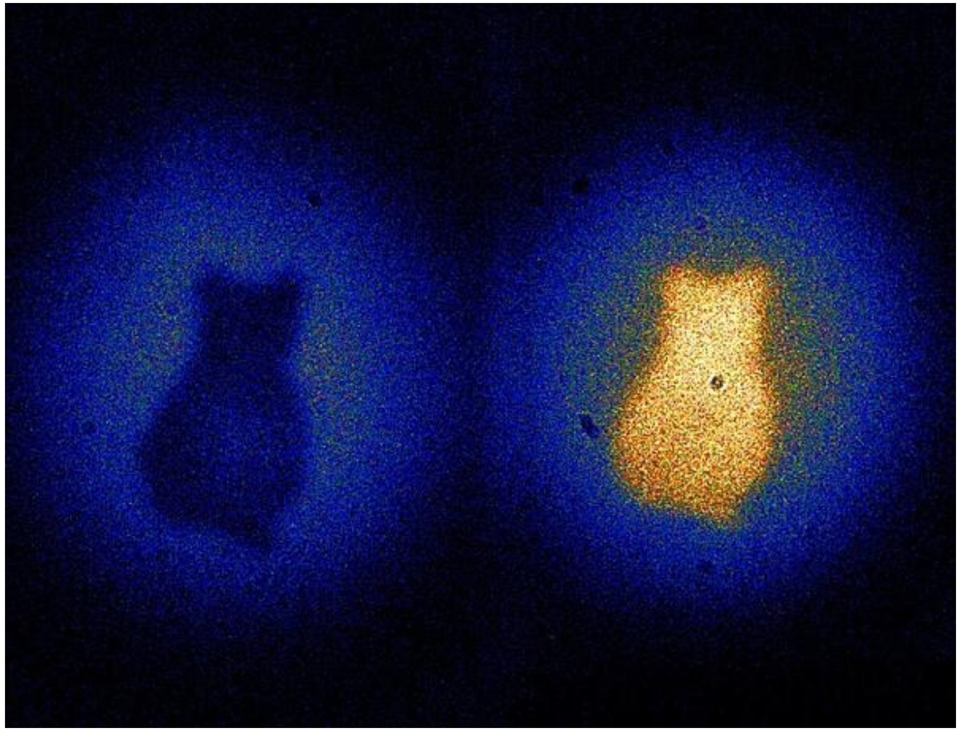
Measurement of **E**ntanglement **E**ntropy in high energy particle collisions



Quantum imaging of Schrödinger's cat, Science 05 Sep 2014

Is entanglement deeply connected to the fundamental structure of our visible universe…?

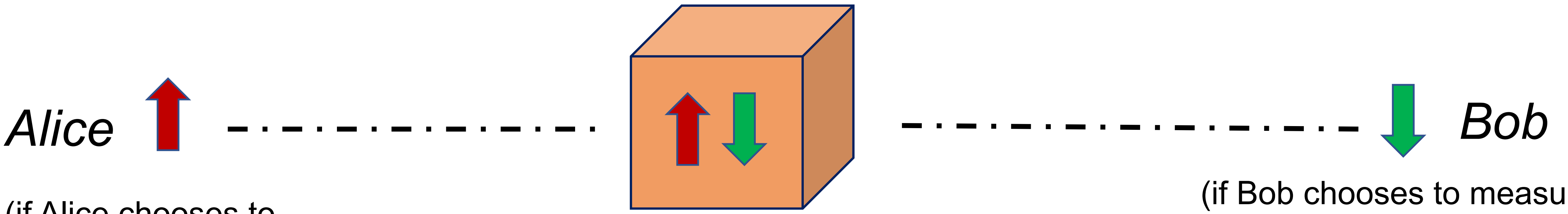
Kong Tu

BNL

06. 08. 2021

A story of Alice and Bob

"spooky action at a distance…"



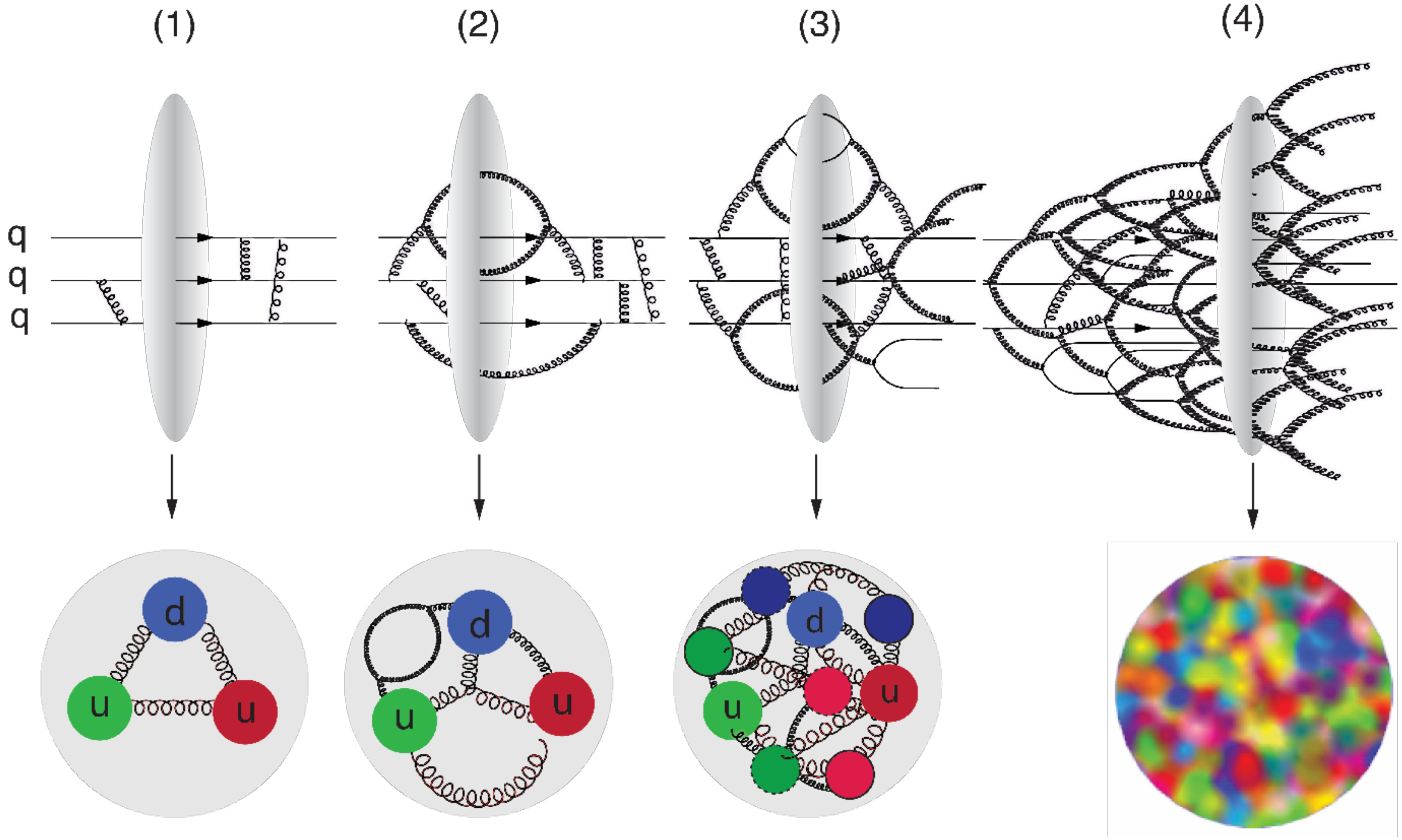
(if Alice chooses to measure its spin in z axis)

(if Bob chooses to measure its spin in z axis too)

100% correlated spin projection results,
no matter how far Alice and Bob is apart.

Known as the Einstein-Podolsky-Rosen paradox, the **EPR paradox**.
This quantum feature is the *quantum entanglement*.

Proton



Proton going from low → high energy

Proton - a quantum mechanical pure state.

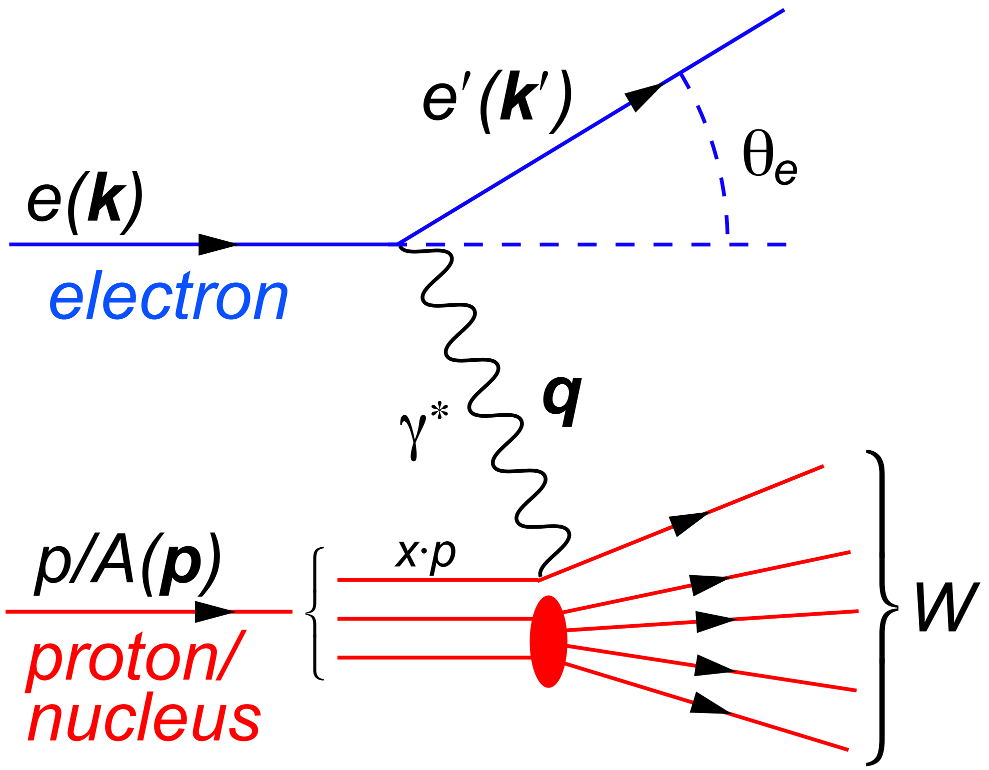
All partons are entangled quantum mechanically.

- e.g., all the states of partons **cannot** be written as,

$$|\Psi\rangle = |\Psi_1\rangle \otimes |\Psi_2\rangle \otimes |\Psi_3\rangle \ldots$$

DIS and nucleon structure

Deep Inelastic Scattering

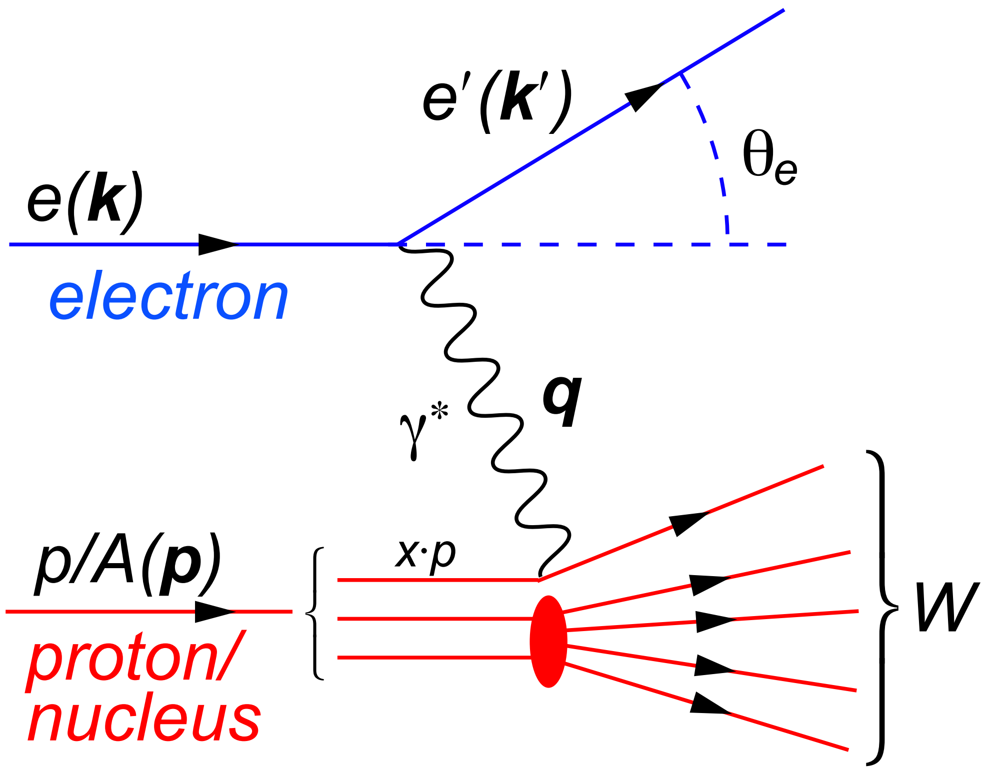


1. Resolution ~ $Q^2 = -q^2$
2. Momentum fraction ~ $x_{\mathrm{bj}} = \dfrac{Q^2}{2Pq}$

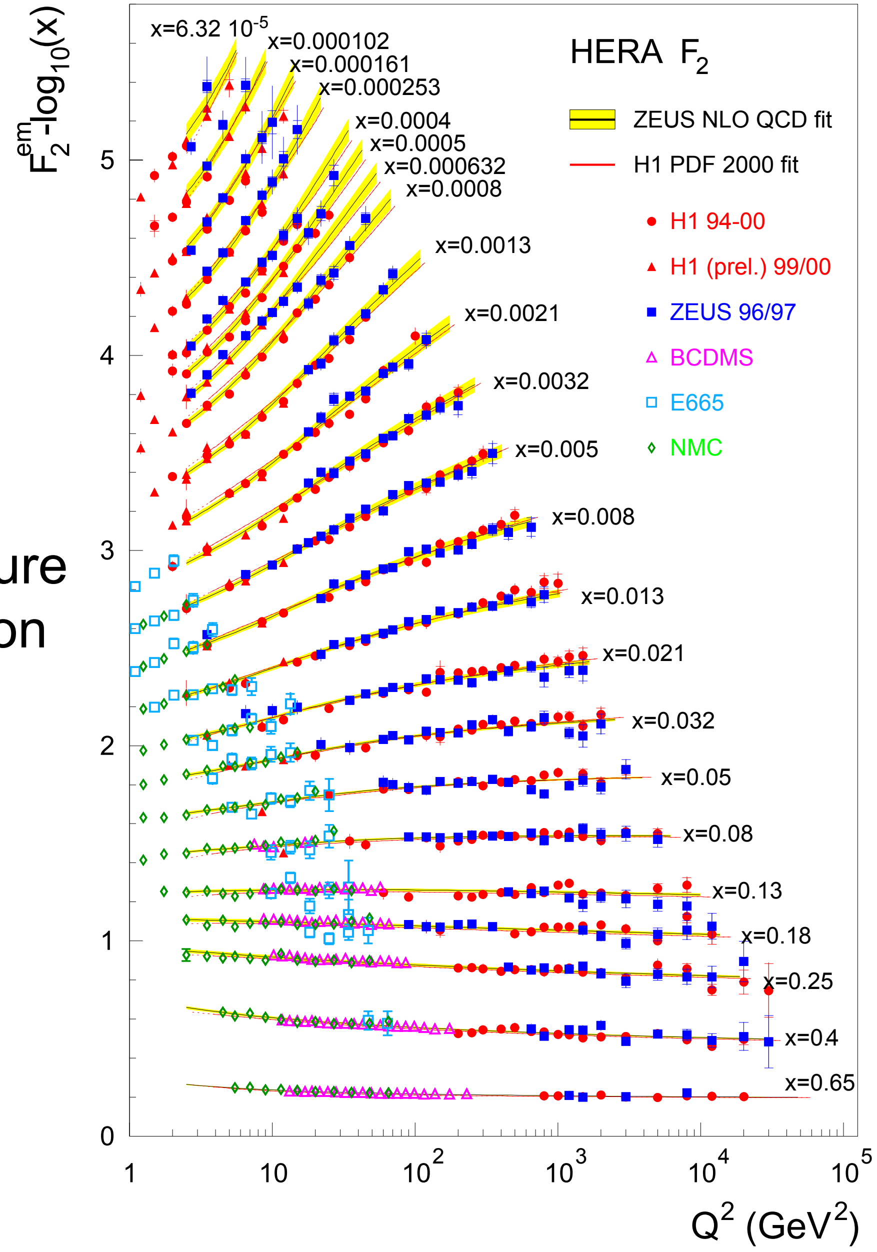
   "Exposure time"

DIS and nucleon structure

Deep Inelastic Scattering



structure function



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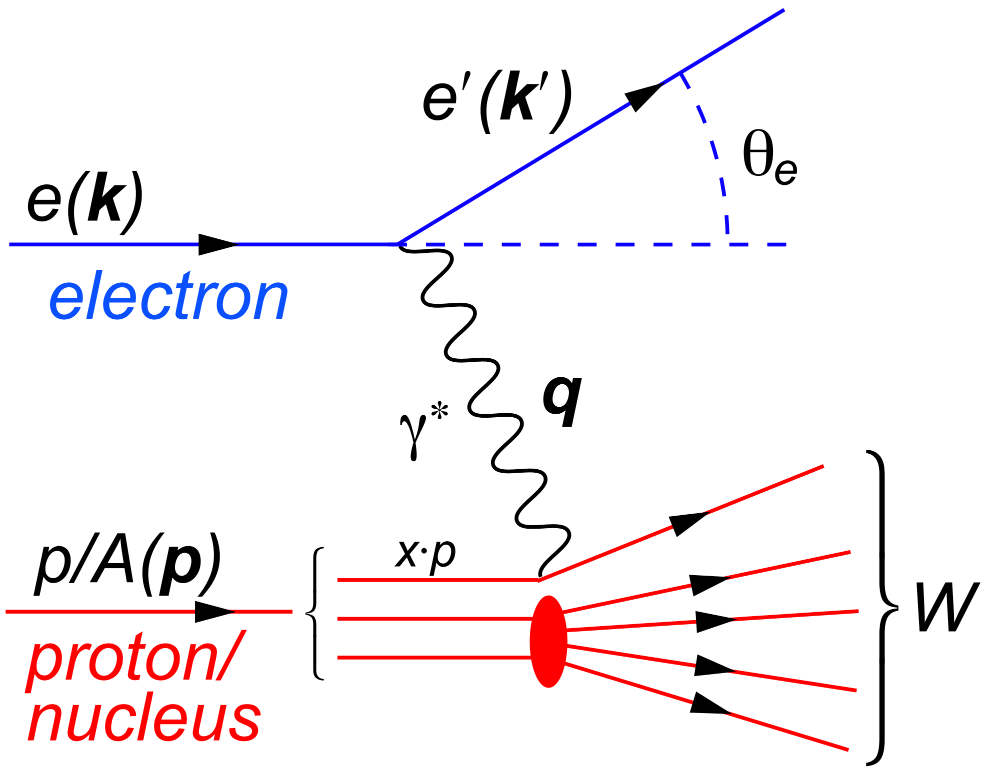
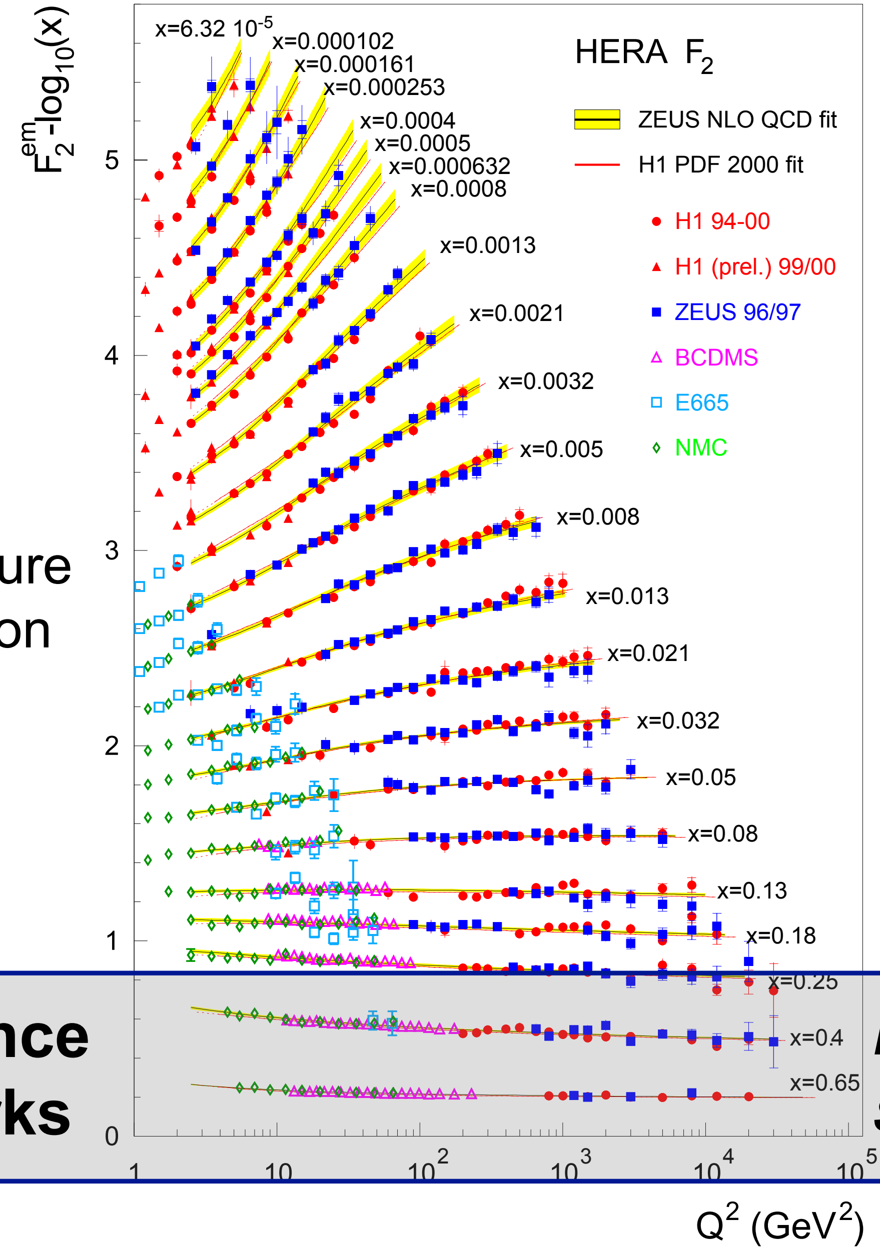


structure function



Valence Quarks

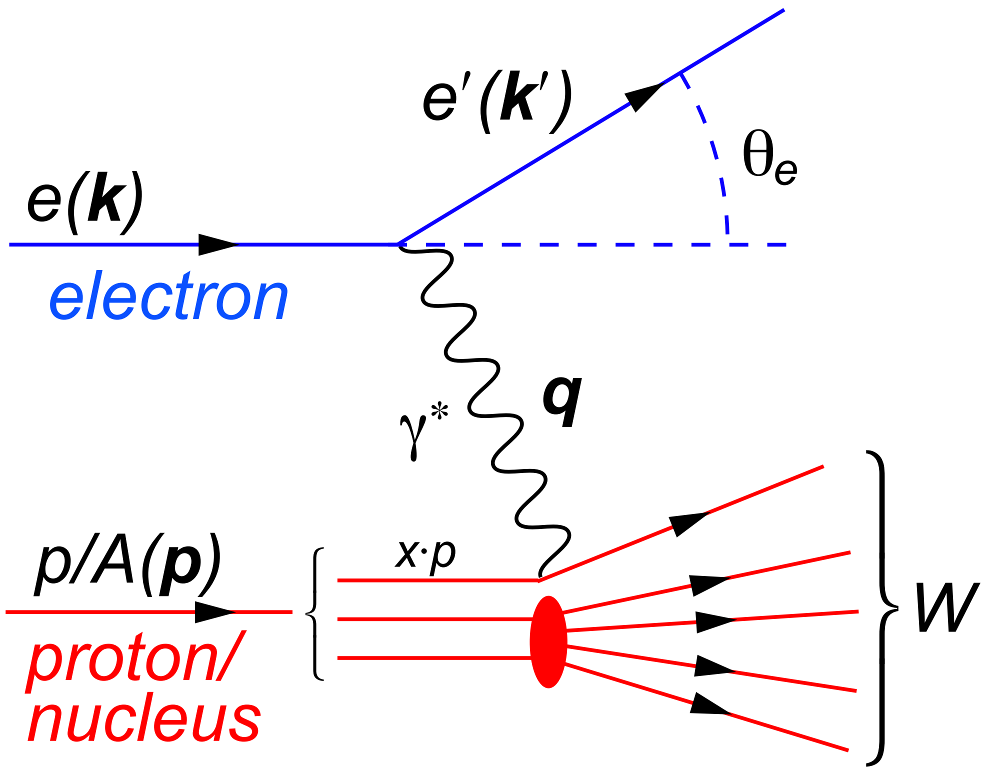
Bjorken-scaling

1. Resolution ~ $Q^2 = -q^2$
2. Momentum fraction ~ $x_{\mathrm{bj}} = \dfrac{Q^2}{2Pq}$

   "Exposure time"

DIS and nucleon structure

Deep Inelastic Scattering



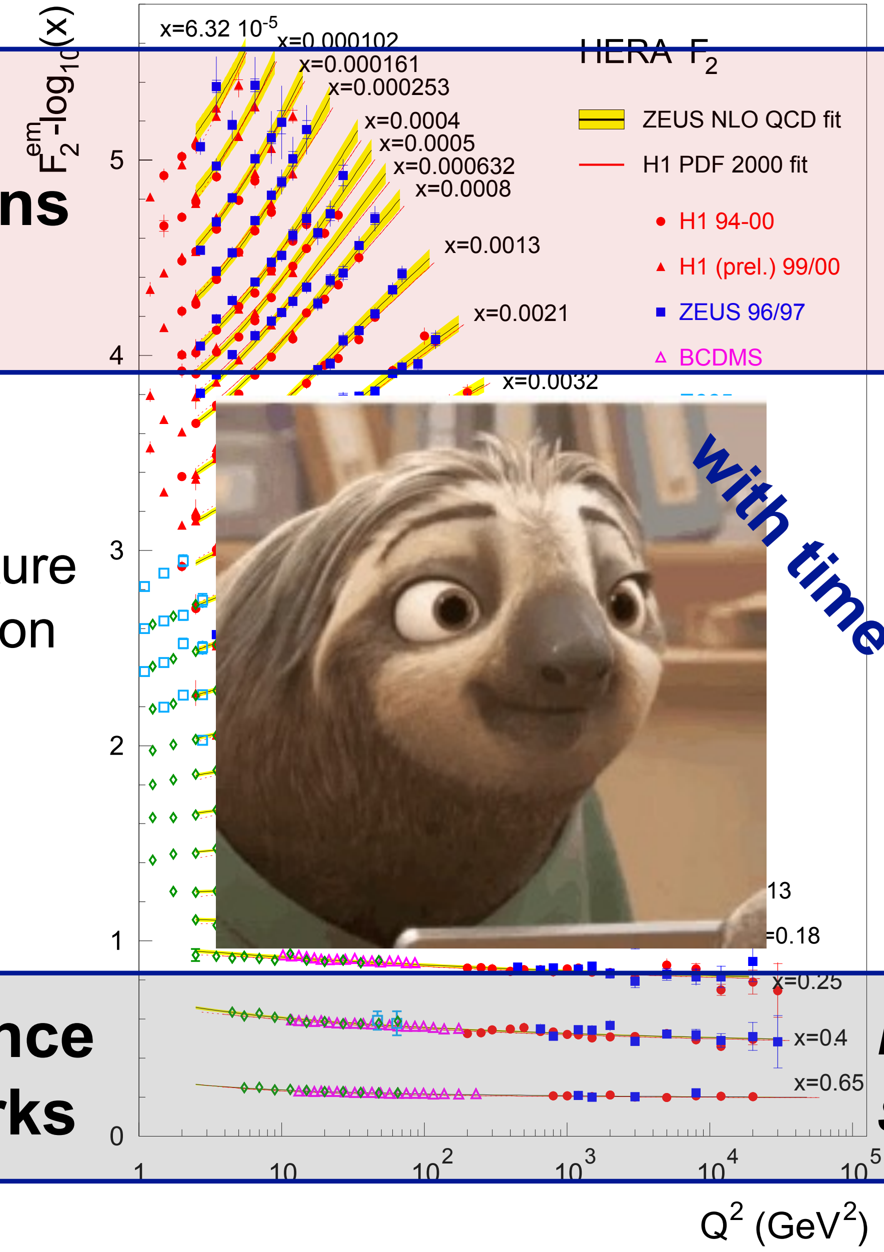
1. Resolution ~ $Q^2 = -q^2$
2. Momentum fraction ~ $x_{\mathrm{bj}} = \dfrac{Q^2}{2Pq}$

“Exposure time”

structure function

Gluons

Scaling violation



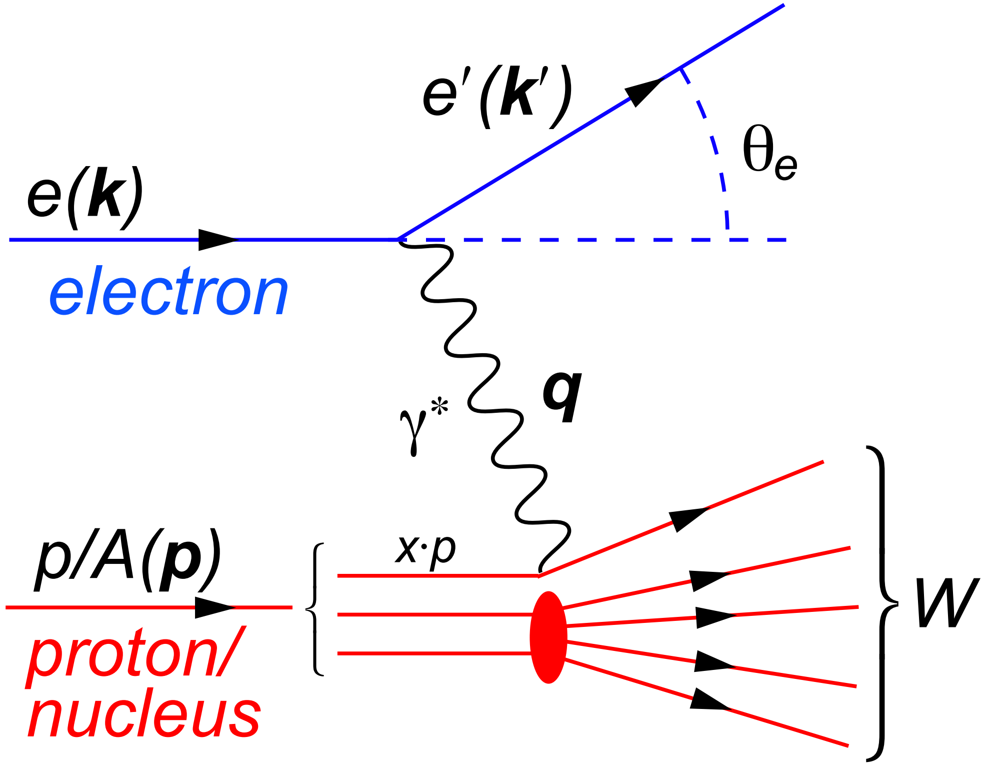
with time dilation ...

Valence Quarks

Bjorken-scaling

DIS and nucleon structure

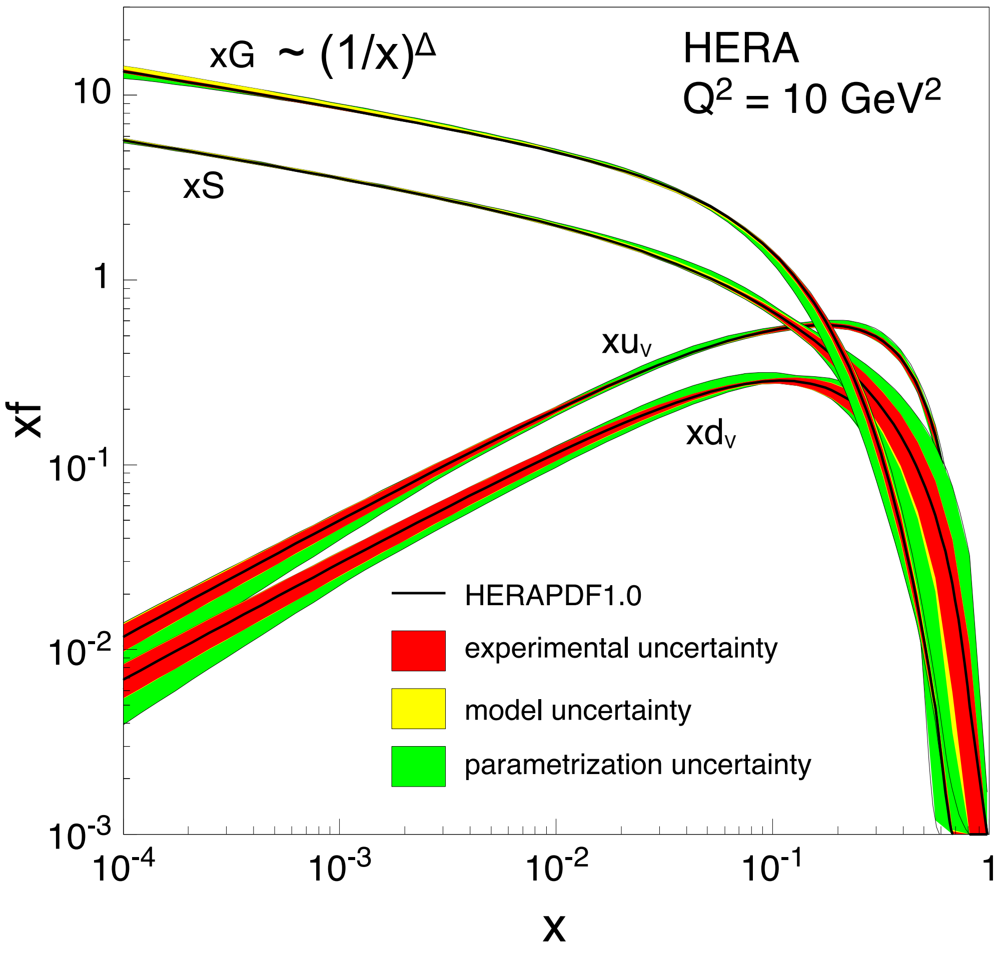
Deep Inelastic Scattering



1. Resolution ~ $Q^2 = -q^2$
2. Momentum fraction ~ $x_{\mathrm{bj}} = \dfrac{Q^2}{2Pq}$

   "Exposure time"

Parton Distribution Functions (PDFs)

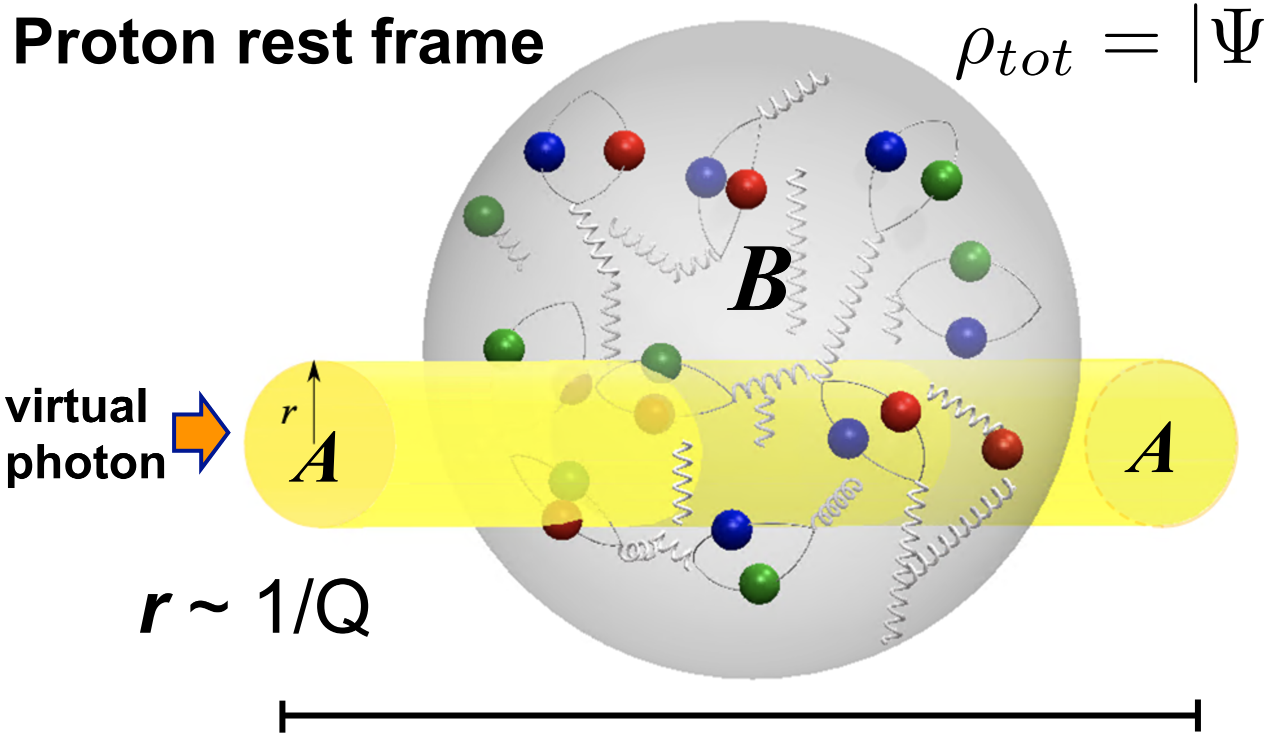


Entanglement Entropy (EE)

Pure state

Proton rest frame

$$\rho_{tot} = |\Psi\rangle\langle\Psi|$$

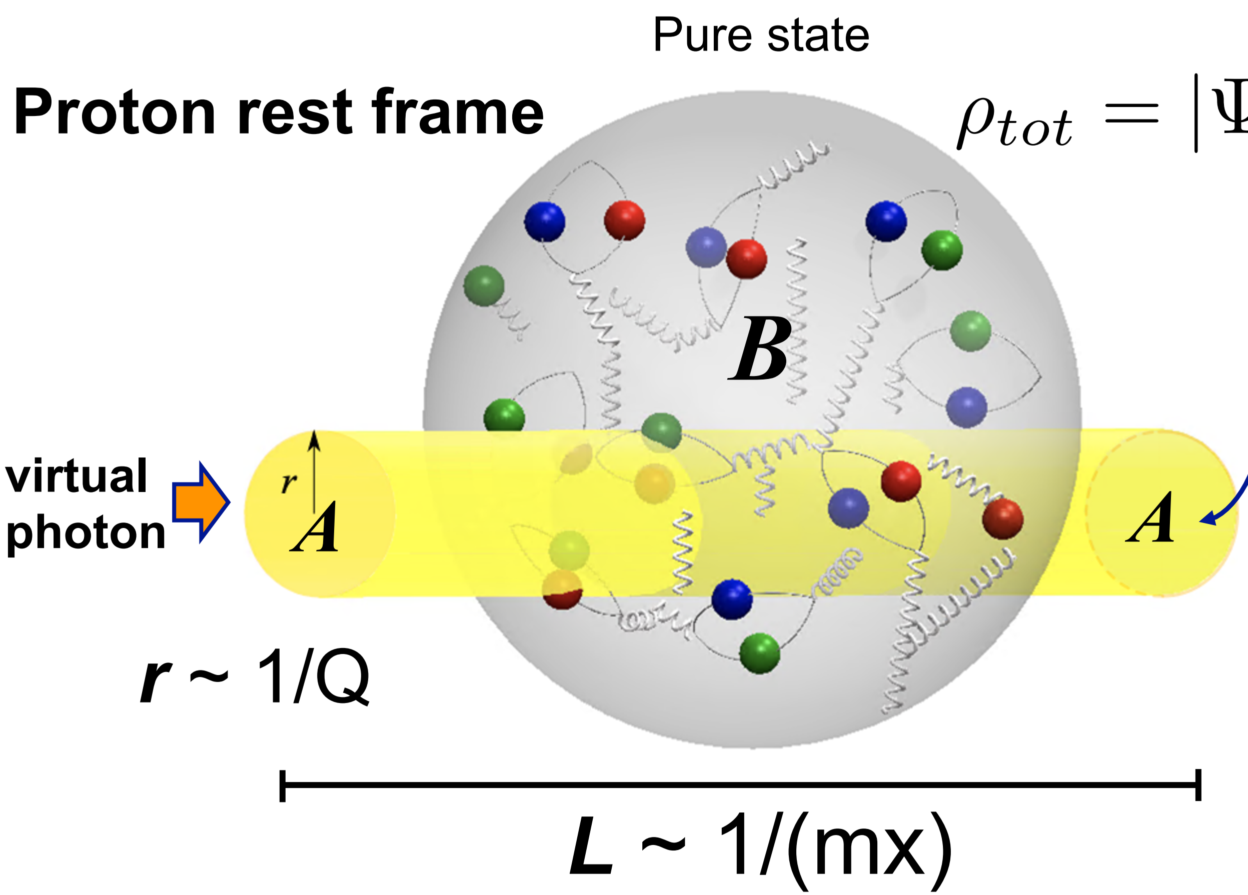


r ~ 1/Q

L ~ 1/(mx)

Entanglement Entropy (EE)

Proton rest frame



$$\rho_{tot} = |\Psi\rangle\langle\Psi|$$

$$\rho_A \equiv \mathrm{Tr}_{\mathrm{B}}(\rho_{\mathrm{tot}})$$

(reduced density matrix)

$$S_A = -\mathrm{Tr}\rho_{\mathrm{A}} \ln \rho_{\mathrm{A}}$$

(von Neumann entropy)

Von Neumann entropy

From Wikipedia, the free encyclopedia

In quantum statistical mechanics, the **von Neumann entropy**, named after John von Neumann, is the extension of classical Gibbs entropy concepts to the field of quantum mechanics. For a quantum-mechanical system described by a density matrix ρ, the von Neumann entropy is[1]

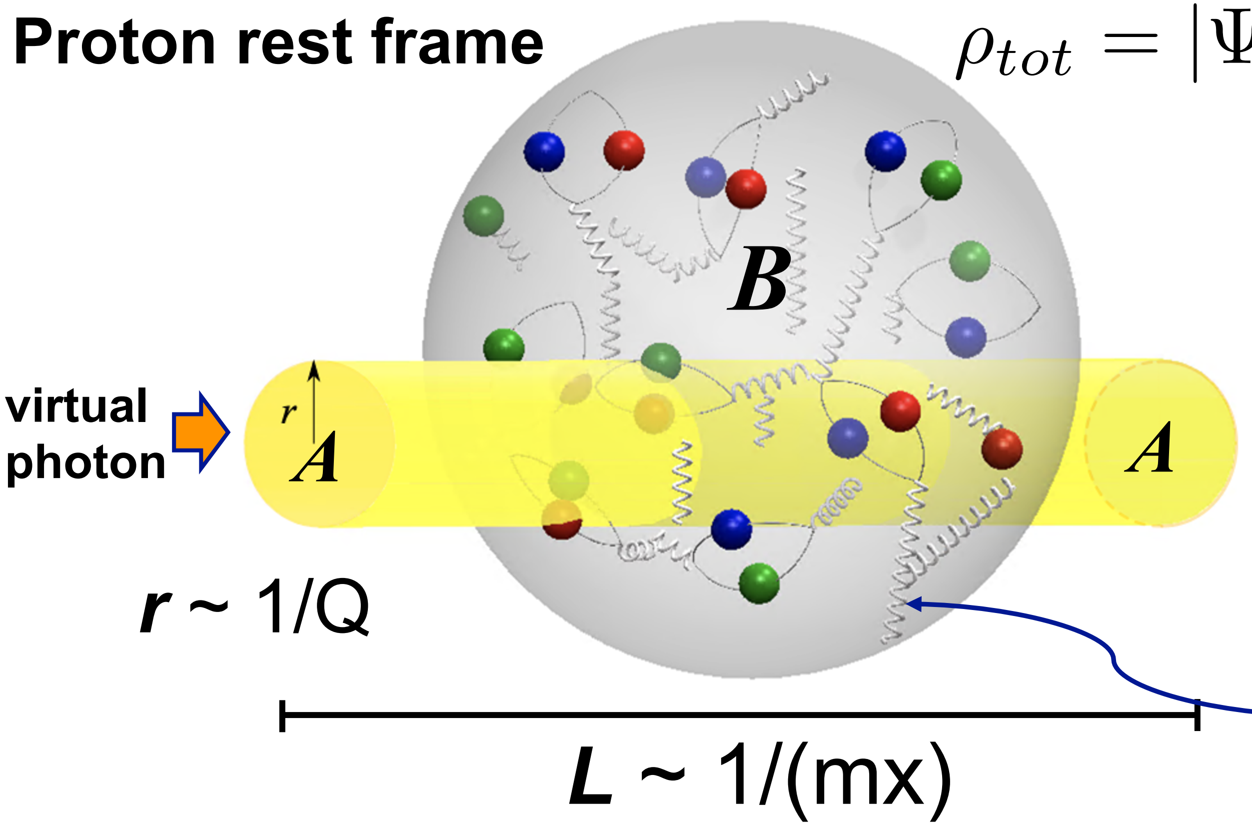
$$S = -\operatorname{tr}(\rho \ln \rho),$$

Entanglement Entropy (EE)

Proton rest frame

Pure state

$$\rho_{tot} = |\Psi\rangle \langle\Psi|$$



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$$\rho_B \equiv \mathrm{Tr_A}(\rho_{tot})$$
(reduced density matrix)

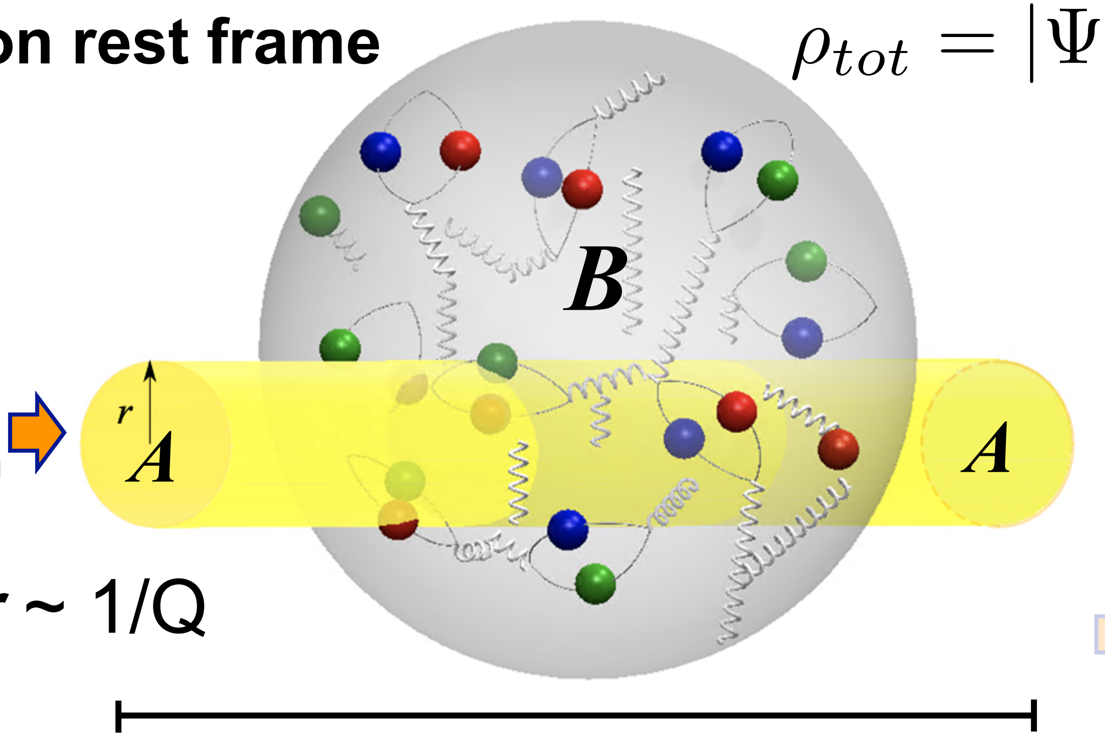
$$S_B = -\mathrm{Tr}\rho_B \ln \rho_B$$
(von Neumann entropy)

Entanglement Entropy (EE)

Pure state

Proton rest frame

$$\rho_{tot} = |\Psi\rangle\langle\Psi|$$



virtual photon

$r \sim 1/Q$

$L \sim 1/(mx)$

$$\rho_A \equiv \mathrm{Tr}_B(\rho_{tot})$$

(reduced density matrix)

$$S_A = -\mathrm{Tr}\rho_A \ln \rho_A$$

(von Neumann entropy)

$$\rho_B \equiv \mathrm{Tr}_A(\rho_{tot})$$

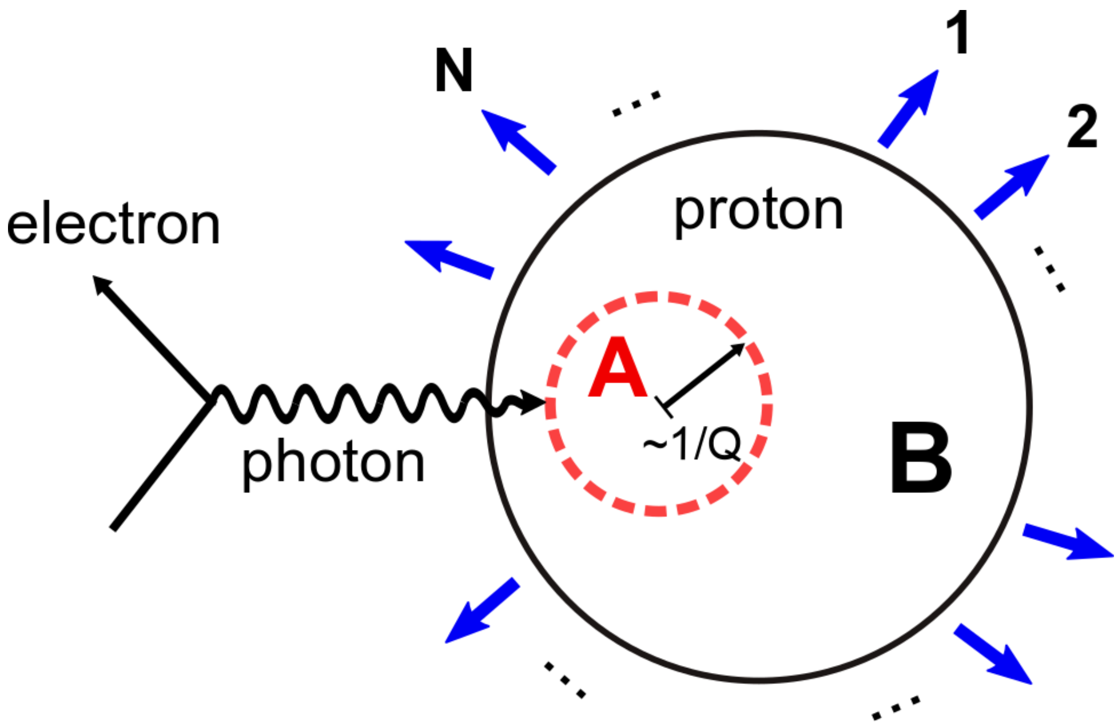
(reduced density matrix)

$$S_B = -\mathrm{Tr}\rho_B \ln \rho_B$$

(von Neumann entropy)

Expectation – EE $S_A = S_B \neq 0$

EE in DIS



Fixed (x,Q^2)

S_A in DIS

$$\rho_A \equiv \mathrm{Tr}_{\mathrm{B}}(\rho_{\mathrm{tot}})$$

(Kharzeev & Levin 2017)

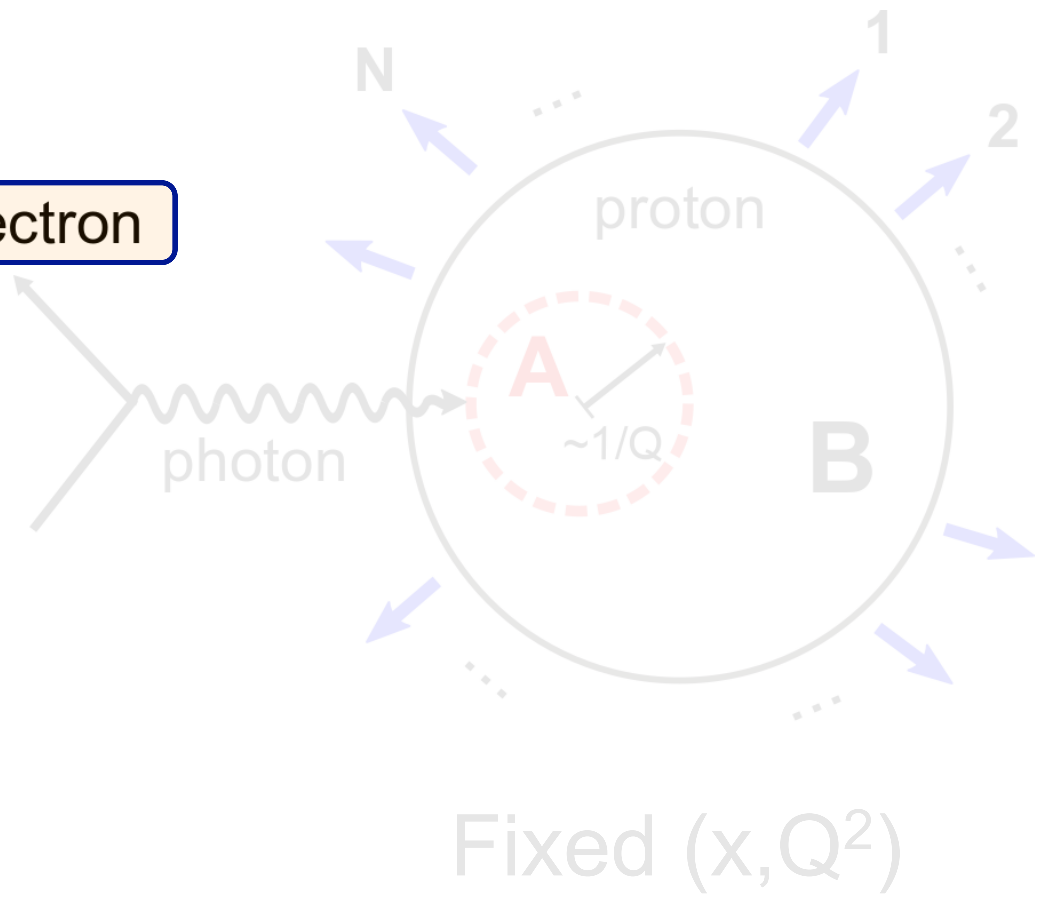
$$S_A = \ln\left[xG(x,Q^2)\right]$$

gluon entropy for low x

(Kharzeev & Levin 2021)

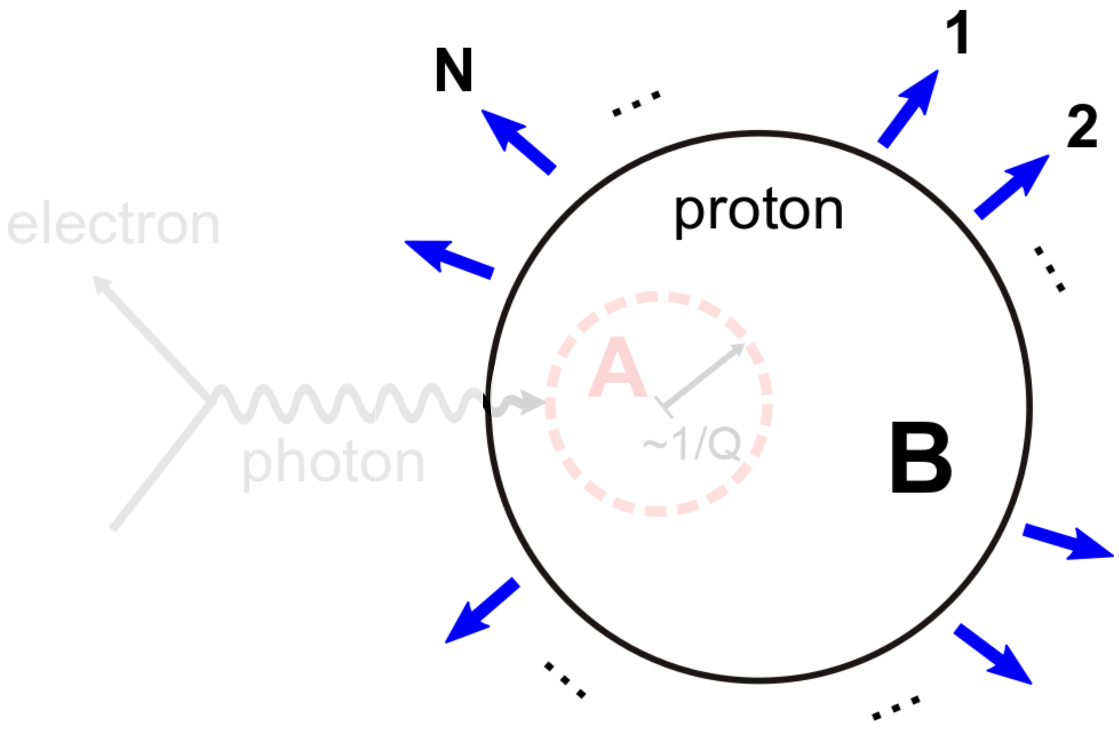
In DIS, sea quarks contributions are very important, recently realized.

arXiv:2102.09773



S_B in DIS

$$\rho_B \equiv \mathrm{Tr}_{\mathrm{A}}(\rho_{tot})$$



Fixed (x,Q^2)

$$S_B = -\sum P_N \log P_N$$

hadron entropy

P_N is charged multiplicities

EE in DIS

(Kharzeev & Levin 2017)

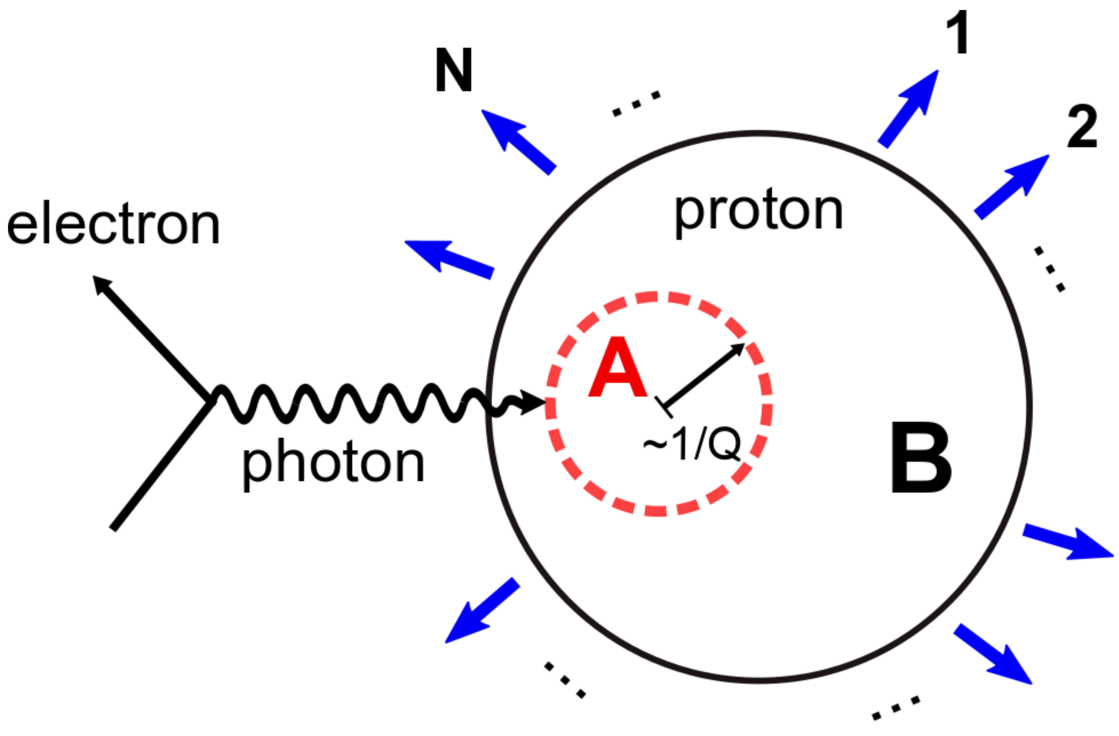
$$S_A = \ln\left[xG(x,Q^2)\right]$$

gluon entropy for low x

$$S_B = -\sum P_N \log P_N$$

hadron entropy

P_N is charged multiplicities

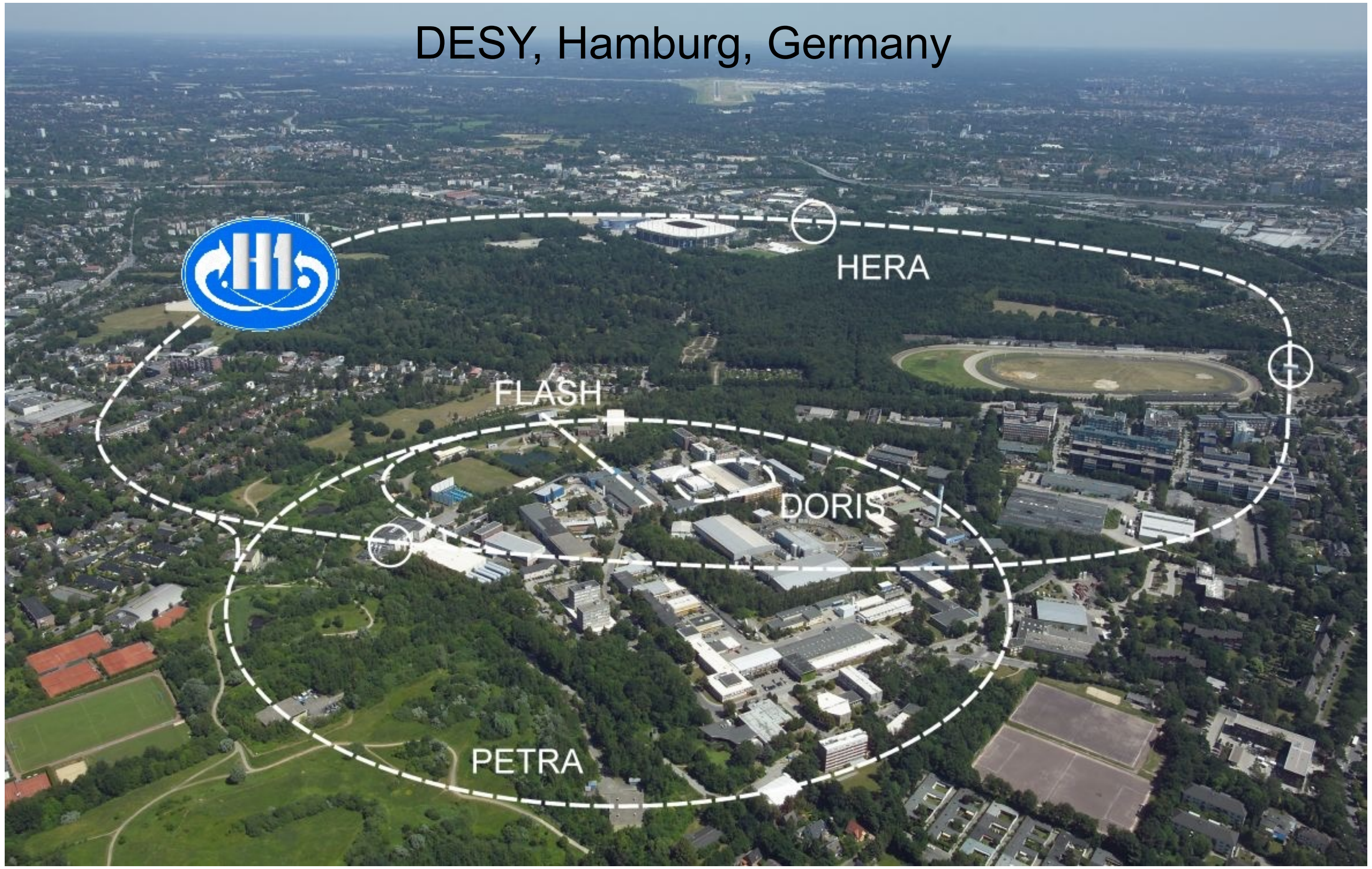


Fixed (x,Q^2)

Measurement - DIS data

H1 experiment in Museum

CJC (main detector, like the STAR TPC)
Stefan Schmitt, H1 spokesperson

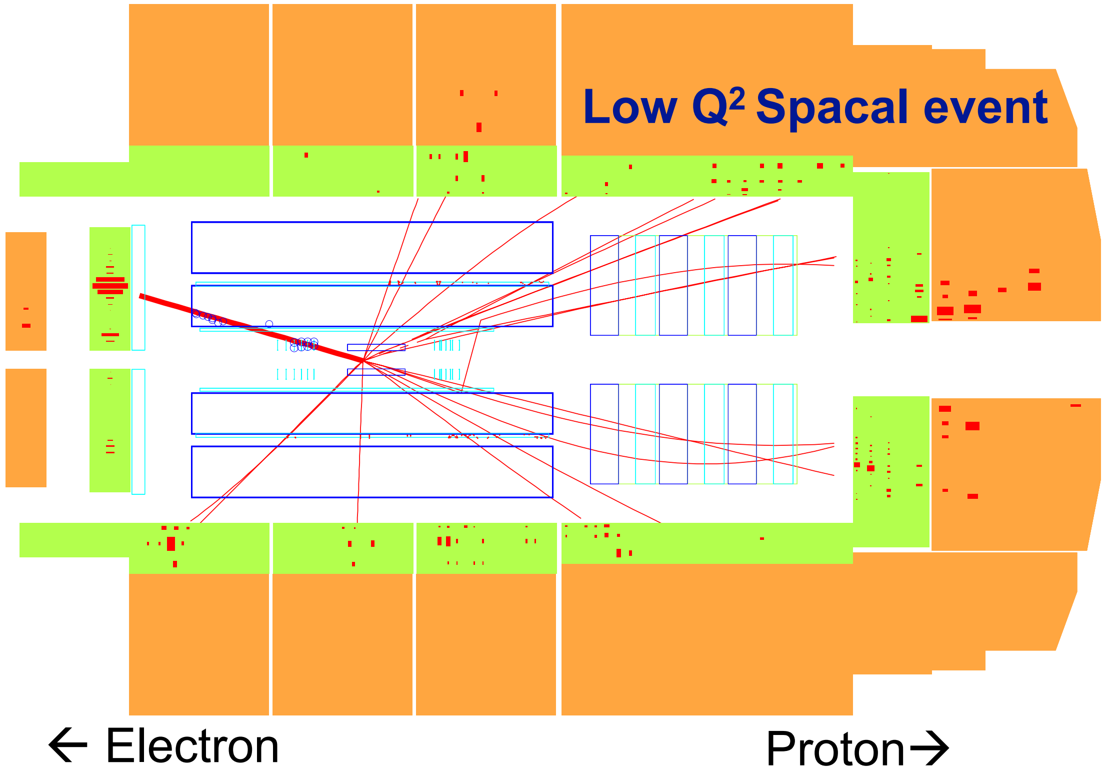


(HERA - 6.3 km in circumference)

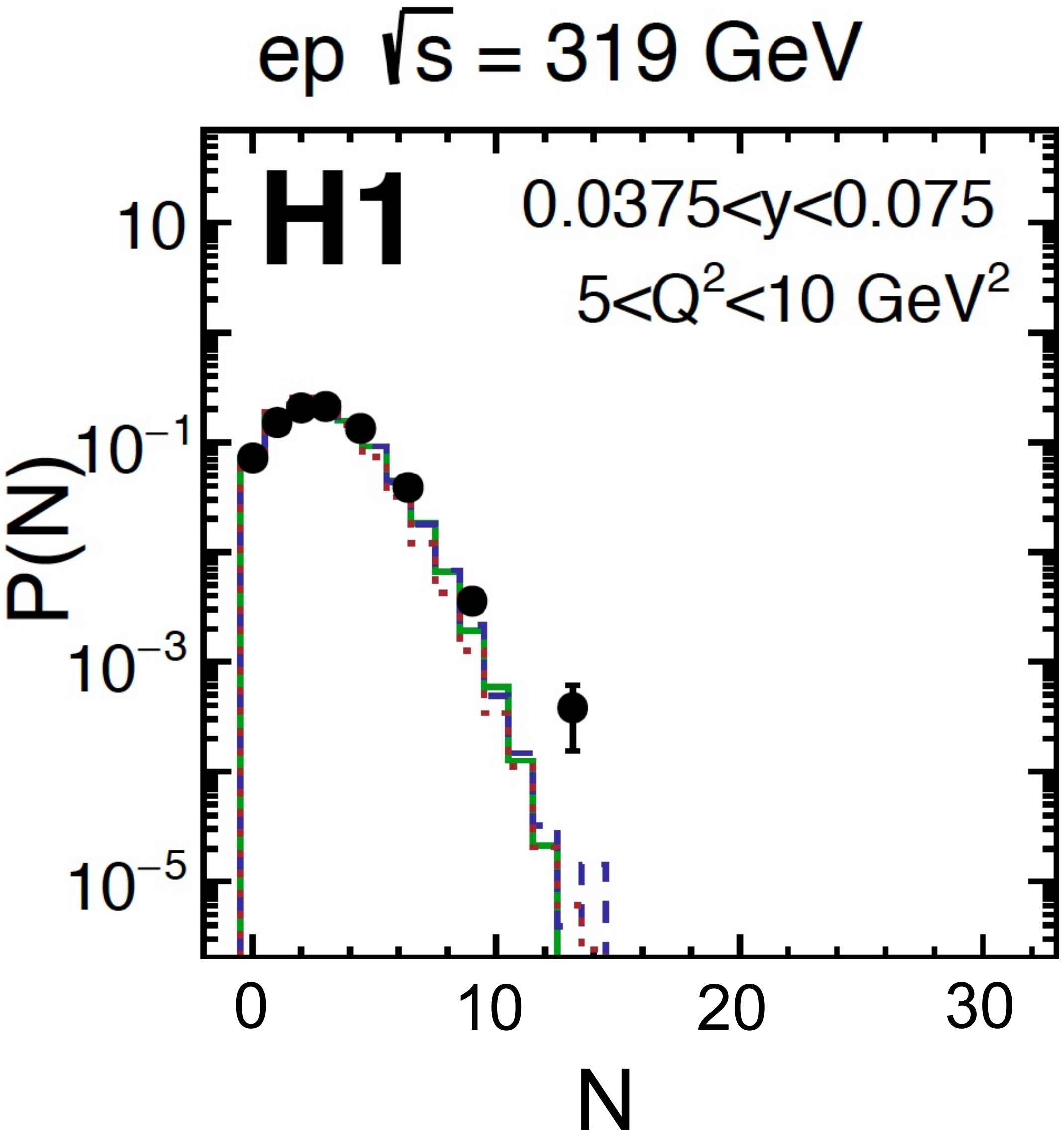
HERA experiments were shut down in 2007

H1 data

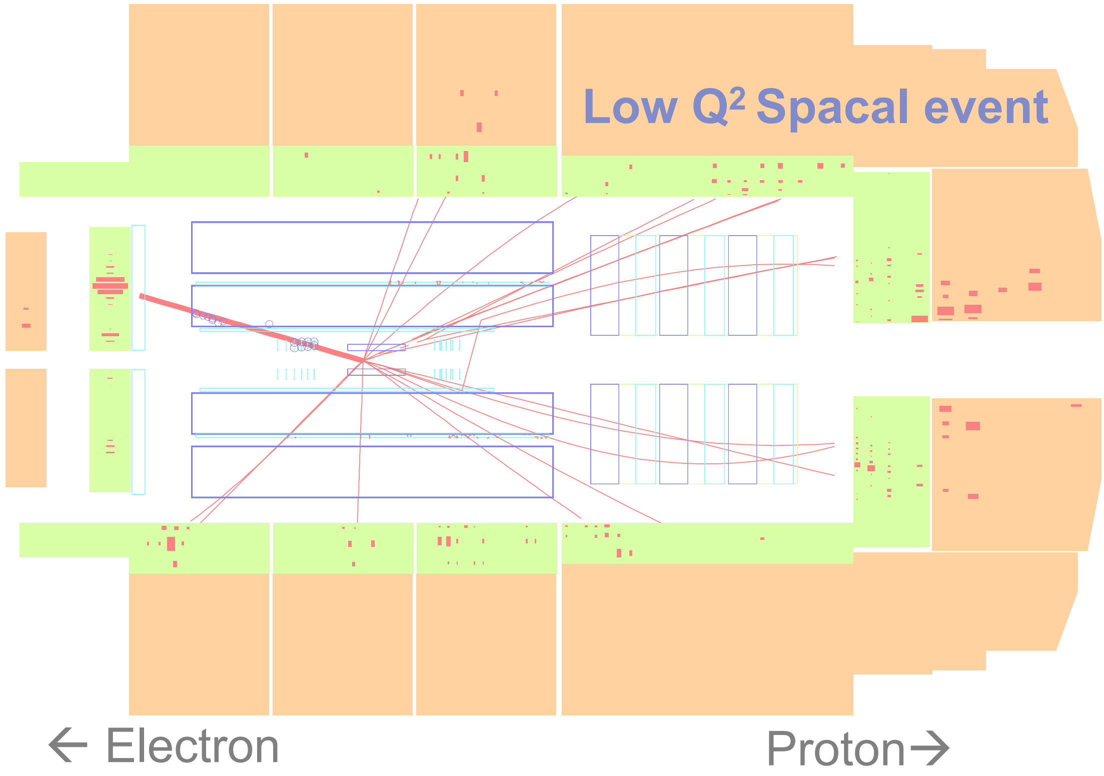
Event display



H1 data



Event display



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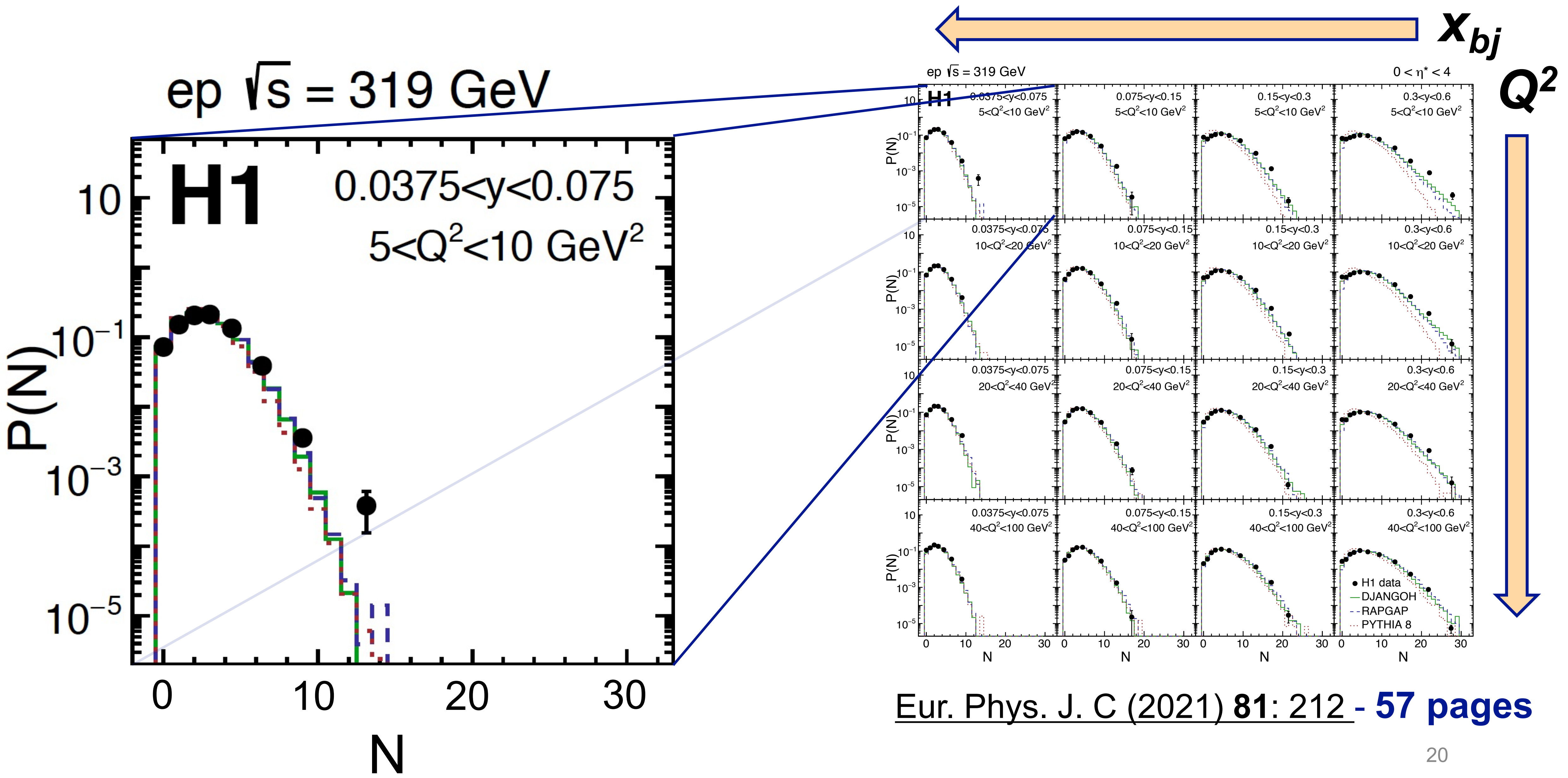
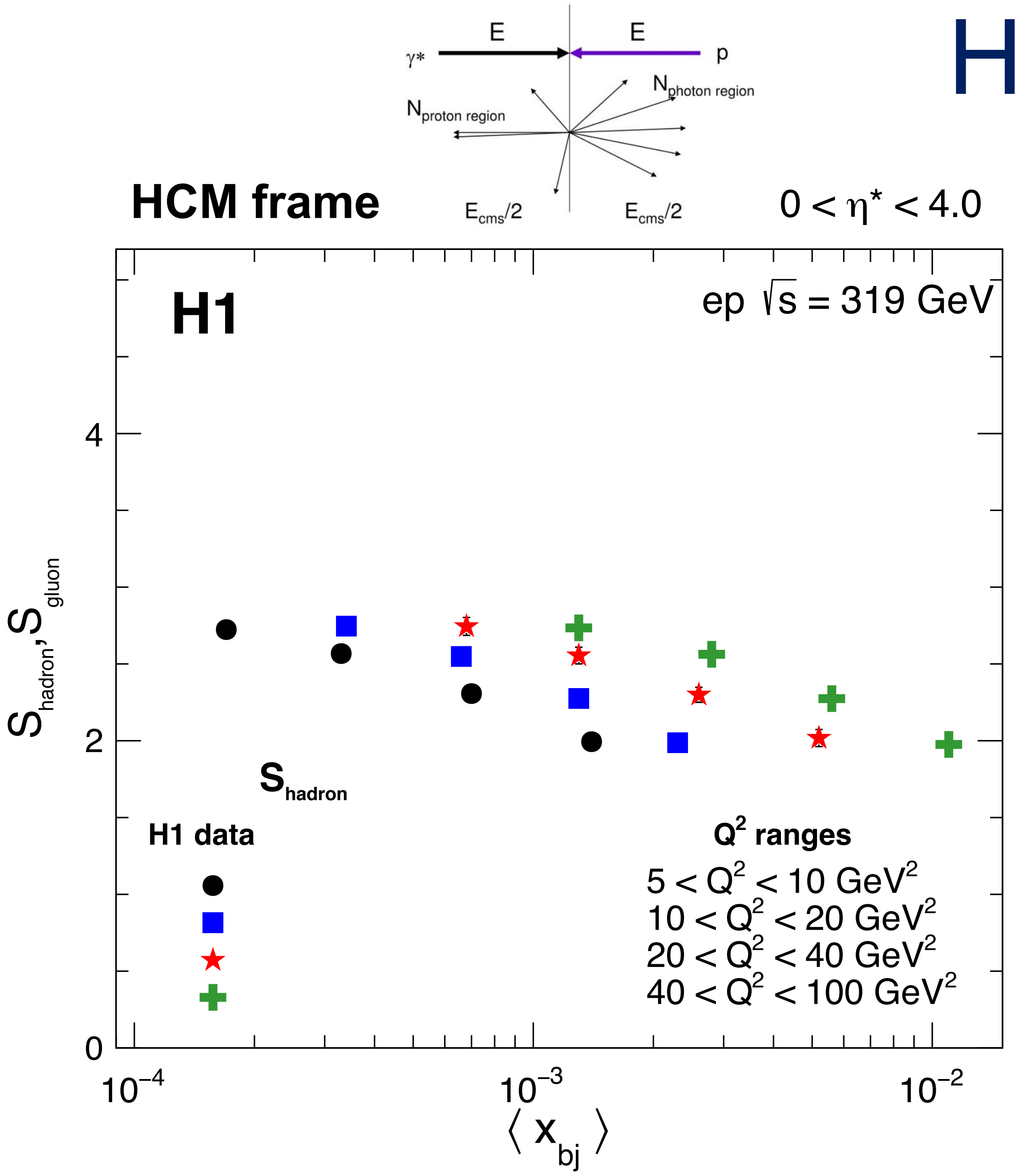
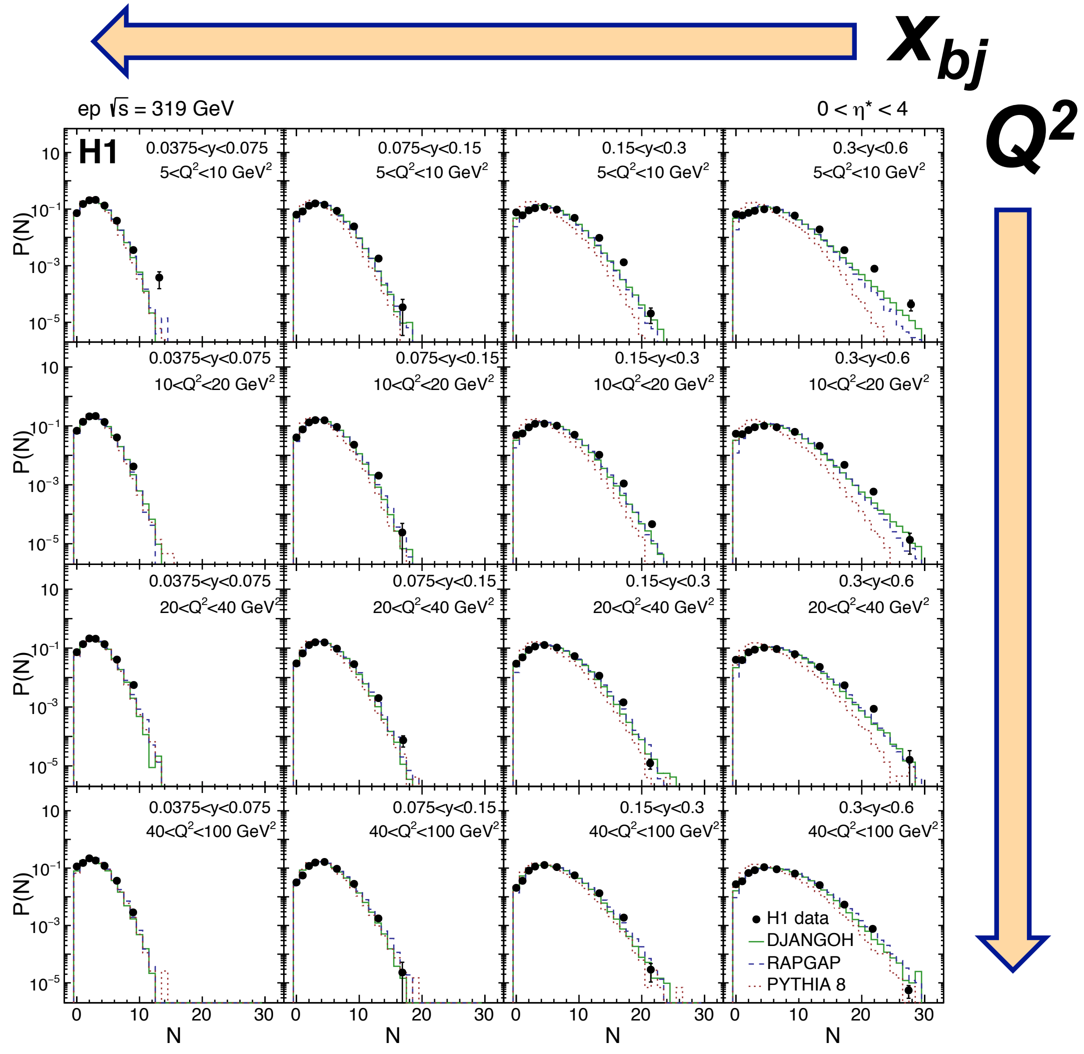


Eur. Phys. J. C (2021) **81**: 212 - **57 pages**

H1 data





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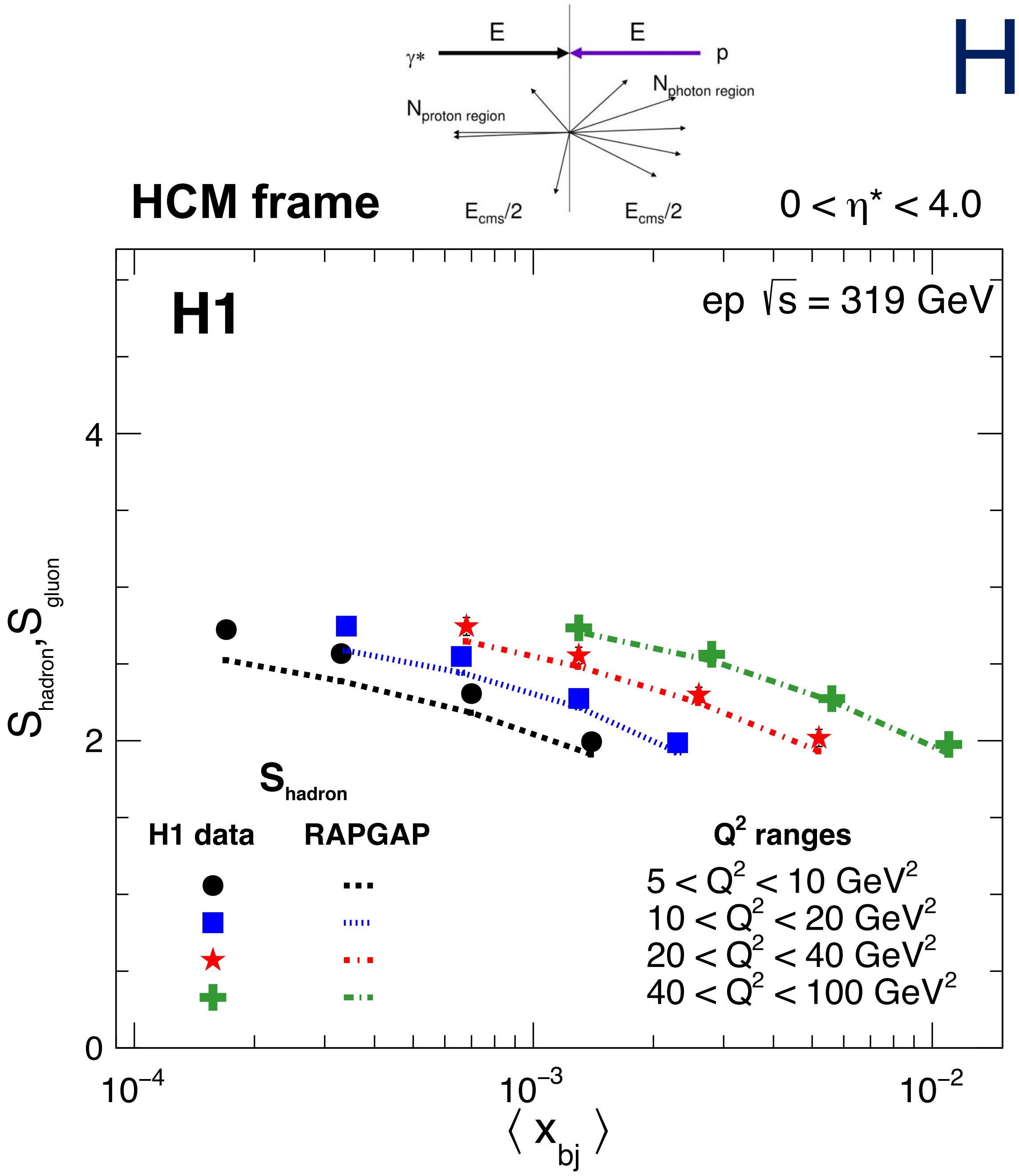

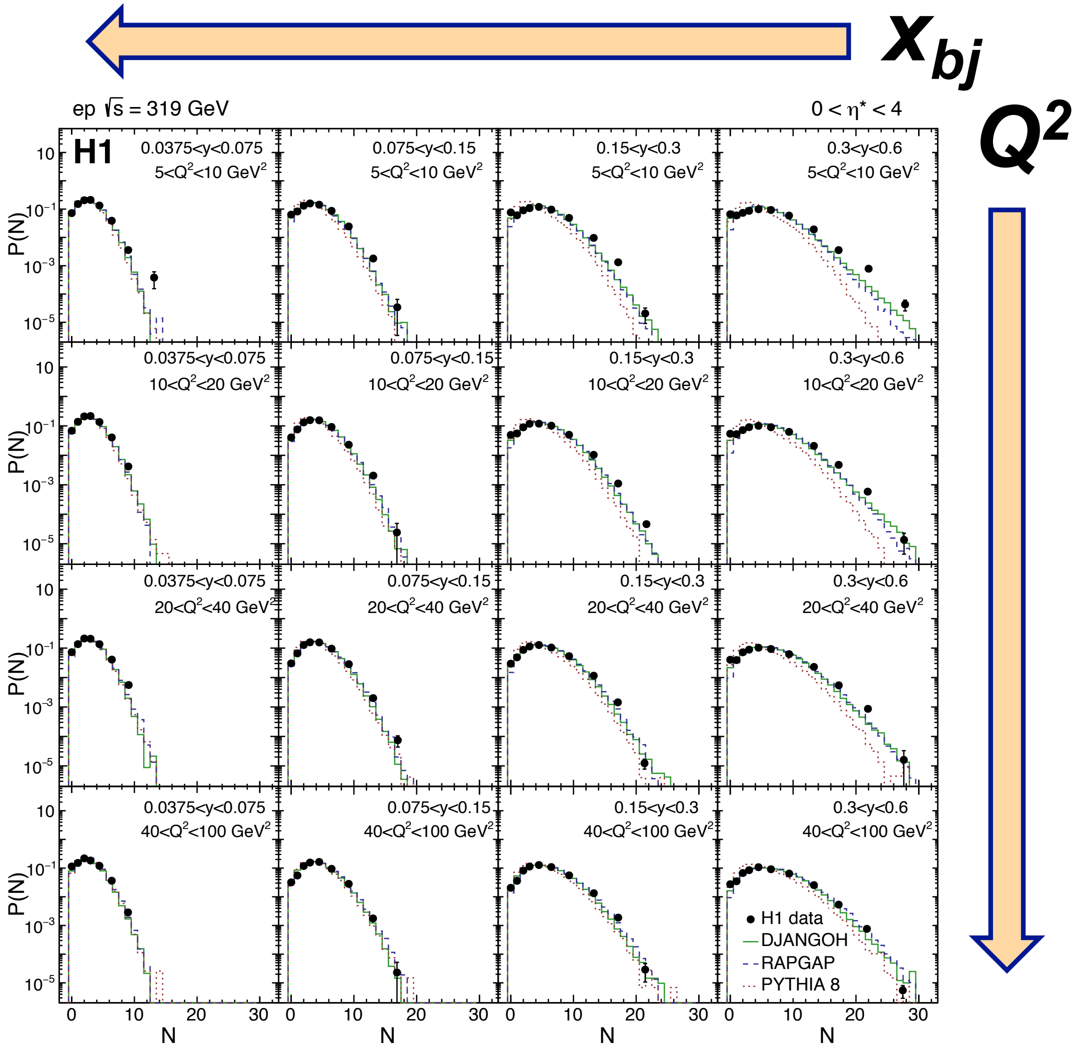

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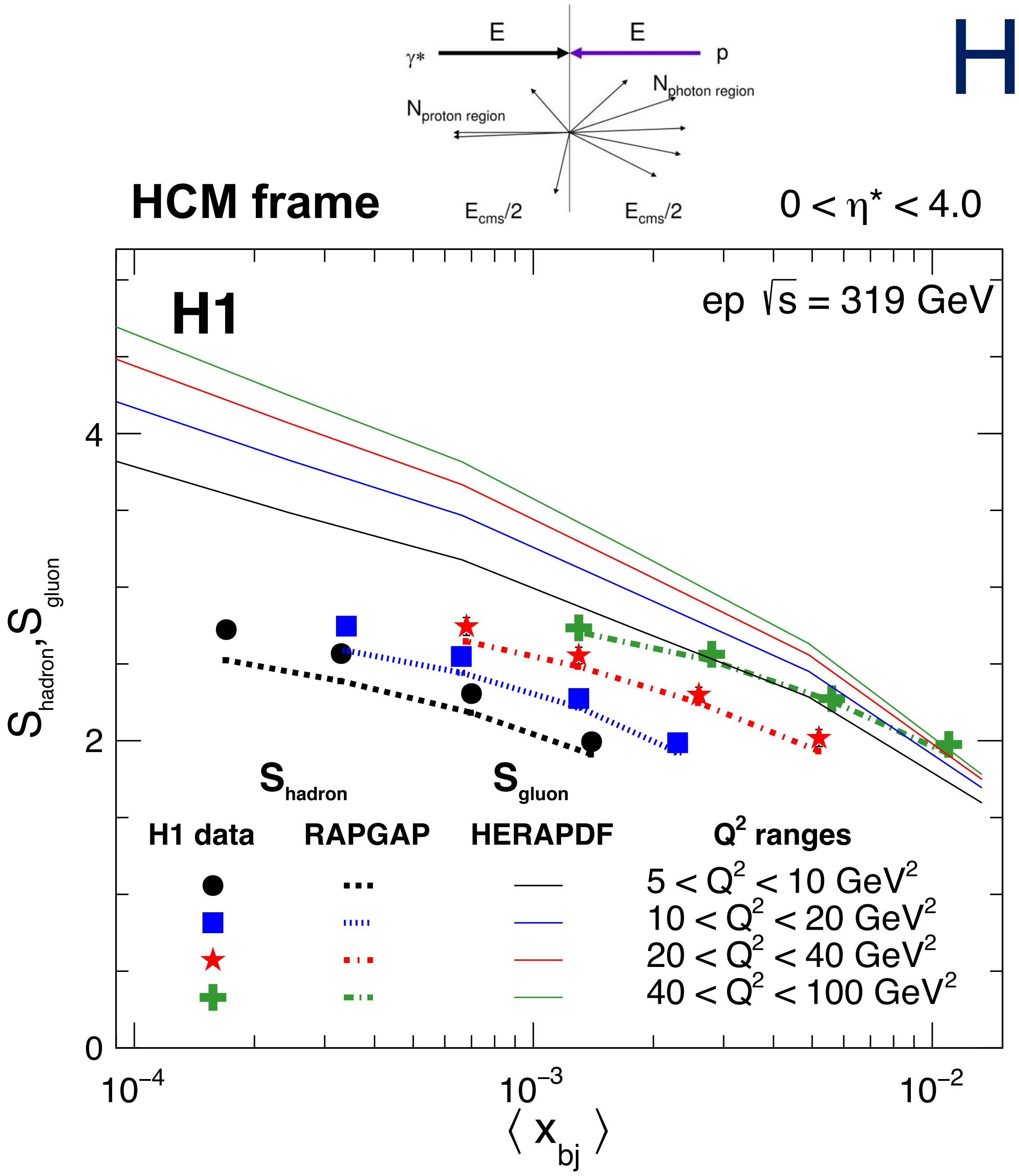

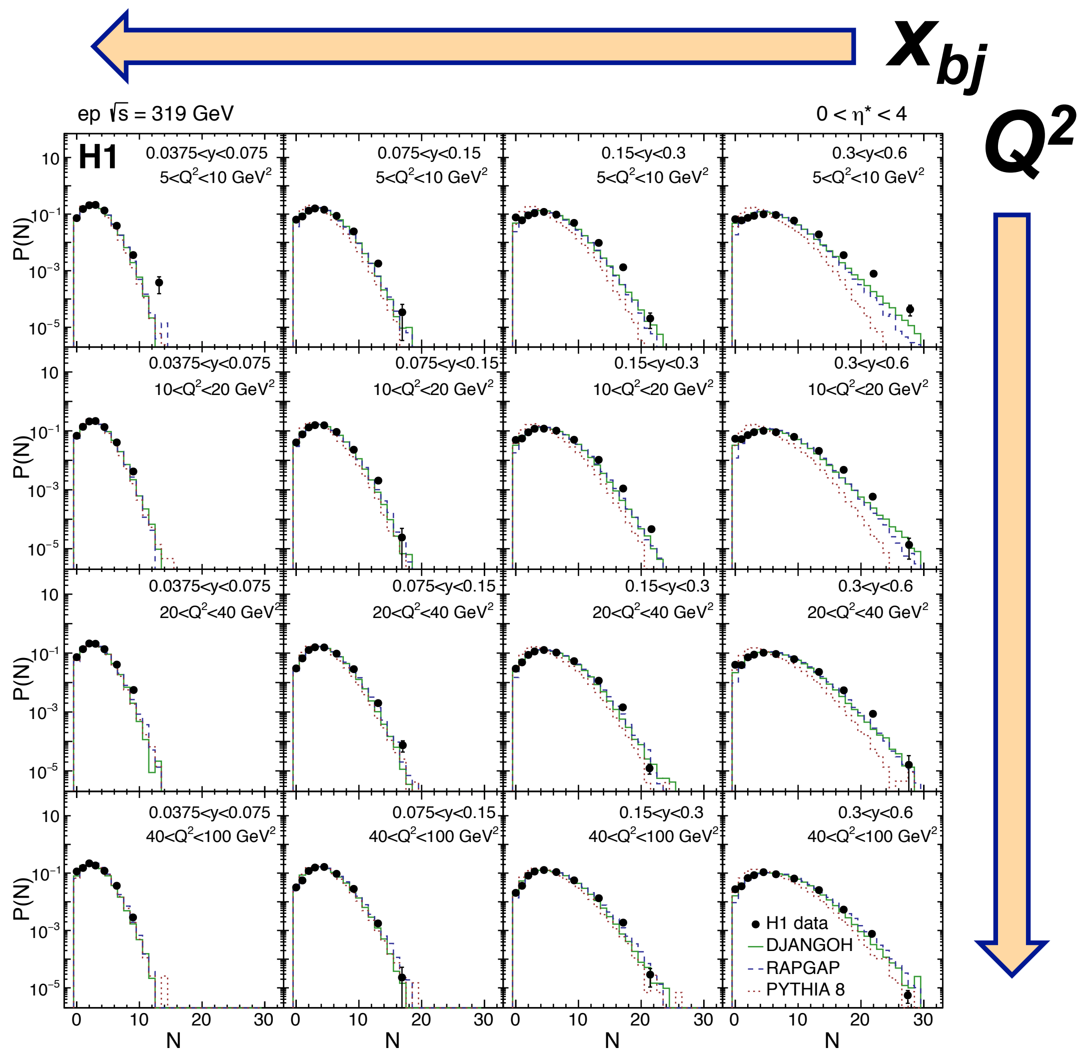

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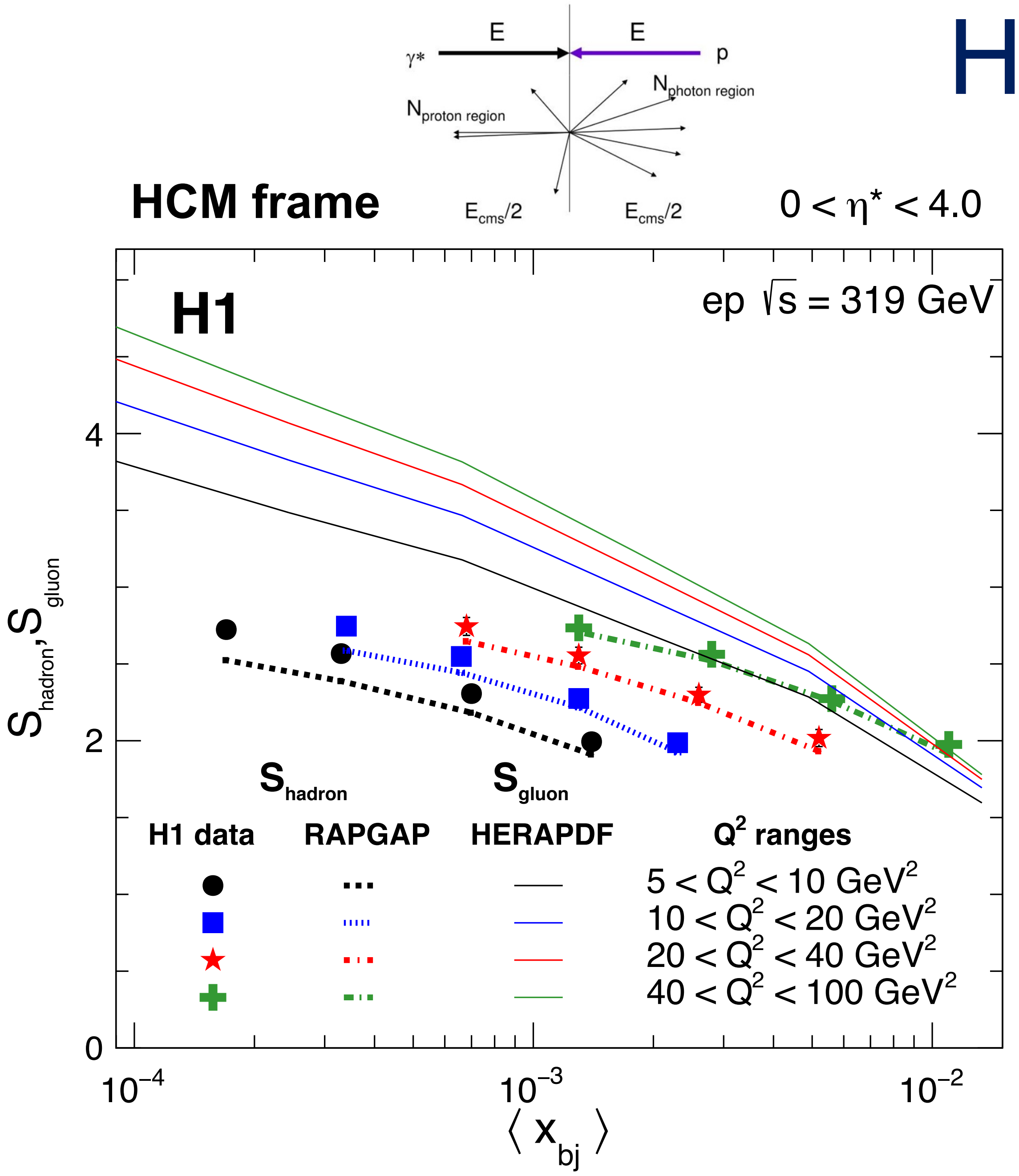
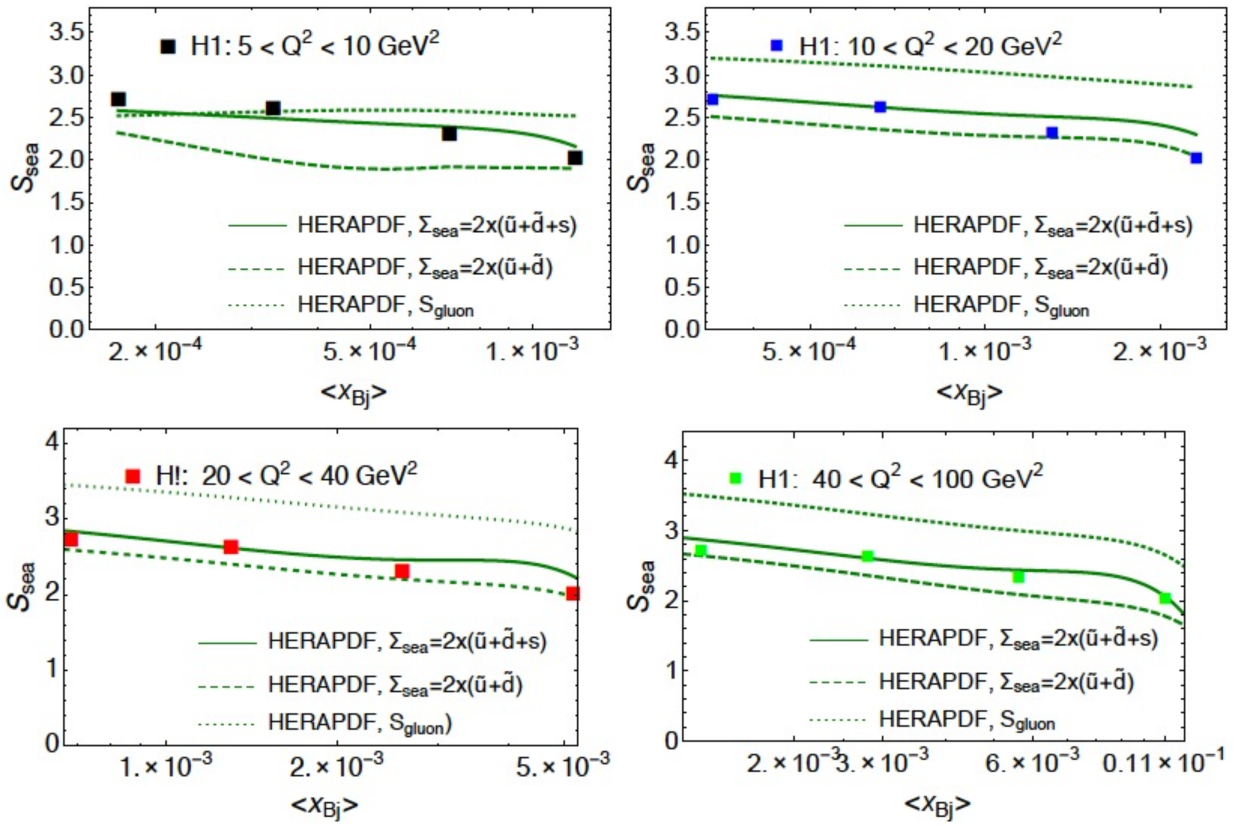


New results from sea quarks



arXiv:2102.09773

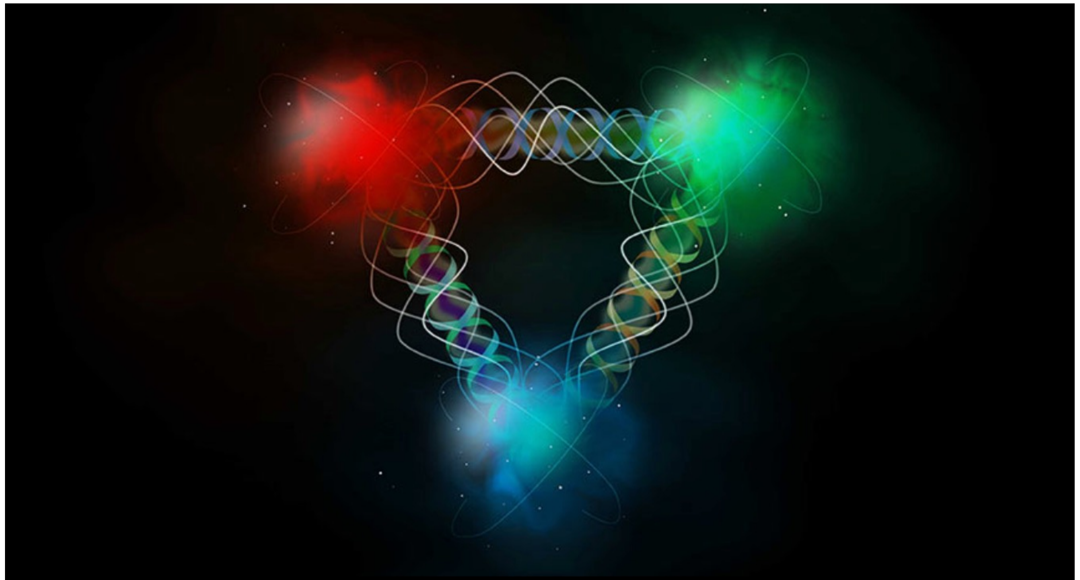
Summary

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

Science News Article

- First experimental hint of entanglement using EE in high energy collisions (both in pp and ep DIS)

Summary

EE timeline

(Kharzeev & Levin 2017)

$$S_A = \ln\left[xG(x, Q^2)\right]$$

gluon entropy for low-x in pp

(Kharzeev & Levin 2021)

$$S_A = \ln\left[\Sigma_{sea}\right]$$

quark entropy for low-x in DIS

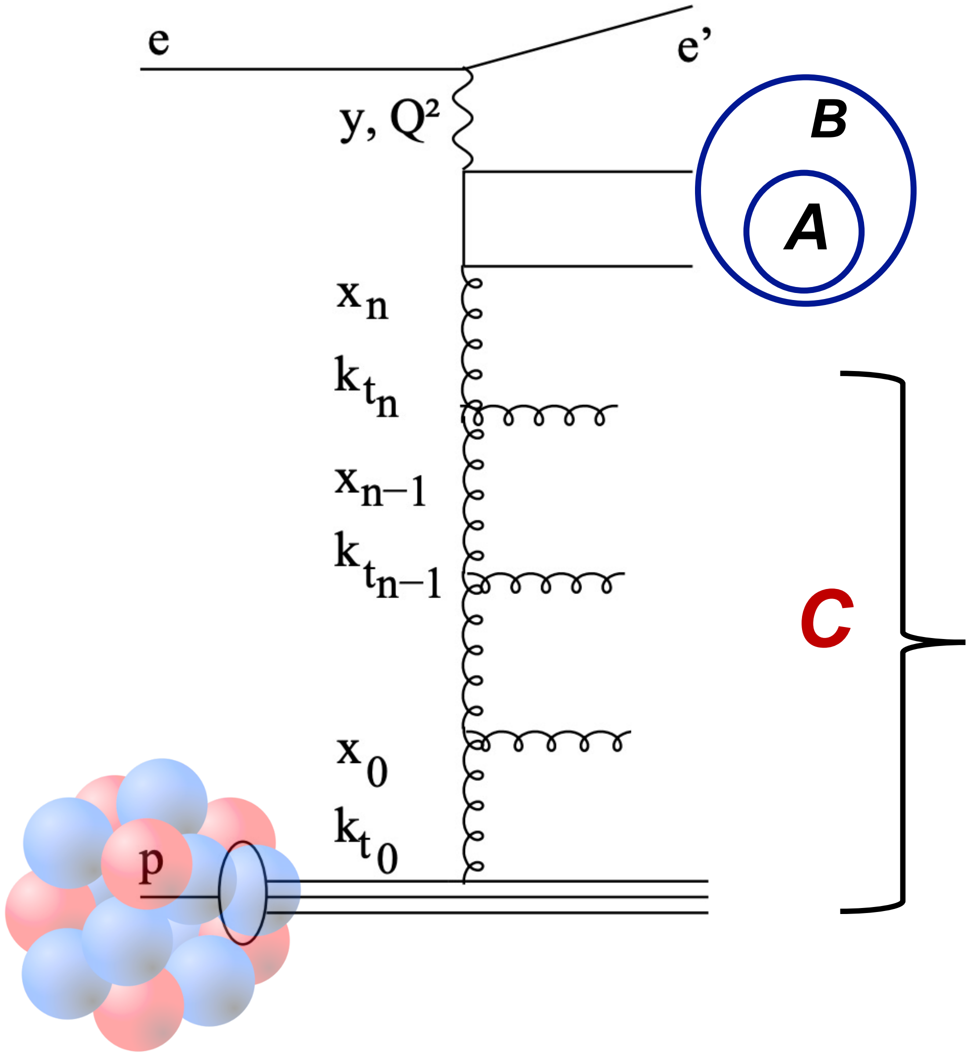
...

- First experimental hint of entanglement using EE in high energy collisions (both in pp and ep DIS)

- Promising theory in EE. But still with many questions and works ahead.

What's next?

DIS



- First experimental hint of entanglement using EE in high energy collisions (both in pp and ep DIS)
- Promising theory in EE. But still with many questions and works ahead.

- Large acceptance with target region. Correlation in rapidity?
- How about nucleus? eA?

(A dedicated prediction is on the way)

Stay tuned!