Overview of Generalized Parton Distribution Measurements

叶志鸿

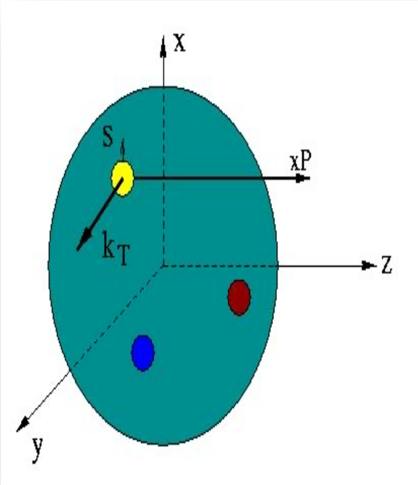
清华大学物理系

第一届强相互作用自旋物理会议, 山东-青岛，07/27~07/30, 2026

Nucleon's 3D Structure

Tsinghua University

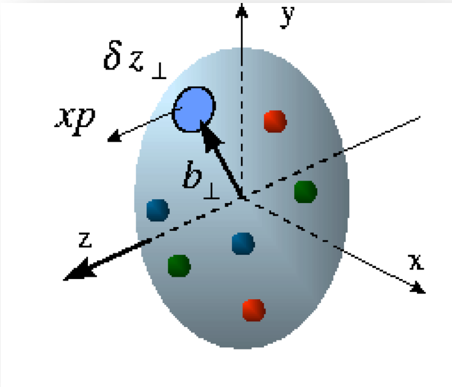
$W_p^u(x,k_T,\boldsymbol{r_T})$ Wigner distributions **5D**



$d^2\boldsymbol{r_T}$

d^2k_T

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



TMD
$f_1^u(x,k_T)$, $h_1^u(x,k_T)$,…

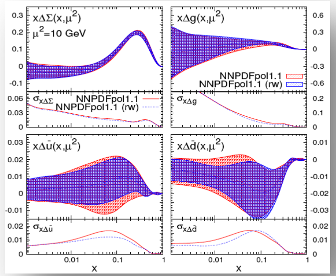
3D

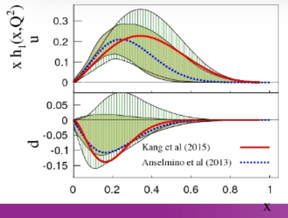
GPDs/IPDs
$H^u, E^u, \widetilde{H}^u, \widetilde{E}^u$

d^2k_T

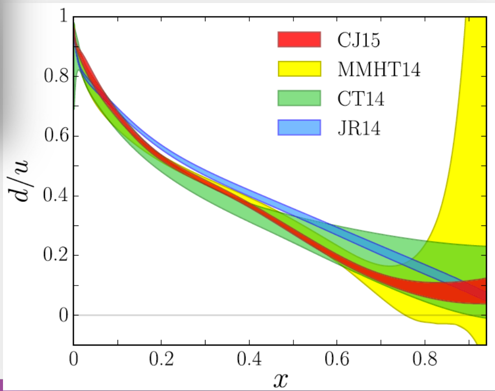
d^2r_T

dx & Fourier Transfor





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

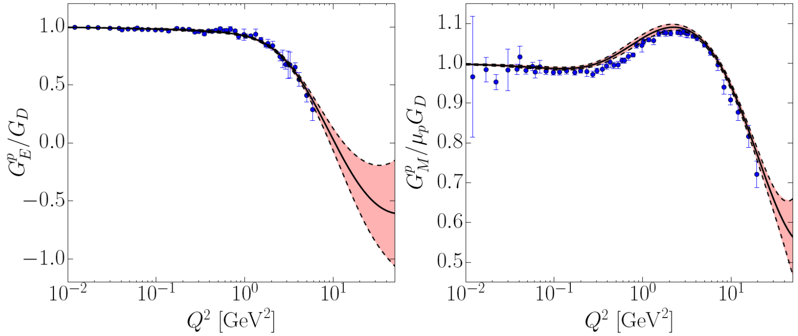


PDFs
$f_1^u(x)$, $g_1^u(x)$,
$h_1^u(x)$,…

1D

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

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



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

- *x → Longitudinal quark momentum fraction (not experimental accessible)*
- *ξ → Longitudinal momentum transfer. In Bjorken limit: $\xi = x_B/(2-x_B)$*
- *t → Total squared momentum transfer to the nucleon: $t = (P-P')^2$*

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

❑ 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

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

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

Axial&Pseudoscalar Form Factors

$$H^q(x,0,0) = q(x), x > 0$$

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

PDFs

❑ Access parton distributions in 3D

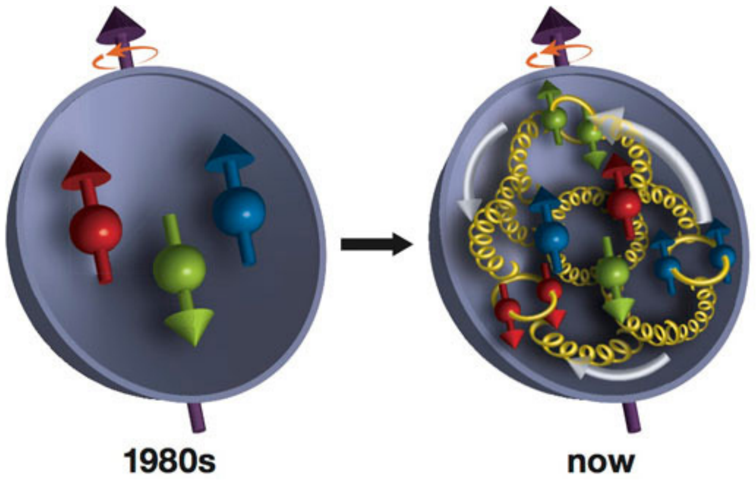
X. Ji, PRL 78, 610 (1997)
M. Diehl, Physics Reports 388 (2003) 41–277,
Belitsky, Radyushkin, Physics Reports 418 (2005) 1–387

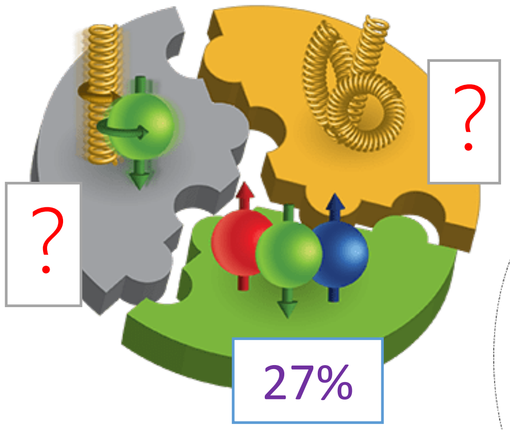
Generalized Parton Distributions

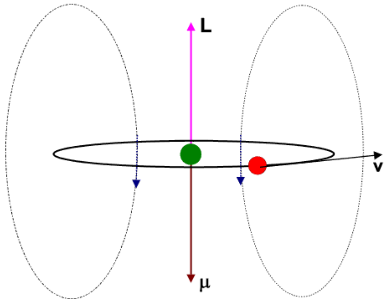
Tsinghua University

➢ Proton's Spin Puzzle

X. Ji, F. Yuan, Y. Zhao, Nature Review Physics, 2021







❑ Two ways of spin-decomposition:

✓ Ji's (frame-independent): $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$

DIS   DIS+RHIC

✓ Jaffe-Manohar's (in $P_z \to \infty$ frame): $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + l_q + \frac{1}{2}\Delta G + l_g$

❑ How to access Angular Momenta?

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

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

<u>Generalized Parton Distributions (GPD)</u>

GPD Measurements

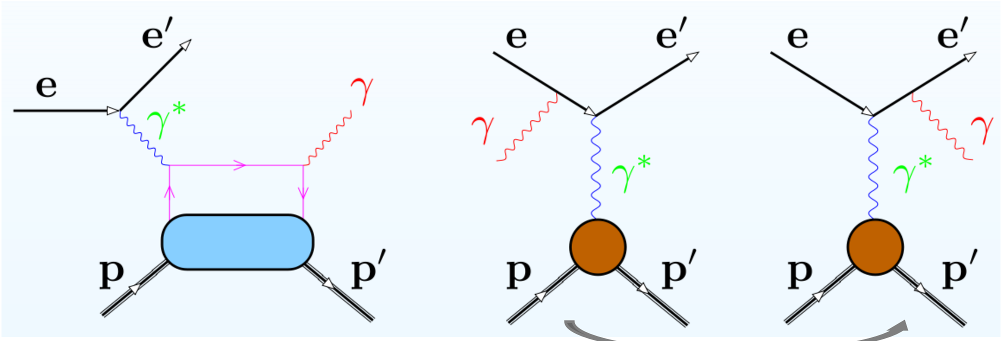
Tsinghua University

➢ Deep Virtual Compton Scattering (DVCS):

❑ Golden channel to study GPD

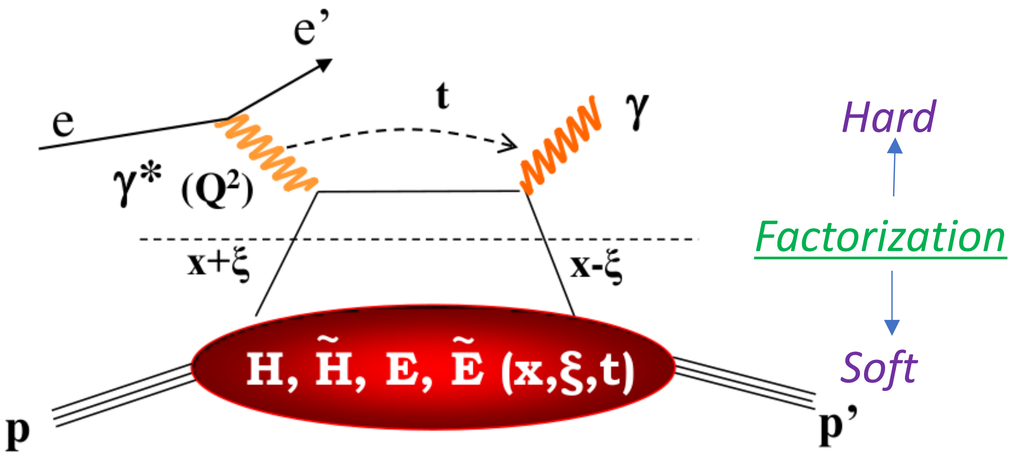
❑ Contain two processes

$$\frac{d\sigma}{dQ^2 dx_B dt d\phi} \propto \left|\tau_{DVCS}\right|^2 + I + \left|\tau_{BH}\right|^2$$



DVCS

Bethe-Heitler (BH)



❑ Access GPDs via Interference Terms

$$I = \left|\tau_{DVCS}\tau^*_{BH} + \tau^*_{DVCS}\tau_{BH}\right|^2$$

Large & well-known from Nucleon FF, F_1 & F_2

❑ **DVCS only measures Compton Form Factors (CFFs):**

Re($\mathcal{H}$) Im($\mathcal{H}$)

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

GPD Measurements

➢ Deep Virtual Compton Scattering (DVCS):

- ❑ With polarization: $\sigma^{BH+I+DVCS} = \underbrace{\sigma_{UU}}_{unpol} + \underbrace{P_L\sigma_{LU}}_{beam\ pol} + \underbrace{S_{L,T}\sigma_{UL,UT}}_{target\ pol} + \underbrace{P_L S_{L,T}\sigma_{LL,LT}}_{double\ pol}$

- ❑ Asymmetry:

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

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

- ❑ Separate CFFs by angular modulations:

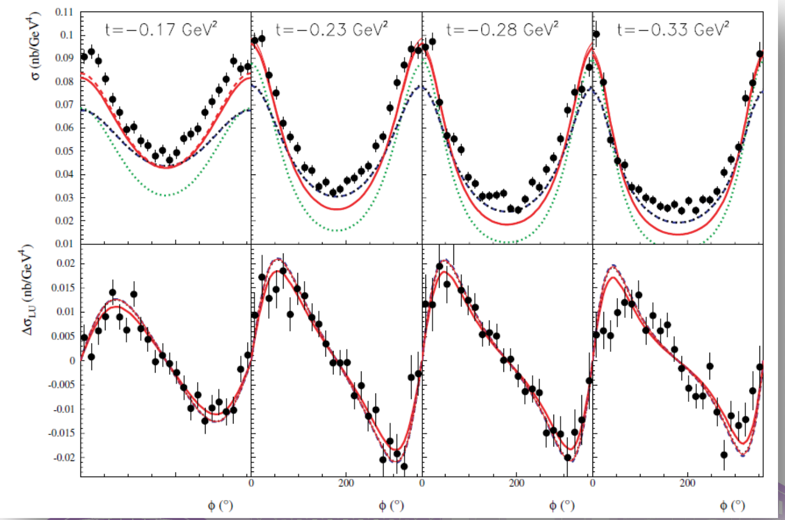
$$d\sigma^{I}_{UU} = \frac{-K_I}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \sum_{n=0}^{3} c^{I}_{n,\mathrm{unp}} \boxed{\cos(n\phi),}$$

$$d\sigma^{DVCS}_{UU} = \frac{1}{Q^2} \sum_{n=0}^{2} c^{DVCS}_{n,\mathrm{unp}} \boxed{\cos(n\phi),}$$

$$d\sigma^{I}_{LU} = \frac{-K_I}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \sum_{n=1}^{2} s^{I}_{n,\mathrm{unp}} \boxed{\sin(n\phi),}$$

$$d\sigma^{DVCS}_{LU} = \frac{1}{Q^2} s^{DVCS}_{1,\mathrm{unp}} \boxed{\sin\phi,}$$

Belitsky, Mueller, PRD (2009,2010), NPB (2014)



JLab, Hall-A, Camacho PRL 97 262002

GPD Measurements

➢ Jlab12GeV DVCS Experiments:

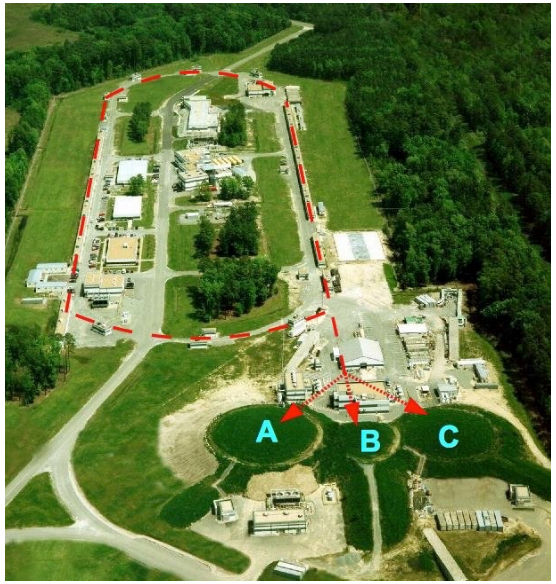
- ❑ Multiple observables needed to decouple 8 CFFs→XS & asym
- ❑ DVCS not sensitive to flavor → p&n targets needed for u & d
- ❑ 3D → wide kinematic-coverage + high rate

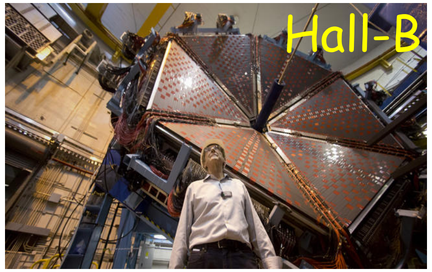
Approved 12GeV DVCS experiments:

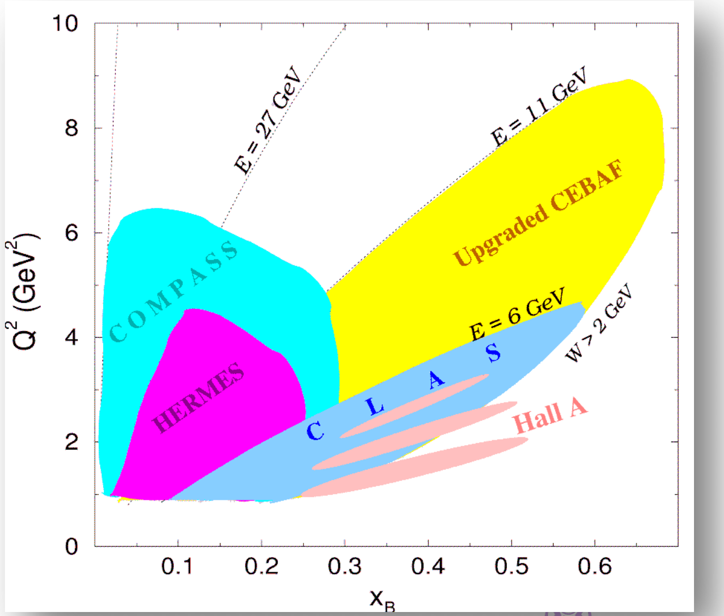
- E12-16-010B (Hall-B): unpol. proton, XS
- ~~E12-12-010 (Hall-B): trans. pol. HDIce, BSA~~
- E12-11-003 (Hall-B): unpol. Deuteron, BSA
- E12-06-119 (Hall-B): long-pol proton, BSA, TSA,
- E12-06-113 (Hall-B): unpol. Deuteron, BSA
- E12-06-114 (Hall-A&C): unpol. proton, XS & BSA, limited coverage
- E12-13-010 (Hall-C): unpol. proton, XS , limited coverage
- E12-15-001 (Hall-C): proton, XS, limited coverage
- ***LOI:*** nDVCS w/ TDIS setup (Hall-A), tagged neutron, XS

My group involved

❖ Lack of polarized beam & target data
❖ Lack of neutron data (Deuteron or He3)







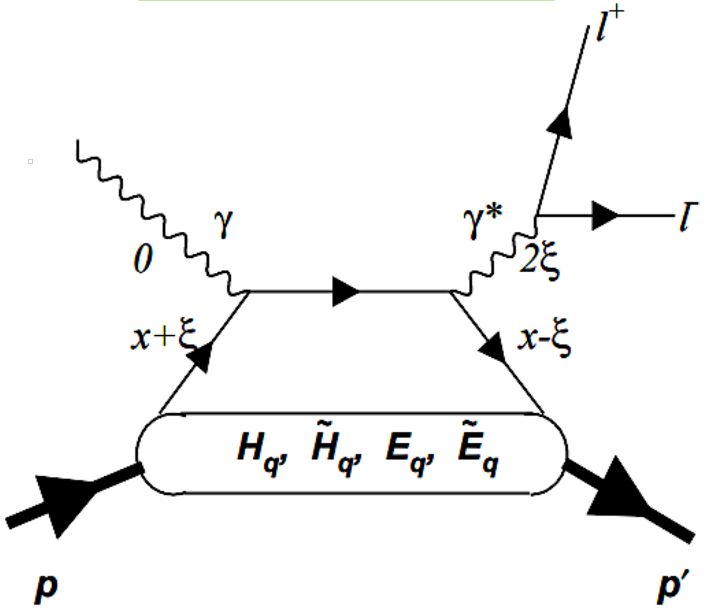
GPD Measurements

清華大学 Tsinghua University

➢ Three additional exclusive processes

Timelike Compton Scattering:

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

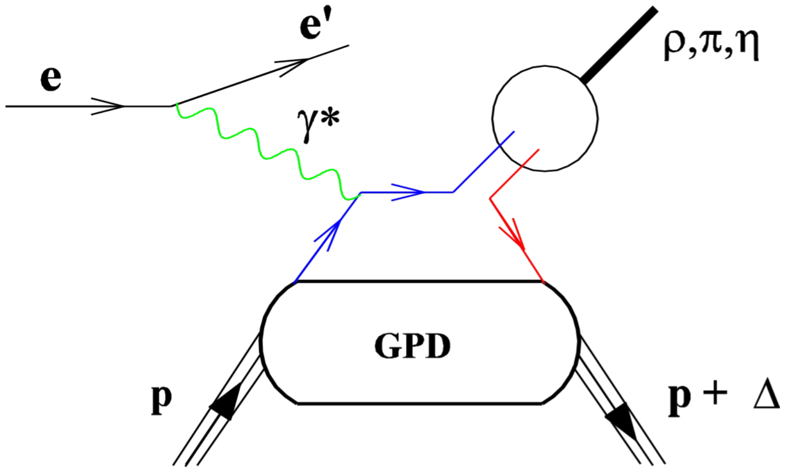


- ✓ Inverse of the space-like DVCS
- ✓ Extract the real part of CFFs
- ✓ Complementary to DVCS

宋勤涛（周四，大会报告）

Deep Virtual Meson Production

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

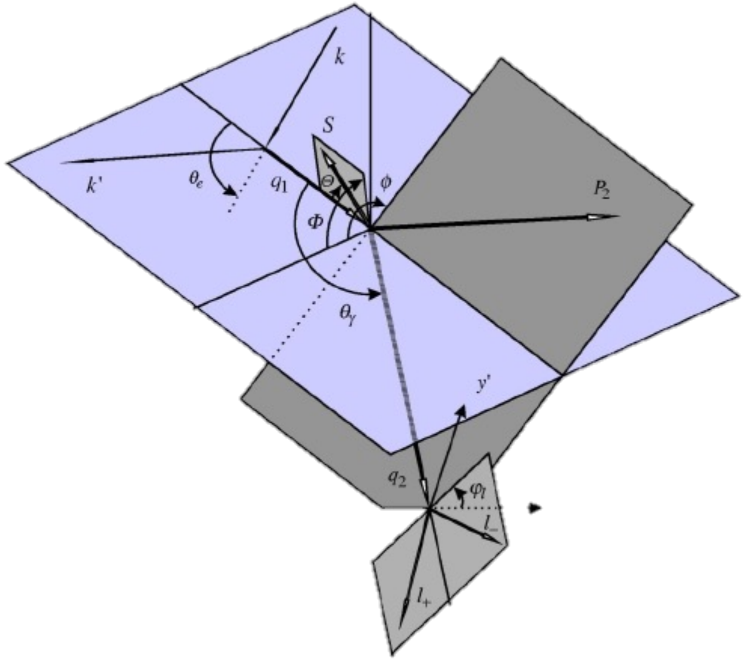


- ✓ Vector mesons → H, E.
- ✓ Pseudoscalar mesons → $\tilde{H}$ & $\tilde{E}$.
- ✓ neutron + pseudoscalar → to $\tilde{E}$
- ✓ sensitive to chiral-odd GPDs (H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$)

唐广（周二下午，分会场二）

Double-DVCS:

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



- ✓ Lepton pairs in the final states
- ✓ Access GPDs ***beyond the x=ξ limit***
- ✓ NO approved experiments

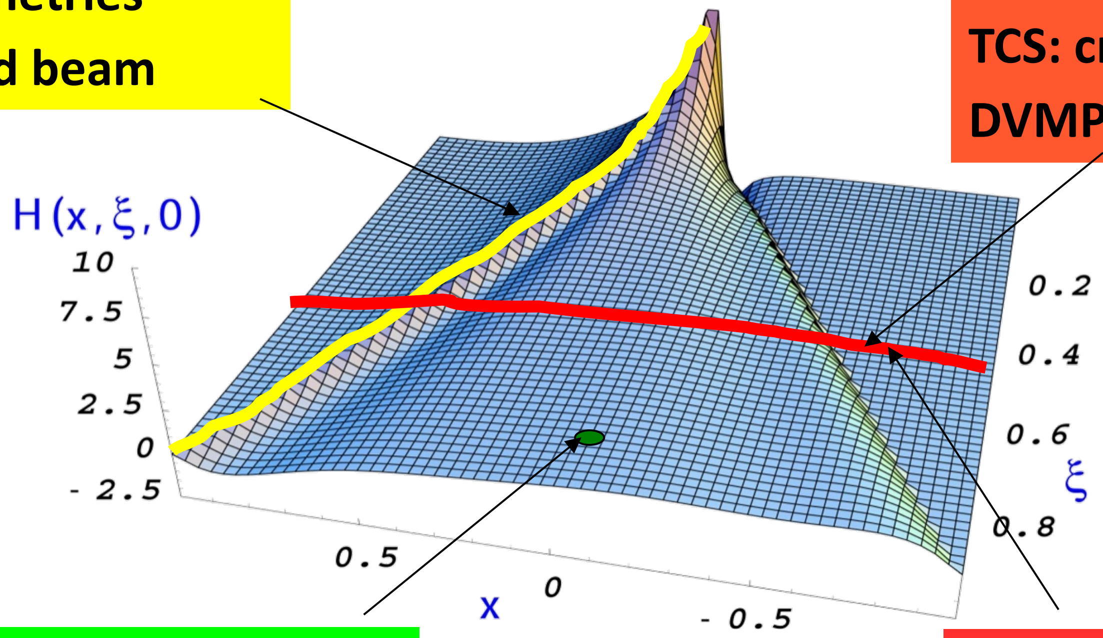
GPD Measurements

Tsinghua University

- **Three additional exclusive processes**
  - **All processes together are crucial to fully extract GPDs**

(Im, x=ξ)
DVCS: spin asymmetries
TCS with polarized beam

(Re)
DVCS: charge asymmetry
TCS: cross-section, beam asymmetry
DVMP: cross-section, asymmetries



(Im, x ≠ ξ, x < |ξ|)
Double DVCS

($|\mathrm{Im}|^2+|\mathrm{Re}|^2$)
DVCS: cross section
DVMP: cross-section, asymmetries

GPD Extraction

➢ Current Status:

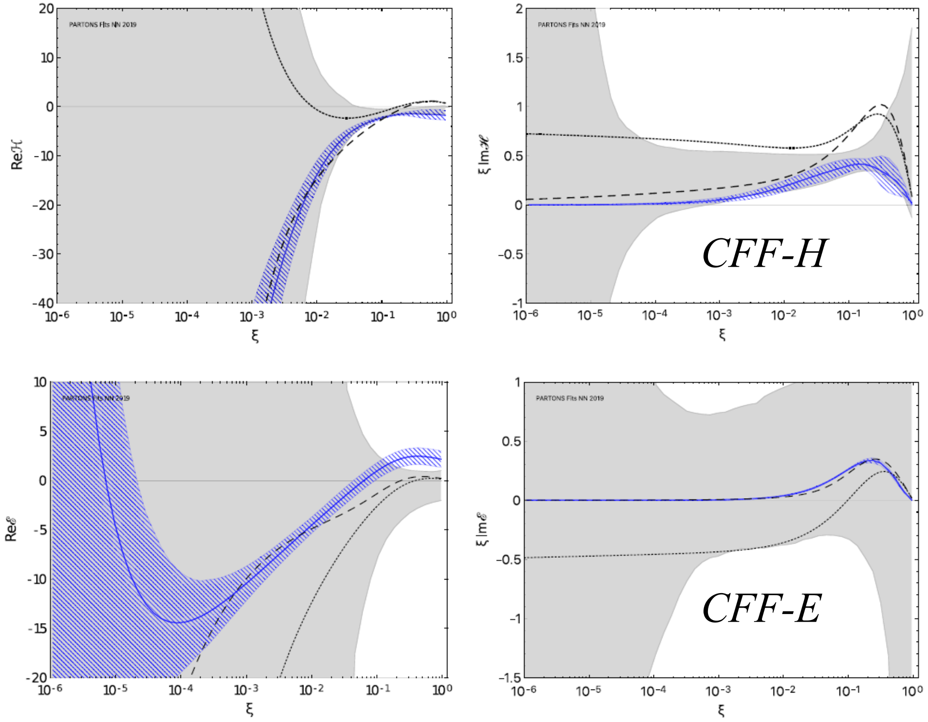
❑ Very limited DVCS data available

✓ CLAS, Hall-A, COMPASS, HERMES, ZEUS, H1

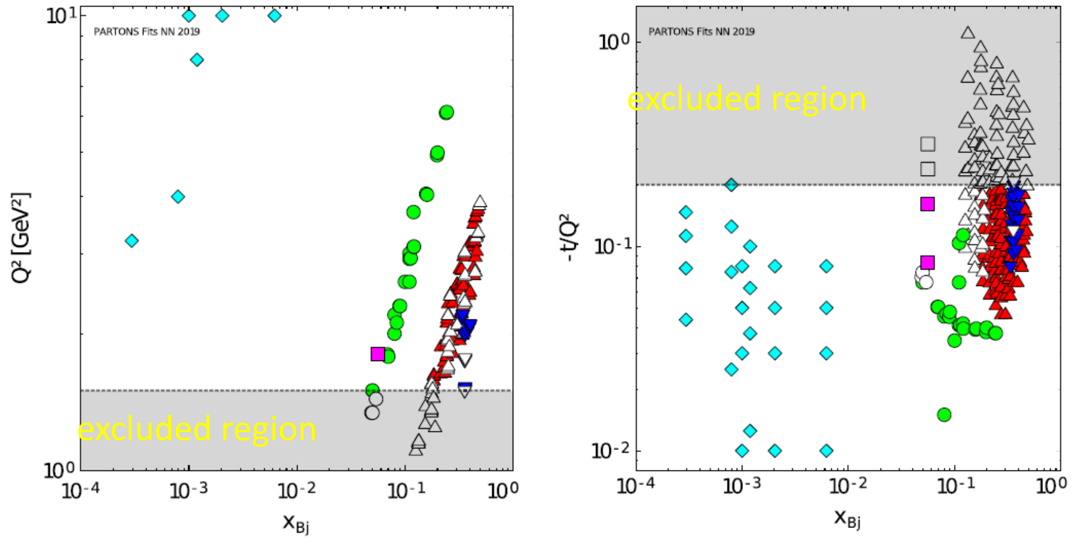
❑ Previous global fits(XSs → CFFs+Models → GPDs)

Blue: fit with model constrained, Moutarde et. al. EPJ (2018)

Gray: unbiased fit by PARTONS Collaboration, EPJ (2019)

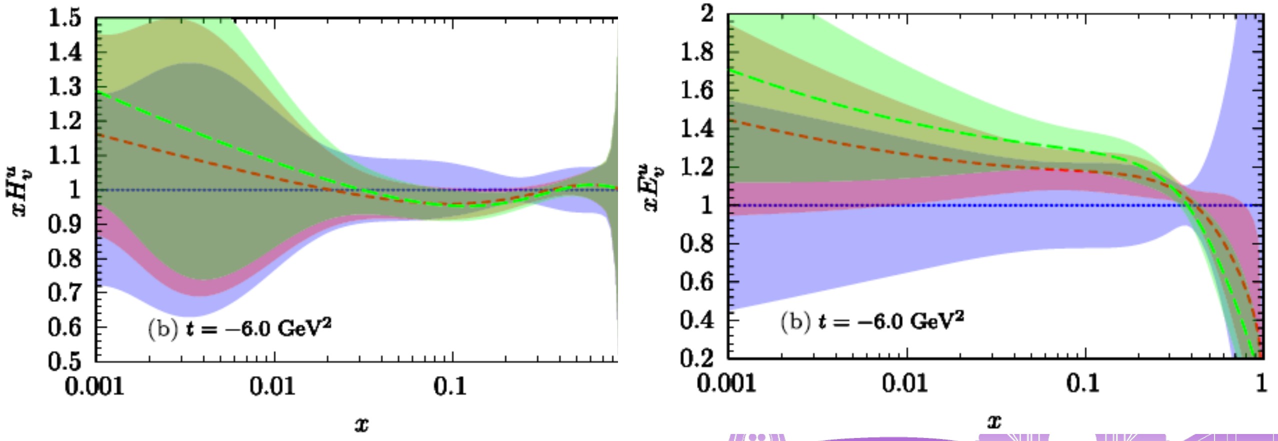


Guidal, Moutarde Vanderhaeghen, Rep. Prog. Phys. 76 (2013)
d' Hose, et. al., Eur. Phys. J. A (2016) 52: 151
X. Ji, National Science Review, 213-223 (2017)



❑ Recent global analysis

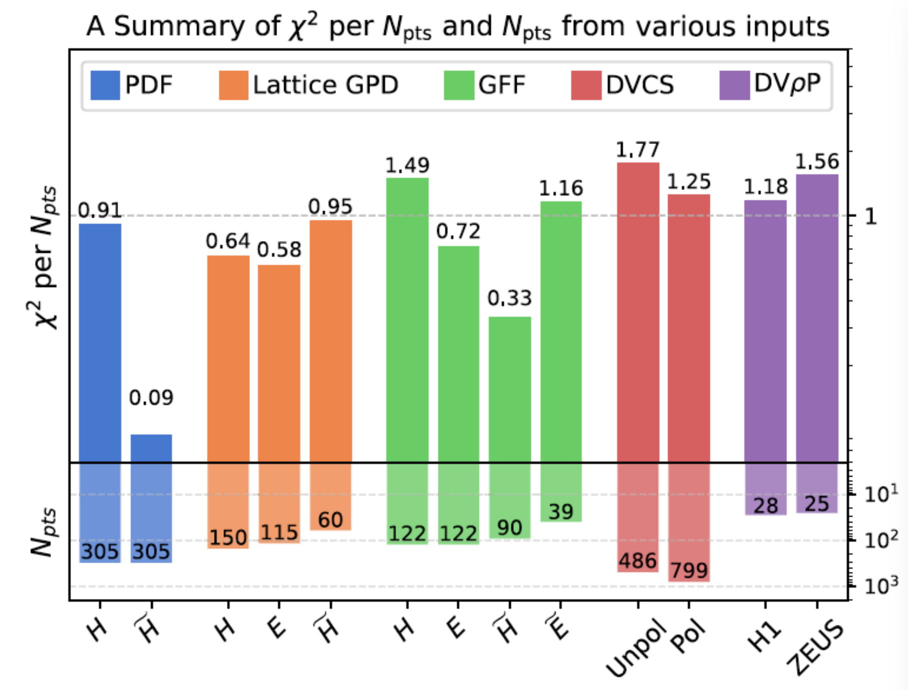
MMGPDs Collaboration, Physical Review D 109, 074042 (2024)

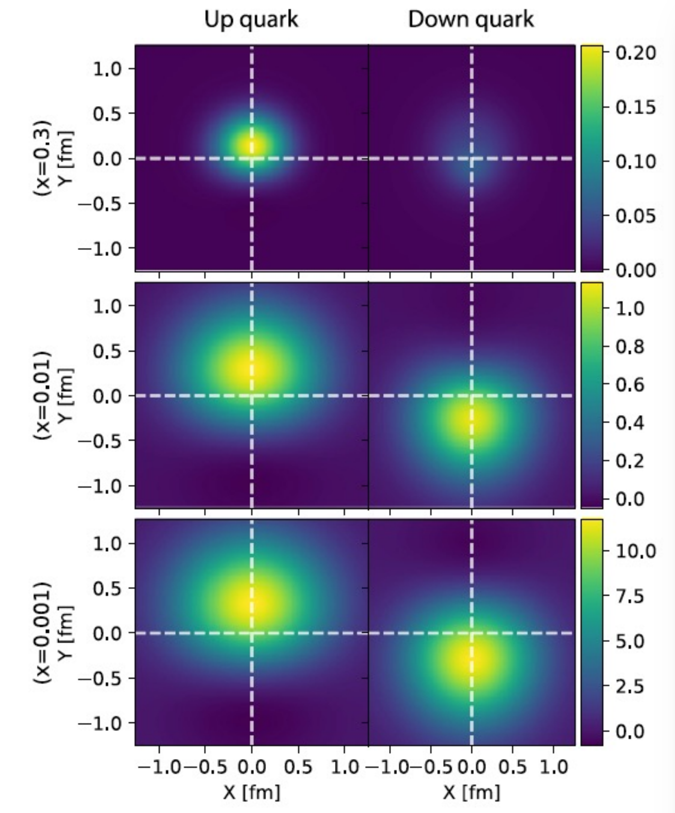


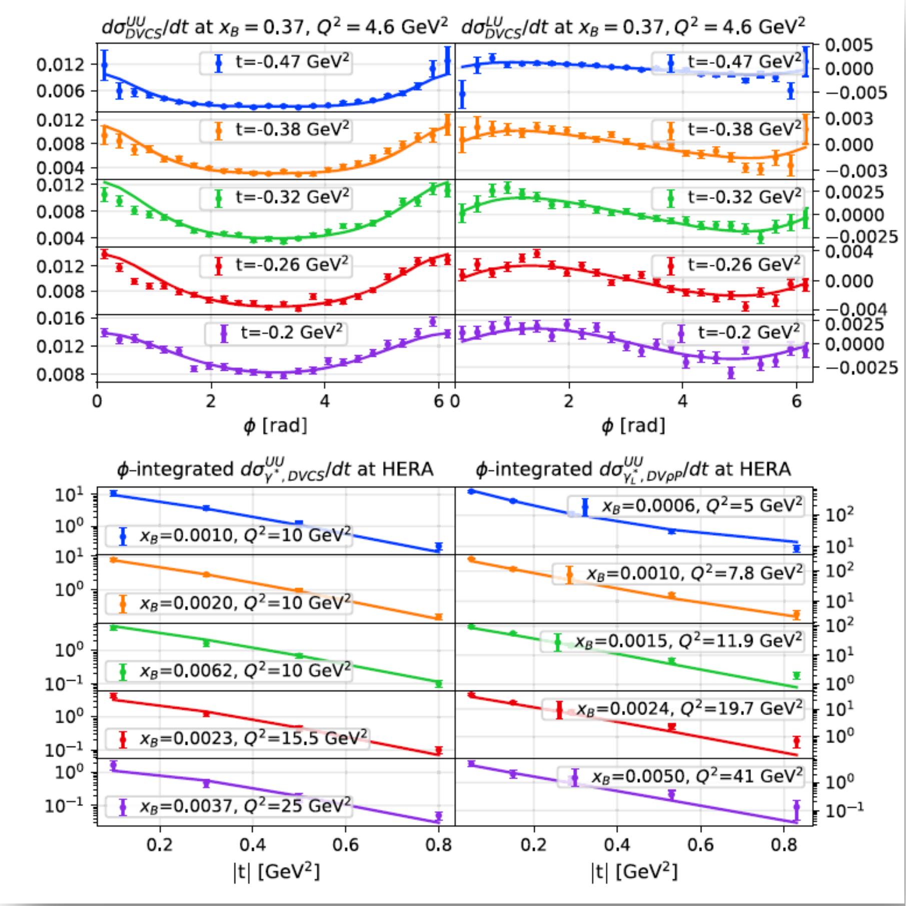
GPD Extraction

➢ Exp. Data + Lattice Results:

❑ **GUMP1.0**: Y. Guo, F. P. Aslan, X. Ji, M. G. Santiago, Physical Review Letters 135, 261903 (2025)







❑ **Lattice data provide essential inputs**

❑ **Still very limited exclusive data for meaningful GPD extraction**

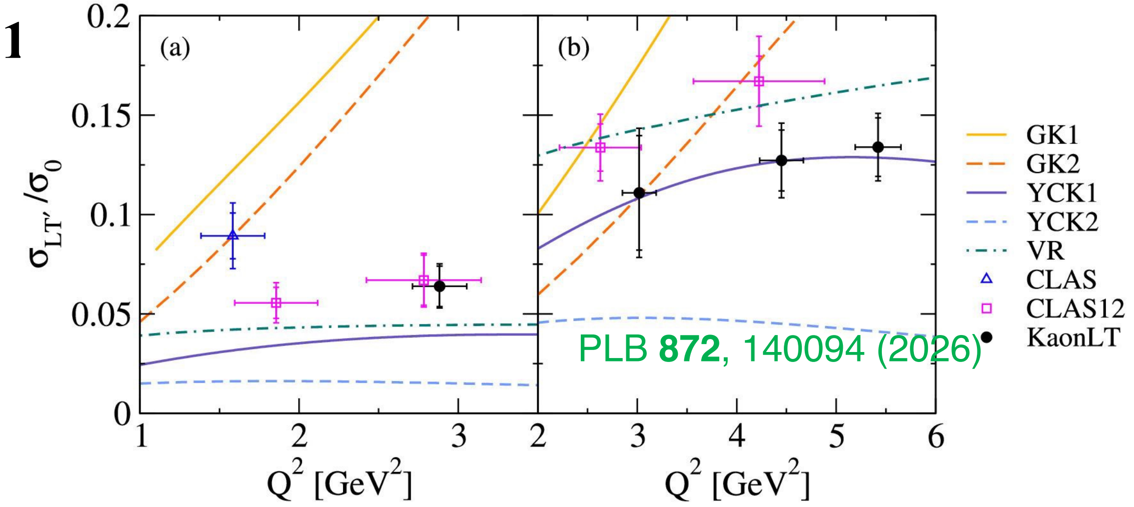
New GPD Experiments in Hall-C

Tsinghua University

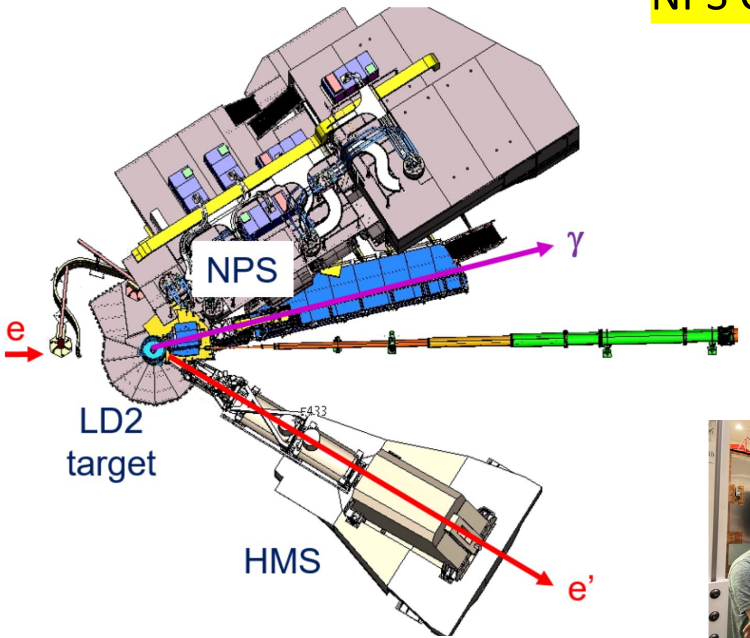
❑PionLT/KaonLT Experiment in Hall C (completed in 201

- ✓ DVMP w/ π^+/K$^+$to improve GPD models
  $(e + p \rightarrow e' + \pi^+/K^+ + n/\Lambda)$
- ✓ First extract of Q2-depdt of σ_{LT}/σ_0 in asymmetries

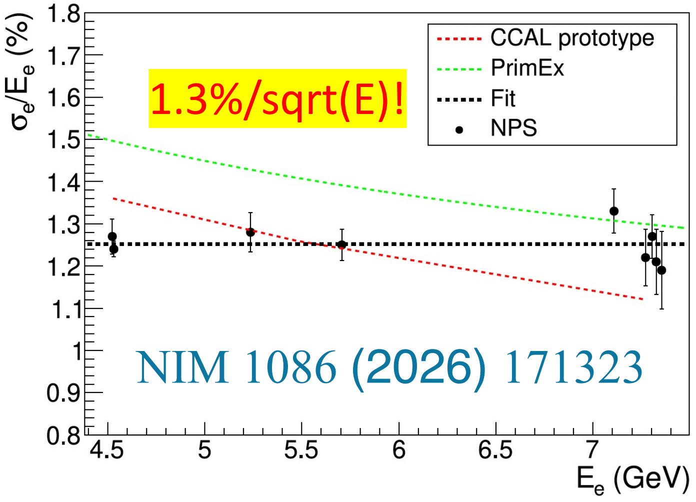
$$A_{LU}(Q^2, x_B, t, \phi) = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi},$$

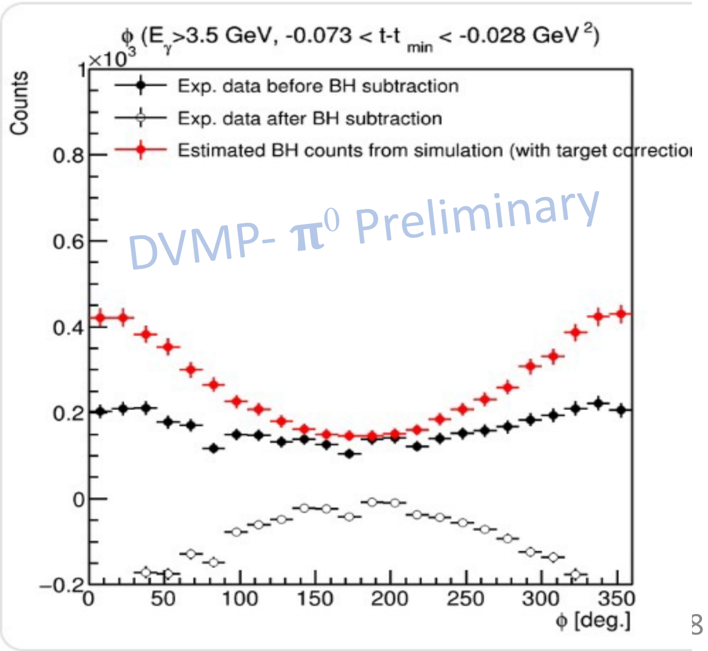


❑DVCS&DVMP w/ NPS Experiments (1st part completed in 2024):



NPS Calorimeter





张耀鹏报告(周三下午，分会场一)

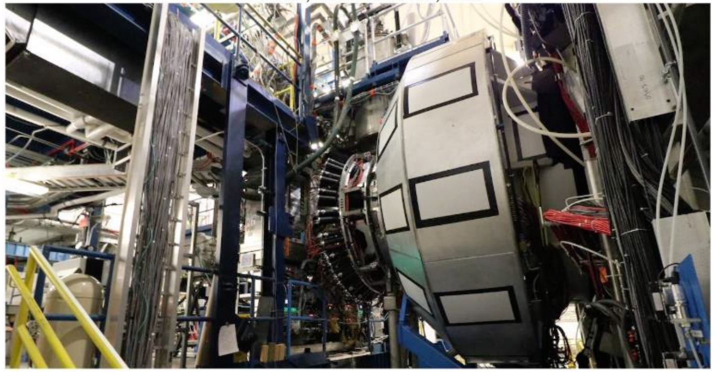
New GPD Experiments w/ CLAS12

- **First Neutron DVCS with CLAS12 central neutron detector**

  Phys. Rev. Lett.133, 211903 (Nov. 2024),

- **ALERT measured DVCS/DVMP in He4**
  - RG-L (w/ tagged DIS & SRC)
  - Completed in 2025, analysis ongoing
  - ✓ 1 GPD in He4 (coherent DVCS)
  - ✓ Nuclear-GPD in He4 (incoherent)

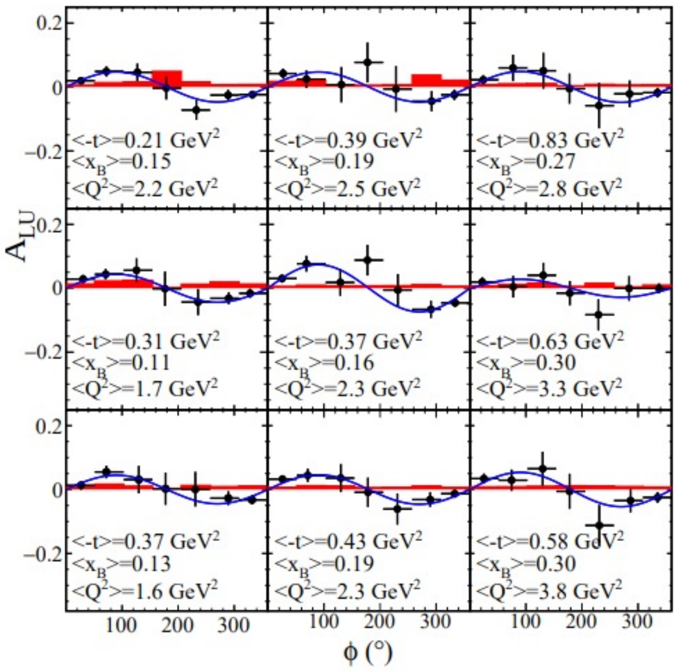
TUESDAY, NOVEMBER 26, 2024

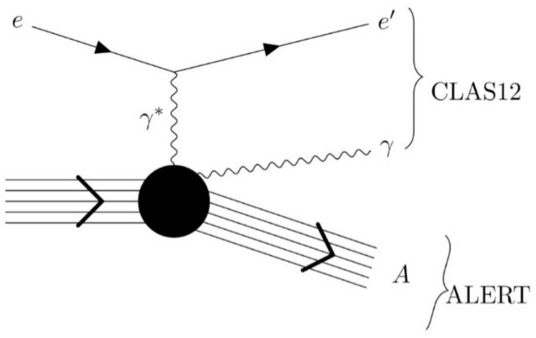


A view of the Central Neutron Detector in Hall B's CEBAF Large Acceptance Spectrometer for 12 GeV (CLAS12).

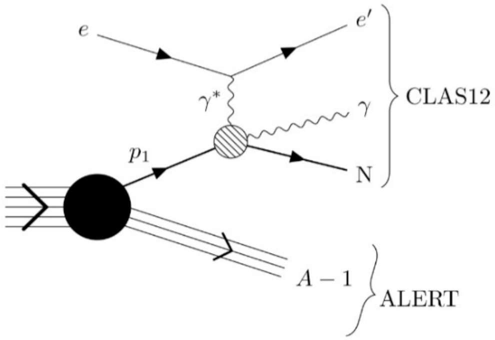
Accessing the Lesser-Known Nucleon

Protons and neutrons – known collectively as nucleons – are the building blocks of matter, but protons have received more attention in certain types of nuclear physics experiments. Until now. New results published in Physical Review Letters describe a first-time glimpse of the internal structure of the neutron thanks to the development of the Central Neutron Detector installed in Experimental Hall B's CLAS12 detector. To read the full story, click here.





Coherent-DVCS



Incoherent-DVCS

- **Global GPD analysis to extract proton properties**

Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

arXiv:2503.18152

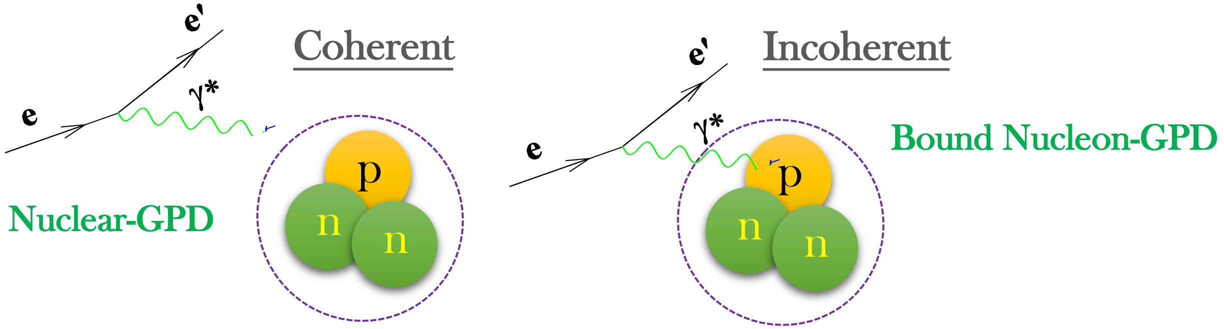
Open database for GPD analyses

V.D. Burkert[1], A. Camsonne[1], P. Chatagnon[1,2], K. Cichy[3], M. Constantinou[4], H. Dutrieux[5], I. M. Higuera-Angulo[1], C. Mezrag[2], D. Richards[1] P. Sznajder[6]

Nuclear GPDs

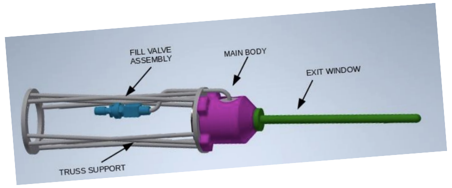
- **DVCS w/ Light Nuclei:**

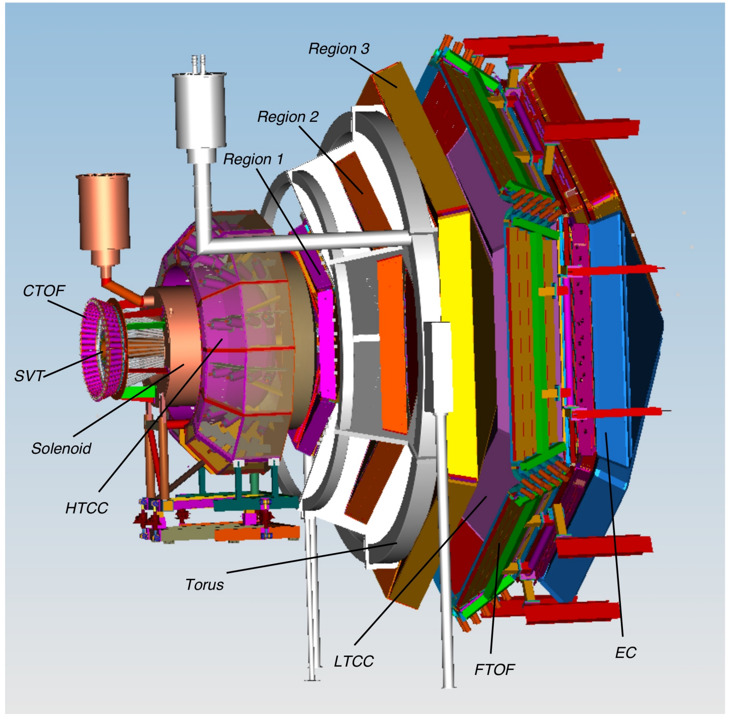
  - New Experiment: DVCS off He3 and H3 (4 GPD for spin ½):



- In Parallel with approved CLAS12 Tritium-SIDIS (C12-21-004)
- Advantages:
  - ✓ Isolate neutron/proton contributions
  - ✓ Flavor-dependence GPD: $H_u^{He3} = H_d^{H3}$
  - ✓ To be compared w/ free-nucleon GPDs
  - ✓ Probe of "EMC Effect" in GPD
  - ✓ Theory-prediction for A=3 available

^3H & ^3He

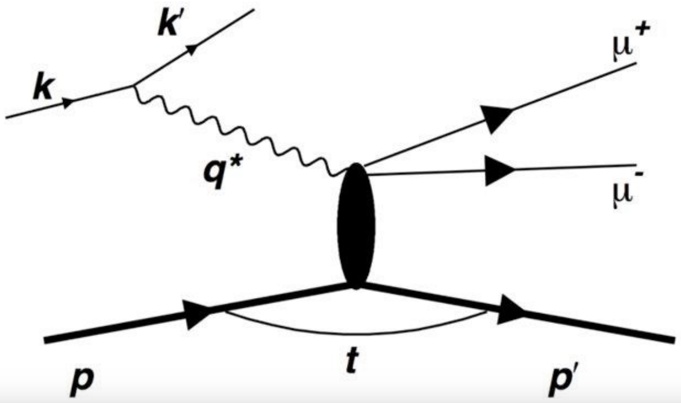


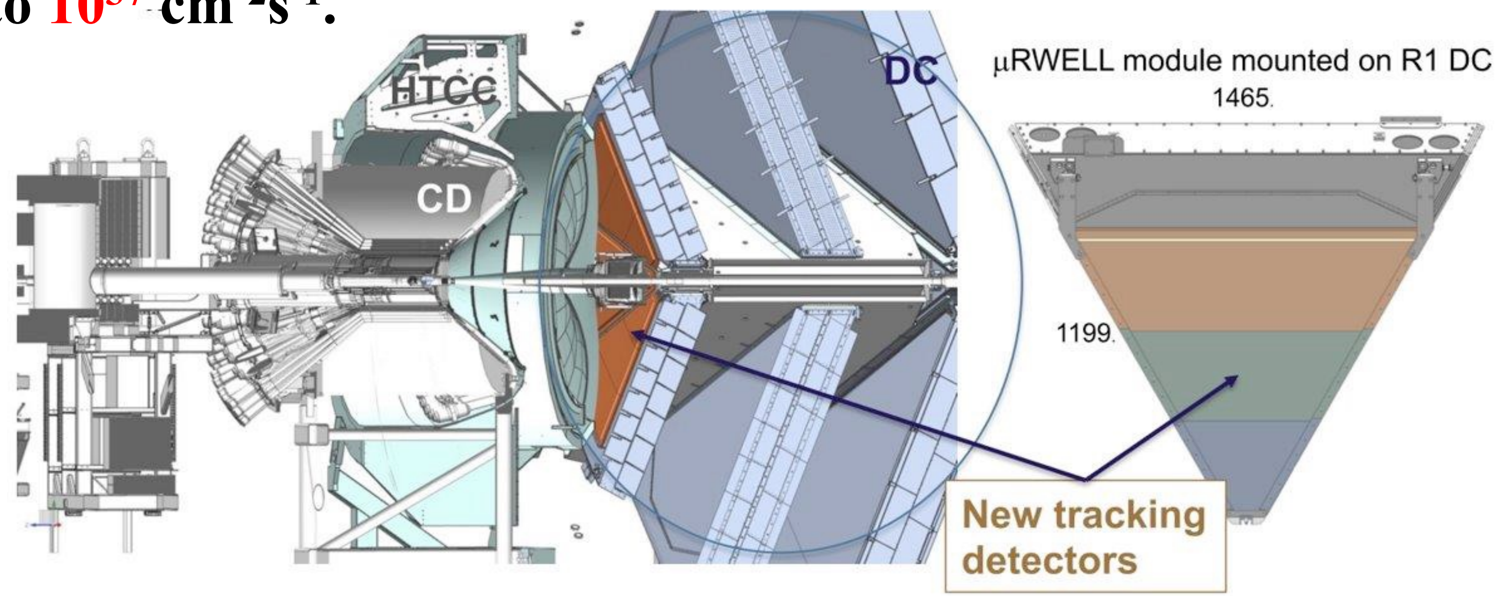


Future Upgrade-μCLAS12

- **CLAS12 luminosity to be upgraded to 10^{37} cm^{-2}s^{-1}.**
  - DC to muRWELL trackers
  - Add forward trackers

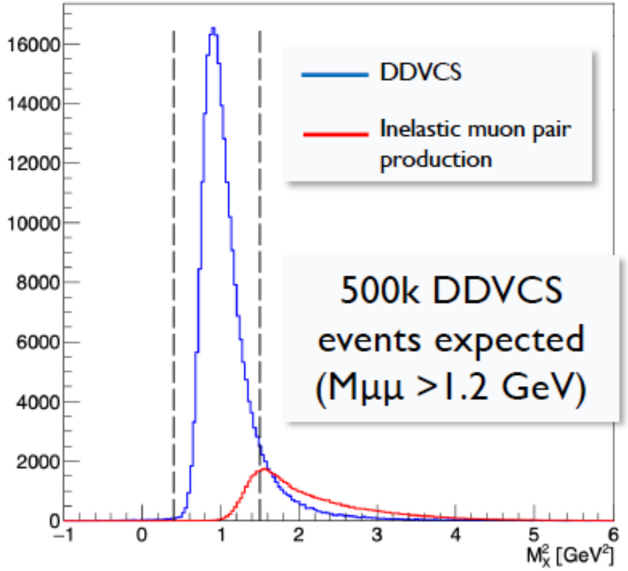
- **Enable the Double-DVCS measurements**

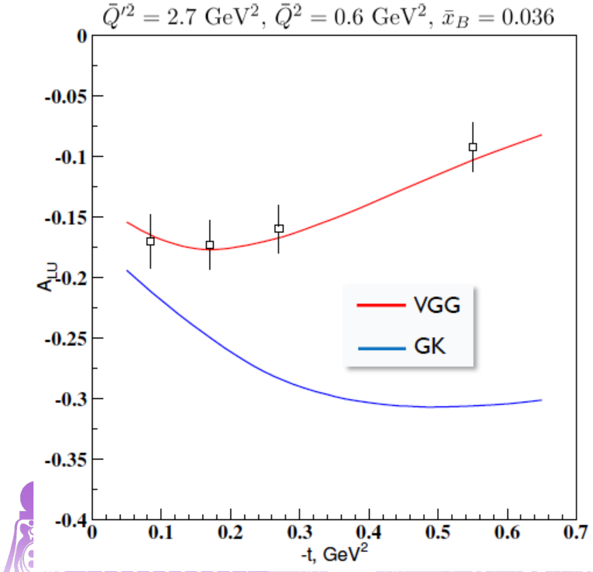




Electro- and photo-production of muon pairs with μCLAS12: Double Deeply Virtual Compton Scattering, Timelike Compton Scattering, and J/ψ production

A Proposal to PAC 53





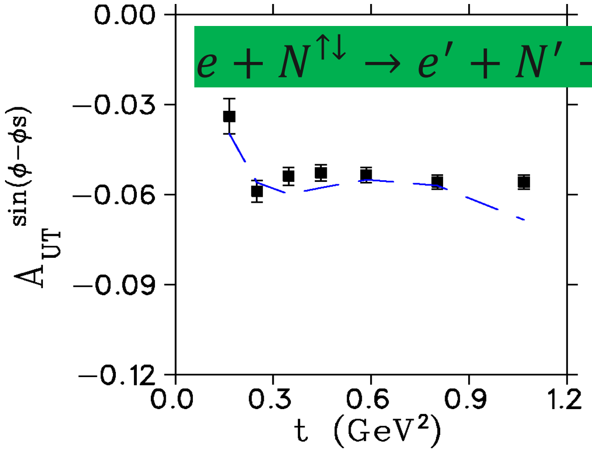
200 days to distinguish models at small-t region

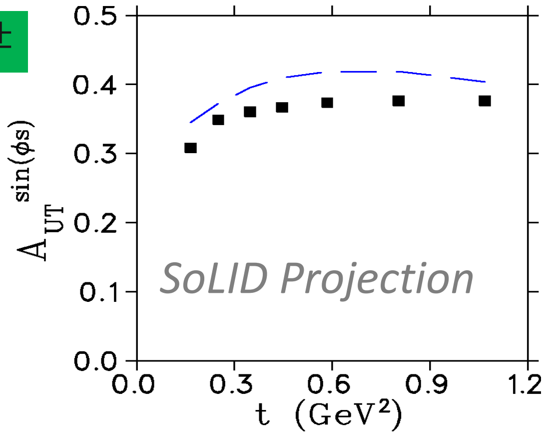
GPD Measurements on SoLID

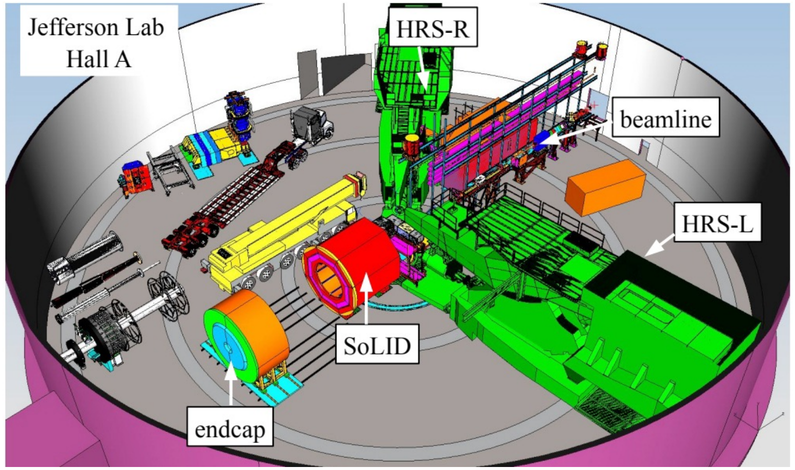
➢The Solenoidal Large Intensity Device (SoLID):

- ✓handle 10^{37}-10^{39} cm^{-2} s^{-1} luminosities
- ✓full 2π azimuthal acceptance;
- ✓Polarized p&n targets.

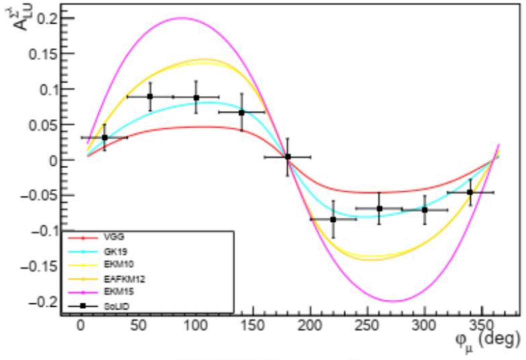
❑ **Provide 4D/5D mappings of TMD & GPD; PVDIS for d/u & BSM**



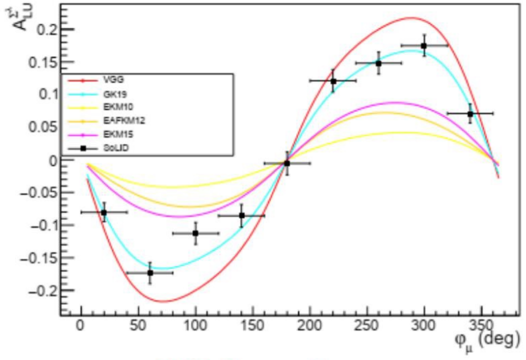




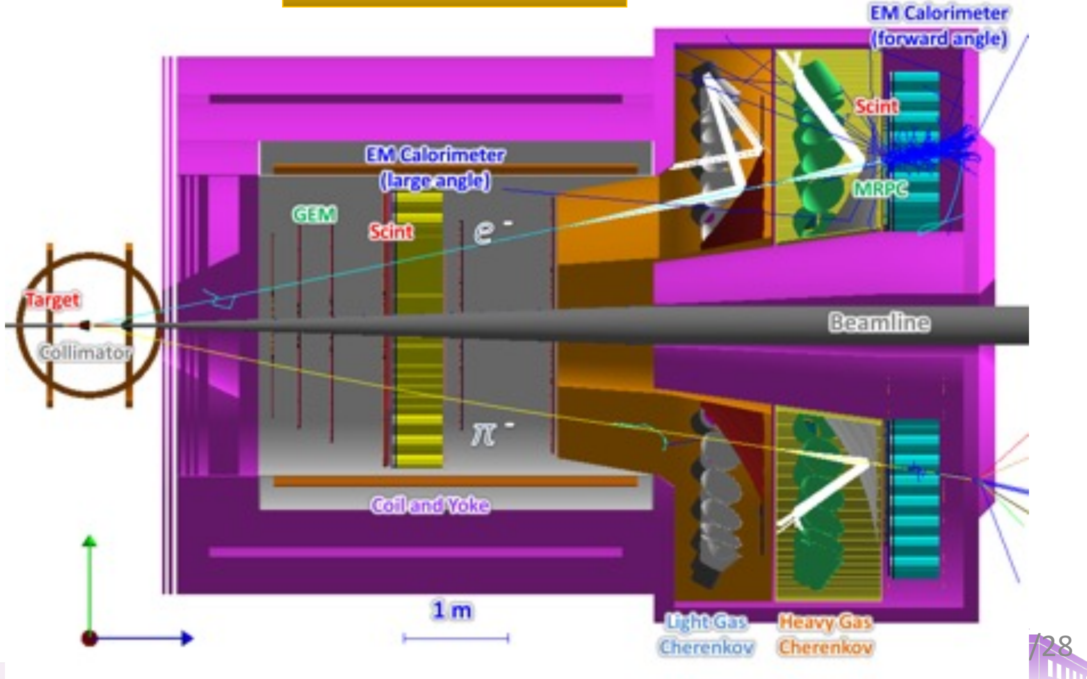
SIDIS &J/Psi& GPD



DVCS-like region



TCS-like region

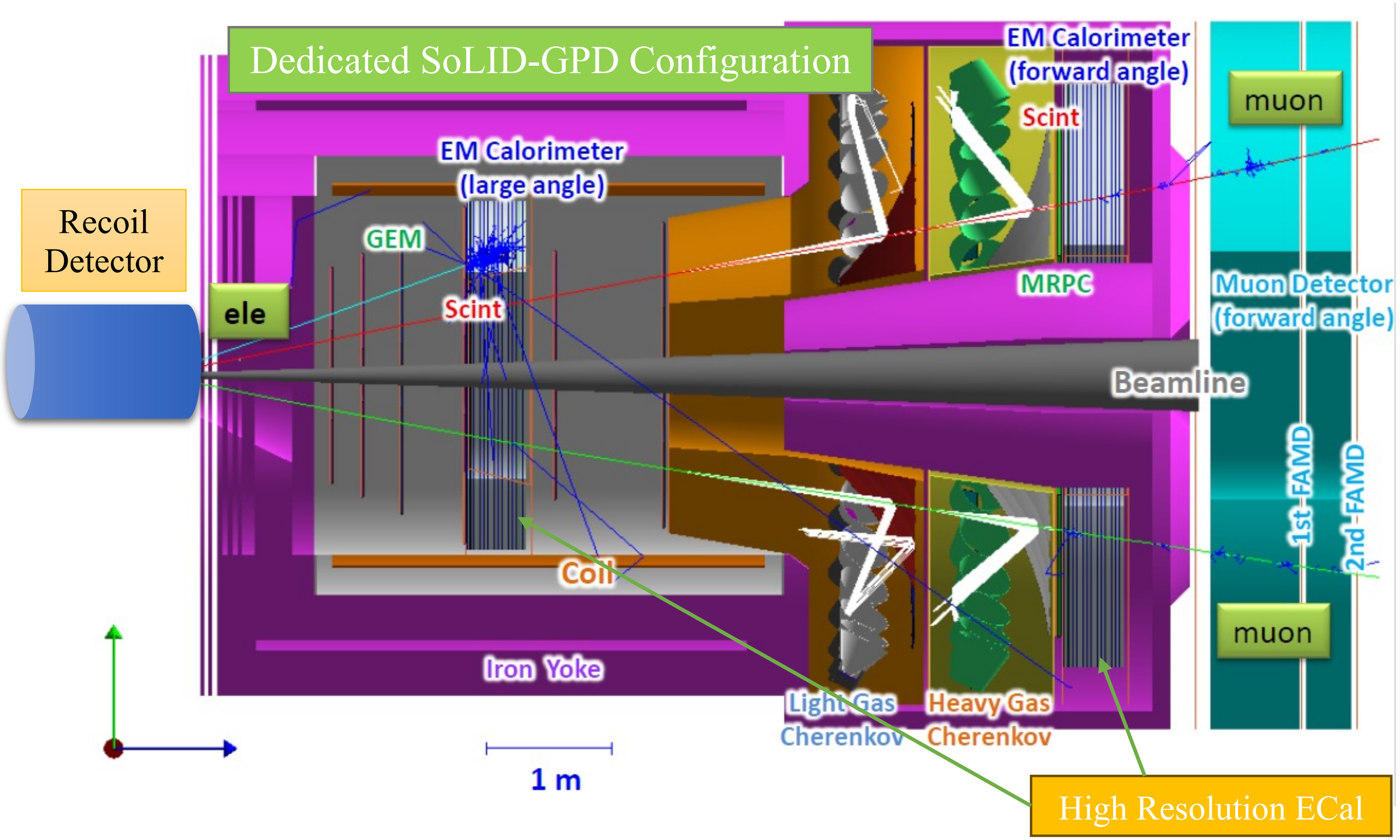


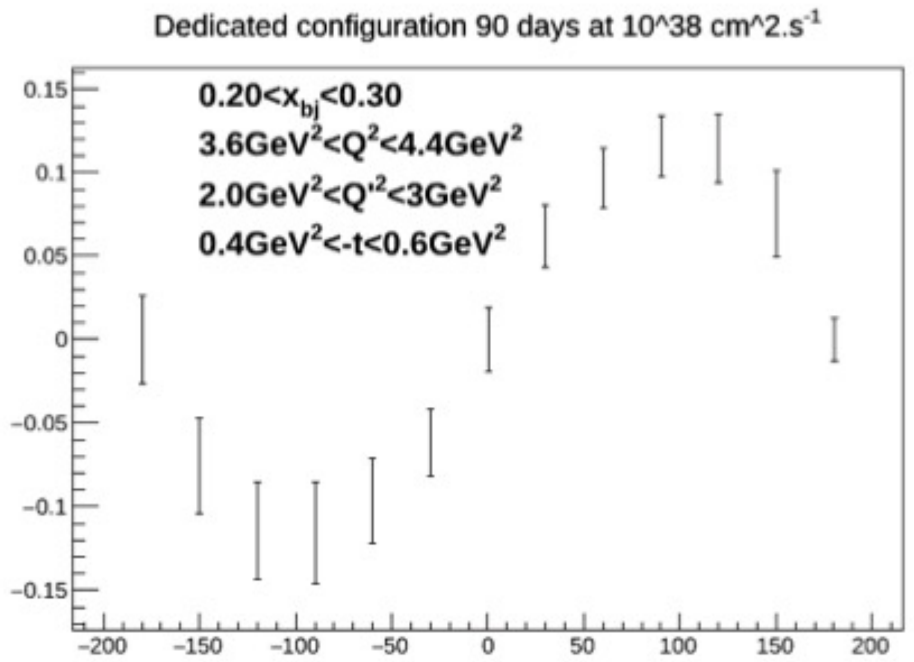
GPD Measurements on SoLID

清華大學 Tsinghua University

➢ Dedicated Setup for New GPD Experiments

❑ SoLID is needed to upgrade to unlock its full power of GPD measurement





DDVCS Projection@SoLID

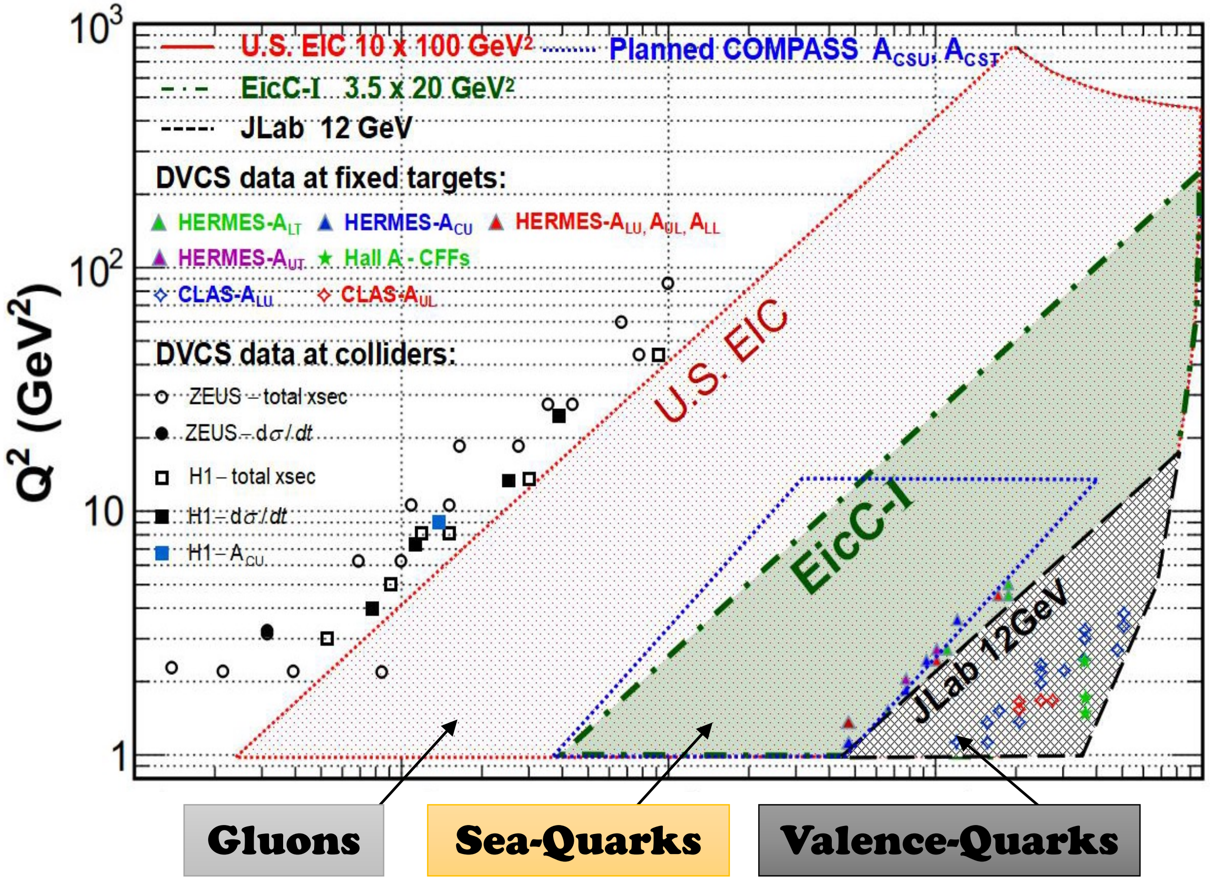
✓ DVCS with polarized He3 & SIDIS → better ECal resolution + recoil proton detector

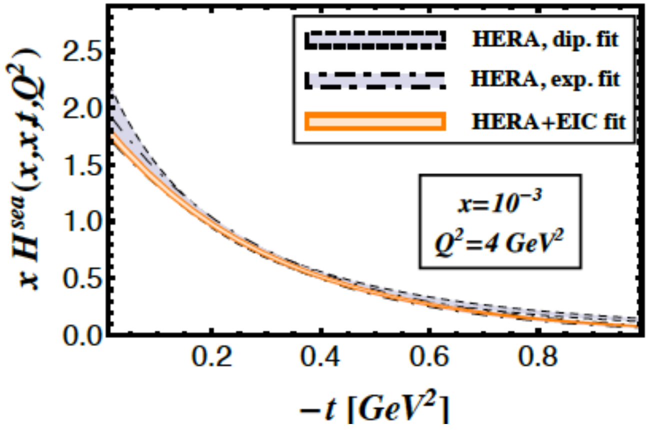
✓ DDVCS with J/Psi (LOI 12-12-005) → +muon detectors

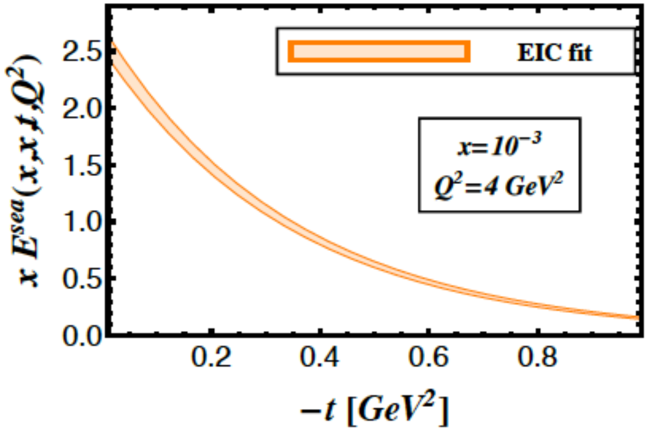
GPD Experiments on EIC

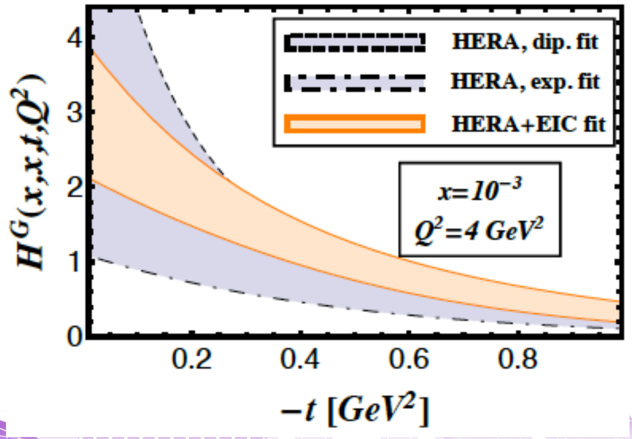
- Unlock the full power of DVMP
- Large Q^2 to go beyond the x=ξ limit
- From valence to sea+gluons
- Solve spin- puzzle : JLab12 + EicC + EIC+COMPASS + Theories

U.S. EIC Yellow-Report





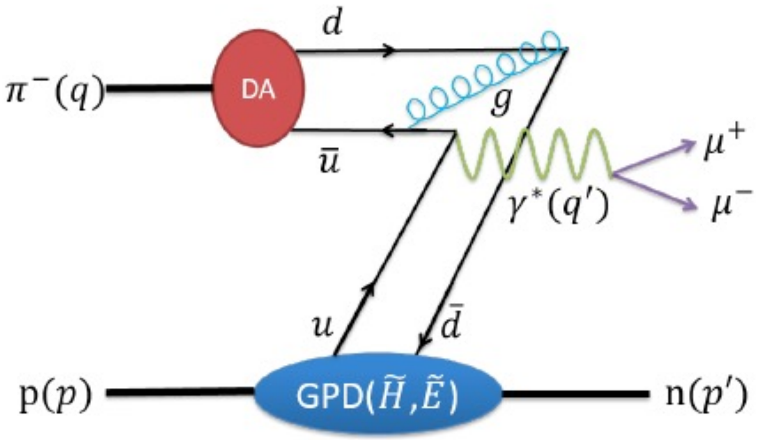




GPD Experiments w/ Hadron Beam

- **Hard-Exclusive Hadron-scattering in time-like region**

H. Kawamura, S. Kumano, Phys. Rev. D 89 (2014) 5, 054007,
D. Muller, et. al., Phys. Rev. D 86 (2012) 031502

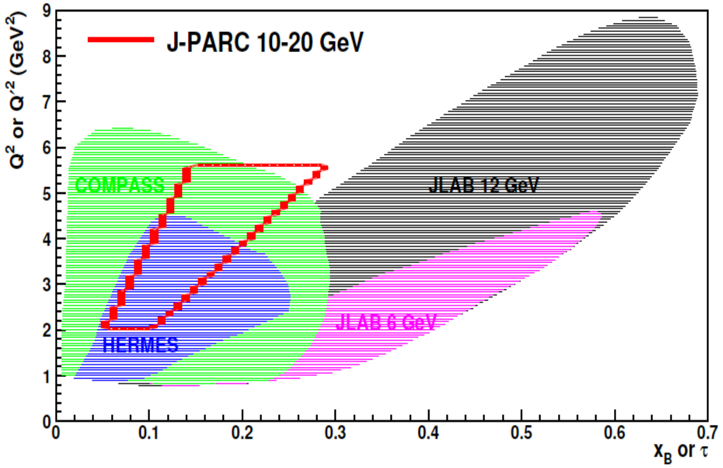


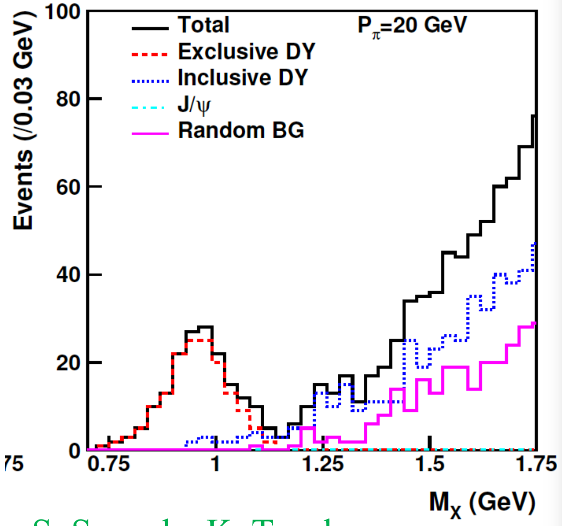
❑ CFF from Pion-included exclusive Drell-Yan (COMPASS&AMBER):

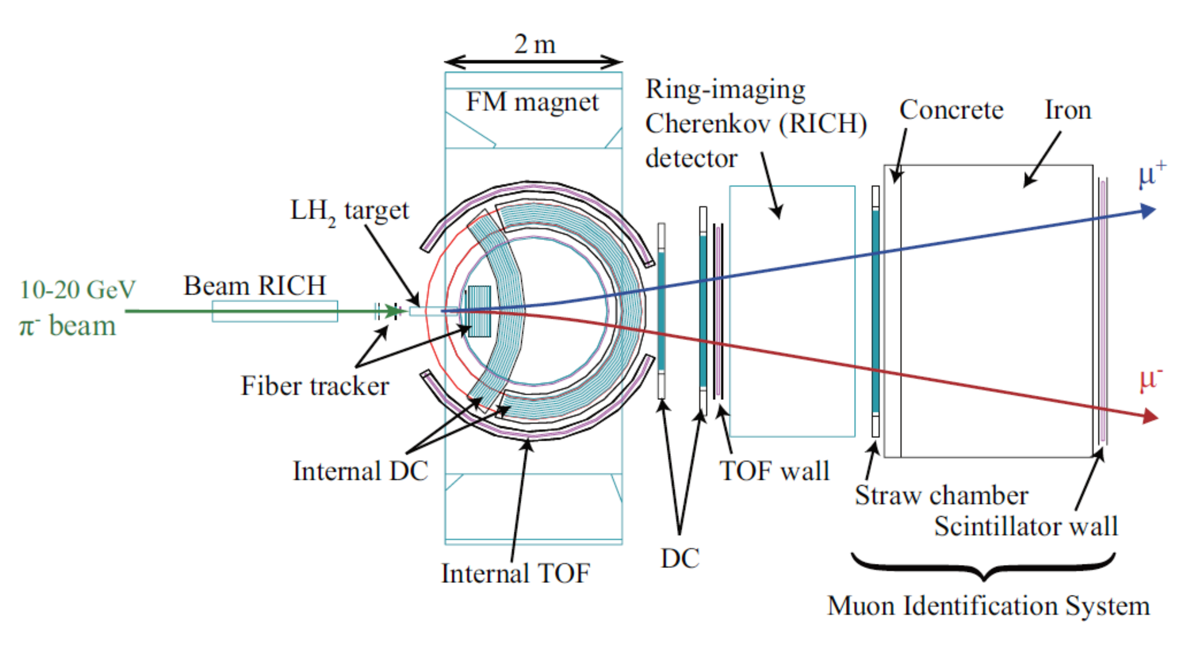
$$\left.\frac{d\sigma_L}{dtdQ'^2}\right|_\tau = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8}f_\pi^2\left[(1-\xi^2)|\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)|^2 - 2\xi^2{\rm Re}\left(\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)^*\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right) - \xi^2\frac{t}{4m_N^2}|\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)|^2\right],$$

S. Goloskokov, P. Kroll, Phys. Lett. B 748 (2015) 323
J.-W. Qiu and Z. Yu PRD 109 (2024) 074023

❑ J-PARC E50 Proposal w/ MARQ Detector







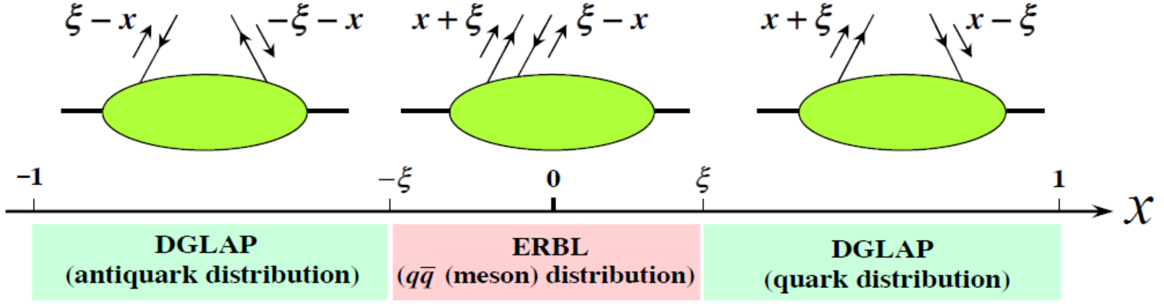
T. Sawada, W. C. Chang, S. Kumano, J. C. Peng, S. Sawada, K. Tanaka, Phys. Rev. D 93 (2016) 114034

GPD Experiments w/ Hadron Beam

Tsinghua University

- **(anti)-Proton-included (J-PARC):** S. Kumano, M. Strikman, K. Sdoh, Phys. Rev. D 80 (2009) 074003

  - Access to Efremov-Radyushkin-Brodsky-Lepage (ERBL) region (not accessible in lepton scattering)

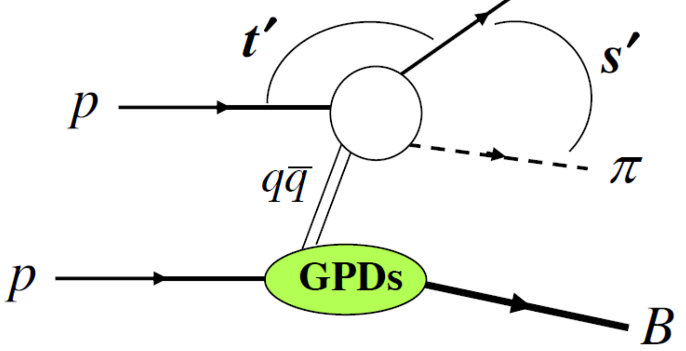


$-1 < x < \xi \quad (x + \xi < 0, x - \xi < 0)$ $\xi < x < 1 \quad (x + \xi > 0, x - \xi > 0)$

$-\xi < x < \xi \quad (x + \xi > 0, x - \xi < 0)$

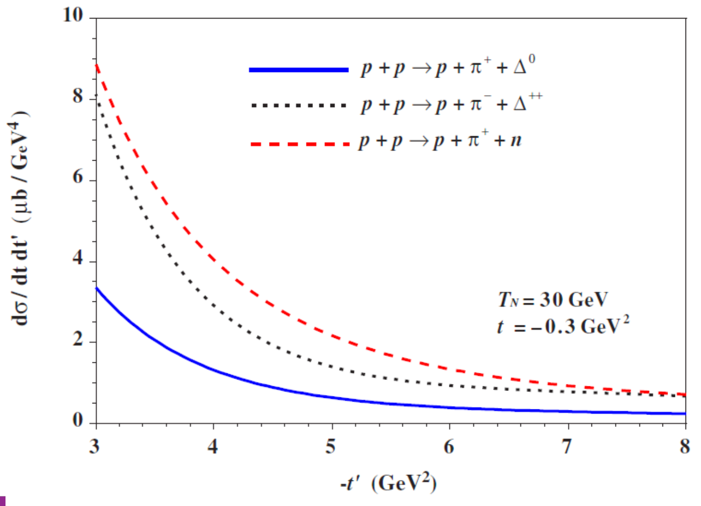
Hard reaction with

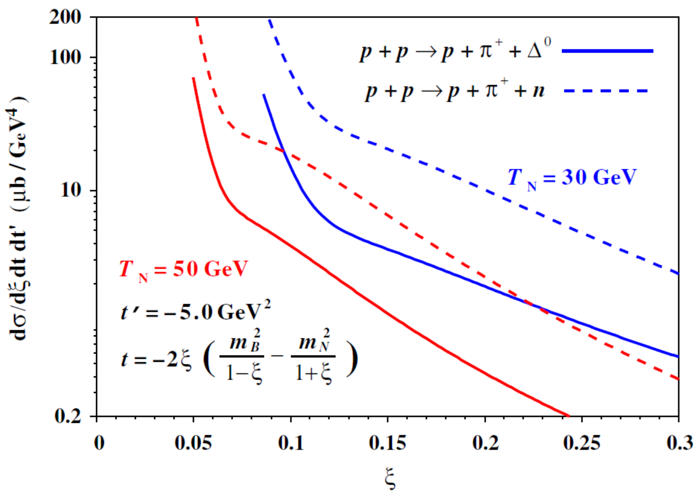
$|s'|, |t'|, |u'| \gg M_N^2, \ |t| \ll M_N^2$



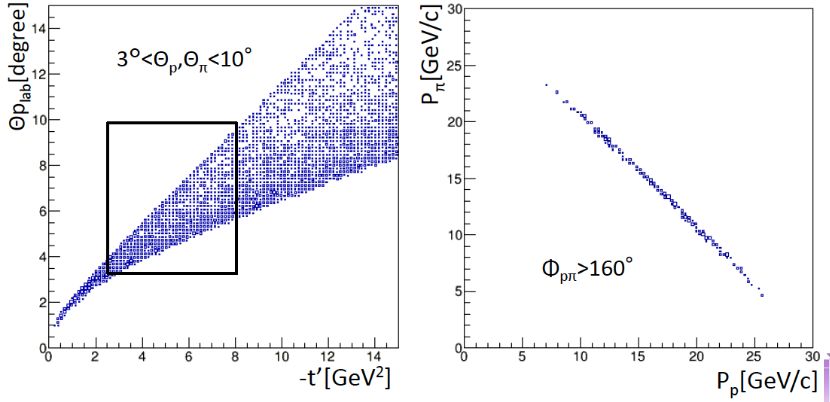
- Factorization in special kinematic regions
  - ✓ p&π must forward & opposite, carrying most of momentum

- Very large XS (ub level)





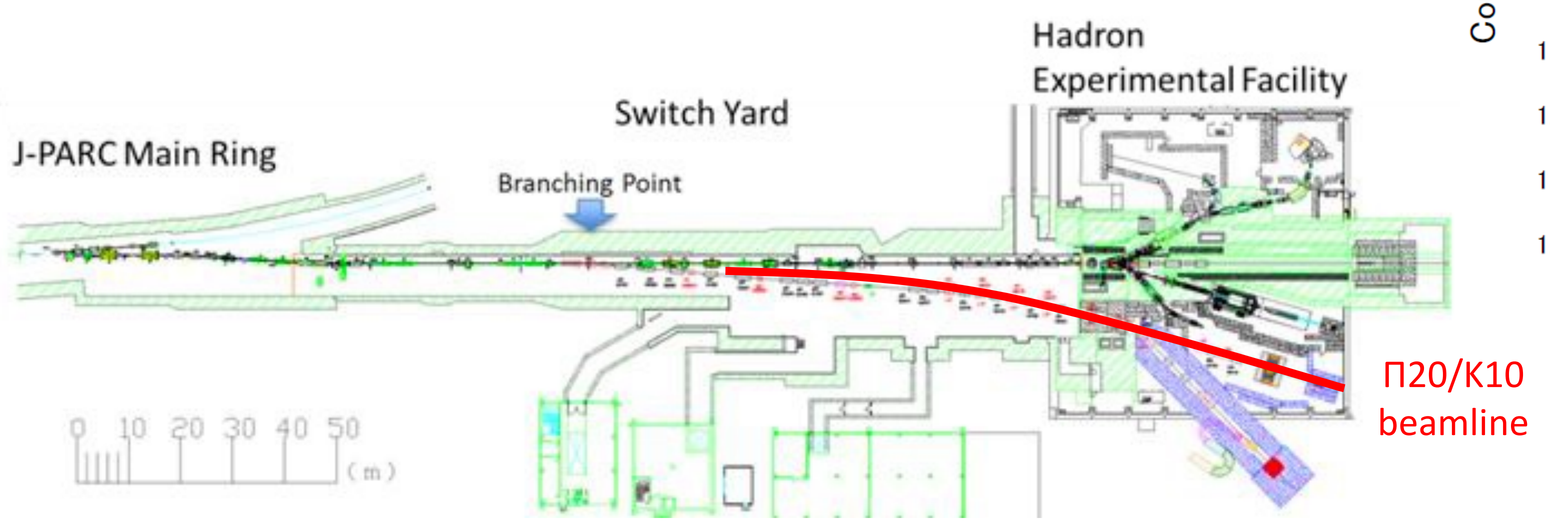
$p + p \to p + \pi^+ + n$ • $T_p = 30$ GeV

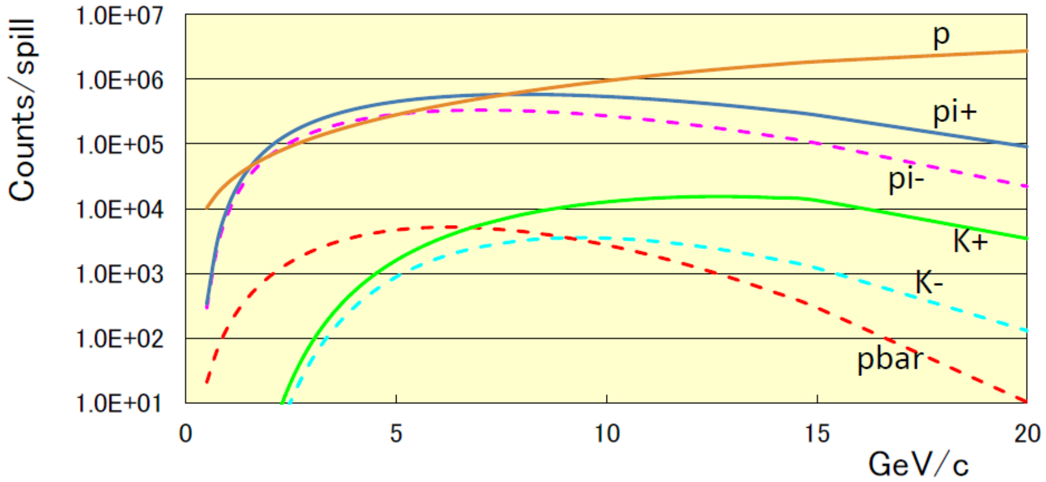


GPD Experiments w/ Hadron Beam

➢ J-PARC π20/K10 beamline

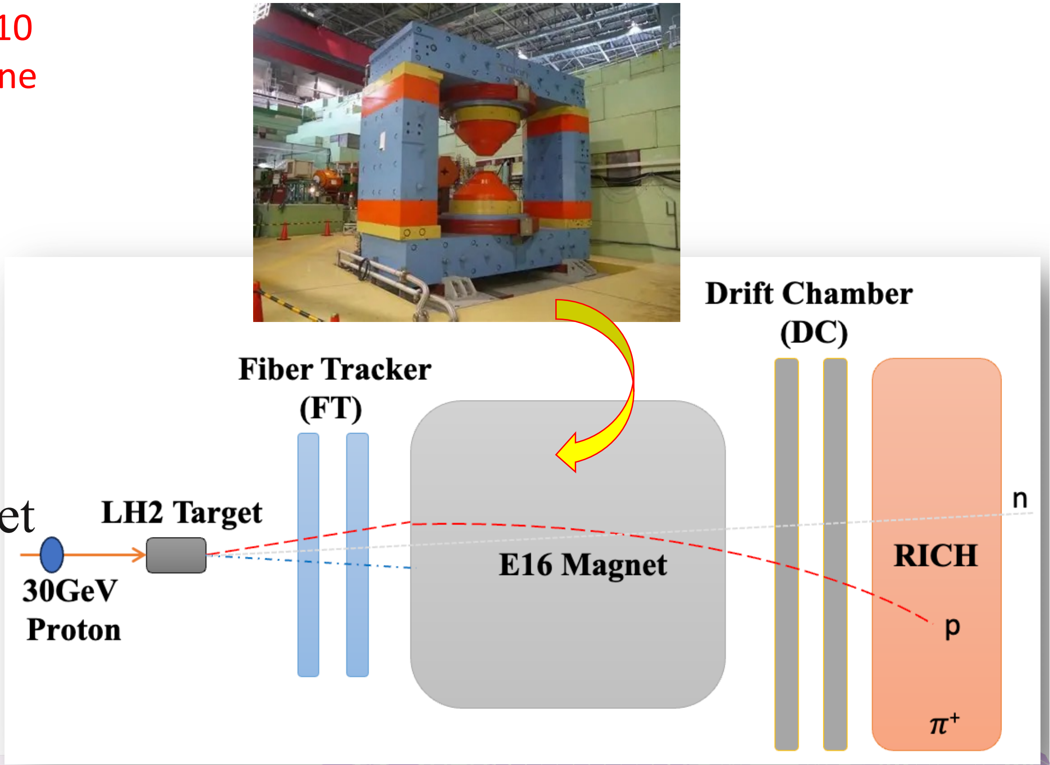
- ❑ π&K separation not ready, dominated by 20GeV protons





Workshop on π20 and K10 at J-PARC (Aug5-6) :
https://indico.rcnp.osaka-u.ac.jp/event/2904/

- ❑ Measure GPD using p/p̄ secondary beam@π20 w/ MARQ
- ❑ An early experiment w/ parts of MARQ detector & E16 magnet

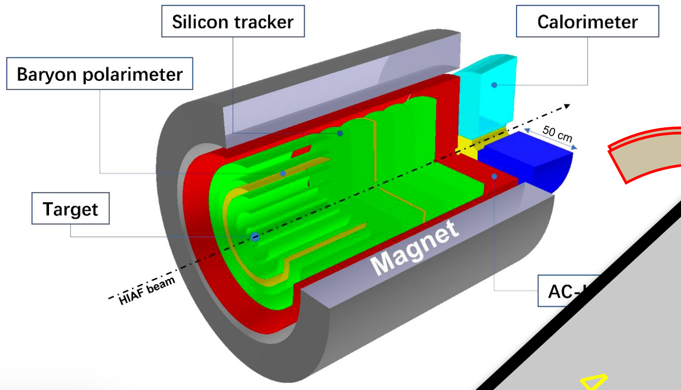


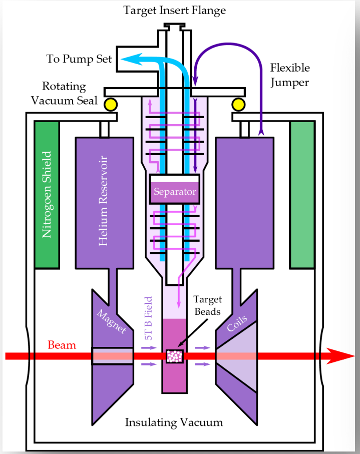
✓ Proposal under development: by Natsuki Tomida (Kyoto), Zhihong Ye (Tsinghua), et. al.

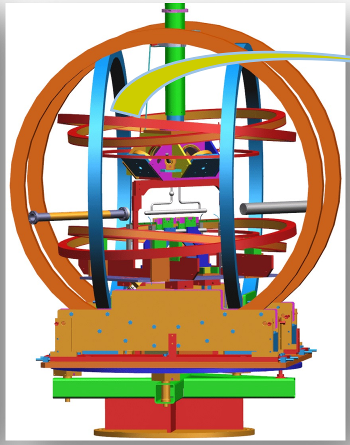
Opportunities at HIAF

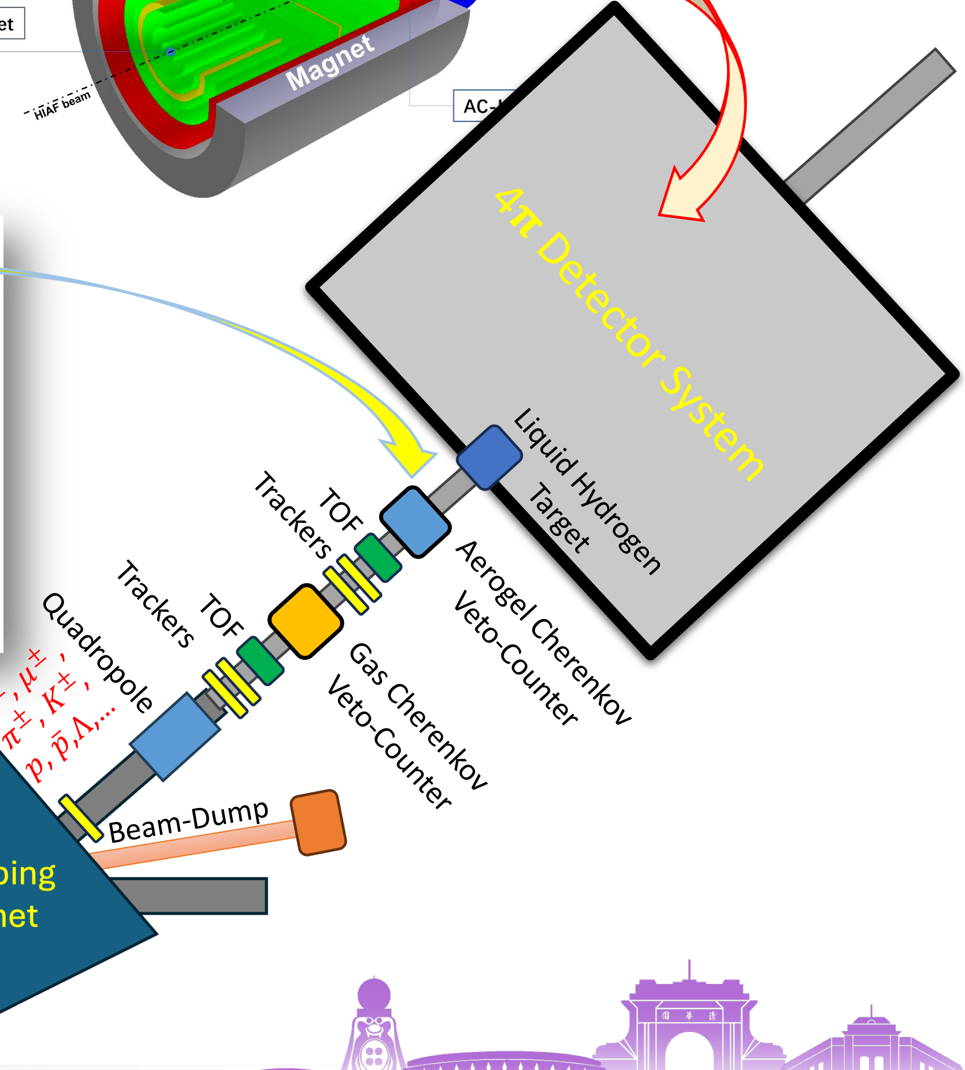
➢ Polarized Targets + 4π Detector:

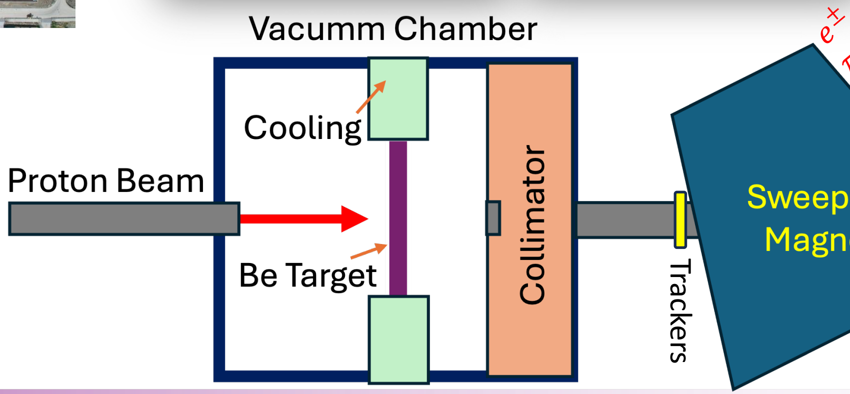
L (s^{-1})	π^+	π^-	K^+	K^-	μ^+	μ^-
6cm Be	4.5×10^7	2.7×10^7	1.8×10^5	0.6×10^5	4.8×10^6	9×10^7
6cm Pt	1.3×10^8	8.1×10^7	3.6×10^6	1.2×10^6	1.4×10^7	2.7×10^8











❑ Joined Workshop of Physics w/ J-PARC &HIAF Secondary Beam in late 2026

Summary

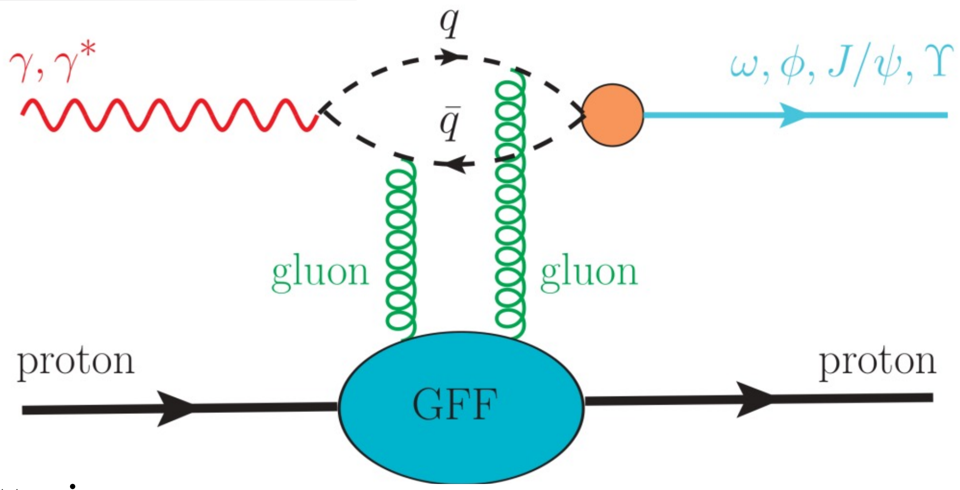
- ❑ GPDs correlate longitudinal momentum with transverse position
- ❑ Deep exclusive experiments only constrain CFFs;
- ❑ Extracting GPDs requires complementary observables and global analysis w/ models & lattice QCD results
- ❑ Pioneering studies been done at DESY, COMPASS, JLab-6GeV
- ❑ Precision studies underway at JLab12GeV in valence region
- ❑ EicC & EIC unlock full kinematic region, extend to sea & gluon GPD
- ❑ Measurement of GPD w/ hadron beams are about to be explored
- ❑ Opportunities for GPD experiments w/ polarized targets & 4π detector at HIAF

THANKS!

清華大學
Tsinghua University

Generalized Parton Distributions

➢ Proton Pressure & Shear Force



- Similar to EM FF, Gravitational Form Factor (GFF):

$$\frac{d\sigma}{dt} = \mathcal{N} \times \frac{e^2}{64\pi(s-M^2)^2} \times \frac{[A_g(t)+\eta^2 D_g(t)]^2}{A_g^2(0)}$$

Guo,X.Ji&Y.Liu, Phys.Rev.D 103, no.9, 096010 (2021)

- $A_g(t)$ from J/Psi near threshold production in electron-proton scattering

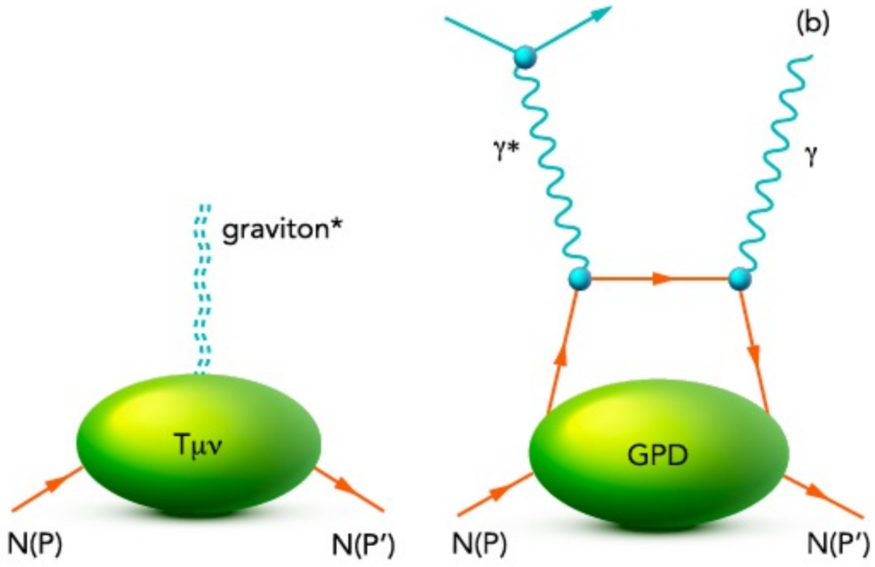
$A_g(t)$ →Quark kinematic energy in proton → Proton mass

- $D_g(t)$ from GPD: $\mathrm{Re}\mathcal{H}(\xi,t) \overset{\mathrm{lo}}{=} D(t) + \mathcal{P}\int_{-1}^{1} \mathrm{d}x \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) \mathrm{Im}\mathcal{H}(x,t)$

- Proton Pressure & Shear Force:

$$p(r) = \frac{1}{6m}\frac{1}{r^2}\frac{d}{dr}r^2\frac{d}{dr}\tilde{D}(r) \qquad s(r) = -\frac{1}{4m}r\frac{d}{dr}\frac{1}{r}\frac{d}{dr}\tilde{D}(r)$$

$$\tilde{D}(r) = \int \frac{d^3\mathbf{\Delta}}{(2\pi)^3} e^{-i\mathbf{\Delta} r} D(-\mathbf{\Delta}^2)$$



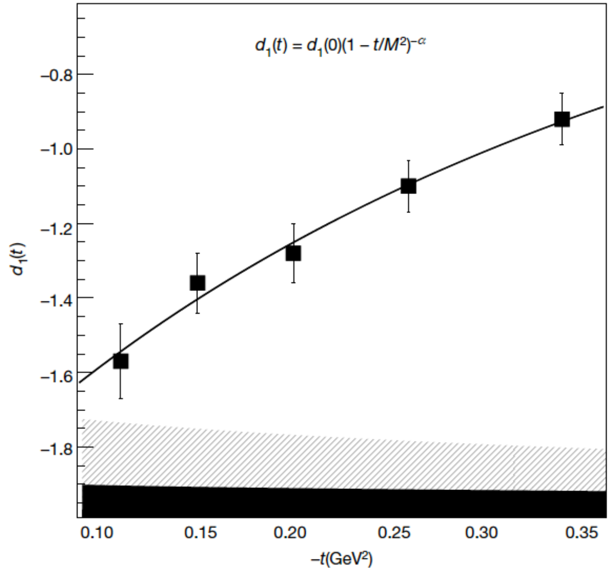
Generalized Parton Distributions

Tsinghua University

➢ Proton Pressure & Shear Force

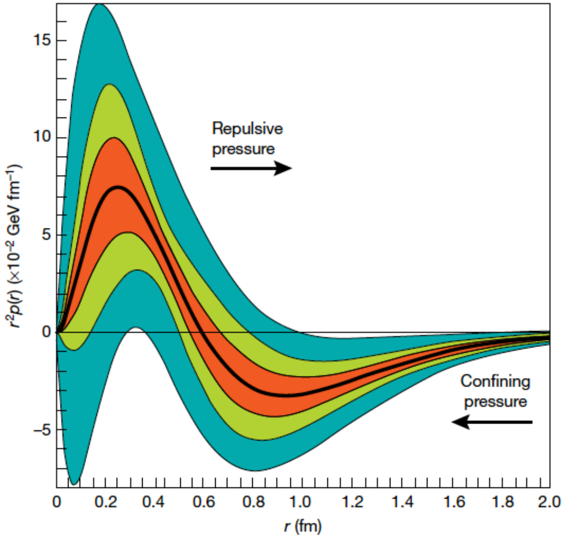
❑ Define a fitting function on GPD data:

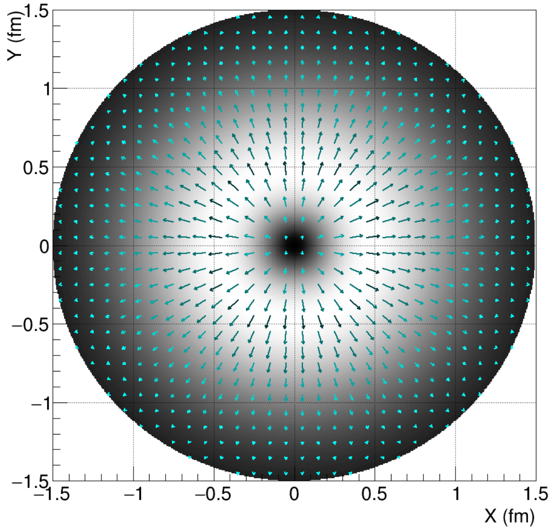
$$D(t) = D\left[1 + \frac{-t}{M^2}\right]^{-\alpha}, \quad \begin{aligned} D &= -1.47 \pm 0.06 \pm 0.14 \\ M^2 &= +1.02 \pm 0.13 \pm 0.21 \text{ GeV}^2 \\ \alpha &= +2.76 \pm 0.23 \pm 0.48 \,, \end{aligned}$$

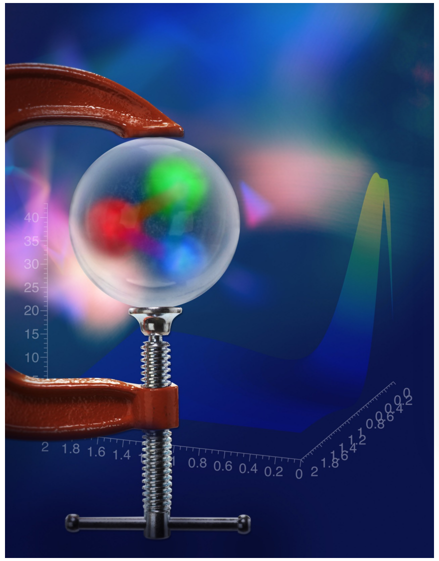


❑ "Obtain" Proton Pressure:

Pressure at Proton "center": 10^{35}P， x10 than neutron star center







Generalized Parton Distributions

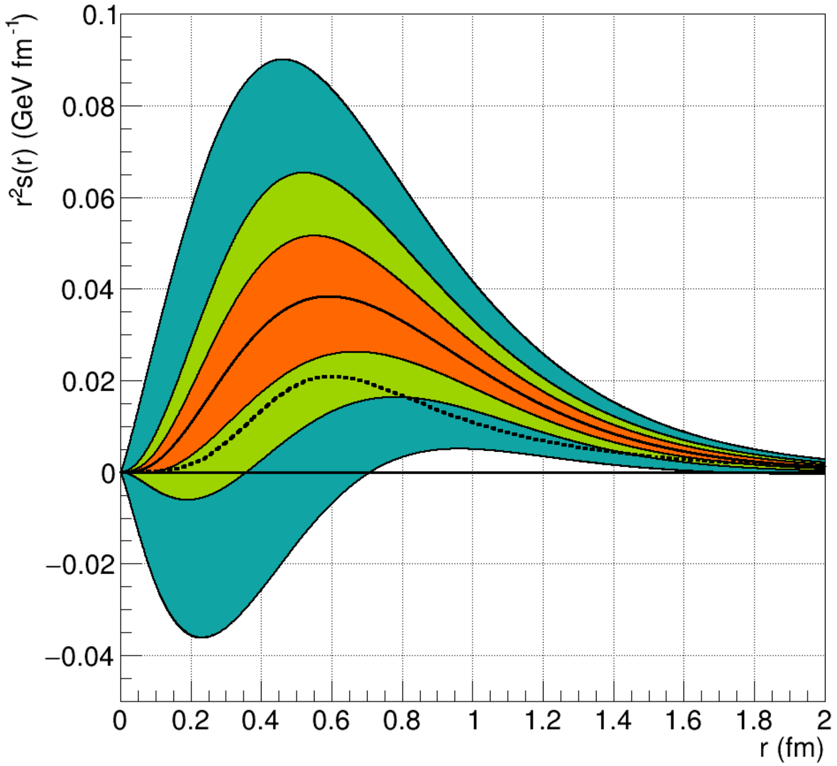
Tsinghua University

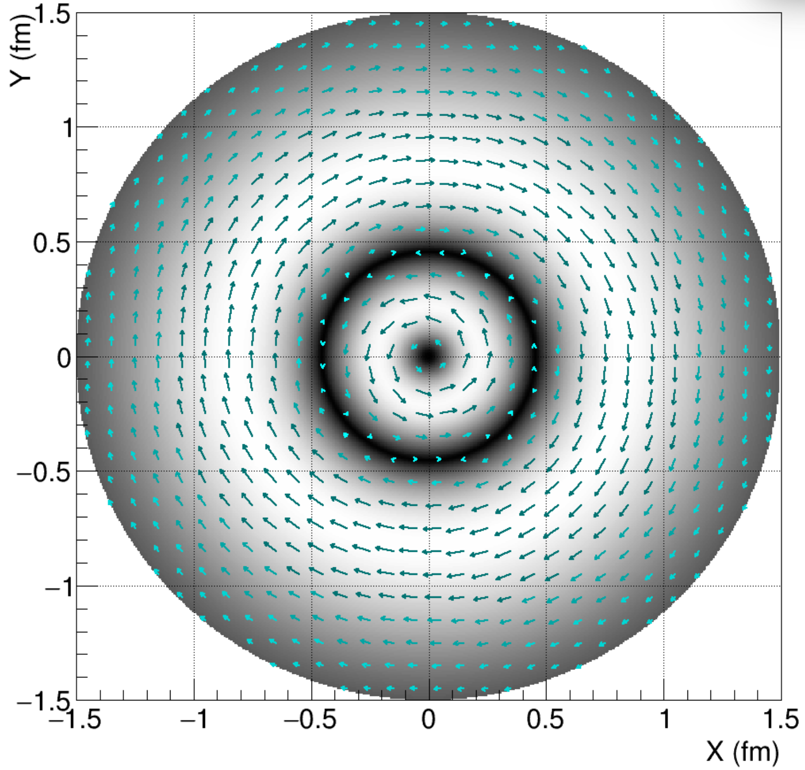
➢ Proton Pressure & Shear Force

❑ "Obtain" Shear Force:

- Proton's shear force changes direction@0.45fm， max@0.55fm
- 0.55fm is max of color confinement， ~650kg gravity on Earth


nature
Explore content
About the journal
Publish with us
Subscribe
nature > letters > article
Letter | Published: 16 May 2018
The pressure distribution inside the proton
V. D. Burkert, L. Elouadrhiri & F. X. Girod
Nature 557, 396–399 (2018) | Cite this article
14k Accesses | 301 Citations | 386 Altmetric | Metrics

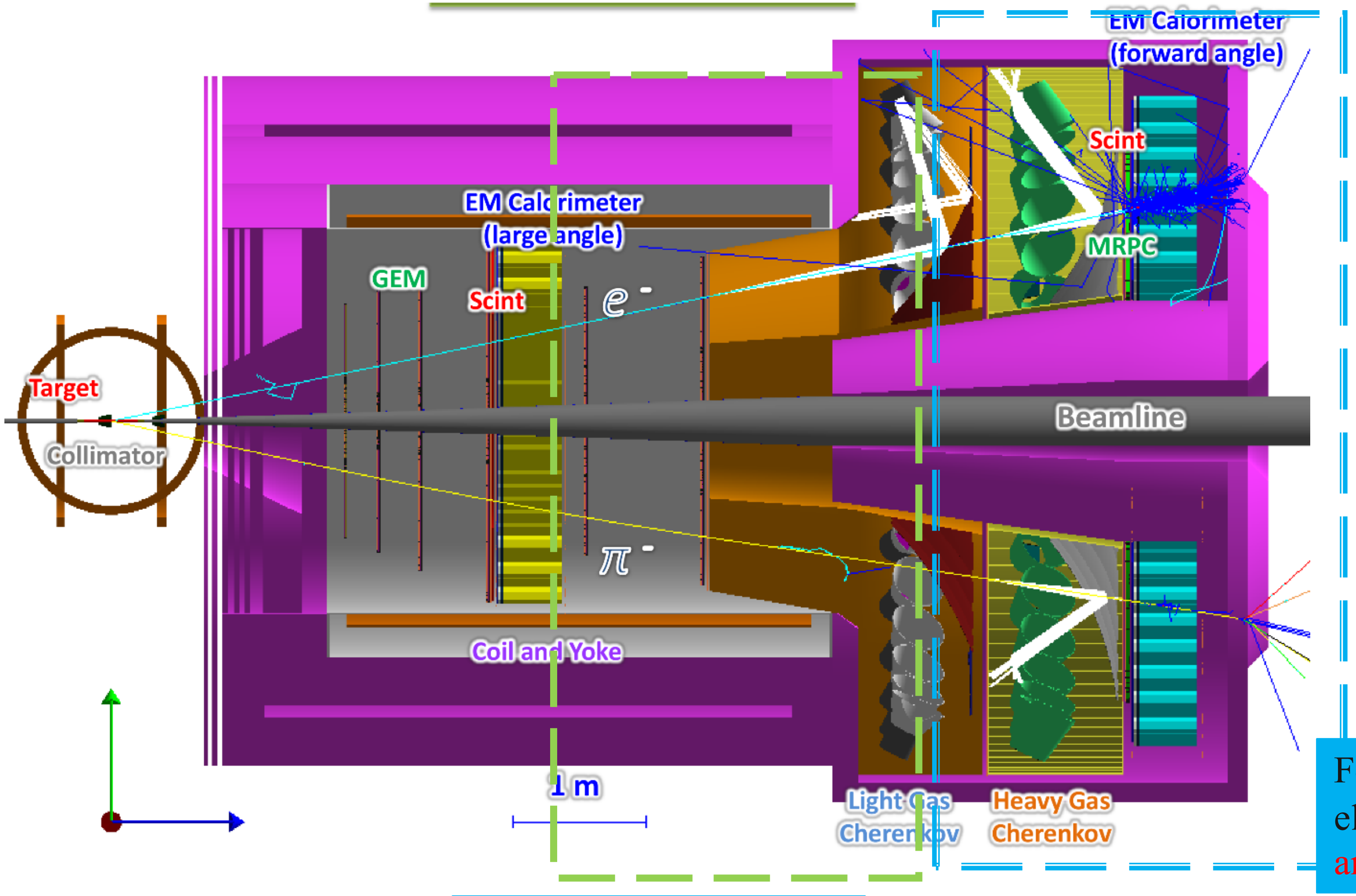




GPDs on SoLID

Tsinghua University

➢ **Exclusive Measurement based on SIDIS/JPsi Setup**



Forward-Angle : electrons, pion, photons and proton

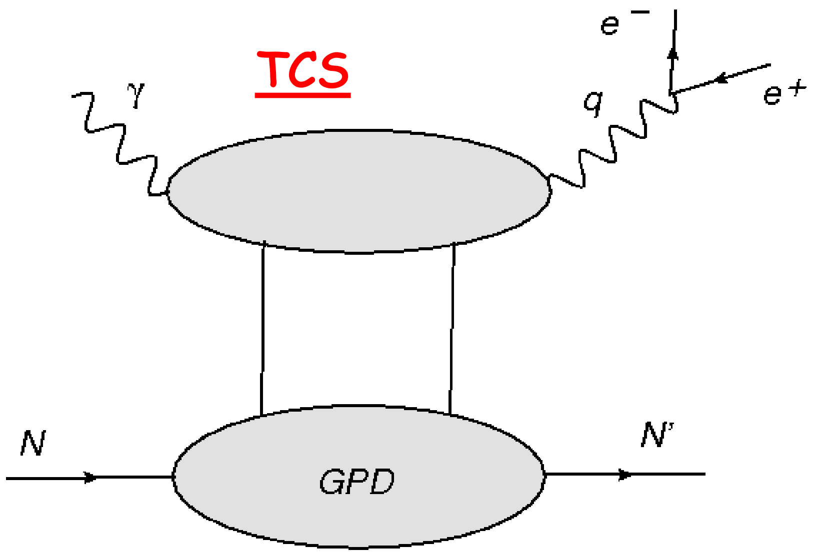
Large-Angle→electrons, photons and proton

GPD Experiments on SoLID

Tsinghua University

- **SoLID-TCS:** $\gamma + N \rightarrow N + l^{+} + l^{-}$

H. Moutarde et al. arXiv:1301.3819, 2013

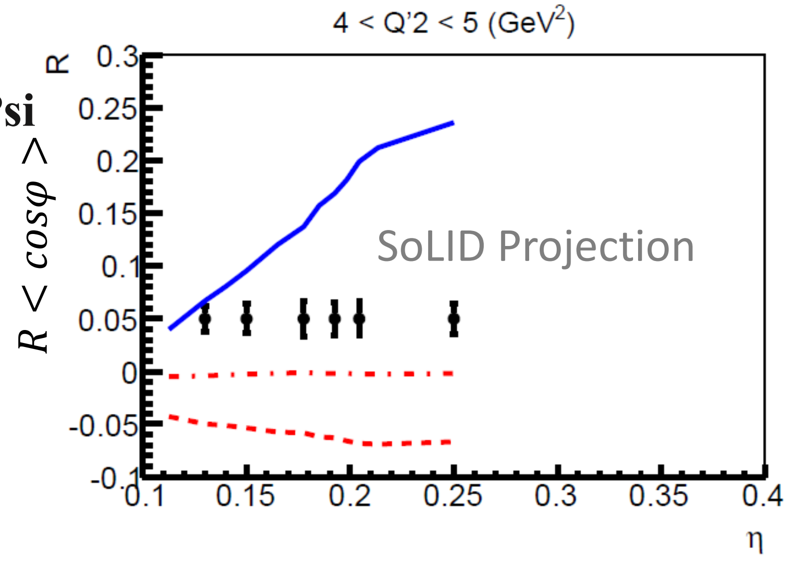


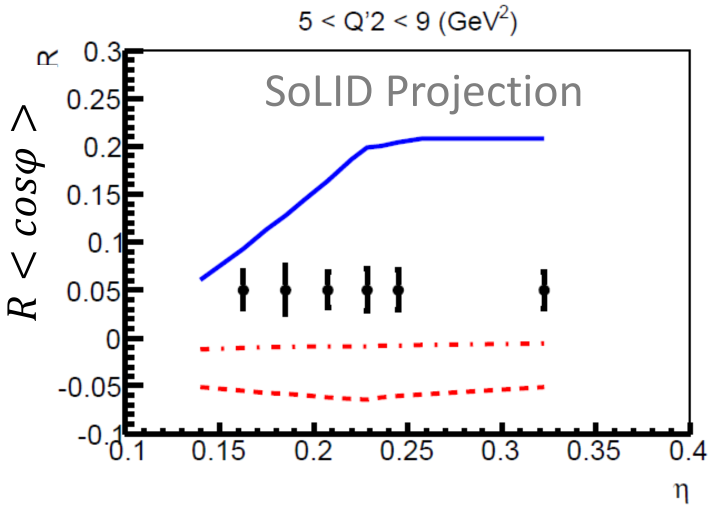
- **Time-Like Compton Scattering (TCS):**
  - ✓ Re-CFF (Im-CFF) via unpolarized (circularly polarized) photons
  - ✓ Different angular moments for TCS & BH Interference-terms

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

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

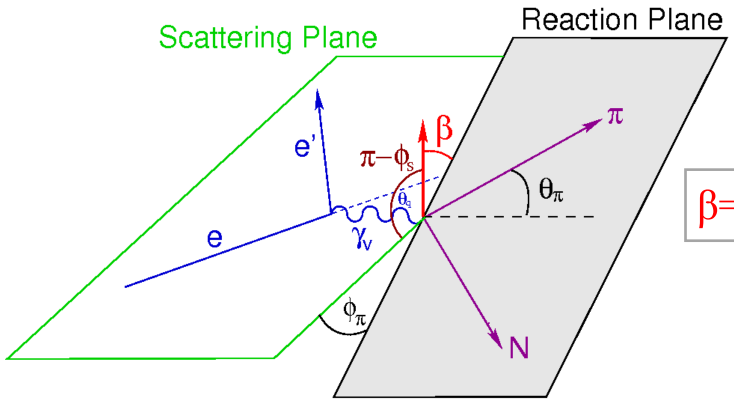
- **SoLID-TCS: Parallel data taking with J/Psi**
  - ✓ Unpolarized ^{1}H target
  - ✓ Indirect photon-production
  - ✓ Extract $cos\varphi$ and sinφ modules





GPD Experiments on SoLID

➢ SoLID-DVMP: $e + N^{\uparrow\downarrow} \to e' + N' + \pi^{\pm}$



β=(φ-φS)

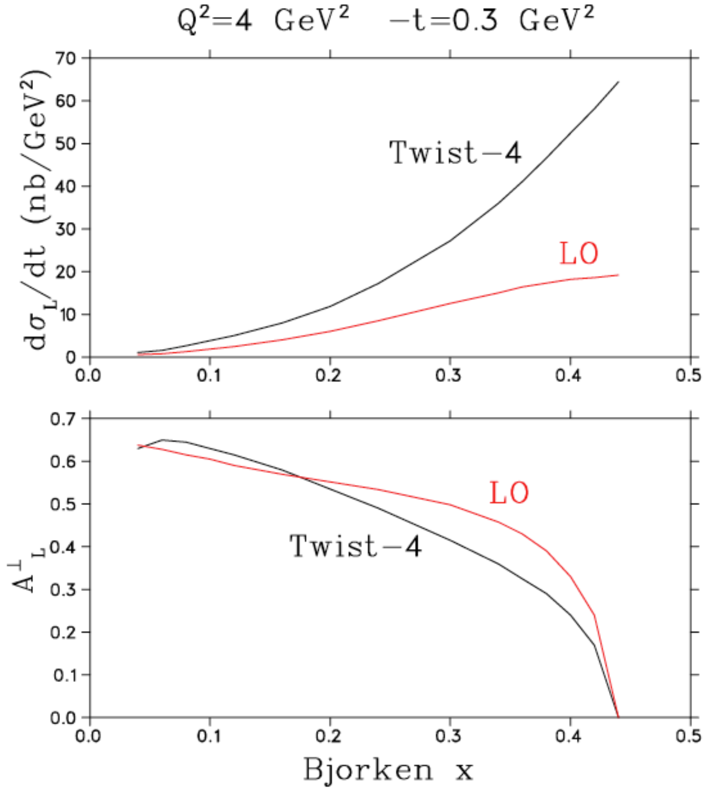
❑ DVMP advantages:

- ✓ Probe different hadrons for quark flavor separation
- ✓ Vector mesons for ***H*** **and *E*;** Pseudoscalar mesons for $\widetilde{H}$ and $\tilde{E}$ Sensitive to transverse GPDs **(**$H_T, E_T, \widetilde{H}_T, \tilde{E}_T$**)**

❑ DVMP disadvantages:

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

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



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

- ✓ test onset of factorization at mid Q^2； reduce higher-twist effects

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

GPD Experiments on SoLID

清華大學 Tsinghua University

➤ SoLID-DVMP: $e + N^{\uparrow\downarrow} \to e' + N' + \pi^{\pm}$

❑ **Asymmetry (no L/T separation):** $A(\phi,\phi_s) = \dfrac{d^3\sigma_{UT}(\phi,\phi_s)}{d^2\sigma_{UU}(\phi)} = -\sum_k A_{UT}^{\sin(\mu\phi+\lambda\phi_s)_k} \sin(\mu\phi+\lambda\phi_s)_k$

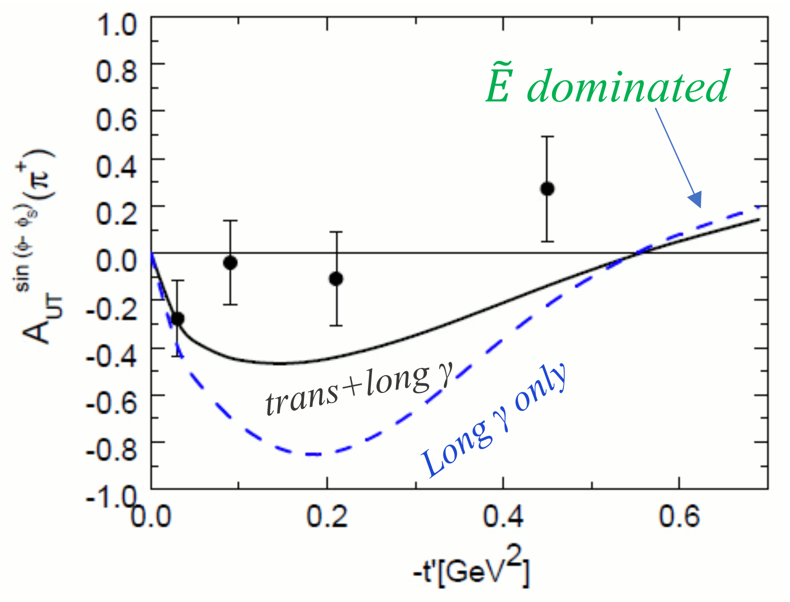
$$A_{UT}^{\sin(\phi-\phi_s)} \sim \frac{d\sigma_{00}^{+-}}{d\sigma_L\binom{++}{00}} \sim \frac{\mathrm{Im}(\tilde{E}^*\tilde{H})}{|\tilde{E}|^2} \text{ where } \tilde{E} \gg \tilde{H}$$

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

helicities: [pion, neutron, photon, proton]

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

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

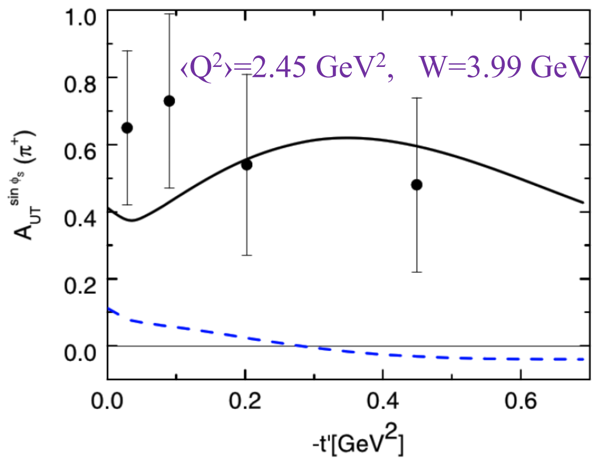


HERMES Data:

- ✓ 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 Experiments on SoLID

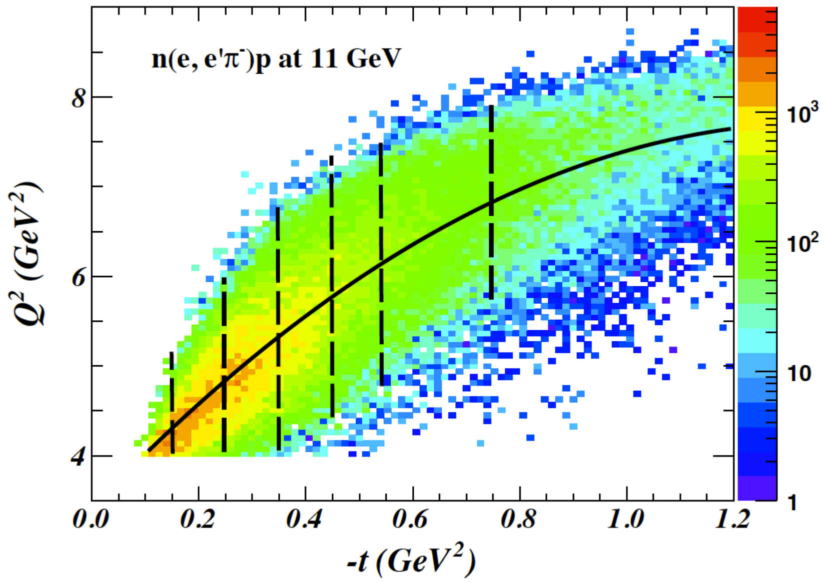
Tsinghua University

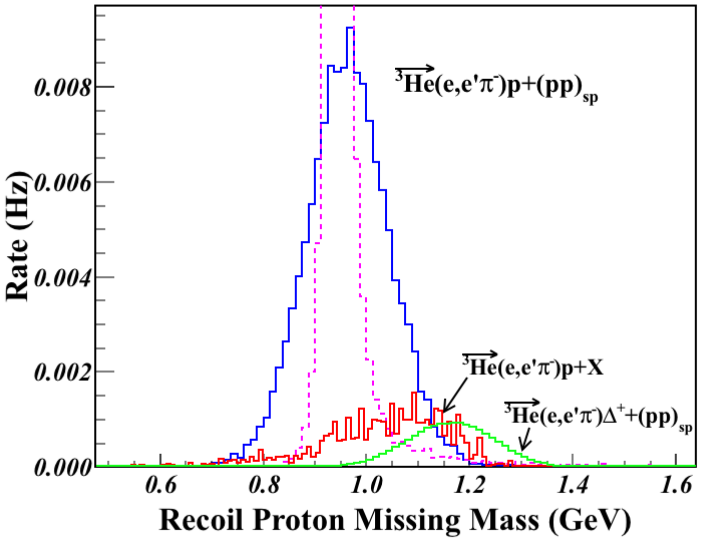
➢ SoLID-DVMP: $e + N^{\uparrow\downarrow} \rightarrow e' + N' + \pi^{\pm}$

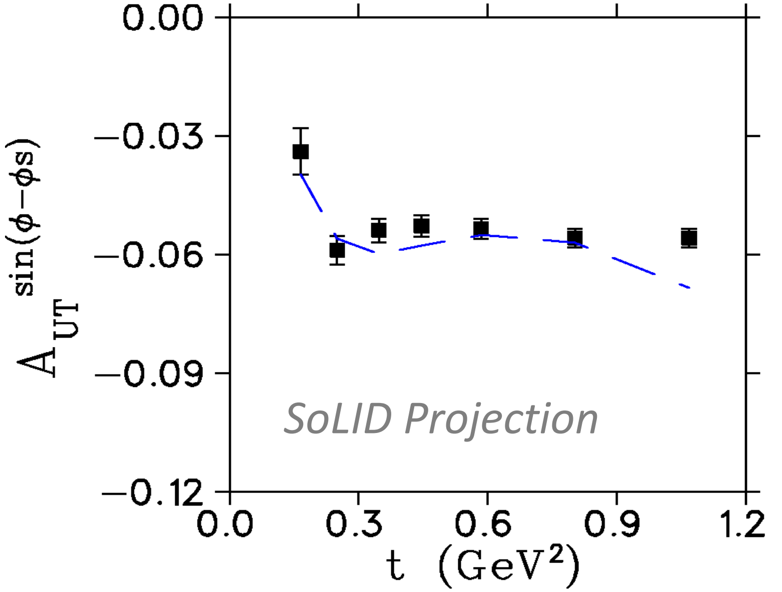
❑ **SoLID will provide the first polarized DVMP data before EIC**

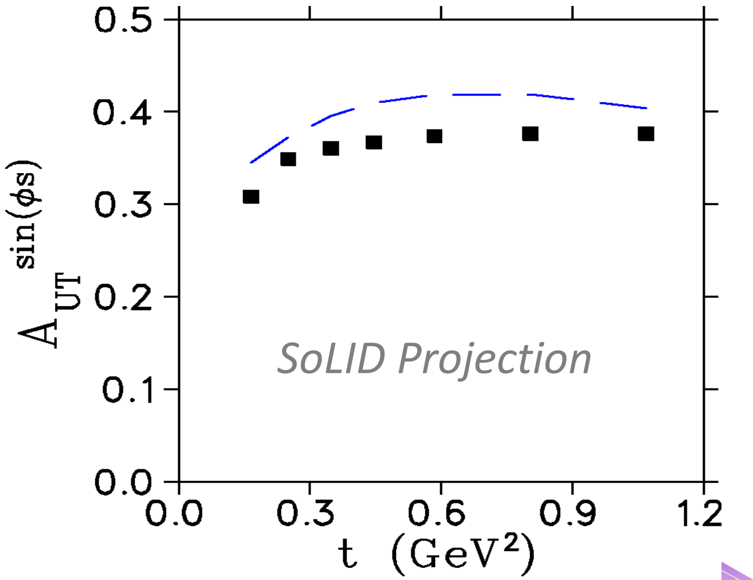
SoLID Projected Data:

- ❑ 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+



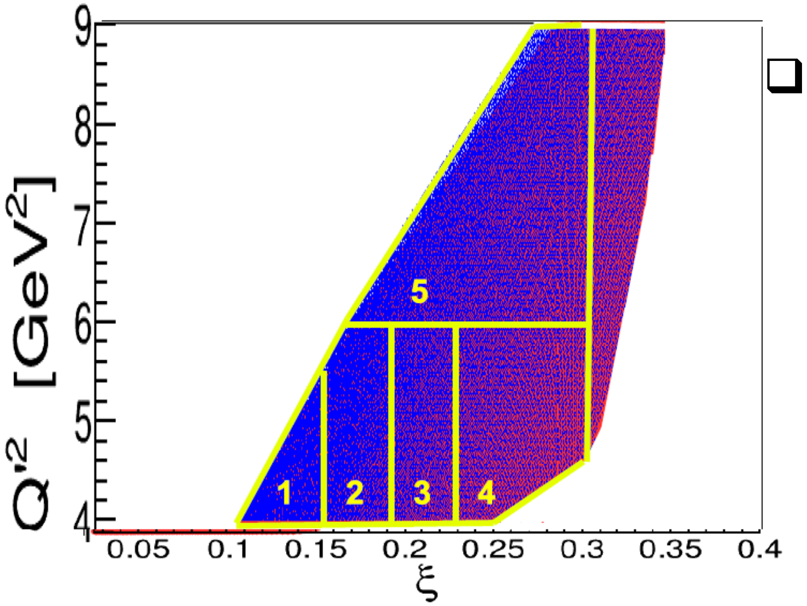




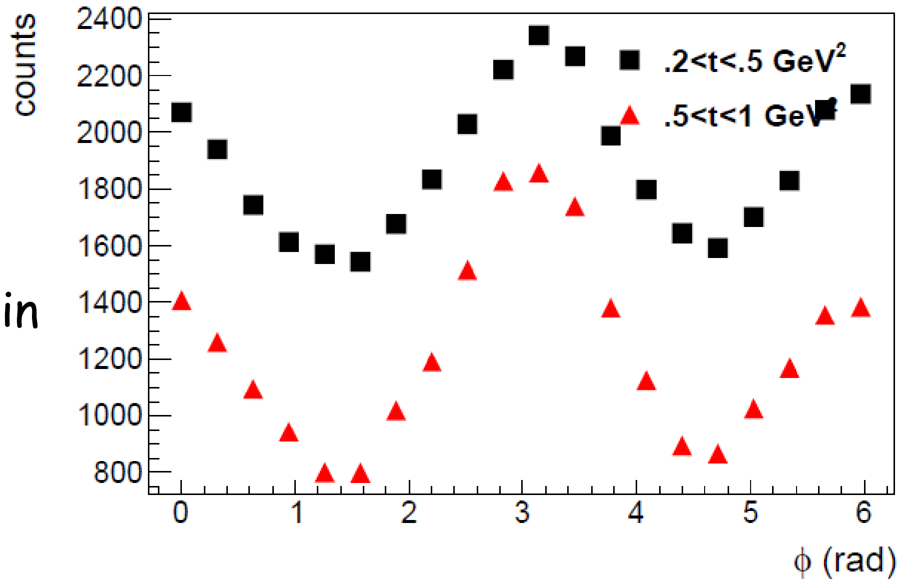


GPDs on SoLID

- **SoLID-TCS:** (E12-12-006A, M. Boer, P. Nadel-Turonski, J. Zhang, Z. Zhao)



- ❑ Proper Q2 and ξ binning
- ❑ Fit to the angular distribution in each bin



- ❑ Projections of two highest bins