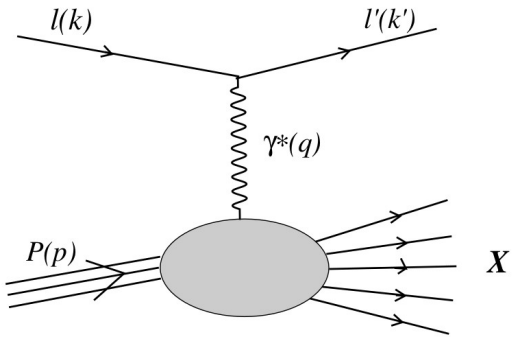
# Hard Exclusive reactions beyond DVCS
# Compton-like and (vector mesons) production
# for Generalized Parton Distributions studies

PARTONIC STRUCTURE OF THE HADRONS

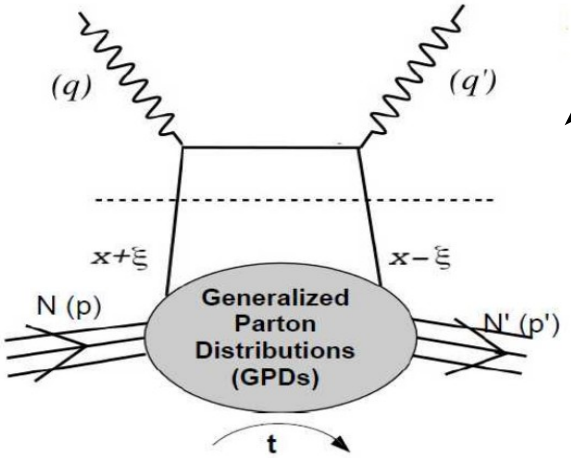
Marie Boër, Virginia Tech,
Nov. 10th, 2022
BARYONS conference, Sevilla, Spain

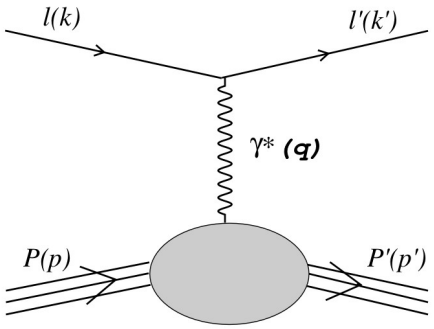
# Towards multidimensional partonic structure of the nucleon




Deep Inelastic Scattering:
Probabilistic density interpretation
**"x", longitudinal momentum fraction of the partons**

Hard Exclusive Scattering:
Both **"x" and "position"**
Known final state

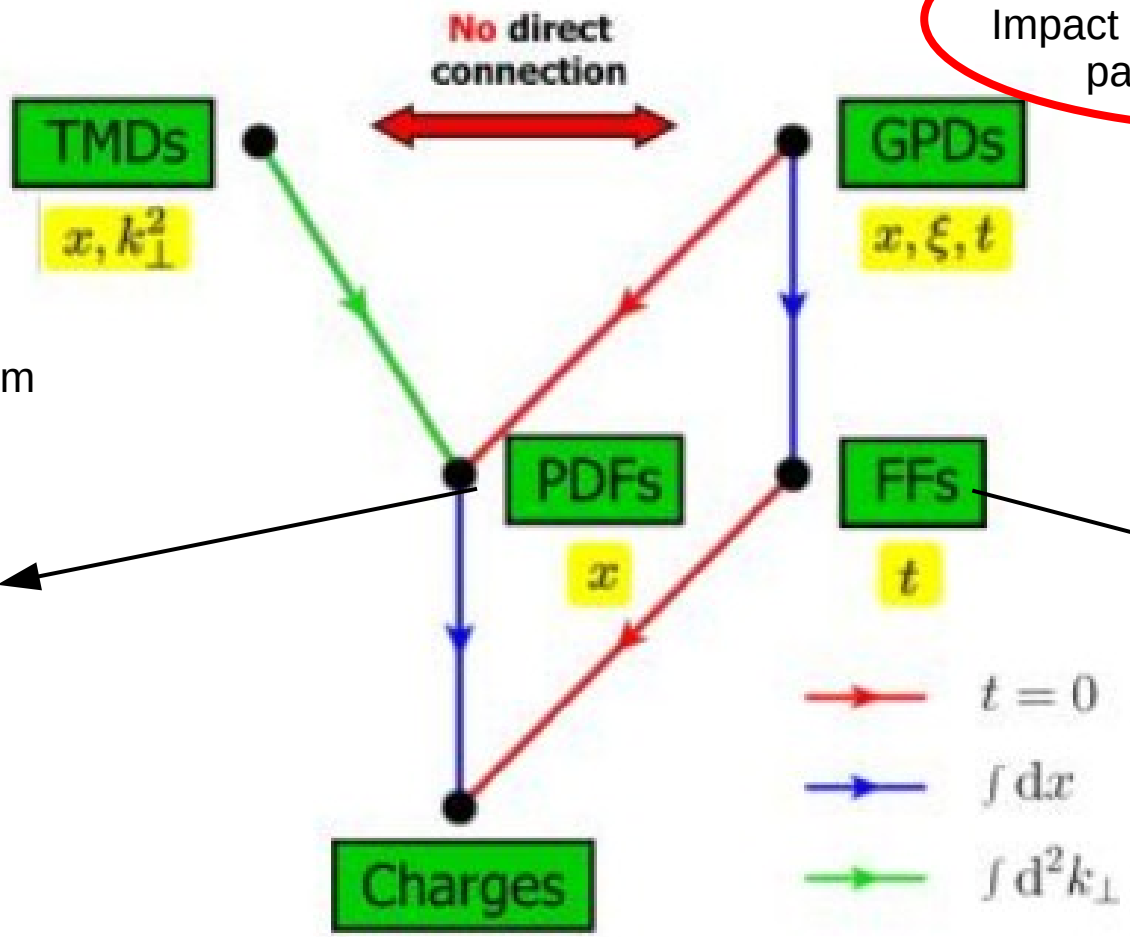


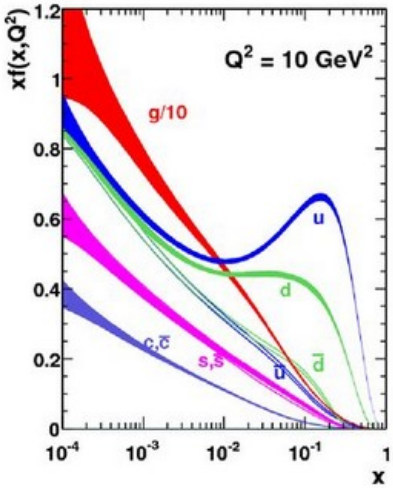

Elastic scattering:
**transverse position of quarks**
Access to momentum transfer t

# Towards multidimensional partonic structure of the nucleon

Generalized Parton Distributions
Impact parameter versus “x”;
partonic densities




Longitudinal momentum
Partonic density




Form Factors
“Transverse position”

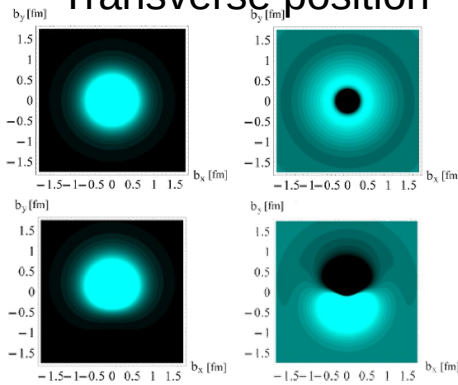


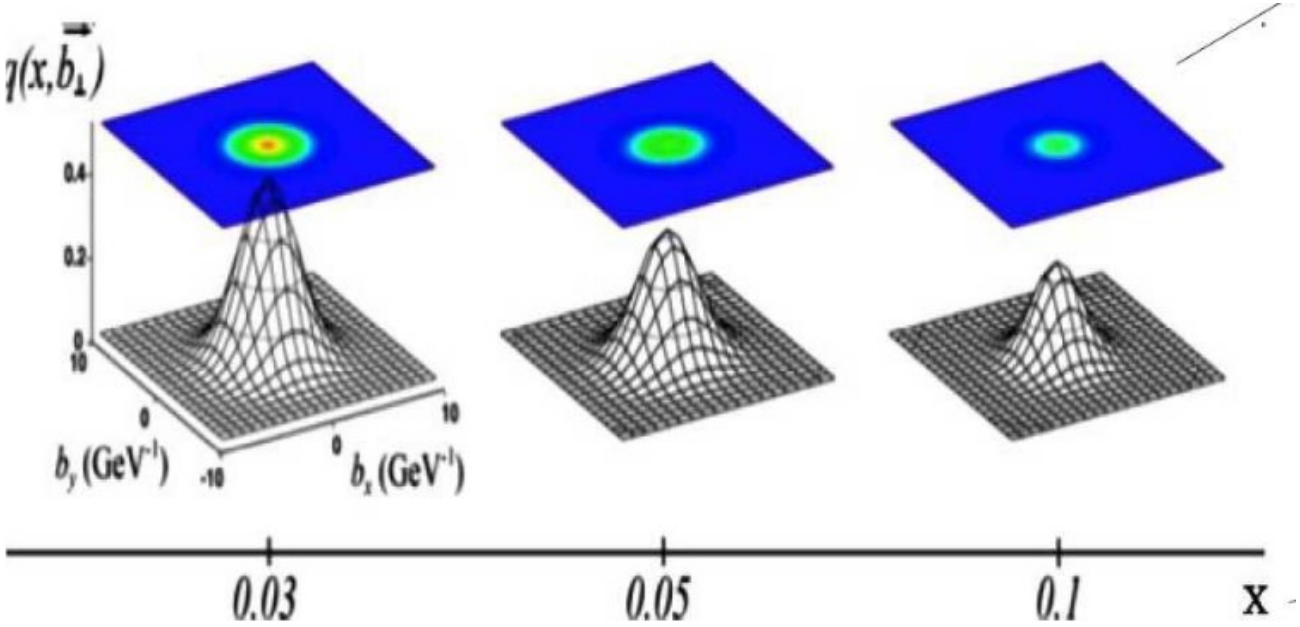

Diagram: C. Lorcé
Pdf: HERA
FFs: M. Vanderhaegen

# Generalized Parton Distributions

See talk from
C. Mezrag Monday
For theoretical
motivations

One of the interpretation of GPDs: tomographic imaging of the nucleon
(other: spin, angular momenta correlation, “pressure”…)

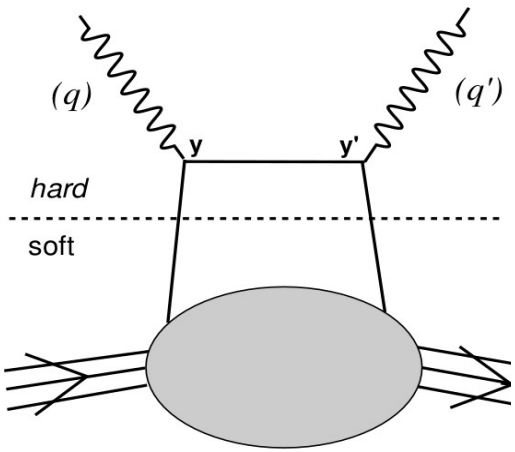
**Momentum dependent impact parameter distributions**
Quarks and gluons transverse position versus their longitudinal momentum

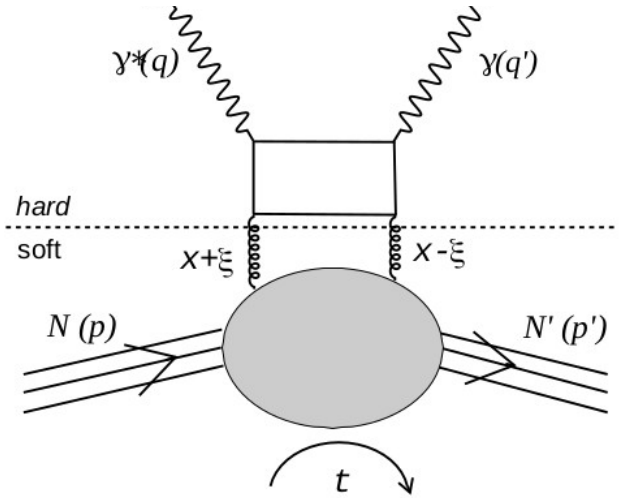



gluons dominate | gluons, sea quarks "meson cloud" | valence quarks region

# What reactions?

**GPDs with Compton-like reactions** **γ (*) N → γ'(*) N'**




Leading order / leading twist generic handbag diagram

**DVCS**: final photon is real, incoming is spacelike (Spacelike Deeply Virtual Compton Scattering)

**TCS**: incoming is real, final is timelike (Timelike Deeply Virtual Compton Scattering)

**DDVCS**: incoming is spacelike, outgoing is timelike Double Deeply Virtual Compton Scattering

**Other**: multi-photons, photon+meson, ...

Quark GPDs; as function of x (// momentum fraction), ξ (skewness), t (squared momentum transfer) + $Q^2$, $Q'^2$: evolution not being taken into account in this work. $Q^2/Q'^2$ relevant for DDVCS

**Can be seen as the "cleanest" way to access GPDs, since no meson wave function**

**Most measurements = DVCS; GPD models constrained by DVCS mainly**
**→ we want to go further with complementary channels**

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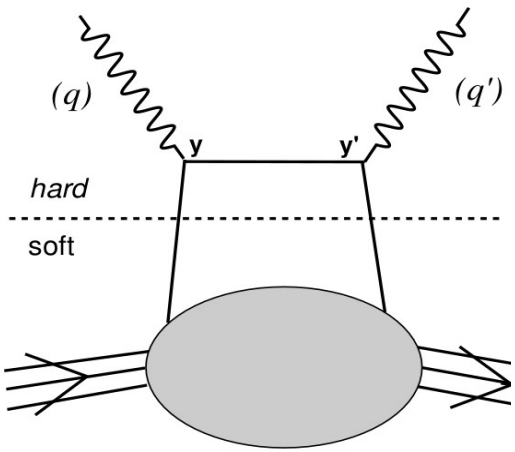


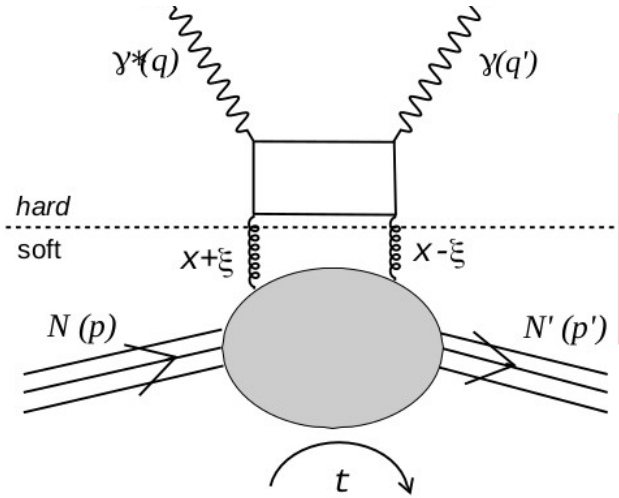


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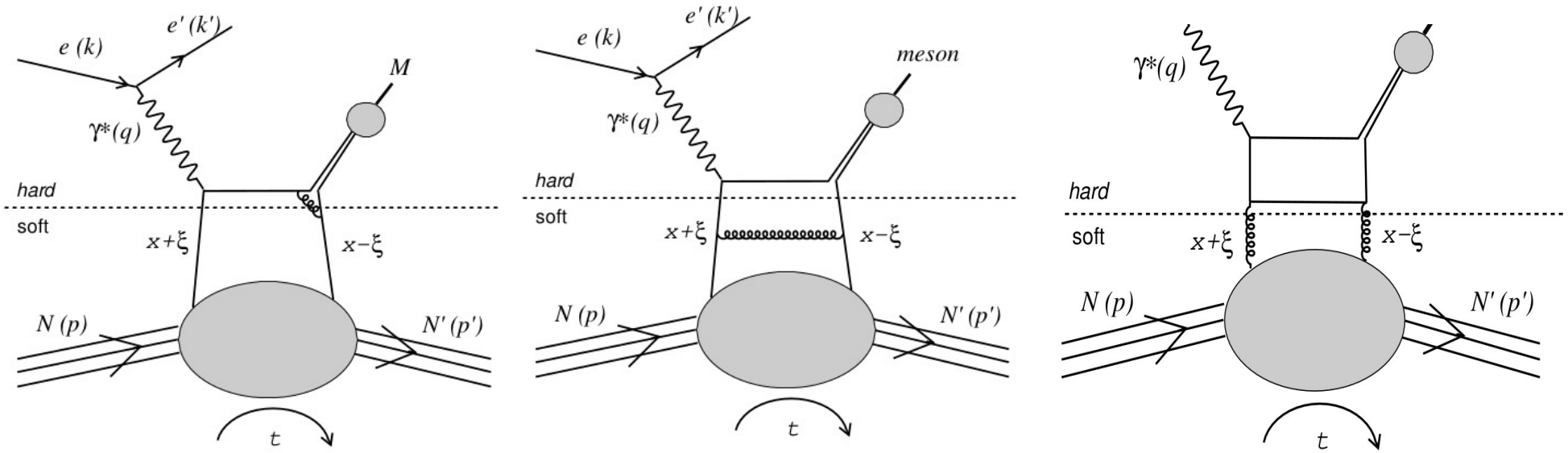
**GPDs with Hard Exclusive Meson Production (few example of diagrams, we focus on VM)** **γ (*) N → (VM) N'**

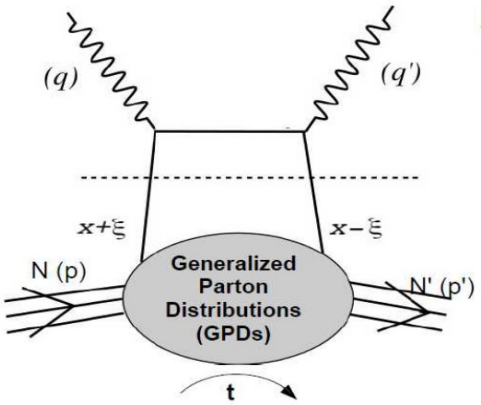


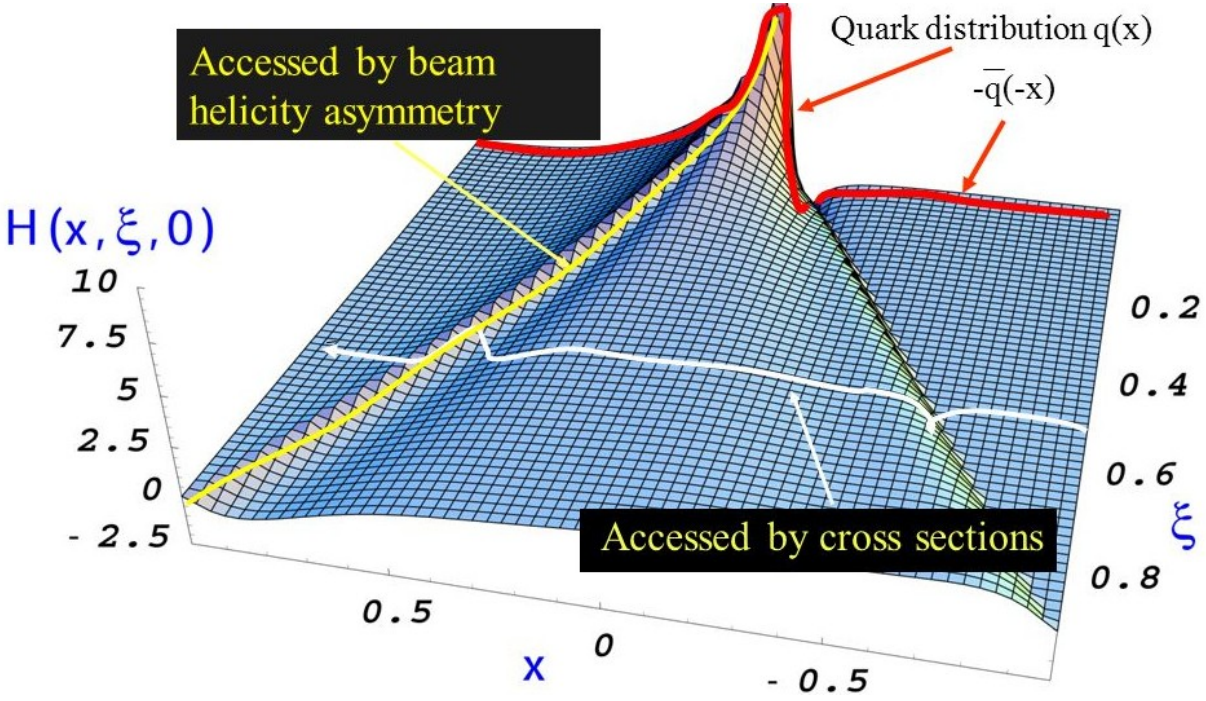

- Flavor decomposition
- Enhancement of sensitivity to certain GPDs
- Direct access to gluon GPDs with heavy mesons…

- VM: can be directly compared to Compton reactions (same spin-parity), large cross sections. Caveat: meson production, gluons at leading twist. Need models.

To go beyond DVCS and what is done in other experiments → looking for high precision VM (unpolarized, polarized) program at JLab Hall C/Hall A for GPDs multichannel CFFs fits and deconvolution

# Generalized Parton Distributions (DVCS or TCS, “diagonal”)



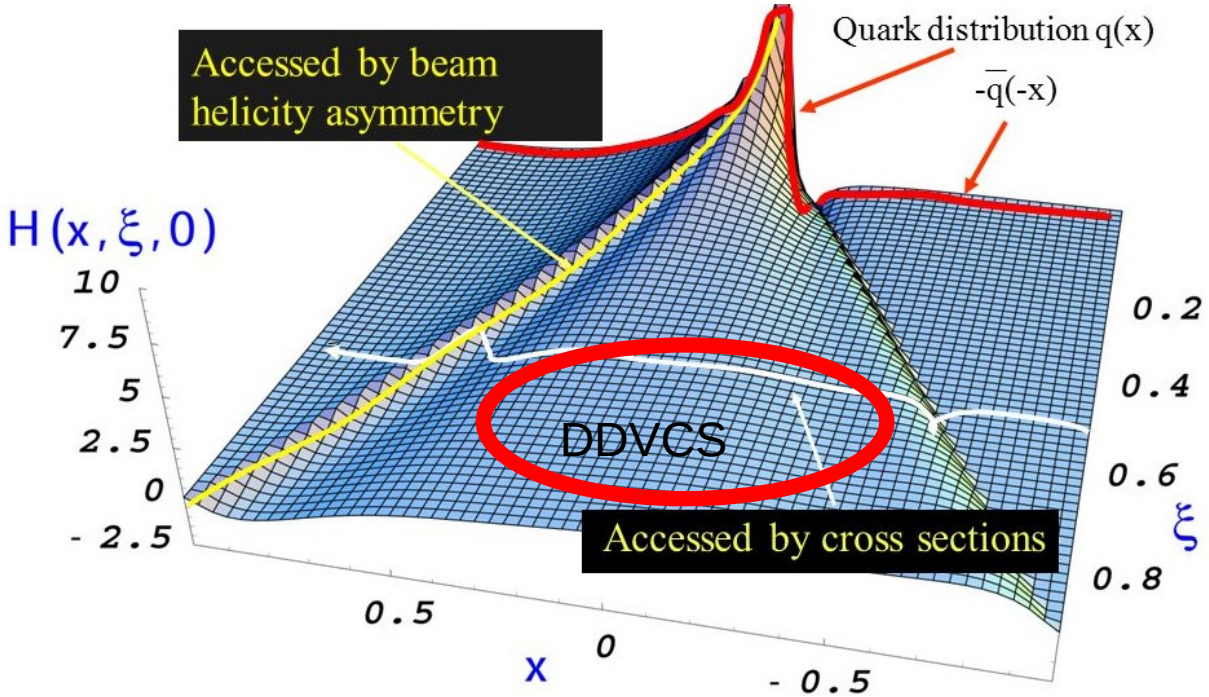




Extracted at ξ (skewness // momentum) and t (momentum transfer ²) from experimental data [can’t access x]

Various “parts” of the GPD accessible via different reactions or observables

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

# Generalized Parton Distributions: “off diagonal”




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

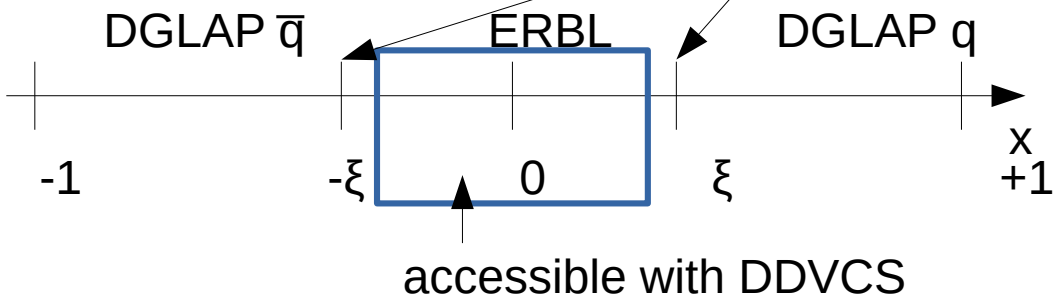
“off diagonal”: $$T^{DDVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x - (2\xi' - \xi) + i\varepsilon} dx + \ldots \sim P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x - (2\xi' - \xi)} dx - i\pi H(2\xi' - \xi,\xi,t) + \ldots$$

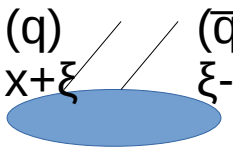
# GPD regions: interpretations

**What do we learn?**

M. Diehl's representations:

limit between the 2 regions:
Im(CFFs) from DVCS and TCS



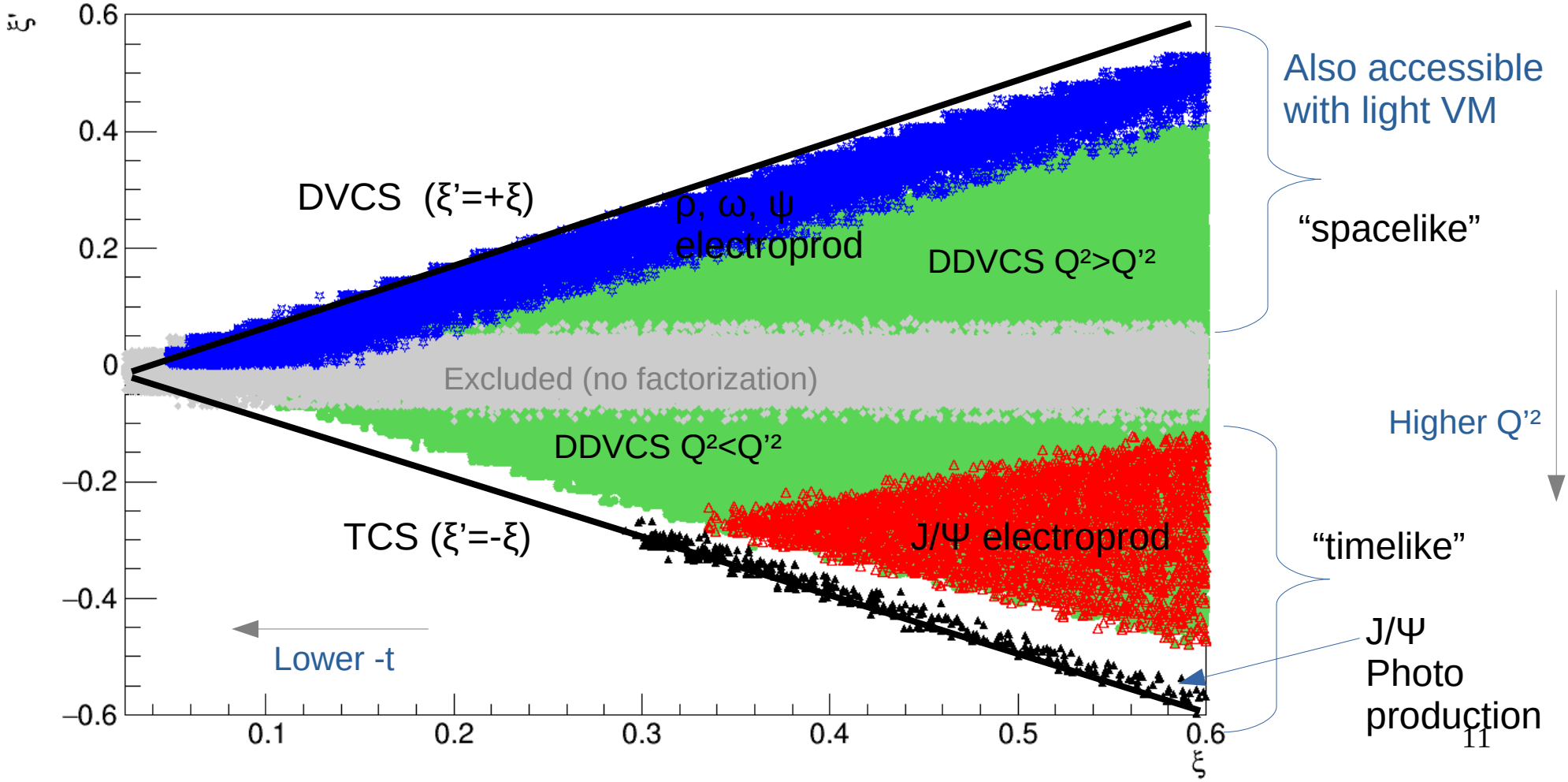

partonic interpretation from M. Diehl in ERBL region

**TCS and DVCS access Im(CFFs) at x = ±ξ**
=> complementary measurements, **access same CFFs**,
- GPD **universality** studies with independent TCS data set
- higher twist/order studies in comparison, can help understanding “effects” seen in DVCS
- combined data set for additional constraints to GPDs

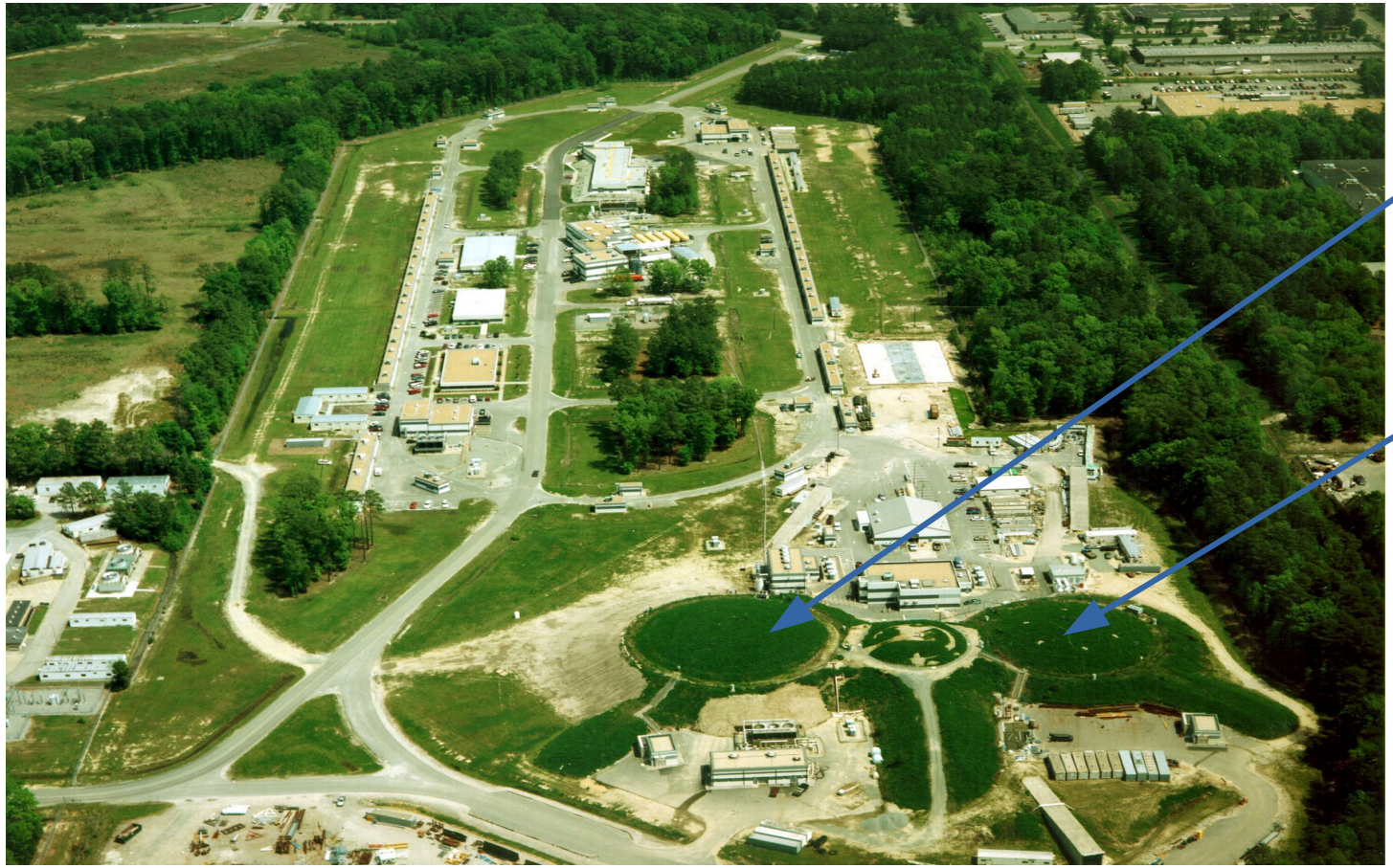
DDVCS (and meson masses*) give a lever arm for going “off diagonal”, needed to **extrapolate to zero skewness**
- tomographic interpretations
- can move from “timelike” to “spacelike” region
- complementary observables for GPD data sets in multichannel approach

# Using DDVCS Q'² and meson masses to go "off-diagonal"

11 GeV beam, -t<1 GeV², W²<2 GeV², Q'² (TCS, DDVCS>2 GeV²), Q² (electroprod. > 1 GeV²)

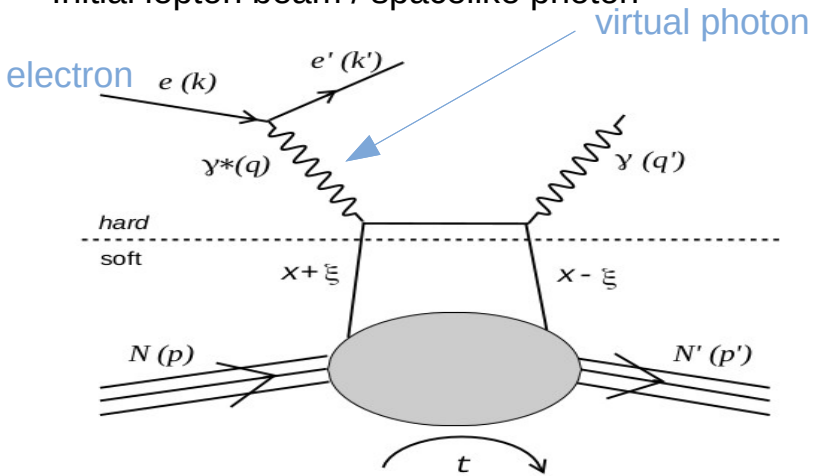


# Accessing TCS, DDVCS and hard exclusive VM at JLab
# With new experiments in Hall A and Hall C



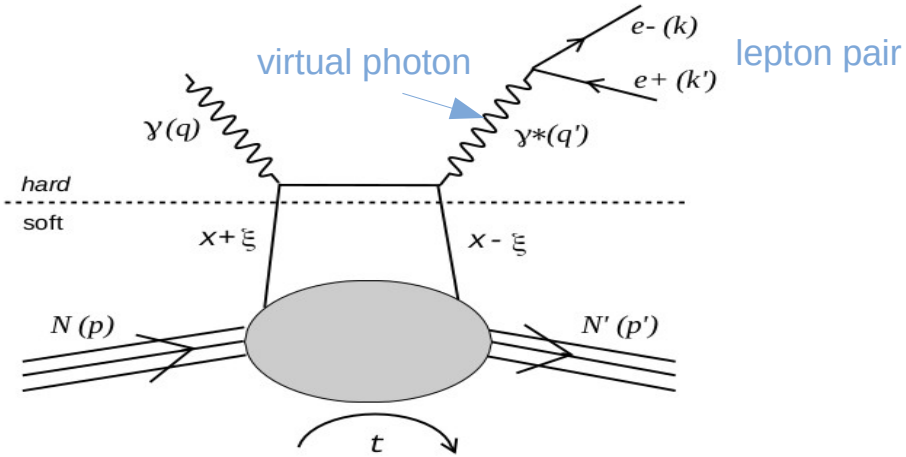
# Timelike Compton Scattering

Initial lepton beam / spacelike photon




**Deeply Virtual Compton Scattering (DVCS)**

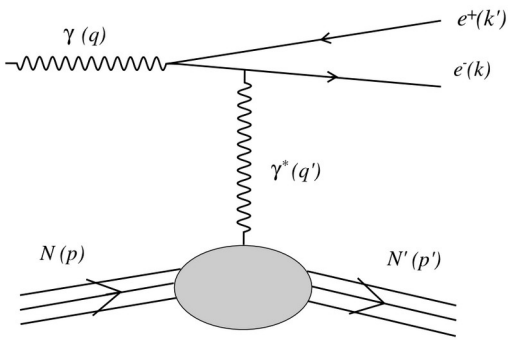
Final lepton pair / timelike photon



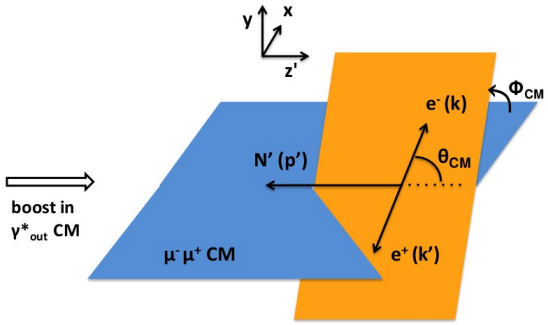

**Timelike Compton Scattering (TCS)**

Interference with "BH"
Harmonics in φ ($\varphi_S$)

Measuring cross section,
beam/target spin asymmetries...




BH interfers with TCS



# TCS program: what can we get, motivations, JLab (potential) experiments

| 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 conditionnal |
| Circularly polarized beam | Easiest observable to measure at JLab | Im(H), Im($\tilde{H}$) Sensitivity to quark angular momenta, in particular for neutron | CLAS 12, SoLID approved NPS conditionnal |
| 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($\tilde{H}$) | no / "for free"? |
| Transversely polarized target | Polarized target, and high luminosity: binning in θs, φs | Im($\tilde{H}$), Im(E) | NPS conditionnal |
| 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 |

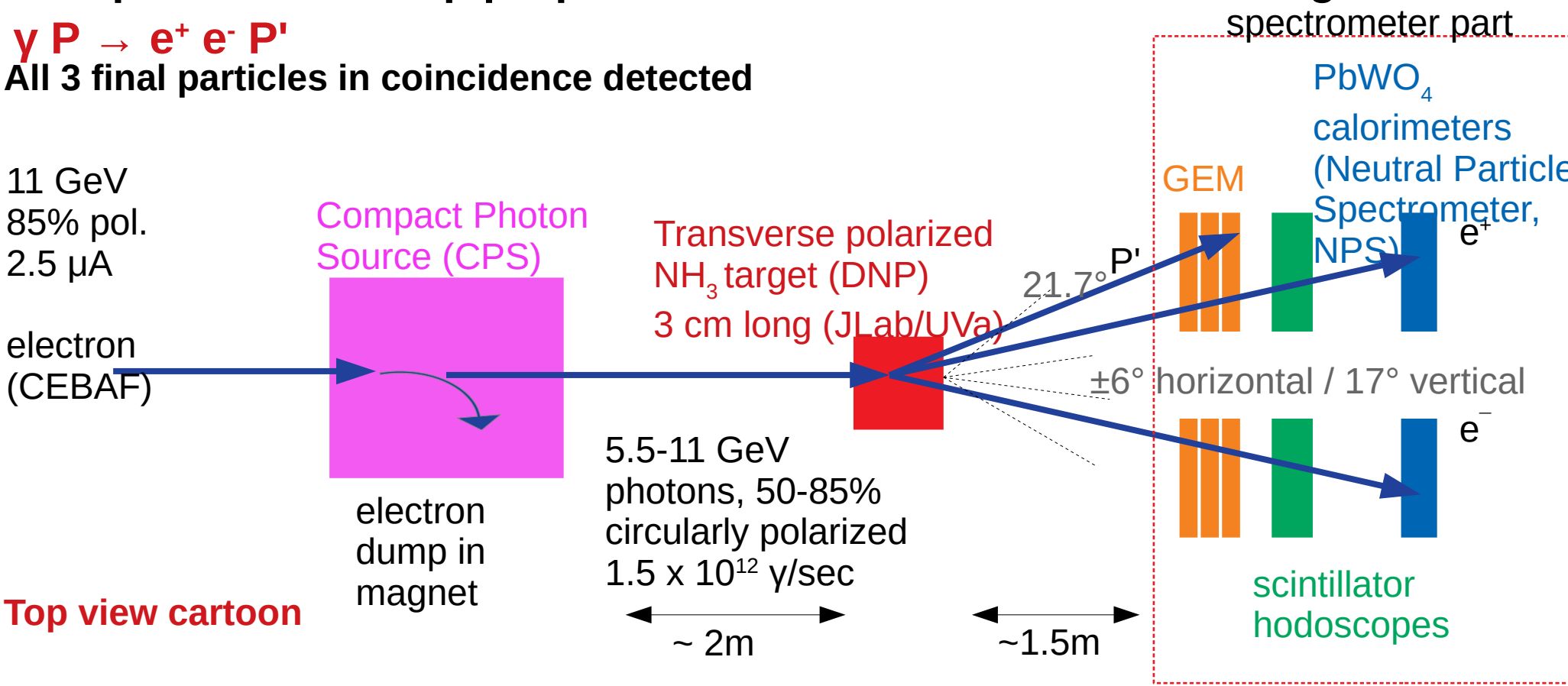
**TCS off the neutron**

- similar, need higher luminosity and proton or neutron tagging
- target spin asymmetries are expected to be larger, and beam spin asymmetries are smaller

# Experimental setup proposed for Hall C with transverse target

**$\gamma P \rightarrow e^+ e^- P'$**

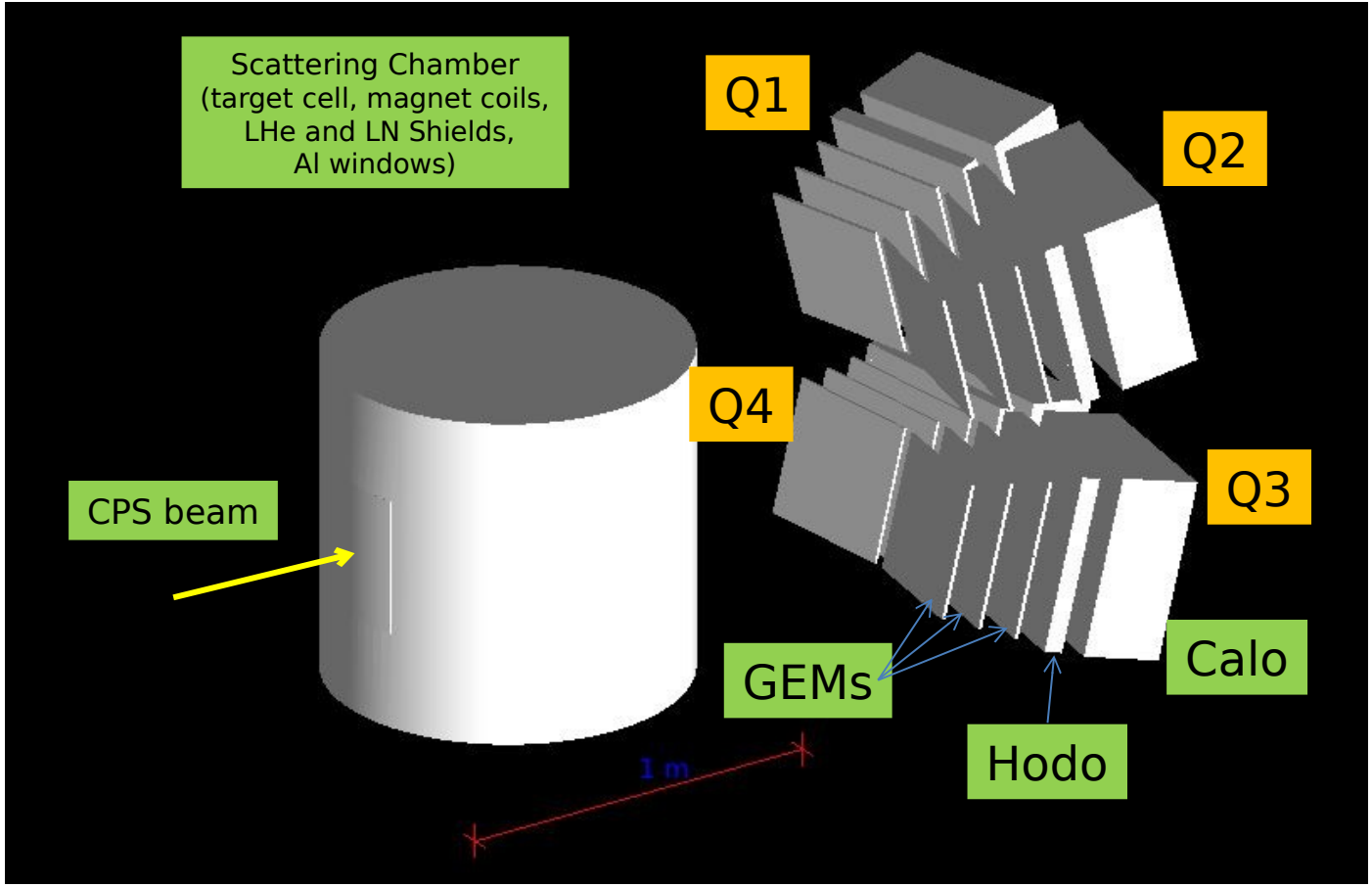
**All 3 final particles in coincidence detected**




Trigger: GEMs, hodoscopes, calorimeters (all 3 particles)

**Integrated luminosity: 5.85 x $10^5$ $pb^{-1}$ for 30 PAC days of "physics"**

# Experimental setup proposed for Hall C with transverse target

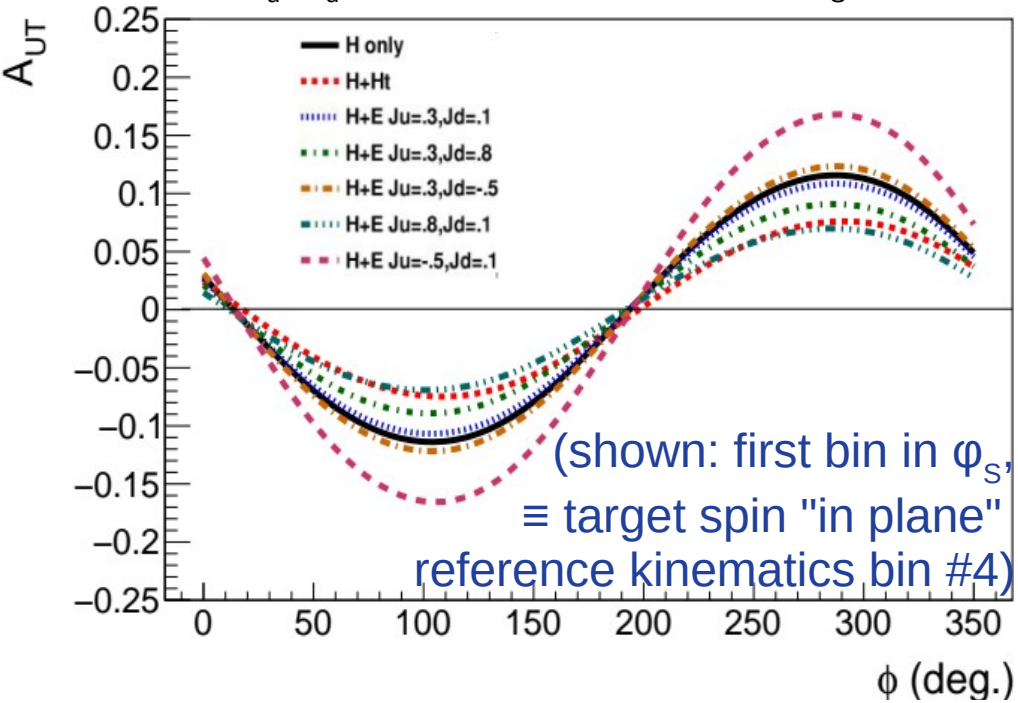



Setup to measure Timelike Compton Scattering at Jefferson Lab
(credit: V. Tadevosyan)

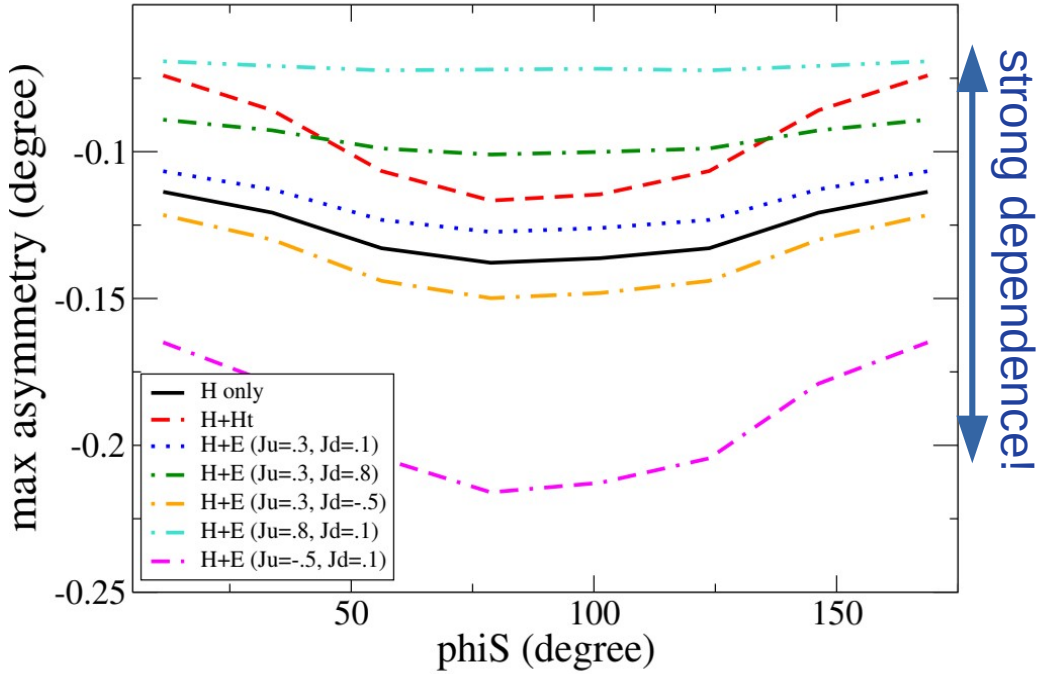
# TCS in Hall C with transverse target

Transverse target spin asymmetry "as will be measured in Hall C"

Dependence in GPD parametrization and $J_u$, $J_d$ (VGG model) vs φ and $\varphi_s$



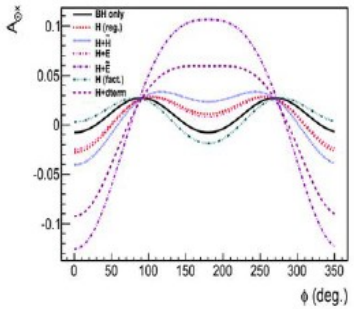

Sin(φ) moment of transverse spin asymmetry vs $\varphi_s$, Dependence in GPD E and $J^{u,d}$ (VGG model)

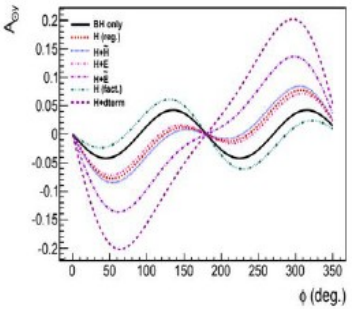



- **Unique access to GPD E of the proton and quark angular momenta**
- **GPD universality studies (TCS vs DVCS)**
- **Independent observables for GPD data sets and global fits in valence region**
- **Most knowledge on GPDs from DVCS: complex conjugate, TCS access same information**

# What else for precision TCS measurements?

Double spin asymmetries: highly model dependent
Unique access to Re(CFFs)



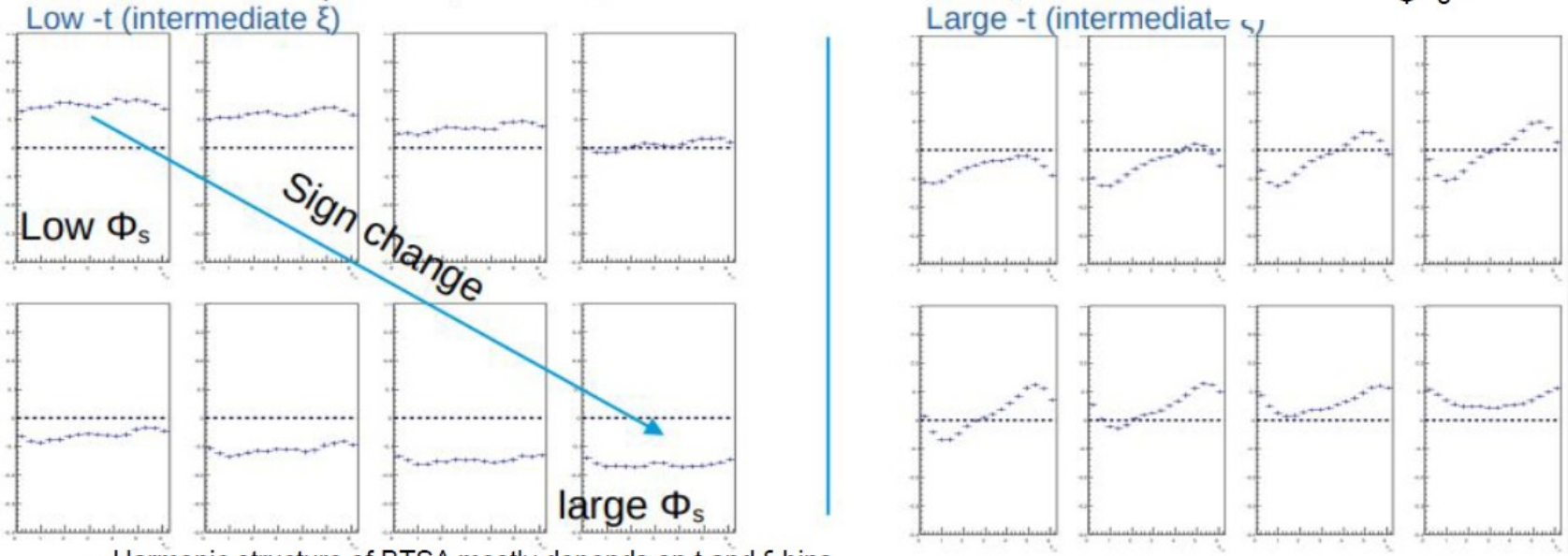




## Projected (ideal) BTSA distributions

Evolutions of the shapes vs Φ, bins in $\Phi_s$ from 0 to π at intermediate ξ and for 2 bins

Φ=0°

Φ=90°



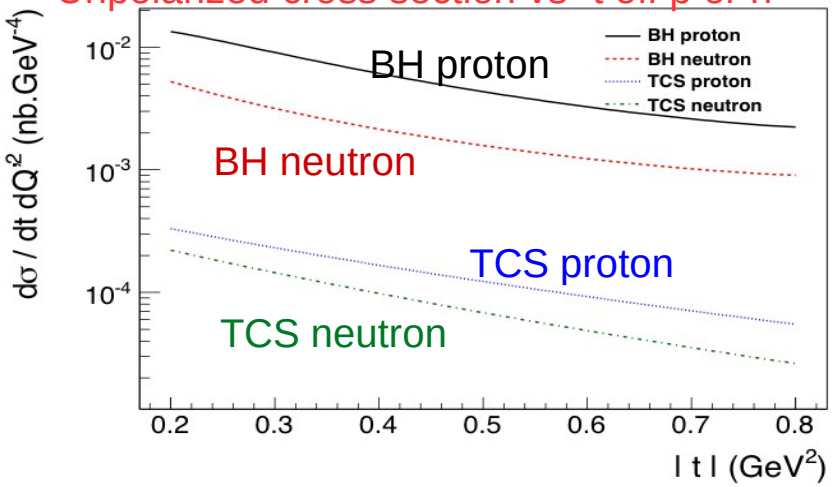

-Harmonic structure of BTSA mostly depends on t and ξ bins
-BH doesn't cancel, nor is it TCS "only". Harder to interpret but any information is a major input to models and especially for discriminating Double Distribution "types" vs other kinds (strongly differ on Re CFF)

Projections: M.B., Brannon Semp

# Other observables for TCS

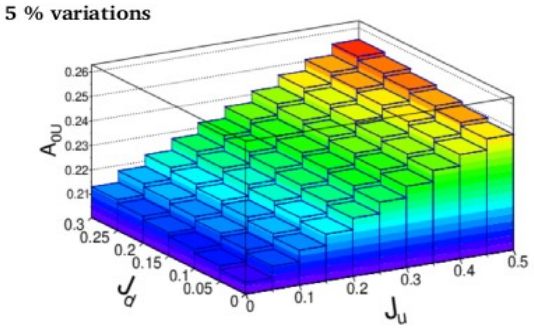
- **Neutron: flavor separation and spin**

Unpolarized cross section vs -t off p or n




- σ off neutron not suppressed, sizeable asymmetries
- similar sensitivities to GPDs expected
- strong sensitivity to $J_u$, $J_d$

BSA proton

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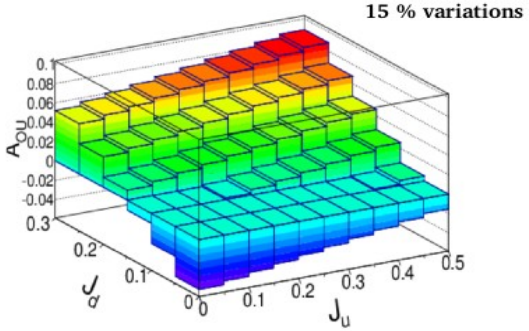


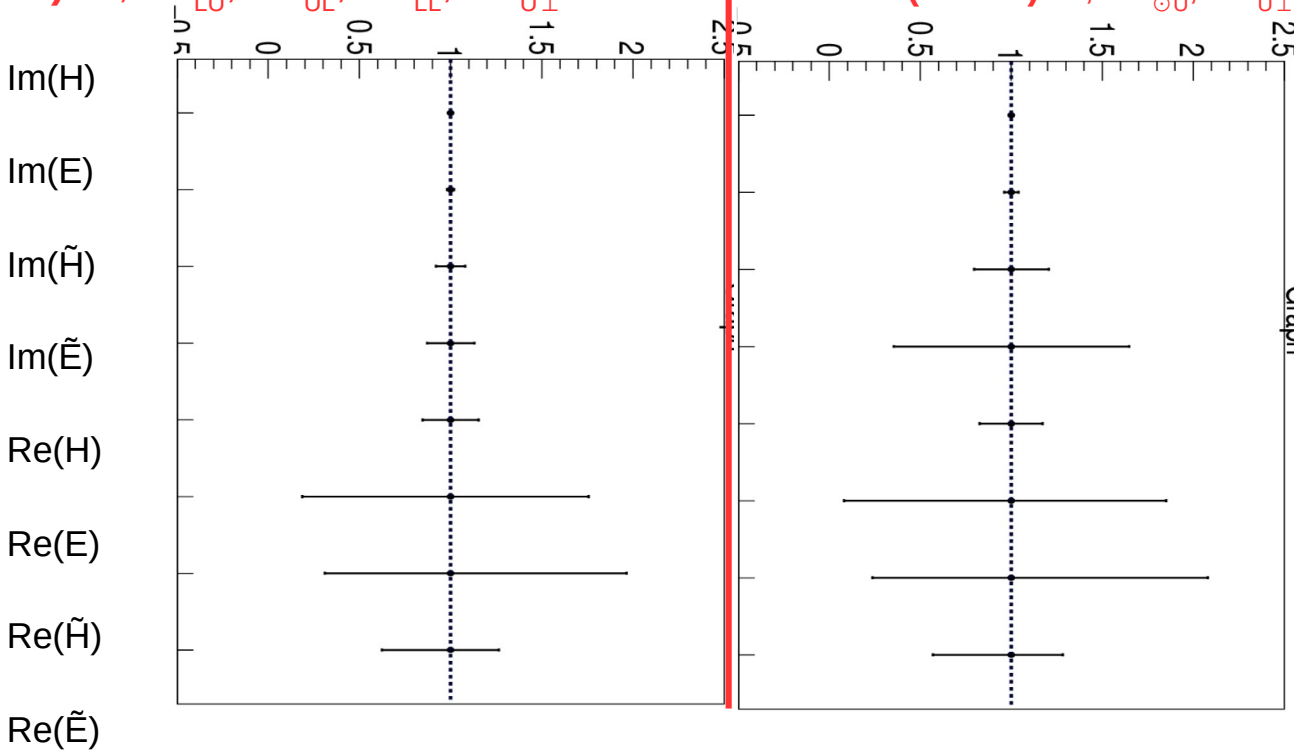

- **Unpolarized and polarized neutron**: off $LD_2$, $ND_3$...
- **Nuclear targets (Hall C, A?)**: possible extension of PR12-18-005 off unpolarized $N_2$
- **Precision unpolarized measurement (Hall C, A?):** off LH2, similar setup
- **Longitudinally polarized target (Hall C, A?):** single and double spin asymmetries (Im+Re $\tilde{H}$, E...)
- **Linearly polarized beam (GlueX ? Hall A/C ?)**: Re(H)

**Projections made for several observables, working on realistic MC and new proposals**

# Compton Form Factors extracted from DVCS and TCS at twist 2

**DVCS+TCS (6 independent obs.):** $\sigma$, $\Delta\sigma_{LU}$, $\Delta\sigma_{UL}$, $\Delta\sigma_{LL}$, $\Delta\sigma_{U\perp}$

**DVCS (4 obs.)**: $\sigma$, $\Delta\sigma_{LU}$, $\Delta\sigma_{UL}$, $\Delta\sigma_{LL}$
**+ TCS (4 obs.)**: $\sigma$, $\Delta\sigma_{\odot U}$, $\Delta\sigma_{U\perp}$




4+4 independent observables → equivalent 6 independent when combined

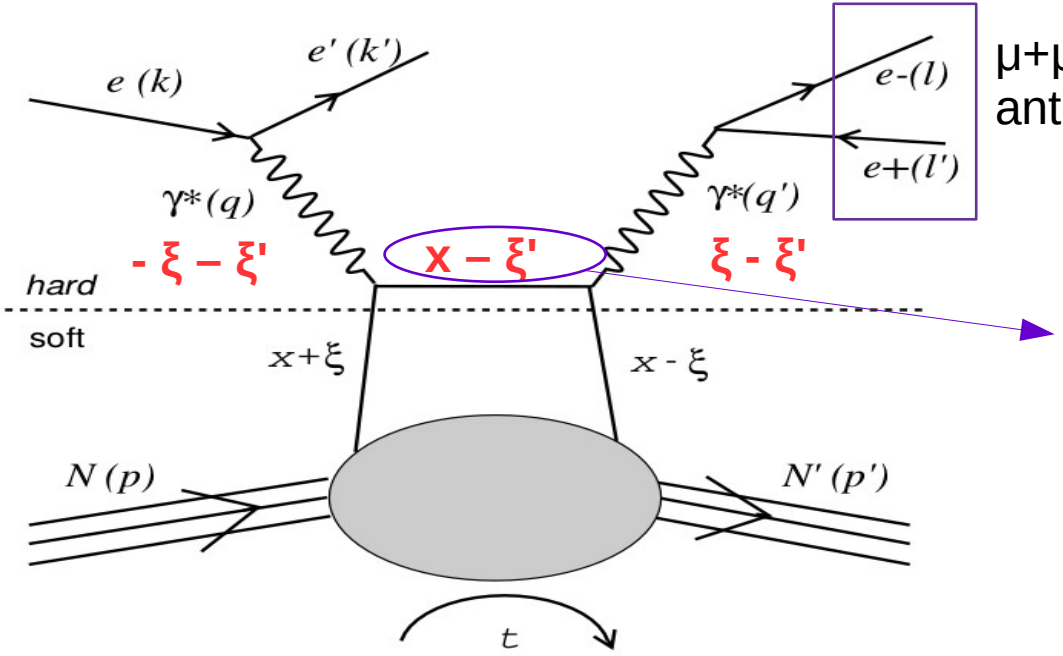
*assume low higher twist effects + GPD universality

Pseudo-data with 5% error on unpolarized $\sigma$, 7% pol. $\sigma$,16 bins $\varphi$, **8** params CFFs fits

JLab 12 GeV short term realistic scenario: unpolarized + beam pol. for both DVCS and TCS. longitudinal target single+double asym for DVCS, or transverse target for TCS

- Similar result combined fits with 4+4 observables than 6+6 observables → **all CFFs extracted**, independent information brought by the 2 processes

# Double Deeply Virtual Compton Scattering (notations)




μ+μ- → avoid antisymmetrisation

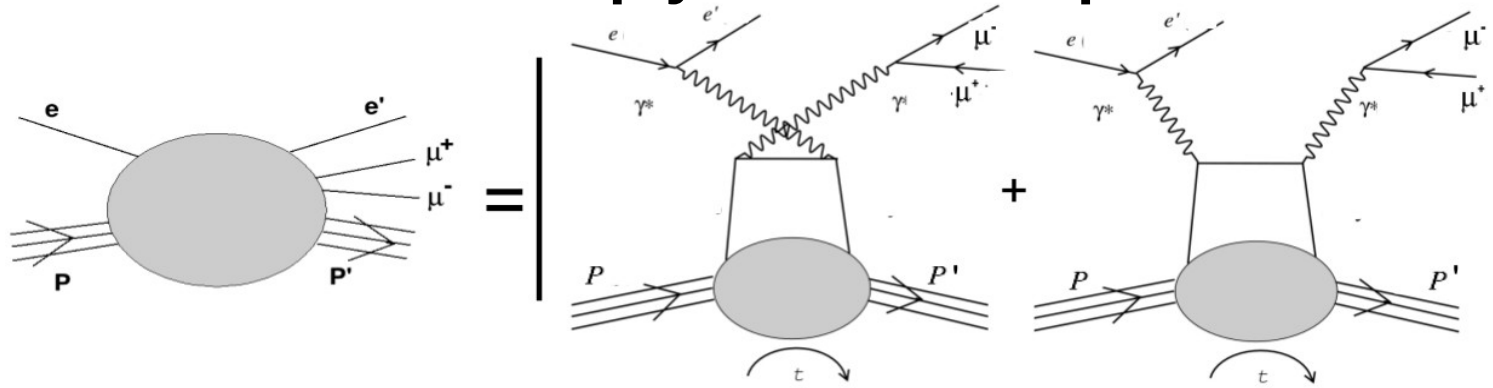
- ξ = + component of P=(p+p') in light cone frame. GPDs depend on it. "skewness"
- ξ' = + component of $\bar{q}$=(q+q')/2 in light cone frame. quark propagator can be related to $x_{bj}$

Special cases (at asymp. limit): DVCS: ξ'=ξ; TCS: ξ'=-ξ

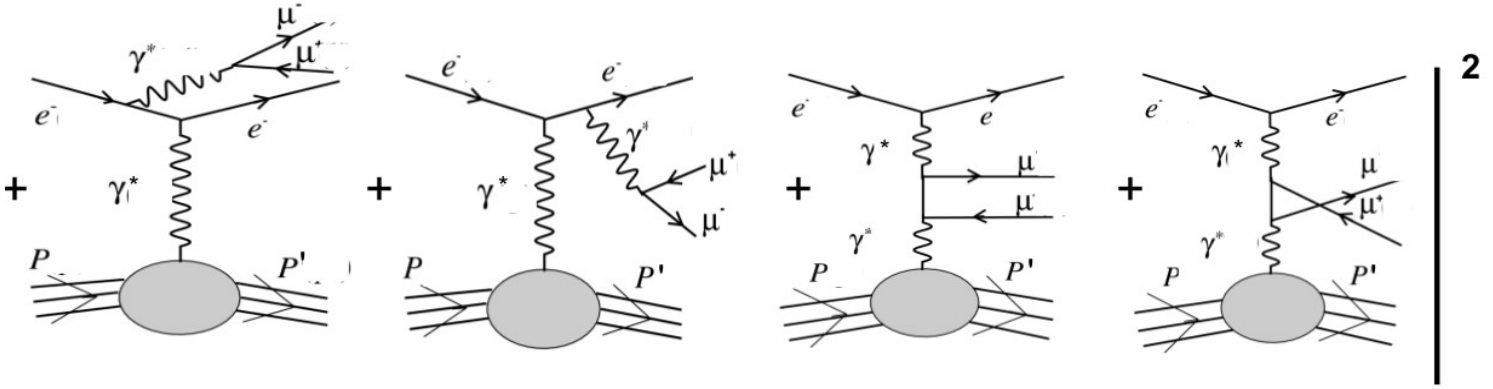
Mesons: fixing Q'² at meson mass squared

Lever arm to go "off diagonal"
Provided by relative virtuality of the photons

# Double Deeply Virtual Compton Scattering

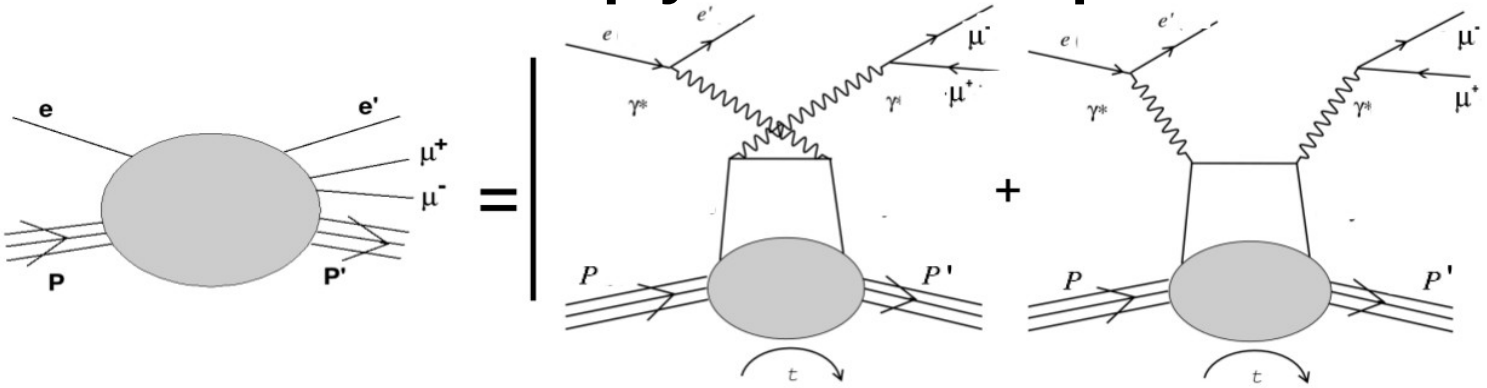



DDVCS



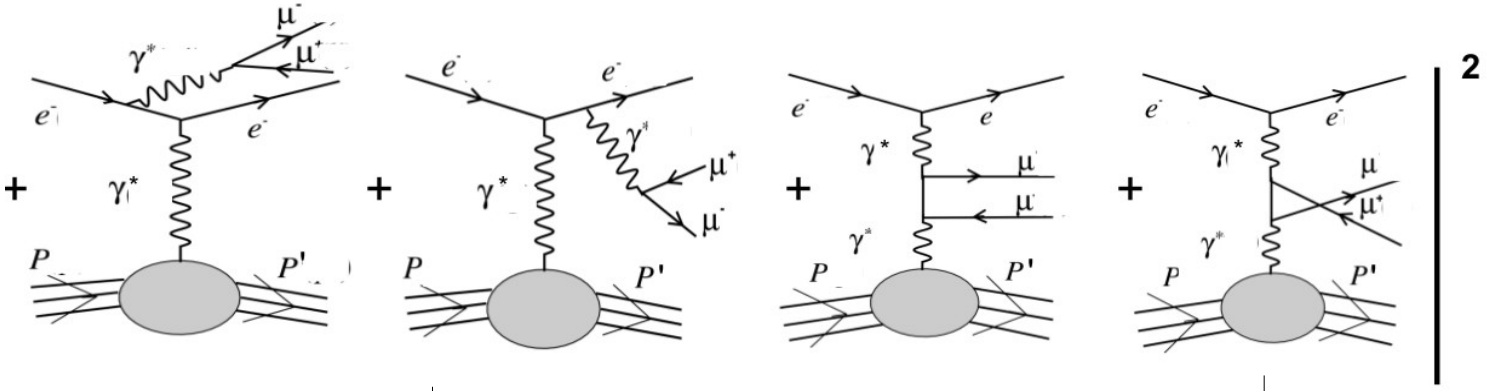

BH$_1$ BH$_2$

# Double Deeply Virtual Compton Scattering




no favored direction for γ* emission or decay leptons

**DDVCS**



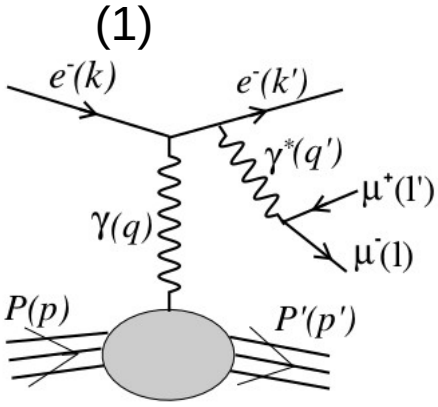

**$BH_1$**

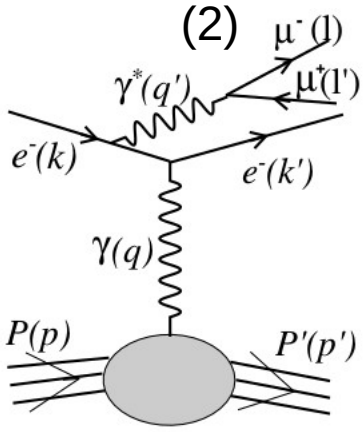
peak when γ' becomes collinear to e
related to $\varphi_{LH}$=0,
and depends $\cos\theta_{\gamma\gamma}$ (kinematics)
and "γ"→e' angle

**$BH_2$**

2 peaks when μ+ or μ- become collinear to γ
related to $\varphi_{LH}$=0 and 180°,
and depends $\cos\theta_{\gamma\gamma}$ (kinematics) which position
the value of $\theta_{CM}$ for the peaks

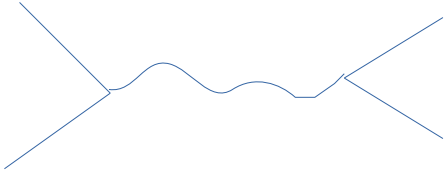
# Experimental and interpretation challenges



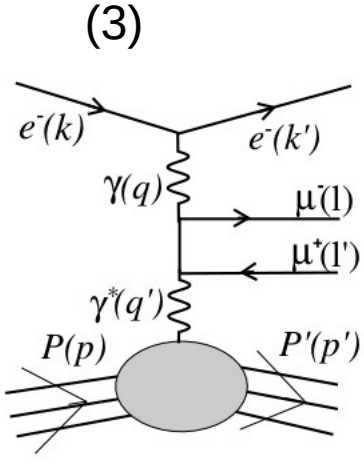



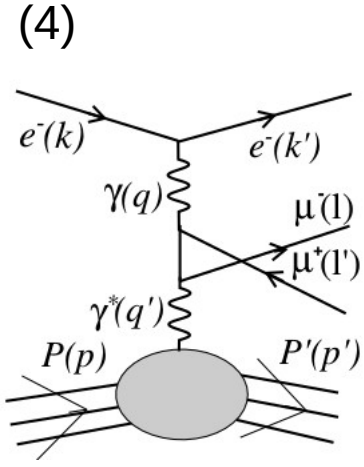

## Interference with Bethe-Heitler

equivalent to pair production from e+e- annihilation

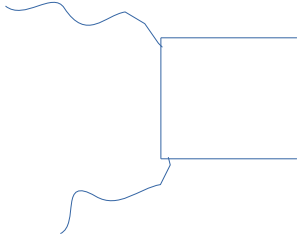


notations: γ1 connected to the beam and pair
and γ2 connected to the nucleon
see BH associated to DVCS when $Q'^2 \rightarrow 0$



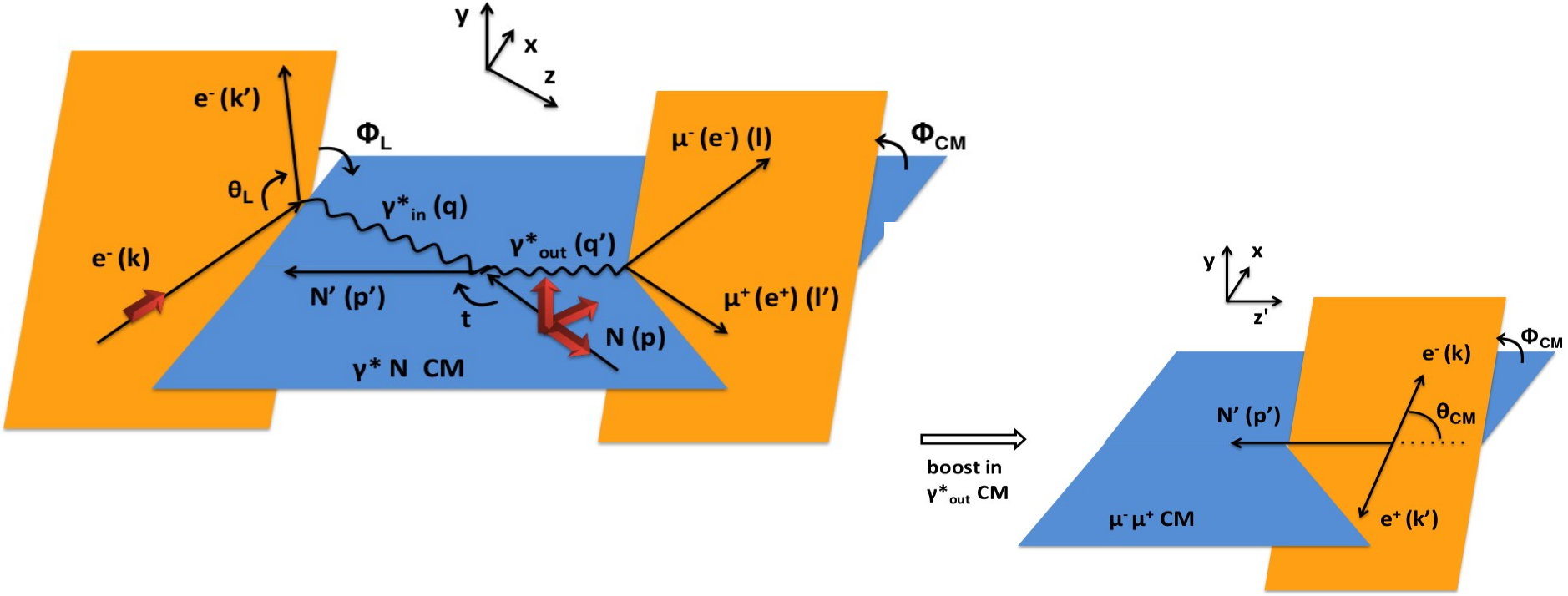




pair production from 2 virtual photons interaction

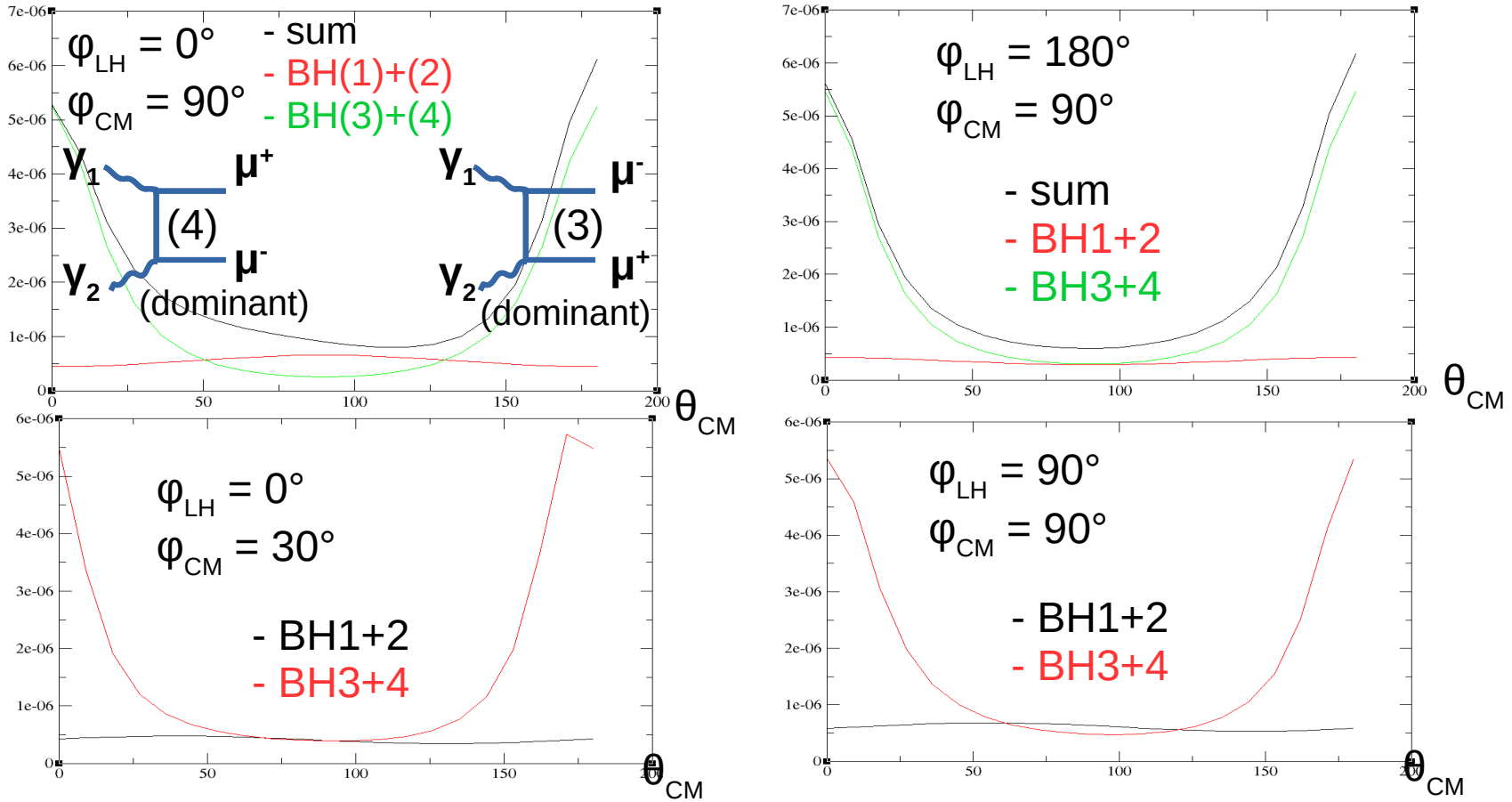


notations: γ1 connected to the beam
and γ2 connected to the nucleon
see "BH" associated to TCS when $Q^2 \rightarrow 0$

**Problem**: very complicated shapes in angular distributions. Coming from interferences between the different diagrams and correlations between the angles



# Dealing with Angular correlations: polar angle distributions

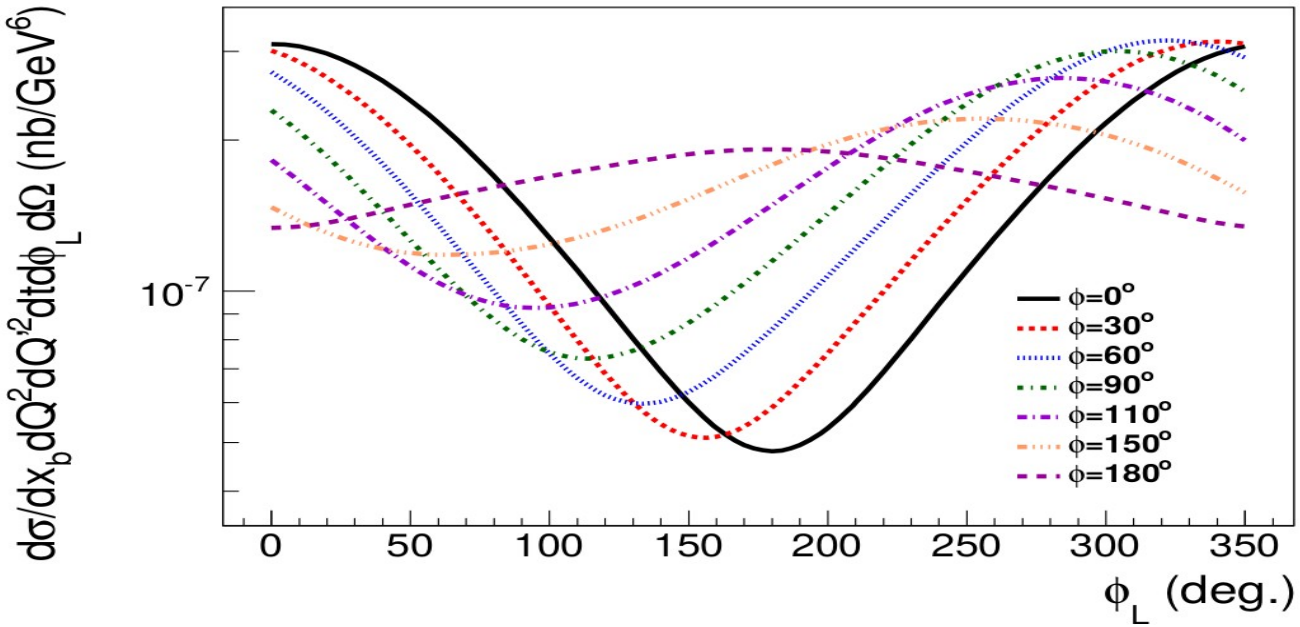



Can be understood from TCS phenomenology == importance to interpret DDVCS from TCS, not DVCS

peaks at 0° and 180° : associated to bh(3) and (4) peaks. bh(1) and (2) almost flat in θ

**All Figs**.: xbj=.24, $Q^2$=3.6 GeV², $Q'^2$=1.7 GeV², -t=.19 GeV². Axis: $d\sigma/dxdtdQ^2dQ'^2d\varphi d\varphi d\theta$ nb/GeV⁶

**correlation between the azymutal angles in DDVCS**



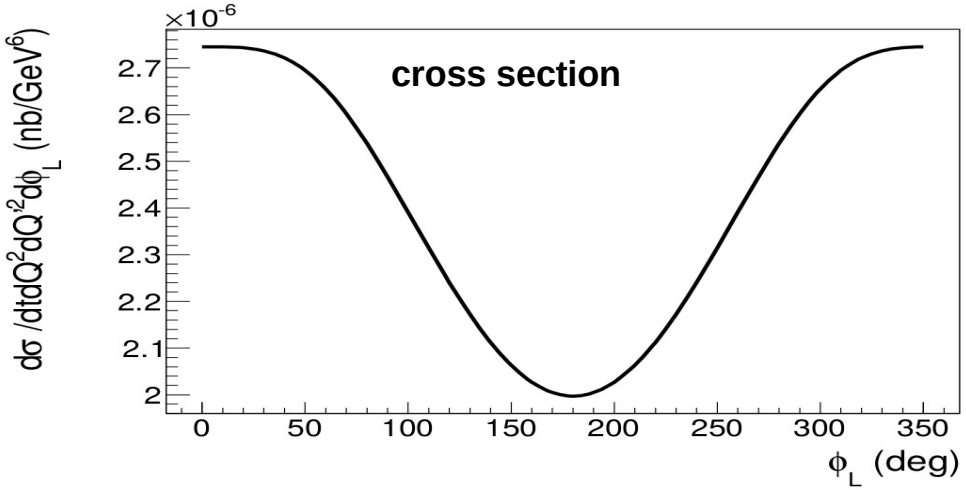

- To extract CFFs: 2D fits in $\varphi_{CM}$, $\varphi_{LH}$, as a function of ξ, ξ', t or ξ' replaced by $\langle Q^2/Q'^2 \rangle$ (bin)
- extract Im($\mathcal{H}$) (ξ', ξ, t) with unpolarized cross section and beam asym. (to measure first)

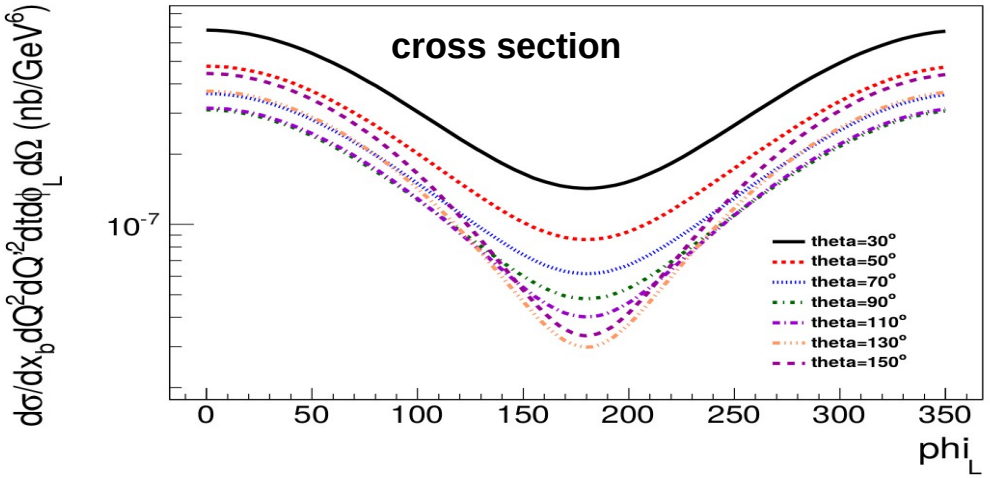
**GPDs from DDVCS can be extracted, but one need to**
**1) take angular correlation into account (similar than TCS)**
**2) 2 or 3D fits of angles**

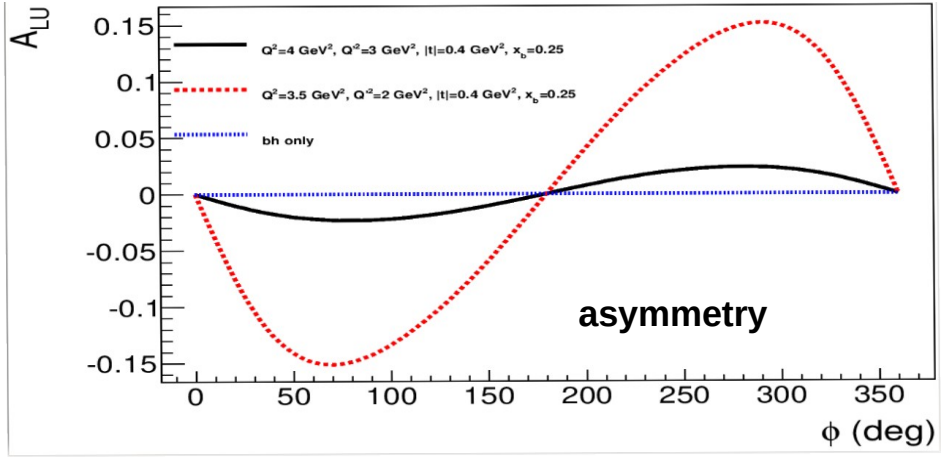
**$\varphi_L$ behavior**. similar than DVCS; **but correlations with final angles and "BH2"**

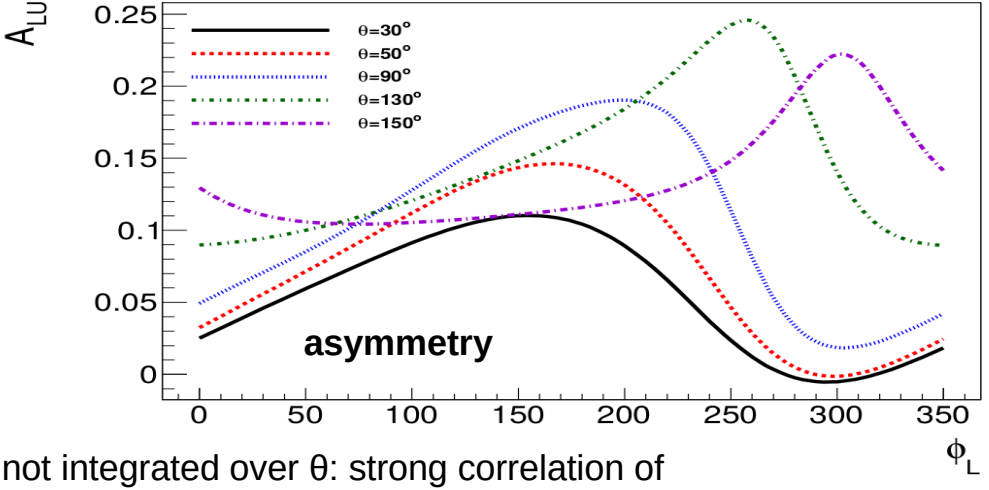
**$\Phi_{CM}$, $\theta_{CM}$: !!! difficult need good interpretation, redefinition of observables...**

# Observables for DDVCS measurements at JLab



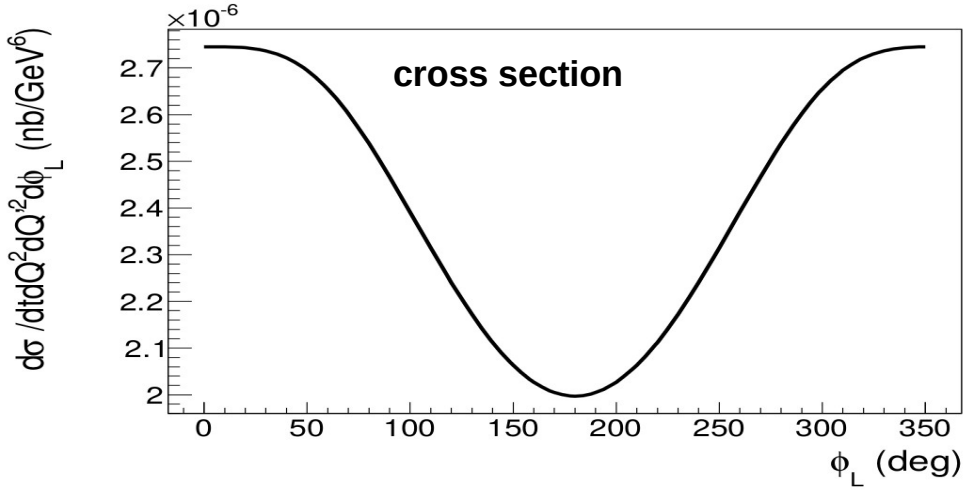



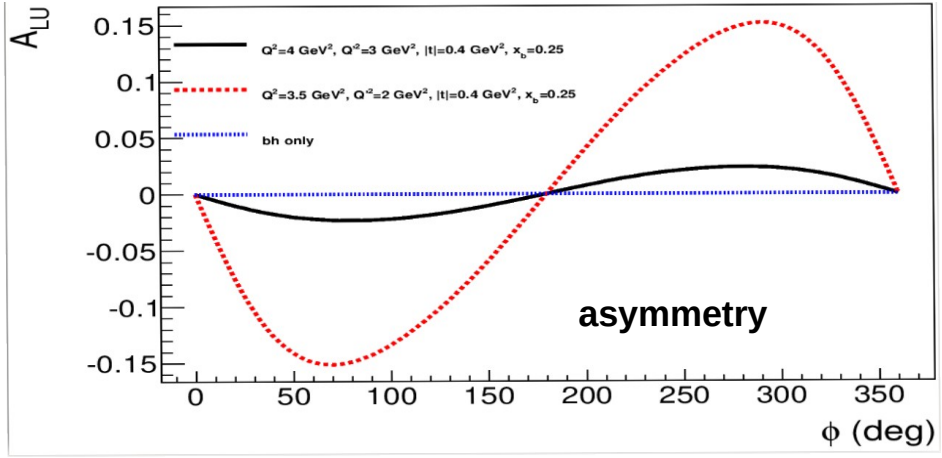




left= integrated over θ, right=not integrated

if not integrated over θ: strong correlation of $A_{LU}$ with θ (rate of "BH2")

# Observables for DDVCS measurements at JLab




left= integrated over θ, right=not integrated

**unpolarized cross section**
access |DDVCS|*|BH| term
it represent up to 10% of total x-section

can access Im(H), maybe Re(H)
if good enough precision on the measurement
also need $\varphi_{CM}$ vs $\varphi_{LH}$ mapping

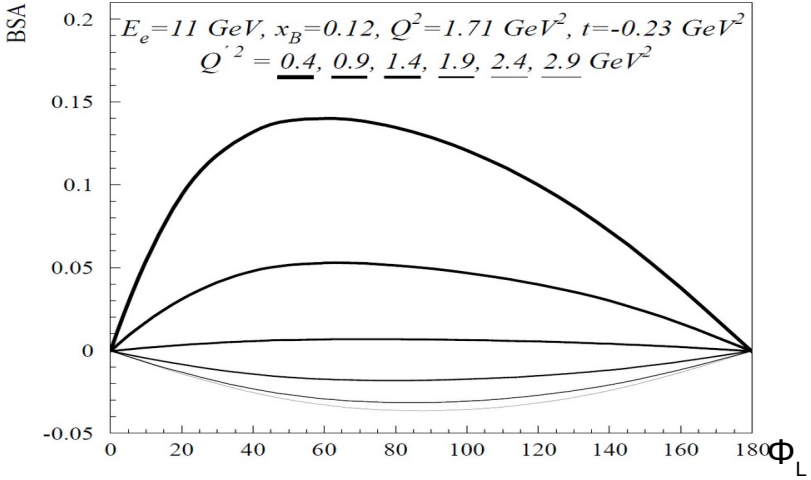
**beam spin asymmetry**.
purely coming from interference between BH(1+2)*DDVCS
asymmetries are sizeable.
however, shapes are complex
need of 2D $\varphi_{CM}$ vs $\varphi_{LH}$ mapping to access Im(H)
Change of sign to be observed in different kinematic regions

# Observables for DDVCS measurements at JLab

## Sign change in BSA and interplay “spacelike” “timelike” regions

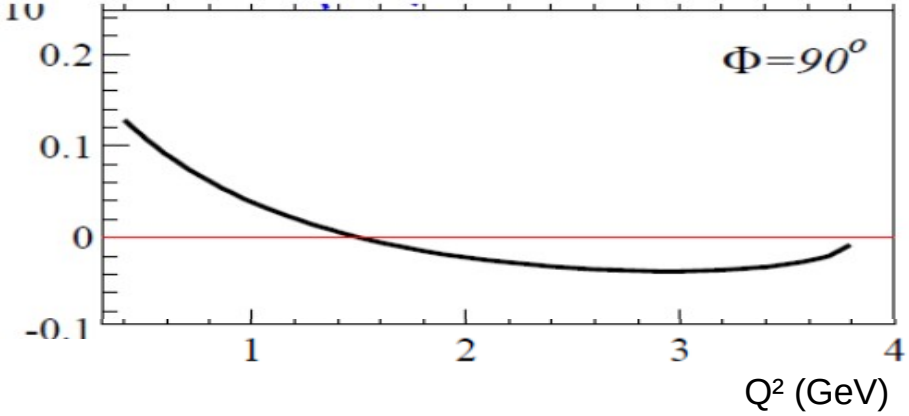
**Calculations from M. Guidal**

→ scan of BSA in $Q'^2$ at fixed $Q^2$




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

asymmetry $Q^2$ scan

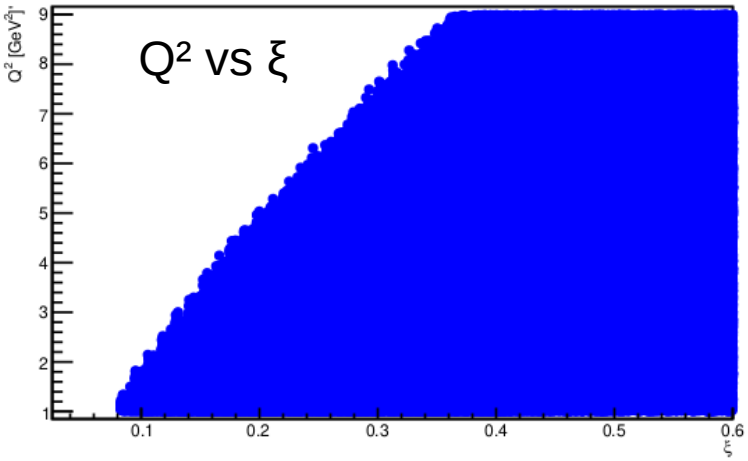


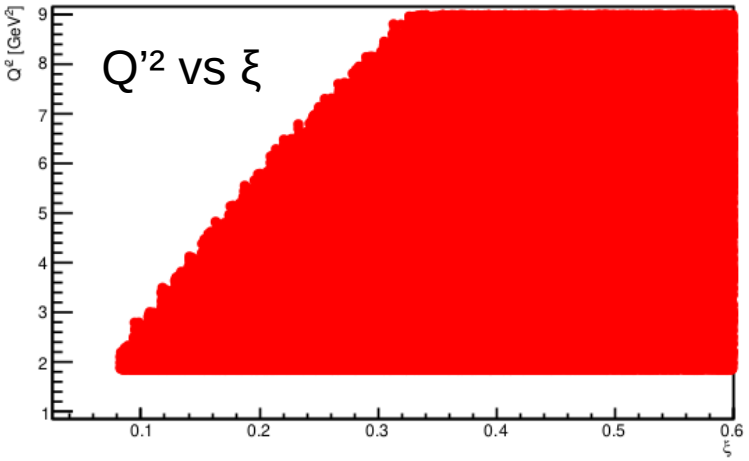

•Probing GPDs at $x \neq \xi$ → tomographic interpretations....

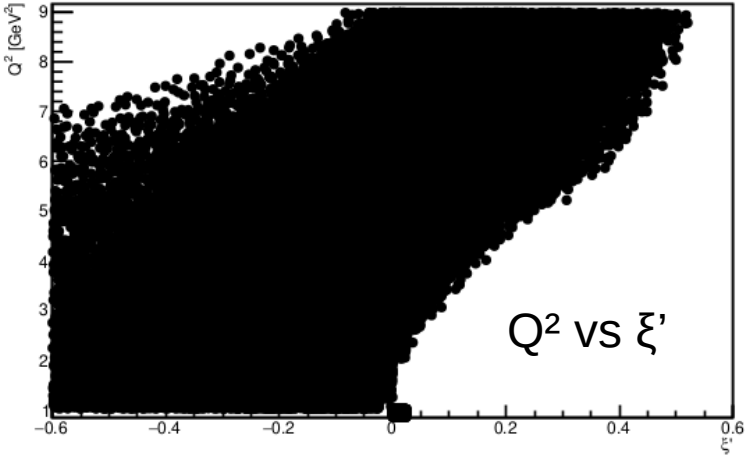
• Expectation of sign change for observables sensitive to Im (DDVCS) when moving from « spacelike » to « timelike » region

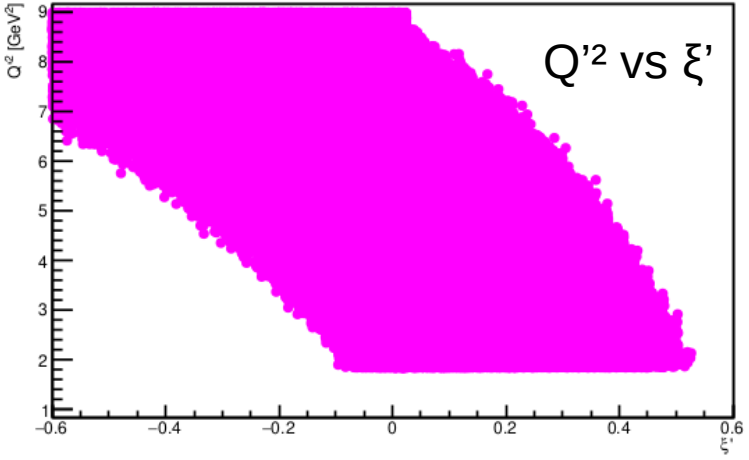
→ this reaction is unique for probing effects between these 2 regions.

# Accessible kinematics with DDVCS at JLab Hall C

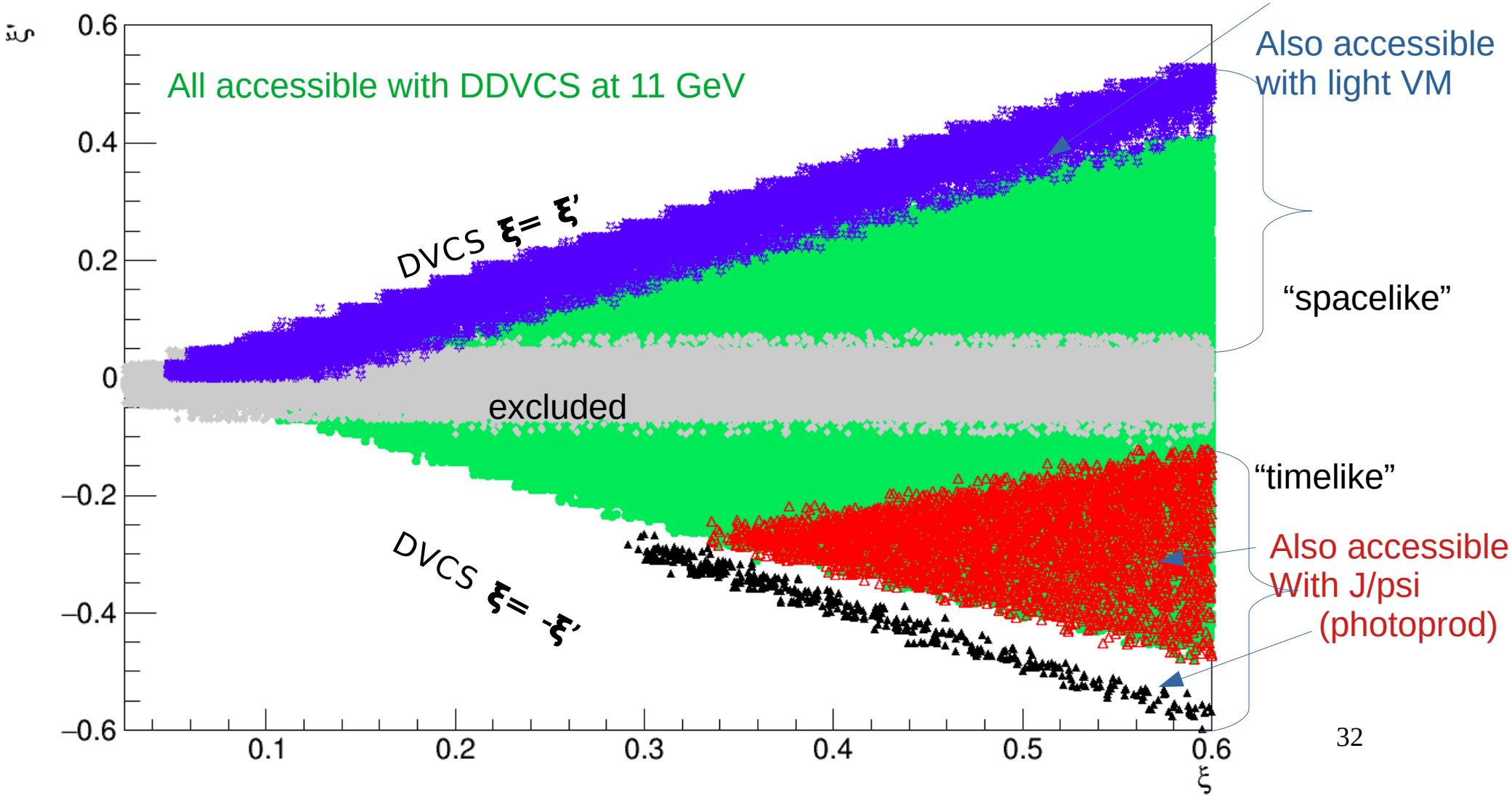


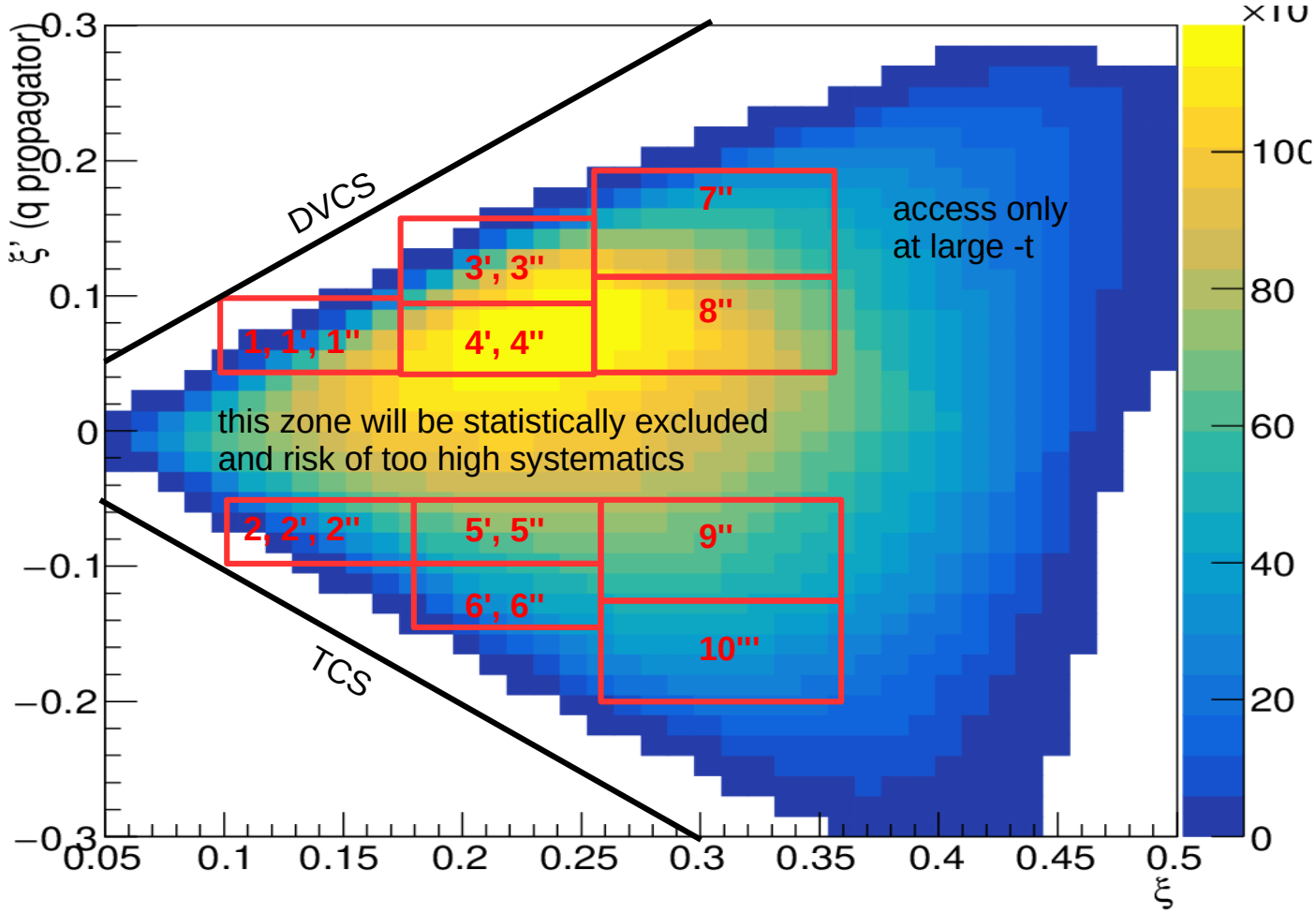



# ξ vs ξ' with DDVCS and other reactions



# Binning in ξ, ξ', all t: going "off-diagonal" for tomographic views



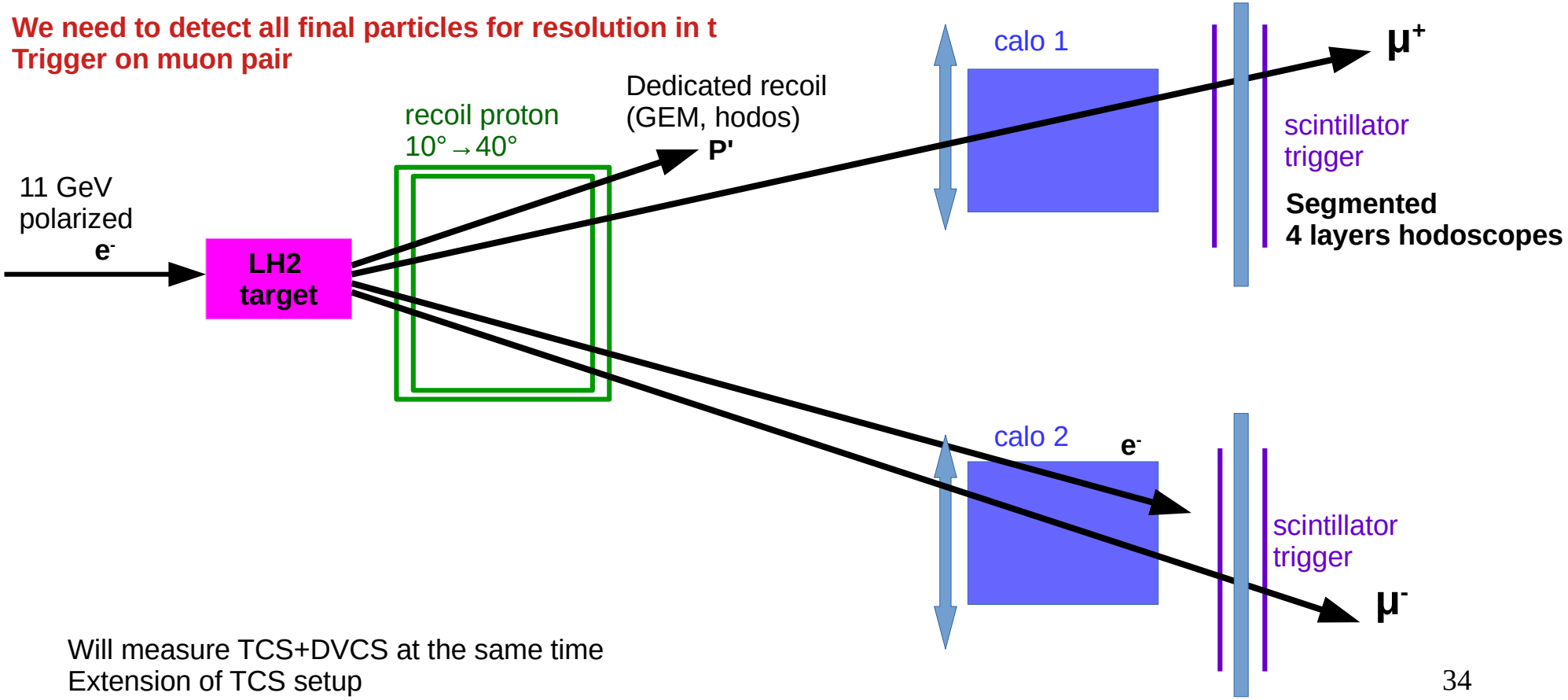

| Bin in ξ | code # large/low t |
|---|---|
| A) .1 < ξ < .18 (all t bins) | |
| 1) .05 < ξ' < .1 | 1, 7, 17 |
| 2) -.05 > ξ' >-.1 | 2, 8, 18 |
| B) .18 < ξ < .26 (t bins 2 and 3) | |
| 3) .1 < ξ' < .15 | 3, 9 |
| 4) .05 < ξ' < .1 | 4, 10 |
| 5) -.05 > ξ' > -.1 | 5, 11 |
| 6) -.1 > ξ' > -.15 | 6, 12 |
| C) .26 < ξ < .36 (t bin 3) | |
| 7) .12 < ξ < .2 | 13 |
| 8) .05 < ξ < .12 | 14 |
| 9) -.05 > ξ > -.12 | 15 |
| 10) -.12 > ξ > -.2 | 16 |

Bins in t: (1) 0 < -t < 0.15 GeV², (2) 0.15 < -t < 0.35 GeV², (3) 0.35 < -t < 0.55 GeV² (indicated ', '')

# Possible setups for DDVCS in Hall C

**ideal detector position for different bins, assuming previous distributions "at vertex" are similar to the one with magnetic field**
**symmetric configuration for μ+ and μ- ⇒ better for interpretation and treatment of BH2**

**We need to detect all final particles for resolution in t**
**Trigger on muon pair**

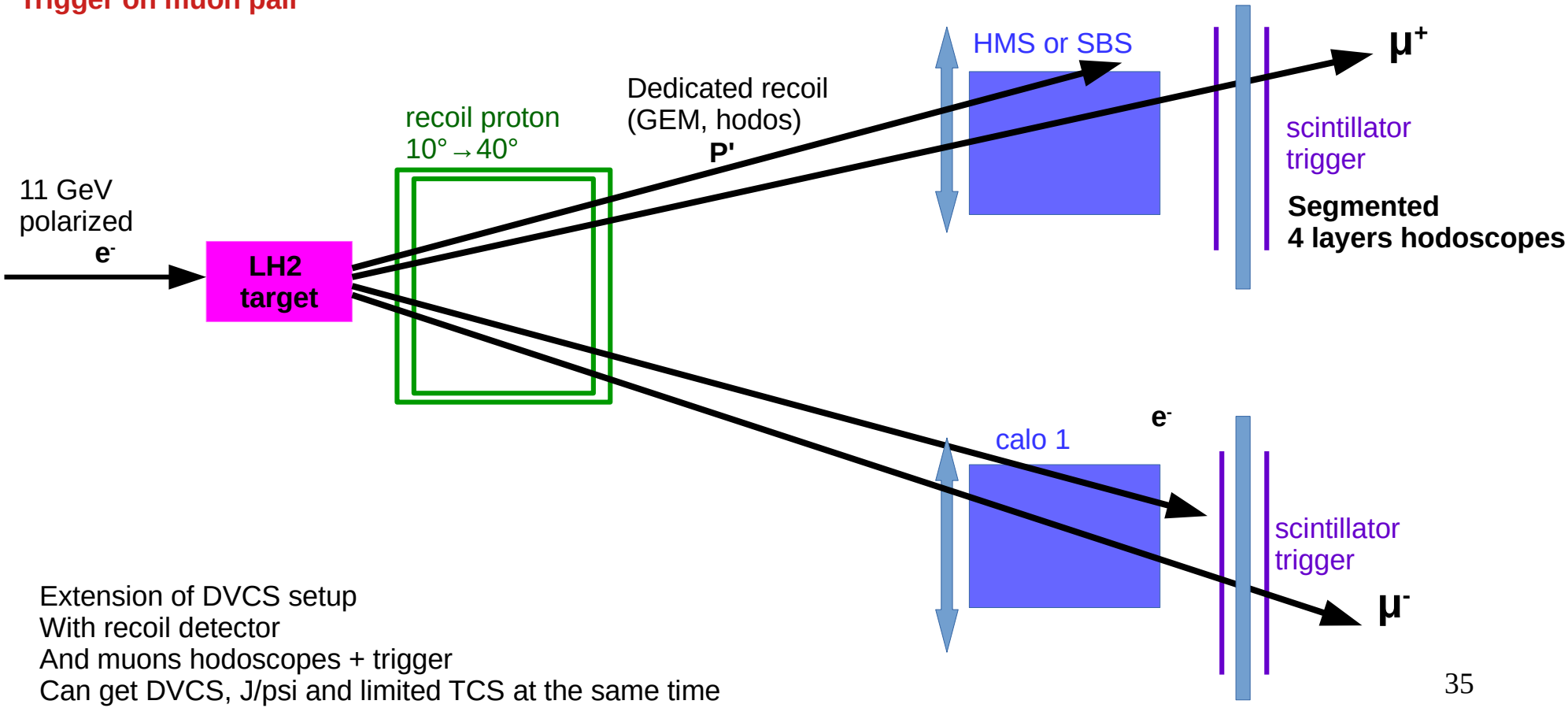



Will measure TCS+DVCS at the same time
Extension of TCS setup

# Possible setups for DDVCS in Hall C

**asymmetric configuration for μ+ and μ- ⇒ wider acceptance and can go together with DVCS (and VM?)**

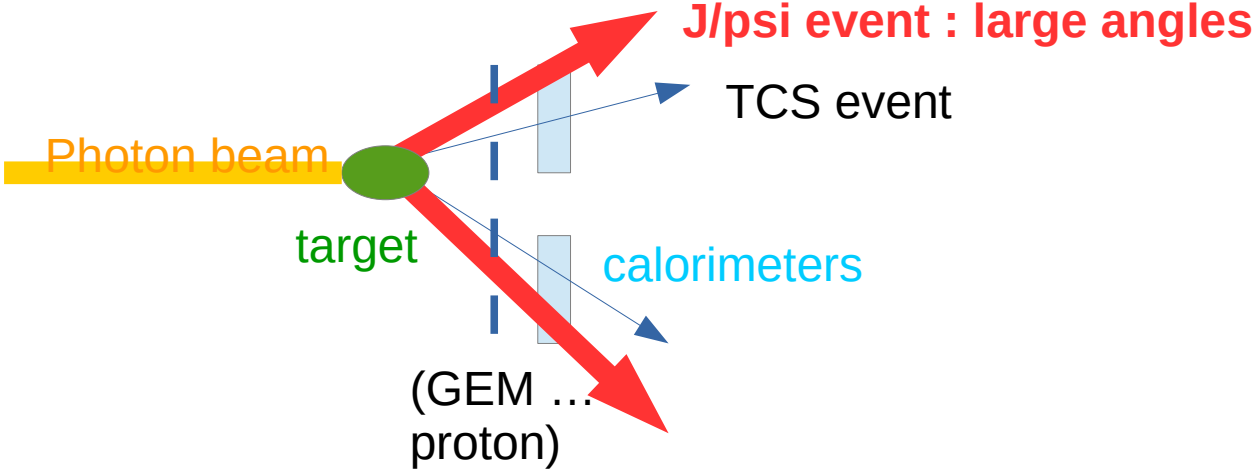
**We need to detect all final particles for resolution in t**
**Trigger on muon pair**




Extension of DVCS setup
With recoil detector
And muons hodoscopes + trigger
Can get DVCS, J/psi and limited TCS at the same time

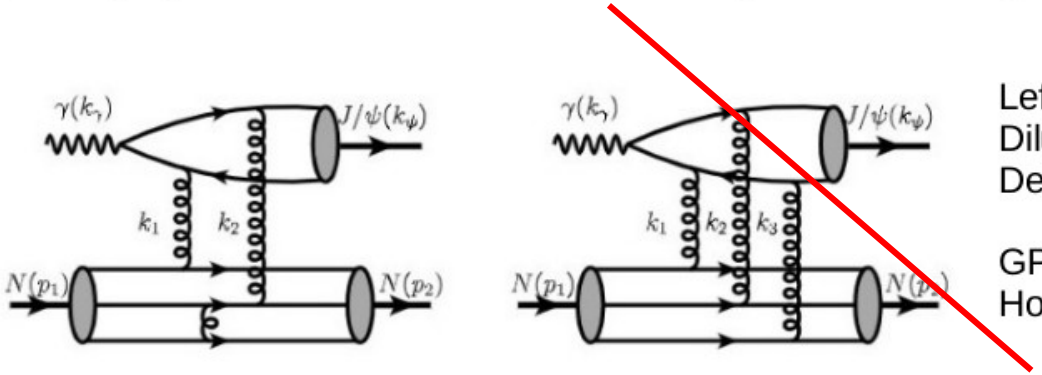
# Heavy meson: polarized J/ψ [near threshold – or energy upgrade]

"starting from TCS setup"




C-parity violiation? Factorization?

- New magnet allow extension to parallel measurements of J/psi near threshold transverse target (never proposed, MC studies done – our setup can do it at larger angles)

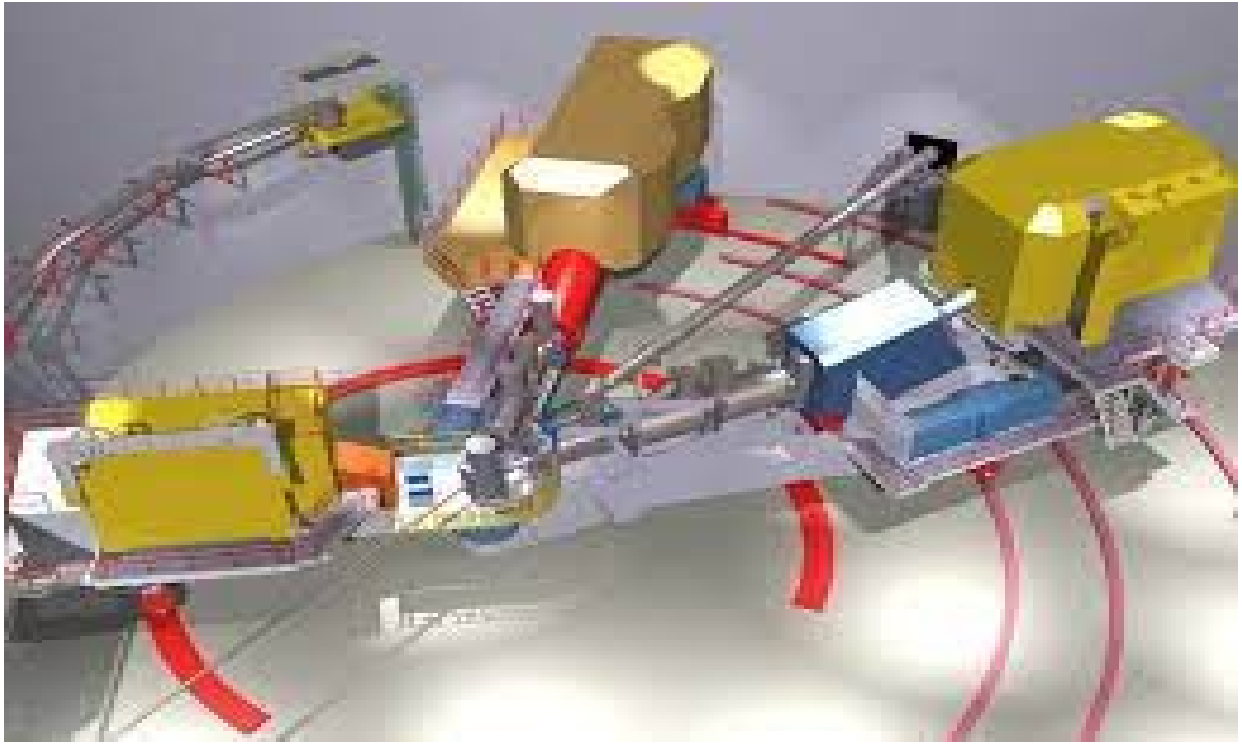



Left-right asymmetries:
Diluted, or large?
Depends on production mechanism

GPD interpretation near threshold?
How to parametrize N structure?

# Going further with light VM

* currently exploring what can be done in Hall C and how, with minimal technical developments.



**ρ, φ:**
Minimal modifications, SHMS+HMS. Need cherenkov for PID

**ω:** added NPS

Without intensity and energy upgrade: polarized measurements, already learn a lot

With energy upgrade: ‘mass” and energy evolution for VM. Improve both GPD knowledge and meson wave-function parametrization, also critical for GPD interpretations

# SUMMARY

- Most GPD models constrained by DVCS, most of the measurements and future experiments
  Only so much can be accessed with DVCS:: universality, NLO, higher twist, deconvolution...
- DDVCS is a “golden channel” for GPD studies to deconvolute x and xi, interplay between spacelike and timelike region…
  - developing muon detector for Hall C
  - new experiments to be proposed in 2023, Hall A, B, C at JLab
- TCS for GPD universality, studies of higher twist, unique access to some observables...
- Meson: flavor separation, spin, lever arm with mass… Need theory+exp work together
- Currently developing full program for high precision measurements at JLab Hall C and A for TCS, DDVCS and VM (light and heavy) for multi-channel approach
  - Developing full GEANT4 and finalizing projections
  - Developing muon detector for Hall C DDVCS and VM
  - Looking for more collaborators