# Nucleon spin structure study in lepton-nucleon scatterings

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Yuxiang Zhao (赵宇翔)
Quark Matter Research Center, Institute of Modern Physics

中国科学院近代物理研究所

# Outline

- Introduction of nucleon spin structure study
- Transverse spin structure study
  - ✓**TMD** physics (**T**ransverse **M**omentum **D**ependent PDFs)
  - ✓Experiments: JLab Hall A (US), COMPASS (CERN)
- Electron-Ion Collider in China (EicC)
- Summary

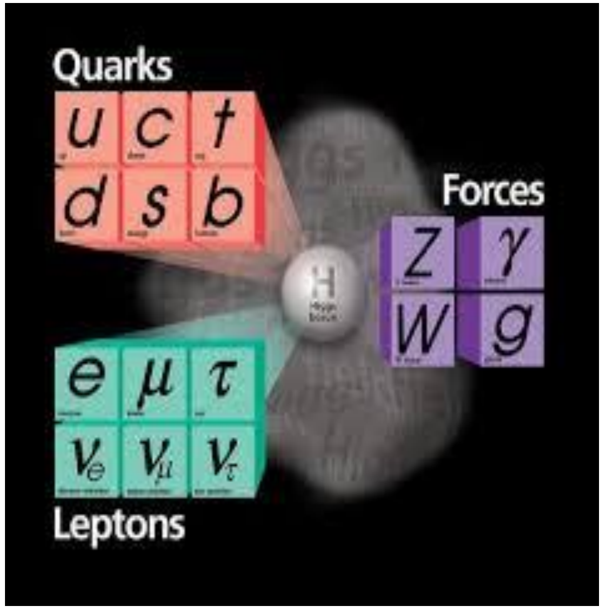
# Celebration of Higgs boson discovery

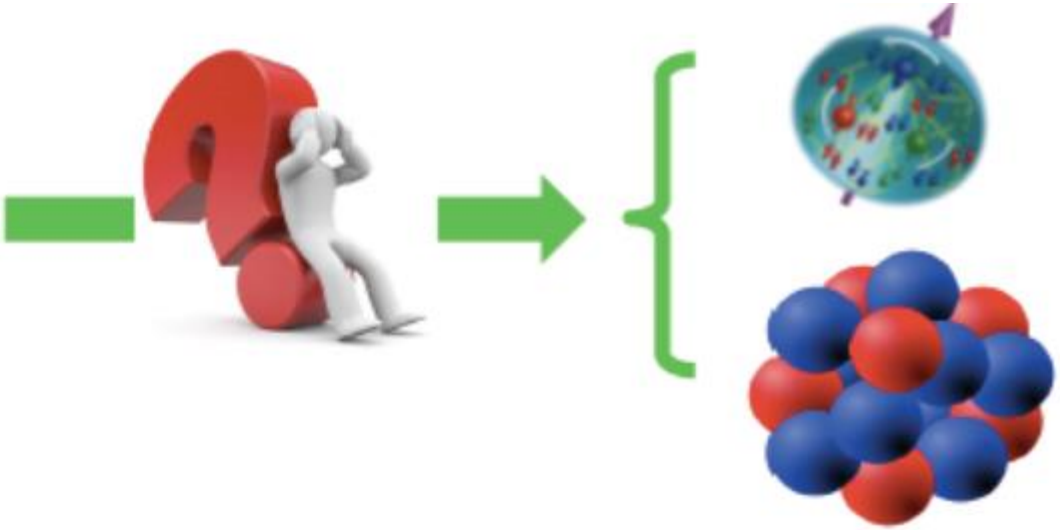

**2013 Nobel prize in physics**

… for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles …

*However… do we really understand the building blocks of our visible world?*

# We know very little...



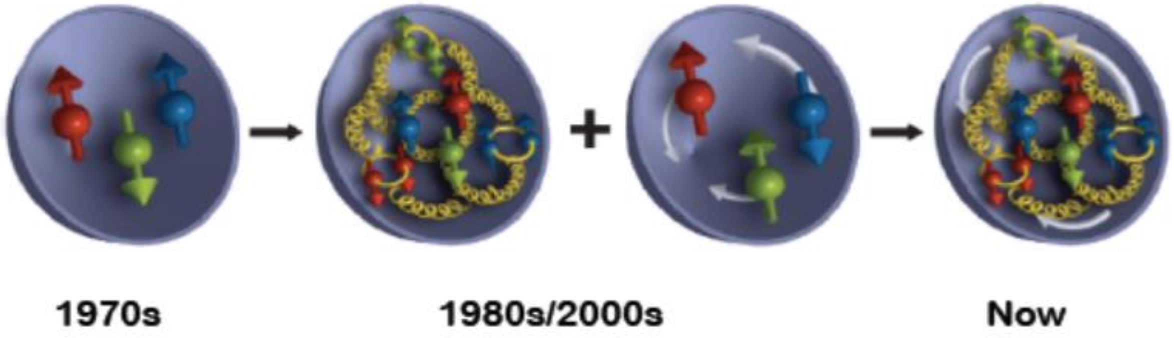



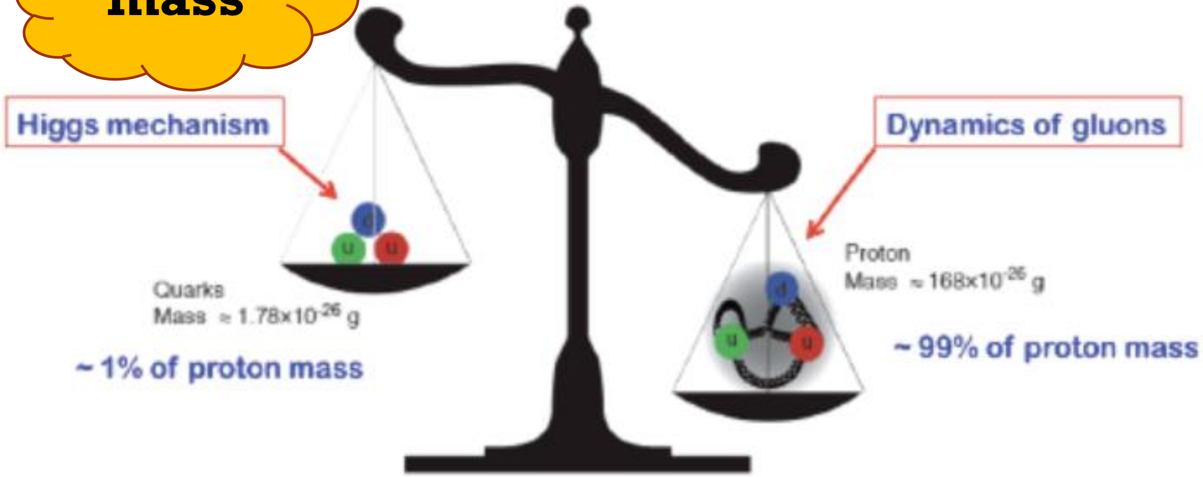
Spin structure

Mass structure

**spin**

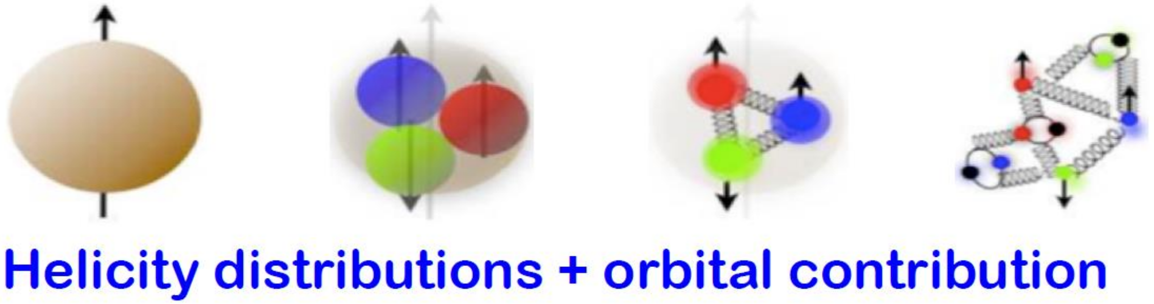
**mass**



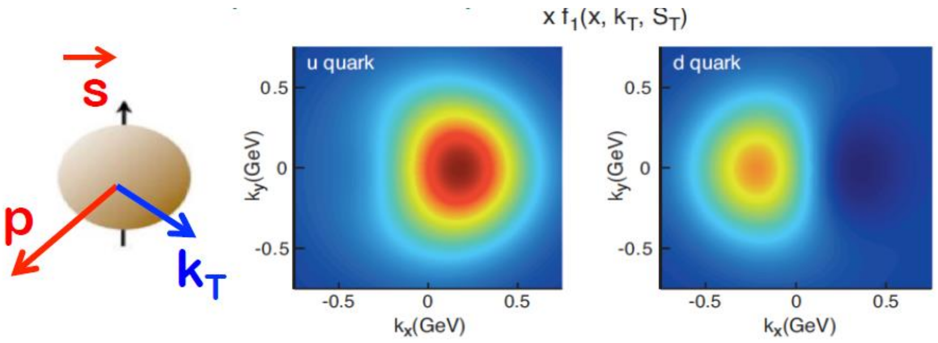



# Open Questions driving the spin physics

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




- **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?**

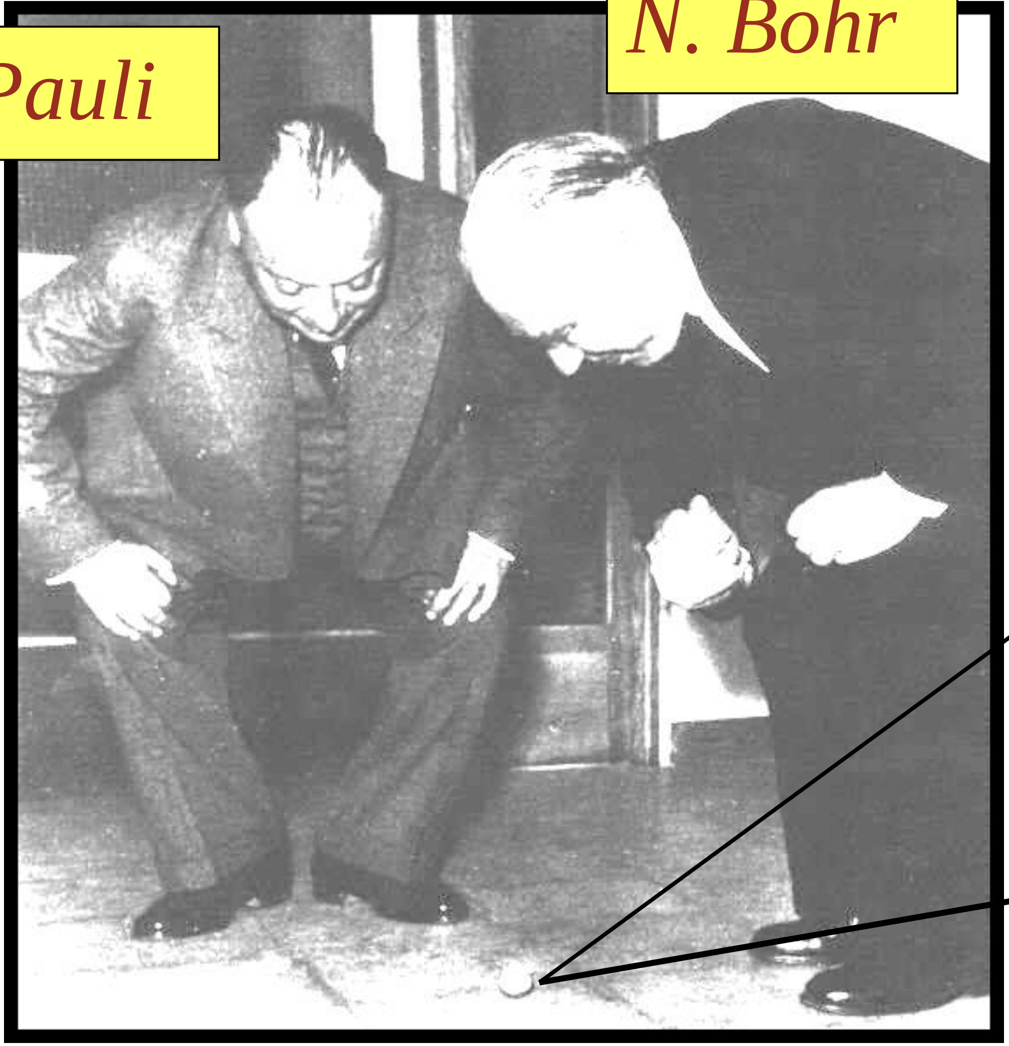
Deformation of parton's
**spatial distribution**
When hadron is polarized?

→ **GPDs!**

# Spin experiments

W. Pauli

N. Bohr



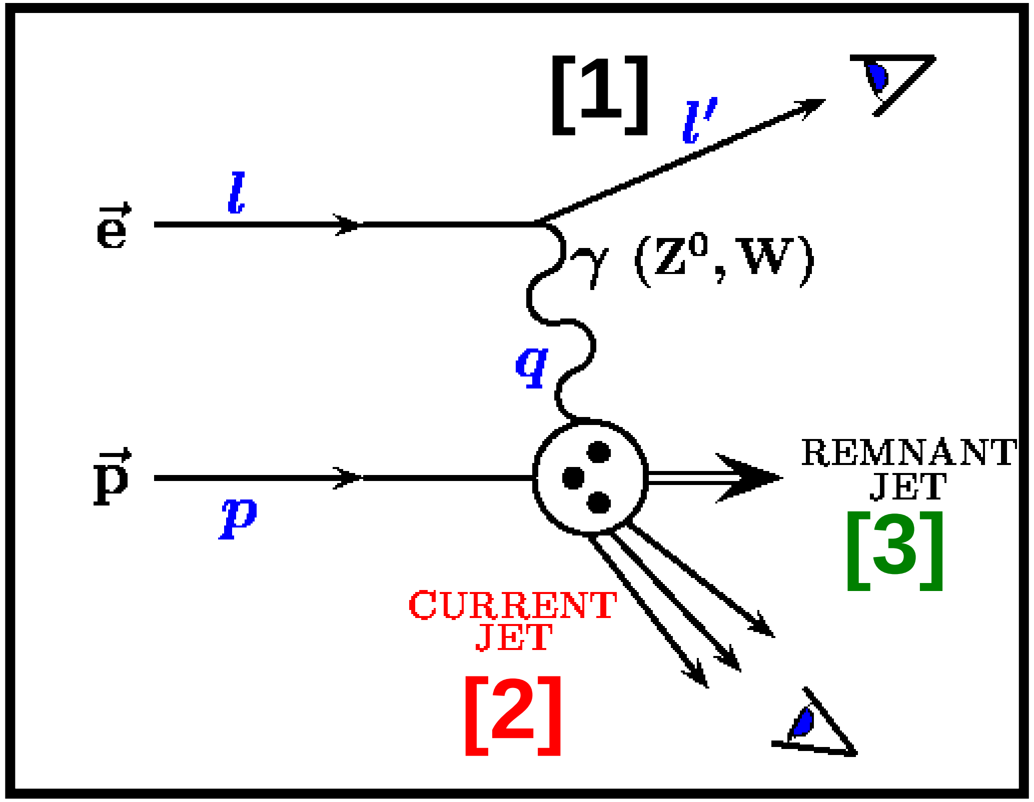
University of Lund

1951-5-31

*A simple "spin" experiment*

# Our "top": Lepton-Nucleon Scatterings

QED tool to study QCD nature of the nucleon




$$Q^2 = -q^2 = sxy$$

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

$$y = \frac{p \cdot q}{p \cdot l}$$

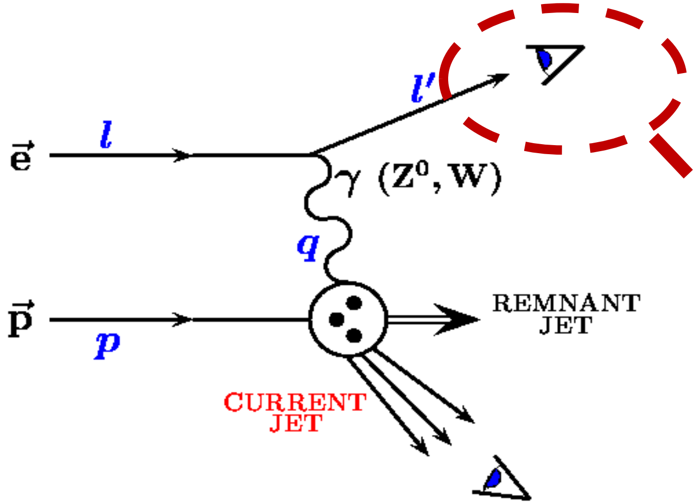
$$s = 4E_e E_p$$

$$W = (q+p)^2$$

- QED probe is clean
- $\alpha_{EM}$ ~1/137 with broad Q coverage
- One-photon exchange approximation: ~1% accuracy
- Detection scale is determined by $Q^2$: $1\text{GeV}^2$ ~ nucleon size

| | | |
|---|---|---|
| **Observe scattered electron/muon** | [1] | → **inclusive** |
| **Observe current jet/hadron** | [1]+[2] | → **semi-inclusive** |
| **Observe remnant jet/hadron as well** | [1]+[2]+[3] | → **exclusive** |

# Structure functions and PDFs : Unpolarized case




$$\frac{d\sigma}{dx\,dy} = \frac{e^4}{4\pi^2 Q^2}\cdot\left\{\frac{y}{2}\cdot F_1 + \frac{1}{2xy}\cdot\left(1-\frac{y}{2}-\frac{y^2}{4}\cdot\gamma^2\right)\cdot F_2\right\}$$

Only scattered leptons are detected

**Experimental observables**

Unpolarized cross section

$Q^2 << M_Z^2$

$F_1$ , $F_2$

Unpolarized structure functions

**Quark-Parton Model**
**QPM**

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

**Callan-Gross equation**

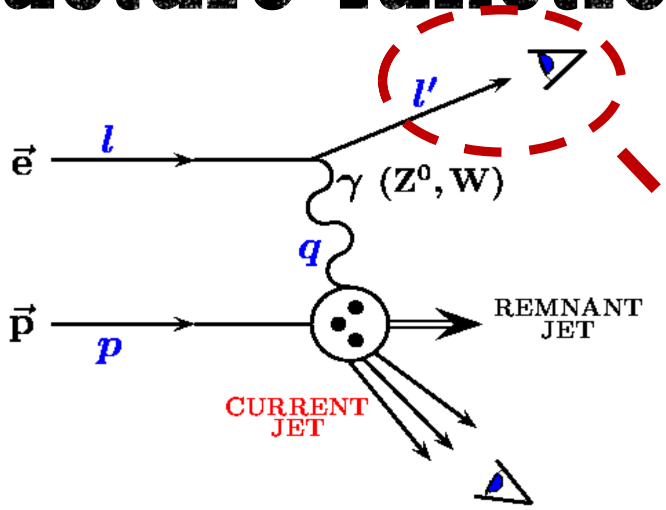
**PDFs**

Unpolarized pdfs

$$f_1(x) = q^{\uparrow}(x) + q^{\downarrow}(x)$$

$$F_2(x) = x\sum_q e_q^2\left(f_1^q(x) + f_1^{\bar{q}}(x)\right)$$

# Structure functions and PDFs : Polarized case




$$\frac{d\Delta\sigma}{dx\,dy} = \lambda \cdot \frac{e^4}{4\pi^2 Q^2} \cdot \left[ \left( 1 - \frac{y}{2} - \frac{y^2}{4} \cdot \gamma^2 \right) \cdot g_1 - \frac{y}{2} \cdot \gamma^2 \cdot g_2 \right]$$

$$d\sigma = d\bar{\sigma} \pm d\Delta\sigma$$ beam/target helicity flips

Only scattered leptons are detected

**Experimental observables**

$A_{LL}$ , $A_{LT}$ $(A_1, A_2)$

$Q^2 << M_Z^2$

Polarized structure functions

$g_1$ , $g_2$

**Quark-Parton Model**
**QPM**

**PDFs**

Polarized pdfs

Helicity distribution

$\Delta q = q^{\uparrow}(x) - q^{\downarrow}(x)$

$$g_1(x) = \frac{1}{2} \sum_q e_q^2 \Delta q(x).$$

# The "spin puzzle", 30 years ago

$$\Gamma_1^{p,n} = \int_0^1 g_1^{p,n}(x,Q^2)dx$$

$$\Gamma_1^p = \frac{1}{12}(\Delta u - \Delta d) + \frac{1}{36}(\Delta u + \Delta d - 2\Delta s) + \frac{1}{9}(\Delta u + \Delta d + \Delta s)$$

measurement

Neutron decay

Hyperon decay

Axial current, i.e. quark contribution to the spin

Trigger: **EMC at CERN** - J. Ashman et al., NPB 328, 1 (1989)

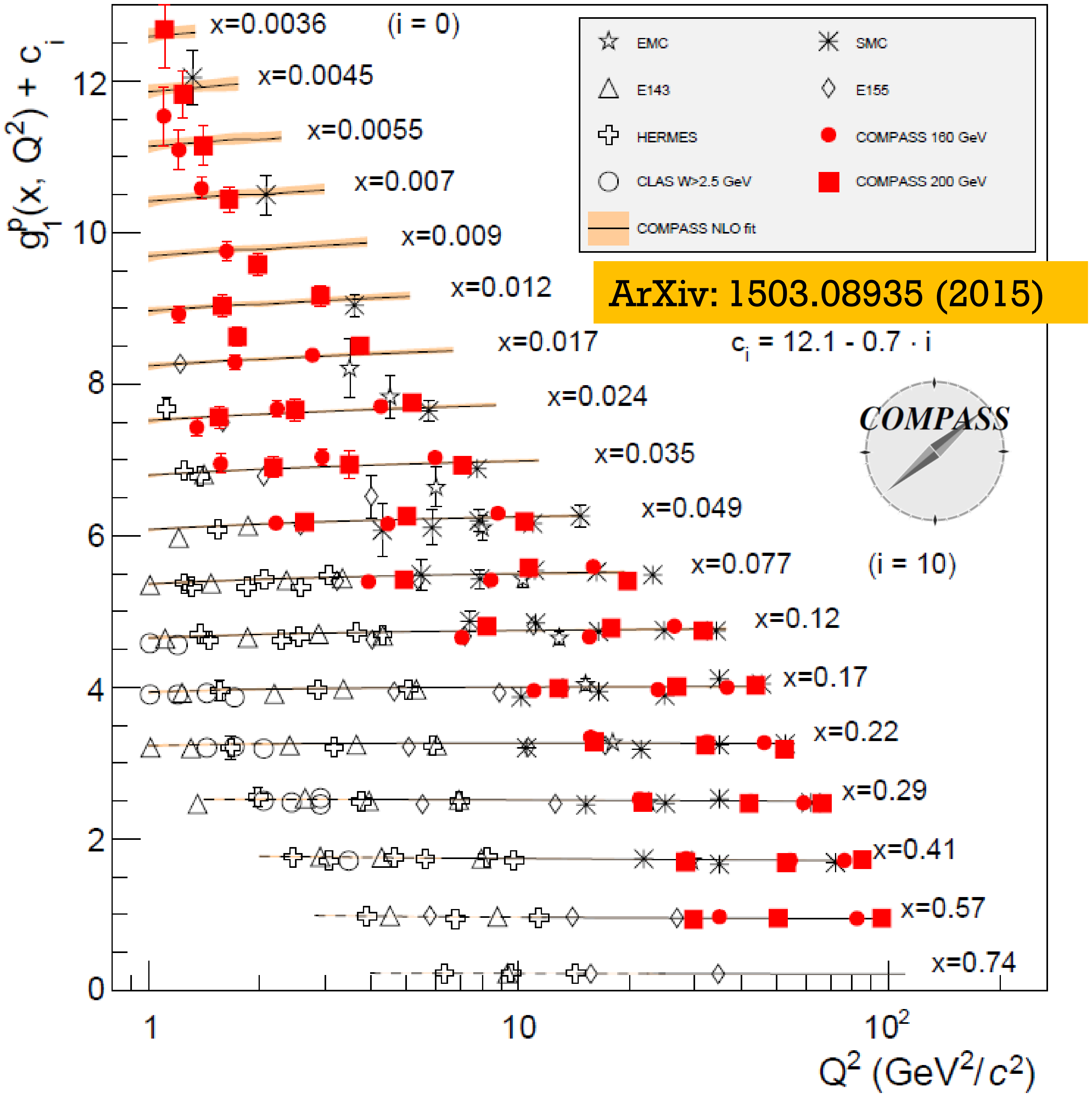
EMC: $\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$ **"proton spin crisis"**

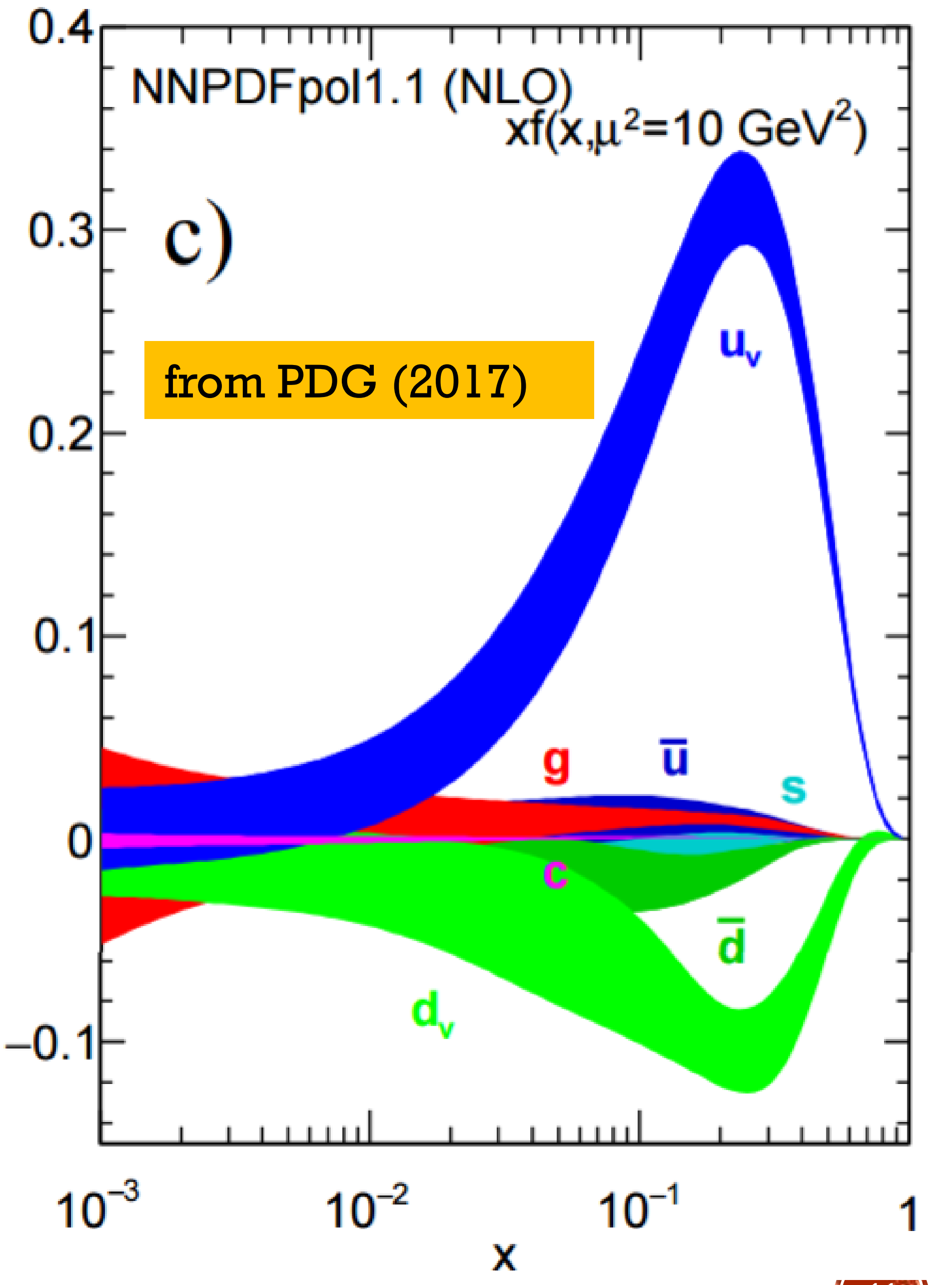
**CQM worked so well with the baryon magnetic moments and it predicts**

$$\Delta\Sigma = \Delta u + \Delta d = \frac{4}{3} - \frac{1}{3} = 1$$

Followed by measurements: **SMC at CERN; E142, E143, E154, E155 at SLAC; HERMES; COMPASS; Jlab…**

+ Huge number of theoretical papers (QCD analysis)


x=0.0036
(i = 0)
x=0.0045
x=0.0055
x=0.007
x=0.009
x=0.012
x=0.017
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
ArXiv: 1503.08935 (2015)
$c_i$ = 12.1 - 0.7 · i
COMPASS
$g_1^p(x, Q^2) + c_i$
$Q^2$ (GeV$^2$/$c^2$)


NNPDFpol1.1 (NLO)
$xf(x,\mu^2=10$ GeV$^2)$
c)
from PDG (2017)
$u_v$
g
$\bar{u}$
s
c
$\bar{d}$
$d_v$
x

# "Spin puzzle" and ways out

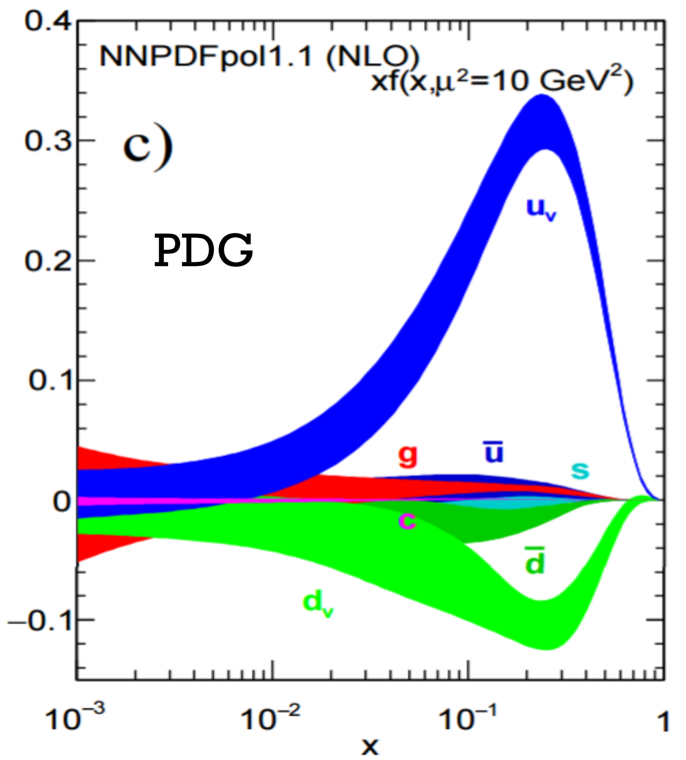
## The "puzzle"

**ΔG positive**

**High impact of RHIC data**

EMC: $\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$

**In inclusive DIS, one is not really measuring Δq , but rather:** $\Delta q' = \Delta q - \frac{1}{2\pi}\alpha_s(Q^2) \cdot \Delta g$




ΔΣ

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

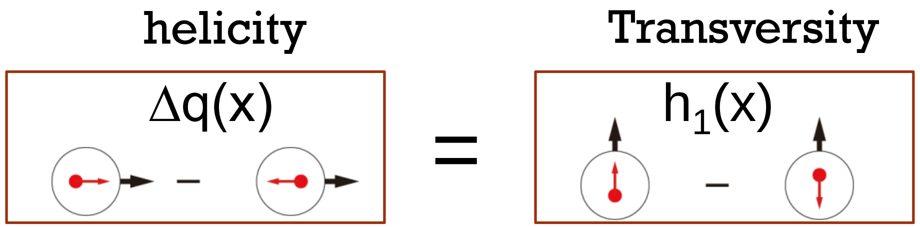
|  | $\langle\Delta g\rangle^{[0,1]}$ | $\langle\Delta g\rangle^{[10^{-3},1]}$ | $\langle\Delta g\rangle^{[0.05,0.2]}$ |
|---|---|---|---|
| NNPDFpol1.1 | $+0.03 \pm 3.24$ | $+0.49 \pm 0.75$ | $+0.17 \pm 0.06$ |
| DSSV08 | — | $0.01^{+0.70}_{-0.31}$ $(+0.10)$ | $0.01^{+0.13}_{-0.16}$ |
| DSSV++ | — |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

ΔG

***Orbital angular motion???***

# The handle: Transversity distribution $h_1(x)$

Non-relativistic:




In fact: Not

- **Relativistic:** Lorentz boost and rotation do not commute
  - Imply the relativistic nature of quark dynamics
  - Exist of orbital angular momentum of quarks

- Interesting features:
  - Chiral odd nature, valence-like behavior, simple QCD evolution
  - Soffer's inequality: $|h_1(x)| < \frac{1}{2}(f(x) + \Delta q(x))$
  - First moment, tensor charge ( VS axial charge in longitudinal case)
  - Sum rule: $\frac{1}{2} = \frac{1}{2}\Sigma h_1^q + L_q + L_g$

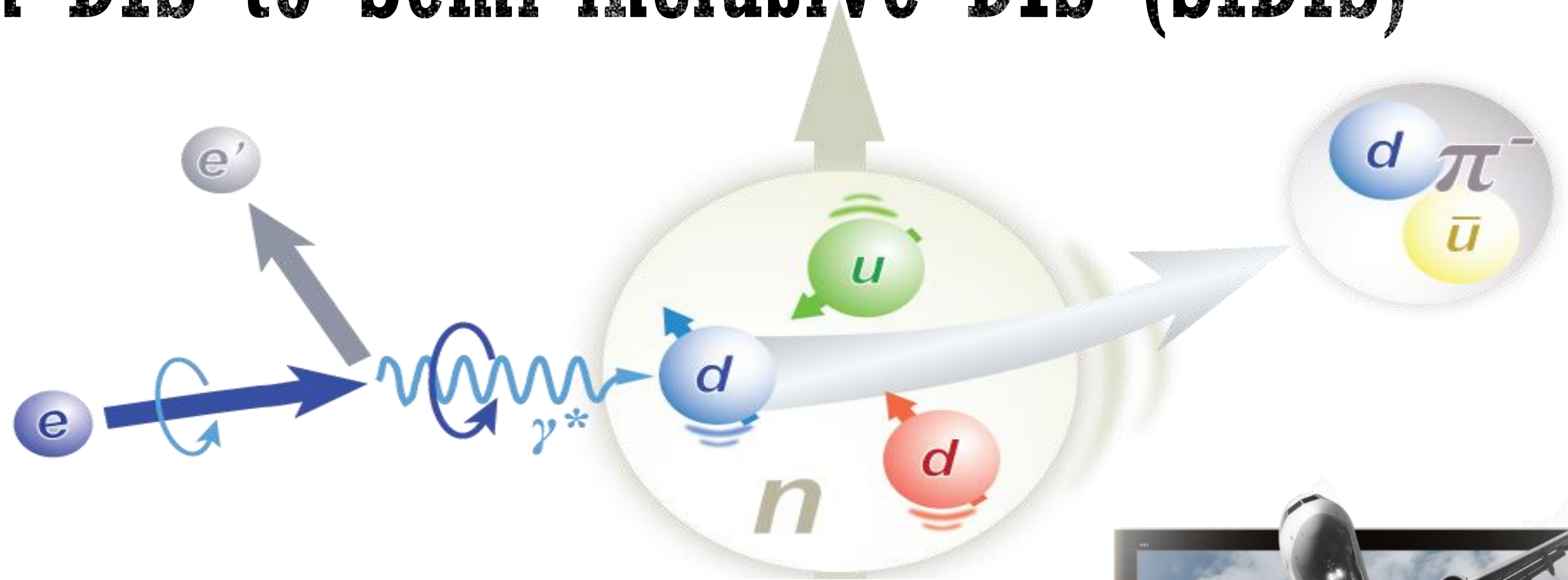
$$g_T = \delta u - \delta d$$

$$\delta q(Q^2) = \int_0^1 dx[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)]$$

**OPE**: $g_2 \sim (m_q/M)h_1(x) + \ldots$

Impossible to measure in inclusive DIS → SIDIS

# From DIS to Semi-inclusive DIS (SIDIS)



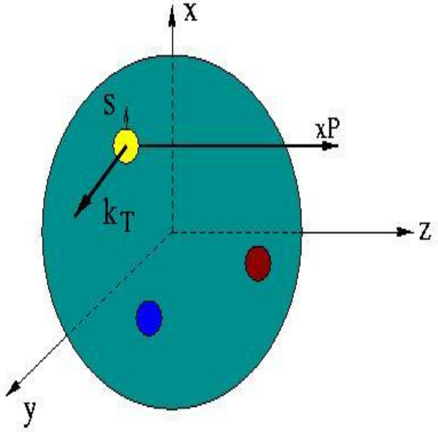

- Chiral odd transversity function coupled with chiral odd Collins fragmentation function

- SIDIS: **Involves a set of transverse momentum ($k_T$) dependent PDFs (TMDs): from 1D to 3D**

# Unified view of nucleon structure

$W_p^u(x,k_T,r)$ *Wigner distributions* **(X. Ji)**

**6D Dist.**




$d^3r$ → **TMD PDFs**: $f_1^u(x,k_T)$, .. $h_1^u(x,k_T)$

$d^2k_T\, dr_z$ → **GPDs/IPDs**

**3D imaging**

TMD PDFs → $d^2k_T$ → PDFs

GPDs/IPDs → $d^2r_T$ → PDFs

GPDs/IPDs → *dx & Fourier Transformation* → Form Factors

**PDFs**

$f_1^u(x)$, .. $h_1^u(x)$

**1D**

*Form Factors*

$G_E(Q^2)$,

$G_M(Q^2)$

# Leading-Twist TMDs

| Nucleon Polarization | Quark polarization: Unpolarized (U) | Quark polarization: Longitudinally Polarized (L) | Quark polarization: Transversely Polarized (T) |
|---|---|---|---|
| U | $f_1$ = | | $h_1^\perp$ = − <br> Boer-Mulders |
| L | | $g_1$ = − <br> Helicity | $h_{1L}^\perp$ = − <br> Worm Gear |
| T | $f_{1T}^\perp$ = − <br> Sivers | $g_{1T}$ = − <br> Worm Gear | $h_1$ = − <br> Transversity <br> $h_{1T}^\perp$ = − <br> Pretzelosity |

*Nucleon Spin* *Quark Spin* **Survive the $k_T$ integration, yield 1D pdfs**

# Leading-Twist TMDs

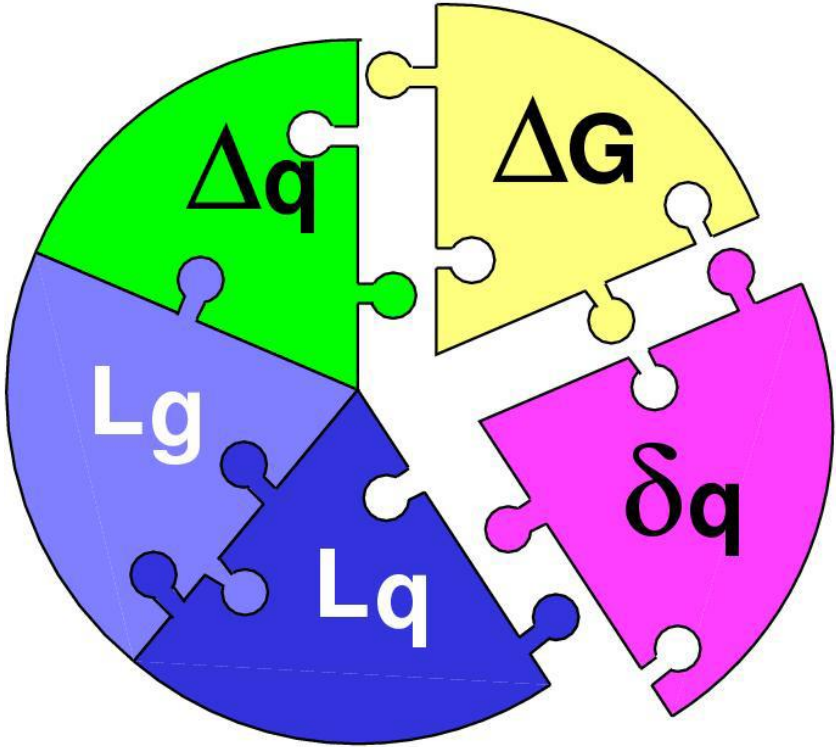
| Nucleon Polarization | | Quark polarization | | |
|---|---|---|---|---|
| | | Unpolarized (U) | Longitudinally Polarized (L) | Transversely Polarized (T) |
| | T | $f_{1T}^{\perp}$ = − <br> Sivers | $g_{1T}$ = − <br> Worm Gear | $h_1$ = − <br> Transversity <br> $h_{1T}^{\perp}$ = − <br> Pretzelosity |


*Nucleon Spin* *Quark Spin*

**Survive the $k_T$ integration, yield 1D pdfs**

# Spin structure of a nucleon

Fundamental question:




An effort of more than 30 years

| | Quark Spin | Gluon Spin |
|---|---|---|
| SLAC -> 2000 | E80 – E155 | |
| CERN ongoing | EMC, SMC, COMPASS | |
| DESY ->2007 | HERMES | |
| JLab ongoing | Hall A,B,C | |
| RHIC ongoing | (BRAHMS), (PHENIX), STAR | |

SIDIS/DIS

Polarized p+p

**Moreover:**

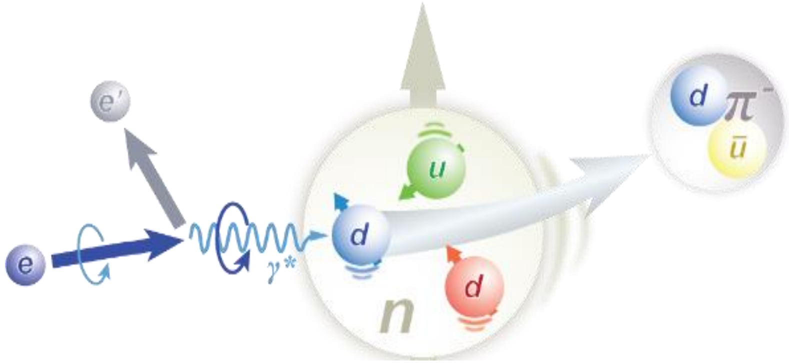
**spin as a powerful tool to understand QCD**

Finally, EIC is approaching…

# Outline

- Introduction of nucleon spin structure study
- Transverse spin structure study
  - ✓ **TMD** physics (**T**ransverse **M**omentum **D**ependent PDFs)
  - ✓ Experiments: JLab Hall A (US), COMPASS (CERN)
- Electron-Ion Collider in China (EicC)
- Summary

# TMDs in SIDIS Cross Section




$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\cdot$$

$$\{F_{UU,T} + \ldots$$
$$+ \varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$$

**Unpolarized**

$$+ S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$
$$+ S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \sin(\phi_h-\phi_S)\cdot(F_{UT}^{\sin(\phi_h-\phi_S)} + \ldots)$$
$$+ \varepsilon\sin(3\phi_h-\phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]$$

**Polarized Target**

$$+ S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$
$$+ S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]\}$$

**Polarized Beam and Target**

$f_1$ =

Boer-Mulder $h_1^\perp$ =

$h_{1L}^\perp$ =

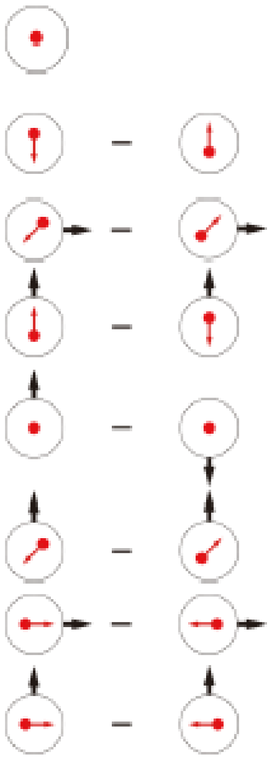
Transversity $h_{1T}$ =

Sivers $f_{1T}^\perp$ =

Pretzelosity $h_{1T}^\perp$ =

$g_1$ =

$g_{1T}^\perp$ =



$S_L$, $S_T$: Target Polarization; $\lambda_e$: Beam Polarization

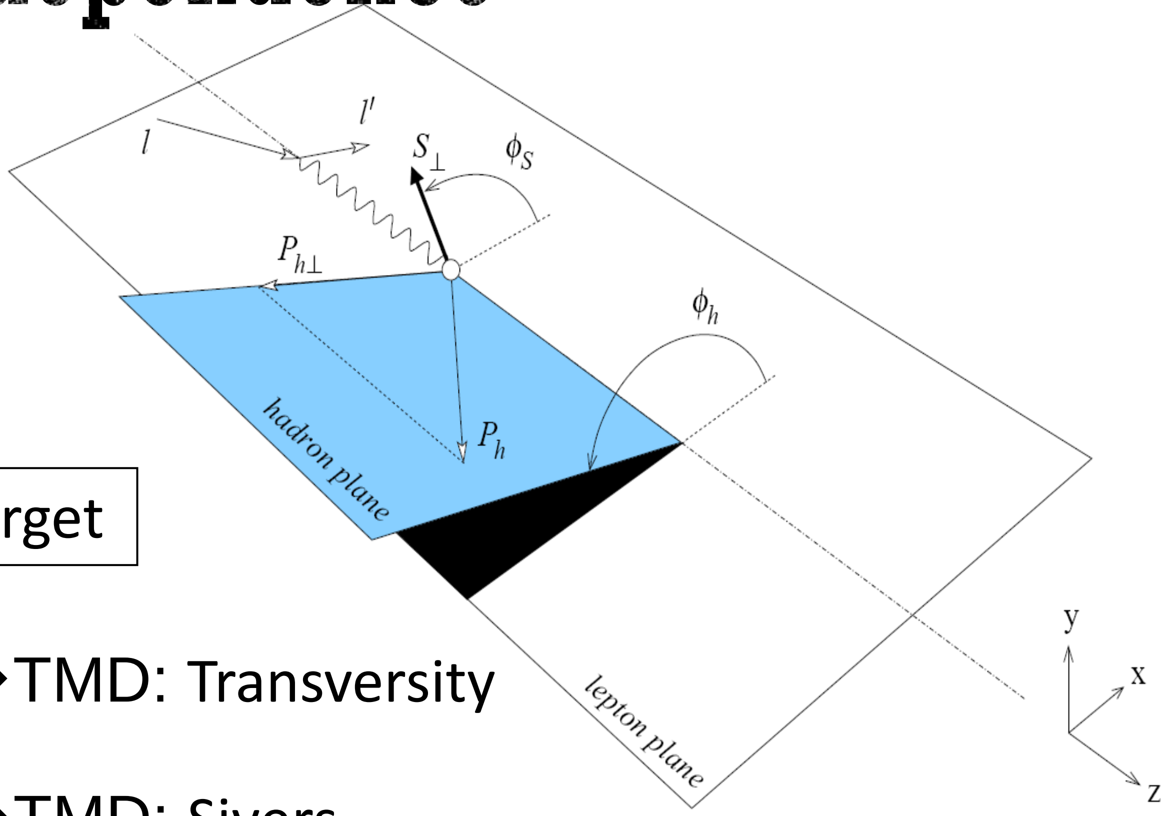
**Target SSA, beam-target DSA measurements**

# Separation of Collins, Sivers and Pretzelosity through azimuthal angular dependence

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity}\sin(3\phi_h - \phi_S)$$




**UT**: **U**npolarized beam + **T**ransversely polarized target

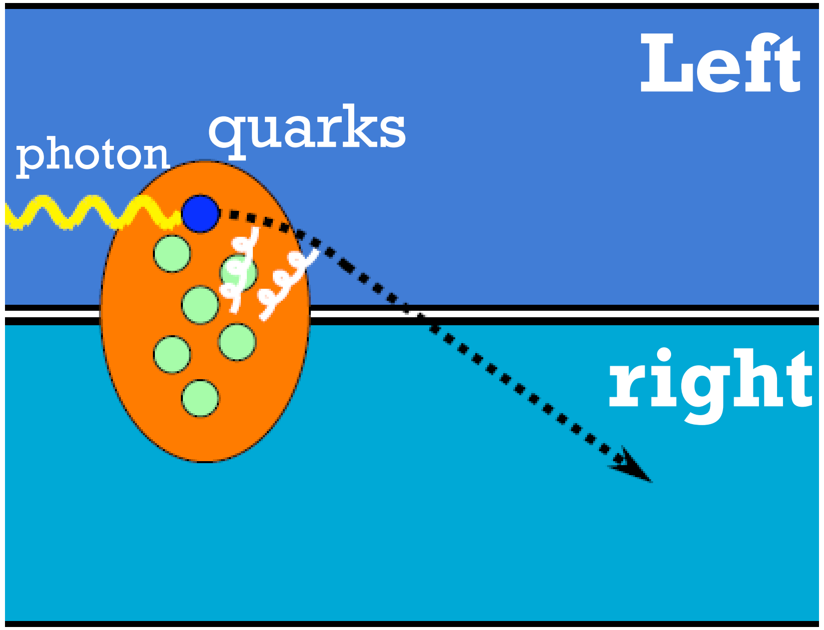
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$ →TMD: Transversity

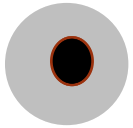
$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$ →TMD: Sivers

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$ →TMD: Pretzelosity

# Physics pictures of TMDs: internal dynamics

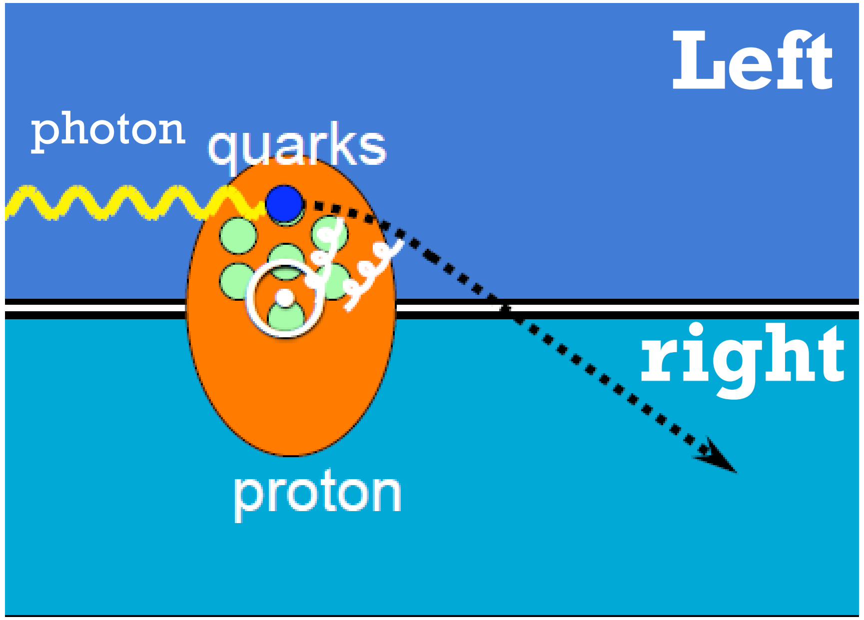
Top view





Nucleon spin

**SIDIS Sivers effects**

Top view

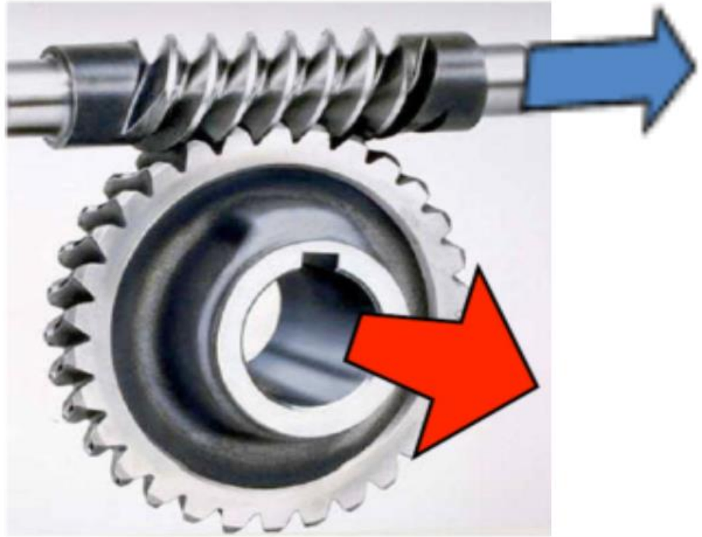


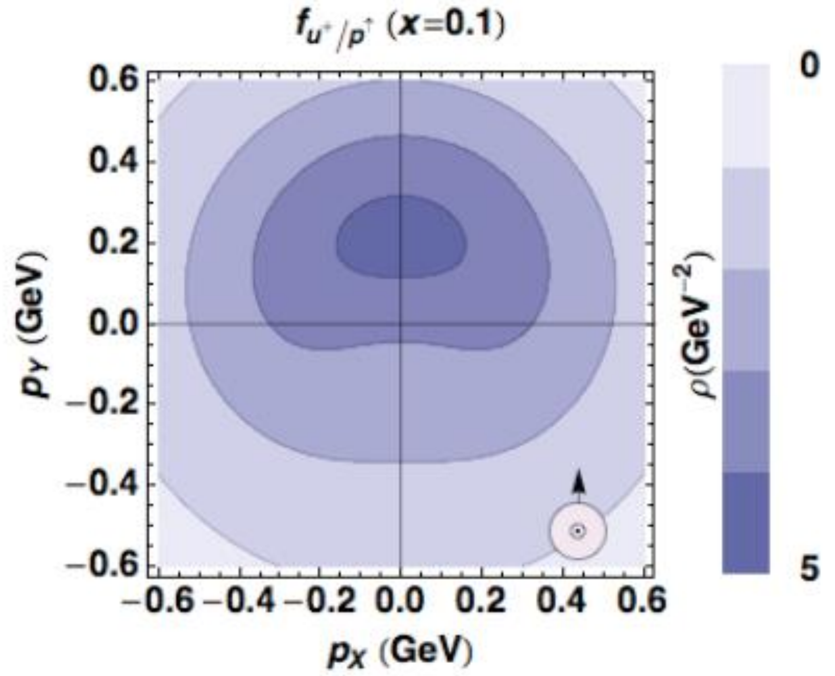

- QCD: the final state interaction has to be attractive, since quark and remnants form a color antisymmetric state
- The presence of spin can distort the distribution of quarks in transverse space, orbital angular momentum of quarks is required

Ji, Yuan PLB 543 (02); Belitsky, Ji, Yuan NPB656 (03); Burkardt PRD66 (02); Diehl EPJC 25 (02); Diehl, Hagler EPJC44 (05)

# Physics pictures of TMDs: internal dynamics

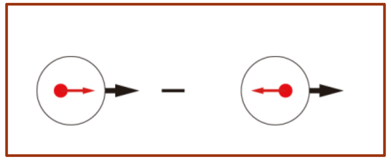
**Worm-Gear**






Boost to Infinite momentum frame (relativistic quark models):

**Pretzelosity**



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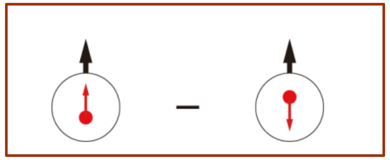
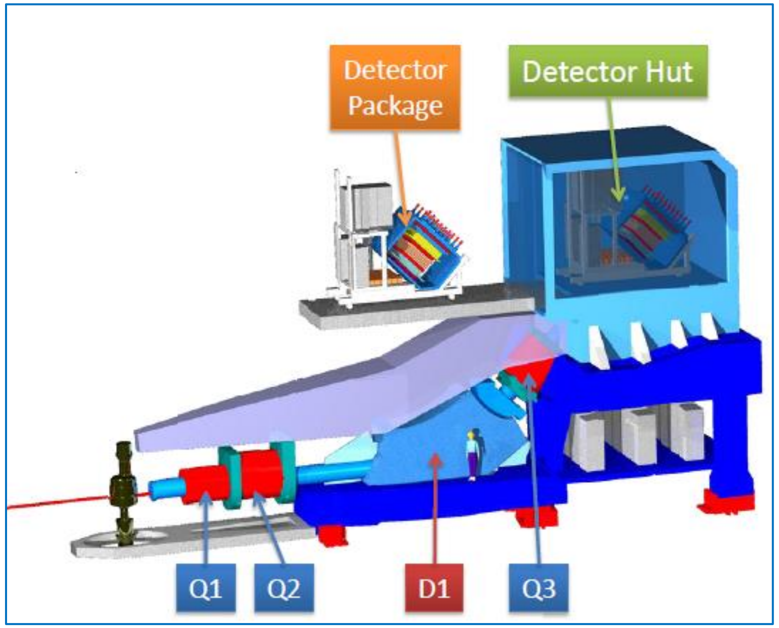


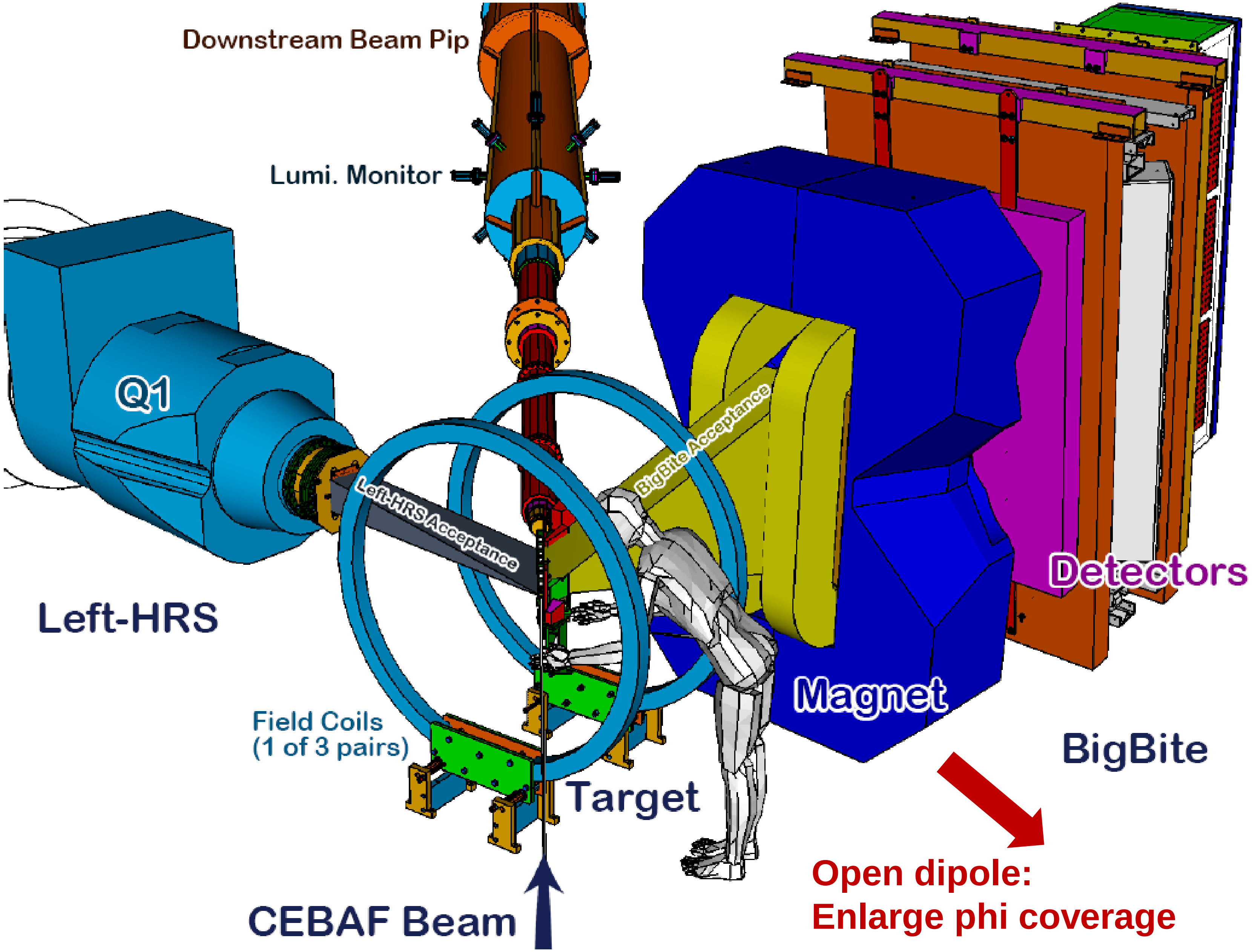
= Pretz.

Jefferson Lab
EXPLORING THE NATURE OF MATTER


- 6 GeV experiment:
  - E06-010 Transversity experiment
  - First TMD experiment on a neutron target at Jlab
  - My Ph.D experiment
- 12 GeV: SoLID

# Setup of E06-010 experiment at JLab



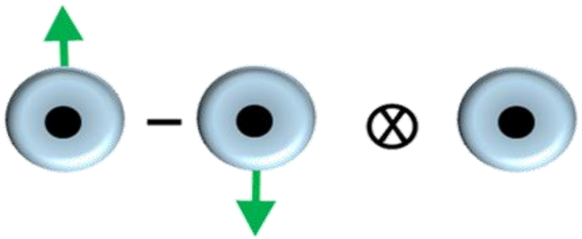



# Pion SIDIS SSA --- Collins and Sivers asymmetries

X. Qian et al. (Hall A Collaboration) **PRL 107 072003 (2011)**

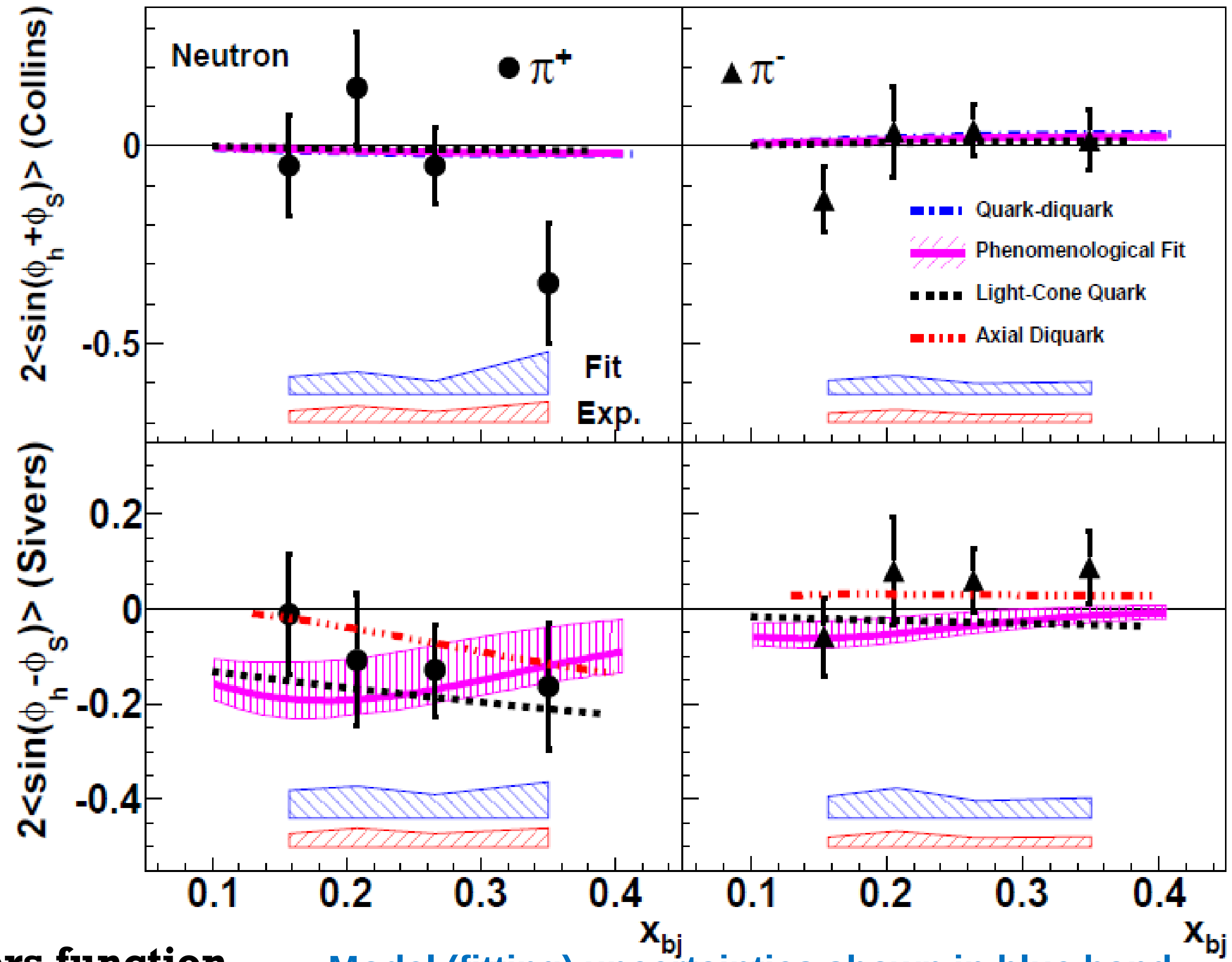

## Sizable Collins $\pi^+$ asymmetries at x=0.34?

- Hints of violation of Soffer's inequality?
- **Data are limited by stat. Needs more precise data!**




## Negative Sivers $\pi^+$ Asymmetry

- Consistent with HERMES/COMPASS
- **Independent demonstration of negative d quark Sivers function**




Model (fitting) uncertainties shown in blue band

# Kaon SIDIS SSA --- Collins and Sivers asymmetries

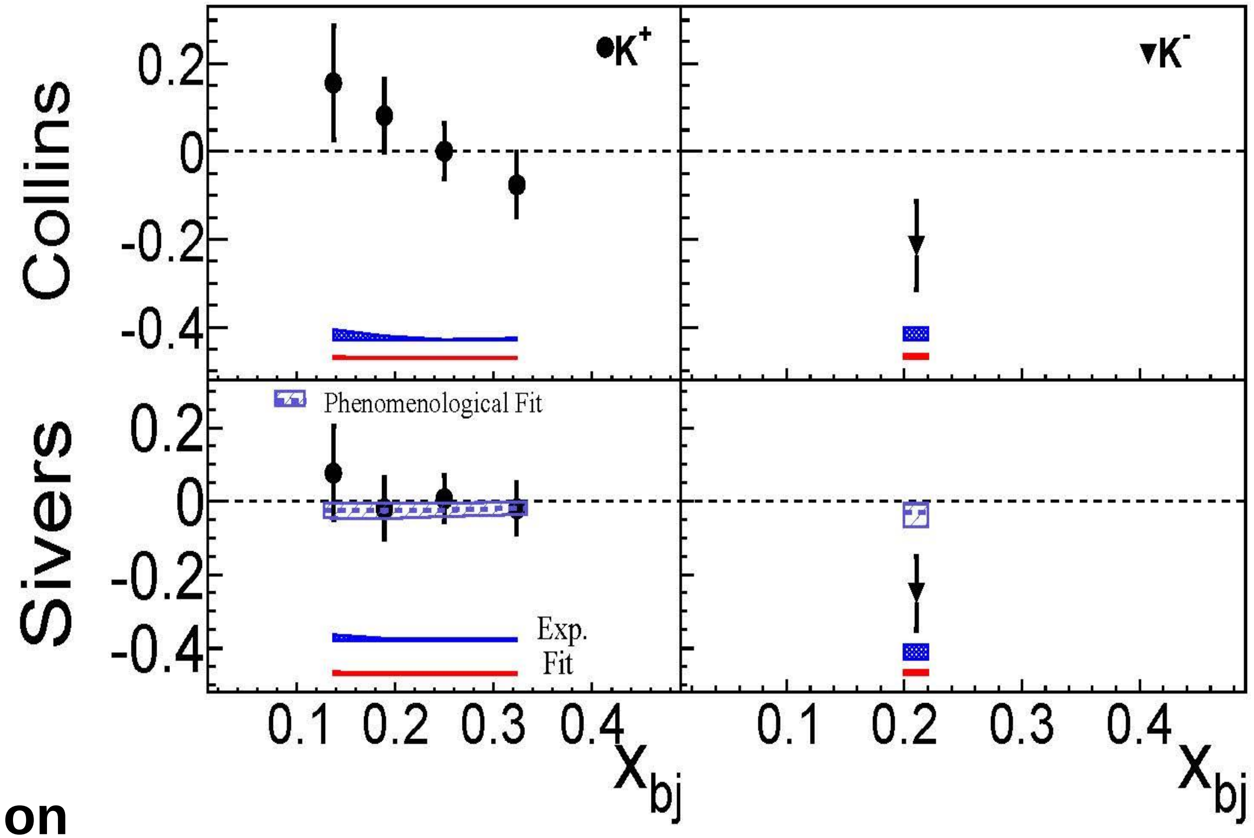
Y. X. Zhao*, et al (Hall A Collaboration)
**Phys. Rev. C 90, 055201**

**Collins effect**

- ✓**Hermes: $\pi^- > \pi^+$ and kaon > pion**
- ✓**Unfavored Collins fragmentation function plays a more important role???**

**Sivers effect**

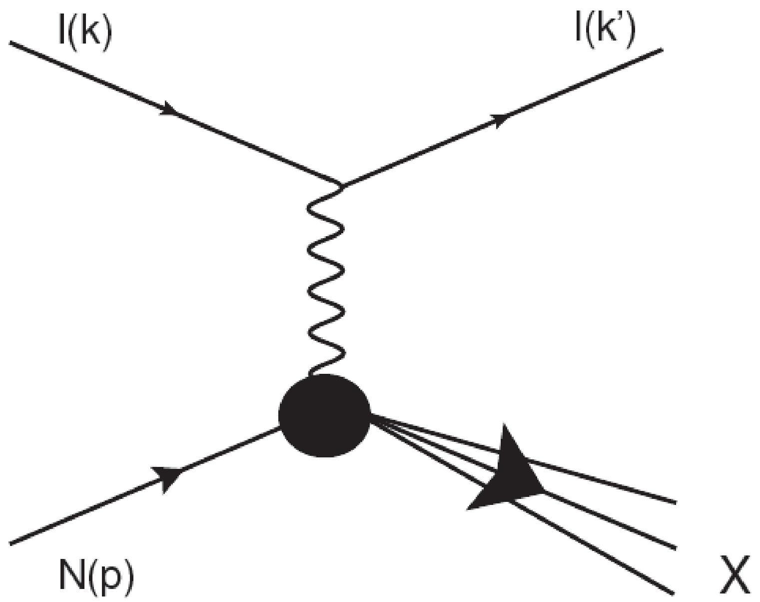
- ✓**Difference between $\pi^+$ and $K^+$: d-bar, s-bar**
- ✓**Sea quark effect, fragmentation effect**




**kaon data:**

1. Validation of TMD factorization
2. Higher twist effects
3. Current/target fragmentation effects
4. Favored/unfavored Fragmentation function

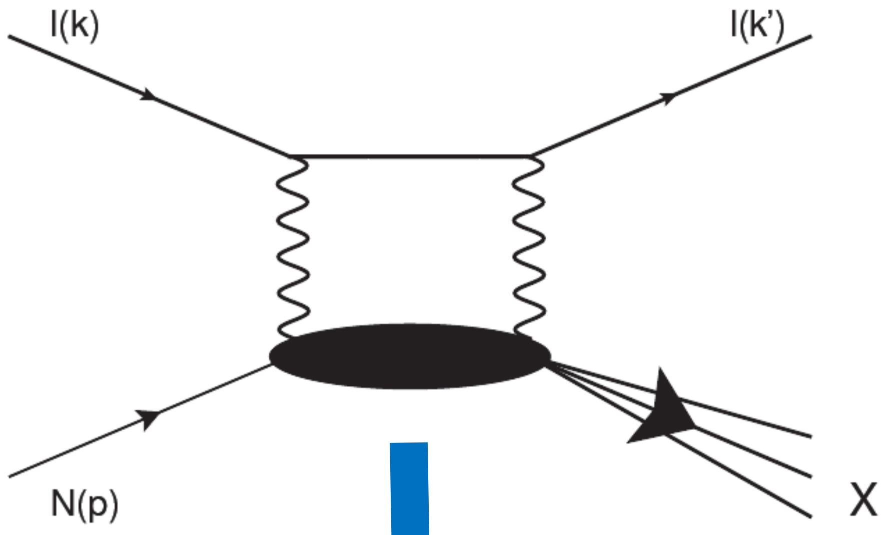
# Inclusive electron SSA




Assuming T-reversal invariance

**SSA=0 at Born level**

**Two photon-exchange contributions**

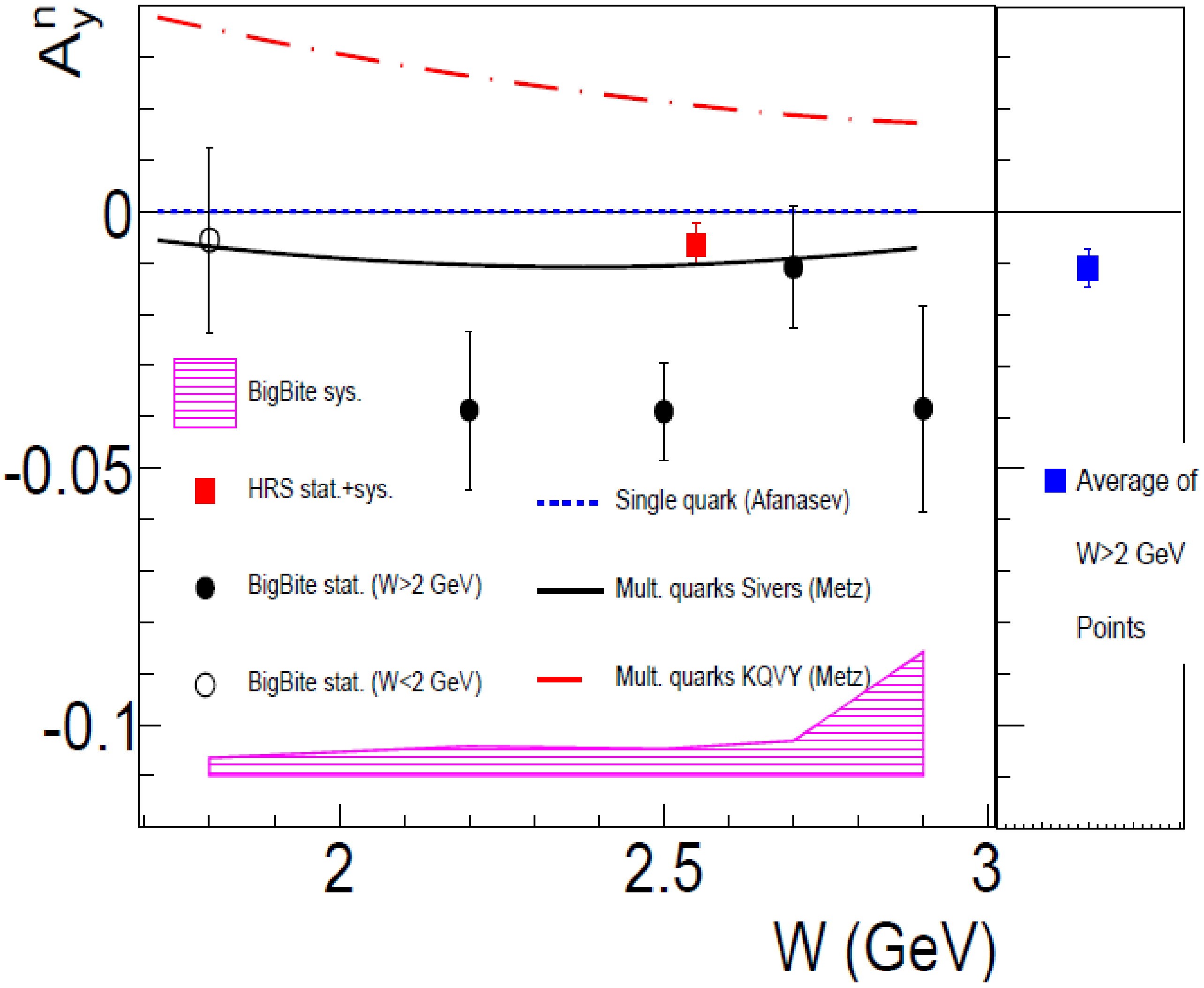


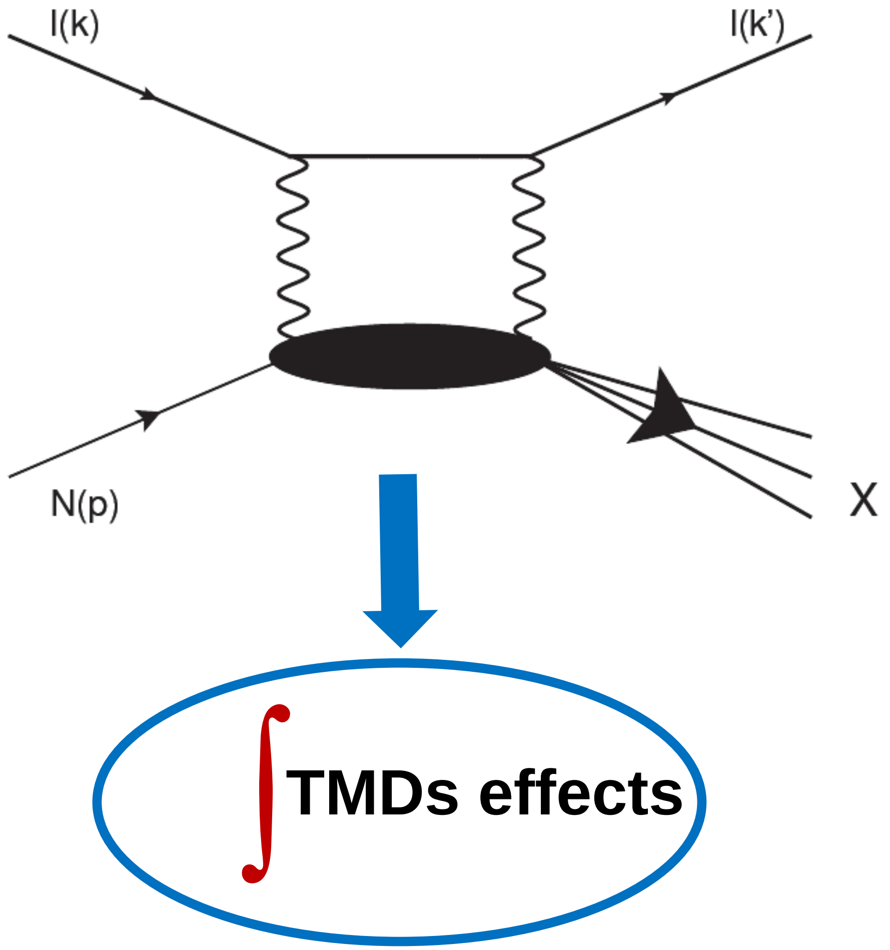

∫ TMDs effects

**Target-Normal SSA**

# Inclusive electron SSA

J. Katich*, X. Qian*, Y. X. Zhao* et al.
**Phys. Rev. Lett. 113,022502 (2014)**

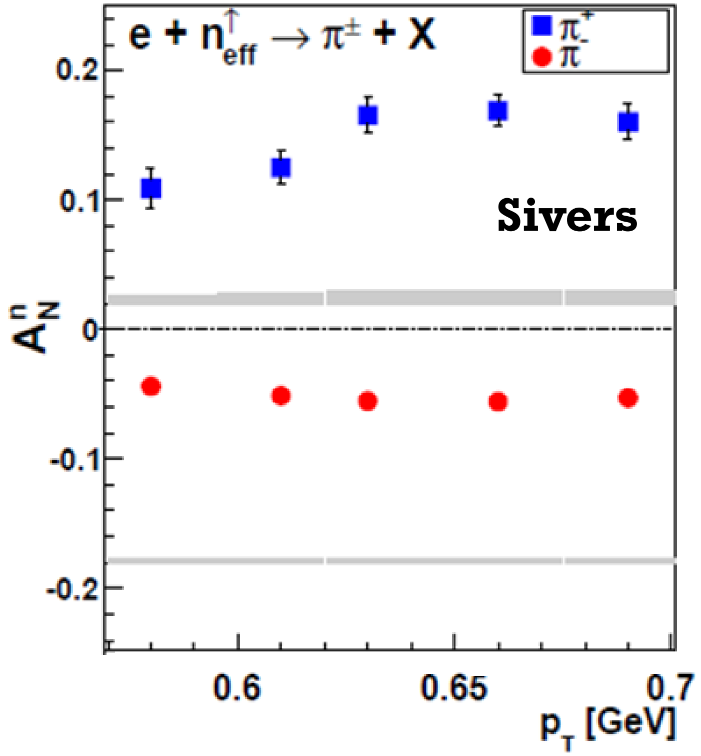



**Target-Normal SSA**

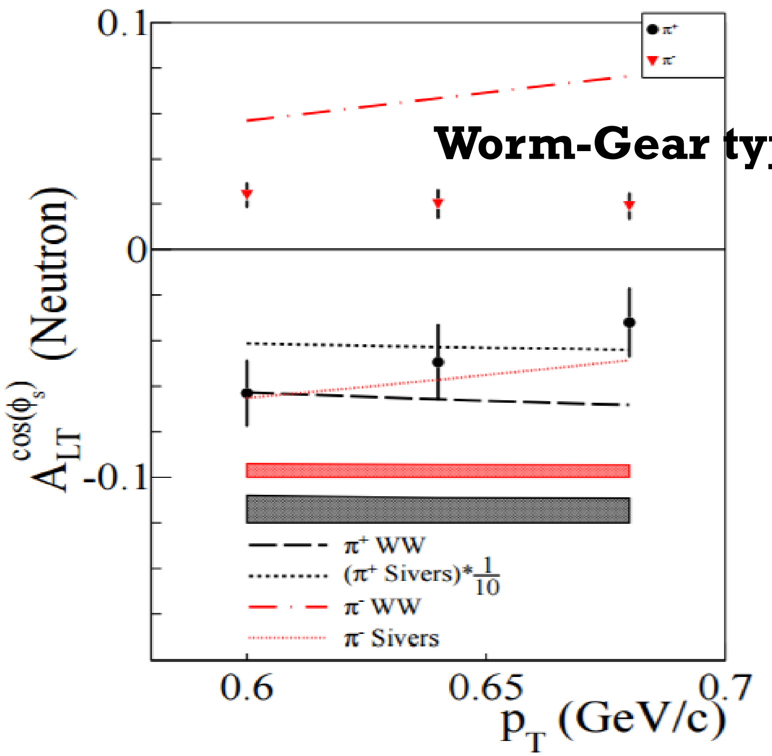
# Inclusive hadron SSA/DSA

$$A_{UT}(x_F, p_T) = \frac{1}{P}\frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = A_N \sin\phi_S$$

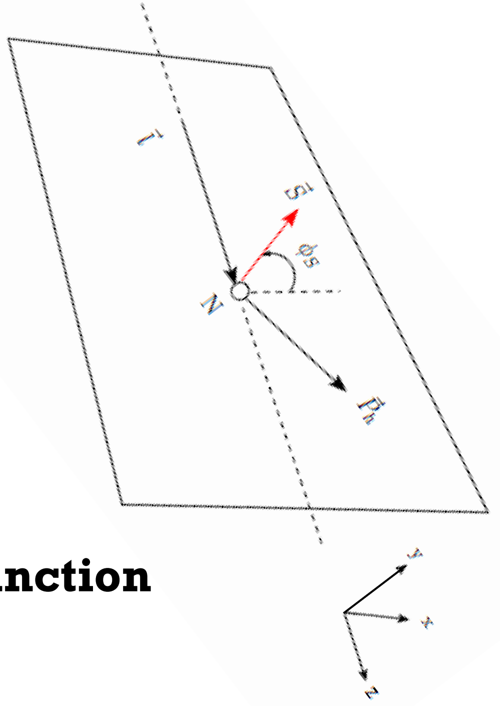



K. Allada*, Y. X. Zhao* et al. (Hall A Collaboration)
**Phys. Rev. C 89, 042201(R)**

$$A_{LT} = \frac{1}{|P_B P_{target}|}\frac{d\sigma^{\uparrow\rightarrow} - d\sigma^{\downarrow\rightarrow}}{d\sigma^{\uparrow\rightarrow} + d\sigma^{\downarrow\rightarrow}} = A_{LT}^{\cos(\phi_s)}\cos(\phi_s)$$



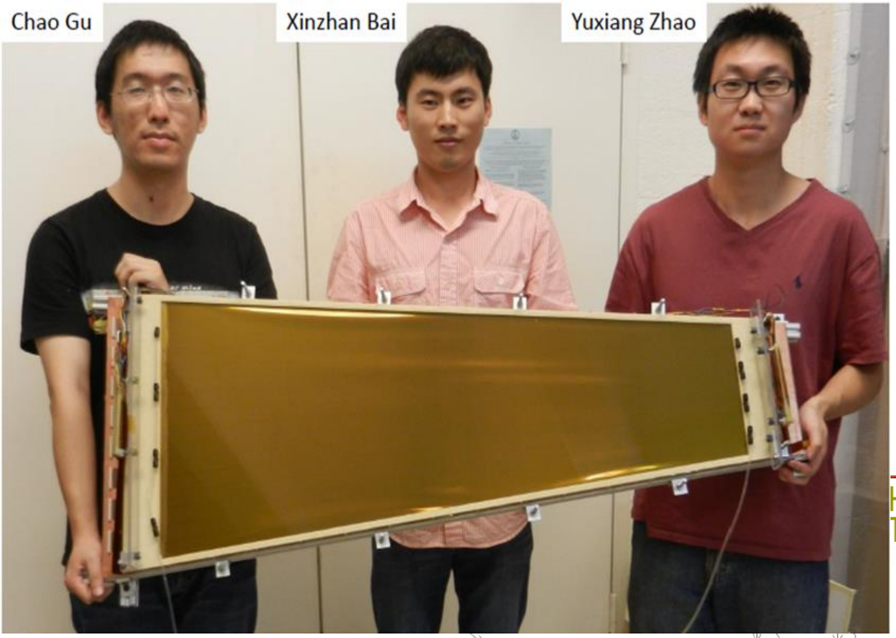

Y.X.Zhao* et al. (Hall A Collaboration)
**Phys. Rev. C 92, 015207 (2015)**

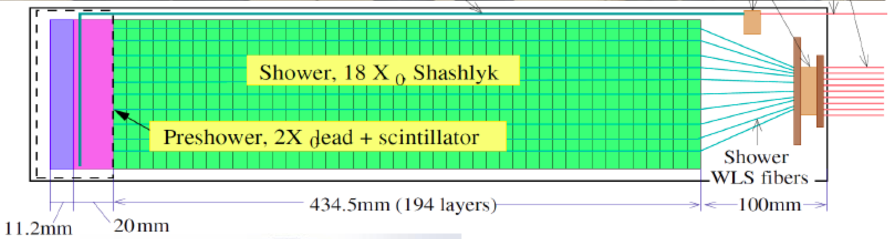


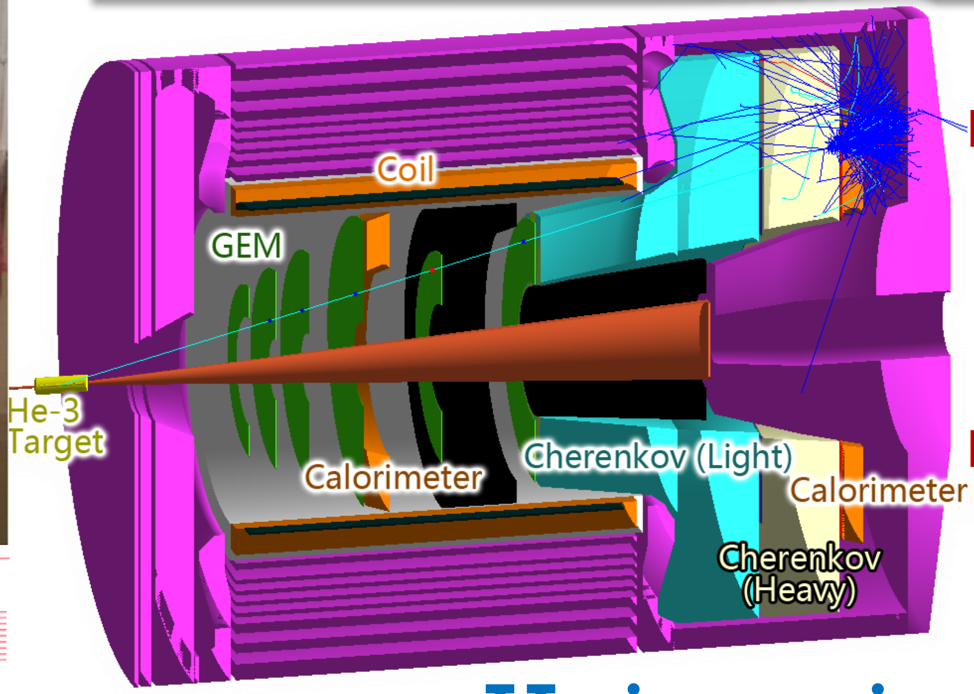
$\int$ TMDs

# The SoLID Spectrometer proposed at JLab

***From exploration to precision study***



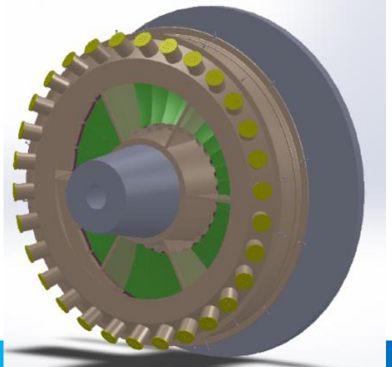




**High Luminosity**

$10^{37}$ without baffles
$10^{39}$ with baffles

**Large acceptance**:
4D-mapping (x, z, pt, Q2)

# Unique in x>0.1 region

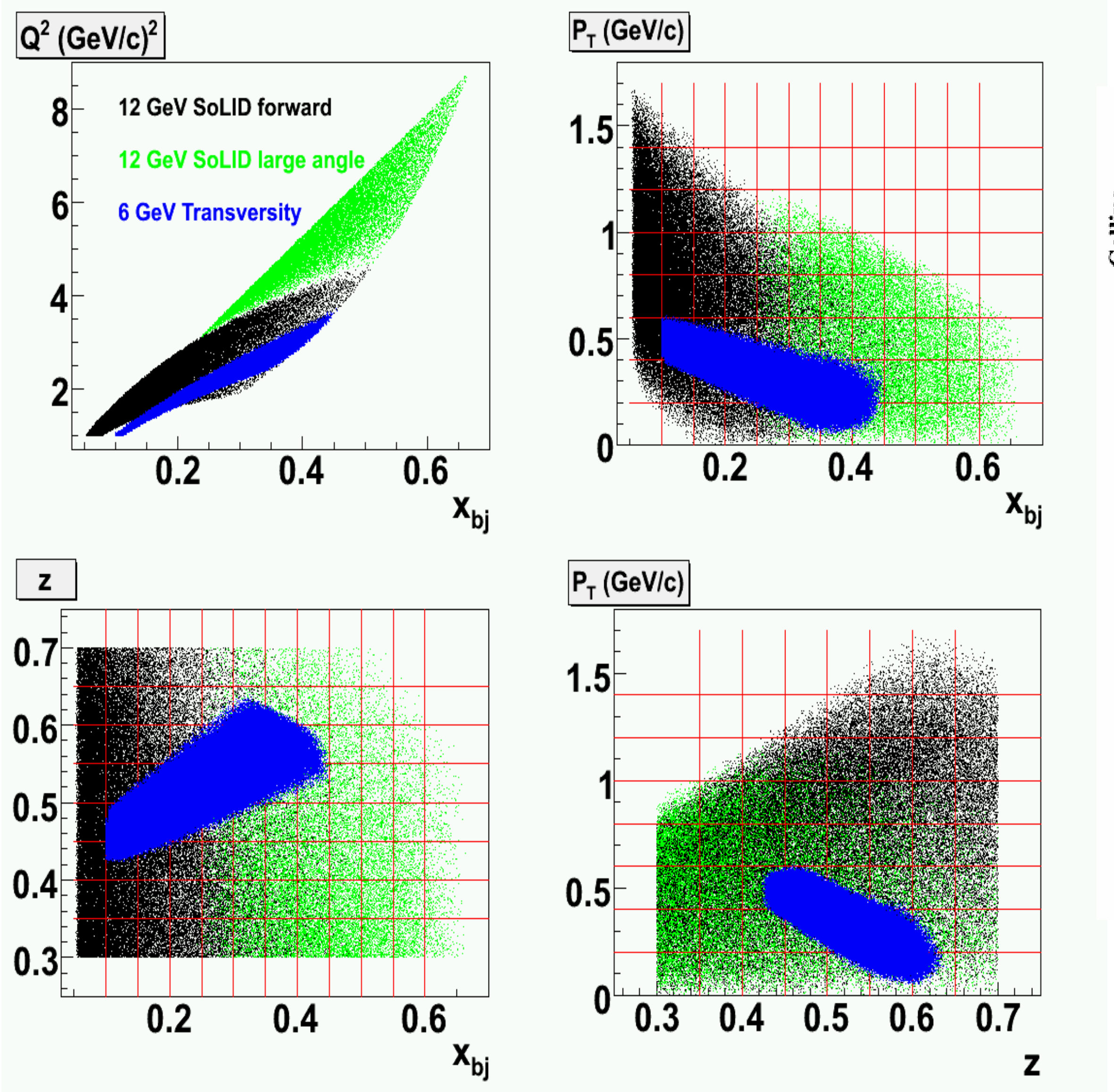


**E12-10-006:** 90 days — Single Spin Asymmetry on Transverse $^3$He

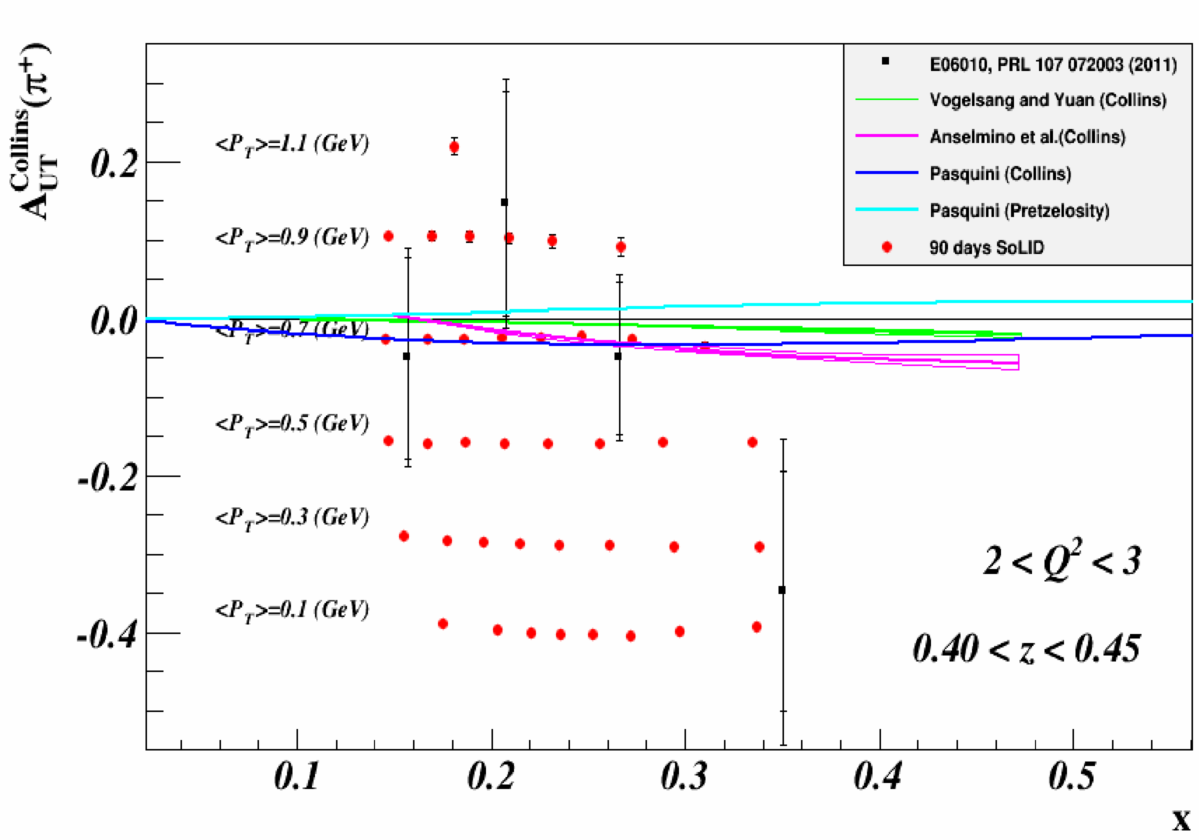
**E12-11-007:** 30 days — Single and Double Spin Asymmetry on $^3$He

**E12-11-108:** 120 days — Single and Double Spin Asymmetries on Transverse Proton

# Phase space coverage




One example on Collins asymmetry

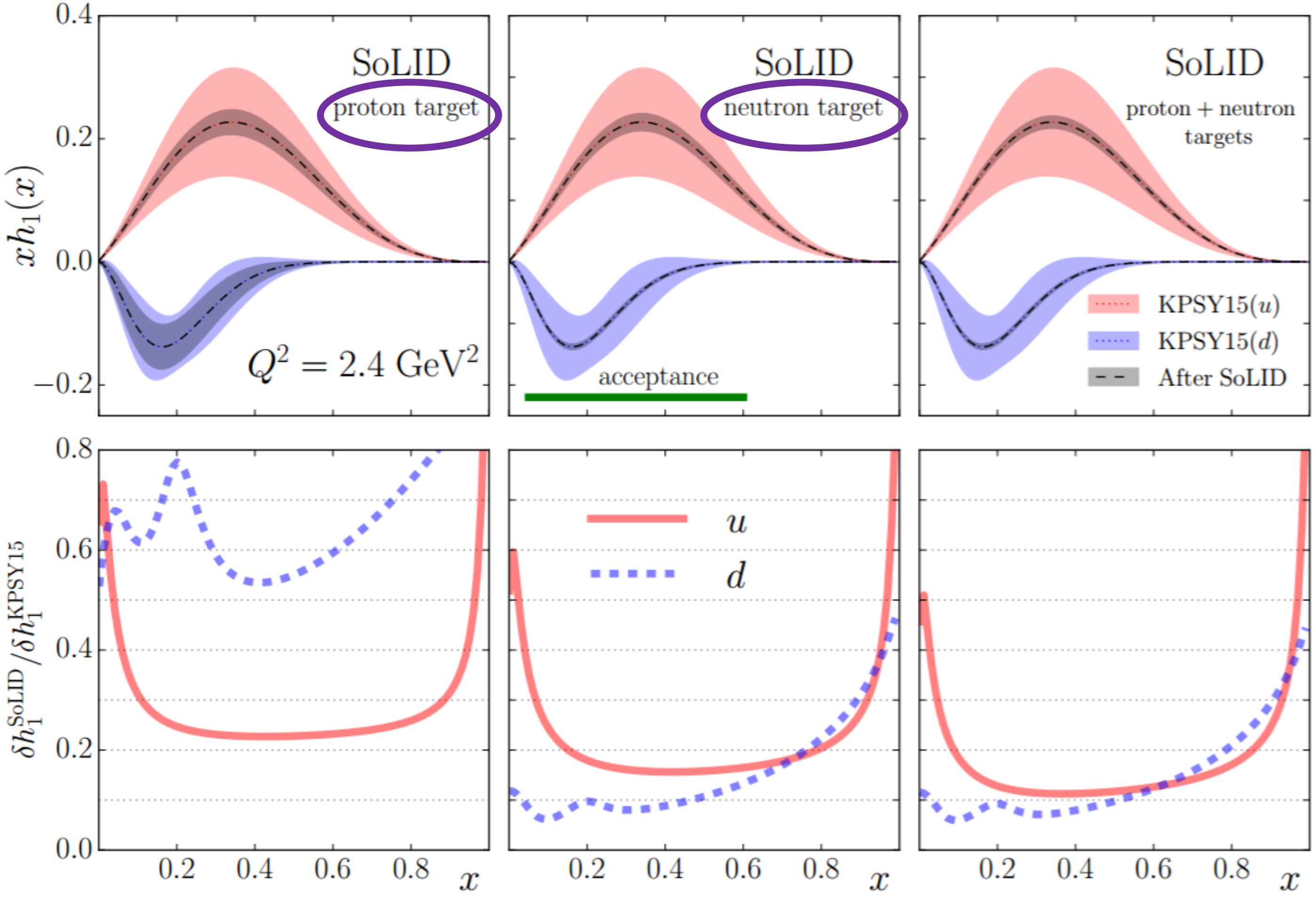


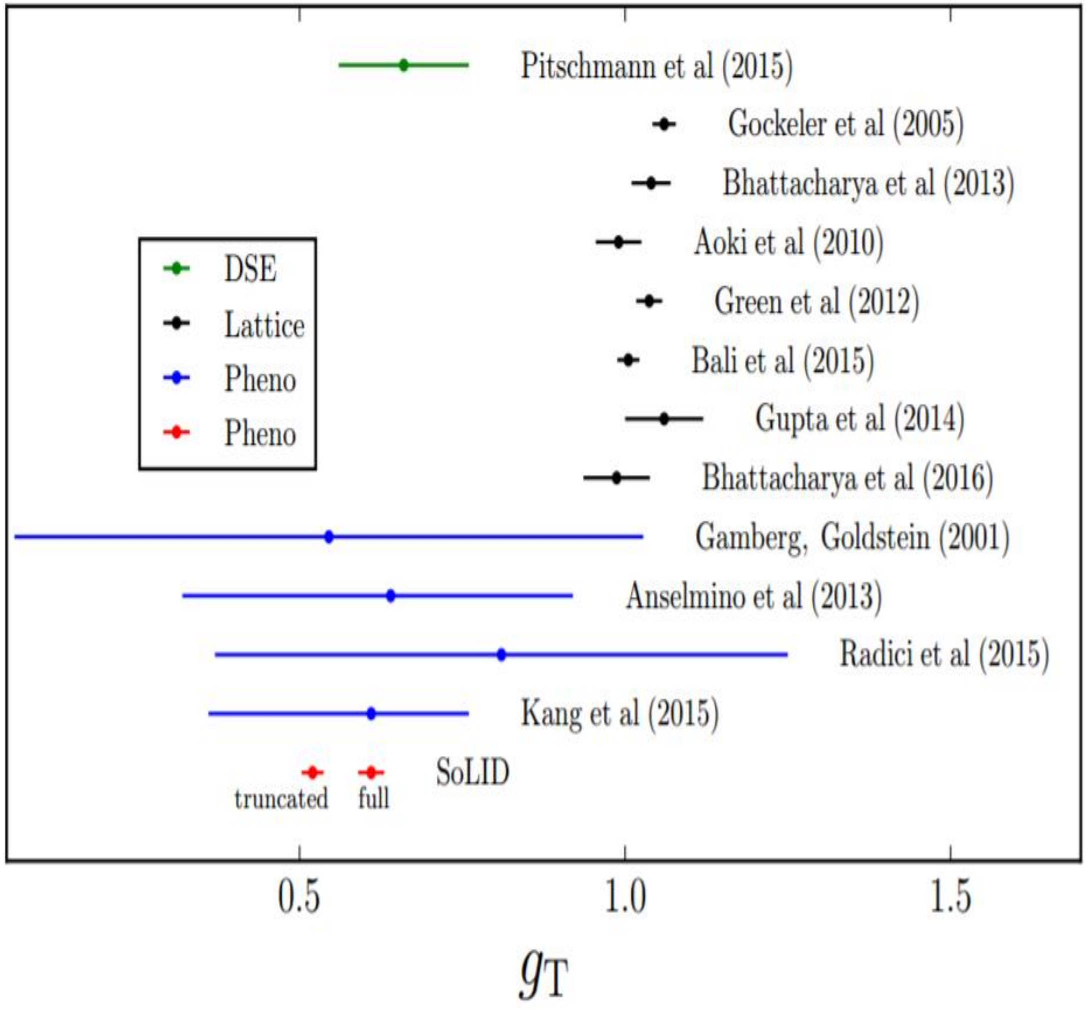

**$P_T$ vs. x for one ($Q^2$, z) bin**
**Total > 1400 data points**

# Transversity and Tensor charge from SoLID

$$g_T^{(\text{truncated})} = +0.55^{+0.018}_{-0.018}\,, \qquad g_T^{(\text{full})} = +0.64^{+0.021}_{-0.021}$$

Z. Ye et al., PLB 767, 91 (2017)



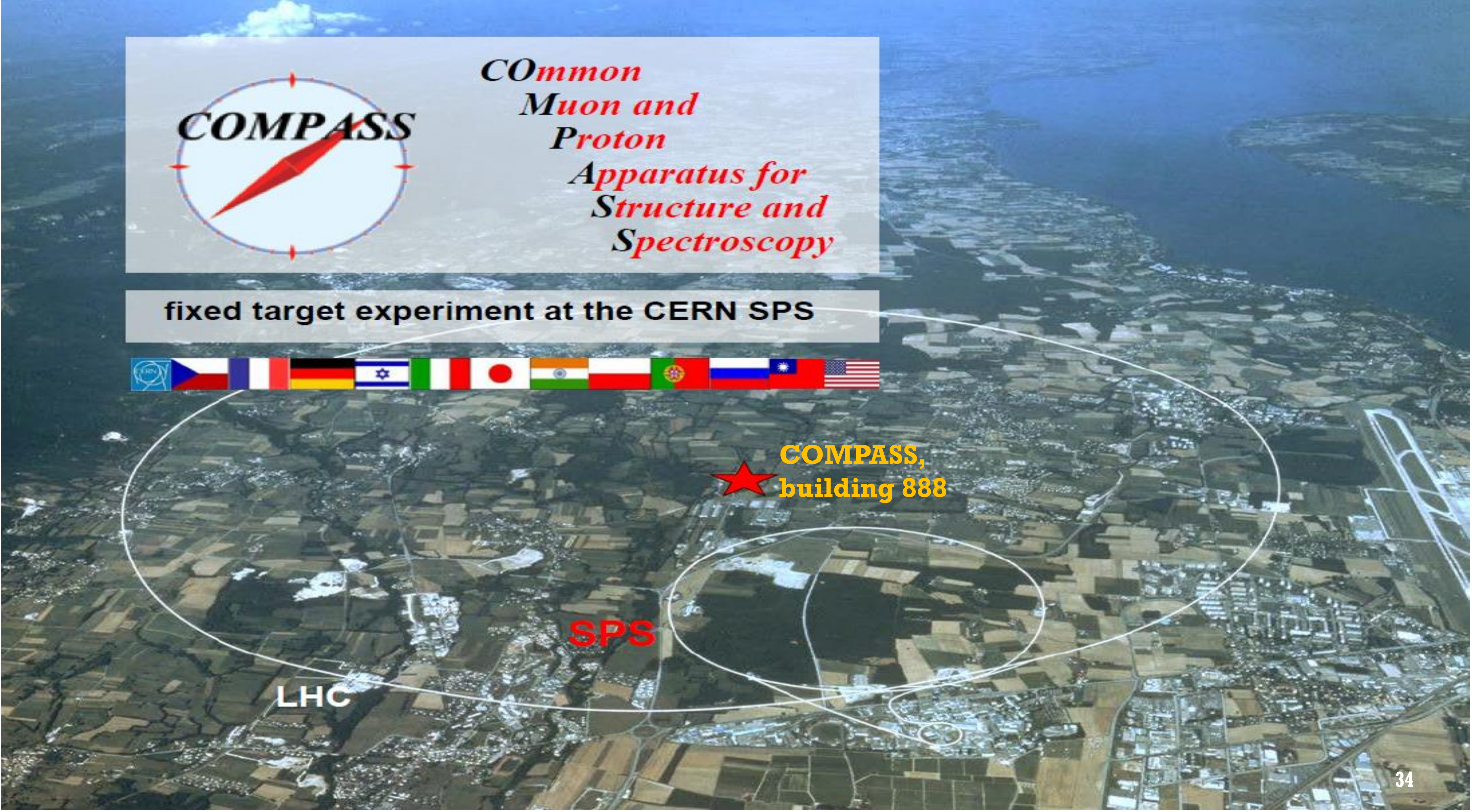

$$g_T = \delta u - \delta d$$

$$\delta q(Q^2) = \int_0^1 dx[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)]$$

COMPASS

*CO*mmon *M*uon and *P*roton *A*pparatus for *S*tructure and *S*pectroscopy

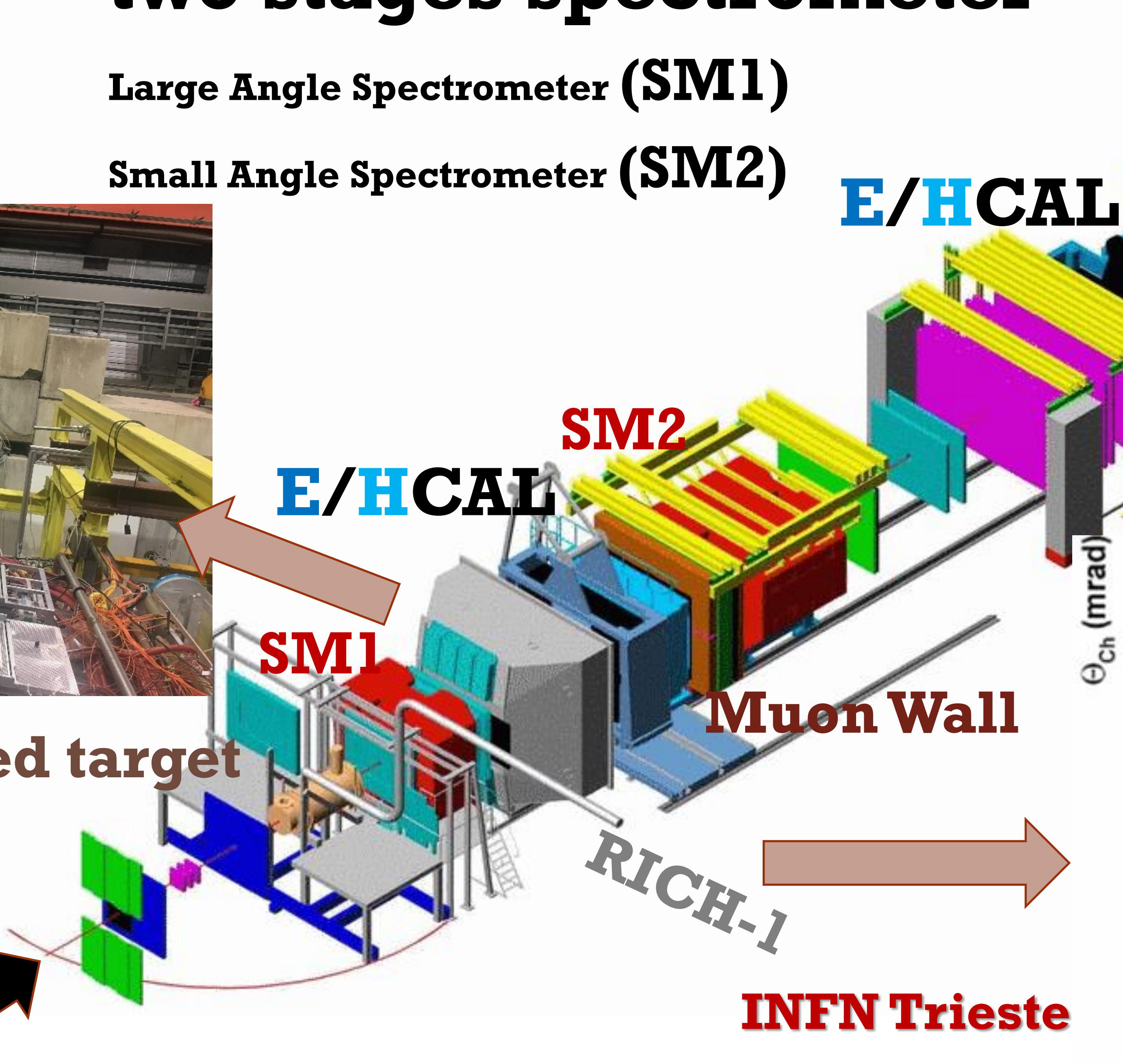
fixed target experiment at the CERN SPS

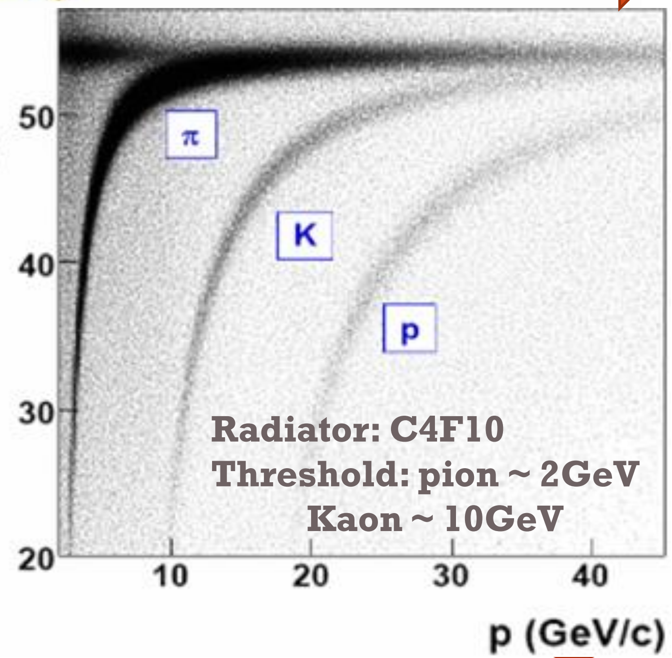


# two stages spectrometer

**Large Angle Spectrometer (SM1)**

**Small Angle Spectrometer (SM2)**

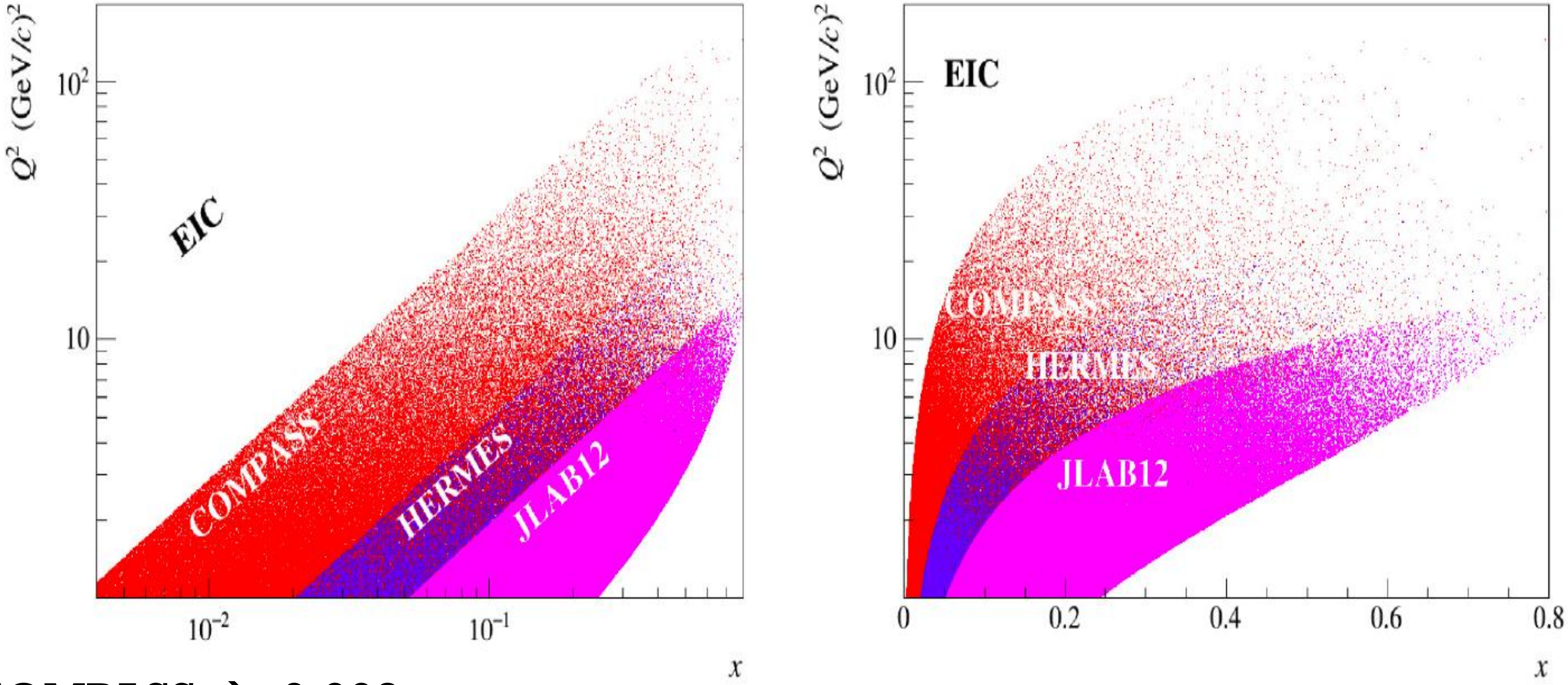


# COMPASS data taking

| | | | | |
|---|---|---|---|---|
| Muon beam | deuteron ($^6LiD$) | | 2002<br>2003<br>2004 | 80% L/20% T target polarization |
| | | Trans. deuteron | | |
| | | | 2006 | L target polarisation |
| | proton ($NH_3$) | | 2007 | 50% L /50% T target polarization |
| Hadron | LH target | | 2008<br>2009 | |
| Muon beam | proton ($NH_3$) | Trans. proton | 2010 | T target polarization |
| | | | 2011 | L target polarization |
| Hadron | Ni target | | 2012 | Primakoff |
| Muon beam | $LH_2$ target | | 2012 | Pilot DVCS & unpol. SIDIS |
| Hadron | Proton ($NH_3$) | | 2014<br>2015 | Pilot DY run<br>DY run (T target polarization) |
| Muon beam | $LH_2$ target | | 2016<br>2017 | DVCS & unpol. SIDIS |
| Hadron | Proton ($NH_3$) | | 2018 | DY run (T target polarization) |

# Kinematic coverage

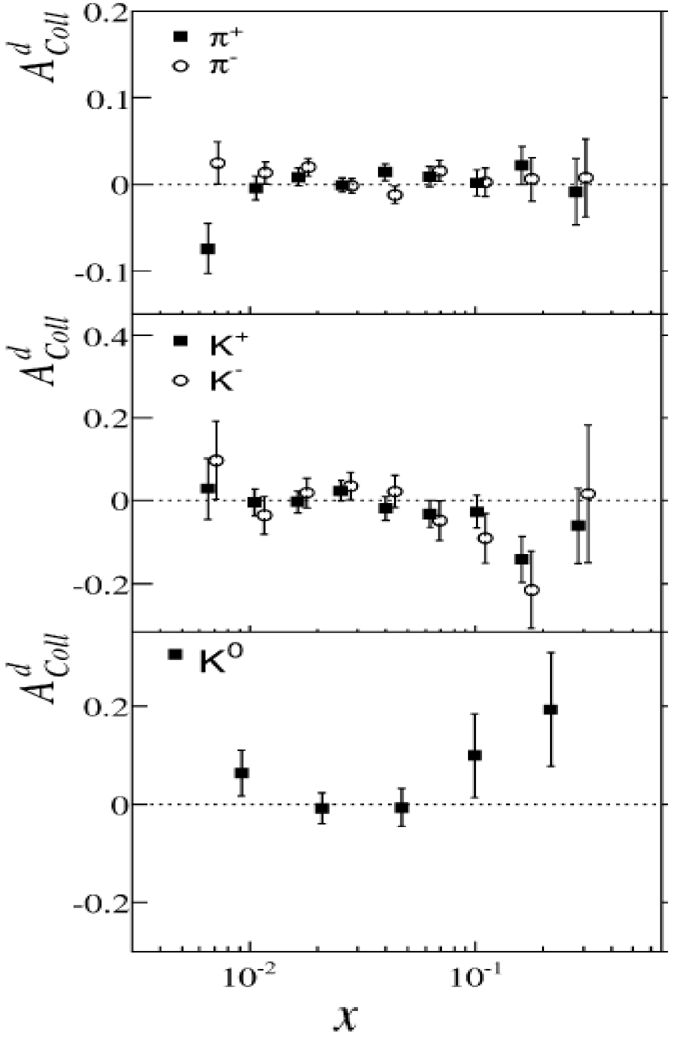



COMPASS → 0.003

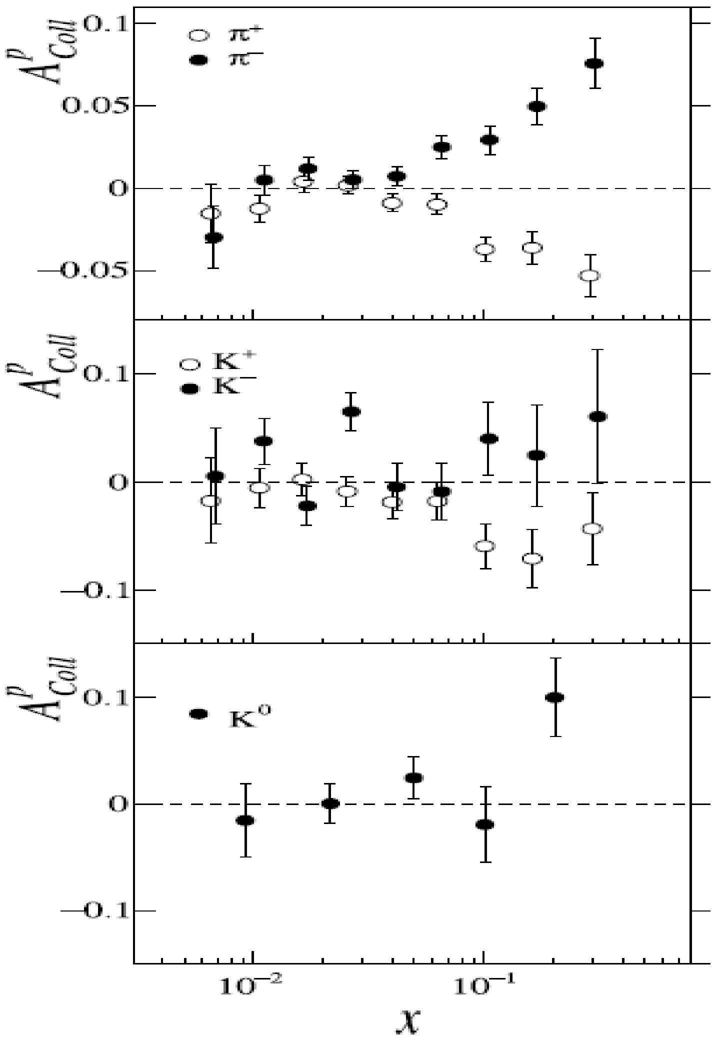
# Collins asymmetries from COMPASS

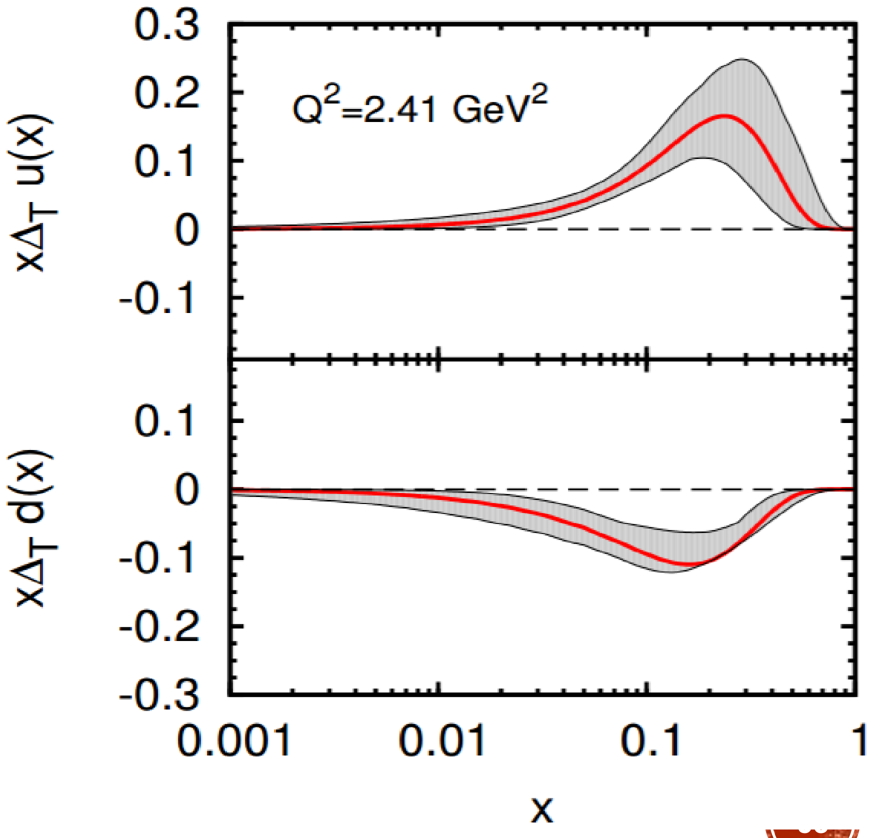
- PRL 94, 202002 (2005)
- NPB 765 (2007) 31-70
- PLB 673 (2009) 127-135
- PLB 692 (2010) 240-246
- PLB 713 (2012)10-16
- PLB 717 (2012) 376-382
- PLB 717 (2012) 383-389
- EPJC (2013) 73:2531
- PLB 736 (2014) 124-131
- PLB 744 (2015) 250-259
- PLB 753 (2016) 406-411

## Deuteron target




## Proton target

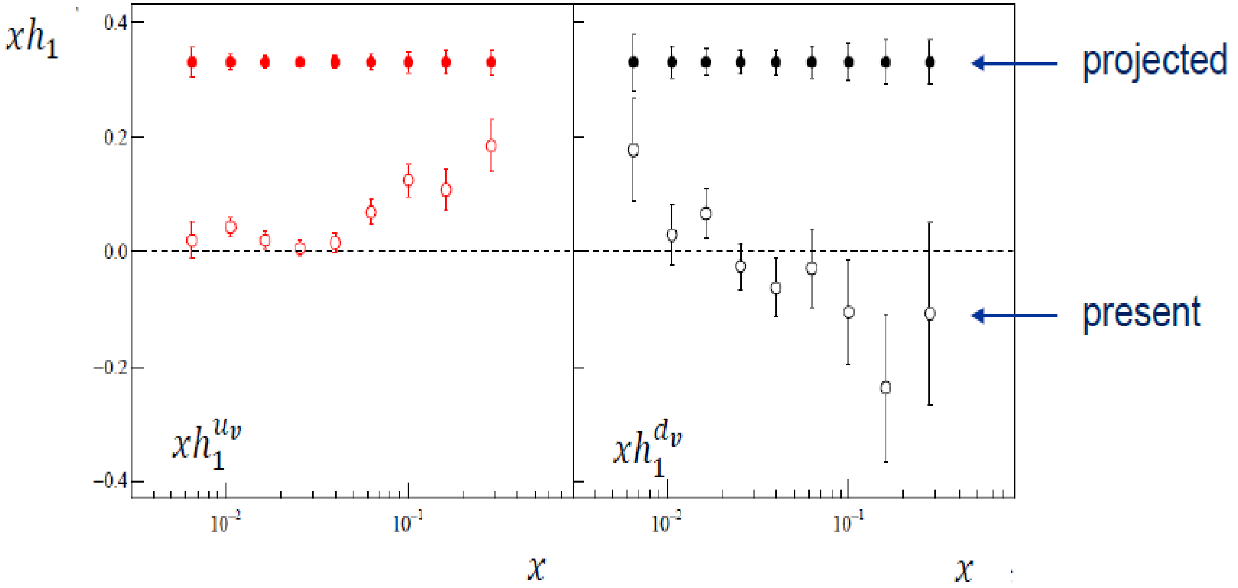


# COMPASS 2021: TMDs study using Deuteron target

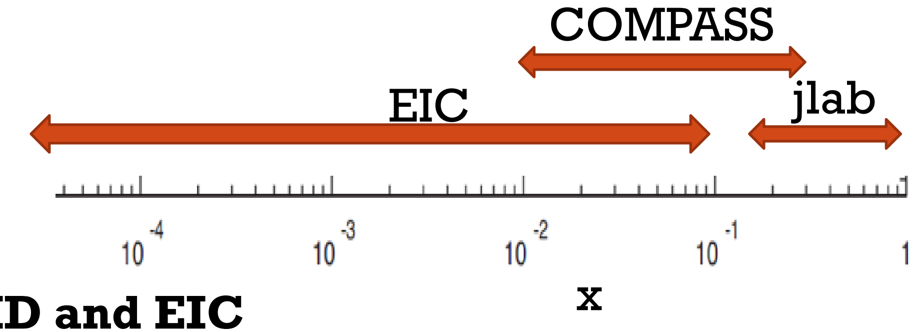
## d-Quark Transversity

**INFN, Sezione di Trieste, e Università di Trieste, Trieste, Italy**
*J. Agarwala, F. Bradamante, A. Bressan, C. Chatterjee, A. Cicuttin, M. Crespo, S. Dalla Torre, S. Dasgupta, A. Kerbizi, S. Levorato, N. Makke, A. Martin, A. Moretti, G. Sbrizzai, A. Szabelski, S. Tessaro, F. Tessarotto, Y. Zhao*




Tensor charge   x range: 0.008 --- 0.210

| | $\delta_u = \int_{\Omega_x} dx h_1^{u_v}(x)$ | $\delta_d = \int_{\Omega_x} dx h_1^{d_v}(x)$ | $g_T = \delta_u - \delta_d$ |
|---|---|---|---|
| present | 0.218 ± 0.036 | -0.206 ± 0.110 | 0.424 ± 0.093 |
| projected | 0.218 ± 0.025 | -0.206 ± 0.043 | 0.424 ± 0.054 |

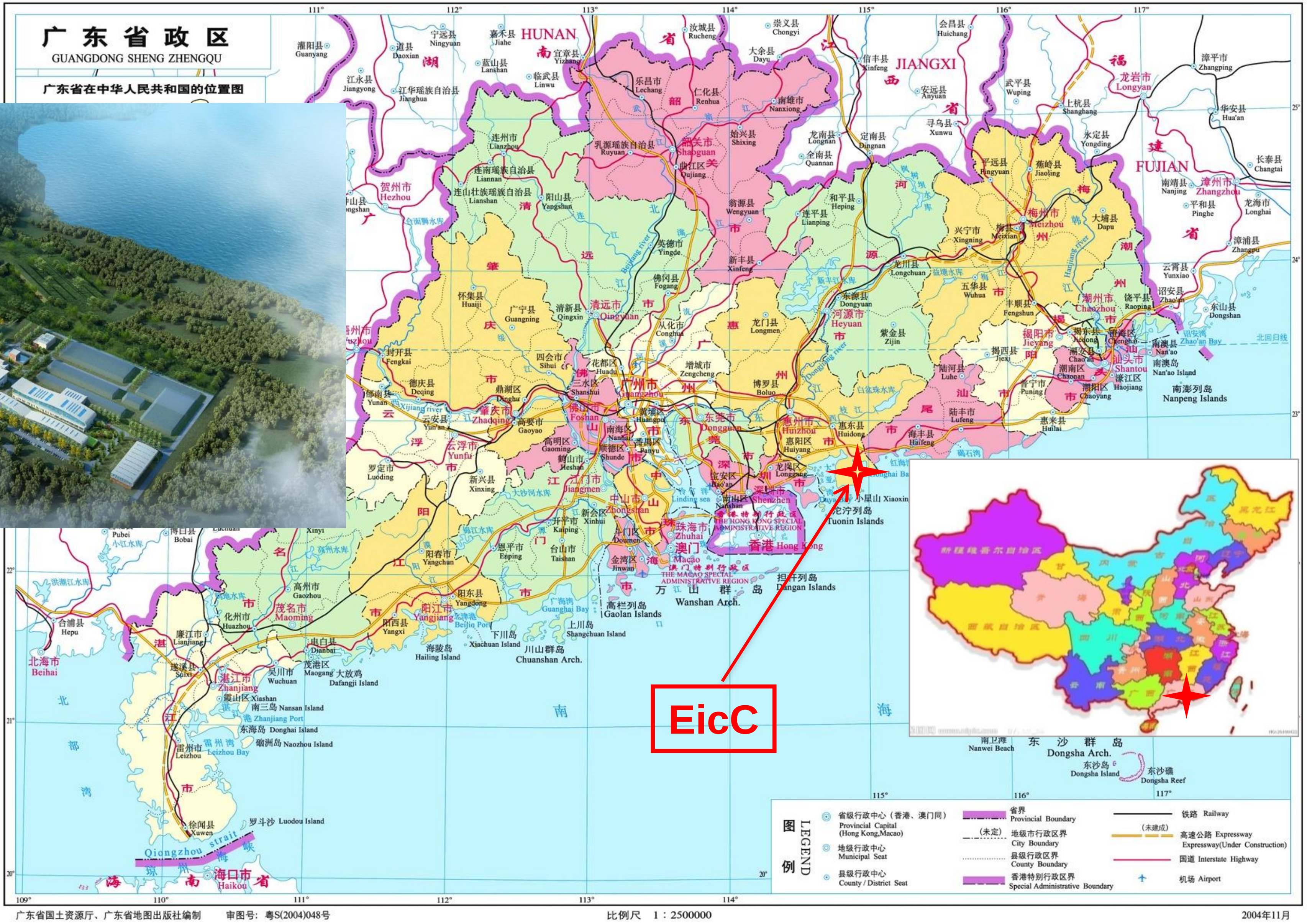



**To complete the SIDIS program at COMPASS,**
**full set of data on P and N will be available before SoLID and EIC**
**To pave the road for a future EIC in physics and PID beyond 8 GeV (ToF limit)**

# Outline

- Introduction of nucleon spin structure study
- Transverse spin structure study
  - ✓ **TMD** physics (**T**ransverse **M**omentum **D**ependent PDFs)
  - ✓ Experiments: JLab Hall A (US), COMPASS (CERN)
- **Electron-Ion Collider in China (EicC)**
- Summary

# Where we are talking about…Huizhou in Guangdong province




Coast city

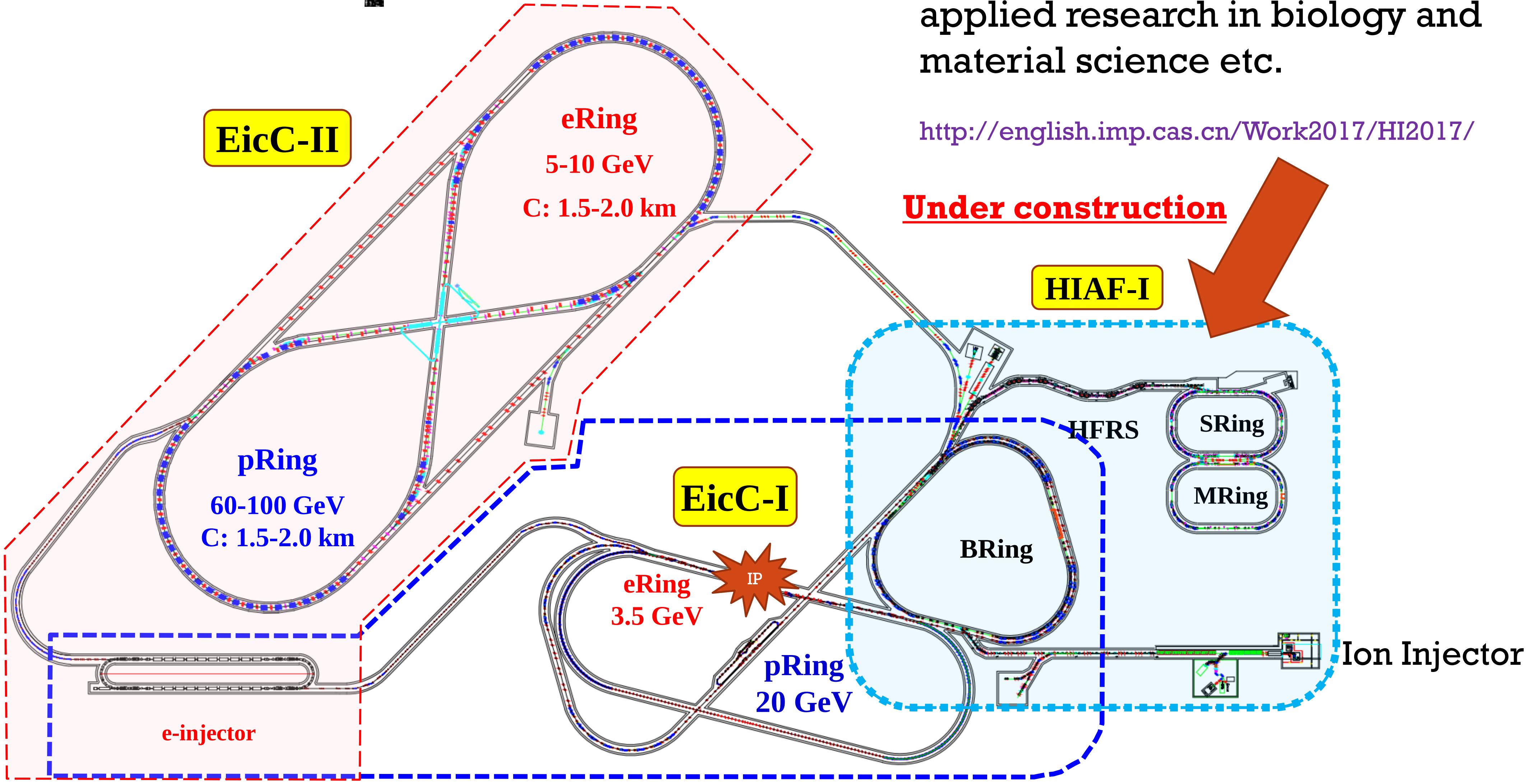
Nice weather

Strong support from local government

# Accelerator complex overview

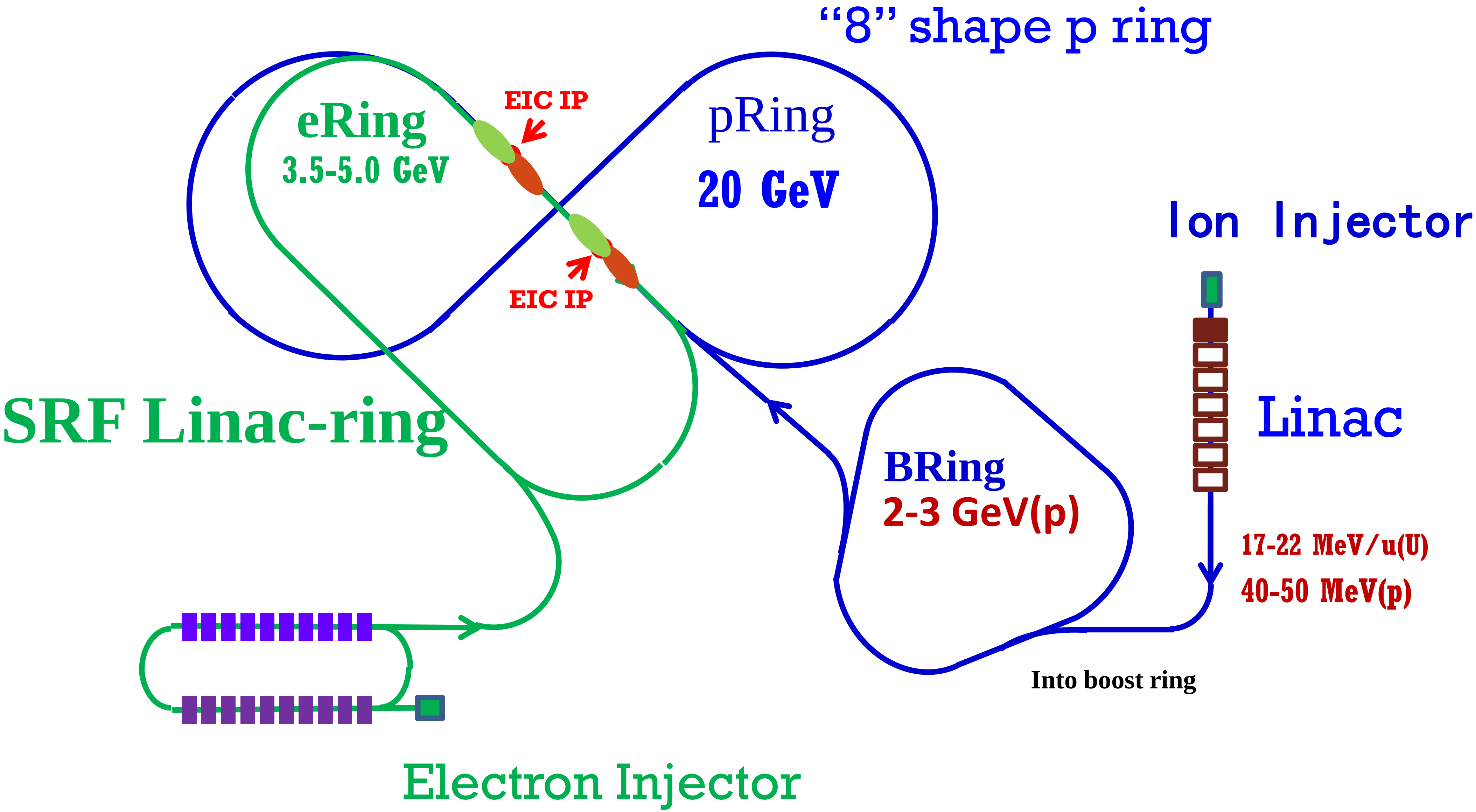
High intensity ion beams for atomic physics, nuclear physics, applied research in biology and material science etc.

http://english.imp.cas.cn/Work2017/HI2017/



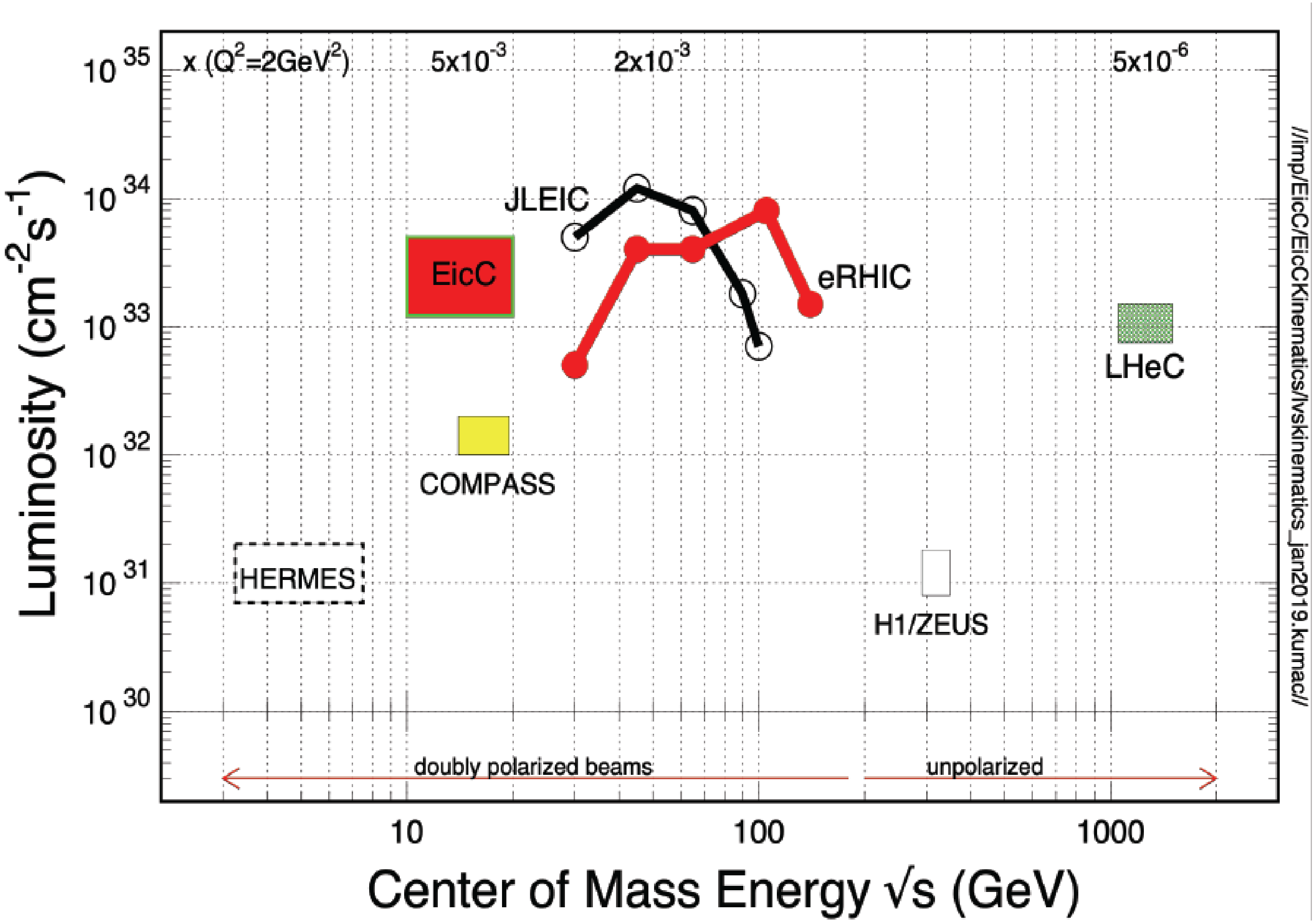

High-Intensity Heavy Ion Accelerator Facility (HIAF)

# EicC-I beam



"8" shape p ring
eRing
3.5-5.0 GeV
EIC IP
EIC IP
pRing
20 GeV
Ion Injector
SRF Linac-ring
BRing
2-3 GeV(p)
Linac
17-22 MeV/u(U)
40-50 MeV(p)
Into boost ring
Electron Injector

# EicC beam energy and luminosity




**EicC:**

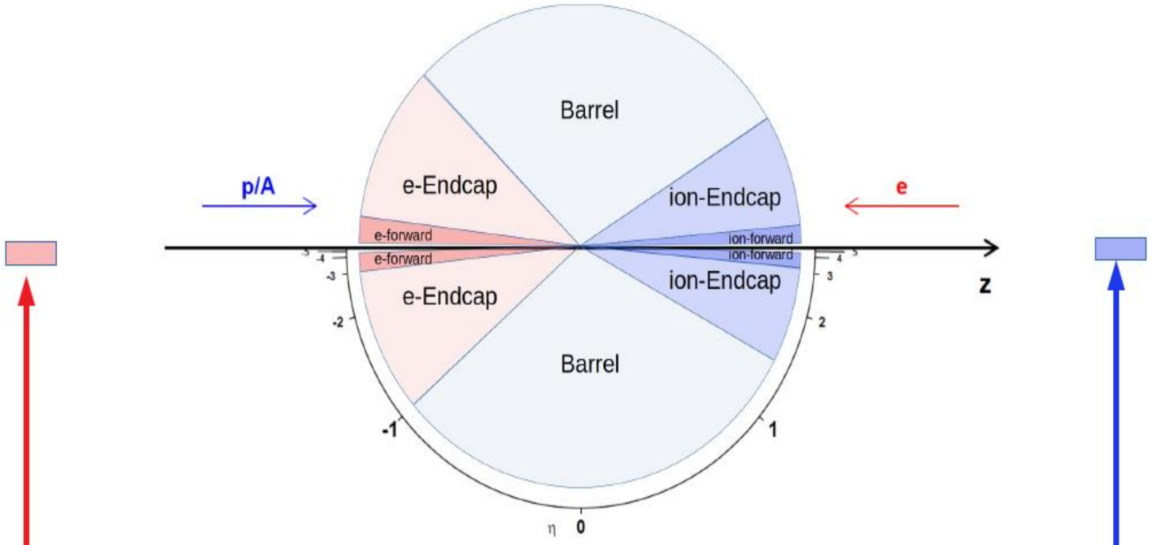
**Beam energy: 3.5 GeV e + 20 GeV P**

**Polarization: e 80%, P 70%**

**Inst. Lumi.:** $(2\text{-}4)\times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$

**Also D, He-3, heavy nuclear beam**

# EicC detector conceptual design




General requirements

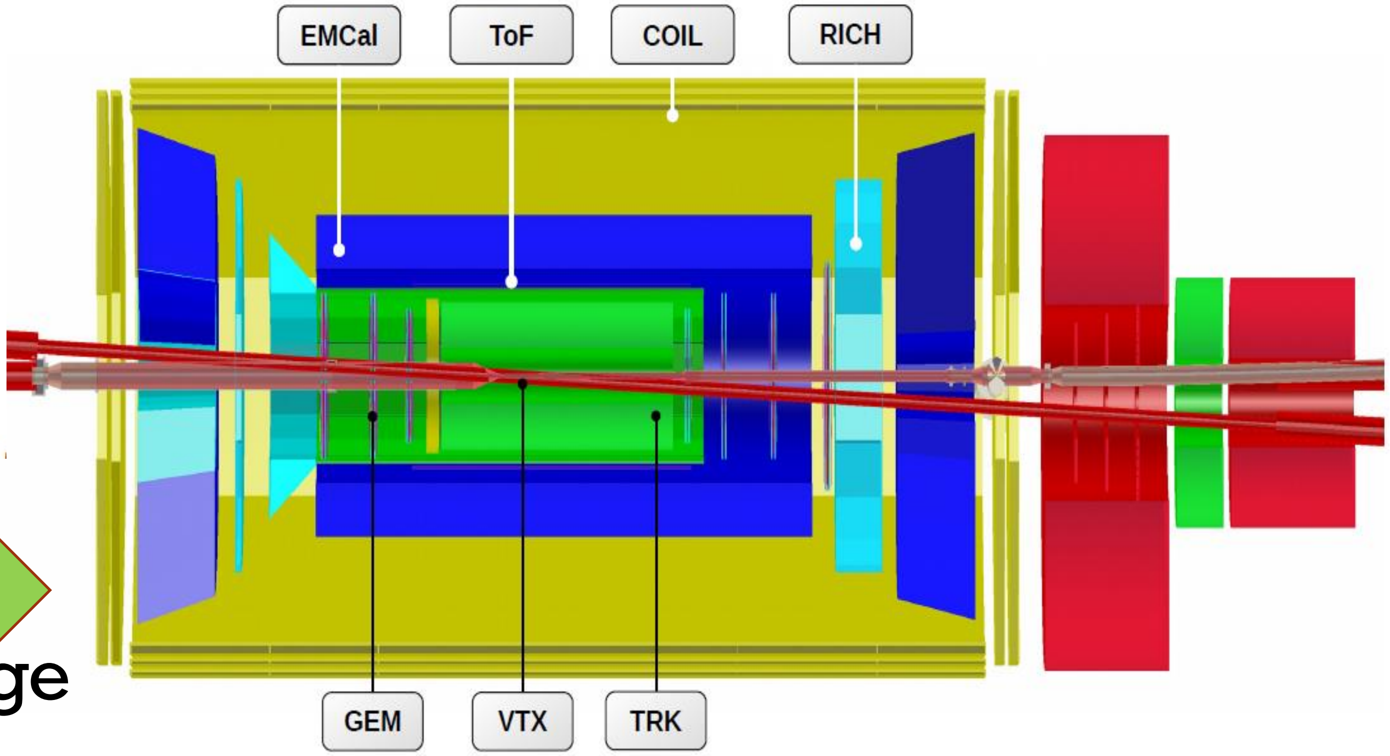
For electron:

For $Q^2 > 1 GeV^2$, $-3 < \eta < 2$ is sufficient.

For lower $Q^2$, a dedicated detector

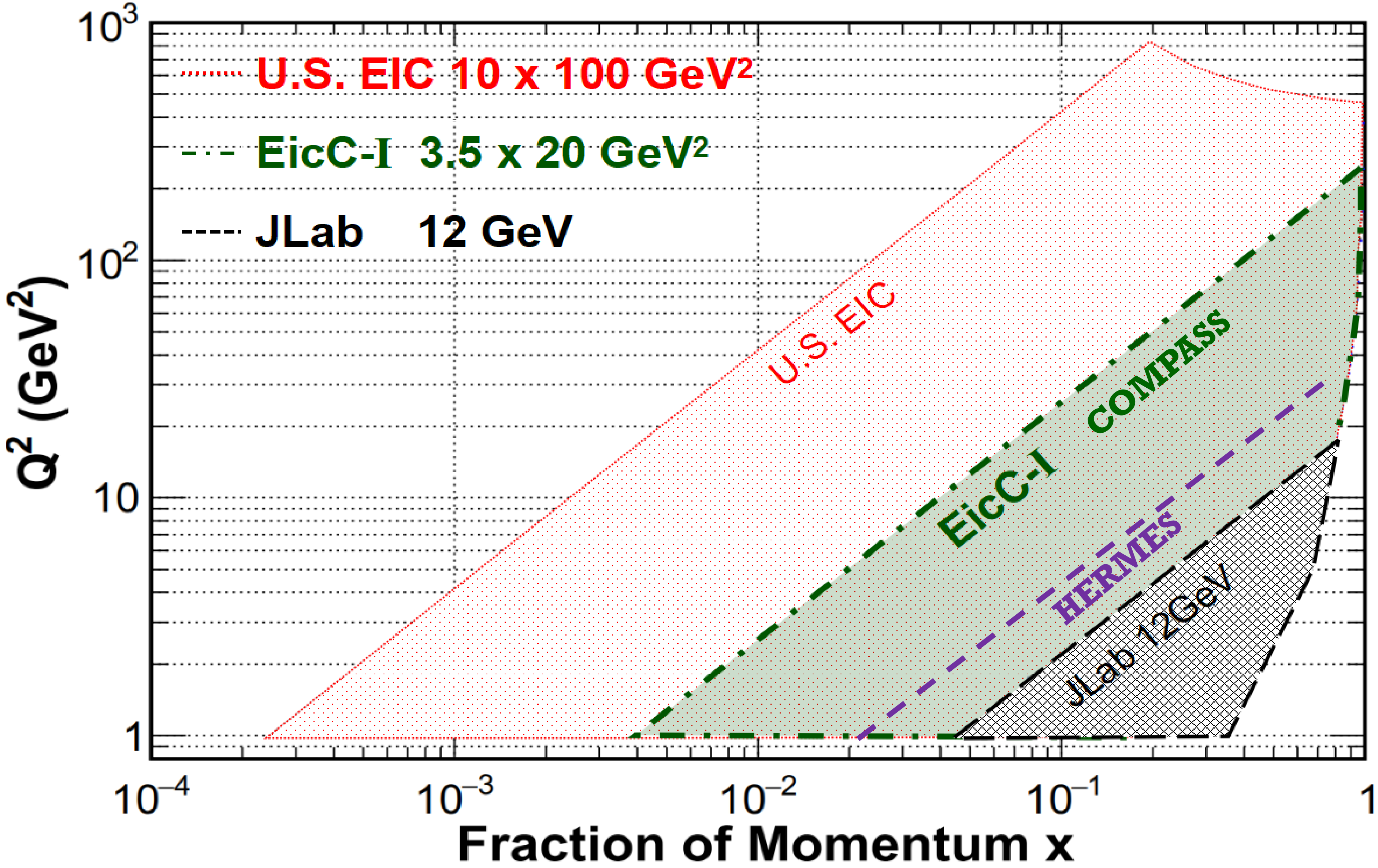
For hadrons:
central detector: $-3 < \eta < 3.5$
- $-3<\eta<1$ : π/K/p separation < 5 GeV/c
- $1<\eta<3\sim4$ : π/K/p separation < 10~15 GeV/c

$\eta>4$ : detectors in the far-forward region.

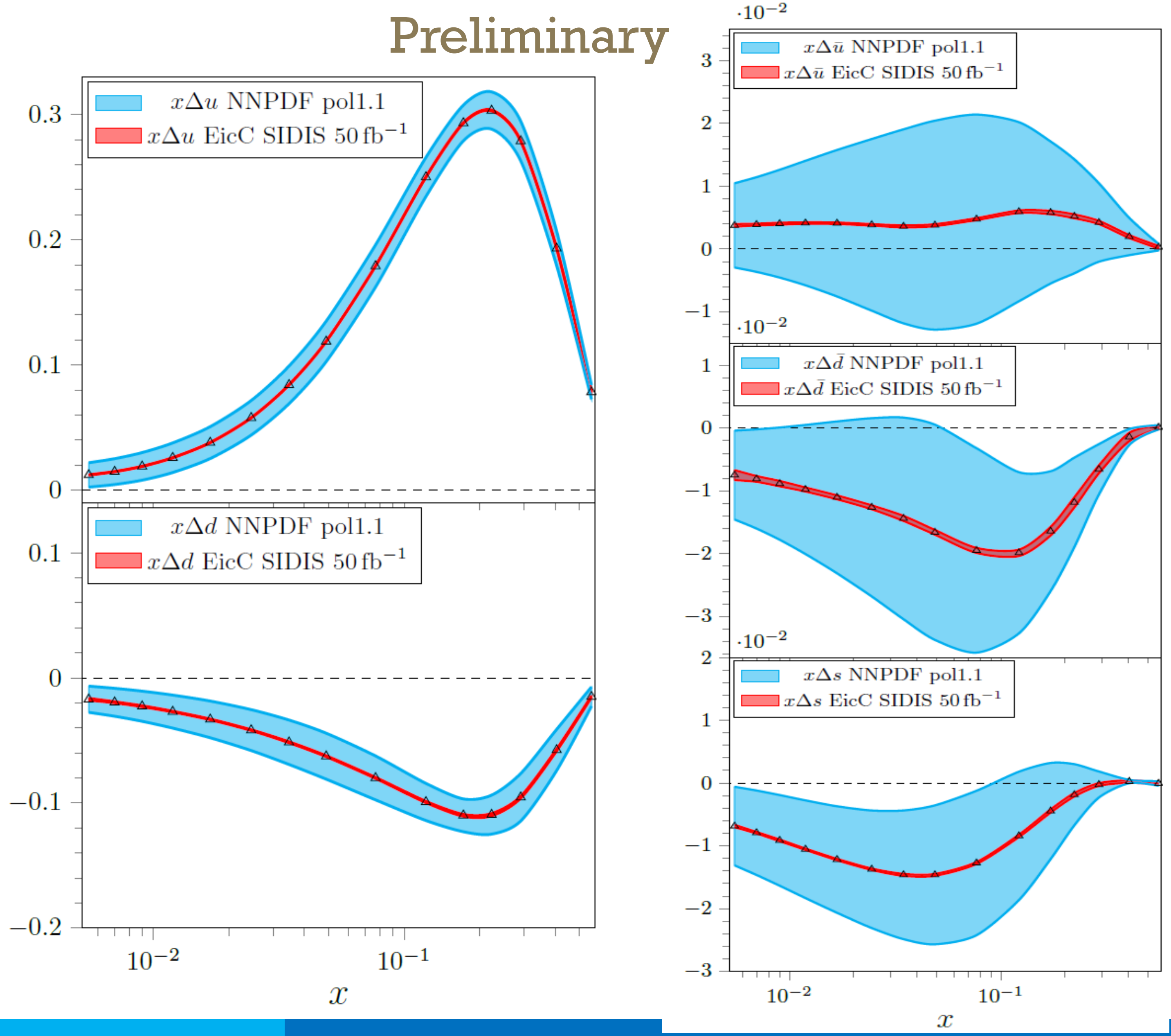



Very first design,
Still in the very…very… early stage
Detector options are open

# An Electron-Ion Collider proposed in China (EicC)



# Projections on helicity distributions (EicC)




## LO analysis

EicC SIDIS data:

- Pion(+/-), Kaon(+/-)
- **ep:** 3.5 GeV X 20 GeV
- **eHe-3:** 3.5 GeV X 40 GeV
- Pol.: e(80%), p(70%), He3(70%)
- Lumi:
  - ep 50 fb-1
  - eHe3 50 fb-1

Fragmenation functions used: DSS

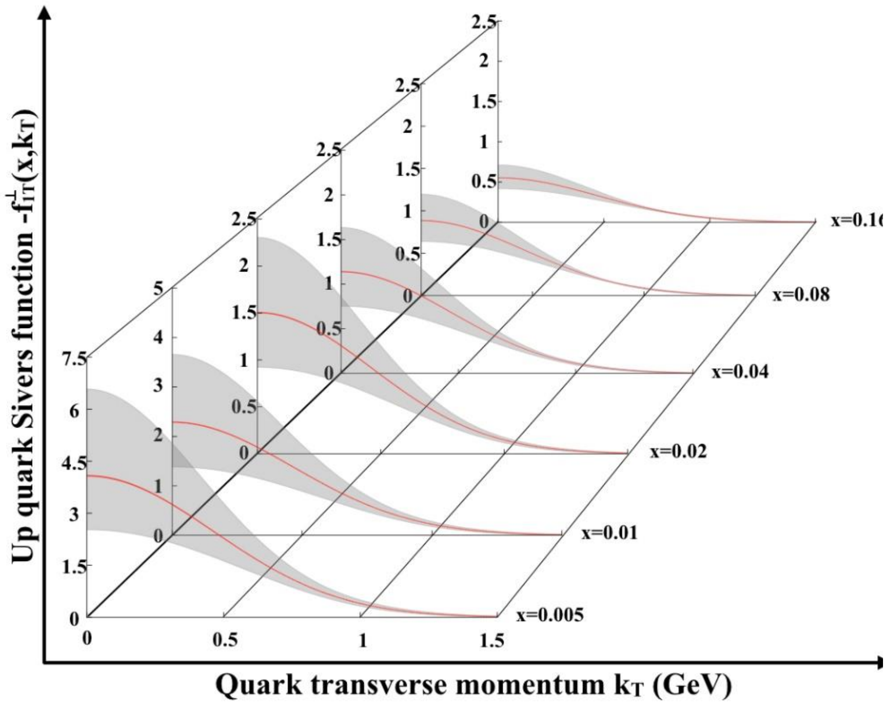
# EicC projections on Sivers TMDs

EicC SIDIS data:
- ✓ e x p 3.5GeV x 20 GeV
- ✓ e x he3 3.5GeV x 40 GeV(He3)

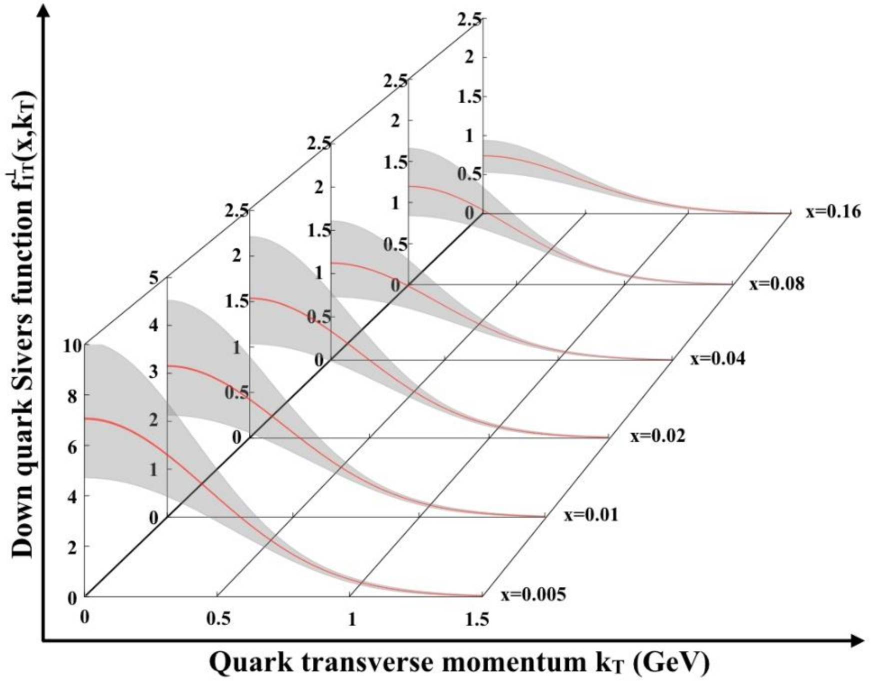
Lumi:
- ✓ Ep 50 $fb^{-1}$
- ✓ eHe3 50 $fb^{-1}$ (per nucleus)

Pion, Kaon SIDIS measurements

U quark sivers EicC VS world data




d quark




Preliminary

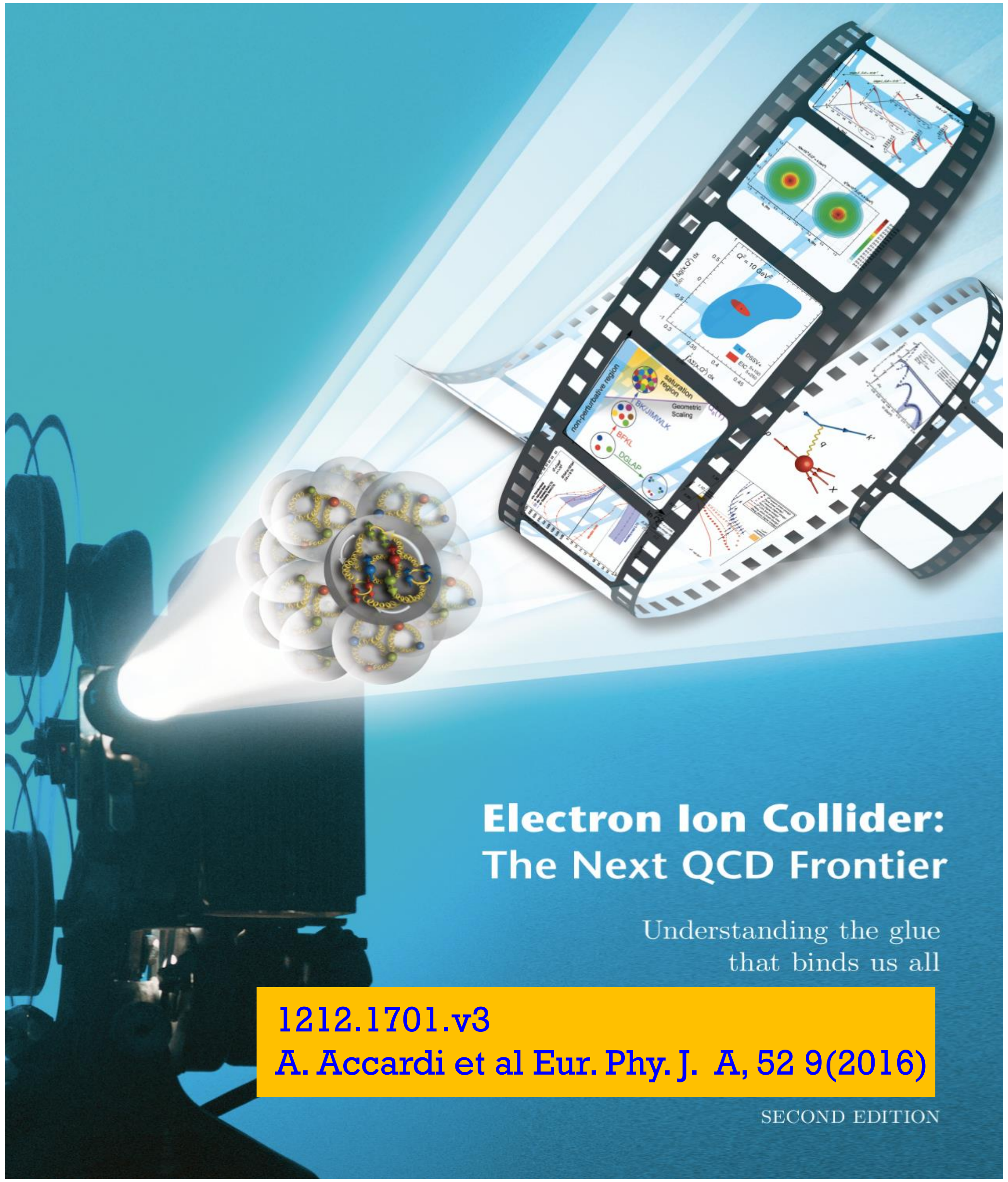
## LO study

Only u,ubar,d,dbar included

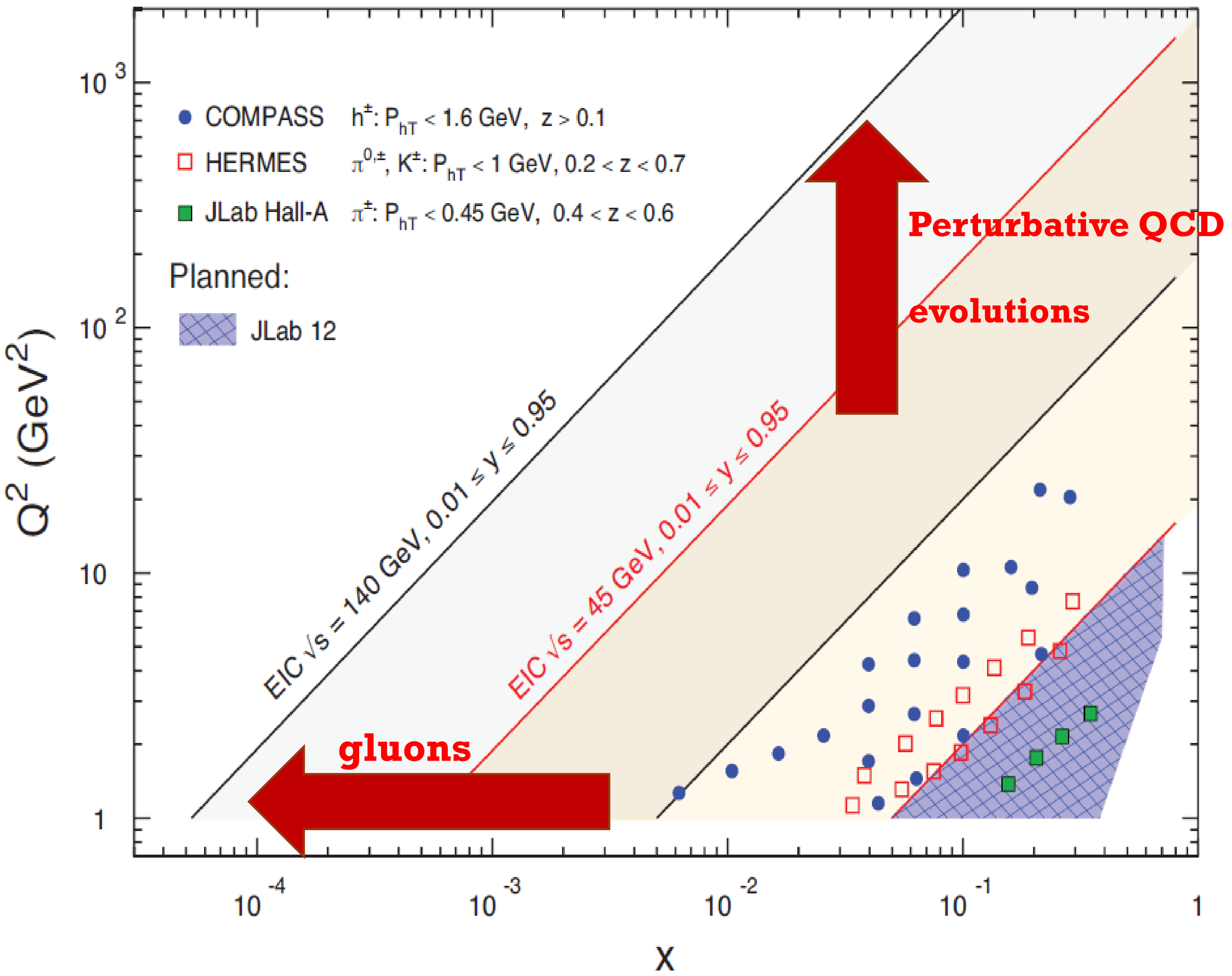
Current & target fragmentation un-distinguished clearly yet:

$W > 2.3$ GeV
$W' > 1.6$ GeV
$0.3 < z < 0.7$
$Q^2 > 1$ $GeV^2$

# US Electron-ion Collider



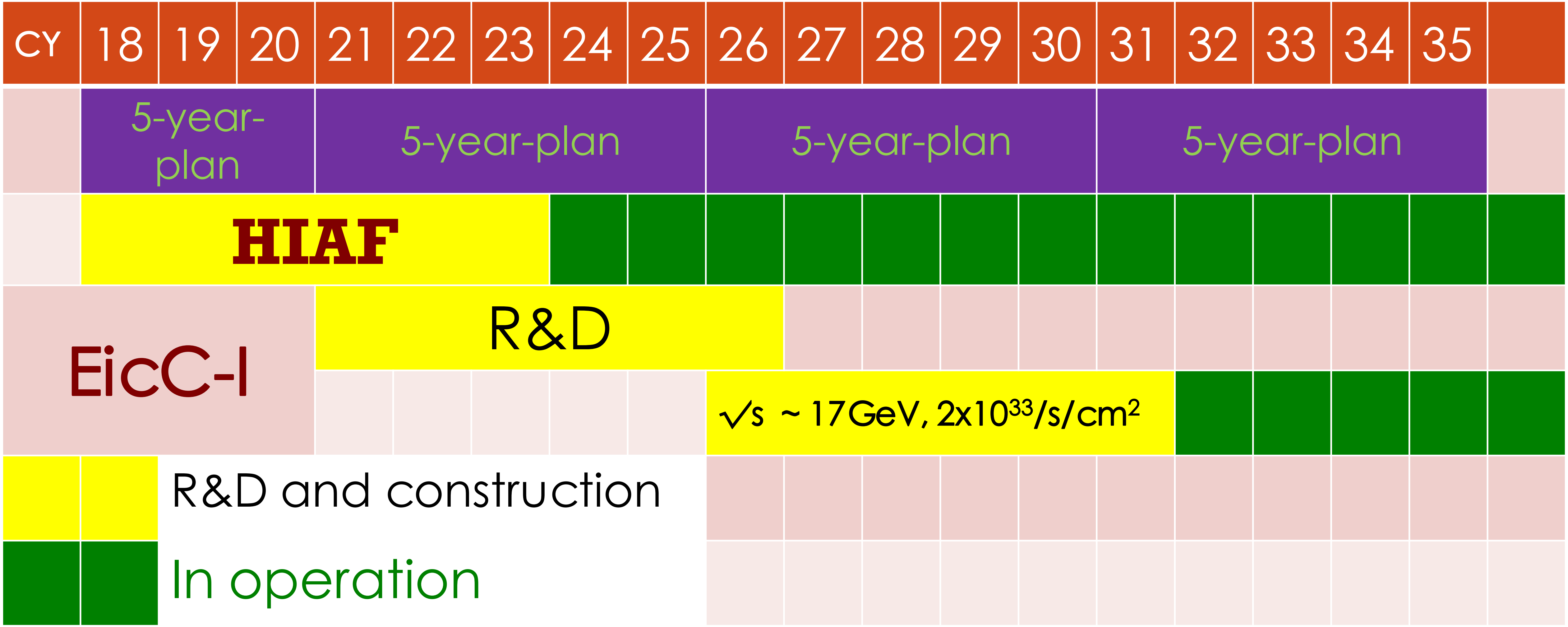

1212.1701.v3
A. Accardi et al Eur. Phy. J. A, 52 9(2016)



# Summary

- Spin physics is an interesting field (another frontier, EIC is coming to be real)
- TMDs:3D imaging
  - ➢ Transverse imaging, access quark orbital angular momentum, confined motion of quarks, QCD dynamics
- **We are now experiencing** the transition from exploratory study to high precision study in multi-dimensions
  - ➢ large acceptance and high luminosity
- **Within 3 years:** COMPASS will probably finish the data collection for TMDs study, $0.008<x<0.2$ with proton and deuteron target
- **Around 2025:** SoLID data will probably be available, the most powerful measurement in valence region ($x>0.1$)
- **EicC: flavor separations in sea quark regions, high precision measurements for 1D helicity, TMDs and GPDs!**

# Timeline for the EicC




EicC white paper will be ready by the end of 2019 → put project in line in the next 5-year-plan

# Thanks for your attention

# Backups

# Message to be taken away with you

1. SIDIS: one of the most effective way to investigate the structure of the nucleon
2. SIDIS on transversely polarized target gives access to TMD PDFs
3. A relatively **NEW field**, first experimental data only in 2005 by HERMES and COMPASS
4. Most of the data have been collected on proton targets
5. Only few data exist on a Deuteron target (COMPASS, 2002-2004 runs) and a He-3 target at Jlab Hall A (my Ph.D experiment)

6. EicC in China is moving forward step by step, an opportunity to take leadership in high/medium energy nuclear physics all over the world … … welcome to join us!

# SIDIS on transversely polarized target

- **JLab6**(n only, over)
- **HERMES**(p only, over)
- **COMPASS**(d 2002,2003, 2004 <u>25%</u> p 2007 <u>50%</u>, 2010 <u>100%</u>)

- **COMPASS 2021,d, probably last SIDIS experiment at COMPASS, full year of running**
- **JLab12**(p, d, He-3 > 2019, SoLID data ~ 2025)

- **EicC (p, d, He-3 White paper to be submitted to the government by the end of this year)**
- **US EIC** (p, d, He-3 > 2025)

# Structure functions and (unpol./pol.)PDFs

## Experimental observables

Unpolarized cross section

$Q^2 << M_Z^2$

$F_1$ , $F_2$

Unpolarized structure functions

**Quark-Parton Model QPM**

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

**Callan-Gross equation**

## PDFs

Unpolarized pdfs

$f_1(x)=q^{\uparrow}(x) + q^{\downarrow}(x)$

$$F_2(x) = x\sum_q e_q^2 (f_1^q(x) + f_1^{\bar{q}}(x))$$

$A_{LL}$ , $A_{LT}$ $(A_1, A_2)$

$Q^2 << M_Z^2$

Polarized structure functions

$g_1$ , $g_2$

**QPM**

No $g_2$ interpretation in QPM

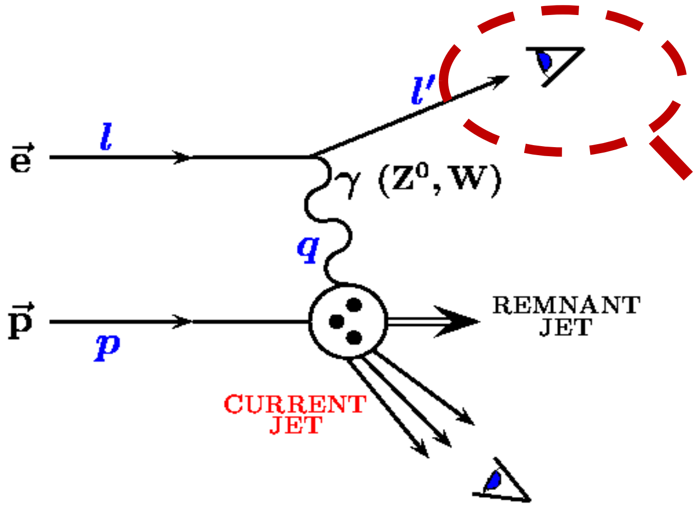
Polarized pdfs

Helicity distribution

$\Delta q=q^{\uparrow}(x) - q^{\downarrow}(x)$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \Delta q(x).$$

# Structure functions and PDFs : Unpolarized case




$$\frac{d\sigma}{dx\,dy} = \frac{e^4}{4\pi^2 Q^2} \cdot \left\{ \frac{y}{2} \cdot F_1 + \frac{1}{2xy} \cdot \left( 1 - \frac{y}{2} - \frac{y^2}{4} \cdot \gamma^2 \right) \cdot F_2 \right\}$$

Only scattered leptons are detected

**Experimental observables**

Unpolarized cross section

$Q^2 << M_Z^2$

$F_1$ , $F_2$

Unpolarized structure functions

**Quark-Parton Model QPM**

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

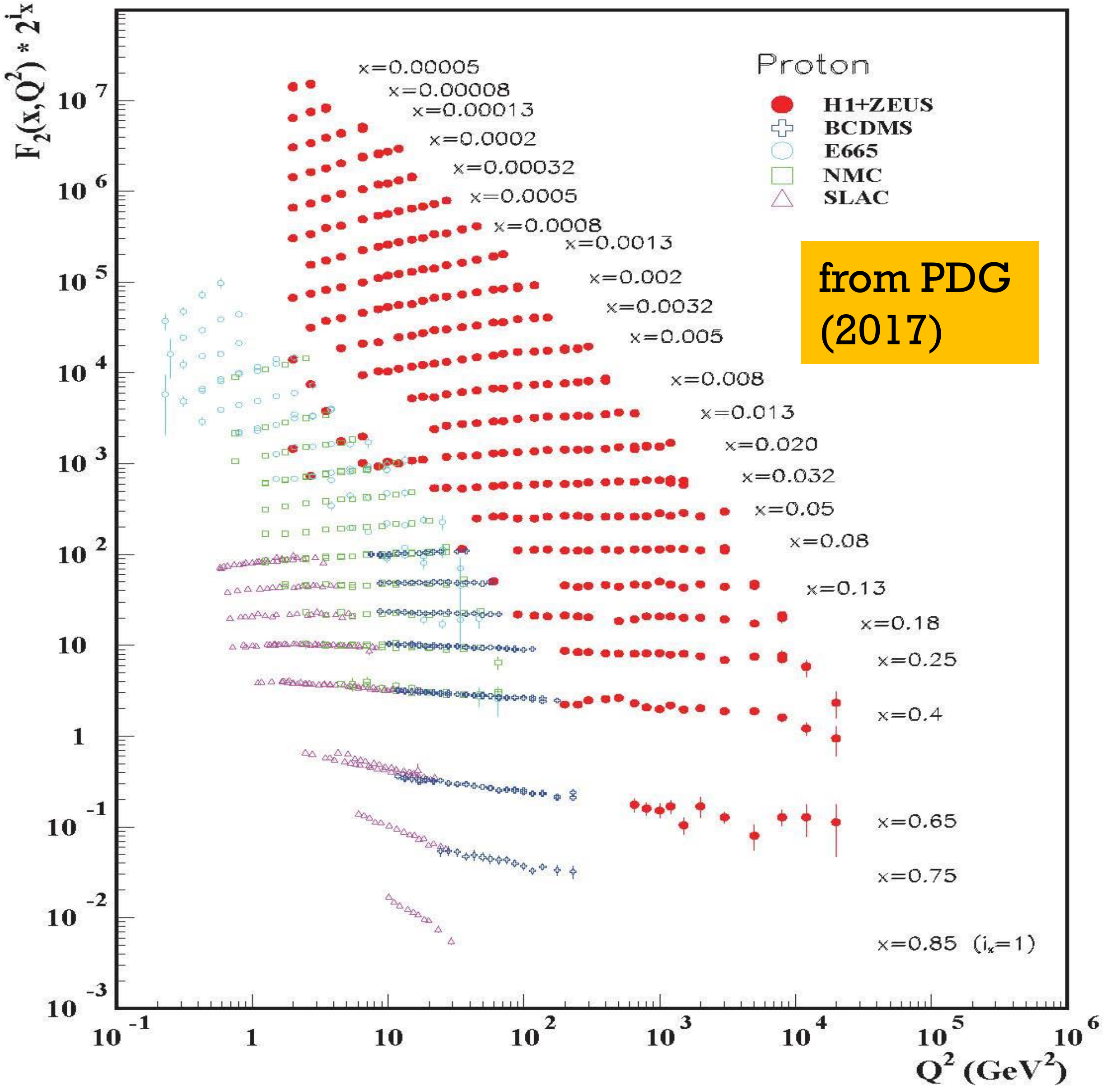
**Callan-Gross equation**

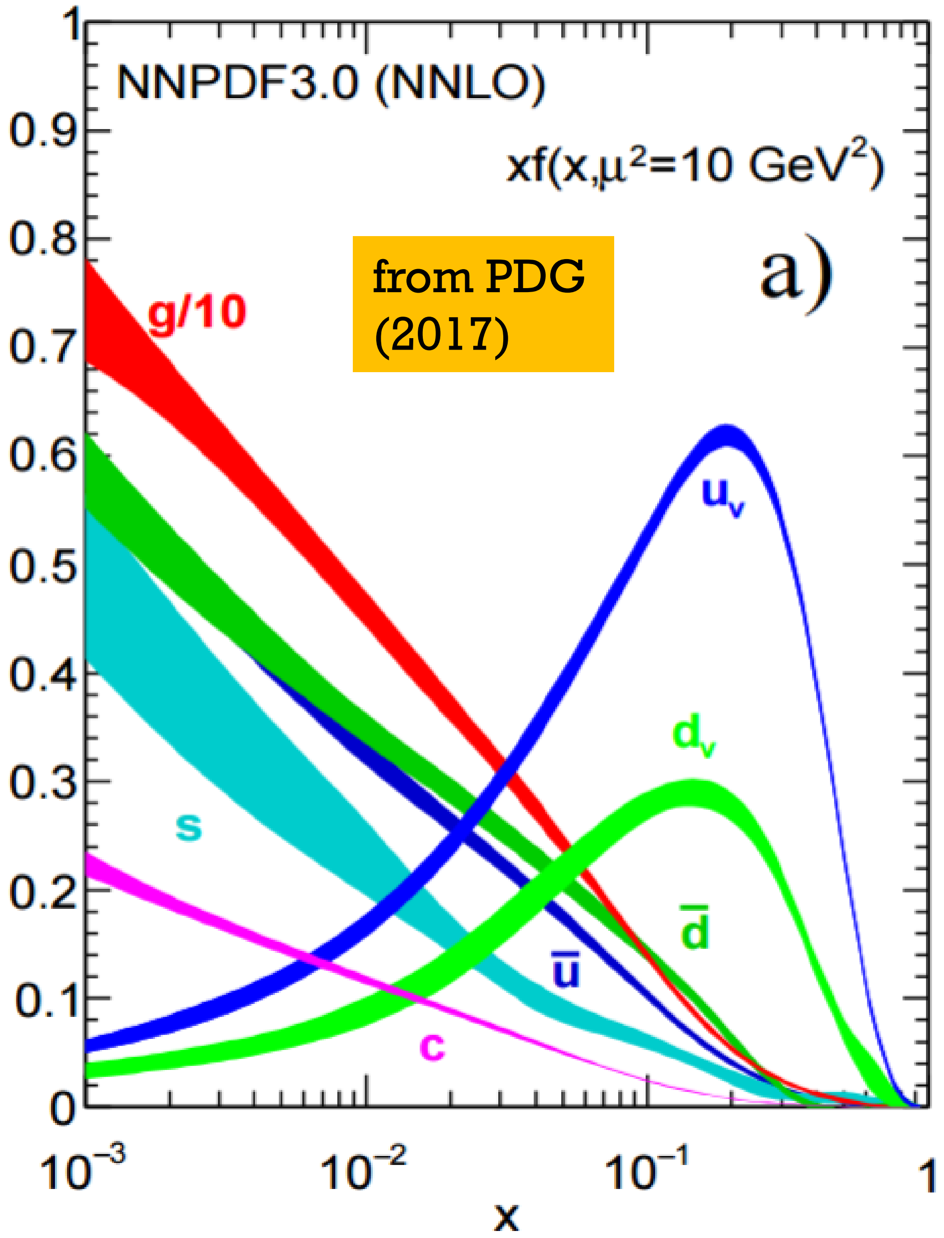
**PDFs**

Unpolarized pdfs

$$f_1(x) = q^{\uparrow}(x) + q^{\downarrow}(x)$$

$$F_2(x) = x \sum_q e_q^2 (f_1^q(x) + f_1^{\bar{q}}(x))$$




Nucleon momentum: ~50% by quarks, ~50% by gluons

# Current status of helicity studies

- Light sea, still large uncertainties
- Strange quark helicity?
- SU(3) flavor symmetry?
- Usage of SIDIS data, fragmentation functions are involved
- $\Delta$G

… still a very hot topic

**New and clean inputs: Parity Violation in DIS**

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

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

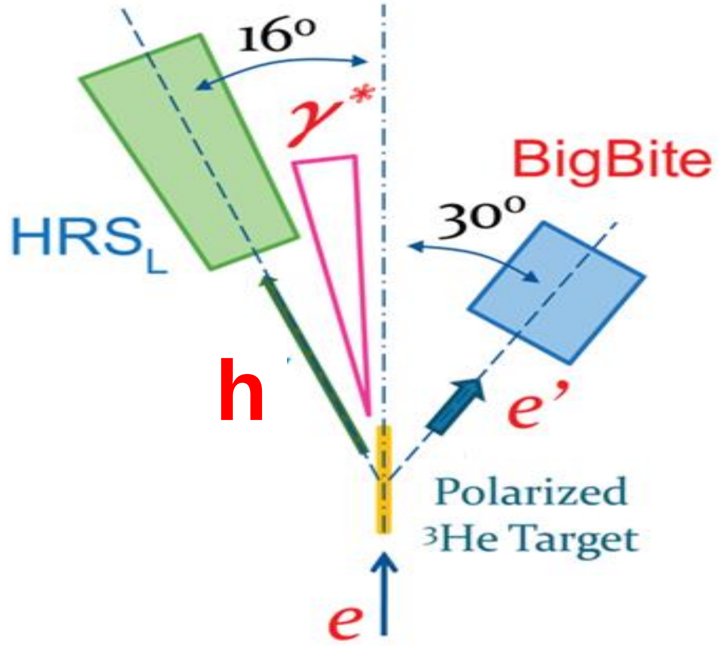
$$g_5^{p,\gamma Z} = \frac{1}{3}(\Delta u_V + \Delta c - \Delta\bar{c}) + \frac{1}{6}(\Delta d_V + \Delta s - \Delta\bar{s})$$

$$g_1^{W^-} = \Delta u + \Delta\bar{d} + \Delta c + \Delta\bar{s}$$

$$g_5^{W^-} = -\Delta u + \Delta\bar{d} - \Delta c + \Delta\bar{s}$$

Elke et al, PRD88,114025 (2013)
Y.X.Zhao, et al LOI-12-16-007 (JLab)
Y.X.Zhao ArXiv: 1701.02780 (2017)
Y.X.Zhao, et al EPJA 53 (2017) 55

# Highlights of E06-010 experiment




- Beam energy: 5.89 GeV (30Hz)
- $^3$He target: (World record!!!)
  - ✓ Transversely and vertically polarized
  - ✓ In beam polarization: ~60%
  - ✓ Spin flips: 20 minutes
  - ✓ $L(n)$ = ~$10^{36}$ $cm^{-2}$ $s^{-1}$
- BigBite:
  - ✓ 3 Drift chambers, pre-shower, scin. ,shower
  - ✓ Momentum: 0.6 --- 2.5 GeV
- LHRS:
  - ✓ VDC, S1, S2m(CTOF),
    A1, $CO_2$ gas Cer., RICH, lead glass
  - ✓ Momentum: 2.35 GeV
  - ✓ PID: electron, pion, kaon, proton separation

| (2.35GeV) | Electron | Pion | Kaon | Proton |
|---|---|---|---|---|
| Aerogel 1(n=1.015) | √ | √ | x | x |
| CO2 Gas Cherenkov | √ | x | x | x |
| RICH | Large ring | Large ring | Middle ring | Small ring |
| Lead Glass | Large signal | Small signal | Very small | Very small |

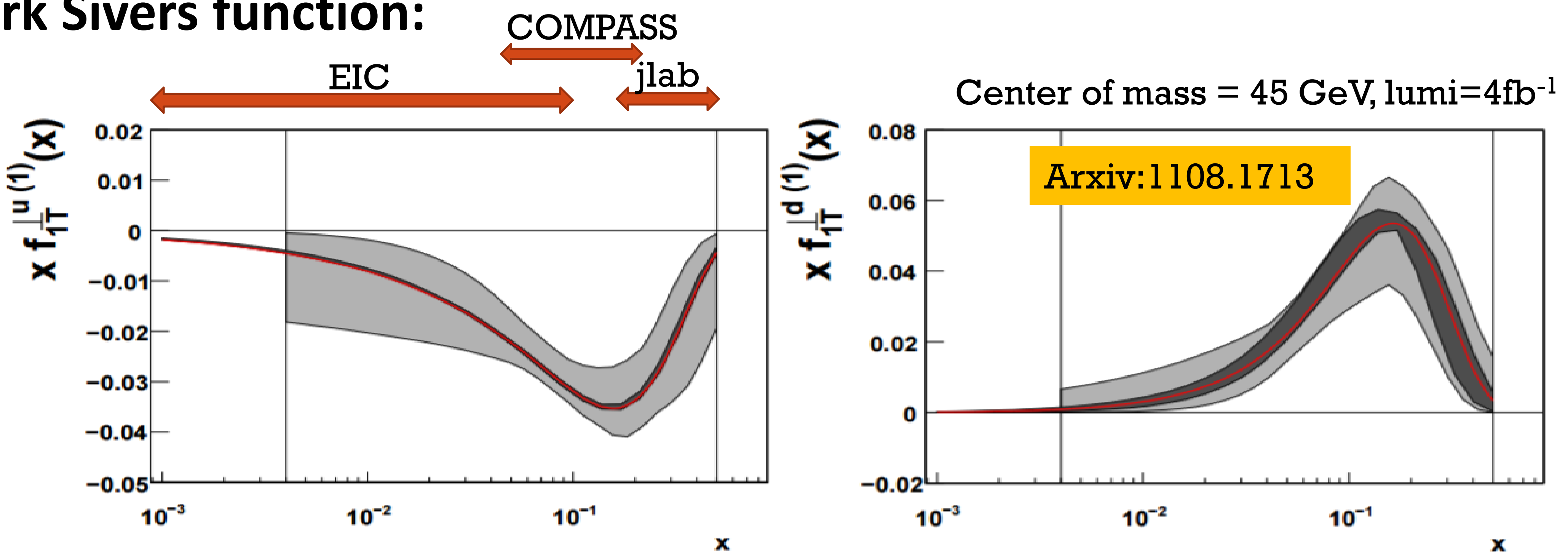
- Trigger: Singles triggers on HRS/BigBite
  Coincidence trigger
- Polarized target and Beam

→

- SIDIS or Inclusive
- SSA or DSA

# Before EIC

- **Transversity and Tensor Charge:**
  - SoLID: excellent job in x>0.1 region, negligible uncertainty for $g_T$ integration over x>0.1
  - COMPASS proton + deuteron data: x>0.008 region, combined with SoLID, $g_T$ uncertainty for x>0.008 will be at ~1% level
  - Keep in mind: quark nature of Transversity, EIC -> valence and sea quark region (x>0.01)
- **Quark Sivers function:**



# Unique for EIC on TMDs study

- High precision quantitative measurements of all quark TMDs
  → full azimuthal angular coverage, high luminosity
- First measurements of the TMDs for anti-quarks and gluons (gluon TMDs)
- Multi-dimensional mapping in broad kinematics region
  → "model free" study, format of PDFs, dynamics
- Systematic studies of perturbative QCD techniques and QCD evolution
  → TMD evolution VS DGLAP evolution
- $P_T$ coverage: TMD factorization VS Collinear twist-3 (quark-gluon-quark correlation)
- Higher Twist study, limitations in existing fixed target experiments

# Message to be taken away with you --- Timeline SIDIS on transversely polarized target

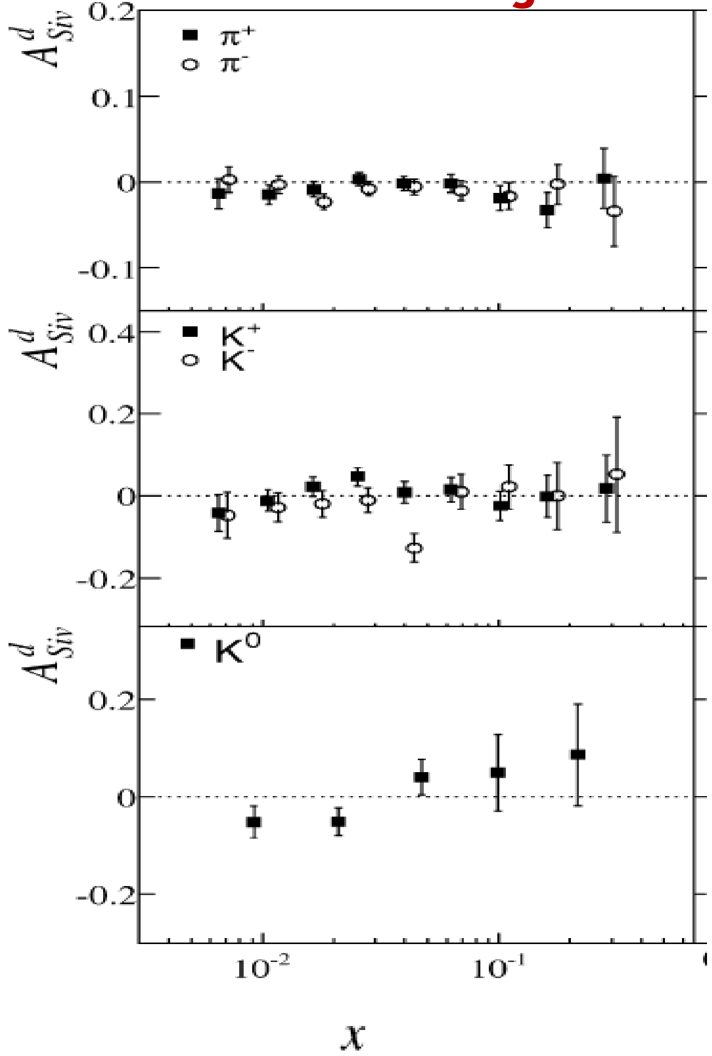
- **JLab6**(n only, over)
- **HERMES**(p only, over)
- **COMPASS**(d 2002,2003, 2004 <u>25%</u> p 2007 <u>50%</u>, 2010 <u>100%</u>)
- **COMPASS 2021,d, probably last SIDIS experiment at COMPASS, full year of running**
- **JLab12**(p, d, He-3 > 2019, SoLID data ~ 2025)

- **EIC** (p, d, He-3 > 2025), **also Chinese EIC at HIAF is proceeding…**

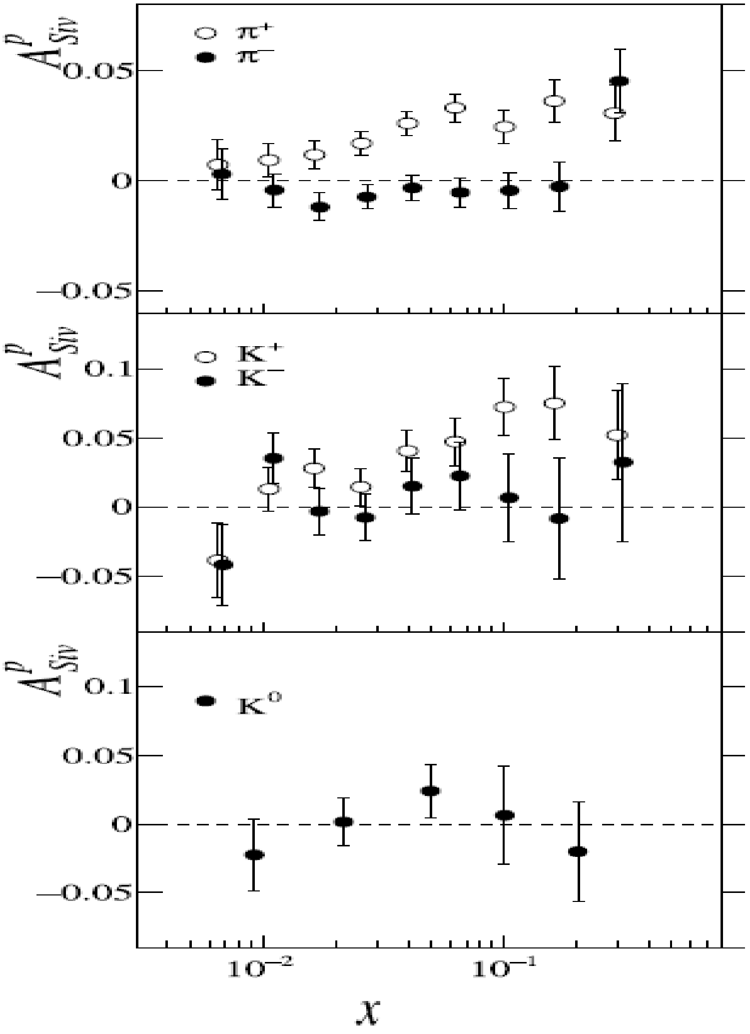
# Sivers asymmetries from COMPASS

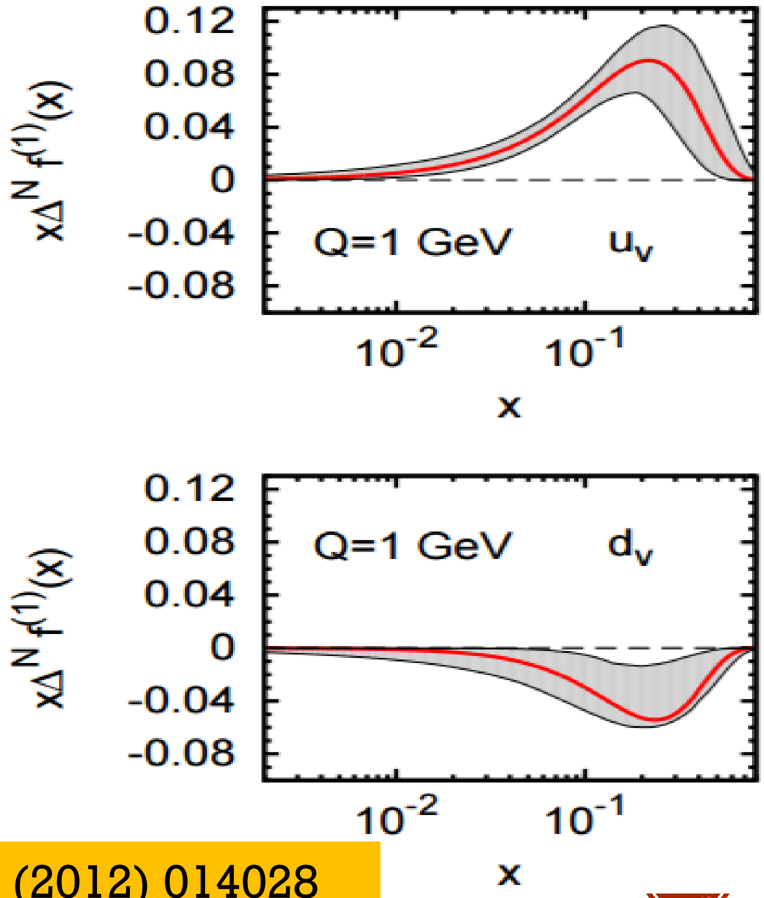
- PRL 94, 202002 (2005)
- NPB 765 (2007) 31-70
- PLB 673 (2009) 127-135
- PLB 692 (2010) 240-246
- PLB 713 (2012)10-16
- PLB 717 (2012) 376-382
- PLB 717 (2012) 383-389
- EPJC (2013) 73:2531
- PLB 736 (2014) 124-131
- PLB 744 (2015) 250-259
- PLB 753 (2016) 406-411

**Deuteron target**




**Proton target**



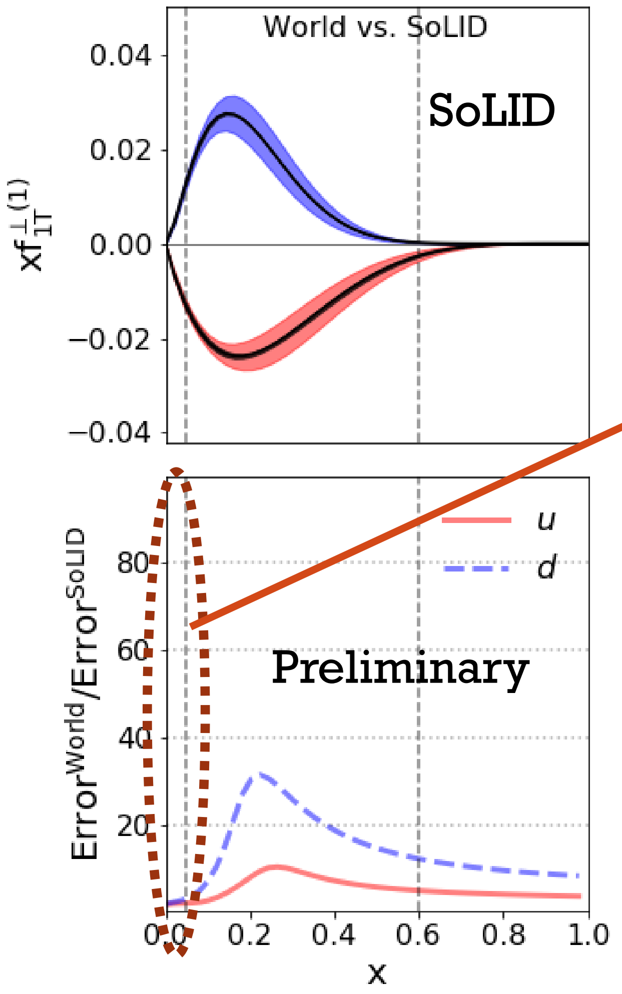




Note: A different convention (notation, sign) was used by Anselmino

PRD 86 (2012) 014028

# Where EicC stands

Sivers




SoLID and Jlab12 measurements will do excellent job for x>0.1

For x<0.1, COMPASS will finish the SIDIS program after 2021

## EicC: flavor separations in sea quark region

**high luminosity,**
**large acceptance,**
**much better azimuthal angle coverage (VS fixed target),**
**4D kinematics mapping,**
**P and N data, PID for pion and kaon,**
**go beyond Collins, Sivers and leading twist**
**→Pretzelosity, Worm-Gear, higher twist modulations**

Transverse momentum distribution

**Unpolarized Xs and multiplicity**

**With PID and broad, multidimensional kinematics**