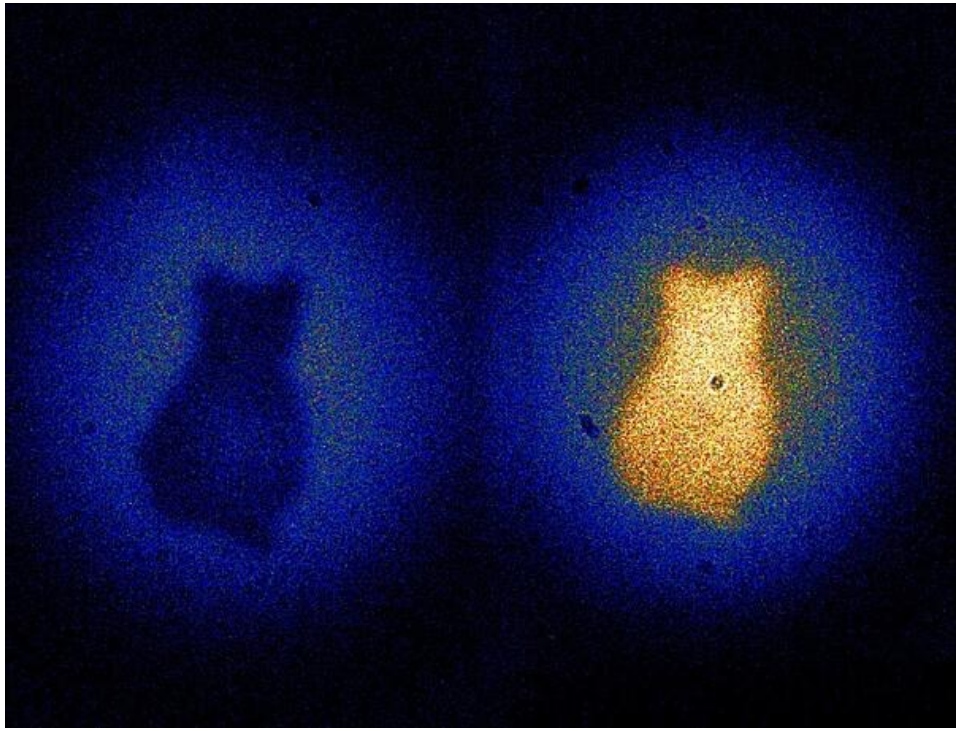
Measurement of **E**ntanglement **E**ntropy in high energy particle collisions



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

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

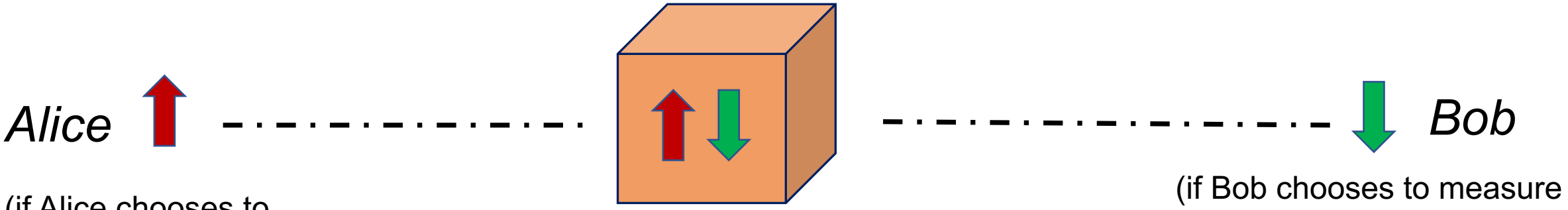
Kong Tu

BNL

06. 10. 2022

A story of Alice and Bob

"spooky action at a distance…"



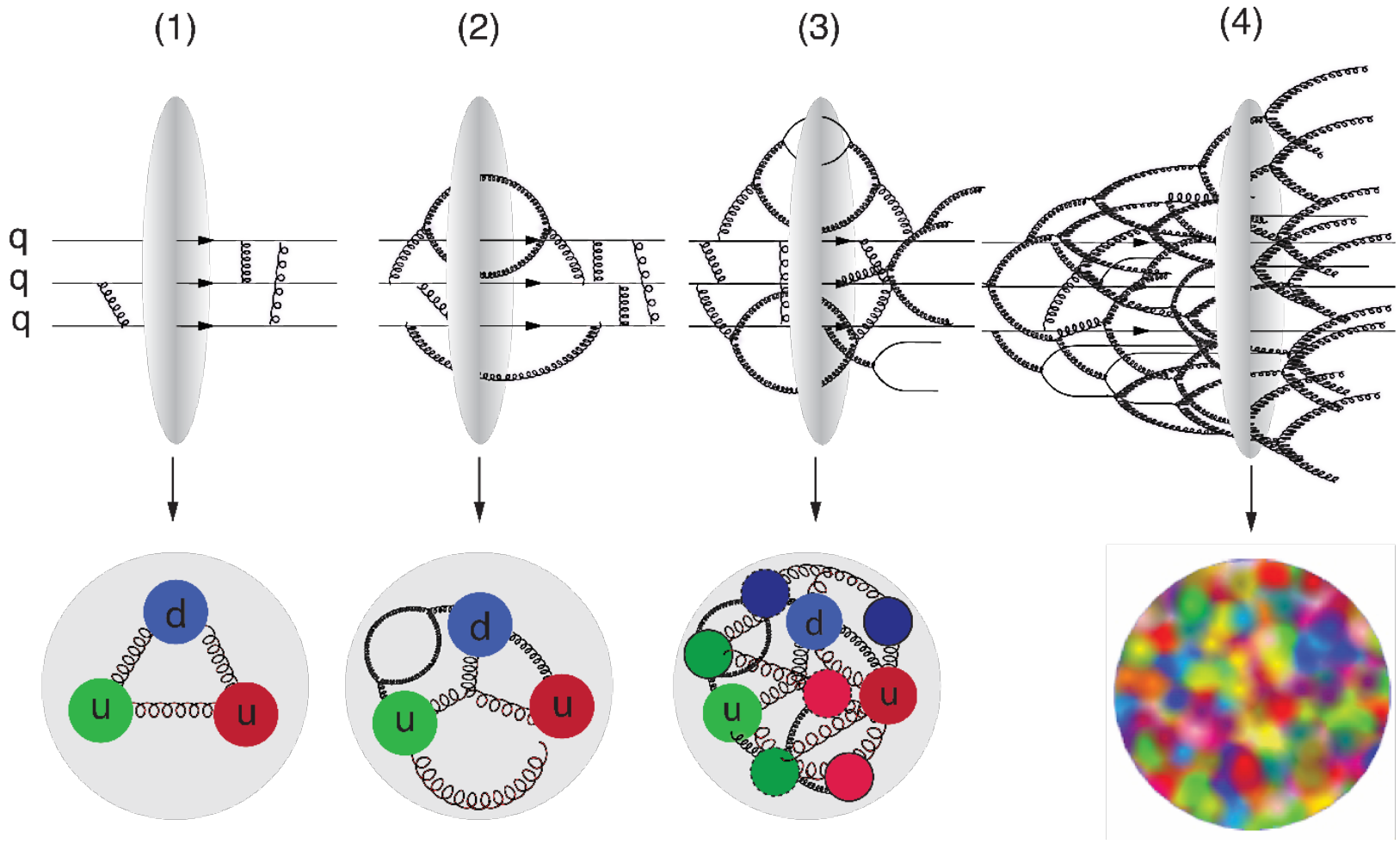
(if Alice chooses to measure its spin in z axis)

(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 - a quantum mechanical pure state.

All partons are entangled quantum mechanically.

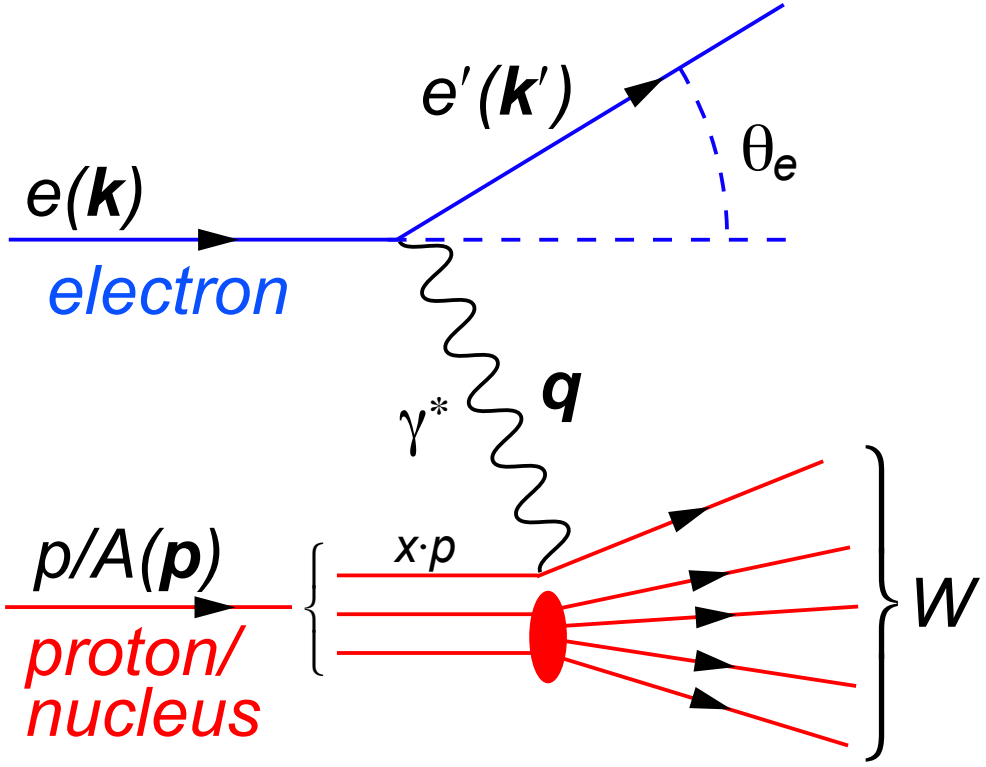
- e.g., all the states of partons **cannot** be written as,

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

Proton going from low → high energy

DIS and nucleon structure

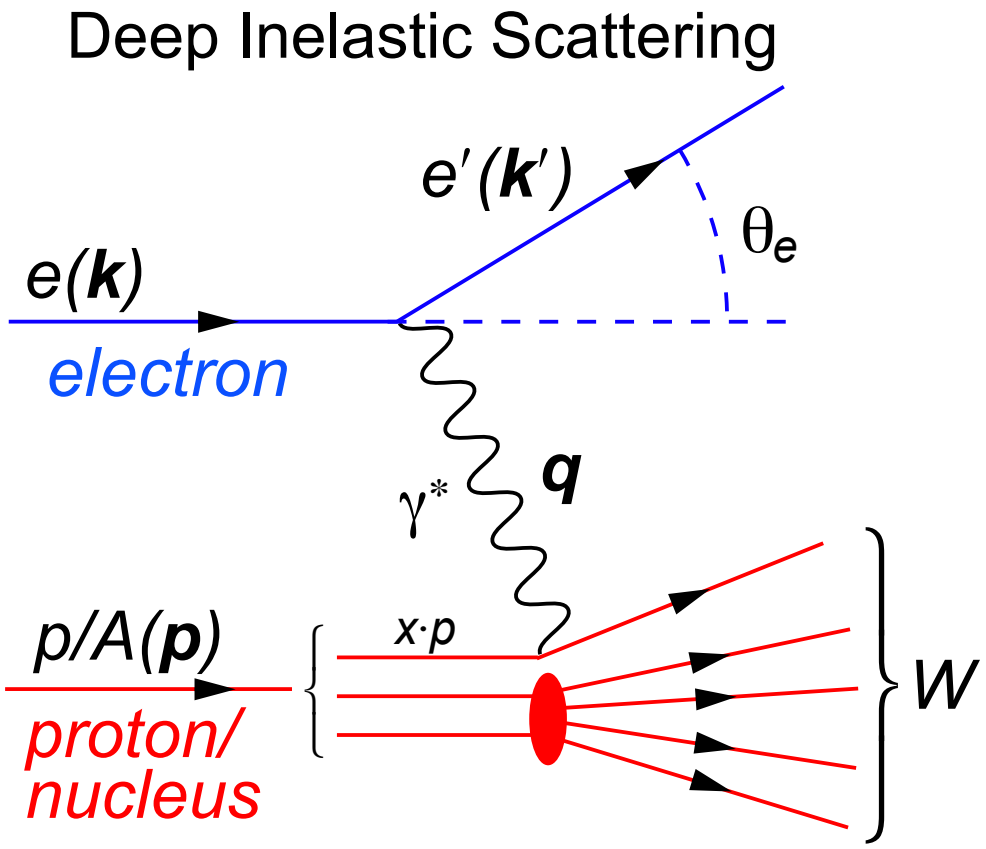
Deep Inelastic Scattering



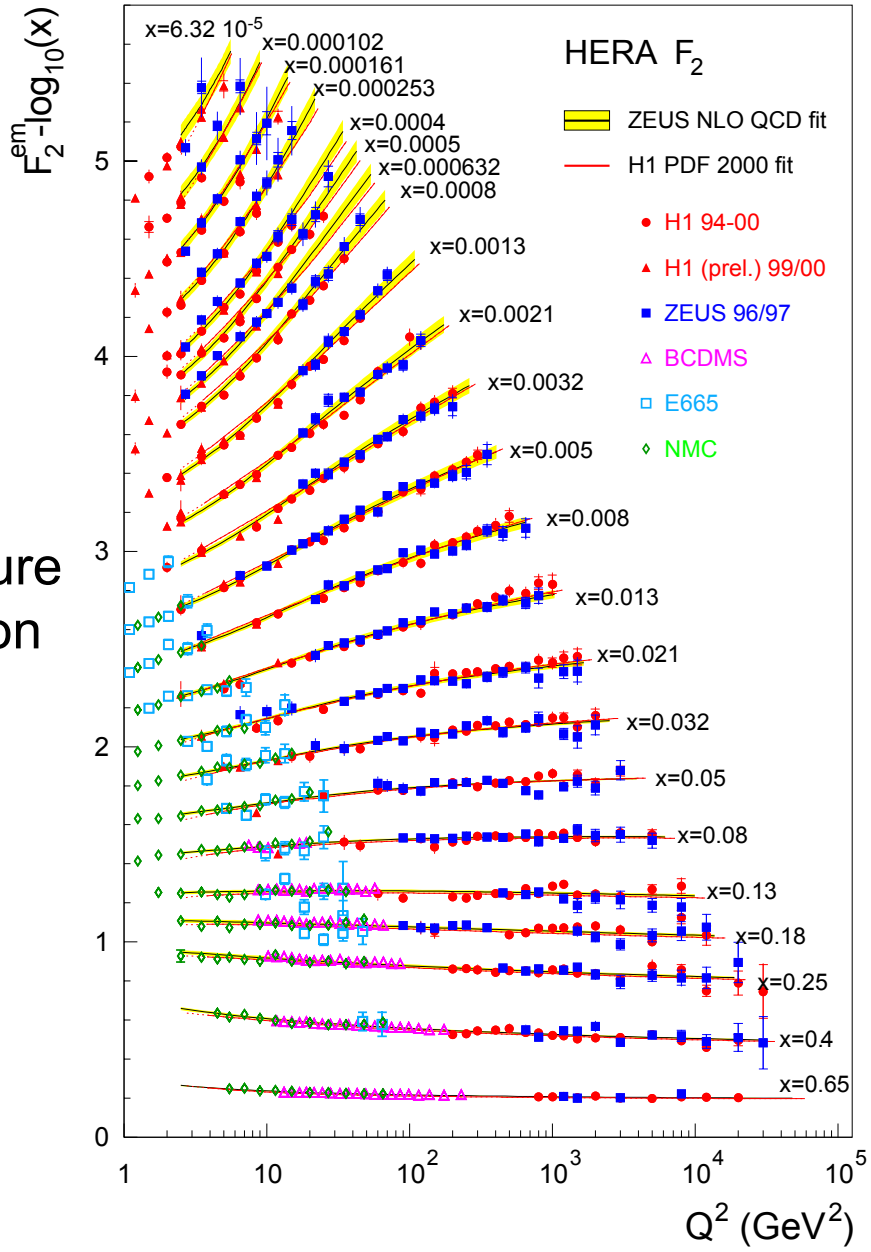
1. Resolution ~ $Q^2 = -q^2$
2. Momentum fraction ~ $x_{\mathrm{bj}} = \dfrac{Q^2}{2Pq}$

   "Exposure time"

DIS and nucleon structure



structure function



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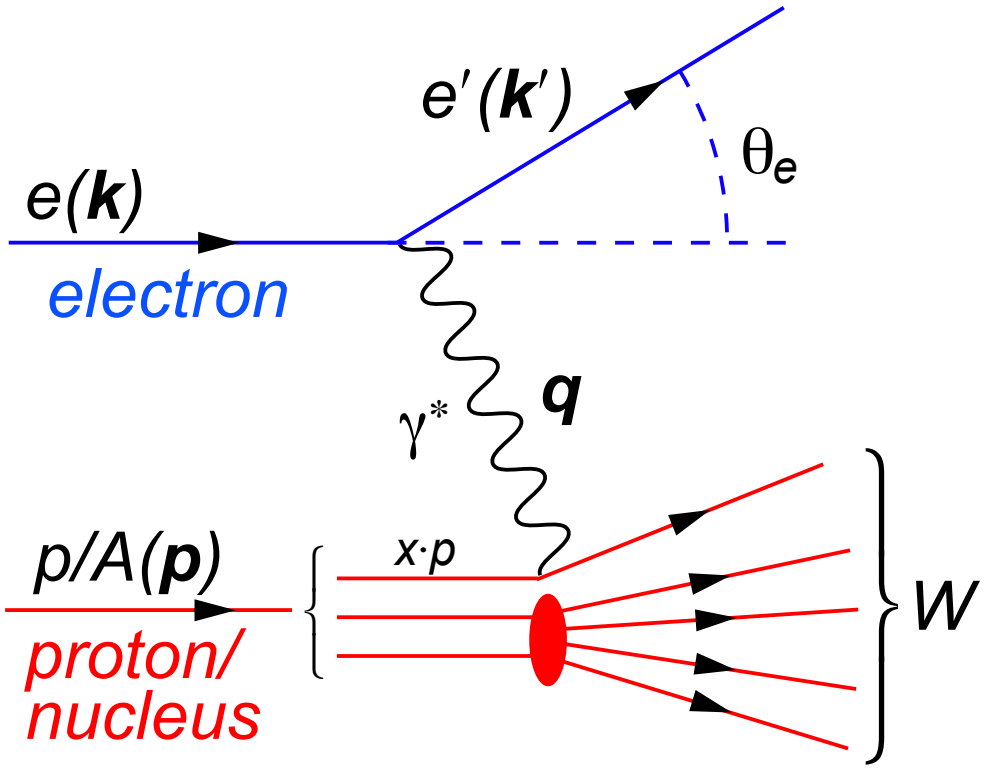

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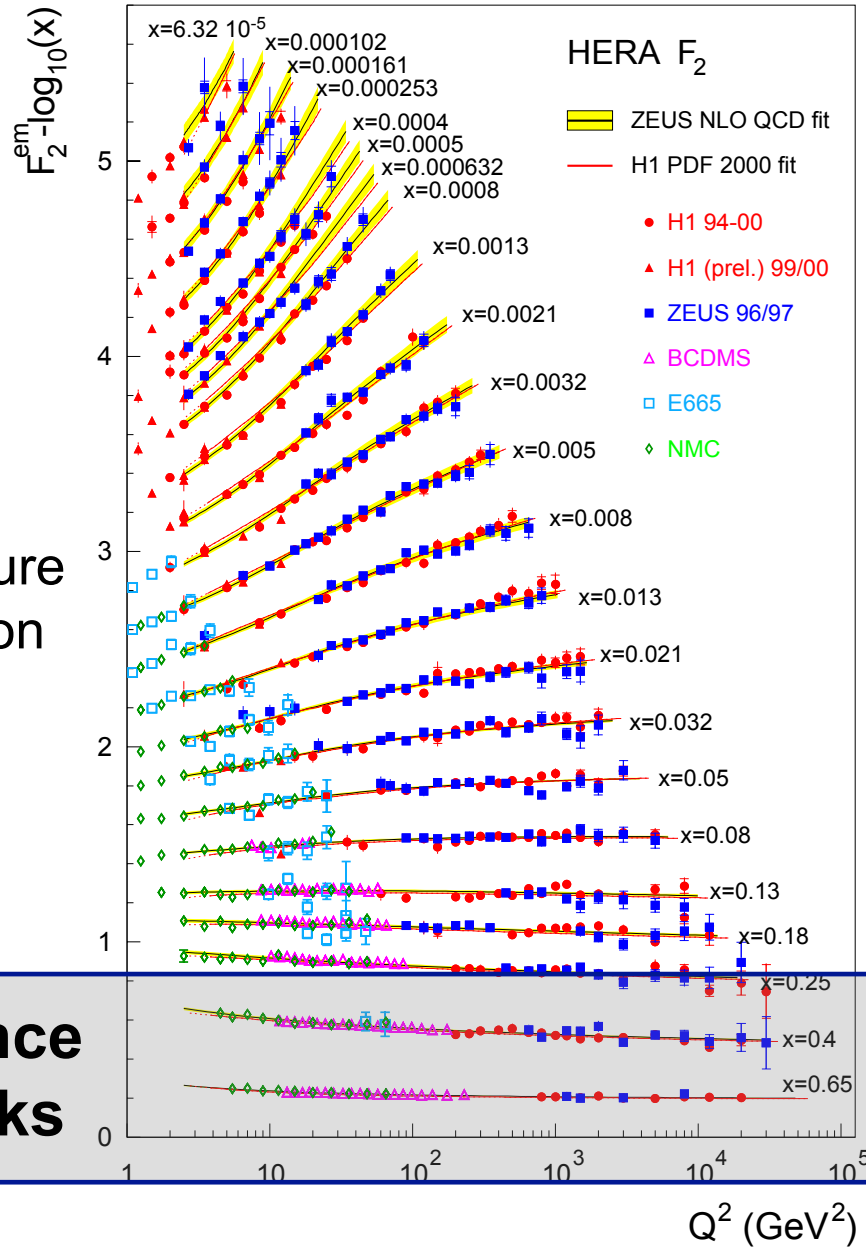
   "Exposure time"

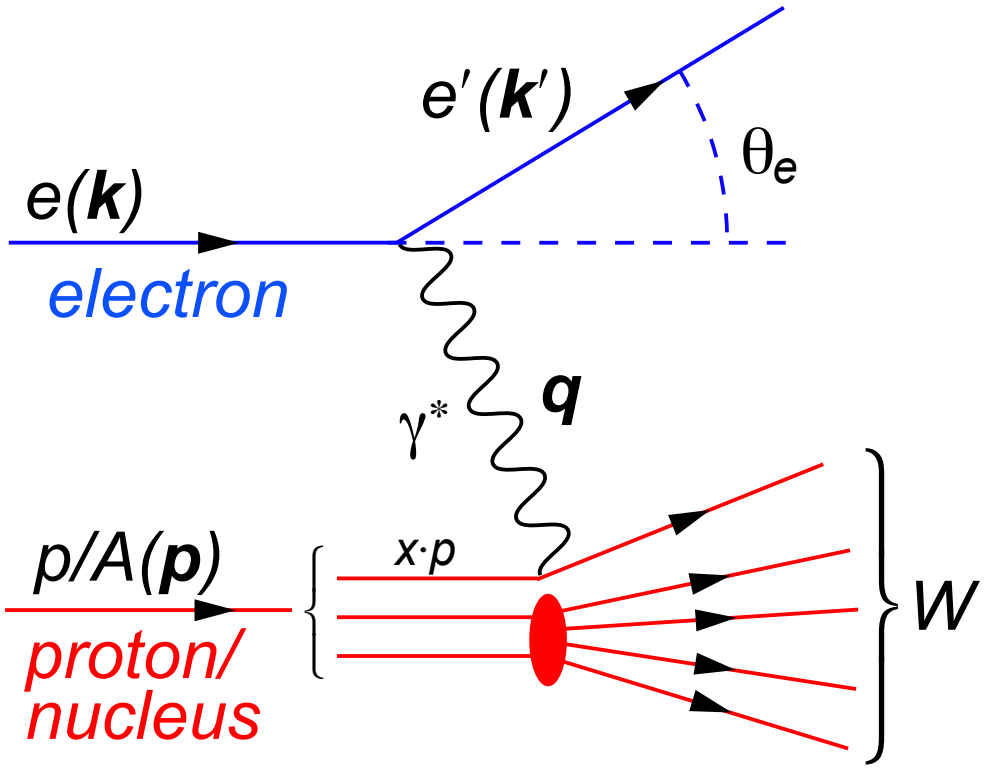
structure function



Valence Quarks *Bjorken-scaling*

DIS and nucleon structure

Deep Inelastic Scattering

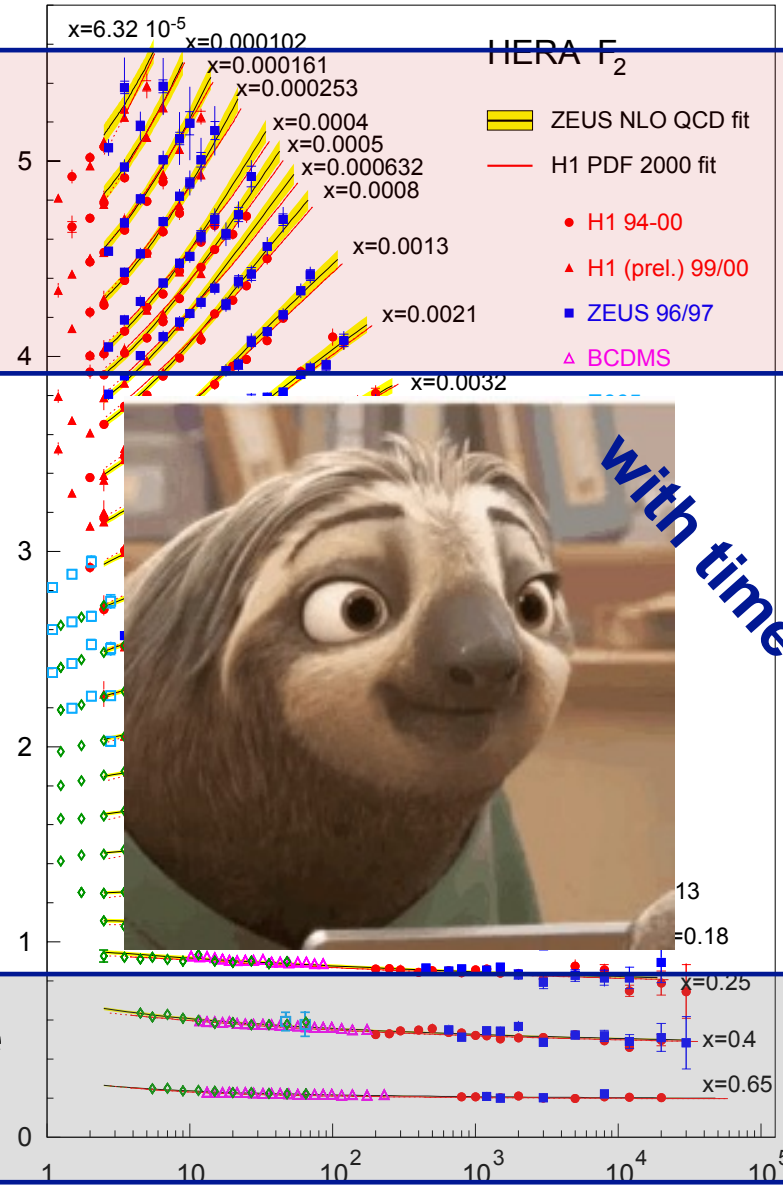


1. Resolution ~ $Q^2 = -q^2$
2. Momentum fraction ~ $x_{\mathrm{bj}} = \dfrac{Q^2}{2Pq}$

   "Exposure time"

Gluons

structure function



Scaling violation

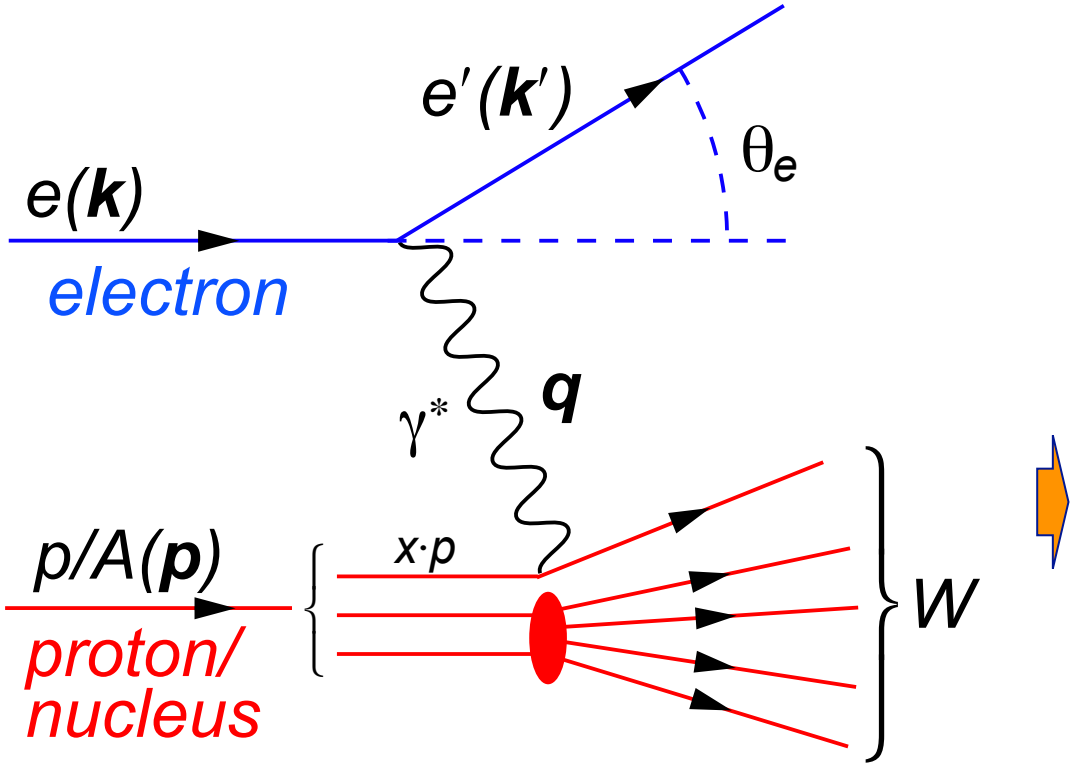
with time dilation …

Valence Quarks

Bjorken-scaling

DIS and nucleon structure

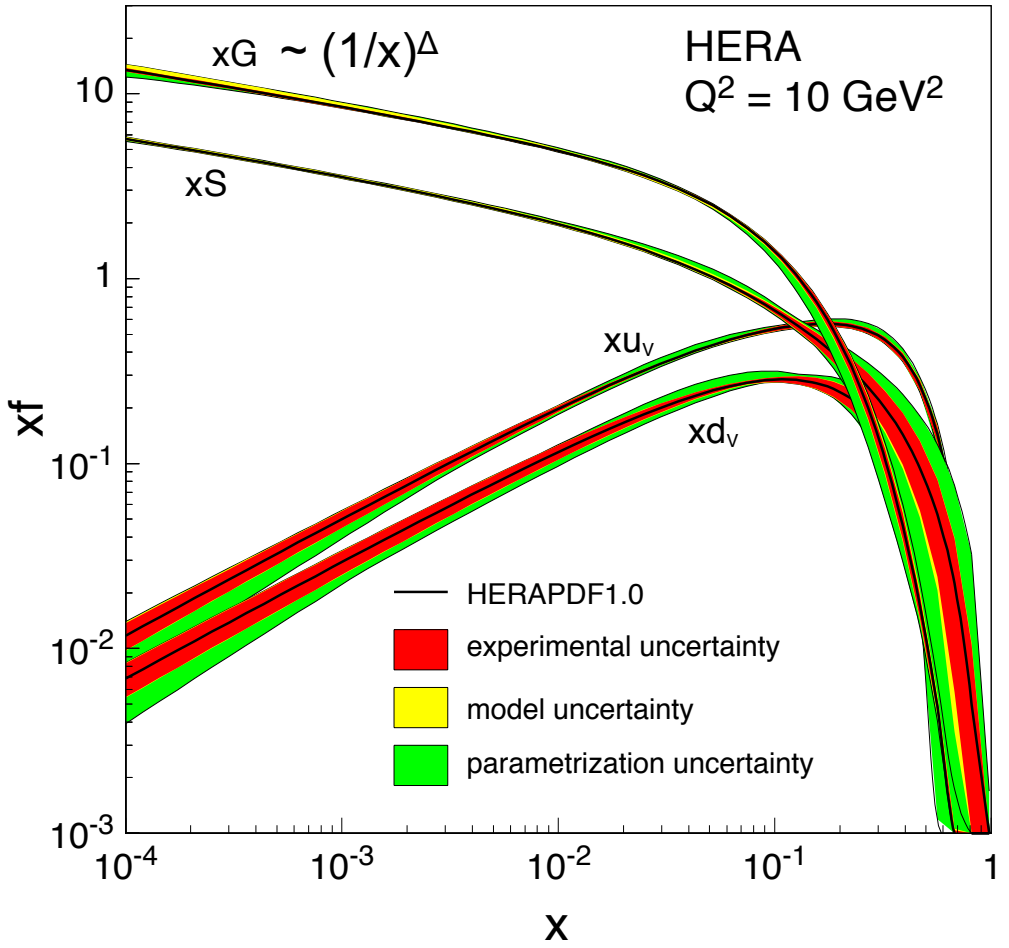
Deep Inelastic Scattering



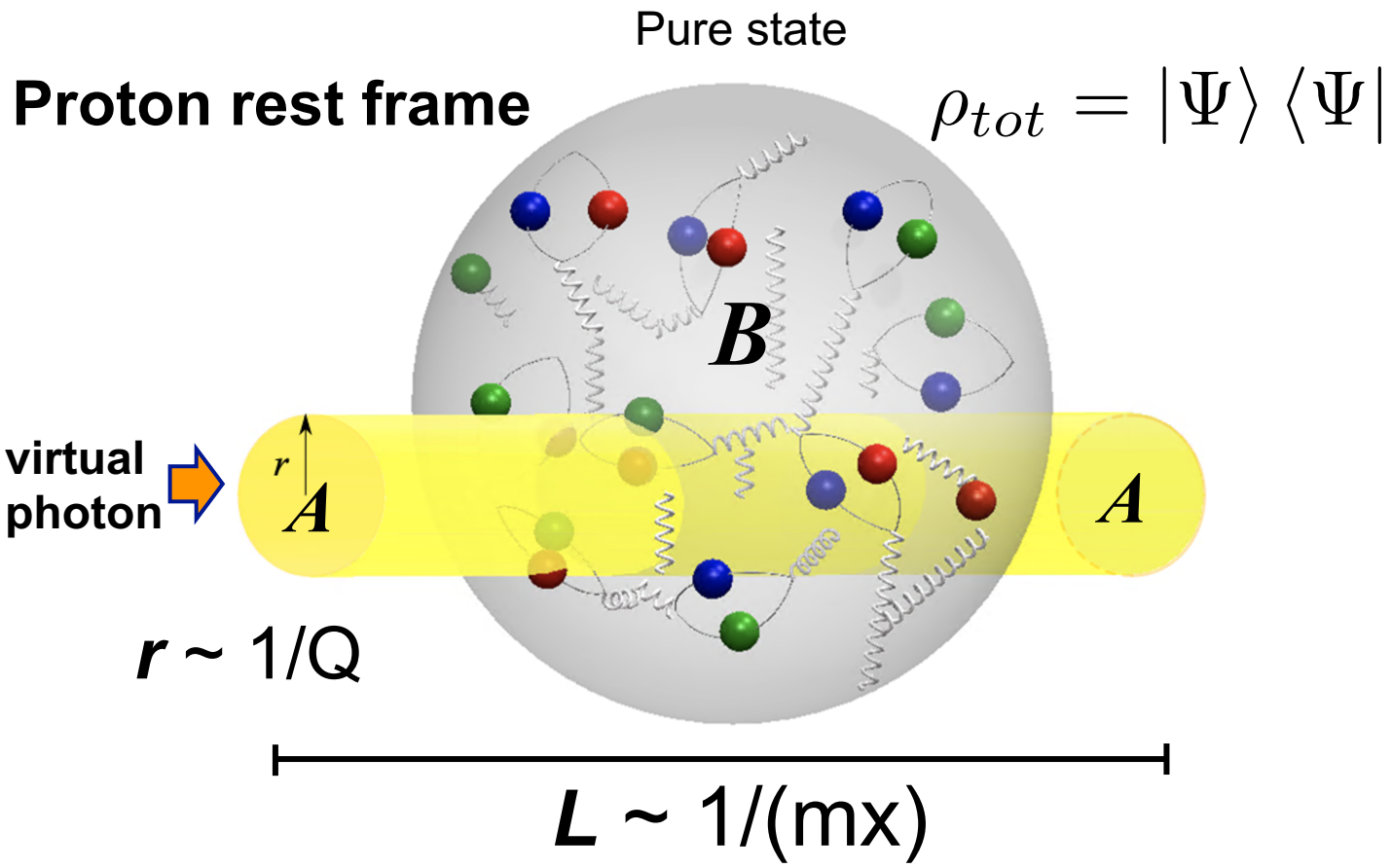
1. Resolution ~ $Q^2 = -q^2$
2. Momentum fraction ~ $x_{\mathrm{bj}} = \dfrac{Q^2}{2Pq}$

   "Exposure time"

Parton Distribution Functions (PDFs)



Entanglement Entropy (EE)

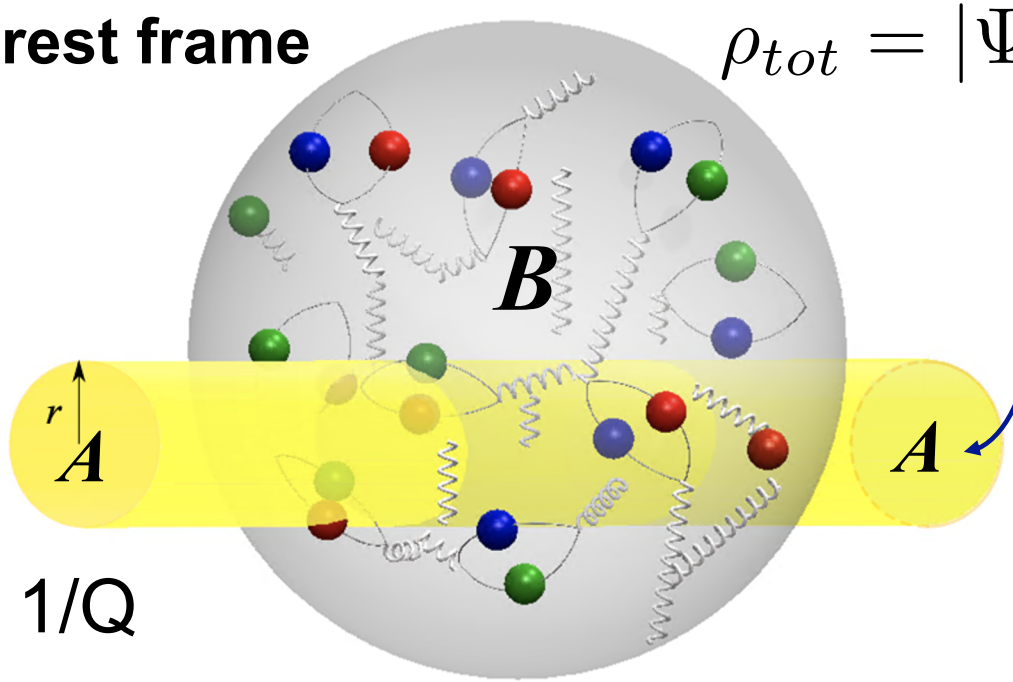


Entanglement Entropy (EE)

Pure state

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

Proton rest frame



virtual photon

r ~ 1/Q

L ~ 1/(mx)

$\rho_A \equiv \mathrm{Tr_B}(\rho_{\mathrm{tot}})$

(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]

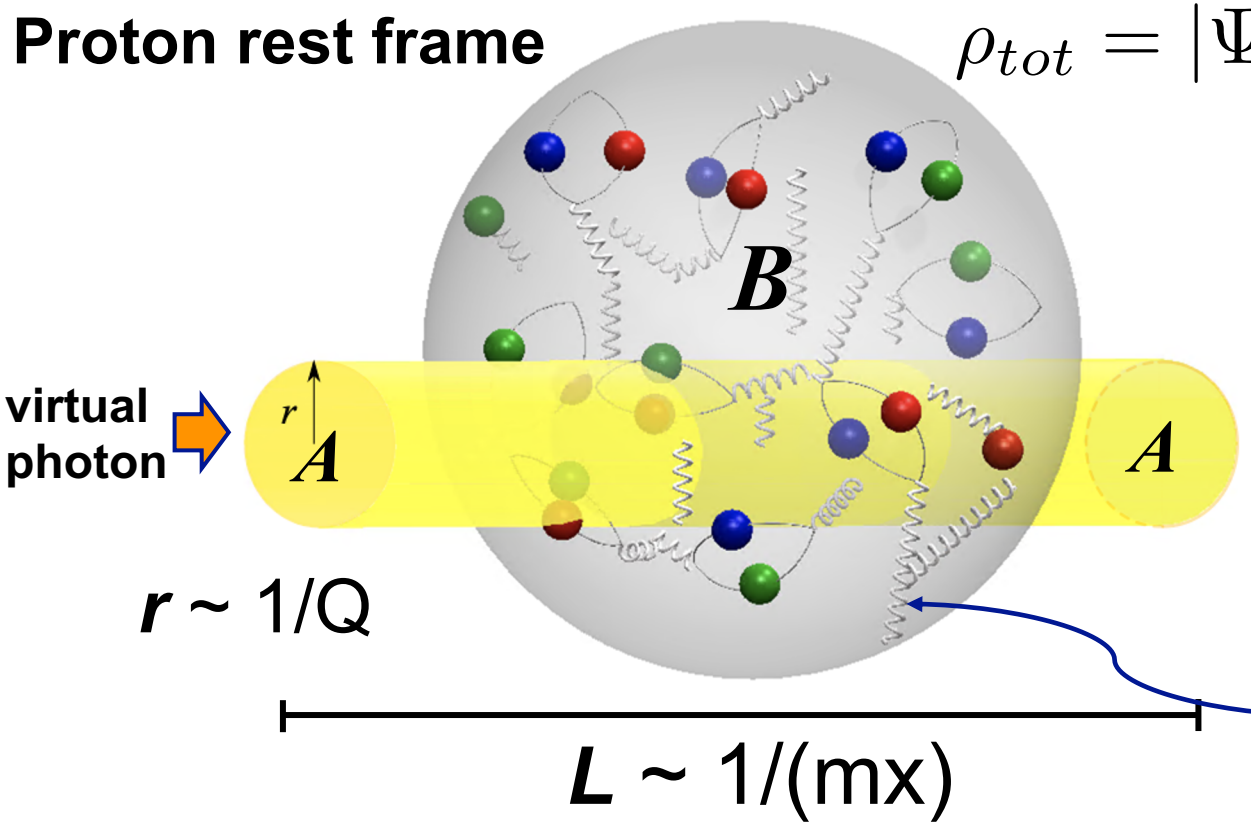
$$S = -\operatorname{tr}(\rho \ln \rho),$$

Entanglement Entropy (EE)

Pure state

Proton rest frame

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



$\rho_A \equiv \mathrm{Tr_B}(\rho_{tot})$

(reduced density matrix)

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

(von Neumann entropy)

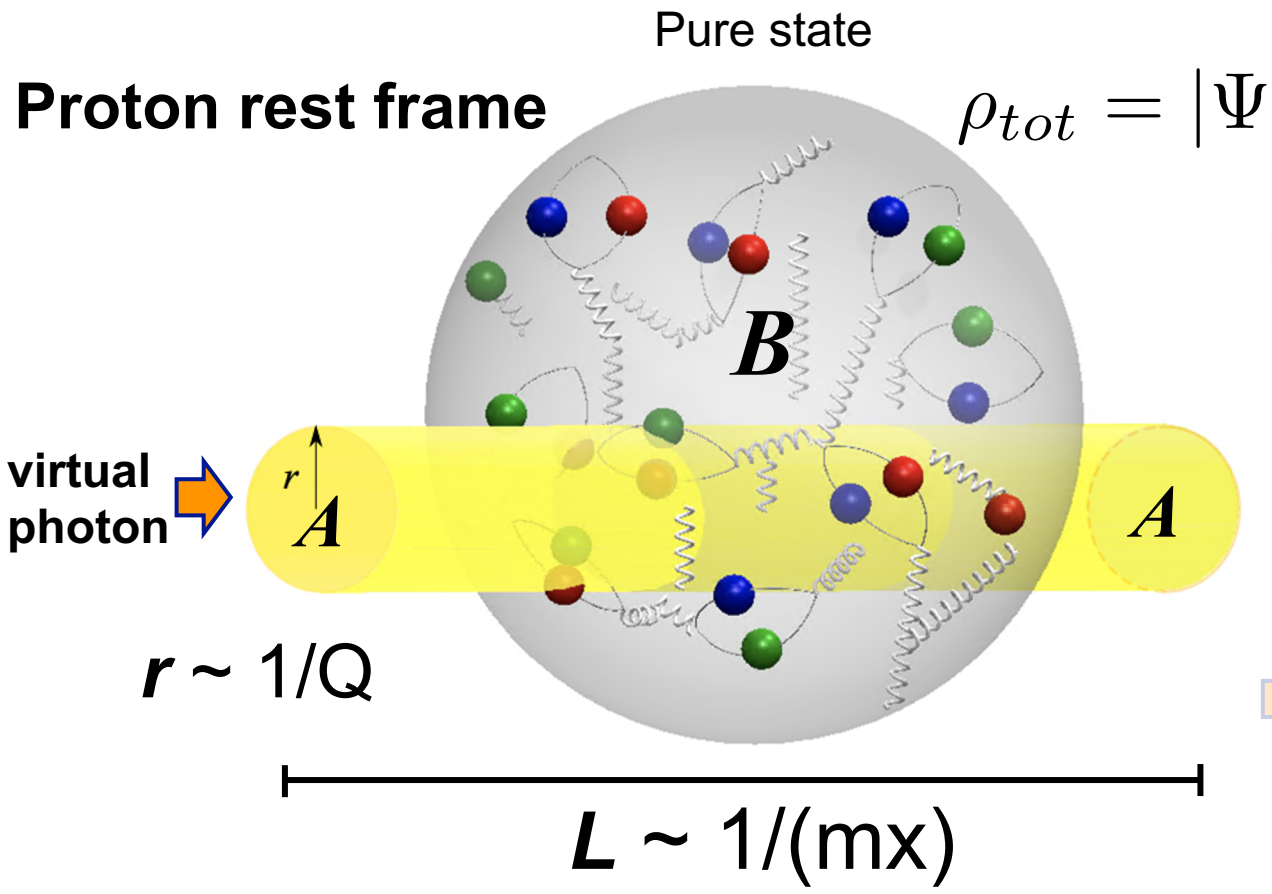
$\rho_B \equiv \mathrm{Tr_A}(\rho_{tot})$

(reduced density matrix)

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

(von Neumann entropy)

Entanglement Entropy (EE)



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(von Neumann entropy)

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

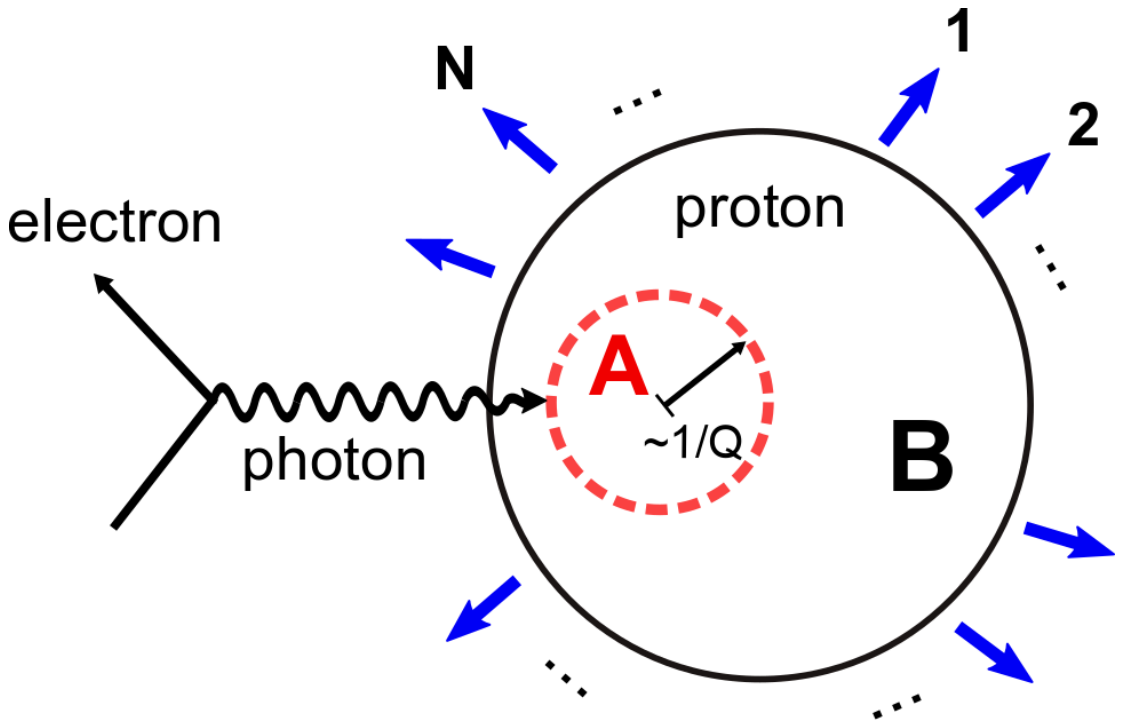
(reduced density matrix)

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

(von Neumann entropy)

Expectation – EE $S_A = S_B \neq 0$

EE in DIS



Fixed (x,Q^2)

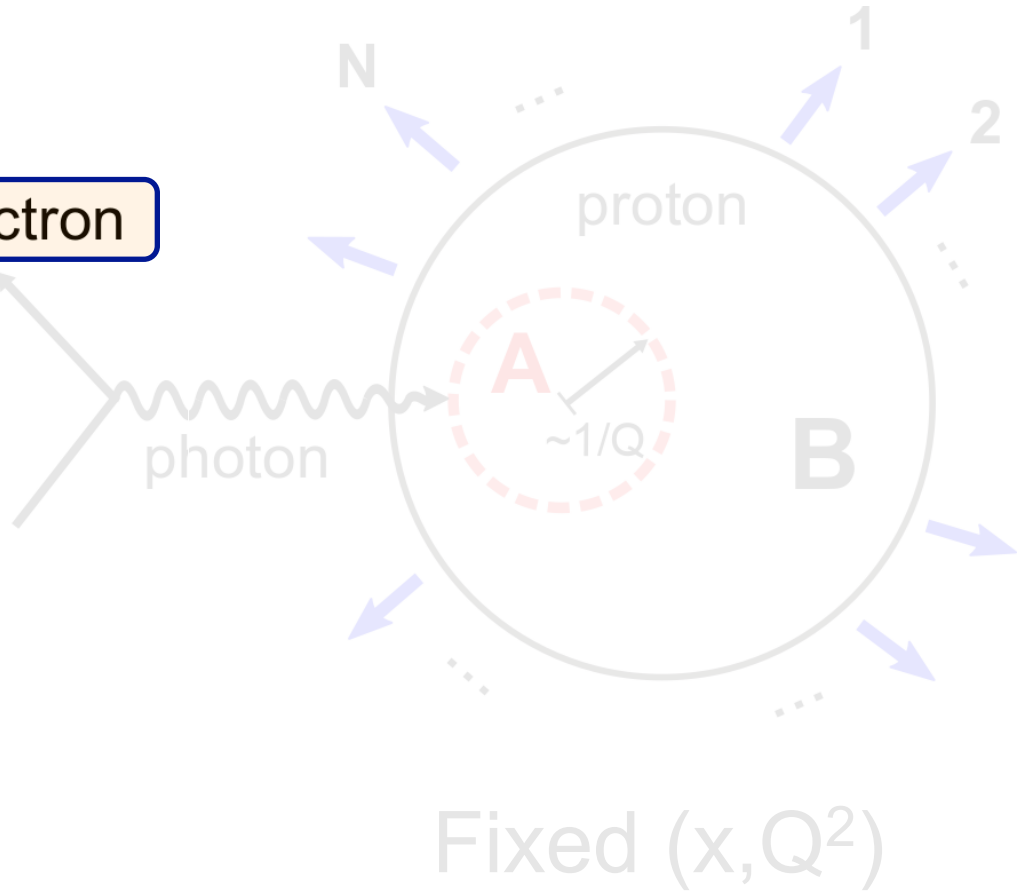
S_A in DIS

(Kharzeev & Levin 2017)

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

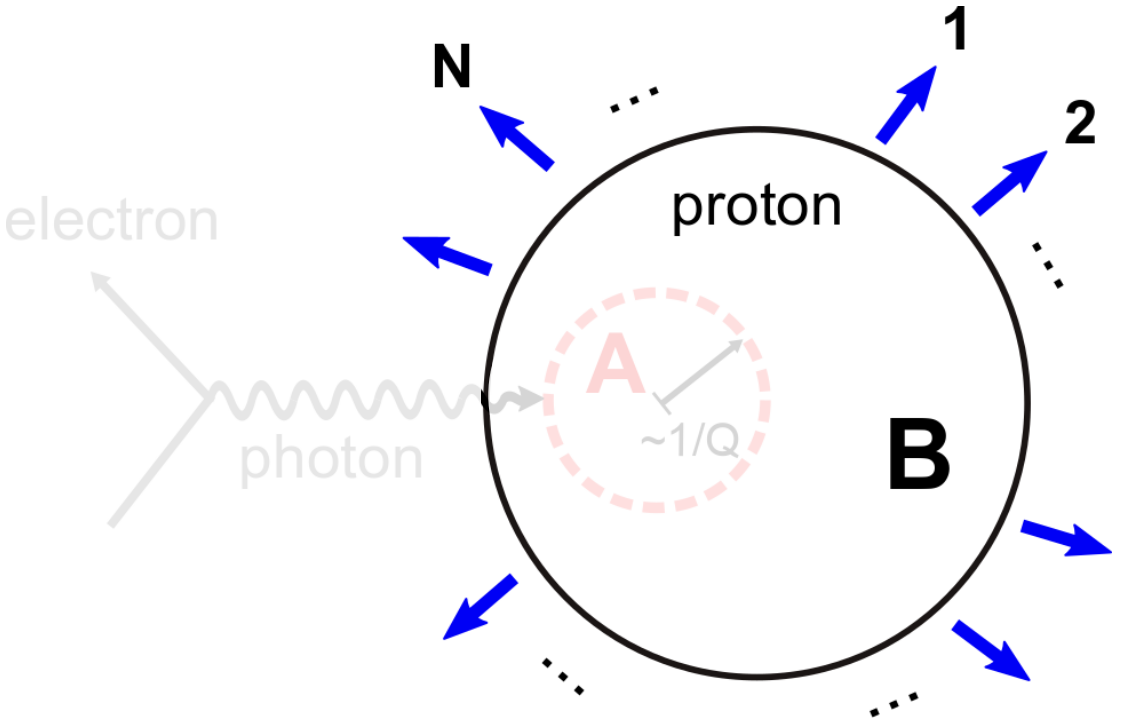
gluon entropy for low x

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



S_B in DIS

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



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

hadron entropy

P_N is charged multiplicities

Fixed (x,Q^2)

EE in DIS

(Kharzeev & Levin 2017)

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

gluon entropy for low x

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

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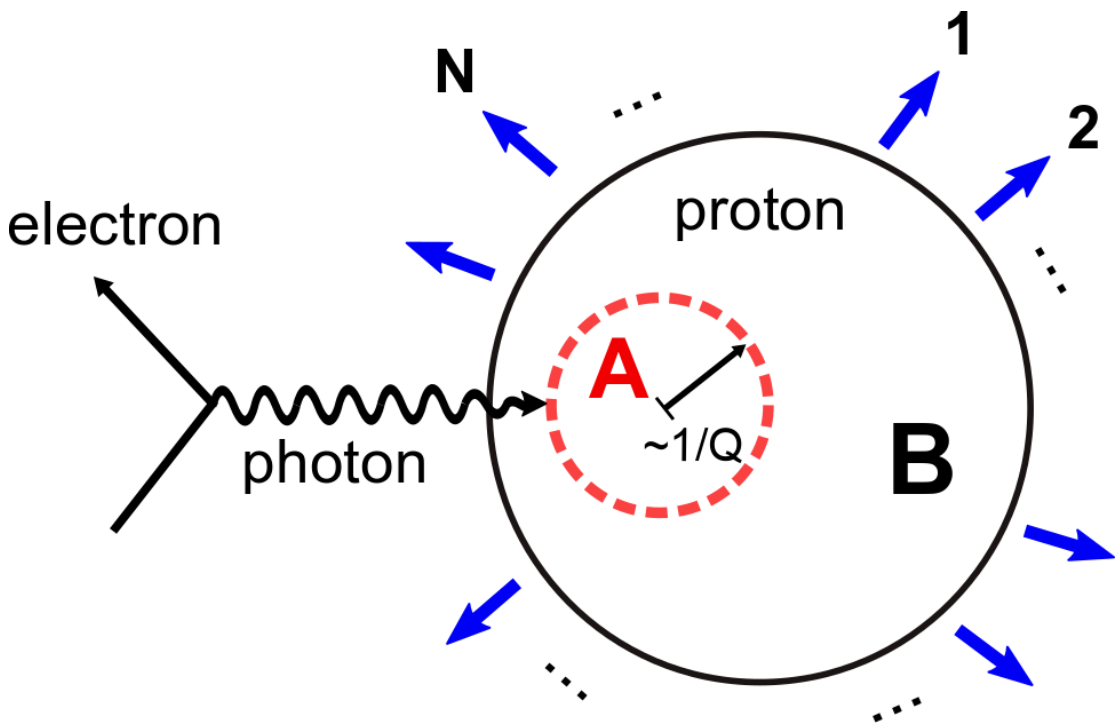
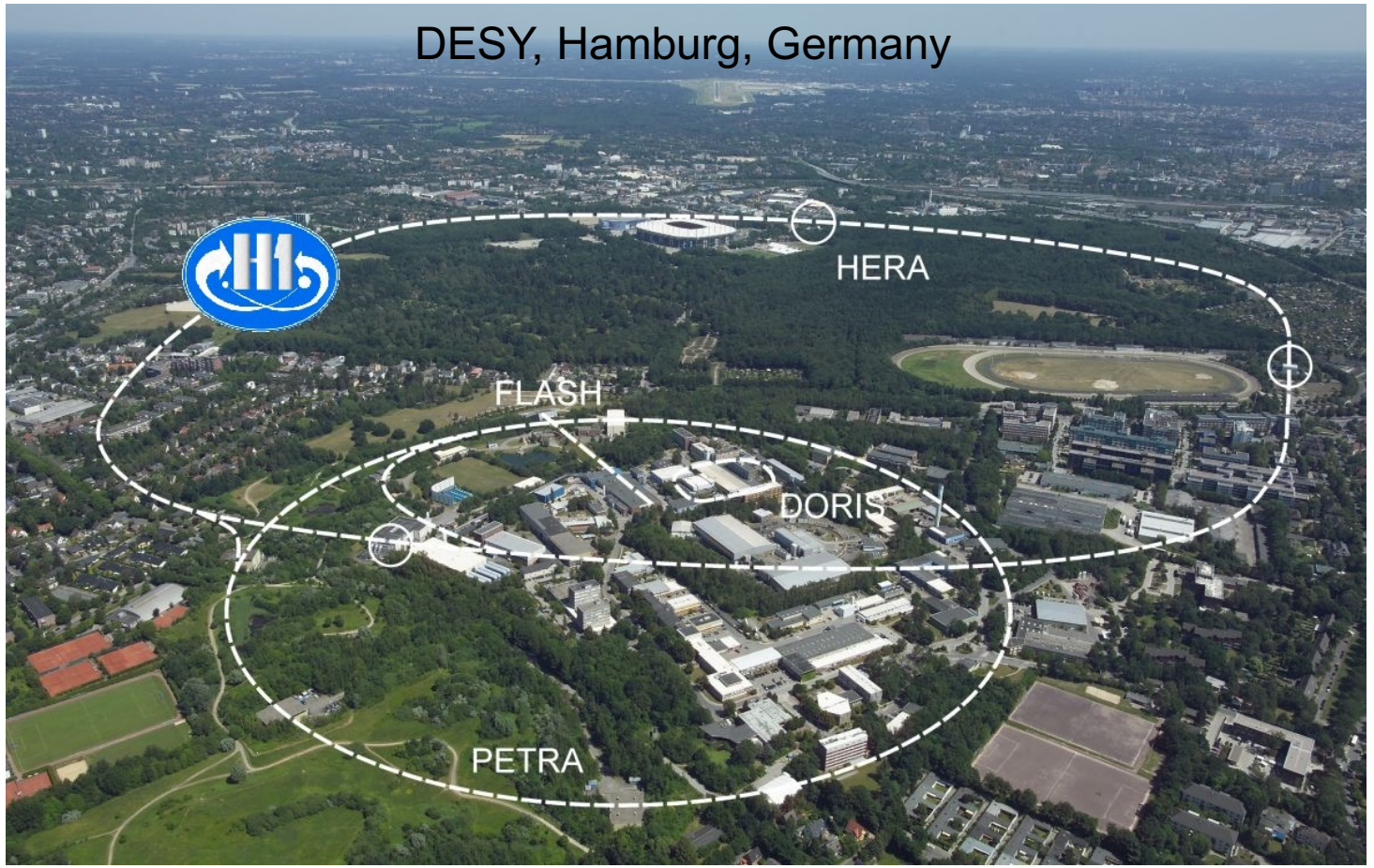


Fixed (x,Q^2)

Measurement - DIS data

H1 experiment in Museum

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

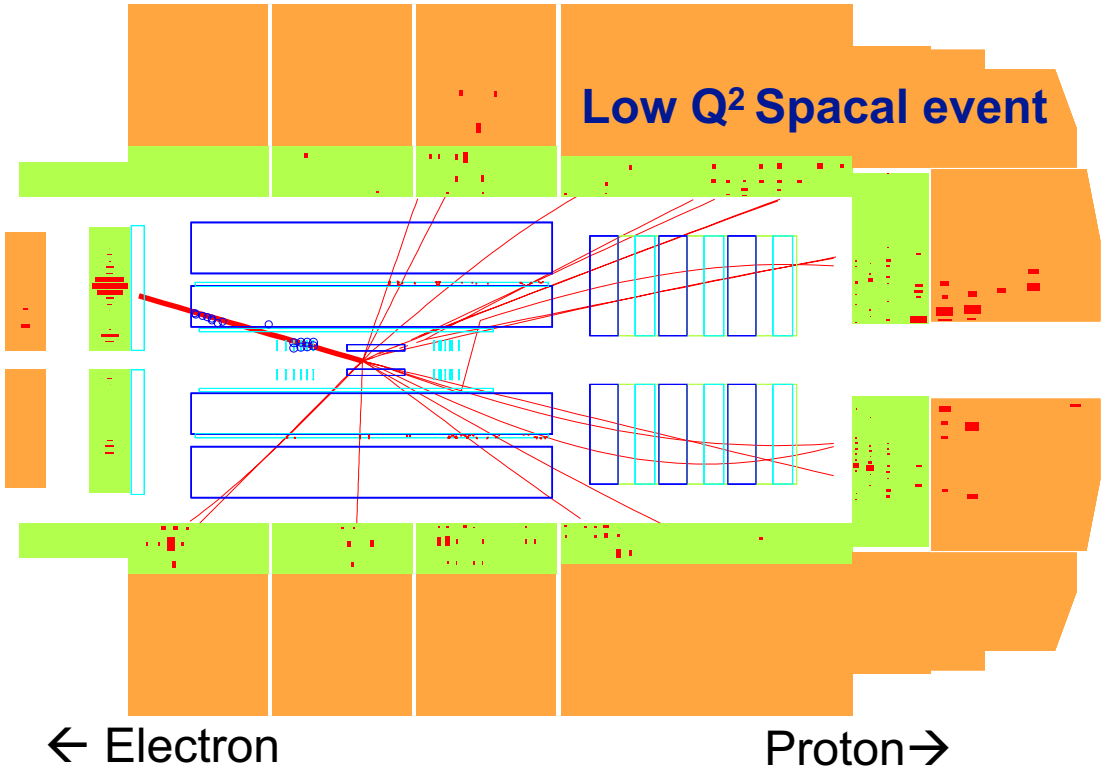


(HERA - 6.3 km in circumference)

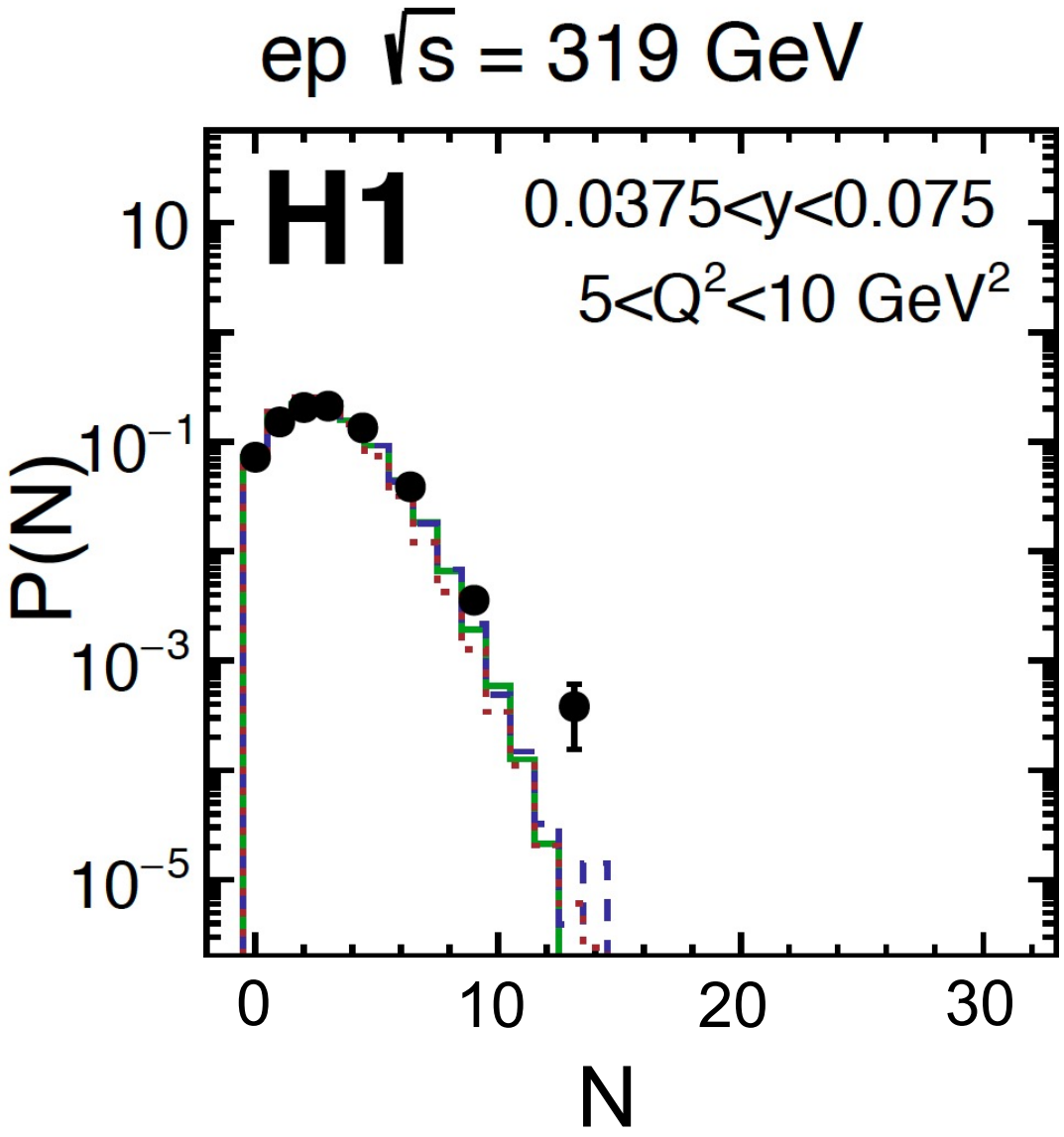
HERA experiments were shut down in 2007

H1 data

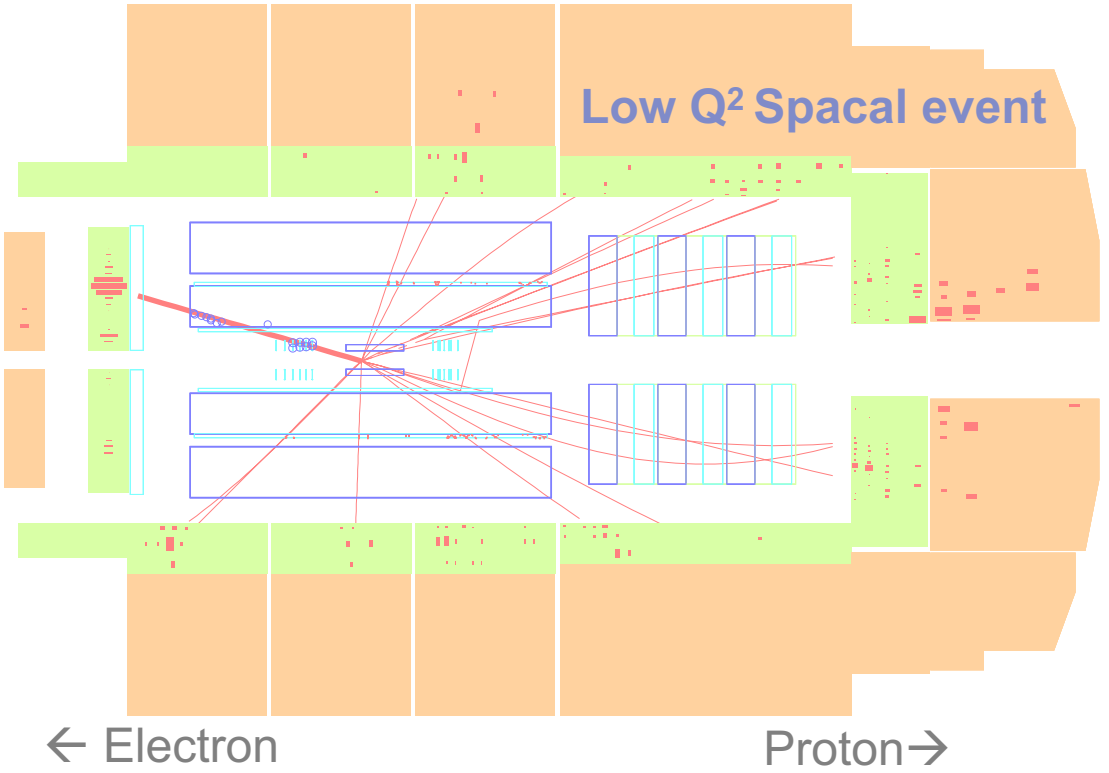
Event display



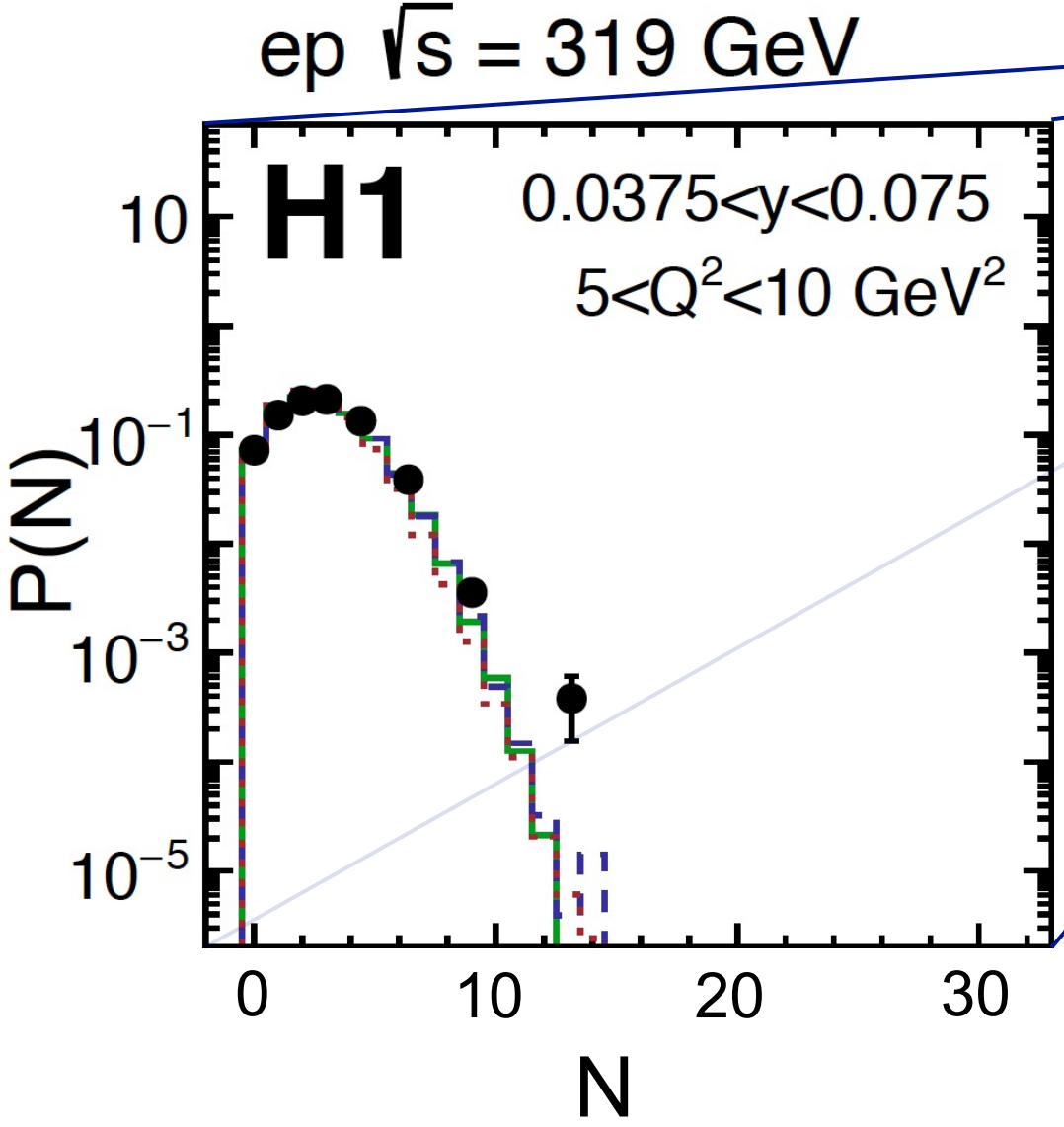
H1 data

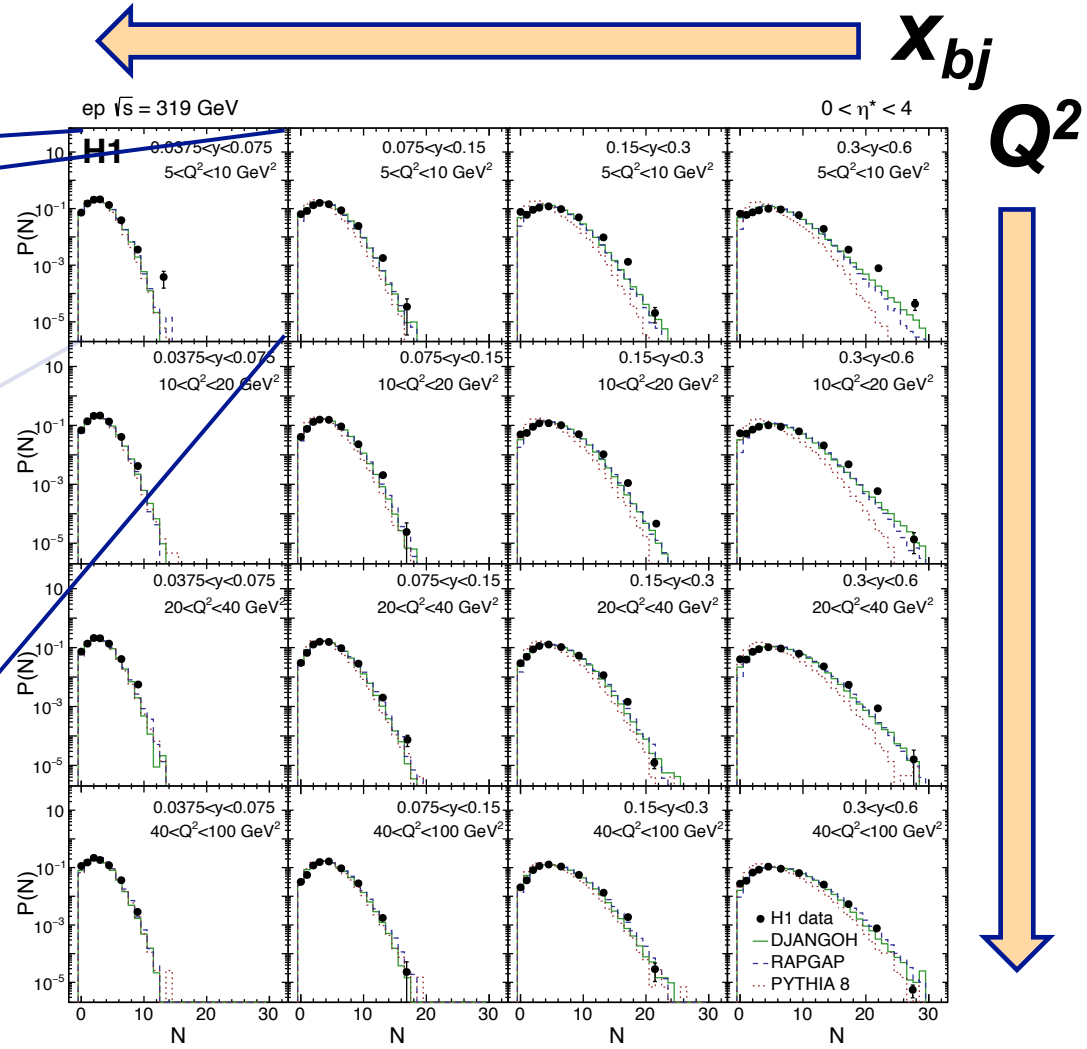


Event display



H1 data





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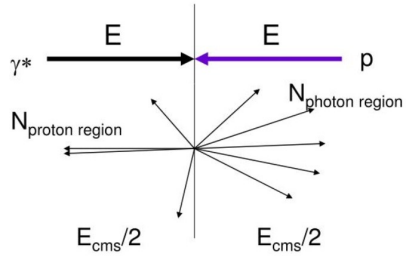
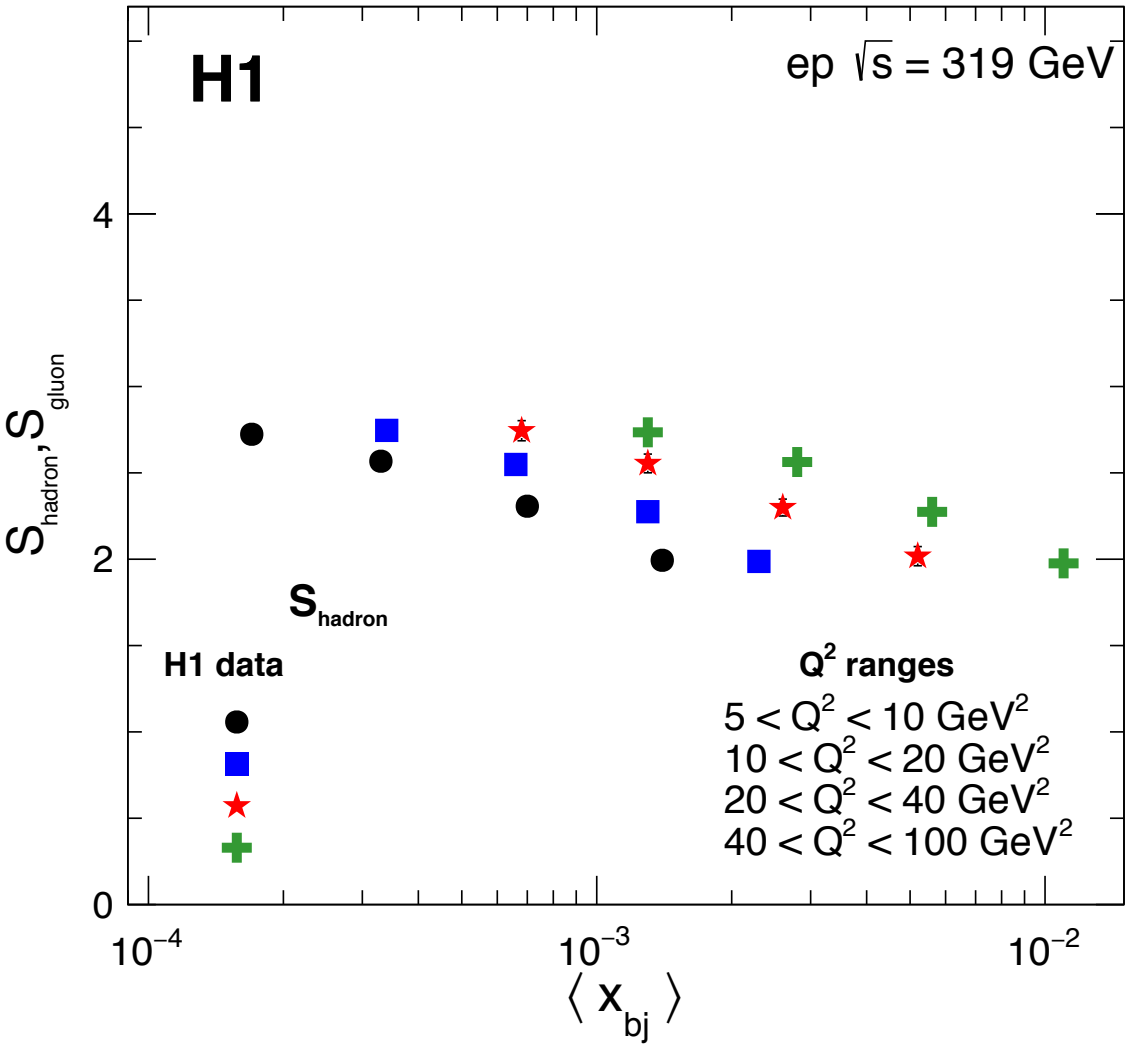
H1 data



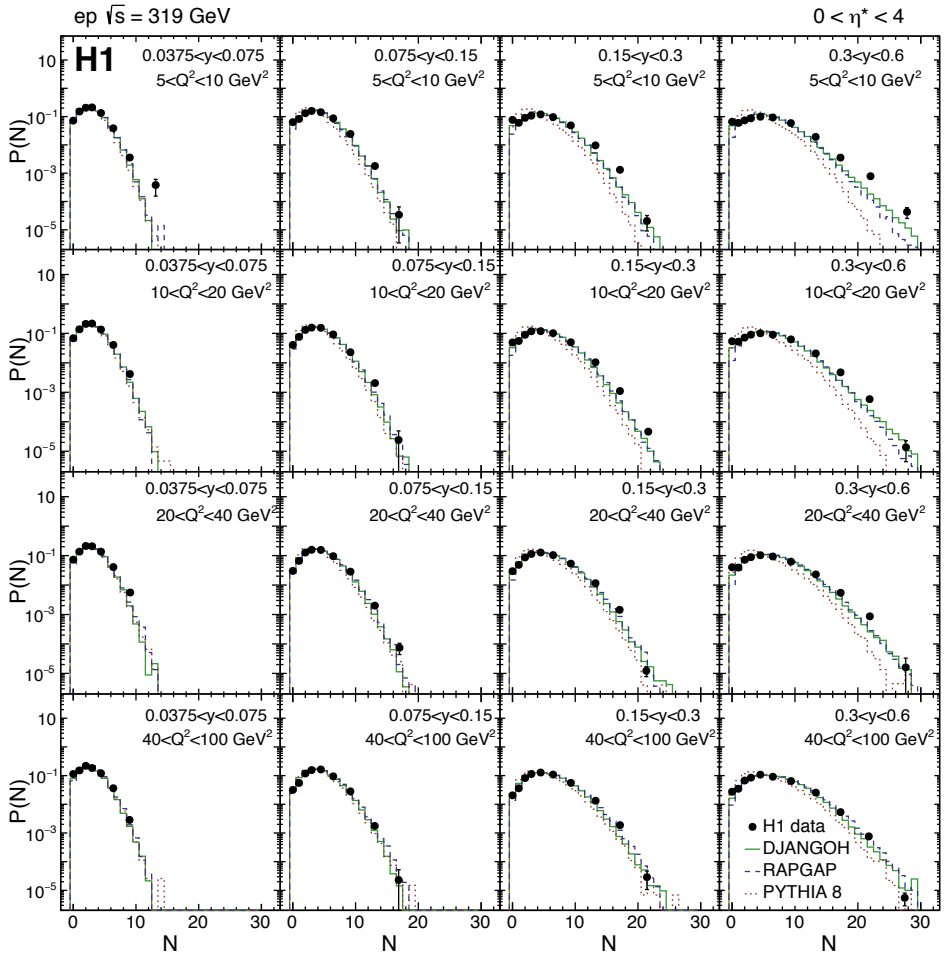
HCM frame

$0 < \eta^* < 4.0$



x_{bj}

Q^2



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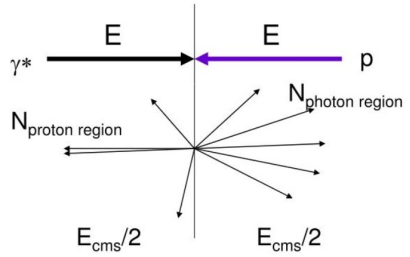

HCM frame

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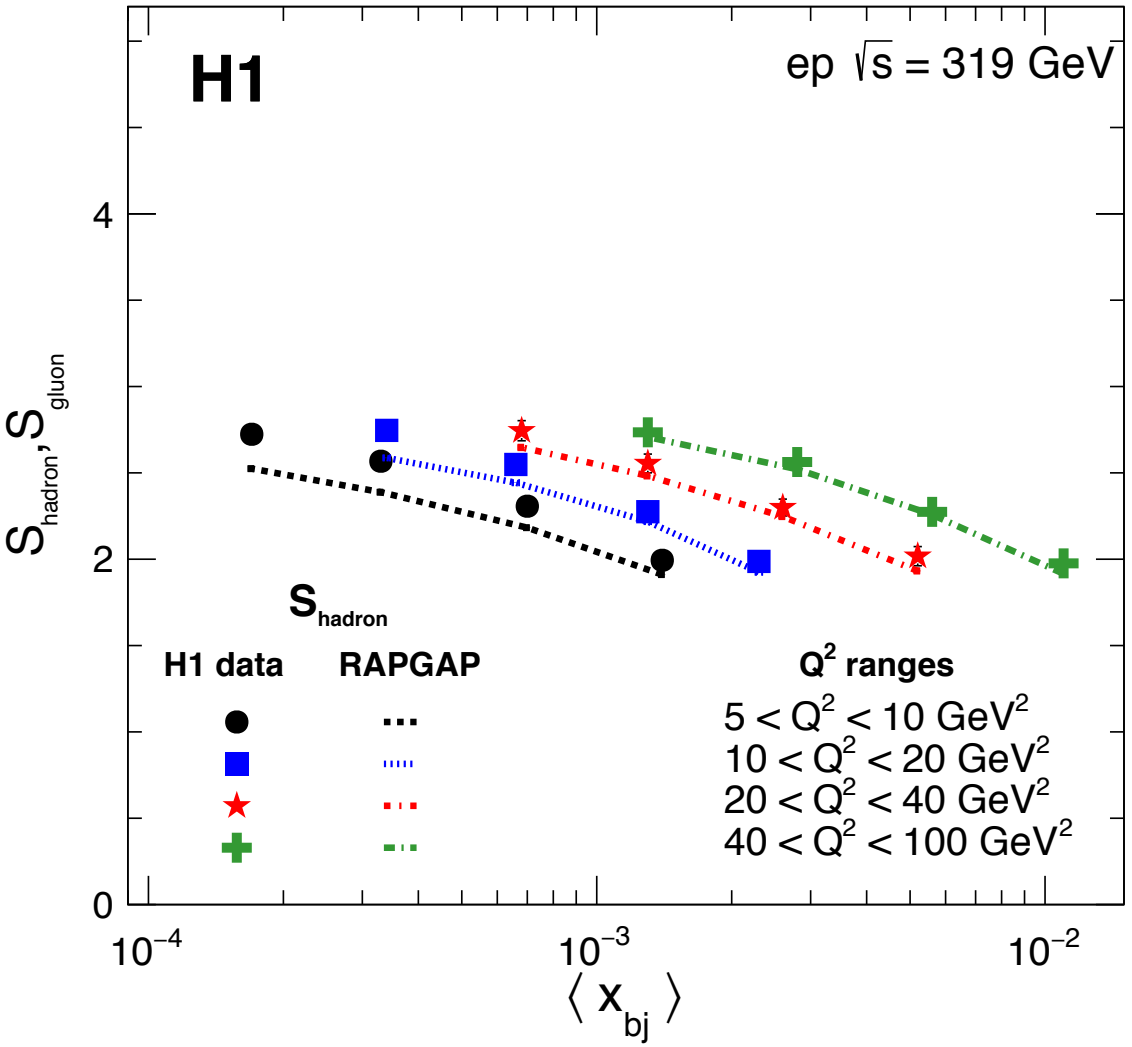
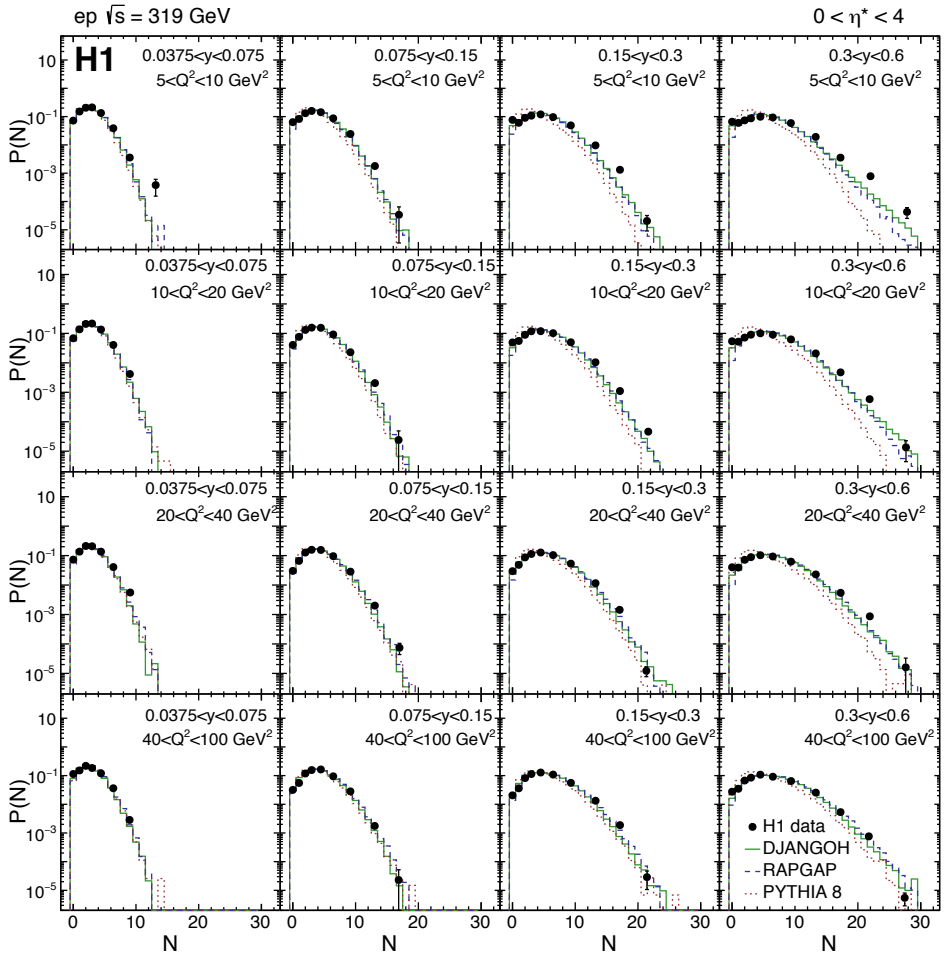


x_{bj}

Q^2



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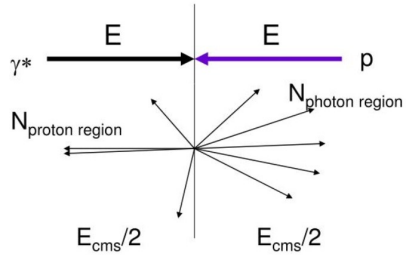
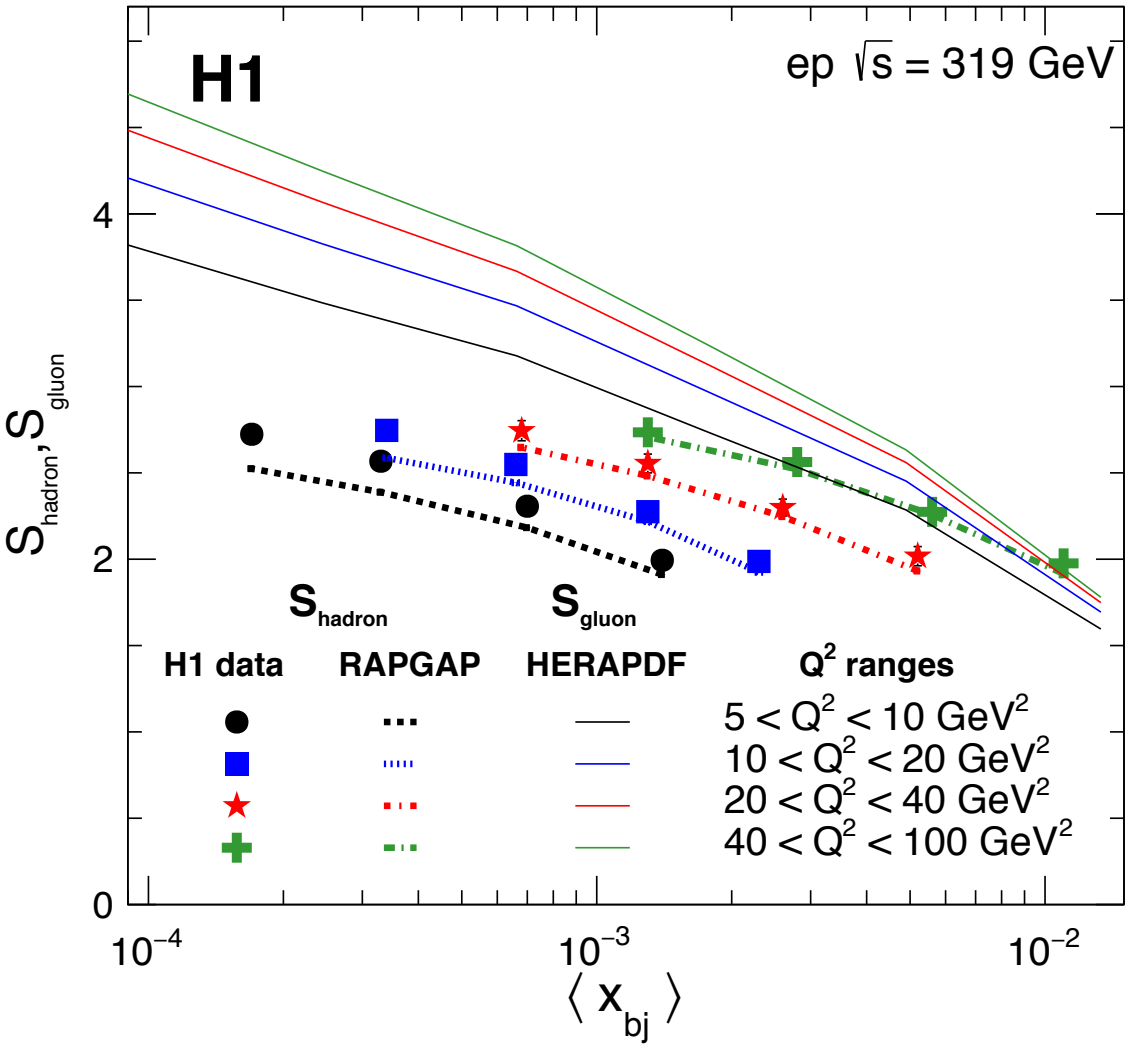
H1 data



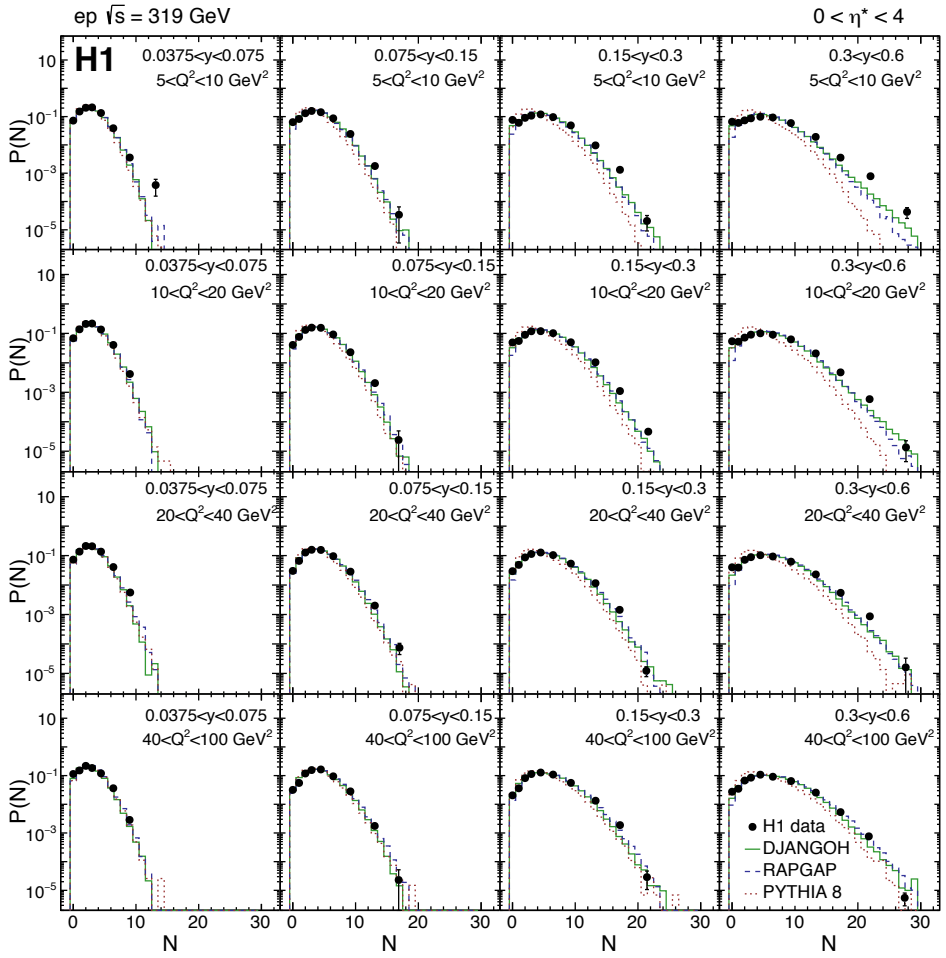
HCM frame

$0 < \eta^* < 4.0$



x_{bj}

Q^2



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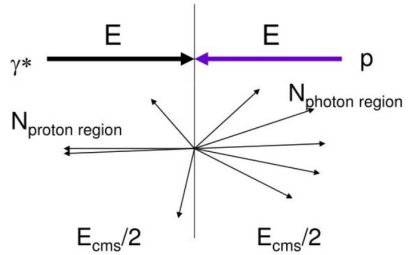
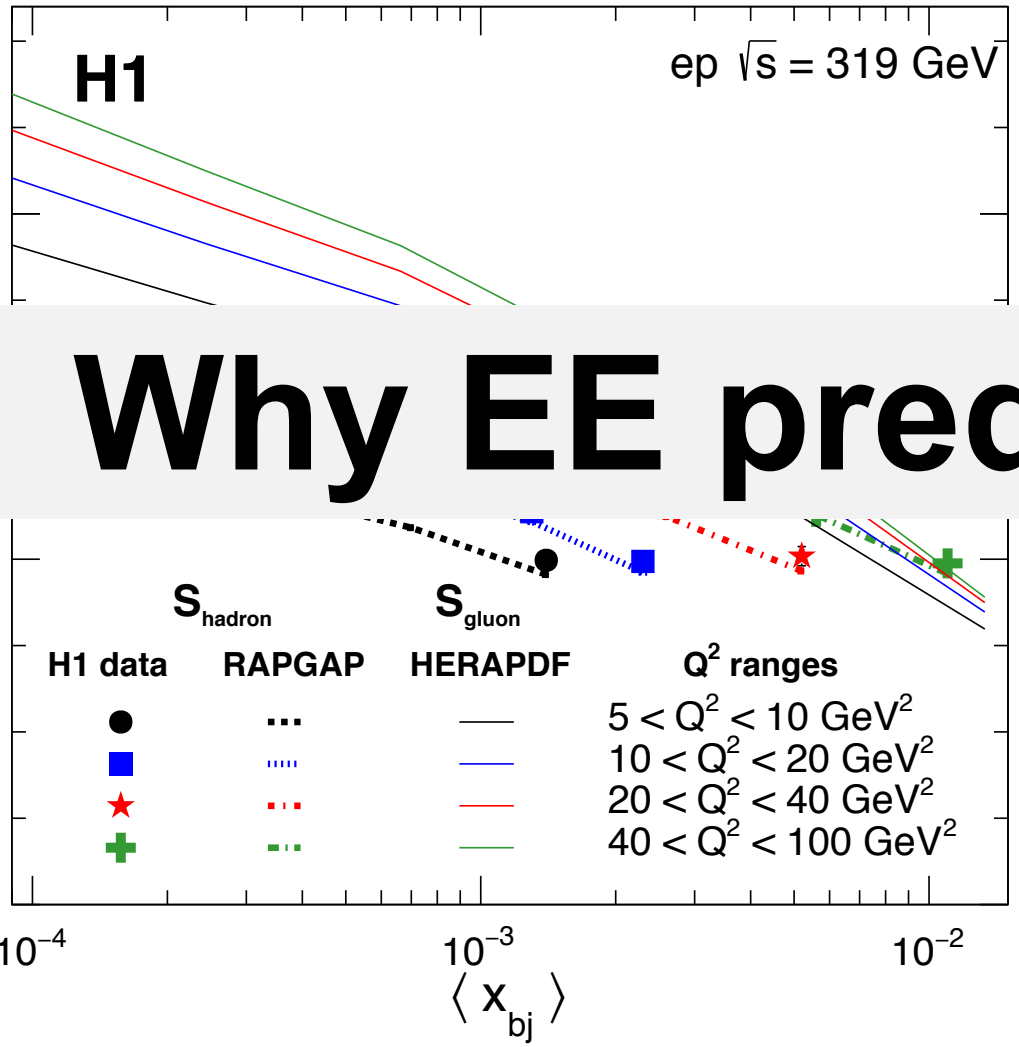
H1 data

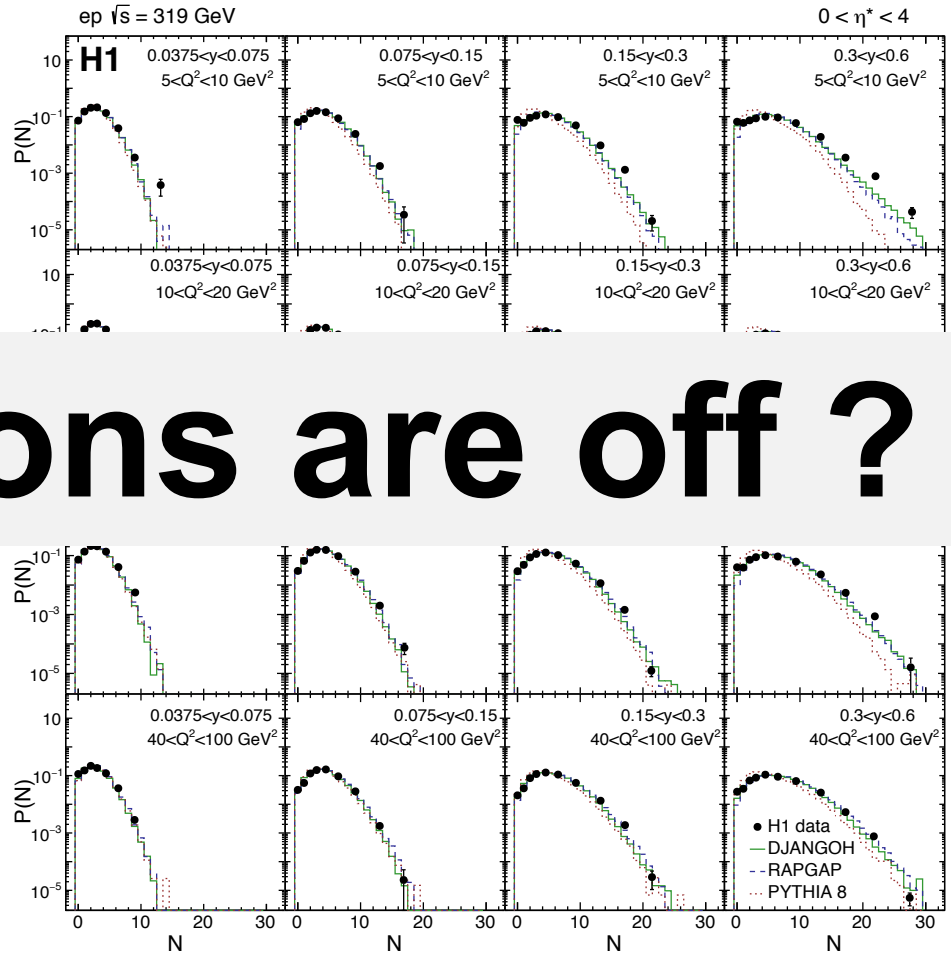


HCM frame $0 < \eta^* < 4.0$



x_{bj}

Q^2



Why EE predictions are off ?

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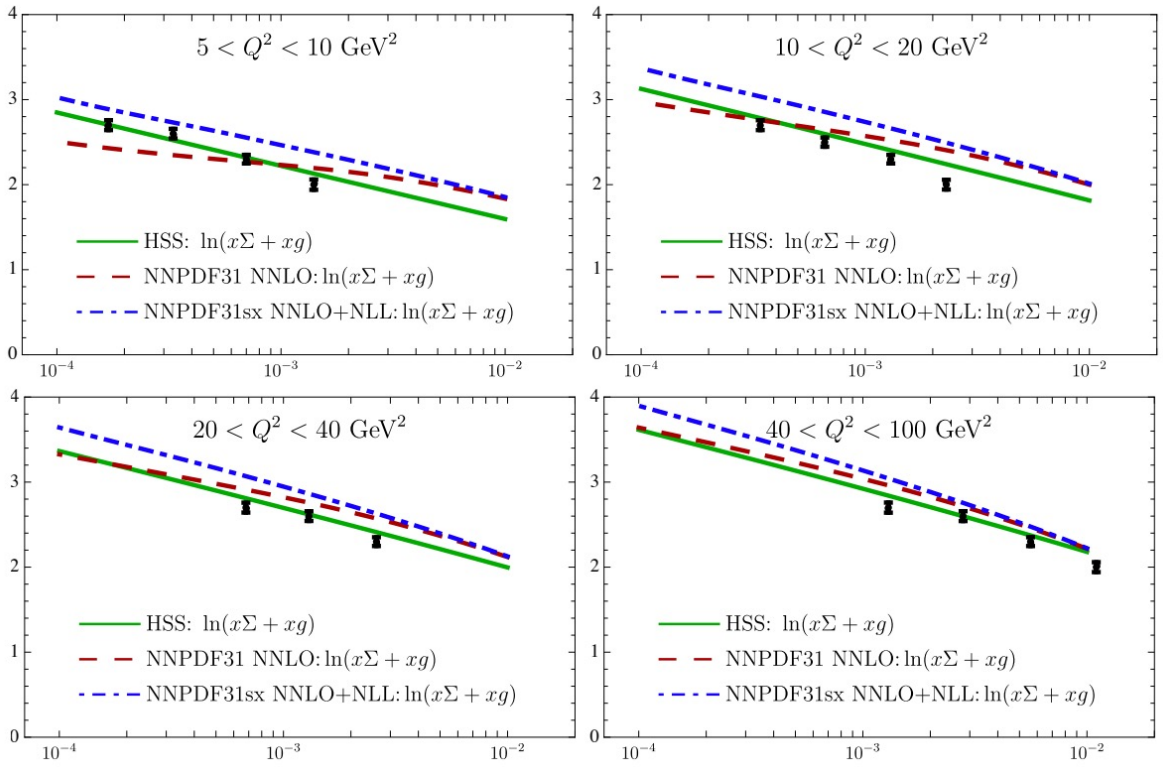
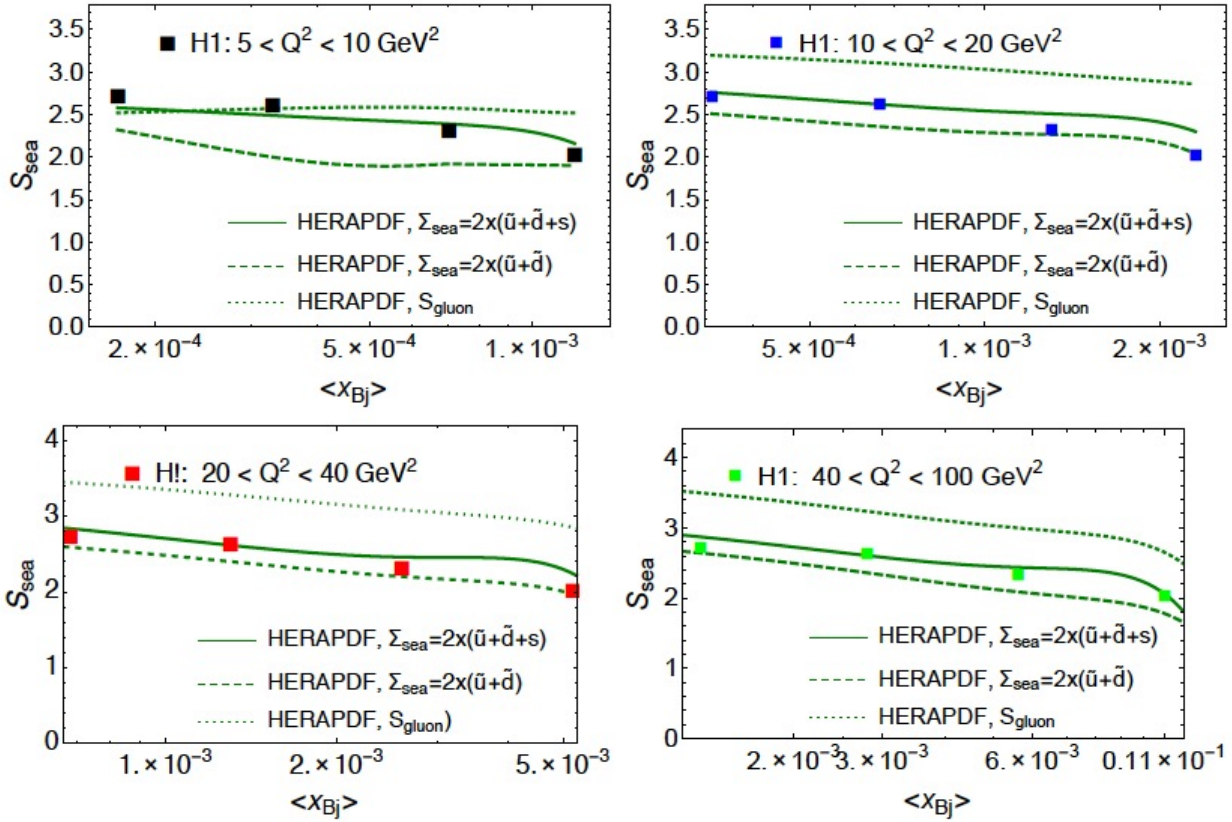
H1 data triggered many interests

sea quarks & gluons



Eur.Phys.J.C 82 (2022) 2, 111

sea quarks

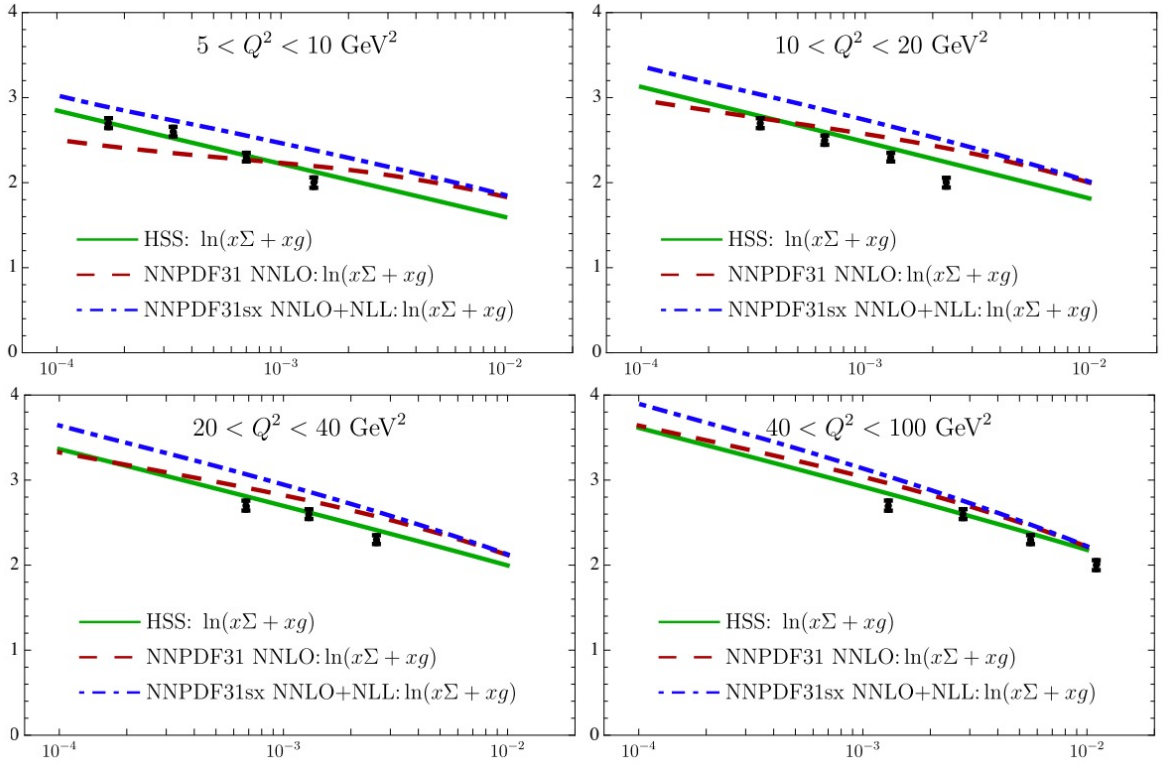


Kharzeev & Levin, arXiv:2102.09773

Not only gluons, but also sea quarks, as well as sea quarks AND gluons

H1 data triggered many interests

sea quarks & gluons



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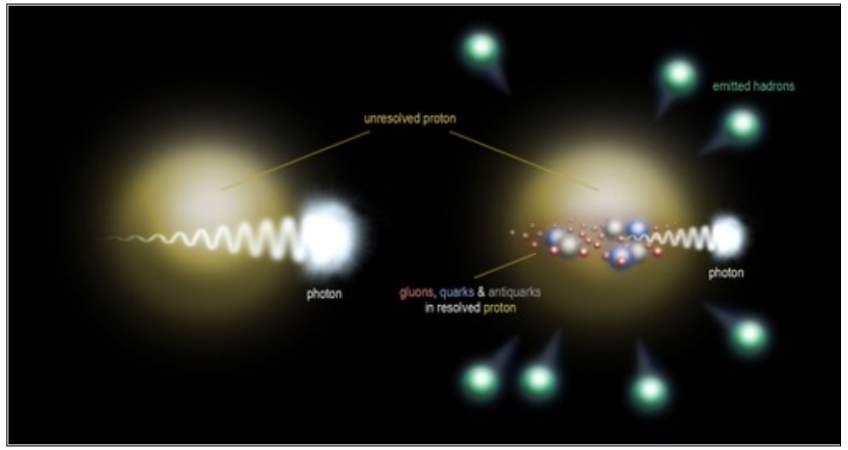
Interior of protons is maximally entangled

17 March 2022

EurekAlert!: [https://www.eurekalert.org/news-releases/946725]



If a photon carries too little energy, it does not fit inside a proton (left). A photon with sufficiently high energy is so small that it flies into the interior of a proton, where it 'sees' part of the proton (right). Maximum entanglement then becomes visible between the 'seen' and 'unseen' areas. (Source: IFJ PAN)

Fragments of the interior of a proton have been shown by scientists from Mexico and Poland to exhibit maximum quantum entanglement. The discovery, already confronted with experimental data, allows us to suppose that in some respects the physics of the inside of a proton may have much in common not only with wellknown thermodynamic phenomena, but even with the physics of... black holes.

Some recent news!

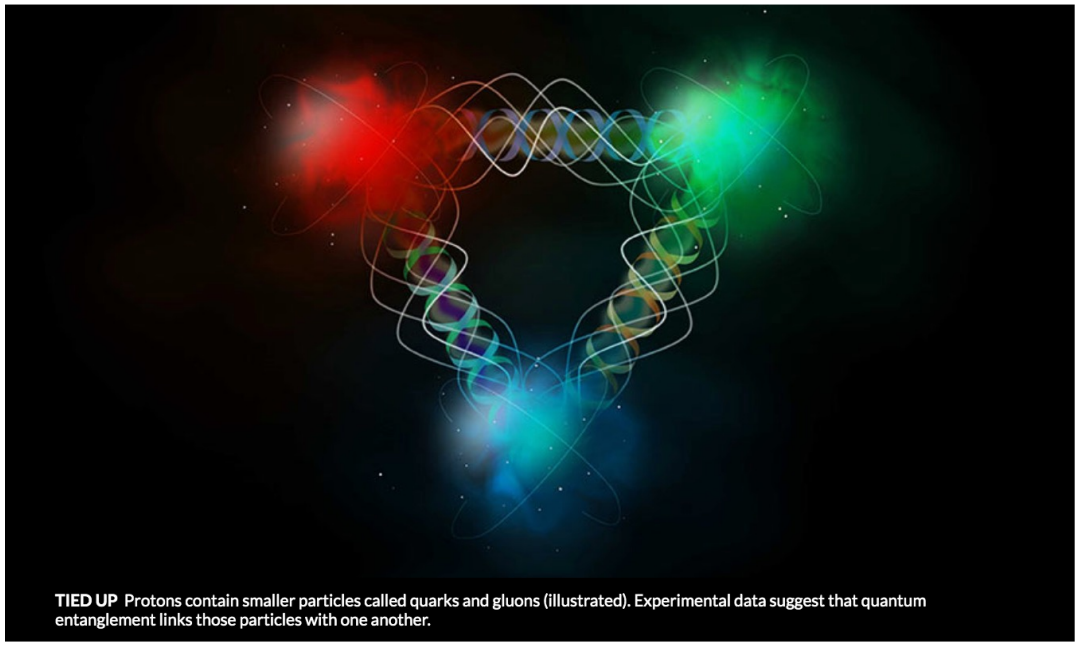
Summary

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)
(Hentschinski & Kutak 2022)

$$S_A = \ln\left(x\Sigma + xG\right)$$

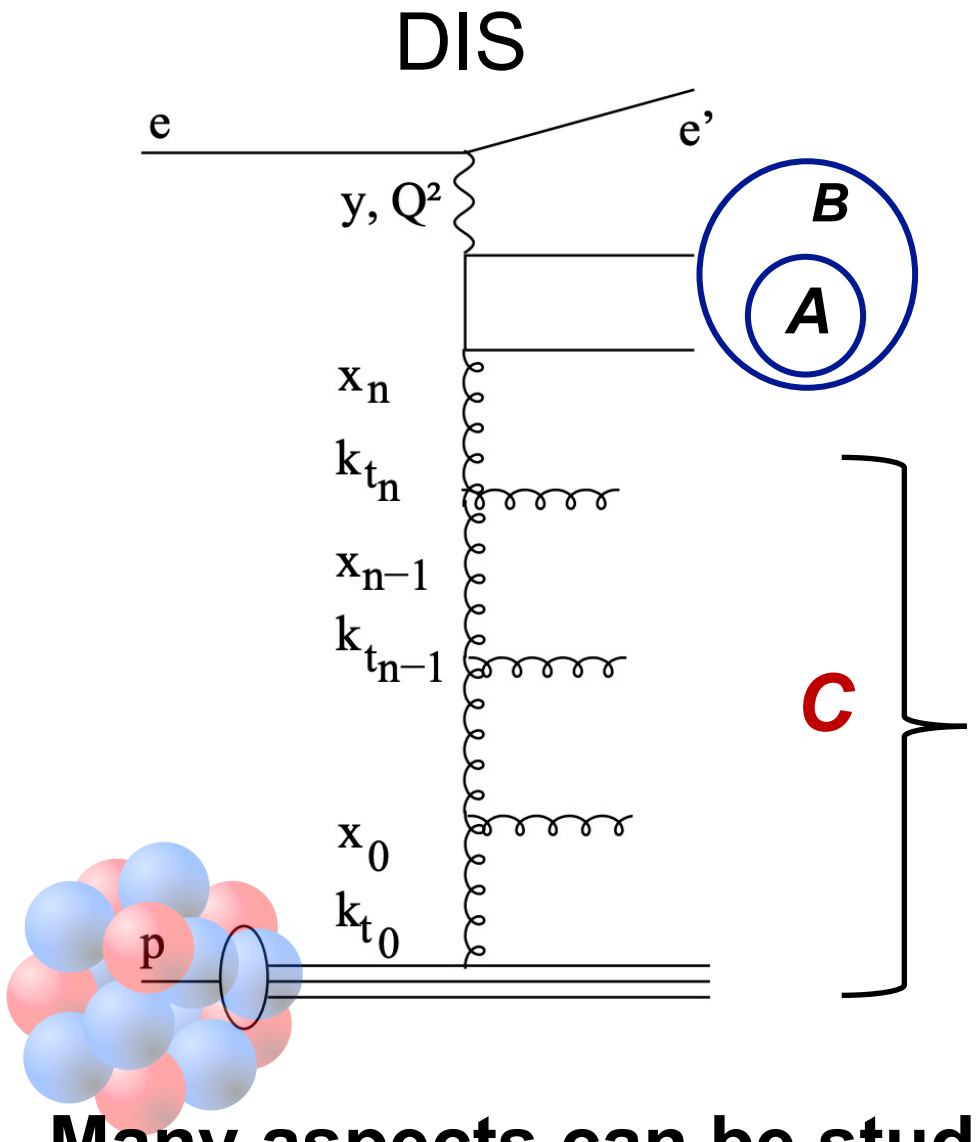
quark and gluons entropy
for low-x in DIS

...

- 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?



- 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?
- Photoproduction, diffractive DIS in ep?
- How about nucleus? eA?

Many aspects can be studied using HERA data and more at the EIC