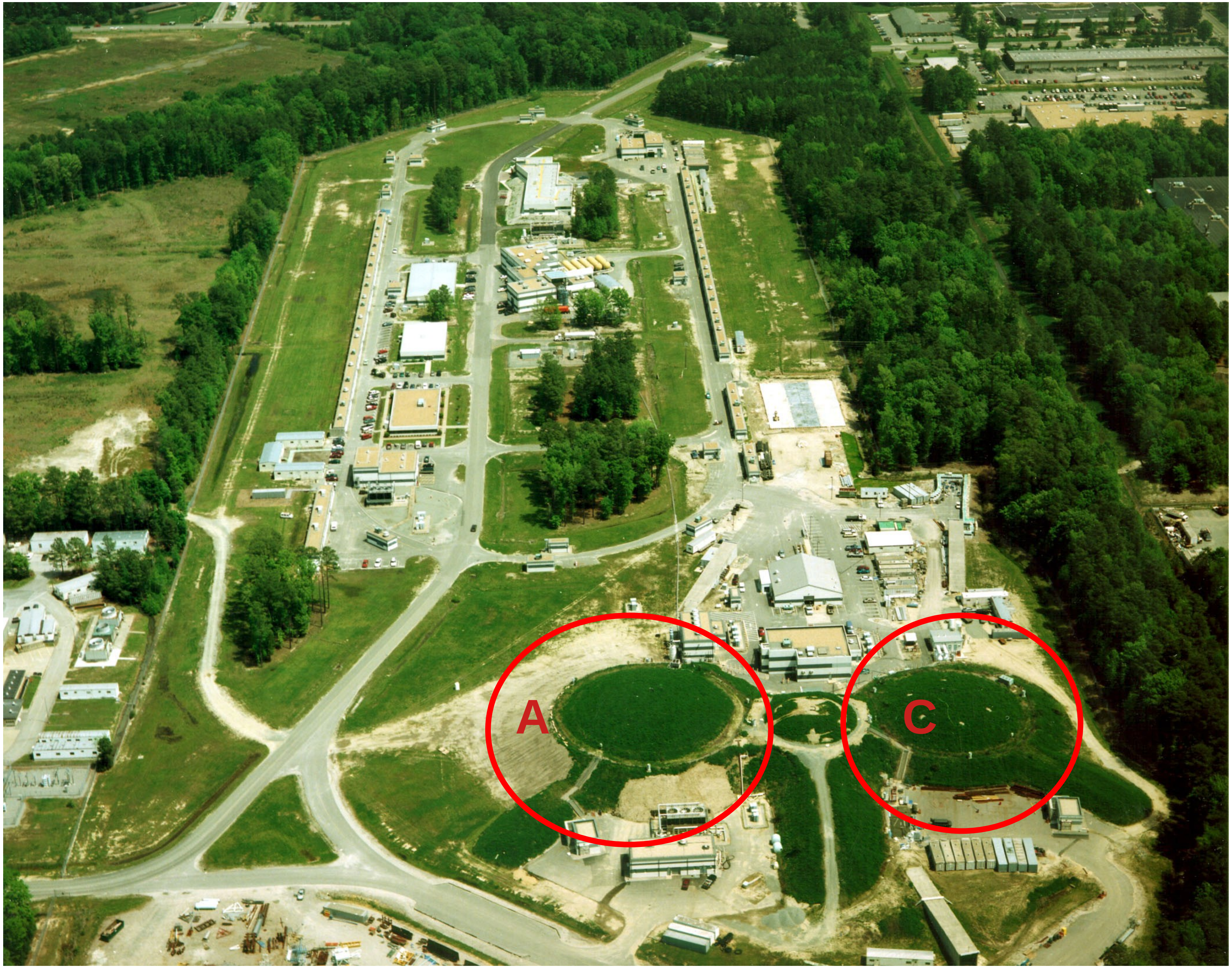
Generalized Parton Distributions

Current and future programs for hard exclusive physics at JLab Hall A & C

Marie Boër (Virginia Tech)

CIPANP, Lake Buena Vista, FL, Sept 1st, 2022

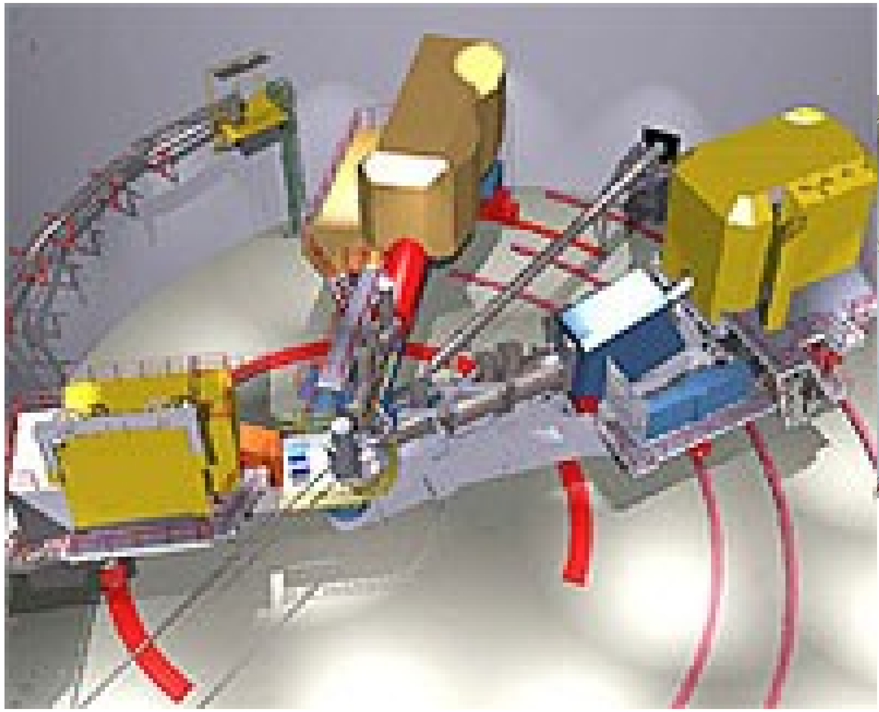
Jefferson Lab and CEBAF accelerator site
Newport News, VA



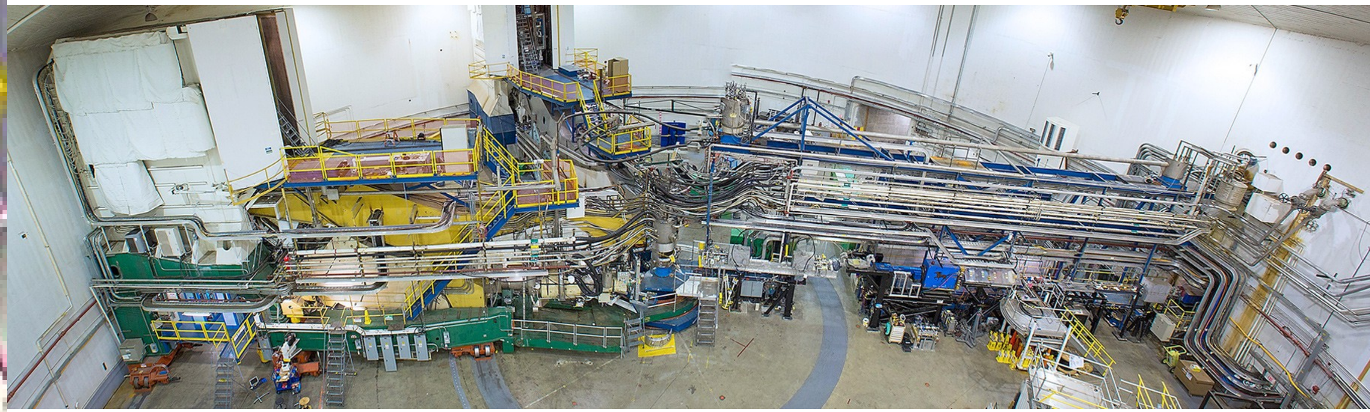
Hall A and Hall C “inside the hills”

Hall A & C low acceptance high resolution spectrometer,
medium energy, high intensity beam, dedicated experiments

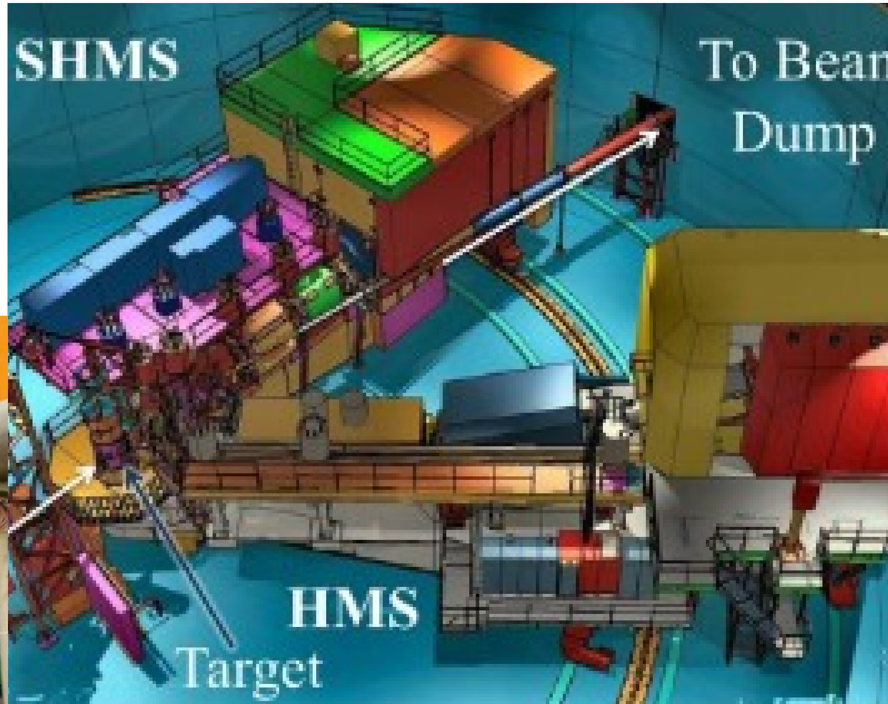
1995 – present
Current configurations



A

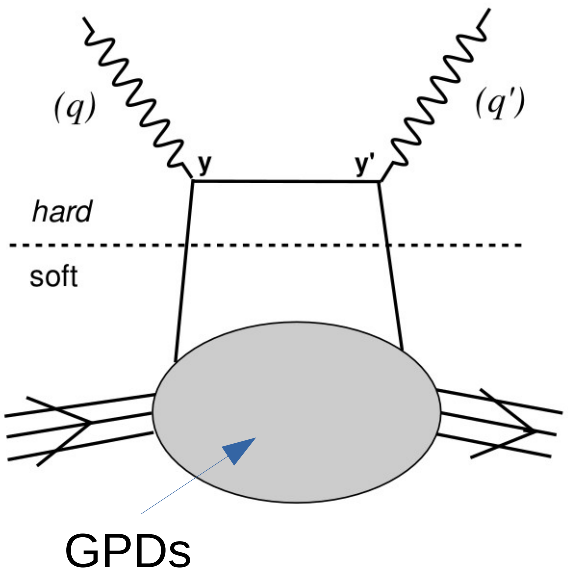


C

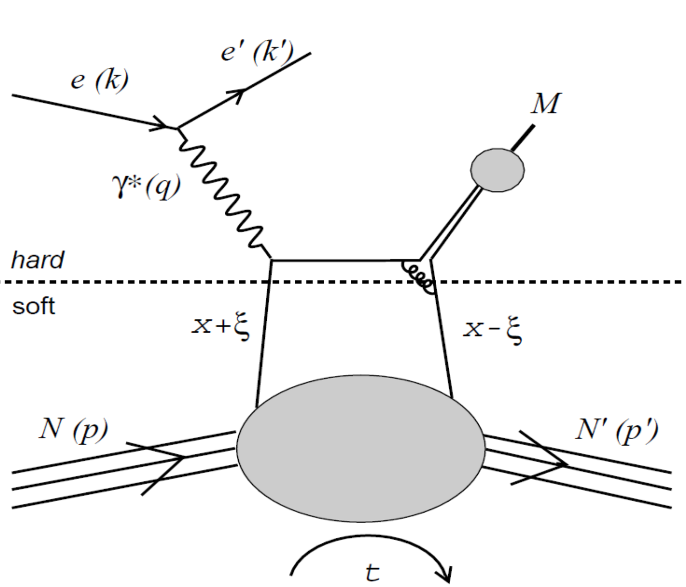


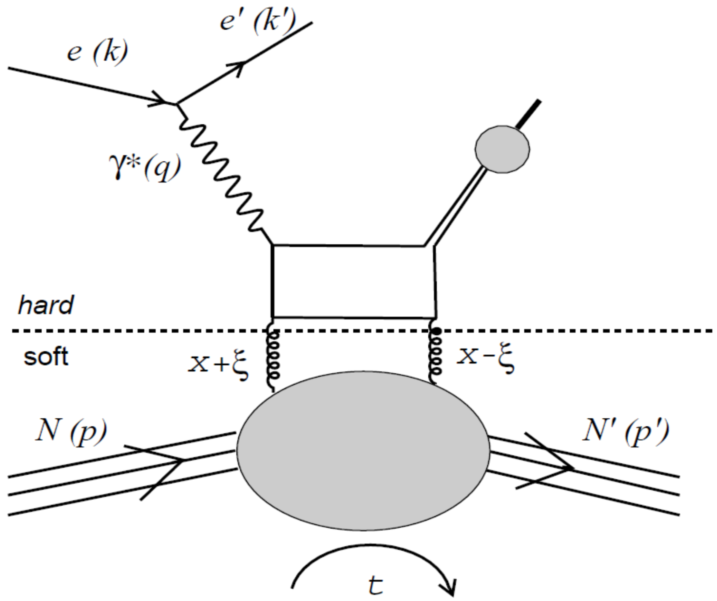
Hard Exclusive reactions and Generalized Parton Distributions

Compton-like



Mesons (HEMP)





Leading order diagrams for Compton-like, light or heavy flavored meson production at JLab

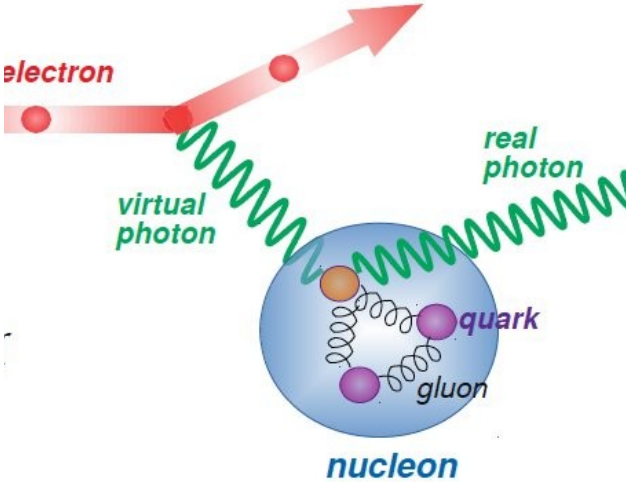
Compton like: DVCS, TCS, DDVCS with spacelike and/or timelike photons; multi-photons…

Mesons:
- VM with the same spin-parity as for photons, factorization is proved, complement multi-channel approaches in fitting GPDs
- Pseudo-Scalar: access “parity odd” combinations
- Other and multi-mesons: chiral-odd GPDs… / Transisition GPDs
- Heavy mesons, quarkonia: can we interpret in terms of GPDs at JLab?

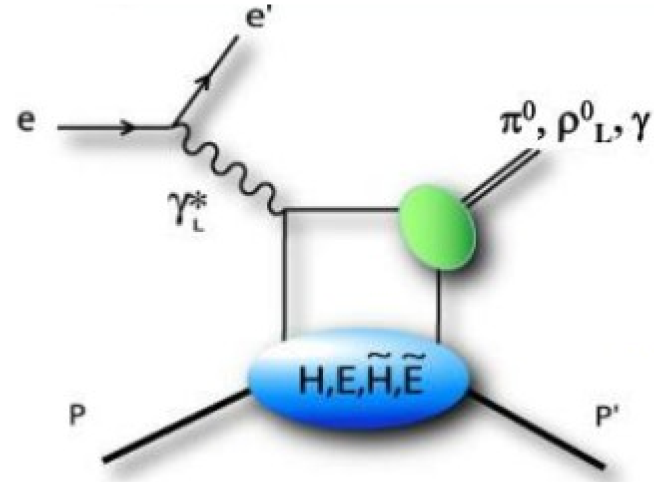
Flavor decomposition with P vs N and with mesons

Generalized Parton distributions: 2+1D in position space

GPDs contain information about correlation between transverse distribution and longitidinal mom x.



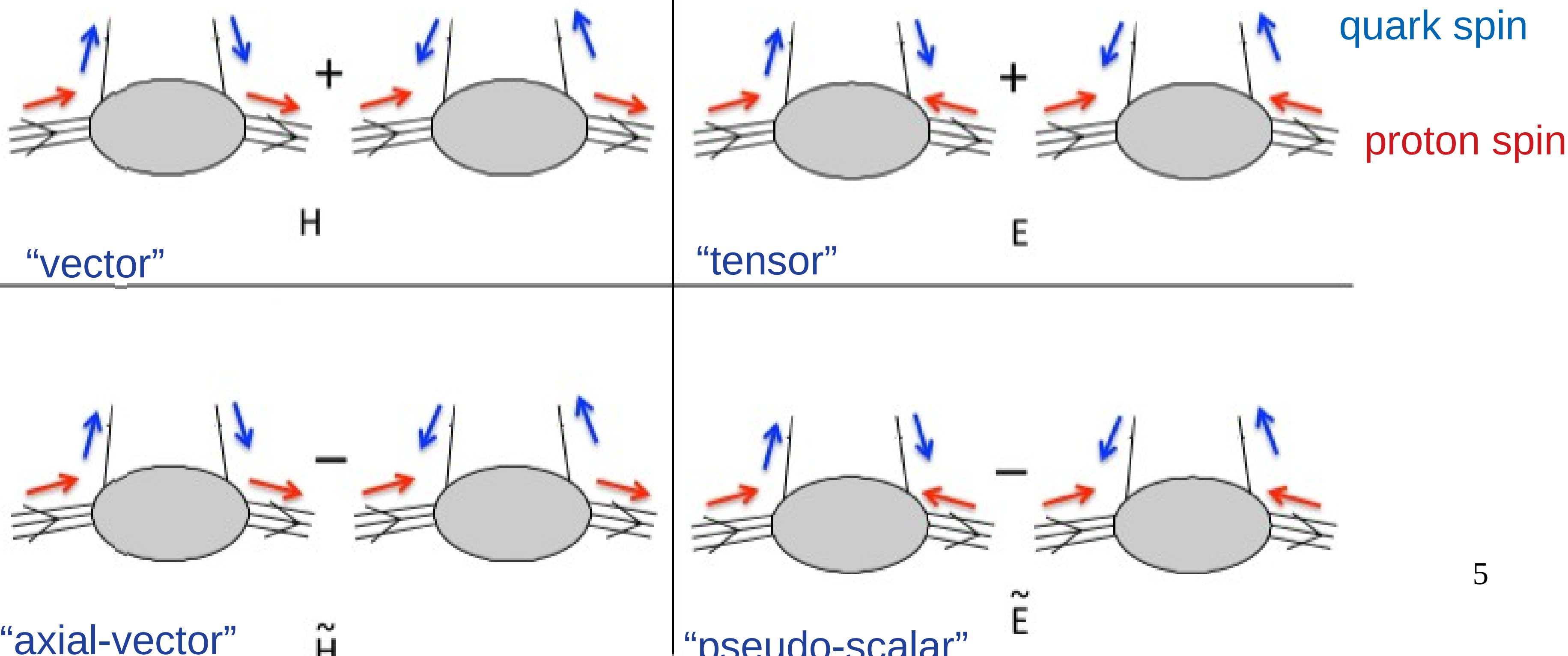
Proton remains intact,
all final particle detected:
exclusive scattering



without nucleon spin flip | **with nucleon spin flip**

unpolarized GPDs

polarized GPDs



Motivations

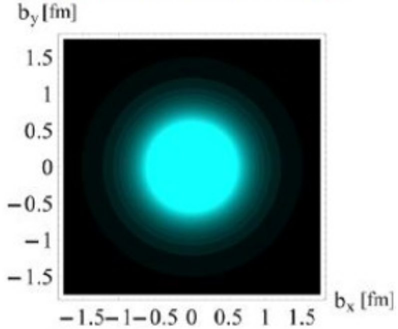
3D mapping of the nucleon ⇒ tomography

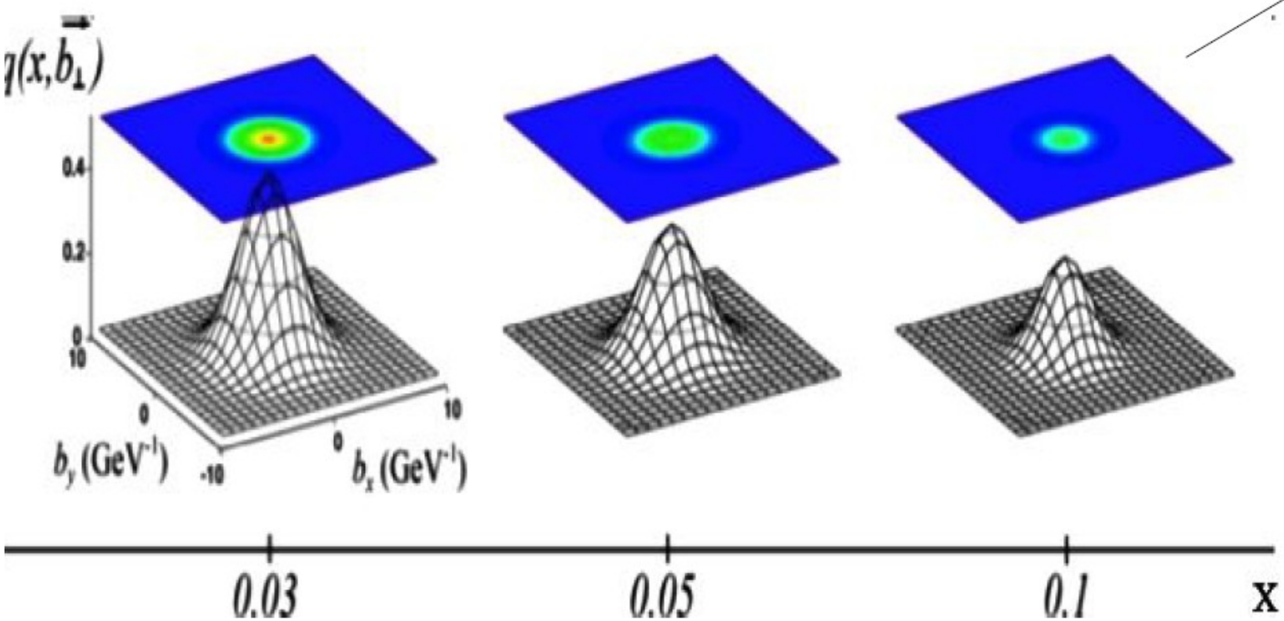
Transverse parton distributions for different region in x
→ probabilistic interpretation ≡ gluons, valence quark regions

"momentum dissected Form Factors"

integral over x

transverse charges from Elastic Scat.





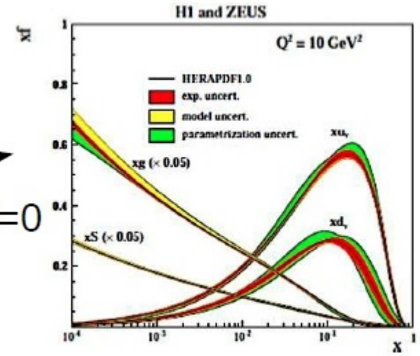
gluons dominate

gluons, sea quarks "meson cloud"

valence quarks region

parton densities from Deep Inelastic Scat.

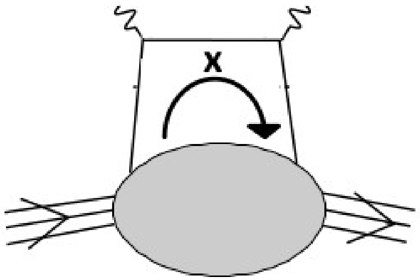
t=0



Spin physics: sum rules...

Multi-reactions fitting approach

ξ, t = measurable
x = loop
x±ξ = propagator



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

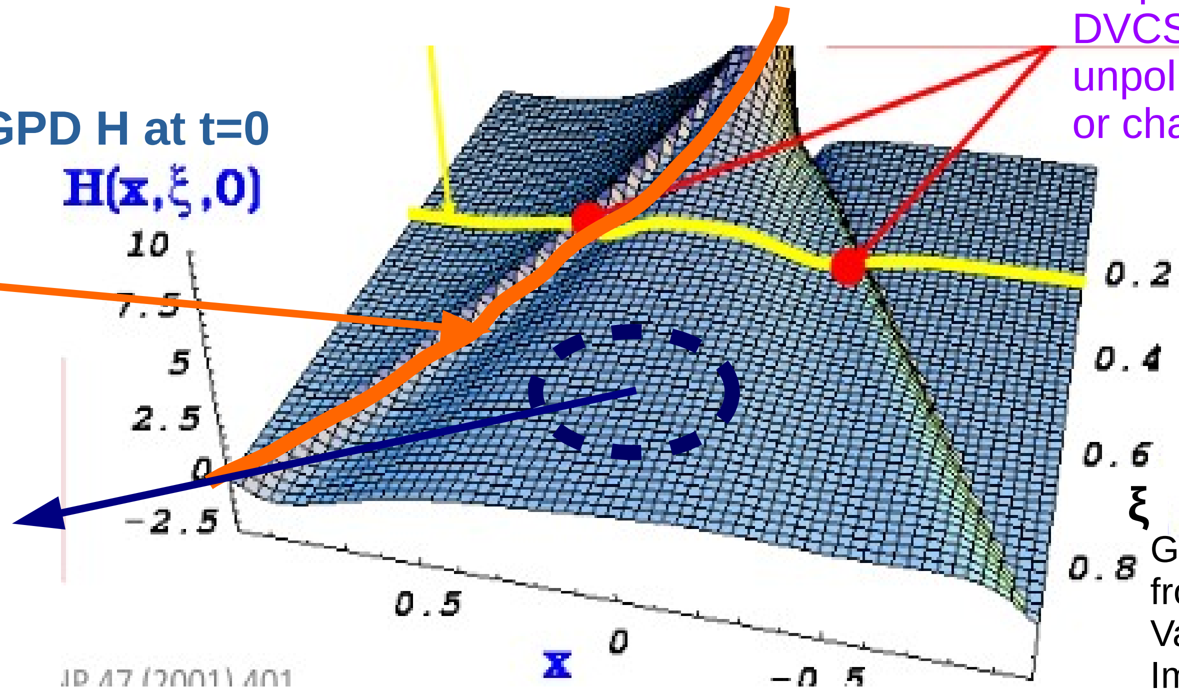
Re (CFF noté $\mathcal{H}$) $(\mathcal{H})$ Im $(\mathcal{H})$

Compton Form Factor
Indirect access to GPDs
Here : propagator for DVCS or TCS. With DDVCS or HEMP, “lever arm”with Q’² or M

Re part → ∫dx GPD
DVCS and TCS,
unpol or double pol. σ
or charge asymmetries

GPD H at t=0

Im part → GPD at x= ± ξ
DVCS and TCS unpol σ,
single spin pol. σ



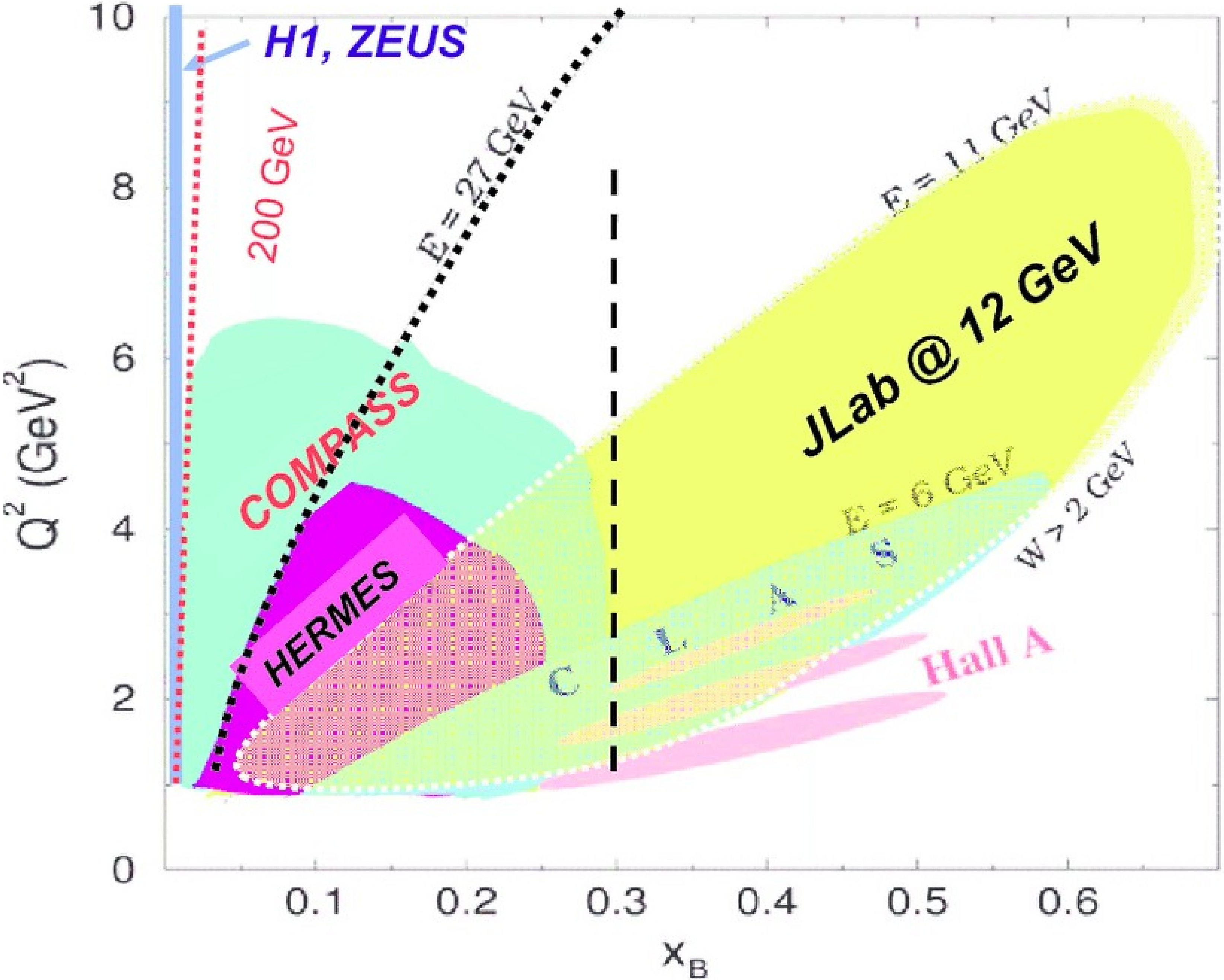
Off diagonal:
DDVCS, HEMP

GPD in VGG model, from Guichon, Vanderhaeghen, Guidal
Image: M. Guidal

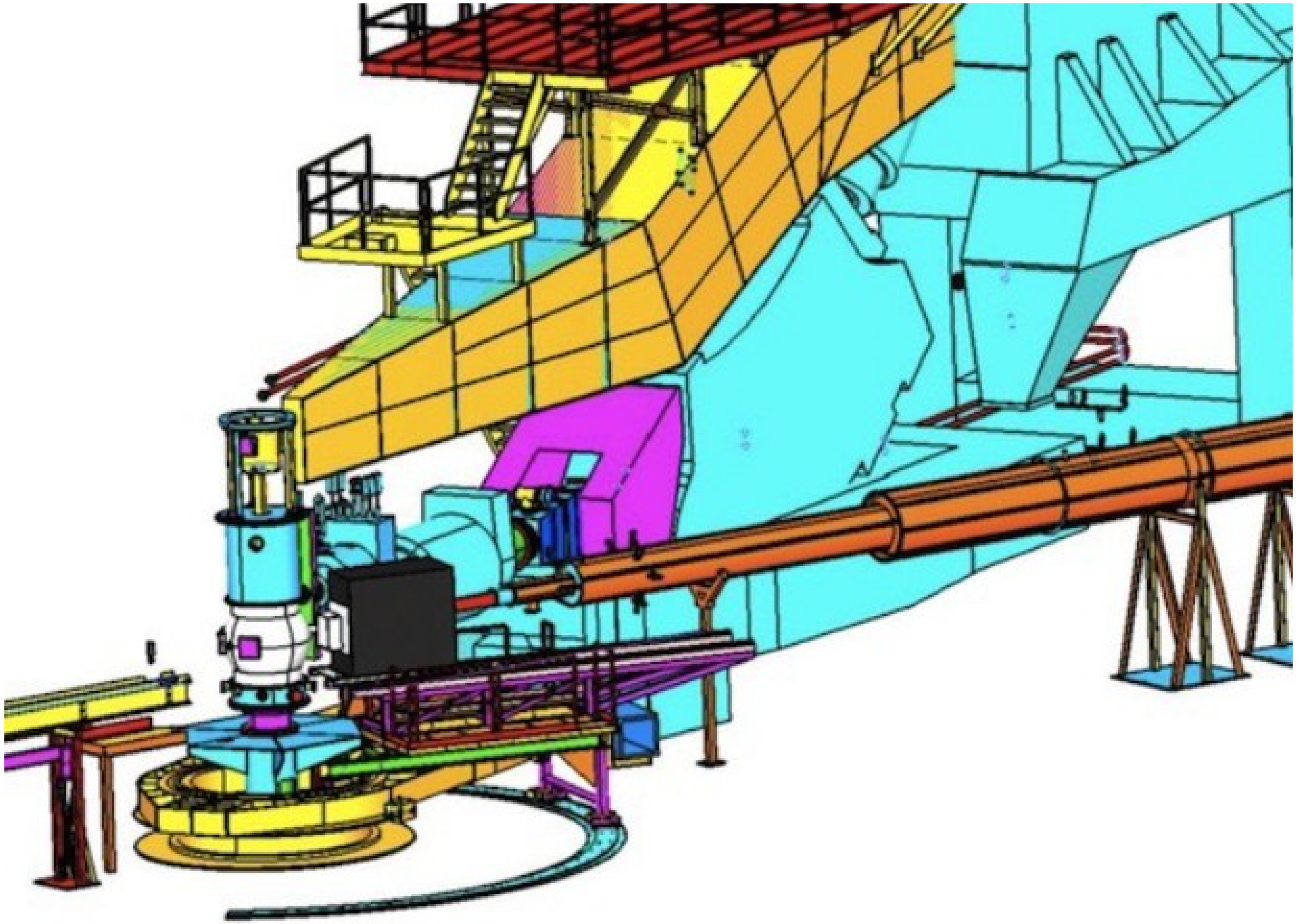
⇒ **multi-observables / multi-reactions fitting approach**
Here LO and leading twist

Context

Complementarity with world-wide experiments and JLab 6 GeV era measurement
(fig. From C. Munoz, 2014, not the most up to date)



DVCS recent measurements in Hall A



E12-006-114 experiment
2014-2016
11 GeV electron

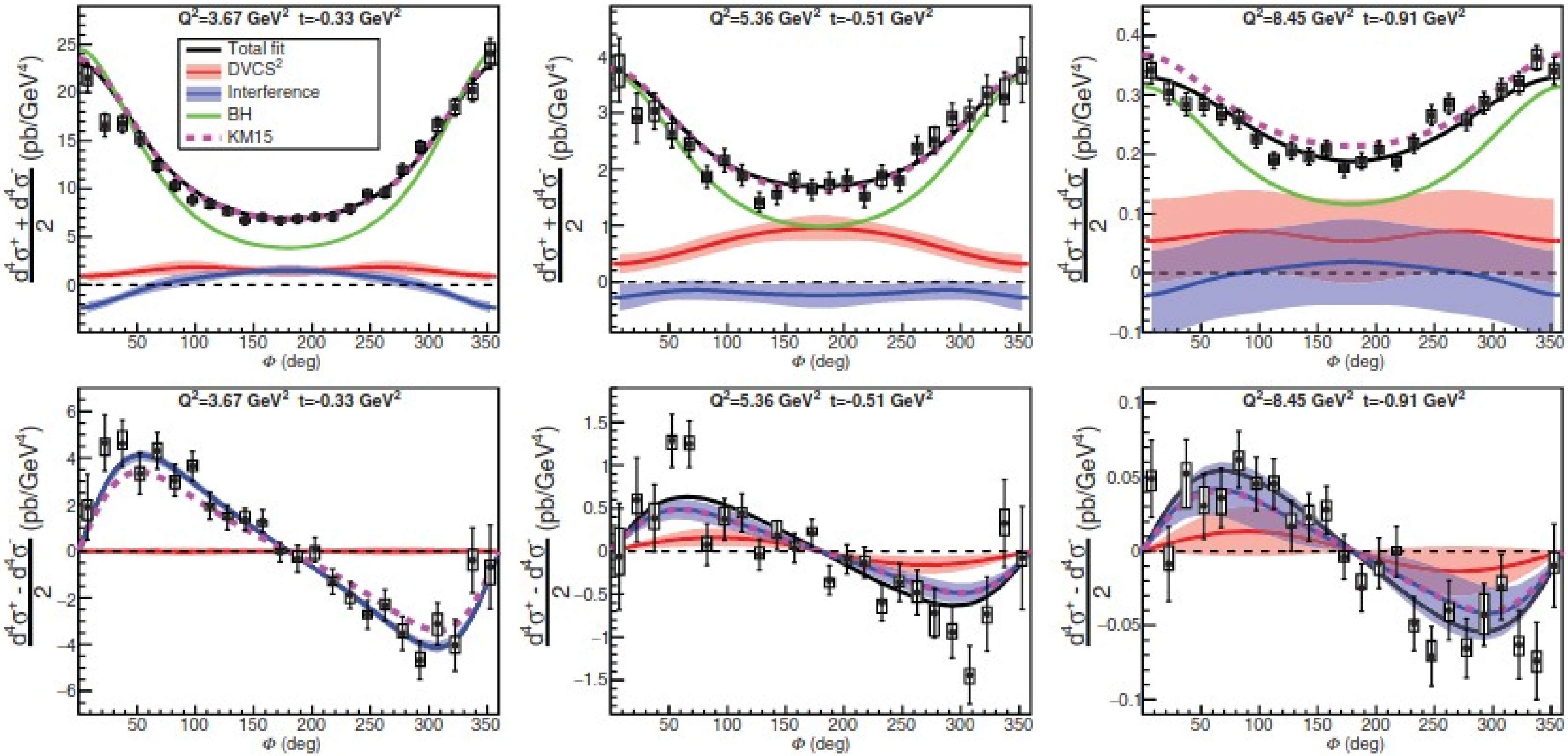
PbF2 calorimeter
Electron in spectrometer
Missing mass for the proton

DVCS in Hall A

Published in PRL 128, 252002 (2022), F. Georges et al.

Kinematics and unpolarized cross sections

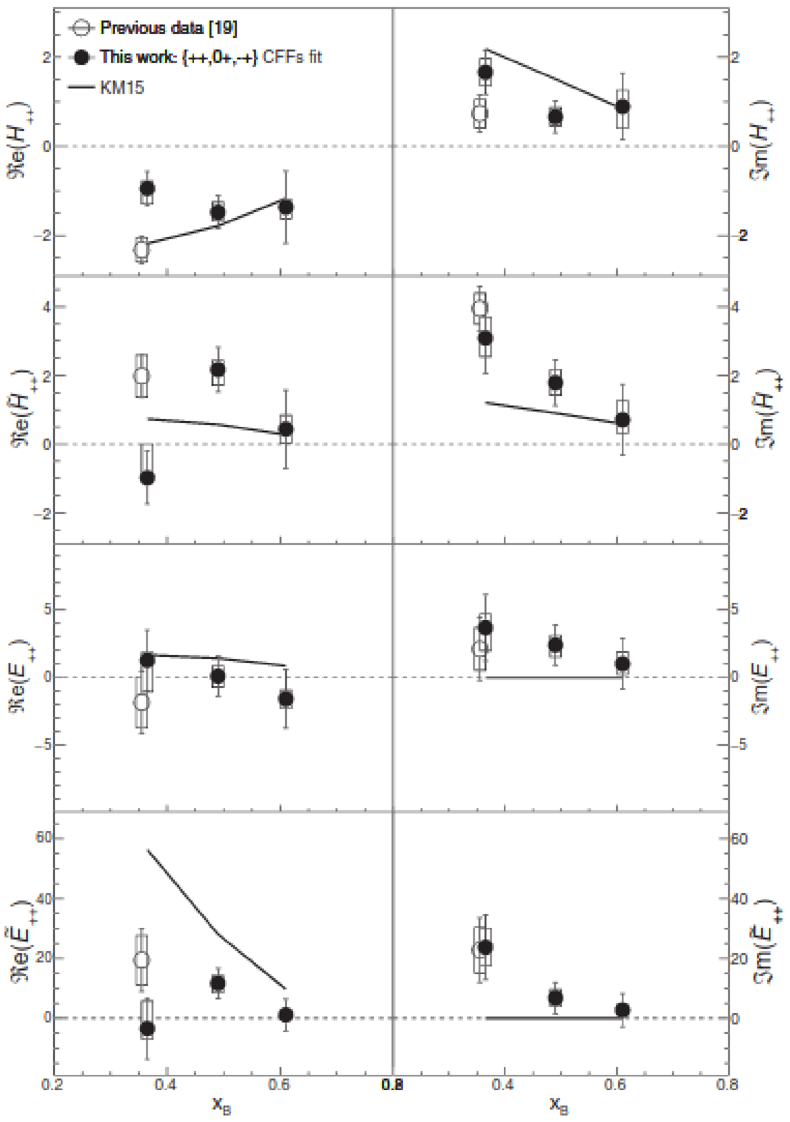
Setting	Kin-36-1	Kin-36-2	Kin-36-3	Kin-48-1	Kin-48-2	Kin-48-3	Kin-48-4	Kin-60-1	Kin-60-3
x_B		0.36			0.48			0.60	
E_b (GeV)	7.38	8.52	10.59	4.49	8.85	8.85	10.99	8.52	10.59
Q^2 (GeV^2)	3.20	3.60	4.47	2.70	4.37	5.33	6.90	5.54	8.40
E_γ (GeV)	4.7	5.2	6.5	2.8	4.7	5.7	7.5	4.6	7.1
$-t_{\min}$ (GeV^2)	0.16	0.17	0.17	0.32	0.34	0.35	0.36	0.66	0.70
$\int Q dt$ (C)	1.2	1.7	1.3	2.2	2.2	3.7	5.7	6.4	18.5
Number of data bins		672			912			480	

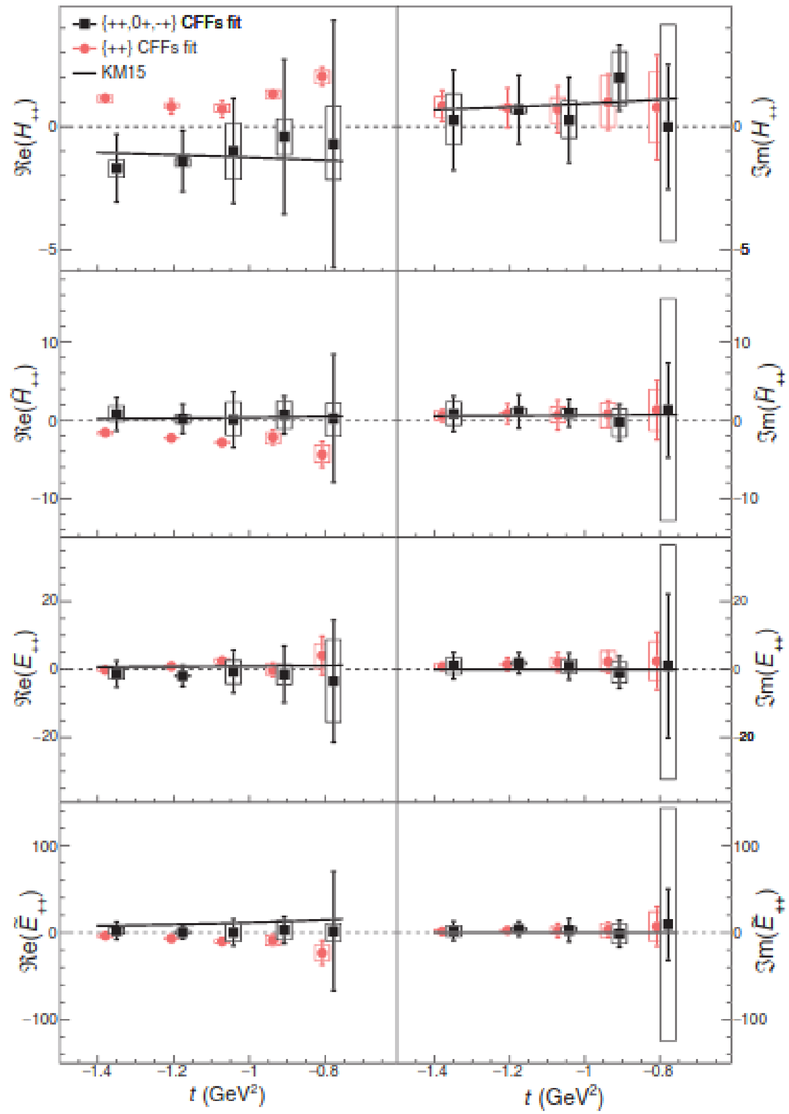


DVCS in Hall A: extracted CFFs

Published in PRL 128, 252002 (2022), F. Georges et al.

Average over t | Xbj=.6





Fit formalism: . M. Braun, A. N. Manashov, D. Müller, and B. M. Pirnay, Phys. Rev. D 89, 074022 (2014)
12 CFFs with higher twists, fix xbj & t with E, Q^2, t, xbj dependence.

All CFF extracted and correlations taken into account. H (Im and Re) extracted
Compatible with 0 for helicity-flip CFFs: complementary measurements to come / other Halls

Hard Exclusive neutral pion in Hall A

Published in PRL 127, 152301 (2021), M. Dlamini et al.

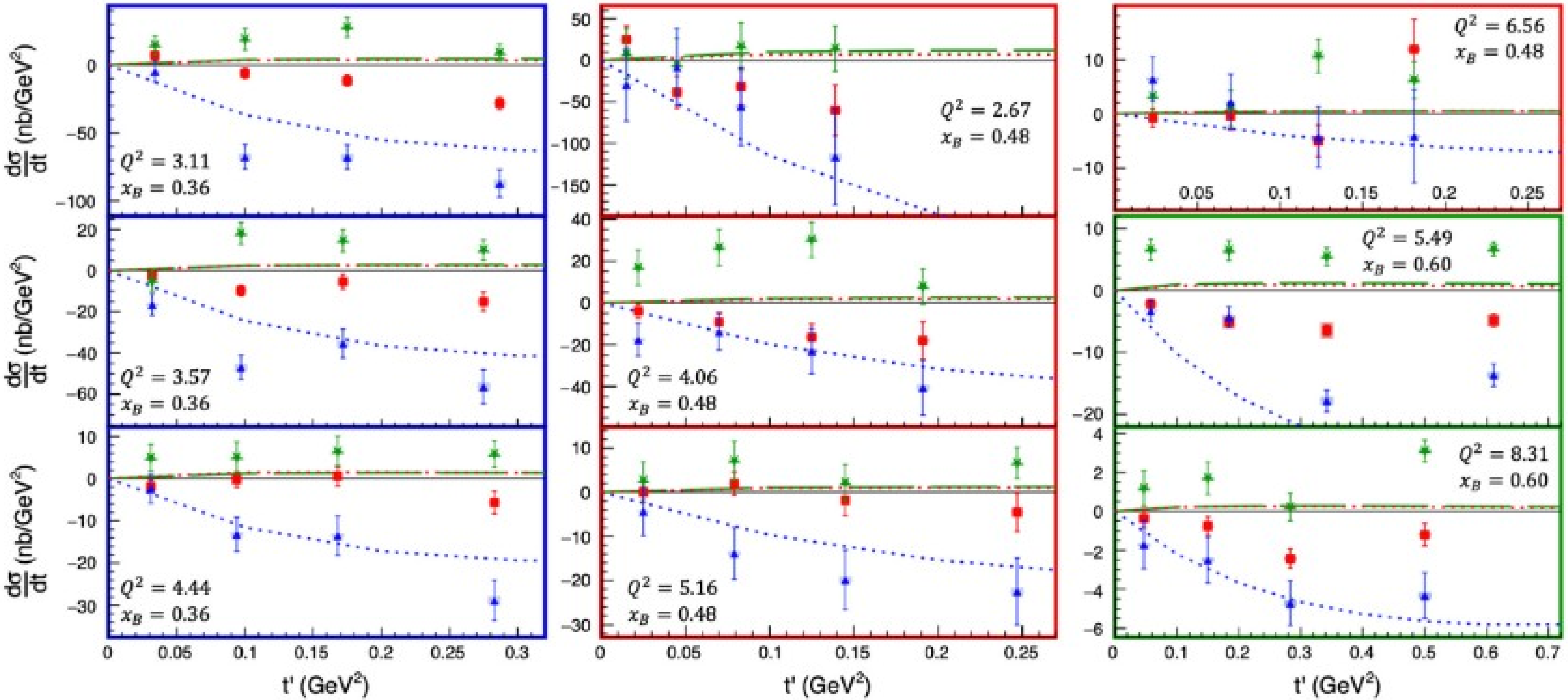
Kinematics

x_B label	0.36			0.48				0.60	
$\langle x_B \rangle$	0.36	0.36	0.36	0.48	0.45	0.46	0.46	0.59	0.60
E (GeV)	7.38	8.52	10.59	4.49	8.85	8.85	10.99	8.52	10.59
Q^2 (GeV^2)	3.11	3.57	4.44	2.67	4.06	5.16	6.56	5.49	8.31
W^2 (GeV^2)	6.51	7.29	8.79	3.81	5.62	6.67	8.32	4.58	6.46
$-t_{min}$ (GeV^2)	0.16	0.17	0.17	0.33	0.35	0.35	0.36	0.67	0.71
ϵ	0.61	0.62	0.63	0.51	0.71	0.55	0.52	0.66	0.50

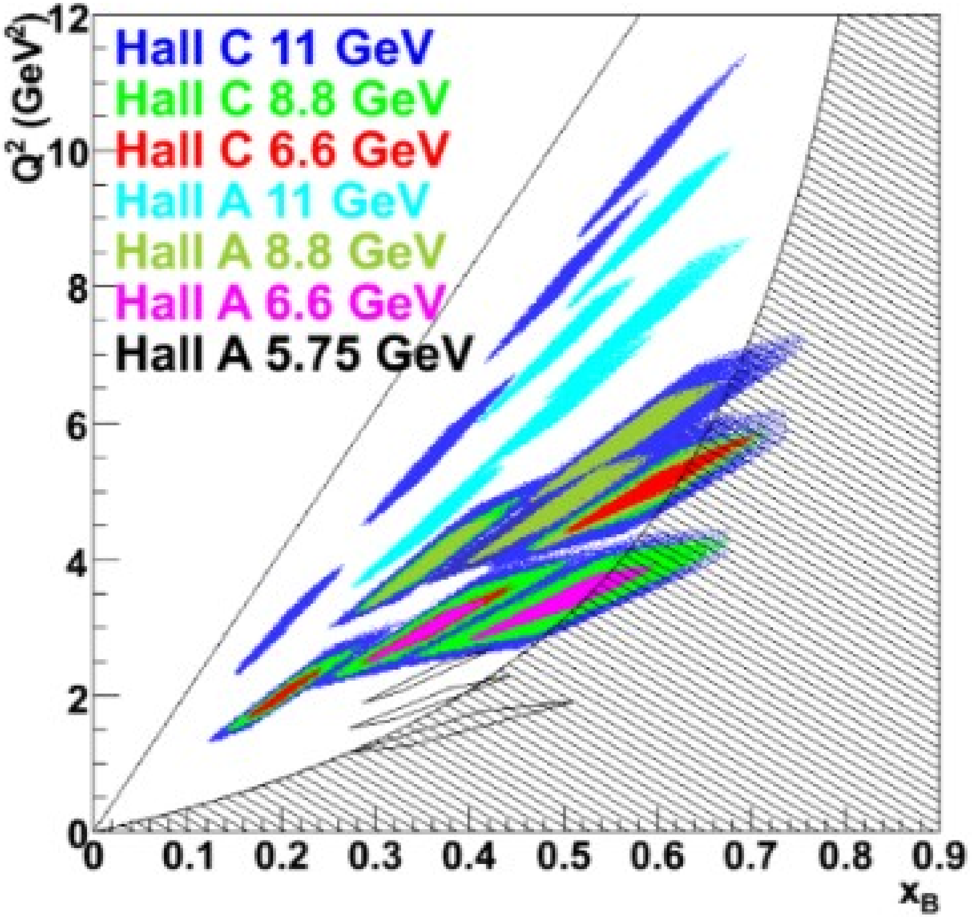
Extracted pion structure function (all kinematics): large higher twist effects?

L/T separation will be complemented by other experiments

dσTT (blue triangles), dσLT (red squares), dσLT0 (green stars)
--- with transversity GPDs (GK)



Upcoming DVCS program in Hall C



Complement phase space and statistics
DVCS "moved" to Hall C with new spectrometer HMS and NPS

Up to 11 GeV electron
Missing mass for proton

DVCS proton experiment expected in 2023

Neutron experiment approved at PAC52 (2022)

New calorimeter: Neutral Particle Spectrometer (NPS)

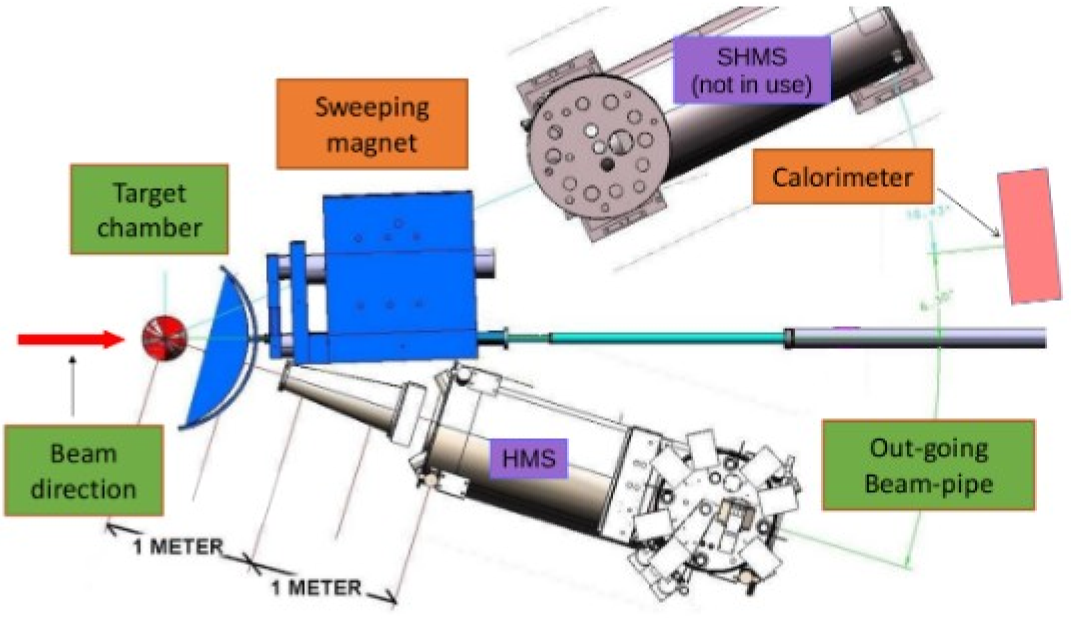
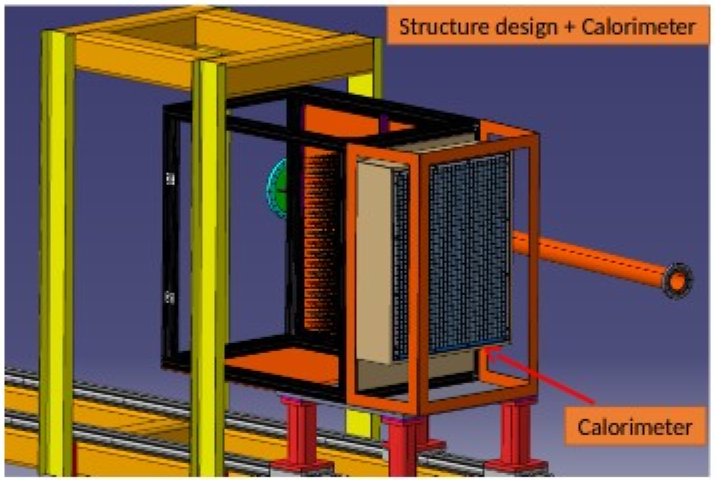
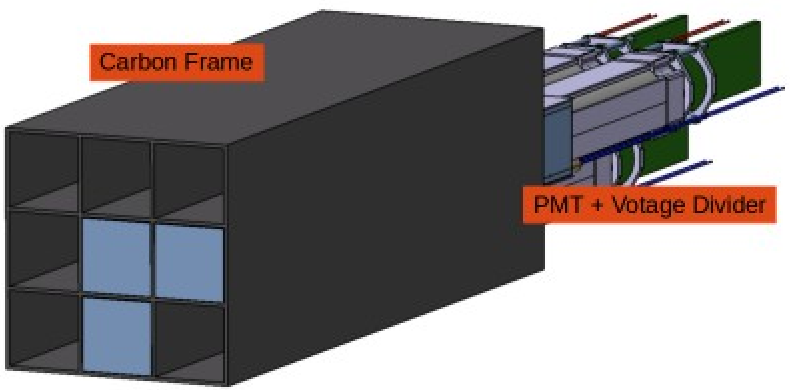


FIGURE 3: Hall C Layout for the DVCS.



(a) Structural design of the calorimeter.



(b) Earliest design of the carbon frame for the calorimeter.

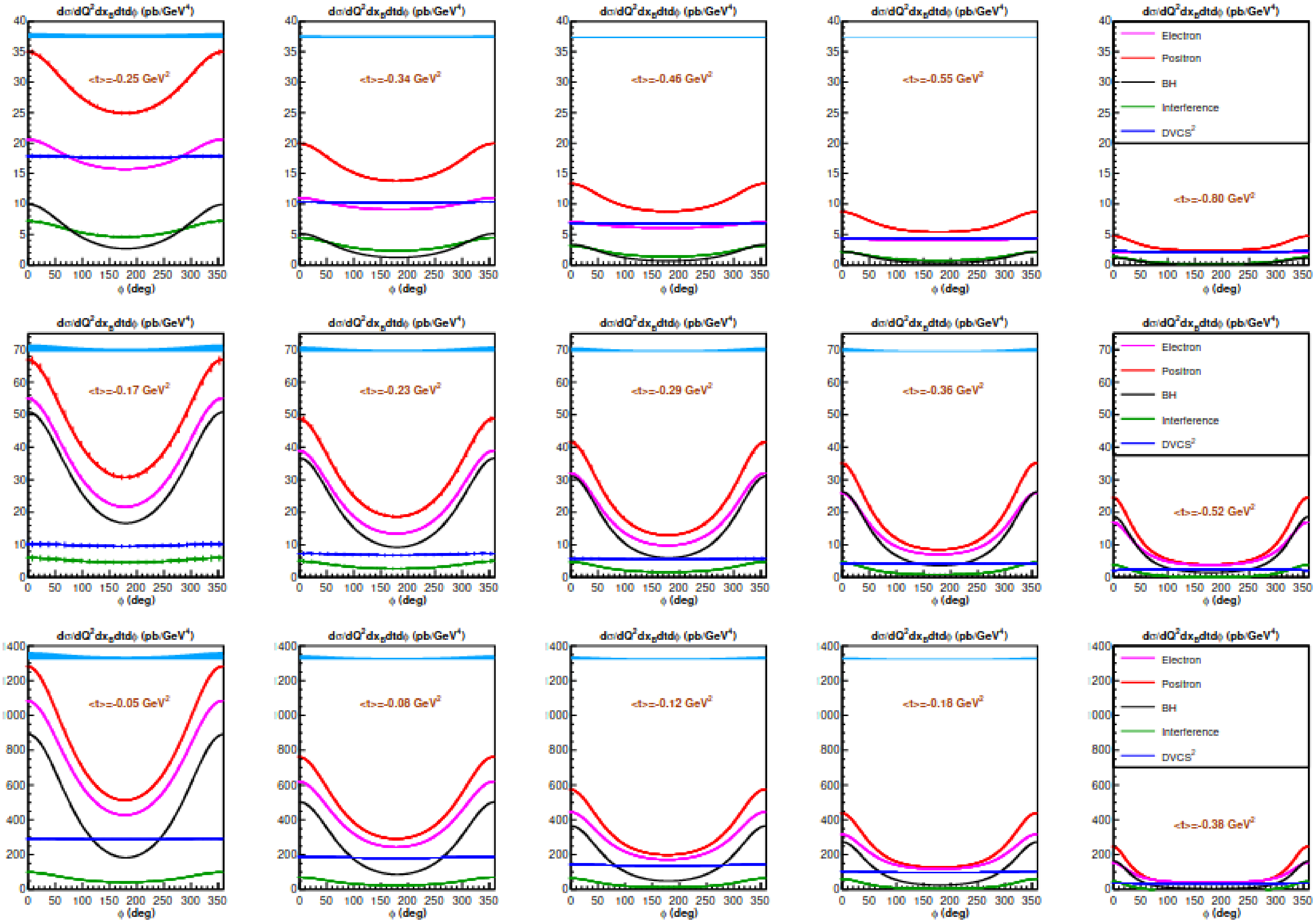
From Ho-San Ko, 2020

NPS spectrometer currently being assembled (by the end of the year)
Pictures from July 2022

NPS spectrometer currently being assembled (by the end of the year)
Pictures from July 2022

Many contributors and institutes, here the Orsay group engineers and technicians in July 2022 at JLab

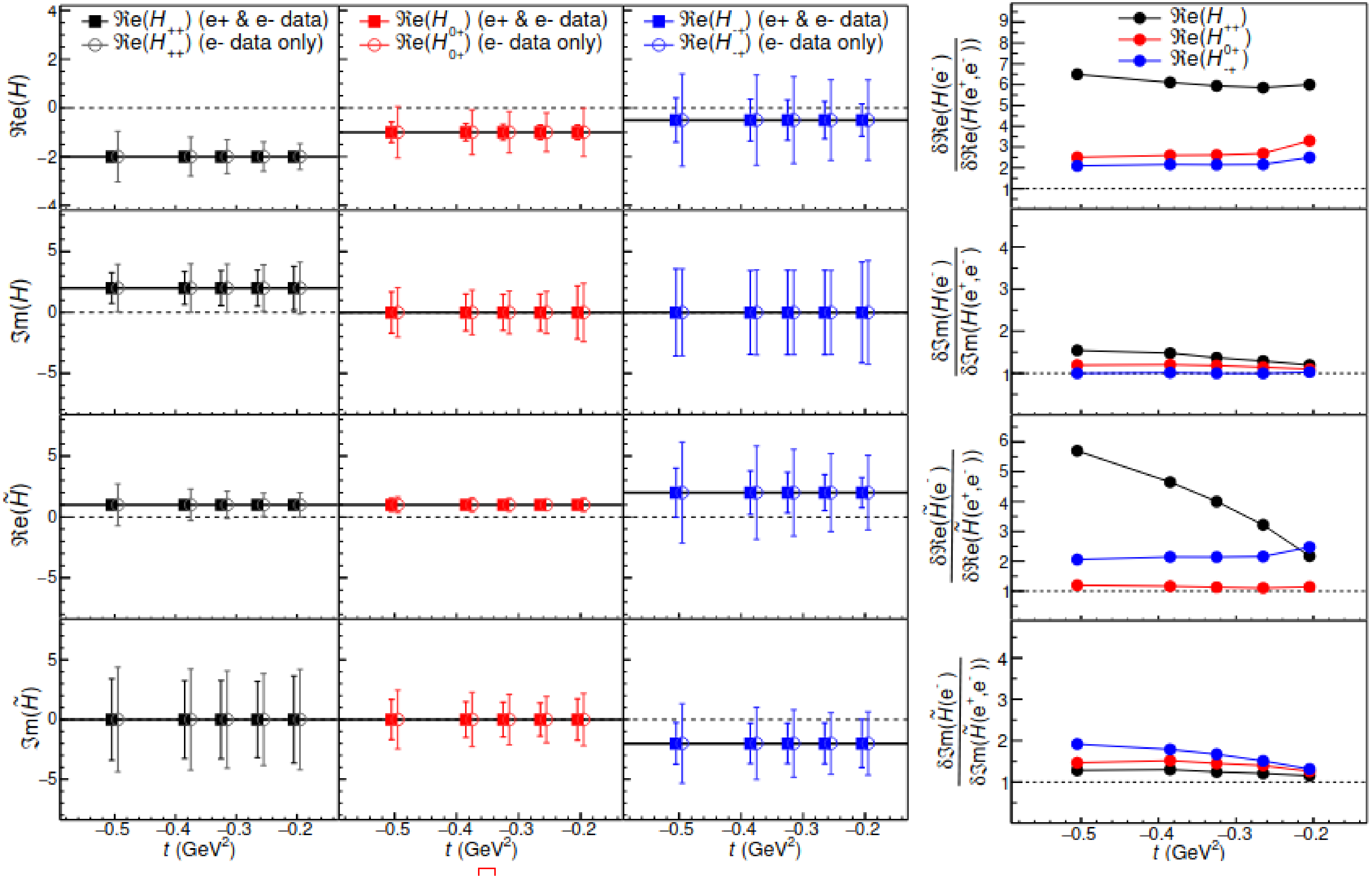
Future with positron beam? (projections for Hall C)



Projected cross sections at various kinematics

hep/ex-2105.06540, Afanasev et al.

Future with positron beam? (projections for Hall C)



Projected extracted CFFs with electron+positron DVCS results

hep/ex-2105.06540, Afanasev et al.

Other reactions for multi-channel CFF extraction

- some meson measurements have been done, but not with a “GPD physics” emphazis (not presented here)

- non-DVCS (or pion) measurements belong to the future in Hall A & C

Compton-like reactions (proposed projects for Hall A & C presented here)

Hard Exclusive Meson production (not discussed here)

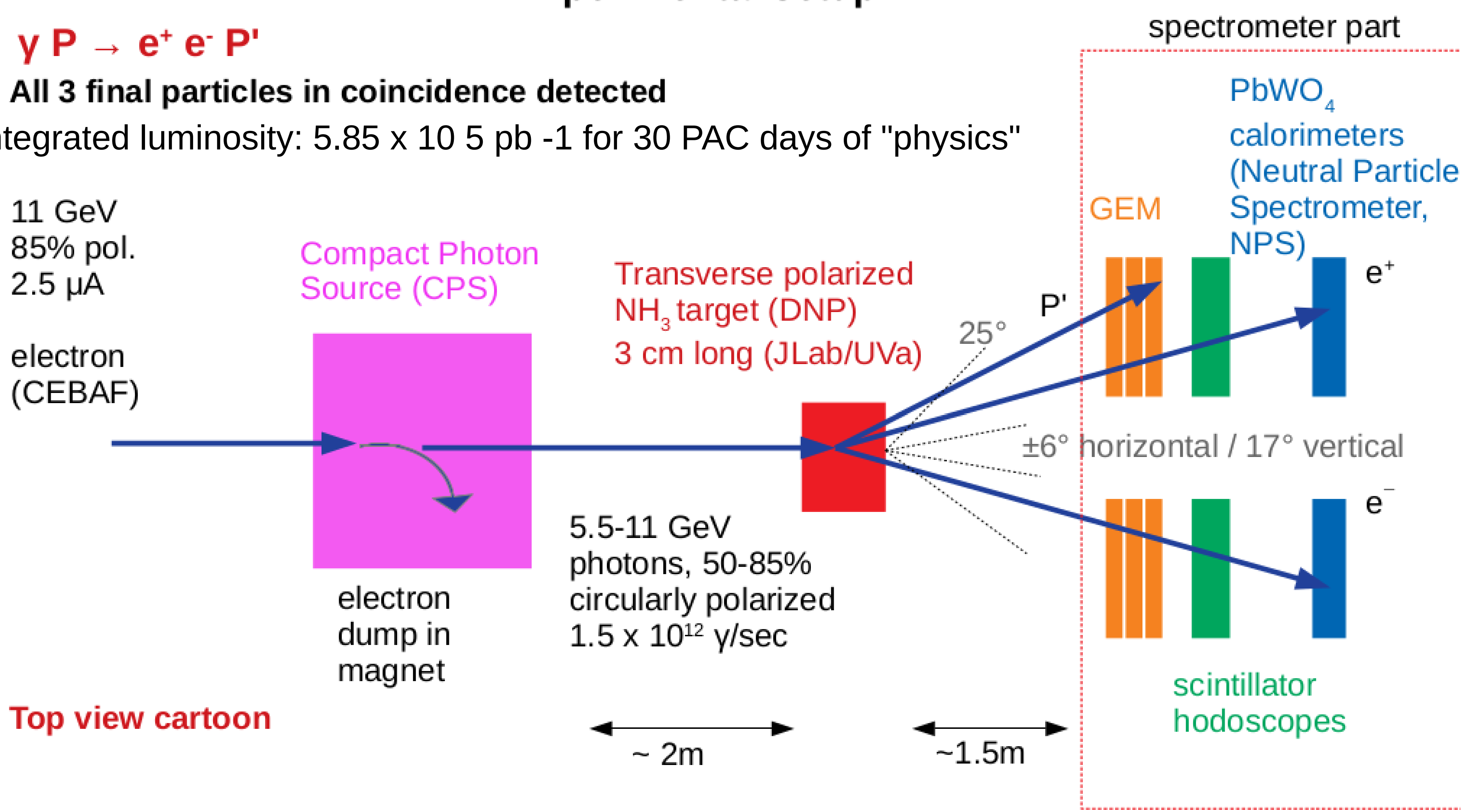
Future: proposed Timelike Compton Scattering in Hall C

Experimental setup

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

All 3 final particles in coincidence detected

Integrated luminosity: 5.85 x 10 5 pb -1 for 30 PAC days of "physics"

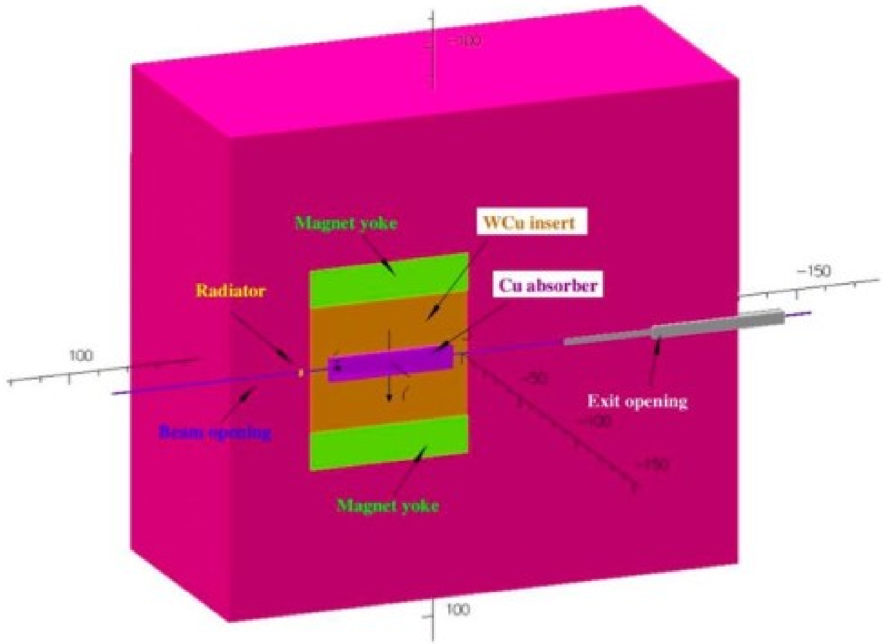


Trigger: GEMs, hodoscopes, calorimeters (all 3 particles)

PAC52 (deferred) encourages the efforts and loves the physics, but several technical aspects need more efforts/people in particular to handle high rates. The collaboration is actively working on returning

Future: proposed Timelike Compton Scattering in Hall C

Compact Photon Source



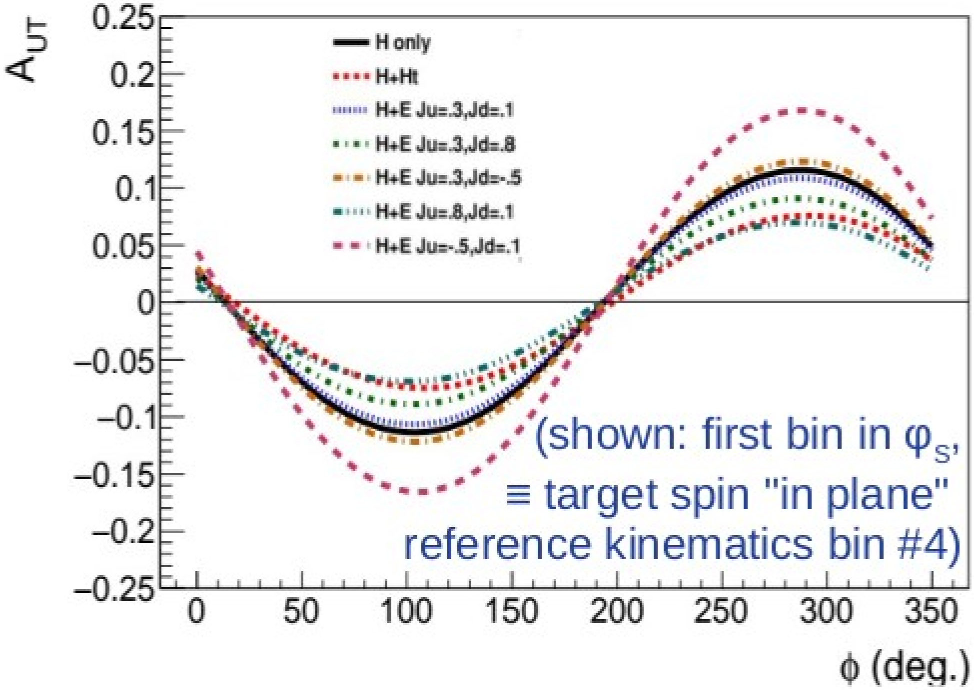
Compact Photon Source under development in Hall C at JLab:

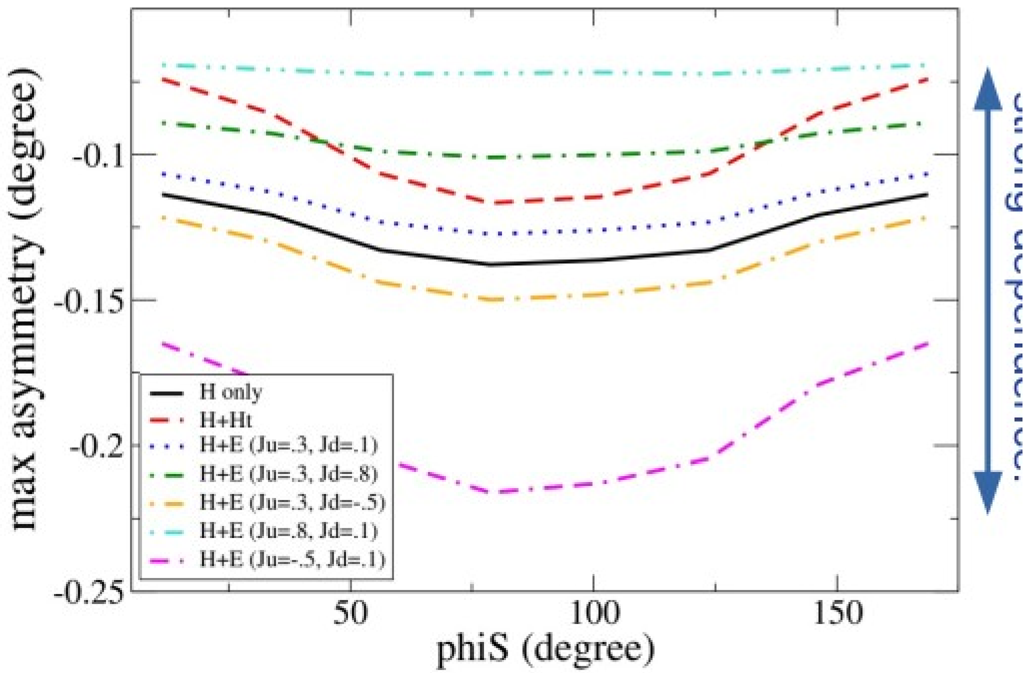
- Combines polarized photon source, collimator and beam dump;
- High intensity directed brem. photon beam (**1.5×10^{12} γ/s in [5.5 GeV, 11 GeV]** range from **2.5 μA primary e- beam** on **10% X_0 Cu radiator**, **~1 mm spot size** at 2 m from radiator);
- 3.2 T warm magnet to bend incoming electrons to local beam dump;
- Highly shielded design (W/Cu alloy) to minimize prompt and residual radiation.

CPS can also be used in Hall A and with SoLID (later in this talk) for high intensity un-tagged photon beam measurements. For GPDs: TCS, heavy mesons, multiple mesons...

Future: proposed Timelike Compton Scattering in Hall C

Dependence in GPD parametrization and J_u, J_d (VGG model) vs φ and φ_S





TSA with various quark angular momenta scenarios
(choice of same parameters as Jlab DVCS experiments)

- strong model dependence
- large sensitivity to angular momenta

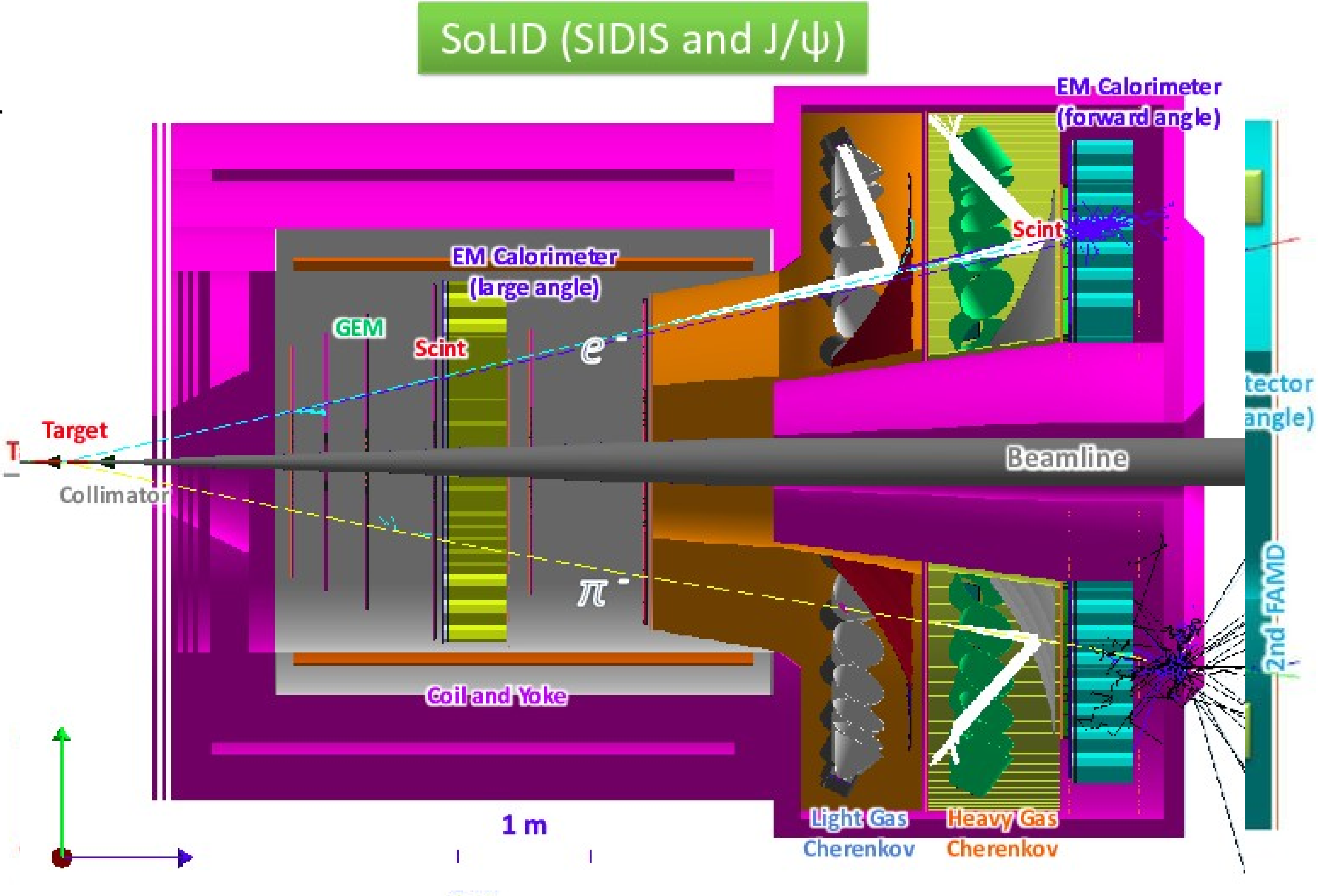
Sinus momenta versus spin angle
=> discriminates model
=> huge dependence in J(quarks)

BH cancels: asym from Compton contribution

TCS with SoLID spectrometer

Unpolarized and beam polarized cross sections

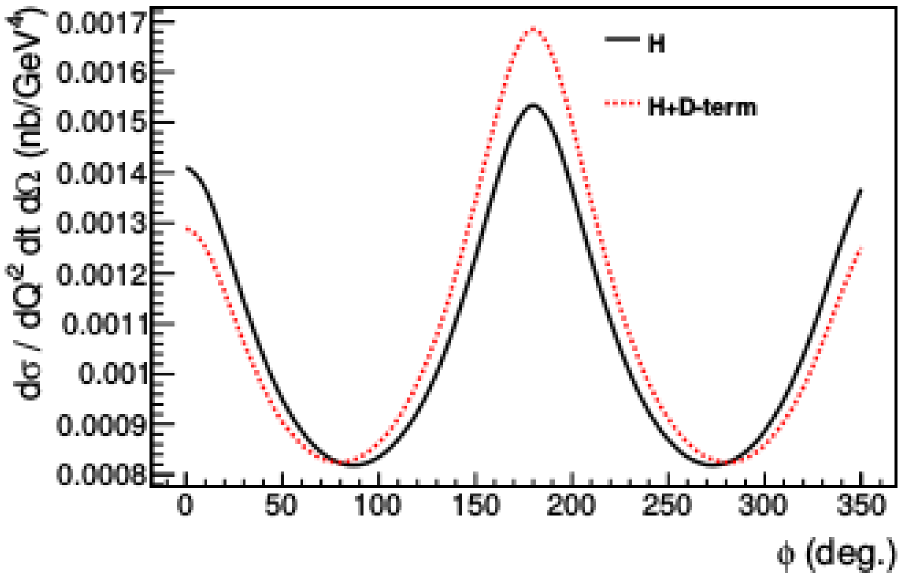
SoLID spectrometer



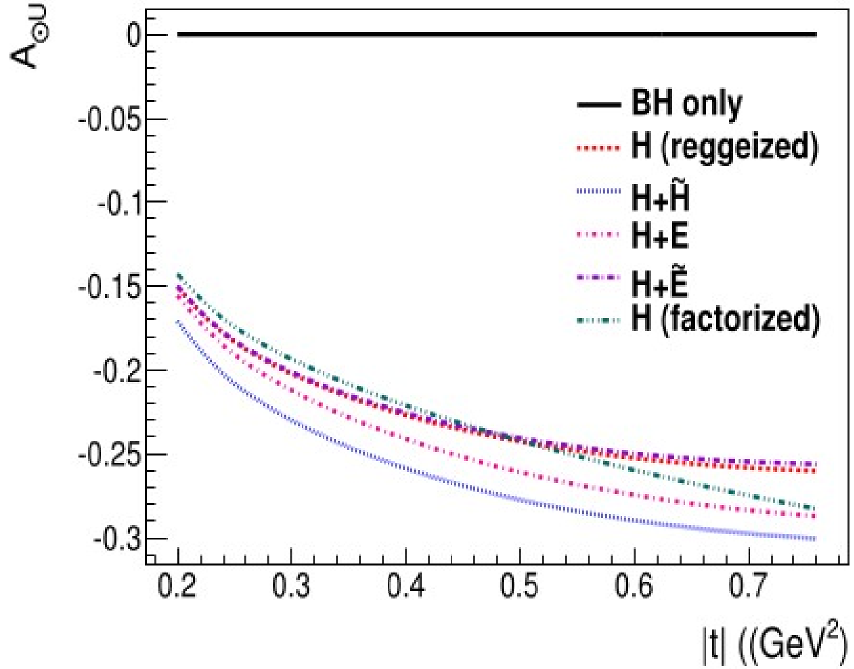
High intensity and large acceptance. Highly considered for future in Hall A.

TCS with SoLID high precision measurement for GPDs universality

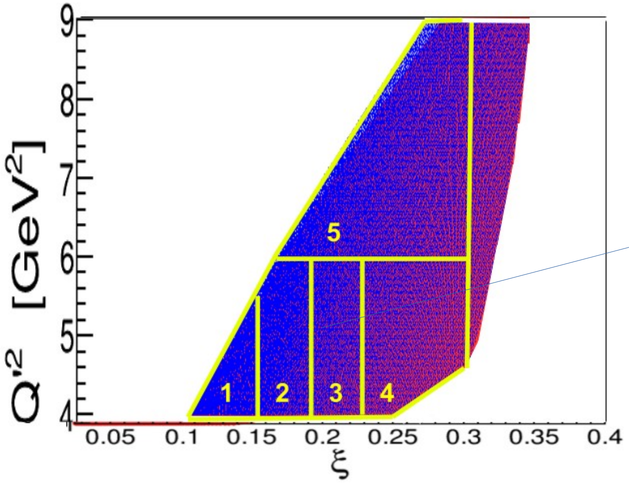
unpolarized x-sec vs φ, sensitivity to D-term (GPD H = VGG)



parametrization and t- dependence of beam spin asymmetry

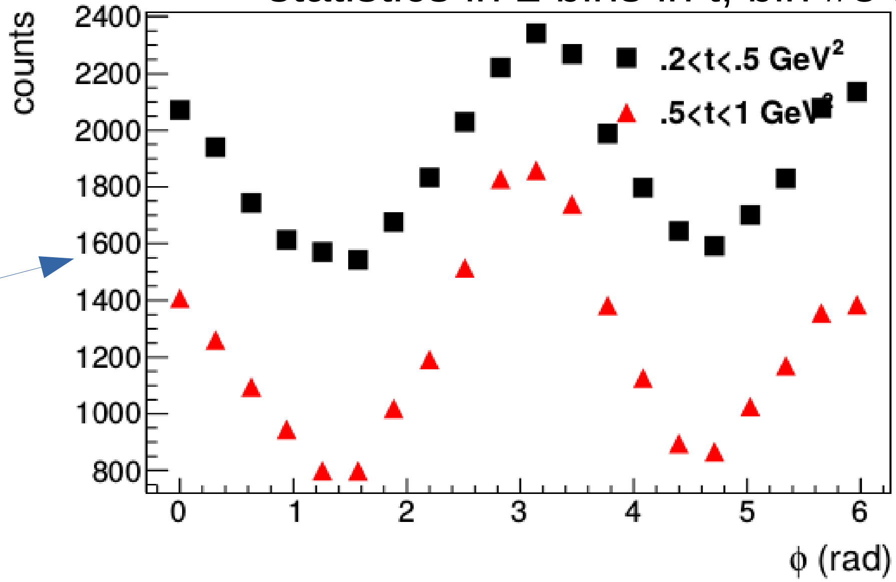


- Unpolarized cross section
- Beam spin asymmetry



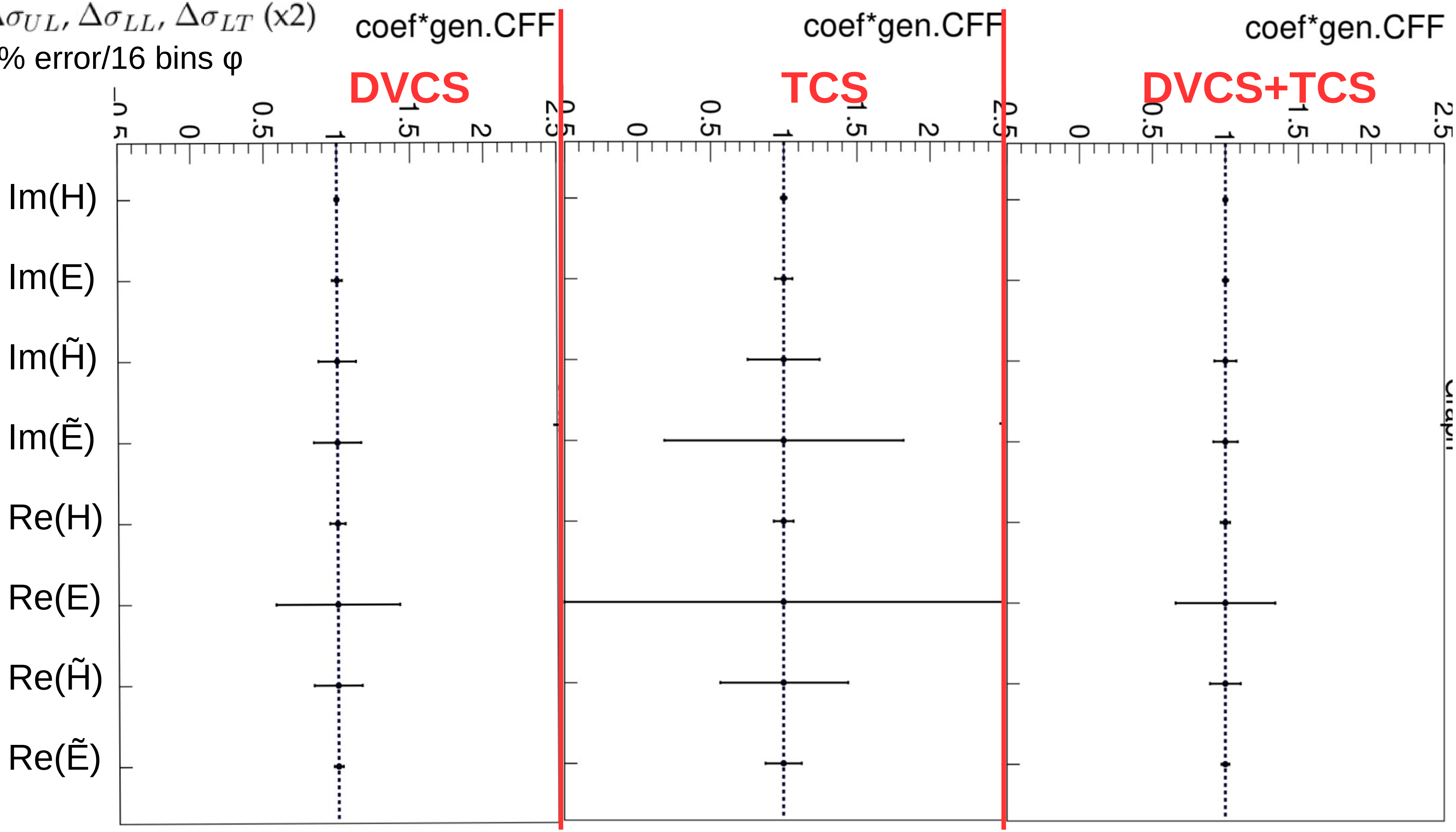
bin 3

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



Global fits of Compton Form Factors with TCS

5) σ, $\Delta\sigma_{LU}$, $\Delta\sigma_{UT}$ (x2)
$\Delta\sigma_{UL}$, $\Delta\sigma_{LL}$, $\Delta\sigma_{LT}$ (x2)
7% error/16 bins φ



8 independent variables for each process: all unpolarized and polarized cross section differences
$-t=.2$ GeV², $\xi=.15$, $Q^2=2$ GeV² or $Q'^2=4.5$ GeV², E=11 GeV for DVCS, θ=90° for TCS
at asymptotic limit

This figure: assumes Hall A + Hall C + complementary measurements.
SoLID only: universality studies for GPD H, with Hall C: GPD E

Double Deeply Virtual Compton Scattering Prospects in Hall A & C

SoLID DDVCS: LOI in 2015, not yet turned into full proposal.
Recent physics and technical developments taken into consideration, the collaboration aims at coming soon with a new version.

Hall C DDVCS: in progress, not yet proposed

Going “off-diagonal” with DDVCS, extrapolation to zero skewness for tomographic interpretations

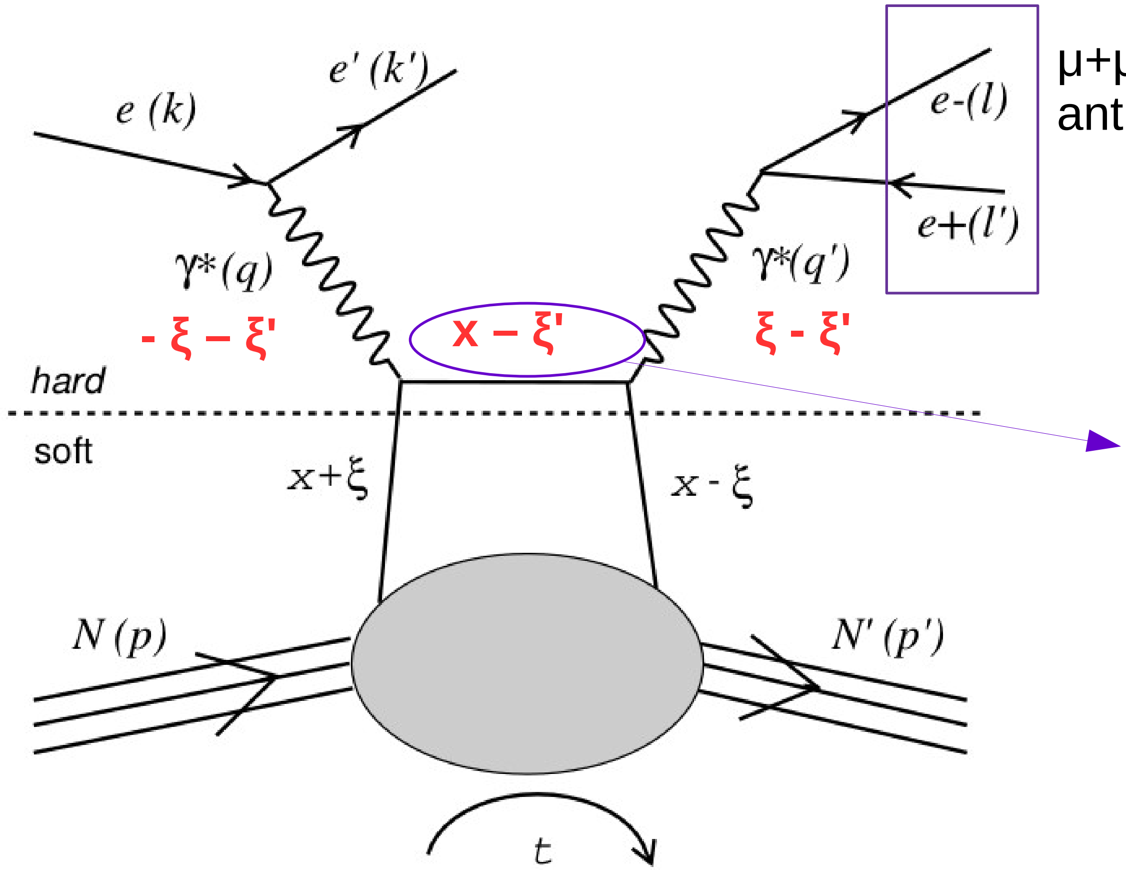
$$T^{DDVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x-(2\xi'-\xi)+i\varepsilon}dx + \ldots \sim \quad P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x-(2\xi'-\xi)}dx - i\pi H(2\xi'-\xi,\xi,t) + \ldots$$

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

→ lever arm by 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

Accessing GPDs with Double Deeply Virtual Compton Scattering



μ+μ- → avoid antisymmetrisation

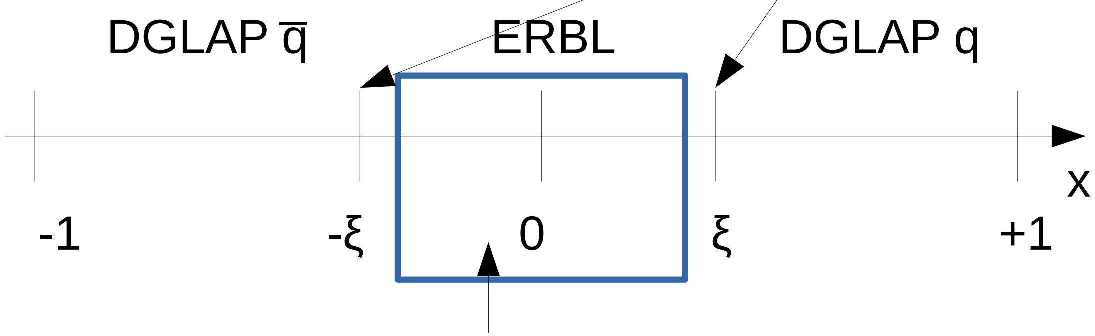
- ξ = + component of P=(p+p') in light cone frame. GPDs depend on it. "skewness"
- ξ' = + component of q̅=(q+q')/2 in light cone frame. quark propagator can be related to x_{bj}

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

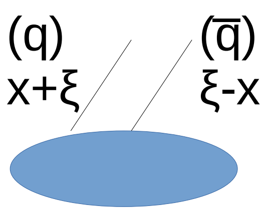
What do we learn?

M. Diehl's representations:

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

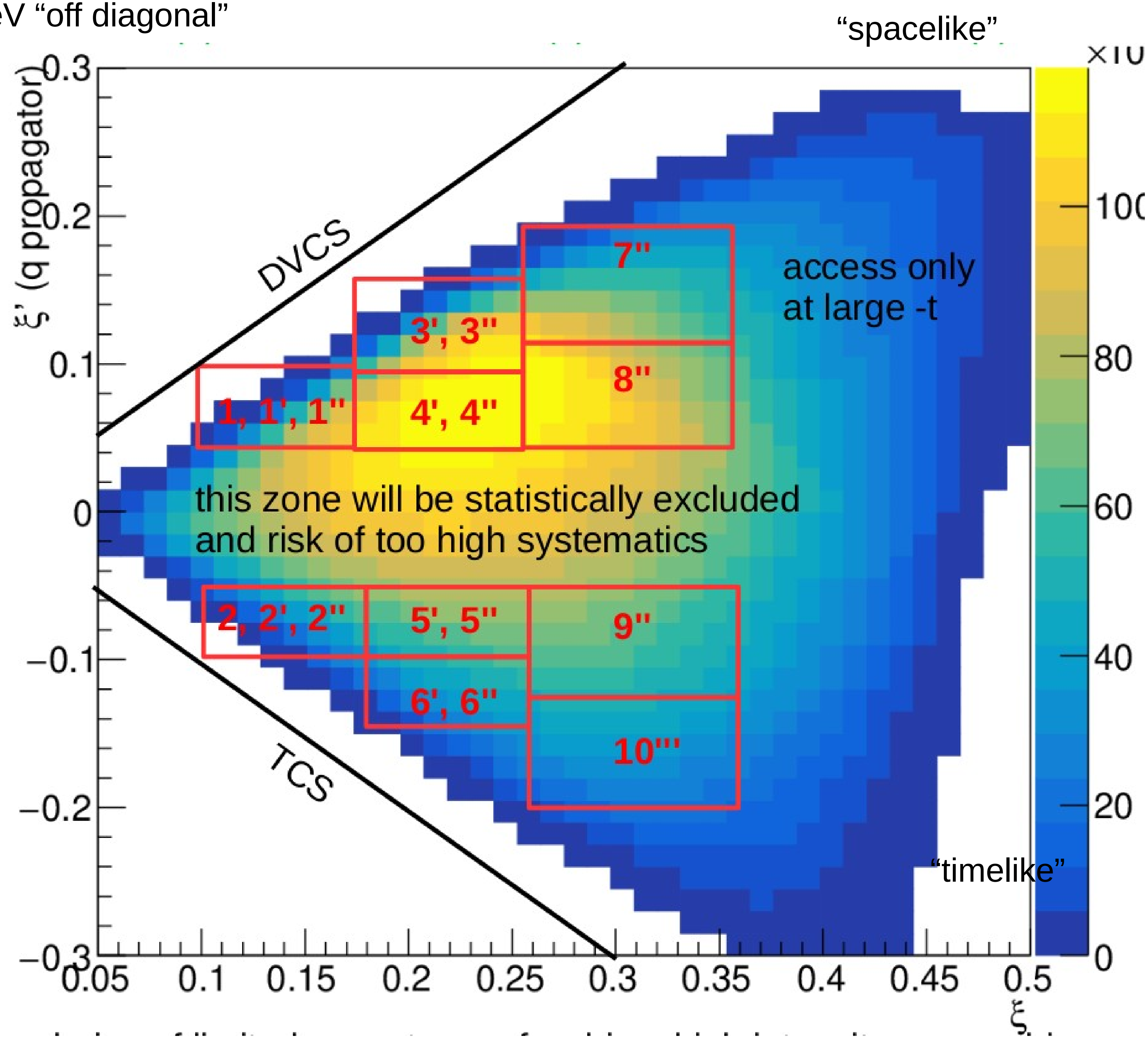


accessible with DDVCS



partonic interpretation from M. Diehl in ERBL region

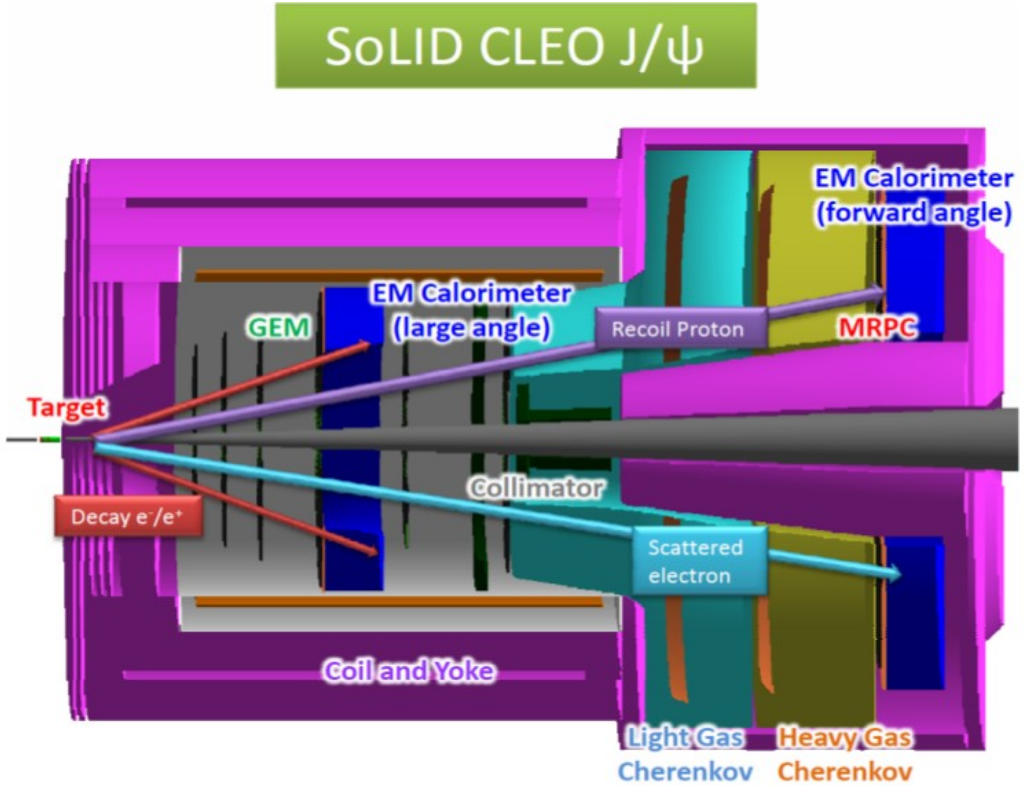
11 GeV “off diagonal”



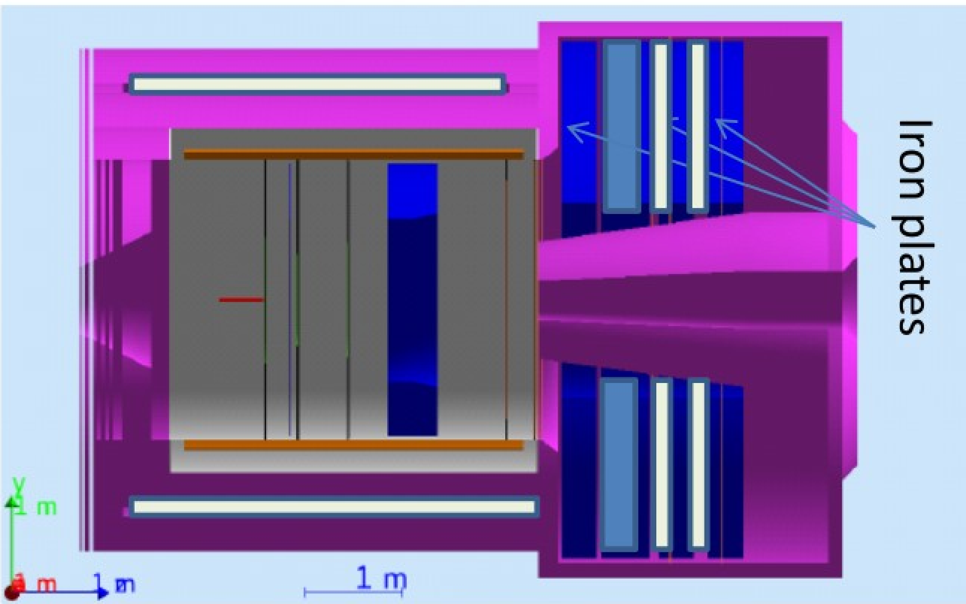
DDVCS with SoLID: proposed experimental setup

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

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



Dedicated setup



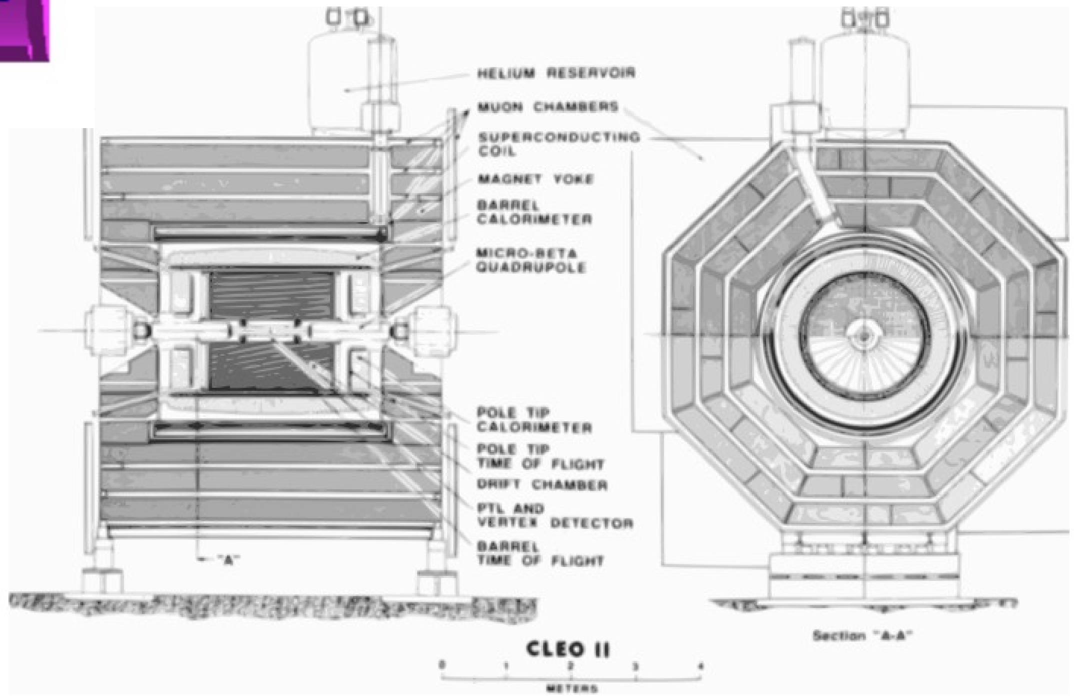
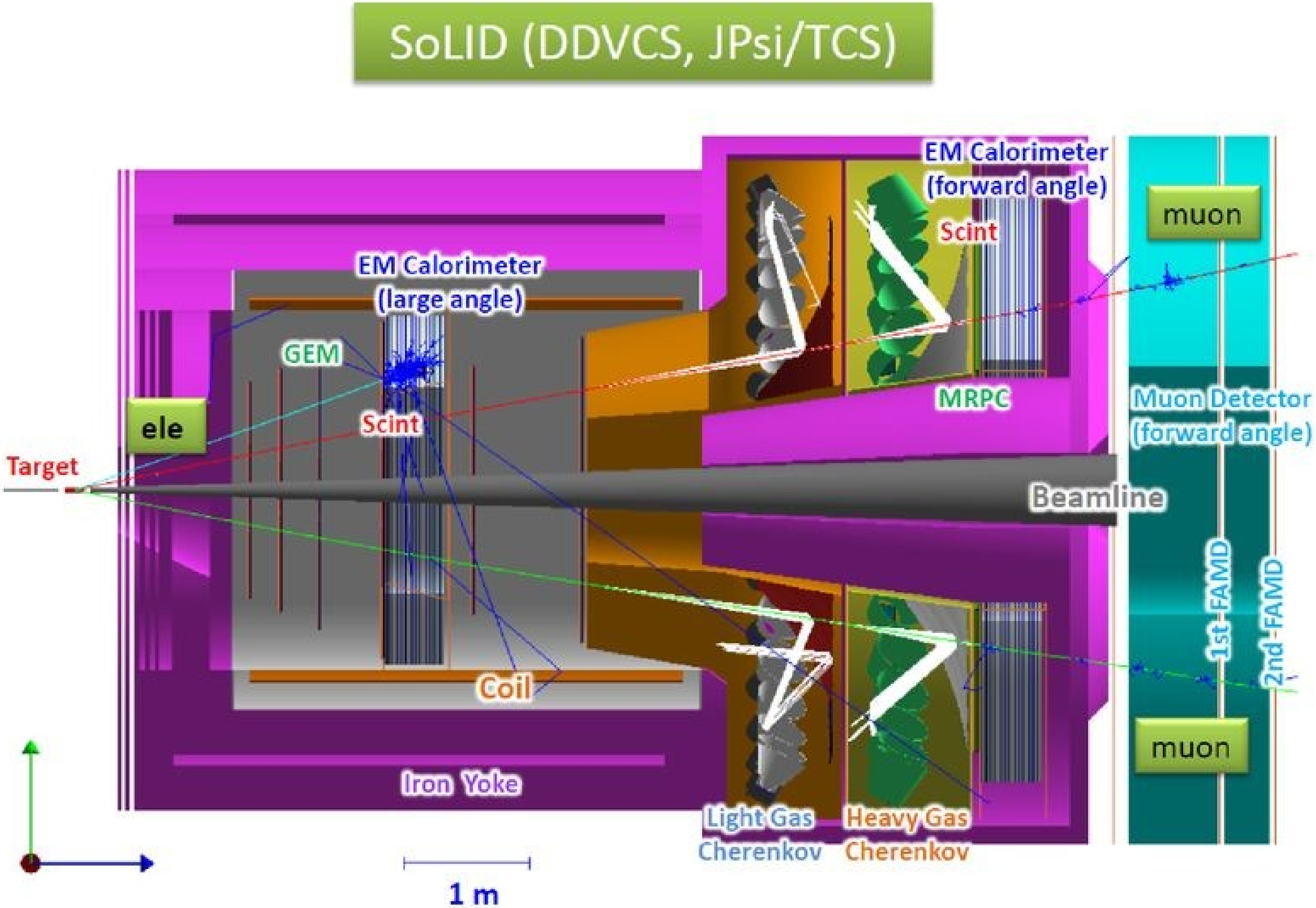


Figure 10: CLEO II setup with muon chambers installed inside the iron yoke.

Detector Configuration

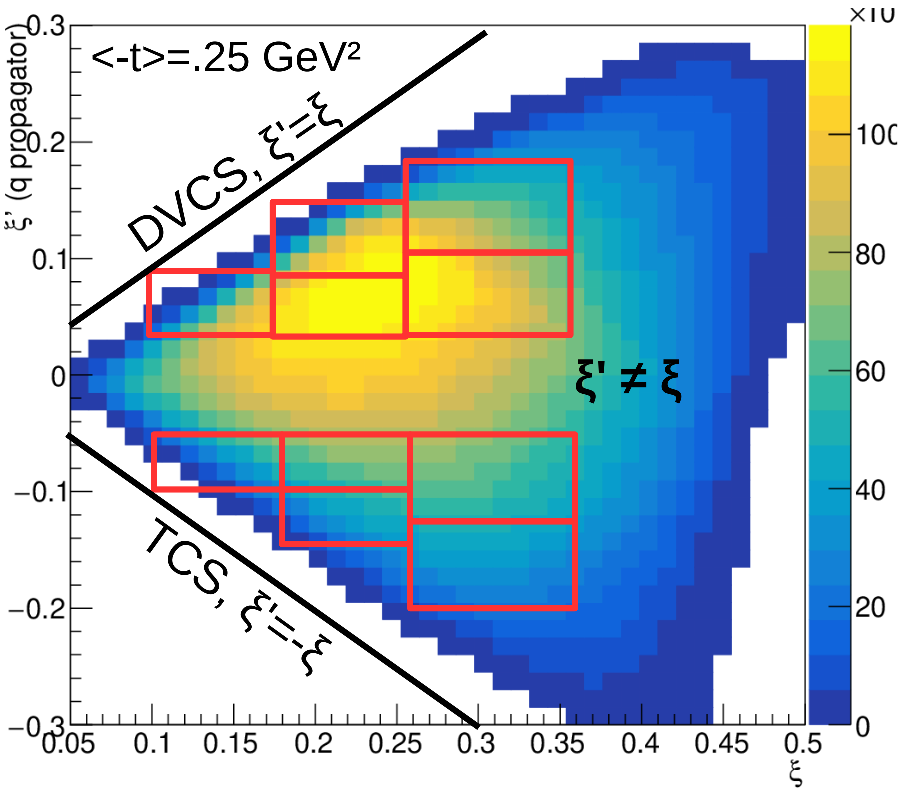


(credit A Camsonne)

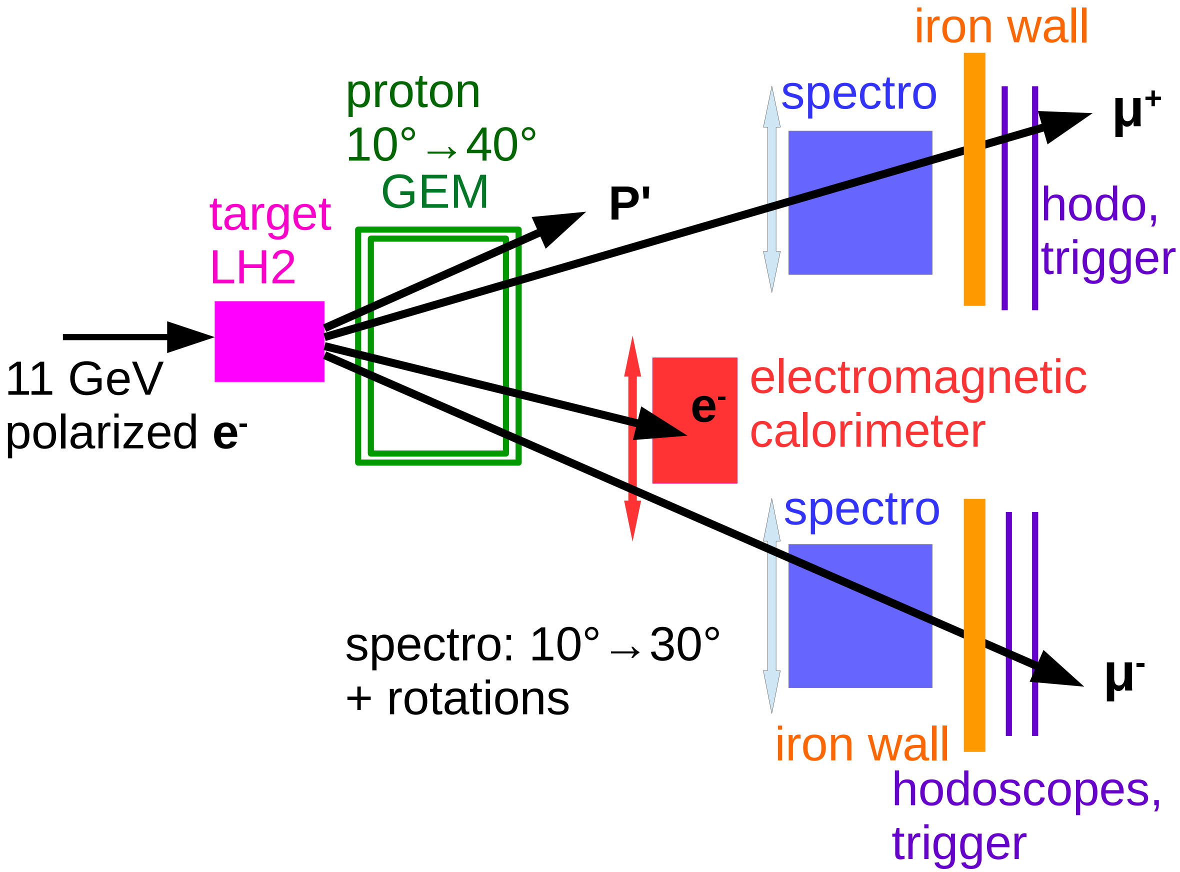
Prospects for DDVCS at JLab Hall C: e P → e' $\mu^+\mu^-$ P

- mesurements: σ(unpol.) + asymmetry(beam)
- GPDs can be extracted from 2D fits: φ_{pair} vs φ_L at fix E, xbj, t, (Q^2, Q'^2 if no evolution)

"off diagonal" GPD access: ξ' (±x) vs ξ,



one idea for a setup in Hall C :
80 days at 75 μA, LH2 target. L=5.10^{38} cm^{-2}s^{-1}



Other setups "investigated"
- DVCS-like setup with proton detector + HMS + muon segmented hodoscopes
- similar with Hall A SBS spectrometer, for experiment in Hall C

SUMMARY

History of high precision DVCS measurement since 2005, in the 6 GeV era

Recent publications of DVCS Hall A results

CFFs extracted from DVCS

Upcoming DVCS in Hall C with new NPS spectrometer

High precision measurements
and improvements with
Upcoming Hall C experiment

Flavor decomposition with neutron

Multichannel:

CPS for high intensity photon beam

TCS, DDVCS programs (proposed/in progress)

Meson: worth more experiments

New for multichannel fit approaches
Requires high intensity
For the near future

Future SoLID spectrometer, potential energy upgrade, positron beam, new reactions...