Accessing GPDs through exclusive photo- and electro-production of lepton pairs

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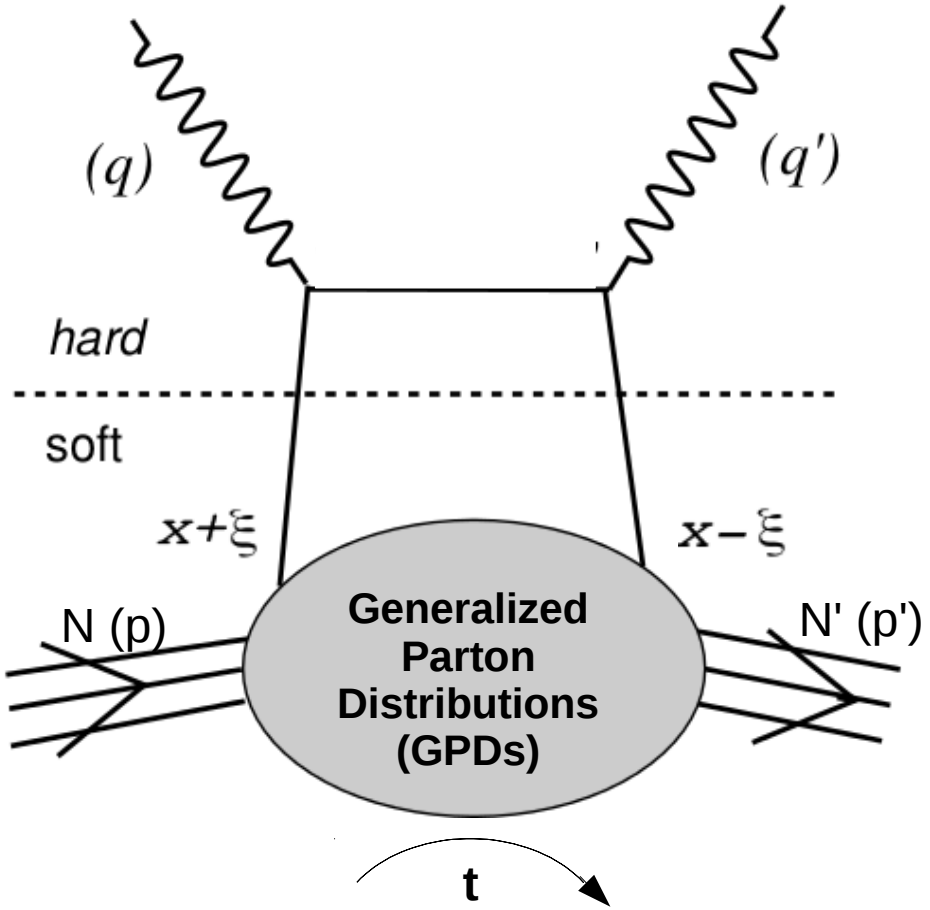
"Next Generation GPD studies with exclusive meson production at EIC"

Photo- and electro-production of a lepton pair

γ (q) N (p) → γ (q') N' (p') → e+ e- N'



Deeply Virtual Compton Scattering:
$q^2 < 0$, $q'^2 = 0$

Timelike Compton Scattering:
$q^2 = 0$, $q'^2 > 0$

Double Deeply Virtual Compton Scattering:
$q^2 < 0$, $q'^2 > 0$, $-q^2 \neq q'^2$

TCS versus DVCS: see also Jakub's presentation
- studies of GPD universality, global fits, higher twist/order effects...

DDVCS:
- lever arm with $q'^2 / q^2 \rightarrow$ access GPDs at $x \neq \xi$
- "timelike" and "spacelike" regions → sign change expected for some asymmetries

Compton Form Factors and GPDs

DVCS amplitude decomposition into Compton Form Factors:

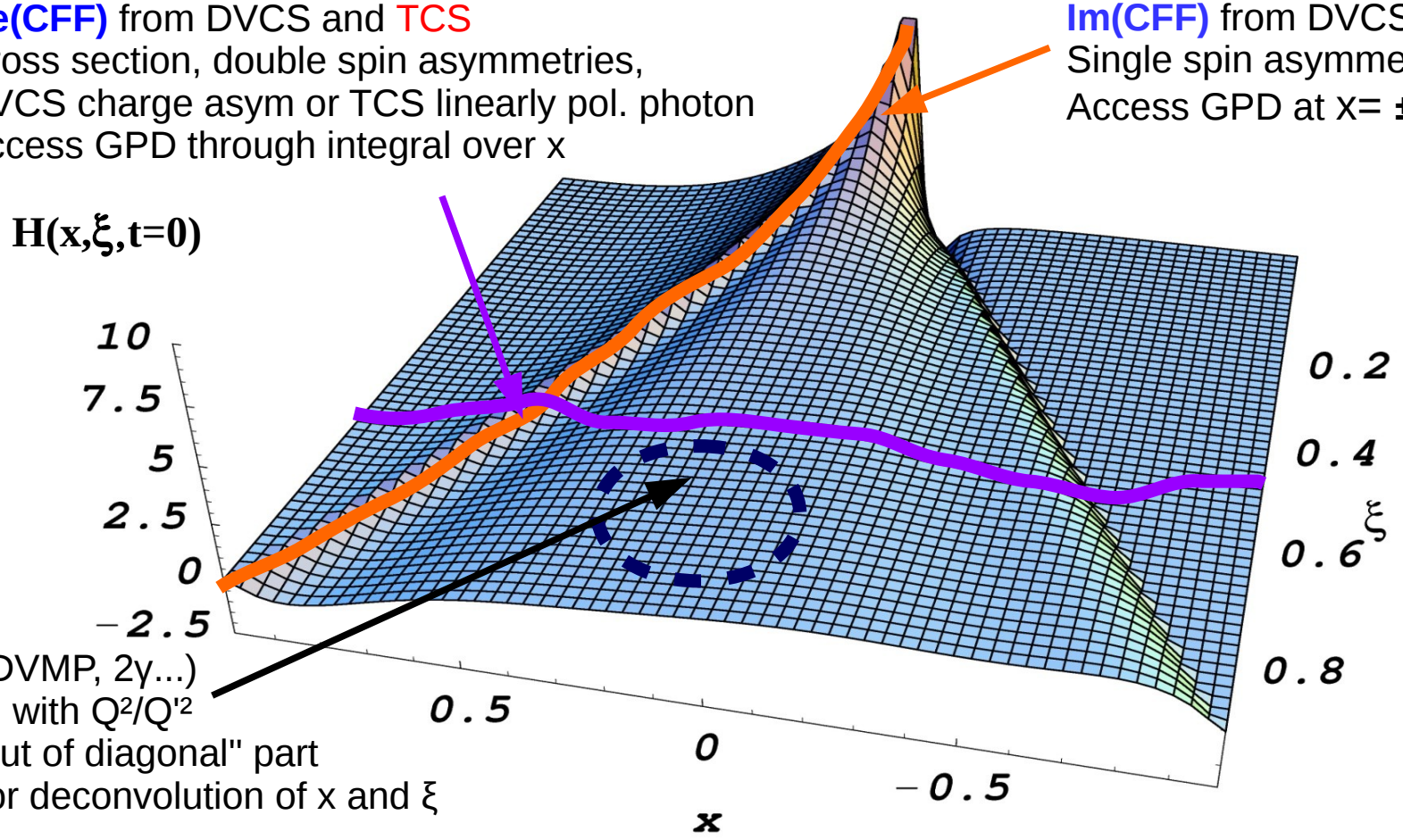
ξ, t = measurable
x = integrals

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim \underbrace{P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx}_{\mathrm{Re}(\mathcal{H})} \underbrace{- i\pi H(\pm\xi,\xi,t)}_{\mathrm{Im}(\mathcal{H})} + \ldots$$

Probing GPD x vs ξ dependence with experimental observables:

Re(CFF) from DVCS and TCS
Cross section, double spin asymmetries,
DVCS charge asym or TCS linearly pol. photon
Access GPD through integral over x

Im(CFF) from DVCS and TCS
Single spin asymmetries
Access GPD at x= **±ξ**

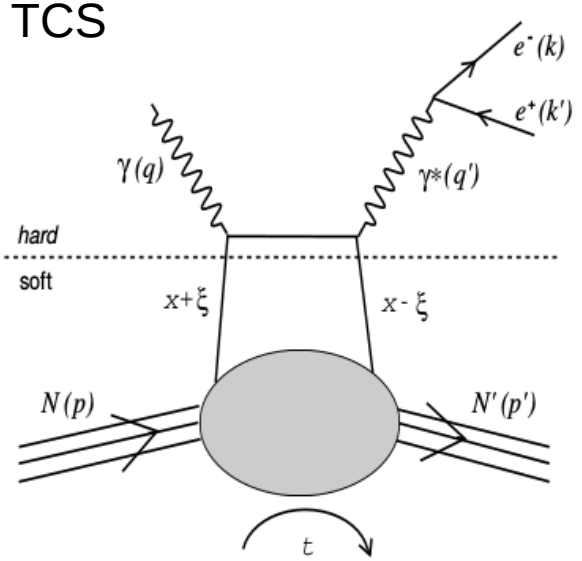


DDVCS (DVMP, 2γ...)
Lever arm with Q^2/Q'^2
Access "out of diagonal" part
Needed for deconvolution of x and ξ

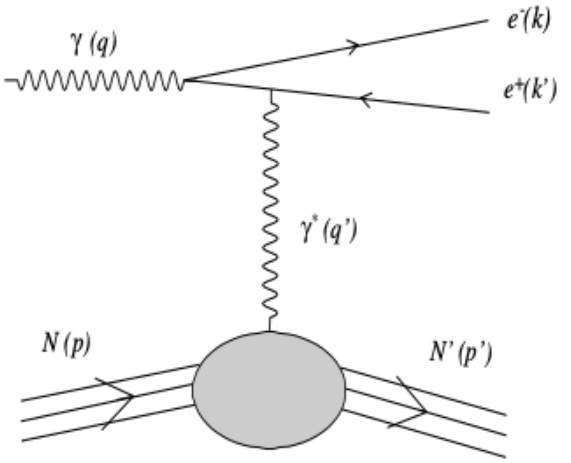
TCS: physics impact and plans for measurements at JLab

$\gamma N \rightarrow e^+e^- N' = TCS + BH$

TCS



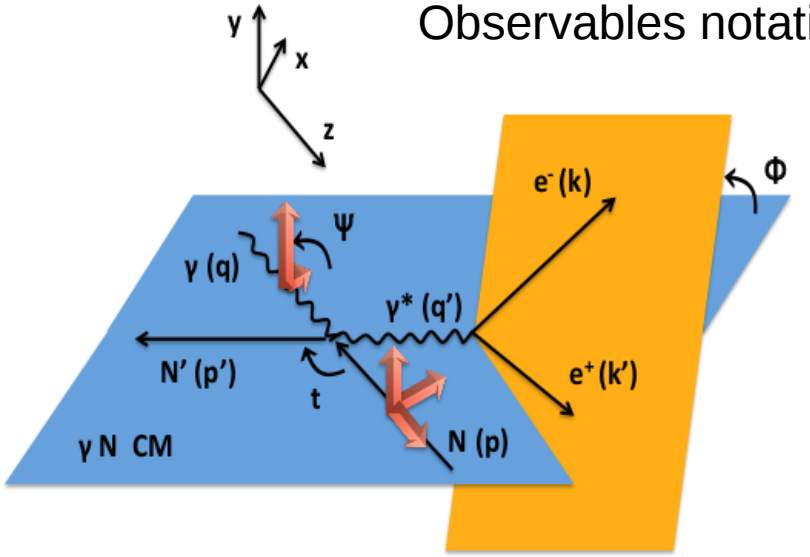
Bethe-Heitler

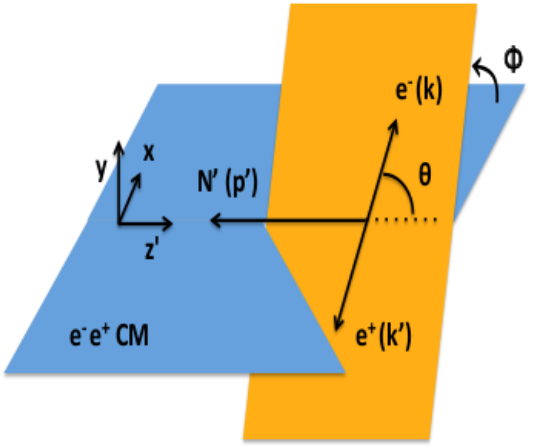


Unpolarized and circularly polarized beam: 5-differential → ξ, Q'^2, t, φ, θ

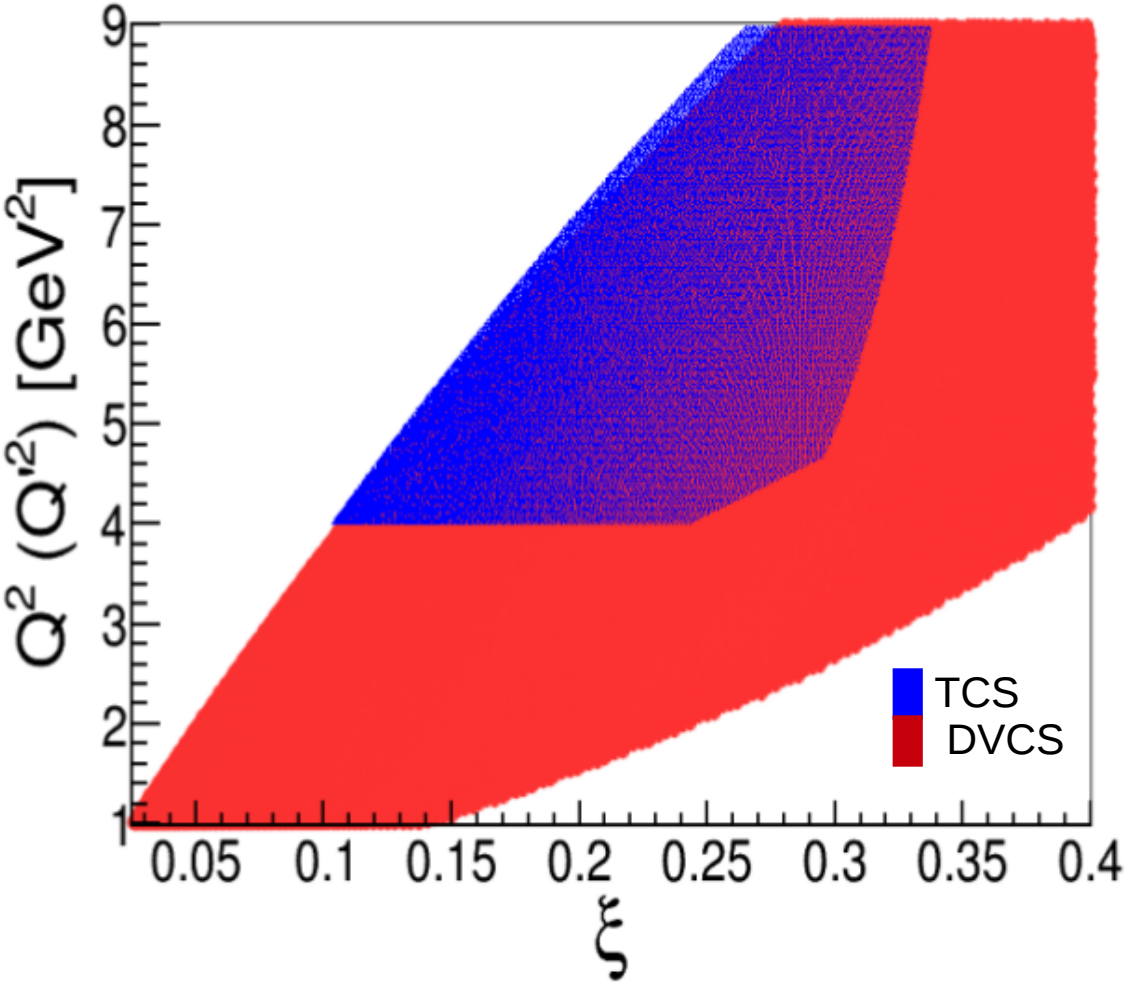
Polarized target: φ_S, θ_S; Linearly polarized beam: Ψ_S

Observables notation, index: ⊙ or L = γ polarization, x, T, z = N polarization





Comparing DVCS and TCS in CFF extraction



ξ vs Q² (Q'²) for DVCS and TCS
"JLab-like" phase-space
$0 < -t < 1$ GeV²
$s > 4$ GeV², E= 11 GeV for DVCS
$5 < E_\gamma < 11$ GeV for TCS
mass cut: out of resonences region

Fits of CFFs from DVCS and TCS observables at same (ξ, t) points

CFF extraction from twist 2 and LO DVCS and TCS independently and combined

Interpretations, depending on size of NLO and higher twist

- small effects: combine DVCS+TCS observables → global fits
- small/moderate effects: independent analysis → constraint on GPD universality
- large effects: observation of higher twist in spacelike (DVCS) vs timelike (TCS)

Fitting CFFs with DVCS versus TCS

ξ=.2, -t=.15 GeV²

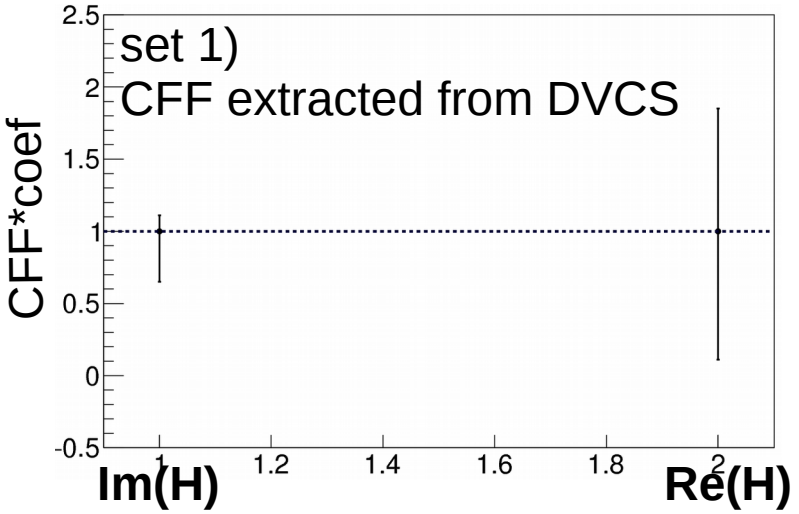
set of obs.	DVCS (Q^2=2.5 GeV², E=11 GeV)	TCS (Q'^2=4.5 GeV², θ=90°)
1) proton σ, $\Delta\sigma_{LU}$	Im(H) and Re(H) extracted Im(Ht) with 200% uncertainty	Im(H) and Re(H) extracted
2) proton σ, $\Delta\sigma_{LU}$, $\Delta\sigma_{UL}$, $\Delta\sigma_{LL}$	Im(H), Re(H) and Im(Ht) extracted	Im(H), Re(H) and Im(Ht) extracted

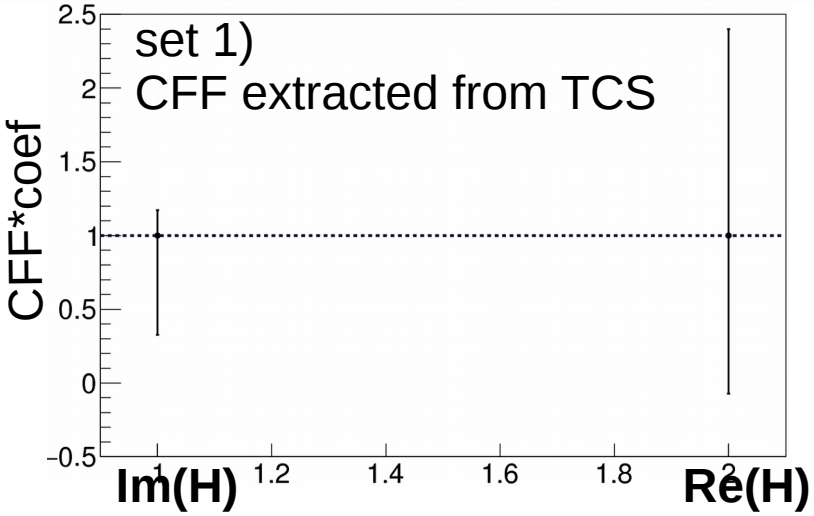
Pseudo-data
5% unpol, 7% pol
per 16 bins in φ
twist 2, LO

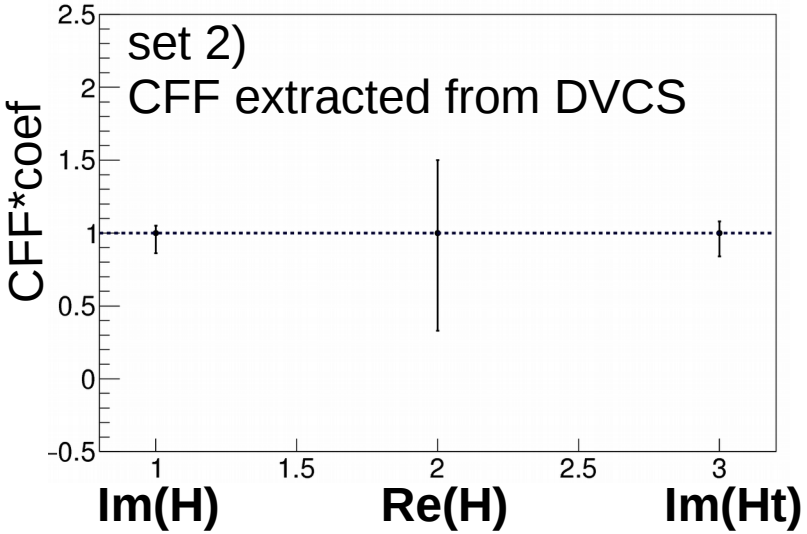
gen CFF coef=1

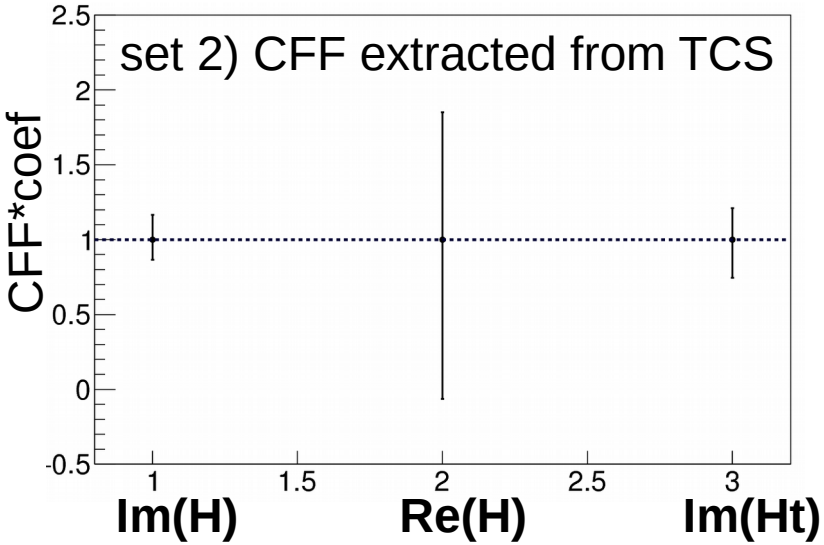
→Fit φ distribution from set of observables using VGG model and 7 independent CFFs

→interpret uncertainties: DVCS & TCS can be compared









Accessing Im(E) and proton versus neutron in DVCS and TCS

ξ=.2, -t=.15 GeV²

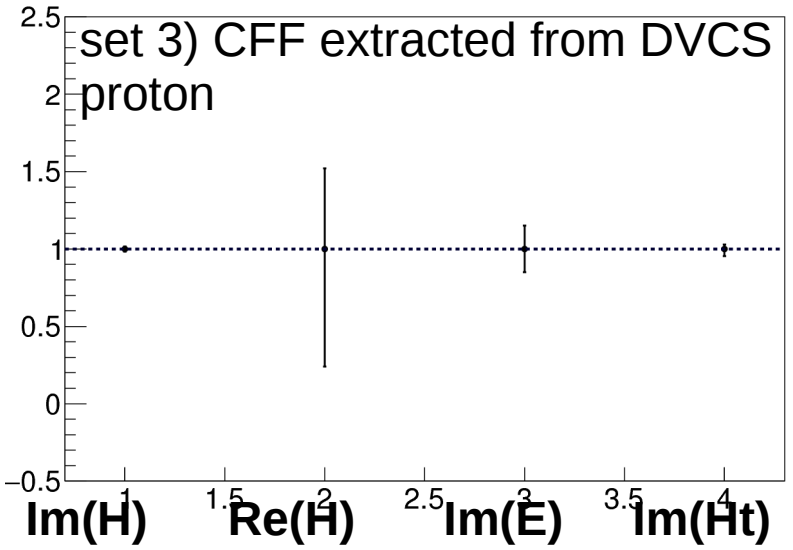
set of obs.	DVCS (Q^2=2.5 GeV², E=11 GeV)	TCS (Q'^2=4.5 GeV², θ=90°)
3) proton σ, $\Delta\sigma_{LU}$, $\Delta\sigma_{UX}$, $\Delta\sigma_{UY}$	Im(H), Re(H), Im(E), Im(Ht) extracted	Im(H), Re(H), Im(E) and Im(Ht) extracted
4) neutron σ, $\Delta\sigma_{LU}$, $\Delta\sigma_{UL}$, $\Delta\sigma_{LL}$	Im(H) and Im(E) extracted	Im(H), Im(E) and Im(Ht) extracted

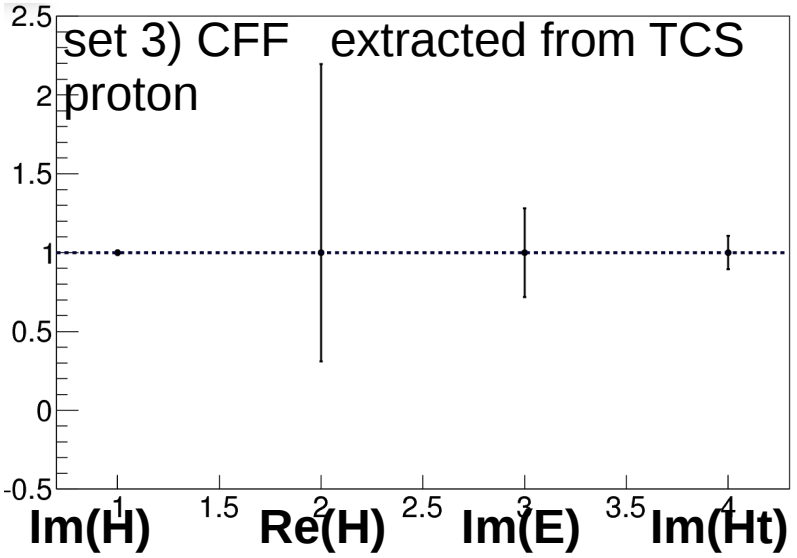
GPD E & angular momenta studies: what observables?

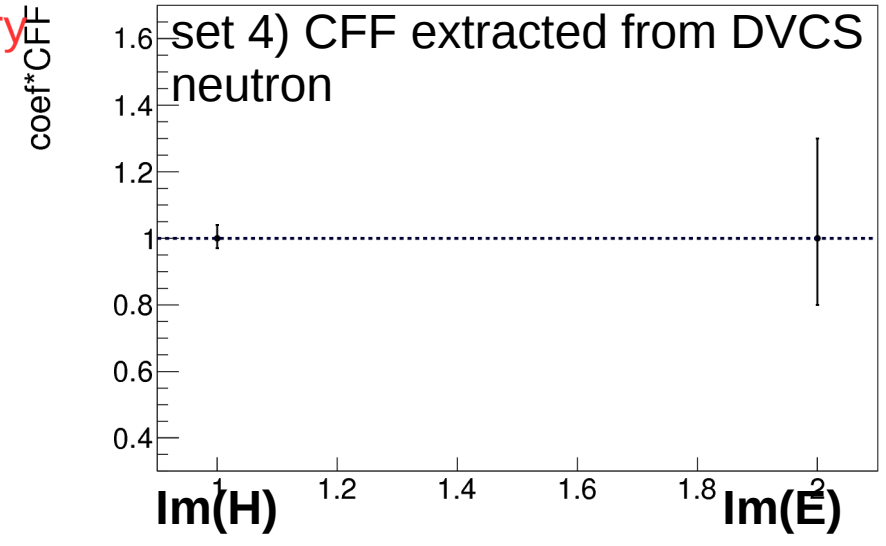
for flavor separation from both DVCS & TCS

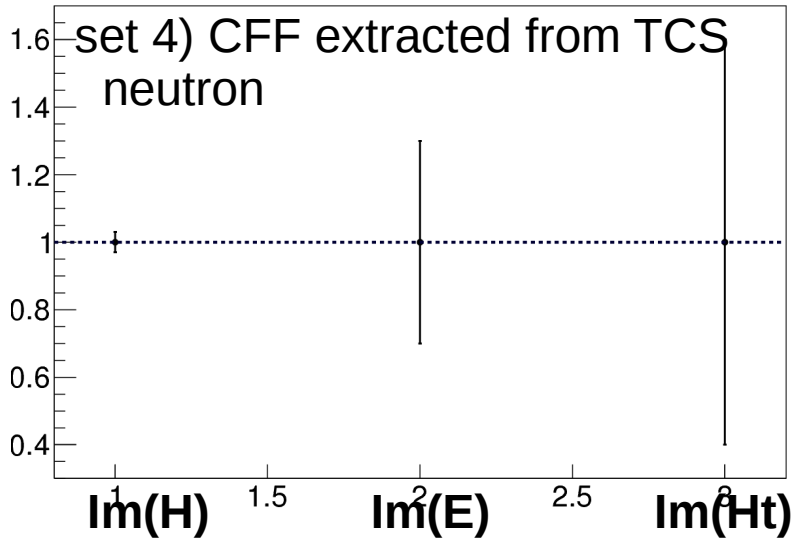
→complementary measurements

→universality studies



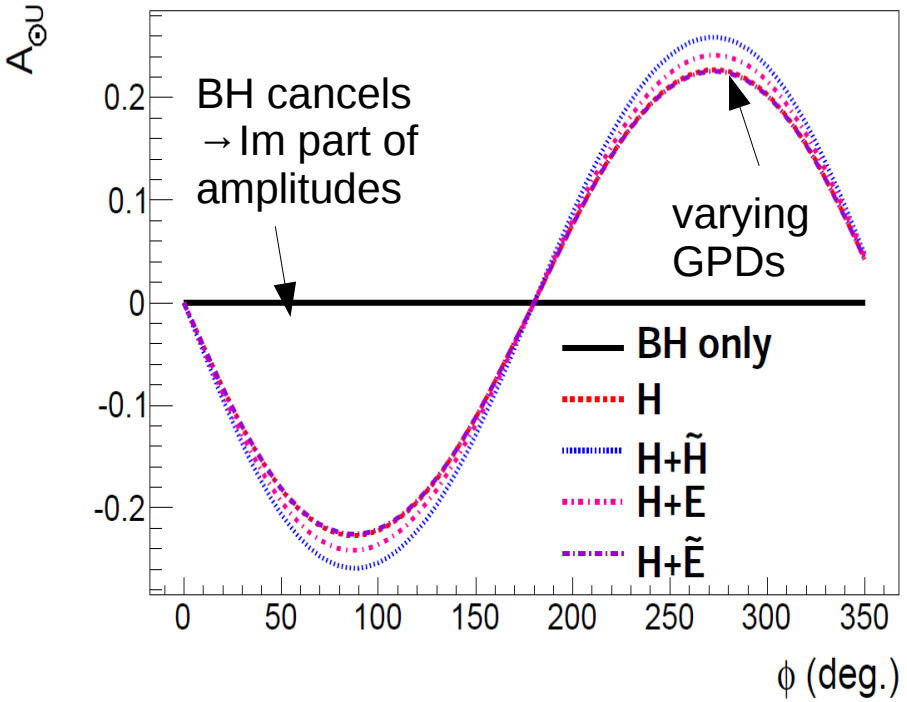




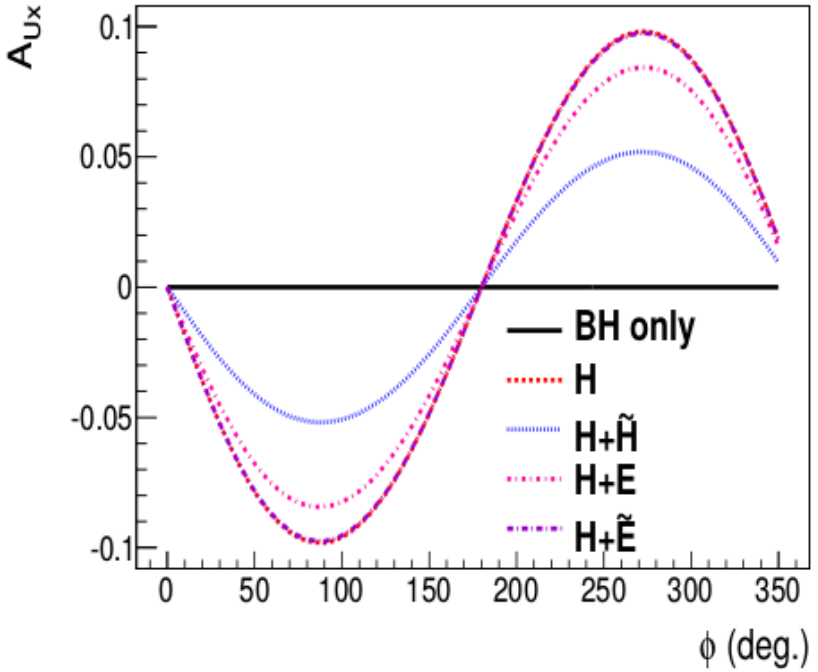


TCS beam spin (circular) and target spin asymmetries

Circularly polarized beam asymmetries



Transverse target asymmetries



Single spin asymmetries:
- Access Im(CFFs), BH cancel
- large and sensitive to GPD parametrization

Unpolarized cross section, double spin asym.:
- Access Im+Re(CFFs), large contribution of BH
- difficult to measure, strongly model dependent

- **Experiments at JLab for measuring unpolarized cross section and $A_{\odot u}$**

Started in Hall B, accepted Hall A
Hall B : E12-12-01 PAC39 (2012) / Hall A : E12-12-006A PAC43 (2015)

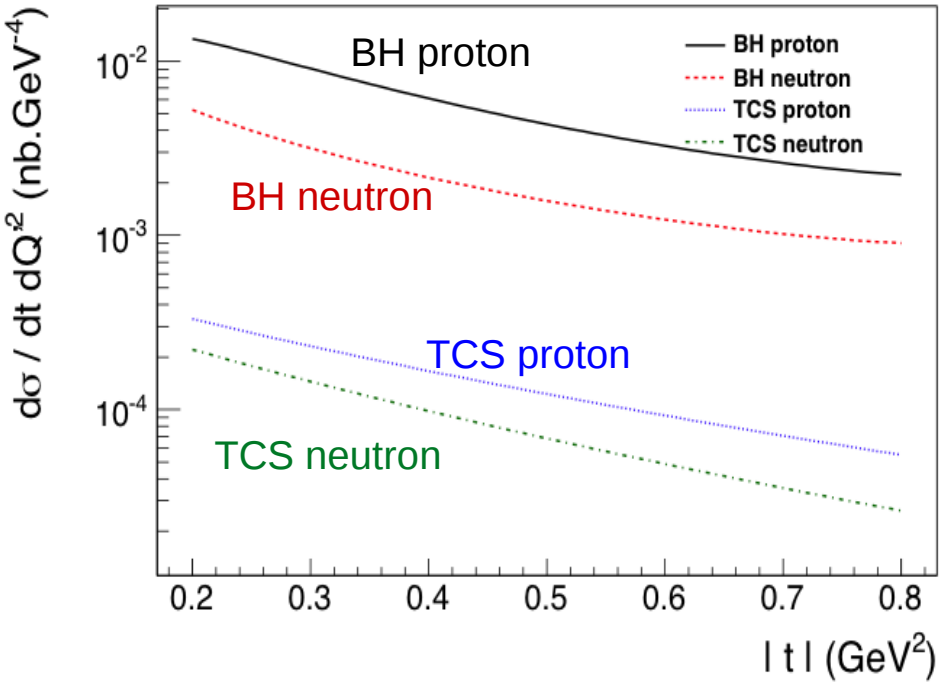
- **Experiment at JLab for measuring A_{UT}** : LOI 12-15-007 PAC43 (2015) / proposal just submitted
- **Future possibilities:**

- linear γ polarization: real part of CFFs →GlueX upgrade in luminosity?
- longitudinal target: Im(CFFs), neutron →SoLID, CLAS12, NPS setup / luminosity upgrades?

Figures from: MB, M. Guidal, M. Vanderhaeghen, EPJA 51 (2015) no.8, 103.

Future projects (?): TCS off the neutron

Unpolarized cross section vs -t



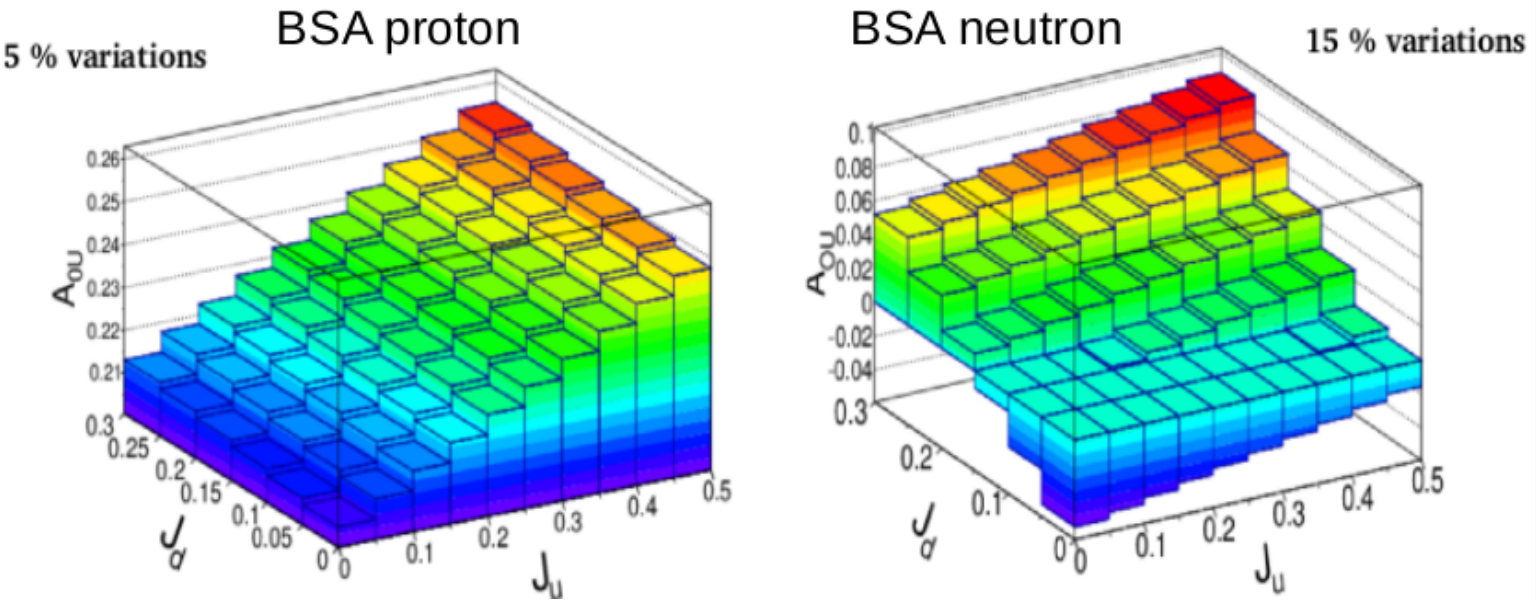
- TCS off the neutron not drastically suppressed compared to proton → measurable

- sensitive to GPD parametrization → flavor separation

- Needs: recoil detector + photon energy measurement, high luminosity

- Interests: strong sensitivity to angular momenta, large target asymmetries, sign flip in beam spin asym

Figure on right: varying $J_{u,d}$ in GPD E parametrization in VGG (model dependent)



Figs from MB, M. Guidal, M. Vanderhaeghen, EPJA 52 (2016) 33

TCS observables, interests and plans at JLab

Observable (proton target)	**Experimental challenge**	**Main interest for GPDs**	**JLab experiments**
Unpolarized cross section	1 or 2 order of magnitude lower than DVCS, require high luminosity	Im + Re part of amplitude. Re(H), Im(H)	CLAS 12, SoLID approved NPS proposed
Circularly polarized beam	Easiest observable to measure at JLab	Im(H), Im($\widetilde{H}$) Sensitivity to quark angular momenta, in particular for neutron	CLAS 12, SoLID approved NPS proposed
Linearly polarized beam	Need high luminosity, at least 10x more than for circular beam, and electron tagging	Re(H), D-term. Good to discriminate models and very important to bring constrains to real part of CFF	GlueX (?)
Longitudinaly polarized target	Polarized target	Im($\widetilde{H}$)	no
Transversely polarized target	Polarized target, and high luminosity: binning in θs, φs	Im($\widetilde{H}$), Im(E)	NPS proposed
Double spin asymmetry with circularly polarized beam	Polarized target, very high luminosity, precision measurement	Real part of all CFF	no / "for free"?
Double spin asymmetry with longitudinally polarized beam	Polarized target, electron tagging, very high luminosity and precision	Not the most interesting, Im(CFFs) but difficult to measure	no

TCS off the neutron

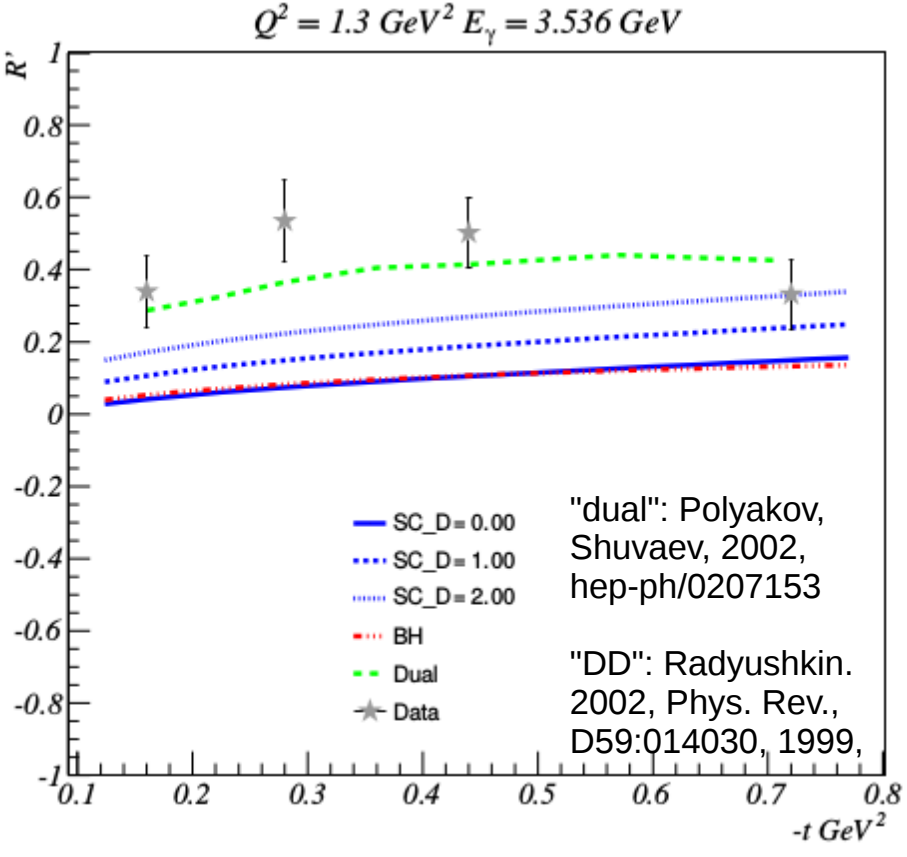
- similar conclusion, need 10 to 100x higher luminosity.
- target spin asymmetries are expected to be larger, and beam spin asymmetries are smaller
- important measurement for GPDs flavor separation, and its sensitivity to quark angular momenta

CLAS 12 experiment E12-12-001 : first TCS measurement ongoing

Data are on tape, analysis is started. From quasi-real photon, E(e)=11 GeV

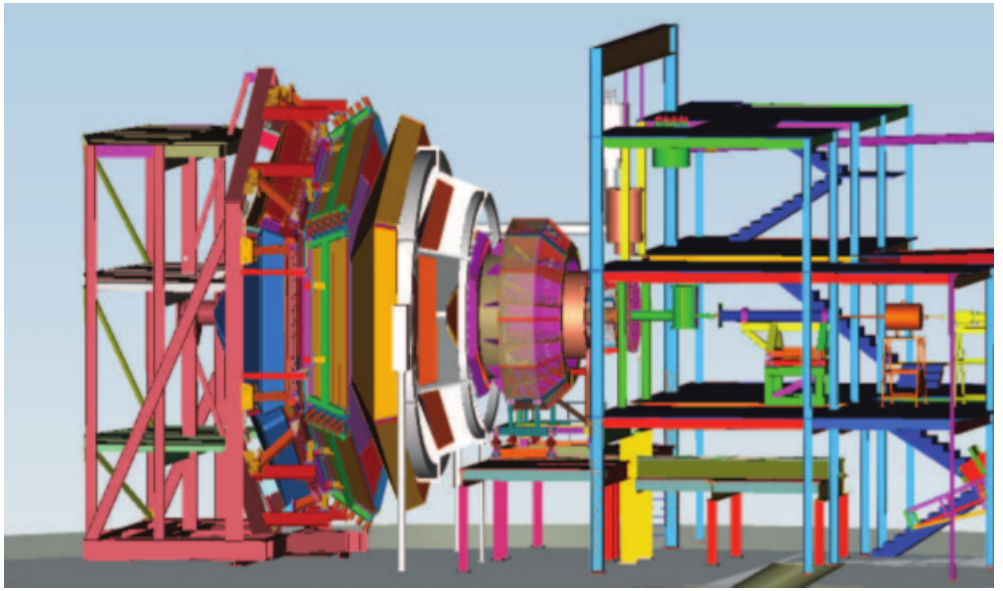
$$R = \frac{2\int_0^{2\pi} d\varphi \cos\varphi \frac{dS}{dQ'^2\, dt\, d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ'^2\, dt\, d\varphi}}$$

projection, first cosφ moment
→real part of amplitudes



"dual": Polyakov, Shuvaev, 2002, hep-ph/0207153

"DD": Radyushkin. 2002, Phys. Rev., D59:014030, 1999,



Left figure: measurement at 6 GeV in CLAS & model prediction for R
(R' is "experimental" R, with a sum over bins)

- feasibility and analysis technics demonstrated

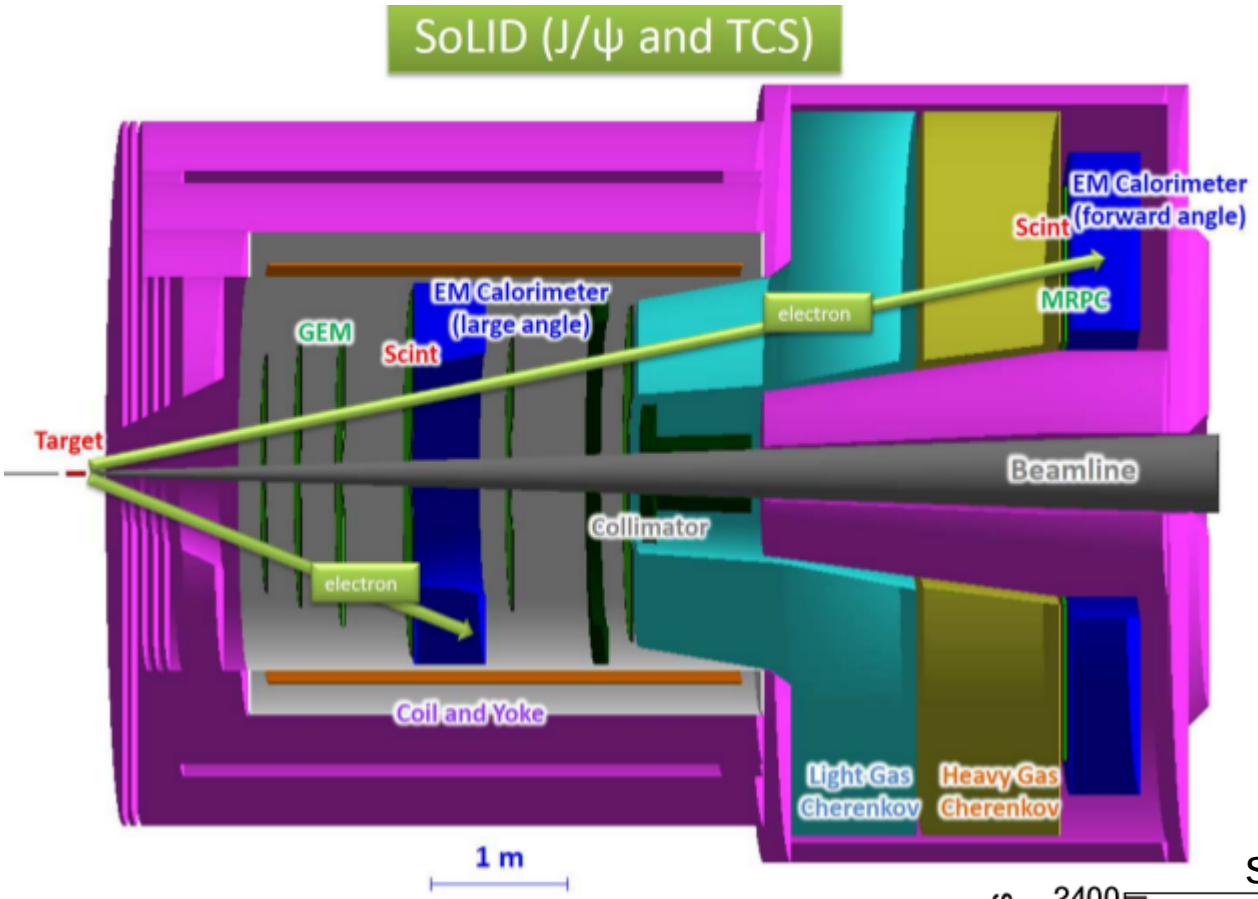
- theory curve for different GPD / D-term parametrizations.

- discriminates between "dual" and "double distristribution" type models, sensitive to real part of amplitudes.

Fig: from R. Paremuzyan

TCS with SoLID: complementary to CLAS 12 with high luminosity

E12-12-006A PAC43

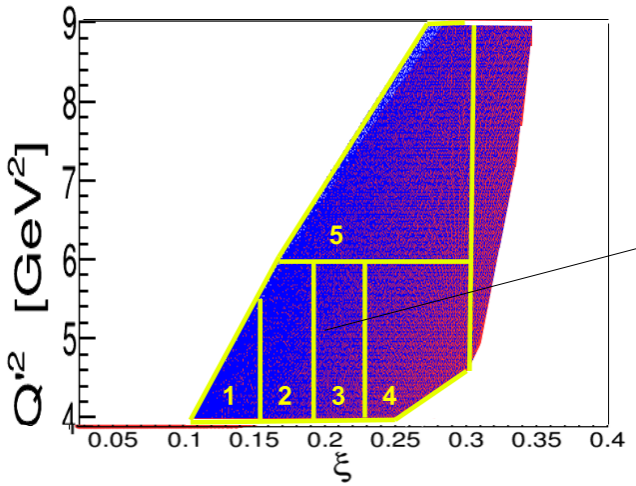


SoLID setup for J/ψ approved exp.

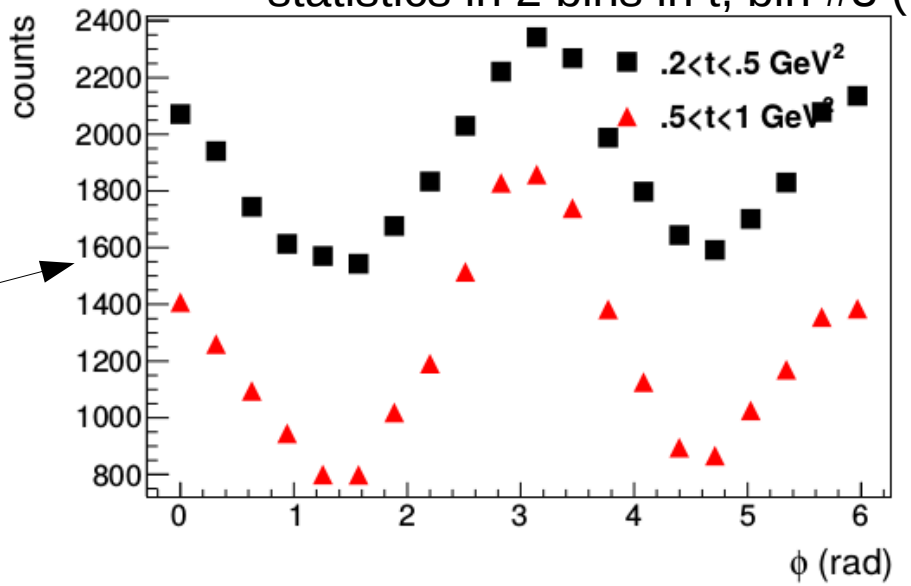
- no beam time request for TCS
- 50 days approved up to 10^37 cm^{-2}

Similar as CLAS12, with larger statistic, narrower acceptance
→binning in Q'^{2}: evolution...
→studies of GPD universality by comparing H extracted from TCS and DVCS

statistics in 2 bins in t, bin #3 (Q'^{2}, ξ)



bin 3



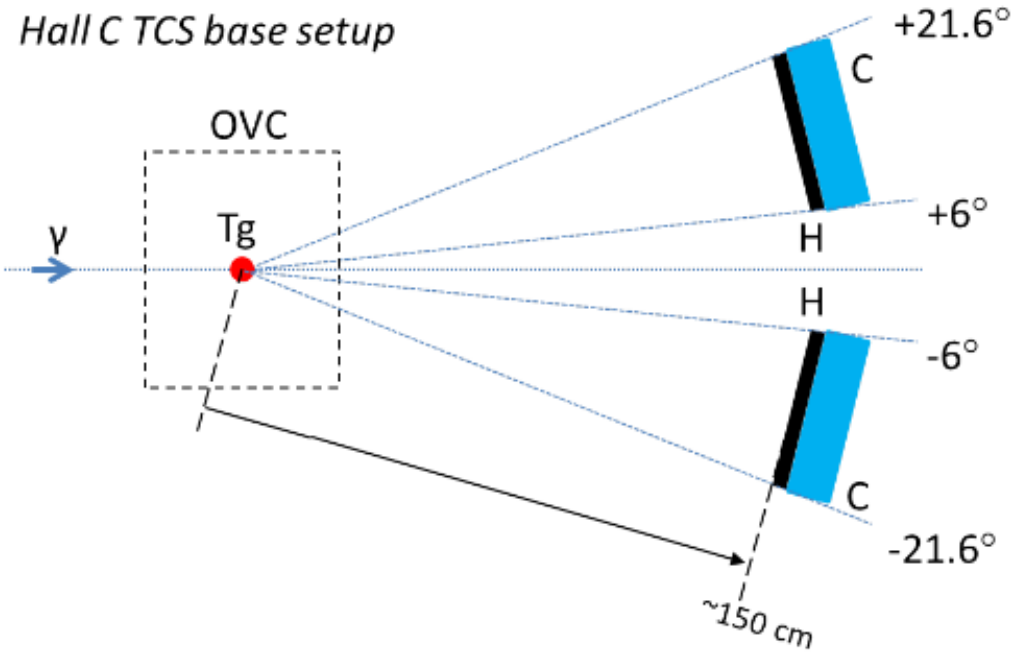
NPS proposed experiment using a transversely polarized target

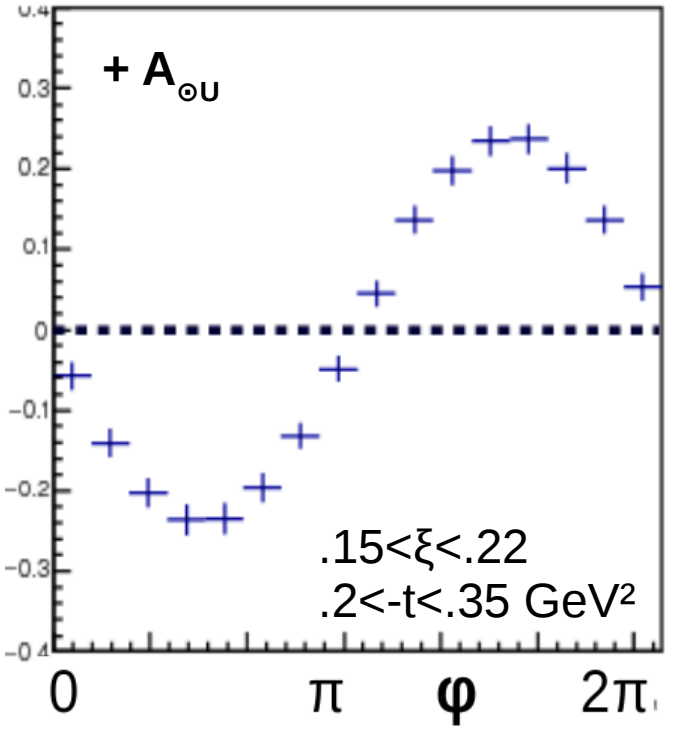
Physics case: *submitted to PAC46, 2018

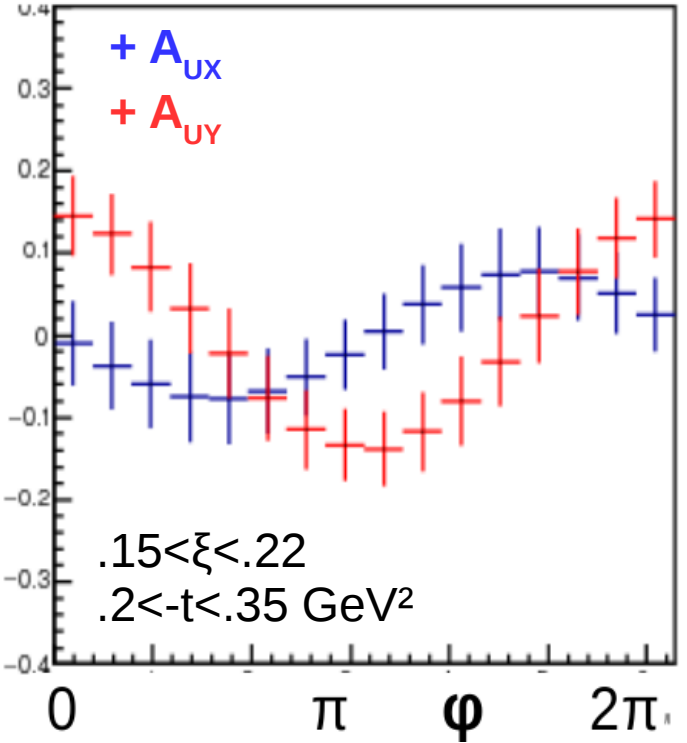
- GPDs universality and higher twist effects, high level precision to compare with DVCS
- Im(E) and angular momenta
- complementarity DVCS in twist 2 global fit approach

Main advantages:

- transversely polarized target NH3
- real photon beam, circularly polarized
- high photon luminosity, ~6e5 pb-1





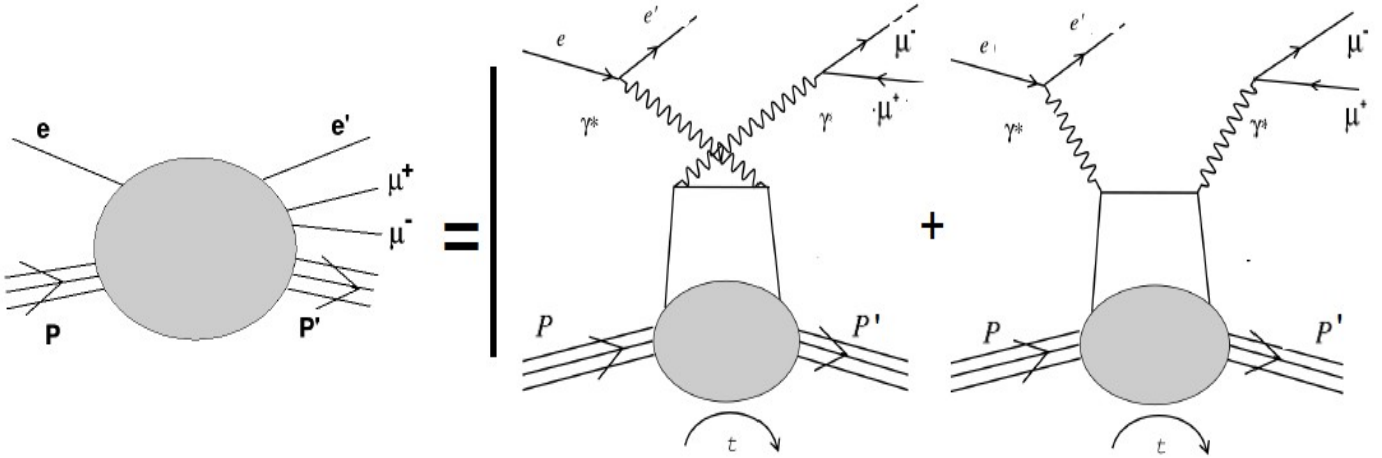


Bins: 8 in (ξ, t, Q'²), 16 in φ, 16 in φ_s

Double Deeply Virtual Compton Scattering

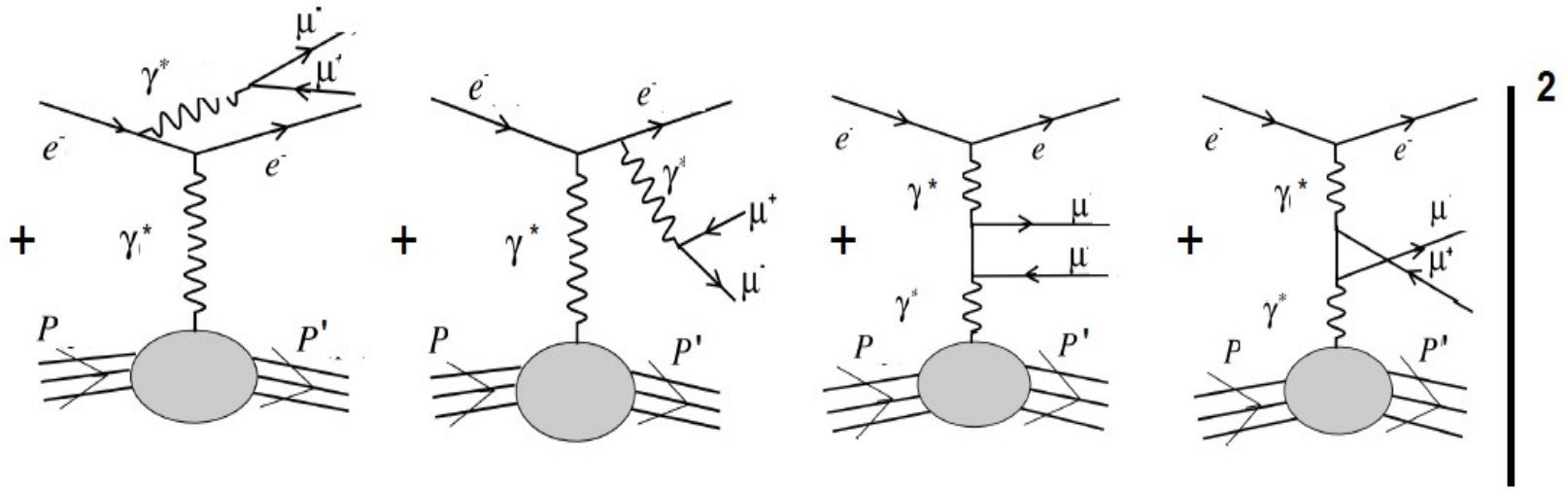
Interest: access the off diagonal part of (x, ξ) distribution of CFF, ...

Studies: DDVCS from e- beam, decaying in dimuons to avoid anti-symetrization which would be a challenge for extracting GPDs out of experimental observables, plus experimental determination of kinematic variables.



leading order, leading twist diagrams

DDVCS



BH_1 behaves like DVCS-like BH

BH_2 behaves like TCS-like BH

Accessing GPDs with DDVCS reaction

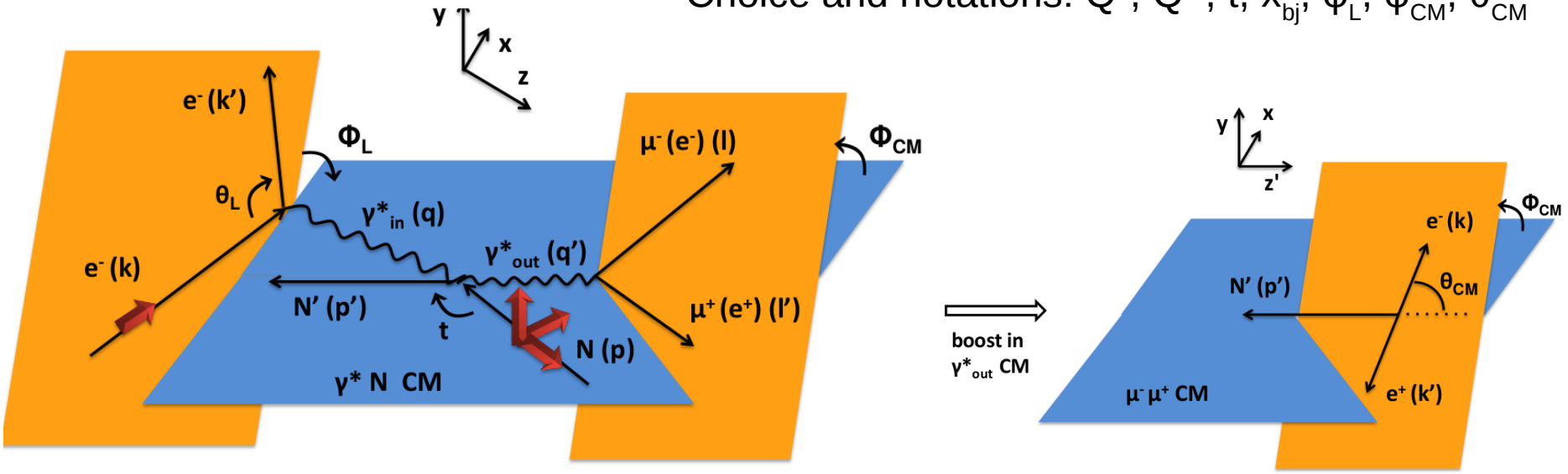
$$T^{DDVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x - (2\xi' - \xi) + i\varepsilon} dx + \ldots \sim P \int_{-1}^{+1} \frac{H(x,\xi,t)}{x - (2\xi' - \xi)} dx - i\pi H(2\xi' - \xi, \xi, t) + \ldots$$

$$\xi' = \frac{x_B}{2 - x_B} \qquad \xi = \xi' . \frac{Q^2 + Q'^2}{Q^2}$$

→ lever arm by varying Q^2 vs Q'^2 to vary the propagator and extract CFF at $x \neq \pm\xi$

→ equivalent to meson mass in DVMP, without adding complication from DA parametrization

7 independent variables for unpolarized cross section.
Choice and notations: Q^2, Q'^2, t, x_{bj}, φ_L, φ_{CM}, θ_{CM}

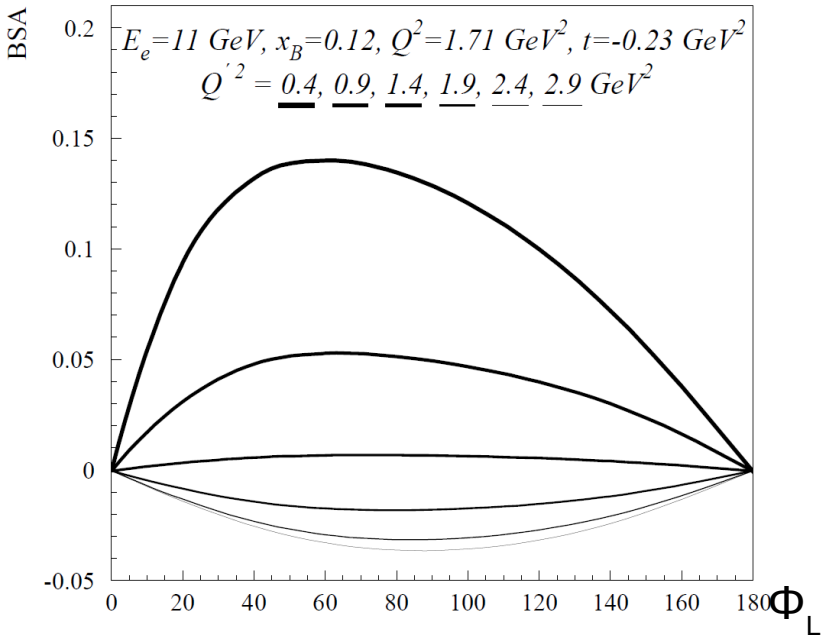


Nucleon tomography and sign change in DDVCS beam spin asymmetry

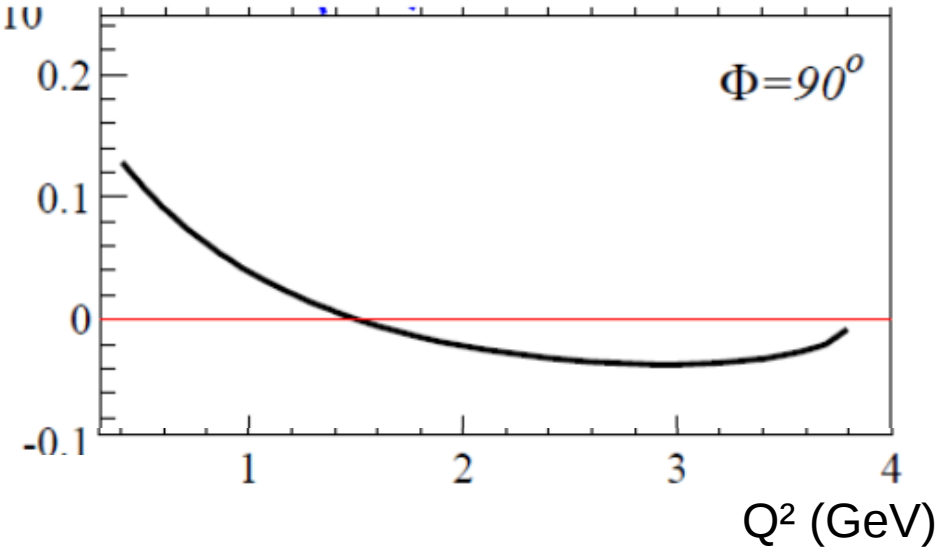
Calculations from M. Guidal

→ scan of BSA in Q'^2 at fixed Q^2

→ sign change in BSA vs Φ_L and vs φ_{CM} when $Q'^2 \approx Q^2$



asymmetry Q^2 scan



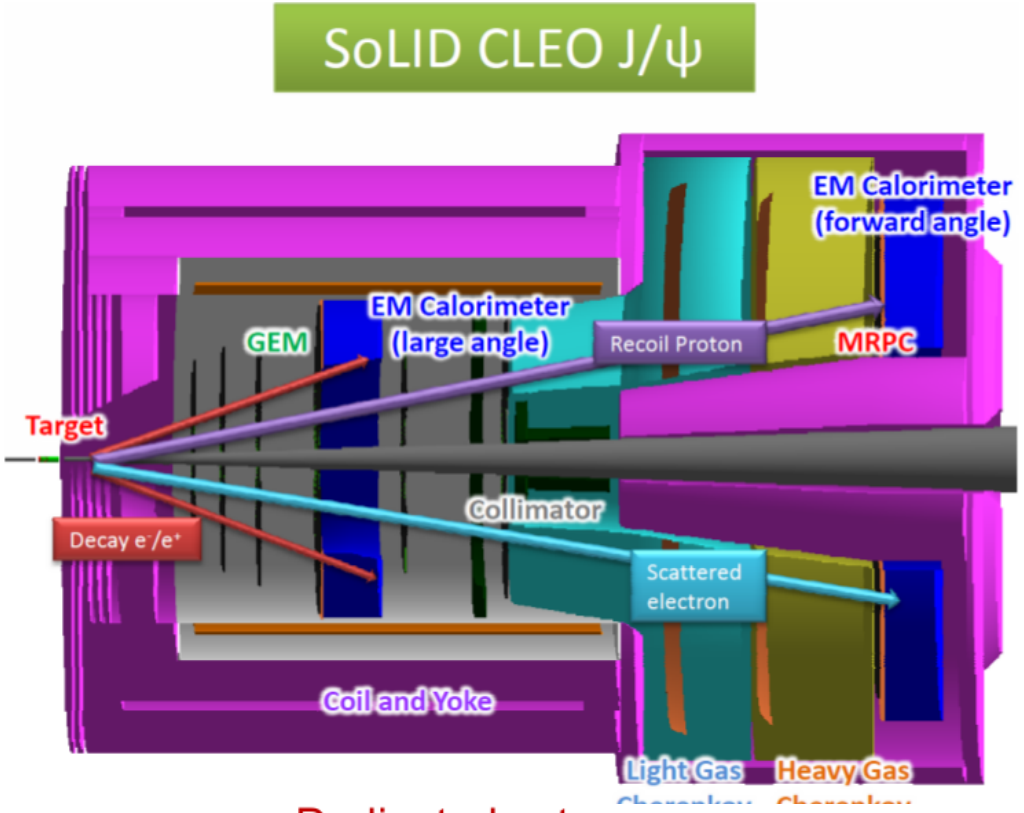
- **Probing GPDs at x ≠ ξ → tomographic interpretations….**
- **Expectation of sign change for observables sensitive to Im (DDVCS) when moving from « spacelike » to « timelike » region**

→ this reaction is unique for probing effects between these 2 regions.

- Cross section + beam spin asymmetry projects in development for JLab Hall A and B, for exploratory measurements with aim of future dedicated experiment at very high luminosity

SoLID: LOI12-15-005 (2015)
CLAS12 note: (2015), LOI12-16-004 (2016)

DDVCS with SoLID: experimental setup

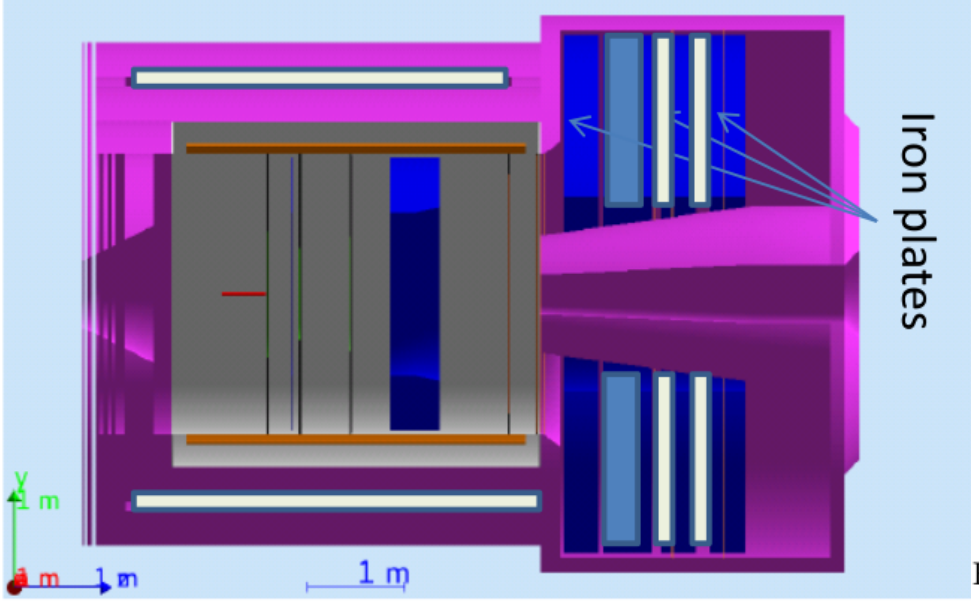


- J/Ψ setup: electrons, (proton)
- CLEO muon chambers: muon pair

50 days at 10^37 cm^{-2}
reasonnable rates: measurement feasible

To do:
- GPD extraction from simulations / impact
- optimal setup
- updated rates

Dedicated setup



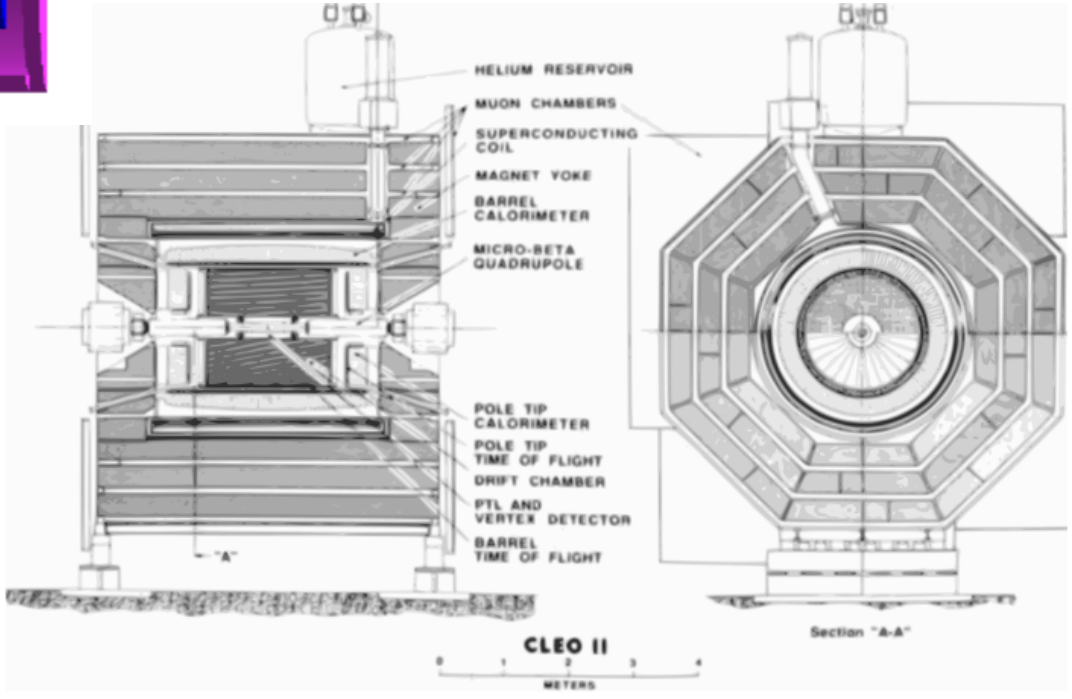


Figure 10: CLEO II setup with muon chambers installed inside the iron yoke.

DDVCS with CLAS12 in Hall-B

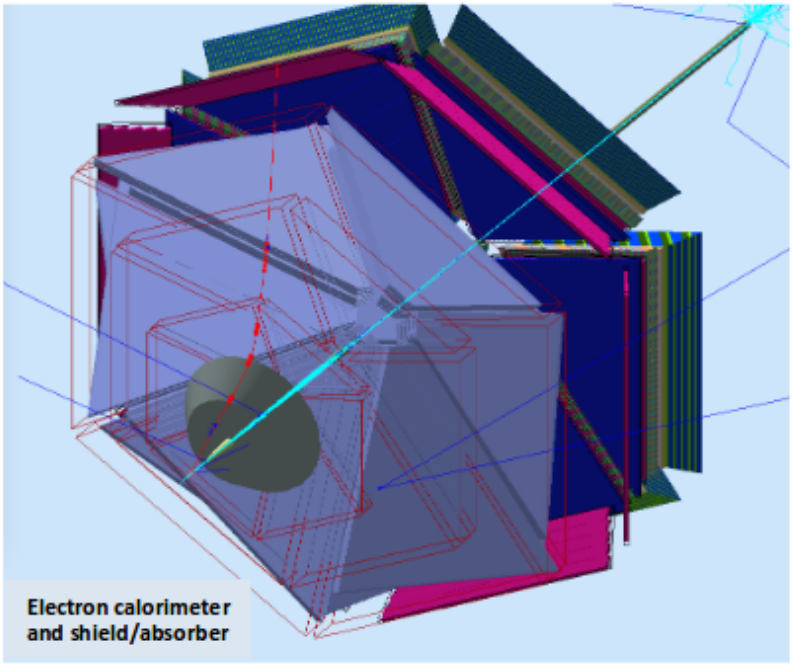
Two main challenges in DDVCS measurements:

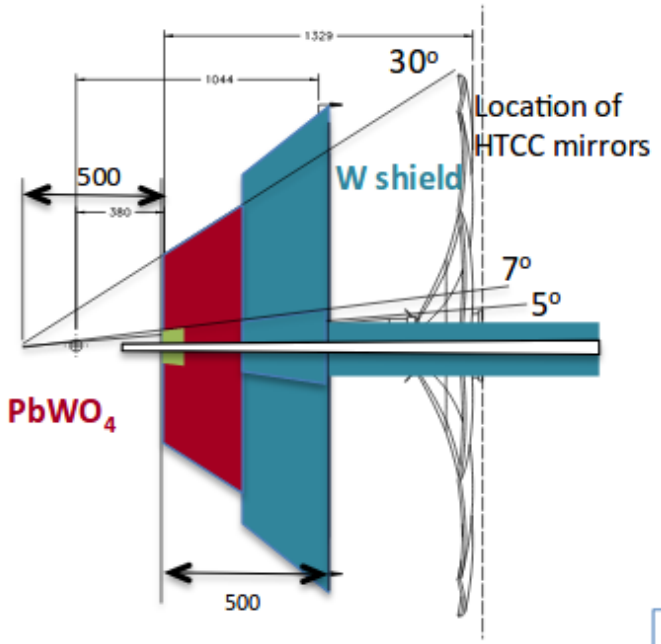
- cross section is two to three orders of magnitude smaller than the DVCS cross section
- decay leptons of the outgoing virtual photon must be distinguishable from the incoming-scattered lepton

Both challenges can be solved with by studying di-muon electroproduciton, $ep \rightarrow e'p'\mu^+\mu^-$

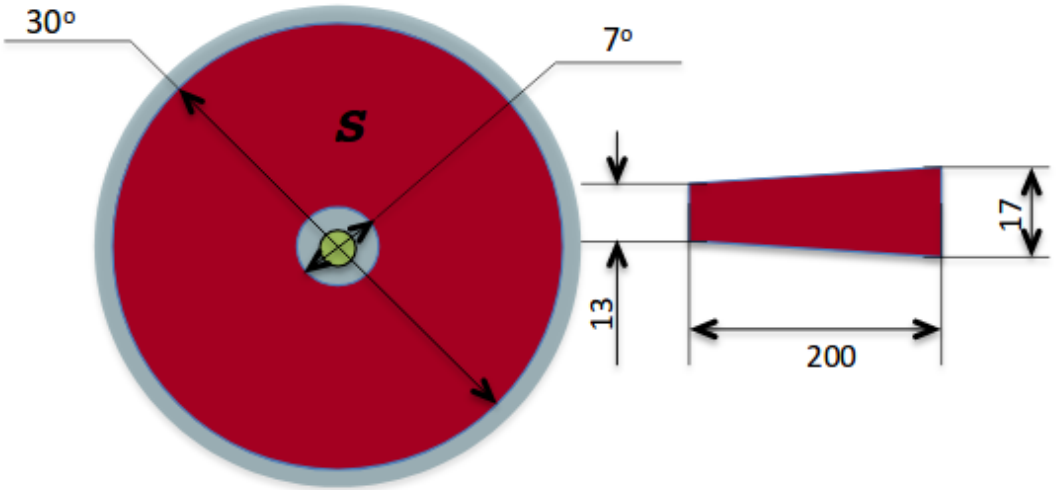
CLAS12 FD will be blocked with heavy shielding/absorber from electromagnetic and hadronic backgrounds to be able to run at luminosities ~10^{37} cm^{-2} s^{-1}, and will be used as muon detector

Scattered electrons will be detected in a compact $PbWO_4$ calorimeter that is part of the shielding





$$S = \pi l^2[(tg^2(30^o) - tg^2(7^o)] = 3600\,cm^2;\ l = 60\,cm$$



$PbWO_4$ modules with APD readout - ~ 1500 modules

Tools, status and possible extensions into studies for EIC

Formalism for TCS:

- unpolarized and beam (circularly + linearly) and/or target (// and T) polarized cross sections
- calculations made at "JLab" energy, from quark VGG GPDs

Formalism for DDVCS:

- unpolarized and beam polarized cross sections
- at "JLab" energy, from quark VGG GPDs

Framework and Event generator

- TCS from real or quasi-real photon into e+e- and μ+μ-, all polarization configurations
- DDVCS into μ+μ-, unpolarized and beam polarized
- **plans: extension to other processes such as DVMP, and to other kinematics for EIC studies**

model (any process)

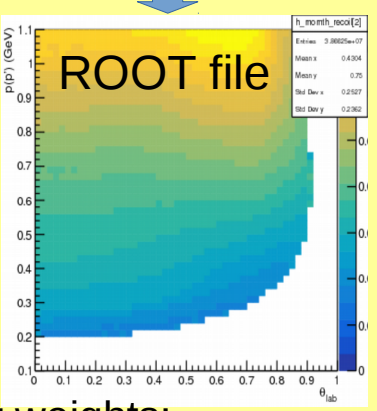
$$\frac{d^4\sigma}{dQ'^2 dt d\Omega}(\gamma p \to p' e^+ e^-) = \frac{1}{(2\pi)^4}\frac{1}{64}\frac{1}{(2ME_\gamma)^2}\,|\,T^{BH}+T^{TCS}\,|^2$$

grids of polarized BH / TCS / BH+TCS

```
 1.816930e-02 1.090707e-02 1.105740e-02 1.852696e-02
4 1.859244e-02 1.048393e-02 1.181284e-02 1.777151e-02
4 1.861872e-02 1.045765e-02 1.285992e-02 1.672443e-02
4 1.824557e-02 1.083079e-02 1.409615e-02 1.548821e-02
4 1.750952e-02 1.156685e-02 1.540050e-02 1.418385e-02
```

New models input are very welcome

MAIN EXE



event weights:
polarized, unpolarized,
asymmetries, only BH...
here: TCS/BH p(P) vs θ(lab)

user input file (here: TCS)

Variable name	usage	limits (grid)	default value
Experimental configuration	Beam and target parameters		
Beam type	real photon (0) initial electron (1)	0 or 1	0 or 1
Beam energy (if electron beam)	used to calculate the photon flux	[~ 6, 12] GeV	11
Luminosity	used for normalization	-	10^{35} cm^{-2}
out leptons	electron (1) or muon (2)	1 or 2	2
Target lenght	luminosity	-	15 cm
Target composition (A,Z)	luminosity	single atoms	(1,1) or 1001
Target = p (1) or n (2)	weight	1, 2	1
	Polarization options		
Beam polarization dilution factor	polarized cross sections	[0, 1]	0.8
Beam pol. vector direction	case linearly polarized	1 (x-axis), 2 (y-axis) or 3 (45°)	1
Target polarization direction	polarized targets	0 (unpolarized), 1 (x-axis), 2 (y-axis), 3 (z-axis)	3
Target dilution factor	polarized targets	0 to 1	0.7
Kinematics	Kinematic range		
Photon energy	photon	[4.5, 11.5]	[5, 10.5]
-t	Mandelstam variable	xx	[.05, .7]
Q'^2	final photon virtuality	xx	[.09, .3]
θ_{CM}	azimuthal angle of decay leptons	[40°, 140°]	[40°, 140°]
Q^2_{max}	quasi-real photons maximal virtuality	0 to ~ 0.5	0.3

Summary

• Comparison of "Compton-like" processes → test of GPD universality, timelike vs spacelike...

• Higher twist / NLO contributions evaluation

• Global fits: access same GPDs, combination into multi-observables approach

• First TCS measurements ongoing at JLab, projects at larger luminosity with more independent observables →independent extraction of GPDs from TCS, complementarity to DVCS measurements, "just photons"

• Accessing GPDs at $x \neq \xi$ with DDVCS

• Framework developed for simulations, feasibility studies, rates of future experiments: plan extensions to EIC kinematics and other reactions (DVMP...)