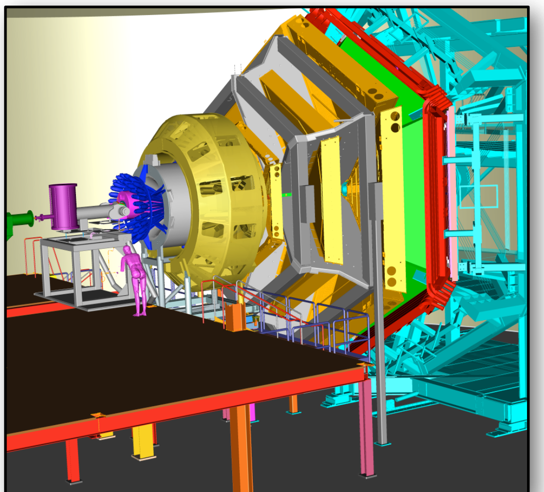
Positrons at JLab

Advancing nuclear science in Hall B



Volker D. Burkert

Jefferson Laboratory

Jefferson Laboratory, Newport News, September 12-15, 2017

Why positrons?

- Much of the science program in nuclear/hadron physics with *external lepton beams* can be obtained more easily with electrons than with positrons
  - e^+ obtained through secondary process, e.g. e^-+X-> e^-+γ ->e^+ e^- X positron beam current much lower
  - e^+ polarization obtained through polarization transfer

    e^- X -> e^- γ_p X …; γ_p -> e^+_p e^- X, so typically lower, but can be high for high e^+ energy.
- In some cases low or modest positron beam currents may be sufficient to access *high impact science* that is not accessible (or is more difficult to access) with electron beam alone.
- Opportunities if large acceptance detectors can be employed.

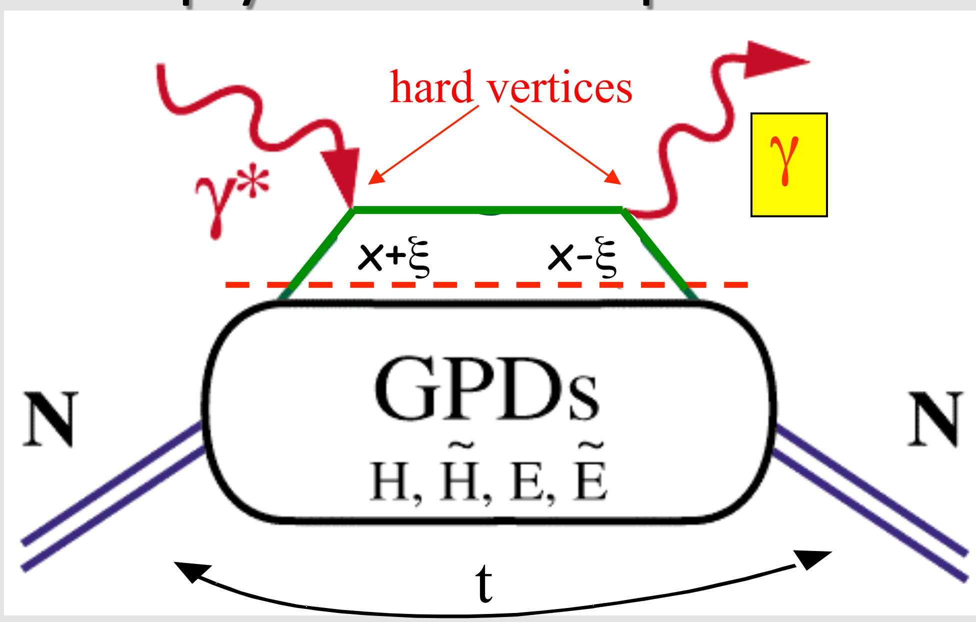
High Impact Science Program for Positrons?

- Deeply Virtual Compton Scattering (DVCS)
  - Extraction of all contributing Compton Form Factors (CFF) and GPDs
  - Full 3D-imaging of quarks in proton
  - Access the gravitational form factors - quark confinement forces, spin distribution, mass distribution in protons
- Two-photon contributions to electron-proton elastic scattering
  - How well do we know the fundamental electromagnetic elastic proton form factors?
  - What can we do better with positron beams?
- What are the equipment options in the near/medium term O(5) years for nuclear/hadron physics experiments with positron beams?
- Long term options? Positron Science @ EIC, e.g. measurement of charge asymmetry $xF_3(Q^2)$, …

The GPD program with DVCS

GPDs depend on 3 variables, e.g. *E(x, ξ, t)*. They probe the quark structure at the amplitude level.

Deeply Virtual Compton Scattering (DVCS)



x – longitudinal quark momentum fraction

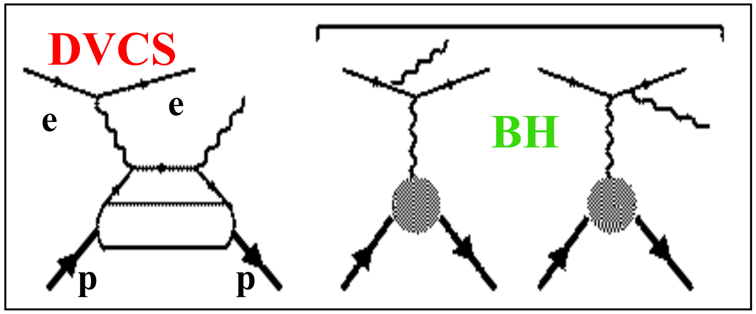
2ξ – longitudinal momentum transfer

$$\xi = \frac{x_B}{2 - x_B}$$

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

How to access the GPDs/CFFs?

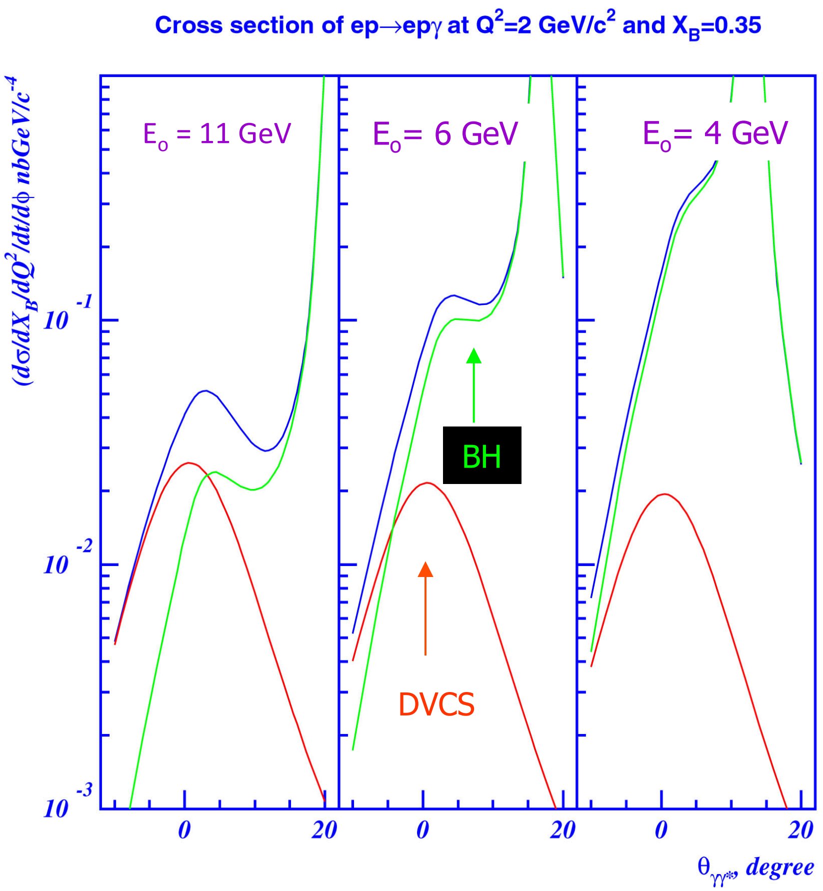
Accessing GPD through DVCS



$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |\mathcal{A}^{DVCS} + \mathcal{A}^{BH}|^2$$

$\mathcal{A}^{BH}$: given by elastic form factors F_1, F_2
$\mathcal{A}^{DVCS}$: determined by GPDs

$$I \sim 2(\mathcal{A}^{BH})\mathrm{Im}(\mathcal{A}^{DVCS})$$



BH-DVCS interference generates **spin-dependent** and **charge-dependent** cross section differences => use spin-polarized electrons/positrons and polarized targets.

GPDs & Compton FFs

- DVCS amplitude contains convolution integrals of the form

$$\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} = \mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} - i\pi H(\xi,\xi,t),$$

- There are 8 GPD-related quantities that can be extracted from the DVCS process:

Compton Form Factors (CFF)

$$H_{Re}(\xi,t) \equiv \mathcal{P}\int_0^1 dx\,[H(x,\xi,t) - H(-x,\xi,t)]\,C^+(x,\xi),$$

$$E_{Re}(\xi,t) \equiv \mathcal{P}\int_0^1 dx\,[E(x,\xi,t) - E(-x,\xi,t)]\,C^+(x,\xi),$$

$$\tilde{H}_{Re}(\xi,t) \equiv \mathcal{P}\int_0^1 dx\left[\tilde{H}(x,\xi,t) + \tilde{H}(-x,\xi,t)\right]C^-(x,\xi),$$

$$\tilde{E}_{Re}(\xi,t) \equiv \mathcal{P}\int_0^1 dx\left[\tilde{E}(x,\xi,t) + \tilde{E}(-x,\xi,t)\right]C^-(x,\xi),$$

$$H_{Im}(\xi,t) \equiv H(\xi,\xi,t) - H(-\xi,\xi,t),$$

$$E_{Im}(\xi,t) \equiv E(\xi,\xi,t) - E(-\xi,\xi,t),$$

$$\tilde{H}_{Im}(\xi,t) \equiv \tilde{H}(\xi,\xi,t) + \tilde{H}(-\xi,\xi,t),$$

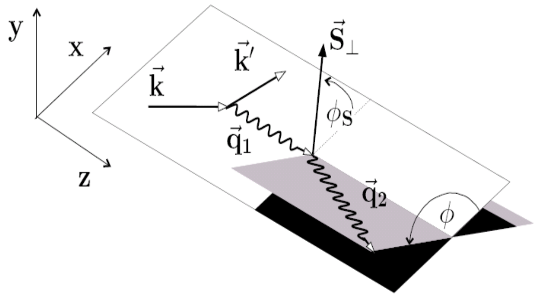
$$\tilde{E}_{Im}(\xi,t) \equiv \tilde{E}(\xi,\xi,t) + \tilde{E}(-\xi,\xi,t),$$

with:

$$C^{\pm}(x,\xi) = \frac{1}{x-\xi} \pm \frac{1}{x+\xi}$$

Structure of differential cross section

Polarized Beam, unpolarized Target:



$$\sigma_{ep\to e\gamma p} = \sigma_{\rm BH} + e_\ell\,\sigma_{\rm INT} + P_\ell e_\ell\,\tilde\sigma_{\rm INT} + \sigma_{\rm VCS} + P_\ell\,\tilde\sigma_{\rm VCS}$$

where σ even in ϕ $\qquad \sigma_{\rm INT} \propto {\rm Re}\,\mathcal{A}_{\gamma^* N\to\gamma N}$

$\tilde\sigma$ odd in ϕ $\qquad \tilde\sigma_{\rm INT} \propto {\rm Im}\,\mathcal{A}_{\gamma^* N\to\gamma N}$

	beam charge	beam pol.	combination
	e^-	difference	$-\tilde\sigma_{\rm INT} + \tilde\sigma_{\rm VCS}$
e^+	difference	none	$\sigma_{\rm INT}$
$\vec{e}^{\,+}$	difference	fixed	$P_\ell\,\tilde\sigma_{\rm INT} + \sigma_{\rm INT}$

only pol. e^-	need Rosenbluth to separate $\tilde\sigma_{\rm INT}$ from $\tilde\sigma_{\rm VCS}$ (different y at same x_B and Q^2)
unpol. e^- and e^+	get $\sigma_{\rm INT}$
pol. e^- and pol. e^+	get $\sigma_{\rm INT}$ and separate $\tilde\sigma_{\rm INT}$ from $\tilde\sigma_{\rm VCS}$

Structure of differential cross section

Polarized Target:

$$\sigma_{ep\to e\gamma p} = \sigma_{\rm BH} + e_\ell\,\sigma_{\rm INT} + P_\ell e_\ell\,\tilde\sigma_{\rm INT} + \sigma_{\rm VCS} + P_\ell\,\tilde\sigma_{\rm VCS}$$

$$+ S\big[P_\ell\,\Delta\sigma_{\rm BH} + e_\ell\,\Delta\tilde\sigma_{\rm INT} + P_\ell e_\ell\,\Delta\sigma_{\rm INT} + \Delta\tilde\sigma_{\rm VCS} + P_\ell\,\Delta\sigma_{\rm VCS}\big]$$

where polarization S can be longitudinal or transverse

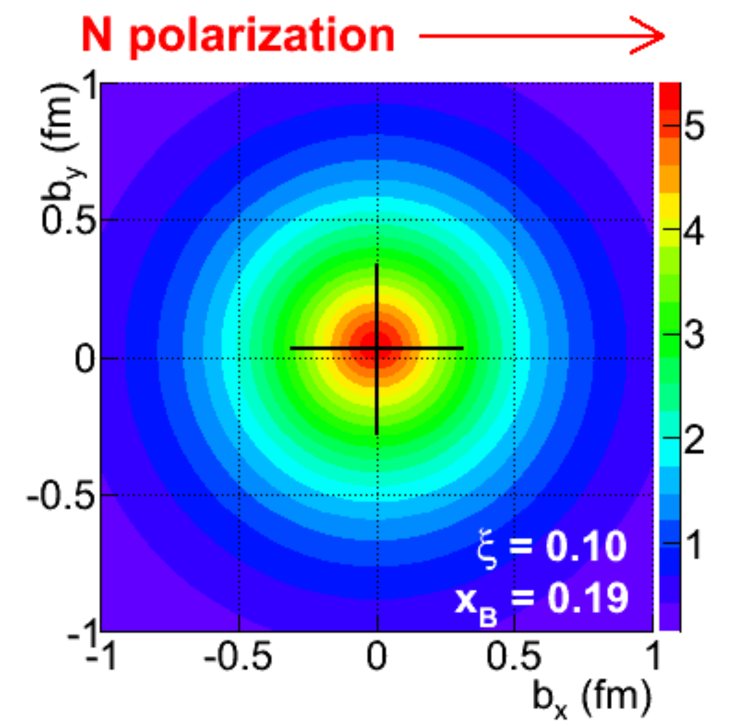
beam charge	beam pol.	target pol.	combination
e^-	none	difference	$-\Delta\tilde\sigma_{\rm INT} + \Delta\tilde\sigma_{\rm VCS}$
e^+ difference	none	fixed	$S\,\Delta\tilde\sigma_{\rm INT} + \sigma_{\rm INT}$
→ e^+ difference	fixed	fixed	$S\,\Delta\tilde\sigma_{\rm INT} + SP_\ell\,\Delta\sigma_{\rm INT} + P_\ell\,\tilde\sigma_{\rm INT} + \sigma_{\rm INT}$

only pol. e^-	need Rosenbluth to separate $\Delta\tilde\sigma_{\rm INT}$ from $\Delta\tilde\sigma_{\rm VCS}$
unpol. e^- and e^+	can separate $\Delta\tilde\sigma_{\rm INT}$ from $\Delta\tilde\sigma_{\rm VCS}$
pol. e^- and pol. e^+	can separate $\Delta\tilde\sigma_{\rm INT}$ from $\Delta\tilde\sigma_{\rm VCS}$ and get $\Delta\sigma_{\rm INT}$

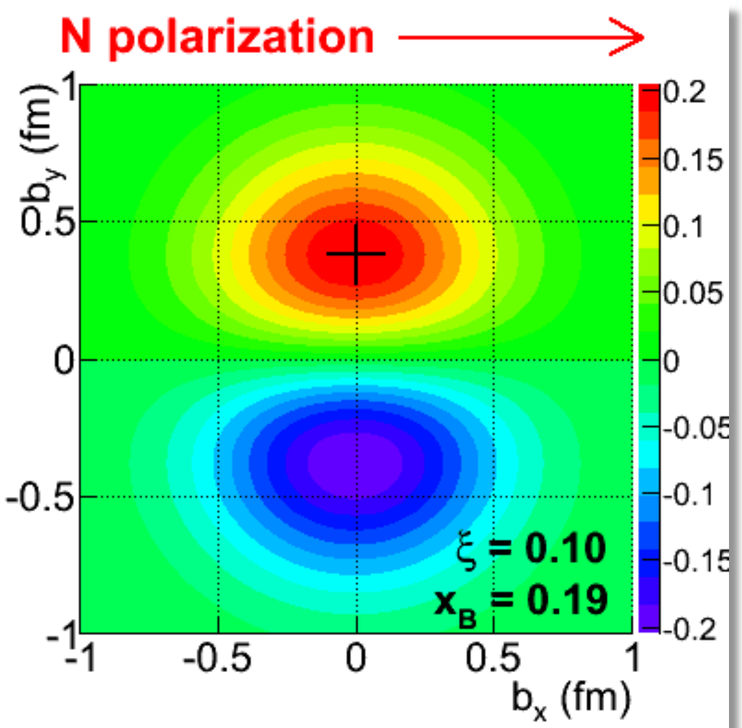
GPDs and imaging in transverse space

The GPD can be accessed in ***DVCS*** processes with ***polarized beam and/or target***.
Fourier transform in Mandelstam variable ***t*** ➔ charge densities in b space.

$$\rho_X(x,\vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2}\left[H(x,0,t) - \frac{E(x,0,t)}{2M}\frac{\partial}{\partial b_y}\right] e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp}$$



Contribution of *H+E*



Contribution of *E*

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Accessing the forces & pressure on quarks

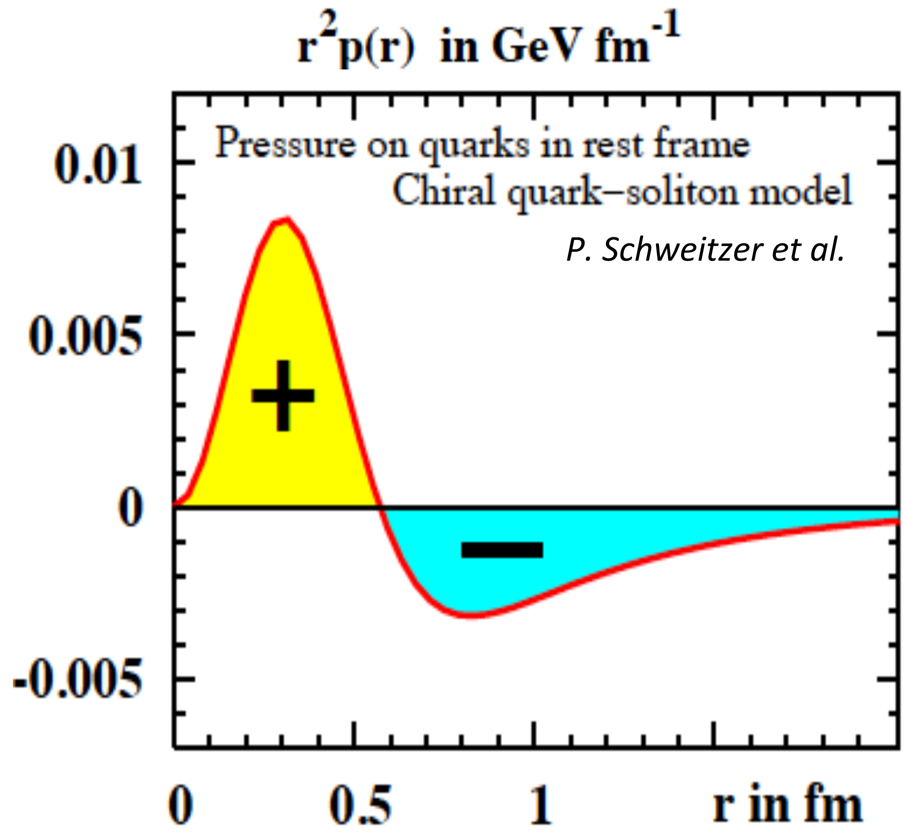
Nucleon matrix element of EMT contains:

$M_2(t)$: Mass distribution inside the nucleon
$J(t)$: Angular momentum distribution
$d_1(t)$: Shear forces and pressure distribution

$$M_2^q(t) + \frac{4}{5} d_1(t)\xi^2 = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x H^q(x,\xi,t)$$

To determine *$d_1(t)$* we need $\mathcal{Re}\{H^q\}$ and $\mathcal{Im}\{H^q\}$

Measuring *$d_1(t)$* will access the pressure distribution and shear forces on quarks in protons => how is confinement realized.

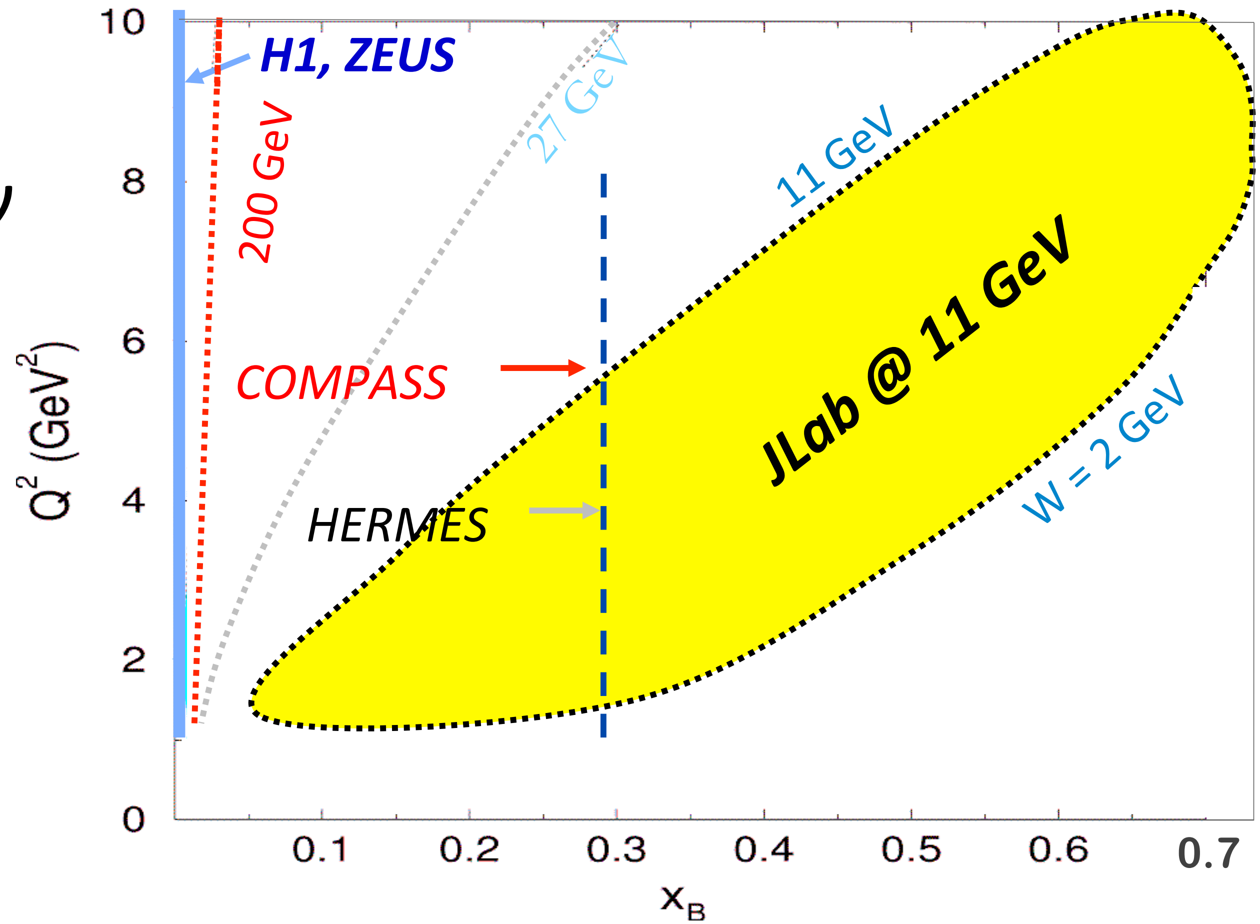


High-impact part of the GPD program. Form factors *$M_2(t)$* and *$J(t)$* may also be accessed.

Coverage of DVCS @ 11GeV

$e^- p \rightarrow e^- p \gamma$

$e^+ p \rightarrow e^+ p \gamma$

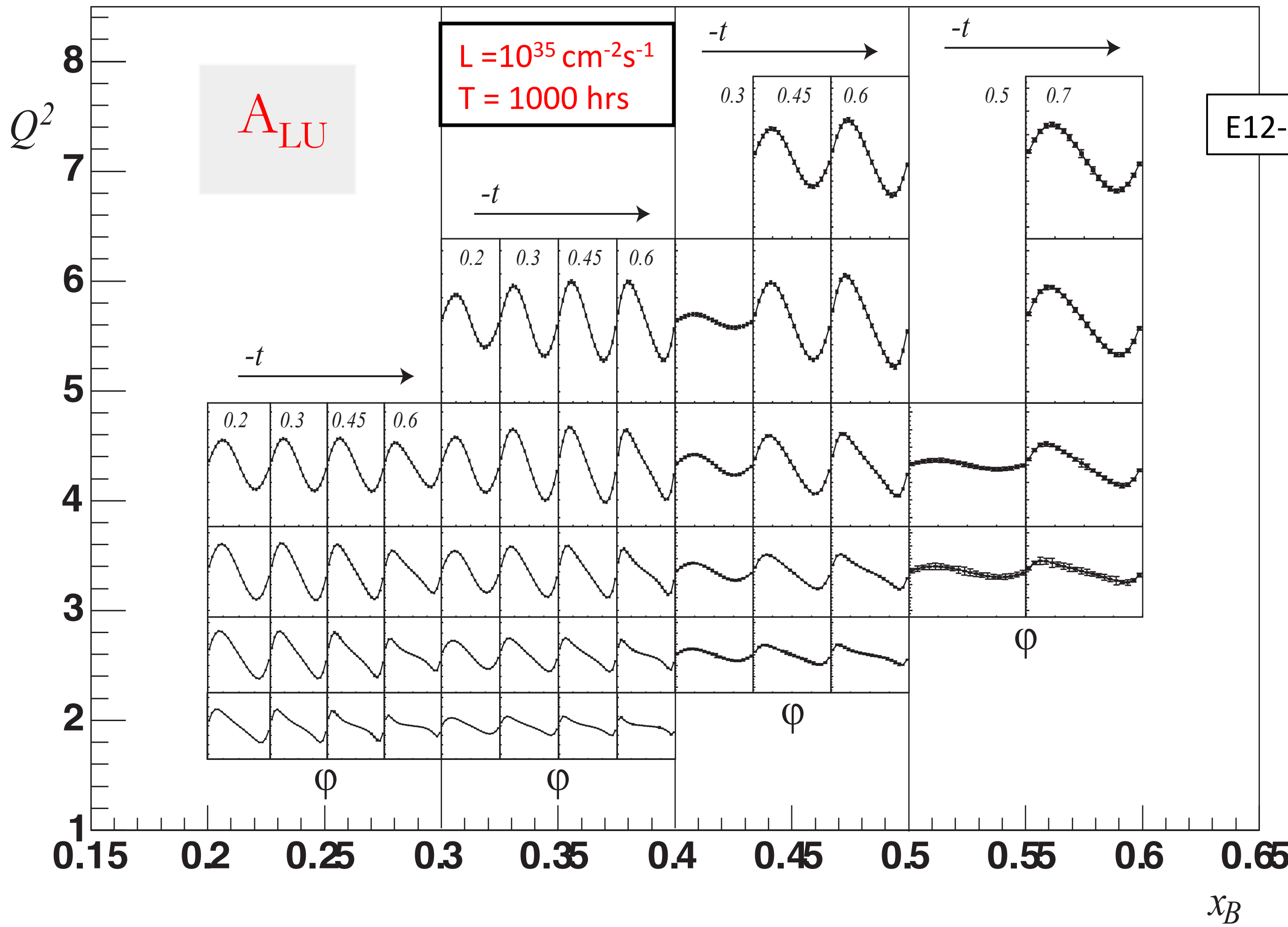


Large range in x and in –t is essential for imaging
=> high luminosity, large acceptance

A_{LU} projections for JLab@12GeV

$\Delta\sigma_{LU} \sim \sin\phi \{F_1 H + \xi(F_1+F_2)\widetilde{H} + kF_2 E\} d\phi$

$\vec{e}^- p \to e^- p \gamma$



E12-06-119

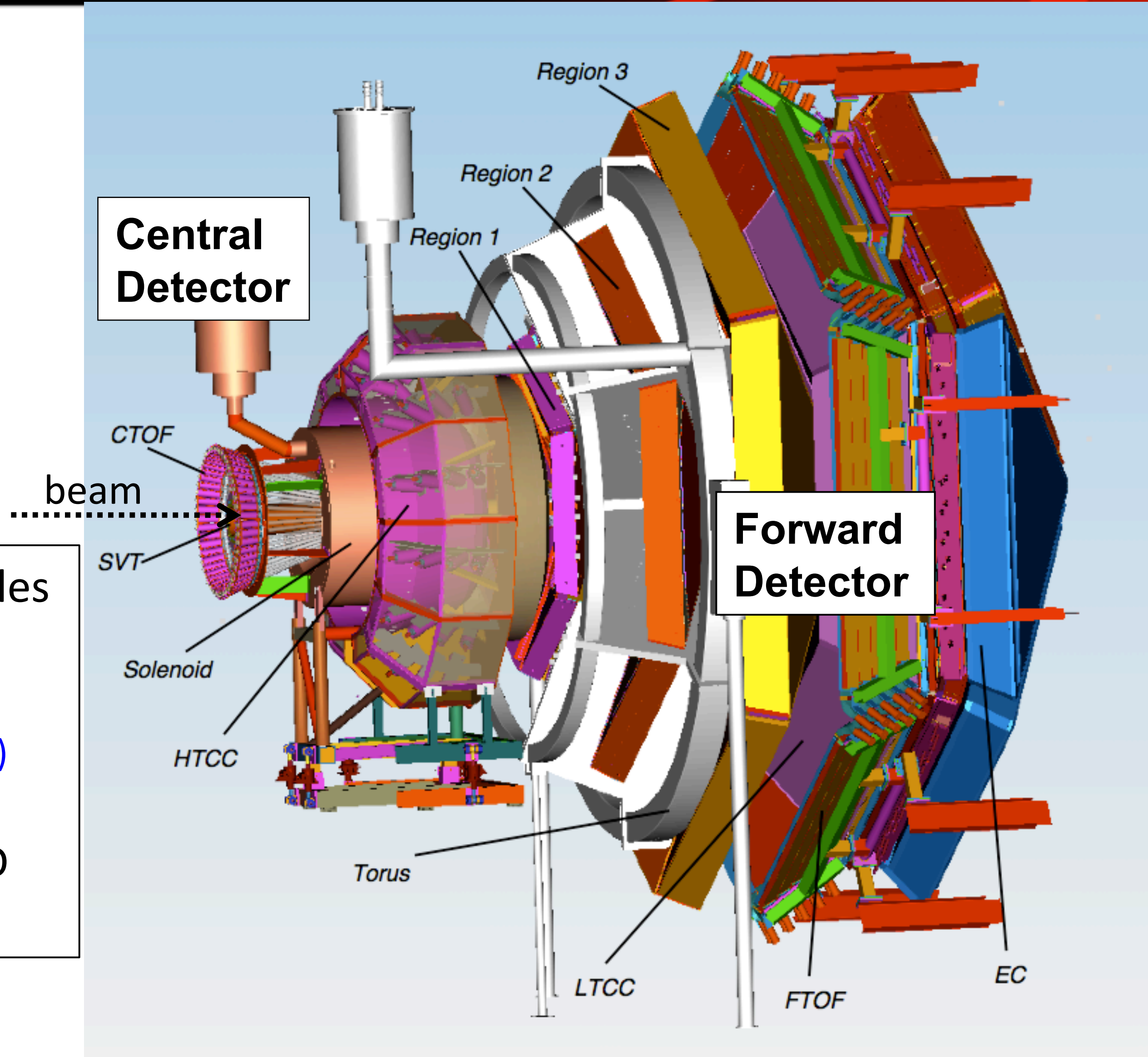
With e^+ beams of same luminosity larger errors from lower polarization.
FOM ~ $(P_{e+}/P_{e-})^2$
≈ 1/2

CLAS12

DVCS kinematics:

$e^- p \rightarrow e^- p \gamma$

$e^+ p \rightarrow e^+ p \gamma$



e^-/e^+ scattered to small angles detected in CLAS12 FD

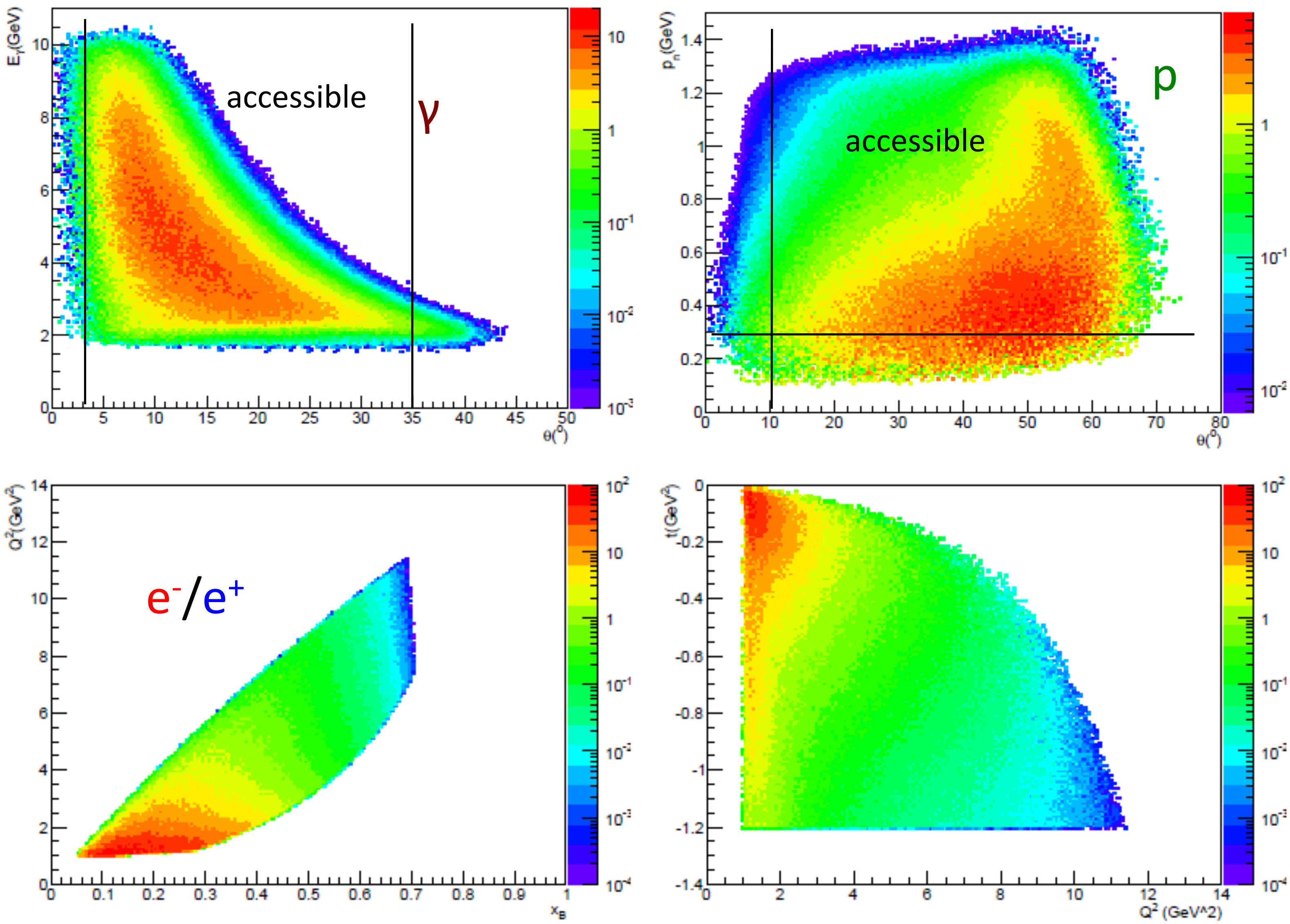
$\theta_{e-} = 6^o–35^o$ / θ_{e+} $6^o–35^o$

(reverse Torus field)

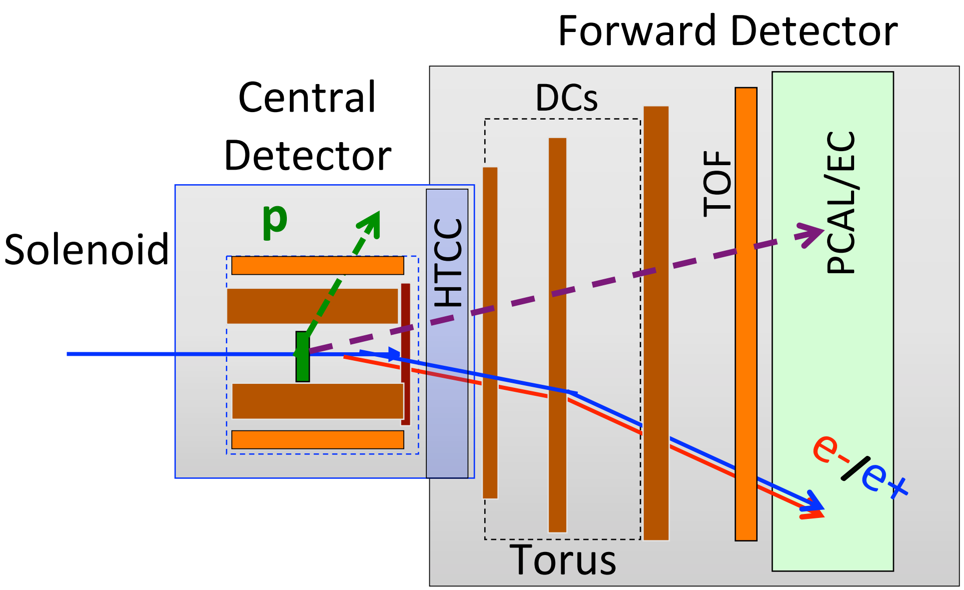
Proton in full CLAS12 CD/FD

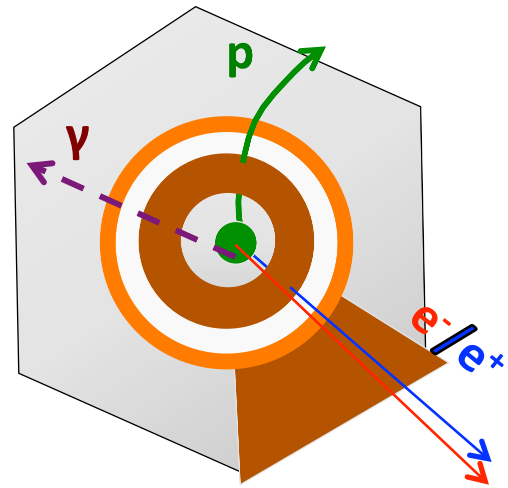
θ_p = 10 -70^o

DVCS kinematics $E_{e+/e-}$ = 11 GeV



CLAS12 e^+p/e^-p experiment (generic)





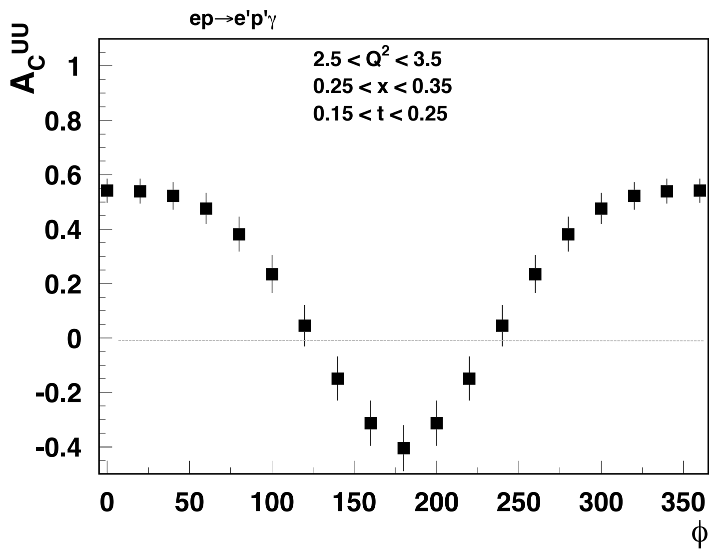
Central Detector:
- Charged particle tracking in solenoid field
- Polar angle range θ = 35 - 125°
- Azimuthal angle range Δϕ= 360°
- Particle ID by TOF for p < 1.5 GeV/c

Forward Detector:
- Charged particle tracking in Torus field
- Polar angle range θ = 6 - 35°
- Azimuthal angle range (0.6 – 0.9)x2π
- e^+/e^- ID in HTCC & ECAL

Event selection:
Detect/identify all particles -> exclusivity

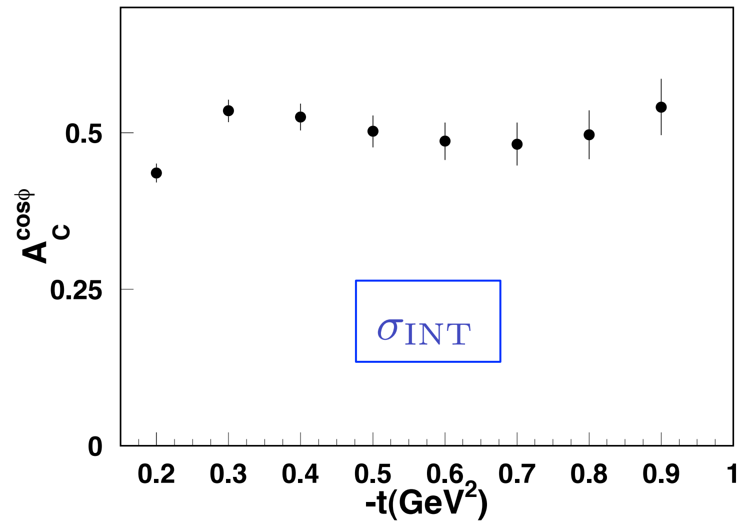
Charge Asymmetries – Target unpolarized

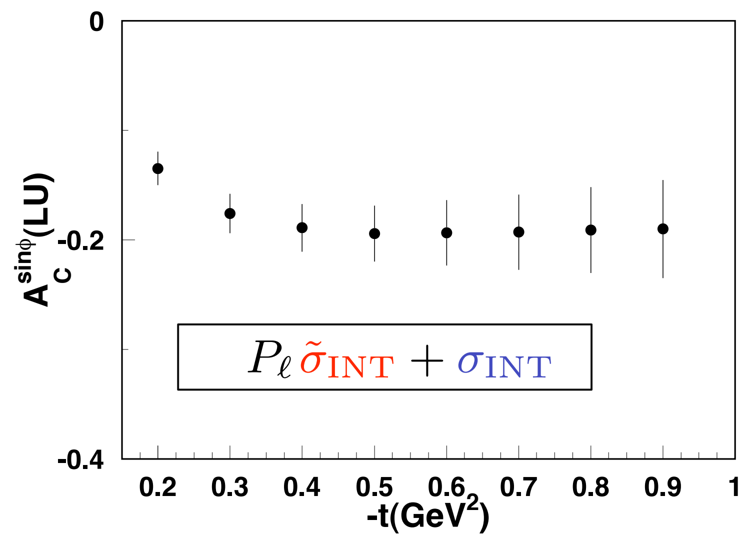
Positrons: L = $2 \times 10^{34} cm^{-2}s^{-1}$; P=0.6
Electrons: L = $10^{35} cm^{-2}s^{-1}$; P=0.8
E=11 GeV, 1000hrs.



Dual model: V. Guzey (2009)

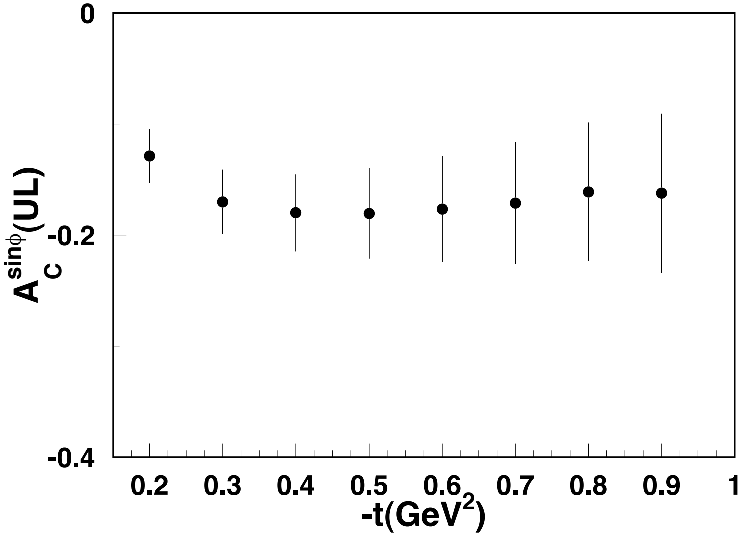
Charge asymmetries $A_c = e^+ - e^- / e^+ + e^-$ in VCS are large and show strong azimuthal modulations. They can be measured with good accuracy.



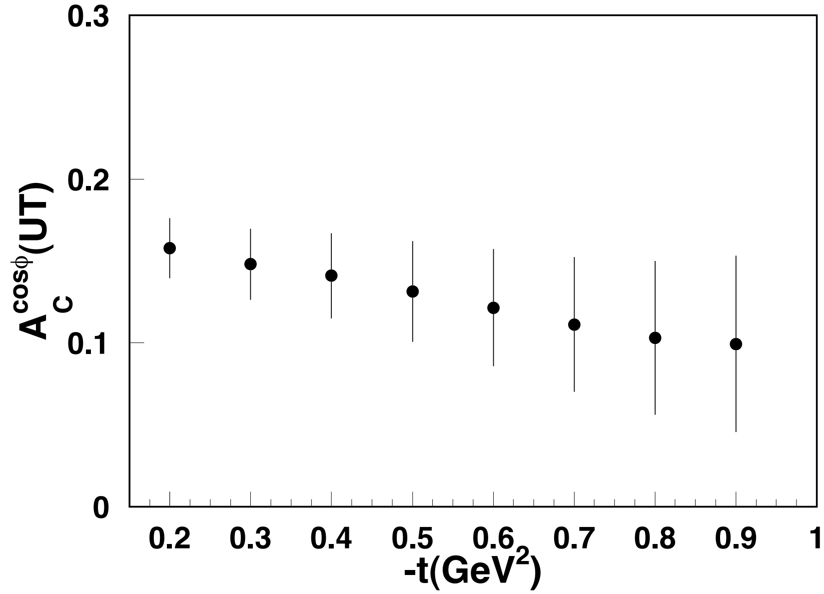


Charge Asymmetries – Target polarized

$S\,\Delta\tilde{\sigma}_{\mathrm{INT}} + \sigma_{\mathrm{INT}}$



$S\,\Delta\tilde{\sigma}_{\mathrm{INT}} + S P_\ell\,\Delta\sigma_{\mathrm{INT}} + P_\ell\,\tilde{\sigma}_{\mathrm{INT}} + \sigma_{\mathrm{INT}}$



Other bins in Q^2 and x are measured simultaneously.

Errors on polarized target asymmetries marginal, would benefit from higher positron luminosity.

Summary of DVCS part

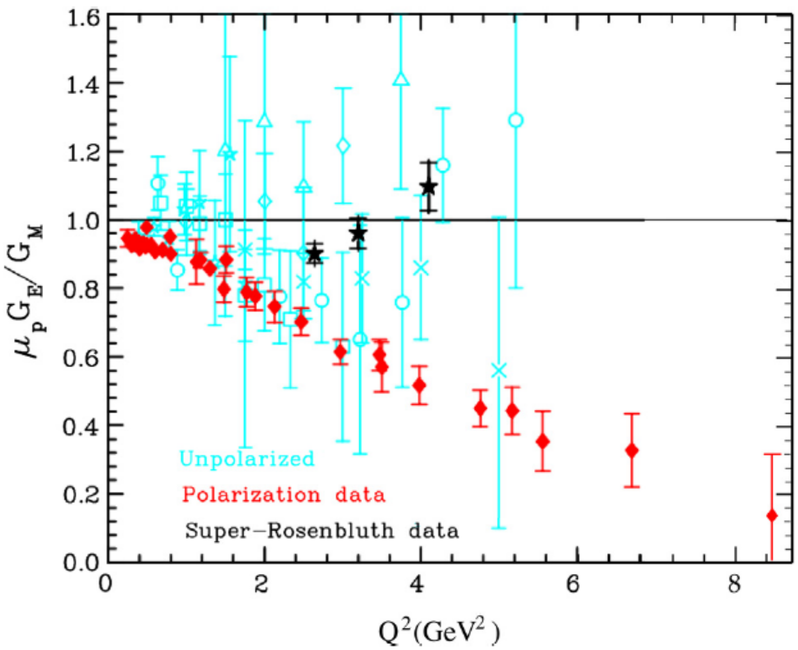
- DVCS is a crucial part of the JLab physics program at 12 GeV. It provides the cleanest access to the GPDs and is the basis for the 3D imaging of the nucleon. *=> M. Defurne*

- Positron beams (polarized/unpolarized) of the same energy as electrons will significantly enhance the GPD program by allowing the separation of different combination of GPDs in the charge-dependent interference terms of the cross section.

- Positron beams will directly address questions regarding quark confinement forces and the angular momentum distribution in protons. *=> F.X. Girod*

- A positron current of ~10nA and P_{e+} = ~0.6 is required for an initial GPD program with positrons.

Two-photon effects in elastic ep scattering



- 2γ effects are significant in cross section differences but largely cancel in the G_E/G_M ratio from polarization measurements.

- Can the full discrepancy between the polarization data and the Rosenbluth data be explained with contributions from 2γ effects alone?

=> Measure 2γ effects in elastic cross section ratio of e^+p/e^-p

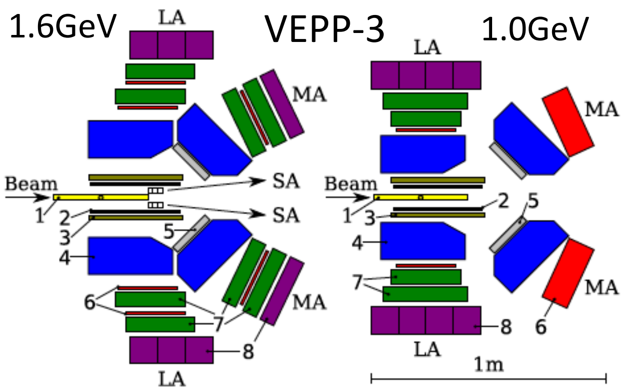
$$R_{2\gamma} \approx 1 - 2\delta_{\gamma\gamma}$$

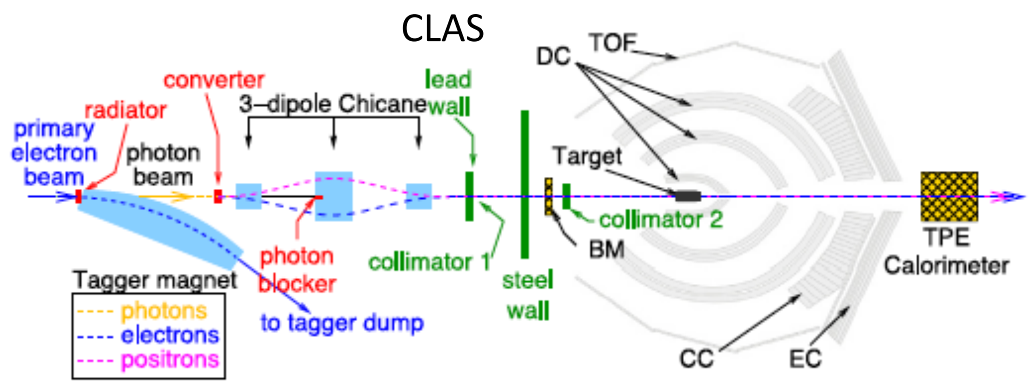
($\delta_{\gamma\gamma}$ is 2γ correction from interference of 1γ and 2γ amplitudes)

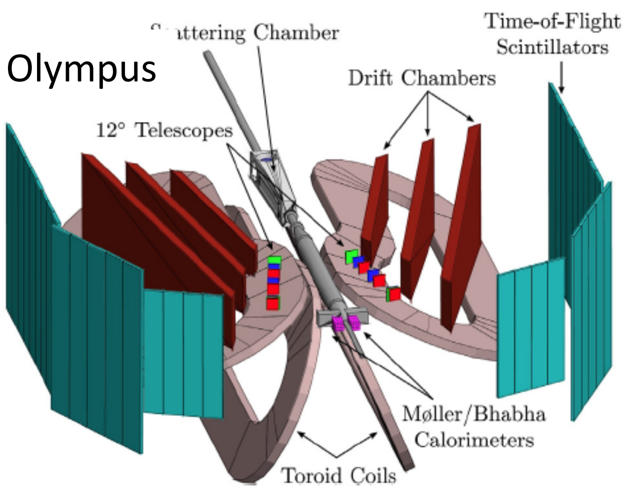
Expected effects are small O(%), making experiments challenging to 1) get sufficient statistics and 2) to keep systematic uncertainties at < 1%.

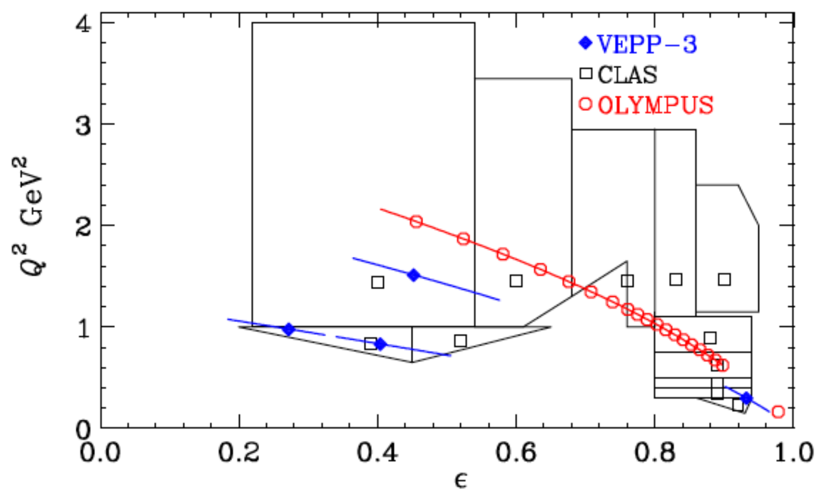
Three recent e^+/e^- experiments

Review article *"Two-photon exchange in elastic electron-proton scattering", A.Afanasev, P.G. Blunden, D. Hassel, B.A. Raue, PPNP 95 (2017) 245-278*









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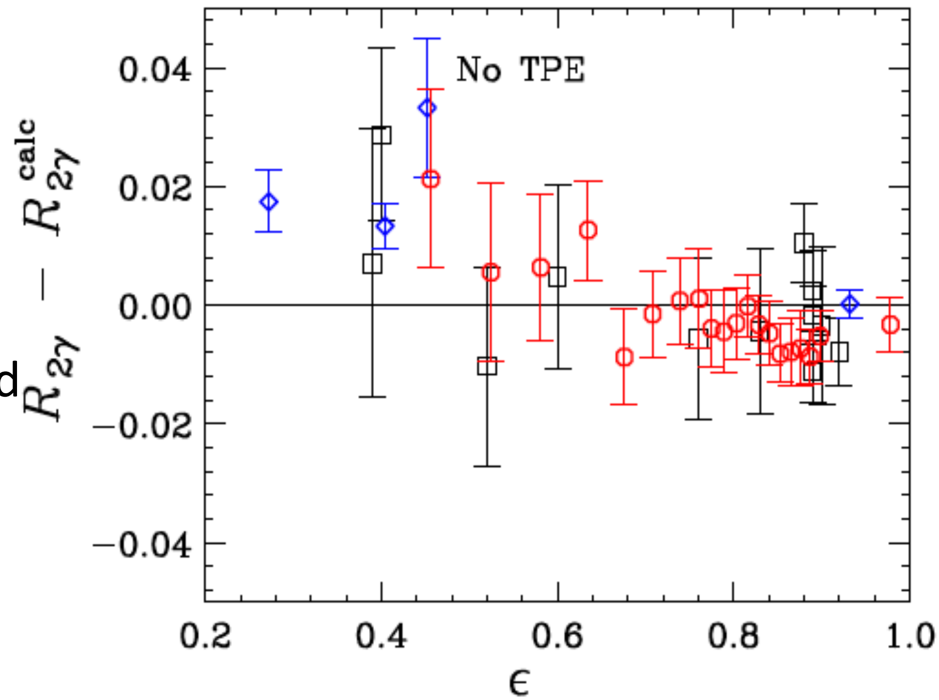
Conclusions from direct 2γ searches

- The 3 experiments are in reasonable agreement with several theoretical calculations that include different models for 2γ effects.

Caveat: Agreement requires shifting the CLAS and the Olympus results by one and two times their correlated uncertainties.

" The $\delta_{\gamma\gamma} = 0$ hypothesis is ruled out at greater than 99.5% confidence level"



"The results of these experiments are ***by no means definitive***. Most of the data are well below where the form factor discrepancy is significant ($Q^2 > 2GeV^2$). Questions regarding the sources of the discrepancy remain largely unanswered" (my emphasis)

"There is a clear need for similar experiments at larger Q^2 and at ε <0.5".

What to do?

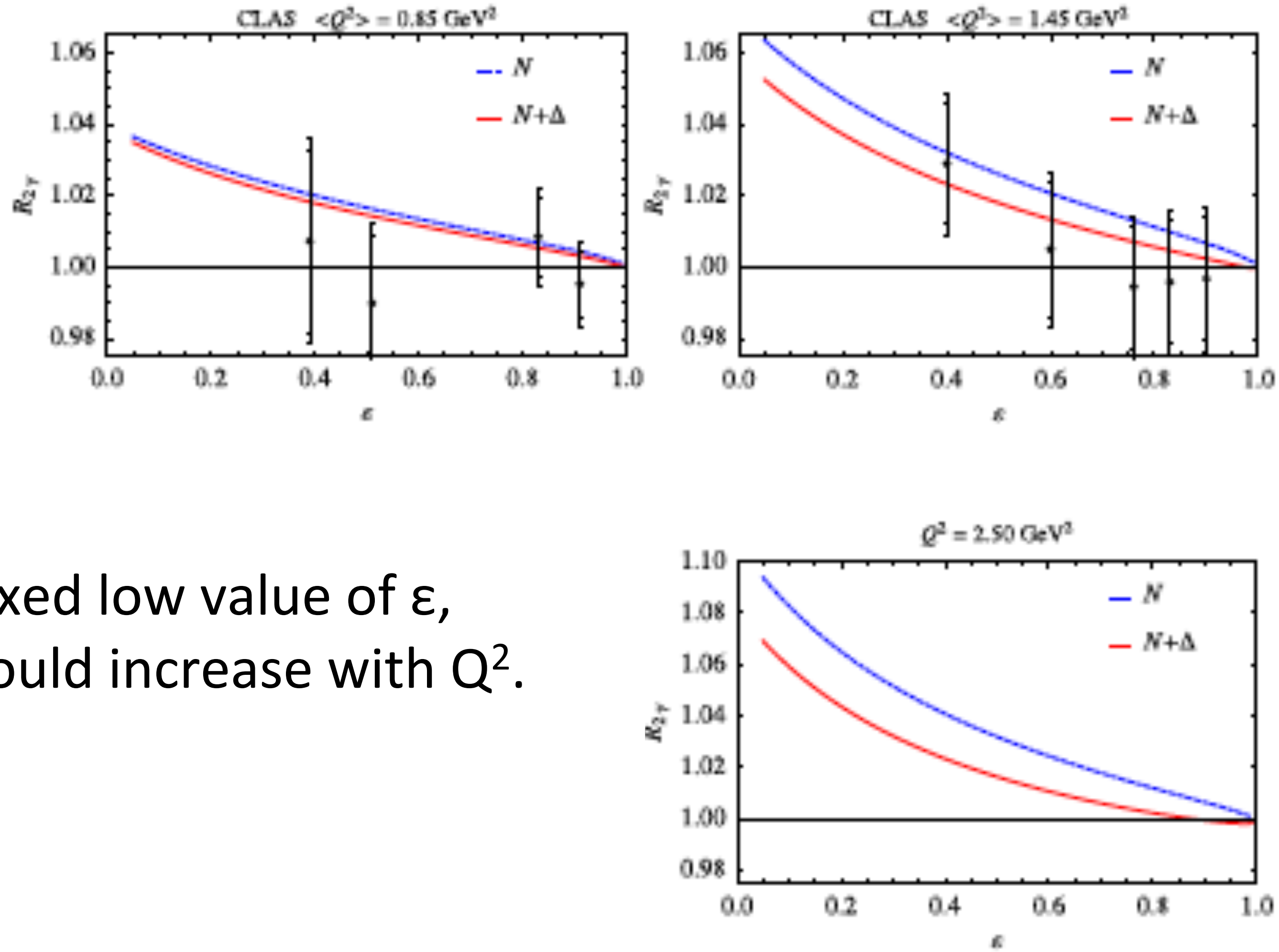
- After 3 dedicated recent experiments (one making use of CLAS), and after many earlier attempts to measure 2γ exchange contribution we only know that they do exists and that the results are not inconsistent with the discrepancy observed in elastic ep scattering.

What are the contributing factors to the limited success?

- Kinematics coverage in Q^2 and in ε are mostly where effects are expected to be small
- Systematic uncertainties are marginal in some cases
- Rates at higher Q^2 and smaller ε are low, corresponding to high energy and large electron scattering angles.

Can we do better at JLab ?

CLAS data & predictions



At fixed low value of ε,
$R_{2\gamma}$ should increase with Q^2.

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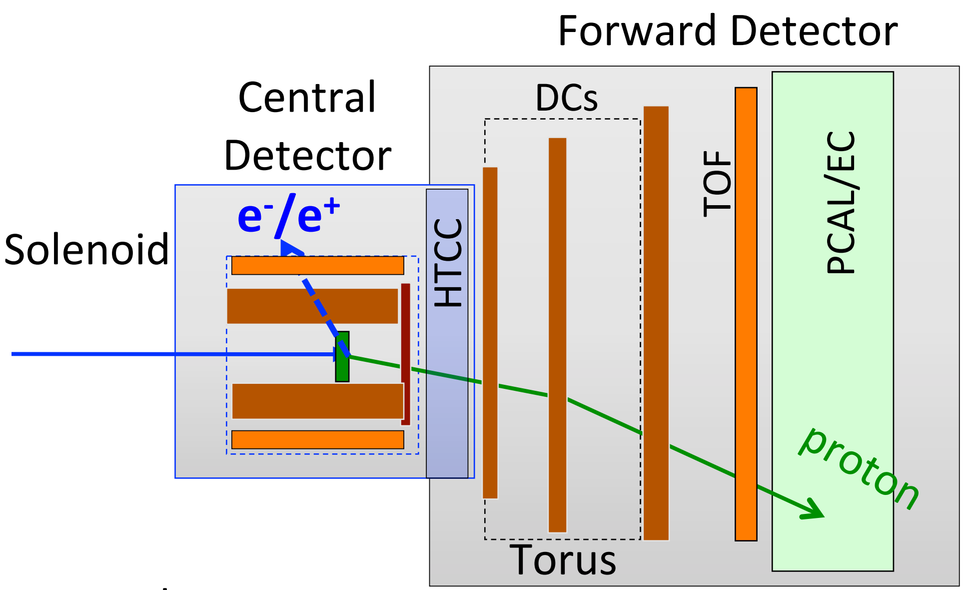
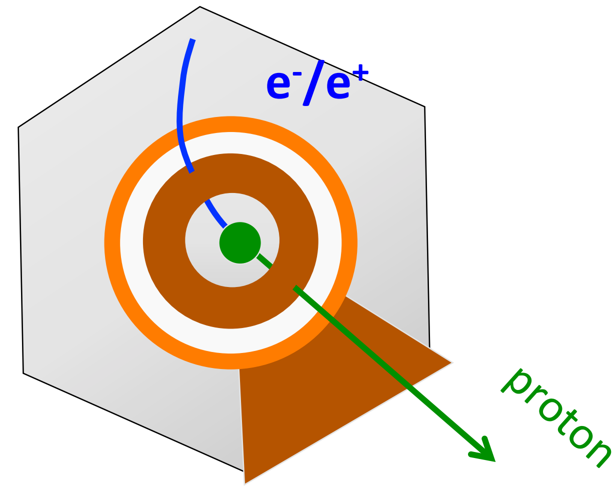
A possible scenario with *CLAS12*

Assumptions on beam properties

- Positron beam current: $I_{e+} \approx 60$ nA
- Beam profile: $\sigma_x, \sigma_y < 0.4$mm
- Polarization: not needed, so phase space at e^+ source can be chosen for maximum yield
- Extract electron beam from same source to keep systematic effects low ?
- Switching from e^+ to e^- beam in ≤ 1 day (keep machine stable, control of systematic errors)
- Luminosity (5 cm lH_2 target): $0.8x10^{35}cm^{-2}s^{-1}$
- Use Central Detector for e^+/e^- detection θ_e=40-125°
- Use Forward Detector for proton detection θ_p=7-35°

CLAS12 $e^{+/-}p/e^{+/-}p$ experiment (generic)





Central Detector:

- Charged particle tracking in solenoid field
- Polar angle range θ = 35 - 125°
- Azimuthal angle range Δϕ= 360°
- Particle ID by TOF for p < 1.5 GeV/c
- No direct electron/positron ID

Event selection:

-> back-to-back e-p kinematics

- > ep -> eX missing mass: $M_x = M_p$

Forward Detector:

- Charged particle tracking in Torus field
- Polar angle range θ = 6 - 35°
- Azimuthal angle range (0.6 – 0.9)x2π
- Particle ID by TOF for p < 6 GeV/c
- e^-/e^+ rejection in HTCC

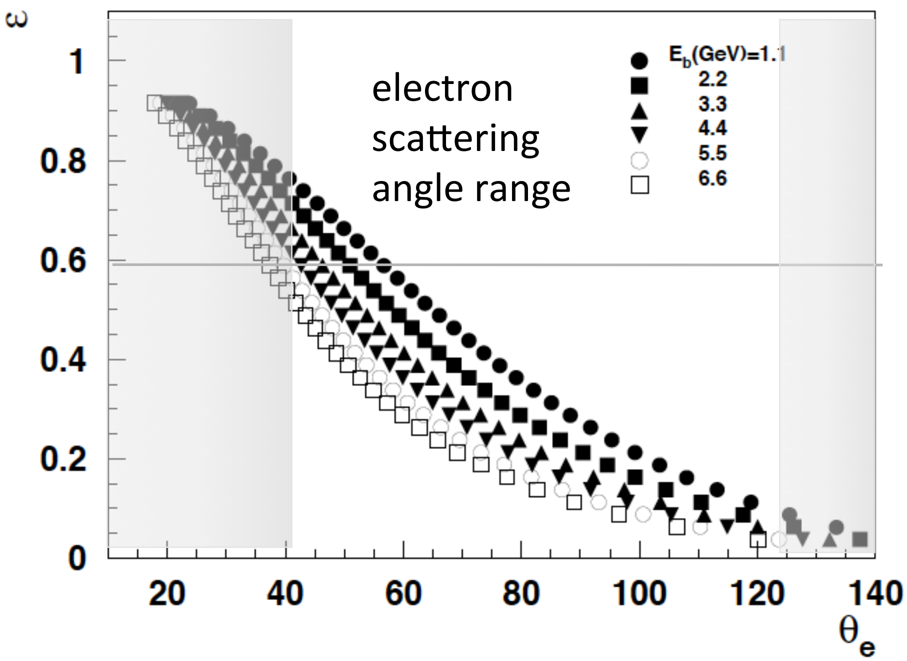
If direct electron/positron ID needed:

=> replace Central Neutron Detector with e.m. calorimeter

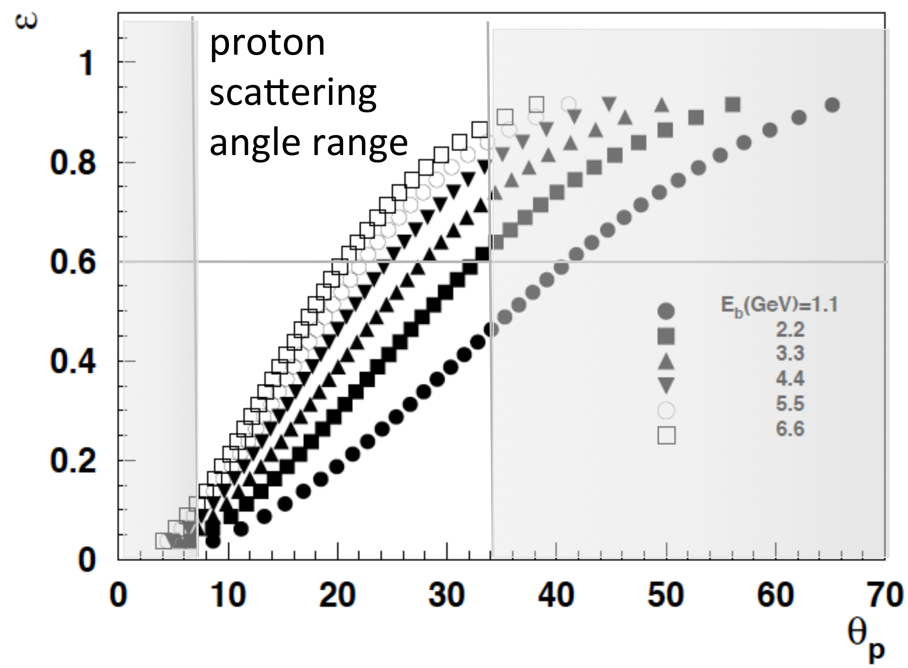
CLAS12 Design Parameters

	Forward Detector	Central Detector
Angular range Tracks Photons	 $5^0 – 35^0$ $2.5^0 – 35^0$	 $35^0 – 125^0$ ---
Resolution $\delta p/p$ (%) $\delta\theta$ (mr) $\Delta\phi$ (mr)	 0.3 @ 5 GeV/c 1 3	 2 @ 1 GeV/c 3 1.5
Photon detection Energy (MeV) $\delta\theta$ (mr)	 >150 4 @ 1 GeV	 --- ---
Neutron detection N_{eff}	 < 0.7 (EC+PCAL)	 0.1 (CND)
Particle ID e/π π/p π/K K/p $\pi^0 \rightarrow \gamma\gamma$	 Full range < 5 GeV/c < 2.5 GeV/c < 4 GeV/c Full range	 --- < 1.25 GeV/c < 0.65 GeV/c < 1.0 GeV/c ---

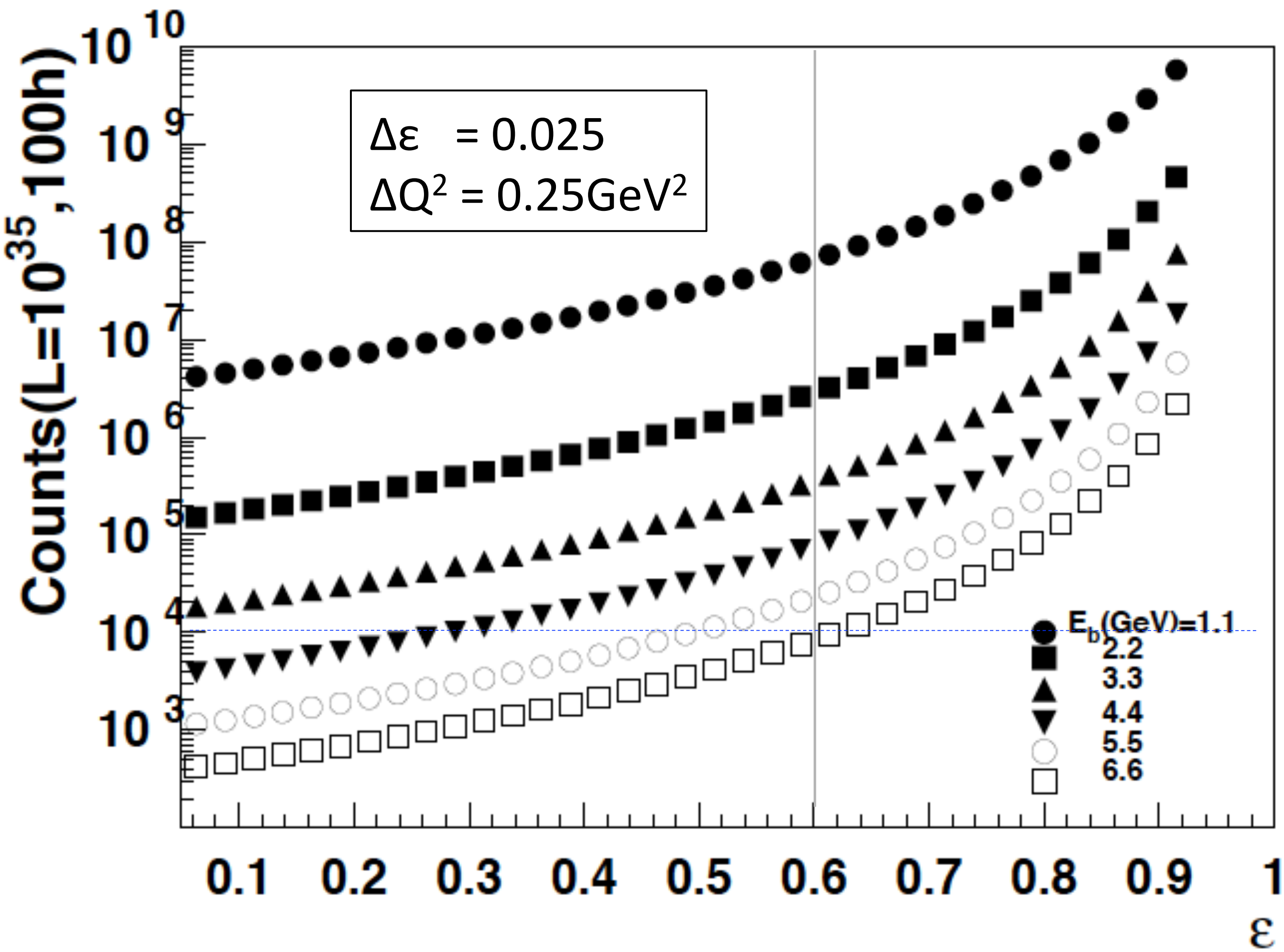
Limits in scattering angles



Kinematics graphs and rate estimates by Harut Avakian

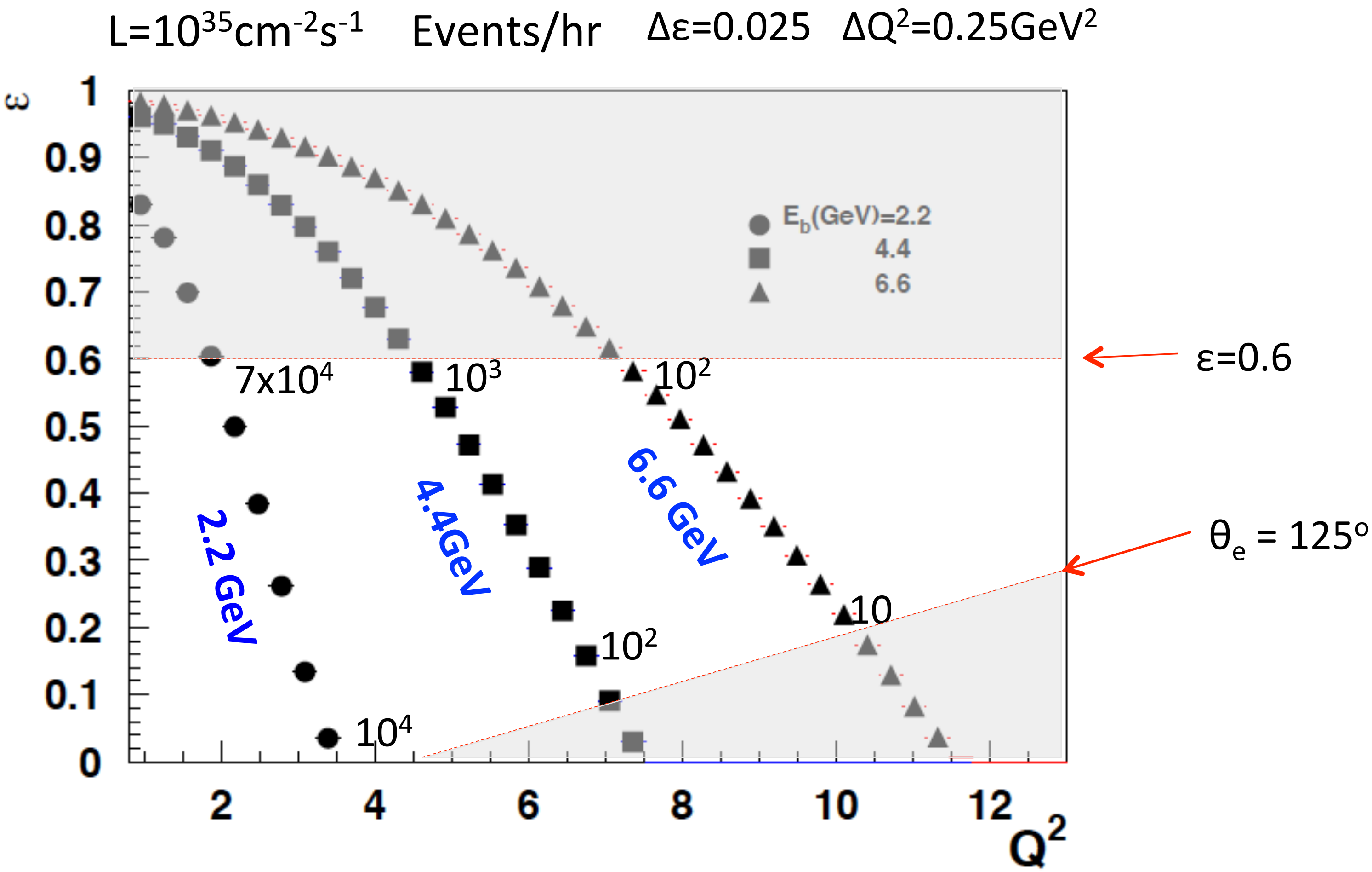


Rate calculations



1% stat.

Event rates for $e^{+/-}p \rightarrow e^{+/-}p$ with CLAS12



Other equipment option – Hall A / C

Detector	Beam current (nA)	Target length (cm)	Luminosity (10^{35})	e^+/e^- $\Delta\Omega$ (sterad)	FOM	FOM/ FOM(CLAS12)
HRS	60	10	1.6	0.006	0.0096	0.0024
HMS	60	10	1.6	0.006	0.0096	0.0024
BigBite	60	20	3.2	0.080	0.26	0.065
SBS	60	20	3.2	0.070	0.22	0.055
CLAS12	60	5	0.8	5.0*	4.0	1

FOM = $L \times \Delta\Omega_{ep}$

- HRS/HMS – due to limited solid angle may be competitive for positron currents I_{e+} >> 1 µA or if high resolution is needed.
- BigBite Spectrometer or SBS – may be used as electron spectrometer with large solid angles.

*) includes a factor 2/3 for proton detection

Summary of 2-photon physics

- Positron beams (unpolarized) of ~60nA will enable a 2-γ program in elastic $e^{+/-}p$ scattering to significantly extend previous measurements at VEPP-3, CLAS, Olympus.
- As polarization is not required positrons may be drawn from the source in phase space where the unpolarized yield is maximum.
- Such data may resolve the discrepancy between Rosenbluth separation and polarization transfer elastic form factor measurements.
- CLAS12 can be used with additional electron trigger at large angles to reach low ε kinematics.
- Physics with positrons in the high luminosity halls may require currents O(1 μA), assuming currently available equipment options.

Conclusions

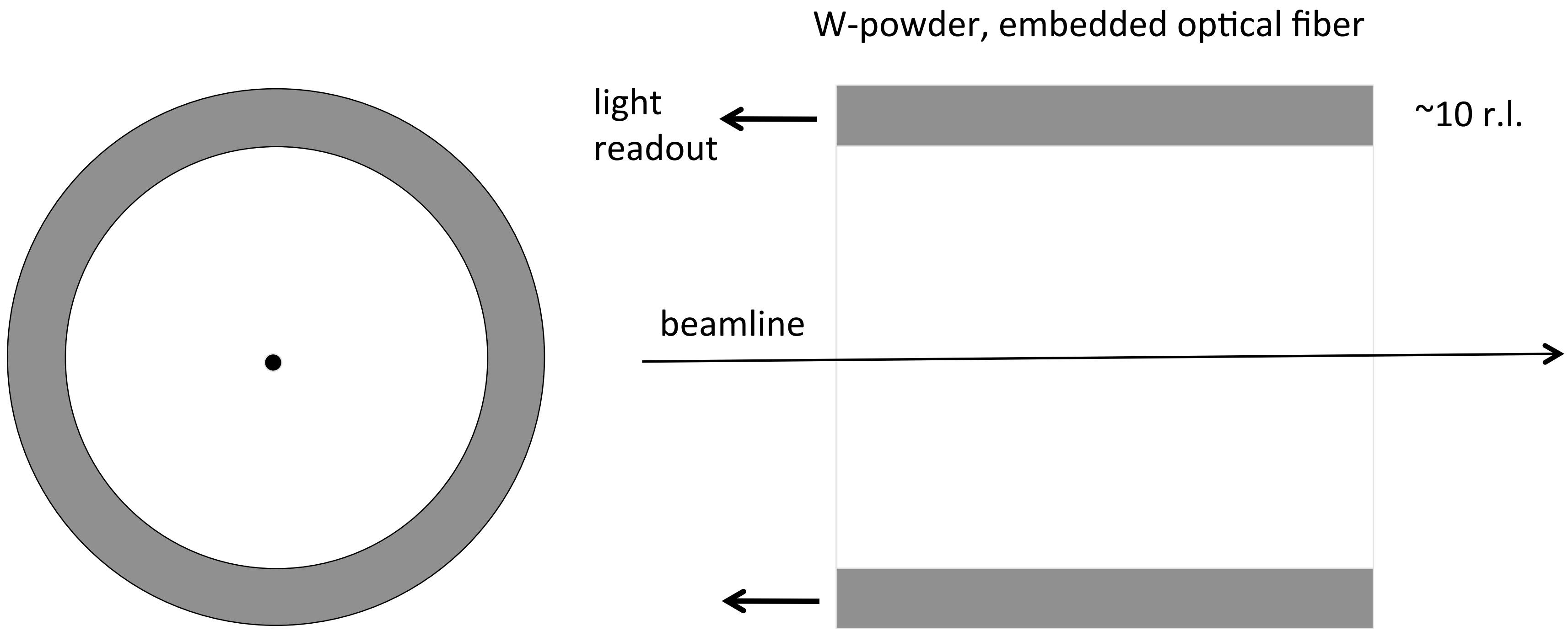
CLAS12 provides equipment options for nuclear/hadronic science with positrons/electrons beam that promise high impact in two areas:

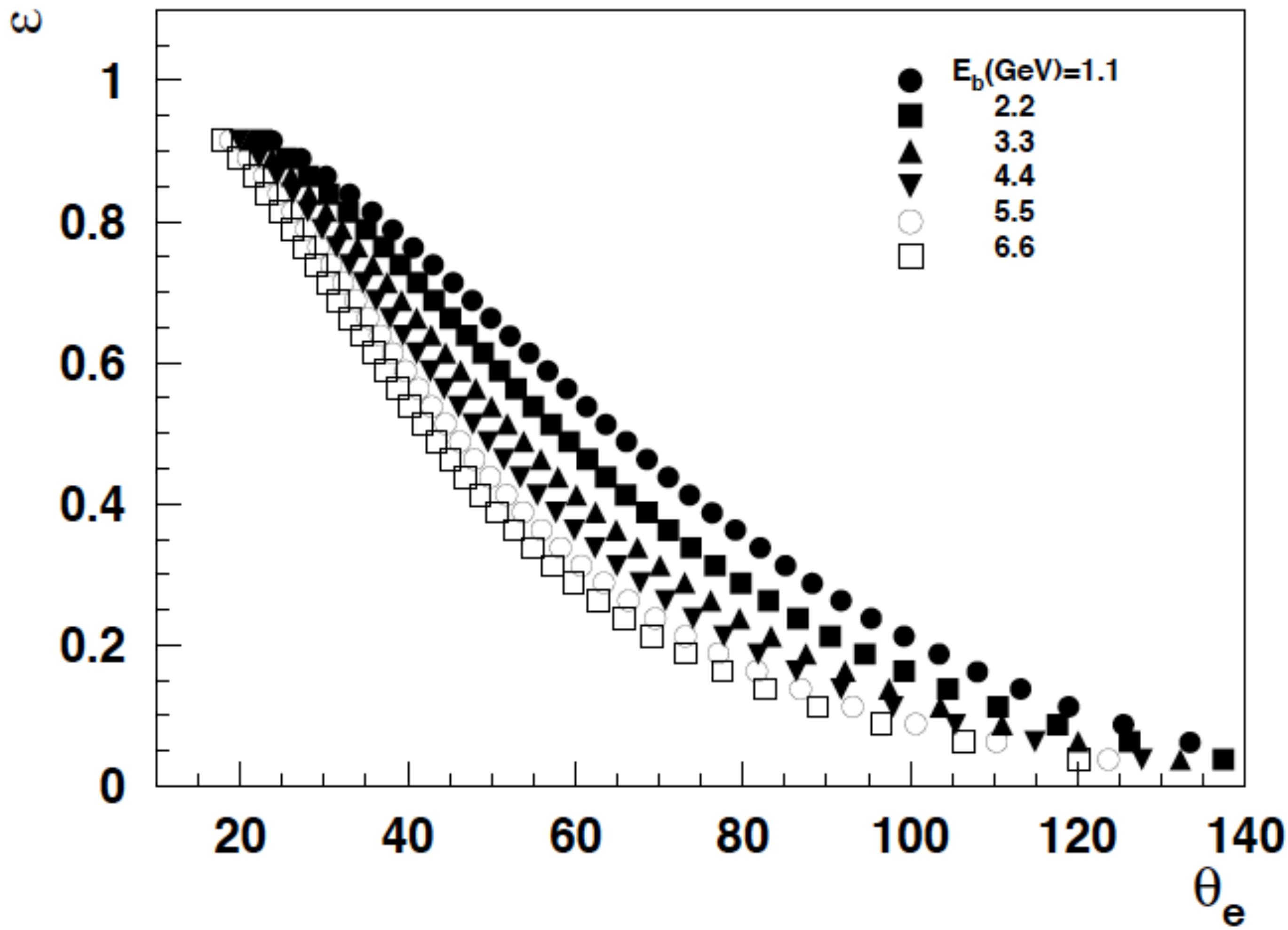
- The extension of the GPD program in DVCS with strong sensitivity to the real part of scattering amplitude $\{\mathcal{A}\}$, which enables more direct access to the gravitational form factors that relate to fundamental properties of the nucleon.

- The quantitative assessment of the 2-photon contributions in elastic ep scattering, with high statistics data in a large kinematic range.

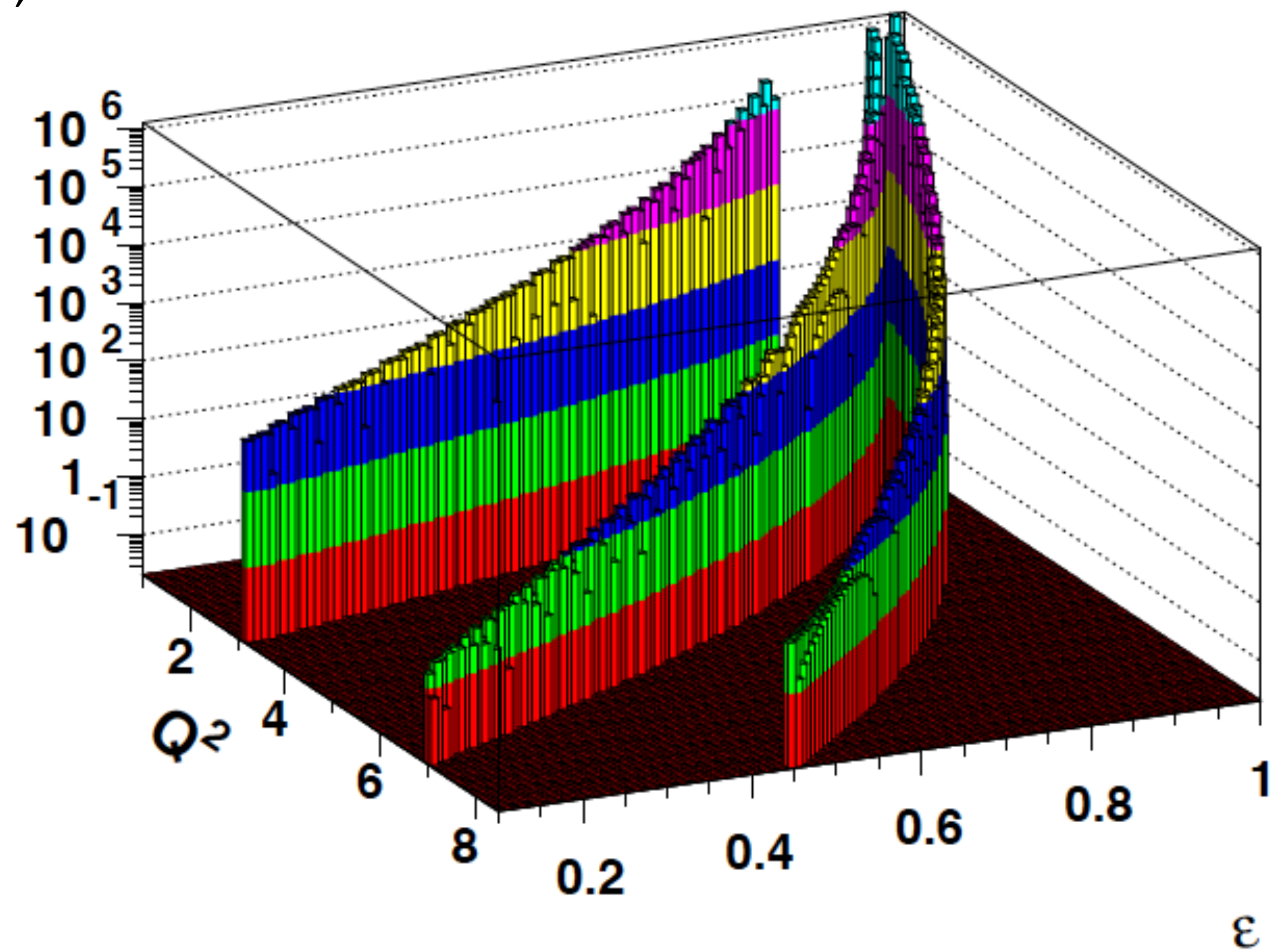
Many details remain to be worked out.

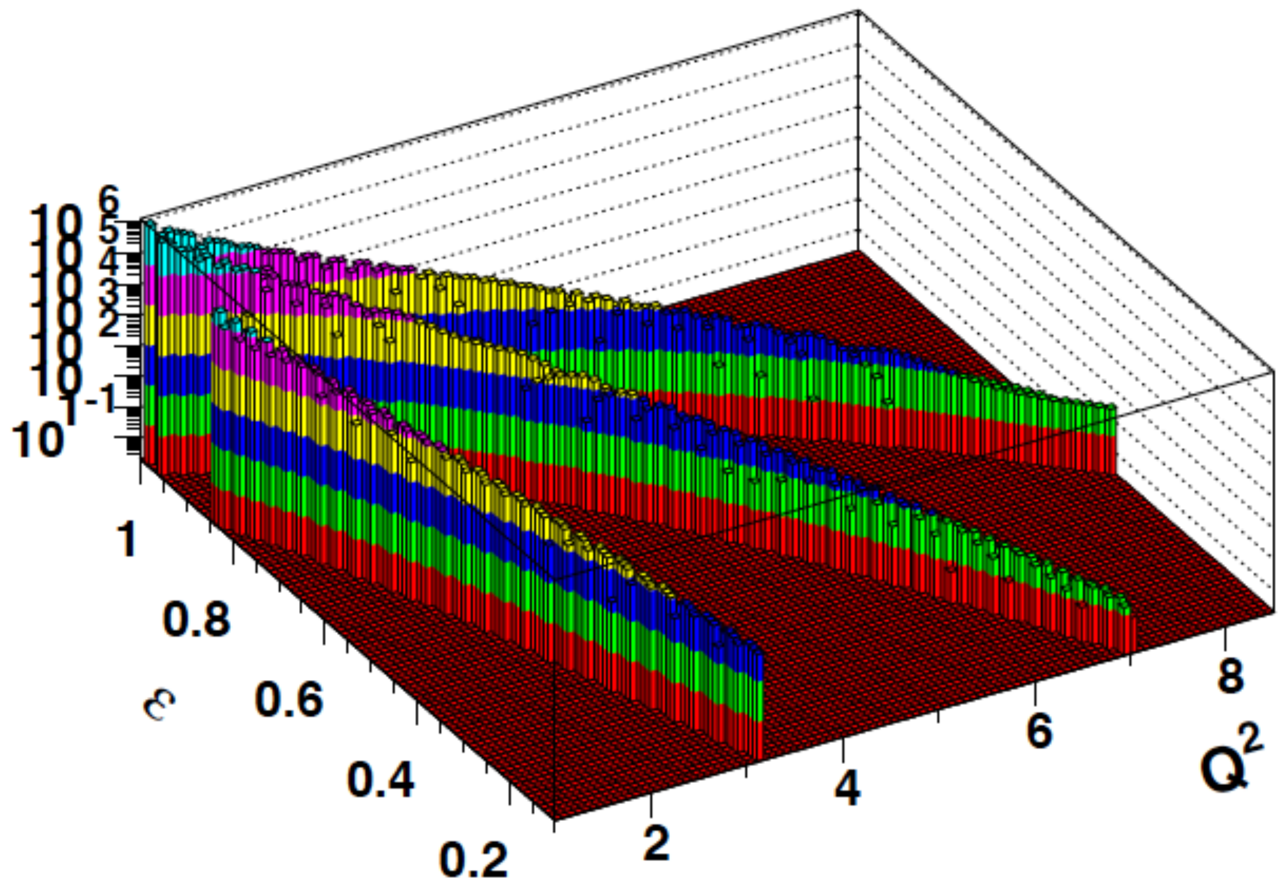
EC for electron detection in CLAS12 CD



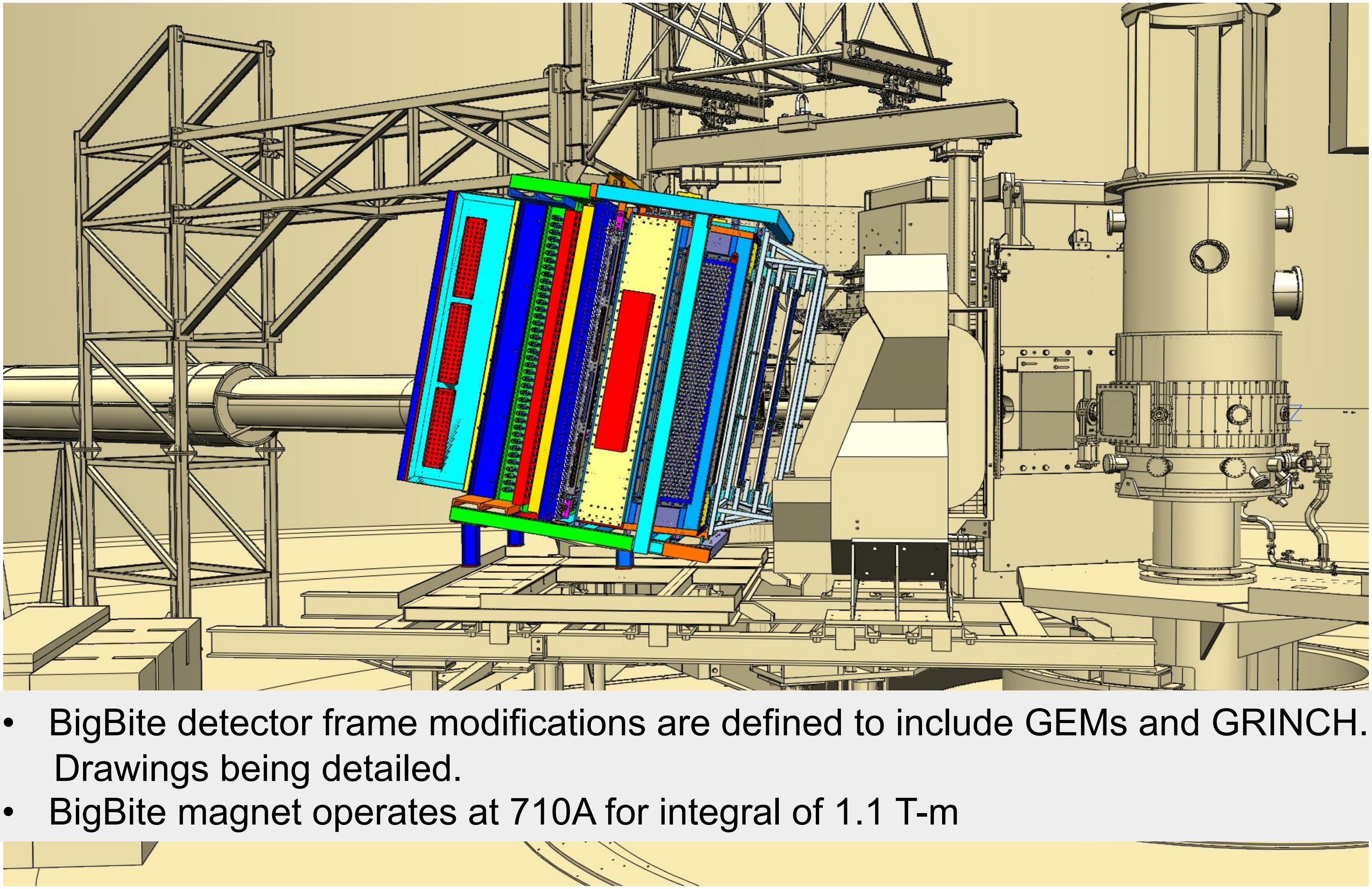

ω
1
0.8
0.6
0.4
0.2
0
20
40
60
80
100
120
140
θe
Eb(GeV)=1.1
2.2
3.3
4.4
5.5
6.6

E=2.2, 4.4, 6.6 GeV




ε
1
0.8
0.6
0.4
0.2
2
4
6
8
Q2

BigBite



- BigBite detector frame modifications are defined to include GEMs and GRINCH. Drawings being detailed.
- BigBite magnet operates at 710A for integral of 1.1 T-m

SBS Equipment