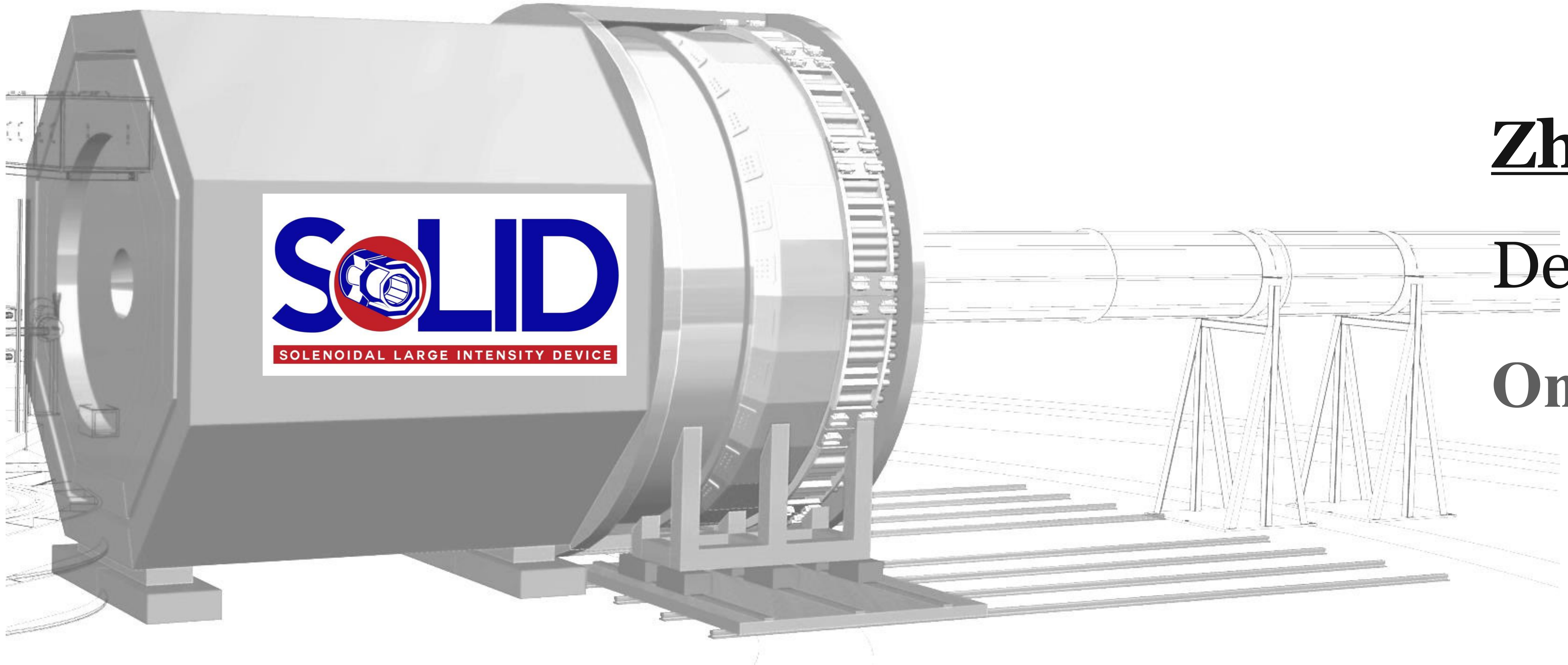
SoLID Spin, TMD & GPD Programs



Zhihong Ye,

Department of Physics, Tsinghua University

On behalf of the SoLID Collaboration

SPIN2025, Qingdao, 09/23/2025

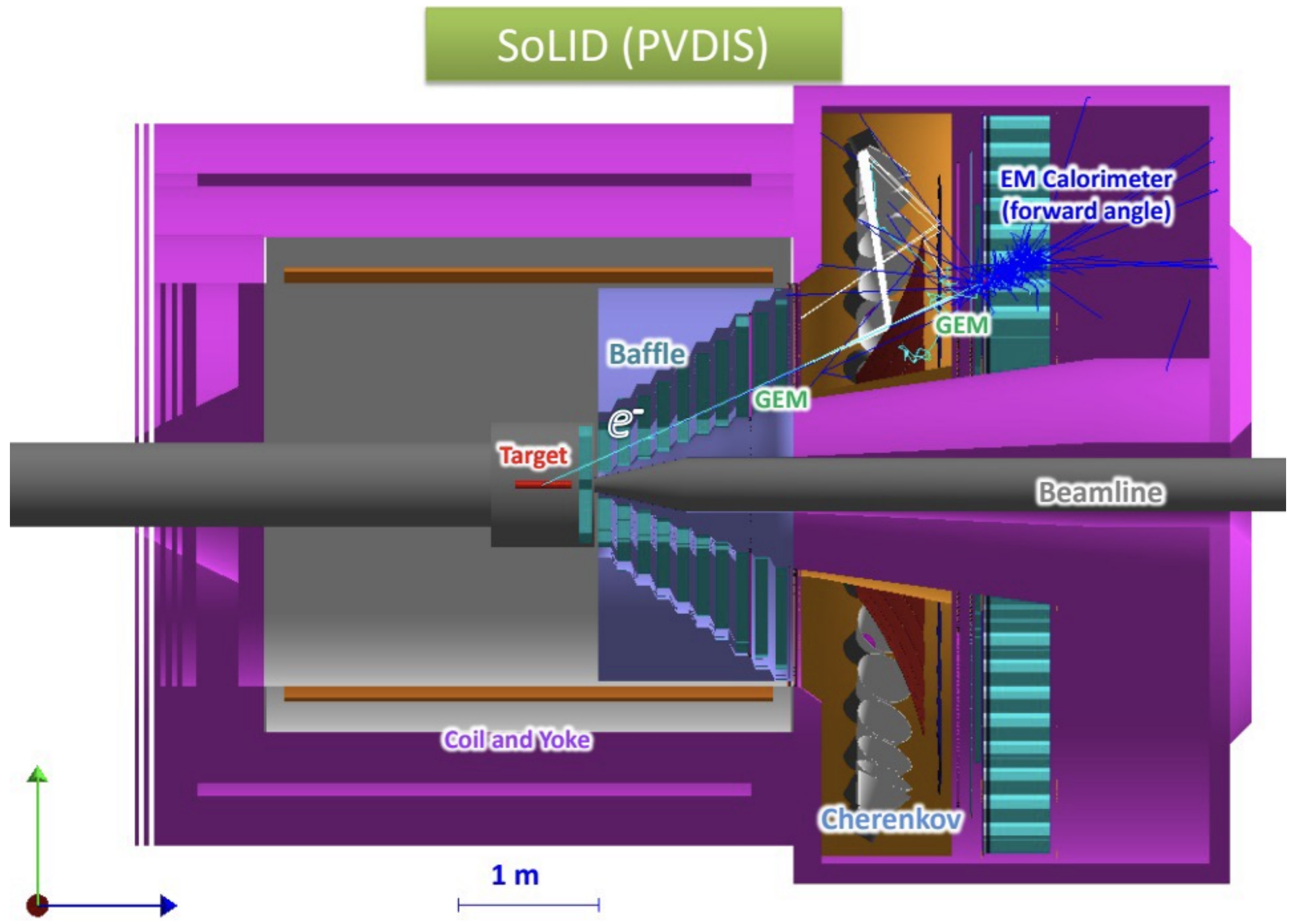
SoLID@12-GeV JLab: QCD at the intensity frontier

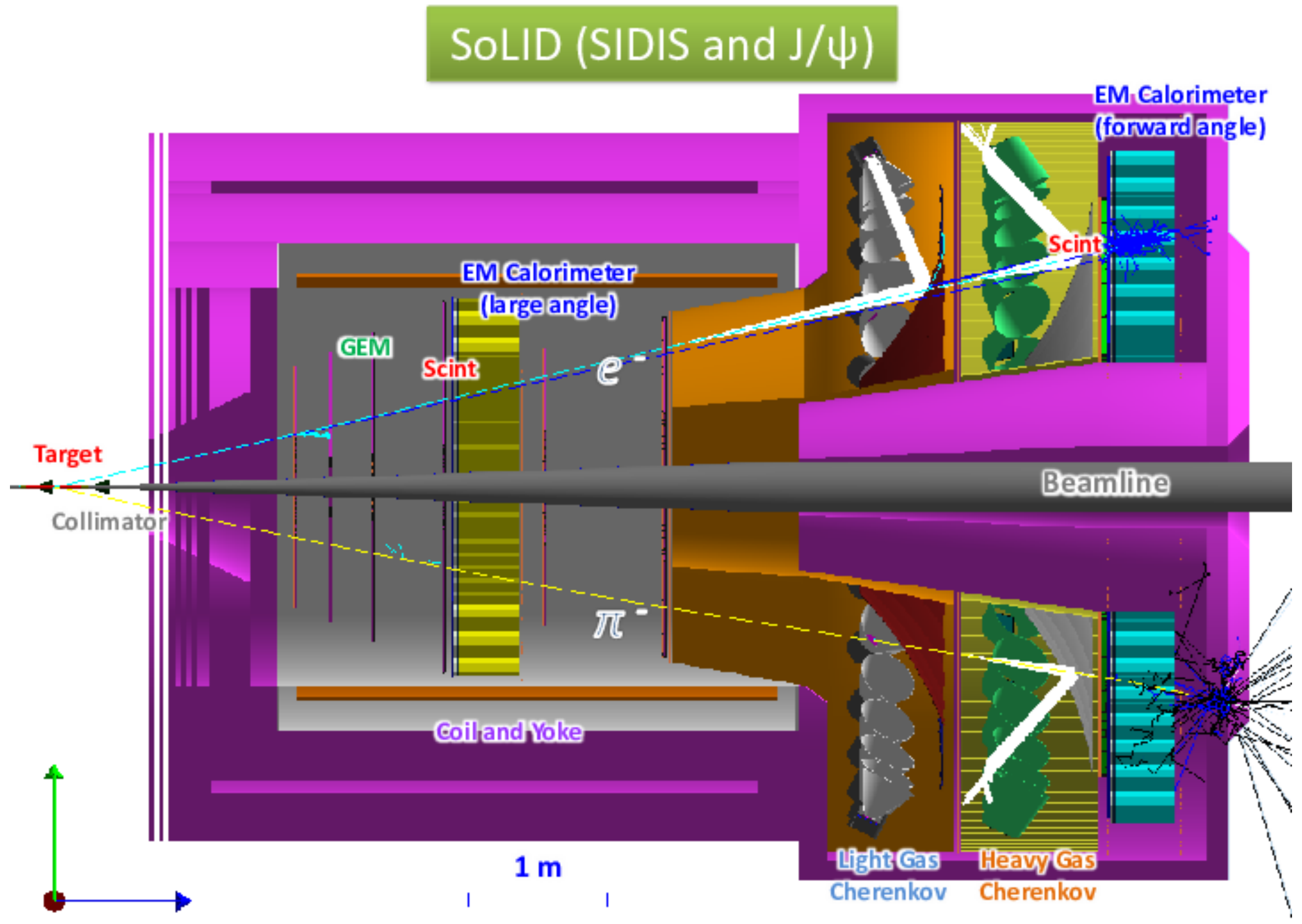
- **SoLID** will ***maximize*** the science return of the 12-GeV CEBAF upgrade by **combining...**

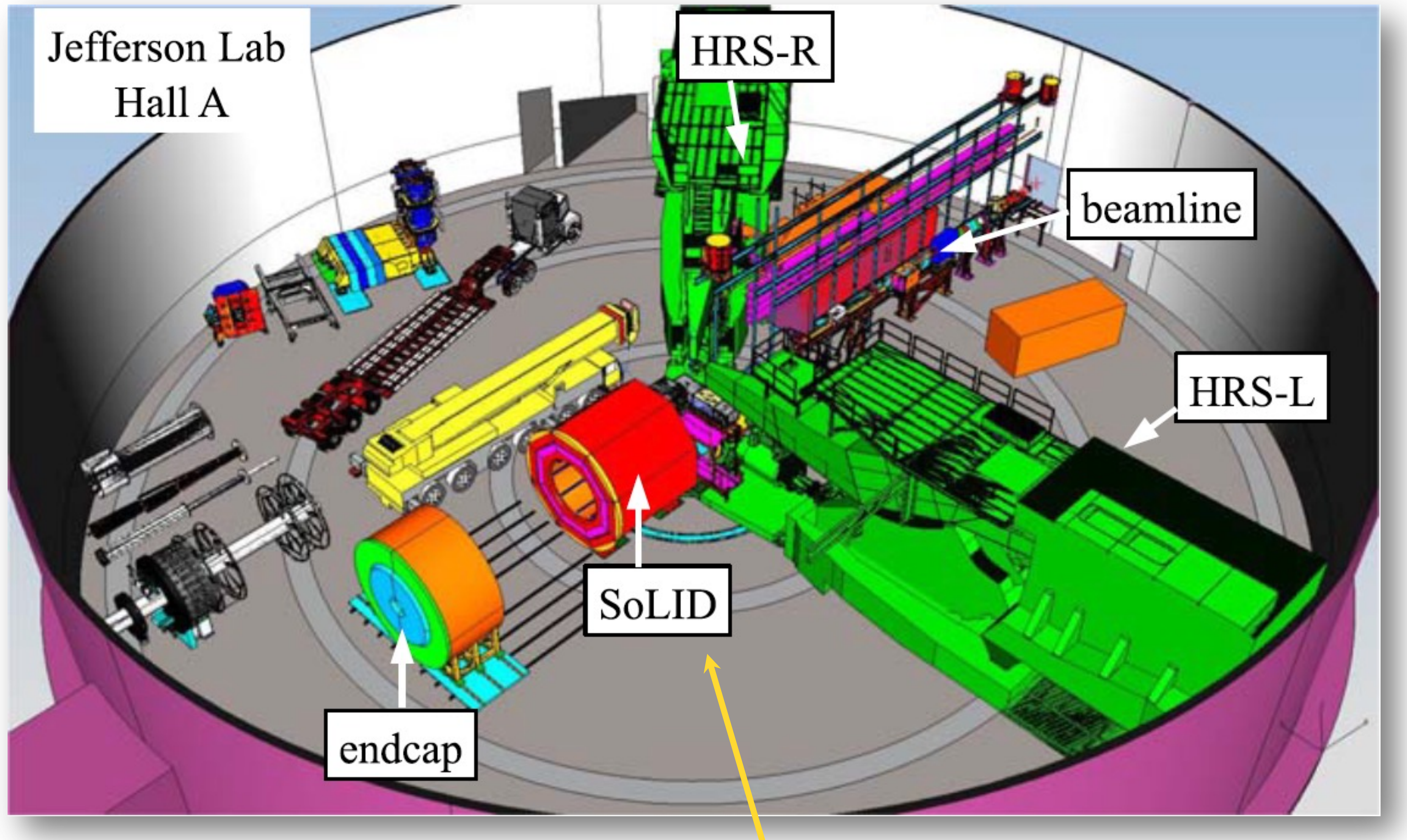
High Luminosity
$10^{37\text{-}39}$ /cm²/s
[>100x CLAS12][>1000x EIC]

+

Large Acceptance
Full azimuthal ϕ coverage

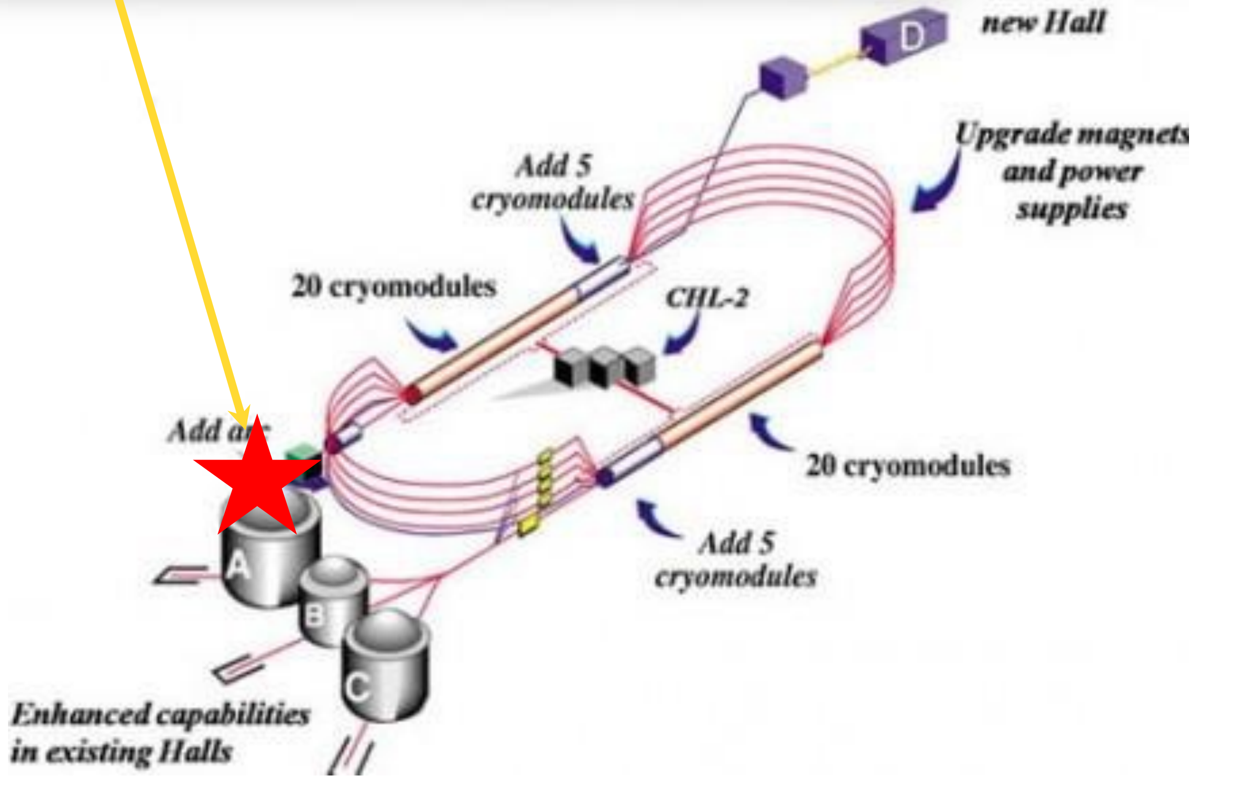






- Perform high-luminosity valence quark tomography， Search new physics w/ parity-violation deep inelastic scattering (PVDIS), and measure precise J/ψ production near threshold
- Synergizing with the pillars of EIC science (**<u>proton spin</u>** and **<u>mass</u>**)

*SoLID whitepaper: J. Phys. G: Nuclear and Particle Physics **50,** 110501 (2023)*
*12GeV physics: Progress in Particle and Nuclear Physics **127**, 103985 (2022)*




SoLID and Future Programs at JLab
Haiyan Gao
08:30 - 09:10

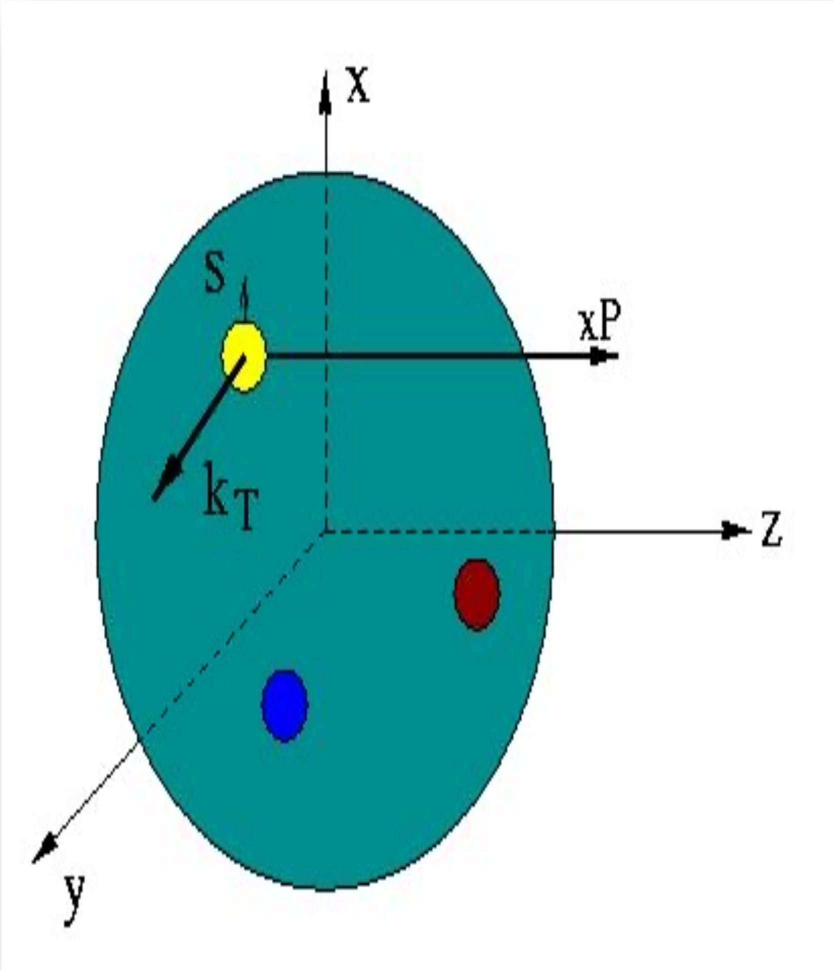
Plenary talk on this Friday

Nucleon's 3D Structure

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

5D

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

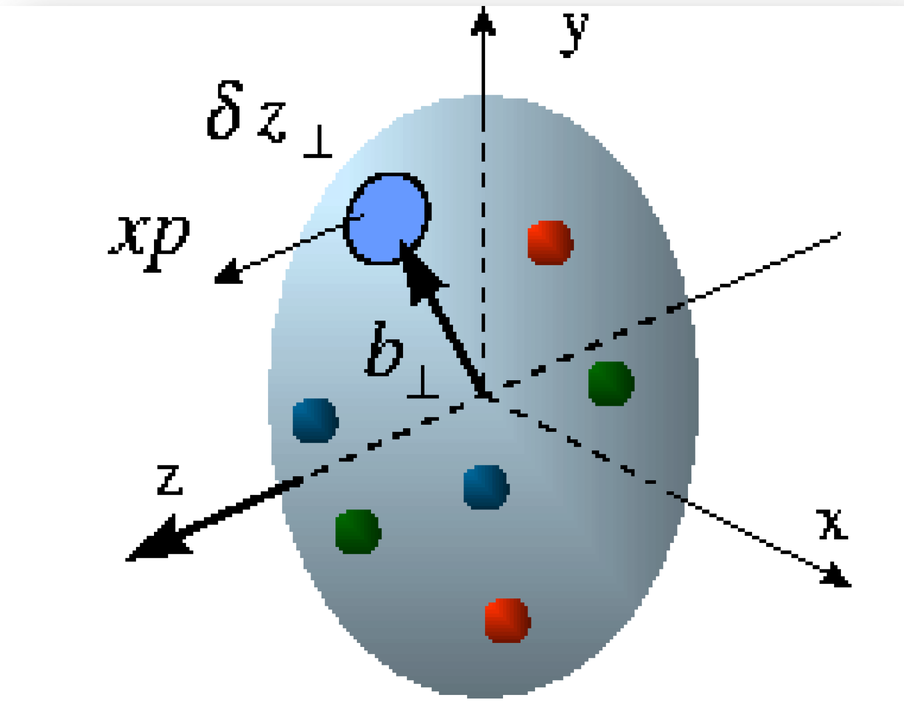


$d^2\boldsymbol{r_T}$

d^2k_T

TMD
$f_1^u(x,k_T)$, $h_1^u(x,k_T)$,…

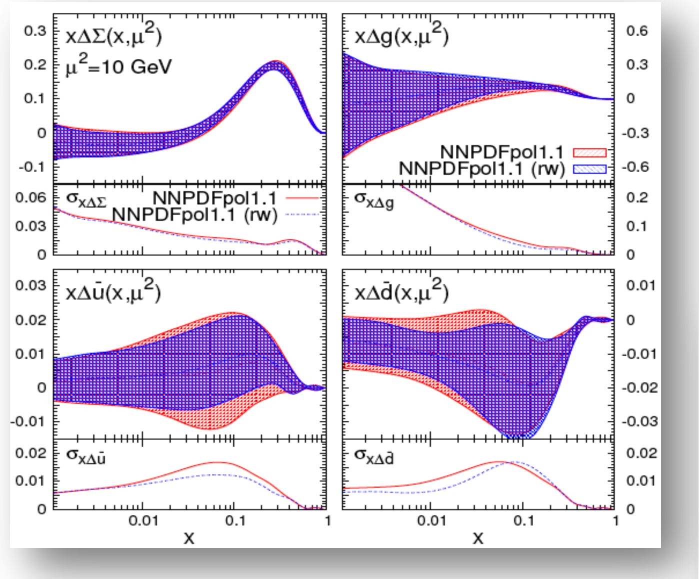
GPDs/IPDs
$H^u, E^u, \widetilde{H}^u, \widetilde{E}^u$



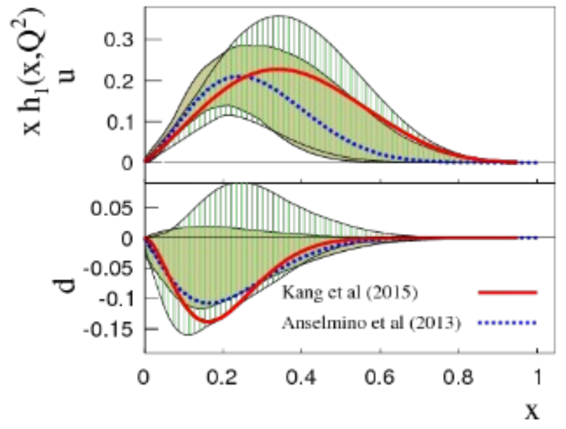
d^2k_T

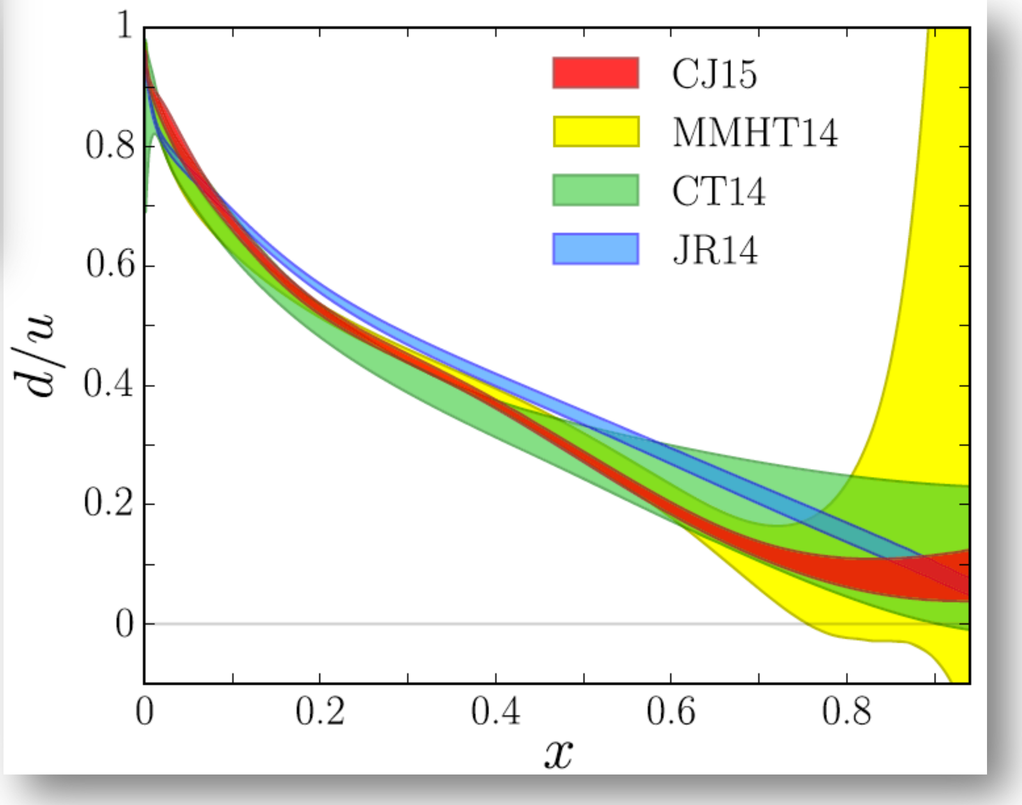
d^2r_T

dx & Fourier Transformation



A. Accardi et. al.
B. Phys. Rev. D 93, 114017 (2016)



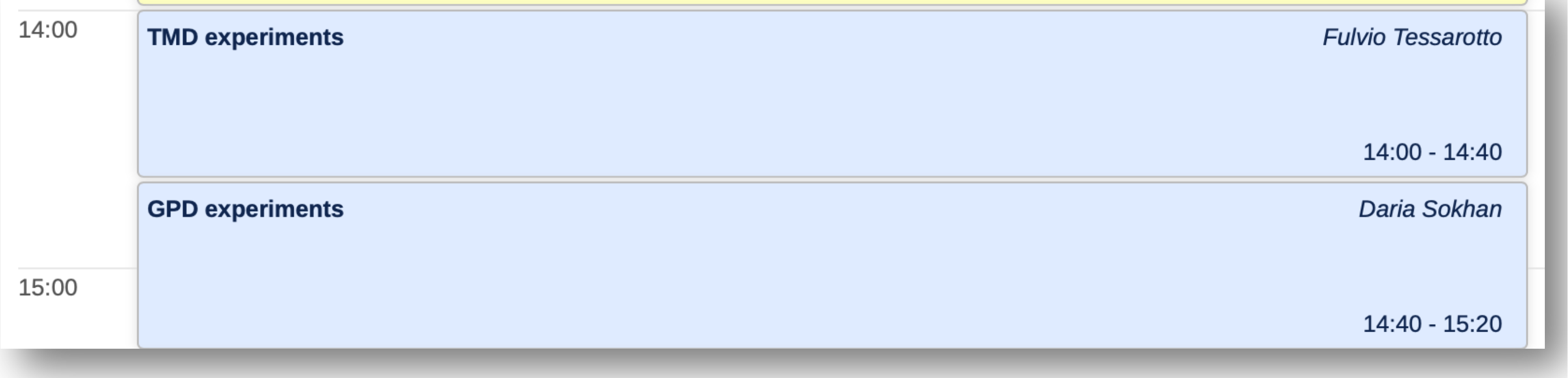


PDFs
$f_1^u(x)$, $g_1^u(x)$,
$h_1^u(x)$,…

1D

Form
Factors
$G_E(Q^2)$,
$G_M(Q^2)$

TMD & GPD Plenary Talks on Monday



14:00
TMD experiments *Fulvio Tessarotto*
14:00 - 14:40

15:00
GPD experiments *Daria Sokhan*
14:40 - 15:20

SoLID-SIDIS Programs

- Approved SIDIS & J/Psi 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 Spin Asymmetries on Transversely Polarized Proton @ 120 days, **Rating A**
  - ☐ **E12-12-006:** Near Threshold Electroproduction of J/ψ at 11 GeV (60 days), **Rating A**

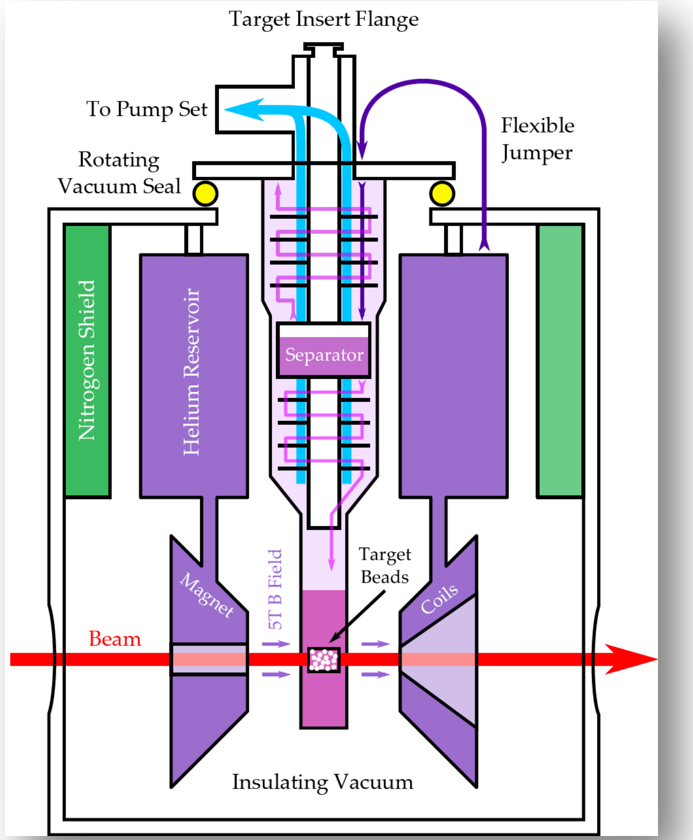
Prof. Haiyan Gao's plenary talk on Friday

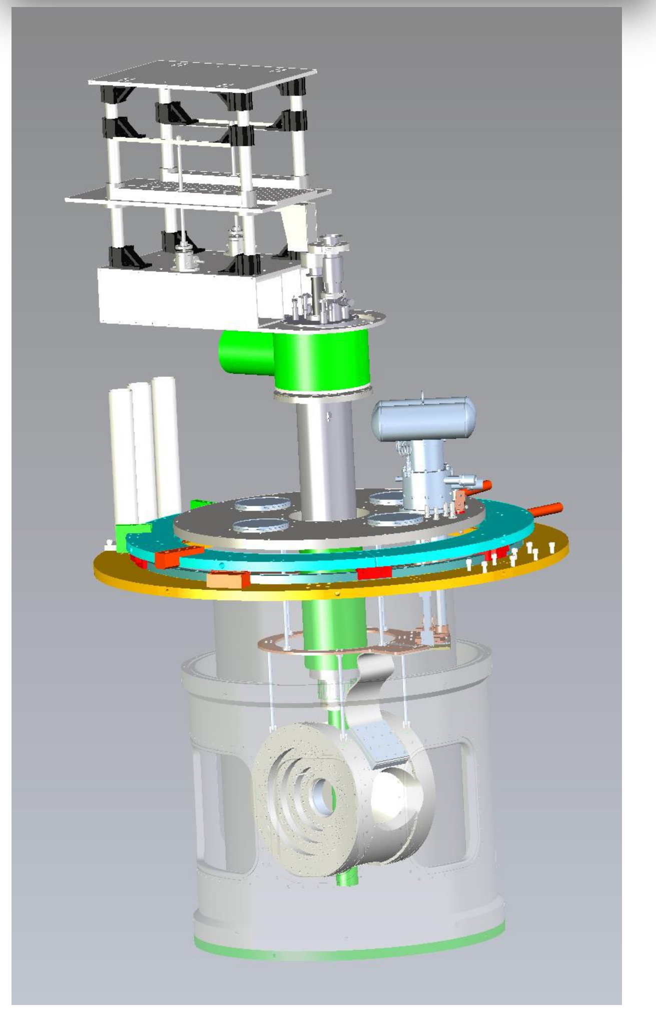
- Approved Run-Group:
  - ✓ (TMD) SIDIS Dihadron with Transversely Polarized 3He (E12-10-006A)
  - ✓ (TMD) SIDIS in Kaon Production with Polarized 3He & Proton (E12-11-108B/E12-10-006D)
  - ✓ (Spin) Ay with Transversely Polarized 3He (E12-11-108A/E12-10-006A)
  - ✓ (Spin) g2 n and d2 n with Transversely and Longitudinally Polarized 3He (E12-11-007A/E12-10-006E)
  - ✓ (GPD) Deep exclusive $\pi-$ Production with Transversely Polarized 3He (E12-10-006B)
  - ✓ (GPD) Time-Like Compton Scattering (E12-12-006A)
- Run-Group under development (with upgrades):
  - ✓ (GPD) DVCS with polarized targets
  - ✓ (GPD) Doubly DVCS

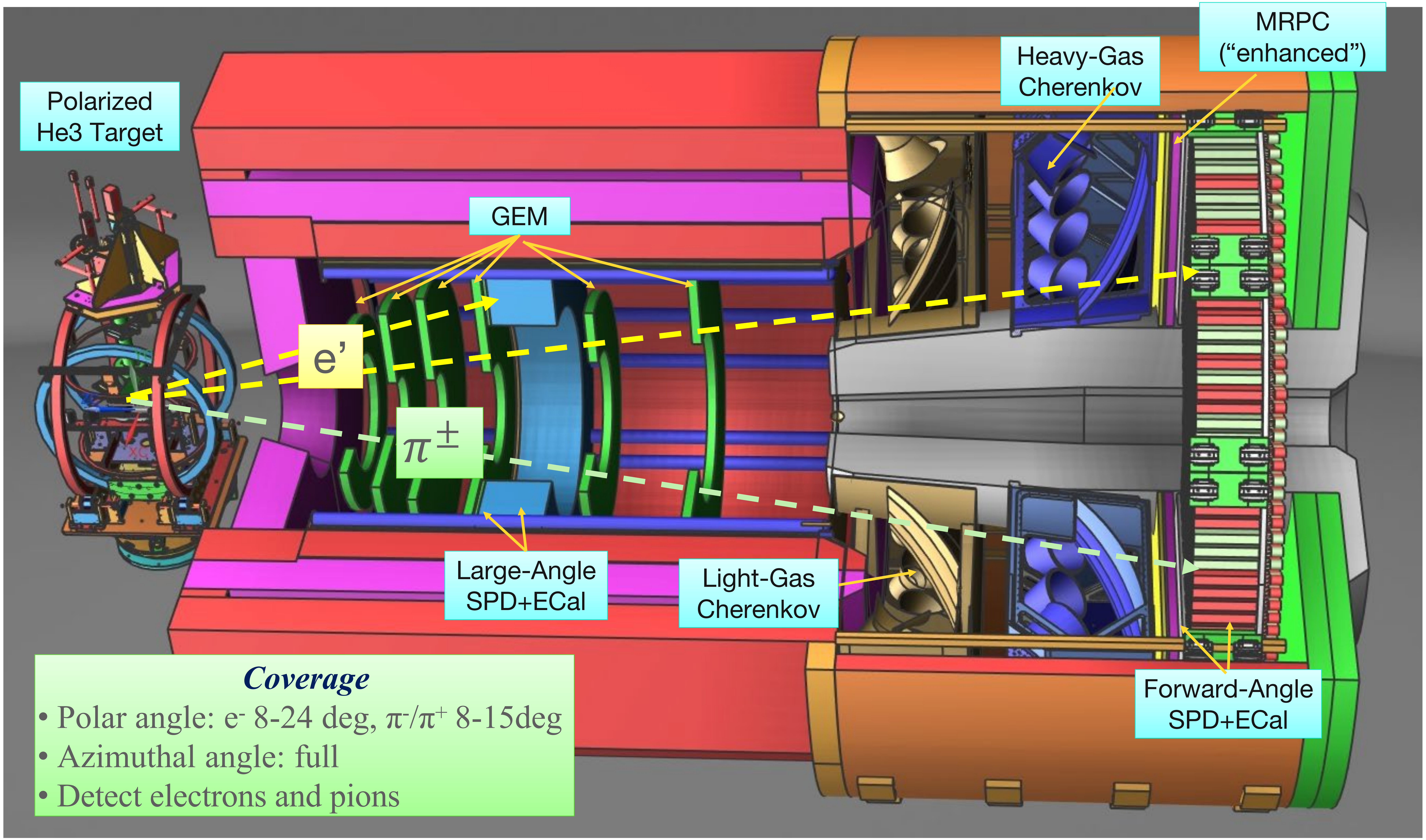
This talk

SoLID-SIDIS(&J/Psi) Configuration

Polarized NH3
(DNP) Target







Polarized
He3 Target

GEM

Heavy-Gas
Cherenkov

MRPC
(“enhanced”)

Large-Angle
SPD+ECal

Light-Gas
Cherenkov

Forward-Angle
SPD+ECal

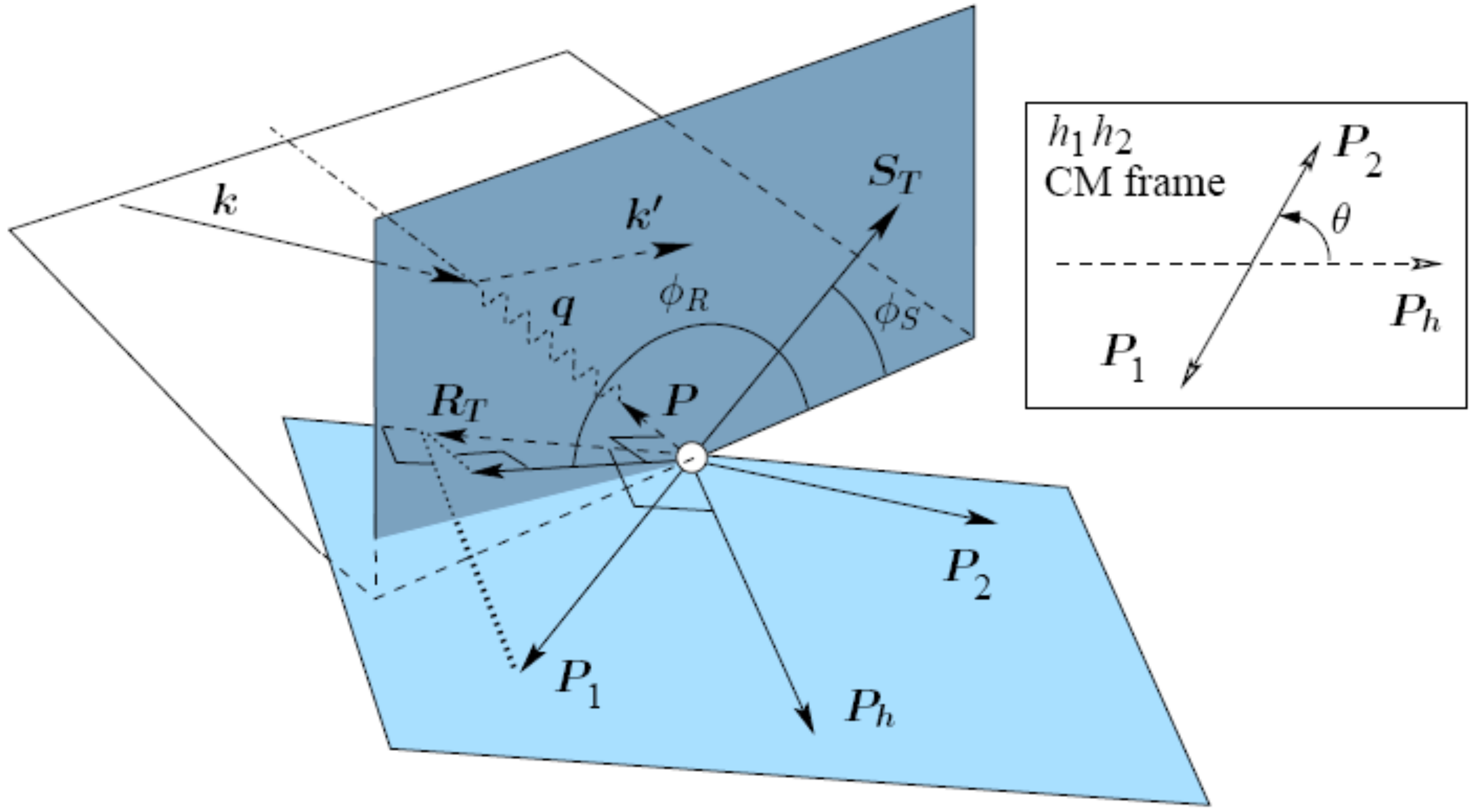
Coverage

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

SoLID-SIDIS Study

➢ Di-Hadron Productions $e + N \rightarrow e' + \pi^+ + \pi^- + X$

See Anselm Vossem's Plenary talk on Monday



- ❑ From SoLID-SIDIS data, look for additional pion, obtain asymmetries

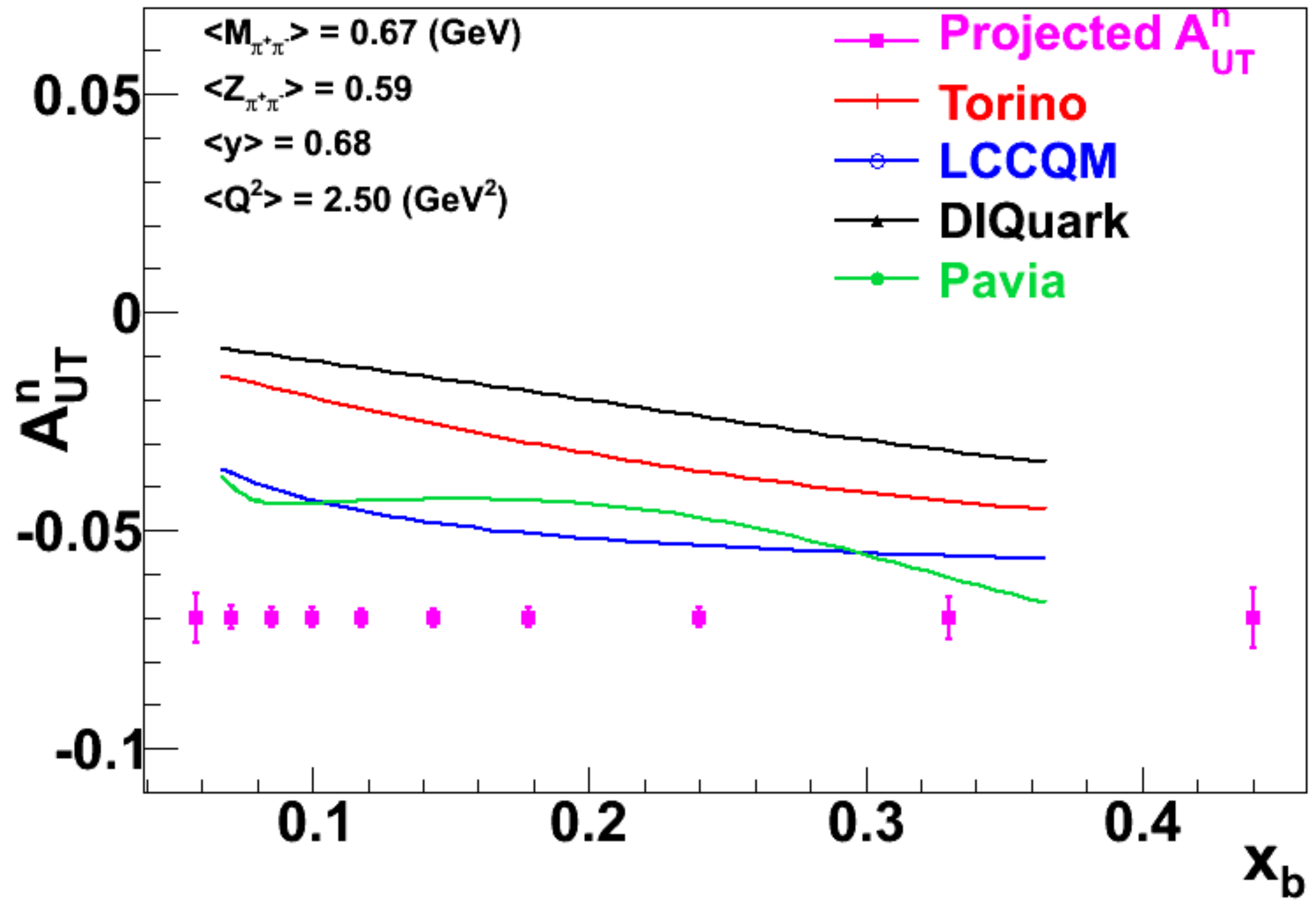
$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}(x,y,z,M_h,Q) = \frac{1}{|S_T|}\,\frac{\frac{8}{\pi}\int d\phi_R\, d\cos\theta\, \sin(\phi_R+\phi_S)\,(d\sigma^{\uparrow}-d\sigma^{\downarrow})}{\int d\phi_R\, d\cos\theta\,(d\sigma^{\uparrow}+d\sigma^{\downarrow})} = \frac{\frac{4}{\pi}\,\varepsilon\int d\cos\theta\, F_{UT}^{\sin(\phi_R+\phi_S)}}{\int d\cos\theta\,(F_{UU,T}+\varepsilon\, F_{UU,L})} \; .$$

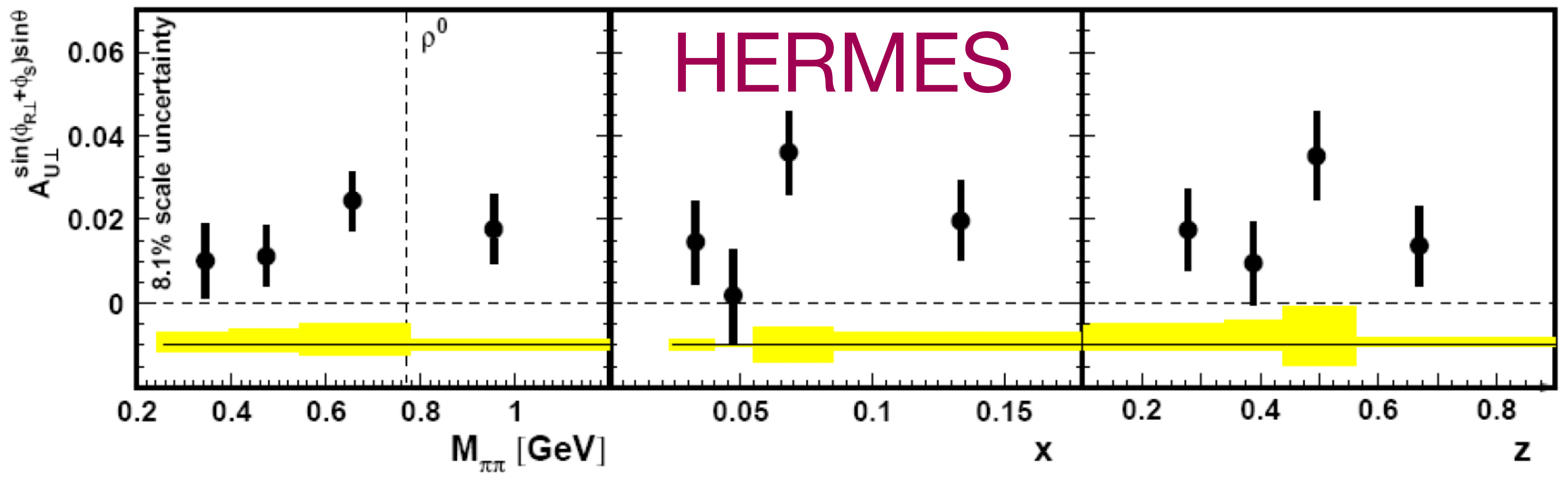
- ❑ From SoLID-SIDIS data, look for additional pion, obtain asymmetries

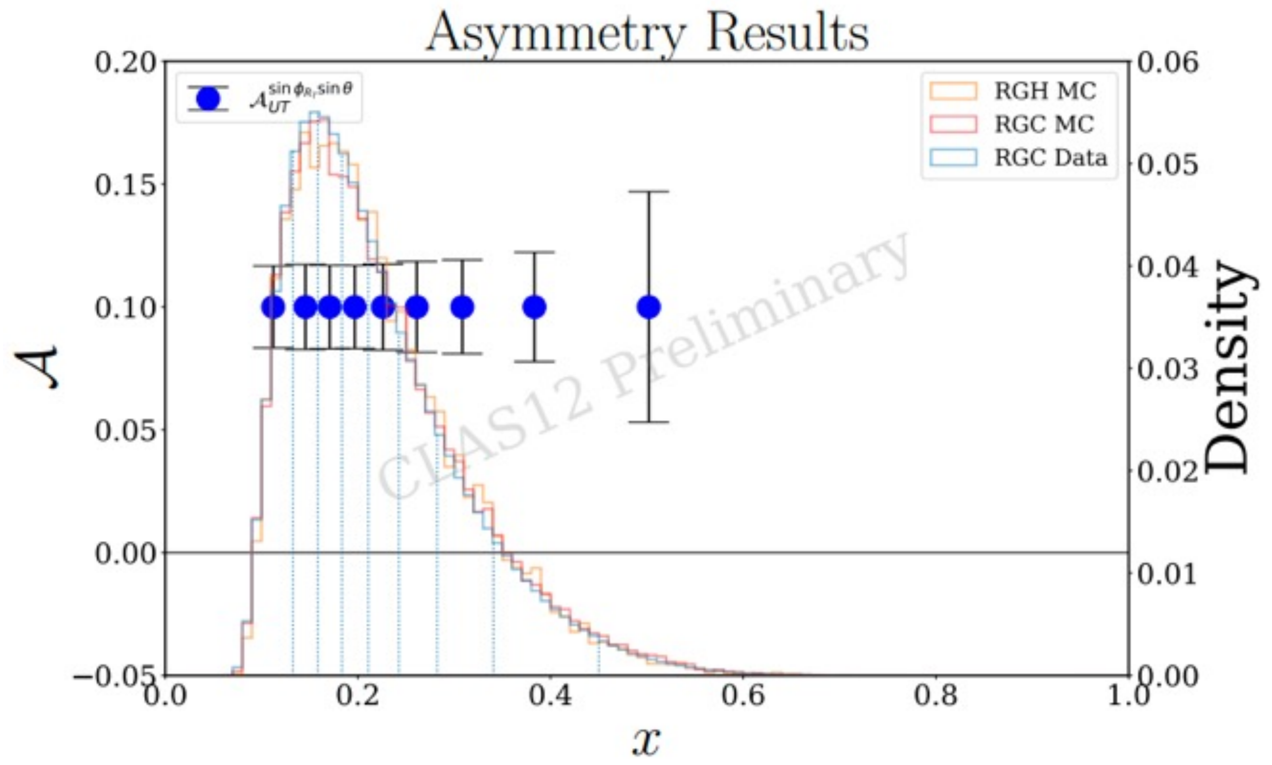
$$F_{UT}^{\sin(\phi_R+\phi_S)} = x\,\frac{|\boldsymbol{R}|\sin\theta}{M_h}\,h_1(x)\,H_1^{\sphericalangle}(z,\cos\theta,M_h^2) \quad ,$$

- ❑$\sin(\phi_R + \phi_s)$ link to Di-Hadron fragmentation function $H_1^{\sphericalangle}$

- ❑ Important input to existing limited world data







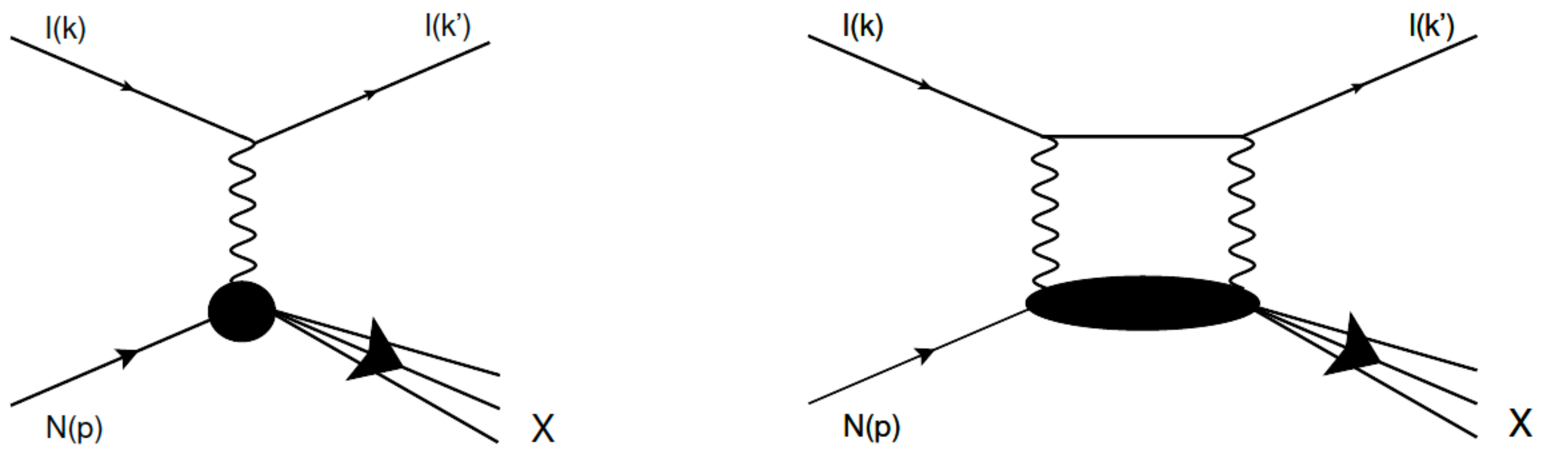
SoLID-Spin Study

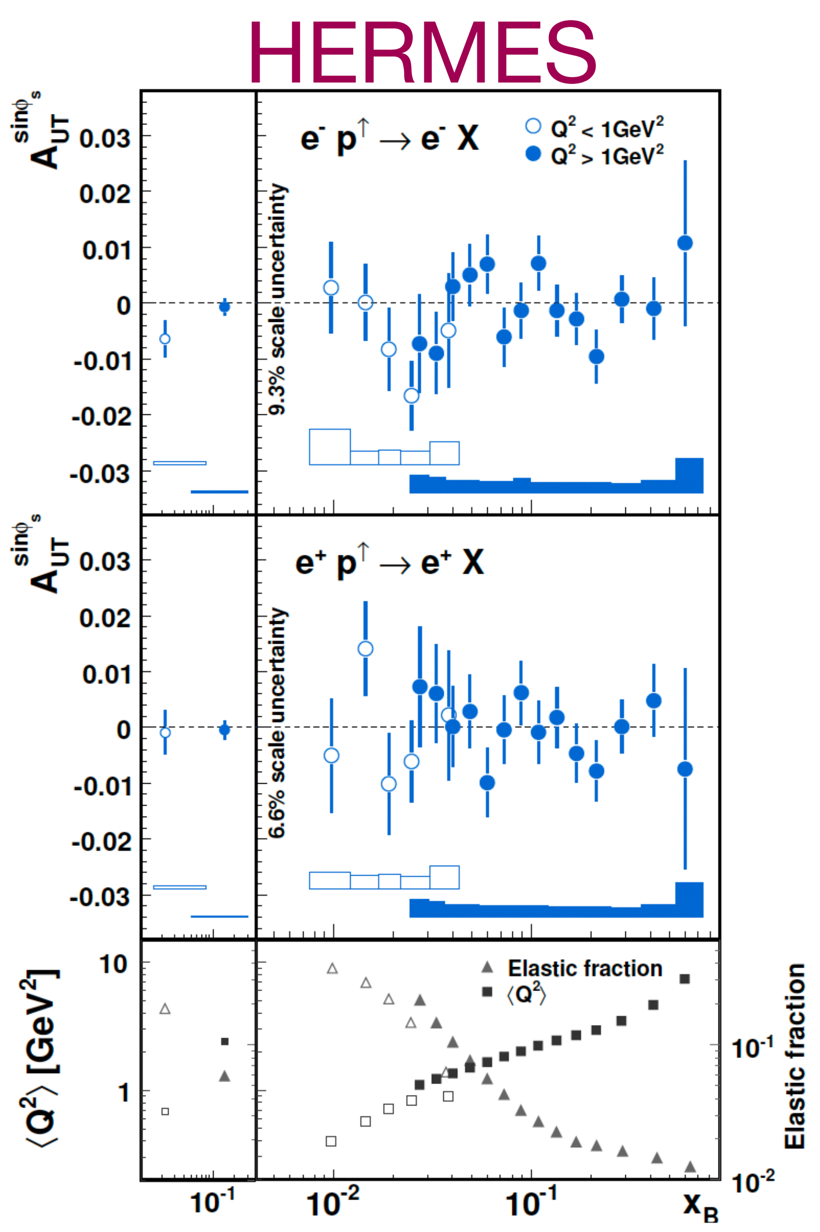
- Ay (E12-11-108A/E12-10-006A): $e + \vec{N}_{\Rightarrow} \rightarrow e' + X$

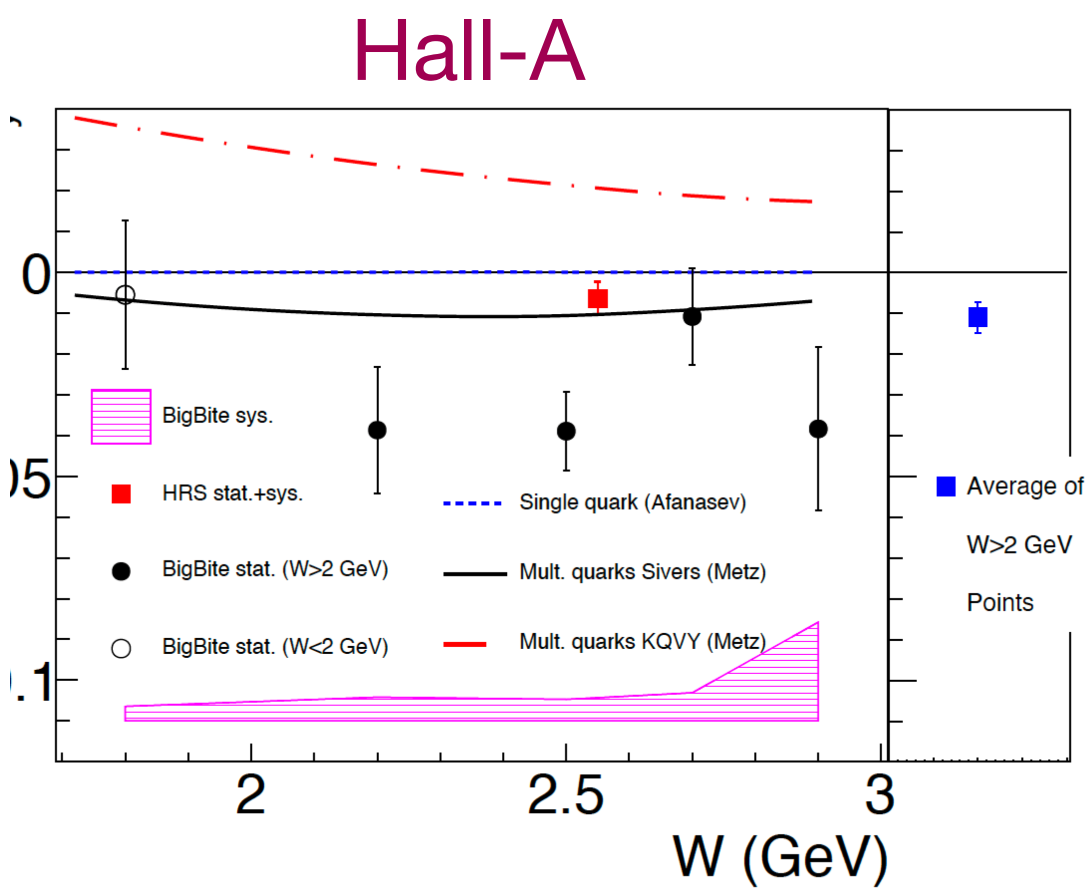
☐ Target-Spin Asymmetry of inclusive DIS with transversely polarized nucleons

$$A_{UT} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = A_y \sin\phi_S$$

☐ If no zero, link to interference of one-photon and two-photon exchanges



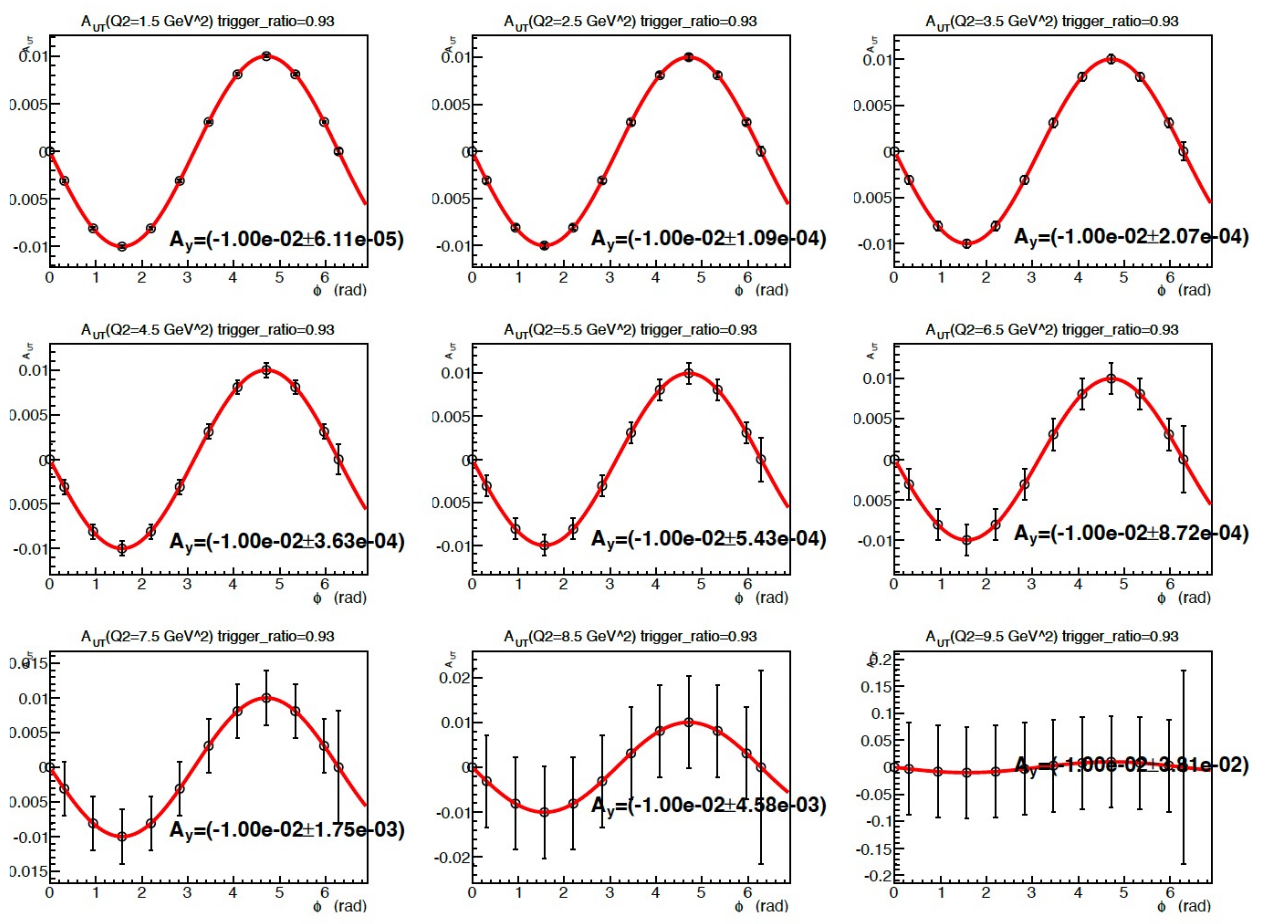


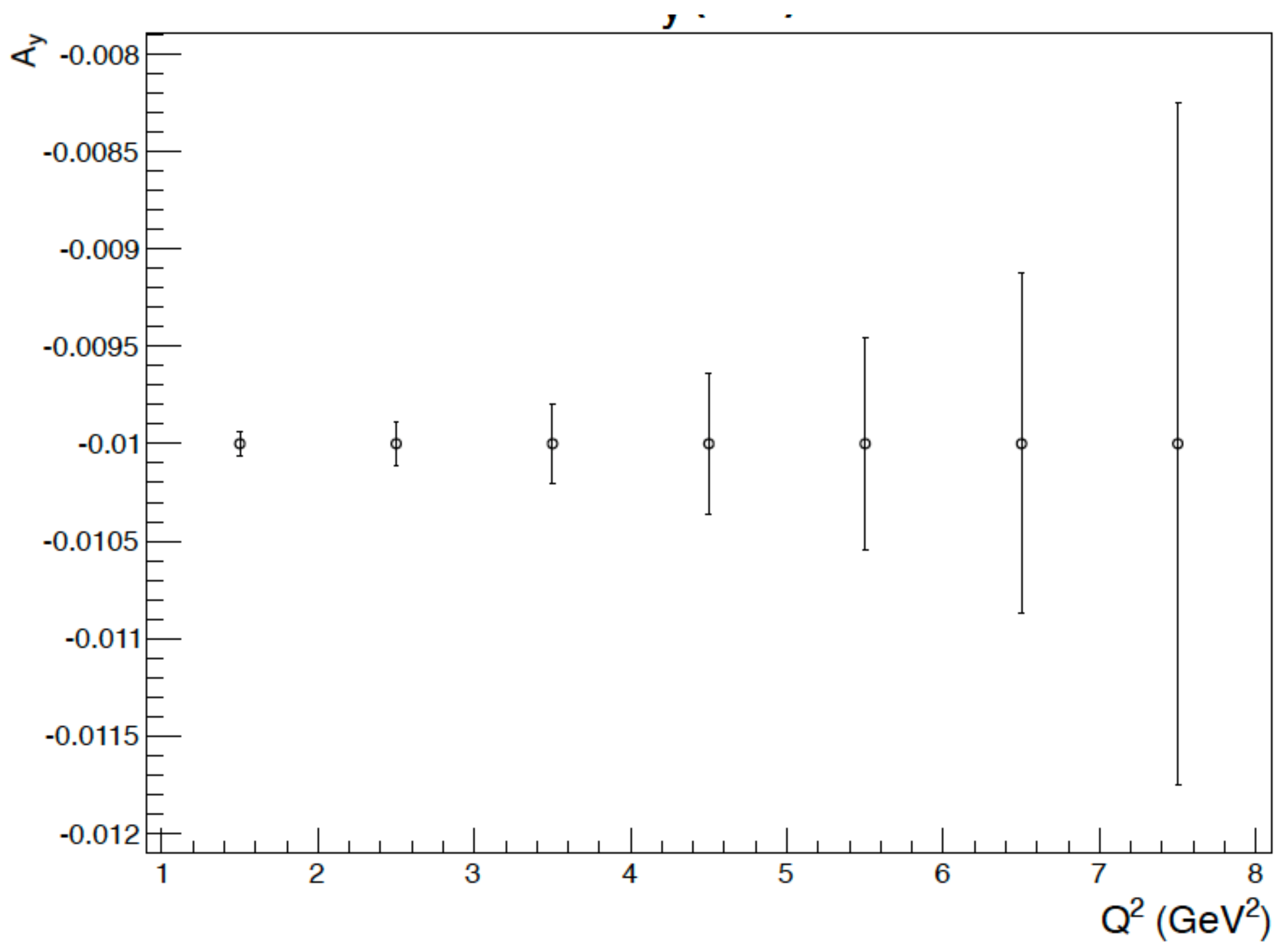


☐ Correlations of the transverse nucleon spin and the transverse partonic motion

☐ Extract asymmetries of inclusive XS w/ transversely polarized proton (NH3) and neutron (He3) from SoLID-SIDIS data

☐ Ay from $\sin(\phi_s)$ modules

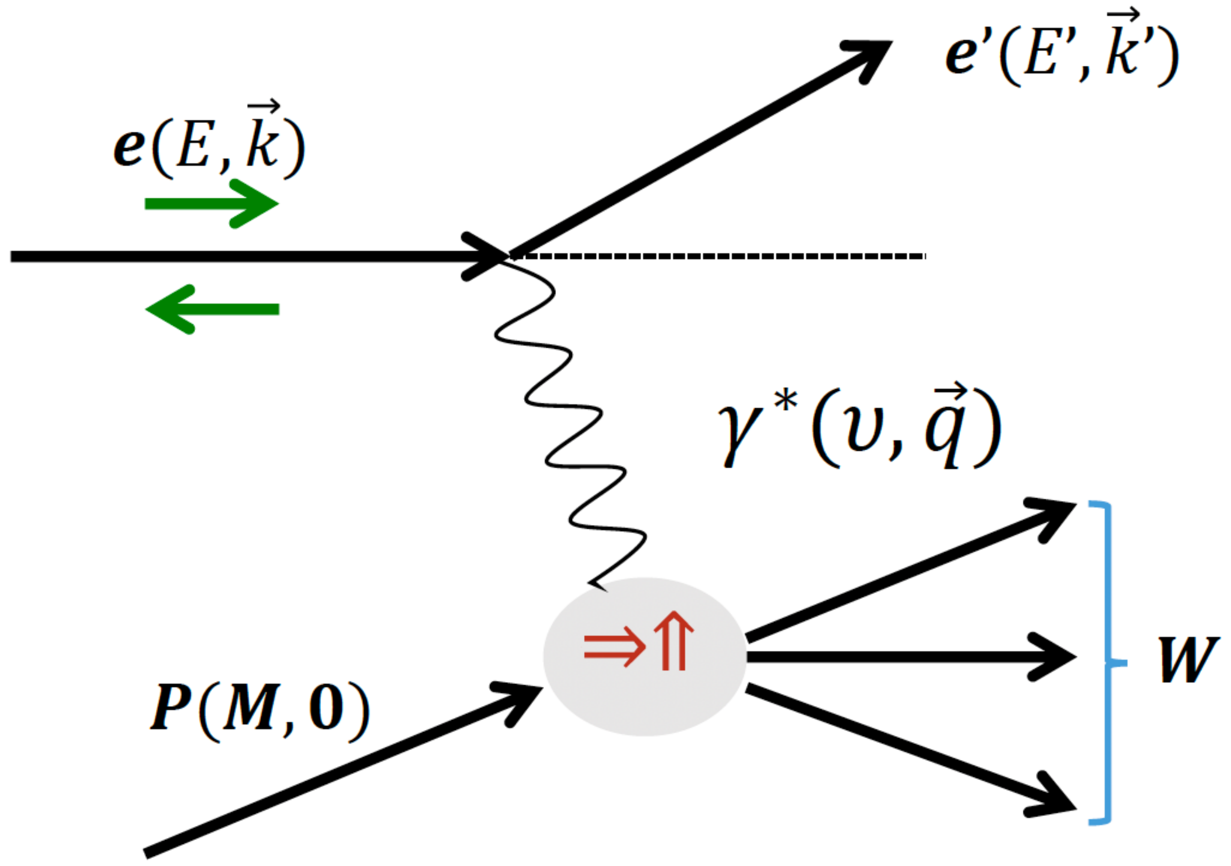




SoLID-Spin Study

➢ g2n & d2n (E12-11-007A/E12-10-006E) $e + \vec{N}_{\Uparrow,\Rightarrow} \rightarrow e' + X$

See Xiaochao Zheng'Plenary talk on Monday



- ❑ Beam-Spin Asymmetries of inclusive DIS measurements with polarized target:

$$A_{\parallel} = \frac{\sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\downarrow\Uparrow} + \sigma^{\uparrow\Uparrow}} \qquad A_{\perp} = \frac{\sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}}{\sigma^{\downarrow\Rightarrow} + \sigma^{\uparrow\Rightarrow}} \qquad \Delta\sigma_{\parallel,\perp} = 2\sigma_0 A_{\parallel,\perp}$$

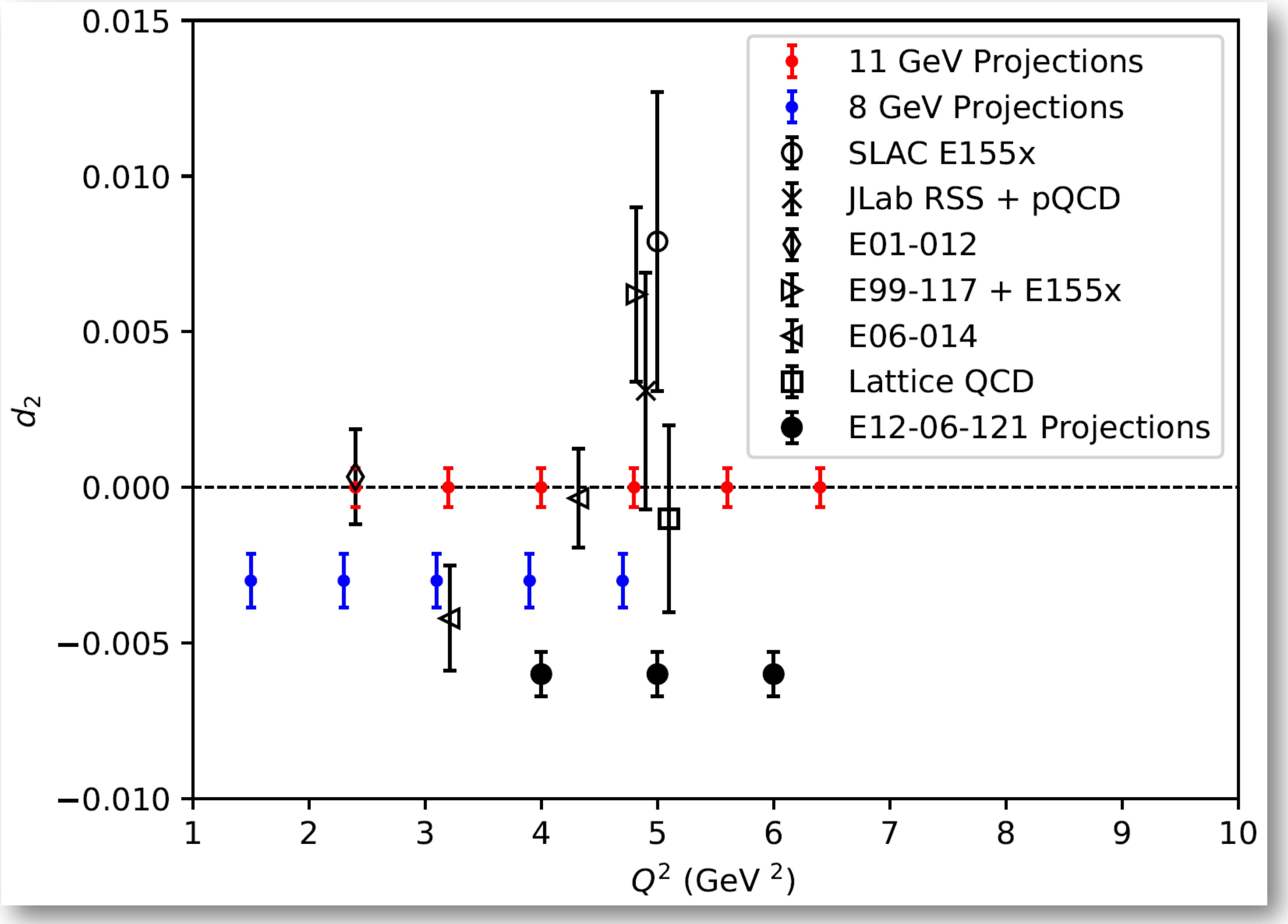
- ❑ Extract inclusive XS from E12-10-006 (Transversely) & E12-11-007 (Longitudinally) polarized 3He target

$$g_1 = \frac{MQ^2}{4\alpha^2}\frac{\nu E}{(E-\nu)(2E-\nu)}\left[\Delta\sigma_{\parallel} + \tan\frac{\theta}{2}\Delta\sigma_{\perp}\right],$$
$$g_2 = \frac{MQ^2}{4\alpha^2}\frac{\nu^2}{2(E-\nu)(2E-\nu)}\left[-\Delta\sigma_{\parallel} + \frac{E+(E-\nu)\cos\theta}{(E-\nu)\sin\theta}\Delta\sigma_{\perp}\right]$$

- ❑ g_1 related to the polarized PDF: $g_1 = \frac{1}{2}\sum_i e_i^2\,\Delta q_i(x)$

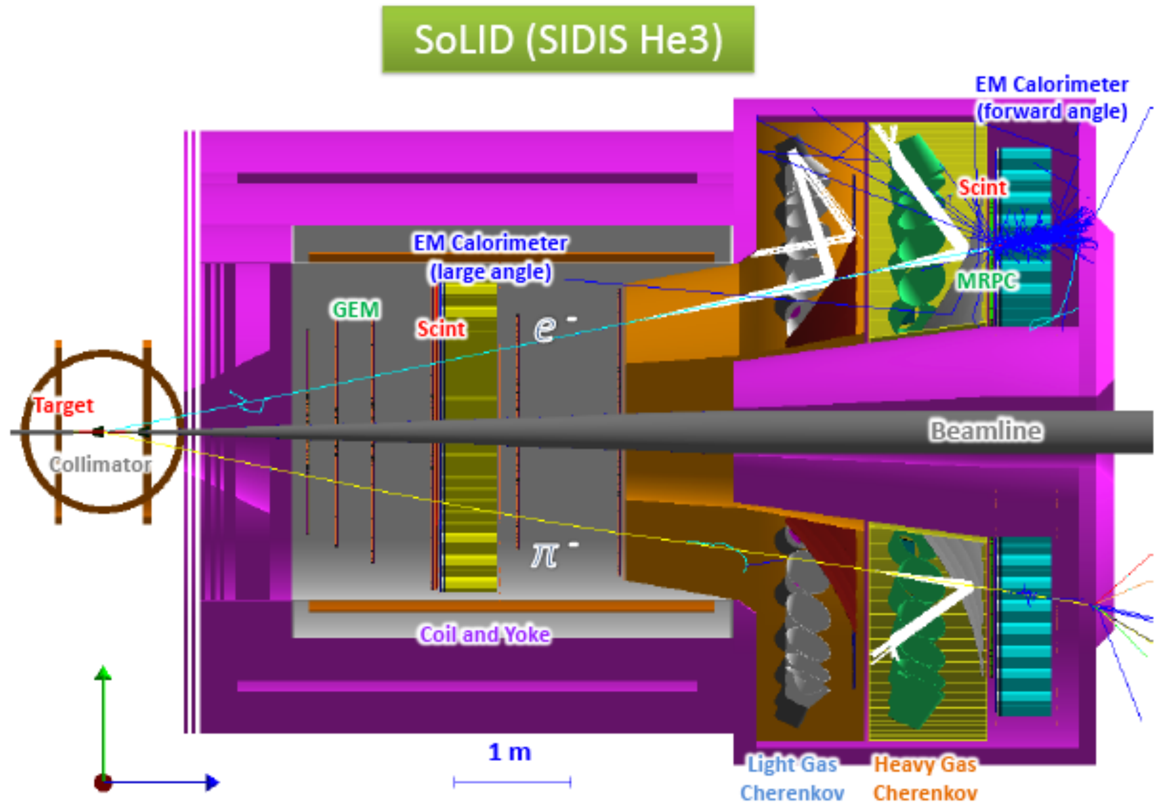
- ❑ g_2 carries information of quark-gluon interaction

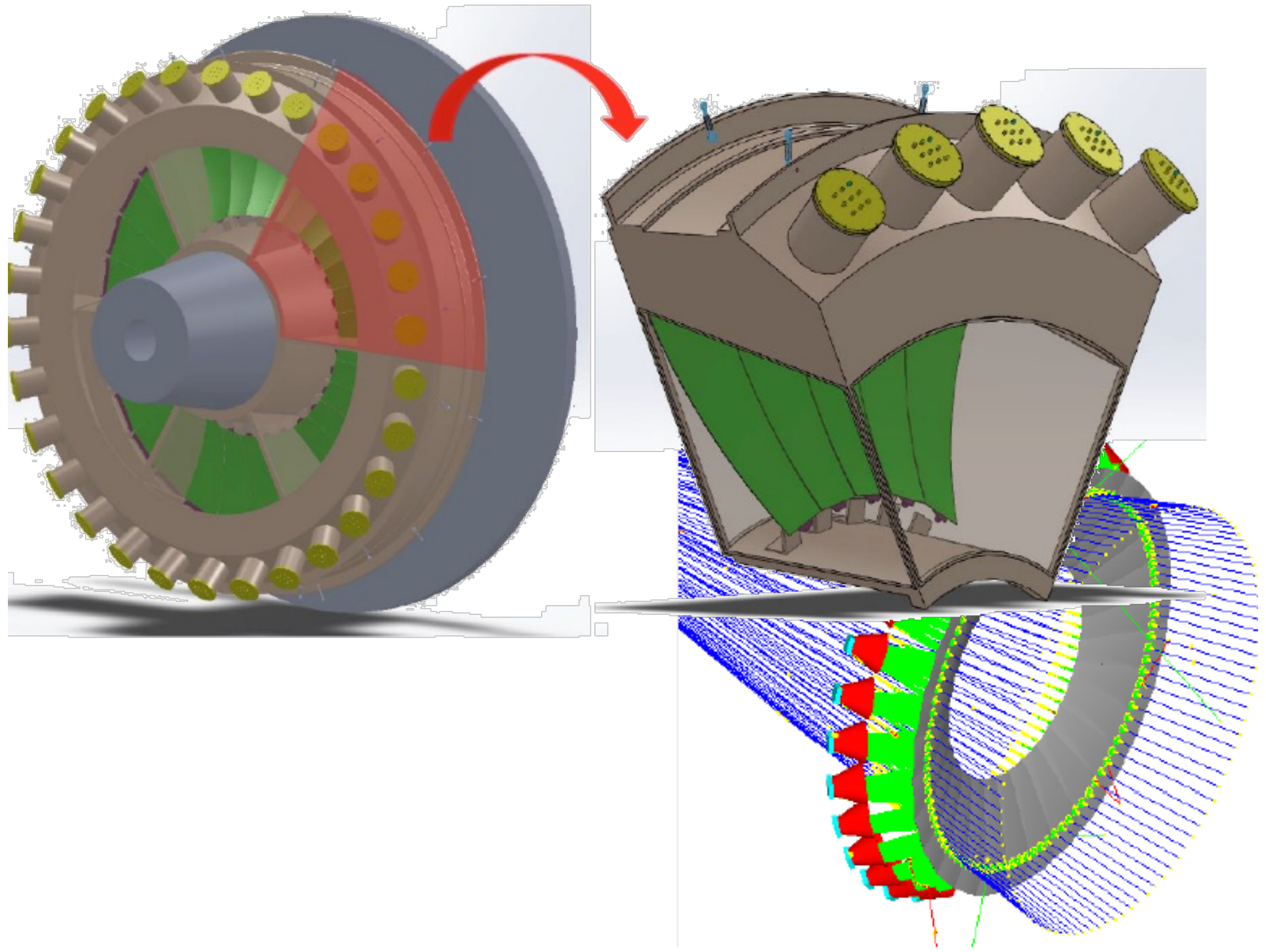
$$d_2(Q^2) = \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx$$



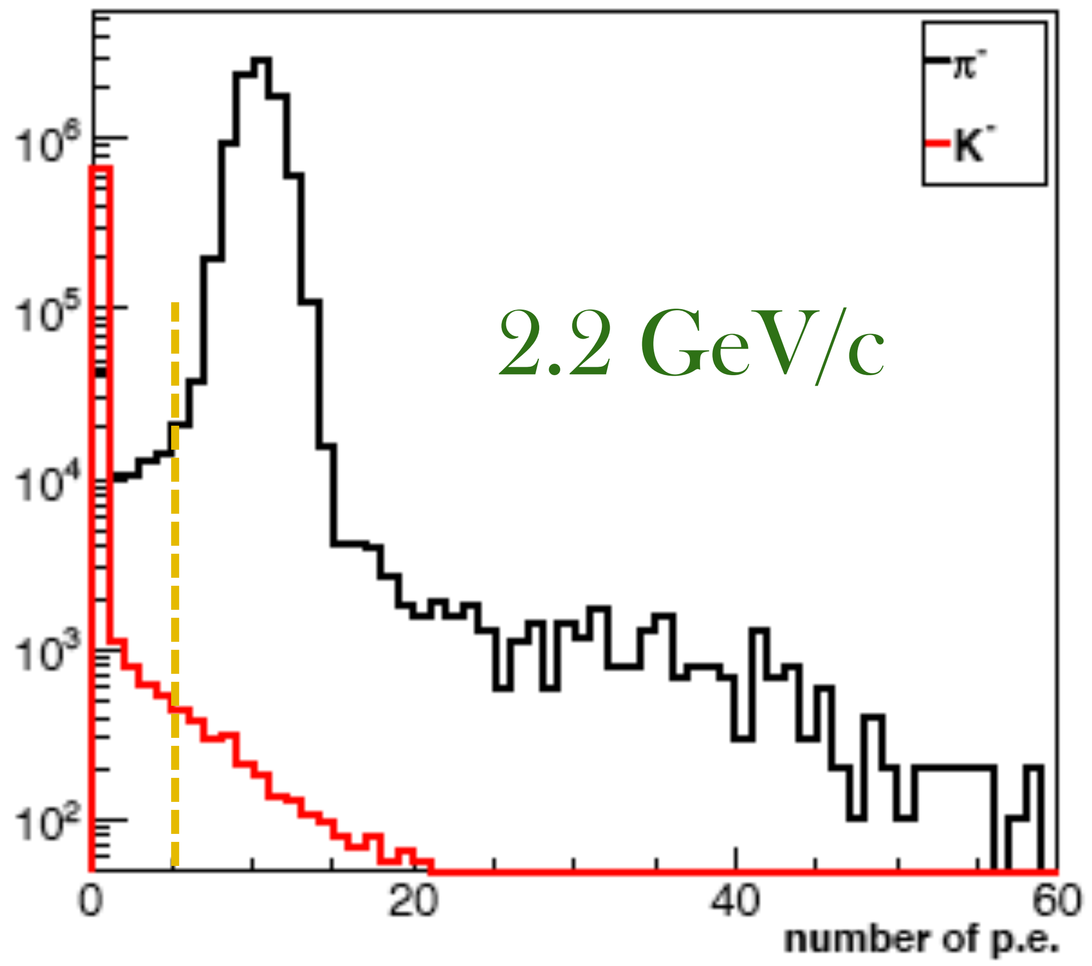
Kaon Identification on SoLID

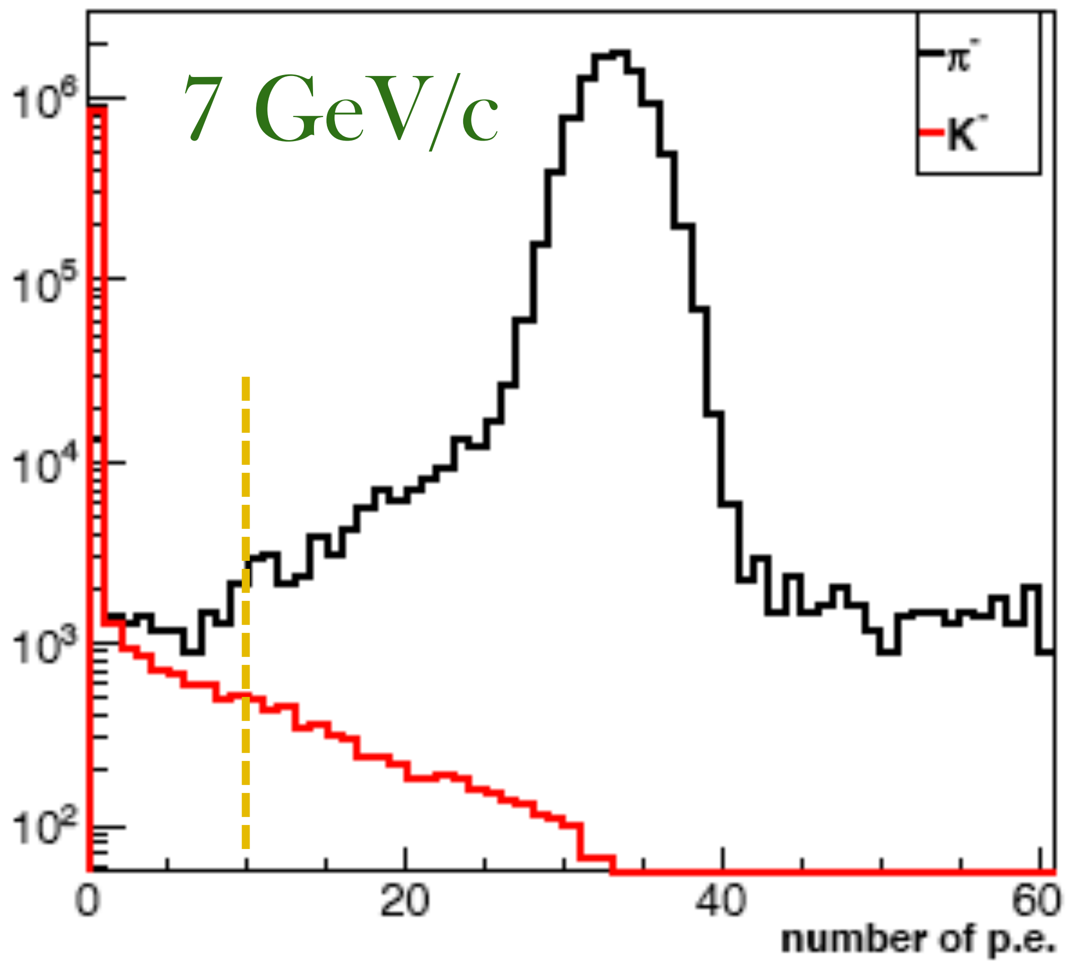
➢ Heavy Gas Cherenkov Detector (HGC)





- ❖ The HGC uses C_4F_8O/C_4F_{10} gas at 1.5 atm under 20 °C
- ❖ Designed for **π**/K separation from 2.2 GeV/c to 7 GeV/c
- ❖ During the offline analysis, the veto signals of the HGC can suppress pions and detect kaons (e.g. cut < 5 N.P.N.)

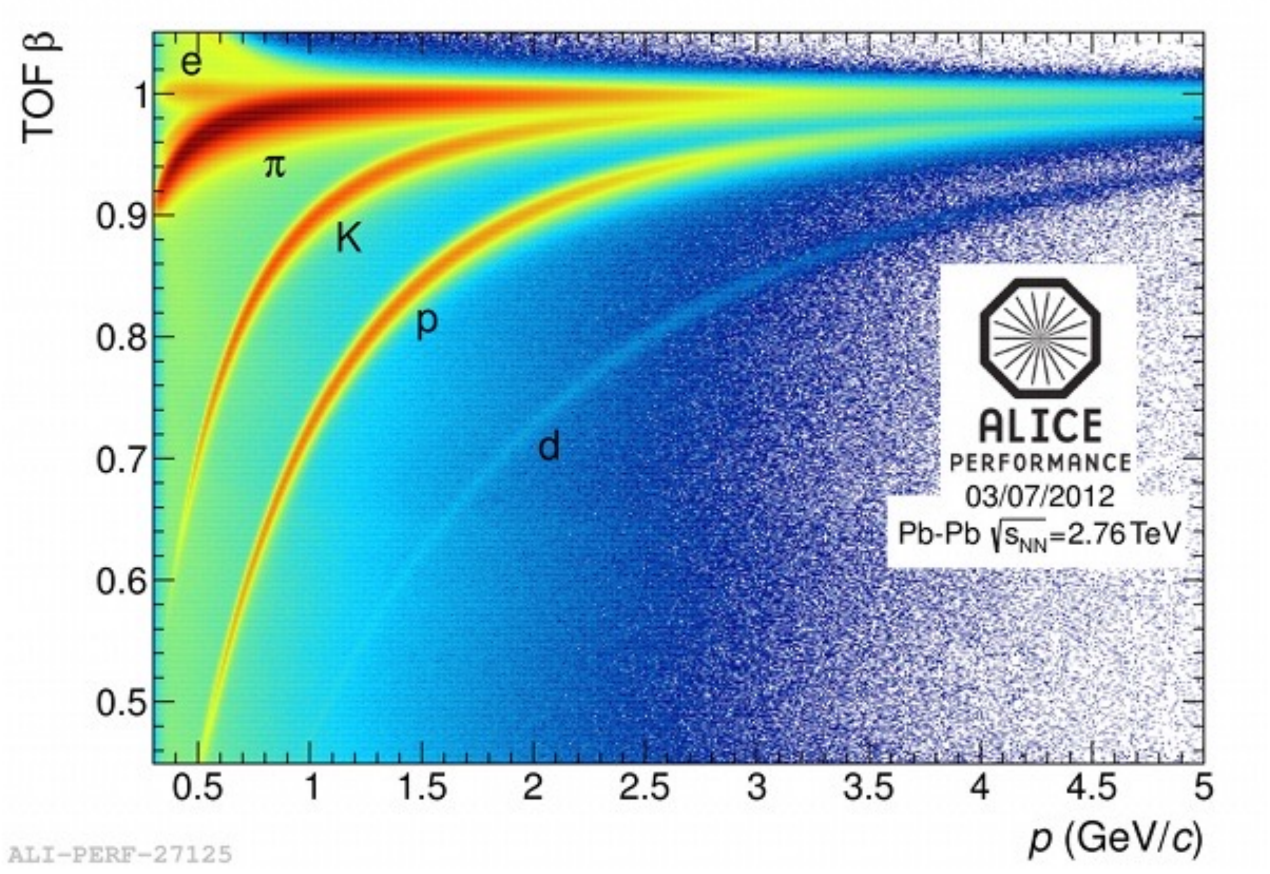




- ❖ Geant4 simulation shows that the HGC can suppress pions by 1/100 at 2.5 GeV/c and by 1/400 at 7 GeV/c

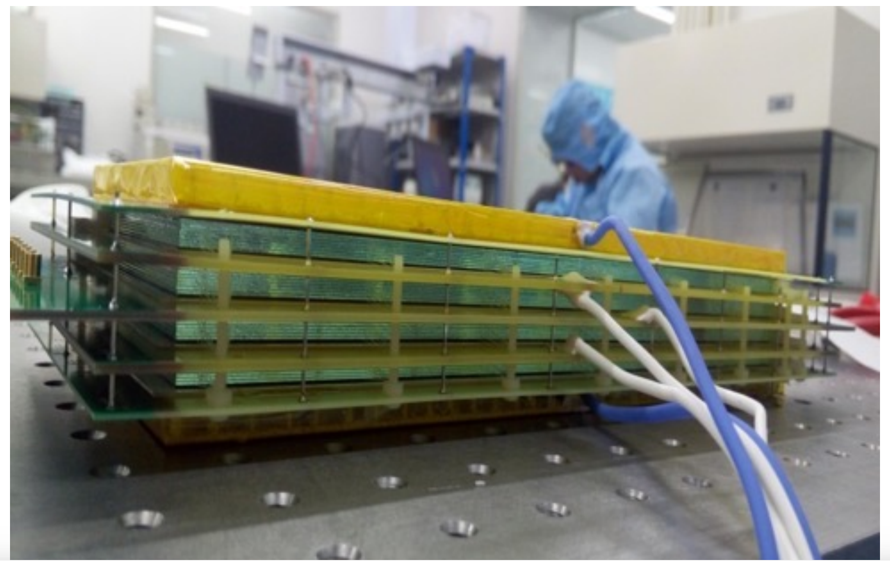
Kaon Identification on SoLID

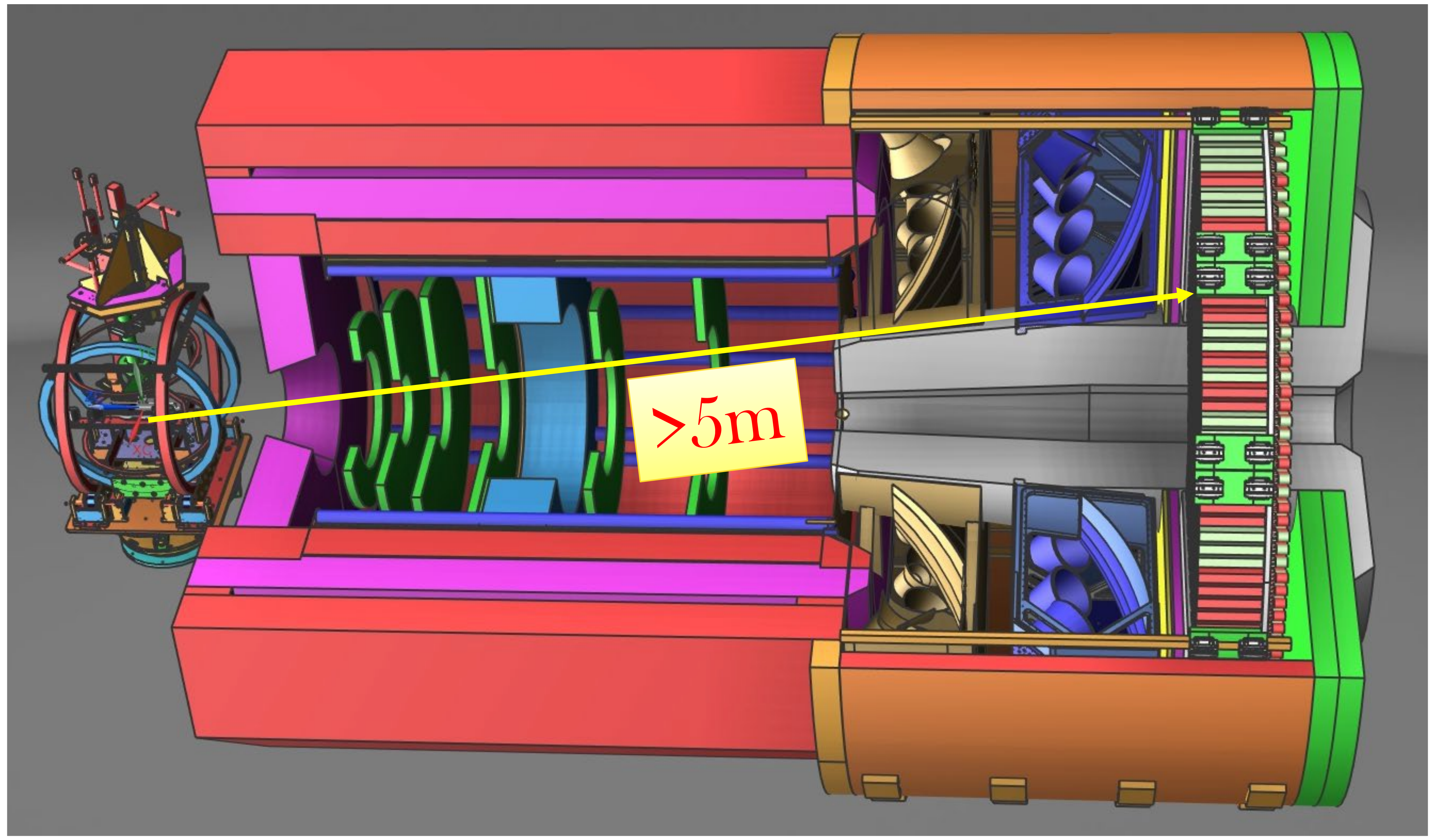
➢ Time of Flight (TOF):

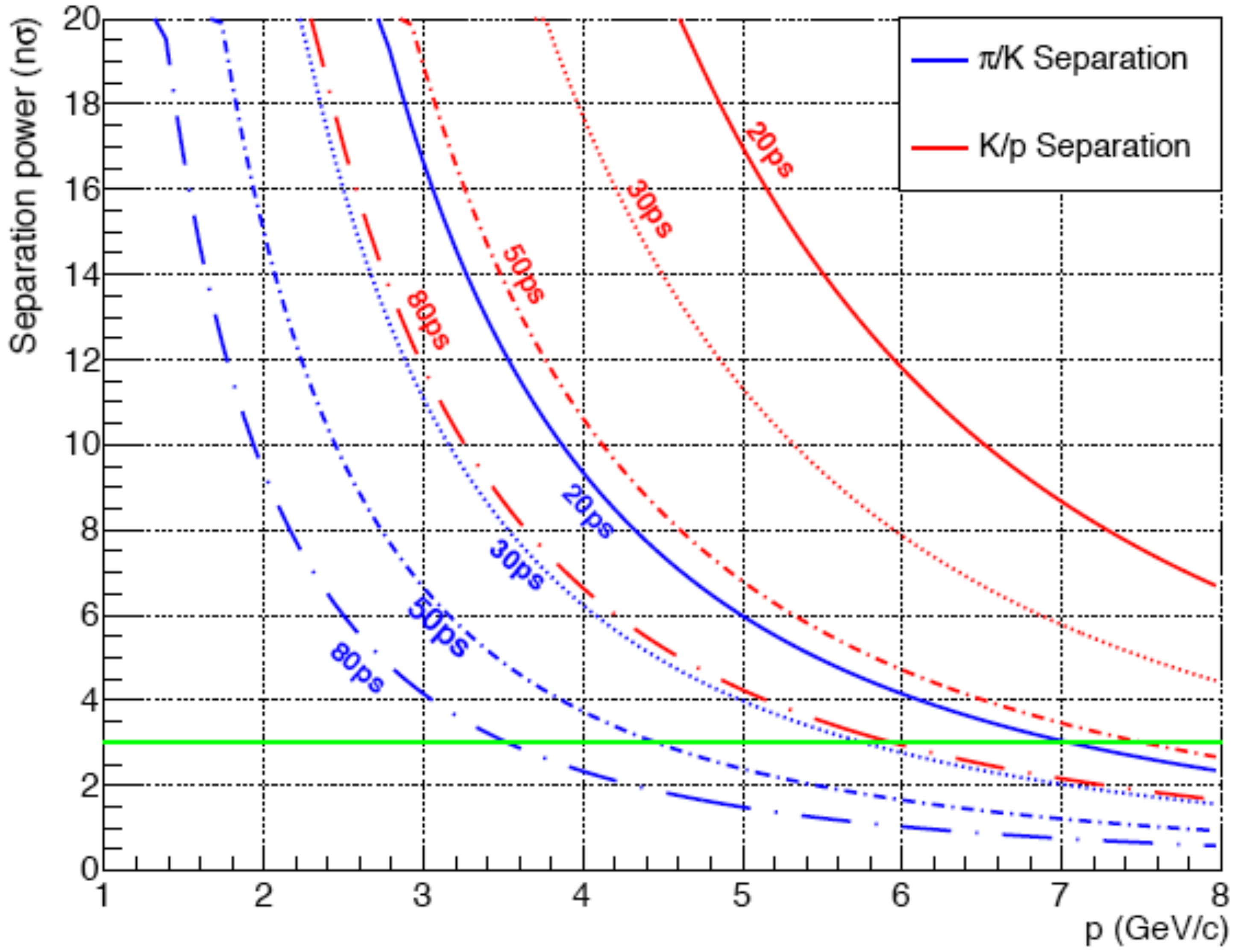


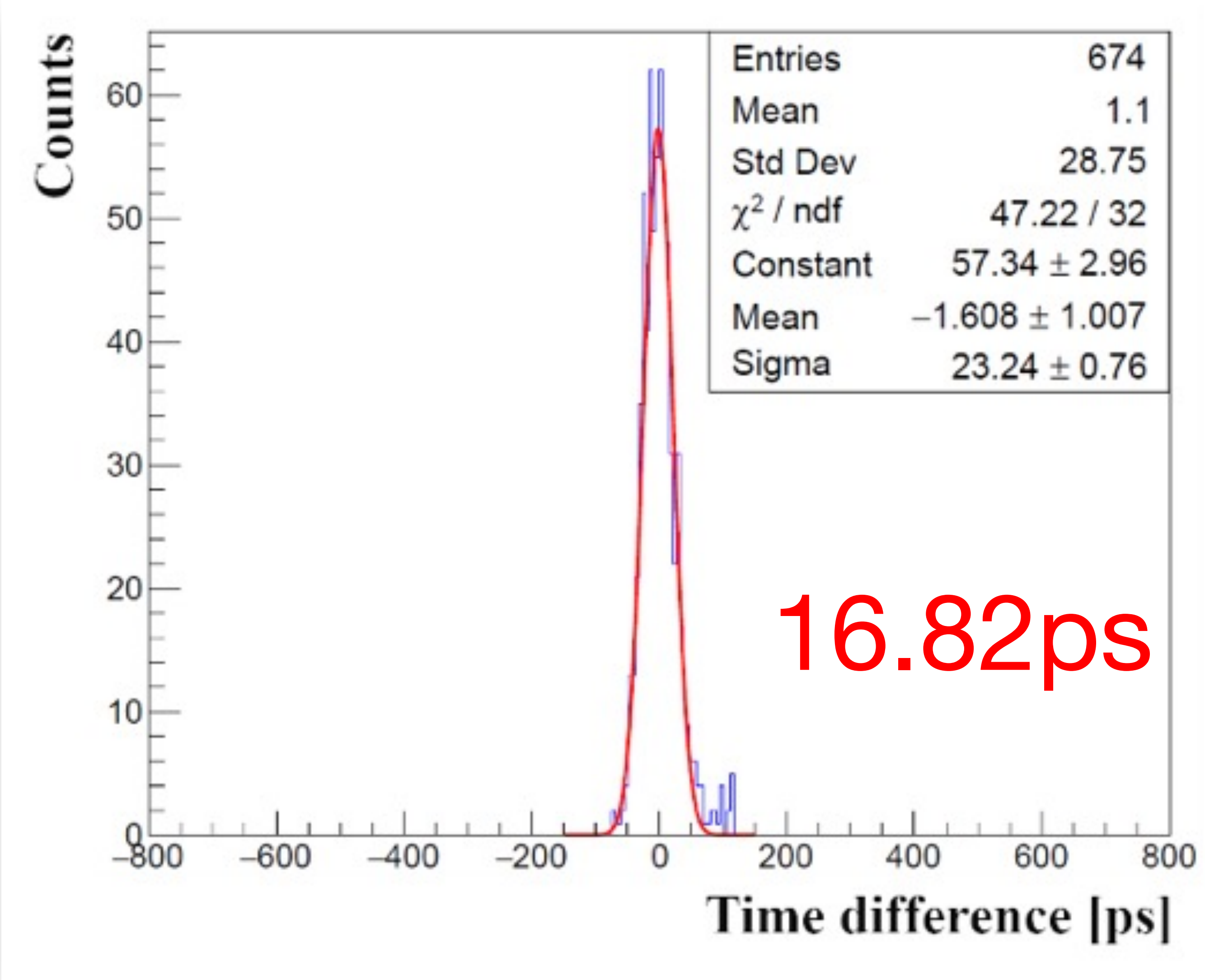
- ☐ The TOF-Beta has been a powerful quantities to perform PID: $\beta = \frac{p}{\sqrt{p^2 + m^2c^2}}$
- ☐ Particles with same momenta & different reach detectors at diff. time: $\Delta t = t_1 - t_2 \simeq \frac{Lc}{2p^2}(m_1^2 - m_2^2))$
- ☐ Define the separation power: $n_\sigma = \Delta t/\sigma_{TOF}$
- ☐ For 5m flight-path, separate **π** /K up to 6 GeV/c w/ 30 ps resolution
- ☐ Tsinghua's mRPC meet requirement (R&D still needed).

Y. Yu et al 2022 JINST 17 P02005



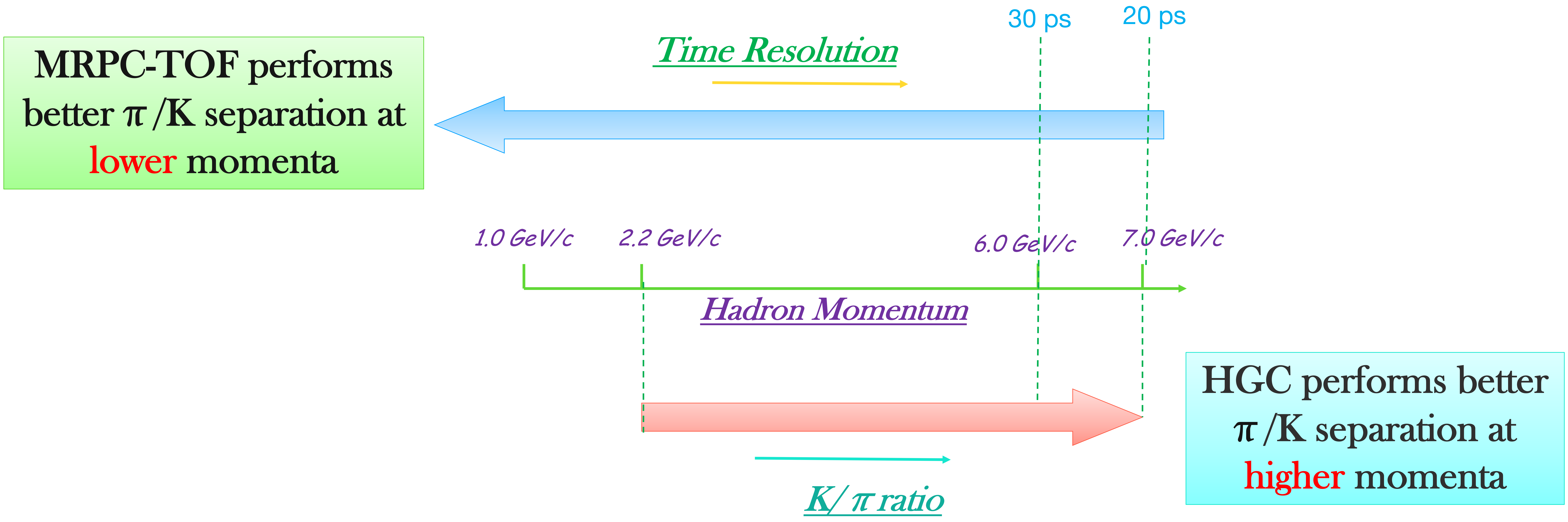






Kaon Identification on SoLID

- Combination of HGC and MRPC:



MRPC-TOF performs better π /K separation at lower momenta

30 ps

20 ps

Time Resolution

1.0 GeV/c

2.2 GeV/c

6.0 GeV/c

7.0 GeV/c

Hadron Momentum

K/ π ratio

HGC performs better π /K separation at higher momenta

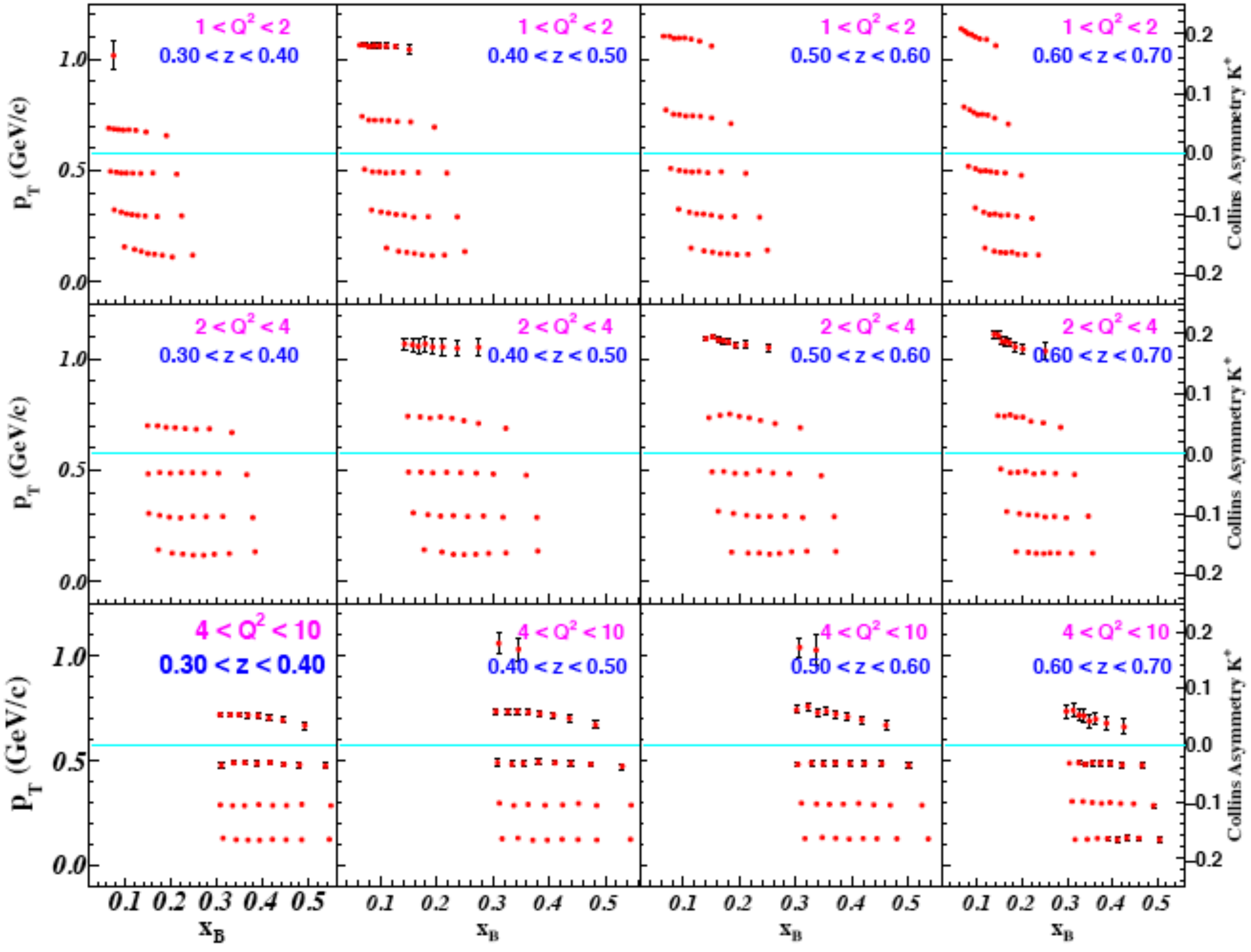
Strategy:

- ✓ MRPC w/ 30 ps time-resolution to do π/K separation at lower momentum;
- ✓ HGC to do pi/K separation at lower momentum;

SoLID Kaon-SIDIS

- Projection of Kaon-SIDIS: $e + \vec{N}_{\Uparrow,\Rightarrow} \to e' + K^{\pm} + X$

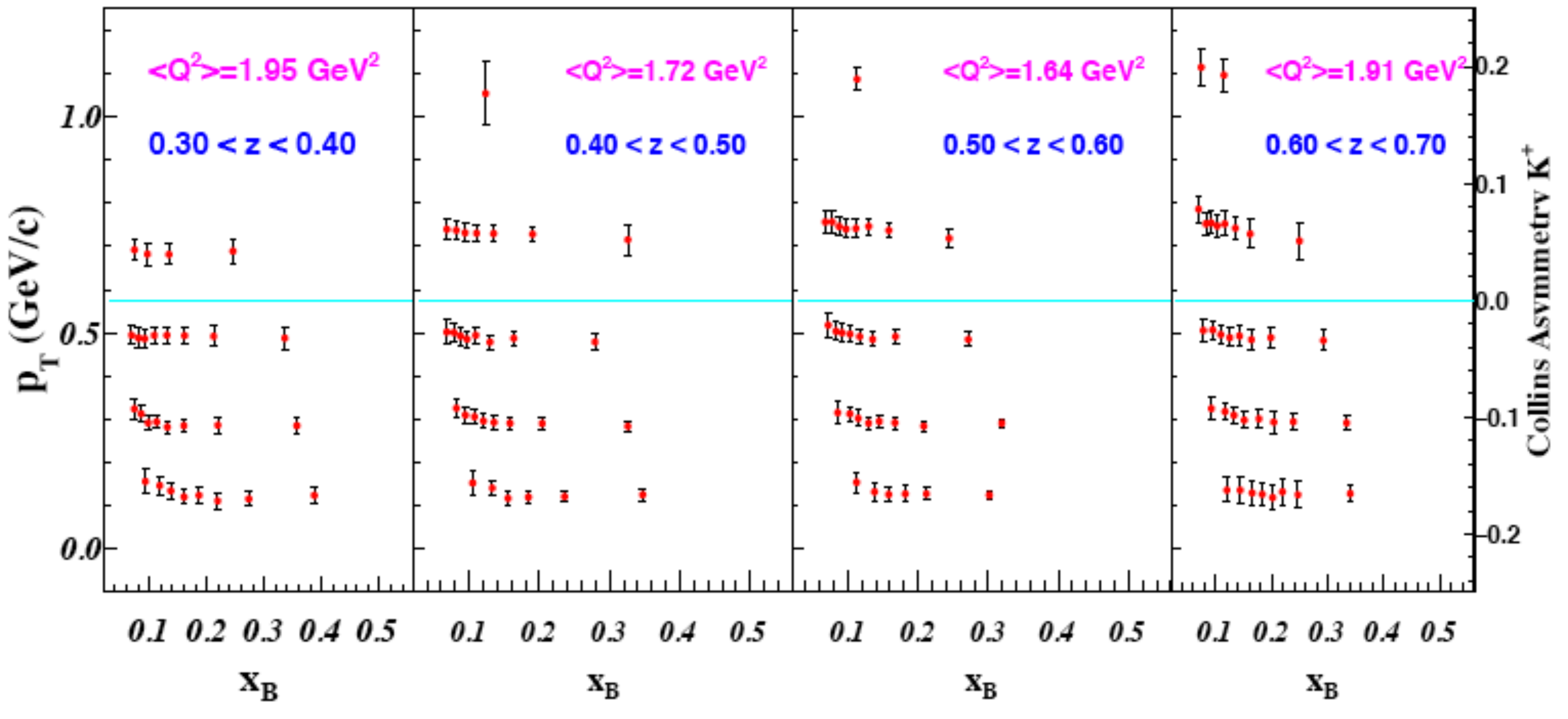
4D binning for He3 setup



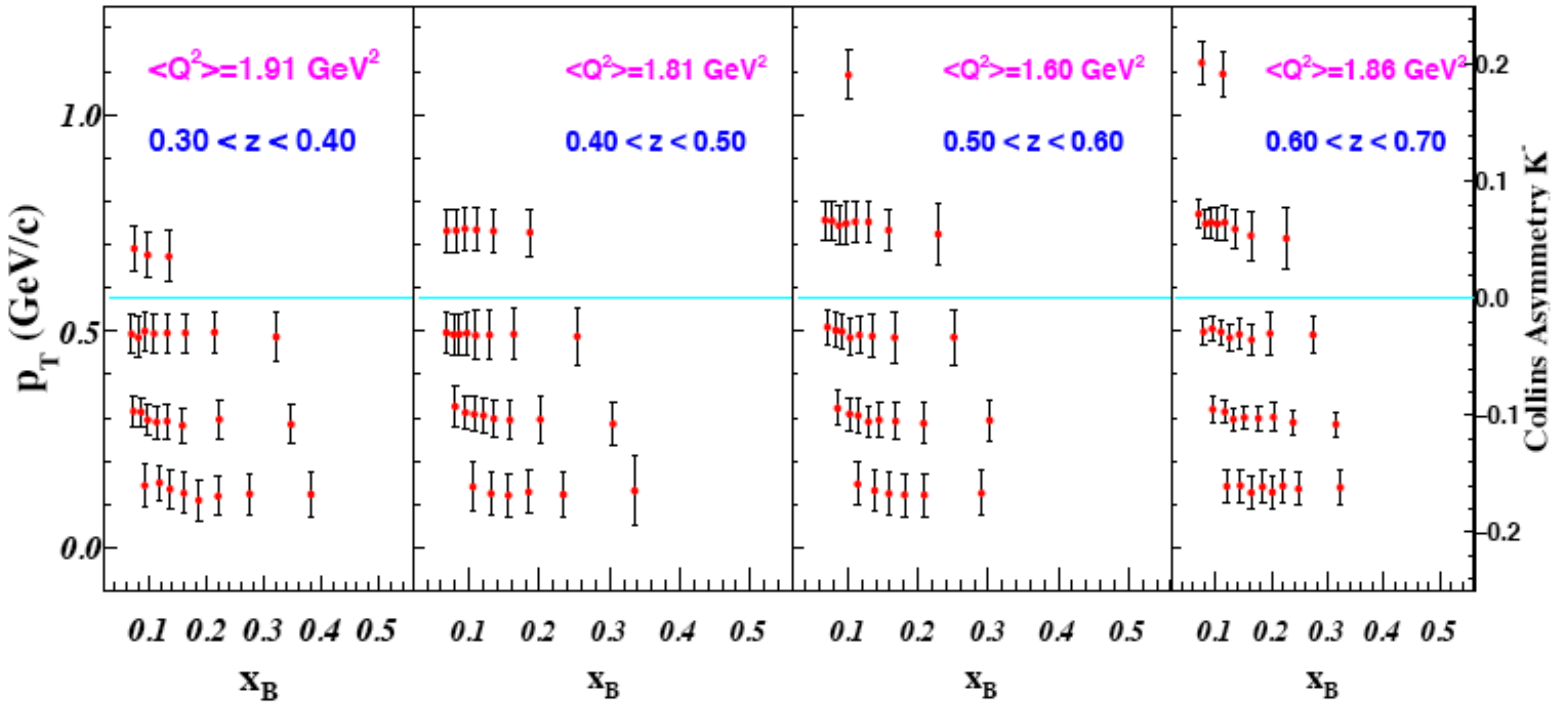
(a) $\vec{n}(e,e'K^+)X$

430 bins for Collins TSA (similar for K-)

4D binning for NH3 setup



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



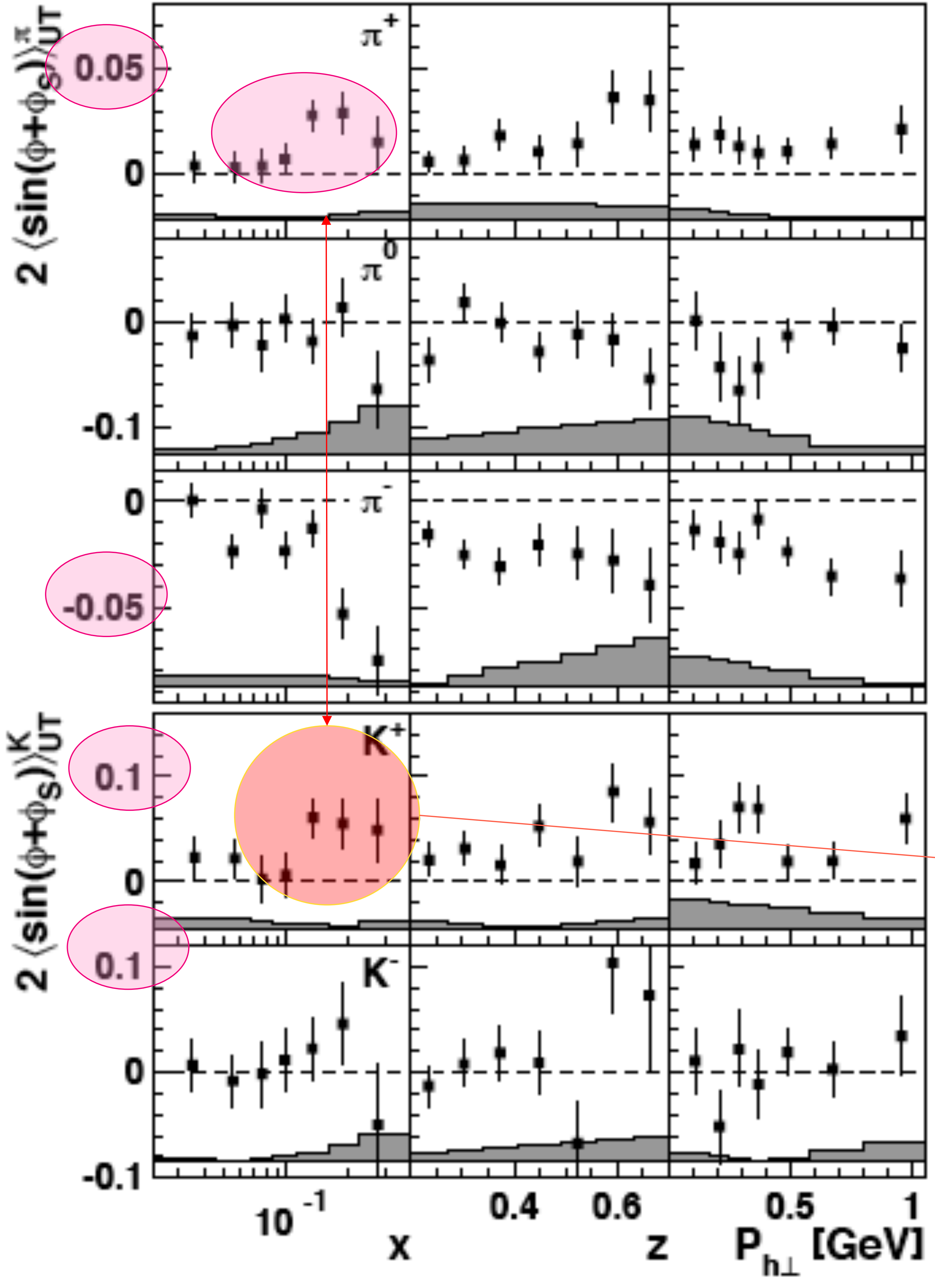
(b) $\vec{p}(e,e'K^-)X$

120 bins for Sivers and Collins TSA separately!

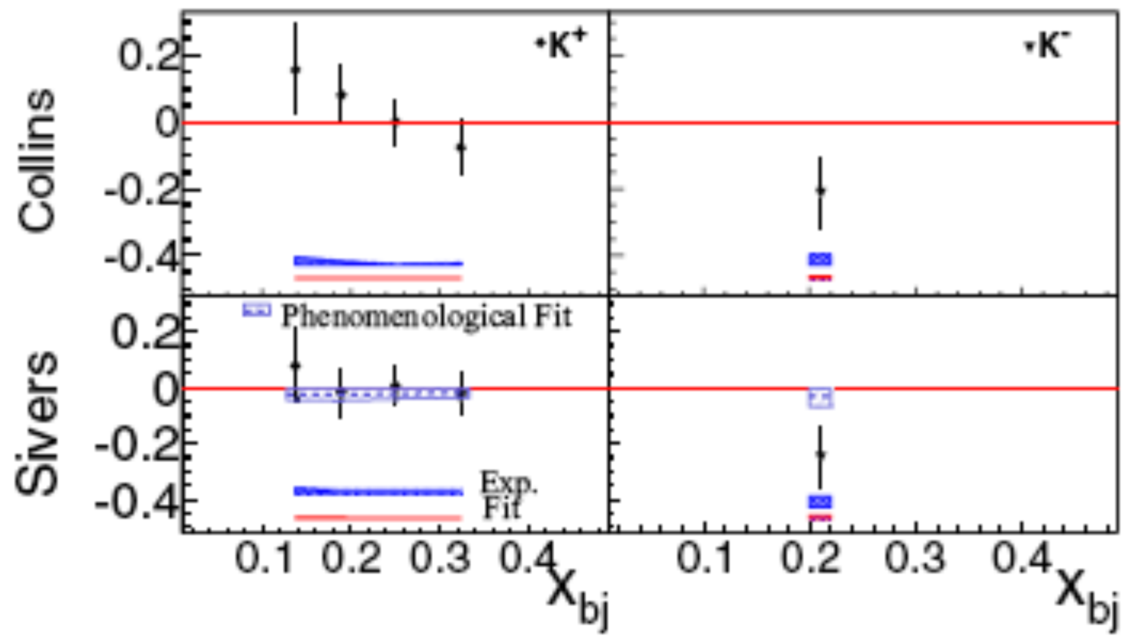
SoLID Kaon-SIDIS

- Add Precise Kaon-SIDIS data

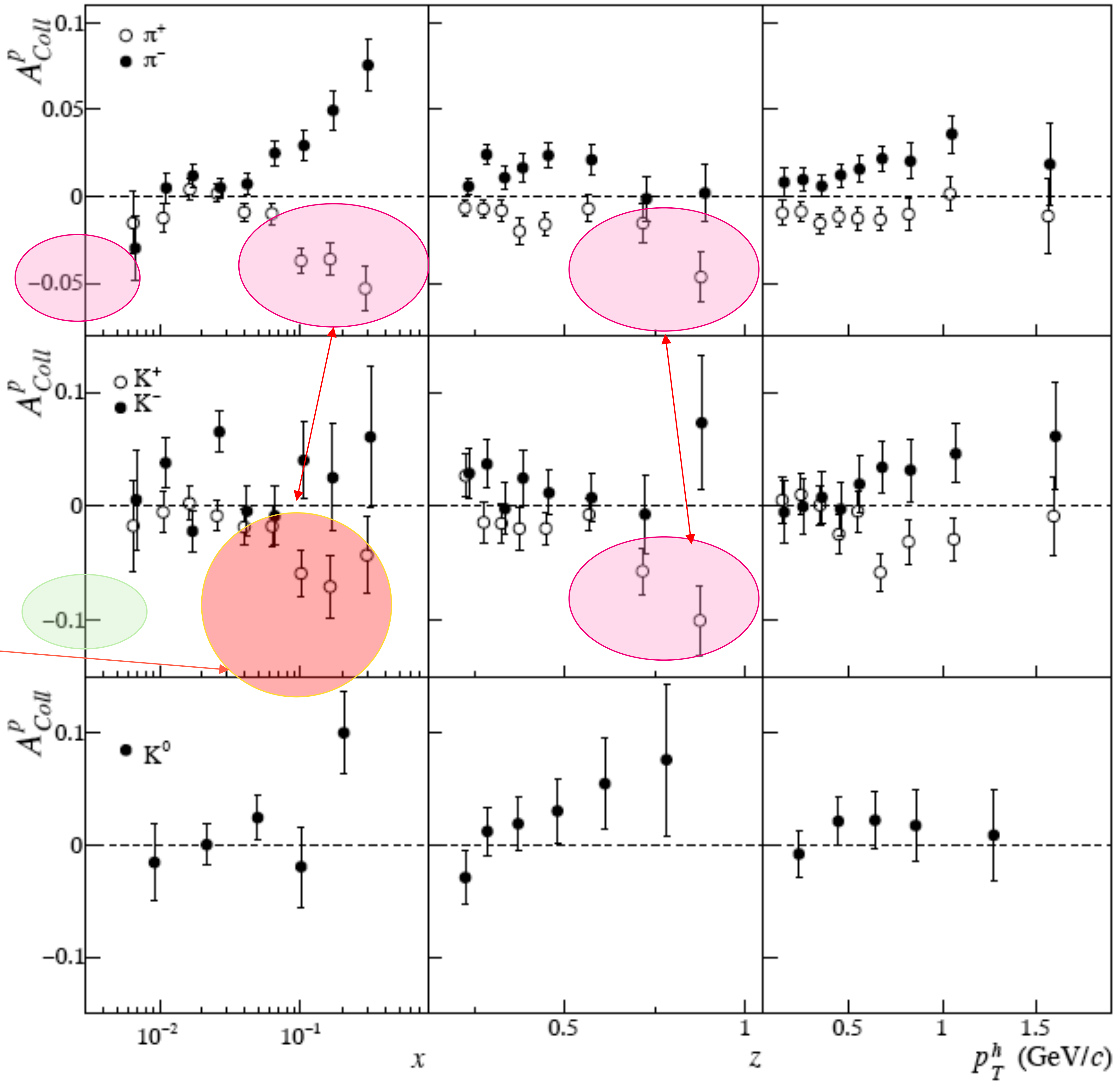
HERMES Data with transversely polarized proton



Hall-A with transversely polarized neutron (He3)



COMPASS Data with transversely polarized proton



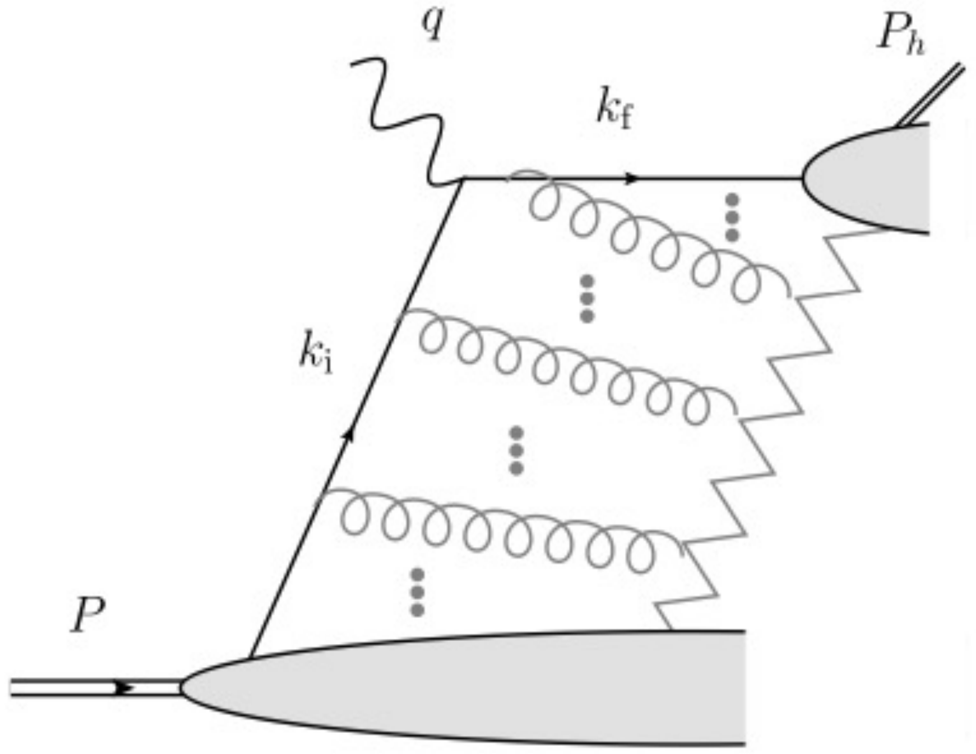
- Kaon asymmetries are same sizes or even larger as the pion asymmetries?!
- HERMES & COMPASS K+ results have opposite signs!
- SoLID Kaon data can resolve disagreement

SoLID Kaon-SIDIS

- Test Factorization

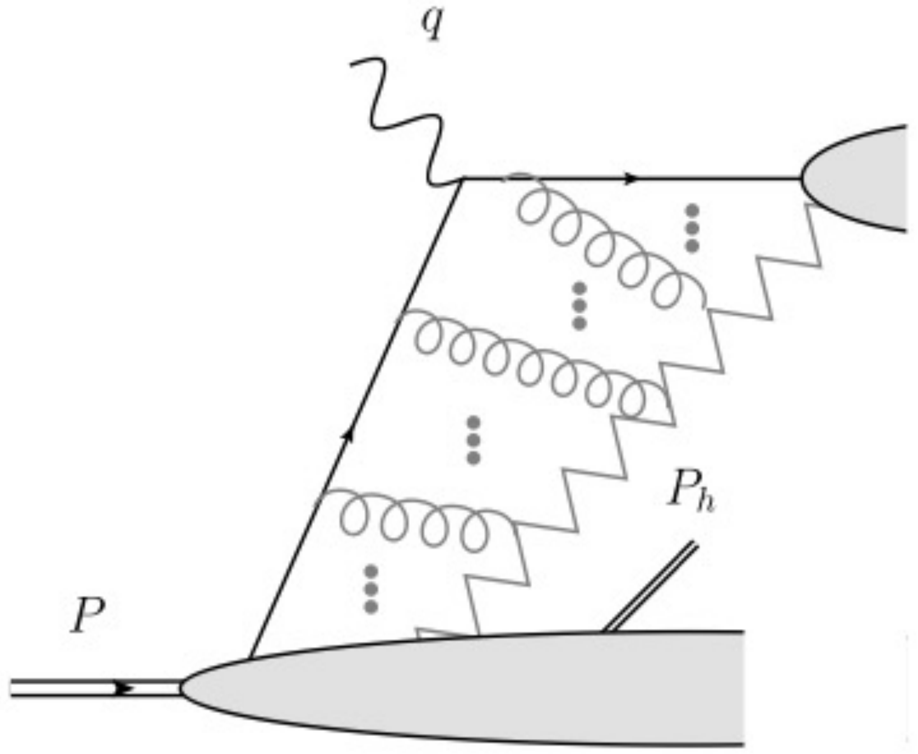
☐ Current fragmentation region is not clearly defined

Current Fragmentation

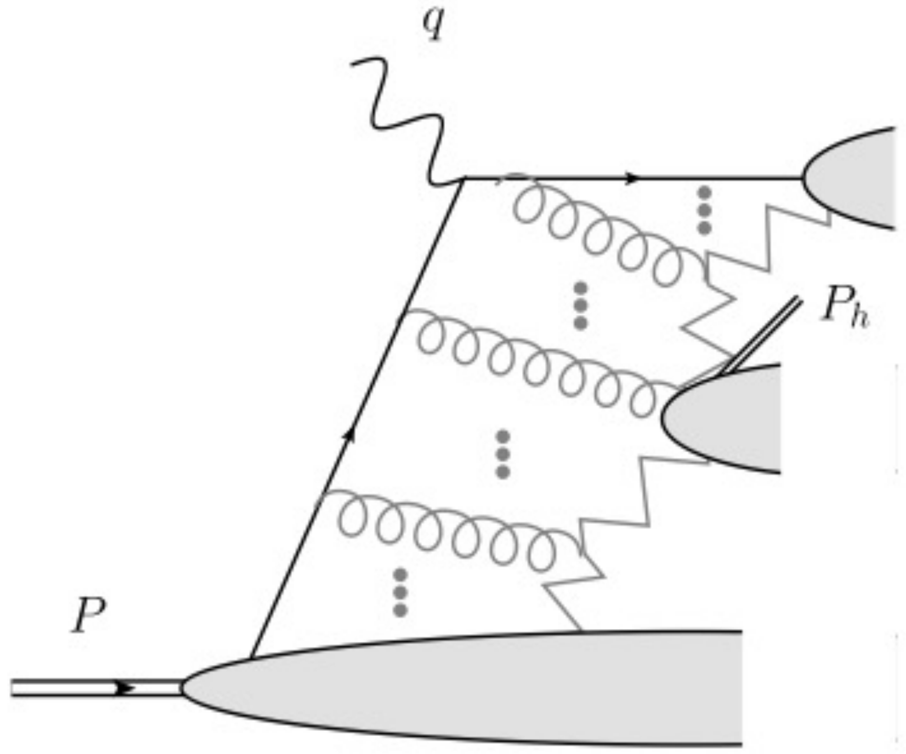


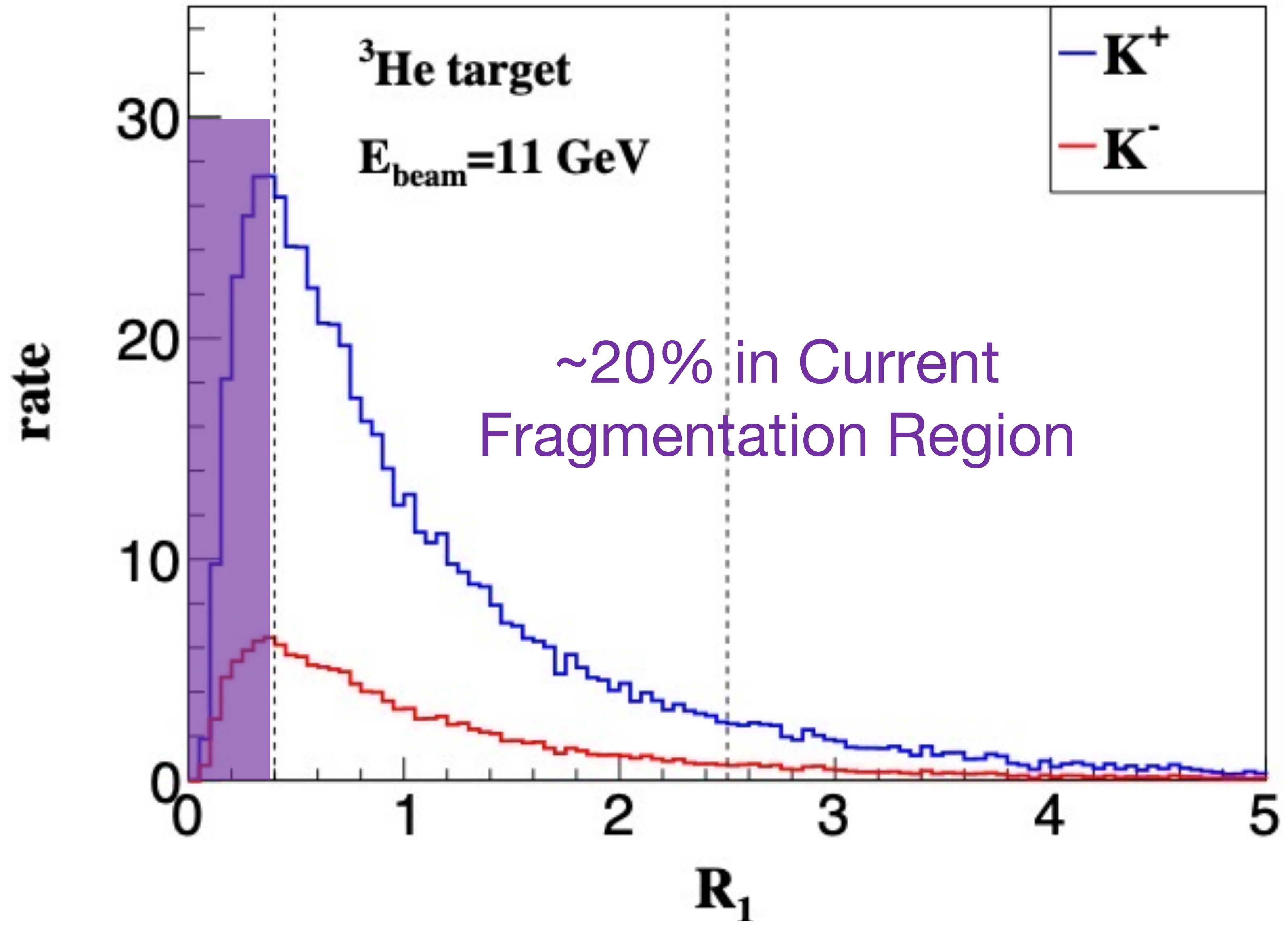
✓ Factorizable!

Target Fragmentation

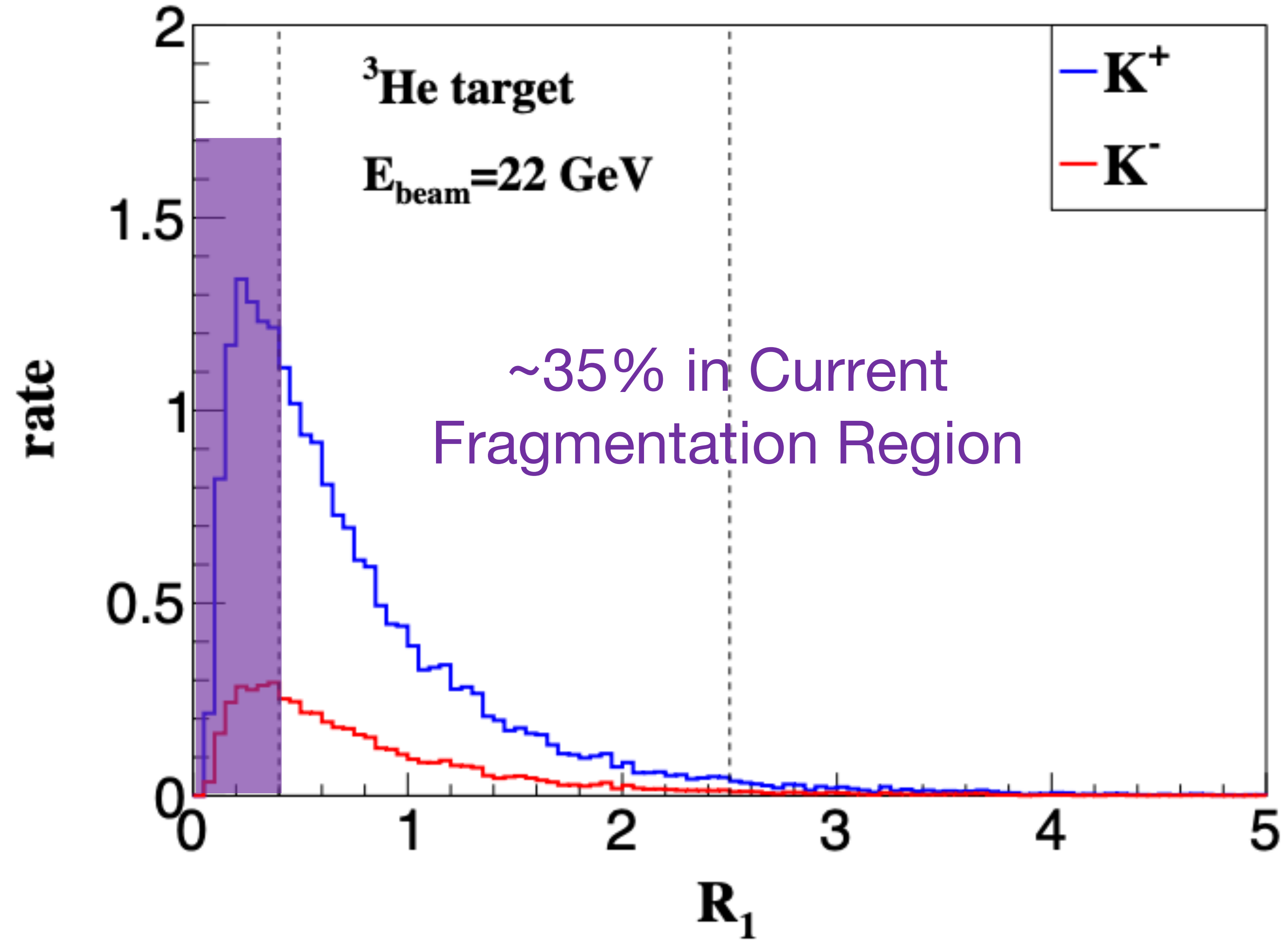


???





~20% in Current Fragmentation Region



~35% in Current Fragmentation Region

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

☐ Model estimation:

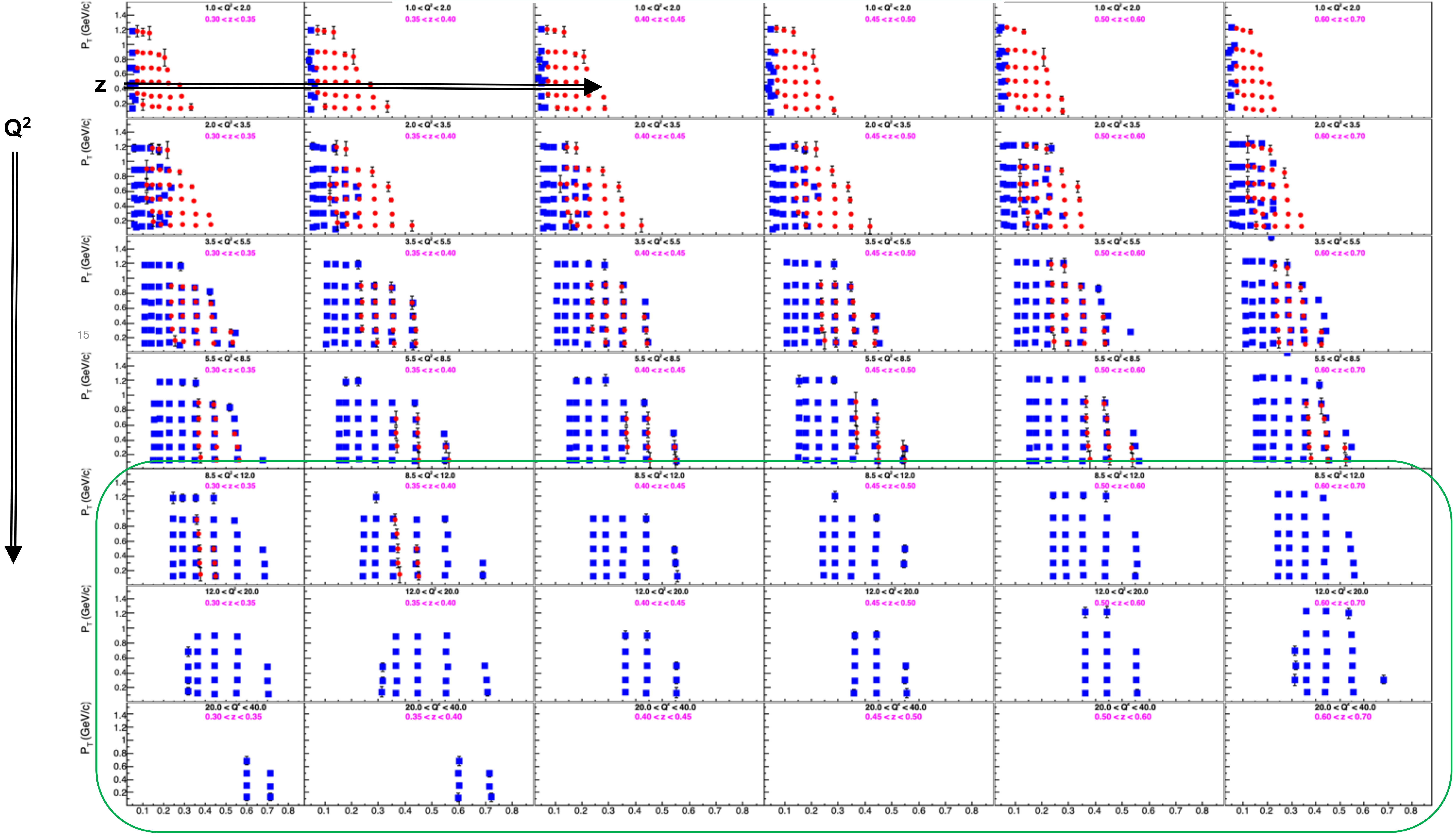
- 70% pions and 20% kaons are valid for JLab@11GeV.
- 35% kaons are valid for JLab@22GeV

Boglione, et. al. Phys. Lett. B 766, 245 (2017)

SoLID-SIDIS @ 22GeV

- 11GeV vs 22GeV

Unpolarized Kaon-SIDIS Projection



- 11GeV, 69days
- ■ 22GeV, 100days

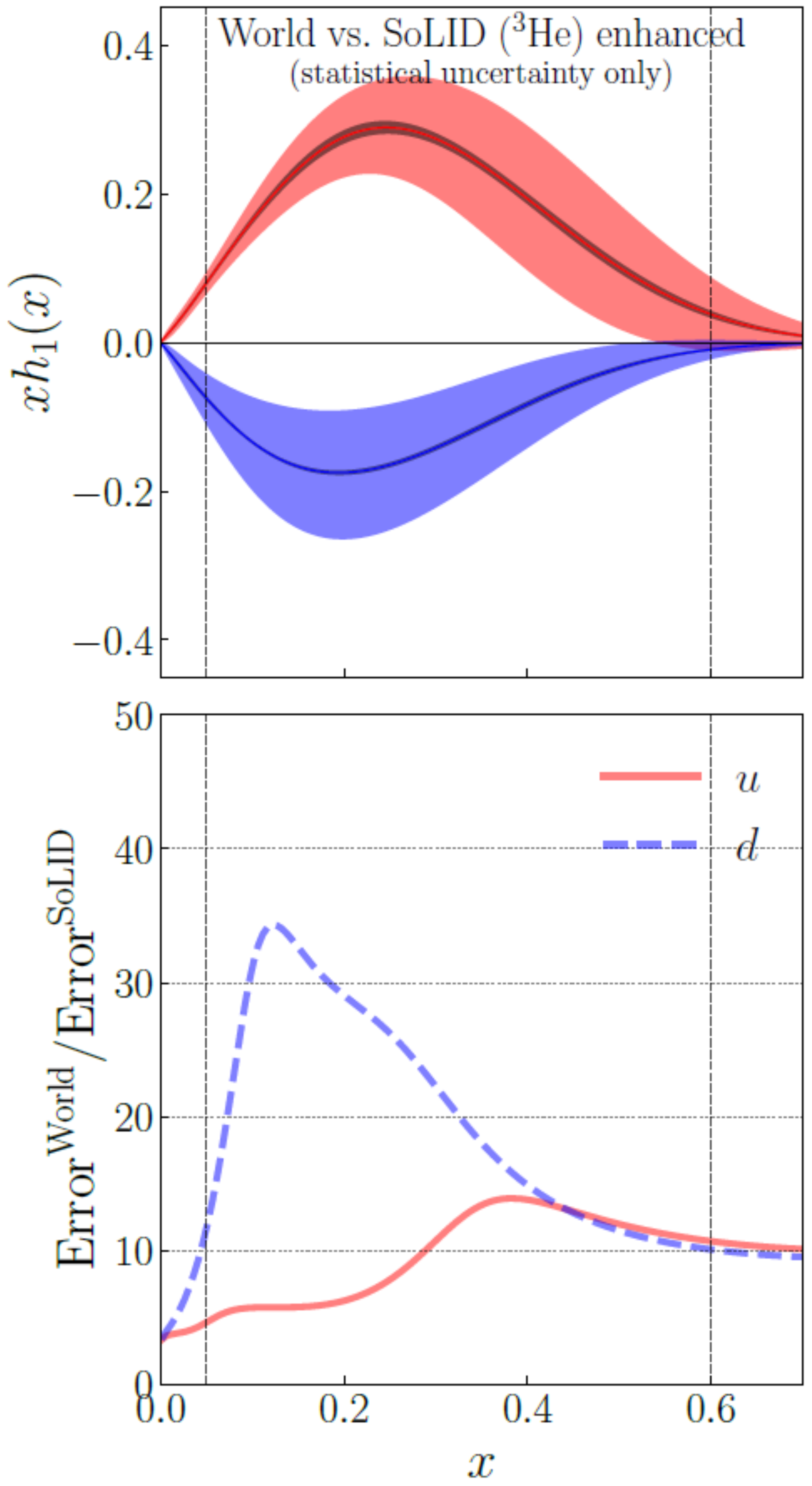
Note:

- Only statistical uncertainties
- Assume pi/K separation in full momentum ranges

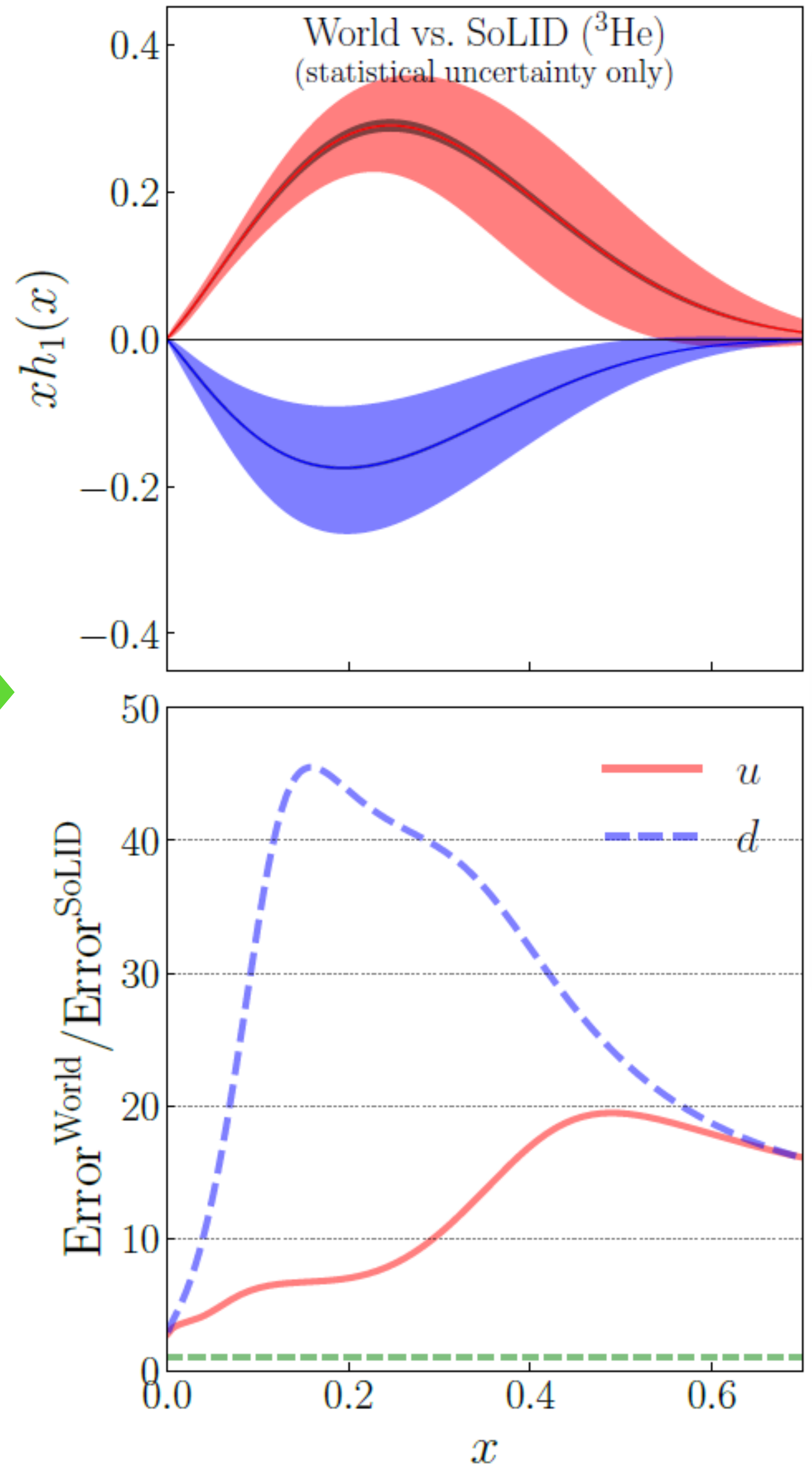
SoLID-SIDIS @ 22GeV

- Projection at 22GeV:

Transversity



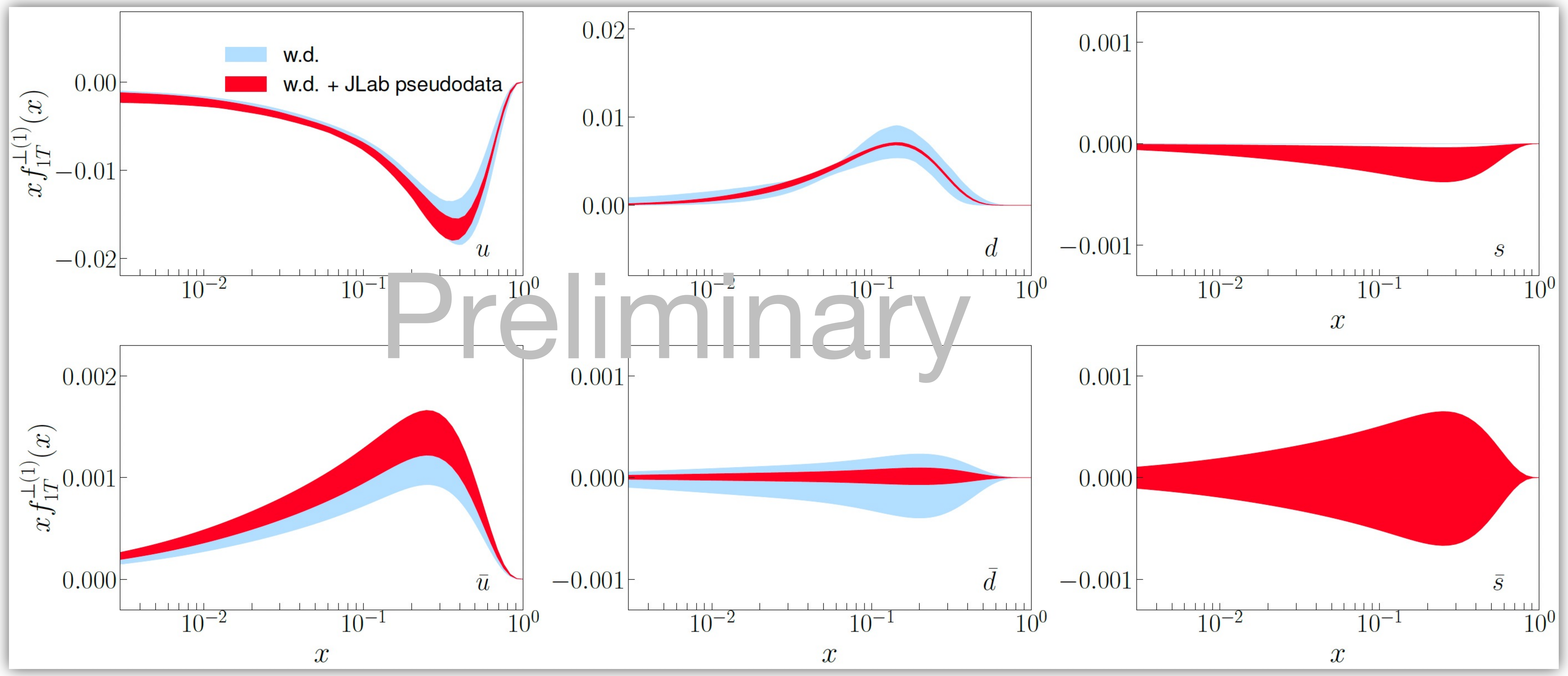
11+8.8 GeV (He3 pion)



22+11+8.8 GeV (He3 pion)

by Vlad Khachatryan et. al.

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

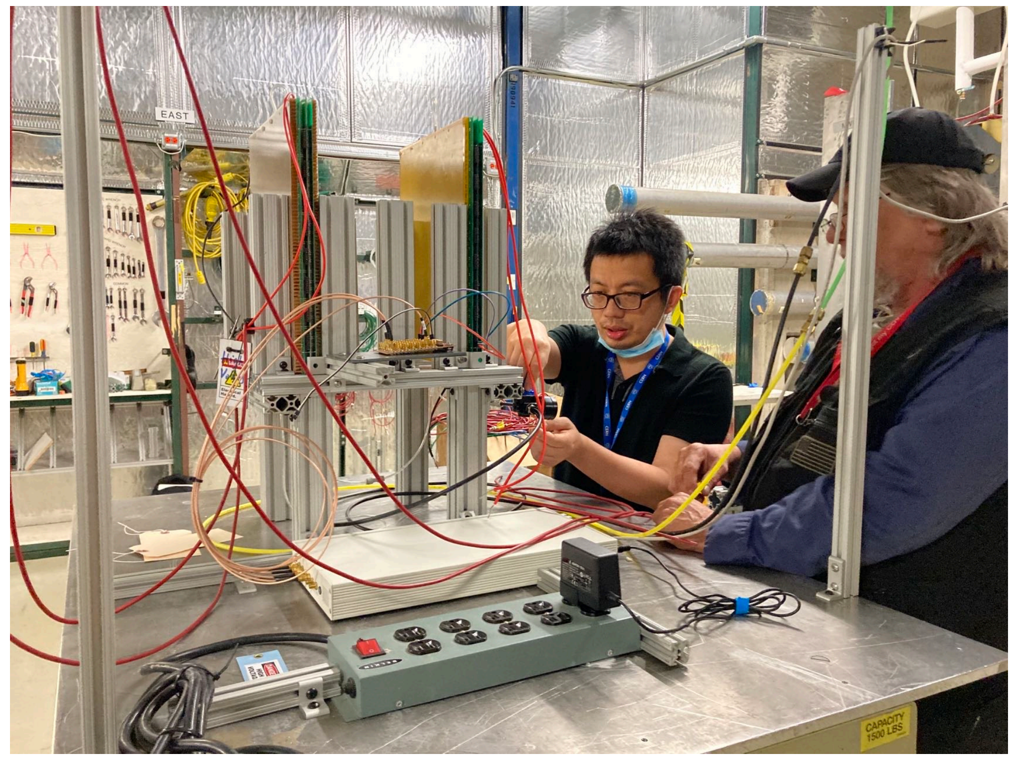


By Tianbo Liu et. al.

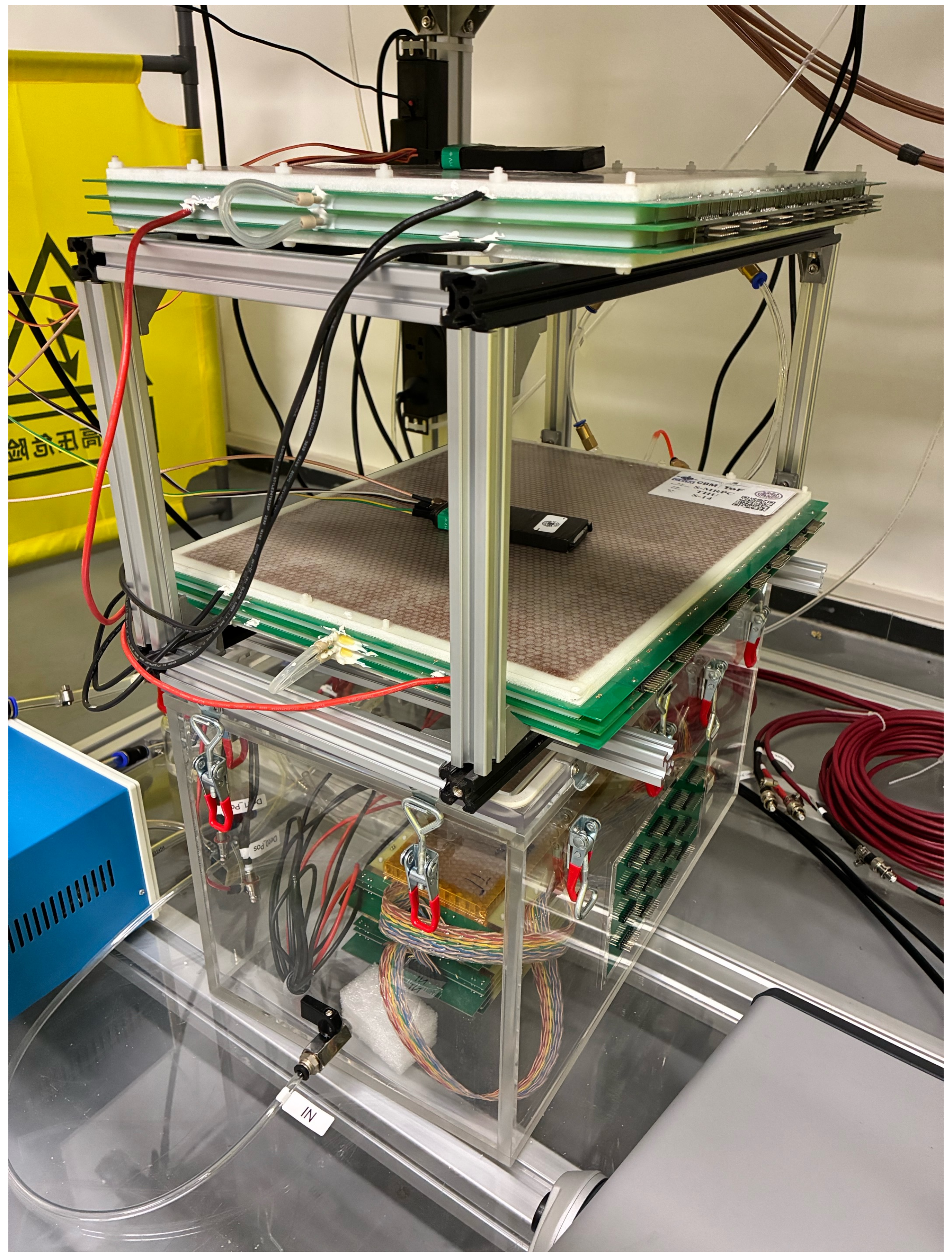
- SoLID pion & kaon data @ 11GeV and 22GeV can greatly improve determination of TMDs for light quarks!

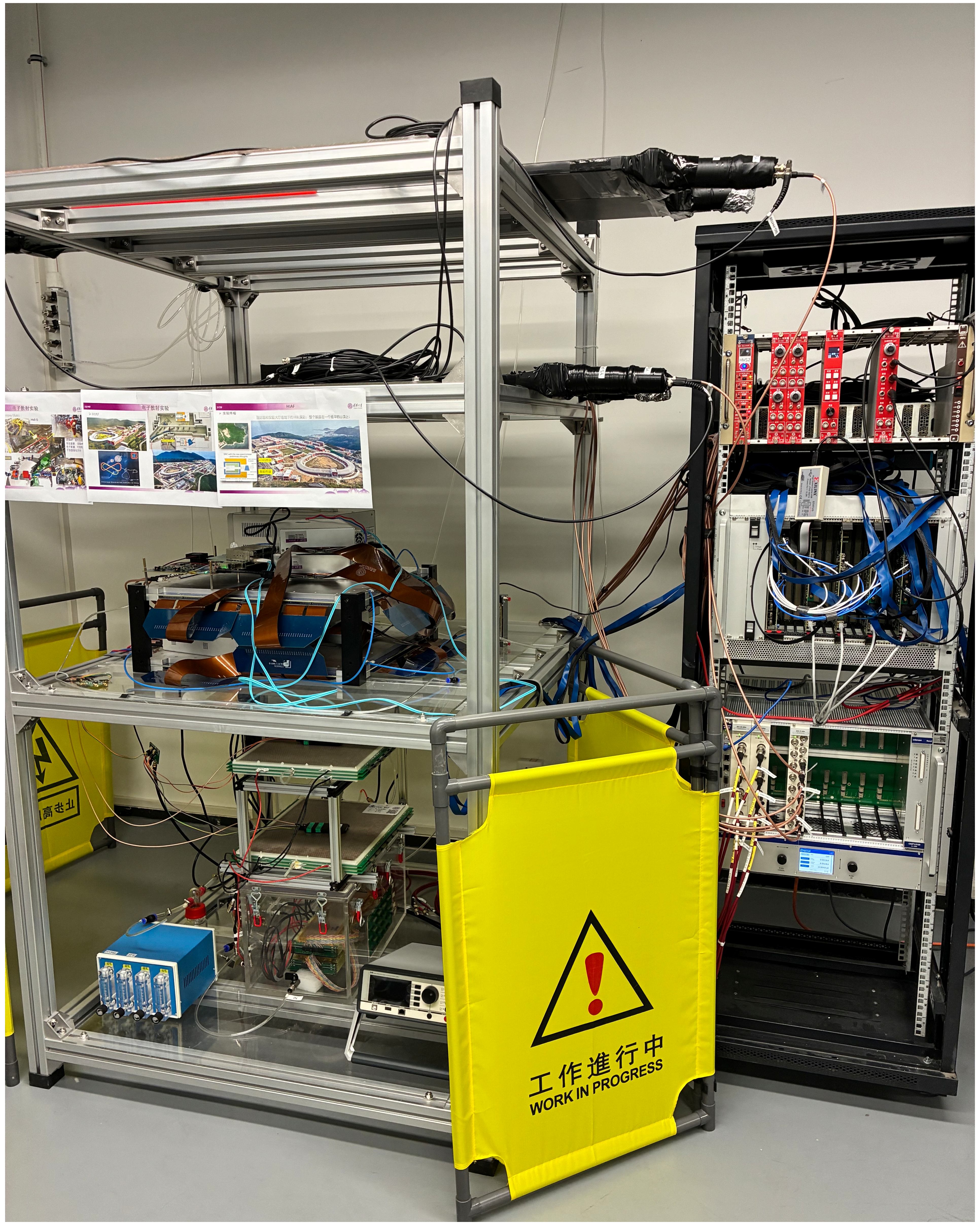
MRPC R&D at Tsinghua

- MRPC tech synergy with US-EIC (2nd) detector
- Awarded by US EIC generic R&D fund ($80K per year)
- 4 mRPC at JLab, two high-rate versions to be shipped soon
- Preparing beam test at JLab w/ other SoLID detectors



2022 FermiLab MRPC & fMCP Test (Tsinghua +UIC)



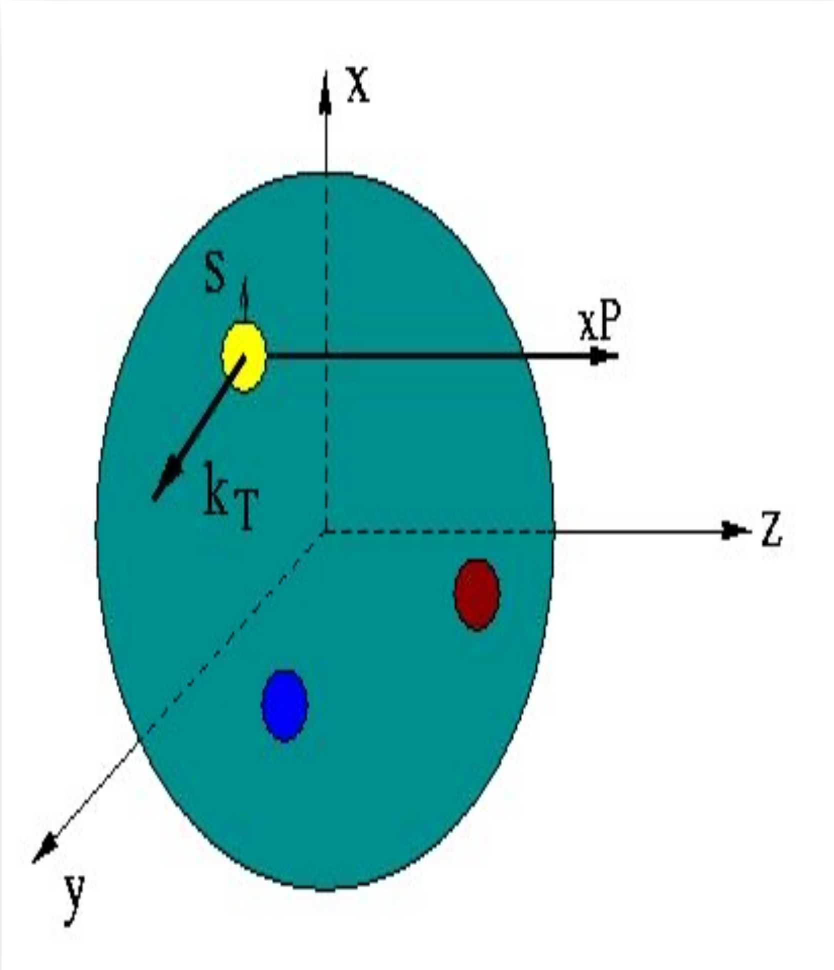


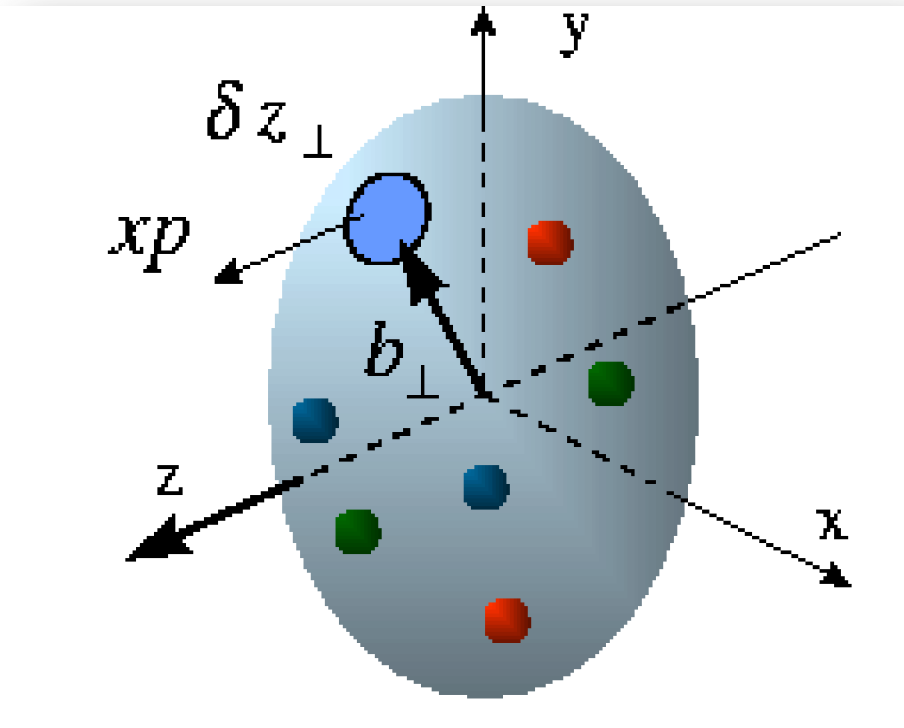
Nucleon's 3D Structure

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

5D

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





$d^2\boldsymbol{r_T}$

d^2k_T

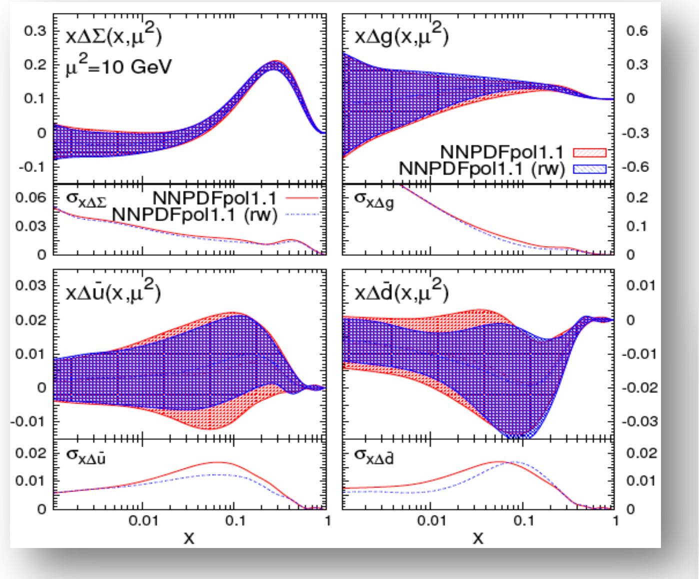
TMD
$f_1^u(x,k_T)$, $h_1^u(x,k_T)$,…

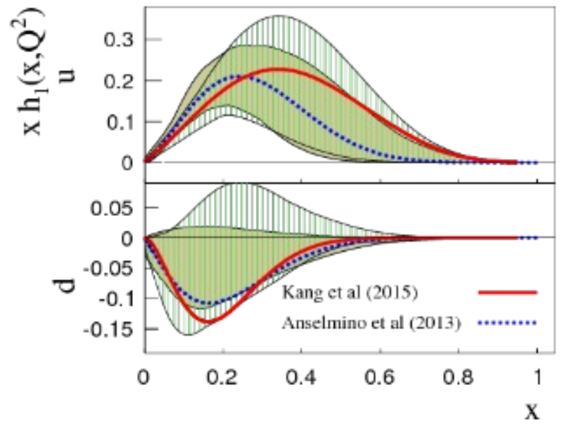
GPDs/IPDs
$H^u, E^u, \widetilde{H}^u, \widetilde{E}^u$

d^2k_T

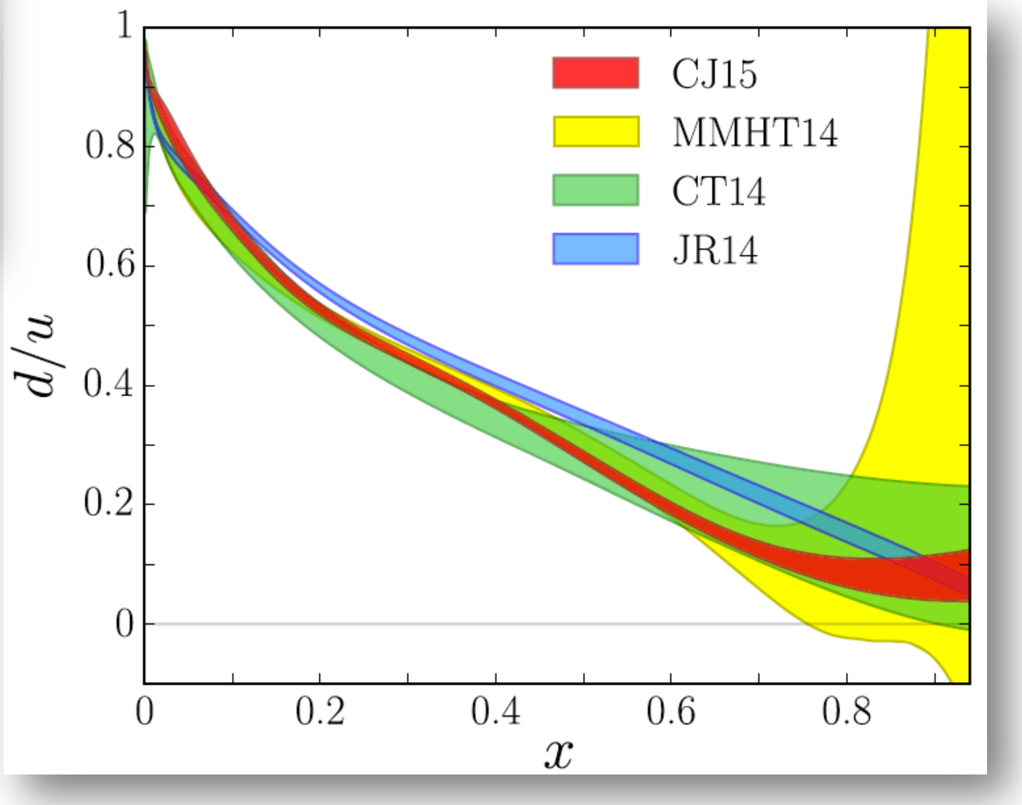
d^2r_T

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
$G_E(Q^2)$,
$G_M(Q^2)$

Plenary Talks of TMD & GPD on Monday

14:00
TMD experiments *Fulvio Tessarotto*
14:00 - 14:40

15:00
GPD experiments *Daria Sokhan*
14:40 - 15:20

Generalized Parton Distributions

- **Deep Virtual Compton Scattering (DVCS):**

❑ Golden channel to study GPD

❑ DVCS only measures Compton Form Factors (CFFs):

$$\tau_{DVCS} \propto \int_{-1}^{+1} \frac{H(x,\xi,t)}{x\pm\xi\mp i\varepsilon}dx = \overset{\text{Re}(\mathcal{H})}{P\int_{-1}^{+1}\frac{H(x,\xi,t)}{x\pm\xi}dx} \overset{\text{Im}(\mathcal{H})}{- i\pi H(\pm\xi,\xi,t)},$$

(8 CFFs for $H, E, \widetilde{H}, \widetilde{E}$)

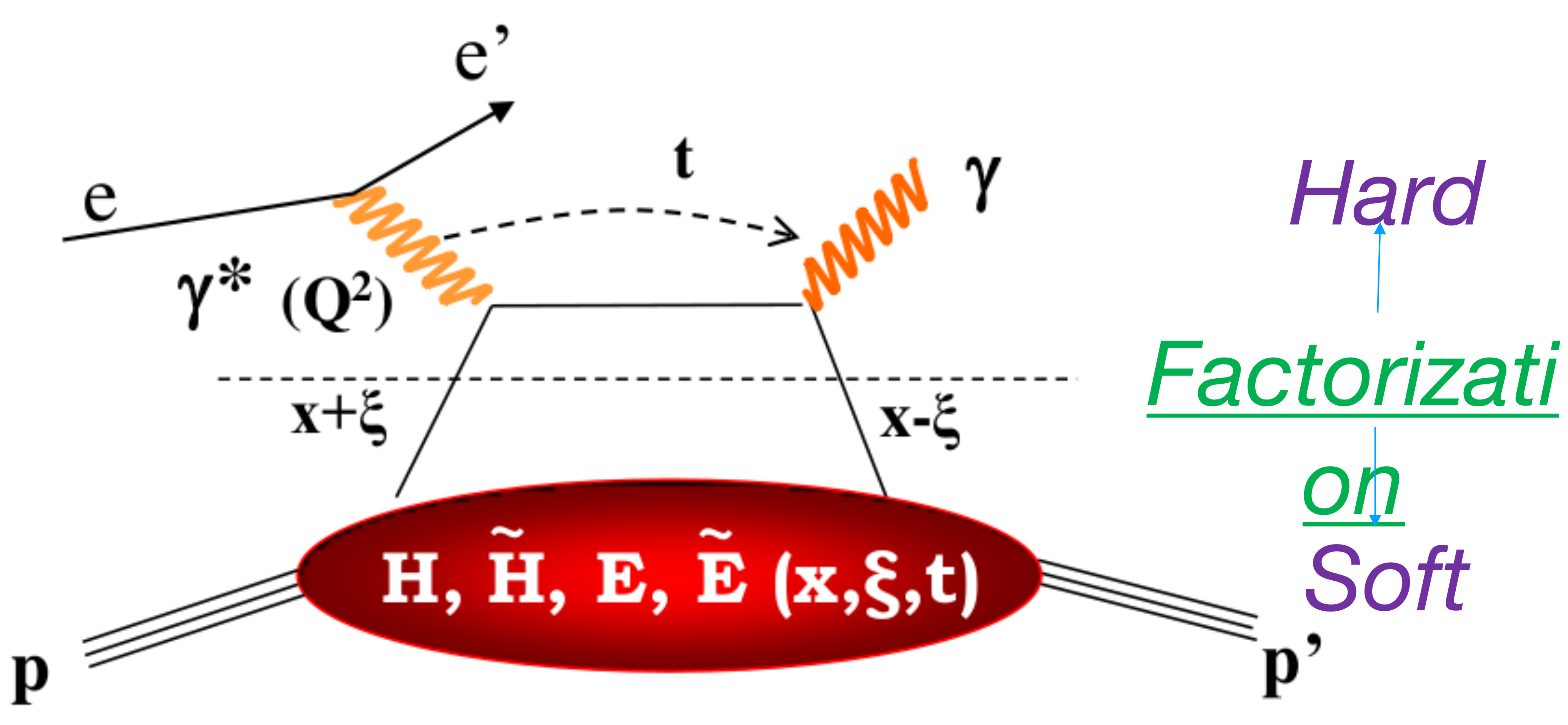
❑ Asymmetry:

$$A = \frac{I}{\left|\tau_{DVCS}\right|^2 + I + \left|\tau_{BH}\right|^2} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

❑ Decouple GPDs by angular modulations:

$$\mathrm{d}\sigma_{UU}^{\mathrm{I}} = \frac{-K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \sum_{n=0}^{3} c_{n,\mathrm{unp}}^{\mathrm{I}} \cos(n\phi \qquad \mathrm{d}\sigma_{LU}^{\mathrm{I}} = \frac{-K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \sum_{n=1}^{2} s_{n,\mathrm{unp}}^{\mathrm{I}} \sin(n\phi),$$

$$\mathrm{d}\sigma_{UU}^{\mathrm{DVCS}} = \frac{1}{Q^2}\sum_{n=0}^{2} c_{n,\mathrm{unp}}^{\mathrm{DVCS}} \cos(n\phi), \qquad \mathrm{d}\sigma_{LU}^{\mathrm{DVCS}} = \frac{1}{Q^2} s_{1,\mathrm{unp}}^{\mathrm{DVCS}} \sin\phi,$$



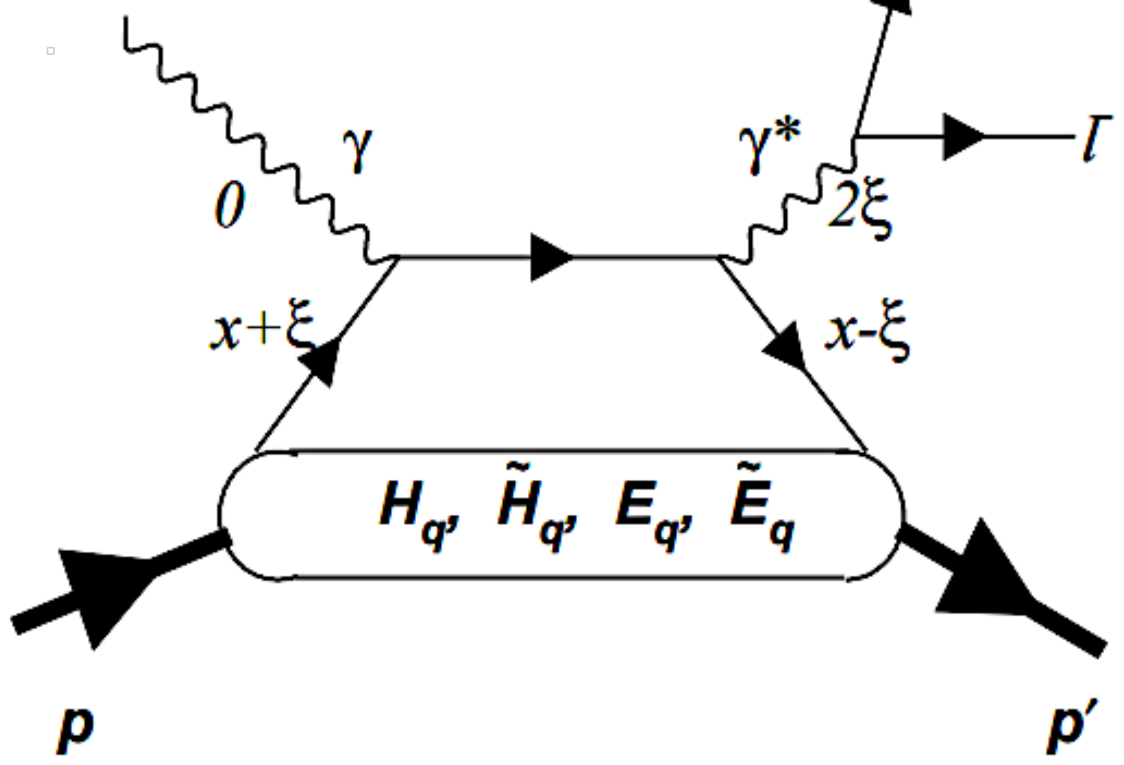
Polarization	Asymmetries	CFFs
Longitudinal Beam	A_{LU}	$Im\{\mathcal{H}_p,\widetilde{\mathcal{H}}_p,\mathcal{E}_p\}$ $Im\{\mathcal{H}_n,\widetilde{\mathcal{H}}_p,\mathcal{E}_n\}$
Longitudinal Target	A_{UL}	$Im\{\mathcal{H}_p,\widetilde{\mathcal{H}}_p\}$ $Im\{\mathcal{H}_n,\mathcal{E}_n,\widetilde{\mathcal{E}}_n\}$
Long. Beam *+ Long. Target*	A_{LL}	$Re\{\mathcal{H}_p,\widetilde{\mathcal{H}}_p\}$ $Re\{\mathcal{H}_n,\mathcal{E}_n,\widetilde{\mathcal{E}}_n\}$
Transverse Target	A_{UT}	$Im\{\mathcal{H}_p,\mathcal{E}_p\}$ $Im\{\mathcal{H}_n,\mathcal{E}_n\}$
Long. Beam +Trans.Targt	A_{LT}	$Re\{\mathcal{H}_p,\mathcal{E}_p\}$ $Re\{\mathcal{H}_n,\mathcal{E}_n\}$

Generalized Parton Distributions

- **Three additional exclusive processes → Crucial to fully extract GPDs**

Timelike Compton

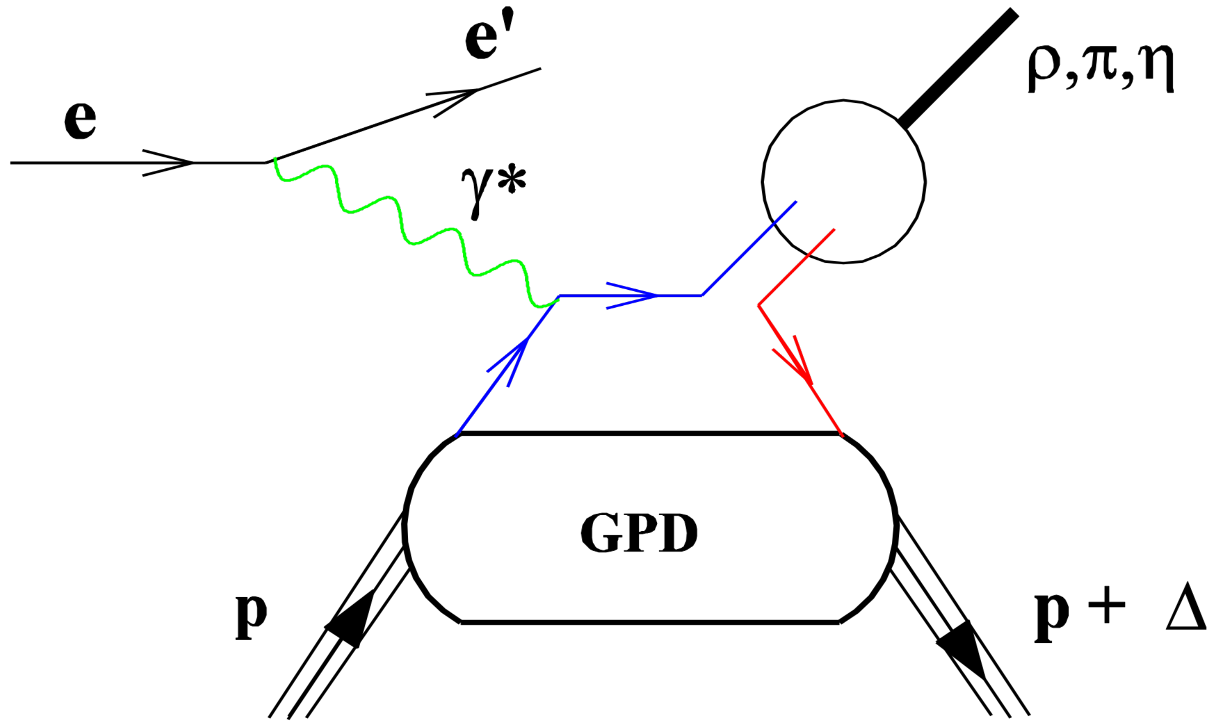
$\gamma + N \rightarrow N + l^{+} + l^{-}$



- ✓ Inverse of the space-like DVCS
- ✓ Extract the real part of CFFs
- ✓ Complimental to DVCS
- ✓ New experiments: CLAS12, SoLID

Deep Virtual Meson

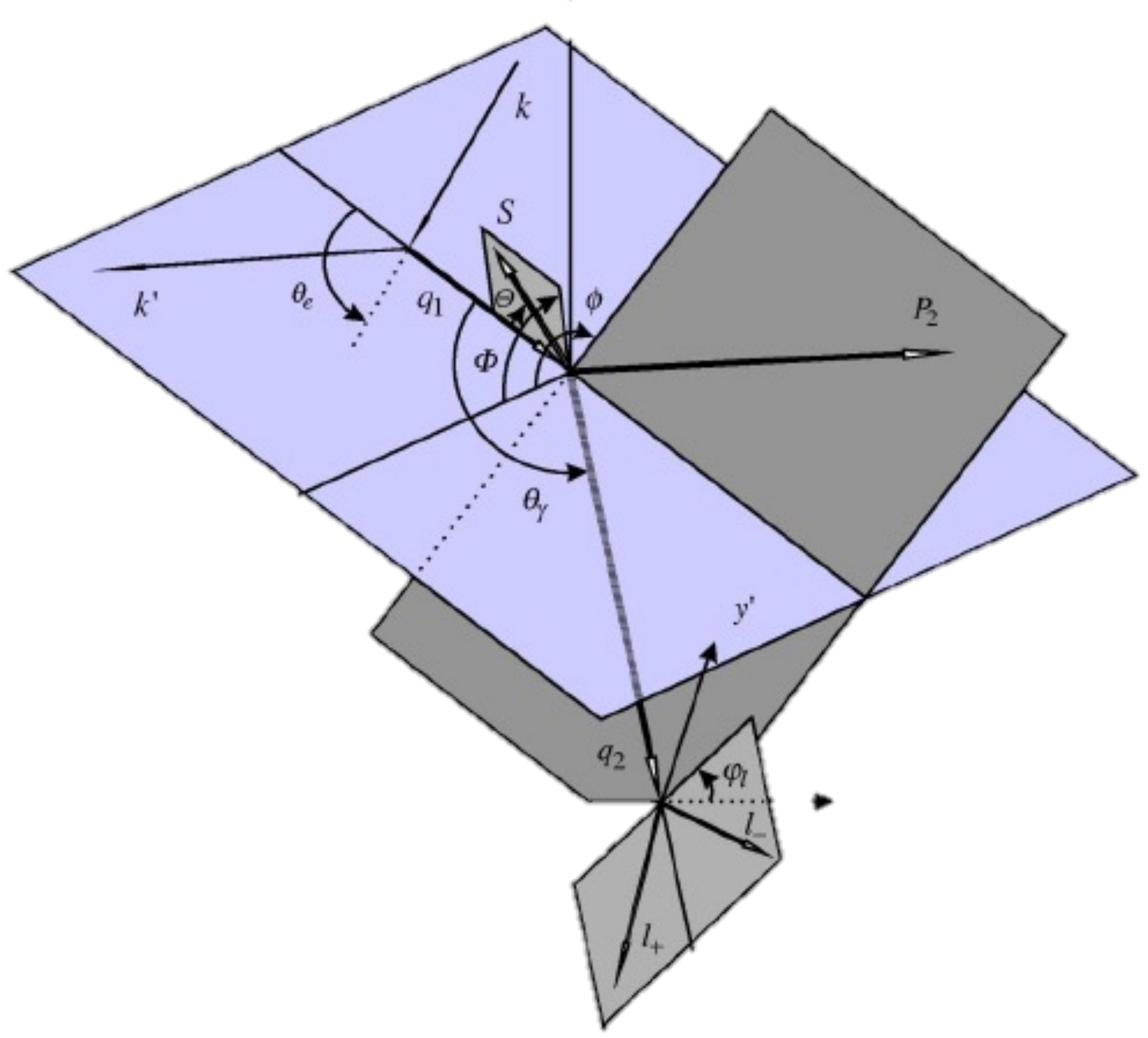
$e + N \rightarrow e' + N' + \pi^{0,\pm}\ (K^{0,\pm}, \eta, \rho, \omega, \ldots)$



- ✓Vector mesons sensitive to H, E.
- ✓Pseudoscalar mesons sensitive to $\tilde{H}$ and $\tilde{E}$.
- ✓neutron + pseudoscalar uniquely sensitive to $\tilde{E}$
- ✓sensitive to chiral-odd GPDs ($H_T, E_T, \tilde{H}_T, \tilde{E}_T$)
- ✓New experiments: CLAS12, SoLID, Hall-C

Double-DVCS:

$e + N \rightarrow e' + N + l^{+} + l^{-}$

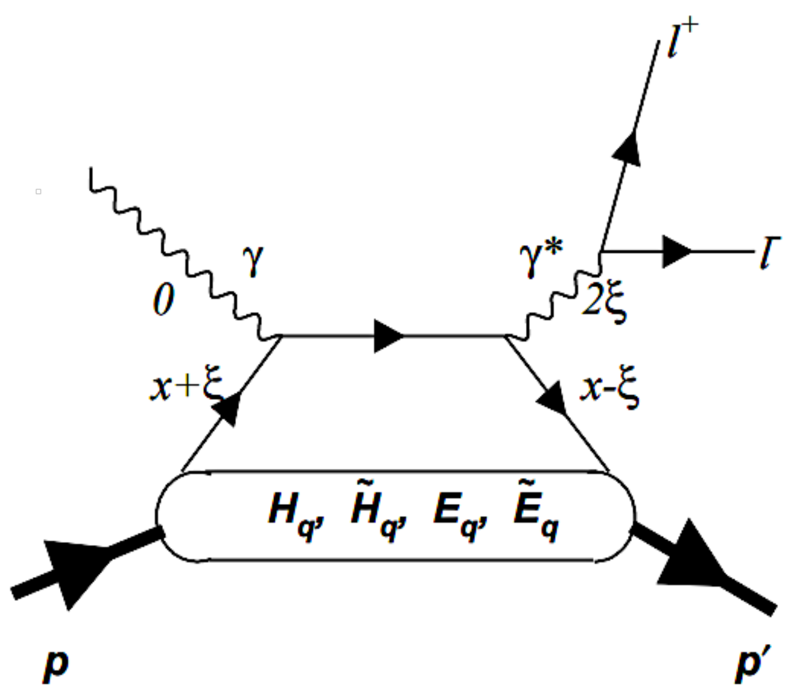


- ✓ Lepton pairs in the final states
- ✓ Access GPDs ***beyond the x=ξ limit***
- ✓ New experiments: NONE

❑ Much less been done!

Generalized Parton Distributions

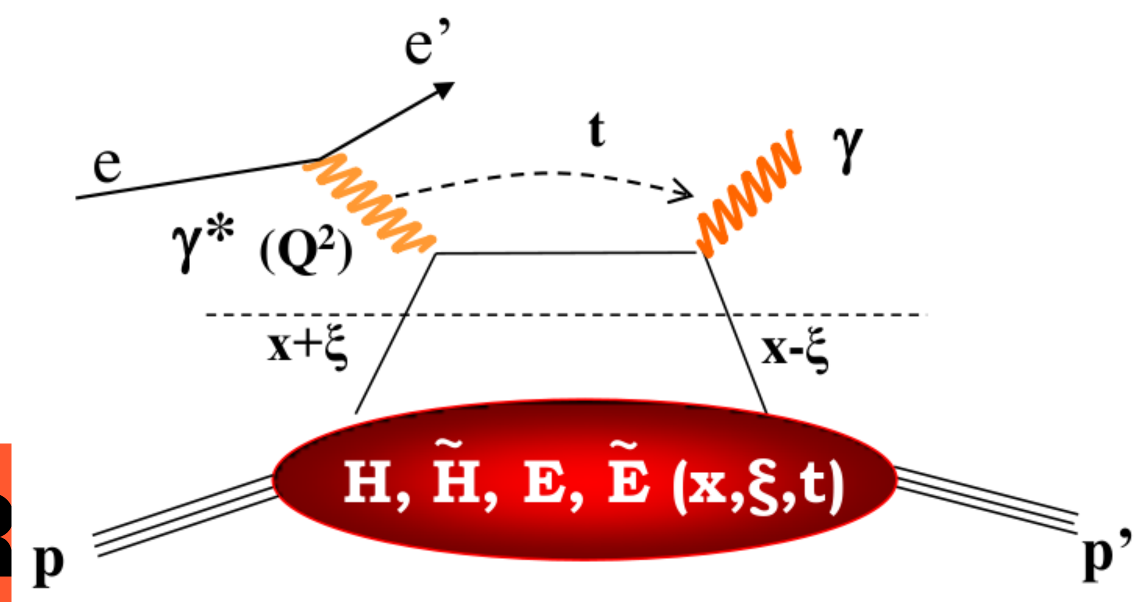
- Exclusive processes to fully extract GPDs



(Im, x=□)

DVCS: spin asymmetries

TCS with polarized beam

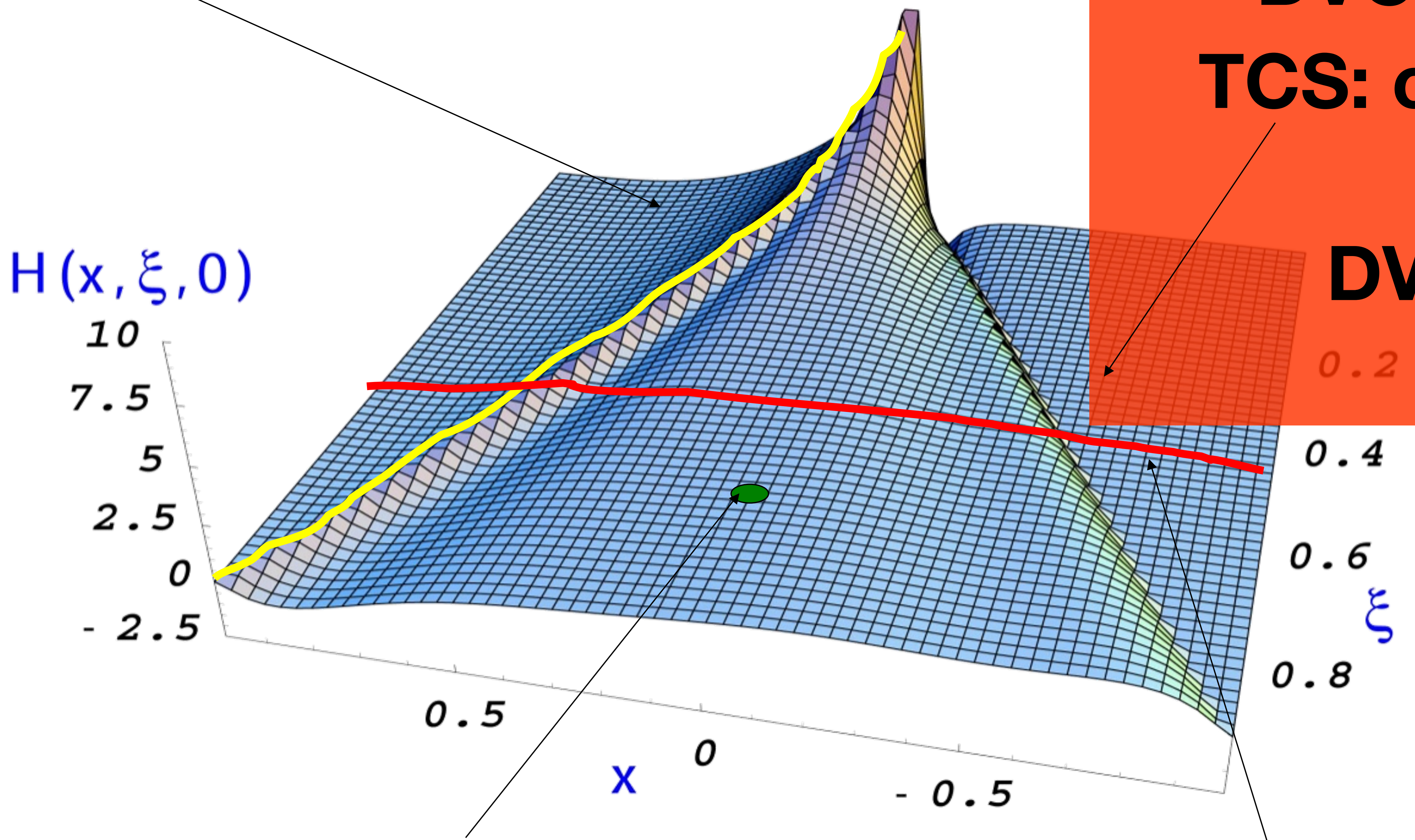


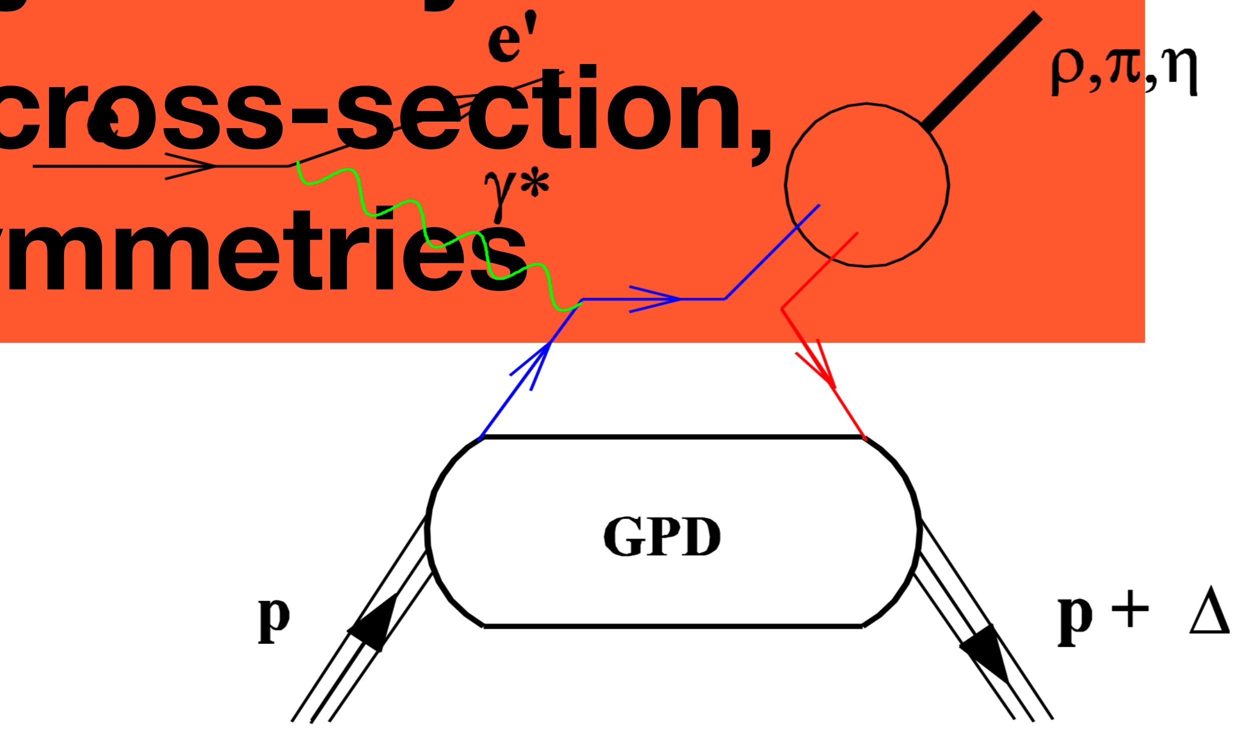
(R

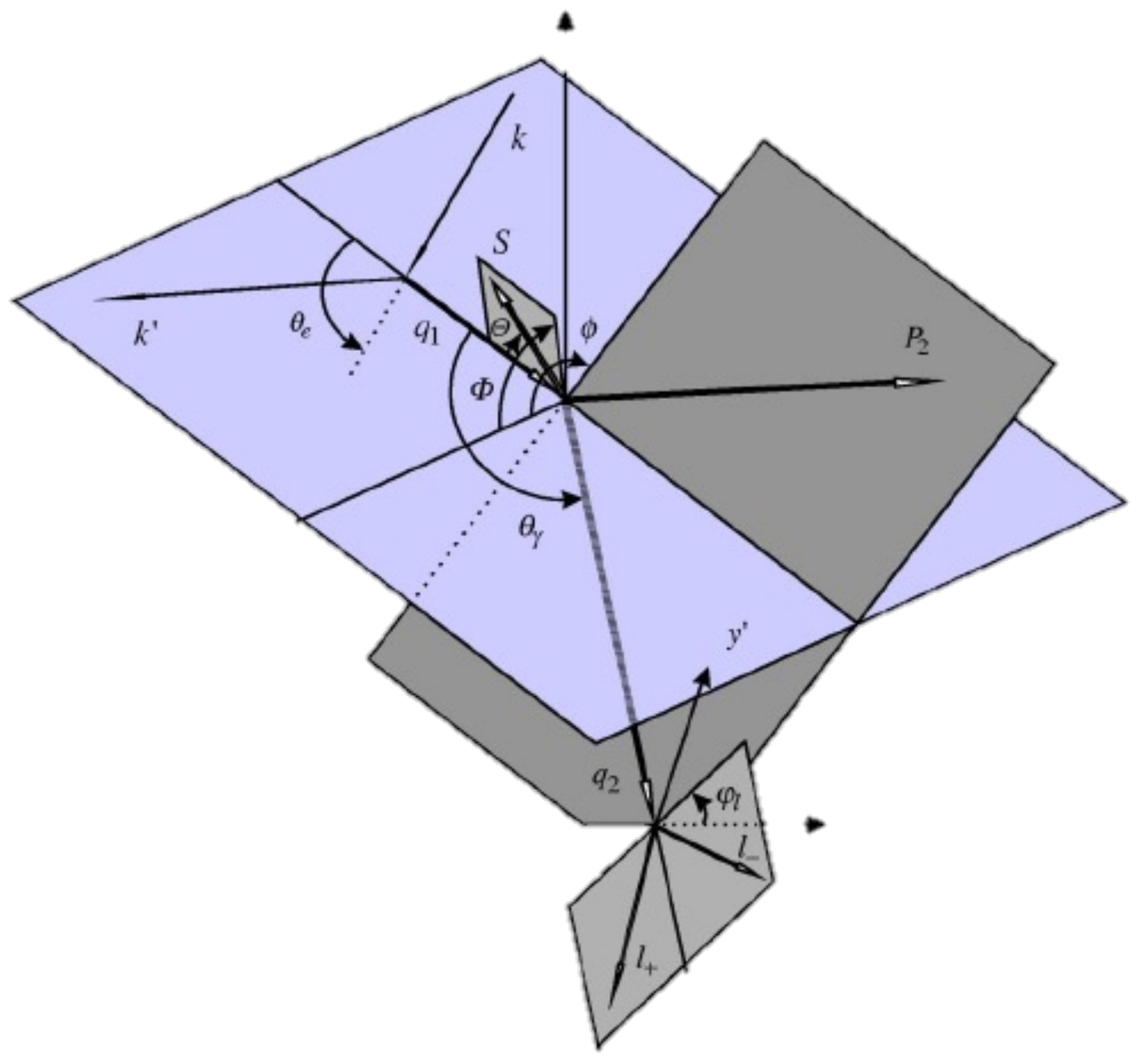
DVCS: charge asymmetry

TCS: cross-section, lin beam asymmetry

DVMP: cross-section, asymmetries







(Im, $x \neq \xi$, $x < |\xi|$)

Double DVCS

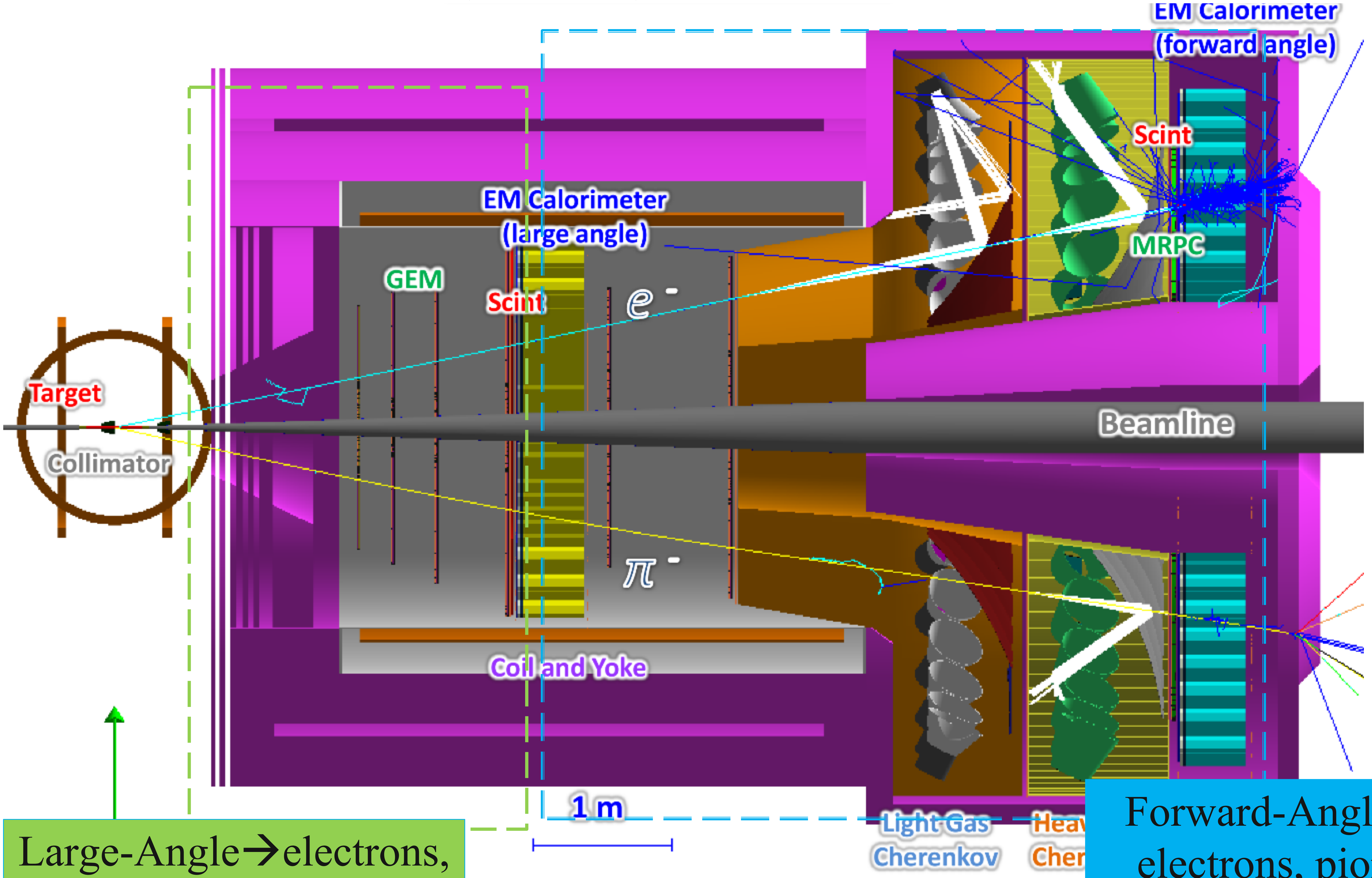
($|Im|^2+|Re|^2$)

DVCS: cross section

DVMP: cross-section, asymmetries

GPD Study on SoLID

- Current SIDIS/Jpsi Setup for GPDs:



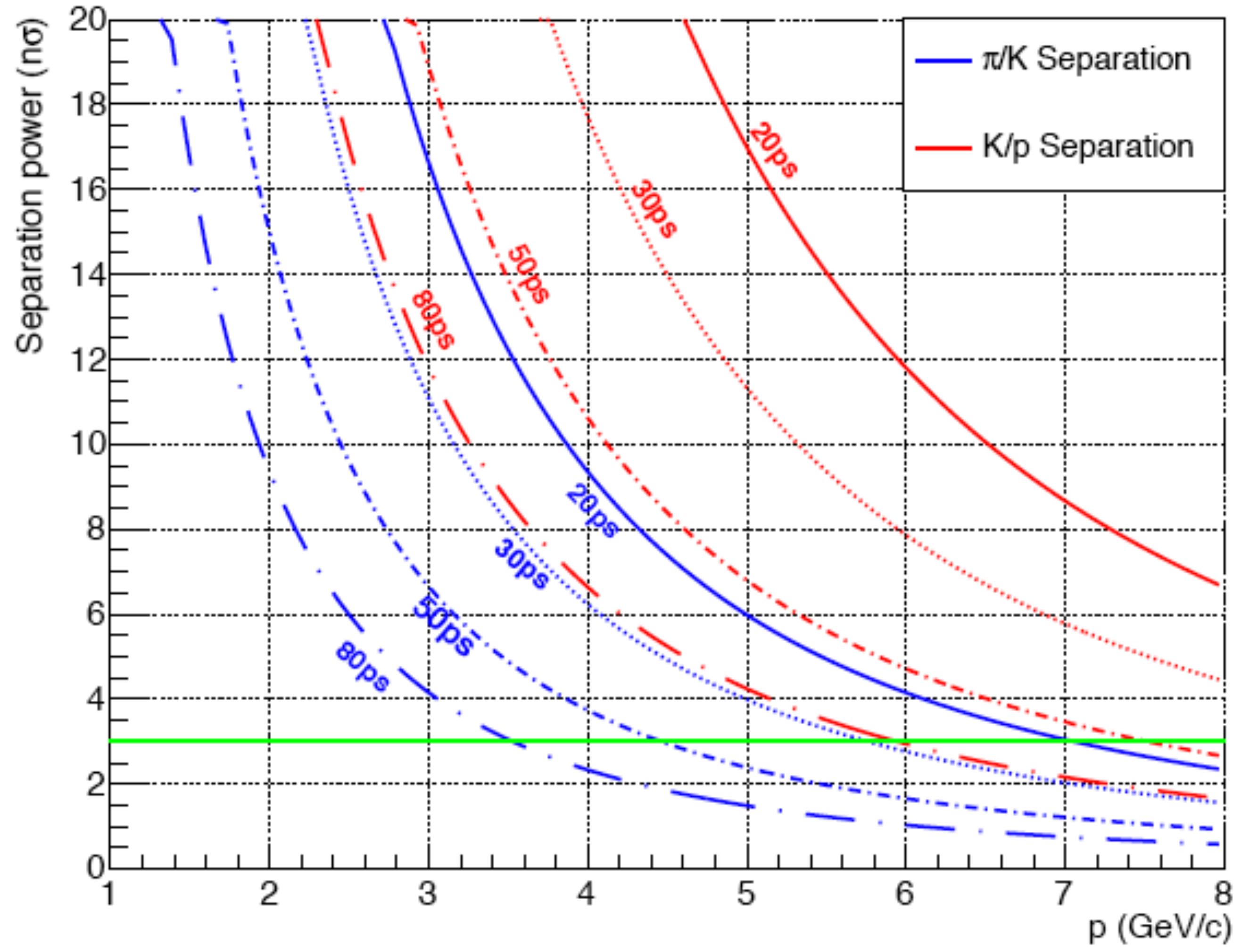
Large-Angle→electrons, photons and proton

Forward-Angle : electrons, pion, photons and proton

- Electron resolutions :
  δP/P ~ 2%,
  δθ ~ 0.6mrad,
  δΦ ~ 5mrad
  δVertex ~ 0.5cm

- Photon determined by ECAL:
  δx_EC = 1cm,
  δy_EC=1cm,
  δE/E= 5%/sqrt(E)

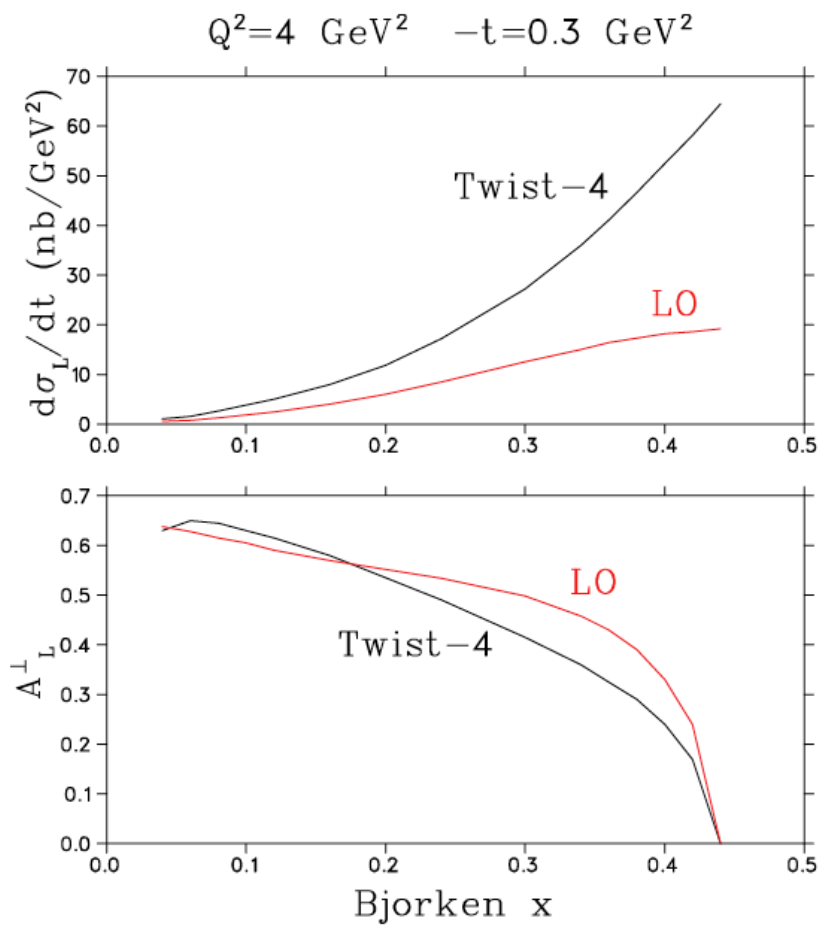
- Proton determined by TOF



GPD Study on SoLID

- **SoLID-DVMP:** $e + \vec{n} \rightarrow e' + p + \pi^-$
  - ☐ Reduced high-twist effect in DVCS Asymmetries
  - ☐ Asymmetry (no L/T separation):

$$A(\phi,\phi_s) = \frac{d^3\sigma_{UT}(\phi,\phi_s)}{d^2\sigma_{UU}(\phi)} = -\sum_k A_{UT}^{\sin(\mu\phi+\lambda\phi_s)_k} \sin(\mu\phi+\lambda\phi_s)_k$$



- ☐ Analyze angular modules to decouple LT contribution

$$A_{UT}^{\sin(\phi-\phi_s)} \sim \frac{d\sigma_{00}^{+-}}{d\sigma_L\binom{++}{00}} \sim \frac{\mathrm{Im}(\tilde{E}^*\tilde{H})}{|\tilde{E}|^2} \text{ where } \tilde{E} \gg \tilde{H}$$

$$A_{UT}^{\sin(\phi_S)} \sim \mathrm{Im}[M^*_{0+++}M_{0-0+} - M^*_{0-++}M_{0+0+}],$$

helicities: [pion, neutron, photon, proton]

$$\mathcal{M}_{0-,++} = e_0\sqrt{1-\xi^2}\int \mathrm{d}x\mathcal{H}_{0-,++}H_T,$$

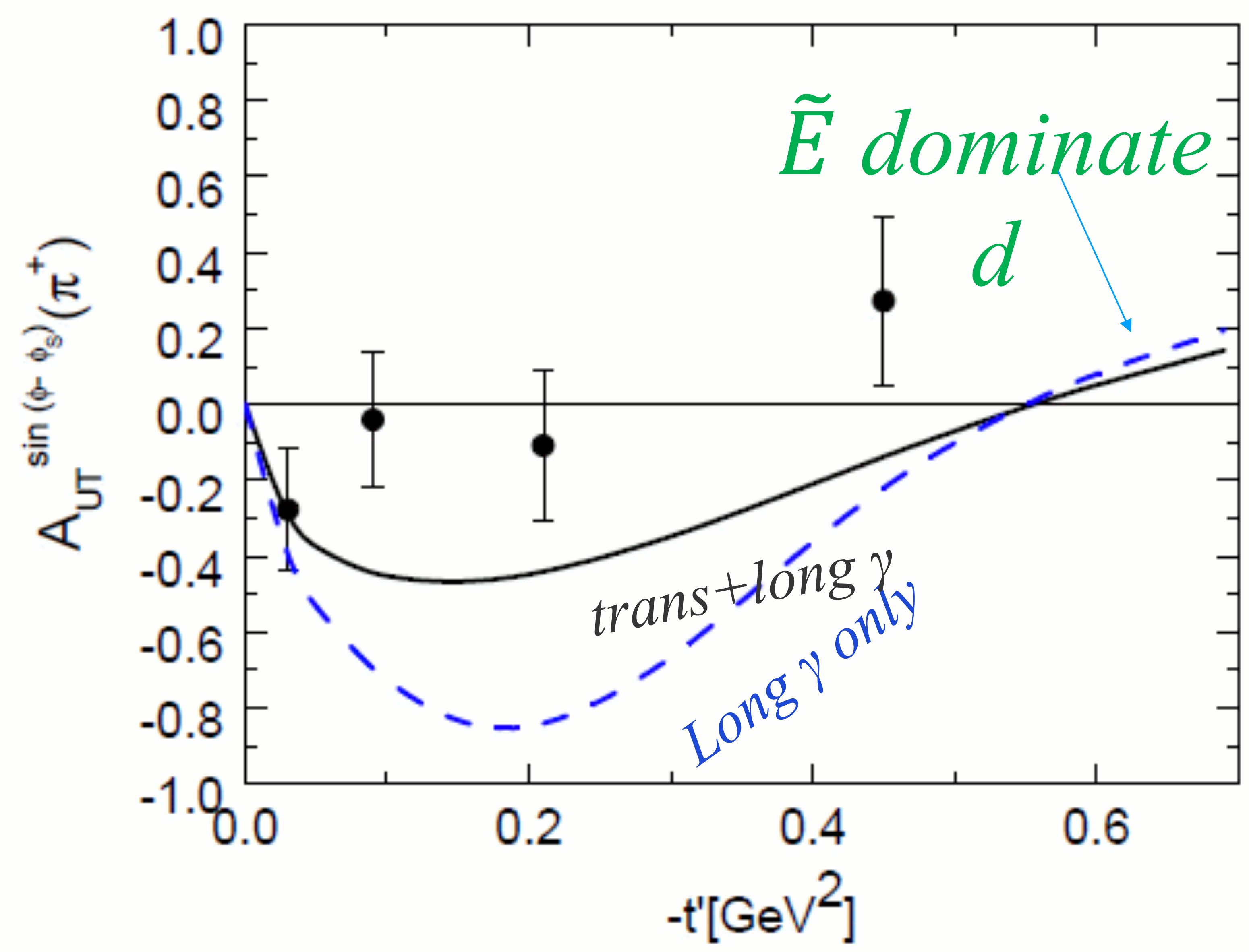
$$\mathcal{M}_{0+,\pm+} = -e_0\frac{\sqrt{t_{\min}-t}}{4m}\int \mathrm{d}x\mathcal{H}_{0-,++}\bar{E}_T.$$

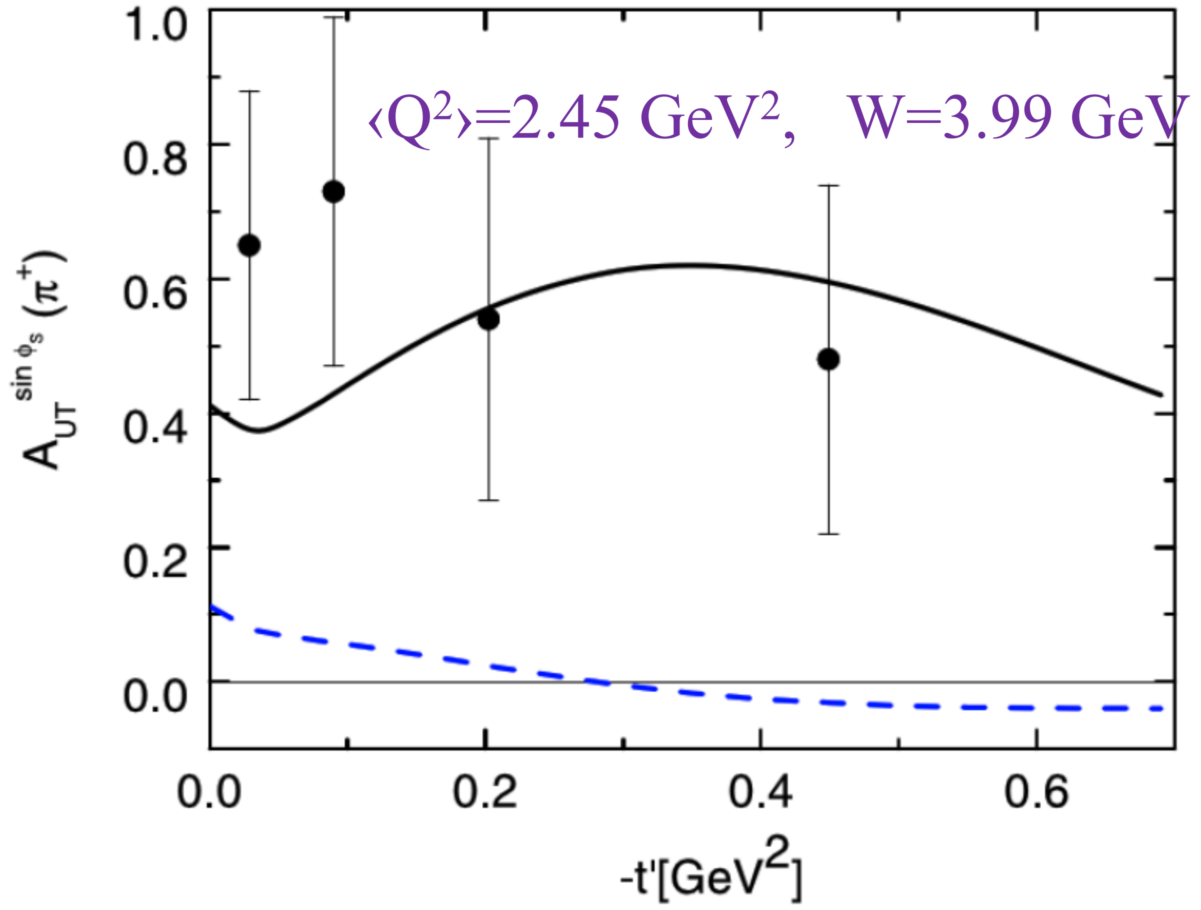
HERMES Data:

- ✓ π^+, 27.6 GeV, trans ^{1}H, w/o L/T separation
- ✓ ‹x_B›=0.13, ‹Q2›~2.4 GeV^2,
- ✓ Consistent with GPD models based on the $\tilde{E}$ dominance

S. Goloskokov et. al. PLB 682(2010)345

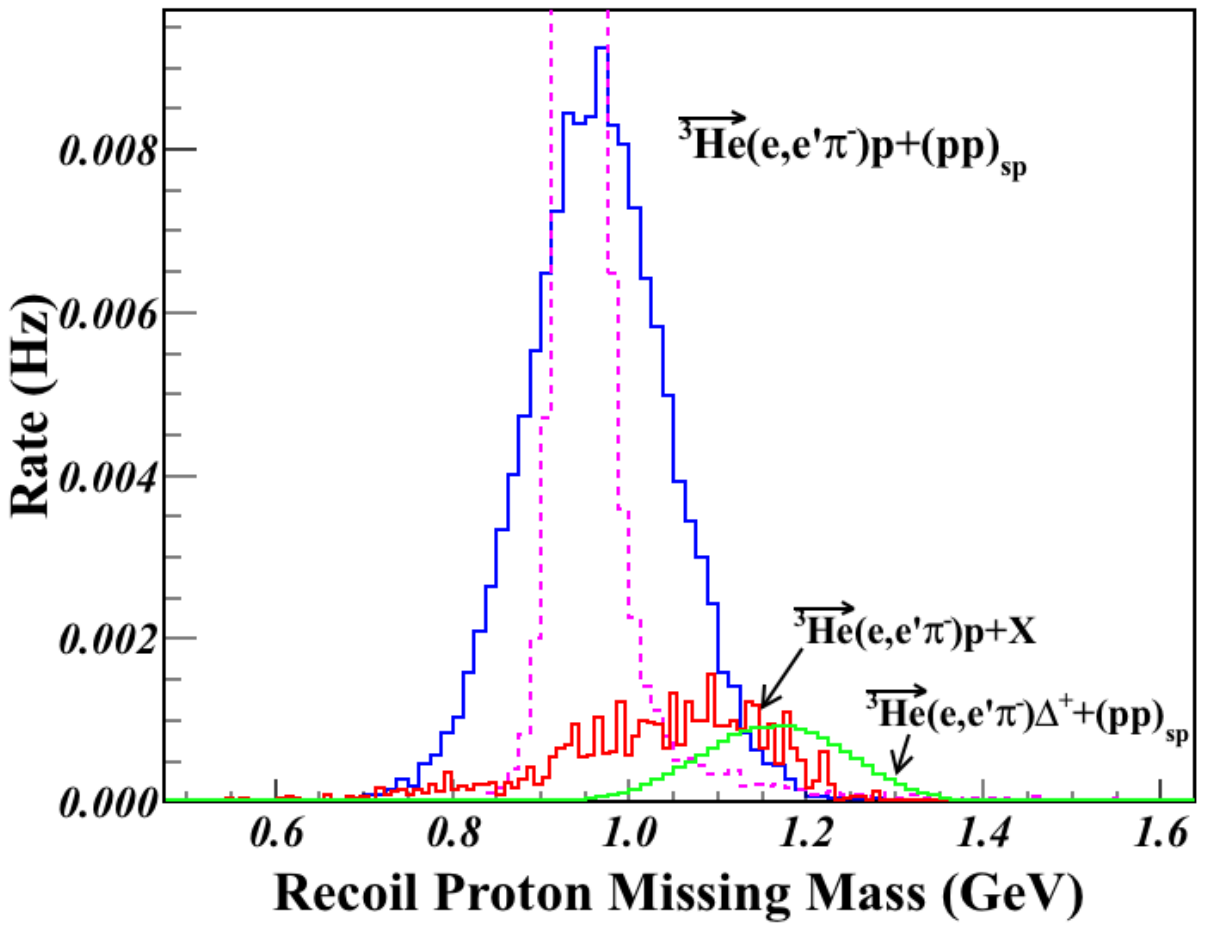
Eur Phys.J. C65(2010)137

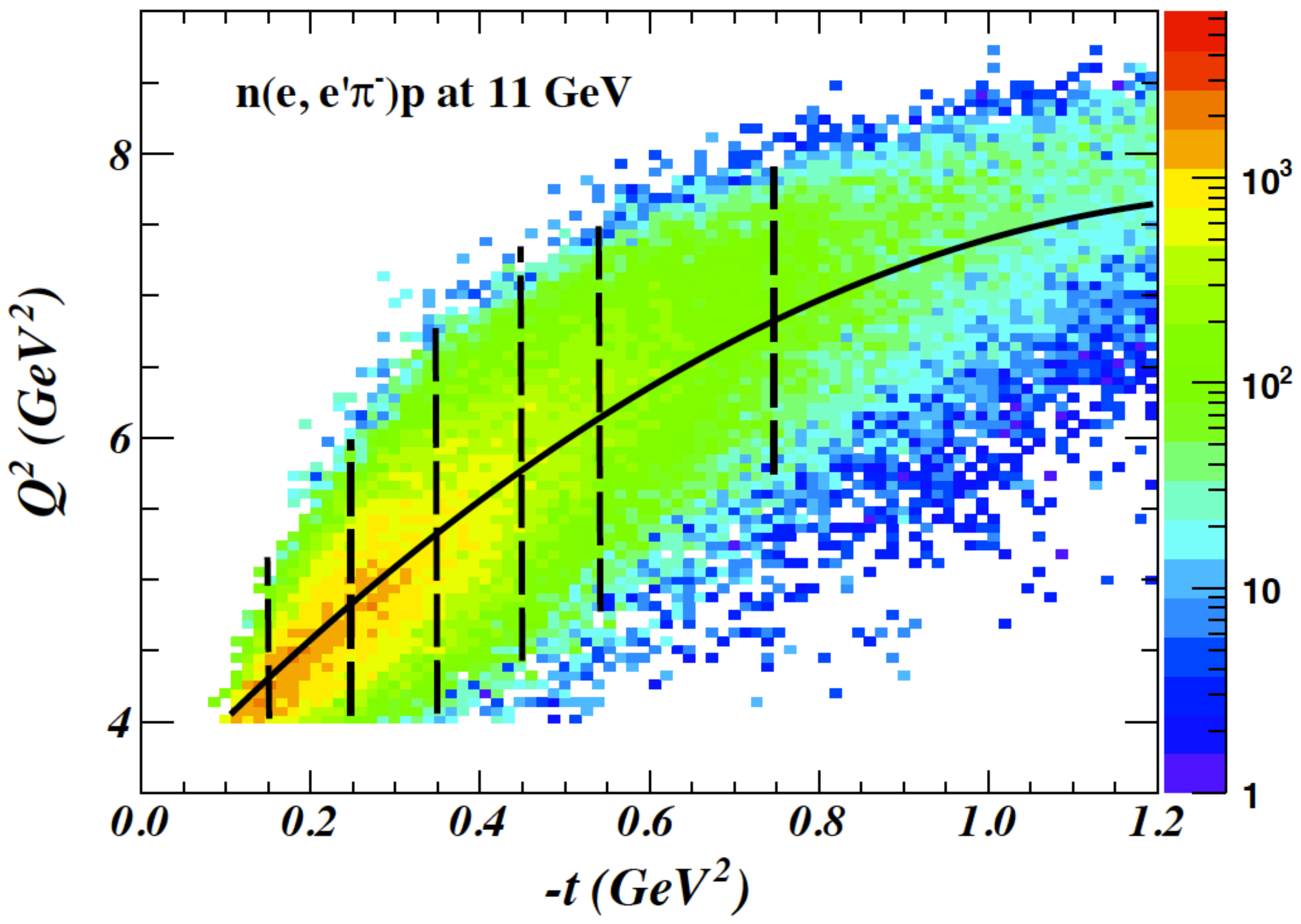




GPD Study on SoLID

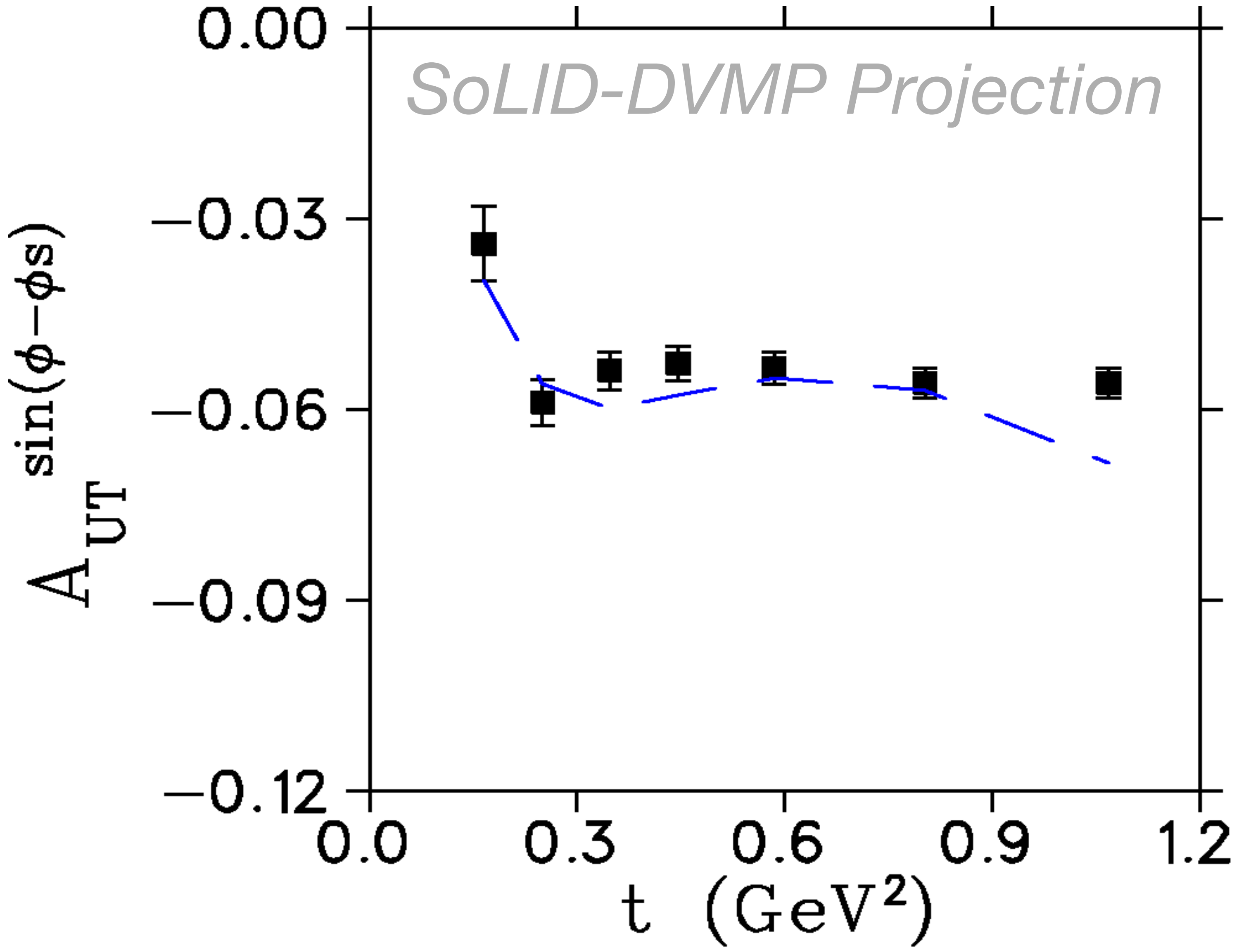
- **SoLID-DVMP:** $e + \vec{n} \rightarrow e' + p + \pi^-$
  - ❑ Reconstruct DVMP events via Missing Mass from SIDIS data
  - ❑ Extract the first neutron DVMP asymmetries

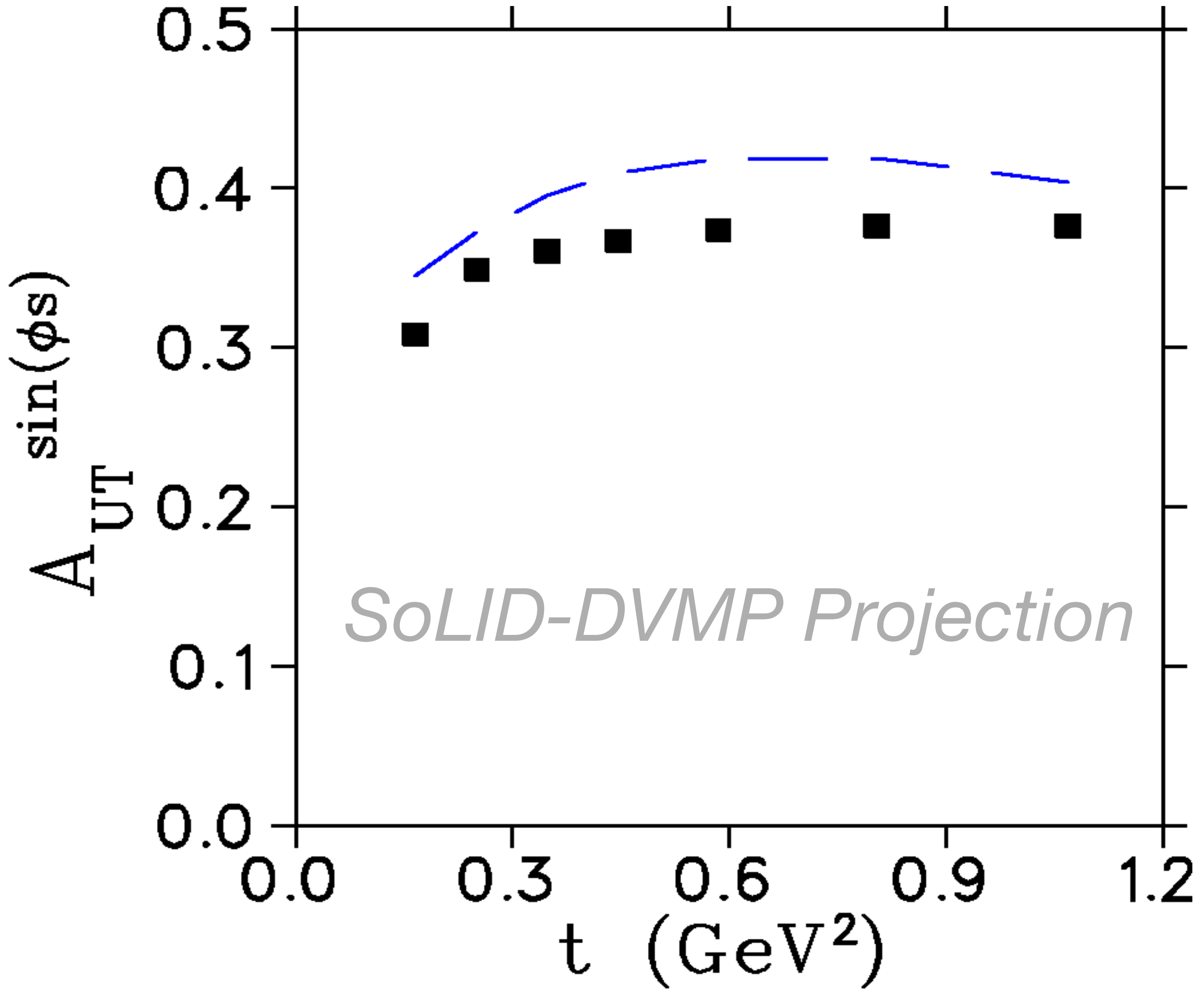




SoLID Projected Data:

- ❑ π^-, 11.0 GeV, trans ^{3}He, w/o L/T separation
- ❑ Q2>4 GeV^2, large t coverage
- ❑ Simultaneous extraction of all angular moments
- ❑ Precision improved x10+
- ❑ Pioneer study before EIC





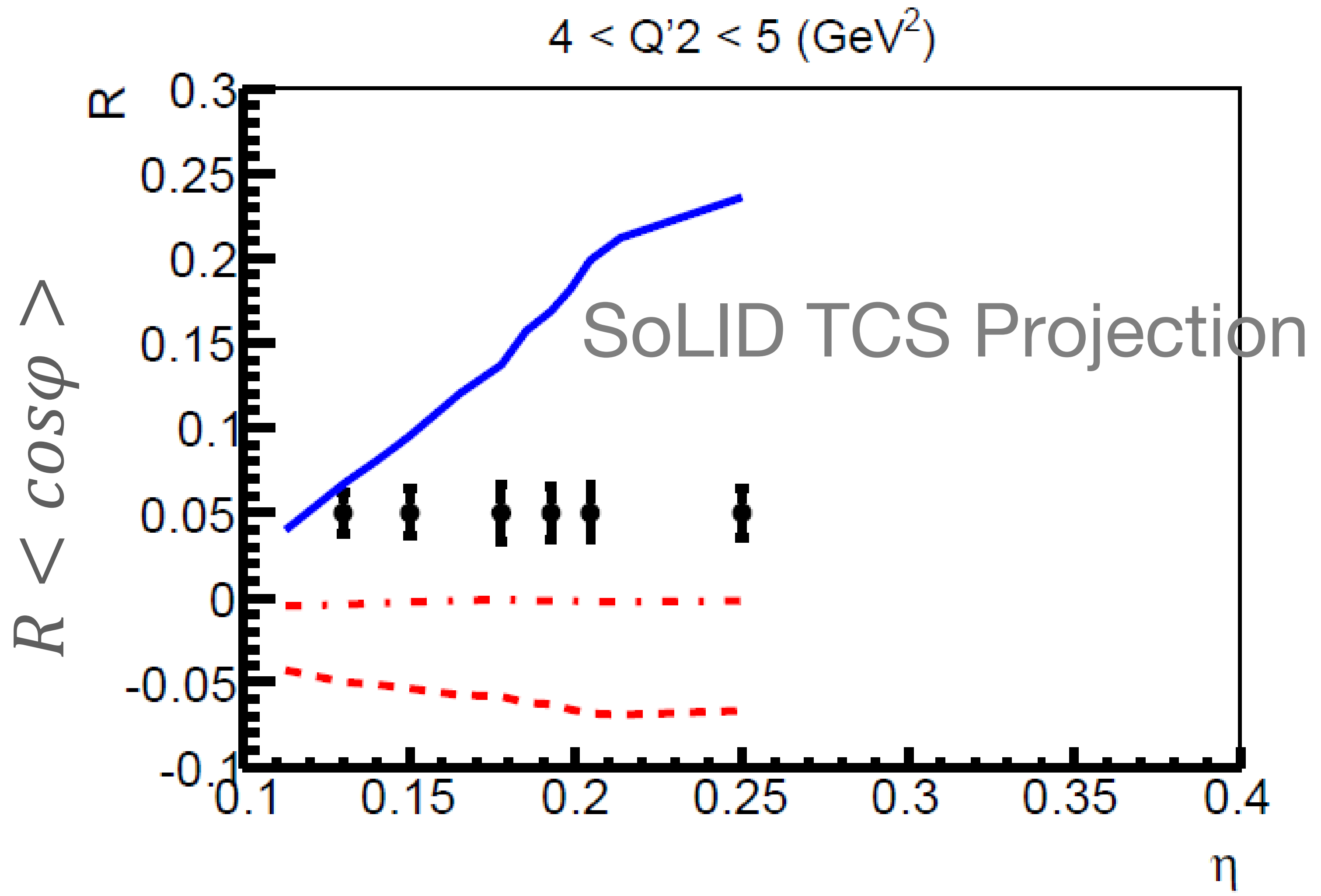
GPD Study on SoLID

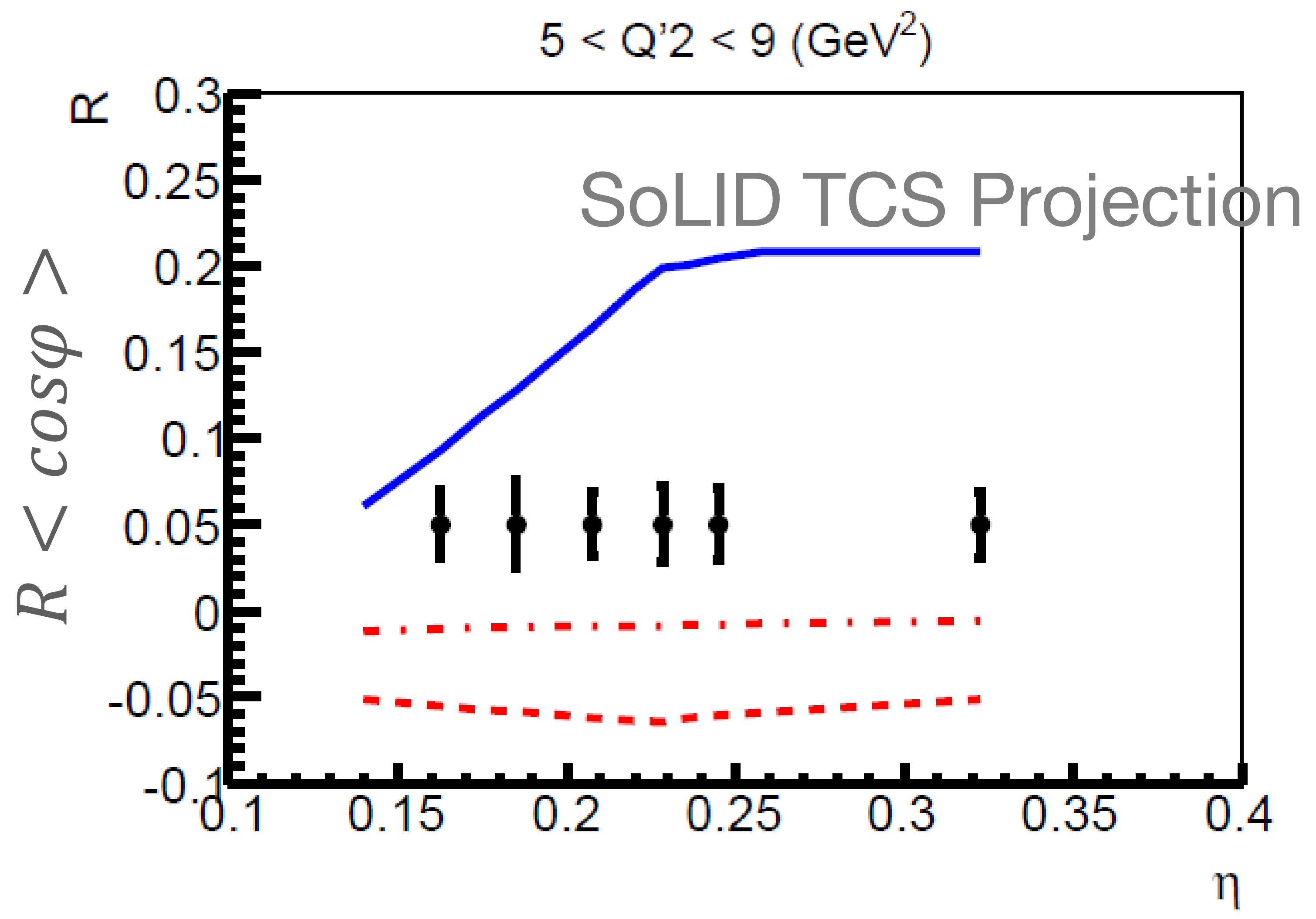
- **SoLID-TCS:** $\gamma + N \rightarrow N + e^{+} + e^{-}$
  - ☐ Time-Like Compton Scattering (TCS):
    - ✓ Different angular moments for TCS & BH Interf.-terms

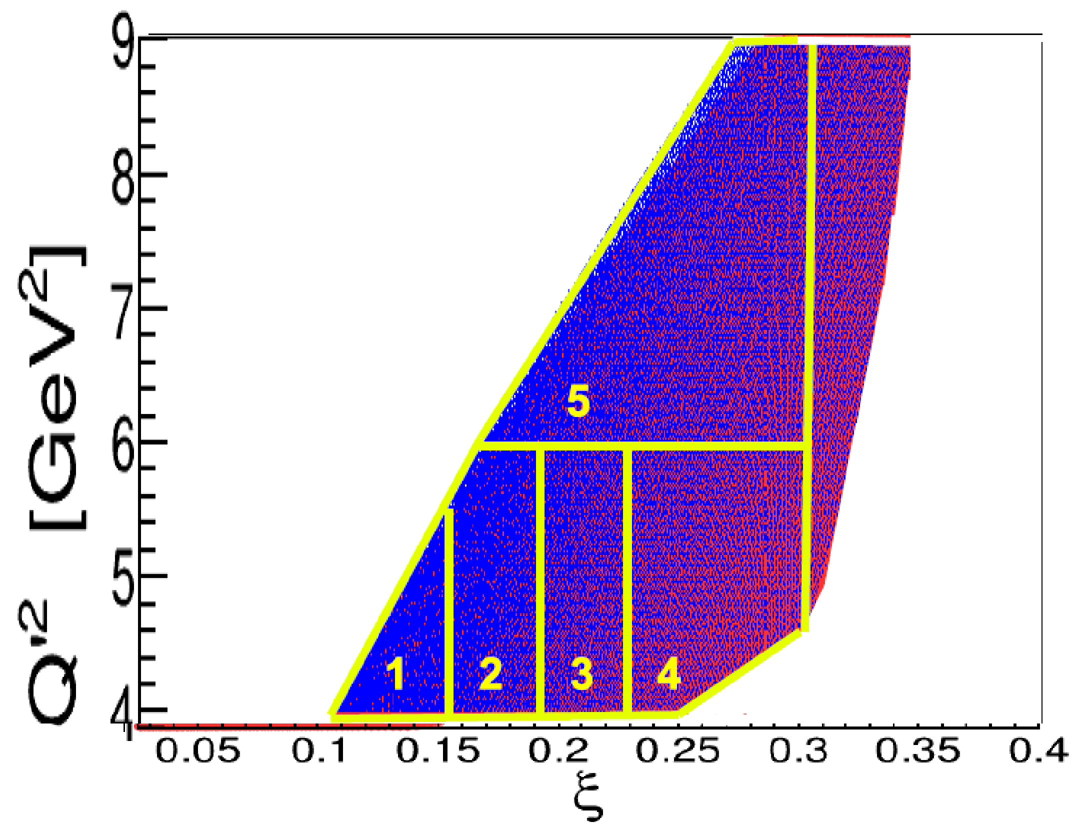
$$\sigma_{INT}^{TCS,unpol} \propto \boldsymbol{\cos\varphi}\, Re\widetilde{M}^{--},\ \sigma_{INT}^{TCS,cir-pol} \propto \boldsymbol{\sin\varphi}\, Im\widetilde{M}^{--}$$

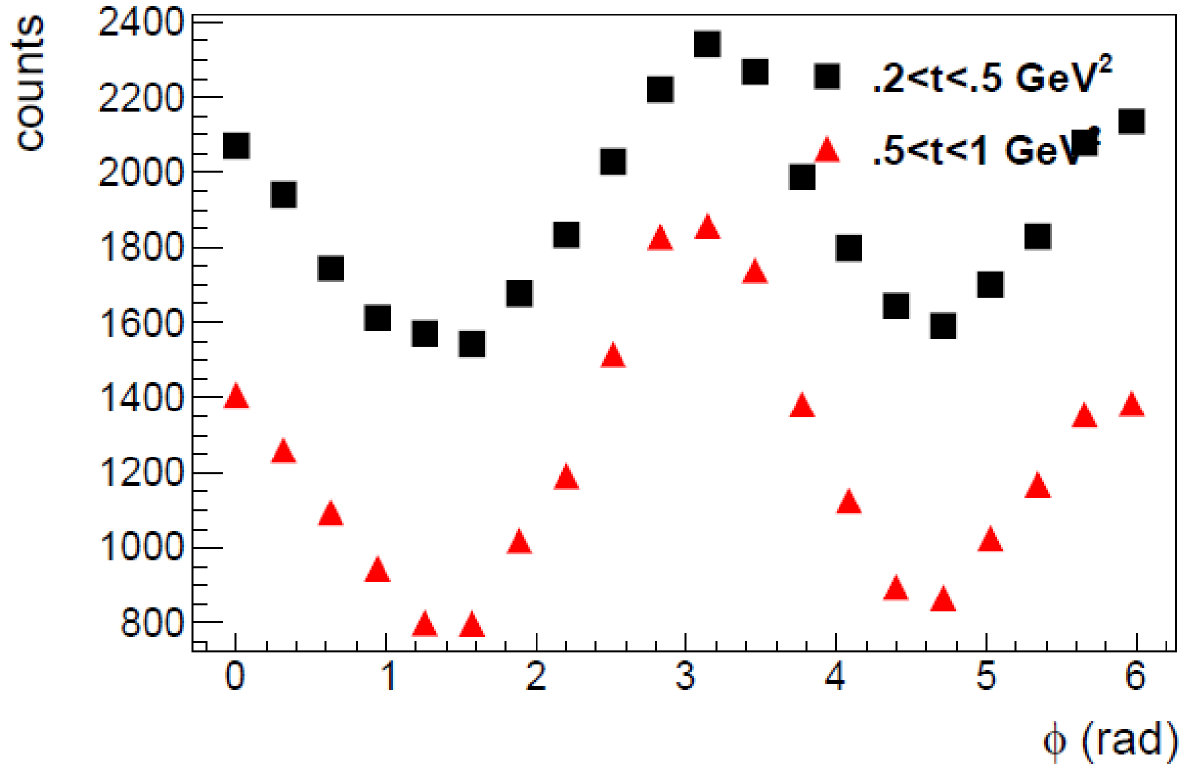
$$\tilde{M}^{--} = \frac{2\sqrt{t_0 - t}}{M}\frac{1-\eta}{1+\eta}\left[F_1\mathcal{H}_1 - \eta(F_1+F_2)\tilde{\mathcal{H}}_1 - \frac{t}{4M^2}F_2\mathcal{E}_1\right]$$

  - ☐ SoLID-TCS: Parallel data taking with J/Psi
    - ✓ Unpolarized LH2 target; Indirect photon-production
    - ✓ Extract $cos\varphi$ and $\sin\varphi$ modules





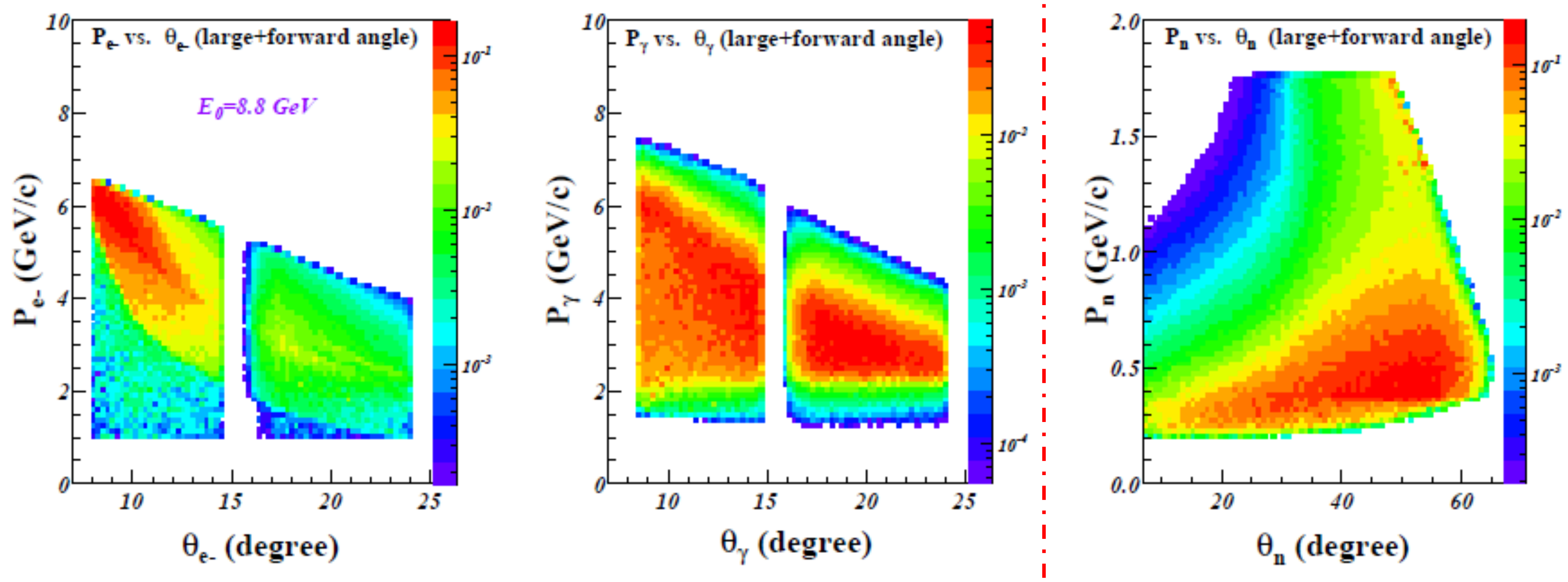




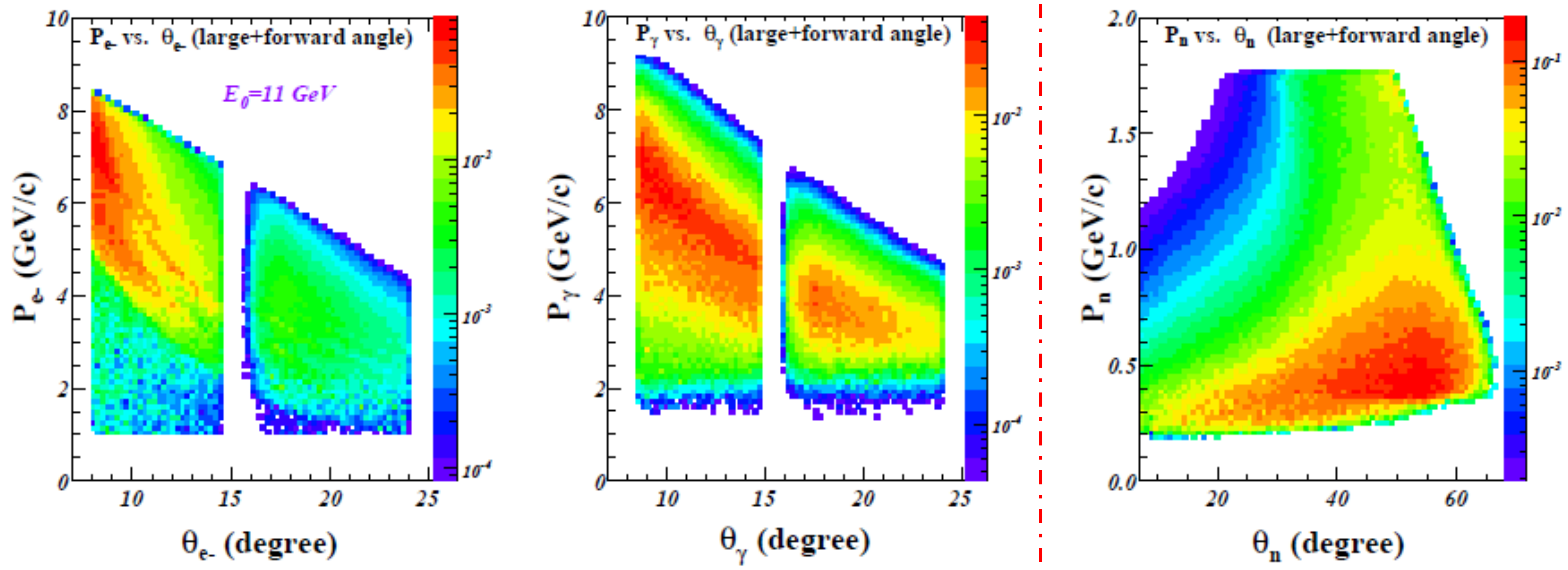
GPD Study on SoLID

- **SoLID-DVCS:** $e + \vec{n} \rightarrow e' + n + \gamma$

✓ Acceptance



(a) E_{beam}=8.8 GeV



(b) E_{beam}=11 GeV

Missing Mass Reconstruction:

✓ Integrated Rate:

E_0	8.8 GeV	11 GeV
Single Rates (Hz)		
e- (FAEC)	64.78	36.17
e- (LAEC)	2.57	1.70
γ (FAEC)	45.37	40.54
γ (LAEC)	31.05	28.83
Coincidence Rates (Hz)		
e-(FAEC)+γ(FAEC+LAEC)	36.06	20.50
e-(LAEC)+γ(FAEC+LAEC)	1.46	1.00

✓ DVCS Asymmetries

$$A_{BS} = \frac{N^+ - N^-}{N^+ + N^-}\frac{1}{P_e}$$

$$A_{TS} = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}\frac{1}{fP_TP_n},$$

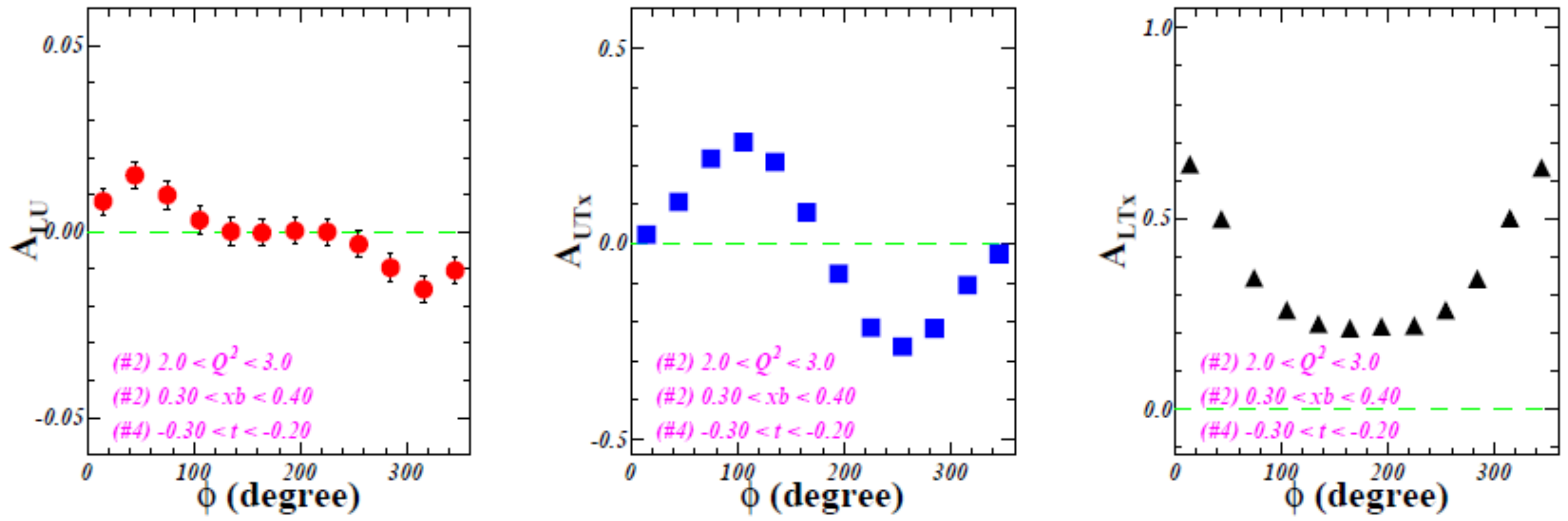
$$A_{DS} = \frac{(N^{+\uparrow} + N^{-\downarrow}) - (N^{+\downarrow} + N^{-\uparrow})}{N^{+\uparrow} + N^{+\downarrow} + N^{-\uparrow} + N^{-\downarrow}}\frac{1}{fP_TP_nP_e},$$

GPD Study on SoLID

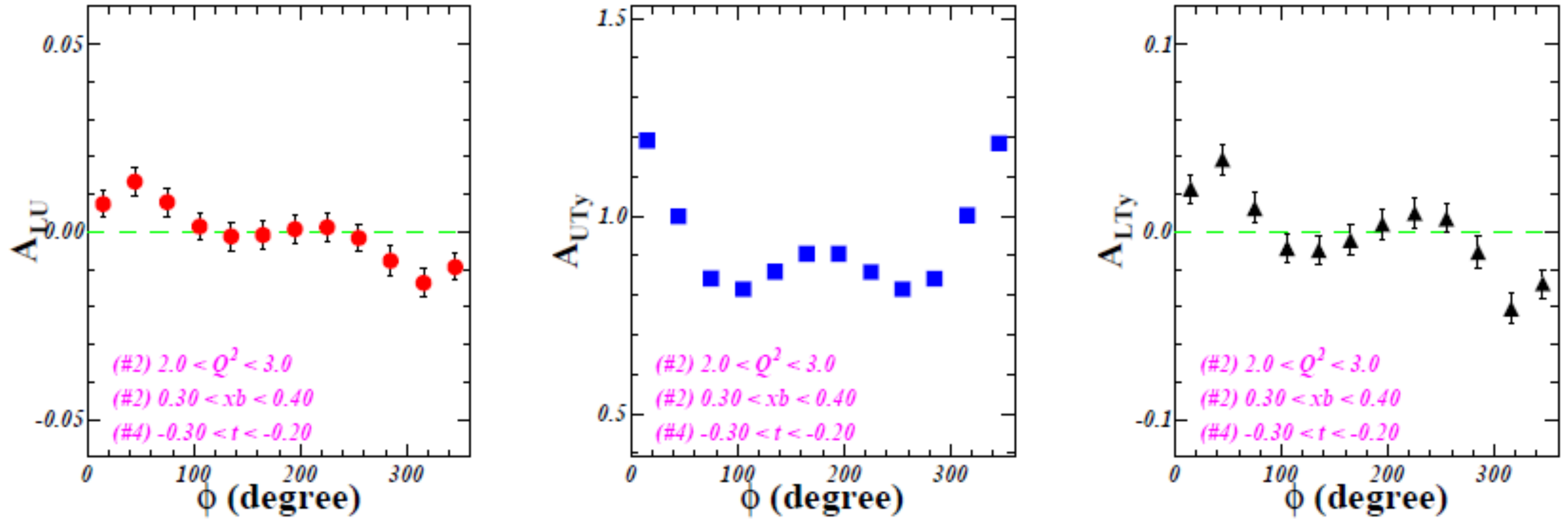
- **SoLID-DVCS:** $e + \vec{n} \rightarrow e' + n + \gamma$

21 days on E0=8.8GeV, 48 days on E0=11GeV

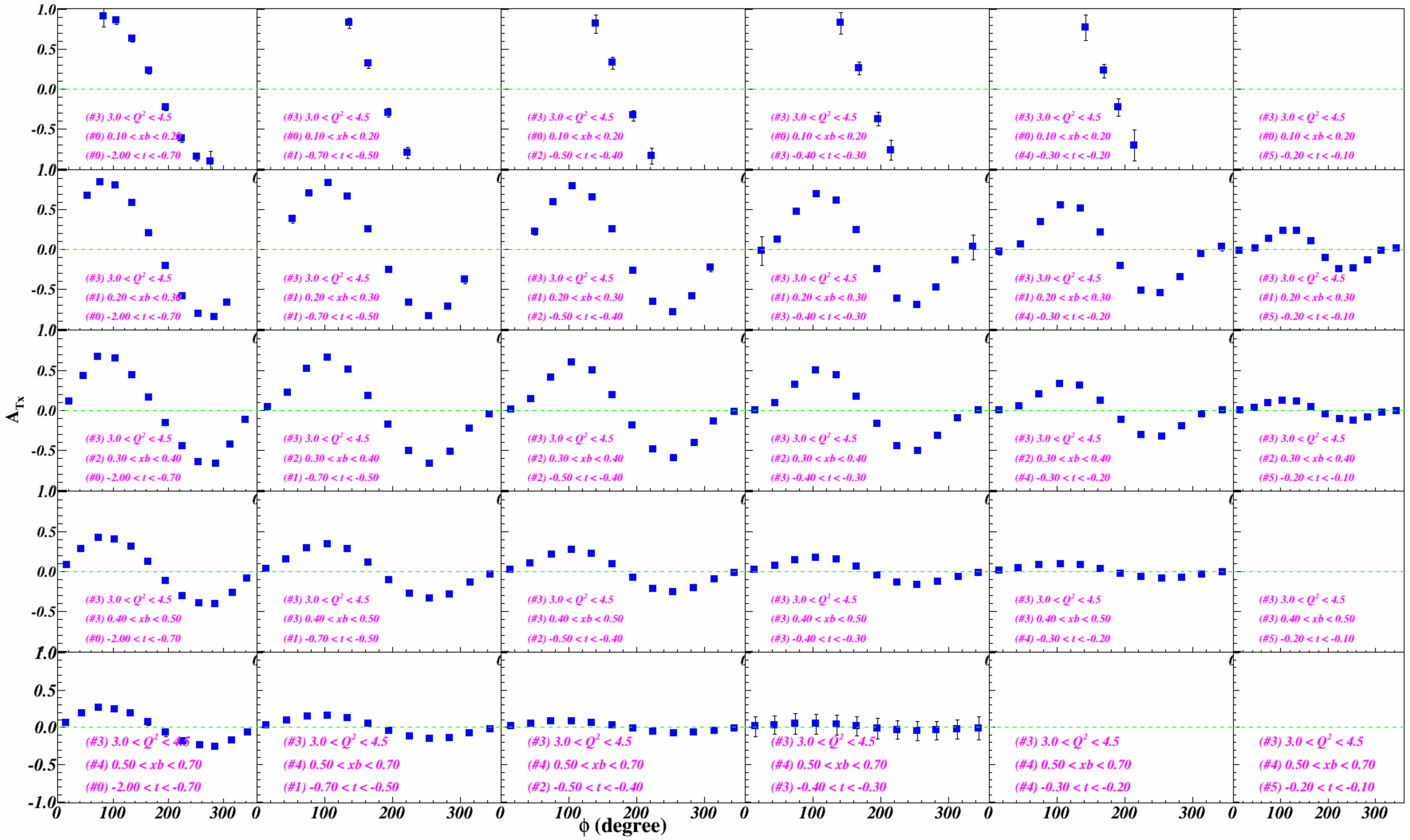
  - ✓ Asymmetry Projection:



(a) Tx Polarization



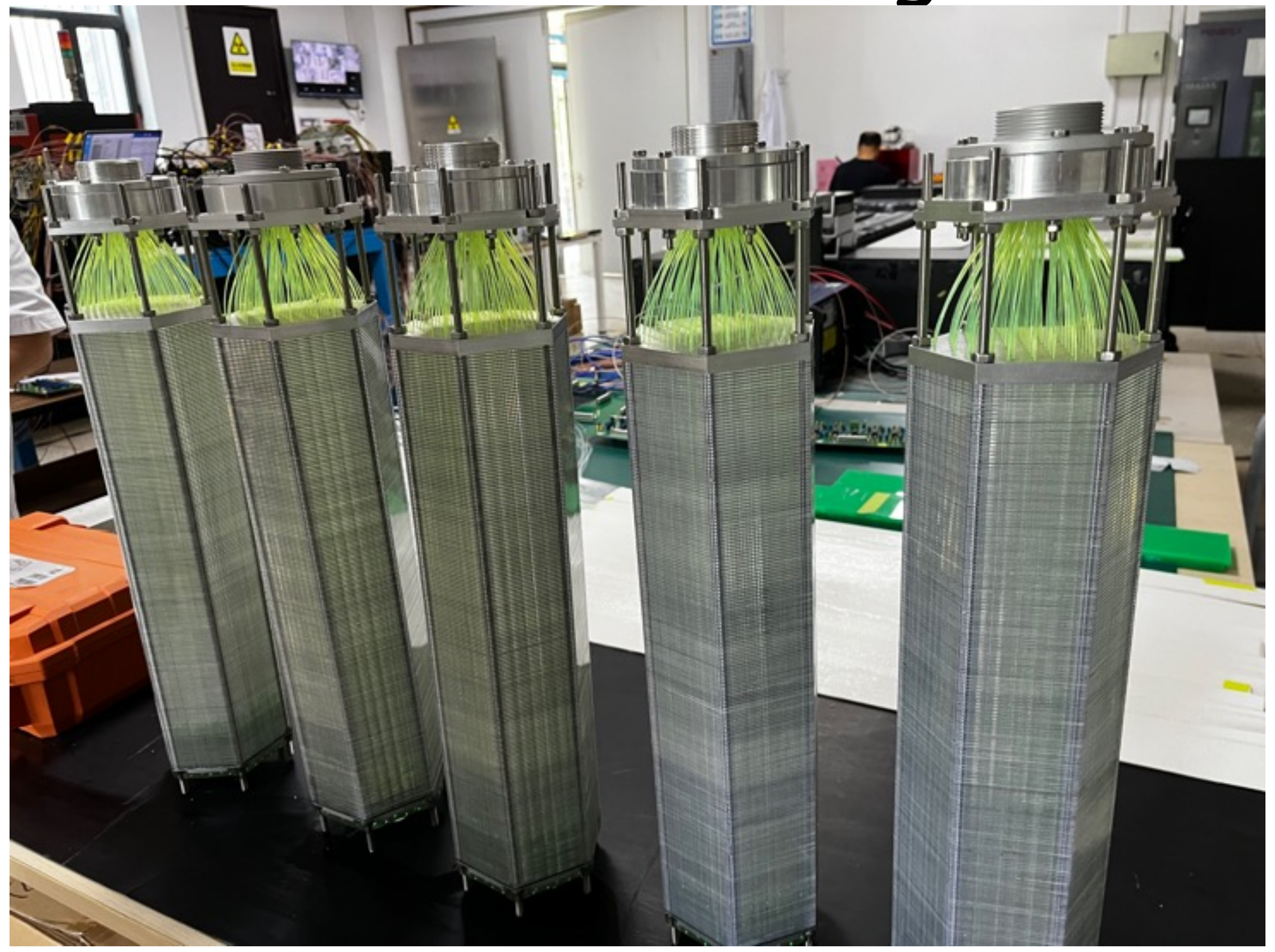
(b) Ty Polarization

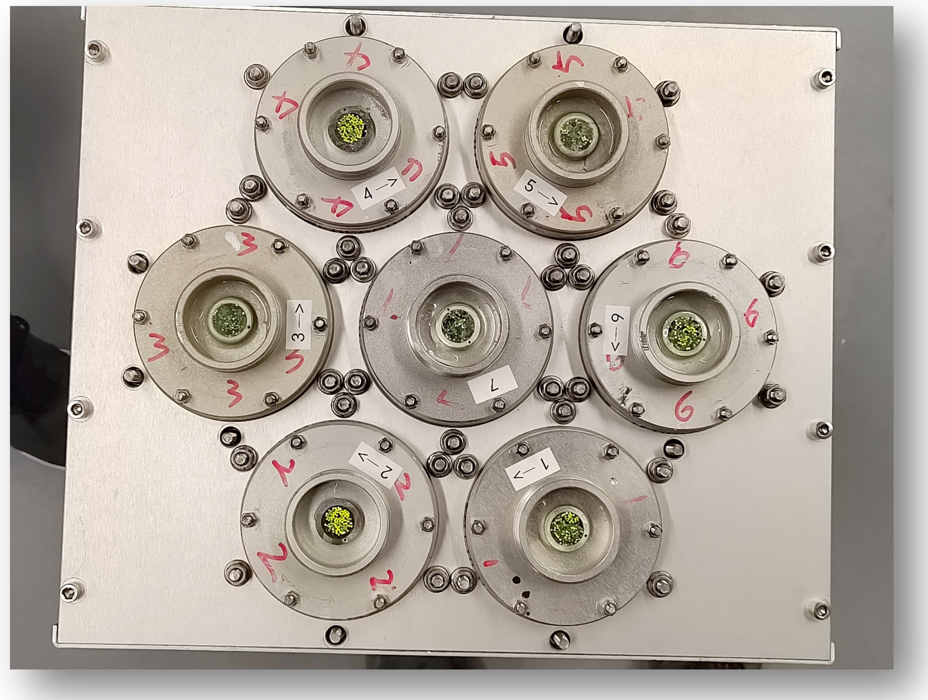


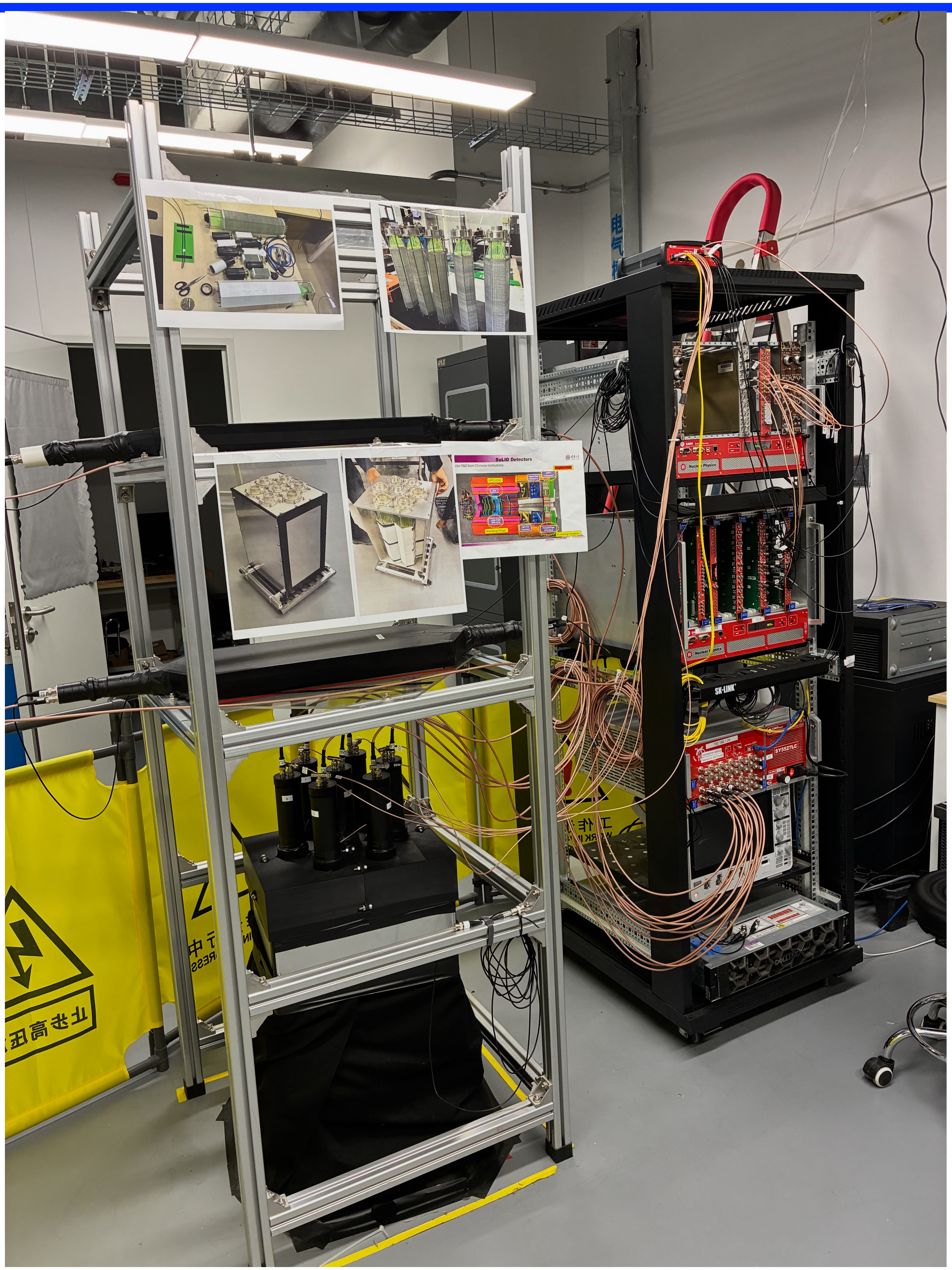
- Two transversely polarized direction
- 5-Q2-bins:
- BSA, TSAx5x2, DSAx2 → 25 such kind of plots

ECAL for SoLID-DVCS

- ECAL Supermodules (Shangdong Univ. & Tsinghua)
  - ☐ SoLID Shashlyk ECal for e/pi seperation
  - ☐ Modules shipped from SDU to Tsinghua in late 2023
  - ☐ Assemble super-modules in summer 2024
  - ☐ To be send to JLab in late 2025 for beam testing



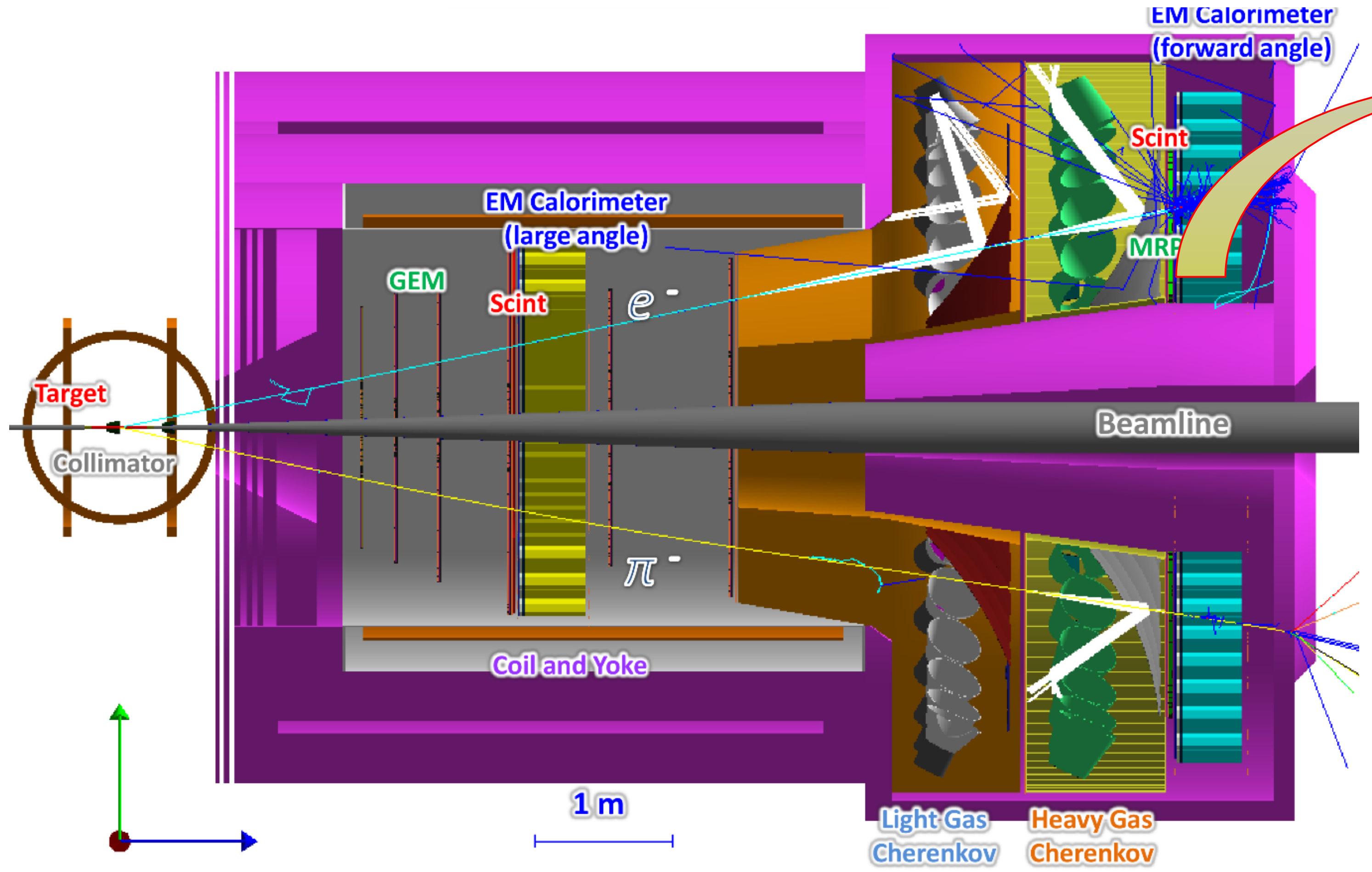




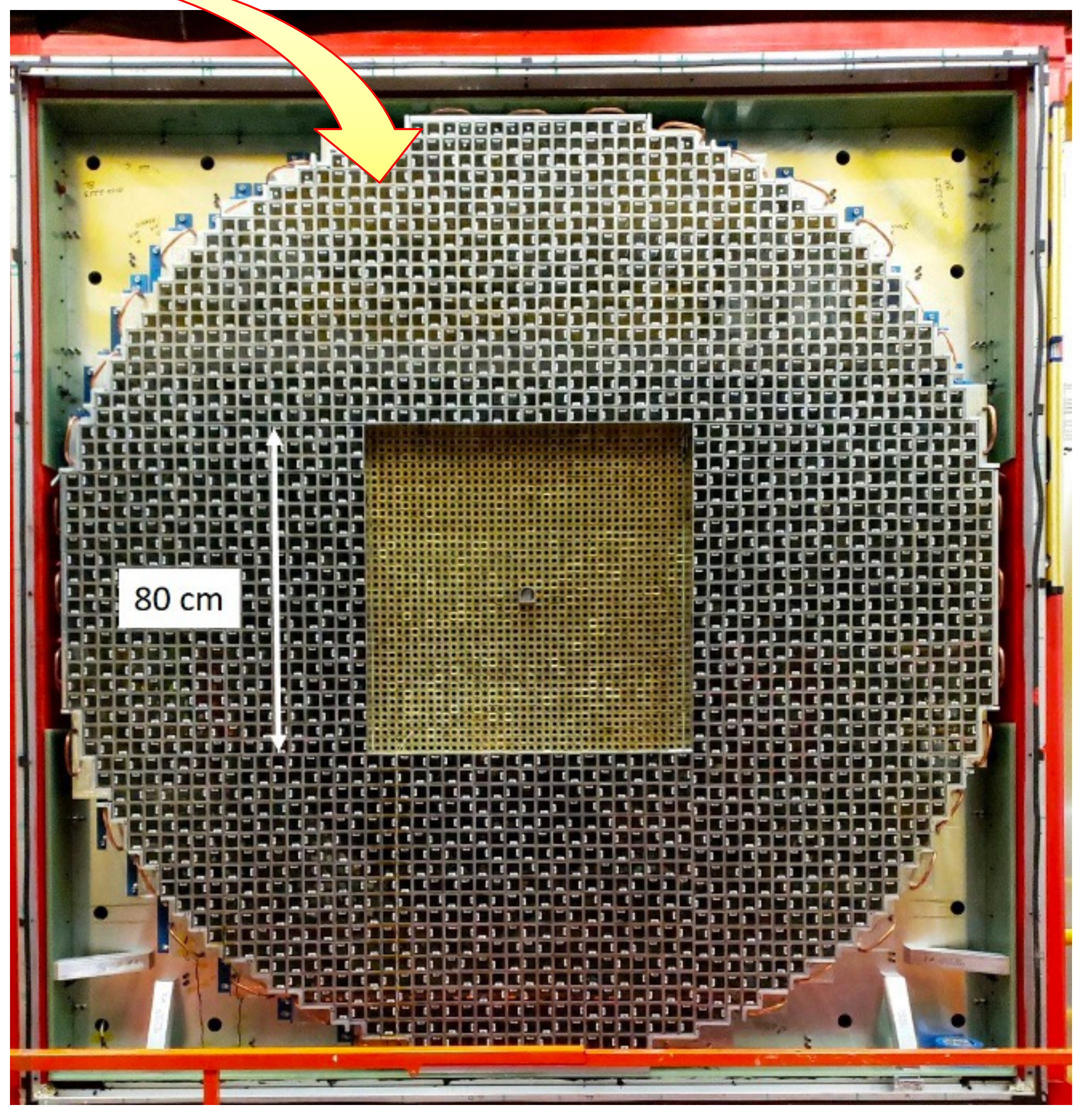
ECAL for SoLID-DVCS

➢ Upgrade to PbWO4 ECAL?

- ☐ SoLID Shashlyk ECal are not optimized for photon detection
- ☐ Possible upgrade to PbWO4 ECal (reuse of ECAL from the NPS experiments or eta-factory (Hall-D)

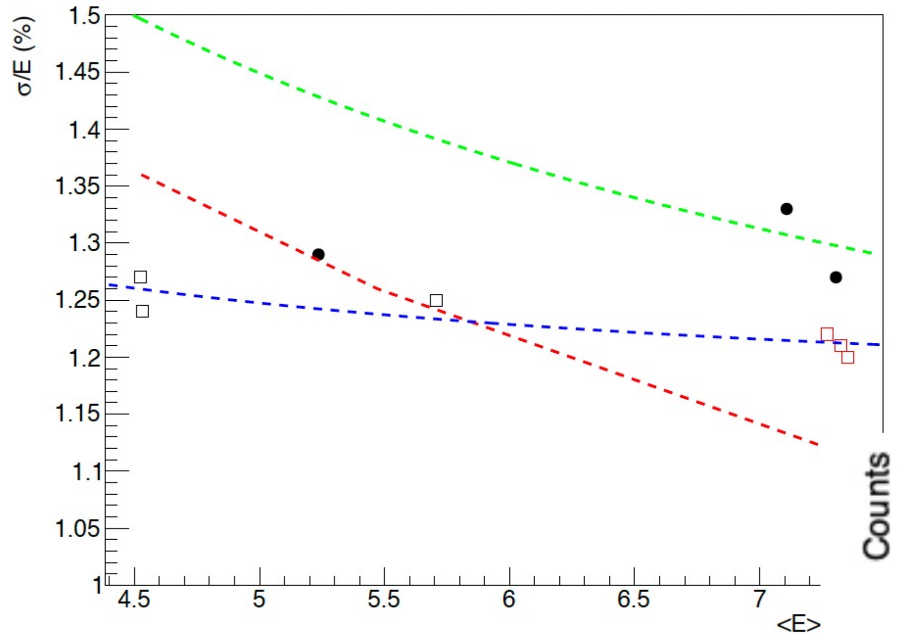


ECAL for eta factory@GLUEX

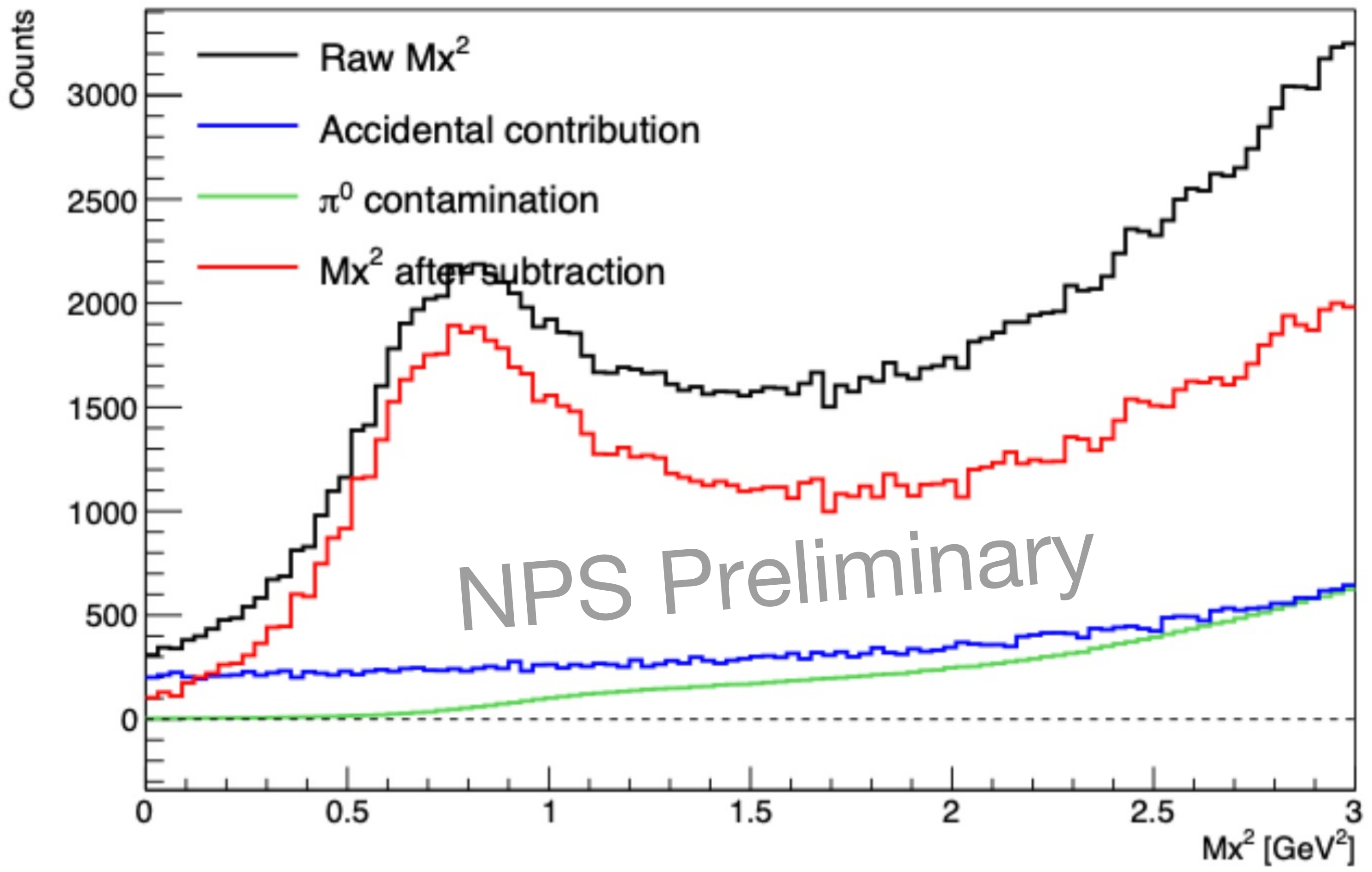


SoLID ECal :
- δE/E ~5%/sqrt(E)
- Position~10mm

NPS ECal :
- δE/E ~ 1.3%/sqrt(E)
- Position~2.5mm



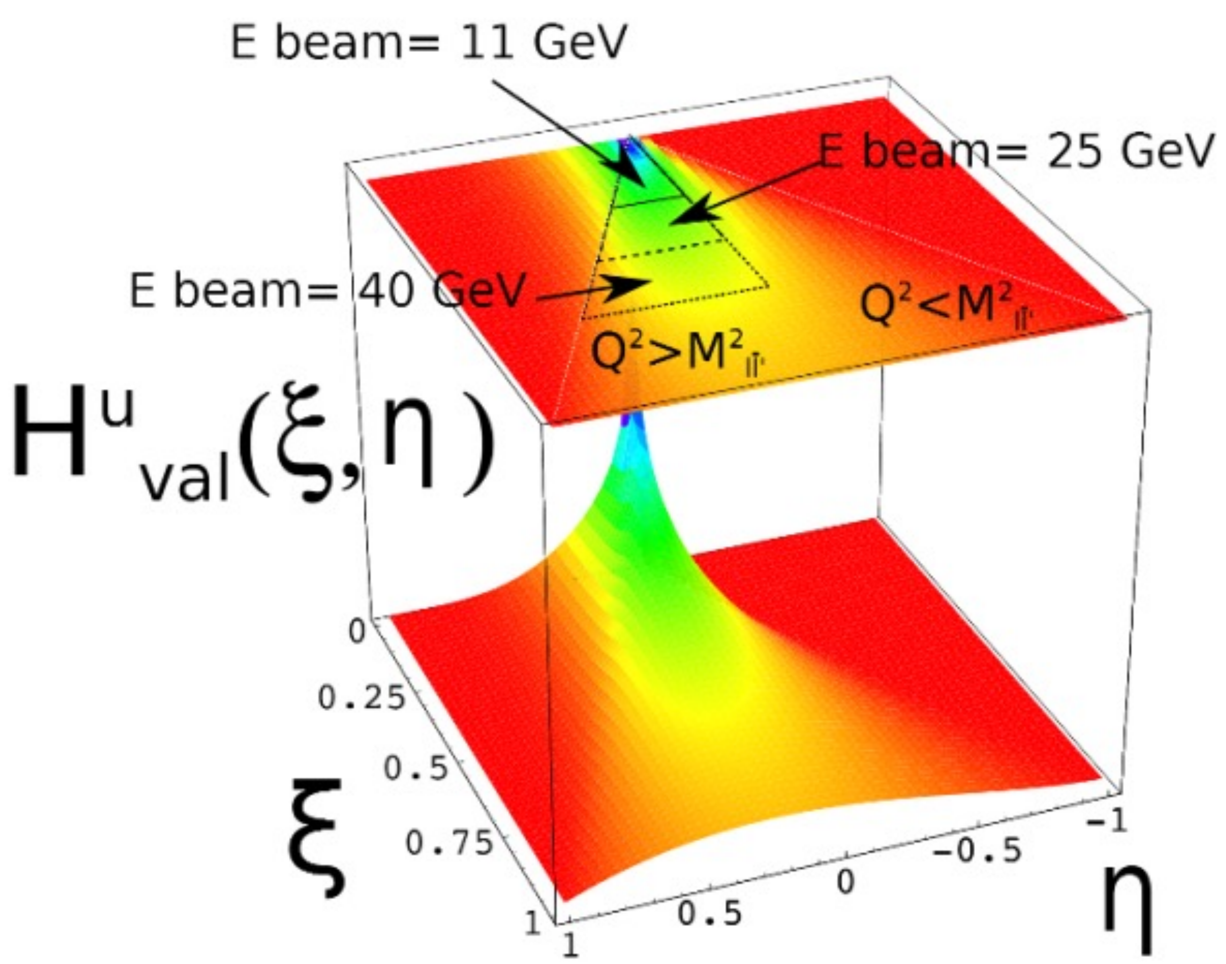
NPS ECAL

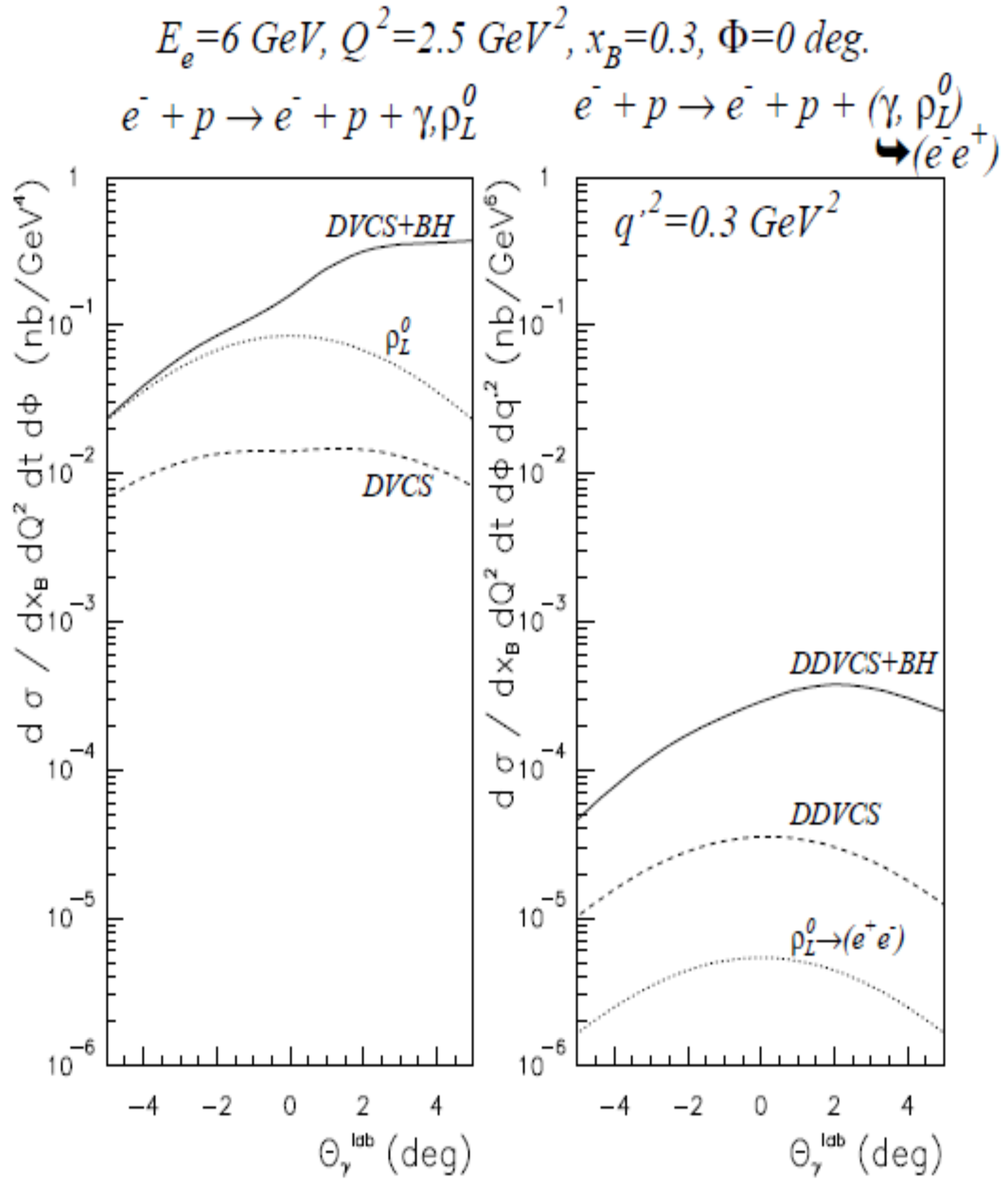


Hall-C DVCS experiments with NPS calorimeter (See Yaopeng Zhang'talk this afternoon at 2pm)

GPD Study on SoLID

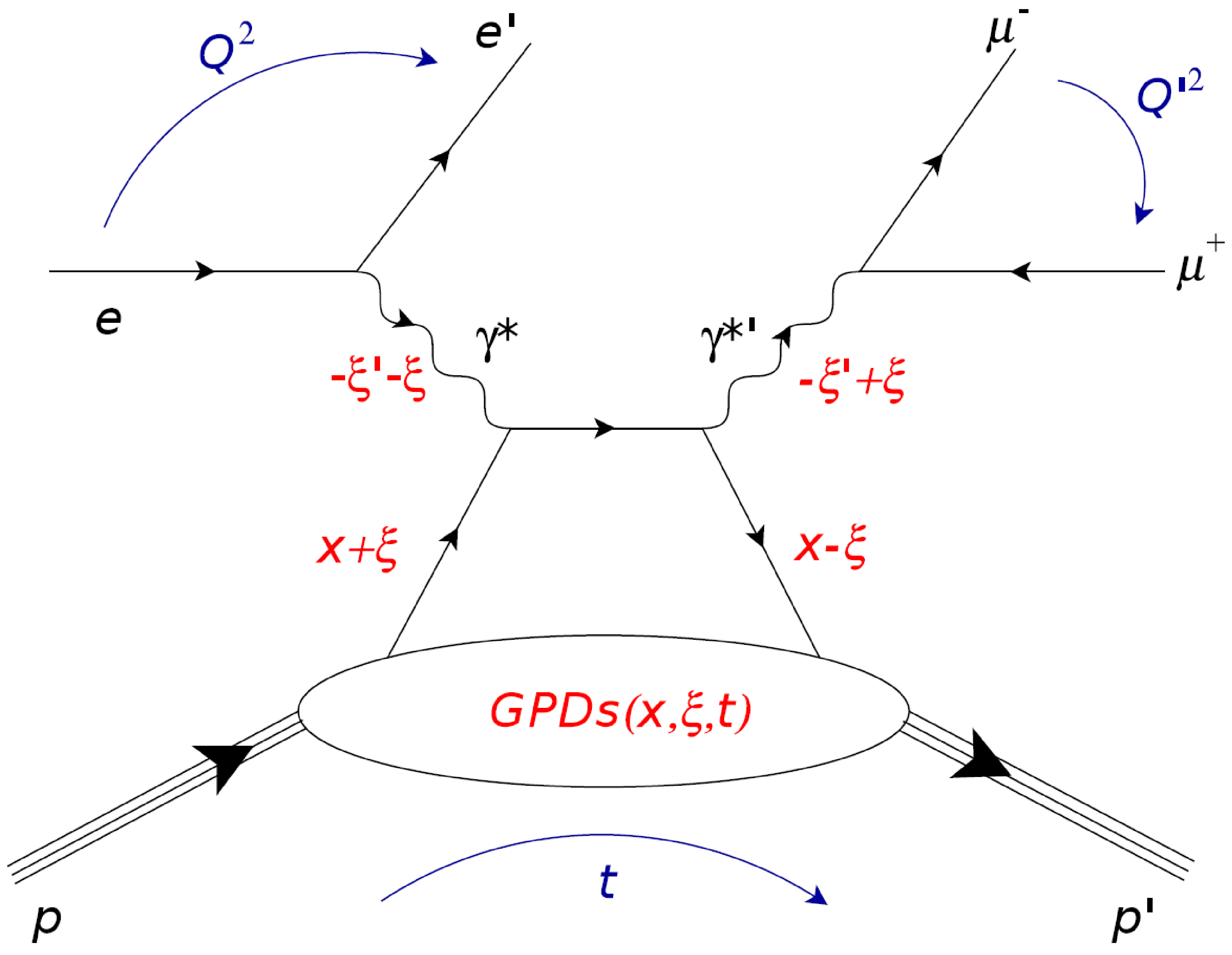
- **SoLID-DDVCS:** $e+N \rightarrow e'+N+l^{+}+l^{-}$
  - Doubly DVCS explores wide off-axis kinematic region of GPDs, beyond DVCS and TCS.





- The exclusive reaction has small cross-section
- Needs high luminosity and large acceptance.
- SoLID is likely the best place to do DDVCS

S. Zhao et al. EPJ A 57 (2021) 240



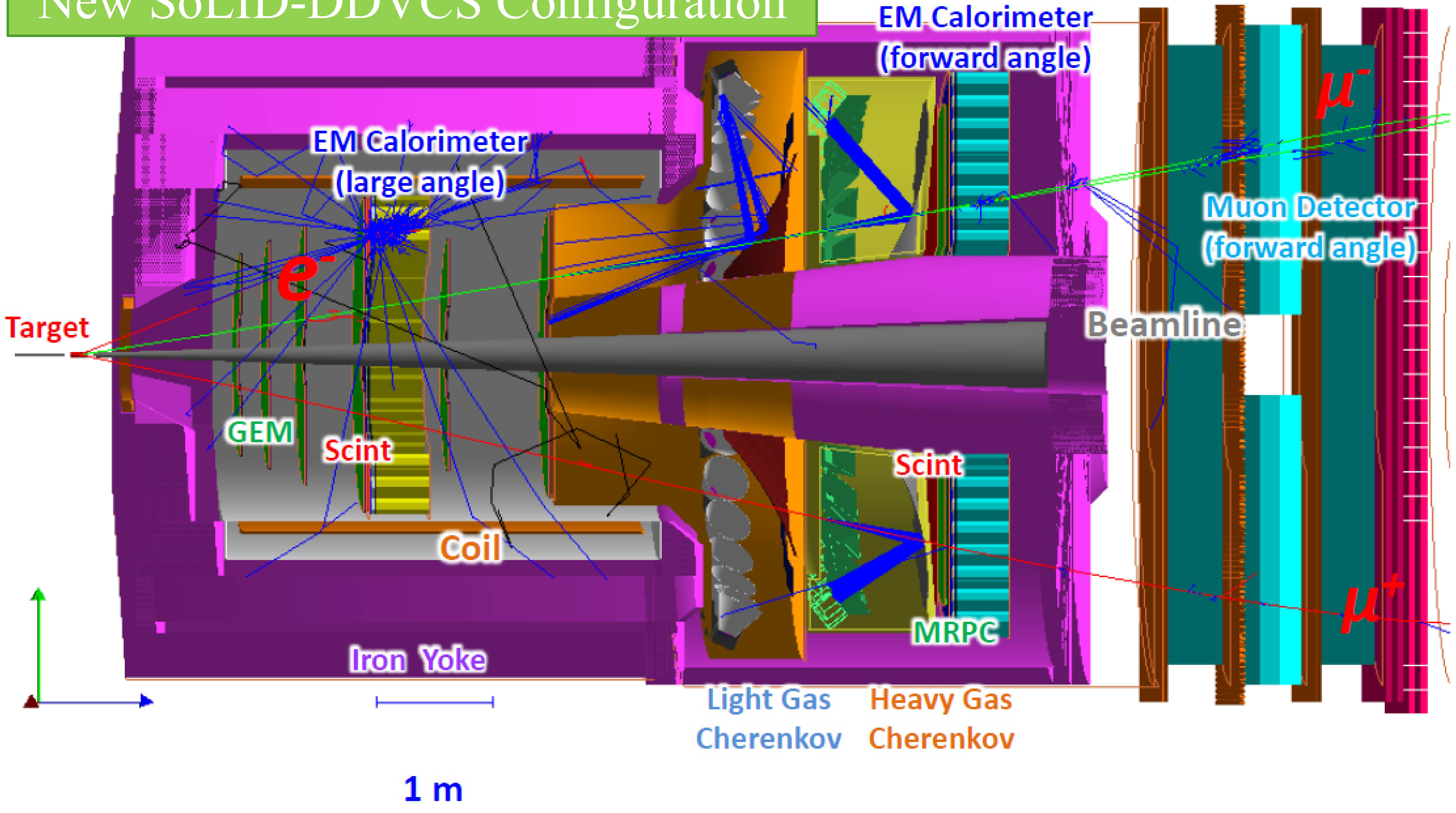
$$\xi' = \frac{Q^2 - Q'^2 + t/2}{2Q^2/x_{\rm B} - Q^2 - Q'^2 + t}$$

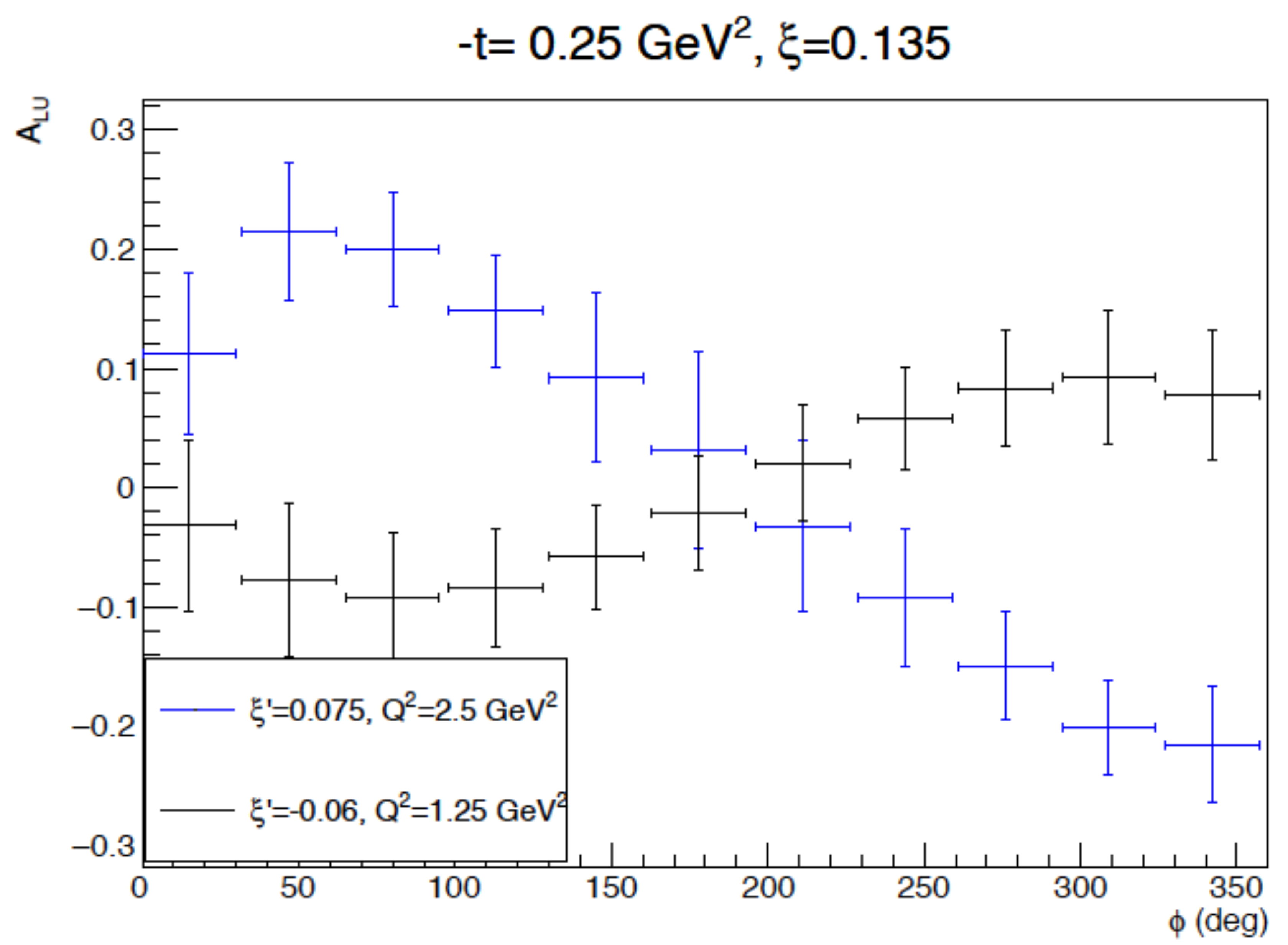
$$\xi = \frac{Q^2 + Q'^2}{2Q^2/x_{\rm B} - Q^2 - Q'^2 + t}$$

GPD Study on SoLID

- **SoLID-DDVCS:** $e+N \rightarrow e'+N+l^{+}+l^{-}$
  - ☐ Detector upgrade needed to measure muons
    - ✓ DDVCS with J/Psi +muon detectors → New LOI submitted to PAC51 in 2023

New SoLID-DDVCS Configuration





Summary

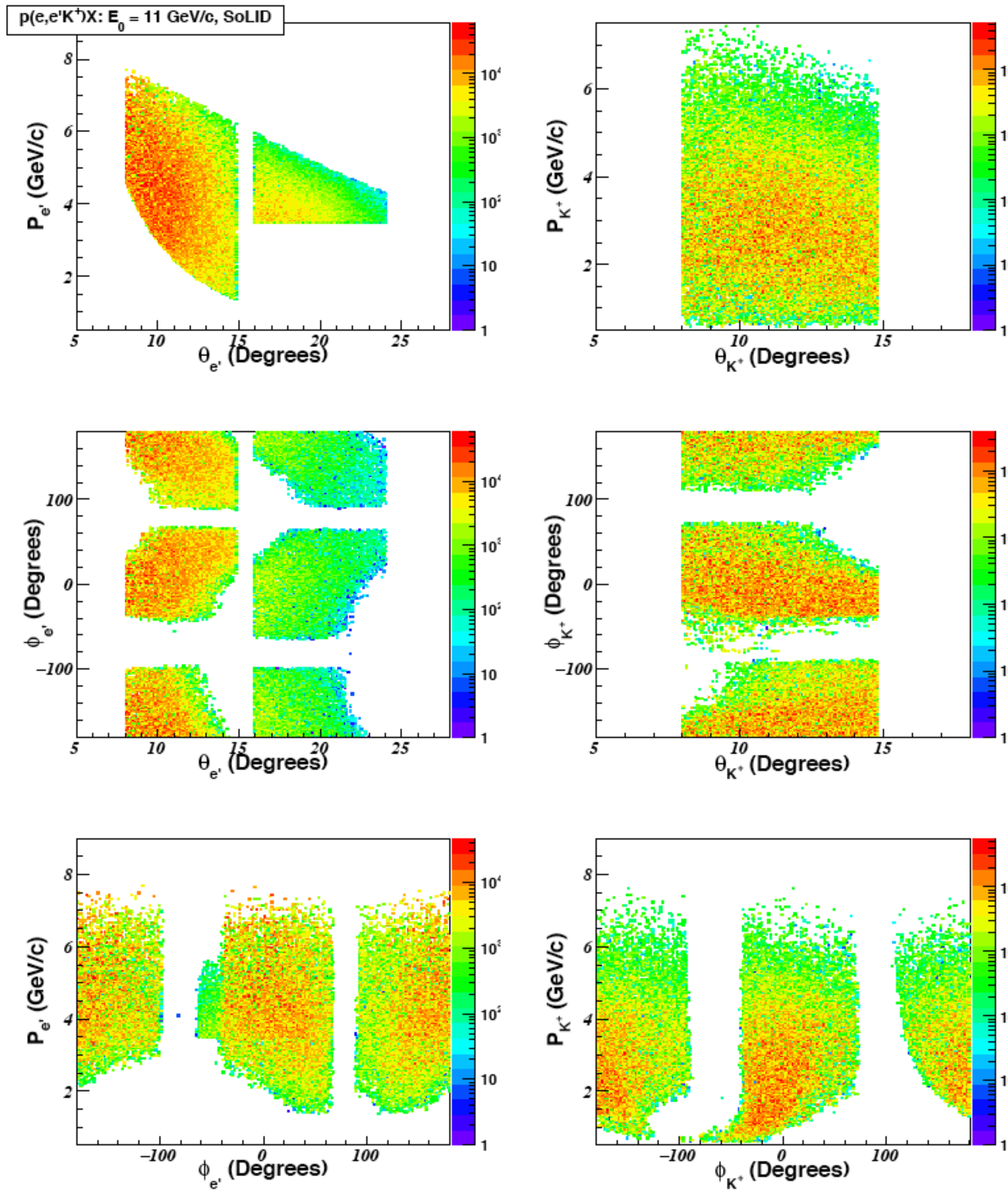
- SoLID: large acceptance + very high luminosity → full exploitation of JLab12 potential
  - ✓ pushing the limit of the luminosity frontier
  - ✓ highlighted in 2023 NSAC LRP and facility review
- SoLID SIDIS with long. and trans. polarized protons and neutrons (Haiyan's talk on Friday)
- Several run-group have been approved to do spin, TMD and GPD study
- Several new run-group are under developments for DVCS and Doubly-DVCS measurements.

Backup Slides

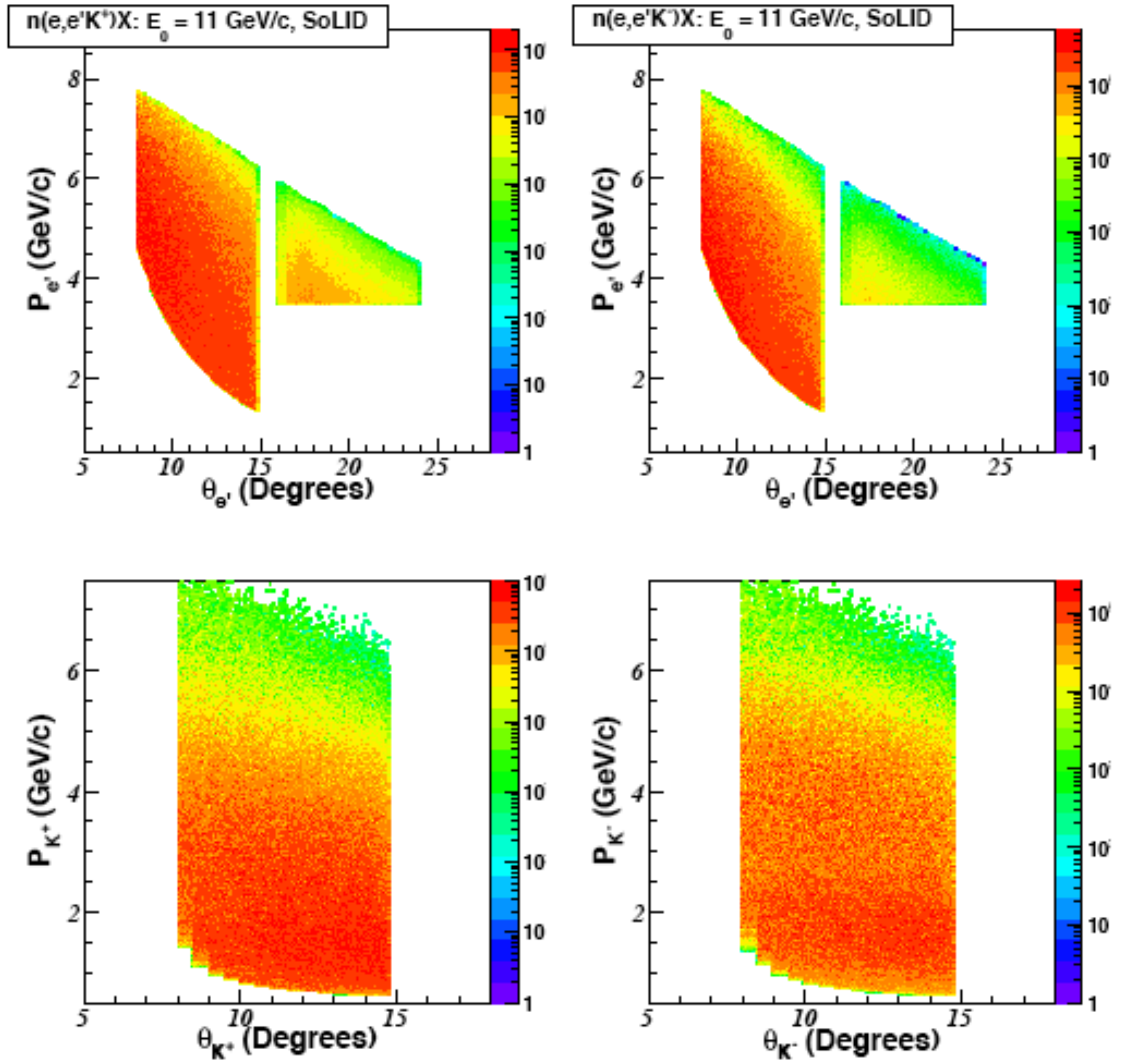
SoLID Kaon-SIDIS

- SoLID Acceptance for Kaons:

SoLID-SIDIS with NH3



SoLID-SIDIS with He3

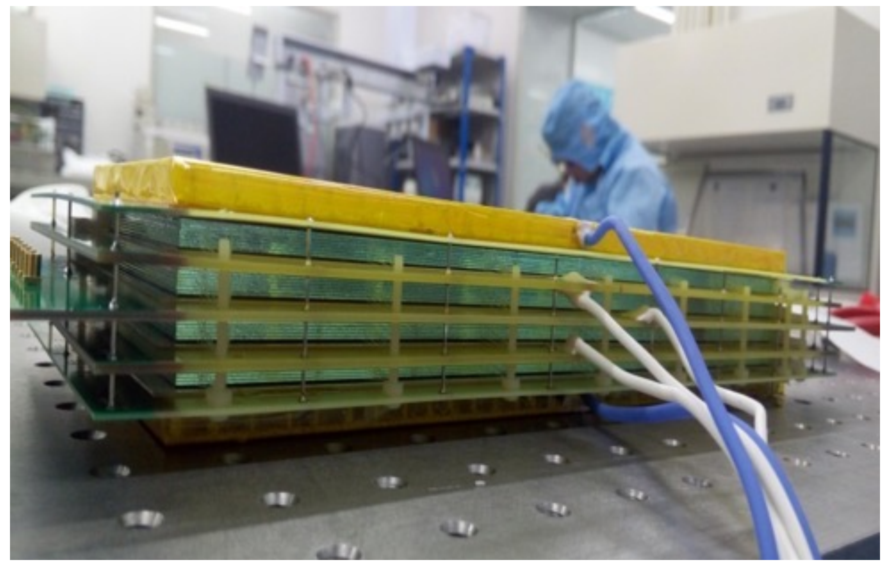


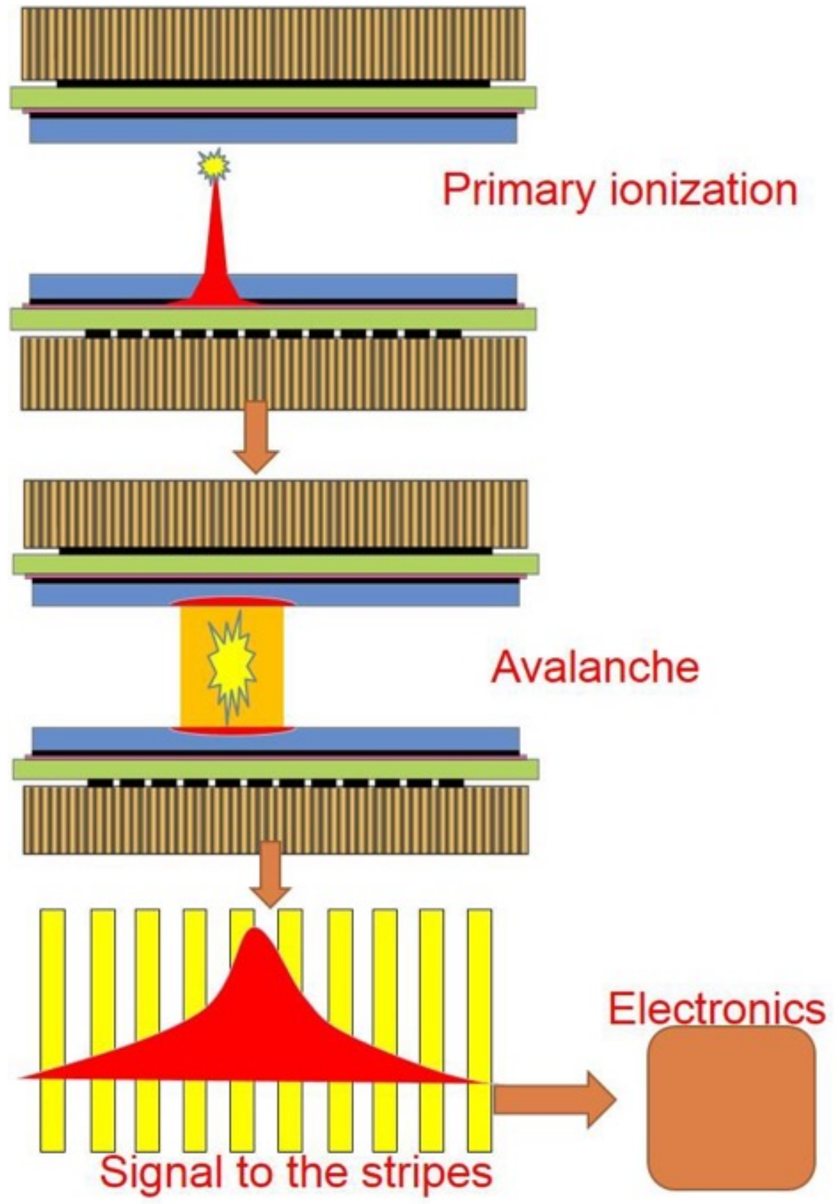
SoLID-SIDIS Coincident Rates (Hz)				
Polarized Target	^{3}He (”n”)		NH$_3$ (”p”)	
Beam Energy	8.8 GeV	11 GeV	8.8 GeV	11 GeV
e-(FAEC+LAEC)+K^+(FAEC)	359.3	575.6	4.9	10.4
e-(LAEC+LAEC)+K^-(FAEC)	83.2	144.1	0.93	2.7
e-(FAEC+LAEC)+π^+(FAEC)	1555.0	2185.9	20.3	37.4
e-(LAEC+LAEC)+π^-(FAEC)	1012.5	1449.6	10.2	20.7

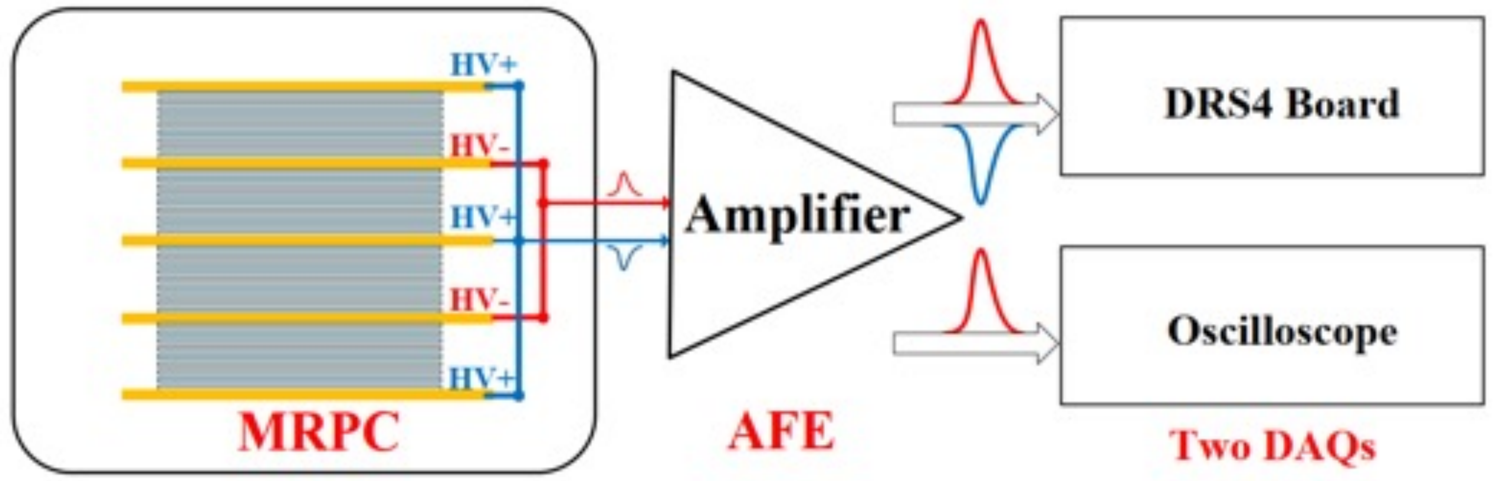
MRPC R&D at Tsinghua

❑ Multi-layer Resistive Plate Chambers (MRPC) by Y. Wang @ Tsinghua

- ✓ Low-resistivity glass plates, gas (95% F134a + 5% iso-butane), HV(~12kV)
- ✓ High rates (>30kHz/cm^2), radiation-hard, magnet safe
- ✓ Some spatial resolution (by strip pitch, 0.5cm~1.0cm)
- ✓ Low cost, easy manufacturing,
- ✓ Used by ALICE, STAR, CBM, CEE, NICA, etc.





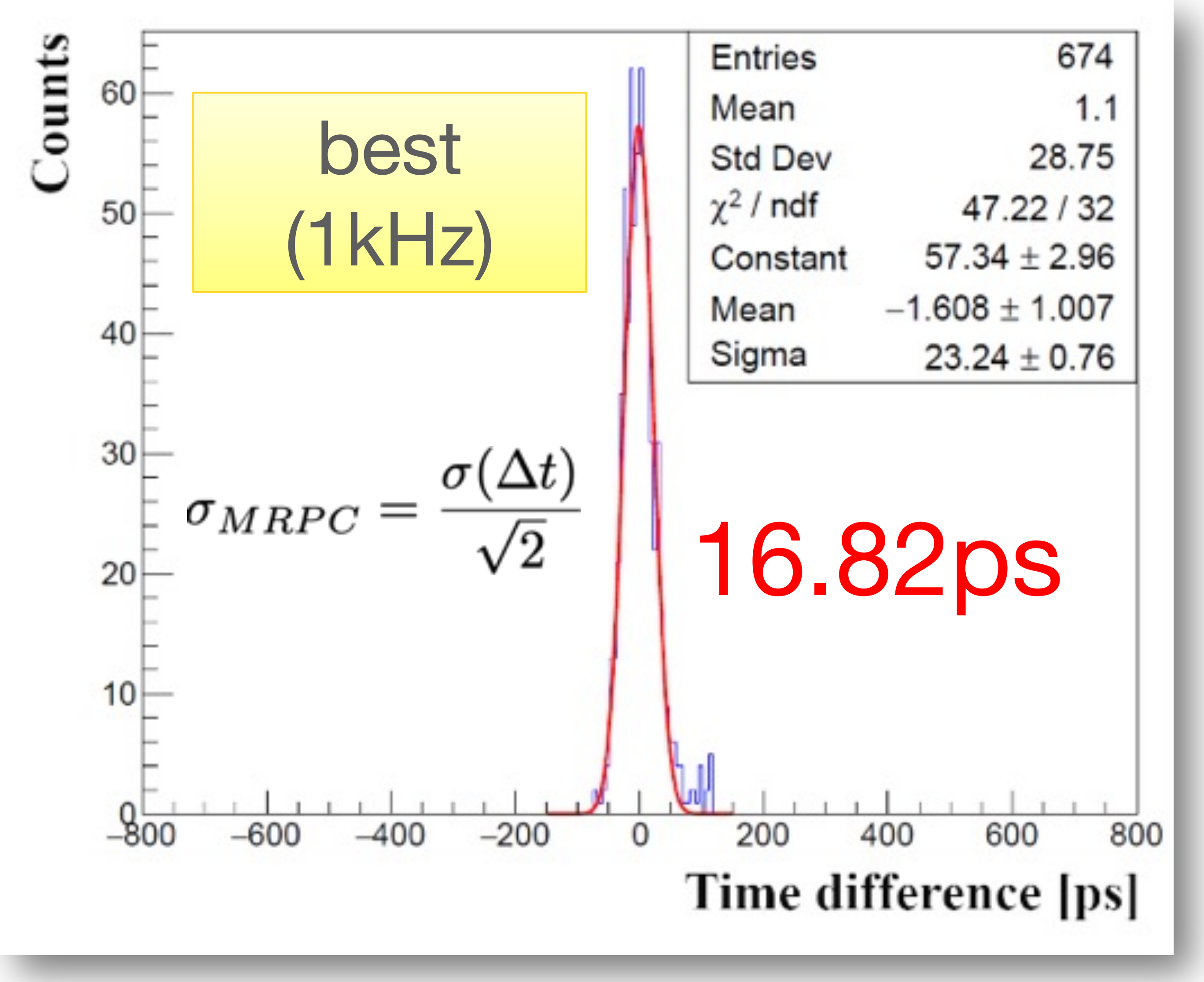


❑ Developed for SoLID's high-rate & -background environment

- ✓ Low resistance glass ($10^{10}\Omega \cdot cm$, best quality)
- ✓ 32-gaps (4 stacks), 400um thin glasses
- ✓ 104um gas-gap + waveform-sampling → 20ps & 95% efficiency at 15kHz
- ✓ 128um gas-gap + ToT method → 20ps at 15kHz
- ✓ Small sizes & not sealed yet

Y. Yu et al 2022 JINST 17 P02005

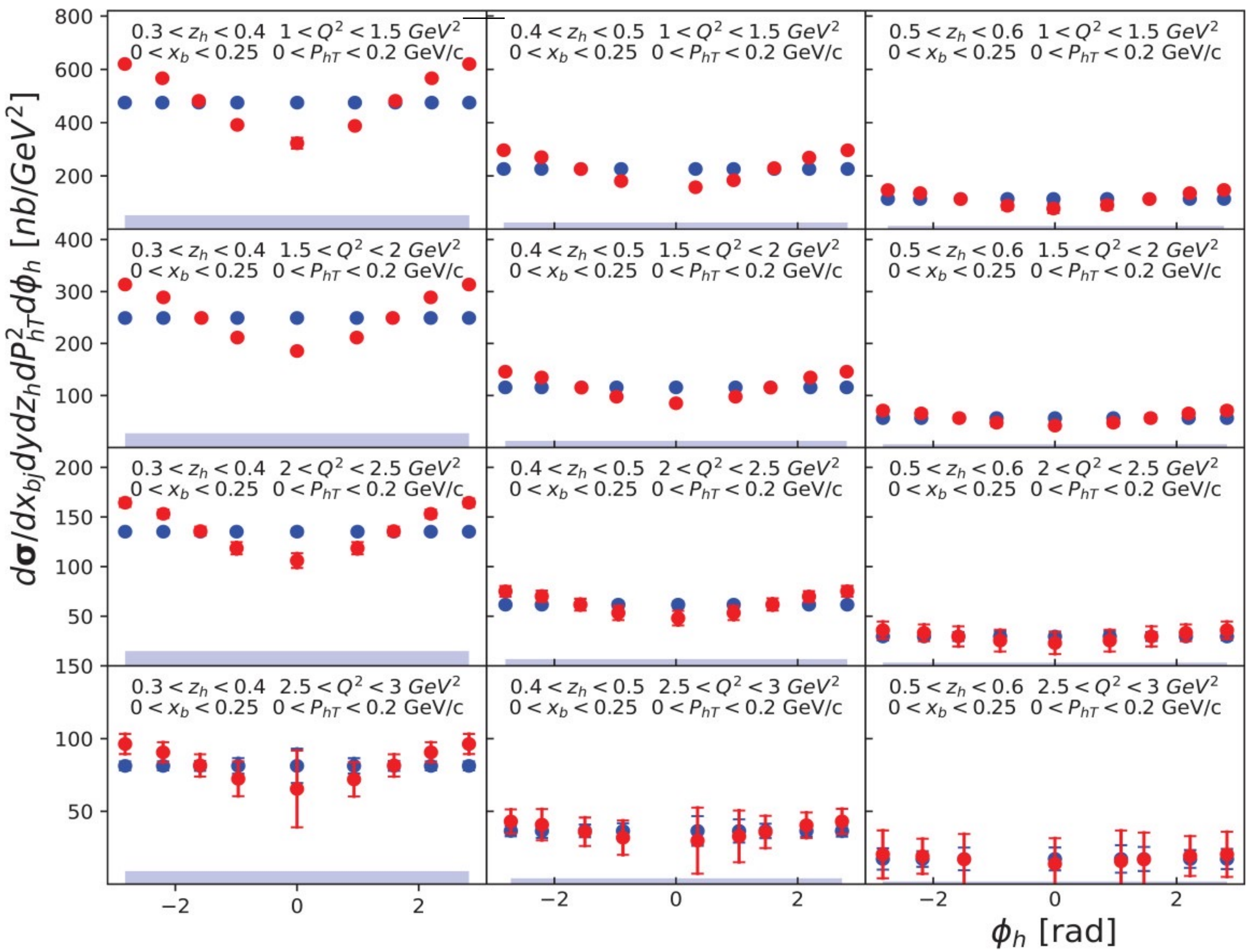
Y. Yu et al 2020 JINST 15 C01049



SoLID-SIDIS Study

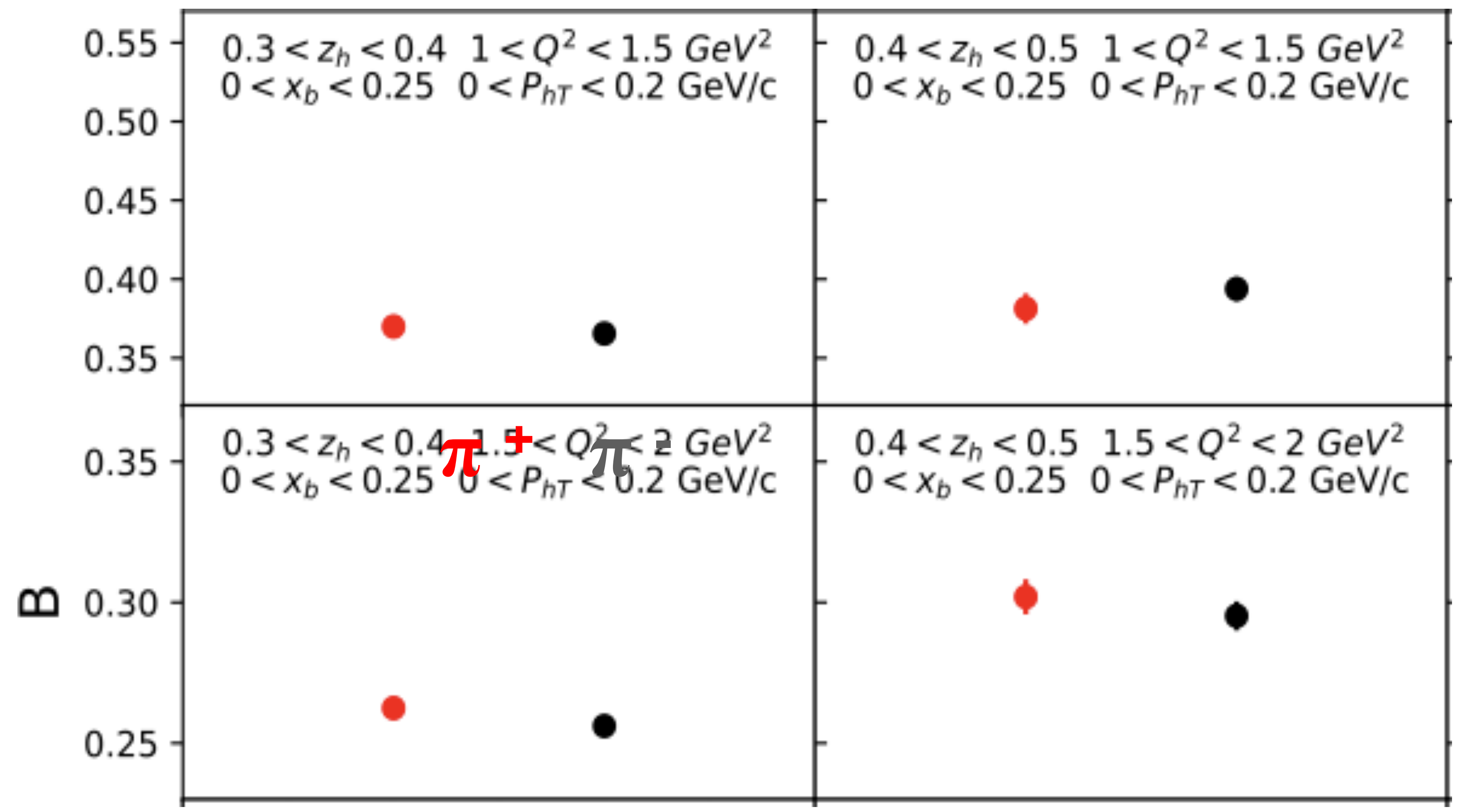
- **Unpolarized Cross-Section** off He3:
  - ☐ Projected π^+ unpolarized cross section errors with and without azimuthal terms. **~2000 bins in 5D**

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



- ☐ A naive probe for the azimuthal modulation effect

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

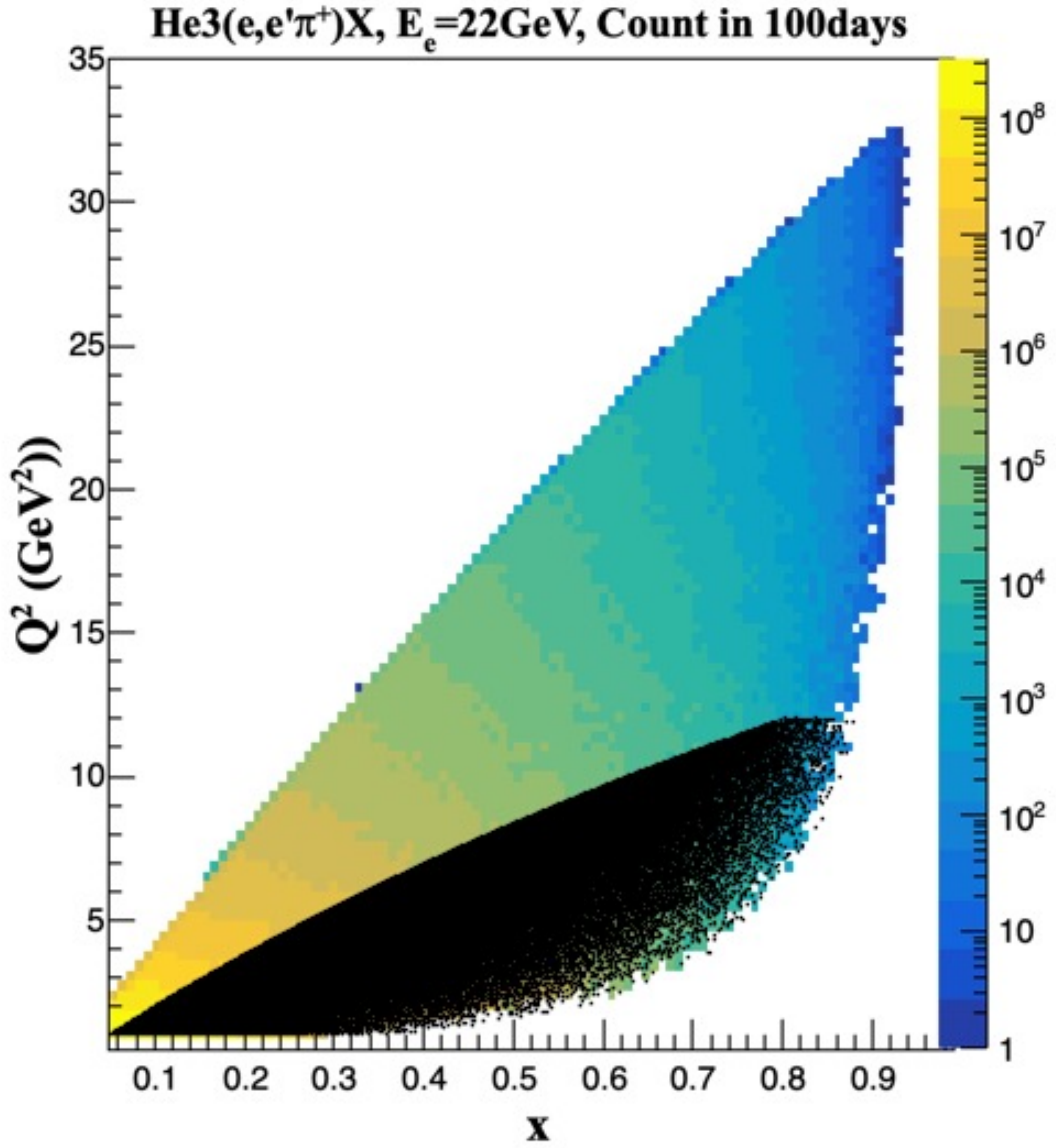


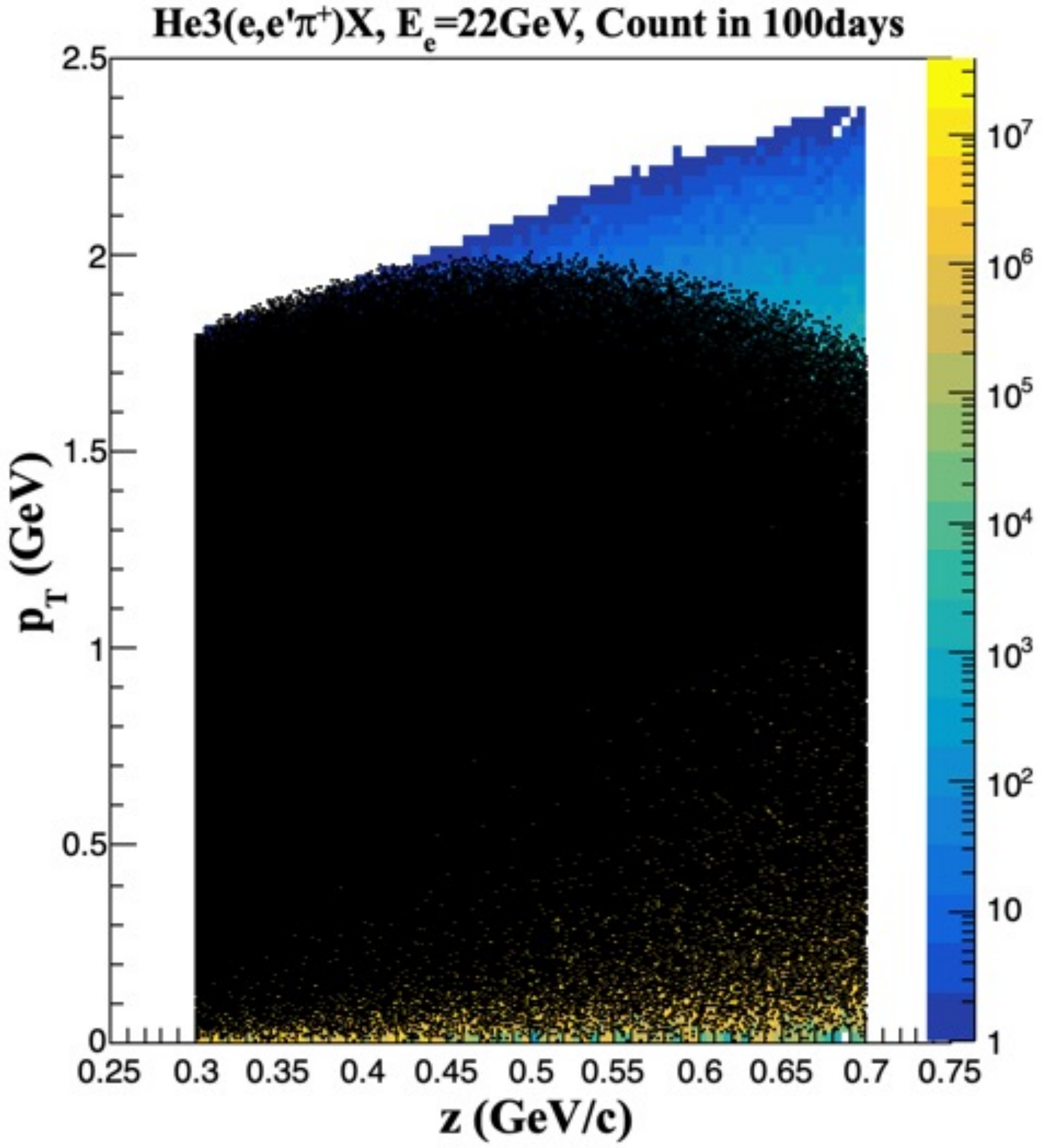
by Shuo Jia, et. al.

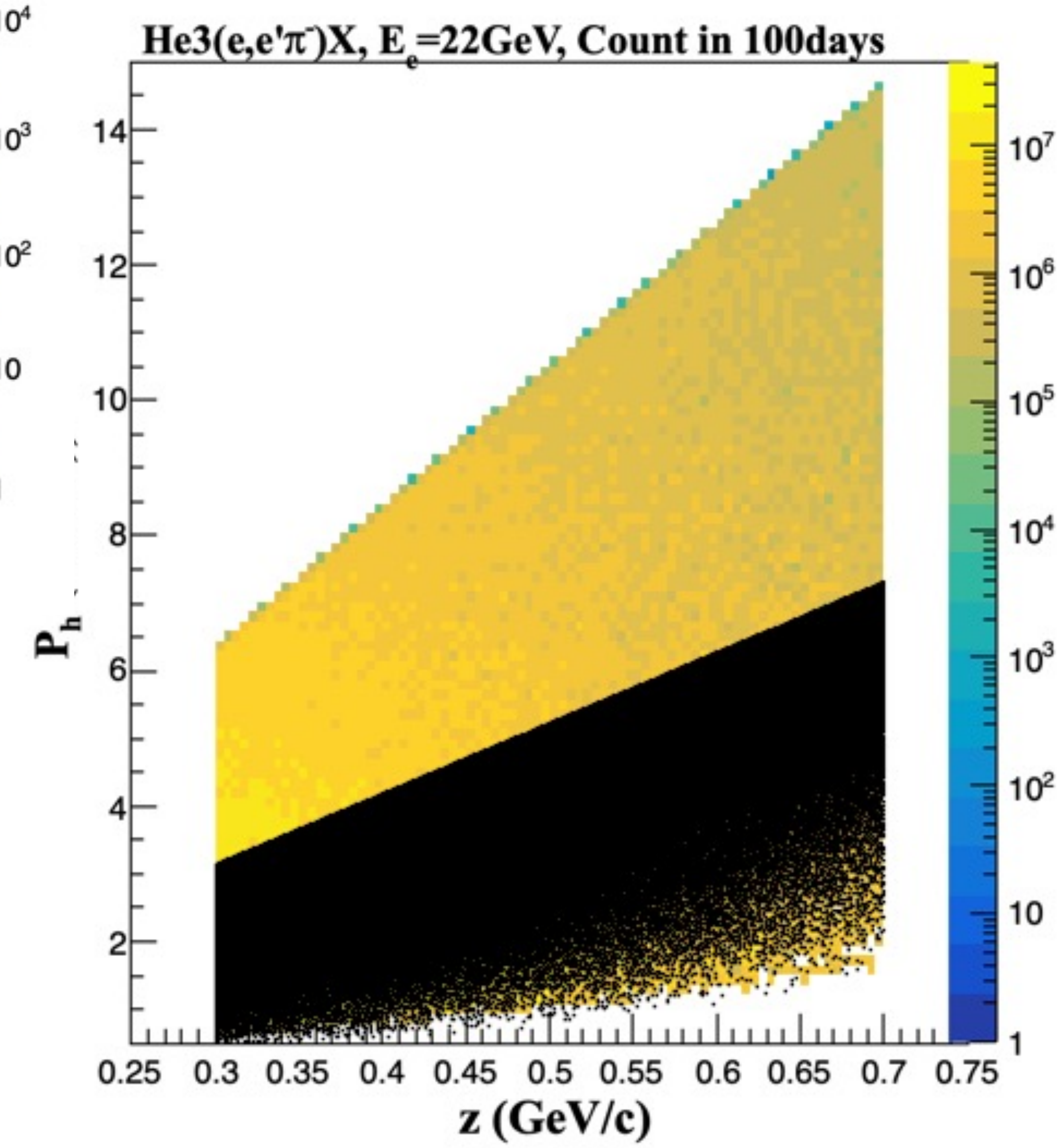
SoLID-SIDIS at 22GeV

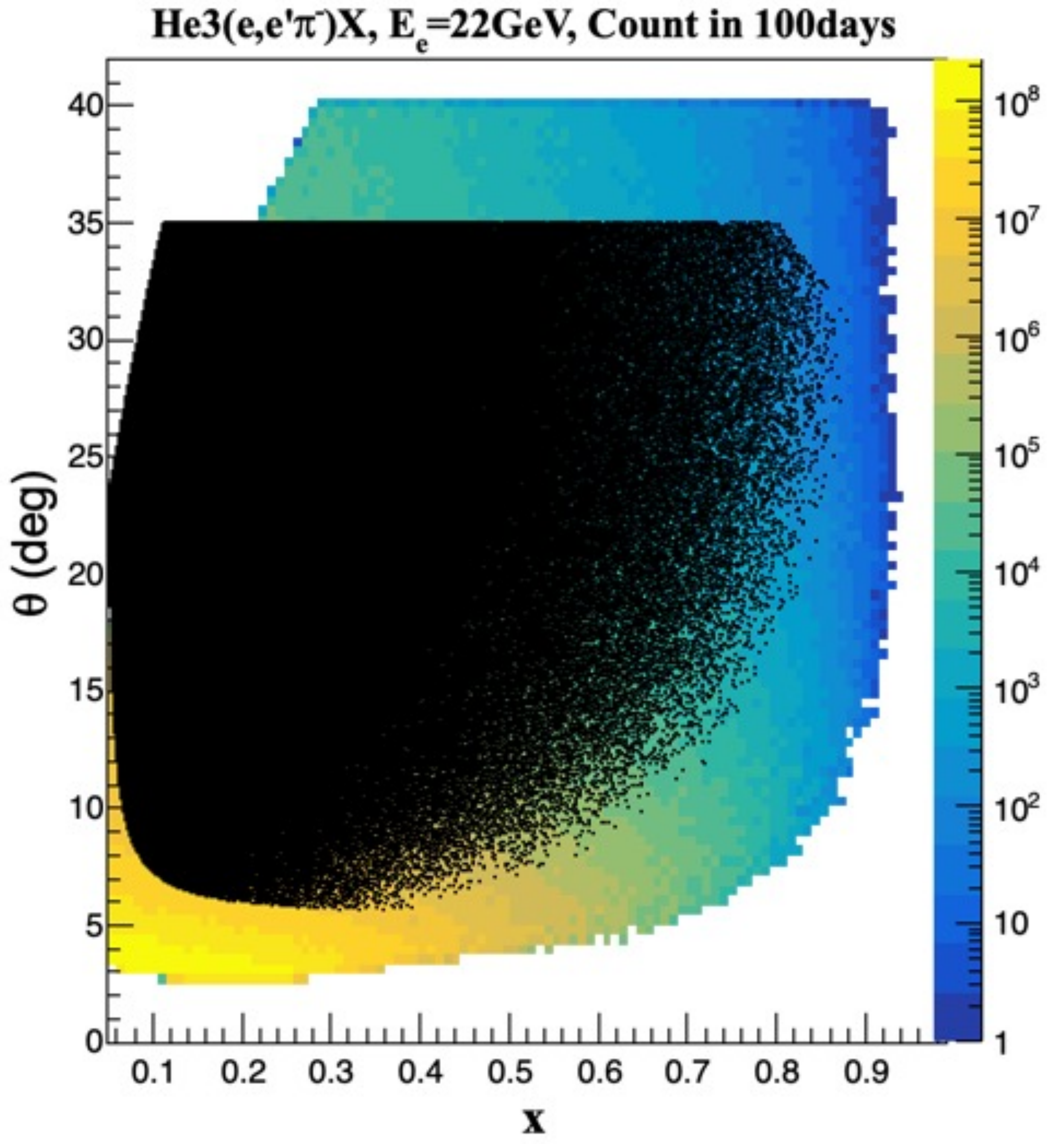
- Larger Phase-Space

Back dots→11GeV
Color dots→22GeV



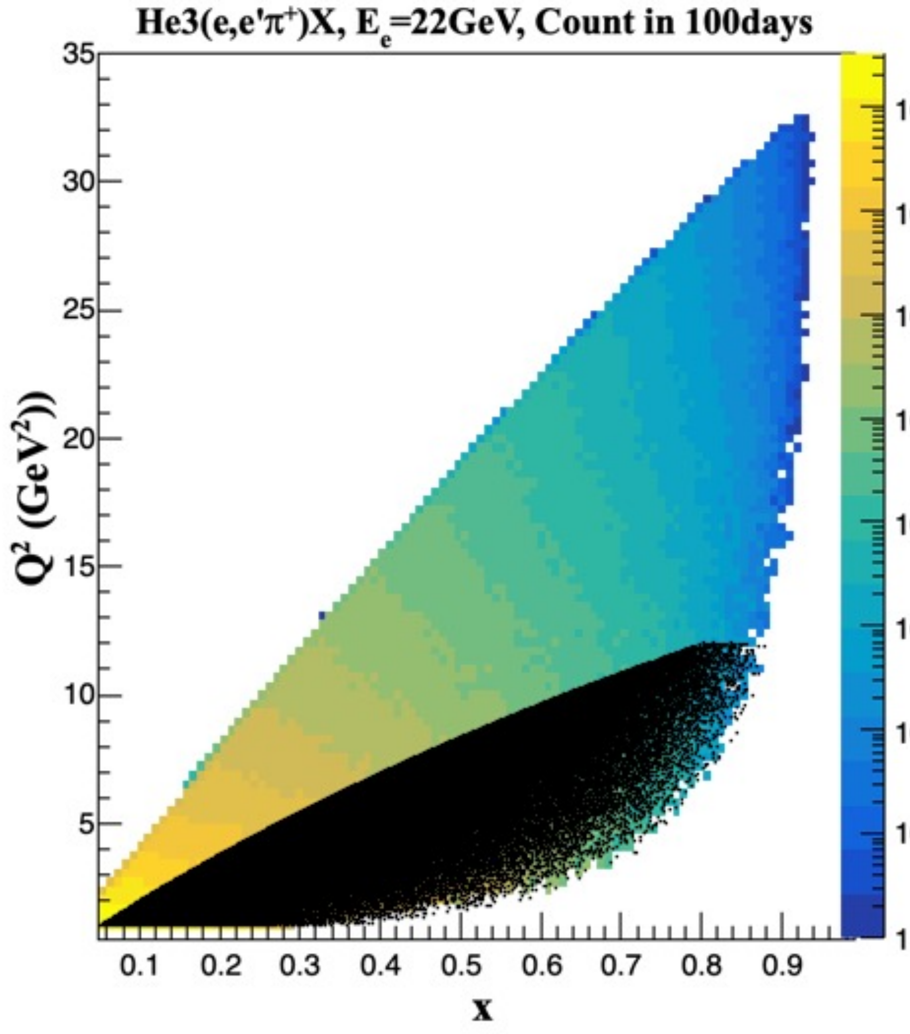


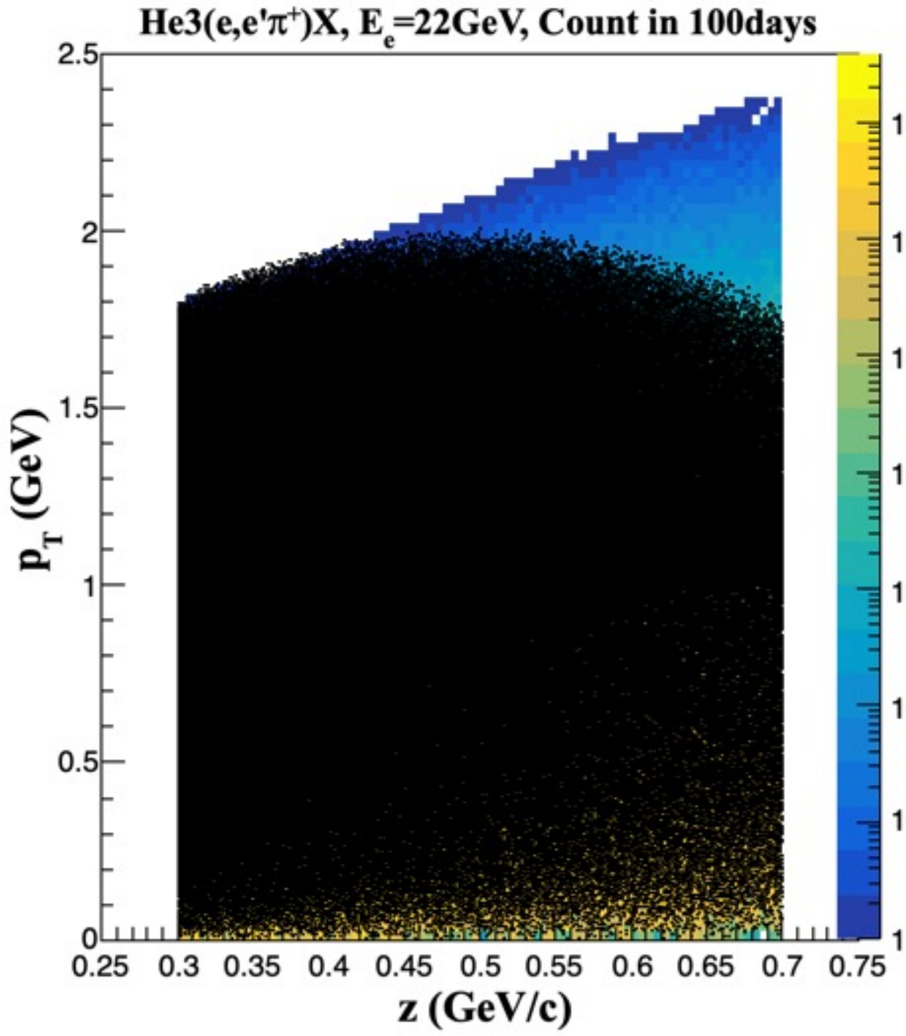




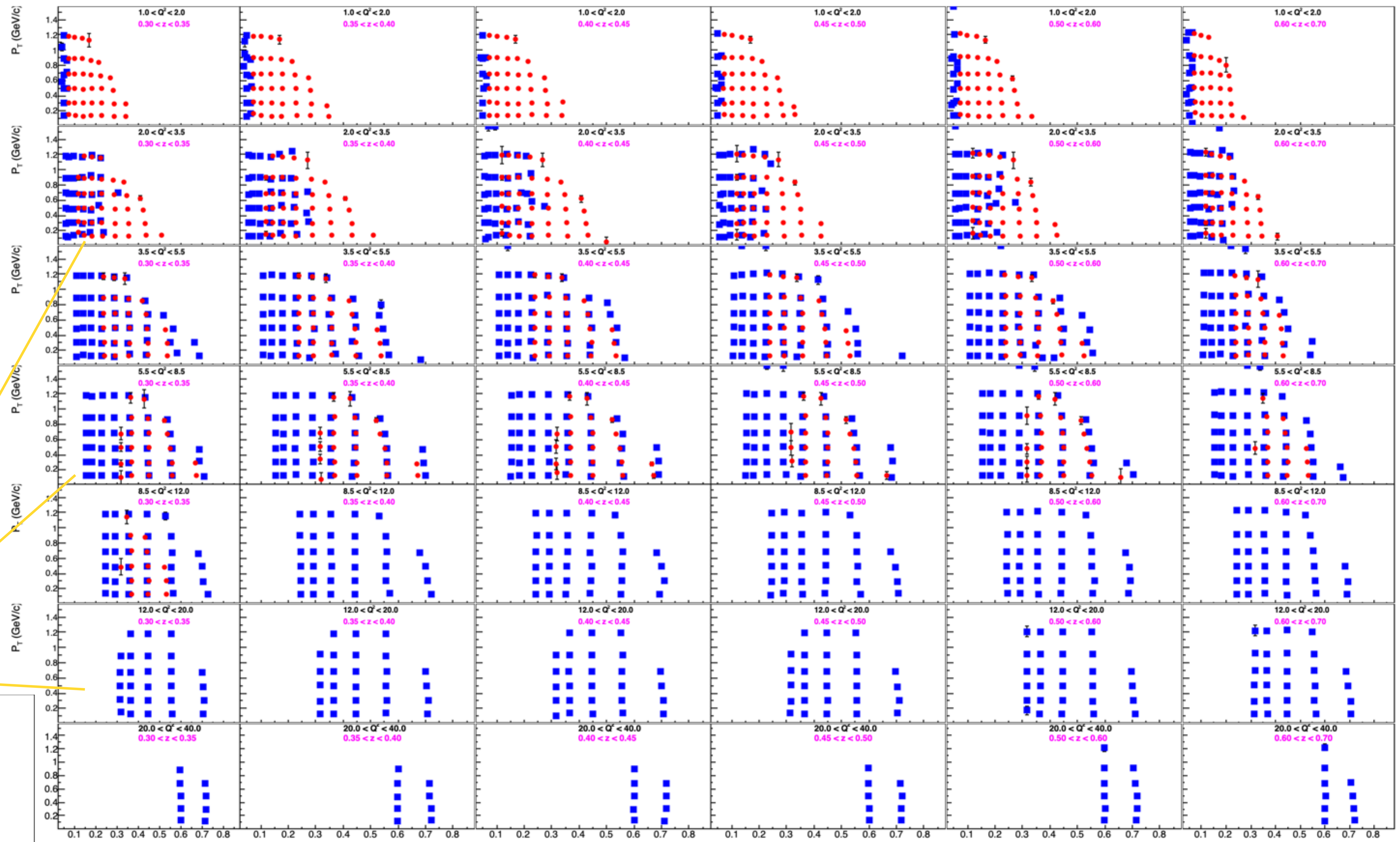
SoLID-SIDIS @ 22GeV

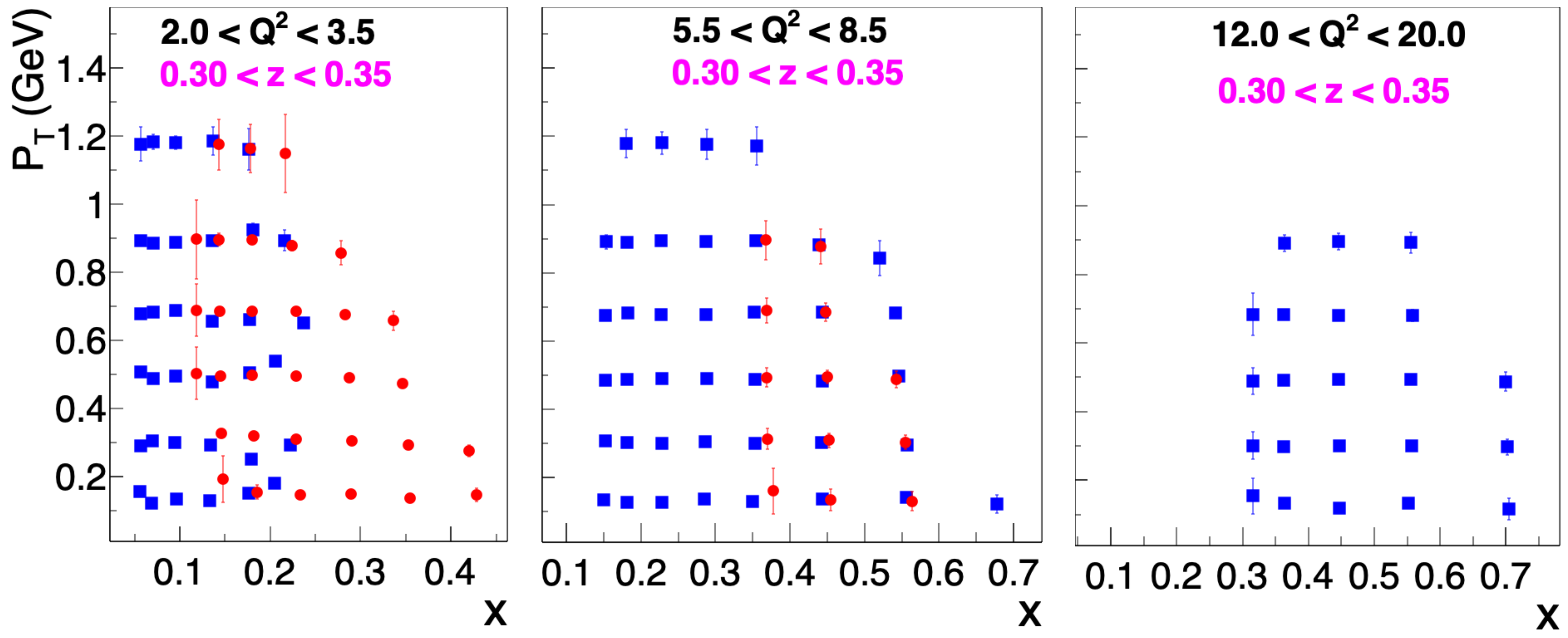
- 11GeV vs 22GeV





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





(Unpolarized) Pion-SIDIS Projection

Note:

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

Generalized Parton Distributions

❑ 8 Leading-Twist GPDs:

Chiral Even $H^{q/g}, E^{q/g}, \widetilde{H}^{q/g}, \widetilde{E}^{q/g}$

Chiral Odd $H_T^{q/g}, E_T^{q/g}, \widetilde{H}_T^{q/g}, \widetilde{E}_T^{q/g}$

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$2\widetilde{H}_T + E_T$
	L		$\widetilde{H}$	$\widetilde{E}_T$
	T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

❑ Access parton distributions in 3D

X. Ji, PRL 78, 610 (1997)
M. Diehl, Physics Reports 388 (2003) 41-277,
Belitsky, Radyushkin, Physics Reports 418 (2005) 1-387

❑ Connect to FF & PDFs: e.g.

$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$$
$$\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$$

Dirac&Pauli Form Factors

$$\int_{-1}^{1} dx \widetilde{H}^q(x,\xi,t) = G_A^q(t)$$
$$\int_{-1}^{1} dx \widetilde{E}^q(x,\xi,t) = G_P^q(t)$$

Axial&Pseudoscaler Form Factors

$$H^q(x,0,0) = q(x), x > 0$$
$$\widetilde{H}^q(x,0,0) = \Delta q(x), x > 0$$

PDFs

❑ How to access Angular Momenta?

✓ Ji's Sum Rule (X. Ji, PRL 78, 610 (1997))

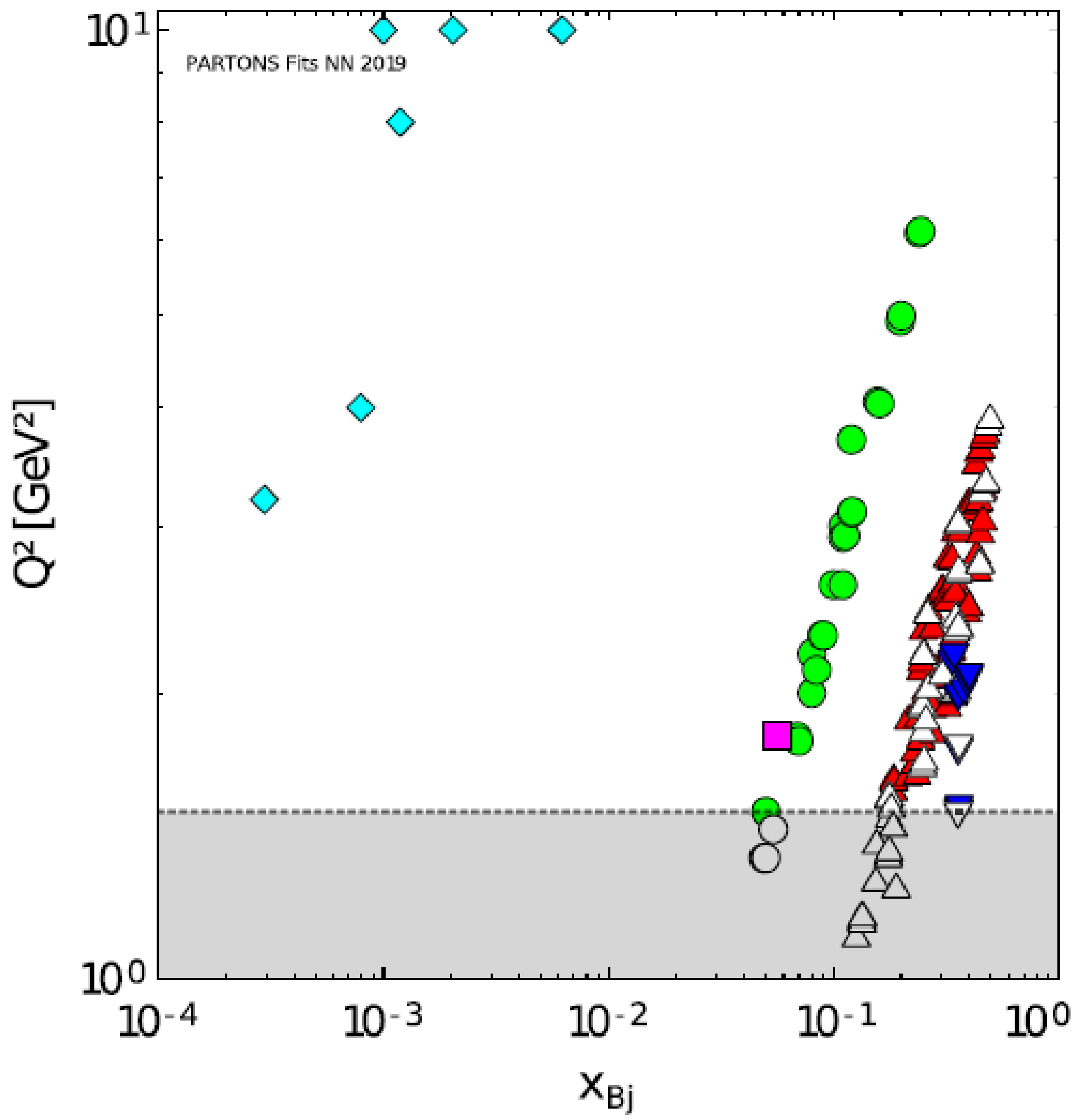
$$J_{q/g} = \lim_{t,\xi \to 0} \frac{1}{2} \int x dx \left[\boldsymbol{H^{q/g}}(x,\xi,t) + \boldsymbol{E^{q/g}}(x,\xi,t) \right]$$

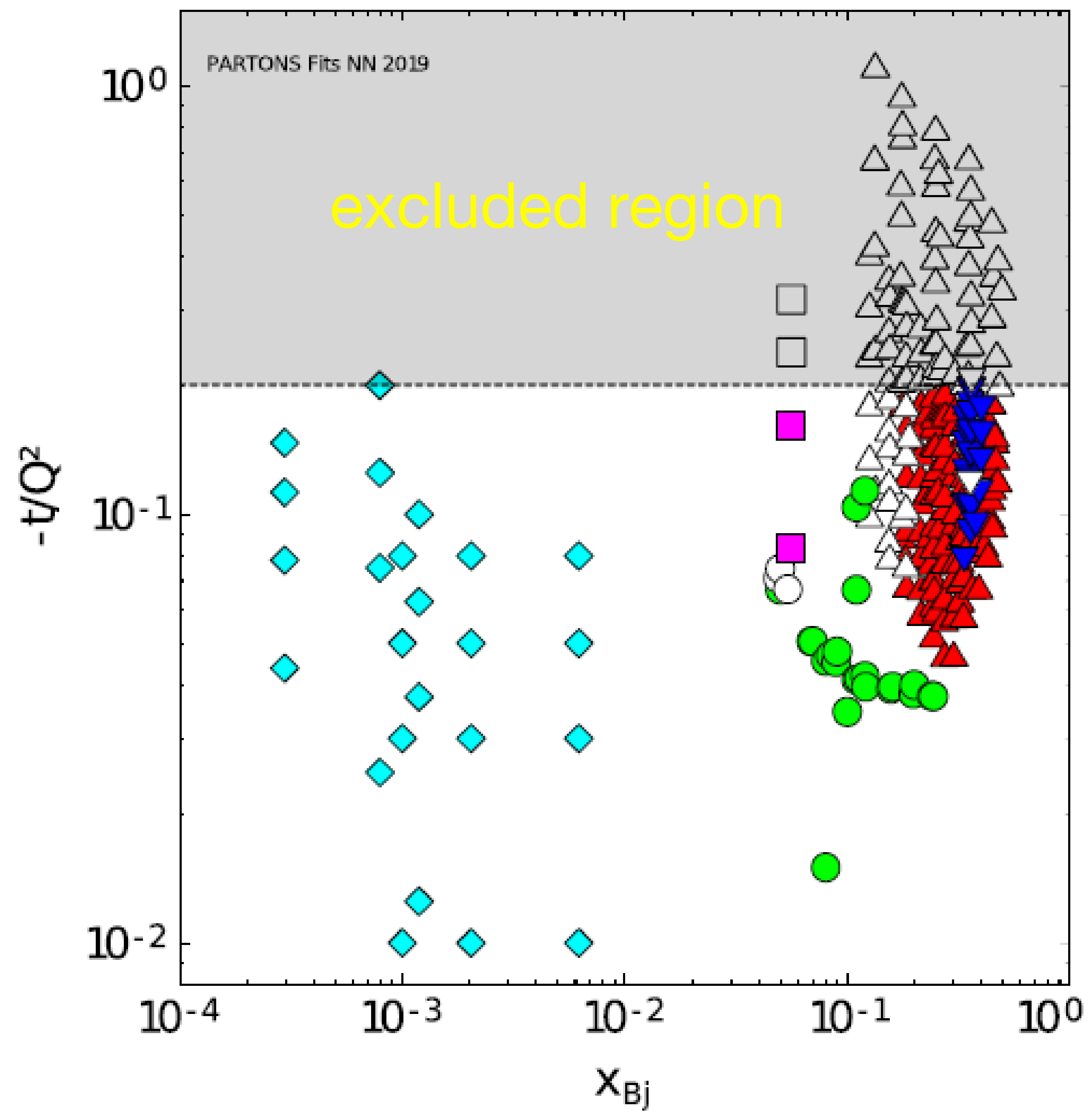
Generalized Parton Distributions (GPD)

Generalized Parton Distributions

- **Current Status:**

❑ Exploration stage (CLAS, Hall-A, COMPASS, HERMES, ZEUS, H1)



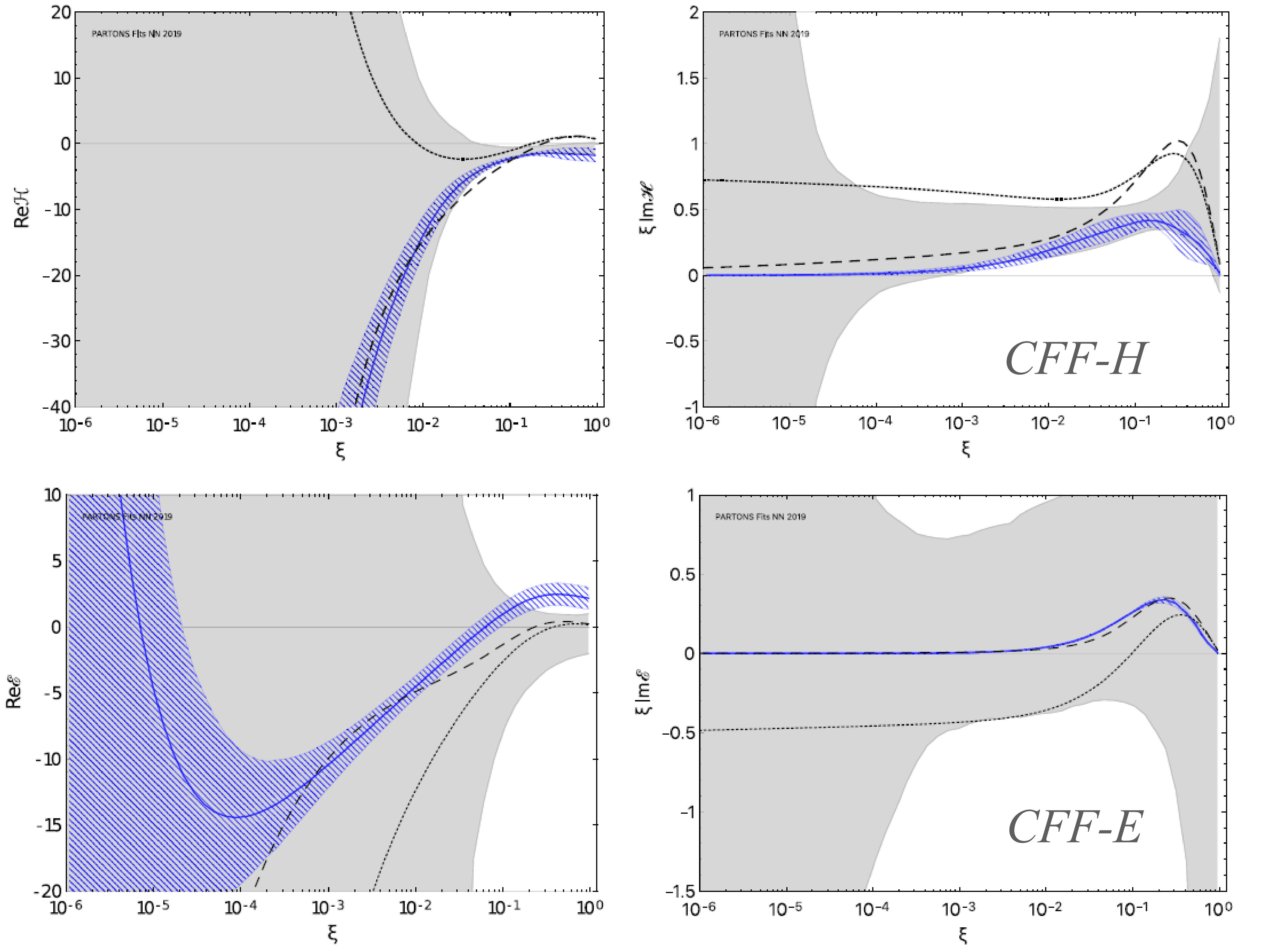


Guidal, Moutarde Vanderhaeghen, Rep. Prog. Phys. 76 (2013)
d' Hose, et. al., Eur. Phys. J. A (2016) 52: 151
X. Ji, National Science Review, 213-223 (2017)

❑ More data needed!

❑ Global Fits

Blue: fit with modle-constrain, Moutarde et. al. EPJ (2018)
Gray: unbias fit by PARTONS Collaboration, EPJ (2019)



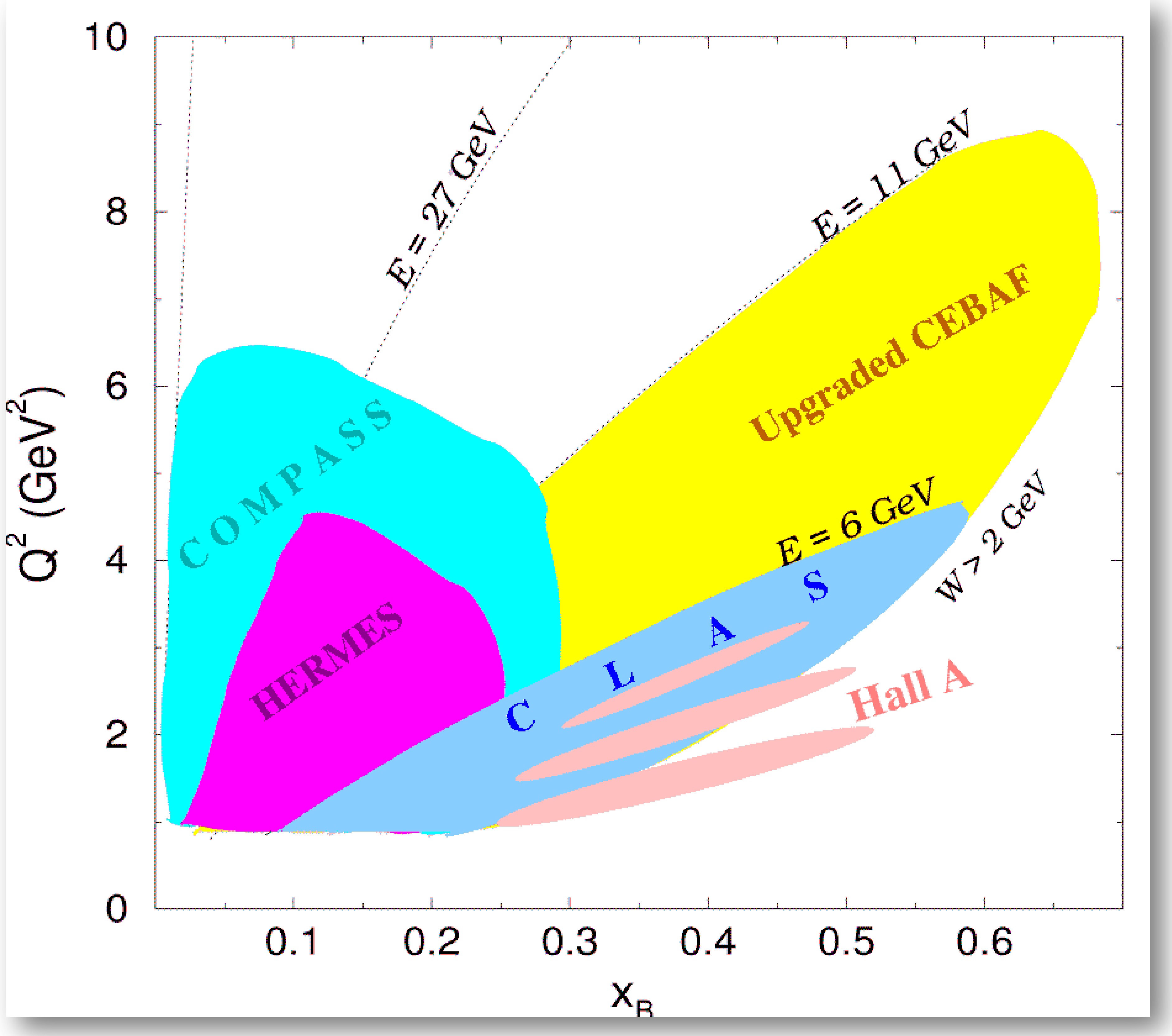
GPD Study on SoLID

Jlab12GeV DVCS Experiments:

- ☐ Need multiple observables to decouple 8 CFFs, → XS, BSA, TSA, DSA
- ☐ DVCS not directly sensitive to flavor → proton & neutron needed for u & d
- ☐ 3D → wide kinematic-coverage + high rate

Approved 12GeV DVCS experiments:

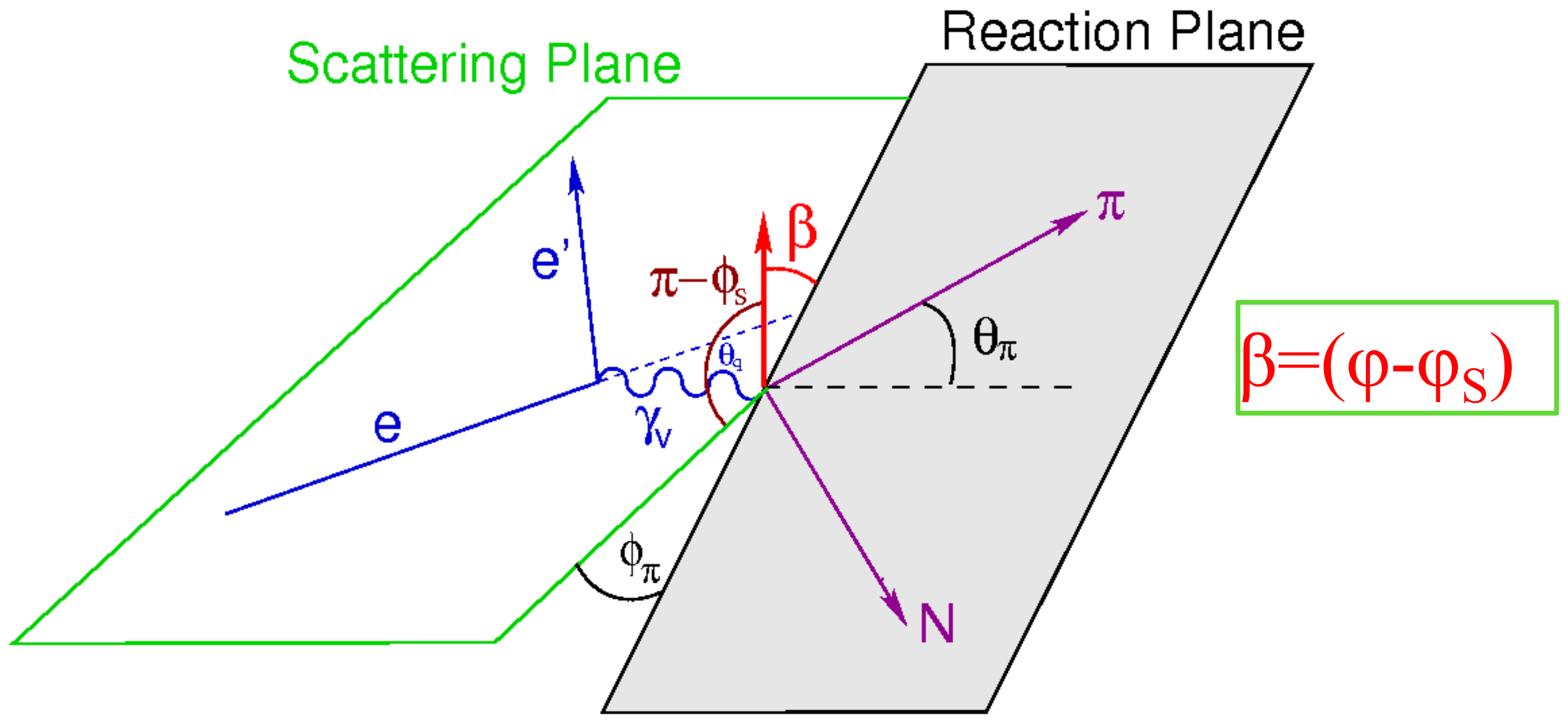
- E12-16-010B (Hall-B): unpol. proton, XS
- E12-11-003 (Hall-B): unpol. Deuteron, BSA
- E12-06-119 (Hall-B): long-pol proton, BSA, TSA,
- C12-12-010 (Hall-B): *conditional approved*, trans. pol. Proton, TSA,BSA
- C12-15-004 (Hall-B): *conditional approved*, long. pol. Deuteron, TSA, BSA
- E12-06-114 (Hall-A&C): unpol. proton, XS & BSA, limited coverage
- E12-13-010 (Hall-C): unpol. proton, XS,
- E12-15-001 (Hall-C): proton, XS
- ***LOI:*** nDVCS w/ TDIS setup (Hall-A), tagged neutron, XS



- SoLID (SIDIS configuration) will provide:
  - DVCS asymmetries w/ polarized beam & target data
  - DVCS neutron data (Deuteron or He3)

GPD Study on SoLID

- **SoLID-DVMP:** $e + \vec{n} \rightarrow e' + p + \pi^-$



☐ DVMP advantages:

- ✓ Direct probe of quark flavor
- ✓ Pseudoscaler mesons sensitive to $\tilde{H}$ and $\tilde{E}$ (uniquely w/ neutron)
- ✓ Sensitive to transverse GPDs ($H_T, E_T, \tilde{H}_T, \tilde{E}_T$)

☐ DVMP disadvantages:

- ✓ Usually requires $Q^2 > 10$ GeV^2 for factorization
- ✓ Higher twist contaminations
- ✓ Long. photons to link to GPD (LT separation)

$$2\pi \frac{d^2\sigma}{dt d\phi} = \epsilon \frac{d\sigma_{\mathrm{L}}}{dt} + \frac{d\sigma_{\mathrm{T}}}{dt} + \sqrt{2\epsilon(\epsilon+1)} \frac{d\sigma_{\mathrm{LT}}}{dt} \cos\phi + \epsilon \frac{d\sigma_{\mathrm{TT}}}{dt} \cos 2\phi$$

☐ DVMP w/ asymmetries: *Belitsky & Műller PLB 513(2001)349, CIPANP 2003).*

- ✓ $A_L^\perp$ displays factorization even at only $Q^2 \sim 2$-4 GeV^2:

$$A_L^\perp = \frac{\sqrt{-t'}}{m_p} \frac{\xi\sqrt{1-\xi^2}\,\mathrm{Im}(\tilde{E}^*\tilde{H})}{(1-\xi^2)\tilde{H}^2 - \frac{t\xi^2}{4m_p}\tilde{E}^2 - 2\xi^2\mathrm{Re}(\tilde{E}^*\tilde{H})}.$$