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

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Outline

- Recent results on particle production at the LHC

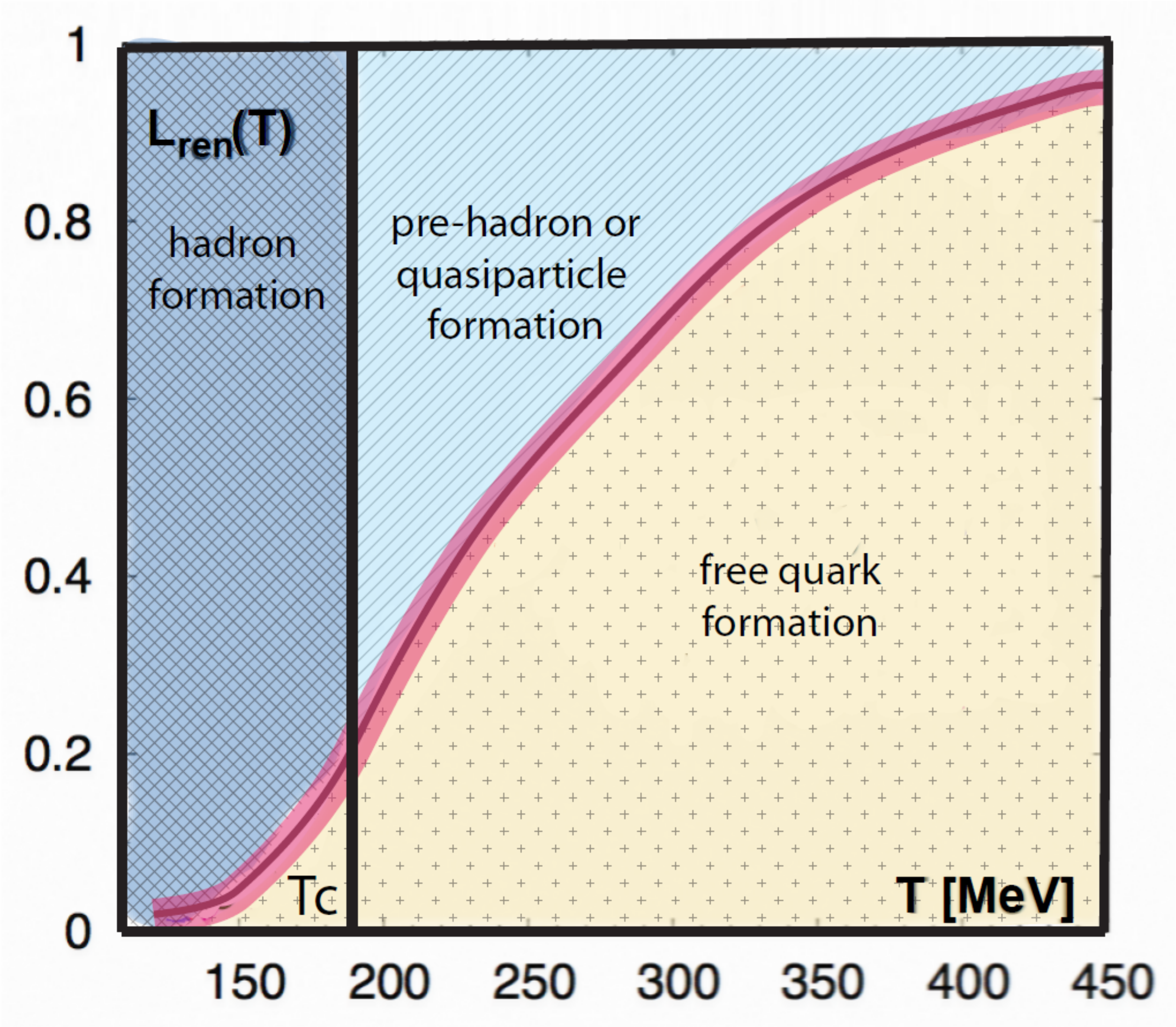
- The role of flavor during the transition
- Loosely bound objects

- Early ‘thermalization’ in elementary systems through quantum entanglement

- Entanglement entropy = Thermodynamic entropy ?
- Parton-hadron duality in elementary collisions
- Generalization to heavy ion systems. Decoherence ?

- Conclusions, outlook and experimental verification

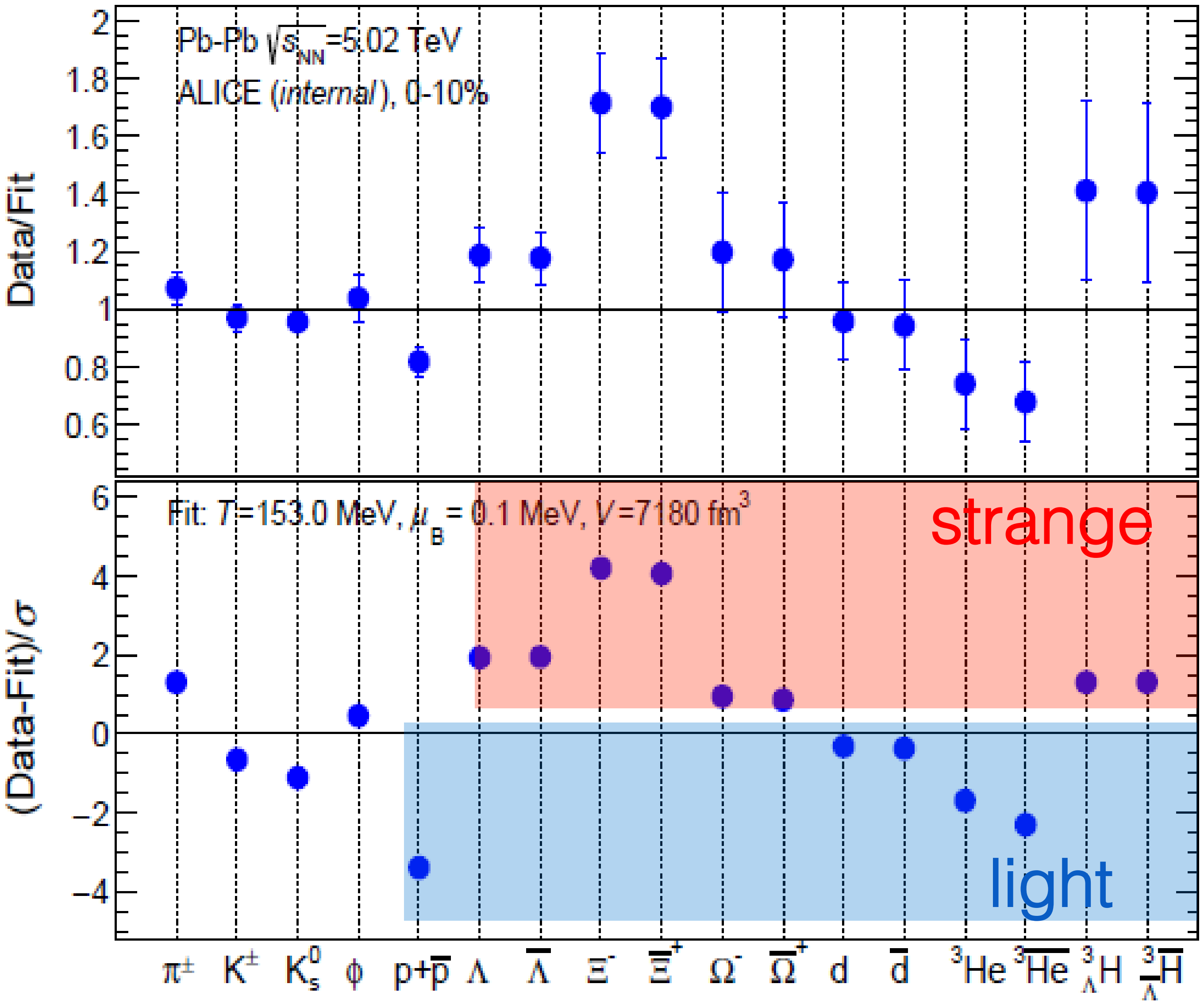
Lattice order parameters in the QCD cross-over



RB, C. Markert, PLB691 (2010) 208
Data: Bazavov et al., arXiv:1105:1131

- Present understanding: equilibration at phase boundary
- QGP matter requires equilibration. Hydrodynamics requires early equilibration.
- Success of Statistical Hadronization Model (SHM) implies equilibration at phase boundary.

Is there a flavor hierarchy in the hadronic yields measured at the LHC ?

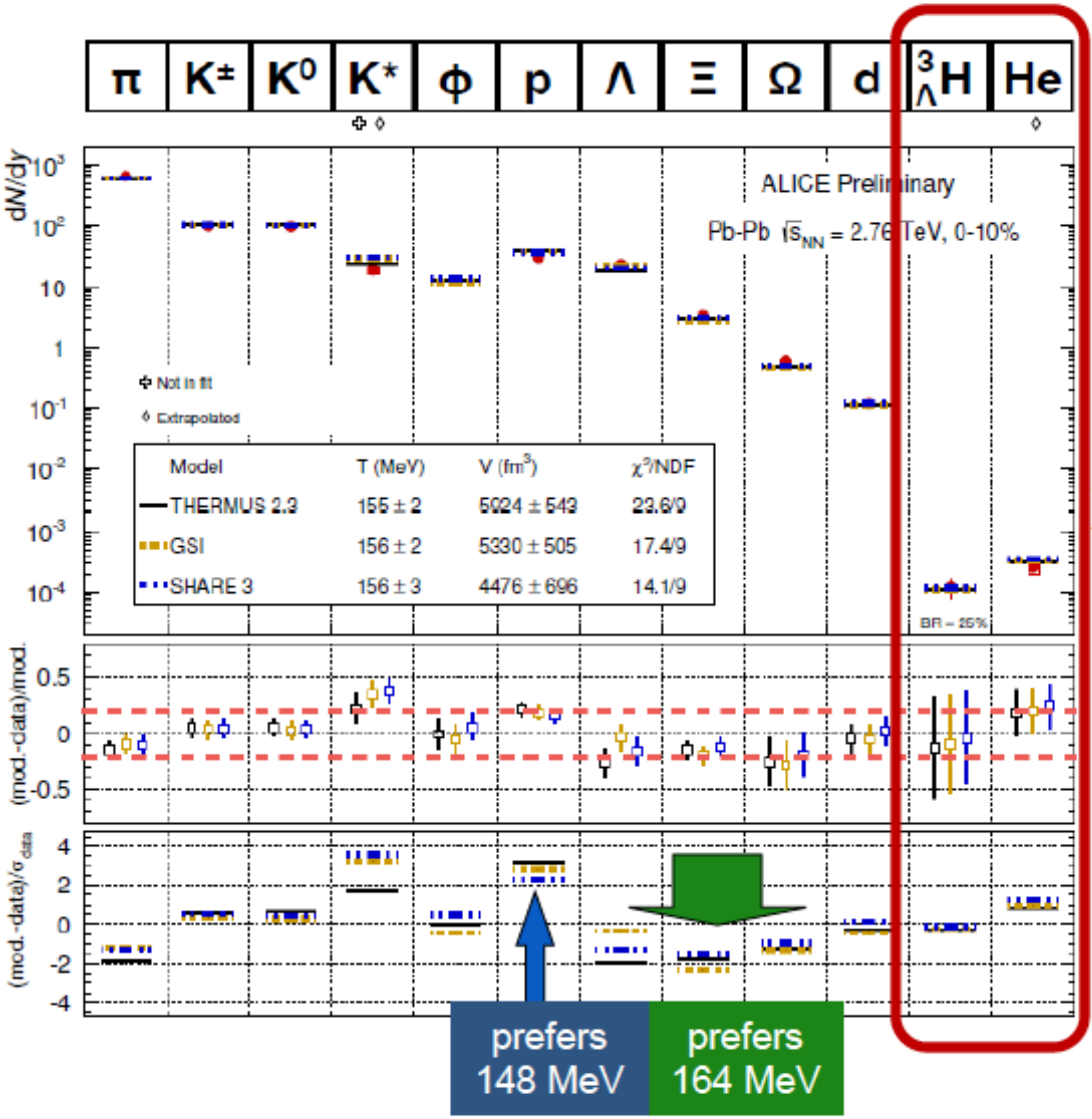


GSI-Heidelberg model fit

The new 5.02 TeV show a more pronounced and more precise tension between strange and non-strange particles in the baryonic sector.

Fluctuation measurements from STAR in 200 GeV AuAu collisions comparing proton freeze-out to kaon/Lambda freeze-out based on HRG model comparisons confirm different freeze-out temperatures (see arXiv: 1805.00088) and new data from ALICE & STAR (QM18))

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



Model	T (MeV)	V (fm³)	χ^2/NDF
THERMUS 2.3	155 ± 2	5924 ± 543	23.6/9
GSI	156 ± 2	5330 ± 505	17.4/9
SHARE 3	156 ± 3	4476 ± 696	14.1/9

prefers 148 MeV

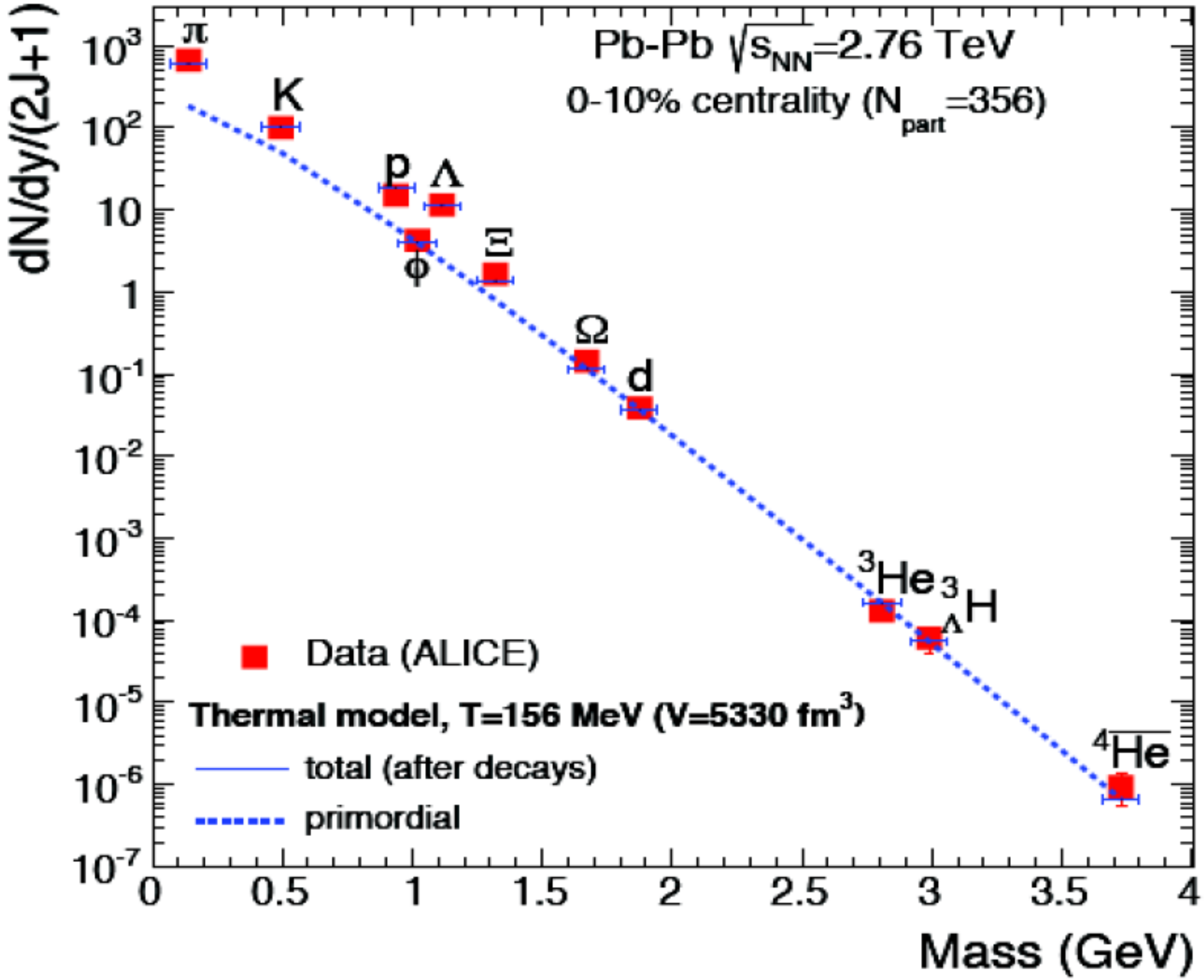
prefers 164 MeV

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 ?

Is the entropy/baryon indeed fixed at freeze-out and the yields need to reflect the chemical yields even if the particle dissolves in the dense hadronic phase ?

Thermal model for light nuclei ‘works’ remarkably well



How can loosely bound objects ‘survive’ the fireball heat bath ?

- PBM & Stachel et al.: The ‘snowball in hell’ approach. (J.Phys.G21(1995) L17 and PLB 697 (2011) 203)

- Λ separation energy in hypertriton is 130 keV, i.e. a factor 1000 less than the chemical freeze-out temperature of the fireball

- Successful description of composite objects with SHM implies no entropy production after chemical freeze-out

Cluster and loosely bound state production in relativistic nuclear collisions

- 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)

- Hypertriton: 130 KeV separation energy, deuteron-lambda structure, rms radius: 10.3 fm, extreme halo state

- 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 and entanglement

Groundbeaking paper (experimental):

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

Quantum thermalization through entanglement in isolated many-body system

Initial state evolution for relativistic particle collisions (pp, e^+e^-)

D. Kharzeev, E. Levin, arXiv:1702.03489

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

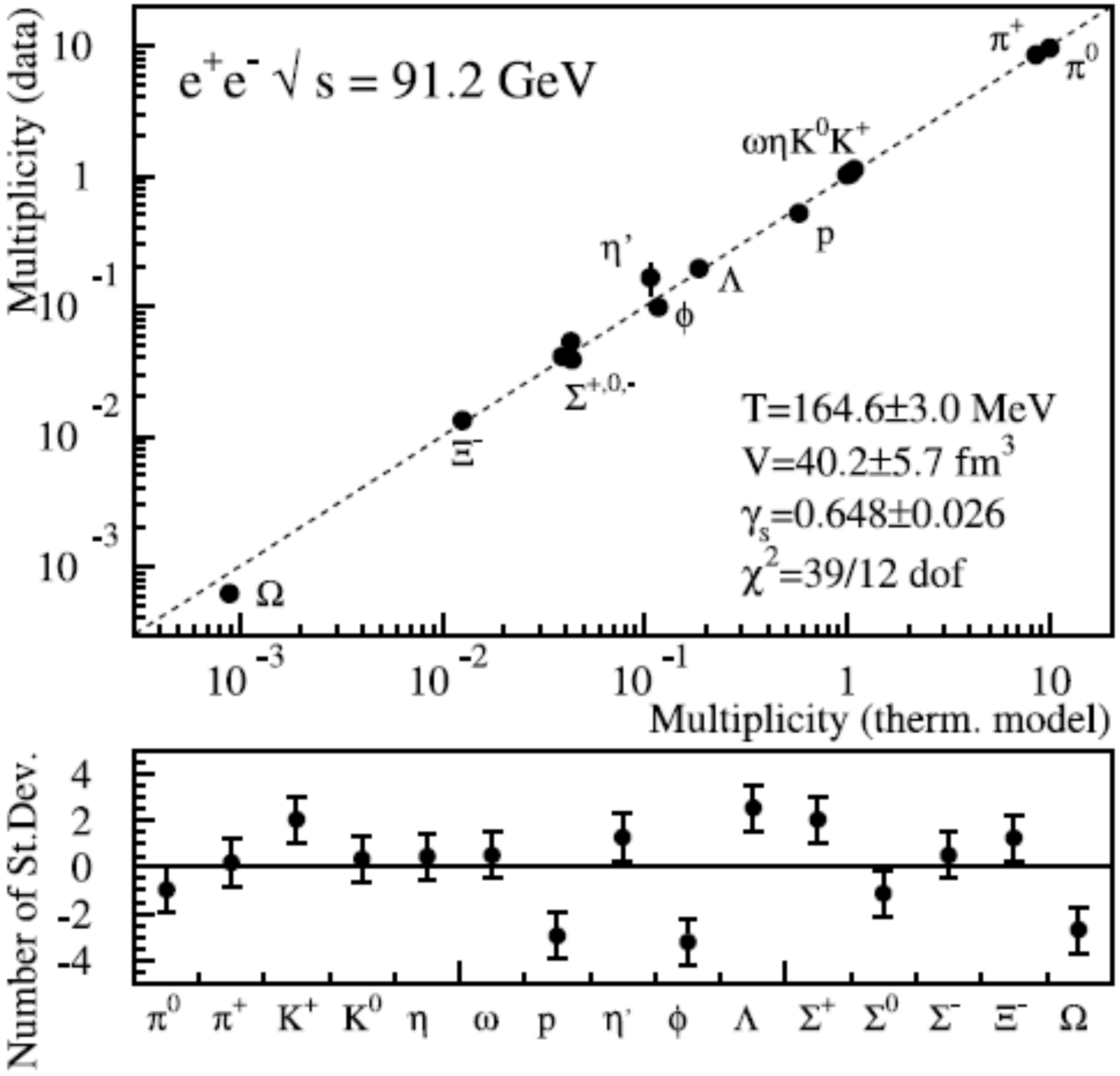
Thermal radiation and entanglement in proton-proton collisions at the LHC

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

Possible explanation for ‘thermal behavior’ in elementary relativistic collisions



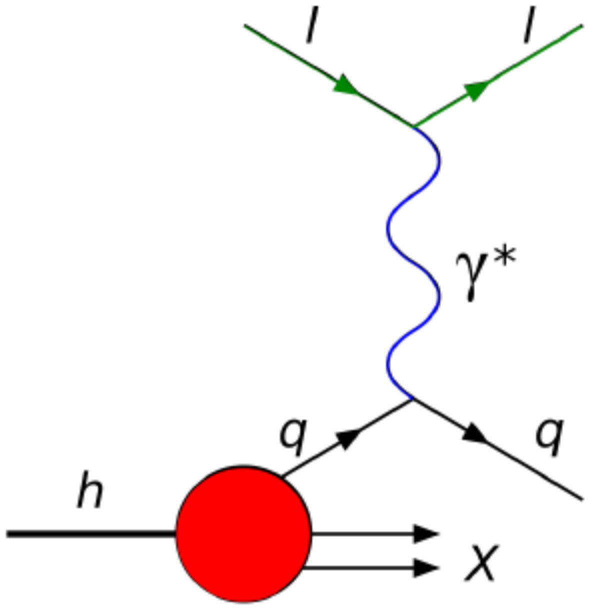
[Becattini, Casterina, Milov & Satz, EPJC 66, 377 (2010)]

Why entanglement ?

"...we never experiment with just one electron or atom or (small) molecule. In thought experiments, we sometimes assume that we do; this invariably entails ridiculous consequences ... ."

Erwin Schrödinger, 1952

The proton in the basic parton model



In parton model, the proton is pictured as a collection of point-like quasi-free partons that are frozen in the infinite momentum frame due to Lorentz dilation.

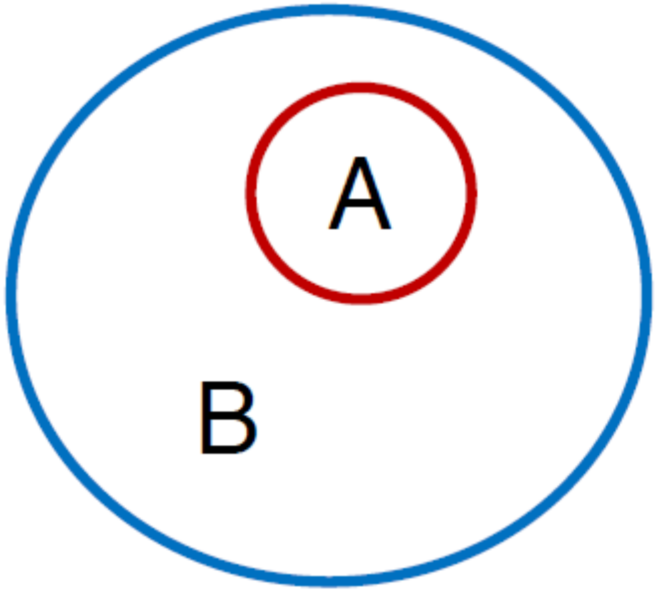
The DIS cross section is given by the incoherent sum of cross sections of scattering off individual partons.

How to reconcile this with quantum mechanics?

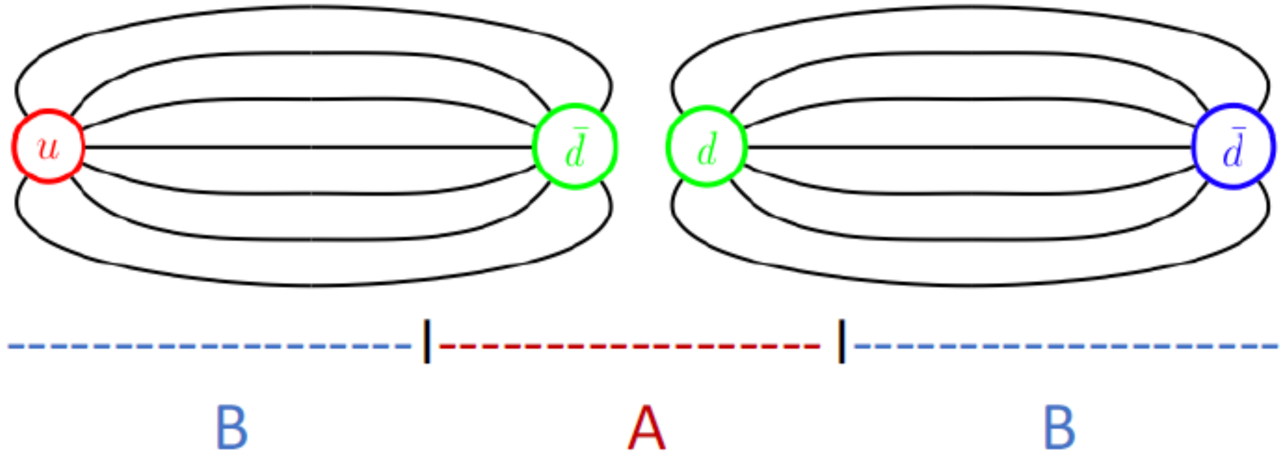
Quantum entanglement in transverse and longitudinal direction

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: $S_A = -\mathrm{tr}\left[\hat{\rho}_{\mathrm{A}} \ln \hat{\rho}_{\mathrm{A}}\right]$



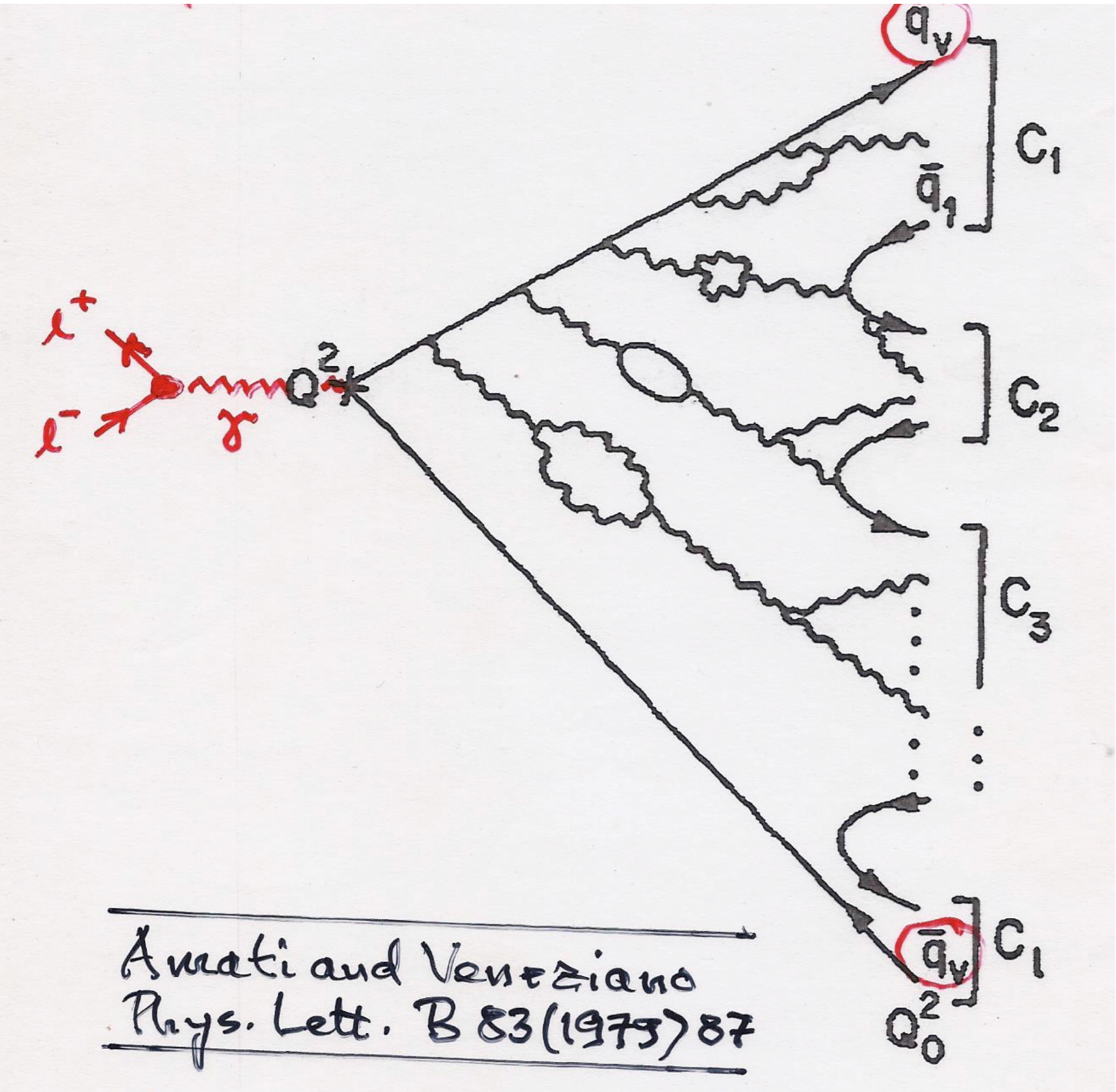
Longitudinal:
Particle production in QCD strings:



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

Conceptually similar to old hadronzation models (R.Stock, NeD2016, Phuket)



Amati and Veneziano
Phys. Lett. B 83(1979) 87

Veneziano-Webber model

QCD DGLAP

HERWIG Cluster

Parton Cascade (Ellis-Geiger)

But DGLAP has to be applied on the energy dependent gluon saturation scale to take into account the high production of ‘clusters’ from soft processes in the initial state (see. T. Lappi, arXiv:1104.3725)

Entanglement entropy from QCD evolution (slide from Dima Kharzeev)

The (3+1) case is cumbersome, but the result is the same, with $\Delta = \bar{\alpha}_s \ln(r^2 Q_s^2)$

What is the physics behind this relation?

$$S = \ln[xG(x)]$$

It signals that all $\exp(\Delta Y)$ partonic states have about equal probabilities $\exp(-\Delta Y)$ – in this case the **entanglement entropy is maximal**, and the proton is a **maximally entangled state** (a new look at the parton saturation and CGC?)

Can we get from initial state entanglement entropy to final state hadron entropy ?

If the Second Law applies to entanglement entropy (EE) (a number of indications, e.g. from black hole physics), then the entropy of hadronic final state in DIS has to be equal or larger than the EE of the initial state measured through the structure function:

$$S_{\rm hadrons} \geq S_{EE}(x)$$

Indications from holography that the entropy does not increase at strong coupling; this leads to

$S_{\rm hadrons} \simeq S_{EE}(x)$ **parton liberation** ?

Parton-hadron duality could lead to specific fluctuations of the final hadron multiplicity

What is the relation between the parton and hadron multiplicity distributions?

Let us assume they are the same ("EbyE parton-hadron duality"); then the hadron multiplicity distribution should be given by

$$P_n(Y) \;=\; e^{-\Delta Y}(1 - e^{-\Delta Y})^{n-1}.$$

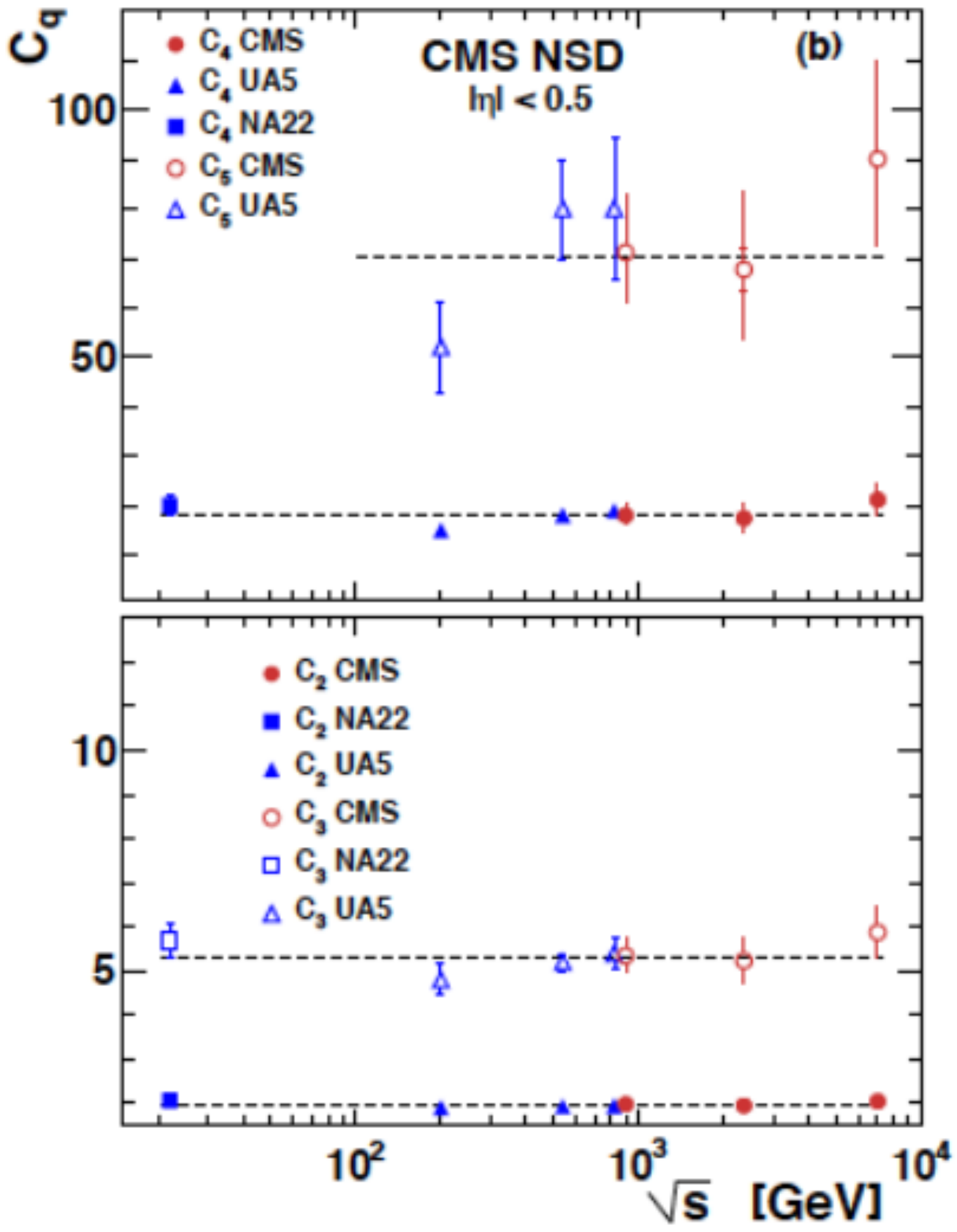
Consider moments

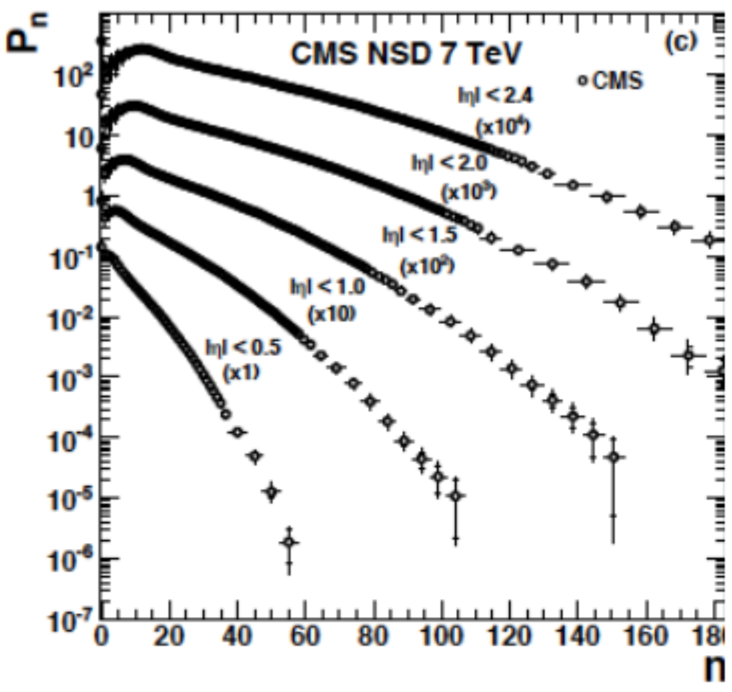
$$C_q = < n^q > / < n >^q$$

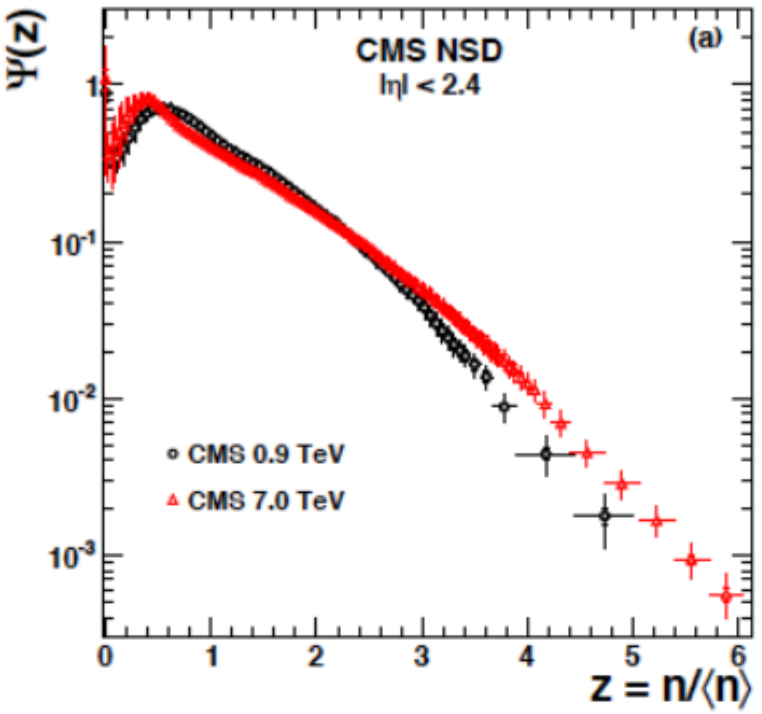
Test in pp at the LHC

CMS (arXiv:1011.5531)

KNO scaling violated







The moments can be easily computed by using the generating function

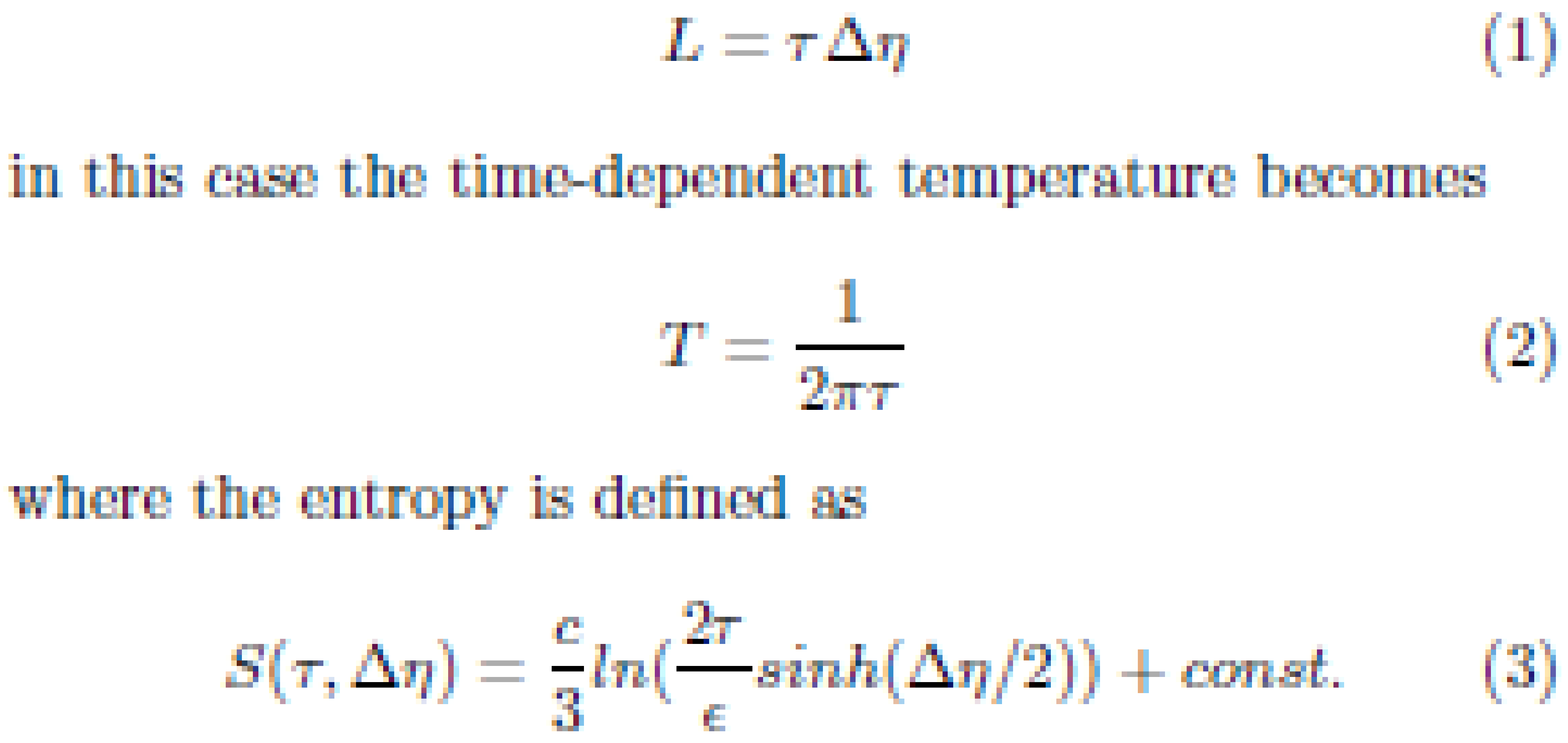
$$C_q = \left(u\frac{d}{du}\right)^q Z(Y,u)\Big|_{u=1}$$

theory	exp (CMS)	theory, high energy limit
$C_2 = 1.83$	$C_2 = 2.0\pm0.05$	$C_2 = 2.0$
$C_3 = 5.0$	$C_3 = 5.9\pm0.6$	$C_3 = 6.0$
$C_4 = 18.2$	$C_4 = 21\pm2$	$C_4 = 24.0$
$C_5 = 83$	$C_5 = 90\pm19$	$C_5 = 120$

It appears that the multiplicity distributions of final state hadrons are very similar to the parton multiplicity distributions – this suggests that the entropy is close to the entanglement entropy

Relationship between entanglement and temperature (see also S. Floerchinger (QM 2018))

- For conformal fields the relationship between entanglement entropy and temperature can be derived (Calabrese, Cardy (2004)):



$$L = \tau \Delta\eta \tag{1}$$

in this case the time-dependent temperature becomes

$$T = \frac{1}{2\pi\tau} \tag{2}$$

where the entropy is defined as

$$S(\tau, \Delta\eta) = \frac{c}{3} ln(\frac{2\tau}{\epsilon} sinh(\Delta\eta/2)) + const. \tag{3}$$

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.

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.

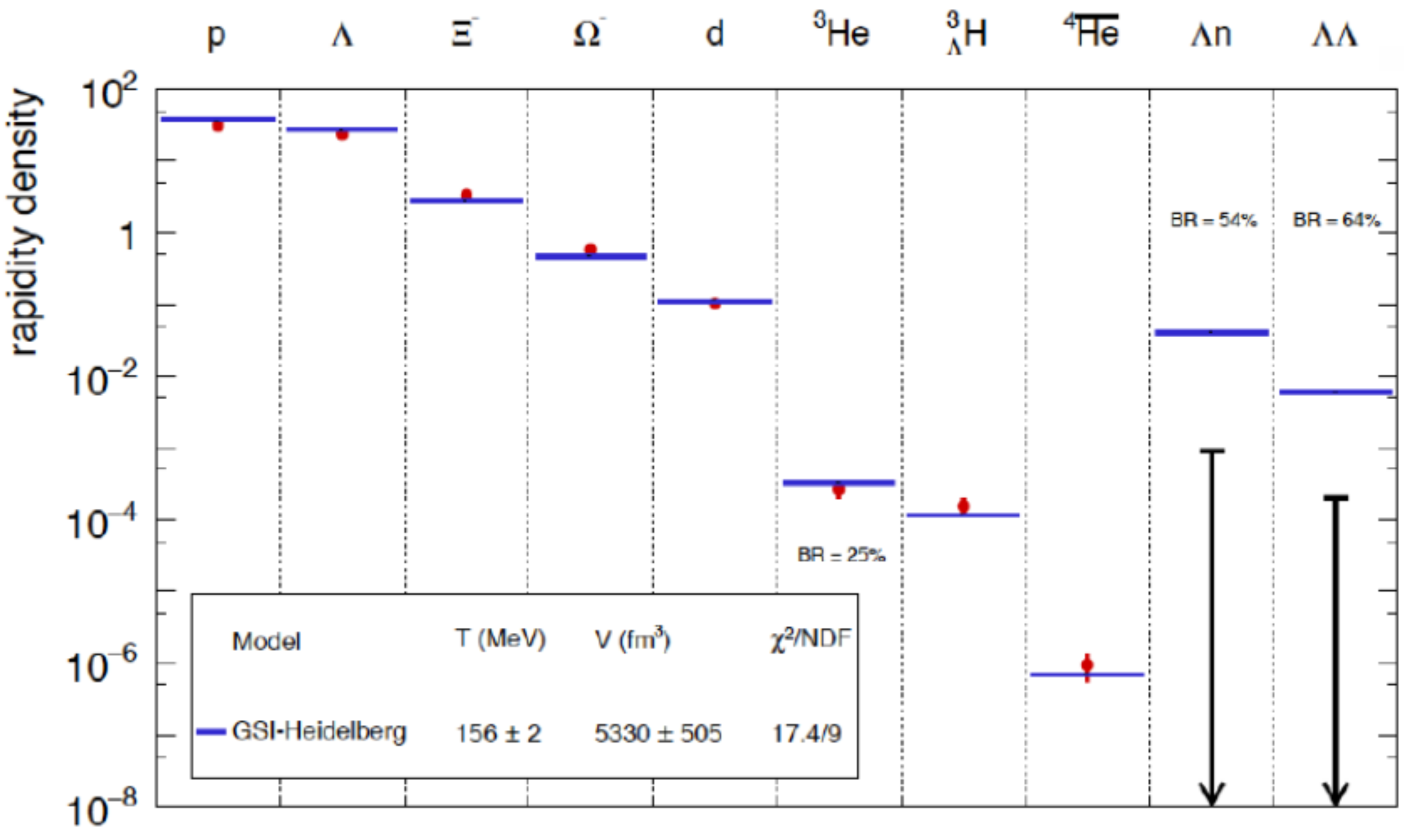
- The relationship between the entanglement entropy and the 'thermal' temperature needs to be quantitatively established.

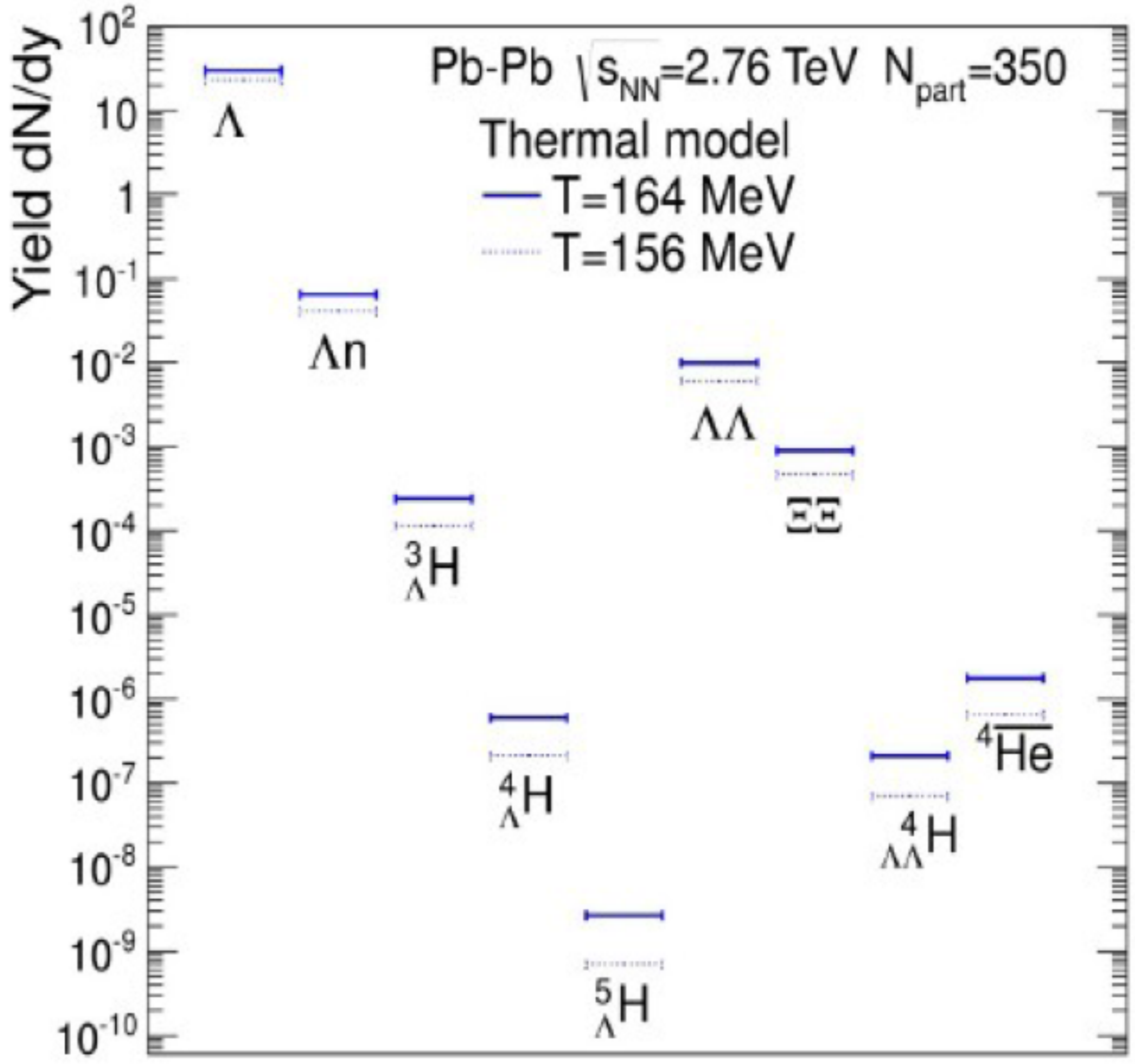
  (see e.g. Pajares et al., arXiv:1805.12444)

Experimental conclusions and outlook

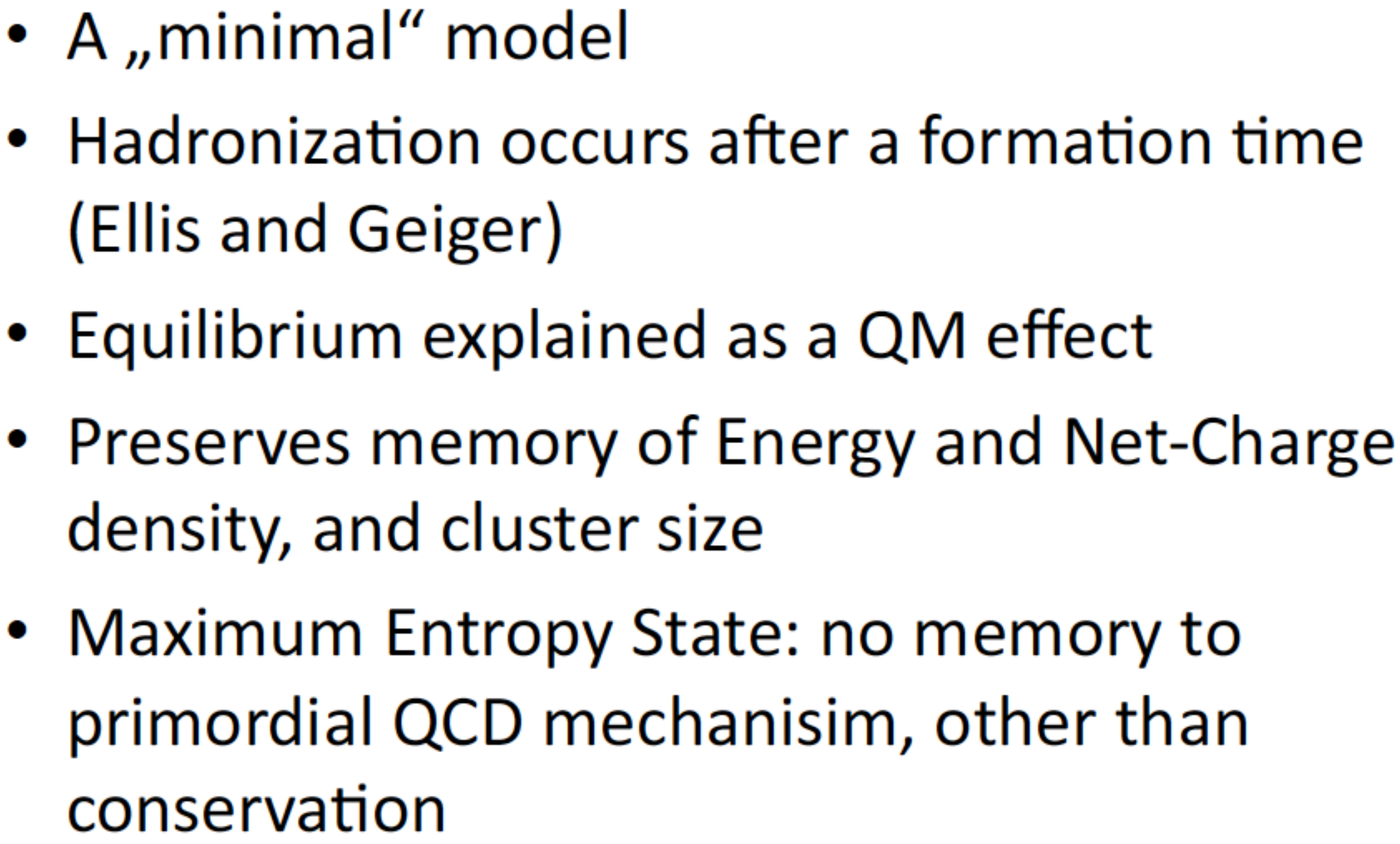
- Hadron multiplicity fluctuations in elementary collisions show already intriguing patterns that point at entanglement. Similar studies in heavy ion collisions are underway.

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





Reinhard’s conclusions from Phuket 2016= my conclusions from Trento 2018



- A „minimal“ model
- Hadronization occurs after a formation time (Ellis and Geiger)
- Equilibrium explained as a QM effect
- Preserves memory of Energy and Net-Charge density, and cluster size
- Maximum Entropy State: no memory to primordial QCD mechanisim, other than conservation