

# Azimuthal decorrelation in lepton-jet and charged particle multiplicity measurements at HERA

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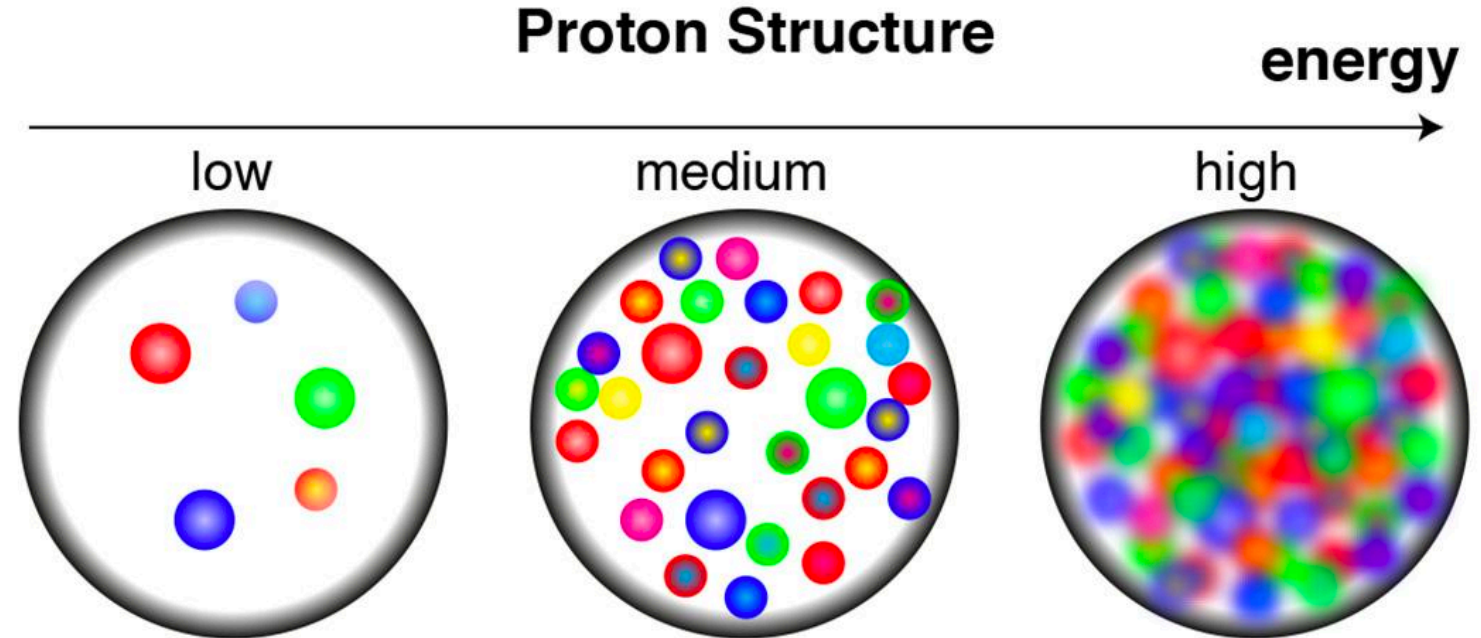
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# Proton structure

One of the most fundamental building blocks, e.g., proton – is much more complicated than what was originally thought.



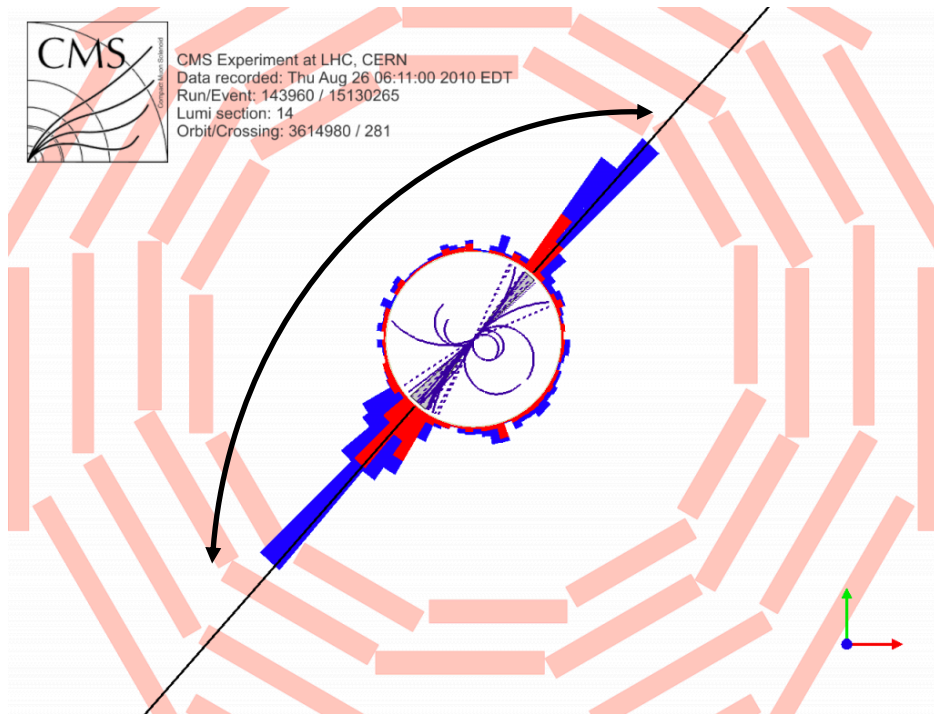
One of many **big questions**,

- What is the *pathway towards uncovering the mystery of confinement?*
- What is the dynamic picture for partons at high energy?
- ...

# Angular correlation in pp collisions

Dijets angular correlations can probe

- Parton radiation effect
- Higher order perturbative effects
- ...

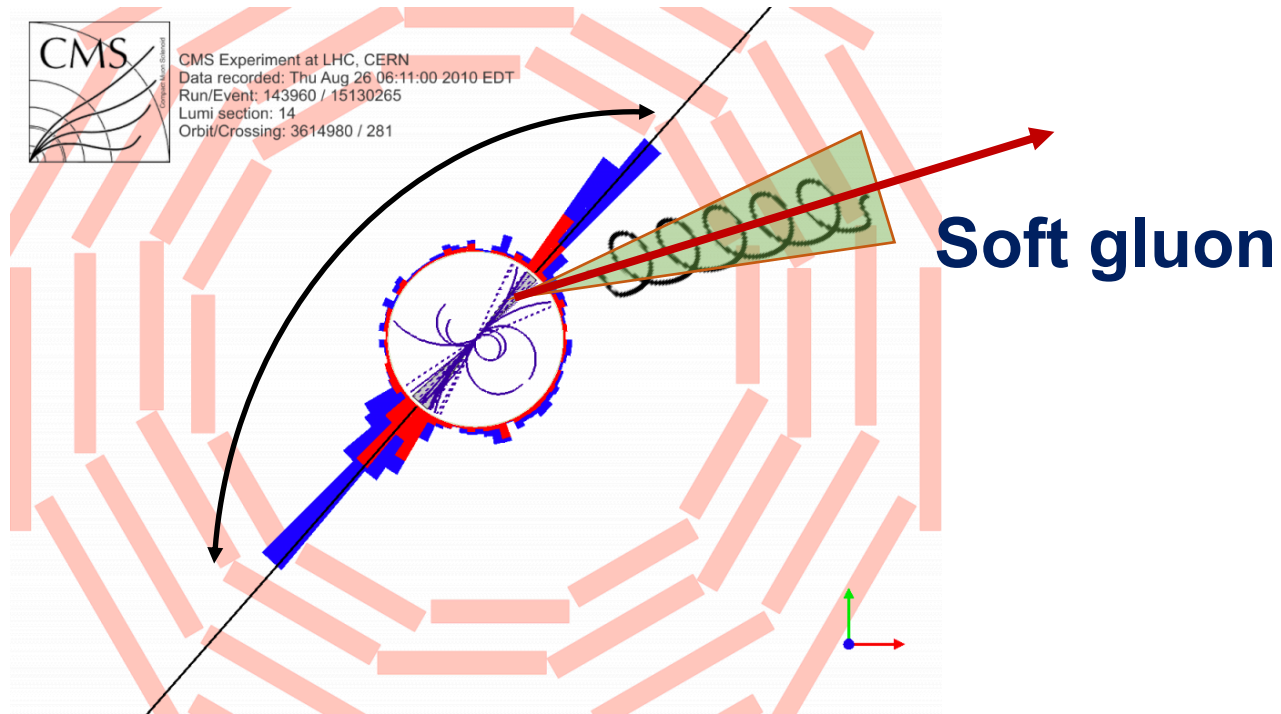


$\Delta\phi = |\phi_1 - \phi_2|$  back-to-back jets expects  $\sim \pi$

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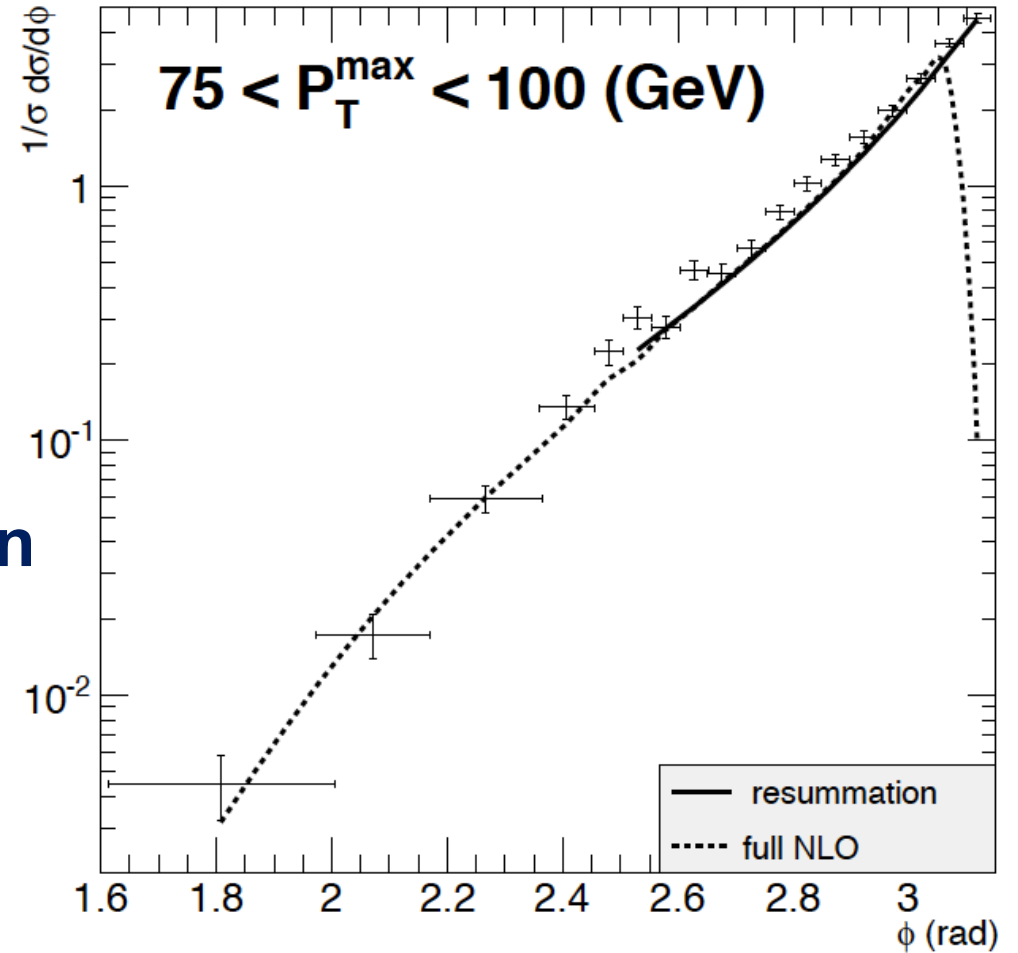
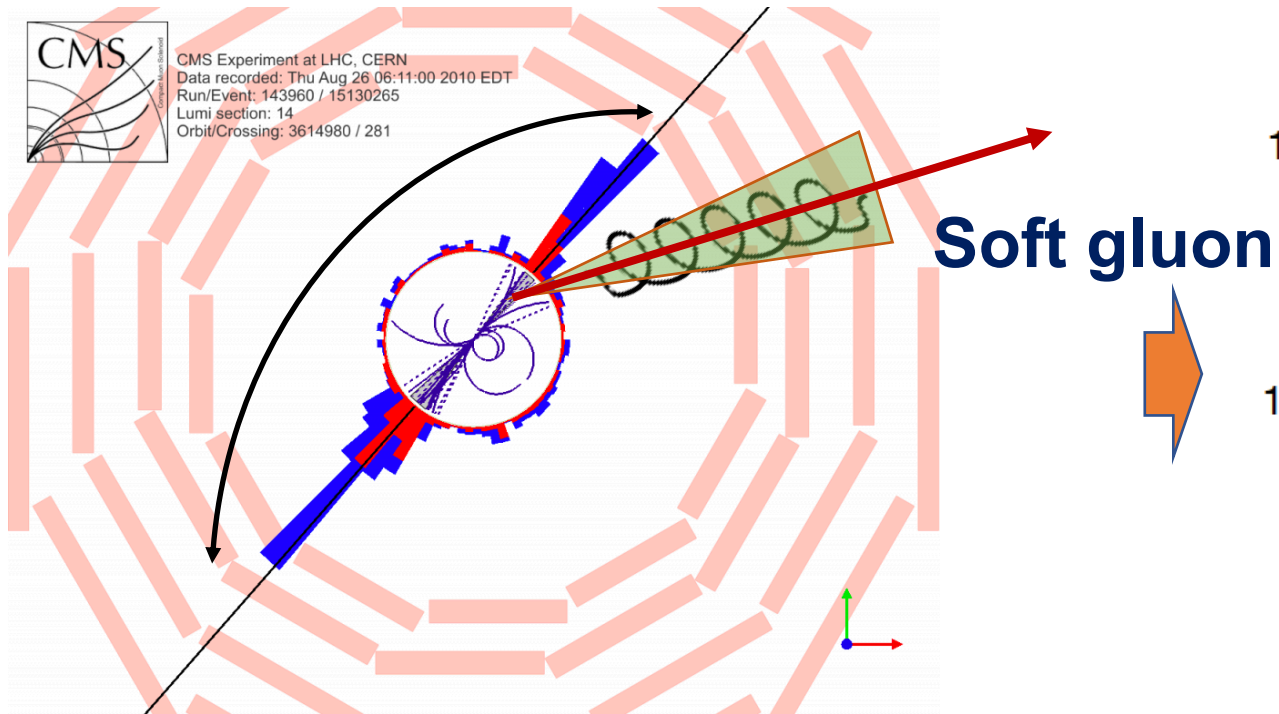


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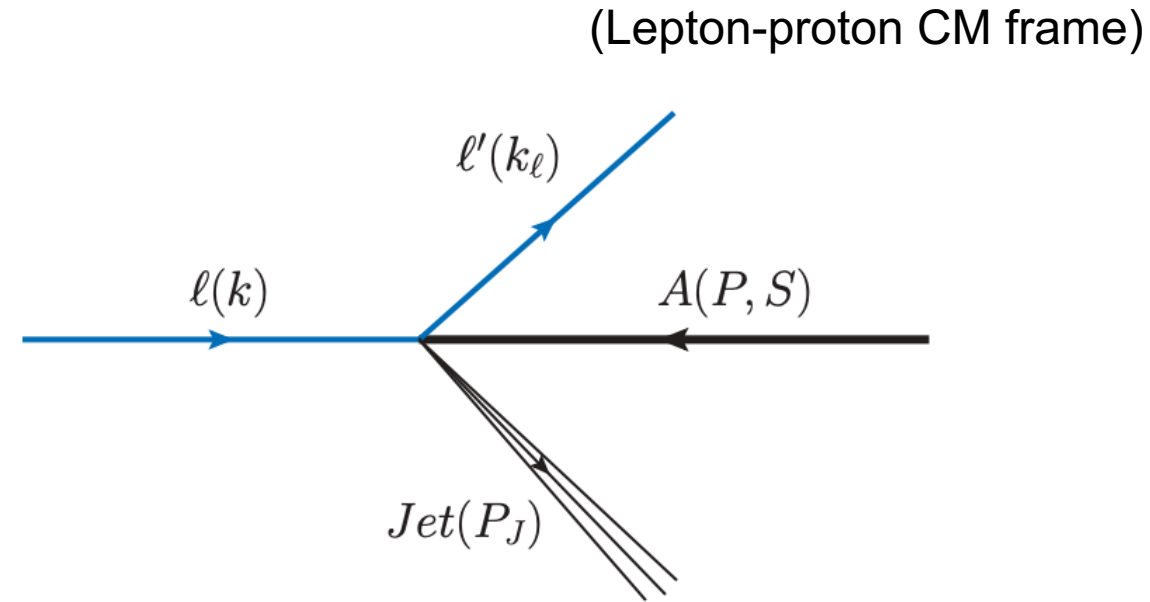
$\Delta\phi = |\phi_1 - \phi_2|$  back-to-back jets expects  $\sim \pi$

NLO calculation describes data very well  
(Phys. Rev. D 92, 094007 (2015))

# Application in ep DIS - TMDs

- New idea about looking at azimuthal correlation between scattered lepton and jet – sensitive to transverse momentum dependent parton distributions (TMDs)

(Phys. Rev. Lett. 122, 192003 (2019))

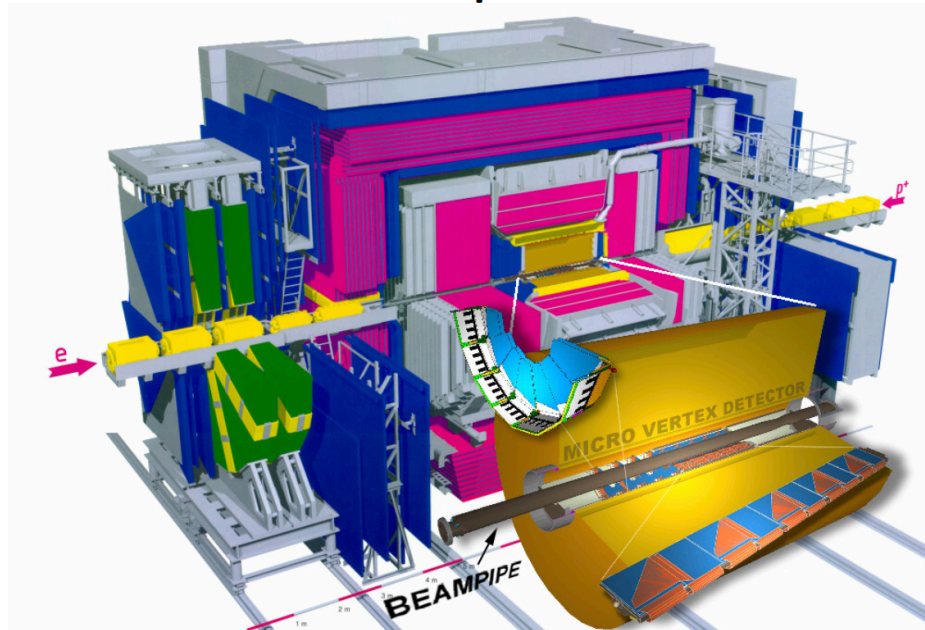


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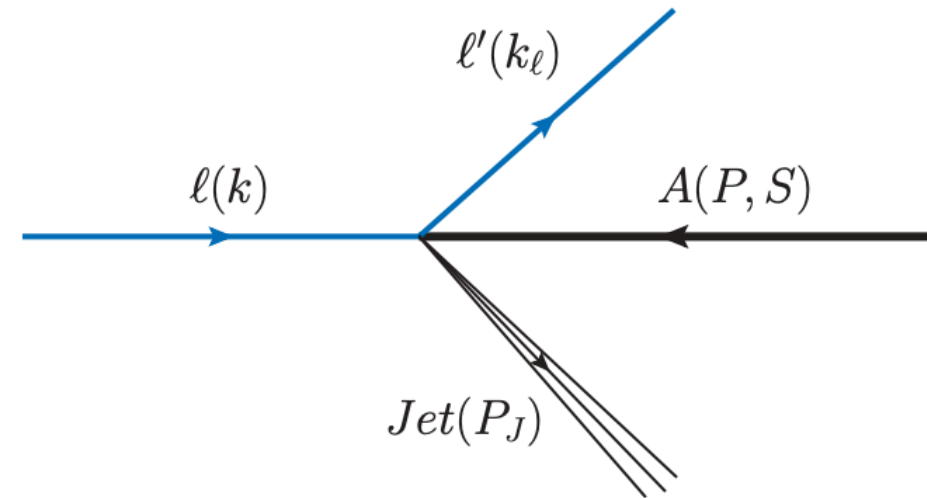
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## ZEUS Experiment



(Lepton-proton CM frame)



## Experimental attempt



Lepton-jet correlation in ep DIS:

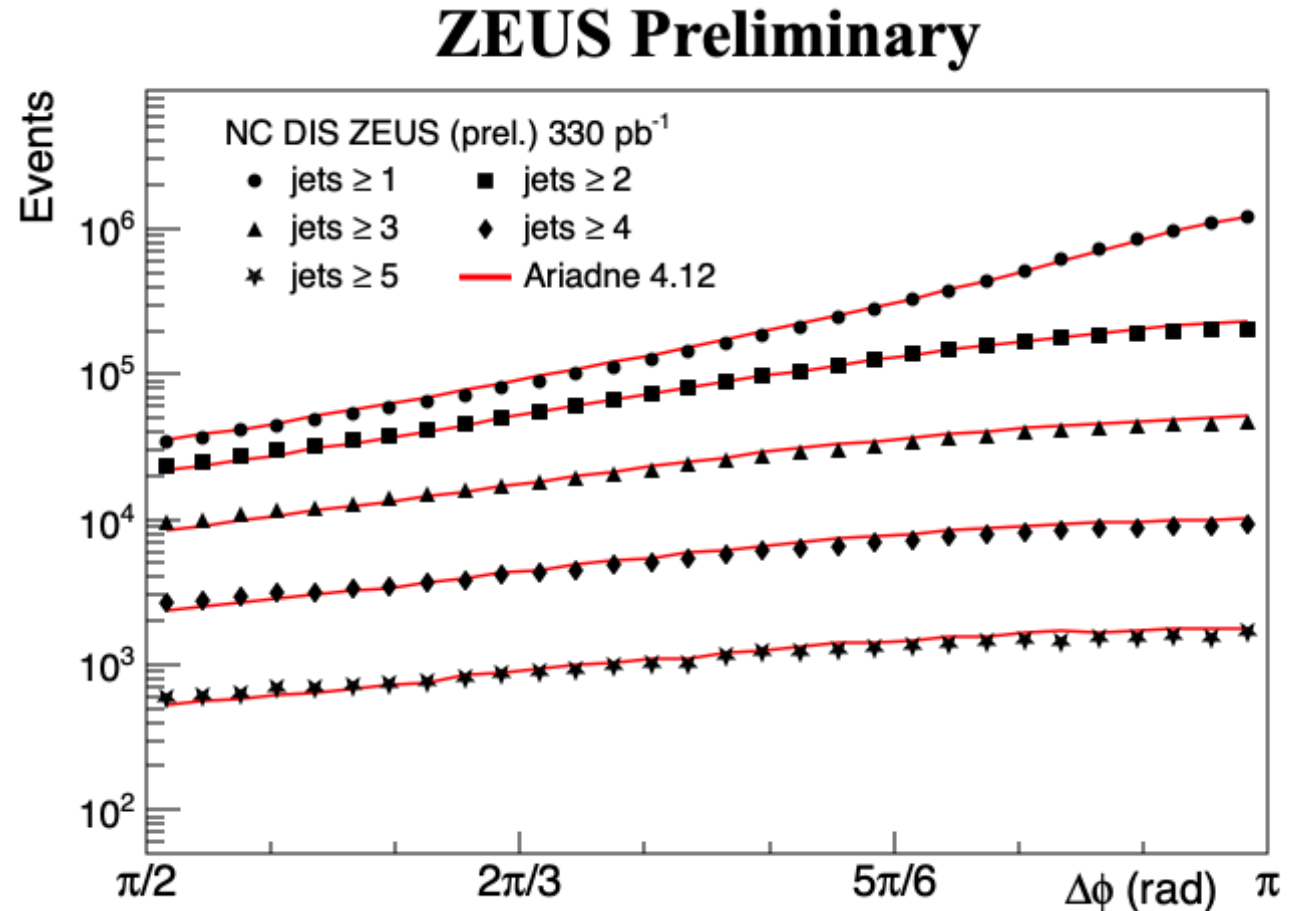
- Access small Bjorken-x at HERA
- $Q^2$  dependence on TMD evolution
- Non-perturbative effects

# ZEUS preliminary results

More details see Amilkar Quintero's DNP talk. Click [here](#)

Data from HERA-II with  $27.6 \times 920 \text{ GeV}^2 \text{ ep}$ :

- Luminosity  $\sim 330 \text{ pb}^{-1}$
- $10 < Q^2 < 350 \text{ GeV}^2$
- $E_{\text{lepton}} > 10 \text{ GeV}$
- $E_{T,\text{jet}} > 2.5 \text{ GeV}, |\eta_{\text{jet}}| < 1.0$



- Ariadne MC model describes data reasonably well
- some deviations are seen at lower angle, might be due to gluon radiations



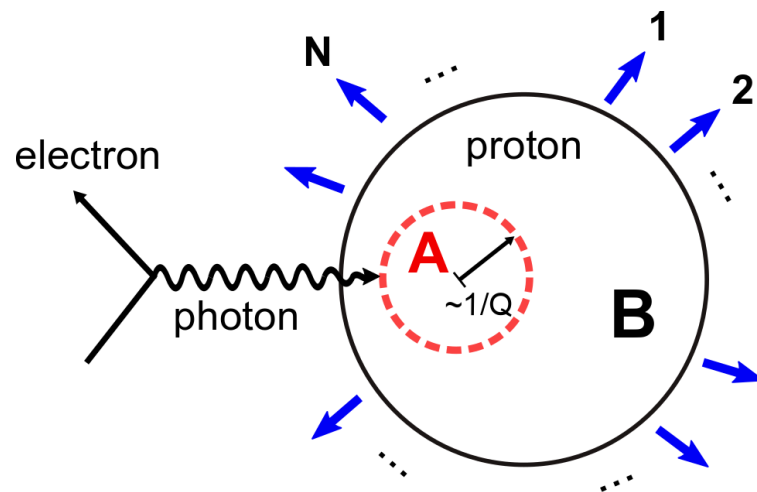
# Taking one step further in ep DIS

- How does MC describe HFS particle productions besides jets?
- What's the role of gluons in particle production?

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New idea about probing proton structure at low- $x$  via quantum entanglement in DIS



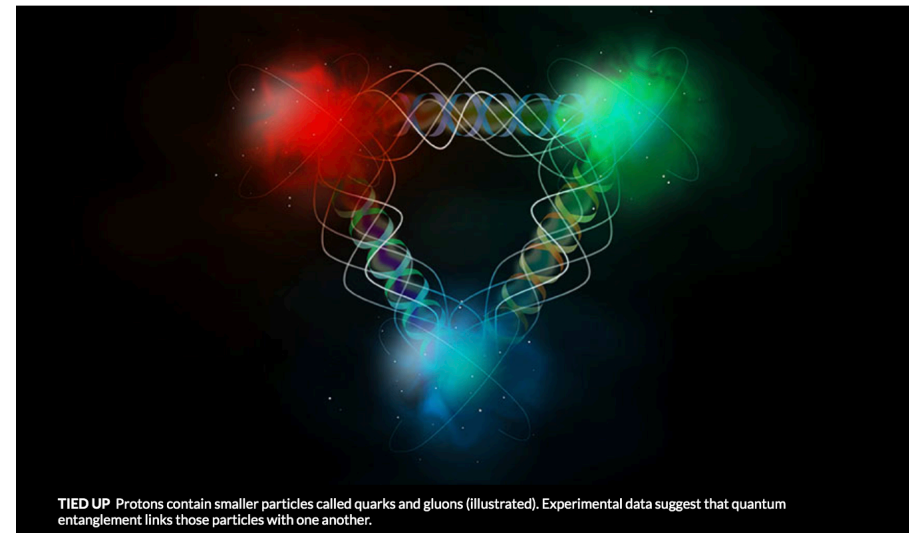
$$S_{\text{gluon}} = \ln[xG(x, Q^2)] \sim S_{\text{hadron}} = - \sum p(N) \ln p(N)$$

(Phys. Rev. Lett. 124, 062001 (2020))

NEWS QUANTUM PHYSICS, PARTICLE PHYSICS

## An experiment hints at quantum entanglement inside protons

LHC data suggests the subatomic particle's constituent quarks and gluons share weird links  
BY EMILY CONOVER 11:18AM, MAY 17, 2019



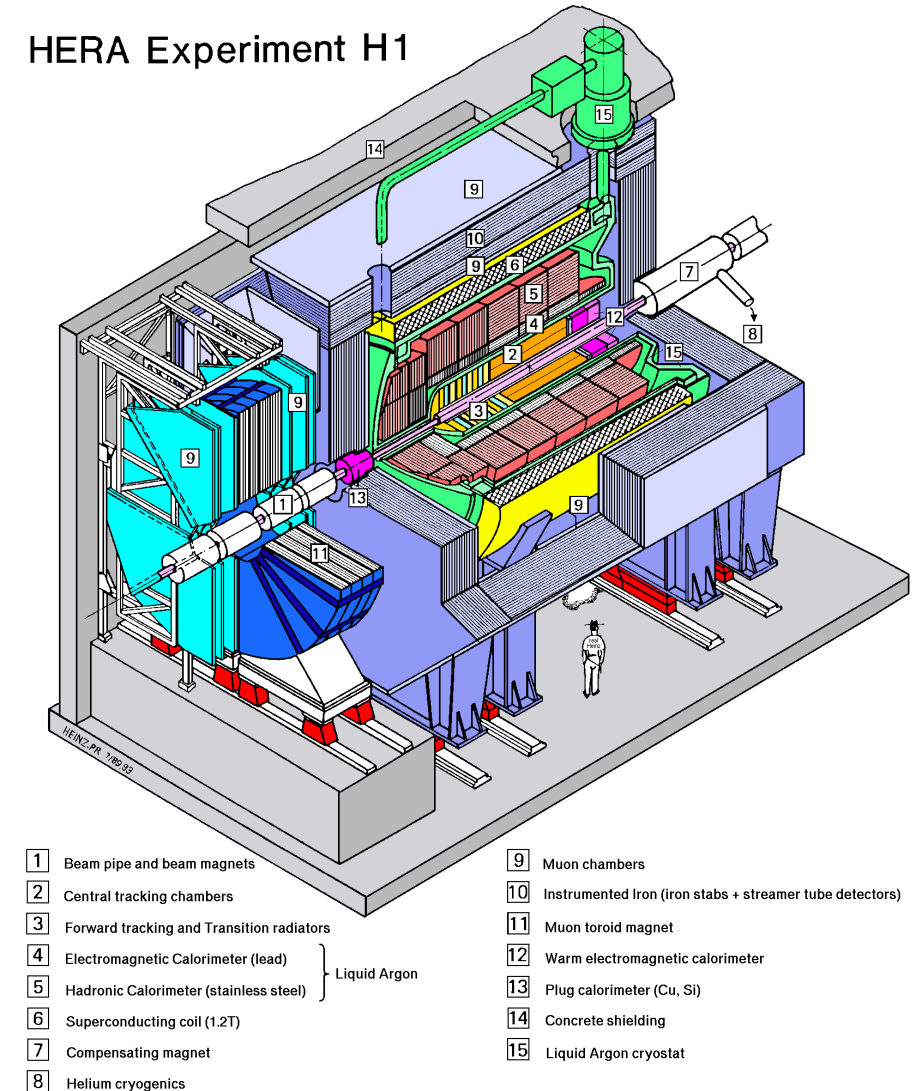
TIED UP Protons contain smaller particles called quarks and gluons (illustrated). Experimental data suggest that quantum entanglement links those particles with one another.

SCIFY/SHUTTERSTOCK

<https://www.sciencenews.org/article/experiment-hints-quantum-entanglement-inside-protons>

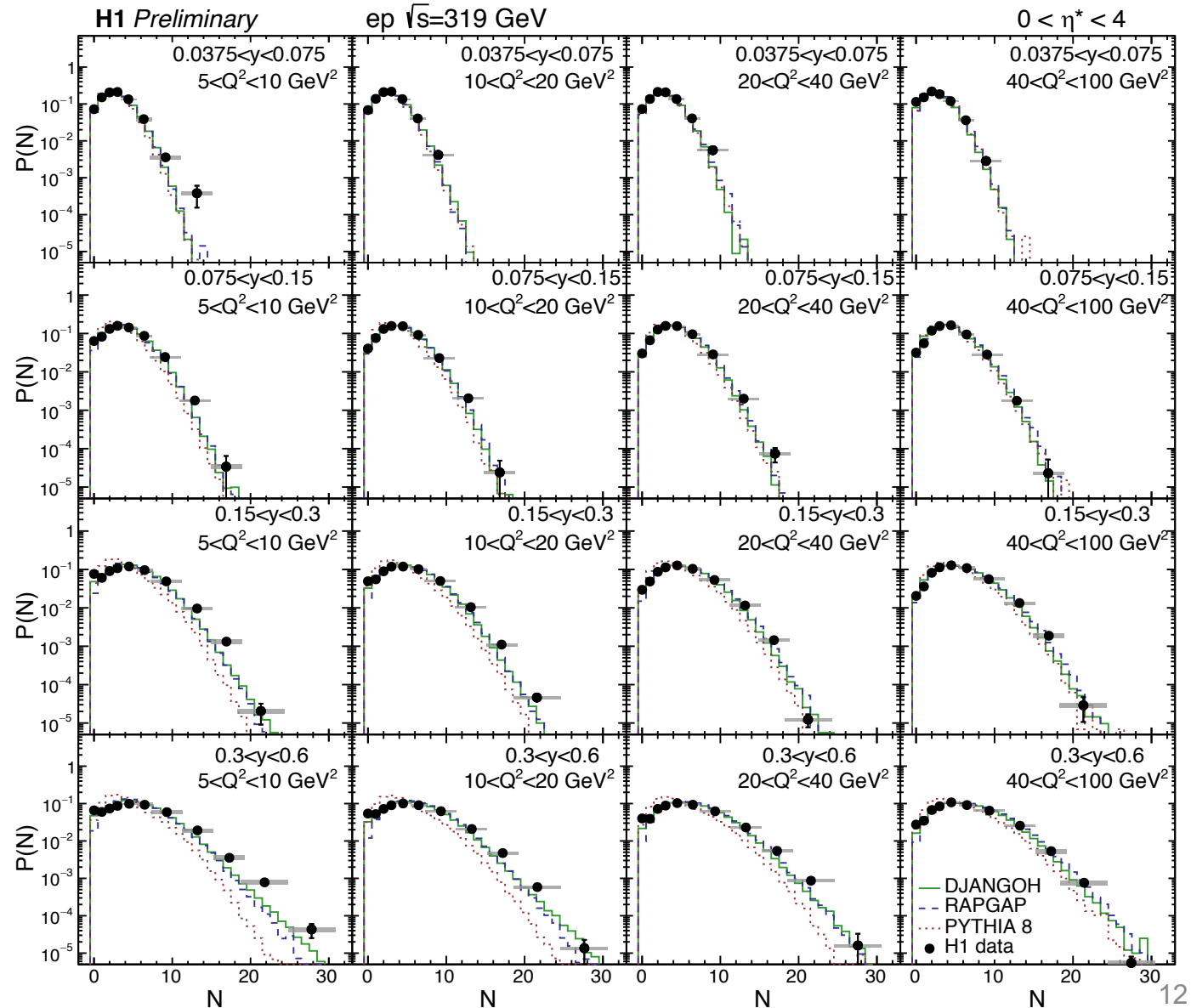
# H1 analysis

- DIS  $e+p$  at  $27.6 \times 920 \text{ GeV}^2$  collisions
- $5 < Q^2 < 100 \text{ GeV}^2$
- $0.0375 < y < 0.6$
  
- Measure charged particle multiplicity distributions,  $p(N)$ , in bins of  $y$  and  $Q^2$
- Moments of multiplicity
- Hadron entropy (new observable)  
(Phys. Rev. Lett. 124, 062001 (2020))
  
- Compare with MC models and entanglement model



# Charged particle multiplicity

- Tracks are within  $|\eta_{\text{lab}}| < 1.6$  and  $p_t > 0.15$  GeV
- Tracks are boosted in Hadronic center-of-mass frame (HCM) with  $|\eta^*| < 4.0$
- Compare with DJANGO 1.4, RAPGAP 3.1, and PYTHIA 8
- Low- $Q^2$  are not well described by MCs

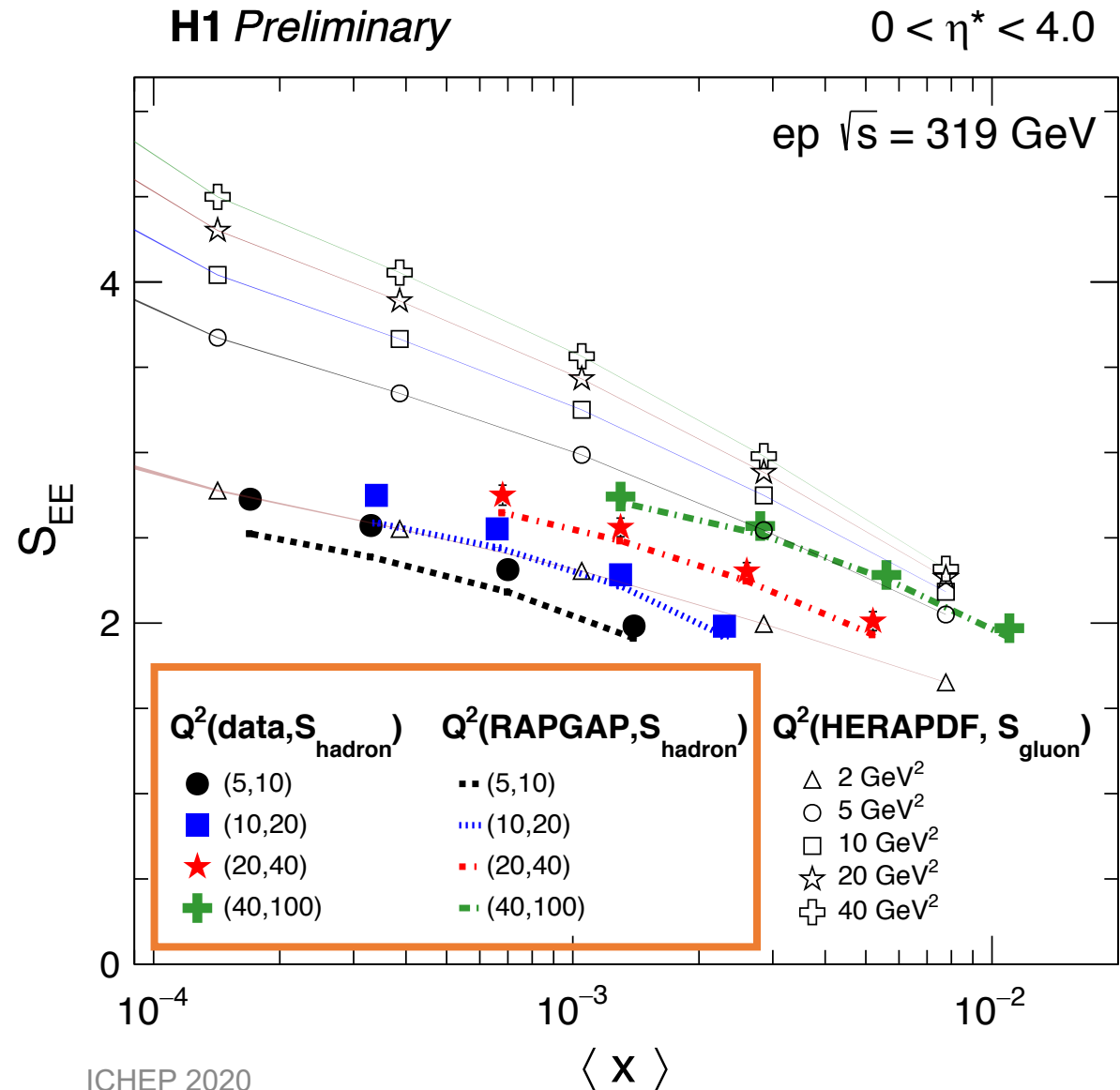


# Hadron entropy

$$S_{\text{hadron}} = - \sum p(N) \ln p(N)$$

## DATA and MC comparison

- High  $Q^2$  and high  $x$  are in good agreement with MC
- Low- $x$  and lower  $Q^2$  are not. Clearly difference is seen.



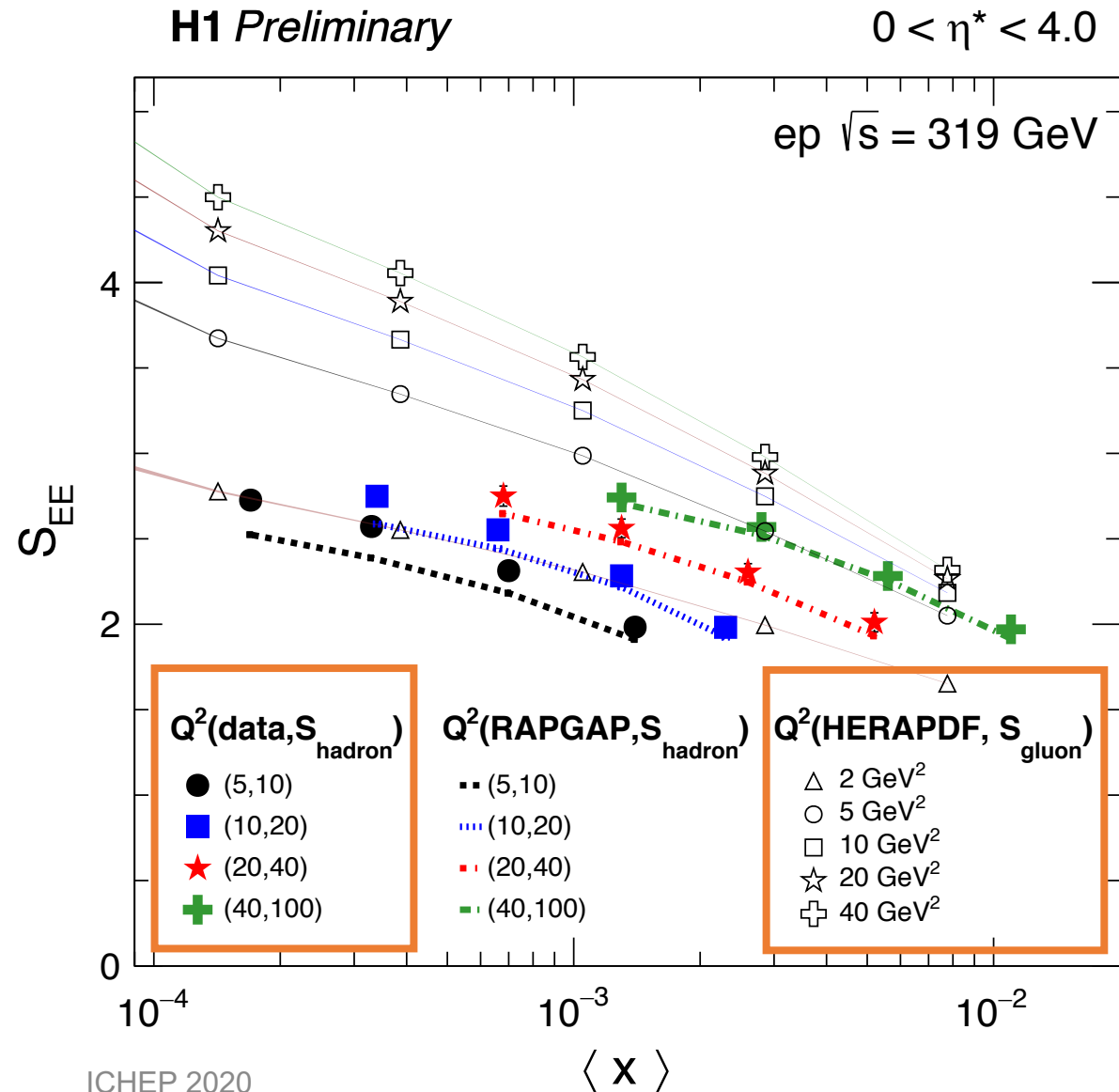
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## DATA and theory comparison

- Entanglement entropy from gluon density overpredicted the magnitude of entropy
- Indication of theory of entanglement entropy still has room to be improved.



# Summary

- First studies of lepton-jet correlation in ep DIS by ZEUS collaboration – sensitive probe to the TMDs
- First time measurement of hadron entropy from HFS of charged particles by H1 collaboration – searching for *quantum entanglement* of partons in ep DIS.

(paper will come out by the end of summer)

- Both measurements have set a baseline for future experiment of Electron-ion Collider at BNL in ep and eA.
- Stay tuned for further developments from H1 and ZEUS as many new projects are on-going!