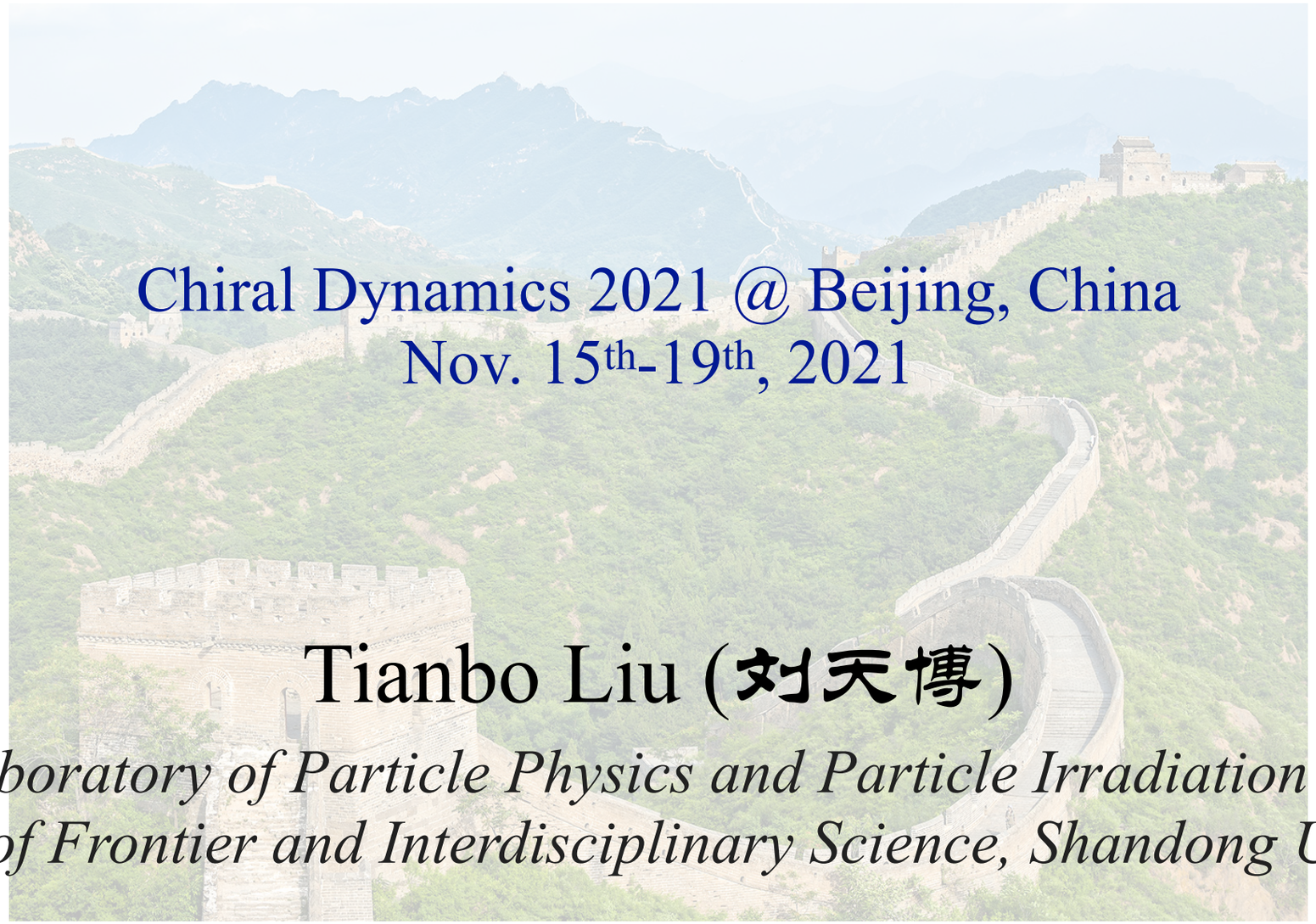
Beijing, 2021

Overview of TMD Studies



Chiral Dynamics 2021 @ Beijing, China
Nov. 15th-19th, 2021

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SHANDONG UNIVERSITY, QINGDAO

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Key Laboratory of Particle Physics and Particle Irradiation (MOE)
粒子科学技术研究中心
Research Center for Particle Science and Technology

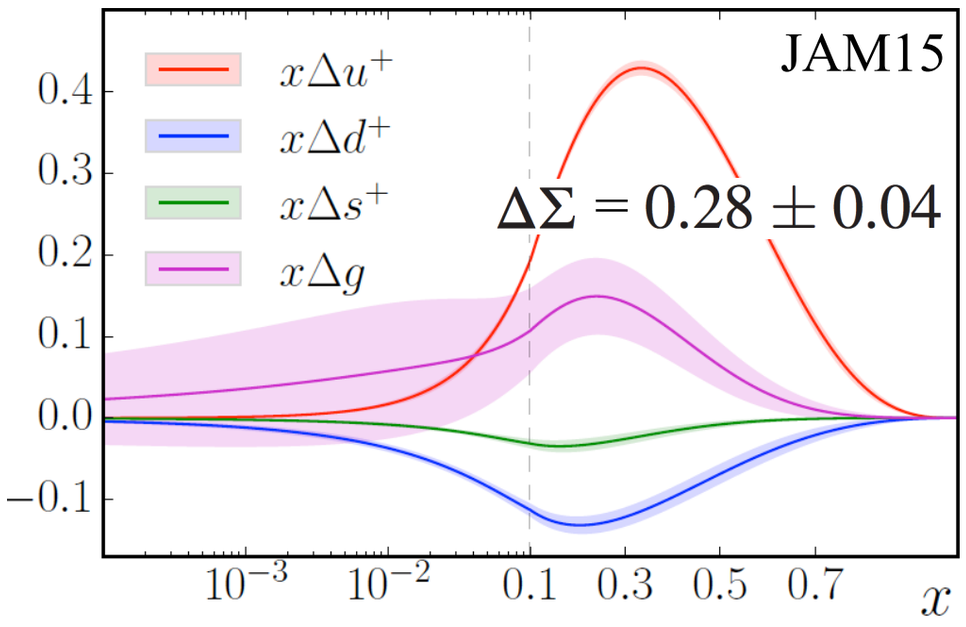
Nucleon Spin Structure

Proton spin puzzle

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Spin decomposition

$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



JAM Collaboration, PR D 93, 074005 (2016).

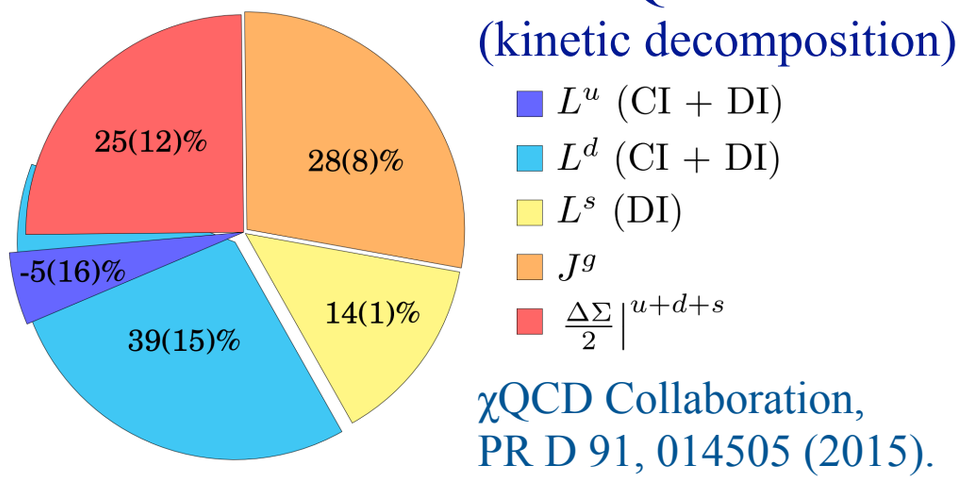
JAM17: $\Delta\Sigma = 0.36 \pm 0.09$

JAM Collaboration, PRL 119, 132001 (2017).

Quark spin only contributes a small fraction to the nucleon spin.

J. Ashman *et al.*, PLB 206, 364 (1988); NP B328, 1 (1989).

Lattice QCD
(kinetic decomposition)



χQCD Collaboration,
PR D 91, 014505 (2015).

Gluon spin from LQCD: $S_g = 0.251(47)(16)$

50% of total proton spin

Y.-B. Yang *et al.* (χQCD Collaboration), PRL 118, 102001 (2017).

Access to $L_{q/g}$

It is necessary to have transverse information.

3*D* imaging of the nucleon.

Unified View of Nucleon Structure

Light-front wave function $\Psi(x_i, k_{Ti})$

5D

GTMD $F(x, \Delta_T, k_T)$ ⟷ **Wigner distribution** $\rho(x, b_T, k_T)$

Generalized Transverse Momentum Dependent

$\Delta_T = 0$; $\int d^2k_T$; $\int d^2k_T$

3D

TMD $f(x, k_T)$; **GPD** $H(x, \xi, t)$ ⟷ **IPD** $H(x, \xi, b_T)$

$\int d^2k_T$; $t = 0$; $\int dx$; $\int dx$

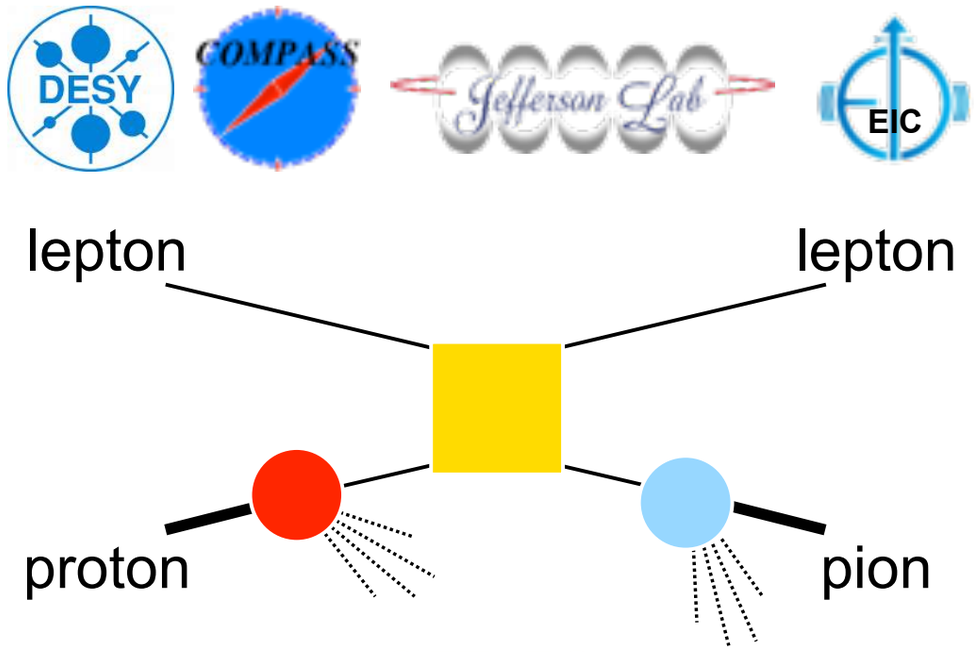
1D

PDF $f(x)$; **Form factor** $F(t)$ ⟷ **Charge density** $\rho(b_T)$

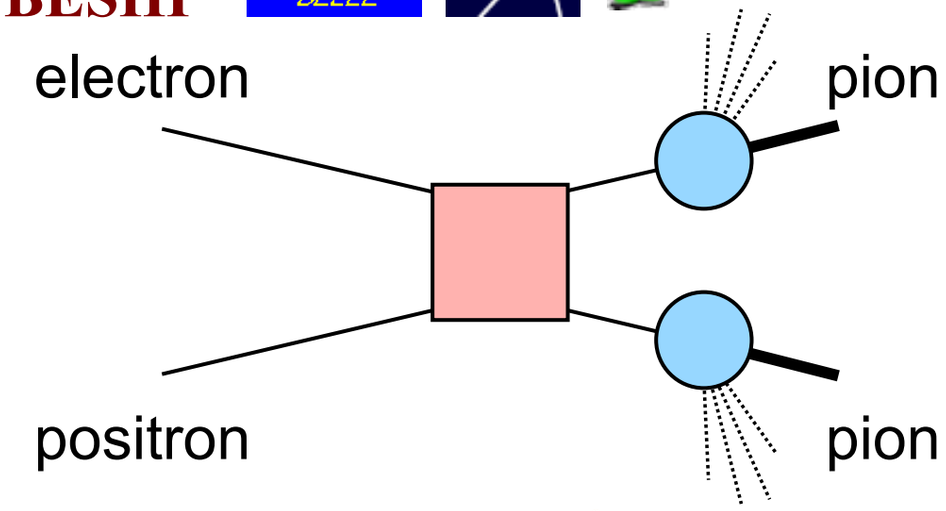
$\int dx$; $t = 0$; $\int db_T$

Charge g

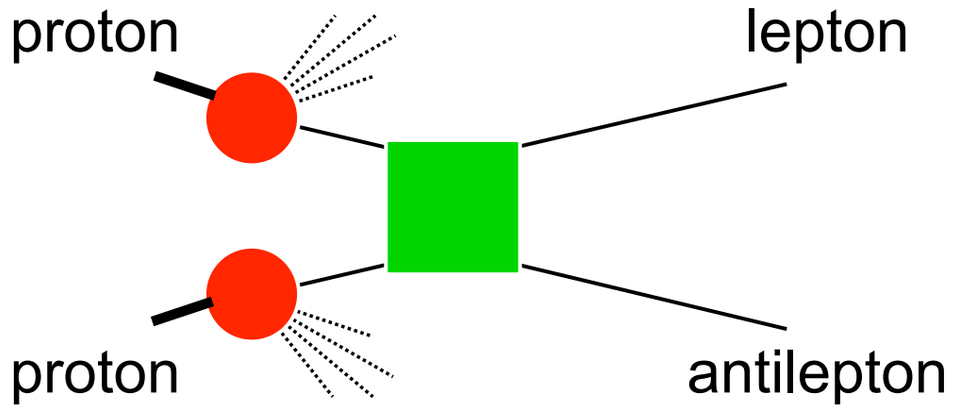
Access TMDs through Hard Processes



SIDIS



e^-e^+ to pions



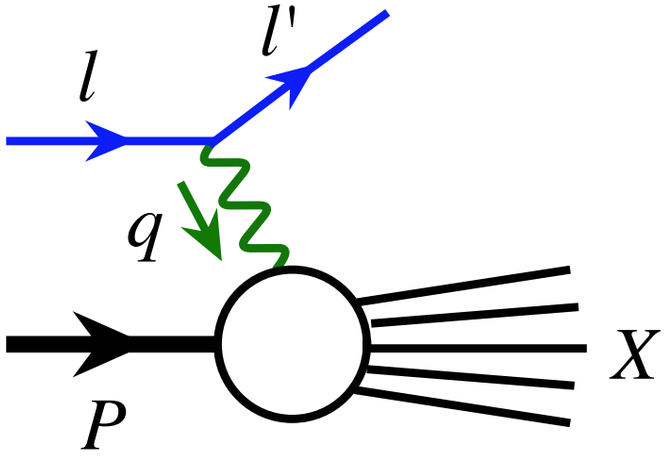
Drell-Yan

- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

Lepton-Hadron Deep Inelastic Scattering

Inclusive DIS at a large momentum transfer $Q \gg \Lambda_{\rm QCD}$

- dominated by the scattering of the lepton off an active quark/parton
- not sensitive to the dynamics at a hadronic scale ~ 1/fm
- collinear factorization: $\sigma \propto H(Q) \otimes \phi_{a/P}(x, \mu^2)$
- overall corrections suppressed by $1/Q^n$

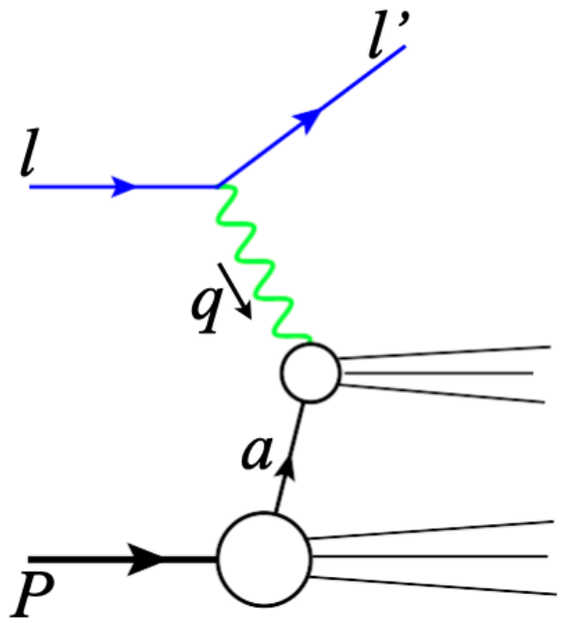


QCD factorization

- provides the probe to "see" quarks, gluons and their dynamics indirectly
- predictive power relies on

— precision of the probe

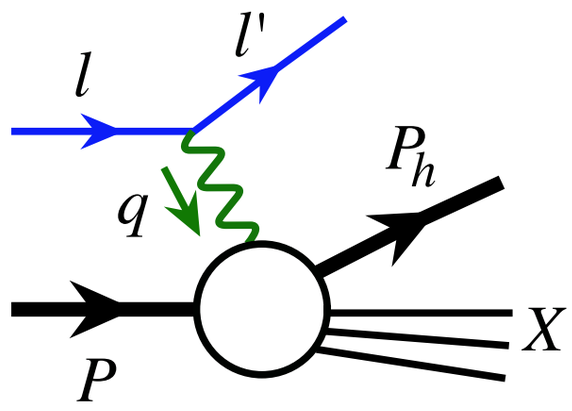
— universality of $\phi_{a/P}(x, \mu^2)$

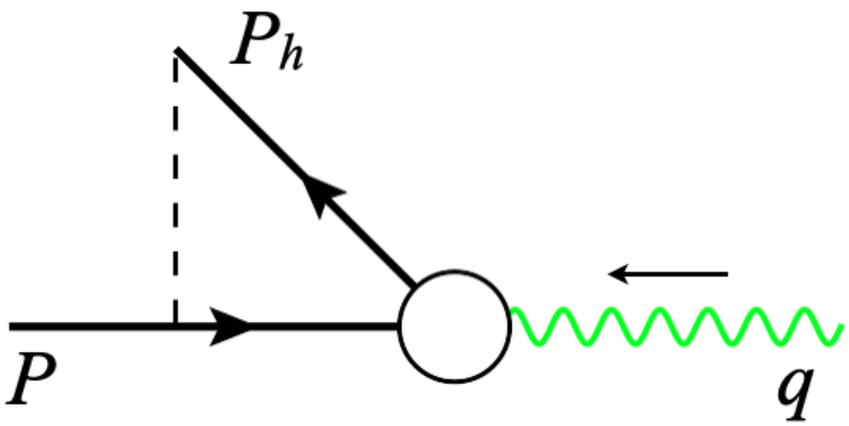


Semi-inclusive Deep Inelastic Scattering

Semi-inclusive DIS: a final state hadron (P_h) is identified

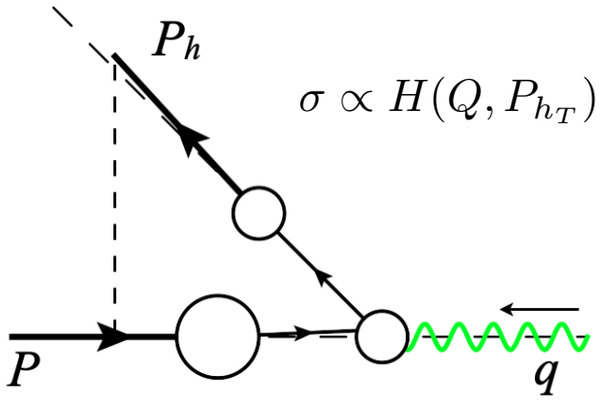
- enable us to explore the emergence of color neutral hadrons from colored quarks/gluons
- flavor dependence by selecting different types of observed hadrons: pions, kaons, …
- a large momentum transfer Q provides a short-distance probe
- an additional and adjustable momentum scale P_{hT}





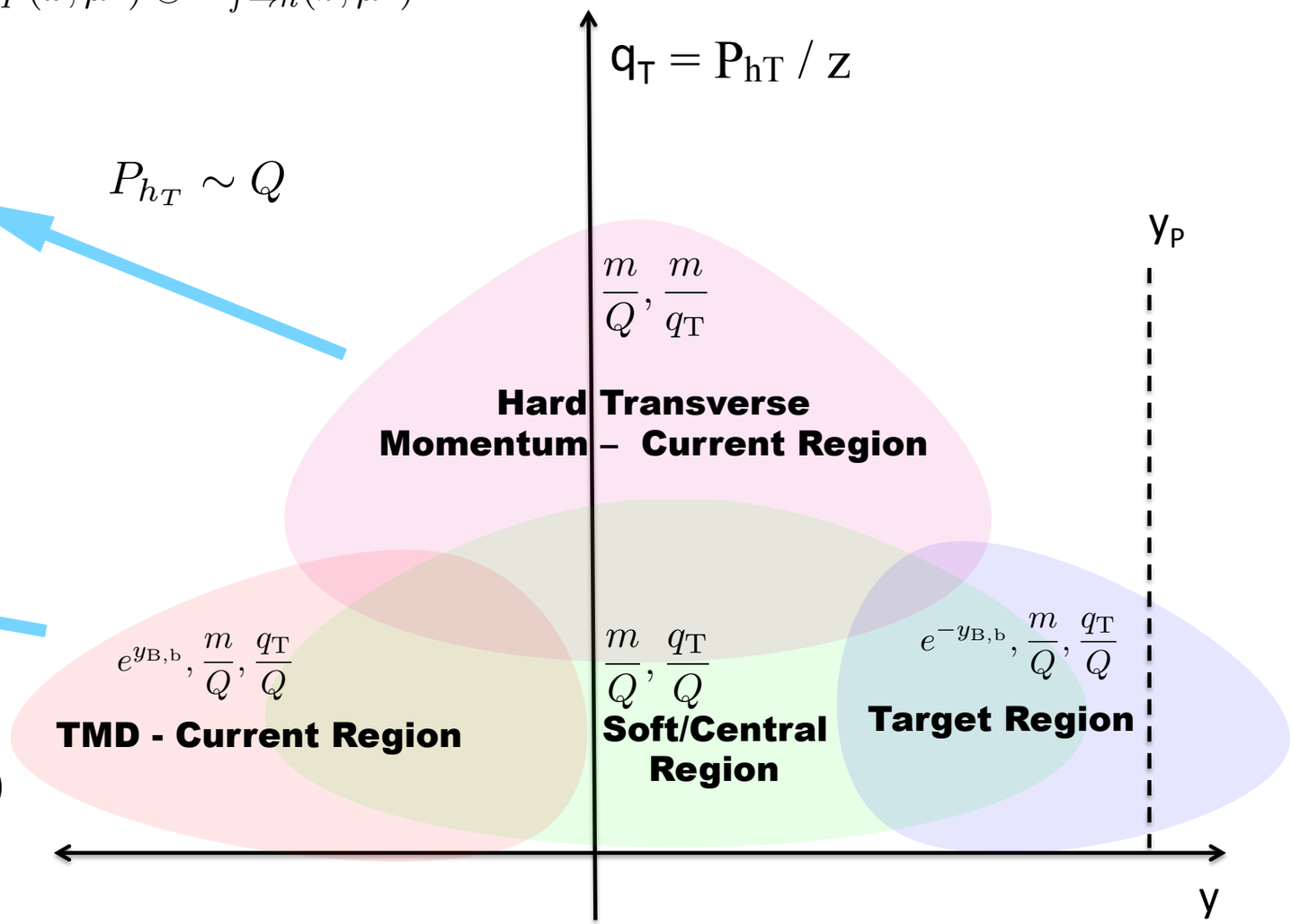
SIDIS Kinematic Regions

Sketch of kinematic regions of the produced hadron

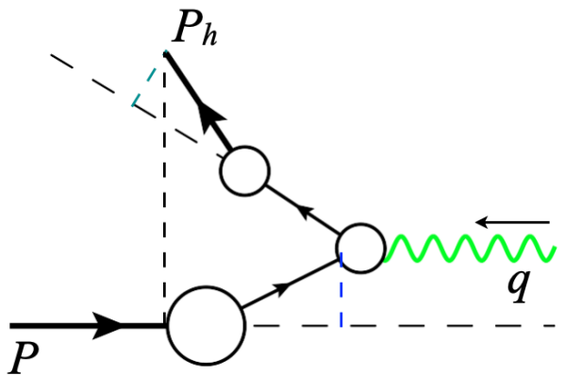


$$\sigma \propto H(Q, P_{h_T}) \otimes \phi_{a/P}(x, \mu^2) \otimes D_{f\to h}(z, \mu^2)$$

$P_{h_T} \sim Q$



$P_{h_T} \ll Q$



$$\sigma \propto H(Q) \otimes \phi_{a/P}(x, k_T, \mu^2) \otimes D_{f\to h}(z, p_T, \mu^2)$$

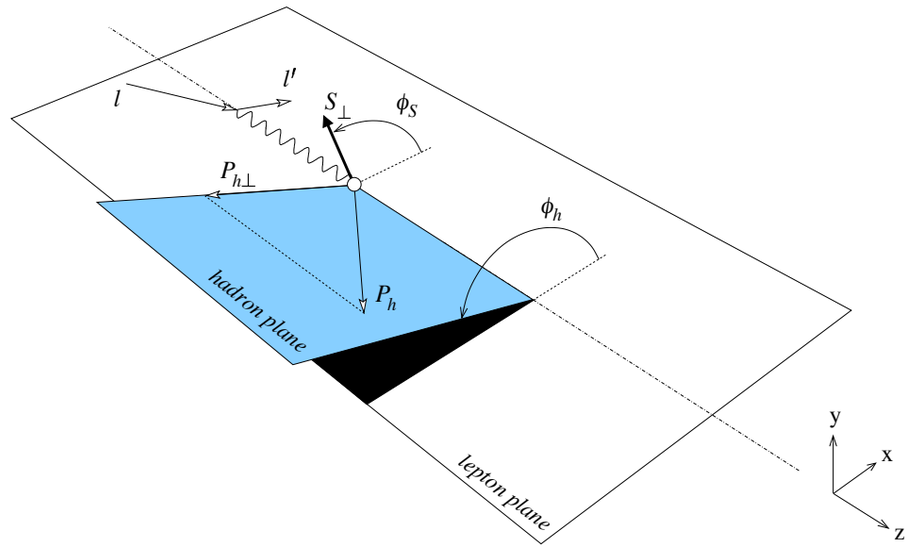
P_{hT} is defined in the photon-hadron frame

[Figure from JHEP10(2019)122]

SIDIS in Trento Convention

SIDIS differential cross section

18 structure functions $F(x_B, z, Q^2, P_{hT})$,
(one photon exchange approximation)



[Trento conventions, PRD70,117504 (2004)]

$$\frac{\mathrm{d}^6\sigma}{\mathrm{d}x_B\mathrm{d}y\mathrm{d}z\mathrm{d}P_{hT}^2\mathrm{d}\phi_h\mathrm{d}\phi_S}$$

$$= \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)$$

$$\times\{F_{UU,T}+\epsilon F_{UU,L}+\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h+\epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\lambda_e\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h$$

$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}F_{UL}^{\sin\phi_h}\sin\phi_h+\epsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right]+\lambda_e S_L\left[\sqrt{1-\epsilon^2}F_{LL}+\sqrt{2\epsilon(1-\epsilon)}F_{LL}^{\cos\phi_h}\cos\phi_h\right]$$

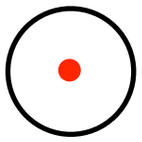
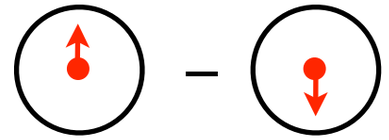
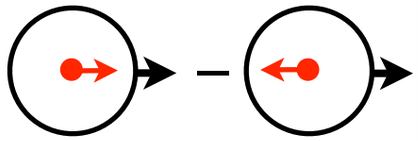
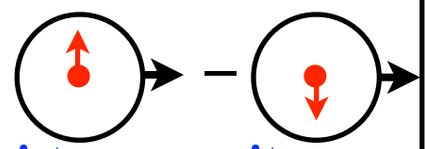
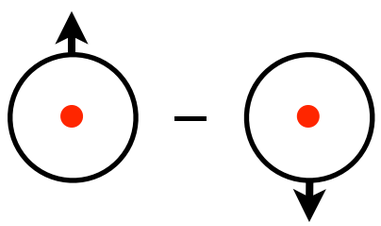
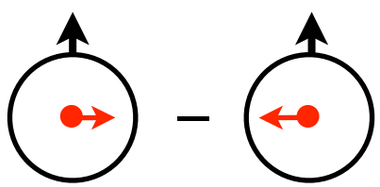
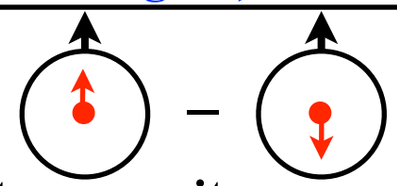
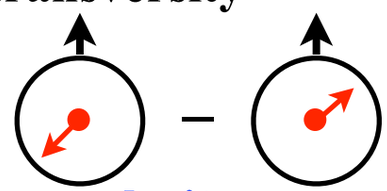
$$+S_T\left[\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\sin(\phi_h-\phi_S)+\epsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)\right.$$

$$\left.+\epsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\quad+\sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S+\sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\right]$$

$$+\lambda_e S_T\left[\sqrt{1-\epsilon^2}F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\right.$$

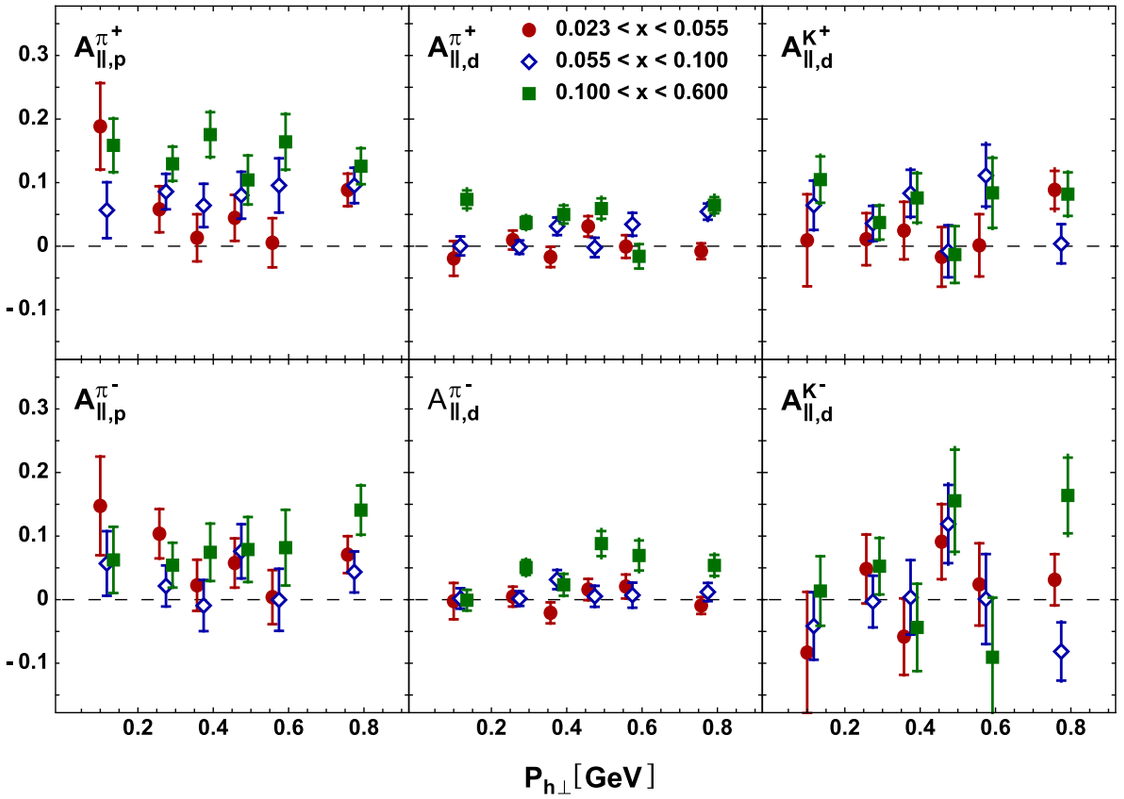
$$\left.+\sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos\phi_S}\cos\phi_S+\sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\right]\}$$

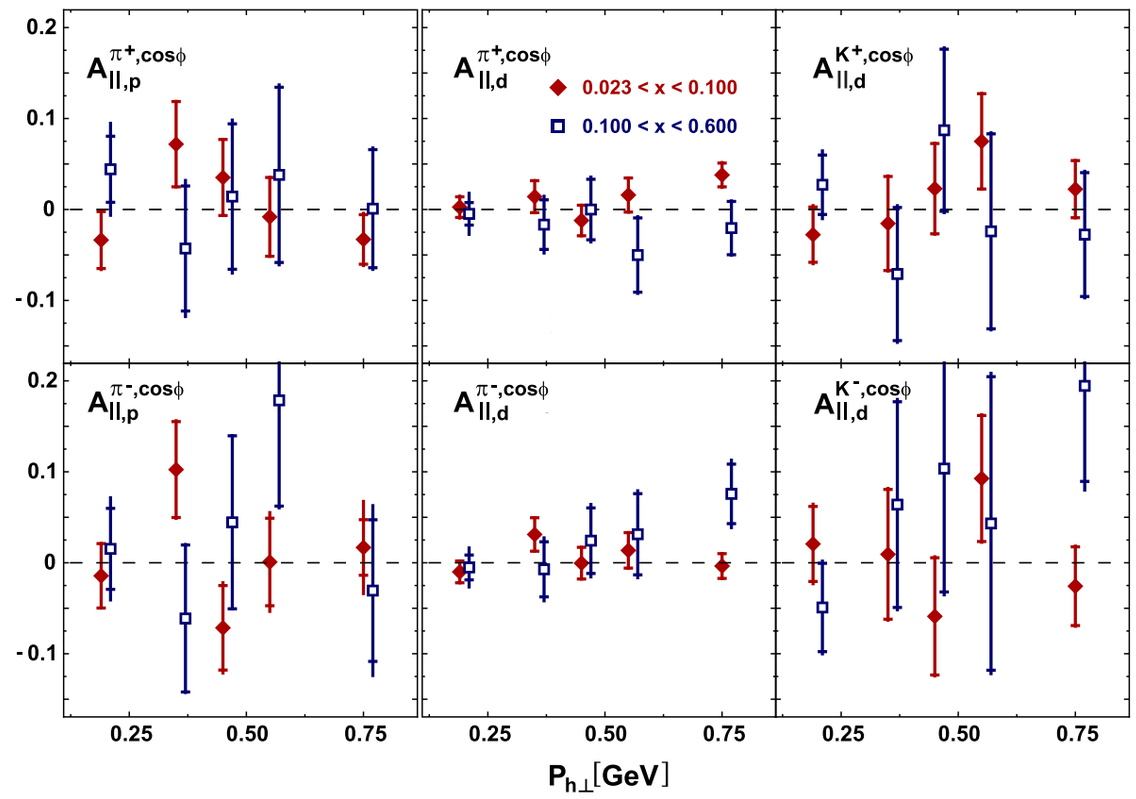
Leading Twist TMDs

Nucleon Polarization \ Quark Polarization	U	L	T
U	f_1  **unpolarized**		$h_1^\perp$  **Boer-Mulders**
L		g_{1L}  **helicity**	$h_{1L}^\perp$  **longi-transversity (worm-gear)**
T	$f_{1T}^\perp$  **Sivers**	g_{1T}  **trans-helicity (worm-gear)**	h_1  **transversity** $h_{1T}^\perp$  **pretzelosity**

Some Recent Measurements

Longitudinal double spin asymmetry



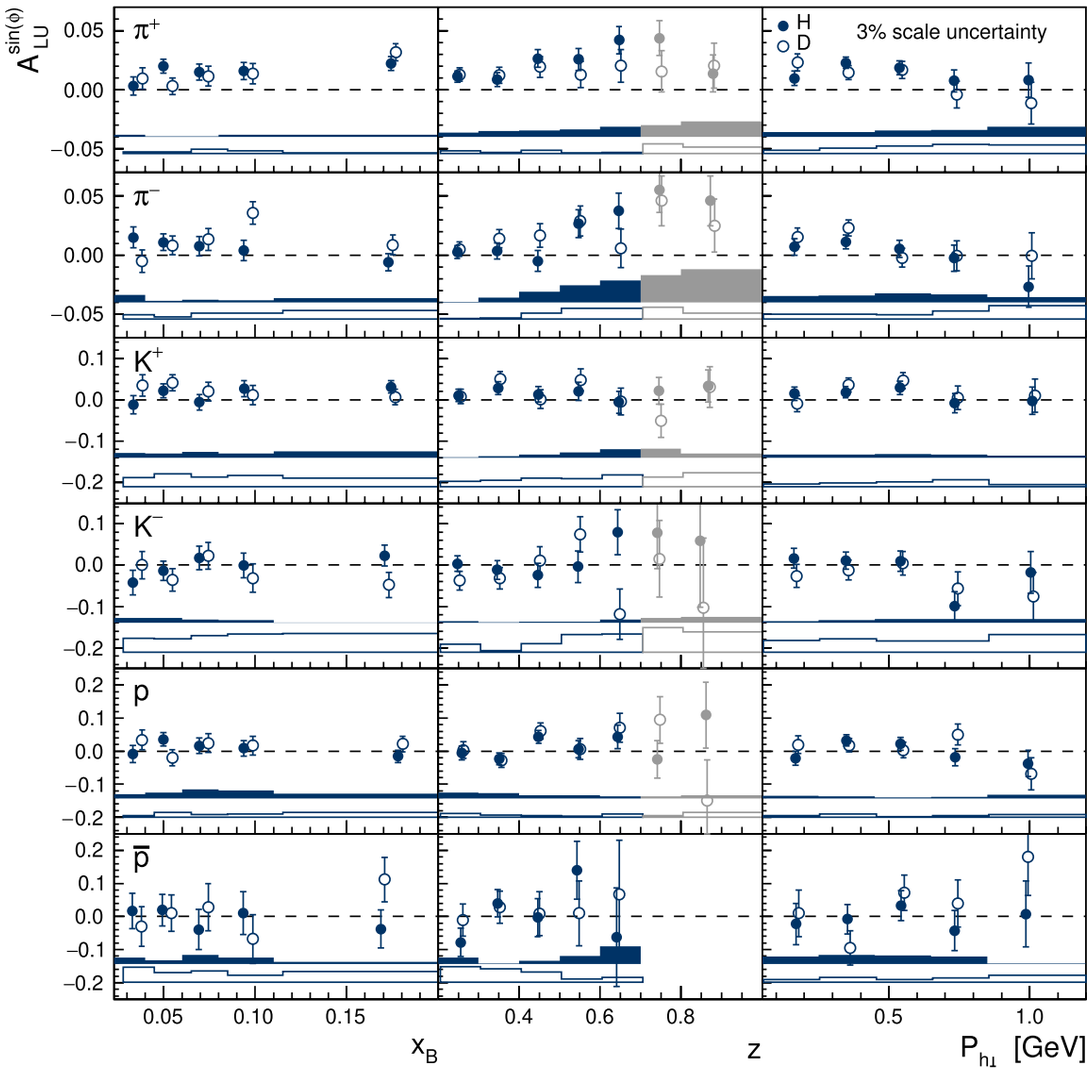


No strong dependence on transverse momentum or azimuthal angle is observed.

HERMES Collaboration, Phys. Rev. D 99, 112001 (2019).

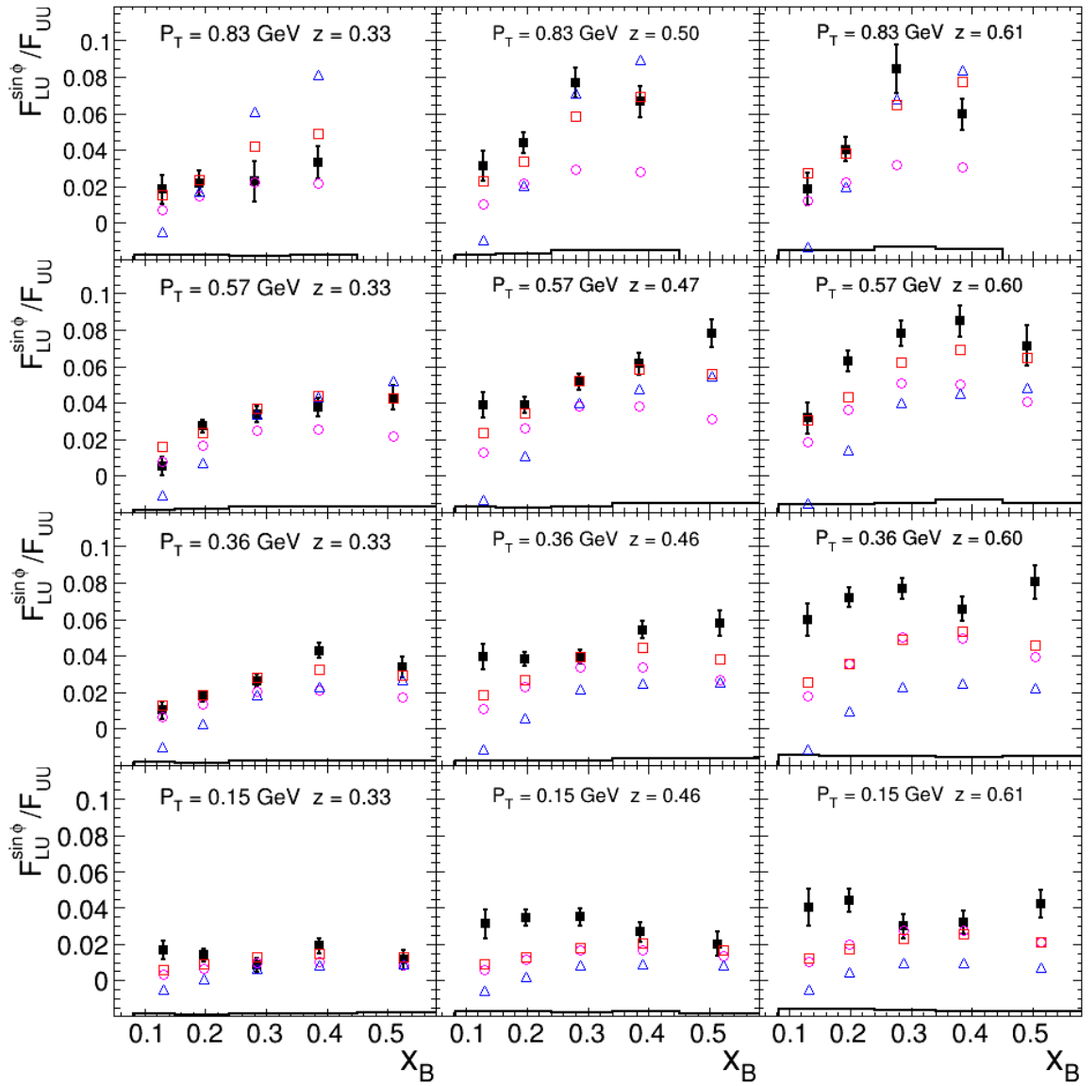
Some Recent Measurements

Beam spin asymmetry



First presented for $K^{\pm}, p, \bar{p}$

HERMES Collaboration, Phys. Lett. B 797, 134886 (2019).

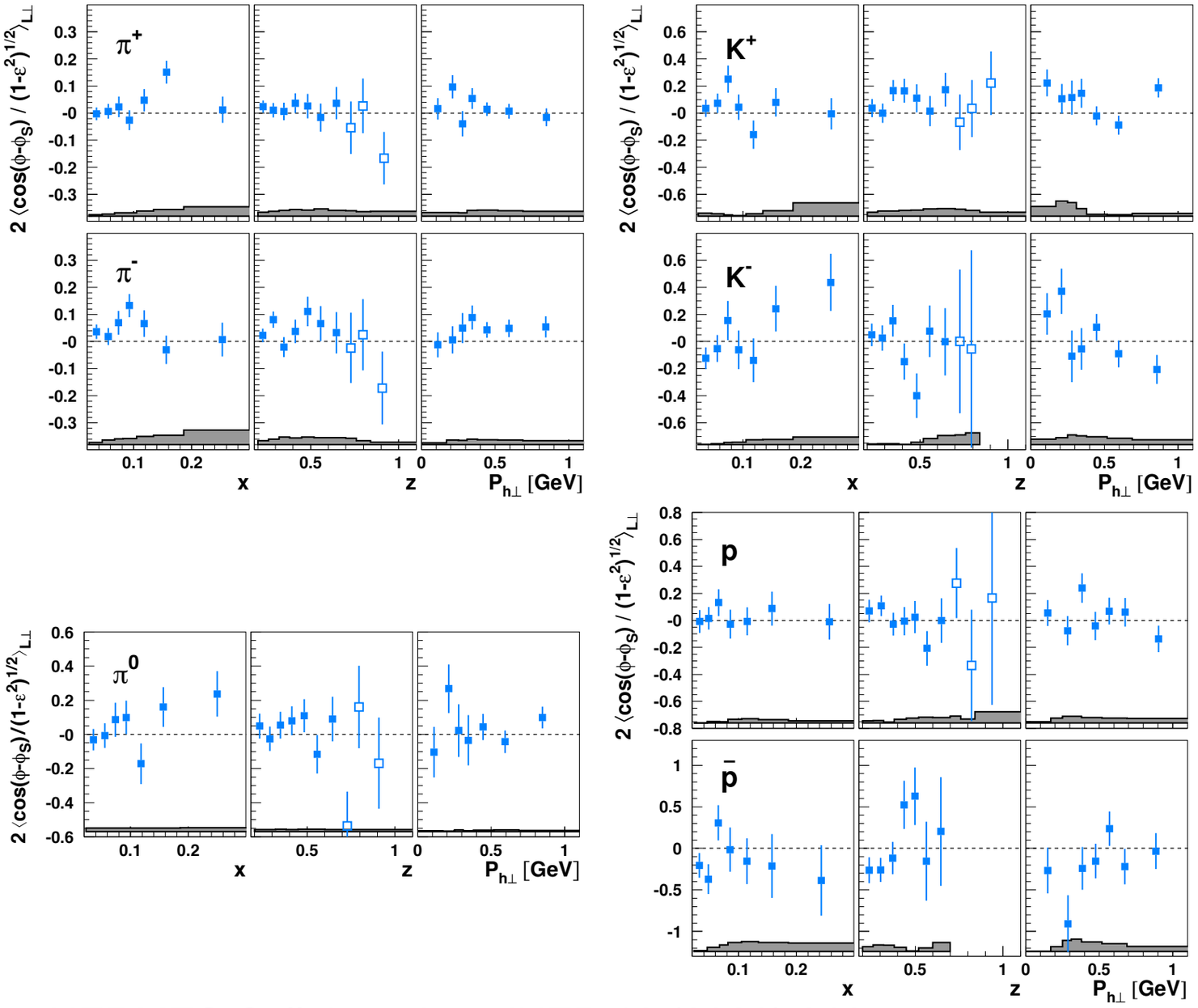


3D extraction for π^+

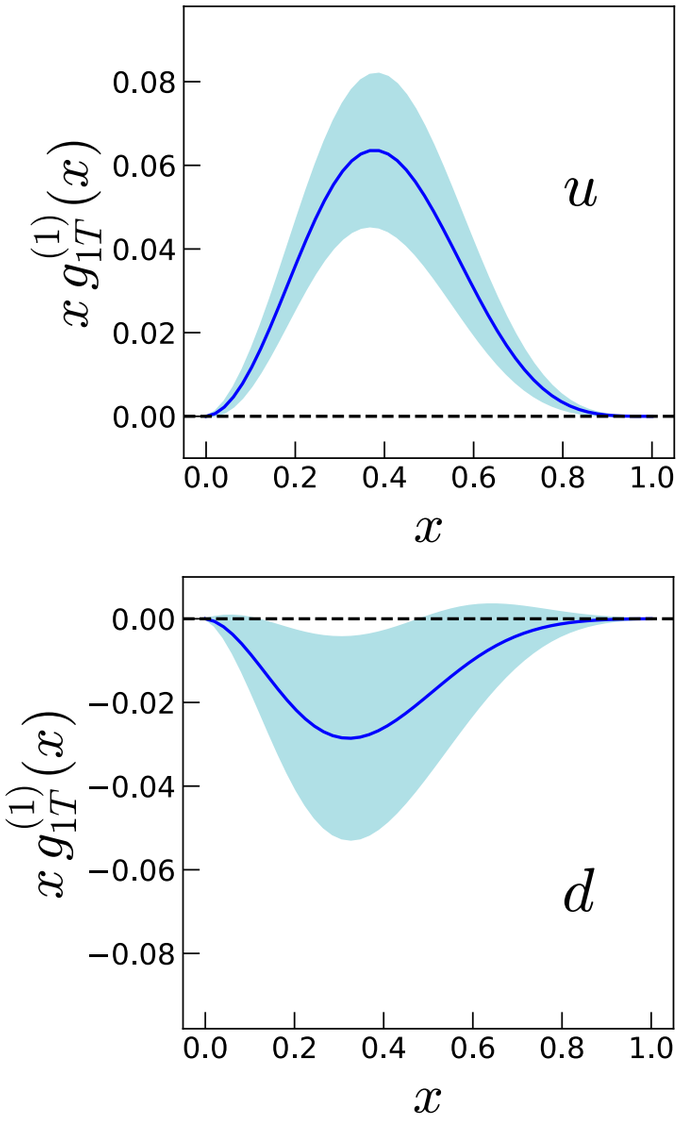
CLAS Collaboration, arXiv:2101.03544.

Some Recent Measurements

Longitudinal transverse double spin asymmetry



HERMES Collaboration, JHEP 12 (2020) 010.

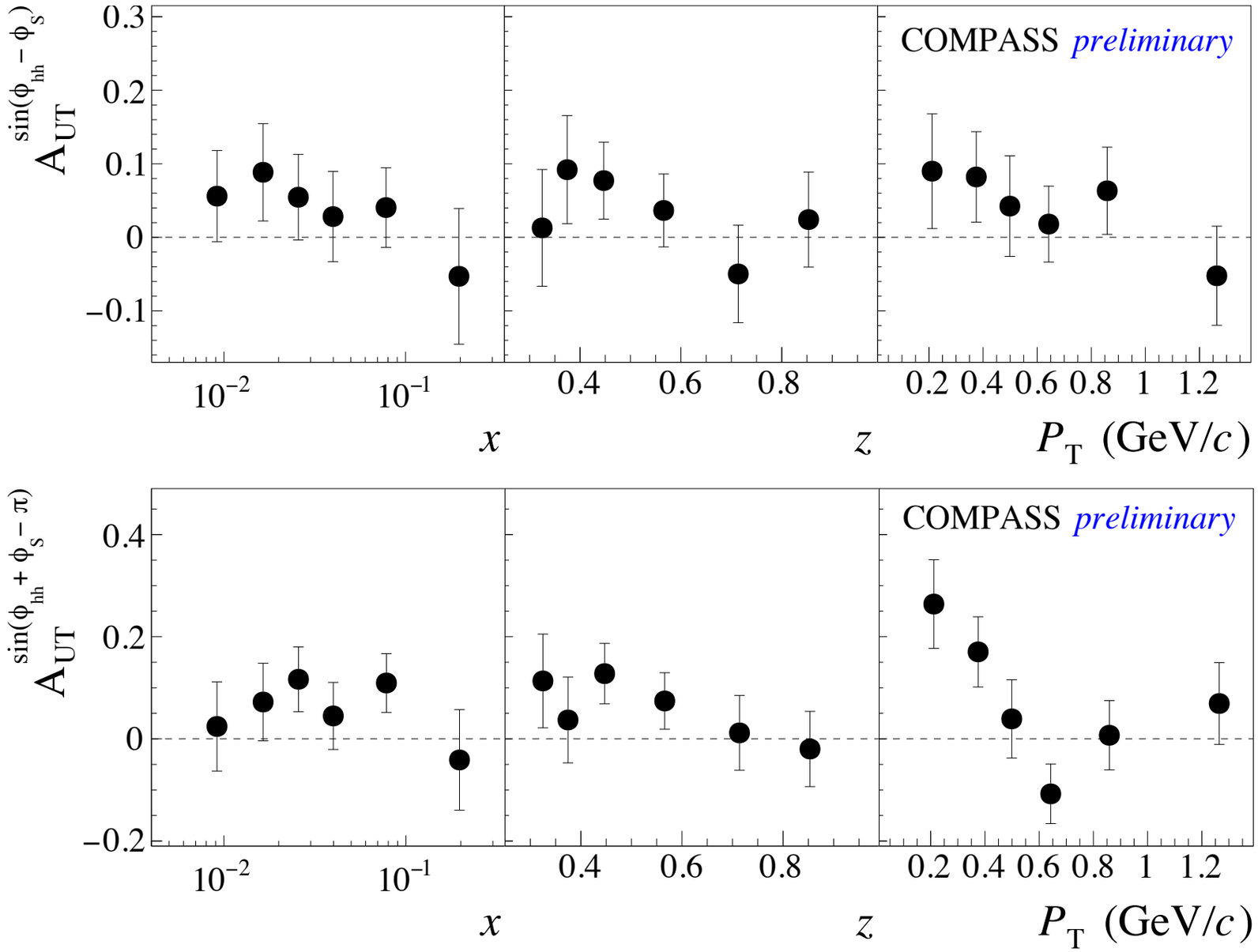


Global fit of worm-gear TMD

S. Bhattacharya, Z.B. Kang, A. Metz, G. Penn, D. Pitonyak, arXiv:2110.10253.

Some Recent Measurements

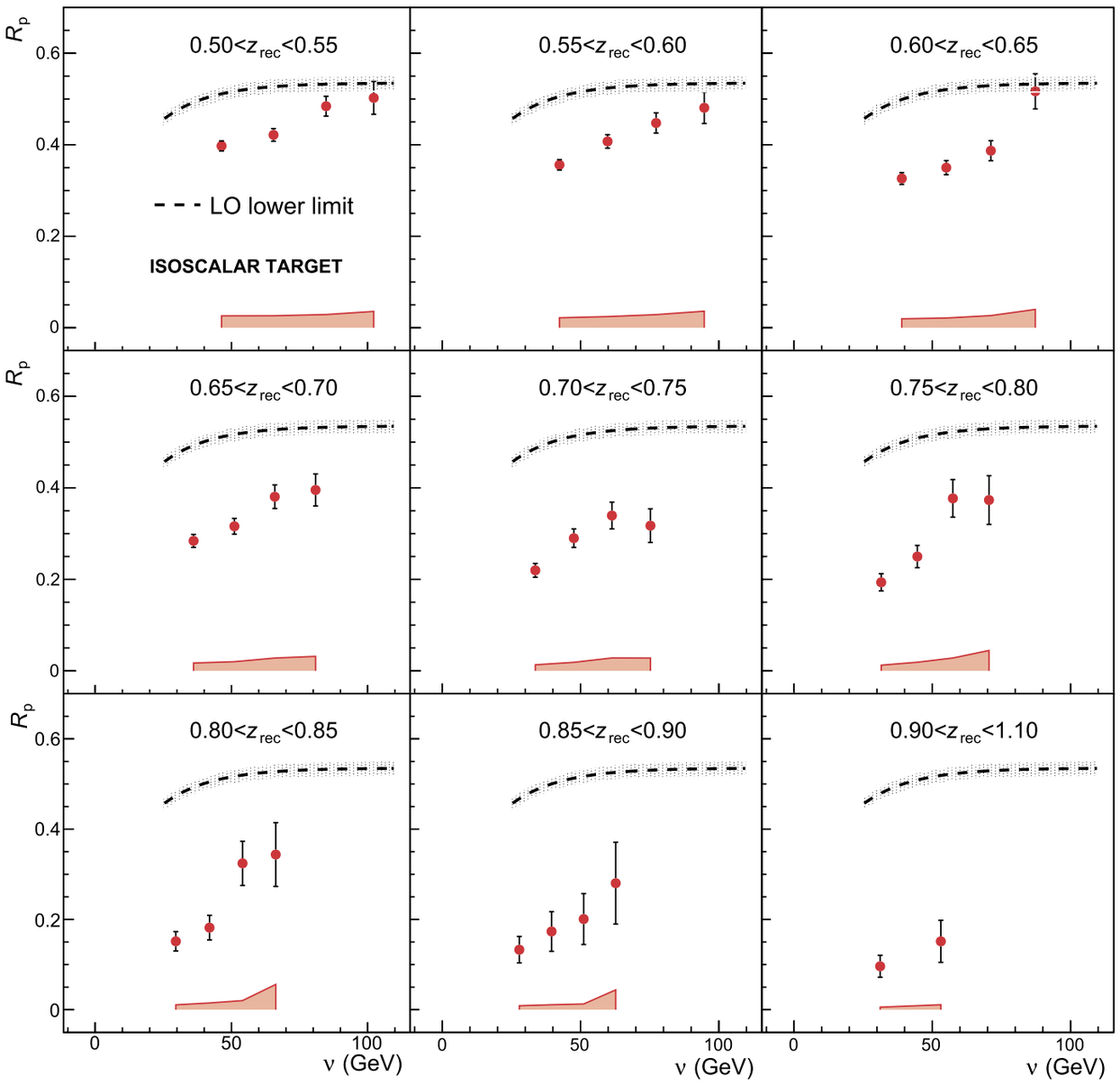
Transverse single spin asymmetries for ρ^0



COMPASS Collaboration, arXiv:2107.10099.

Some Recent Measurements

Antiproton over proton multiplicity ratio



$$R_p(x, Q^2, z) = \frac{dM^{\bar{p}}(x, Q^2, z)/dz}{dM^{p}(x, Q^2, z)/dz} = \frac{4.5(\bar{u}+\bar{d})D_{fav} + (5u+5d+2s+2\bar{s})D_{unf}}{4.5(u+d)D_{fav} + (5\bar{u}+5\bar{d}+2s+2\bar{s})D_{unf}}$$

$$R_p > \frac{\bar{u}+\bar{d}}{u+d}$$

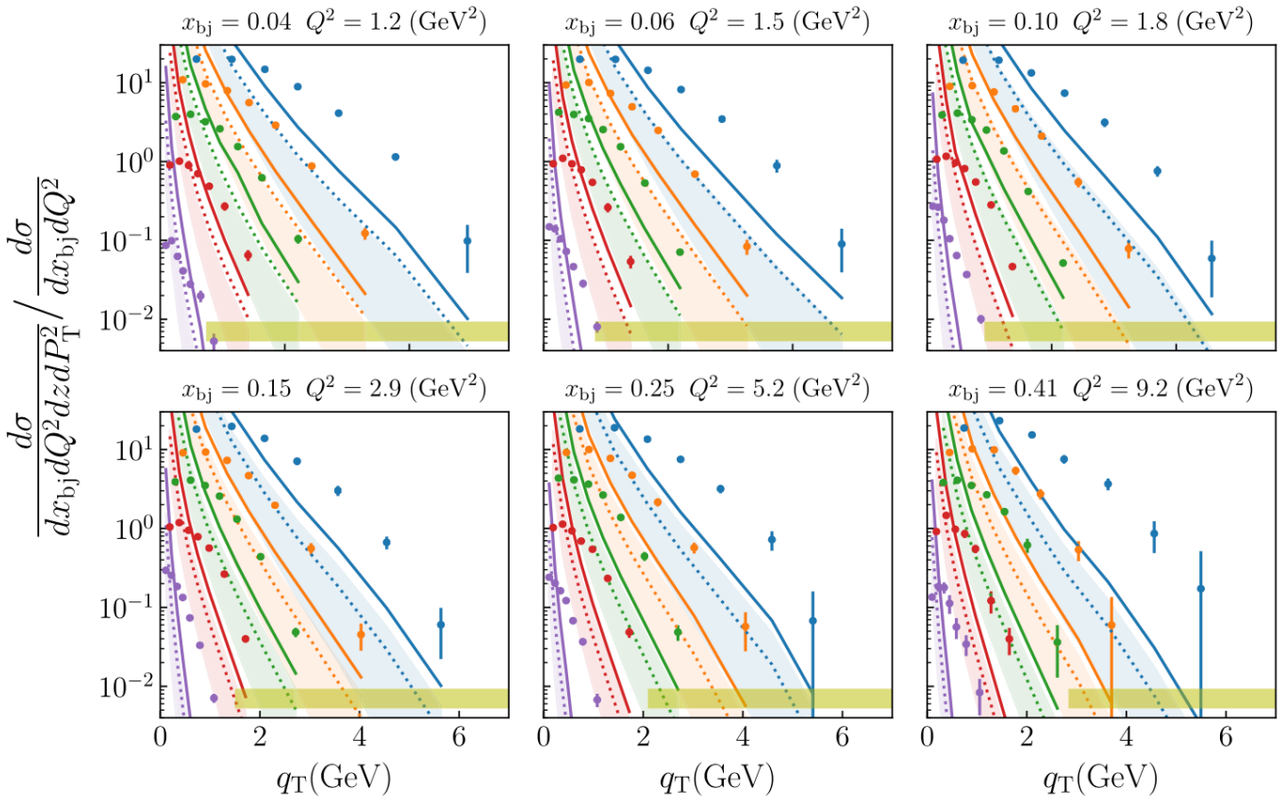
Below LO pQCD lower limit

Unexpected strong dependence on ν by LO pQCD

COMPASS Collaboration, Phys. Lett. B 807, 135600 (2020).

Some Recent Measurements

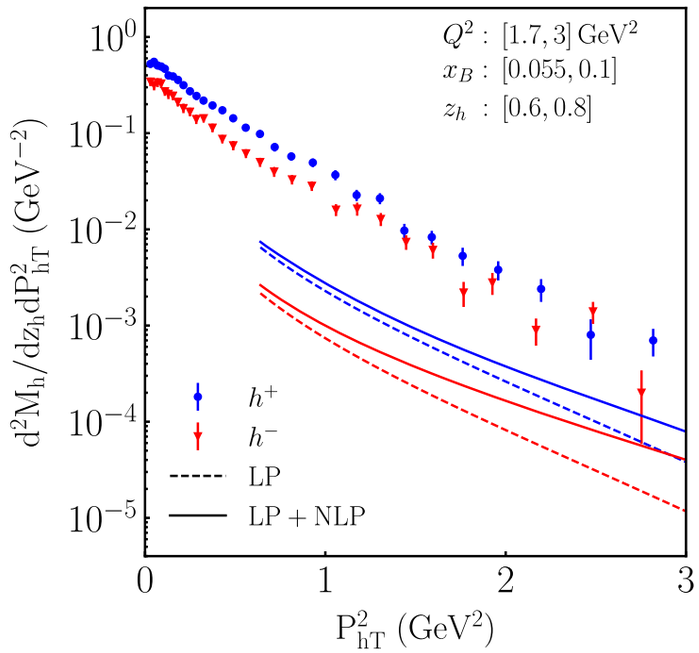
Challenge at large transverse momentum



About an order of magnitude discrepancy

J.O. Gonzalez-Hernandez, T.C. Rogers, N. Sato, B. Wang, Phys. Rev. D 98, 114005 (2018).

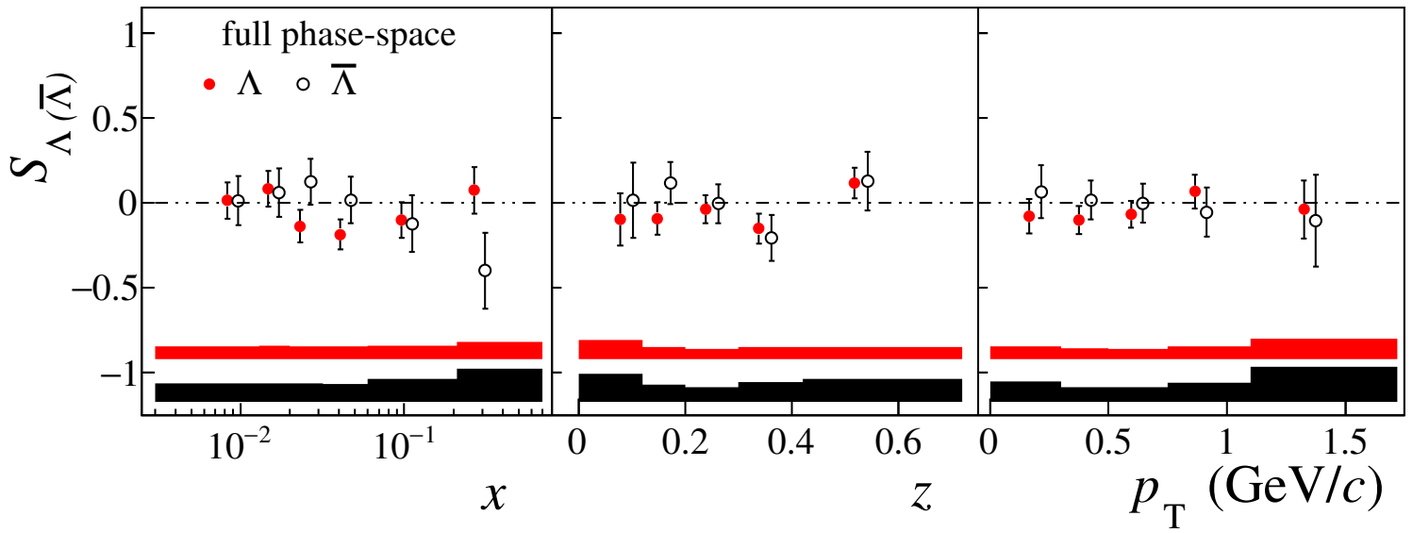
Power correction

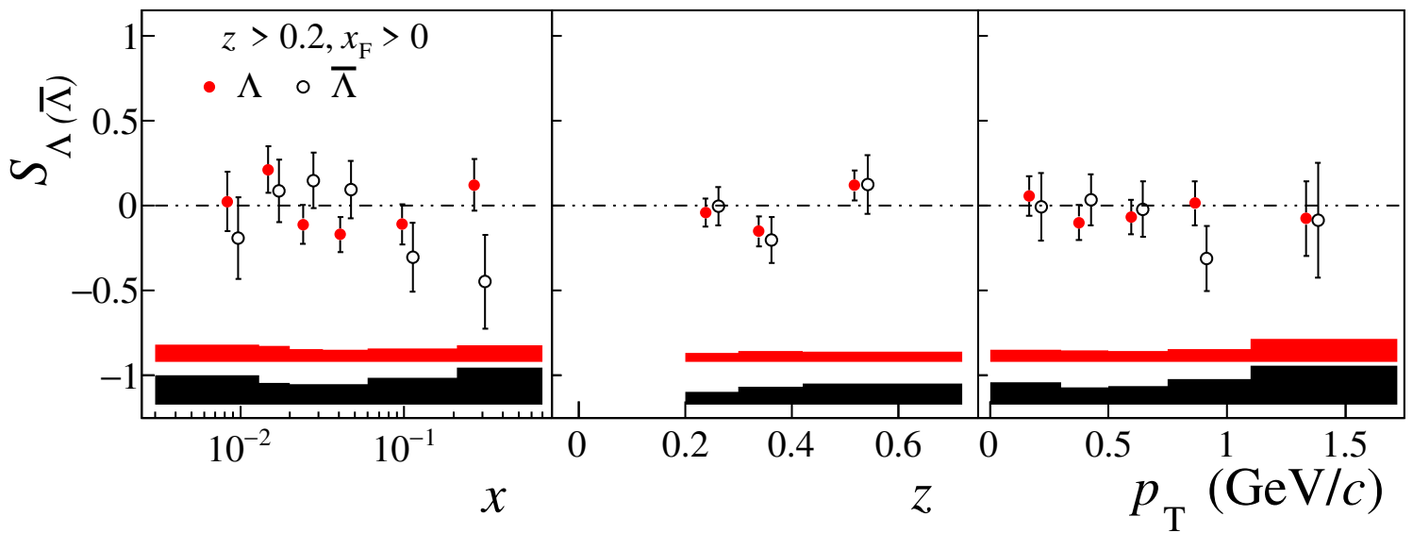


T. Liu and J.W. Qiu, Phys. Rev. D 101, 014008 (2020).

Some Recent Measurements

$\Lambda(\bar{\Lambda})$ polarization



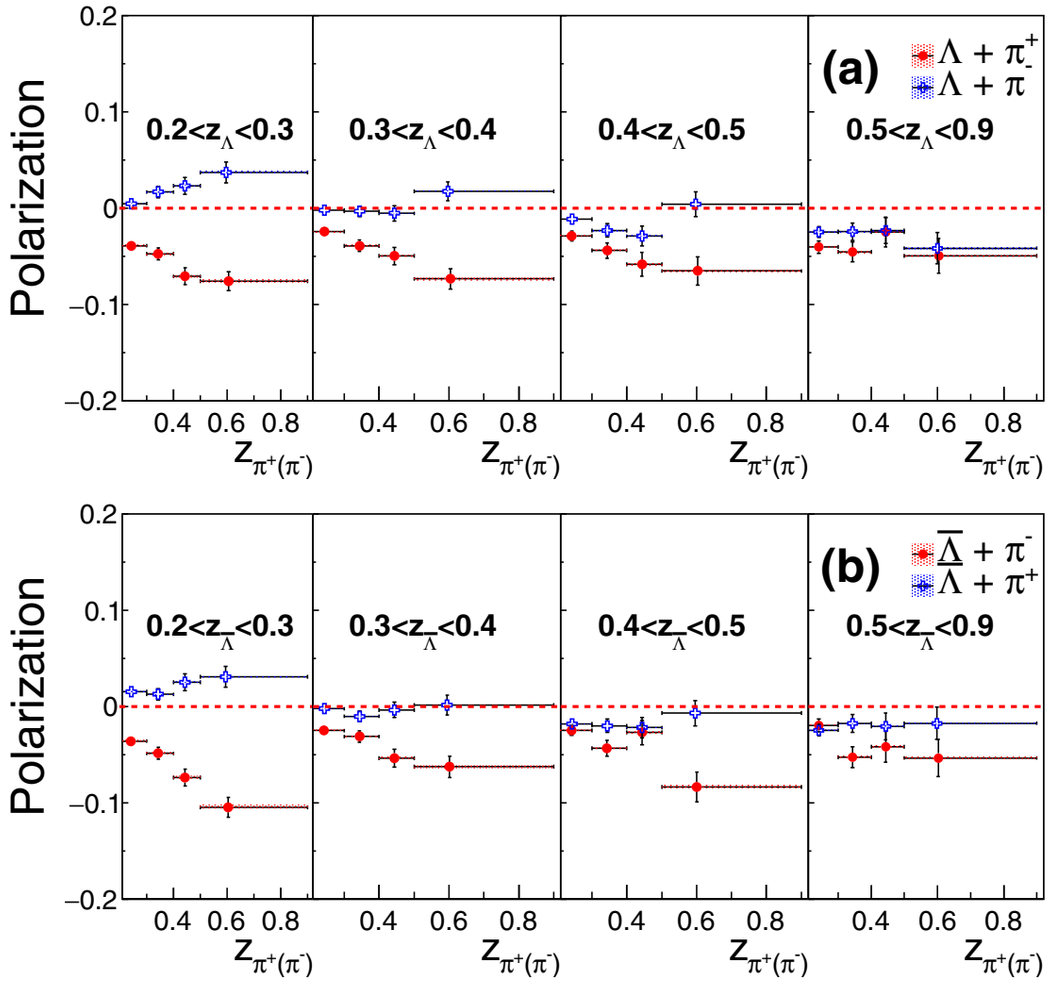


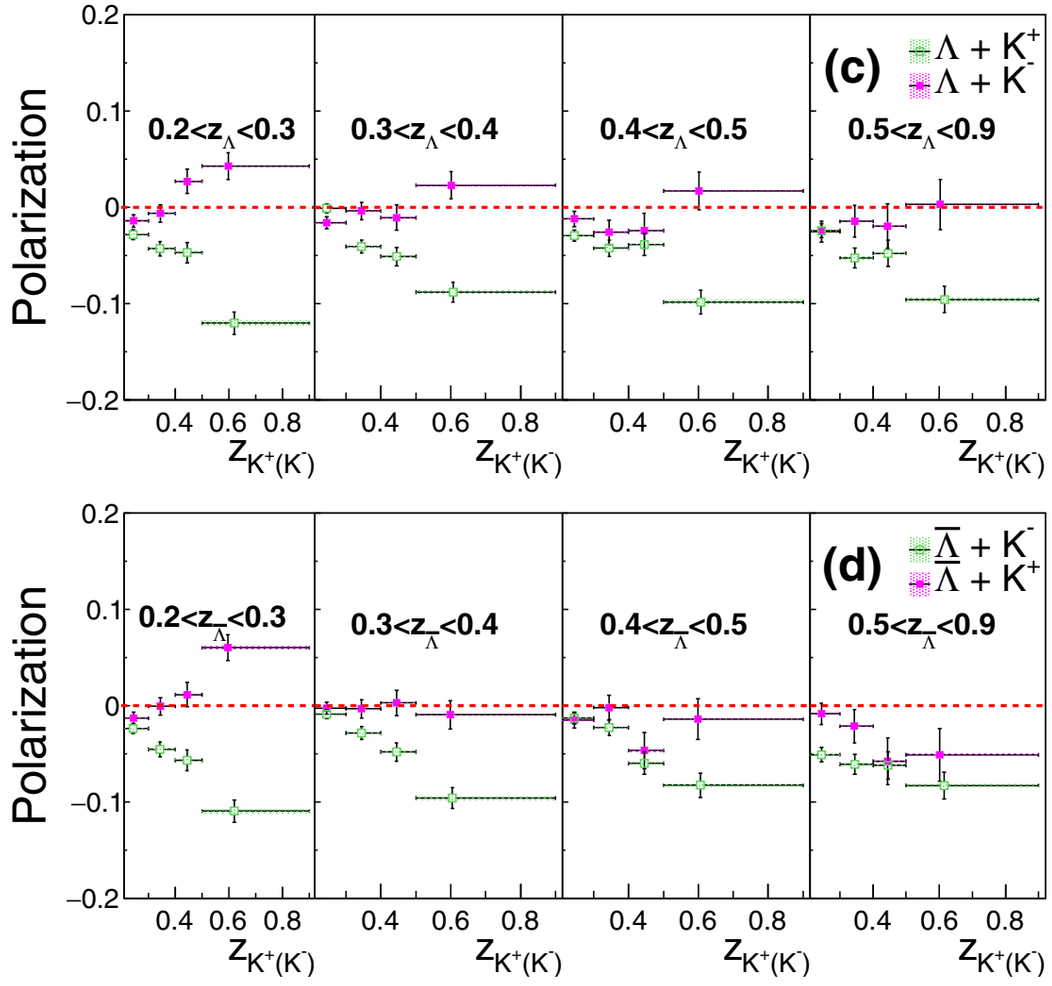
Consistent with zero

COMPASS Collaboration, arXiv:2104.13585.

Some Recent Measurements

$\Lambda(\bar{\Lambda})$ polarization in e^+e^- annihilation

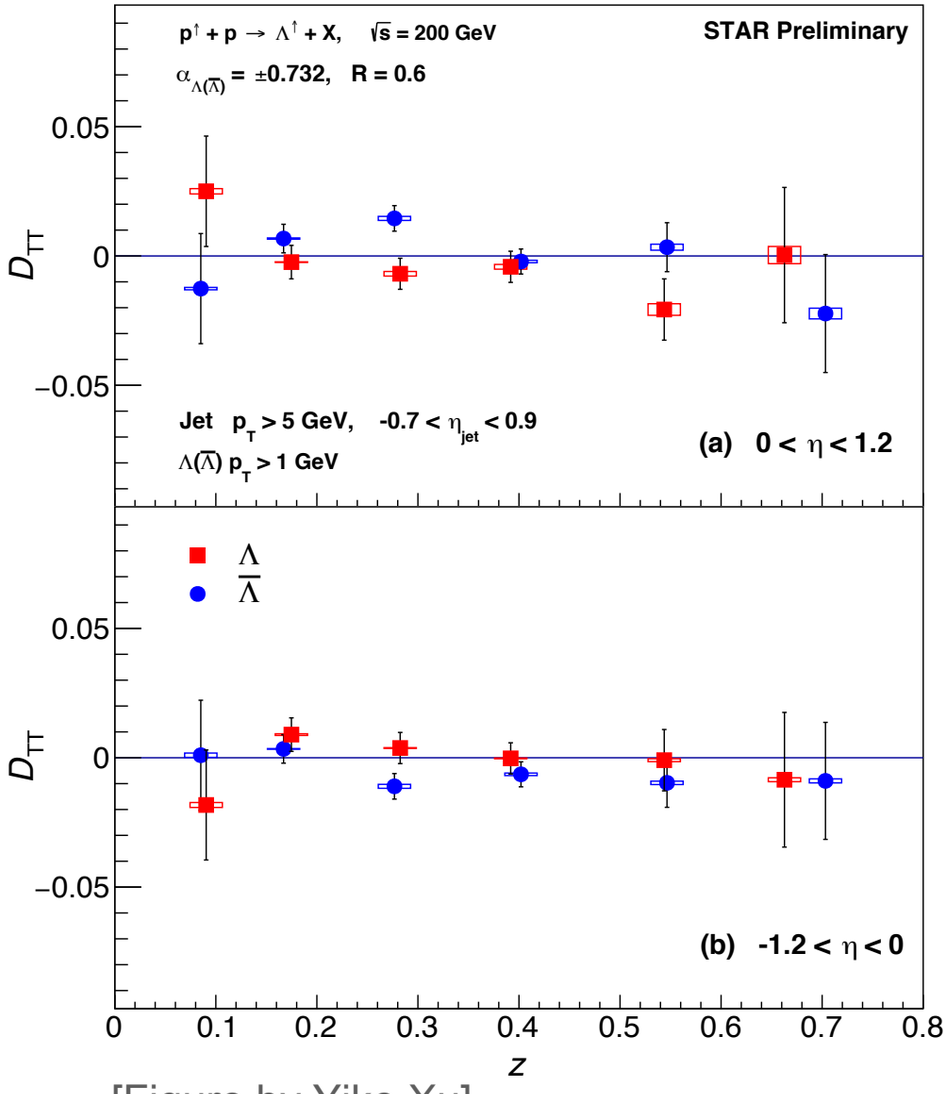




Belle Collaboration, Phys. Rev. Lett. 122, 042001 (2019).

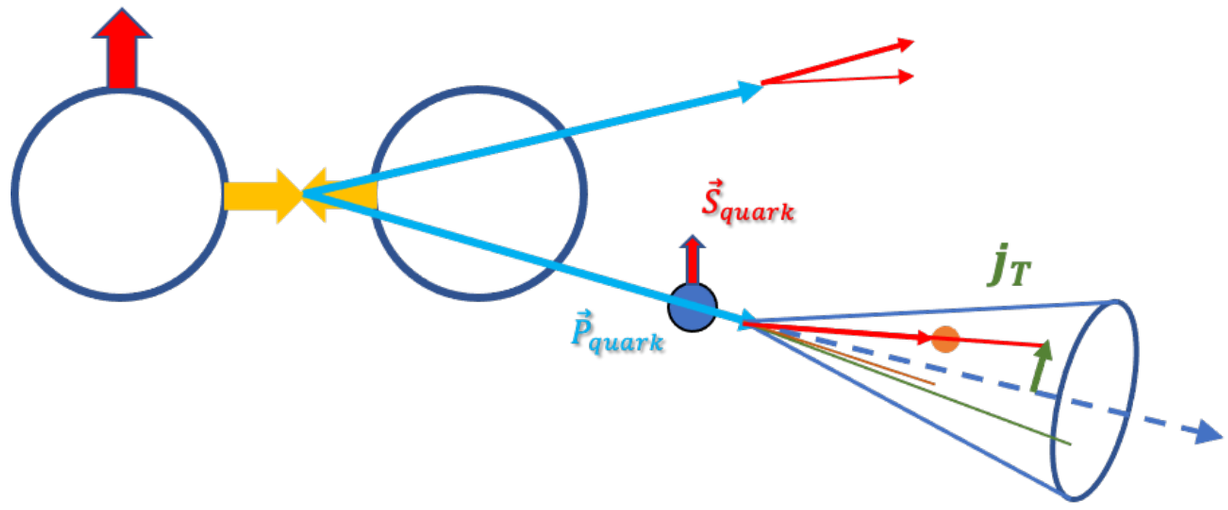
Some Recent Measurements

$\Lambda(\bar{\Lambda})$ polarization in *pp* collision



[Figure by Yike Xu]

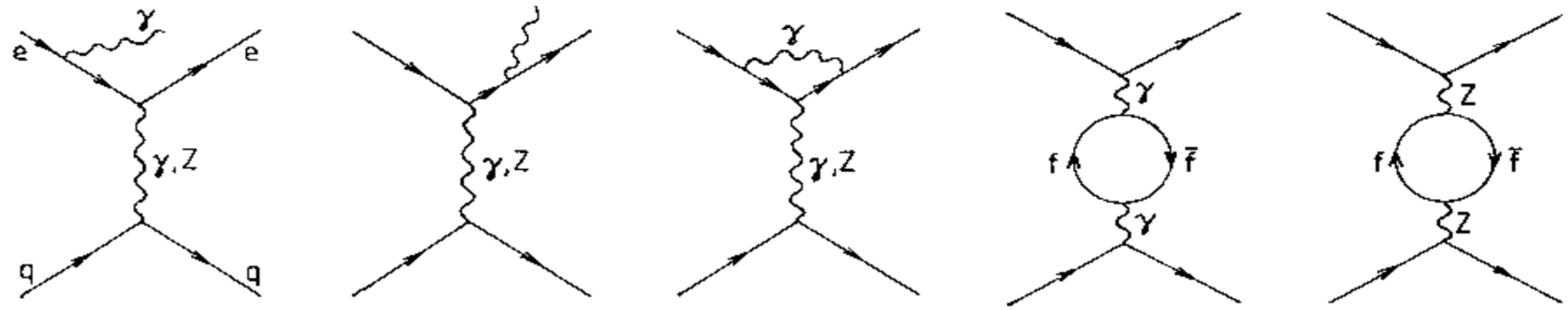
STAR Collaboration

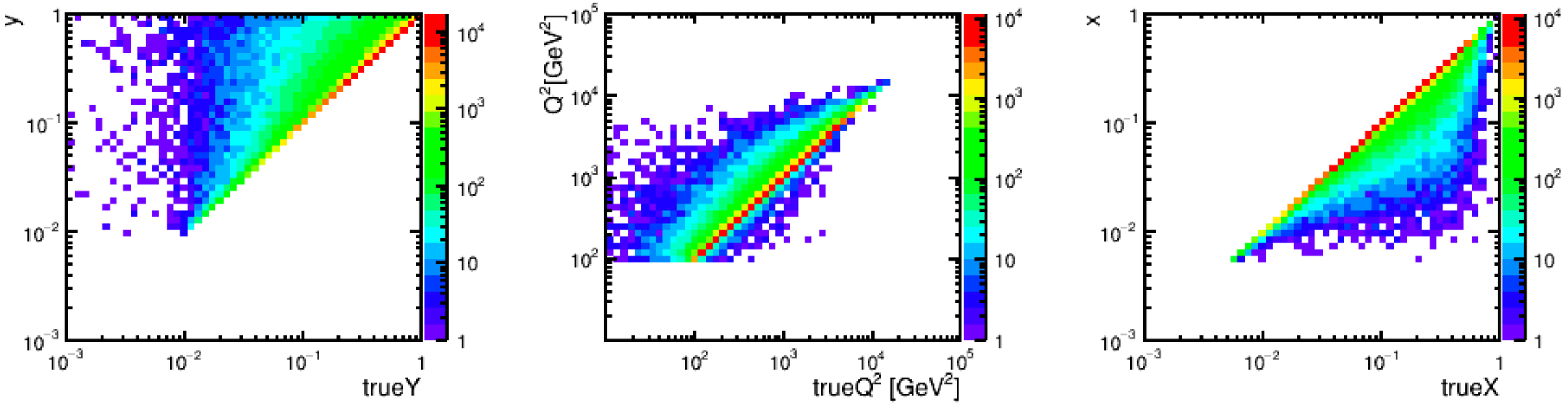


[Figure by Ting Lin]

$$z = \frac{\boldsymbol{p}_{\Lambda} \cdot \boldsymbol{p}_{jet}}{|\boldsymbol{p}_{jet}|^2}$$

Kinematics with Radiative Effects



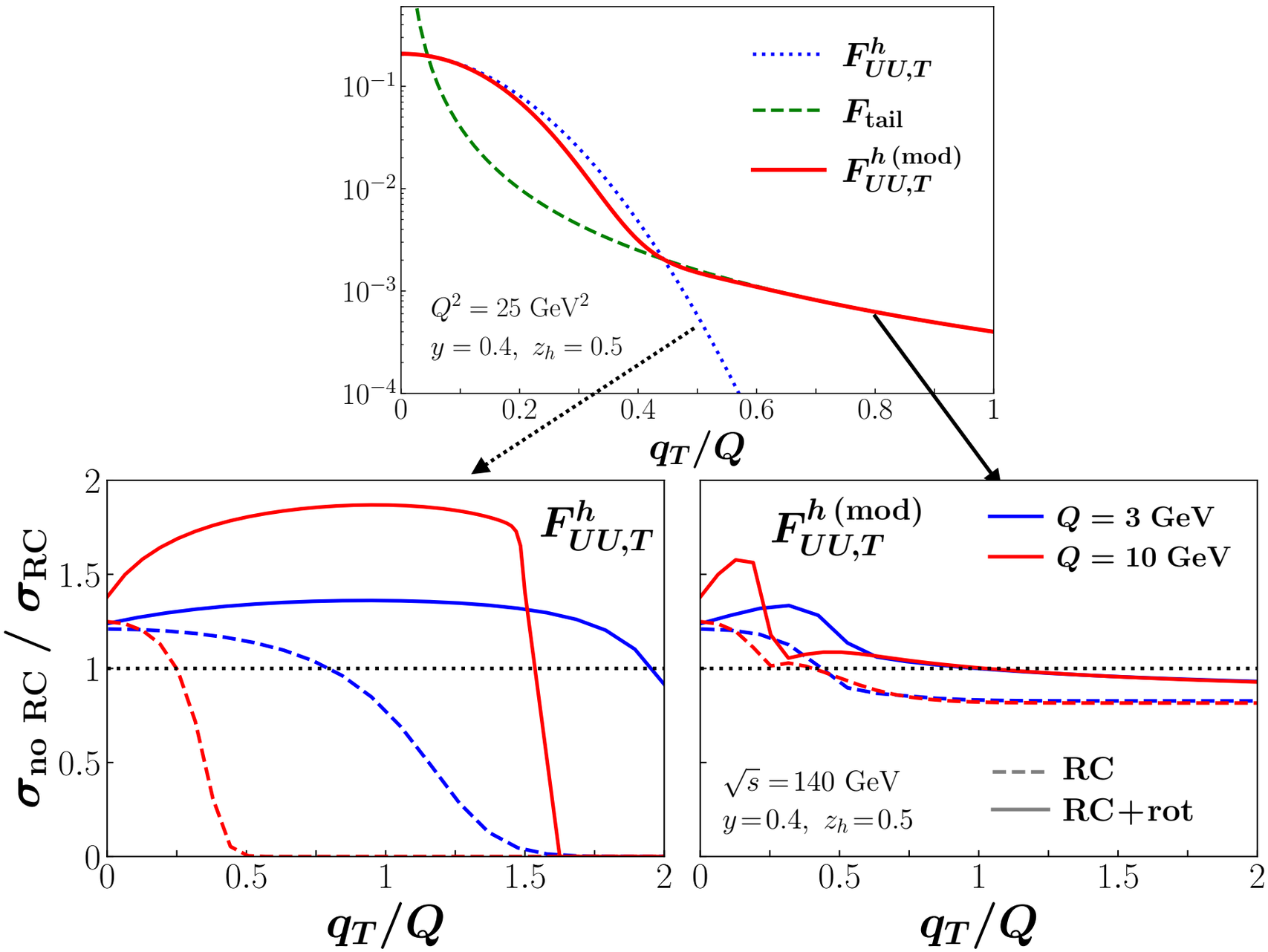


[Figures from X. Chu at 2nd EIC YR workshop]

Kinematic experienced by the parton ≠ *Kinematic reconstructed from observed momenta*

QED radiation will have significant impact due to kinematic shift, although α is small.

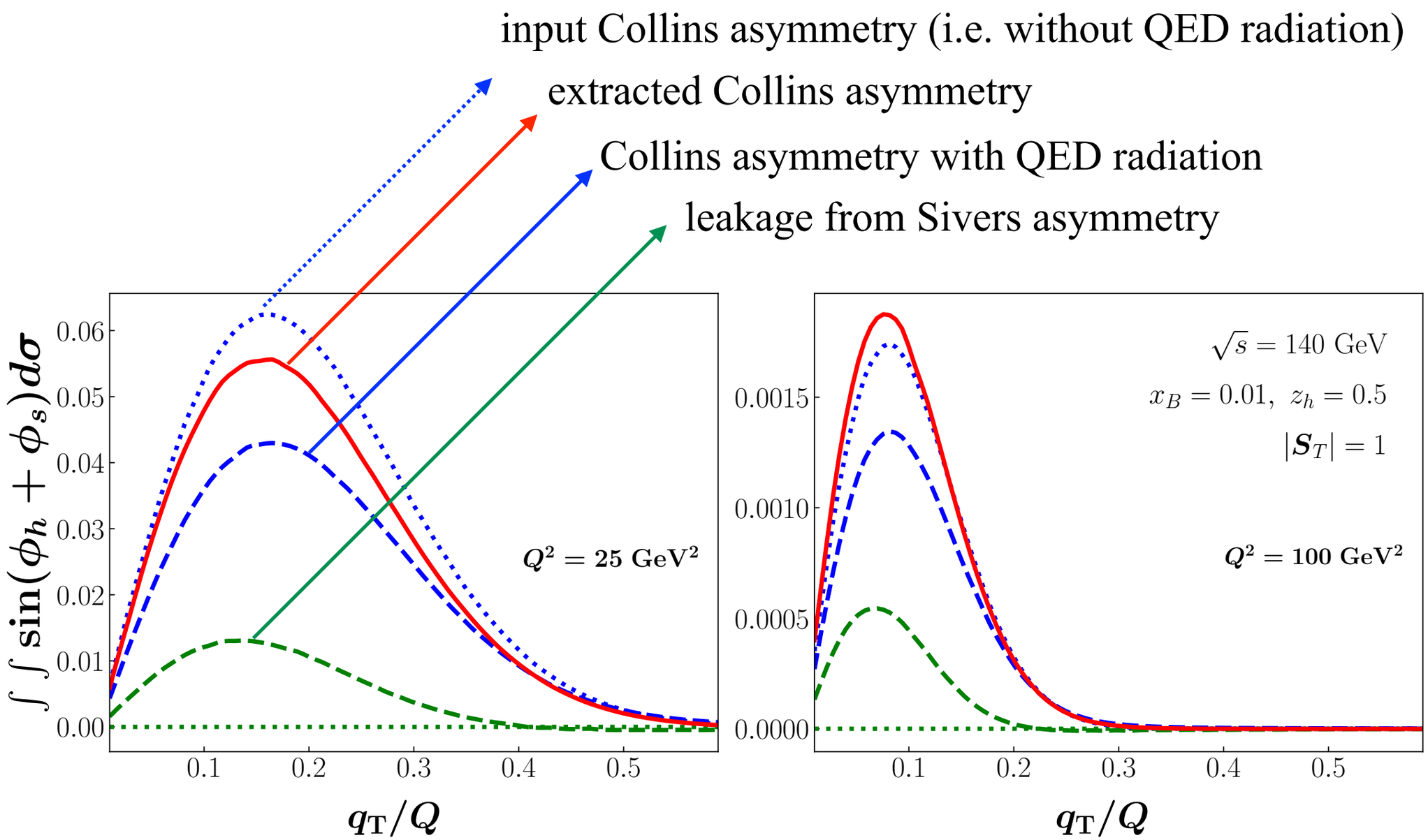
Impact of QED Effects: P_{hT} Distribution



T. Liu, W. Melnitchouk, J.W. Qiu, N. Sato, PRD2021 and JHEP2021.

Impact of QED Effects: Azimuthal Asymmetries

Collins asymmetry:

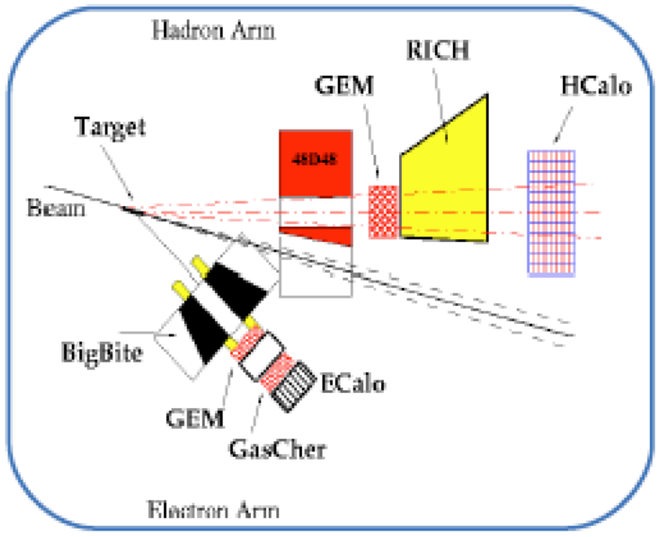


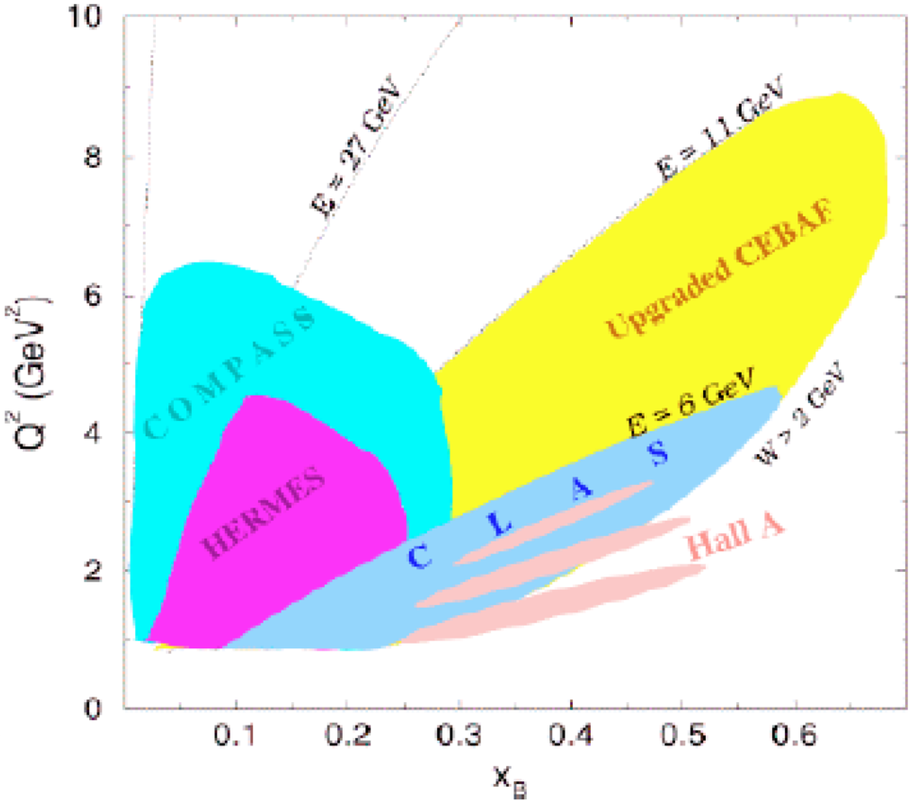
T. Liu, W. Melnitchouk, J.W. Qiu, N. Sato, PRD2021 and JHEP2021.

Multi-Hall SIDIS Program @ JLab-12

Hall A: Super BigBite

SIDIS with ^{3}He, high x, Q^2

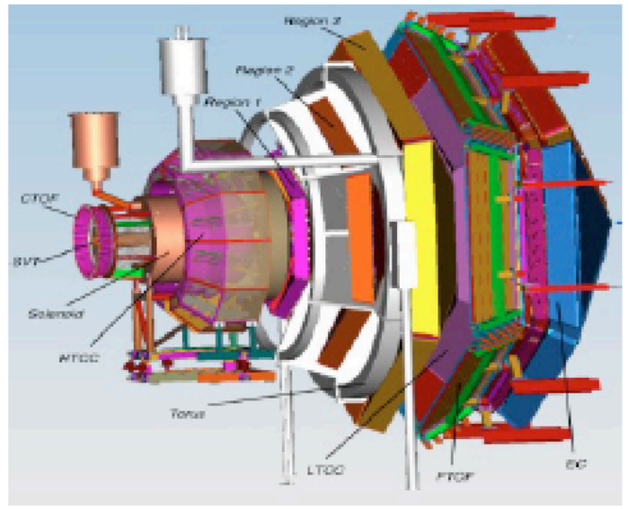




Hall B: CLAS12

SIDIS with polarized H/D

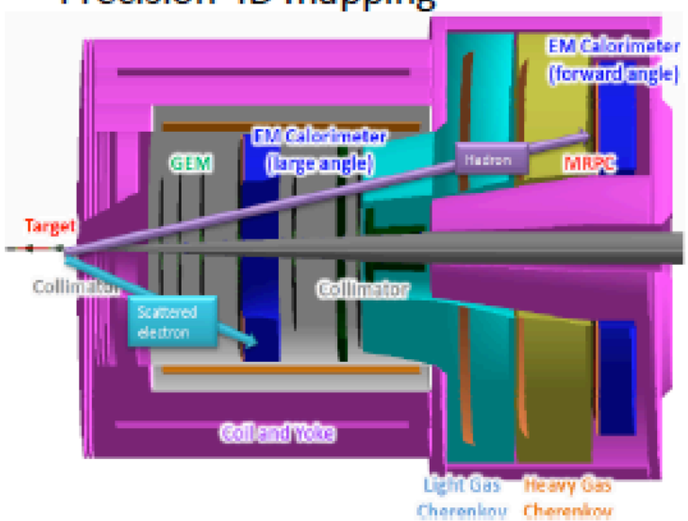
Comprehensive SIDIS program



Hall A: SoLID

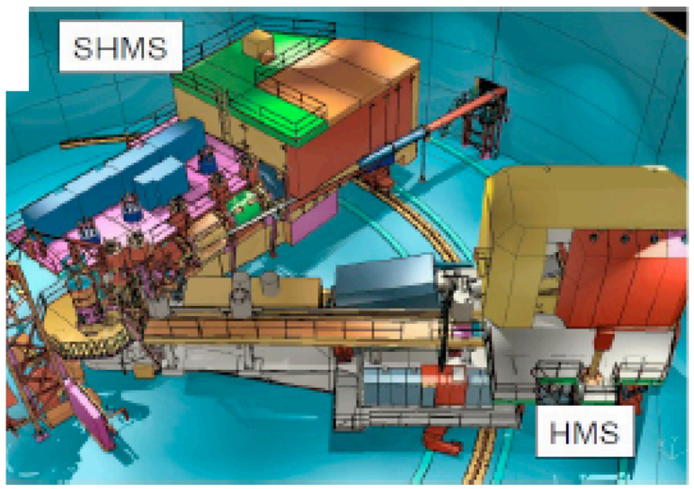
SIDIS with polarized ^{3}He/NH_3

Precision 4D mapping



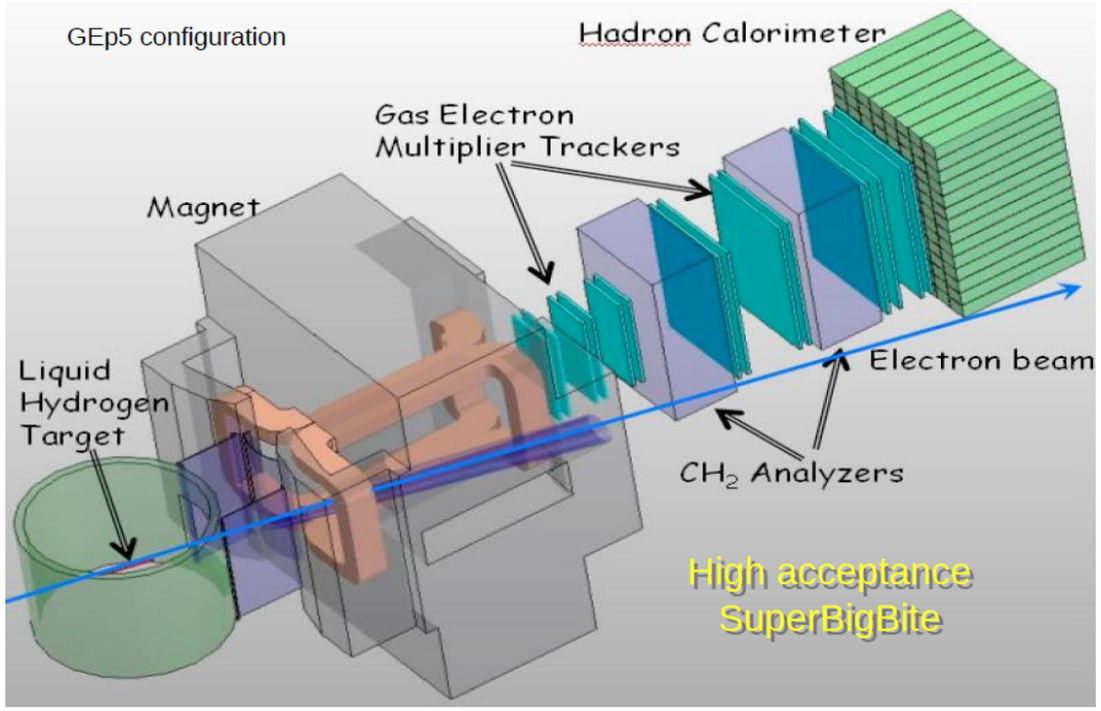
Hall C: SHMS

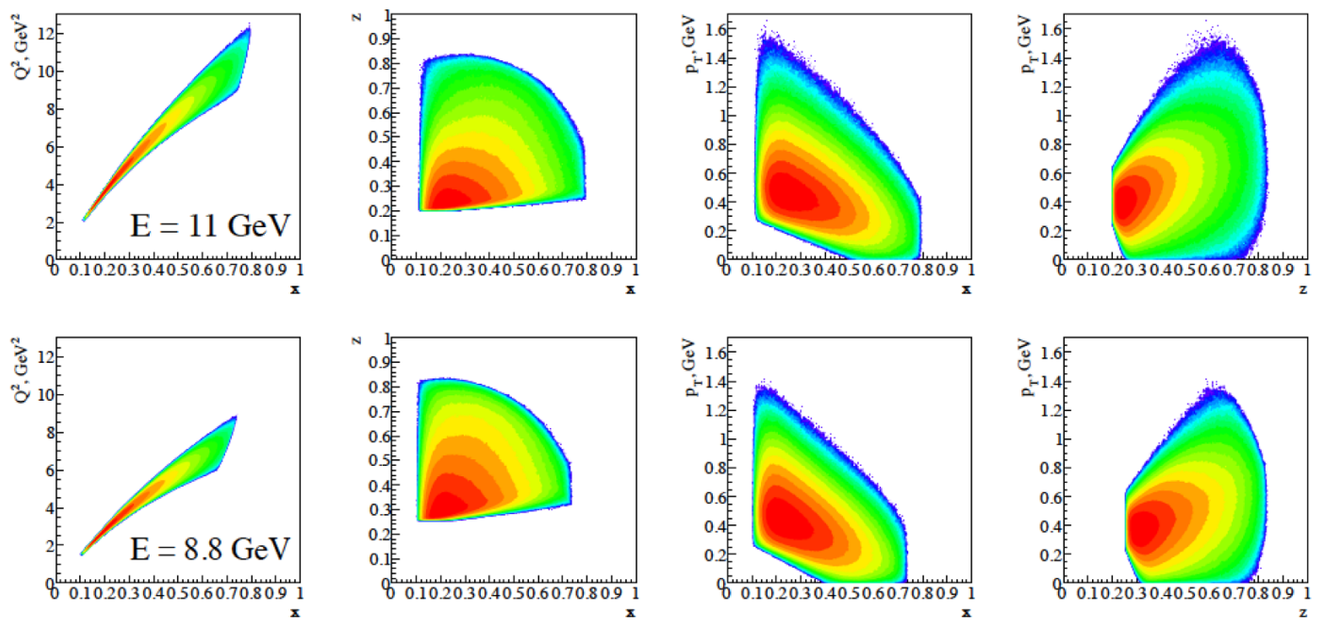
SIDIS with unpolarized H/D



SBS SIDIS Program

SuperBigbite Spectrometer

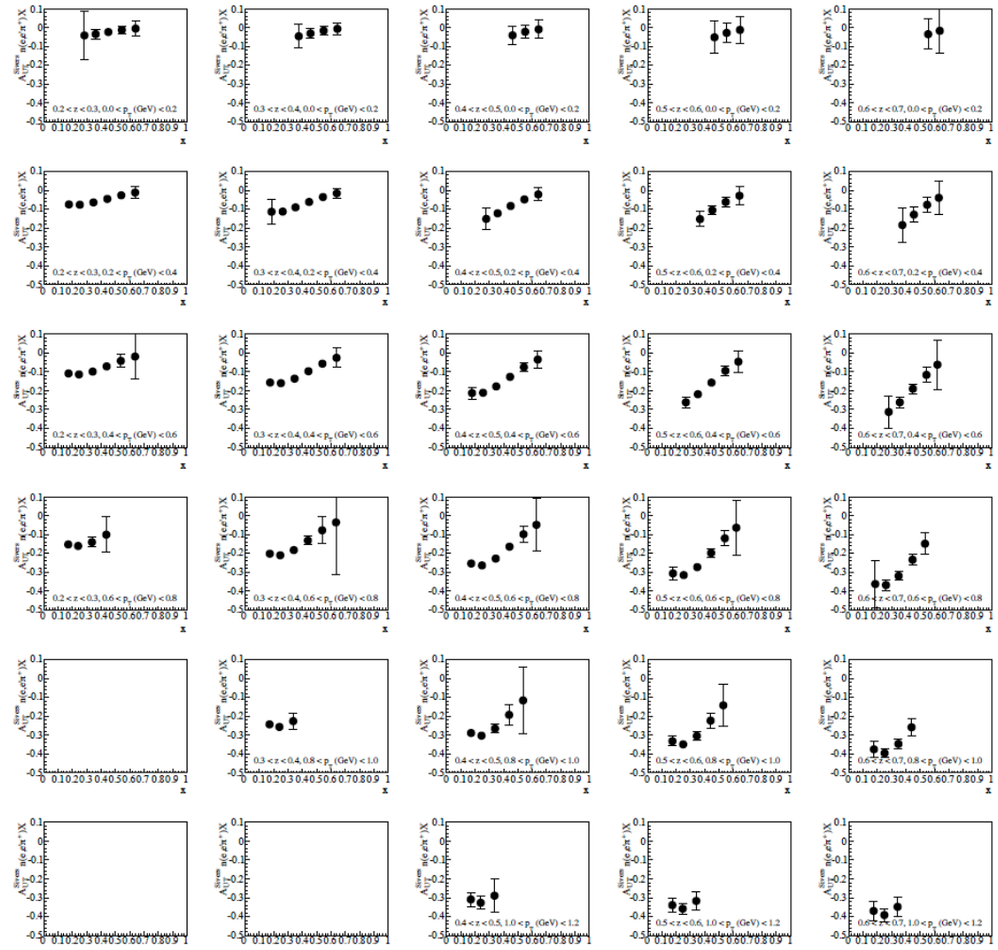




E12-09-018: 64 days

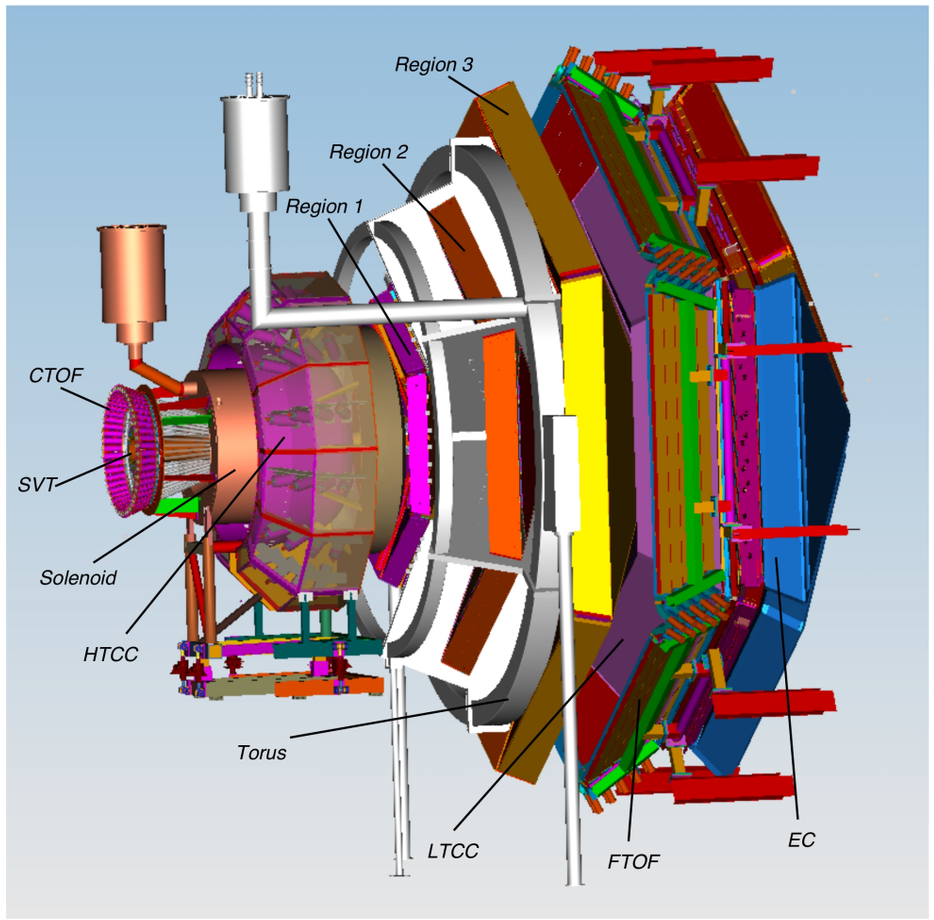
neutron (^{3}He) target

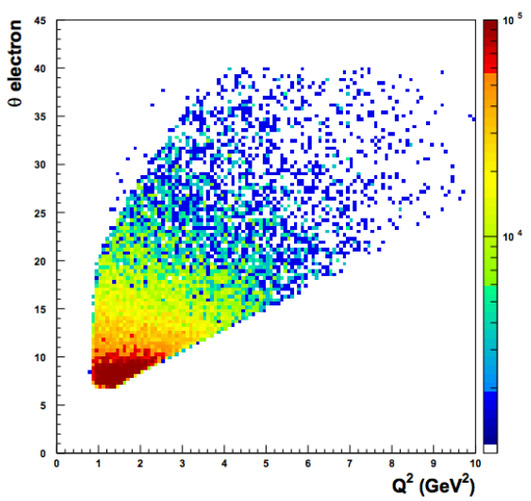
3D mapping example

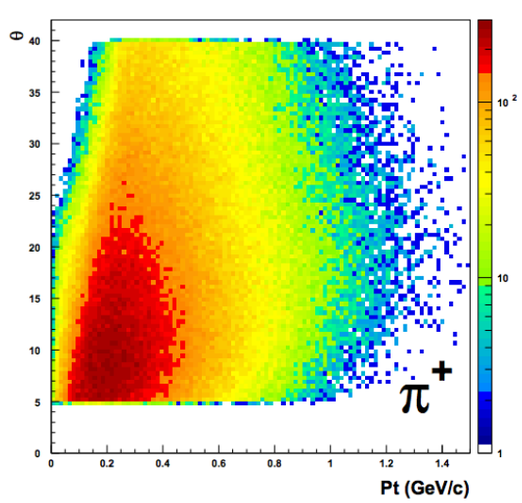


Projected data of E12-09-018

CLAS12 SIDIS Program

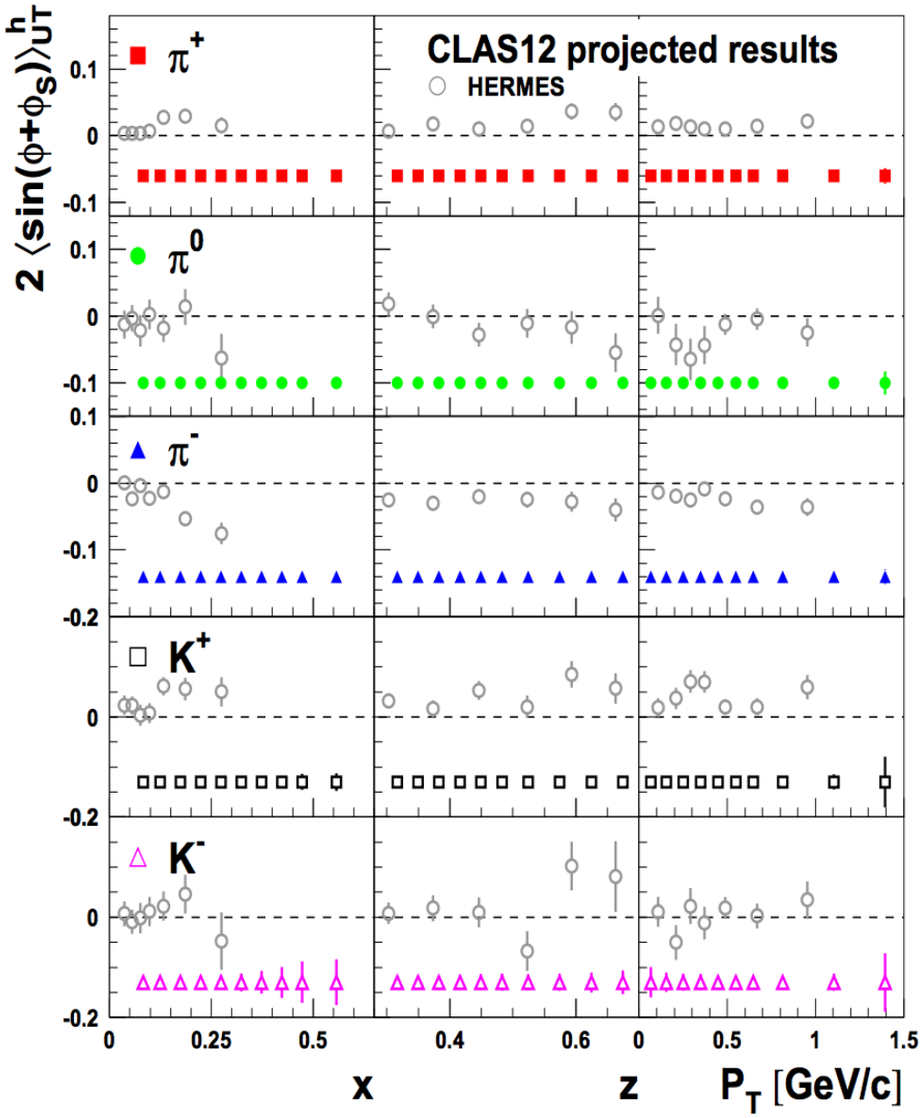






E12-09-007, E12-09-008
E12-09-009, E12-07-107
NH_3 and ND_3 targets

C12-11-111, HDice target



Projected data of C12-11-111

Hall C SIDIS Program (typ. $x/Q^2 \sim$ constant)

[R. Ent, DIS2016]

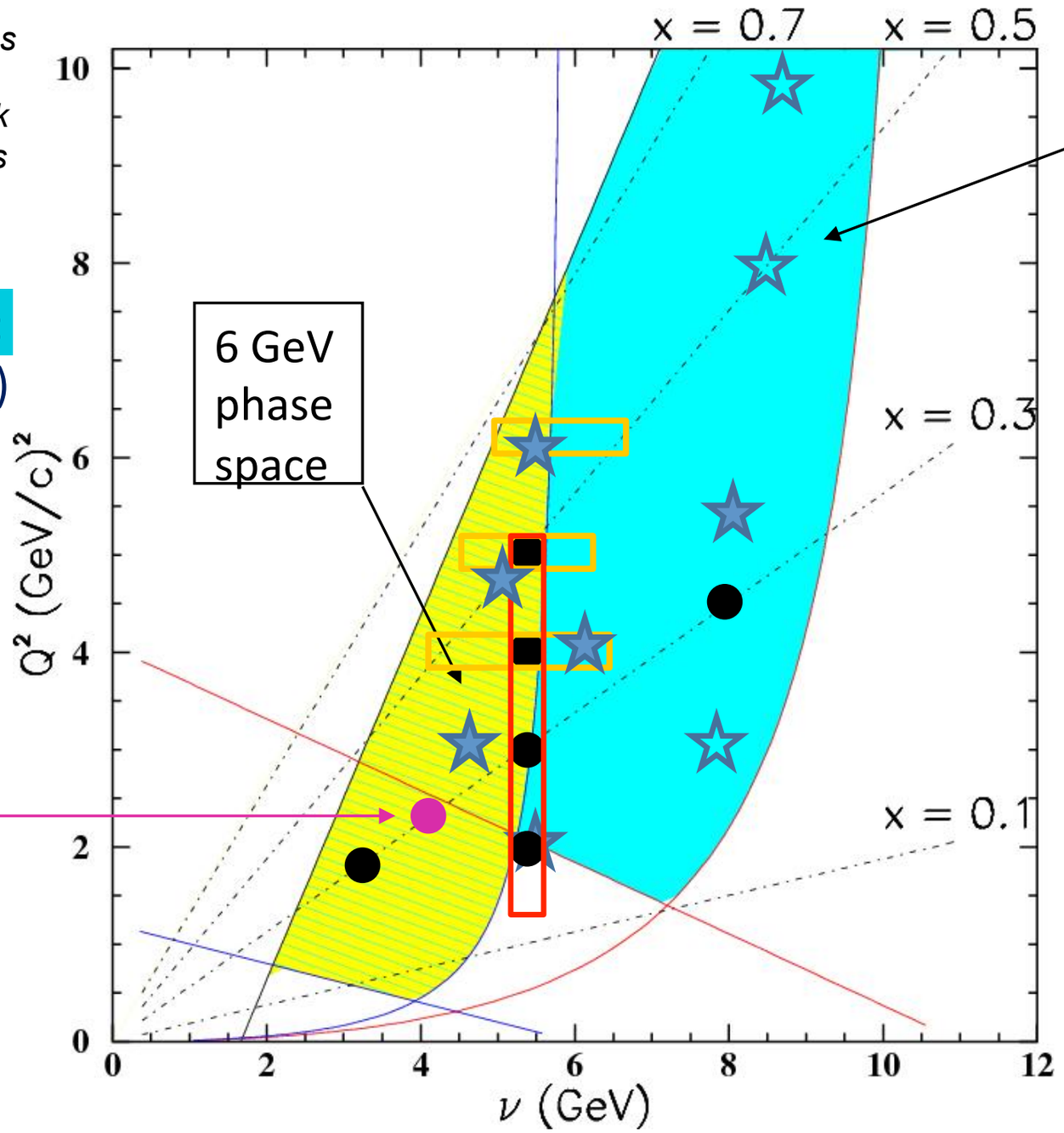
HMS + SHMS (or NPS) Accessible Phase Space for SIDIS

Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

★ E12-13-007
Neutral pions:
Scan in (x,z,P_T)
Overlap with
E12-09-017 &
E12-09-002

☆ Parasitic with
E12-13-010

E00-108
(6 GeV)



Charged pions:

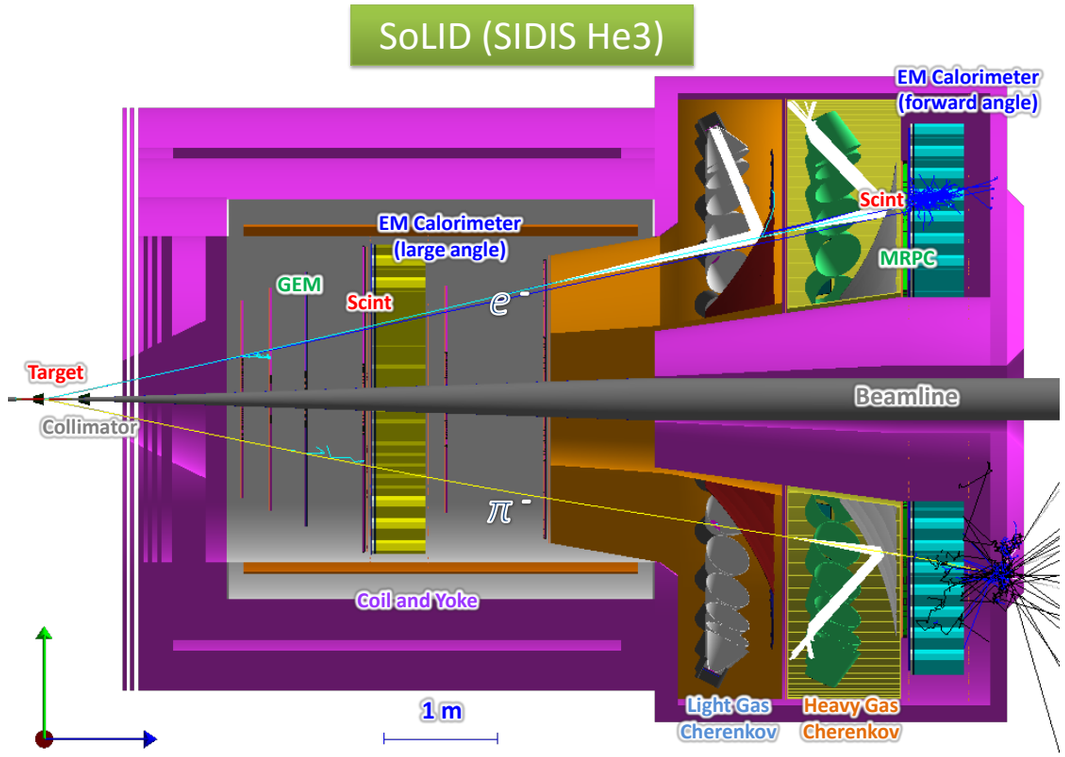
E12-06-104
L/T scan in (z,P_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

E12-09-017
Scan in (x,z,P_T)
+ scan in Q^2 at fixed x

E12-09-002
+ scans in z

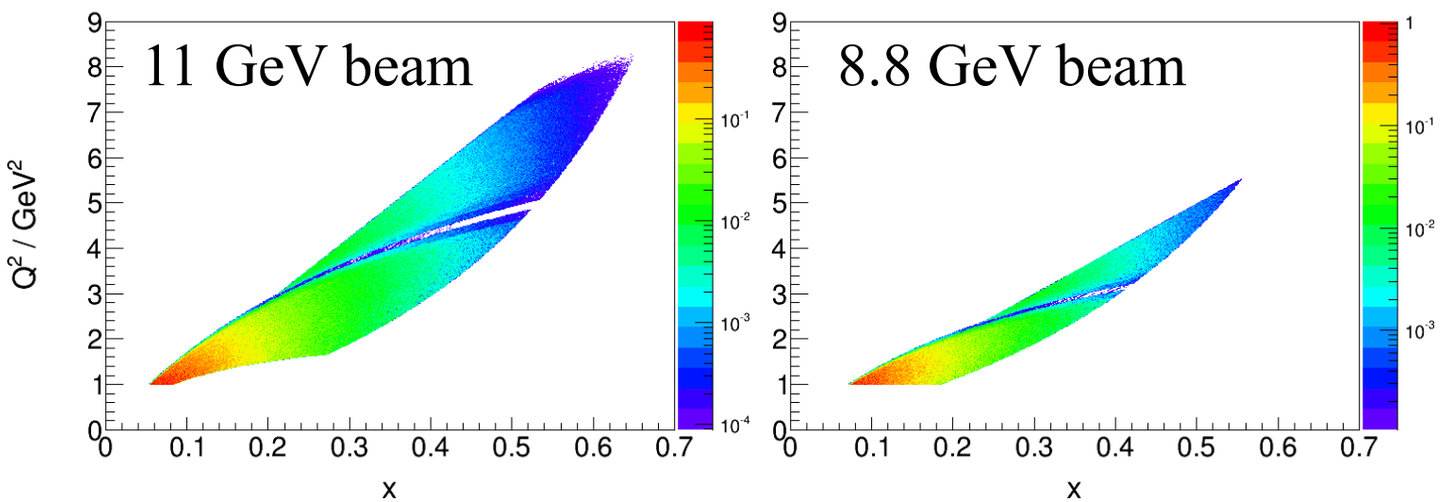
SoLID SIDIS Program

Solenoidal **L**arge **I**ntensity **D**evice

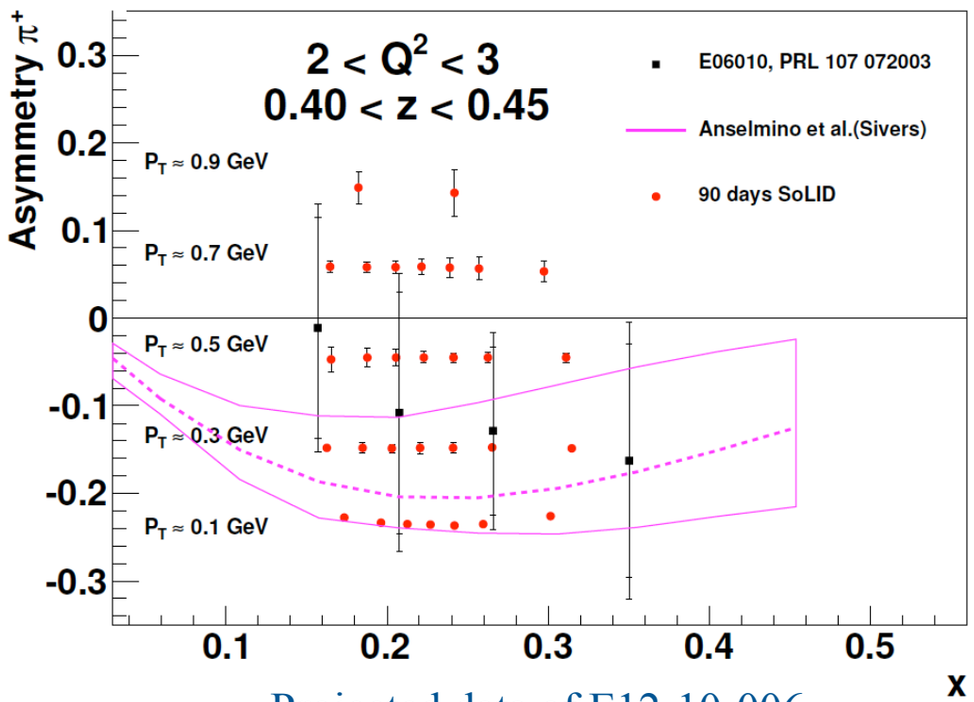


- High luminosity ~ 10^{37} cm^{-2} s^{-1}
- Large acceptance, full azimuthal coverage
- In beam polarization: ~60% (^{3}He), ~70% (NH_3)
- 4D bins with high precision

E12-10-006: Transversely polarized ^{3}He, 90 days.
E12-11-007: Longitudinally polarized ^{3}He, 35 days.
E12-10-008: Transversely polarized NH_3, 120 days.



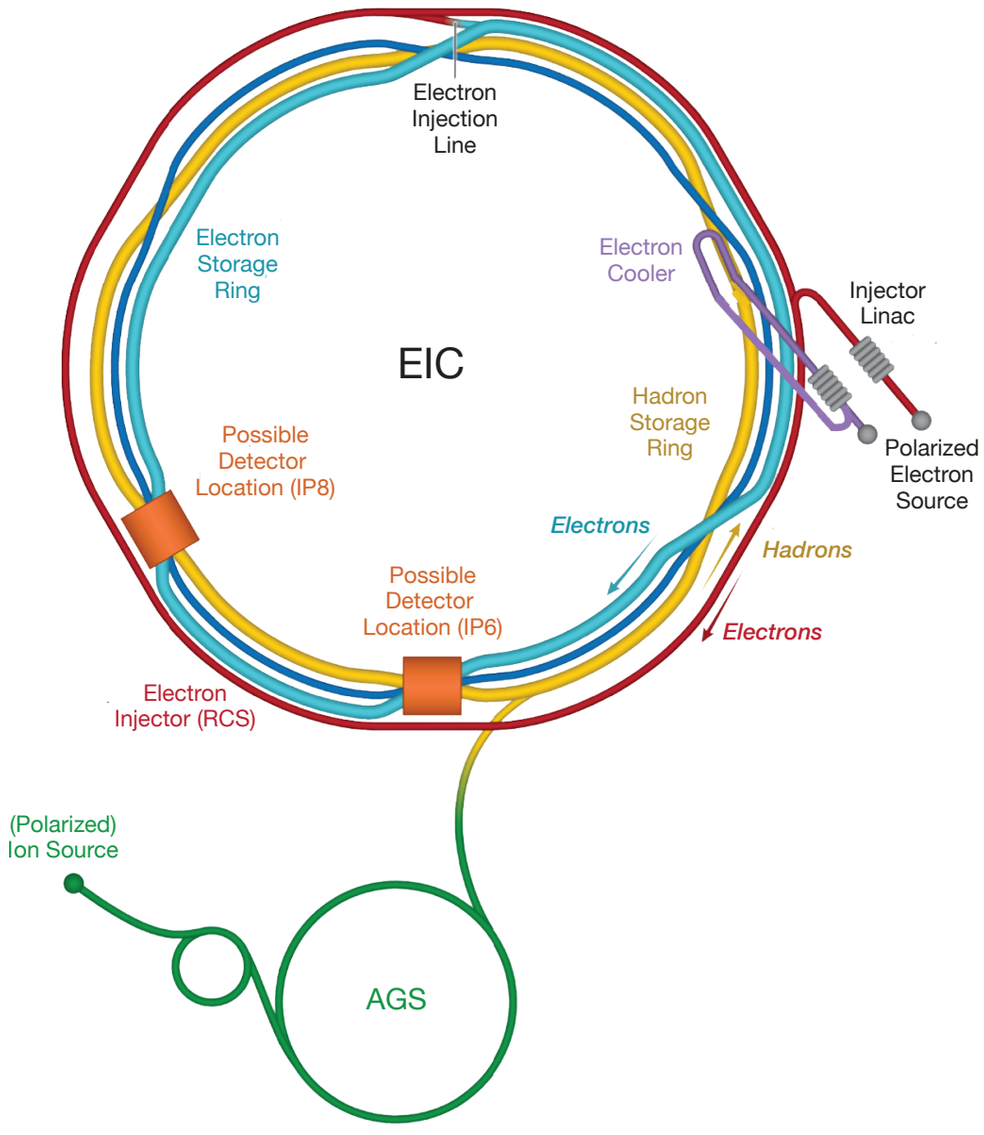
High statistics (example)



Projected data of E12-10-006

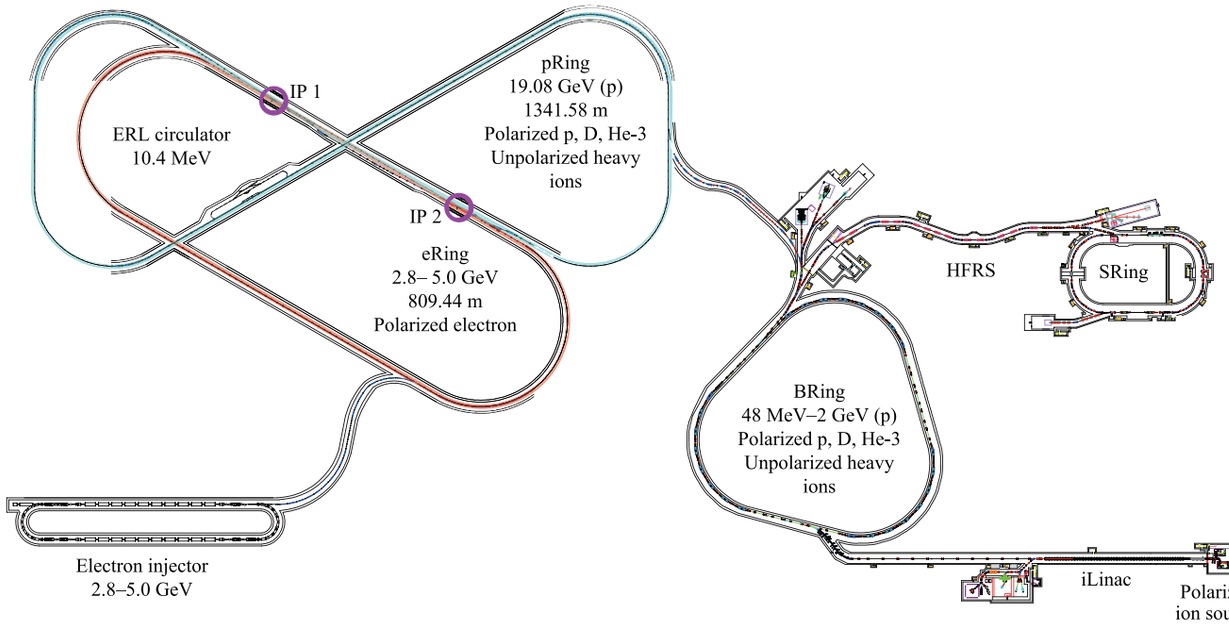
Electron-Ion Colliders

EIC



[Figure from EIC Yellow Report]

EicC



[Figure from EicC Whitepaper]

Summary

- Lepton-hadron semi-inclusive deep inelastic scattering is a powerful process to extract TMDs.
- Many SIDIS measurements were presented in recent years
  - double spin asymmetries: LL, LT
  - beam spin asymmetry
  - target single spin asymmetry for ρ^0 production
  - multiplicity ratio of antiparticle and particle
  - …
- Complimentary processes, *pp* and e^+e^-, are also important for TMD studies
  - *e.g.*, Λ polarization, …
- Theoretical framework
  - power correction, radiative correction, …
- Future experiments for precise measurement of TMDs
  - JLab12, EIC, EicC

Thank you!