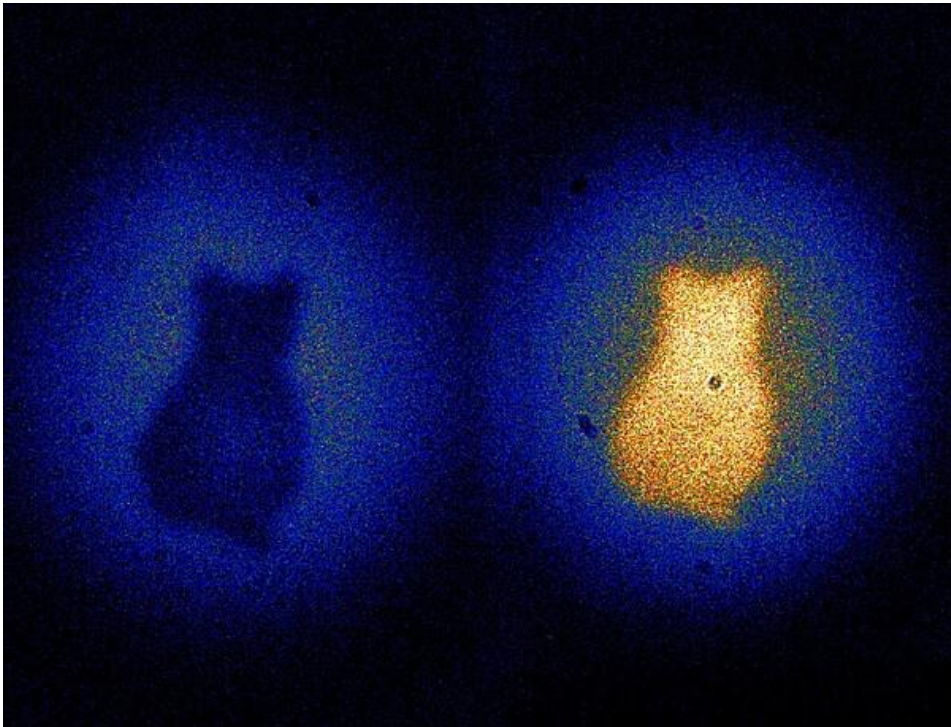


# Measurement of Entanglement Entropy in high energy particle collisions



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

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

Kong Tu

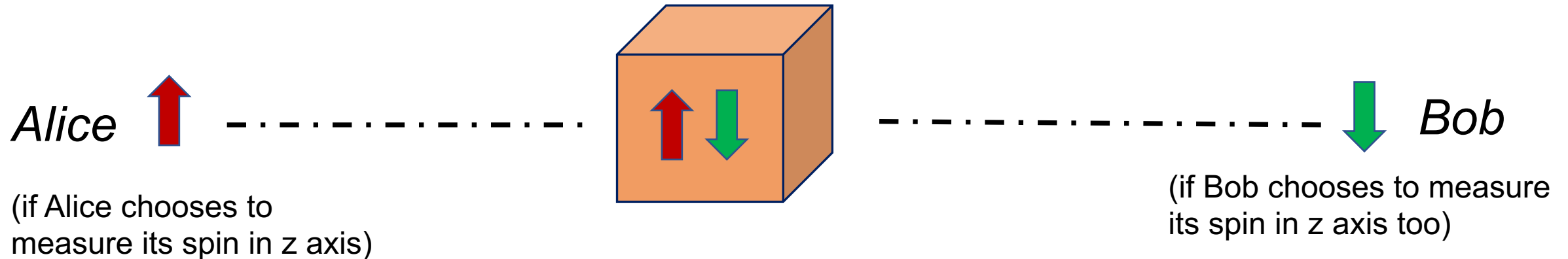
BNL

07. 28. 2021



# A story of Alice and Bob

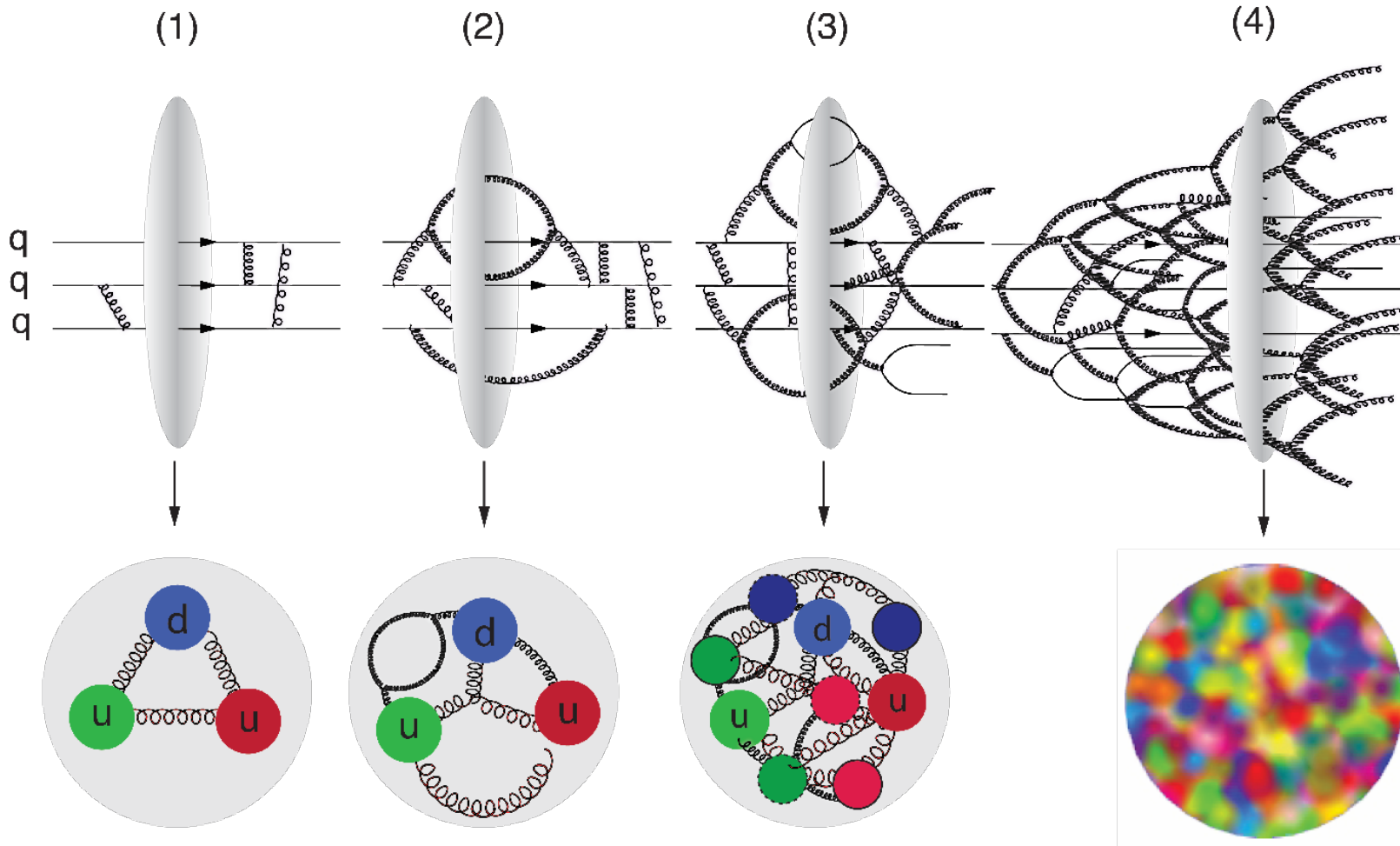
*“spooky action at a distance...”*



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  $\rightarrow$  high energy

Proton - a quantum mechanical pure state.

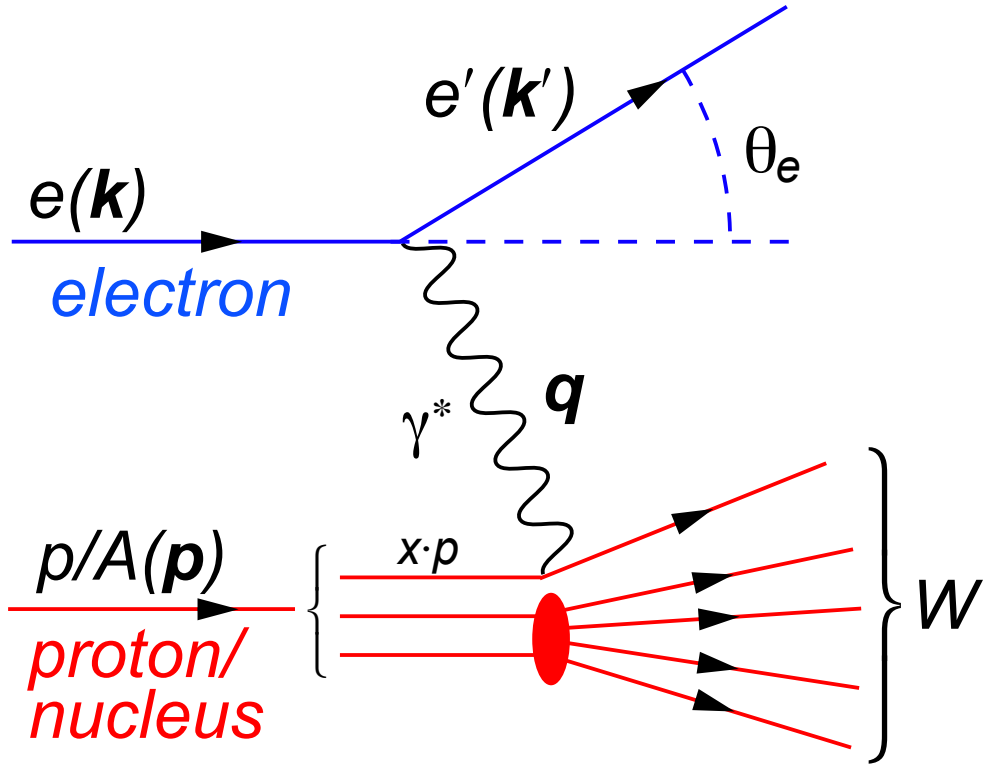
All partons are entangled quantum mechanically.

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

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

# DIS and nucleon structure

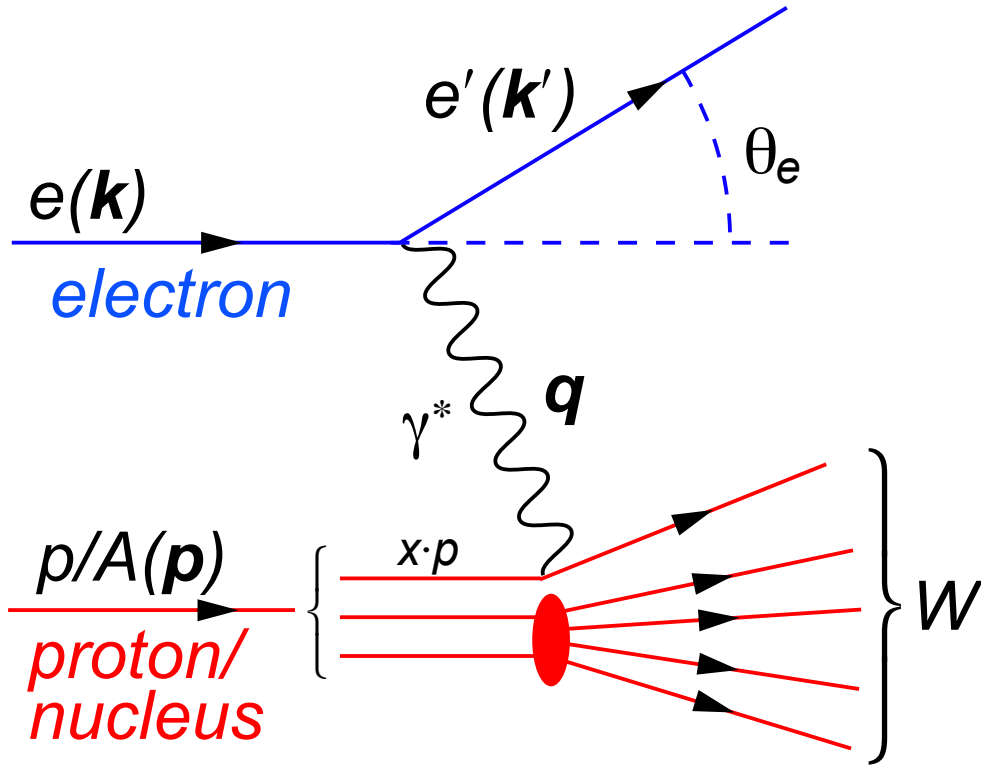
## Deep Inelastic Scattering



1. Resolution  $\sim Q^2 = -q^2$
2. Momentum fraction  $\sim x_{bj} = \frac{Q^2}{2Pq}$   
"Exposure time"

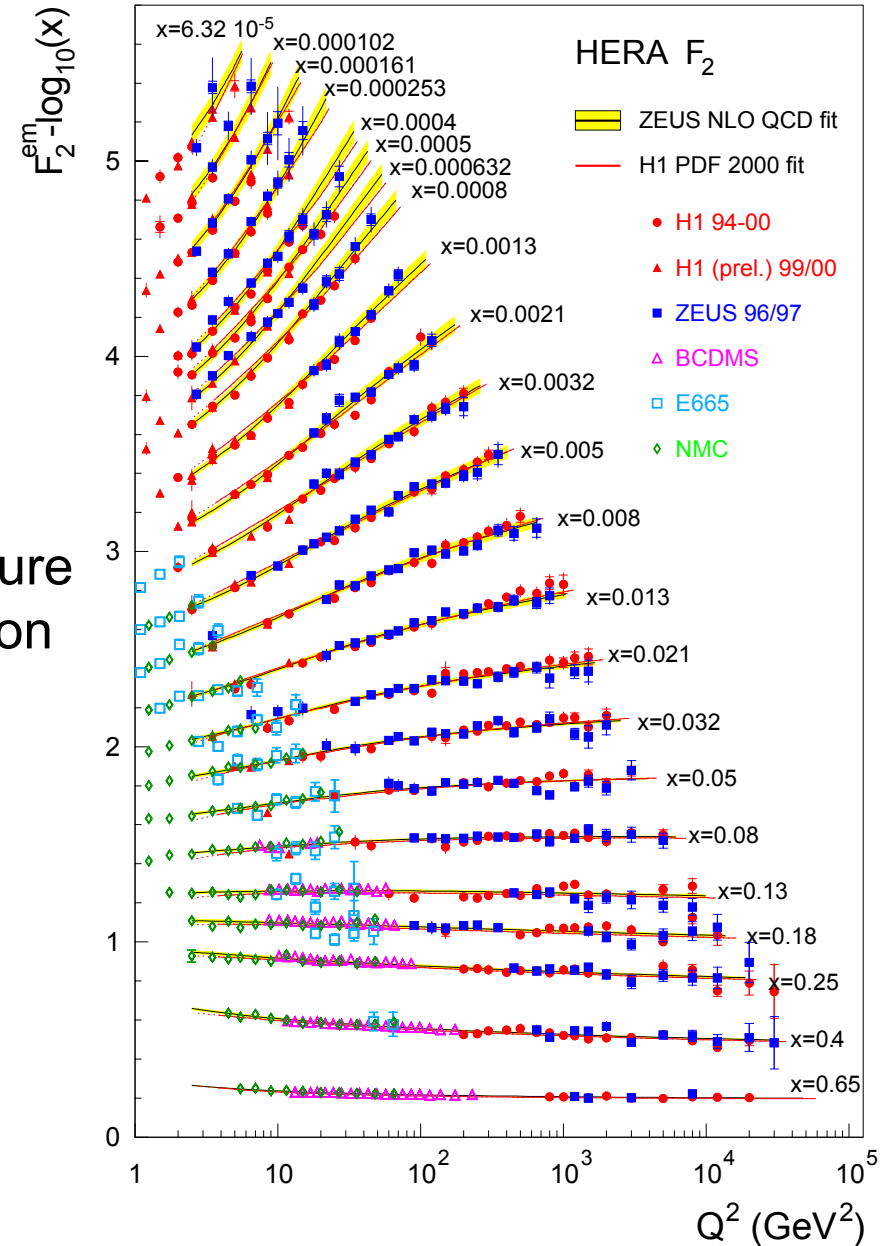
# DIS and nucleon structure

## Deep Inelastic Scattering



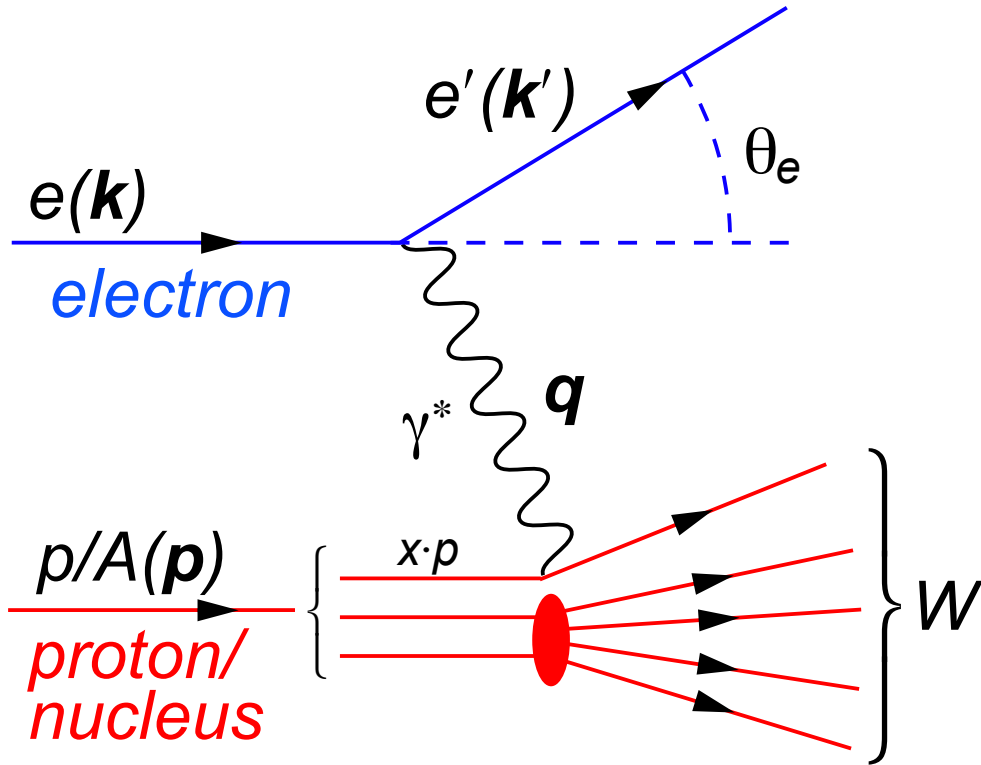
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structure function



# DIS and nucleon structure

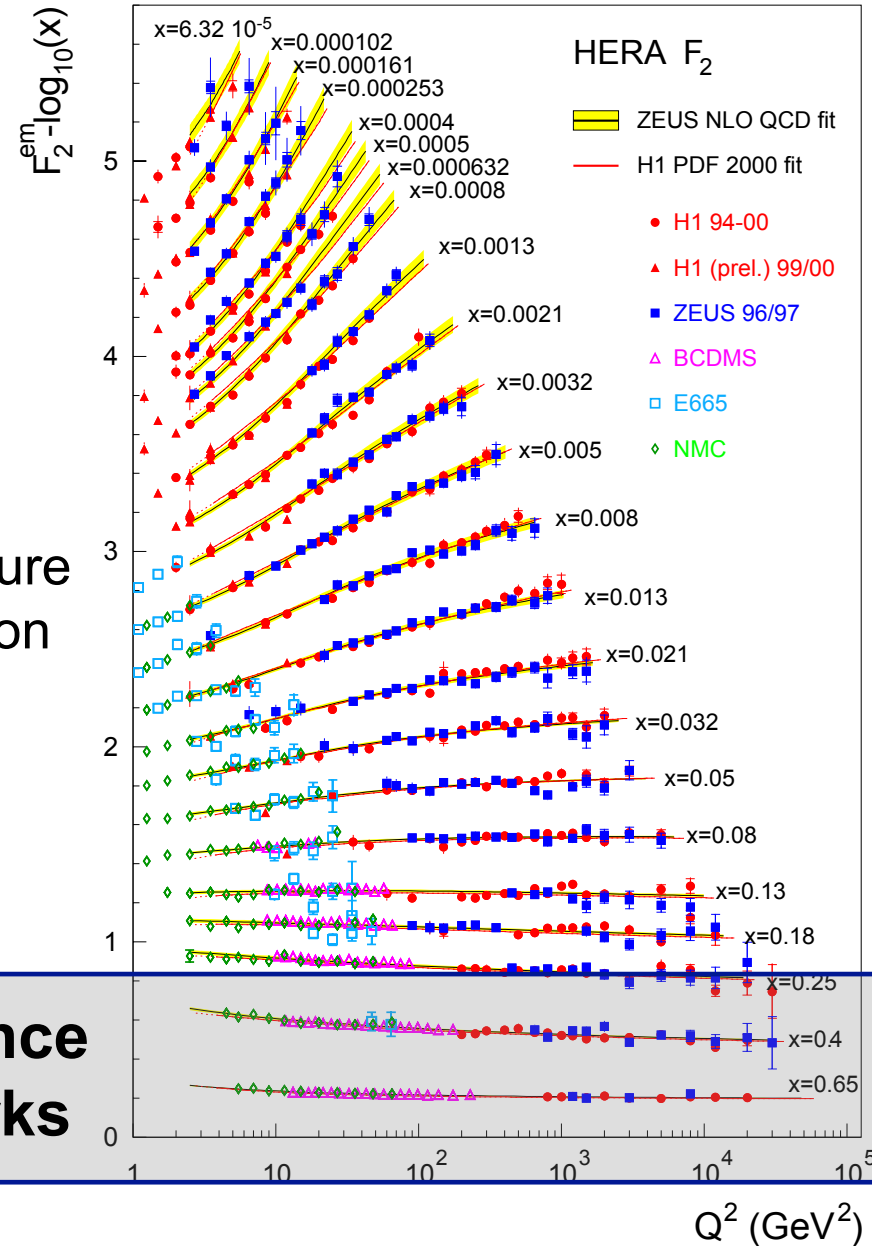
## Deep Inelastic Scattering



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"Exposure time"

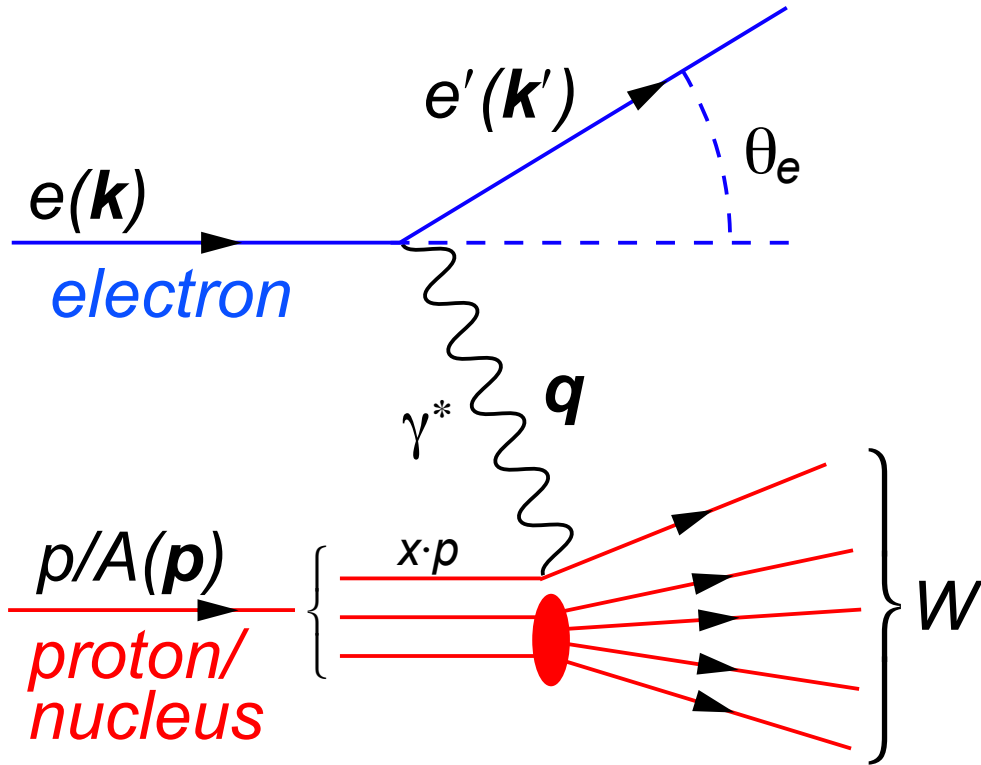
structure function

**Valence Quarks**



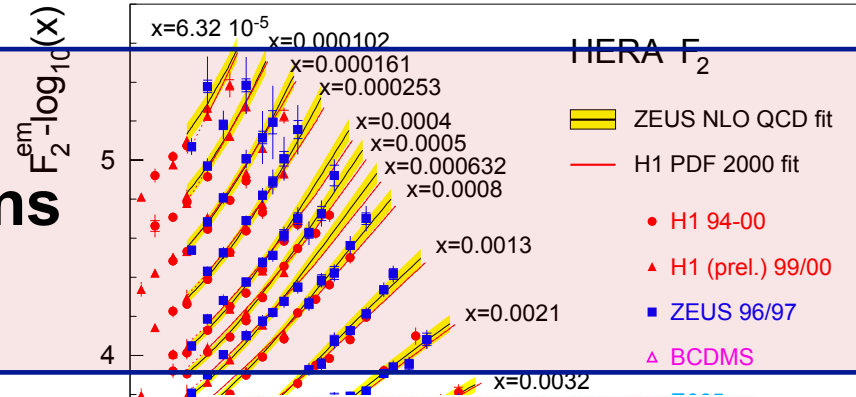
# DIS and nucleon structure

## Deep Inelastic Scattering



1. Resolution  $\sim Q^2 = -q^2$
2. Momentum fraction  $\sim x_{bj} = \frac{Q^2}{2Pq}$   
"Exposure time"

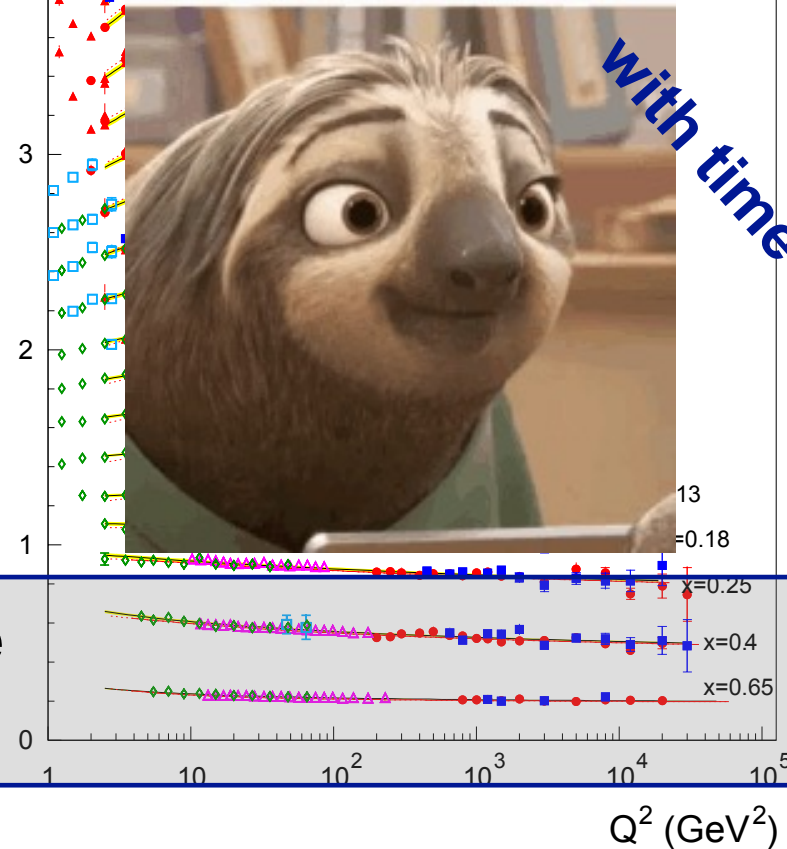
### Gluons



Scaling violation

structure function

### Valence Quarks

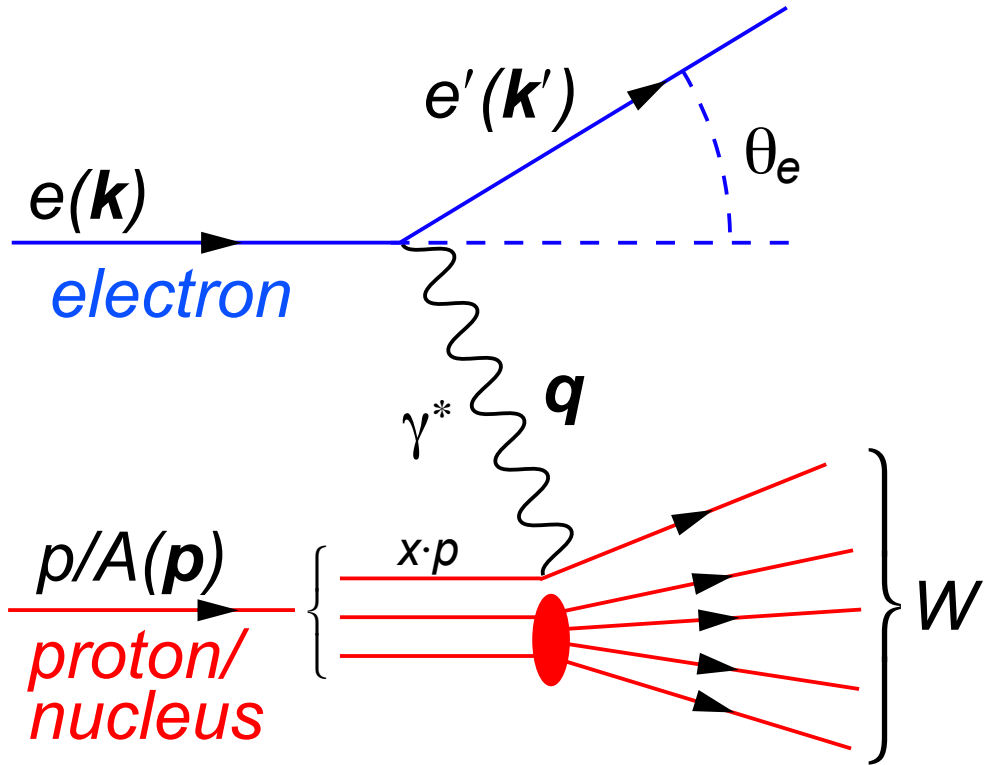


Bjorken-scaling

With time dilation ...

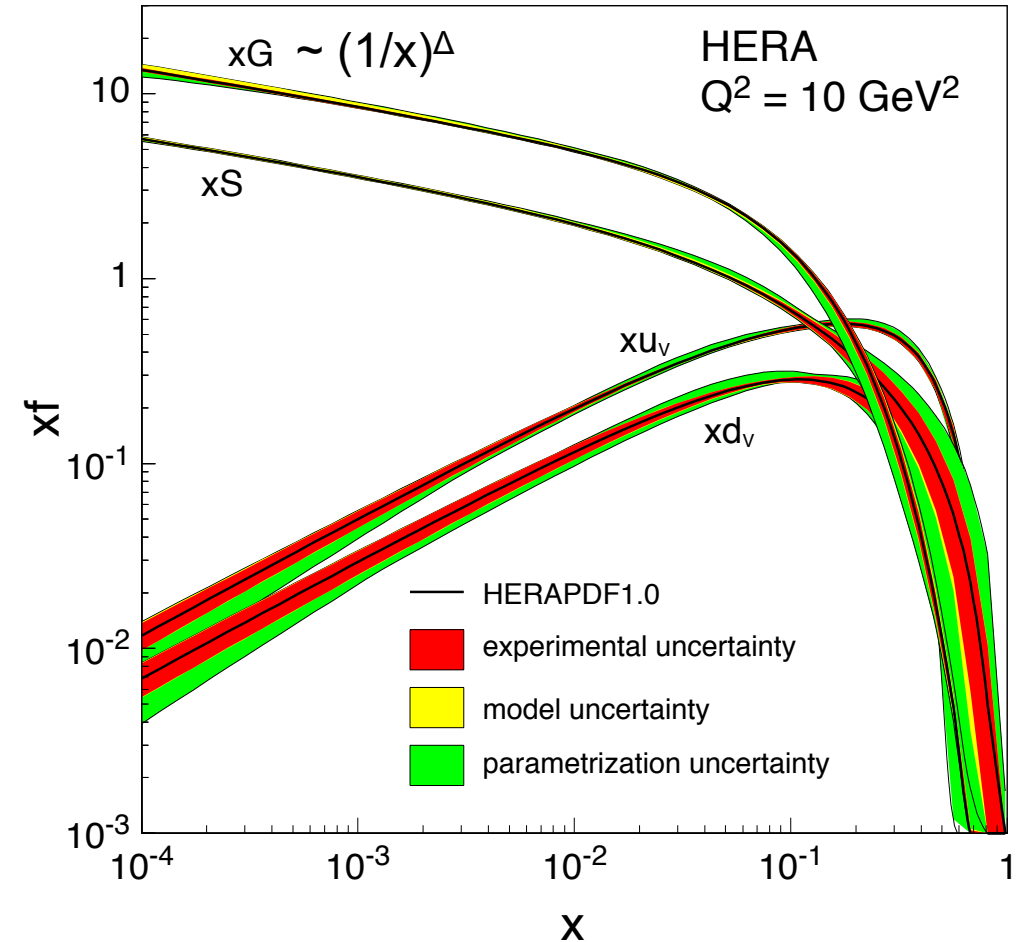
# DIS and nucleon structure

## Deep Inelastic Scattering



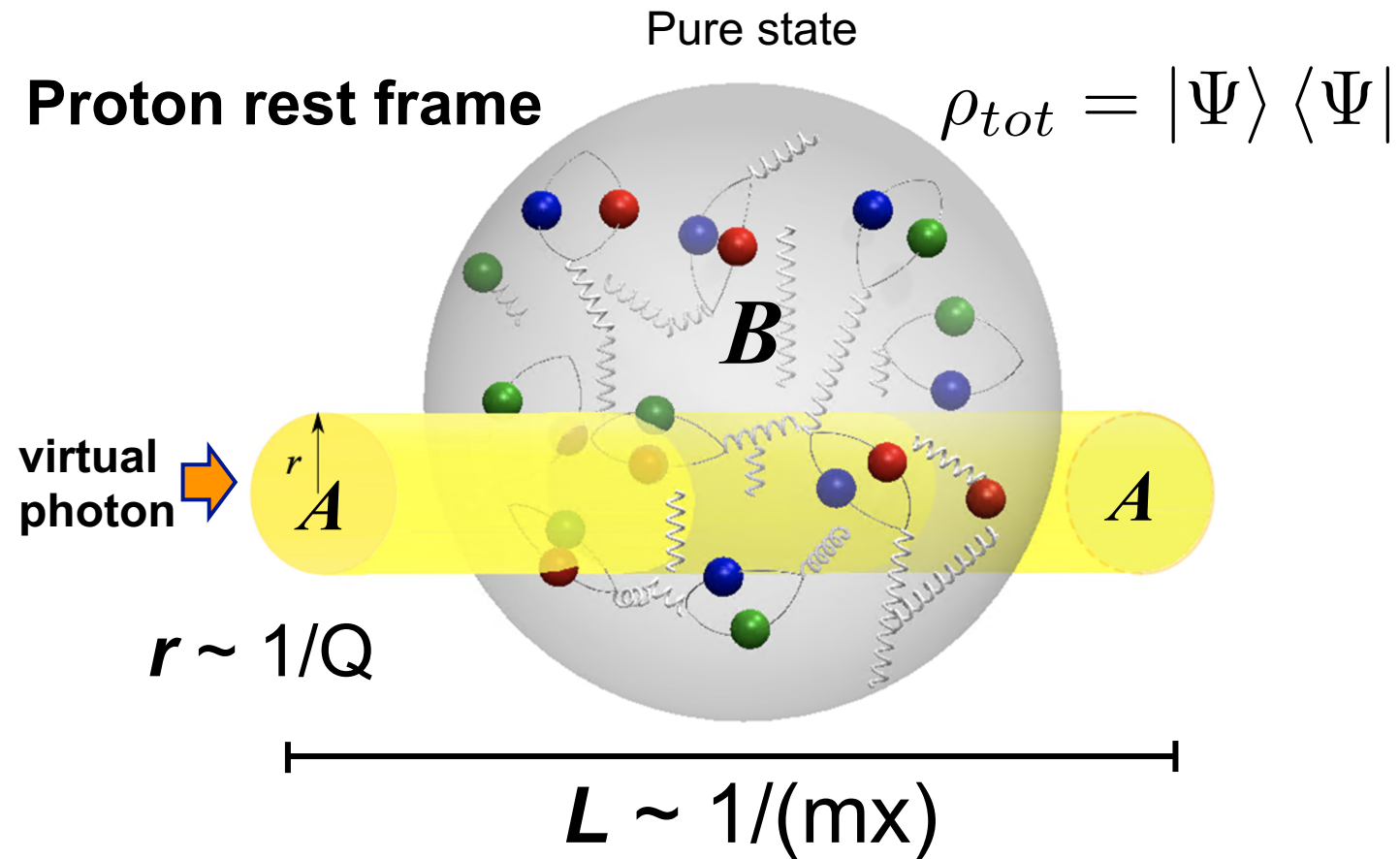
1. Resolution  $\sim Q^2 = -q^2$
2. Momentum fraction  $\sim x_{bj} = \frac{Q^2}{2Pq}$   
"Exposure time"

## Parton Distribution Functions (PDFs)

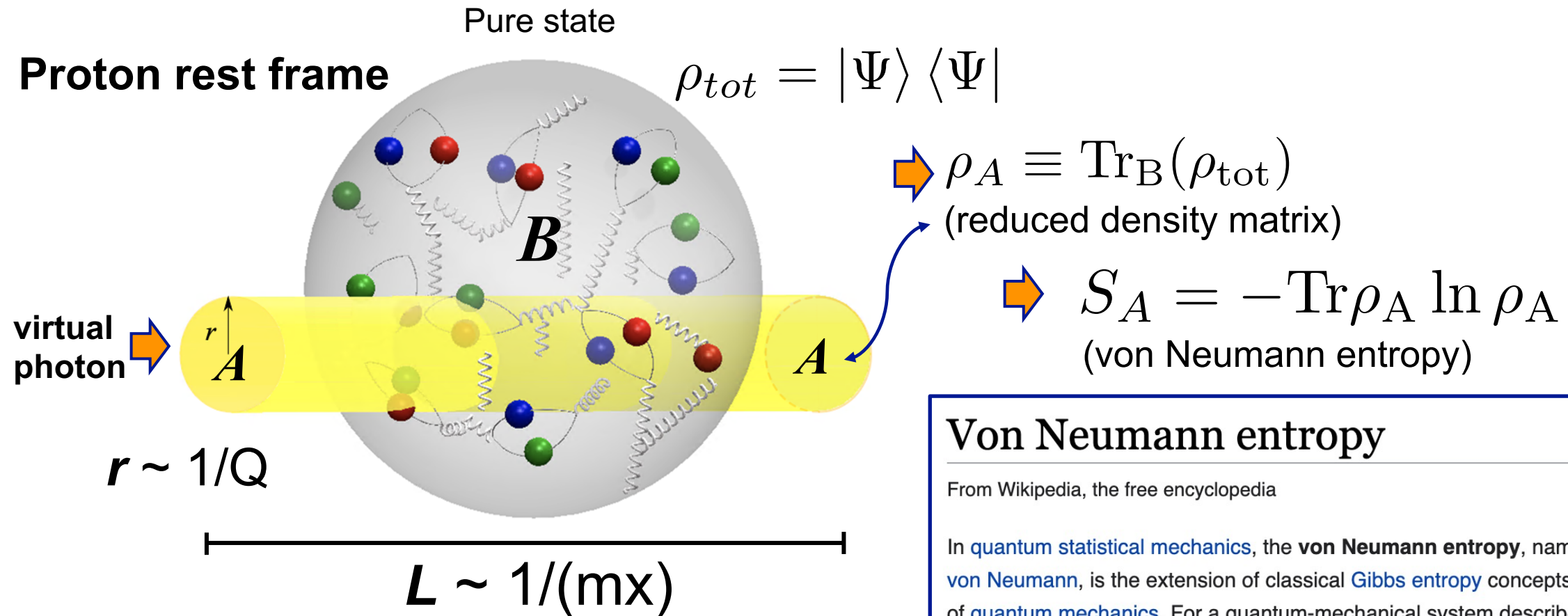




# Entanglement Entropy (EE)



# Entanglement Entropy (EE)



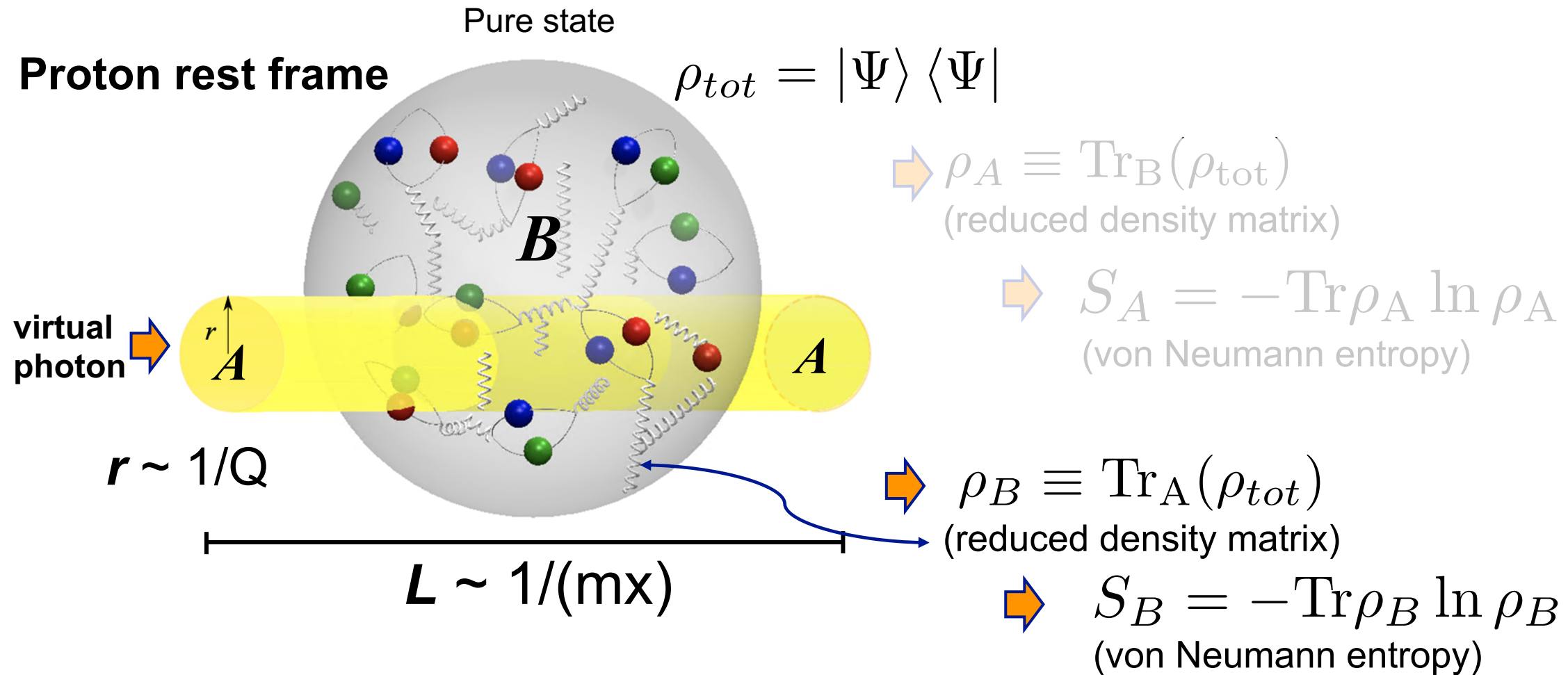
## Von Neumann entropy

From Wikipedia, the free encyclopedia

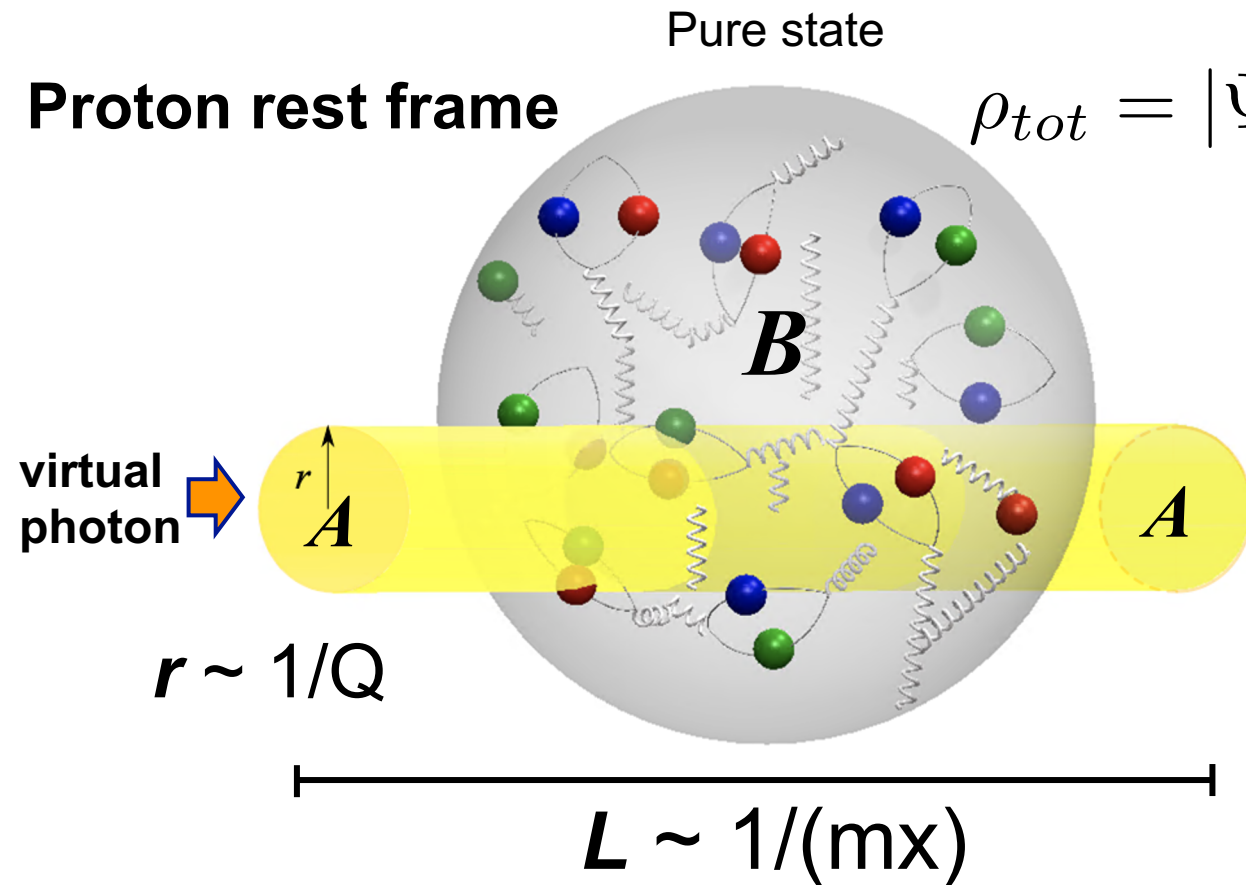
In [quantum statistical mechanics](#), the **von Neumann entropy**, named after [John von Neumann](#), is the extension of classical [Gibbs entropy](#) concepts to the field of [quantum mechanics](#). For a quantum-mechanical system described by a [density matrix](#)  $\rho$ , the von Neumann entropy is<sup>[1]</sup>

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

# Entanglement Entropy (EE)



# Entanglement Entropy (EE)



→  $\rho_A \equiv \text{Tr}_B(\rho_{tot})$   
(reduced density matrix)

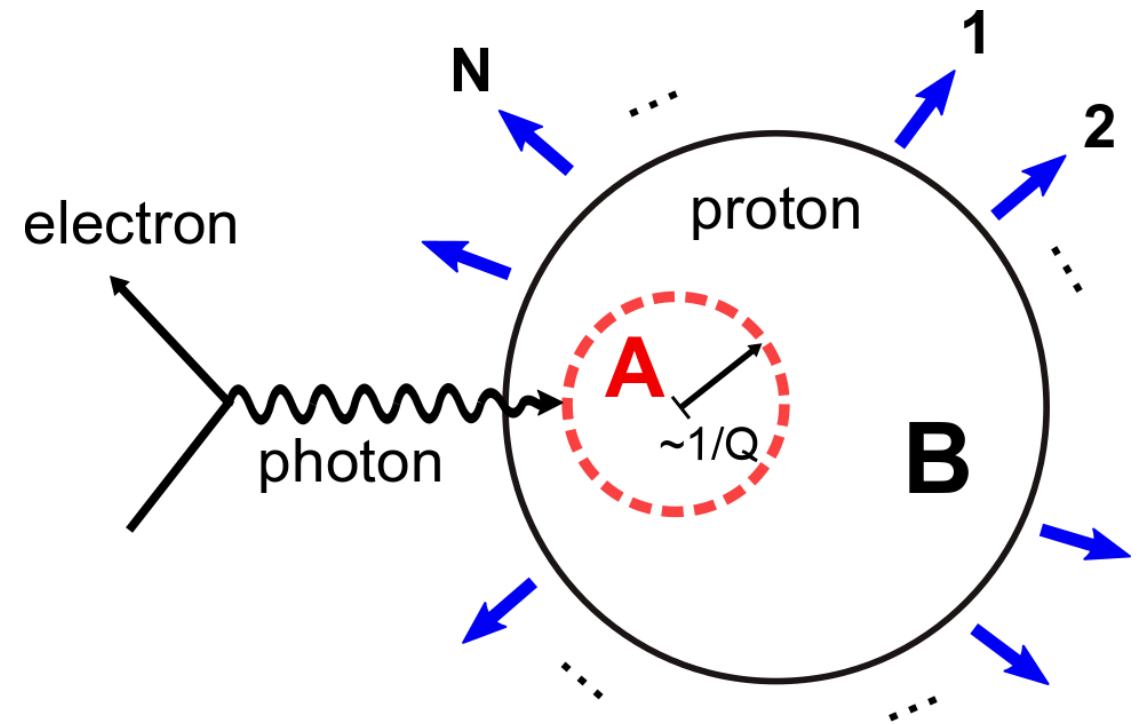
→  $S_A = -\text{Tr} \rho_A \ln \rho_A$   
(von Neumann entropy)

→  $\rho_B \equiv \text{Tr}_A(\rho_{tot})$   
(reduced density matrix)

→  $S_B = -\text{Tr} \rho_B \ln \rho_B$   
(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)

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

gluon entropy for low  $x$



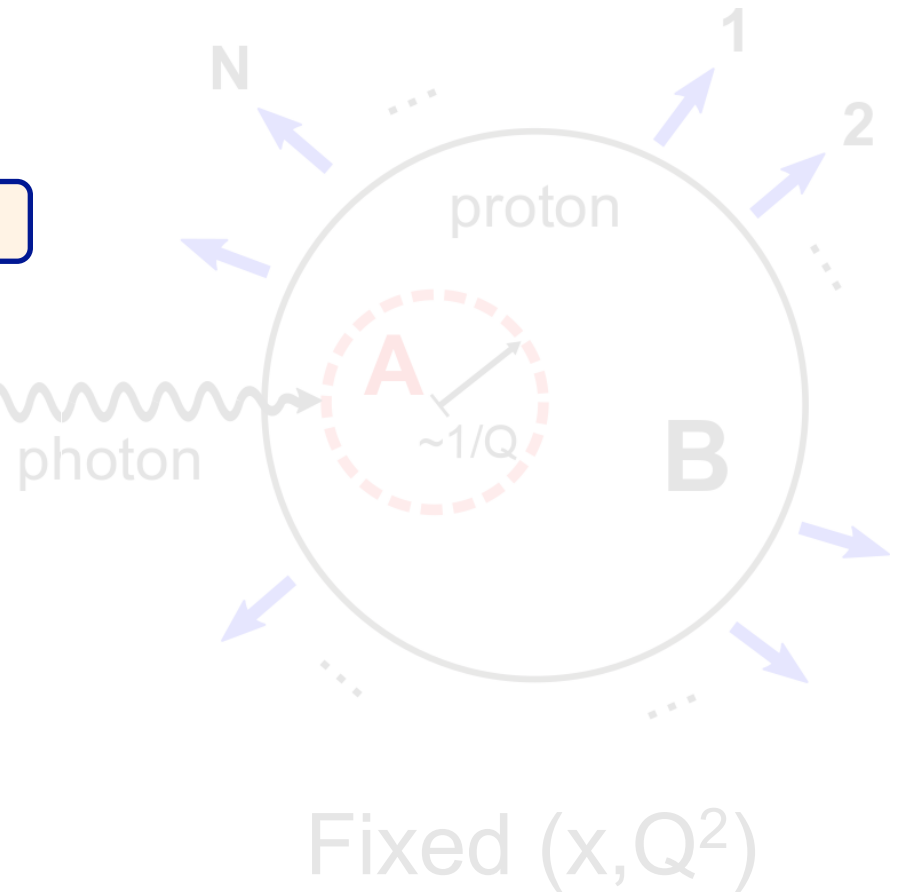
(Kharzeev & Levin 2021)

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

arXiv:2102.09773

electron

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

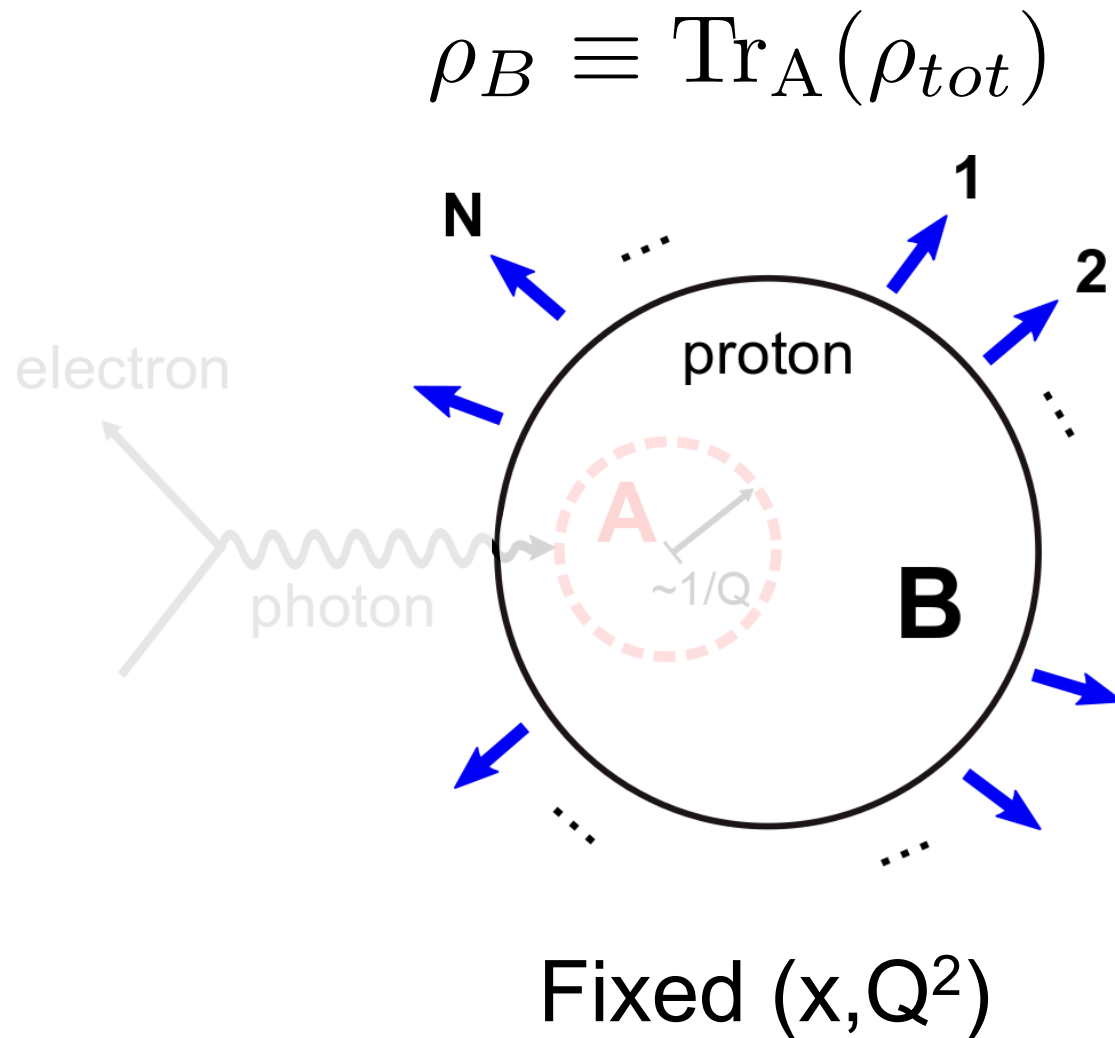


# $S_B$ in DIS

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

hadron entropy

$P_N$  is charged multiplicities



# EE in DIS

(Kharzeev & Levin 2017)

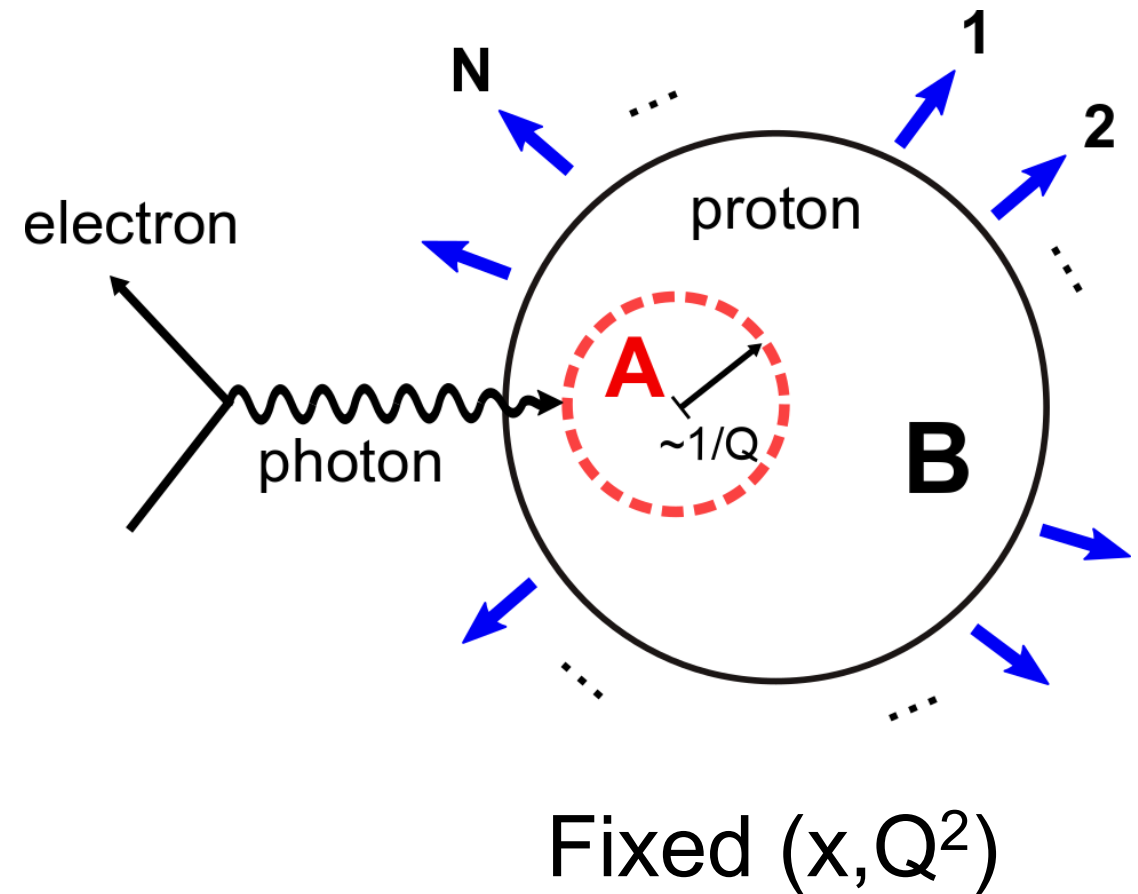
$$S_A = \ln [xG(x, Q^2)]$$

gluon entropy for low  $x$

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

hadron entropy

$P_N$  is charged multiplicities

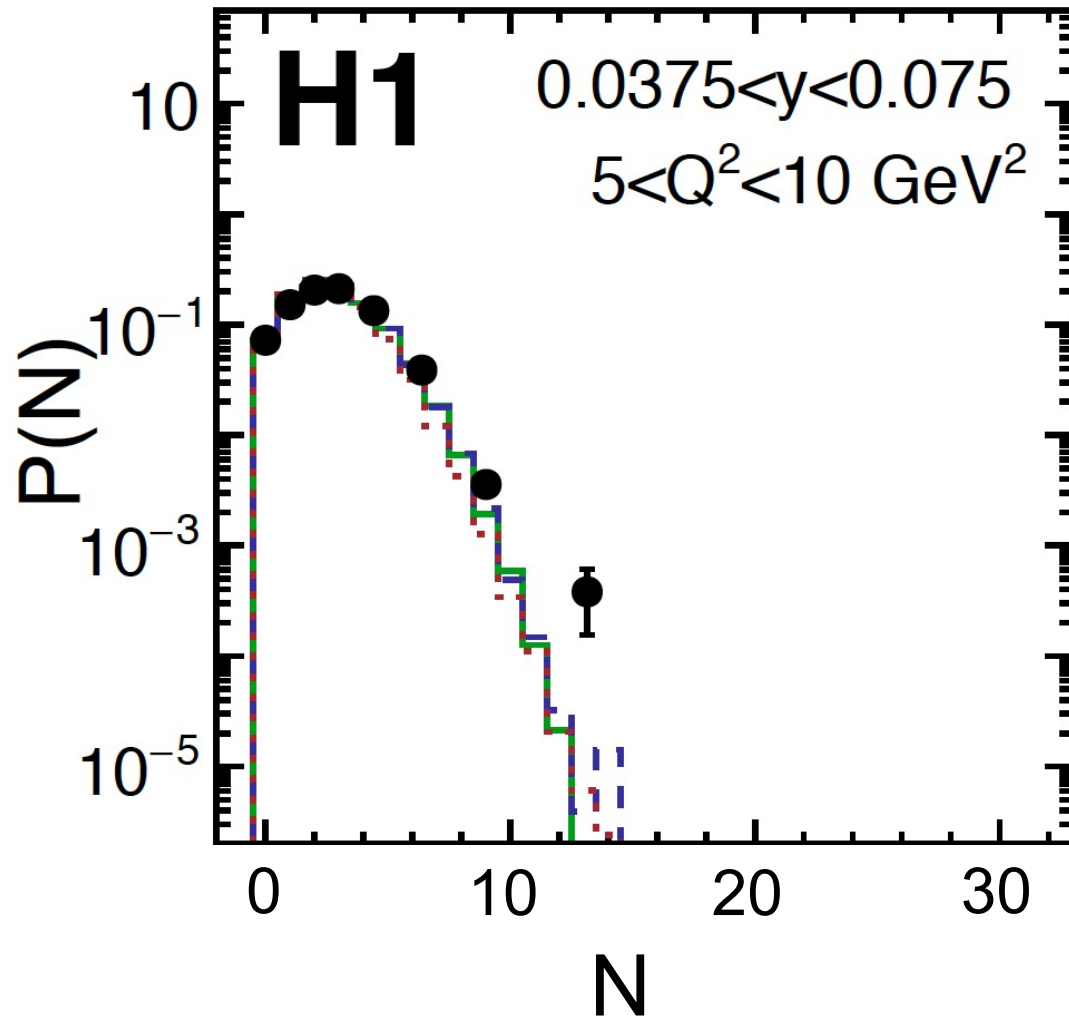




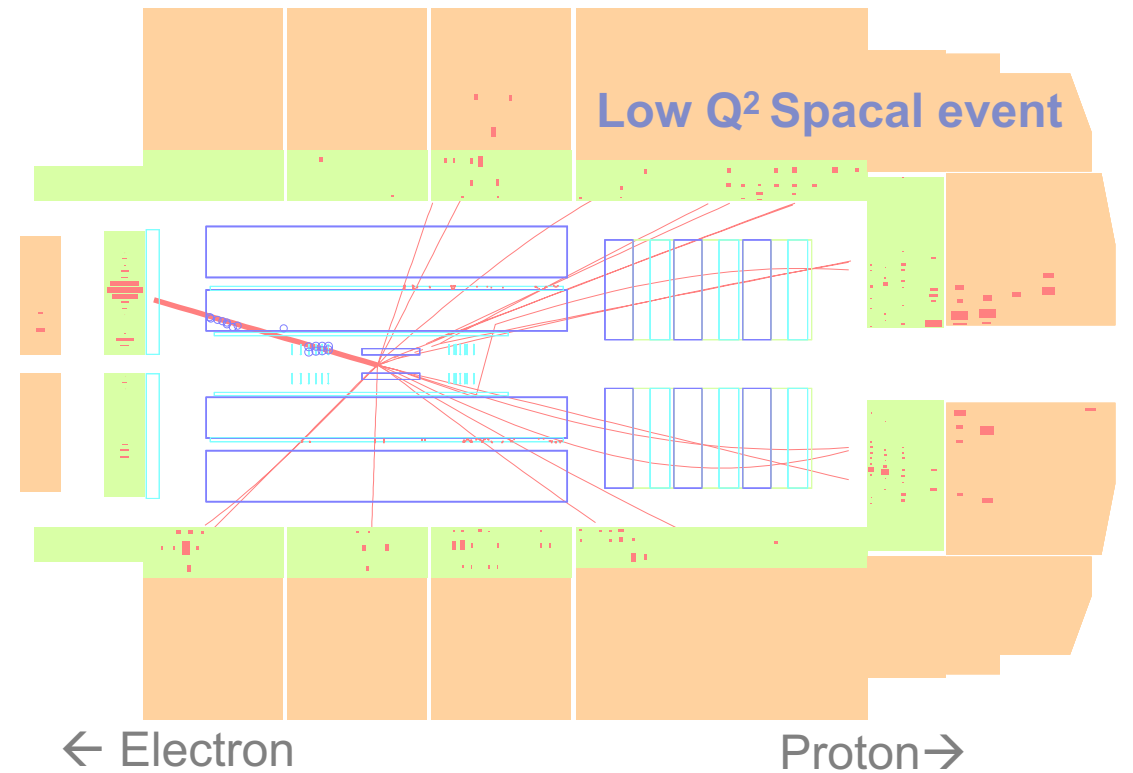


# H1 data

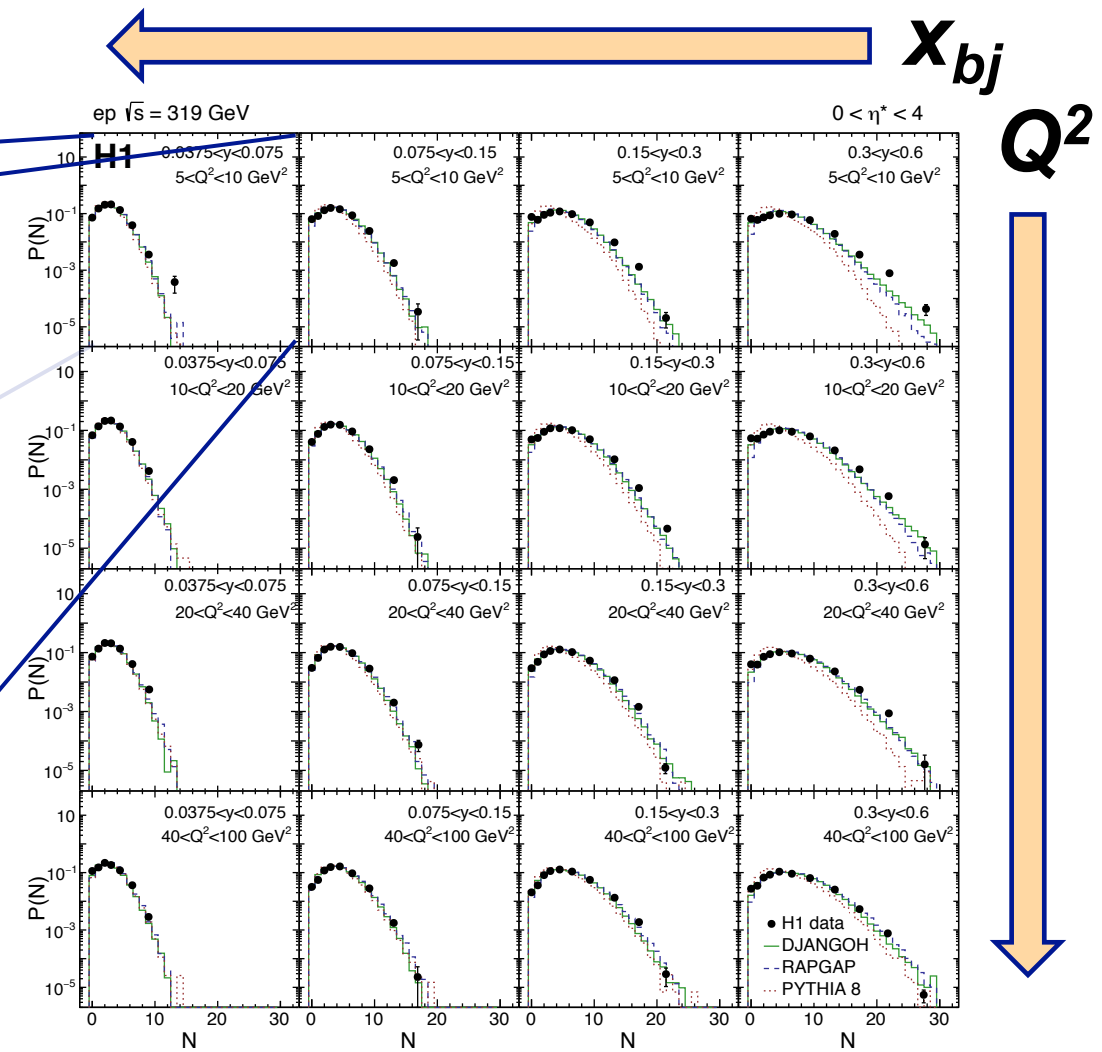
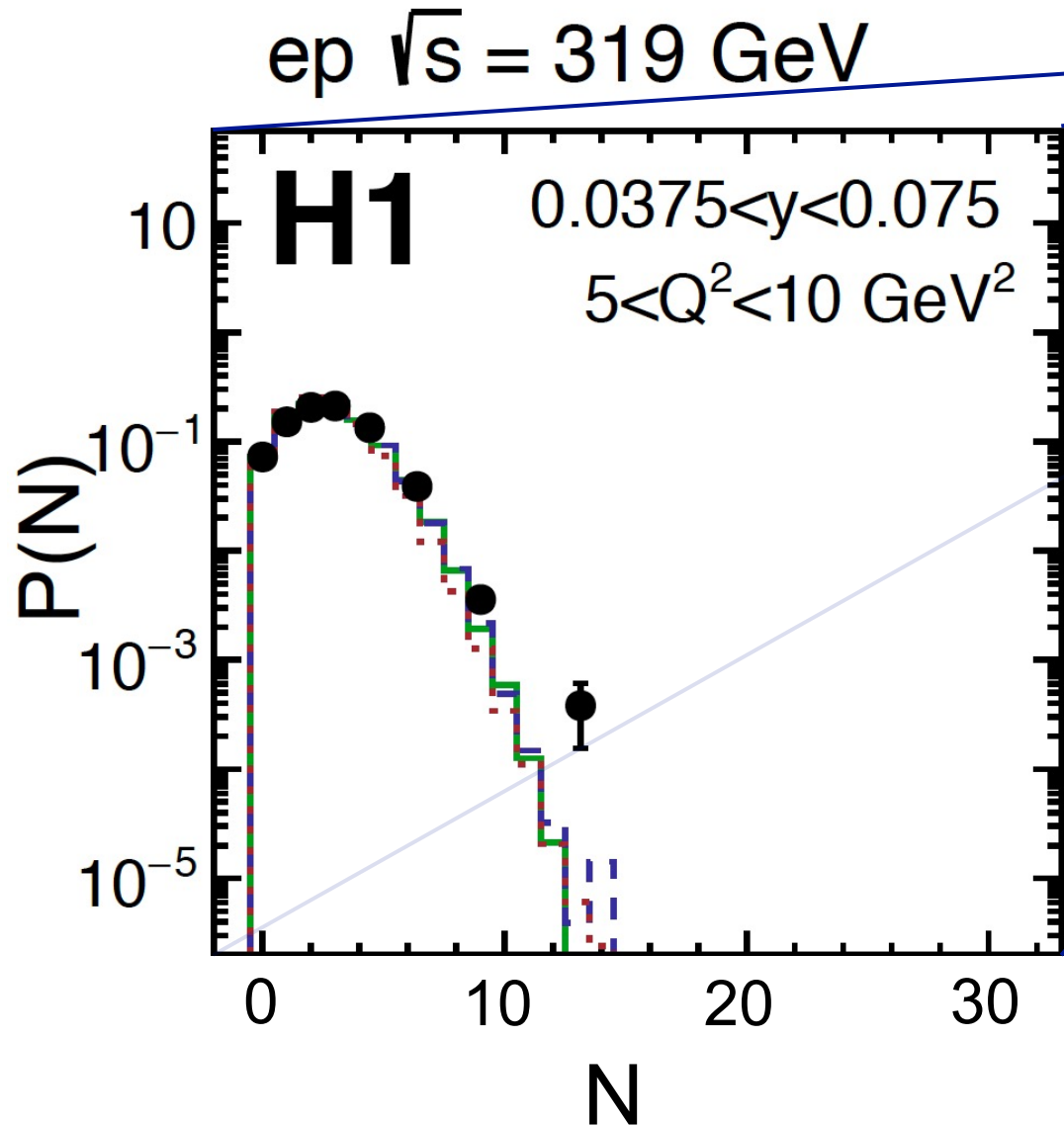
ep  $\sqrt{s} = 319$  GeV



## Event display



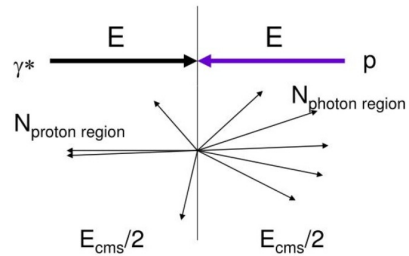
# H1 data



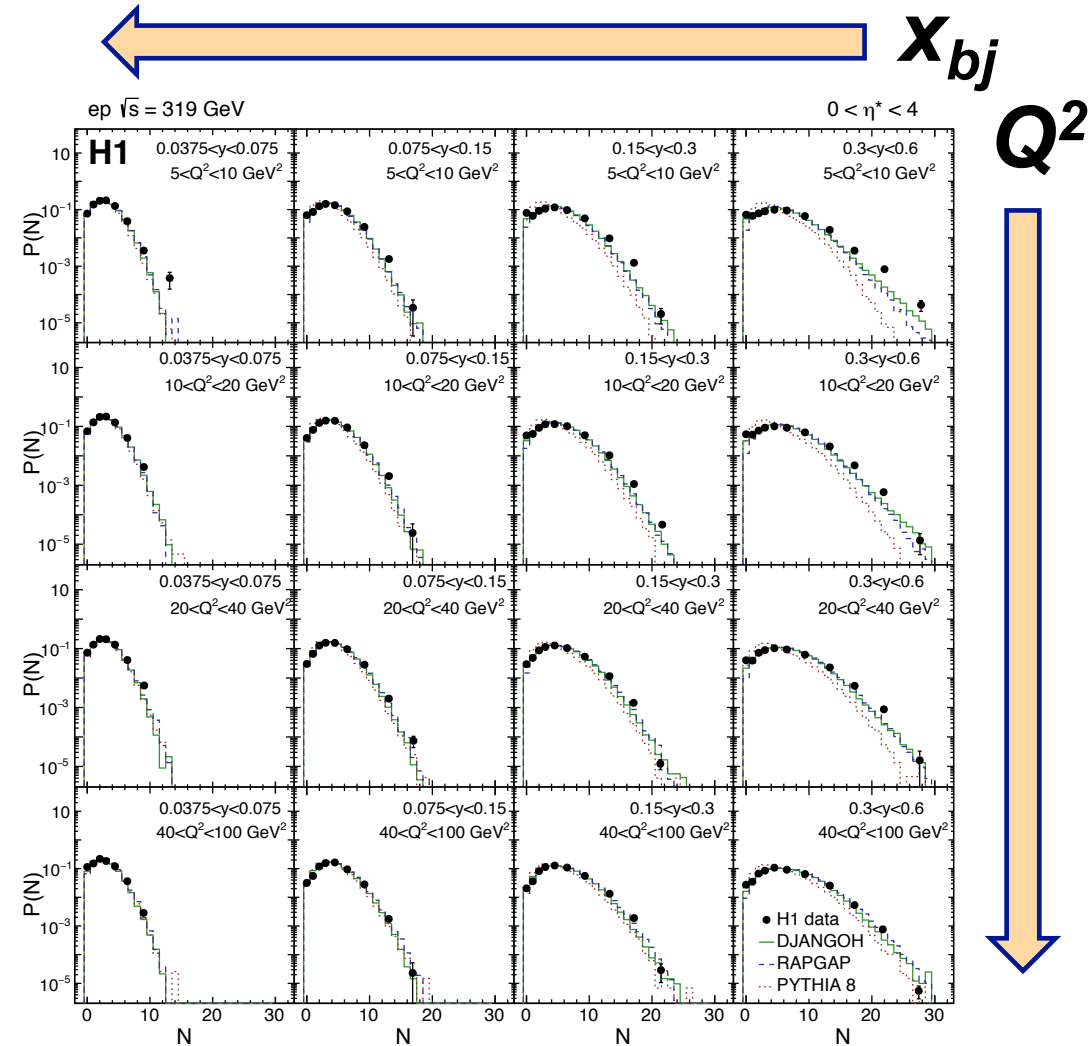
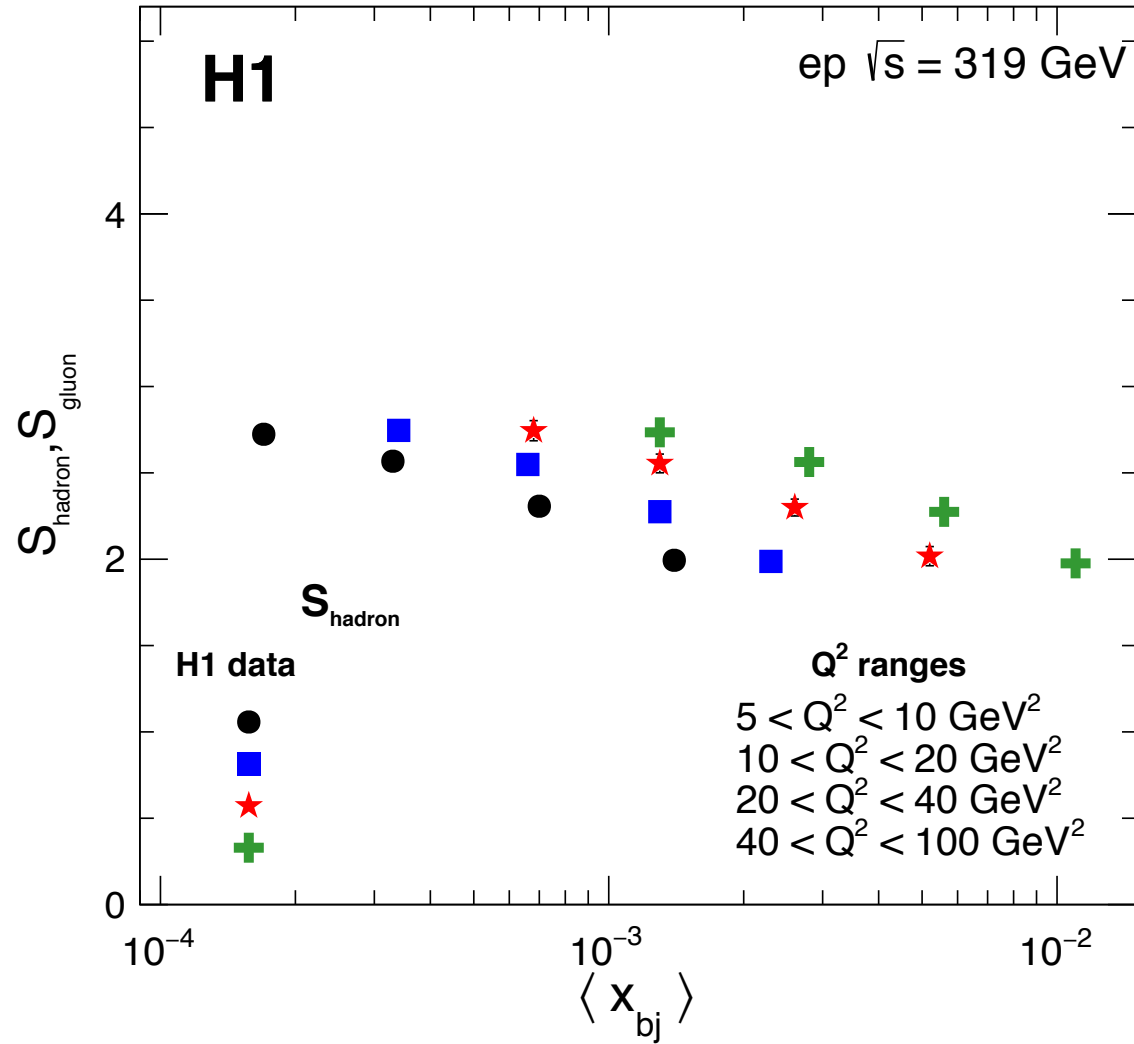
Eur. Phys. J. C (2021) 81: 212 - 57 pages

# H1 data

HCM frame



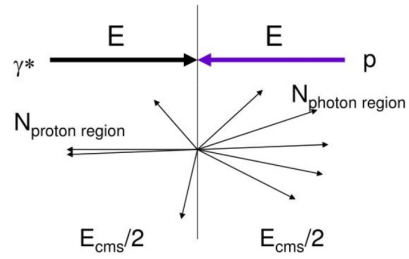
$$0 < \eta^* < 4.0$$



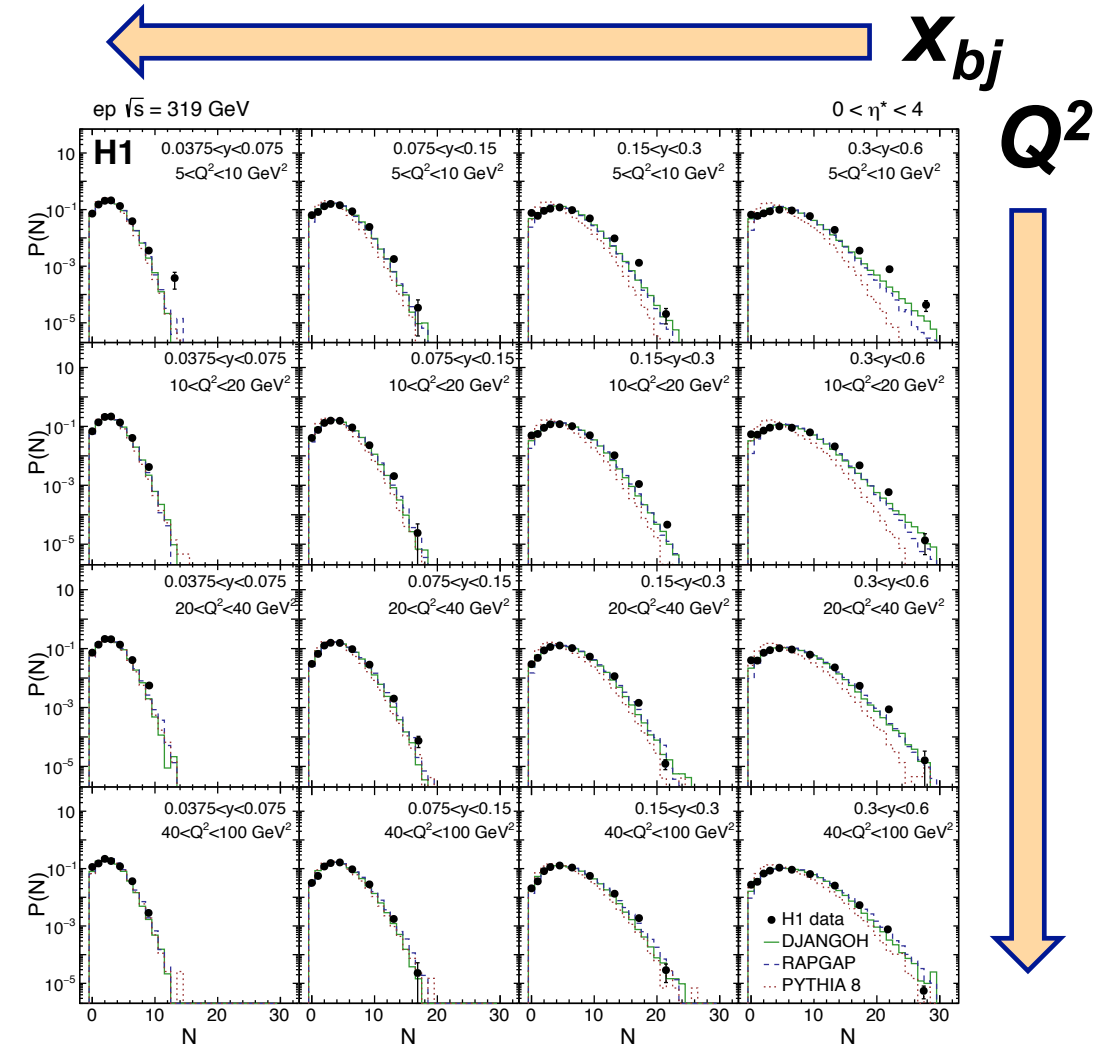
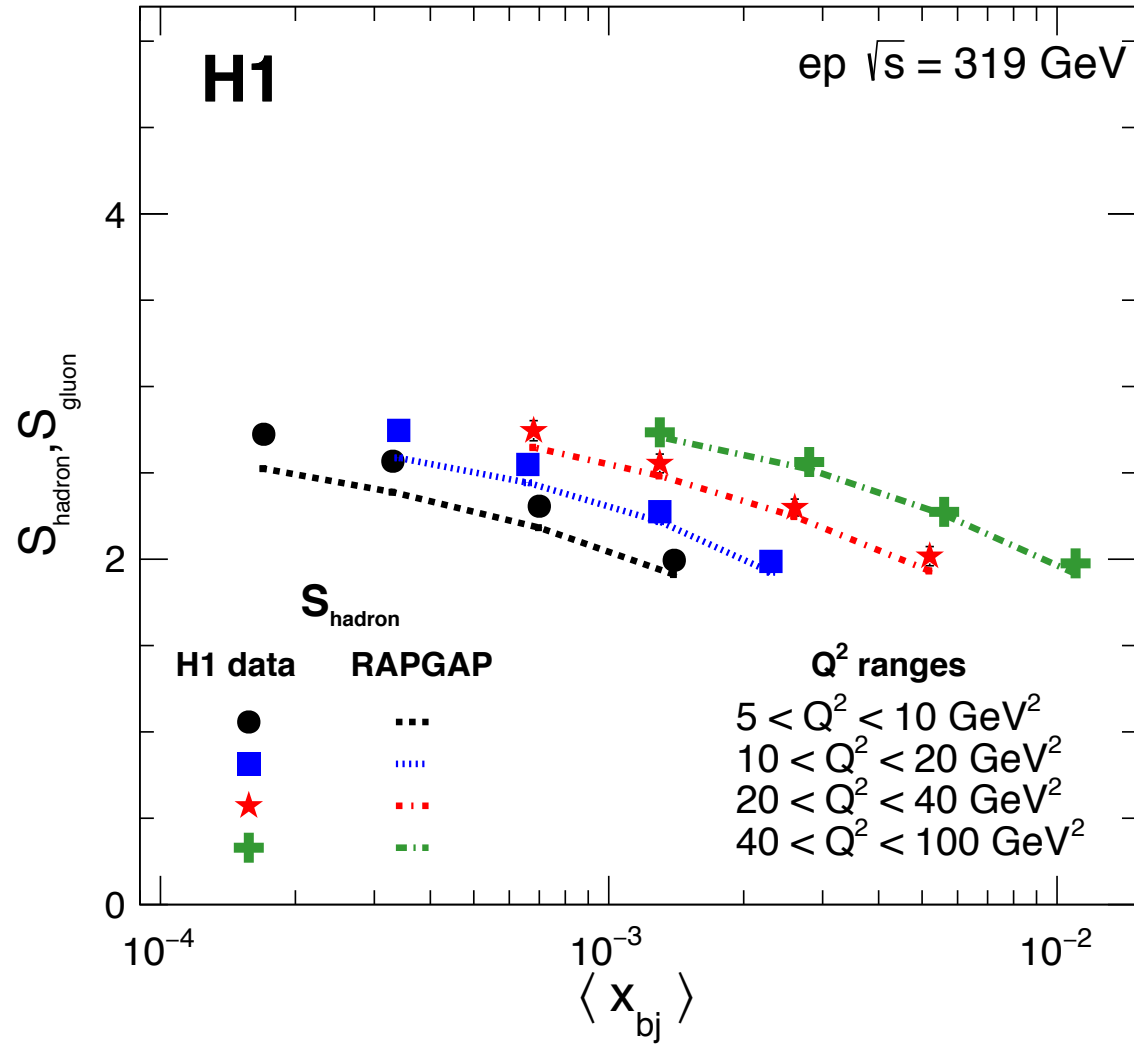
Eur. Phys. J. C (2021) 81: 212 - 57 pages

# H1 data

HCM frame



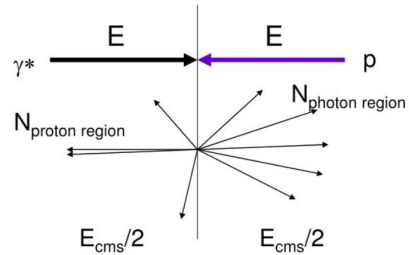
$$0 < \eta^* < 4.0$$



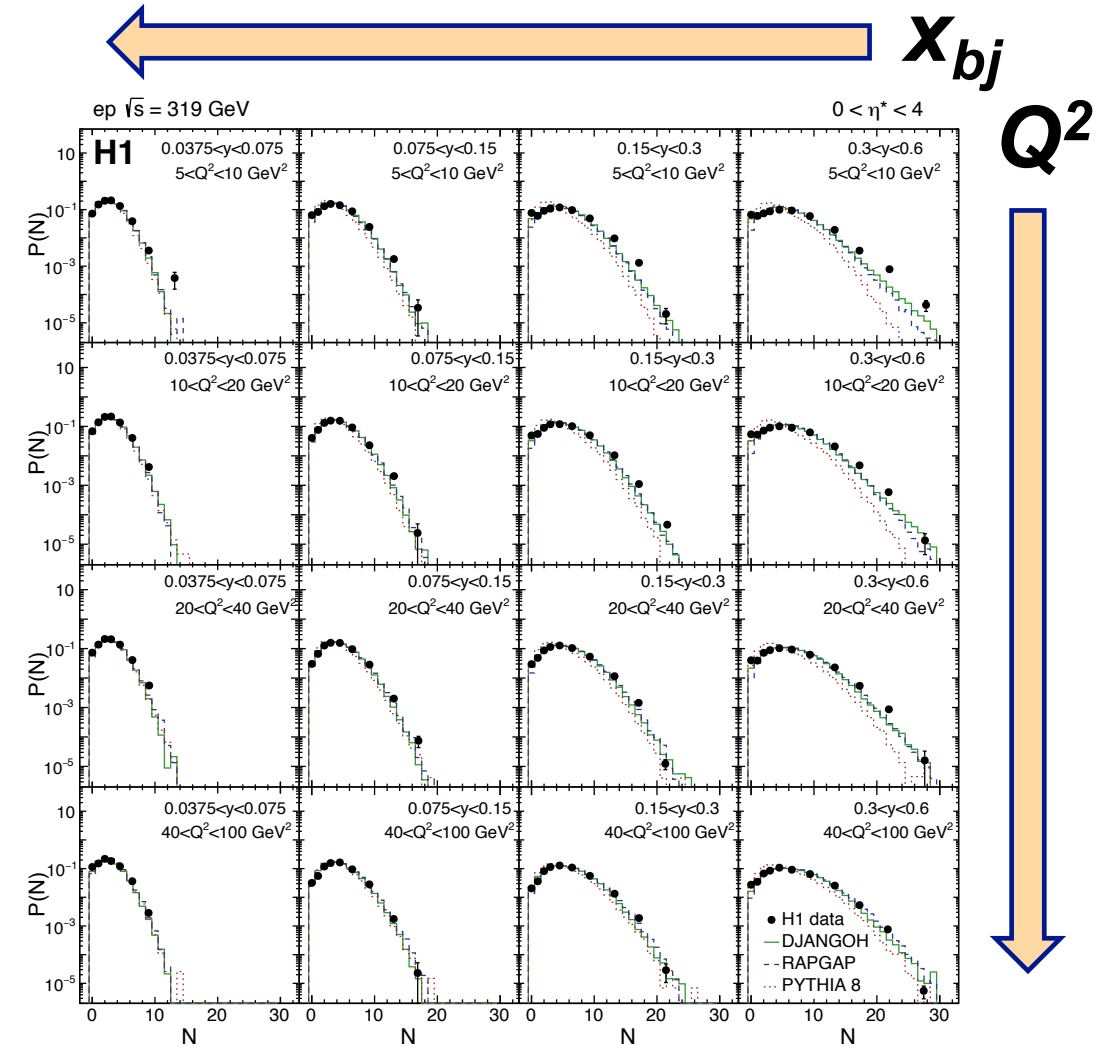
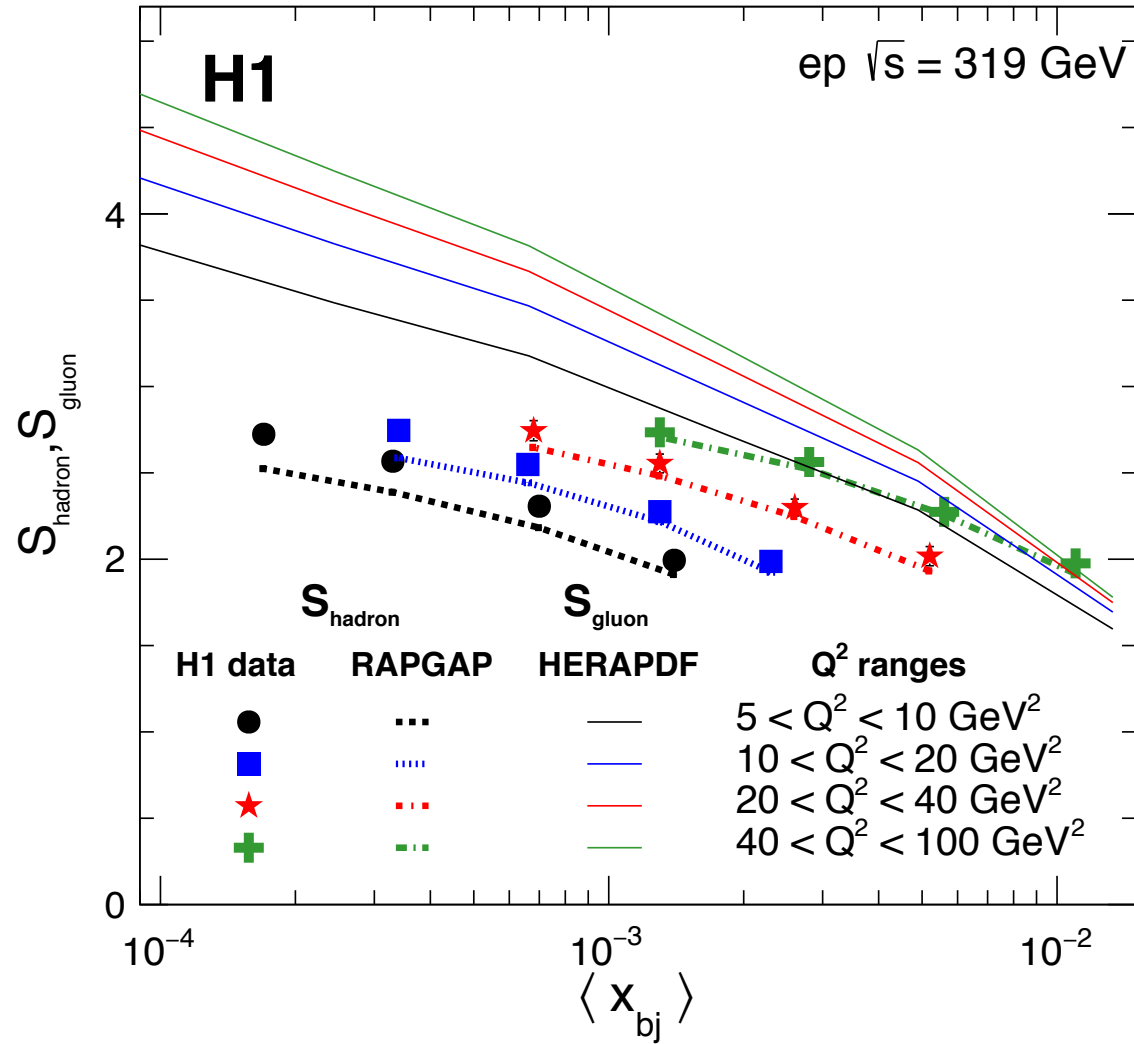
Eur. Phys. J. C (2021) 81: 212 - 57 pages

# H1 data

HCM frame

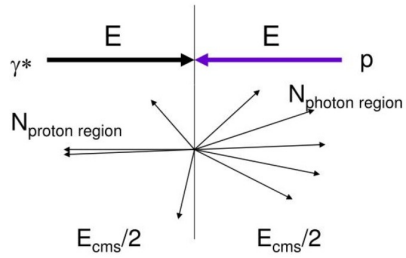


$$0 < \eta^* < 4.0$$



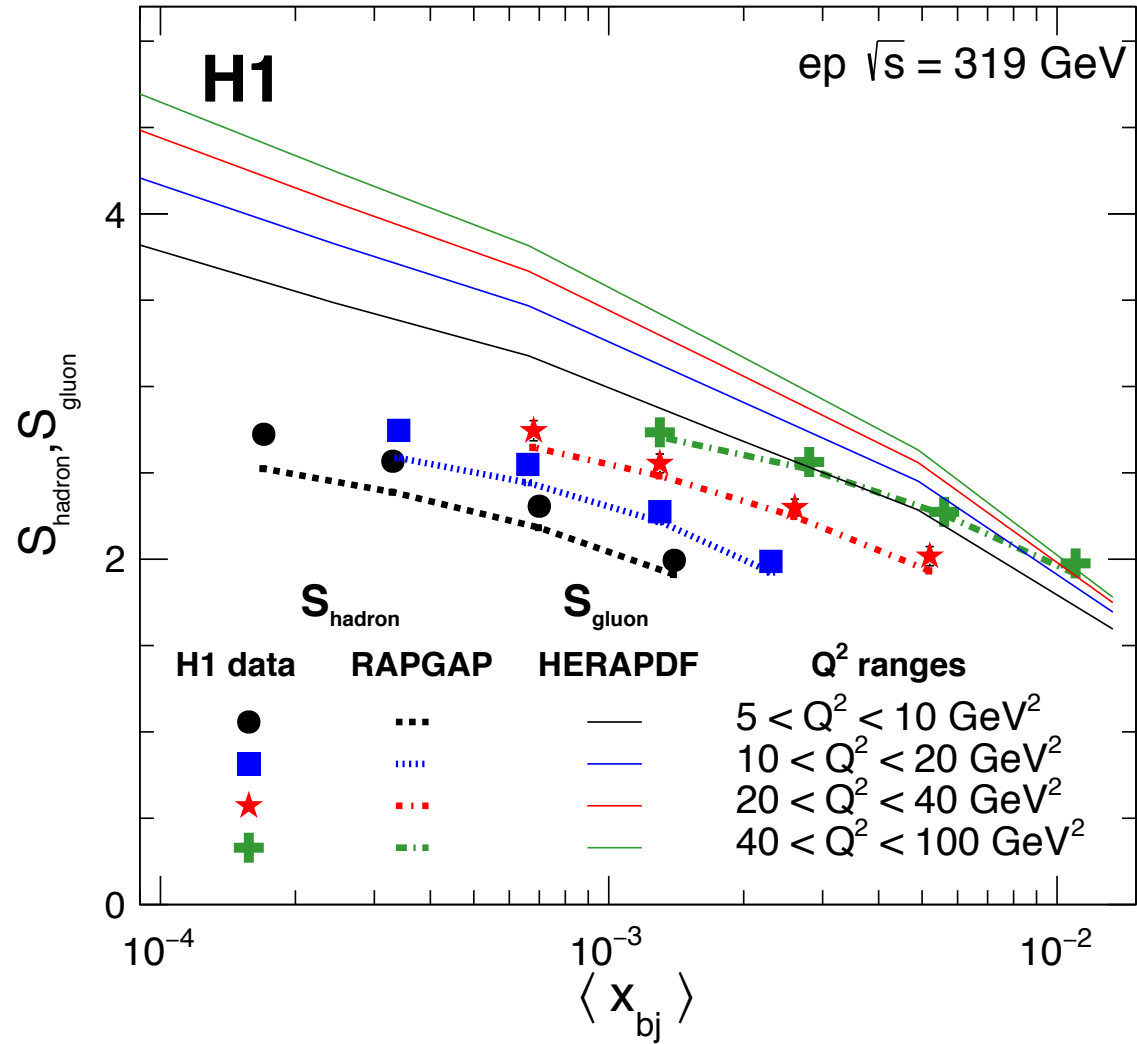
Eur. Phys. J. C (2021) 81: 212 - 57 pages

# H1 data

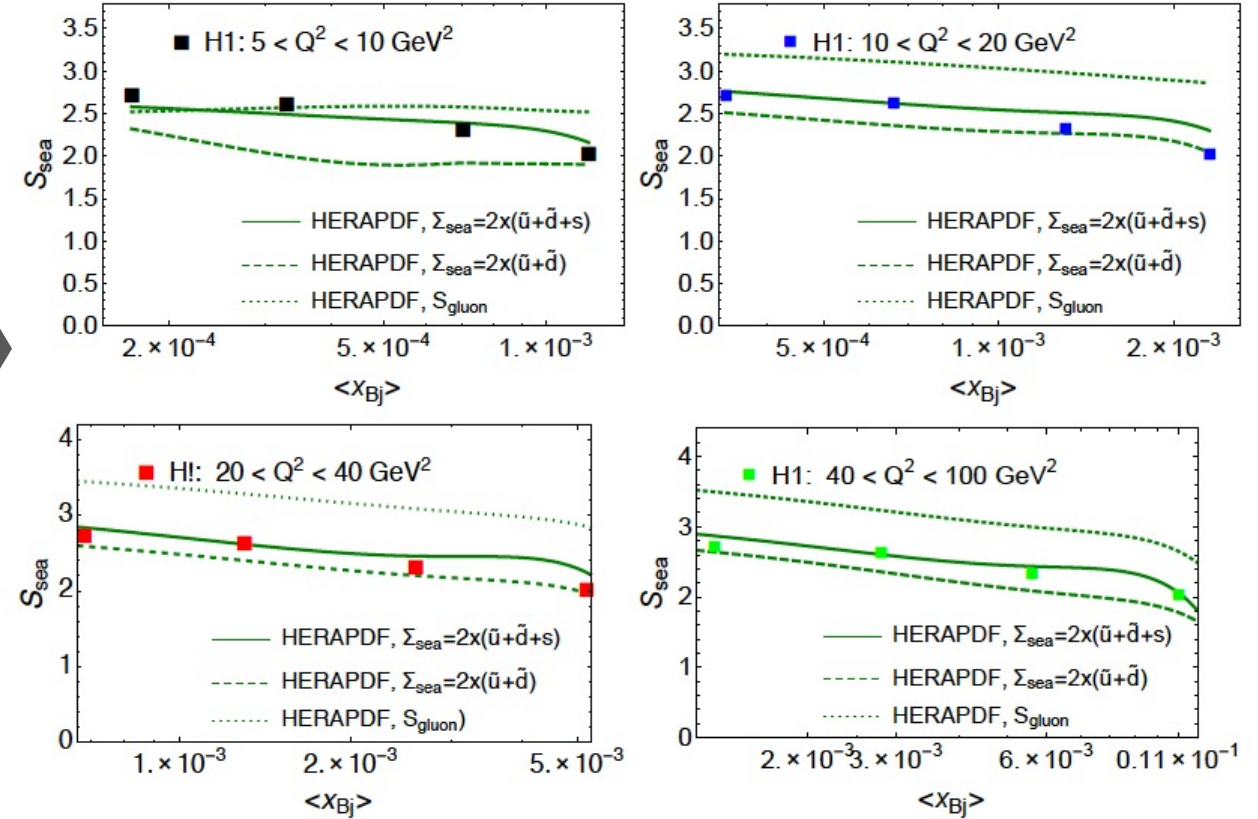


HCM frame

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



## New results from sea quarks



arXiv:2102.09773

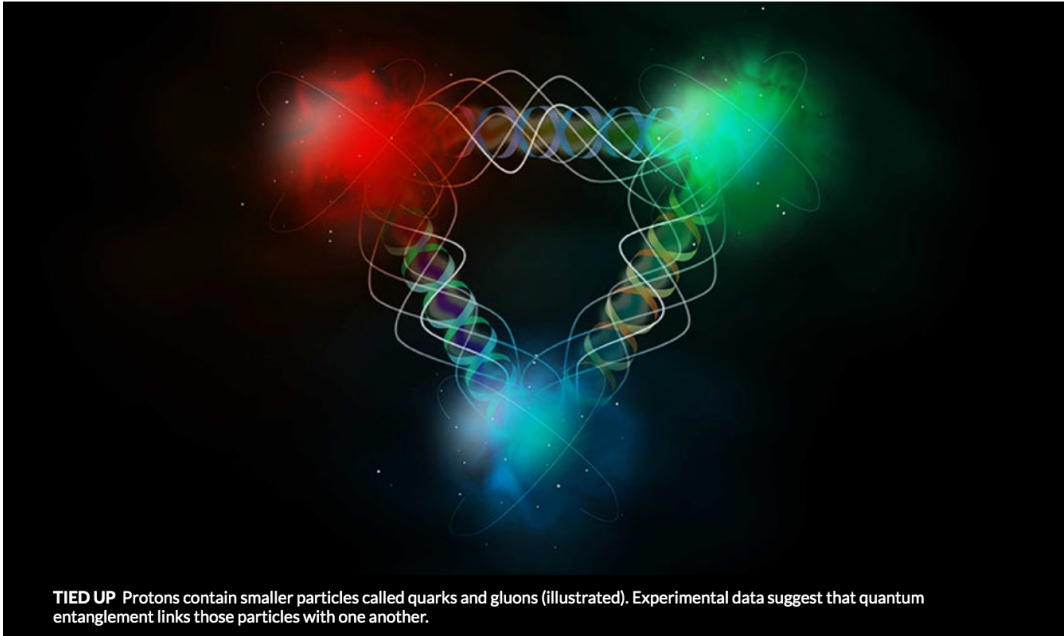
# Summary

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)

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

gluon entropy for low-x in pp



(Kharzeev & Levin 2021)

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

quark entropy for low-x in DIS

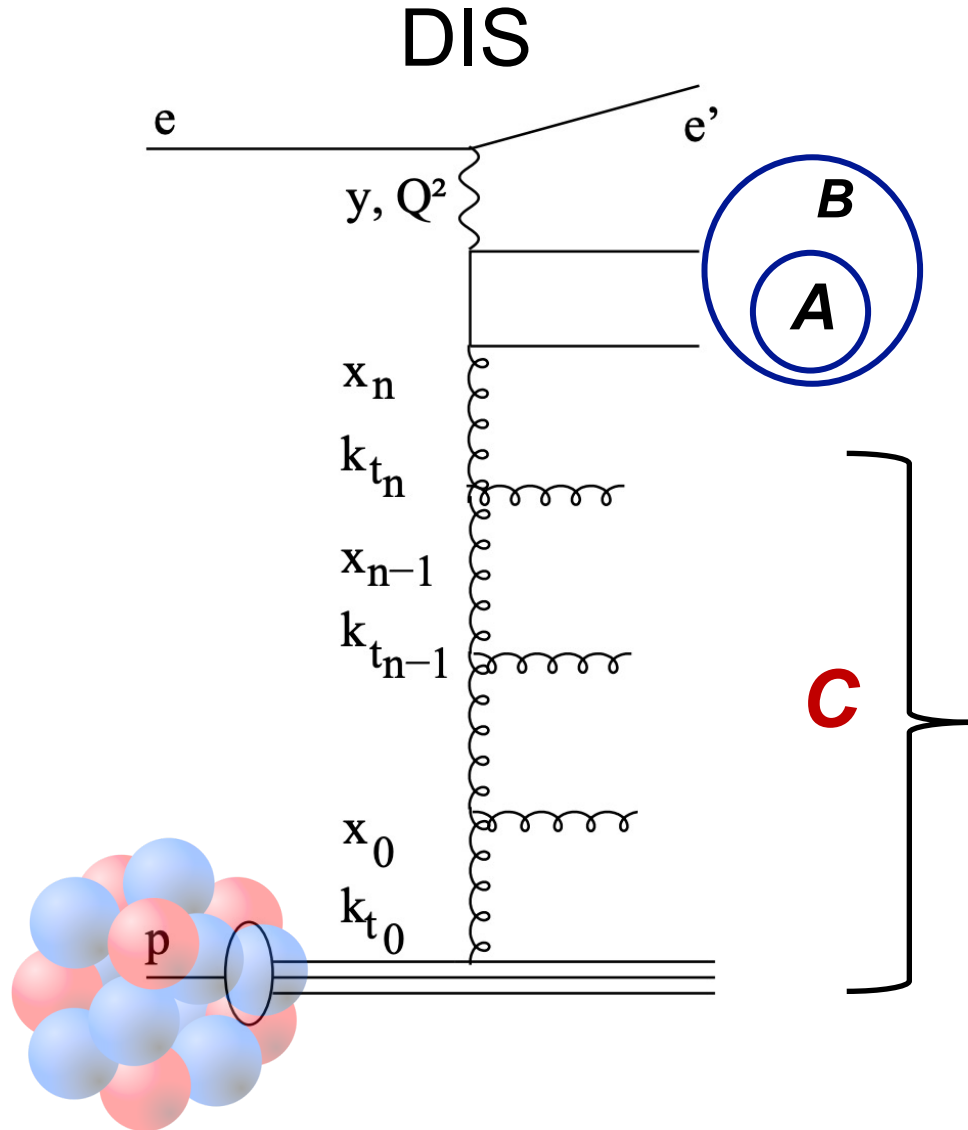


...

- 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?



- 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 at the EIC?

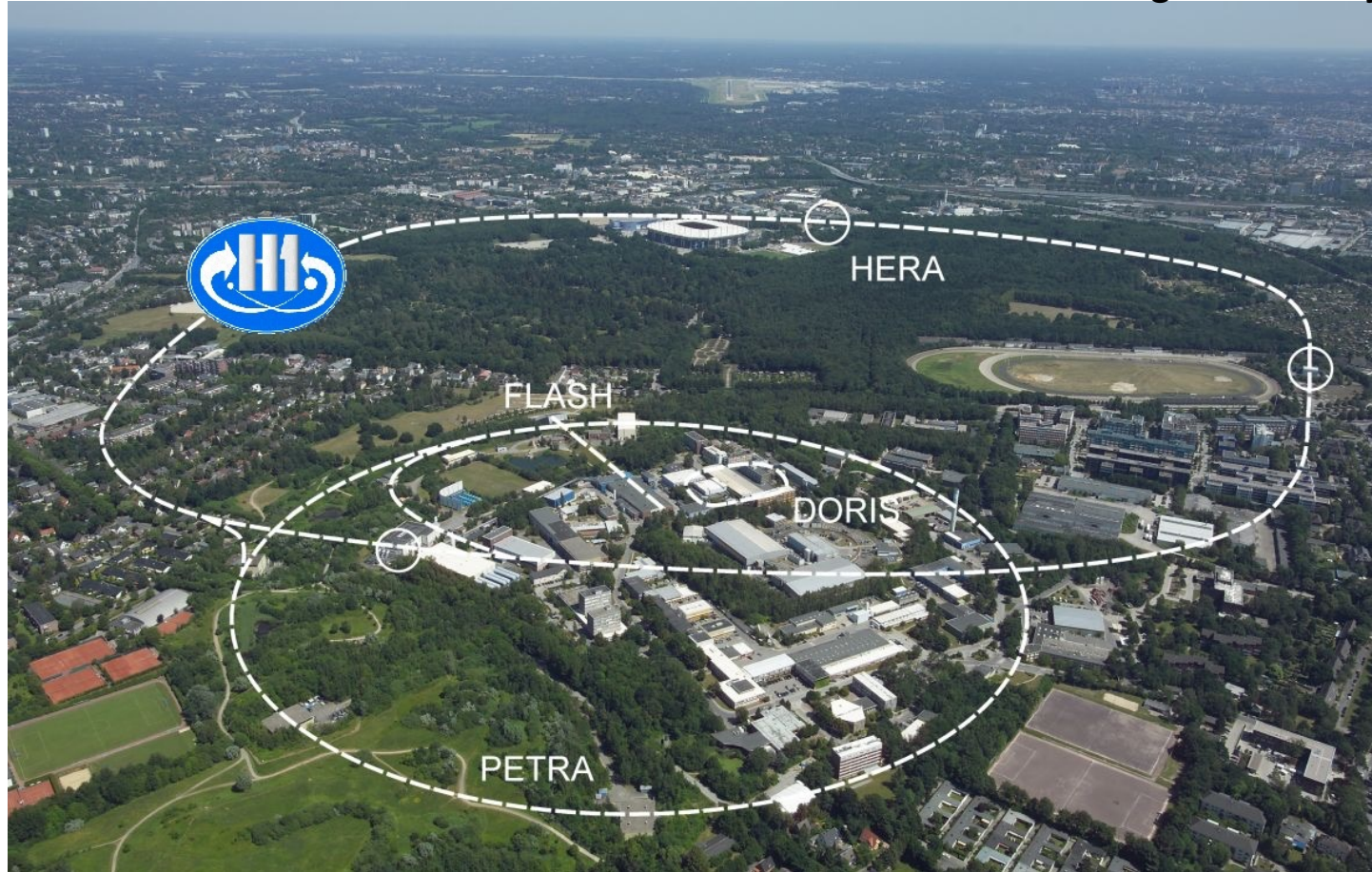
**(A dedicated prediction is on the way)**

**Stay tuned!**

# Backup

# Measurement - DIS data

DESY, Hamburg, Germany



(HERA - 6.3 km in circumference)