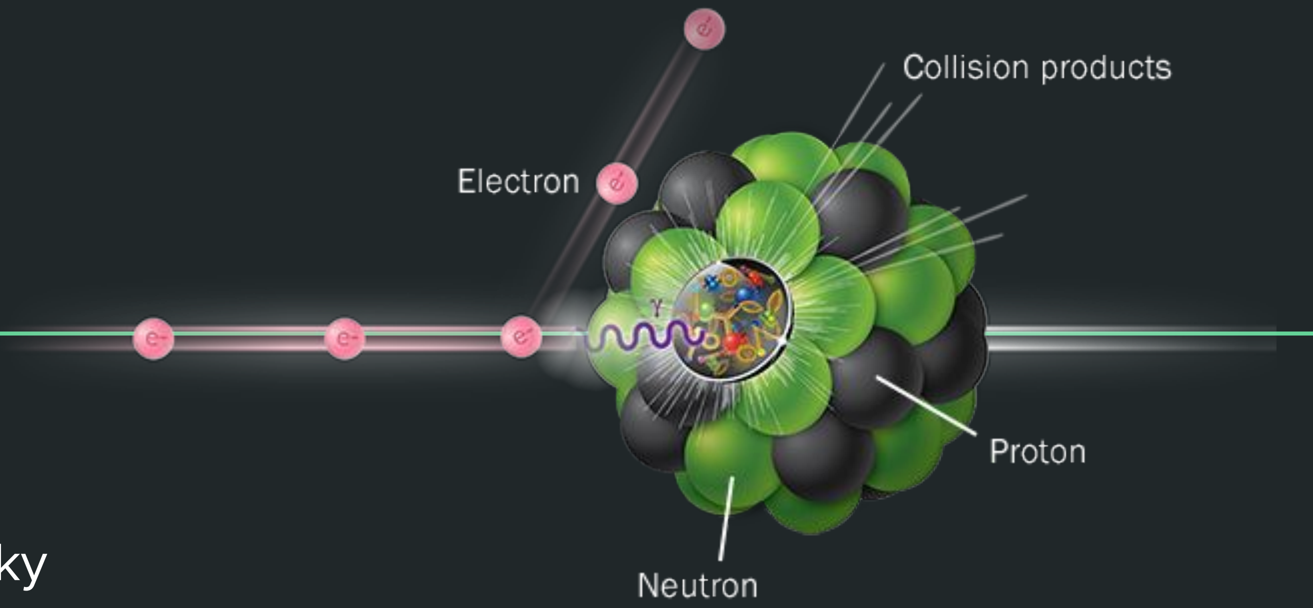
# Experimental Measurements at the EIC




Renee Fatemi
University of Kentucky

Lecture III

# Questions from Wednesday

1. In a nutshell could you explain the concept of factorization one more time?

2. 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.

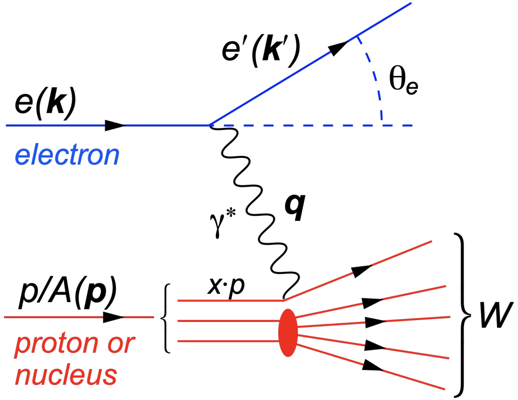
3. What can the EIC tell us about the helicity strange distribution?

4. Can parton helicities be further constrained by investigating GPDs via DVCS processes?

5. What type of eID and PID detectors are being proposed?

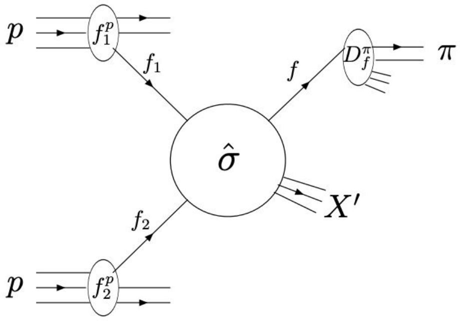
1. In a nutshell could you explain the concept of factorization one more time?

$$\sigma(ep \to e'X) \propto f(x, Q^2)\hat{\sigma}\left(\hat{s}, \hat{t}, \hat{u}\right)$$



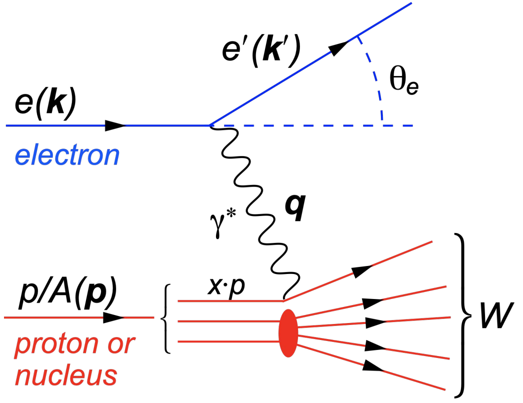

A factorization proof permits an observable, such as a cross-section or asymmetry, to be written as the multiplication (convolution) of two independent functions. In this case the parton PDF and the partonic cross-section.

$$\sigma(pp \to \pi X) \propto f_1(x, Q^2) f_2(x, Q^2)\hat{\sigma}\left(\hat{s}, \hat{t}, \hat{u}\right) D_\pi(z, Q^2)$$

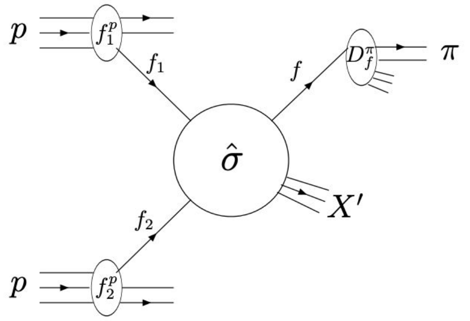


1. In a nutshell could you explain the concept of factorization one more time?

$$\sigma(ep \to e'X) \propto f(x, Q^2)\hat{\sigma}\left(\hat{s}, \hat{t}, \hat{u}\right)$$




A factorization proof permits an observable, such as a cross-section or asymmetry, to be written as the multiplication (convolution) of two independent functions. In this case the parton PDF and the partonic cross-section.




$$\sigma(pp \to \pi X) \propto f_1(x, Q^2) f_2(x, Q^2)\hat{\sigma}\left(\hat{s}, t, \hat{u}\right) D_\pi(z, Q^2)$$

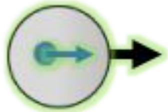
If factorization holds for both processes then the PDFs should be universal. Same is true for FF.

2. 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.

At leading twist in a collinear framework there are three functions that completely define partonic kinematics


$f(x)$ Number density of partons of flavor f with momentum fraction x inside a nucleon

$\Delta f(x)$ Number density of longitudinally polarized partons inside longitudinally polarized nucleons (Helicity)



$\Delta_T f(x)$ Number density of transversely polarized partons inside a transversely polarized nucleon (Transversity)

2. 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.

**The Jaffe-Manohar Sum rule is formulated in the context of the helicity distributions.**

R. L. Jaffe, A. Manohar, The G(1) problem: fact and fantasy on the spin of the proton, Nucl. Phys. B 337 (1990) 509–546.

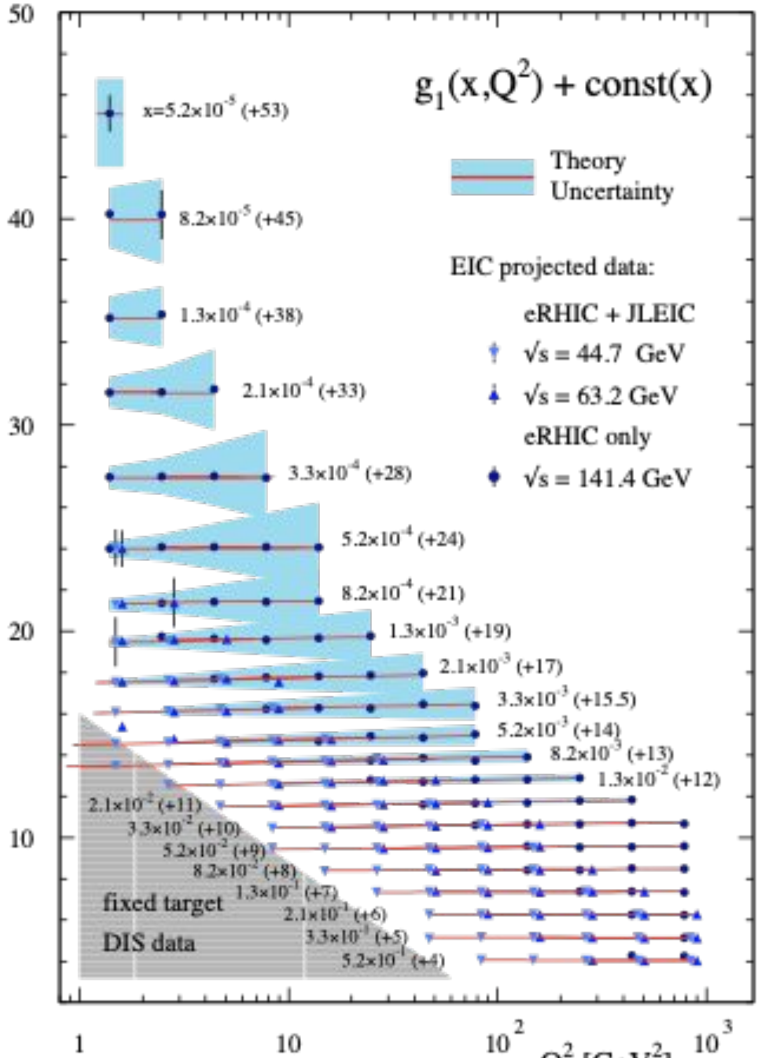
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + 1\Delta G(\mu) + L_{Q+G}(\mu)$$

$\Delta f(x)$ Number density of longitudinally polarized partons inside longitudinally polarized nucleons (Helicity)

**It is not possible to use J M formulation for the “transverse” spin sum rule.**

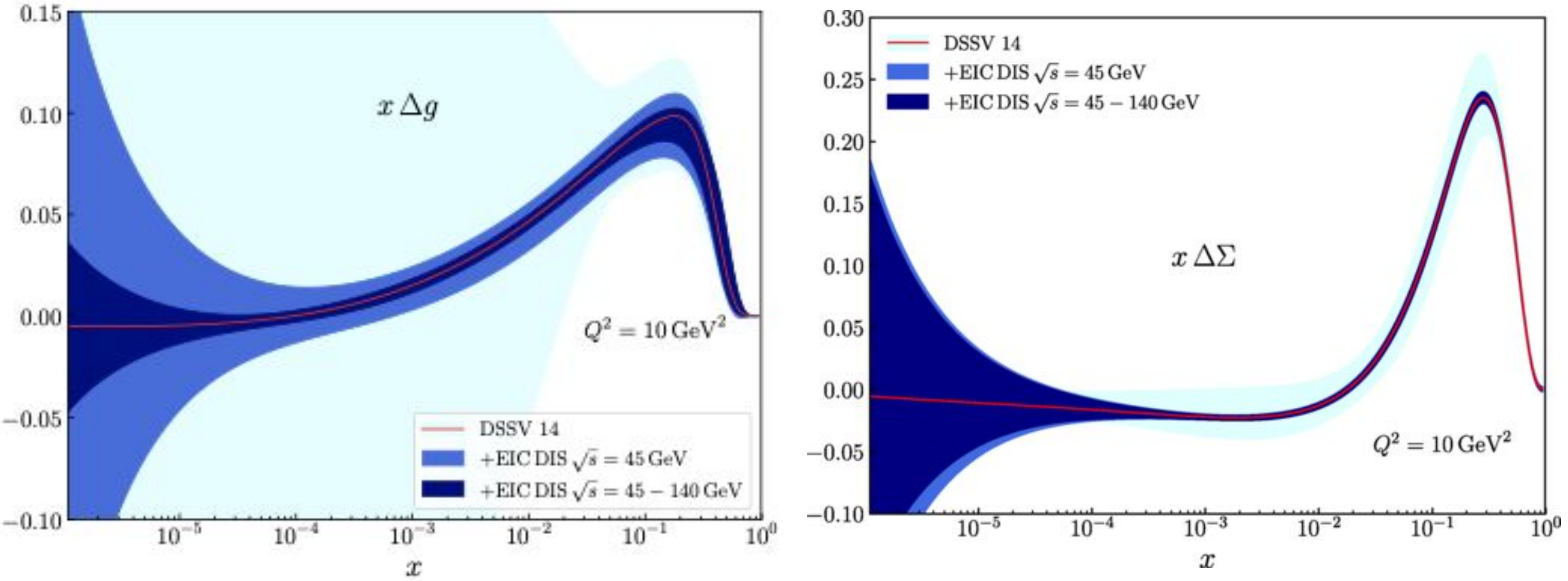
# And here is your reward for all you hard work!

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 $g^{P}_{1}$ in my bins of x and $Q^2$!




Phys. Rev. D **102**, 094018

# Constraints on Helicity Distributions from Inclusive DIS



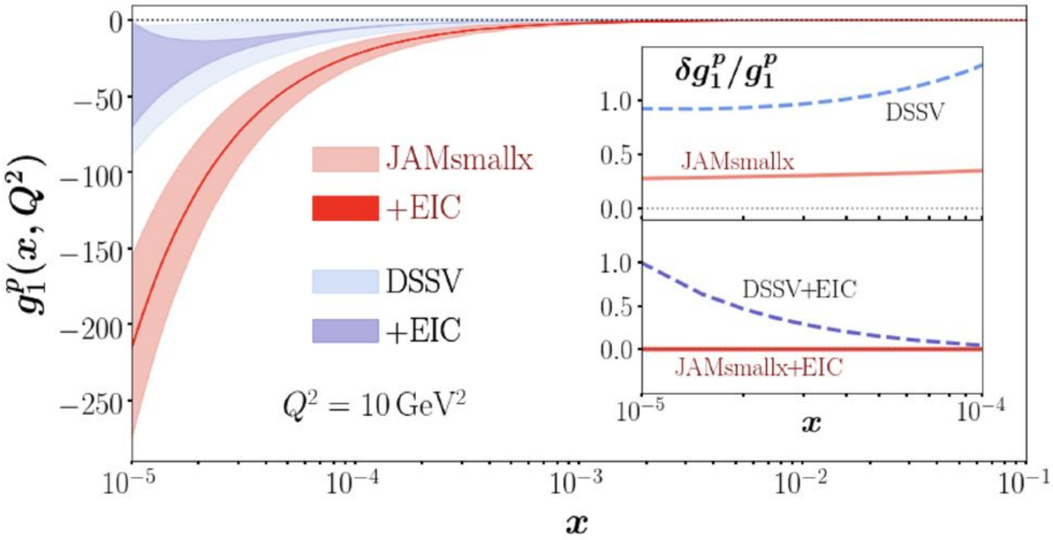

Phys. Rev. D **102**, 094018

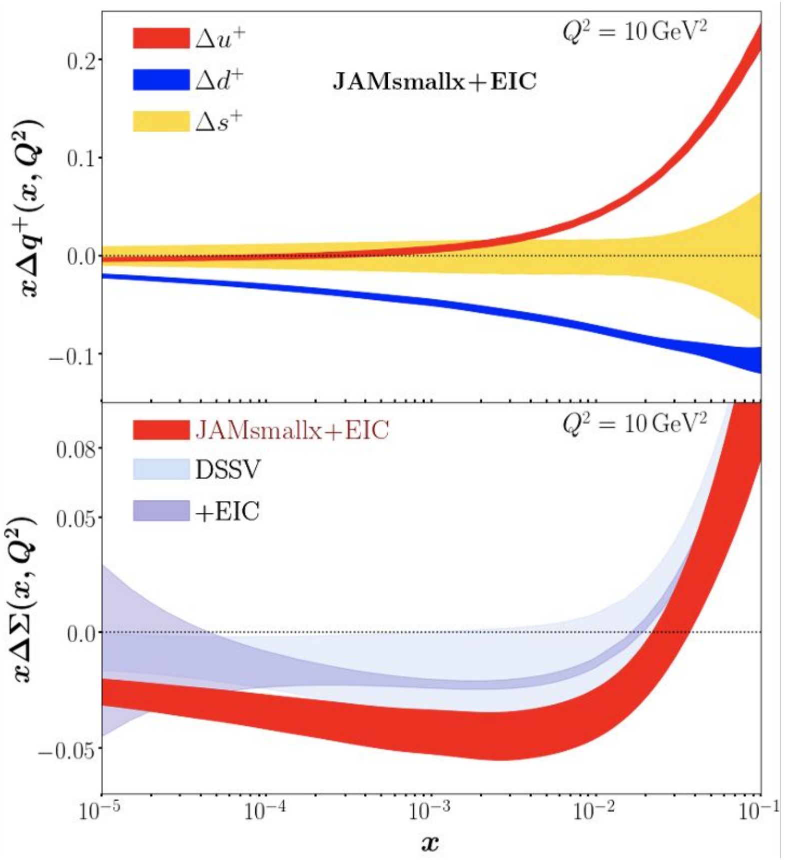
# How low can we go? *Experiments never go low enough …*

*Yellow Report : 2103.05419*

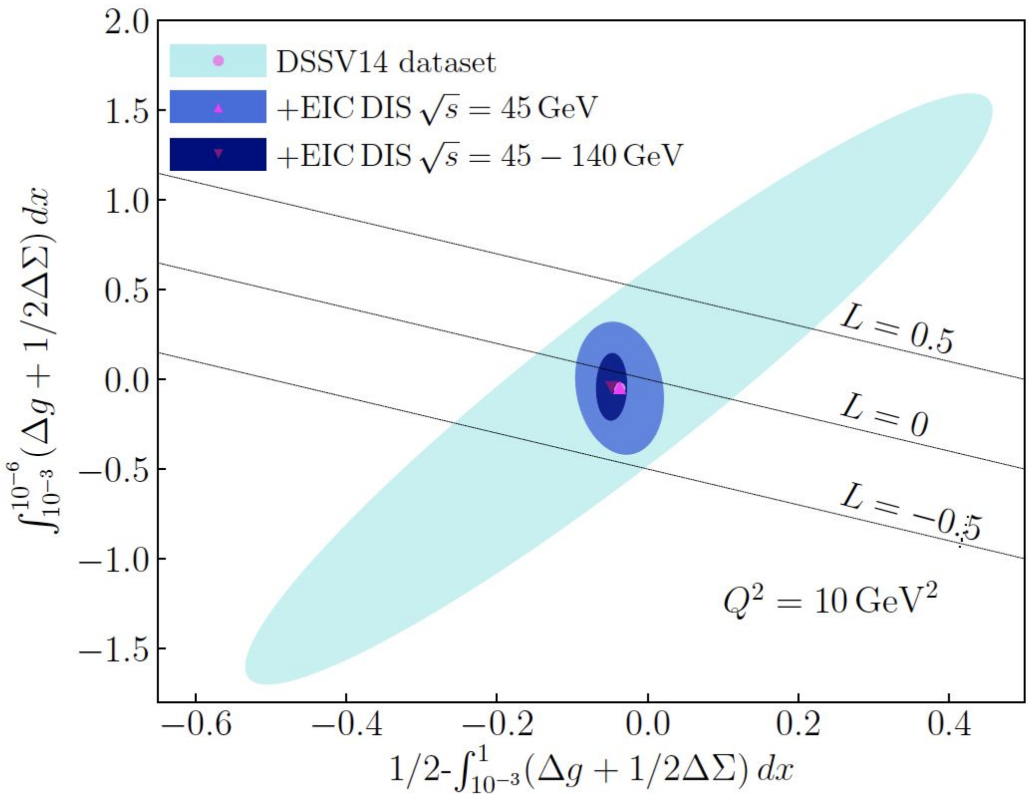
Work by Pitonyak, Sievert and Kovchegov point to a new evolution in x that can ***predict*** low x gluon helicity contribution.

New constraints by JAMsmallx (2102.06159)



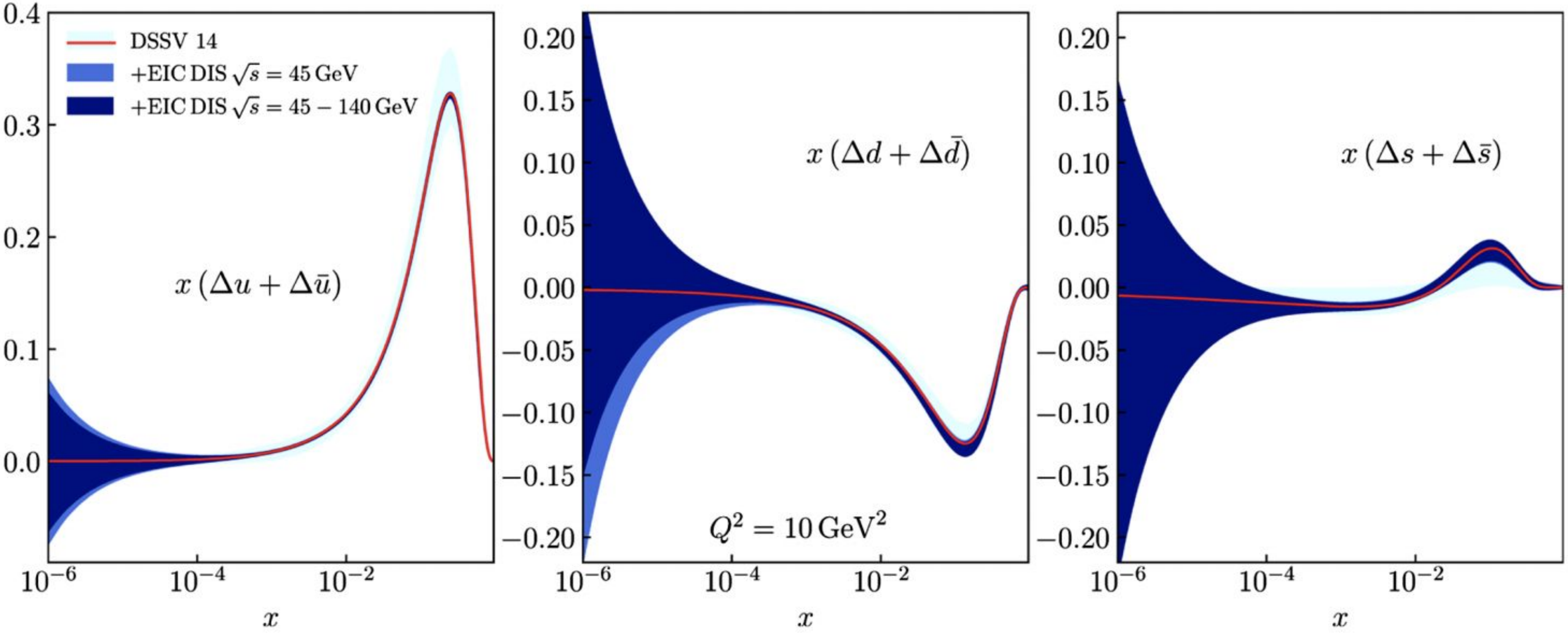



# Constraints on OAM from Inclusive DIS



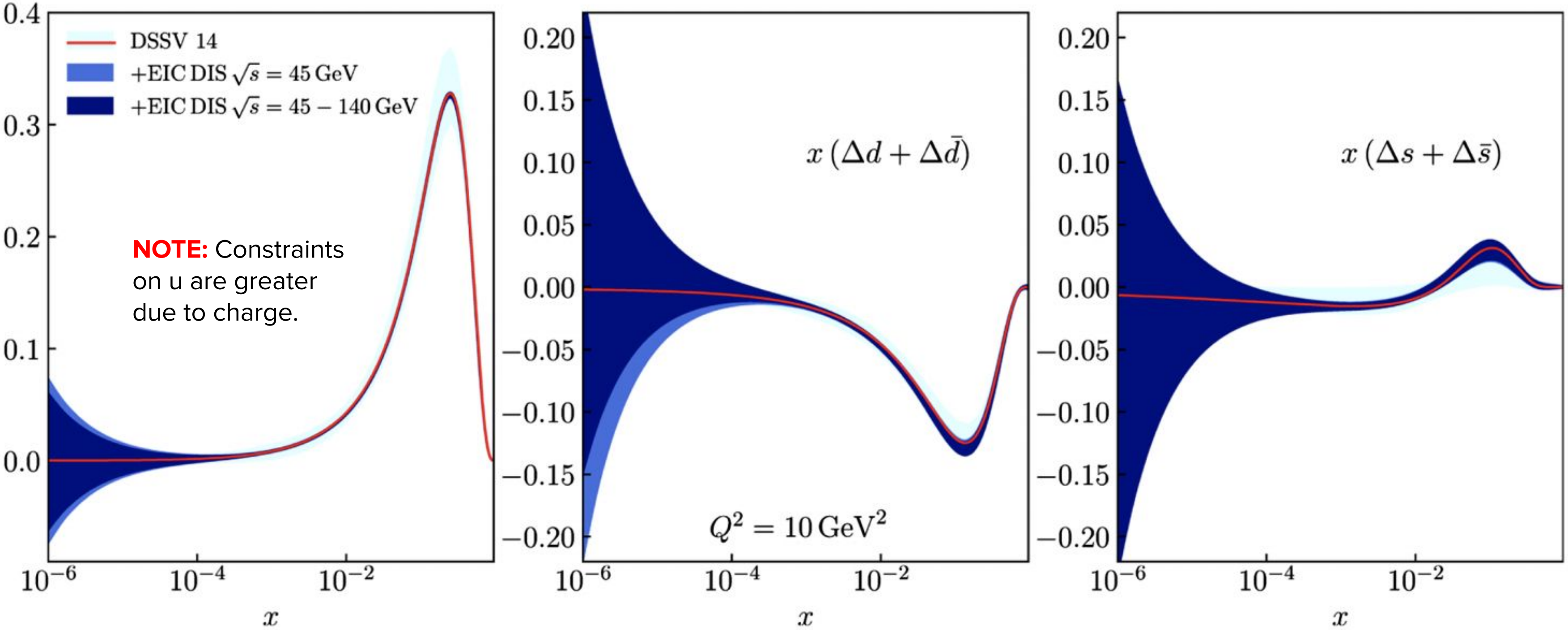

Phys. Rev. D **102**, 094018

# Limits of inclusive DIS ➔ flavor separation




Phys. Rev. D **102**, 094018

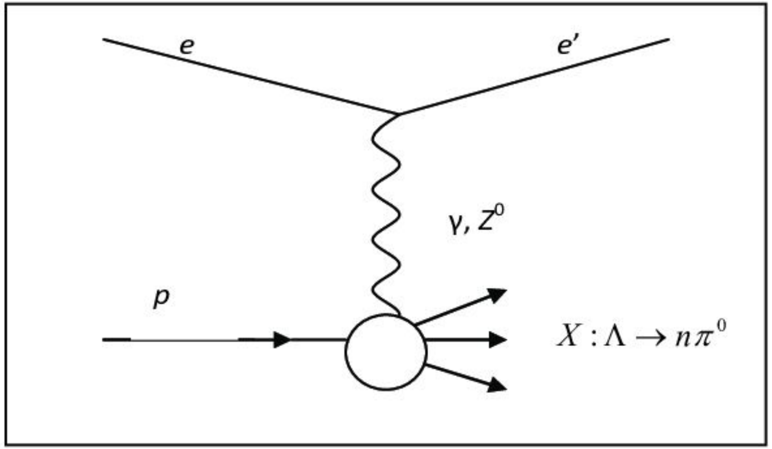
# Limits of inclusive DIS ➔ flavor separation




**NOTE:** Constraints on u are greater due to charge.

Phys. Rev. D **102**, 094018

# Parity Violating Asymmetries

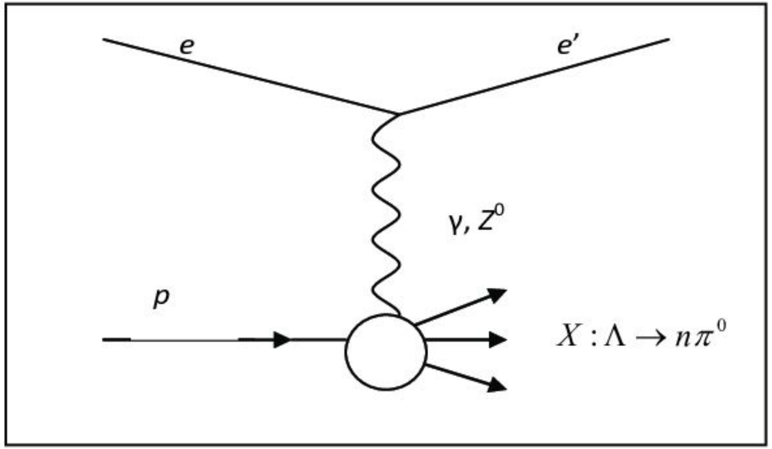



- Inclusive DIS has contributions from both virtual photon and $Z^0$ exchange.
- Can isolate the contributions from ***γ****** - $Z^0$ interference by looking at single spin asymmetries

$$A_{\rm PV}^{\rm hadron} = \frac{\sigma^{(+)} - \sigma^{(-)}}{\sigma^{(+)} + \sigma^{(-)}} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}[g_V^e \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A^e \frac{Y_-}{Y_+}\frac{g_1^{\gamma Z}}{F_1^\gamma}].$$

**Spin sort only by proton beam, integrate over e- beam.**

# Parity Violating Asymmetries




- Inclusive DIS has contributions from both virtual photon and $Z^0$ exchange.
- Can isolate the contributions from $\gamma^*$ - $Z^0$ interference by looking at single spin asymmetries

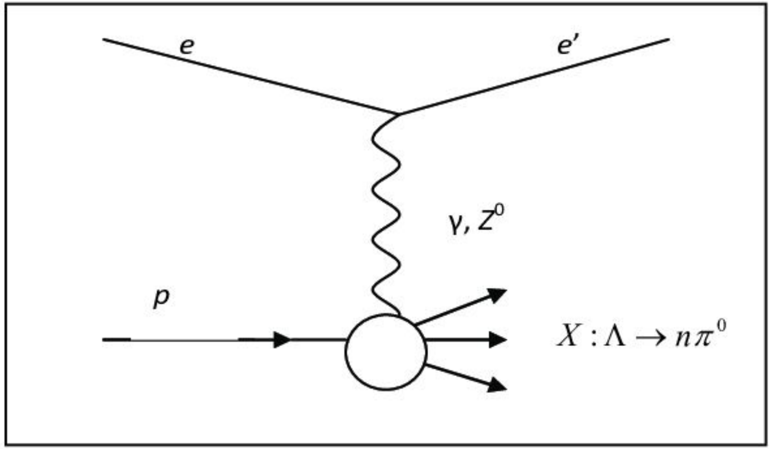
$$A_{PV}^{\text{hadron}} = \frac{\sigma^{(+)} - \sigma^{(-)}}{\sigma^{(+)} + \sigma^{(-)}}$$

$$= \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V^e \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A^e \frac{Y_-}{Y_+}\frac{g_1^{\gamma Z}}{F_1^\gamma}\right].$$

**Spin sort only by proton beam, integrate over e- beam.**

**Structure functions from virtual photon exchange.**

# Parity Violating Asymmetries



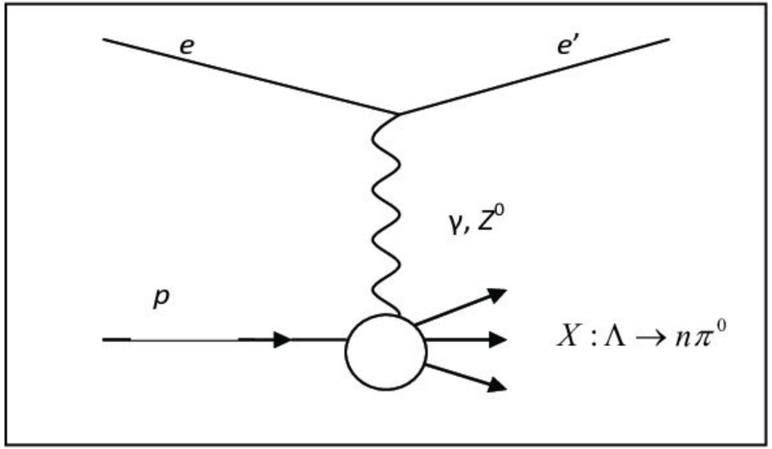

$$A_{\rm PV}^{\rm hadron} = \frac{\sigma^{(+)} - \sigma^{(-)}}{\sigma^{(+)} + \sigma^{(-)}} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}[g_V^e \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A^e \frac{Y_-}{Y_+} \frac{g_1^{\gamma Z}}{F_1^\gamma}].$$

$$g_1^{\text{proton, }\gamma Z} \approx \frac{1}{9}(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} + \Delta c + \Delta\bar{c})$$

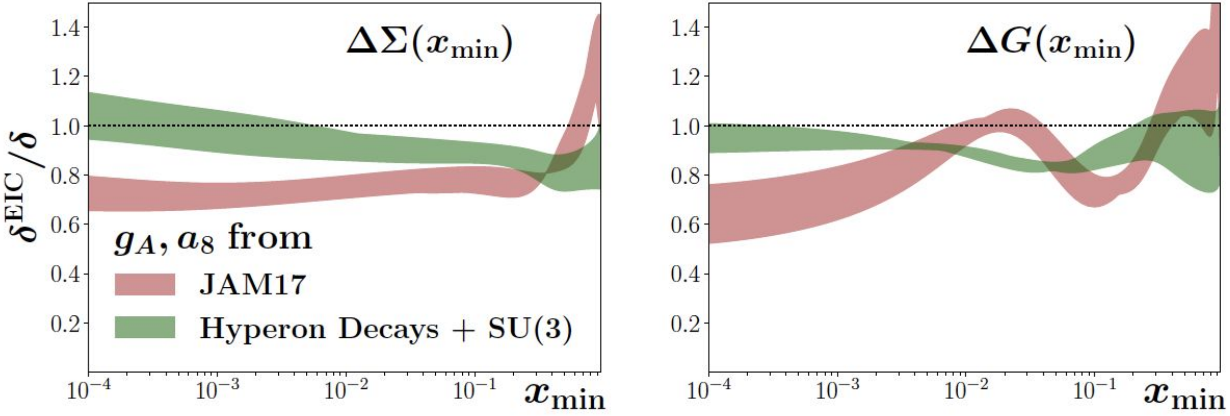
$$g_5^{\text{proton, }\gamma Z} = \frac{1}{3}(\Delta u_V + \Delta c - \Delta\bar{c}) + \frac{1}{6}(\Delta d_V + \Delta s - \Delta\bar{s})$$

# Parity Violating Asymmetries

$$A_{PV}^{\text{hadron}} = \frac{\sigma^{(+)} - \sigma^{(-)}}{\sigma^{(+)} + \sigma^{(-)}}$$
$$= \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V^e \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A^e \frac{Y_-}{Y_+}\frac{g_1^{\gamma Z}}{F_1^\gamma}\right].$$




Constraints depend on source of axial coupling constant.

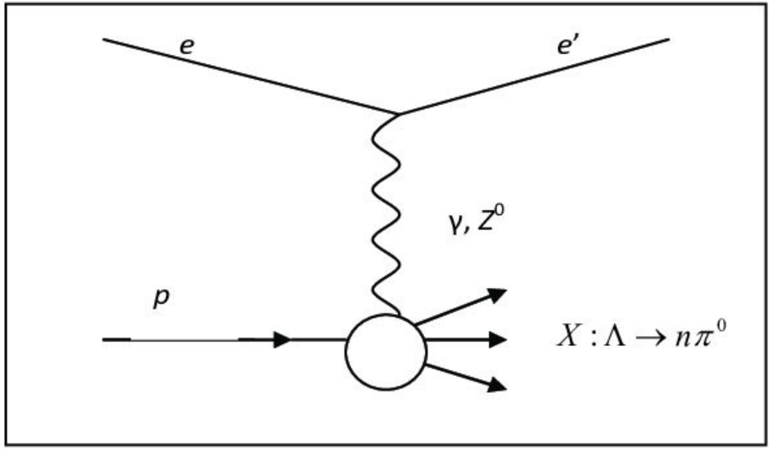



*Yellow Report : 2103.05419*

# Parity Violating Asymmetries

**Spin sort on e- beam**

$$A_{\rm PV}^{\rm electron} = \frac{\sigma^R - \sigma^L}{\sigma^R + \sigma^L}$$
$$= \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A^e \frac{F_1^{\gamma Z}}{F_1^\gamma} + g_V^e \frac{Y_-}{2Y_+}\frac{F_3^{\gamma Z}}{F_1^\gamma}\right],$$



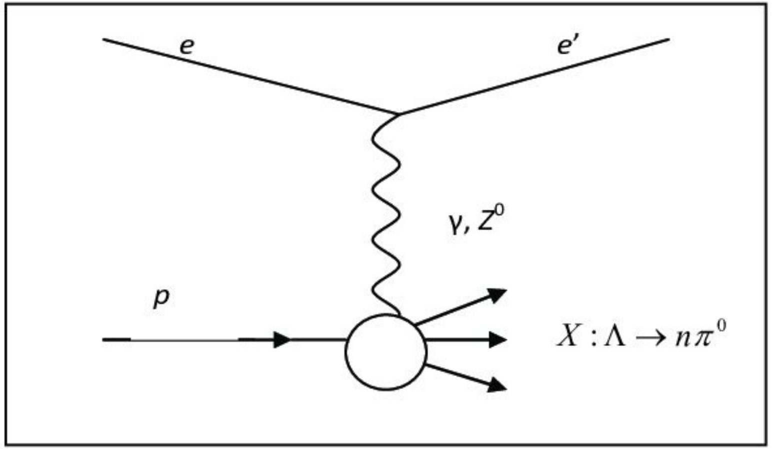

$$F_1^{\text{proton},\ \gamma Z} \approx \frac{1}{9}(u + \bar{u} + d + \bar{d} + s + \bar{s} + c + \bar{c}),$$
$$F_3^{\text{proton},\ \gamma Z} = \frac{2}{3}(u_V + c - \bar{c}) + \frac{1}{3}(d_V + s - \bar{s}),$$

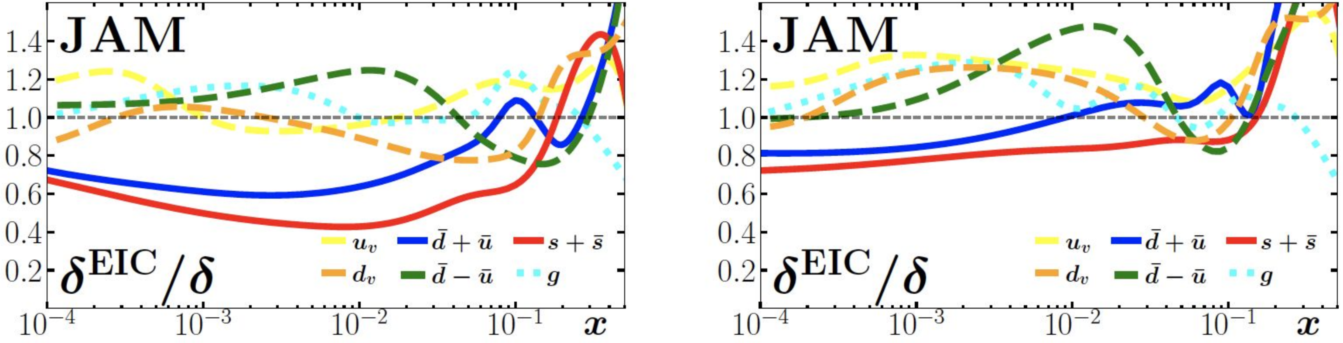
# Parity Violating Asymmetries

$$A_{\mathrm{PV}}^{\mathrm{electron}} = \frac{\sigma^R - \sigma^L}{\sigma^R + \sigma^L}$$

$$= \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V^e \frac{Y_-}{2Y_+}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right],$$

**Spin sort on e- beam**




*Yellow Report : 2103.05419*

Potential to constraint strange contribution - depends on electron ID systematics.

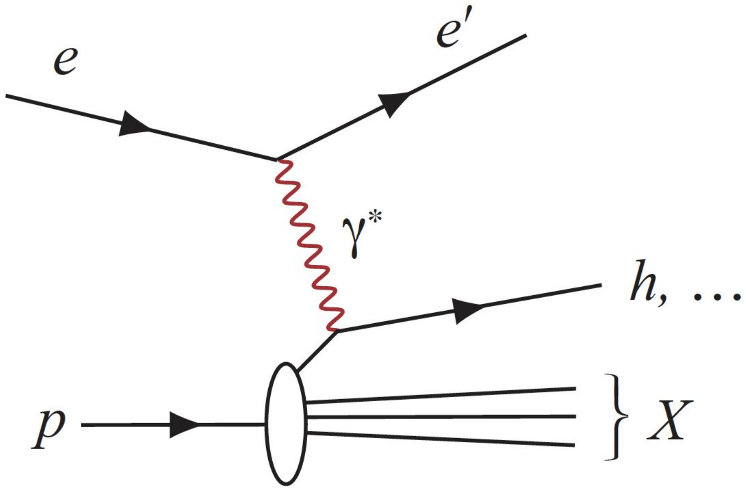
slido

# How can we separate quark and anti-quark helicity distributions?

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

# Semi-inclusive Deep Inelastic Scattering (SIDIS)

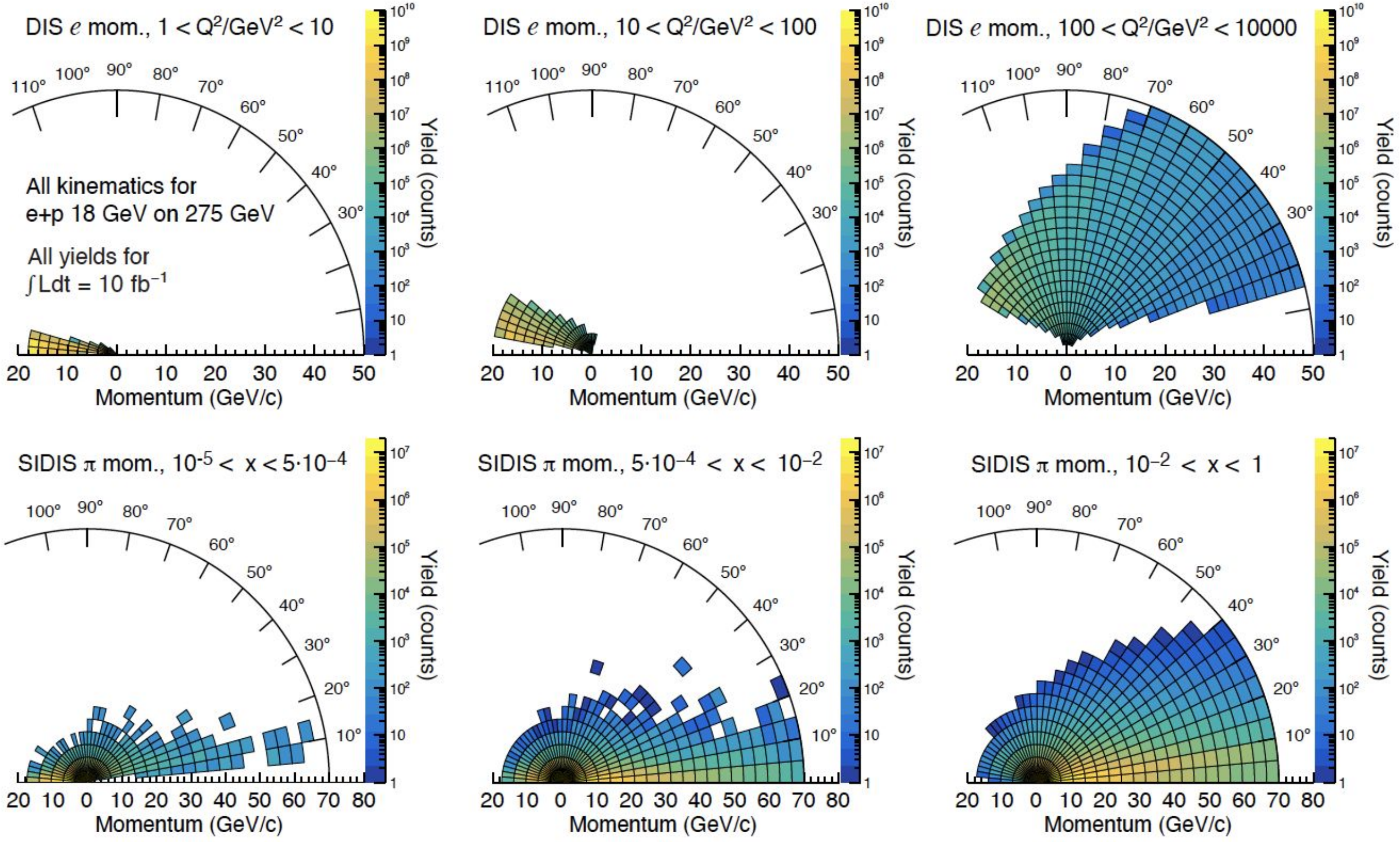
- Identify and reconstruct scattered electron as in inclusive DIS and use it to determine kinematics
- In addition to e- tag final state hadrons.
- Hadrons serve as quark flavor filter. For example:
  - $\pi$+ ➔ u+dbar   $\pi$- ➔ d+ubar
  - **K+** ➔ u+sbar   **K-** ➔ s+ubar
- Requires knowledge about fragmentation functions $D(z, Q^2)$ and this introduces additional uncertainties.
- Z is the momentum fraction of the scattered quark carried by the hadron. The correlation between the hadron and the fragmenting parton's flavor increases as z ➔ 1.
- Low z hadrons are more likely to originate from the proton remnant, rather than the hard interaction.




$$z = \frac{p \cdot p_h}{p \cdot q}$$

# Where do the hadrons live?

*Yellow Report : 2103.05419*

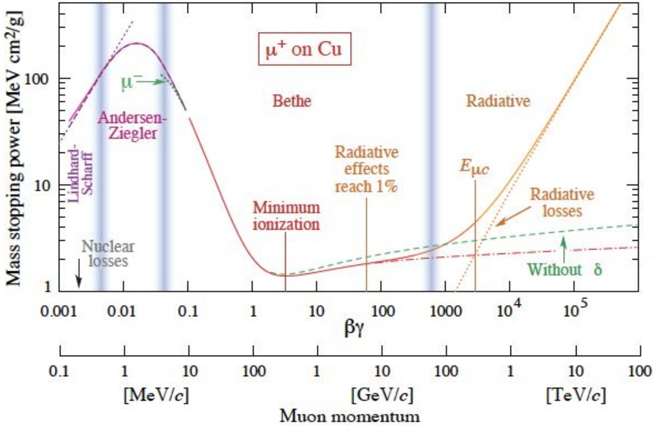


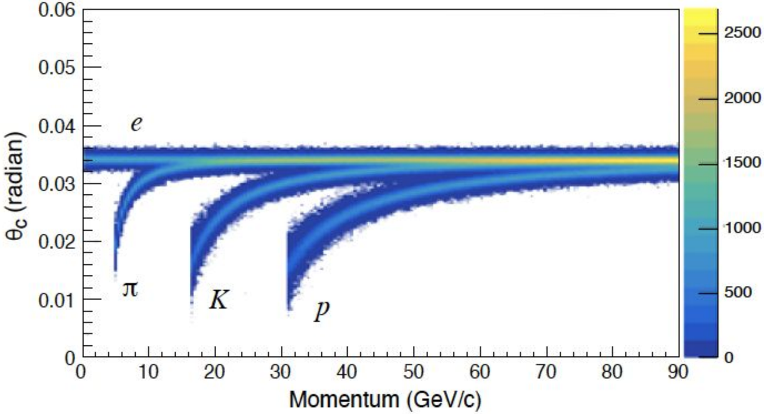

Need PID for pions and Kaons up to 50 GeV in forward direction

# Hadron PID ➜ velocity

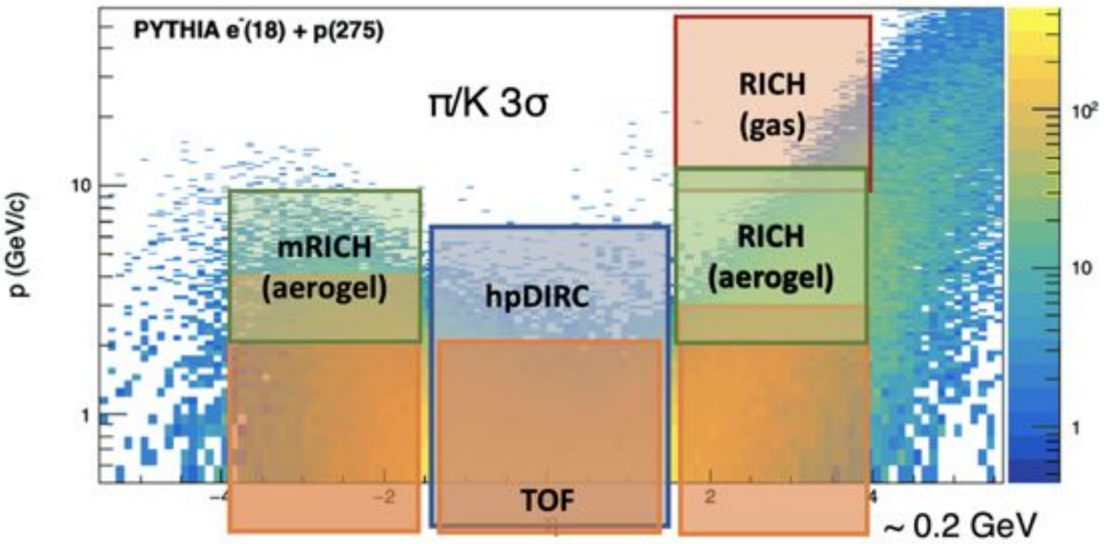
1. Time-of-Flight (TOF)
 - Direct measurement of of particle velocity
 - Required tracking to measures the momentum p
 - Extract $\beta$ from scintillator/silicon detector plus start time detector
 - Mass = $\beta\boldsymbol{\gamma}$/p

2. Velocity dependent interactions with materials



# Yellow Report Requirements and Proposed Technology

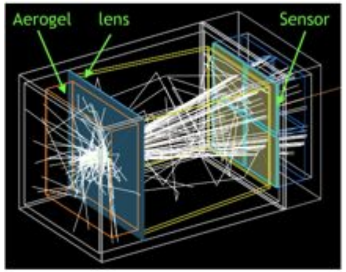



*Greg Kalicy and Xiaochun He*

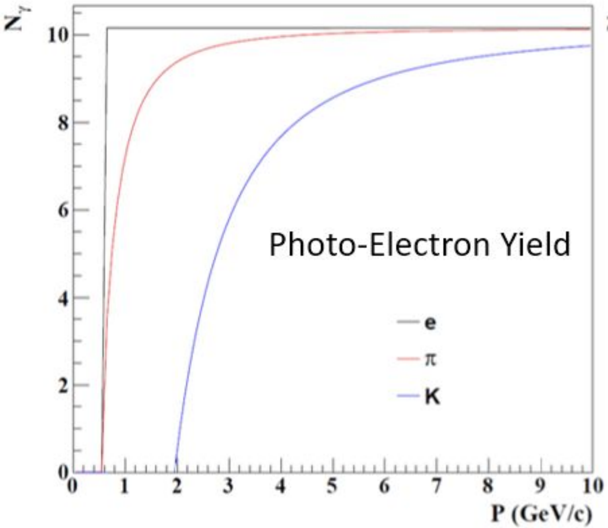
Table 8.6 Requested PID momentum coverage for 3σ pion/kaon separation. (Yellow Report)

| Pseudorapidity Range | Momentum Range |
|---|---|
| $-3.5 < \eta < -1.0$ | $\leq 7$ GeV/$c$ |
| $-1.0 < \eta < 0.5$ | $\leq 10$ GeV/$c$ |
| $0.5 < \eta < 1.0$ | $\leq 15$ GeV/$c$ |
| $1.0 < \eta < 1.5$ | $\leq 30$ GeV/$c$ |
| $1.5 < \eta < 2.5$ | $\leq 50$ GeV/$c$ |
| $2.5 < \eta < 3.0$ | $\leq 30$ GeV/$c$ |
| $3.0 < \eta < 3.5$ | $\leq 20$ GeV/$c$ |

- mRICH - modular Ring Imaging Cerenkov Detector. Aerogel based with Frensel lens. Used for both electron ID and PID.



# Yellow Report Requirements and Proposed Technology



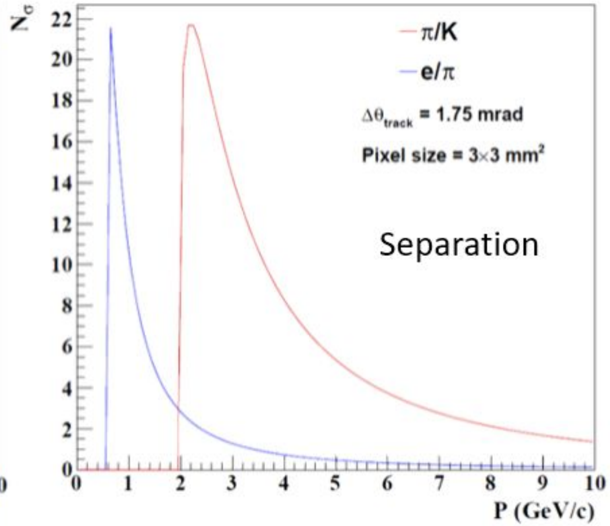
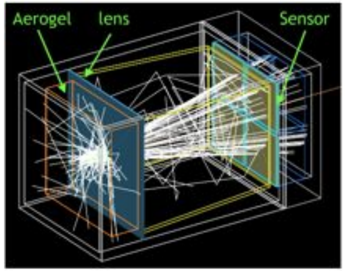



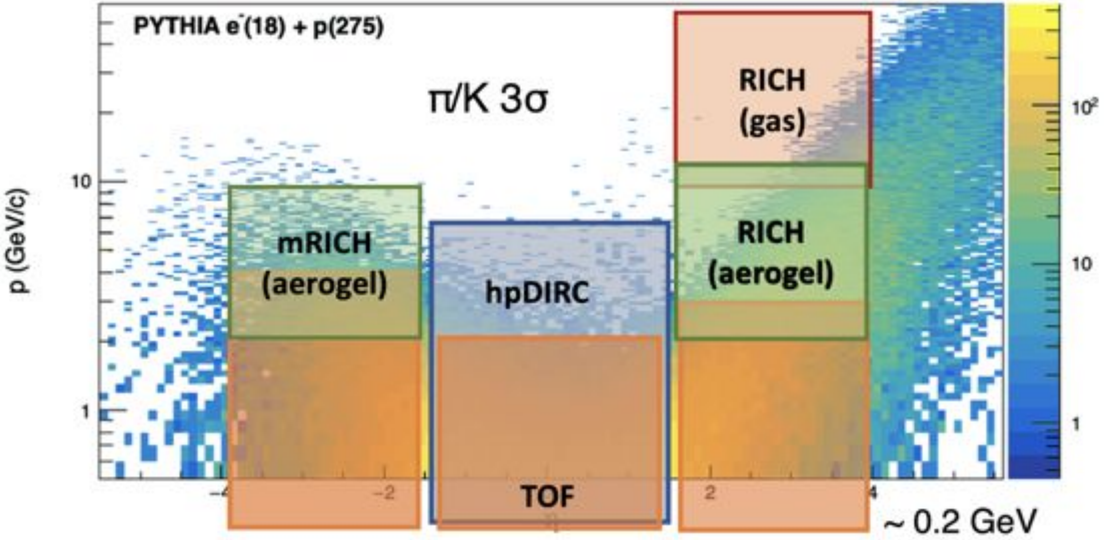

Table 8.6 Requested PID momentum coverage for 3σ pion/kaon separation. (Yellow Report)

| Pseudorapidity Range | Momentum Range |
|---|---|
| $-3.5 < \eta < -1.0$ | $\leq 7$ GeV/$c$ |
| $-1.0 < \eta < 0.5$ | $\leq 10$ GeV/$c$ |
| $0.5 < \eta < 1.0$ | $\leq 15$ GeV/$c$ |
| $1.0 < \eta < 1.5$ | $\leq 30$ GeV/$c$ |
| $1.5 < \eta < 2.5$ | $\leq 50$ GeV/$c$ |
| $2.5 < \eta < 3.0$ | $\leq 30$ GeV/$c$ |
| $3.0 < \eta < 3.5$ | $\leq 20$ GeV/$c$ |

- mRICH - modular Ring Imaging Cerenkov Detector. Aerogel based with Frensel lens.
- mRICH - eID out to ~ 2GeV
- mRICH - pi/K PID out to ~7GeV



# Yellow Report Requirements and Proposed Technology

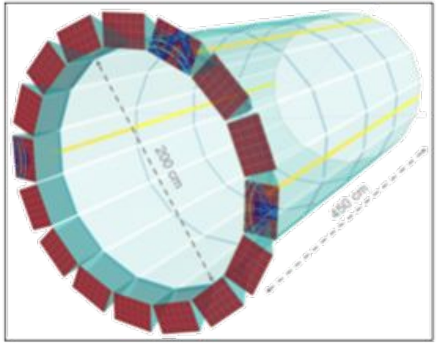



*Greg Kalicy and Xiaochun He*

Table 8.6 Requested PID momentum coverage for 3σ pion/kaon separation. (Yellow Report)

| Pseudorapidity Range | Momentum Range |
|---|---|
| $-3.5 < \eta < -1.0$ | $\lesssim 7$ GeV/$c$ |
| $-1.0 < \eta < 0.5$ | $\lesssim 10$ GeV/$c$ |
| $0.5 < \eta < 1.0$ | $\lesssim 15$ GeV/$c$ |
| $1.0 < \eta < 1.5$ | $\lesssim 30$ GeV/$c$ |
| $1.5 < \eta < 2.5$ | $\lesssim 50$ GeV/$c$ |
| $2.5 < \eta < 3.0$ | $\lesssim 30$ GeV/$c$ |
| $3.0 < \eta < 3.5$ | $\lesssim 20$ GeV/$c$ |

- DIRC - Detection of internally reflected Cerenkov
- DIRC - use material (like quartz) with index n > 2, allows for total internal reflection and propagation to light to end of material.
- DIRC - allow for pi/K separation up to 6 GeV with very thin detector
- hpDIRC - “high performance” DIRC provides ring focusing and therefore improved resolution



# Yellow Report Requirements and Proposed Technology

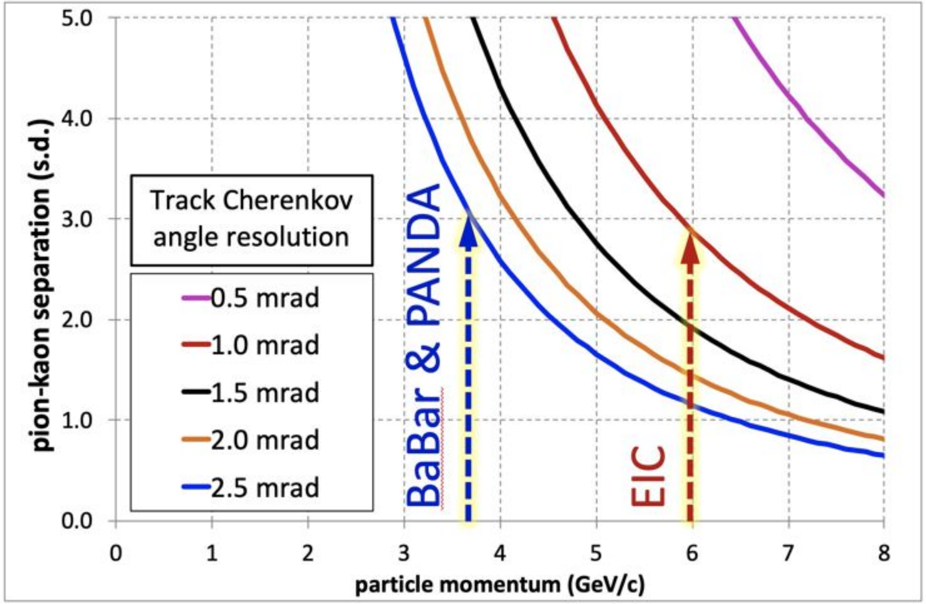
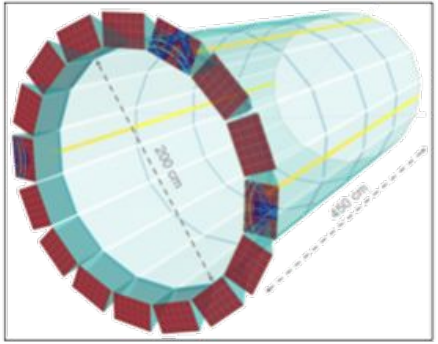



Table 8.6 Requested PID momentum coverage for 3σ pion/kaon separation. (Yellow Report)

| Pseudorapidity Range | Momentum Range |
|---|---|
| $-3.5 < \eta < -1.0$ | $\leq 7$ GeV/$c$ |
| $-1.0 < \eta < 0.5$ | $\leq 10$ GeV/$c$ |
| $0.5 < \eta < 1.0$ | $\leq 15$ GeV/$c$ |
| $1.0 < \eta < 1.5$ | $\leq 30$ GeV/$c$ |
| $1.5 < \eta < 2.5$ | $\leq 50$ GeV/$c$ |
| $2.5 < \eta < 3.0$ | $\leq 30$ GeV/$c$ |
| $3.0 < \eta < 3.5$ | $\leq 20$ GeV/$c$ |

- DIRC - Detection of internally reflected Cerenkov
- DIRC - use material (like quartz) with index n > 2, allows for total internal reflection and propagation to light to end of material.
- DIRC - allow for pi/K separation up to 6 GeV with very thin detector
- hpDIRC - "high performance" DIRC provides ring focusing and therefore improved resolution



# Yellow Report Requirements and Proposed Technology

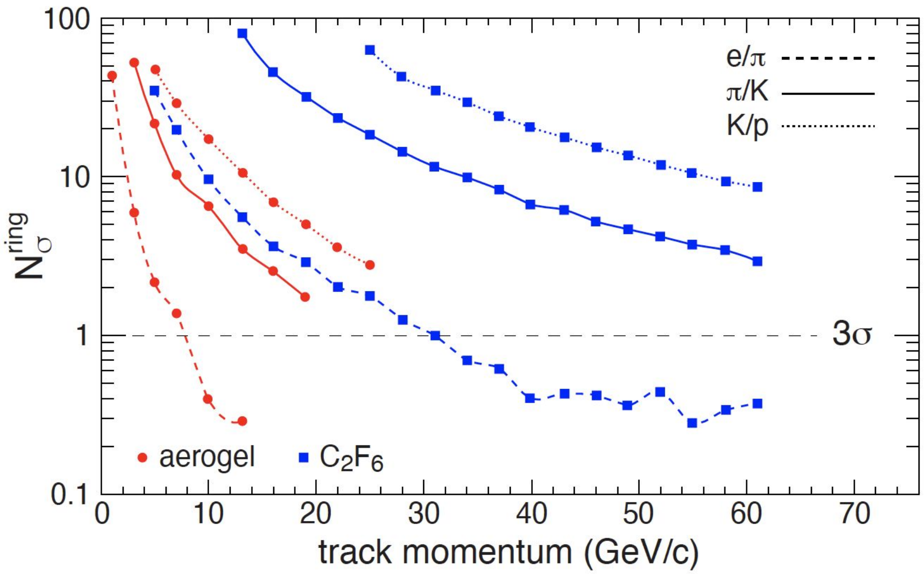
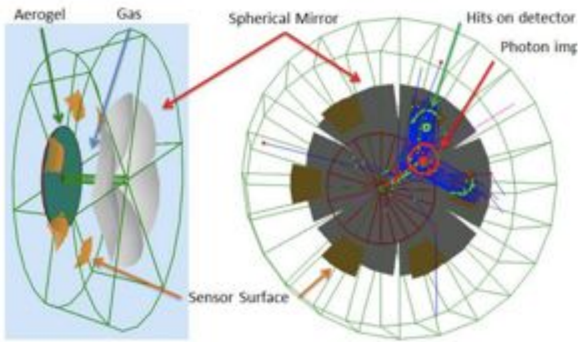


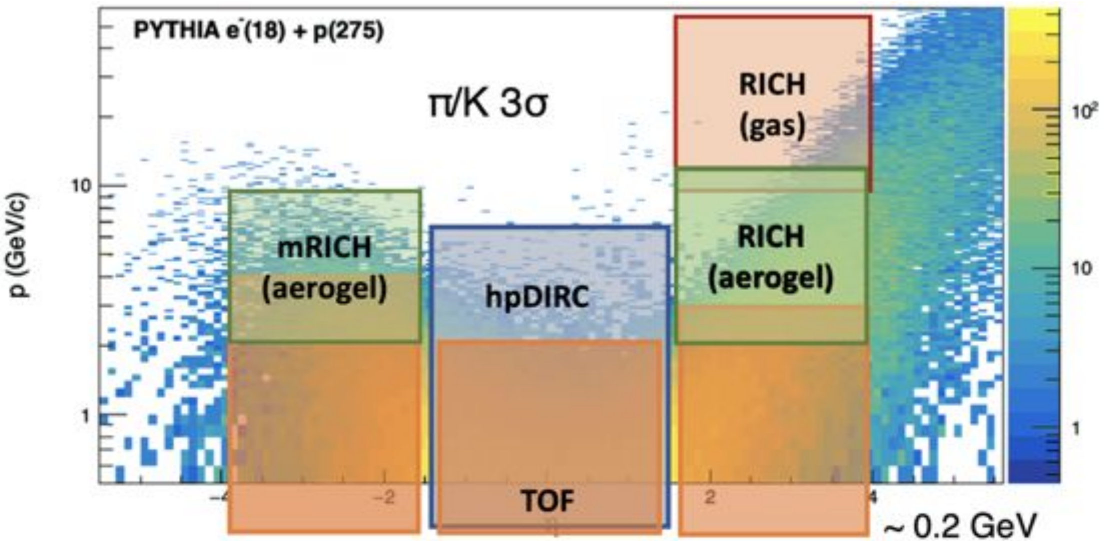

Table 8.6 Requested PID momentum coverage for 3σ pion/kaon separation. (Yellow Report)

| Pseudorapidity Range | Momentum Range |
|---|---|
| $-3.5 < \eta < -1.0$ | $\leq 7$ GeV/$c$ |
| $-1.0 < \eta < 0.5$ | $\leq 10$ GeV/$c$ |
| $0.5 < \eta < 1.0$ | $\leq 15$ GeV/$c$ |
| $1.0 < \eta < 1.5$ | $\leq 30$ GeV/$c$ |
| $1.5 < \eta < 2.5$ | $\leq 50$ GeV/$c$ |
| $2.5 < \eta < 3.0$ | $\leq 30$ GeV/$c$ |
| $3.0 < \eta < 3.5$ | $\leq 20$ GeV/$c$ |




- dRICH - “Duel” RICH
- dRICH - uses two different radiators to allow for full momentum coverage
- dRICH - takes the most real estate

# Yellow Report Requirements and Proposed Technology




*Greg Kalicy and Xiaochun He*

Table 8.6 Requested PID momentum coverage for 3σ pion/kaon separation. (Yellow Report)

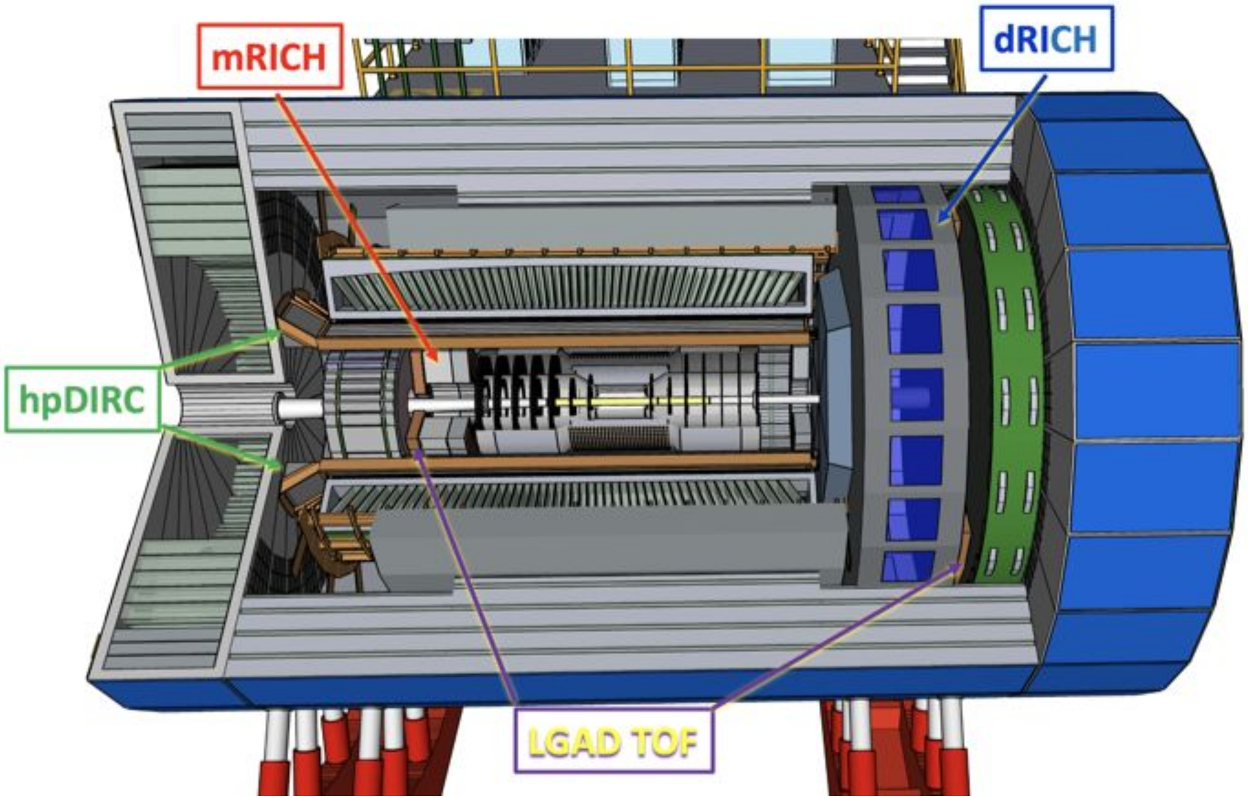
| Pseudorapidity Range | Momentum Range |
|---|---|
| $-3.5 < \eta < -1.0$ | $\leq 7$ GeV/$c$ |
| $-1.0 < \eta < 0.5$ | $\leq 10$ GeV/$c$ |
| $0.5 < \eta < 1.0$ | $\leq 15$ GeV/$c$ |
| $1.0 < \eta < 1.5$ | $\leq 30$ GeV/$c$ |
| $1.5 < \eta < 2.5$ | $\leq 50$ GeV/$c$ |
| $2.5 < \eta < 3.0$ | $\leq 30$ GeV/$c$ |
| $3.0 < \eta < 3.5$ | $\leq 20$ GeV/$c$ |

**TOF**

Extends PID coverage to lower momentum range and complements the RICH-based PID coverage. In the barrel region, hpDIRC and TOF provide an overlapping coverage from ~200 MeV/c to 2 GeV/c.

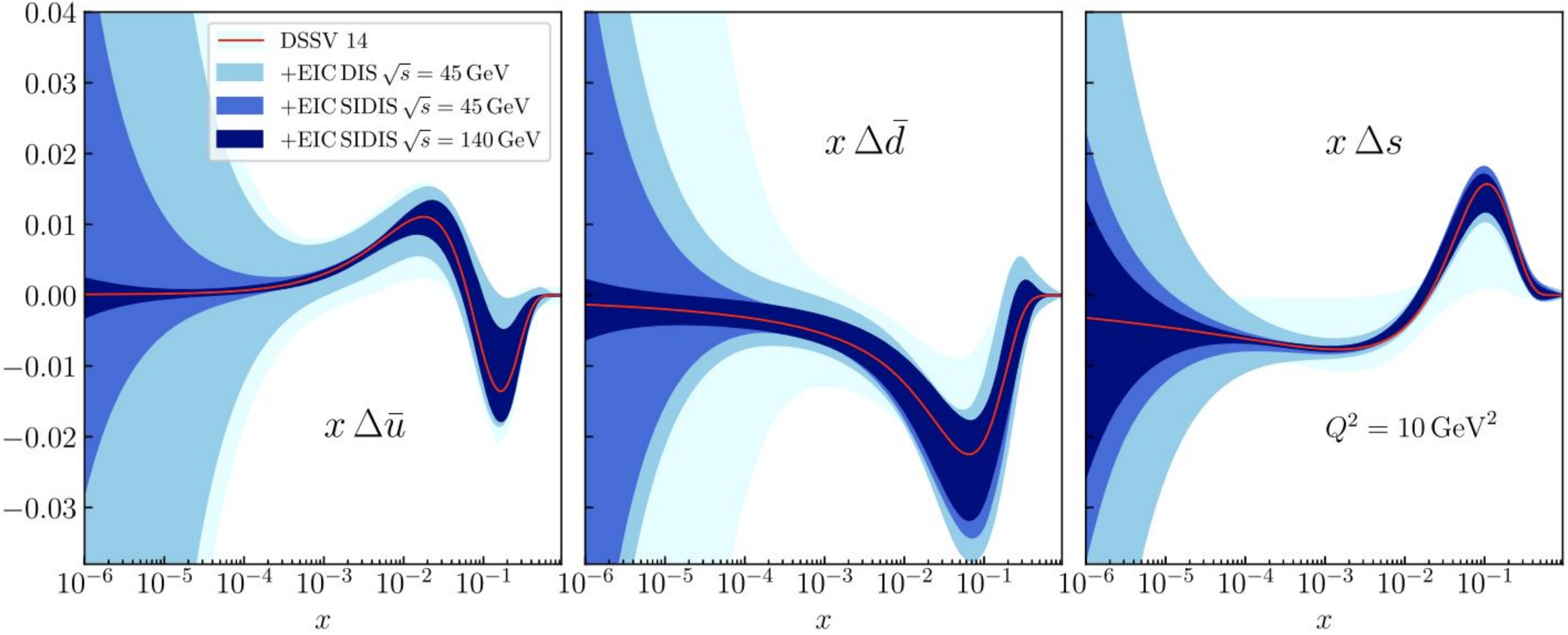
*Greg Kalicy and Xiaochun He*

# Implementation in ECCE detector (very similar in ATHENA)




*Greg Kalicy and Xiaochun He*

# Constraints from SIDIS at an EIC



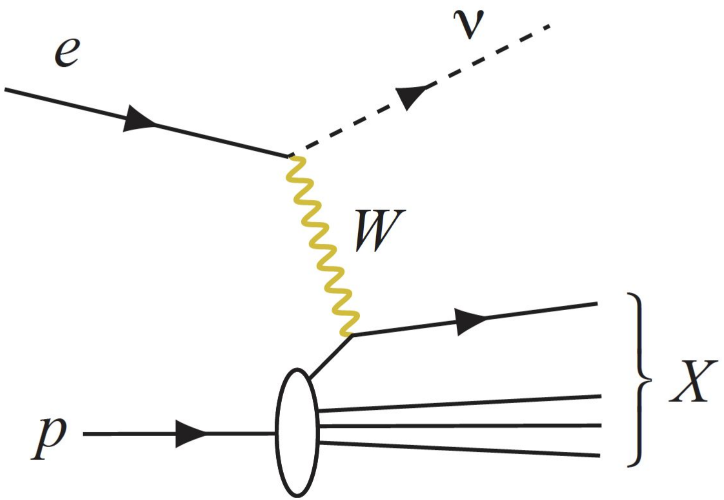

Phys. Rev. D **102**, 094018

# Charged Current Interactions

- At high $Q^2$ the virtual photon is replaced with $W^{+/-}$
- Scattered electron is replaced by neutrino, which goes undetected
- Rely on hadronic recoil for reconstruction of kinematics via Jaquet-Blondel method

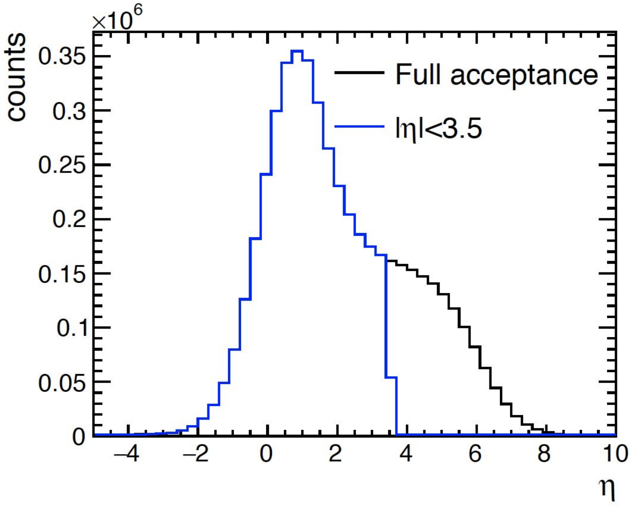
$$Q^2_{JB} = \frac{p_T^2}{1 - y_{JB}} \qquad y_{JB} = \frac{(E - p^z)}{2E} \qquad x_{JB} = \frac{Q^2_{JB}}{s y_{JB}}$$

- Here $p_T^{\ 2}$ and $(E-p^z)$ are summed over all hadrons in the final state. Challenge is to collect entire final state and to optimize resolution.
- Advantage is there are no fragmentation functions

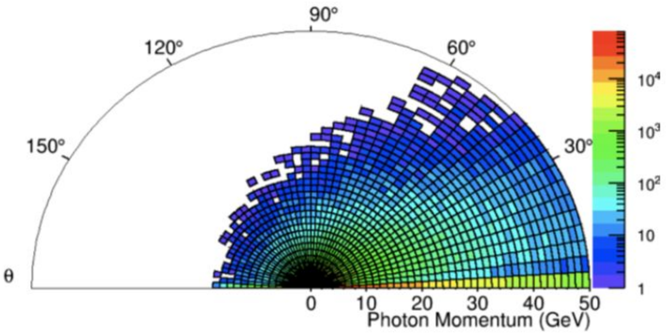


# Where is the CC final state?

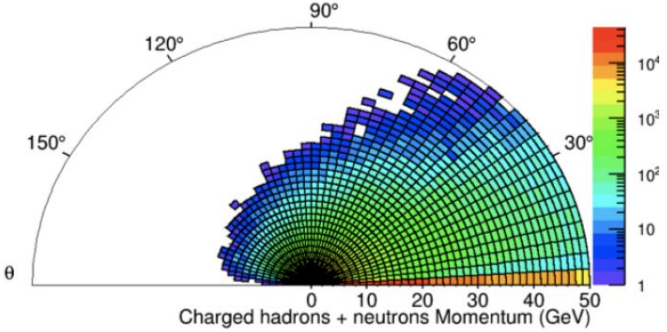
- Requires both hadronic and electromagnetic calorimetry and tracking detectors in the forward region.
- Even with far forward coverage, many particles will be lost down the beamline.




Yellow Report : 2103.05419




**(a)** e+p CC 18x275 GeV




**(b)** e+p CC 18x275 GeV

# Single Spin Asymmetry $A_L^W$

$$A_L^{W^-,N} \equiv \frac{d^2\Delta\sigma^{W^-,N}/dxdy}{d^2\sigma^{W^-,N}/dxdy}$$

The spin dependent CC cross-section for scattering of a left-handed electron (W-exchange) off of a longitudinally polarized nucleon target with helicity $\lambda = \pm 1$.

$$\frac{d^2\Delta\sigma^{W^-,N}}{dxdy} =$$
$$= \frac{1}{2}\left[\frac{d^2\sigma^{W^-,N}(\lambda_N=-1)}{dxdy} - \frac{d^2\sigma^{W^-,N}(\lambda_N=+1)}{dxdy}\right]$$
$$= \frac{2\pi\alpha_{em}^2}{xyQ^2}\eta\left[2Y_- x g_1^{W^-,N} - Y_+ g_4^{W^-,N} + y^2 g_L^{W^-,N}\right] \quad (1)$$

Discus relation: gL = g4 - 2xg5

g1 and g5 related to sea-quark distributions!

$$g_1^{W^-,p}(x) = \Delta u(x) + \Delta\bar{d}(x) + \Delta c(x) + \Delta\bar{s}(x) \; ,$$
$$g_5^{W^-,p}(x) = -\Delta u(x) + \Delta\bar{d}(x) - \Delta c(x) + \Delta\bar{s}(x)$$

Very clean, but statistically limited observable.

Phys. Rev. D 88, 114025 (2013)

# Summary of Lectures I-III

1. Deep dive into experimental analysis - use helicity distributions as example
   a. Introduction to inclusive scattering
   b. Longitudinal spin asymmetries (single and double spin) and structure functions
   c. Electron identification and kinematic reconstruction
   d. Polarization, relative luminosity and radiative corrections
   e. Constraints from inclusive EIC measurement 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 SIDIS EIC measurements on helicity PDFs
   d. Quick introduction to charge-current interactions and JB reconstruction.

Lecture IV - Broaden our scope into Transverse Momentum Distributions (TMDs) and Generalized Parton Distributions (GPDs)