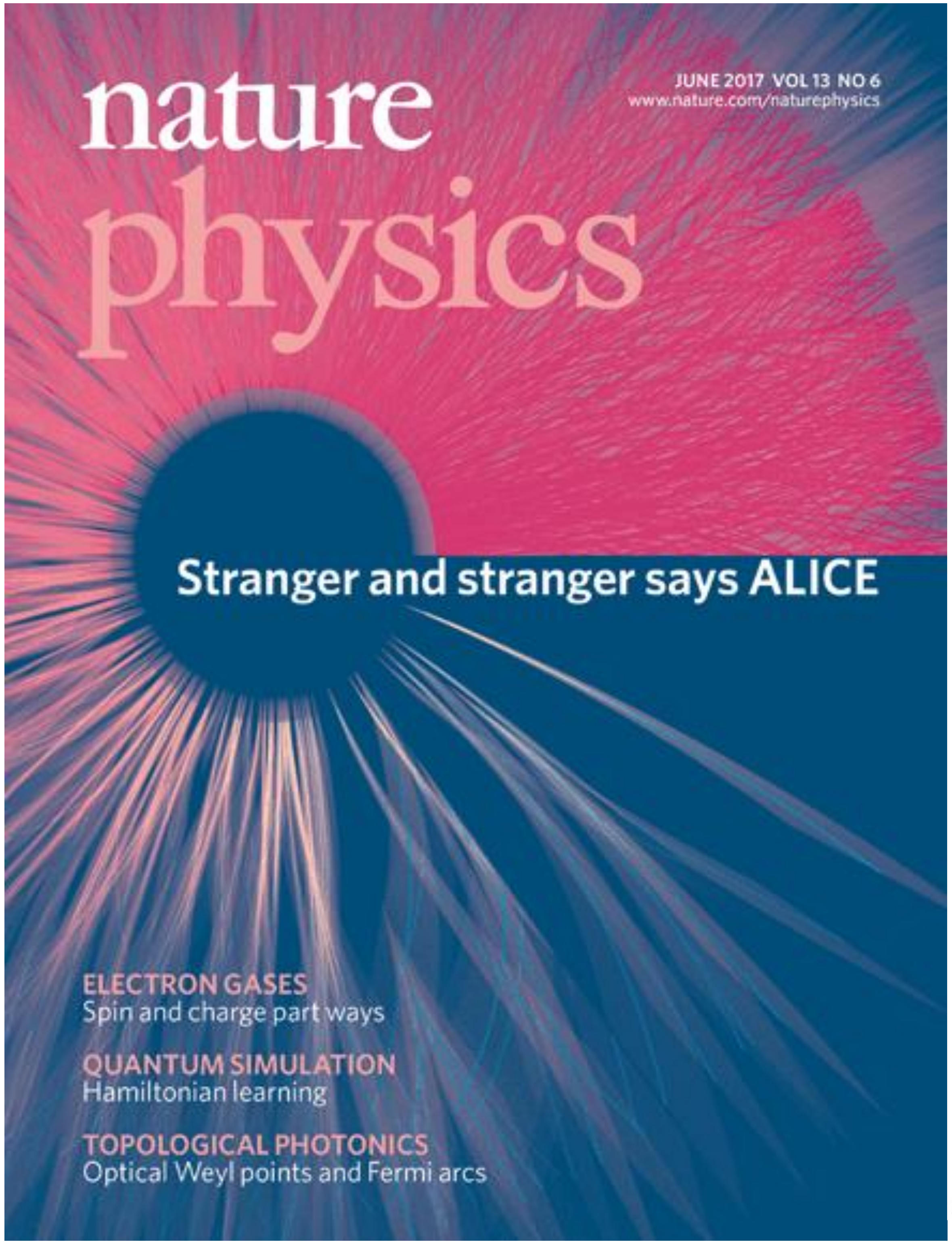
The QCD Phase Transition
– where do we stand ?

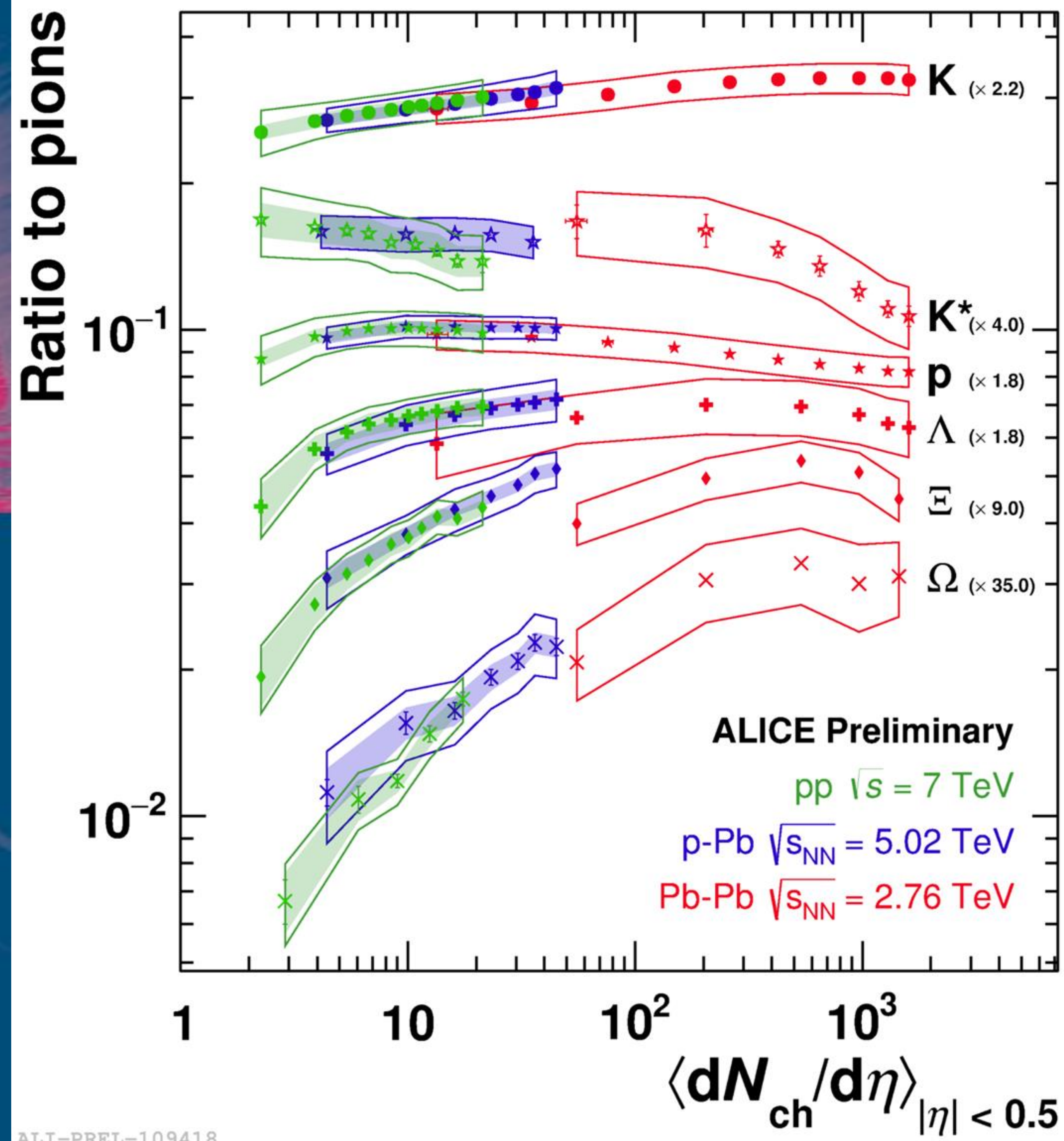
Discovery of the deconfined phase (SPS/RHIC results) by 2005
Signatures: jet quenching (partonic energy loss), quark scaling of large anisotropic flow (hydrodynamics, viscosity limit), photon temperature, J/ψ melting, strangeness enhancement,……..





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





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
- ……

Characterization of the transition on the lattice: The evolution of the pseudo-critical temperature and the order of the PT

Calculations are sensitive to the action and lattice spacing

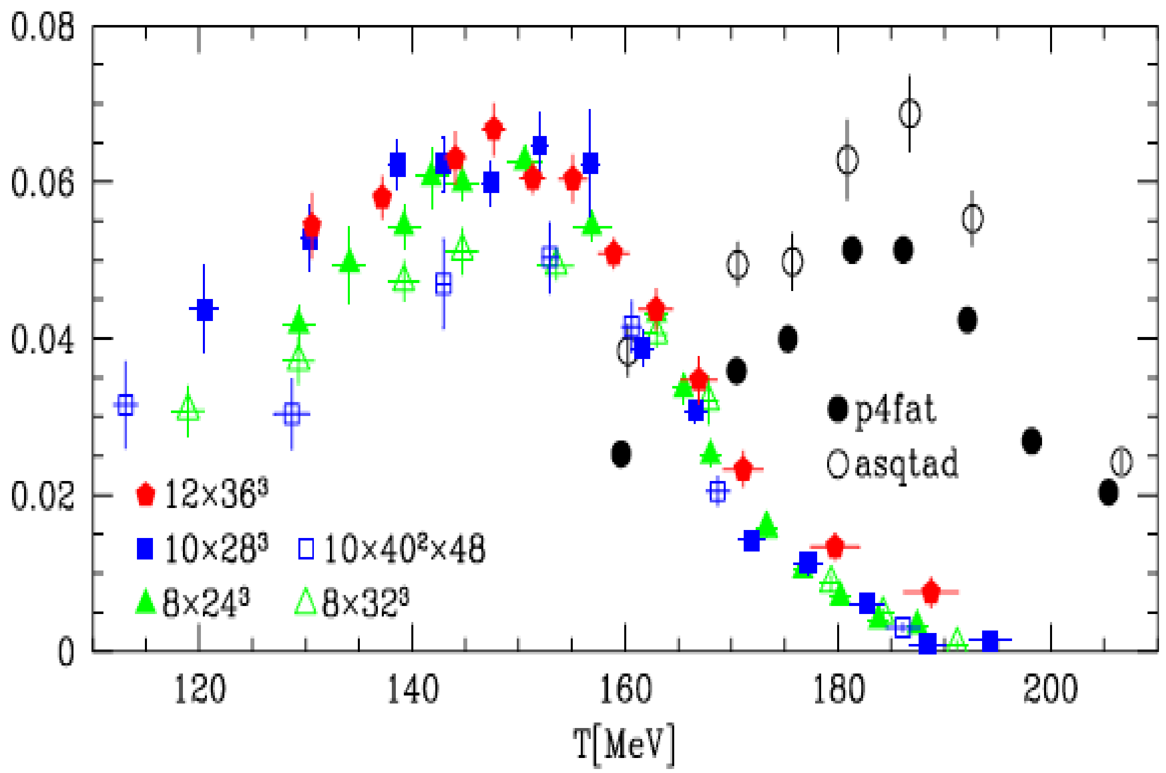
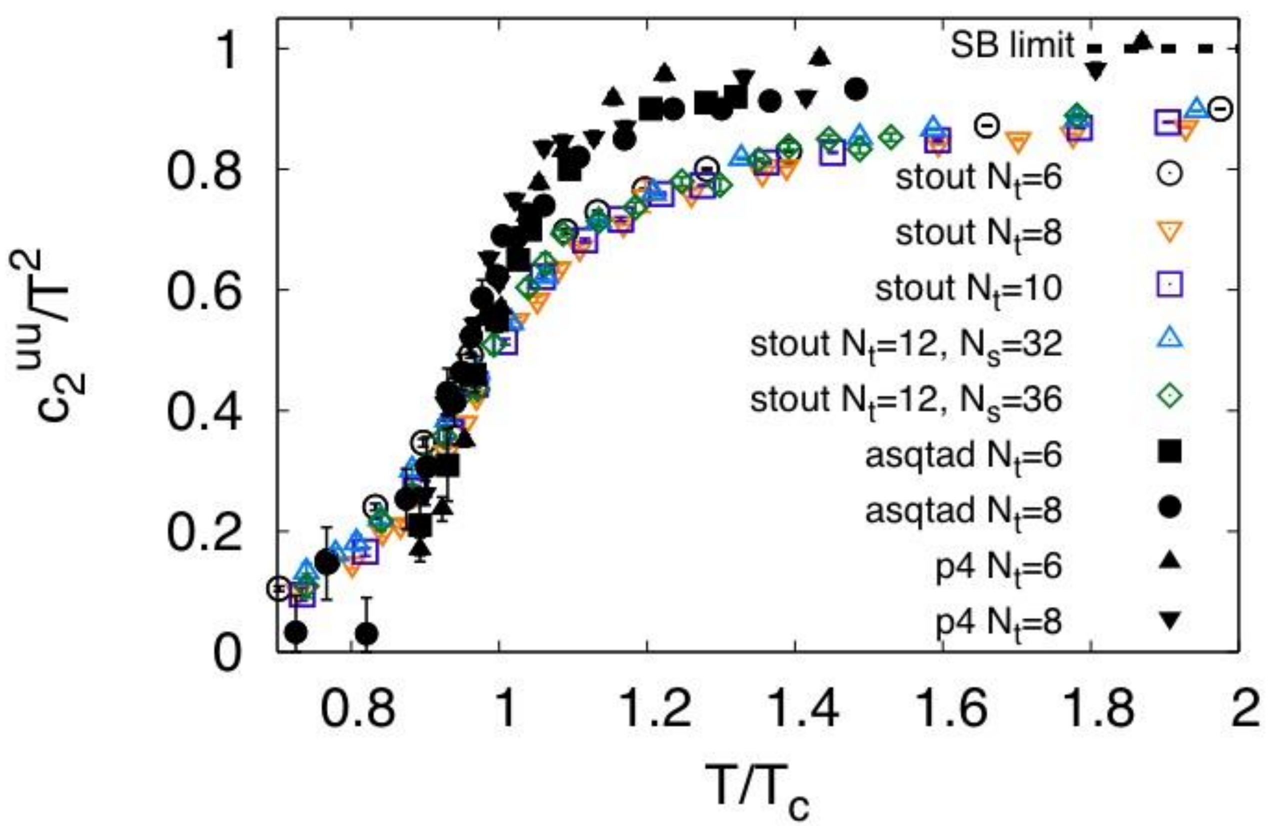


Figure 5: Renormalized chiral susceptibility normalized by T^4. Open colored symbc are results on smaller volumes (with aspect ratio N_s/N_t around 3), whereas filled colored symbols are results on larger volumes (with aspect ratio four). For comparison results of the 'hotQCD' collaboration with two different fermion actions on $N_t = 8$ are also shown, they have been rescaled by an appropriate factor (see text).



WB (0903.4155)

The order of the QCD phase diagram

No discontinuity in the order parameter, no steepness in the order parameter, but a peak in the derivative as a function of temperature (for deconfinement measures) or quark mass (for chirality measures), Fig.1 in the Aoki et al., Nature paper (2006). **We have an analytic crossover.**

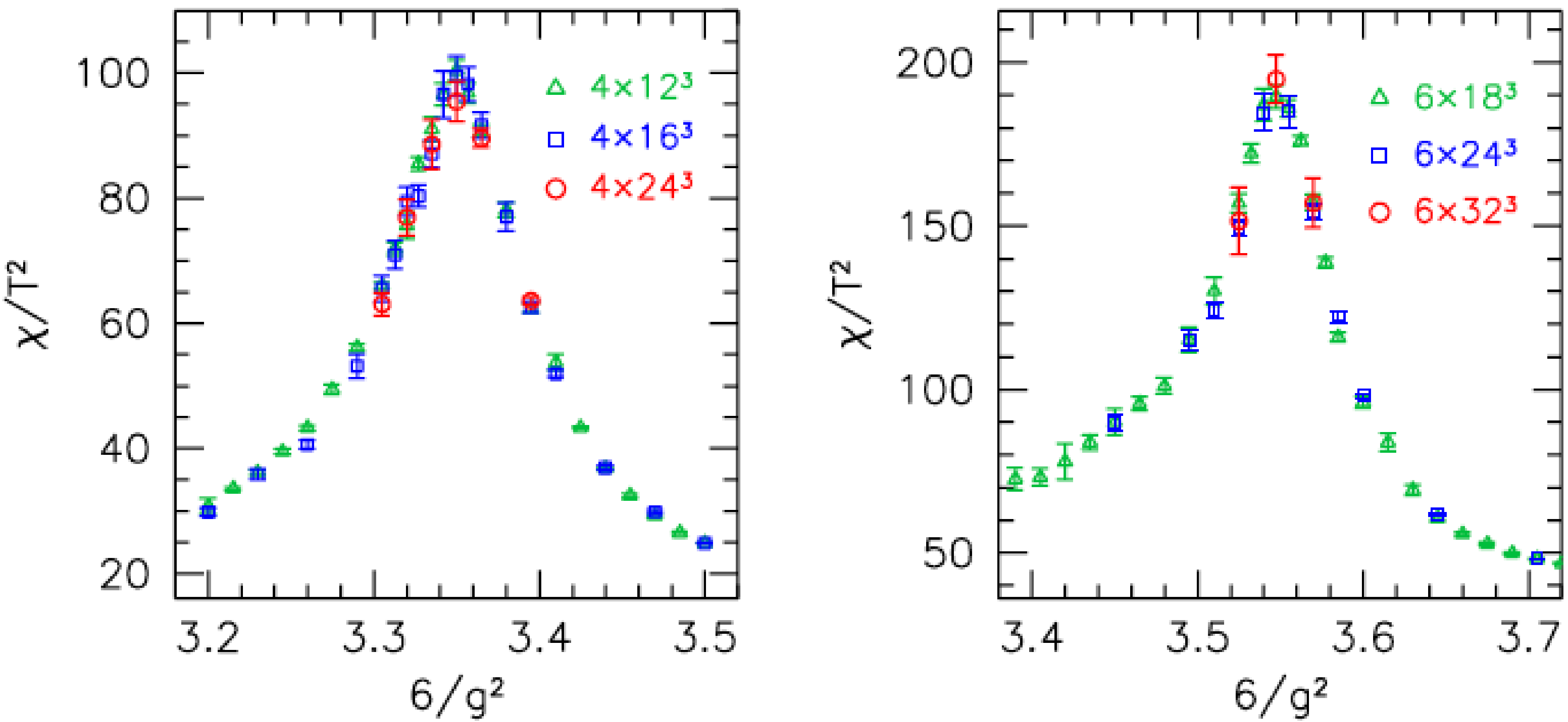
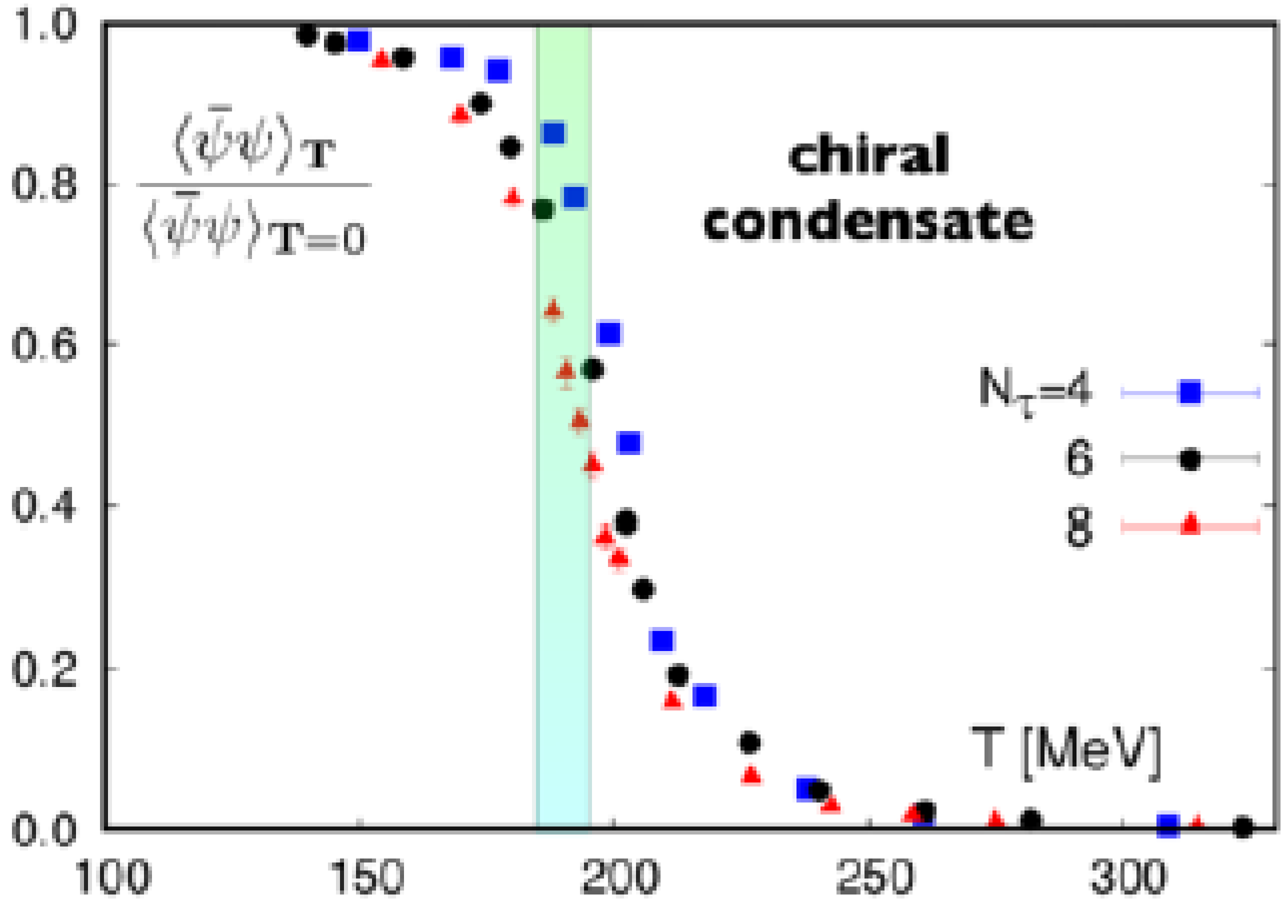
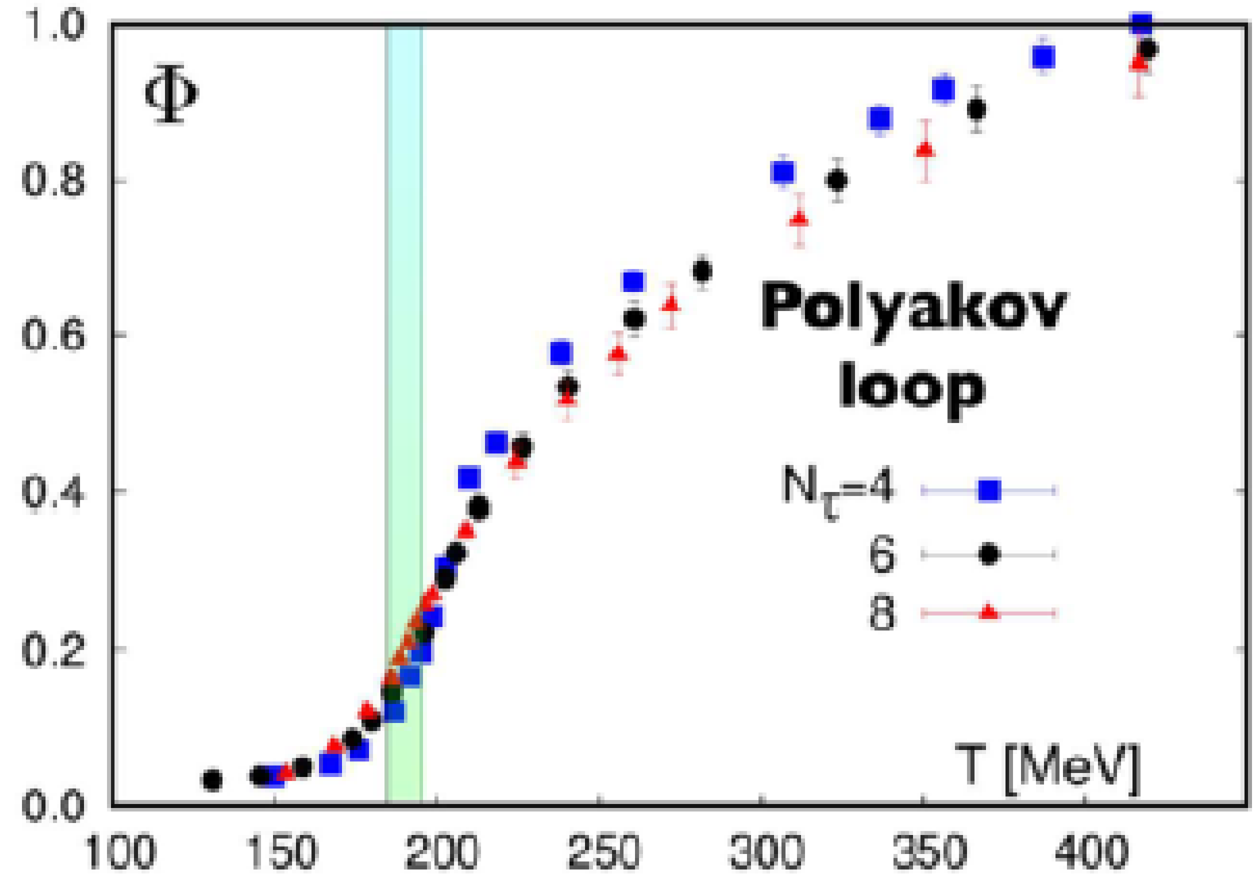


Figure 1: Susceptibilities for the light quarks for N_t=4 (left panel) and for N_t=6 (right panel) as a function of $6/g^2$, where g is the gauge coupling (T grows with $6/g^2$). The largest volume is eight times bigger than the smallest one, so a first-order phase transition would predict a susceptibility peak that is eight times higher (for a second-order phase transition the increase would be somewhat less, but still dramatic). Instead of such a significant change we do not observe any volume dependence. Error bars are s.e.m.

The order parameters of the QCD phase diagram

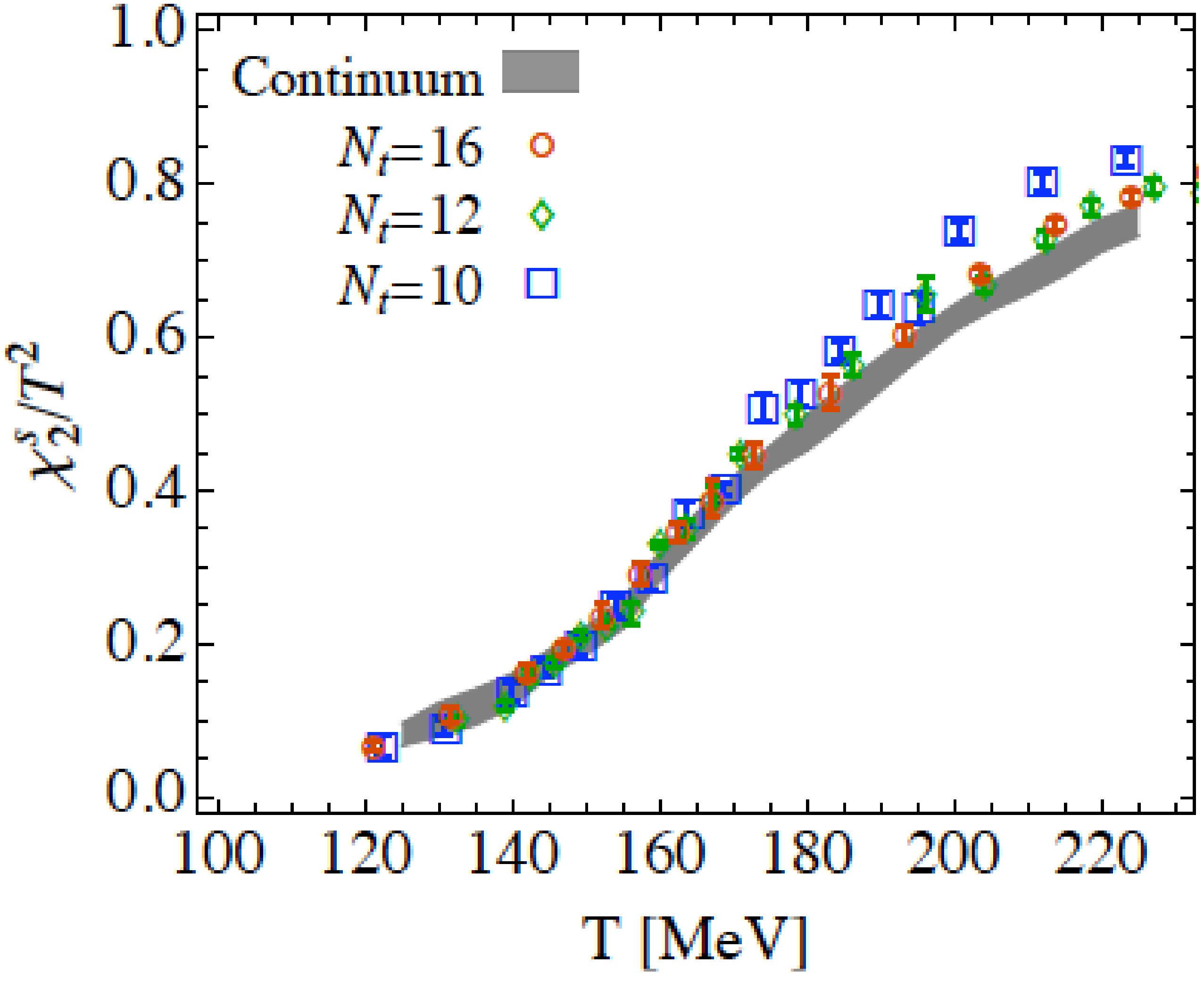
Chiral restoration vs. deconfinement.
Always at the same pseudo-critical temperature ?

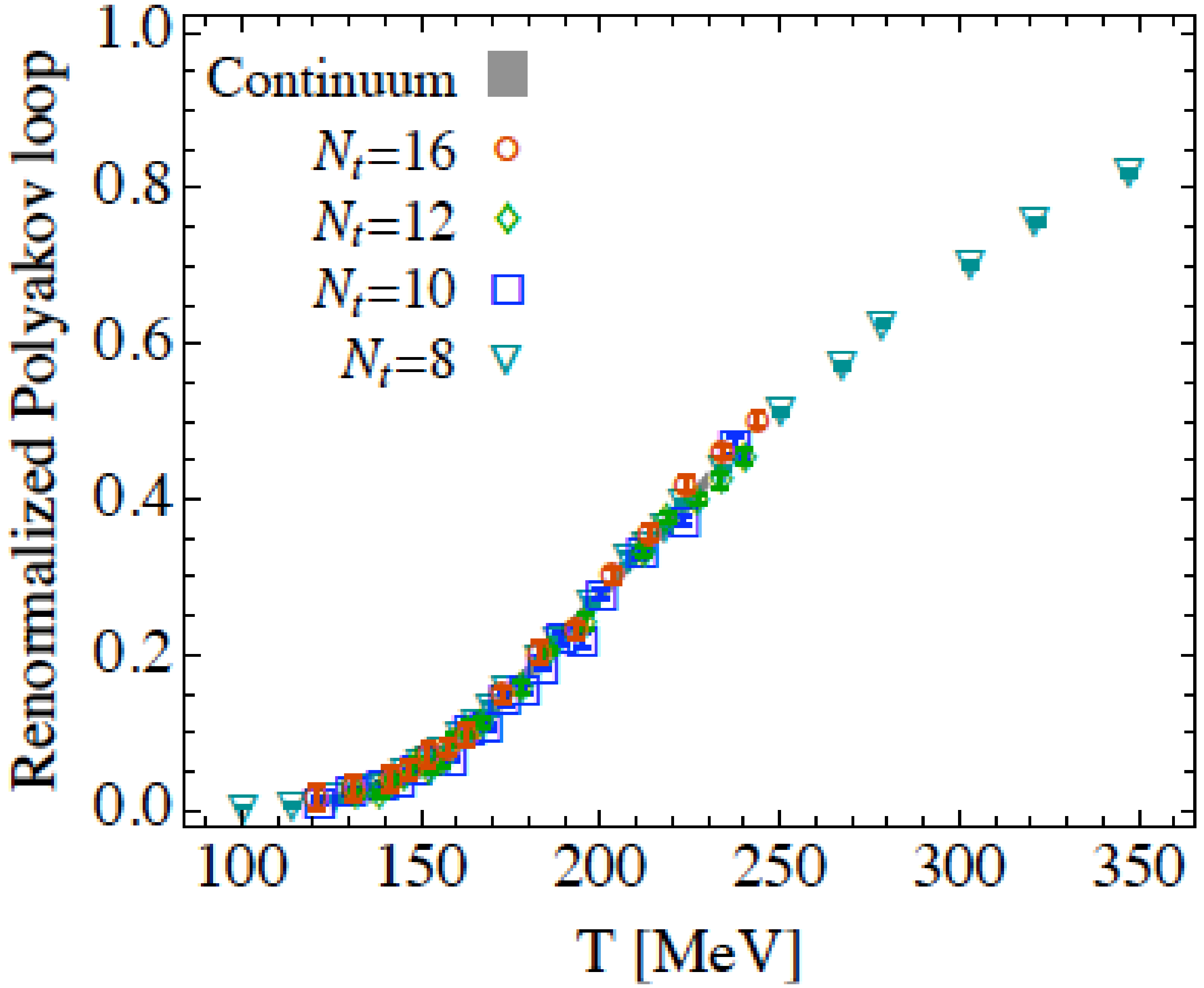




The order parameters of the QCD phase diagram

Which ones a ‘good’, which ones are ‘bad’ ?
Deconfinement parameters (1005.3508):

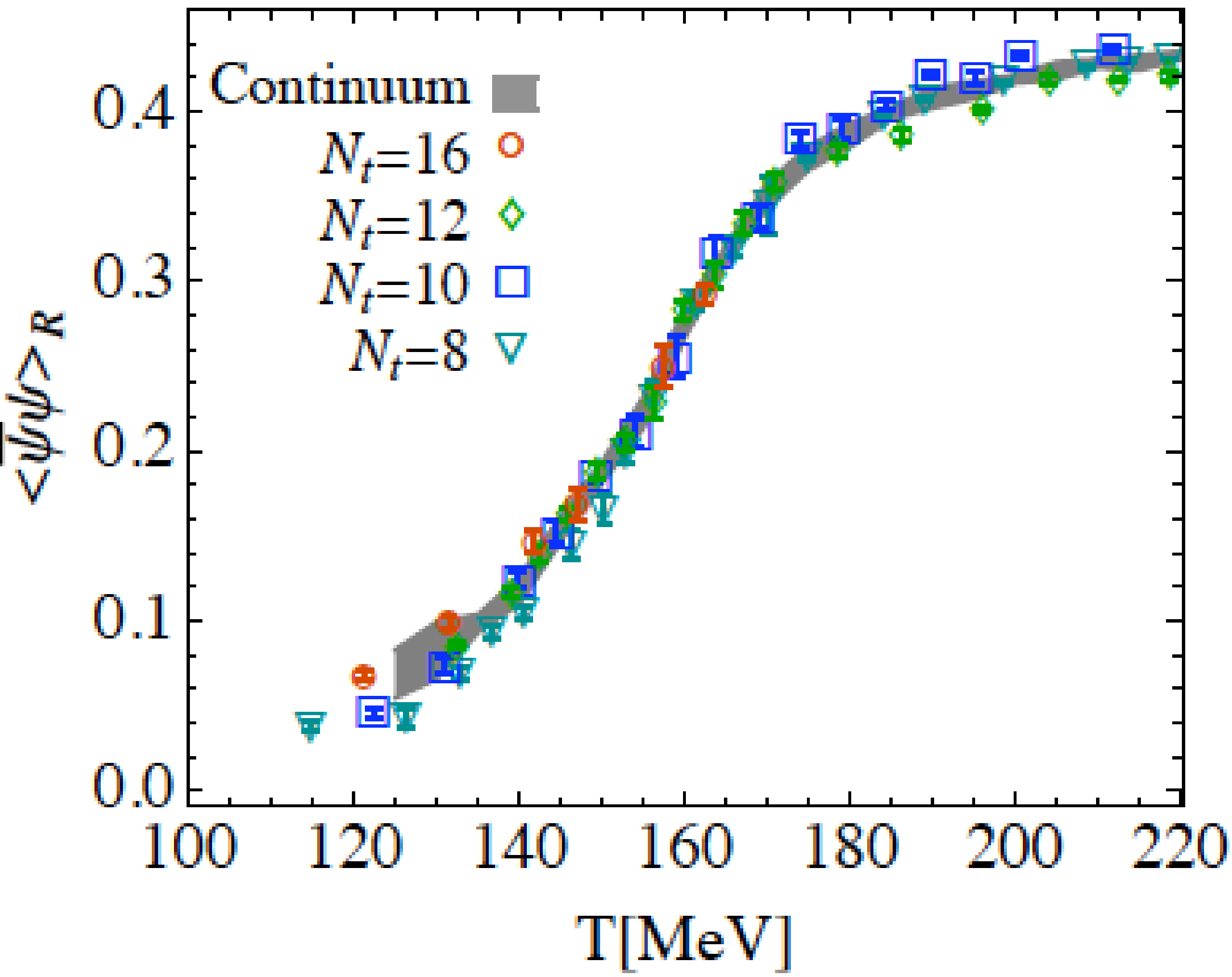


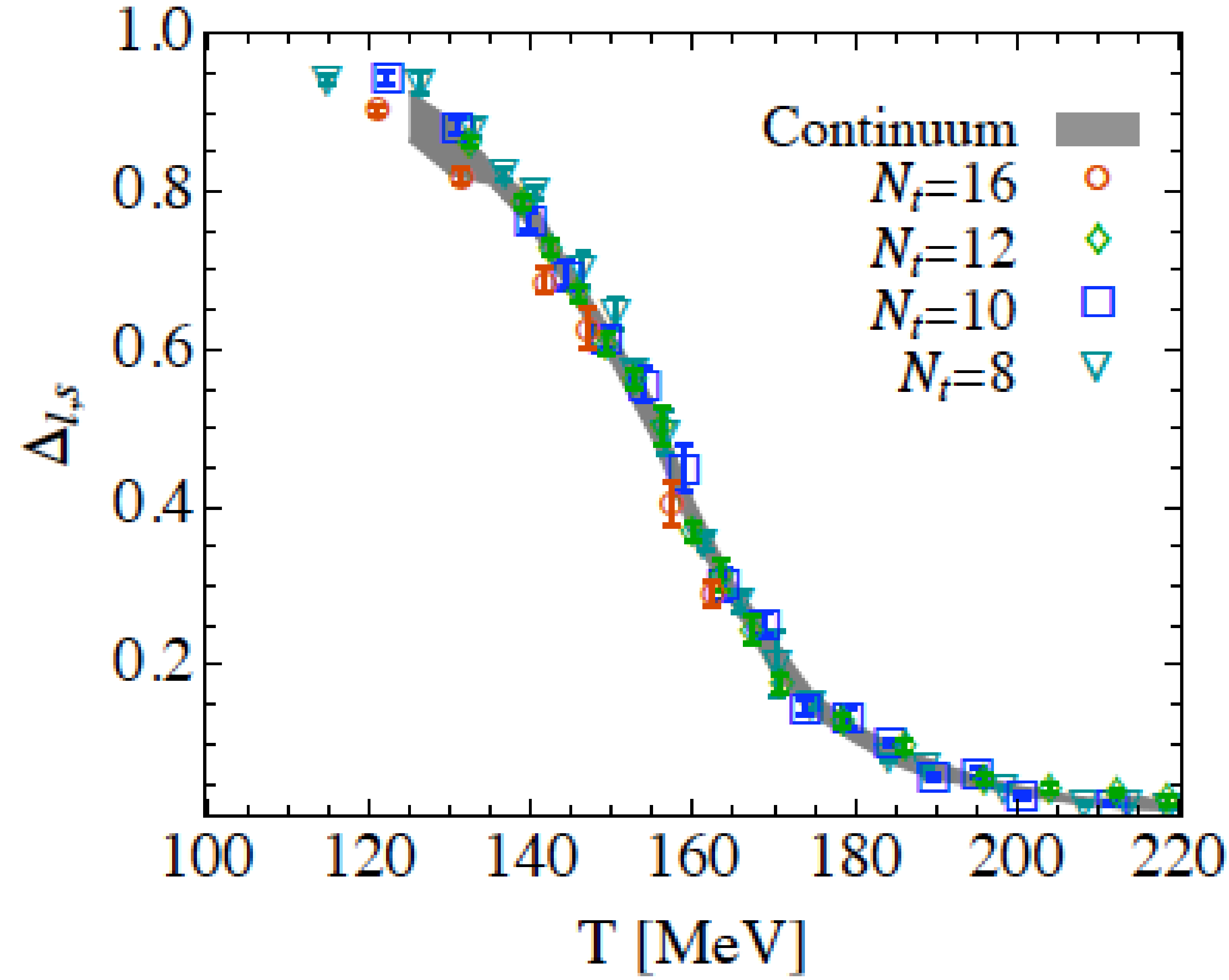


The order parameters of the QCD phase diagram

Which ones a ‘good’, which ones are ‘bad’ ?

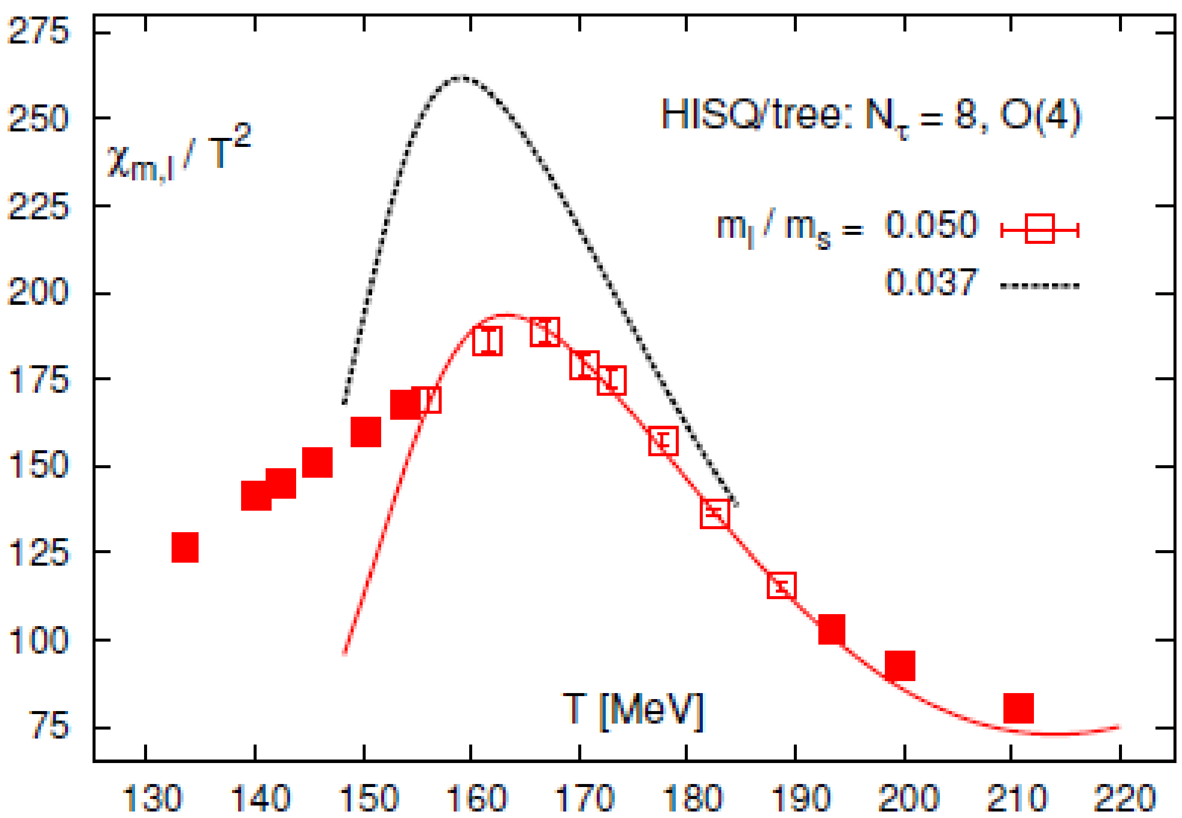
Chiral parameters (1005.3508)

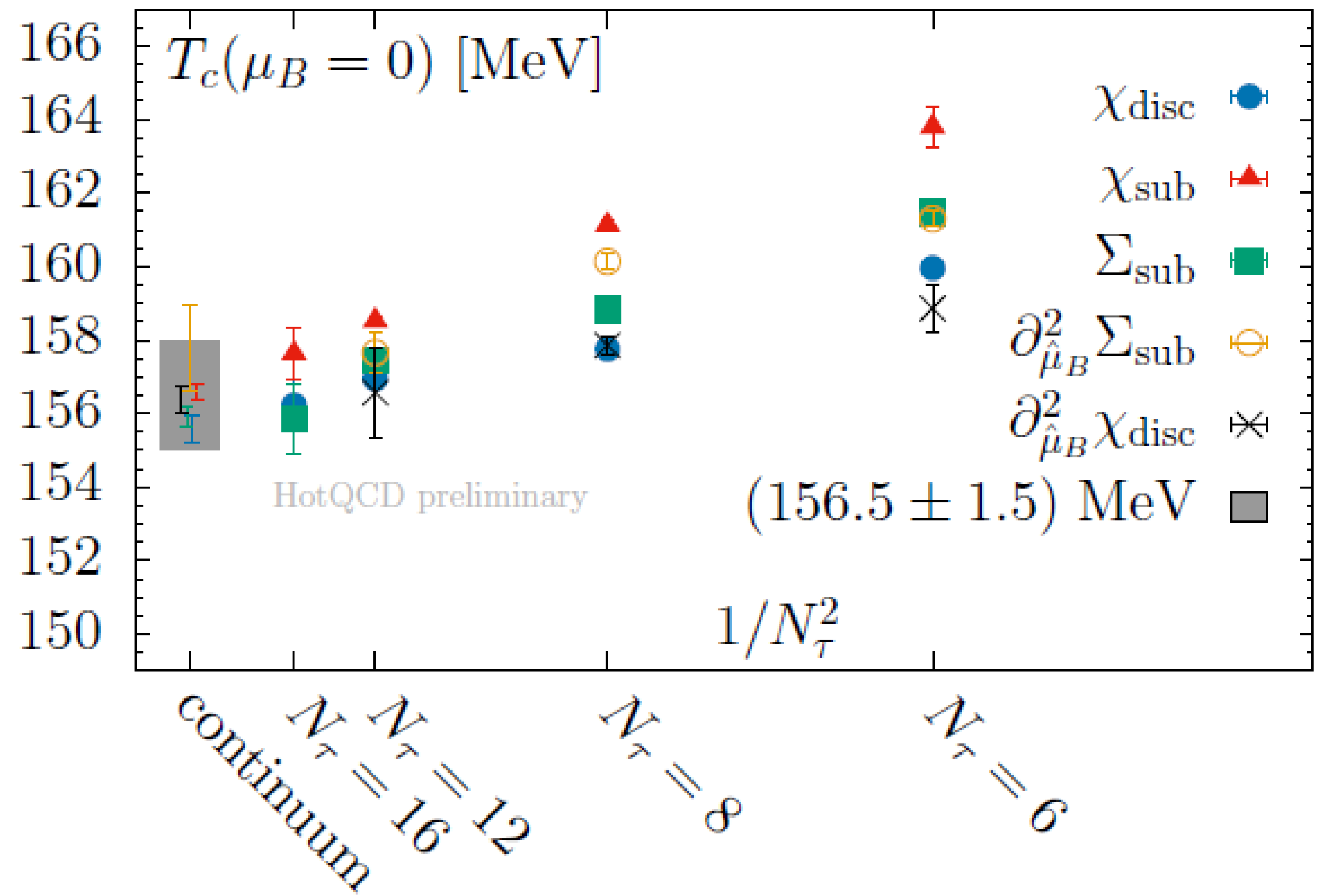




The order parameters of the QCD phase diagram

The chiral transition defines the common wisdom

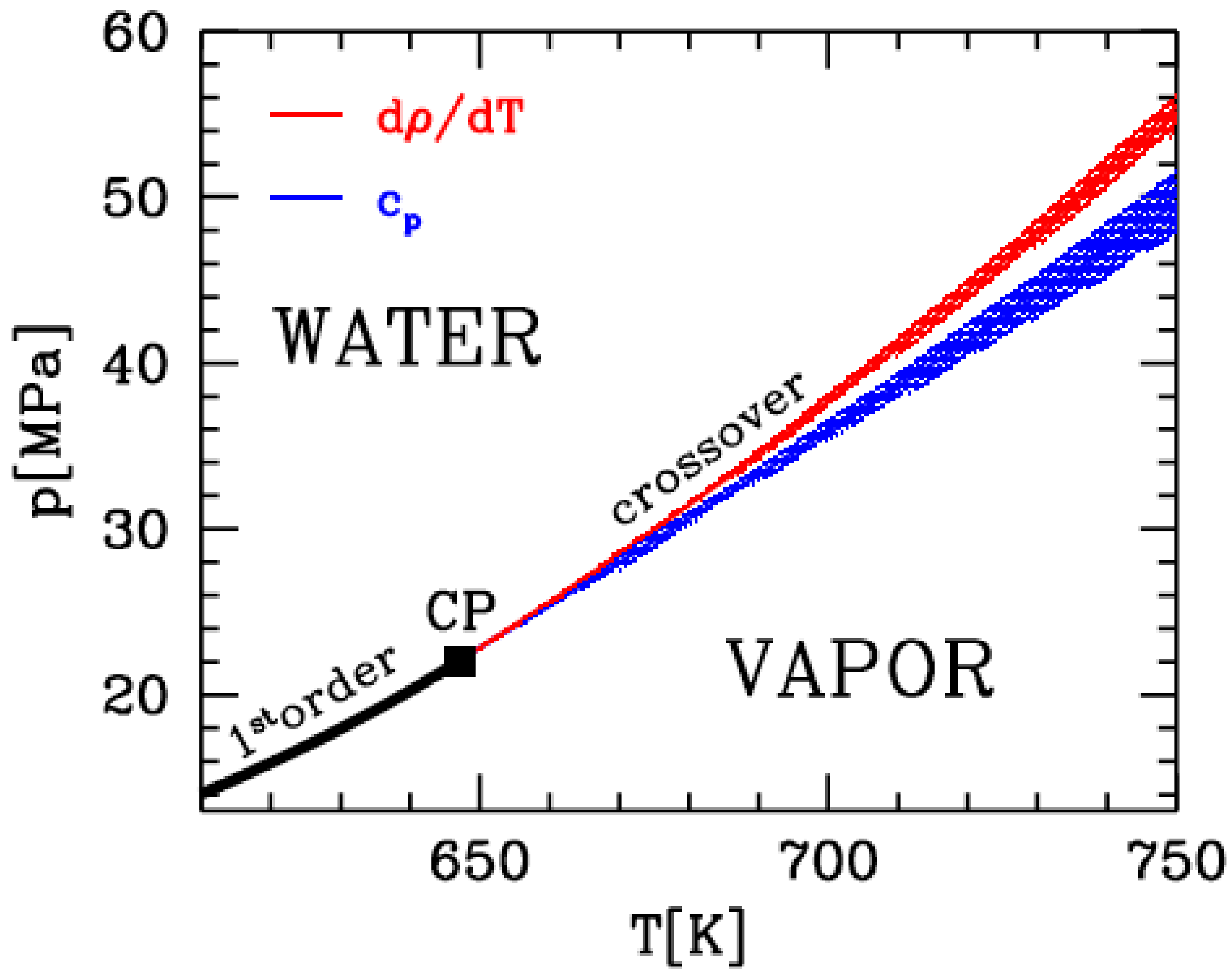




HotQCD (1504.05274)
T_{pc}: 154+- 9 MeV

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

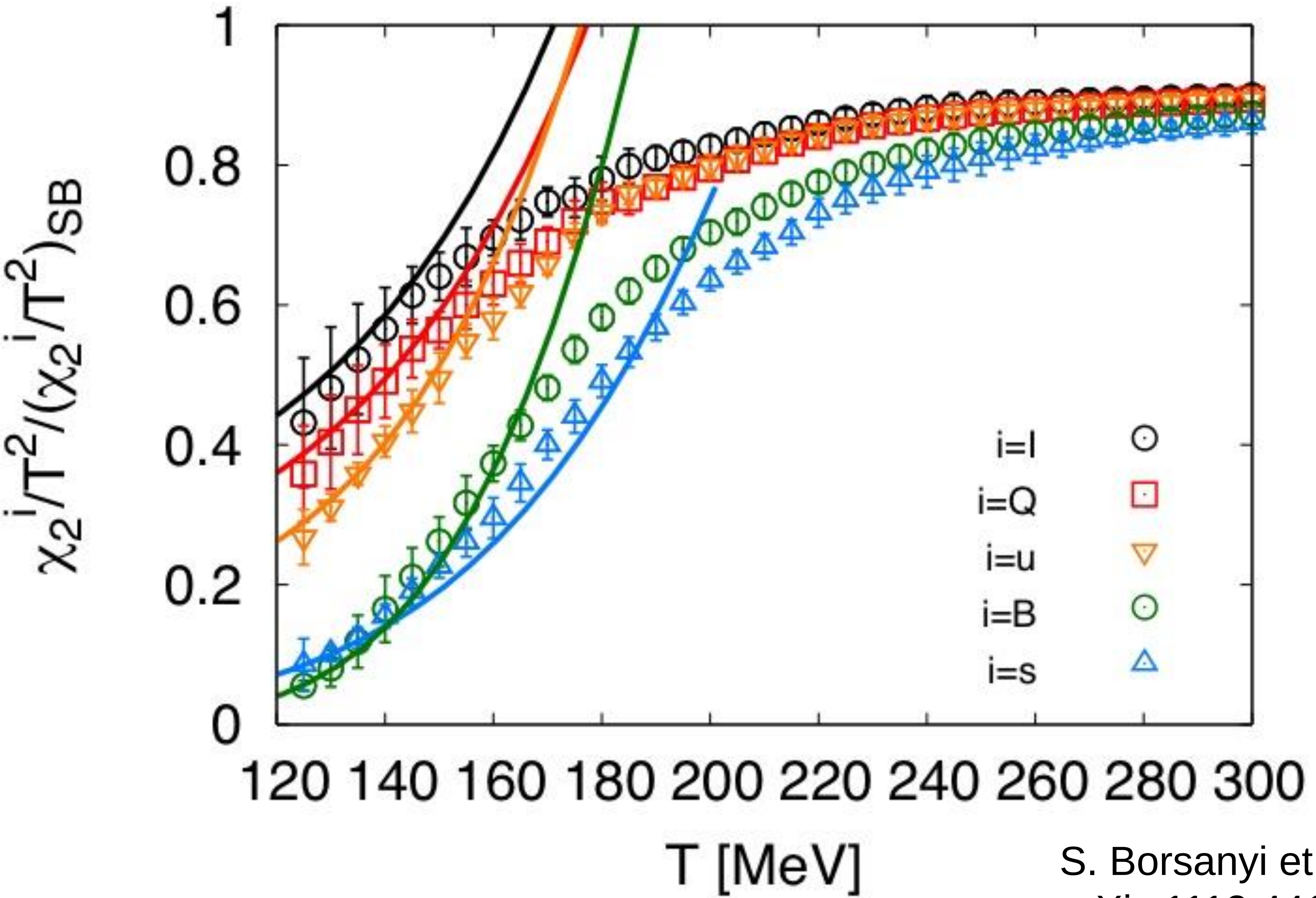
Order parameters in an analytic cross-over region



from the
WB mystery paper

Figure 1: The phase diagram of water around its critical point (CP). For pressures below the critical value (p_c) the transition is first order, for $p > p_c$ values there is a rapid cross-over. In the cross-over region the critical temperatures defined from different quantities are not necessarily equal. This can be seen for the temperature derivative of the density ($d\rho/dT$) and the specific heat (c_p). The bands show the non-negligible experimental uncertainties (see [14]).

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



S. Borsanyi et al., arXiv:1112.4416

The pseudo-critical bottomline

Chiral parameters converge to a tight pseudo-critical temperature of 156 +- 1.5 MeV

Confinement parameters do not converge nicely and span a region of +- 20-30 MeV around 160 MeV.

Can chiral restoration decouple from the confinement transition ?

How do we understand hadronization if different quantum numbers show a different transition behavior ?

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

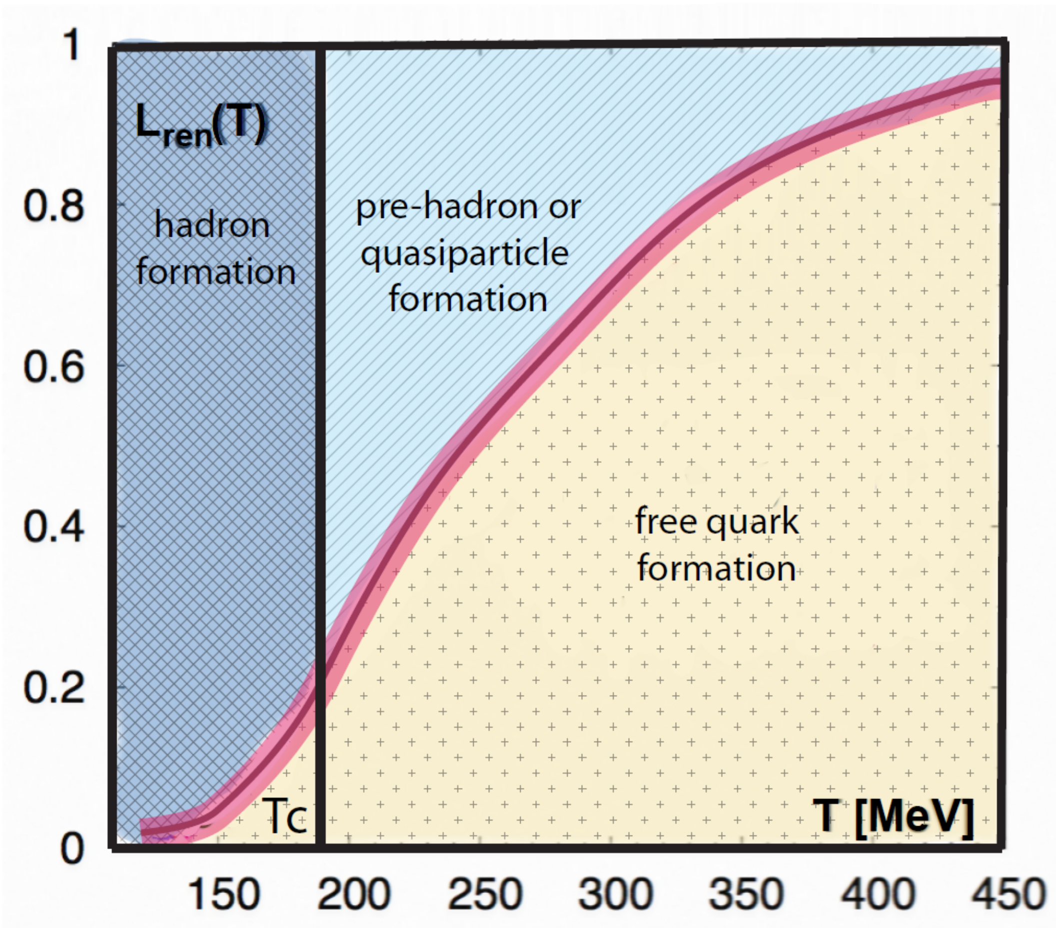
There is none. Its relation to the chemical freeze-out temperature from statistical hadronization models (GSI-Heidelberg 156 +- 2 MeV) is fascinating, but any simple explanation defies logic to some extent.

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

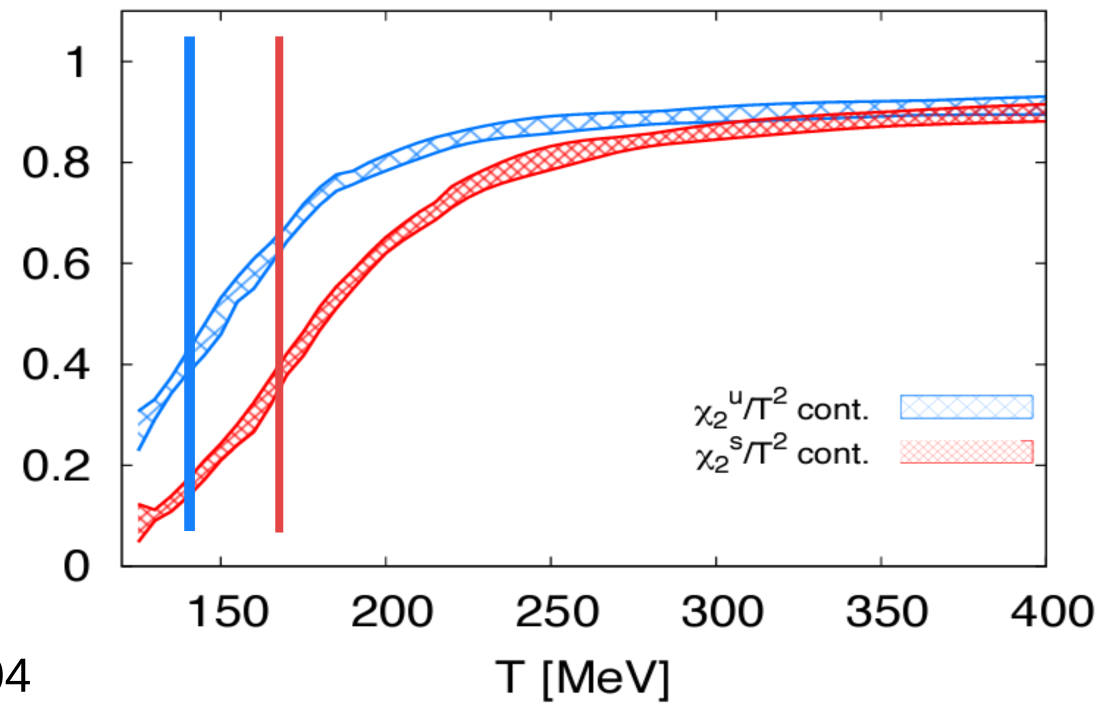
A. Andronic, P. Braun-Munzinger, K. Redlich. J. Stachel

Nature **volume 561**, pages 321–330 (2018)

Lattice order parameters in the QCD cross-over



RB, C. Markert,
PLB691 (2010) 208



C. Ratti et al.,
PRD 85 (2012) 014004

- In a regime where we have a smooth crossover and where quark masses (even for the s-quark) could play a role why would there be a single freeze-out surface ?

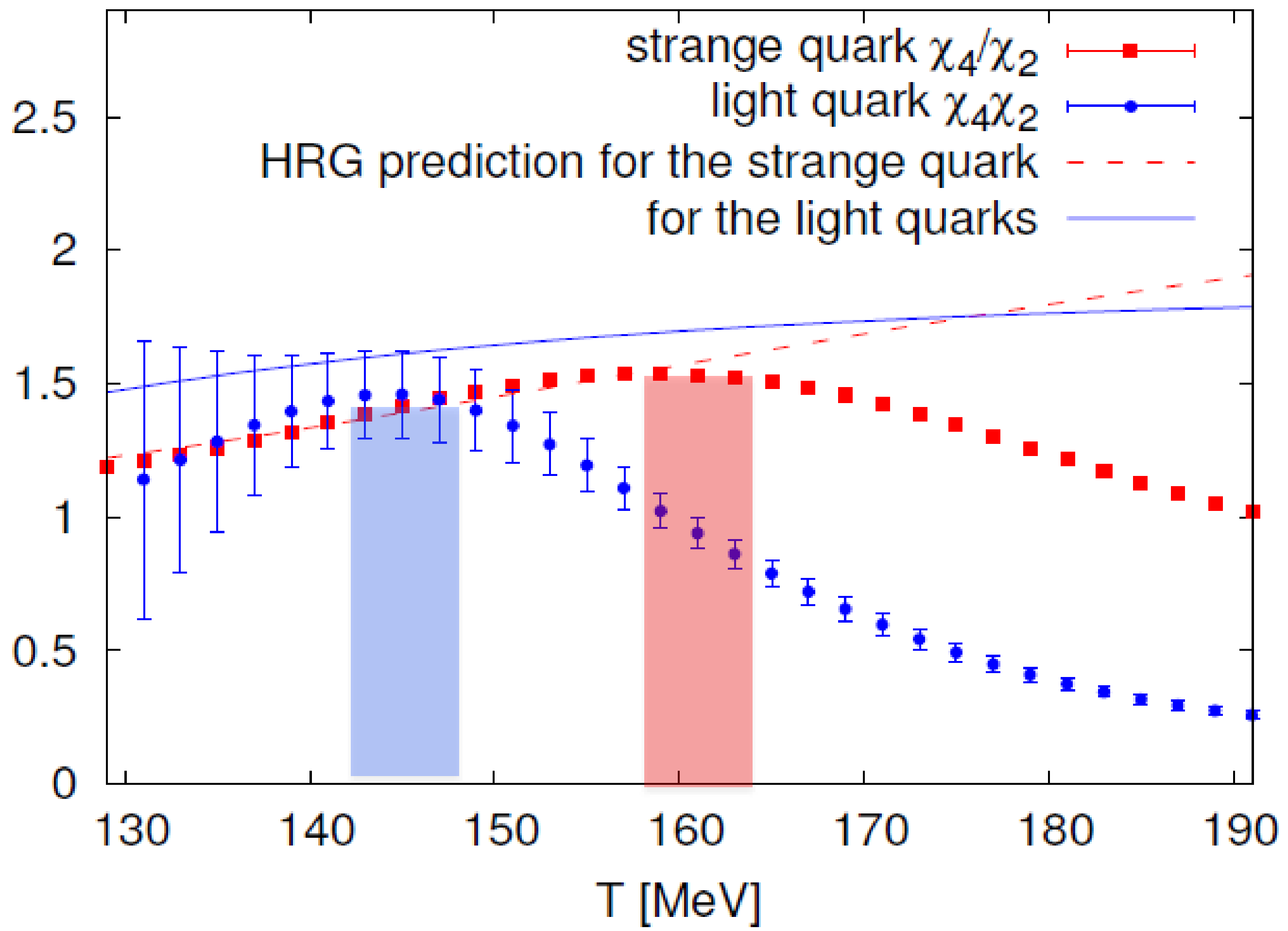
- We can calculate thermodynamic quantities for a static equilibrated system at a fixed temperature

- But are pseudo-critical temperatures extracted from flavor dependent susceptibilities as relevant for hadronization properties as chirality ?

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

$$\kappa_B \sigma_B^2 \equiv \frac{\chi_{4,\mu}^B}{\chi_{2,\mu}^B} = \frac{\chi_4^B(T)}{\chi_2^B(T)} \left[\frac{1 + \frac{1}{2}\frac{\chi_6^B(T)}{\chi_4^B(T)}(\mu_B/T)^2 + \ldots}{1 + \frac{1}{2}\frac{\chi_4^B(T)}{\chi_2^B(T)}(\mu_B/T)^2 + \ldots} \right]$$

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



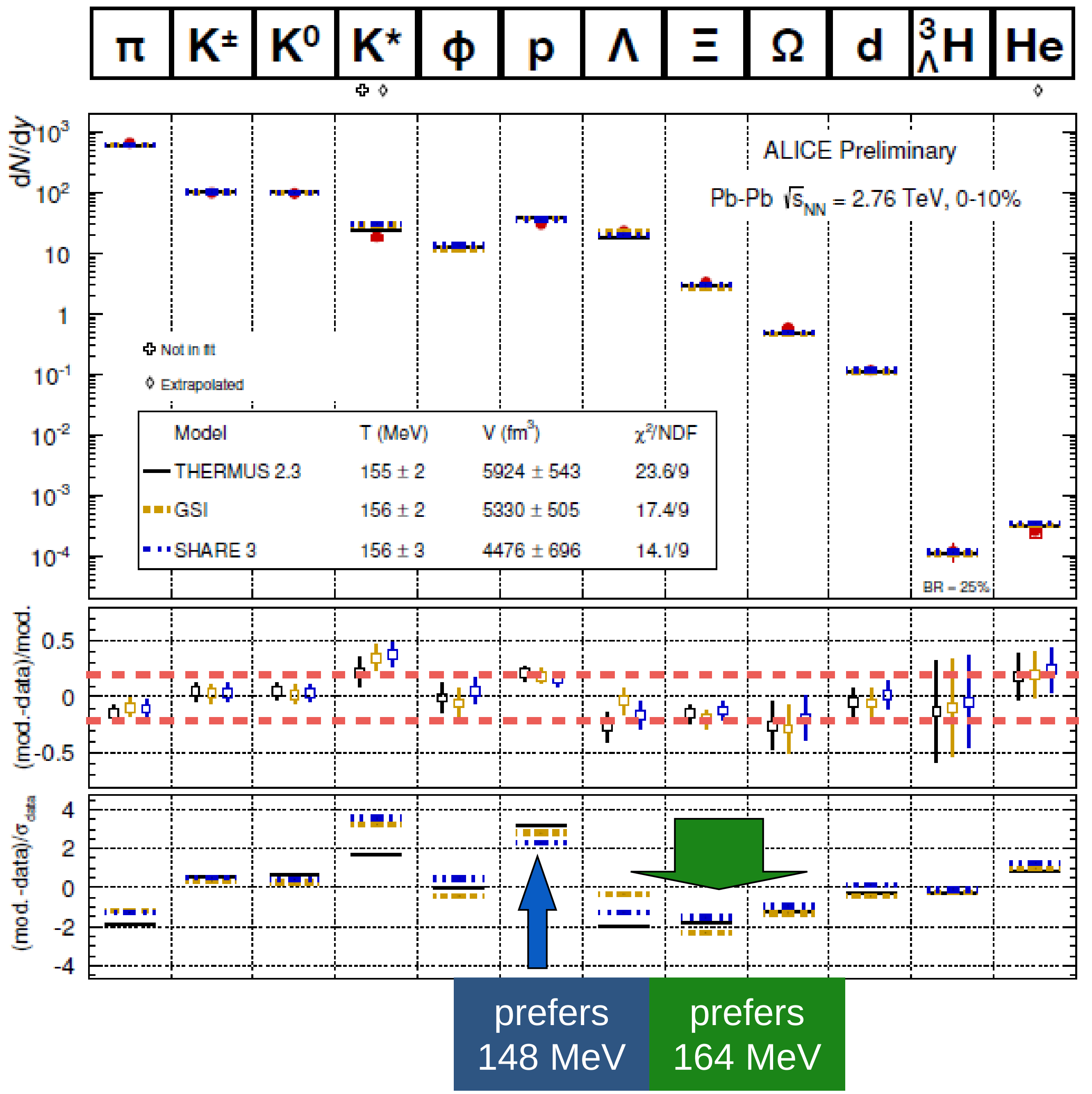
R. Bellwied & WB Collab., PRL (2013), arXiv:1305.6297

<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



Data: ALICE, QM 2014, arXiv:1408.6403

This looks like a good fit, but it is not

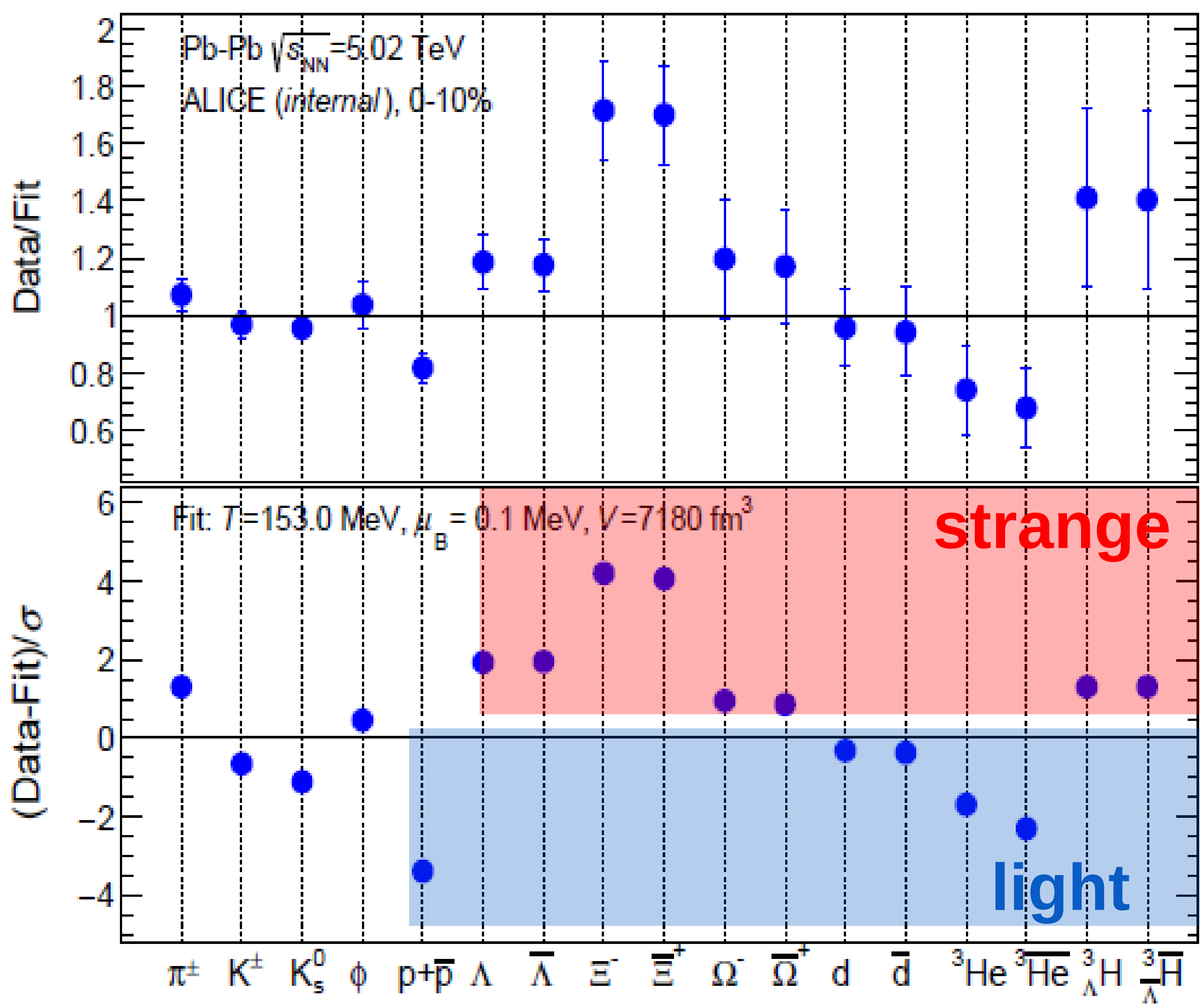
χ^2/NDF improves from 2 to 1 when pions and protons are excluded.

Fit to pions and protons alone yield a temperature of 148 MeV. Strange baryons yield 164 MeV

<u>Several alternate explanations:</u>

- Inclusion of Hagedorn states
- Non-equilibrium fits
- Baryon annihilation
- Interacting hadron gas
- S-matrix approach
- *<u>Different T_{ch} for light and strange</u>*

And things get worse with higher precision at higher energy



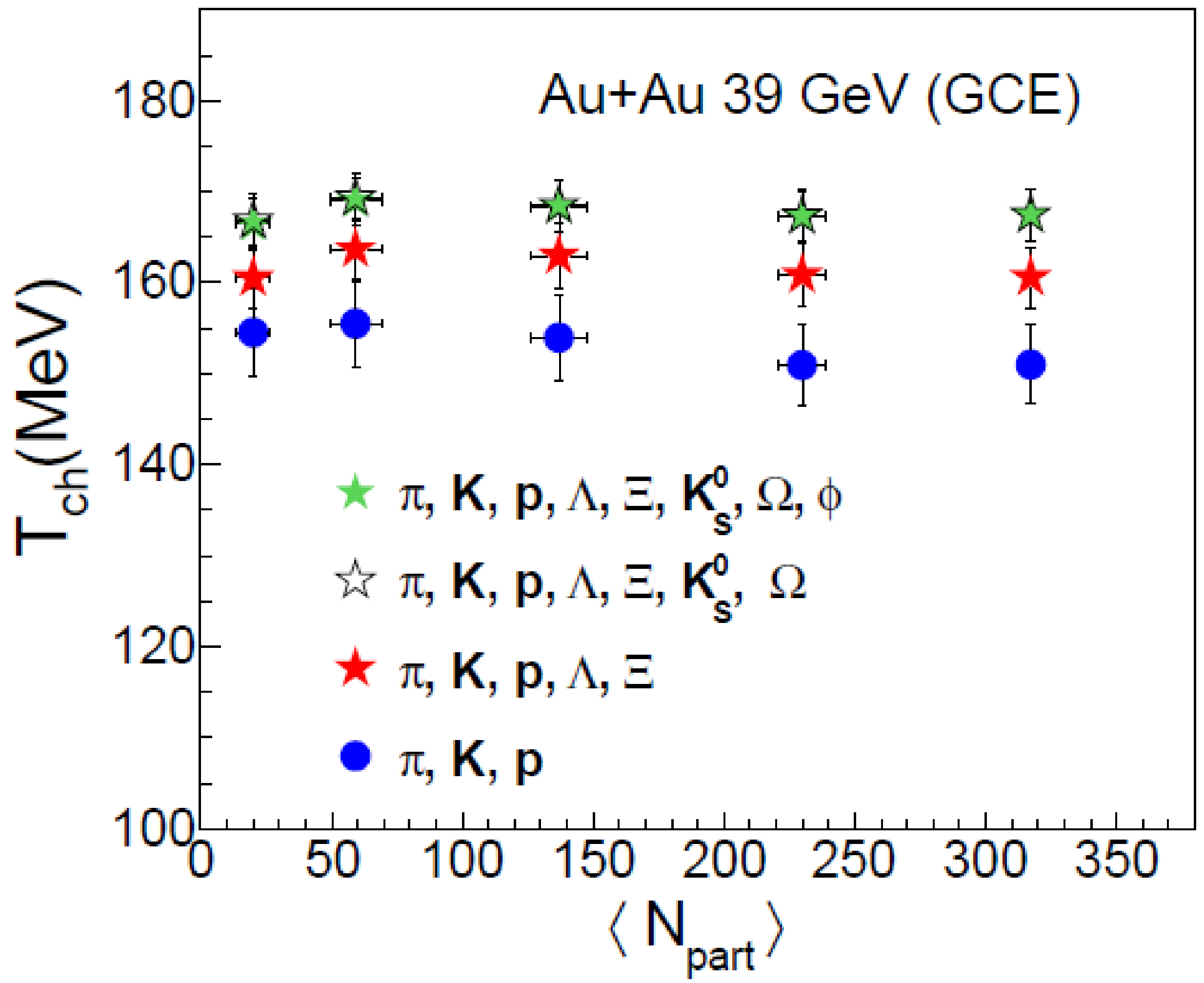
The new 5.02 TeV show a more pronounced and more precise tension between strange and non-strange particles in the baryonic sector (-3σ effect in protons vs. +5σ effect in Ξ baryons)

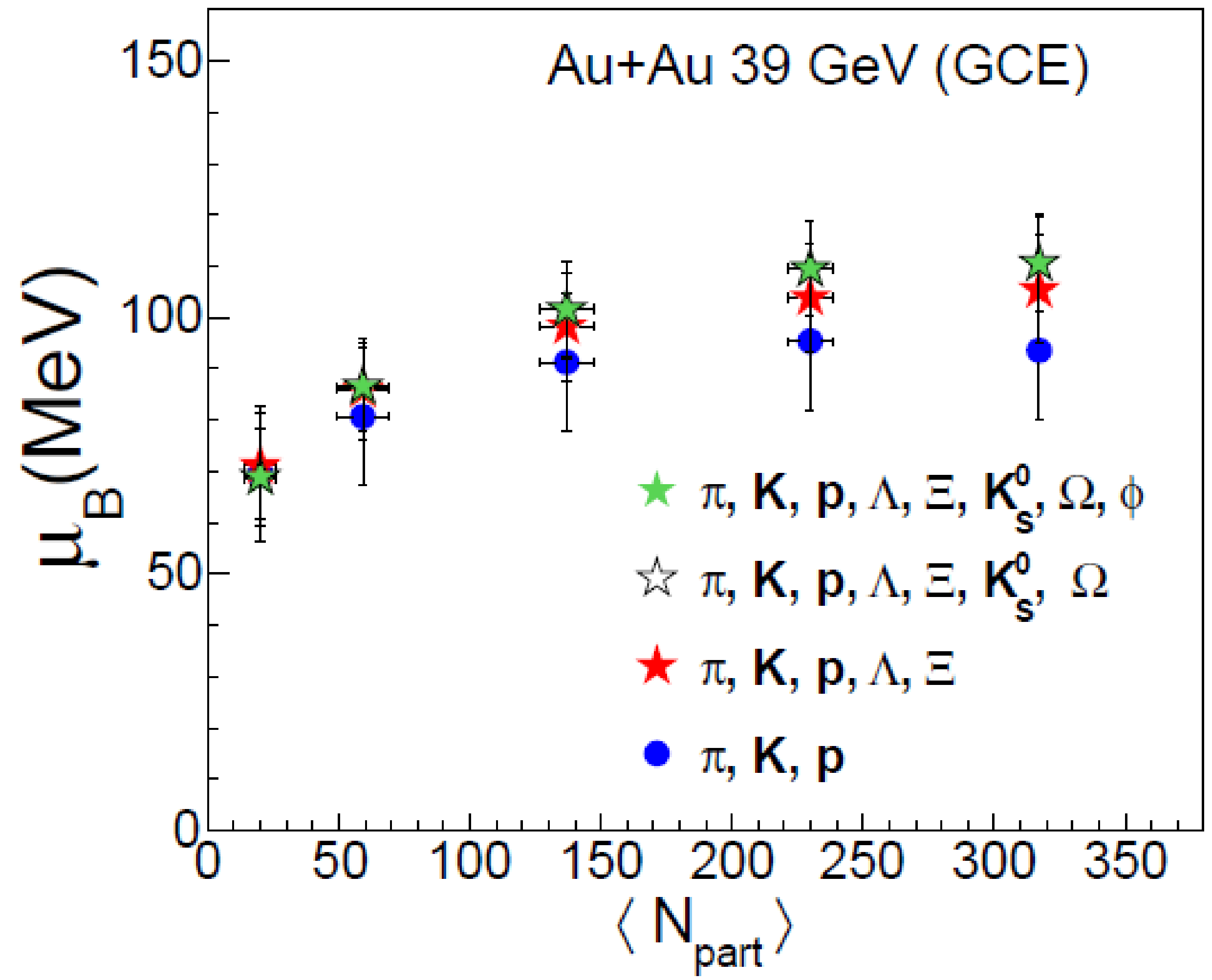
Data: ALICE (preliminary)
Fit: GSI-Heidelberg (preliminary)

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)

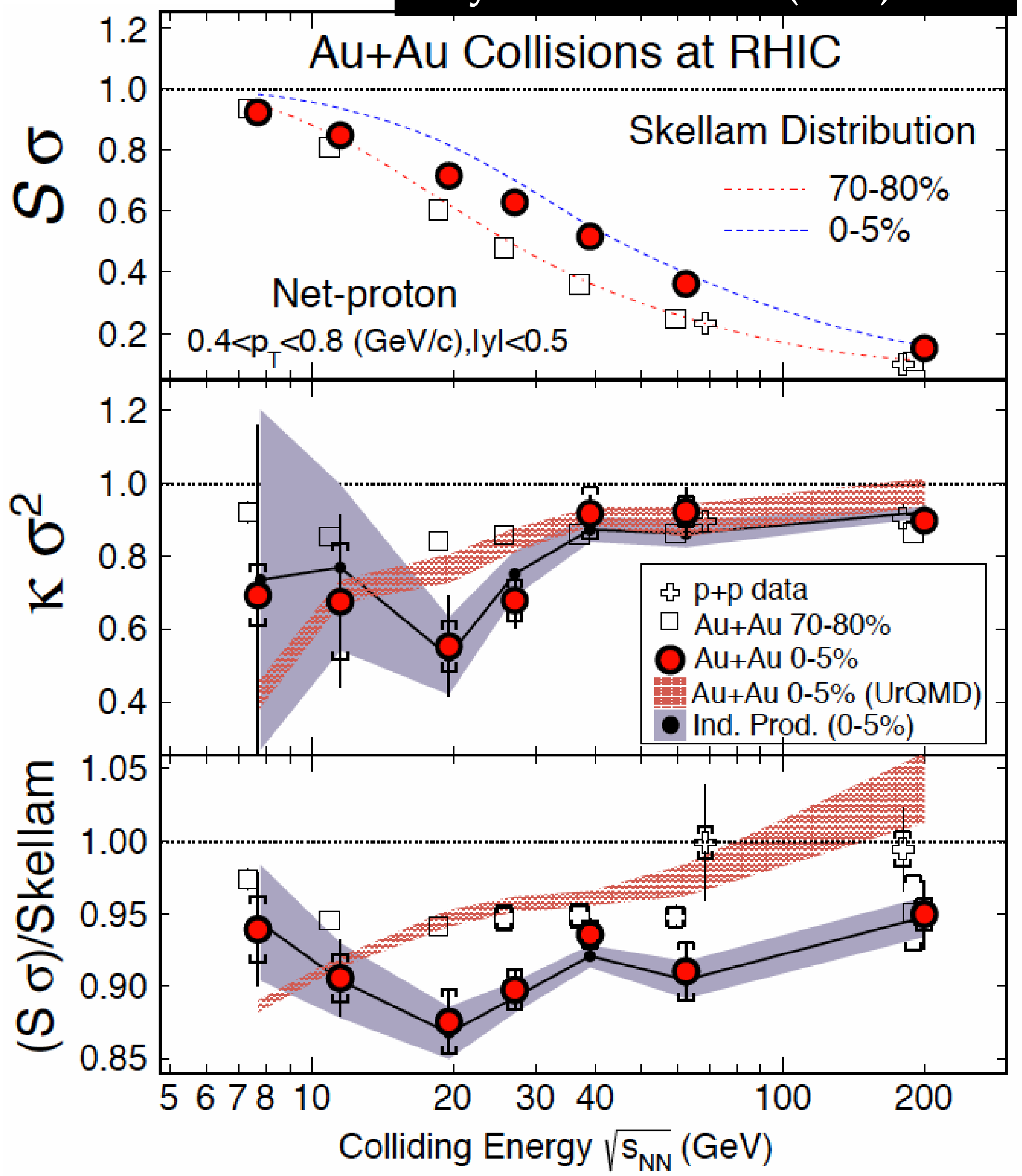




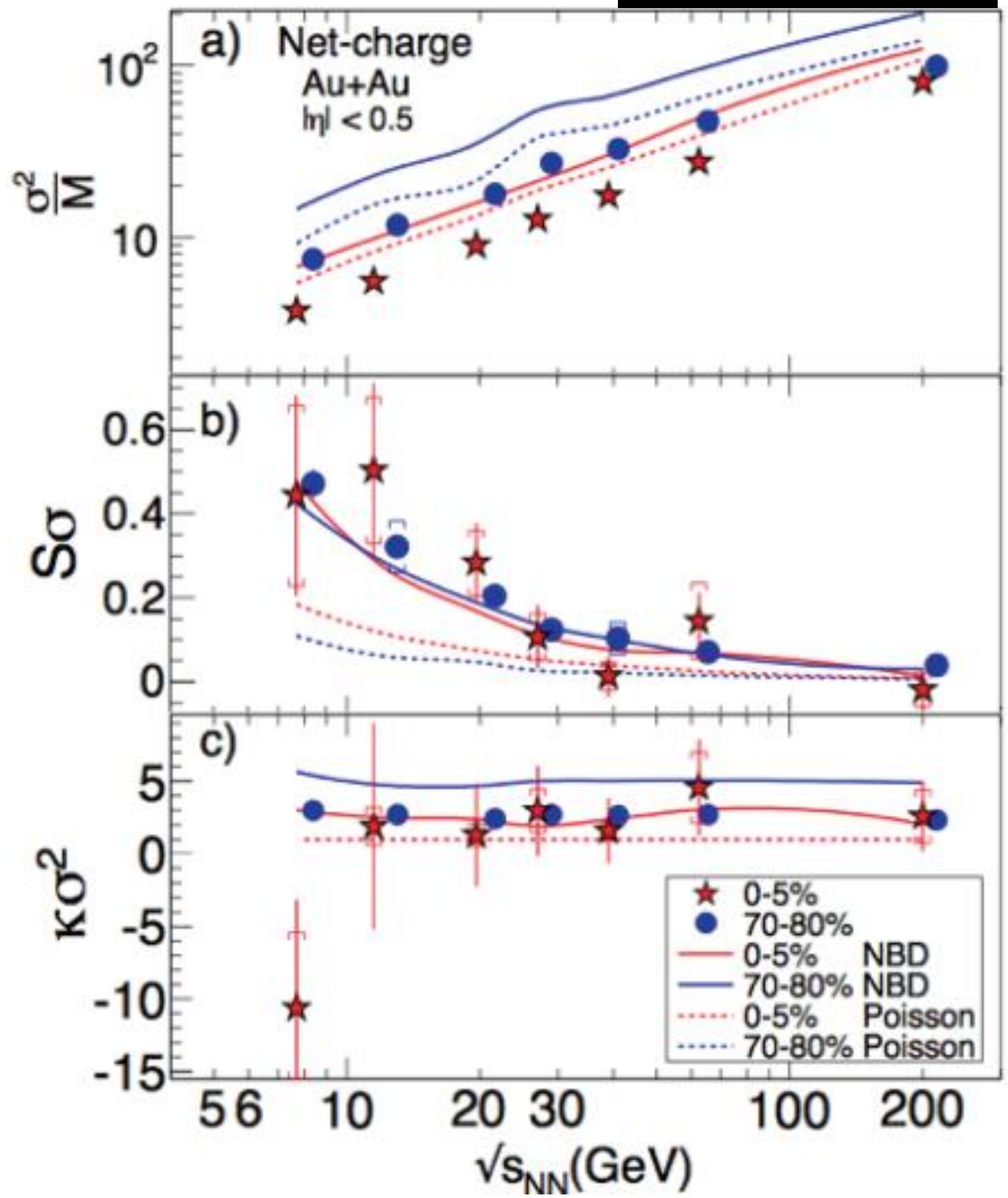
This is a long known fact in SHM, always argued as ‘the more states the better’, but all additional states (to π,k,p) are strange states

Higher moment ratios for net-charge and net-proton distributions (STAR 2014)

Phys. Rev. Lett. 112 (2014) 32302



arXiv:1402.1558



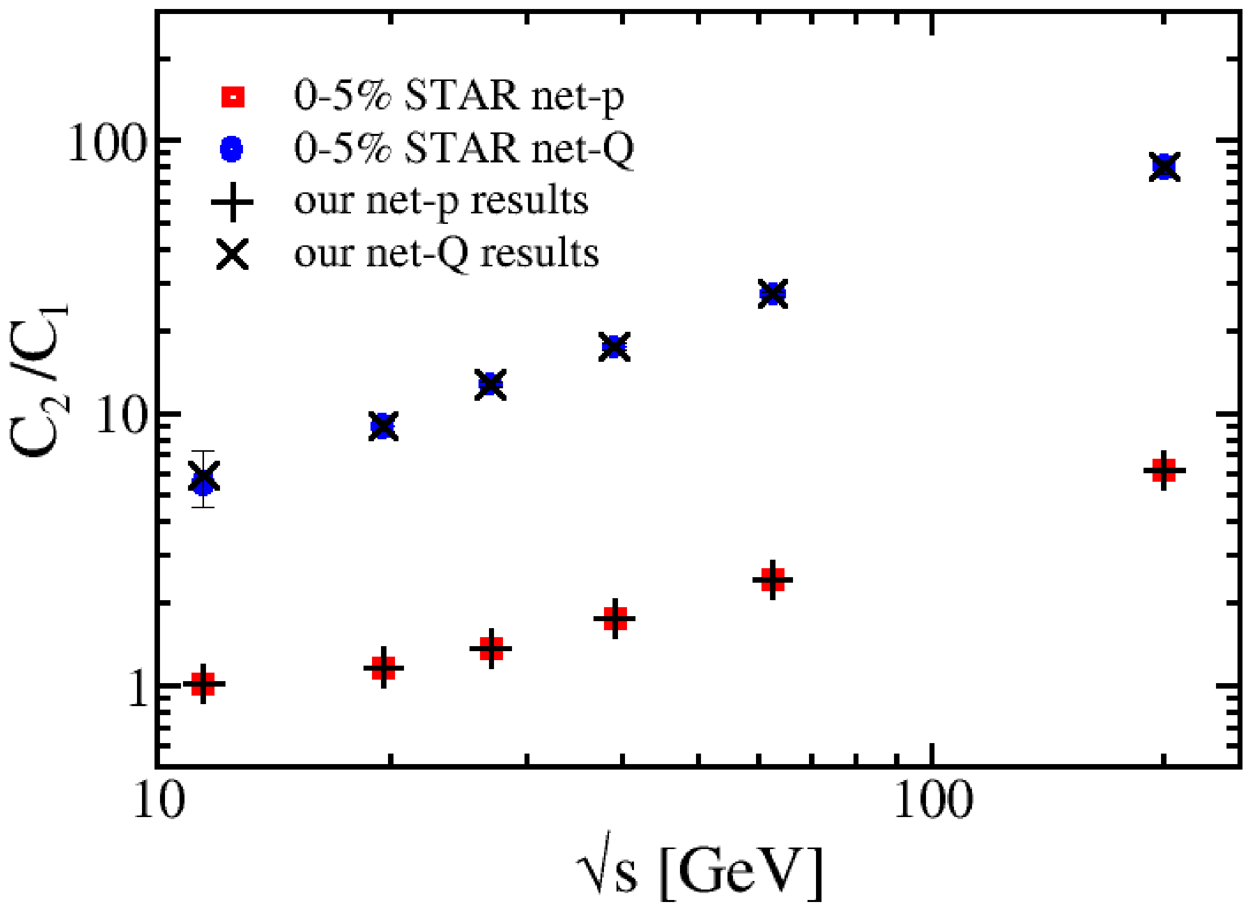
Fluctuations are more sensitive to chemical freeze-out as simple yields. They can be directly compared to susceptibilities on the lattice (P.Alba et al., PRC, (arXiv:1504.03262))

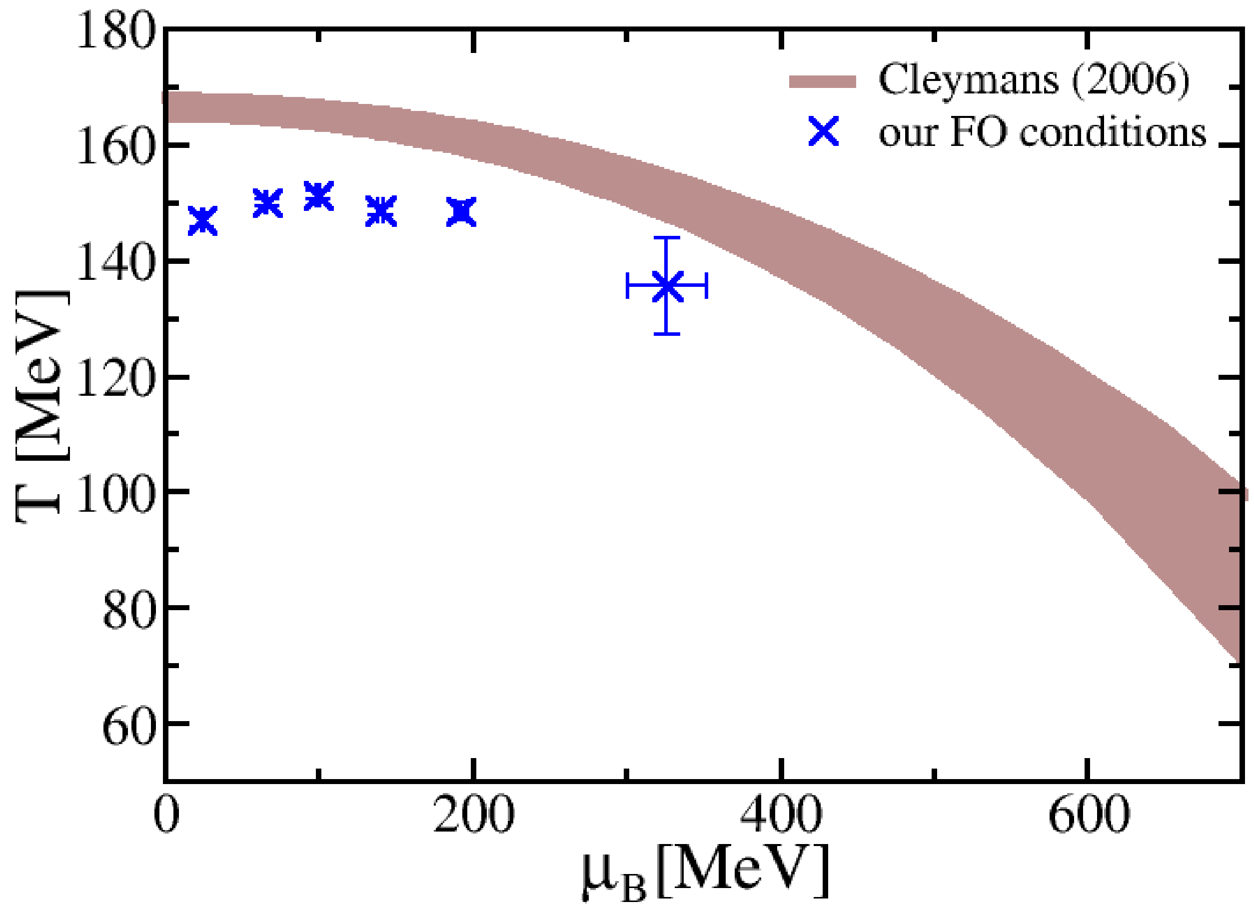
HRG (PDG 2008) analysis of STAR results (charge & proton)

Alba, Bellwied, Bluhm, Mantovani, Nahrgang, Ratti, PLB (2014), arXiv:1403.4903

HRG in partial chemical equilibrium: resonance decays for resonances up to 2 GeV/c^2 and weak decays taken into account), experimental cuts applied.

Use the lowest moments with the smallest errors and least ‘criticality’, i.e. σ^2/M



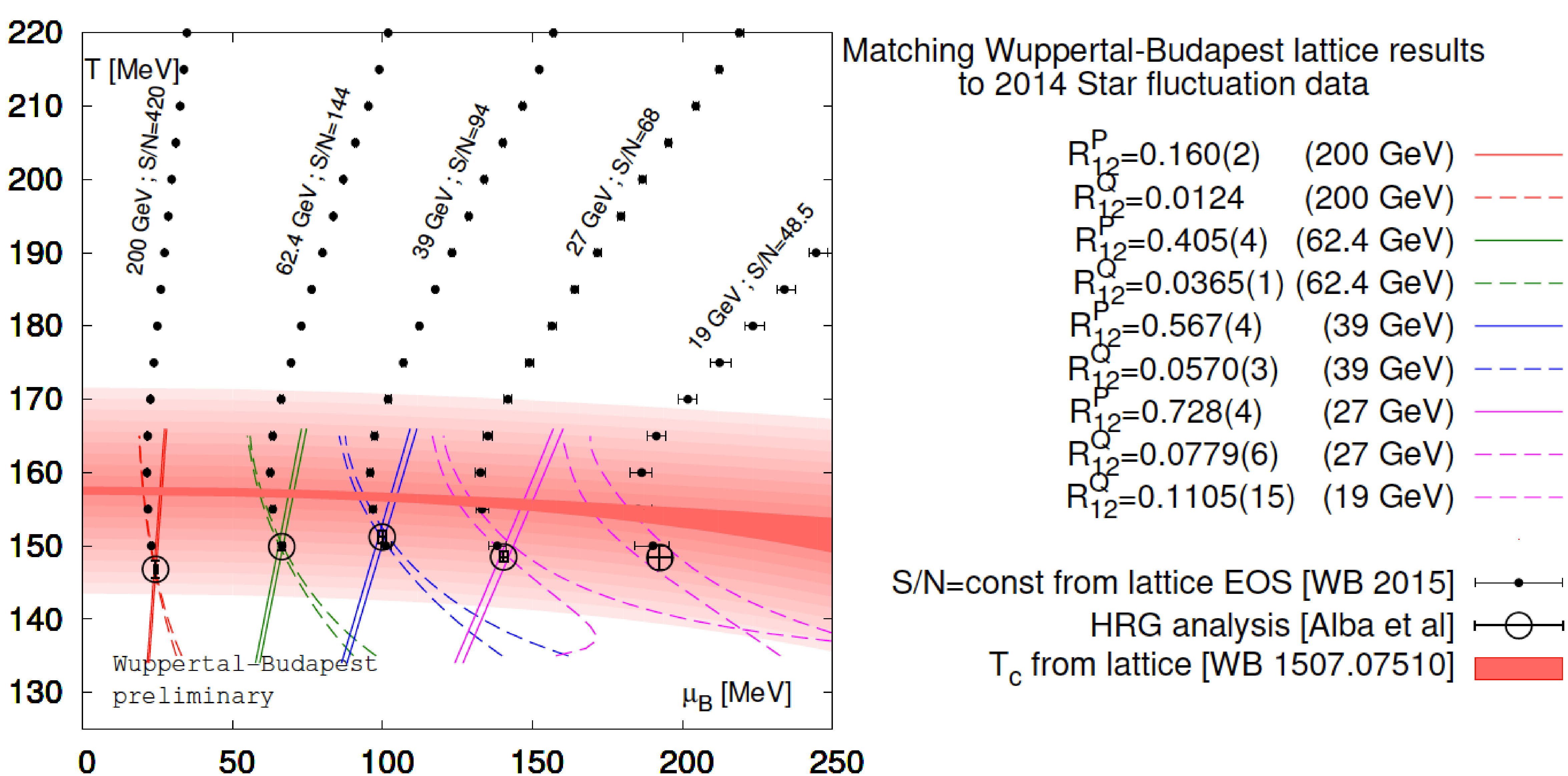


Result: intriguing ‘lower’ freeze-out temperature (compared to SHM yield fits) with very small error bars (due to good determination of c_2/c_1)

(Results were confirmed with STAR 2.0 results)

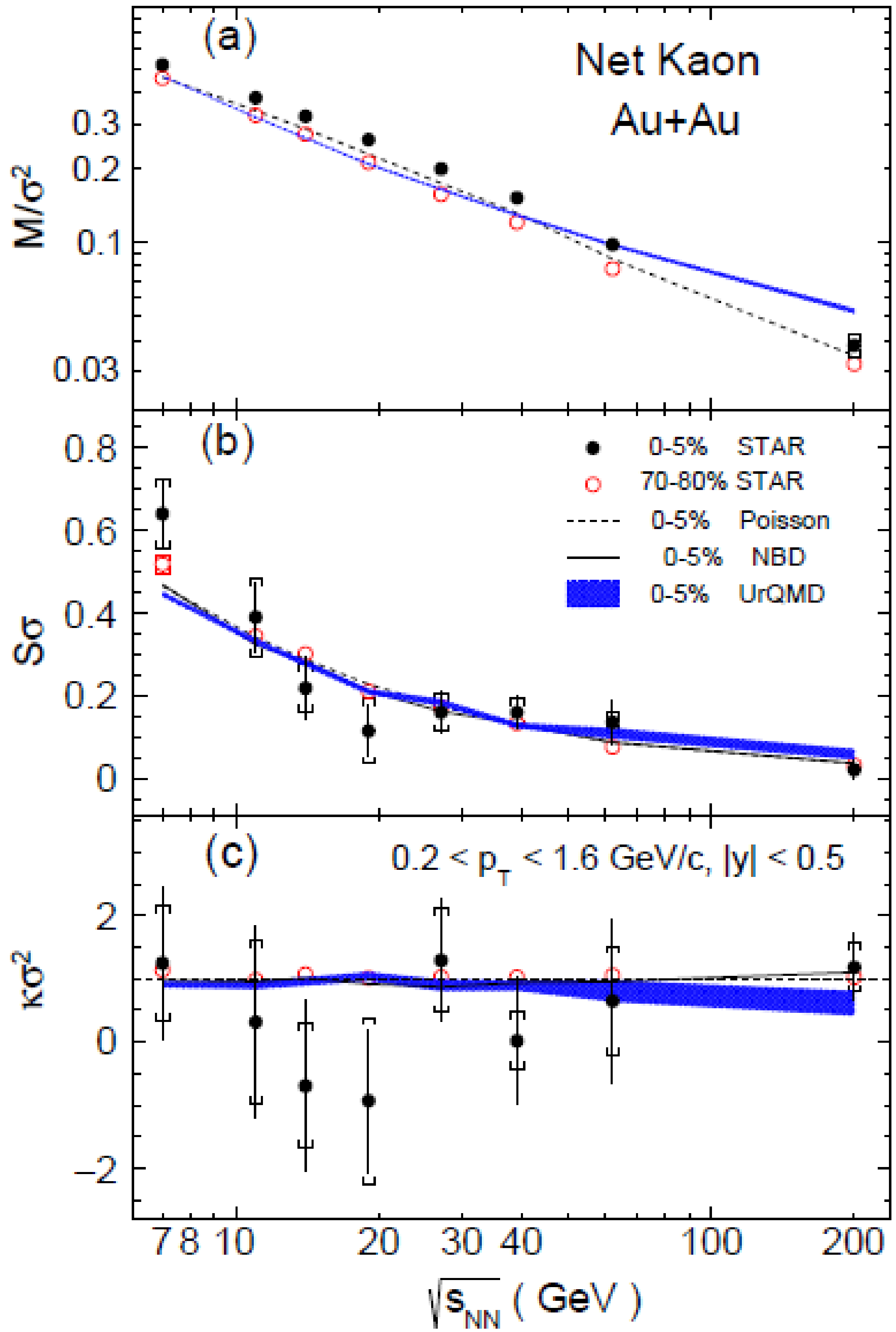
The light quark freeze-out surface is well defined

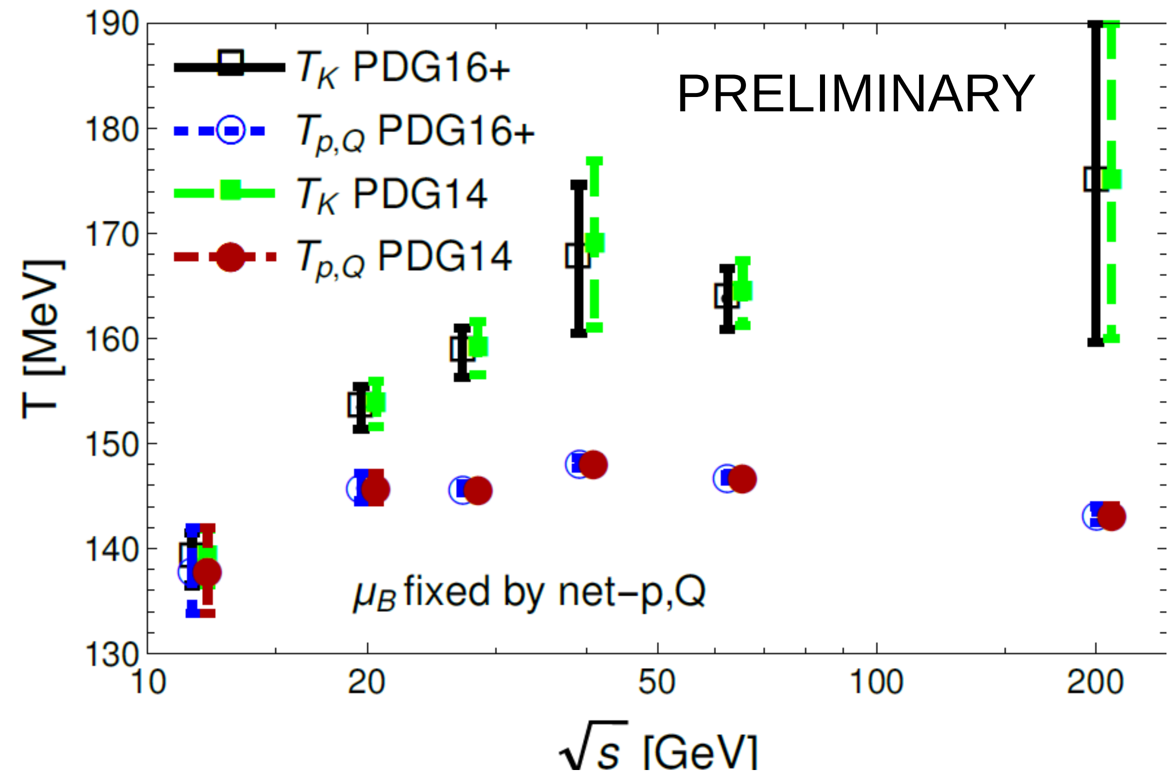
Lattice: improved actions, realistic masses, continuum extrapolations –
HRG: implementations improved, better PDG, more states
General agreement between baryon number and charge freeze-out

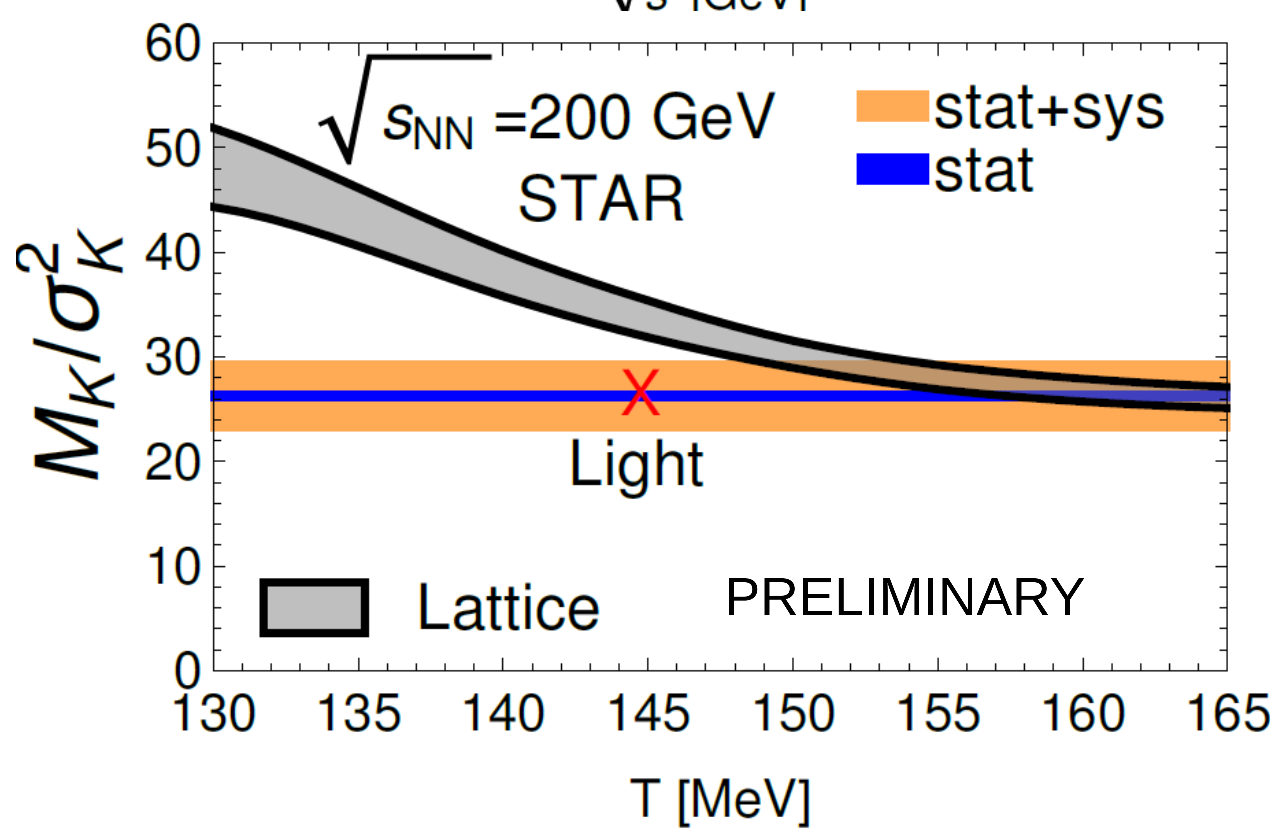


The spread in the lattice range is effectively covered by the light vs strange quark susceptibilities

Fit σ^2/M for net-kaons in the same fashion than for net-proton and net-charge (Data: STAR, arXiv:1611.07132)



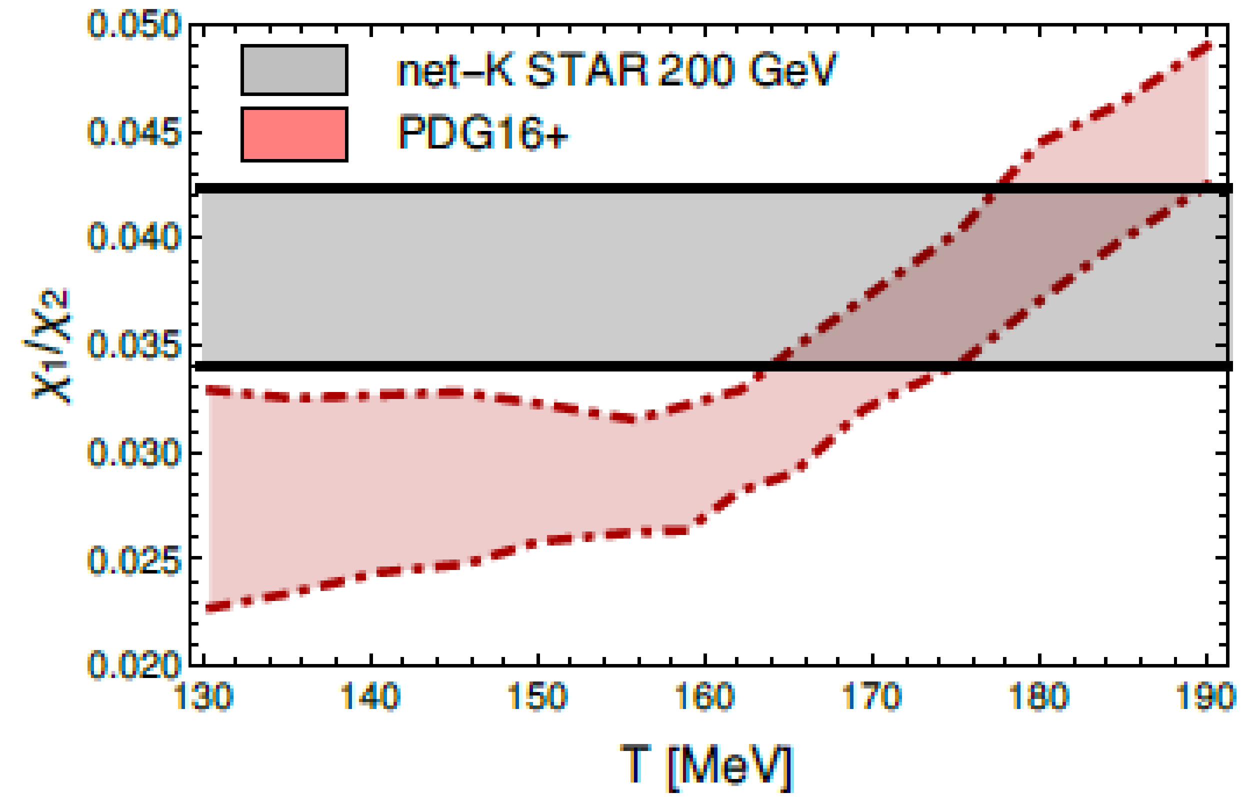


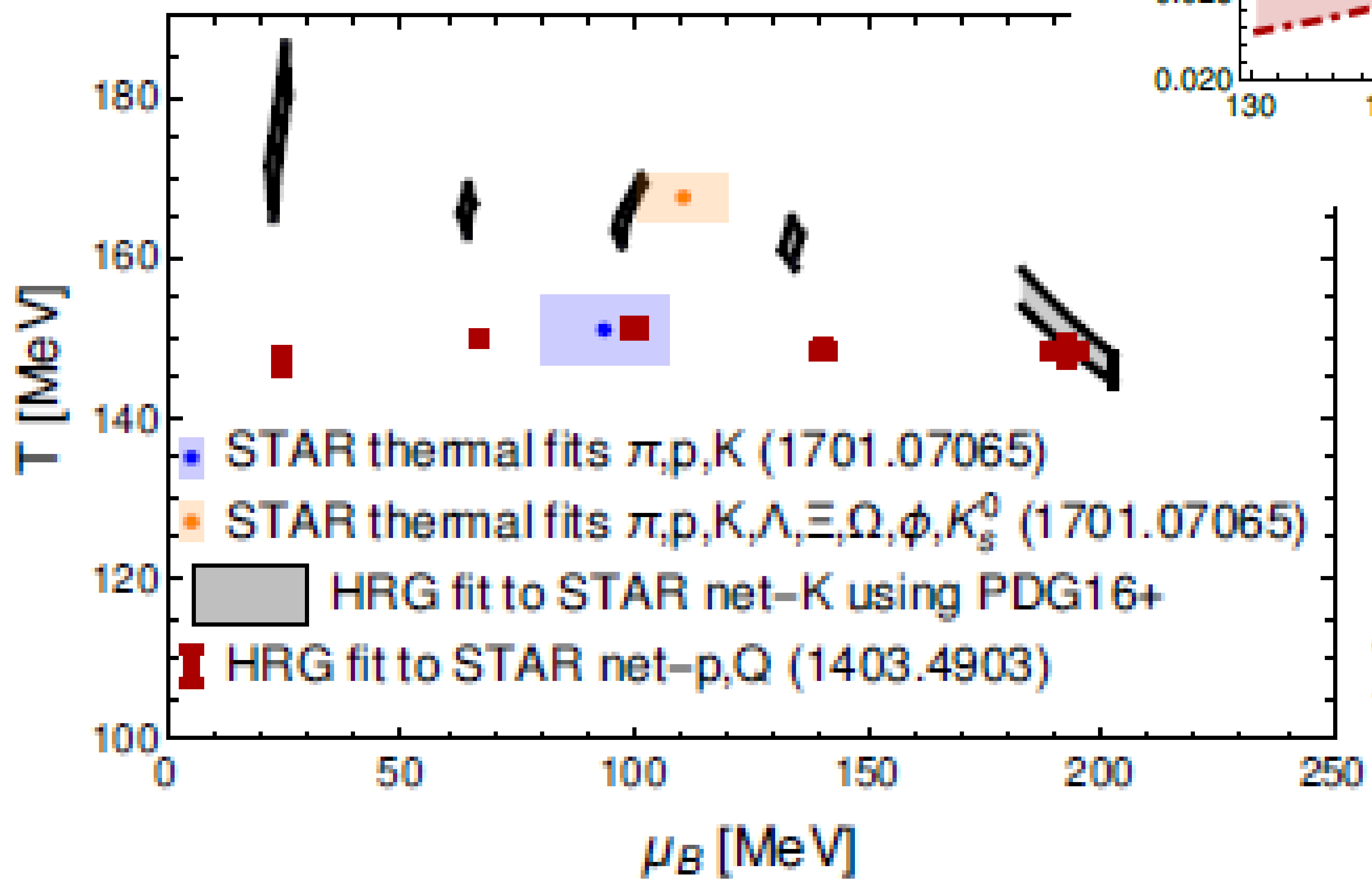


JNH, Ratti et al., arXiv:1607.02527

Are these results very dependent on μ_B?

Pink bands based on lattice QCD isentropes

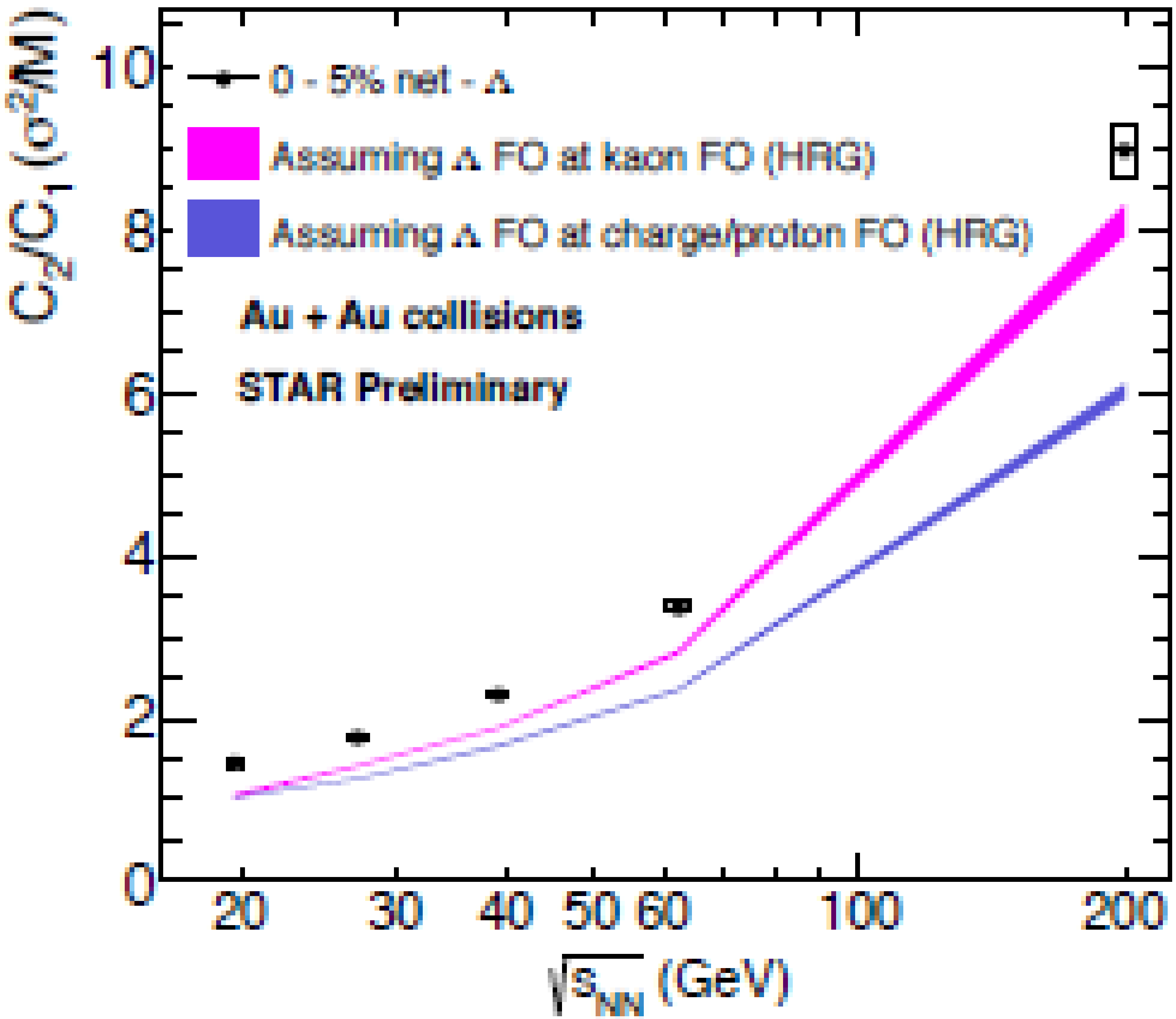




J. Noronha-Hostler, C. Ratti, P. Parotto, R. Bellwied, arXiv:1805.00088

The Lambdas follow the Kaons and NOT the protons

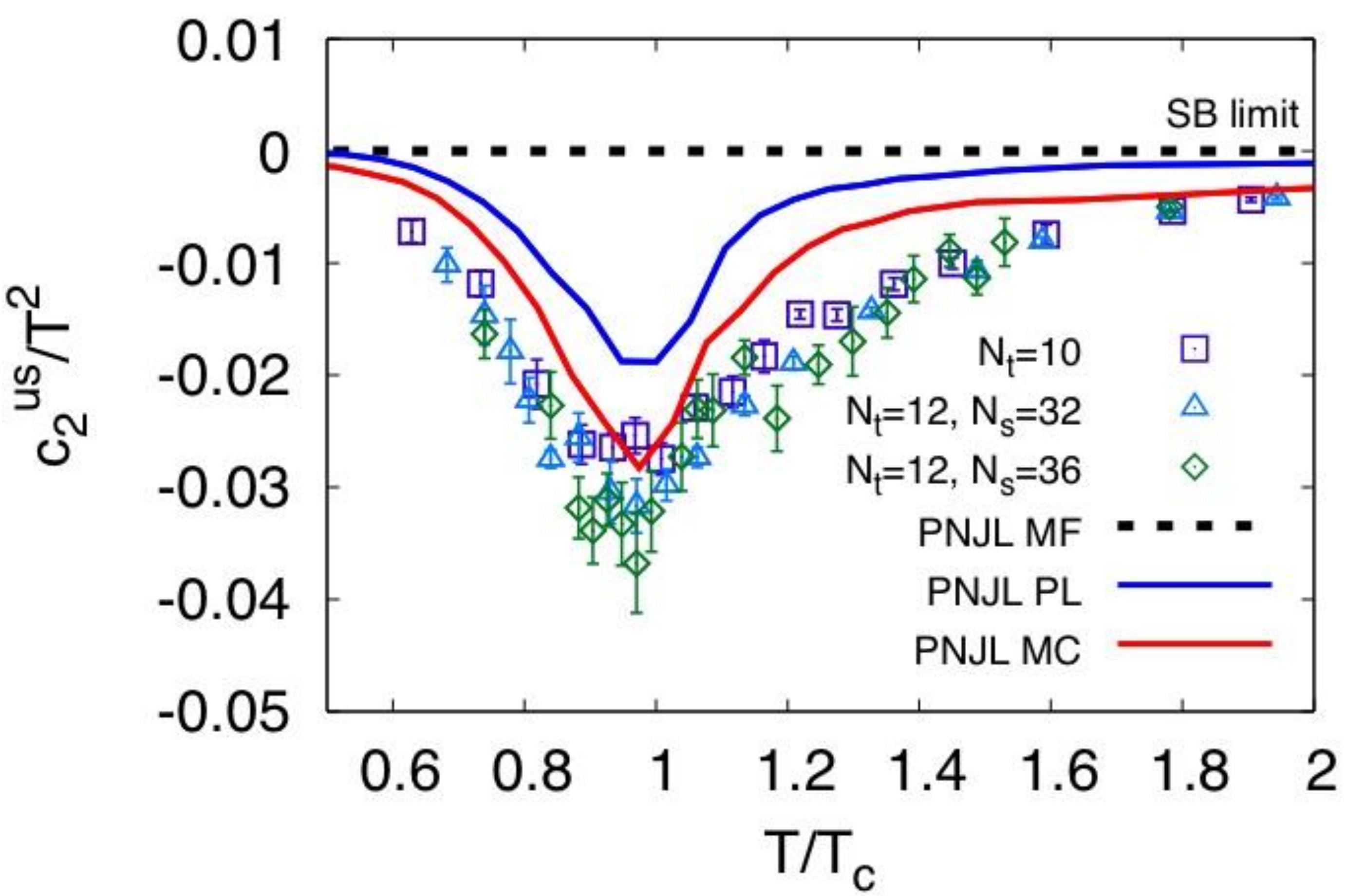
(strangeness dominance over baryon number ?)



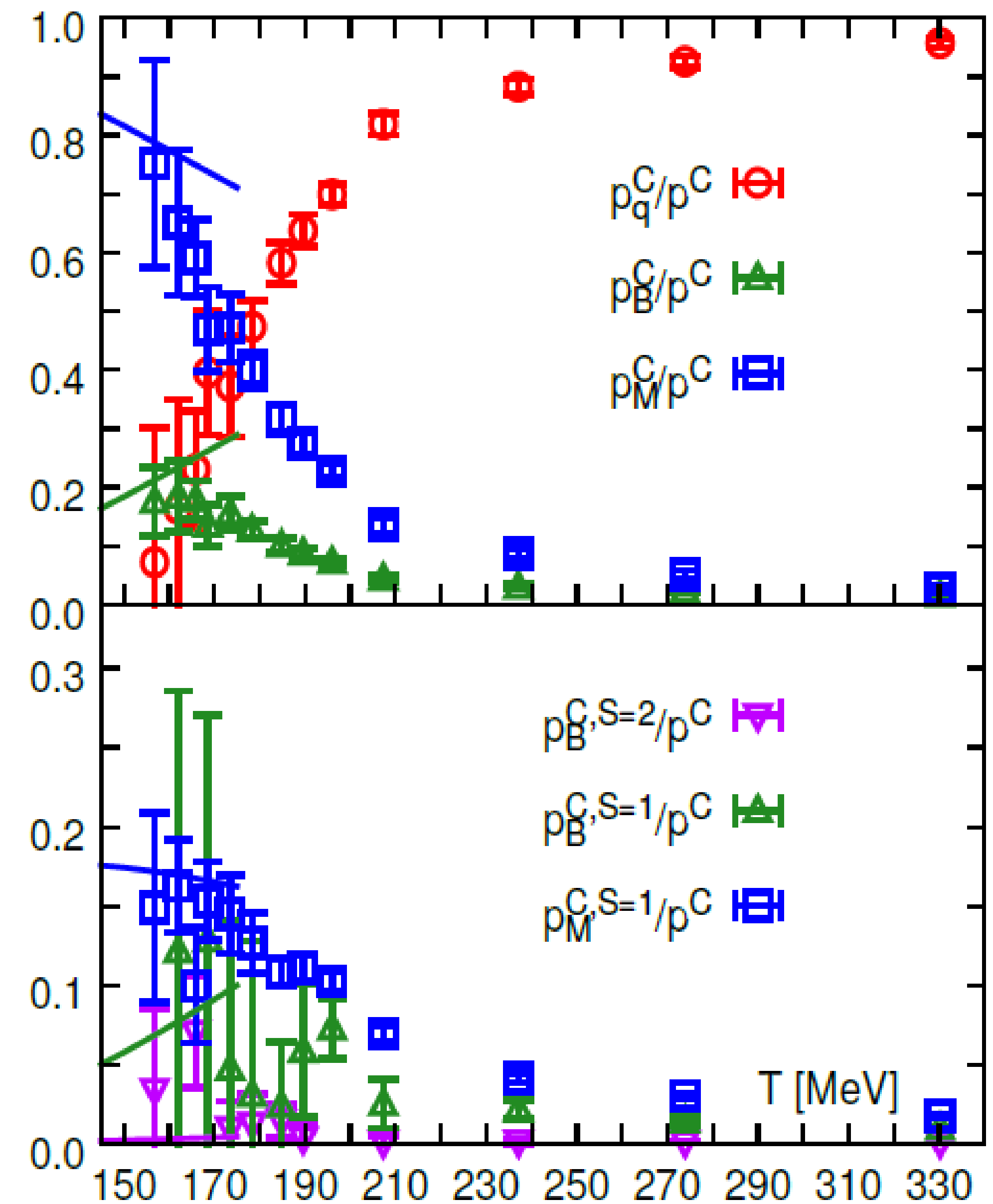
N. Kulathunga (UH), Ph.D. thesis, Nov.2018

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

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



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



The thermal charm opportunities / challenges

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

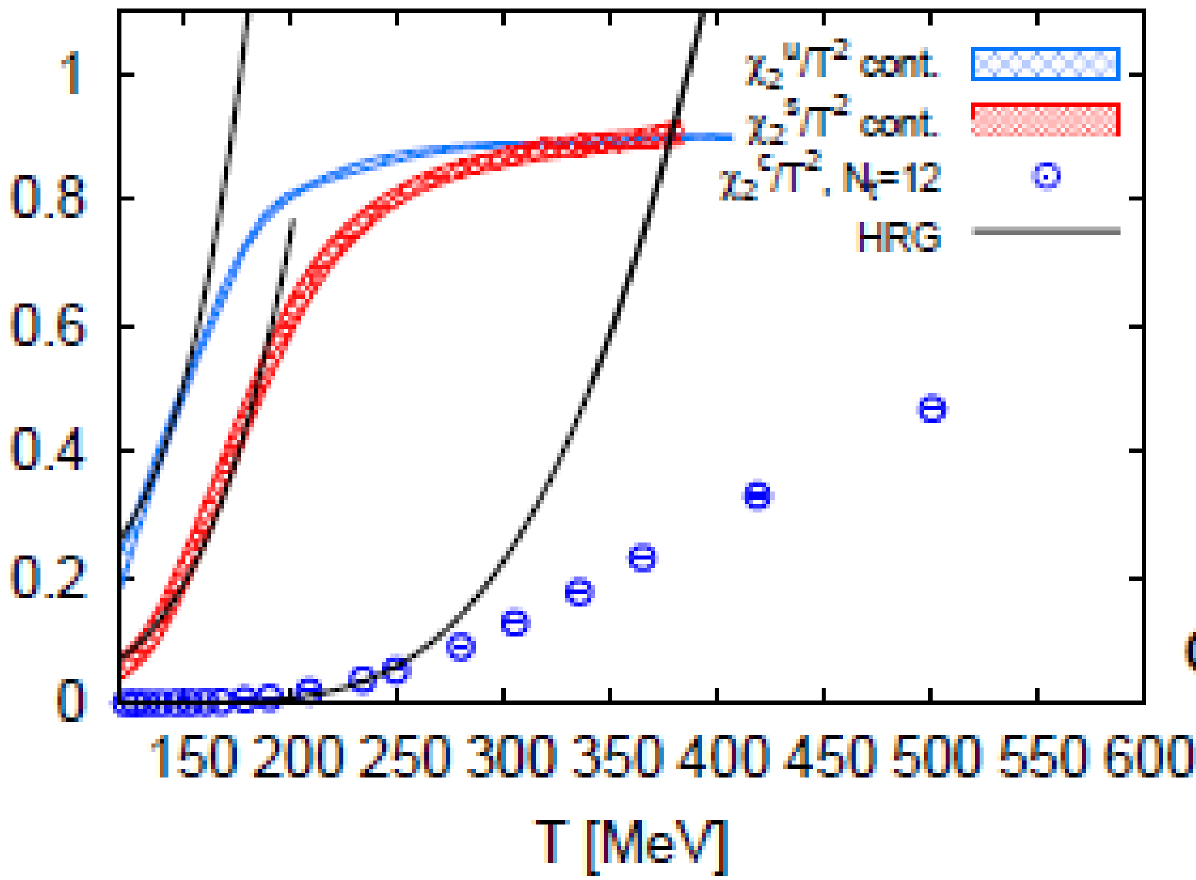
- Is there a flavor (quark mass) or other quantum number dependence when looking at lattice results from the QGP side (WB et al.)?
- Is there a hadron mass dependence when looking at HRG results from the hadronic side (Vovchenko et al.)?

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

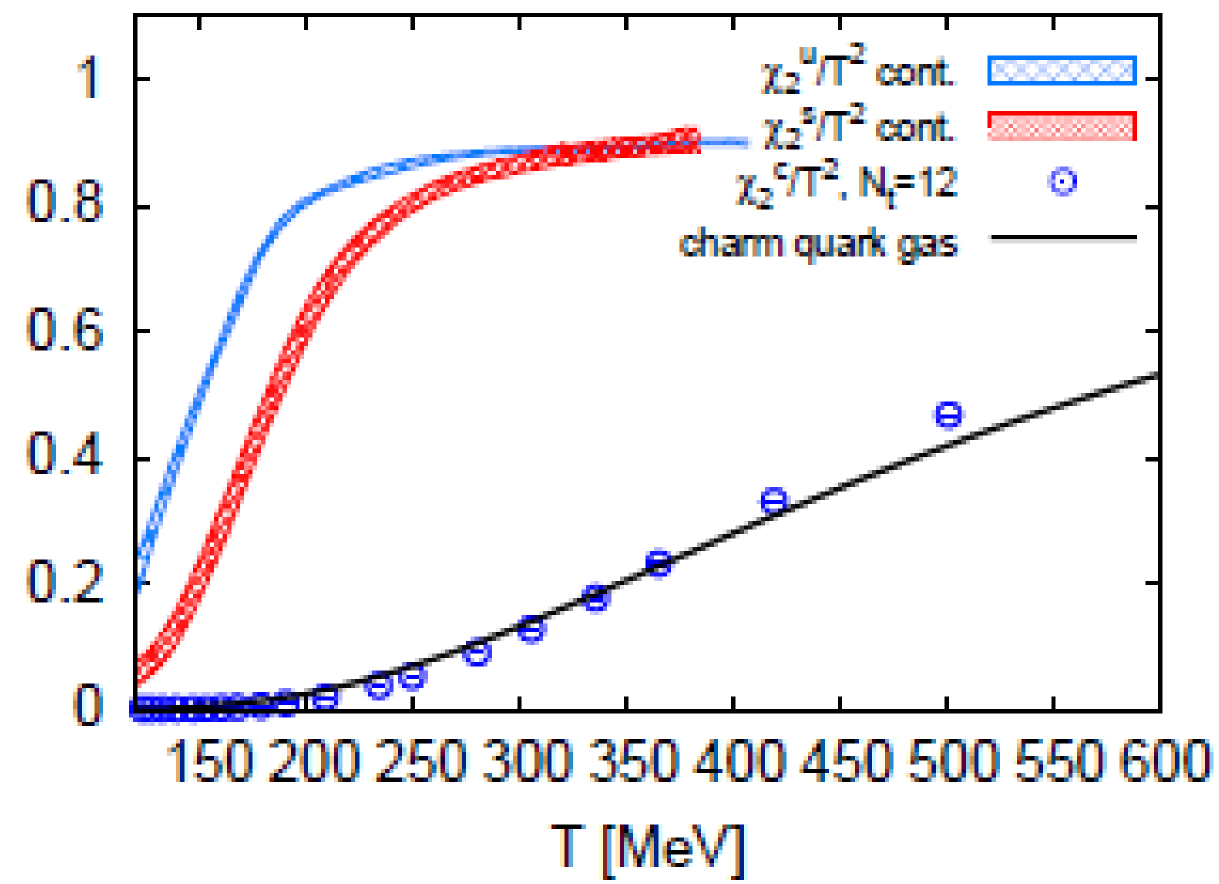
Charm fluctuation measurements could be used to explore a flavor dependent decoupling temperature for produced particles (Graf et al. (1802.07908)).

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

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

HotQCD (1404.4043): open charm susceptibilities (χ_{BC}) start deviating near T_{pc}

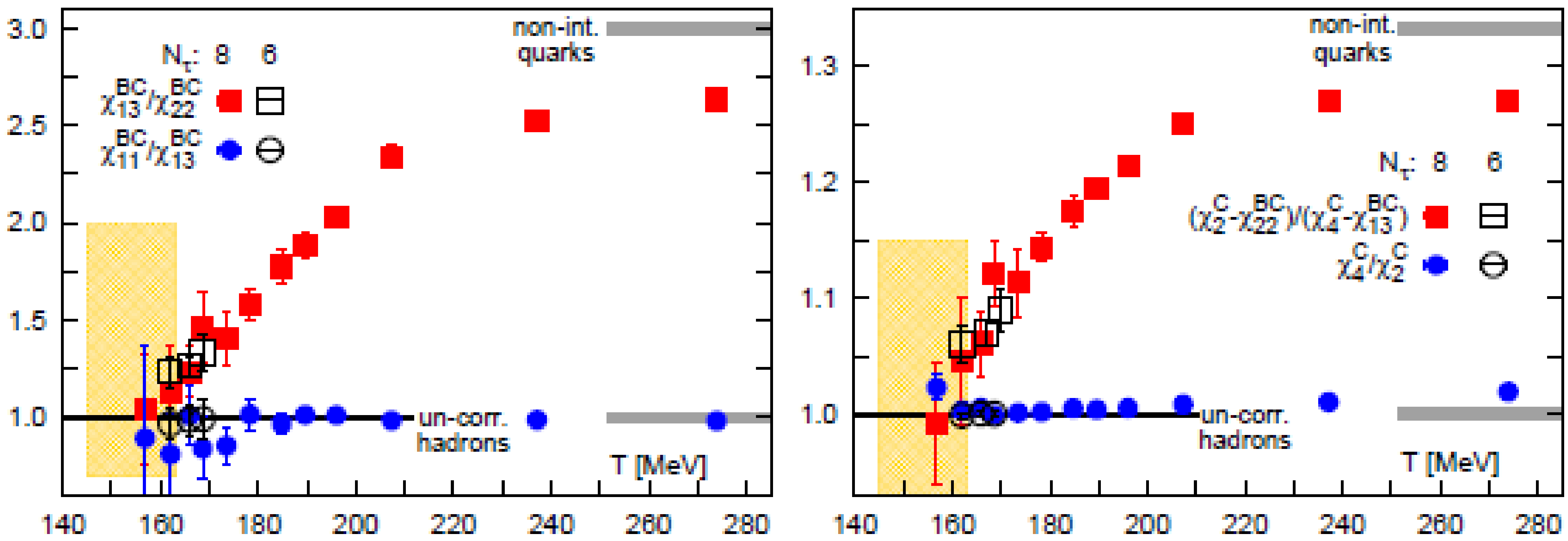
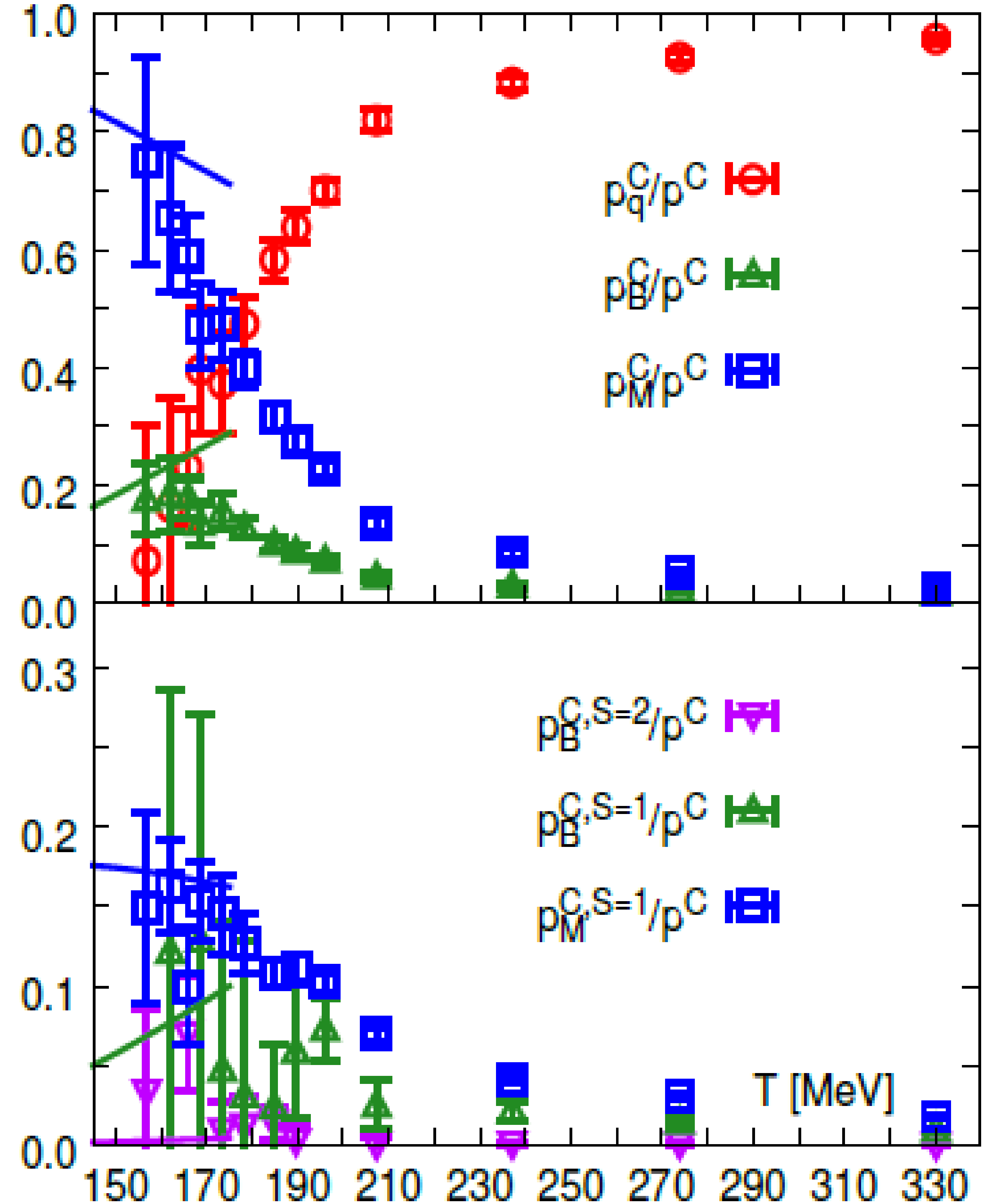


Figure 2: The left hand figure shows two ratios of fourth order baryon-charm(BC) correlations. In an uncorrelated hadron gas both ratios receive contributions only from charmed baryons. Similarly, for the right hand figure the ratio χ_4^C/χ_2^C is dominated by and $(\chi_2^C - \chi_{22}^{BC})/(\chi_4^C - \chi_{13}^{BC})$ only receives contributions from open charm mesons. The horizontal lines on the right hand side of both figures show the infinite temperature non-interacting charm quark gas limits of the respective quantities. The shaded region indicates the chiral crossover temperature at the physical pion mass in the continuum limit, $T_c = (154 \pm 9)$ MeV, determined from the maximum of the chiral susceptibility [3]. Calculations have been performed on lattices of size $32^3 \cdot 8$ (filled symbols) and $24^3 \cdot 6$ (open symbols).

Mukherjee et al. (1509.0887)

FIG. 2. (Top) Fractional contributions of partial pressures of charm quark-like (p_q^C), meson-like (p_M^C), and baryon-like (p_B^C) excitations to the total charm partial pressure (p^C). (Bottom) Fractional contributions of partial pressures of charm-strange meson-like ($p_M^{C,S=1}$), charm-singly-strange baryon-like ($p_B^{C,S=1}$) and charm-doubly-strange baryon-like ($p_B^{C,S=2}$) excitations to the total charm partial pressure (p^C). The solid lines show the corresponding partial pressures obtained from HRG model including additional quark model predicted charm hadrons (see text).



Hadronic contribution to the pressure out to 210 MeV (1.4 T_{pc})

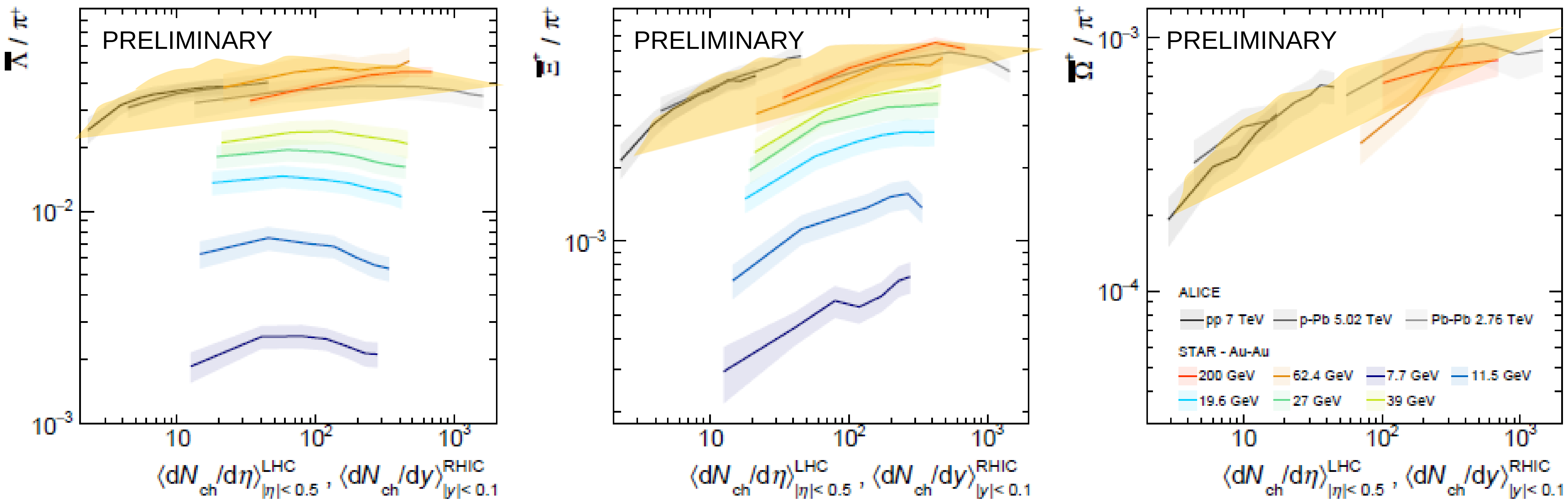
So let's assume there is a separate freeze-out hypersurface for strangeness – do we care ?

Strange matter creation ?:

1.) strangeness enhancement vs. suppression
2.) strange resonance formation
3.) exotica

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 ?

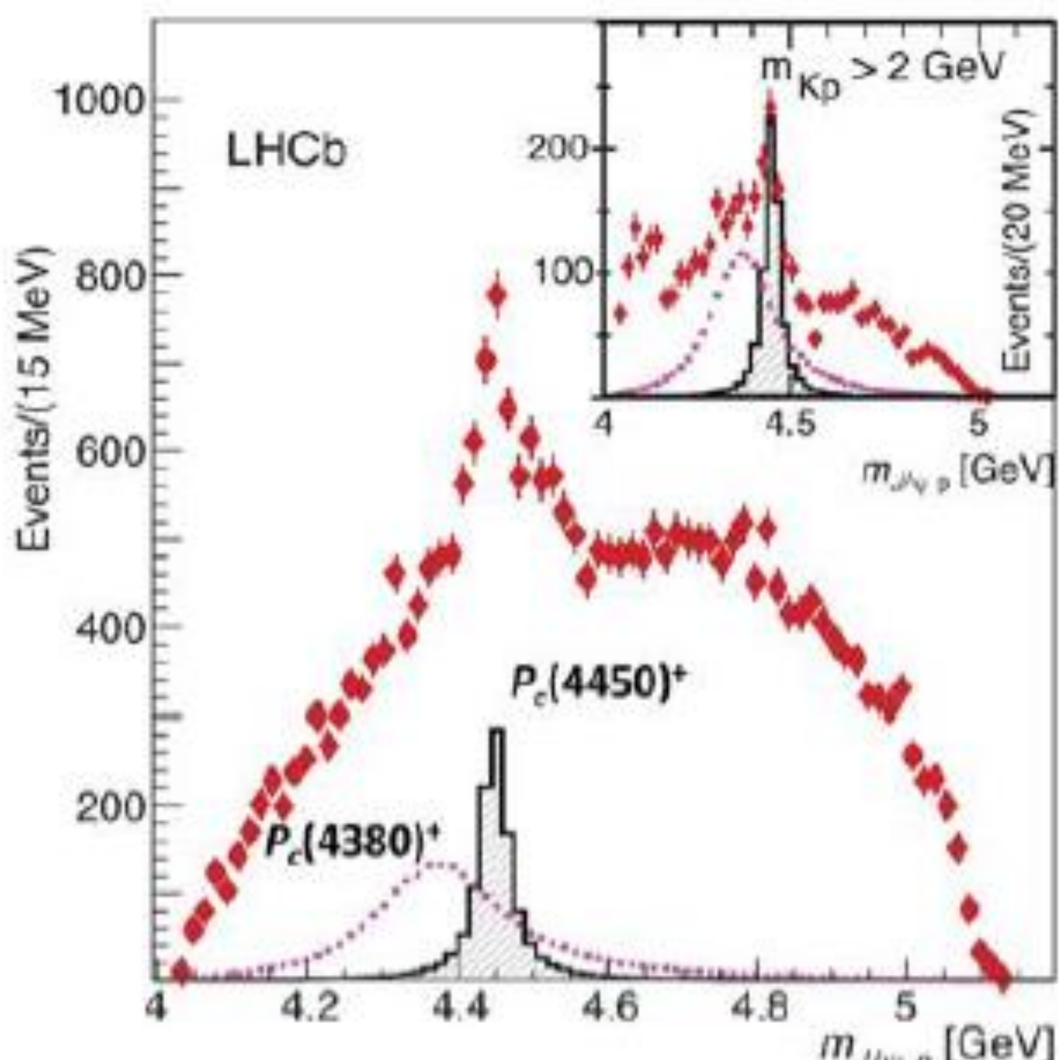


Above 39 GeV the curves seem to fall together, no more energy dependence. The volume dependence is still there (γ_s dependence ?). A higher T freeze-out surface in PbPb will lead to actual strangeness enhancement

Exotica:
Penta- and Tetra-quarks from LHCb

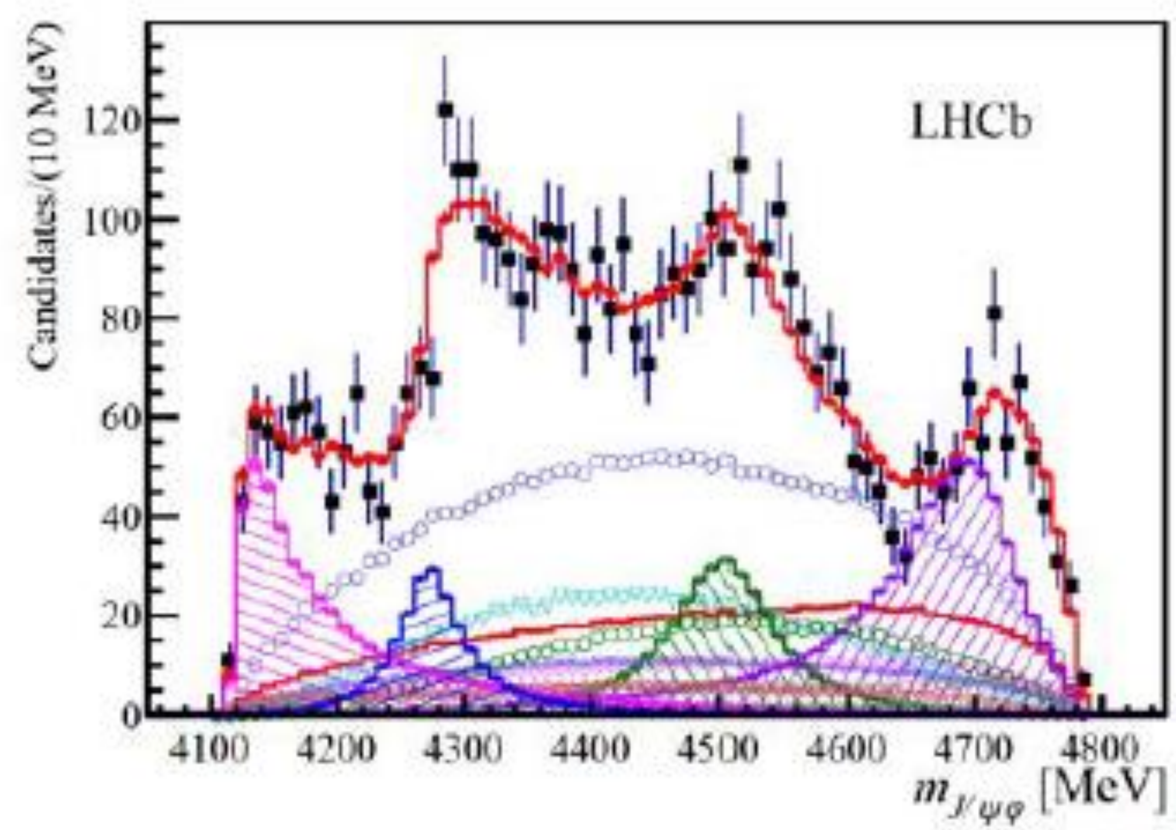
Penta-quark in 2015, 9σ evidence by 2016

In the charm sector: J/ψ p resonance
In Λ_b decays to J/ψ p K^-



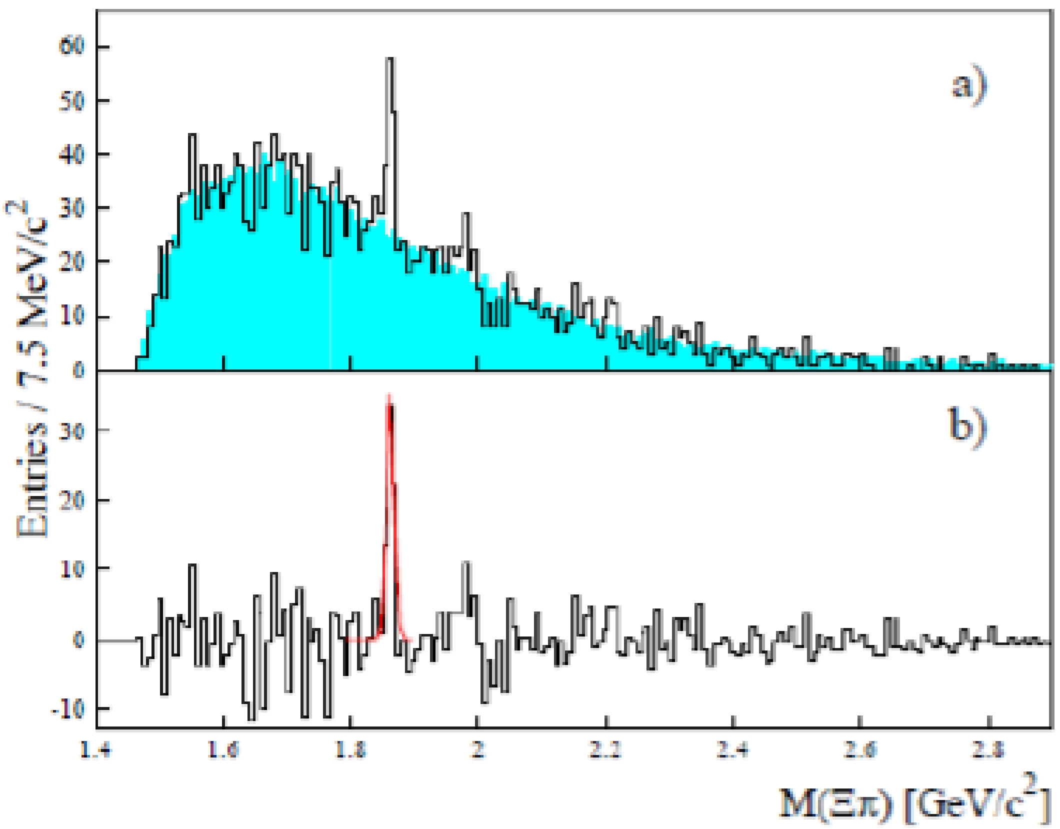
Tetra-quarks in 2016

In the charm sector: J/ψ ϕ resonance
In B^+ decays to J/ψ ϕ K^+

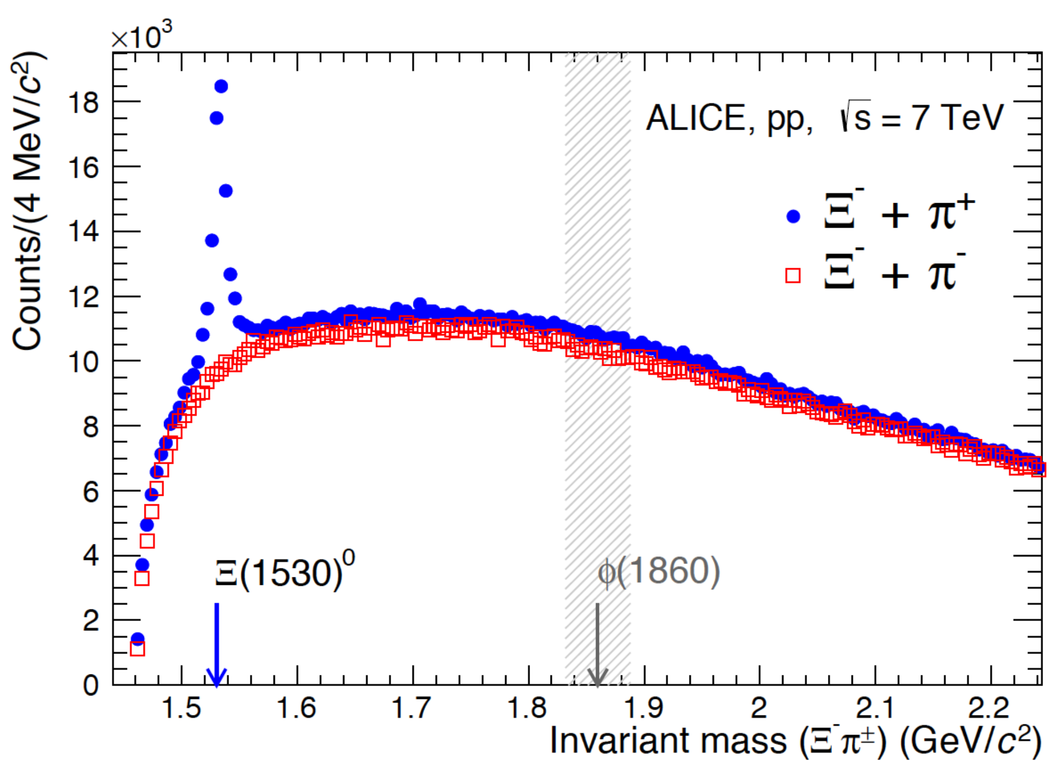


Why nothing in the strange sector ?

Exotica in strange sector ?



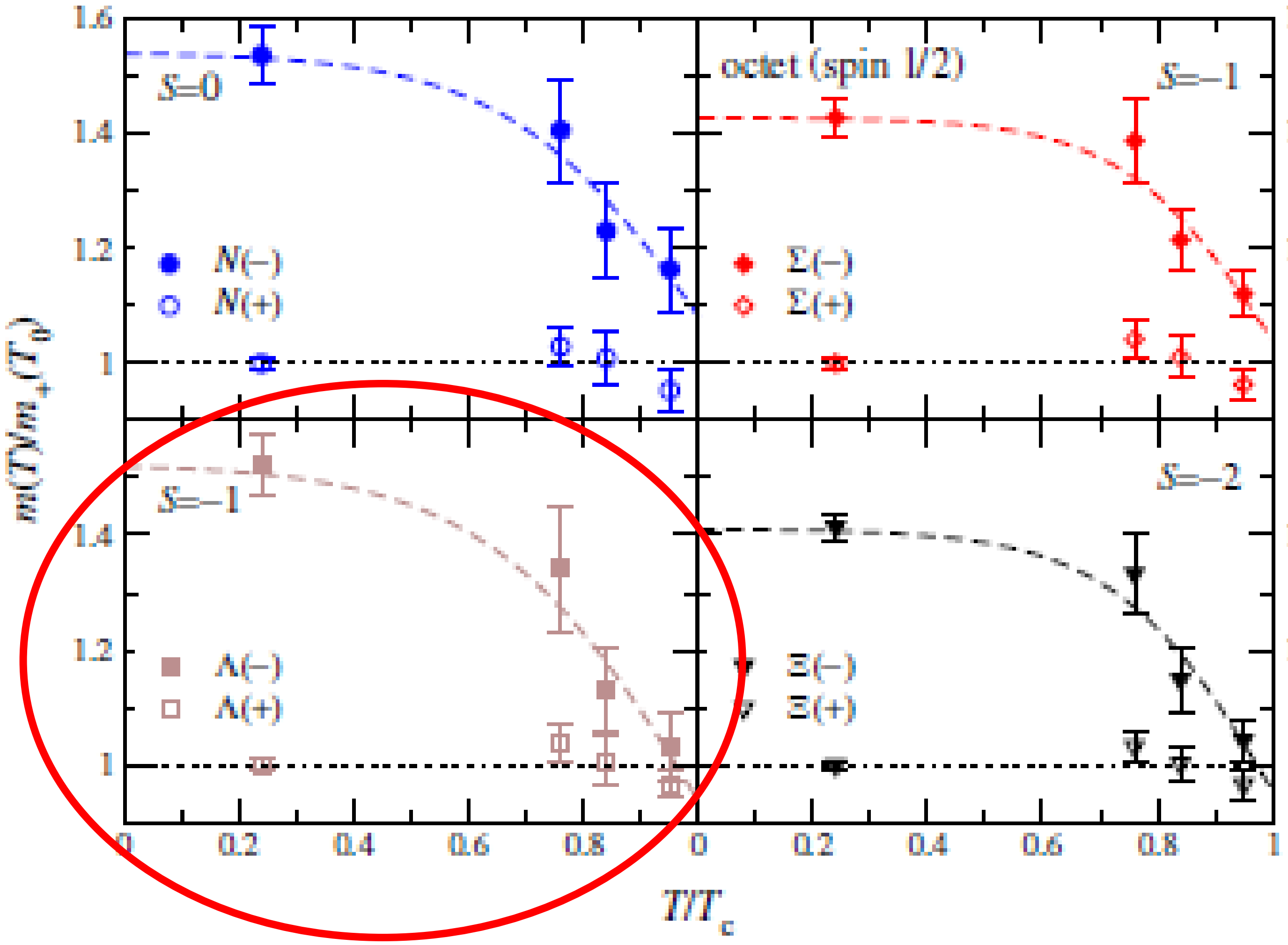
Famous pentaquark candidate from NA49 (2008) in Ξπ channels (φ(1860)) (dsdsubar)
Never retracted, never confirmed



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 !!



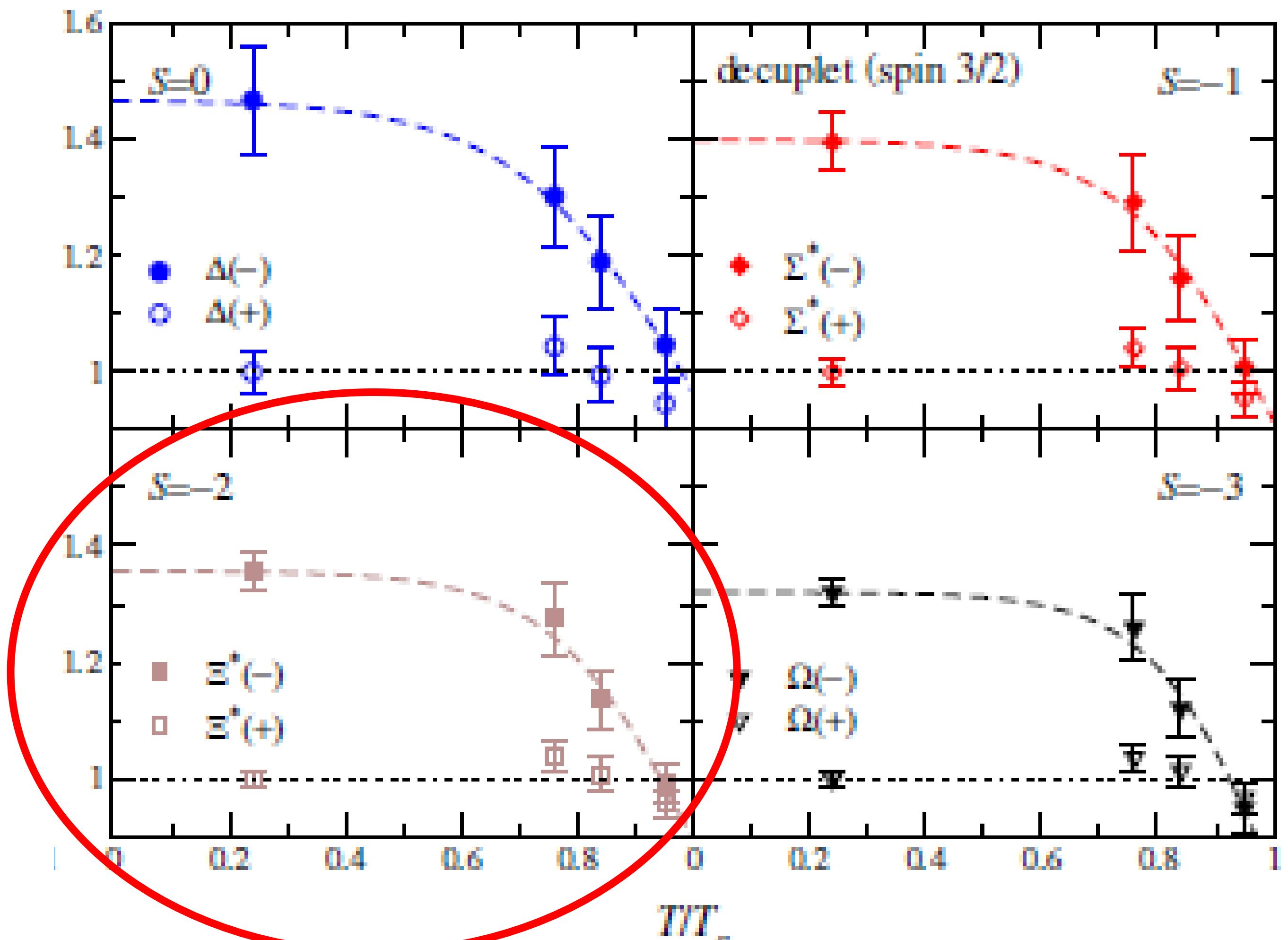
Chiral restoration in the strange baryonic resonance sector

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.

Possible experimental verificiation
(in the strange sector)

Difficult to find appropriate chiral partners that are experimentally accessible:

In the octet sector: ½ states for the Λ : positive parity $\Lambda(1115)$,
negative parity $\Lambda(1405)$

In the decuplet sector: 3/2 states for the Ξ: positive parity $\Xi(1530)$
negative parity $\Xi(1820)$

In ALICE: ongoing work by Corey Myers and Jihye Song (UH)

Quark Mass dependence

Integrate the $R(\tau)$ ratio

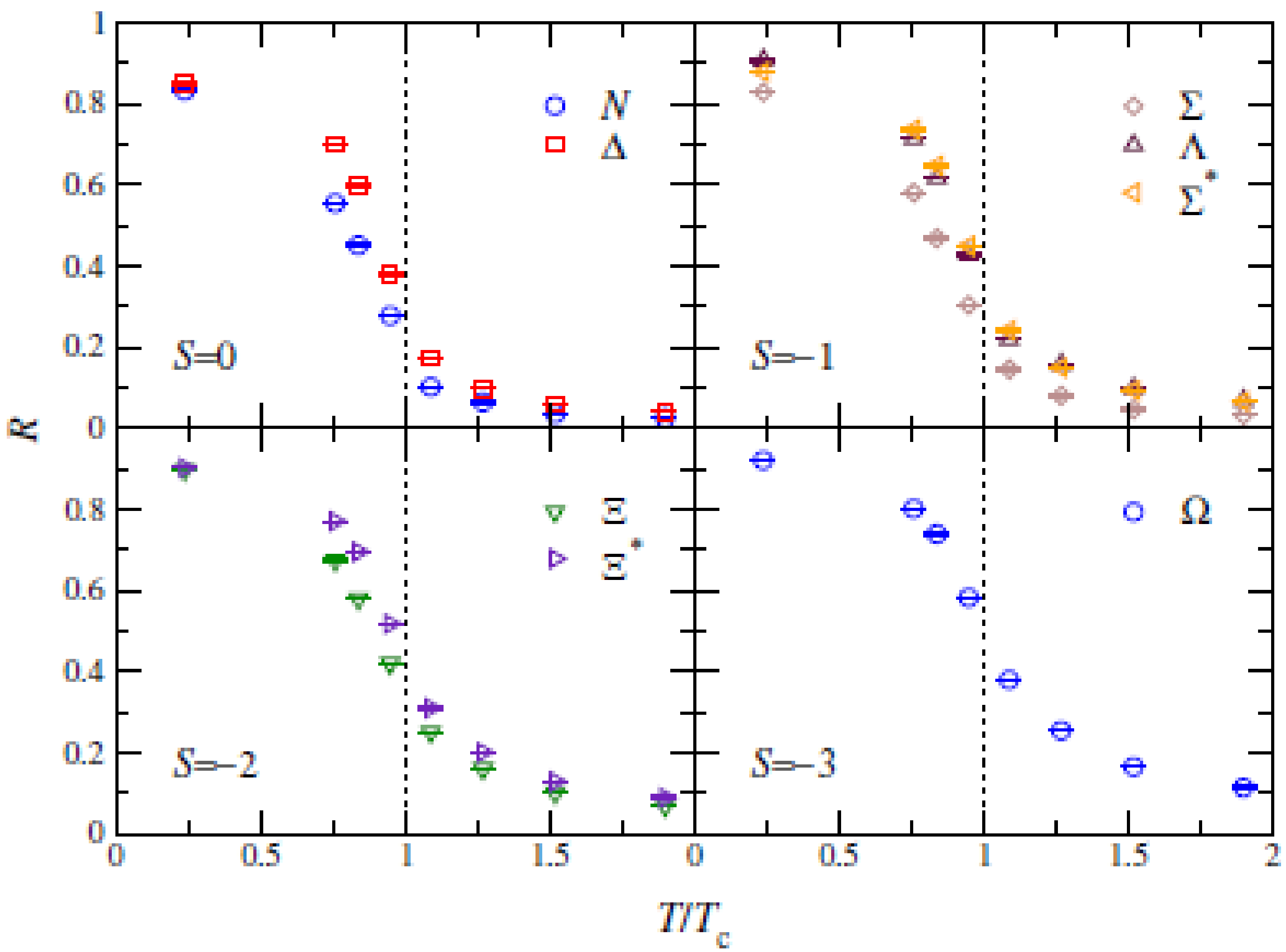
$$R(\tau) = \frac{G_+(\tau) - G_-(\tau)}{G_+(\tau) + G_-(\tau)}$$

$\Rightarrow$ quasi-order parameter

$$R = \frac{\sum_n R(\tau_n)/\sigma^2(\tau_n)}{\sum_n 1/\sigma^2(\tau_n)}$$

Interesting new pseudo-order parameter for the phase transition:

Parity doubling Ratio R



Seems to indicate slight quark mass dependence in the chiral transition

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.

- On the issue of flavor: We have measured the differences between proton, Lambda and Kaon fluctuations. We need to measure and understand the differences of Lambda vs. Omega vs phi-meson fluctuations.
- Reinhard’s old question: how can a Lambda freeze-out earlier than a proton ?.

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.

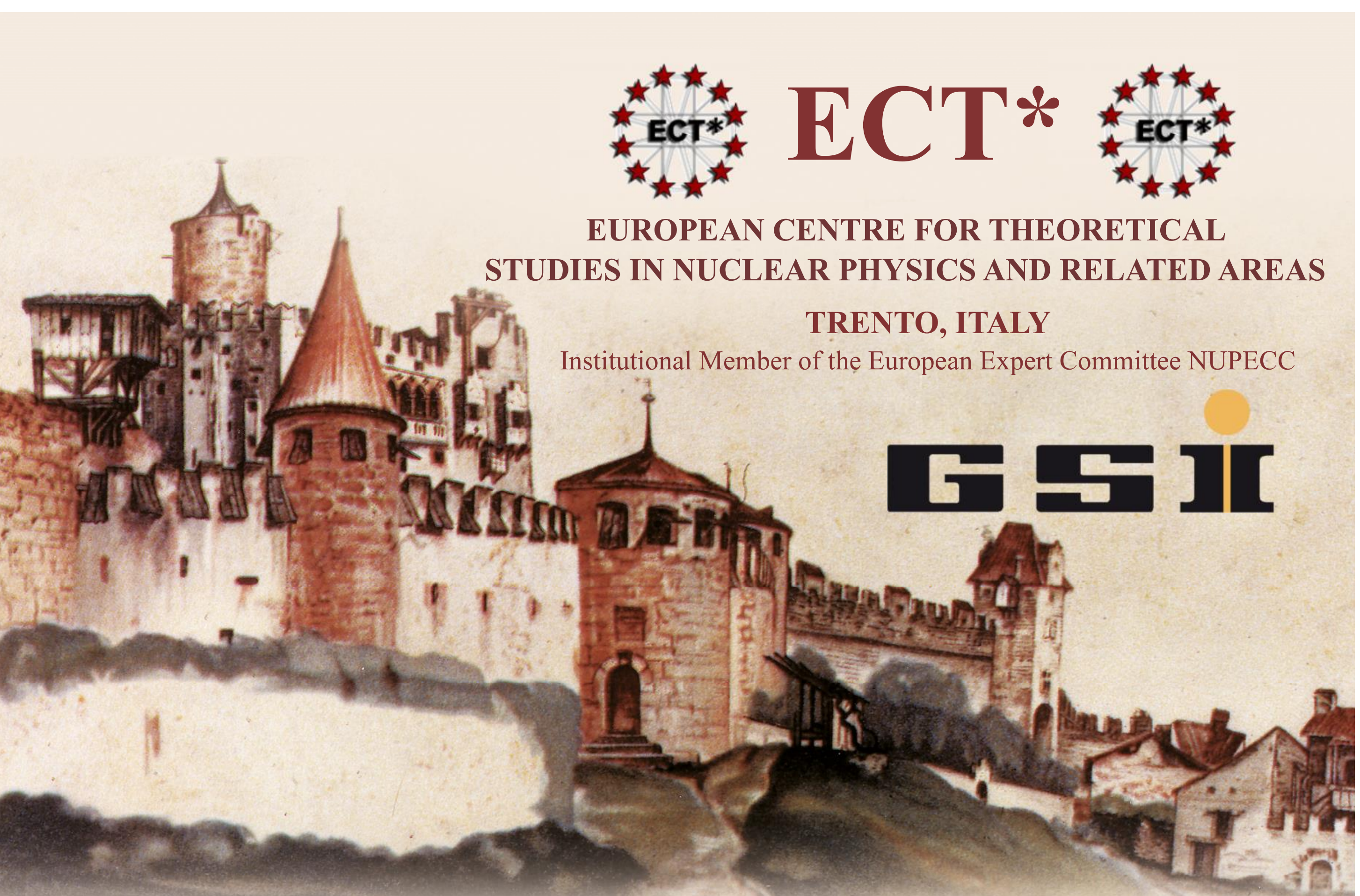
- If the abundance of strange quarks is sufficiently high (LHC) this could lead to *enhancements in the strange hadron yields (evidence from ALICE)* and it could lead to *strangeness clustering (exotic states: dibaryons, strangelets)* or *higher mass strange Hagedorn states* (as predicted by Quark Models).
- 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 (UH Theory Group): The phases can be linked in a hydrodynamic calculation by using a mixed EOS from lattice and HRG with varying flavor-dependent switching temperatures.

Backup

Composite particle production in relativistic particle collisions through quantum entanglement

R. Bellwied (University of Houston)



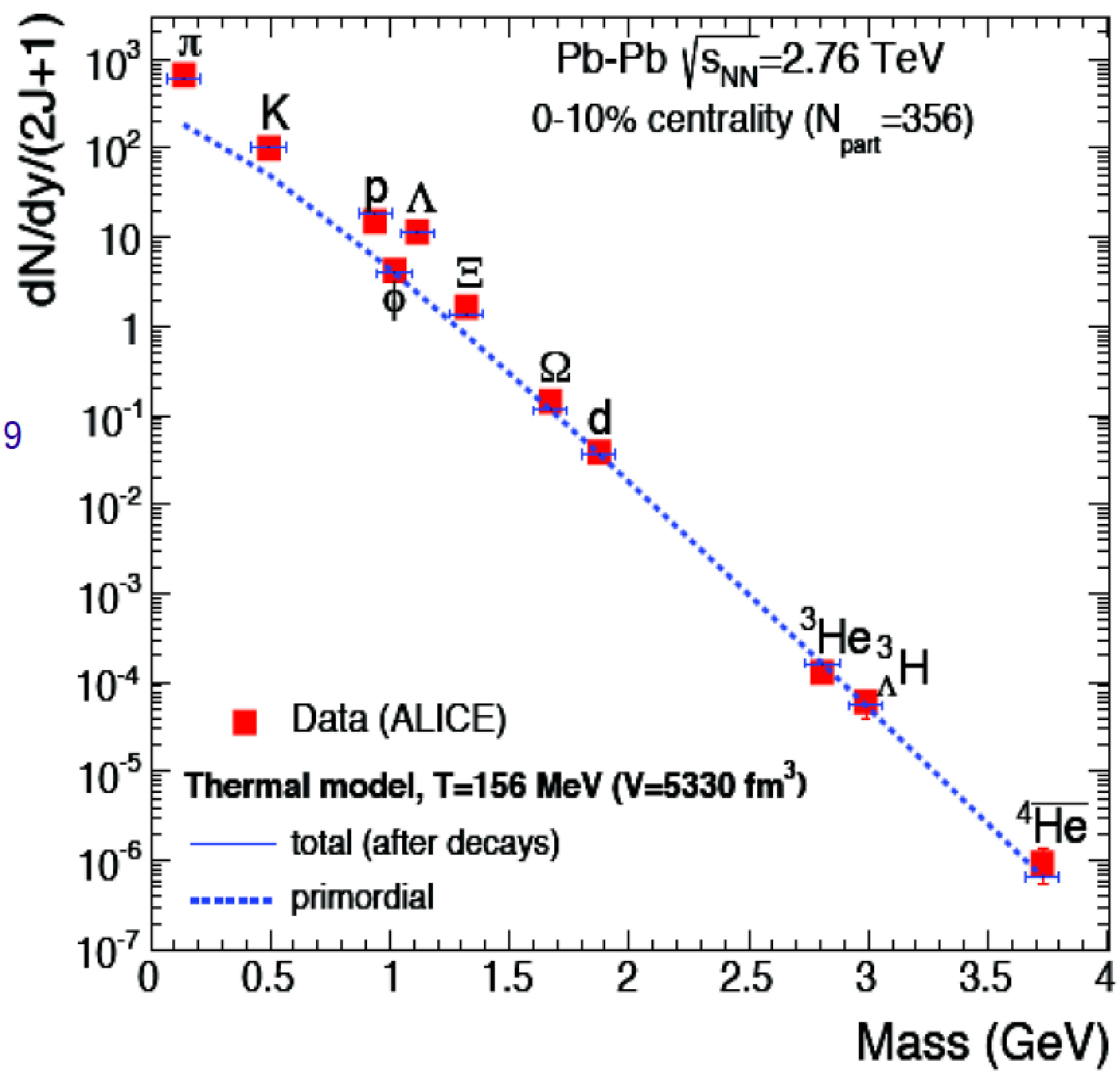
see also arXiv:1807.04589

Observables of hadronization and the QCD phase diagram in the crossover domain

October 15-19, 2018
Trento, Italy

Light and hyper-nuclei yields are in agreement with thermal model predictions

9



Both hypernuclei and molecular states (deuteron, ^{4}He) are well described by a thermal model with a temperature around 156 MeV. Hypernuclei are dominated by light quark properties

Bound states with binding energies in the keV range are described by thermodynamics frozen at 156 MeV ?

Can we find a mechanism that 'thermalizes' the quark system and fixes the entropy/baryon in the initial state ?

The Quantum Mechanics of partons and 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

Theoretical Conclusions and outlook

- Partons in proton collisions are entangled transversely and longitudinally during the expansion of the QCD.
- Entanglement entropy is extensive (volume dependent), just like thermodynamic entropy.
- The reduced density matrix for a conformal field theory is locally thermal. *Entanglement generates 'thermalization'.*

- 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).
- This should impact the hadron multiplicity fluctuations and the final yields of hadrons including loosely bound objects.

- The relationship between the entanglement entropy and the 'thermal' temperature needs to be quantitatively established. (see e.g. Pajares et al., arXiv:1805.12444)

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.

•Particle production looks thermal but is driven by parton-hadron duality, which also means that composite hadronic objects are formed from a single multi-quark QCD string.

•The entanglement entropy translates one to one into the final hadronic entropy and stays constant throughout the system evolution.

•All light quark hadron yields are frozen in during the initial state at a common ‘temperature’. Entanglement entropy calculated over extended volume at QCD crossover. Temperature should related to Hagedorn temperature.

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.