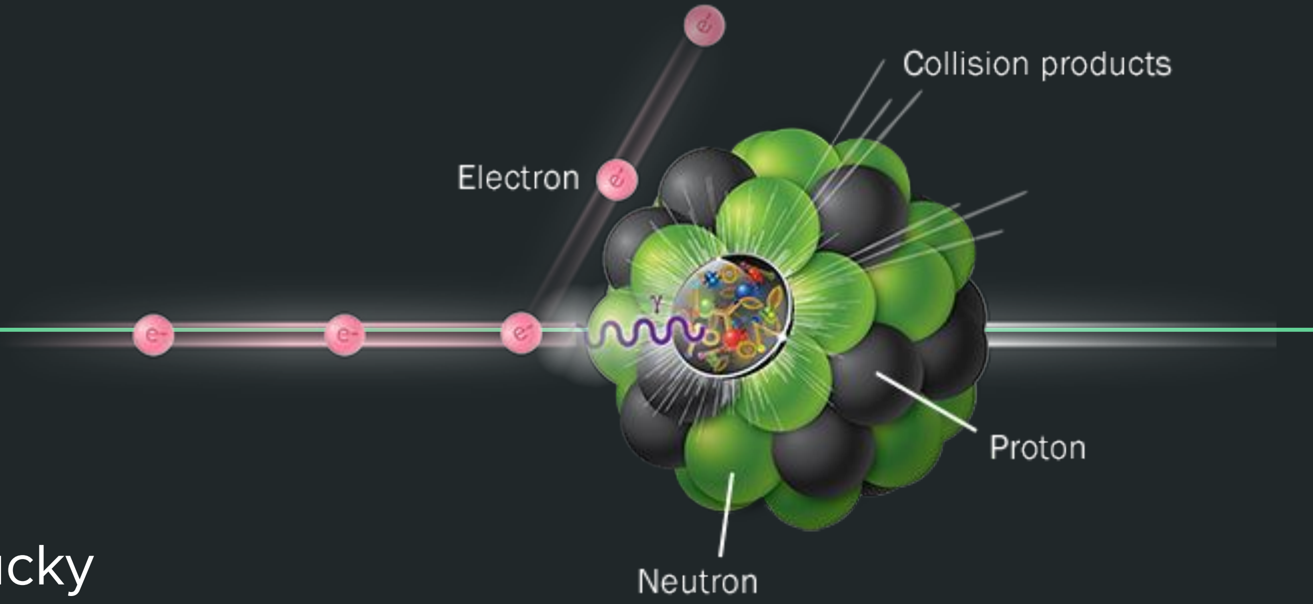
Experimental Measurements at the EIC



Renee Fatemi
University of Kentucky

slido

Where are you in your lifelong study of nuclear science?

ⓘ Start presenting to display the poll results on this slide.

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This week you were introduced to QCD and the EIC. What topics or questions most intrigued you?

ⓘ Start presenting to display the poll results on this slide.

The EIC Program is a nuclear physics candy store!

How do nucleon properties like **mass** and **spin** emerge from the quark and gluon degrees of freedom?

What is the gluon density at low x? At what scale does **gluon saturation** occur?

How is the charge and spin of the partons distributed in **coordinate** and **momentum** space within the nucleon?

How does **dense nuclear matt**er change these parton distributions? How does it modify the hadronization process?

The Plan

1. Deep dive into experimental analysis - use helicity distributions as example
    a. Introduction to inclusive scattering
    b. Spin asymmetries and structure functions
    c. Electron identification and kinematic reconstruction
    d. Polarization, relative luminosity and radiative corrections
    e. Constraints from an EIC on helicity PDFs

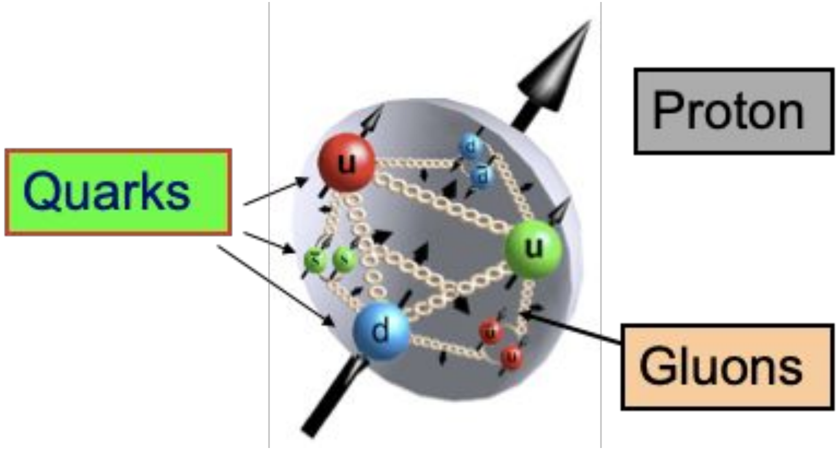
2. Flavor separation and sea quark helicity distributions
    a. Introduction to semi-inclusive scattering
    b. Hadron kinematics and PID
    c. Constraints from an EIC on helicity PDFs
    d. Introduction to charge-current interactions

3. Broaden our scope into Transverse Momentum Distributions (TMDs) and Generalized Parton Distributions (GPDs)

4. Brief excursion into selected topics (Proton Mass, CLFV, gluon saturation)

Proton Spin Distribution

The proton is composed of 3 spin 1/2 quarks which are constantly interacting via spin 1 gluons. Gluons also interact with each other and produce the virtual $q\bar{q}$ pairs that make up the "**sea**".



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + 1\Delta G(\mu) + L_{Q+G}(\mu)$$

Jaffe-Manohar decomposition

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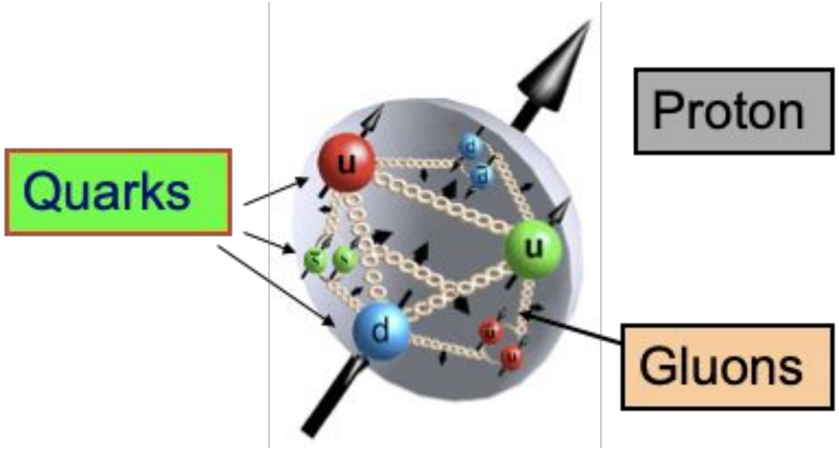

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + 1\Delta G(\mu) + L_{Q+G}(\mu)$$

NOTE : μ is the energy scale, or resolution, used to probe the proton. This angular momentum sum rule is meaningless if this scale is not defined.

Proton Spin Distribution

Proton Spin $\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + 1\Delta G(\mu) + L_{Q+G}(\mu)$

Quark Helicity $\Delta\Sigma(\mu) = \sum_f \int_0^1 \boxed{\Delta q(x,\mu)} dx$

Gluon Helicity $\Delta G(\mu) = \int_0^1 \boxed{\Delta g(x,\mu)} dx$

Helicity PDFs - probability of a parton carrying momentum fraction x to have its spin aligned vs. anti-aligned with the spin of the proton.

Quark and Gluon Orbital Angular Momentum $L_{Q+G}(\mu) = \int_0^1 [l_q(x,\mu) + l_g(x,\mu)] dx$

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Helicity PDFs - probability of a parton carrying momentum fraction x to have its spin aligned vs. anti-aligned with the spin of the proton.

NOTE : Integrals over x run from 0 to 1.

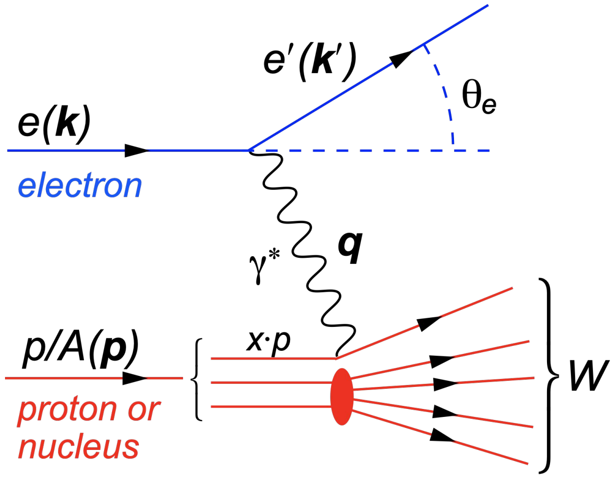
Measuring Helicity PDFs at an EIC

Classic approach via ***Inclusive Scattering***

- Use only the information from the scattered electron to reconstruct the entire interaction

- Advantages are that you maximize statistics because you don't need to know anything about the particles that hadronize from the scattered quark.

- Disadvantages are that you lose information about the type of quark that participated in the hard interaction.



Measuring Helicity PDFs at an EIC

Classic approach via ***Inclusive Scattering***

- The e- beam interacts with the quark electric charge via exchange of a virtual photon that carries four momentum $\mathbf{q}_\mu$

$$q_\mu = k_\mu - k'_\mu$$

- The center of mass energy for the γ^* - N system is **W**

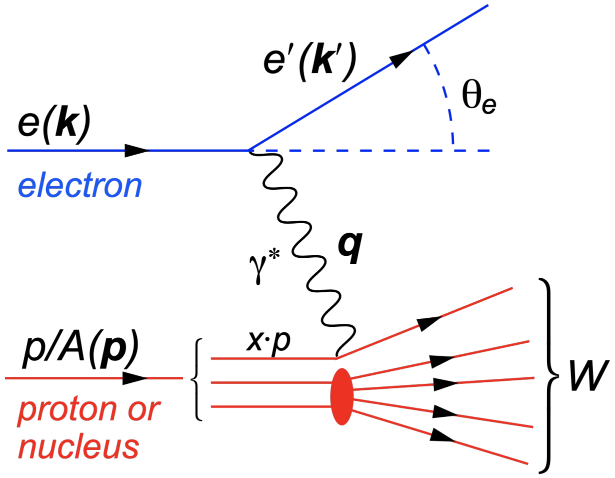
$$W^2 = (p_\mu + q_\mu)^2 = M_p^2 - Q^2 + 2p \cdot q$$

- The four momentum transferred to the nucleon is **Q** :

$$Q^2 = -q^2 = xys$$

- In the infinite momentum frame the Bjorken x variable defined as may be interpreted as the momentum fraction of the proton that is carried by the interacting quark.

$$x = \frac{Q^2}{2\,p \cdot q}$$



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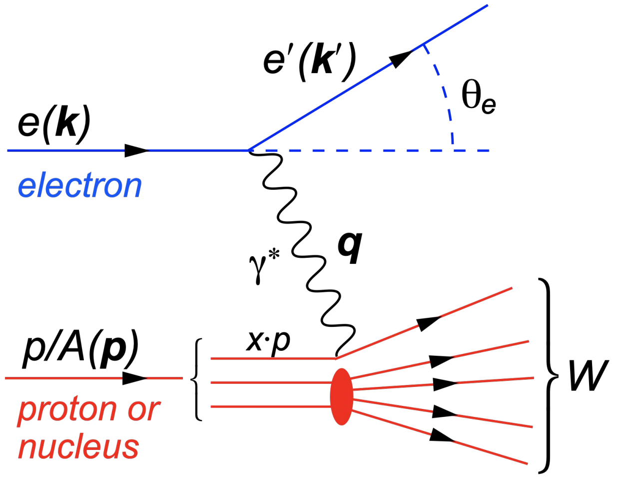

NOTE #1 : Remember the COM energy is defined as $s = (k_\mu + p_\mu)^2$ and $y = Q^2/xs$ is the inelasticity, or the momentum fraction lost by the e- in the proton rest frame.

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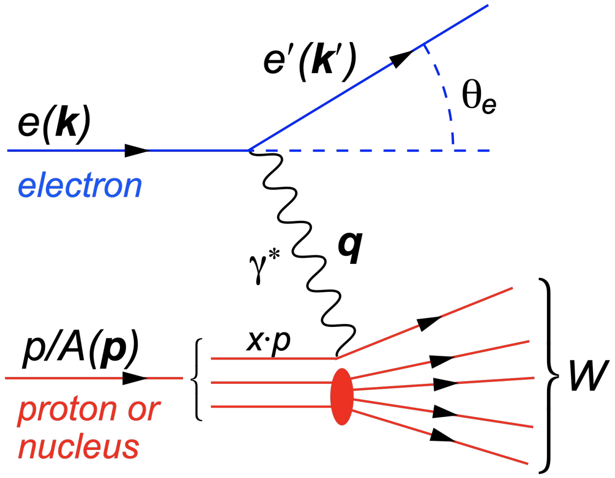

NOTE #2 : Q^2 is used to set the hard scale μ we saw in the PDF definition.

Measuring Helicity PDFs at an EIC

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- The four momentum transferred to the nucleon is **Q** :

$$Q^2 = -q^2 = 4E_p E_e \sin^2(\theta_e/2)$$

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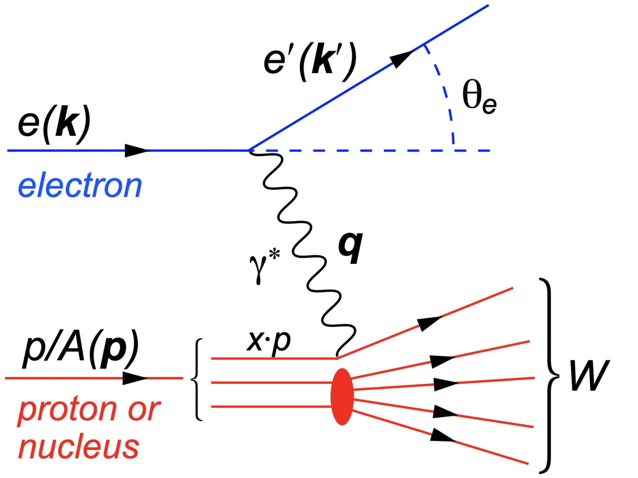
$$x = \frac{Q^2}{2\, p \cdot q}$$

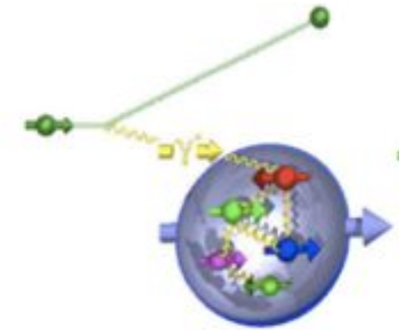


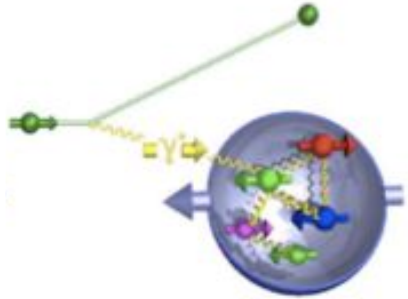
NOTE #3 : In the lab frame, for fixed target experiments, Q^2 is often written in terms of θ_e

Measuring Helicity PDFs at an EIC

- The virtual photon $\gamma^*$is spin 1
- The γ^* polarization is set by the polarization of the e- beam
- Conservation of angular momentum restricts interactions to quarks and γ^* with opposite spin orientation.
- Therefore the spin dependent cross-section must be directly connected to the quark helicity distribution inside the proton!

$$\frac{1}{2}\left[\frac{d\sigma^{\rightleftarrows}}{dx\,dQ^2} - \frac{d\sigma^{\rightrightarrows}}{dx\,dQ^2}\right] = \frac{4\pi\alpha^2}{Q^4} y(2-y) g_1(x, Q^2)$$





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e- helicity = +1
p+ helicity = +1

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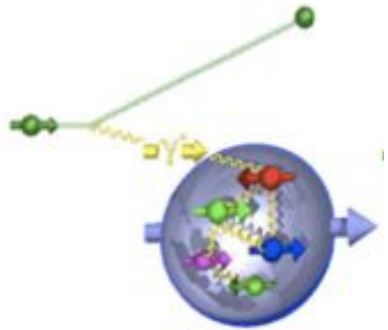
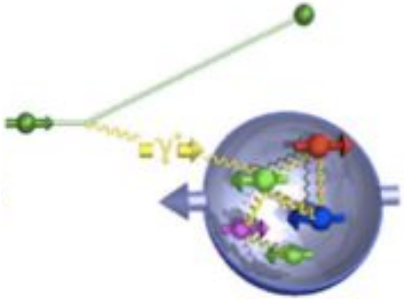
inelasticity

Spin structure function





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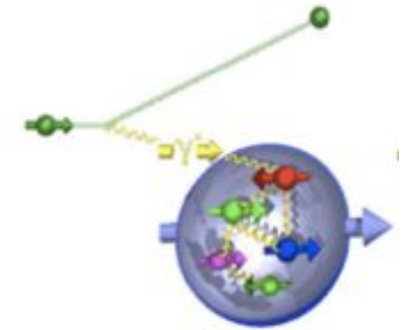

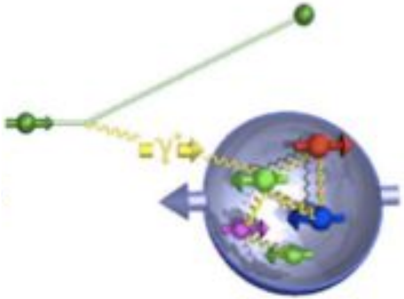

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inelasticity

Spin structure function

NOTE: Terms suppressed by $(xM/Q)^2$ are dropped.

Simple Parton Model

For large Q^2 and to leading order in α_s the spin structure function is related to the charge weighted sum of the quark helicity distribution.

$$g_1(x, Q^2) = \frac{1}{2}\Sigma e_q^2 \left[\Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2)\right]$$

This is completely analogous to the spin ***independent*** structure functions F_1 and F_L

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

$$F_2(x, Q^2) = x\Sigma e_q^2 \left[q(x, Q^2) + \bar{q}(x, Q^2)\right]$$

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NOTE: This is the sum of two spin dependent cross-sections

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

$$F_2(x, Q^2) = x\Sigma e_q^2\left[q(x, Q^2) + \bar{q}(x, Q^2)\right]$$

Measuring Xsecs is hard!

$$\frac{d\sigma}{dx dQ^2} \approx \frac{N_{e-}}{L\epsilon}$$

1. What is your efficiency (ϵ) for detecting scattered e- ?
2. How many scattered e- are reconstructed in the wrong x & Q^2 bin?
3. How well do you know your absolute luminosity (L) ?

Spin Asymmetries are easier to measure

$$A_{LL} = \frac{\frac{N^{++}}{L^{++}\epsilon^{++}} - \frac{N^{+-}}{L^{+-}\epsilon^{+-}}}{\frac{N^{++}}{L^{++}\epsilon^{++}} + \frac{N^{+-}}{L^{+-}\epsilon^{+-}}} \Rightarrow \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}}$$

ϵ falls out if not spin dependent

R = ratio of spin dependent luminosities

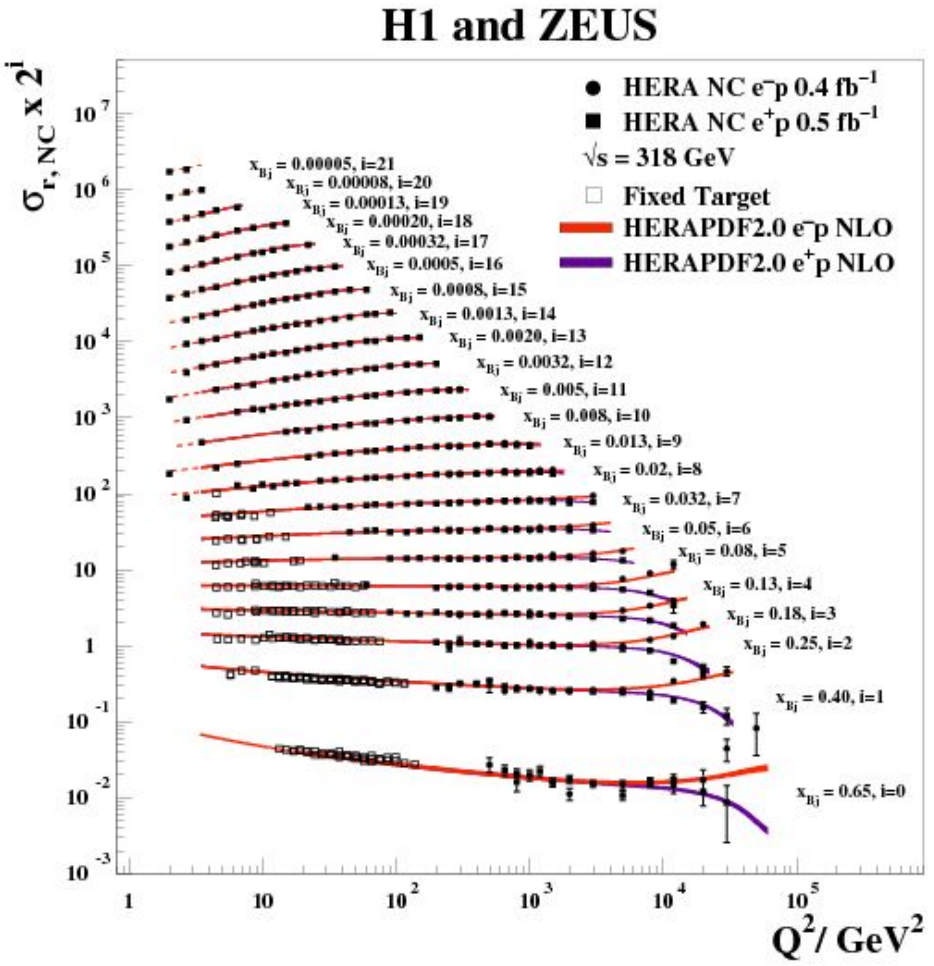
Asymmetries have a price

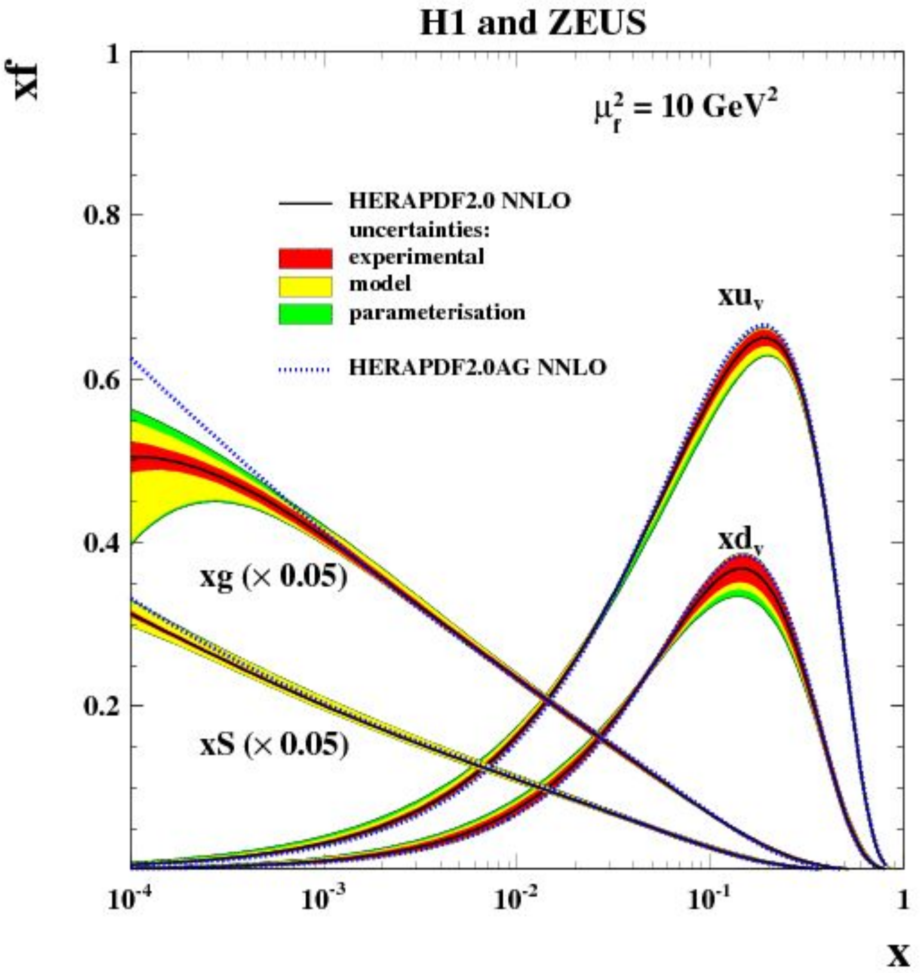
A_{LL} depends on both the spin independent and spin dependent PDFs:

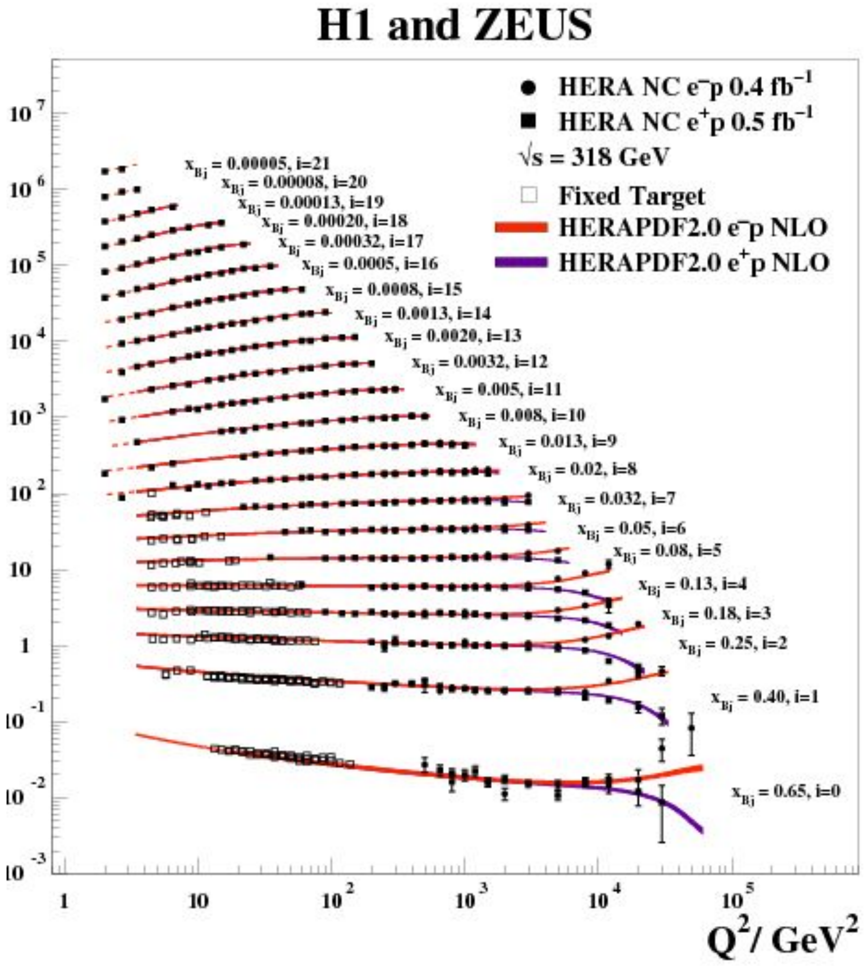
$$A_{LL} \propto \frac{g_1}{F_2}$$

But that is ok because HERA @ DESY, an e-p collider, measured F_2 over a wide range of x and Q^2.

From this data, and others from hadronic collisions and neutrino scattering, the spin independent PDFs are extracted.




H1 and ZEUS
xf
$\mu_f^2 = 10$ GeV^2
HERAPDF2.0 NNLO
uncertainties:
experimental
model
parameterisation
HERAPDF2.0AG NNLO
xu_v
xd_v
xg (× 0.05)
xS (× 0.05)
x


H1 and ZEUS
HERA NC e⁻p 0.4 fb⁻¹
HERA NC e⁺p 0.5 fb⁻¹
√s = 318 GeV
Fixed Target
HERAPDF2.0 e⁻p NLO
HERAPDF2.0 e⁺p NLO
x_{Bj} = 0.00005, i=21
x_{Bj} = 0.00008, i=20
x_{Bj} = 0.00013, i=19
x_{Bj} = 0.00020, i=18
x_{Bj} = 0.00032, i=17
x_{Bj} = 0.0005, i=16
x_{Bj} = 0.0008, i=15
x_{Bj} = 0.0013, i=14
x_{Bj} = 0.0020, i=13
x_{Bj} = 0.0032, i=12
x_{Bj} = 0.005, i=11
x_{Bj} = 0.008, i=10
x_{Bj} = 0.013, i=9
x_{Bj} = 0.02, i=8
x_{Bj} = 0.032, i=7
x_{Bj} = 0.05, i=6
x_{Bj} = 0.08, i=5
x_{Bj} = 0.13, i=4
x_{Bj} = 0.18, i=3
x_{Bj} = 0.25, i=2
x_{Bj} = 0.40, i=1
x_{Bj} = 0.65, i=0
Q^2/ GeV^2

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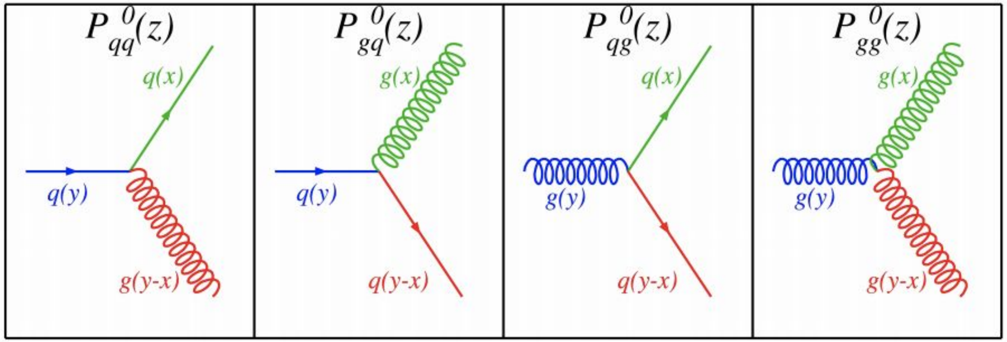
How do we extract information about the gluon from the F2 structure function?

ⓘ Start presenting to display the poll results on this slide.

DGLAP Evolution Equations!

$$\frac{d}{d \ln Q^2} \begin{pmatrix} q \\ g \end{pmatrix} = \begin{pmatrix} P_{q \leftarrow q} & P_{q \leftarrow g} \\ P_{g \leftarrow q} & P_{g \leftarrow g} \end{pmatrix} \otimes \begin{pmatrix} q \\ g \end{pmatrix}$$



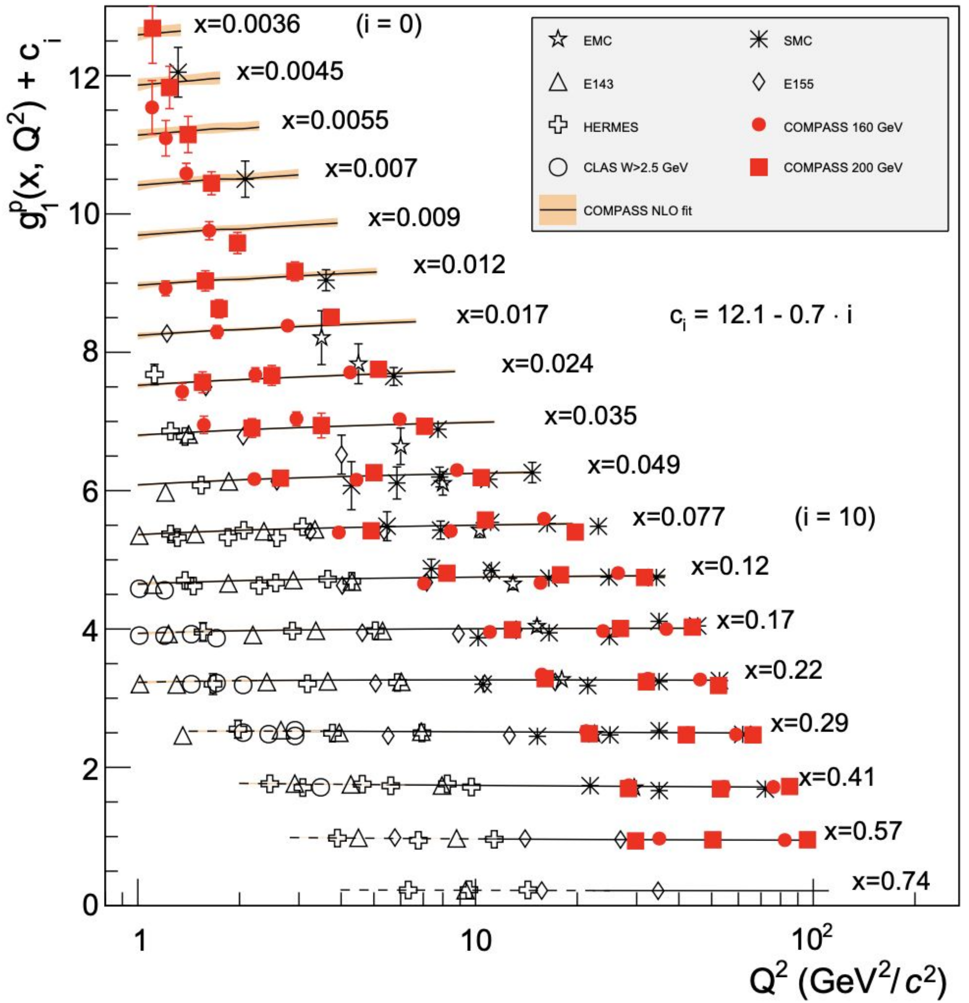
Decades of g_1^p Measurements!

World-wide effort, using lepton beams, used to measure spin structure :

- SLAC
- CERN
- DESY
- JLAB

ALL of these measurements used polarized beams and with fixed polarized target.

NOTE #1 : These data are limited to W > 2.5 GeV. A huge amount of data exists at low W and Q2 from CLAS at JLAB.



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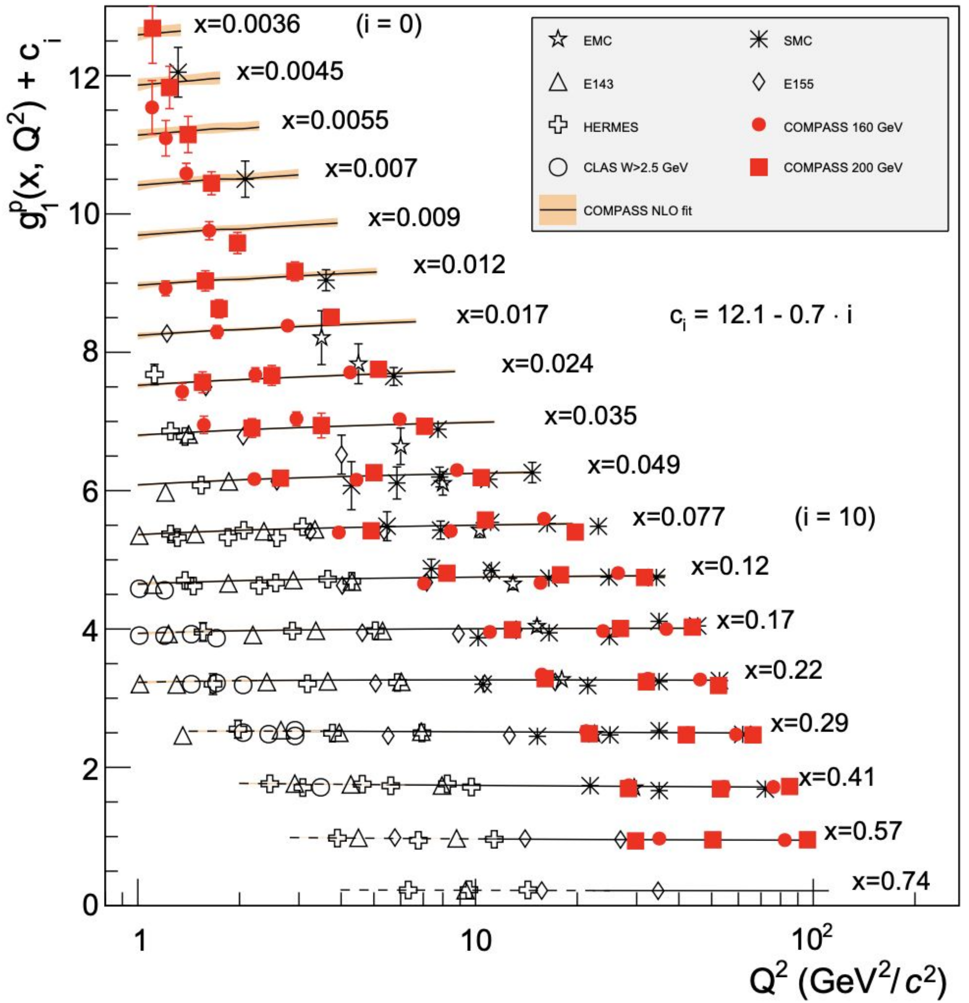
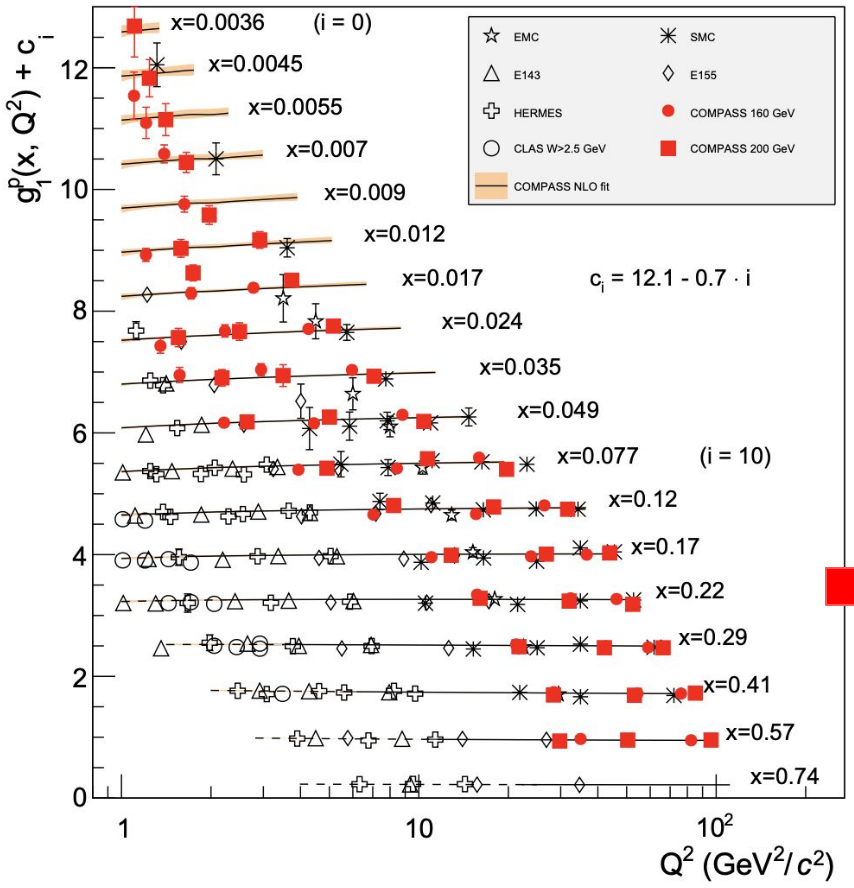
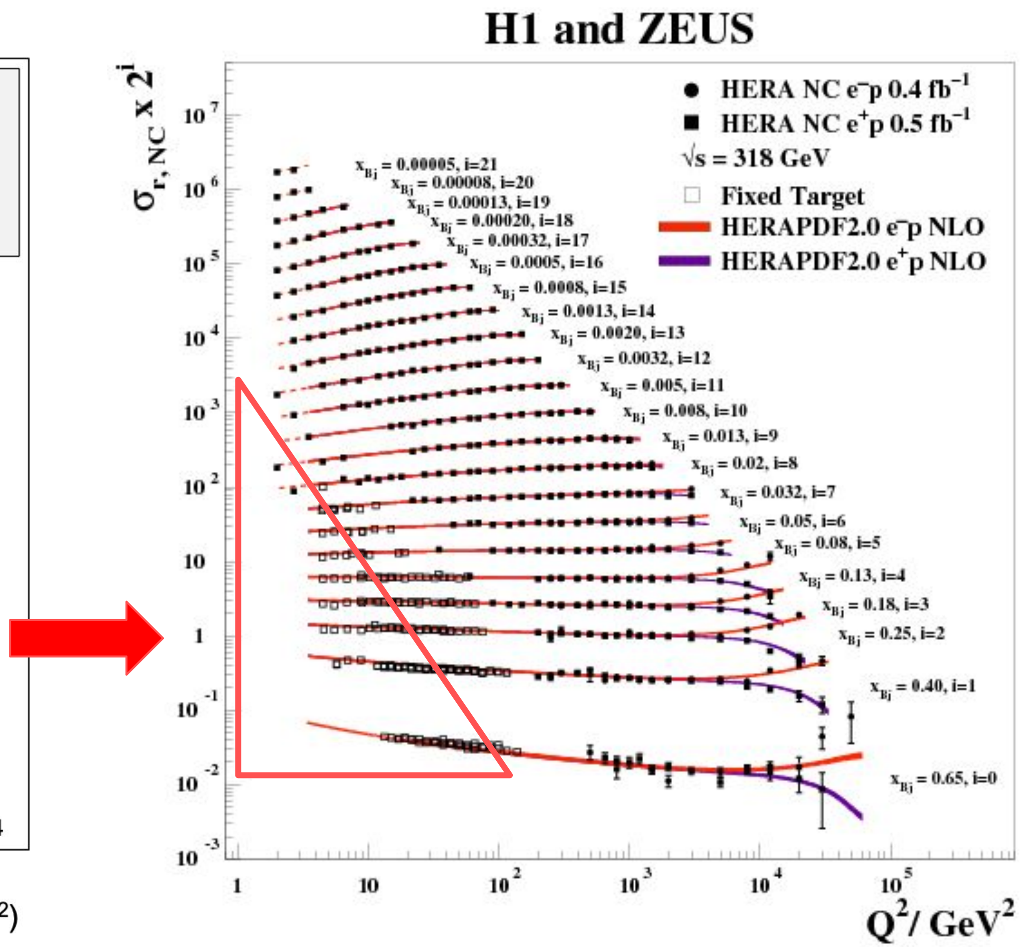
NOTE #2 : The range in x is limited to 0.0036 - 0.74 and Q^2 up to 100 GeV.





$g_1^p(x, Q^2) + c_i$
x=0.0036 (i = 0)
x=0.0045
x=0.0055
x=0.007
x=0.009
x=0.012
x=0.017
c_i = 12.1 - 0.7 · i
x=0.024
x=0.035
x=0.049
x=0.077 (i = 10)
x=0.12
x=0.17
x=0.22
x=0.29
x=0.41
x=0.57
x=0.74
EMC
SMC
E143
E155
HERMES
COMPASS 160 GeV
CLAS W>2.5 GeV
COMPASS 200 GeV
COMPASS NLO fit
Q^2 (GeV^2/c^2)



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Q^2/ GeV^2

Constraints from fixed target DIS&SIDIS

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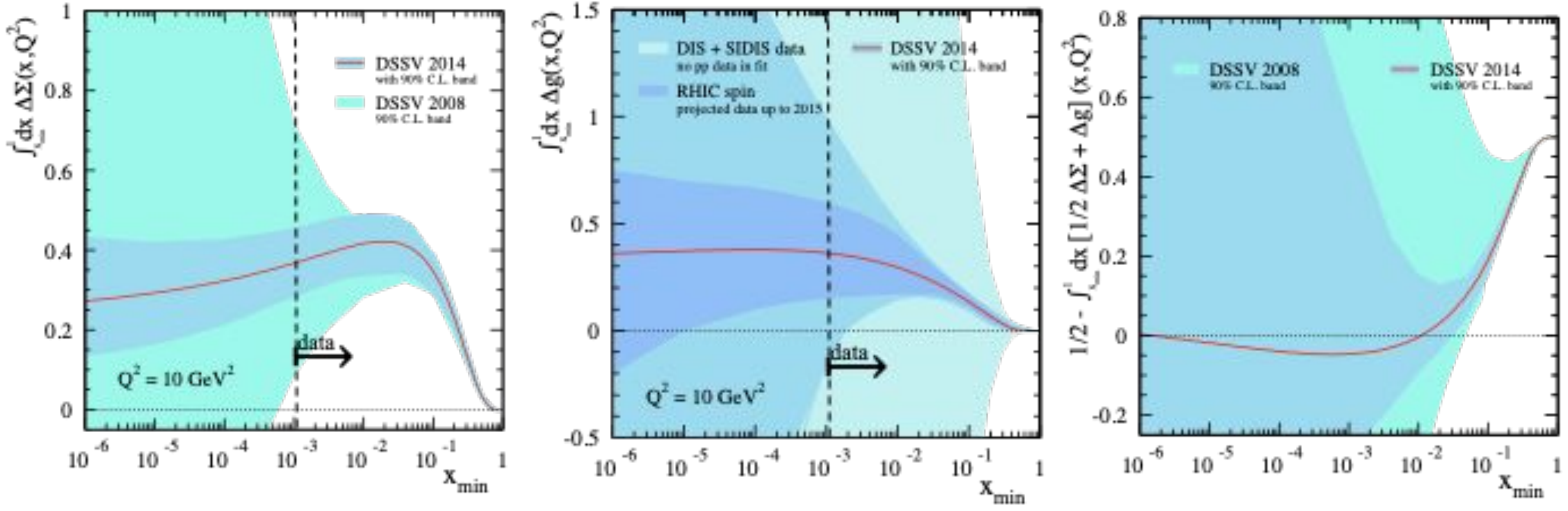
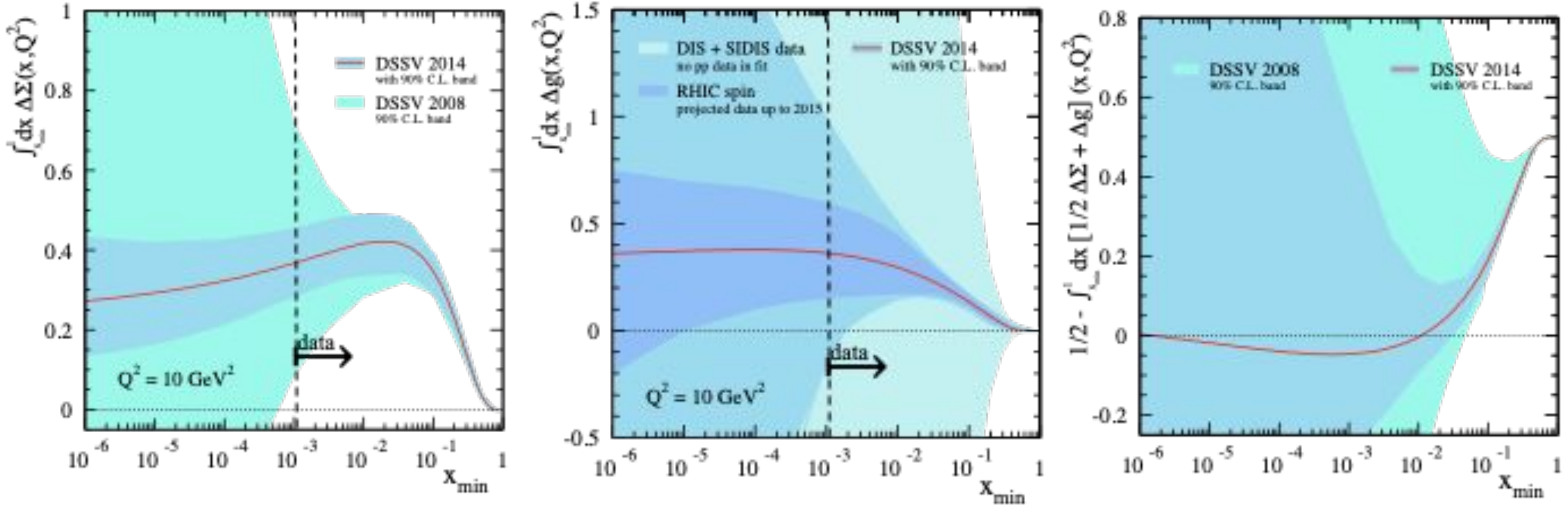


Phys. Rev. D **92**, 094030

Constraints from fixed target DIS&SIDIS + RHIC Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + 1\Delta G(\mu) + L_{Q+G}(\mu)$$



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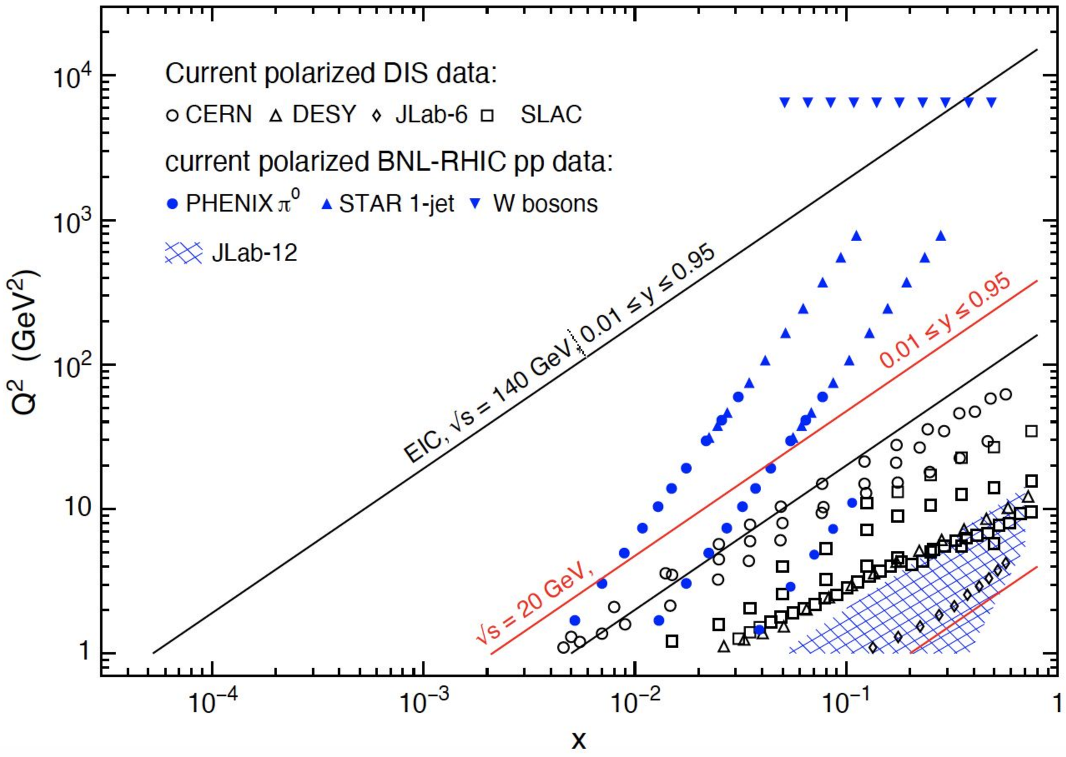
Low x nearly unconstrained - this is why we need an EIC!

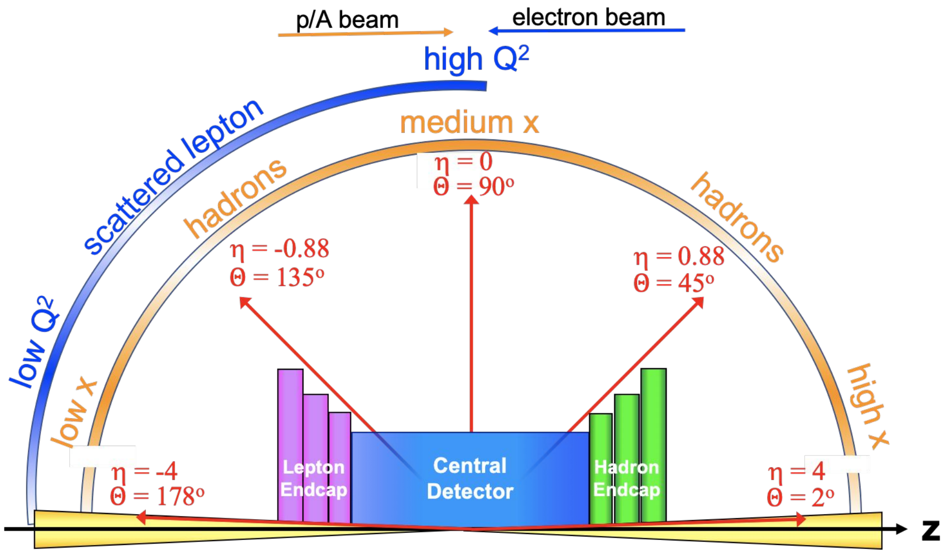


Lets hear your questions on the previous material

ⓘ Start presenting to display the poll results on this slide.

How to measure inclusive channels at the EIC

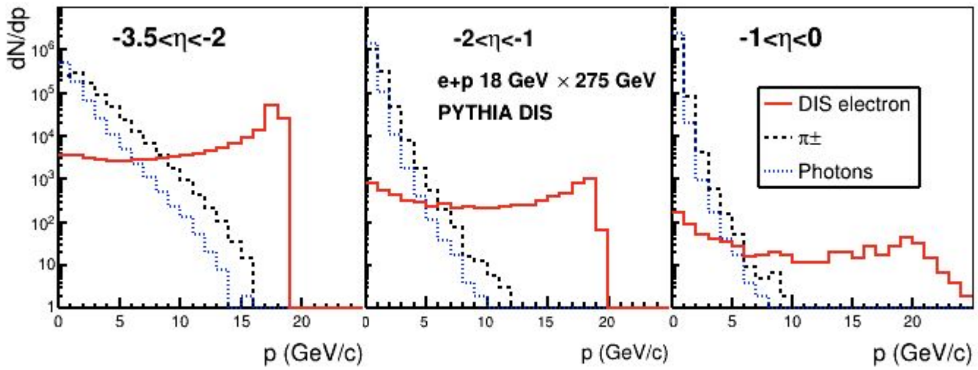
1. Need detector coverage in the "backward" region, in the direction of the incoming electron beam.
   - Tracker in uniform magnetic field for ***momentum*** reconstruction of charged particles
   - Hadronic and electromagnetic calorimeters for ***energy*** reconstruction of light and heavy charged particles as well as photons.

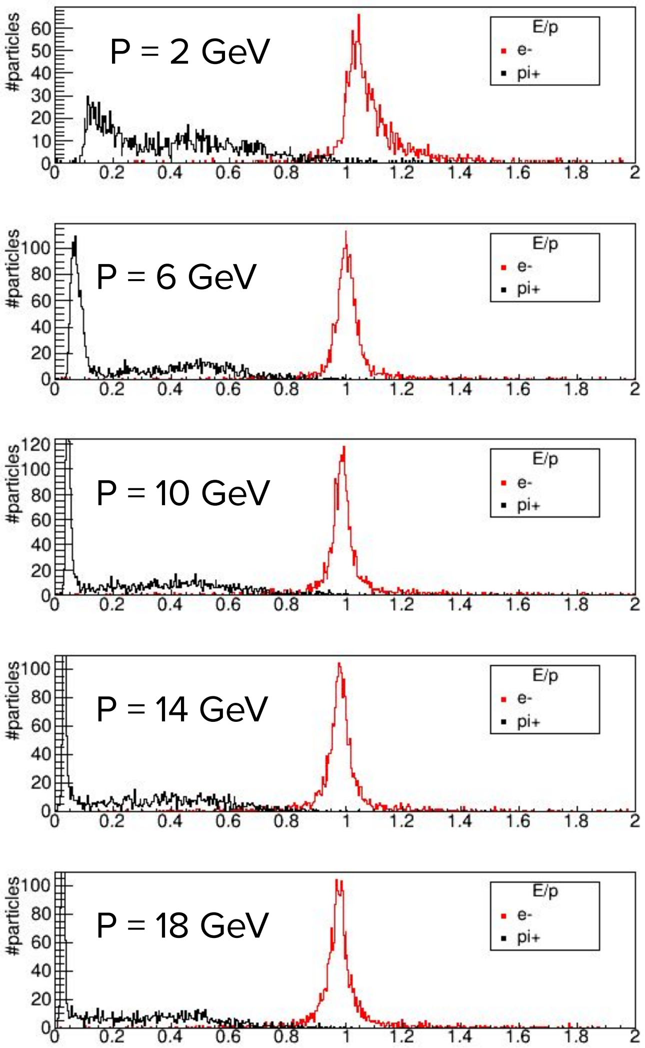


Remember: $\eta = -\ln(\tan(\theta/2))$

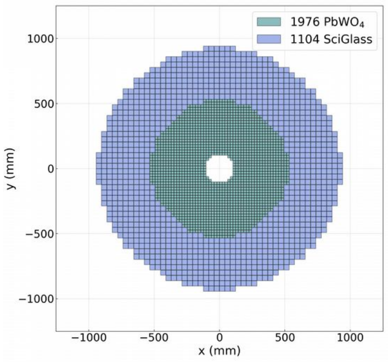
How to measure inclusive channels at the EIC

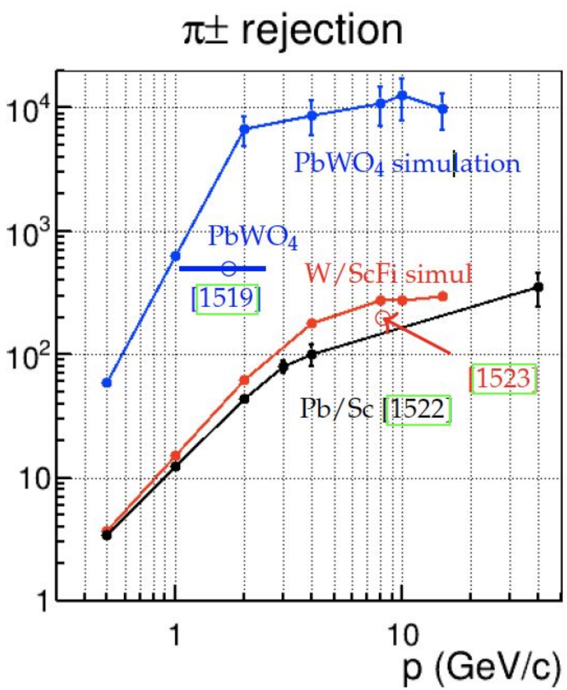
2. Correctly identify scattered electron
   a. Charged π backgrounds increase as move to lower x - need to separate π from e
   b. Classic π/e separation uses a combination of calorimetry (E) and tracking (p).
   c. Efficacy of E/p method driven by calorimeter resolution (width of peak at 1)

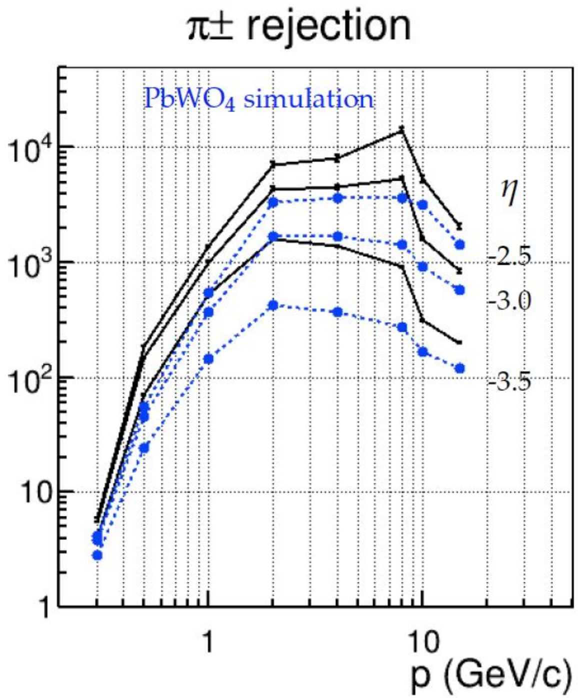




How to experimentally measure inclusive channels at the EIC





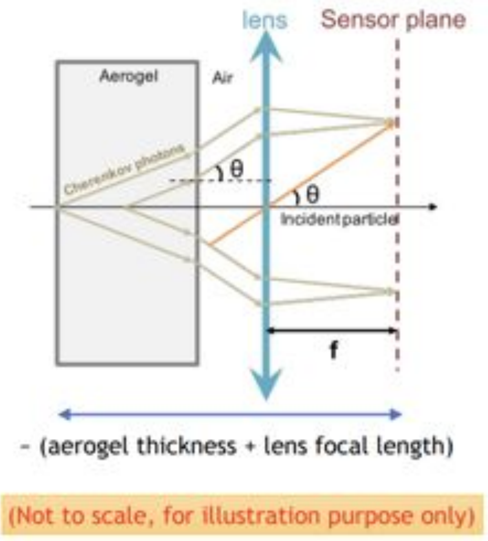


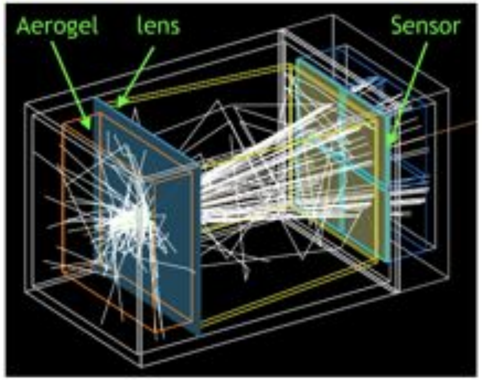
LEFT : Pion rejection based solely on E/p cut - demonstrates effect of calorimeter resolution. Tracking resolution is not included.

RIGHT : Tracking resolution is included and leads to reduction in rejection factors in the forward region.

How to measure inclusive channels at the EIC

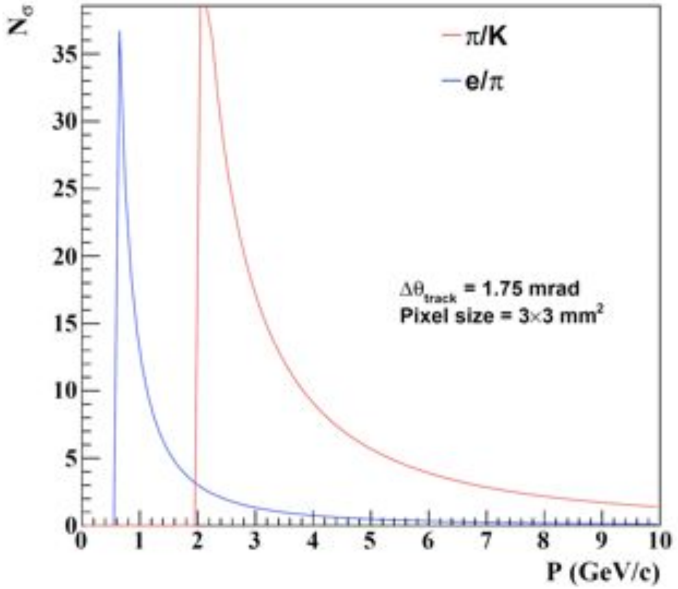
2. Correctly identify scattered electron
   d. Additional π/e separation via a Cerenkov Radiation detector.





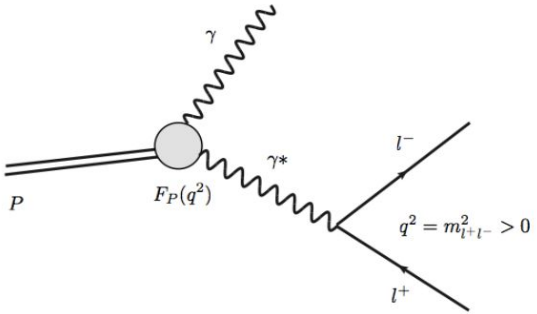
Geant4 Simulation

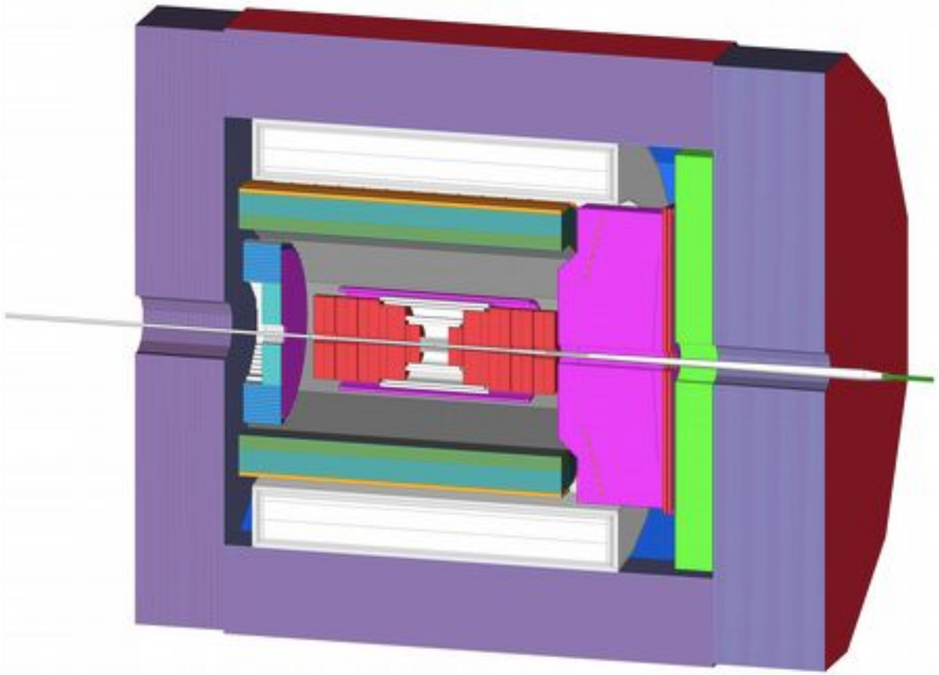
With realistic material optical properties



How to measure inclusive channels at the EIC

2. Correctly identify scattered electron
    e. Interactions with matter and Dalitz decays produce e+e- pairs. This is called pair-symmetric background!





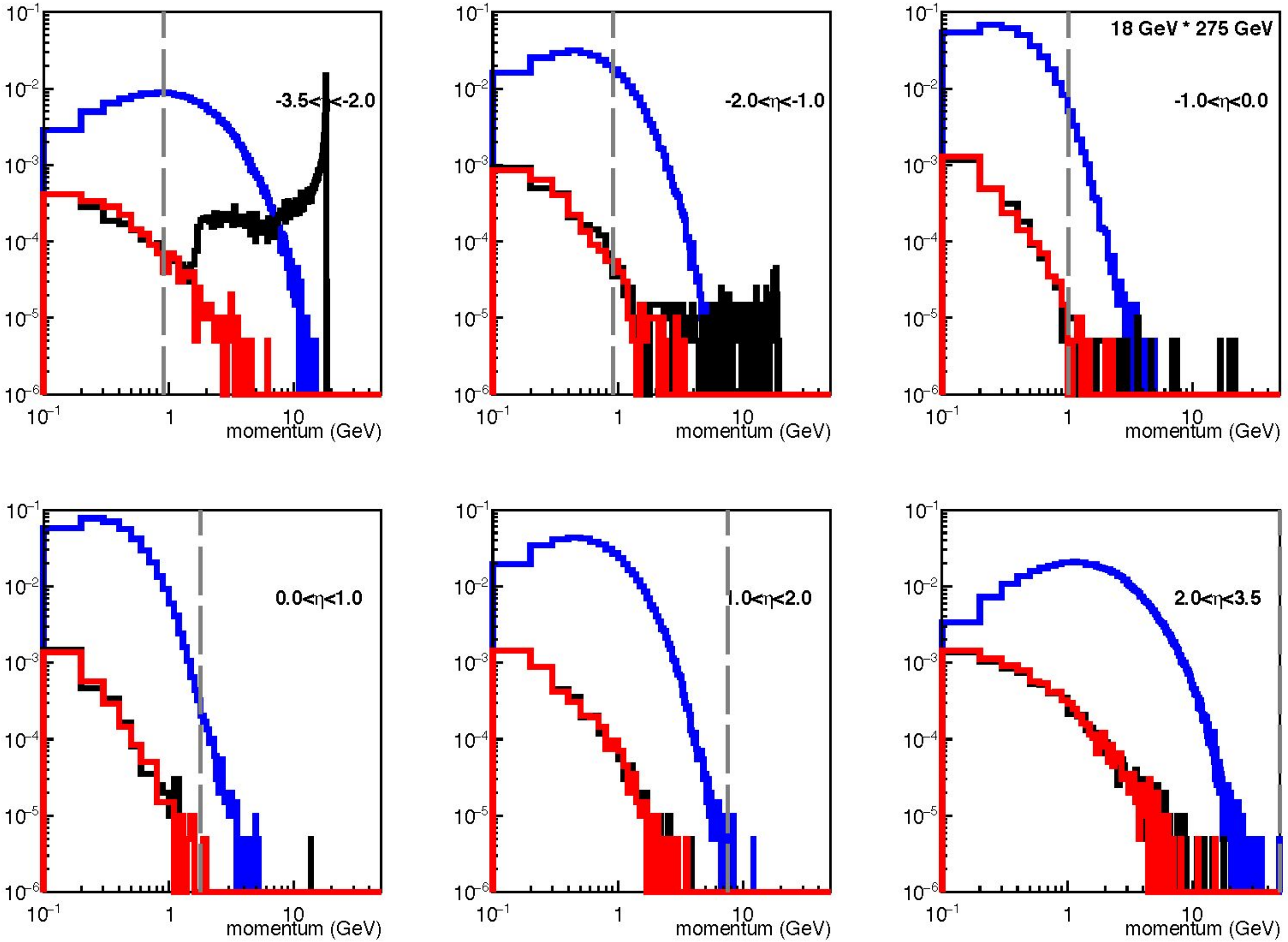
slido

How do you plan to filter out or correct for e- arising from pair-symmetric background contributions?

ⓘ Start presenting to display the poll results on this slide.

18 x 275 GeV

Electrons
Positrons
Pions



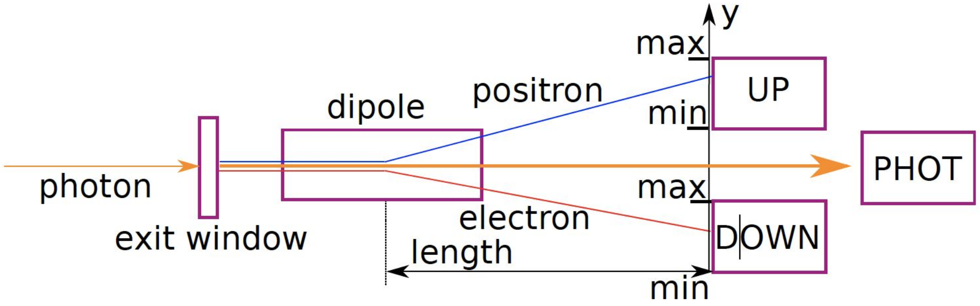
How to measure inclusive channels at the EIC

3. Spin sort your identified electrons and increment your yields - spin dependent ones if you are are measuring asymmetries.

$$A_{LL} = \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}}$$

4. Determine relative luminosity R

- Bremsstrahlung process e+p → e+p+γ
- Large cross-section, calculated to high precision theoretically
- e+e- pairs produced by photons impinging on aluminium window
- Pairs are split by magnetic field and detected separately.
- Photon detector for unconverted photons
- Will achieve 1% accuracy for integrated luminosity and < 10^{-4} for R



How to measure inclusive channels at the EIC

5. Determine polarization of electron and proton beam!
   - Need to be non-destructive
   - Need systematic uncertainty dP/P ~1%
   - Need bunch by bunch analysis

$$A_{LL} = \frac{1}{P_e P_p} \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}}$$

How to measure inclusive channels at the EIC

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   - Must be non-destructive
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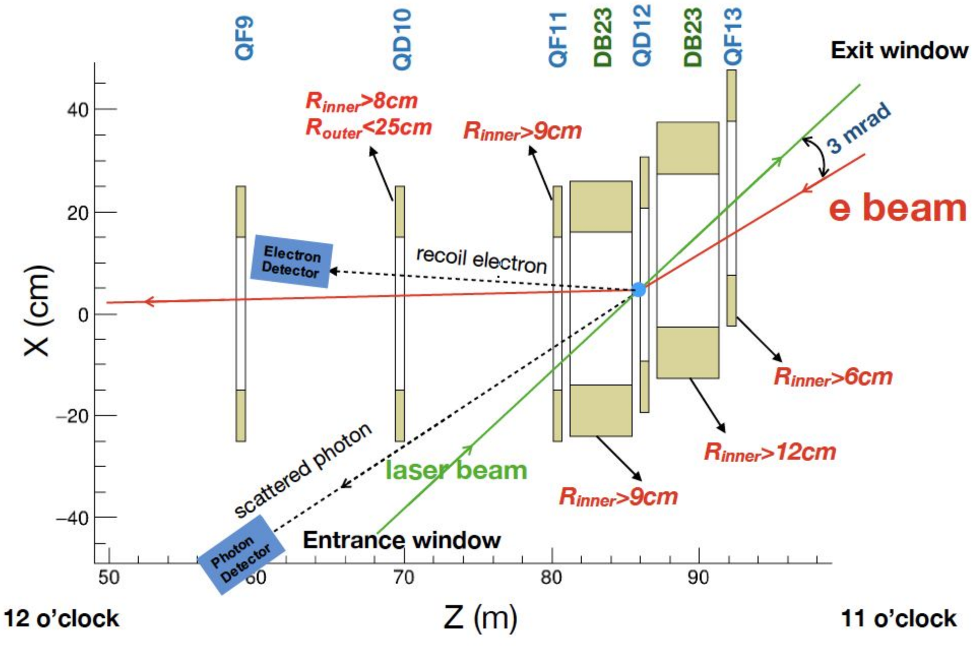
   - For the e beam use Compton Polarimeter and scatter 100% circularly polarized laser light off of electron beam. Both recoil electron and backscattered photon can be detected.



IP2 proposal

How to measure inclusive channels at the EIC

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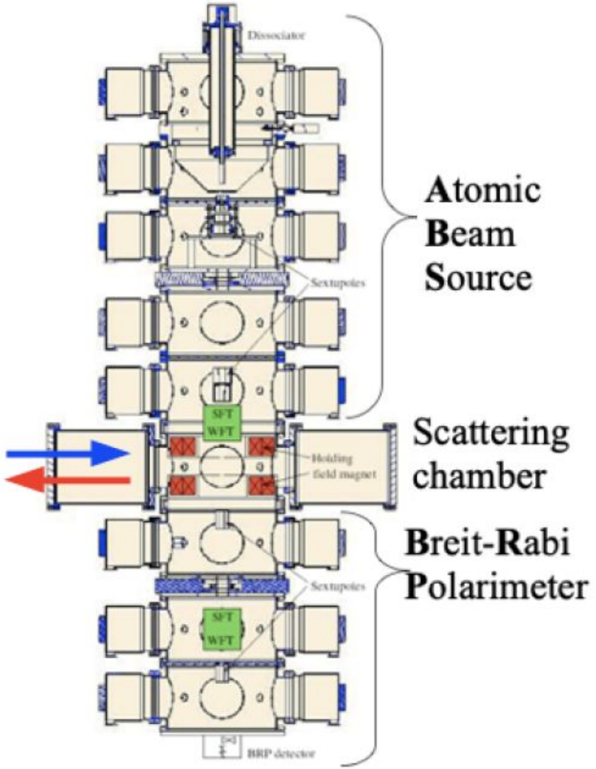
   - For the p beam, absolute measurement is made with hydrogen jet target and L/R silicon detectors to register elastic pp scattering.



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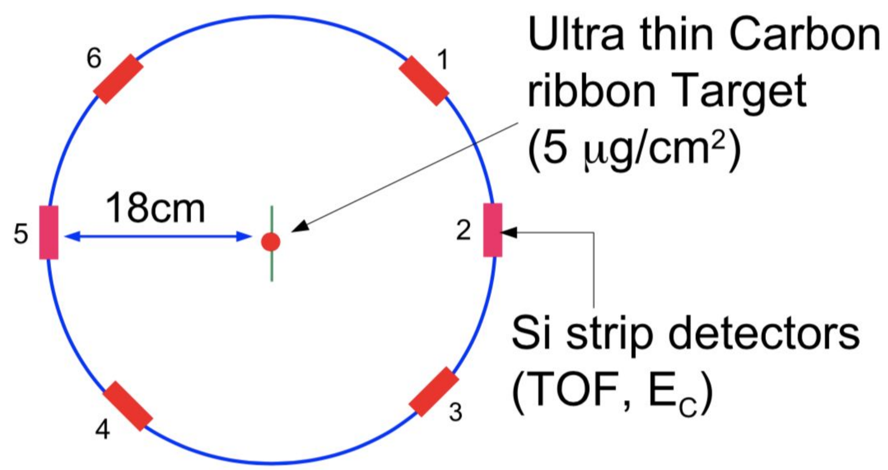
   - Relative measurement made using p-Carbon scattering target, also with L/R Si strip detectors.



How to measure inclusive channels at the EIC

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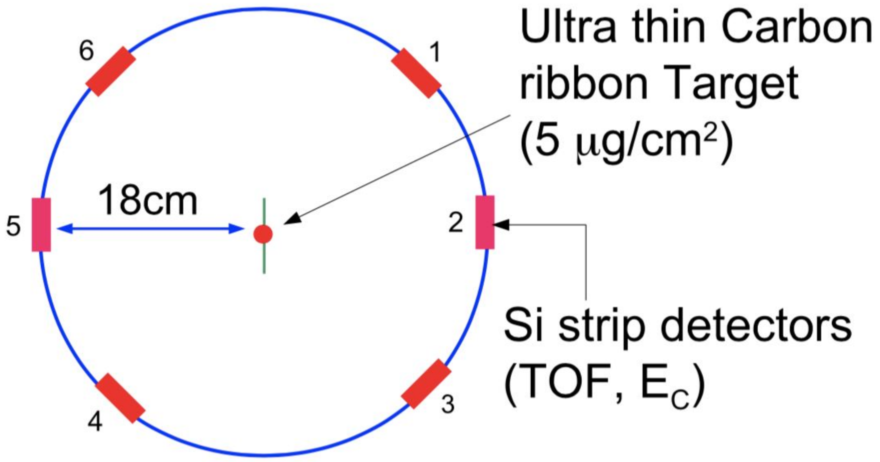

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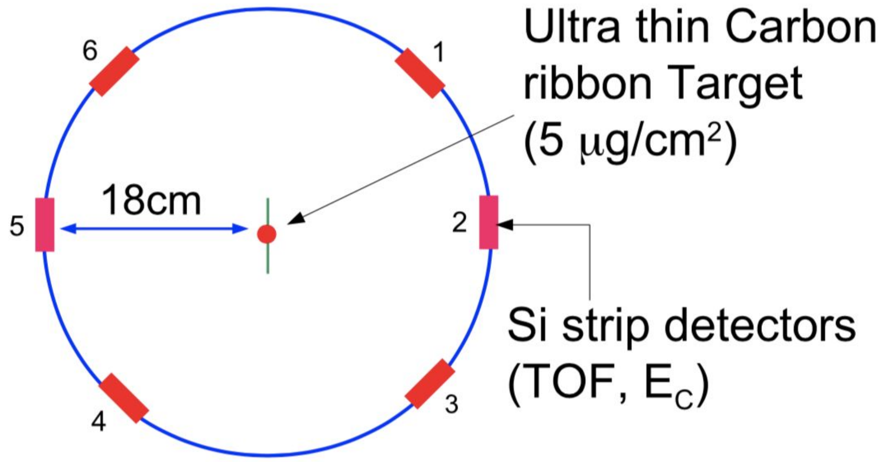
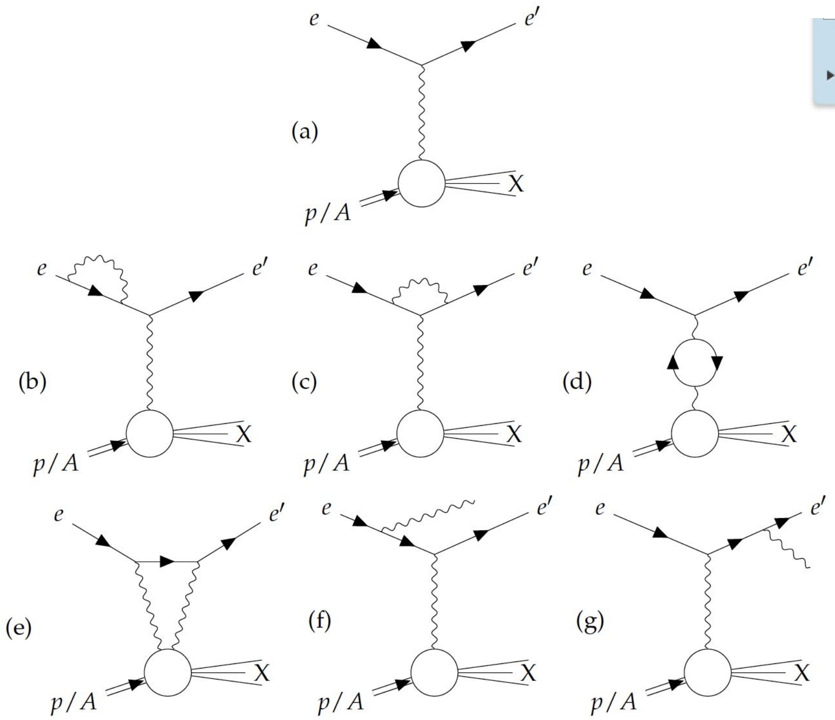


NOTE : Dave Gaskell is expert so you can get all the details next week from him!

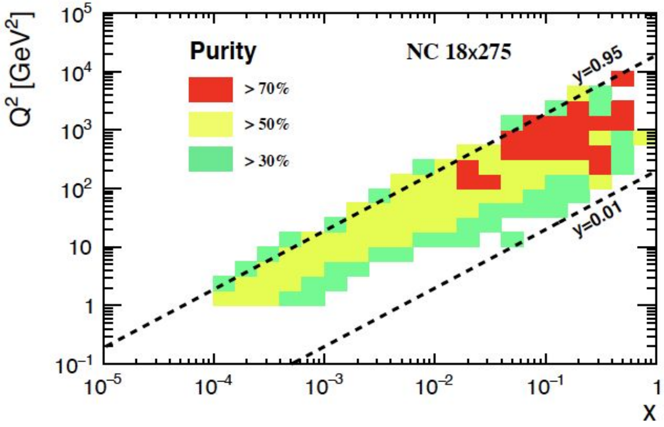
How to measure inclusive channels at the EIC

6. Apply radiative corrections
   - Processes b)-e) do not change kinematics
   - Processes f)-g) do change kinematics - the photon emission reduces the actual Q2 for a given scattering angle.
   - This connection to scattering angle convolutes acceptance and radiative effects.
   - Corrections are applied using theoretical corrections directly to measured asymmetries, or by integrating these calculations into monte carlo simulations.
   - Integration into monte-carlo allows for simultaneous corrections for acceptance, bin migration and radiative effects.

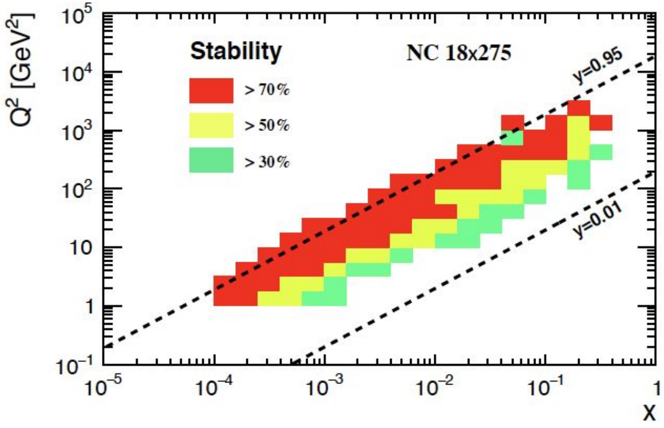


How to measure inclusive channels at the EIC

7. Bin Migration Effects
   - Account for acceptance and detector resolution effects on x, Q^2 & y reconstruction
   - a) Purity : fraction of reconstructed events that should be in that bin. It reflects the bin migration into a given bin.
   - b) Stability: fraction of events generated in a bin that are reconstructed in the same bin. It reflects migration outside of a given bin.
   - Analysis binning should be optimized to keep both of these > 30% for all bins in order to reduce kinematics corrections.
   - All reported x and Q2 values must be corrected for detector effects



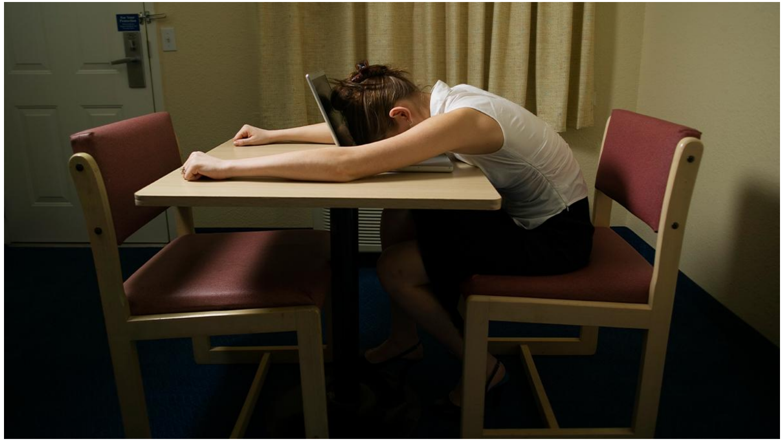
(a) NC 18x275 GeV



(b) NC 18x275 GeV

Recap: Here is what we did to make an A_{LL} measurement

1. Built detectors to measure E and p of electron.
2. Correctly identified e- that took part in hard scattering interaction.
3. Spin sorted the electrons.
4. Measured the relative luminosities.
5. Measured the beam polarizations.
6. Defined my analysis bins to maximize purity and stability.
7. Applied radiative and other kinematic corrections.
8. Extract g1p in my bins of x and Q2!



Questions from Wednesday

1. Why J M equation doesn't include the transverse spin contribution, but only the helicities? I naively think that it gives 3D spin contribution, which should include transverse contribution as well.
2. What can the EIC tell us about the helicity strange distribution?
3. In a nutshell could you explain the concept of factorization one more time?
4. Can parton helicities be further constrained by investigating GPDs via DVCS processes?
5. Discuss the different eID and PID detectors being proposed for each scattering region.