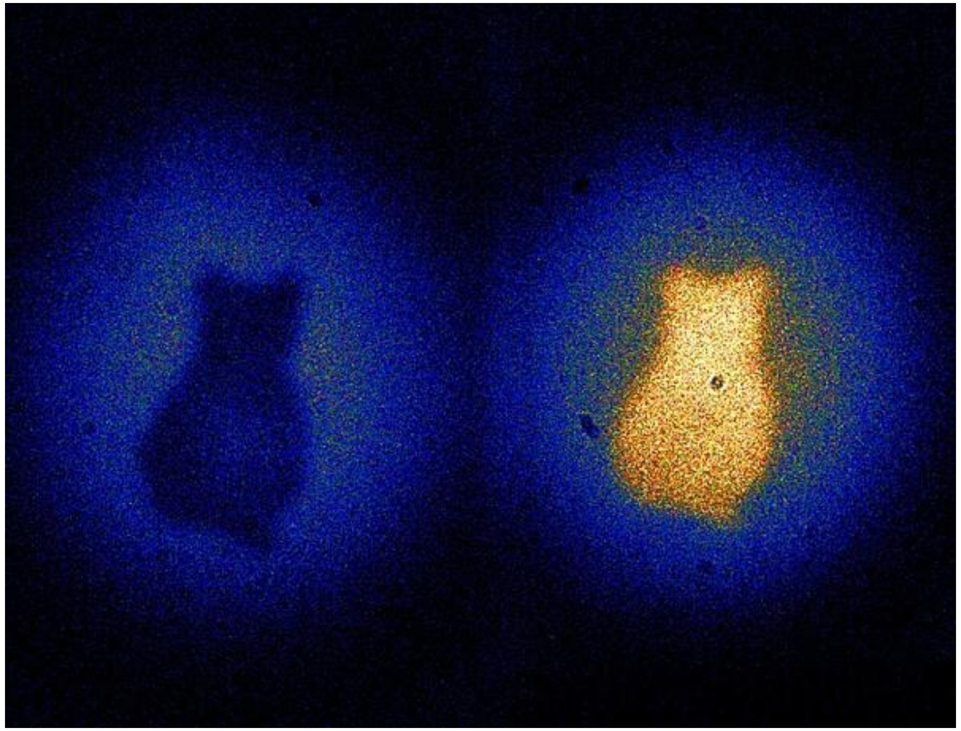
Probing color confinement with quantum entanglement



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

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

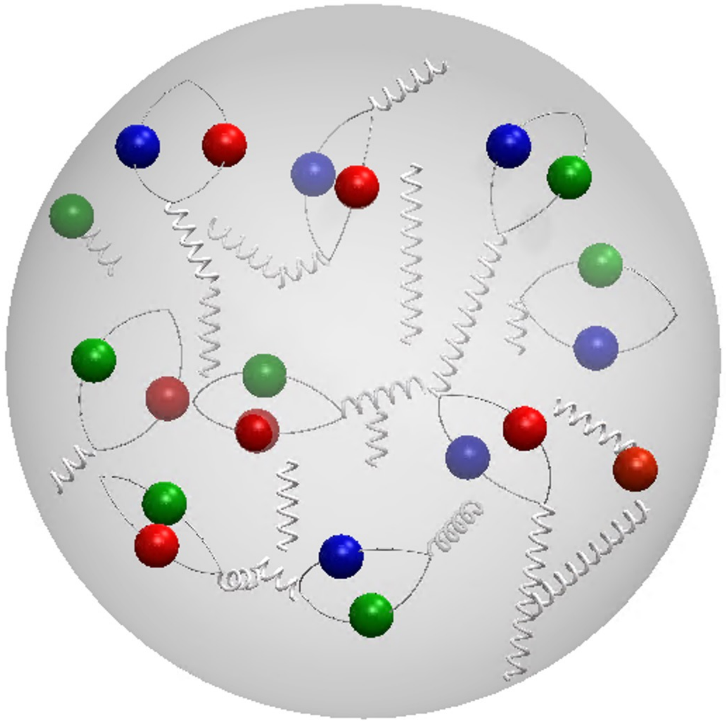
Kong Tu

BNL

06. 15. 2021

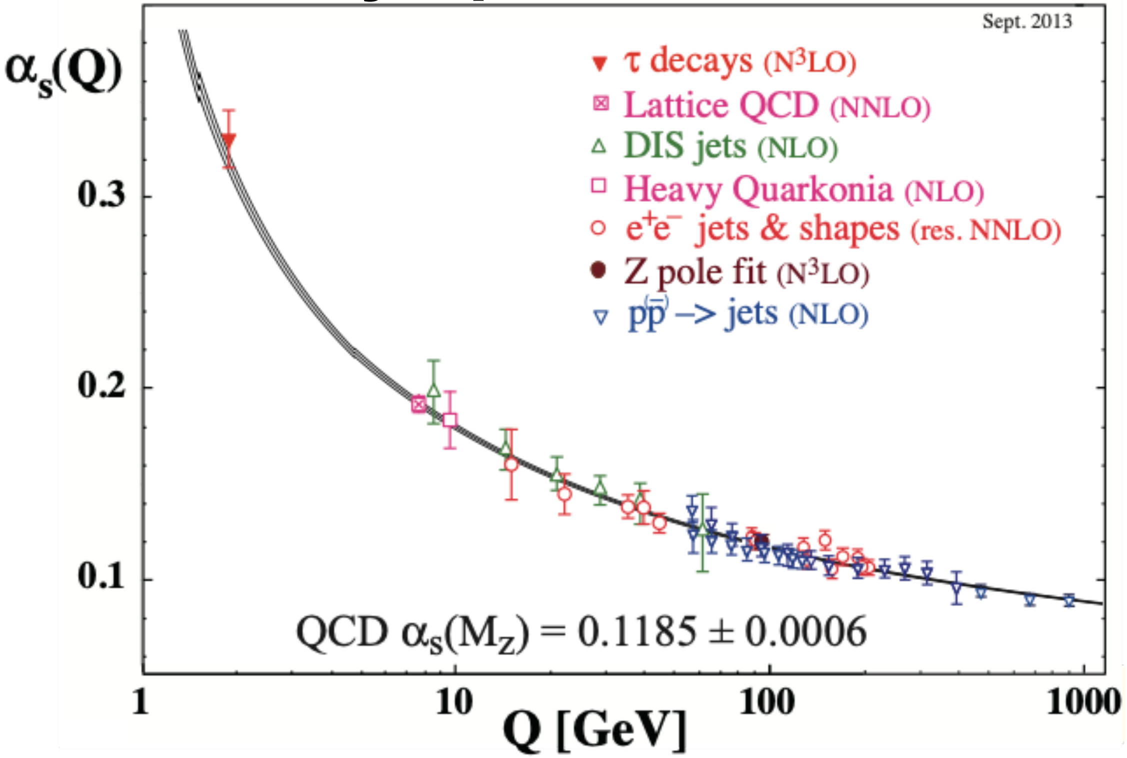
Quantum Chromodynamics

Confinement



Free quarks and gluons
not observed in nature

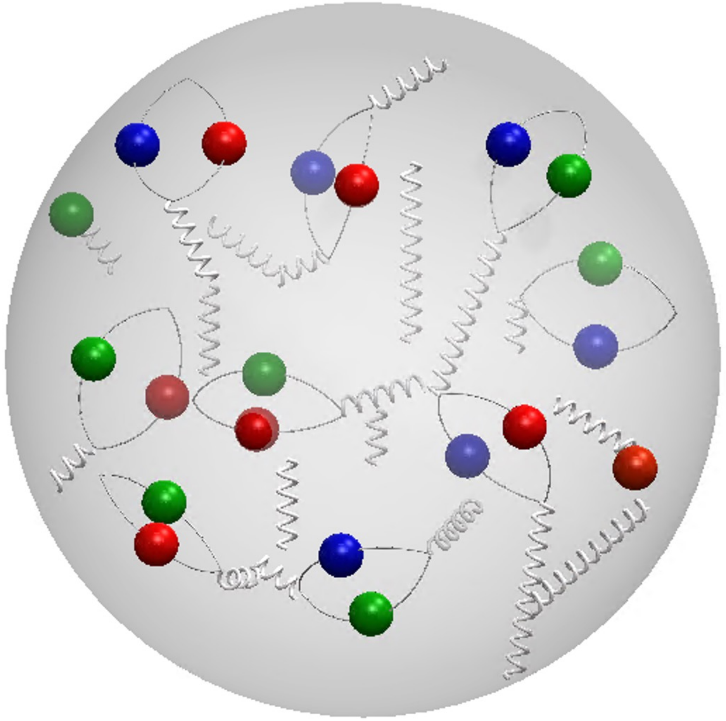
Asymptotic freedom



2004, Gross, Politzer, Wilczek

Quantum Chromodynamics

Confinement



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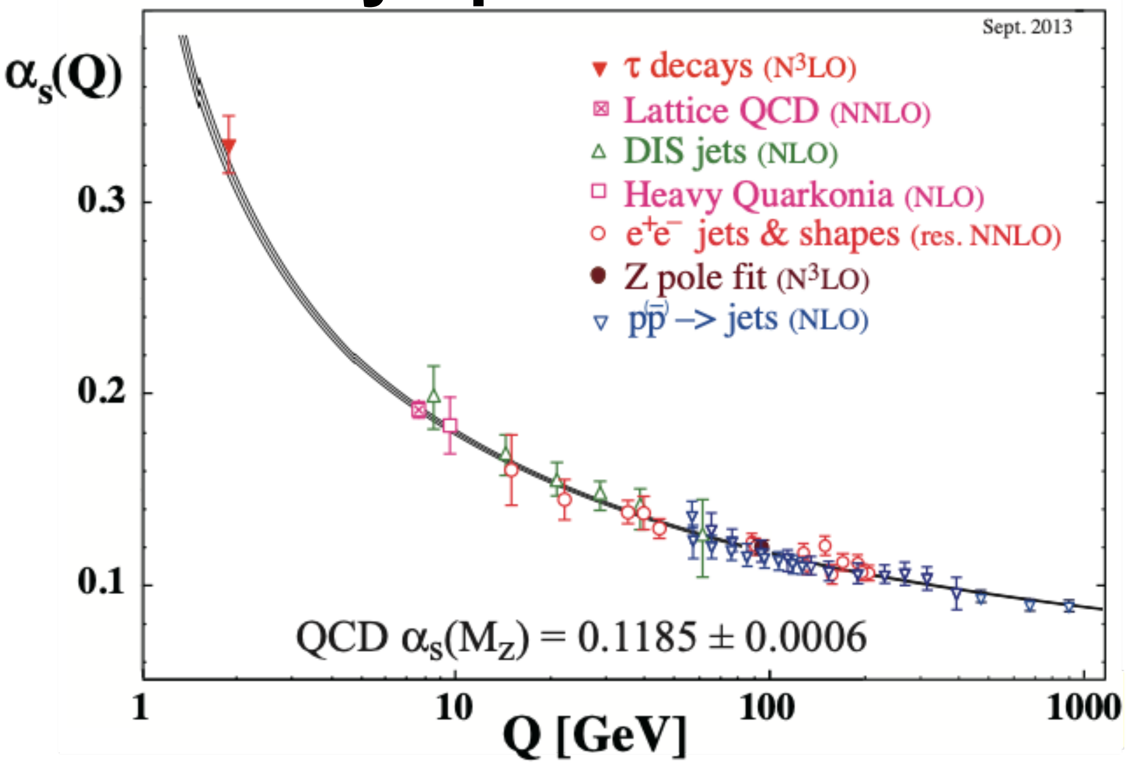


2004, Gross, Politzer, Wilczek

Mystery of Confinement

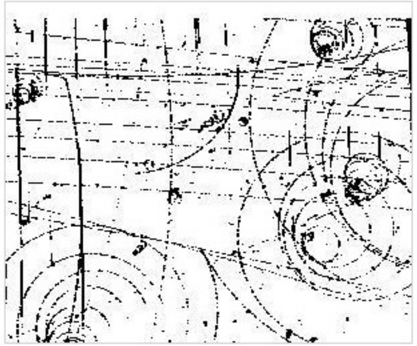
Mystery of Confinement

Theoretical problem

CMI

ABOUT PROGRAMS MILLENNIUM PROBLEMS PEOPLE PUBLICATIONS EVE

Yang–Mills and Mass Gap



The laws of quantum physics stand to the world of elementary particles in the way that Newton's laws of classical mechanics stand to the macroscopic world. Almost half a century ago, Yang and Mills introduced a remarkable new framework to describe elementary particles using structures that also occur in geometry. Quantum Yang-Mills theory is now the foundation of most of elementary particle theory, and its predictions have been tested at many experimental laboratories, but its mathematical foundation is still unclear. The successful use of Yang-Mills theory to describe the strong interactions of elementary particles depends on a subtle quantum mechanical property called the "mass gap": the quantum particles have positive masses, even though the classical waves travel at the speed of light. This property has been discovered by physicists from experiment and confirmed by computer simulations, but it still has not been understood from a theoretical point of view. Progress in establishing the existence of the Yang-Mills theory and a mass gap will require the introduction of fundamental new ideas both in physics and in mathematics.

This problem is: Unsolved

Unsolved QFT problem.

Mystery of Confinement

Theoretical problem

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Yang–Mills and Mass Gap

Progress in establishing the existence of the Yang-Mills theory and a mass gap will require the introduction of fundamental new ideas both in physics and in mathematics.

This problem is: Unsolved

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Mystery of Confinement

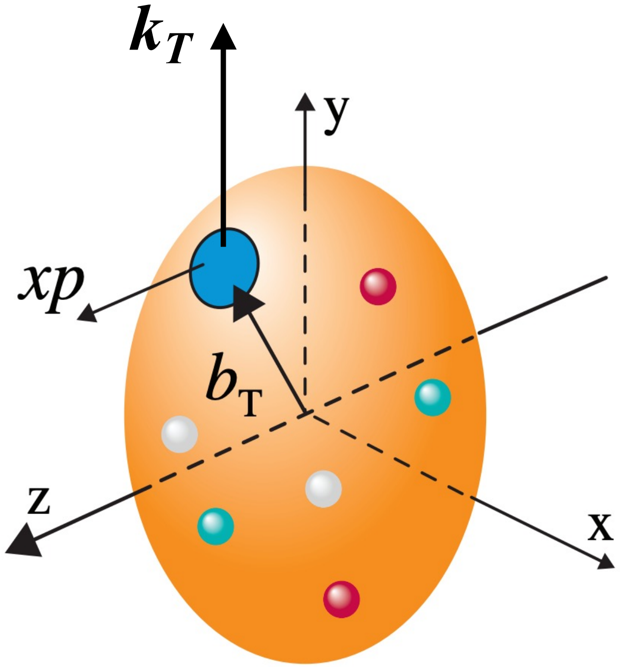
Theoretical problem

Unsolved QFT problem.

Experimental problem

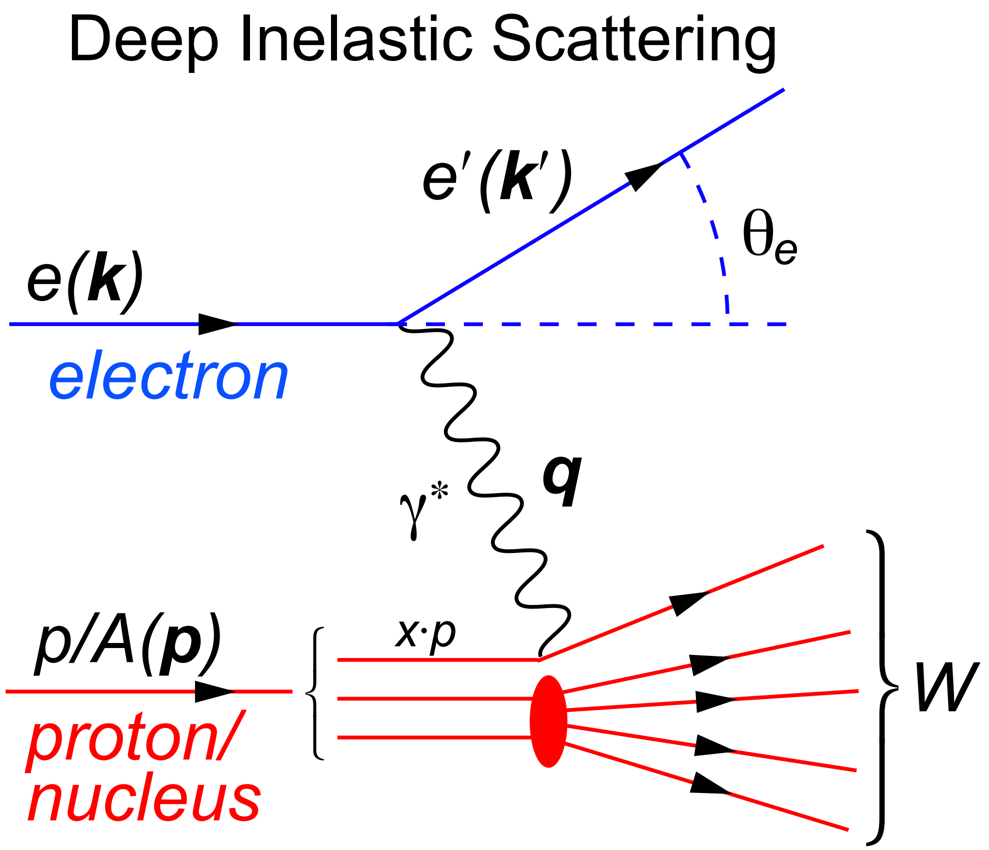
Questions

- Nucleon structure
- Spin
- Hadronization
- …



How does confinement manifest itself in these questions?

DIS and nucleon structure

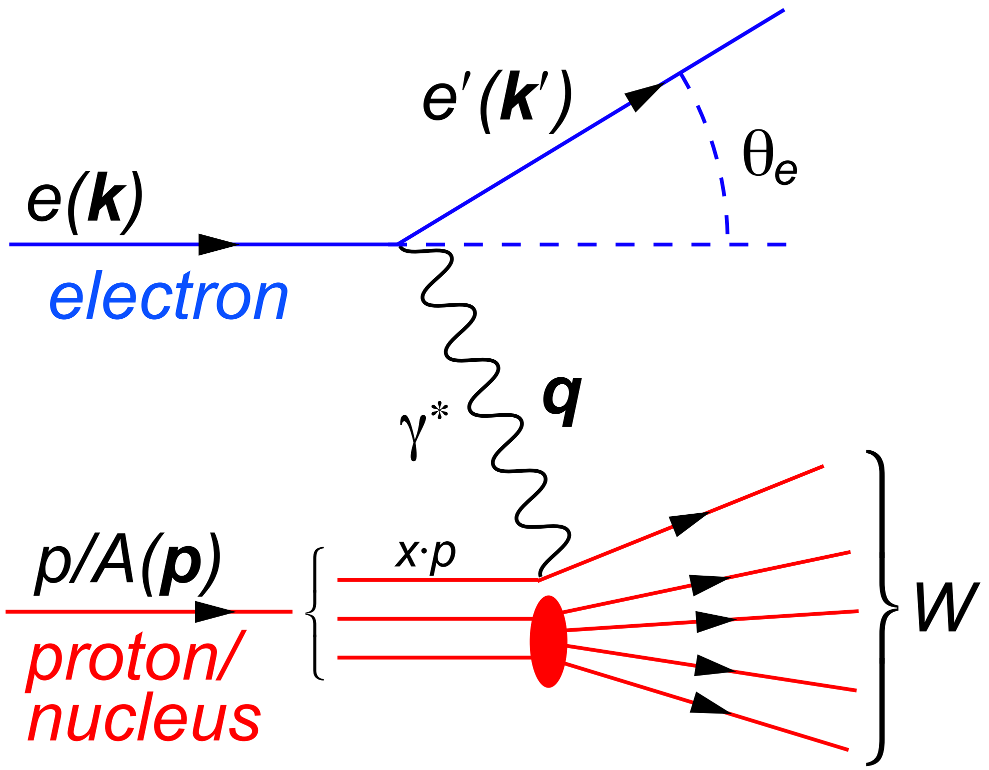


1. Resolution ~ $Q^2 = -q^2$
2. Momentum fraction ~ $x_{\mathrm{bj}} = \dfrac{Q^2}{2Pq}$

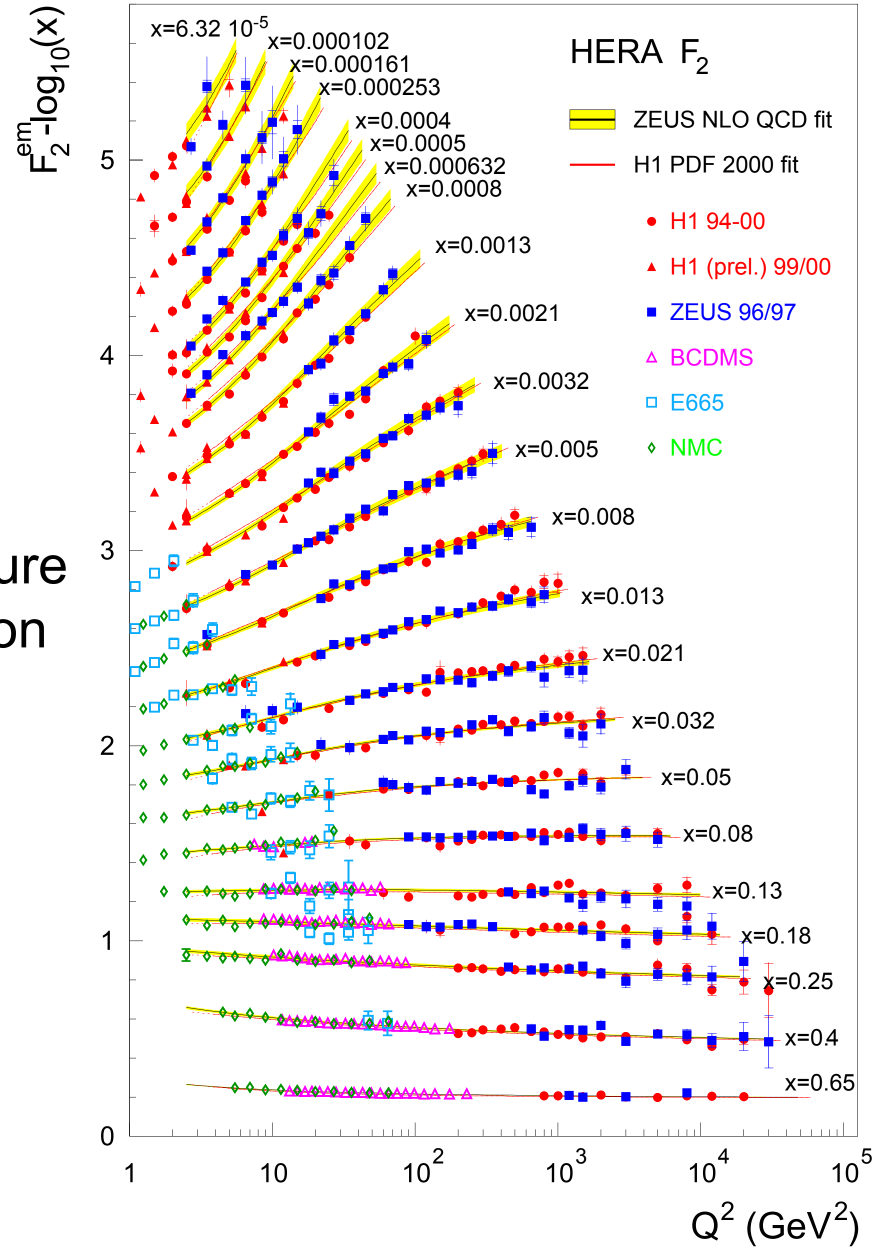
   "Exposure time"

DIS and nucleon structure

Deep Inelastic Scattering



structure function



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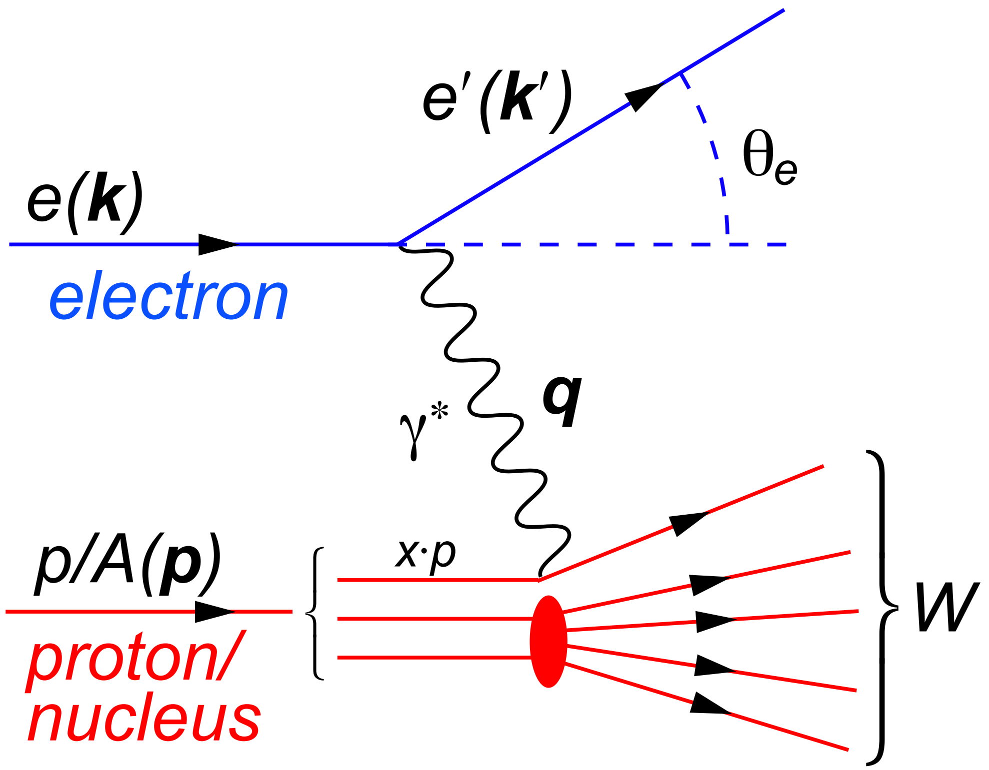

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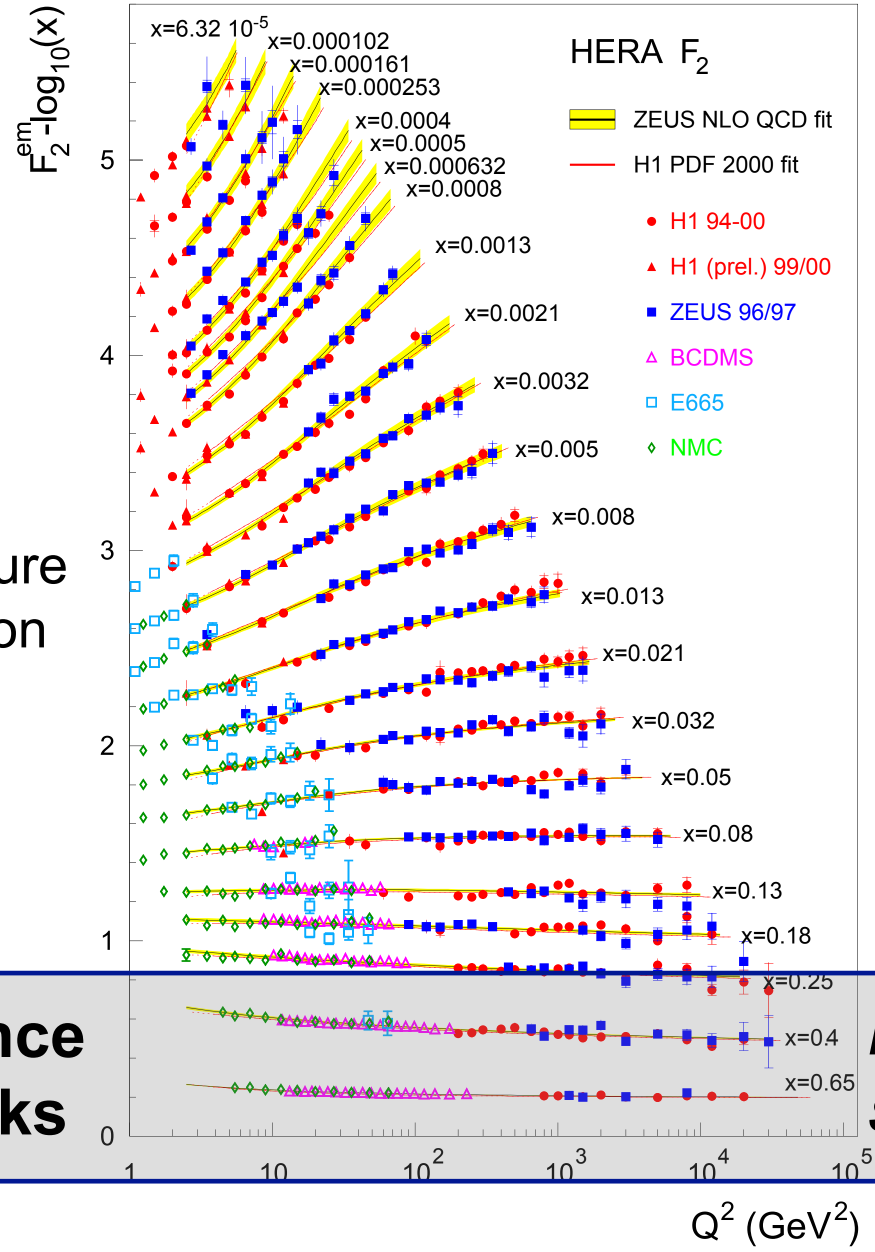

Valence Quarks

Bjorken-scaling

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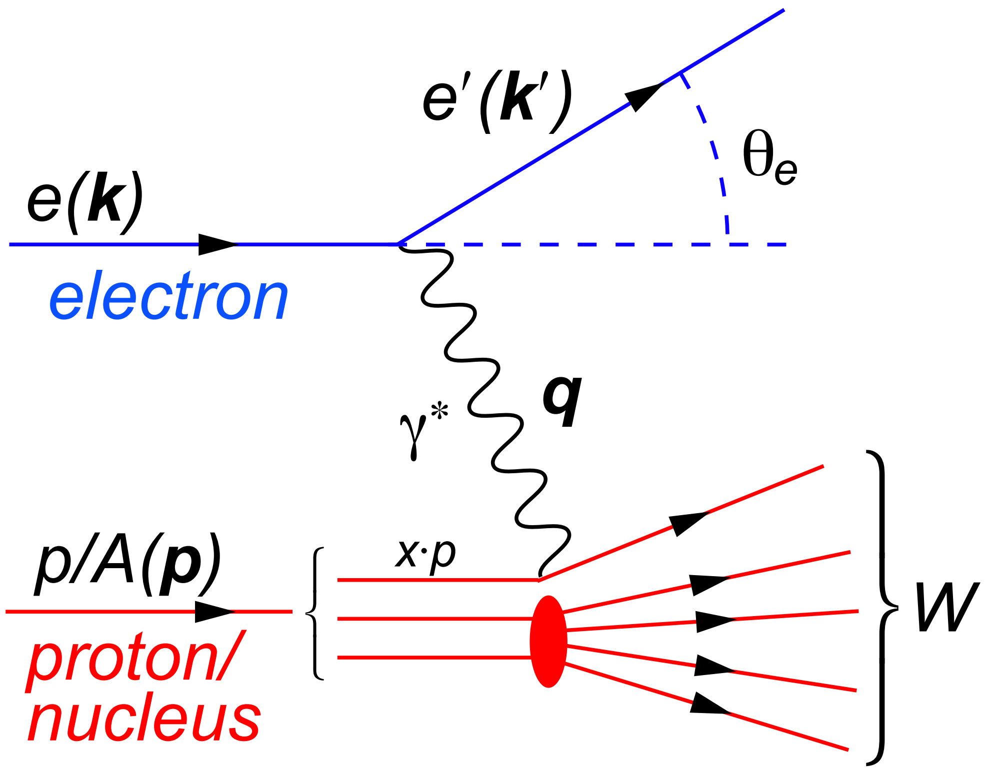

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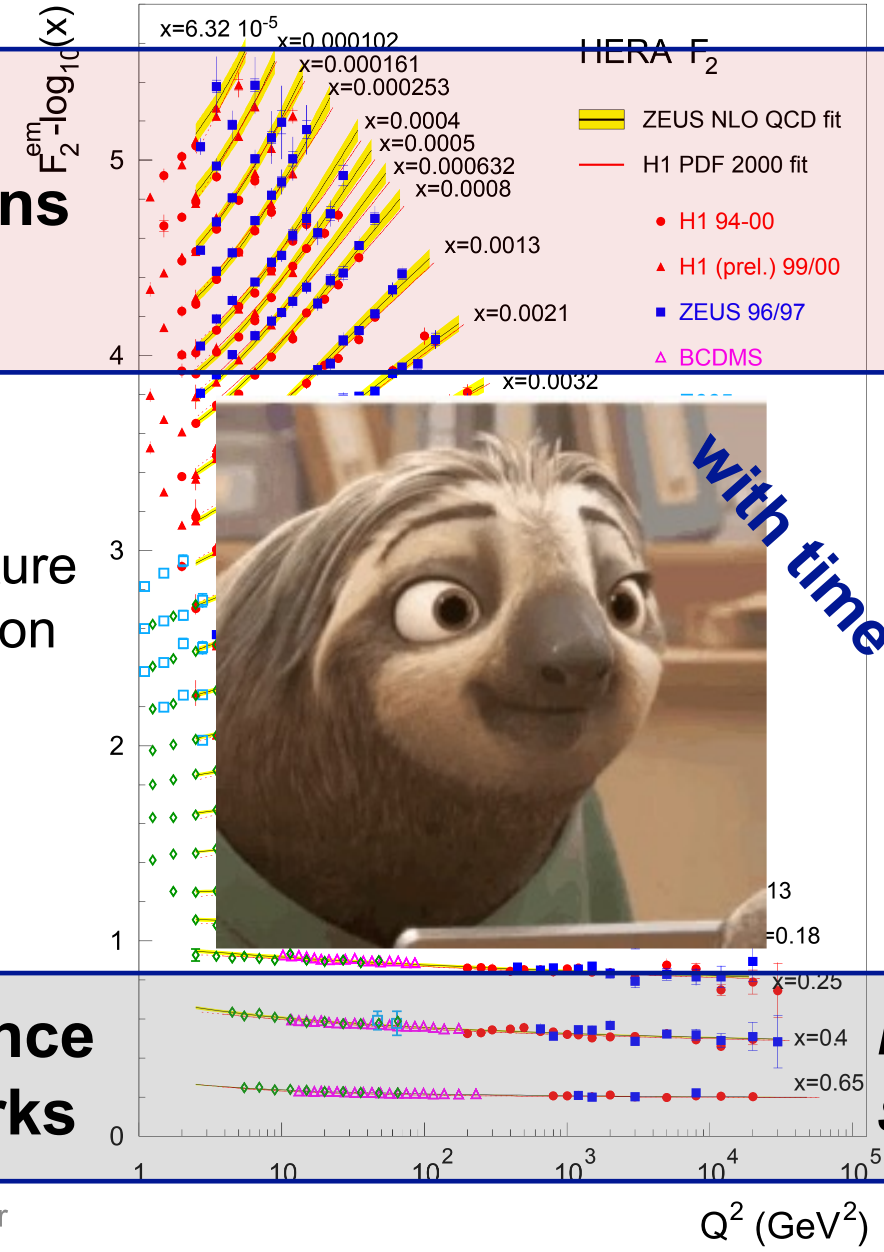
Gluons

Valence Quarks

structure function



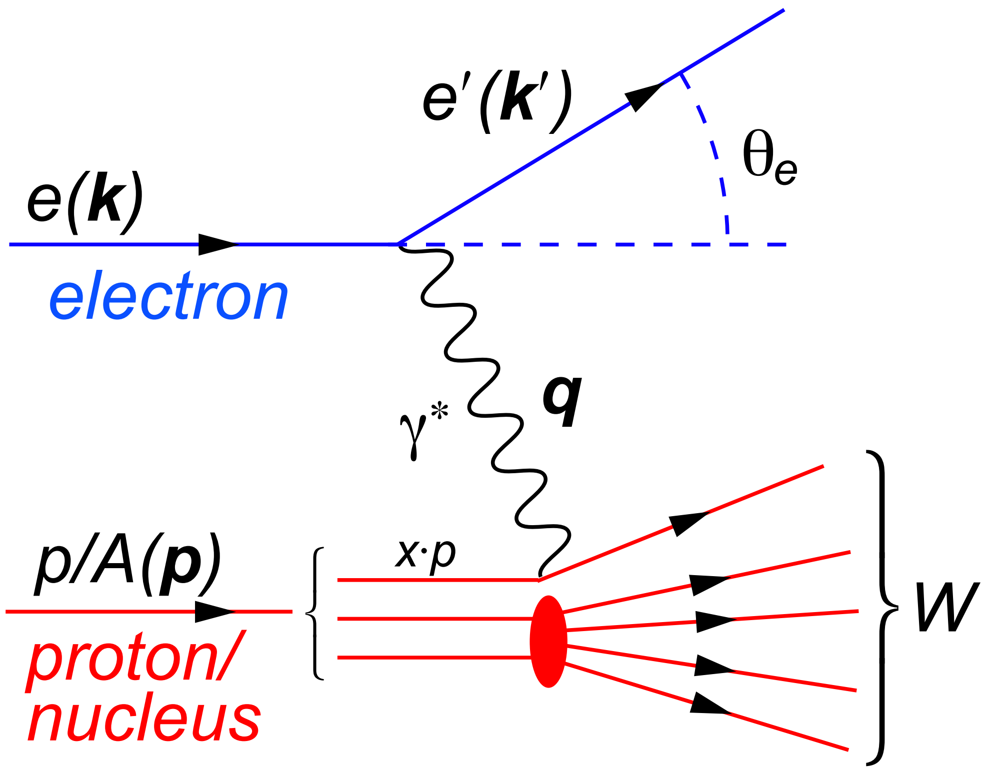
Scaling violation

with time dilation ...

Bjorken-scaling

DIS and nucleon structure

Deep Inelastic Scattering



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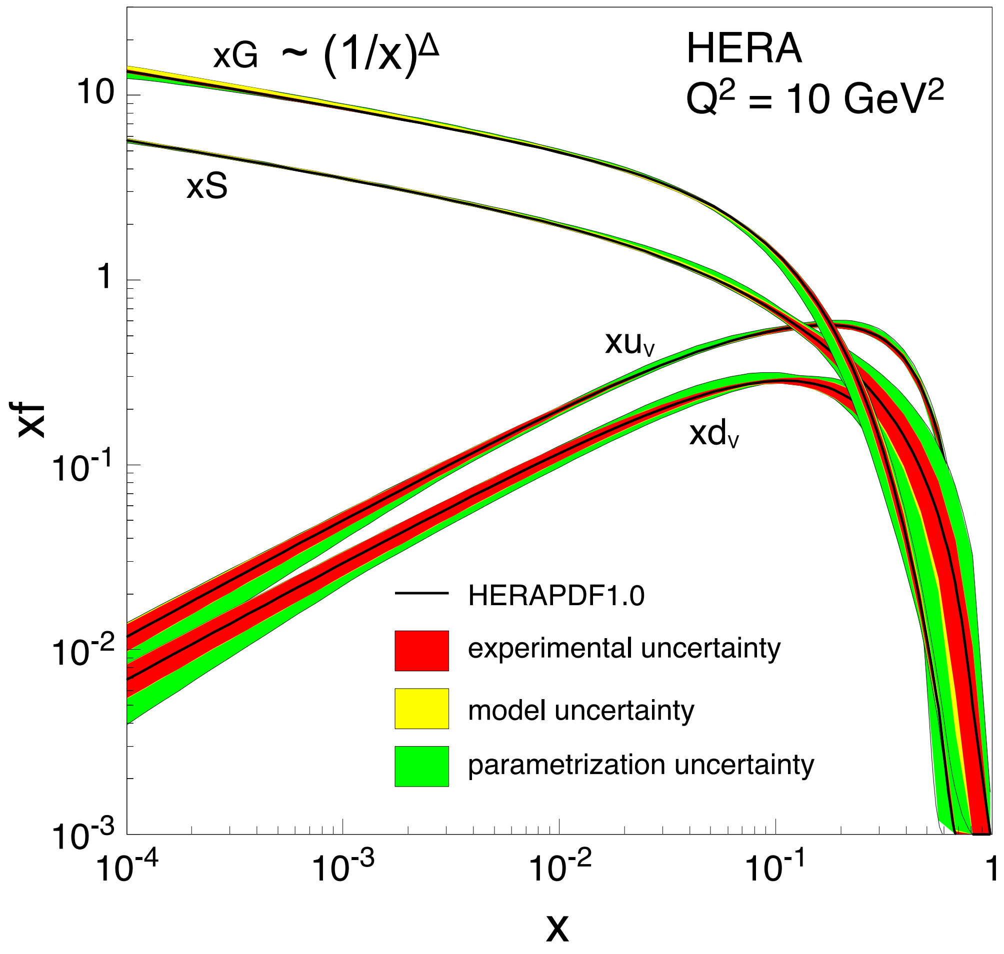
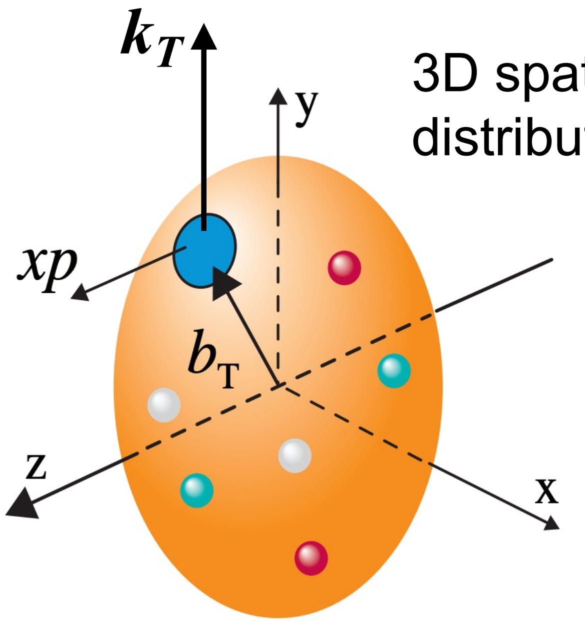
Parton Distribution Functions (PDFs)



3D nucleon structure

"Mother"
Wigner distributions

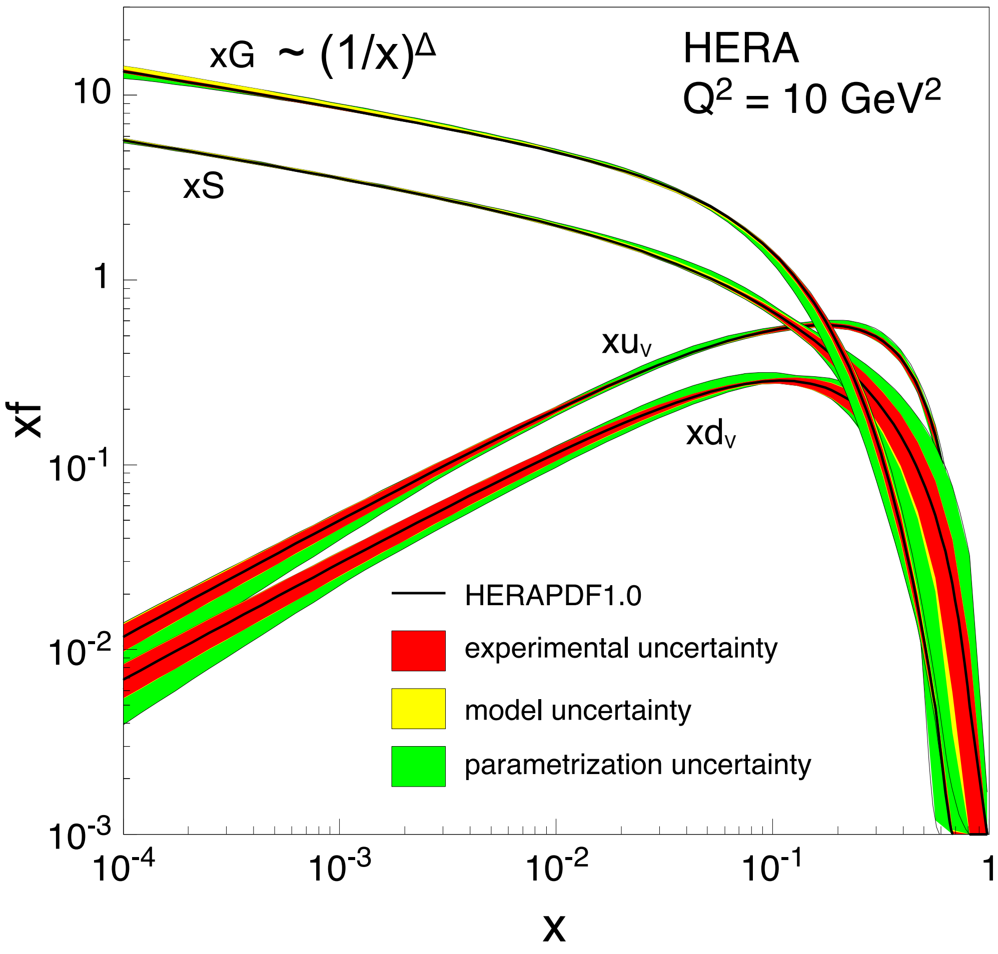


3D spatial & momentum distributions

3D structures:

- Generalized Parton Distributions (GPDs)
- Transverse Momentum Dependent (TMD) PDFs

Parton Distribution Functions (PDFs)



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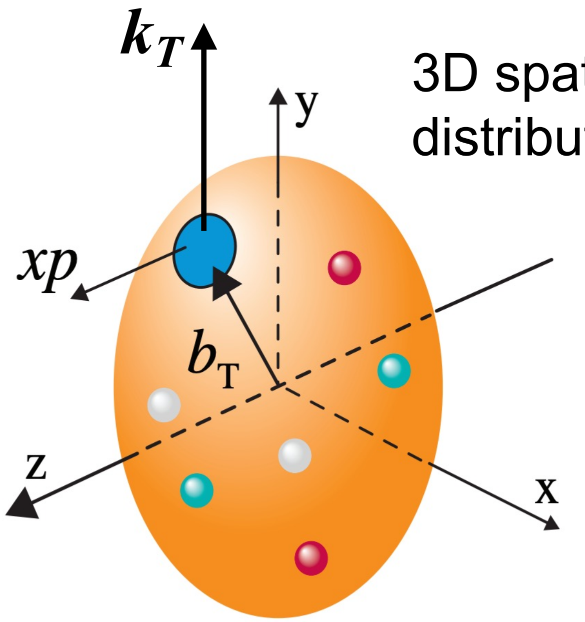

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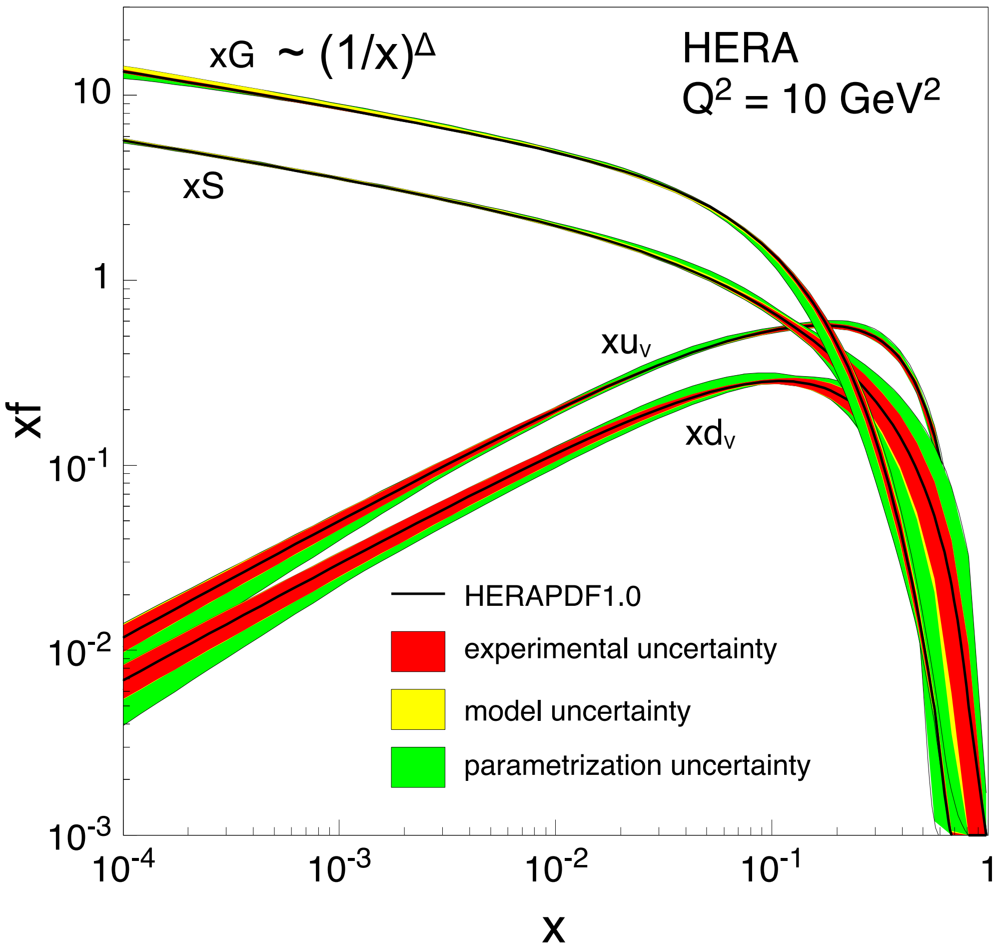
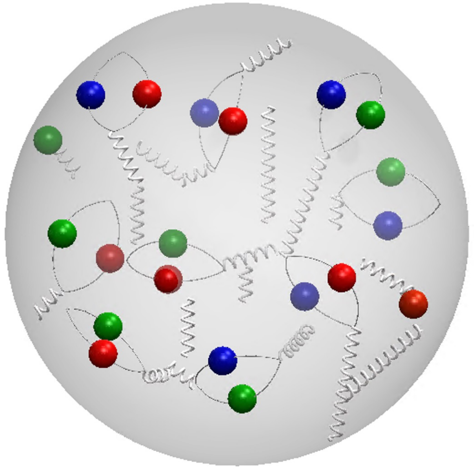


All known nucleon structure is derived from single particle distributions

Structure beyond single parton

Let's imagine

- If we measured all parton distributions (1D ➪ 3D) with our best precisions.
- Consider it solved?



Confinement?

Structure beyond single parton

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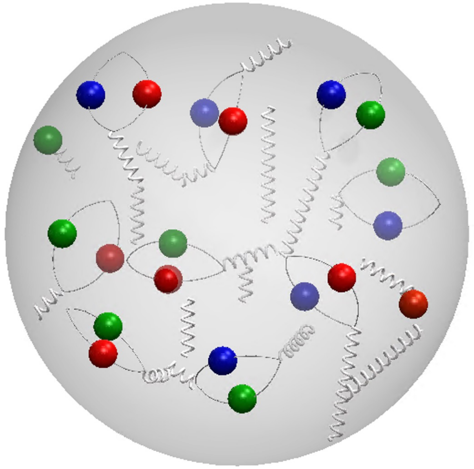
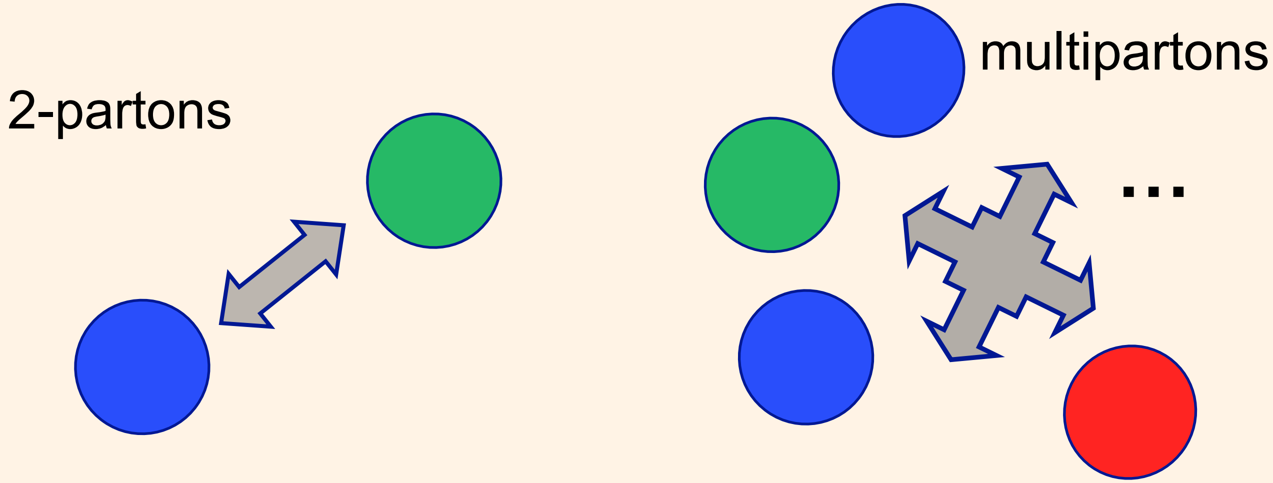


Confinement?

How does *confinement* manifest itself in **parton correlations**?



parton-parton correlations
(density, momentum, spins, etc..)

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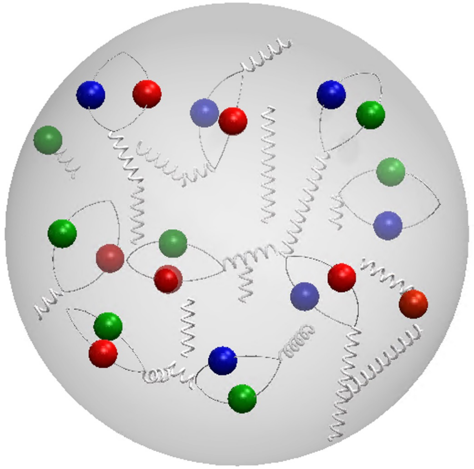

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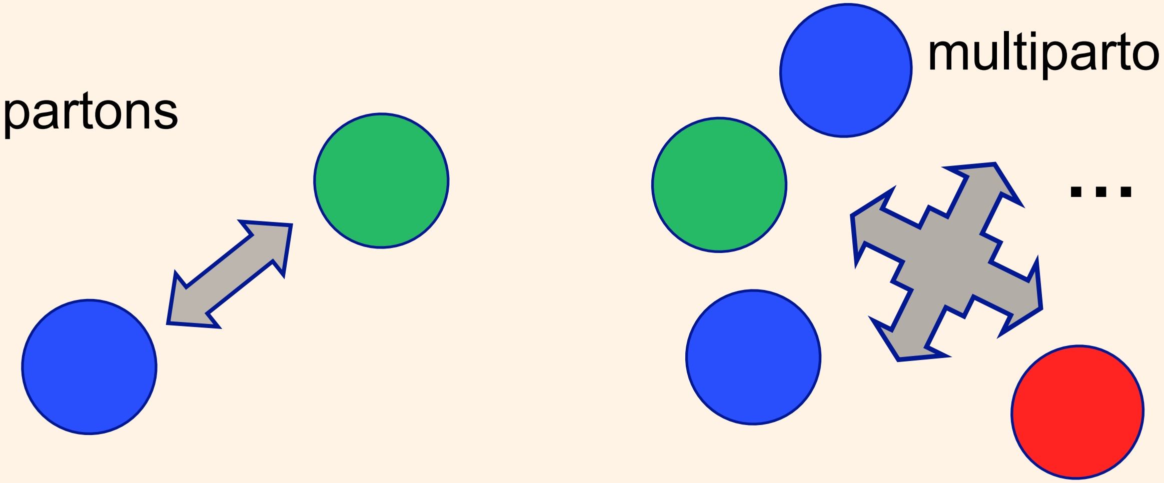


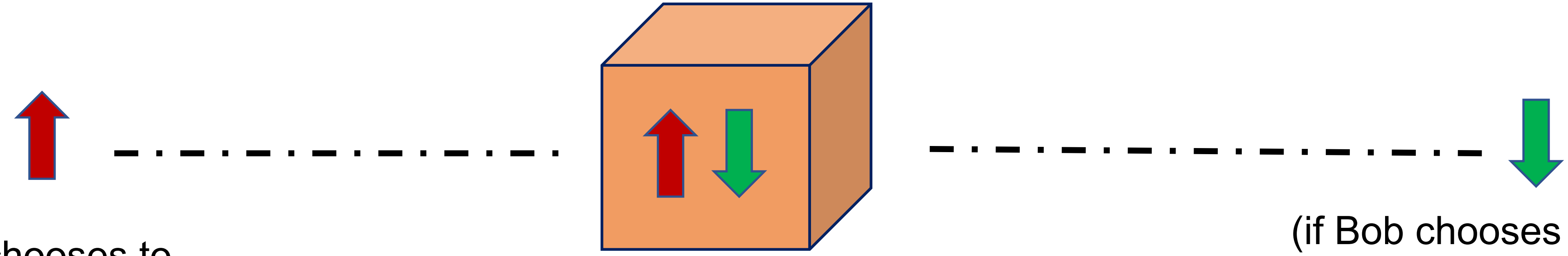
parton-parton correlations
(density, momentum, spins, etc..)

Can *correlation* help understand nucleon structure ?

A story of Alice and Bob

"spooky action at a distance…"

Alice



Bob

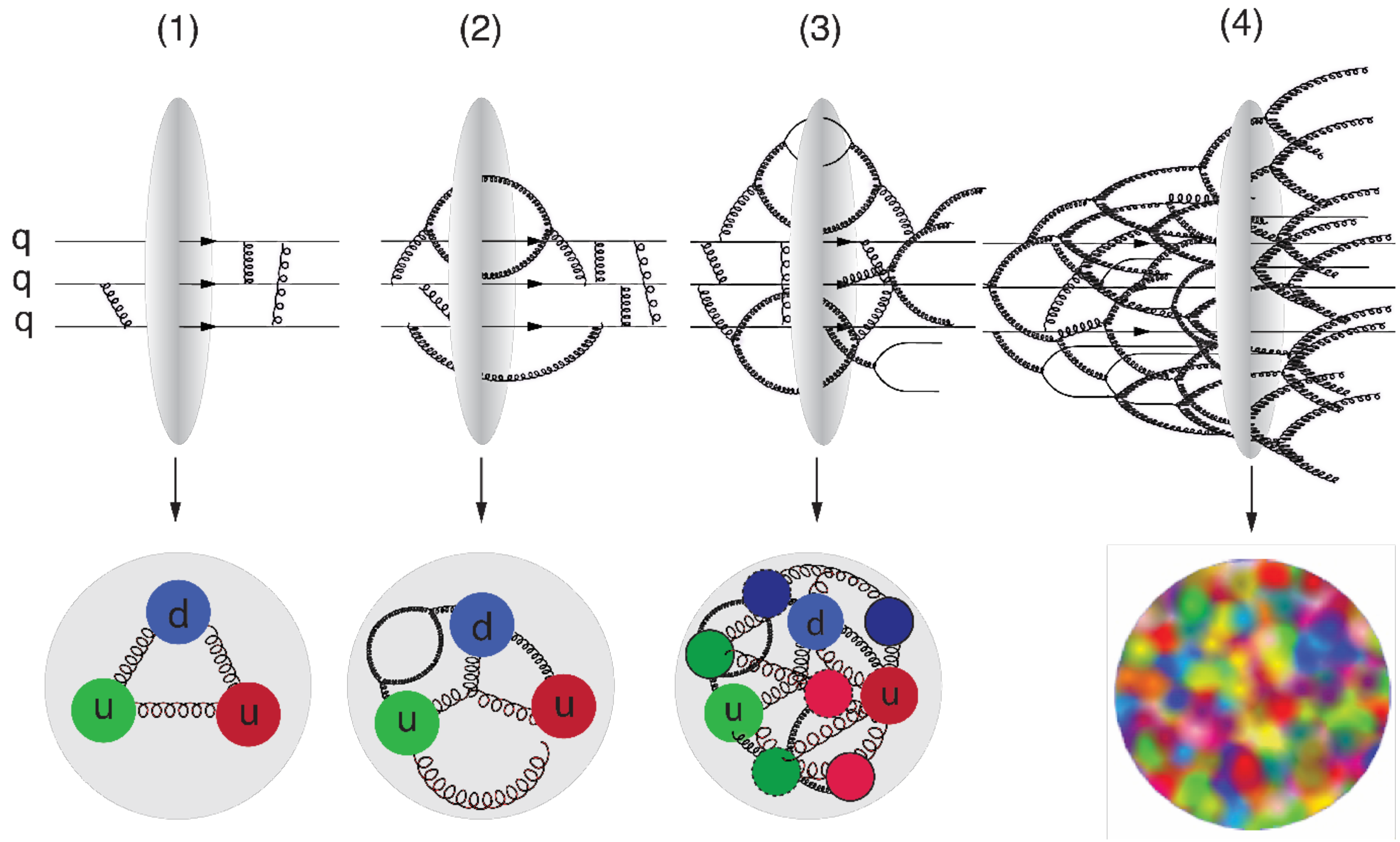
(if Alice chooses to measure its spin in z axis)

(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,

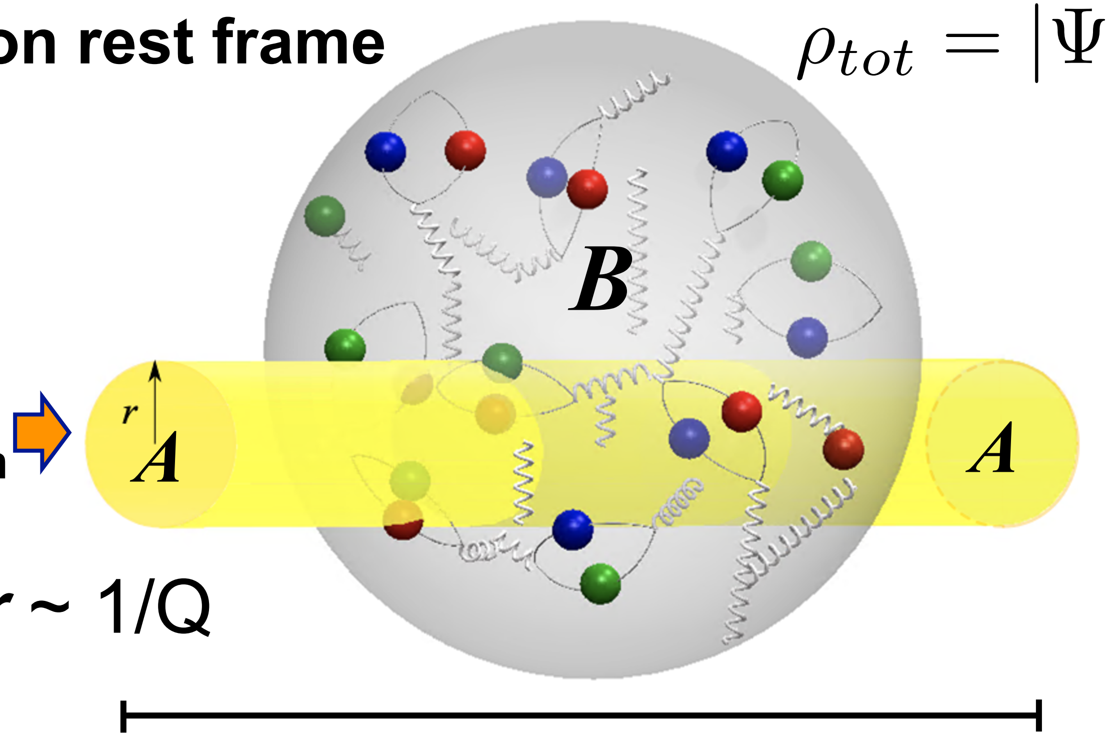
$$|\Psi\rangle = |\Psi_1\rangle \otimes |\Psi_2\rangle \otimes |\Psi_3\rangle \ldots$$

Entanglement Entropy (EE)

Proton rest frame

Pure state

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



r ~ 1/Q

L ~ 1/(mx)

Entanglement Entropy (EE)

Pure state

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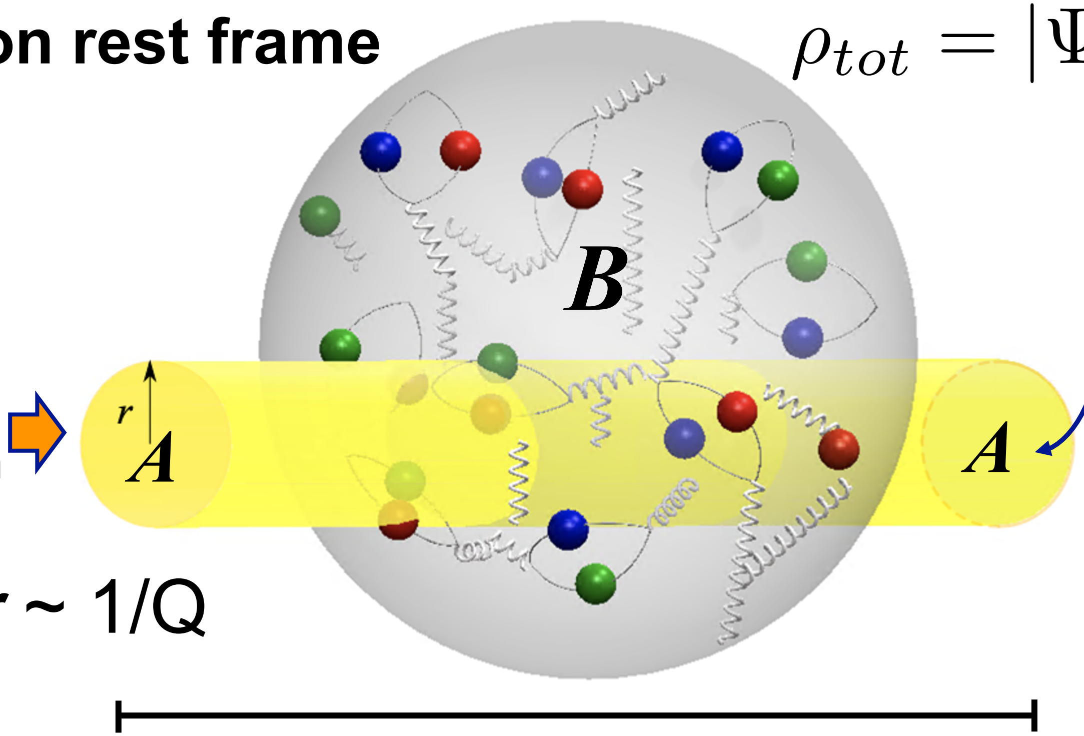

virtual photon

r ~ 1/Q

L ~ 1/(mx)

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

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

(reduced density matrix)

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

(von Neumann entropy)

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]

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

Entanglement Entropy (EE)

Pure state

Proton rest frame

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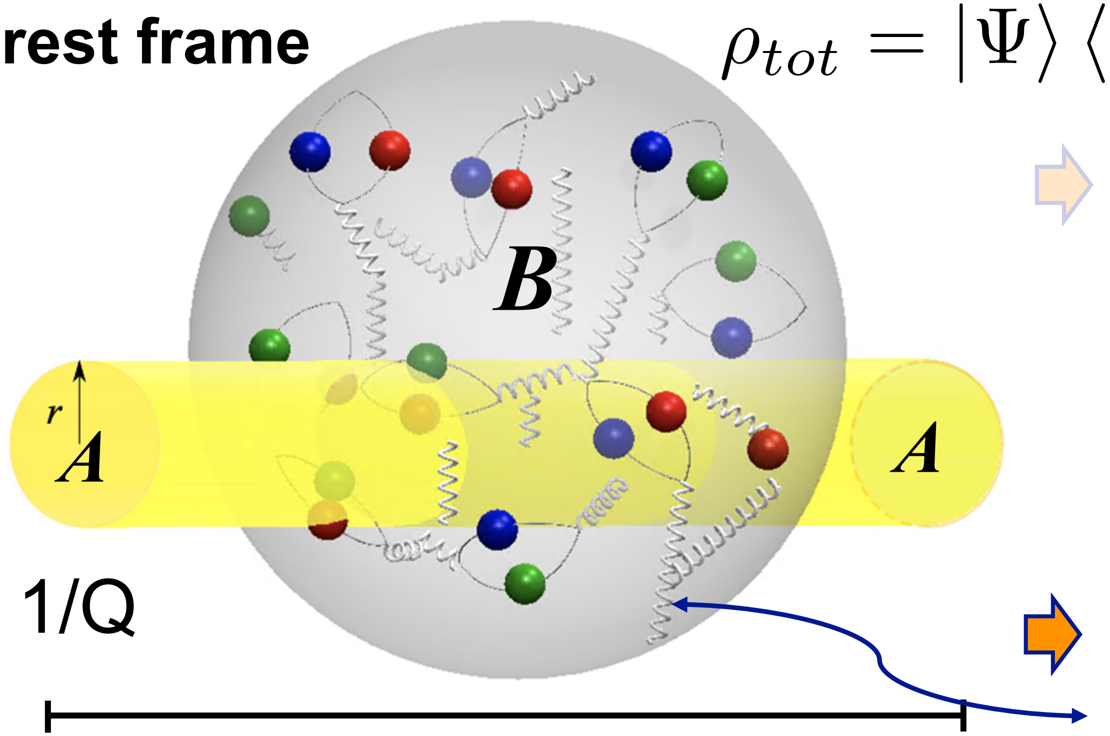

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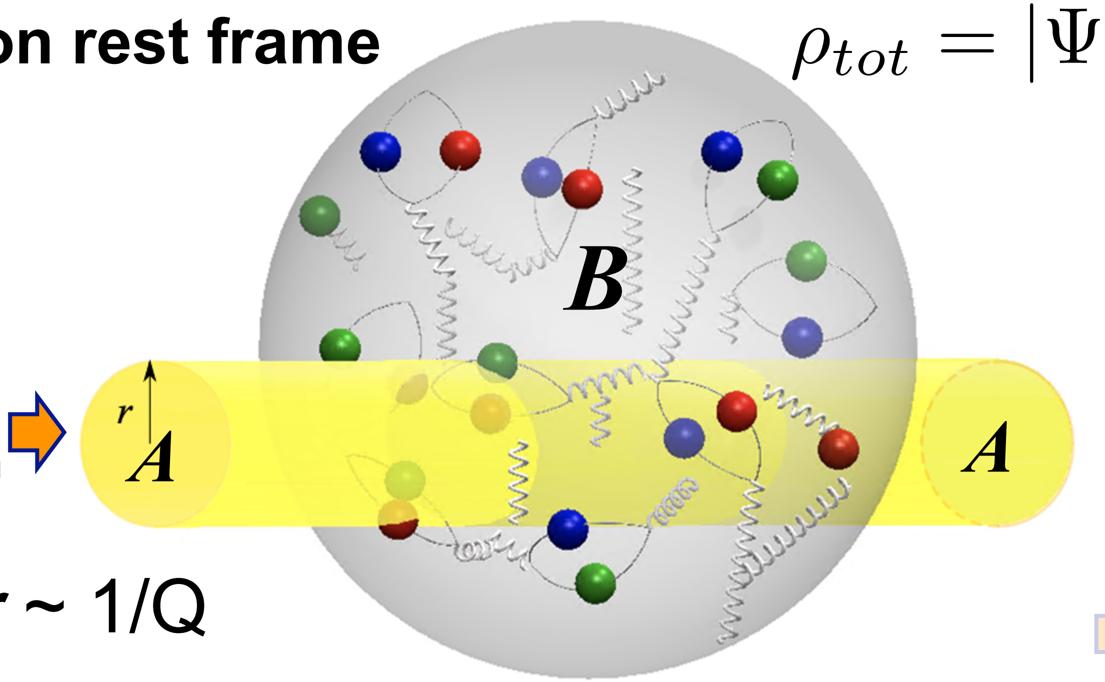

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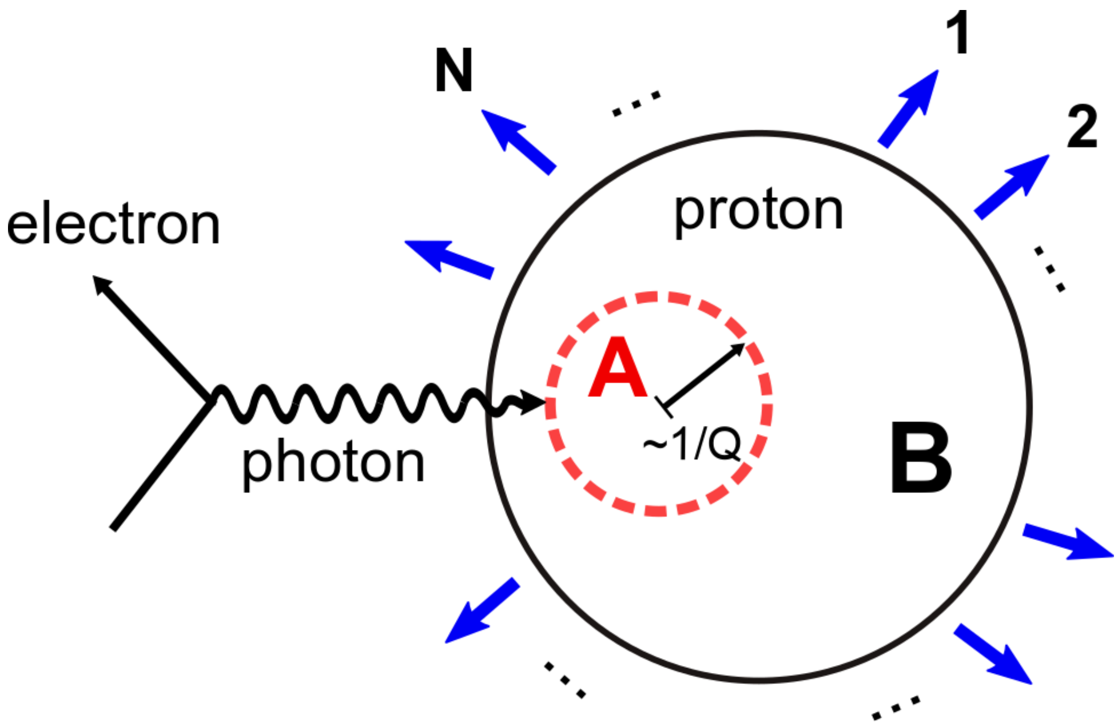
(von Neumann entropy)

Expectation – EE $S_A = S_B \neq 0$

EE in DIS



Fixed (x,Q^2)

S_A in DIS

(Kharzeev & Levin 2017)

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

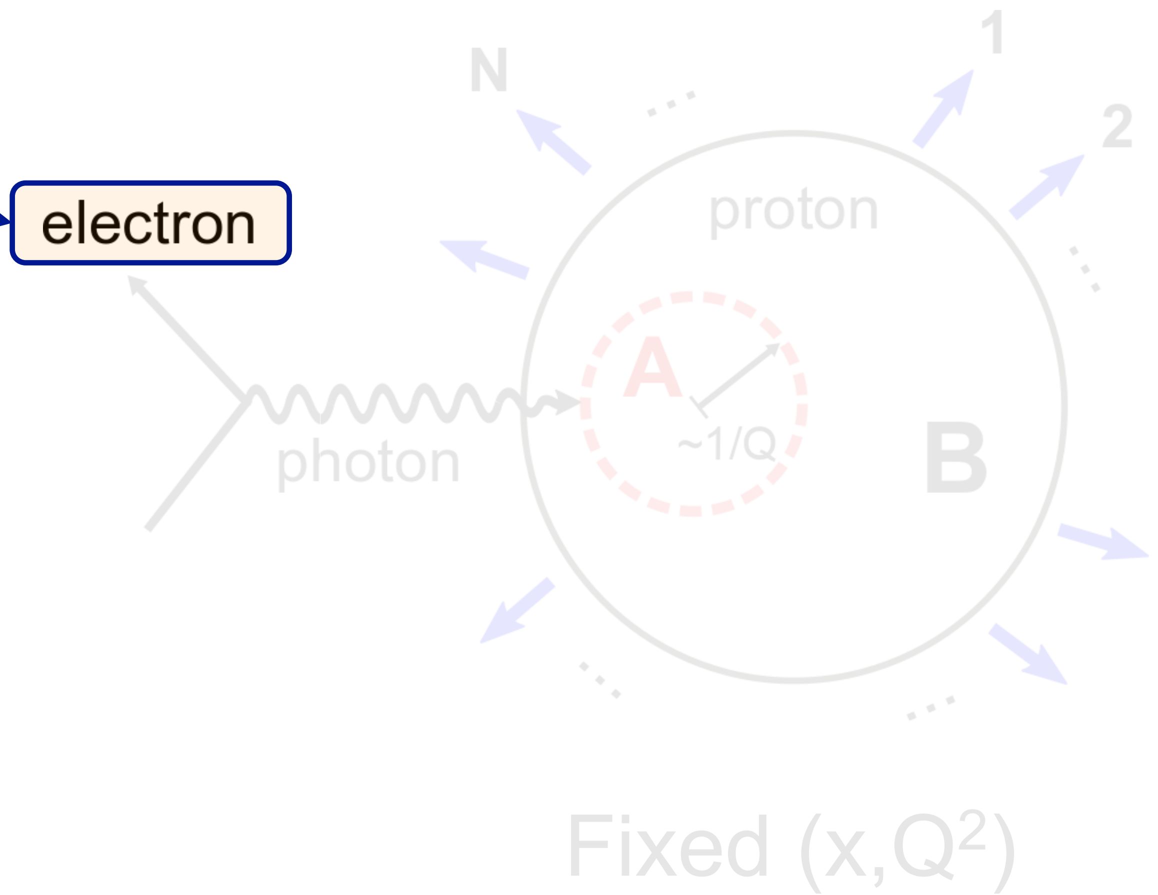
gluon entropy for low x

(Kharzeev & Levin 2021)

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

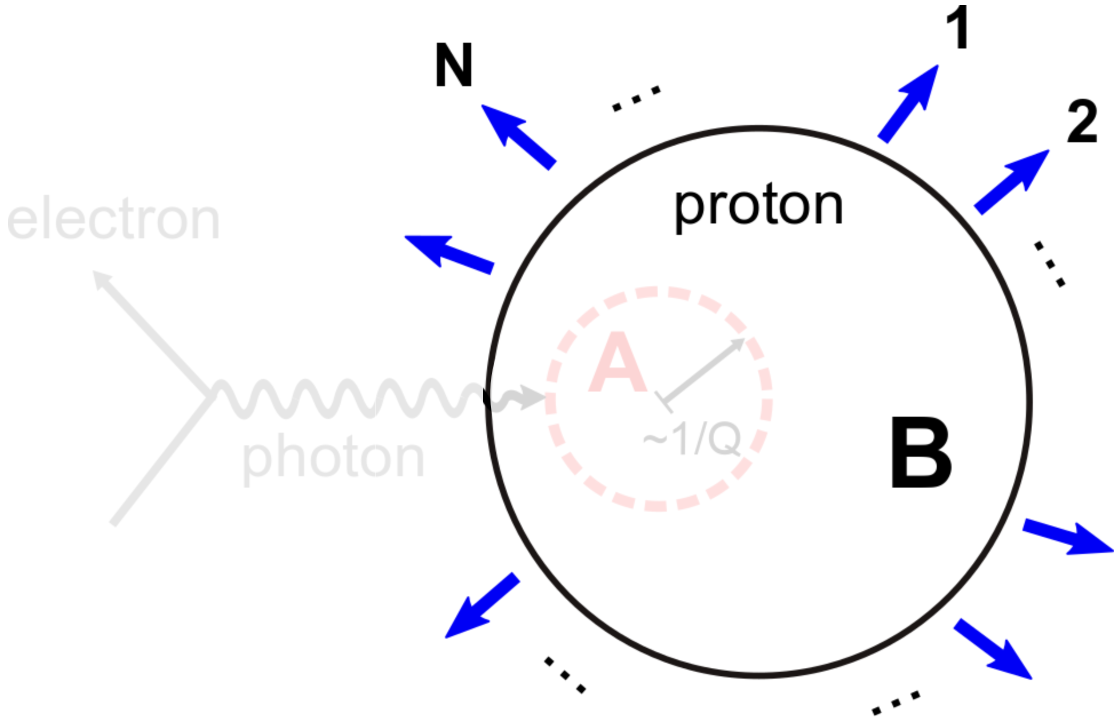
arXiv:2102.09773

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



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

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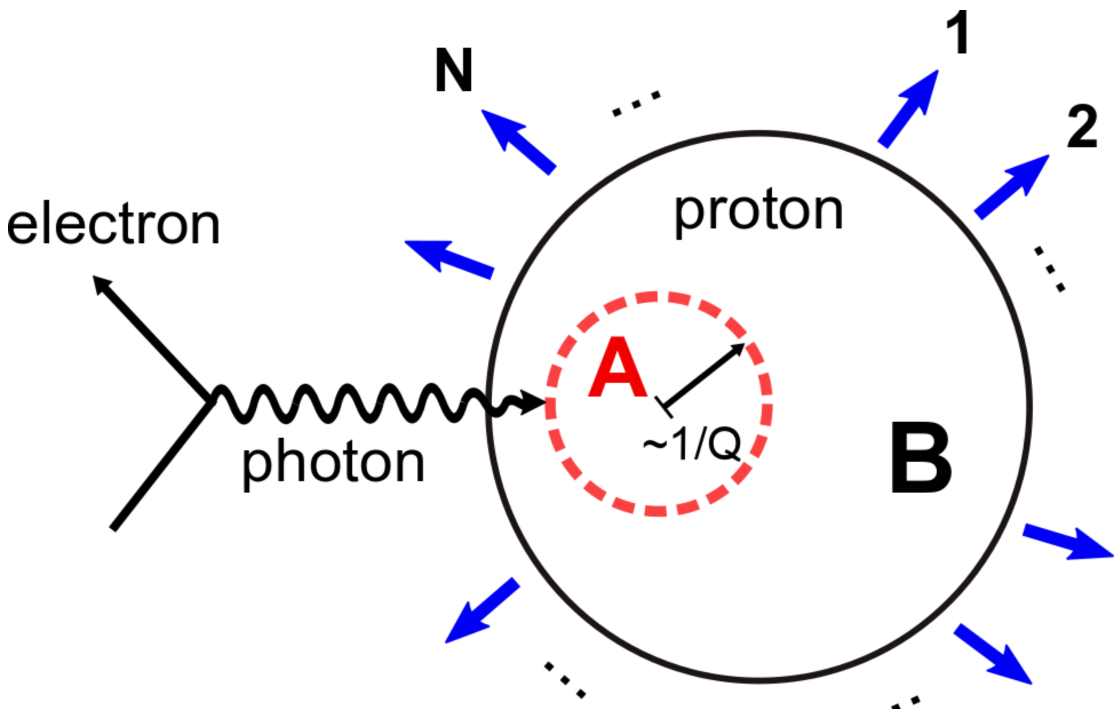
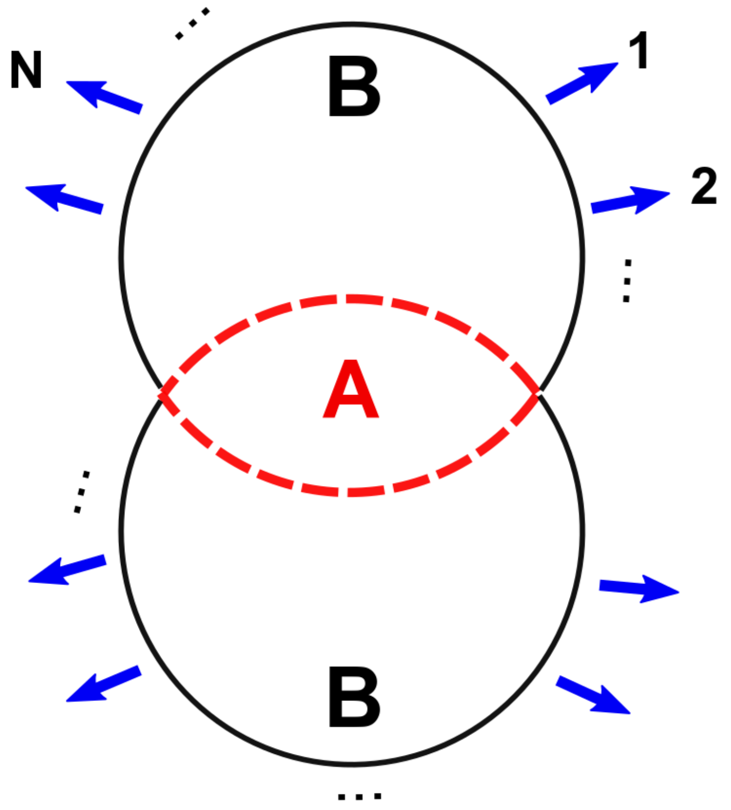


Fixed (x,Q^2)

EE in pp collisions

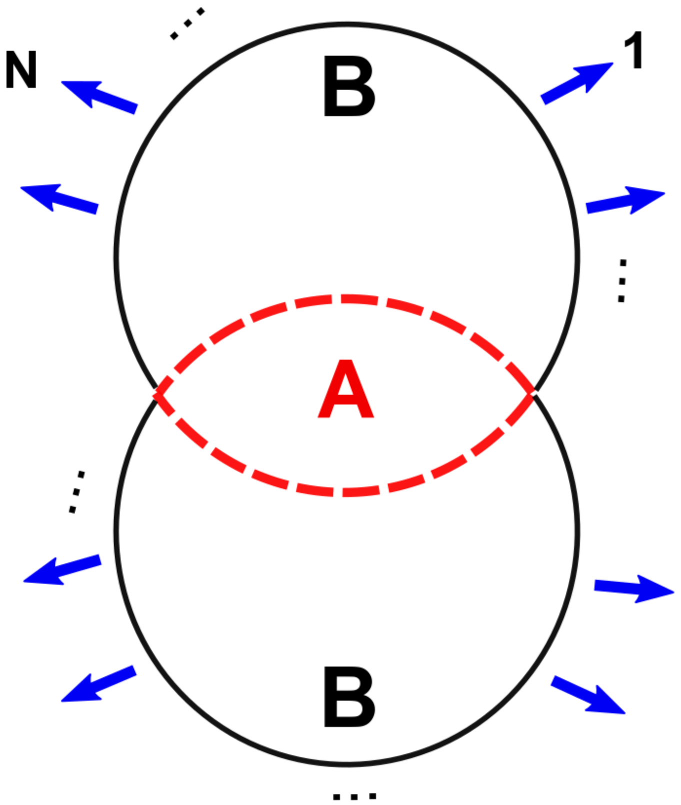
proton-proton collisions



gluon-gluon fusion dominates

EE in pp collisions

proton-proton collisions

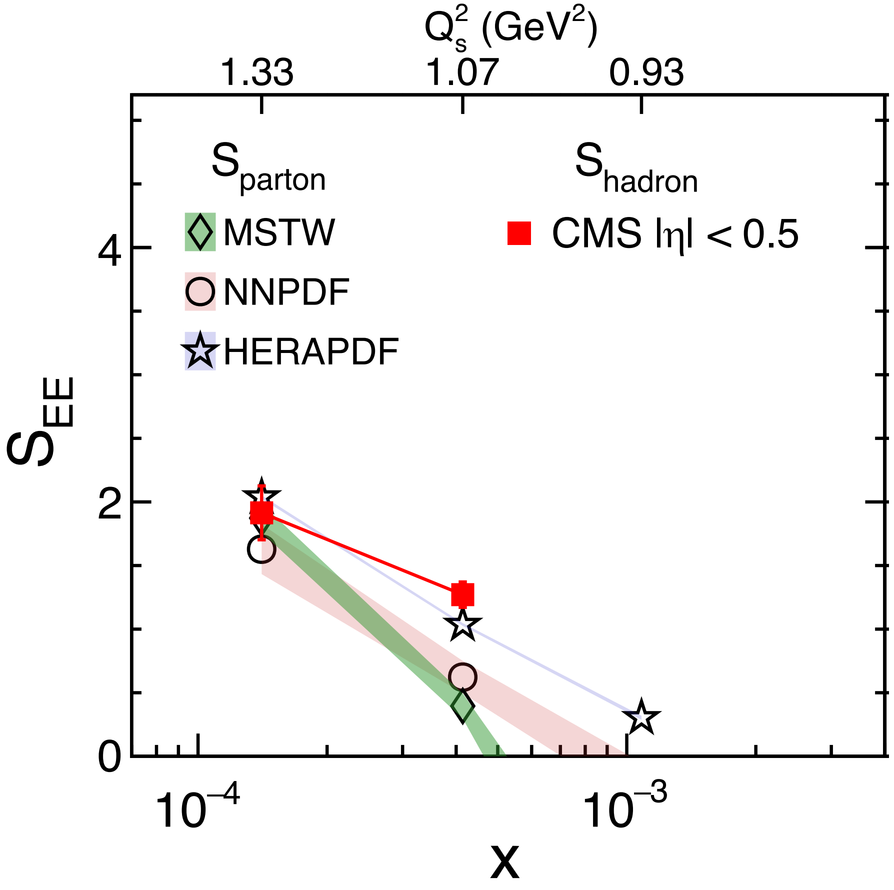


gluon-gluon fusion dominates

Large Hadron Collider has a lot of proton-proton collisions!

Measurement - pp data

Phys. Rev. Lett. 124, 062001 (2020)
(**ZT**, Kharzeev, Ullrich)



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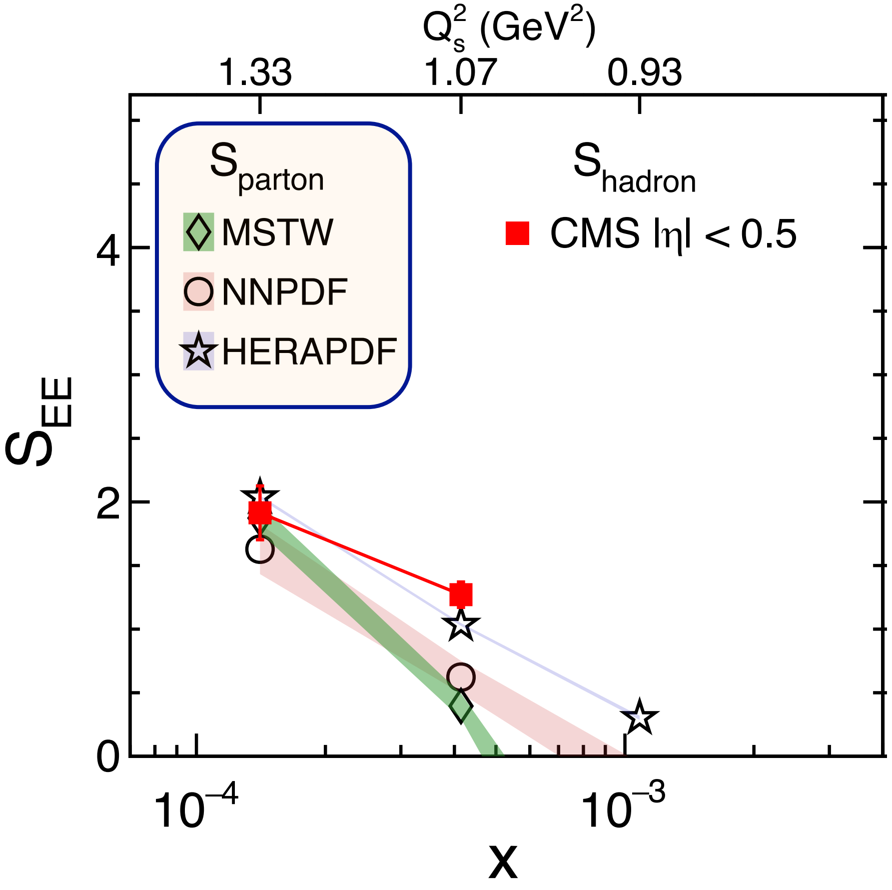

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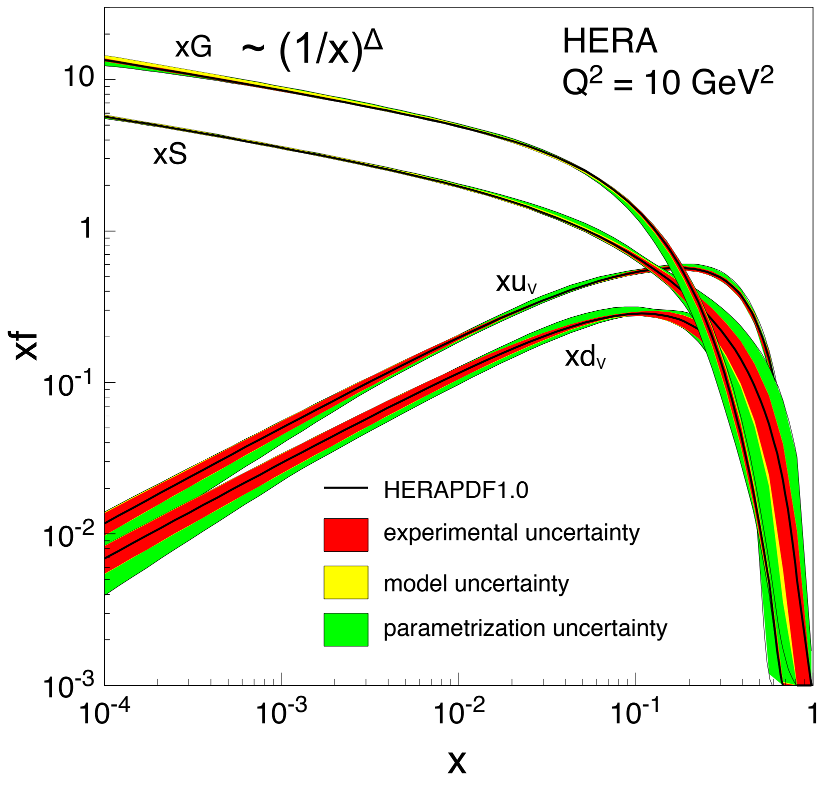

PDF

Measurement - pp data

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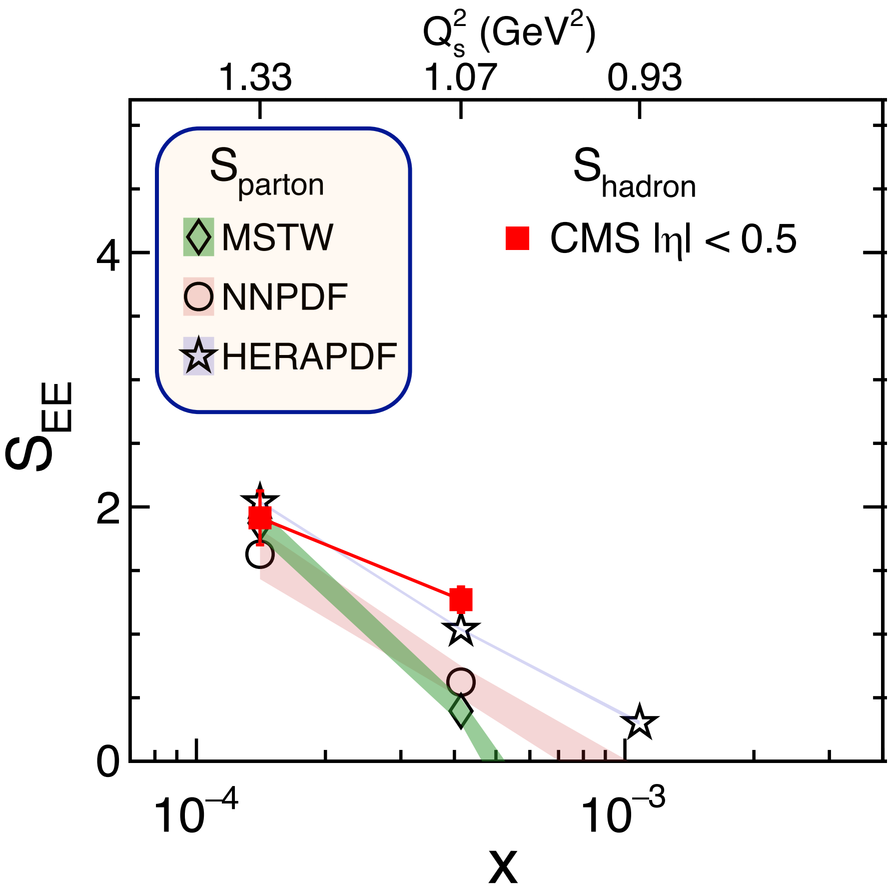
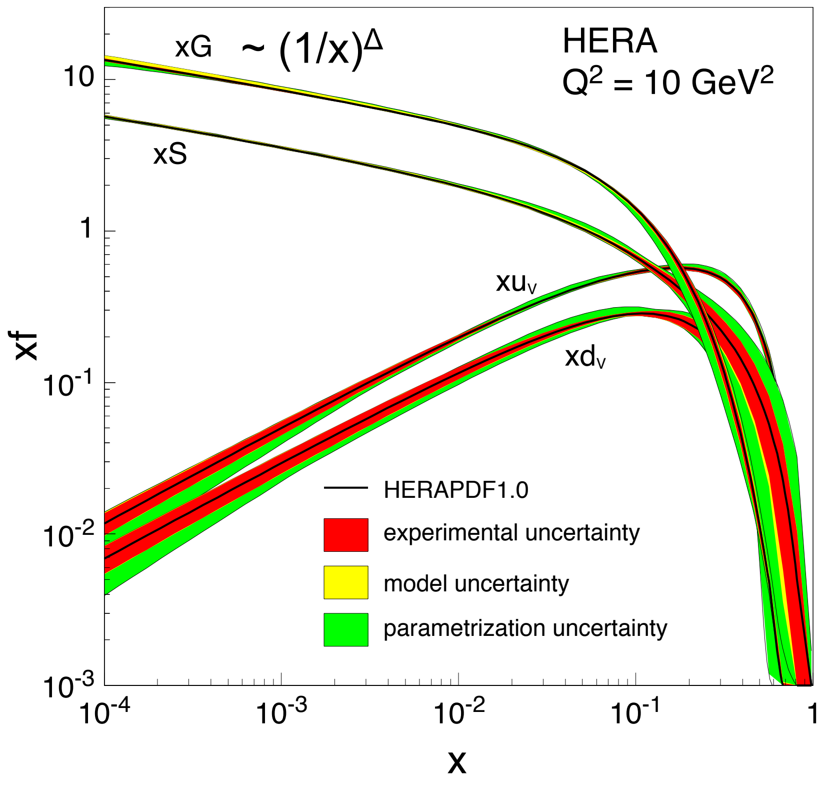


Parton:

- Only gluons are used at low x
- Minimum-bias data - no hard scale in the process, use saturation scale Q_s
- Leading order PDFs only

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



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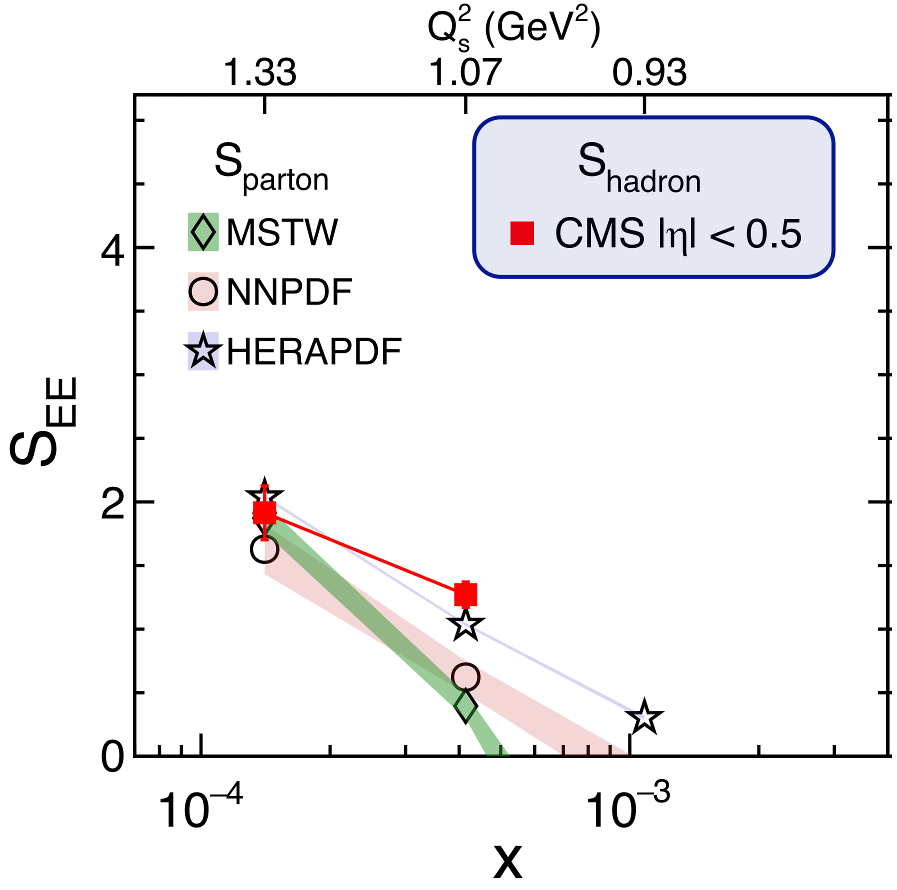

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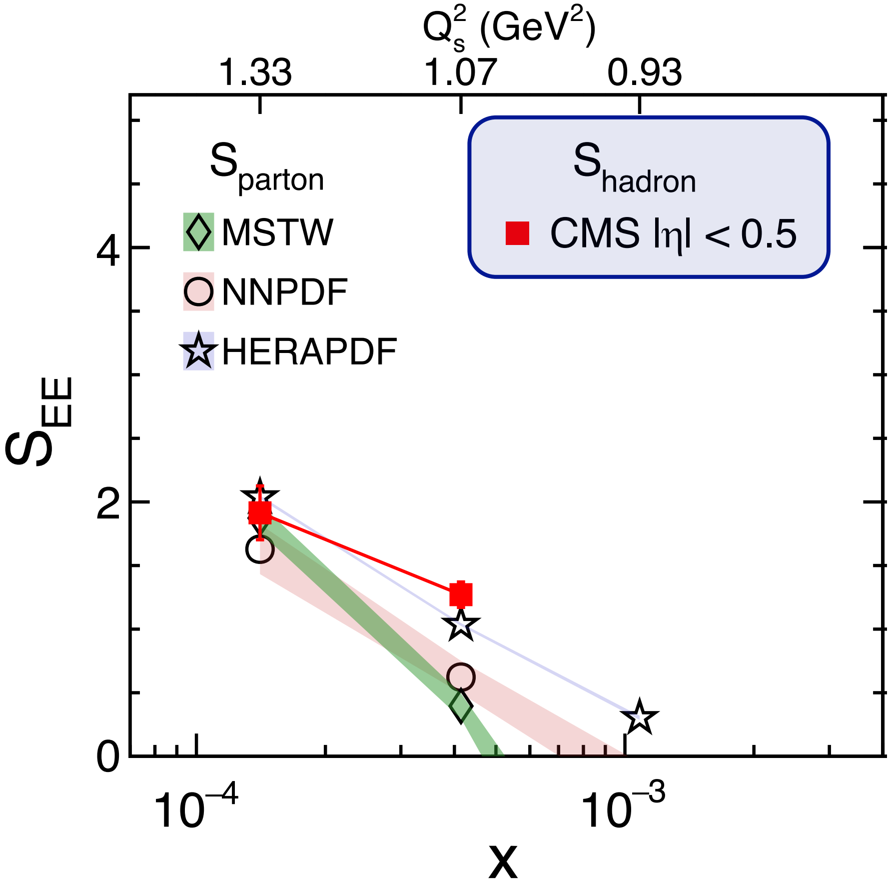

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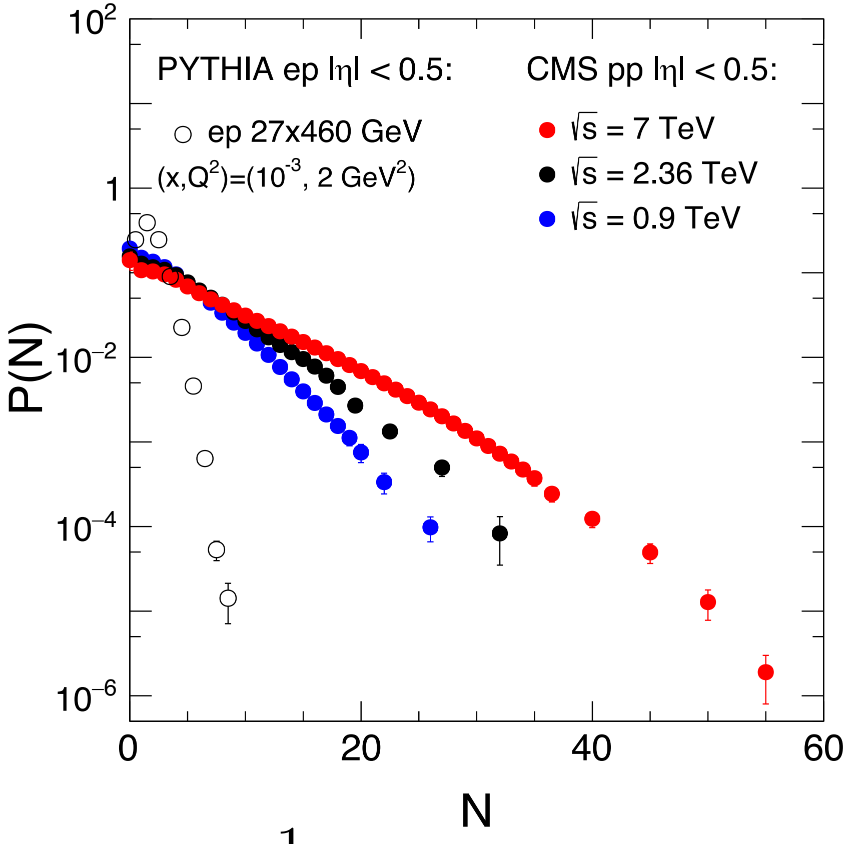

$$\ln\left(\frac{1}{x}\right) \sim y_{\text{proton}} - y_{\text{hadron}}$$

Measurement - pp data

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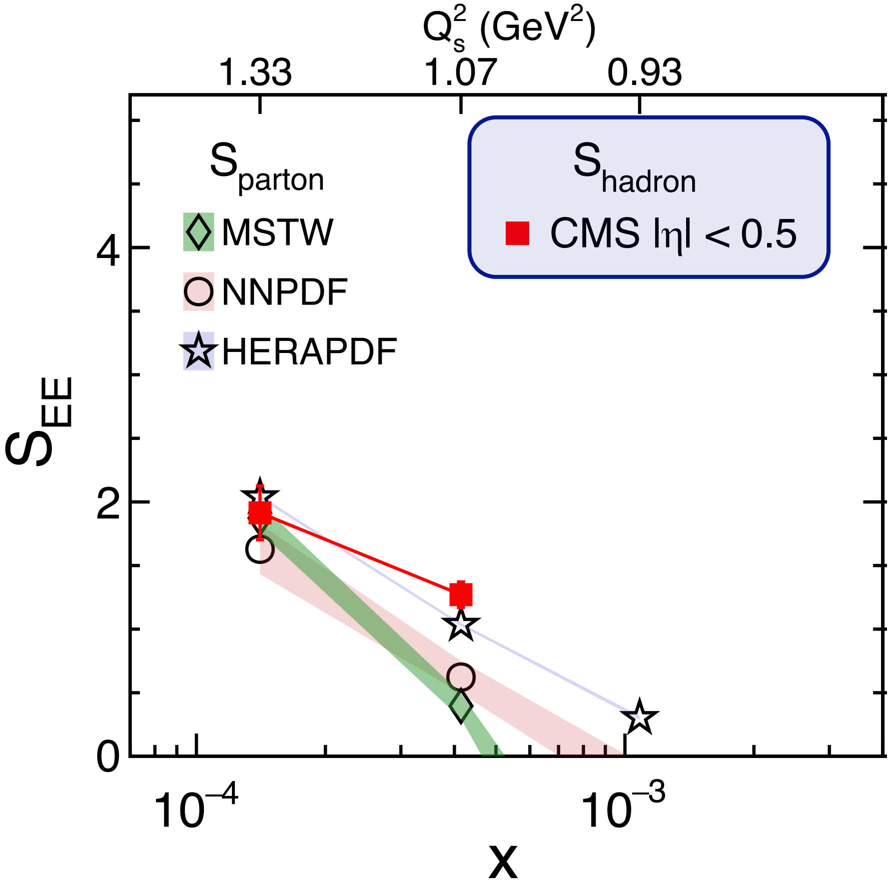
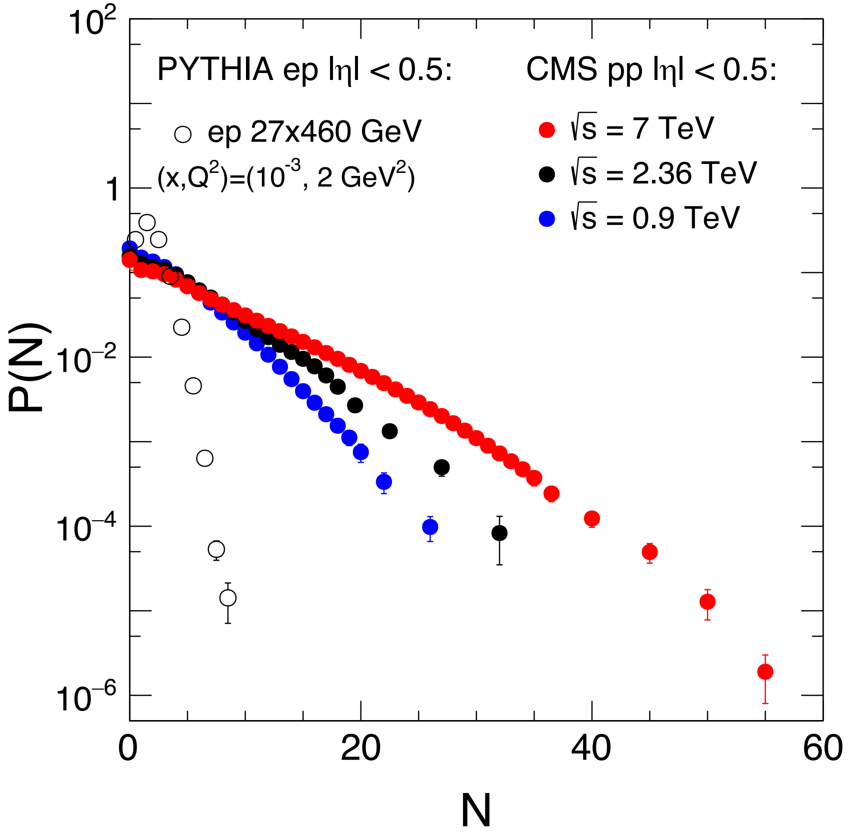


Hadron:

- Kinematics are determined by energy and rapidity
- Caveat - "Local Parton-Hadron Duality"
- Diff. between η and y is small.

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



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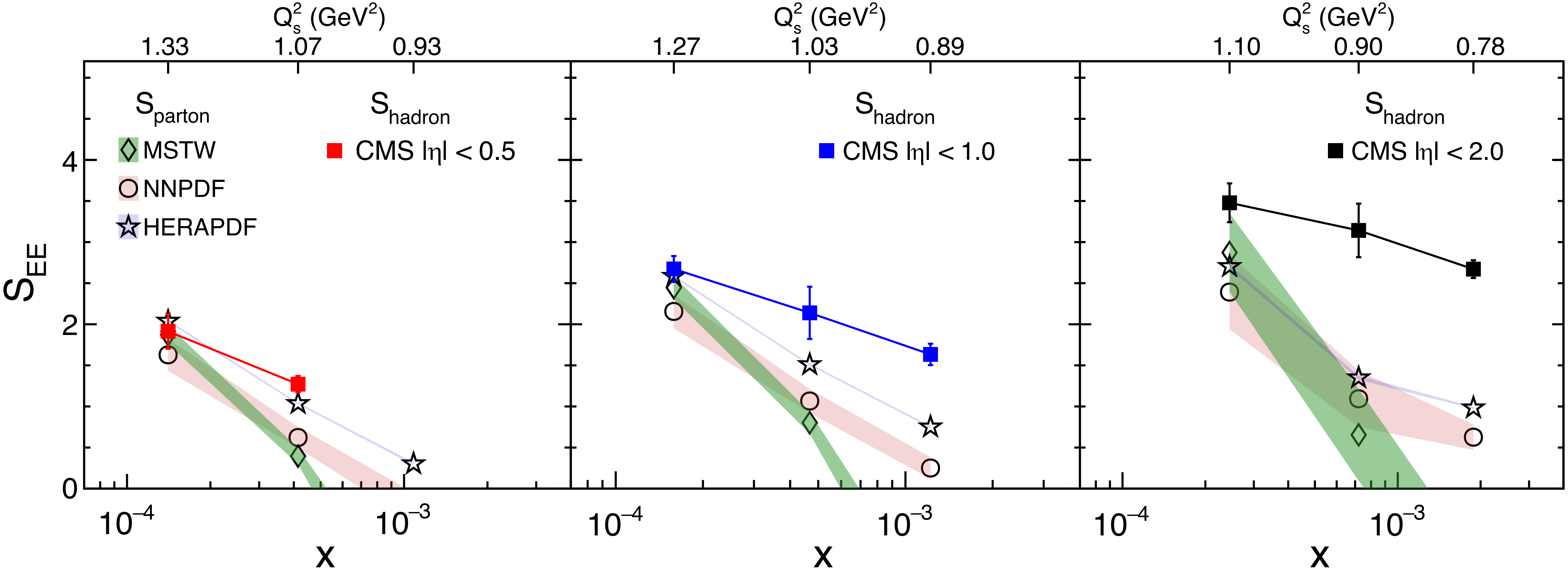
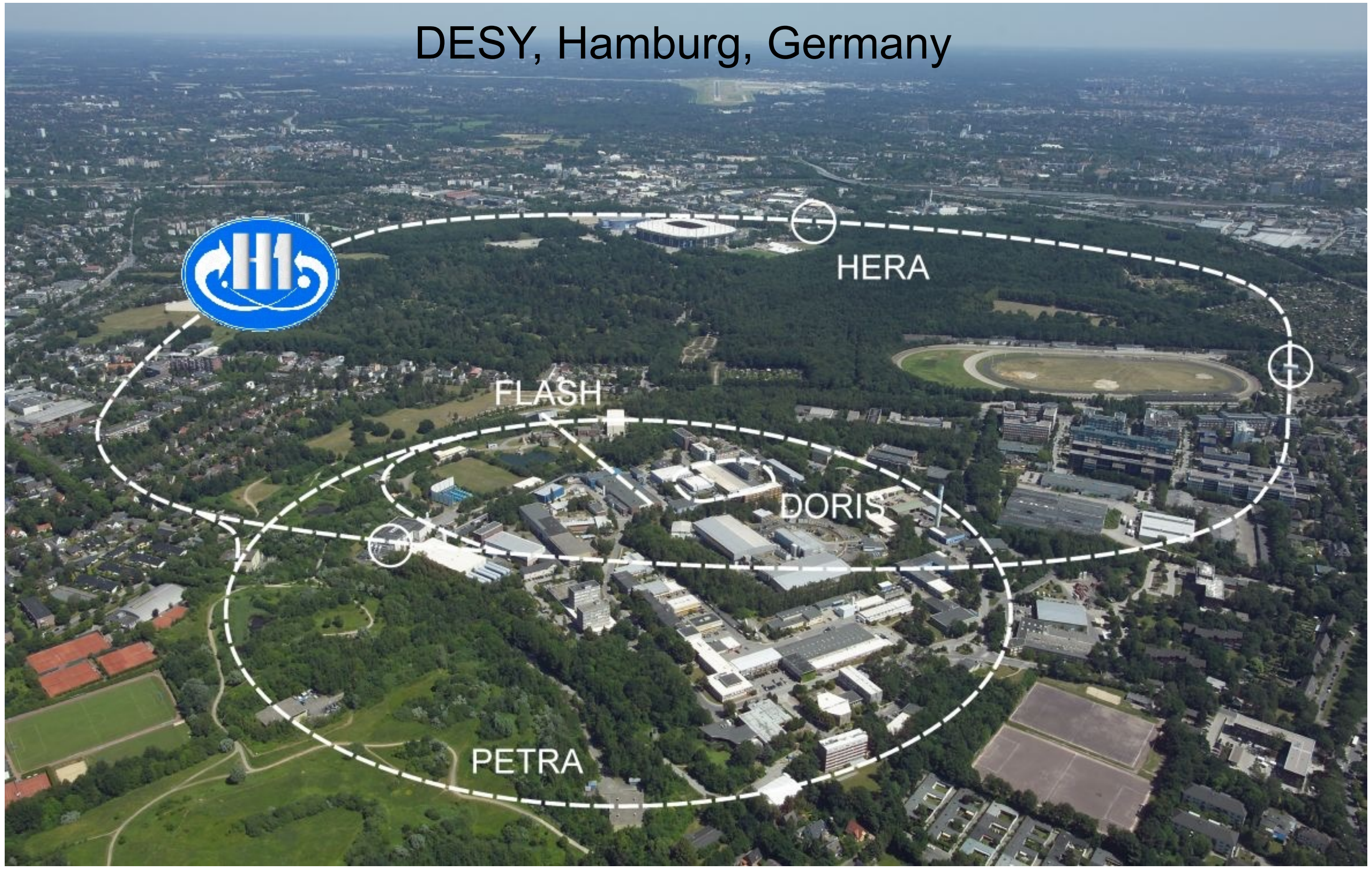


Entanglement hints at pp collisions – agreement towards low x

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

Measurement - DIS data

H1 experiment in Museum

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

2018

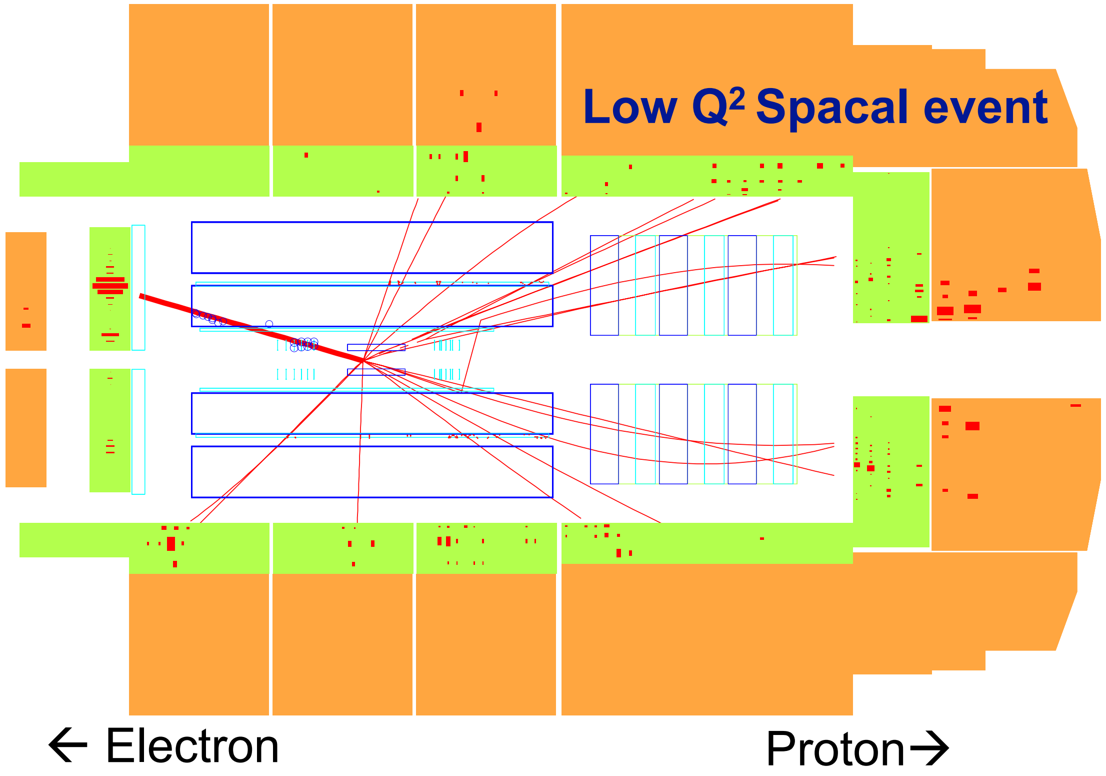
- I proposed to H1 Collaboration to measure EE
- Reanalyzed the HERA top energy e+p data
- Published in EPJC

2021

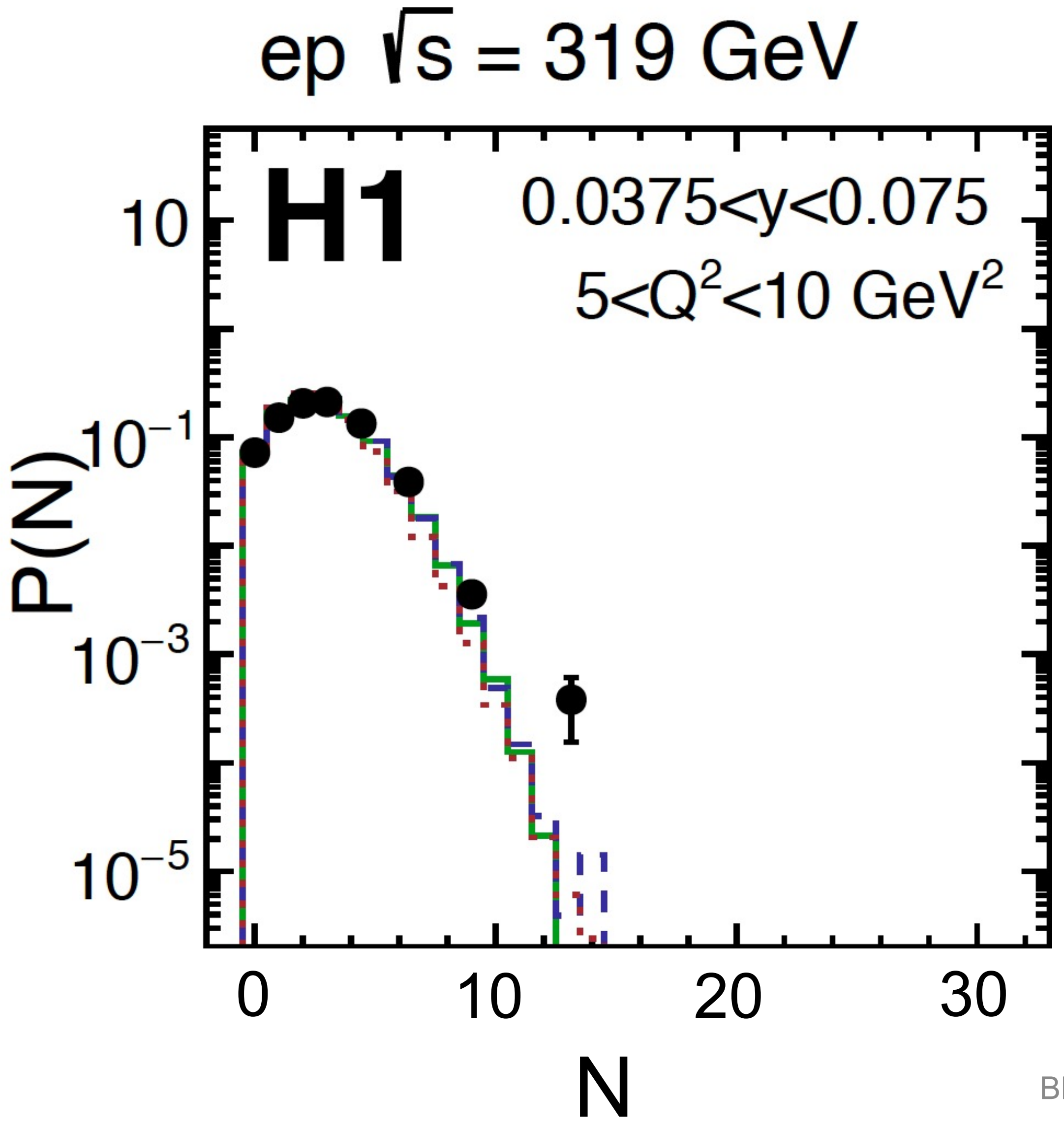
(biking in the tunnel of HERA)

H1 data

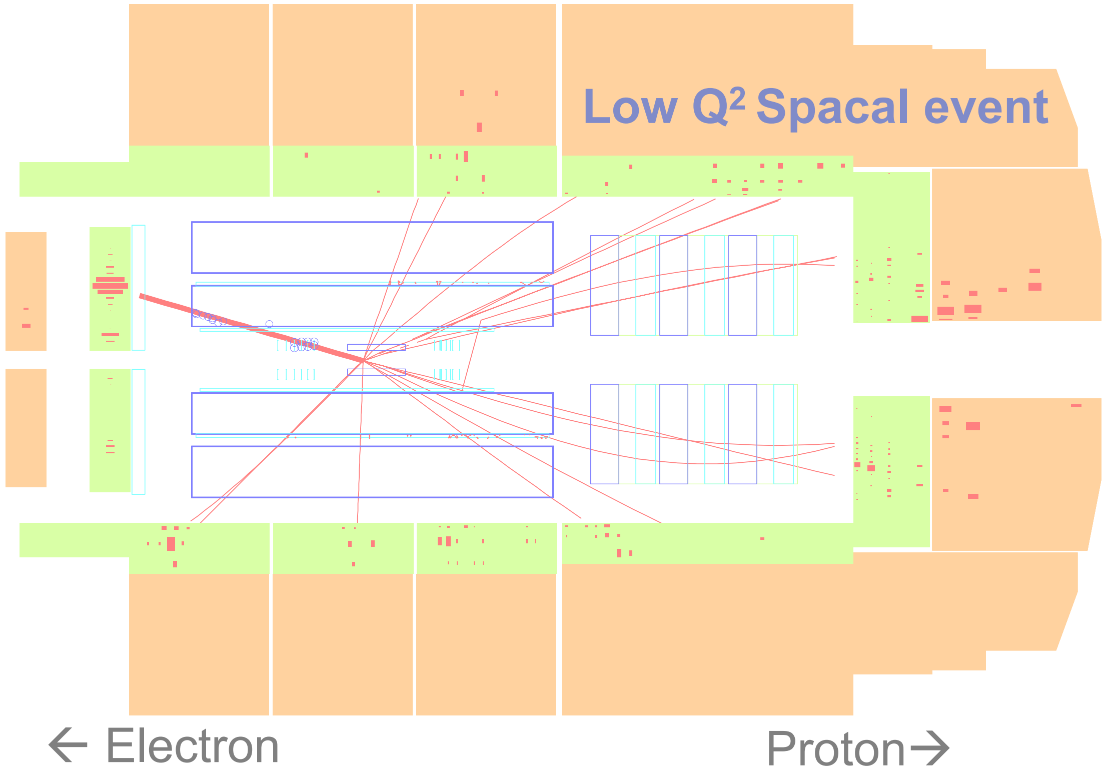
Event display



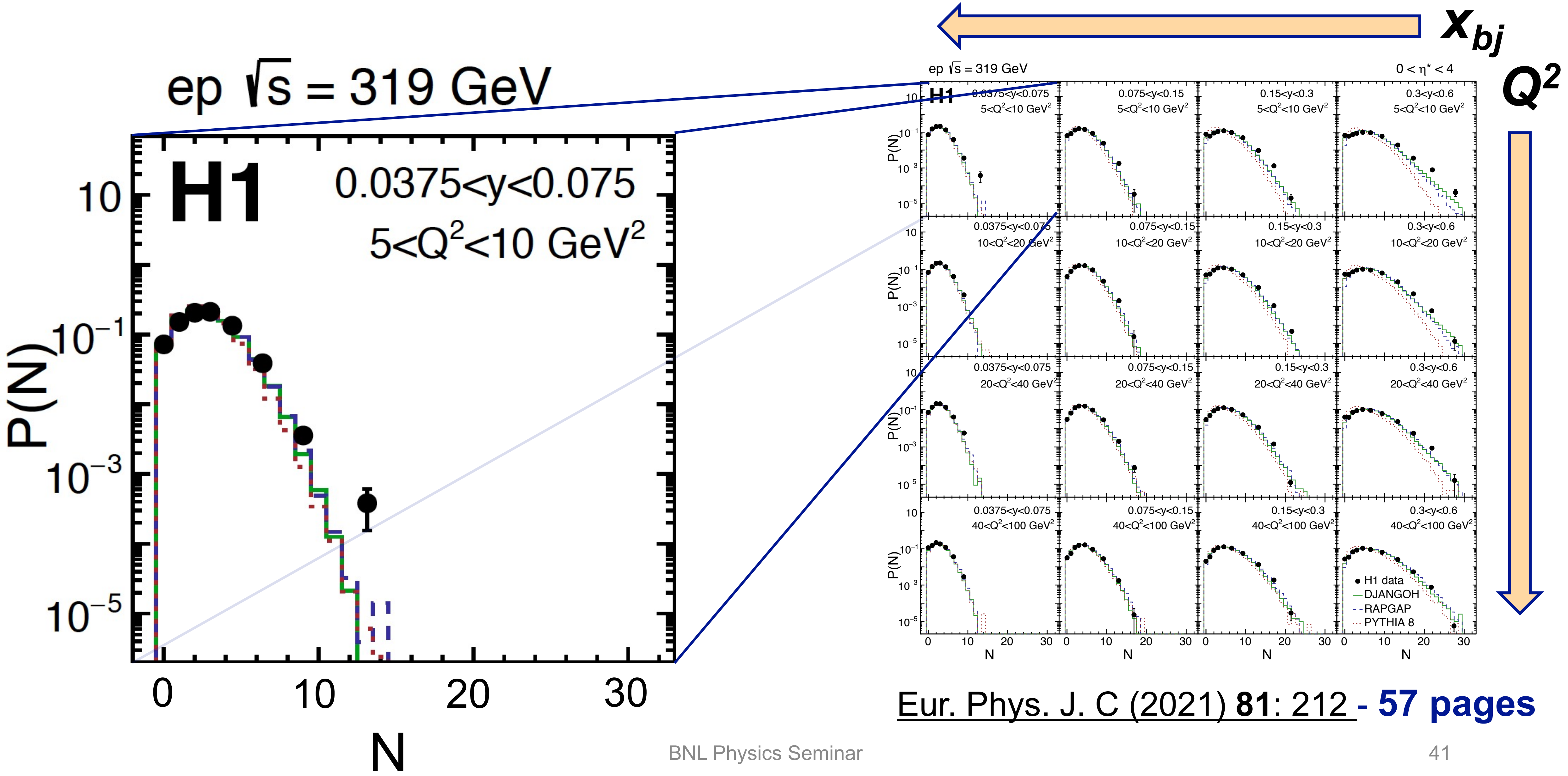
H1 data



Event display

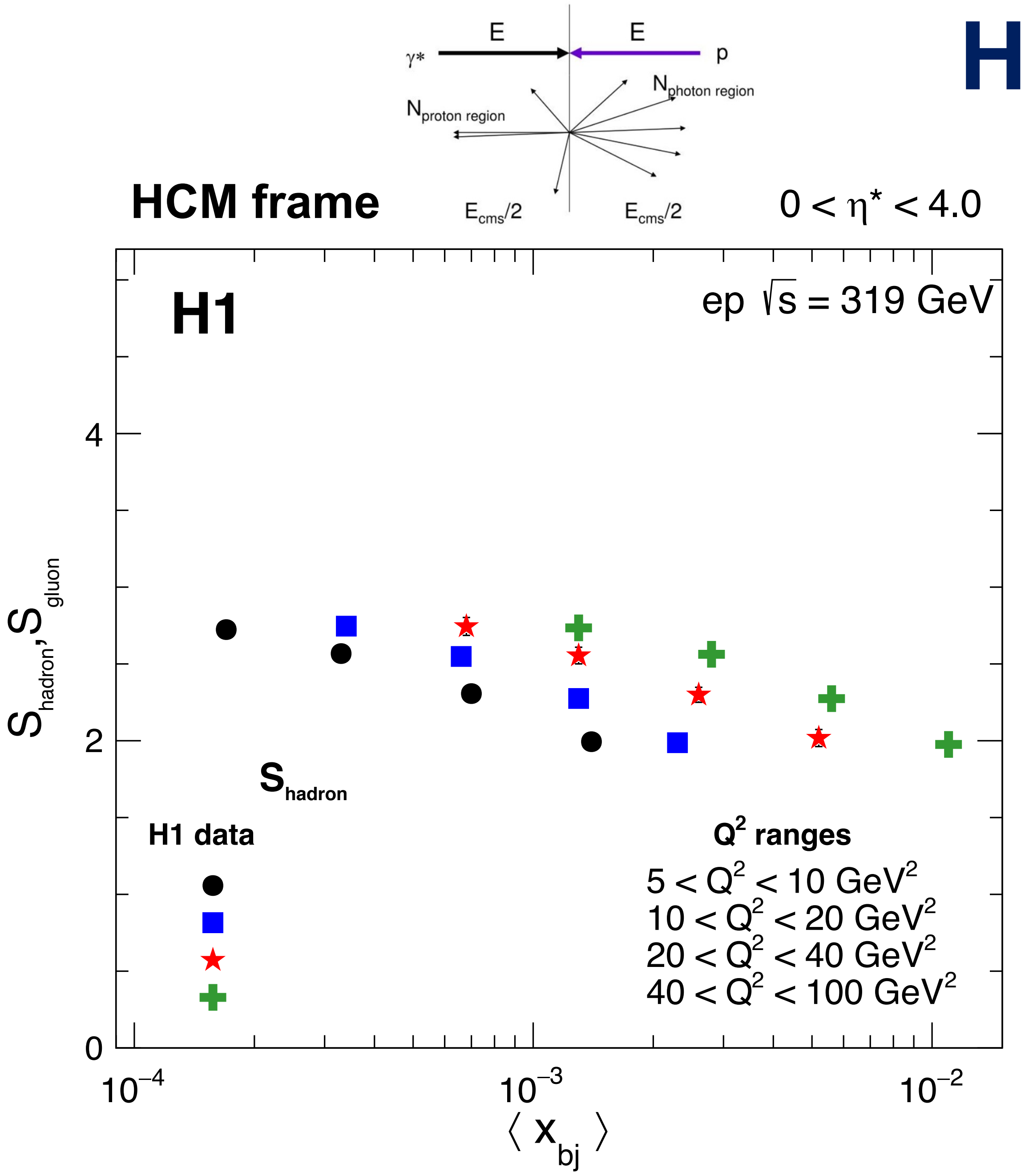


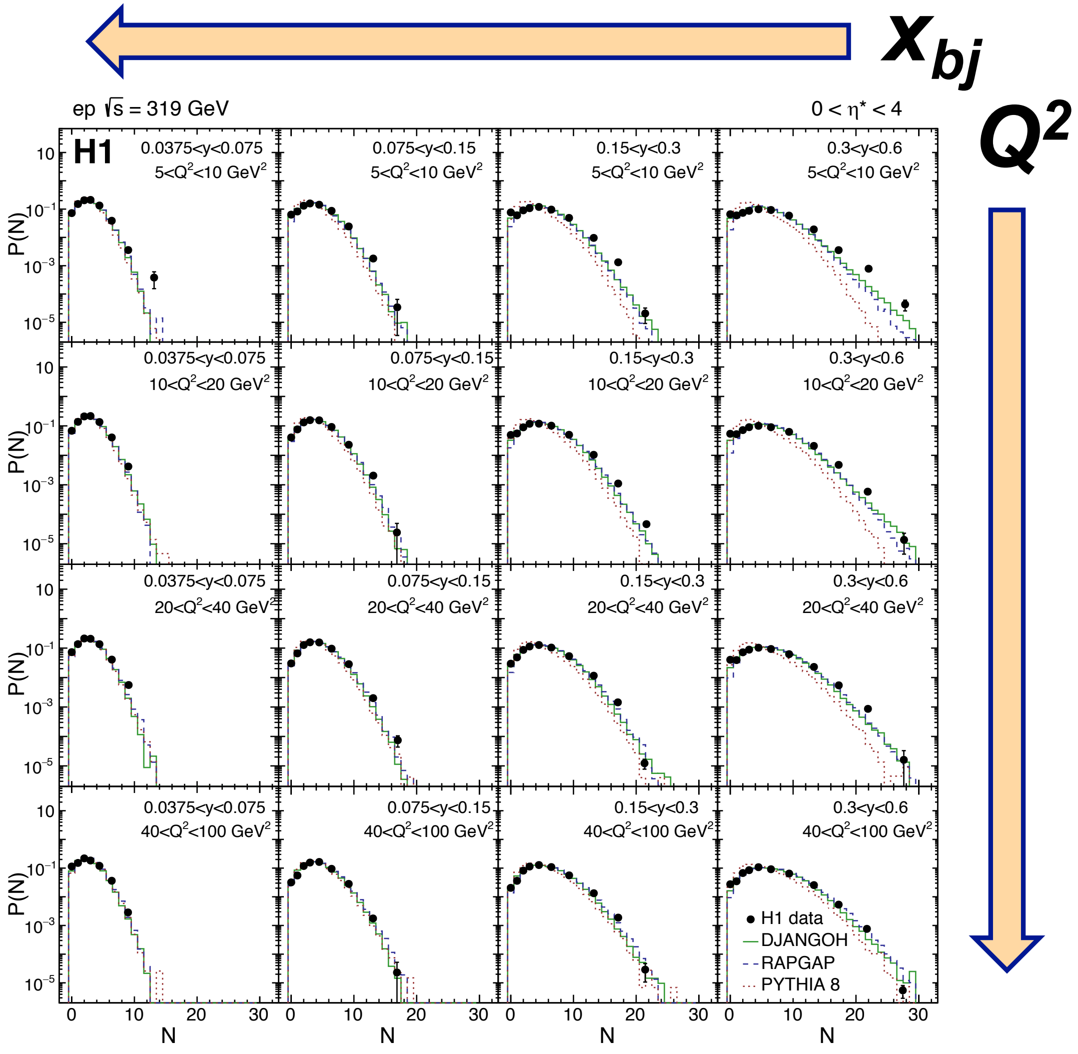
H1 data



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

H1 data





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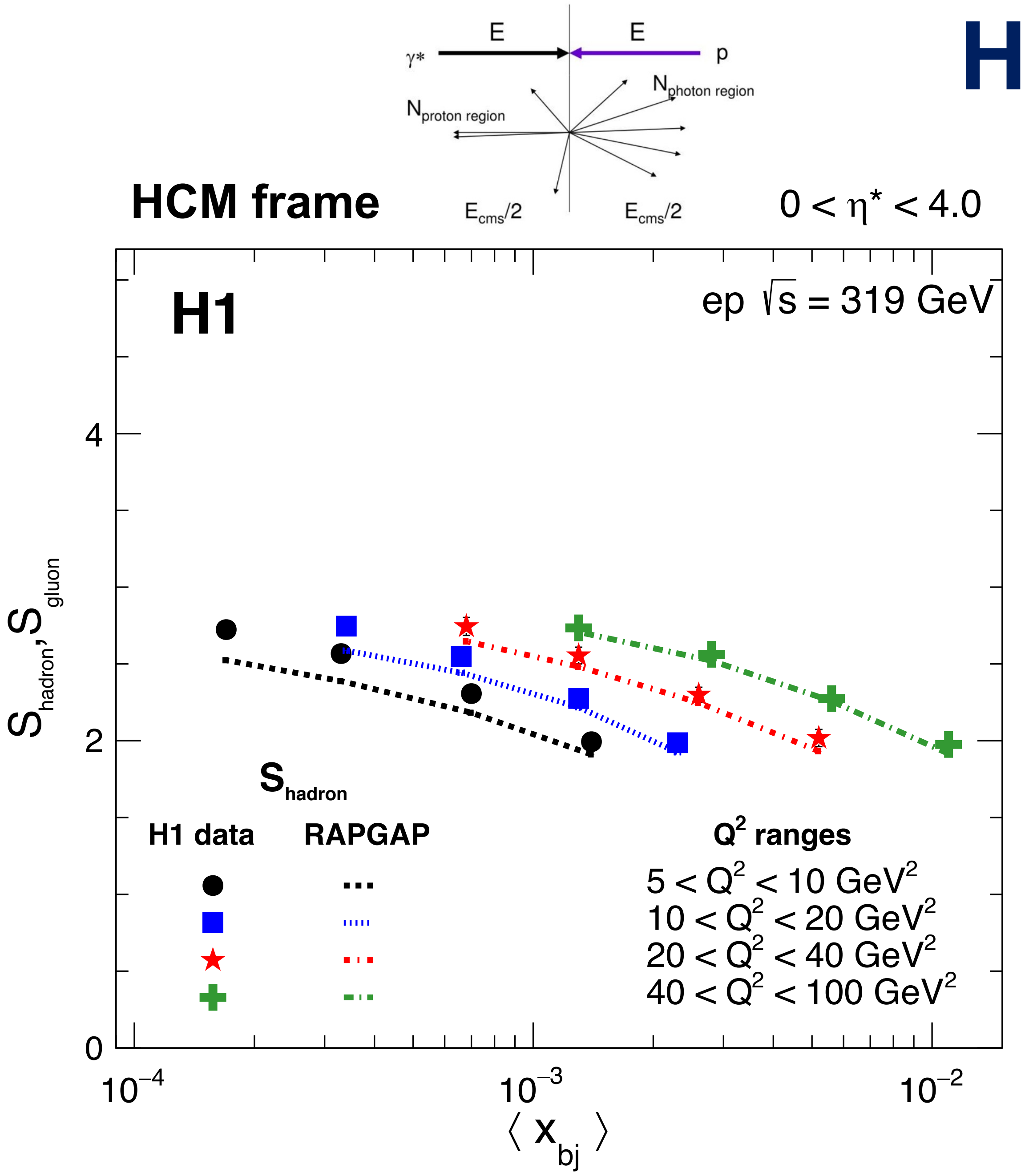

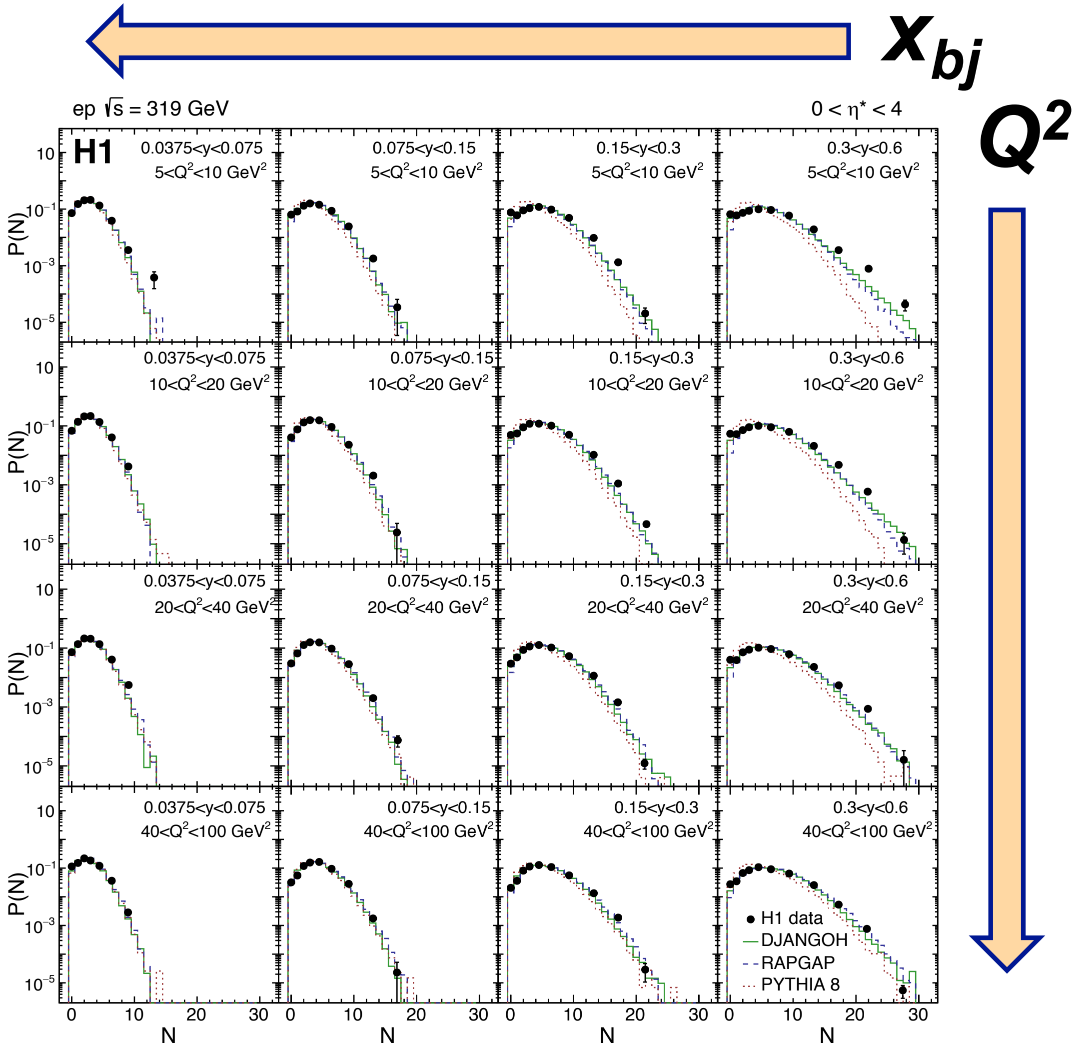

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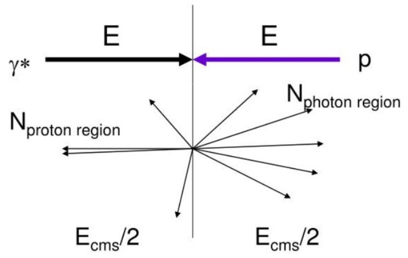
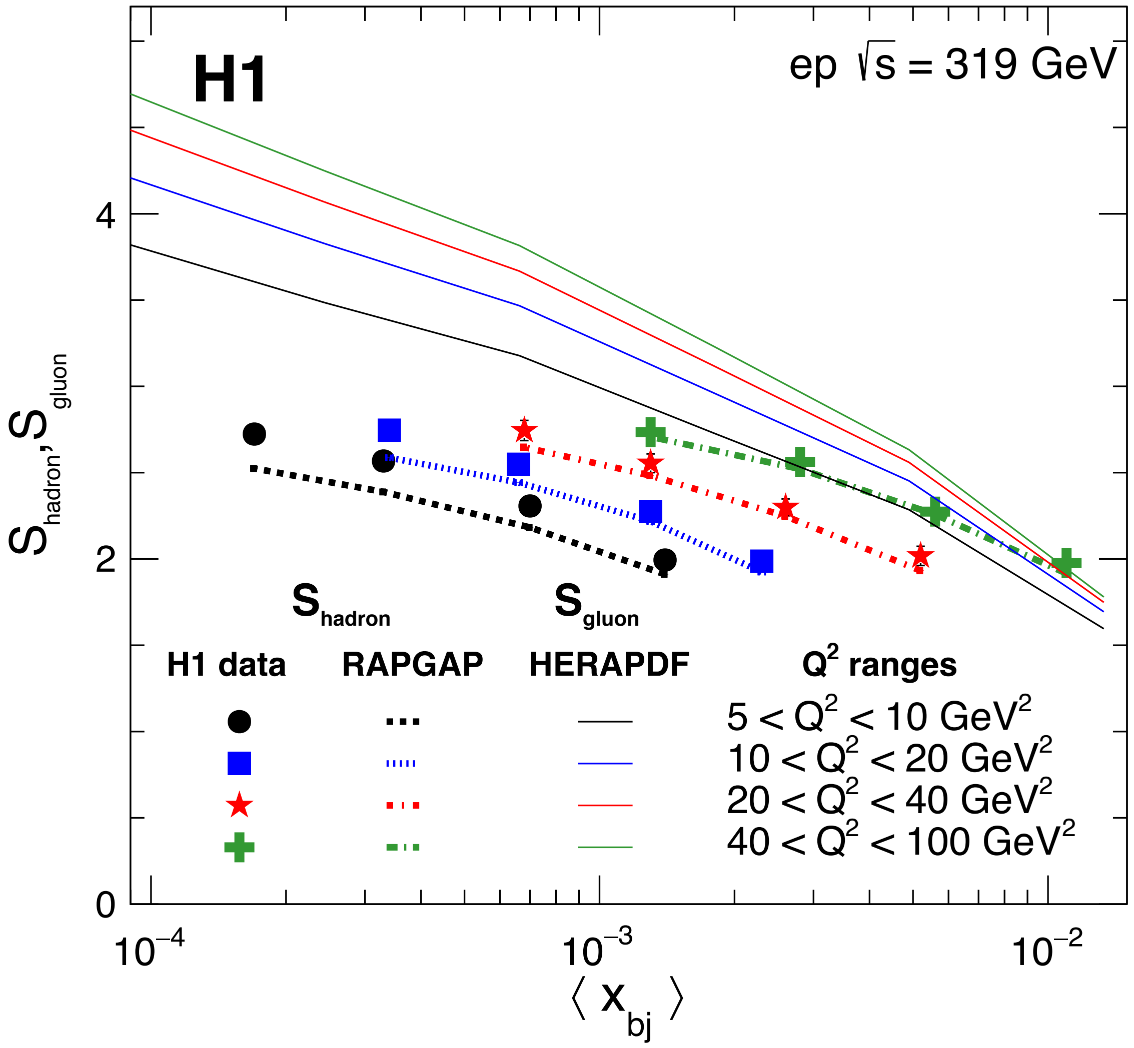
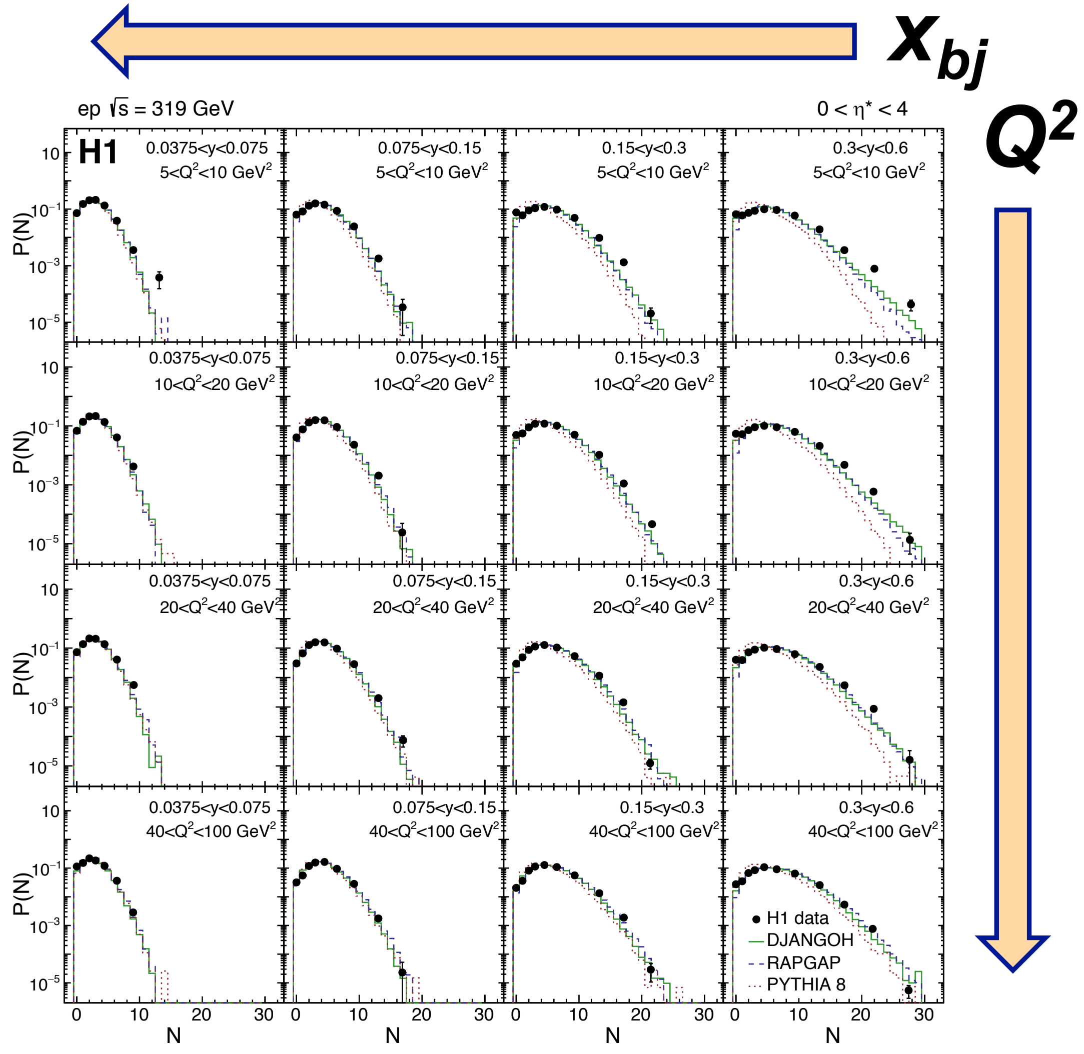


HCM frame

$0 < \eta^* < 4.0$





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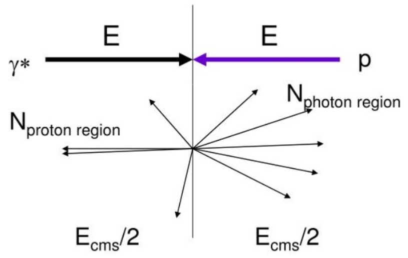

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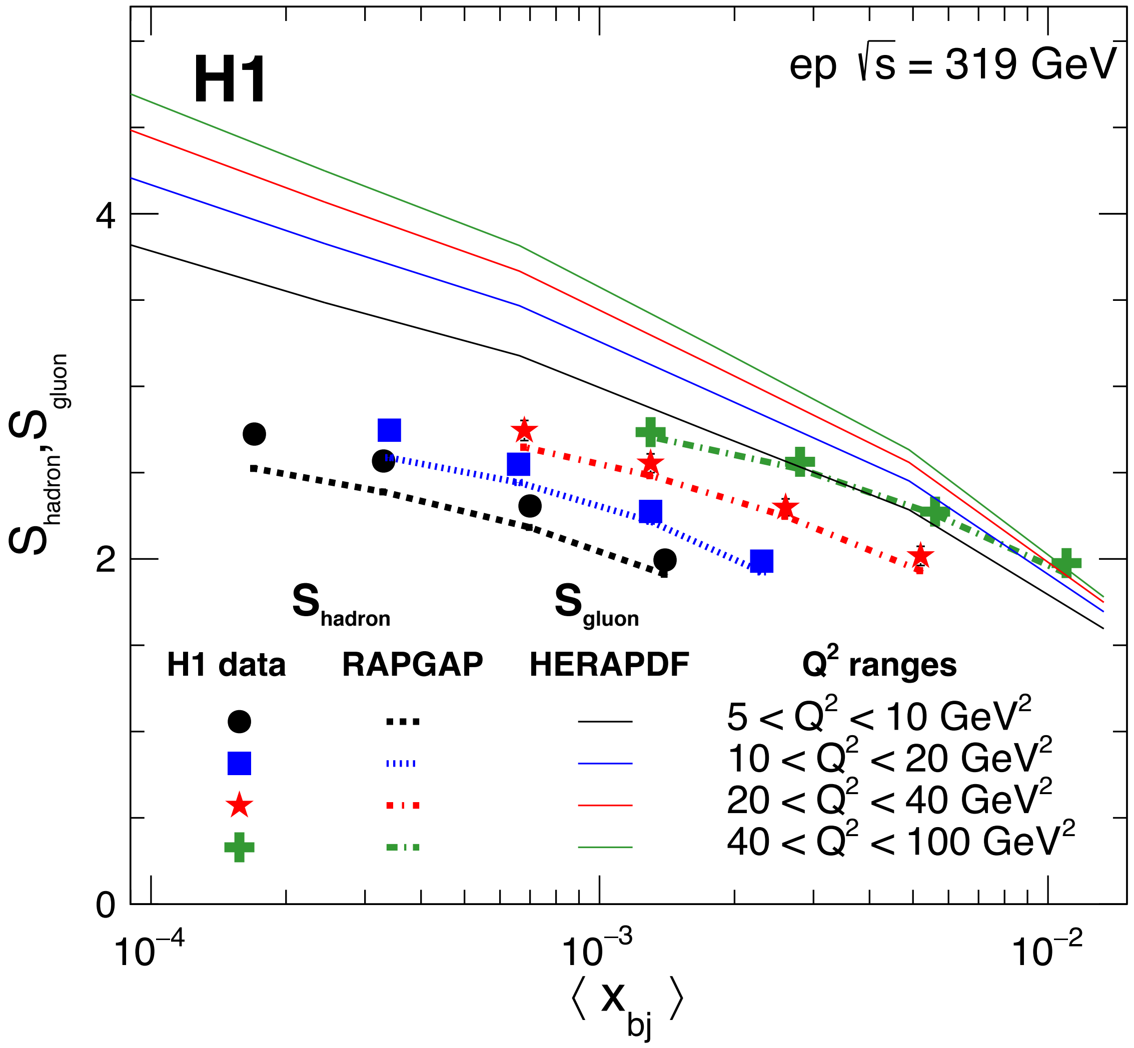
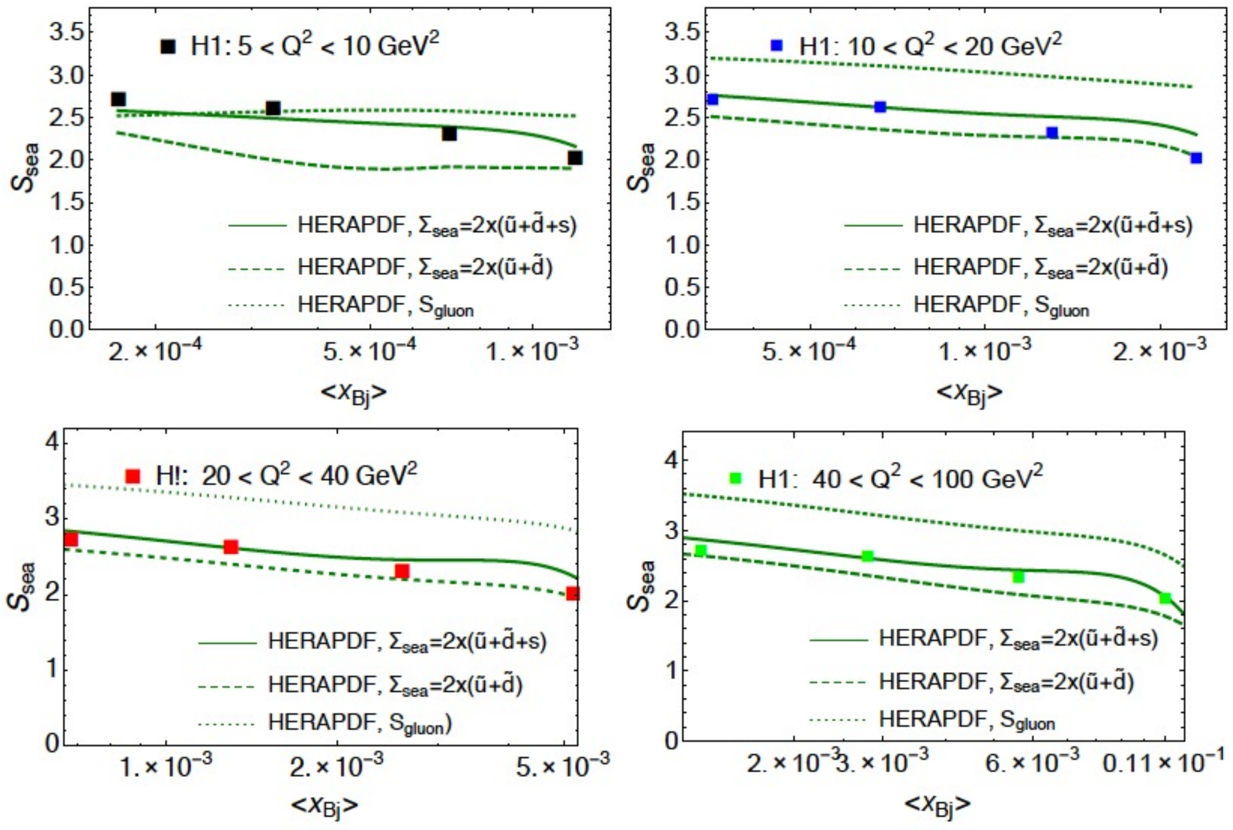


New results from sea quarks



arXiv:2102.09773

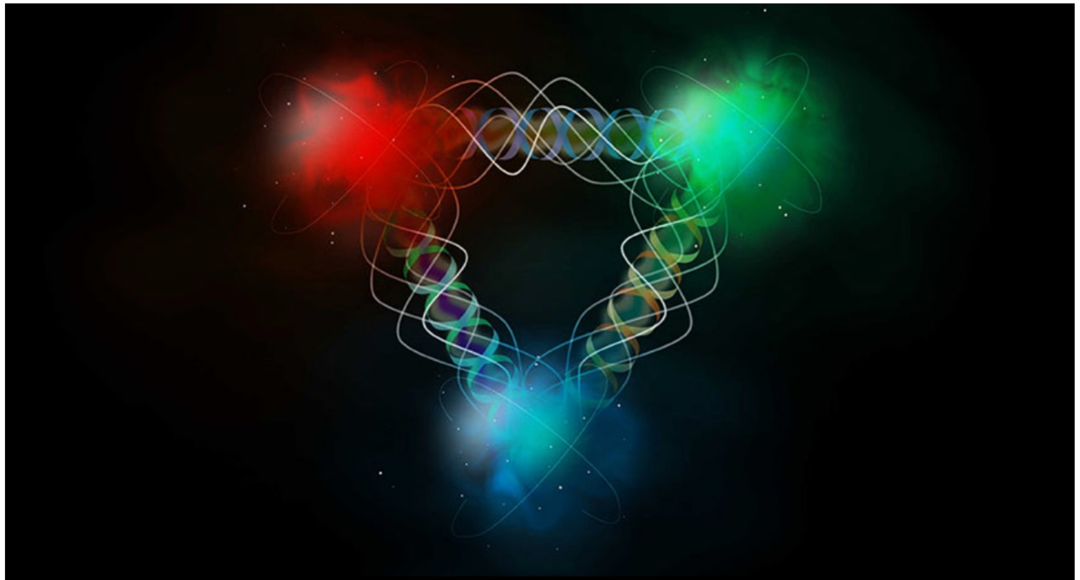
Current status

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)

Current status

EE timeline

(Kharzeev & Levin 2017)

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

gluon entropy for low-x in pp

(Kharzeev & Levin 2021)

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

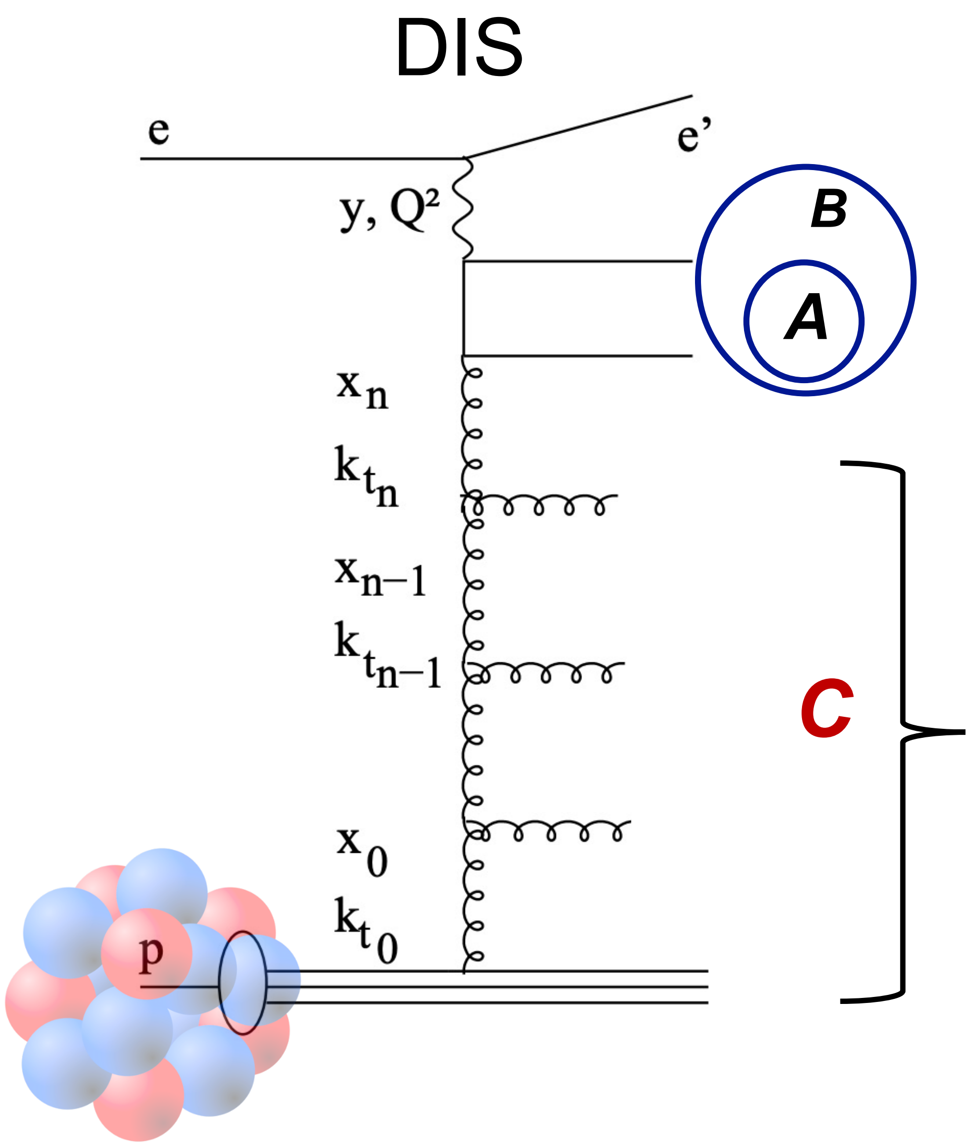
quark entropy for low-x in DIS

...

- 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?



- 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?

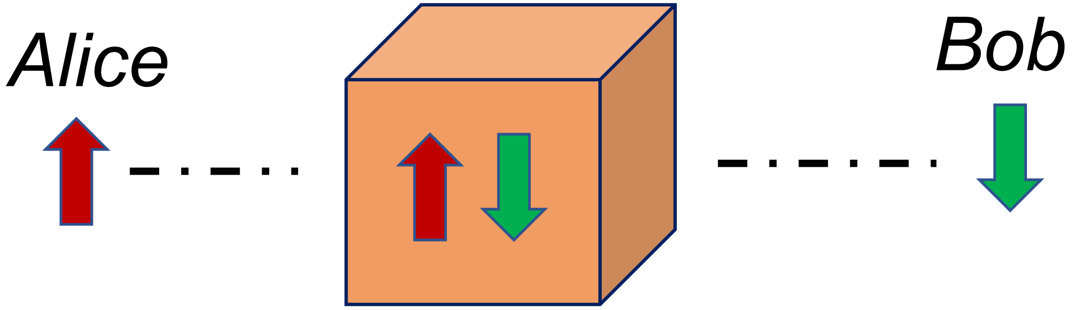
(A dedicated prediction is on the way)

SULI Summer Intern 2021 - Calla Hinderks

Stay tuned!

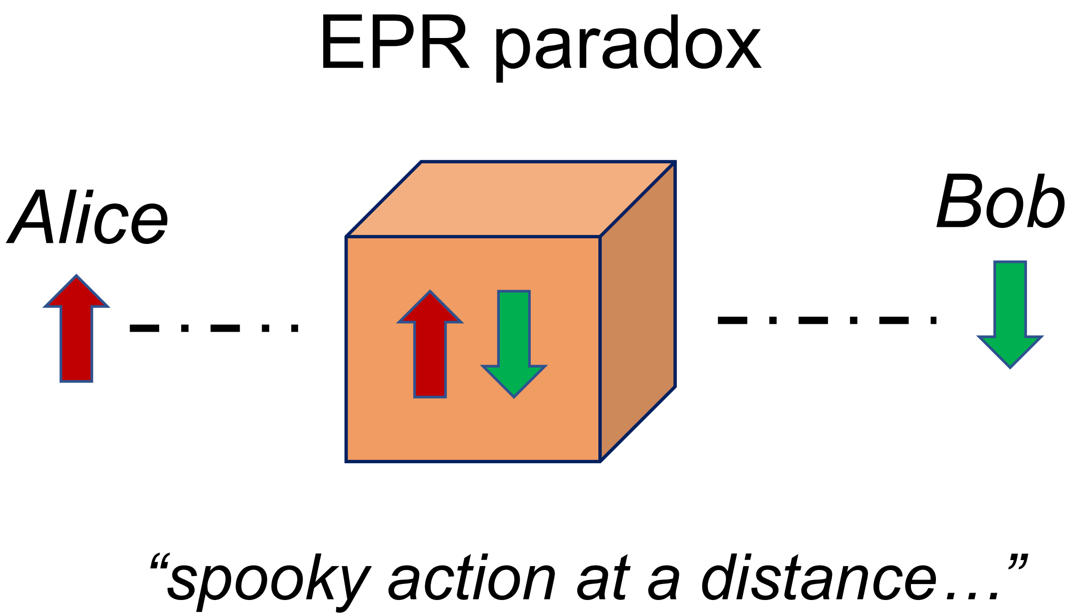
Near future – spin entanglement

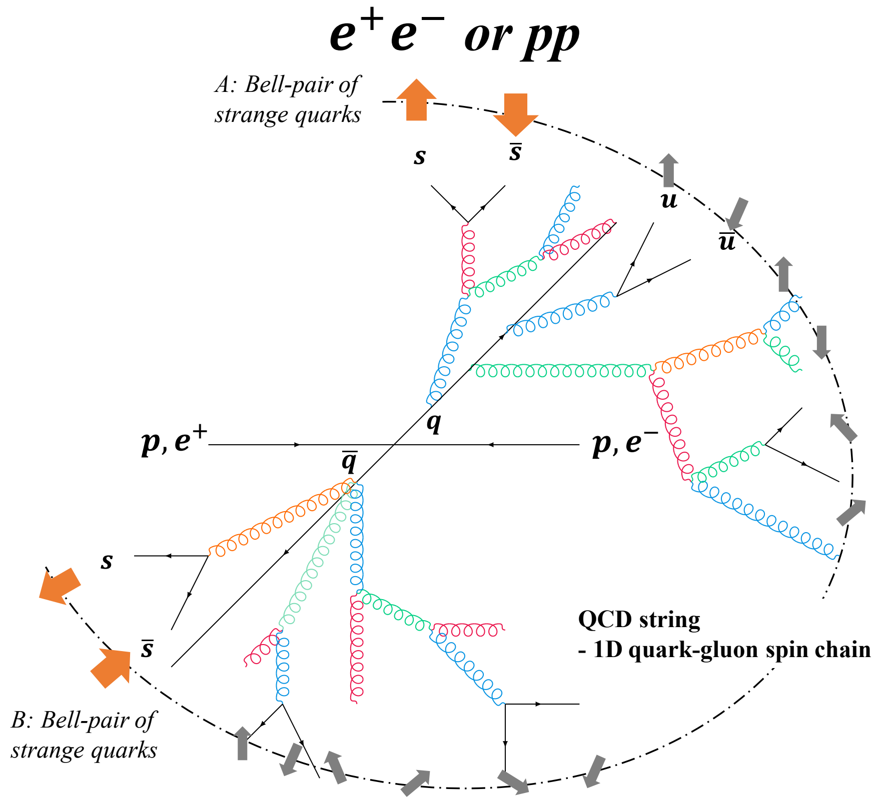
EPR paradox



“spooky action at a distance…”

Near future – spin entanglement





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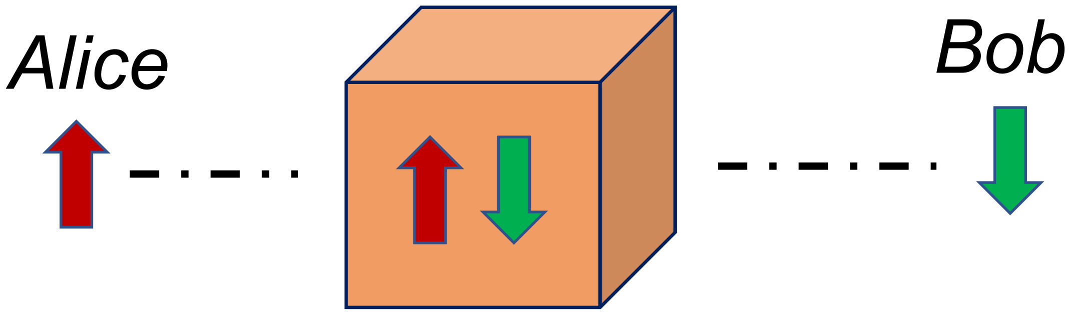
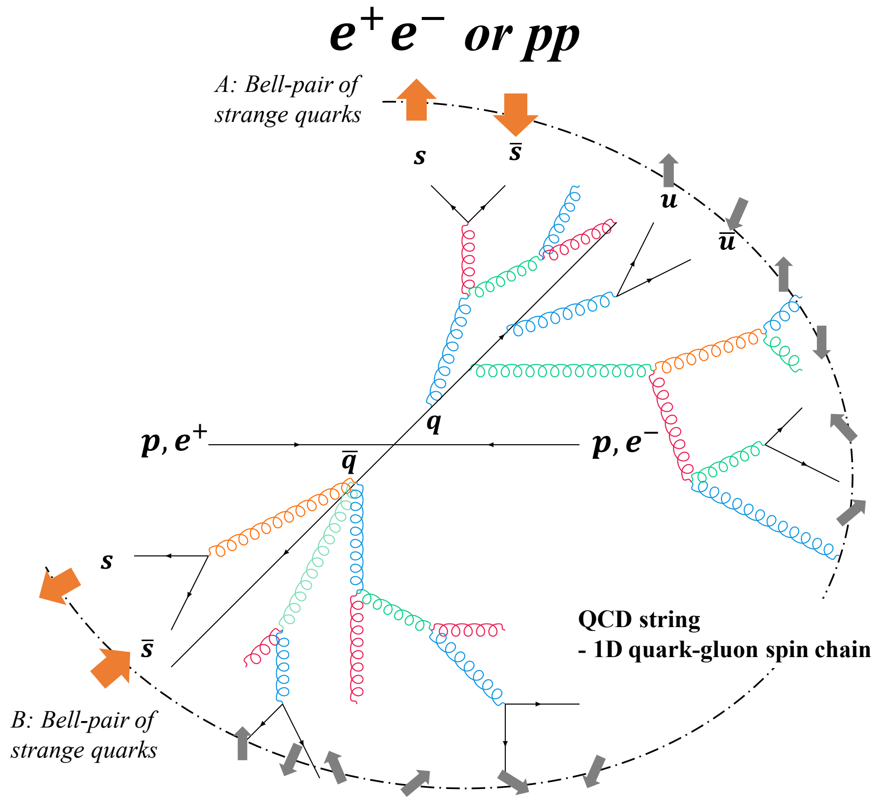


"spooky action at a distance…"

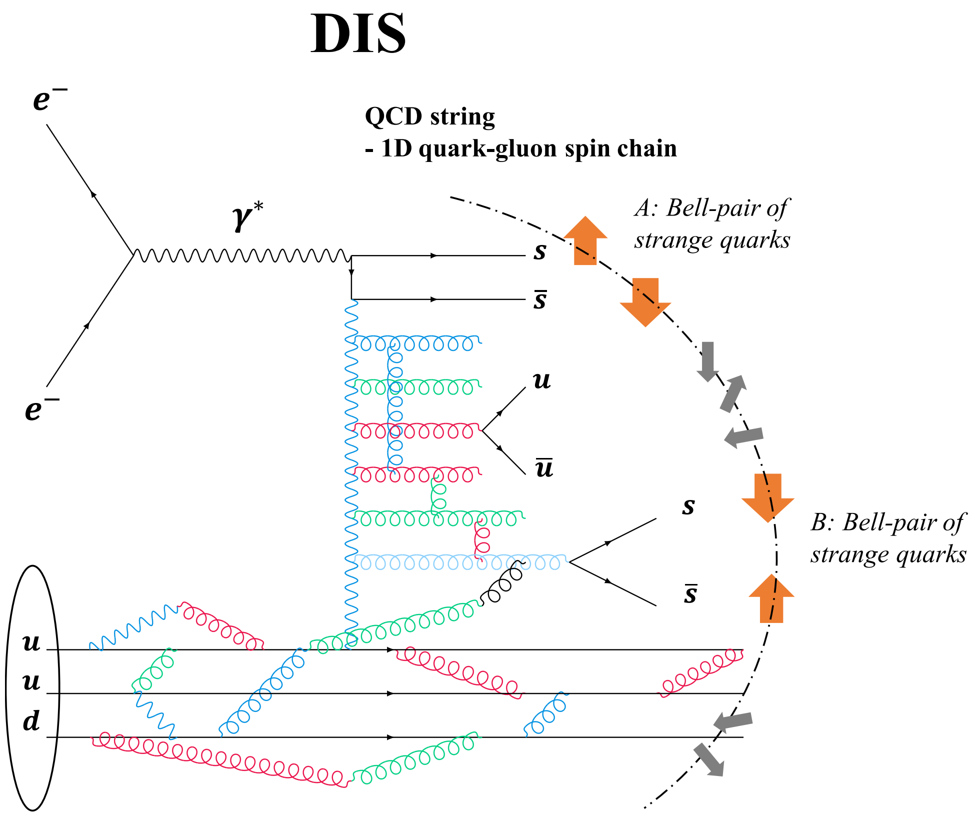


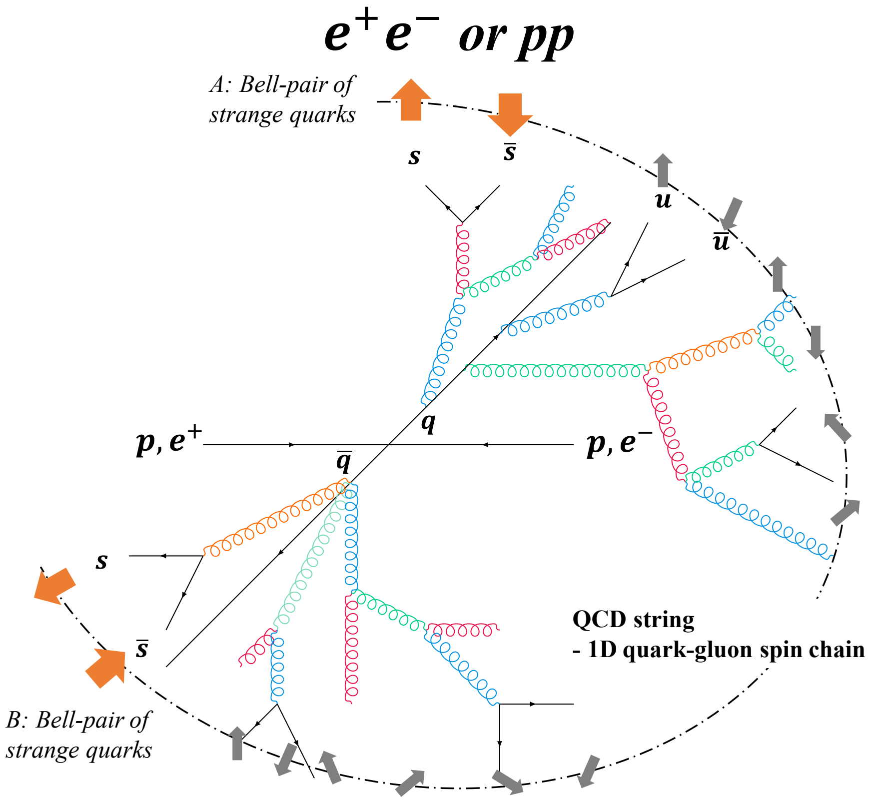
How to know correlations are nonlocal or quantum mechanical?

CHSH inequality test:

$$S = E(A,B) - E(A,b) + E(a,B) + E(a,b)$$

Near future – spin entanglement





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CHSH inequality test:

$$S = E(A,B) - E(A,b) + E(a,B) + E(a,b)$$

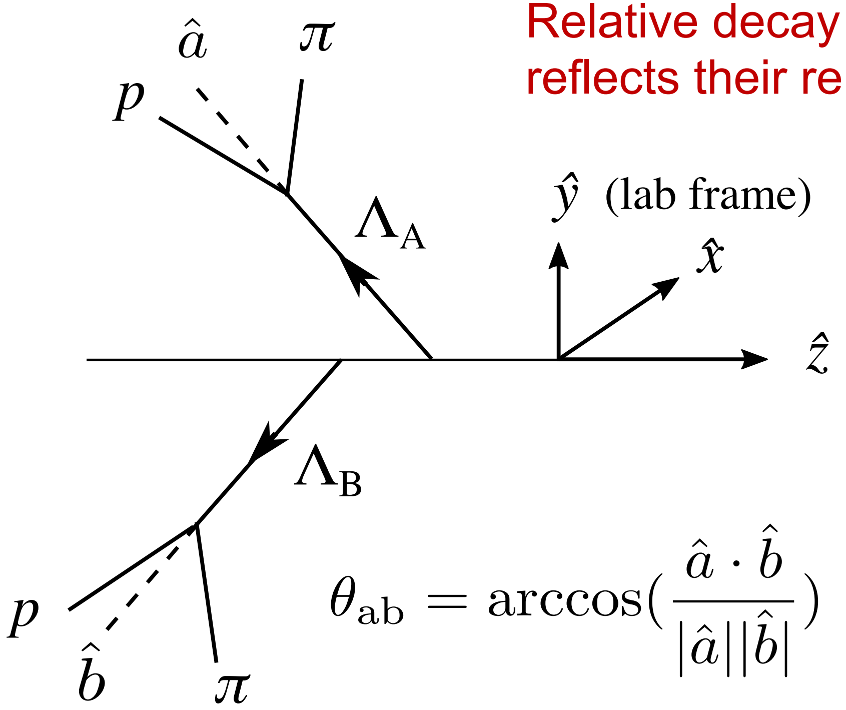
1. $\Lambda\bar{\Lambda}$, $\Lambda\Lambda$ polarizations

Theory development:
W. Gong*, G. Parida, **ZT**, R. Venugopalan
(Manuscript coming soon!)

* Barry M. Goldwater scholarship and featured on BNL Cover:
https://www.bnl.gov/newsroom/news.php?a=218869

ep or *pp* collisions

Relative decay angle reflects their relative spin



$$\theta_{ab} = \arccos\left(\frac{\hat{a}\cdot\hat{b}}{|\hat{a}||\hat{b}|}\right)$$

Λ polarization w.r.t each other in their respective frames

1. $\Lambda\bar{\Lambda}$, $\Lambda\Lambda$ polarizations

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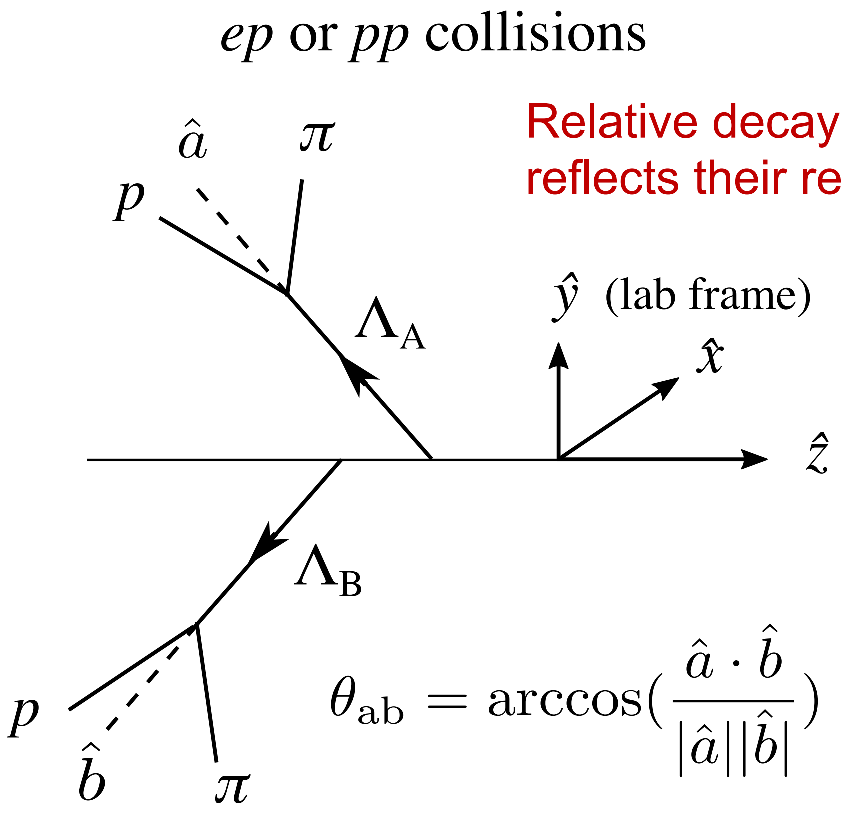
https://www.bnl.gov/newsroom/news.php?a=218869

Experimental Search at RHIC:
Double Λ polarization in pp collisions.
(Approved LDRD project 22-027 - FY22-23)

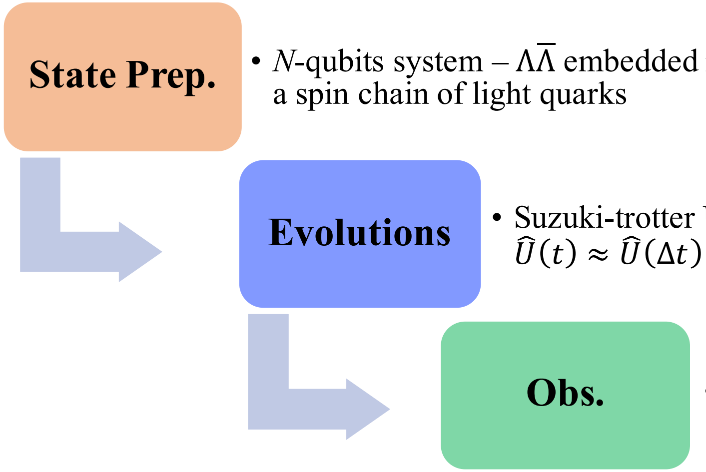


Relative decay angle reflects their relative spin

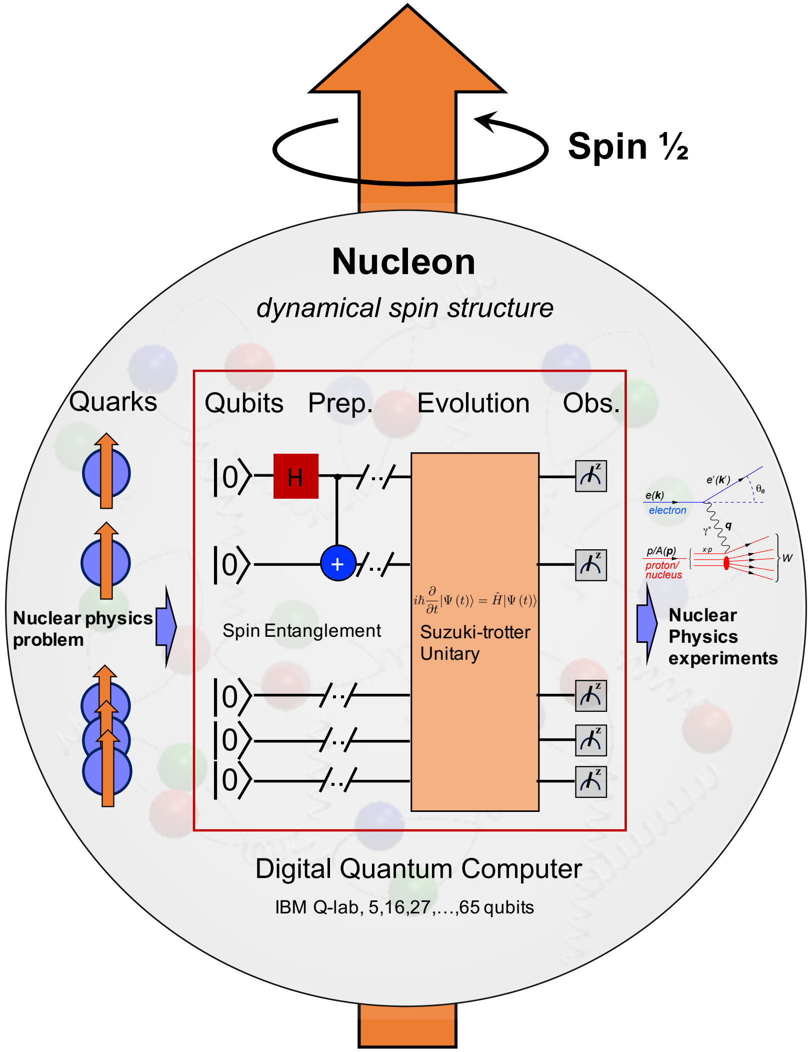
Λ polarization w.r.t each other in their respective frames

2. Quantum simulations

- 1D quark-gluon spin chain with strange quarks with real-time unitary evolution.
- Simulations on a digital quantum computer, where every parton is mapped to a qubit.



- N-qubits system – $\Lambda\bar{\Lambda}$ embedded in a spin chain of light quarks
- Suzuki-trotter Unitary $\hat{U}(t) \approx \hat{U}(\Delta t) \ldots \hat{U}(\Delta t)$
- Measurements, e.g., CHSH inequalities



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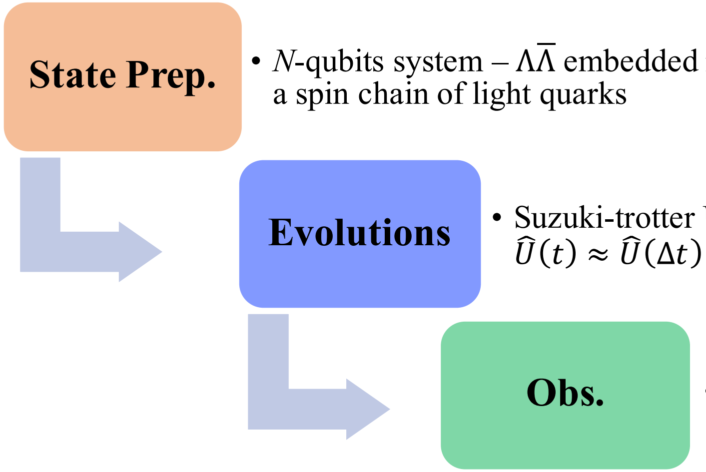

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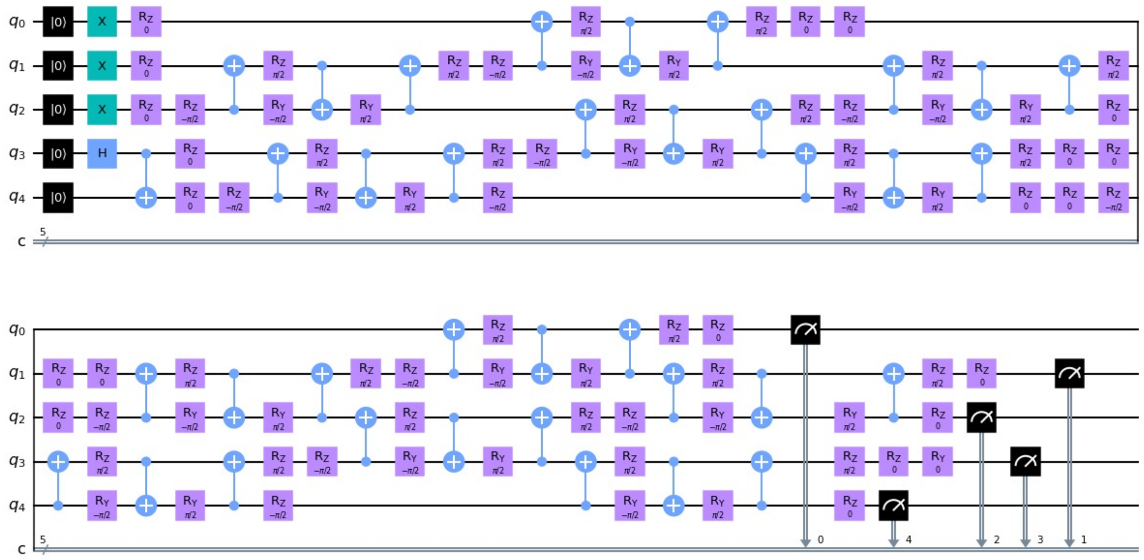
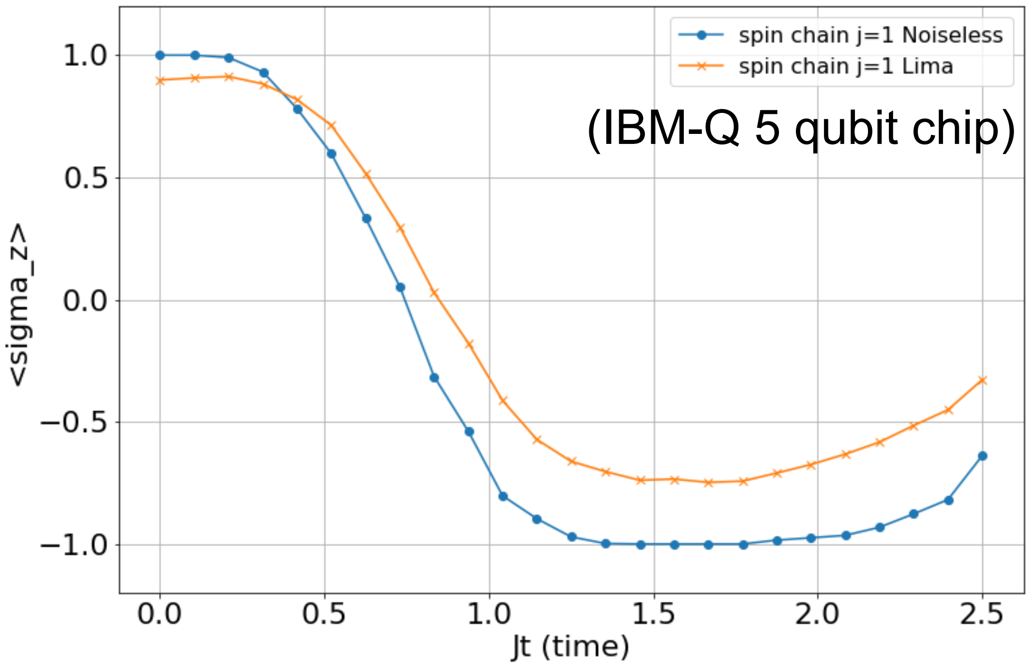
- Measurements, e.g., CHSH inequalities

Initial 5-qubit circuit setup for a Heisenberg spin chain model with 1 Bell-pairs

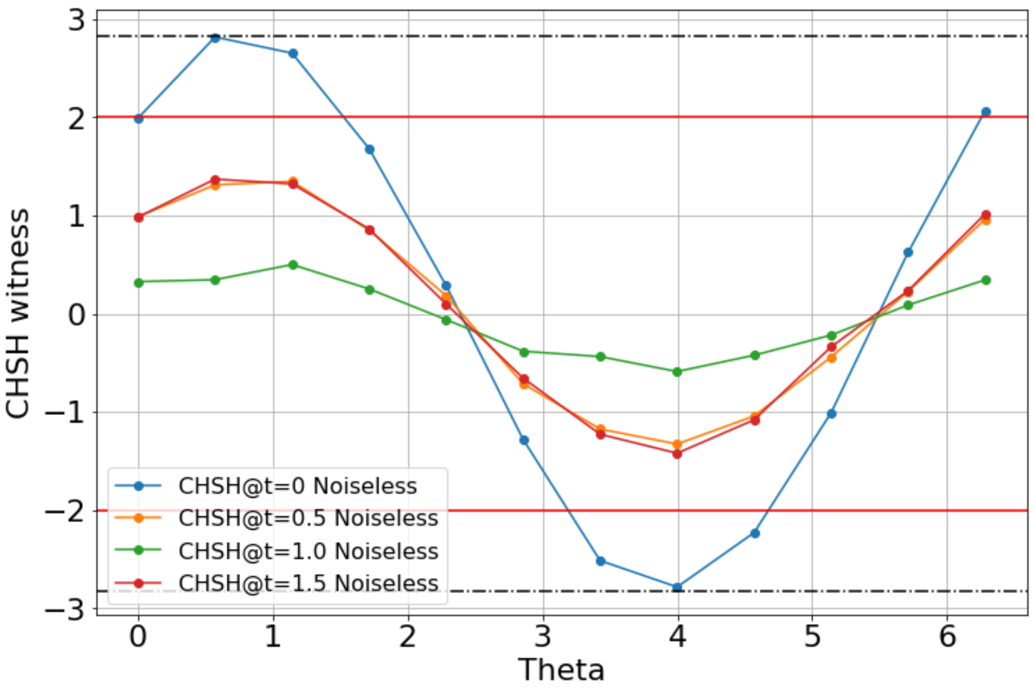


2. Quantum simulations

Proof-of-principle on a real quantum computer – trotterized unitary evolution.



Proof-of-principle on CHSH inequalities



Next step - submit a “large-scale” circuit to the IBM-Q with 27 or 50 qubit chip

(W. Li, **ZT**, R. Venugopalan)

Summary

- Quantum features of QCD strings are essential to our understanding of the fundamental structure, e.g., *confinement*.
- Entanglement Entropy measured in pp and ep DIS – a promising future direction at the Electron-Ion Collider.
- Spin entanglement – a truly interdisciplinary example between the QIS and NP.

(May 2015 *Scientific American*)


PARTICLE PHYSICS

the glue that binds us

Physicists have known for decades that particles called gluons keep protons and neutrons intact—and thereby hold the universe together. Yet the details of how gluons function remain surprisingly mysterious

By Rolf Ent, Thomas Ullrich and Raju Venugopalan

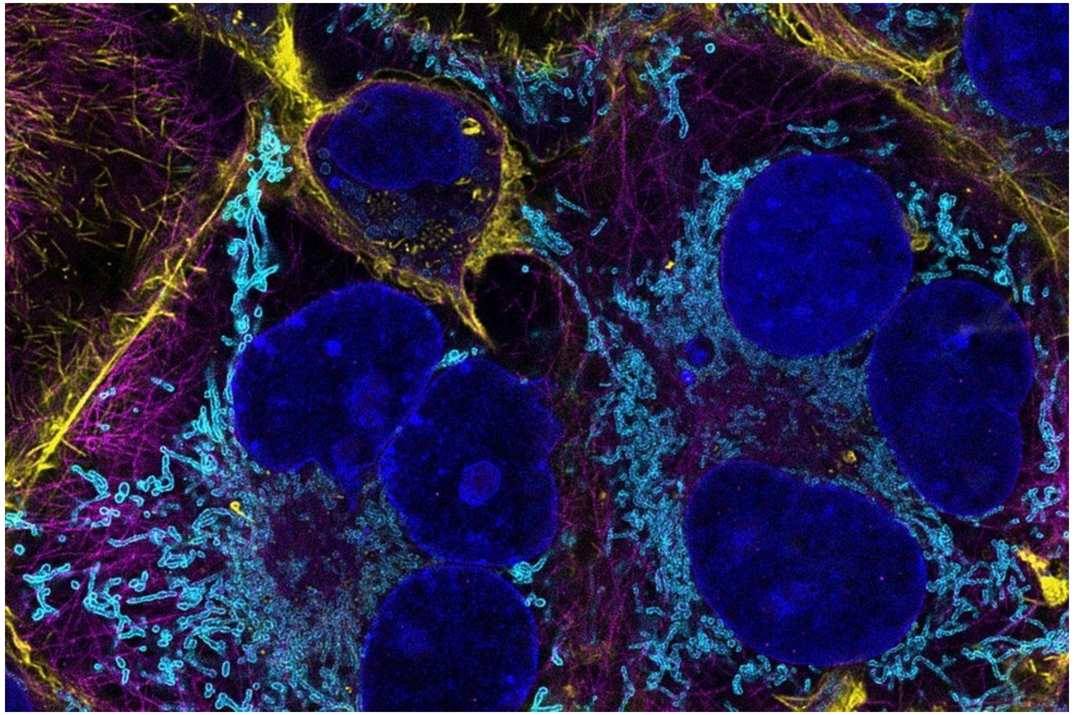
42 Scientific American, May 2015

Illustration by Maria Corte

Backup

Most powerful microscope in the world

Electron Microscope

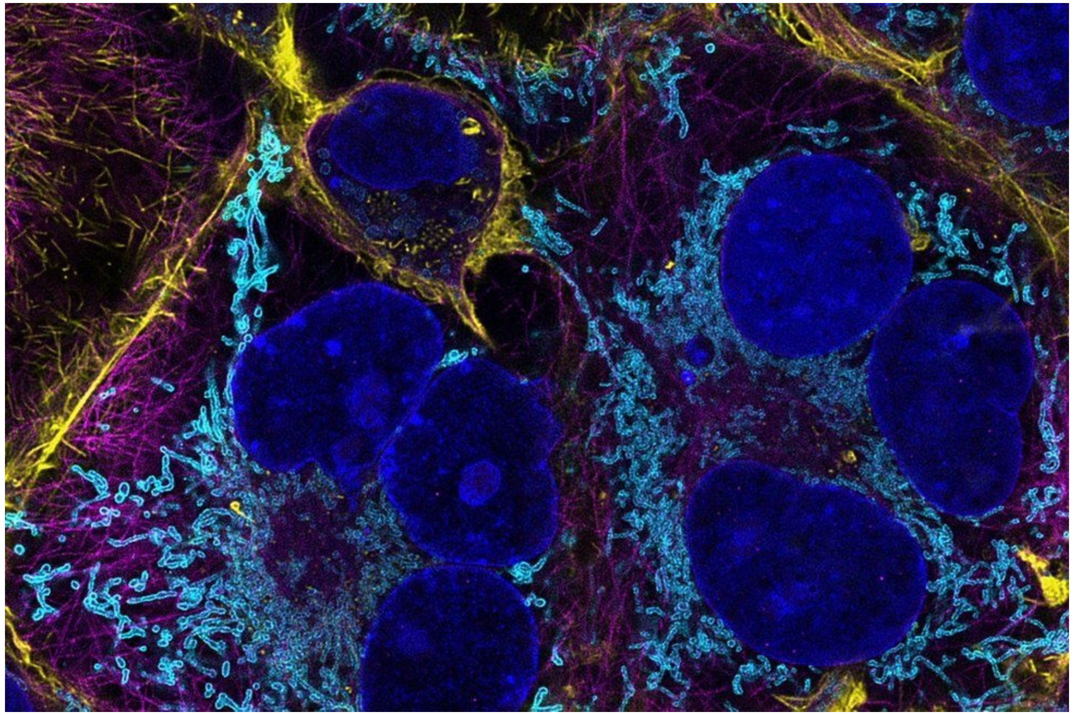


3D images of myelin
- the insulation coating our nerve fibres

~ 0.1-100 nanometer (10^{-9} m)

Most powerful microscope in the world

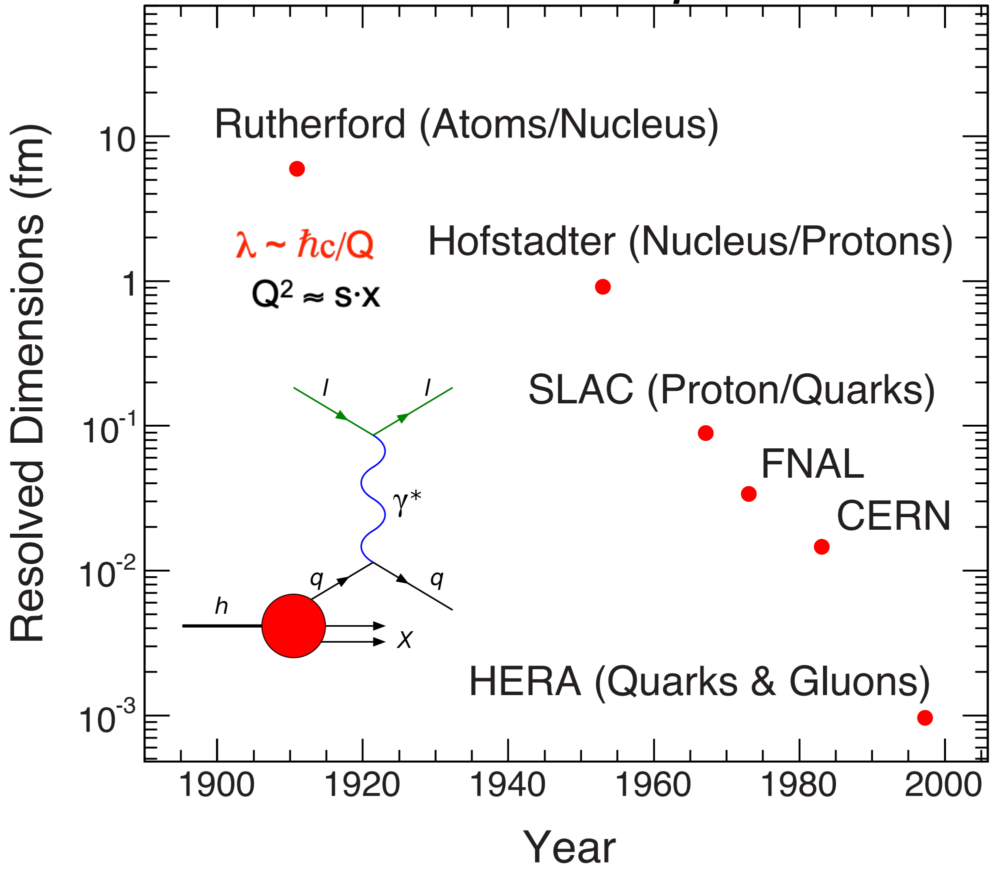
Electron Microscope



3D images of myelin
- the insulation coating our nerve fibres

~ 0.1-100 nanometer (10^{-9} m)

"Femtoscope"



~ 10^{-3} - 1 femtometer (10^{-15} m)

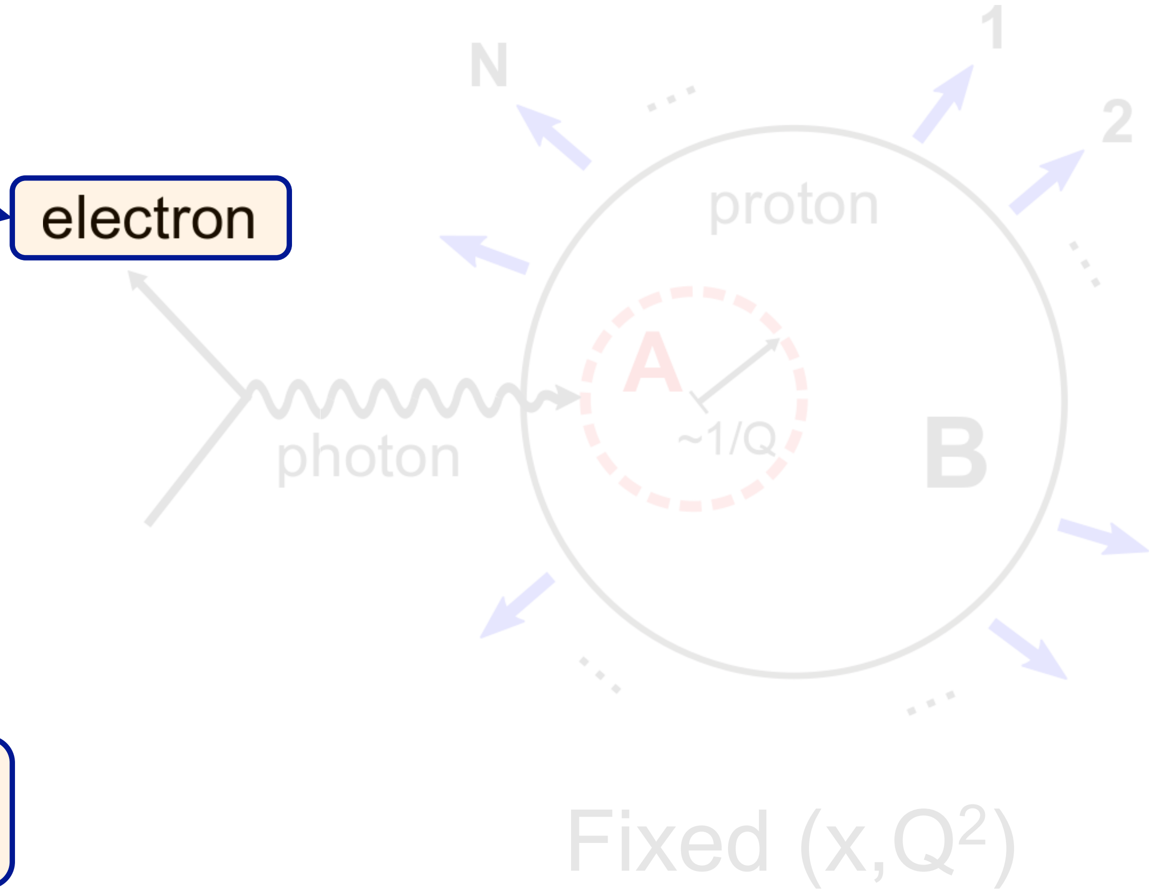
S_A in DIS

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

(Kharzeev & Levin 2017)

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

gluon entropy for low x



DIS at low x

- Exponentially large number of partons - equipartitioned states

$$xG(x,Q^2) \sim \langle \tilde{N} \rangle >> 1$$

S_A in DIS

(Kharzeev & Levin 2017)

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

gluon entropy for low x

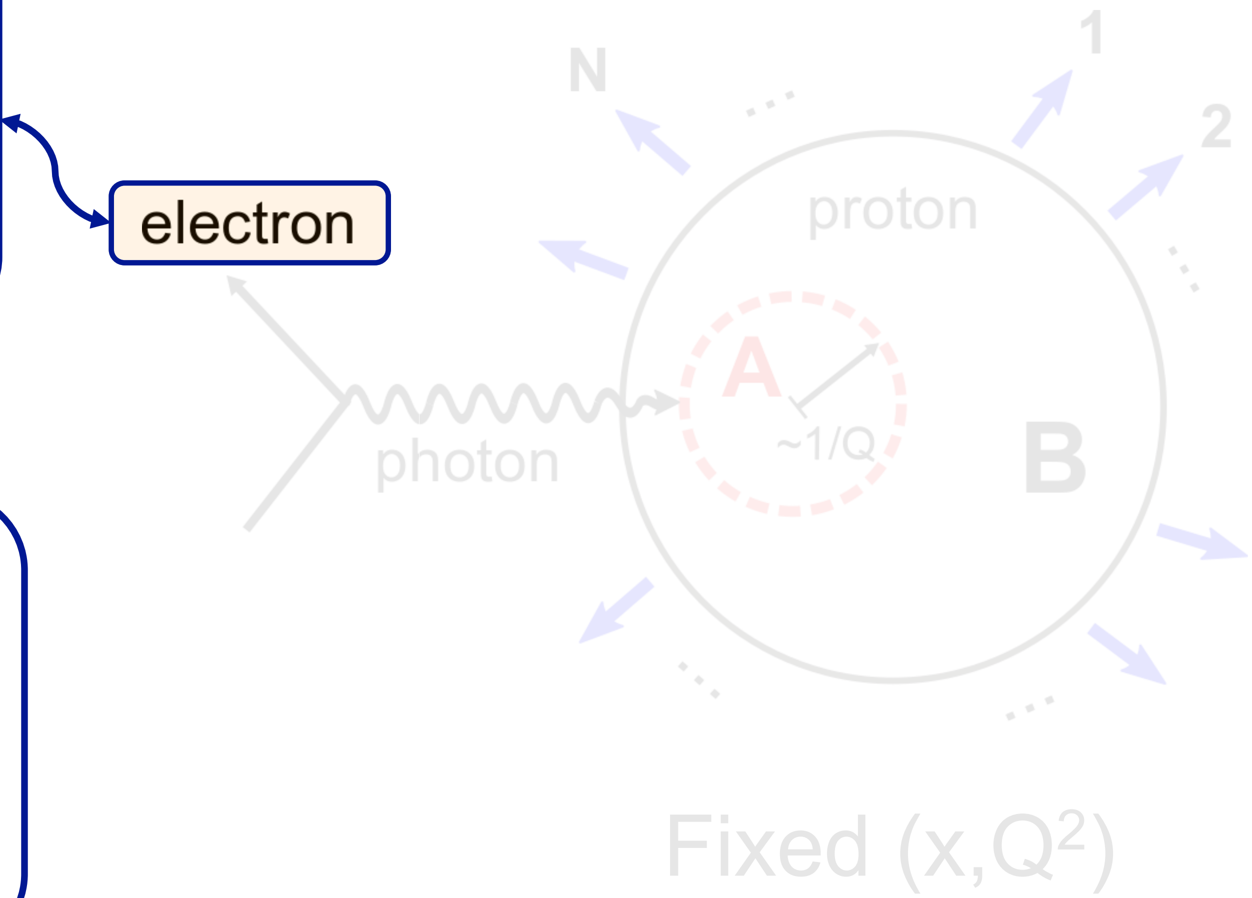
EE in 1+1d CFT?

$$S_{\mathrm{EE}} = \frac{c}{3}\ln\left(\frac{L}{\epsilon}\right)$$

c is central charge, ***L*** is the length of region ***A***, ϵ is resolution scale of the measurement

(see *Int.J.Quant.Inf. 4 (2006) 429*)

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



S_A in DIS

(Kharzeev & Levin 2017)

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

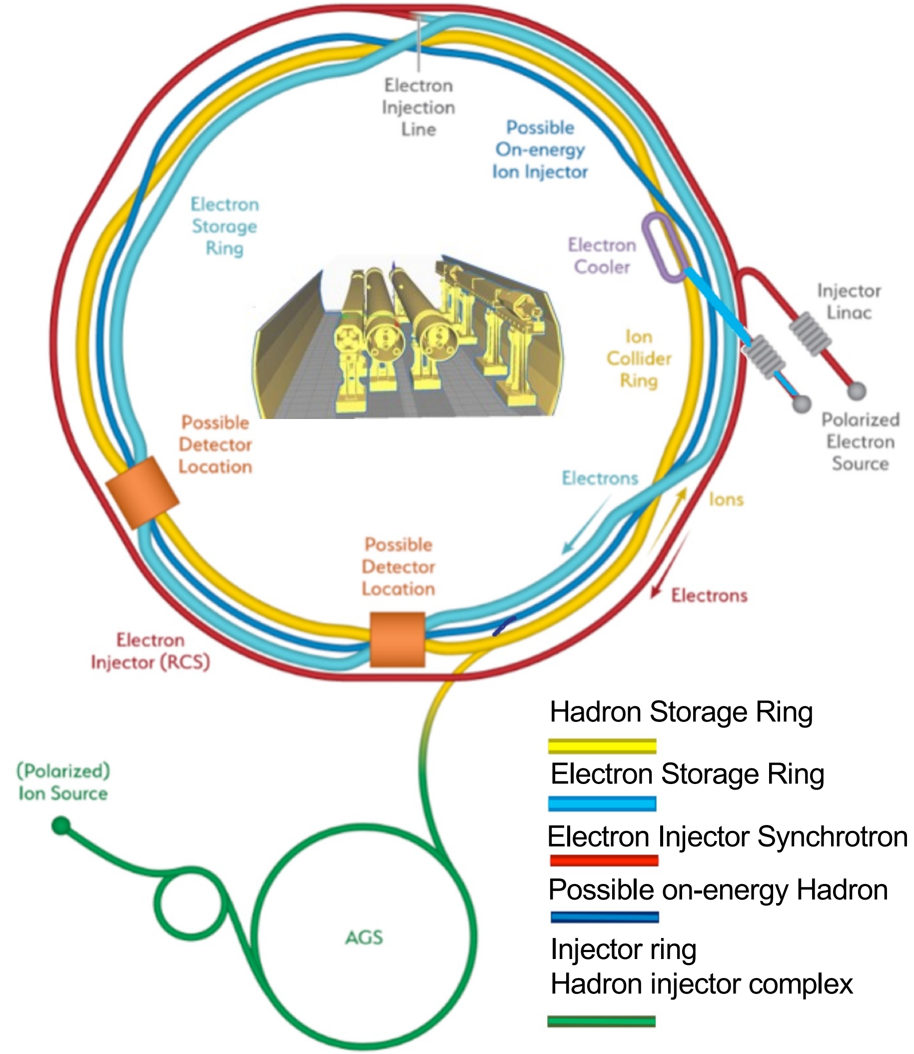
gluon entropy for low x

Theory questions:

Generalized EE in DIS?

- Not equipartitioned?
- Sea quarks?
- other models?

Next generation QCD machine - EIC



Sited at Brookhaven National Laboratory

Electron-Ion Collider

High energy & luminosity accelerator machine with beam polarization.

- $\sqrt{s} \Rightarrow$ 20 – 141 GeV
- $\mathcal{L}_{max} \Rightarrow 10^{34}$ cm^{-2} s^{-1}

Polarization (e & p) ⇒ 80%

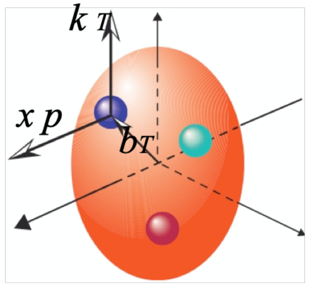
A ⇒ proton to Uranium

EIC project milestones:

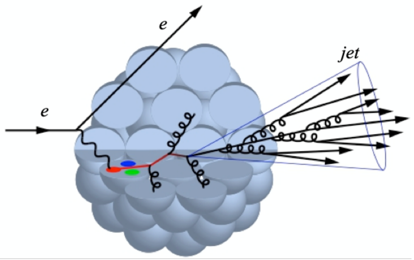
CD-0 (Jan.2020), CD-1 (Mar. 2021)

EIC physics

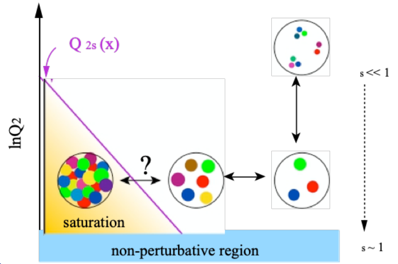
Spin



Tomography



Hadronization



Saturation

High energy & luminosity accelerator machine with beam polarization.

- $\sqrt{s} \Rightarrow$ 20 – 141 GeV
- $\mathcal{L}_{max} \Rightarrow 10^{34}$ cm^{-2} s^{-1}

Polarization (e & p) ⇒ 80%
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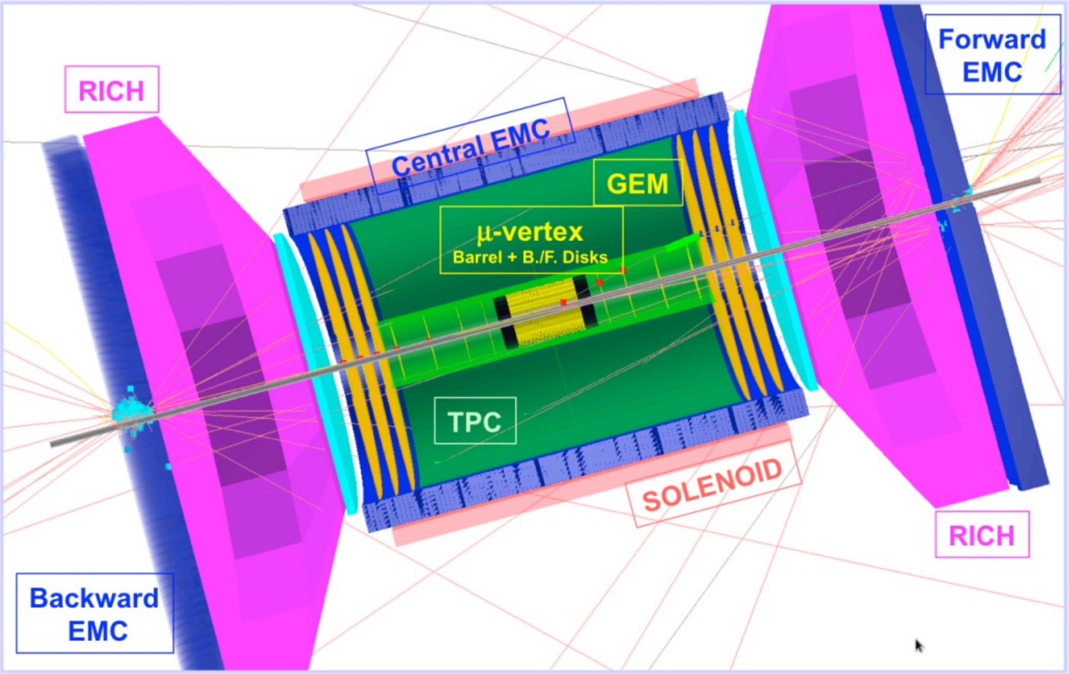
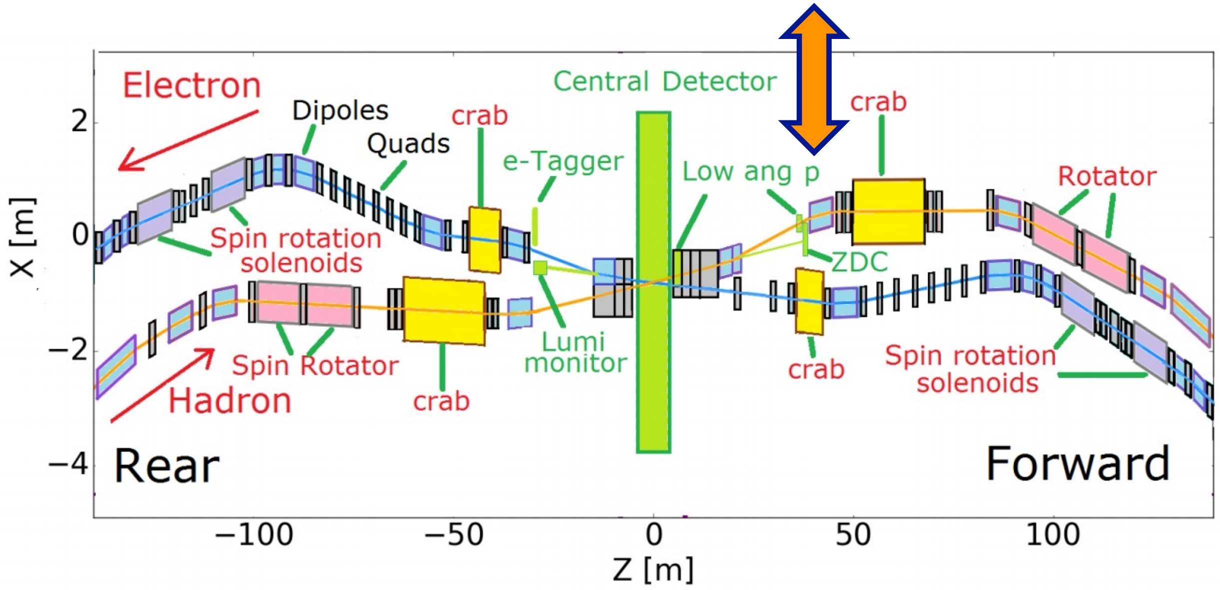
EIC project milestones:
CD-0 (Jan.2020), CD-1 (Mar. 2021)

Detector concepts



General-purpose detector concept
- wide rapidity range (-4,4)

Far forward detections



Complex IR design

Large acceptance with target fragmentation – EE in ep and eA