The 38th Winter Workshop on Nuclear Dynamics

UNIVERSITY OF HOUSTON

Forward Physics in small systems at the LHC

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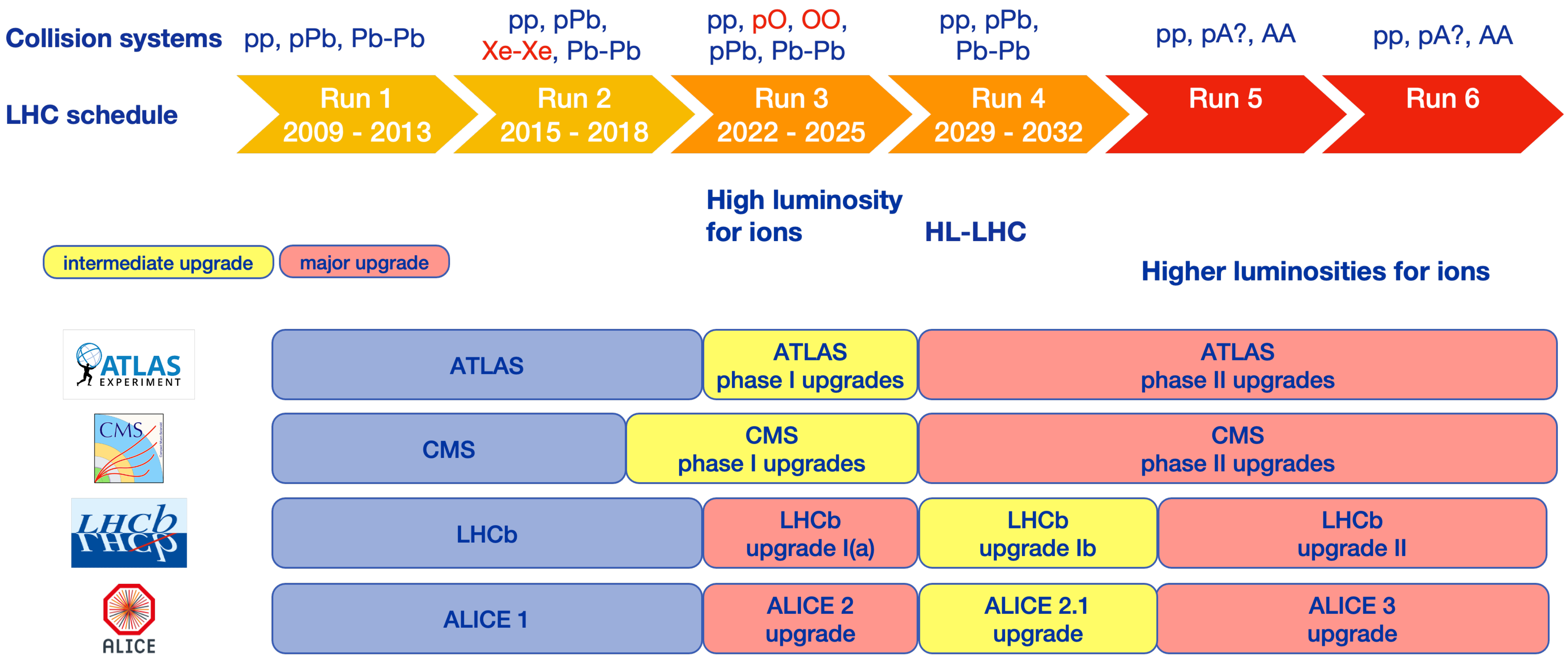
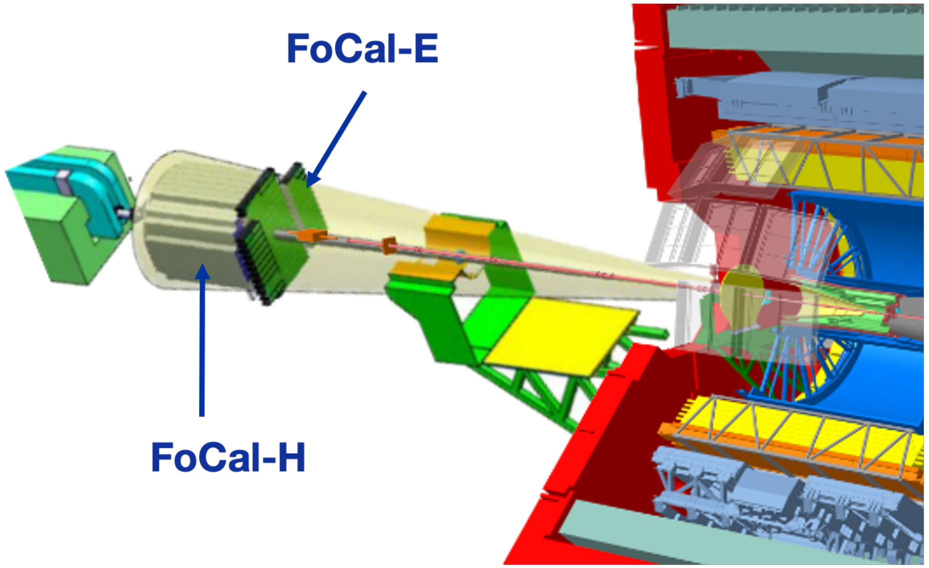
February 6th, 2023

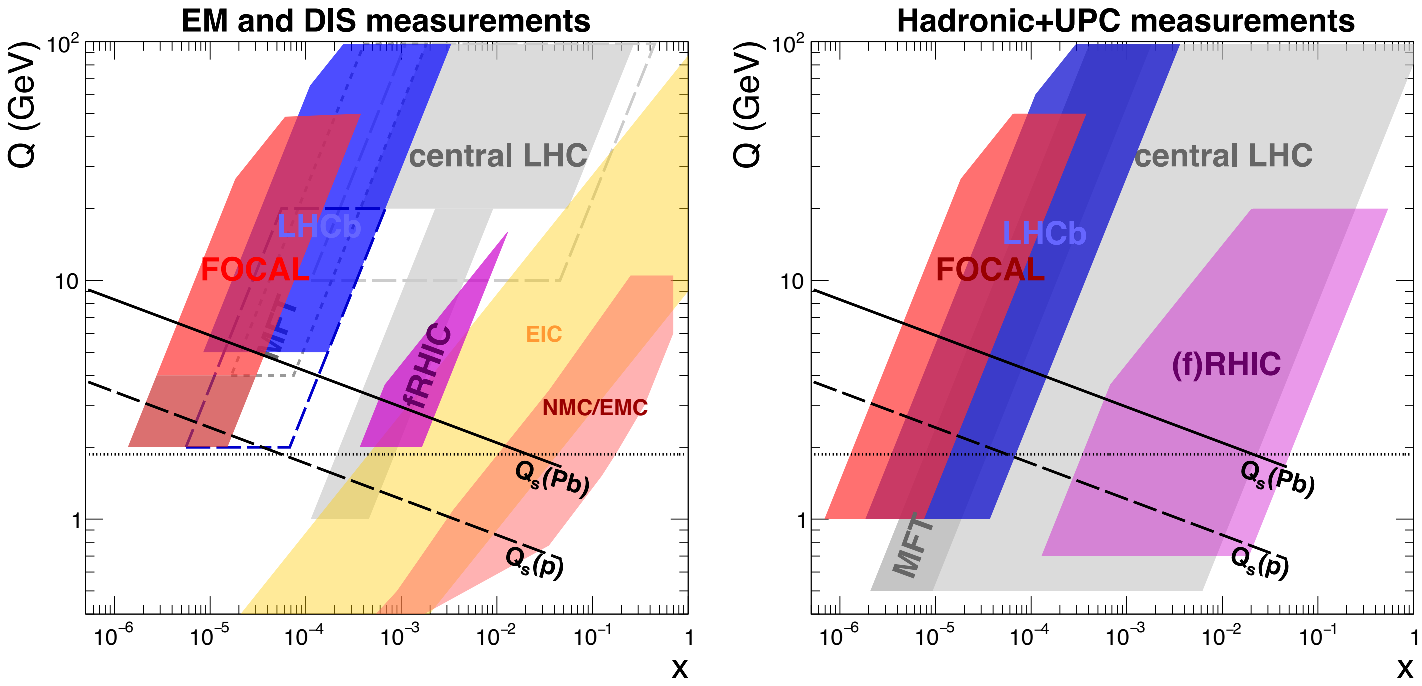
Forward detectors at the LHC



LHC Run 4: all detectors have comprehensive tracking at forward rapidity i.e $|\eta| \rightarrow$ 4 to 5.8

Forward Calorimeter (FoCal) at ALICE





Electromagnetic and hadronic calorimeters covering 3.4 < η < 5.8

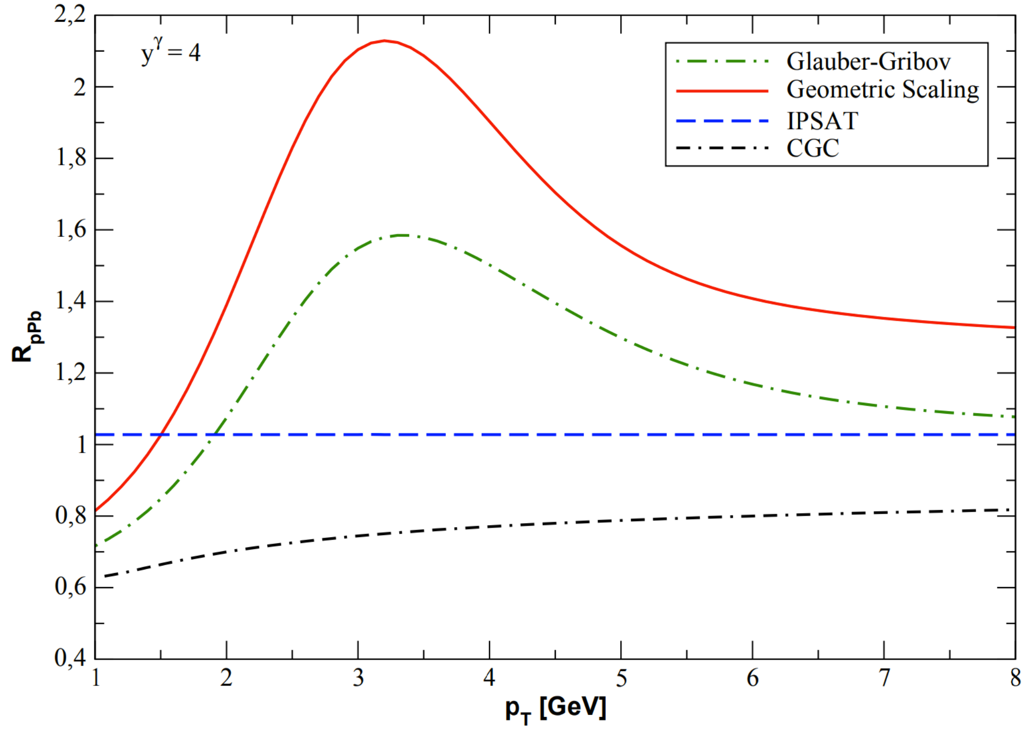
✓ Probes parton densities down to x ~10^{-6}

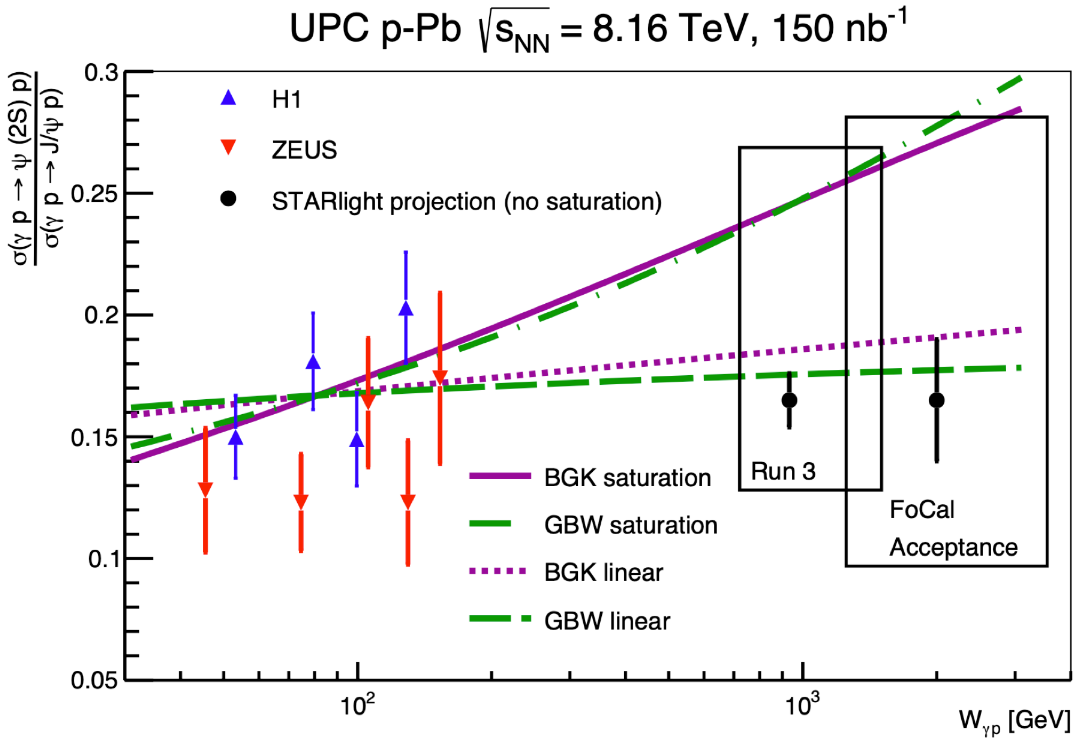
✓ **Lowest x reach** compared with any other **experiment/facility**

$$x_1 \approx \frac{2p_T}{\sqrt{s}} e^{-y}$$

Physics goals of FoCal

https://sites.google.com/lbl.gov/alice-usa/projects



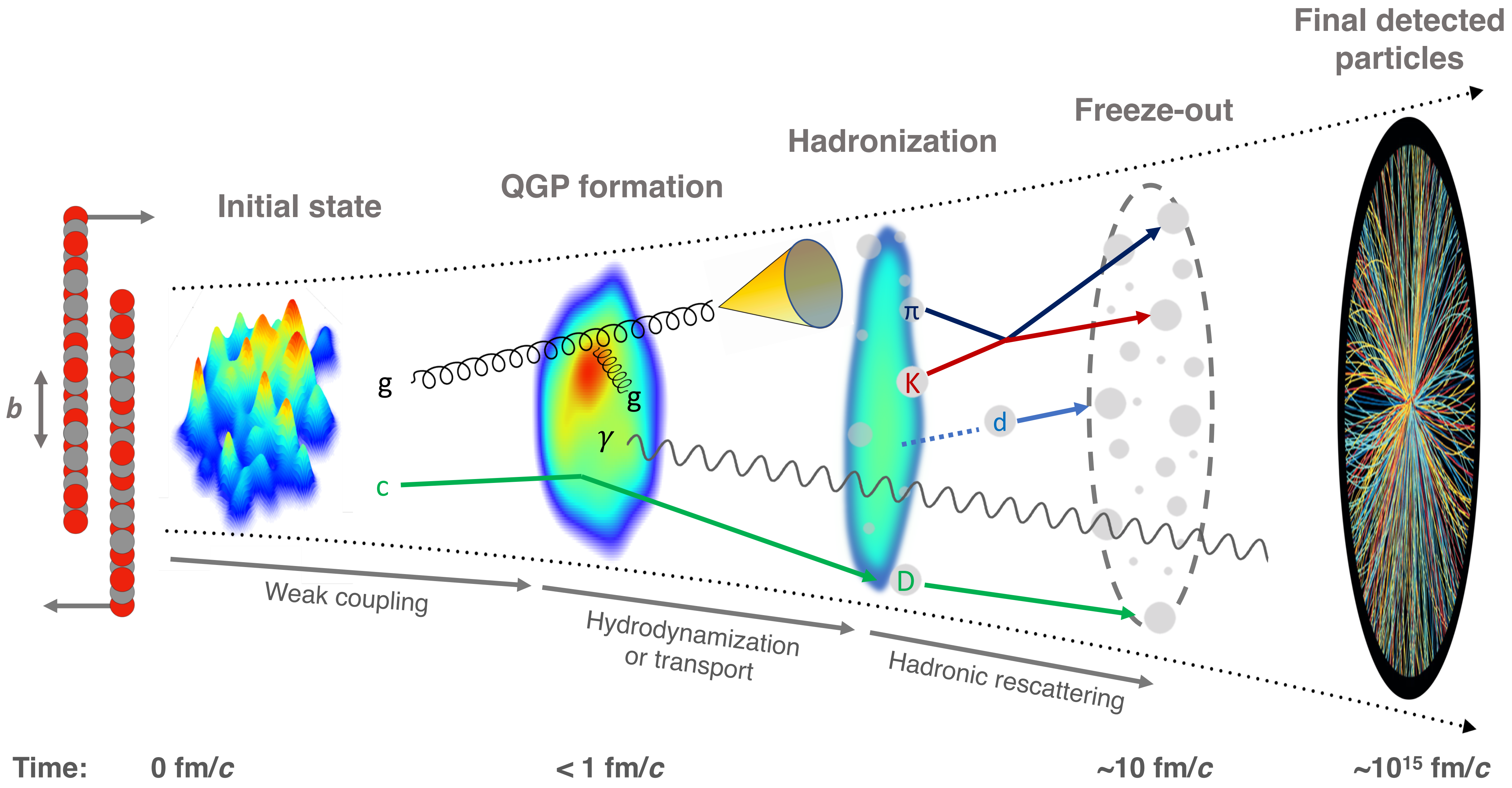


Direct photons in small systems and **vector meson** production in ultra-peripheral collisions

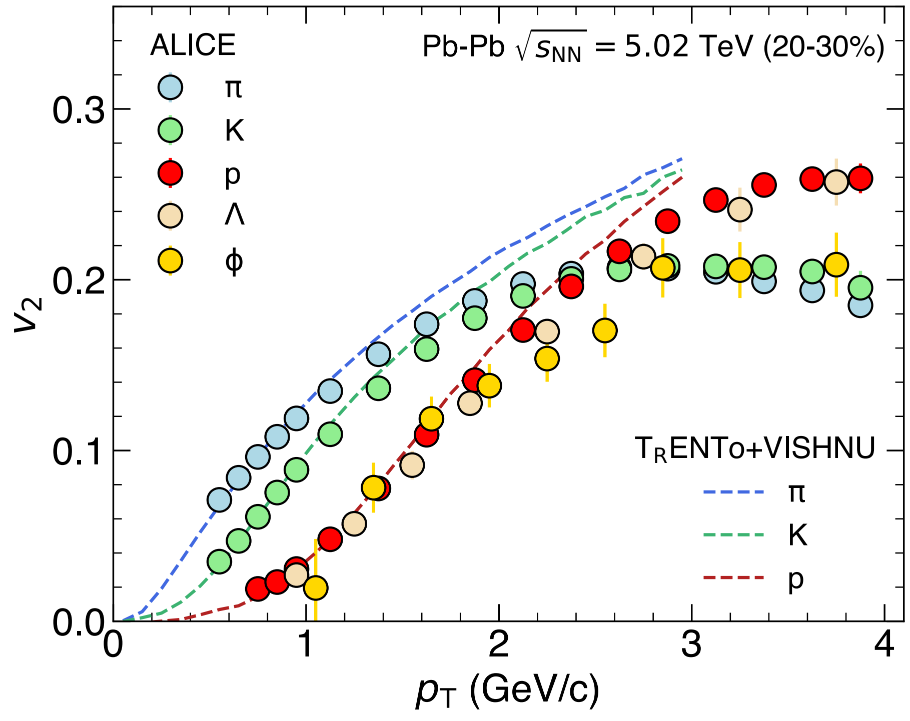
✓Major goal: Explore gluon saturation from various few-body interactions

✓Minor goal: **Investigate emergent hot QCD phenomena**

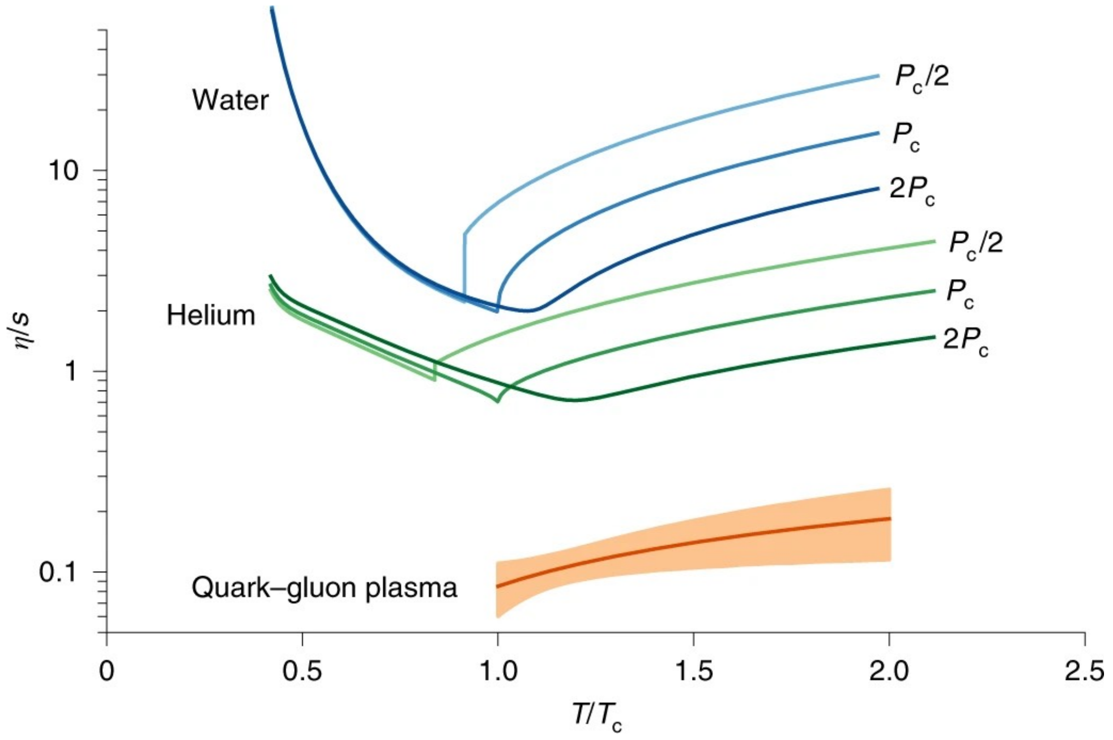
“Standard Model” of heavy-ion physics



Emergent features of hot QCD: **flow**



Nature Physics 15 (2019) 1113–1117

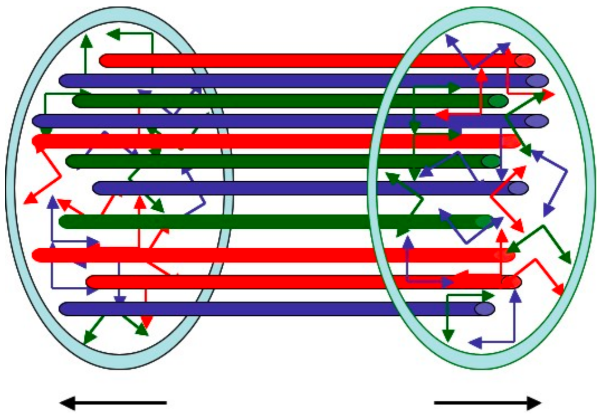


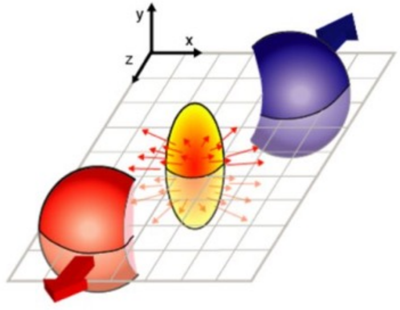
QGP evolves as a perfect fluid

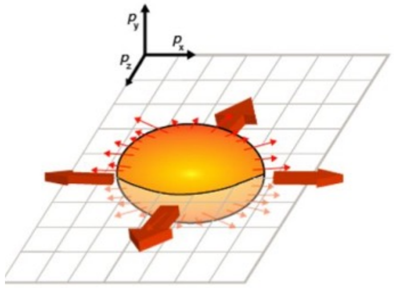
Measured flow described by hydrodynamics with smallest viscosities ever observed

See Govert's talk for state of art findings

FoCal and initial state







Knowledge of **initial state** plays vital role for **understanding QGP flow**

✓ Final state anisotropic flow ∝ initial state eccentricity

Color Glass Condensate (CGC) emerges as testable description of **gluon saturated matter**

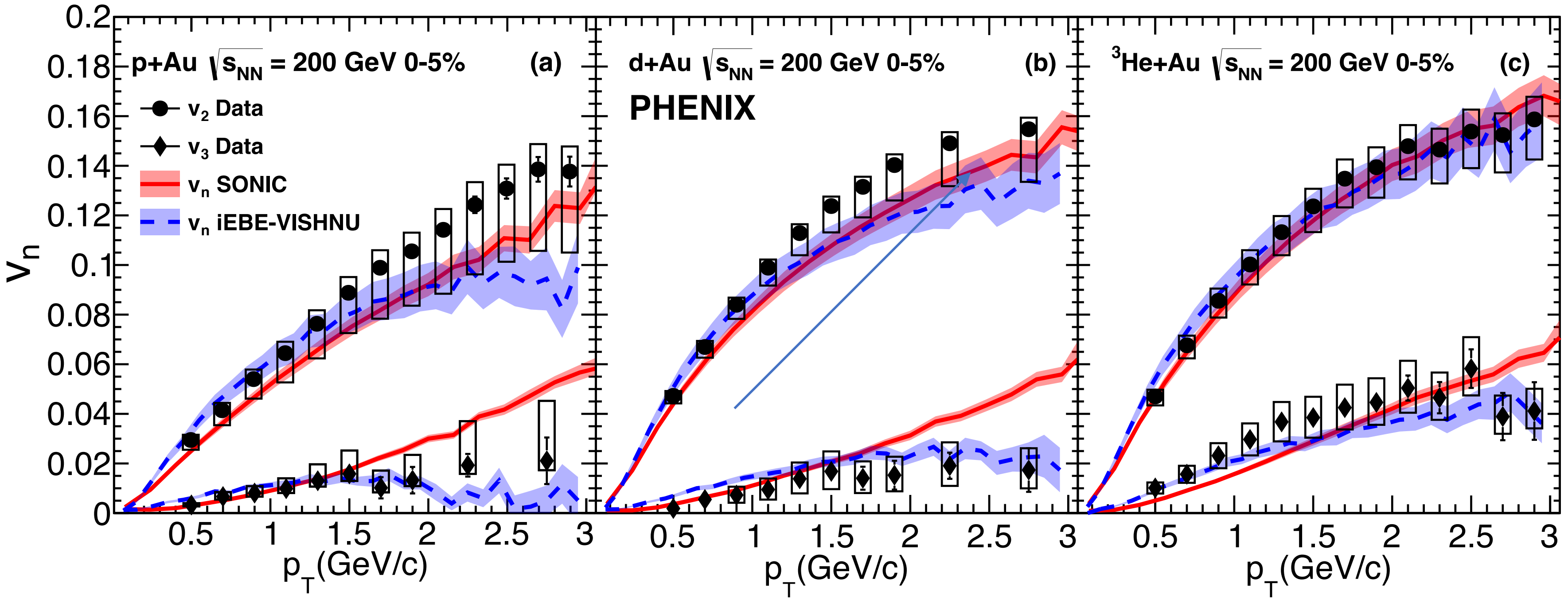
✓ Static color sources at high-*x* generate dynamical gluon fields at low-*x*

✓ Induces long range rapidity correlations for flow measurements from initial state

✓ Rapidity separation of high-*x* sources and low-*x* fields? → **Measurable with FoCal**

Smallest possible QGP droplet?

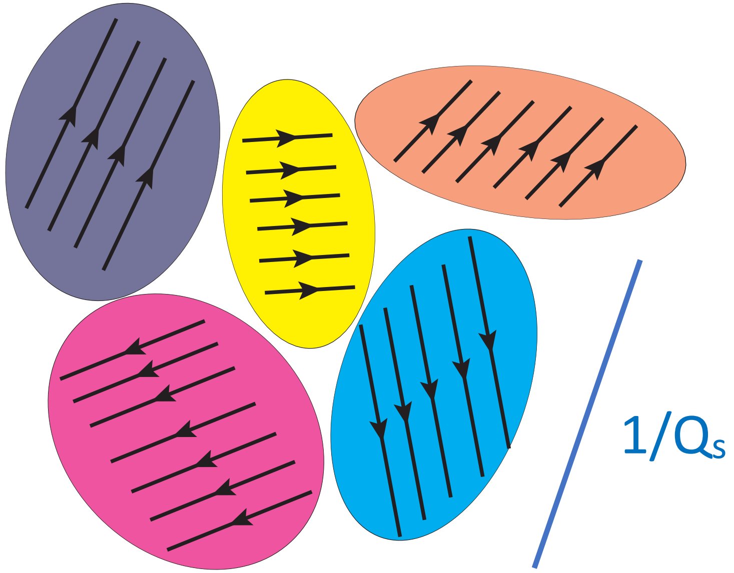
Nature Physics 15 (2019) 214–220



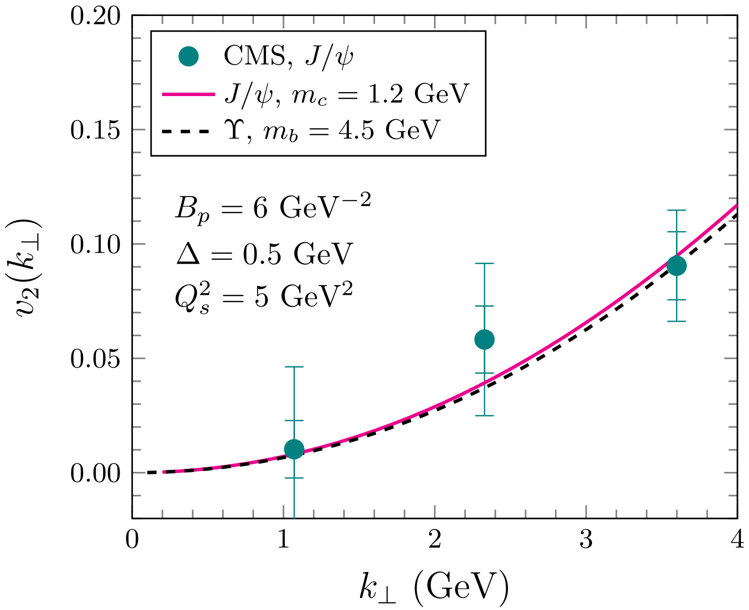
RHIC and LHC measurements **demonstrate charged hadron flow** in high-multiplicity **small systems**

- ✓ Successful hydrodynamic fluid-like description
- ✓ Initial state eccentricity converted to flow via QGP response?

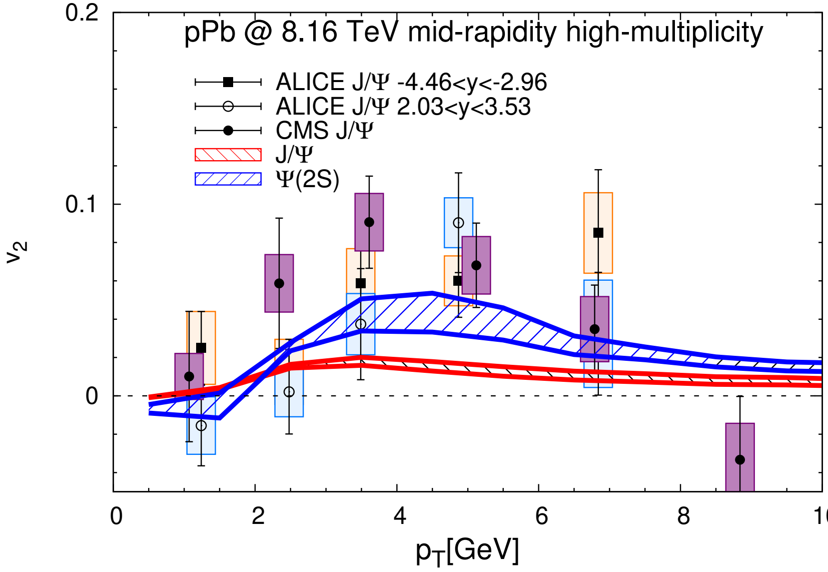
Initial state flow?



Phys. Rev. Lett. 122 (2019) 172302



JHEP 03 (2019) 015



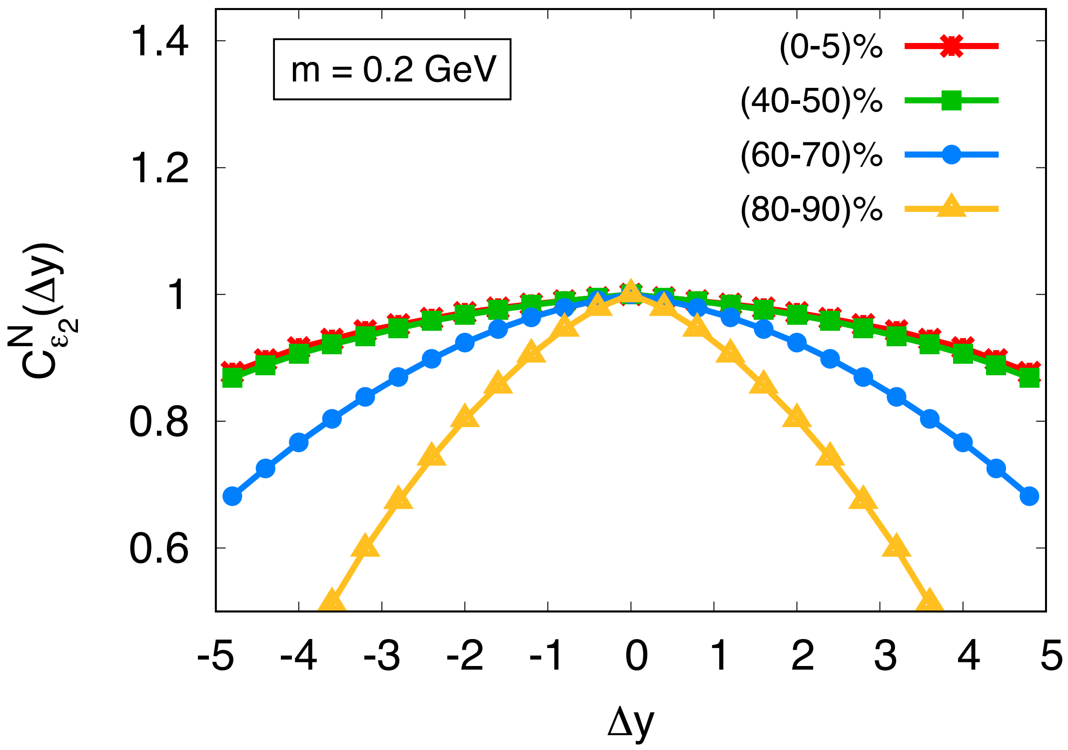
Color domains in **CGC** postulated to induce **initial state flow**

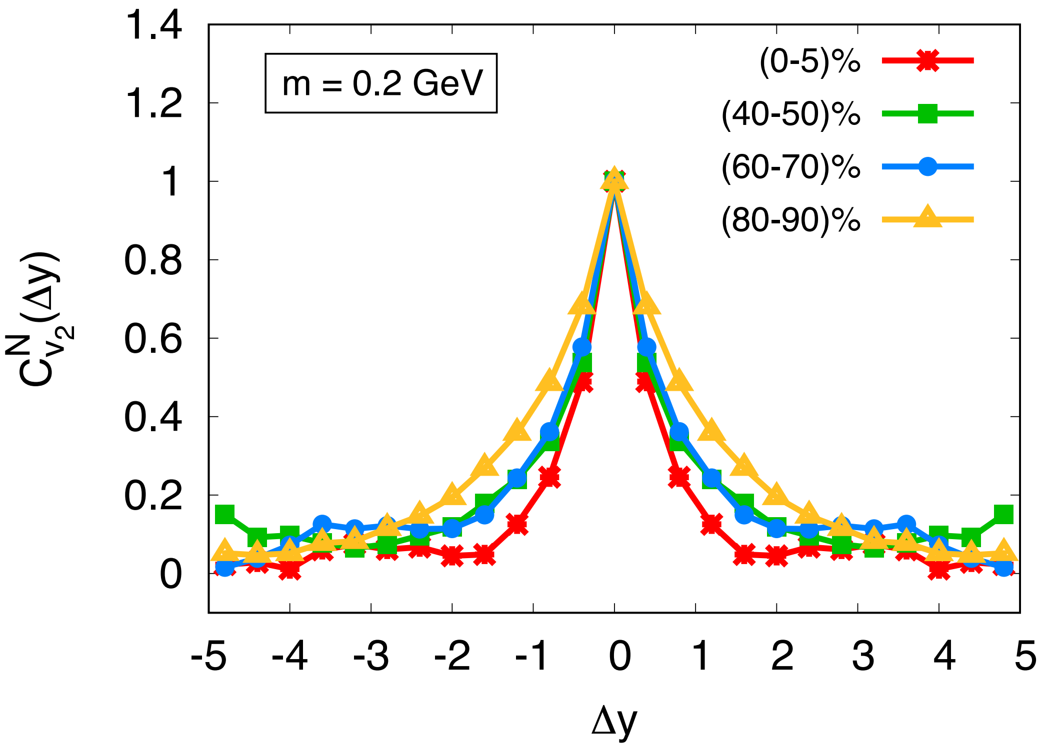
✓ CGC calculations describe measured J/ψ flow in p-Pb collisions at LHC

✓ Transport models that **implement QGP flow underestimate data**

Initial vs. final state flow in p-Pb

Phys. Rev. D 105 (2022) 094023

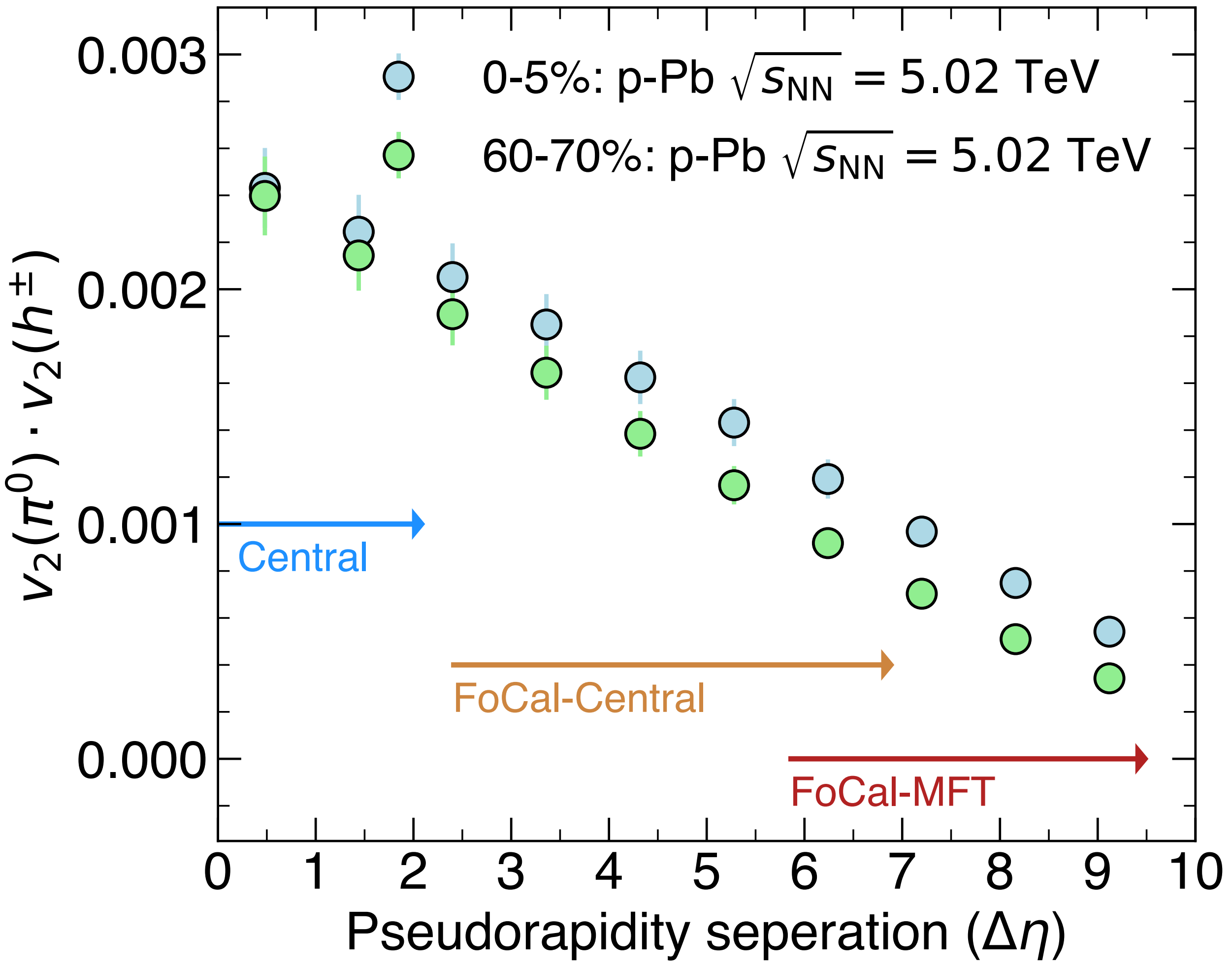




Recent CGC calculations map how **initial state eccentricities evolve with x**

- ✓ Induces measurable **final state hydrodynamic flow** correlation effects over **large rapidity intervals**
- ✓ Show **initial state flow correlations vanish** for particles with separation $|\Delta y| > 2$

Disentangling flow with FoCal



FoCal provides **opportunity** to measure **flow correlations at unique forward coverage with large rapidity gaps**

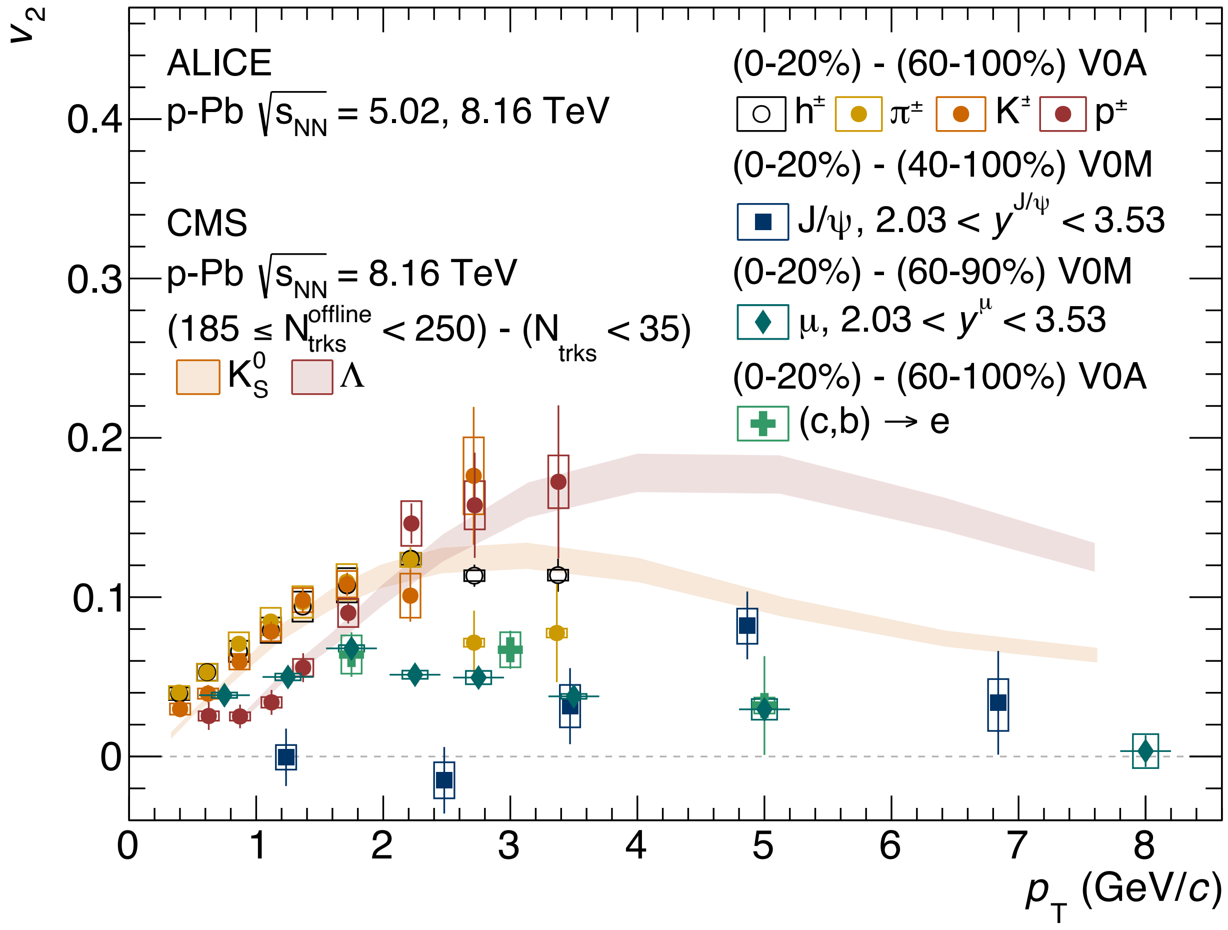
Stronger hydro-like flow correlations in high multiplicity p-Pb collisions:

✓Induce shallower fall for v_2^2 vs. $\Delta\eta$

✓Due to initial state eccentricity effects

Unique test of CGC framework's ability to map **spatial distribution of gluons**

Identified particle flow with FoCal



FoCal can measure **mass dependence of flow** in π, η, ω, and J/ψ channels:

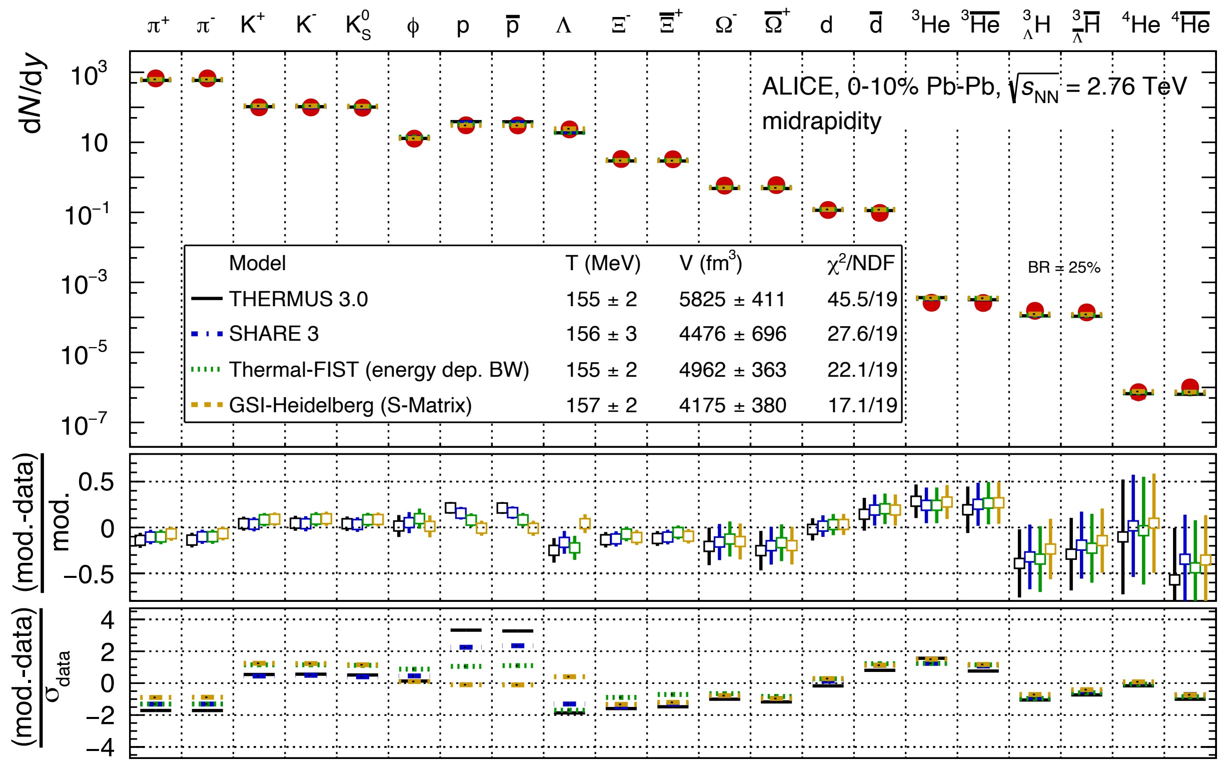
- $v_2 = \langle \cos[2(\phi - \Psi)] \rangle$

Large $\Delta\eta$ separation between ϕ(FoCal) and Ψ(MDT) isolates QGP-like flow correlations

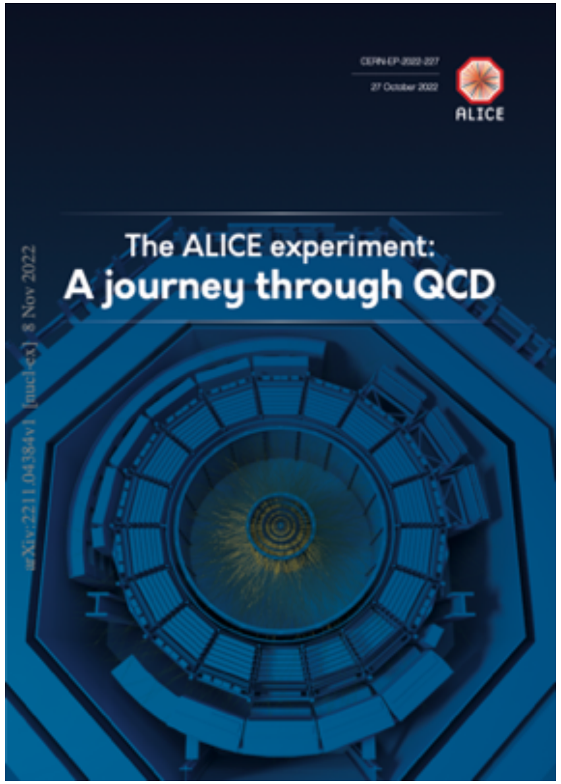
- "Non-flow" contributions require large subtraction for current measurements

Precise tests of **QGP hydrodynamic and transport models for small systems** in forward region

Emergent features of hot QCD: **thermalization**



arXiv:2211.04384

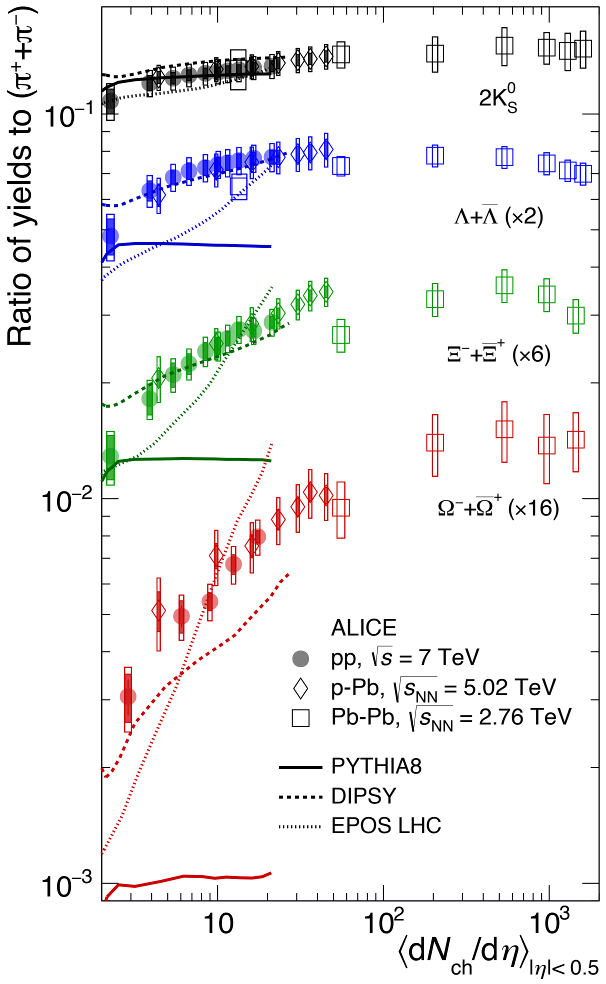


QGP produces hadrons in equilibrium

Thermal model description of particle yields over many orders of magnitude

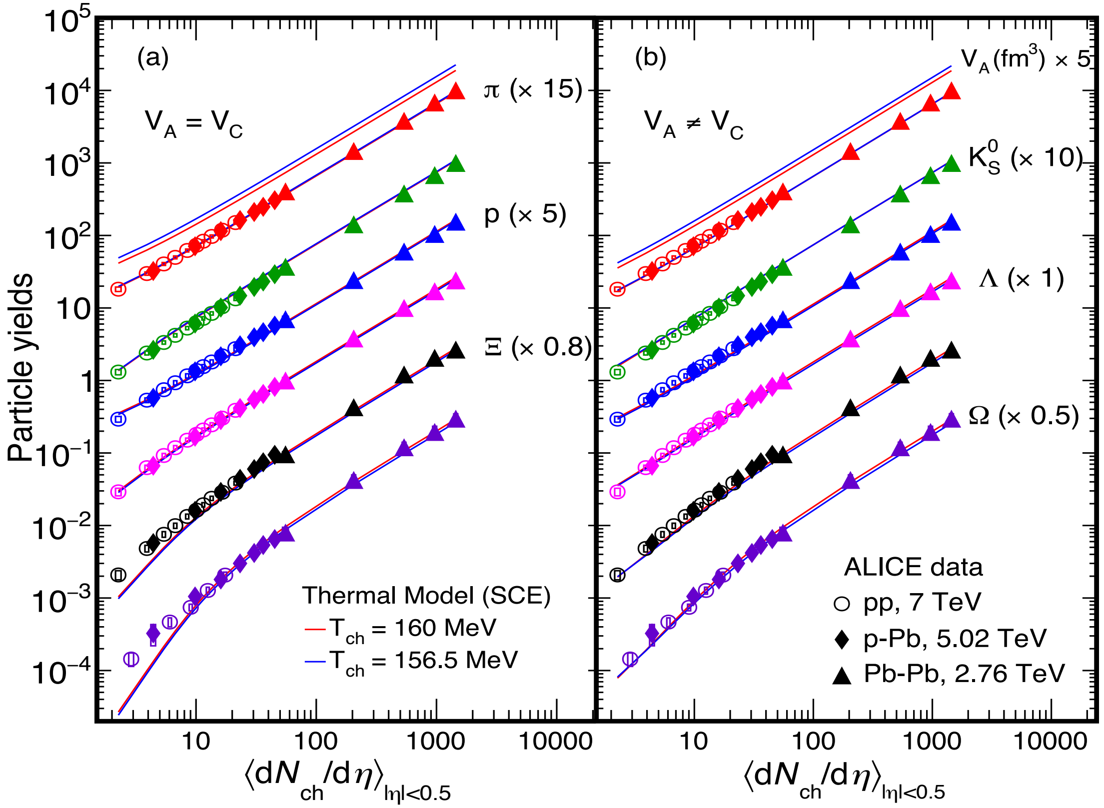
Using only two parameters: temperature and volume

Thermalization in small systems?



Nature Physics 13 (2017) 535–539

Phys. Rev. C 103 (2021) 014904

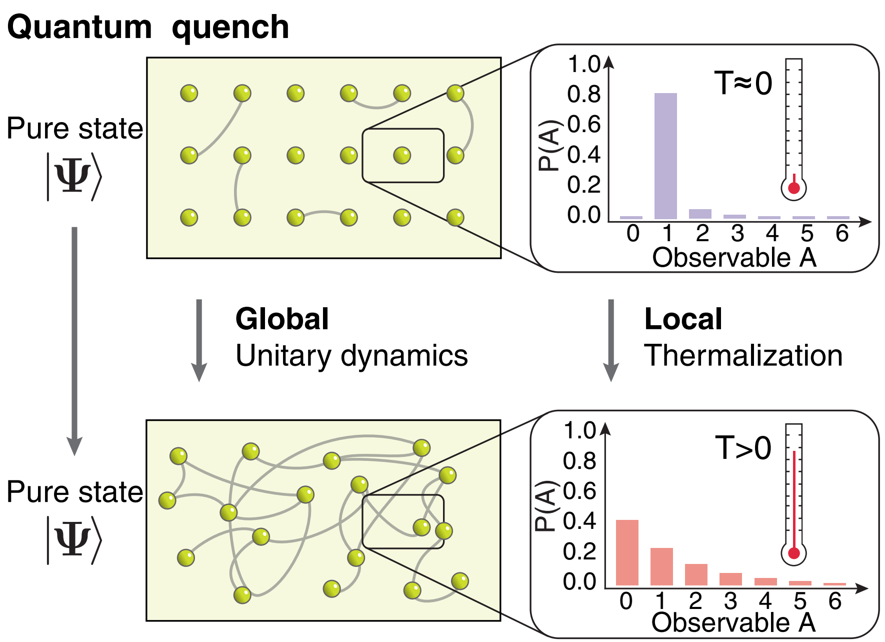


Strangeness enhanced in small systems at **high multiplicity**

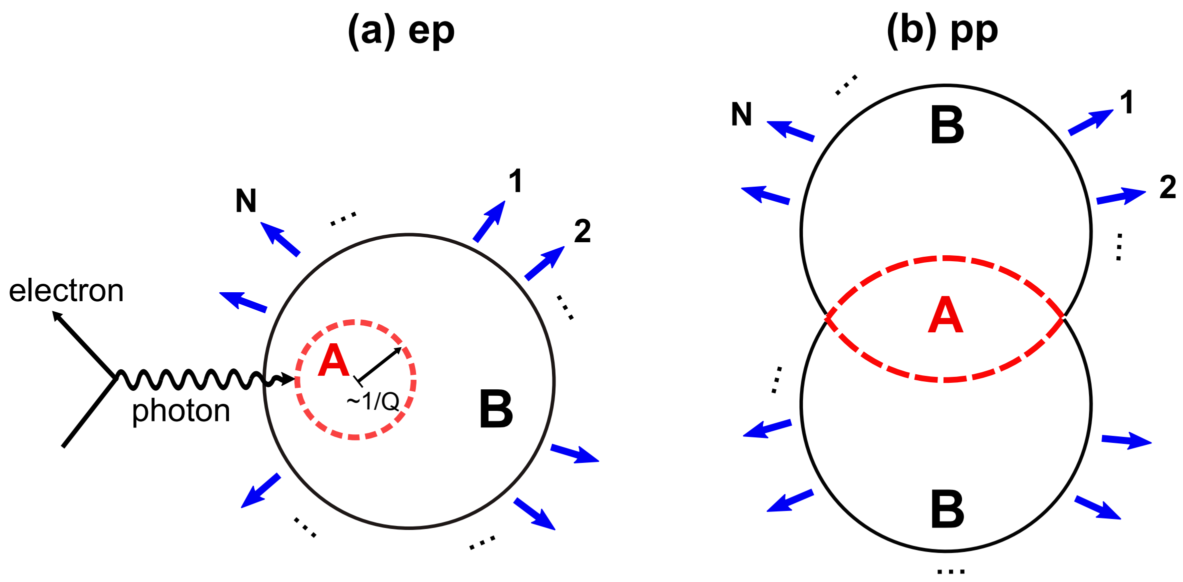
✓ Apparent success of **thermal models** reproducing enhancement?

Quantum entanglement and entropy

Science 353 (2016) 794



Phys. Rev. Lett. 124 (2020) 062001



Quantum entanglement creates entropy and **induces thermalization**

- ✓ Quarks and gluons within proton entangled
- ✓ Does that explain the success of the thermal model for small systems?

[Nobel Prize in Physics 2022]

Entanglement aficionados at Houston

Alek Hutson

Extremely talented graduate student who does all the work

Entanglement aficionados at Houston

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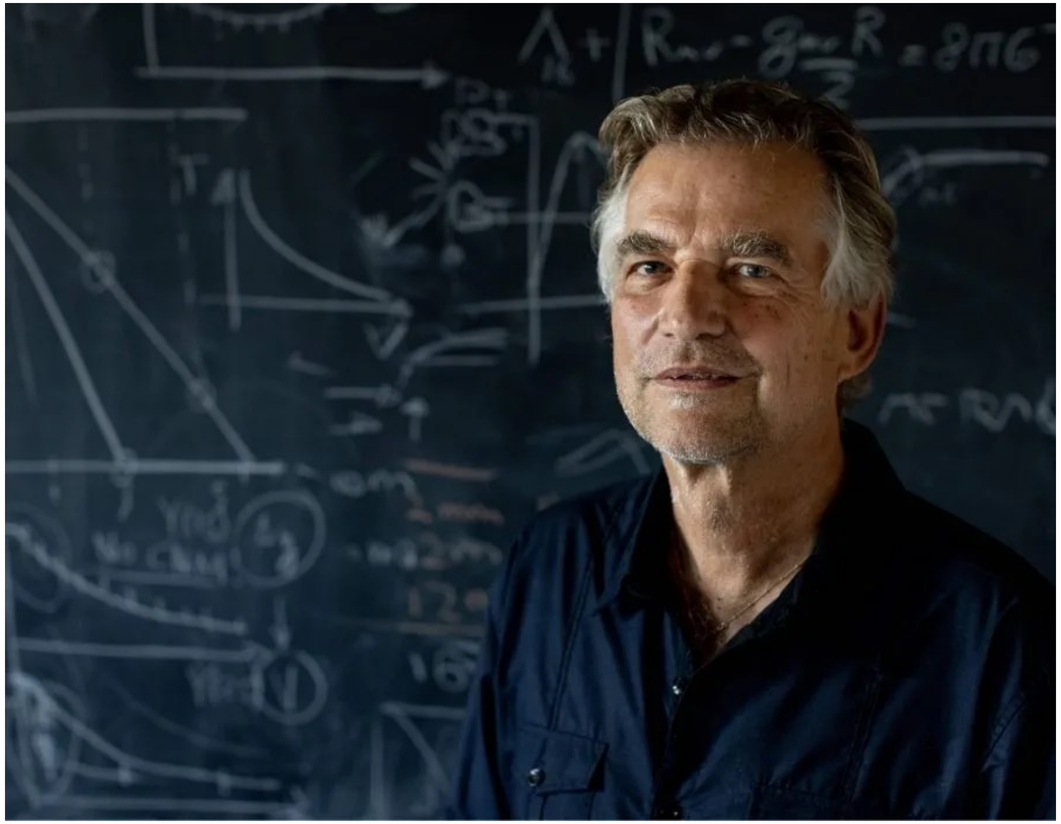
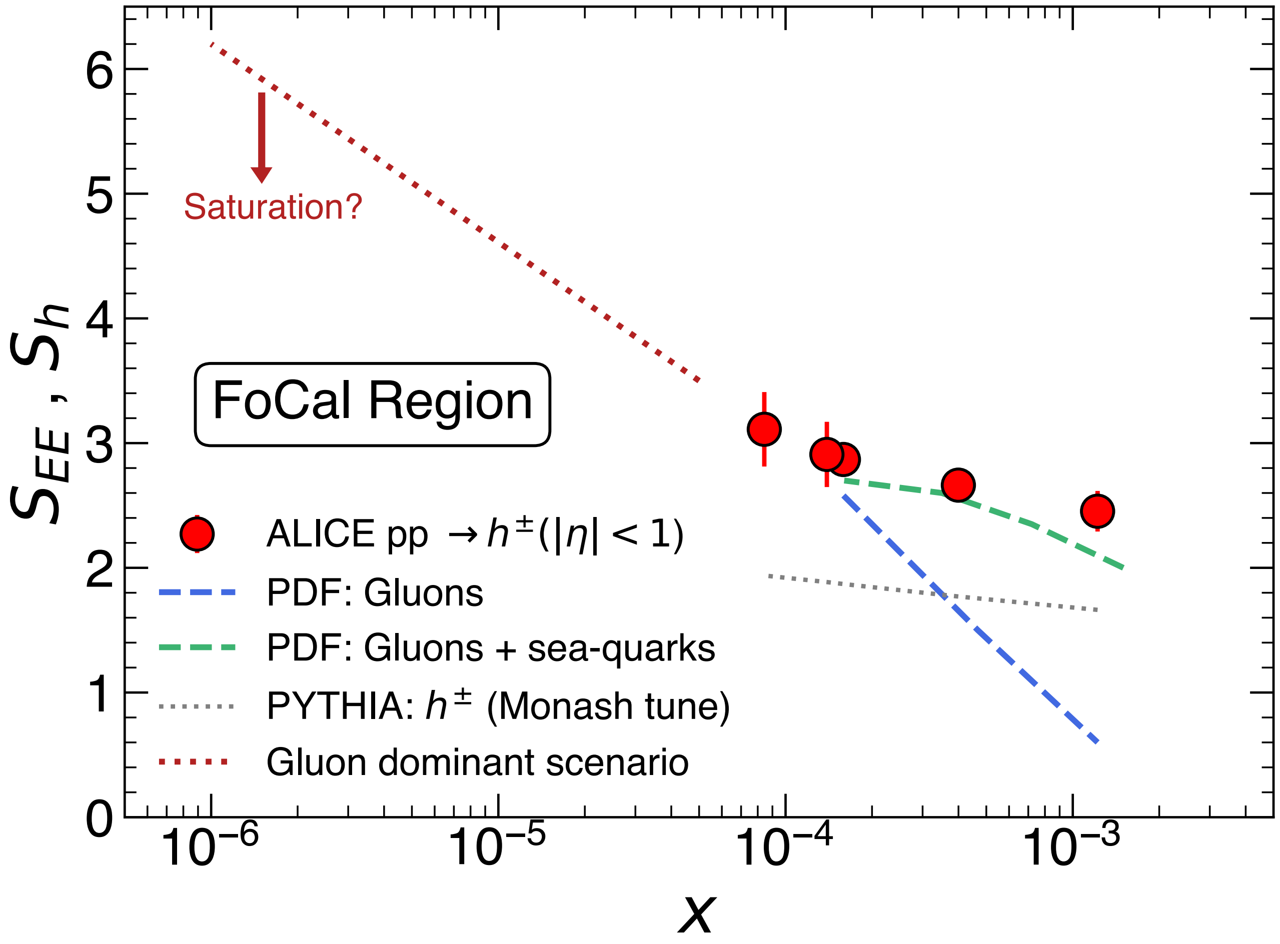


Rene Bellwied

Talks - I think advises Alek??

Probing gluon entanglement with FoCal



Final state entropy can be measured from **multiplicity distributions** in pp collisions

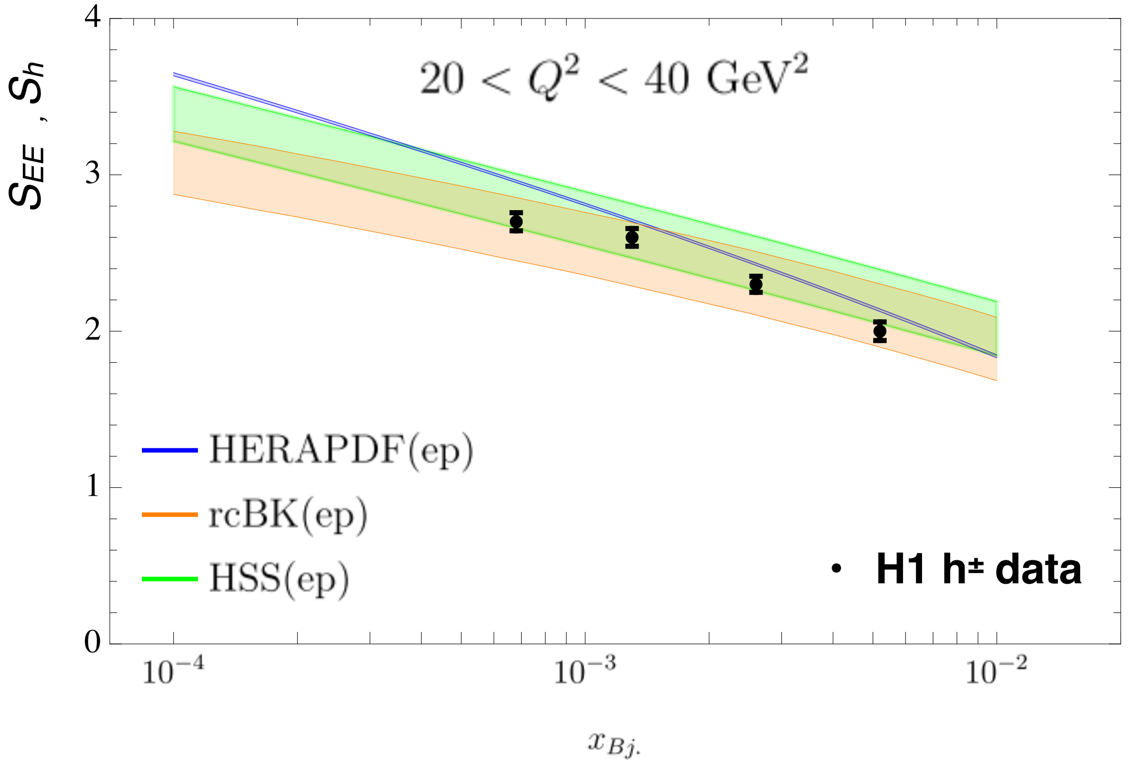
- ✓ S_h (final state) = $\sum -P(N_{\text{hadron}}) \ln [P(N_{\text{hadron}})]$
- ✓ S_{EE} (initial state) = $\ln[xG(x)]$

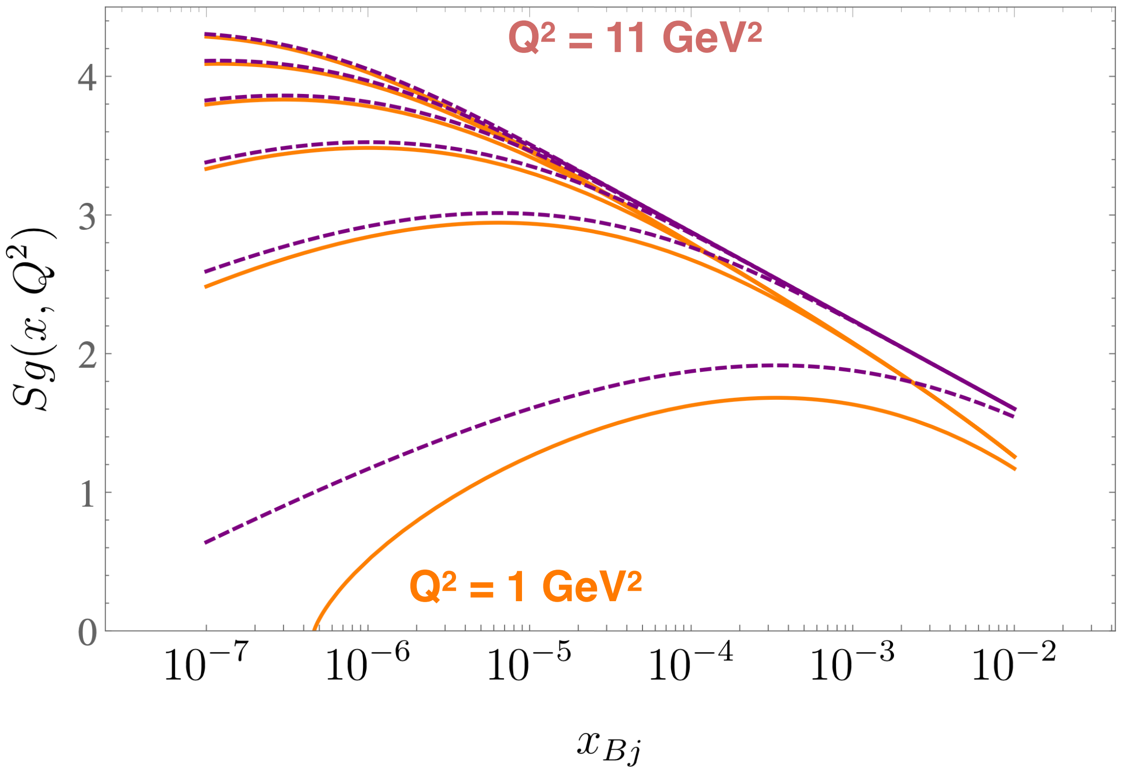
FoCal can explores gluon dominated region at low-*x* via neutral particle multiplicities

- ✓ Non-linear PDFs predict rise and fall of S_{EE}
- ✓ FoCal provides unique probes of thermalization mechanisms & saturation in pp

Entanglement entropy in DIS collisions

Eur. Phys. J.C 82 (2022) 12 1147

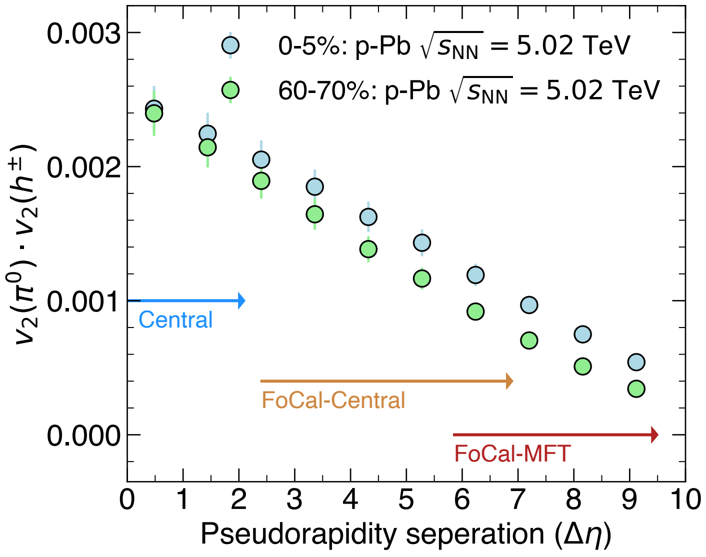


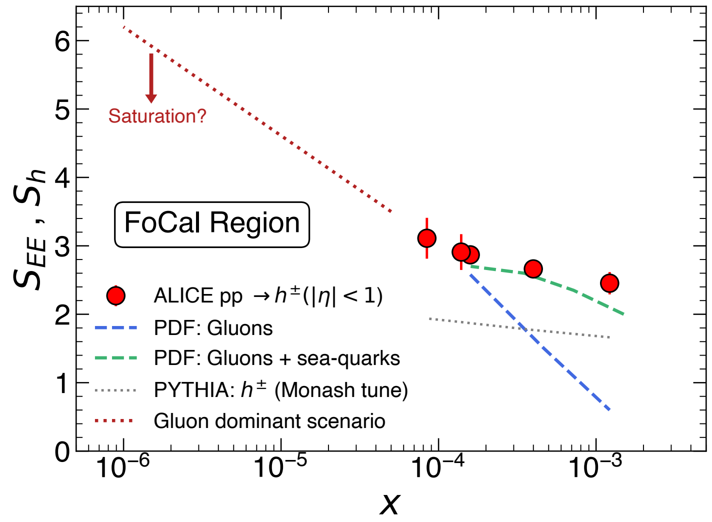


Complimentary studies in DIS collisions at HERA and EIC

- ✓ Probe different and overlapping x and Q^2 regions **compared with FoCal**
- ✓ World data will provide comprehensive investigation into parton entanglement…

Summary of emergent behavior with FoCal





Evolves as a perfect fluid

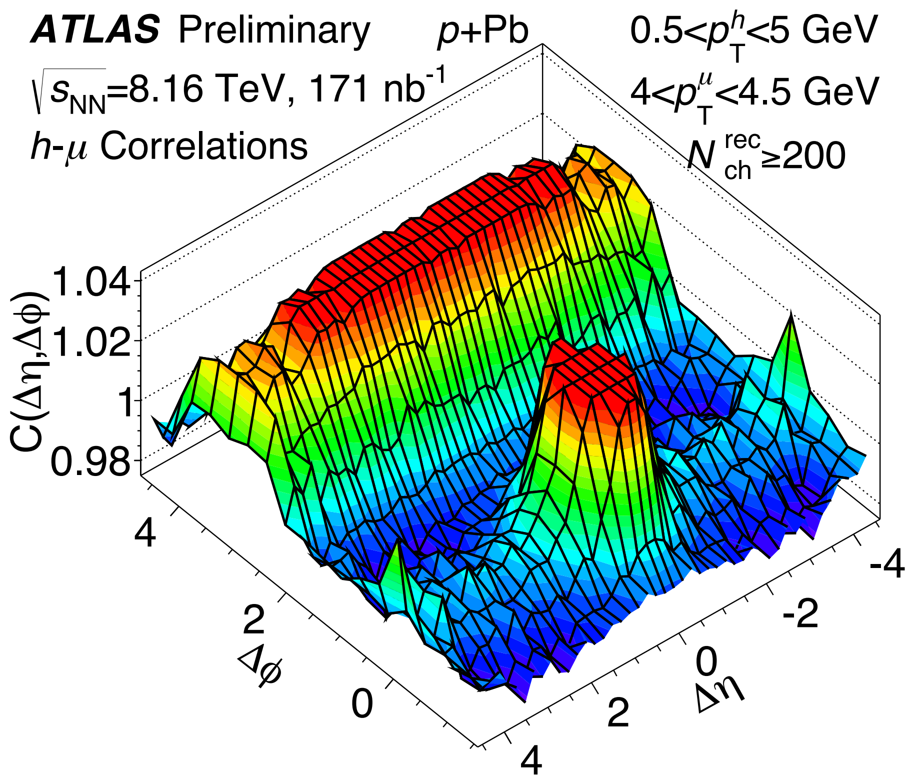
Long range correlations test saturation models and QGP paradigm in small systems

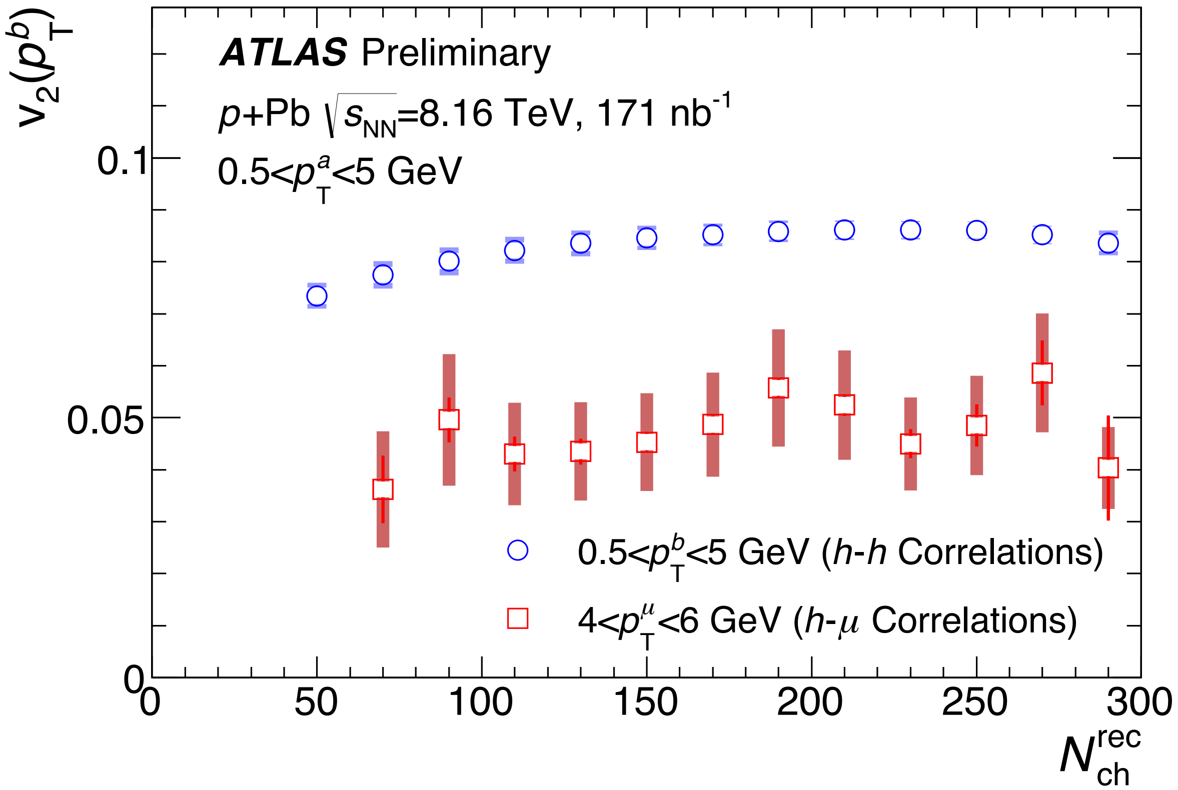
Produces hadrons in equilibrium

Key test of bridge between quantum and statistical physics in proton collisions

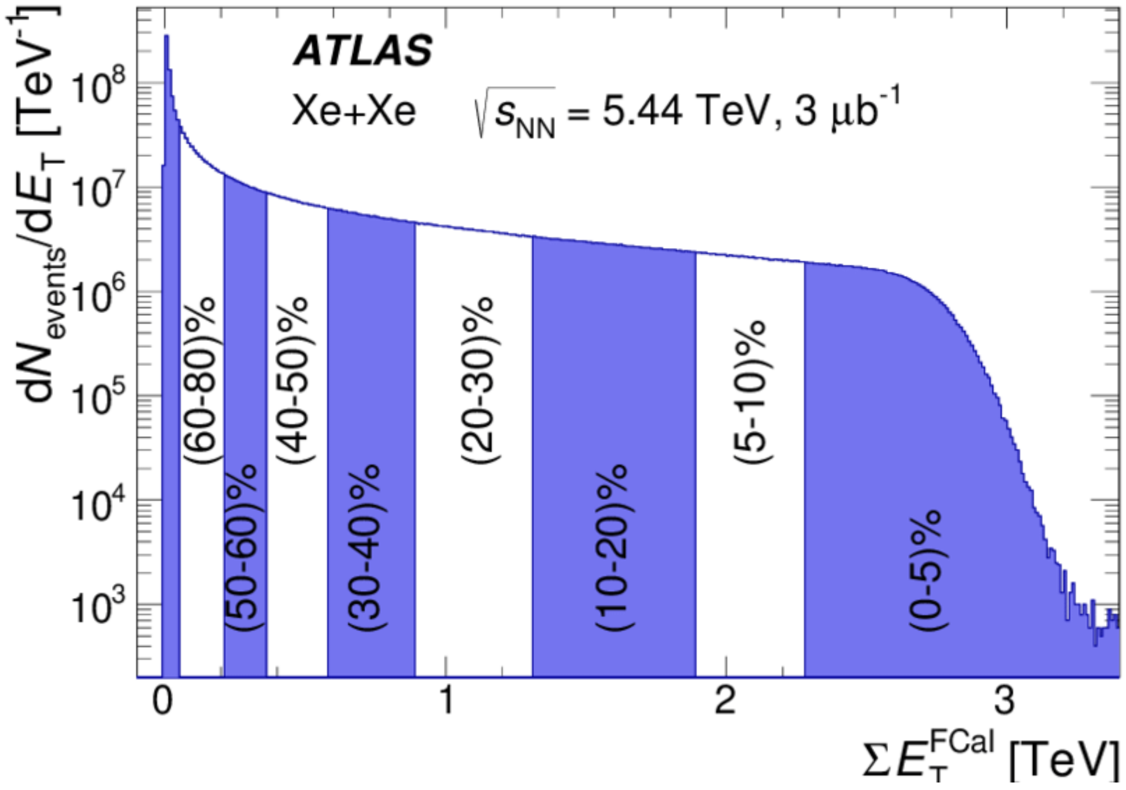
Many more measurements possible!

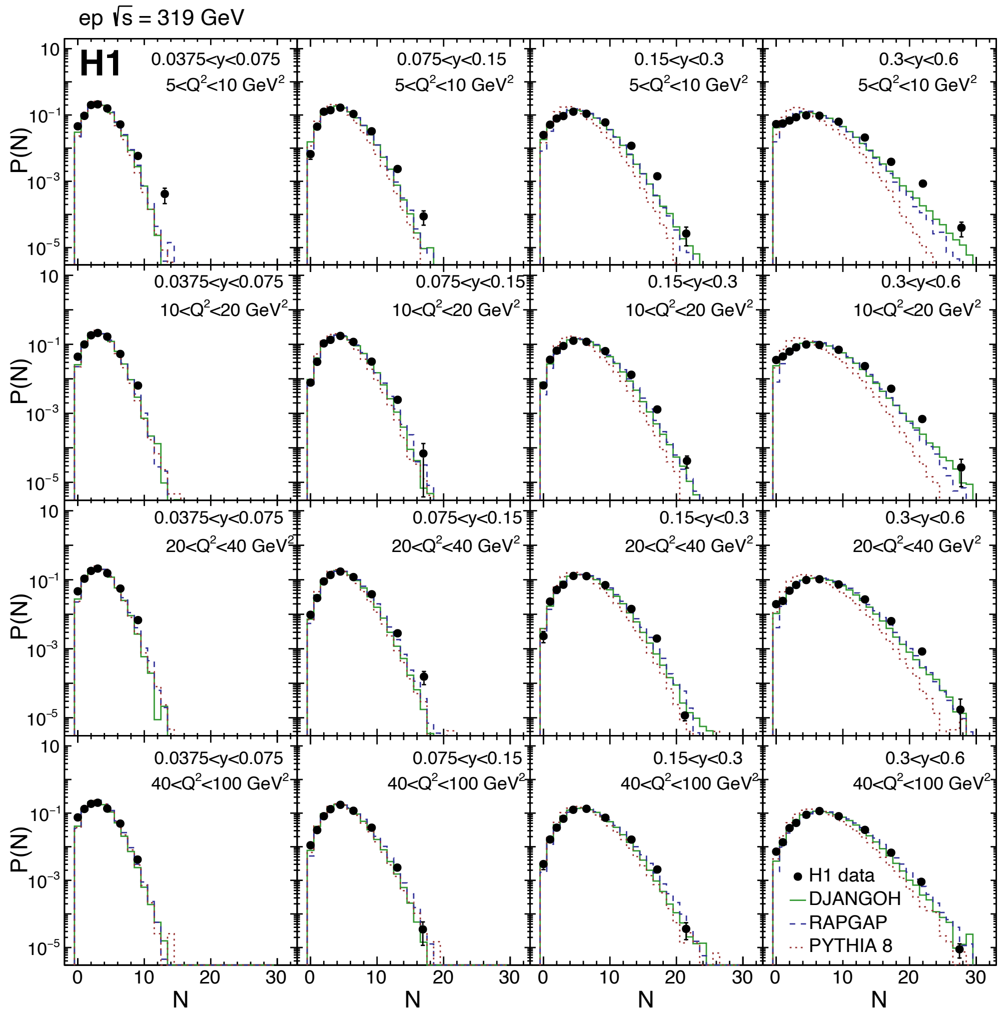
Backup: Long range correlations



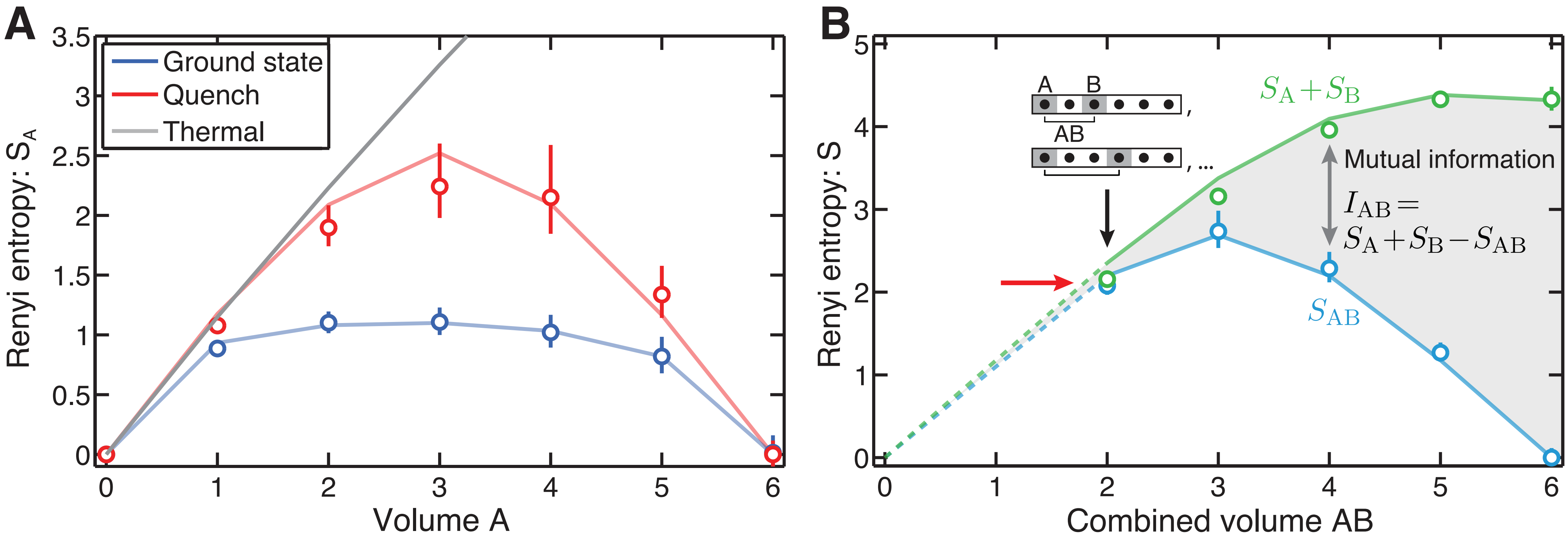


Backup: Entanglement entropy



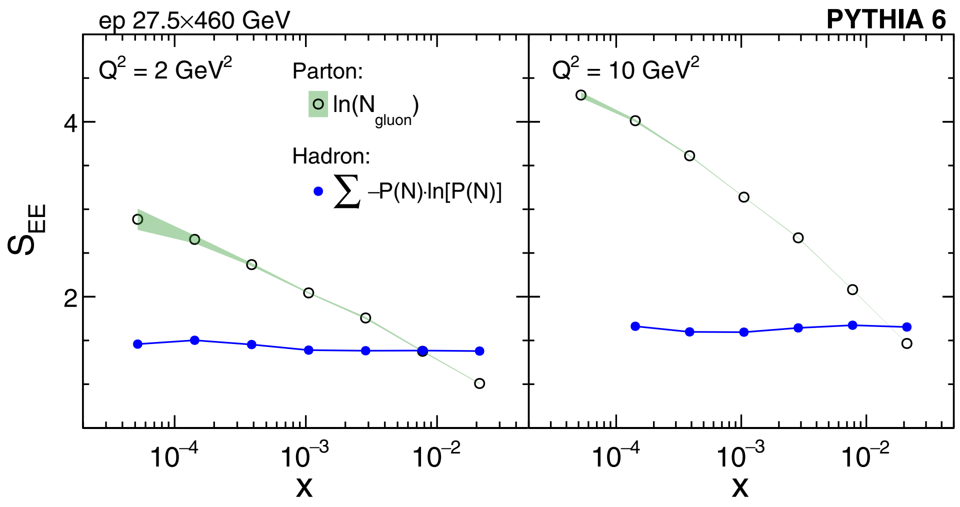


Backup: Entanglement entropy

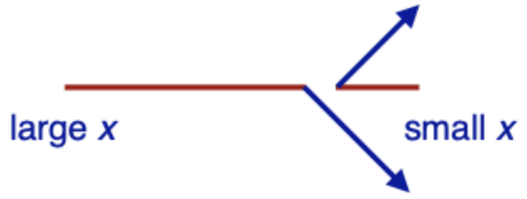


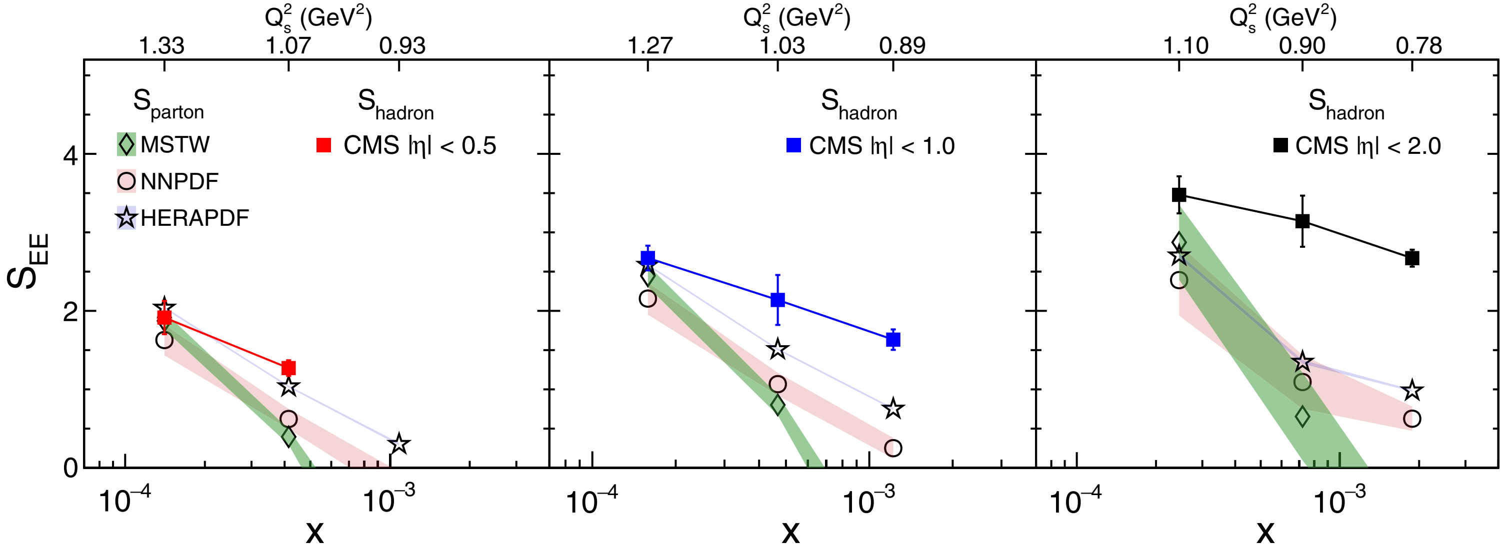
Condensed matter experiment: Bose-Einstein condensate of Rb atoms in 2D

Backup: Entanglement entropy



Both outgoing partons at forward rapidity





Boosted configuration:
One small-x, one large-x parton

$$\hat{s} = x_1 x_2 s \approx (2 p_T)^2$$

$$x_1 \approx \frac{2p_T}{\sqrt{s}} e^{-y}$$