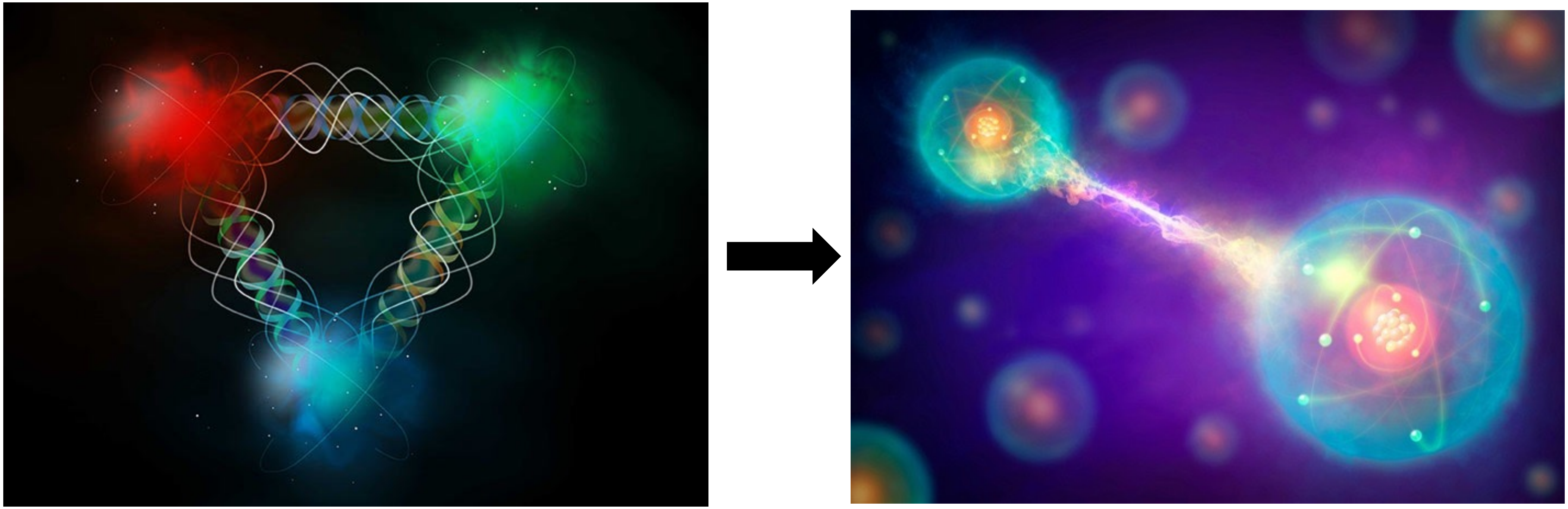
From initial gluon saturation to final state hadrons: quantum entanglement in particle collisions

R. Bellwied (University of Houston)



References: R. Bellwied (arXiv:1807.04589), Tu, Kharzeev, Ullrich (arXiv:1904.11974), and other papers by Kharzeev et al., Floerchinger et al. (arXiv:1702.03489, arXiv:1712.04558, arXiv:1707.05338, arXiv:1712.09362)

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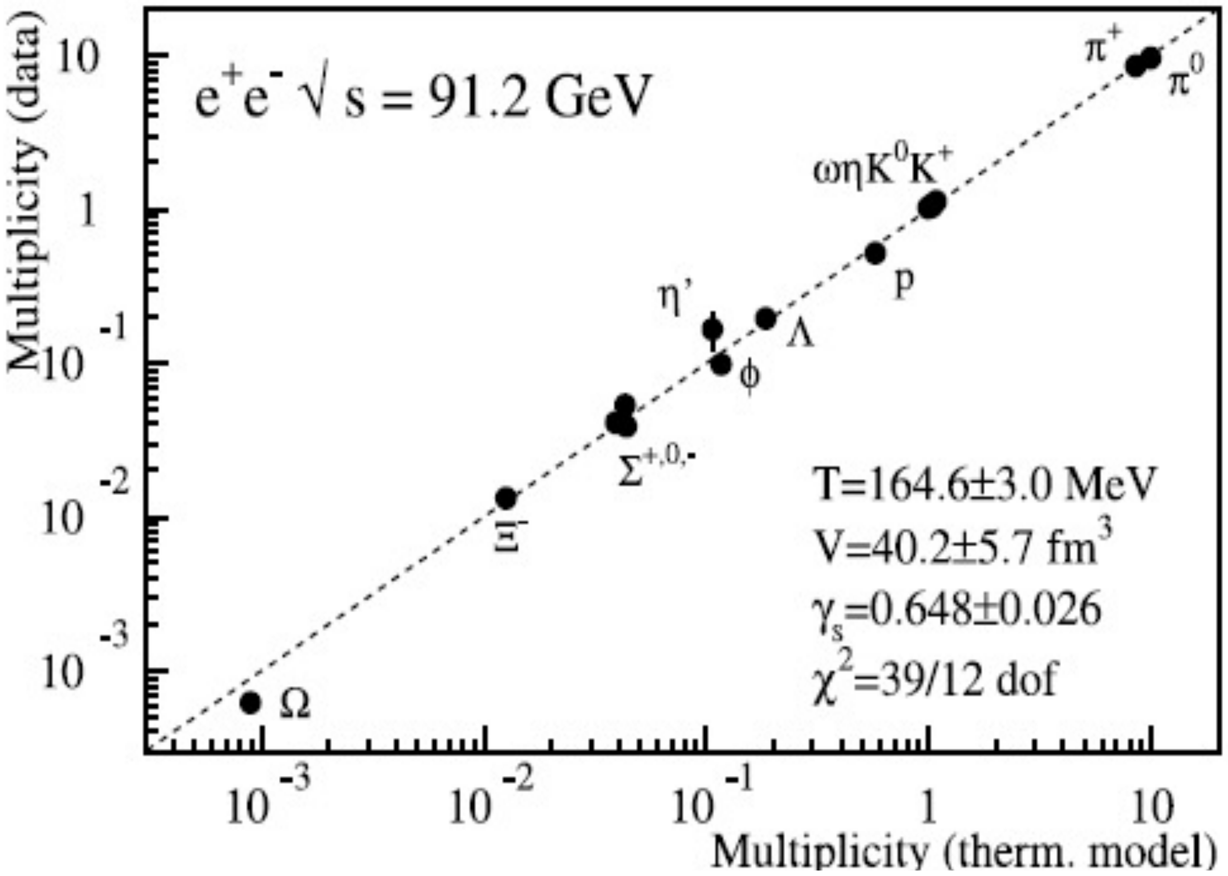
Three basic questions for relativistic particle collisions

- How can the partons thermalize fast enough that hydrodynamical and statistical hadronization models are applicable ?

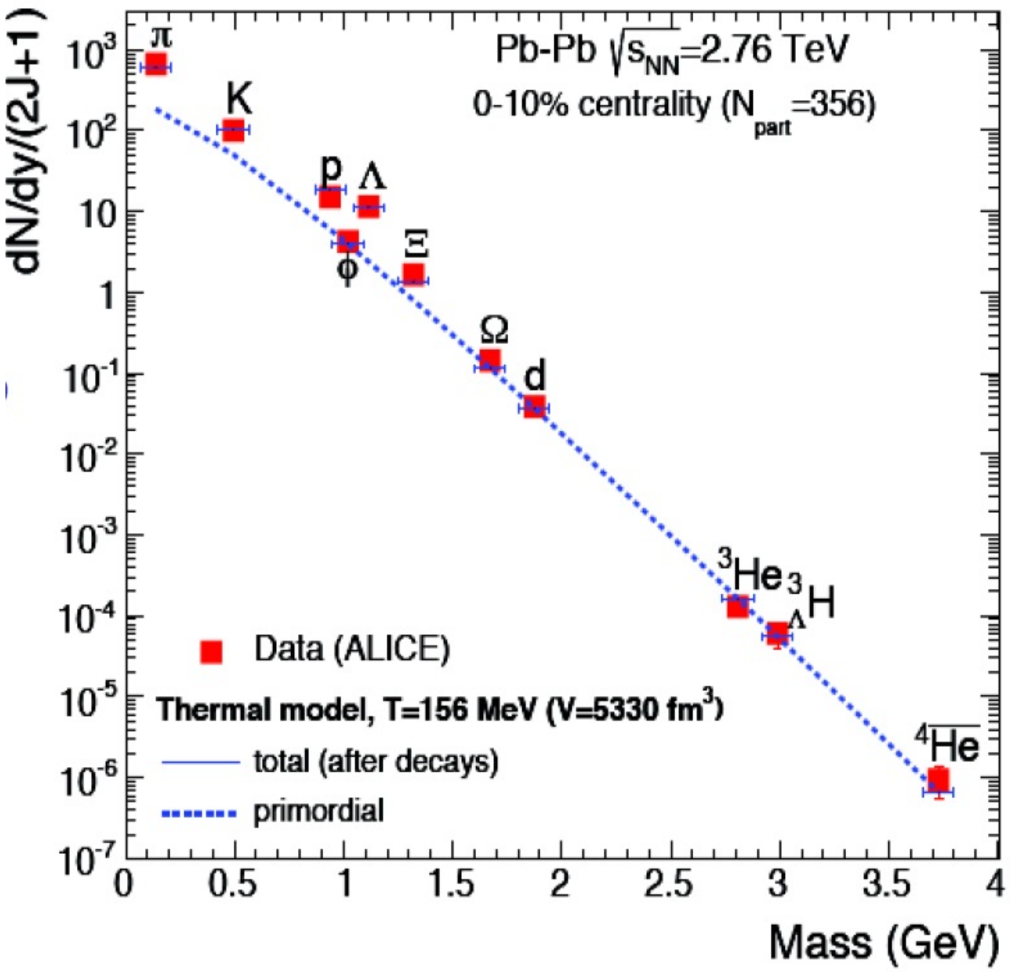
- How can the final state particles in elementary collisions be thermal ?

- How come that there seems to be a one to one relation between the initial parton density and the final state particle density (parton-hadron duality)

‘Thermal behavior’ in elementary relativistic collisions and in light nuclei production



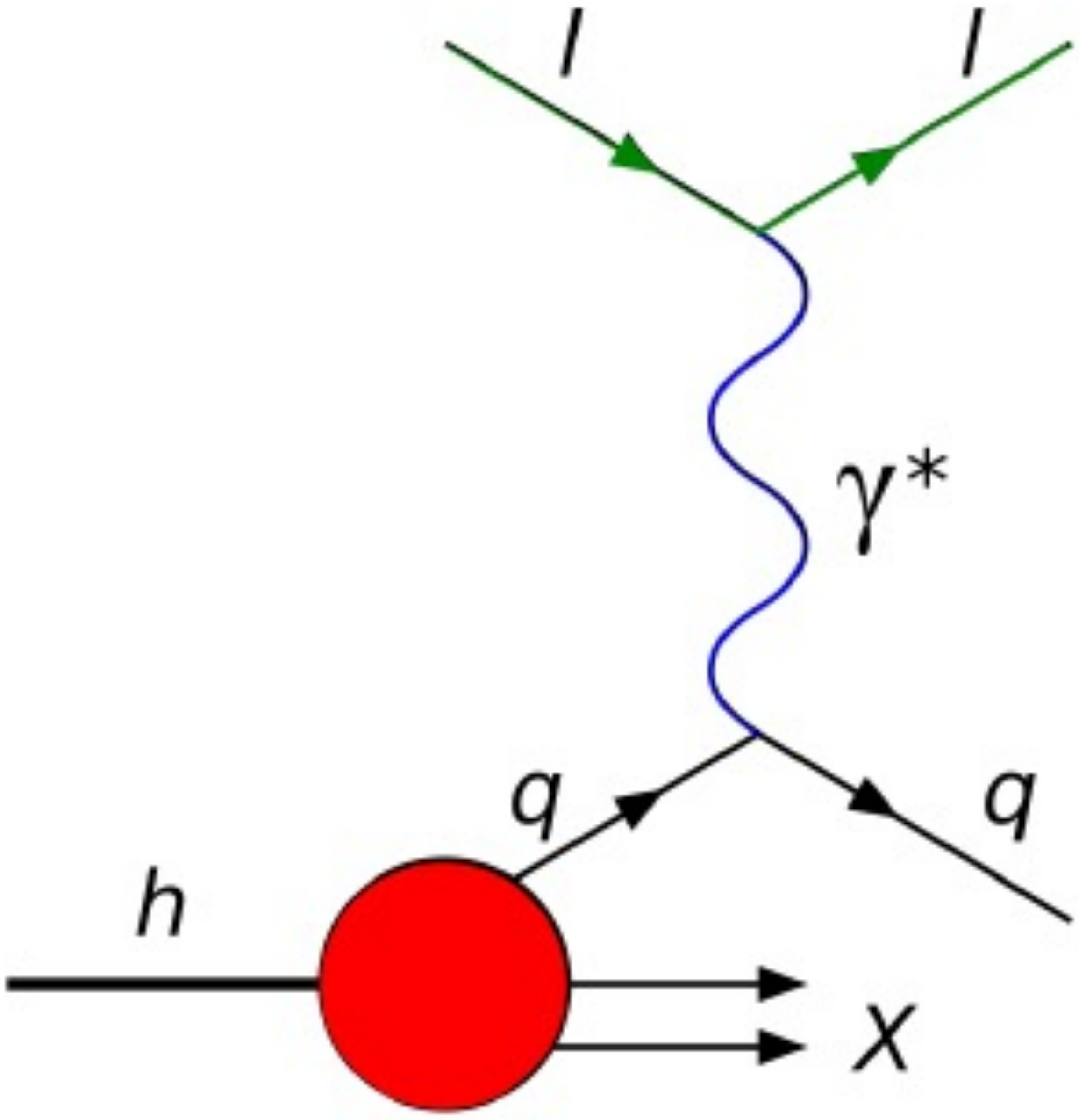
Becattini et al., EPJC 66, 377 (2010)



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

- 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 a statistical hadronization model implies no entropy production after chemical freeze-out

The proton in the basic parton model (PYTHIA etc.)



Any parton model describes the proton as a collection of point-like quasi-free partons frozen in the infinite momentum frame due to Lorentz dilation.

Cross-sections are given by the incoherent sum of cross sections of scattering off individual partons.

These models ignore quantum mechanics

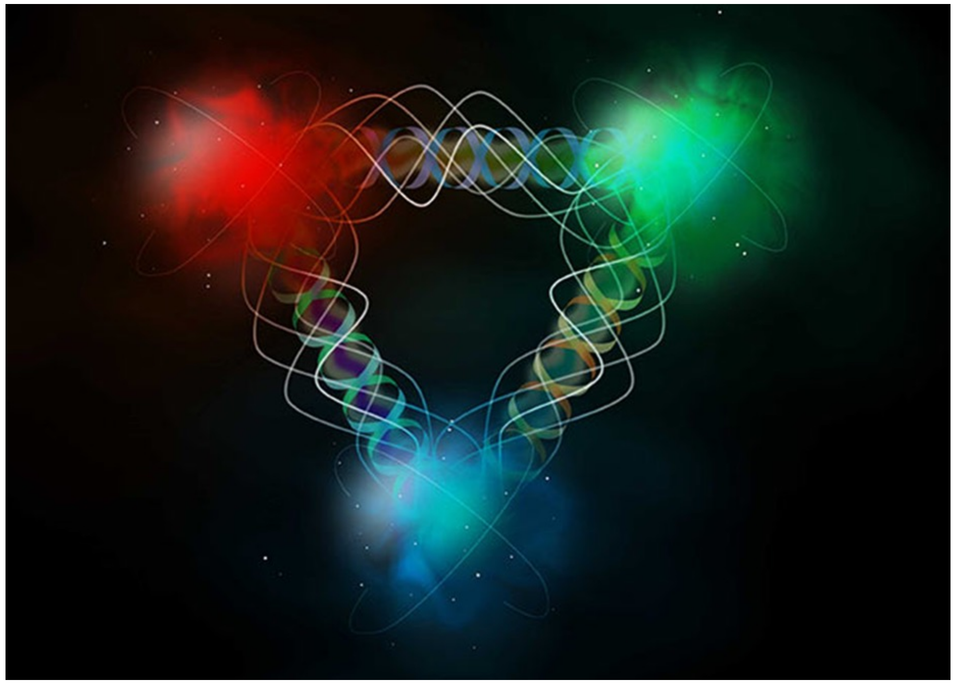
Sometimes 'patched' through DGLAP, cluster (HERWIG), parton cascade (PCM) implementations, but e.g. DGLAP has to be applied on the energy dependent gluon saturation scale to take into account the high production of 'clusters' from soft processes in the initial state (see. T. Lappi, arXiv:1104.3725)

Maybe our picture of independent parton-parton interactions in proton-proton collisions is wrong

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



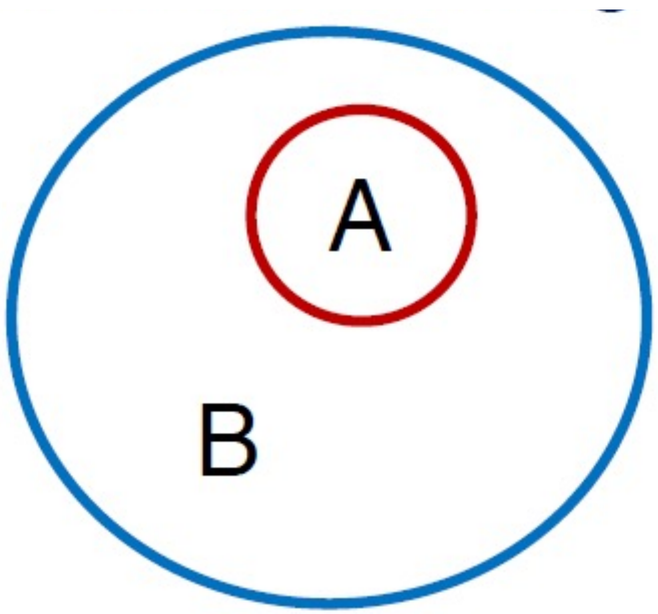
Idea: initial state is entangled transversely (proton confinement) and longitudinally (string formation). Can we measure remnants of coherence ? Are final state multiplicities due to initial state entanglement (all the way out to light nuclei) ?

Entanglement entropy = thermodynamic entropy ? (parton-hadron duality). Is the system not driven by thermalization but by initial coherence, which looks thermal ?

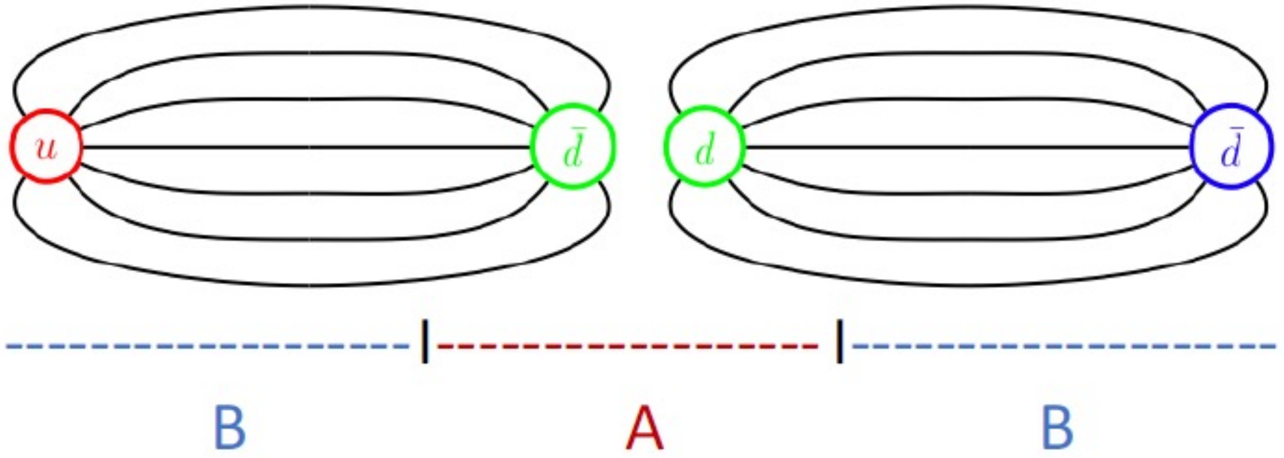
Quantum entanglement in transverse and longitudinal direction

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: $\hat{\rho}_A = \mathrm{tr}_B \hat{\rho}$

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



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

‘Thermalization’ through quantum entanglement ?

Groundbeaking paper (experimental) (published in Science):

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

Quantum thermalization through entanglement in isolated many-body system, but cold and small (quantum quench in BE condensate of ^{87}Rb atoms), effective T = 5-10 J, study impact on neighboring atoms

Even more groundbreaking paper (experimental) (published in Nature Comm):

J. Kong et al., May 2020

nature COMMUNICATIONS

ARTICLE

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Measurement-induced, spatially-extended entanglement in a hot, strongly-interacting atomic system

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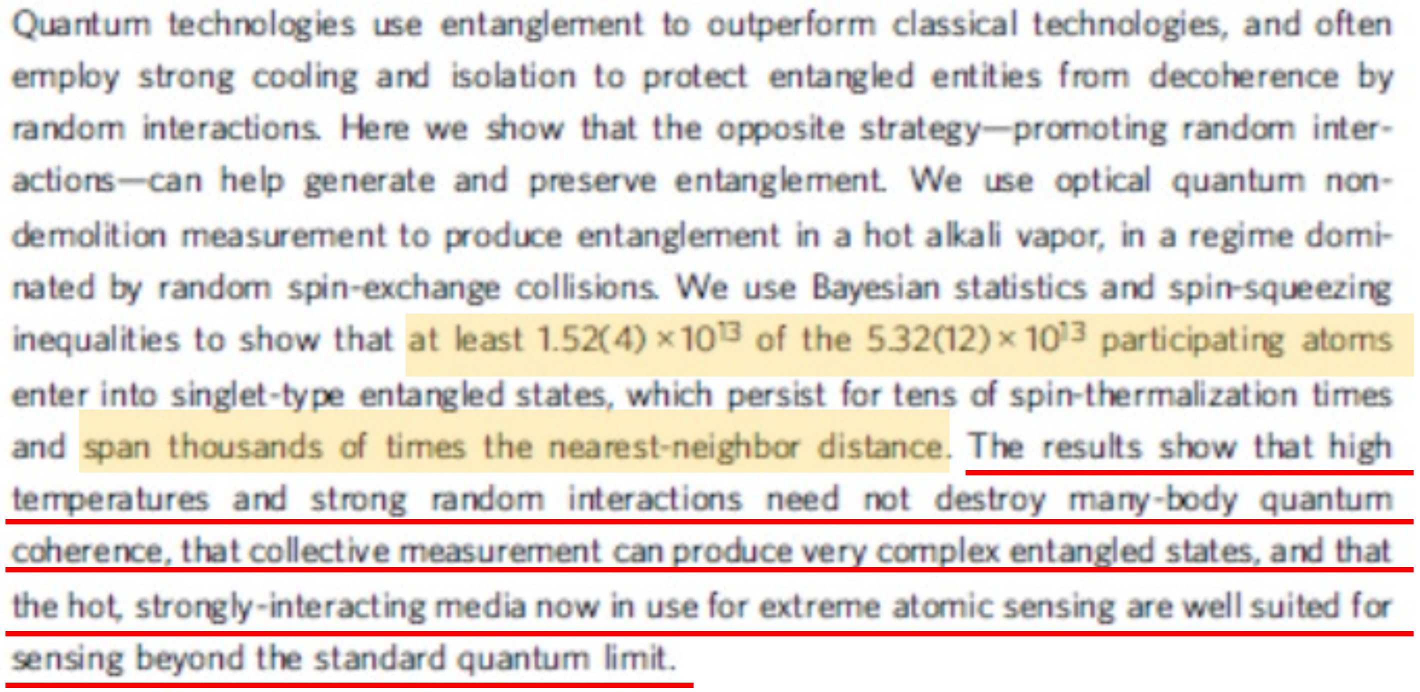


Quantum technologies use entanglement to outperform classical technologies, and often employ strong cooling and isolation to protect entangled entities from decoherence by random interactions. Here we show that the opposite strategy—promoting random interactions—can help generate and preserve entanglement. We use optical quantum non-demolition measurement to produce entanglement in a hot alkali vapor, in a regime dominated by random spin-exchange collisions. We use Bayesian statistics and spin-squeezing inequalities to show that at least $1.52(4) \times 10^{13}$ of the $5.32(12) \times 10^{13}$ participating atoms enter into singlet-type entangled states, which persist for tens of spin-thermalization times and span thousands of times the nearest-neighbor distance. The results show that high temperatures and strong random interactions need not destroy many-body quantum coherence, that collective measurement can produce very complex entangled states, and that the hot, strongly-interacting media now in use for extreme atomic sensing are well suited for sensing beyond the standard quantum limit.

Entanglement entropy from QCD evolution (D. Kharzeev et al.)

Basis: in an entangled proton the number of possible states is given by the parton distribution function which saturates at low x.

The entanglement entropy can then be calculated through the distribution functions. All partonic states have about equal probability, which means the entanglement entropy is maximal and the proton is a maximally entangled state.

$$S = \ln[xG(x)] = S_{initial} \propto ln(N_g)$$

If the second law of thermodynamics applies to entanglement entropy (see black hole physics) then the entropy of the hadronic final state reflects the entanglement entropy of the initial state deduced from the structure function (*parton-hadron duality*)

$$S_{\mathrm{hadrons}} \simeq S_{EE}(x)$$

Idea: Can we measure remnants of coherence ? Are final state multiplicities due to initial state entanglement (all the way out to light nuclei) ? Is the system not driven by thermalization but by initial coherence, which looks thermal ?

Measurements: particle multiplicities as a function of x, particle multiplicities at hadronization trace back to initial parton entanglement (distribution of complex quark states based on string fragmentation ?)

How to map parton entanglement to parton distribution functions and experiment (from 1904.11974)

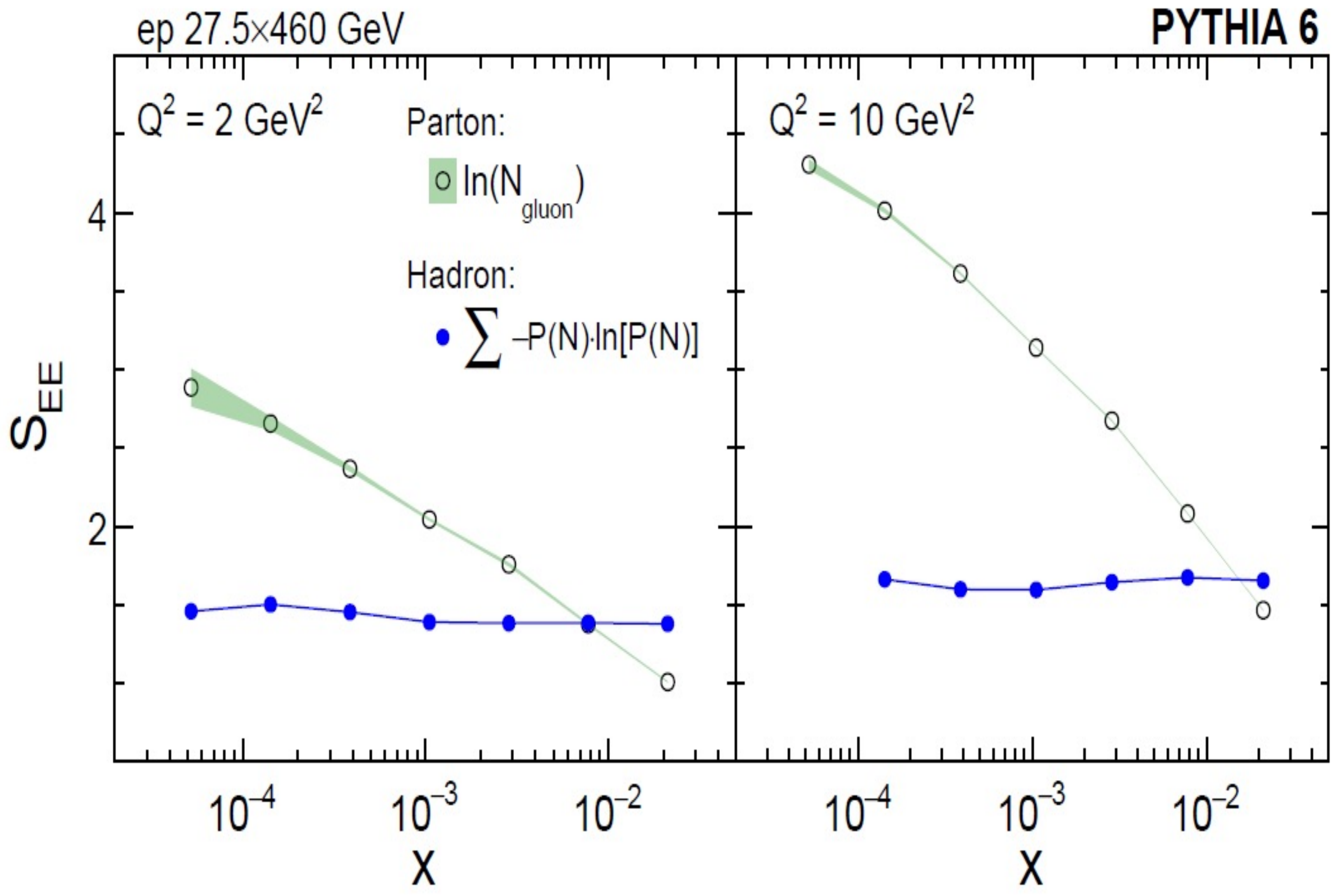
Model Calculations

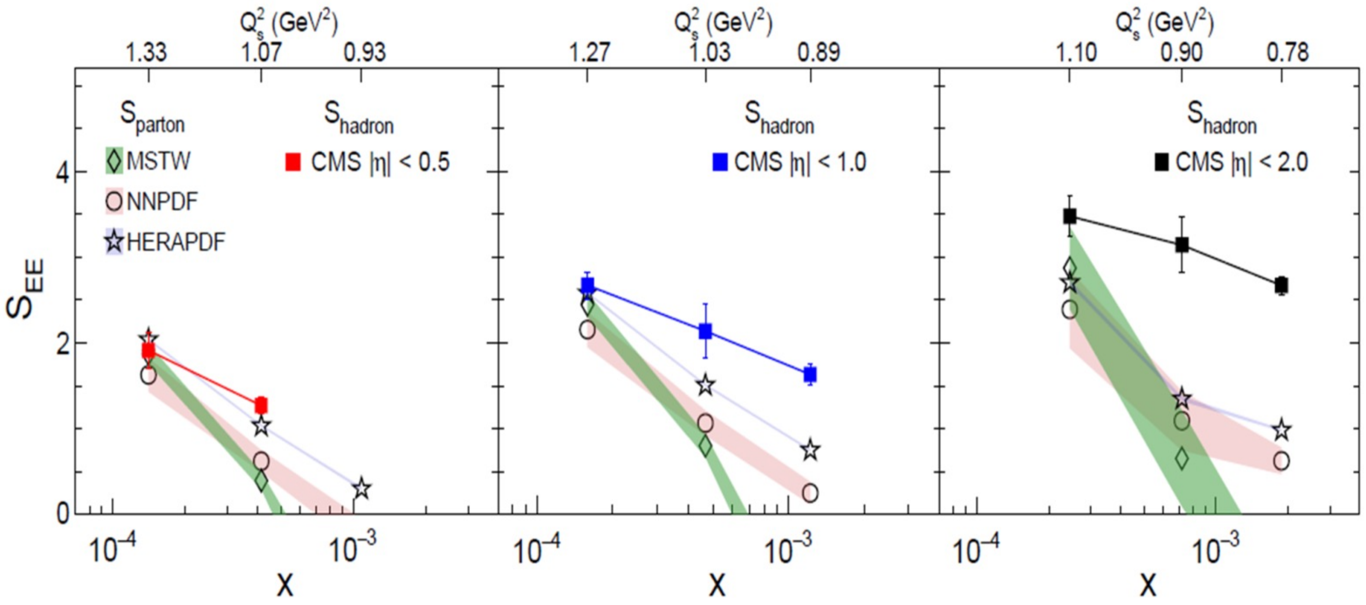
- First we obtain the number of gluons, N_{gluon}, by integrating the gluon distribution xG(x) over a given x range at a chosen scale Q^2. We use the leading order Parton Distribution Function (PDF) set MSTW at the 90% C.L. -> Entanglement Entropy in green

- The Boltzmann entropy of the final-state hadrons is shown as blue filled circles. It is calculated from the multiplicity distribution, P(N), in a rapidity range determined by the x range used to derive N_{gluon}. P(N) is taken from ep DIS events created with the PYTHIA 6 or 8 event generator

- Since x and momentum transfer scale Q^2 are not directly available in pp collisions, an alternative way of comparing the entropy at similar x and scales are used.

$$\ln(1/x) \sim y_{proton} - y_{hadron}$$

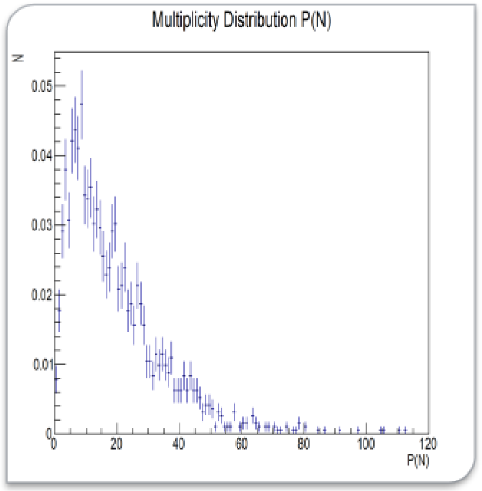




This is slightly more complicated in pp

- **In ep collisions:** y_{proton} is the proton beam rapidity and y_{hadron} is the final-state hadron rapidity. For example, events with 27.5 GeV electrons scattering off 460 GeV protons with x between 3 x10^{-5} and 8 x10^{-5} correspond to a rapidity range of $-3.5 < y < -2.5$.

- **In pp collisions:** two gluon distributions are involved, one from each proton, while we calculate the entanglement entropy from one distribution. Instead of altering the definition of the entanglement entropy, one can modify the P(N) distributions by extrapolating the P(N) distribution to reflect a single proton similar to that in ep collisions, by fitting a generalized Negative Binomial Distribution (NBD) to the P(N) distributions. The final P(N) is then taken as the same NBD function but with only half of the average multiplicity. This approach relies on the assumption that the final-state hadrons are produced coherently by the two colliding protons instead by incoherent and independent fragmentation.



Example: Normalized multiplicity distribution

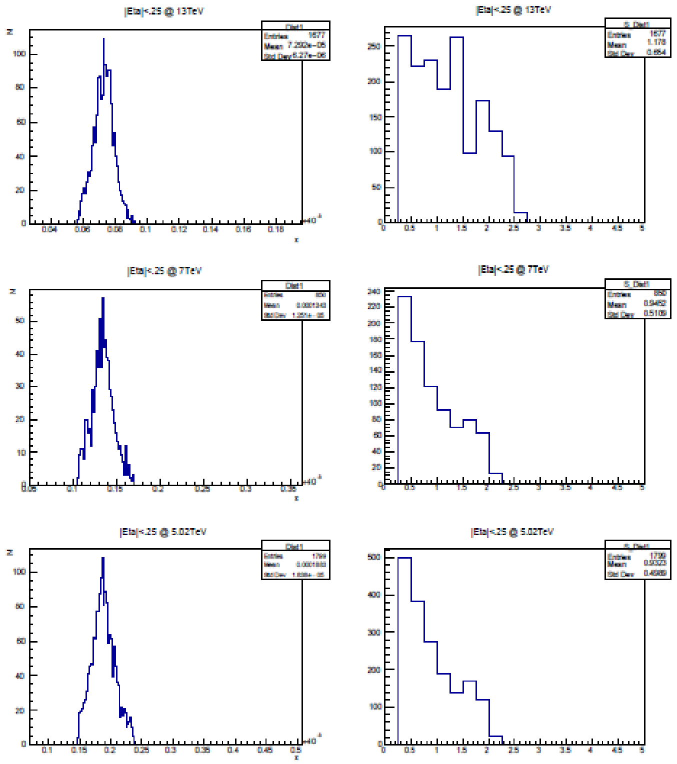
Now that we understand how to calculate the initial state entropy we would like to compare this to the entropy of the final state hadrons.

We measure the hadron entropy using Gibbs entropy formula and summing over the probability distribution P(N).

$$S_{final} \propto \Sigma P(N_h) ln(P(N_h))$$

Example: ALICE 5, 7,13 TeV pp-data: x-distribution S-distribution

η = +-0.25 (preliminary)



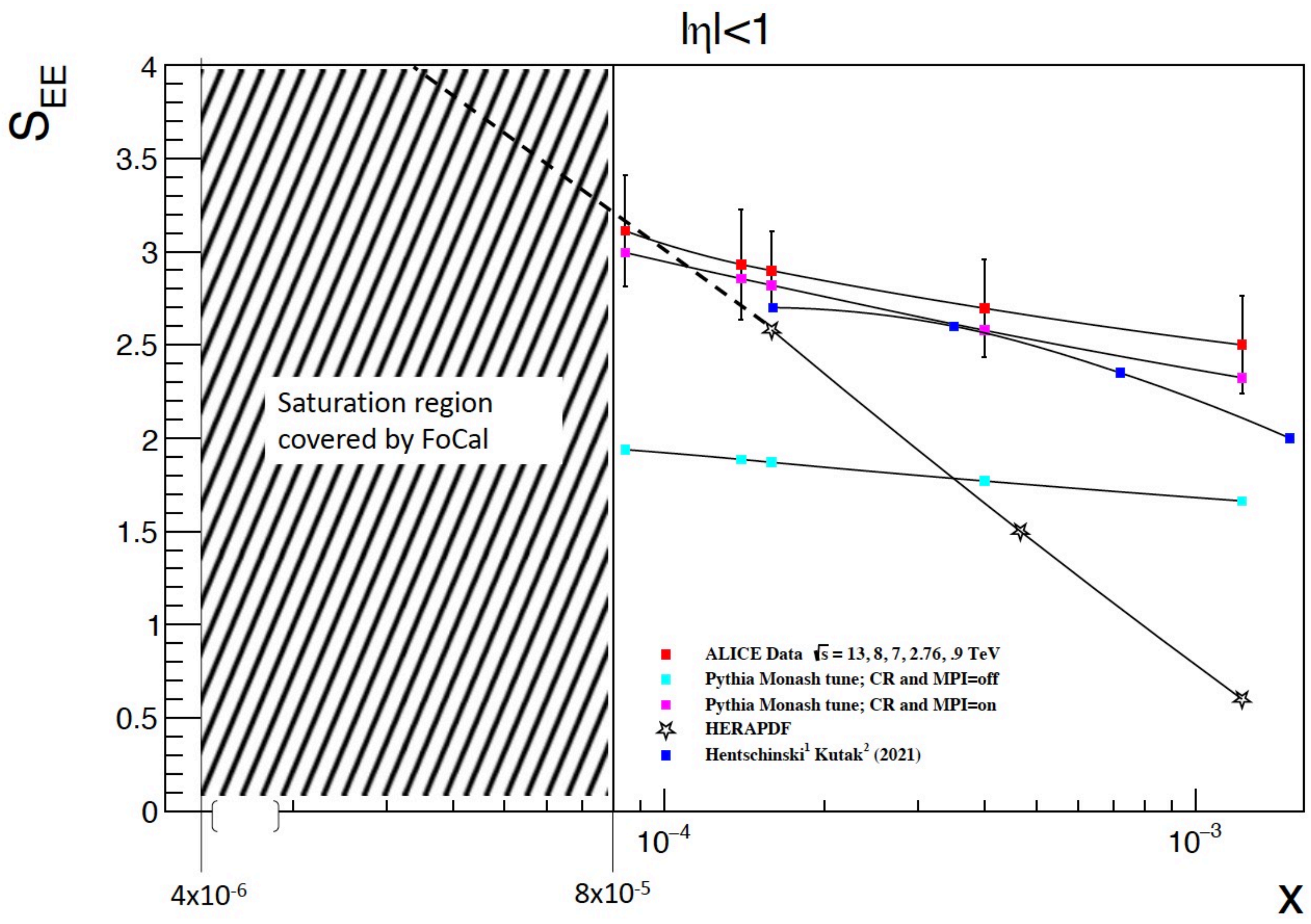
Procedure:

1.) measure multiplicity distributions in a fixed rapidity range

2.) calculated x-value distribution

3.) calculate entropy distribution

Preliminary **ALICE** data from 0.9-13 TeV

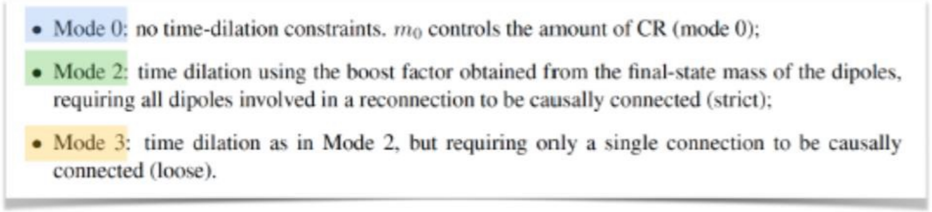


Good agreement between data and NLO PDF at low x, deviation at higher x (potentially solved through sea-quark contribution).

A new forward calorimeter (FoCal) will extend the relevant x-region decisively

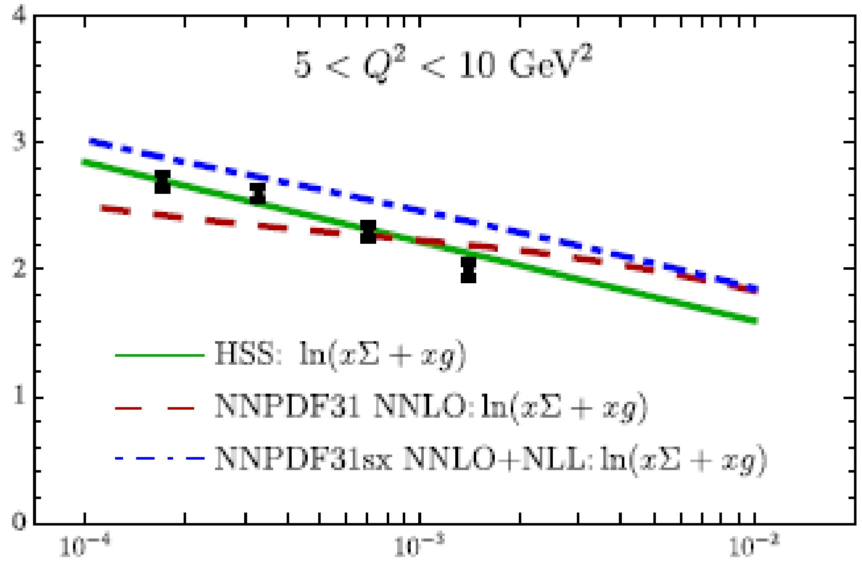
Model Improvements:

PYTHIA (latest tunes): Monash has been upgraded with initial state Multi-Parton Interactions (MPI) and final state Color Reconnection (CR).



- Mode 0: no time-dilation constraints. m_0 controls the amount of CR (mode 0);
- Mode 2: time dilation using the boost factor obtained from the final-state mass of the dipoles, requiring all dipoles involved in a reconnection to be causally connected (strict);
- Mode 3: time dilation as in Mode 2, but requiring only a single connection to be causally connected (loose).

Hentschinski & Kutak (2021):
Disagreement at higher x could be due to significant sea-quark contributions (shown here in comparison to H1 data)



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

- 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.
- All light quark hadron yields are frozen in during the initial state at a common 'temperature'. Entanglement entropy is calculated over an extended volume at QCD crossover. Temperature should then relate to Hagedorn temperature (e.g. Pajares et al., arXiv:1805.12444)

In pp: Hadron multiplicities as a function of x in elementary collisions show already intriguing patterns that point at entanglement.

In AA: *If there is no decoherence phase* (global equilibration), then the 'temperature' from the entangled phase will drive the multiplicity of all states from pion to light nuclei and even hypernuclei and rare multi quark clusters. Measure identified particles as a function of η.

Experimental outlook

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