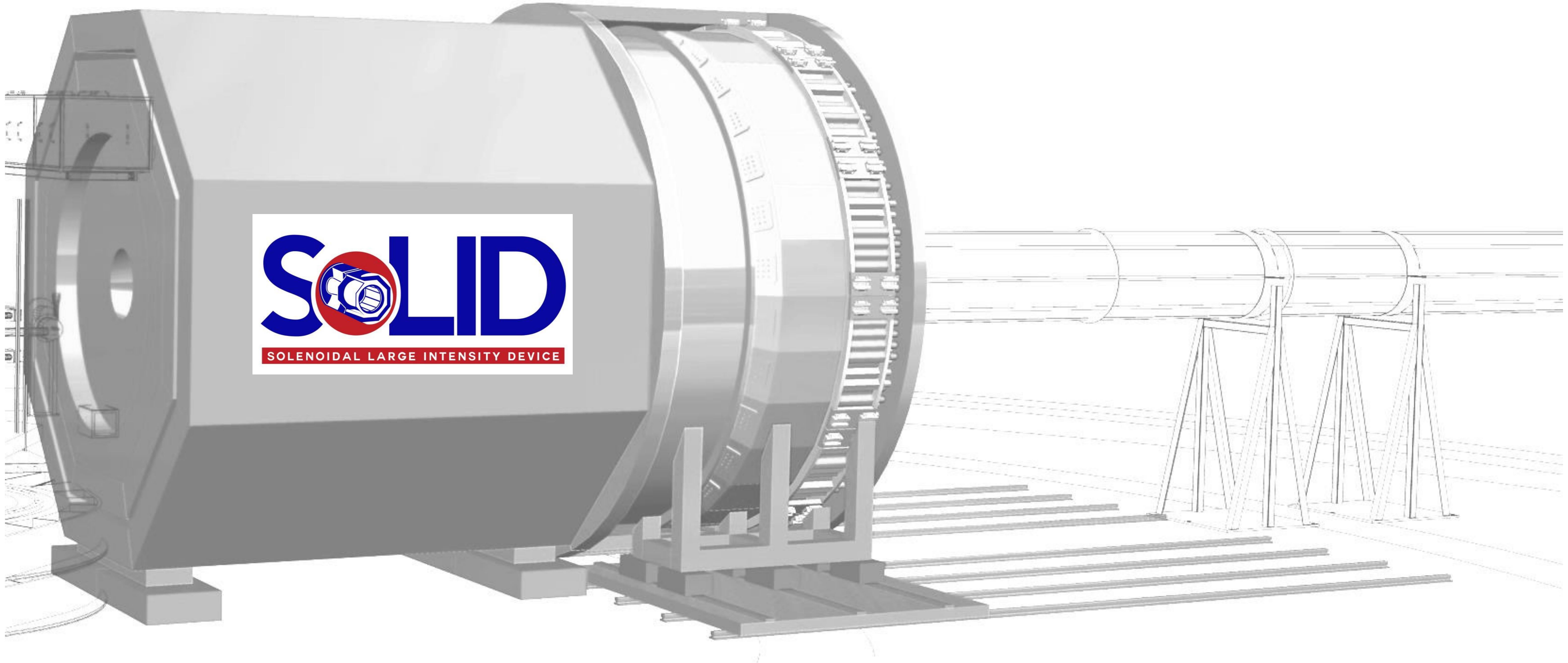
Study of Semi-Inclusive Deep Inelastic Scattering at 22GeV w/ SoLID



Shuo Jia, Duke University
Zhihong Ye, Tsinghua University
On behalf of the SoLID Collaboration

2nd JLab 22GeV-Workshop, Frascati, Italy, 12/09-13/2024

Jefferson Lab

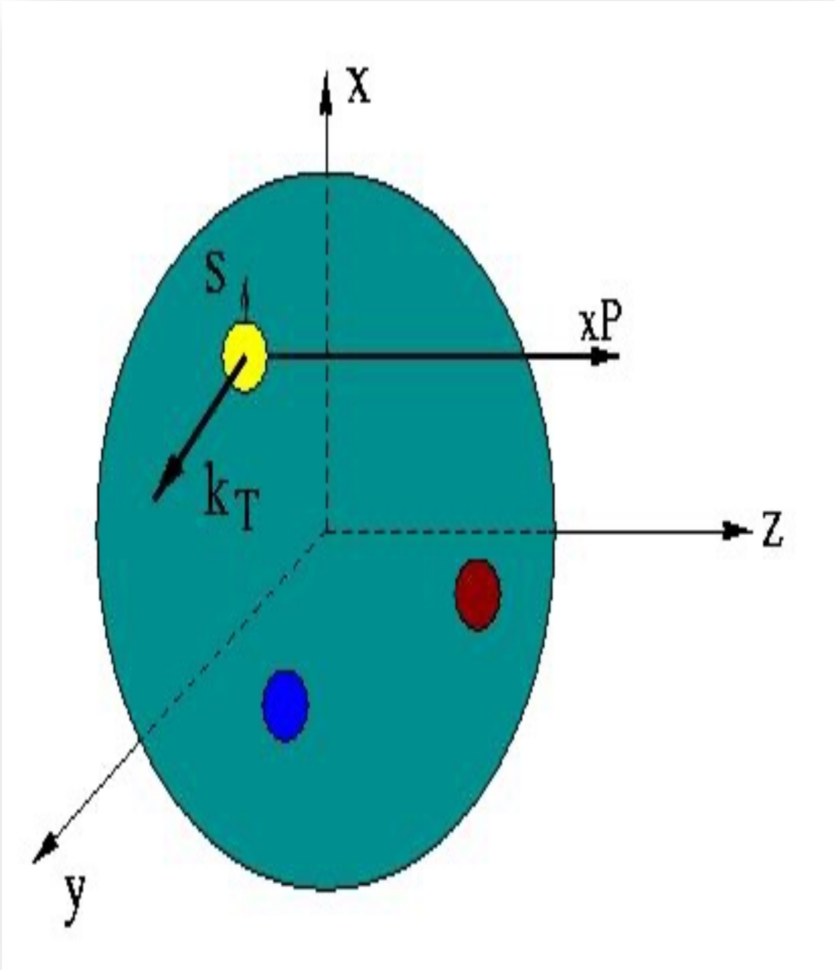
Tsinghua University

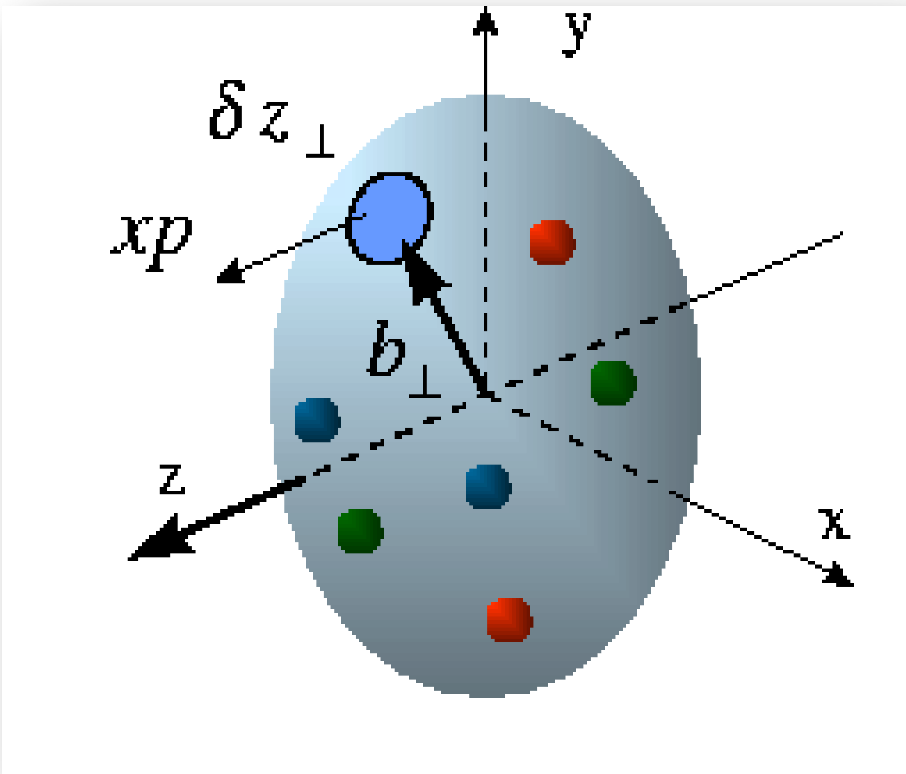
Nucleon's 3D Structure

$W_p^u(x,k_T,\boldsymbol{r_T})$ Wigner distributions

5D

(X. Ji, D. Mueller, A. Radyushkin)





$d^2\boldsymbol{r_T}$

d^2k_T

TMD

$f_1^u(x,k_T)$, $h_1^u(x,k_T)$,…

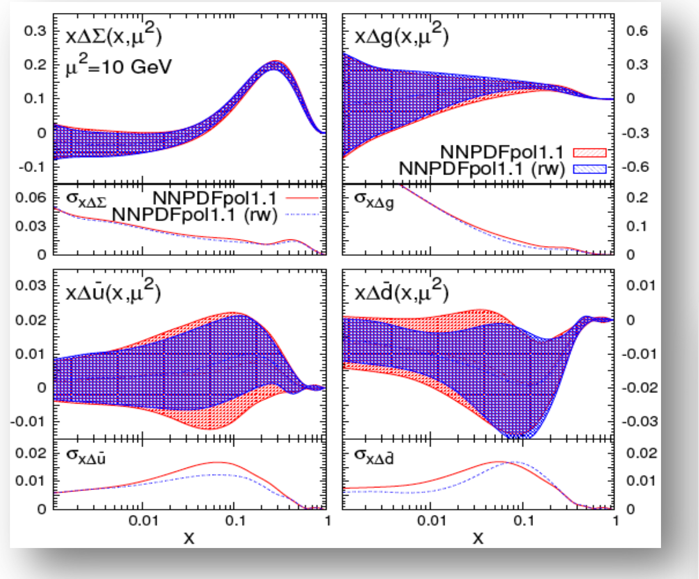
GPDs/IPDs

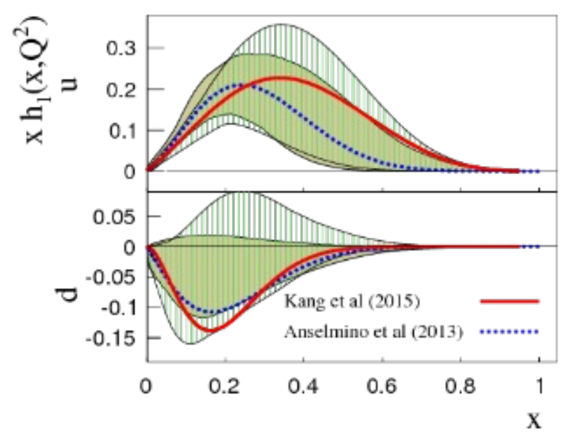
$H^u, E^u, \widetilde{H}^u, \widetilde{E}^u$

d^2k_T

d^2r_T

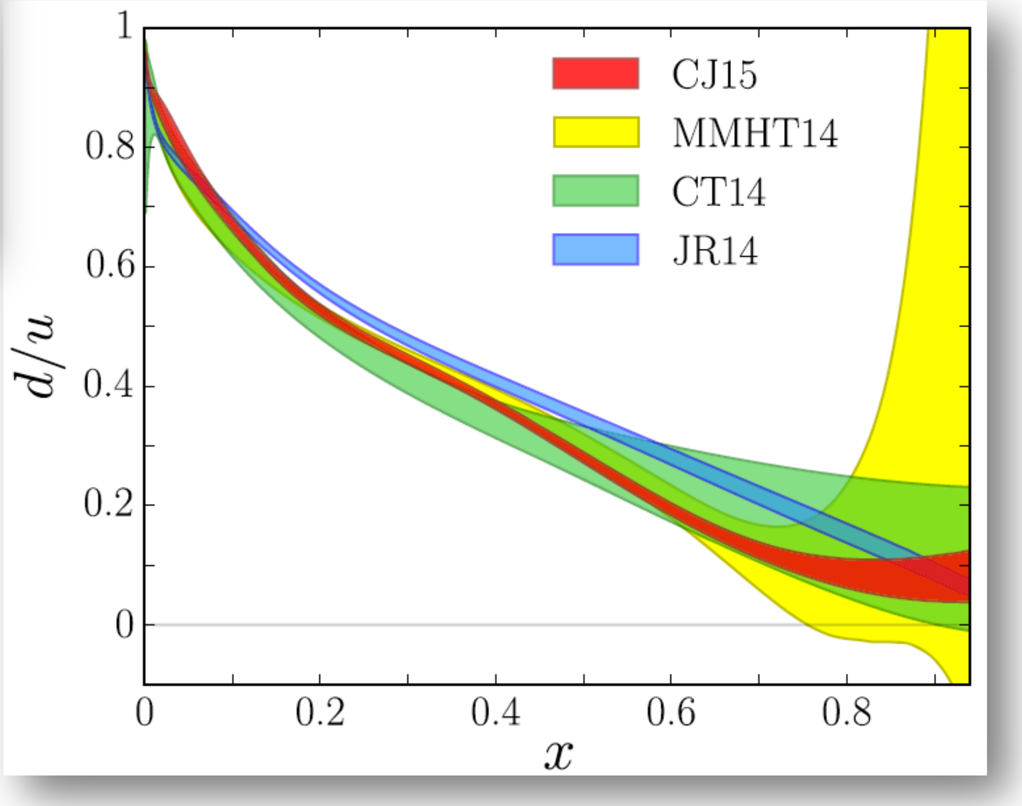
dx & Fourier Transformation





A. Accardi et. al.

B. Phys. Rev. D 93, 114017 (2016)



PDFs

$f_1^u(x)$, $g_1^u(x)$,

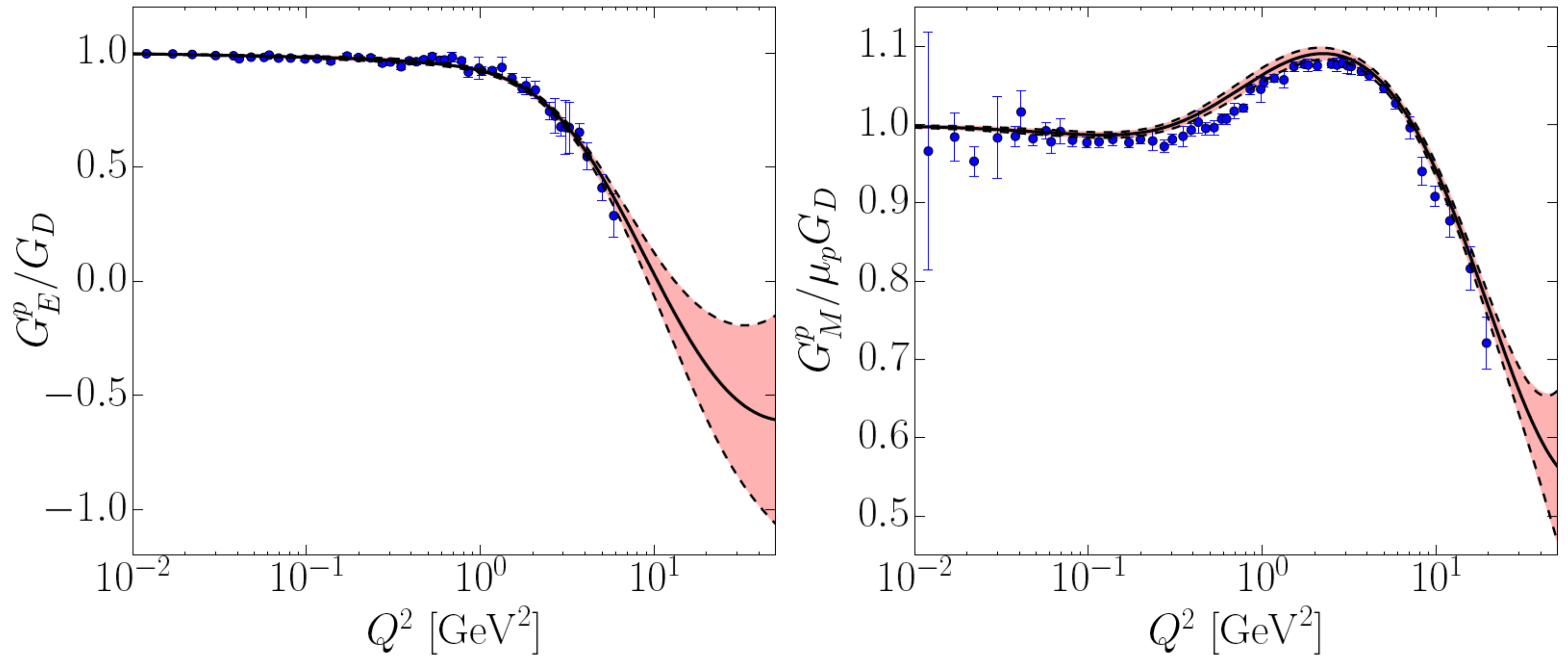
$h_1^u(x)$,…

1D

Form Factors

$G_E(Q^2)$,

$G_M(Q^2)$

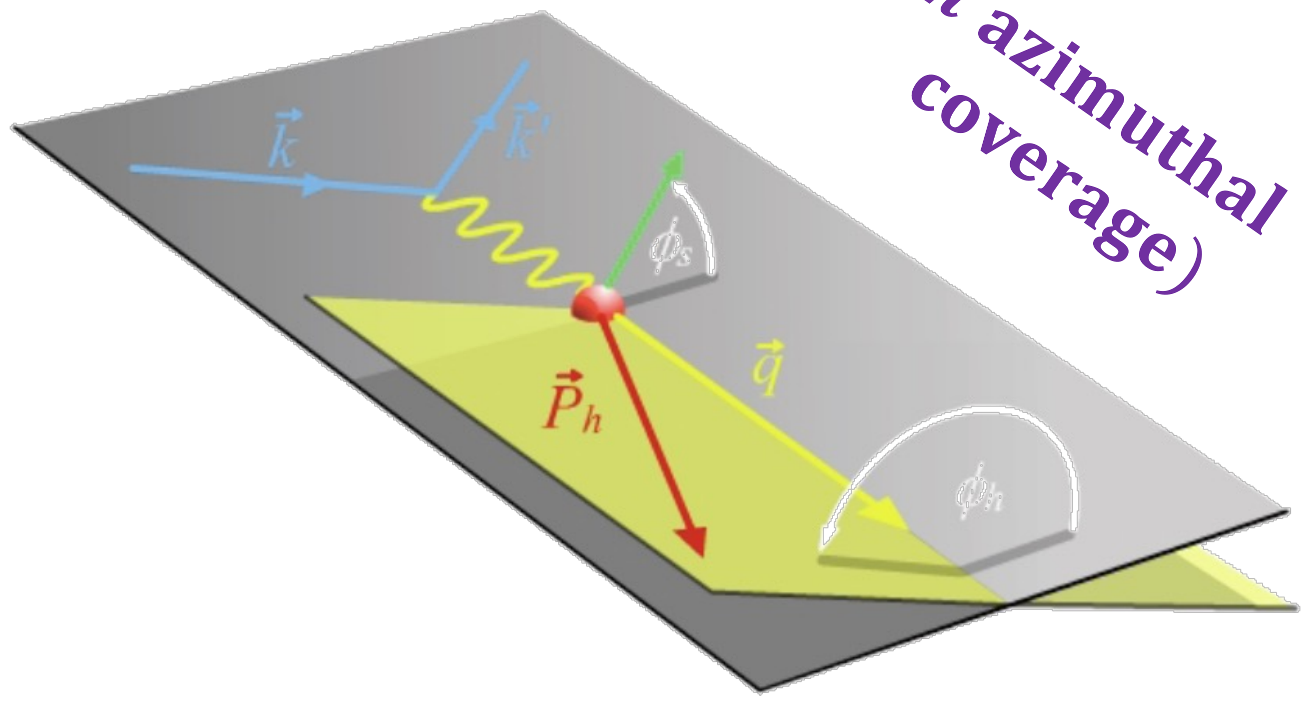


Z. Ye, et. al. Phys. Lett. B 777 8-15 (2018)

Transverse Momentum Distributions

➢ **Semi-Inclusive Deep Inelastic Scattering (SIDIS) with polarized targets:**

(2π azimuthal coverage)



8 Quark-TMDs (leading twist)

Leading Twist TMDs		Quark Polarization: Unpolarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$ Unpolarized		$h_1^\perp(x,k_T^2)$ Boer-Mulders
	L		$g_1(x,k_T^2)$ Helicity	$h_{1L}^\perp(x,k_T^2)$ Long-Transversity
	T	$f_{1T}^\perp(x,k_T^2)$ Sivers	$g_{1T}(x,k_T^2)$ Trans-Helicity	$h_1(x,k_T^2)$ Transversity $h_{1T}^\perp(x,k_T^2)$ Pretzelosity

Unpolarized Density Function:

$$f_1(x) = \int d^2\boldsymbol{k}_\perp \, f_1(x,k_\perp)$$

Helicity Function:

$$g_1(x) = \int d^2\boldsymbol{k}_\perp \, g_{1L}(x,k_\perp)$$

Transversity Function:

$$h_1(x) = \int d^2\boldsymbol{k}_\perp \, [h_{1T}(x,k_\perp) + \frac{k_\perp^2}{2M^2} h_{1T}^\perp(x,k_\perp)]$$

➢ Target Single-Spin Asymmetry (TSA)

$$A_{UT}(\phi_h,\phi_S) = \frac{1}{P_{t,pol}} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

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

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

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

Collins fragmentation function from e^+e^- collisions

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

Unpolarized fragmentation function

➢ Double-Spin Asymmetry (DSA)

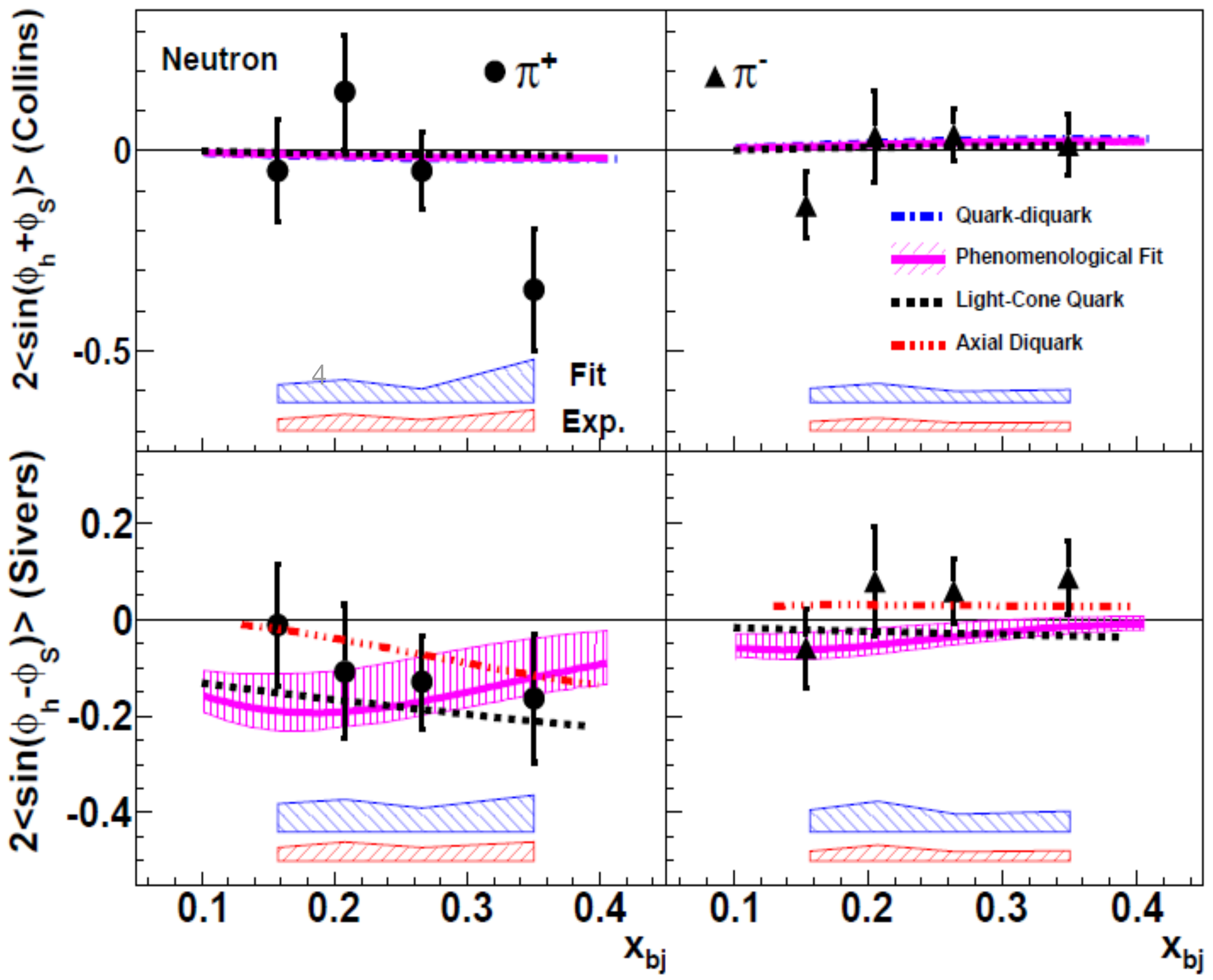
$$A_{LT}^{Worm-Gear} \propto \langle \cos(\phi_h-\phi_s)\rangle_{LT} \propto g_{1T} \otimes D_1$$

Worm-Gear

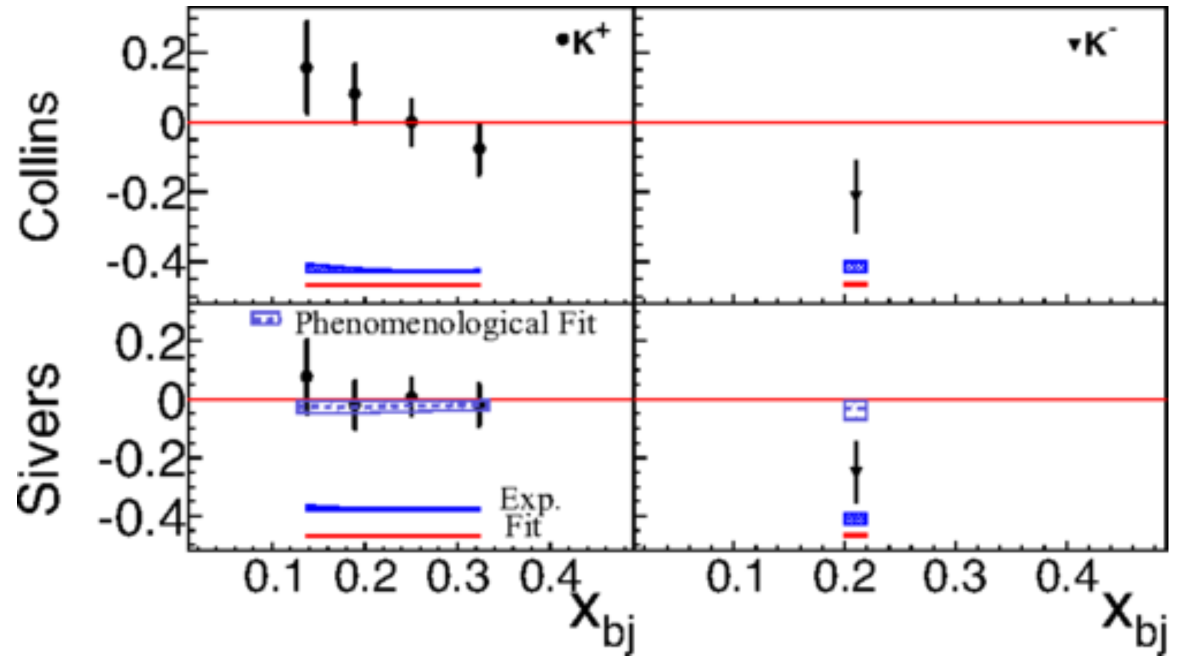
Transverse Momentum Distributions

- Existing TSA data:
  - Limited coverage
  - Mostly pion data
  - 1D or 2D binning

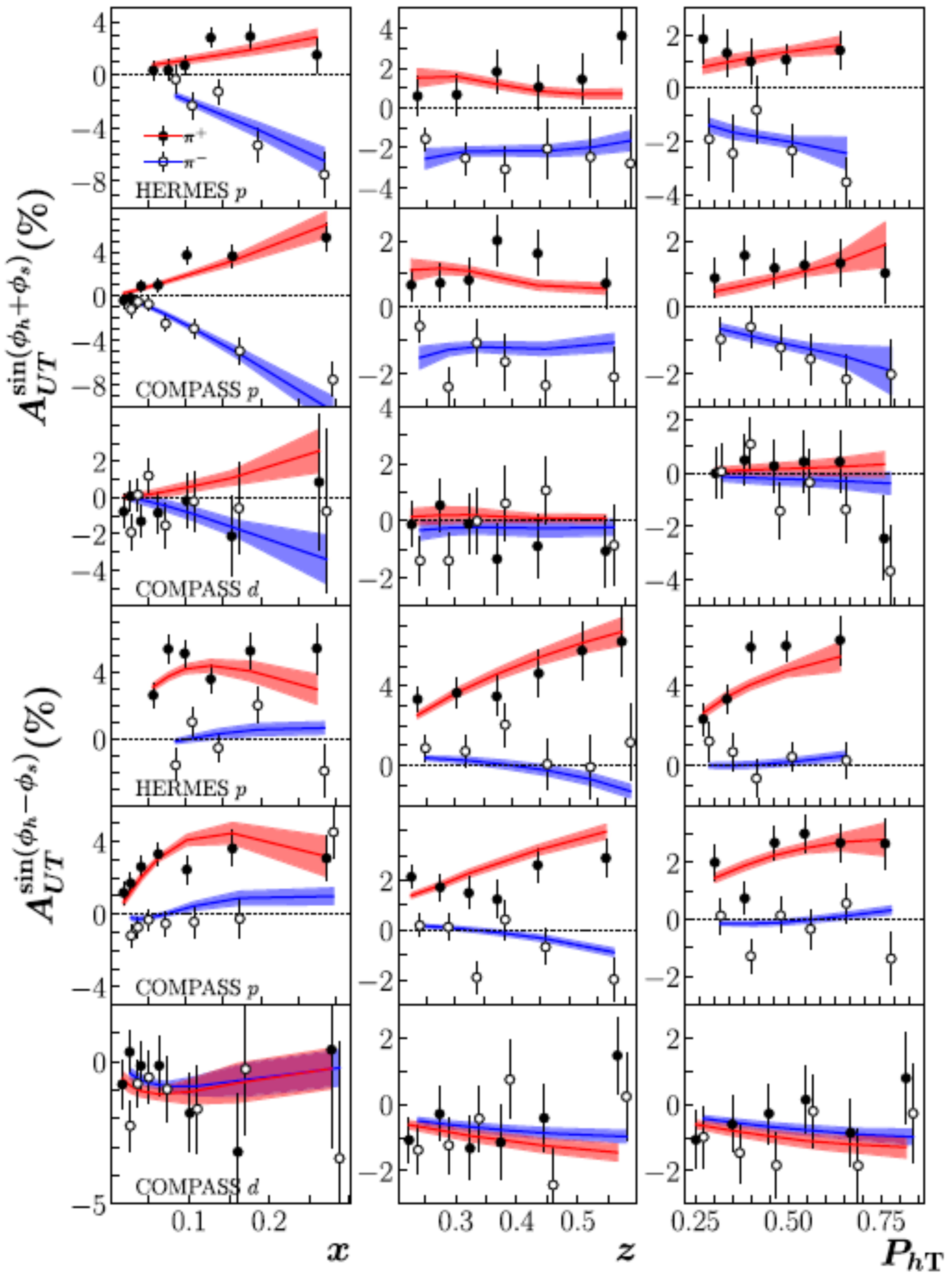
X. Qian et al., Hall-A, Phys. Rev. Lett. 107, 072003 (2011)

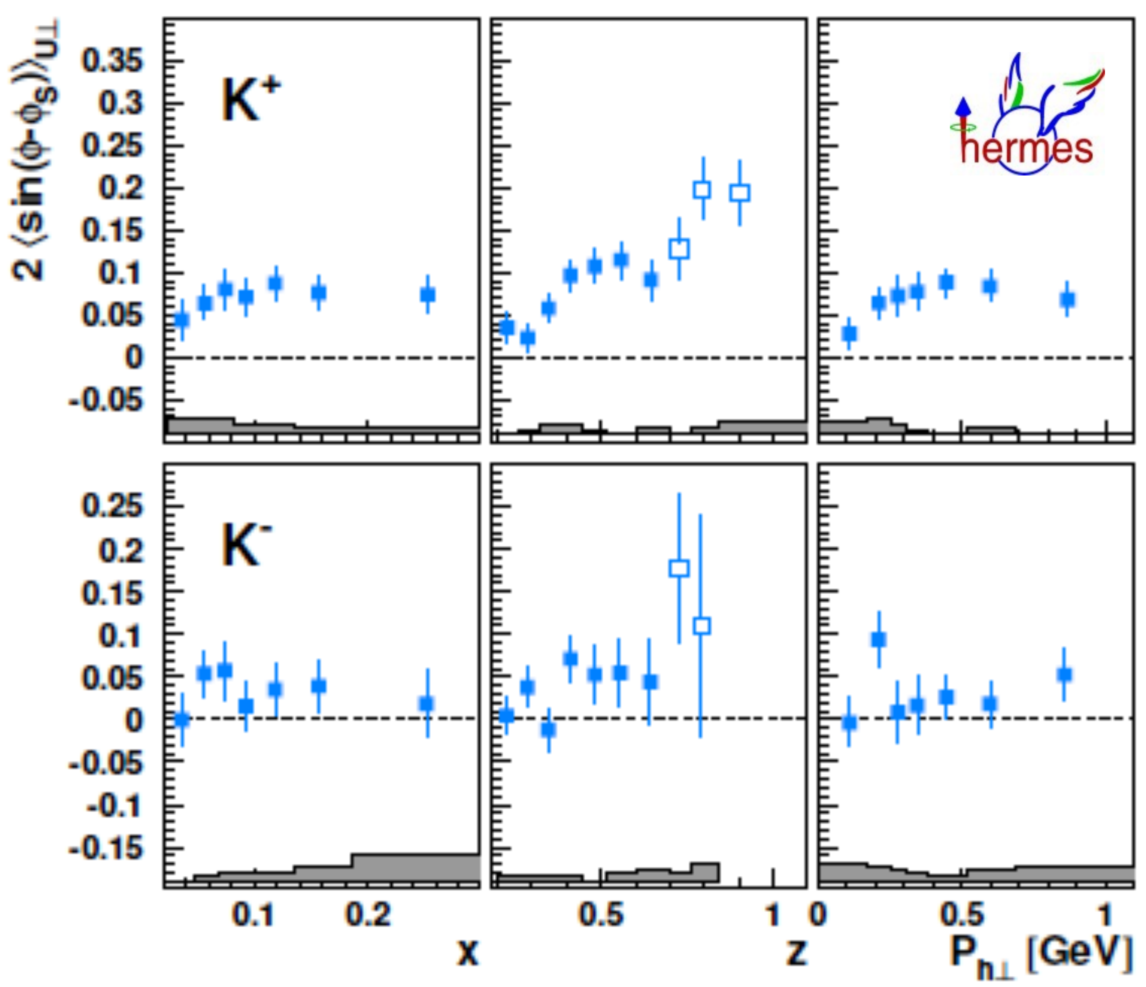


Y. X. Zhao et al., Hall-A, Phys. Rev. C 90, 055201 (2014).



J. Cammarota et al., Phys. Rev. D 102, 054002 (2020)



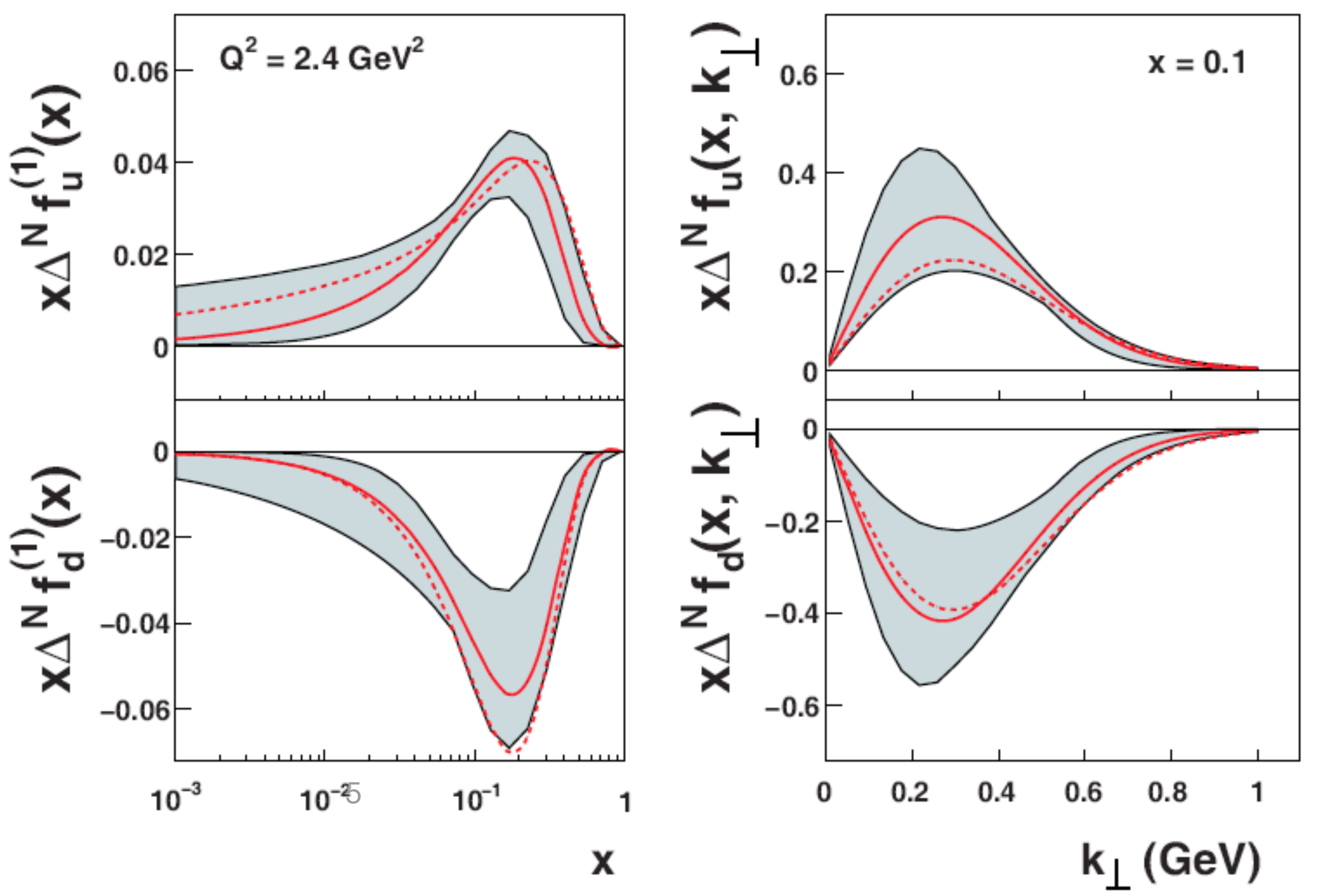


Phys. Rev. Lett. 103, 152002 (2009).
Phys. Lett. B 693 (2010) 11-16
J. High Energy Phys. 12 (2020) 010

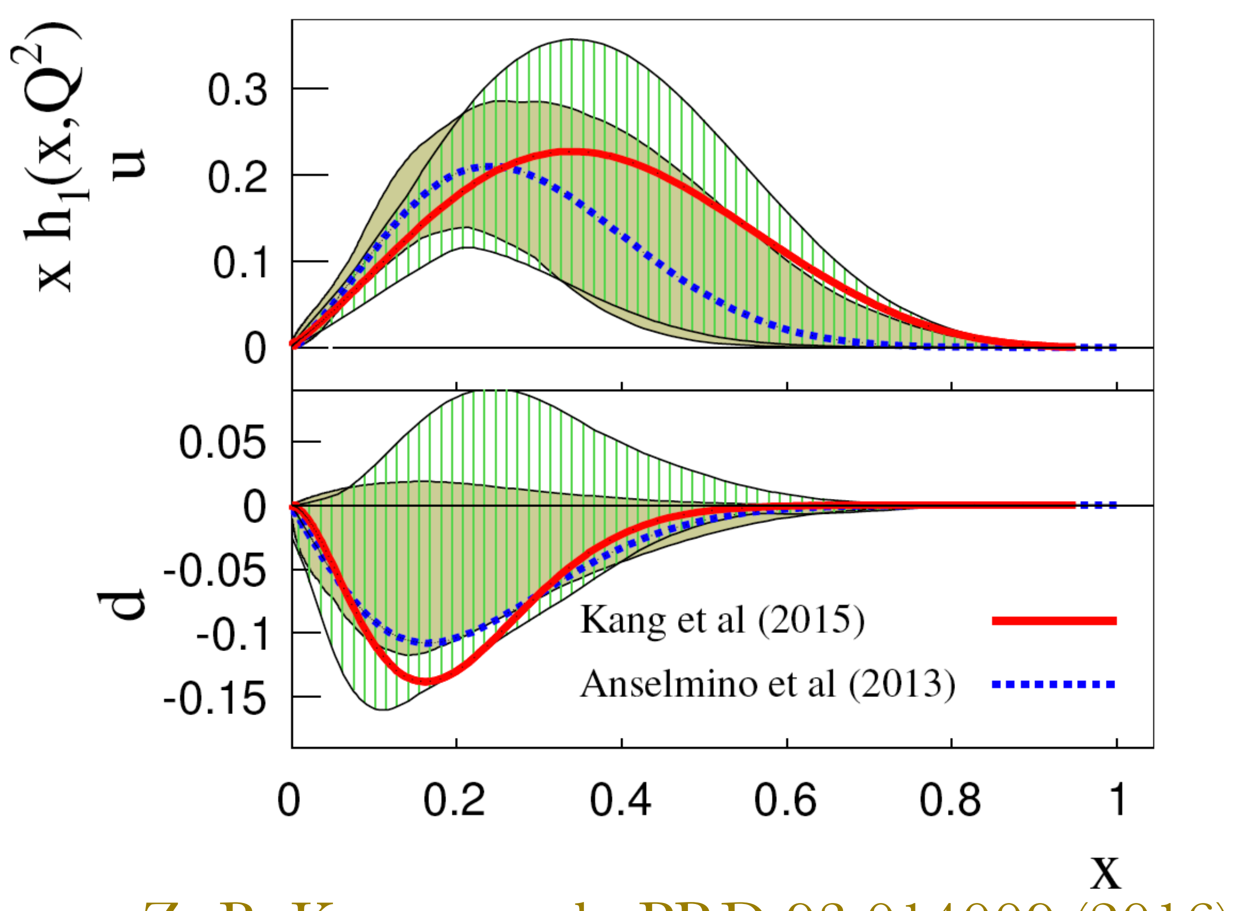
Phys. Lett. B 673 (2009) 127.
Phys. Lett. B744, 250 (2015),
Phys. Lett. B744 770, 138 (2017)

Transverse Momentum Distributions

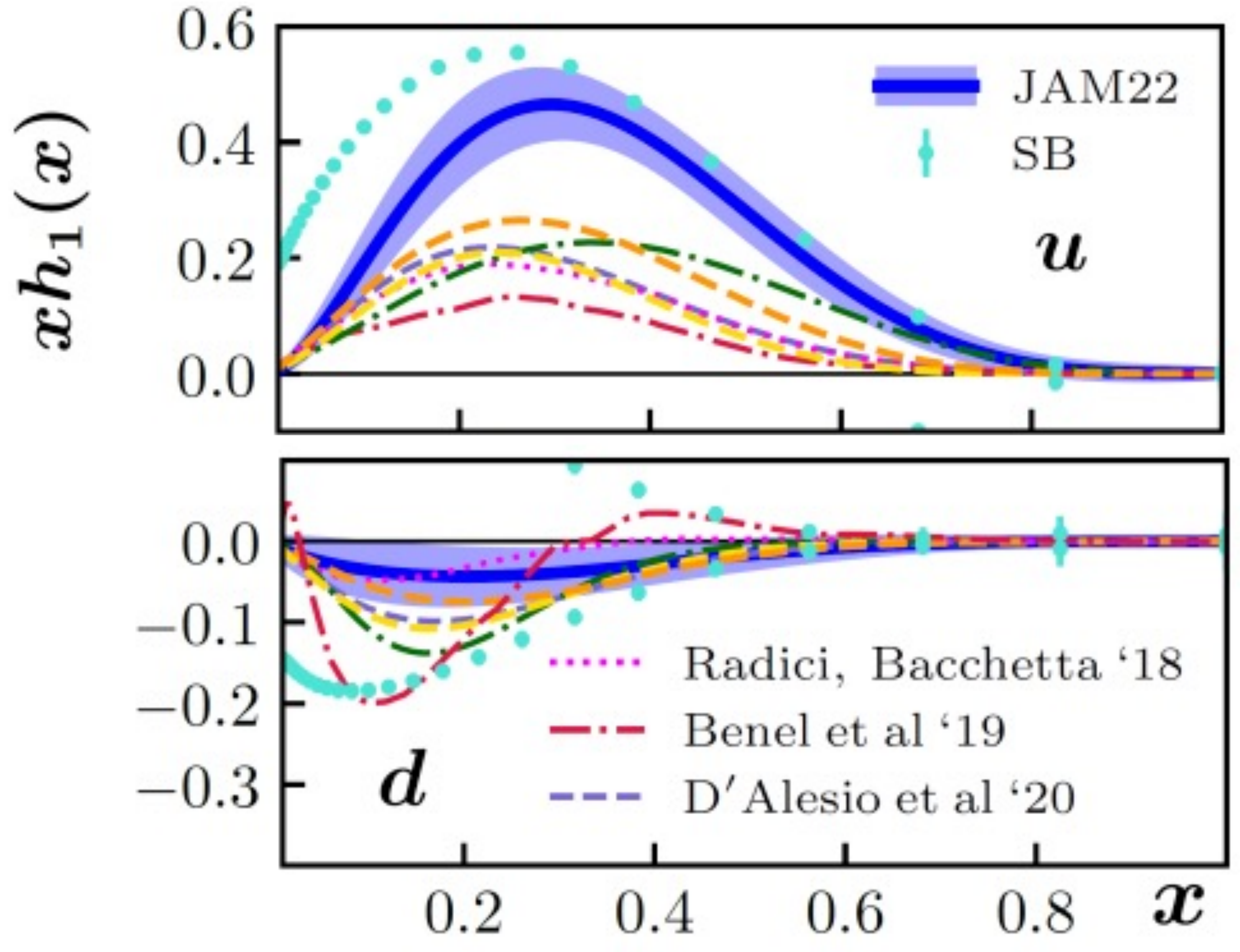
- Global analysis show big errors:



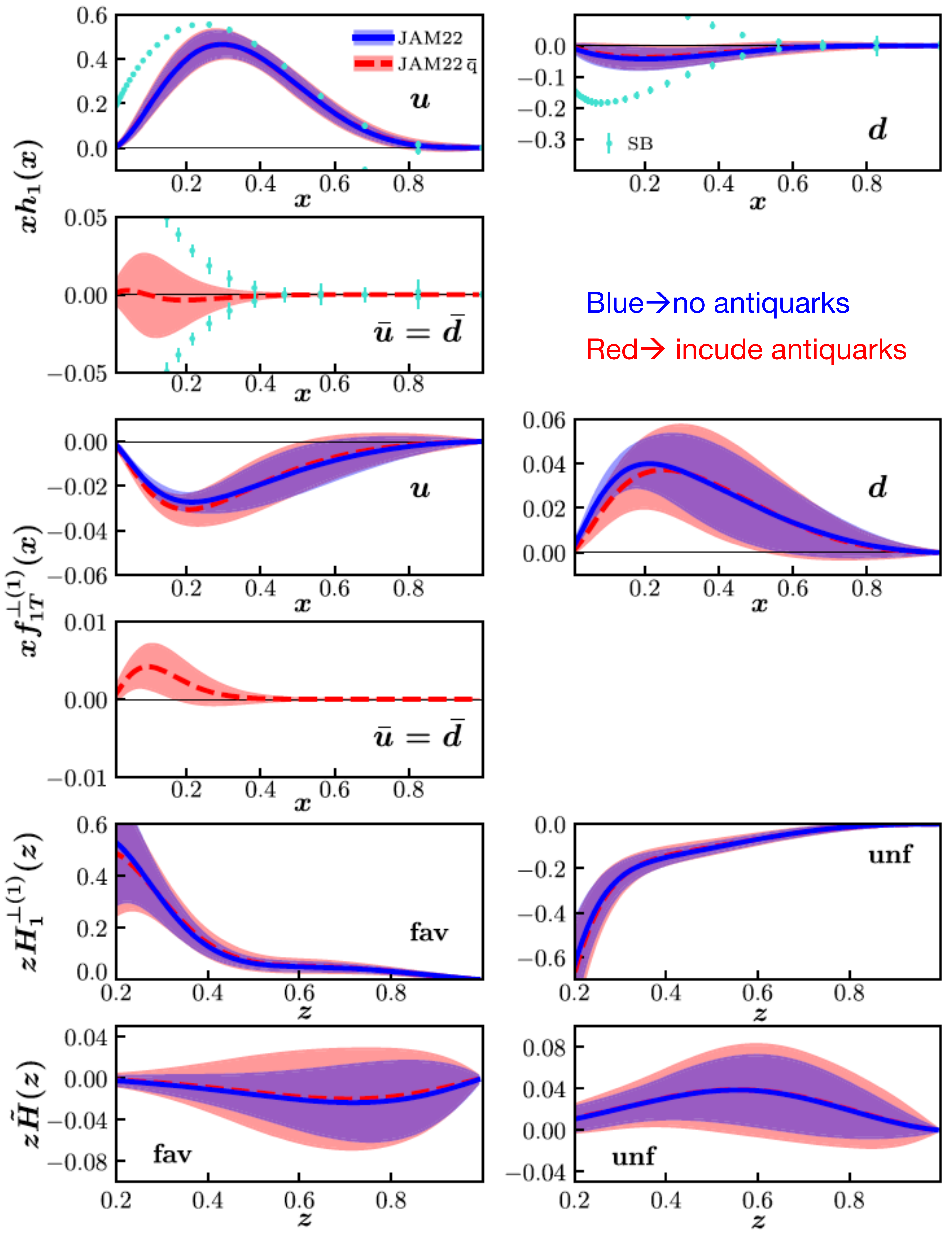
Anselmino et al. , Eur. Phys. J. A39, 89-100 (2009)



Z.-B. Kang, et. al., PRD 93 014009 (2016)



Gamberg et al., Phys. Rev. D 106, 034014 (2022)



Blue→no antiquarks

Red→ incude antiquarks

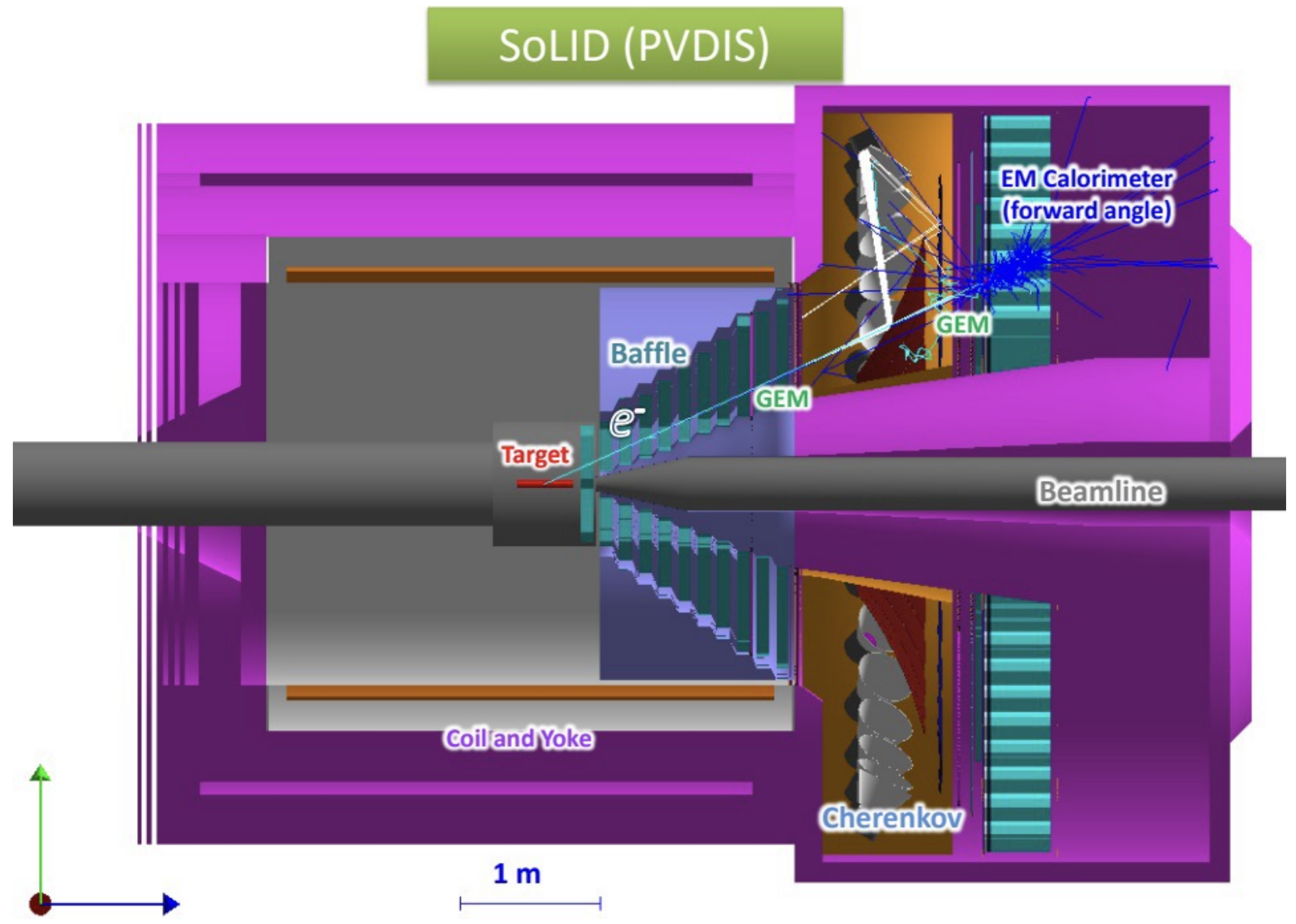
SoLID@12-GeV JLab: QCD at the intensity frontier

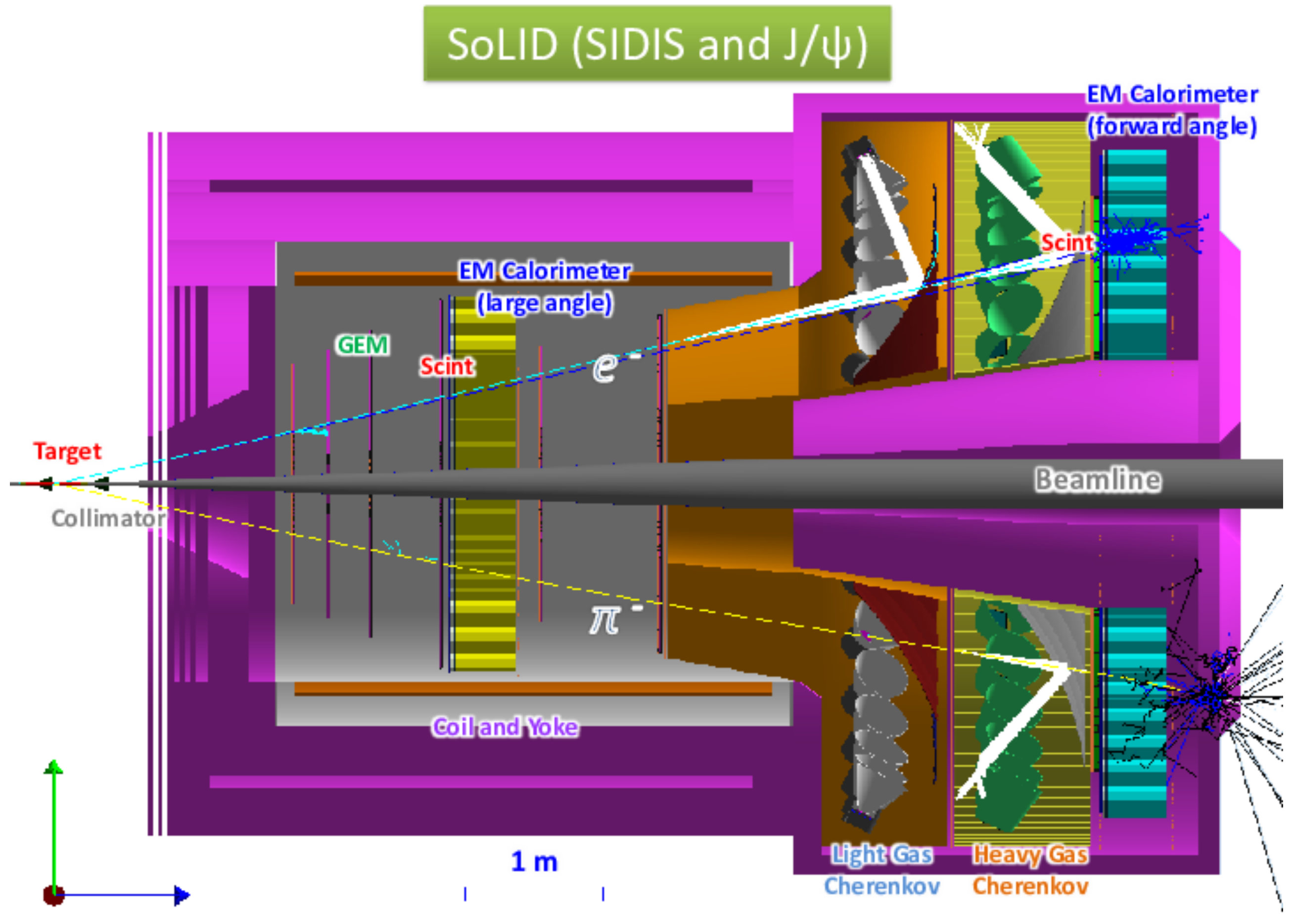
➢ **SoLID** will ***maximize*** the science return of the 12-GeV CEBAF upgrade by **combining...**

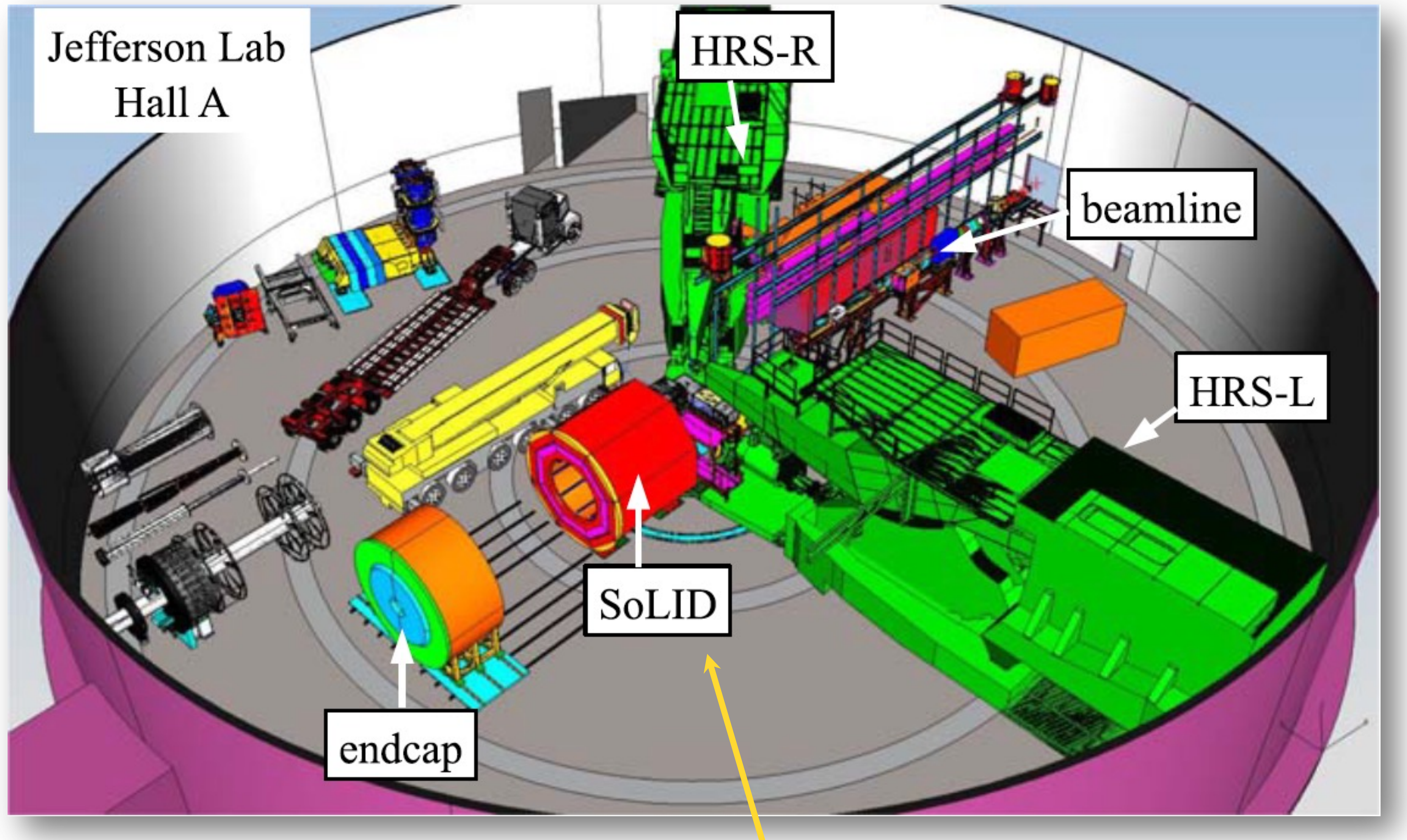
High Luminosity
$10^{37\text{-}39}$ /cm²/s
[>100x CLAS12][>1000x EIC]

+

Large Acceptance
Full azimuthal ϕ coverage

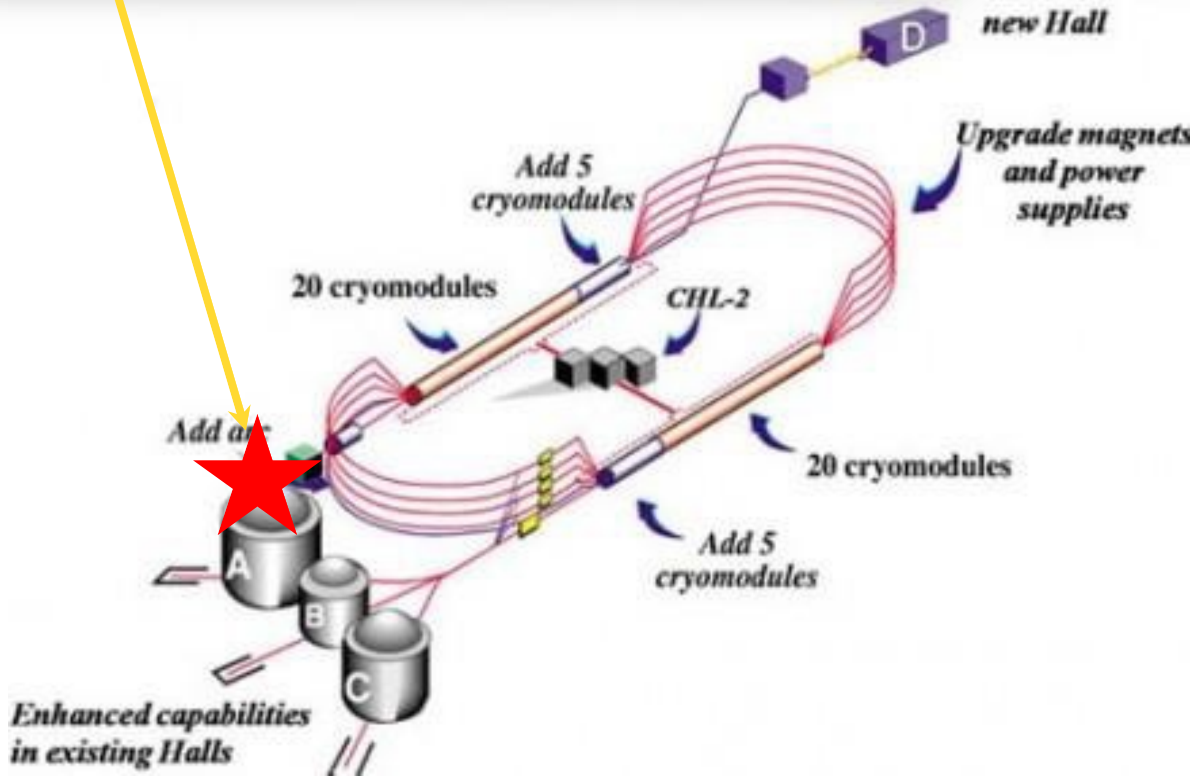






➢ Perform high-luminosity valence quark tomography, Search new physics w/ parity-violation deep inelastic scattering (PVDIS), and measure precise J/ψ production near threshold

➢ Synergizing with the pillars of EIC science (**proton spin** and **mass**)



*SoLID whitepaper: J. Phys. G: Nuclear and Particle Physics **50,** 110501 (2023)*

*12GeV physics: Progress in Particle and Nuclear Physics **127**, 103985 (2022)*

SoLID-SIDIS Programs

- Approved SIDIS proposals:
  - **E12-10-006:**Single Spin Asymmetries on Transversely Polarized ^{3}He @ 90 days, **Rating A**
  - **E12-11-007:**Single and Double Spin Asymmetries on Longitudinally Polarized ^{3}He @ 35 days, **Rating A**
  - **E12-11-108:**Single SpinAsymmetrieson Transversely Polarized Proton @ 120 days, **Rating A**

✓ Polarization: ^{3}He (n)~60%, NH3(p)~80%, beam~85%

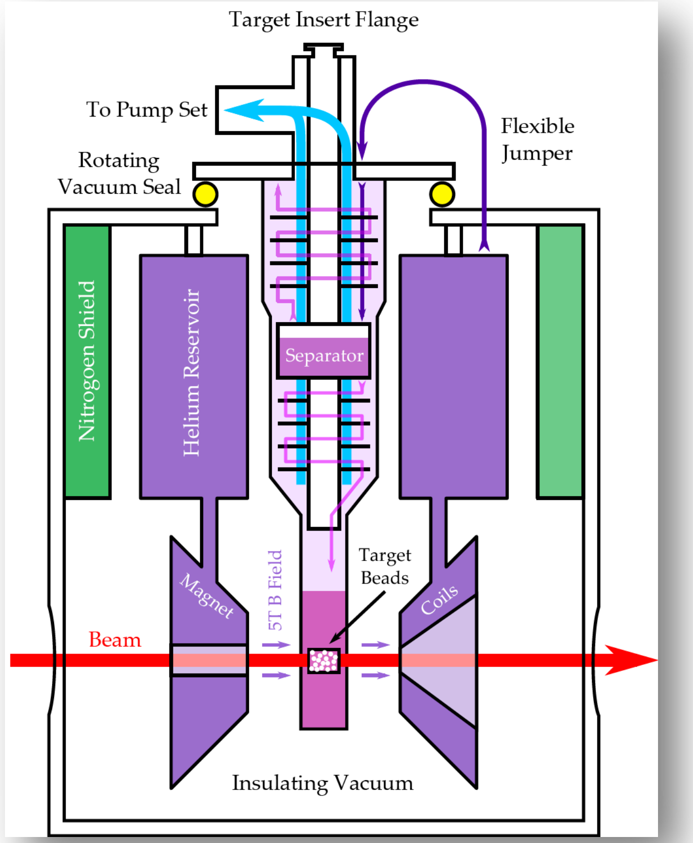
✓ Luminosity (polarized): ~ 10^{36} (n) & ~ 10^{35} cm^{-2} s^{-1} (p)

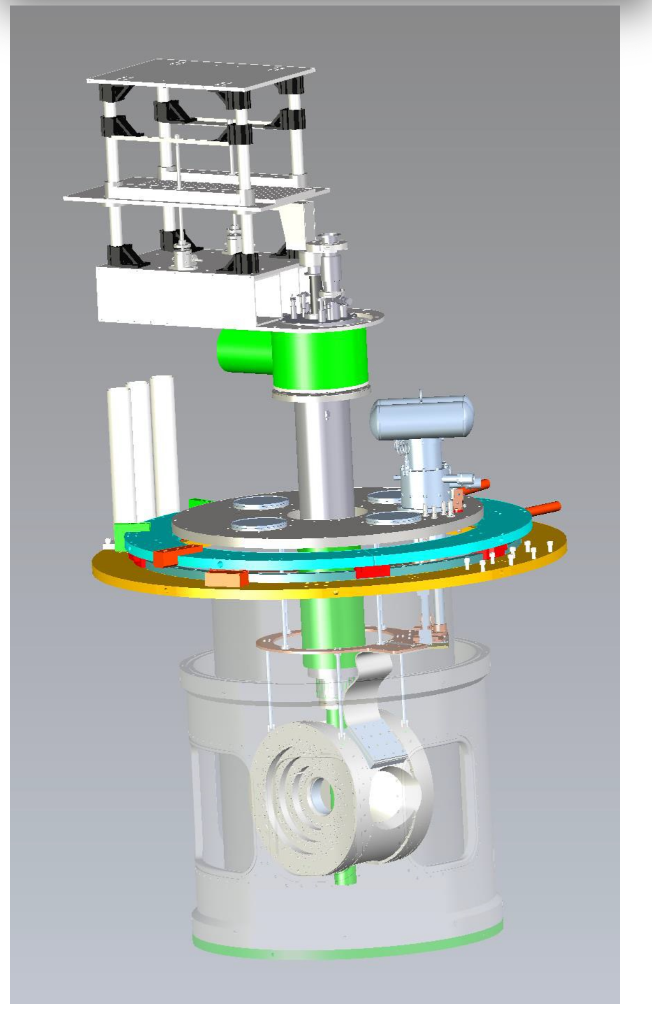
✓ DAQ Rate < 100KHz

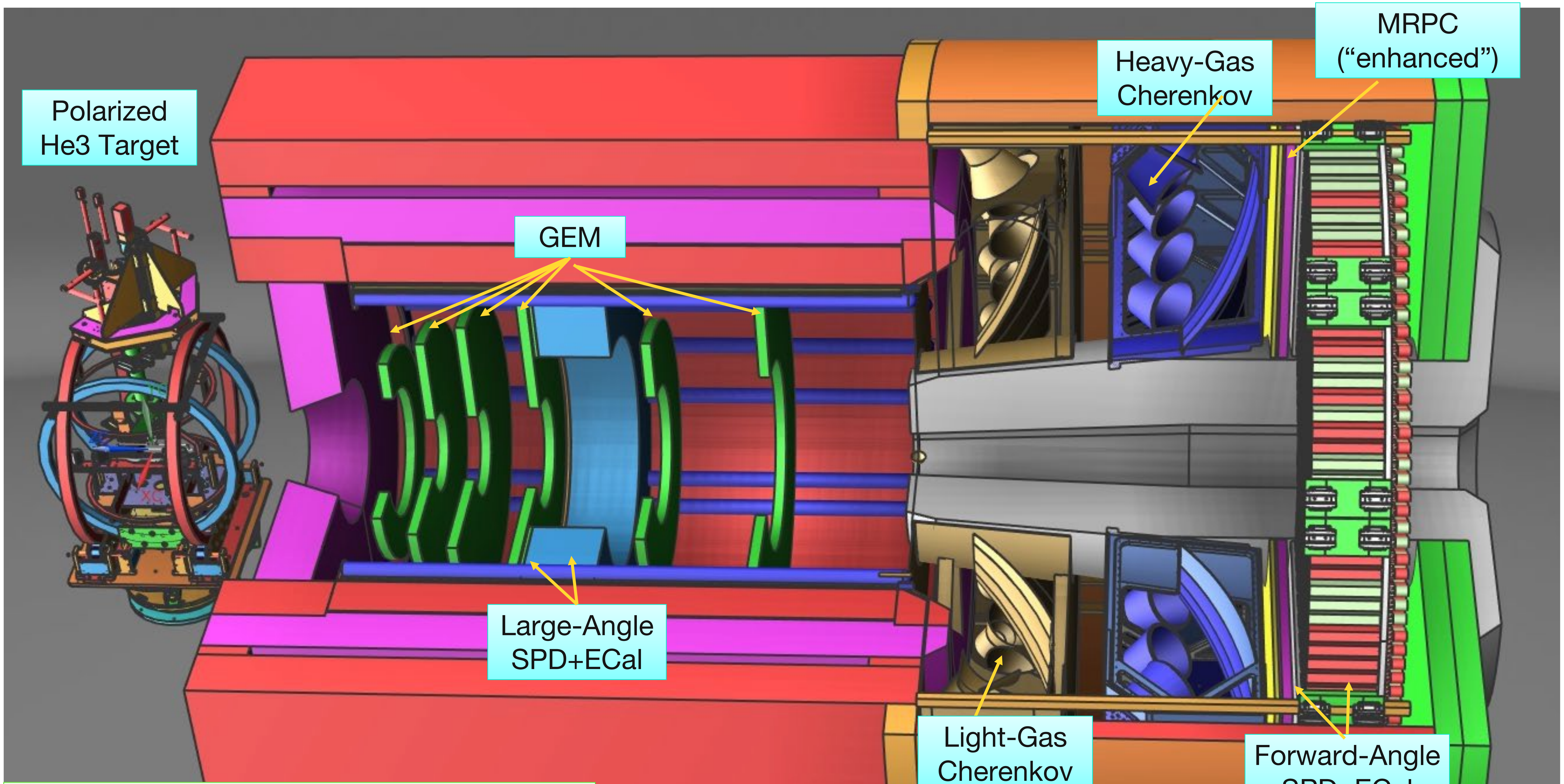
- Run-Group (no additional beam time / reconfiguration):
  - SIDIS in **Kaon** Production with Polarized 3He & Proton (E12-11-108B/E12-10-006D)
  - SIDIS Dihadron with Transversely Polarized 3He (E12-10-006A)
  - ✓ Ay with Transversely Polarized 3He (E12-10-006A)
  - ✓ g2 n and d2 n with Transversely and Longitudinally Polarized 3He (E12-10-006E)
  - ✓ Deep exclusive $\pi-$ Production with Transversely Polarized 3He (E12-10-006B)

SoLID-SIDIS(&J/Psi) Configuration

Polarized NH3 (DNP) Target







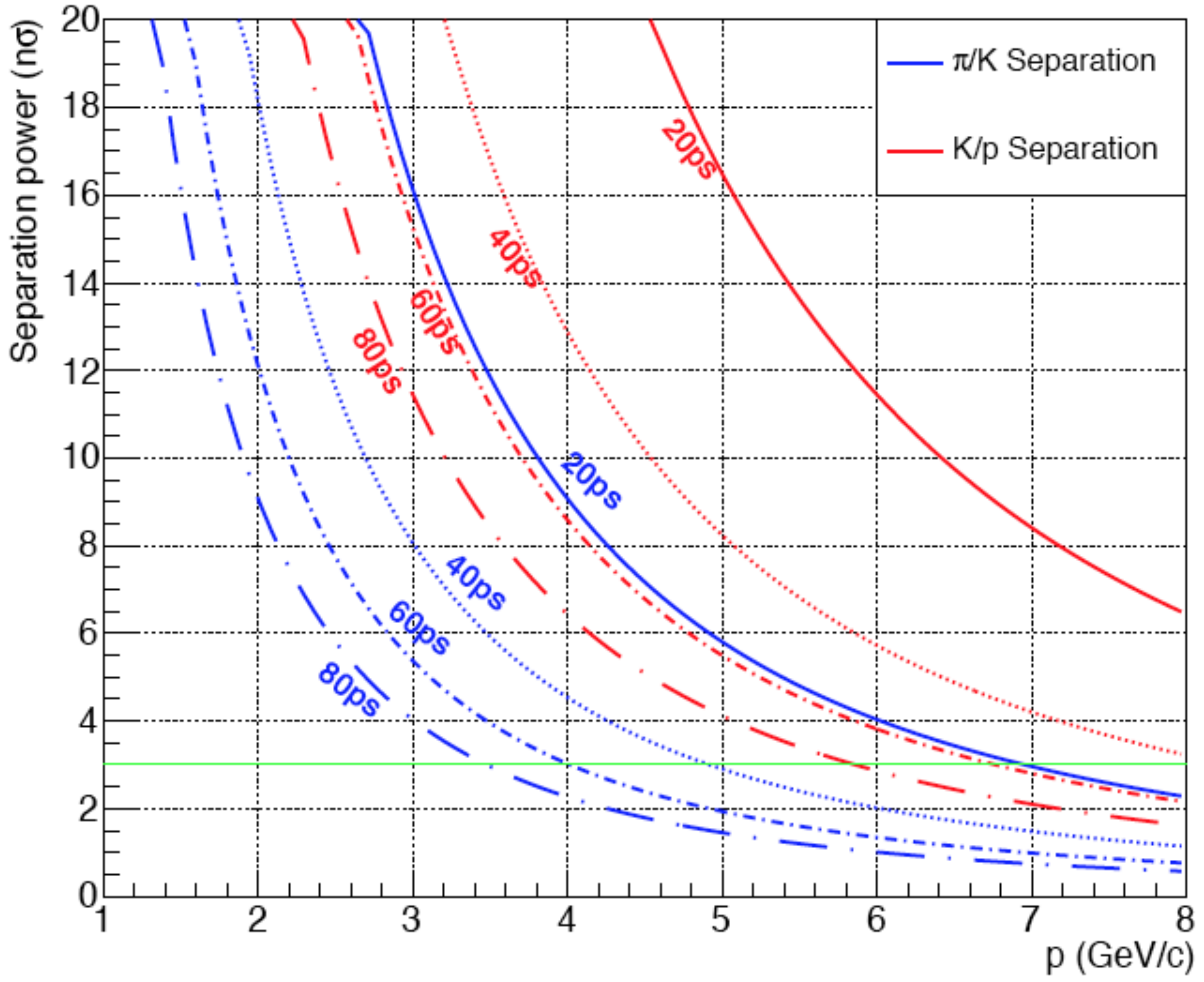
Coverage

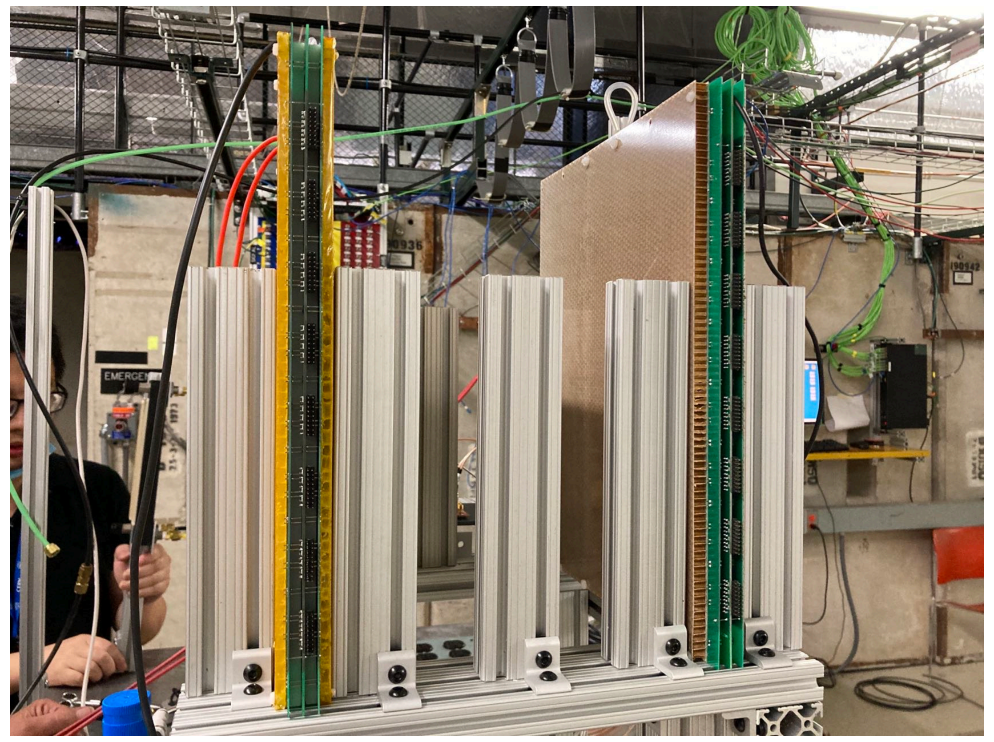
- Polar angle: e^- 8-24 deg, π^-/π^+ 8-15deg
- Azimuthal angle: full

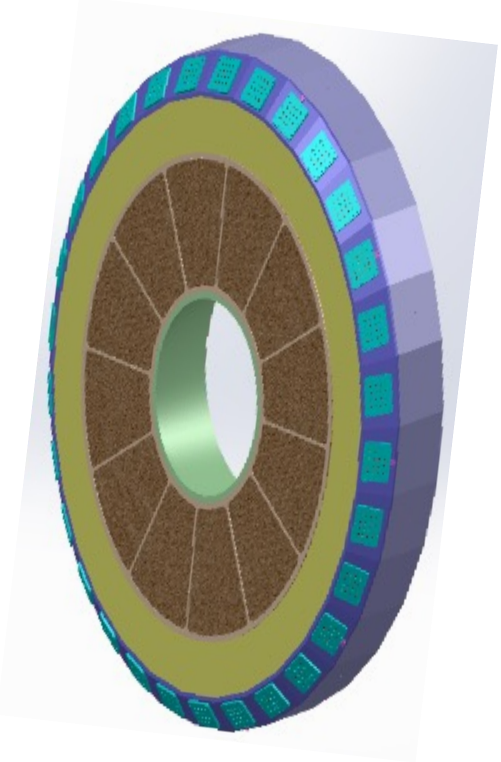
SoLID-SIDIS Programs

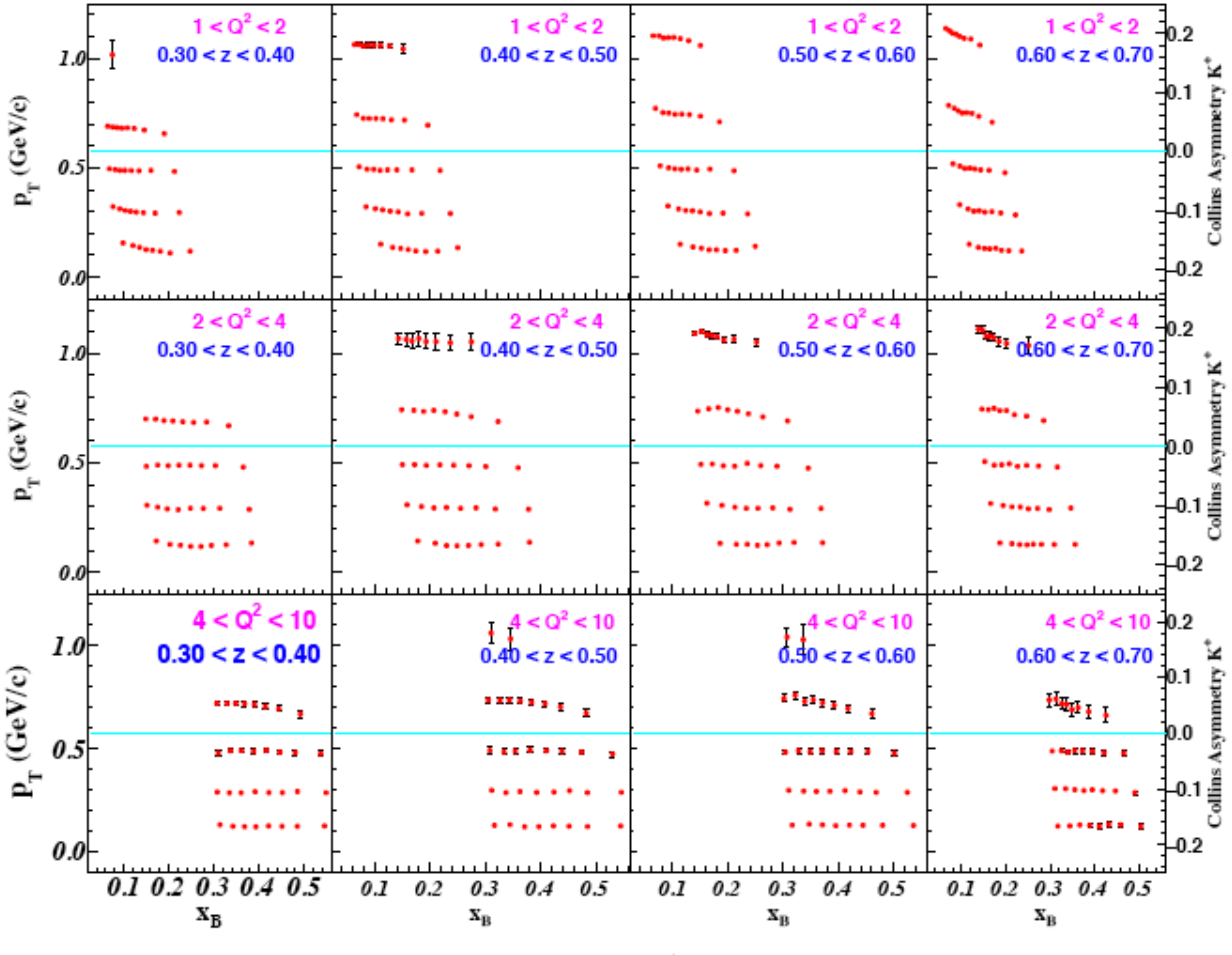
- Kaon-SIDIS:
  - ❑ Look for $K^{\pm}$ production in SIDIS using both the transversely polarized 3He and NH3 Targets
  - ❑ Extract $K^{\pm}$ Collins, Sivers and other TMD asymmetries
  - ❑ Flavor decomposition of u, d and sea quarks' TMDs
  - ❑ Kaon-Identification: HGC + 30ps MRPC-TOF

Totally 430 bins in 4D binning for He3 setup:









(a) $\vec{n}(e, e'K^+)X$

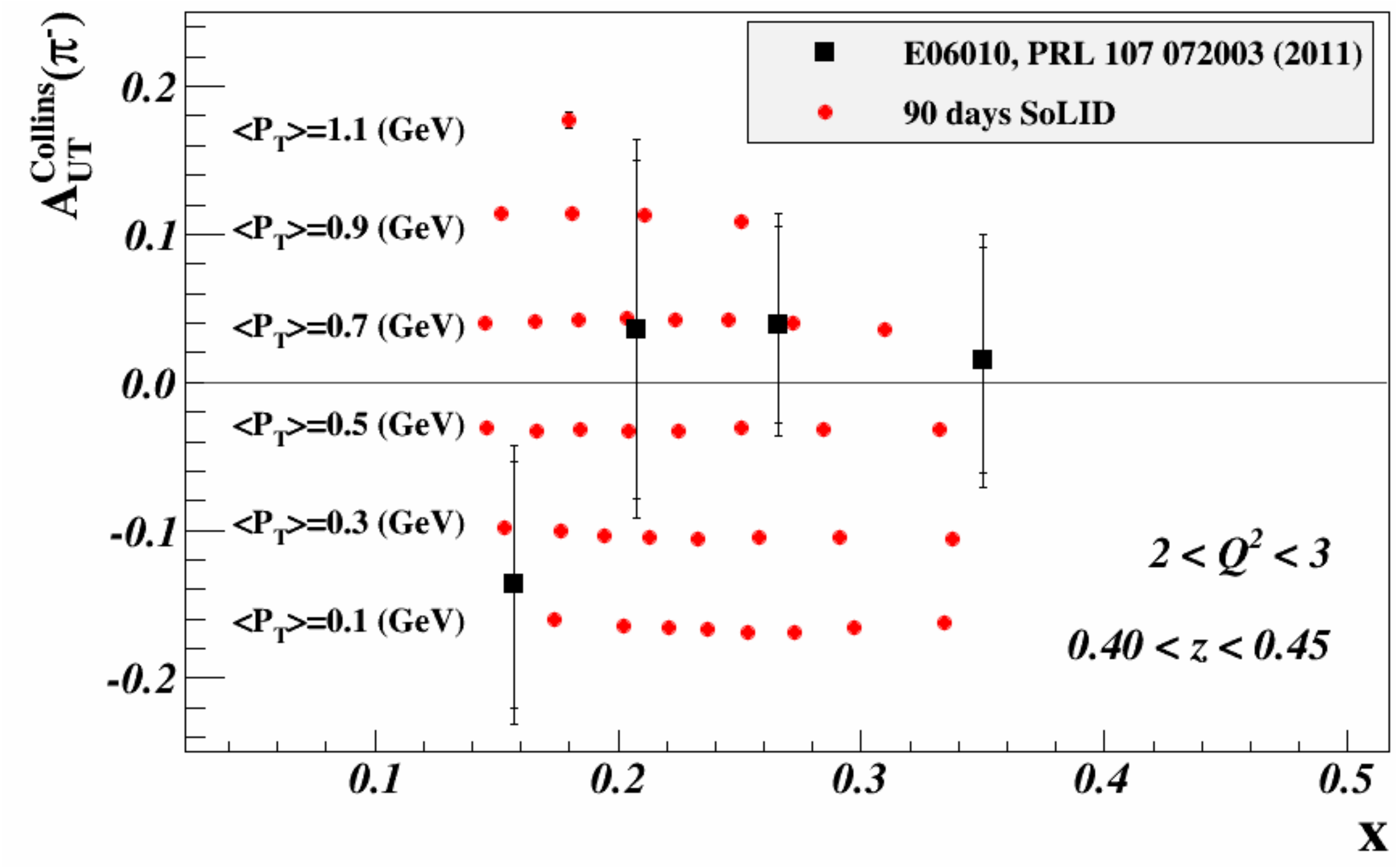
- ❑ **Enhanced configuration**
  - ✓ MRPC modules contributed by Chinese resources (Tsinghua, USTC, etc.)
  - ✓ High-time resolution Readout electronics contributed by other US funding resources (UIC, etc.)

SoLID-SIDIS Projections

➢ Approved SIDIS proposals:

✓Wider phase-space, cover valance quark region

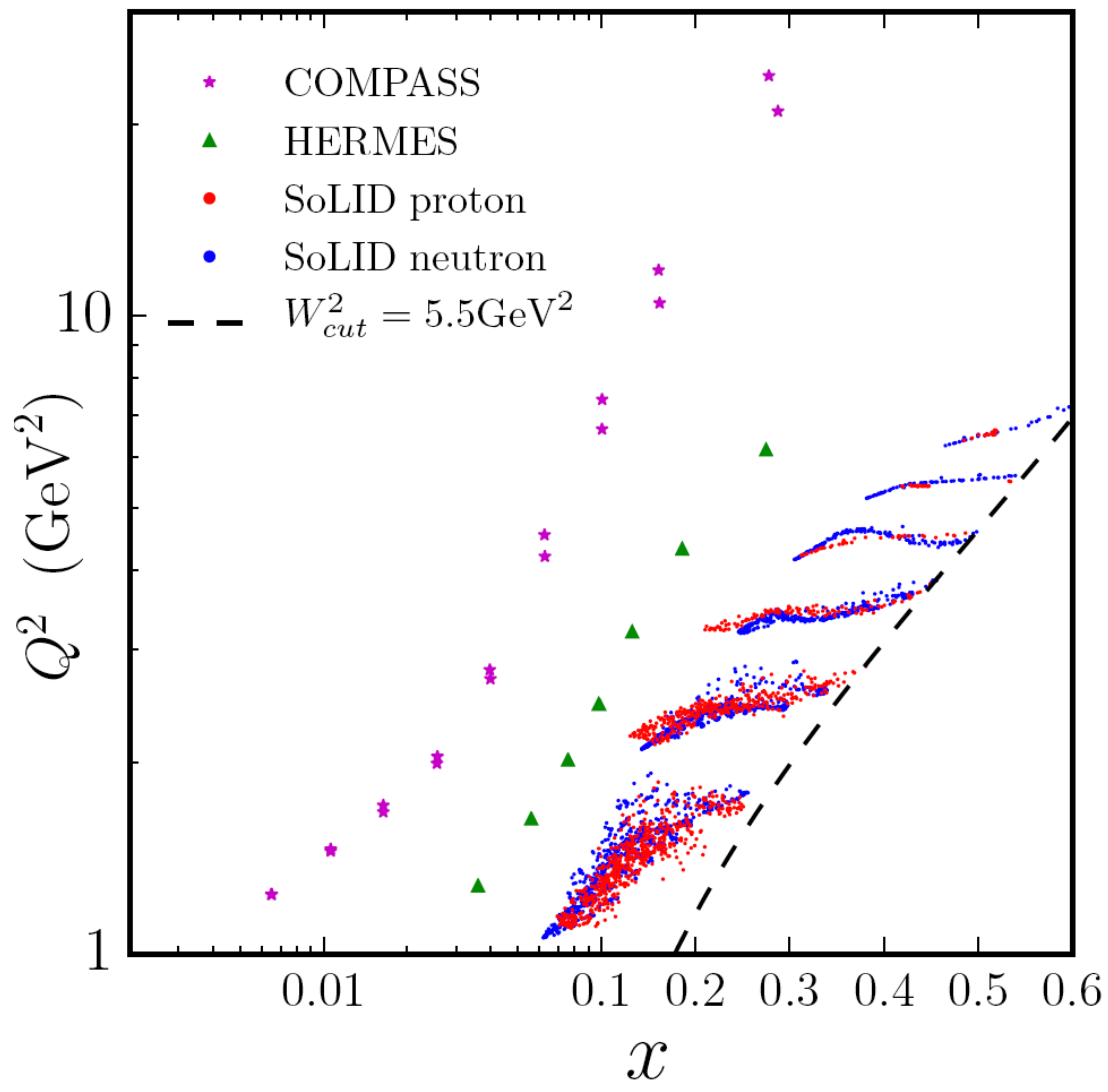
✓ High statistics for **4D binning** in (x, p_T, Q^2, z)



$0.05 < x < 0.6$,
$1\text{GeV}^2 < Q^2 < 8\text{GeV}^2$
$0.3 < z < 0.7$,
$0 < P_T < 1.6\text{GeV}$

Pion-TSA: ~2000 bins for n,
~1000 bins for p

Z. Ye et al, Phys. Lett. B 767, 91 (2017)



✓Full extraction of Collins, Sivers and Pretzelocity from TSA

$$A_{UT}(\phi_h,\phi_S) = \frac{1}{P_{t,pol}}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} = A_{UT}^{Collins}\sin(\phi_h+\phi_S) + A_{UT}^{Pretzelosity}\sin(3\phi_h-\phi_S) + A_{UT}^{Sivers}\sin(\phi_h-\phi_S)$$

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

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

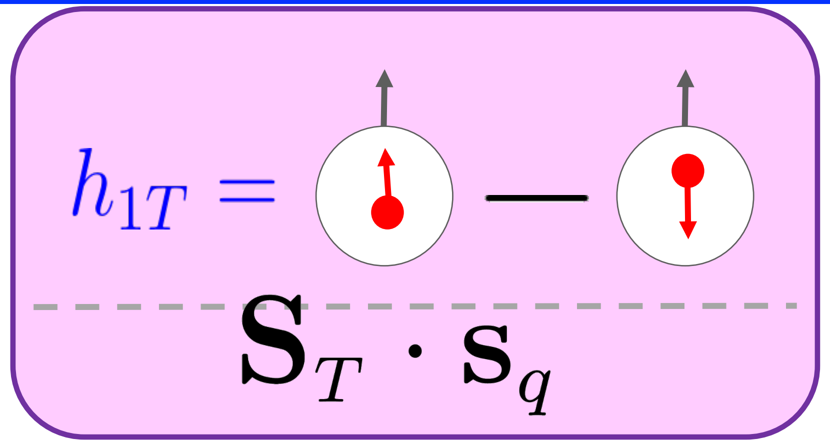
Collins fragmentation function from e^+e^- collisions

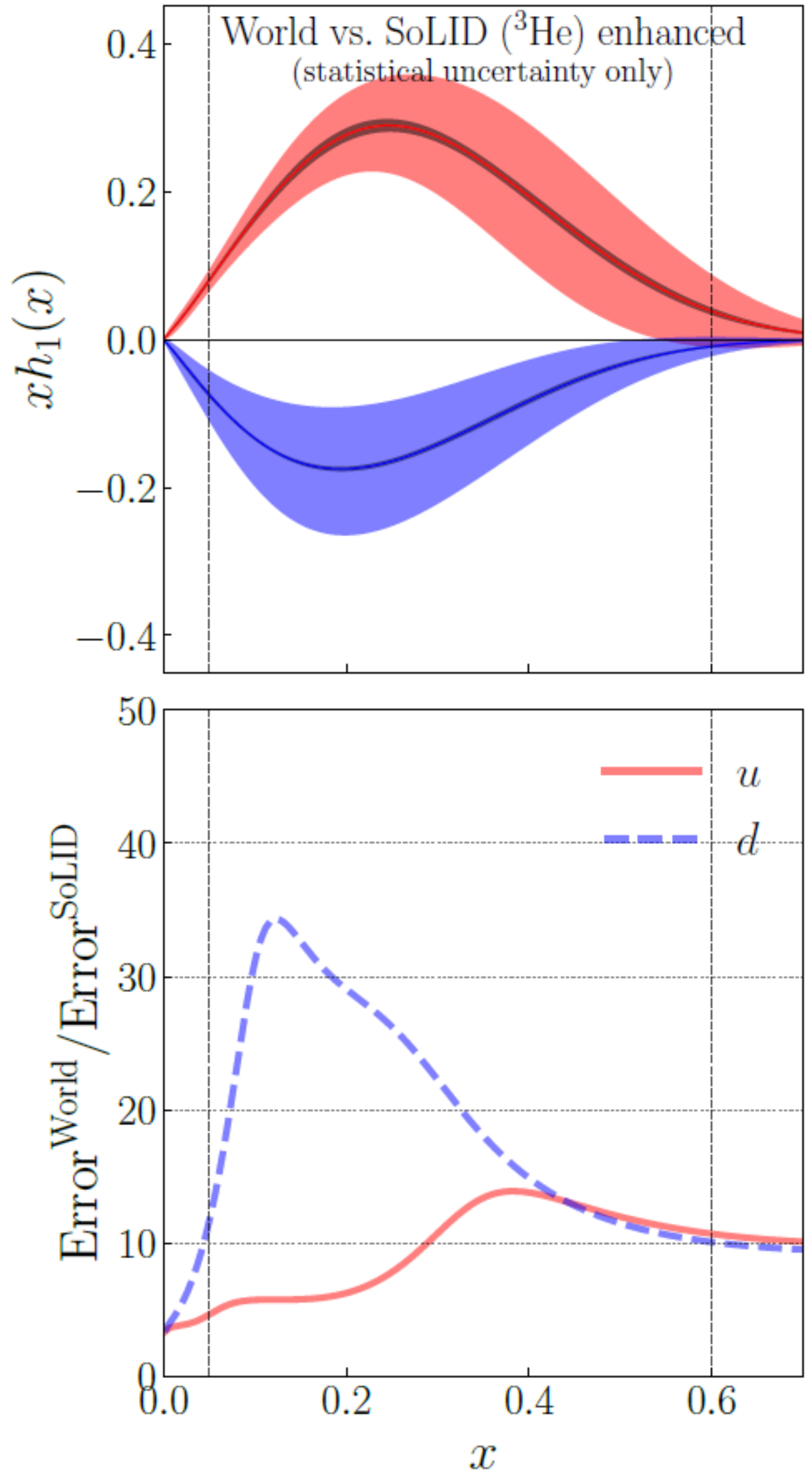
$$A_{UT}^{Sivers} \propto \langle\sin(\phi_h-\phi_S)\rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$

Unpolarized fragmentation function

SoLID-SIDIS Projections

- Transversity & Tensor-Charge from TSA:
  - Chiral-odd, unique for the quarks
  - No mixing with gluons, simpler evolution effect

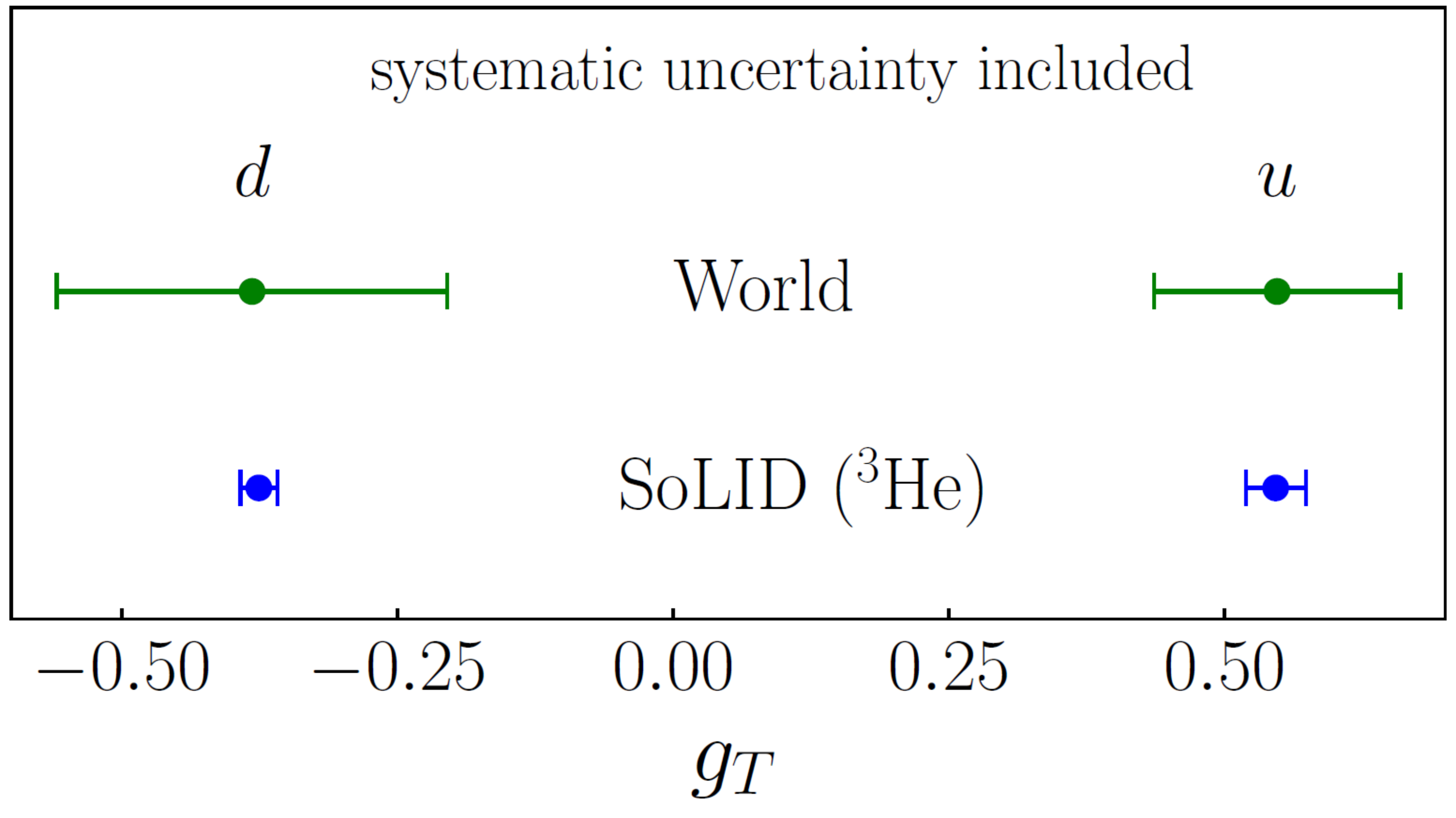




D'Alesio et al., Phys. Lett. B 803 (2020)135347

- Access Tensor charge:

$$g_T^q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x)\right] dx$$



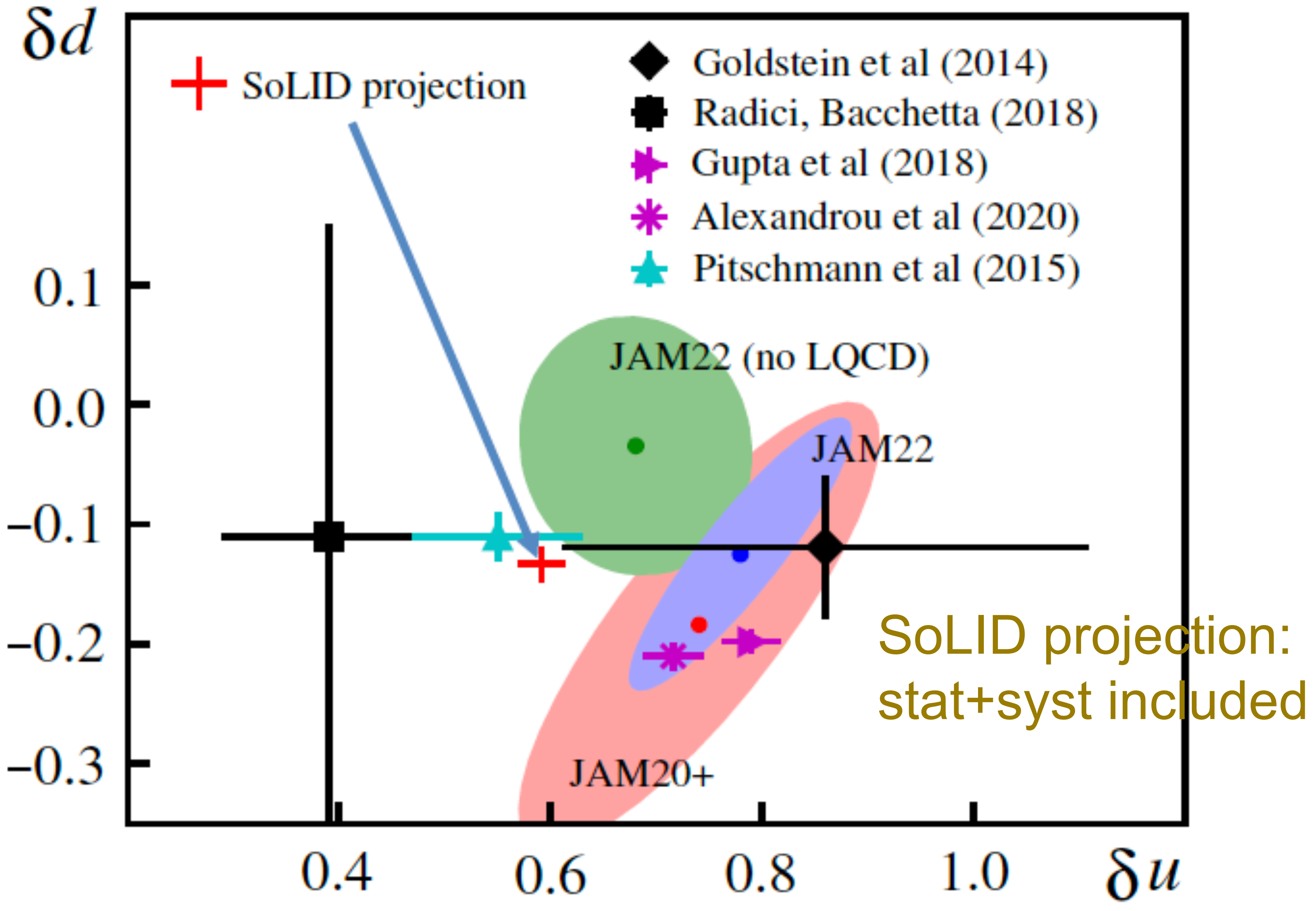
Z. Ye et al, Phys. Lett. B 767, 91 (2017)

J. Phys. G: Nucl. Part. Phys. 50 (2023) 110501

H. Gao, T. Liu and Z. Zhao, PRD 97, 074018 (2018)

J. Cammarota et al, PRD 102, 054002 (2020) (JAM20+)

L. Gamberg et al., Phys.Rev.D 106 (2022) 3, 034014 (JAM22)



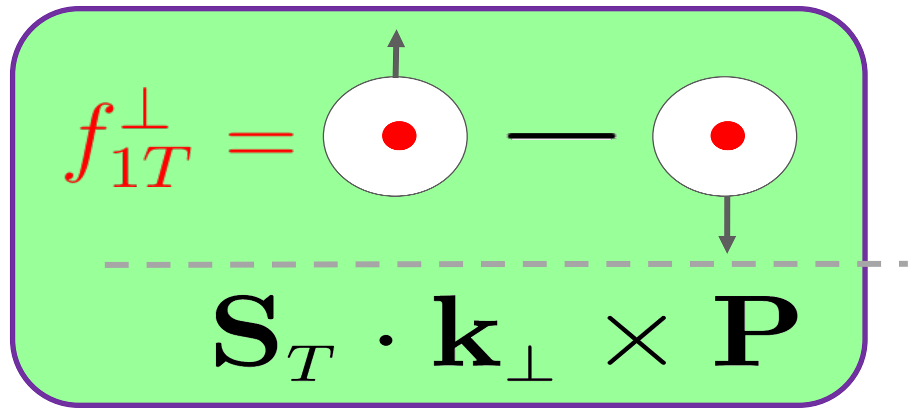
- Tensor charge is connected to neutron and proton EDMs:

$$d_n = g_T^d d_u + g_T^u d_d + g_T^s d_s$$

- ✓ A fundamental QCD quantity dominated by valence quarks
- ✓ Precisely calculated on the lattice
- ✓ SoLID data allows for high-precision test of LQCD predictions
- ✓ A unique opportunity for SM tests and new physics

SoLID-SIDIS Projections

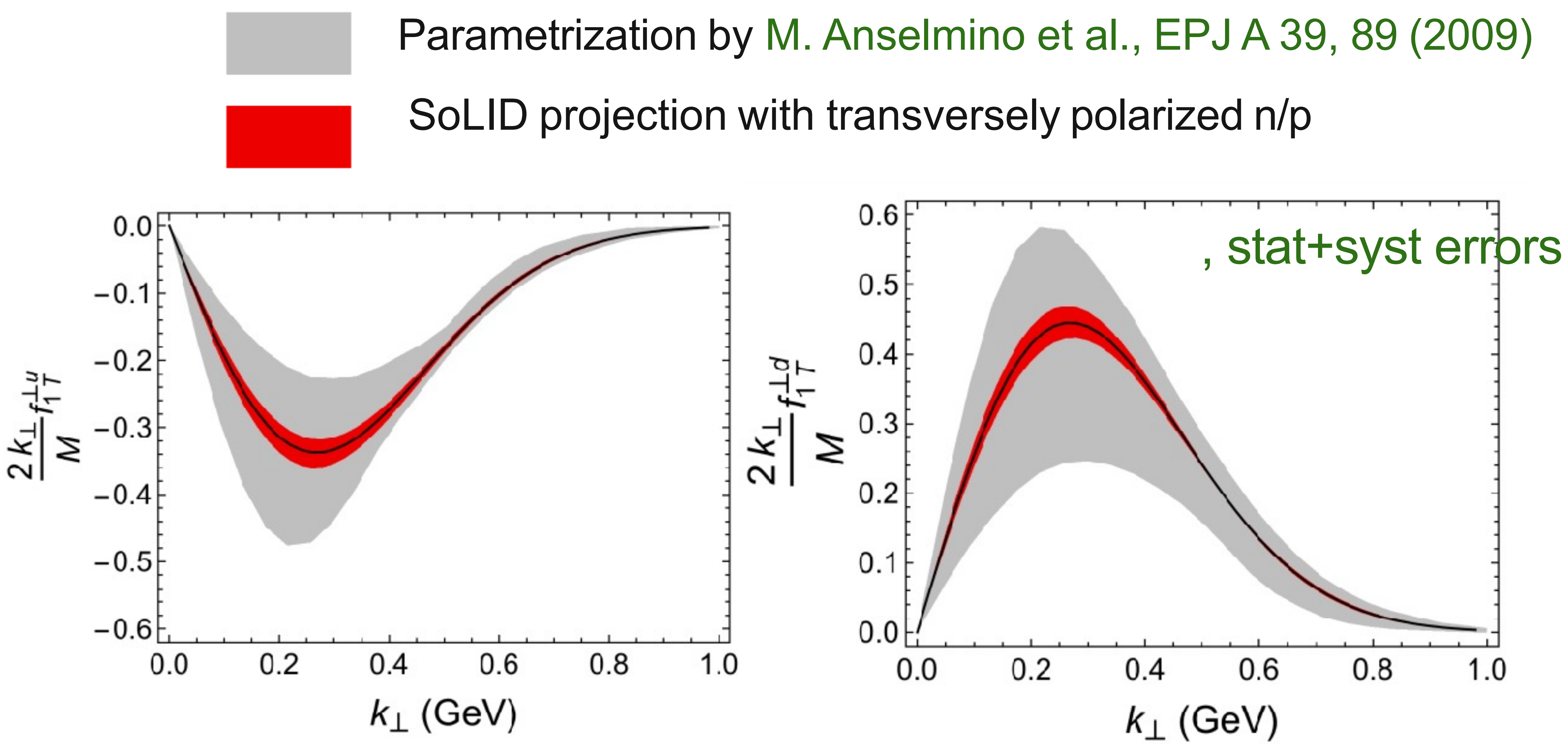
➢ Sivers from TSA:

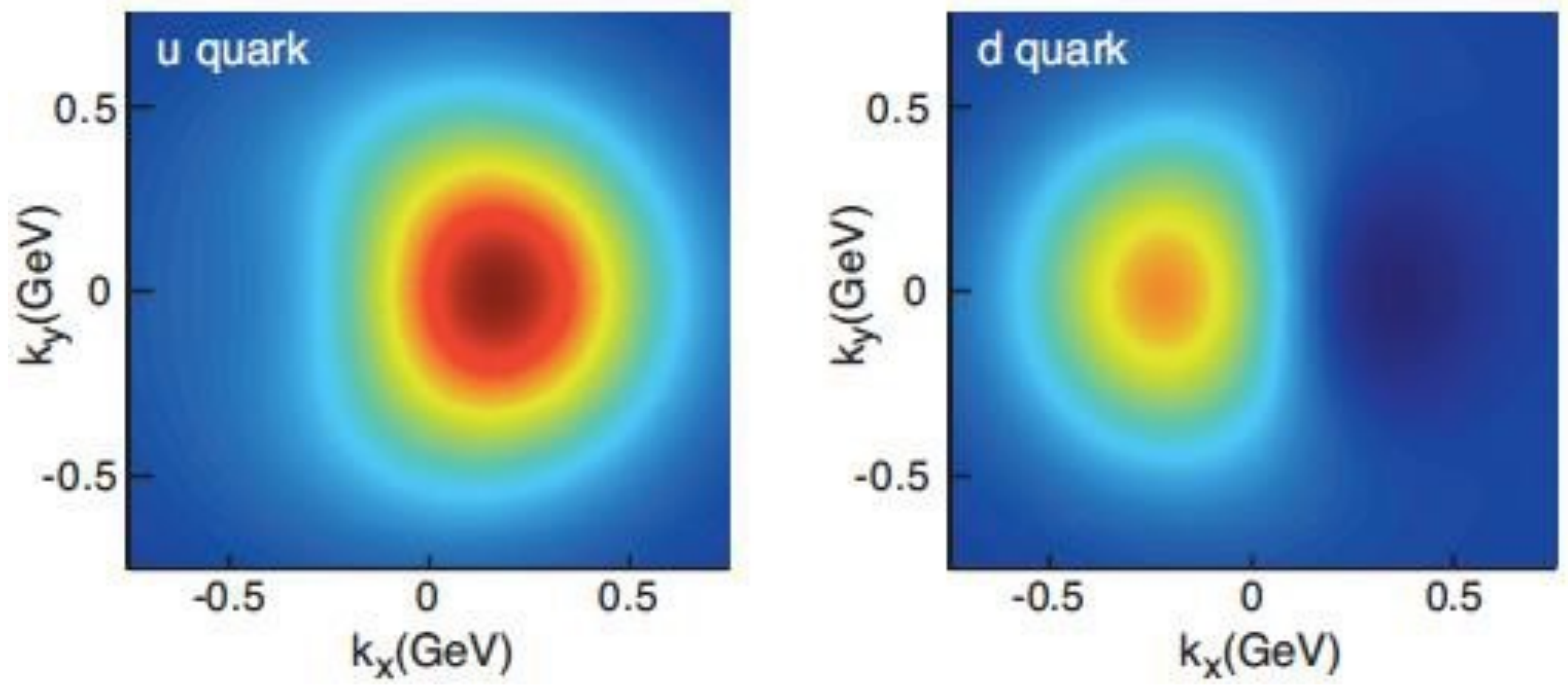


❑ Nucleon spin –quark orbital angular momentum (OAM) correlation – zero if no OAM (collinear, massless quarks)

$$f_{q/p\uparrow}(x, \mathbf{k}_\perp) = f_1^q(x, k_\perp) - f_{1T}^{\perp q}(x, k_\perp) \frac{\widehat{\mathbf{P}} \times \mathbf{k}_\perp \cdot \mathbf{S}}{M}$$

$$\langle \mathbf{k}_\perp \rangle = -M \int dx f_{1T}^{\perp(1)}(x)(\mathbf{S} \times \widehat{\mathbf{P}})$$





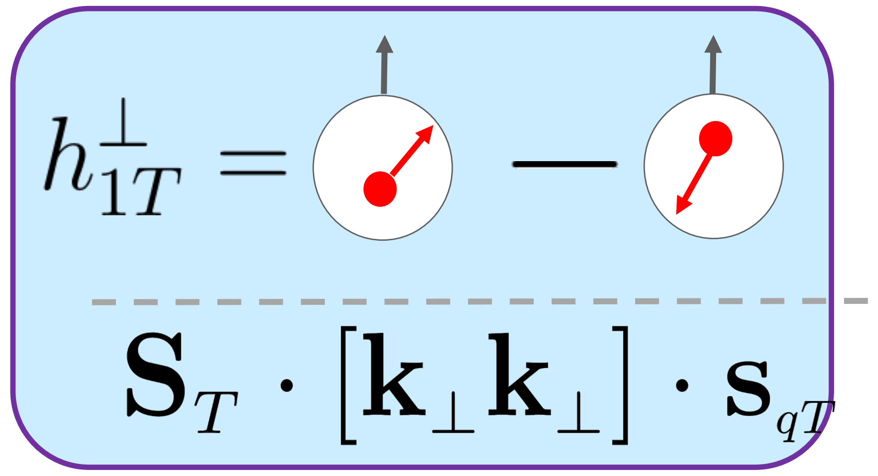
	$\langle k_\perp \rangle^u$	$\langle k_\perp \rangle^d$
	96^{+60}_{-28} MeV	-113^{+45}_{-51} MeV
	$96^{+2.8}_{-2.4}$ MeV	$-113^{+1.3}_{-1.7}$ MeV

❑ Naively time-reversal odd

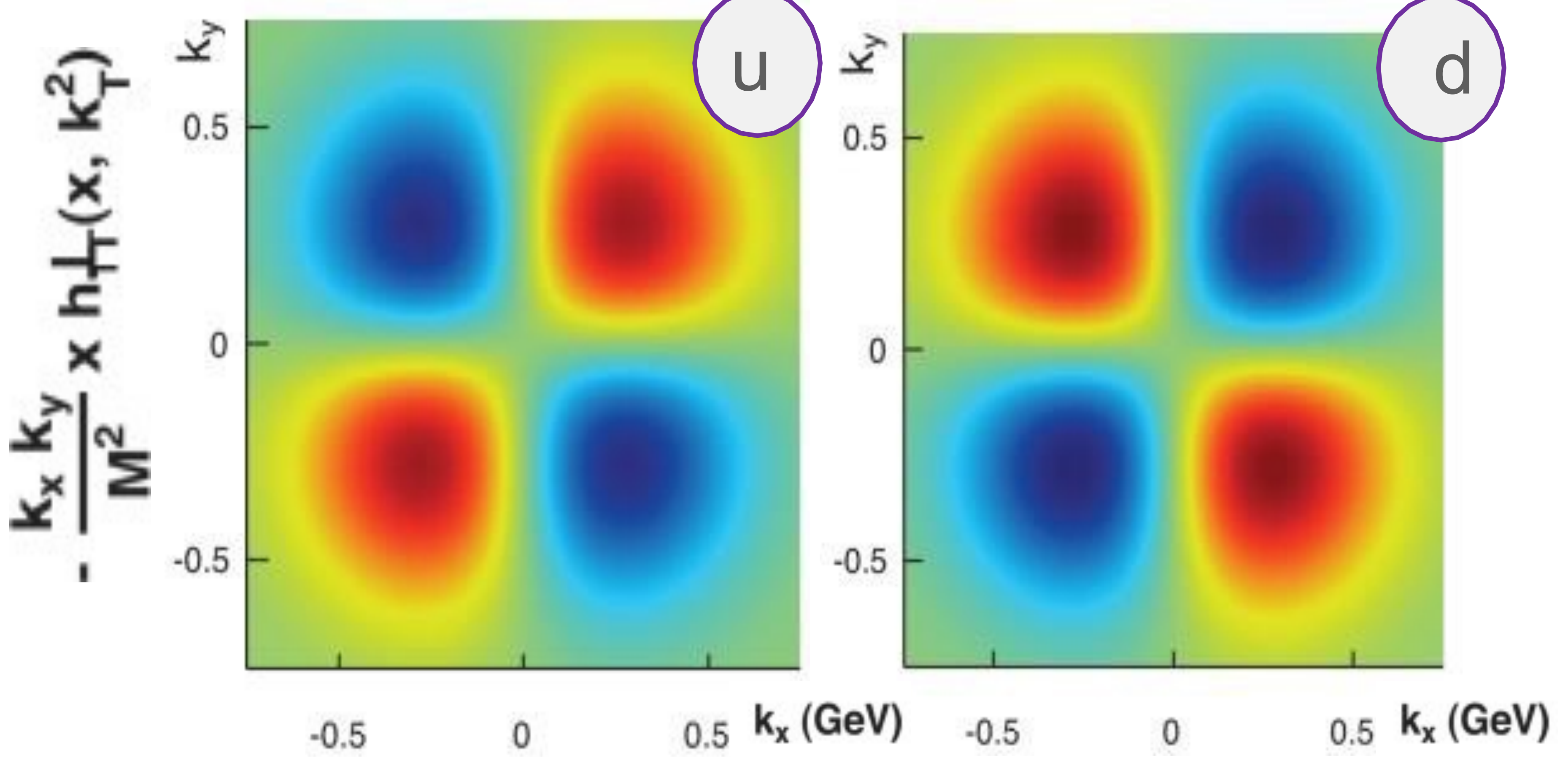
$$f_{1T}^{\perp q}(x, k_\perp)\Big|_{\text{SIDIS}} = -f_{1T}^{\perp q}(x, k_\perp)\Big|_{\text{DY}}$$

SoLID-SIDIS Projections

➢ Pretzelocity from TSA:

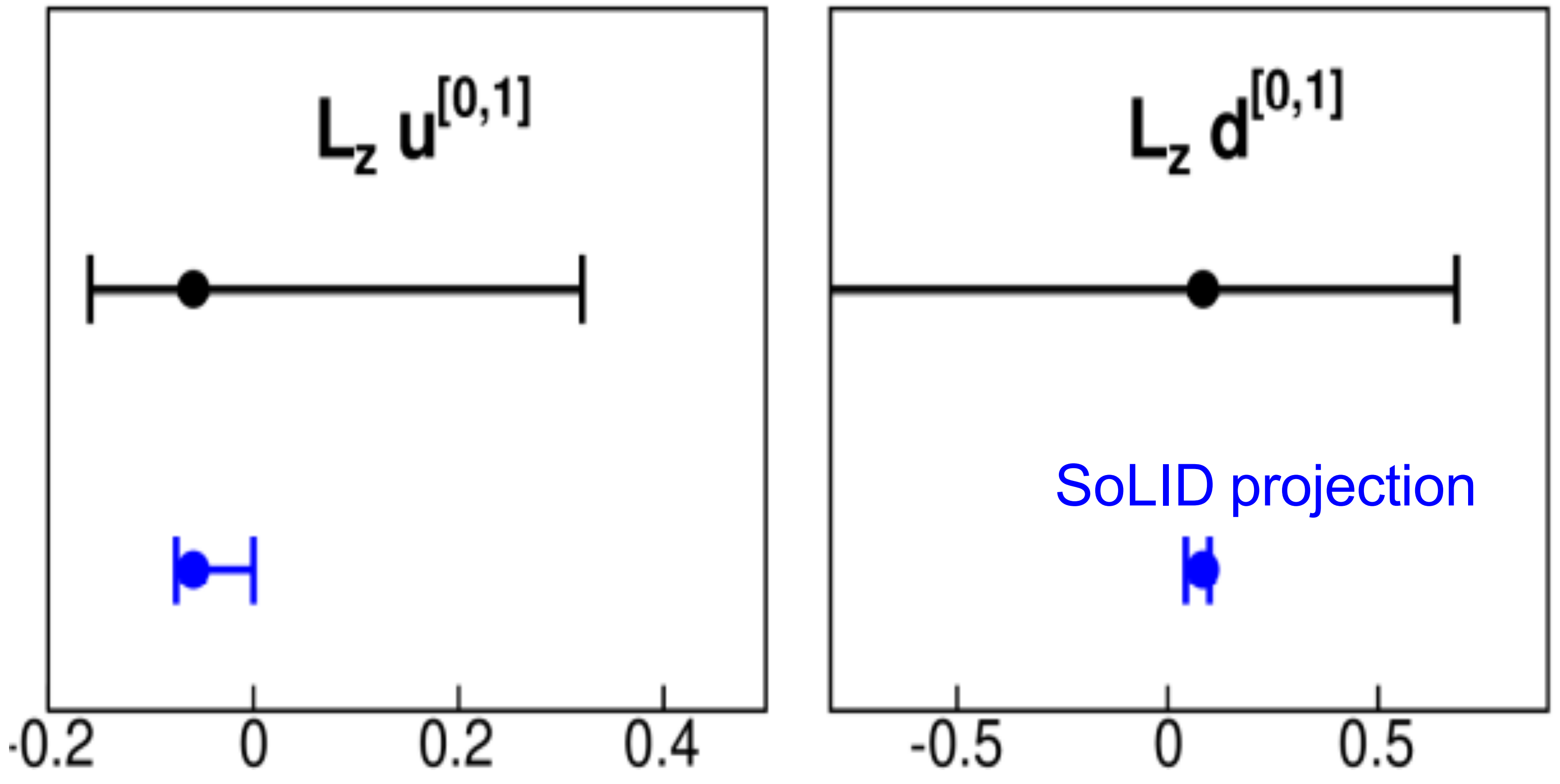


Images from PRD 91 034010 (2015)

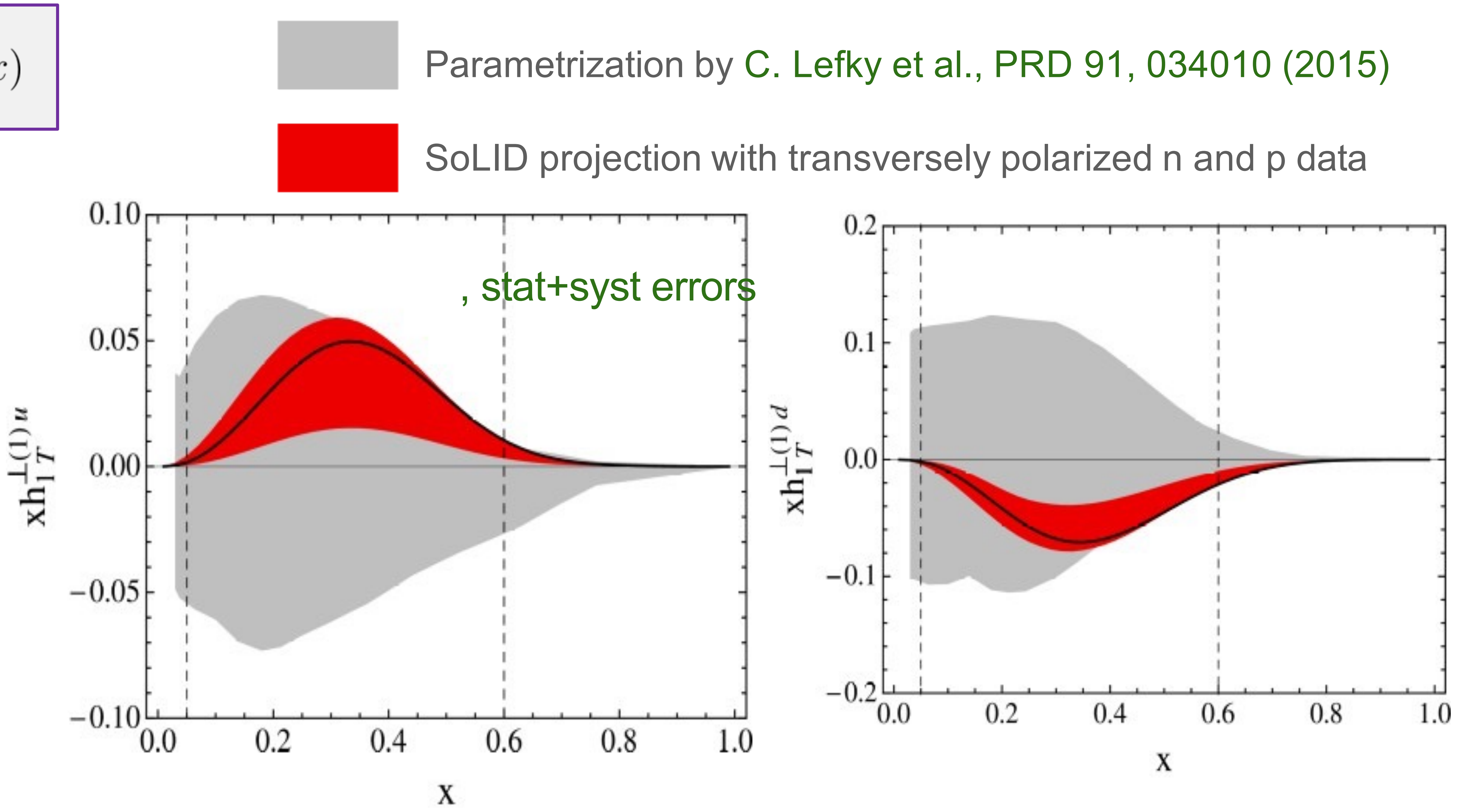


- Chiral-odd, no gluon analogy
- Distribution of transversely polarized quarks in a transversely polarized nucleon
- The difference between helicity and transversity (relativistic effects)
- Relation to OAM (canonical)

$$L_z^q = -\int \mathrm{d}x \mathrm{d}^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M^2} h_{1T}^{\perp q}(x, k_\perp) = -\int \mathrm{d}x h_{1T}^{\perp(1)q}(x)$$



Lefky and Prokudin PRD 91, 034010 (2015)

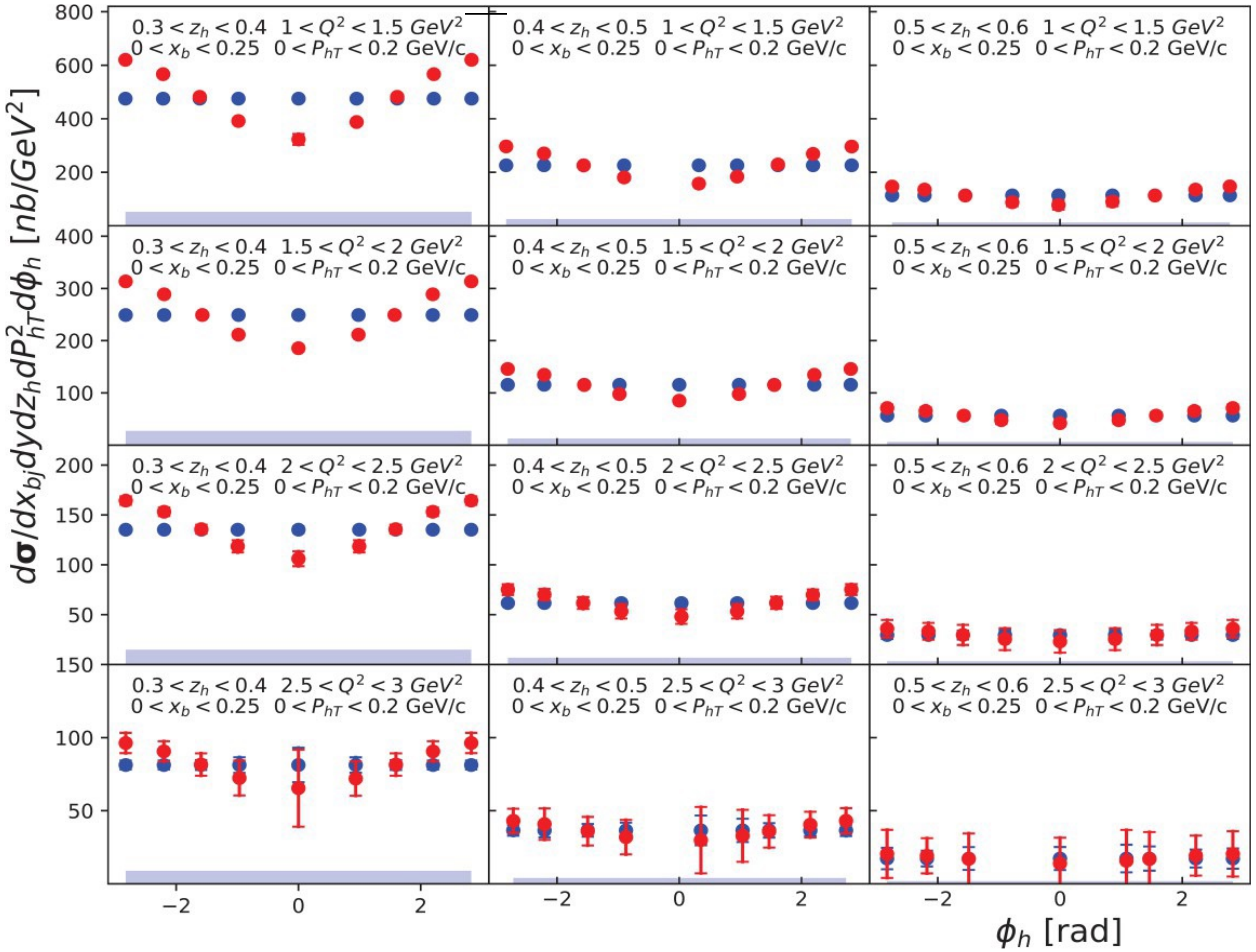


SoLID-SIDIS Projections

➢ Unpolarized Cross-Section off He3:

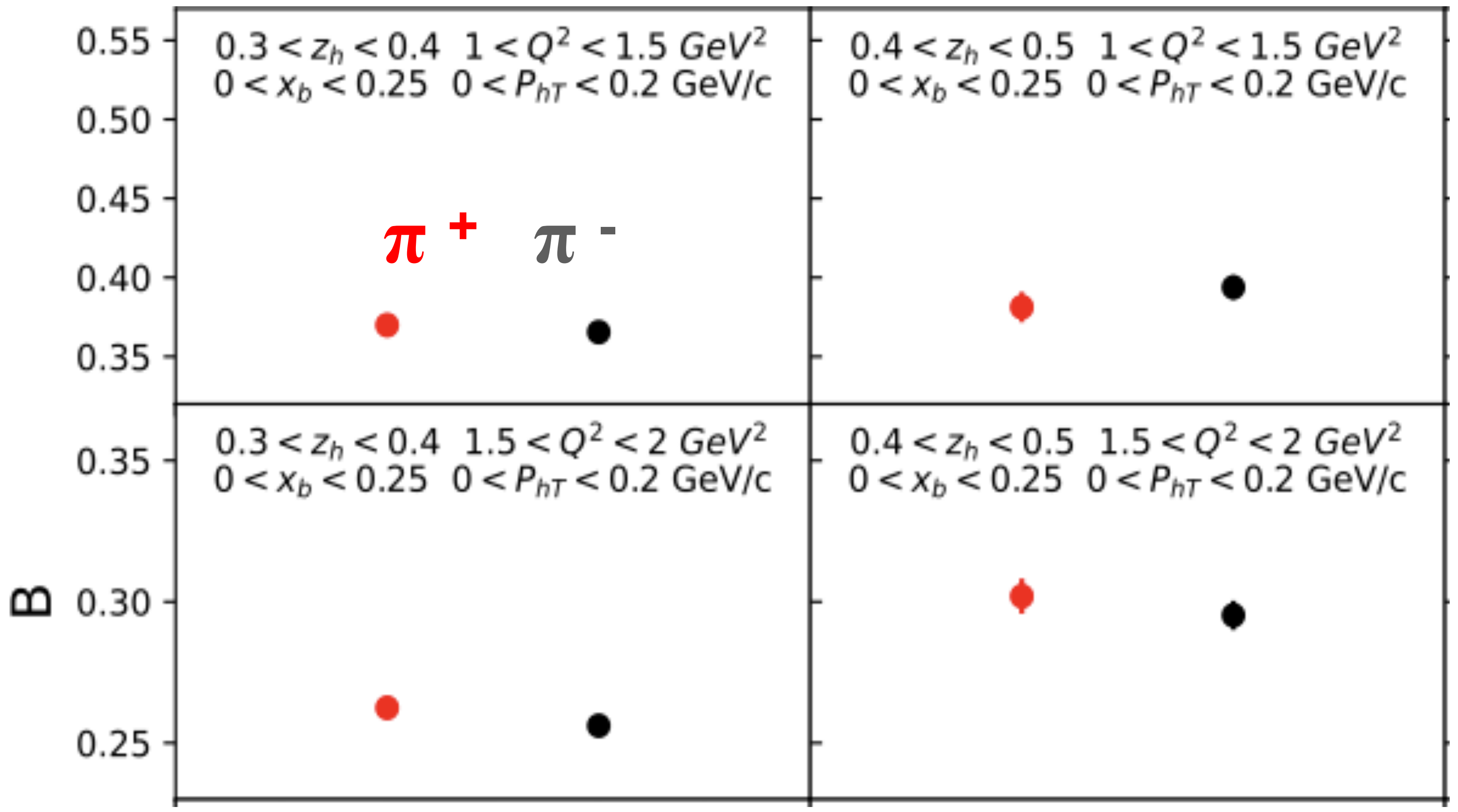
❑ Projected π^+ unpolarized cross section errors with and without azimuthal terms. **~2000 bins in 5D**

$$\frac{d\sigma}{dx_{bj}dydz_h dP_{hT}^2 d\phi_h} \equiv \mathcal{F}_{UU} = \mathcal{F}_{UU,\mathcal{A}} + \mathcal{F}_{UU,\mathcal{B}}\cos(\phi_h) + \mathcal{F}_{UU,\mathcal{C}}\cos(2\phi_h)$$



❑ A naive probe for the azimuthal modulation effect

$$A(1 - B\cdot\cos(\varphi_h) - C\cdot\cos(2\varphi_h))$$

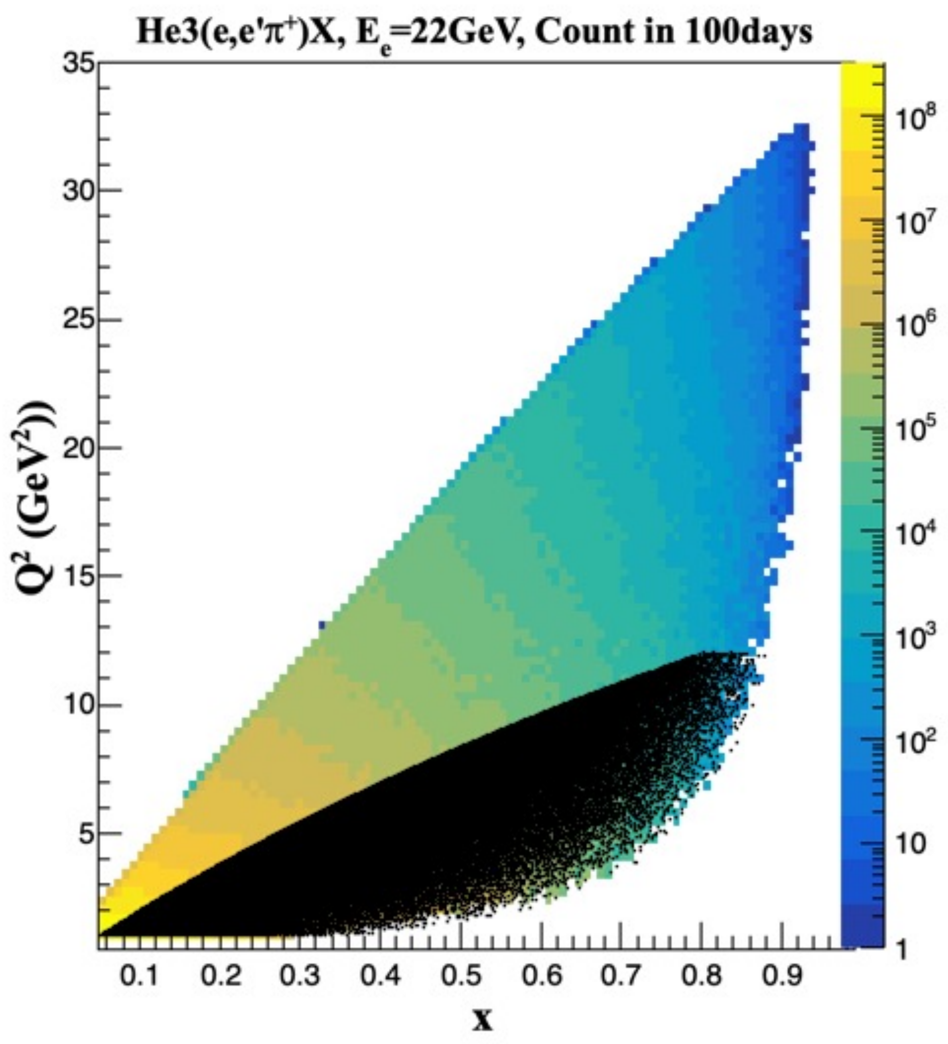


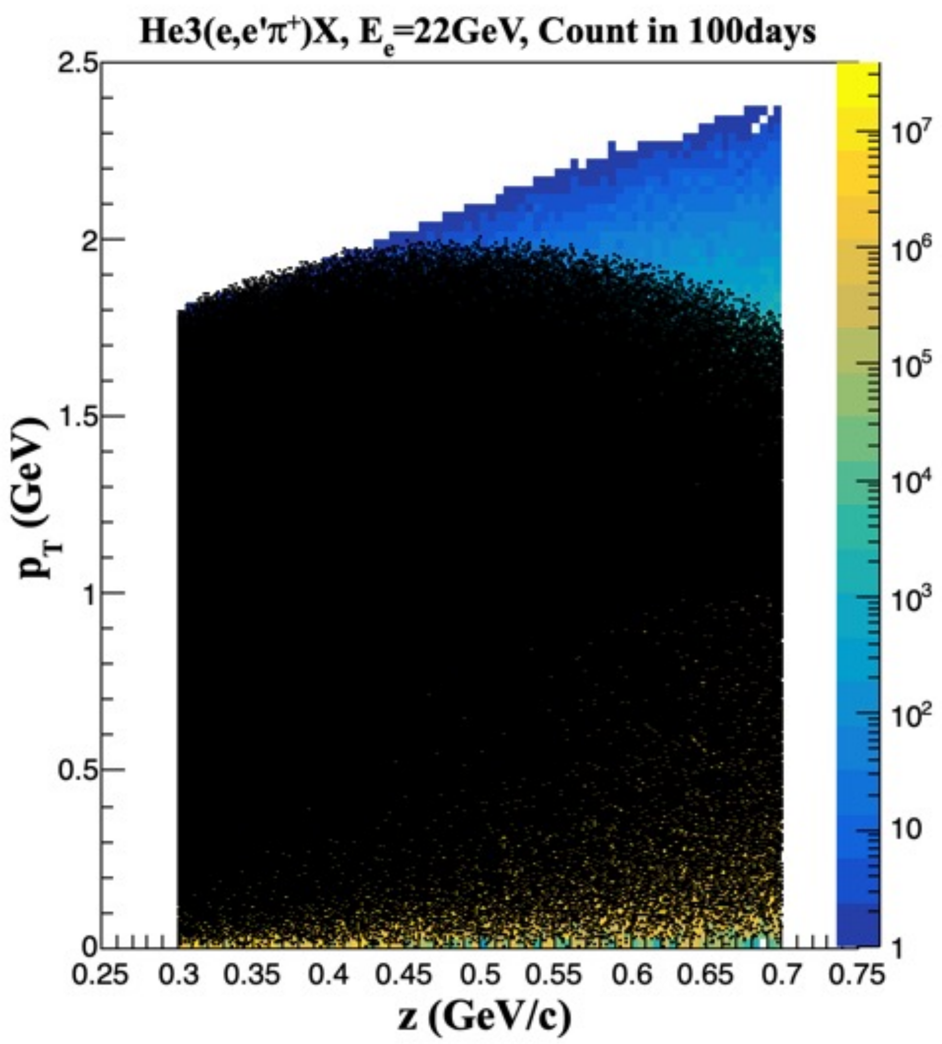
by Shuo Jia, et. al.

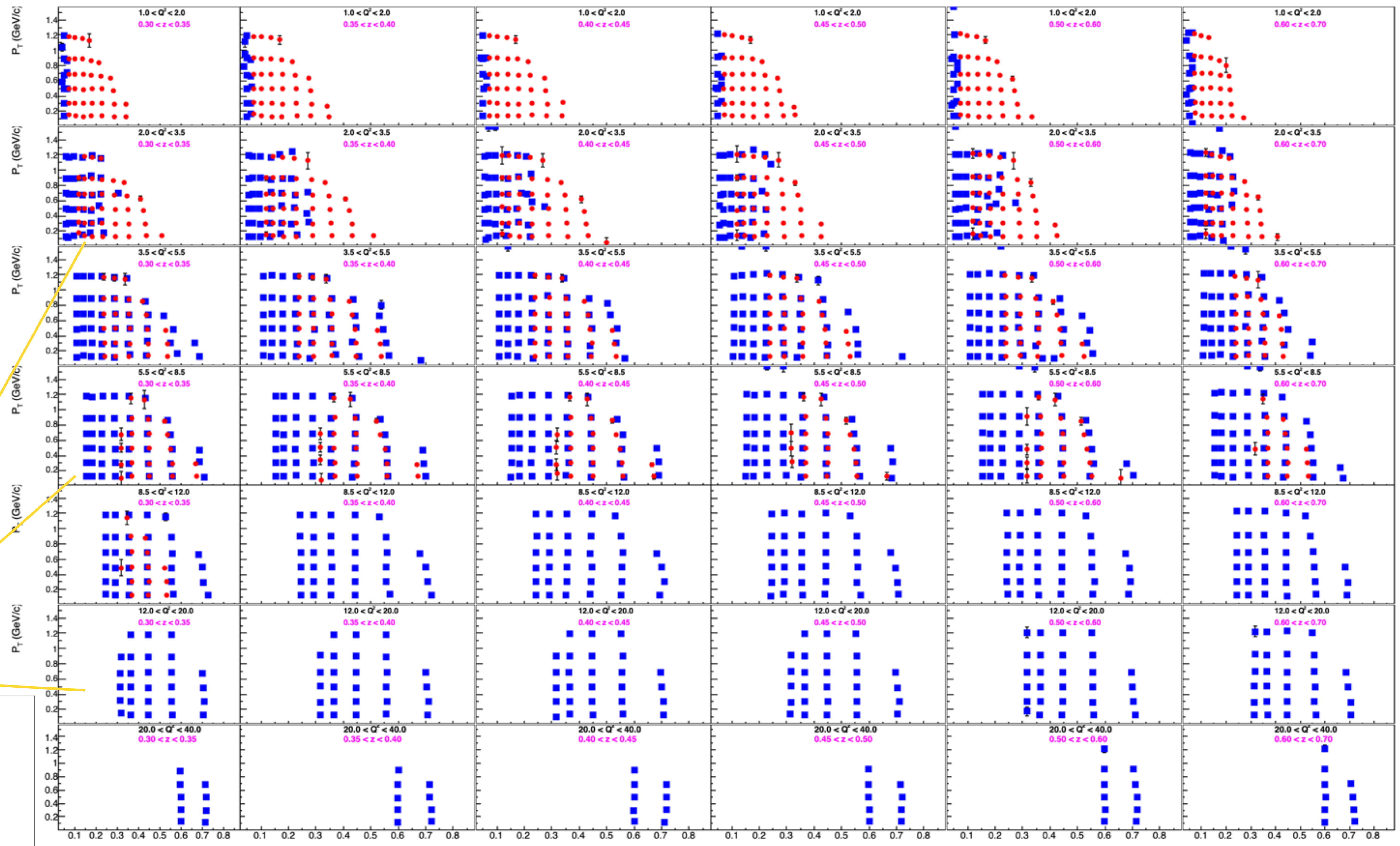
SoLID-SIDIS @ 22GeV

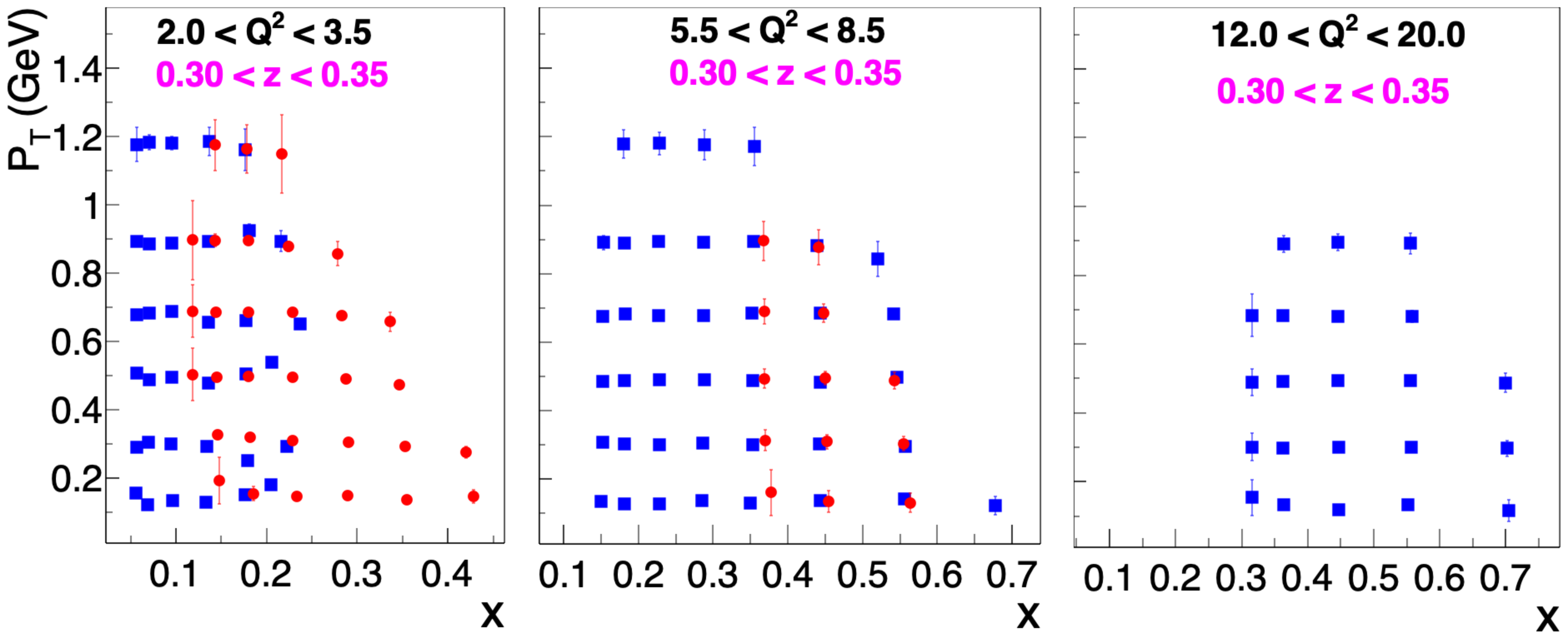
- 11GeV vs 22GeV

• 11GeV, 69days ▪ 22GeV, 100days









(Unpolarized) Pion-SIDIS Projection

Note:

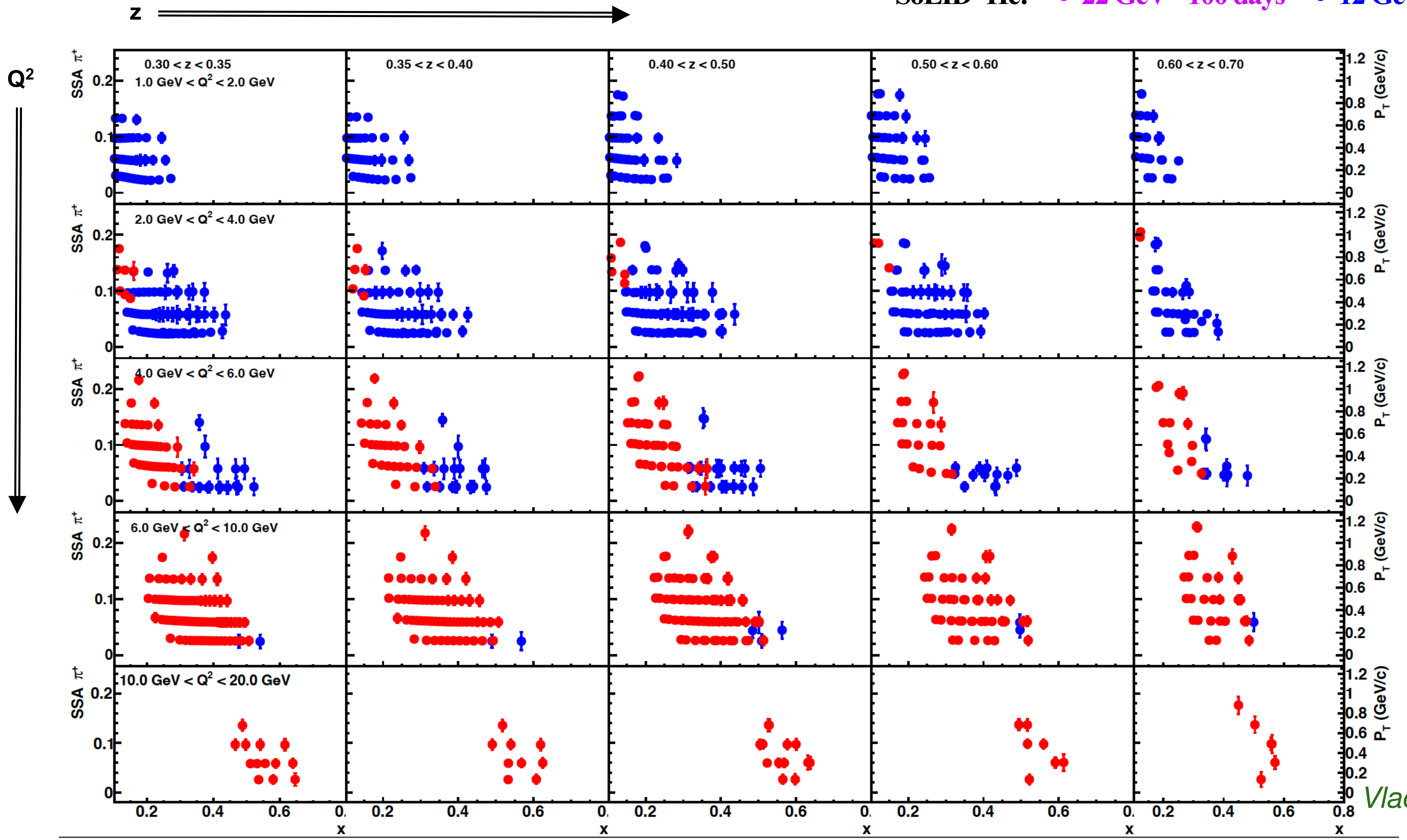
- Bypassed SoLID current acceptance
- Unpolarized-SIDIS events
- Only statistical uncertainties

SoLID-SIDIS @ 22GeV

- 11GeV vs 22GeV

Collins SSA

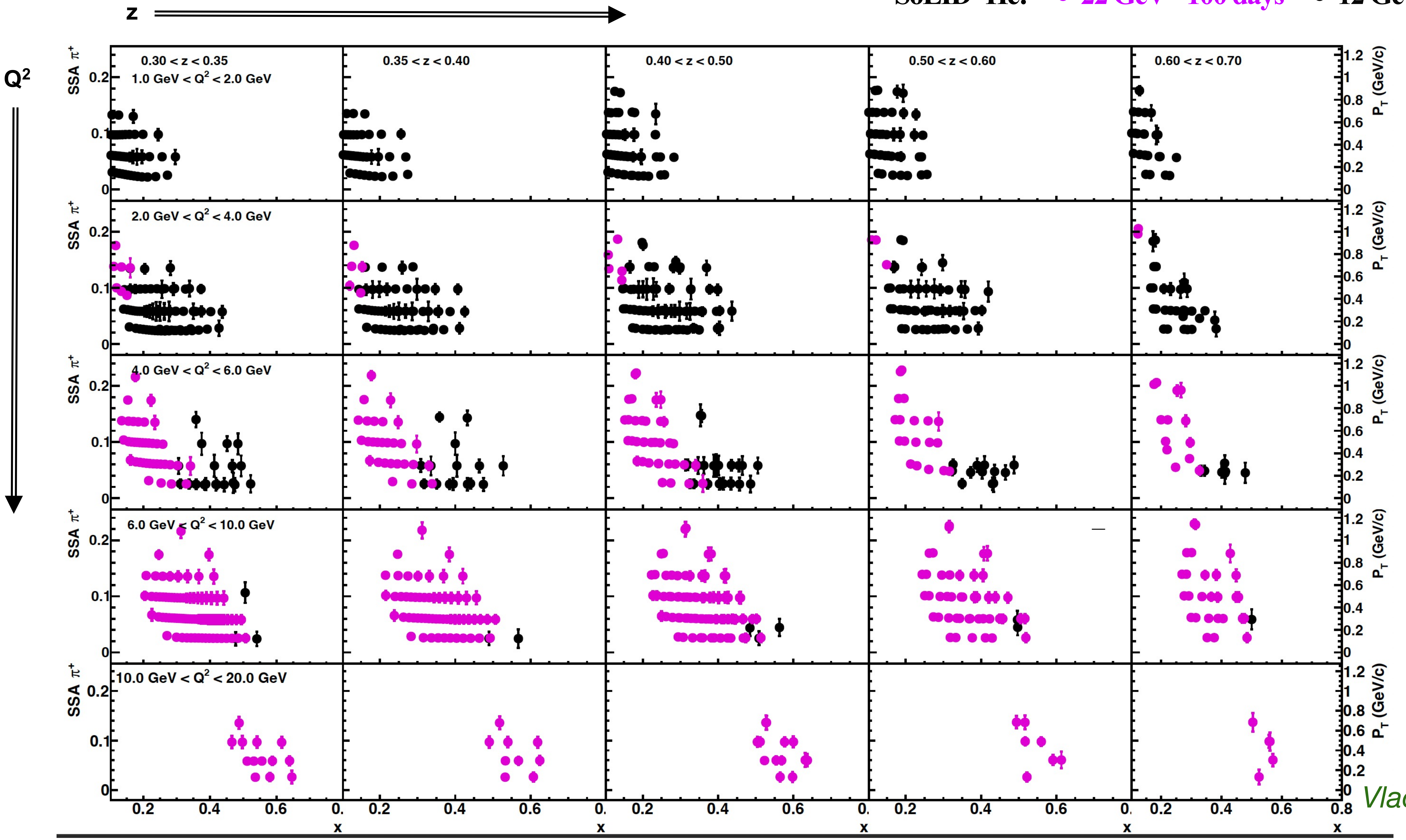
SoLID ^{3}He: • 22 GeV - 100 days • 12 GeV - 69 days



by Shuo Jia, Vlad Khachatryan et. al.

SoLID-SIDIS @ 22GeV

- 11GeV vs 22GeV

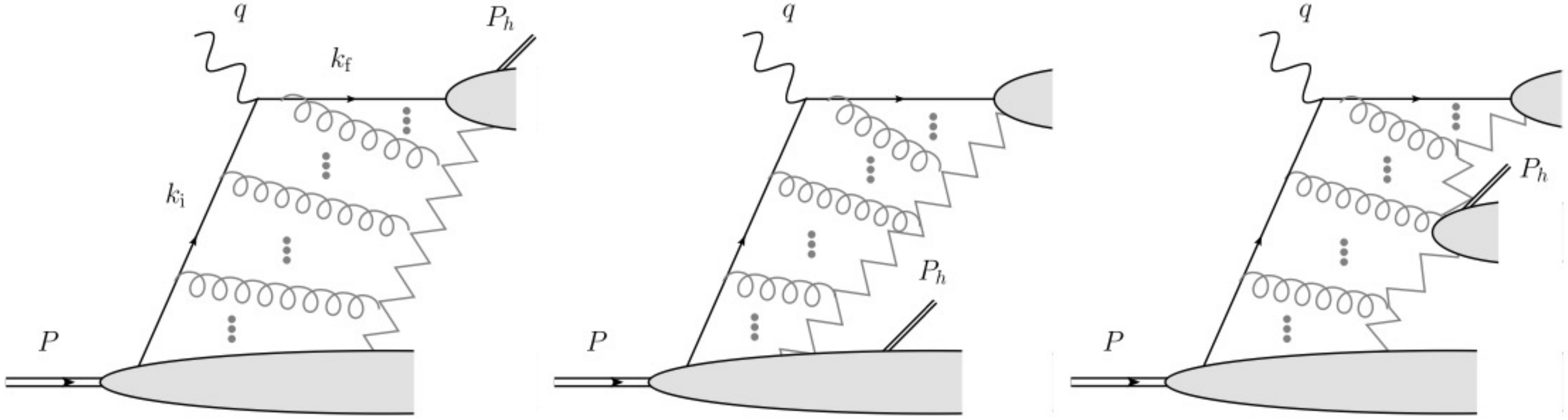


by Shuo Jia, Vlad Khachatryan et. al.

SoLID-SIDIS @ 22GeV

- 11GeV vs 22GeV

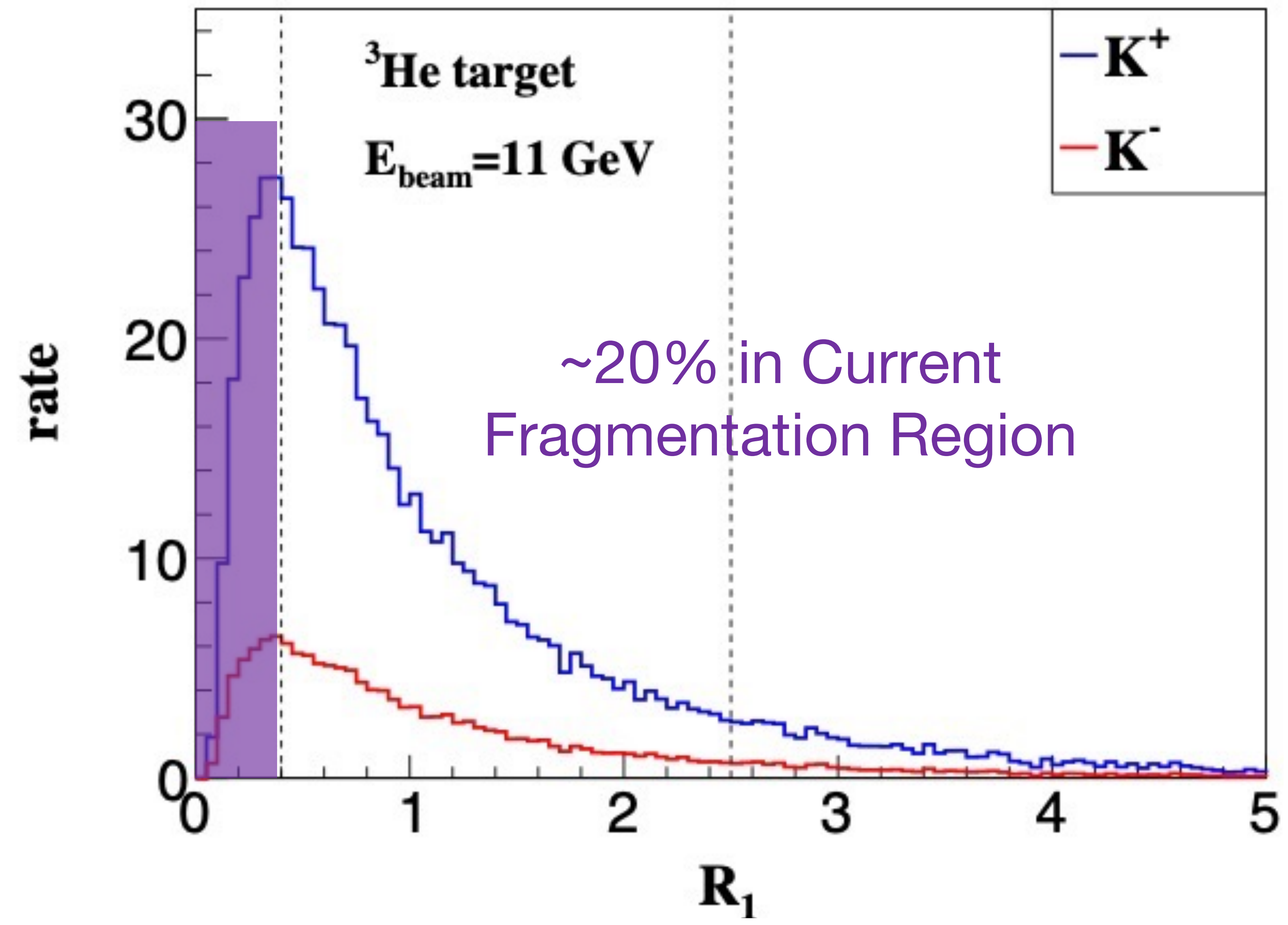
Current Fragmentation | **Target Fragmentation** | **???**

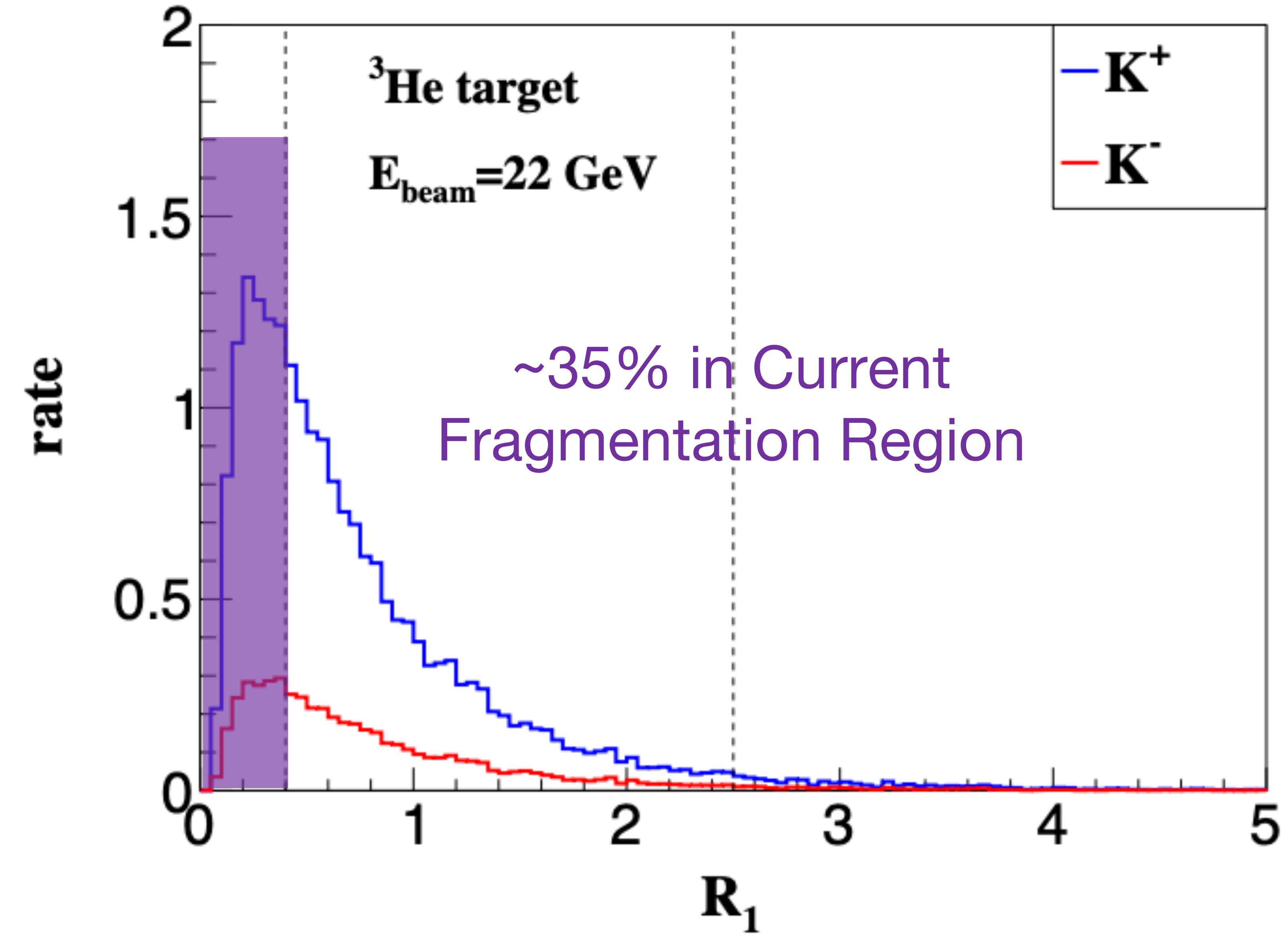


✓ Factorizable!

- ❑ Current fragmentation region is not clearly defined
- ❑ Model estimation: Boglione, et. al. Phys. Lett. B 766, 245 (2017)
  - At 11GeV, 70% pions and 20% kaons are valid.
  - At 22 GeV, 35% kaons are valid; also cleaner for pions with eA
- ❑ Open up kaon phase-space (tight at 11GeV/c)

See Mariaelena Boglione's talk on this Tuesday 14:30





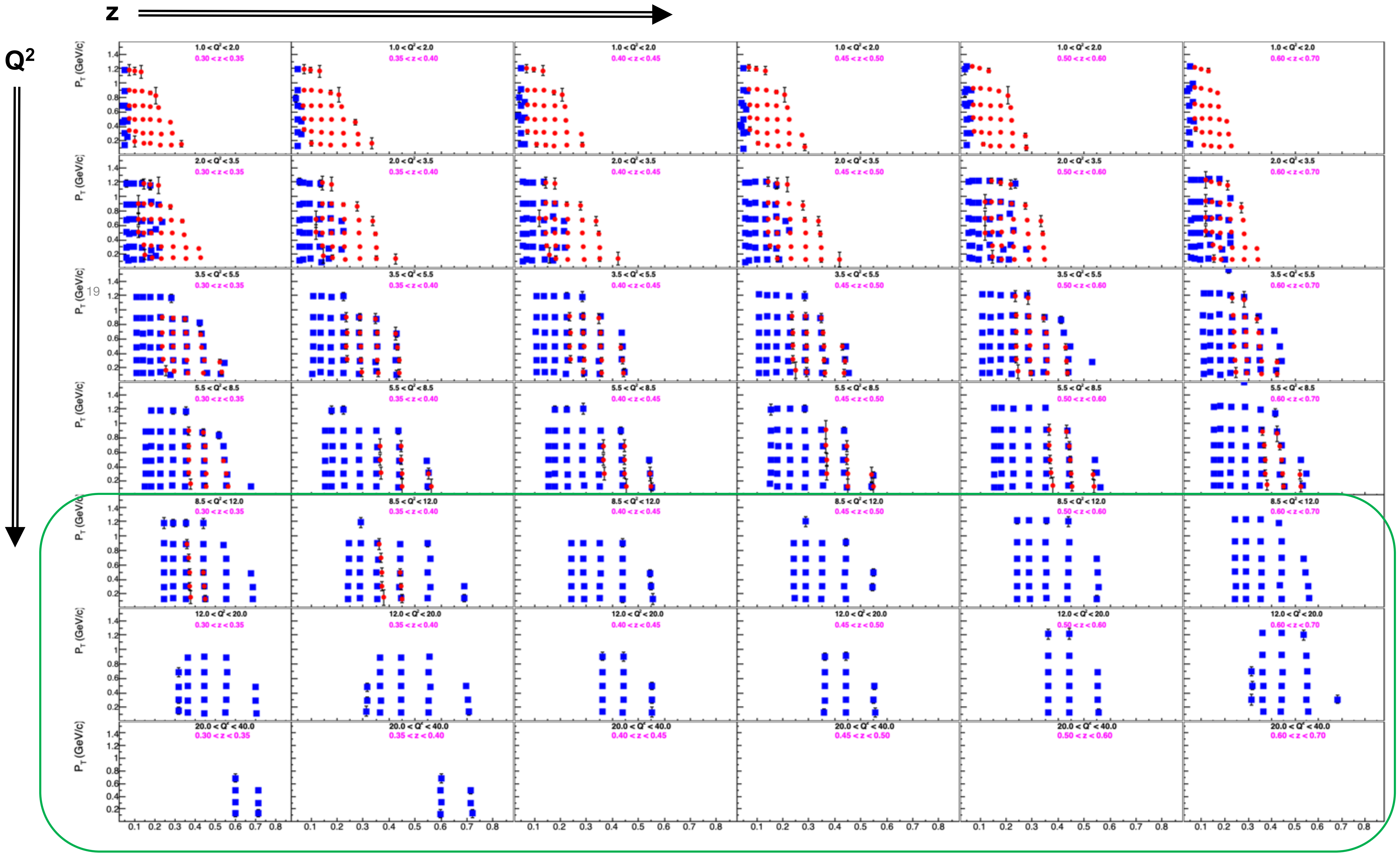
credit to T.B. Liu, based on Boglione, et. al.

SoLID-SIDIS @ 22GeV

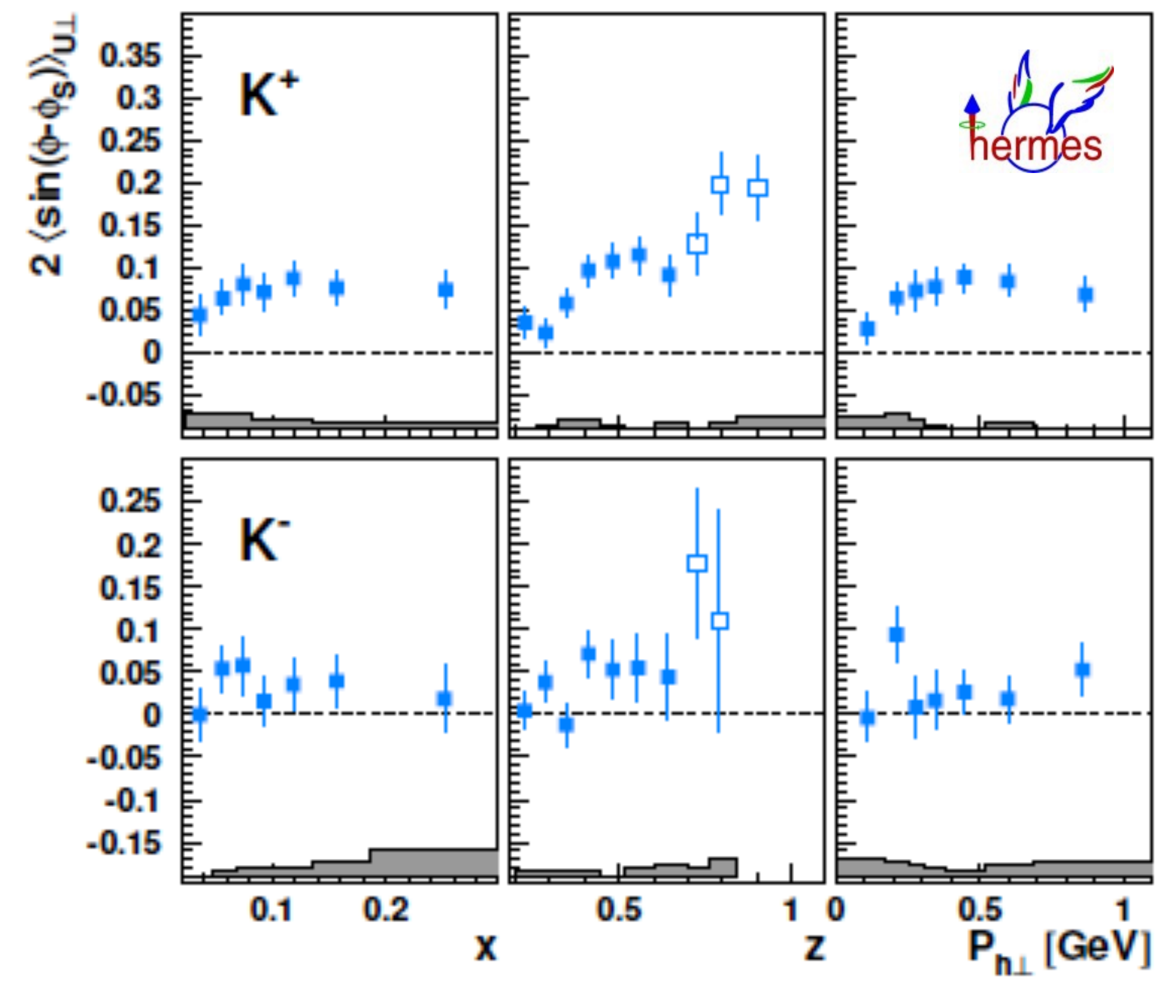
- 11GeV vs 22GeV

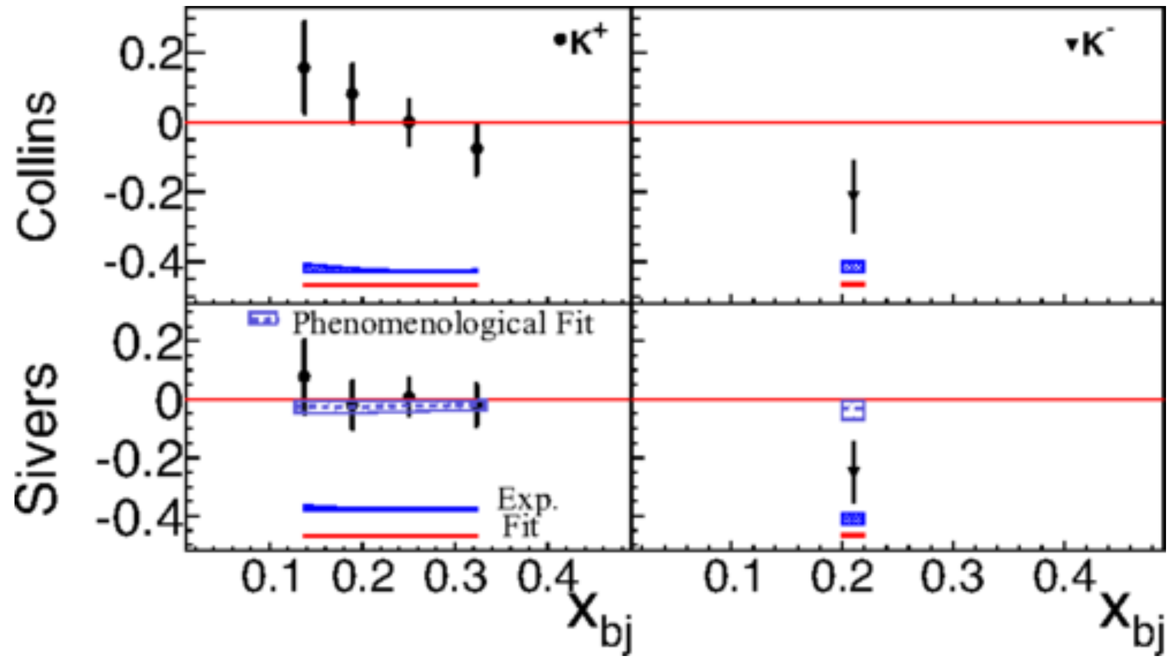
Unpolarized Kaon-SIDIS Projection

- 11GeV, 69days
- 22GeV, 100days



Existing world kaon data





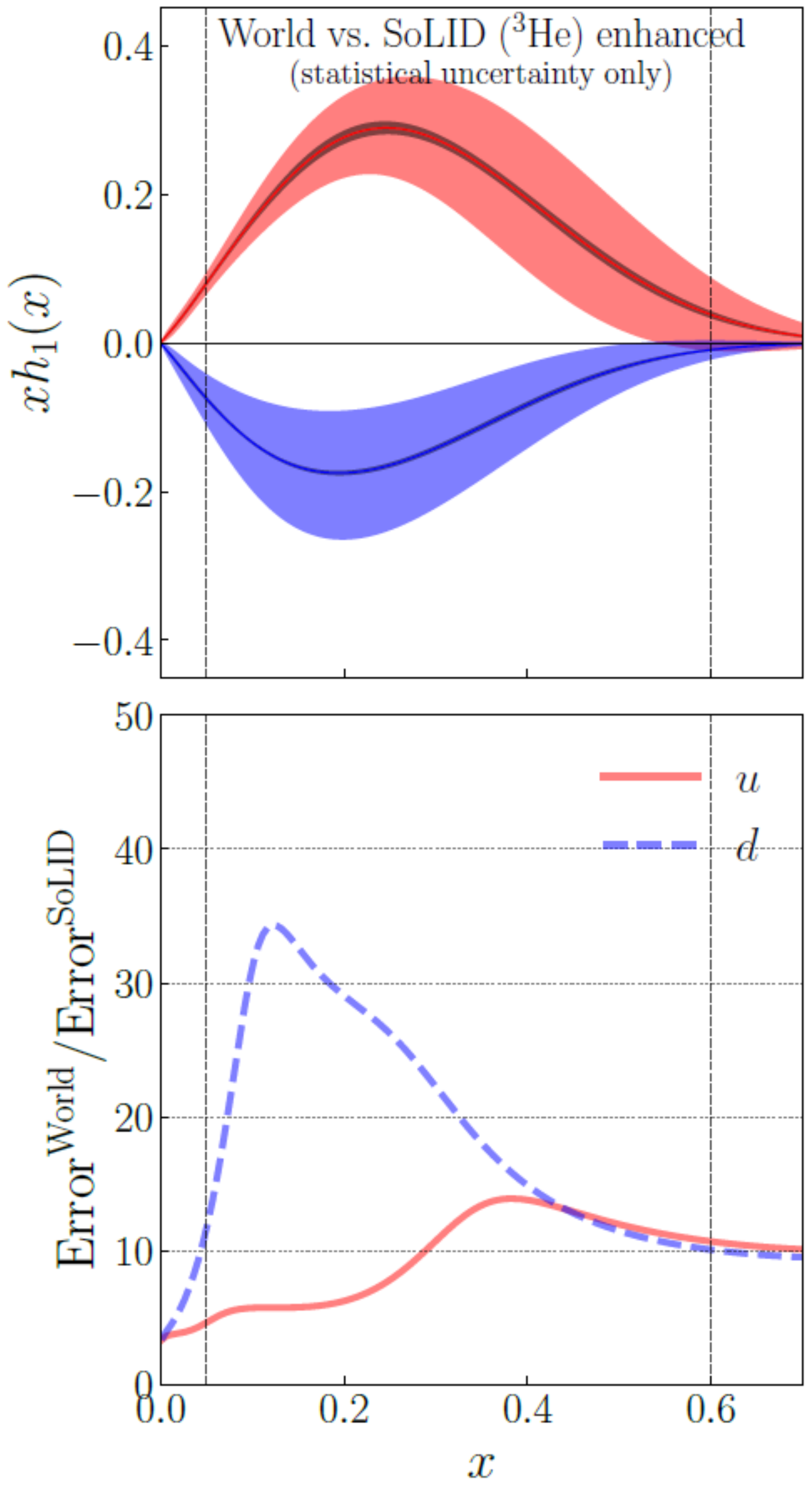
Note:

- Bypassed SoLID current acceptance
- Unpolarized-SIDIS events
- Only statistical uncertainties
- Assume pi/K separation in full momentum ranges

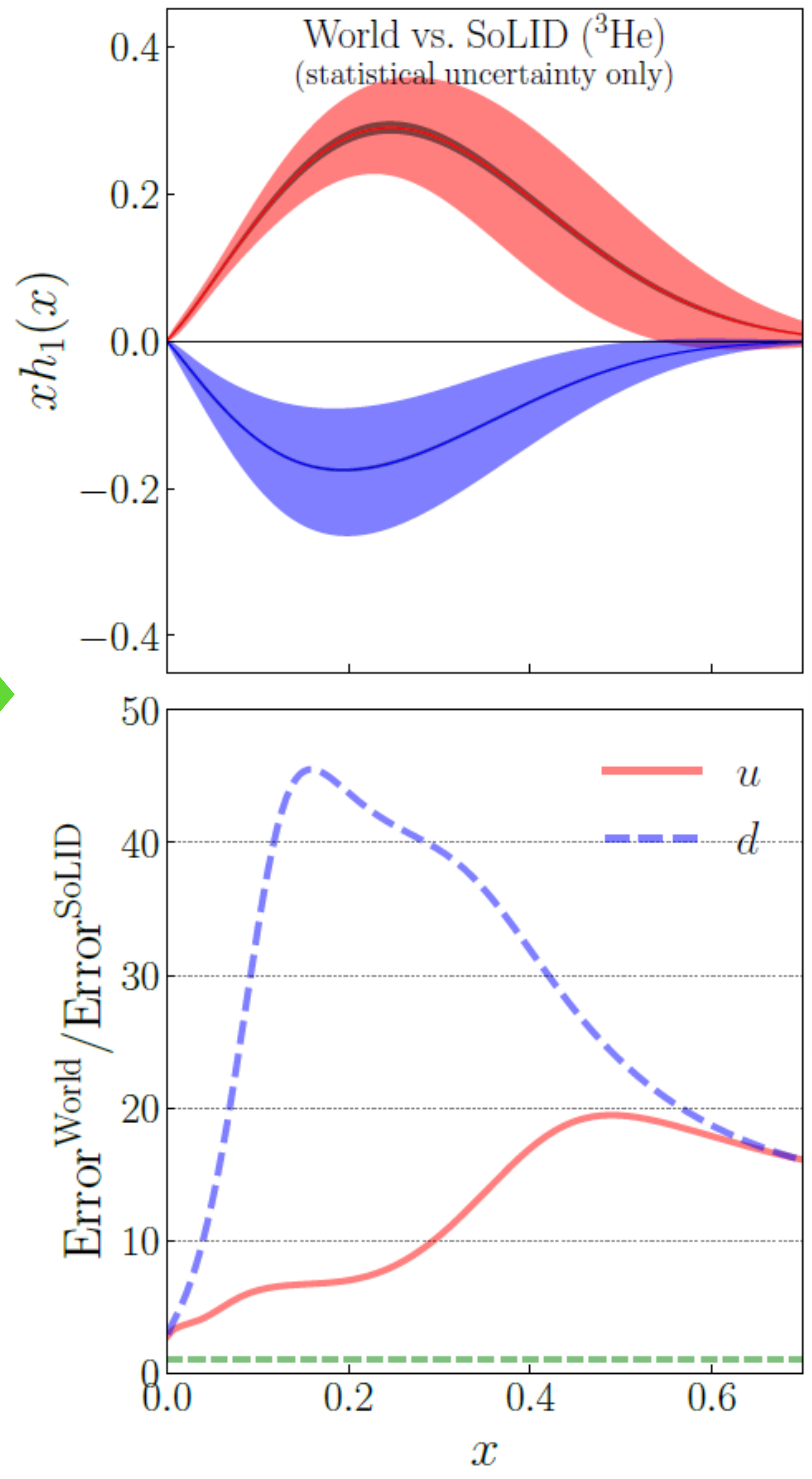
SoLID-SIDIS @ 22GeV

➢ Projection at 22GeV:

Transversity

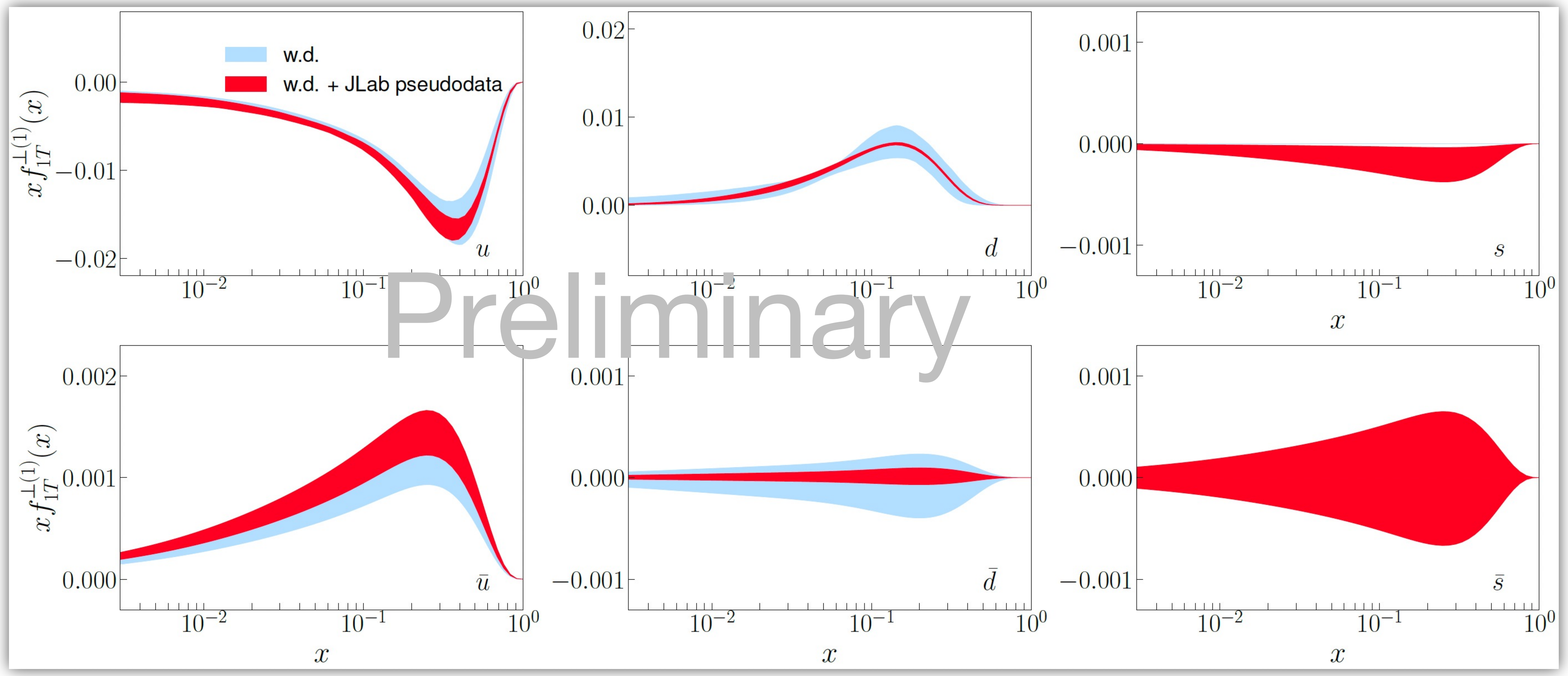


11+8.8 GeV (He3 pion)



22+11+8.8 GeV (He3 pion)

Sivers **22 GeV (pion + kaon)**



By Tianbo Liu et. al.

by Vlad Khachatryan et. al.

Summary

- SoLID: **large acceptance** + **very high luminosity** → full exploitation of JLab12 potential
  - ✓ pushing the limit of the luminosity frontier highlighted in 2023 NSAC LRP and facility review

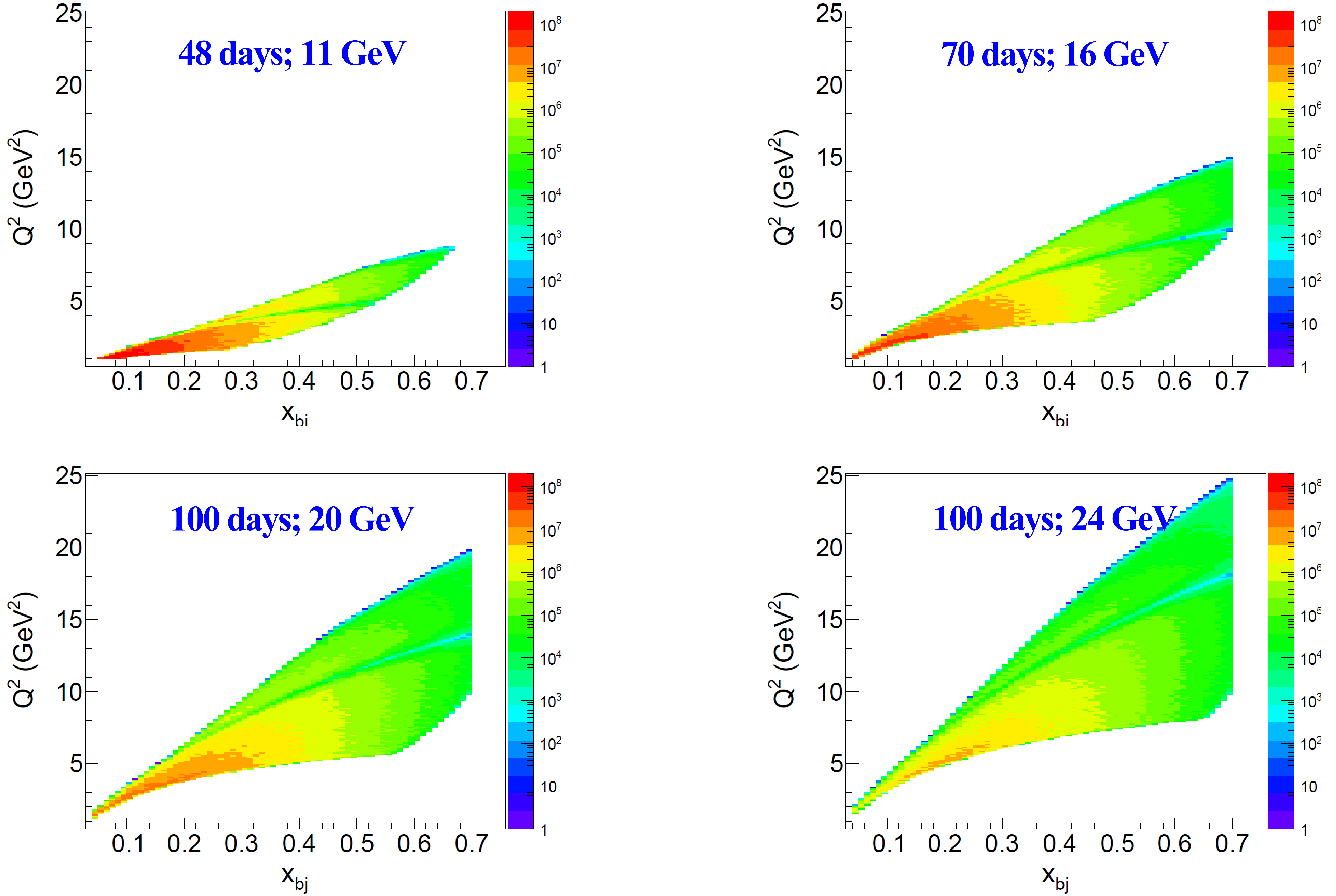
- SoLID SIDIS program is rich and vibrant with unprecedented high precision data in 4D/5D bins to constrain TMD models and examine LQCD, perfect for global fitting

- Naturally extend into 22GeV → day-one detector, higher Q2, lower x, kaon-production

- To do:
  - Simulation of SoLID acceptance at 22GeV
  - A complete impact study of pion & kaon SIDIS data at 11+22GeV, w/ polarized proton He3
  - Investigation of possible detector upgrade needed at higher energy

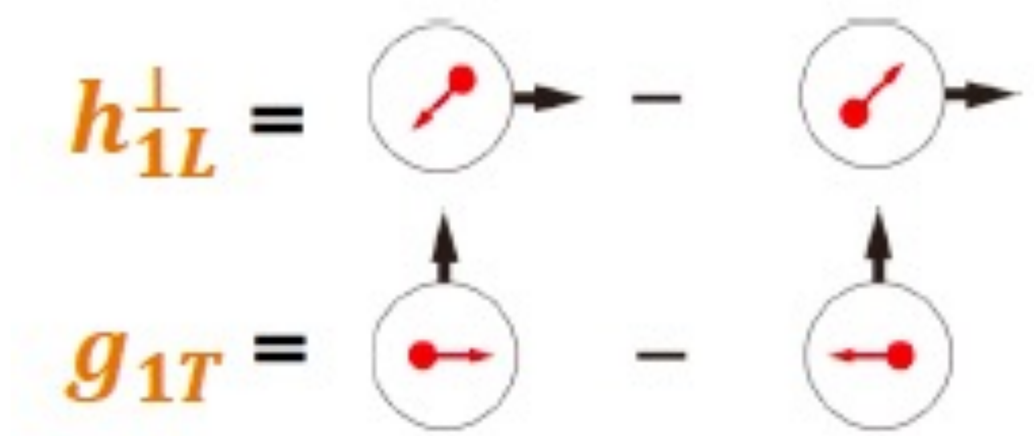
Backup Slides

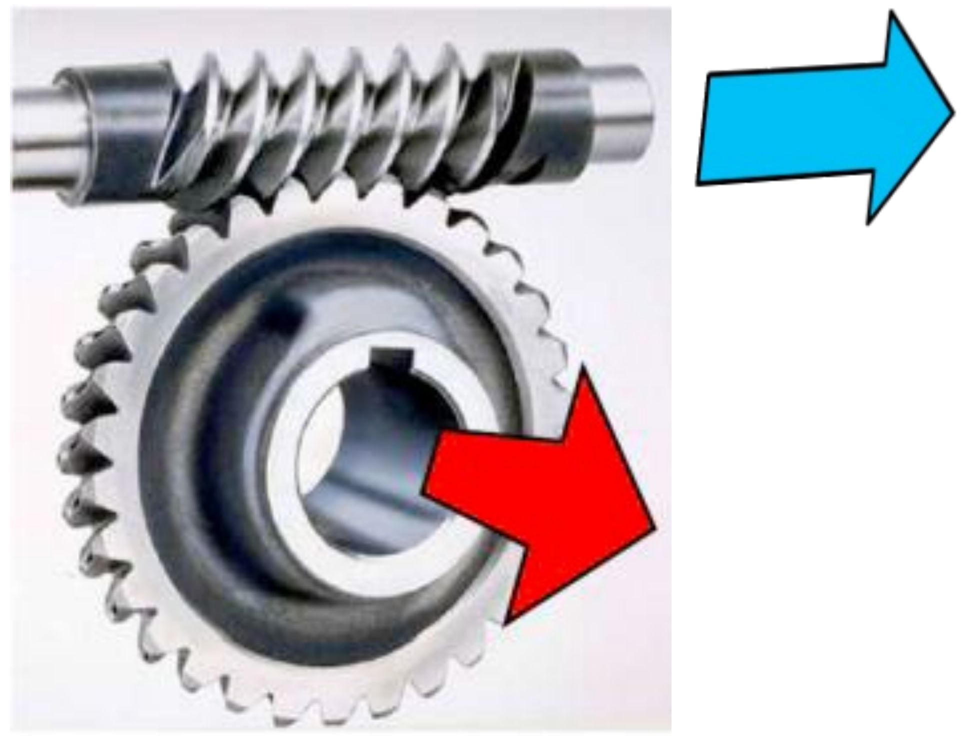
Phase - space examples obtained with the ^{3}He target at various beam energies: Q^2 vs. x_{bj}



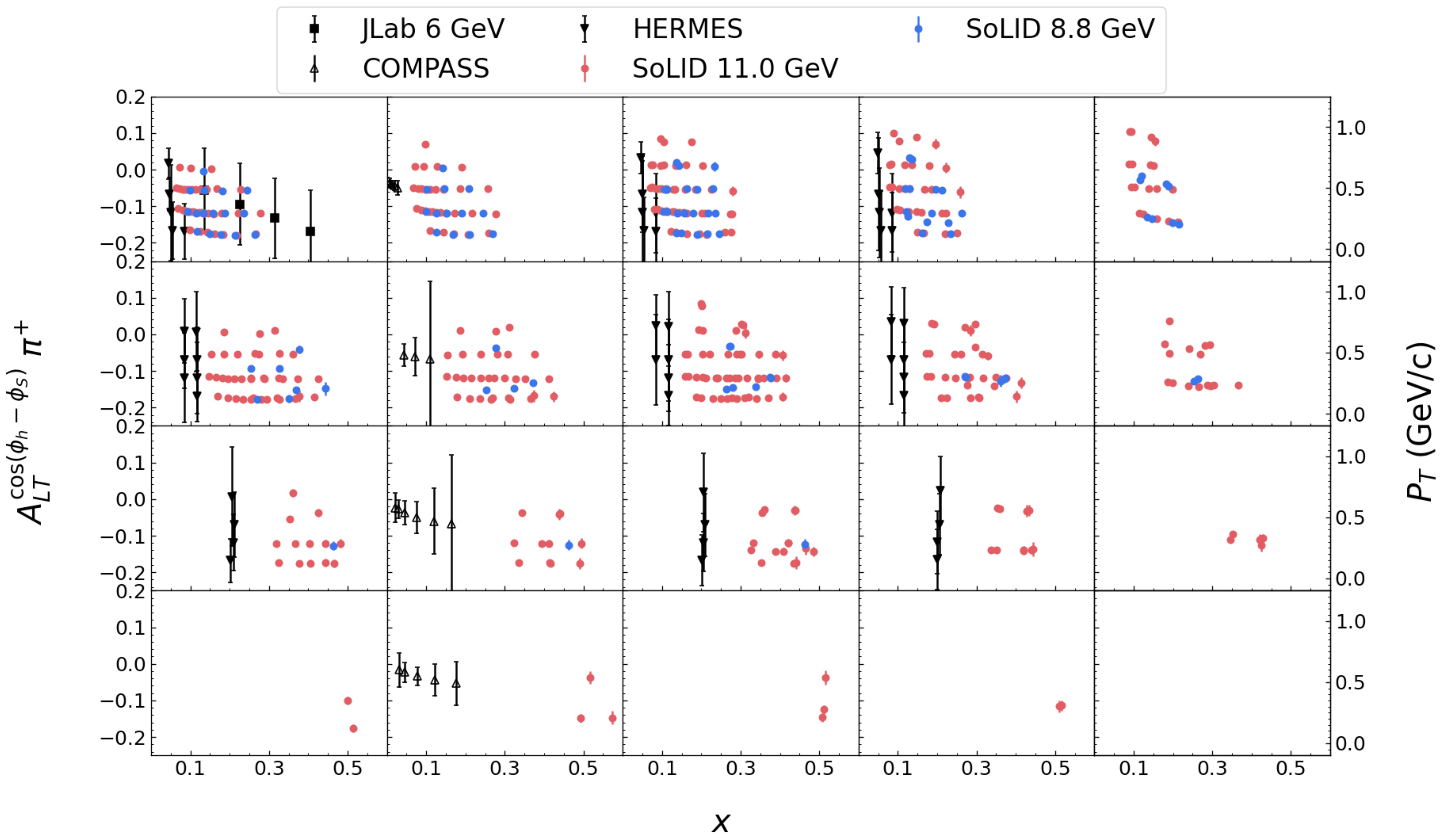
SoLID-SIDIS Projections

- Worm-Gear TMDs from DSA:



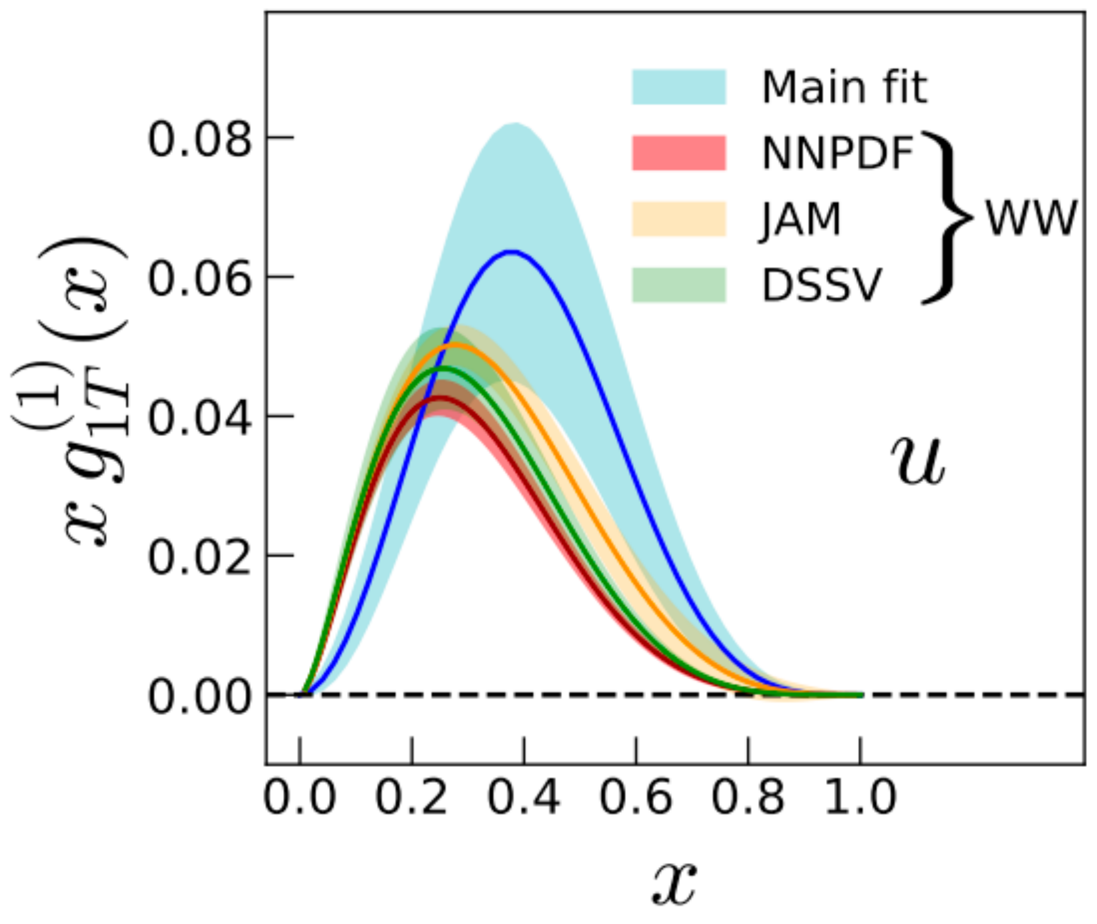


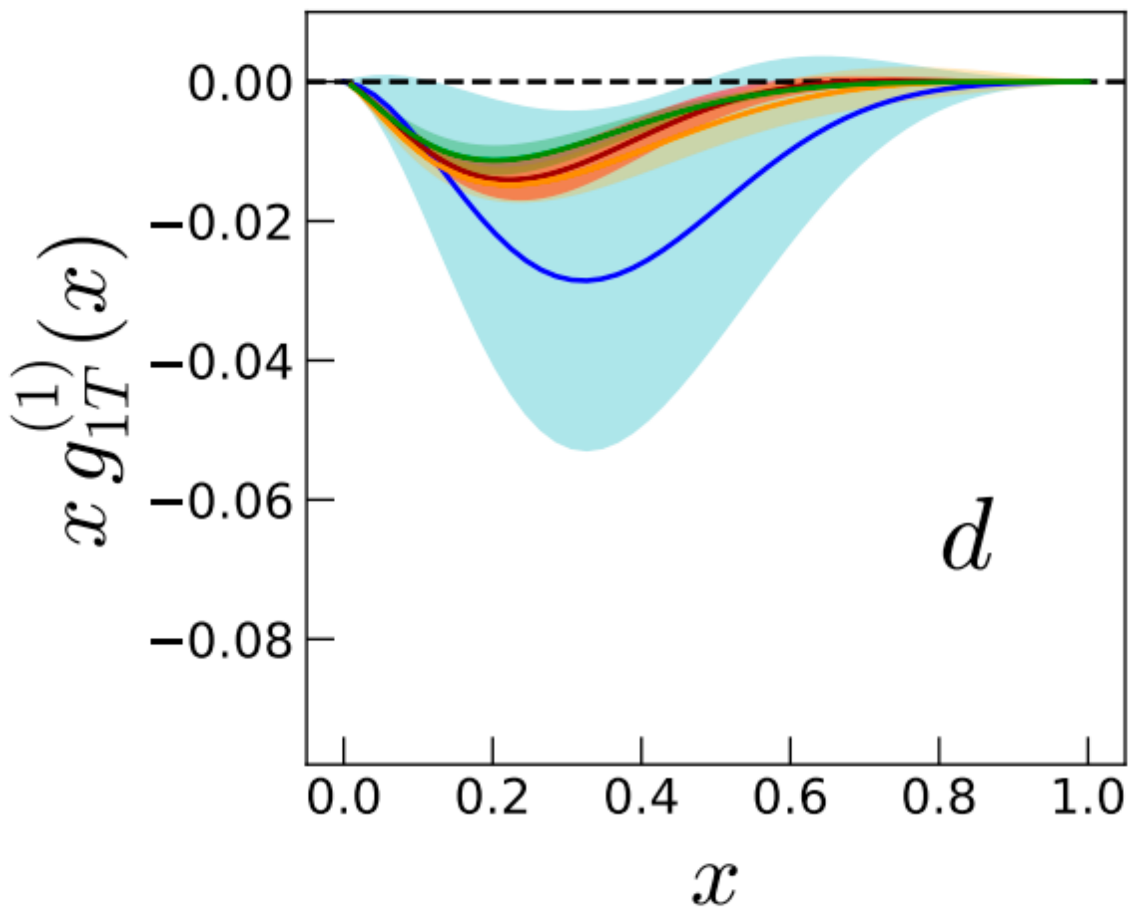
- Dominated by interference between wave function components that differ by one unit of quark OAM
- A genuine sign of intrinsic transverse motion



✓ Double-Spin Asymmetry (DSA)

$$A_{LT}^{Worm-Gear} \propto \langle \cos(\phi_h - \phi_s) \rangle_{LT} \propto g_{1T} \otimes D_1$$

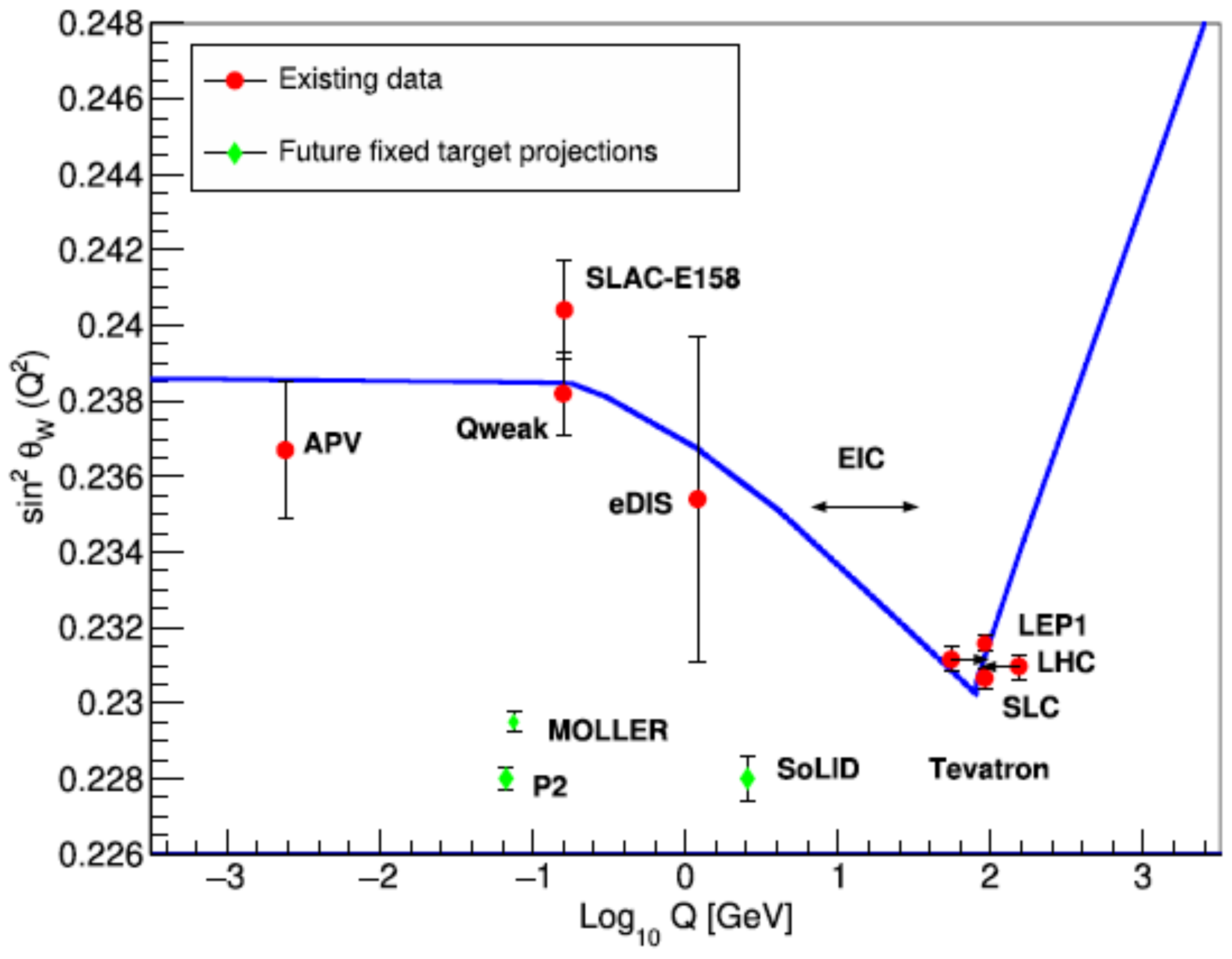


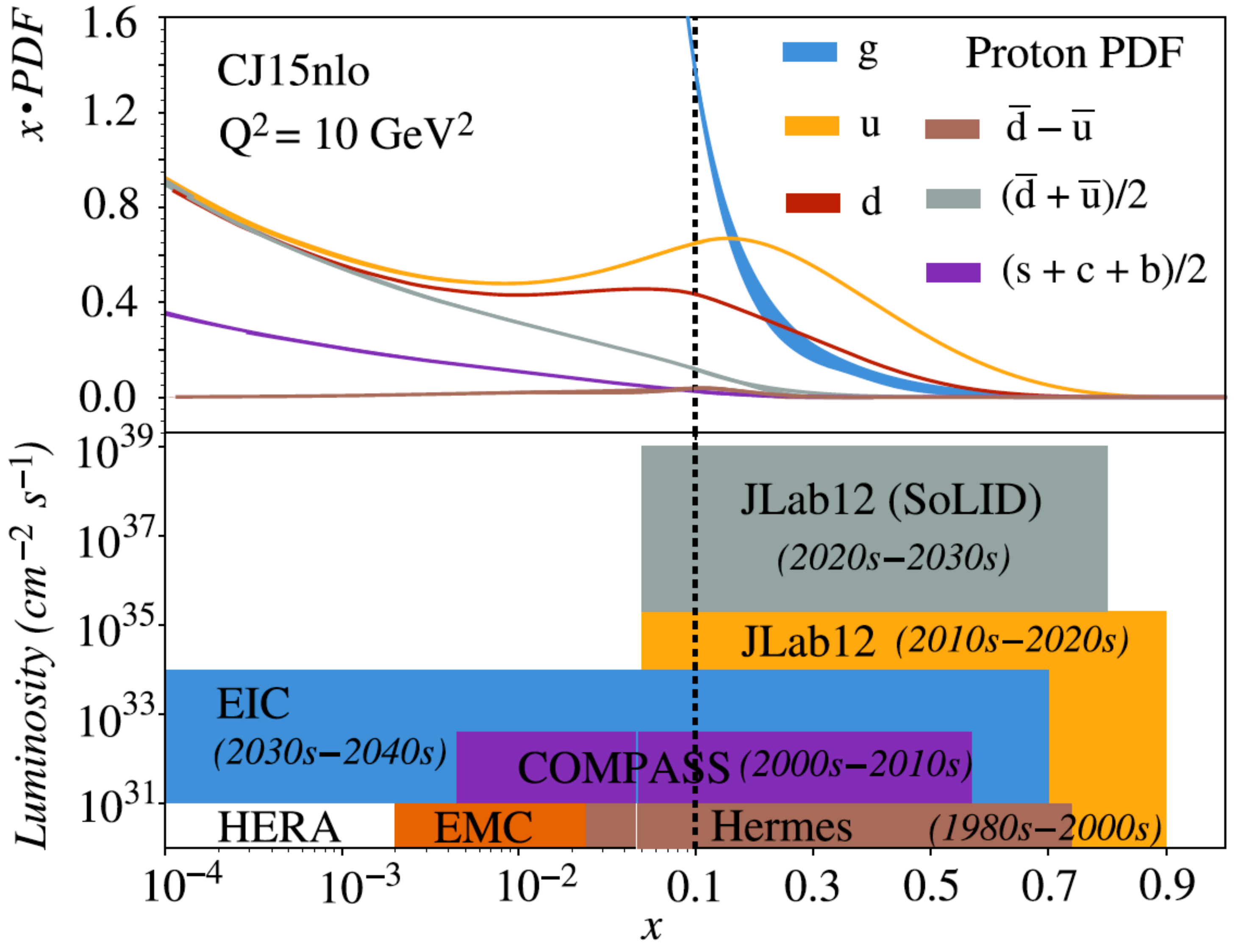


S. Bhattacharya et al., Phys. Rev. D105, 034007 (2022)

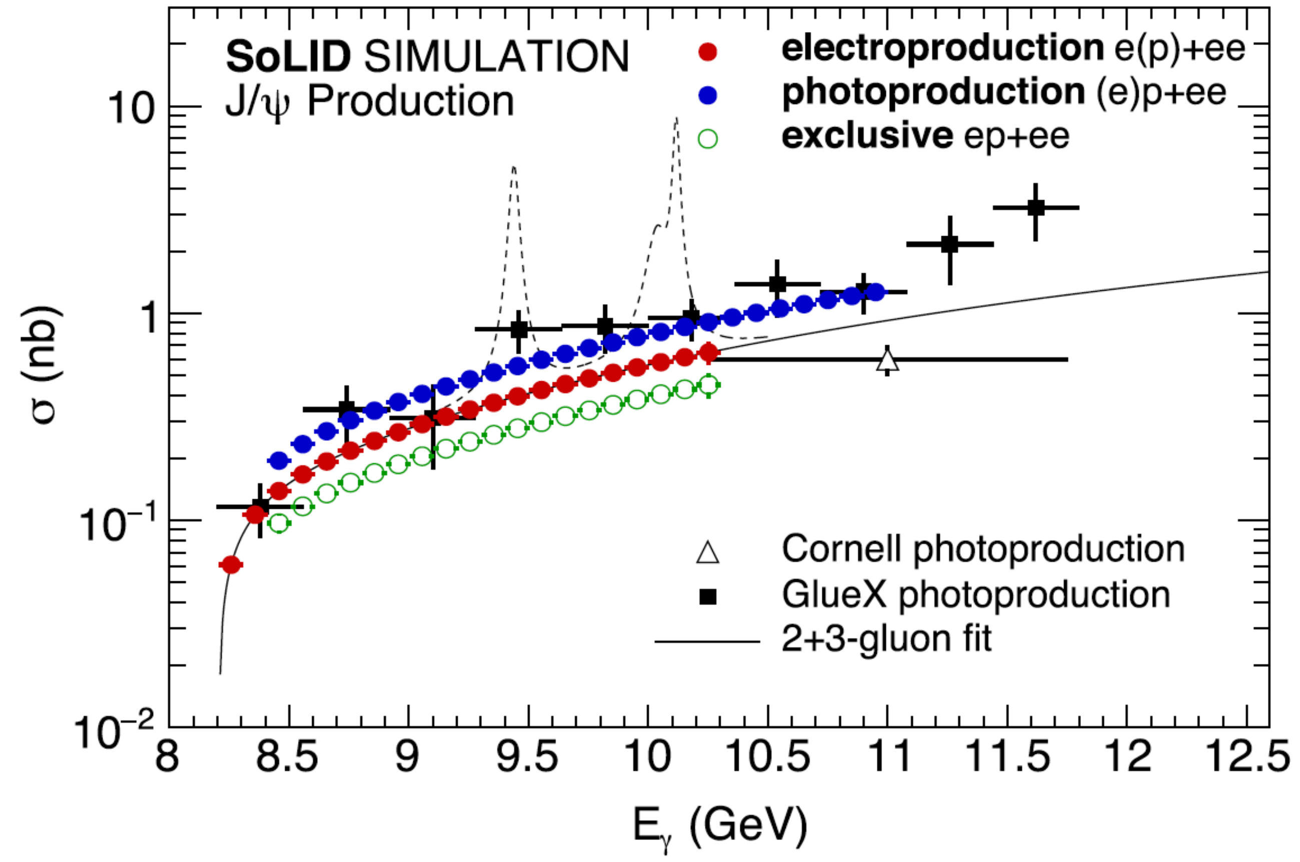
SoLID@12-GeV JLab: QCD at the intensity frontier

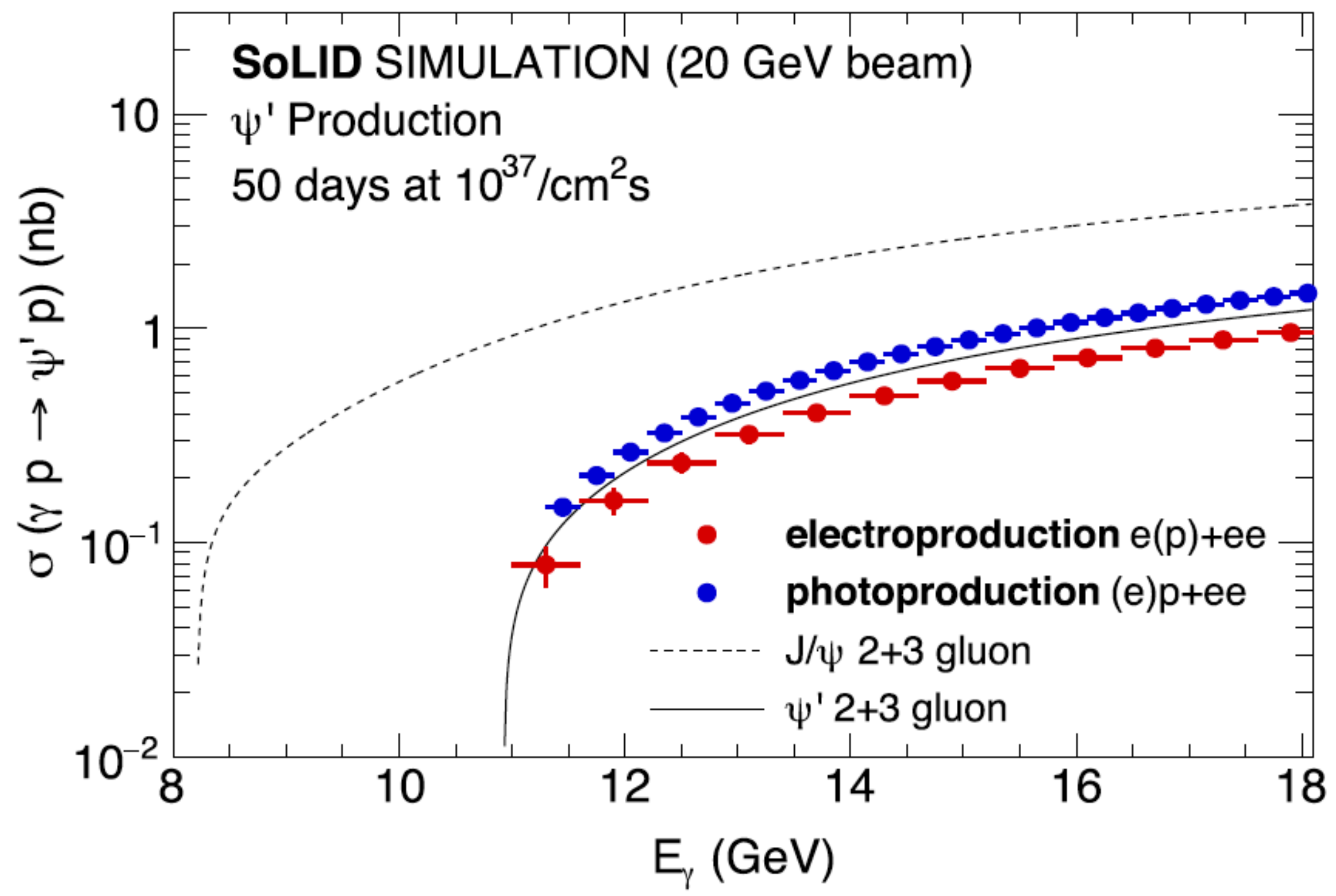
- Research at **SoLID** will have the ***unique*** capability to **explore** the QCD landscape
  - ✓ Pushing the phase space in the search of new physics and of hadronic physics (**PVDIS**)
  - ✓ Superior sensitivity to the differential electro- and photo-production cross section of J/ψ near threshold (**proton mass**)
  - ✓ 3D momentum imaging of a relativistic strongly interacting confined system (**nucleon spin**)





J. Phys. G: Nucl. Part. Phys. 50 (2023) 110501





Transverse Momentum Distributions

➢ Semi-Inclusive Deep Inelastic Scattering (SIDIS) with polarized targets:

Transversely Polarized Nucleon TMDs

→ Nucleon Spin

→ Quark Spin

Relevant Vectors

S_T: Nucleon Spin

s_q: Quark Spin

$k_\perp$: Quark Transverse Momentum

P: Virtual photon 3-momentum (defines z-direction)

$$A_{UT}(\phi_h,\phi_S) = \frac{1}{P_{t,pol}}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

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

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

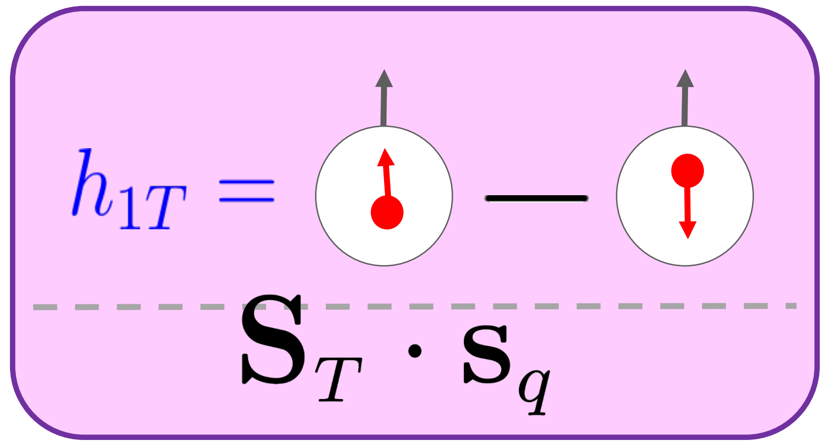
$$A_{UT}^{Pretzelosity} \propto \langle\sin(3\phi_h-\phi_S)\rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp$$

Collins fragmentation function from e^+e^- collisions

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

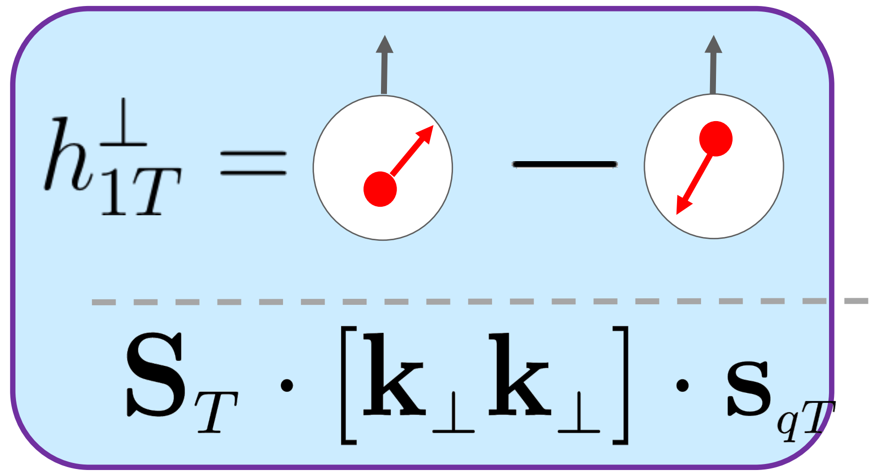
Unpolarized fragmentation function

Transversity



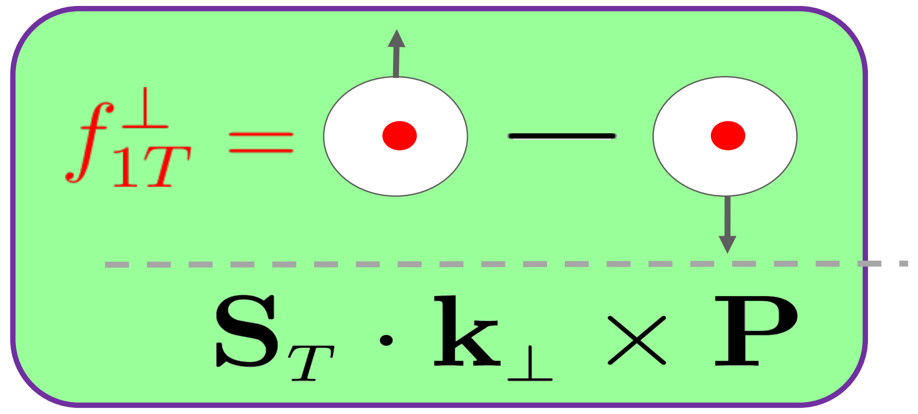
- h_{1T} (h_1) = g_1 (no relativity)
- h_{1T} → tensor charge (confronting lattice QCD calculations)
- Connected to nucleon beta decay and electric dipole moment

Pretzelosity



- Interference between components with quark orbital angular momentum (OAM) difference of 2 units (i.e., s-d, p-p) (model dependence)
- Signature for relativistic effect

Sivers



- Nucleon spin - quark orbital angular momentum (OAM) correlation
- Zero if no OAM (model dependence)

SoLID-SIDIS at 22GeV

- Larger Phase-Space

Back dots→11GeV
Color dots→22GeV