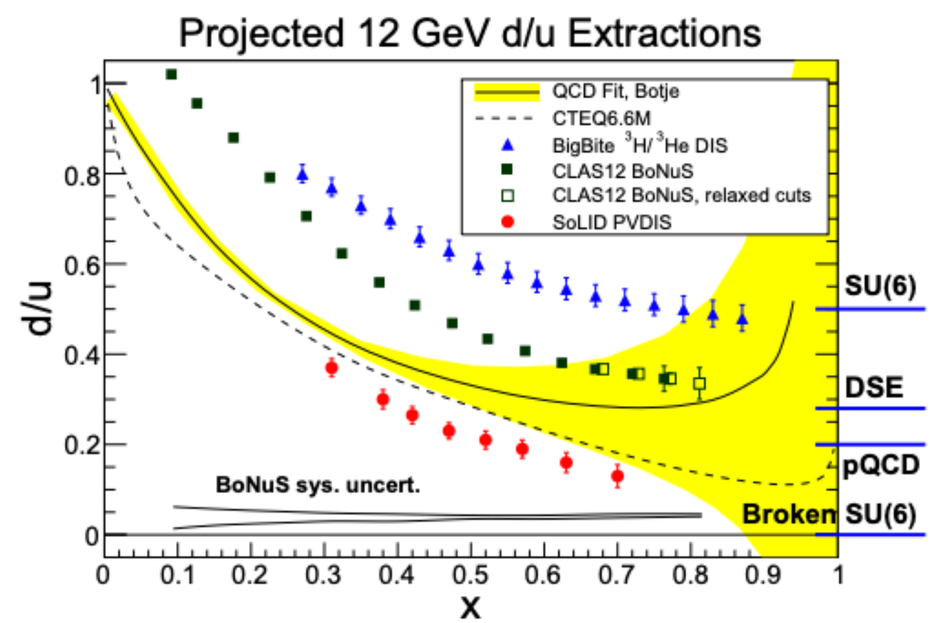
Hadron Structure in Experiments
Part. 3

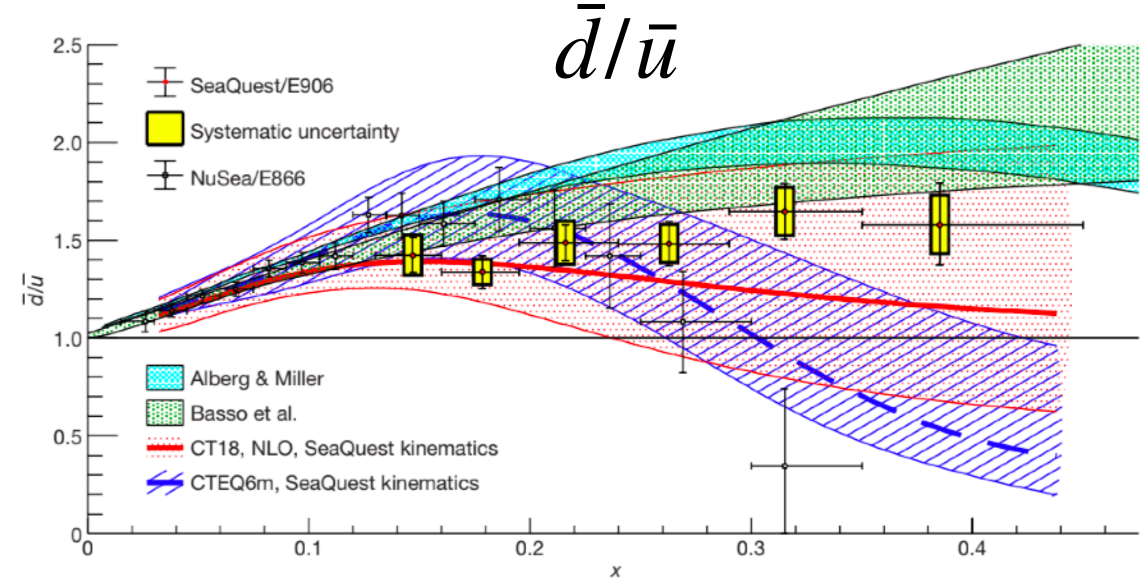
Sanghwa Park

Jefferson Lab
Exploring the Nature of Matter

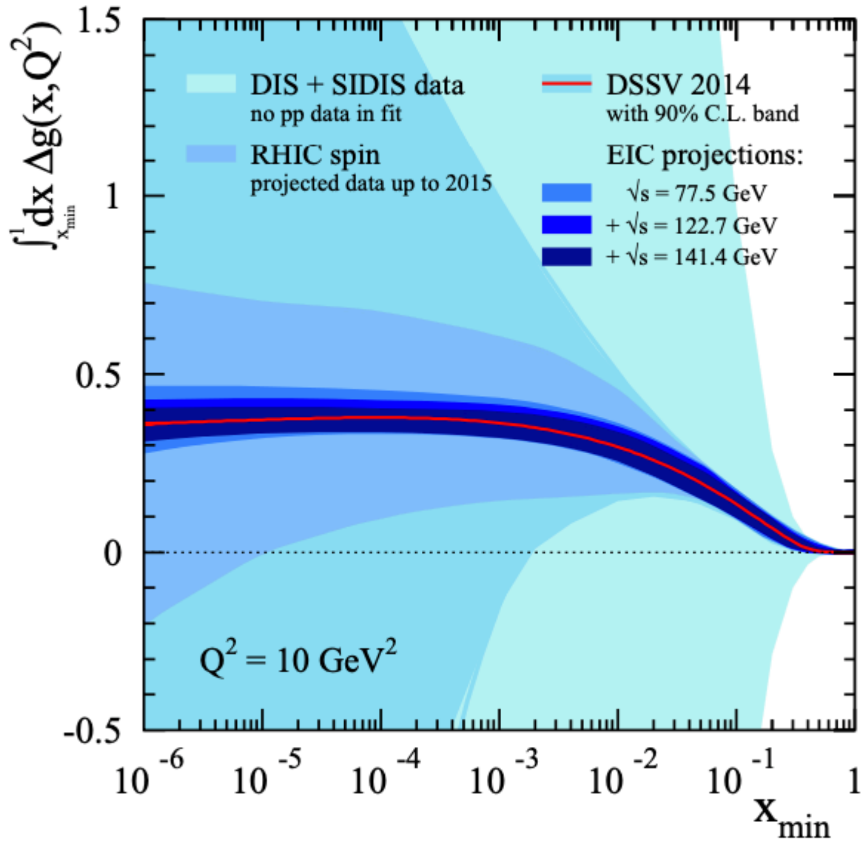
Previously..



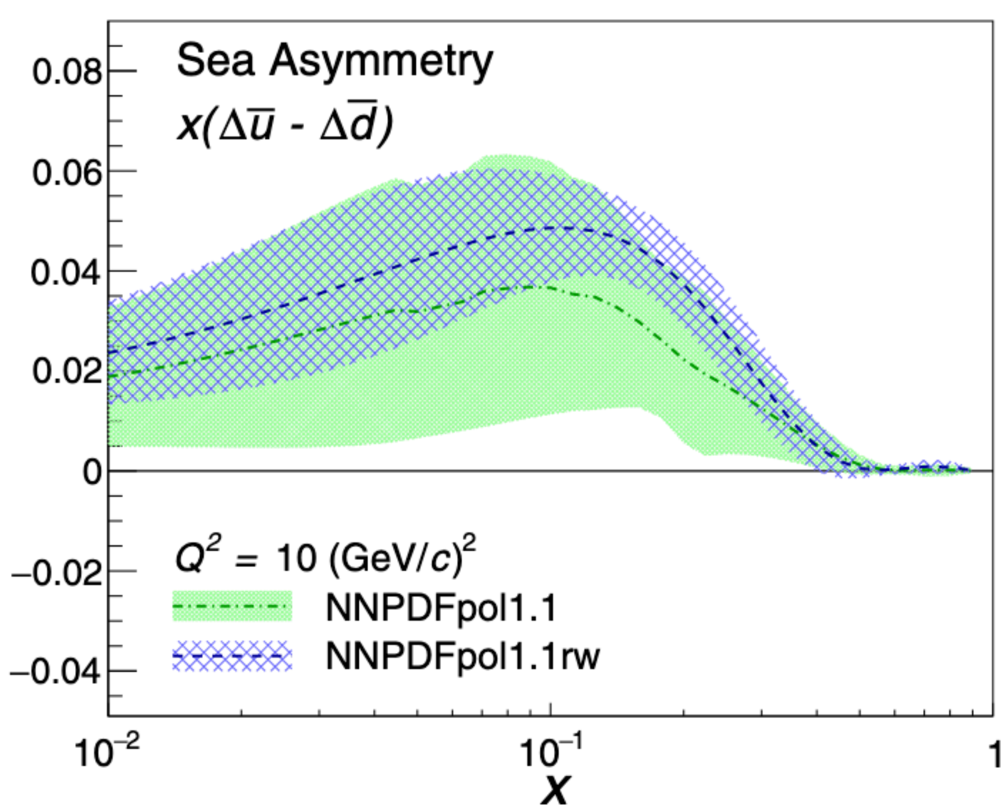
Projected 12 GeV d/u Extractions
QCD Fit, Botje
CTEQ6.6M
BigBite ³H/³He DIS
CLAS12 BoNuS
CLAS12 BoNuS, relaxed cuts
SoLID PVDIS
SU(6)
DSE
pQCD
Broken SU(6)
BoNuS sys. uncert.
d/u
x



$\bar{d}/\bar{u}$
SeaQuest/E906
Systematic uncertainty
NuSea/E866
Alberg & Miller
Basso et al.
CT18, NLO, SeaQuest kinematics
CTEQ6m, SeaQuest kinematics
x



DIS + SIDIS data
no pp data in fit
RHIC spin
projected data up to 2015
DSSV 2014
with 90% C.L. band
EIC projections:
√s = 77.5 GeV
+ √s = 122.7 GeV
+ √s = 141.4 GeV
$Q^2 = 10\ GeV^2$
$\int_{x_{min}}^1 dx\, \Delta g(x,Q^2)$
x_{min}



Sea Asymmetry
$x(\Delta\bar{u} - \Delta\bar{d})$
$Q^2 = 10\ (GeV/c)^2$
NNPDFpol1.1
NNPDFpol1.1rw
x

- Part. 1: Basics of hadron structure experiments
    - Accelerators and particle detectors
    - Deep Inelastic Scattering experiments
    - DIS Kinematics reconstruction

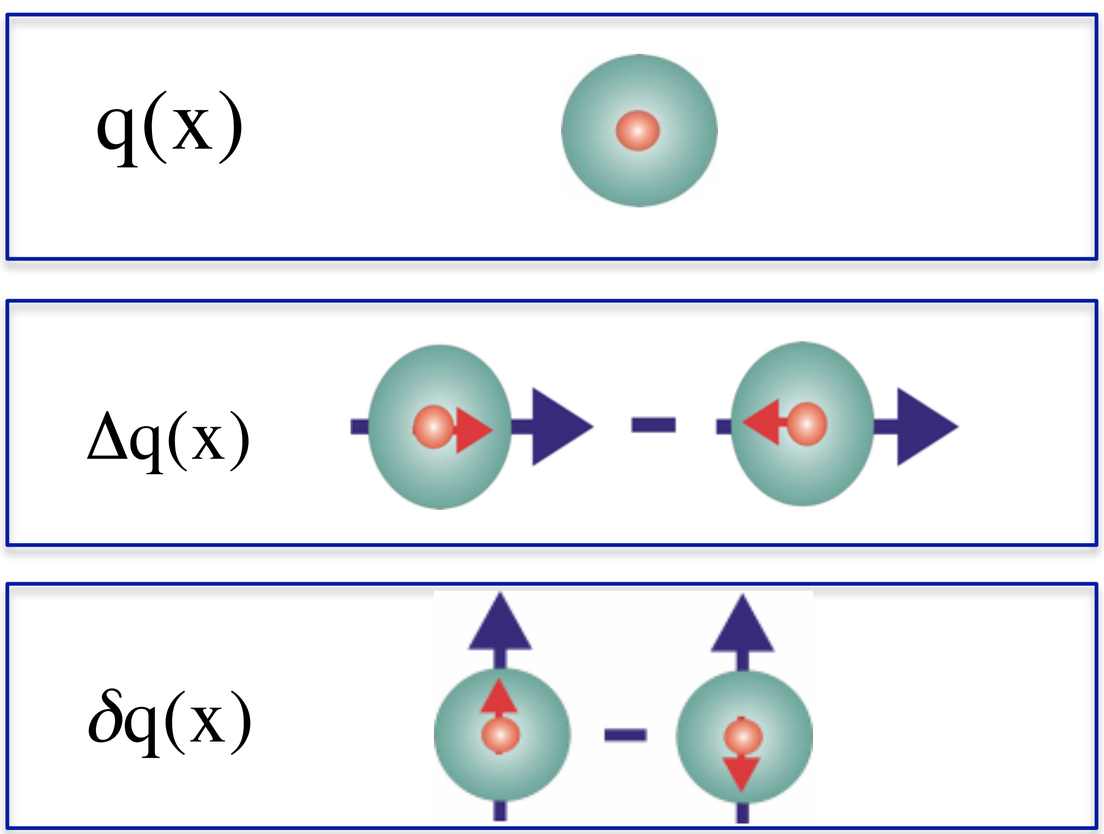
- Part. 2: Collinear observables and measurements
    - Continue on DIS data - PDF extraction
    - Parton distributions at large-x
    - Flavor asymmetry of sea
    - Polarized spin structure

- Part. 3: Beyond collinear
    - TMD measurements
    - GPD measurements
    - Future opportunities

*Special thanks to J. Roche for the materials on GPD measurements.

Collinear PDFs

- Collinear parton picture: three parton distribution functions unveil the information on the 1-dim structure of the proton



Unpolarized parton distribution functions (PDFs)

Helicity PDFs

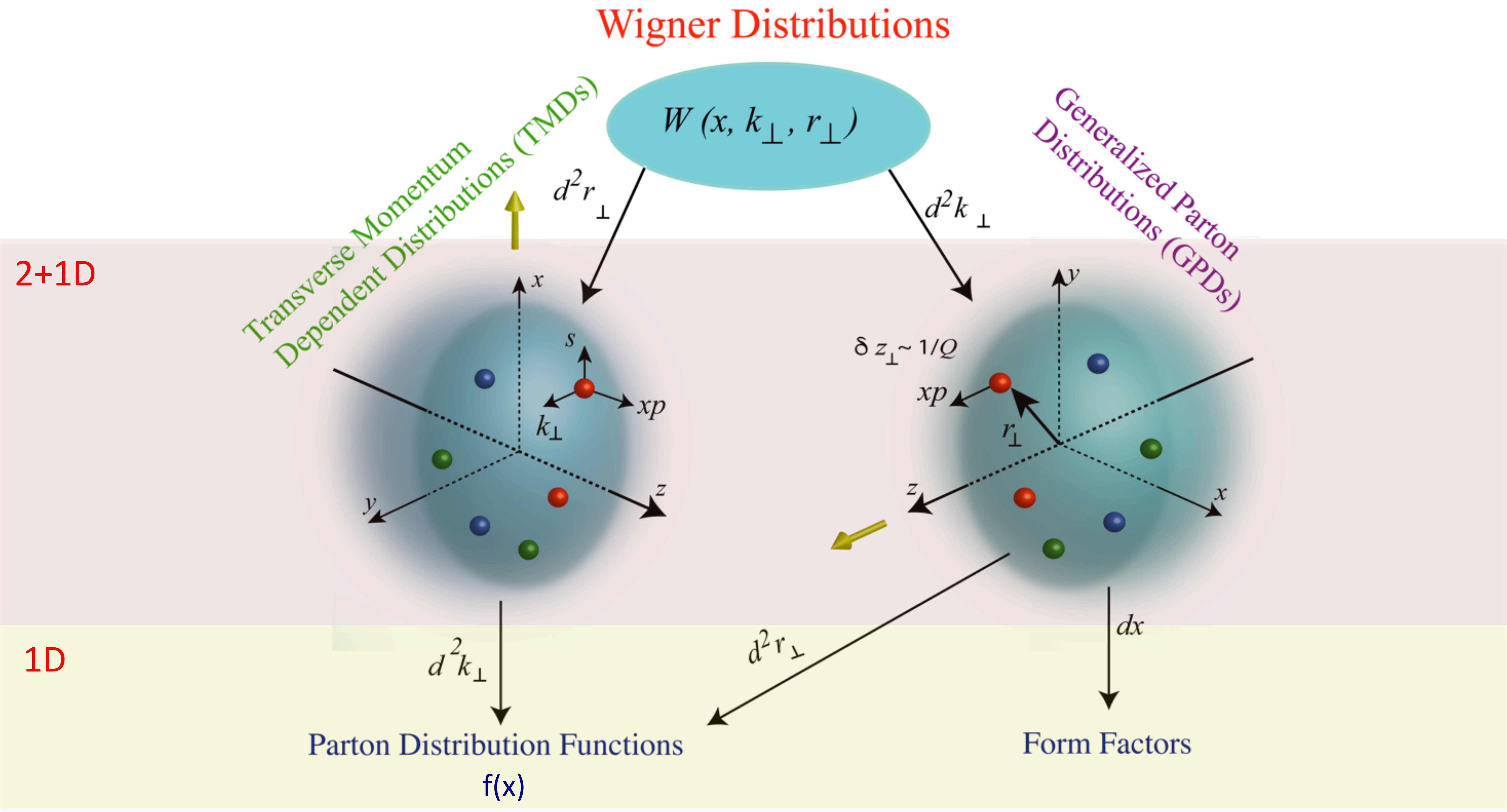
Transversity PDFs

Collinear PDFs

- Collinear parton picture: three parton distribution functions unveil the information on the 1-dim structure of the proton

$q(x) \quad f_1^q(x) = q^{\vec{\Rightarrow}}(x) + q^{\vec{\Leftarrow}}(x)$	Unpolarized parton distribution functions (PDFs)
$\Delta q(x) \quad g_1^q(x) = q^{\vec{\Rightarrow}}(x) - q^{\vec{\Leftarrow}}(x)$	Helicity PDFs
$\delta q(x) \quad h_1^q(x) = q^{\uparrow\Uparrow}(x) - q^{\uparrow\Downarrow}(x)$	Transversity PDFs

2+1D Imaging of Nucleon Structure

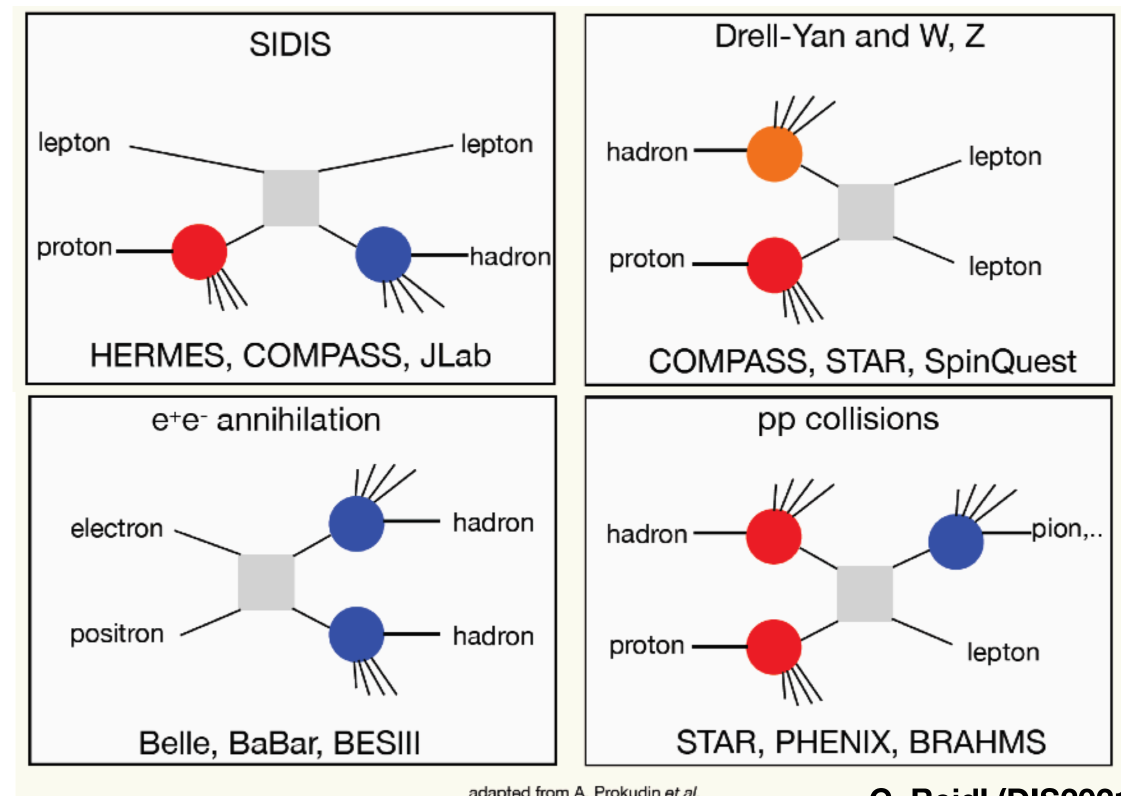


Transverse Momentum Dependent Functions

Leading twist TMD PDFs

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

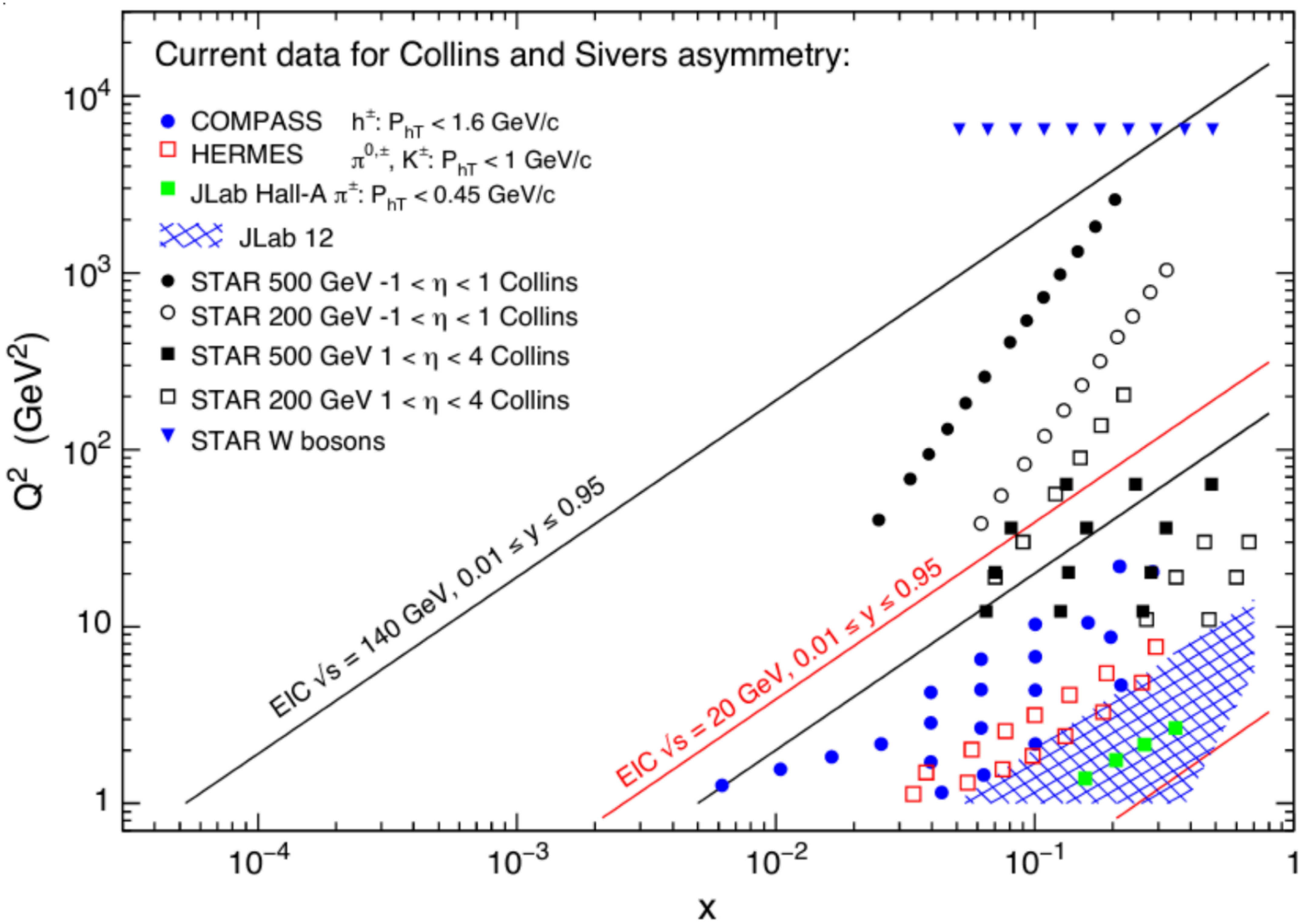
and FFs: $D_1, G_1, H_1^\perp$



C. Reidl (DIS2021)

- Sensitive to confined motion of quarks and gluons inside the nucleon
- Connection to OAM: Off-diagonal part vanishes without parton's transverse motion
  - Pretzelosity: Link to quark OAM (model-dependent)
- Accessed via various processes (SIDIS, DY, e+e-, p+p)
  - TMD factorization and universality test

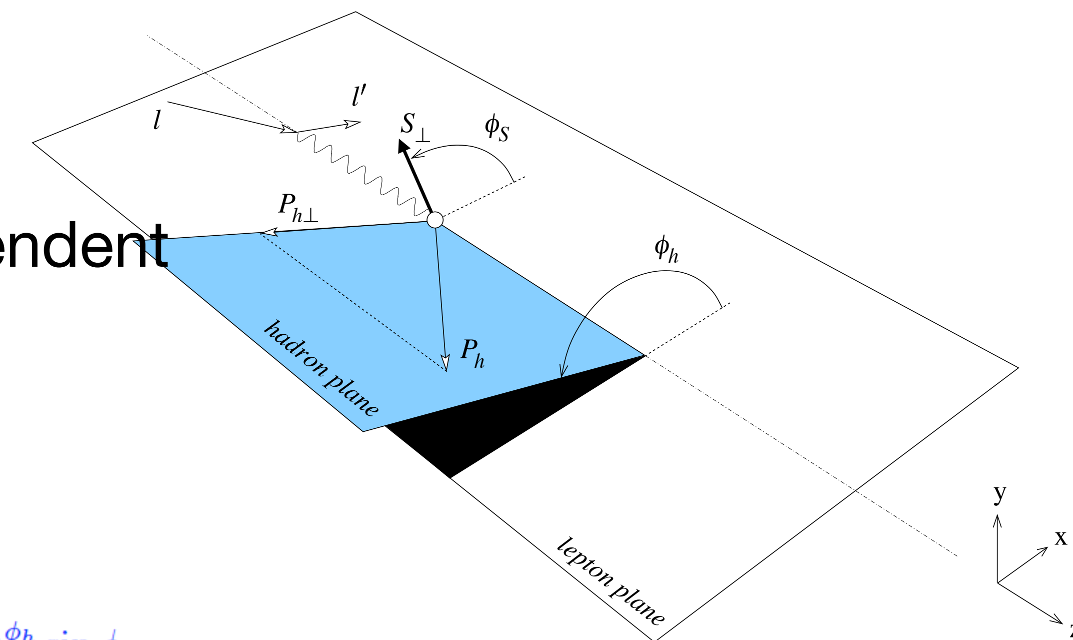
TMD programs



ks

TMDs from SIDIS

- Semi-Inclusive process is ideal to study TMDs
  Naturally have two scales: $Q^2 >> p_T^2, \Lambda_{QCD}^2$
- Access all 8 leading twist TMDs via spin (in)dependent azimuthal modulations



$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\phi_S} \\
&= \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
&\times\Big\{F_{UU,T}+\epsilon F_{UU,L}+\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h+\epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\lambda_e\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h \\
&+S_L\Big[\sqrt{2\epsilon(1+\epsilon)}F_{UL}^{\sin\phi_h}\sin\phi_h+\epsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\Big]+\lambda_e S_L\Big[\sqrt{1-\epsilon^2}F_{LL}+\sqrt{2\epsilon(1-\epsilon)}F_{LL}^{\cos\phi_h}\cos\phi_h\Big] \\
&+S_T\Big[\big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\big)\sin(\phi_h-\phi_S)+\epsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)+\epsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\
&\qquad+\sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S+\sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big] \\
&+\lambda_e S_T\Big[\sqrt{1-\epsilon^2}F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\
&\qquad+\sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos\phi_S}\cos\phi_S+\sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big]\Big\}
\end{aligned}
$$

TMDs from SIDIS

- Semi-Inclusive process is ideal to study TMDs
  Naturally have two scales: $Q^2 \gg p_T^2, \Lambda_{QCD}^2$
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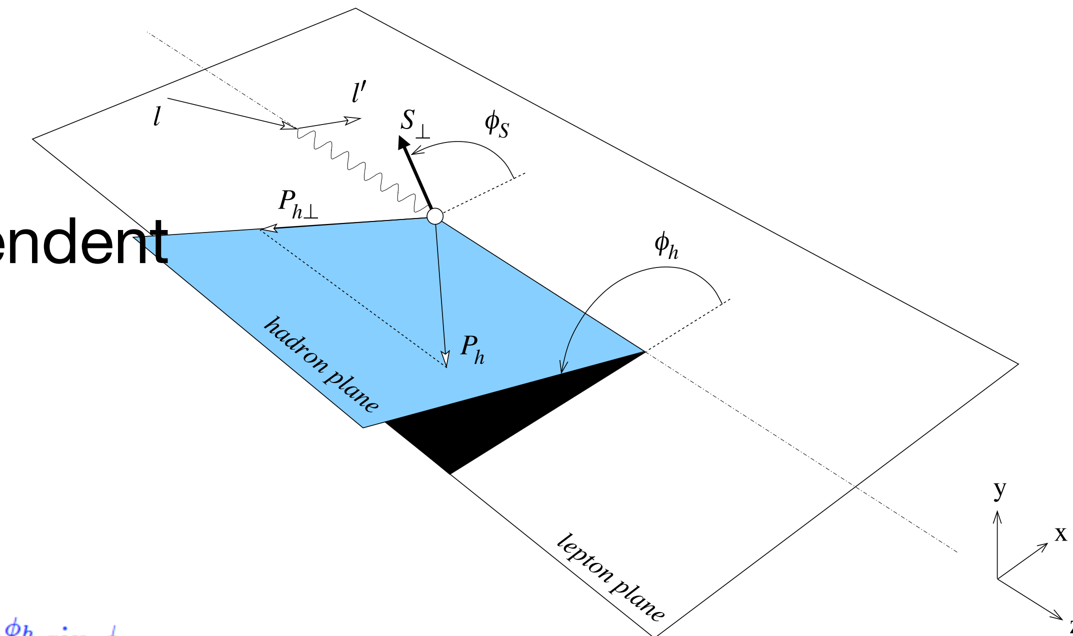


$$\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\phi_S} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$
$$\times\Big\{F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda_e\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h$$
$$+ S_L\left[\sqrt{2\epsilon(1+\epsilon)}F_{UL}^{\sin\phi_h}\sin\phi_h + \epsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] + \lambda_e S_L\left[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}F_{LL}^{\cos\phi_h}\cos\phi_h\right]$$
$$+ S_T\Big[\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\sin(\phi_h-\phi_S) + \epsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \epsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)$$
$$+ \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big]$$
$$+ \lambda_e S_T\Big[\sqrt{1-\epsilon^2}F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)$$
$$+ \sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos\phi_S}\cos\phi_S + \sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big]\Big\}$$

Target single spin asymmetry

$$A_{UT} = \frac{1}{P}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

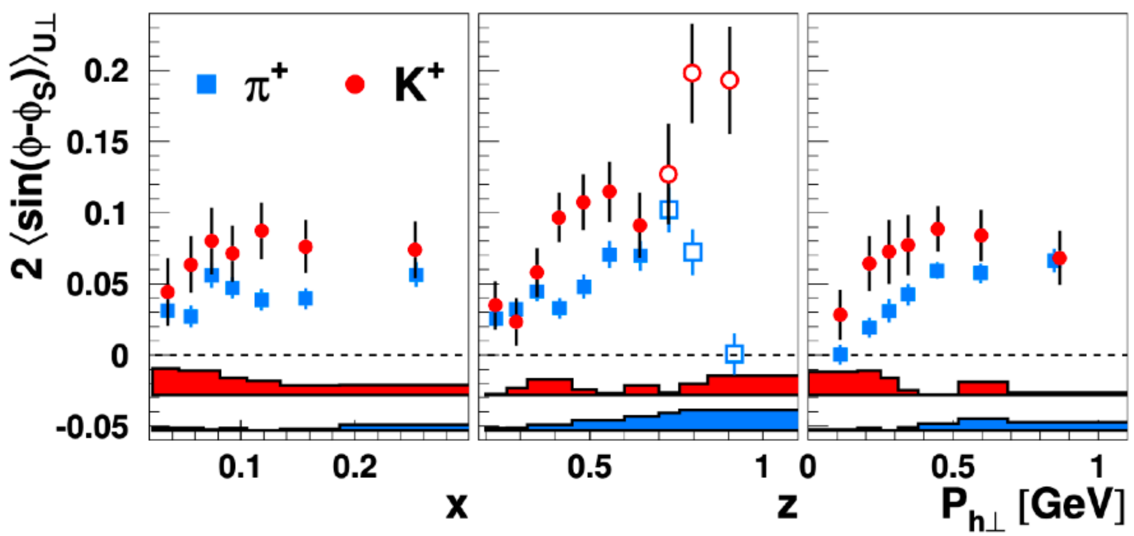
$$A_{UT} = A_{UT}^{Collins} sin(\phi_h + \phi_s)$$
$$+ A_{UT}^{Sivers} sin(\phi_h - \phi_s)$$
$$+ A_{UT}^{Pretzelosity} sin(3\phi_h - \phi_s)$$

TMDs via SIDIS		Quark Polarization: Unpolarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
Nucleon Polarization	U	$F_{UU} \propto f_1 \otimes D_1$ Unpolarized		$F_{UU}^{\cos(2\phi_h)} \propto h_1^\perp \otimes H_1^\perp$ Boer-Mulders
	L		$A_{LL} \propto g_1 \otimes D_1$ Helicity	$A_{UL}^{\sin(2\phi_h)} \propto h_{1L}^\perp \otimes H_1^\perp$ Long-Transversity
	T	$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^\perp \otimes D_1$ Sivers	$A_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T} \otimes D_1$ Trans-Helicity	$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1 \otimes H_1^\perp$ Transversity $A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^\perp \otimes H_1^\perp$ Pretzelosity

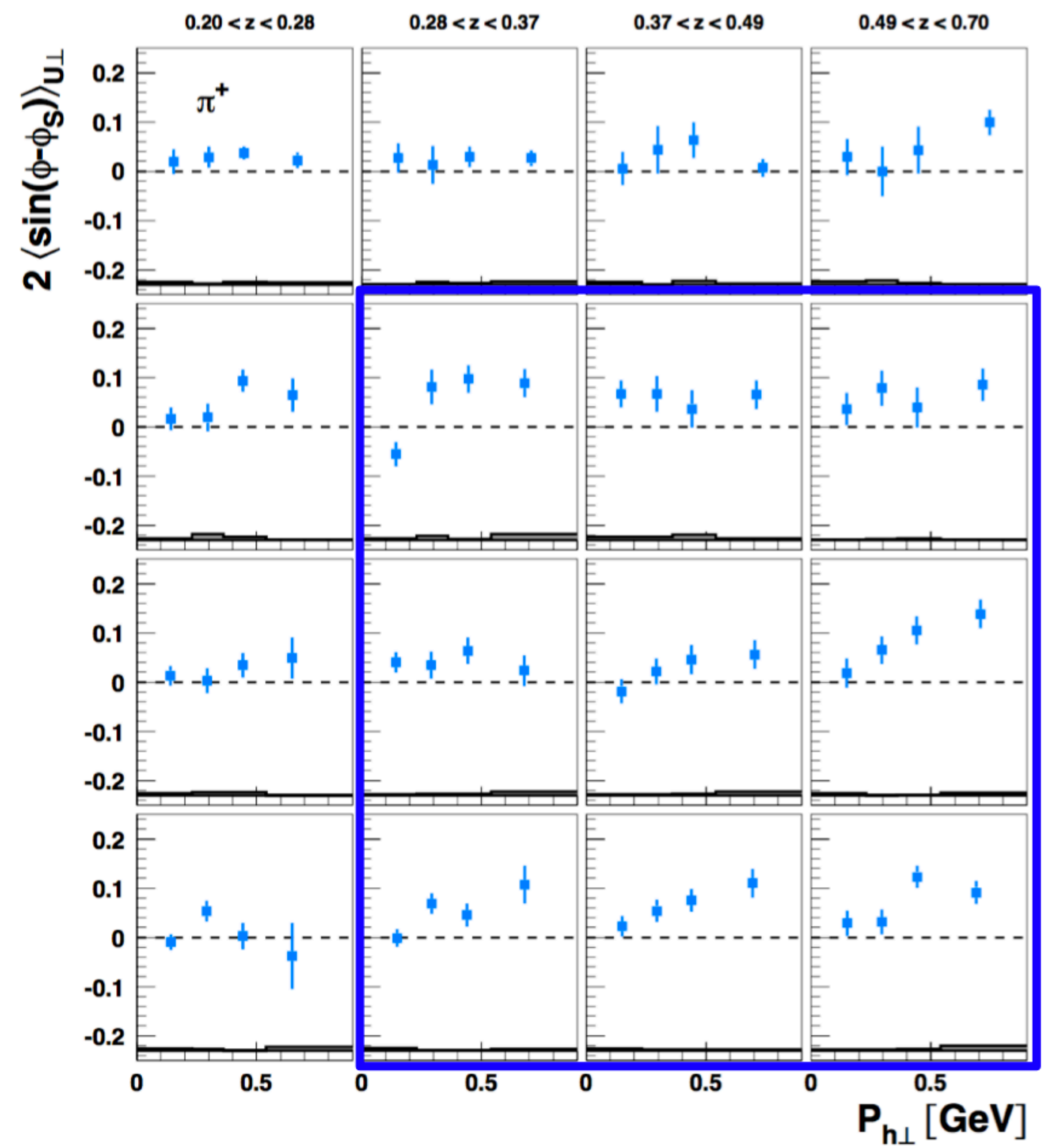
Sivers from HERMES

- **HERMES "TMDs bible"**

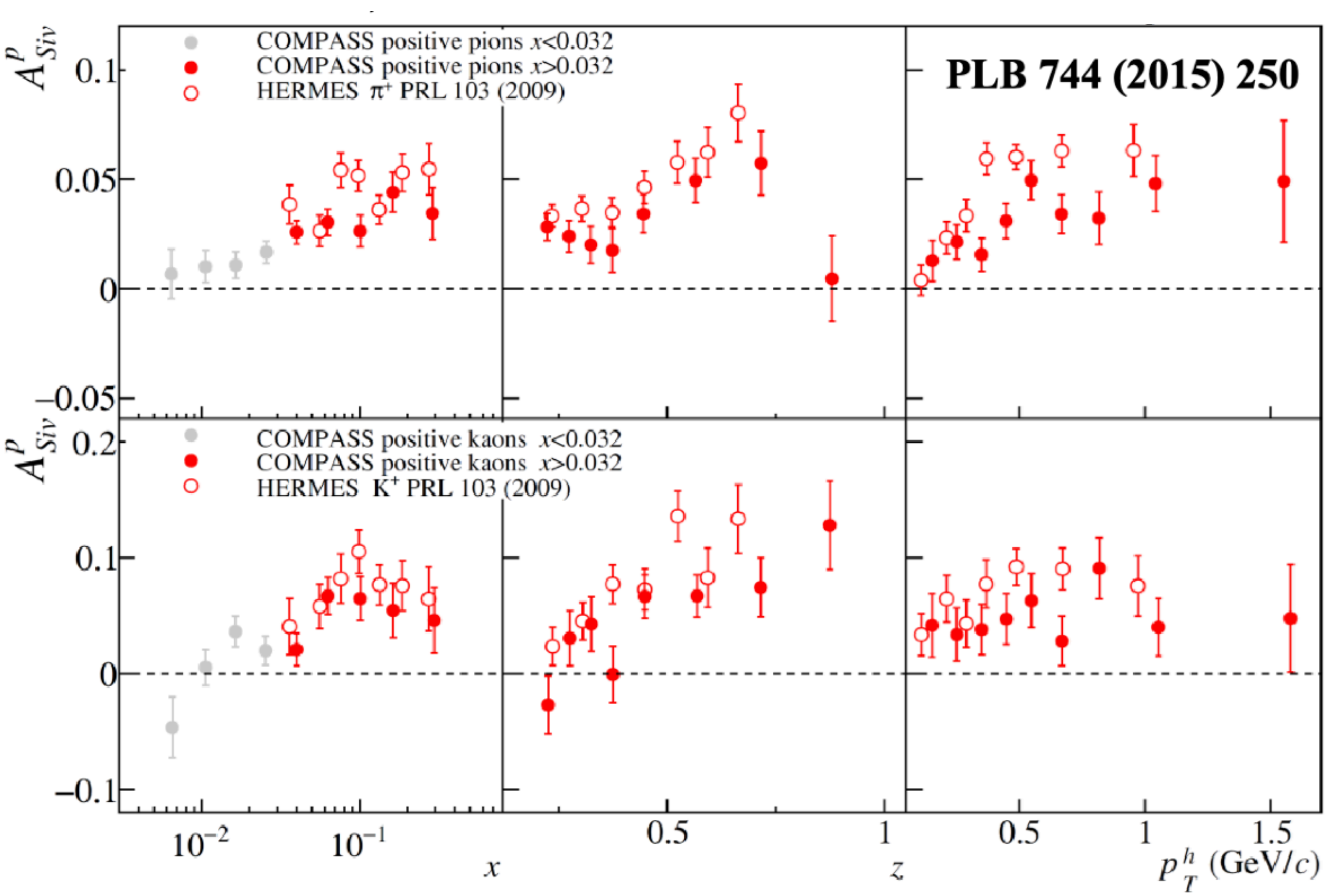
  [HERMES, J. High Energ. Phys. 2020, 10 (2020)]

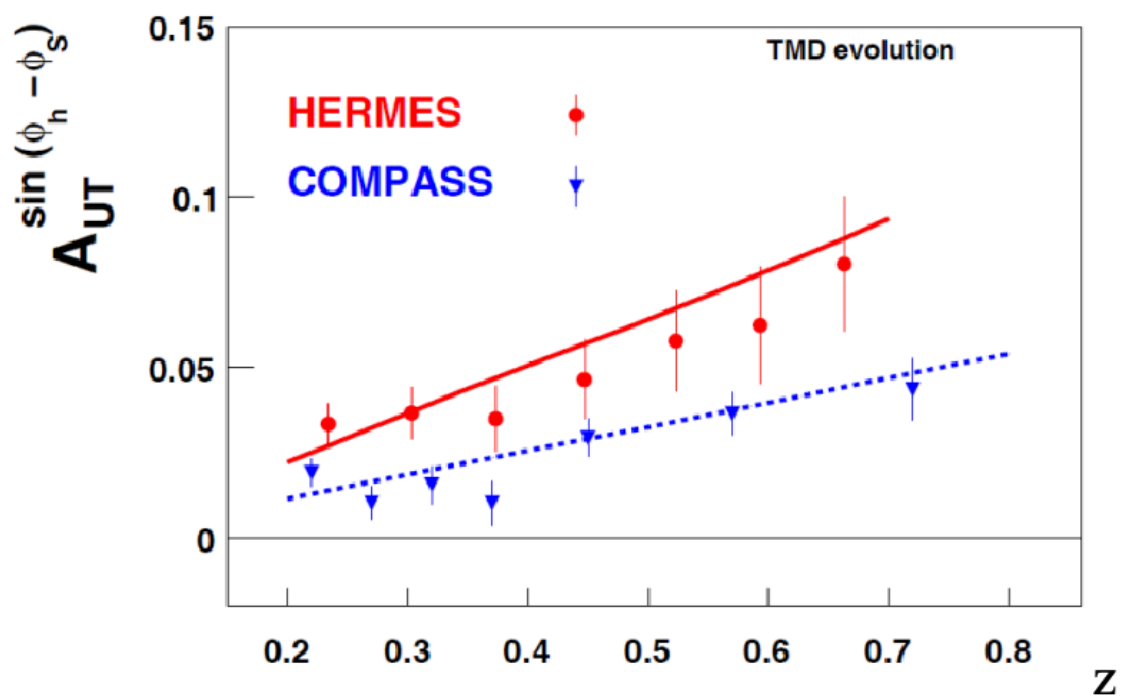


- Large positive amplitude, clear evidence of non zero u-quark Sivers
- Detailed information from the 3D binning (x, z, pT)
- Continuous rising of K+ amplitude due to different contribution from exclusive vector meson decays (less pronounced for kaons)



Sivers from COMPASS



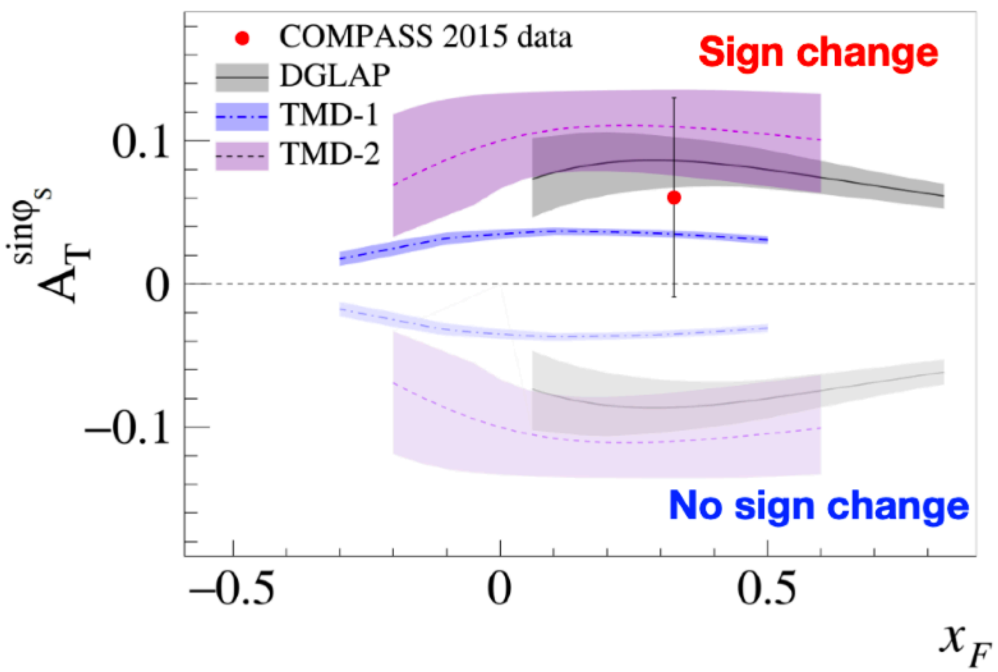


Modified universality

$$f_{q/h^\uparrow}^{SIDIS}(x, k_T, Q^2) = -f_{q/h^\uparrow}^{DY/W^\pm/Z}(x, k_T, Q^2)$$ [Collins, PLB 536 (02)]

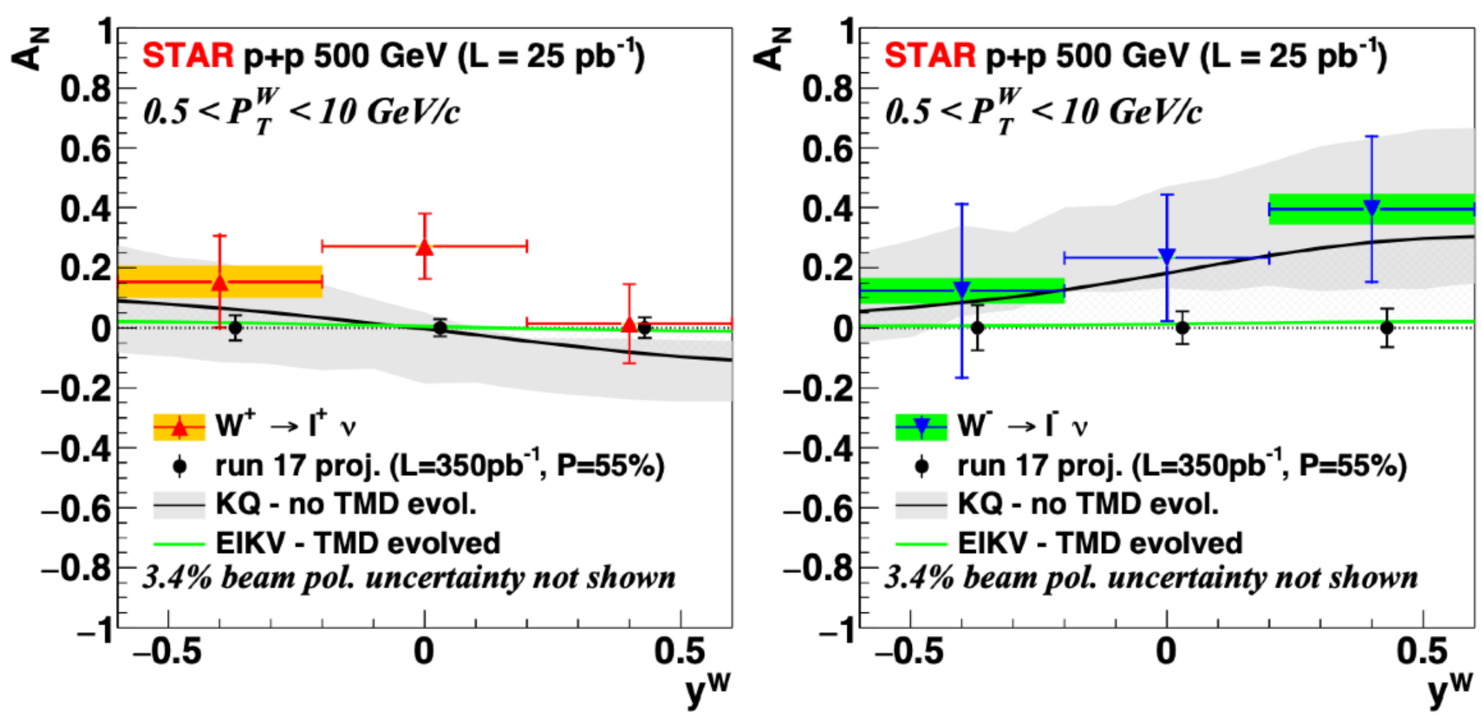
- Sivers sign change: fundamental prediction from the gauge invariance of QCD, direct verification of QCD factorization

[COMPASS, PRL 118 (2017) 112002]



- Measures SIDIS and DY with the same detector
- COMPASS DY results favor the sign change hypothesis

[STAR, Phys. Rev. Lett. 116, 132301 (2016)]

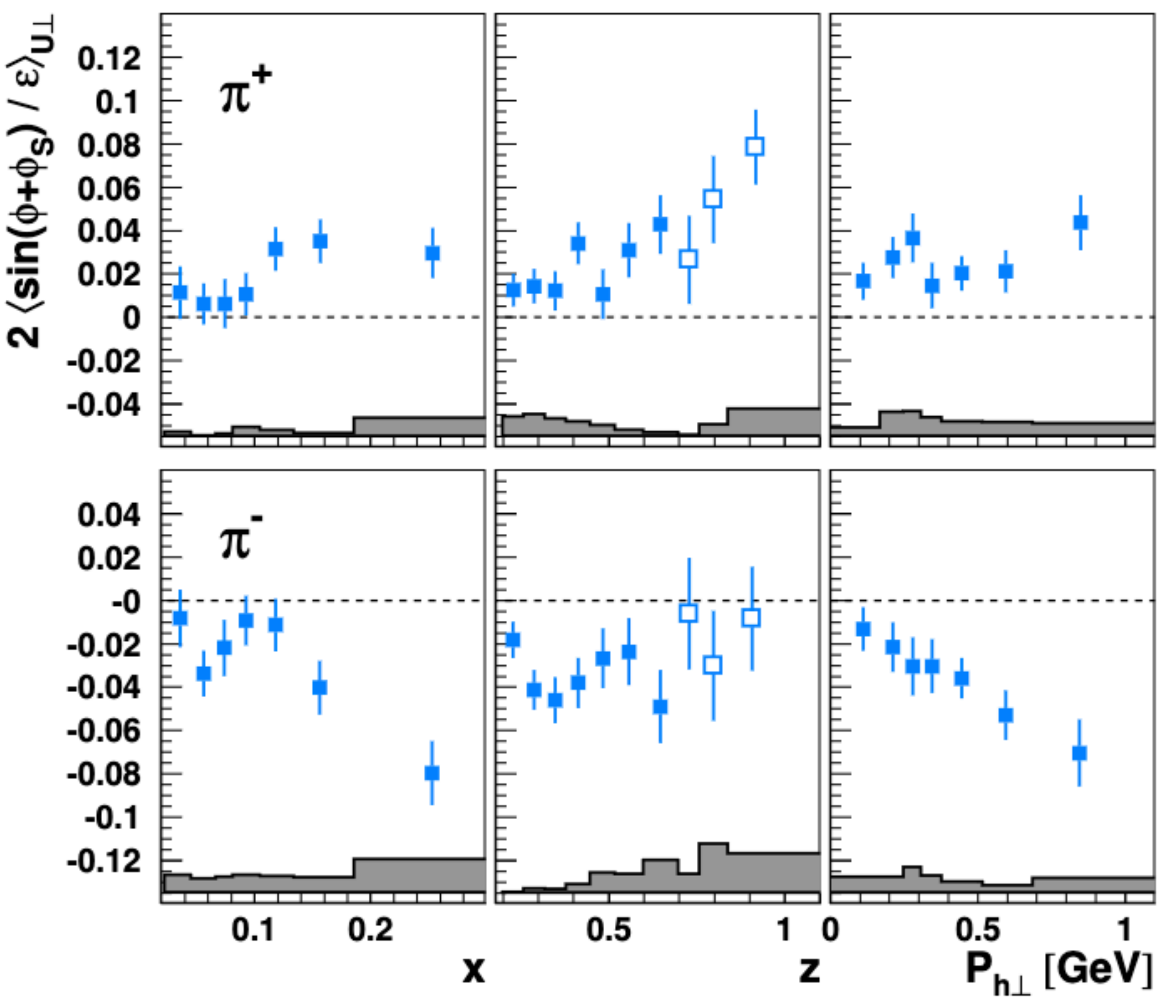


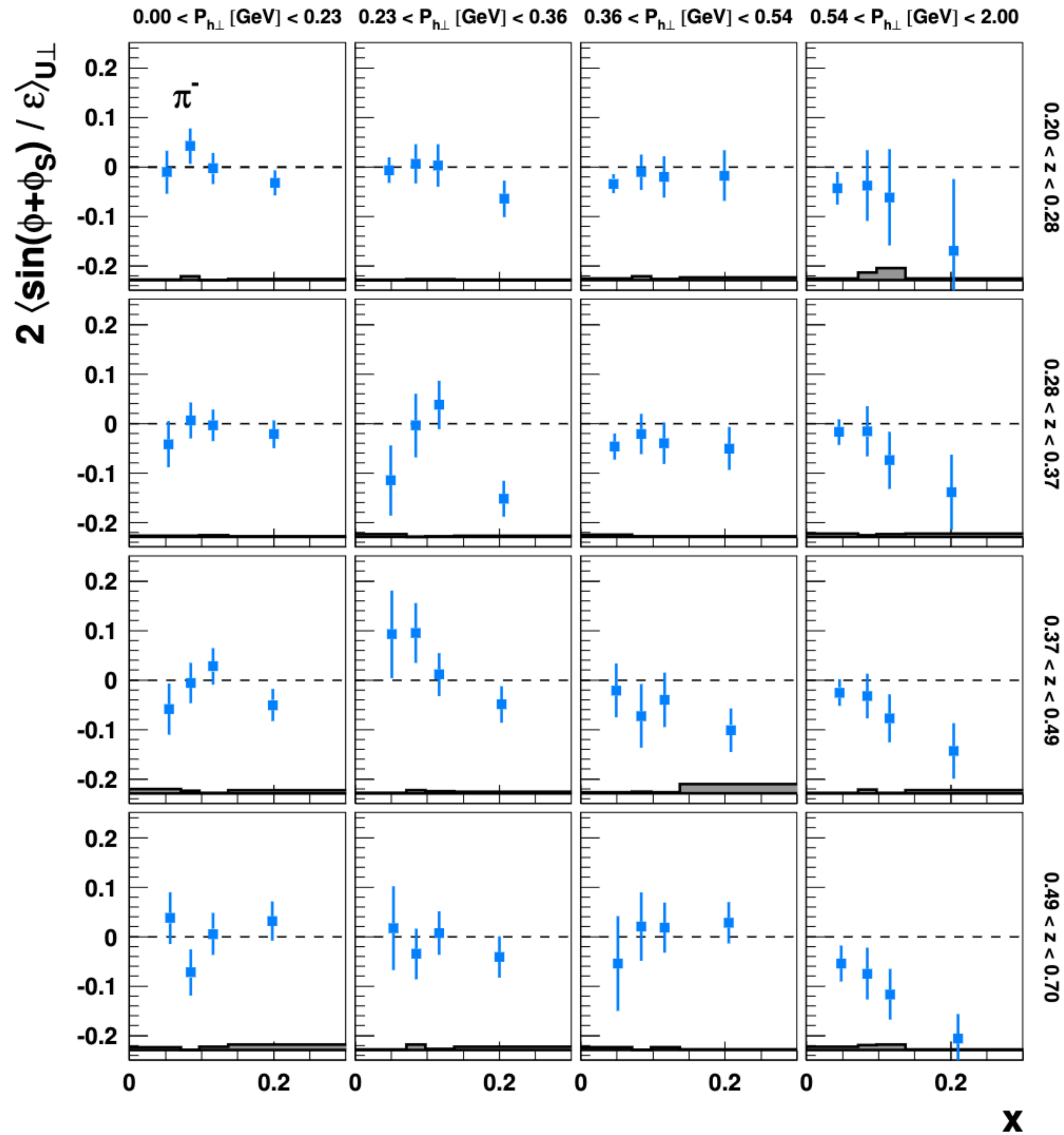
Fully reconstructed W kinematics via its recoil compared to curves with sign-change scenario

Agree with the sign change, improved precision data expected.

Collins asymmetries

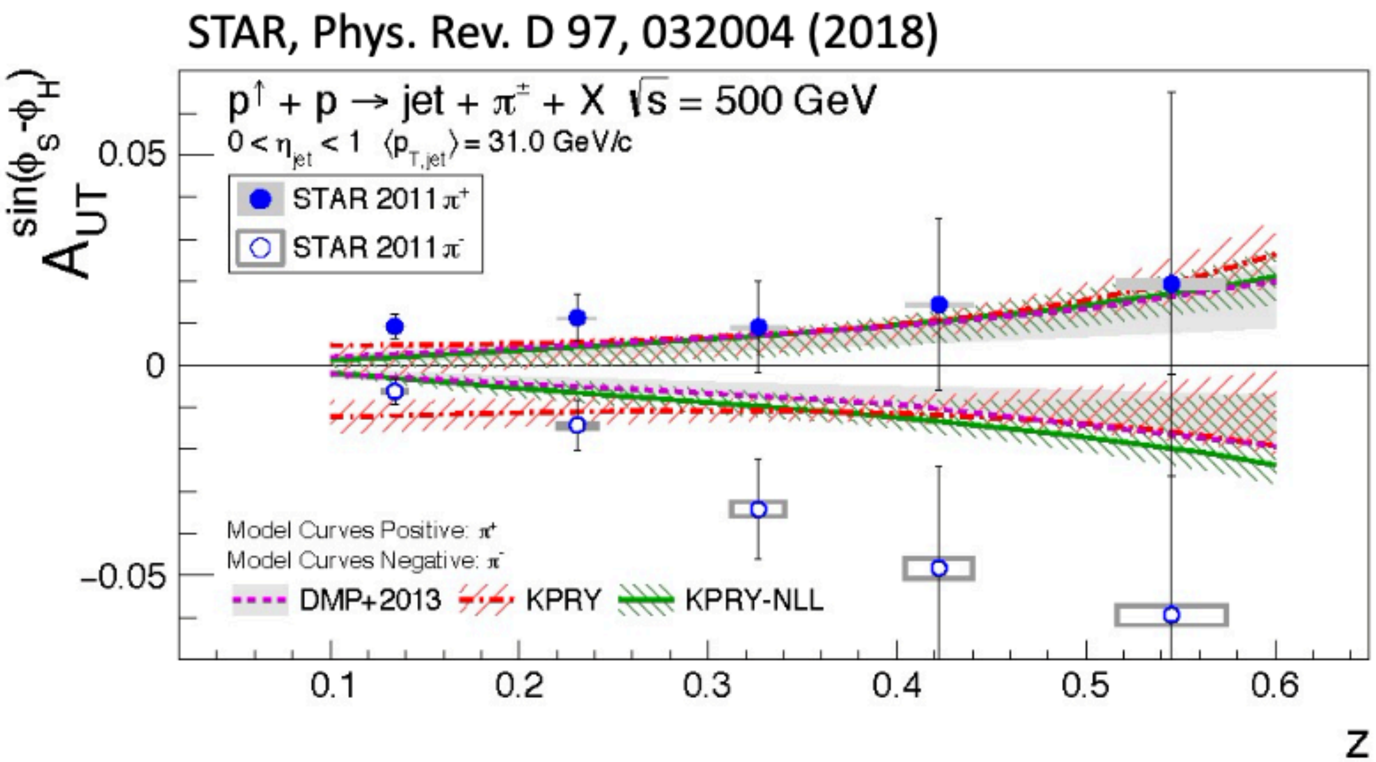
[HERMES, J. High Energ. Phys. 2020, 10 (2020)]

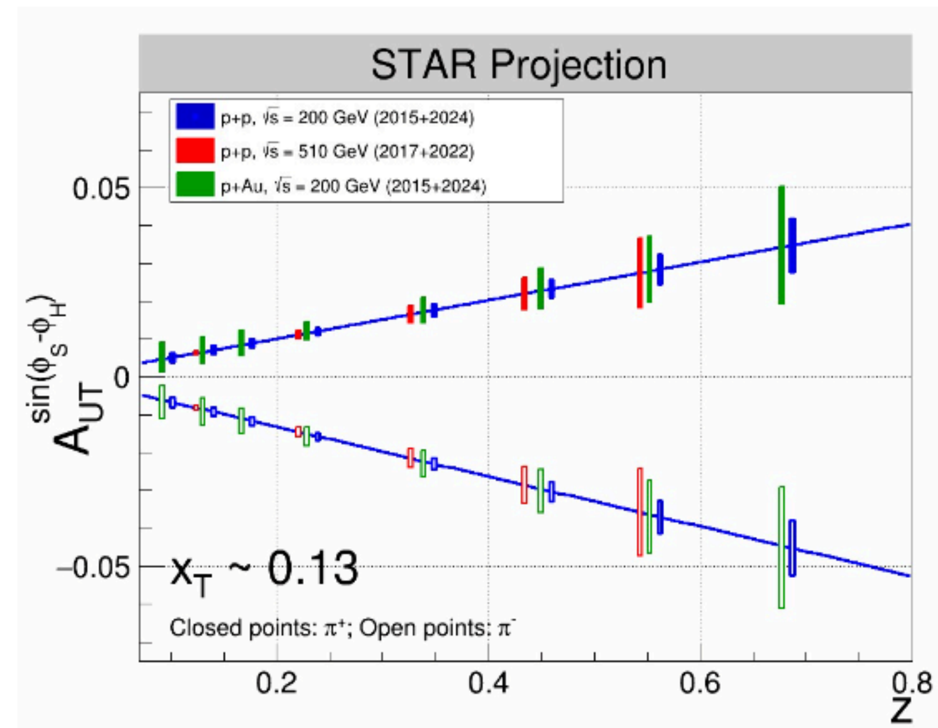




Collins asymmetries

- It can be also measured from hardons within jets in p+p [STAR, PRD 103 (2021) 92009]





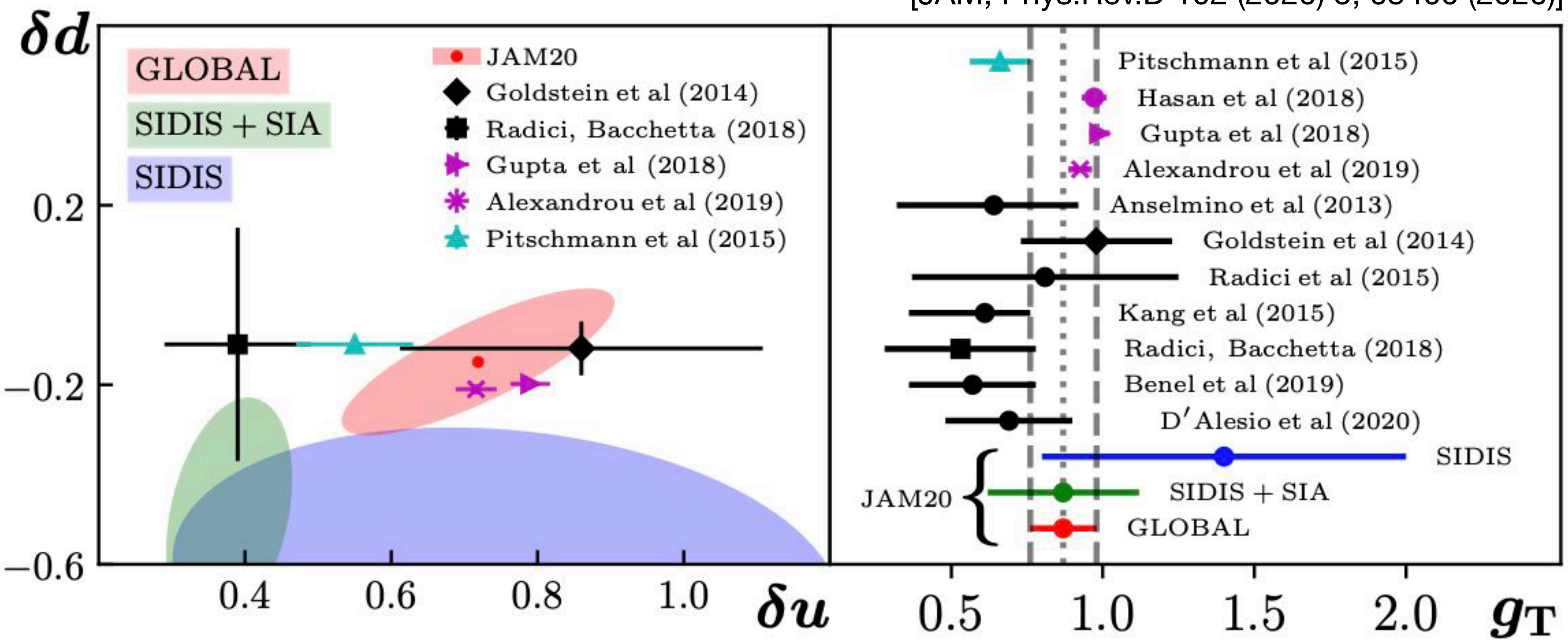
- Transverse spin asymmetries of the azimuthal distribution of pions inside of jets
- First Collins asymmetry measurement in p+p
- Compare with models based on SIDIS/e^+e^- : universality and factorization
- Generally good agreement with STAR data
- No sign of strong TMD evolution in the asymmetries

Transversity

- One of three standard PDFs, however least known due to its chiral odd nature
- Can be observed in combination with additional spin dependent final state effects (e.g Collins asymmetry ~ Transversity x Collins FF)

- Tensor charge
  - lowest moment of transversity $$\delta_T q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x)\right] \mathrm{d}x$$
  - Fundamental quantity of nucleon. Can be compared with Lattice QCD calculation.

[JAM, Phys.Rev.D 102 (2020) 5, 05400 (2020)]



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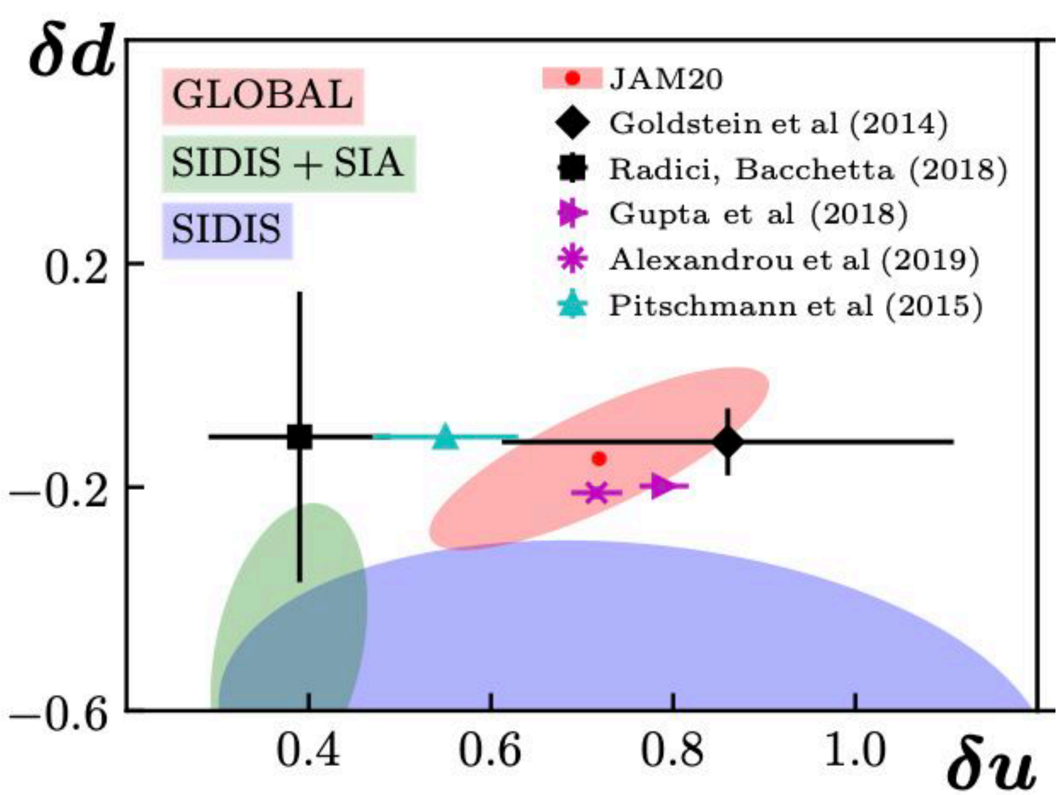
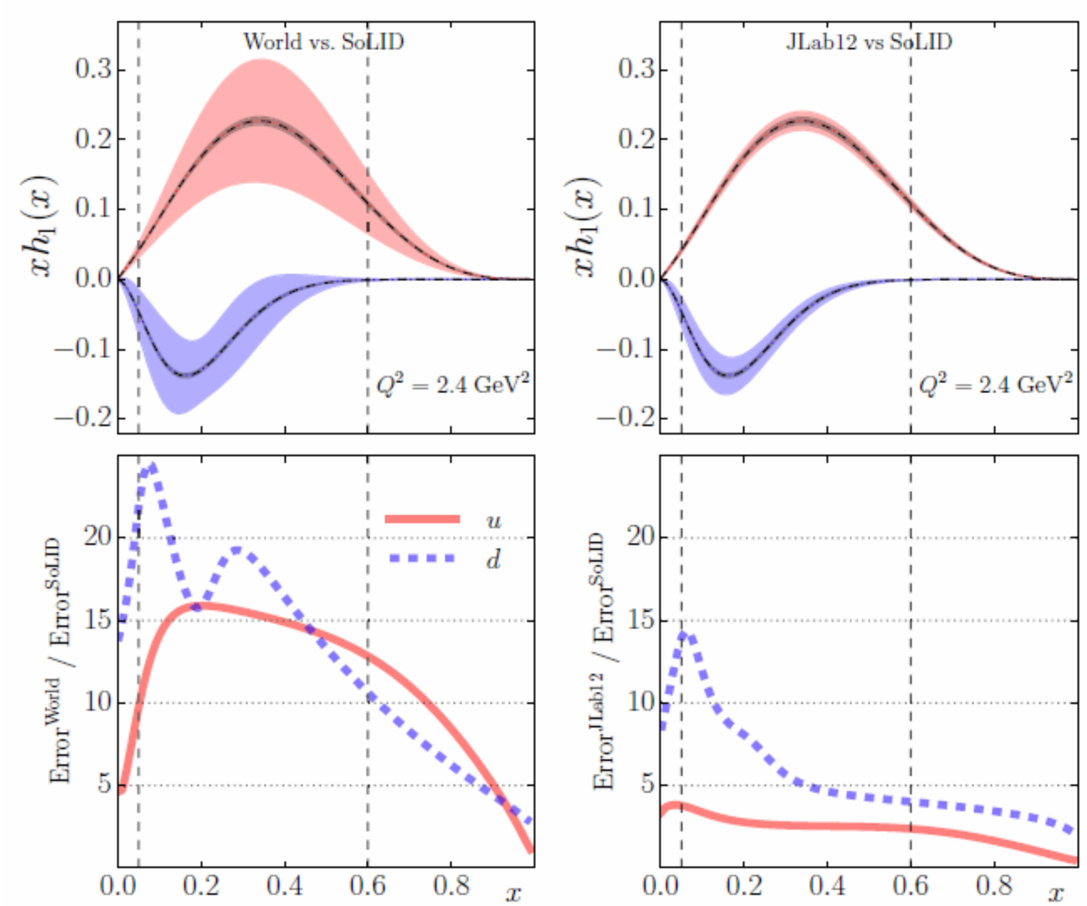
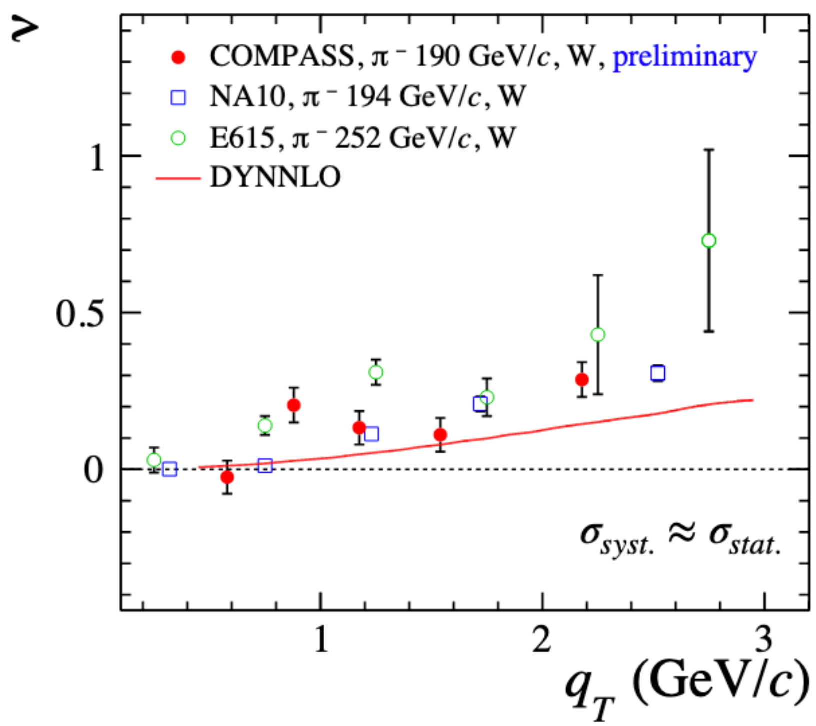




Unpolarized TMDs: Boer-Mulder

- **Unpolarized DY angular distribution**
  - **Pion-induced DY from COMPASS**

$$\frac{d\sigma}{d\Omega} \propto \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1+\lambda\, cos^2\theta_{CS} + \mu\, sin2\theta_{CS}\, cos\phi_{CS} + \frac{\nu}{2} sin^2\theta_{CS}\, cos2\phi_{CS}\right]$$

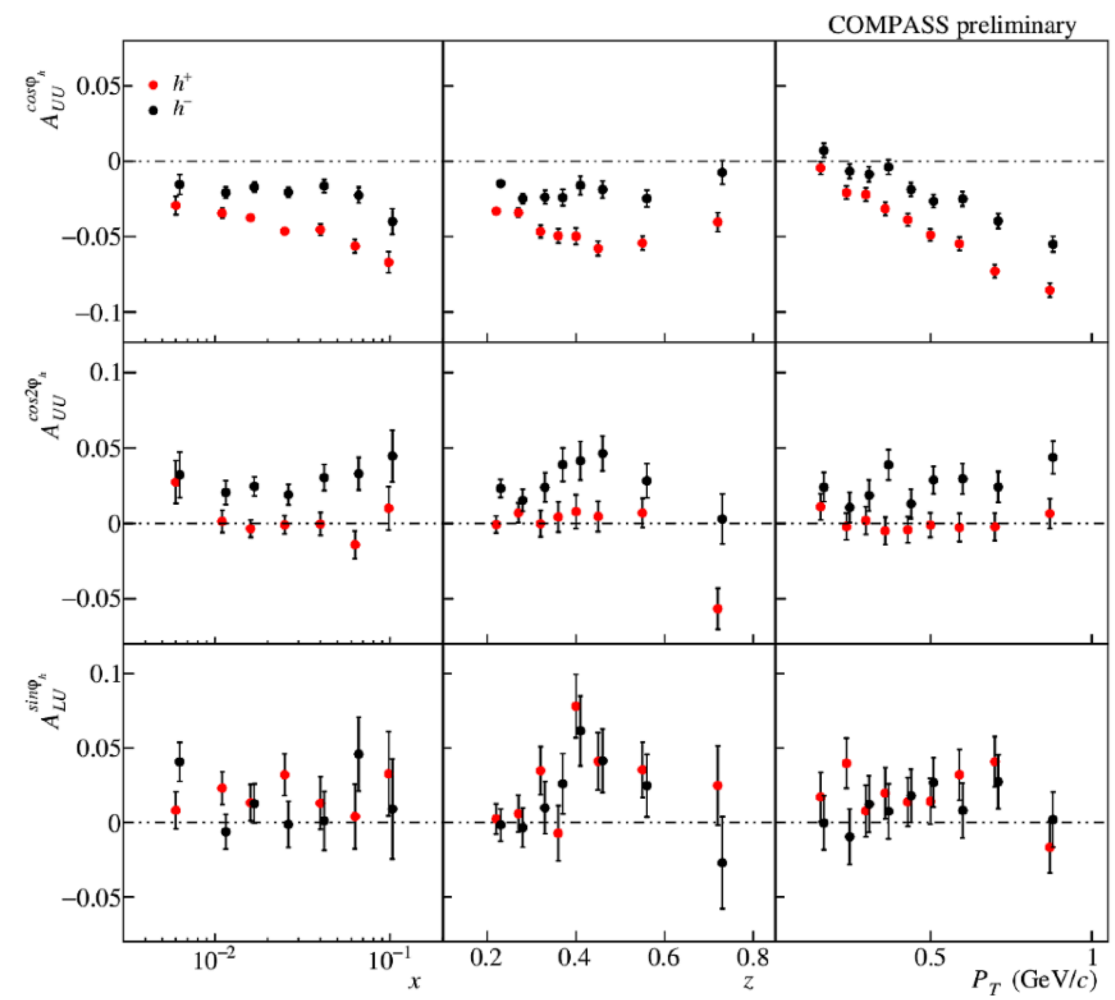


  - Tend to deviate from pQCD calculation, indicating nonzero BM effect

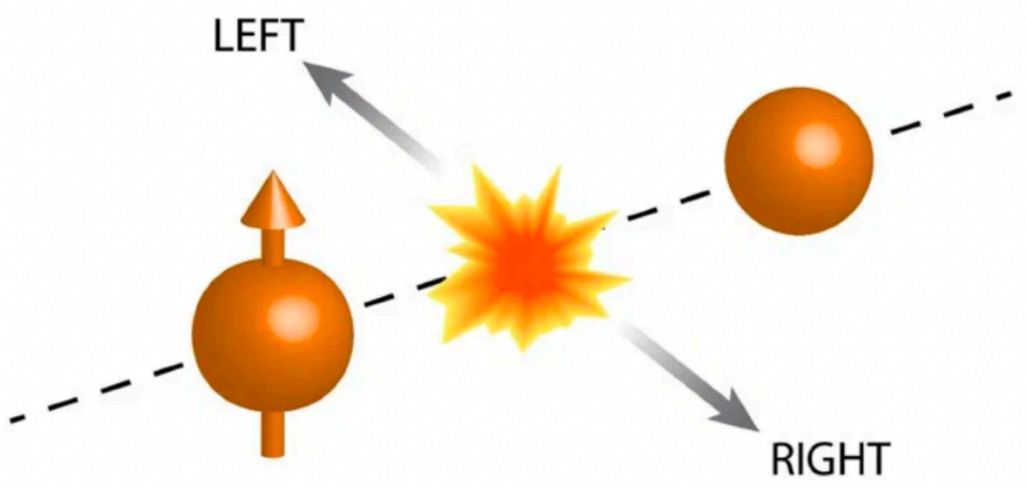
- **First photon-induced DY results at SeaQuest**

- **SIDIS measurements from COMPASS**
  - Transverse momentum distributions and azimuthal symmetries
  - Clear signal and kinematic dependence

$$A_{UU}^{\cos 2\phi_h} = \frac{F_{UU}^{\cos 2\phi_h}}{F_{UU,T} + \varepsilon F_{UU,L}}$$

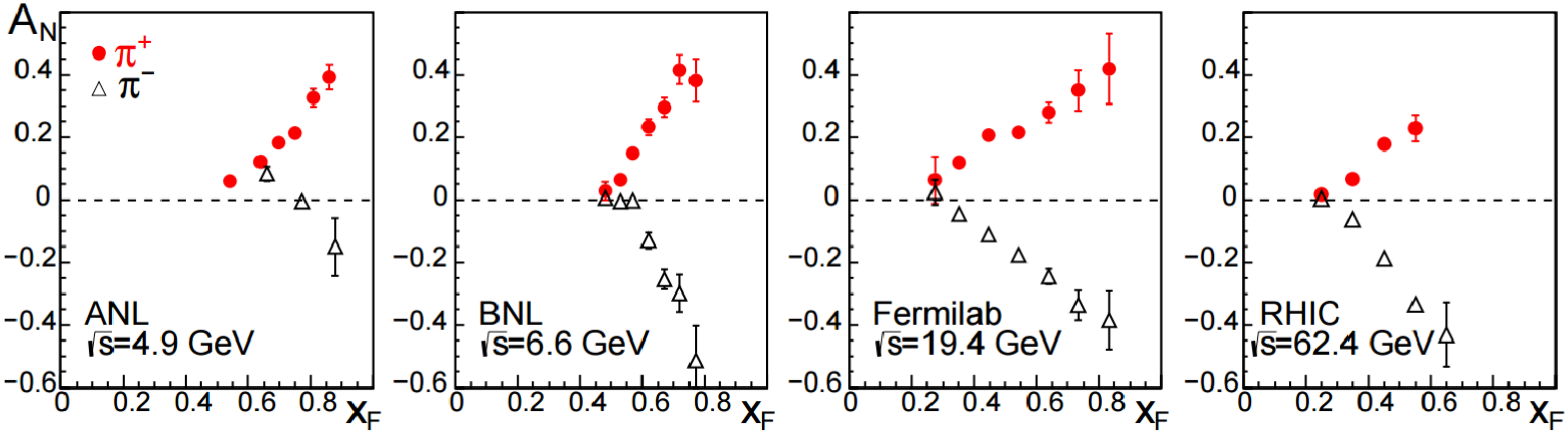


Transverse Single Spin Asymmetries in p+p



Transverse single spin asymmetry (TSSA)

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$



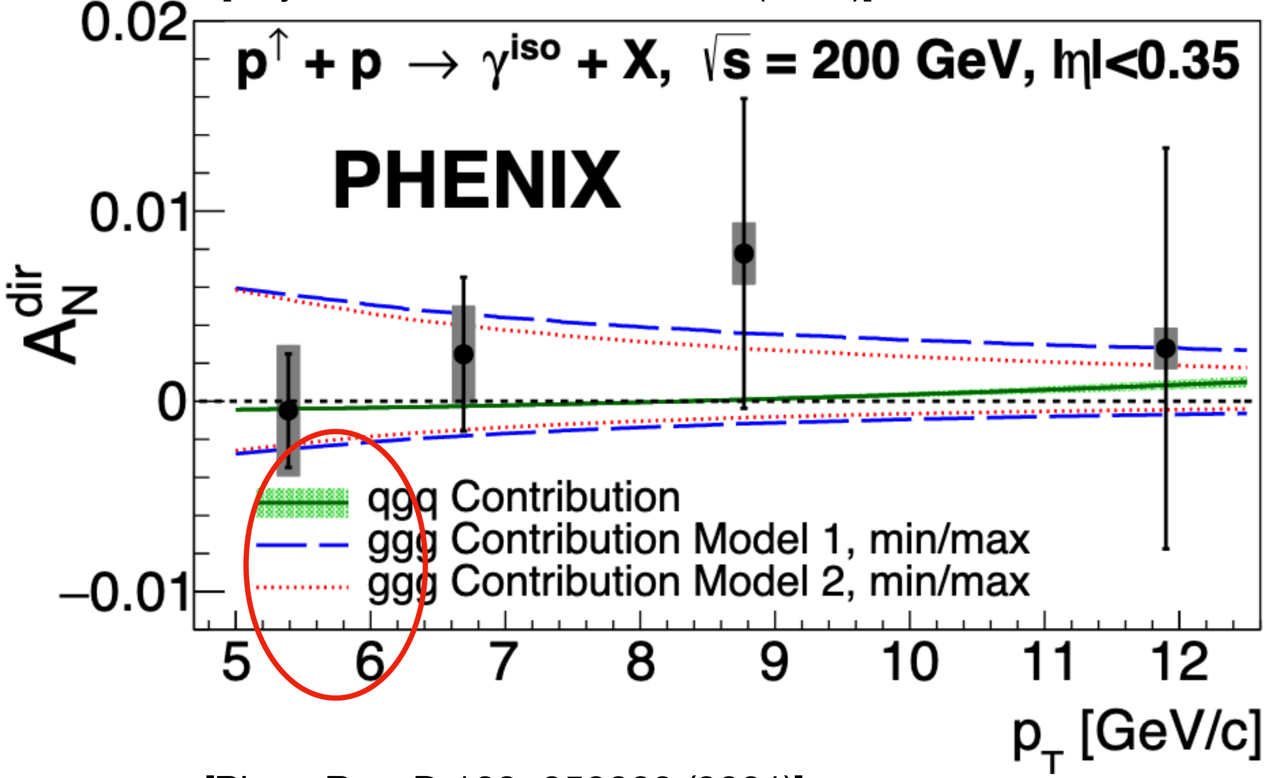
C. A. Aidala, S.D. Bass, D. Hasch, and G. K. Mallot, Rev. Mod. Phys. **85** 655 (2013).

Transverse Single Spin Asymmetries in p+p

- Twist-3 multiparton correlation in collinear framework:
  - Need one hard scale (pT), relevant to most inclusive hadron productions in p+p
  - qgq correlation function: interference between scattering off of quark and gluon versus a single quark of the same flavor
  - ggg correlation function: two gluons versus one gluon

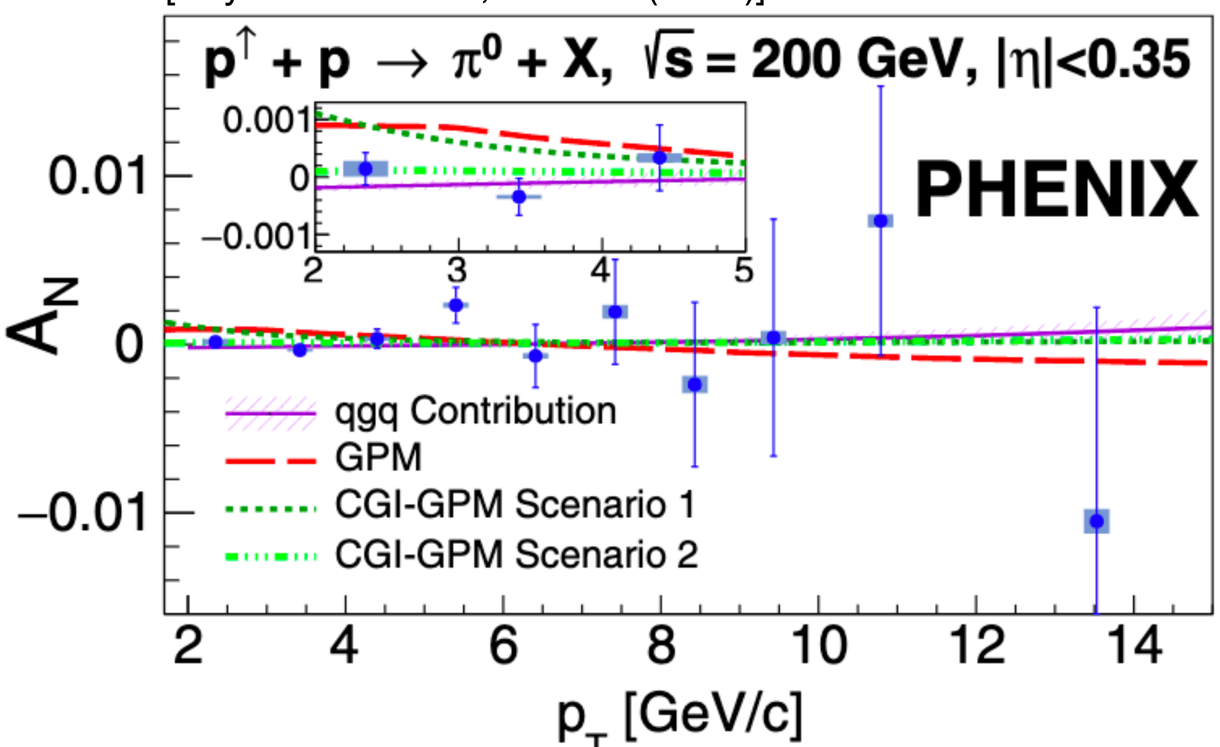
A_N: direct photons

[Phys. Rev. Lett. 127, 162001 (2021)]



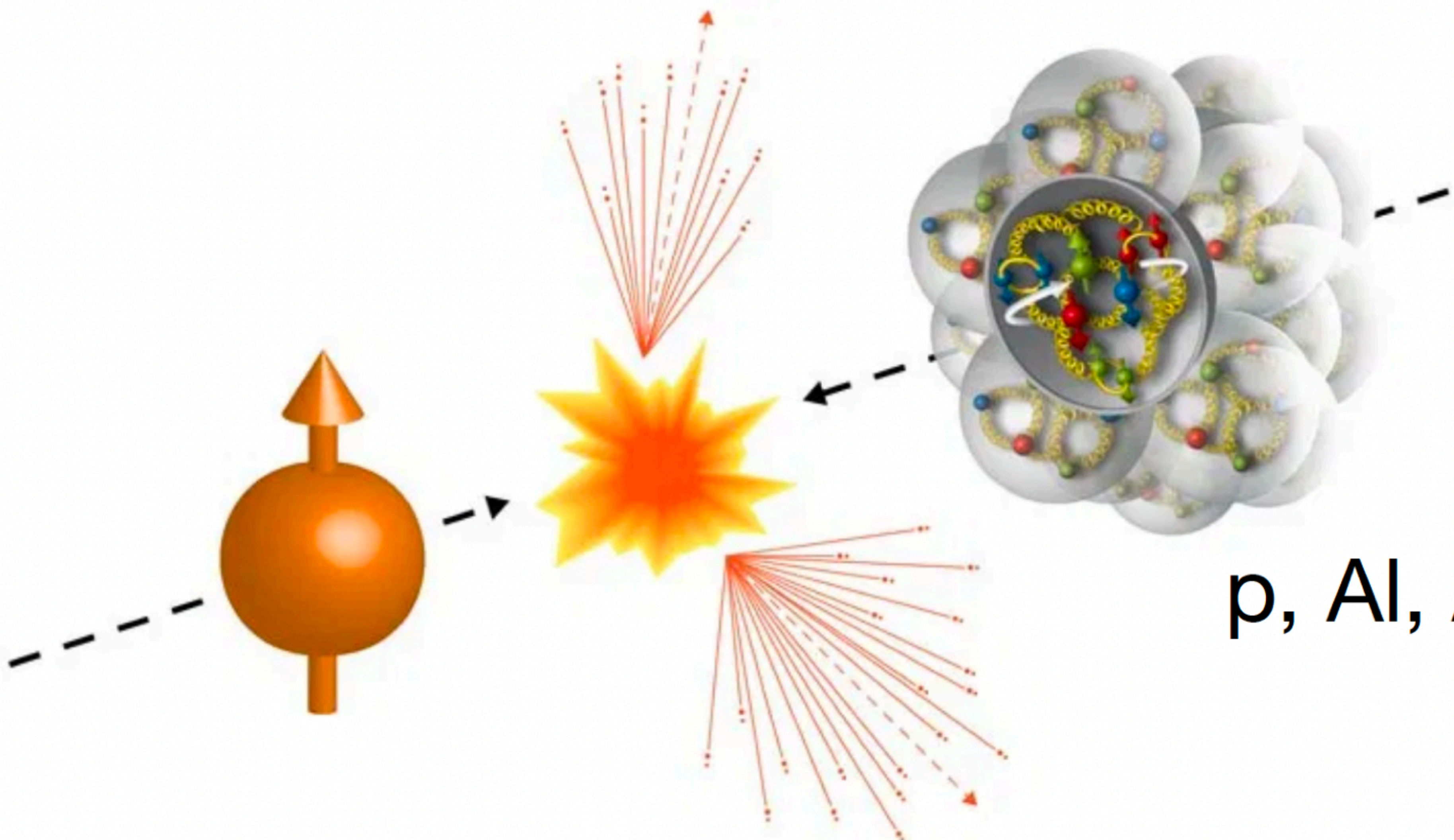
- First measurement of direct photon A_N at RHIC
- Direct photon channel is sensitive to initial state effects only
- Constraint the trigluon correlation functions
- Indirect access to Sivers function

[Phys. Rev. D 103, 052009 (2021)]



- Neutral pion measurement sensitive to both initial and final state effects
- Mid-rapidity measurements are sensitive to gluons
- Asymmetries consistent with zero, new data significantly improved precision compared to previous PHENIX results

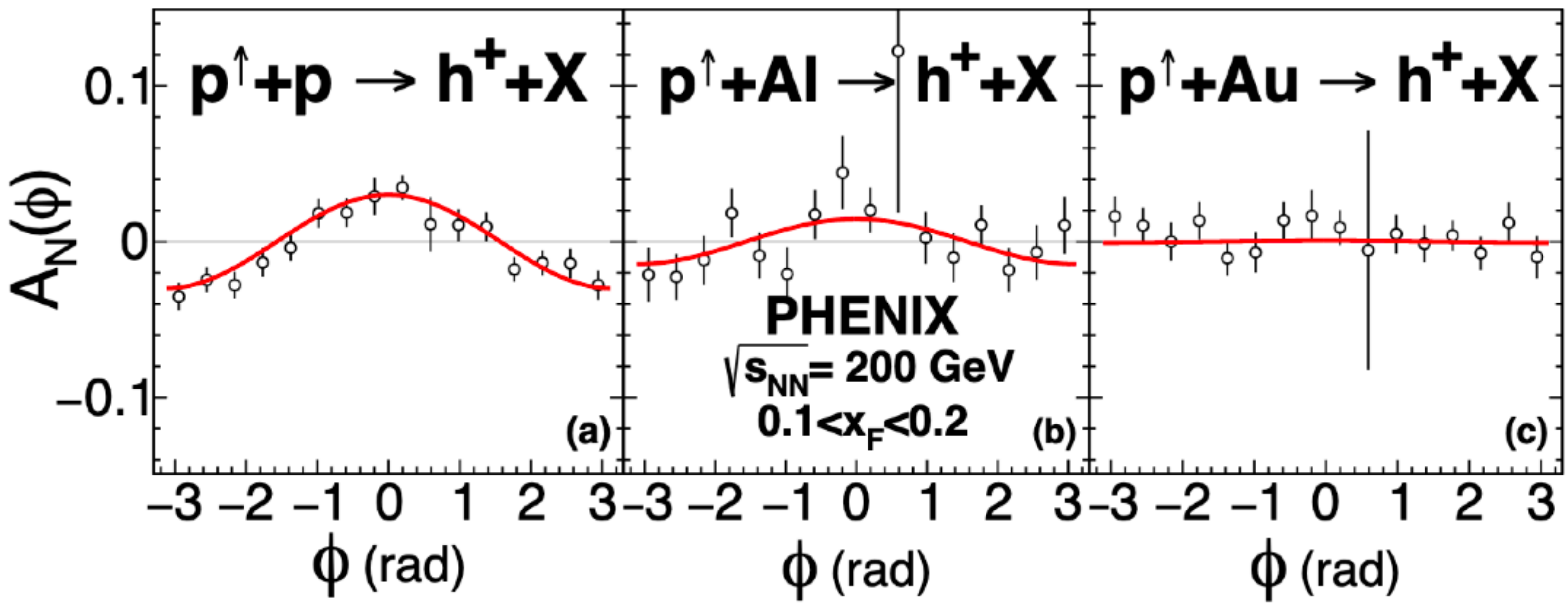
TSSAs in nuclear environment



p, Al, Au

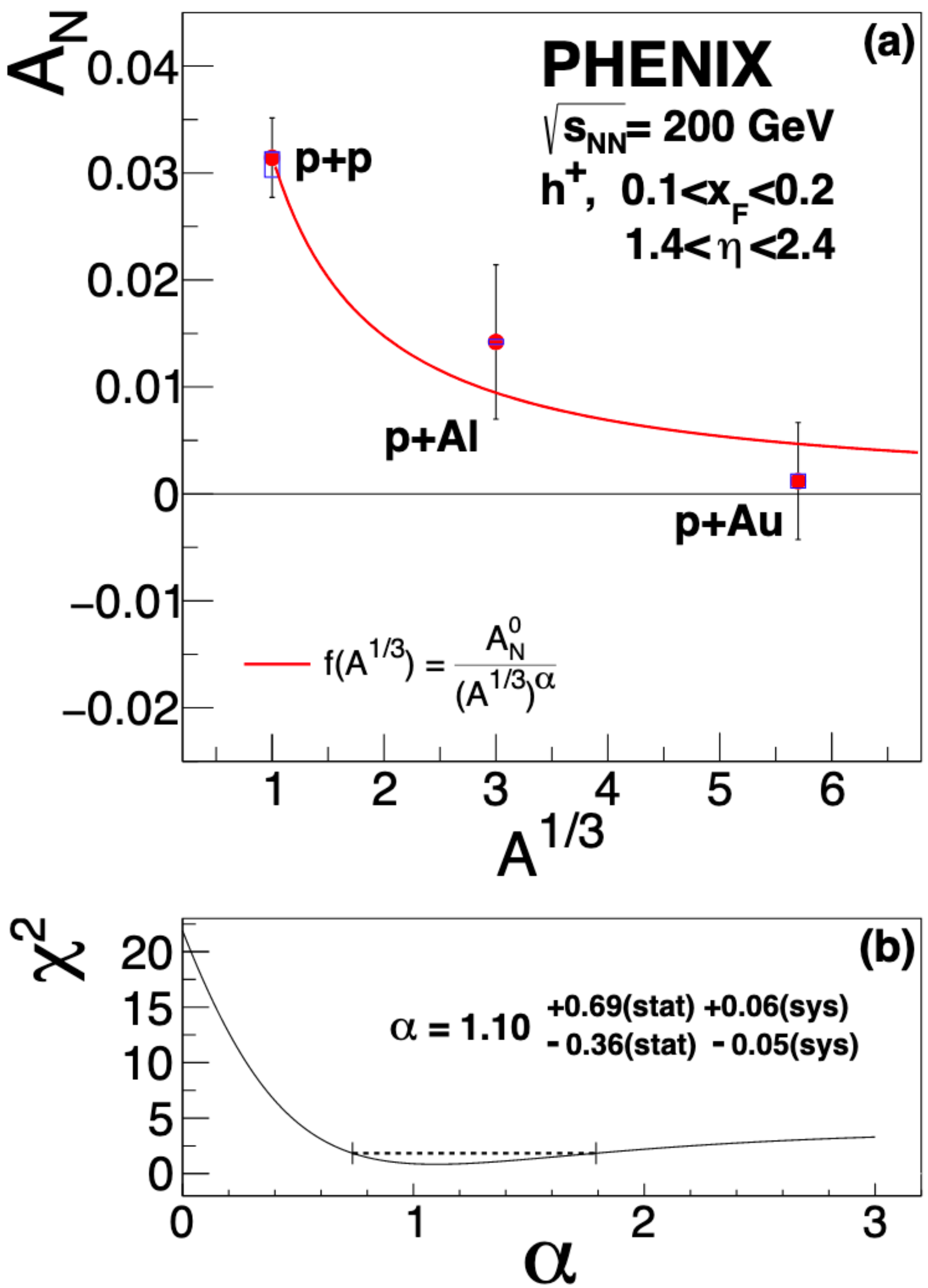
- First time polarized p+A collisions in 2015
- Study nuclear effects in A_N

Charged hadron AN



- Inclusive positively charged hadrons TSSA in the forward region
- Particle composition $\pi^{+}/K^{+}/p$: 45%/47%/5%

Charged hadron AN



- Suppression of A_N in p+Au observed
    - Suppression in p+A is sensitive to saturation scale
    - $A^{1/3}$ suppression in models with gluon saturation effects:

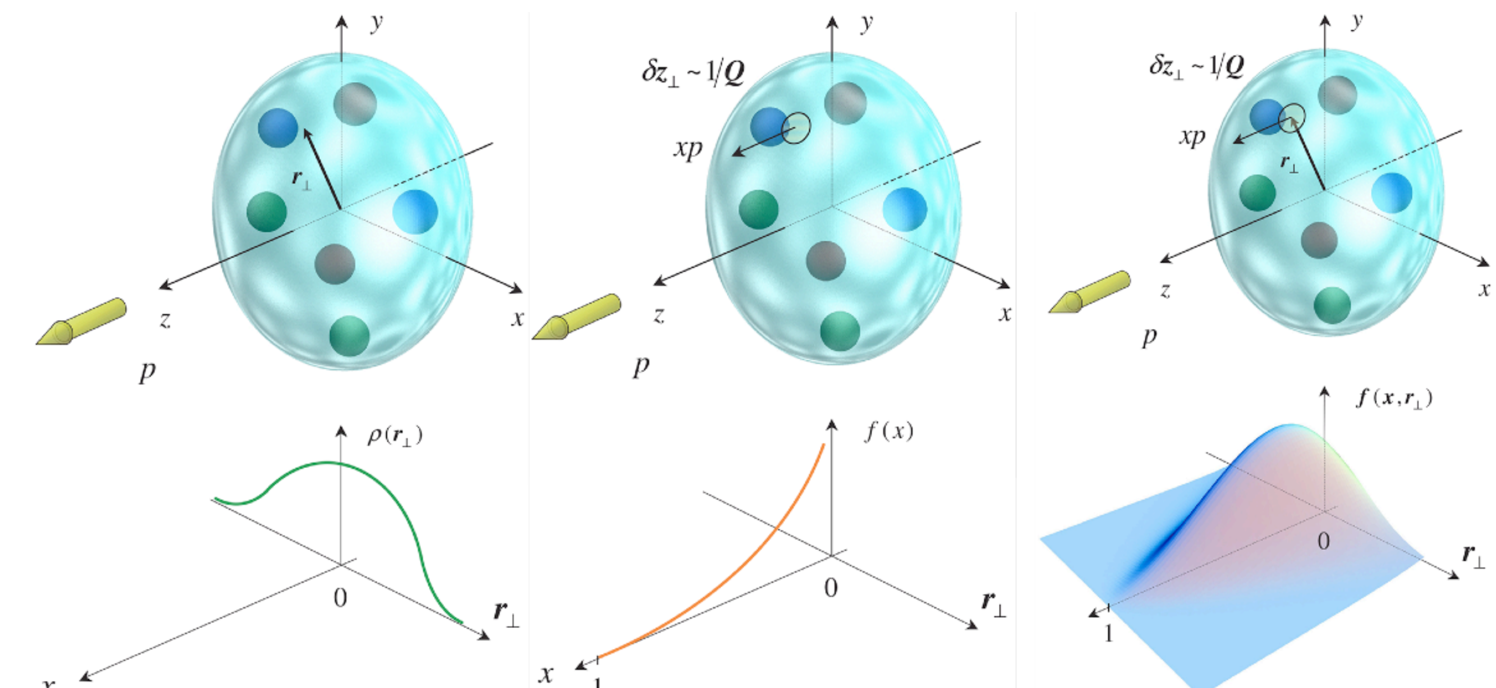
      PRD84 (2011) 034019, PRD95 (2017) 014008
    - <pT> of this measurement > saturation scale in Au

21

- No A dependence observed from mid rapidity pi0 measurements

Generalized Parton Distributions

- **Nucleon Tomography**



Transverse position of partons
Elastic FFs

Long. Momentum distribution
PDFs

GPDs

GPD	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	H_T, $\tilde{H}_T$

Leading-twist GPDs:
4 chiral-even GPDs $H, \tilde{H}, E, \tilde{E}$
- DVCS, DVMP, Pseudoscala mesons
4 chiral-odd GPDs $H_T, \tilde{H}_T, E_T, \tilde{E}_T$
- ρ production, ..

- **Quark OAM contribution to the proton spin**

$$J_\mathrm{q} = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} \mathrm{d}x \, x \left[H^\mathrm{q}(x, \xi, t) + E^\mathrm{q}(x, \xi, t) \right] \qquad J_q = \frac{1}{2}\Delta\Sigma + L_q$$

[X. Ji PRL 78, 610 (1997)]

- **Accessed via exclusive processes;**
- DVCS, DVMP, TCS
- cross section and asymmetries (beam charge, beam spin)

GPD Program

Collider mode e-p forward fast proton

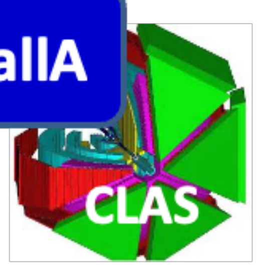
Polarised 27 GeV e-/e+
Unpolarised 920 GeV p
~ Full event reconstruction

Fixed target mode slow recoil proton

hermes

Polarised 27 GeV e-/e+
Long, Trans polarised p, d target
Missing mass technique
2006-07 with recoil detector

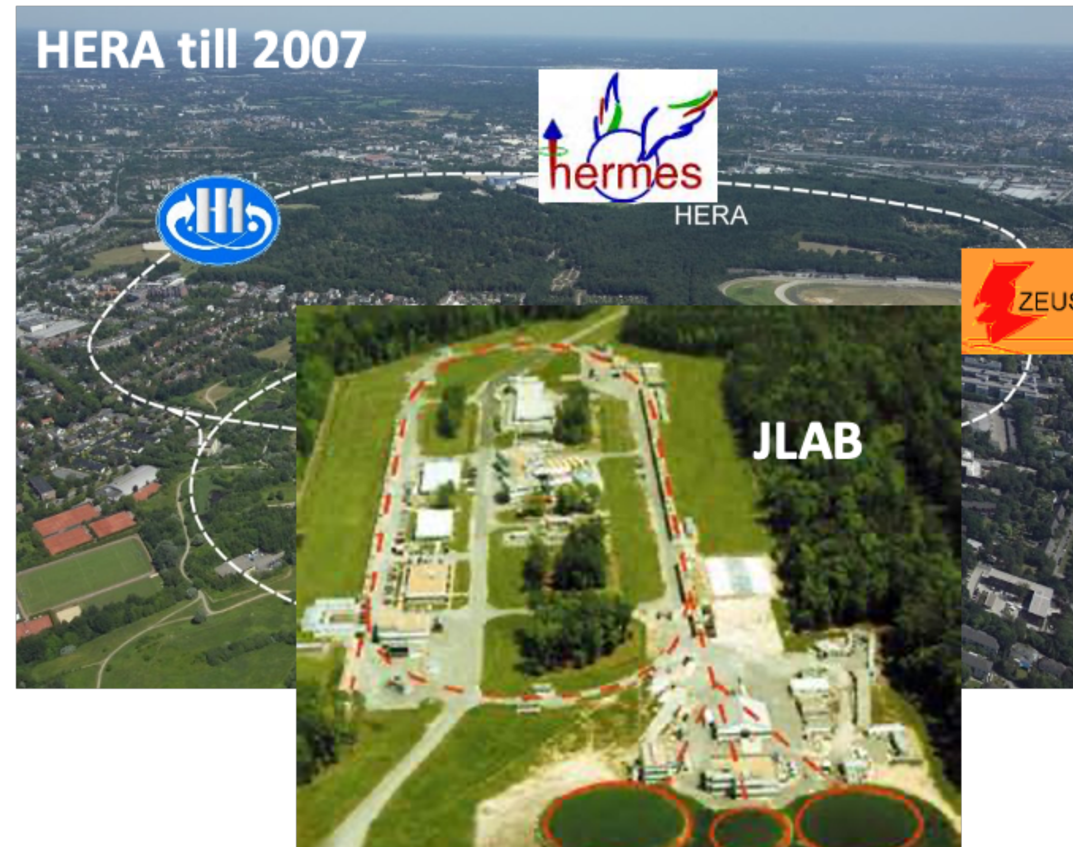
HallA



High lumi, highly polar. 6 & **12 GeV e-**
Long, (Trans) polarised p, d target
Missing mass technique (Hall A)
~ Full event reconstruction (CLAS12)

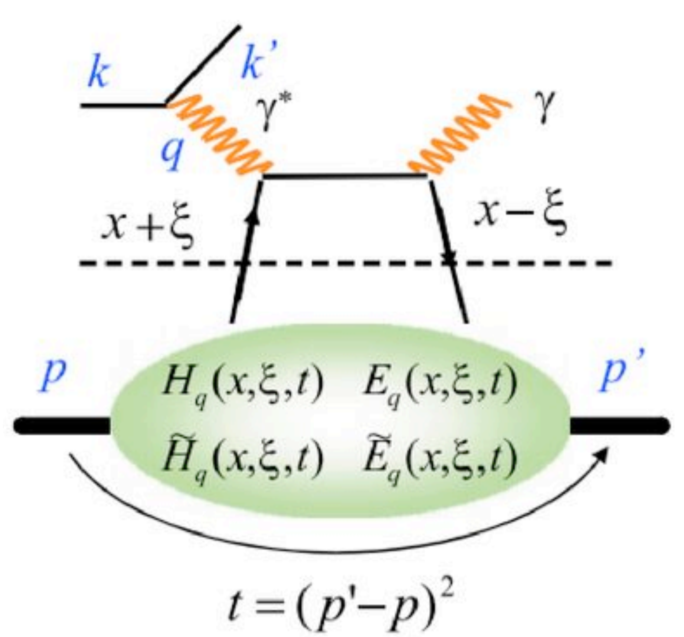
COMPASS

Highly polarised **160 GeV $\mu+/\mu-$**
p target, (Trans) polarised target
with recoil detection



Slide from N d'Hose, Tranversity 2014

Deeply Virtual Compton scattering



- **Sensitive to H and E**
- **GPDs appear in the DVCS amplitude through CFFs**

$$\mathcal{H}_{++}(\xi,t) = \int_{-1}^{1} H(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right)dx$$

$$\sigma_(ep \to ep\gamma) = |DVCS|^2 + |BH|^2 + Interference$$

$q = (p_\mu - p_{\mu'})$: 4-momentum of virtual photon

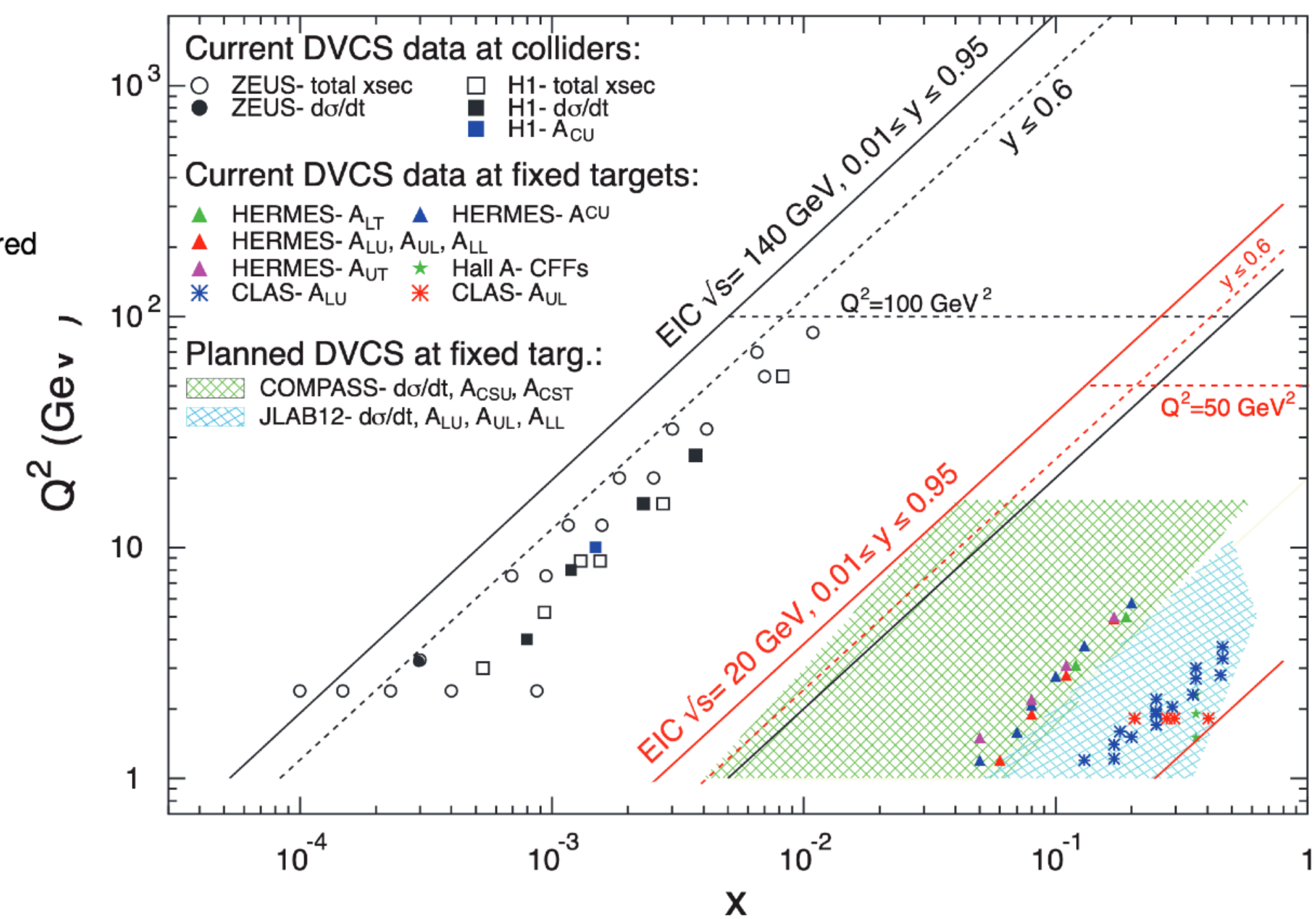
$Q^2 = -q^2$: virtual photon virtuality

$t = (p_P - p_{P'})^2$: 4-momentum transfer to nucleon squared

x: average longitudinal momentum fraction

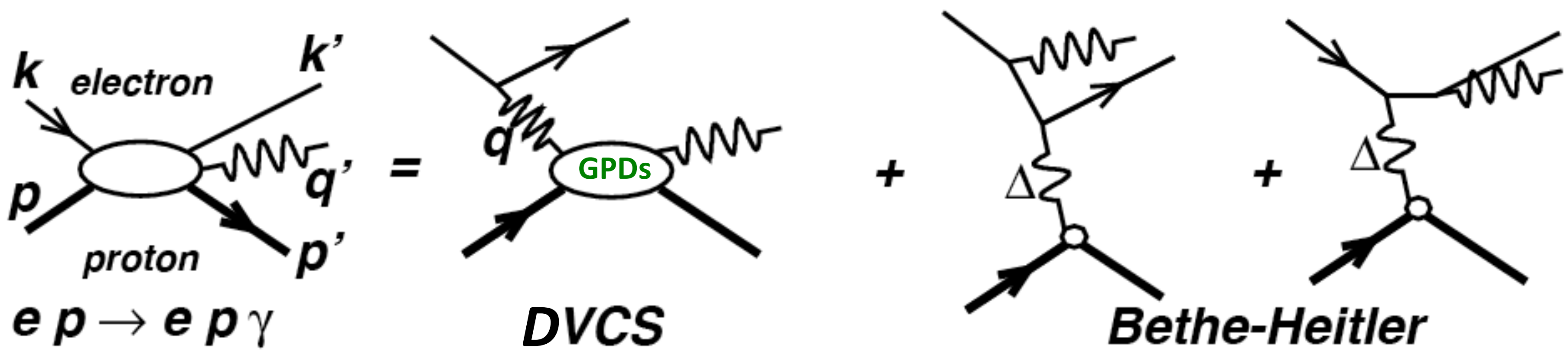
ξ: half of longitudinal momentum fraction transfer

[EIC Yellow Report, arXiv:2103.05419]



DVCS cross section

Measuring DVCS to access GPDs information



$$\frac{d^4\sigma(lp\longrightarrow lp\gamma)}{dx_B dQ^2 dt d\phi} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_l\, d\sigma^{DVCS}_{pol} + e_l(\mathcal{R}e(I) + P_l\, \mathcal{I}m(I))$$

Known if Nucleon FFs are known

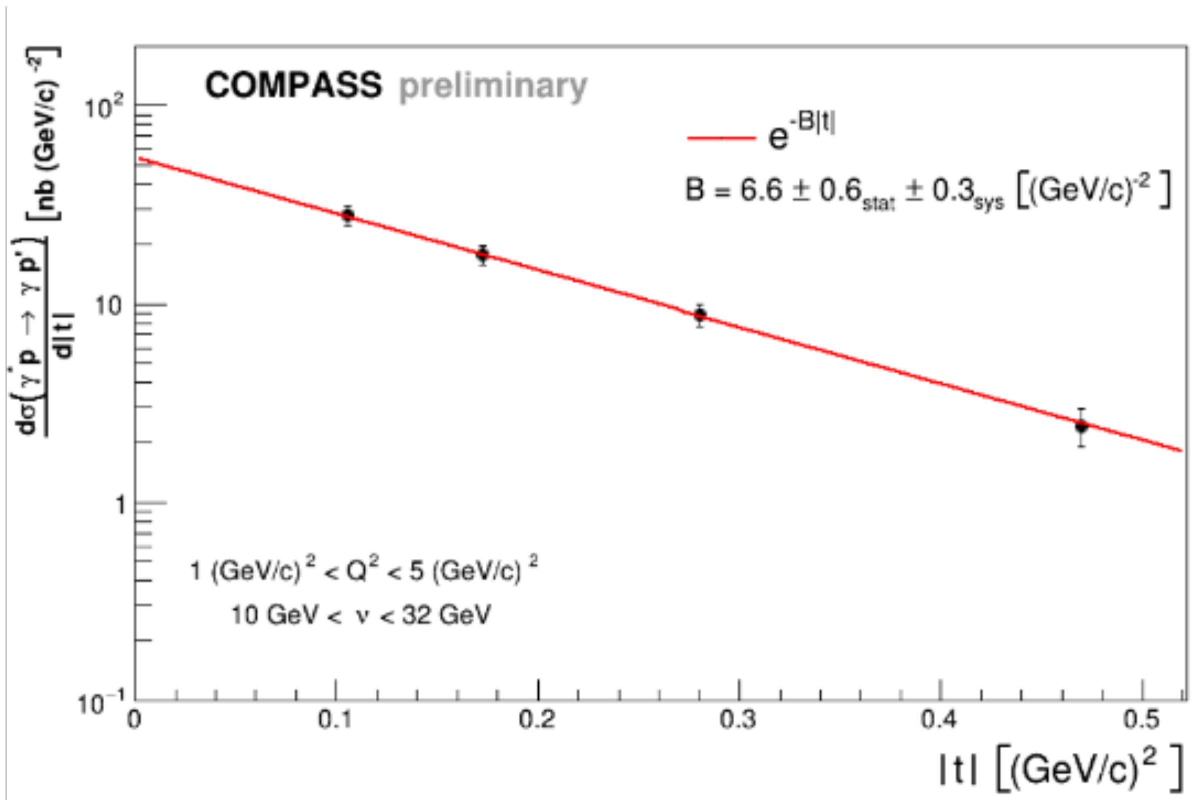
Bilinear combinations of GPD/CFFs

Linear combinations of GPD/CFFs and FFs

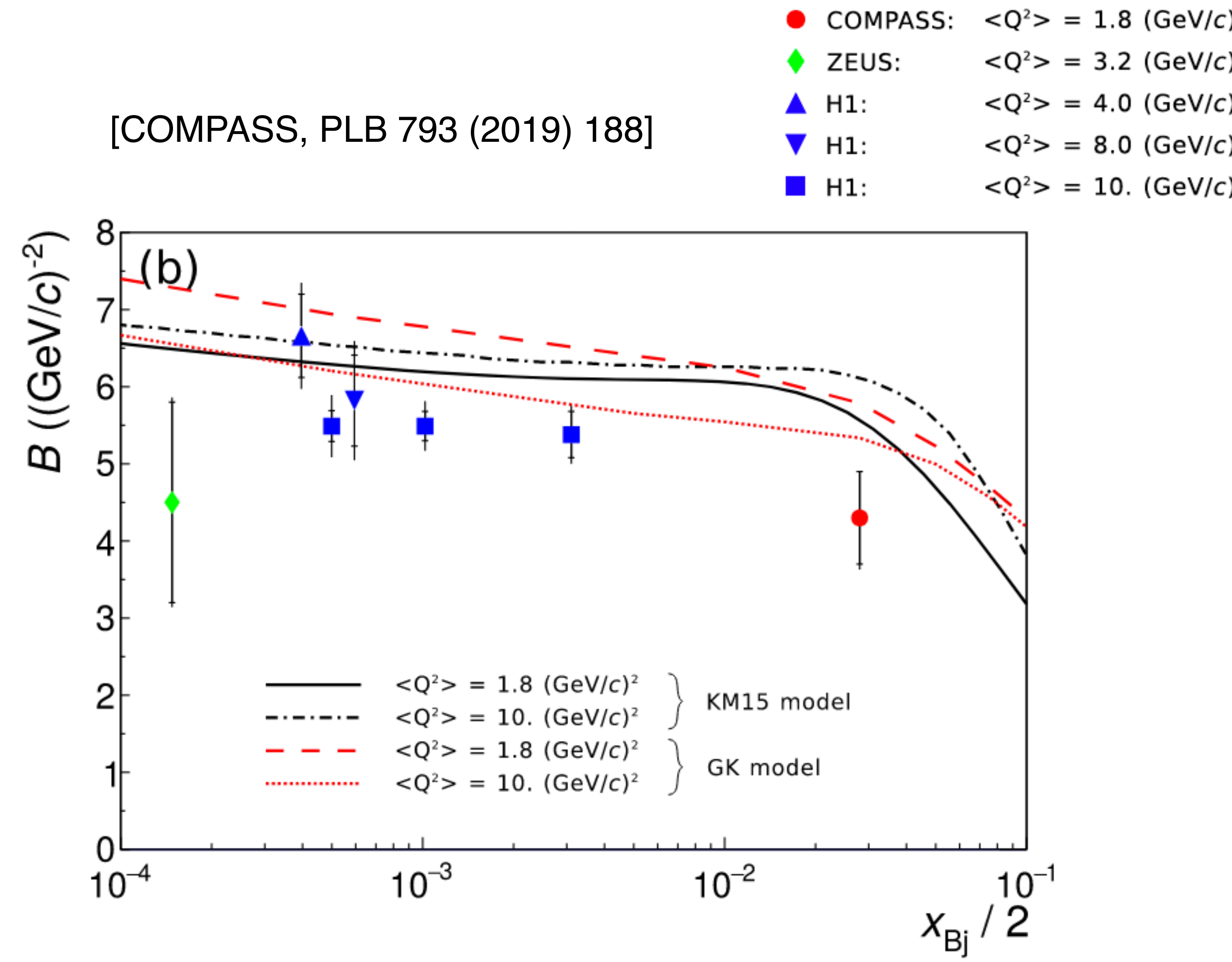
P_l : polarization target or beam

e_l : charge of the lepton beam

t-dependent cross section



[COMPASS, PLB 793 (2019) 188]

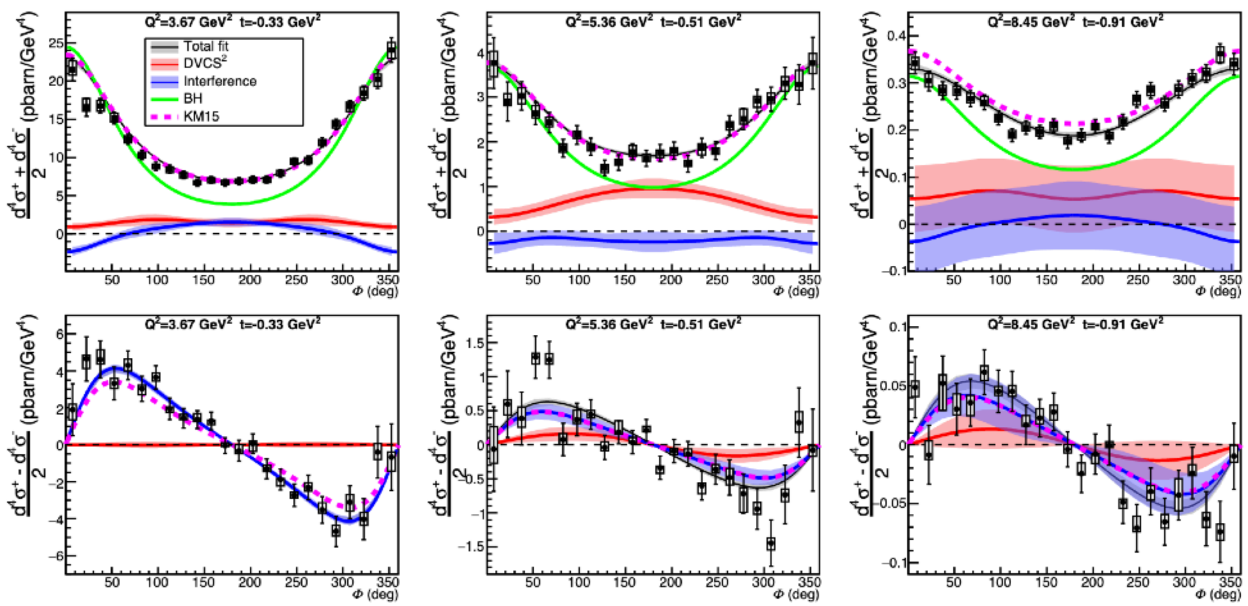


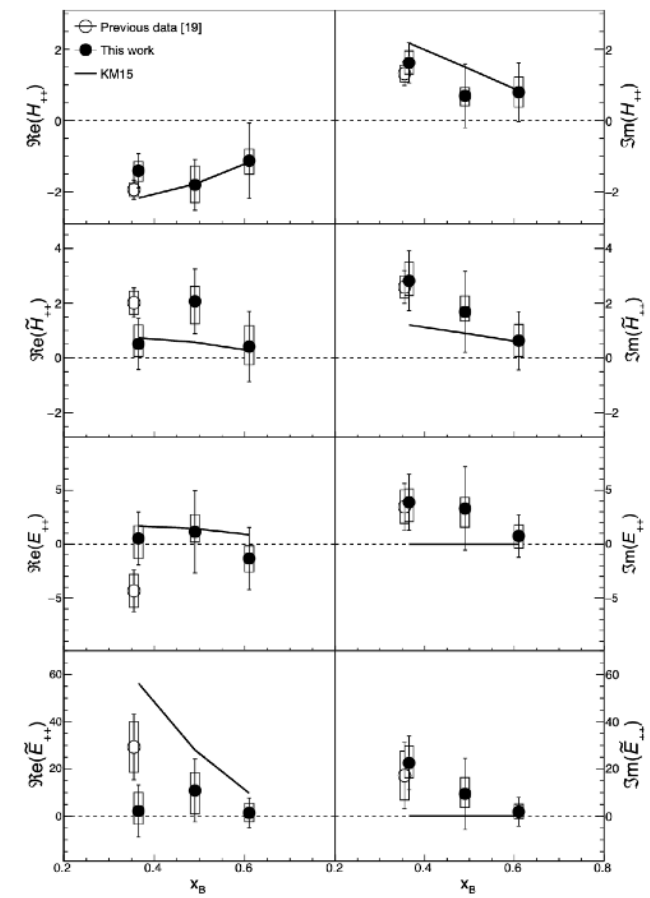
$$d\sigma^{\rm DVCS}/dt \sim e^{-B|t|} \propto c_0^{\rm DVCS} = (Im\mathcal{H})^2$$

t-slope of DVCS cross section related to distance between struck quark and spectator c.m. $\langle r_{perp}^2 \rangle$ $\langle r_\perp^2(x_{Bj})\rangle \approx 2B(x_{Bj})$

DVCS at large-x

- **JLab HallA** arXiv:2201.03714 [hep-ph]
  - First experimental extraction of all four helicity-conserving CFFs

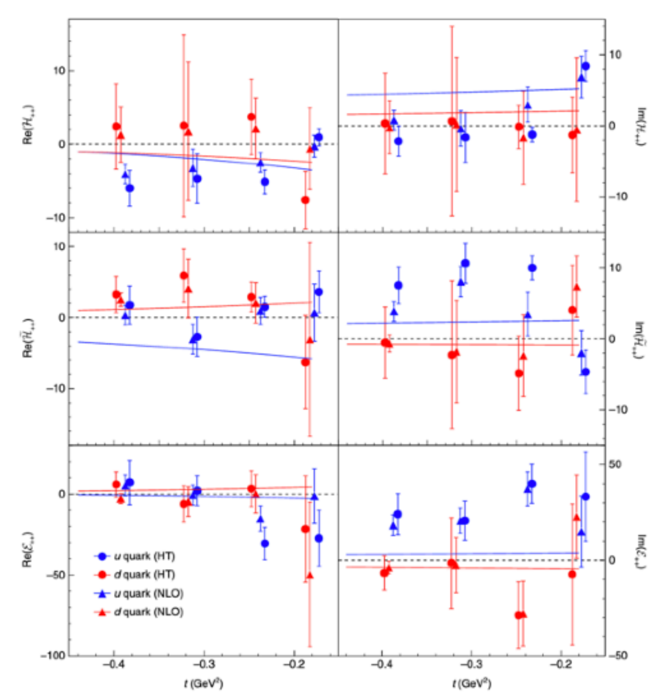




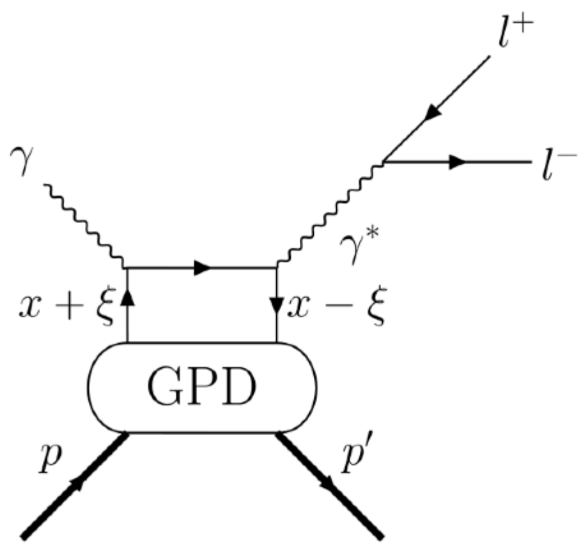
- **DVCS off neutron**
  - Flavor separation of CFFs (combined with proton data)
  - Sensitive to GPD E

[Benali, *et al.*, Nature Physics 16, 191–198 (2020)]

6 GeV data from HallA, NLO and HT analyses



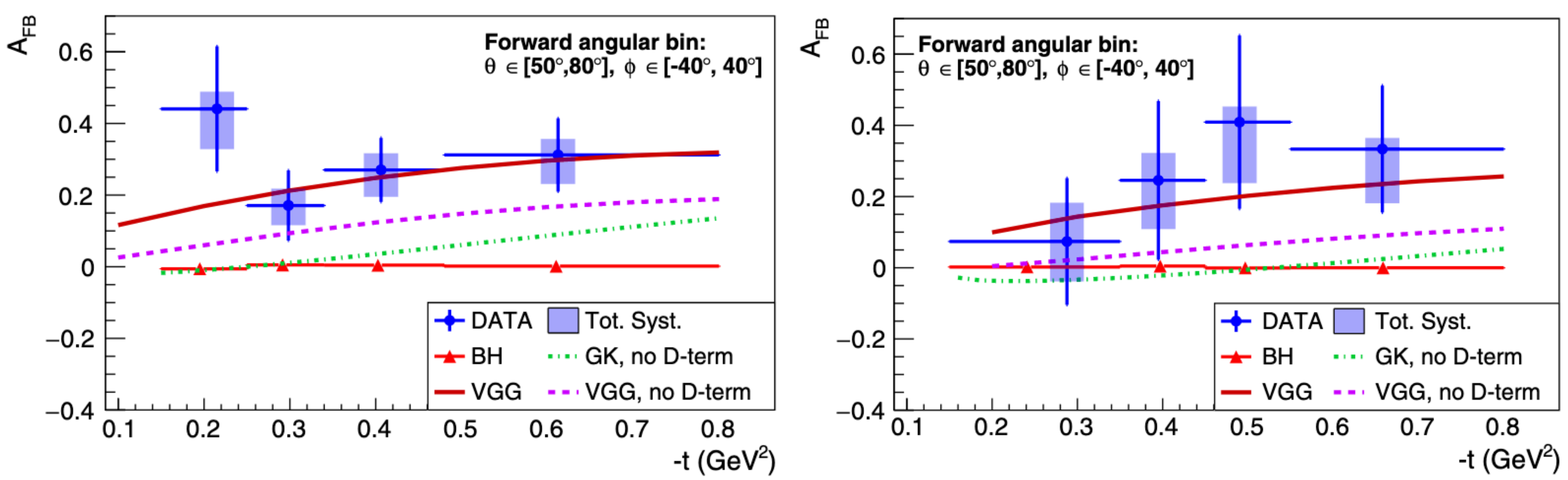
Timelike Compton Scattering



- Time-reversal conjugate process of DVCS
- Both $\mathrm{Im}(\mathcal{H})$ and $\mathrm{Re}(\mathcal{H})$ can be accessed
- Comparison with DVCS: Universality test of GPDs
- Real part of the CFF and nucleon D-term:

  pressure distribution in the nucleon [Burkert et al., Nature 557, 396-399 (2018)]

- **First measurement by CLAS12** [CLAS, Phys. Rev. Lett. 127, 262501 (2021)]



Exclusivity

- Example: DVCS process

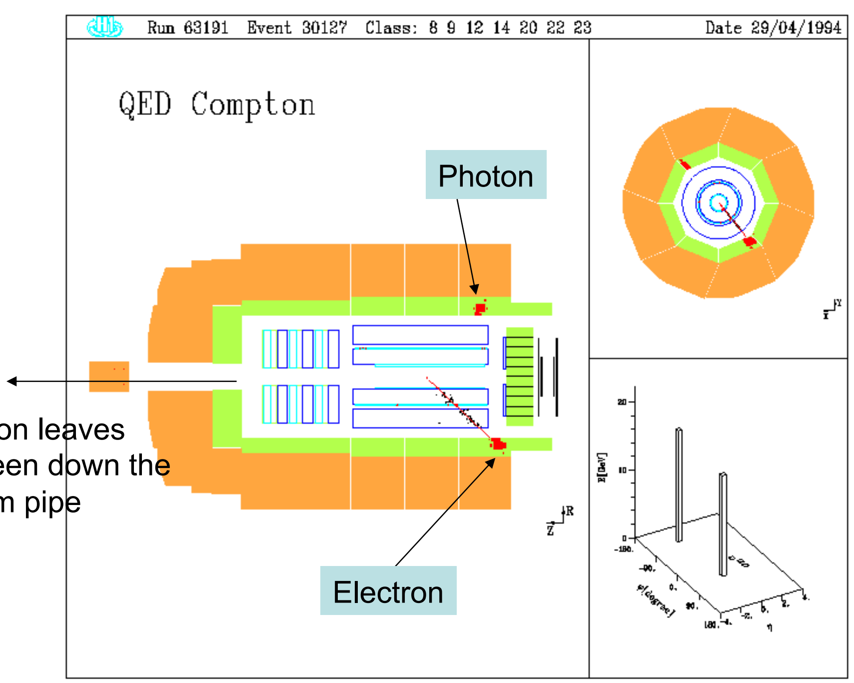
$$e + p \rightarrow e' + \gamma + p'$$

- Would be ideal to have full event reconstruction
- Can measure recoil proton?
  - Forward detector at collider
  - Fixed target: slow recoil

A very simple event :

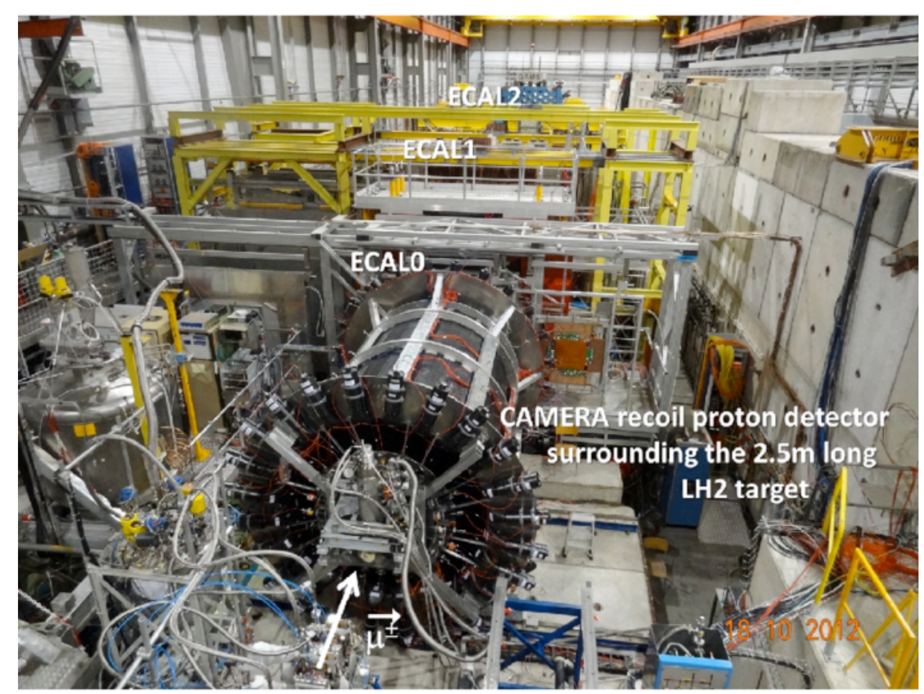
$$ep \rightarrow e\gamma(p)$$

Detect proton using forward tagger



H1 Events

Joachim Meyer DESY 2005



Exclusivity

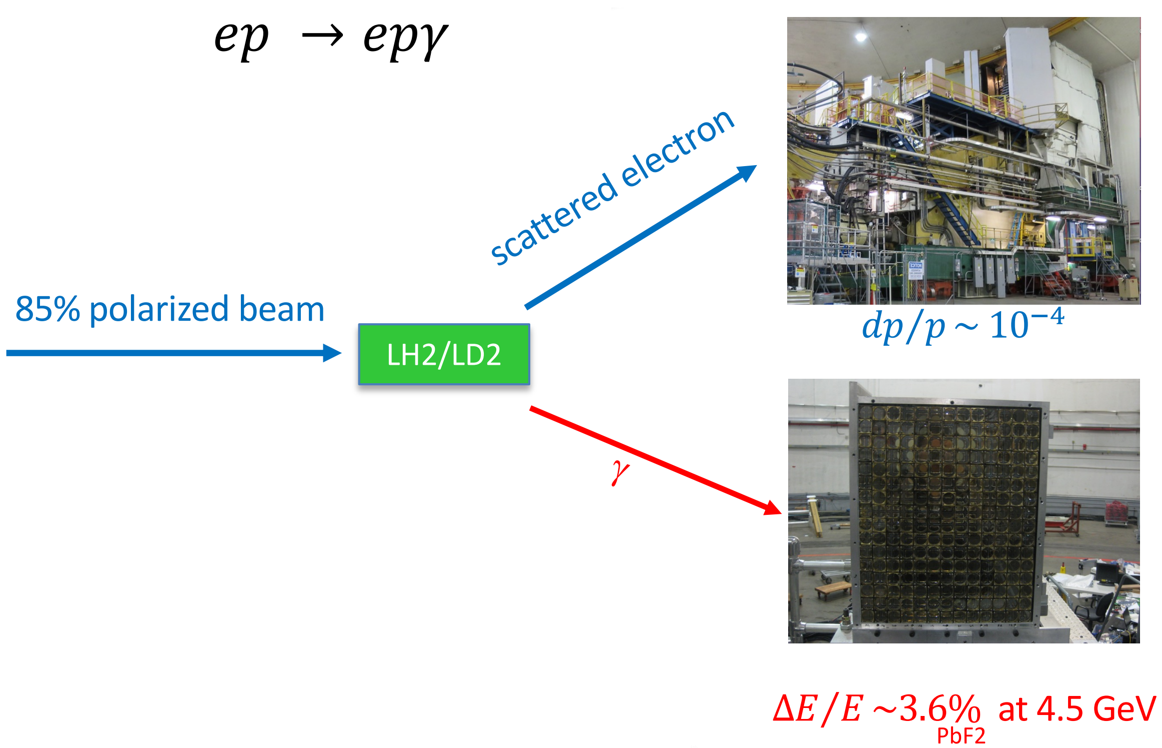
- Example: DVCS process

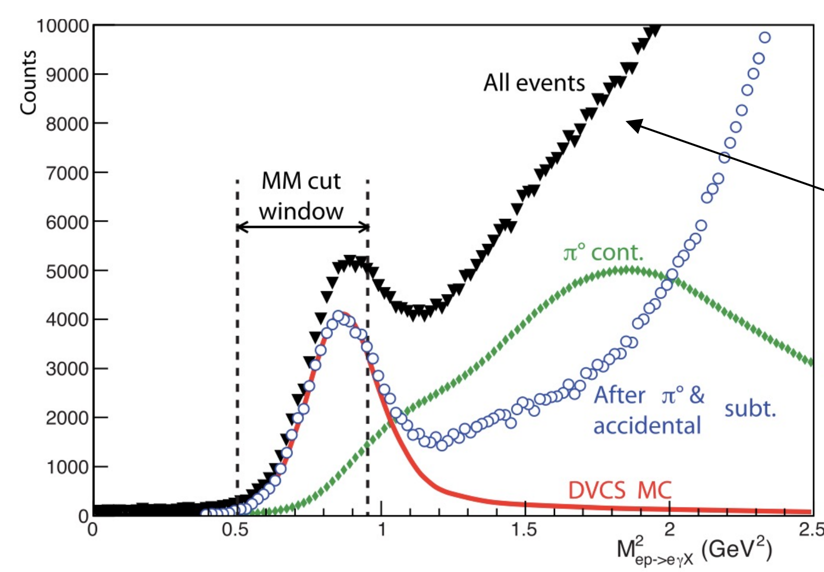
$$e + p \rightarrow e' + \gamma + p'$$

- Would be ideal to have full event reconstruction
- No recoil detector?
  - Missing mass reconstruction

JLab HallA DVCS

$ep \rightarrow ep\gamma$





H(e,e'γ)X

X can be

- p : $ep \rightarrow ep\gamma$
- γp : $ep \rightarrow ep\,\pi^0, \pi^0 \rightarrow \gamma\gamma$
- Nπ: $ep \rightarrow eN\gamma\pi$

…

Exercise: measure π^0

- VIP as an observable (VIO?) of its own measurements, but also very useful for detector calibration, background suppression when looking for other final states.
- From Lecture 1:
    - Neutral pion lifetime is ~10^{-18} sec.
    - Neutral pion decay modes:
        - two photons decay (BR: ~0.988), Dalitz decay (BR: ~0.0117)

Q1: How would you detect the pion?

Q2: What detector would you use?

Q3: How do you know you detected pions?

Exercise: measure π^0

- Invariant mass of pion: 135 MeV/c²
- In two-particle collisions

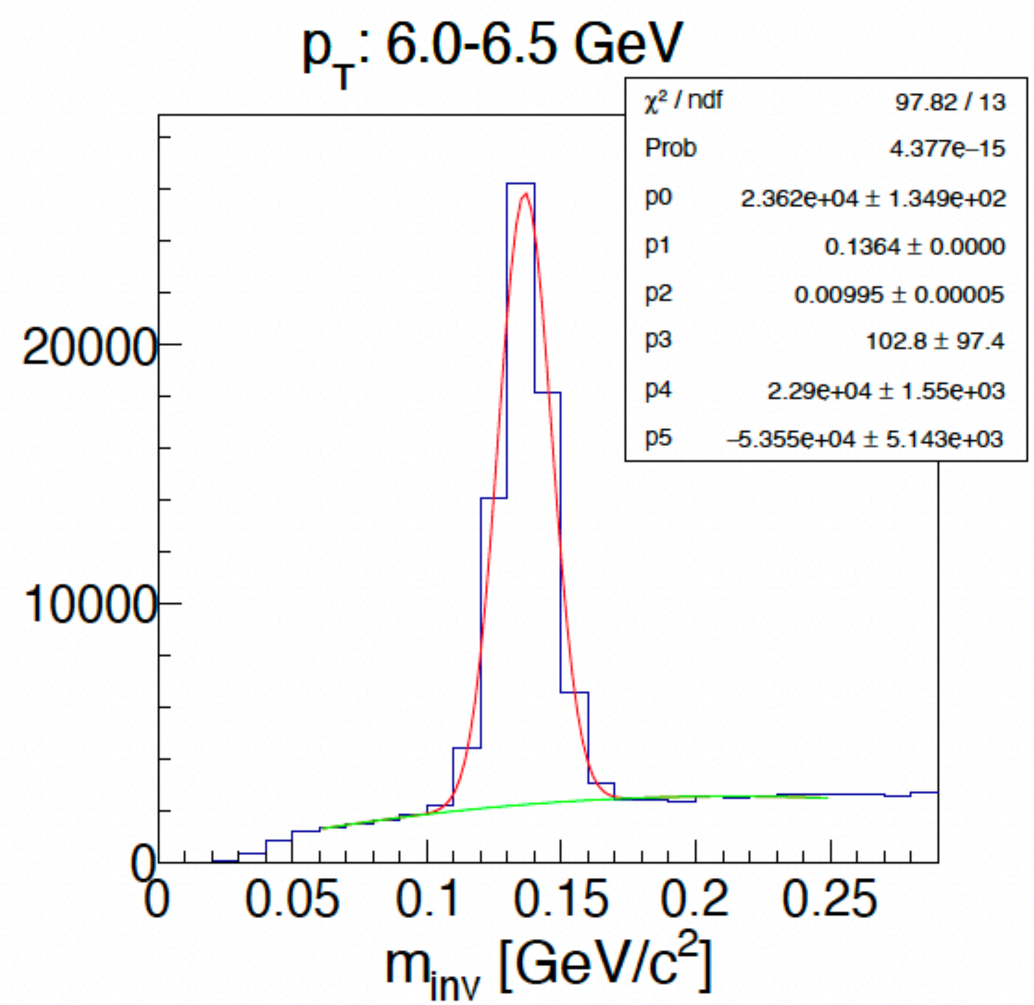
$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$
$$= m_1^2 + m_2^2 + 2\left(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2\right)$$

$$= 2p_1 p_2 (1 - \cos\theta).$$

(for massless)

- For collider:

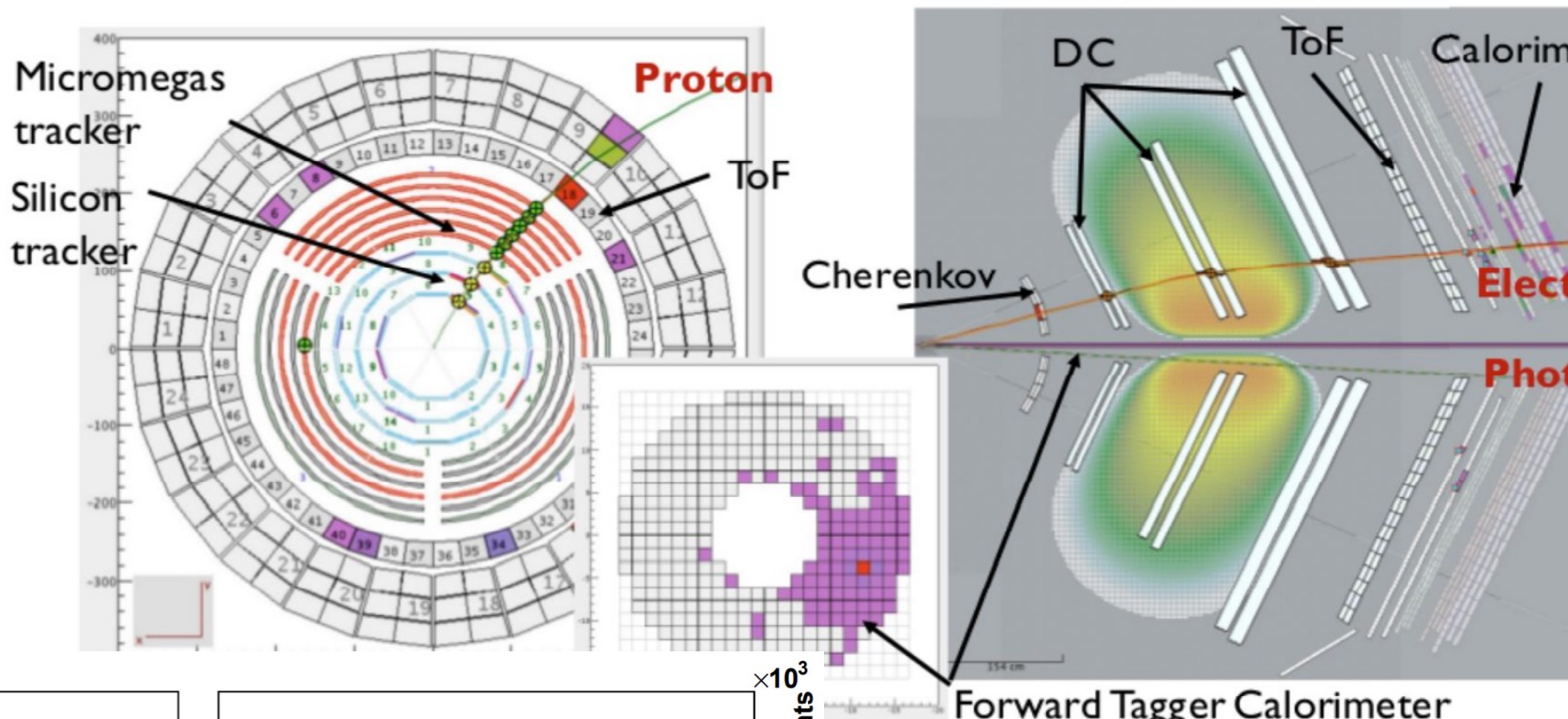
$$M^2 = 2p_{T1}p_{T2}(\cosh(\eta_1 - \eta_2) - \cos(\phi_1 - \phi_2))$$

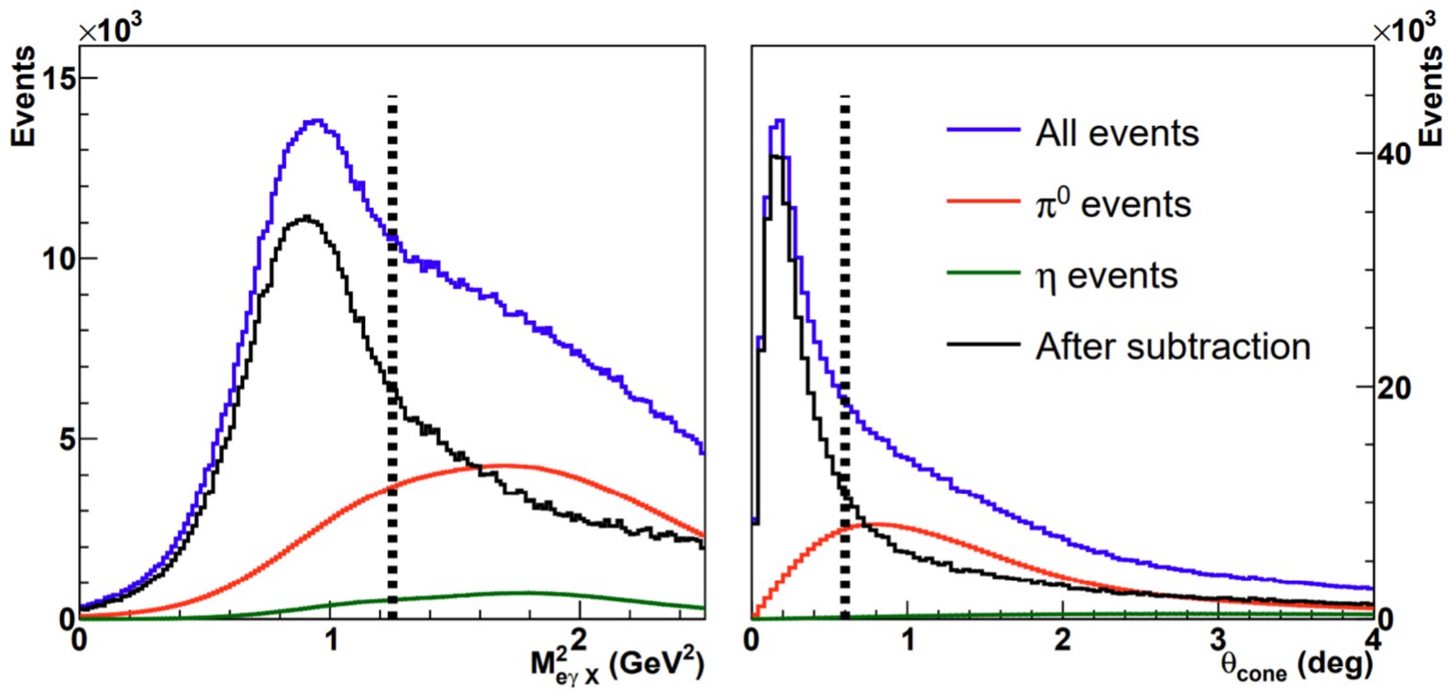


Exclusivity : the CLAS12/JLab scheme

The full exclusivity of the event is insured by:

- **Electron detection**: Cerenkov detector, drift chambers and electromagnetic calorimeter
- **Photon detection**: sampling calorimeter or a small $PbWO_4$-calorimeter close to the beamline
- **Proton detection**: Silicon and Micromegas detector





- **Current and future experiments for hadron structure experiments**

COMPASS

clas
CEBAF Large Acceptance Spectrometer

STAR

LHC spin

SPIN QUEST

Jefferson Lab
HallA, HallC

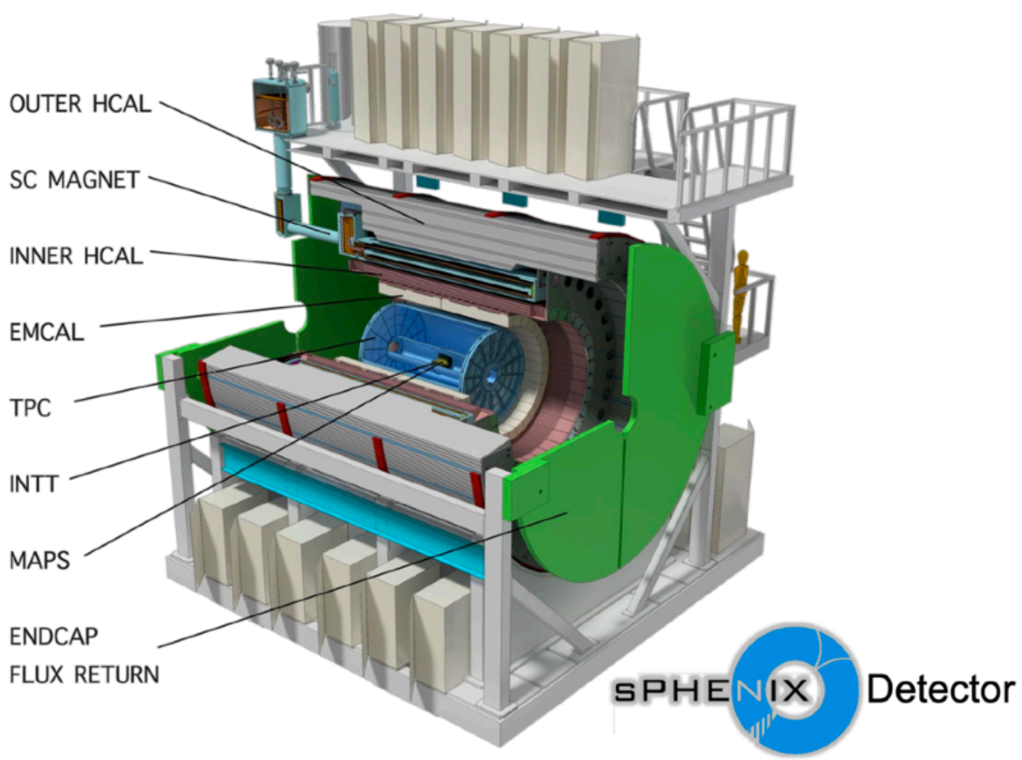
sPHENIX

SPD NICA

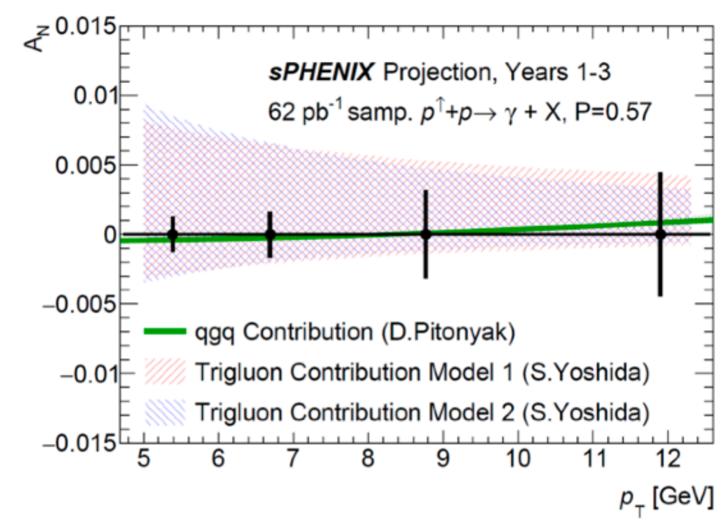
SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

ePIC

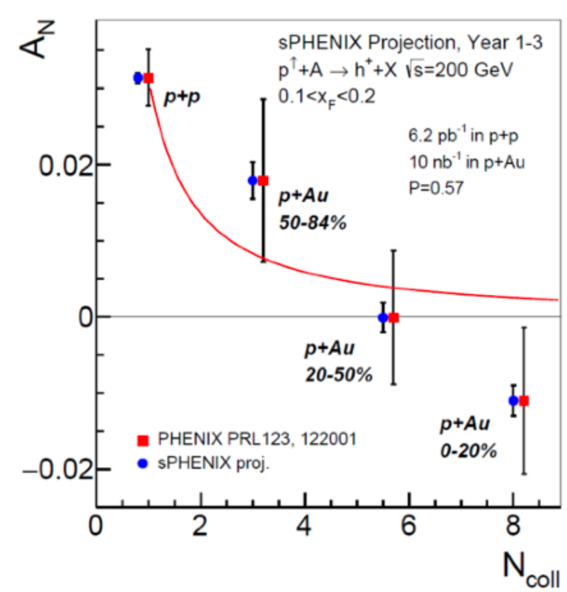
sPHENIX Cold QCD Program



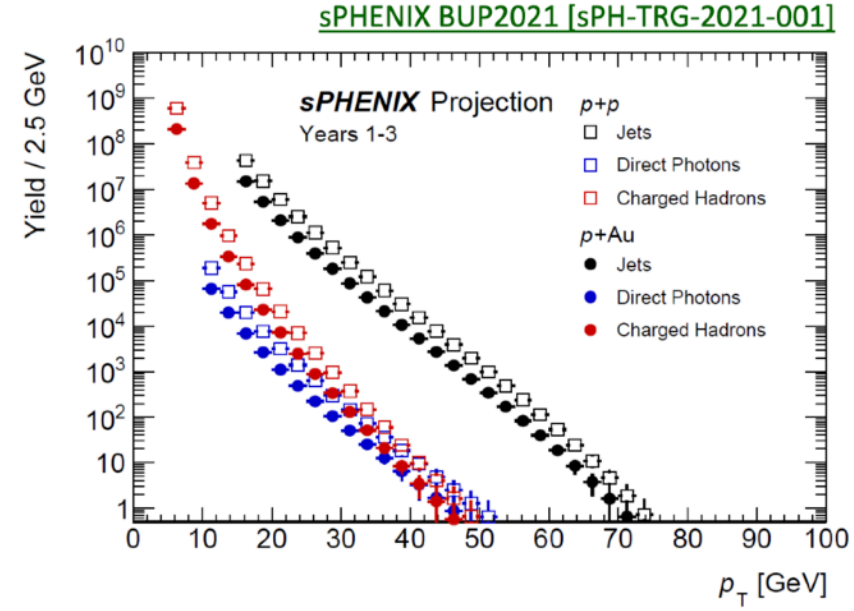
Jet, Heavy flavor, and direct photon measurements will allow us to detailed investigation of the transverse structure of the proton and nuclear effects



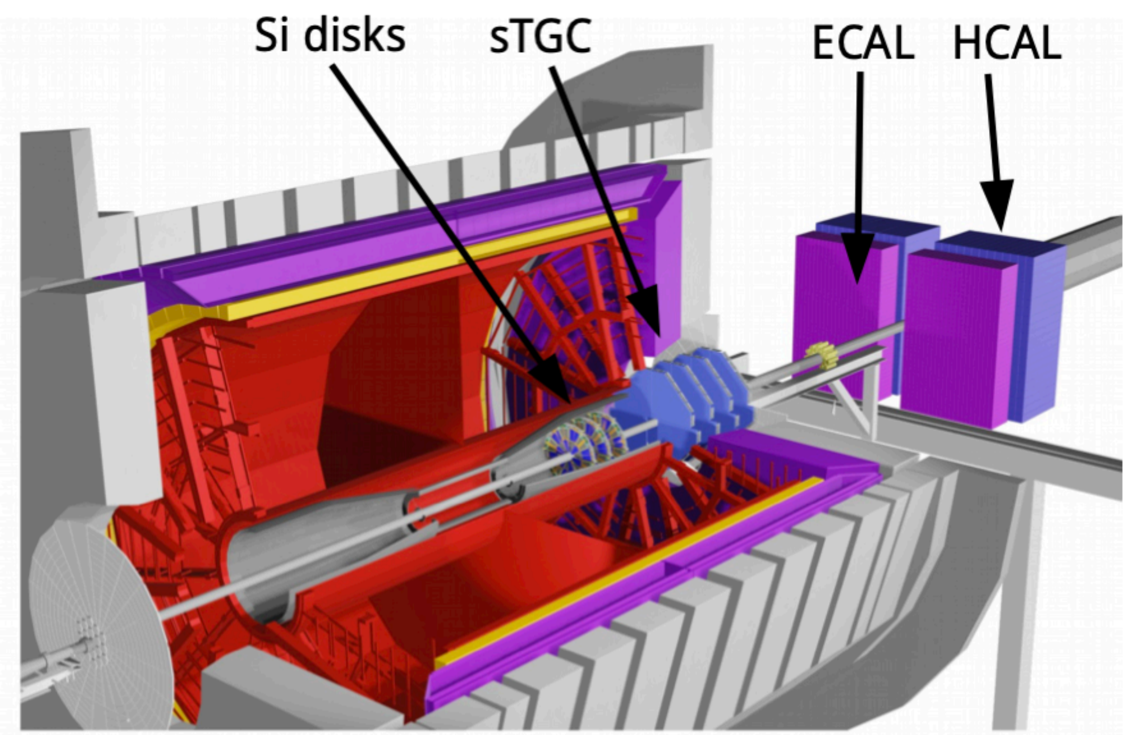
Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z \rvert < 10$ cm	Samp. Lum. $\lvert z \rvert < 10$ cm
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}



sPHENIX BUP2021 [sPH-TRG-2021-001]



STAR Forward Upgrade and Cold QCD Plan



At $2.5 < \eta < 4$

- Si disks + small-strip Thin Gap Chamber (sTGC) for tracking;
- Electromagnetic and hadronic calorimeters.

Detector	p+p and p+A	A+A
ECal	~10%/$\sqrt{E}$	~20%/$\sqrt{E}$
HCal	~50%/$\sqrt{E}$ + 10%	---
Tracking	Charge separation Photon background suppression	0.2< p_T < 2 GeV/c, with 20-30% $1/p_T$

Mid Rapidity → **Forward Rapidity**

$-1.5 < \eta < 1.5$

Physics Topics:

Improve statistical precision:

- Sivers effect in dijet and W/Z production;
- Collins effect for hadrons in jets;
- Transversity and IFF
- Diffractive studies for spatial imaging of nucleon
- Measurement of GPD E_g through UPC J/Ψ
- Nuclear PDF and fragmentation function;

$2.5 < \eta < 4$

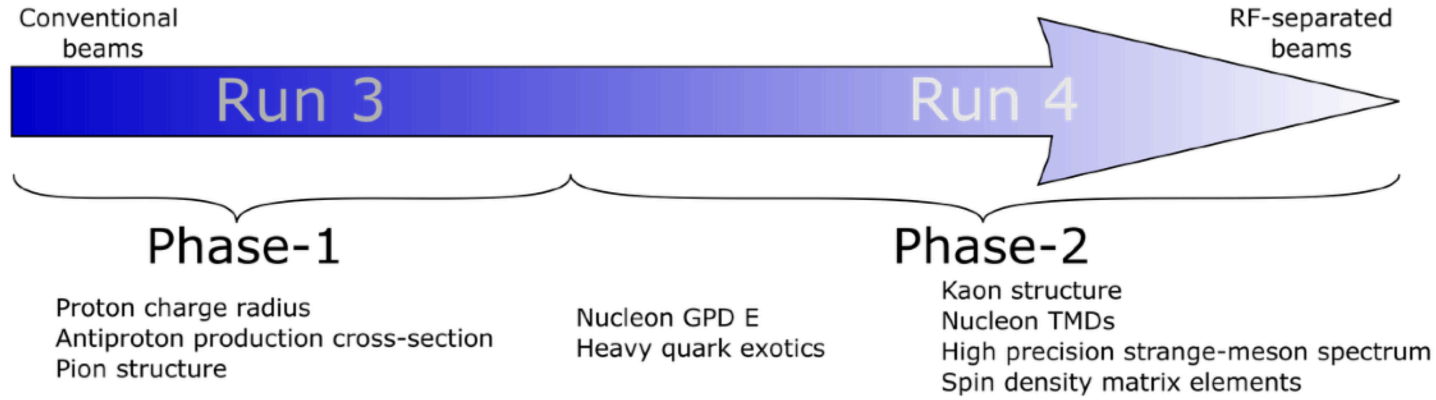
Physics Topics:

- TMD measurements at high x
  - Transversity, Collins;
  - Sivers through DY and jets
- UPC J/Ψ GPD at forward rapidity;
- Nuclear PDFs and FF:
  - R_{pA} for direct photons & DY, and hadrons
- Gluon Saturation through di-hadrons, γ-Jets, di-jets

All of these measurements are critical to the scientific success of EIC to test universality and factorization

Slide from T. Lin (RHIC&AGS Meeting, 2021)

COMPASS++/AMBER



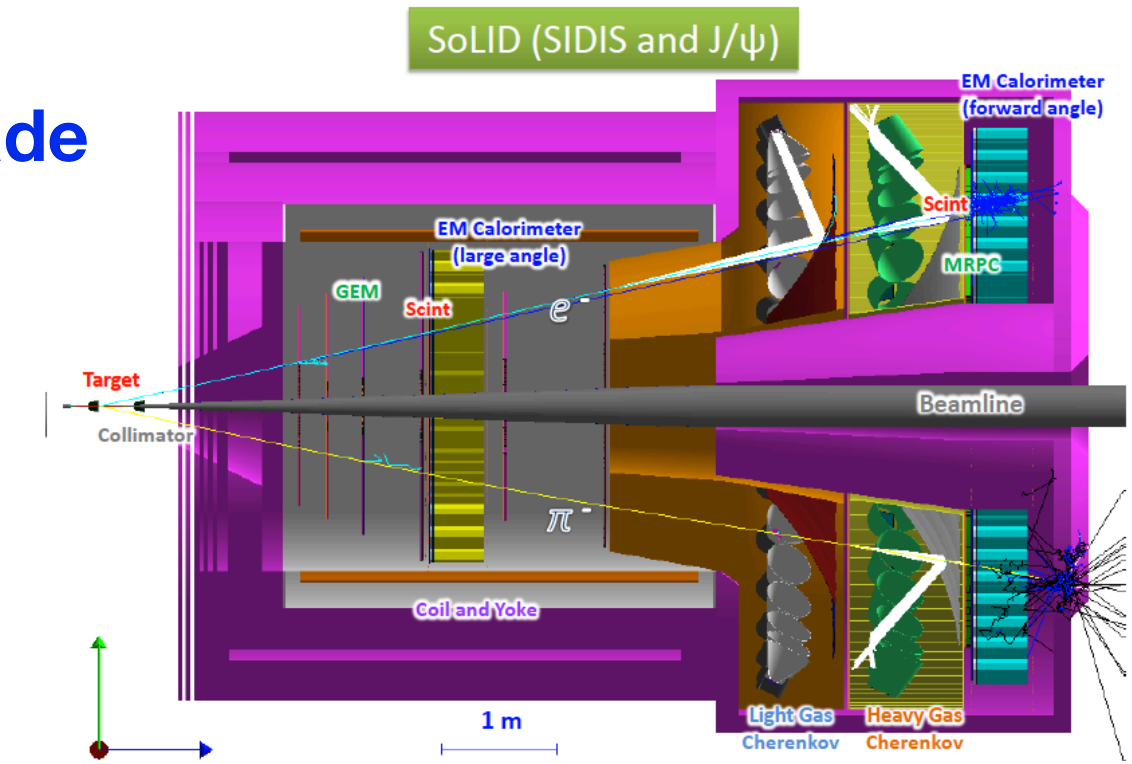
Physics goals						
Nucleon structure	Indirect DM search	Pion structure	Kaon structure	Strange-meson spectrum	Heavy quark exotics	Spin density matrix elements
μ-p elastic scattering DVCS/DVMP on polarised target $\bar{p}$-induced DY on polarised target	$\bar{p}$ production cross section on H and He	π-induced DY π-induced J/ψ production	K-induced DY K-induced J/ψ production Prompt photon production K-induced Primakoff	K-induced spectroscopy	$\bar{p}$-induced spectroscopy	meson-induced vector-meson production

Hardware challenge						
Active TPC SciFi trigger Recoil detector	Liquide H and He targets	Vertex detector	Active absorber Calorimetry	Recoil detector Forward PID	Calorimetry	

COMPASS detector +
Several upgrade

Hadron mass
Hadron radii
Pion and Kaon Structure
Meson polarizabilities
Strange sector hadron spectroscopy

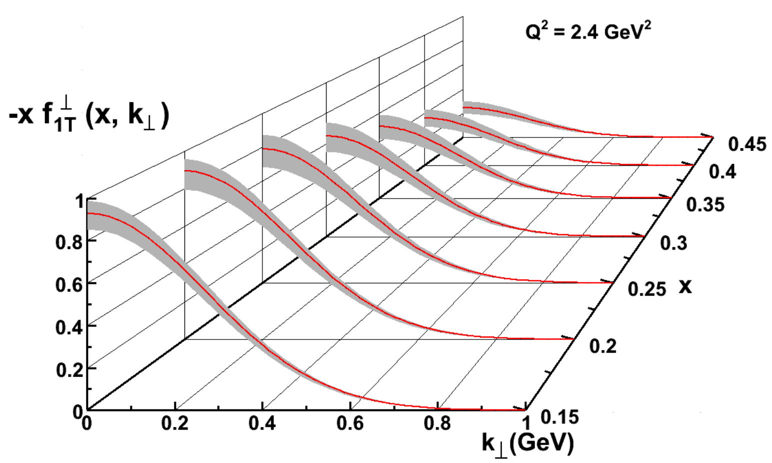
Solenoidal Large Intensity Device



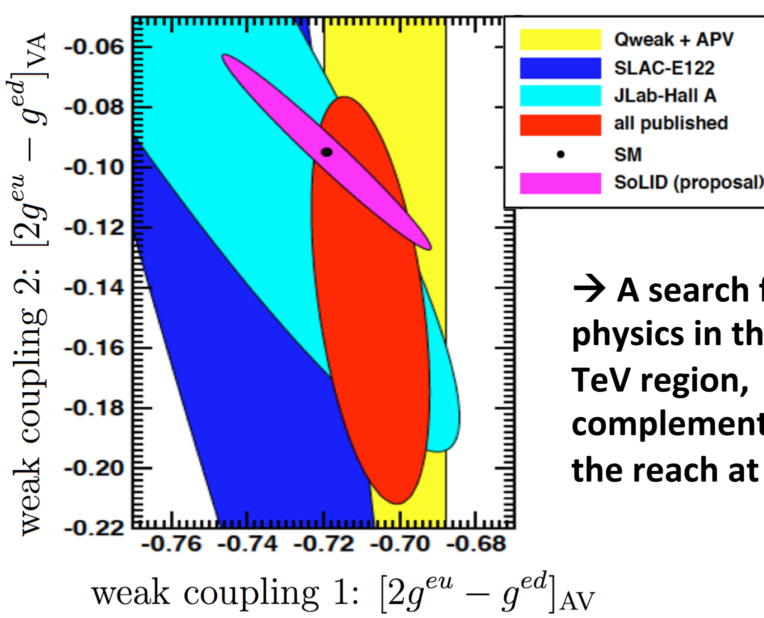
Take full advantage of JLab 12 GeV Upgrade

High luminosity (10^{37} - 10^{39})
Large acceptance with full azimuthal coverage

Rich physics program



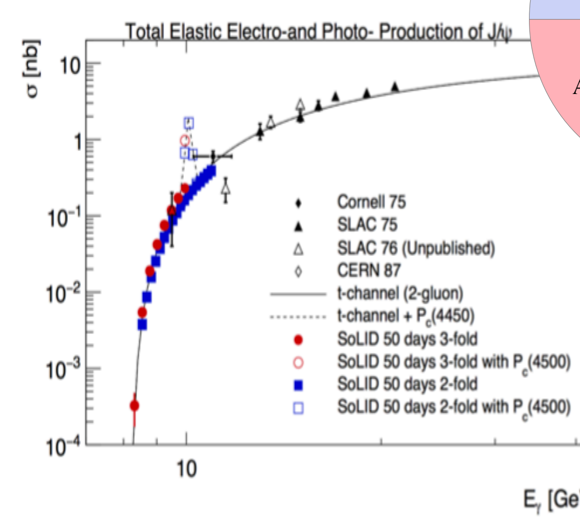
Precision in 3D imaging of the nucleon

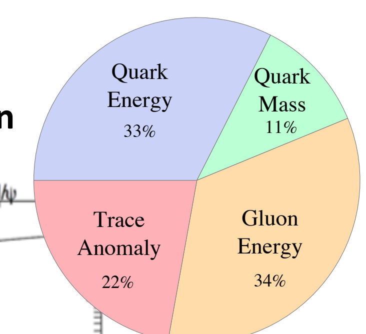


→ A search for new physics in the 10-20 TeV region, complementary to the reach at LHC.

Electroweak couplings

J/ψ production cross section





→ Constrain the QCD trace anomaly, Proton mass , LHCb charmed pentaquark

Near threshold J/psi production

Summary

- Part. 1: Basics of hadron structure experiments
  - Accelerators and particle detectors
  - Deep Inelastic Scattering experiments
  - DIS Kinematics reconstruction

- Part. 2: Collinear observables and measurements
  - Continue on DIS data - PDF extraction
  - Parton distributions at large-x
  - Flavor asymmetry of sea
  - Polarized spin structure

- Part. 3: Beyond collinear
  - TMD measurements
  - GPD measurements
  - Future opportunities