Composite particle production in relativistic particle collisions through quantum entanglement

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Outline

- Recent results on particle production at the LHC

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

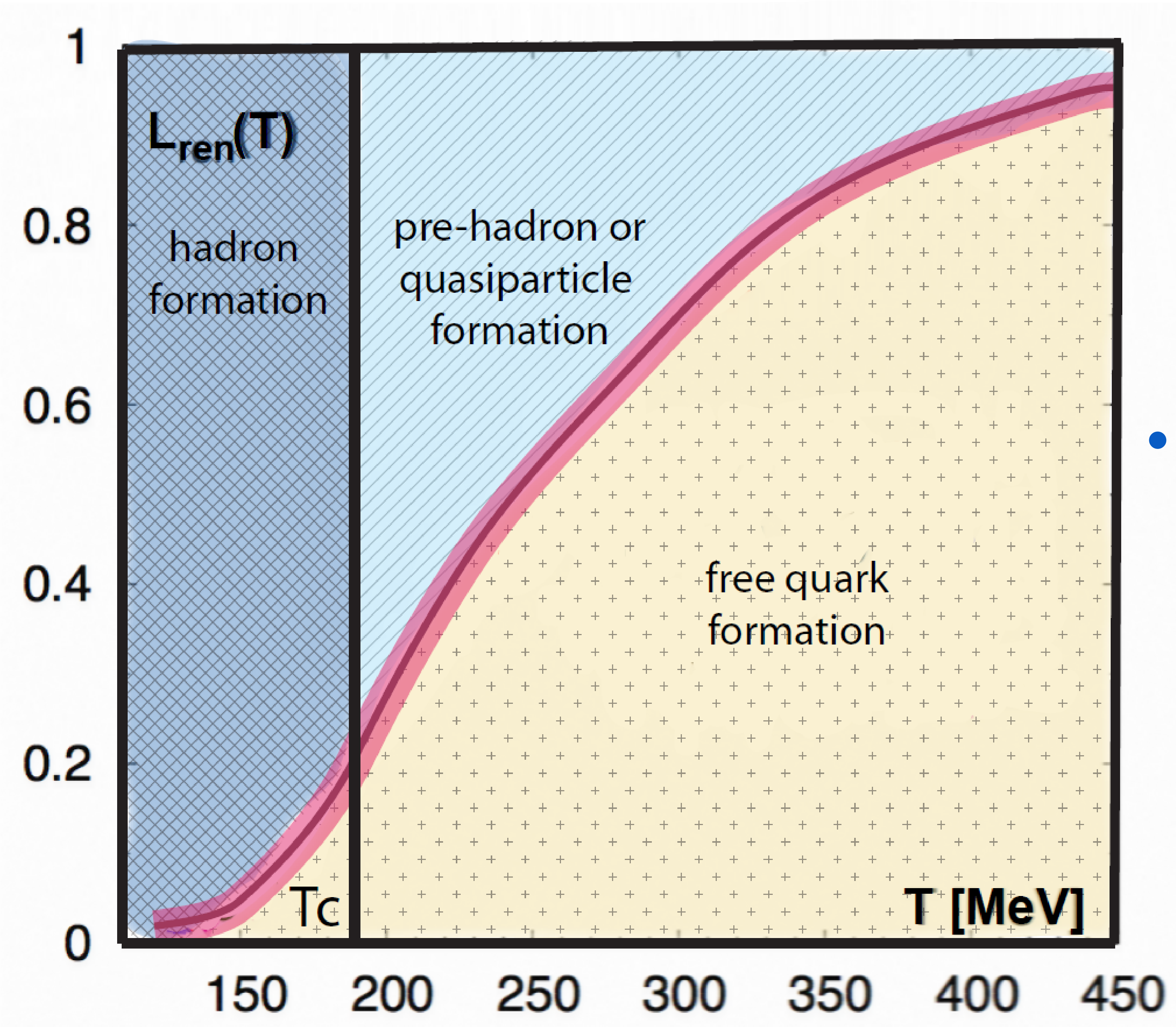
- Early ‘thermalization’ in elementary ststems through quantum entanglement

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

- Conclusions, outlook and experimental verification

Lattice order parameters in the QCD cross-over

e.g. a re-interpretation of the Polyakov Loop calculation in lattice QCD



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

- In a regime where we have a smooth crossover why would there be a single freeze-out surface ?
- In a regime where quark masses (even for the s-quark) could play a role why would there be single freeze-out surface ?
- We can calculate thermodynamic quantities for a static equilibrated system at a fixed temperature

Present Understanding: Equilibration at phase boundary

- Statistical model analysis of (u,d,s) hadron production: an important test of equilibration of quark matter near the phase boundary, **no equilibrium → no QGP matter**

- No (strangeness) equilibration in hadronic phase

- Present understanding: multi-hadron collisions near phase boundary bring hadrons close to equilibrium – supported by success of statistical model analysis

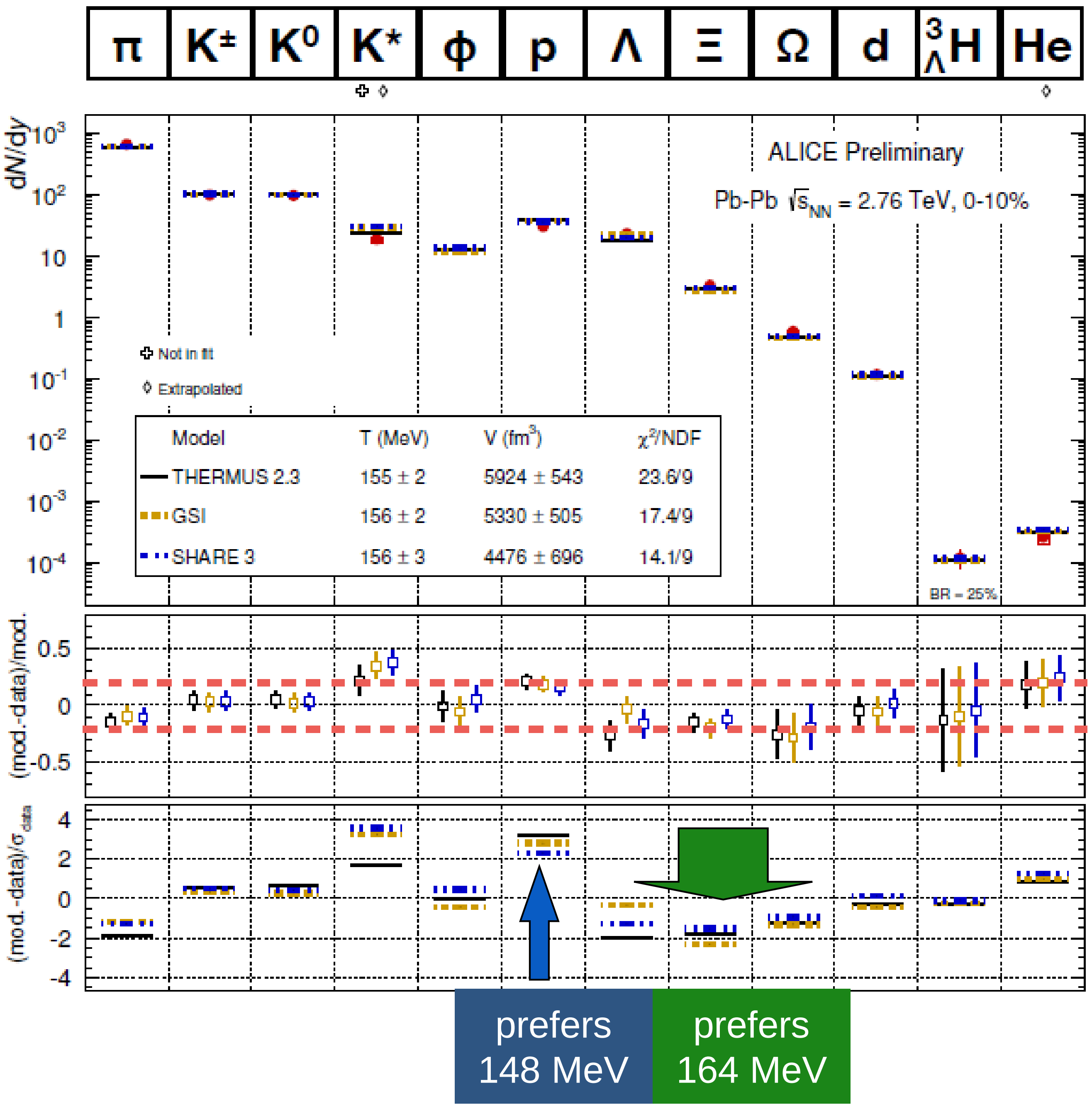
- This implies little energy dependence above RHIC energy

- Analysis of hadron production → determination of T_c

pbm, Stachel, Wetterich,
Phys.Lett. B596 (2004) 61-69

At what energy is phase boundary reached?

SHM model comparison based on yields



This looks like a good fit, but it is not

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

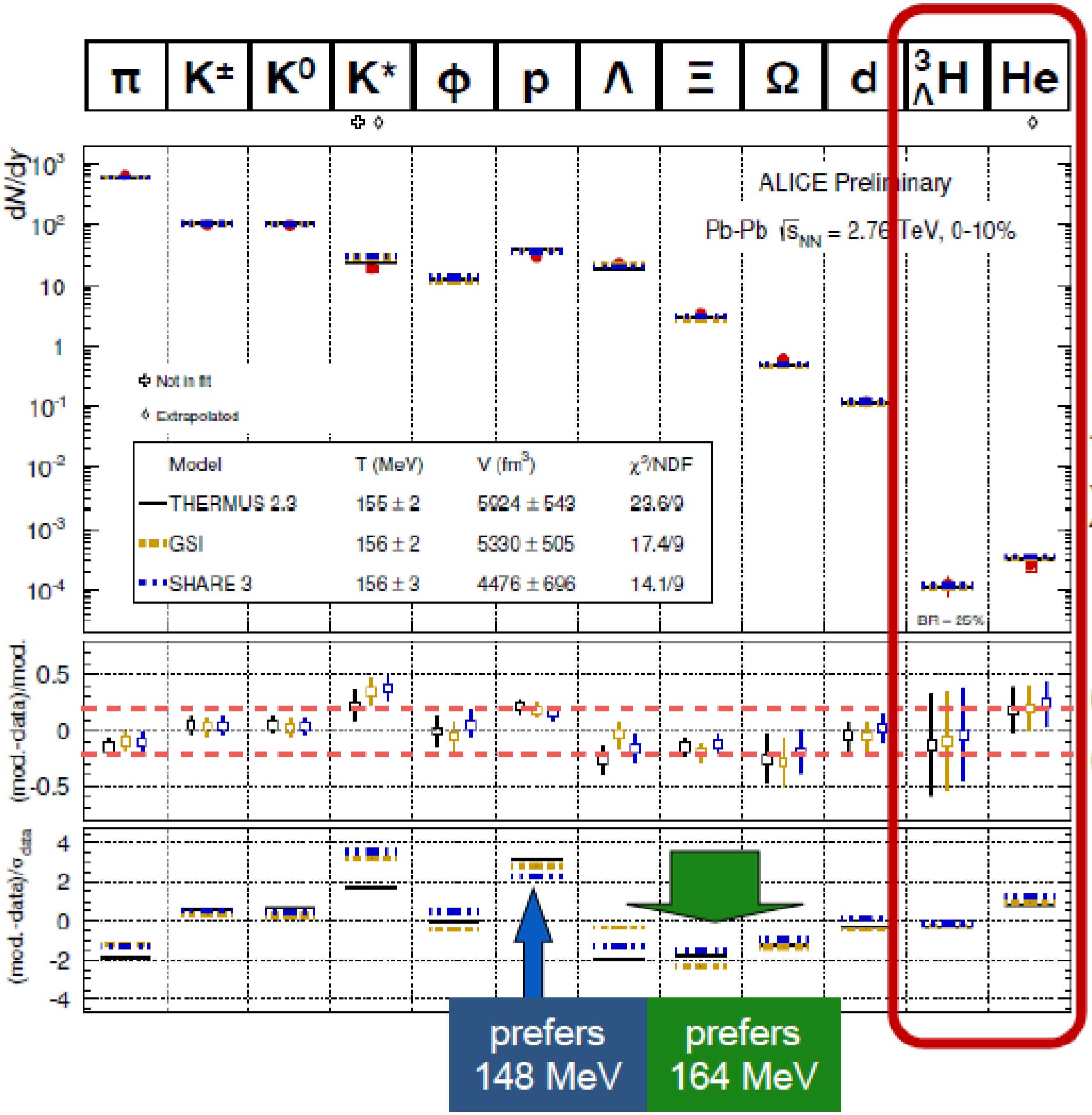
Fit to pions and protons alone yield a temperature of 148 MeV.

<u>Several alternate explanations:</u>

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

Is a common freeze-out surface that important ? Is it supported by lattice QCD ?

Hypernuclei are not enhanced relative to thermal model predictions



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 ?

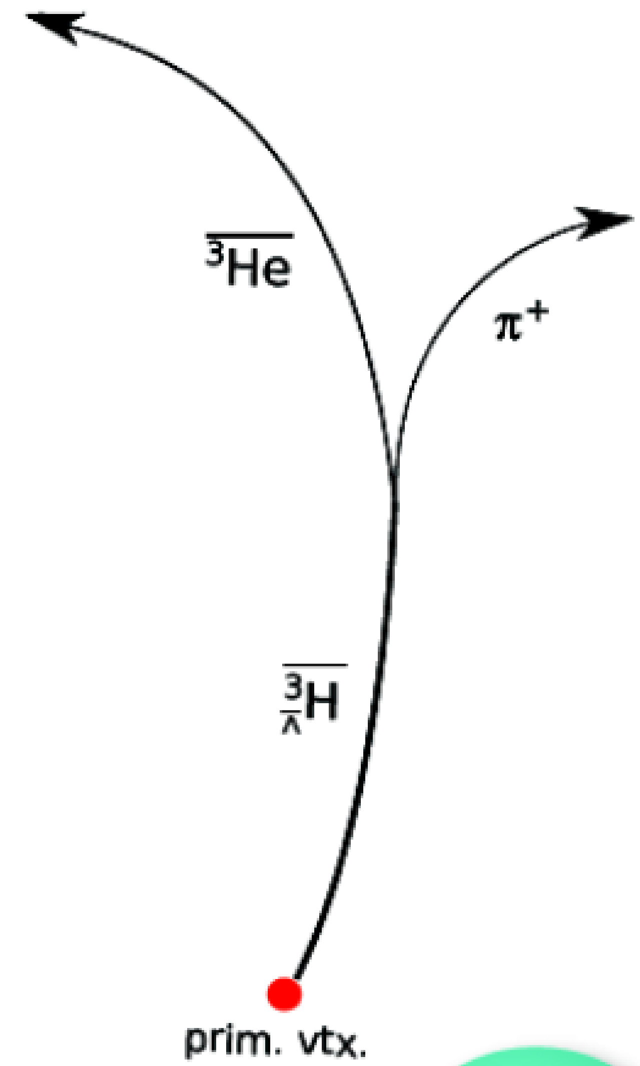
Hypertriton Identification

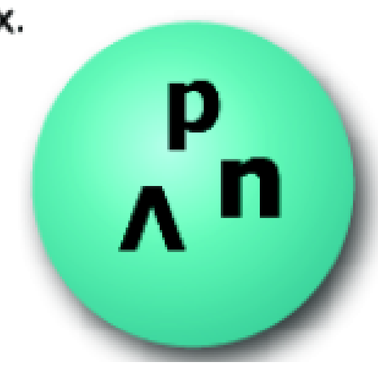
Identification of light nuclei
which are daughter tracks
originating from decay vertices

Lifetime similar to lifetime of free Λ

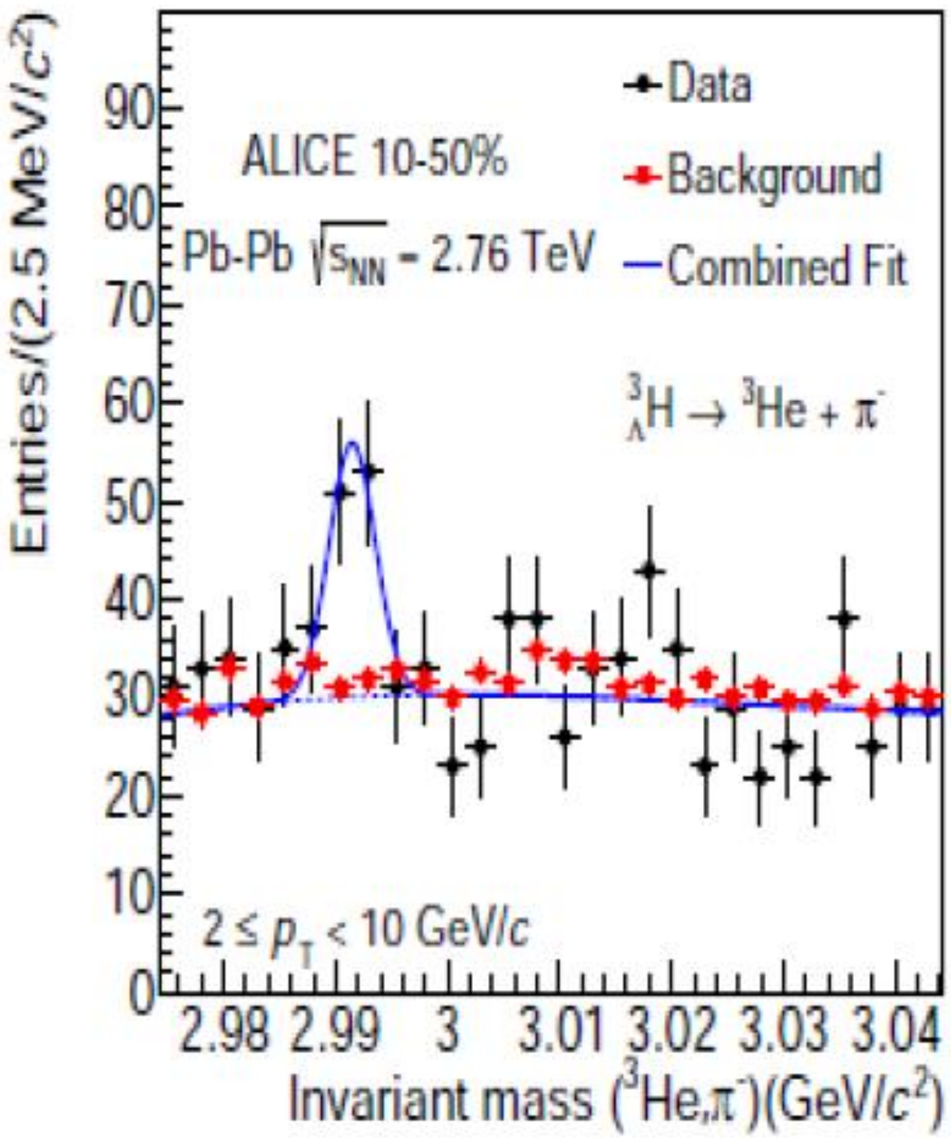
m(Hypertriton) = 2.991 ± 0.002 GeV/c^2

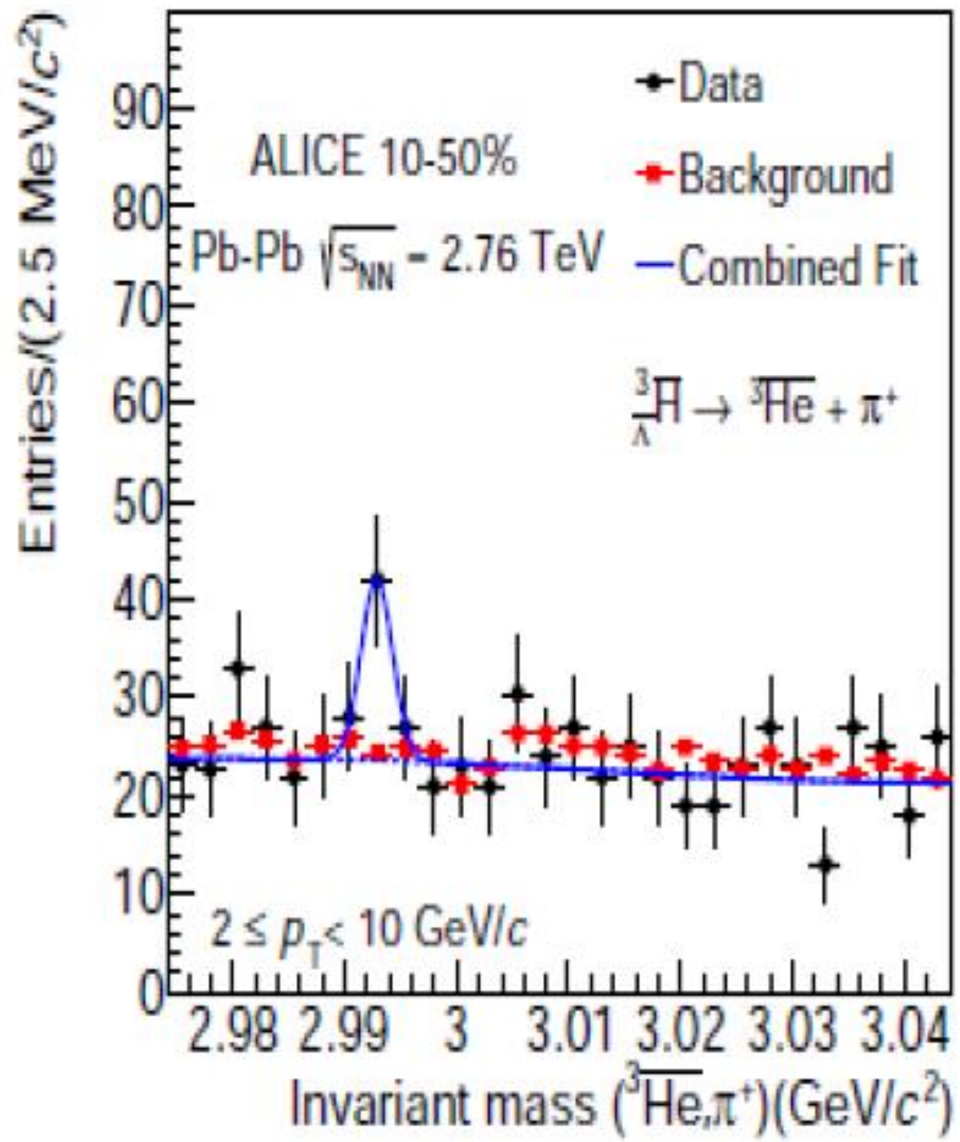
investigated decay channel:
Hypertriton → $^3He + \pi^-$





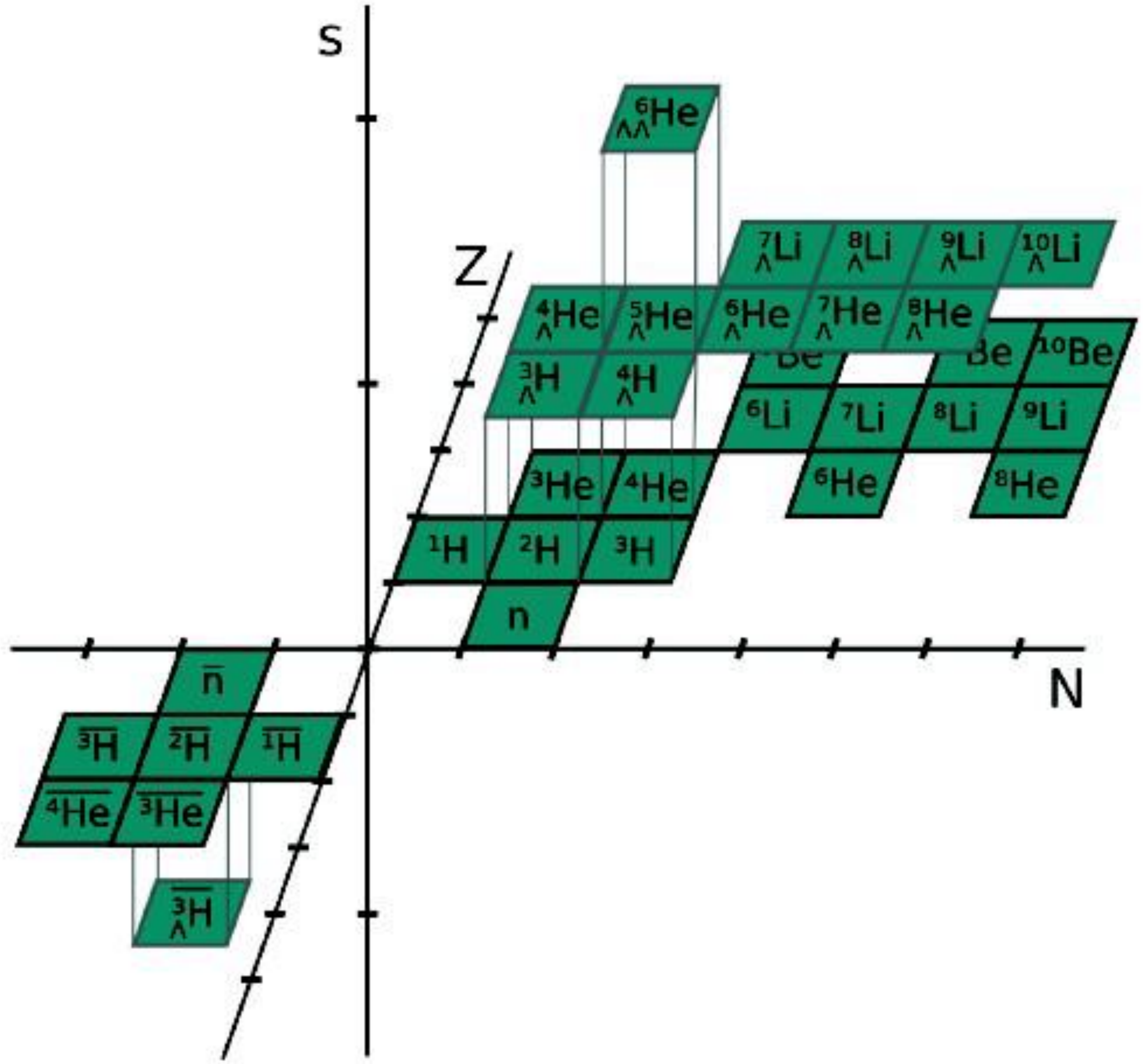
Hypertriton results



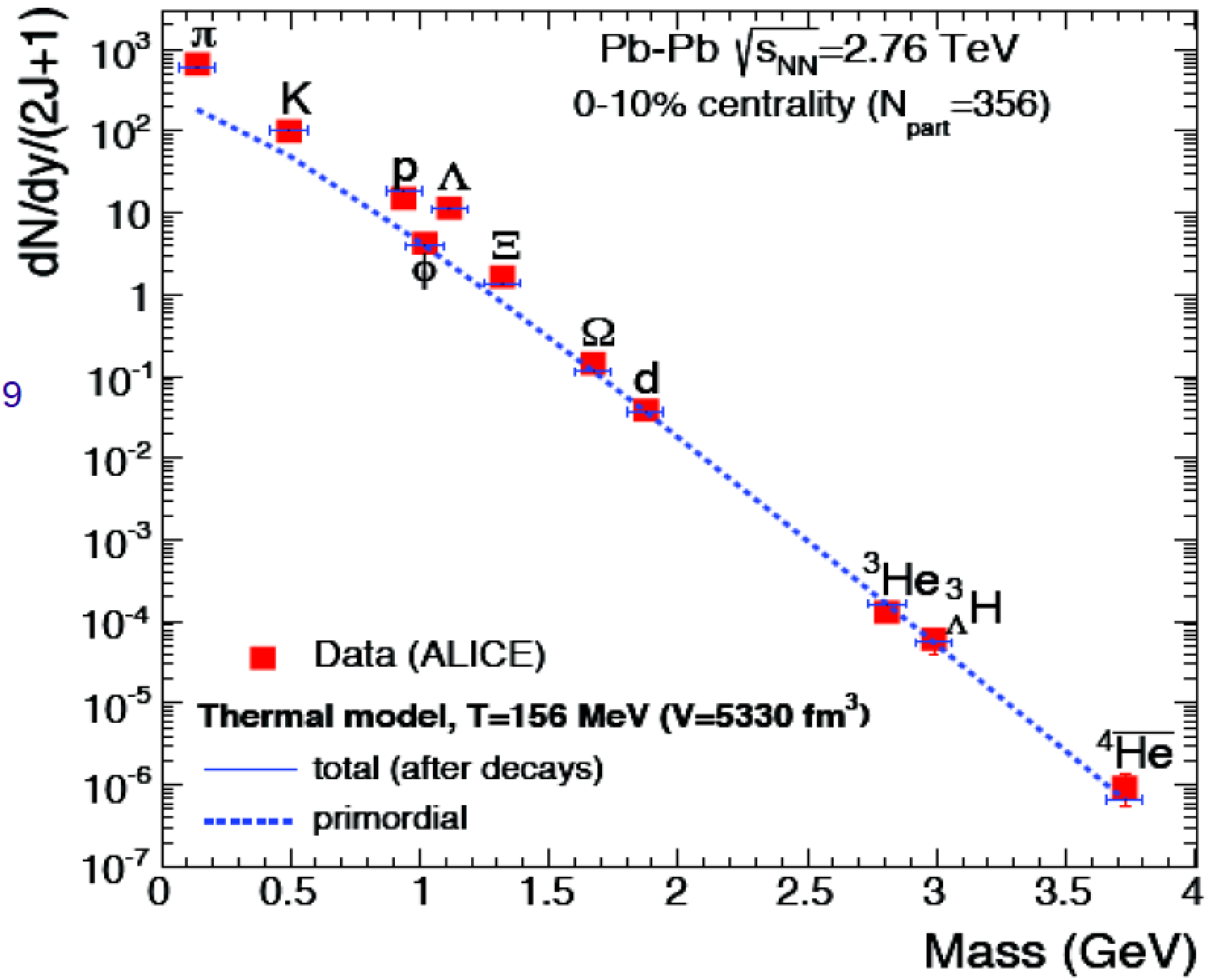


ALICE, arXiv:1506.08453, PLB 754 (2016) 360
ALICE, arXiv:1508.03986, Nature Physics 11 (2015) 811

Generalized Nuclear Chart



Thermal model for light quark particles ‘works’ remarkably well



agreement over 9 orders of magnitude with QCD statistical operator prediction

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
- Successful description of composite objects implies no entropy production after chemical freeze-out
- Λ separation energy in hypertriton is 130 keV, i.e. a factor 1000 less than the chemical freeze-out temperature of the fireball

Cluster and loosely bound state production in relativistic nuclear collisions

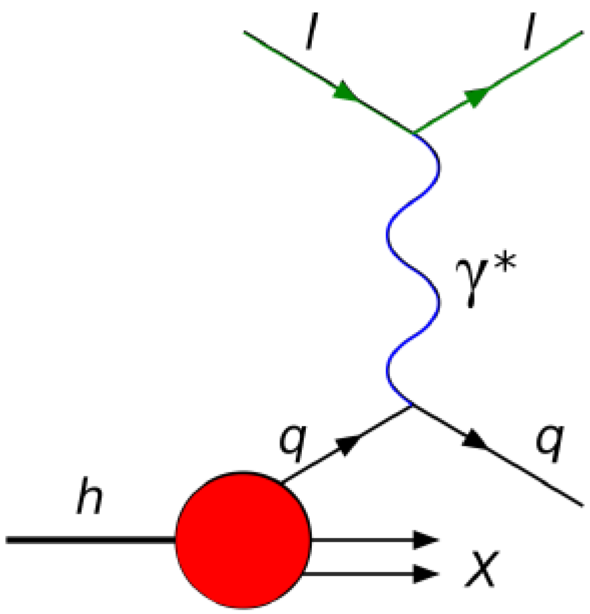
- Artoisenet & Braaten: The size of loosely bound objects (constituents are often separated by more than the range, e.g. deuteron (2.2 MeV BE, 3.1 fm rms separation))

- 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 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?

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 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

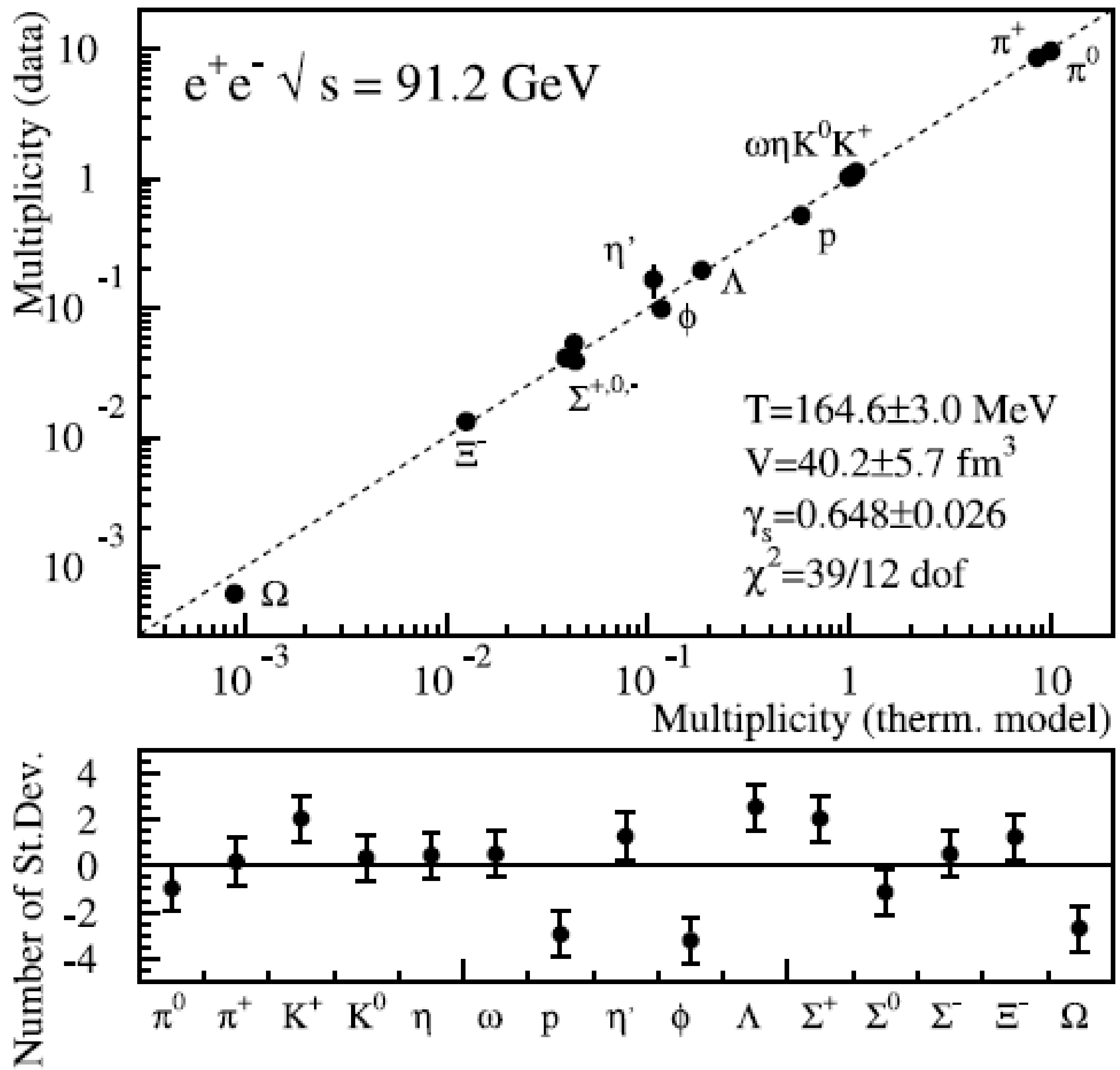
Thermal radiation and entanglement in proton-proton collisions at the LHC

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

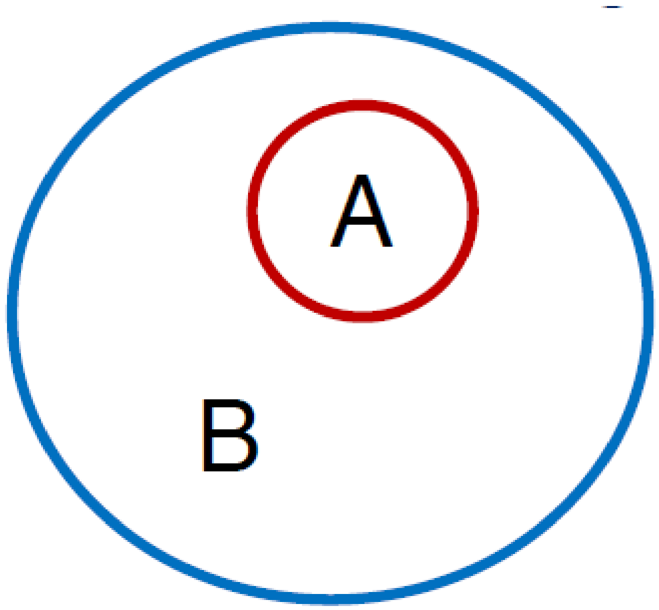


[Becattini, Casterina, Milov & Satz, EPJC 66, 377 (2010)]

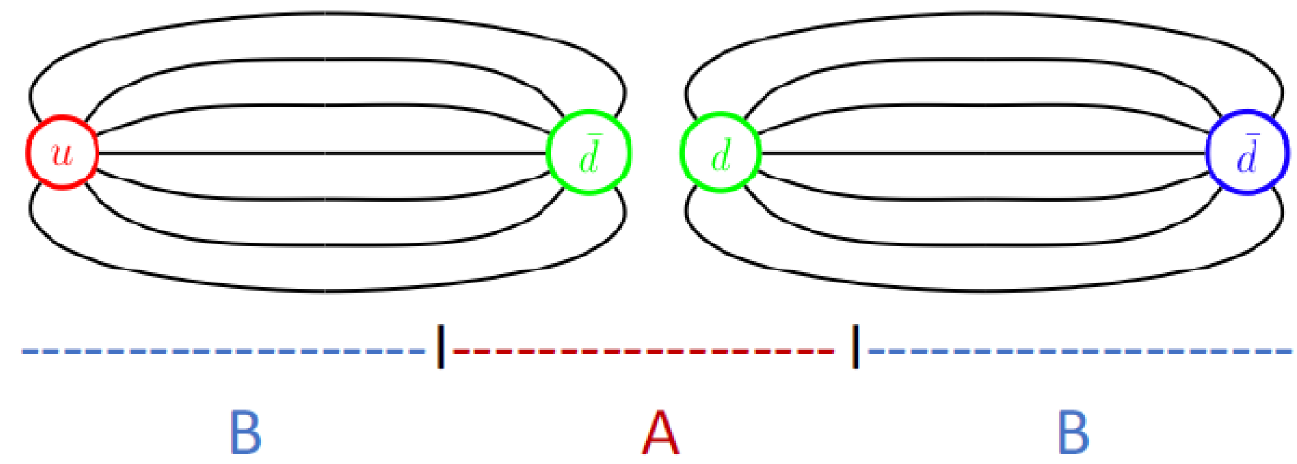
The Quantum Mechanics of partons and entanglement

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



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 ?

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:

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

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

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

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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

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

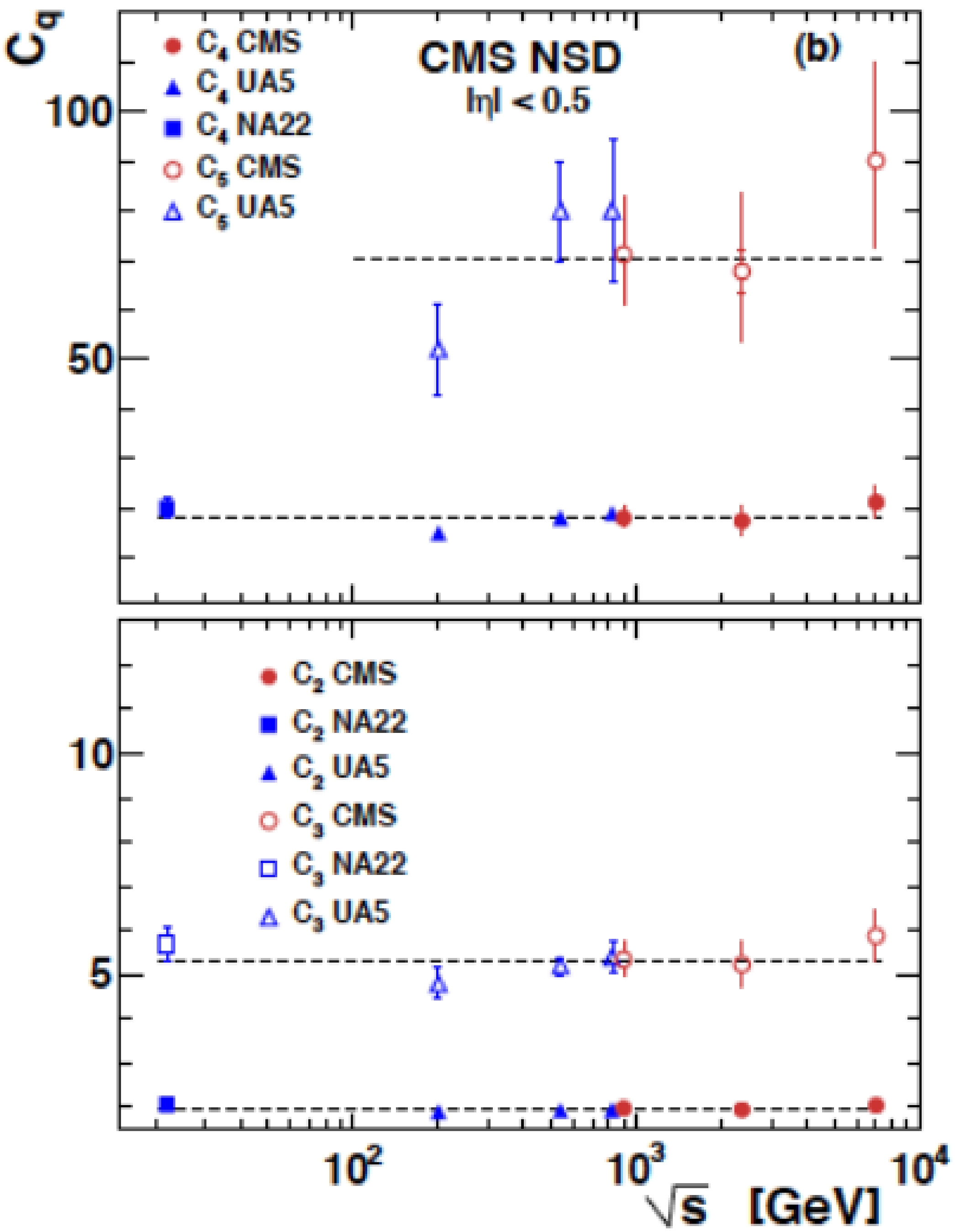
Consider moments

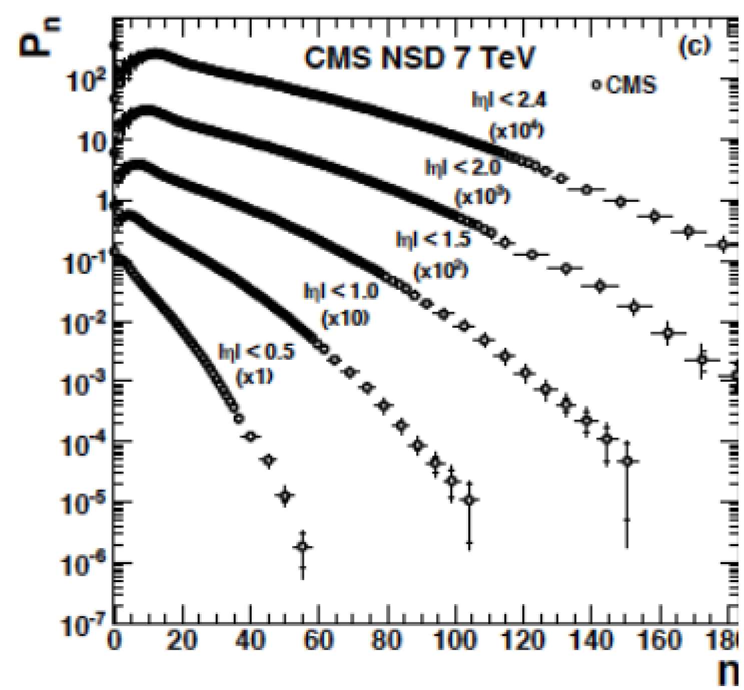
$$C_q = < n^q > / < n >^q$$

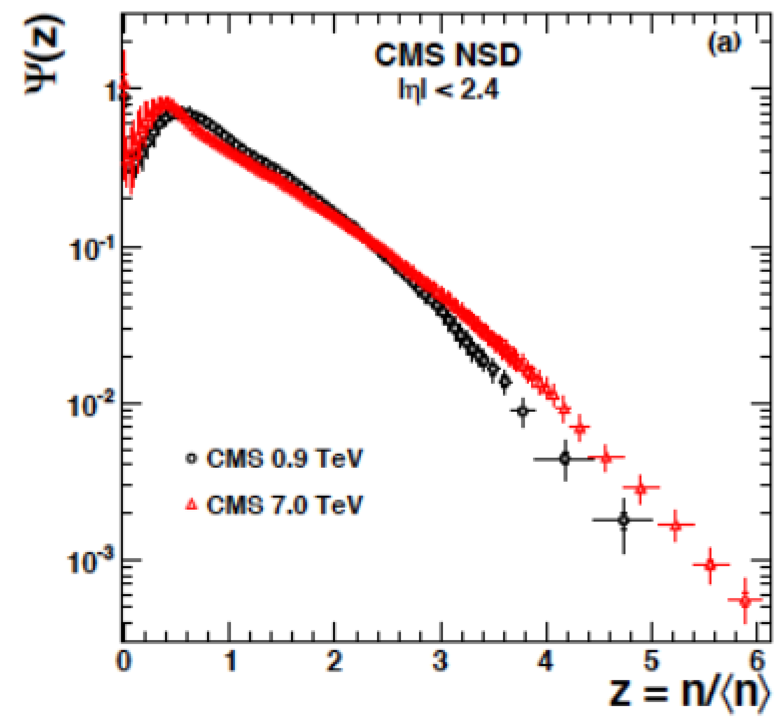
Test in pp at the LHC

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
$C_2 = 1.83$	$C_2 = 2.0 \pm 0.05$	$C_2 = 2.0$
$C_3 = 5.0$	$C_3 = 5.9 \pm 0.6$	$C_3 = 6.0$
$C_4 = 18.2$	$C_4 = 21 \pm 2$	$C_4 = 24.0$
$C_5 = 83$	$C_5 = 90 \pm 19$	$C_5 = 120$

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 (slide from S. Floerchinger)

- For conformal fields, entanglement entropy has also been calculated at non-zero temperature.
- For static interval of length l [Calabrese, Cardy (2004)]

$$S(T,l) = \frac{c}{3} \ln \left(\frac{1}{\pi T \epsilon} \sinh(\pi l T) \right) + \text{const}$$

- Compare this to our result in expanding geometry

$$S(\tau, \Delta\eta) = \frac{c}{3} \ln \left(\frac{2\tau}{\epsilon} \,\text{sinh}(\Delta\eta/2) \right) + \text{constant}$$

- Expressions agree for $l = \tau\Delta\eta$ (with metric $ds^2 = -d\tau^2 + \tau^2 d\eta^2$) and time-dependent temperature

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

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 hadroinc 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'.

Theoretical Conclusions and outlook

- Rapidity intervals in an expanding QCD string are entangled
- Entanglement entropy is extensive in rapidity
- The reduced density matrix for a conformal field theory is locally thermal. Entanglement generates thermalization
- Id entanglement entropy follows the 2nd law of thermodynamics then the initial entropy is reflected in the final entropy which is largely constant during strong coupling (parton-hadron duality).
- This should impact the hadron multiplicity fluctuations and the final yields of loosely bound objects.

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.