Detector design concept of the EIC

Introduction

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Inspired by presentations by Elke Aschenauer, Yulia Furletova, Patrizia Rossi, Bernd Surrow, Thomas Ullrich

Outline

- Introduction
  - Foundations & motivation for the EIC program
  - Basics of Deep Inelastic Scattering and DIS kinematics
- EIC accelerator and detector requirements
- Building blocks of EIC multipurpose detector
  - Tracking detectors
  - Vertex reconstruction
  - Calorimeters
  - Detectors for Particle Identification
- Summary and Tutorial

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- EIC accelerator and detector requirements
- Building blocks of EIC multipurpose detector
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  - Vertex reconstruction

Lecture II

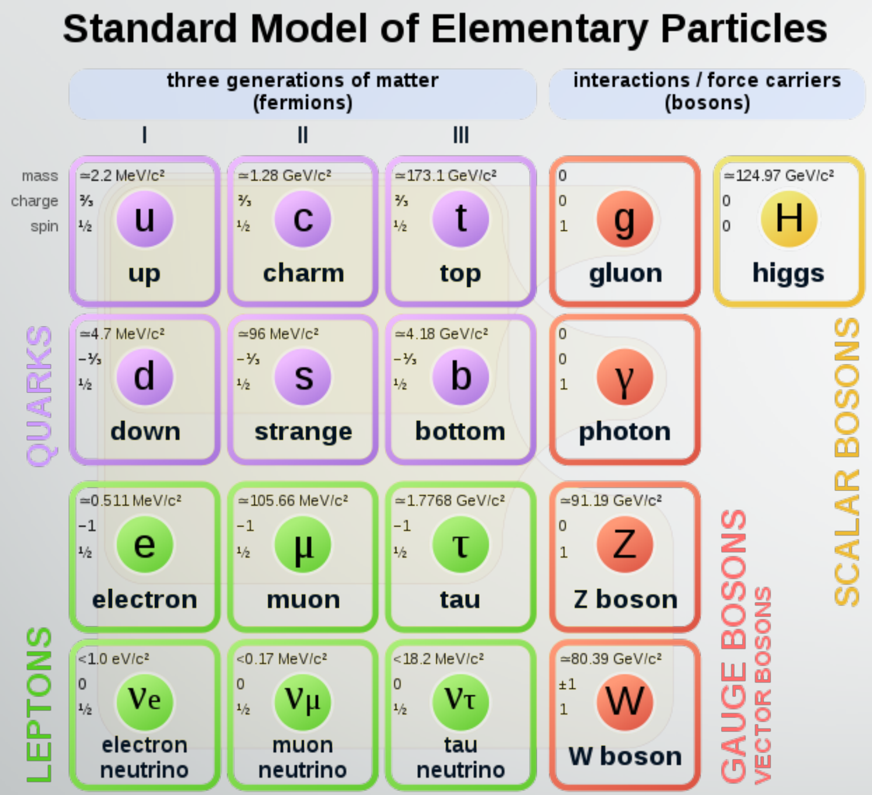
  - Calorimeters
  - Detectors for Particle Identification

Lecture III

- Summary and Tutorial

Lecture IV

The Standard Model

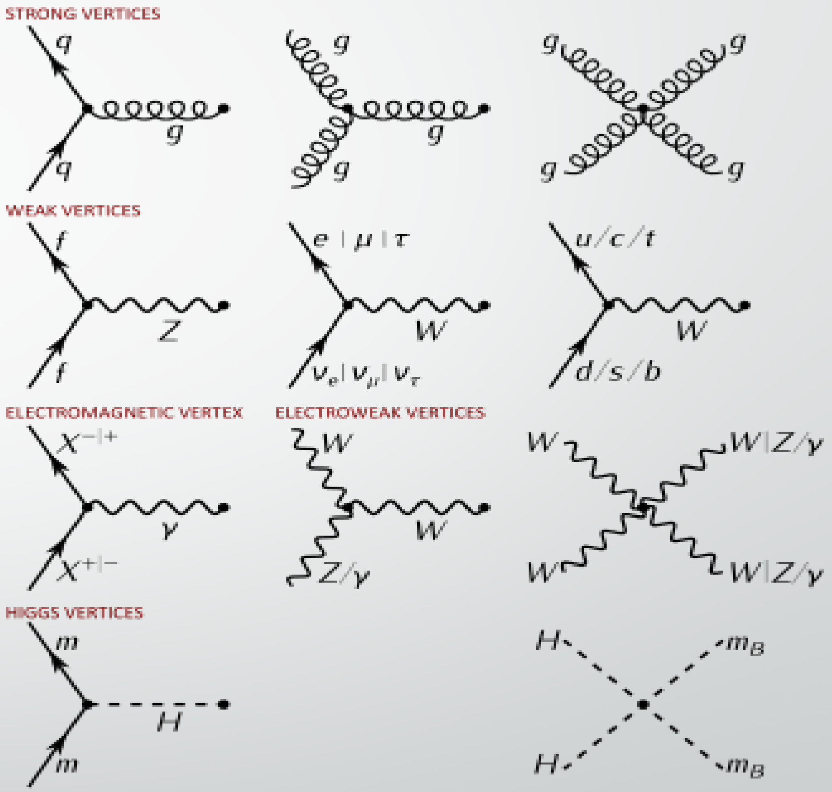


Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass charge spin	≃2.2 MeV/c² ⅔ ½ u up	≃1.28 GeV/c² ⅔ ½ c charm	≃173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c² 0 0 H higgs
QUARKS	≃4.7 MeV/c² −⅓ ½ d down	≃96 MeV/c² −⅓ ½ s strange	≃4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
	≃0.511 MeV/c² −1 ½ e electron	≃105.66 MeV/c² −1 ½ μ muon	≃1.7768 GeV/c² −1 ½ τ tau	≃91.19 GeV/c² 0 1 Z Z boson	GAUGE BOSONS VECTOR BOSONS
LEPTONS	<1.0 eV/c² 0 ½ νe electron neutrino	<0.17 MeV/c² 0 ½ νμ muon neutrino	<18.2 MeV/c² 0 ½ ντ tau neutrino	≃80.39 GeV/c² ±1 1 W W boson	

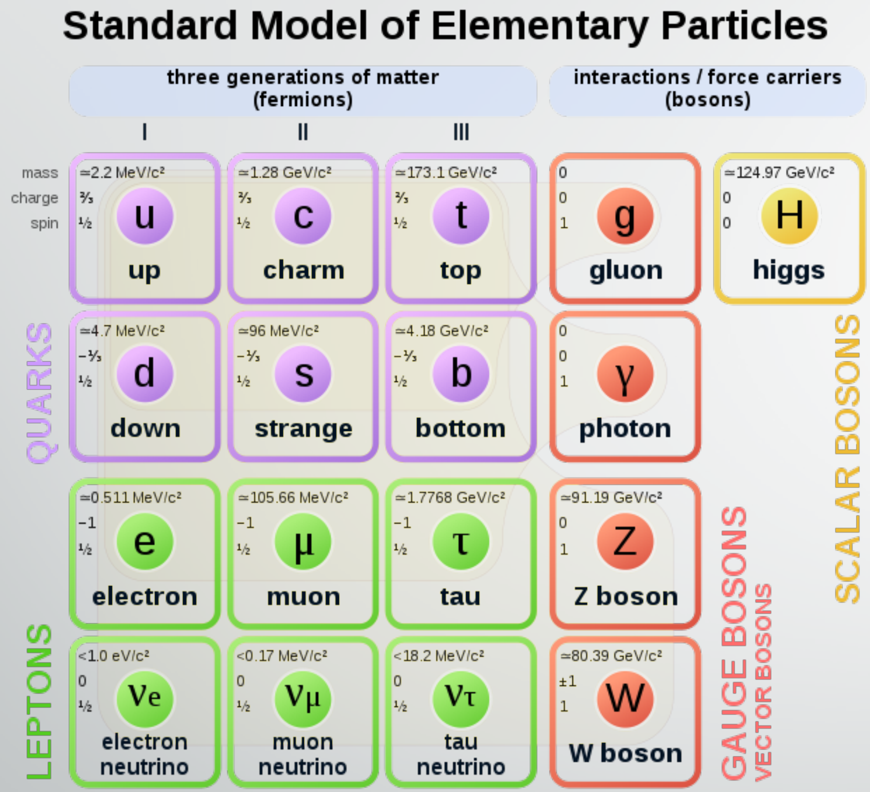
3 generations of quarks and leptons

4 fundamental interactions



- Comprehensive theory describing existing elementary particles and their interactions
- Enormously successful, high predictive power, tested to very high precision and can describe all existing particle data so far*

The Standard Model



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GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

3 generations of quarks and leptons

4 fundamental interactions

2013: F. Englert and P. Higgs:

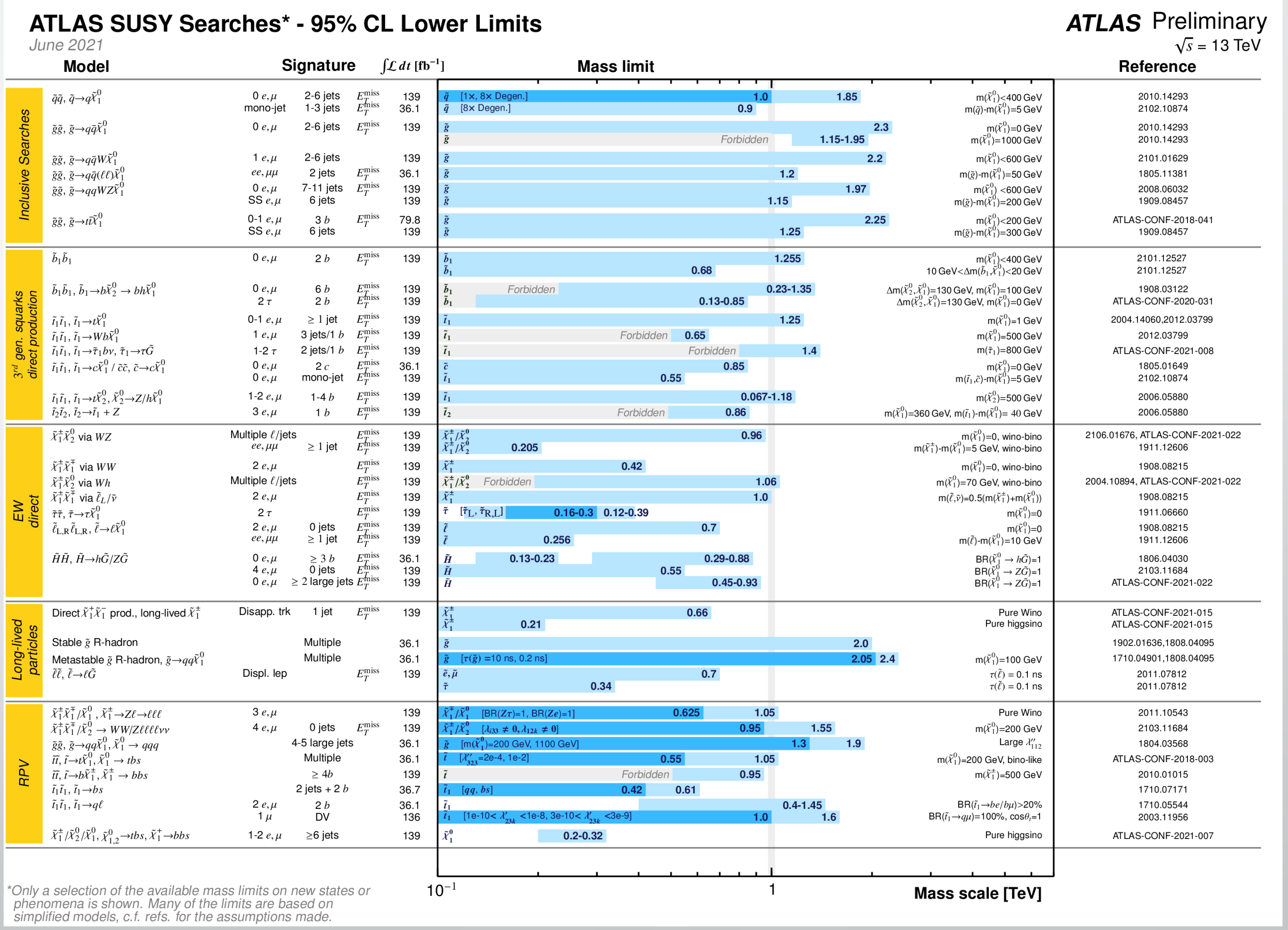
"For the theoretical discovery of a mechanisms that contributes to our understanding of the origin of mass of subatomic particles (e. g. quarks), and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider

- Predicted the existence of Higgs boson giving contribution to particle masses through interactions – confirmed by recent experimental discovery at LHC

Standard Model

- Some Sparticles were expected to exist at/below 1 TeV
- If so, LHC experiments should be able to detect them, especially squarks and gluinos (high cross-sections @ LHC)
- Both ATLAS and CMS continuously push up the limits, but no supersymmetric particles are seen thus far

Mass reach of the ATLAS searches for SUSY (similar for CMS)



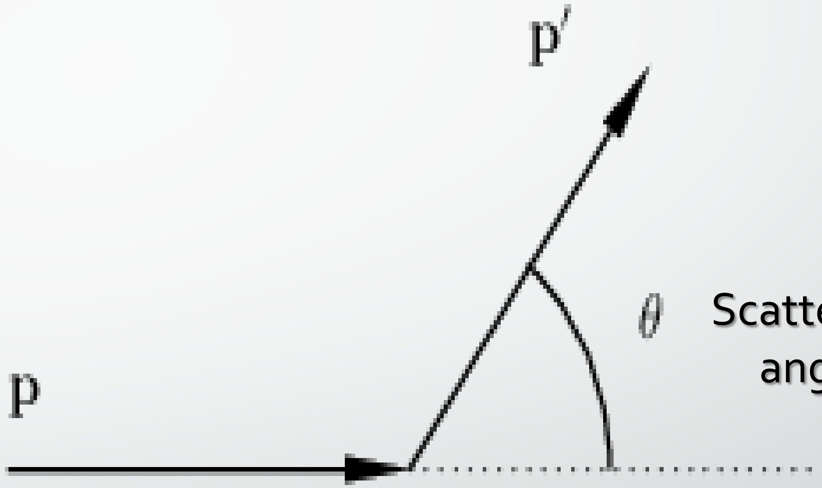
Where it All Begins

- 1911, Rutherford experiment: alpha α-particles on Au-foil
- A now-classic scattering experiment, cross-section:

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{e^4 z^2 Z^2 E'^2}{4|\mathbf{p}|^4 \sin^4\frac{\theta}{2}} = \frac{e^4 z^2 Z^2}{4E^2 \sin^4\frac{\theta}{2}}$$

- Electron scattering case:

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{\alpha^2 \hbar^2 c^2}{4E^2 \sin^4(\theta/2)}$$



Scattered α-particle momentum

Scattering angle

Incoming beam momentum

Momentum transfer $q = p - p'$

Elastic scattering: $E = E'$

High energy limit: $|p| = E$

Nucleon Structure Explorations

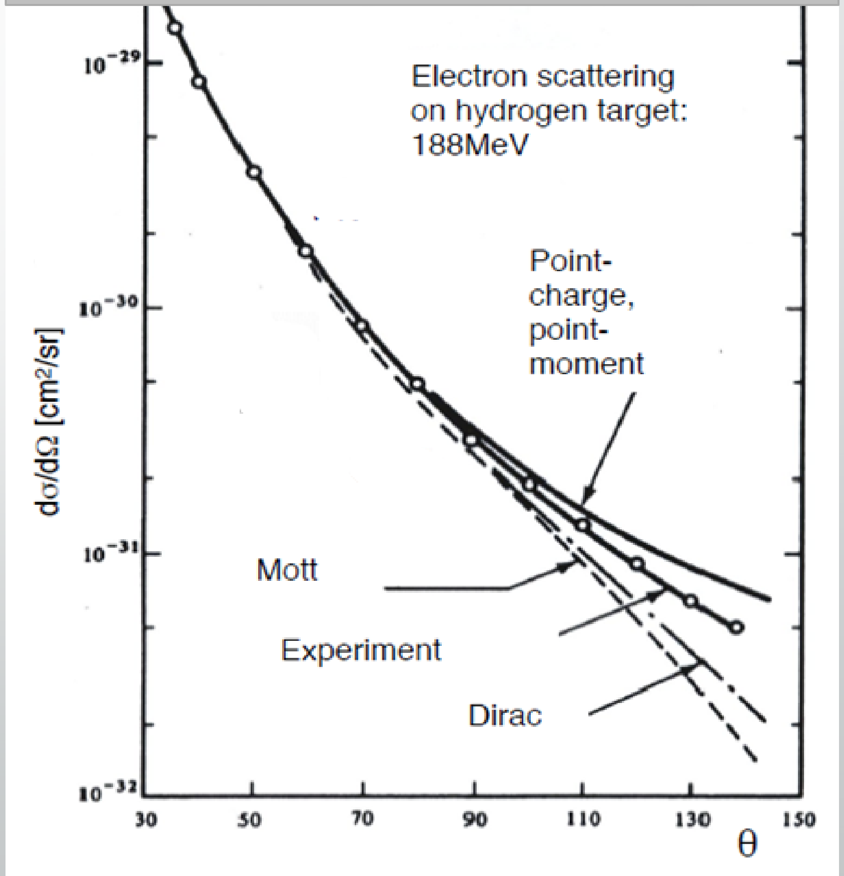
- 1950-1960: Electron (elastic) scattering experiments. Required incorporation of spin effects for relativistic projectile: Mott's cross-section:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott,no recoil}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Rutherford}} \cos^2\frac{\theta}{2}$$

- Dirac cross-section, incorporating relativistic effects (spin for probe and target):

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{\alpha^2\hbar^2c^2}{4E^2\sin^4(\theta/2)}\left(\frac{E'}{E}\right)\left\{\underbrace{\cos^2\left(\frac{\theta}{2}\right)}_{\text{Impact of electron-spin}} - \underbrace{\frac{q^2}{2M^2c^2}\sin^2\left(\frac{\theta}{2}\right)}_{\text{Impact of target-spin (mass M)}}\right\}$$

1961: R. Hofstadter
"...for achieved discoveries concerning the structure of the nucleons"



Nucleon Structure Explorations

- Deviations between experimental data and cross-section predictions due to assumptions of only point-particle Coulomb and magnetic interactions
- Experimental results show that proton is not point-like; it has finite size and structure!
- Description of relativistic *e* scattering of a target with a spatial charge and magnetic moment densities: Rosenbluth formula

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{\alpha^2}{4E^2\sin^4(\theta/2)}\frac{E'}{E}\cos^2\left(\frac{\theta}{2}\right)\left(\frac{G_E^2+\tau G_M^2}{1+\tau}+2\tau G_M^2\tan^2\left(\frac{\theta}{2}\right)\right)$$

$$\tau = -q^2/4M^2$$

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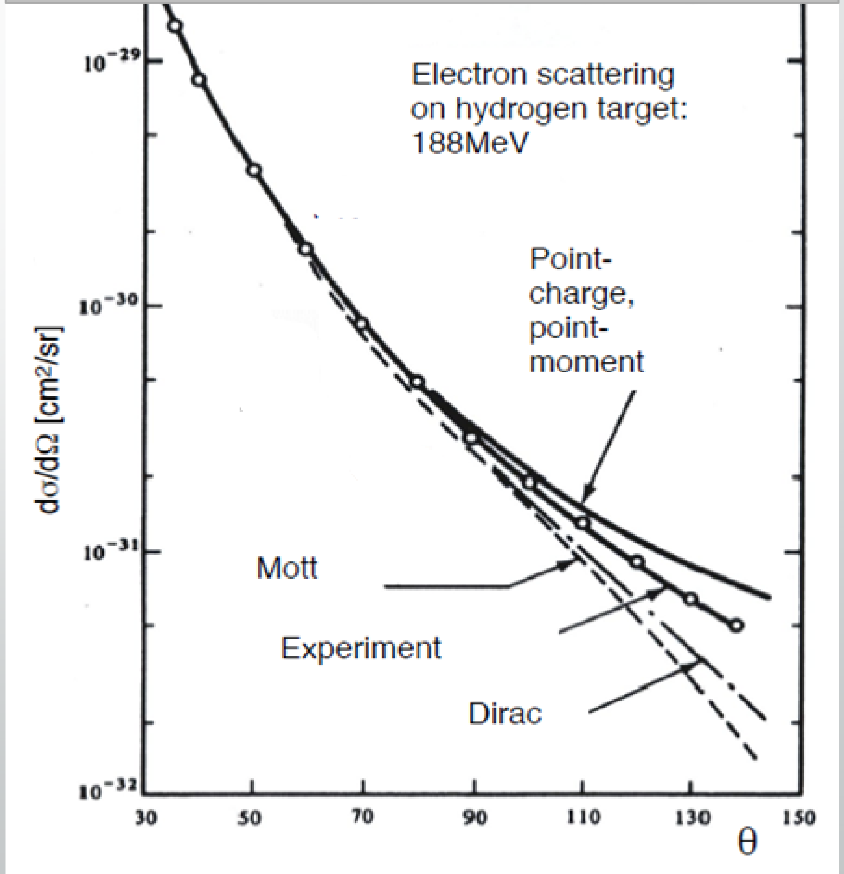
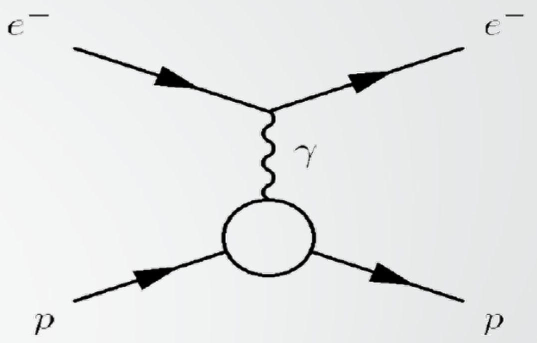


Elastic *ep* Scattering



- Differential cross-section or elastic **ep** scattering – provides information about the average charge and magnetic moment distributions
- Form factors G_E and G_M encode electric charge density and magnetic moment density
- Cannot be calculated from first principles!
- Determined experimentally: measure cross-section for many θ and Q^2 to extract G1 and G2

$$\left(\frac{d\sigma}{d\Omega}\right) = \underbrace{\underbrace{\frac{\alpha^2}{4E^2\sin^4(\theta/2)}}_{\text{Rutherford cross section}}\frac{E'}{E}\cos^2\left(\frac{\theta}{2}\right)}_{\text{Mott cross section}}\left(\frac{G_E^2+\tau G_M^2}{1+\tau}+2\tau G_M^2\tan^2\left(\frac{\theta}{2}\right)\right)$$

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left(\frac{G_E^2+\tau G_M^2}{1+\tau}+2\tau G_M^2\tan^2\left(\frac{\theta}{2}\right)\right)$$

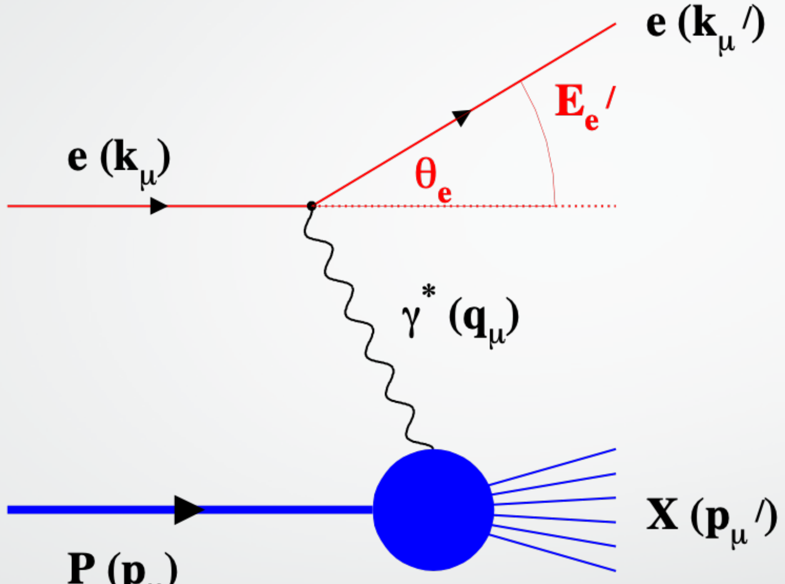
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_M \times \left(G_1(Q^2)+2\tau G_2(Q^2)tan^2\frac{\theta}{2}\right)$$

$$G_1(Q^2) = \frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau} \qquad G_2(Q^2) = G_M^2(Q^2)$$

Kinematics: Electron Scattering

$$k = \begin{pmatrix} E_e \\ 0 \\ 0 \\ -E_e \end{pmatrix}$$

$$p = \begin{pmatrix} E_P \\ 0 \\ 0 \\ E_P \end{pmatrix}$$



$$k' = \begin{pmatrix} E'_e \\ E'_e \sin\theta'_e \cos\phi'_e \\ E'_e \sin\theta'_e \sin\phi'_e \\ E'_e \cos\theta'_e \end{pmatrix}$$

$$p' = \begin{pmatrix} \sum_h E_h \\ \sum_h p_{X,h} \\ \sum_h p_{Y,h} \\ \sum_h p_{Z,h} \end{pmatrix}$$

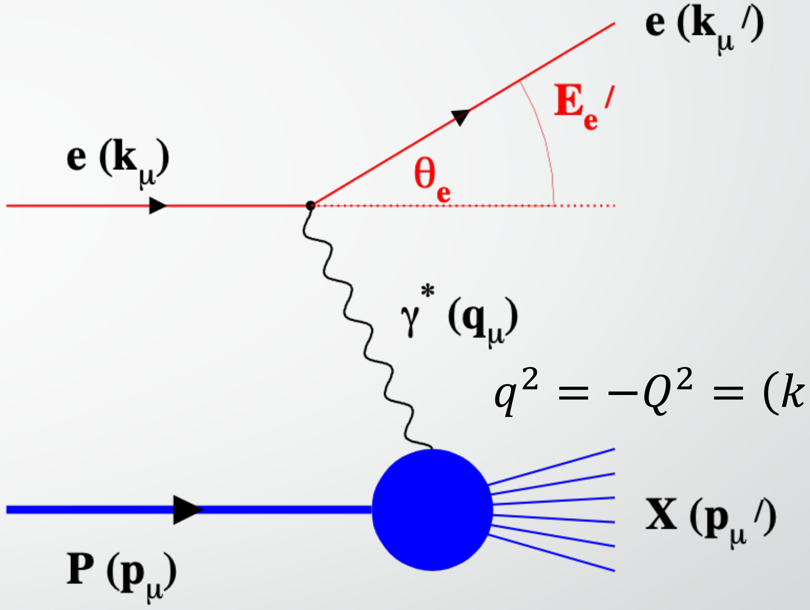
$q^2 = -Q^2 = (k - k')$ – momentum transfer; virtuality

$\nu = E_e - E'_e$ – energy lost by lepton

Kinematics: Electron Scattering

Invariant:	Describes:
$s = (p + k)^2$	Center of mass energy
$Q^2 = -q^2$	Resolving power
$x = \frac{Q^2}{2(p \cdot q)}$	Momentum fraction in struck quark
$y = \frac{p \cdot q}{p \cdot k}$	Inelasticity, fraction of electron energy carried by γ^*
$W^2 = (p + q)^2 = (p')^2$	Invariant mass (squared) of final hadronic state

$$\boxed{Q^2 = s \cdot x \cdot y}$$



$q^2 = -Q^2 = (k - k')$

- Small $Q^2, x = 1$ – elastic scattering
- $0 < x < 1$ – inelastic scattering
- $Q^2 \to \infty$, $\nu \to \infty$ – deep inelastic scattering (DIS)

Resolving Power in DIS

- Evolution of resolution in DIS experiments: increasing Q^2 increases the resolution $\left(\sim {}^{\hbar c}/_{\sqrt{Q^2}}\right)$
- EIC: will probe about 1/500 of proton radius

EIC

Resolution is a few times smaller than target

Resolution **10's** of times smaller than target

Resolution **100's** of times smaller than target

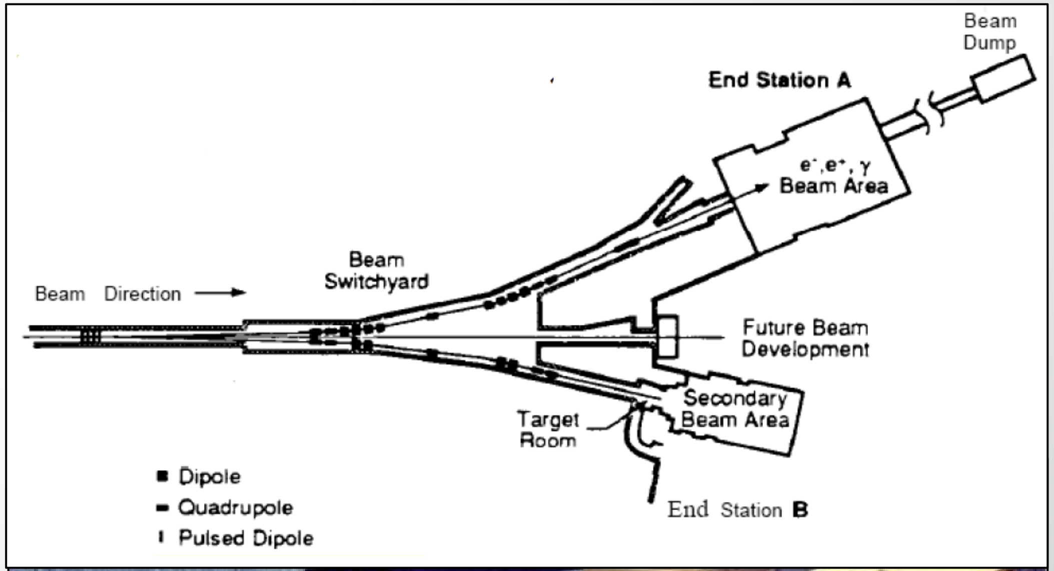
Credit: Yulia Furletova

Nucleon Structure: Going Deeper

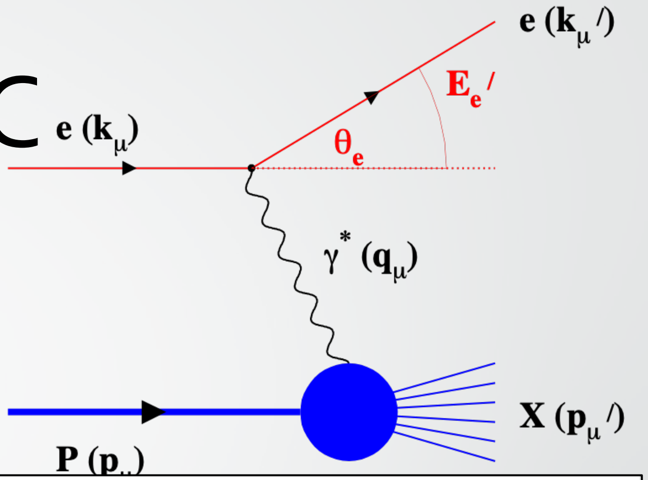
- 1966: SLAC – a dedicated accelerator for ep interaction studies
- A 2 miles long linear accelerator with 20 GeV electron beam
- 1967: elastic vs. inelastic scattering program

$e + p \to e + p$ vs. $e + p \to e + X$

- Inelastic ep scattering – a deeper look at the internal structure



More Kinematics: @ SLAC

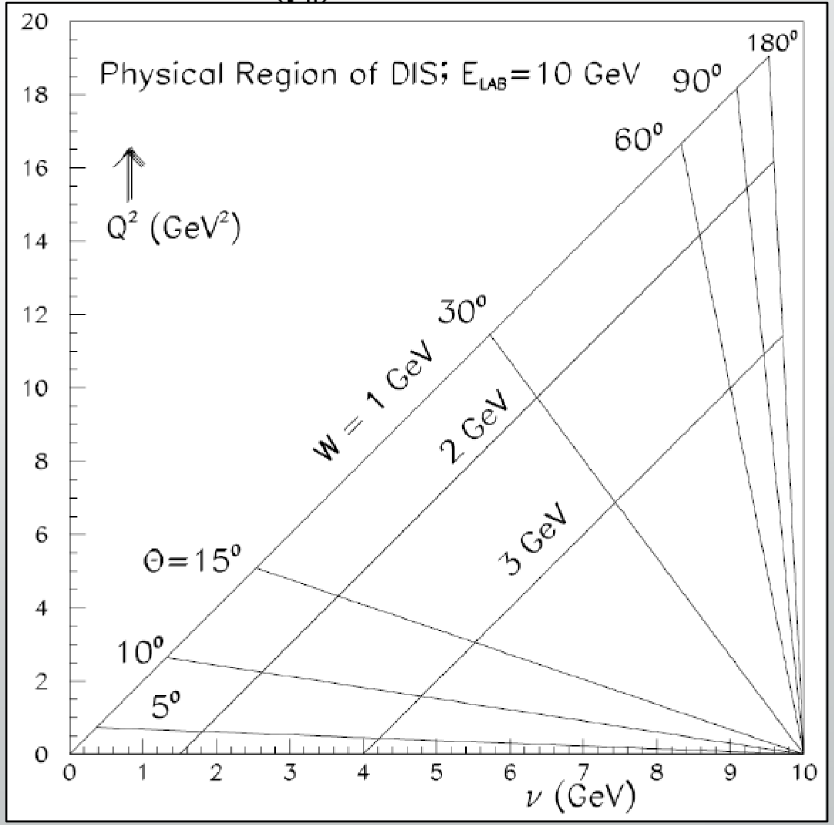


- Proton target is at rest – defines the LAB frame
- Scattered electron angle and energy are measured
- The unobserved hadronic system is "missing" mass W.

$$Q^2 = 4E_e E_e' sin^2(\theta/2)$$

$$E_e' = \left(E_e - \frac{W^2 - M^2}{2M}\right) / \left(1 + \frac{2E_e}{M} sin^2(\theta/2)\right)$$

$$W^2 = M^2 + 2M(E_e - E_e') - 4E_e E_e' sin^2(\theta/2)$$



Cross-sections Summary

Dirac cross-section:

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{E'}{E}\left\{1 + 2\tau \tan^2\left(\frac{\theta}{2}\right)\right\} \qquad \tau = -q^2/4M^2$$

Elastic *ep*:

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{E'}{E}\left\{\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\left(\frac{\theta}{2}\right)\right\}$$

Inelastic *ep*:

$$\left(\frac{d^2\sigma}{dE' d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left\{W_2(Q^2, x) + 2W_1(Q^2, x)\tan^2\left(\frac{\theta}{2}\right)\right\}$$

Mott:

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} \cdot \cos^2(\theta/2)$$

Rutherford:

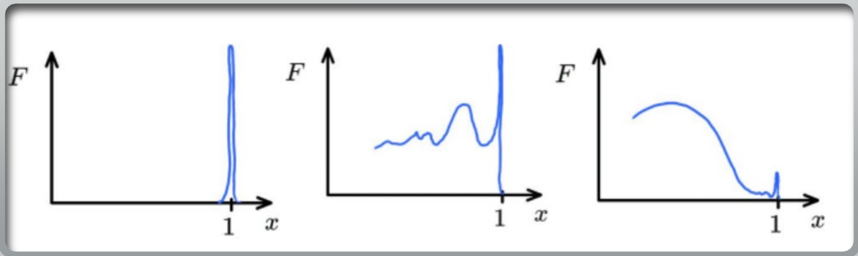
$$\left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} = \frac{4\alpha^2 E'^2}{q^4}$$

DIS Description

- Expressing structure functions W1 and W2 in terms of dimensionless ones:
- $F_1(x,Q^2) = MW_1\,(Q^2,\nu)$ $F_2(x,Q^2) = \nu W_2\,(Q^2,\nu)$ $F_L = F_2 - 2xF_1$
- Cross-section is the expressed as

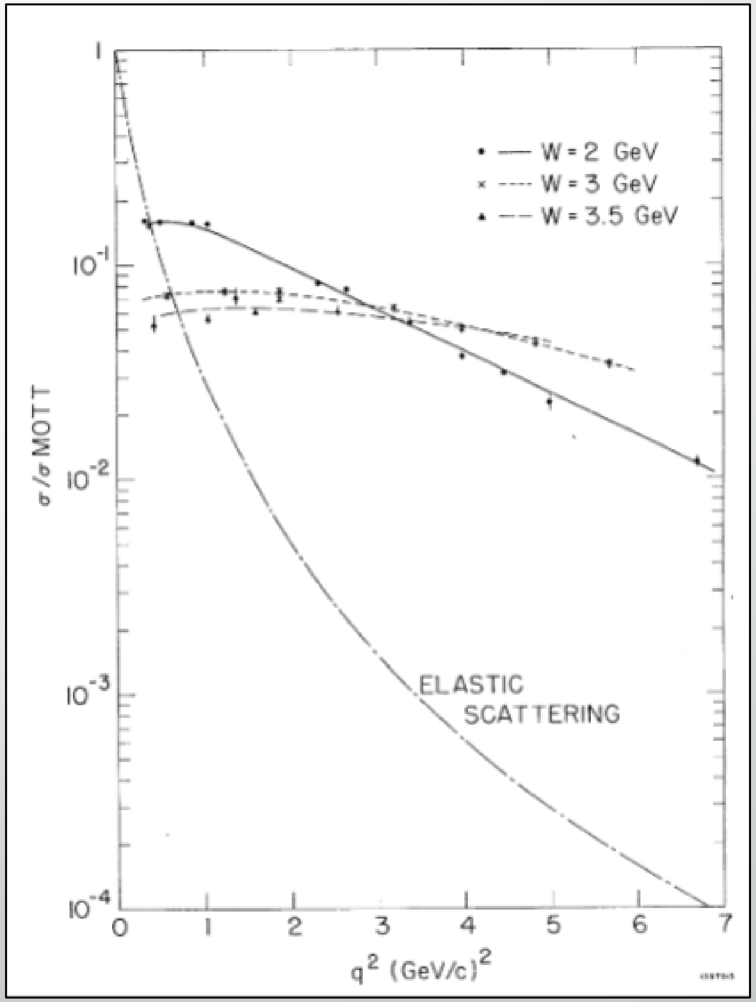
$$\frac{d^2\sigma^{eA\to eX}}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

- If $Q^2 \ll 1/R$ → elastic scattering, $x = 1$
- If $Q^2 \sim 1/R$ → start seeing structure, p is excited to higher energy states
- If $Q^2 \gg 1/R$ → looking deep into the p structure



Hints of Quarks

- SLAC measurements of reduced cross section dependence on Q^2 – only a week dependance observed
- No Q^2 dependance → structure function is nearly constant (form factor of ~ 1) → point-like scattering centers inside the proton!
- The cross-section is invariant with Q_2 and depends only on x – Bjorken scaling



Scaling and Scaling violations

- A closer look: proton structure functions:
- At fixed x: F_1 and F_2 depend weakly on Q^2

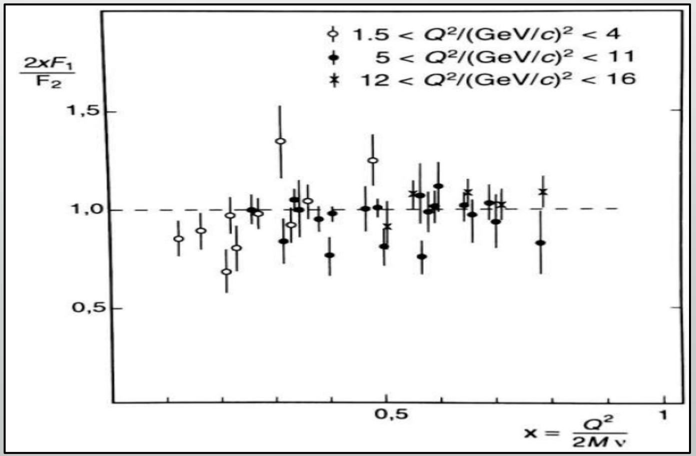
$$F_1(x,Q^2) \sim F_1(x) \qquad F_2(x,Q^2) \sim F_2(x)$$

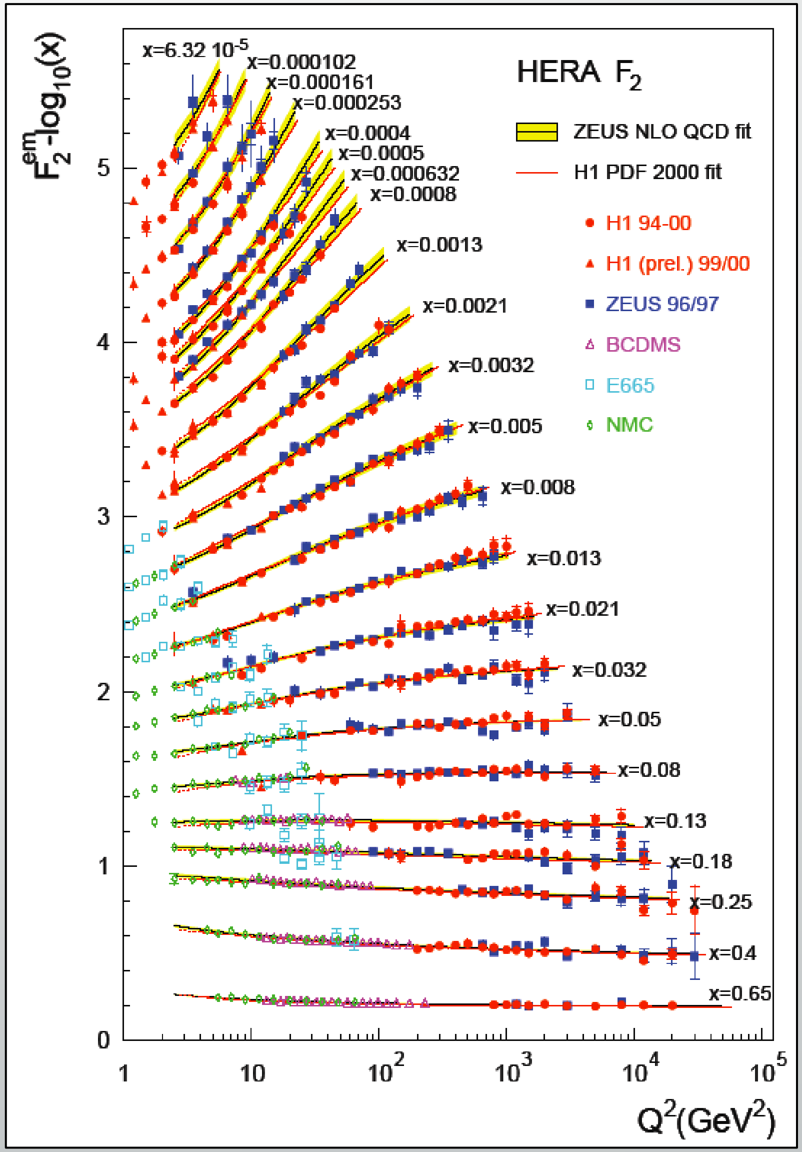
- Comparing DIS and Dirac cross-section equations → *Callan-Gross relation*:

$$F_2(x) = 2xF_1(x)$$

→ proton constituents

are spin ${}^1/_2$ particles





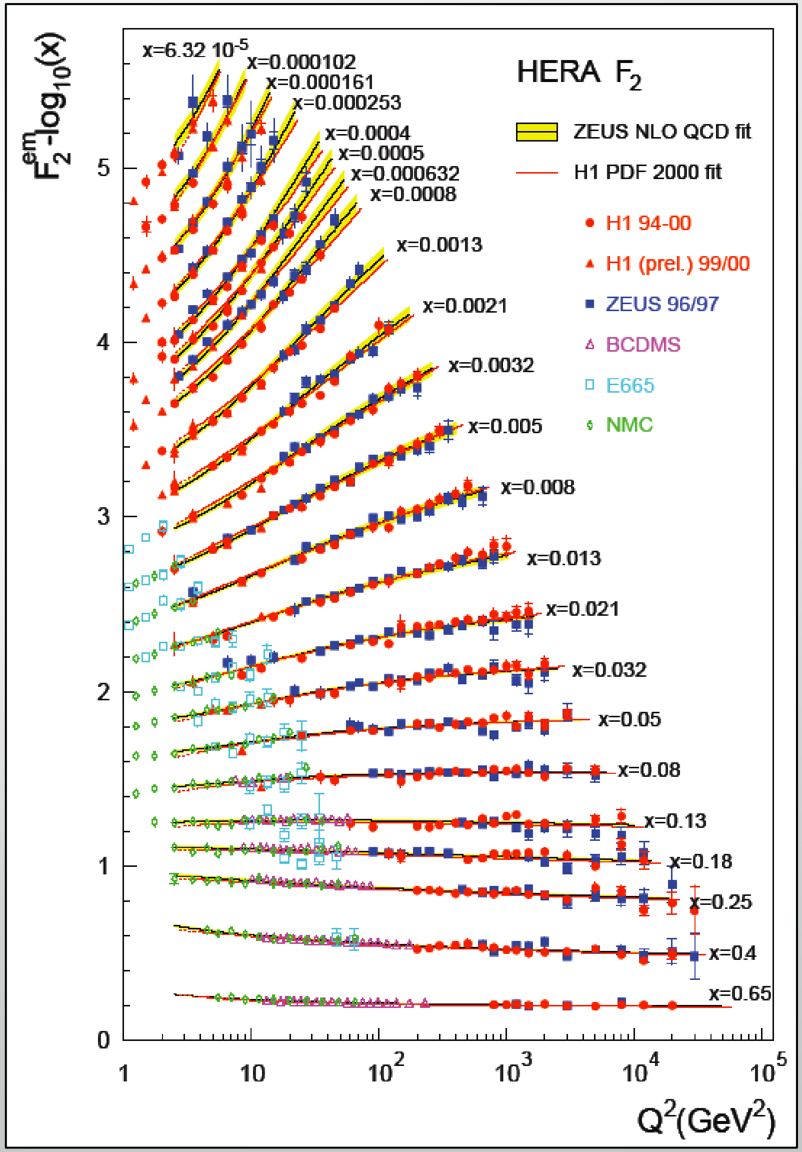
Scaling and Scaling violations

- A closer look: proton structure functions
- Deviations of F_2 from Bjorken scaling at high Q^2 and low x

$$F_2 = F_2(x, Q^2)$$

- "Scaling" → quasi-free particles
- "Scaling violation" → binding of constituents

- F_2 growth with Q^2 at low x → evidence for the QCD interactions between proton's constituents



Quantum Chromo Dynamics

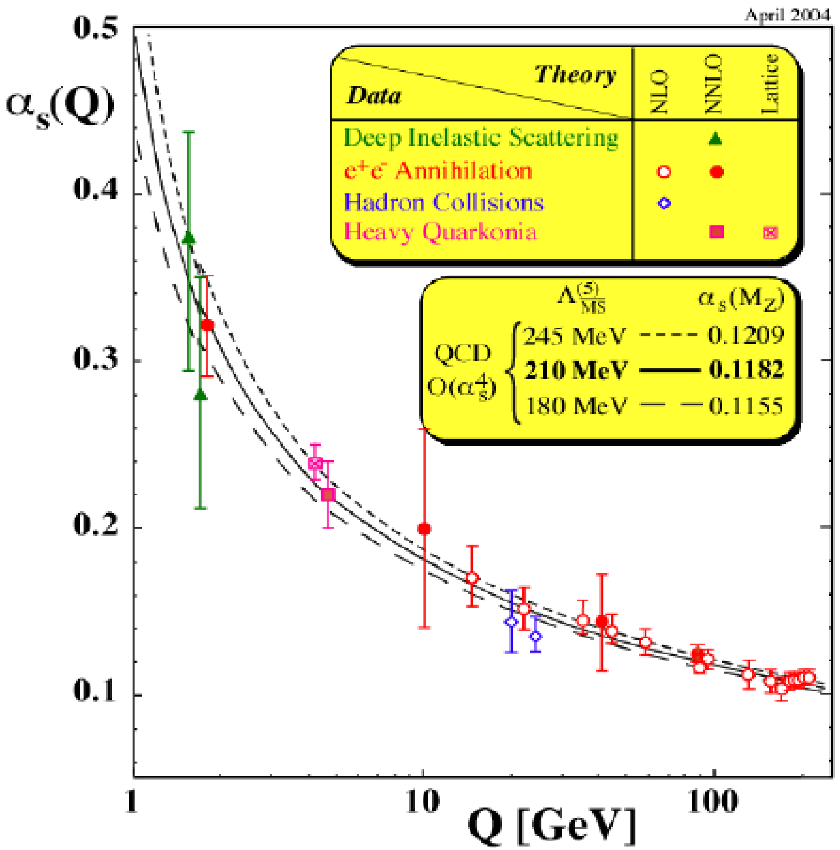
- QCD – the fundamental theory of strong interactions: all nucleons (hadrons) are made of quarks and gluons mediate quark interactions (and self-interactions)

$$\mathcal{L}_{QCD} = \sum_{j=1}^{n_f} \bar{\psi}_j \left(iD_\mu \gamma^\mu - m_j \right) \psi_j - \frac{1}{4} \mathrm{Tr}\, G^{\mu\nu} G_{\mu\nu}$$

- Asymptotic freedom and confinement
  - Large distances: quarks are confined within hadrons and could not be isolated
  - Short distances: quarks move as free particles (within hadrons)

2004: D. Gross, F. Wilczek, D. Politzer

Discovery of asymptotic freedom in QCD



Quantum Chromo Dynamics

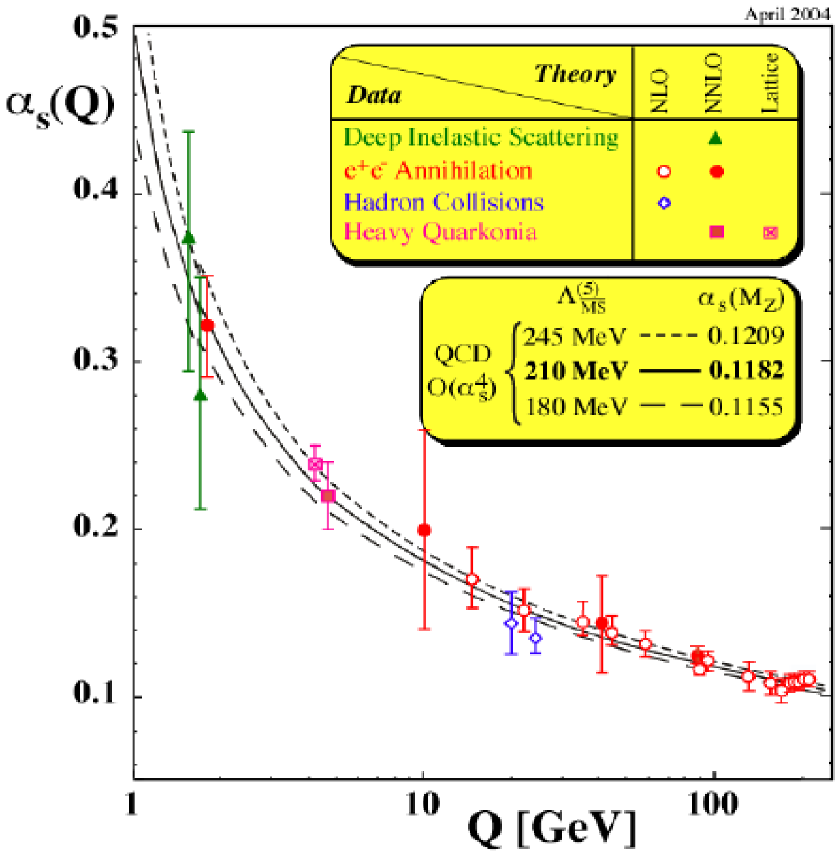
- Perturbative QCD solutions for short-distance physics are tested to better than 1%

- QCD is still unsolved in non-perturbative domain (we rely on lattice calculations, phenomenological descriptions)

- Properties of visible matter (nucleons and other hadrons) emerge through complex structure of the QCD vacuum

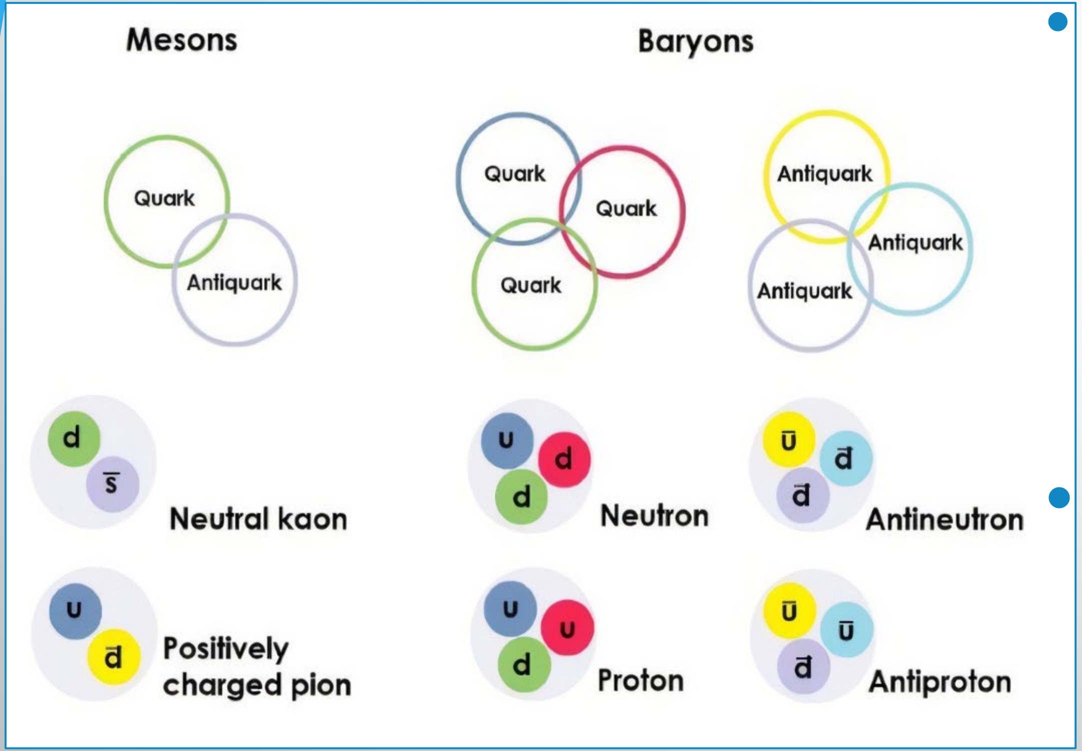
2004: D. Gross, F. Wilczek,
D. Politzer

Discovery of asymptotic freedom in QCD



Partons in Standard Model

- Partons: quarks and gluons
- Hadrons: baryons and mesons, color-neutral objects
  - Baryons: 3 quarks; fermions (half-integer spin)
  - Mesons: quark + antiquark; bosons (integer spin)

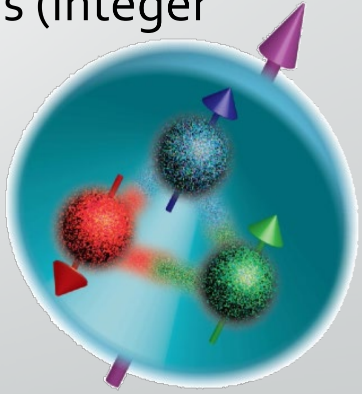


Proton **charge**:+1 Proton **mass**: ~ 1GeV

Proton **spin**: 1/2

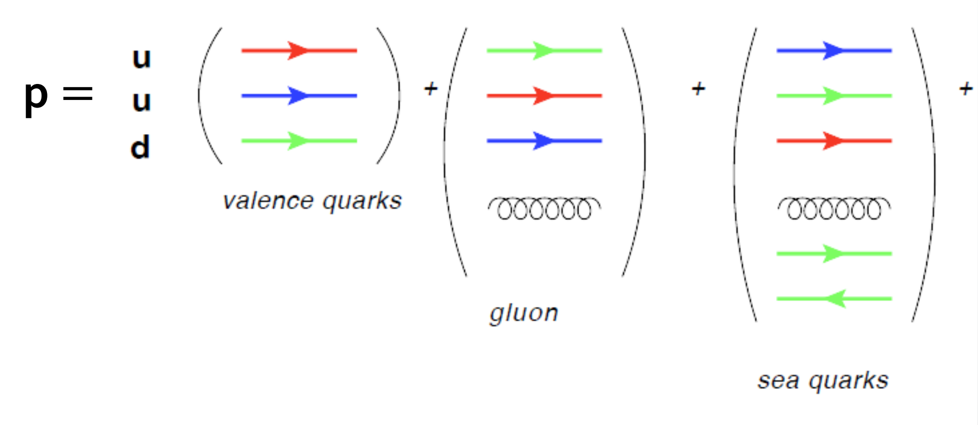
- A closer look at the proton:
  - Constituents: uud
  - Charge? $+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$ ✓
  - Mass?

$$(2.2+2.2+4.7)\ \text{MeV} \neq 1GeV$$ ✗

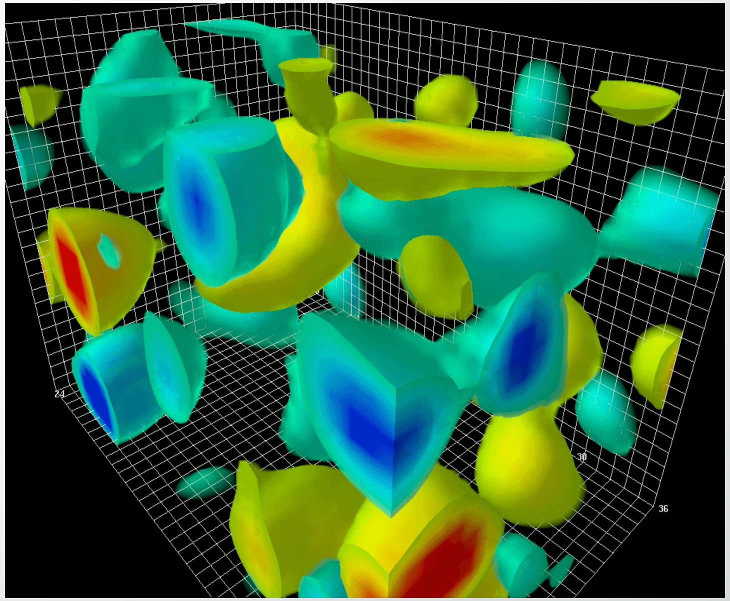


Understanding Nucleon Structure

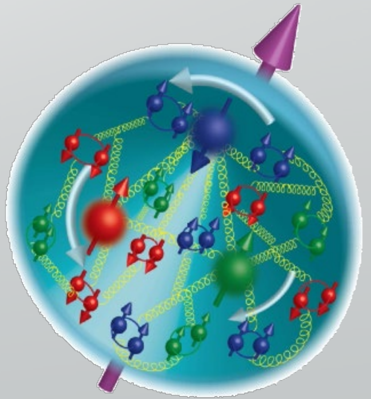
- A rich structure within:



- QCD strong interactions "open" a sea of virtual quark-antiquark pairs within nucleons



(D. Leinweber: Action (~energy) density fluctuations of gluon-fields in QCD vacuum)

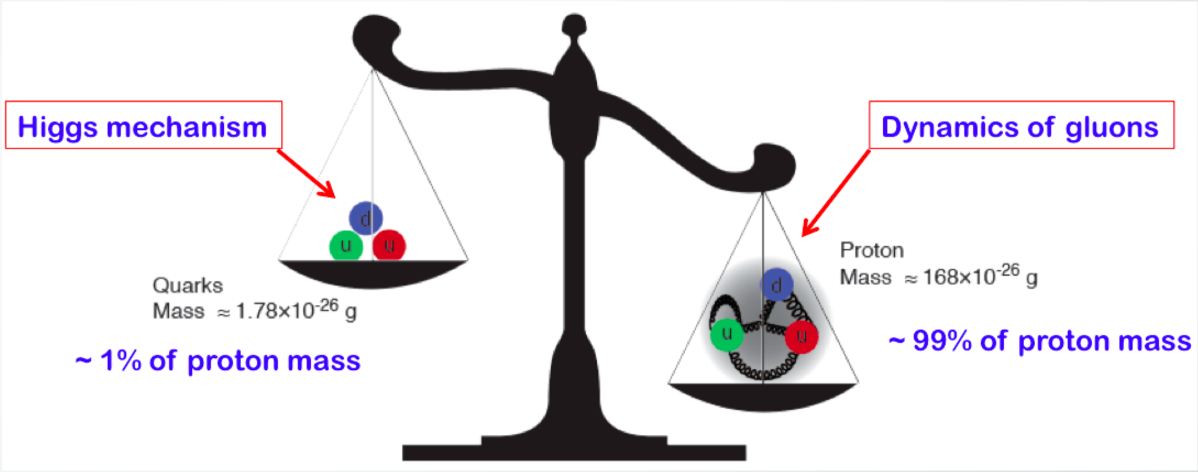


Origin of Mass?

- D. Gross Nobel Prize Lecture (2004):

"It is sometimes claimed that the origin of mass is the Higgs mechanism that is responsible for the breaking of the electroweak symmetry that unbroken forbid quark masses.

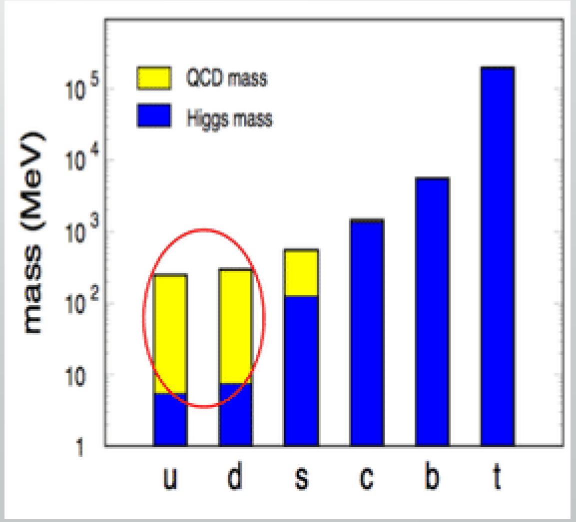
This is incorrect. Most, 99%, of the proton mass is due to the kinetic and potential energy of the massless gluons and the essentially massless quarks, confined within the proton."



Proton mass arises predominantly from interactions & energy in gluonic fields

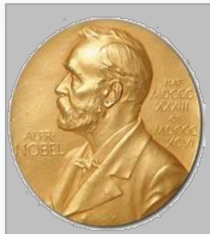
$$M = \underbrace{E_q + E_g}_{\substack{\text{Relativistic motion} \\ \text{Quark energy + Gluon energy}}} + \overbrace{\chi_{m_q} + T_g}^{\substack{\text{Quantum fluctuations} \\ \text{Quark mass + Trace anomaly}}}$$

But how?



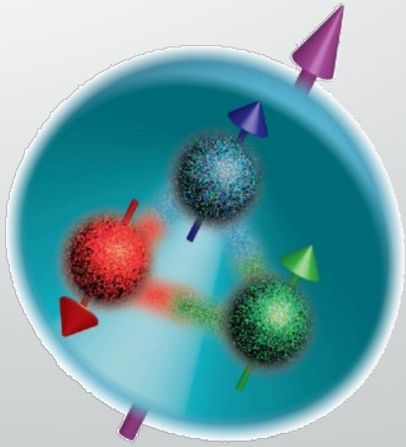
Proton Spin

- 1922: The Stern–Gerlach experiment
- 1925: George Uhlenbeck and Samuel Goudsmit proposed a concept of spin as self-rotating electron
- 1933: Otto Stern et al.: discover anomalous magnetic moment of proton
- "Proton spin crisis":
  - Proton spin $+ {}^{1}/_{2}$
  - EMC experiment: quark contribution $\sim 30\%$



1943: O. Stern

"For his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"



(Simplified) Quark Model

Proton Spin Puzzle

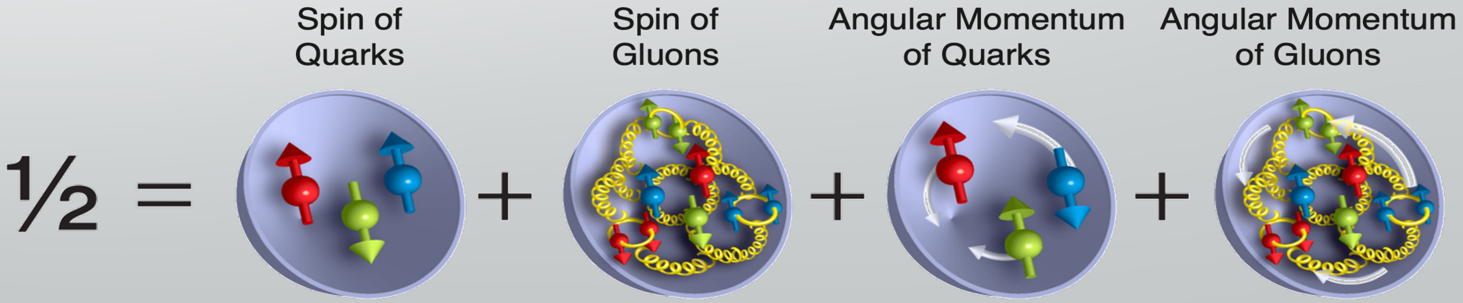
- What are the appropriate degrees of freedom in QCD that would explain the "spin" of a proton?

After 20 years effort

- Quarks (valence and sea): ~30% of spin in limited x-range
- Gluons (latest RHIC data): ~20% of spin in limited x-range

Where is the rest?

- It's not just about the number; it's about the interplay between intrinsic properties and interactions of quarks and gluons



$$\frac{1}{2} = + + +$$

Connecting to Theory

- Experimentally, we observe/measure hadrons and leptons, not partons
- Description of particle production relies *factorization*, the fundamental assumption of Parton model, hadron yields are described by convolution of "$PDF \otimes NLO \otimes FF$“

pp:

$$\left(f_a^i(x_i, Q^2), f_b^j(x_j, Q^2)\right) \otimes \hat{\sigma}\ (ij \to kl) \otimes D_k^h(z', p_T^2)\ ,\ z' = p_T^h / p_T$$

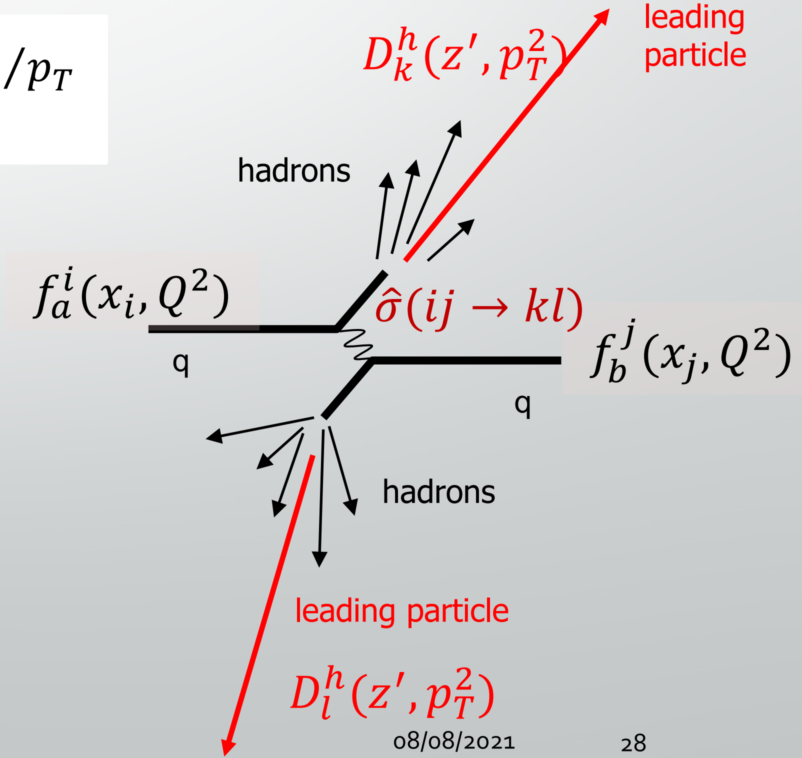
Could simplify via jets: $\frac{d\sigma^{h(k)}}{dp_T^{h\,2}\, dy^h\, dz'} = \frac{d\sigma^{jet(k)}}{dp_T^2\, dy} \frac{1}{z'^2} D_k^h(z', p_T^2)$

ep:

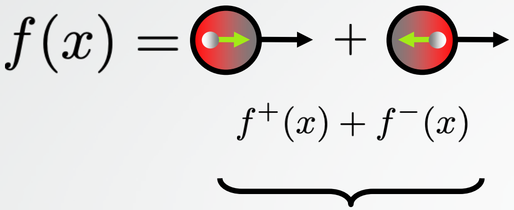
$$f(x_i, Q^2) \otimes \hat{\sigma} \otimes D_k^h(z', p_T^2)$$

e^+e^-:

$$\hat{\sigma} \otimes D_k^h(z', p_T^2)$$



Parton Distribution Functions



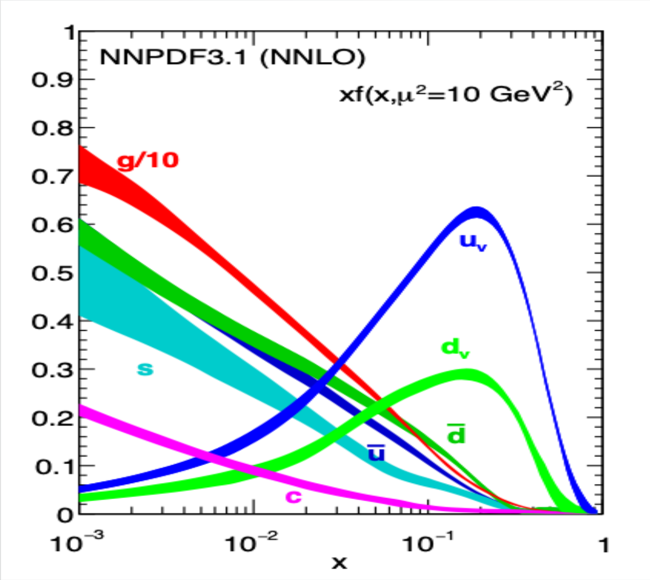
$$f(x) = \underbrace{f^{+}(x) + f^{-}(x)}$$

Measure of probability to find parton f with longitudinal momentum fraction x

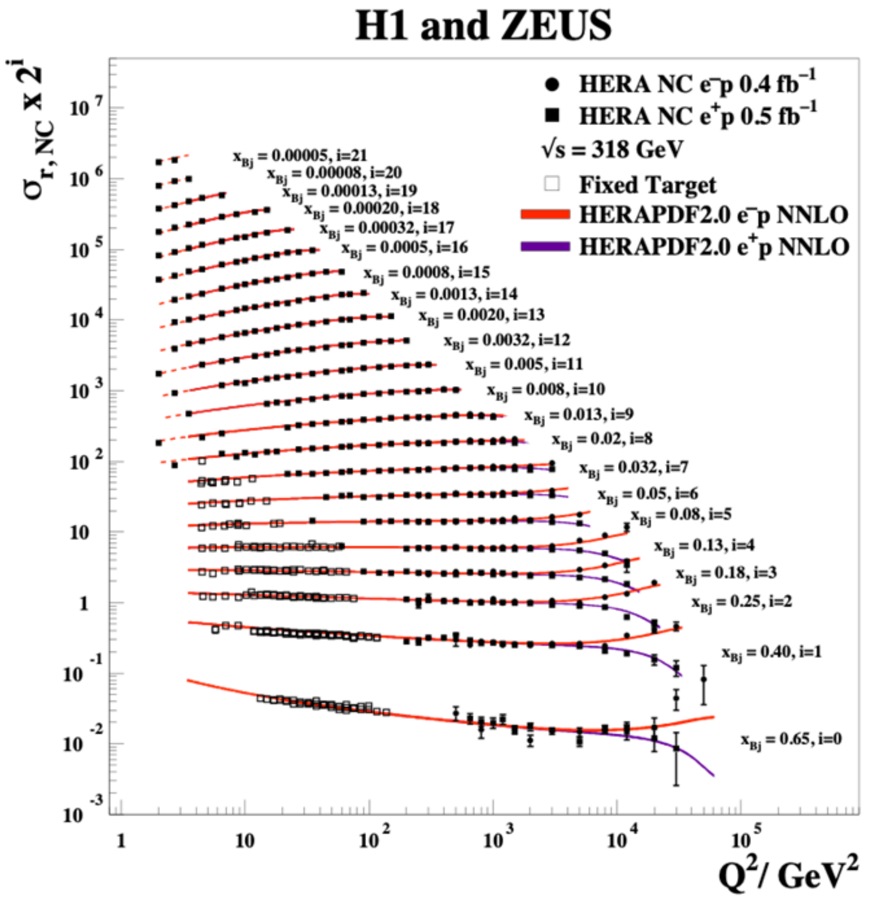
- Unpolarized PDF:

- PDF extraction: global fit to all available data

R. D. Ball et al., EPJ C77 (2017) 663.



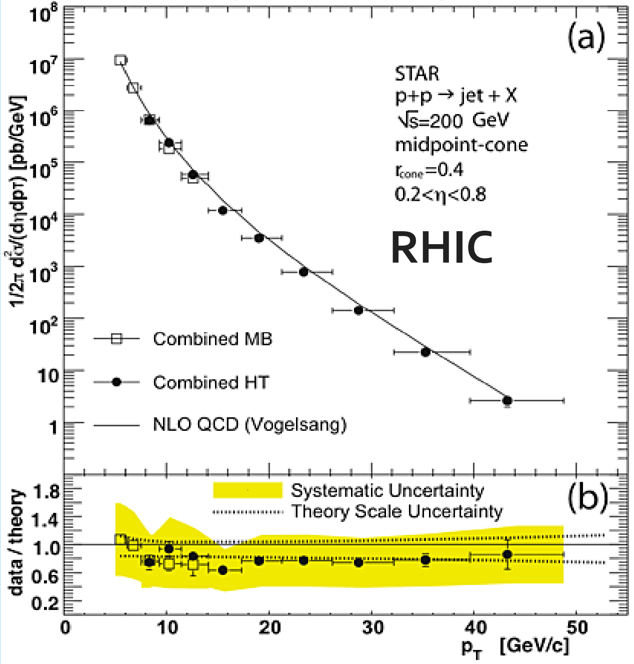
H1 and ZEUS Collaborations (H. Abramowicz et al.), Eur.Phys.J. C75 (2015) no.12, 580.



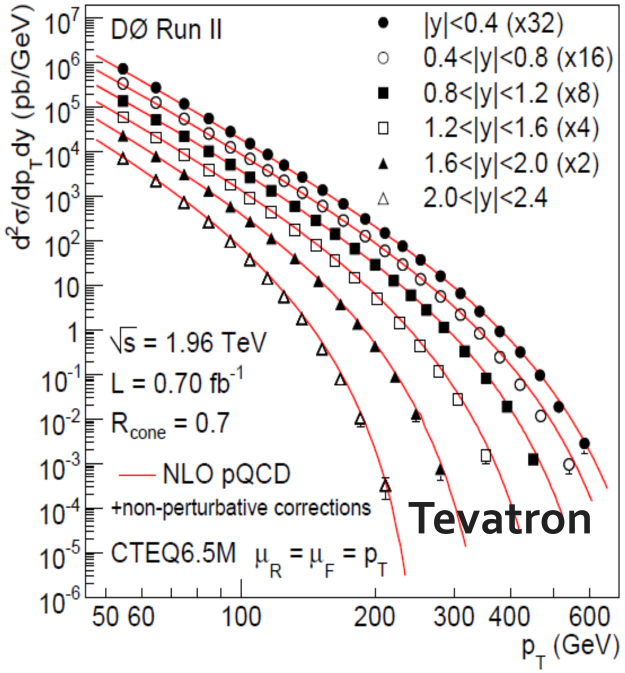
$$d\sigma_{eP} \propto F_2^P = \sum_i e_i^2\, x\, (q_i + \bar{q}_i)$$

Experimental Tests

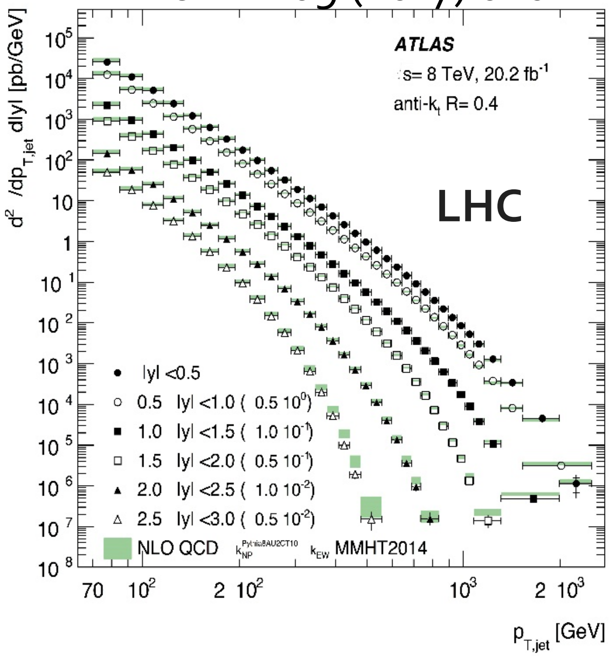
- A remarkable success of QCD!



PRL 97 (2006)252001



PRL101(2008)062001



JHEP 09 (2017) 020

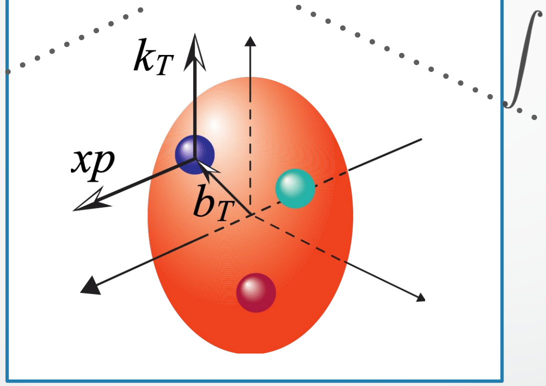
- Inclusive jet cross-sections agree with NLO calculations over many orders of p_T and $\sqrt{s}$
- Cross-sections for pions are also well-modeled; subtleties emerge for heavier particles

PDF Complexity

- Wigner Functions

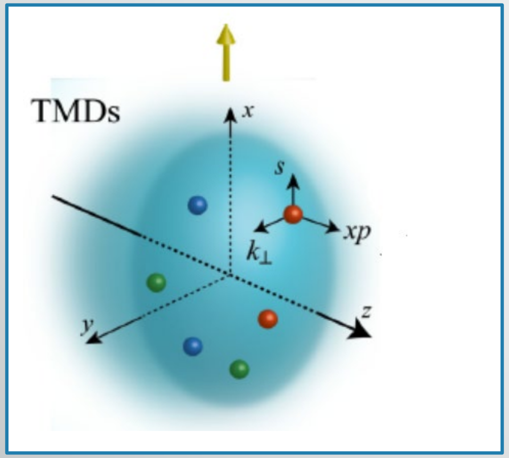
arXiv:1212.1701

$W(x, k_T, b_T)$



$\int d^2 b_T$

Transverse Momentum Dependent distributions



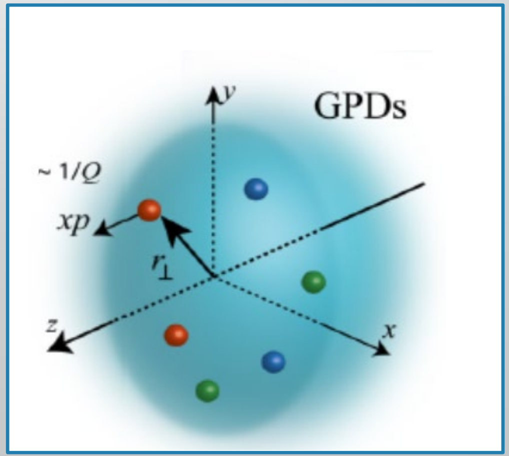
$\int d^2 k_T$

Impact Parameter Dependent distributions

$f(x, b_T)$

Fourier Transform

Generalized Parton Distributions



- Further integrations lead to

TMD: $f(x, k_T) \rightarrow$

GPD: $H(x, b_T) \rightarrow$

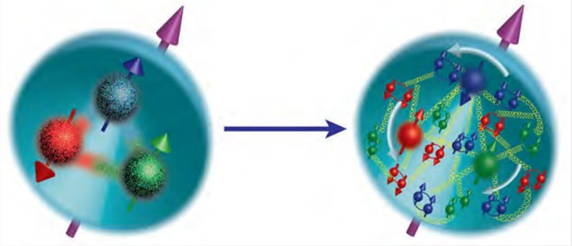
$f_1(x)$ – 1D PDFs

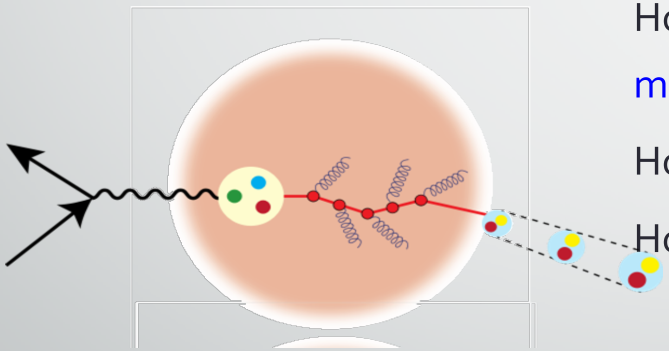
Motivation for EIC

- Open physics questions:

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?

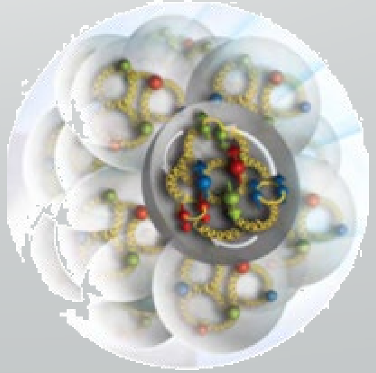




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

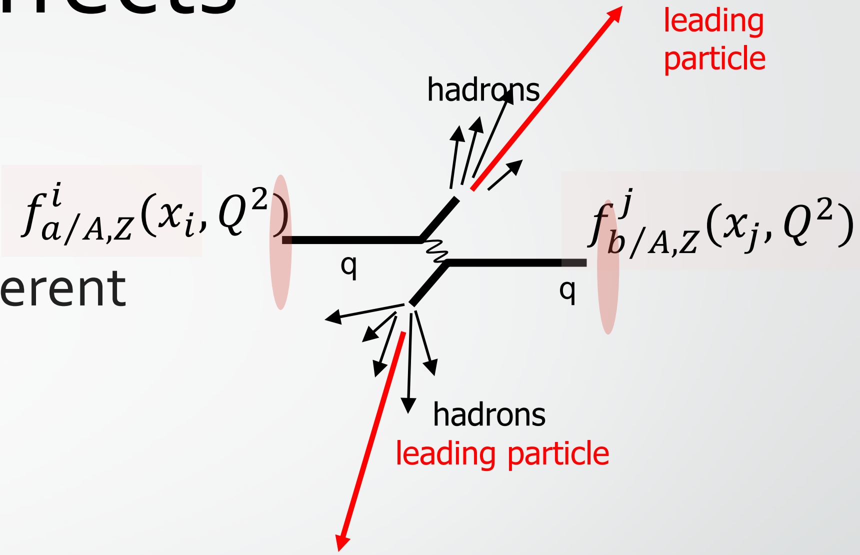


How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

Credit: Bernd Surrow

eA: Nuclear PDF effects



“Why QGP aficionados should care:”

Parton distribution functions for bound nucleons are different than that of a free proton

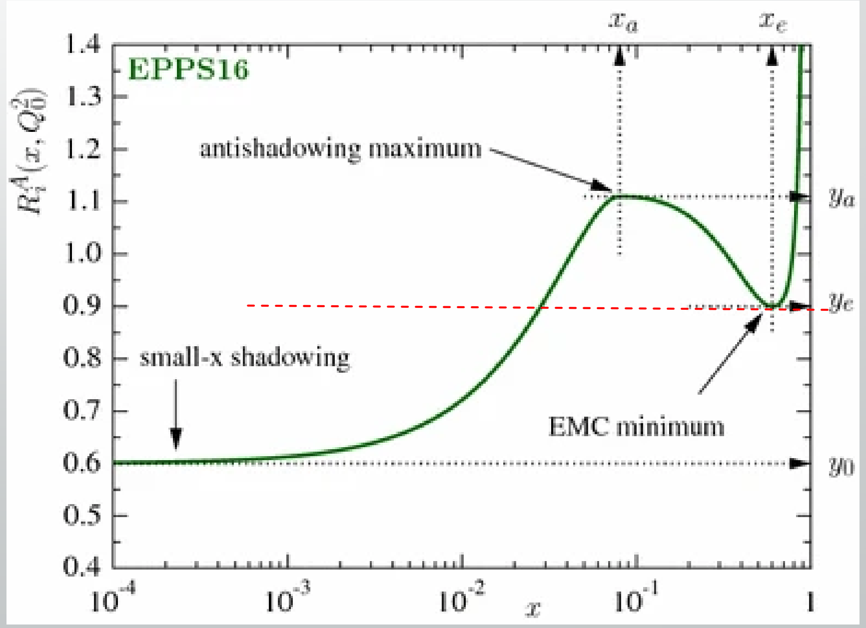
$f^i_{a/A,Z}(x_i, Q^2)$ – Nuclear *parton distribution functions,*

$$f^i_{a/A,Z}(x_i, Q^2) = \frac{Z}{A} f^i_{p/A}(x_i, Q^2) + \frac{A-Z}{A} f^i_{n/A}(x_i, Q^2)$$

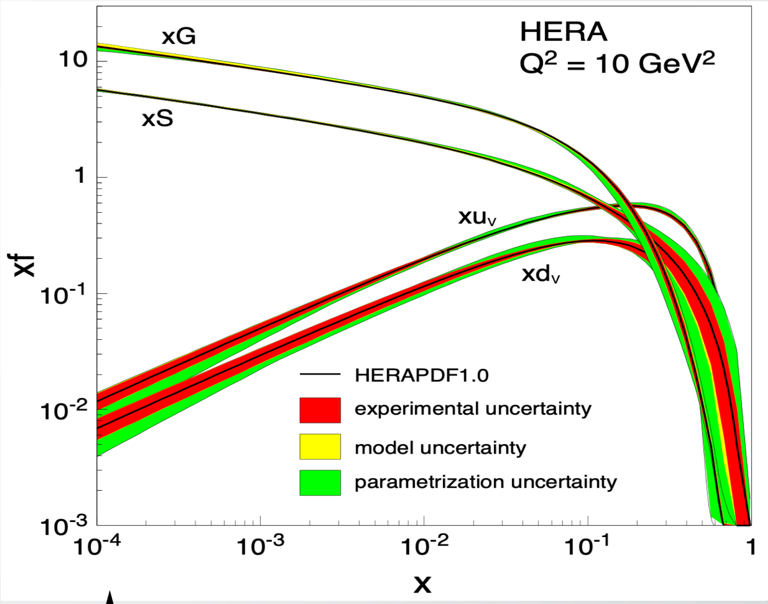
where Bound nucleon PDFs $f^i_{p/A}(x_i, Q^2)$ are connected to free nucleon PDF as (EPPS16, *EPJ C77(2017)163*):

$$f^i_{p/A}(x_i, Q^2) = R^i_A(x_i, Q^2) f^i_p(x_i, Q^2)$$

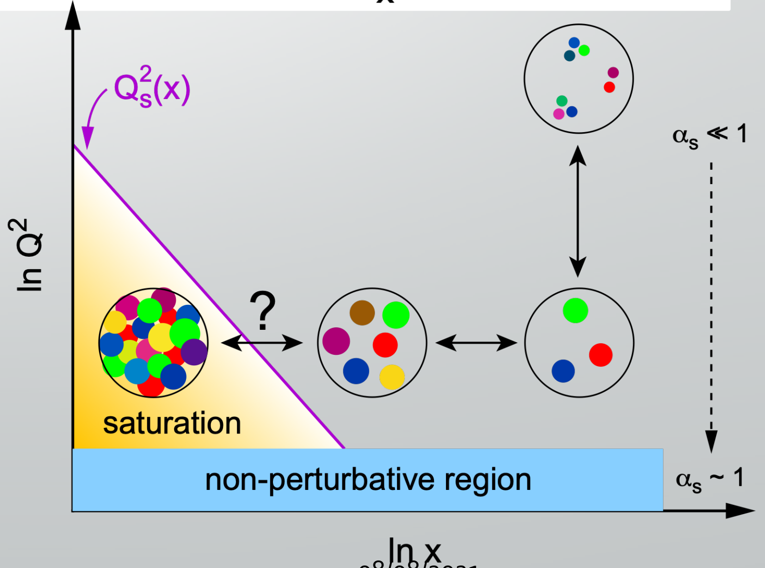
Nuclear PDF effects are critical to properly map QGP properties → eA collisions

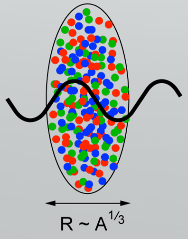


eA: Gluon Saturation



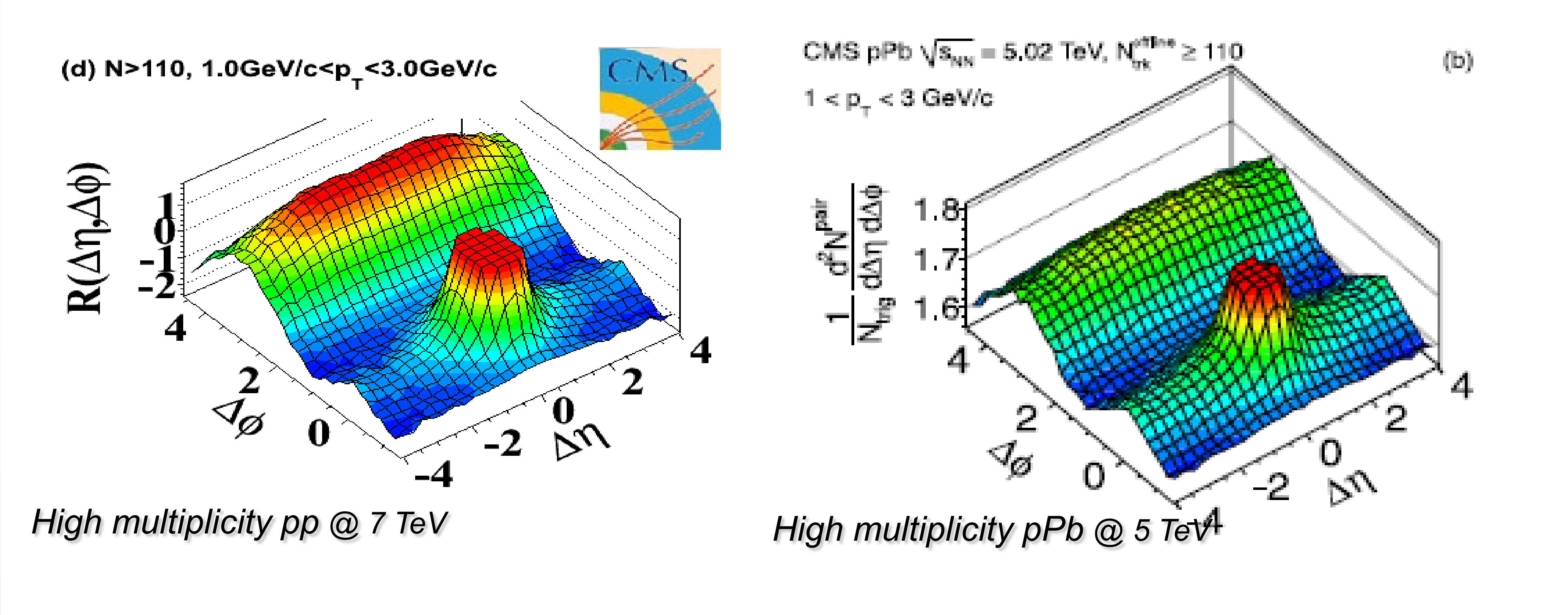
- Could the gluon density $G(x, Q^2)$ continuously grow?
- New idea: Non-Linear Evolution
  - Recombination compensates gluon splitting
  - New evolution equations
  - Saturation of gluon densities characterized by scale $Q_s(x)$
- Saturation → Color-Glass-Condensate (CGC)
- Experimentally, nucleus serves as Q_s amplifier





$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

eA: Long Range Correlations in pp



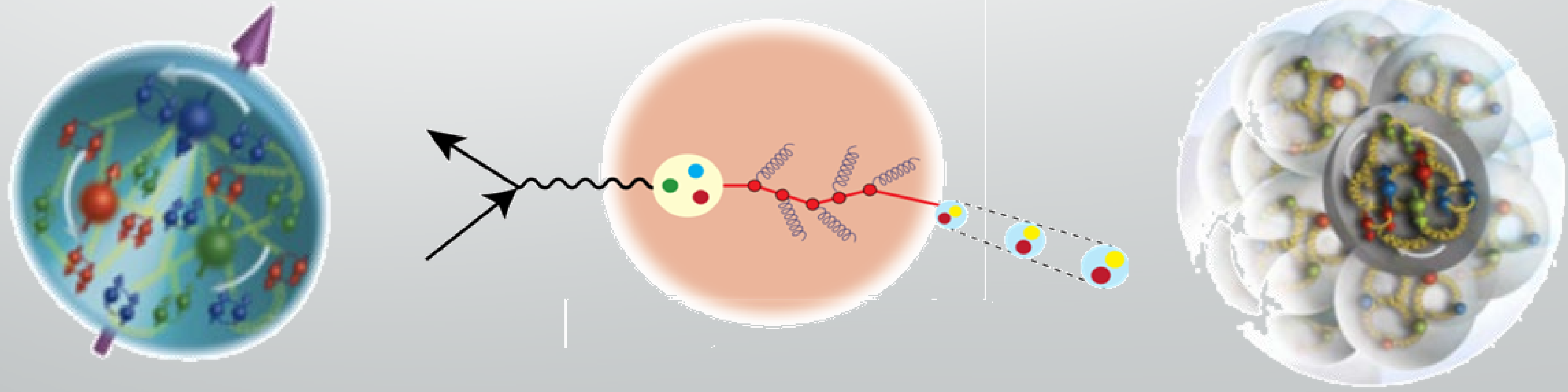
High multiplicity pp @ 7 TeV

High multiplicity pPb @ 5 TeV

- Long range correlations: everywhere! AA collisions, high multiplicity pp, pA
- Is this a manifestation of CGC?
- NOT reproduced in any established MC generators

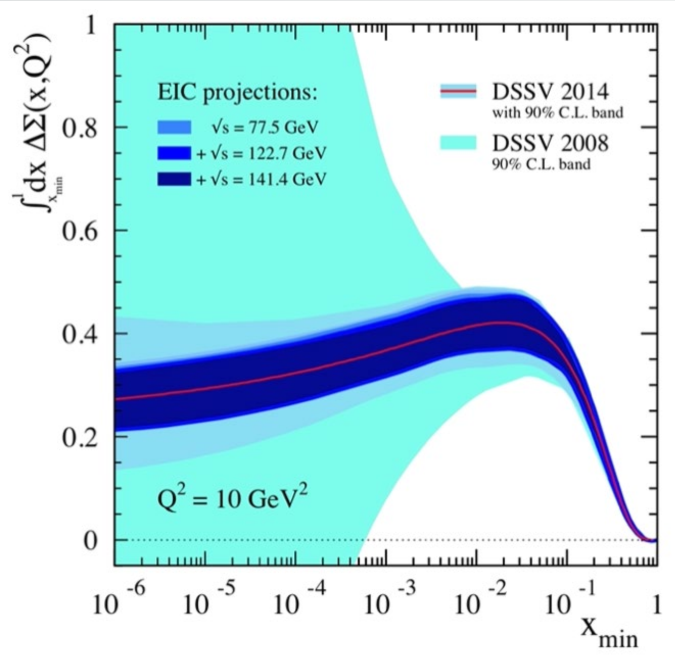
EIC- a new QCD laboratory

- Envisioned as a premier facility to study the structure and dynamics of the visible matter
- Major physics goals:
  - Understanding the properties of hadrons (mass, spin)
  - Complete (3D) imagine of hadrons
    - PDF, TMD, GPD
  - Properties of QCD nuclear matter at high parton densities
  - Emergence of hadrons
    - Hadronization, universality tests

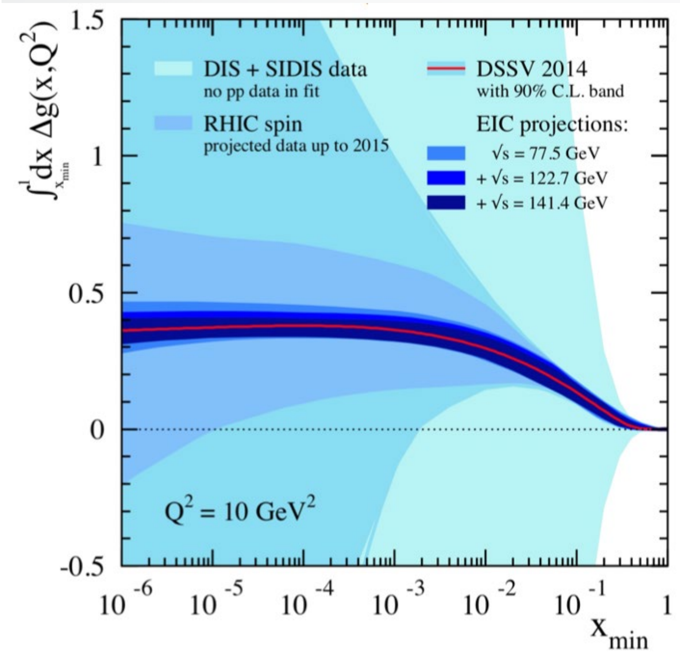


EIC Expected Impact Example

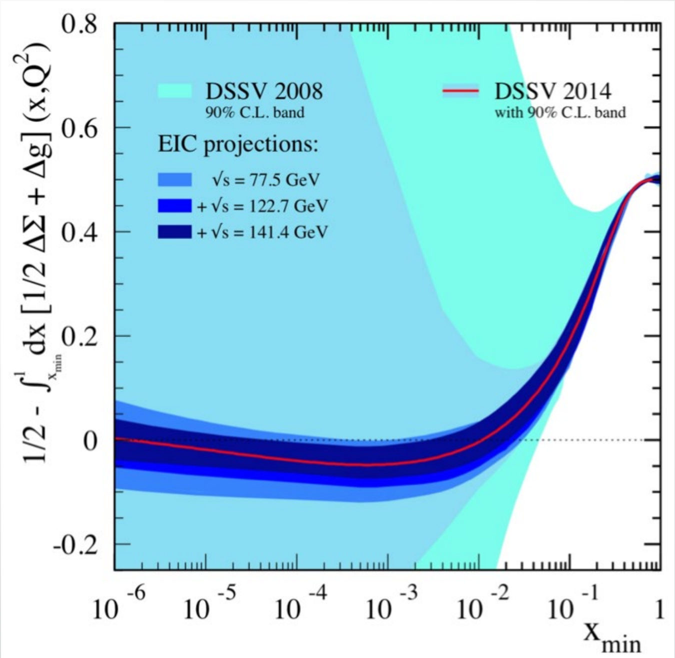
E. Aschenauer, R. Sassot and M. Stratmann, Phys. Rev. D92 (2015) 094030.



Quark Spin



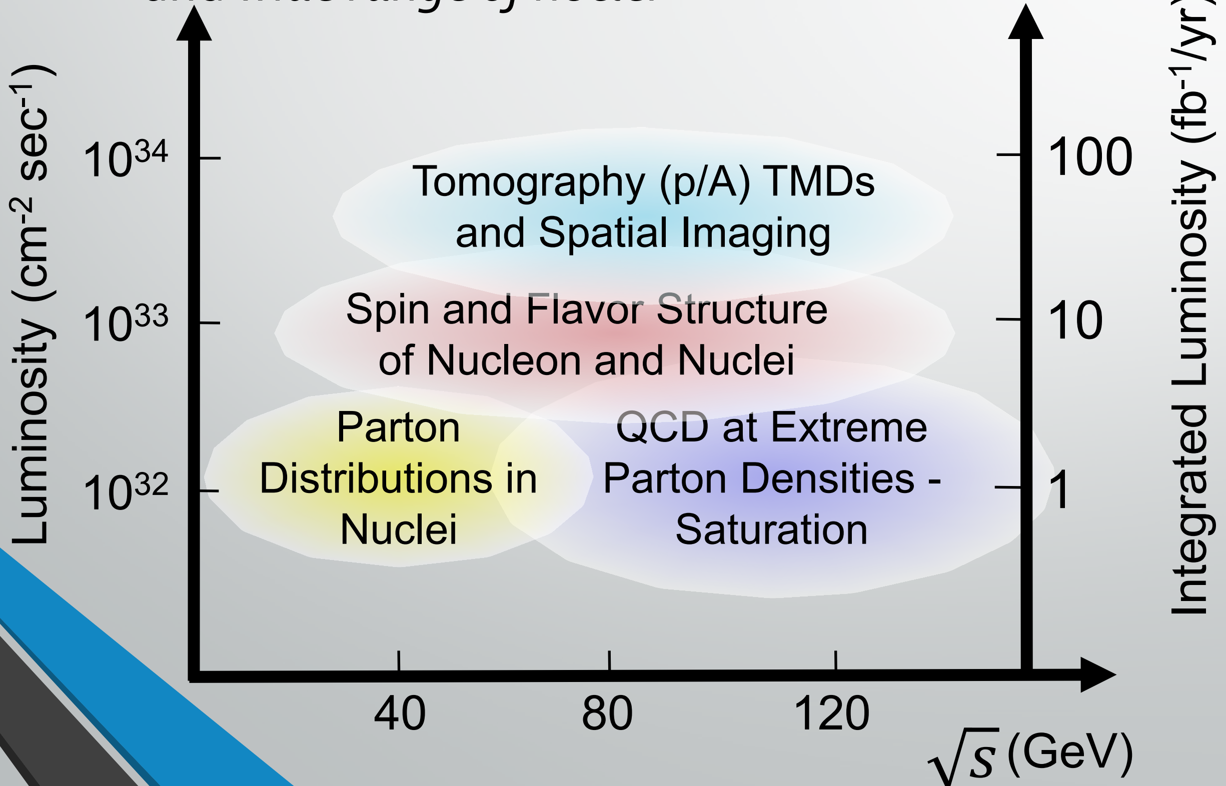
Gluon Spin



Orbital Angular Momentum

"Understanding the Glue that Binds us All"

- EIC: Study structure and dynamics of matter at *high luminosity*, *high energy* with *polarized beams* and *wide range of nuclei*



Tomography (p/A) TMDs and Spatial Imaging

Spin and Flavor Structure of Nucleon and Nuclei

Parton Distributions in Nuclei

QCD at Extreme Parton Densities - Saturation

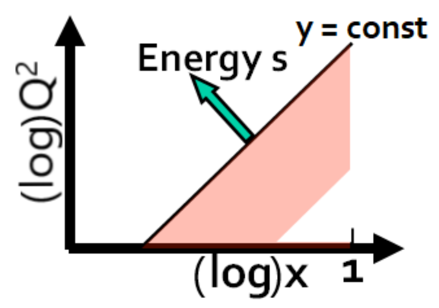
Electron Ion Collider: The Next QCD Frontier

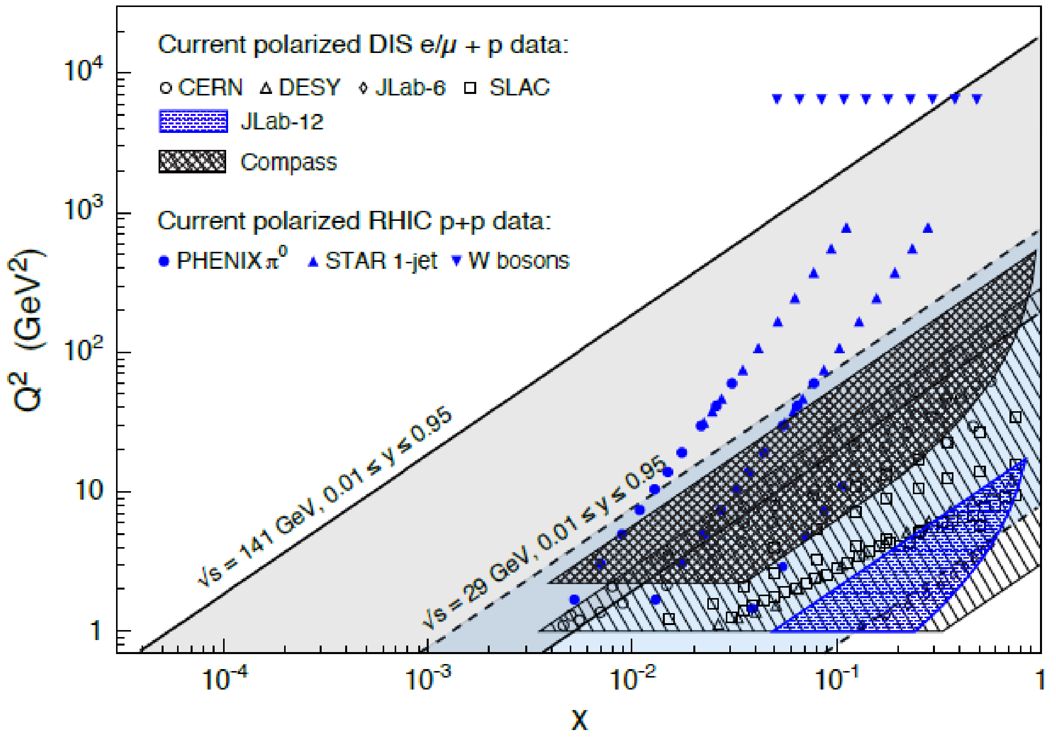
Understanding the glue
that binds us all

SECOND EDITION

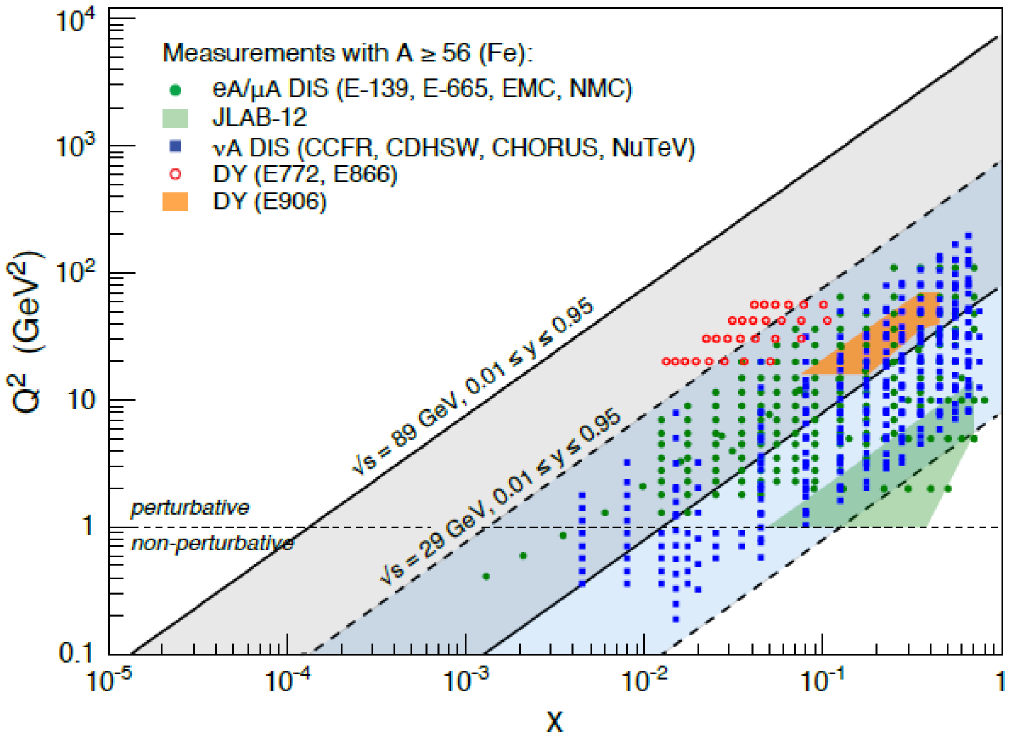
[EIC Whitepaper: arXiv:1212.1701](arXiv:1212.1701) Credit: Bernd Surrow

EIC Kinematic Reach





Polarized ep



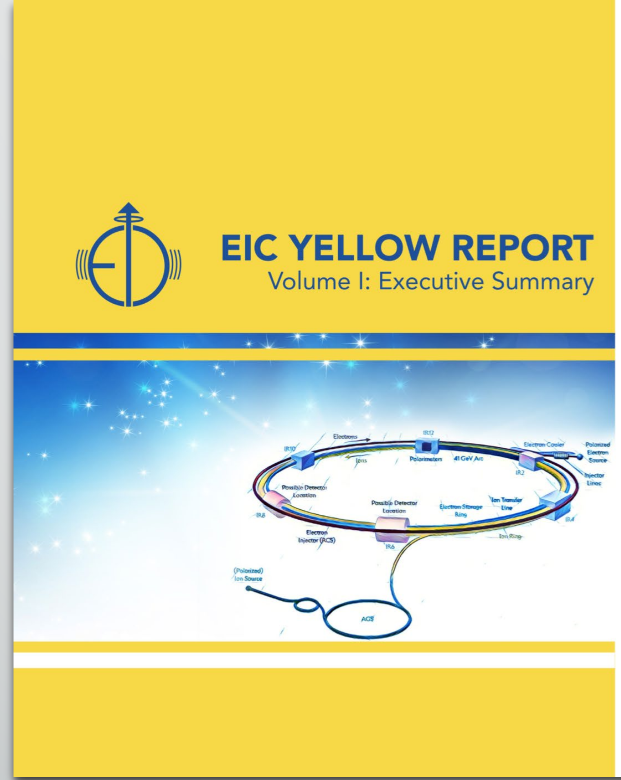
Polarized eA.

Community Effort to Define EIC Detector

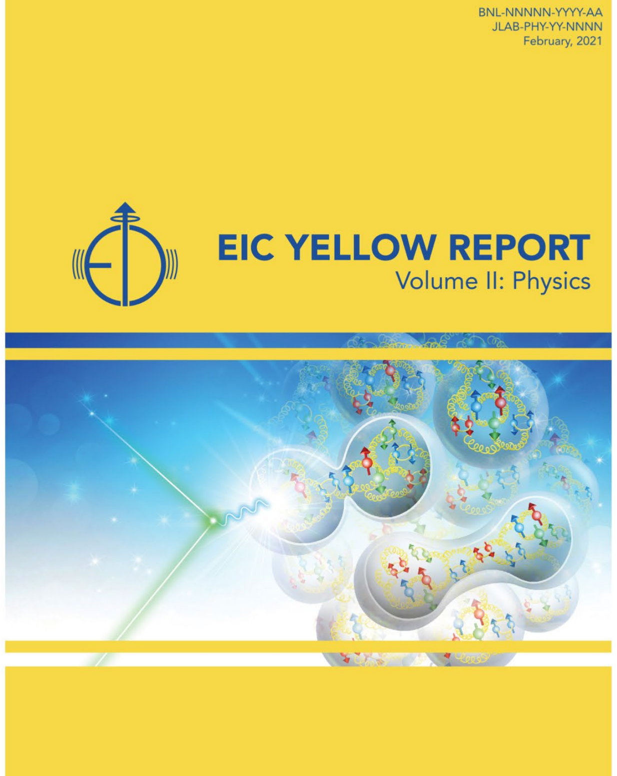
- Major effort in 2019-2021: the Yellow Report
- After EIC CD0, EICUG announced the start of a Yellow Report study in preparation of the EIC program:
- Quantify physics measurements for existing or new physics topics and implications for detector design ("Physics WG")
- Study detector concepts based on the requirements defined above, and quantify implications for physics measurements ("Detector WG")

- A year-long effort with 4 dedicated Yellow Report workshops:
  - 1st YR Workshop: March 19-21, 2020: Temple University, US
  - 2nd YR Workshop: May 22-24, 2020: INFN Pavia, Italy
  - 3rd YR Workshop: September 17-19, 2020, CUA, Washington DC, US
  - 4th YR Workshop: November 19-21, 2020: UCB, Berkeley, US
- Yellow Report summarized the developed input for conceptual and technical design report

Community Effort to Define EIC Detector



EIC YELLOW REPORT
Volume I: Executive Summary



BNL-NNNNN-YYYY-AA
JLAB-PHY-YY-NNNN
February, 2021

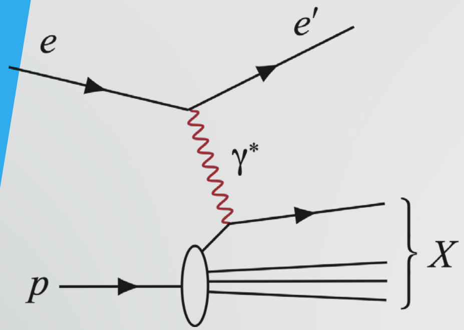
EIC YELLOW REPORT
Volume II: Physics

BNL-NNNNN-YYYY-AA
JLAB-PHY-YY-NNNN
February, 2021

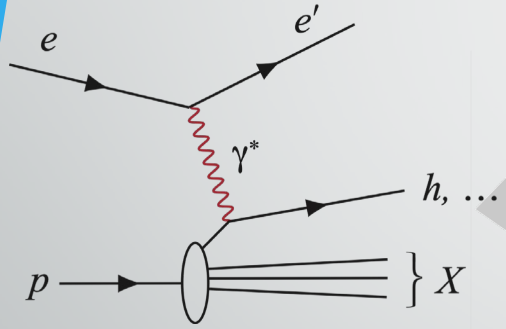
EIC YELLOW REPORT
Volume III: Detector

- ~400 authors / ~150 institutions / ~900 pages with strong international contributions!
- Review, community input, and editorial process completed: https://arxiv.org/abs/2103.05419
- Best reference guide for EIC detector requirements and technologies

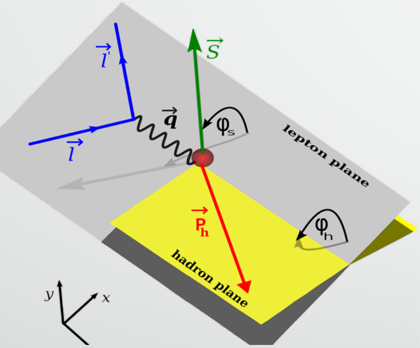
DIS Processes and Final States

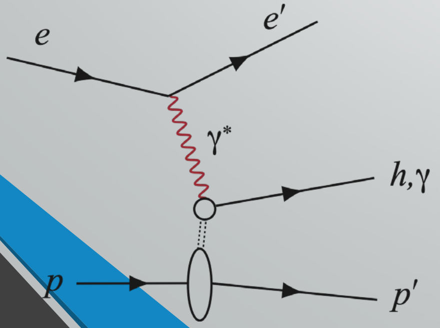


Inclusive DIS



Semi-Inclusive DIS (SDIS)





Deeply-Virtual Compton Scattering (DVCS)

- **Inclusive**: Unpolarized fi(x,Q^2) and helicity distribution Δfi(x,Q2) functions through unpolarized and polarized structure function measurements (F_2, F_L, g_1)

  Define kinematics (x, y, Q^2) through electron (e-ID and E' + θ resolutions are critical) / hadron final state or combination of both depending on kinematic x-Q^2 region

- **SIDIS**: Flavor tagging through hadron identification studying FF / TMD's

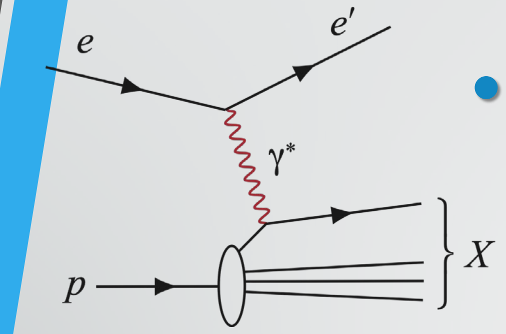
  (Transverse momentum, k_T, dependence) requiring azimuthal asymmetry measurement - Full azimuthal acceptance. Heavy flavor (*c*, *b*): Excellent secondary vertex reconstruction

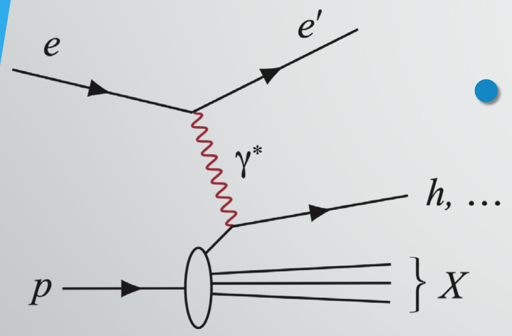
- **Exclusive:** Tagging of final state proton using Roman pot system studying GPD's (Impact parameter, b_T, dependence) using DVCS and VM production

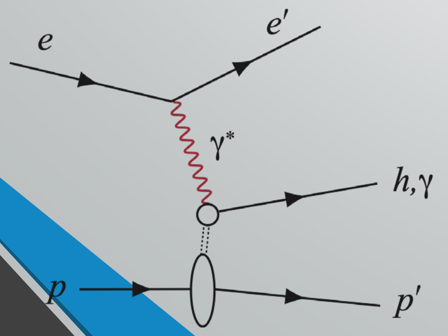
- **eA**: Impact parameter determination / Neutron tagging (ZDC)

Credit: Bernd Surrow

Detector Requirements: How and Why?



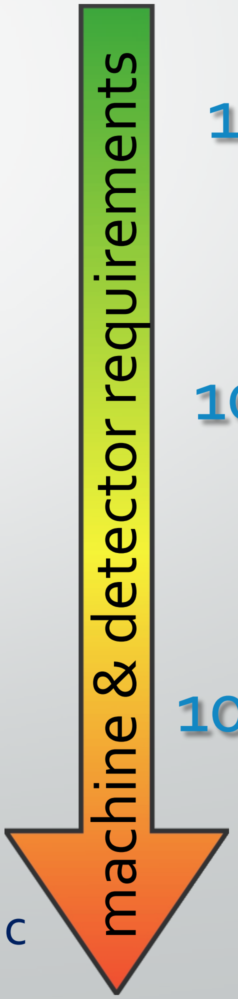




- **Inclusive:** fine binning in x, Q^2
- **SIDIS:** 5-dimensional binning in x, Q^2, z, p_T, θ
- **Exclusive:** 4-dimensional binning in x, Q^2, t, θ

- e ID, reaching lowest x, Q^2
- Hadron PID over wide range is critical
- Forward, backward region is key

$\int \mathcal{L} dt$


machine & detector requirements

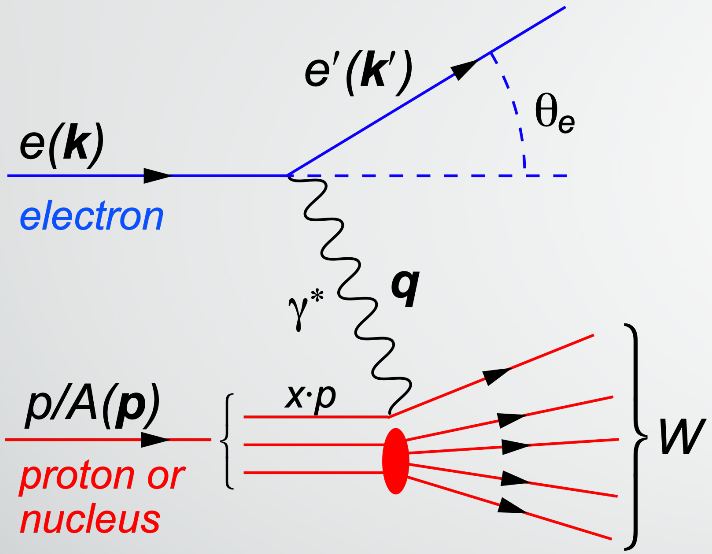
1 fb^{-1}

10 fb^{-1}

10-100 fb^{-1}

Let's start with basic kinematics: how to reconstruct the basic variables from the observed final state

Electron Method



- Squared center of mass energy: from beam parameters

$$s \approx 4E_eE_p$$

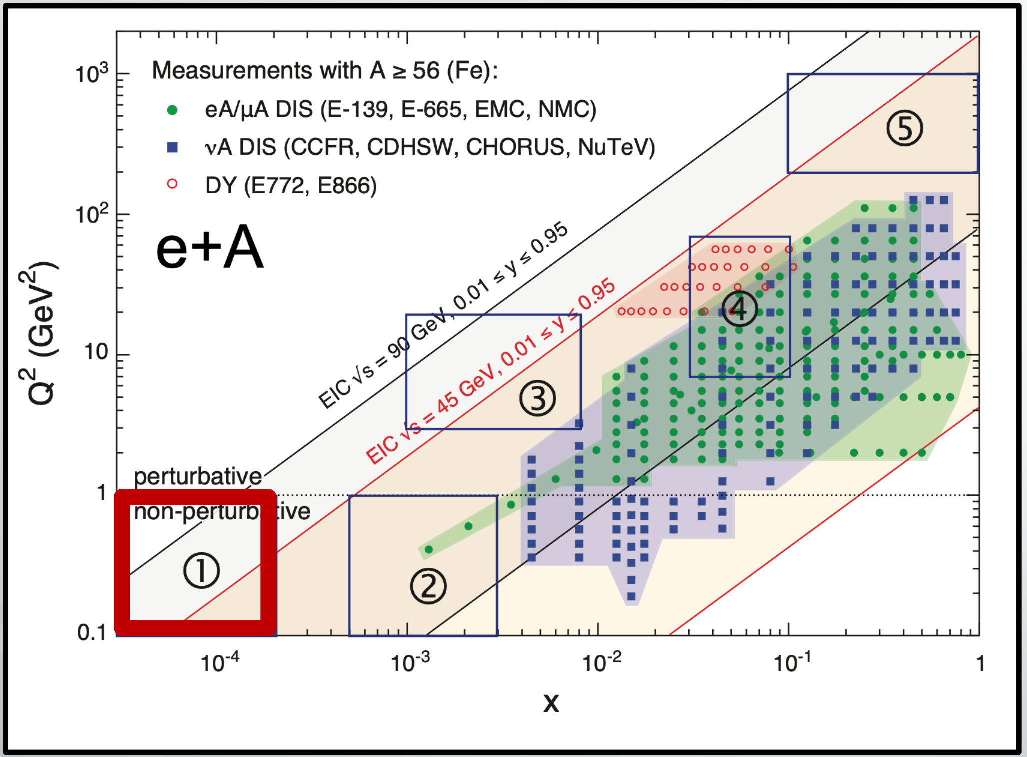
- Squared momentum transfer from scattered electron

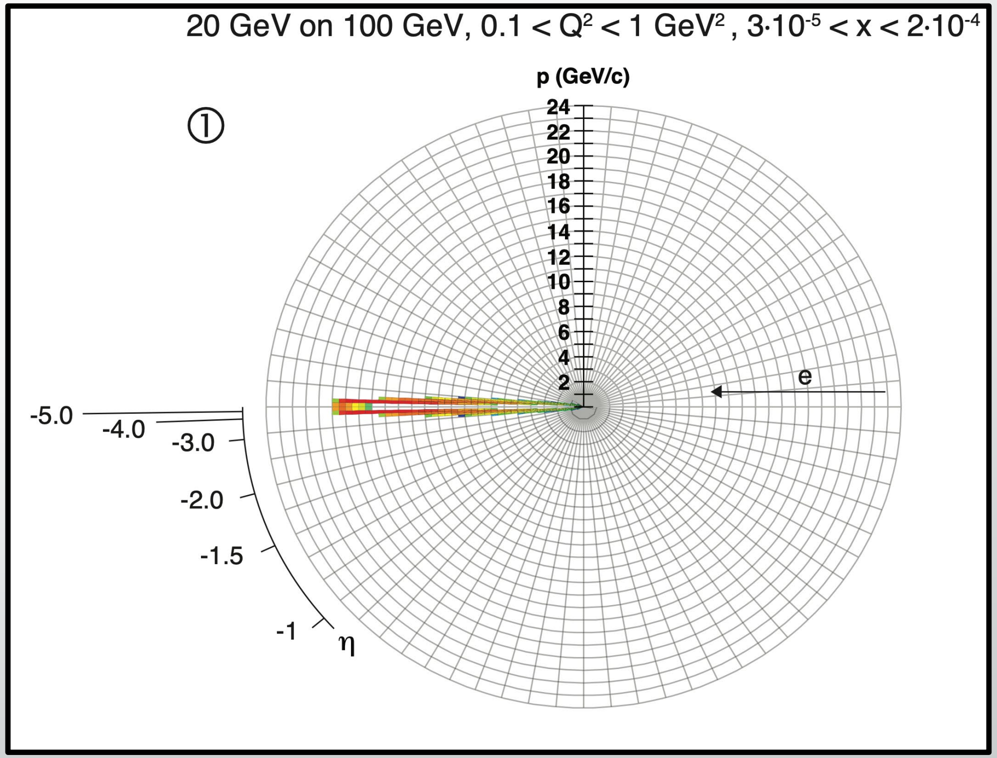
$$Q^2 = 4E_eE_e' sin^2\left(\frac{\theta_e}{2}\right)$$

- Inelasticity: $y = 1 - \frac{E_e'}{E_e} cos^2\left(\frac{\theta_e}{2}\right)$

- Bjorken x is then calculated from $x = \frac{Q^2}{sy}$

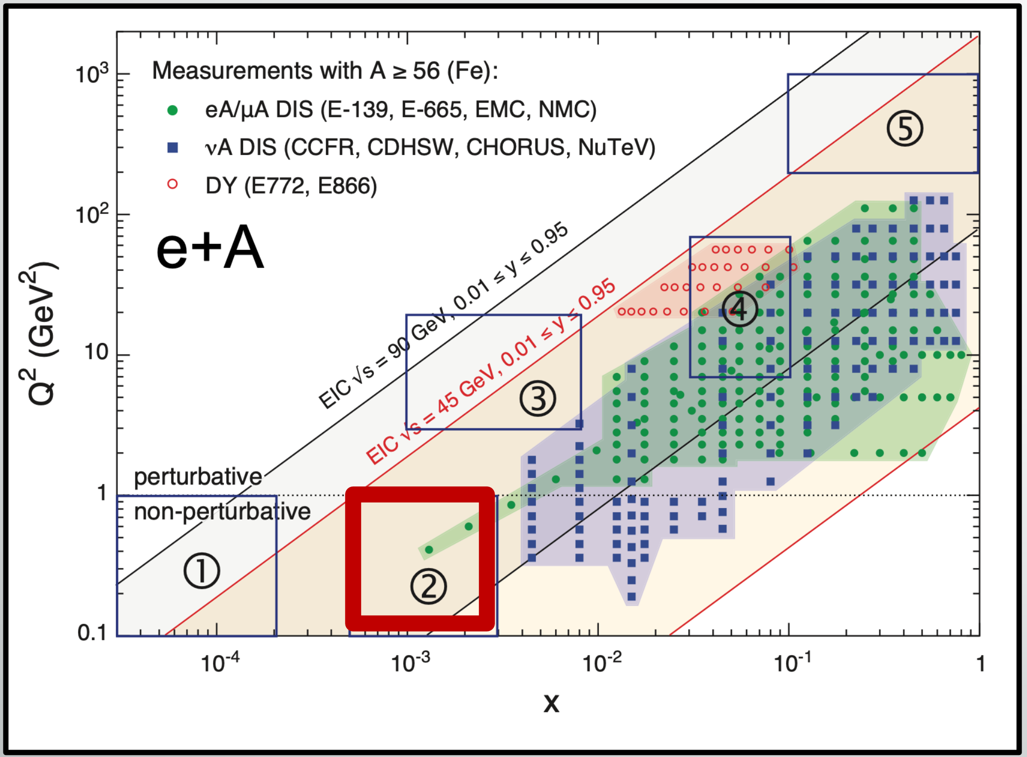
Electron Method: Kinematic Range

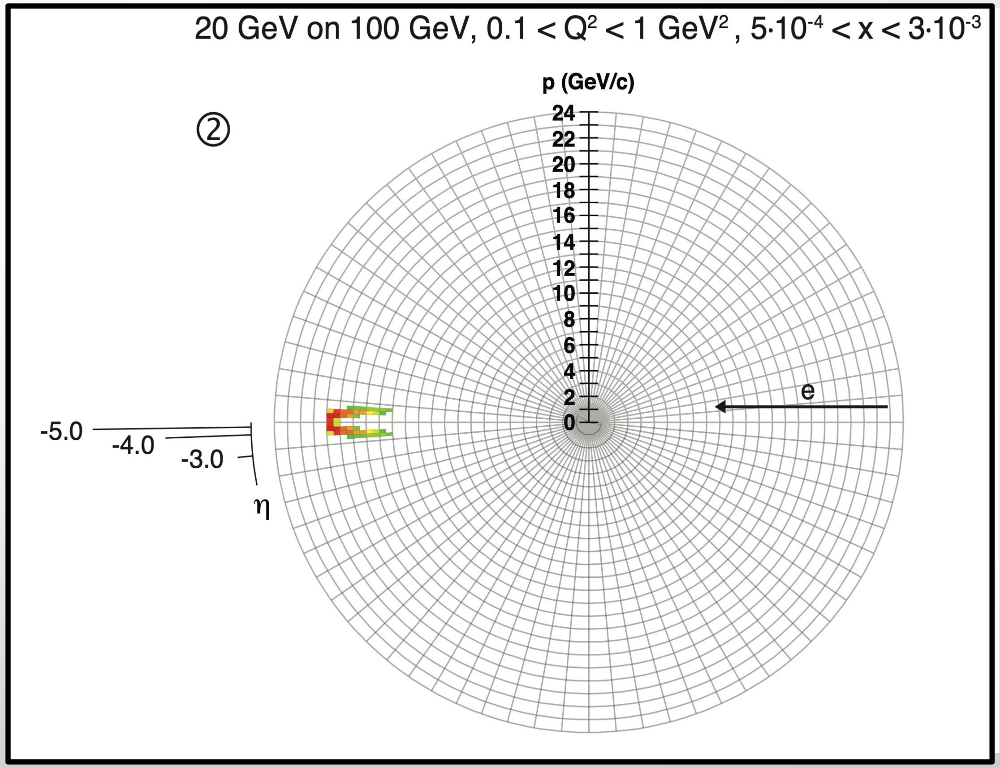




$$\eta = -\ln\tan\left(\frac{\theta}{2}\right)$$

Electron Method: Kinematic Range

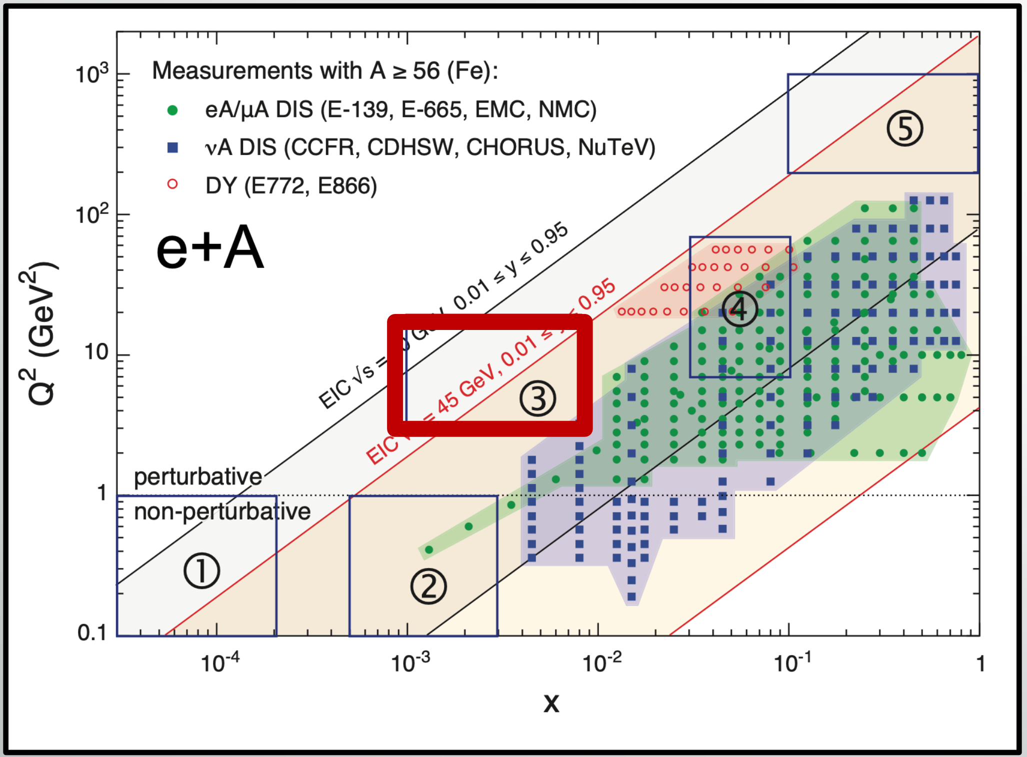


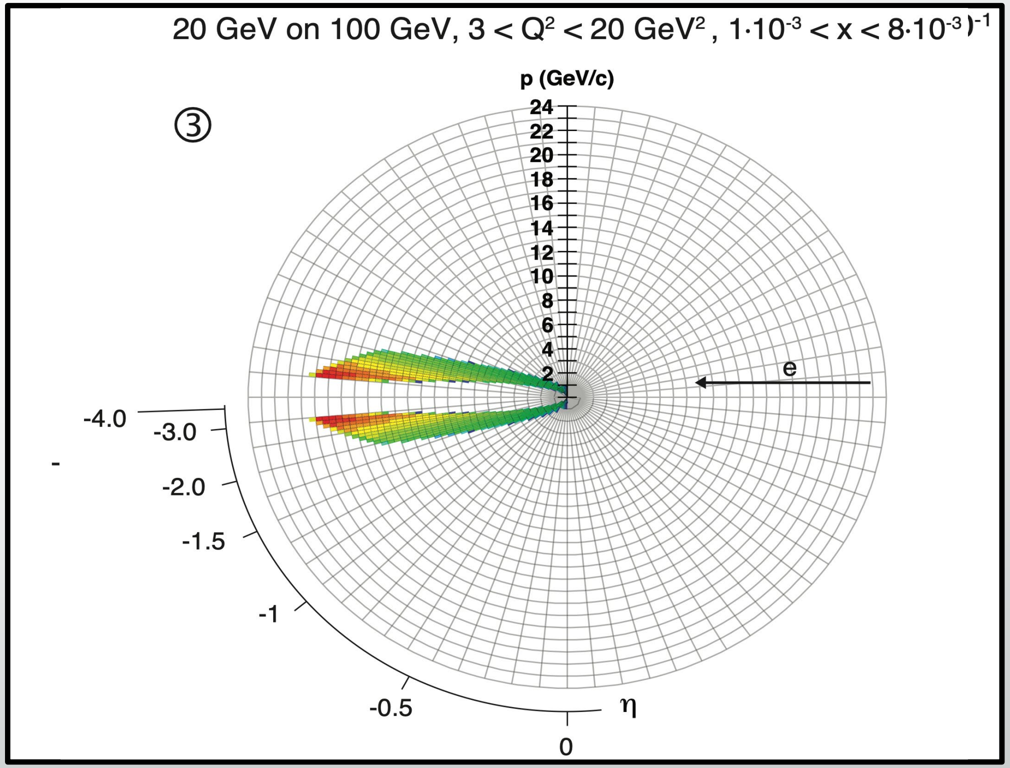


20 GeV on 100 GeV, $0.1 < Q^2 < 1$ GeV^2, $5\cdot10^{-4} < x < 3\cdot10^{-3}$

$$\eta = -\ln\tan\left(\frac{\theta}{2}\right)$$

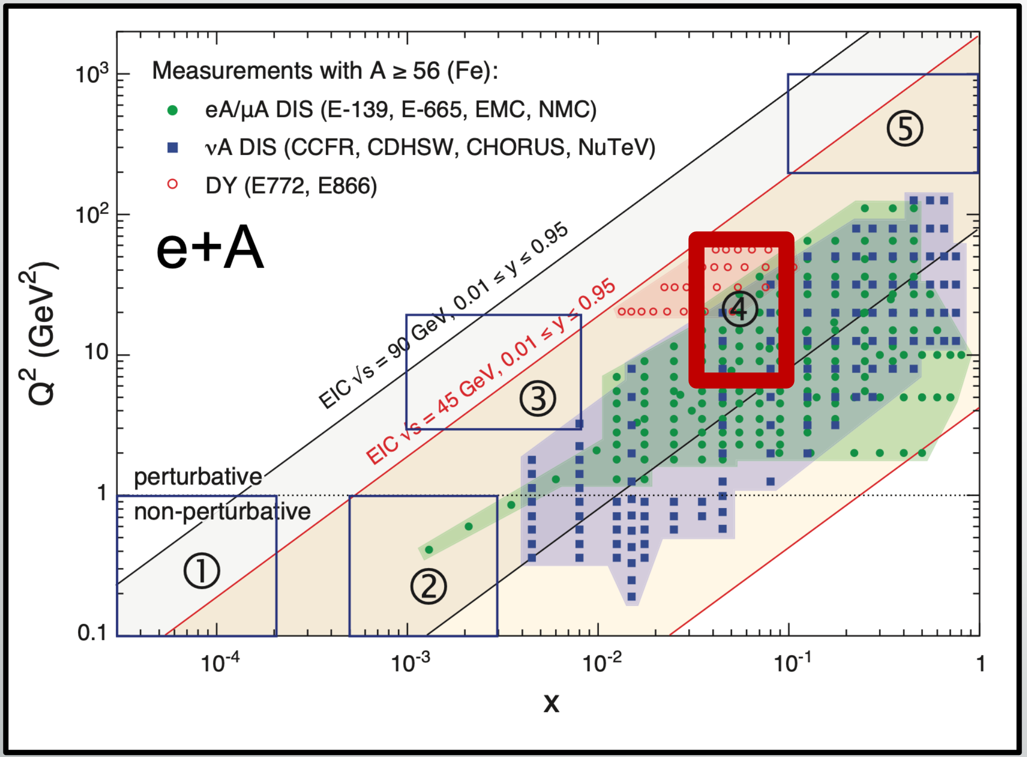
Electron Method: Kinematic Range

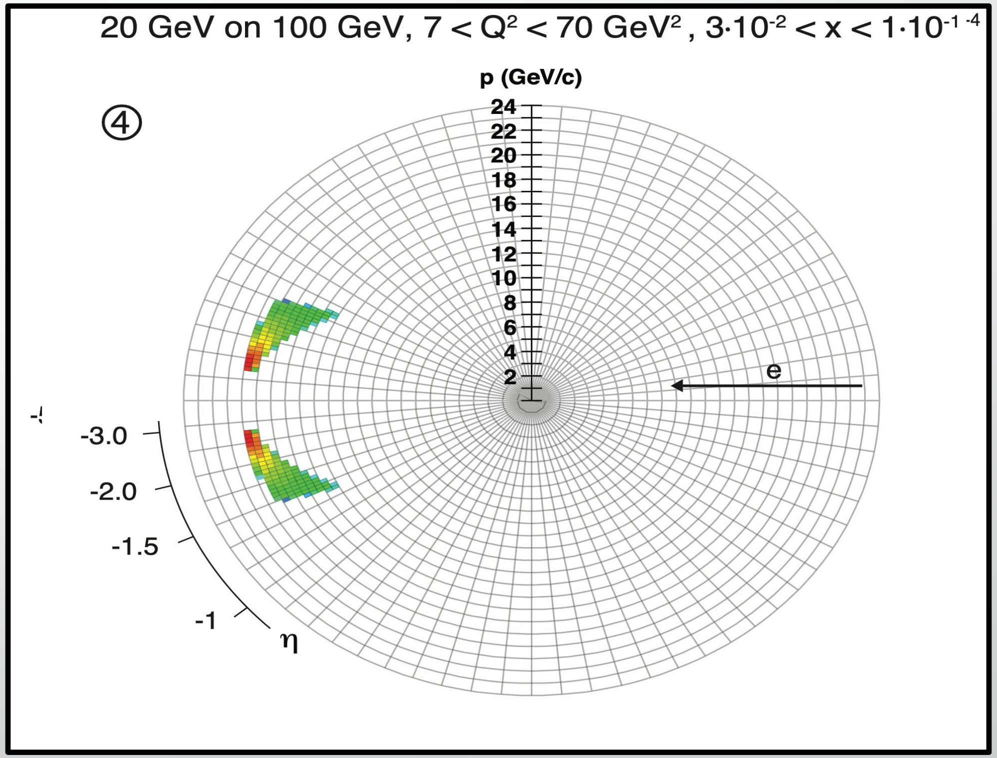




$$\eta = -\ln\tan\left(\frac{\theta}{2}\right)$$

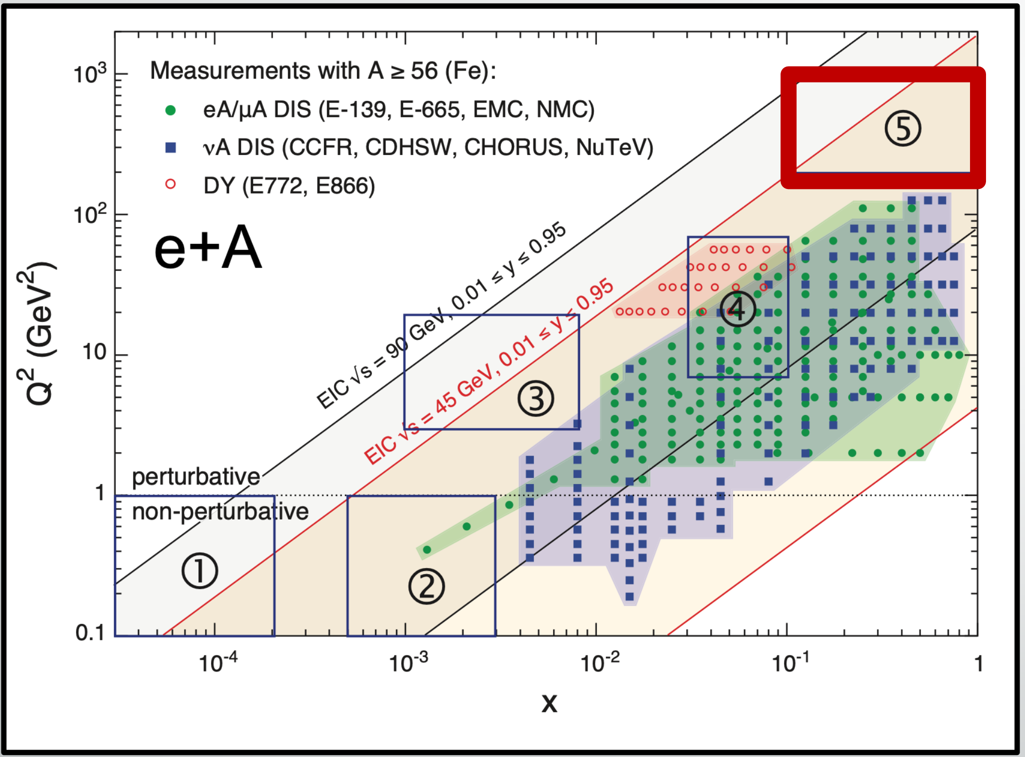
Electron Method: Kinematic Range

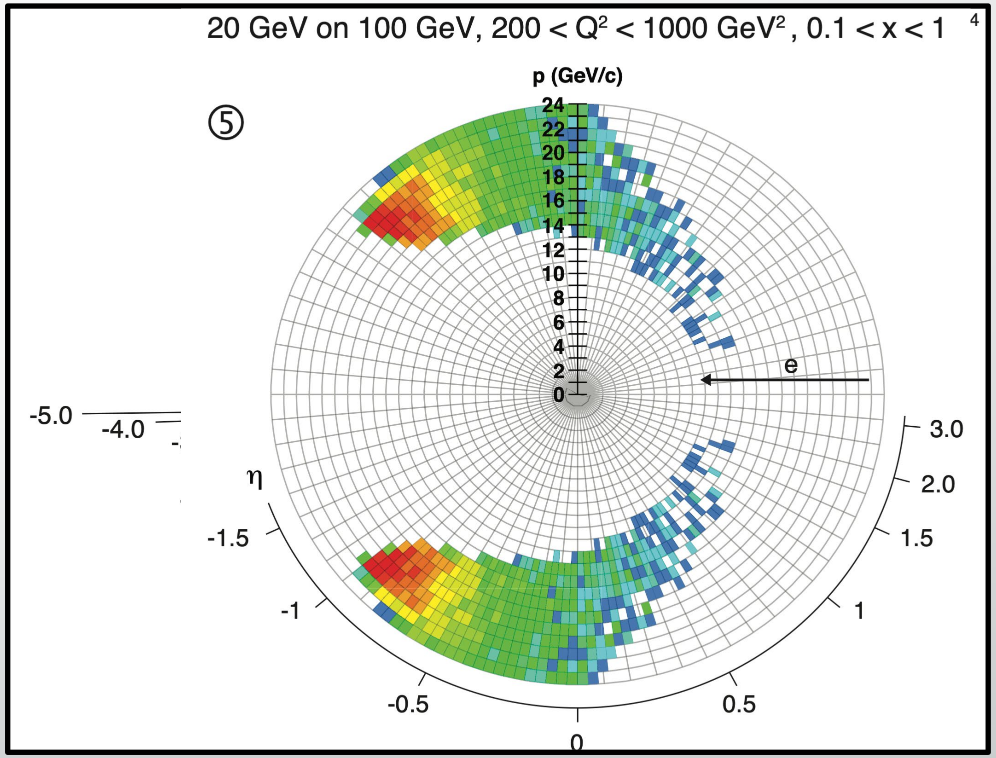




$$\eta = -\ln\tan\left(\frac{\theta}{2}\right)$$

Electron Method: Kinematic Range

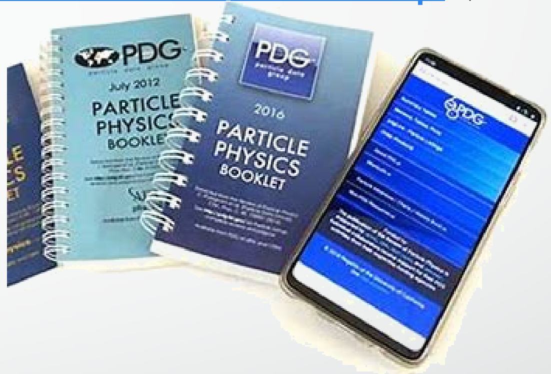




$$\eta = -\ln\tan\left(\frac{\theta}{2}\right)$$

What If There Is No Electron?

- There are over 200 known particles species (see Particle Data Group (PDG))
  - Less than 30 have cτ > 1µm
  - Only 13 have cτ > 500µm



- Stable(-enough) particles:
  - Electrons/positrons ($e^{\pm}$)
  - Photons (γ)
  - Several charged hadrons ($\pi^{\pm}, K^{\pm}, p, \bar{p}$)
  - Neutral hadrons ($n, K^0{}_L$)
  - Muons ($\mu^{\pm}$)
  - Neutrinos (ν)

Could be detected/distinguished by their interactions with the detector! (next lecture)

Need/want to know/measure:

Momentum / Energy
Charge
Origin (vertex)
Particle ID

Kinematics Reconstruction

- Multiple methods are available!

$$\Sigma = \sum_h (E_h - p_{z,h})$$

$$T = \sqrt{(\sum_h p_{x,h})^2 + (\sum_h p_{y,h})^2}$$

$$\tan\frac{\gamma}{2} = \frac{\Sigma}{T}$$

U. Bassler and G. Bernardi, NIM A361 (1995) 197-208

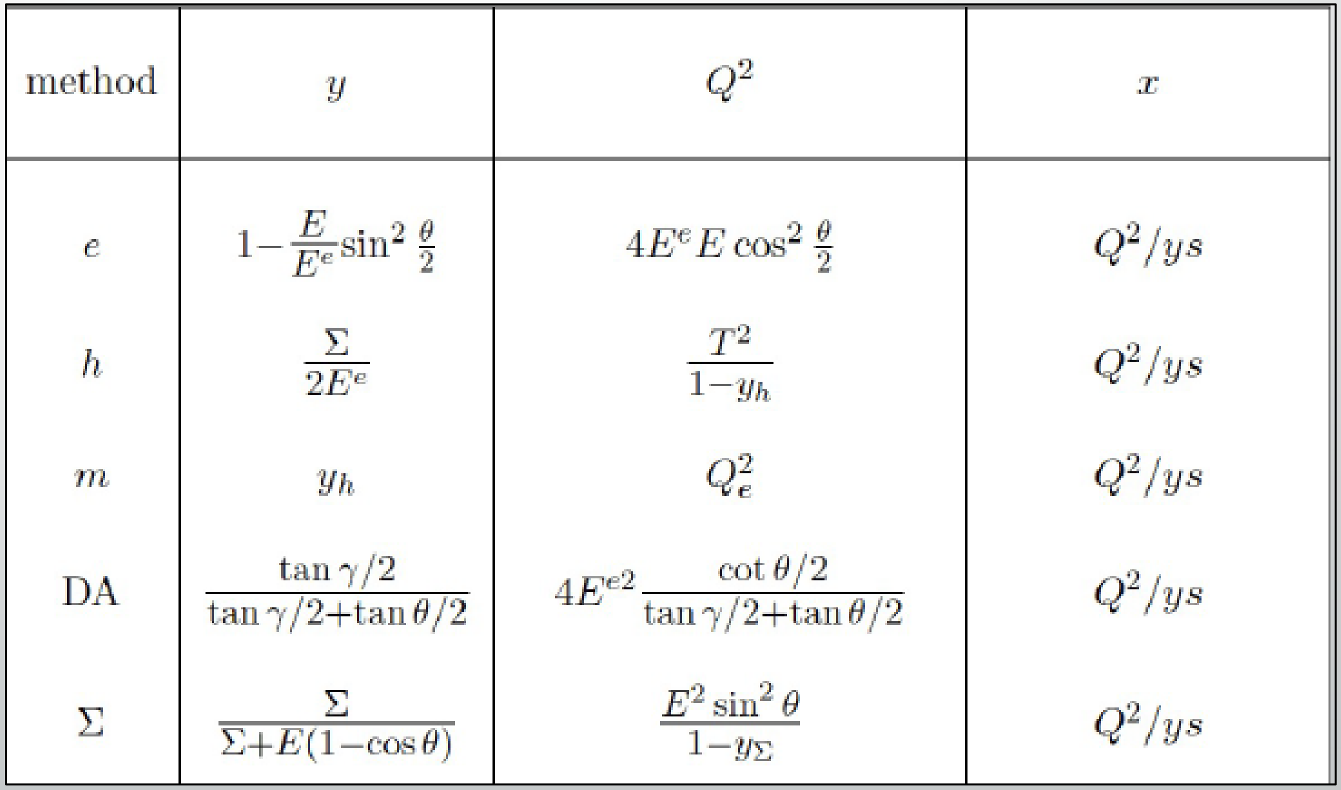
Electron

Hadron (Jacquet-Blondel)

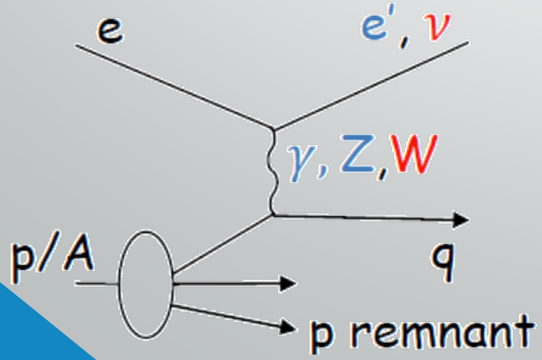
Mixed

Double-angle

Sigma



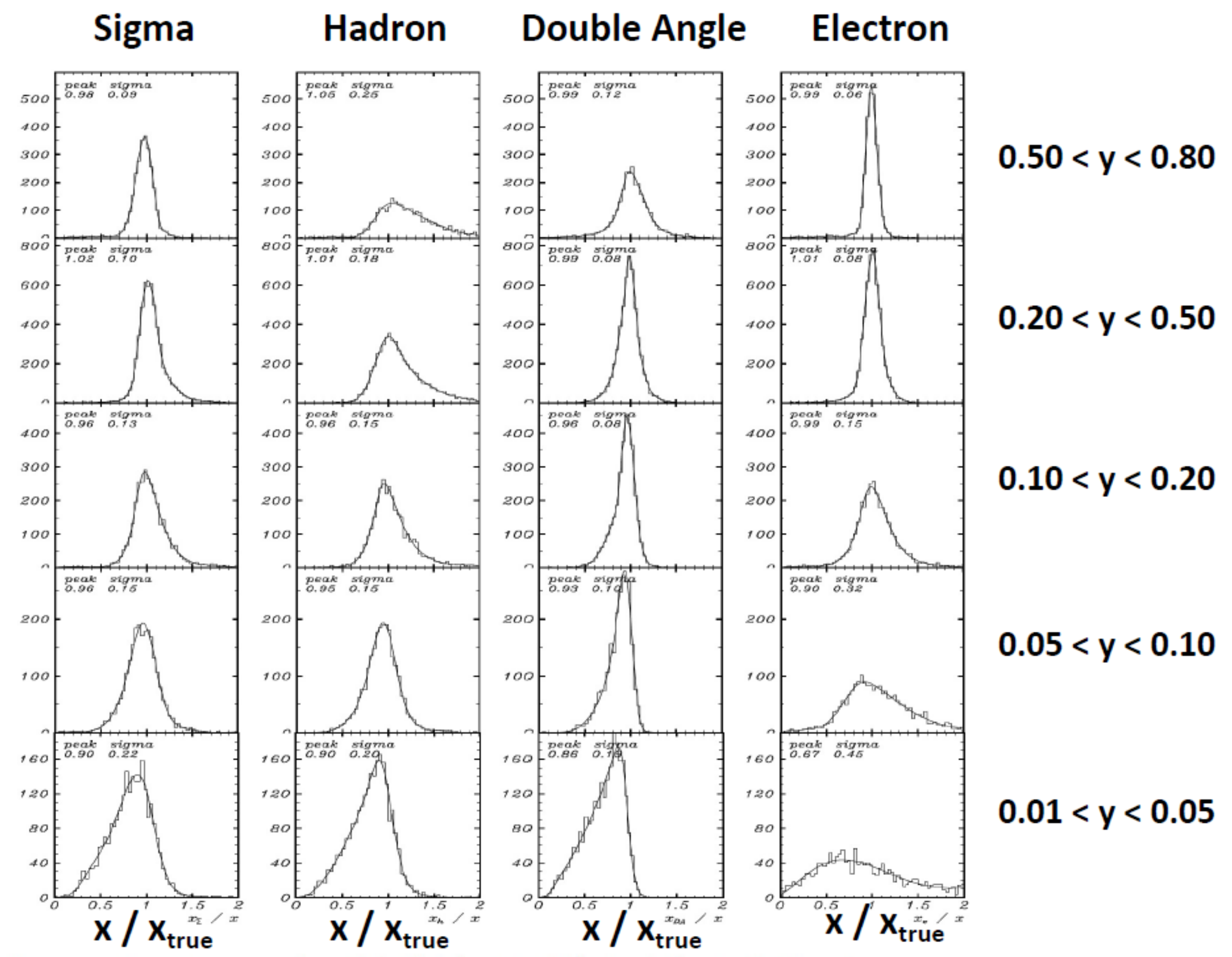
method	y	Q^2	x
e	$1-\frac{E}{E^e}\sin^2\frac{\theta}{2}$	$4E^eE\cos^2\frac{\theta}{2}$	Q^2/ys
h	$\frac{\Sigma}{2E^e}$	$\frac{T^2}{1-y_h}$	Q^2/ys
m	y_h	Q_e^2	Q^2/ys
DA	$\frac{\tan\gamma/2}{\tan\gamma/2+\tan\theta/2}$	$4E^{e2}\frac{\cot\theta/2}{\tan\gamma/2+\tan\theta/2}$	Q^2/ys
Σ	$\frac{\Sigma}{\Sigma+E(1-\cos\theta)}$	$\frac{E^2\sin^2\theta}{1-y_\Sigma}$	Q^2/ys



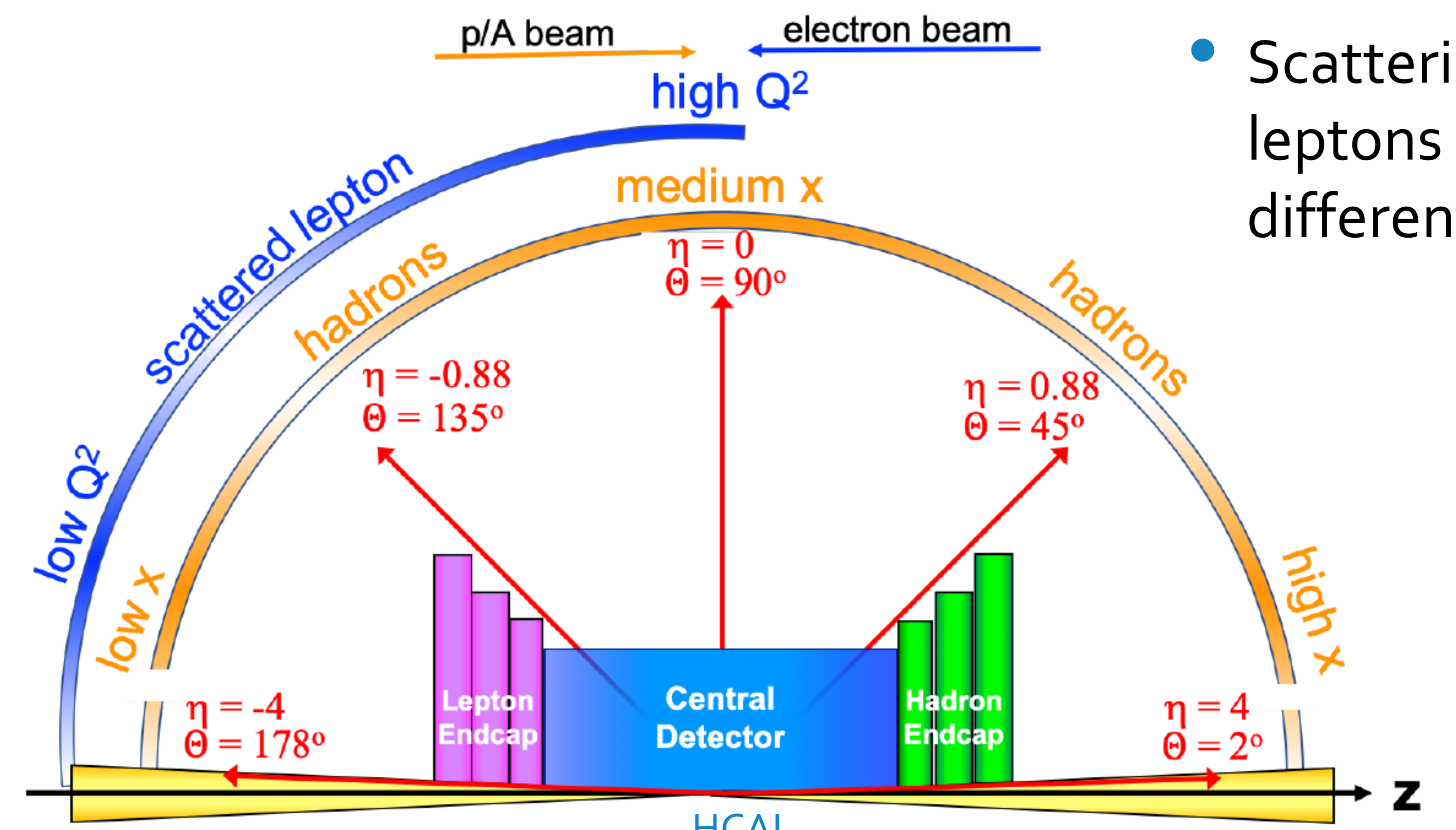
Kinematics Reconstruction

- Advantages/disadvantages for different inelasticity classes
  - Electron method: very precise at the high y (> 0.2); degrades rapidly with decreasing y
  - Hadron method: good precision at low and medium y (y < 0.2); degrades at high y
  - DA method: independent of the absolute energy calibration; precise at high Q^2 (> 100GeV^2), but degrades at low x-low Q^2

U. Bassler and G. Bernardi, NIM A361 (1995) 197-208



EIC General Purpose Detector Schematics



- Scattering patterns for leptons and hadrons for different x and Q^2

very low Q²
scattered lepton

Bethe-Heitler
photons
for luminosity

Luminosity Detector

Low Q²-Tagger

HCAL
EMCAL
PID
Tracking

HCAL
Magnet
EMCAL
PID
Tracking
Vertexing

Tracking
PID
EMCAL
HCAL

particles from nuclear
breakup and
from diffractive reactions

ZDC

Forward Tracking

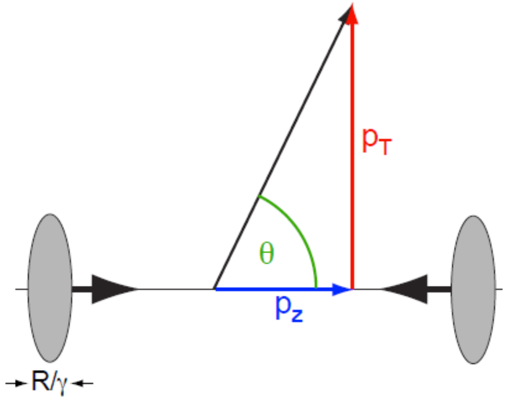
Wrapping Up

- An Electron-Ion Collider will be a new collider facility capable of revolutionizing our knowledge of QCD in the next decades
- The machine design well established: meets all the requirements on high luminosity, high polarization for electron and light hadron beams, a wide range of center of mass energies, variety of ion beams with up to high A
- EIC Detectors requirements are challenging: Hermiticity (forward and backward coverage) & Precision
- EIC R&D program is a vital part of the EIC efforts: many technologies at hand or within reach (many ideas for future)
- Physics requirements and detector concepts developed for Yellow Report

Back Up Slides

Variables Used to Describe Particles

Lorentz-boost invariant observables:

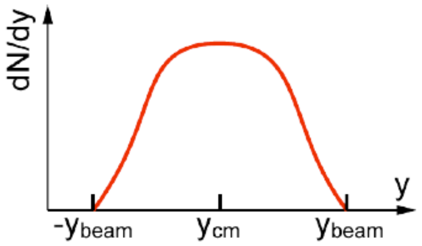


Transverse Momentum: p_T

Rapidity: $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

Boost in z: $y \rightarrow y - \tanh^{-1}\beta$

Pseudo-Rapidity:
$$\begin{aligned}\eta &= -\ln\tan\frac{\theta}{2}\\ y &\rightarrow \eta \quad \text{for} \quad m \rightarrow 0\end{aligned}$$

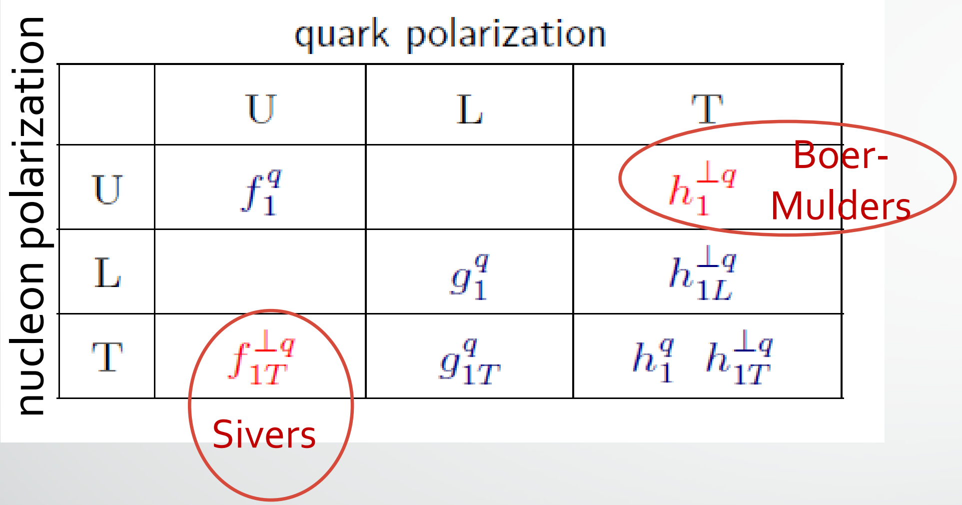


Transverse Energy: $E_T = E\sin\theta$

Invariant Cross-Section: $E\frac{d^3\sigma}{d^3p} = \frac{d^2\sigma}{2\pi p_T dy dp_T}$

Complexity of PDFs and FFs

- TMD PDFs of partons describe the distributions with respect to quark x and k_T

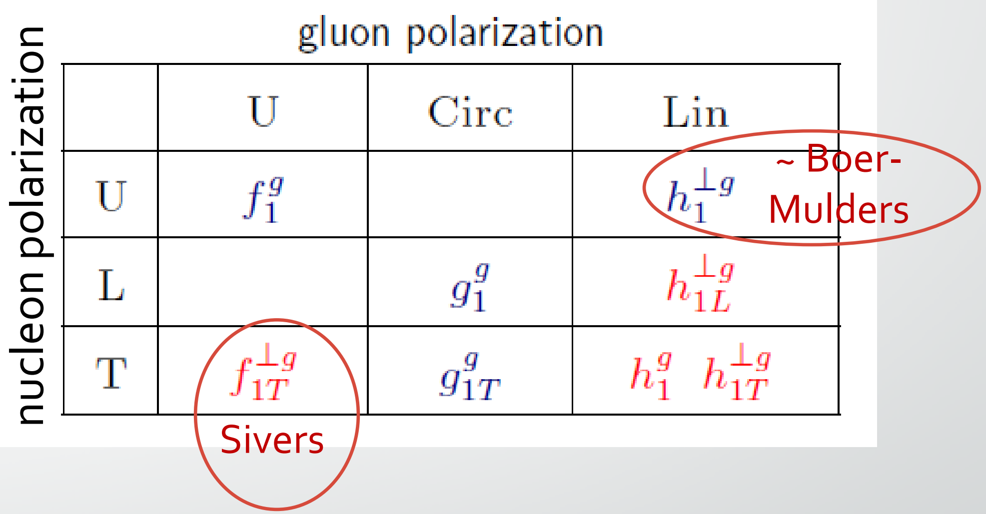


quark polarization / nucleon polarization

	U	L	T
U	f_1^q		$h_1^{\perp q}$
L		g_1^q	$h_{1L}^{\perp q}$
T	$f_{1T}^{\perp q}$	g_{1T}^q	h_1^q $h_{1T}^{\perp q}$

Boer-Mulders

Sivers



gluon polarization / nucleon polarization

	U	Circ	Lin
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g $h_{1T}^{\perp g}$

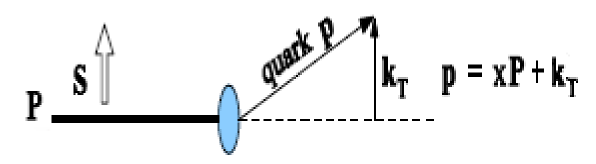
~ Boer-Mulders

Sivers

h_1^q –transversity

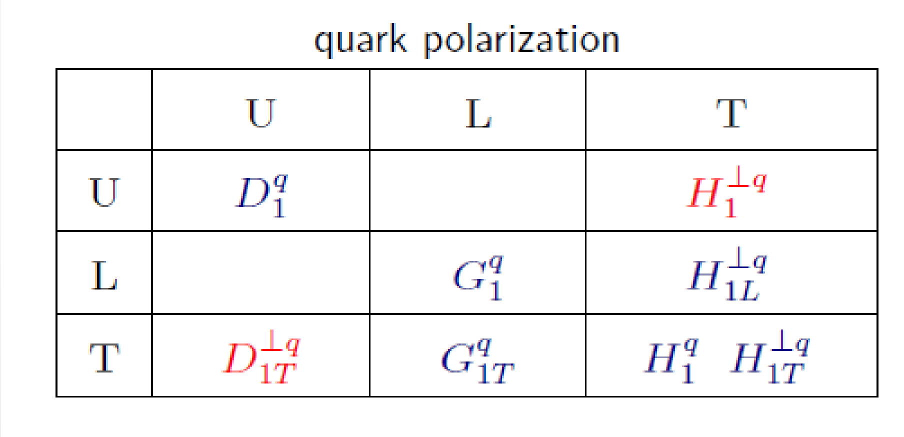
$g_{1T}^q, h_{1L}^{\perp q}$ –worm-gear functions (polarizations of nucleon and quark are ⊥)

$h_{1T}^{\perp q}$ –pretzelocity



Complexity of PDFs and FFs

- Fragmentation Functions are just as complex with similar types of correlations studied
- Interchange the roles of parton and hadron:



quark polarization

	U	L	T
U	D_1^q		$H_1^{\perp q}$
L		G_1^q	$H_{1L}^{\perp q}$
T	$D_{1T}^{\perp q}$	G_{1T}^q	$H_1^q \quad H_{1T}^{\perp q}$

$H_1^{\perp q}$ –Collins fragmentation function

$D_{1T}^{\perp q}$ –Sivers-type / polarizing fragmentation function

Nuclear Structure Functions

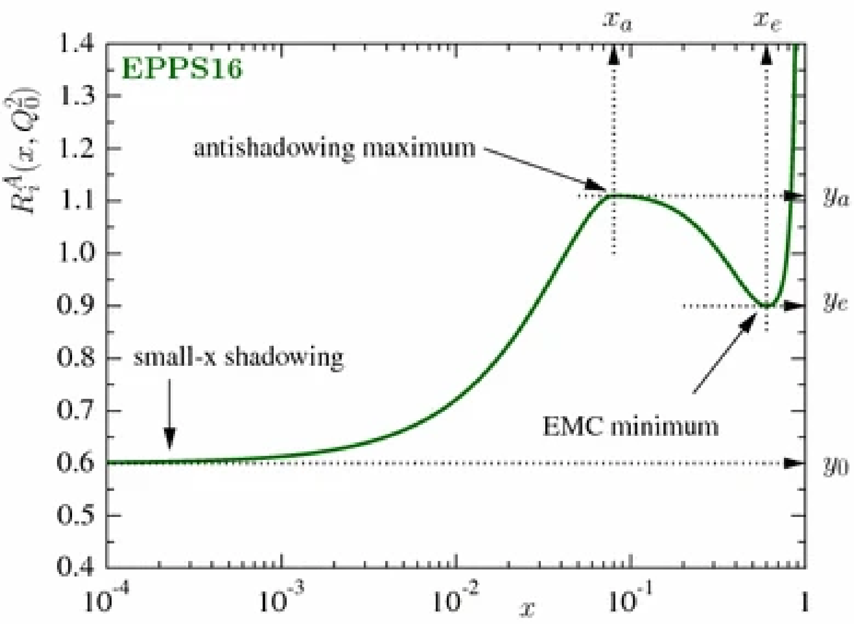
- Inclusive DIS in eA:

$$\frac{d^2\sigma^{eA\rightarrow eX}}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark

gluon

- F2 and FL are benchmark measurements:
- Theory/models have to be able to describe the structure functions and their evolution.
- Leading twist pQCD models parameterize the observed suppression of the structure function with decreasing x using nuclear parton distribution functions (nPDFs)
- Aim at extending our knowledge on structure functions into the realm where gluon saturation effects emerge



Semi-Inclusive DIS

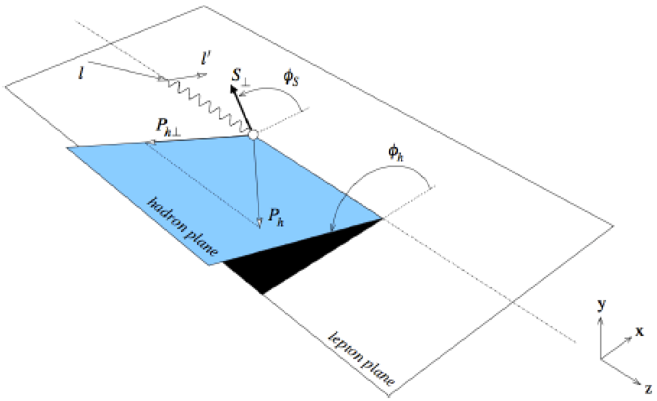
- Process

$$\ell(l,\lambda_\ell) + N(P,S) \to \ell(l',\lambda'_\ell) + h(P_h,S_h) + X$$

- 6 independent kinematical variables

$$x_B = \frac{Q^2}{2P\cdot q} \qquad Q^2 \qquad \phi_S \qquad z_h = \frac{P\cdot P_h}{P\cdot q} \qquad P_{h\perp} = |\vec{P}_{h\perp}|$$

$$y = \frac{P\cdot q}{P\cdot l} \approx \frac{Q^2}{x_B\, S} \quad \text{not independent}$$



(figure from Bacchetta et al, hep-ph/0611265)

- Structure functions at tree level (e.g., hep-ph/0611265)

$$F_{UU,T} = x_B \sum_q e_q^2 \int d^2\vec{k}_\perp\, d^2\vec{p}_\perp\, \delta^{(2)}(\vec{k}_\perp + \vec{q}_\perp - \vec{p}_\perp)\, f_1^q(x_B,\vec{k}_\perp^{\,2})\, D_1^q(z_h,\vec{p}_\perp^{\,2})$$

$$F_{UU}^{\cos 2\phi_h} \sim h_1^\perp \otimes H_1^\perp$$

$$F_{UL}^{\sin 2\phi_h} \sim h_{1L}^\perp \otimes H_1^\perp$$

$$F_{LL} \sim g_1 \otimes D_1$$

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} \sim f_{1T}^\perp \otimes D_1 \qquad \text{[Sivers effect]}$$

$$F_{UT}^{\sin(\phi_h+\phi_S)} \sim h_1 \otimes H_1^\perp \qquad \text{[Collins effect]}$$

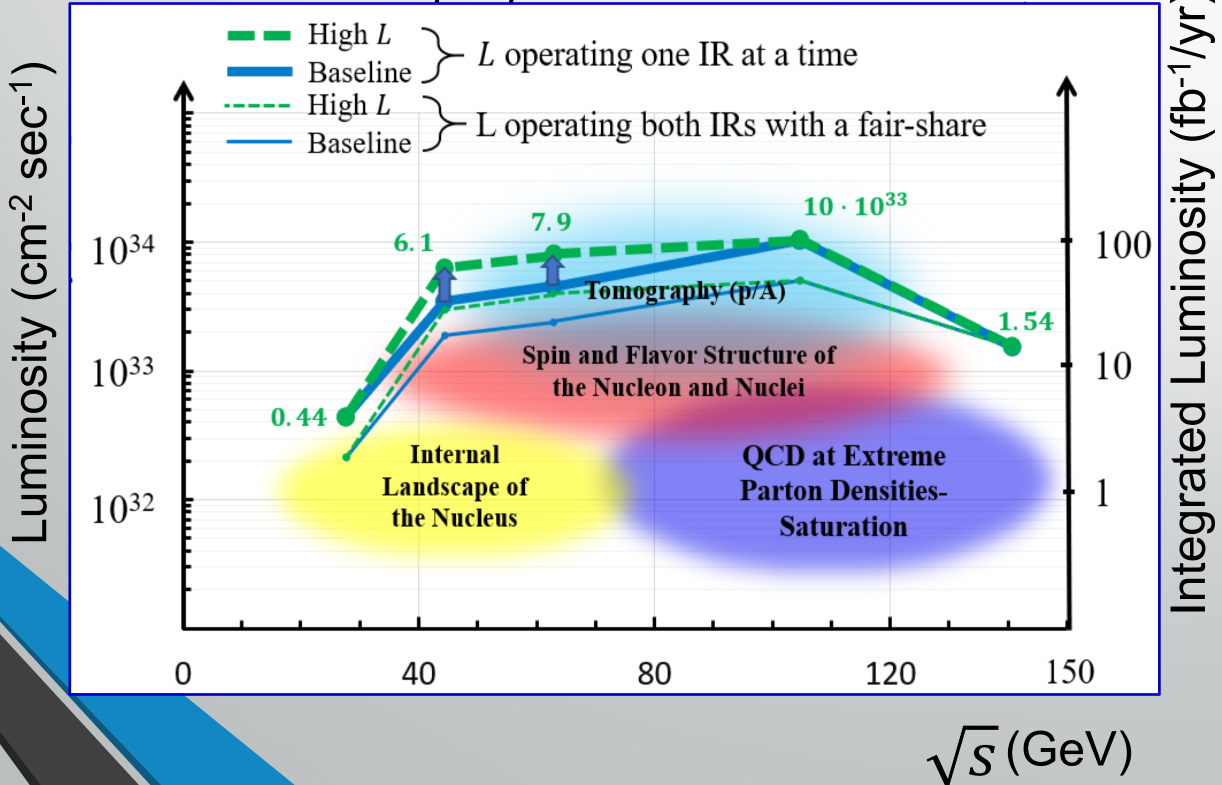
$$F_{UT}^{\sin(3\phi_h-\phi_S)} \sim h_{1T}^\perp \otimes H_1^\perp$$

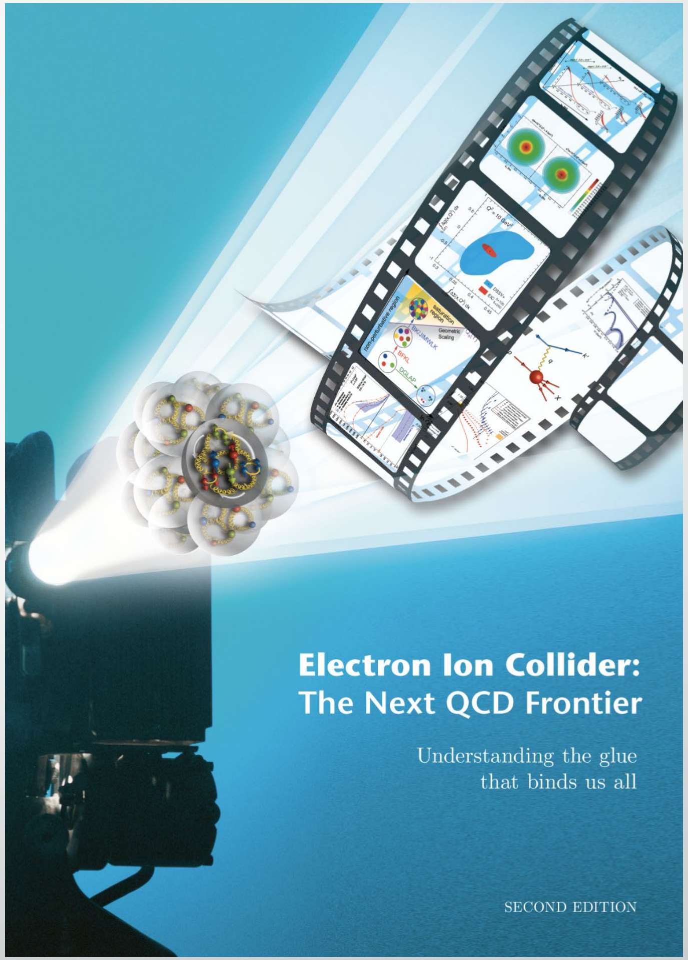
$$F_{LT}^{\cos(\phi_h-\phi_S)} \sim g_{1T} \otimes D_1$$

- transverse parton momenta of TMD-PDFs and TMD-FFs are convoluted
- except for $F_{UU,T}$ expressions are symbolic; in most cases convolutions contain additional powers of transverse parton momenta
- all 8 TMD-PDFs can be studied
- all 8 structure functions have been measured

“Understanding the Glue that Binds us All”

- EIC: Study structure and dynamics of matter at *high luminosity*, *high energy* with *polarized beams* and *wide range of nuclei*





Electron Ion Collider:
The Next QCD Frontier

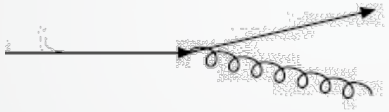
Understanding the glue
that binds us all

SECOND EDITION

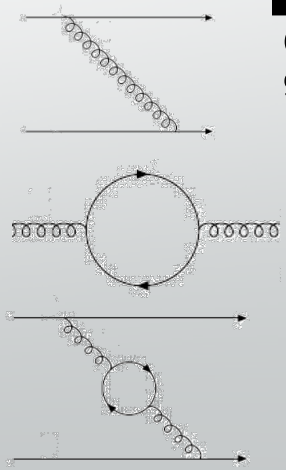
[EIC Whitepaper: arXiv:1212.1701](https://arxiv.org/abs/1212.1701) Credit: Bernd Surrow

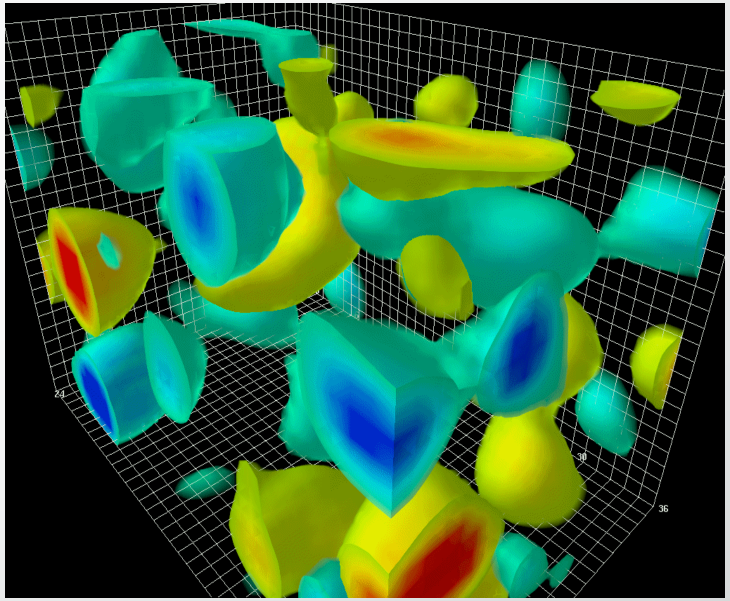
Understanding Nucleon Structure

- Looking deep inside the proton: gluon interactions can be described by the following elementary processes
  - Gluon emission by a quark
  - Gluon splitting

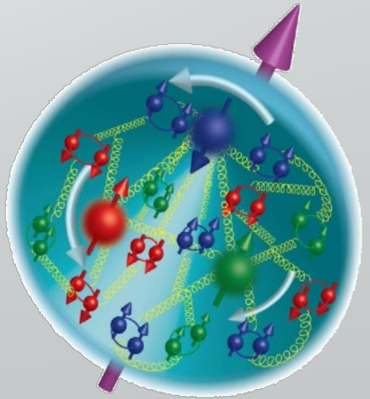


- Lead to build up of quark-antiquark sea:
  - Gluon exchange
  - Gluon splitting + recombination
  - Gluon exchange + splitting + recombination
  - …





(D. Leinweber: Action (~energy) density fluctuations of gluon-fields in QCD vacuum)



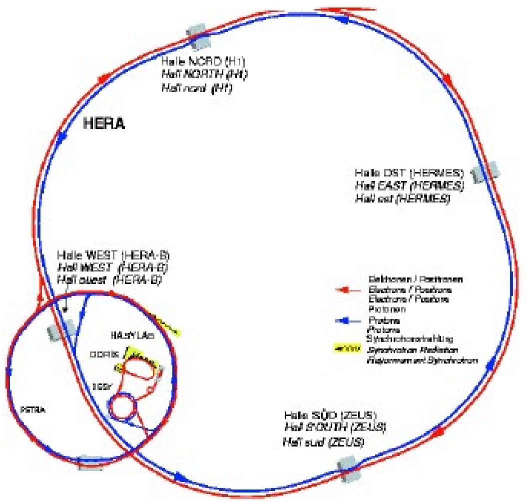
EIC vs. HERA

- HERA: the first electron-proton collider (1992-2007)
- Energies: $\frac{e^-}{e^+}$: $27.5\ GeV$

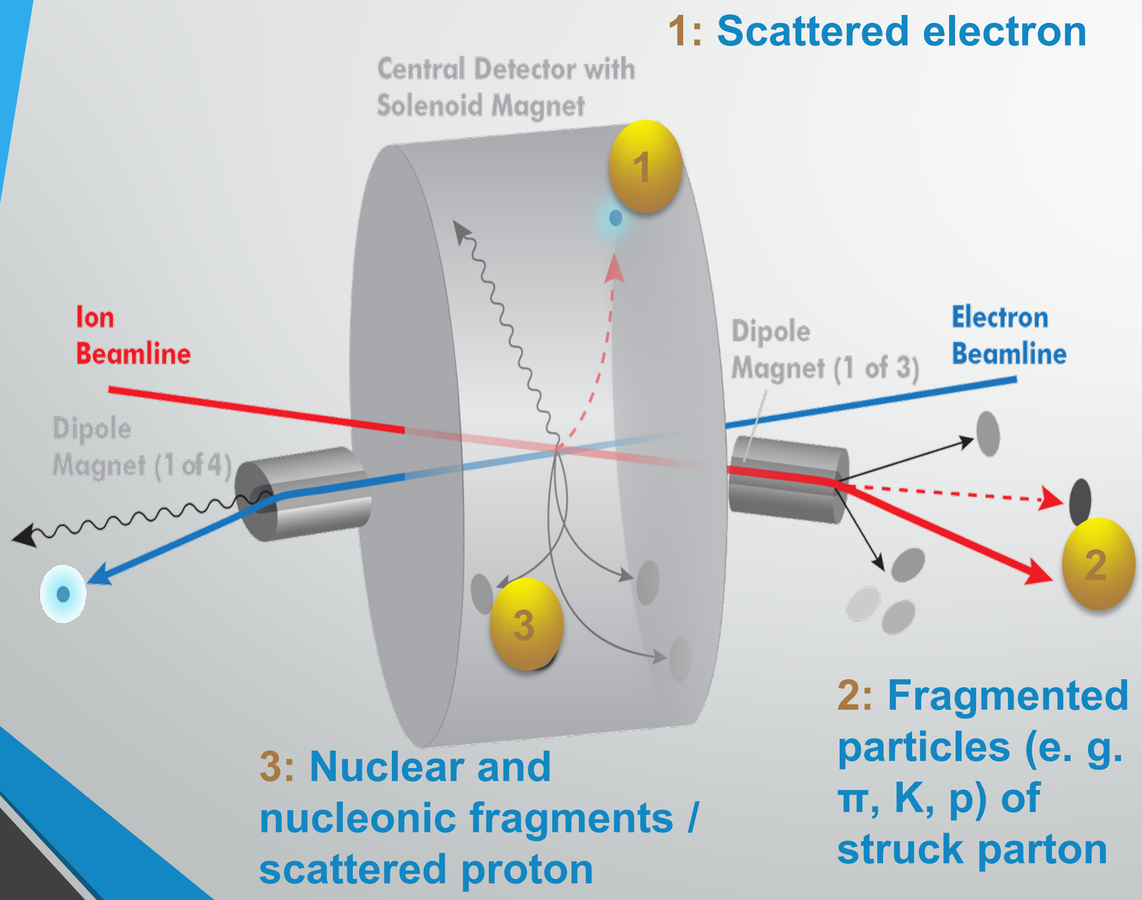
  p: $820\ (920) GeV$

  $\sqrt{s} \sim 320\ GeV$
- Polarization available for e beam
- Two collider-mode experiments: H1, ZEUS
  - Total lumi: $1\ fb^{-1}$
- Two fixed-target experiments: HERMES, HERA-B
- Enormous success, many break-throughs/new physics*

* *Many important measurements also from other programs: COMPASS, JLab6, JLAB12*



Detector Requirements



- The EIC requires a 4π hermetic detector with low mass inner tracking
- Central detector needs to cover the range of $-4 < \eta < 4$ for the measurement of electrons, photons, hadrons, and jets.
- Auxiliary detectors are needed for tagging, lumi, and polarimetry
- Excellent (tracking) momentum resolution
- High spatial vertex resolution
- Excellent (backward) /good electromagnetic calorimeter resolution; good hadronic calorimeter resolution
- Excellent PID

Polarized structure functions

- Constrained by polarized DIS experiments
- Spin-dependent structure functions:

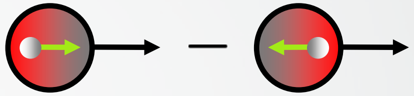
$$g_1(x) = \frac{1}{2}\sum_i e_i^2\left(\triangle\, q_i(x) + \triangle\, \bar{q}_i\,(x)\right)$$

$$\triangle\, q_i(x) = q_i^+ - q_i^-$$

- Experimentally, we measure yield asymmetry $A_1 \sim \frac{N_{\uparrow\downarrow} - N_{\uparrow\uparrow}}{N_{\uparrow\downarrow} + N_{\uparrow\uparrow}}$
- In Parton Model

$$A_1 \sim \frac{g_1(x)}{F_1(x)} = \frac{1}{F_1(x)} f \sum e_f^2 \,\triangle\, q_f(x)$$

$\Delta f(x) =$



$$\underbrace{f^+(x) - f^-(x)}$$

Measure of probability to find parton f with spin aligned to anti-aligned to proton spin at momentum fraction x

Polarized Structure Functions ↔ Polarized PDF

$$\Gamma_1^{\mathrm{p,n}} \equiv \int_0^1 \mathrm{g}_1^{\mathrm{p,n}}(\mathrm{x_B})\mathrm{dx_B} = \frac{1}{2}\sum_{\mathrm{f}} \mathrm{e}_{\mathrm{f}}^2(\Delta \mathrm{q}_{\mathrm{f}}^{\mathrm{p,n}} + \Delta \bar{\mathrm{q}}_{\mathrm{f}}^{\mathrm{p,n}})$$

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

$$\Delta q_i(Q^2) = \int_0^1 \Delta q_i(x, Q^2)dx$$

$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2)dx$$

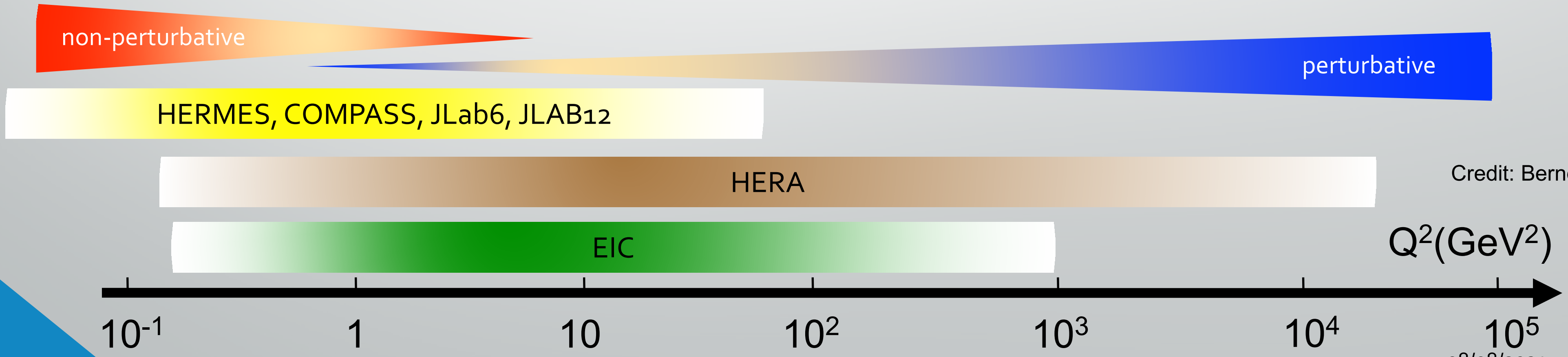
EIC Requirements

- Accelerator:
  - High luminosity: 10^{33}- 10^{34} cm^{-2}s^{-1}
  - Flexible center-of-mass energy
  - High polarization (0.8 for **e** and 0.7 for **p** / light ion beams)
  - Wide range of nuclear beams (d to Pb/U):

Wide kinematic range

Spin structure studies

High gluon density



Credit: Bernd Surrow