# Study of Nucleon Spin-flavor Structure at EicC

1

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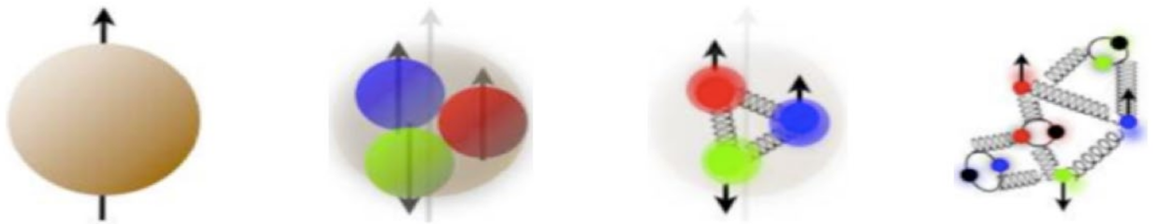
# Outline

- General introductions
- Description of the study for the uncertainty projections
- Projections for EicC (inclusive and SIDIS)

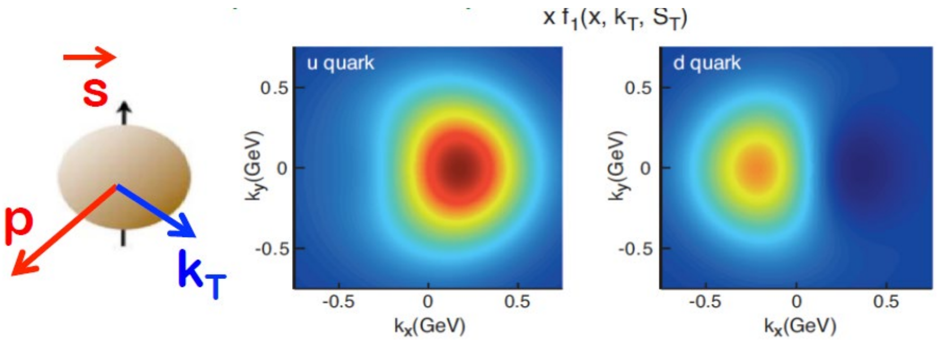
# Questions driving the spin physics

- **How do quarks/gluons + their dynamics make up the proton spin?**



Helicity distributions + orbital contribution

- **How is proton's spin correlated with the motion of the quarks/gluons?**




Deformation of parton's
**confined motion**
When hadron is polarized?

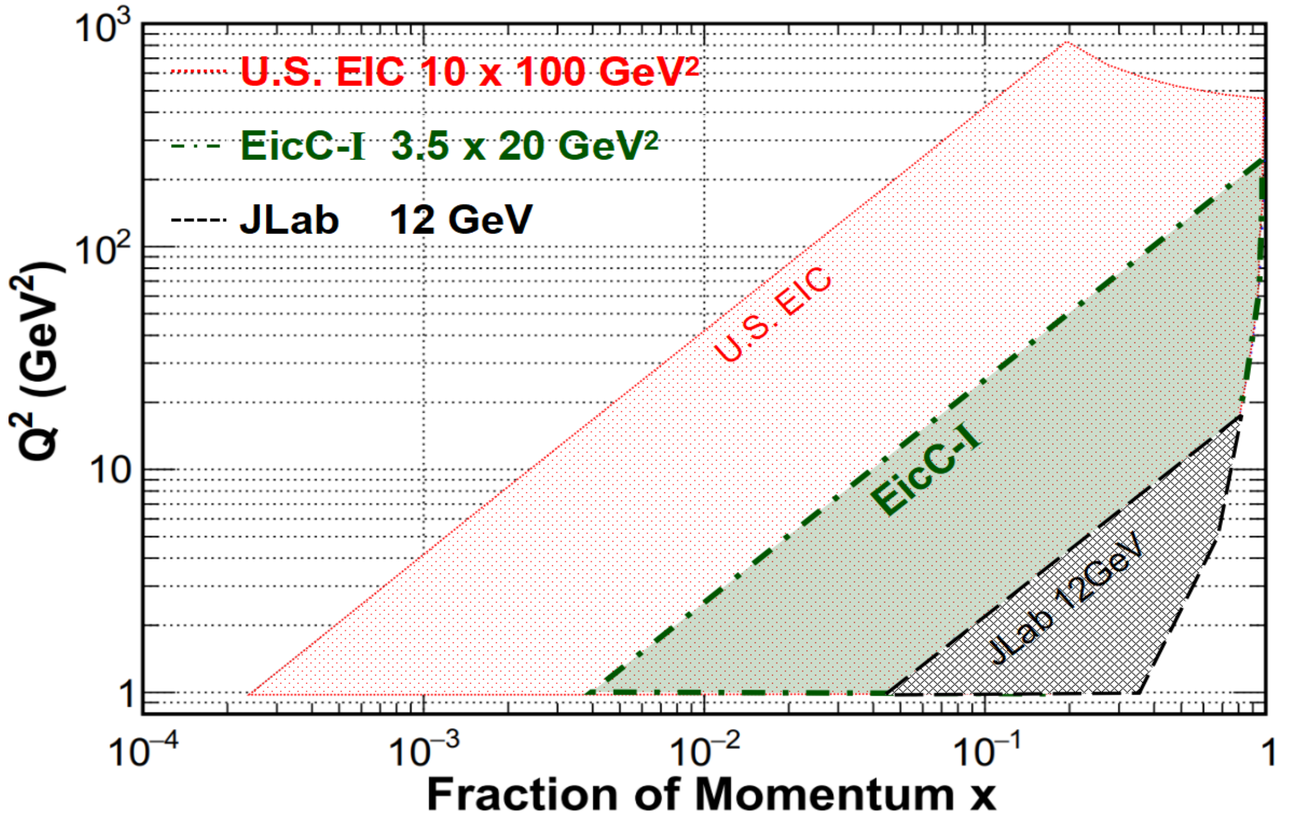
→ TMDs!

- **How does proton's spin influence the spatial distribution of partons?**

Deformation of parton's
**spatial distribution**
When hadron is polarized?

→ GPDs!

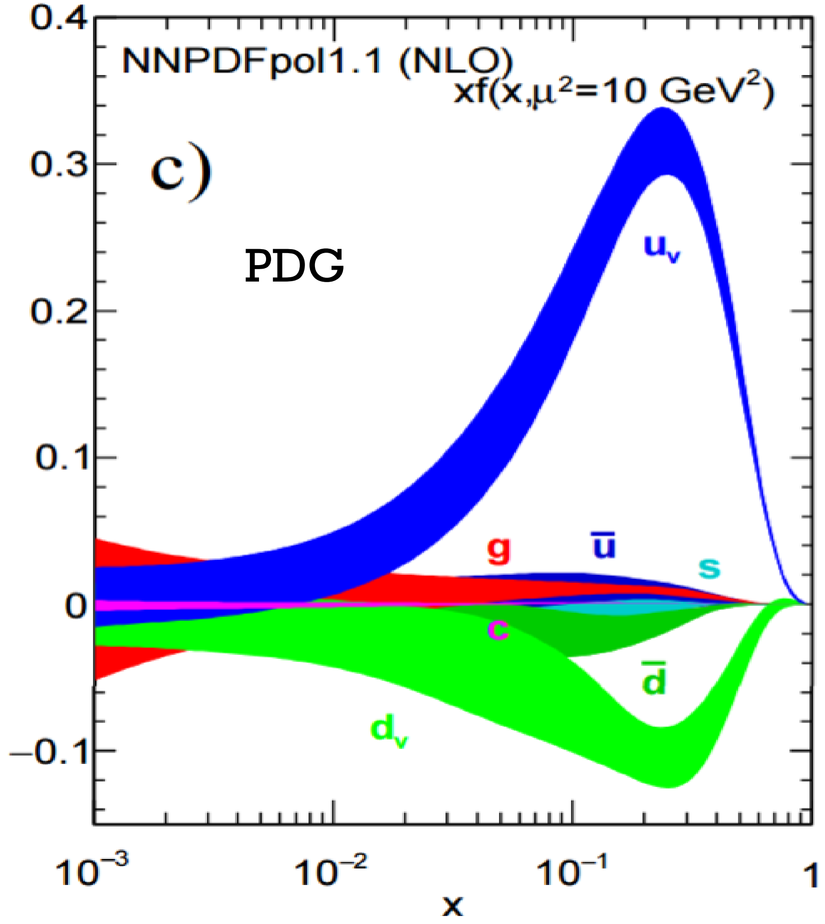
# Phase space coverage of EicC-I




What we can have at EicC-I with **polarized electron and polarized ion beam:**

**<u>Precise measurements</u> for 1D (helicity), 3D (TMDs, GPDs) nucleon spin structure <u>with flavor separations</u> … in the <u>valence/sea quark region</u> …**

# World data of helicity study




ArXiv: 1801.04842 (2018)

| $\Delta f$ | $\langle \Delta f \rangle^{[0,1]}$ NNPDFpol1.1 | $\langle \Delta f \rangle^{[10^{-3},1]}$ NNPDFpol1.1 | $\langle \Delta f \rangle^{[10^{-3},1]}$ DSSV08 |
|---|---|---|---|
| $\Delta u^+$ | $+0.79 \pm 0.07$ | $+0.76 \pm 0.04$ | $+0.793^{+0.028}_{-0.034}$ $(+0.020)$ |
| $\Delta d^+$ | $-0.47 \pm 0.07$ | $-0.41 \pm 0.04$ | $-0.416^{+0.035}_{-0.025}$ $(-0.042)$ |
| $\Delta \bar{u}$ | $+0.06 \pm 0.06$ | $+0.04 \pm 0.05$ | $+0.028^{+0.059}_{-0.059}$ $(+0.008)$ |
| $\Delta \bar{d}$ | $-0.11 \pm 0.06$ | $-0.09 \pm 0.05$ | $-0.089^{+0.090}_{-0.080}$ $(-0.026)$ |
| $\Delta s$ | $-0.07 \pm 0.05$ | $-0.05 \pm 0.04$ | $-0.006^{+0.028}_{-0.031}$ $(-0.051)$ |
| $a_0$ | $+0.18 \pm 0.21$ | $+0.25 \pm 0.10$ | $+0.366^{+0.042}_{-0.062}$ $(+0.124)$ |

$\Delta\Sigma$

| | $\langle \Delta g \rangle^{[0,1]}$ | $\langle \Delta g \rangle^{[10^{-3},1]}$ | $\langle \Delta g \rangle^{[0.05,0.2]}$ |
|---|---|---|---|
| NNPDFpol1.1 | $+0.03 \pm 3.24$ | $+0.49 \pm 0.75$ | $+0.17 \pm 0.06$ |
| DSSV08 | — | $0.01^{+0.70}_{-0.31}$ $(+0.10)$ | $0.01^{+0.13}_{-0.16}$ |
| DSSV++ | — | — | $0.10^{+0.06}_{-0.07}$ |

$\Delta G$

RHIC spin data put strong constraint on $\Delta G$

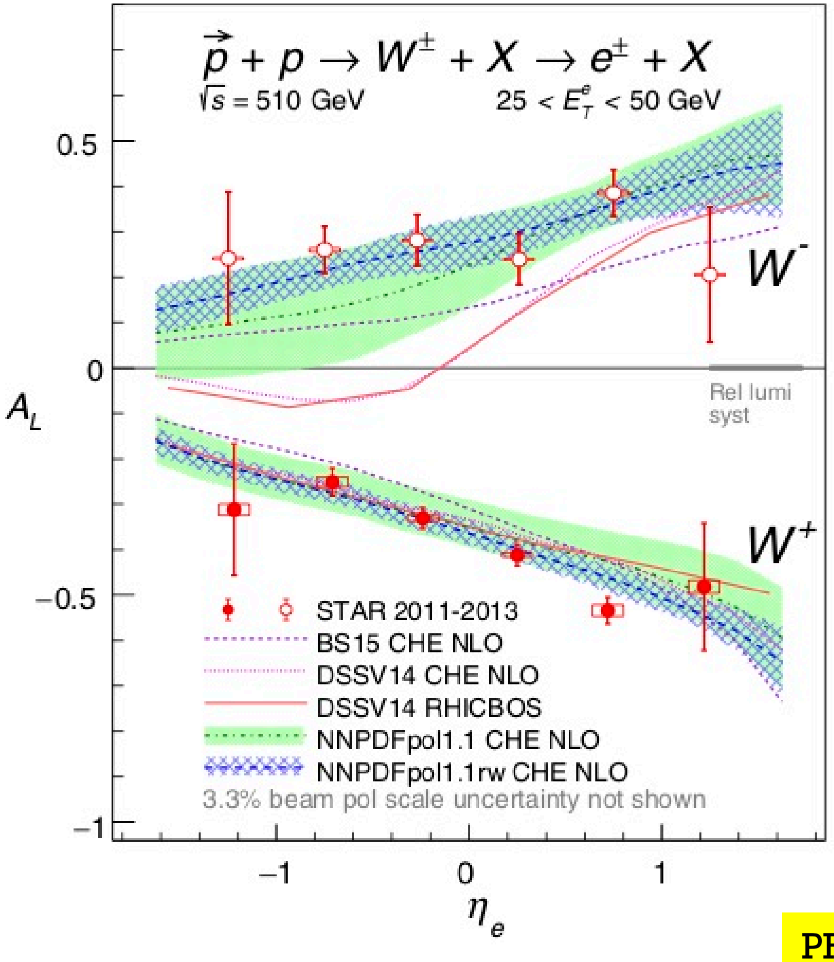
# A few discussions of helicity study

- Light sea, still large uncertainties
  - ✓ Unpol. ubar-dbar < 0, larger than expected → polarized ?
- Strange quark  helicity?
  - ✓ think about unpolarized s, sbar, with s=sbar in most case
  - ✓ May change sign along x
  - ✓ SU(3) flavor symmetry → deltaS+deltaSbar~-0.1, not observed in SIDIS, because of fragmentation functions?

- SIDIS data is very powerful for flavor separation, however fragmentation functions are involved
- Further $\Delta g$ constraint, precise data needed

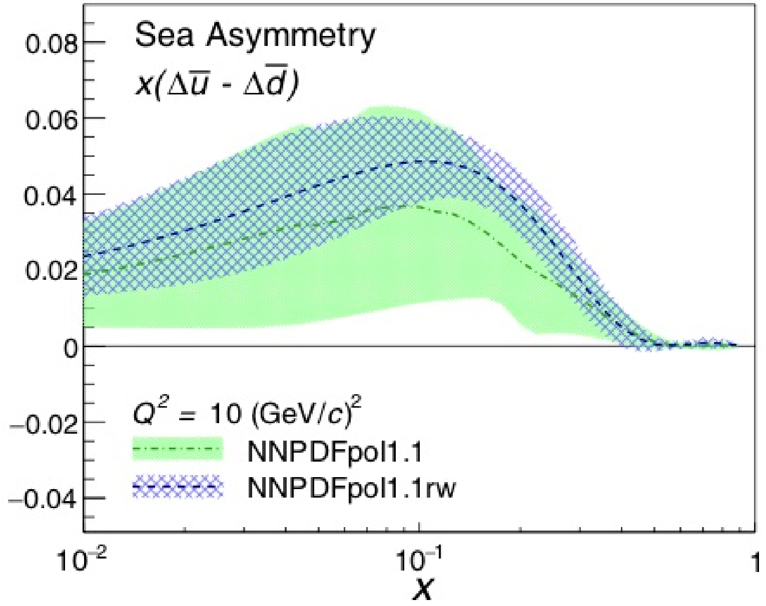
PRL 101(2008)072001, PRL 66(1991)2712, PRD50(1994)R1, PRL 81(1998)5519, PLB332(1994)244, PRD64(2001)052002
PRC63(2001)025208, EPJA18(2003)395, EPJC23(2002)487, PRD75(2007)074027, PRD74(2006)014015, ArXiv: 1801.04842 (2018)

# Spin Asymmetry for W bosons (STAR)




$$A_L^{W^+}(y_W) \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

$$A_L^{W^-}(y_W) \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

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# Polarized structure functions g1 - inclusive and SIDIS

$$A_{\|}(x,Q^2) = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = D(A_1^{p} + \eta A_2^{p})$$

A2 Neglected both at COMPASS and US EIC

Will cause some systematic errors, forget it for now

$$\eta = \frac{\gamma(1-y-\gamma^2 y^2/4 - y^2 m^2/Q^2)}{(1+\gamma^2 y/2)(1-y/2) - y^2 m^2/Q^2} \qquad \gamma = 2Mx/\sqrt{Q^2}$$

$$D = - \frac{y((1+\gamma^2 y/2)(2-y) - 2y^2 m^2/Q^2)}{y^2(1-2m^2/Q^2)(1+\gamma^2) + 2(1+R)(1-y-\gamma^2 y^2/4)}$$

becomes

Used by US EIC simulation

$$D(y) = \frac{y(y-2)}{y^2 + 2(1-y)(1+R)}$$

$$g_1^{p} = \frac{F_2^{p}}{2x\,(1+R)} A_1^{p}$$

If C-G equation is used

Gamma ~ 0

$$A_1^p = \frac{g_1^p}{F_1^p}$$

# Error projections

**Starting point:**

$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{1}{P_e P_p} \frac{N^{++} - N^{+-}}{N^{++} - N^{+-}} = \frac{1}{P_e P_p} A_{measure} = D(y) \frac{g_1}{F_1}$$

$$yield = (1 + \lambda A_{measure}) \cdot \sigma_0 \cdot Lumi \cdot acceptance$$

**In the interested bin, for example (x, Q2) 2D bin in inclusive case:**

$$L = log \prod_{events} yield(x, Q^2)/Normalization(g1)$$
$$Normalization = \int dx \int dQ^2 [1 + \lambda P_e P_p D(y) \frac{g_1}{F_1}] \sigma_0 \cdot lumi \cdot acceptance$$

The second order of derivations of likelihood on g1 will give the error matrix :

$$\sigma_{g_1} = \sqrt{\frac{1}{\sum_{events} P_e^2 P_p^2 D(y)^2 \frac{1}{F_1^2}}}$$

Assumptions:

- A2 is neglected
- acceptance is the same for helicity + and –
- F1 is well known for g1 study

# A few more words about inclusive and SIDIS

**Inclusive:**

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

Only PDFs

**SIDIS:**

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

Fragmentation functions involved

also for F1

LO model to be used for the first step

# LO helicity fit using only EicC SIDIS data

$$\chi^2 = \sum_{\pi^+,\pi^-,K^+,K^-} \left(\frac{A_1^{measure} - A_1^{physics}}{\sigma_{A_1}^{measure}}\right)^2$$

In total 8 measurements in a particular bin

$$A_{1p}^{\pi^+} = \frac{0.5Q_u^2 D^{u\to\pi^+}}{F_{1p}^{\pi^+}}\Delta u + \frac{0.5Q_{\bar{u}}^2 D^{\bar{u}\to\pi^+}}{F_{1p}^{\pi^+}}\Delta\bar{u} + \frac{0.5Q_d^2 D^{d\to\pi^+}}{F_{1p}^{\pi^+}}\Delta d + \frac{0.5Q_{\bar{d}}^2 D^{\bar{d}\to\pi^+}}{F_{1p}^{\pi^+}}\Delta\bar{d} + \frac{0.5Q_s^2(D^{s\to\pi^+} + D^{\bar{s}\to\pi^+})}{F_{1p}^{\pi^+}}\Delta s$$

$$A_{1N}^{\pi^+} = \frac{0.5Q_d^2 D^{d\to\pi^+}}{F_{1N}^{\pi^+}}\Delta u + \frac{0.5Q_{\bar{d}}^2 D^{\bar{d}\to\pi^+}}{F_{1N}^{\pi^+}}\Delta\bar{u} + \frac{0.5Q_u^2 D^{u\to\pi^+}}{F_{1N}^{\pi^+}}\Delta d + \frac{0.5Q_{\bar{u}}^2 D^{\bar{u}\to\pi^+}}{F_{1N}^{\pi^+}}\Delta\bar{d} + \frac{0.5Q_s^2(D^{s\to\pi^+} + D^{\bar{s}\to\pi^+})}{F_{1N}^{\pi^+}}\Delta s$$

Isospin symmetry used: u in proton=d in neutron, s (sbar) is the same for proton and neutron

Note the different expression of A1 from proton and neutron

$$\left(\frac{1}{2}\frac{\partial^2\chi^2}{\partial^2\Delta q}\right)^{-\frac{1}{2}}$$

Gives the uncertainty of different helicities in a particular bin

$$\frac{1}{2}\frac{\partial^2\chi^2}{\partial^2\Delta u} = \sum_{\pi^+,\pi^-,K^+,K^-} \frac{1}{\sigma_{A_{1p}}^2{}^{measure}}\left[\frac{0.5Q_u^2 D^{u\to\pi^+}}{F_{1p}^{\pi^+}}\right]^2 + \frac{1}{\sigma_{A_{1N}}^2{}^{measure}}\left[\frac{0.5Q_d^2 D^{d\to\pi^+}}{F_{1N}^{\pi^+}}\right]^2 + \ldots$$

Fragmentation functions: **DSS (hep-ph/0703242)**

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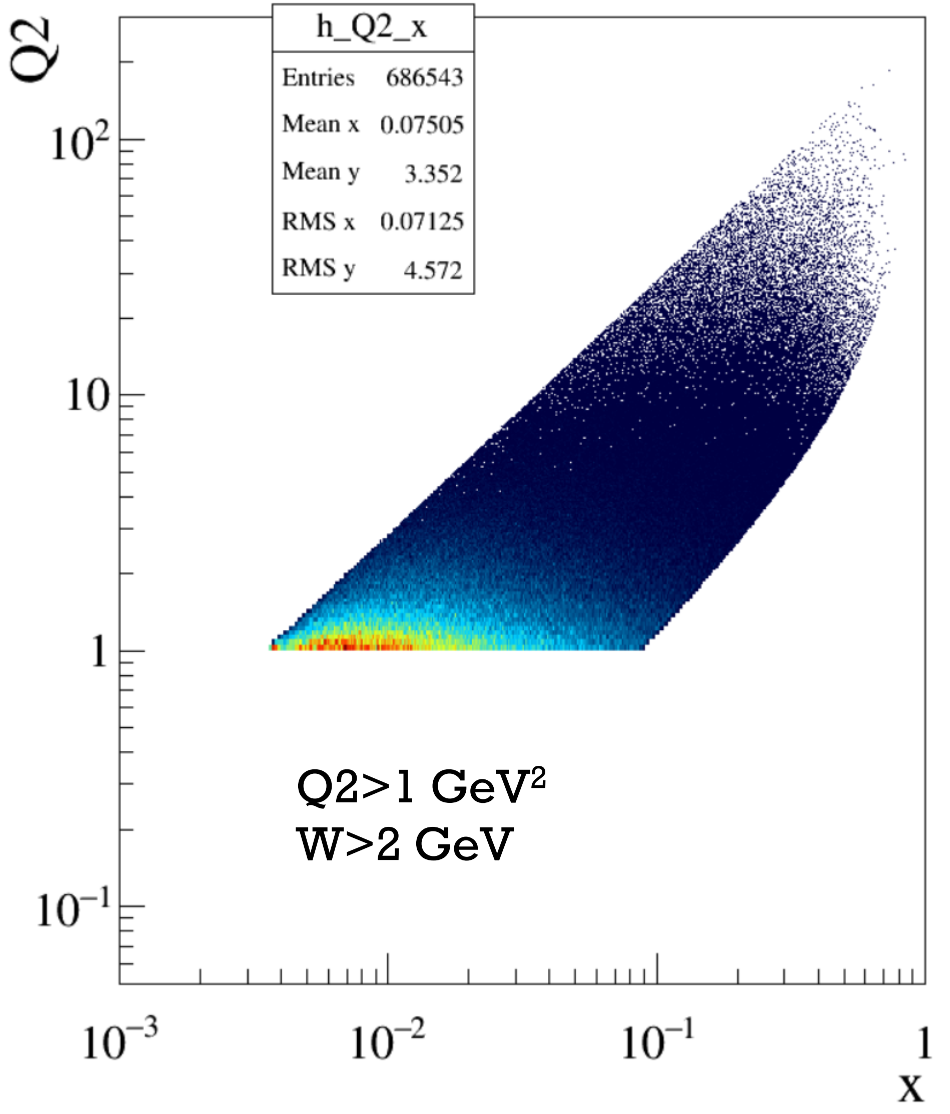
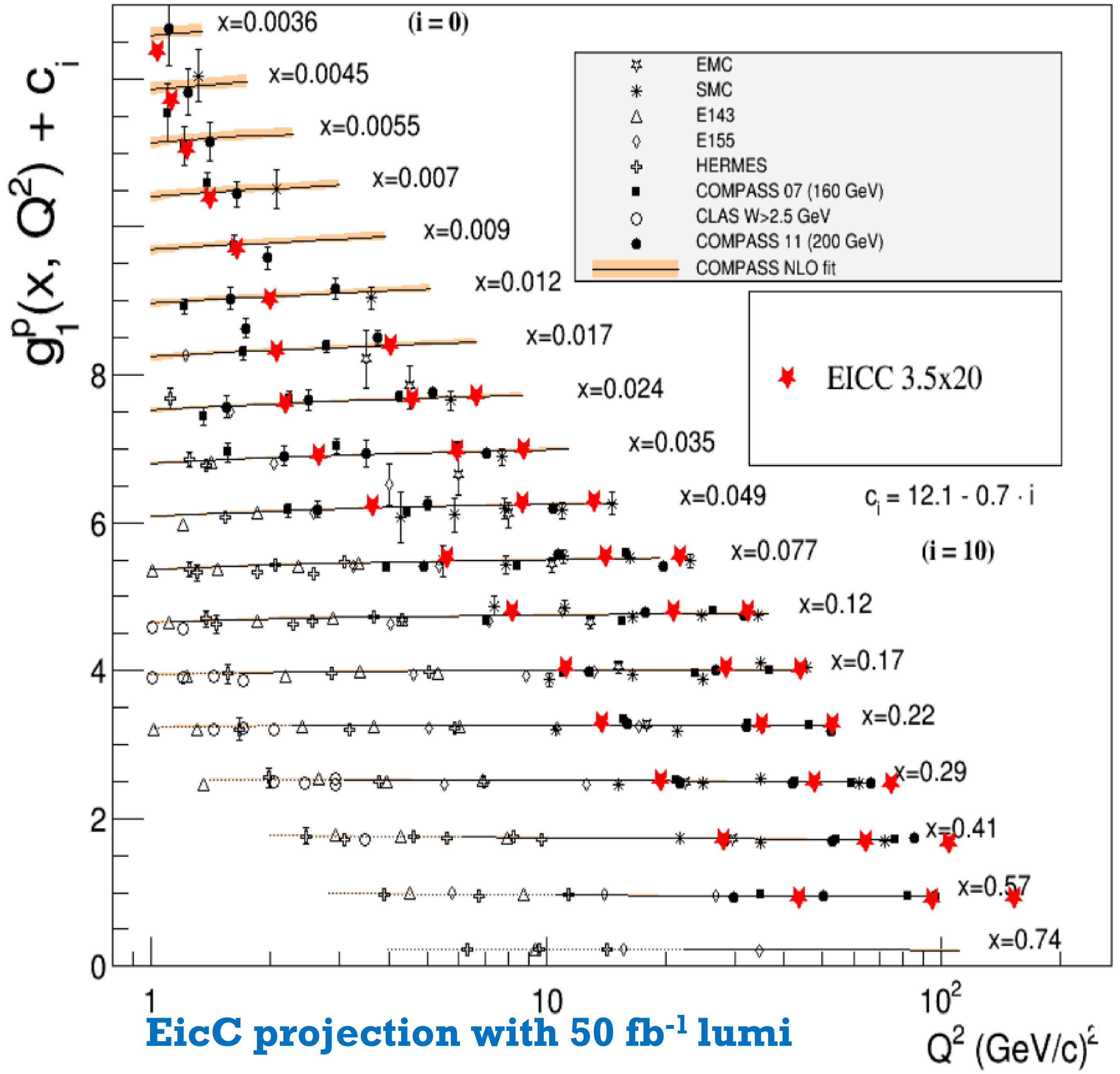
# EicC luminosity considerations

## ❖ Baseline design:

- Beam energy = 3.5 GeV x 20 GeV for e-p and 3.5 GeV x 40/3 GeV/u for e-He3
- Instantaneous luminosity: $2X10^{33}$ /$cm^2$/s → corresponding to 5.2 $fb^{-1}$ with full efficiency per month
- Electron polarization: 80% (uncertainty 2%)
- Proton polarization: 70% (uncertainty 5%)

# Q2 VS x for ep 3.5 x 20 GeV

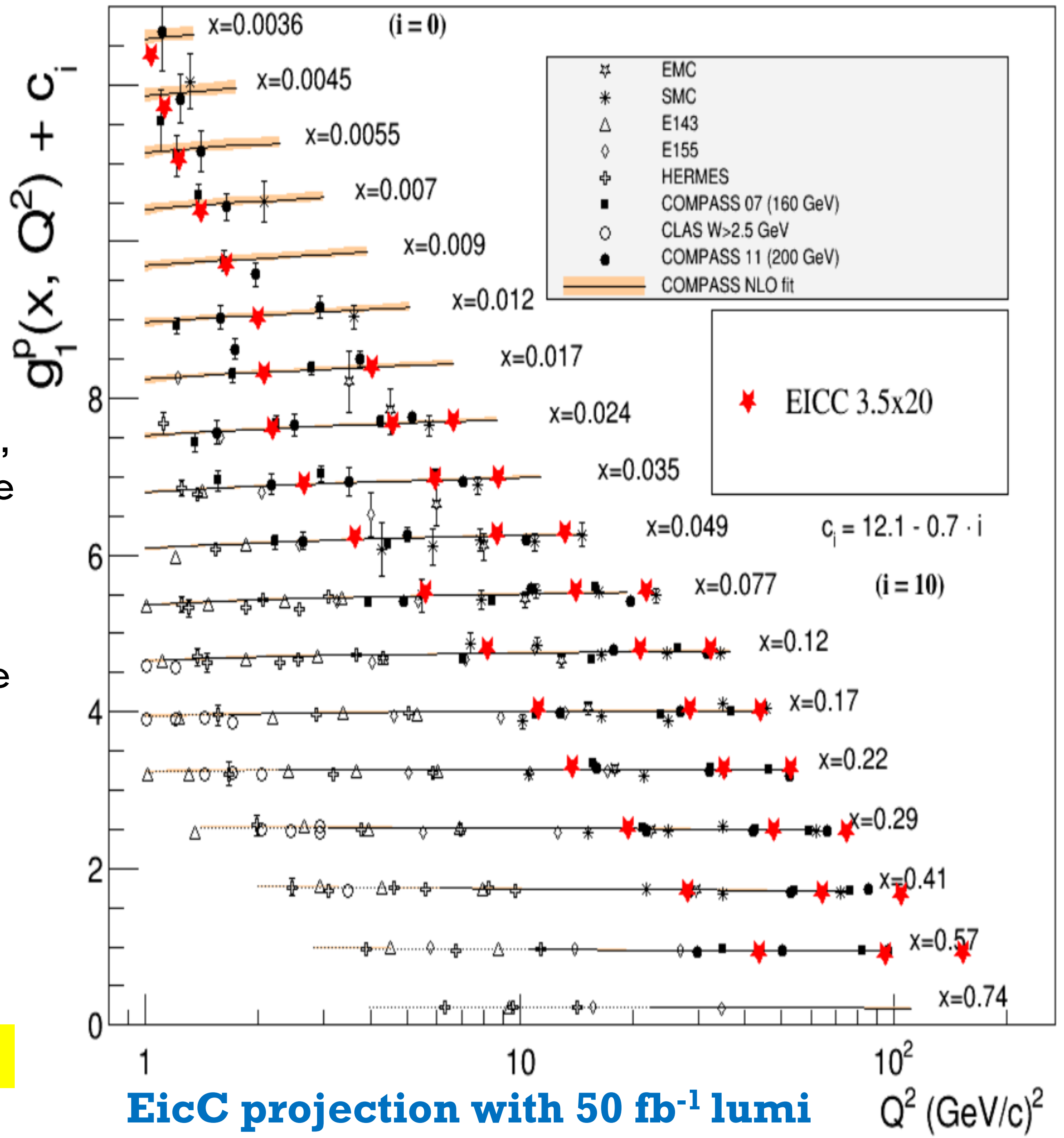


# g1p world data with EicC data

- 3.5 GeV x 20 GeV is basically COMPASS Center of mass energy, COMPASS is around 17.9 GeV, EicC is about 16.7 GeV
- EicC is improving the precision in the low x region that was only accessible by COMPASS, taking advantage of high luminosity and large acceptance at EicC
- High precision of SIDIS data from EicC will be powerful for flavor separations and fragmentation study

**Impact of SIDIS data, see the following slides**




**EicC projection with 50 $fb^{-1}$ lumi**

# Edmond L. Berger's criterial

**Separation of current and target fragmentation for SIDIS data:**

| **W cut** | **Z cut** |
|---|---|
| W>3 GeV | Z>0.5 |
| W>4.8 GeV | Z>0.2 |
| W>7.4 GeV | Z>0.1 |

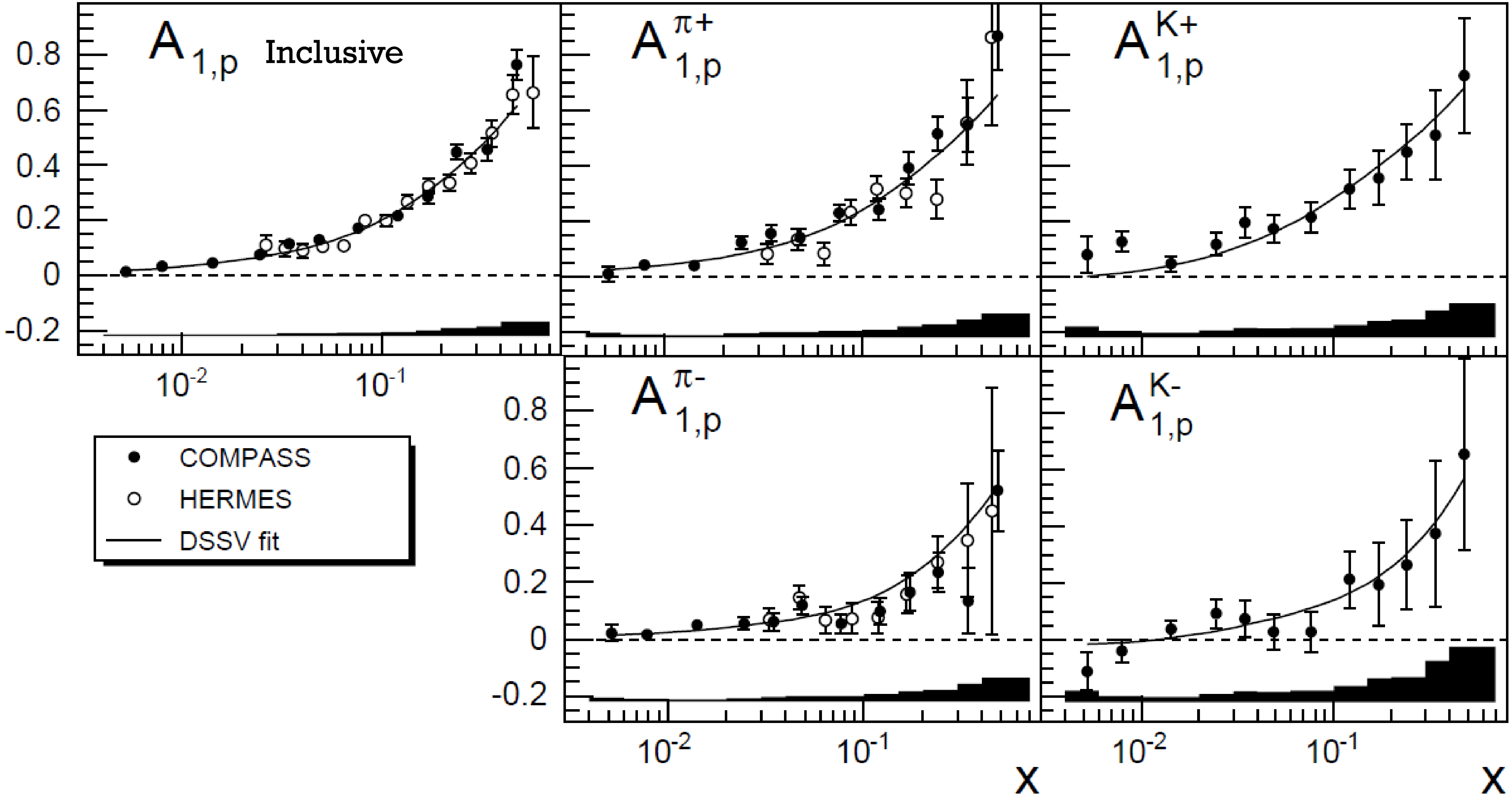
Criterial chosen by COMPASS

Also used by me for the EicC study

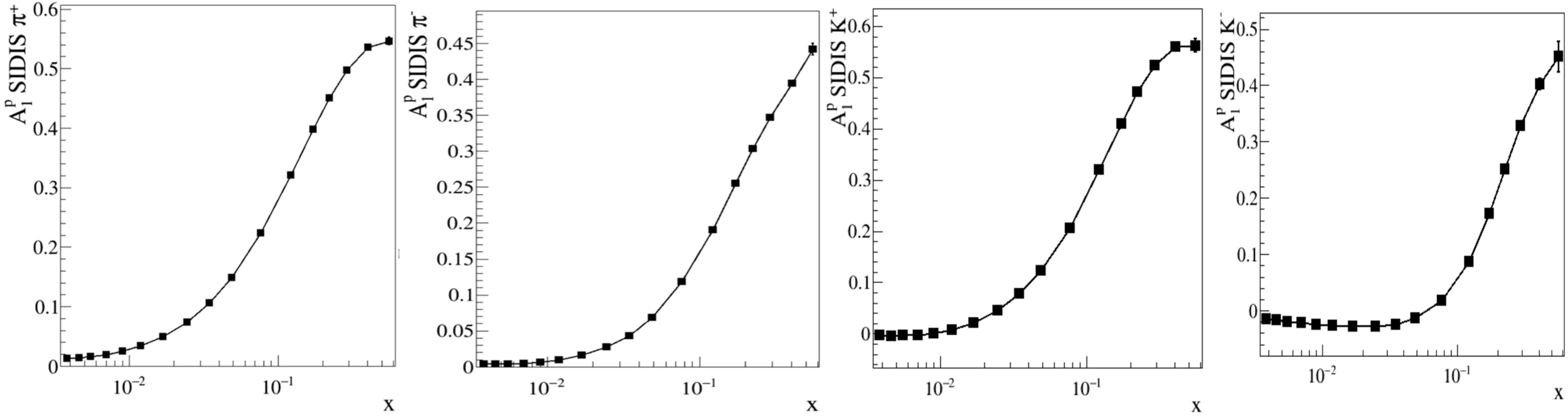
Of course, it is only a criterial…

ANL-HEP-CP-87-45

# COMPASS and HERMES SIDIS measurements

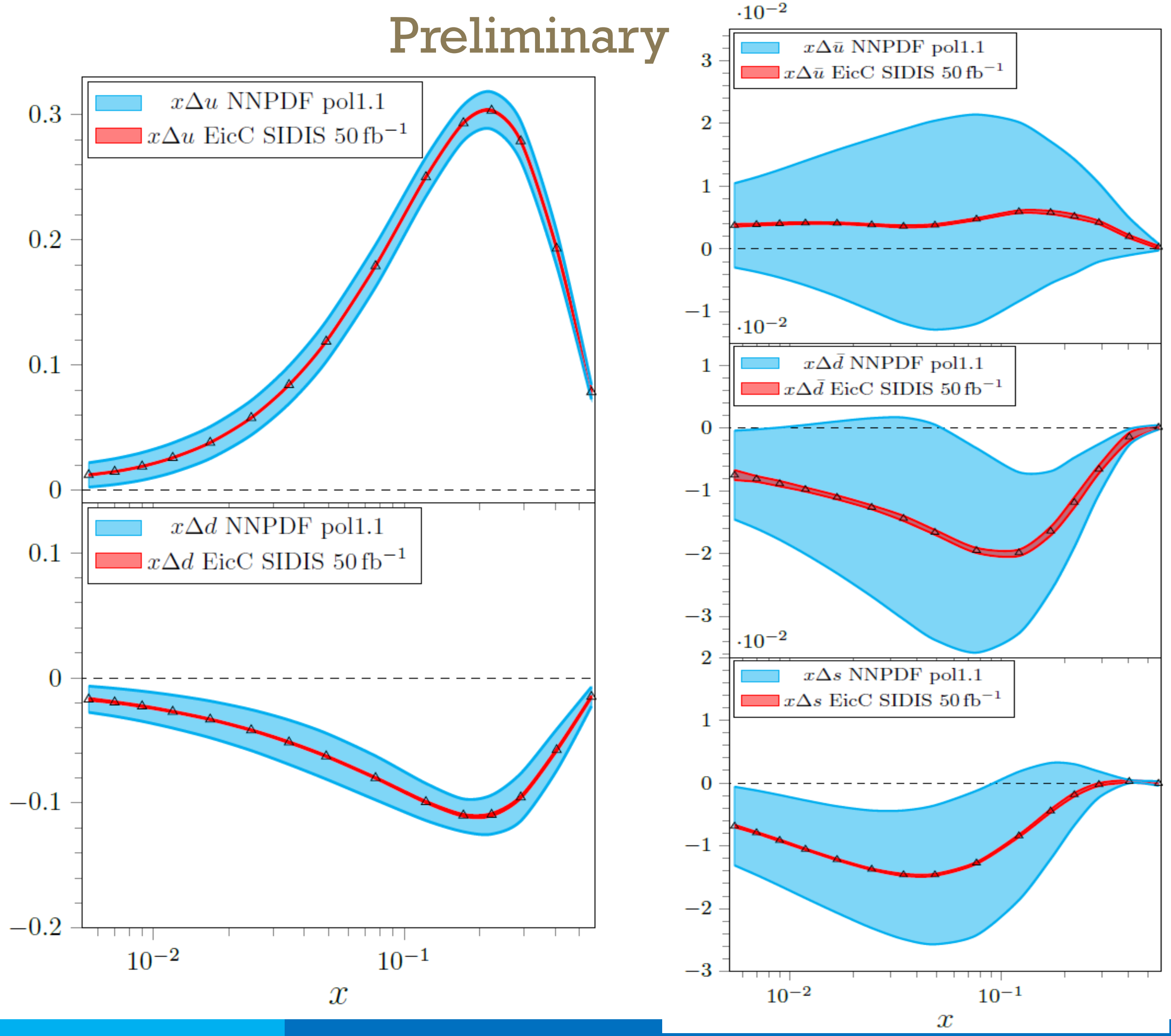


# EicC SIDIS measurements
# --- just an example with only 10 fb-1



# Projections on helicity distributions (EicC), only statistics

Preliminary




## LO analysis

EicC SIDIS data:

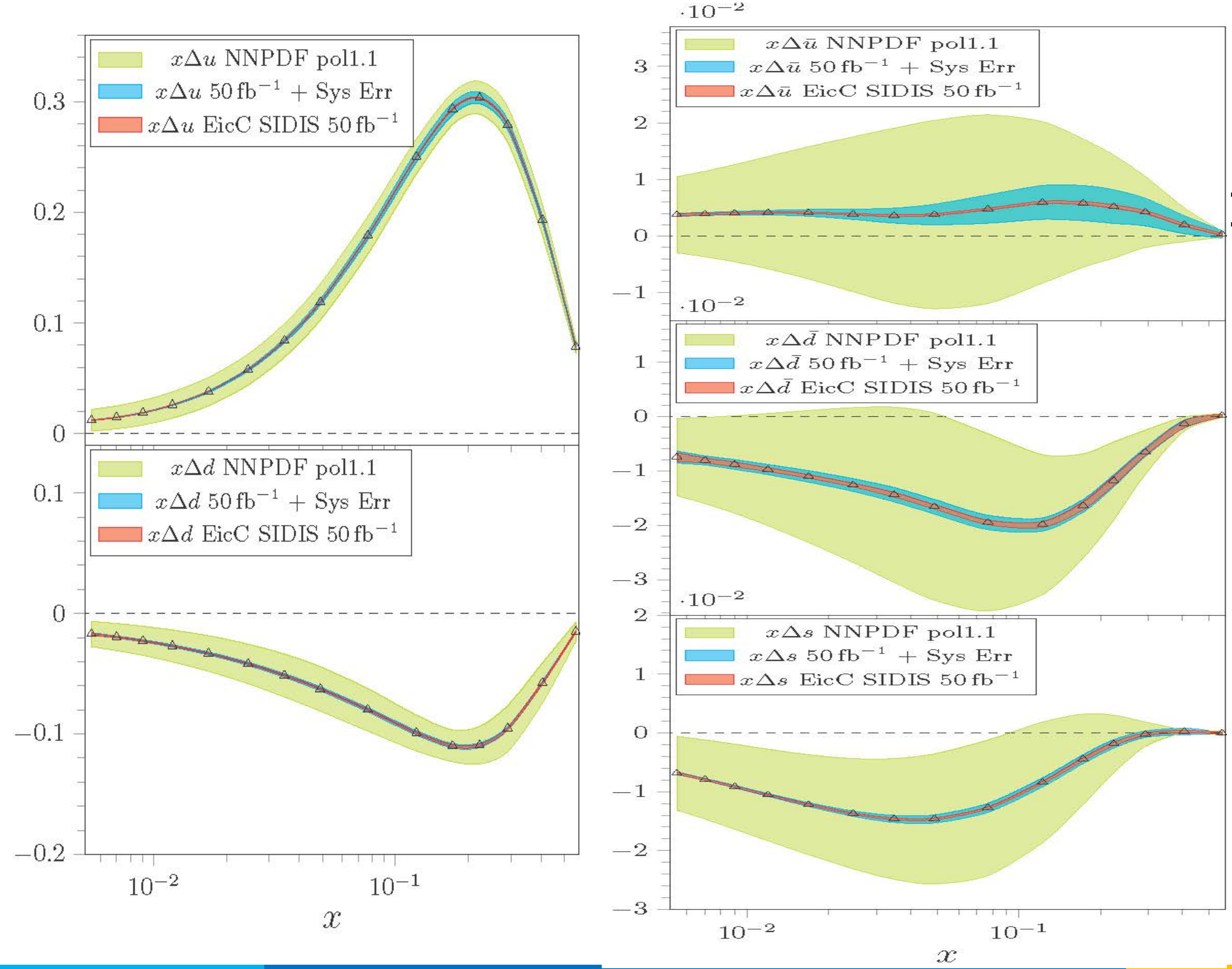
- Pion(+/-), Kaon(+/-)
- ep: 3.5 GeV X 20 GeV
- eHe-3: 3.5 GeV X 40/3 GeV/u
- Lumi:
  - ep 50 fb-1
  - eHe3 50 fb-1 per nuclei

# First look at the systematic uncertainties

Contributions:

- Uncertainty of beam polarizations, 5% for proton (He3) beam, 2% for electron beam
  - Sys. Uncert. on measured asymmetry is proportional to the amplitude of the asymmetry
  - The quadrature sum of sys. and stat. is used for LO fit of helicities
- Uncertainty of fragmentation functions
  - Not considered yet→will be precisely measured at the time of EicC

# Projections of EicC including stat. and sys. uncertainty




## LO analysis

EicC SIDIS data:

- Pion(+/-), Kaon(+/-)
- ep: 3.5 GeV X 20 GeV
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- Lumi:
  - ep 50 fb-1
  - eHe3 50 fb-1 per nuclei

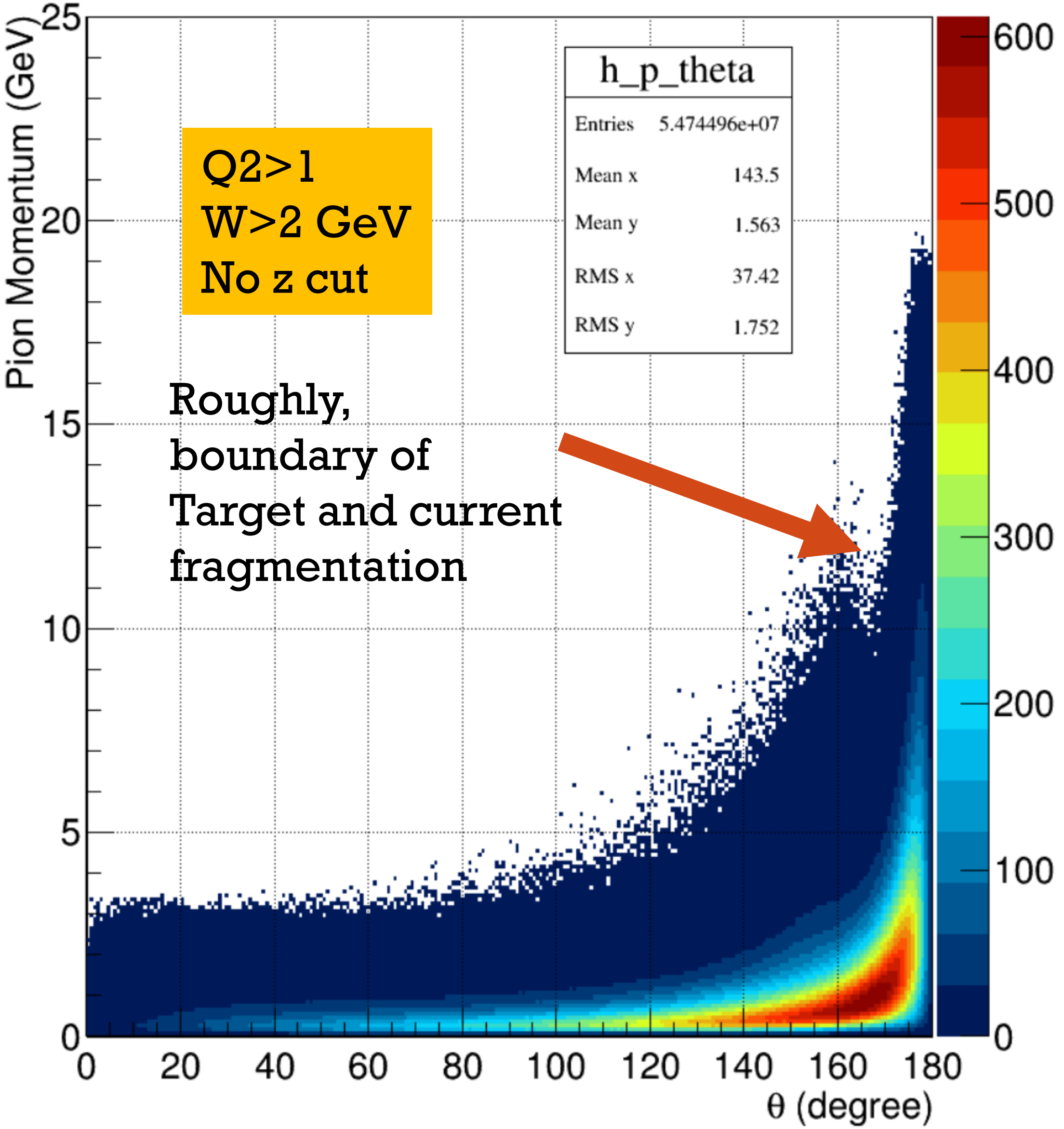
# Summary

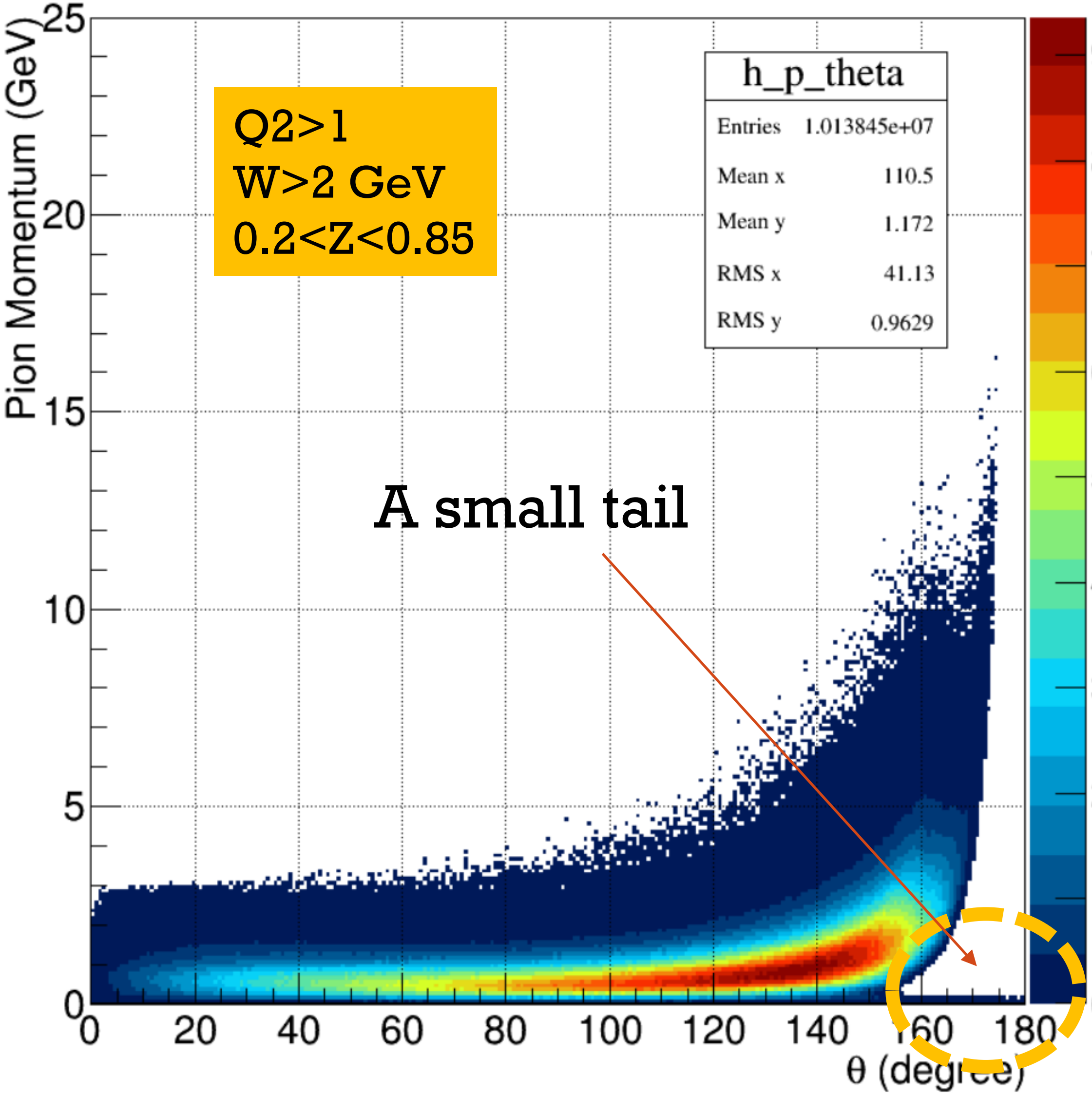
- EicC has the potential to do excellent job in helicity study with flavor separations in the sea-quark dominated region
  - Taking advantage of polarized beams, high luminosity, inclusive/SIDIS processes, PID detectors etc.
- First look at the systematic uncertainty due to uncertainties of beam polarization
  - Polarimetry is believed to be improved at an EIC in the future
  - Fragmentation functions will be measured precisely in the following years

# Backups

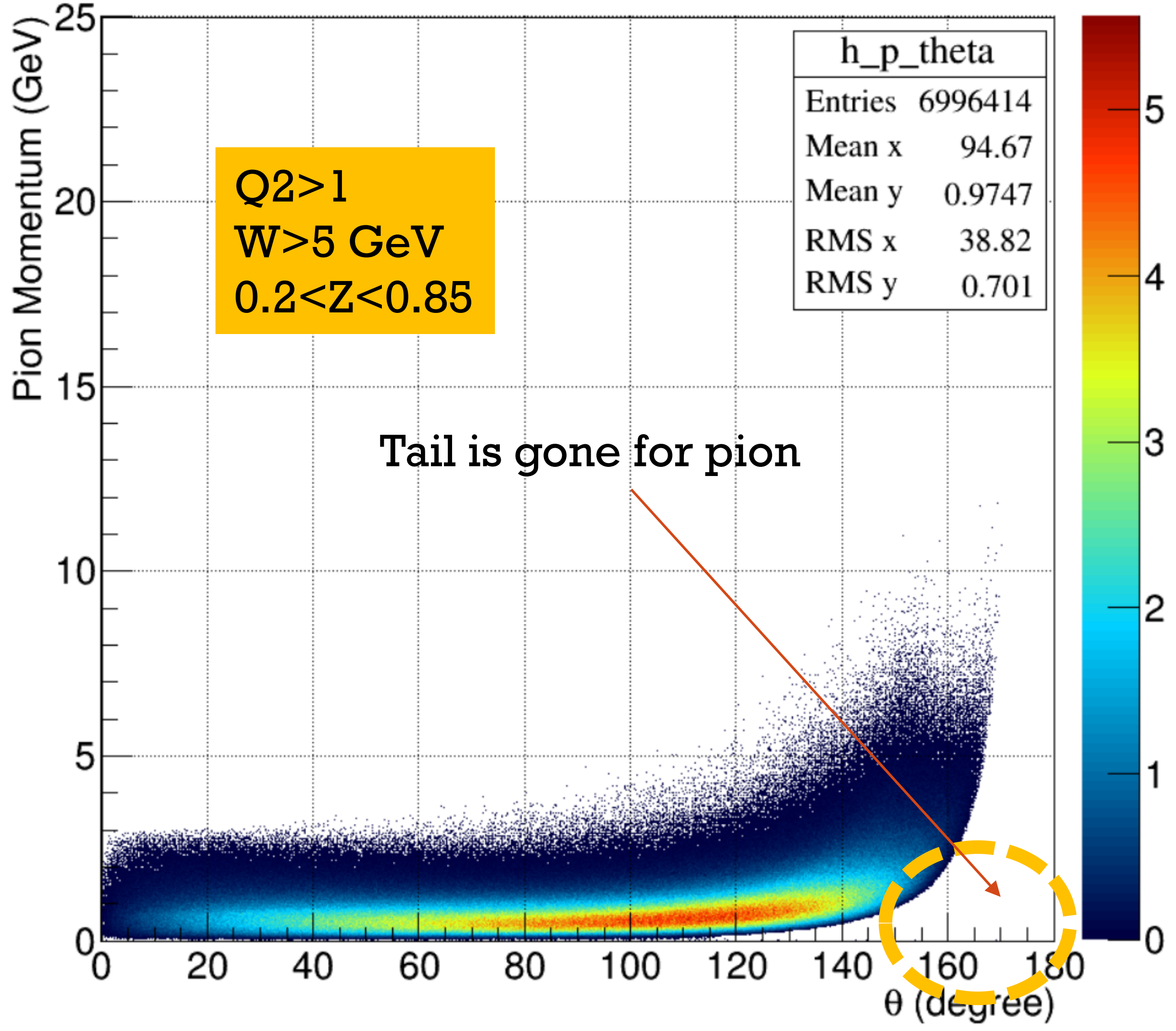
# Pion momentum VS theta

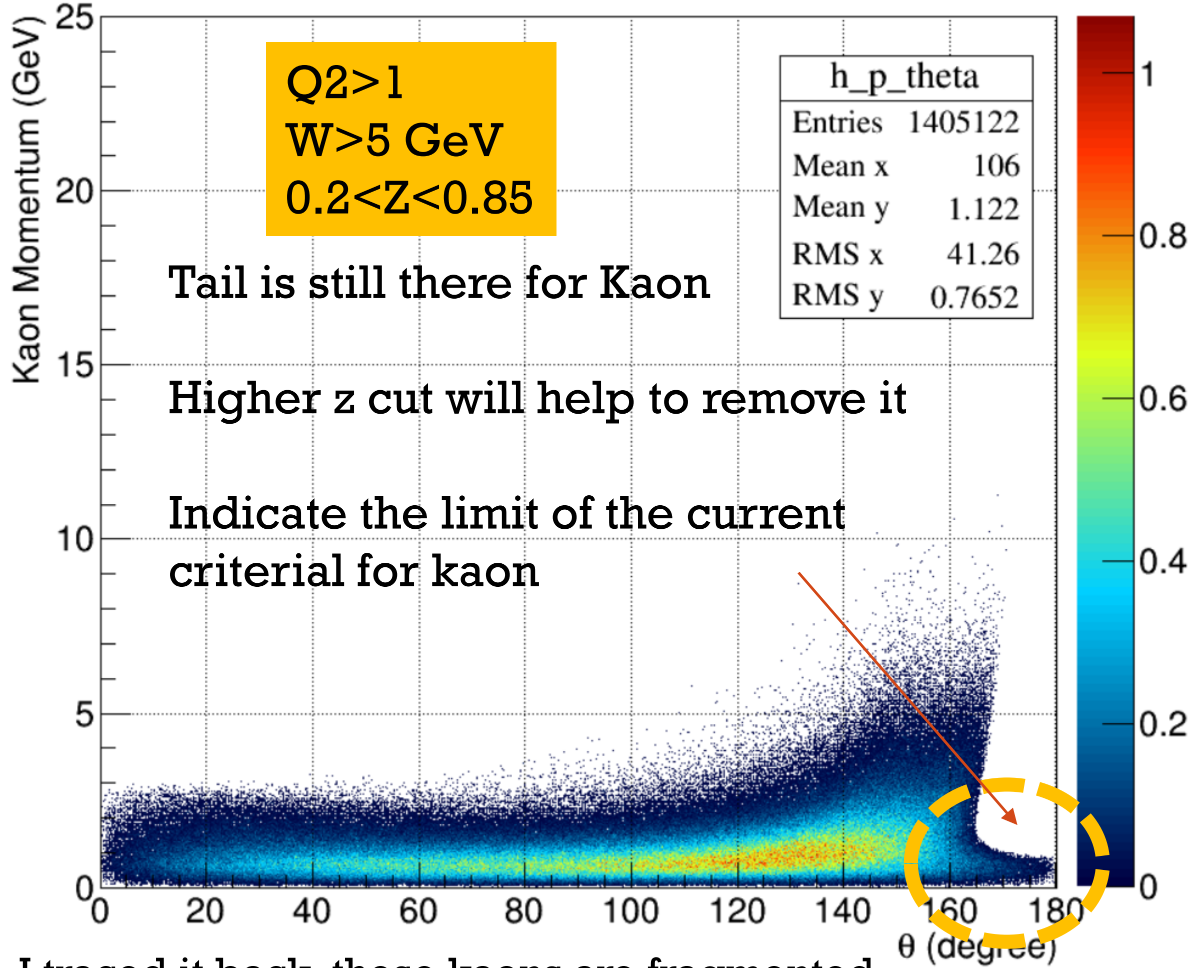
NOTE: my hadron going direction is at 180 degree



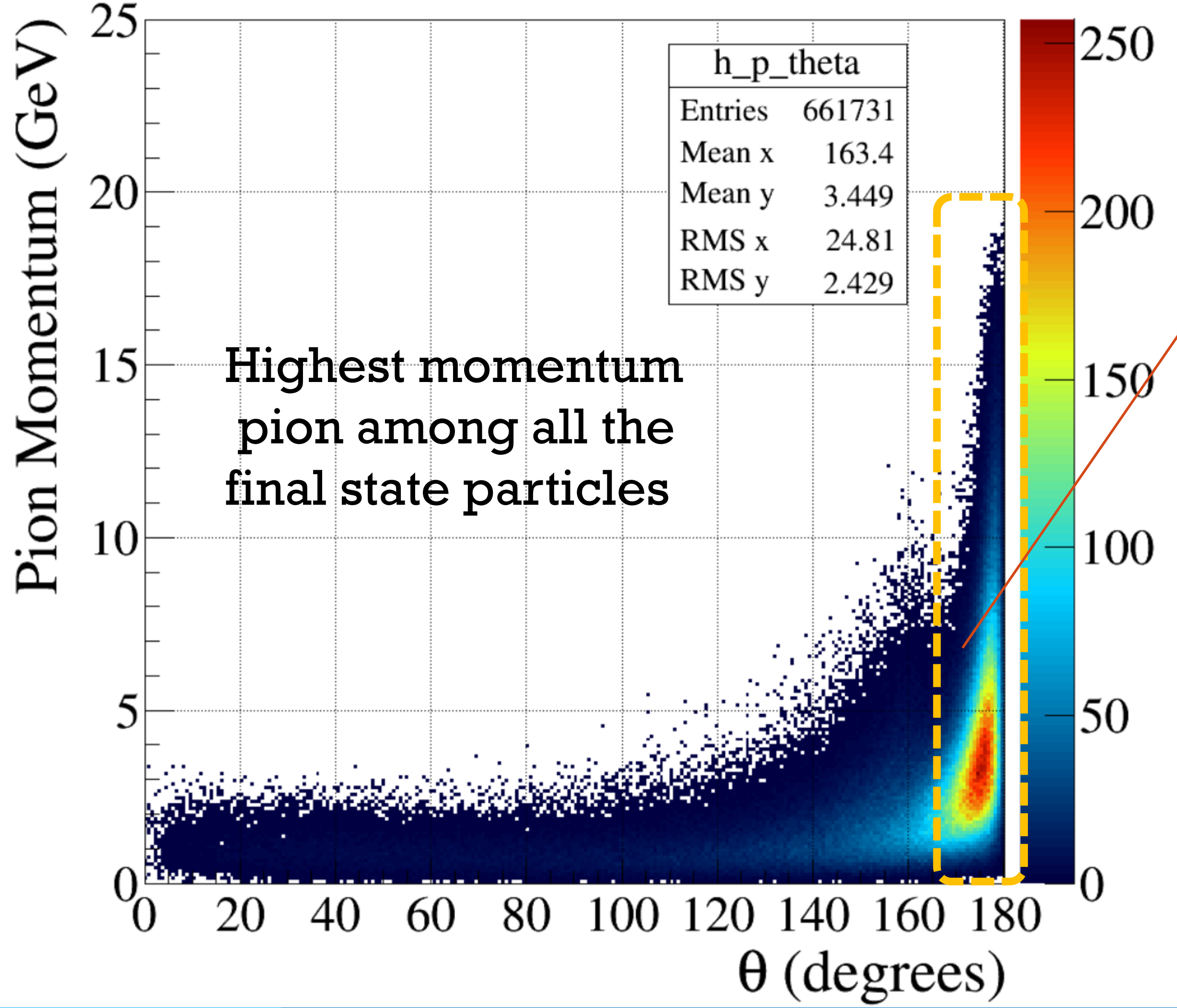
# Pion and Kaon P VS scattering angle using Berger's criterial




I traced it back, these kaons are fragmented from quarks, not from decay. Also indicate that our understanding on kaon fragmentation is limited in order to use it to build a generator

# A very interesting thing in a collider comparing to fix target experiment

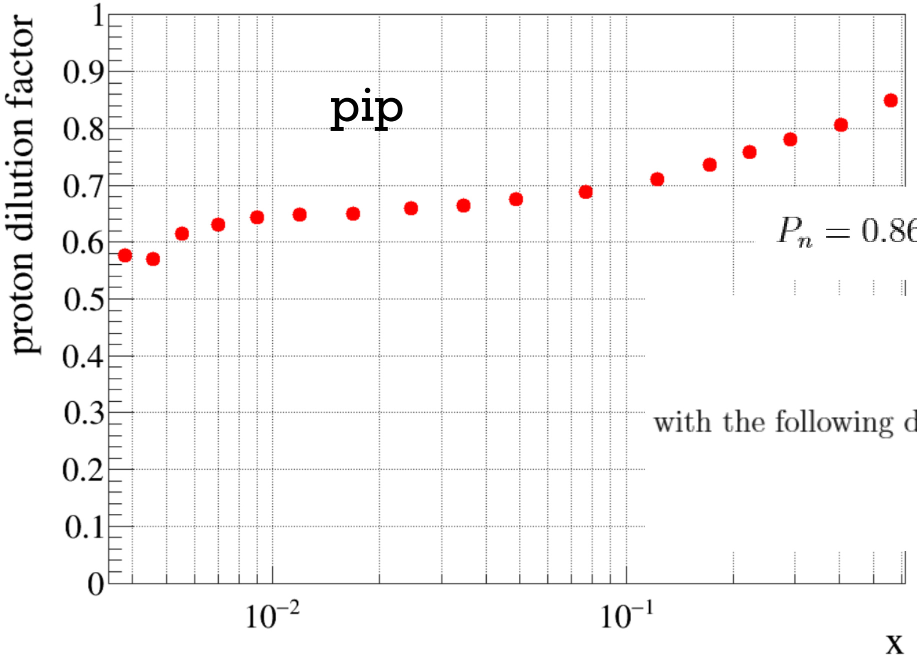



In the very forward angle of proton going direction,
target fragmentation dominates in collider

If z cut is applied, this band will be gone

Fixed target experiment:
Leading hadron carries the high p

# Proton dilution in He-3

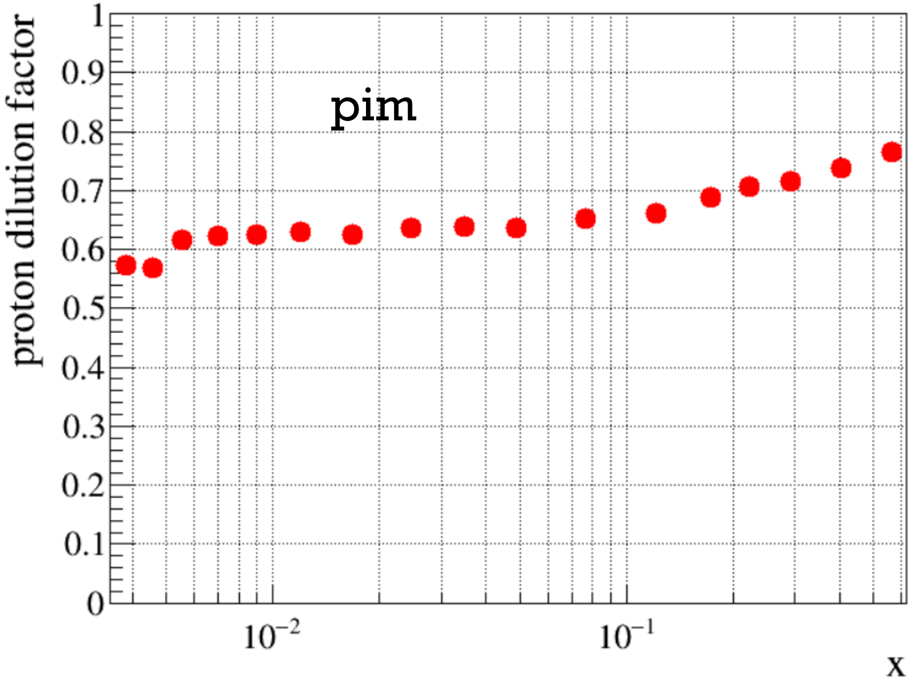


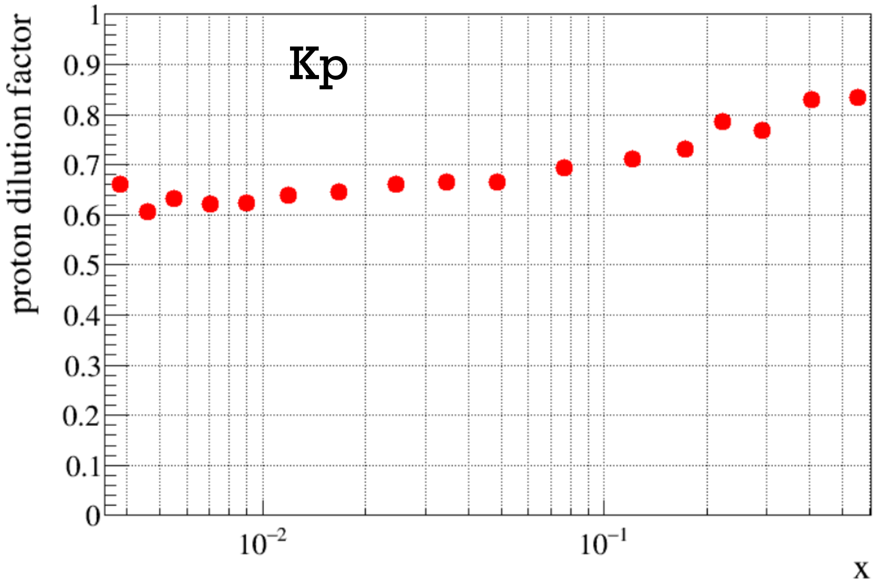

$$P_n = 0.86^{+0.036}_{-0.02}, \qquad P_p = -0.028^{+0.009}_{-0.004}$$

$$A_{^3\mathrm{He}} = P_n(1 - f_p)A_n + P_p f_p A_p,$$

with the following definition:

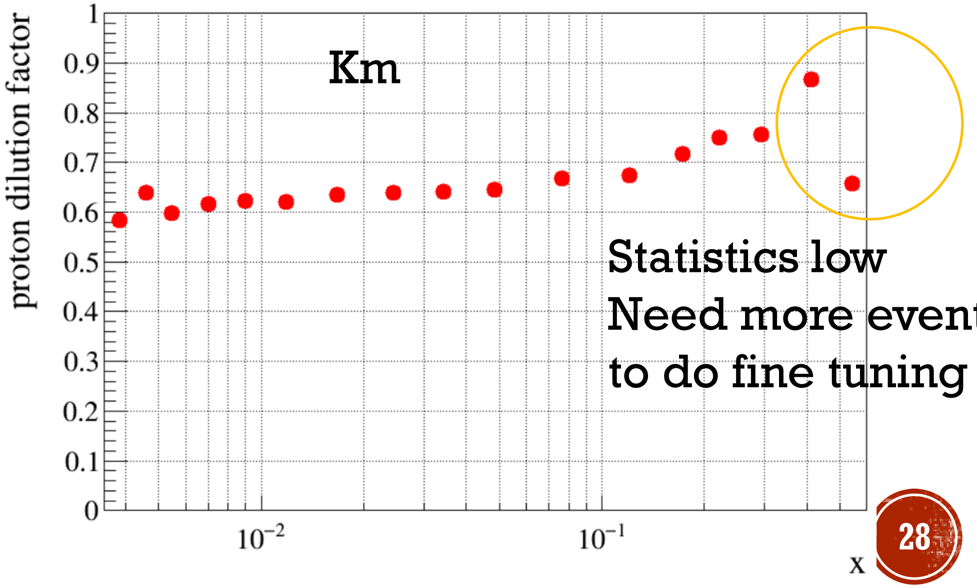
$$f_p = \frac{2\sigma_p^U}{\sigma_{^3\mathrm{He}}^U}.$$




Assumption:
He-3 = n + 2p

A strong assumption for high precision measurements




Statistics low
Need more events
to do fine tuning