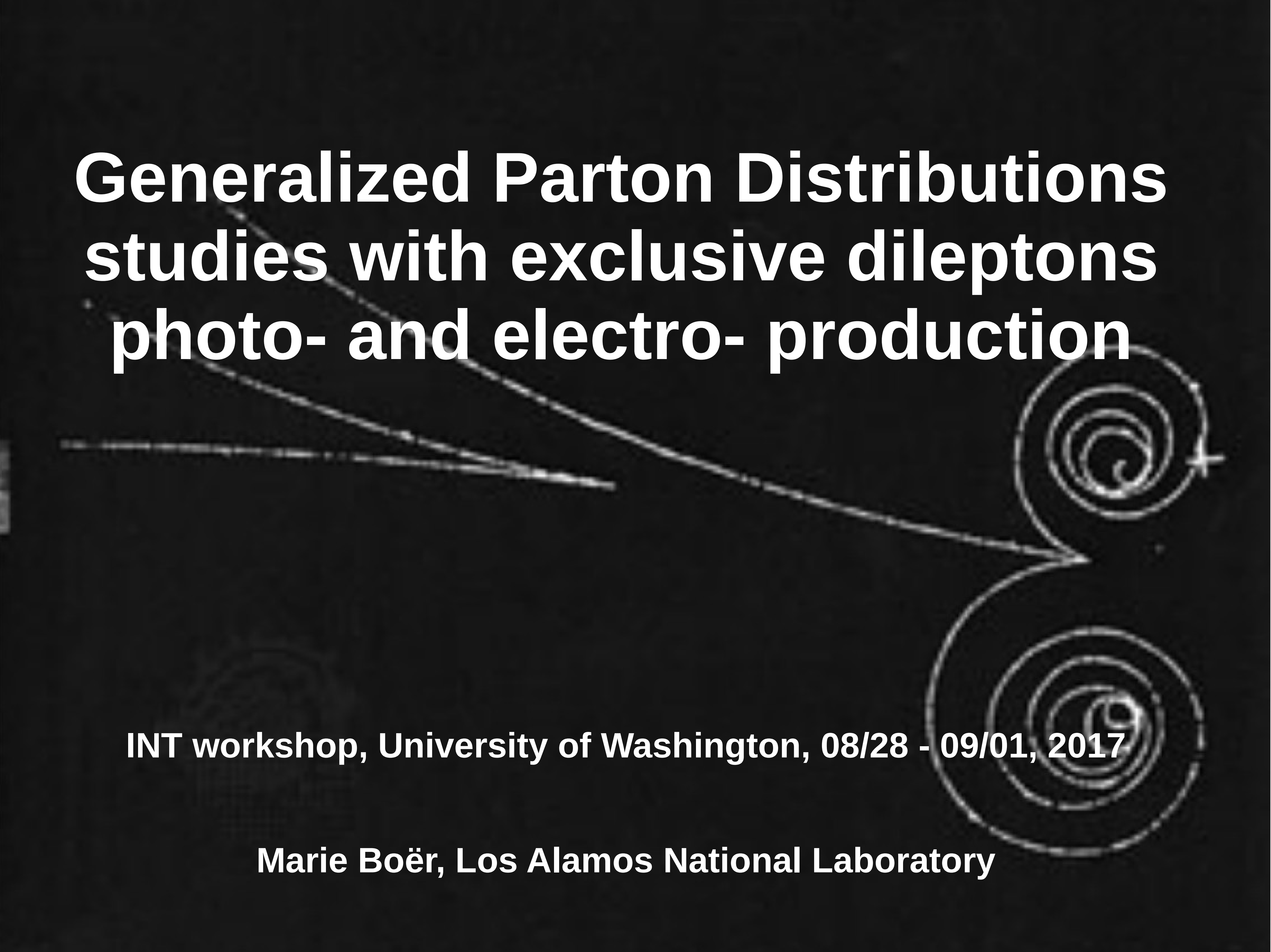


Generalized Parton Distributions studies with exclusive dileptons photo- and electro- production

INT workshop, University of Washington, 08/28 - 09/01, 2017

Marie Boër, Los Alamos National Laboratory

Outline

Timelike Compton Scattering

1) Interest, observables, experimental perspectives

2) Complementarity with DVCS measurements

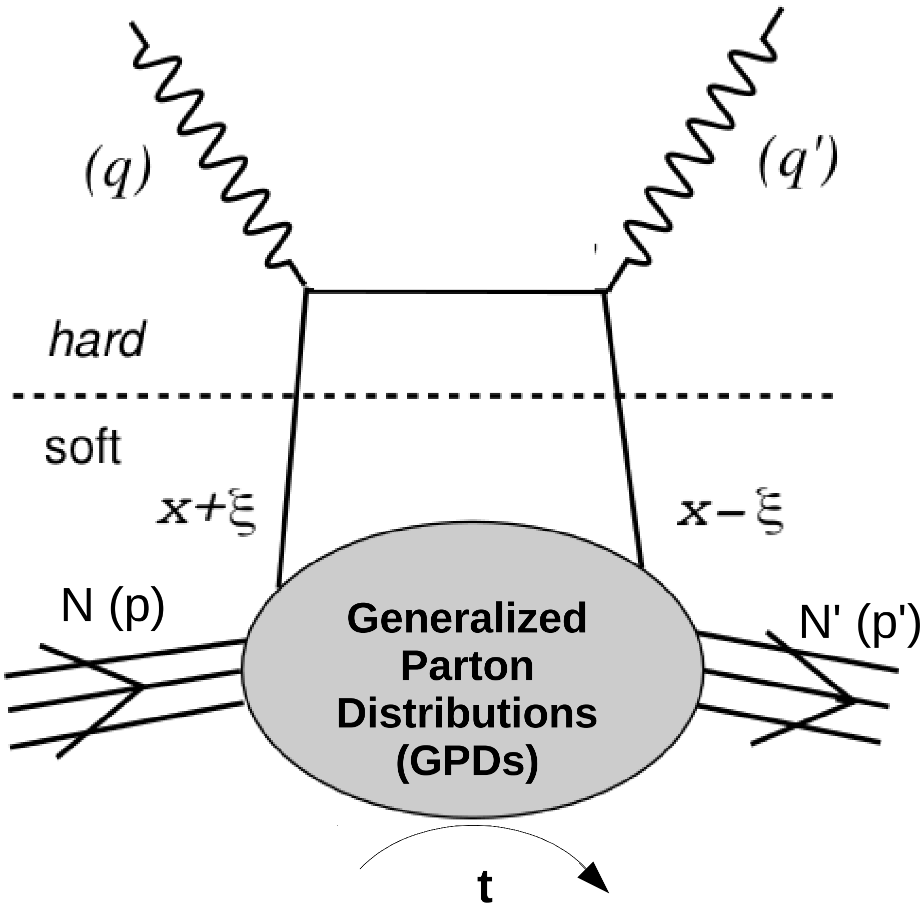
3) Future experiments at JLab

Double Deeply Virtual Compton Scattering

1) Interest, observables

2) Projects for JLab

Generalized Parton Distributions with exclusive Compton processes



γ (*) N → γ(*) N' → e+ e- N'

- outgoing photon is real :
<u>spacelike</u> Deeply Virtual Compton Scattering
DVCS = e N → e' γ N'

- incoming photon is real :
<u>Timelike</u> Compton Scattering (TCS)
TCS = γ N → e^+e^- N'

- both photons are virtual :
<u>Double</u> Deeply Virtual Compton Scattering
DDVCS = e N → e' e^+e^- N'

(e stands for any lepton)

x : average longitudinal momentum fraction of the struck quark
ξ : longitudinal momentum transfer
t : momentum transfer squared
$Q^2 = -q^2$; $Q'^2 = +q^2$: hard scale, photon's virtuality

Accessing GPDs with Deeply Virtual Compton Processes

DVCS amplitude decomposition into Compton Form Factors:

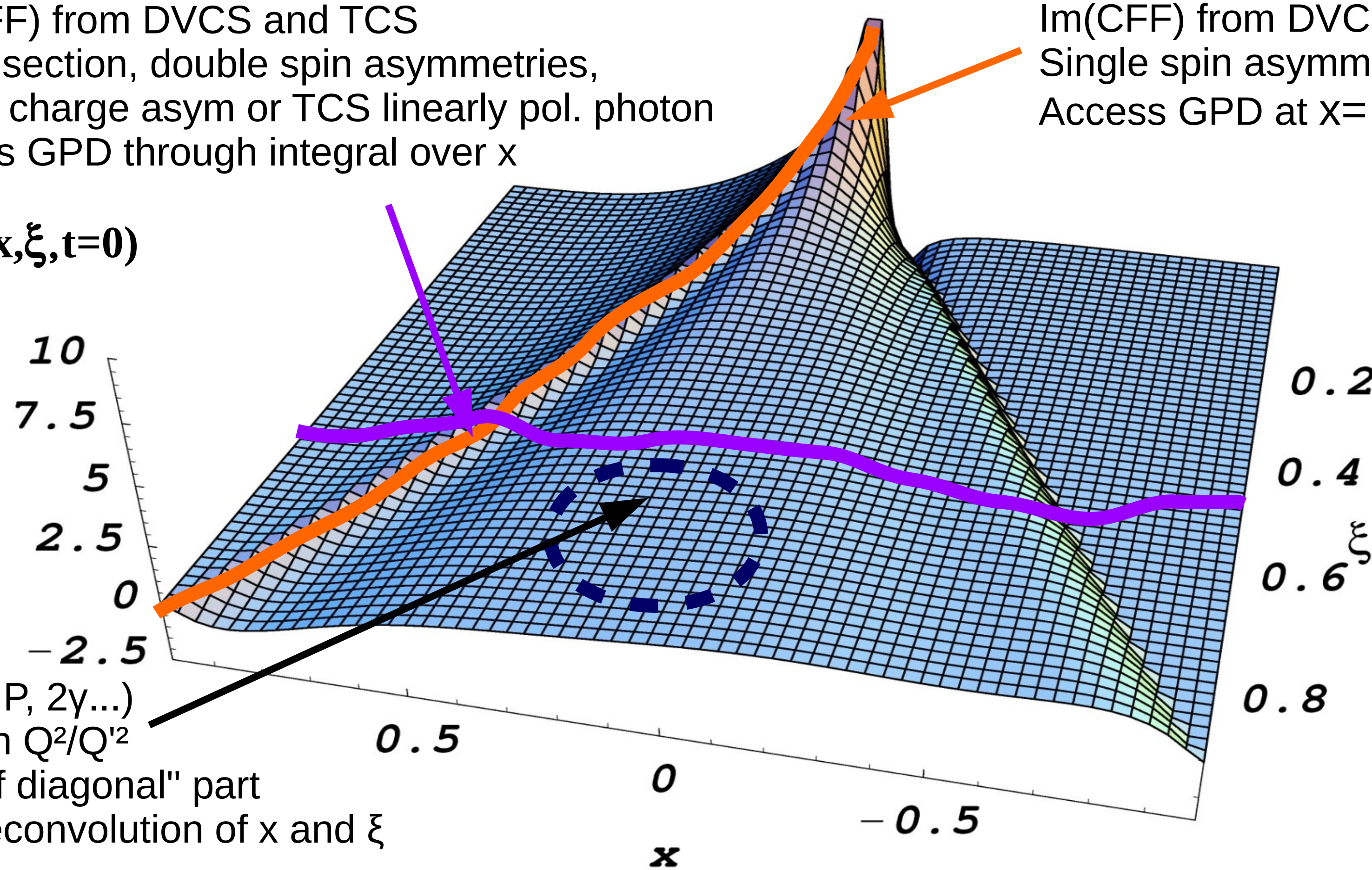
ξ, t = measurable
x = loop only

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

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**

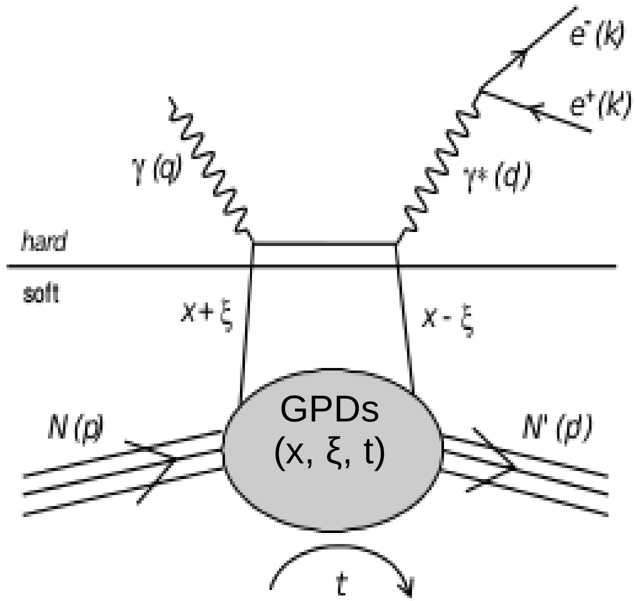


DDVCS (DVMP, 2γ...)
Lever arm with Q^2/Q'^2
Access "out of diagonal" part
Needed for deconvolution of x and ξ

Timelike Compton Scattering

1) Interest, observables

$$\gamma N \rightarrow e^+ e^- N \quad =$$



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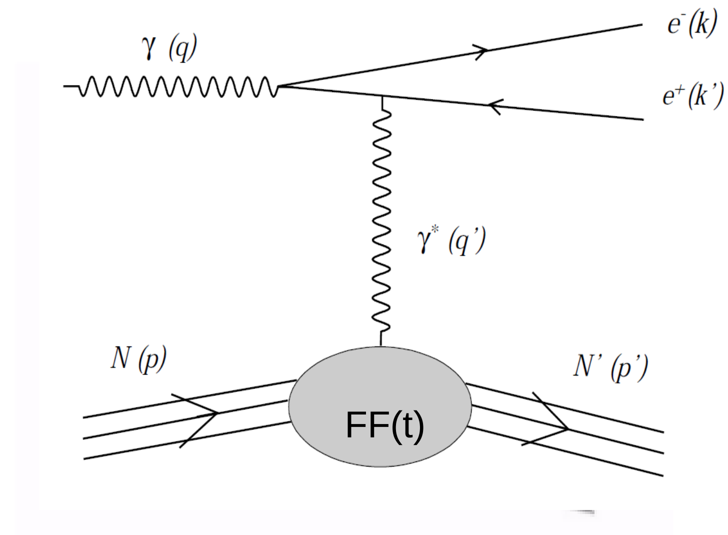


Timelike Compton Scattering (TCS)
sensitive to the nucleon GPDs

Bethe-Heitler (BH)
sensitive to the nucleon Form Factors

x : longitudinal momentum fraction of the struck quark
ξ : longitudinal momentum transfer
t : momentum transfer squared
$Q'^2 = +q'^2$: invariant mass of the lepton pair

Notations for Bethe-Heitler + TCS reaction

- 5 independent variables for unpolarized cross section.

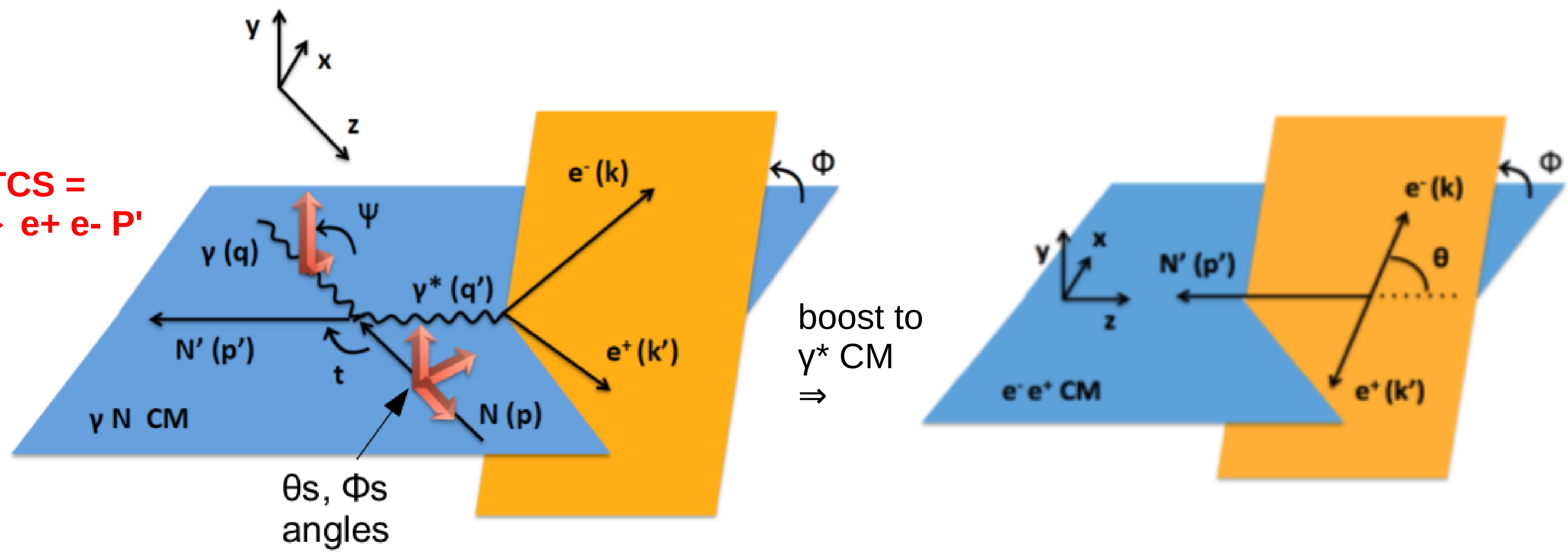
Choice in presented work: Q'^2, t, $E\gamma$, φ, θ or Q'^2, t, ξ, φ, θ

- Linearly polarized beam: Ψ_s, $\Theta_s = 90°$

- Polarized target: φ_s, θ_s

longitudinal: θ_s=0°, along x: φ_s=0° θ_s=90°, along y: φ_s=90°, θ_s=90°

BH+TCS =
γ P → e+ e- P'



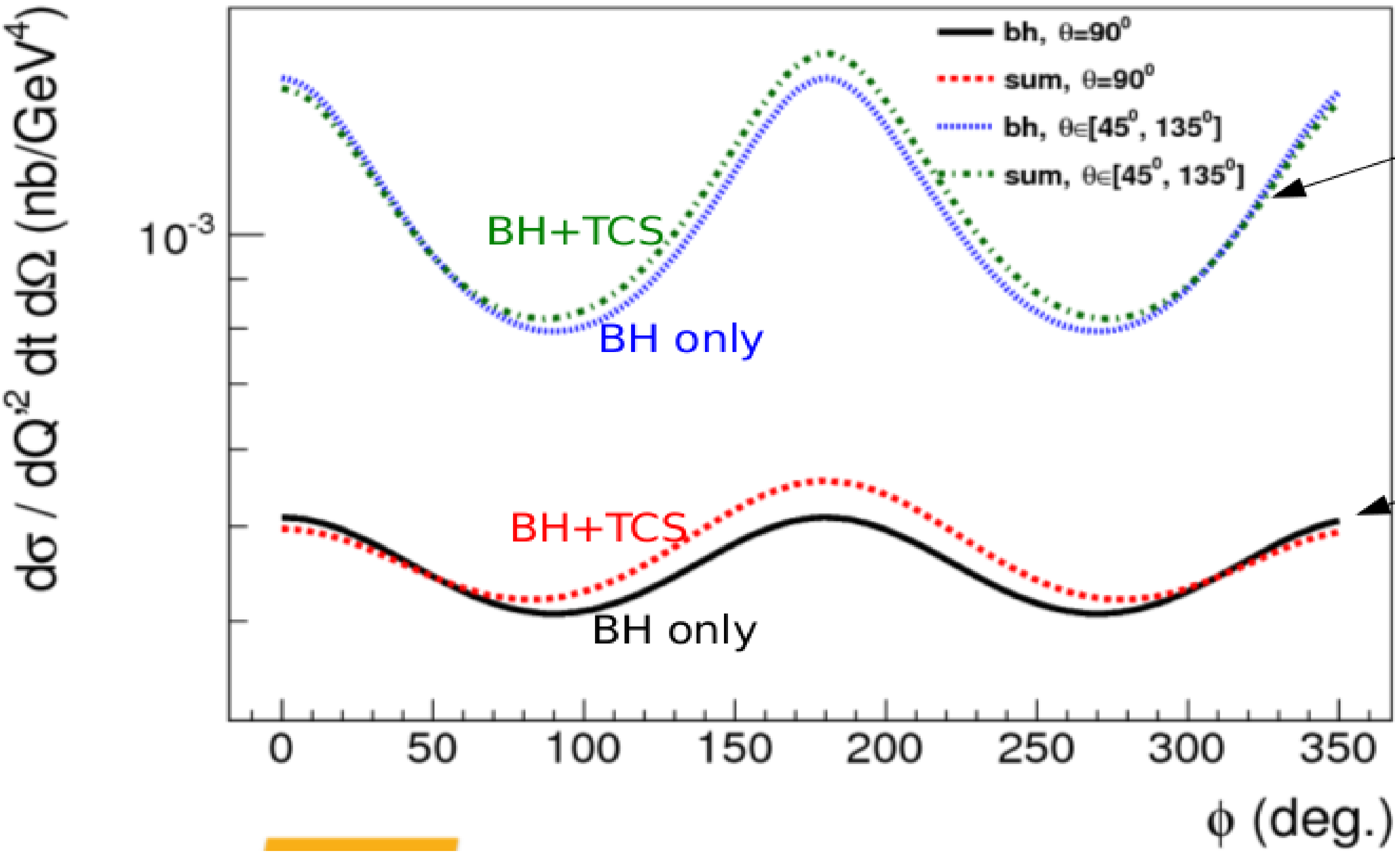
Ψ: (reaction plane, γ spin)
φ: (hadronic plane, e^+e^- pair)
θ: (γ^*, e^-)
θs, Φs: (target spin vector orientation)

Notations: σ = unpolarized cross section, Axx = asymmetry
A⊙u = circularly polarized beam, unpolarized target ; ALu = linearly polarized beam
Aui (i=x, y, z) = unpolarized beam, polarized target along i axis.

Unpolarized cross section : angular dependence

Angular dependence: TCS+BH and "pure Bethe-Heitler" cross section

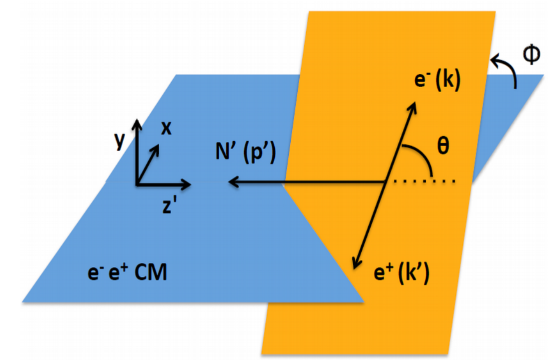
BH singularities : **e^- in γ direction (θ → 0°) => singularity at φ=180°**
e^+ in γ direction (θ → 180°) => singularity at φ=0°



Integrated over polar decay angle

45°<θ<135°

θ=90°



- θ is representative of TCS/BH rate. Unlike for DVCS, TCS/BH << 1 always.
- θ = 90° enhance TCS/BH rate. For experimental purpose integration over [45°, 135°]
- Following examples are for a typical JLab@12 GeV kinematic

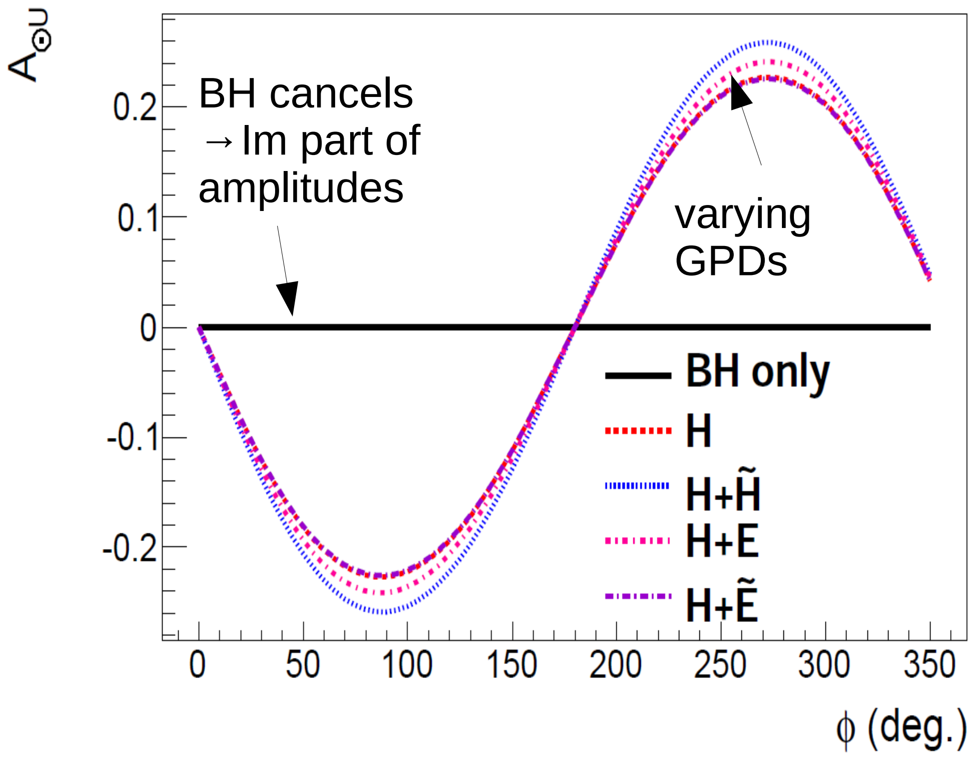
For measuring TCS unpol. cross section:
Started JLab Hall B, accepted Hall A
Hall B : E12-12-01 PAC39 (2012)
Hall A : E12-12-006A PAC43 (2015)

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

Beam spin asymmetry; circular photon: access Im($\mathcal{H}$)

Circularly polarized beam

$A_{\odot U}$ and GPD param. dependence (proton)



Circularly polarized beam:

BH cancels, large and measurable

→Im part of amplitudes

→sensitive to GPD models, mostly H and H̃

→easiest observable to measure

Experiments JLab for measuring $A_{\odot u}$

Started Hall B, accepted Hall A

Hall B : E12-12-01 PAC39 (2012)

Hall A : E12-12-006A PAC43 (2015)

Interference term with circularly polarized beam: from Berger, Diehl, Pire hep/0110062 (2002)

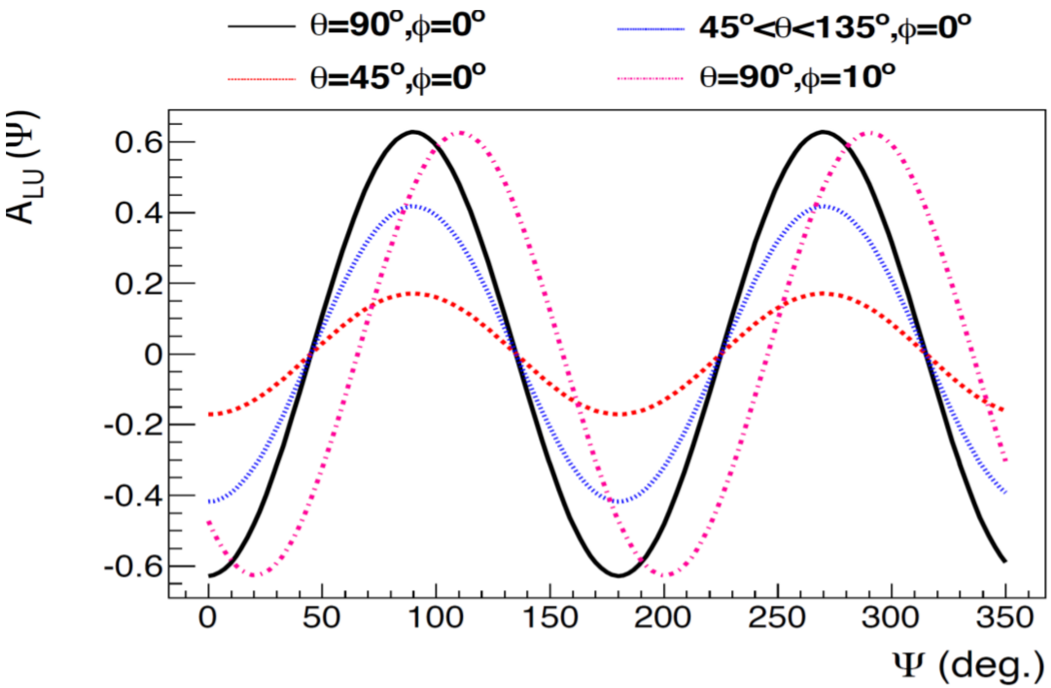
$$\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = \left.\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi}\right|_{\text{eq. (30)}}$$

$$-\,\nu\,\frac{\alpha_{em}^3}{4\pi s^2}\,\frac{1}{-t}\,\frac{M}{Q'}\,\frac{1}{\tau\sqrt{1-\tau}}\,\frac{L_0}{L}\left[\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\,\tilde{M}^{--}\right.$$

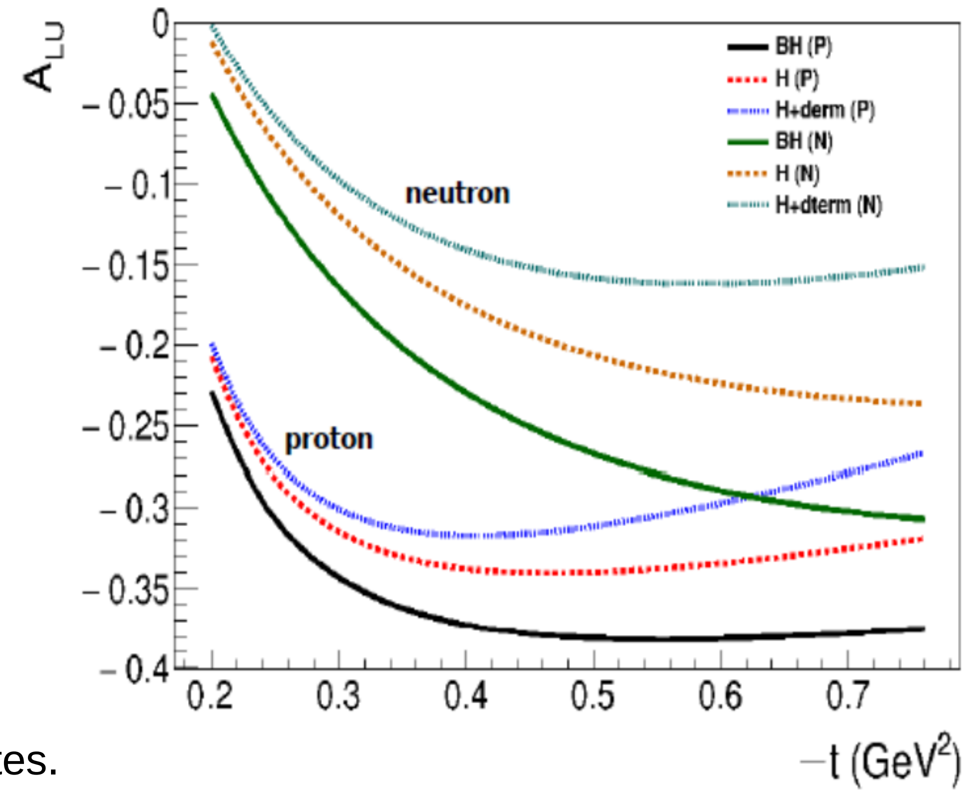
$$\left.-\sin 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Im}\,\tilde{M}^{0-} + \sin 3\varphi\,\sin\theta\,\mathrm{Im}\,\tilde{M}^{+-} + O\!\left(\frac{1}{Q'}\right)\right].$$

Beam spin asymmetries with linearly polarized beam: Re($\mathcal{H}$)

spin angle ψs dependence of beam spin asym.



Linearly polarized beam
A_{LU} (ψ=90°, φ=0) and GPD param. dependence



Linearly polarized beam (cos $2\psi_s$ at φ=0): BH dominates.

→Re part of amplitudes: more impact to constrain GPD models

→more difficult to measure but important. Re(H) mostly.

more complicated to access and interpret than with circular photon polarization, but very important observable:

- unique access to real part of amplitudes
- bring constrains equivalent to beam charge asymmetry for DVCS, only measured by HERMES.

Decomposition of interference term from Goritschnig, Pire, Wagner, hep/1404.0713

$$\frac{d\sigma^{(INT)}_{linpol}}{dQ^2 dt d\Omega_{l^+l^-} d\Phi_h} = -\frac{\alpha^3}{16\pi^2 s^2}\frac{1}{Q^2}\left(\frac{4s\,|\,\Delta_\perp\,|}{Qt}\right)\left(\sin\theta\cos(2\Phi_h+3\phi)\right)\mathrm{Re}\left[\mathcal{H}F_1 - \frac{t}{4M^2}\mathcal{E}F_2 + \eta\tilde{\mathcal{H}}(F_1+F_2))\right]$$

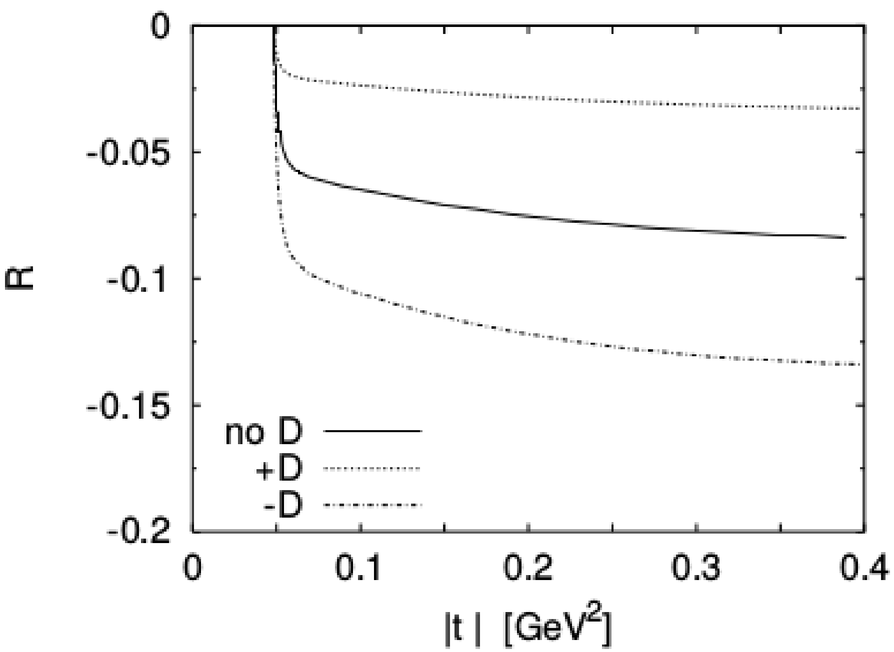
Interest to access real part of amplitudes: projections

- "direct" measurement of unpolarized cross section and beam spin asymmetry vs φ and (ξ, t, Q'²)

- projection of cosφ moments:

unpolarized cross section

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



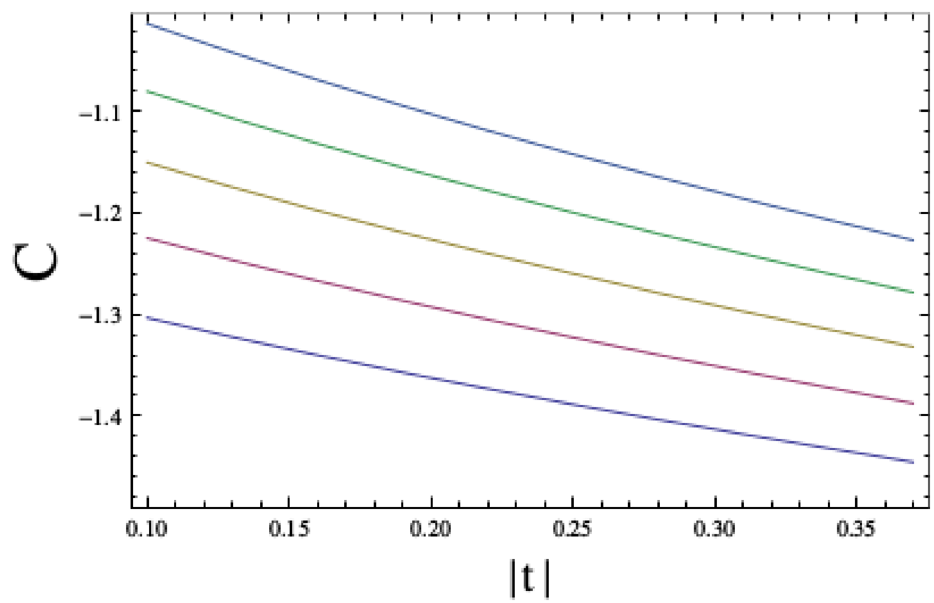
Berger, Diehl, Pire hep/0110062 (2002)

linearly polarized beam:

$$C = \frac{\tilde{R}}{\tilde{R}_3} = \frac{2-3\pi}{2+\pi} \frac{\mathrm{Re}\left[\mathcal{H}F_1 - \frac{t}{4M^2}\mathcal{E}F_2 - \eta\tilde{\mathcal{H}}(F_1+F_2)\right]}{\mathrm{Re}\left[\mathcal{H}F_1 - \frac{t}{4M^2}\mathcal{E}F_2 + \eta\tilde{\mathcal{H}}(F_1+F_2)\right]}\,.$$

$$\tilde{R} = \frac{\int_0^{2\pi} d\Phi_h 2\int_0^{2\pi} d\phi \cos(\phi) \int_{\pi/4}^{3\pi/4} \sin\theta d\theta \frac{d\sigma}{dt dQ^2 d\Omega d\Phi_h}}{\int_0^{2\pi} d\Phi_h \int_0^{2\pi} d\phi \int_{\pi/4}^{3\pi/4} \sin\theta d\theta \frac{d\sigma}{dt dQ^2 d\Omega d\Phi_h}}$$

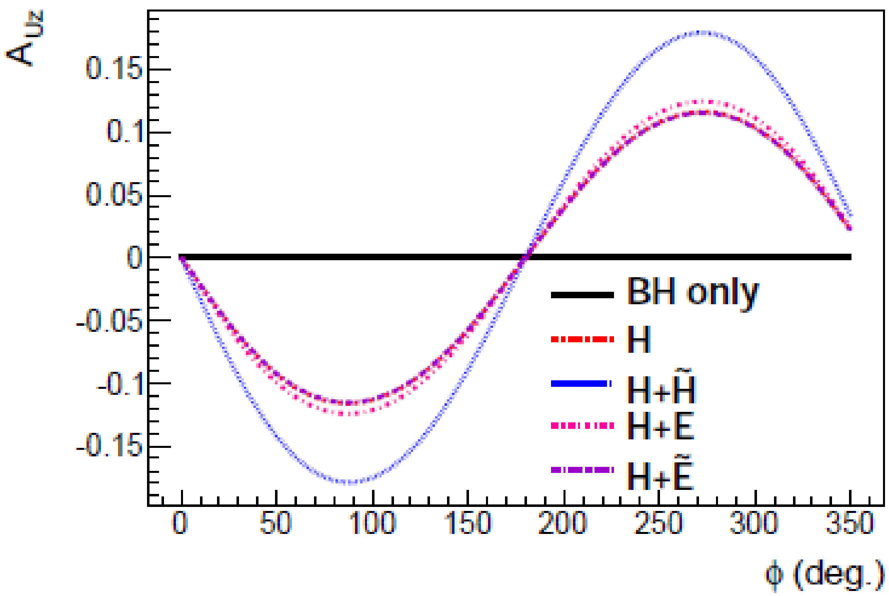
$$\tilde{R}_3 = \frac{2\int_0^{2\pi} d\Phi_h \cos(2\Phi_h) 2\int_0^{2\pi} d\phi \cos(3\phi) \int_{\pi/4}^{3\pi/4} \sin\theta d\theta \frac{d\sigma}{dt dQ^2 d\Omega d\Phi_h}}{\int_0^{2\pi} d\Phi_h \int_0^{2\pi} d\phi \int_{\pi/4}^{3\pi/4} \sin\theta d\theta \frac{d\sigma}{dt dQ^2 d\Omega d\Phi_h}}$$



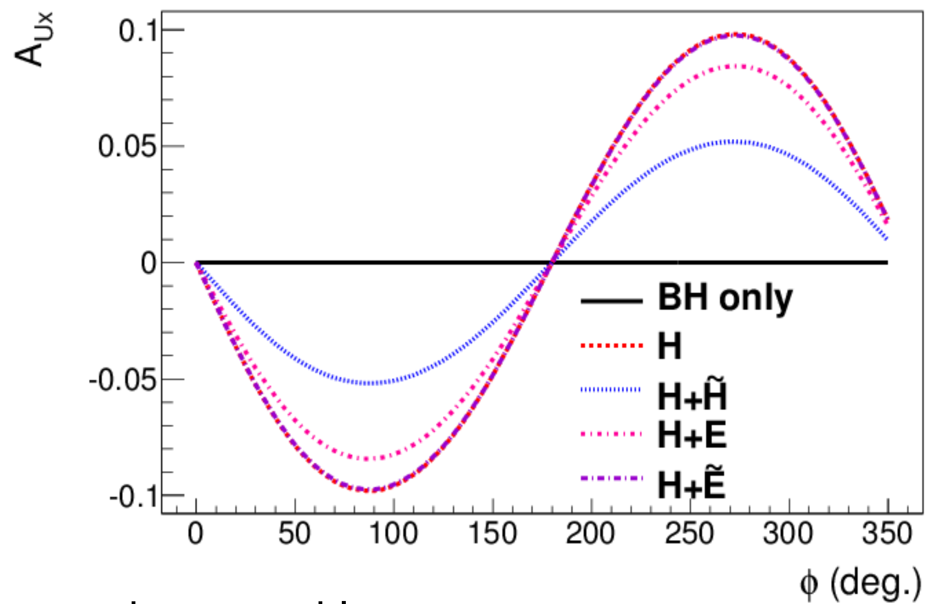
Goritschnig, Pire, Wagner, hep/1404.0713 (2014)

Target spin asymmetries

Longitudinaly polarized target A_{uz} vs φ

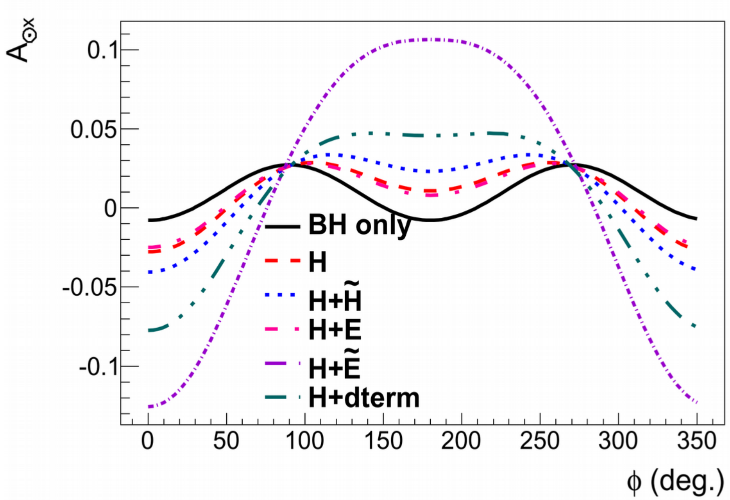


Transversely polarized target.Φs=0°= along x-axis



- Im part of amplitudes, BH contribution cancels. Large and measurable.
- Strong sensitivity to H and H̃. Fits demonstrate also sensitivity to E → transversaly polarized target
- Need high luminosity for transverse target experiments due to binning in Φs + φ
- With quasi-real photon beam: small angles with spin vector, no visible effect expected

double spin asymmetry: strongly model dependent, very high interest but very challenging. Re(CFFs)

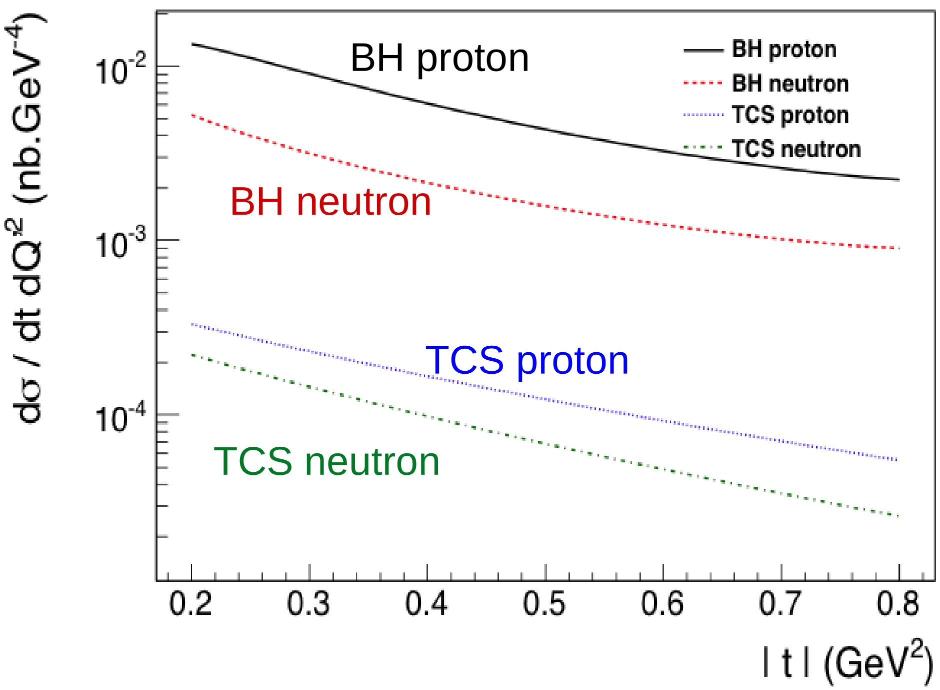


For measuring Au⊥: Hall C
LOI 12-15-007 PAC43 (2015)

For Auz: possible for Hall B
For double A_{ii}: to be demonstrated

Proton versus neutron TCS

Unpolarized cross section vs -t



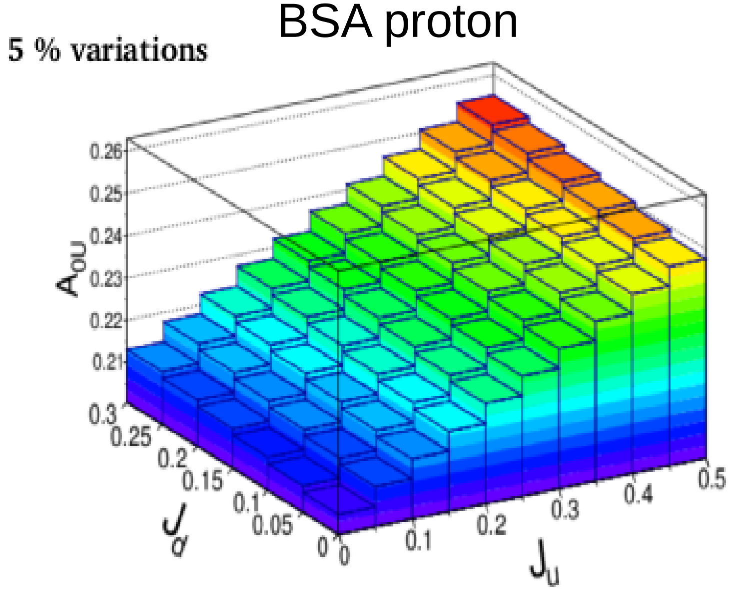
- TCS off the neutron not drastically suppressed compared to proton

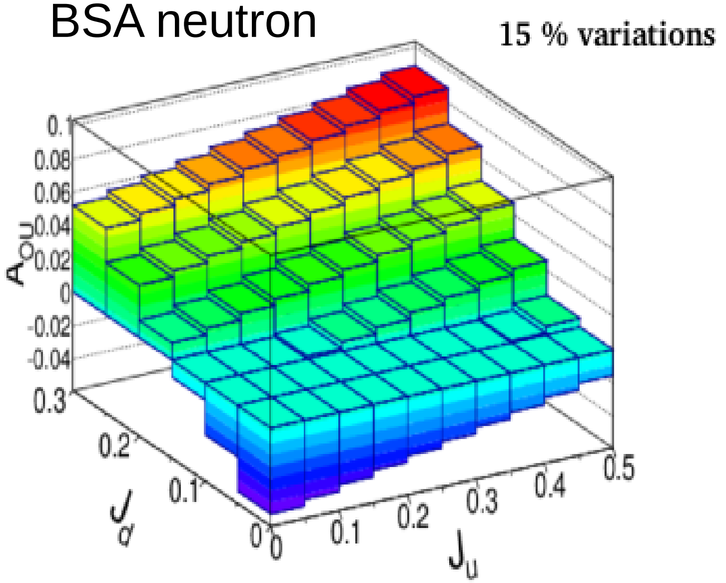
- similar sensitivity to GPDs expected

Experimentally measurable but requires high luminosity experiment, at least 10x compared to proton → interesting for the future with high luminosity experiment

Spin physics:
strong sensitivity to angular momenta for neutron BSA , more than proton

Fig: play with $J_{u,d}$ in GPD E parametrization in VGG (model dependent)

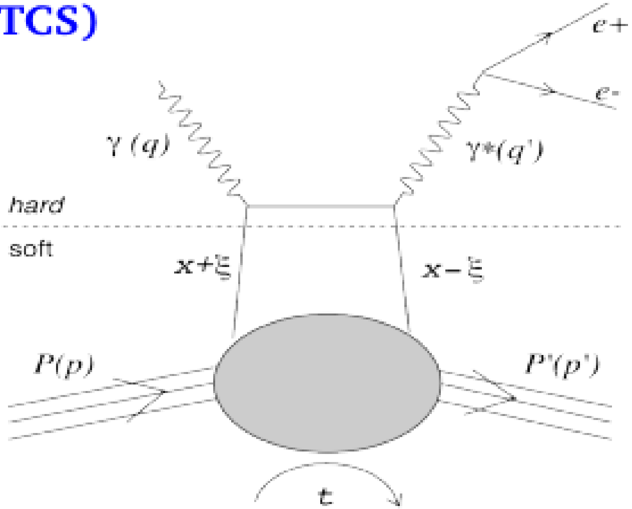




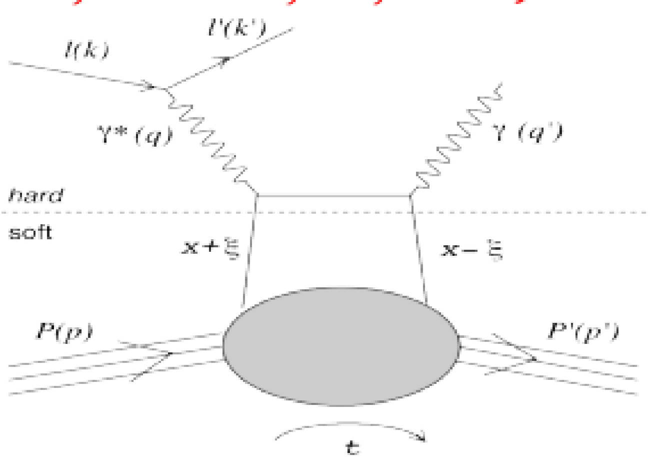
Figs from MB, M. Guidal, M. Vanderhaeghen, EPJA 52 (2016) 33

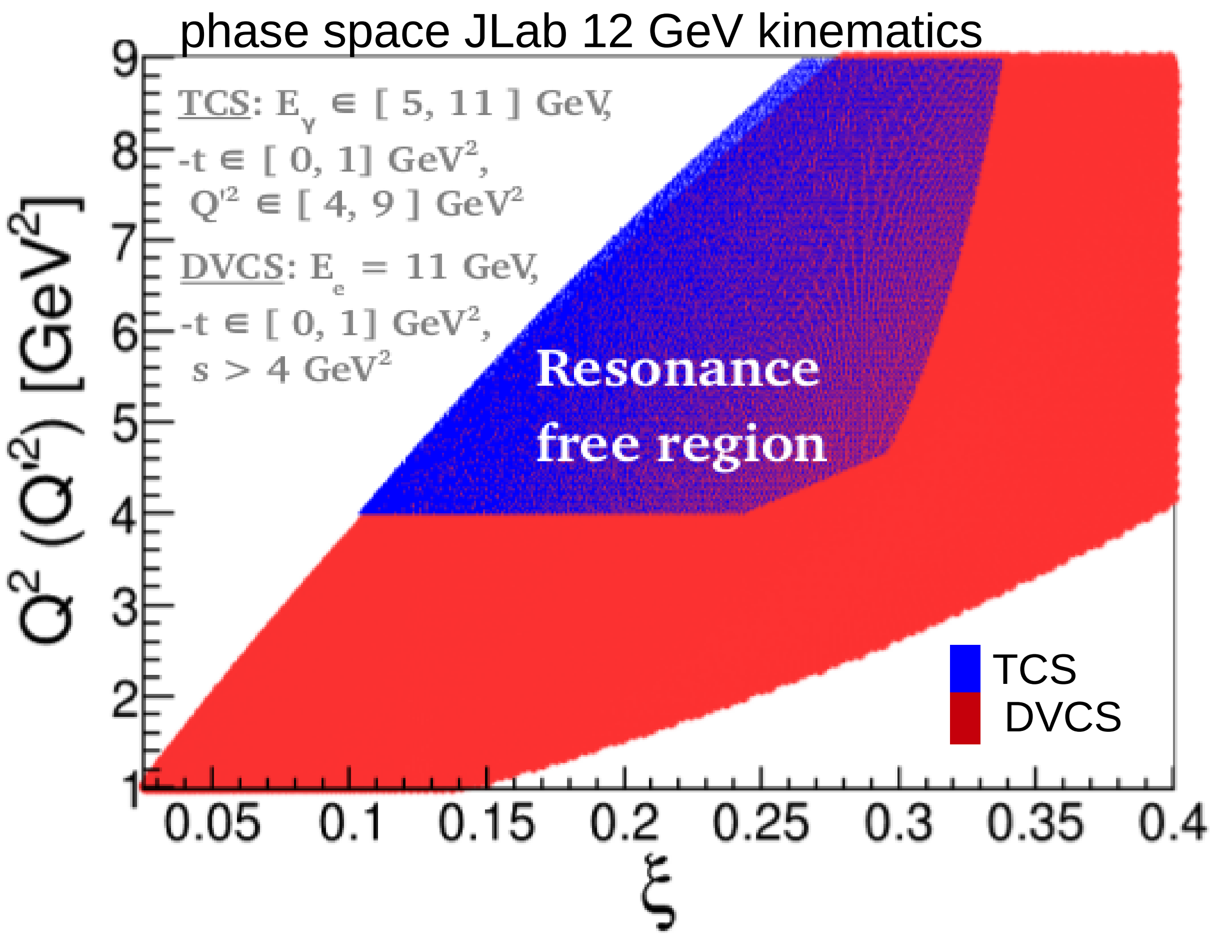
2) Comparing DVCS and TCS

Timelike Compton Scattering (TCS)



Deeply Virtual Compton Scattering (DVCS)
Measurements already published (JLab, HERMES, H1, ZEUS)





Interest of TCS and DVCS in parallel :

- **Universality of GPDs**
- **Complementary observables**
- **Higher twist and higher order effects**

- Common kinematics (ξ, t) to make comparison with DVCS and complementary measurements
- good way to compare a spacelike and timelike "equivalent" reactions

2) Comparing DVCS and TCS

At leading order / leading twist, DVCS and TCS access GPDs at same points, CFF are complex conjugate

→different NLO between timelike and spacelike: a way to study these effects?

→higher twist effect evaluation by comparing extracted CFFs

→cf Maxime's talk on DVCS (Wednesday): discussion about HT vs NLO in DVCS
⇒ TCS could be a good solution for such questions, some effects going in opposite direction, at same Q^2 and Q'^2, ξ, t: comparison of timelike vs spacelike reaction ...

→comparison of value and shape of extracted CFFs in TCS vs DVCS:

- universality of GPDs
- NLO, HT
- complementarity of observables sensitive to different CFFs and/or not suppressed by same kinematic factors

→DVCS with e+ beam not yet measured at JLab, low statistic at HERMES, sum of cross section and lower x_{BJ} in compass: equivalent observable in TCS with linearly polarized beam spin asymmetry ⇒ not better sensitivity to Re(A) in TCS, but some observables may be easier to measure experimentaly than for DVCS

→cf Tanja's talk: with real photon source (TCS) targets can handle higher flux than e- (DVCS)

CFF extraction from future JLab DVCS and TCS experiments

CFF $\mathcal{H}$

Legend
__ generated CFF value = 1
--- limits of CFF variation during fit
[1] approved experiments
[2] conditionally approved
[3] proposal in progress
# of independent parameters: 7
Assumed uncertainties: 5% with 20 points for each observable

Configuration of observables

A. DVCS $\sigma + \Delta\sigma_{LU}$ (Hall A, B, C)[1]

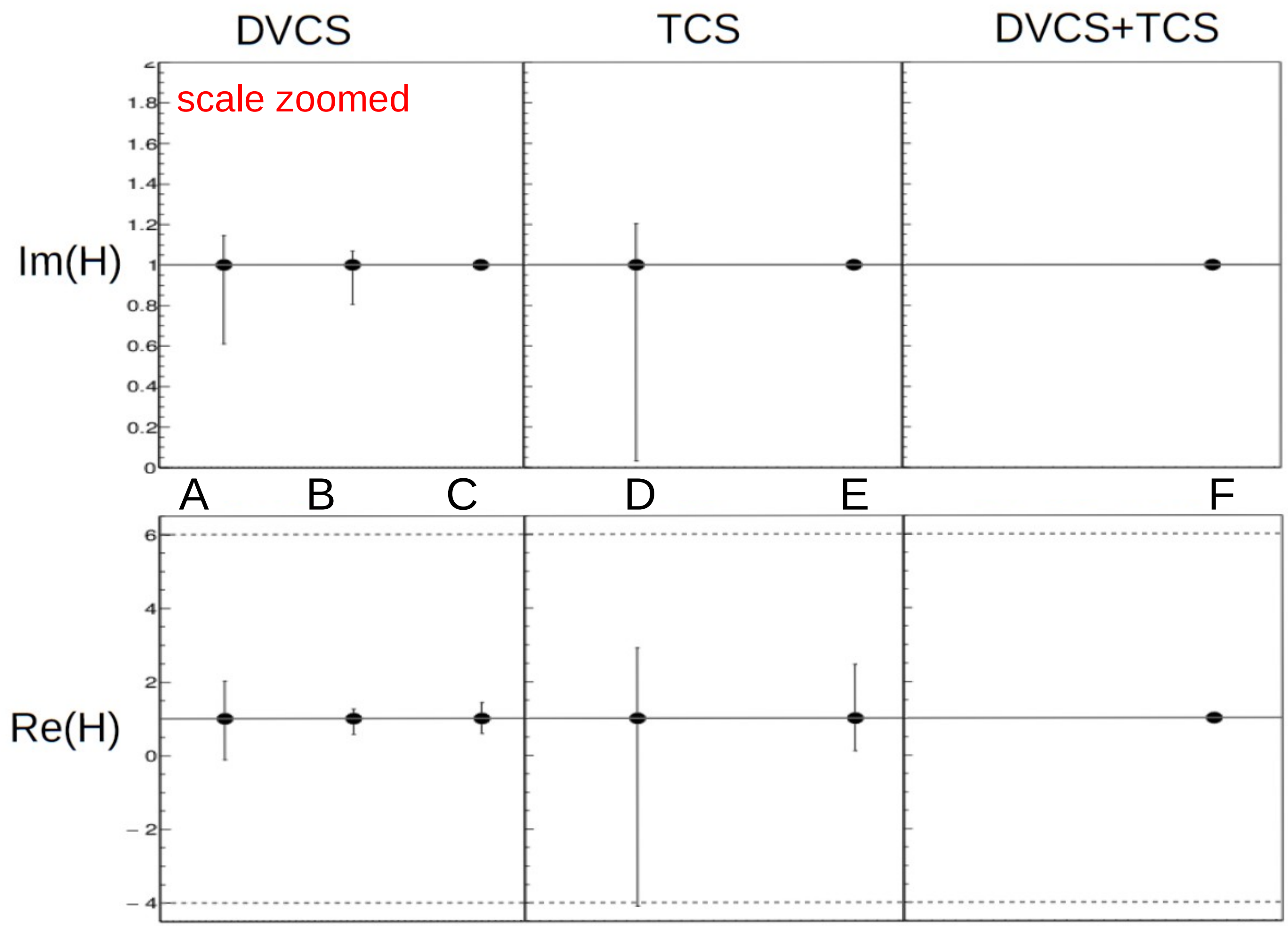
B. DVCS $\sigma + \Delta\sigma_{LU} + \Delta\sigma_{Uz} + \Delta\sigma_{Lz}$ (Hall B)[1]

C. DVCS $\sigma + \Delta\sigma_{LU} + \Delta\sigma_{Uz} + \Delta\sigma_{U\perp}$ (+Hall B)[2]

D. TCS $\sigma + \Delta\sigma_{OU}$ (Hall A, B)[1]

E. TCS $\sigma + \Delta\sigma_{OU} + \Delta\sigma_{U\perp}$ (+Hall C)[3]

F. DVCS $\sigma + \Delta\sigma_{LU} + \Delta\sigma_{Uz} + \Delta\sigma_{Lz}$
$+$ TCS $\sigma + \Delta\sigma_{OU} + \Delta\sigma_{U\perp}$



- DVCS is more sensitive than TCS to Im(H) and Re(H). Reason: DVCS/BH > TCS/BH and TCS << BH

- Future experiments: GPD H with TCS and DVCS. Comparison to confirm GPDs universality. Possible evaluation of NLO / higher twist effects, different in spacelike vs timelike.

- Small uncertainty on Im(H). Other CFF more difficult to extract. Re(E) is the most difficult one from DVCS and TCS: comes only through correlations from many observables once other CFFs are constrained.

- Combined fits: improve uncertainty vs DVCS-only (need some assumptions). Bring more constrains in multi-observables, multi-CFF fits.

CFF extraction from future JLab DVCS and TCS experiments

CFF $\mathcal{E}$

Legend
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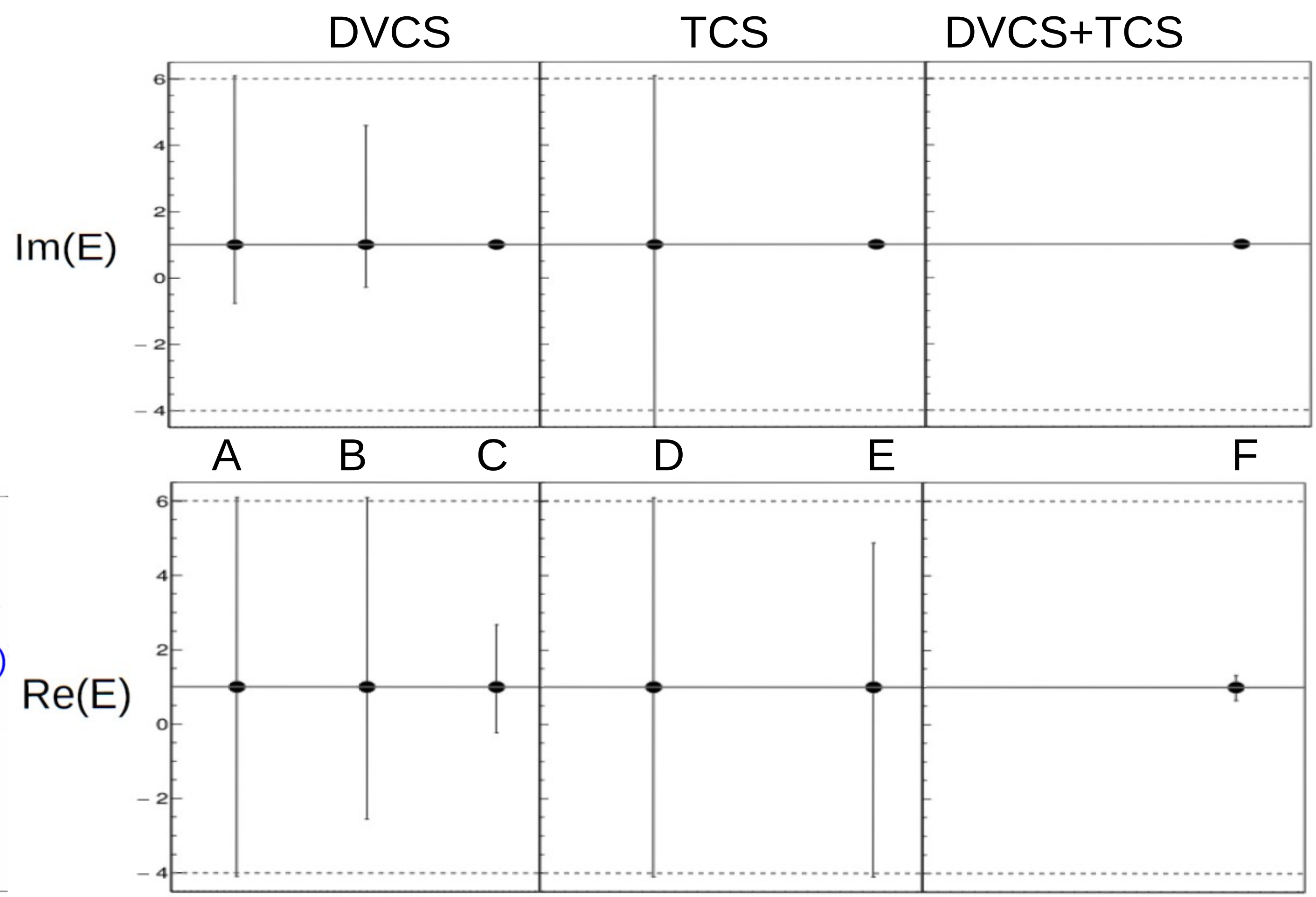
E. TCS $\sigma + \Delta\sigma_{OU} + \Delta\sigma_{U\perp}$ (+Hall C)[3]

F. DVCS $\sigma + \Delta\sigma_{LU} + \Delta\sigma_{Uz} + \Delta\sigma_{Lz}$
$+$ TCS $\sigma + \Delta\sigma_{OU} + \Delta\sigma_{U\perp}$



- Im(E) needs transversely polarized target experiments to be constrained. Similar sensitivity to Im(E) using DVCS or TCS asymmetries.

- Re(E) cannot be constrained with DVCS-only nor TCS-only proposed measurements. But by correlations, combined fits show that Re(E) can be extracted with enough independent observables in the fitting procedure. It is essential for GPD E and its interpretations.

3) TCS observables, interests and experiments 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	Real part of amplitude. Re(H), Im(H)	CLAS 12 SoLID approved
Circularly polarized beam	Easiest observable to measure	Im(H), Im($\tilde{H}$) Sensitivity to quark angular momenta, in particular for neutron	CLAS 12 SoLID approved
Linearly polarized beam	Need high luminosity, at least 10x more than for circular beam, and electron tagging	Re(H), D-term. Good to discriminate model and very important to bring constrains to real part of CFF	no (Hall D?)
Longitudinaly polarized target	Polarized target	Im($\tilde{H}$)	no
Transversely polarized target	Polarized target, and high luminosity: binning in θs, φs	Im($\tilde{H}$), Im(E)	LOI Hall C
Double spin asymmetry with circularly polarized beam	Polarized target, very high luminosity, precision measurement	Real part of all CFF	no
Double spin asymmetry with longitudinally polarized beam	Polarized target, electron tagging, very high luminosity and precision	Not the most interesting, same info as single target spin asymmetries	no

TCS off the neutron
- same 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: first TCS measurement

E12-12-001

- will start this year to have first data and analysis

- first measurement of TCS after exploratory work with CLAS (2012).
In parallel to TCS: near threshold J/ψ in dielectrons

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

projection, first cosφ moment
→real part of amplitudes

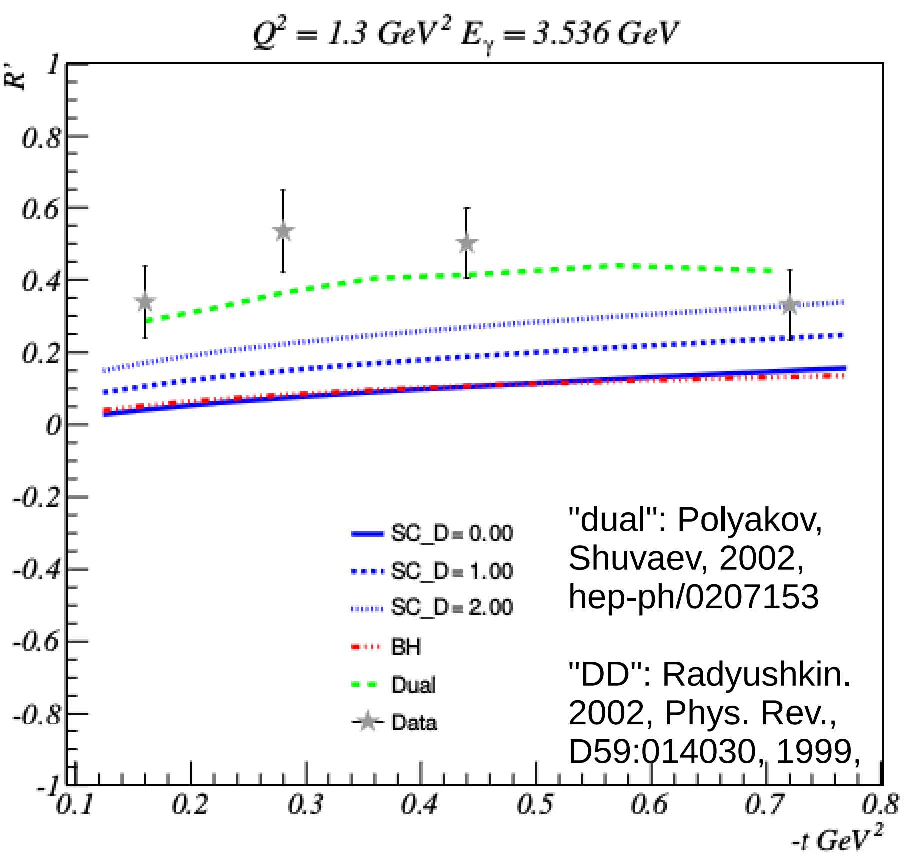


Fig: exploratory measurement at 6 GeV, CLAS model prediction for R
(R' is "experimental" R, with a sum over bins)

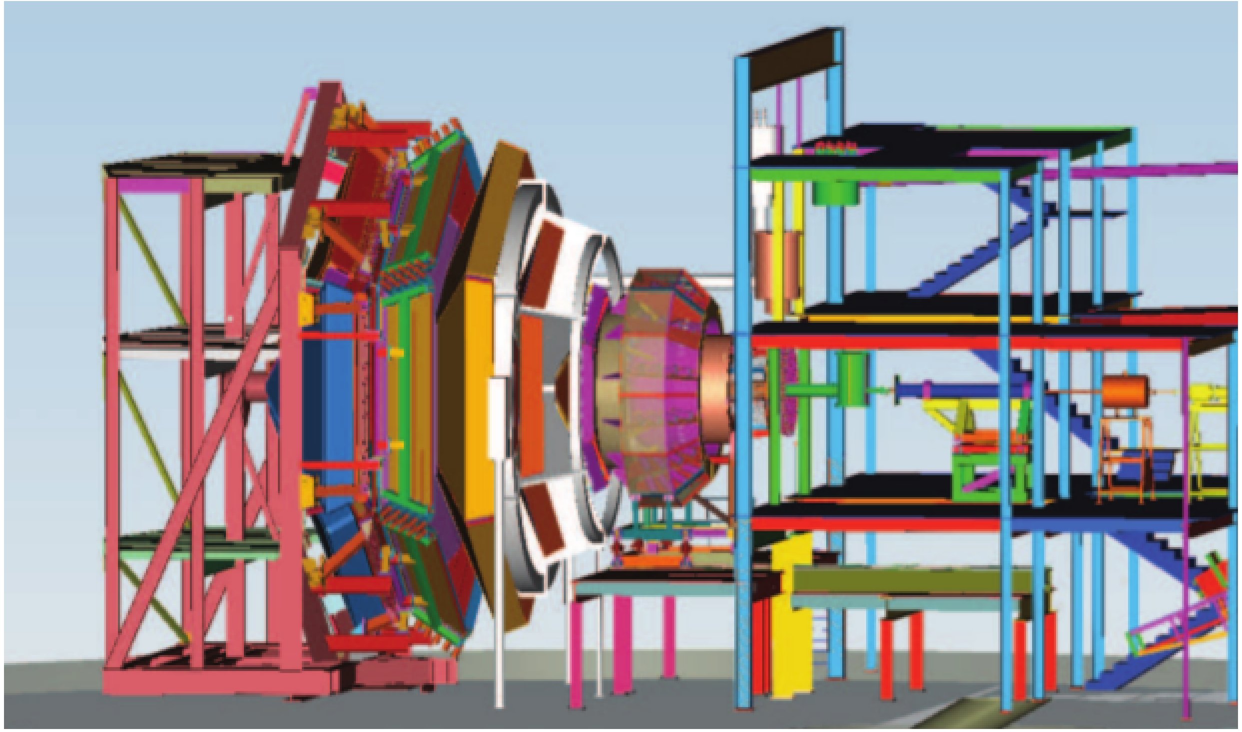
- feasibility and analysis technics demonstrated

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

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

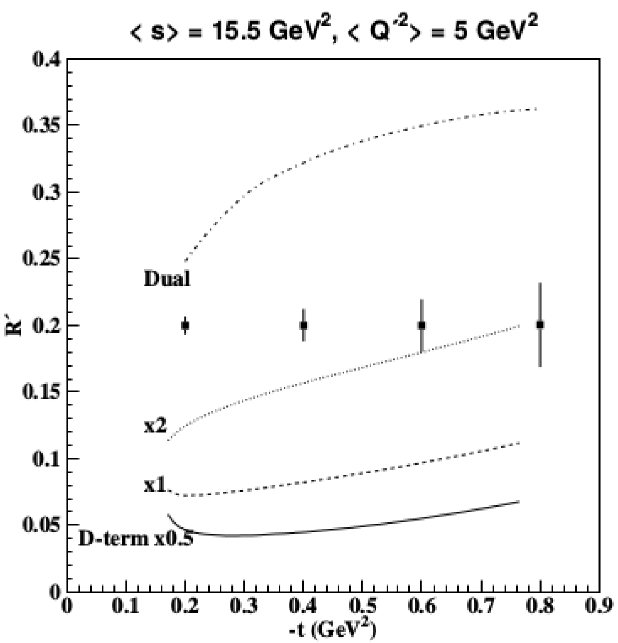
CLAS 12 experiment: first TCS measurement

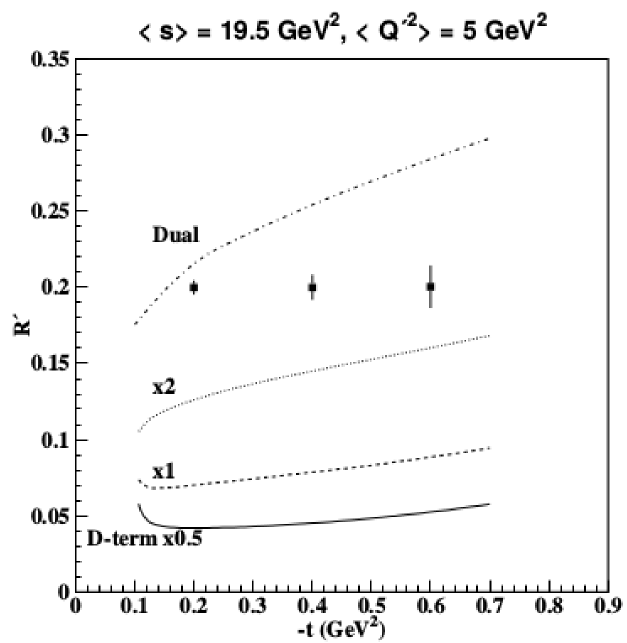
E12-12-001



R contains unpolarized cross section information about real part of amplitudes.

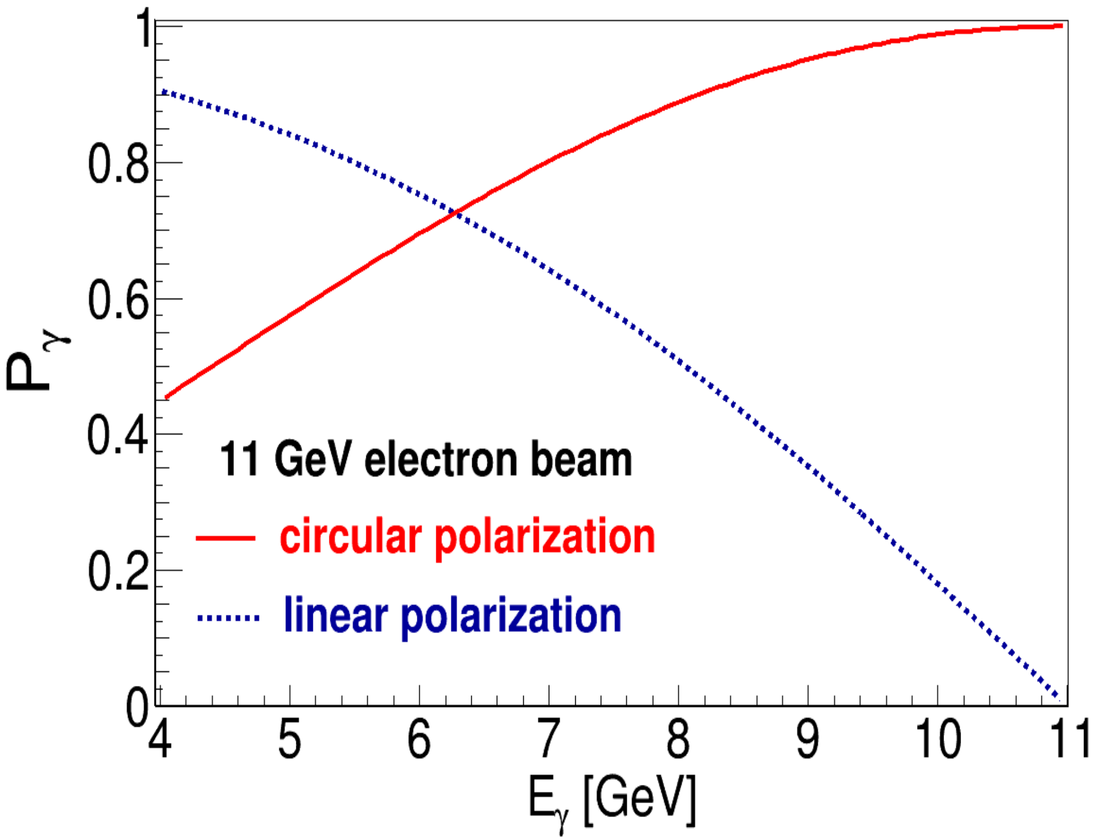
Unpolarized cross section + BSA (circularly polarized photon) come together in 2017 data.





Circularly beam spin asymmetry "for free"

Photon beam polarization for a 100% polarized 11 GeV electron beam (JLab)



circularly polarized beam spin asymmetry will be measured
access Im($\mathcal{H}$)

linearly polarized beam:
require electron tagging, and additional statistic for binning in ψs → not expected from these data, but further measurement could be expected
access Re($\mathcal{H}$)

high circular polarization rate for highest energy quasi-real photons
up to 80% circular polarization for photons.

TCS with SoLID: complementary to CLAS 12 with high luminosity

complementary to CLAS12: same observables, higher luminosity. ≠ acceptance

Observables:

unpolarized cross section, beam spin asymmetry (circular)
R = cosφ moment projection (real part, unpolarized)

2 approaches: several bins in Q'^2 (evolution) versus bins with large statistics

- study of NLO with Q'^2 evolution: binning in Q'^2 to study evolution effects. NLO in timelike versus spacelike

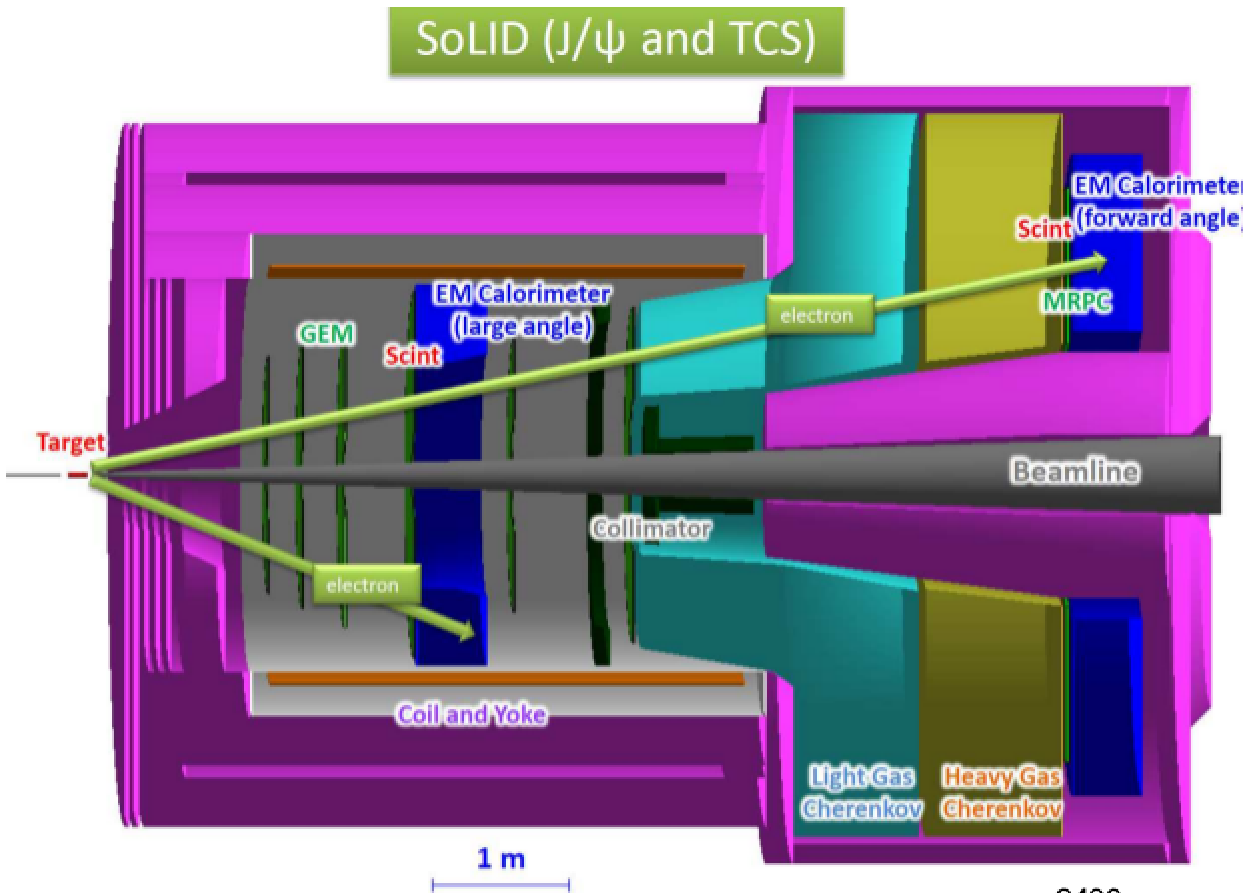
- high statistic for first GPD universality check (GPD H) by comparison of TCS vs DVCS

- possibility to compare extracted H shape: NLO, higher twist studies...

- contribution to fits combining DVCS and TCS? (if universality proved and NLO... under control)

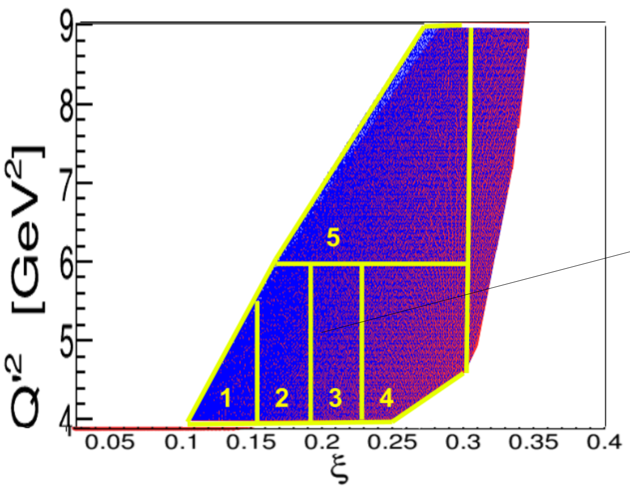
run group proposal with E12-12-006 (SoLID J/ψ)

TCS with SoLID: complementary to CLAS 12 with high luminosity

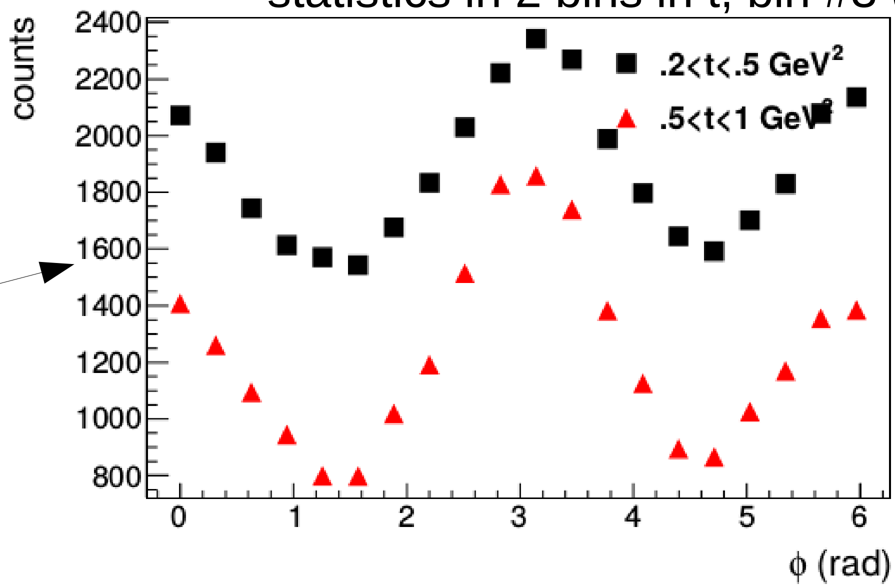


SoLID setup for J/ψ approved exp.

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

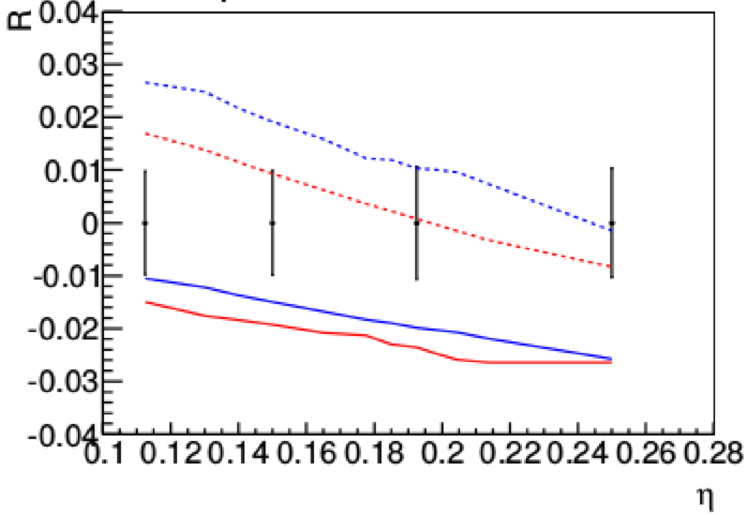


statistics in 2 bins in t, bin #3 (Q'², ξ)

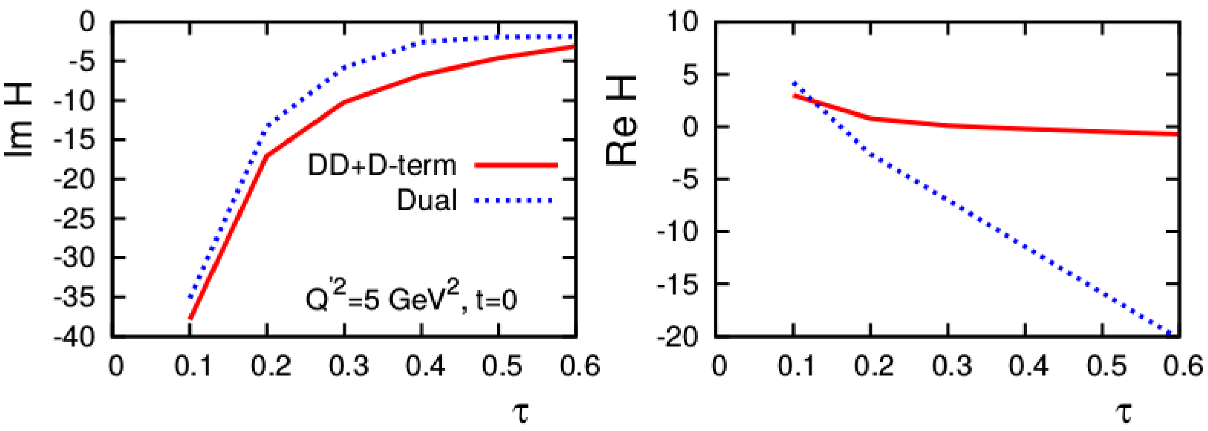


TCS with SoLID: complementary to CLAS 12 with high luminosity

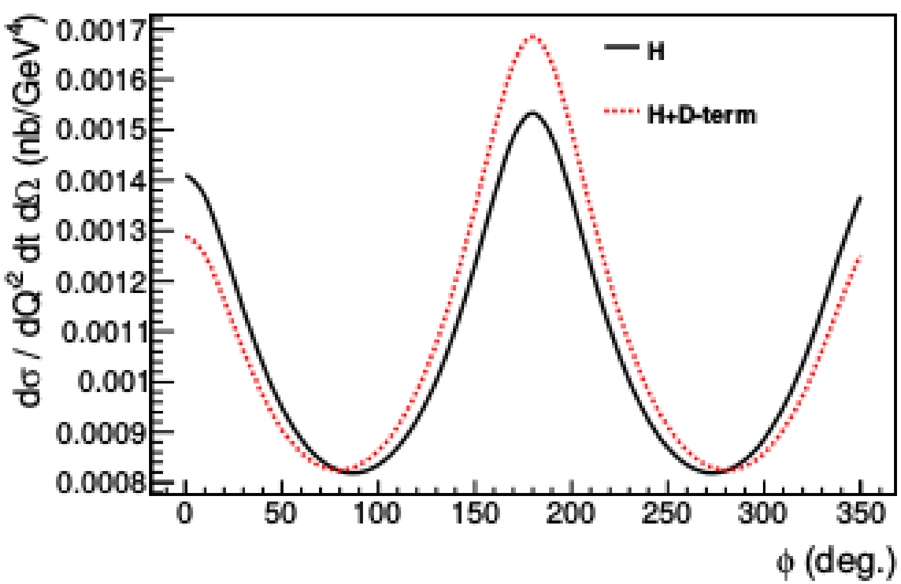
cosφ moment, statistics:



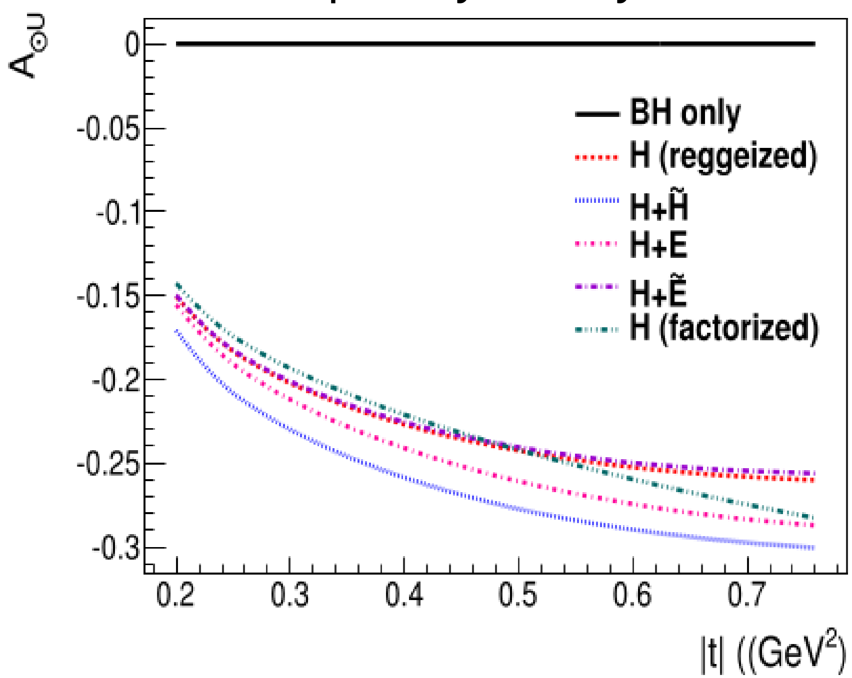
real part of CFF less constrained:



unpolarized x-sec vs φ, sensitivity to D-term (GPD H = VGG)

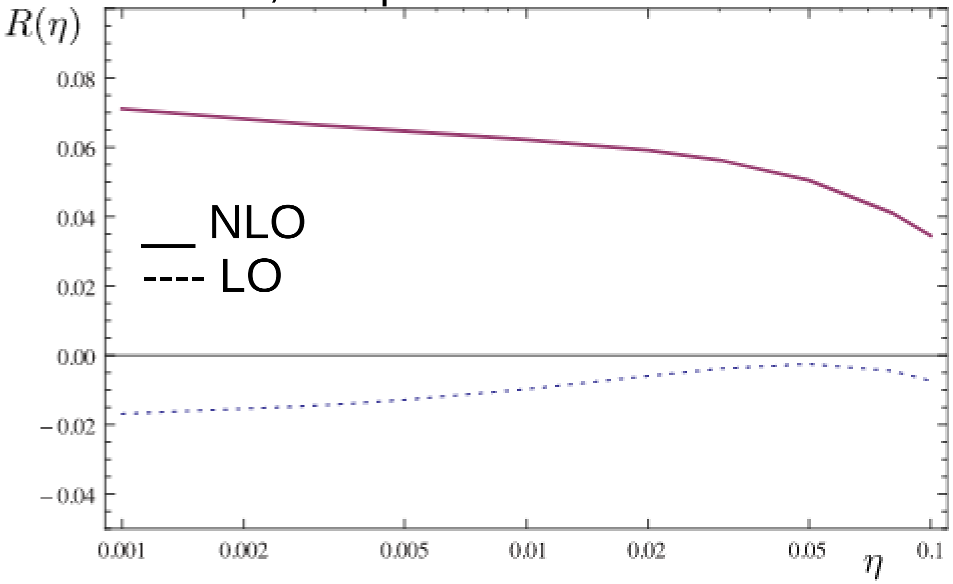


parametrization and t- dependence of beam spin asymmetry



TCS with SoLID: study evolution effects

ratio R, cosφ moment at LO vs NLO



large effects on some observables,
small for some others
(model dependent)

large NLO effects affecting real part of A. →study by measuring unpolarized x-sec and R

	$\mathrm{Re}\mathcal{H}_{\mathcal{D}}$	$\mathrm{Im}\mathcal{H}_{\mathcal{D}}$
LO	-2.59	0
NLO quark contribution	-0.16	-0.85
NLO gluon contribution	0.18	0.16
Full NLO	-2.57	-0.69

TABLE I: Different contributions to the D-term. The values of the real part coincides for spacelike and timelike CFF $\mathcal{H}$, while the imaginary part is non-vanishing only for the timelike case.

NLO structure in timelike different than in spacelike DVCS: can be studied with TCS

TCS in Hall C NPS: target transverse spin asymmetry

Motivations: Im(E) and independent observables for TCS / Complementarity with DVCS (fits)

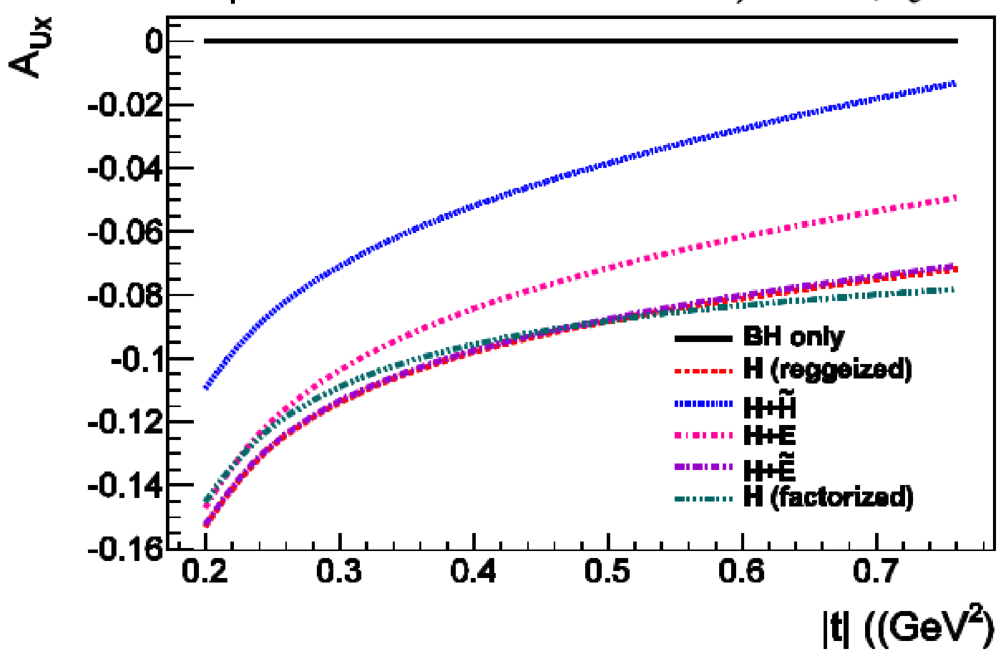
LOI12-15-007

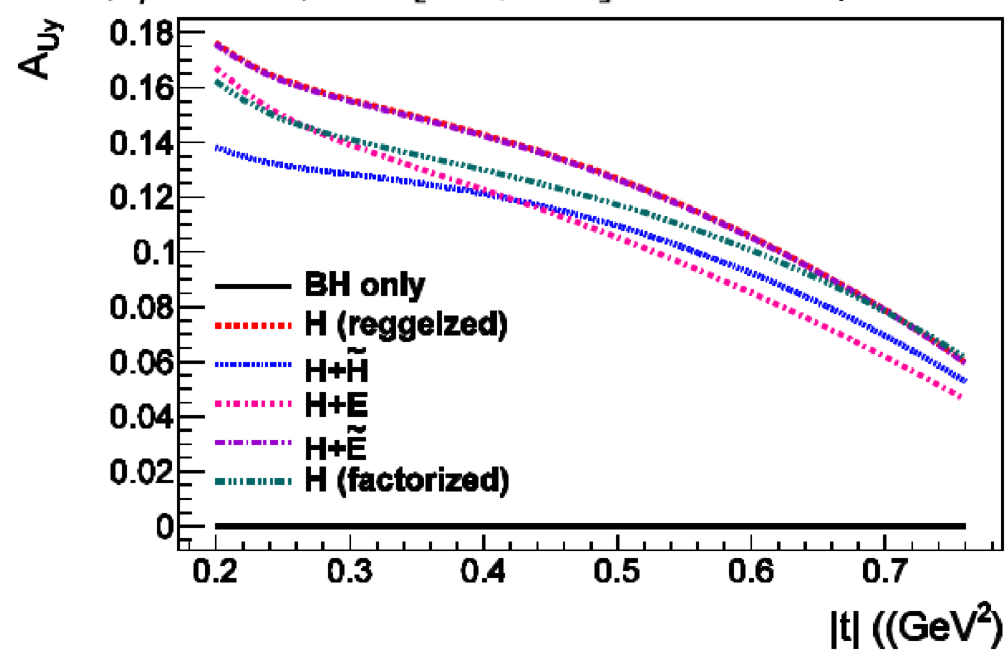
Observables:

- single spin asymmetry with transversely polarized target
- double spin asymmetry: needs uncertainties estimation

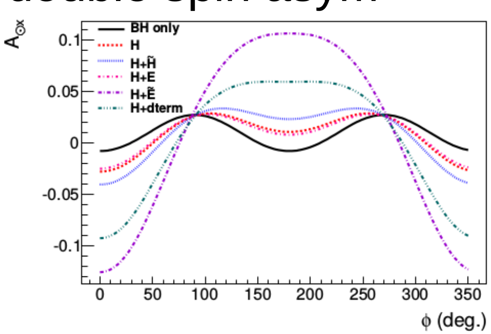
parametrization dependence and t evolution of beam spin asymmetry (// and ⊥ to reaction plane)

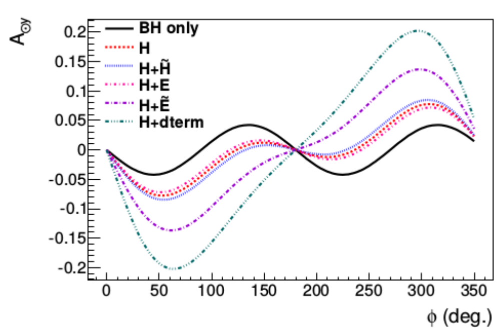
φs=0° $\xi = 0.2, Q'^2 = 7\ GeV^2, \varphi = 90°, \theta \in [45°, 135]$ φs=90°





double spin asym

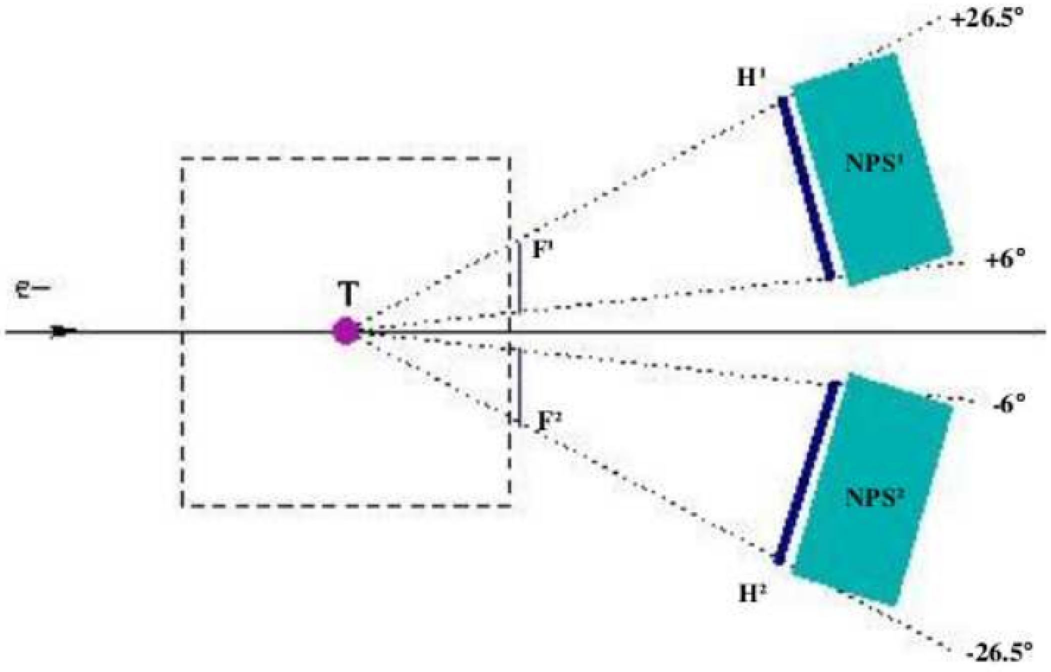




single spin ⊥ target: Im part of A. measurable, sensitive to H, H̃, E

beam + target: Real part. strongly model dependent → important measurement, feasibility to prove from experiment.

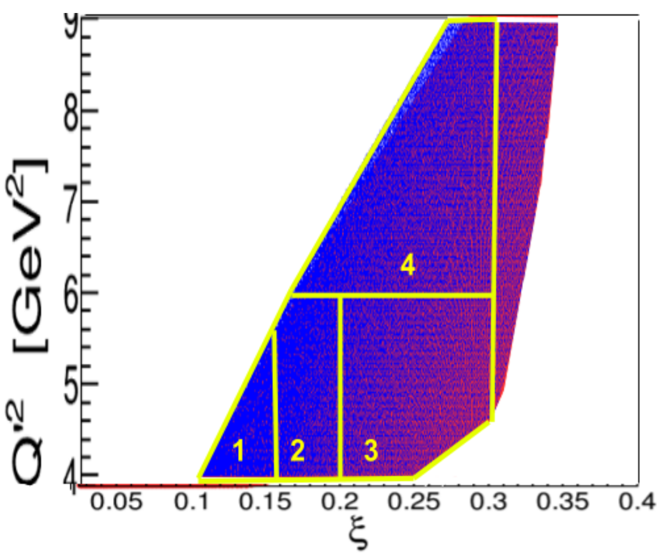
TCS in Hall C NPS: target transverse spin asymmetry

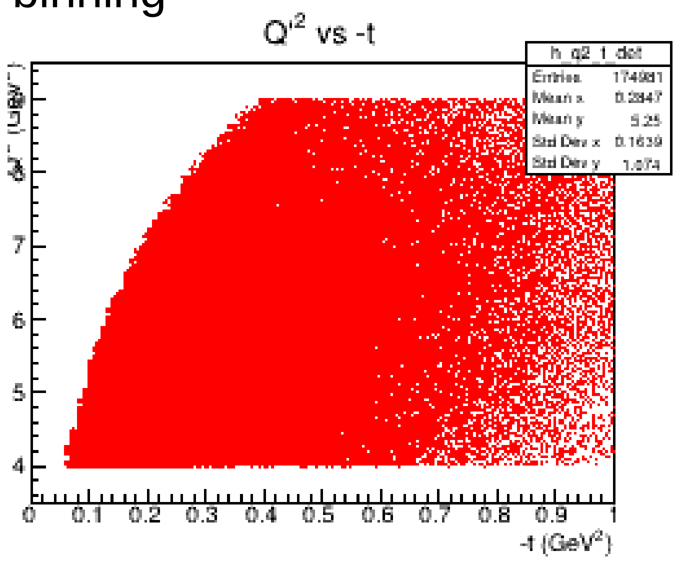


proposed setup for LOI (2015)
still in development, some modifications
since 2015:
- angles are modified
- 2d calorimeter: choice ?
- may use photon source rather than quasi-real photons: higher flux, less corrections

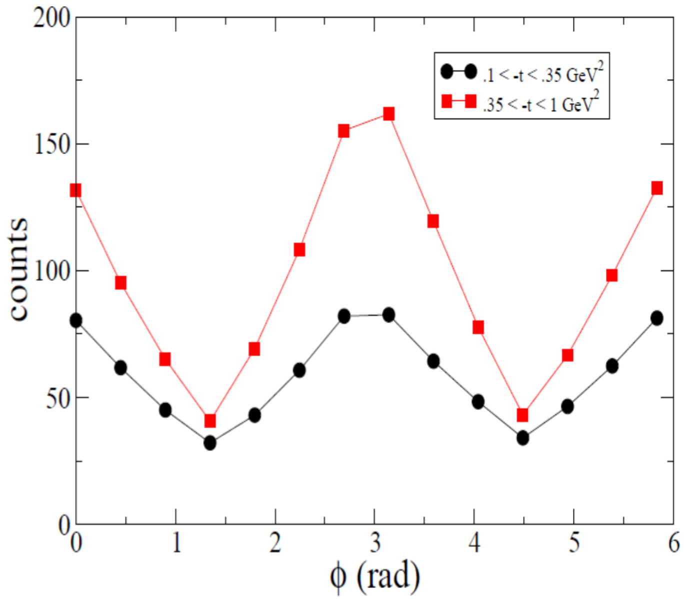
the project and a proposal with dedicated setup in development

phase space and proposed binning

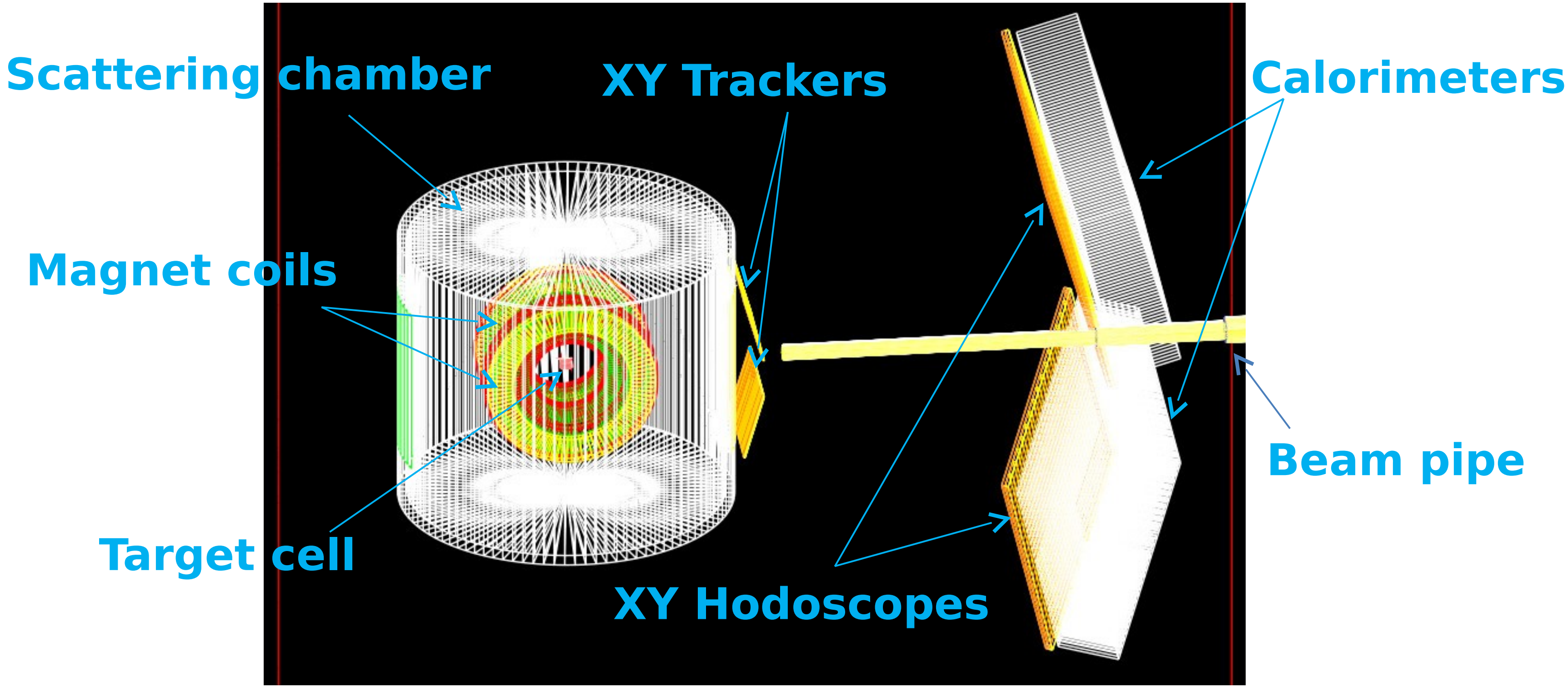




Counting rates, bin 3 (ξ, Q'²)



Hall C TCS Setup



- Photon beam from High Intensity Photon Source ($I \sim 6 \cdot 10^{11}$ γ/s, $E = 5 - 10.5\ GeV$, 1 mm diameter).
- Transversely polarized UVA target (3 cm NH_3 in 5.1 T field, 80% polarization).
- XY trackers (1 mm thick scintillating fibers, 108x48 cm^2 area).
- XY hodoscopes for the recoil proton detection (4 cm wide, 1 cm thick scintillator paddles, 108x48 cm^2 area).
- Lead tungstate calorimeters for e+/e- detection (50x23 matrix of 2x2x18 cm^3 blocks, 1150 channels, 102x47 cm^2 area).

Comments on TCS projects

• **Complementary between Hall B and A**
→ first measurement in Hall B, then more precision with Hall A for unpolarized cross section and BSA

• **TCS with Hall D**:
real photon and linearly polarized beam. exploratory analysis, can be complementary to Hall B measurement and bring constrains to real part of amplitudes

• **TCS with Hall C**
- transversaly polarized target: may come before equivalent DVCS measurement, higher flux could be handle by target in case of using real photon beam

All these experiments are complementary and needed to extract GPDs from TCS

Interest for GPDs:

- "timelike" (TCS) versus "spacelike" (DVCS) → universality,

- comparison DVCS vs TCS: ≠ NLO structure, higher twist by comparison...

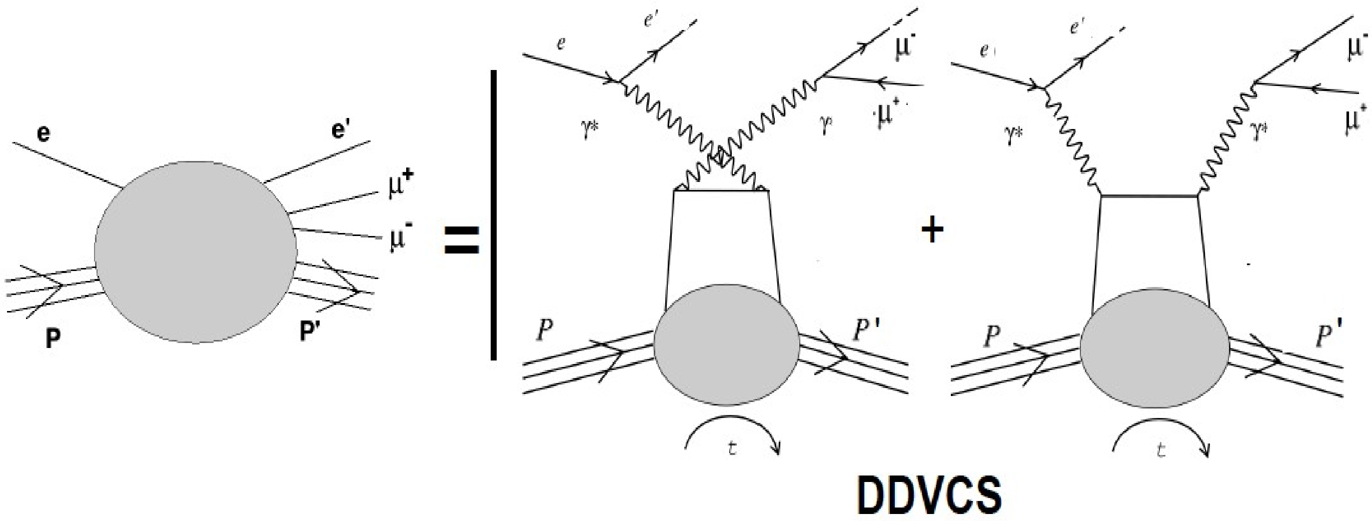
- independent check of GPDs extracted from DVCS at same kinematics

Other possible measurement in near to far future:
- linearly polarized beam (Re($\mathcal{H}$)), longitudinaly polarized target (Im($\tilde{\mathcal{H}}$)), double spin asymmetries (Re(CFF) and strong model dependence)...
- neutron (flavor separation / sensitivity to angular momenta)

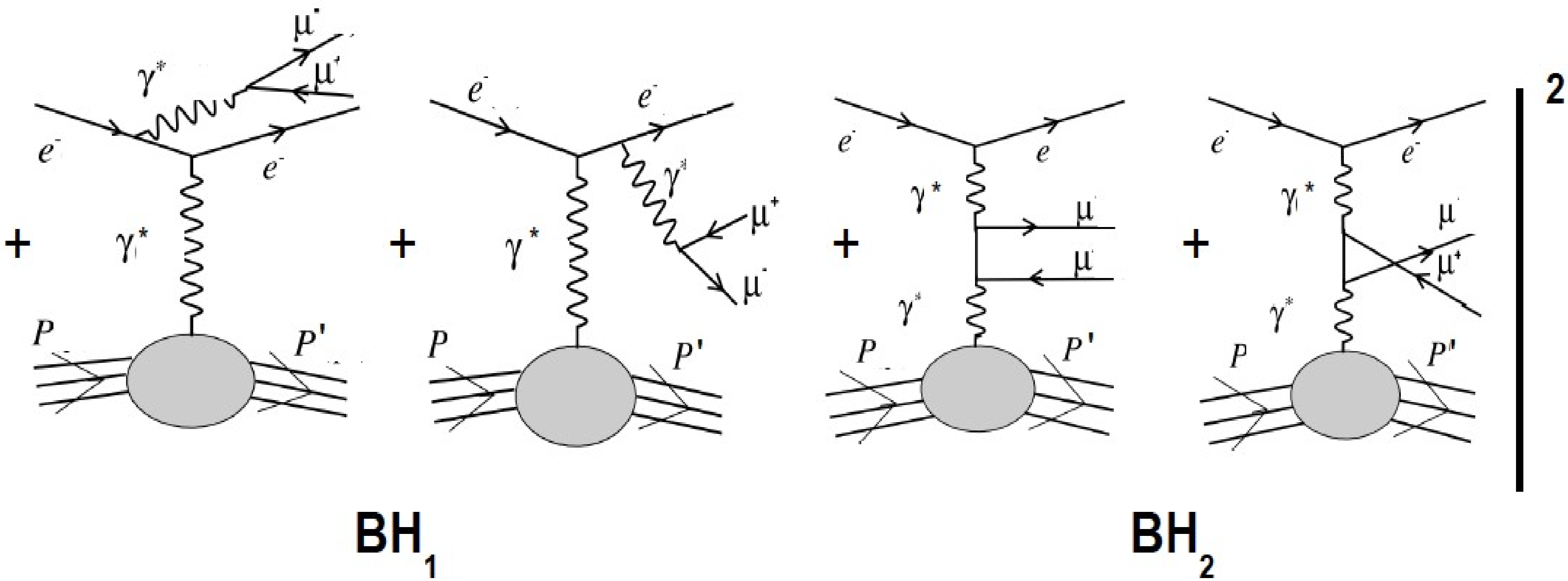
Double Deeply Virtual Compton Scattering

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



behaves like DVCS-like BH

behaves like TCS-like BH

1) Interest, Observables

Access GPDs with DDVCS reaction

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

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

→ lever arm by playing with 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

Theory references:

M. Guidal and M. Vanderhaeghen, Phys. Rev. Lett. **90** (2003) 012001

A. V. Belitsky and D. Mueller, Phys. Rev. Lett. **90**, 022001 (2003)

A. V. Belitsky and D. Mueller,Phys. Rev.D **68**, 116005 (2003).

in this presentation:

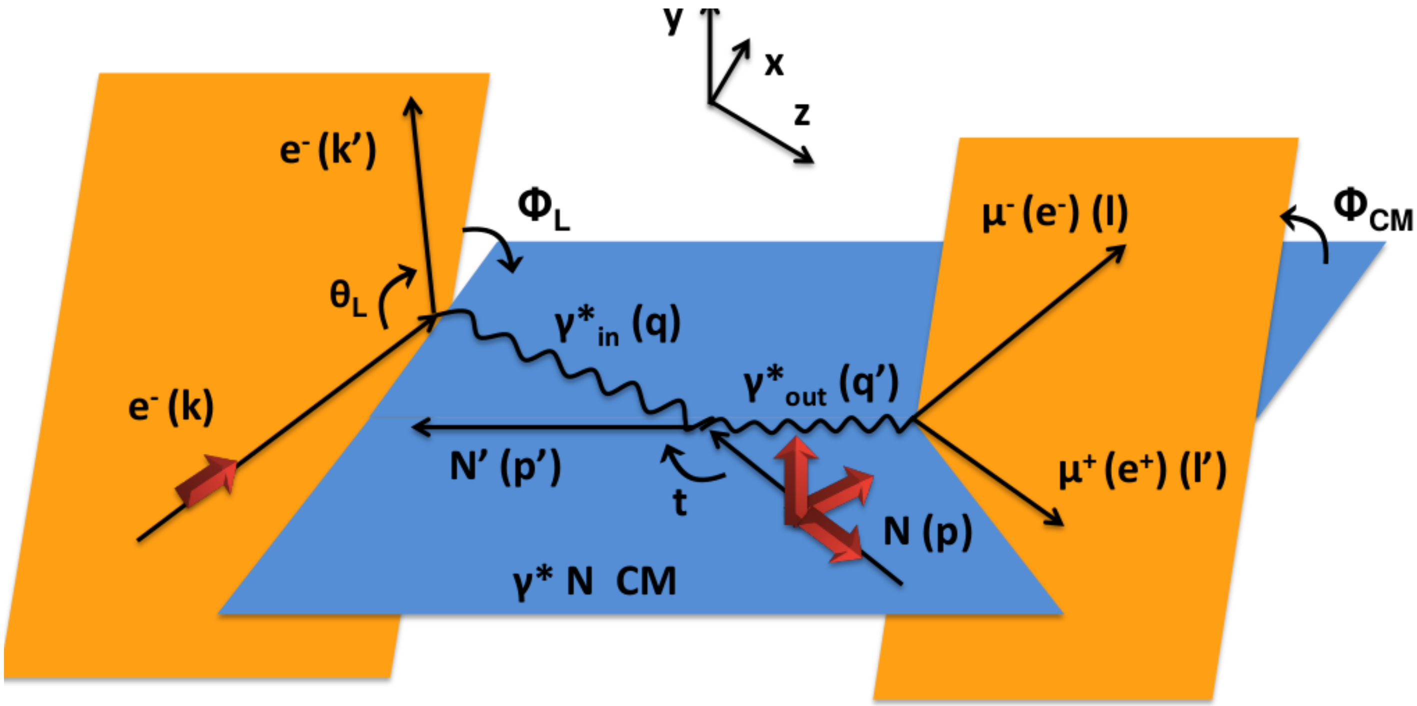
- calculations presented from M. Guidal, talk at ECT* Oct. 2016
- JLab CLAS 12 uses formalism from VGG
- JLab SoLID uses formalism from BM, and rates from VGG.

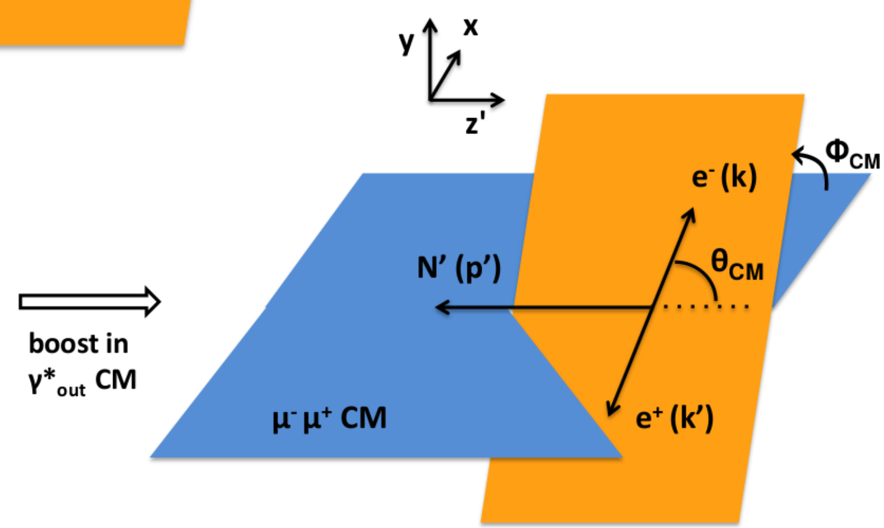
Notations for Bethe-Heitler + DDVCS reaction

BH+DDVCS = e P → e' μ+ μ- P'

- 7 independent variables for unpolarized cross section.

Choice and notations: Q^2, Q'^2, t, x_{bj}, φ_L, φ_{CM}, θ_{CM}



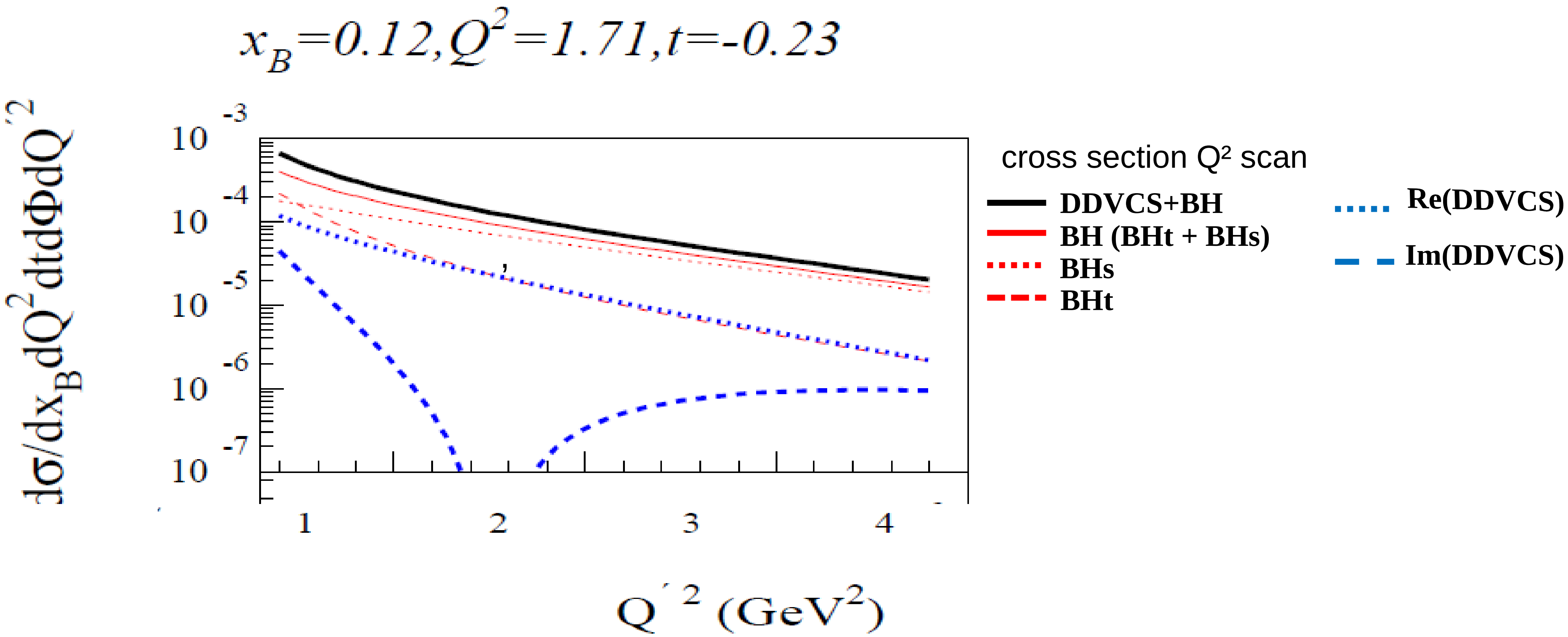


Nucleon tomography and sign change in DDVCS beam spin asymmetry

Calculations and figures from M. Guidal (Trento, 2016)

Im (DDVCS) drop when $Q'^2 \rightarrow Q^2$

no GPD interpretation in this region?

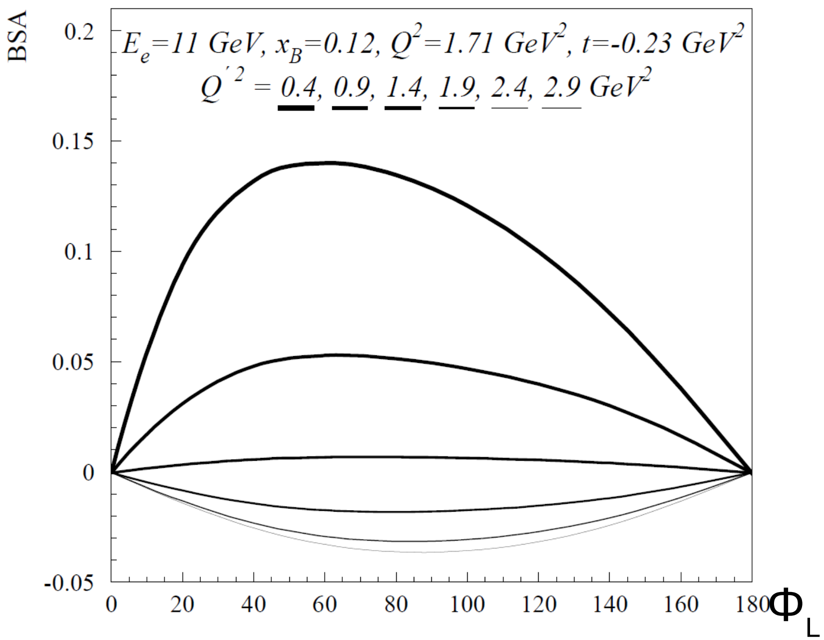


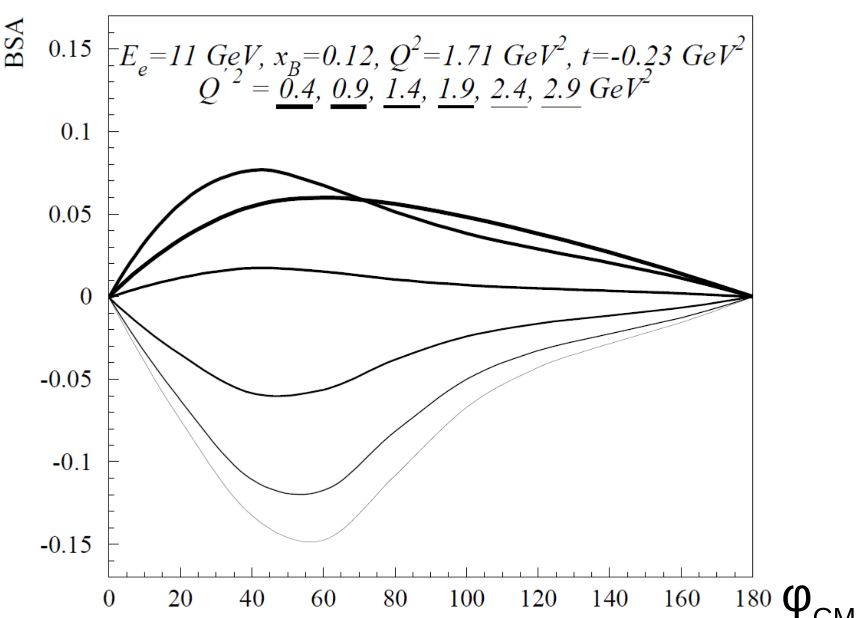
Nucleon tomography and sign change in DDVCS beam spin asymmetry

Calculations and figures from M. Guidal

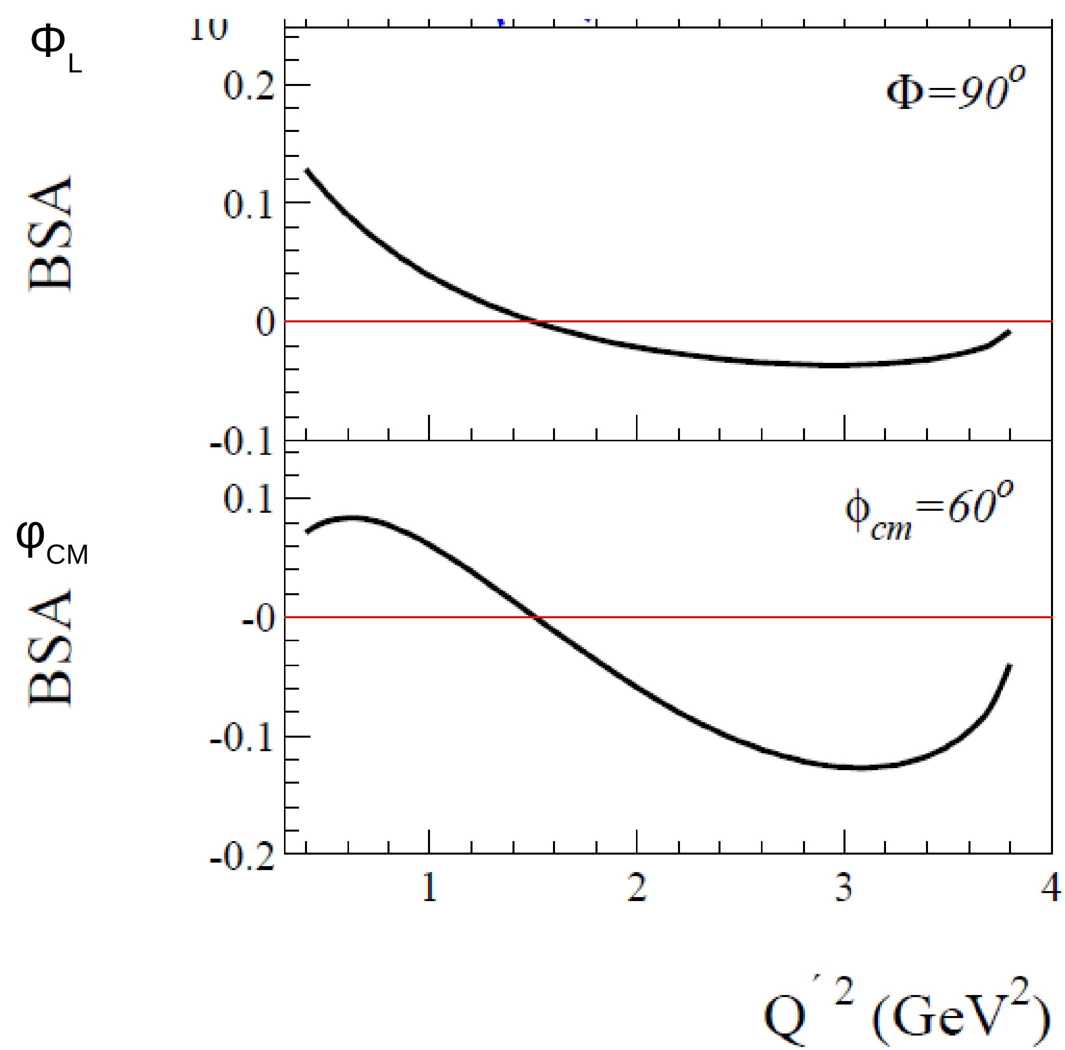
→ scan of BSA in Q'^2 at fixed Q^2

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





asymmetry Q^2 scan



- 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.

2) Experimental efforts: JLab@12 GeV

• Cross section and beam spin asymmetry measurement complementary proposals in development for JLab Hall A and B.

Plans: exploratory measurements with the goal of a future dedicated experiment at very high luminosity

SoLID: LOI12-15-005 (2015)

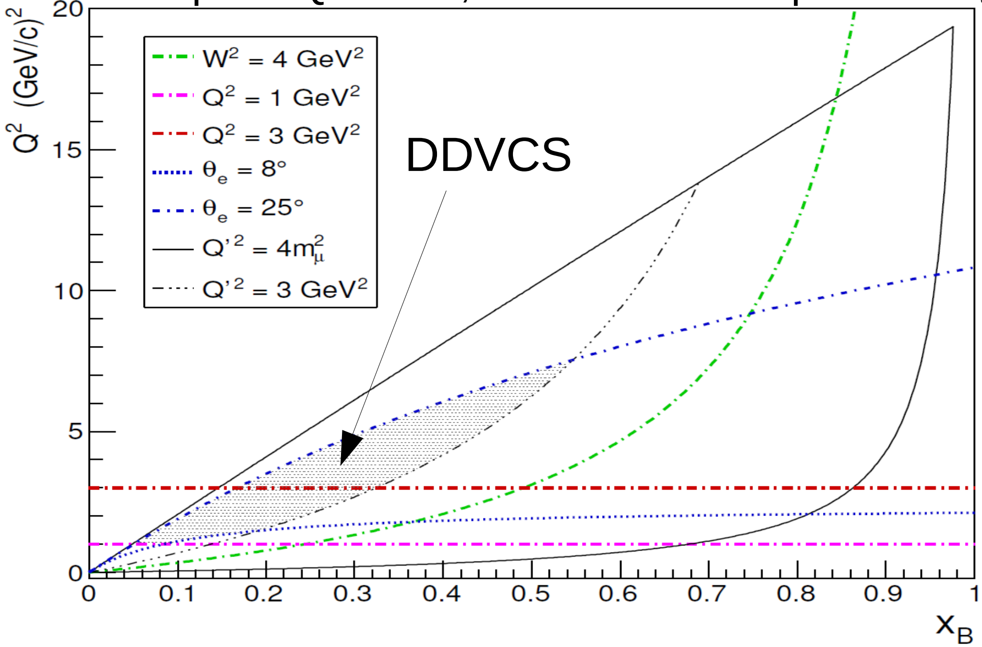
CLAS12 note: (2015), LOI12-16-004 (2016)

Electroproduction of muon pairs with CLAS12: Doube DVCS and J/ψ electroproduction

Measurement of Double Deeply Virtual Compton Scattering in the di-muon channel with the SoLID spectrometer

DDVCS with SoLID: cross section and BSA

Phase space Q^2 vs xB, with SoLID acceptance angular constrains



Goal / project: LOI12-15-005 (2015)

1) exploratory measurement x-sec and BSA (figs below) with non-dedicated setup using J/ψ approved setup + additional muon detectors from CLEO

2) dedicated experiment at very high luminosity

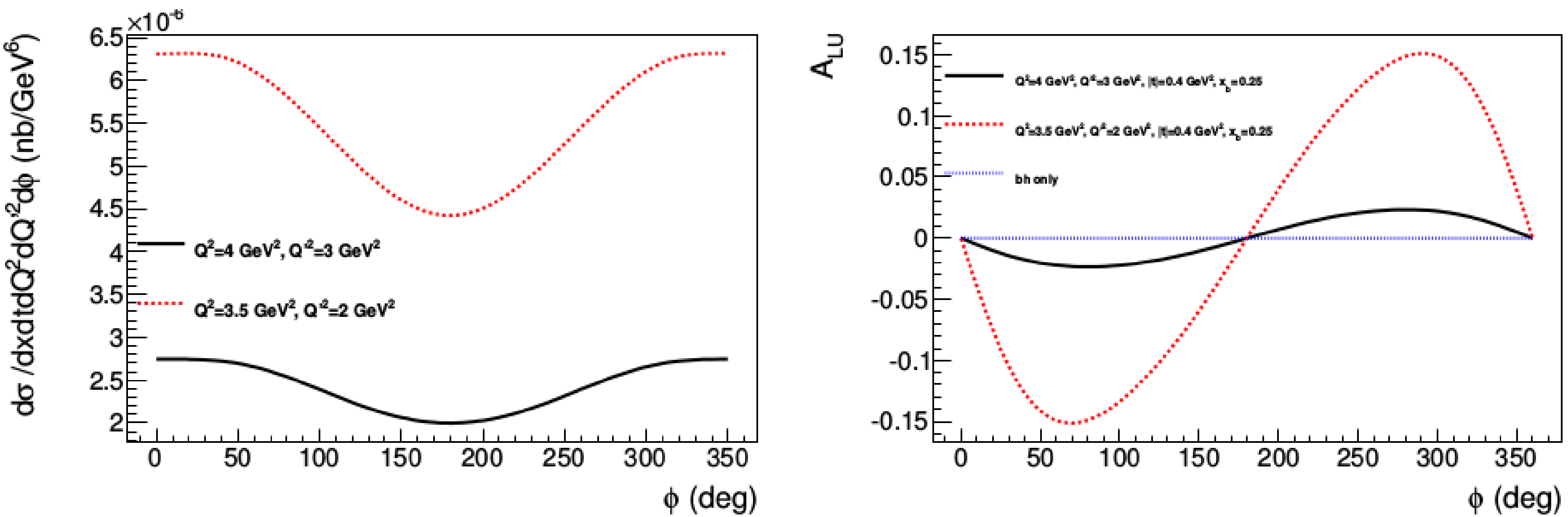
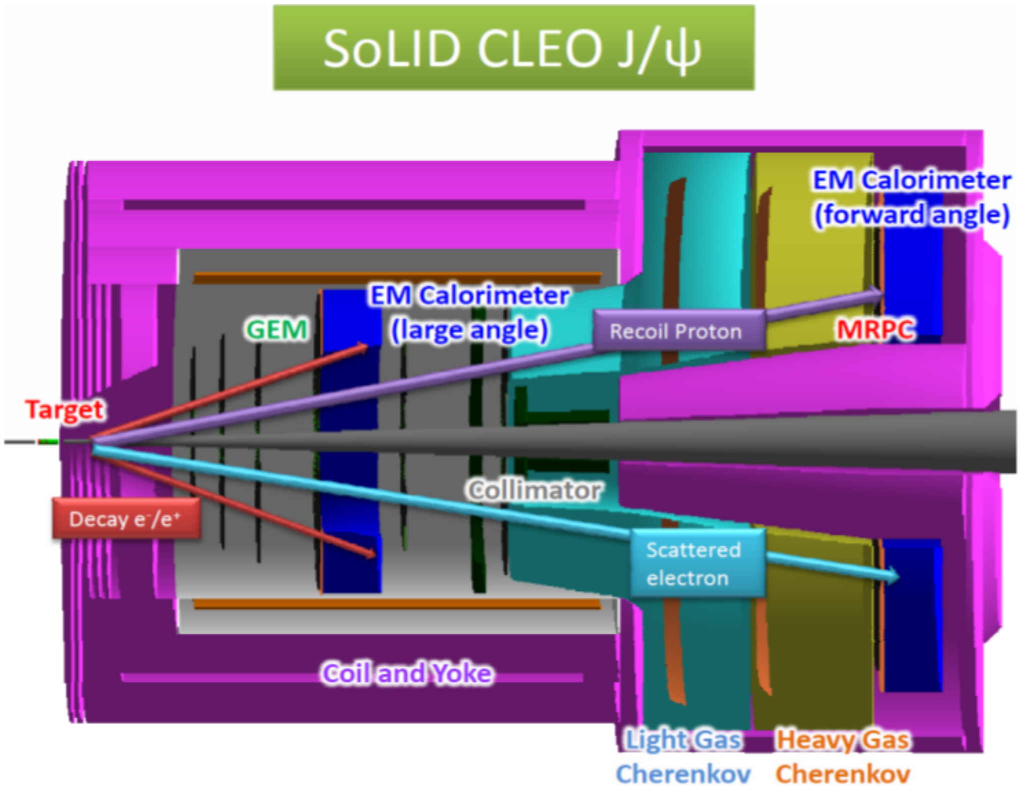


Figure 8: Out-of-plane angular dependence of the differential cross section (left) and the beam spin asymmetry (right) for the $^1H(e, e'p\mu^+\mu^-)$ process at two selected kinematics at E=11 GeV.

DDVCS with SoLID: experimental setup

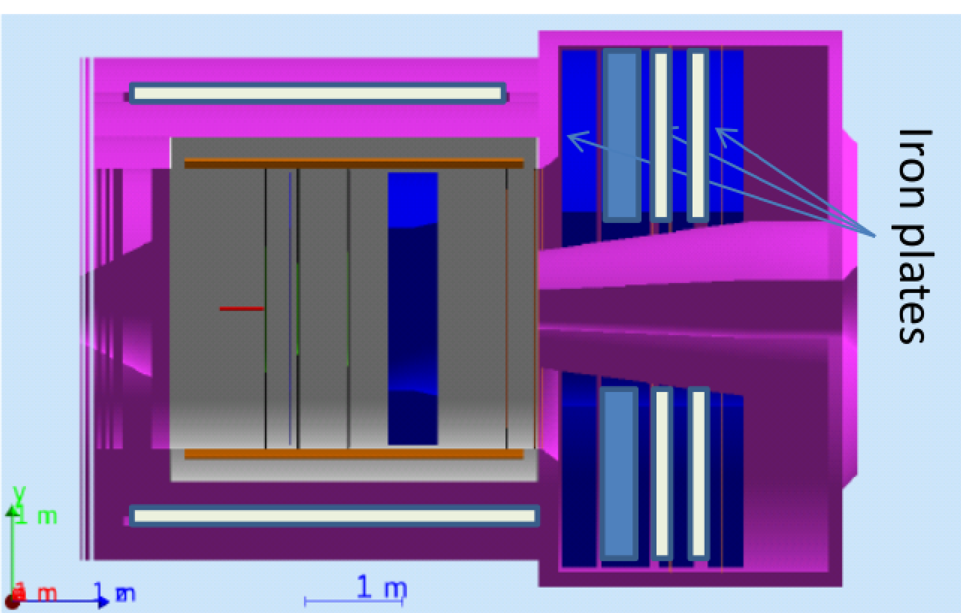


- J/Ψ setup: electrons, (proton)
- CLEO muon chambers: muon pair

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

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

Dedicated setup



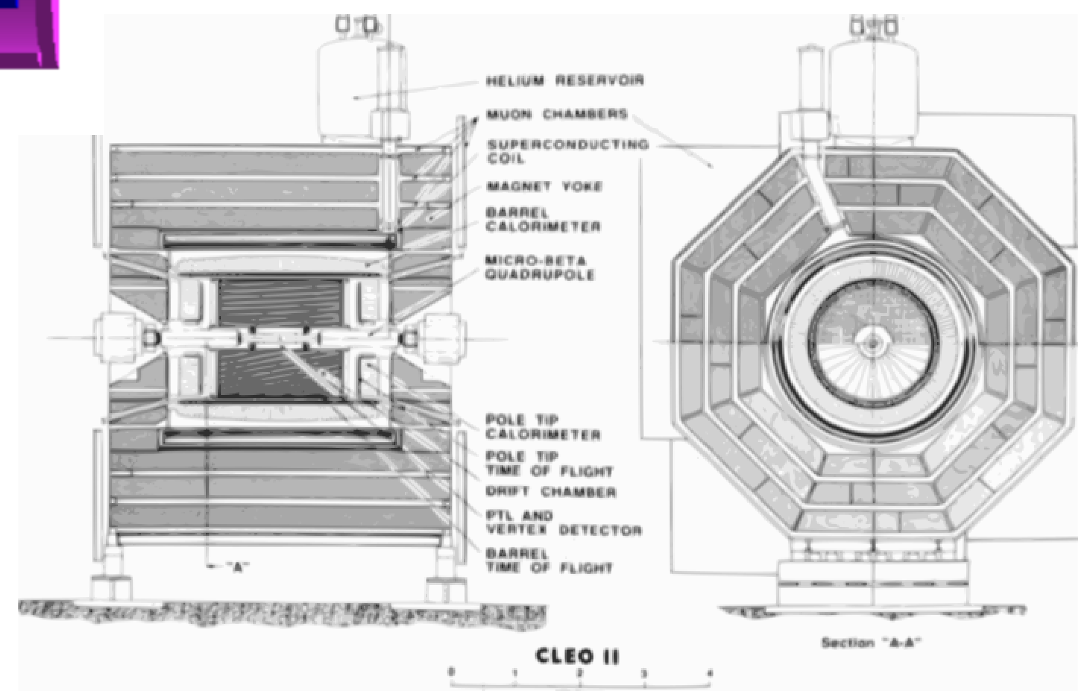
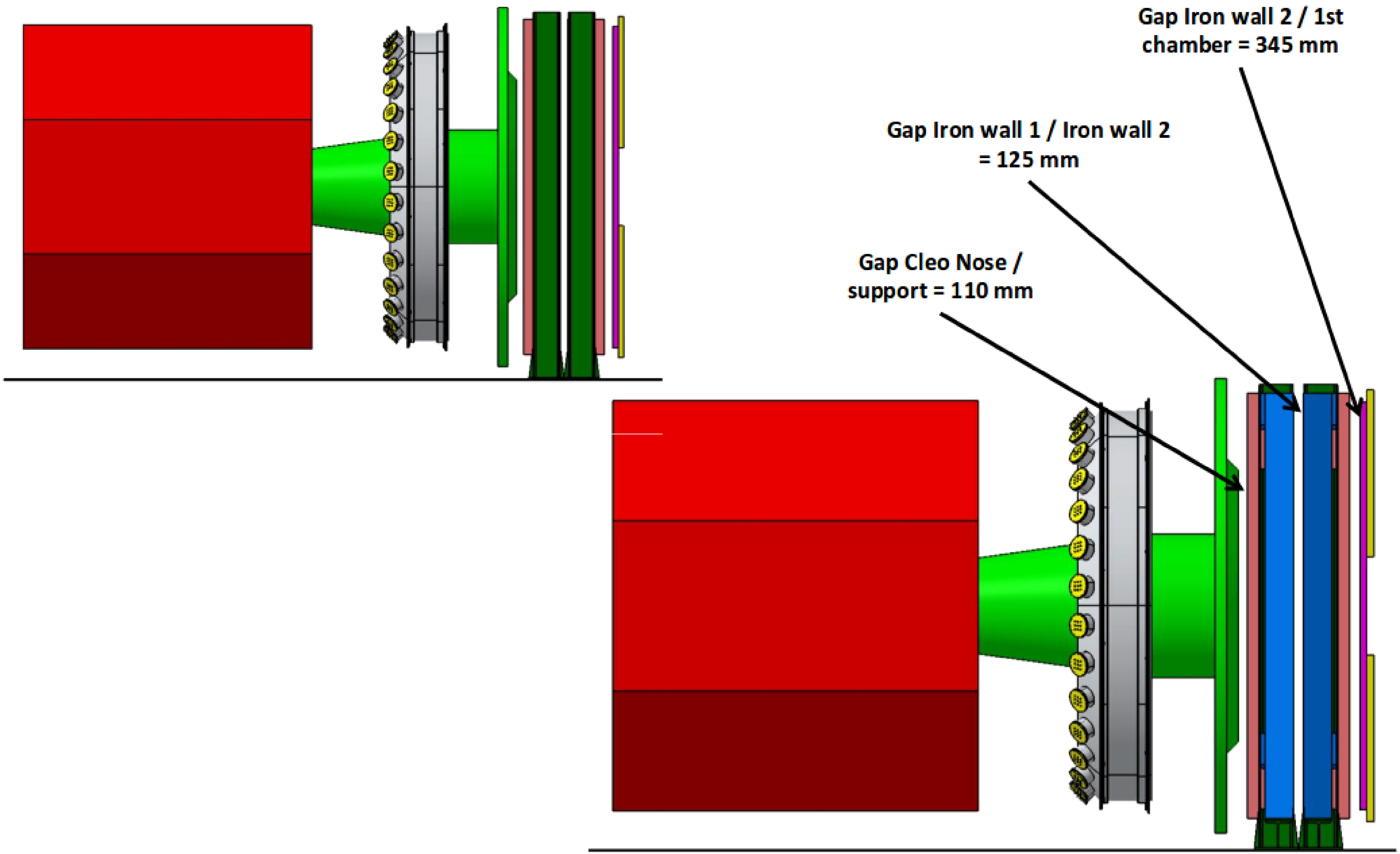


Figure 10: CLEO II setup with muon chambers installed inside the iron yoke.

slide from C. Le Gaillard

Gaps



DDVCS with CLAS12 in Hall-B

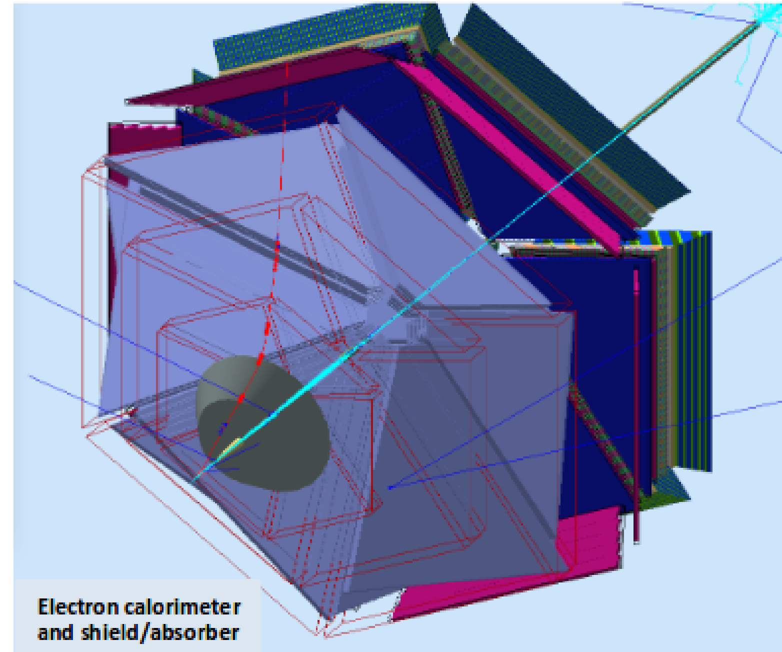
Two main challenges in DDVCS measurements:

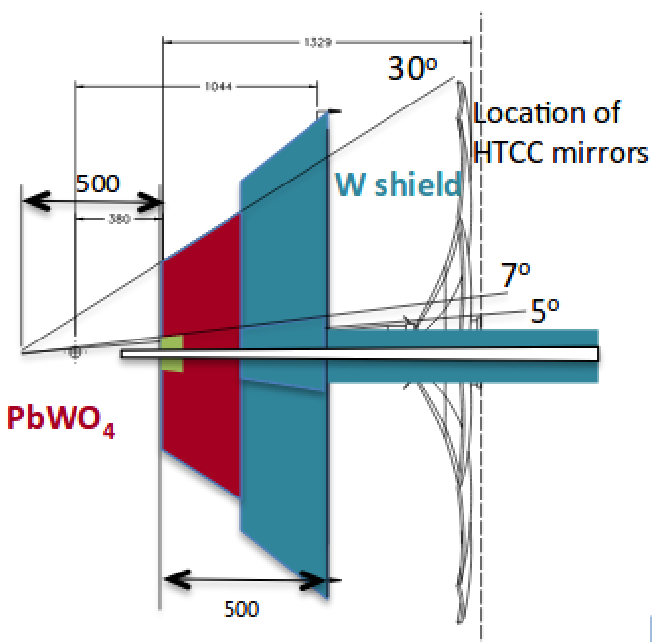
- cross section is two to three orders of magnitude smaller than the DVCS cross section
- decay leptons of the outgoing virtual photon must be distinguishable from the incoming-scattered lepton

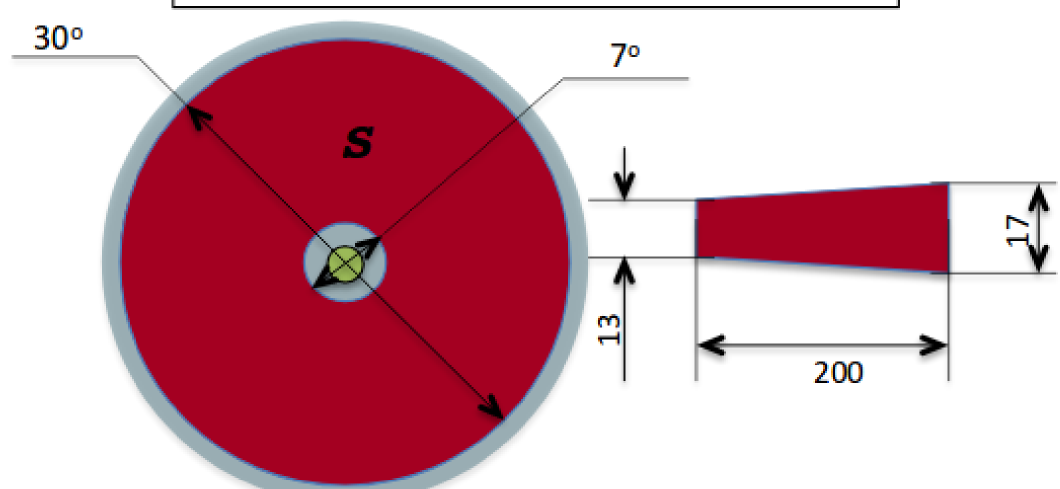
Both challenges can be solved with by studying di-muon electroproduciton, $ep \rightarrow e'p'\mu^+\mu^-$

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

Slide: S. Stepanyan

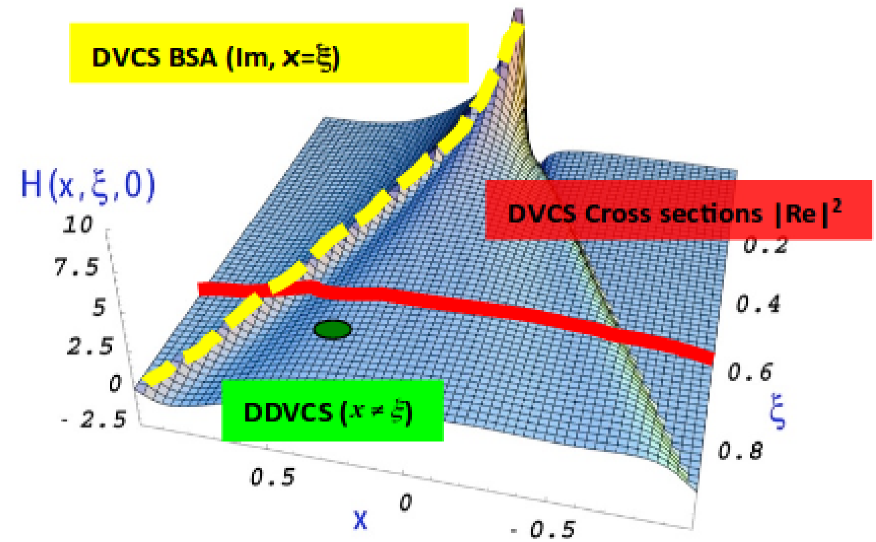
Expected results on beam spin asymmetry

The beam spin asymmetry (BSA) in DDVCS is proportional to the imaginary part the, i.e. in a concise notation:

$$H\left(2\xi'-\xi,\xi,t\right)+H\left(\xi-2\xi',\xi,t\right) \quad \xi'\approx\frac{x_B}{2-x_B}; \quad \xi=\xi'\frac{Q^2+Q'^2}{Q^2}$$

This allows the mapping of GPDs along each of the three axis (x, ξ and t) independently

Prediction of the "handbag" formalism is the sign change of BSA in transitioning from "space-like dominated" to "time-like dominated" regime



BSA for 100 days of running with CLAS12 at luminosity of 10^{37} cm^{-2} s^{-1}

$$ep \to e'\mu^+\mu^-(p')$$

Electron kinematics:

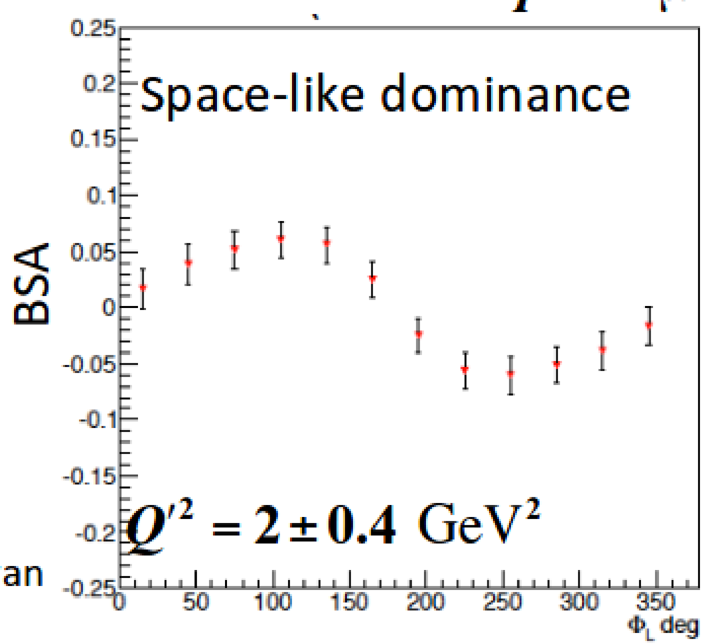
$$Q^2 = 2.5 \pm 0.5\ GeV^2$$

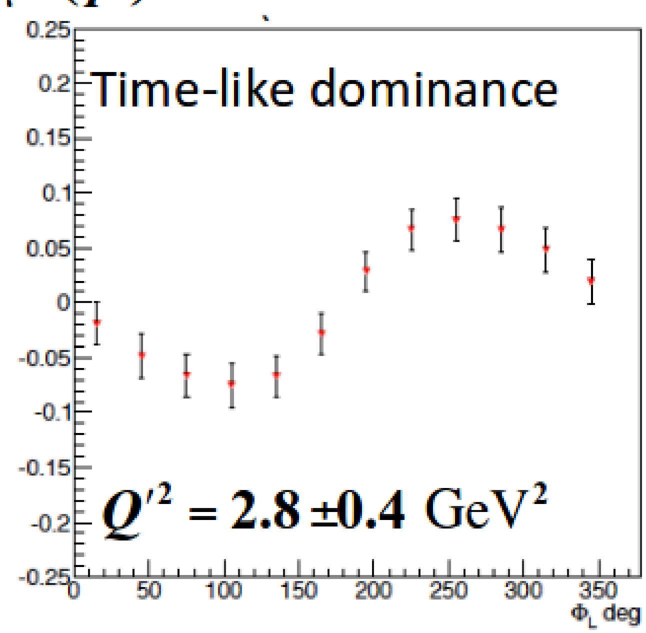
$$x_B = 0.15 \pm 0.05$$

Transferred momentum squared:

$$t = 0.25 \pm 0.15\ GeV^2$$

From Boer, Paremuzyan





Comments on DDVCS projects

• **Complementary:**

- same observables to measure, similar counting rates but rather different acceptance

- both able to make the Q^2 vs Q'^2 scan in <u>different</u> bins (need several bins for extrapolation for GPD extraction at $\xi=0$)

- CLAS12 could run first and make the first measurement of DDVCS

- SoLID would have possibility of upgrade and very high luminosity for precision measurement

• **Strong interest**

- GPD off $x=\xi$ diagonal in a "clean" process (only non perturbative part associated to GPDs)

- crossing between "timelike" and "spacelike" region

- open new perspectives compared to DVCS measurement, already intensively studied.

- complementary to exclusive meson production

• **Alternative to DDVCS studies** for off $x=\xi$ diagonal:

- see Jakub's talk (Monday): 2 photons exclusive production, DVMP (difficulty with DA)...

Summary

- TCS and DDVCS complementary to DVCS to access GPDs in a "clean" channel

- test of GPD universality, timelike vs spacelike, higher twist/order...

- clear physics interest for both TCS and DDVCS

- TCS/BH always small: asymmetries, moments where BH enhance TCS rates

- DDVCS phenomenology would benefit from some new development to help understanding, observables, interpretation...

- experimental interest for TCS, current: Hall A and B for TCS cross section and BSA, Hall C for transversaly polarized TCS. Future: linearly polarized beam, longitudinal target, neutron...

- first TCS measurements from Hall B and D expected soon.

- experimental interest for DDVCS: Hall A and B for cross section and BSA. Need further studies on both experimental and theoretical sides, proposals/idea in development.