Outlook for Generalized Parton Distributions and Deeply Virtual Compton Scattering in Hall A

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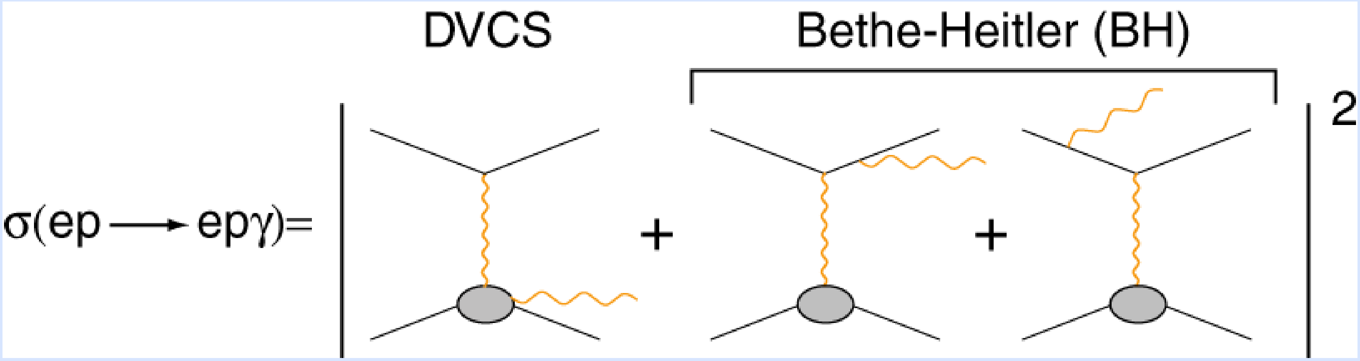
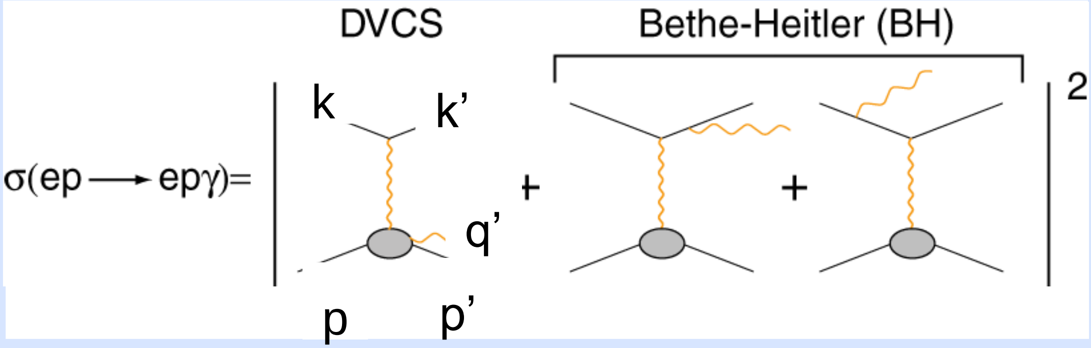


Recent Hall A Results

- H(e,e'γ)p:
  - *Phys. Rev. Lett*. **97**, 262002 (2006): Dec 31, 2006
  - Scaling test
  - Im[BH*DVCS]
  - Re[BH*DVCS]+$\langle\eta\rangle$DVCS^2.
- H(e,e'π^0)p:
  - Preliminary cross section results
- D(e,e'γ)X: X<pnπ
  - Preliminary helicity dependent cross sections.

Experimental observables linked to GPDs



$q = k - k'$
$y = (q \cdot k)/(k \cdot p)$
$\Delta = q - q'$

Using a polarized beam on an unpolarized target, two observables can be measured:

$$\frac{d^4\sigma}{dx_B dQ^2 dt d\varphi} \approx \left|T^{BH}\right|^2 + 2T^{BH} \cdot \mathrm{Re}\ T^{DVCS} + \left|T^{DVCS}\right|^2$$

$$\frac{d^4\overset{\rightarrow}{\sigma} - d^4\overset{\leftarrow}{\sigma}}{dx_B dQ^2 dt d\varphi} \approx 2T^{BH} \cdot \mathrm{Im}\ T^{DVCS} + \left[\left|\overset{\rightarrow}{T^{DVCS}}\right|^2 - \left|\overset{\leftarrow}{T^{DVCS}}\right|^2\right]$$

At JLab energies,

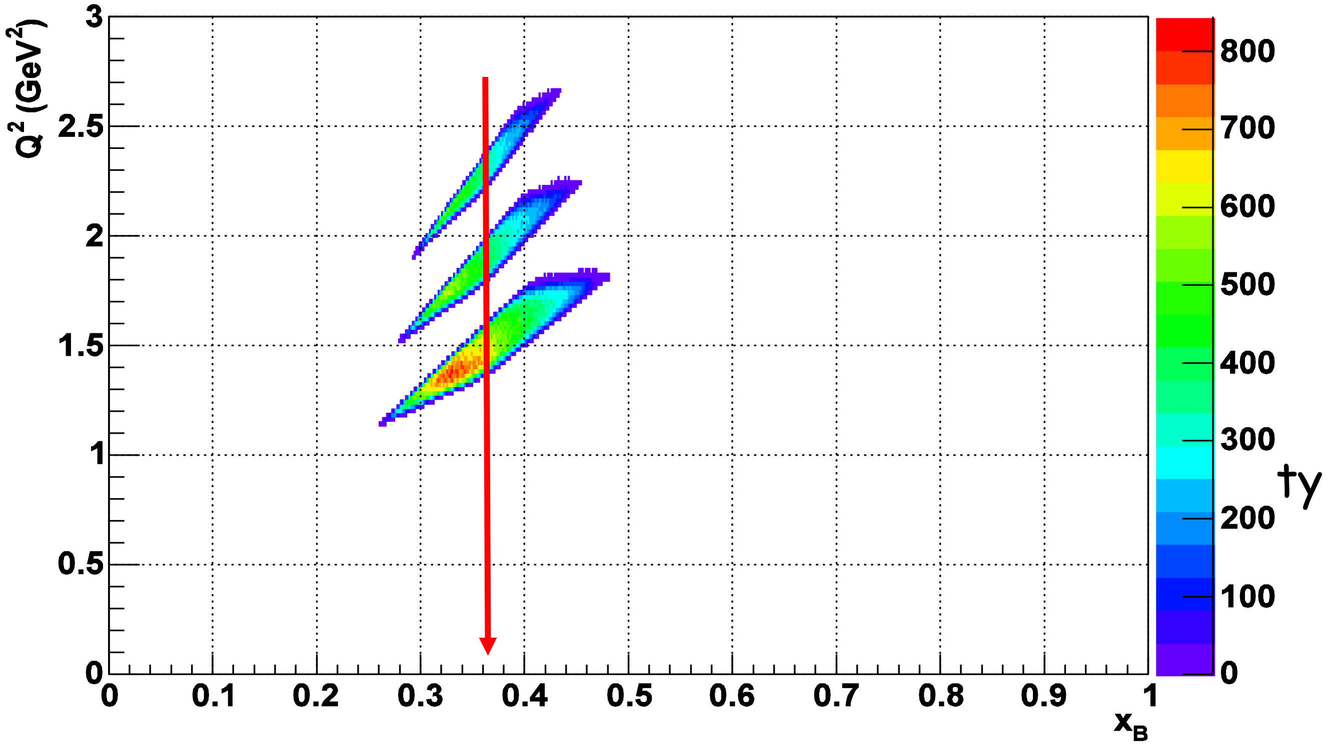
$$\frac{\left|T^{DVCS}\right|^2}{\left|T^{BH}\right|^2} \approx \left[\frac{-\Delta^2}{y^2 Q^2}\right] \frac{\left|GPD\right|^2}{\left[F(-t)\right]^2}$$

Small; maybe, or not.

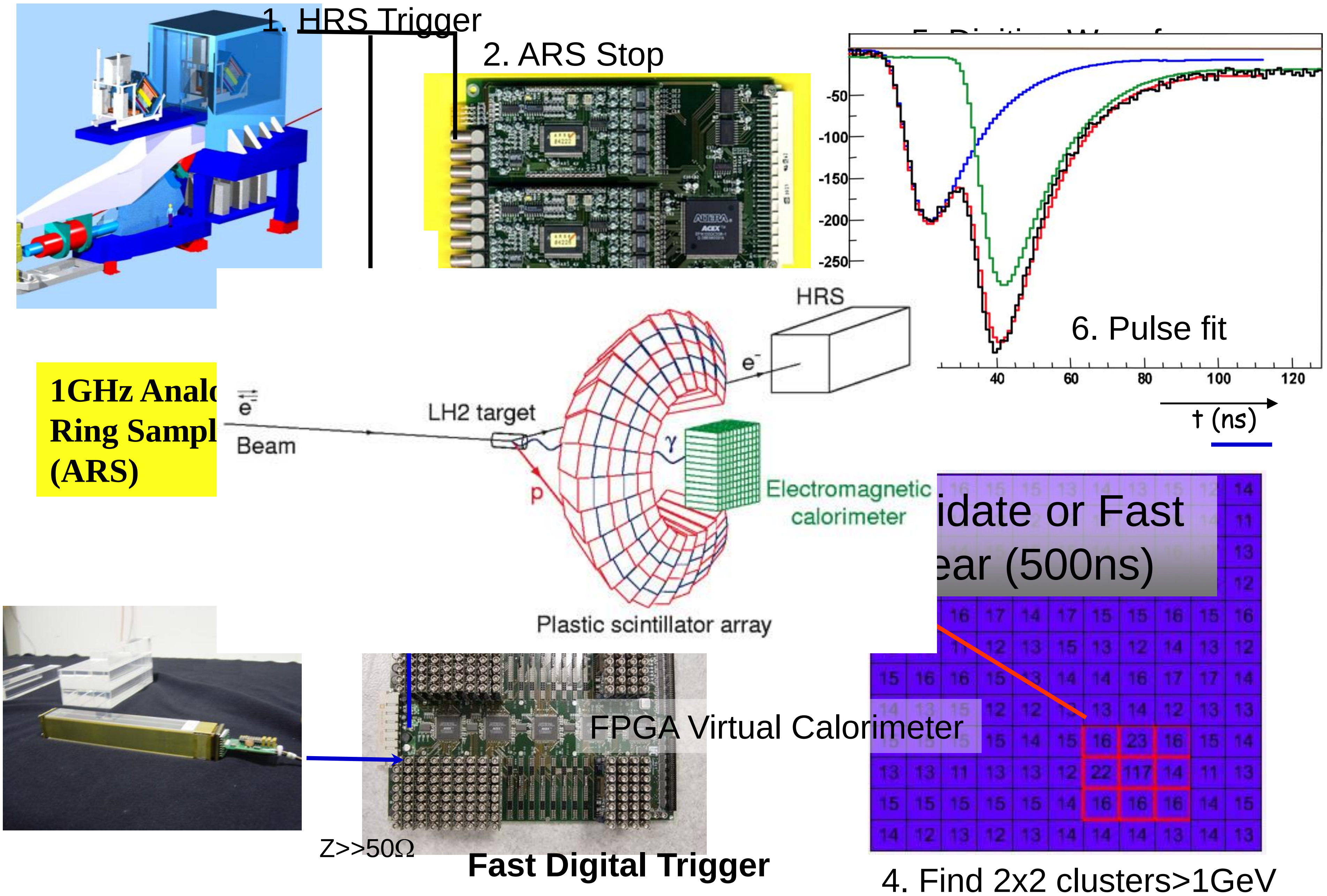
E00-110 kinematics

Kin	Q^2 (GeV^2)	x_B	θ_{γ^*} (deg.)	W (GeV)
1	**1.5**	0.36	**22.3**	1.9
2	**1.9**	0.36	**18.3**	2.0
3	**2.3**	0.36	**14.8**	2.2

The calorimeter is centered on the virtual photon direction.
Acceptance: $\theta_{\gamma\gamma}$ < 150 mrad

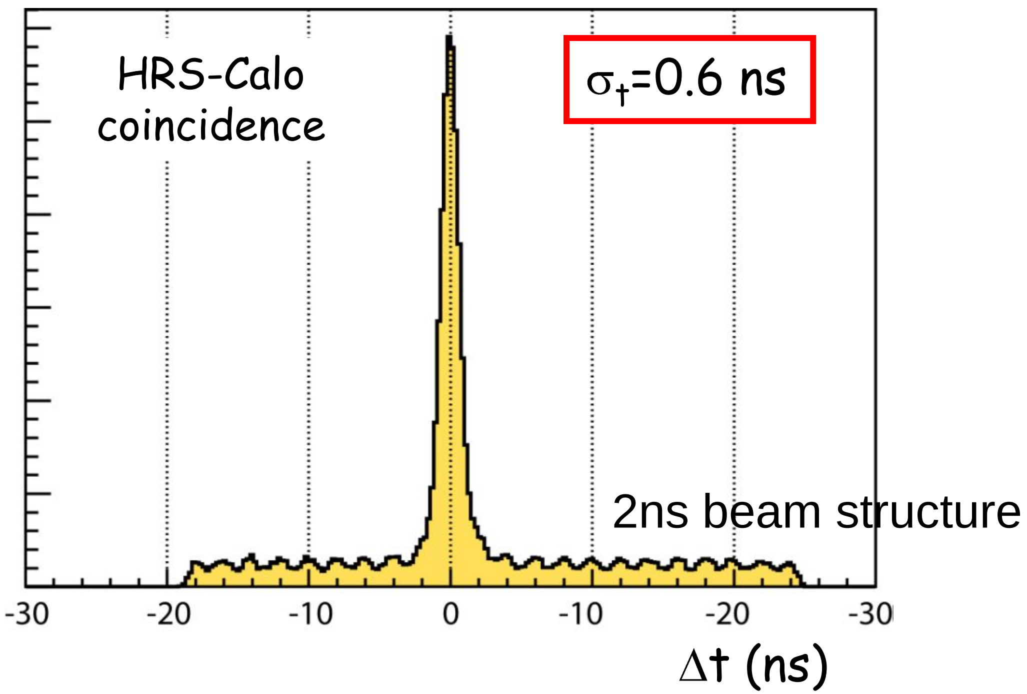


Digital trigger on calorimeter and fast digitizing-electronics



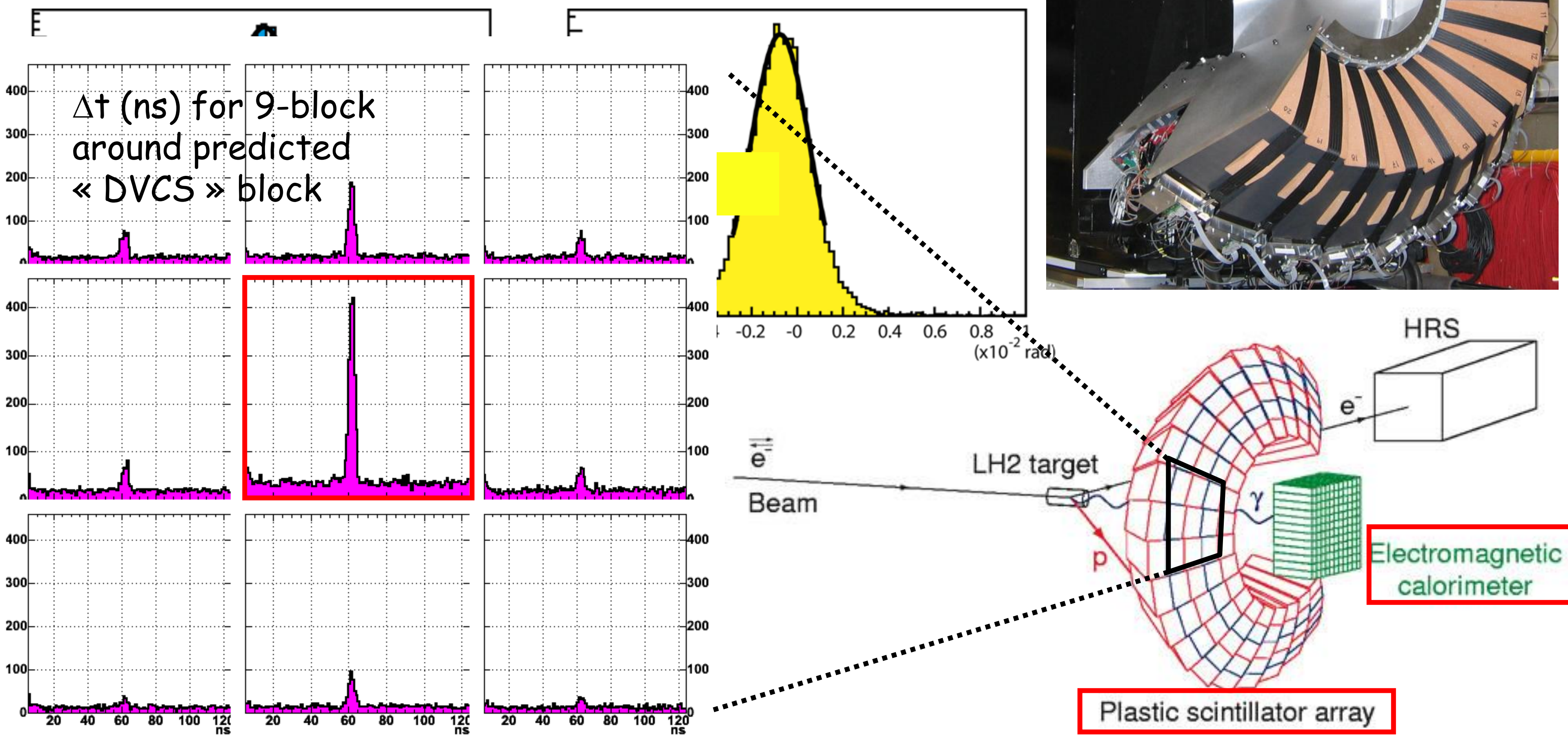
ARS system in a high-rate environment

- 5-20% of events require a 2-pulse fit
- Maintain Energy & Position Resolution independent of pile-up events
  - Maintain Resolution during $\approx 10^{43}/cm^2$ integrated luminosity on H_2
- Optimal timing resolution
- 10:1 True:Accidental ratio at $L=10^{37}/(cm^2\ s)$ unshielded calorimeter



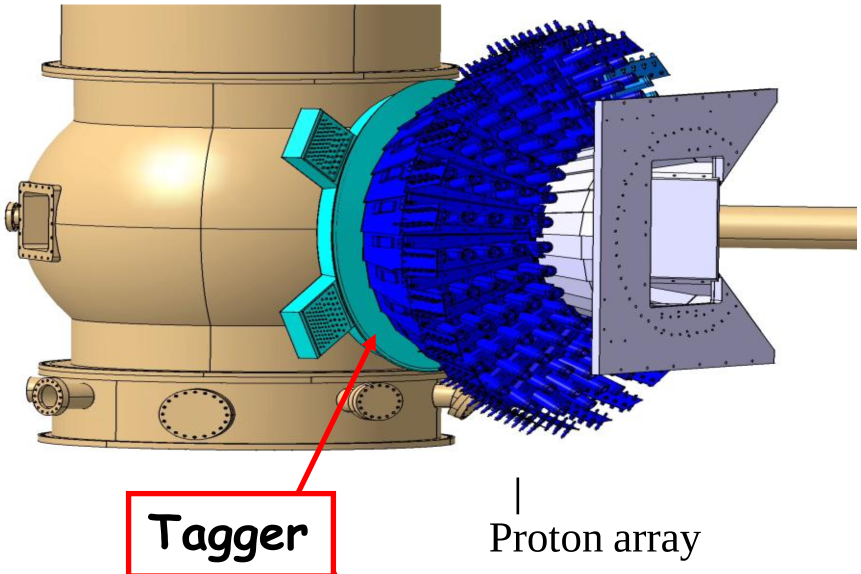
E00-110 experimental setup and performances

- 75% polarized 2.5uA electron beam
- 15cm LH2 target
- Left Hall A HRS with electron package
- 11x12 block PbF2 electromagnetic calorimeter
- 5x20 block plastic scintillator array



Proton tagger : neutron-proton discrimination

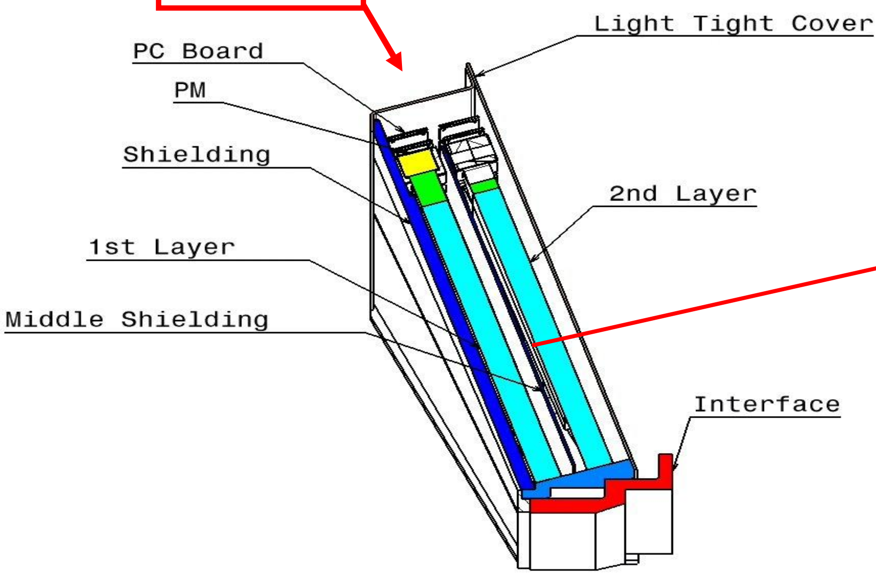
E03-106: D(e,e'γN)N

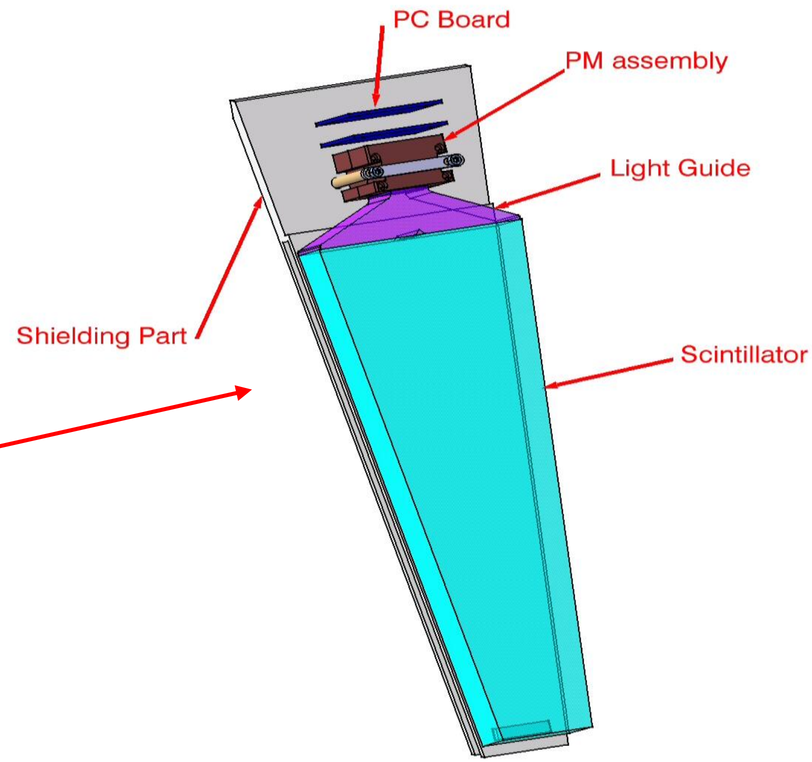


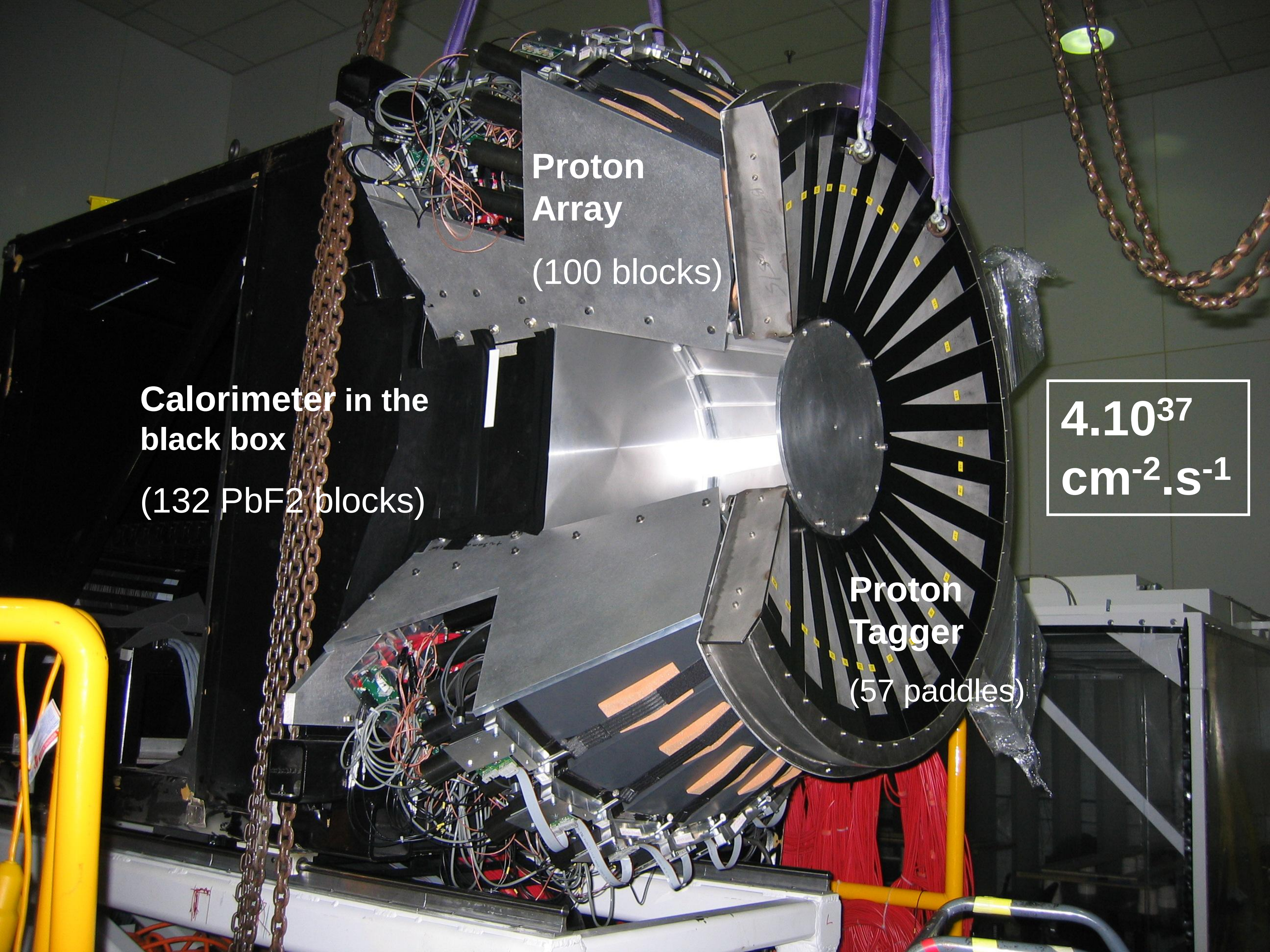
Two scintillator layers:

-1st layer: 28 scintillators, 9 different shapes

-2nd layer: 29 scintillators, 10 different shapes

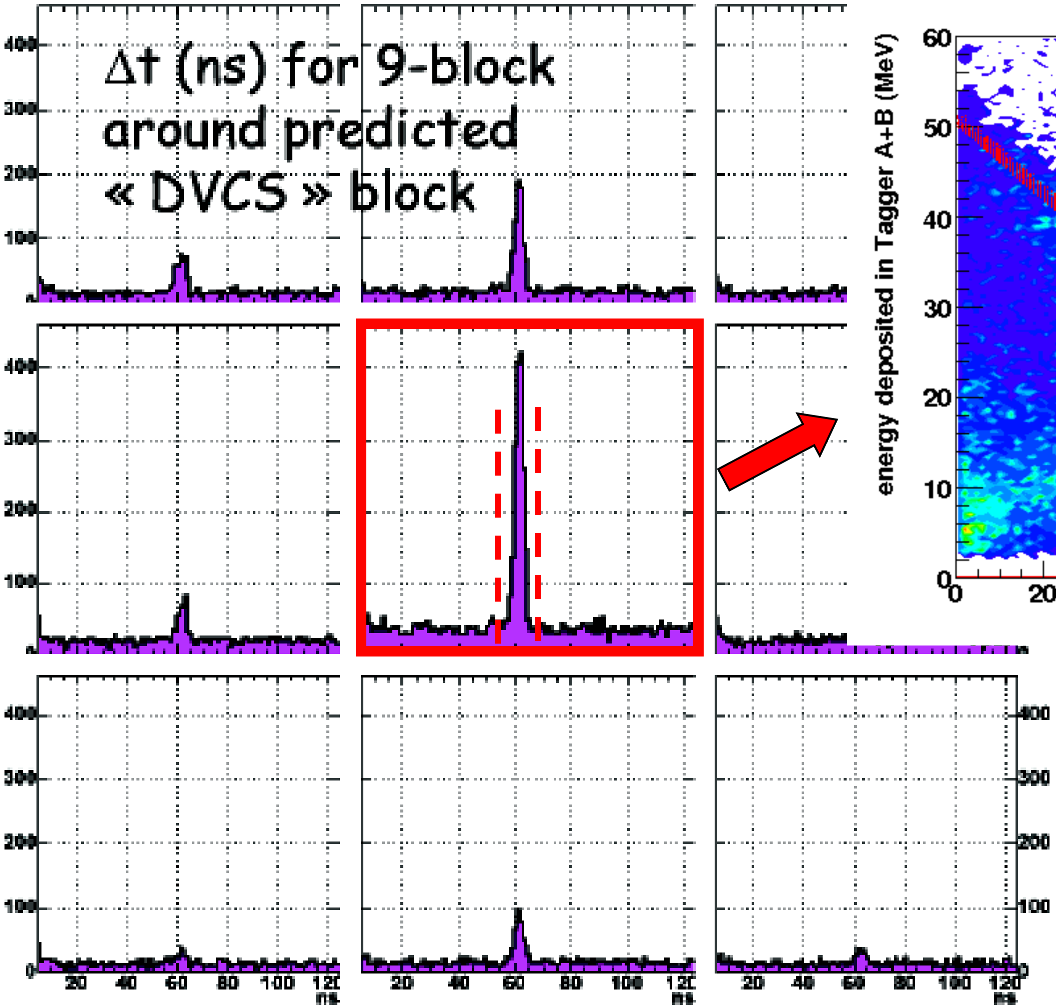


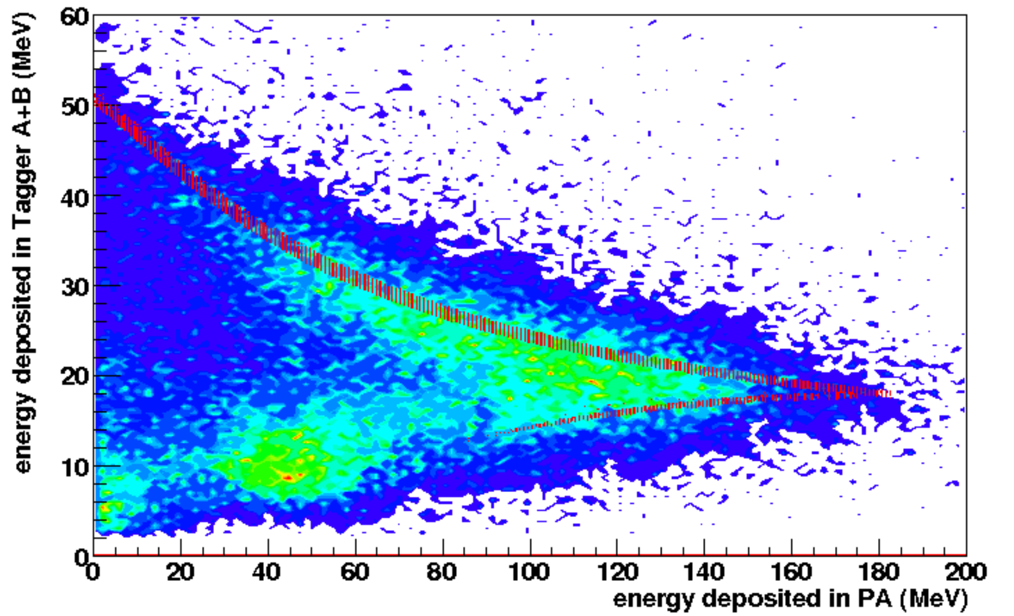



Proton Array
(100 blocks)
Calorimeter in the black box
(132 PbF2 blocks)
Proton Tagger
(57 paddles)
4.10^{37} $cm^{-2}.s^{-1}$

Quadruple coincidence analysis: D(e,e'γp)X

One can **predict** for each (e,e'γ) event the Proton Array block and/or Tagger where the missing nucleon should be (assuming DVCS event).



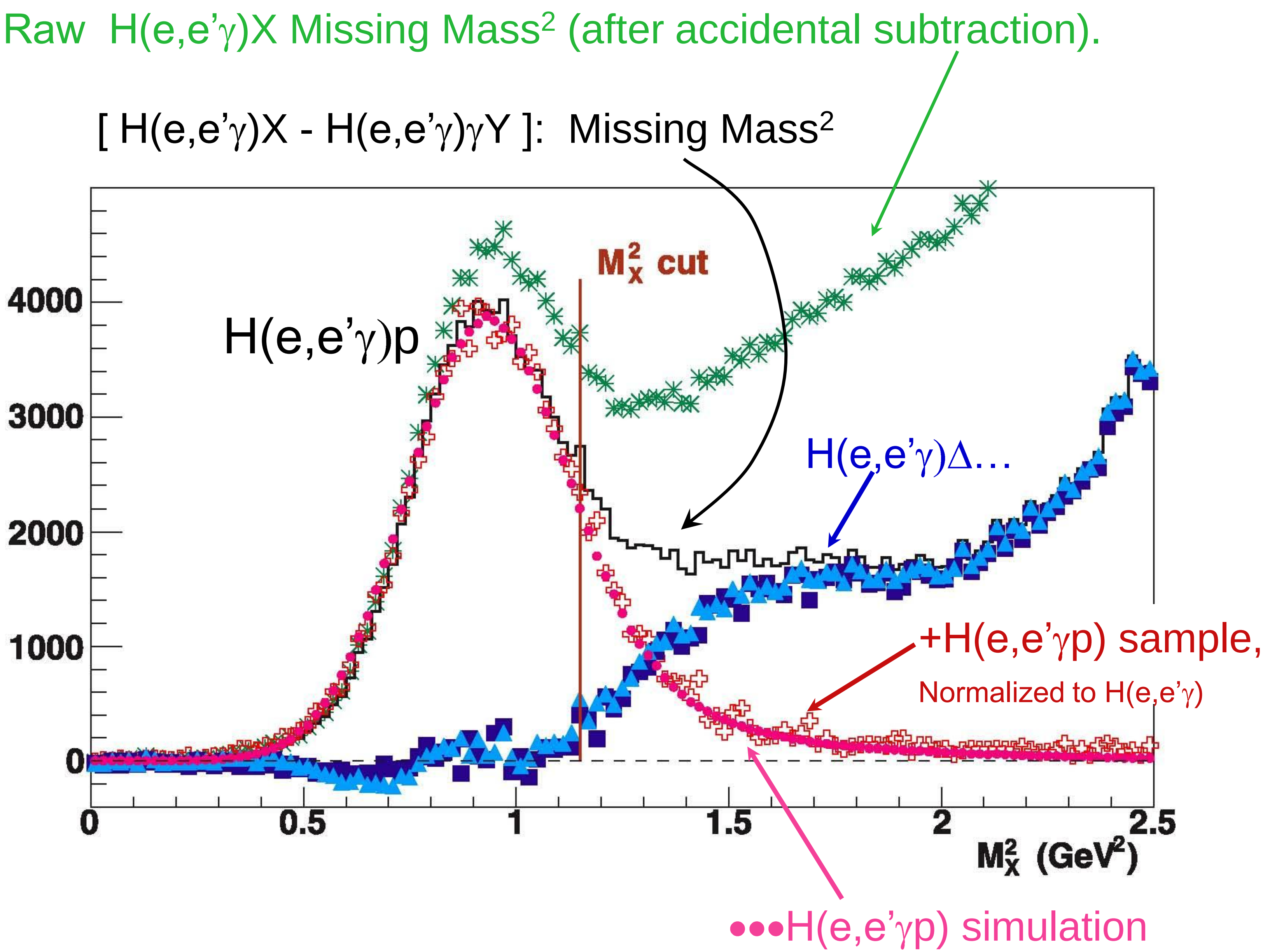


"proton"=Tagger ∩PA

Conclusions on unshielded detectors

- Calorimeter (at 110 cm)
  - Functioned well up to luminosity of $4{\cdot}10^{37}$/cm^2/sec
  - Typically 20% light yield attenuation after 10^{43}/cm^2
  - MAMI-A4 blue light curing for higher integrated luminosity
- Plastic scintillators
  - PA unshielded at 10^{37}/cm^2/sec
  - Tagger shielded at $4{\cdot}10^{37}$/cm^2/sec
  - Both gave good timing signals
  - Both gave adequate pulse height distributions above background (10 MeV e- and γ).
  - Efficiency of neither is understood to better than 50%
- Either abandon recoil detection, or build tracking detector that can survive at elevated luminosity.

H(e,e'γ) Exclusivity



Into the harmonic structure of DVCS

$$\frac{d^4\sigma}{dx_B dQ^2 dt d\varphi} = \frac{1}{\mathrm{P}_1(\varphi)\mathrm{P}_2(\varphi)}\Gamma_1(x_B,Q^2,t)\;\; c_0^{BH} + c_1^{BH}\cos\varphi + c_2^{BH}\cos 2\varphi$$

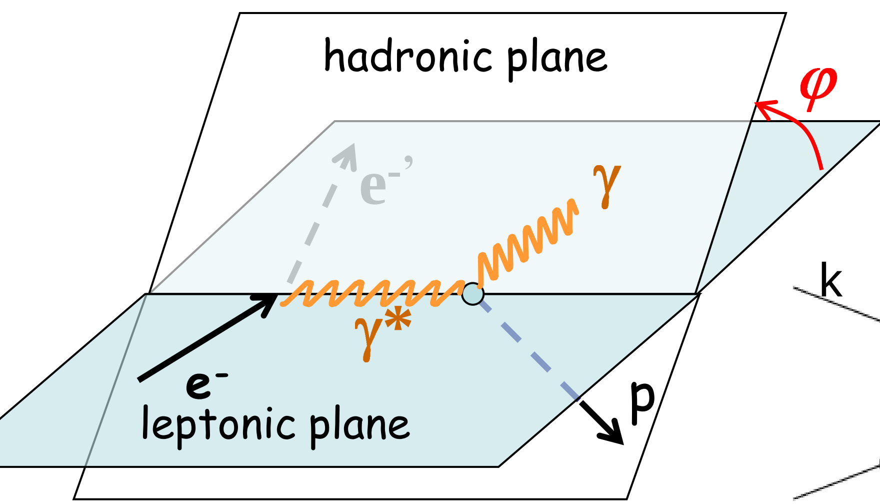
$|T^{BH}|^2$

$$+\frac{1}{\mathrm{P}_1(\varphi)\mathrm{P}_2(\varphi)}\Gamma_2(x_B,Q^2,t)\;\; c_0^I + c_1^I\cos\varphi + c_2^I\cos 2\varphi + c_3^I\cos 3\varphi$$

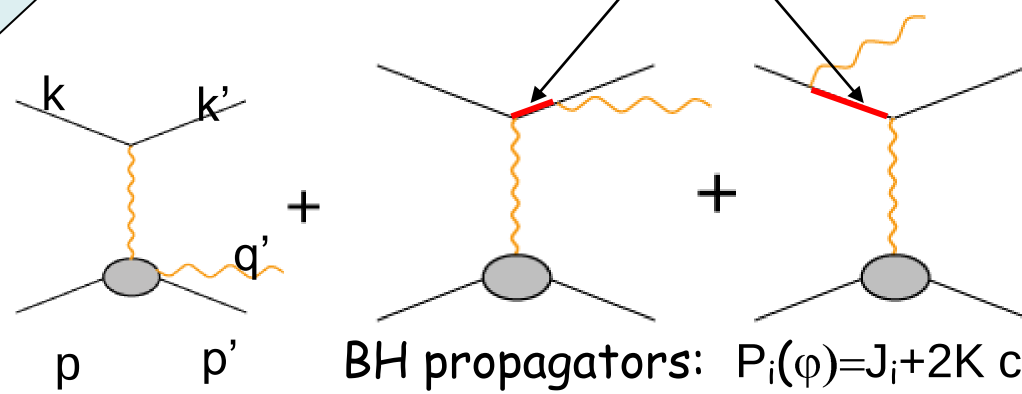
$$+d^4\sigma_T(DVCS)$$

$$\frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{dx_B dQ^2 dt d\varphi} = \frac{\Gamma(x_B,Q^2,t)}{\mathrm{P}_1(\varphi)\mathrm{P}_2(\varphi)}\;\; s_1^I\sin\varphi + s_2^I\sin 2\varphi$$

Interference term



$$\frac{1}{\mathrm{P}_1(\varphi)\mathrm{P}_2(\varphi)}$$



BH propagators: $P_i(\varphi)=J_i+2K\cos\varphi$

Belitsky, Mueller, Kirchner

Analysis - Extraction of observables

Re-stating the problem (difference of cross-section):

$$\frac{d^4\overrightarrow{\sigma}-d^4\overleftarrow{\sigma}}{dx_B dQ^2 dt d\varphi}=\frac{\Gamma(x_B,Q^2,t)}{\mathrm{P}_1(\varphi)\mathrm{P}_2(\varphi)}\left(s_1^I \sin\varphi + s_2^I \sin 2\varphi\right)$$

Observable

$$s_1^I = 8Ky(2-y)\,\mathrm{Im}\,C^I(F)$$

$$C^I(F) = F_1\mathrm{H} + \frac{x_B}{2-x_B}(F_1+F_2)\tilde{\mathrm{H}} - \frac{t}{4M^2}F_2\mathrm{E}$$

Kinematic factors

$$\mathrm{Im}\,\mathrm{H} = \pi\sum_q e_q^2 \quad H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)$$

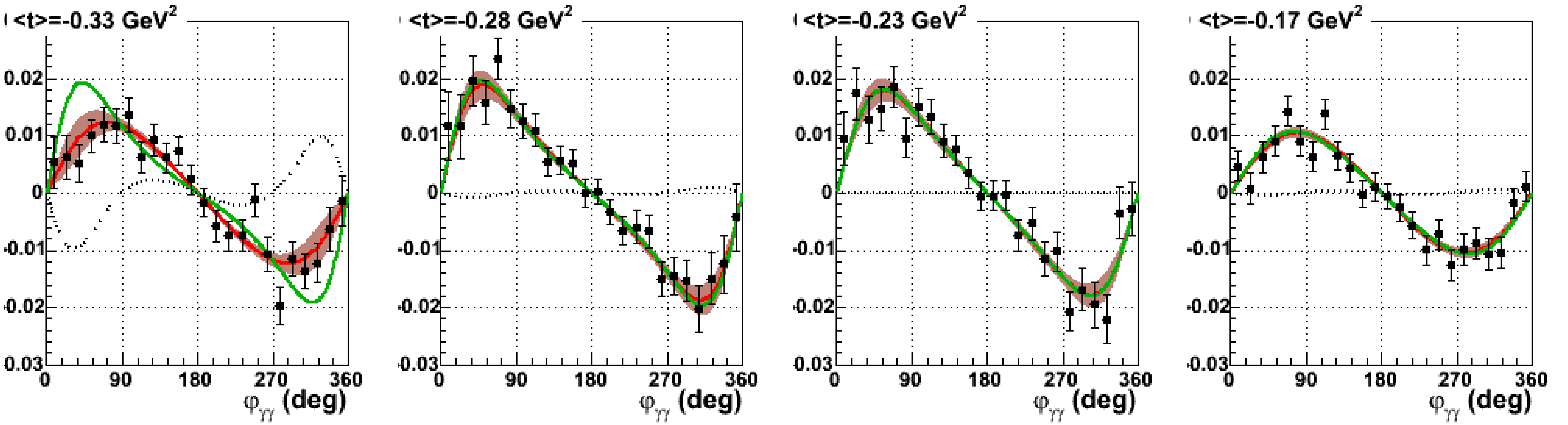
GPD !!!

Cross Section Differences

$$\frac{d^4\sigma^+}{dx_B dQ^2 d\varphi\, dt} - \frac{d^4\sigma^-}{dx_B dQ^2 d\varphi\, dt} \quad [\text{nb/GeV}^4]$$

Corrected for real and virtual radiation

$\langle t\rangle=-0.33\ \text{GeV}^2$ $\langle t\rangle=-0.28\ \text{GeV}^2$ $\langle t\rangle=-0.23\ \text{GeV}^2$ $\langle t\rangle=-0.17\ \text{GeV}^2$



Green solid line: $[P_1P_2]^{-1} \sin(\phi)\ \ \mathrm{Im}[C^I(F)]^{exp}$

Dashed line: $[P_1P_2]^{-1} \sin(2\phi)\ \mathrm{Im}[C^I(F^{eff})]$

- Model independent cross section results.
- $\mathrm{Im}[C^I(F)]^{exp} = BH^*\mathrm{Im}[DVCS] + \langle\eta_{s1}\rangle \mathrm{Im}[DVCS^*DVCS]$.
- Bilinear DVCS term is Twist-3 with no BH enhancement
  - $\langle\eta_{s1}\rangle \approx 0.01$

Helicity Independent Cross Section

$$\frac{d^4\vec{\sigma}+d^4\overleftarrow{\sigma}}{dx_B dQ^2 dt d\varphi} = \frac{\Gamma(s_e,x_B,Q^2,t)}{P_1(\varphi)P_2(\varphi)}\left\{c_0^{BH}+c_1^{BH}\cos\varphi+c_2^{BH}\cos(2\varphi)\right\}$$

$$+\frac{\Gamma(s_e,x_B,Q^2,t)}{P_1(\varphi)P_2(\varphi)}\left\{c_0^I+c_1^I\cos\varphi+c_2^I\cos(2\varphi)\right\}$$

$$+\Gamma_V(s_e,x_B,Q^2,t)\left\{\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\varphi\frac{d\sigma_{LT}}{dt}+\varepsilon\cos(2\varphi)\frac{d\sigma_{TT}}{dt}\right\}$$

$$=\frac{d^4\sigma^{BH}}{dx_B dQ^2 dt d\varphi}$$

$$+\frac{\Gamma(s_e,x_B,Q^2,t)}{P_1(\varphi)P_2(\varphi)}\left\{\left[c_0^I+\eta_{c0}c_0^{DVCS}\right]+\left[c_1^I+\eta_{c1}c_0^{DVCS}\right]\cos\varphi+\ldots\right\}$$

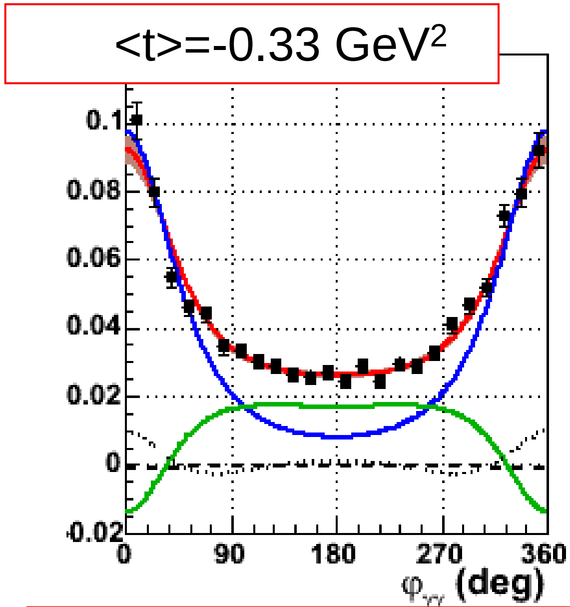
$$c_0^{DVCS}=[\cdots]\left[|H|^2+|\tilde{H}|^2+\ldots\right]$$

$$c_1^I=-8K(2-2y+y^2)\Re e\left[C^I(H,\tilde{H},E)\right]$$

$$\Re e[\mathbf{H}]=P\int_{-1}^{1}dx\left[\frac{1}{\xi-x}-\frac{1}{\xi+x}\right]H(x,\xi,t)$$

Cross Section Sum

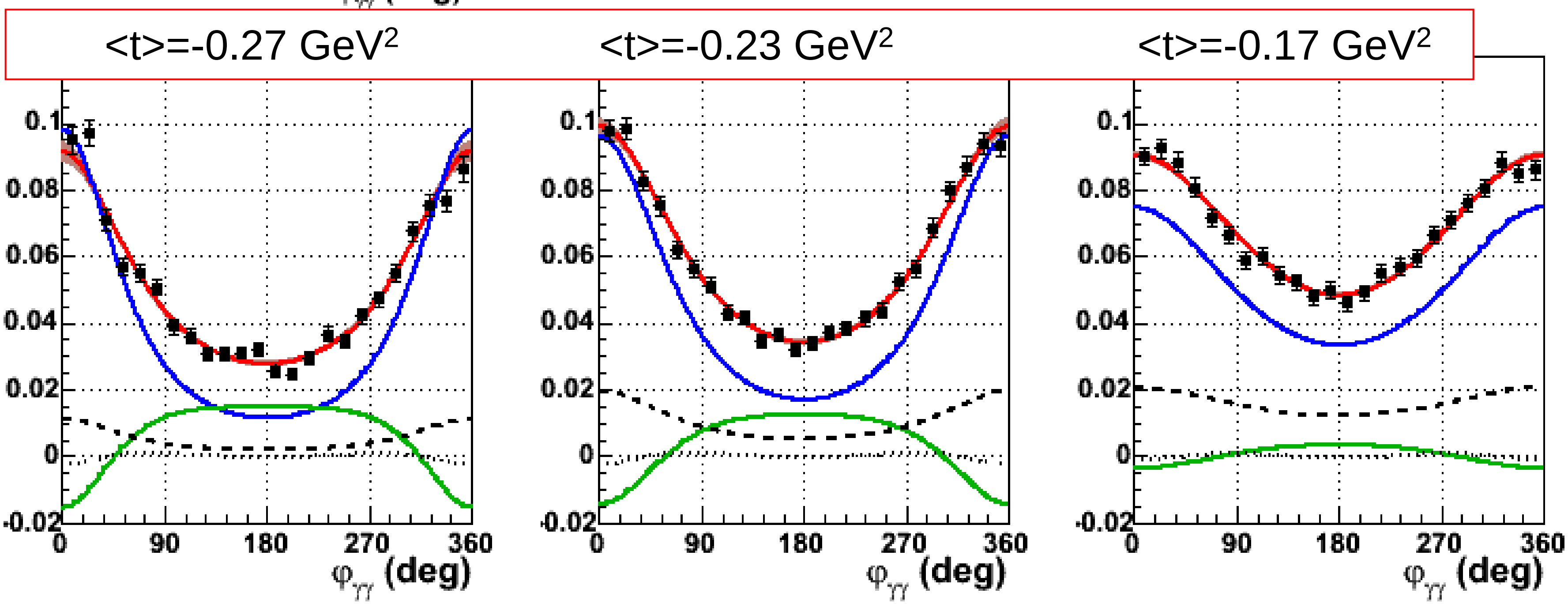
$$\frac{d^4\sigma}{dx_B dQ^2 dt d\varphi} \left[\mathrm{nb.GeV^{-4}}\right] \qquad \langle Q^2 \rangle = 2.3\ \mathrm{GeV}^2 \qquad \langle x_B \rangle = 0.36$$



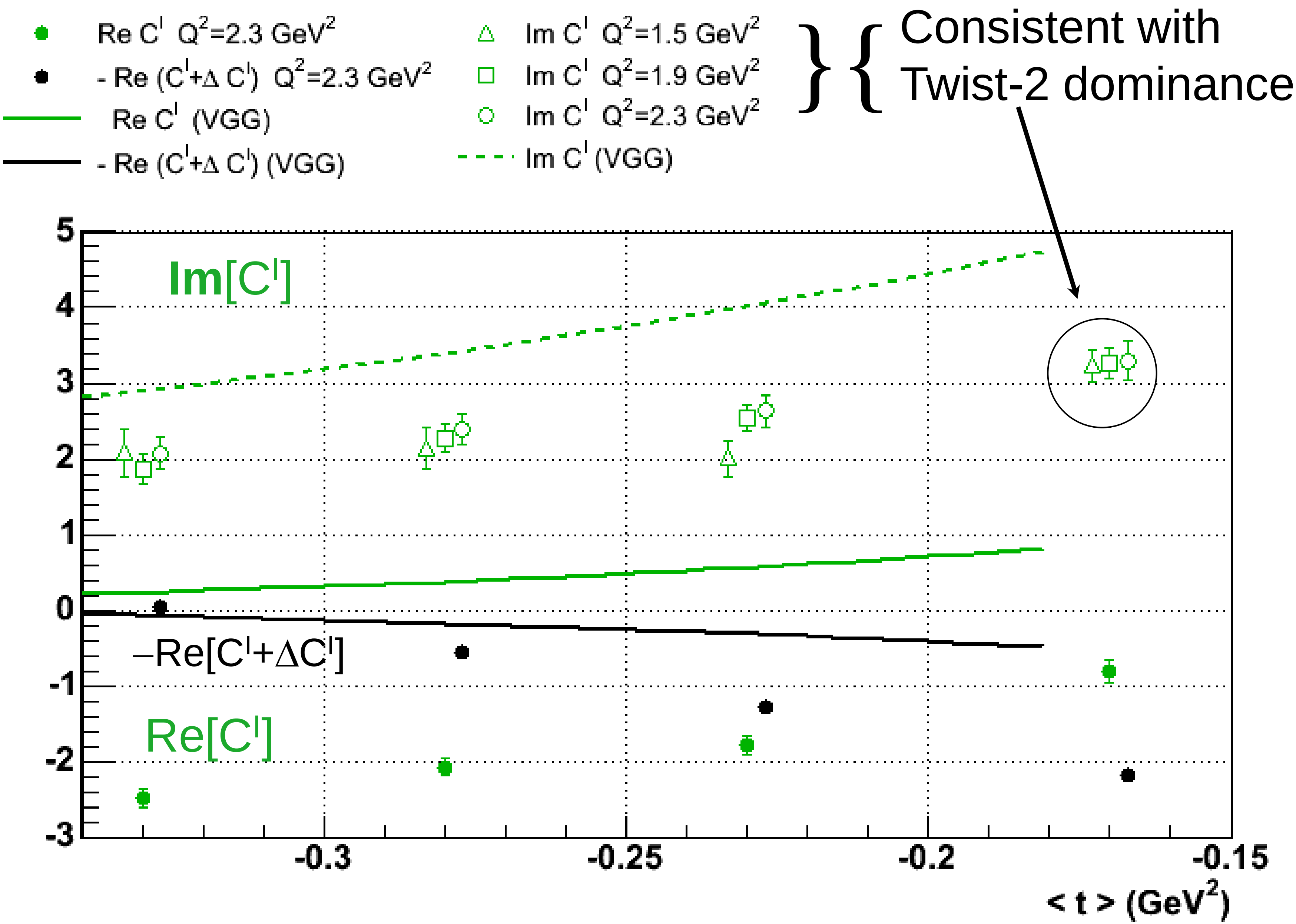
Corrected for real and virtual radiation

C, $C+\Delta C$: can include $\approx \pm\langle\eta\rangle|\mathrm{DVCS}|^2$ term

$\langle\eta\rangle \approx 0.05$



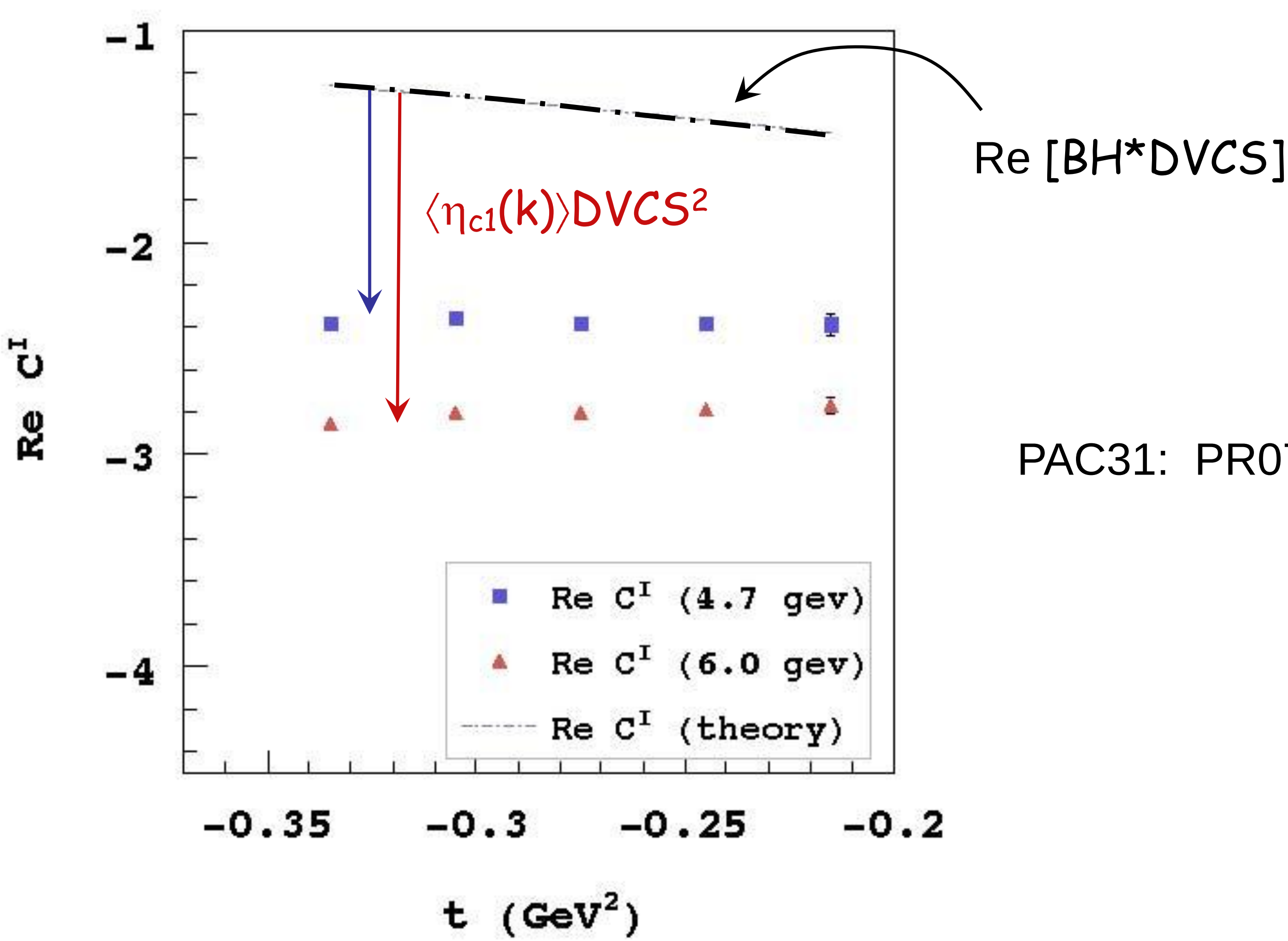
Results: t-dependence, Twist-2



Conclusion at 6 GeV

- High luminosity (>10^{37}) measurements of DVCS cross sections are feasible using trigger + sampling system
- Tests of scaling yield positive results
  - No Q^2 dependence of C_{T2} and C_{T3}
  - Twist-3 contributions in both $\Delta\sigma$ and σ are small
  - Note: DIS has small scaling violation in same x, Q^2 range.
- In cross-section difference, accurate extraction of Twist-2 interference term
- High statistics extraction of cross-section sum.
  - Models must calculate Re[BH*DVCS]+|DVCS|^2
  - $\sigma = [d\sigma(h=+) + d\sigma(h=-)] \neq |BH|^2$
    - Relative Asymmetries contain interference and bilinear DVCS terms in denominator.

VGG model for Re[BH*DVCS]+$\langle\eta_{c1}\rangle$DVCS^2



PAC31: PR07-007

Use Beam Energy dependence at fixed (x_B,Q^2,t) to separate BH*DVCS interference terms from bilinear DVCS^2 term.

DVCS at 11 GeV (Approved by PAC30)

HALL A: H(e,e'γ) (no proton detection) → **100 Days**

3,4,5 pass beam: k = 6.6, 8.8, 11 GeV

Spectrometer: HRS: k'≤4.3 GeV

Calorimeter 1.5 x larger, 1.5 to 3.0 m from target

Similar M_X^2 resolution at each setup.

1.0 GHz Digitizer for PbF2

Calorimeter trigger upgrade

(better π^0 subtraction)

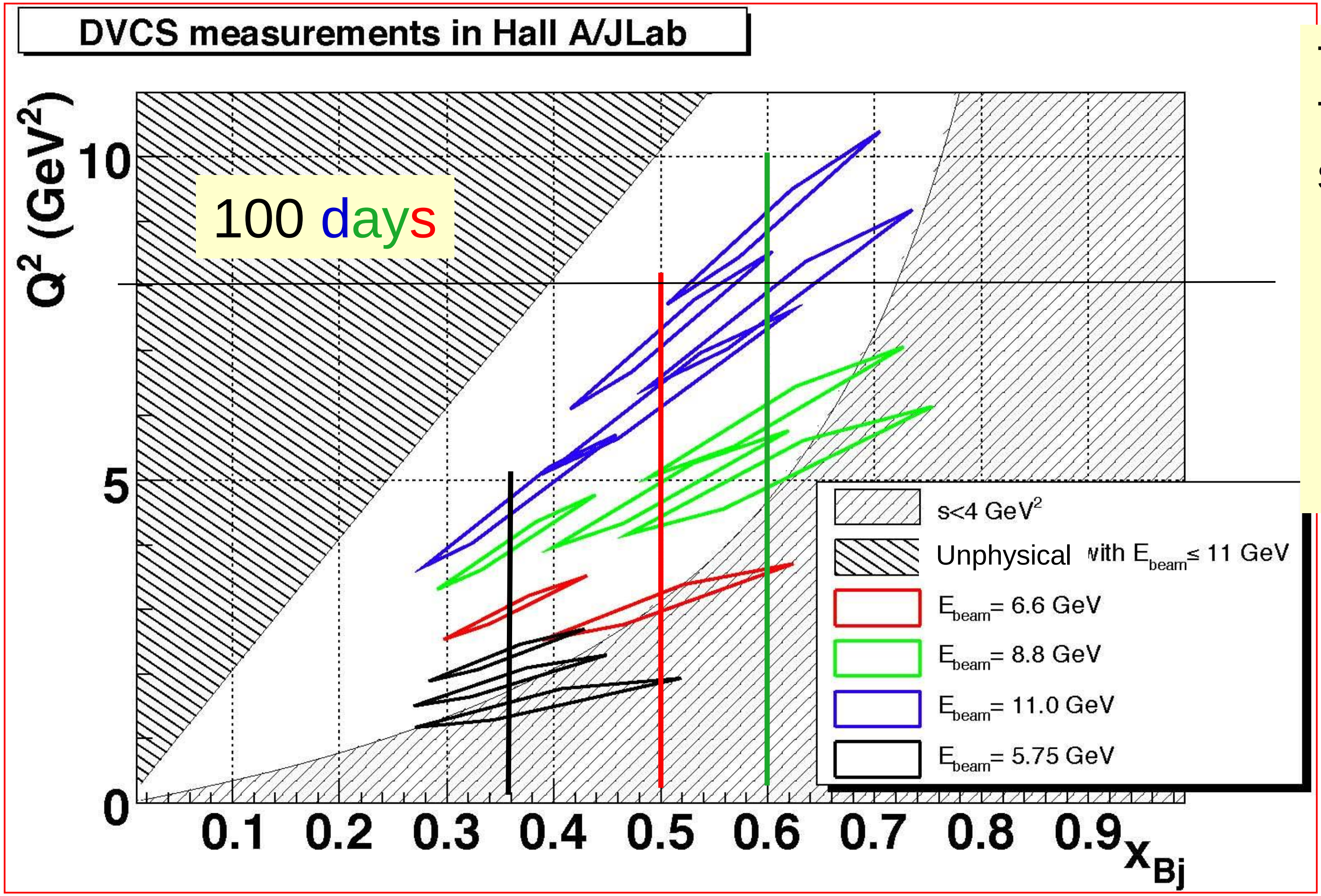
Luminosity x Calo acceptance/block = 4x larger.

Same statistic (250K)/setup

JLab12: Hall A with 3, 4, 5 pass beam

$H(e,e'\gamma)p$

Absolute measurements: $d\sigma(\lambda_e=\pm1)$
250K events/setup

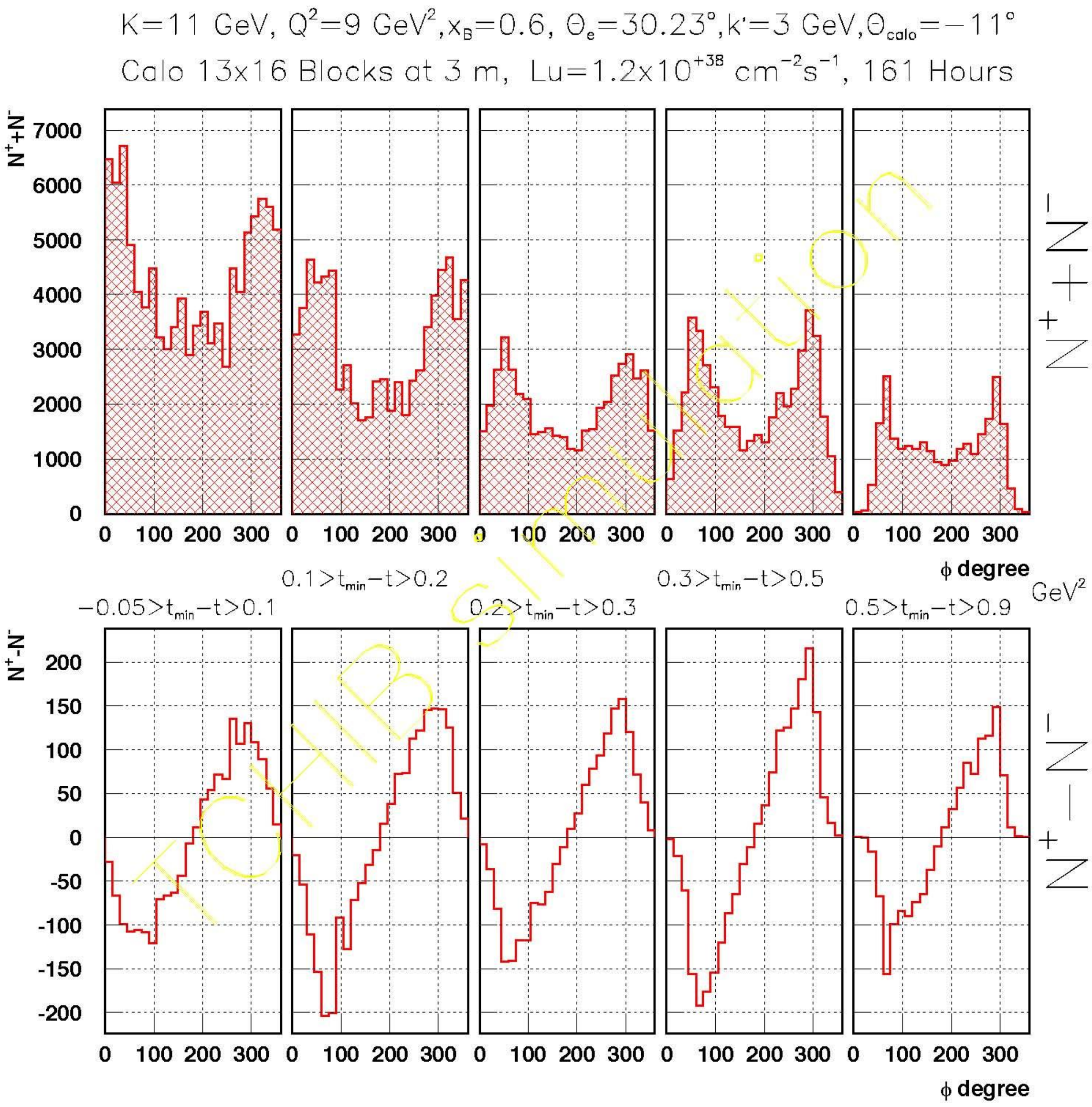


Twist 2 & Twist 3 separation.

Im{DVCS*BH}+ εDVCS^2

Re{DVCS*BH} +ε'DVCS^2

Hall A Projected Statistics: Q^2=9.0 GeV^2, x_{Bj} = 0.60



5 bins in t for
$0.1<t_{min}-t<0.9$ GeV^2
Δt =0.05…0.4 GeV^2

250K exclusive DVCS events total, in each of 11 Q^2 x_{Bj} bins.

Conclusions

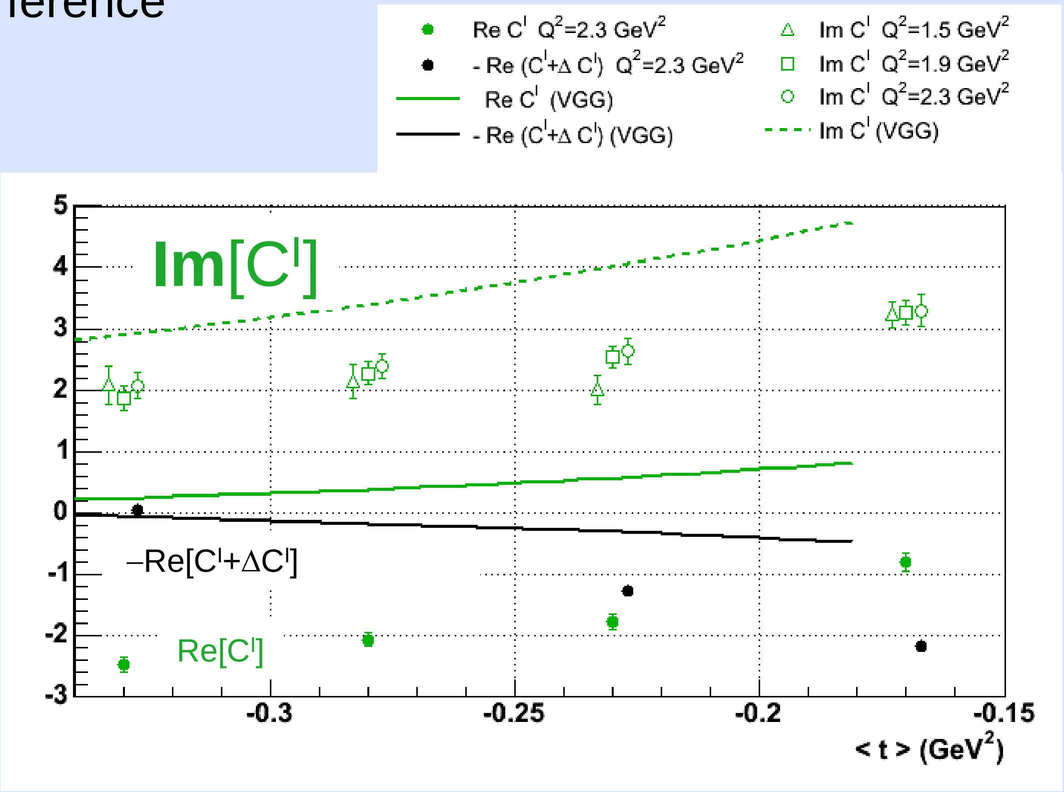
- Precision measurement of H(e,e'γ)p exclusivity
- Precision measurement of H(e,e'γ)p cross sections

Full Program Approved
In Hall A at 11 GeV

□ϕ-dependent cross sections:
  - Twist-2 cos(ϕ) and sin(ϕ) terms
  - Twist-3 cos(2ϕ) and sin(2ϕ) terms small
  - Re & Im parts of BH*DVCS Interference

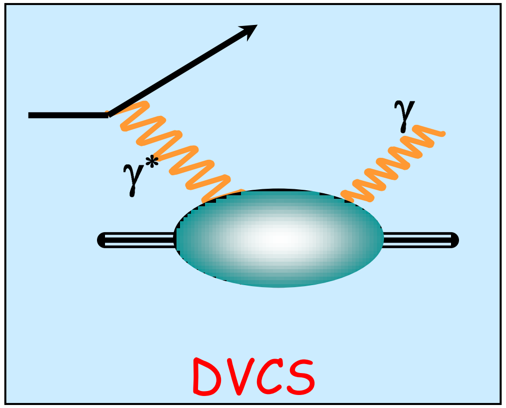
- cos(ϕ) term may contain substantial contributions of both Re[BH*DVCS] and Bilinear DVCS terms.

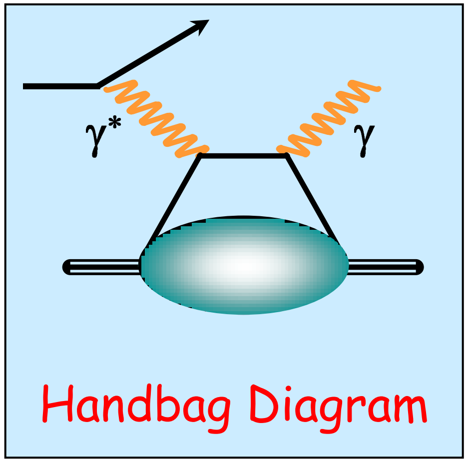
- Future separation of Interference and Cross section terms via "Generalized Rosenbluth"



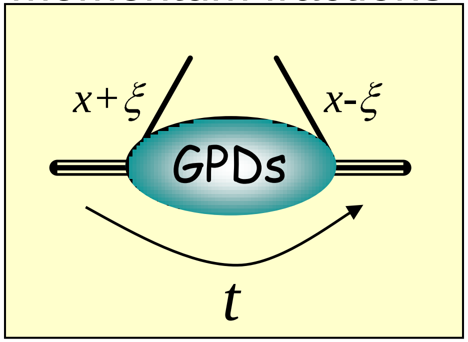
nucl-ex/0607029, submitted to PRL

From DVCS to Generalized Parton Distributions (GPDs)





x±ξ = initial/final momentum fractions



The GPDs enter the DVCS amplitude as an integral over x:

- GPDs appear in the real part through a Principal-value integral over x
- GPDs appear in the imaginary part along the line x=±ξ

$$T^{DVCS} = \int_{-1}^{+1} \frac{GPD(x,\xi,t)}{x-\xi+i\varepsilon}\,dx \quad + \quad \cdots$$

$$= P\int_{-1}^{+1} \frac{GPD(x,\xi,t)}{x-\xi}\,dx \quad - \quad i\pi GPD(x=\xi,\xi,t) \quad + \quad \cdots$$

Generalized Parton Distributions

Non-local single particle density distributions

Nucleon spin structure:

- H=Dirac Vector
- E=Pauli Vector
- H-tilde = Axial Vector
- E-tilde = Pseudo Scalar

Complicated kinematic dependence

$H(x,\xi,t) \rightarrow H(x,\xi,\Delta_\perp^2)$

Each variable has physical significance:

- $\Delta_\perp$: Fourier conjugate to transverse impact parameter
  - Measure size of proton, as function of quark momentum
- $\xi = x_B/(2-x_B)$ = skewness
- $x \pm \xi$ = initial/final momentum fraction
- x = integration variable

DVCS can measure Re & Im part of dispersive integral over x.

Full Separation of four GPDs requires full target (or recoil) spin observables

Up/down flavor separation requires `neutron' target

Full flavor separation requires Deep virtual meson production (factorization?)

Can we measure the Ji Sum Rule?   No!

$$\sum_f \int x[H(x,\xi,0)+E(x,\xi,0)]dx = J_q = \frac{1}{2}\Delta\Sigma + L_q$$

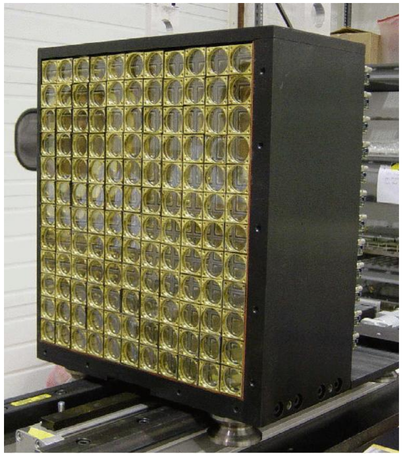
- Purists Requirements
  - Flavor Separations
  - Extrapolate to $t = 0$
  - Integral is independent of ξ (polynomiality), but requires fixed ξ GPDs.
- What can we measure?
  - Flavor unseparated
    - $H(\pm\xi,x,t)$, $E(\pm\xi,x,t)$, $P\int dx\, H(x,\xi,t)/(\xi - x) + \ldots$
  - Partial flavor separation with 'neutron' target?
- Theory input
  - Need more advanced models of GPDs
  - Full Empirical constraints,
    - Form-Factors,
    - Forward Parton Distributions
  - Full Theory constraints
    - Polynomiality (x^n moments are polynomials in ξ).
    - Positivity bounds
  - Lattice QCD input?
- Produce realistic model-dependent error on evaluation of Ji Sum Rule from global fits of GPD parameterizations to all DVCS data.

Radiation Damage

- 20% attenuation during E00-110
- MAMI A4 (parity): Curing of 20-50% attenuation loss with optical curing (16 hr blue light + 8 hr dark).
- E12-06-114 requires 7 curing days
- PR07-007 requires 3 curing days.
- Tests planned with FEL
  - Use small angle C elastic scattering of 100 MeV electrons to produce flux comparable to Moller and π^0 background in DVCS
  - Test Transmission, irradiate, test, cure, test,…
  - Please join us! Contact Julie Roche jroche@jlab.org

Expanded Calorimeter (add 80 blocks)

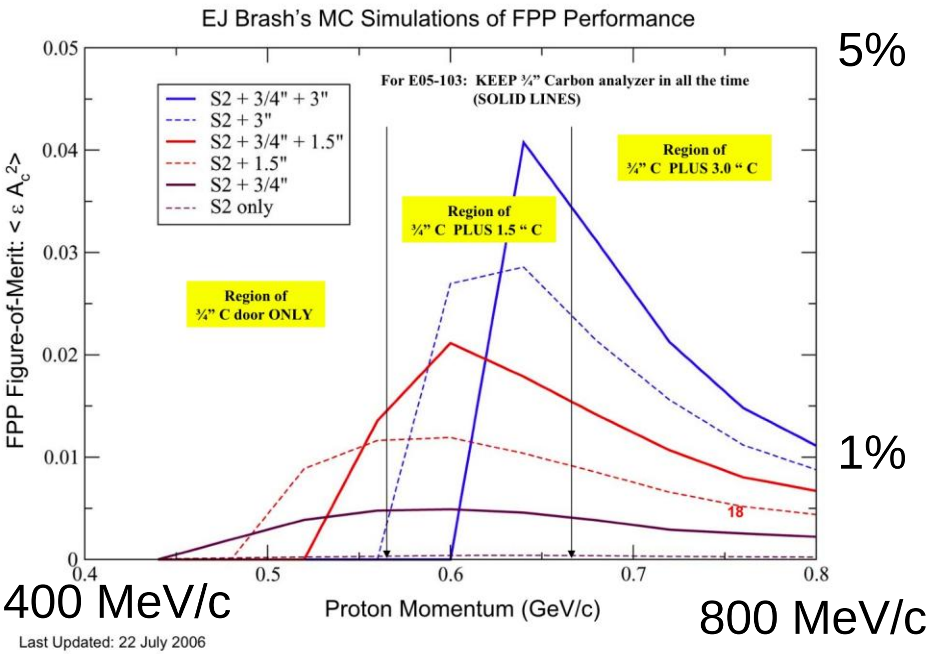
- Upgrade Trigger (Clermont-Ferrand)
  - Improved acceptance for π^0 events.
- Funding to be sought from NSF-MRI (Jan07 deadline) & French IN^2P^3-CNRS. Partial funding available from French ANR
  - Complete in 2 years for PR07-007
  - Implement optical bleaching
  - Collaborators welcome



Recoil Detection

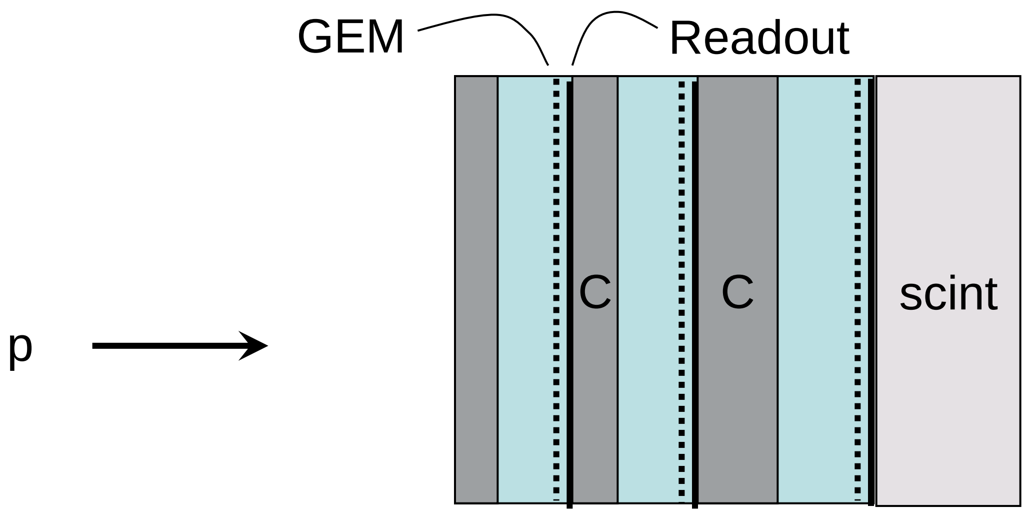
- E12-06-114, PR07-007 recoil detector not needed.
- Coherent D(e,e'γD) requires recoil detection
  - Heavily ionizing recoil deuteron
  - Measure quark spatial profile of high-momentum NN components.
  - Mass density of D, He?
  - Mass$\oplus$Charge densities $\leftrightarrow$ n$\oplus$p densities $\leftrightarrow$ u$\oplus$d densities.
- Reconsider techniques for D(e,e'γN)N
  - Spectator proton detection
  - Revised neutron detector
    - Polarimetry?
  - u/d flavor separation
- Recoil polarimetry is possible alternative to polarized targets:
  - Figure of Merit > 0.5% for p > 500 MeV/c
  - (Luminosity)(Acceptance)=$(10^{37})(0.005)(100\text{mr}/\sin 30)=10^{34}$.
  - CLAS12 Polarized target: $(10^{35})(0.05)(\pi)(0.5) \approx 10^{34}$

Recoil Polarimetry at low momentum



(400 MeV/c < p < 800 MeV/c)

- Interested in finding collaborators to build a prototype tracking detector / polarimeter for tests with PR07-007.
  - Multiple layer sandwich of C analyser and GEM trackers
  - Funding available



$(10\ \text{cm})^3$

Experimental Conclusions

- Full DVCS program for JLab 12 GeV not yet defined.
  - Pending PR07-007
    - Future 6.6, 8.8,11 GeV overlapping kinematics?
    - Separate $DVCS^2$ from BH*DVCS
  - Positron beam feasibility study in progress
    - A. Fryeberger, S. Golge (ODU), B. Wojtsekhowski, E. Voutier?
  - Helicity independent cross sections are essential to interpretation of relative asymmetries.
  - Transversely polarized targets essential for full GPD separations (*a la* G_E/G_M)
    - (CLAS12 LOI PAC30).
    - Recoil polarization technique may offer advantages.
      - Major solenoidal tracking detector with ‘standard’ HRS⊗Calo
- Best Strategy for Quasi-Free D(e,e’γN)N?
- CLAS12 and Hall A have very different systematic uncertainties, strengths, weaknesses.

Physics Conclusions

- Leading twist (GPD) terms must be extracted empirically from Q^2 dependence of Twist-2 (+4+6…) observables.
  - Odd twist observables are explicitly separable
- Full Separation of Re and Im part of Dispersive integrals of proton GPDs feasible with aggressive program
  - (2+1 year in Hall B, 1+1 year in Hall A).
  - $-t$ dependence at variable ξ measures a spatial distribution of a complicated non-local matrix element, but clearly linked to nucleon spatial distribution as a function of quark momentum fraction.
- Prospects for neutron & nuclear observables
  - Matter distributions
  - Quark structure of high momentum NN components for $\xi M > p_F$
    - (S. Liutti, UVA)
- There are more gluons than down quarks in the proton for $x_B > 0.2$
  - 99% of all plots show g(x)/10 !!
  - Need $\gamma^* + p \rightarrow J/\Psi + p$ program to measure "high"-x gluons.
  - Small kinematic window at 12 GeV.
  - 25 GeV fixed target w/ EIC@JLab?
  - "Inverted" Collider [in Hall A?]: 11 GeV electron $\otimes$ 2 GeV/c proton ???
    - SPEAR (J/Ψ co-discovery was an experiment, not an accelerator).

DVCS Collaboration

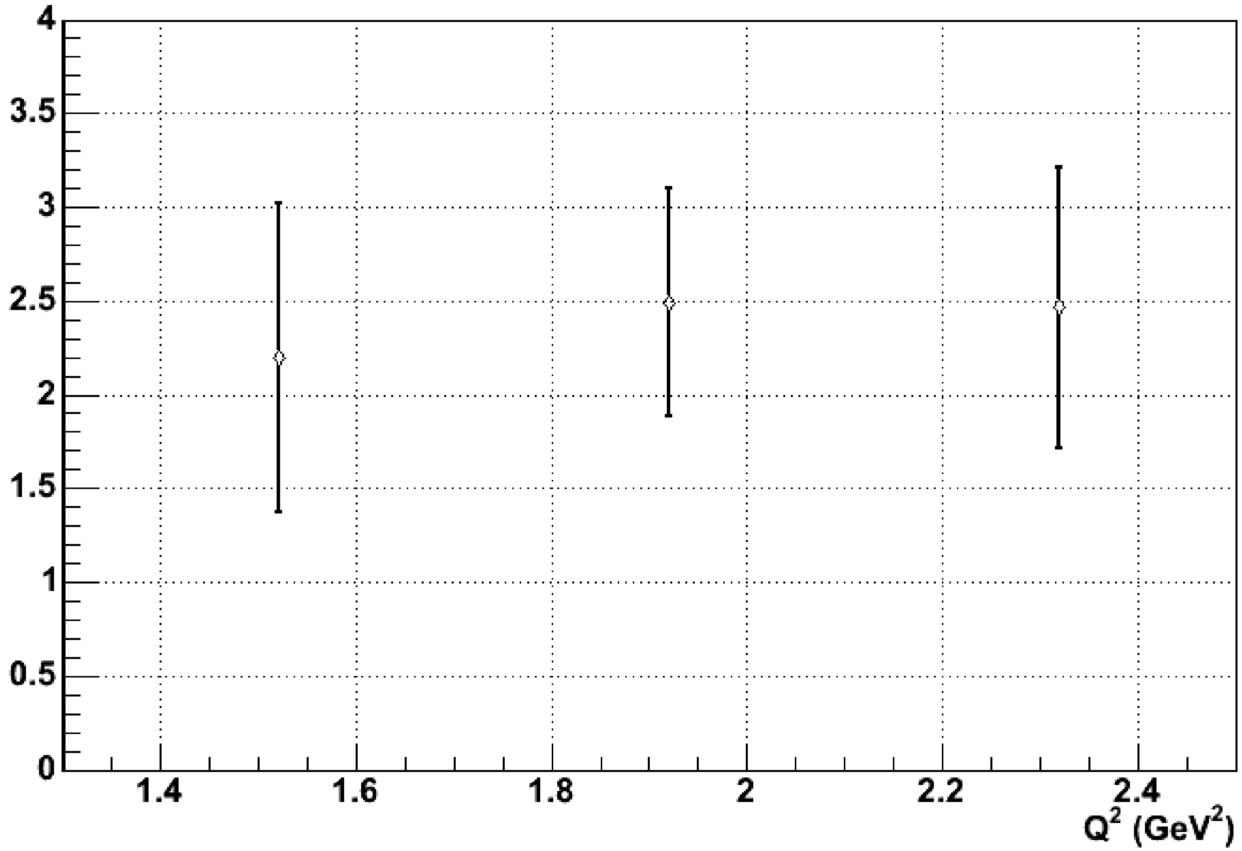
- Current (and previous) Hall A Co-spokespersons
  - C.E.H.-W., P. Bertin (C-F, JLab), C/ Munoz Camacho (LANL), B. Michel (C-F), R. Ransome (Rutgers), J. Roche (OU), F. Sabatié (Saclay), E. Voutier (Grenoble)
- Collaborators (and Leaders) desired and needed
- Instrumental developments
  - Calorimeter calibration, radiation damage & curing.
  - Prototype development of high luminosity tracking.
  - Custom DAQ electronics
- Post-Doc position open at Clermont-Ferrand
- Research Assistant Professor position open at Old Dominion University.
- Students welcome.

Answers to Questions:

Q^2-dependence of Twist-3 term averaged over t: □

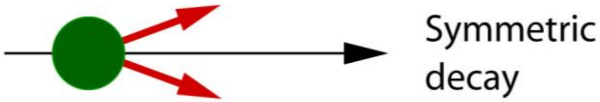
<t>=-0.23 GeV^2

Im[C^I($\mathcal{F}^{eff}$)]: 'sin2φ term'



π^0 Electroproduction & Background Subtraction

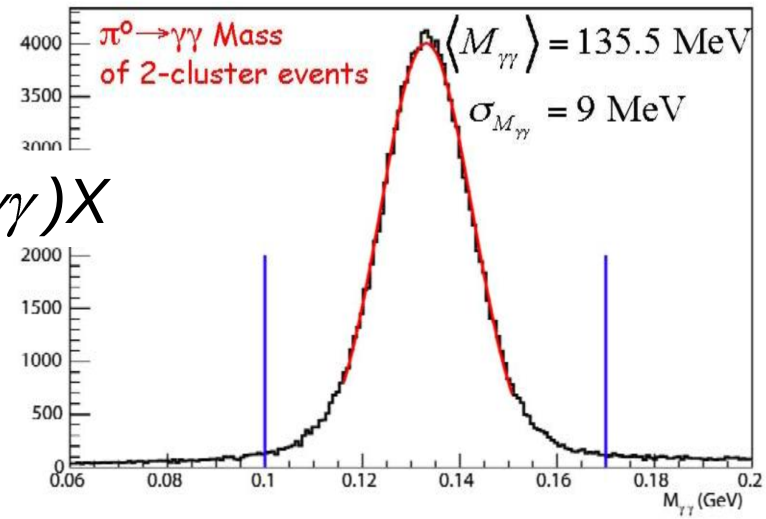
Laboratory frame

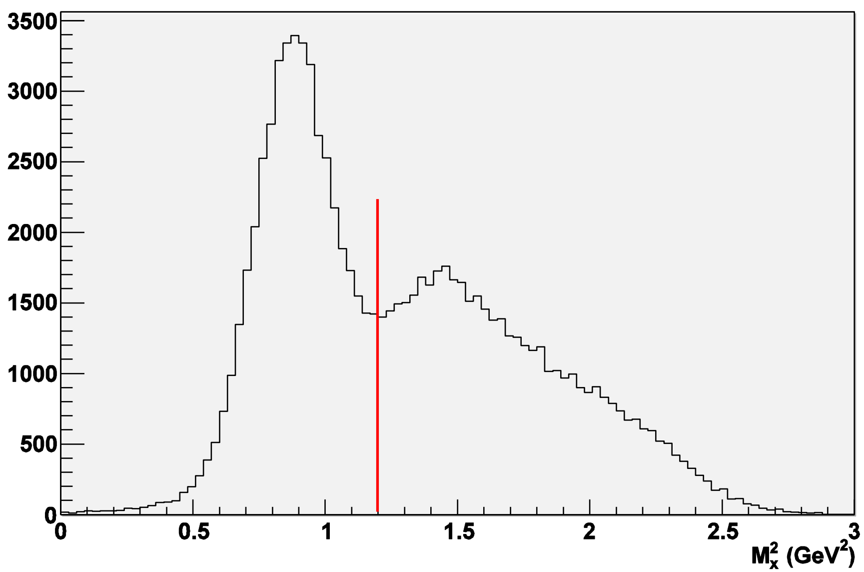


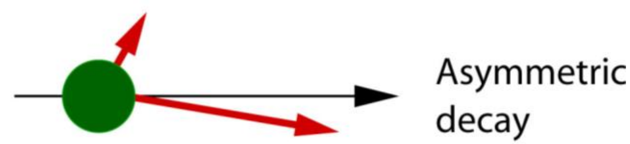
- Minimum $\gamma\gamma$ angle in lab = 4.4° (E00110)

$H(e, e'\gamma\gamma)X$

$\underbrace{\gamma\gamma}$ $M_{\gamma\gamma}$ —



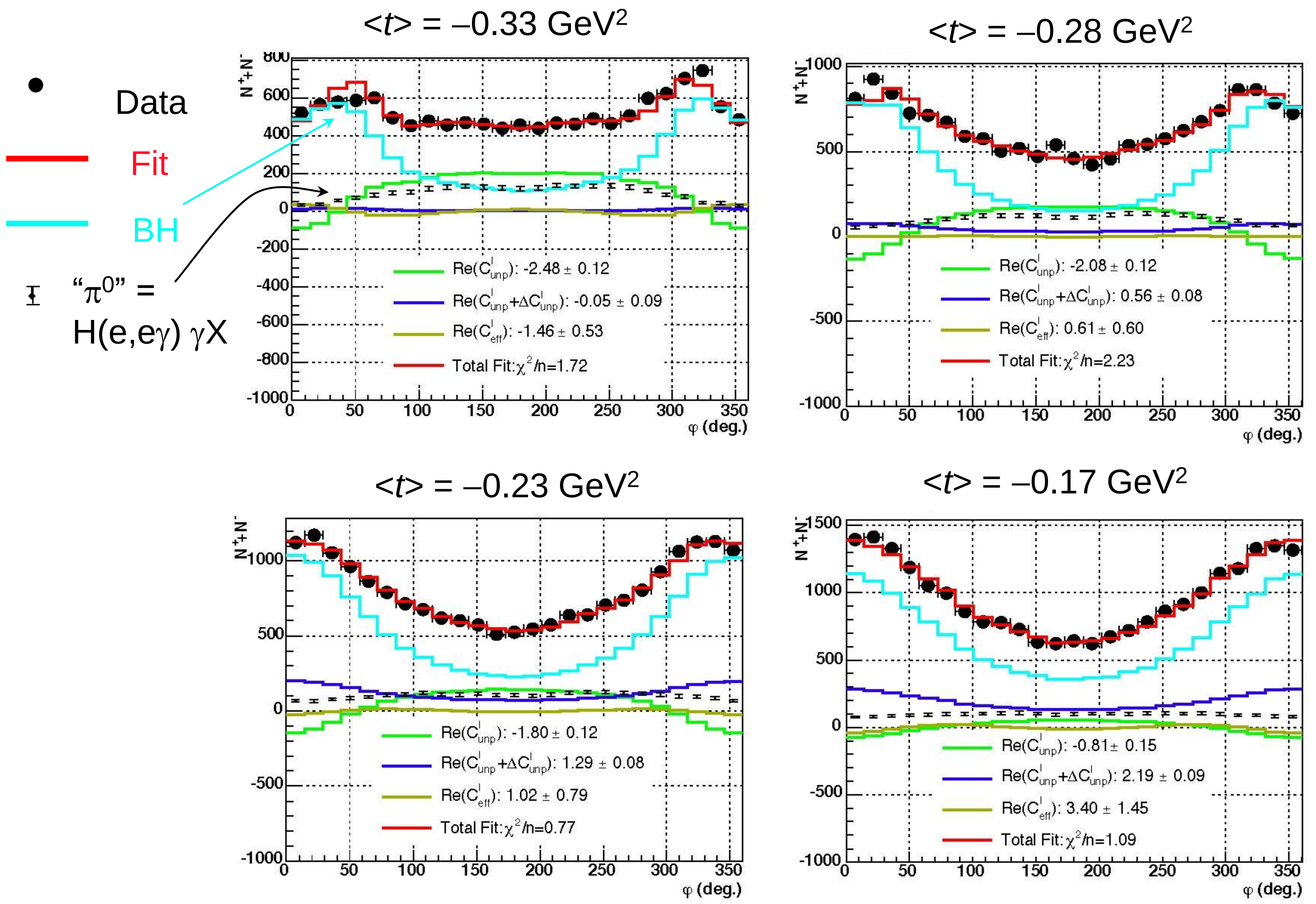




- Asymmetric decay:
- $H(e,e'\gamma)\gamma Y$ One high energy forward cluster…

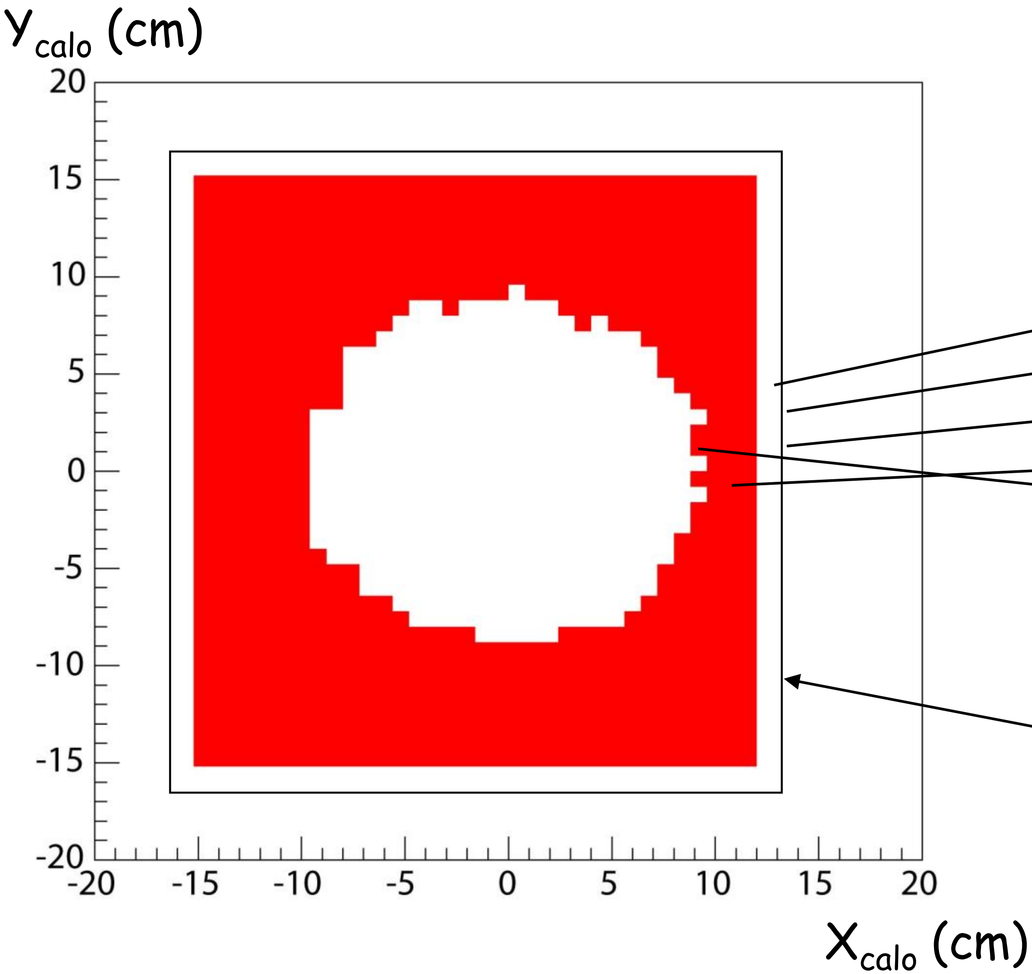
mimics DVCS M_X^2!

Bethe-Heitler and π^0 Contributions Q^2=2.3 GeV^2



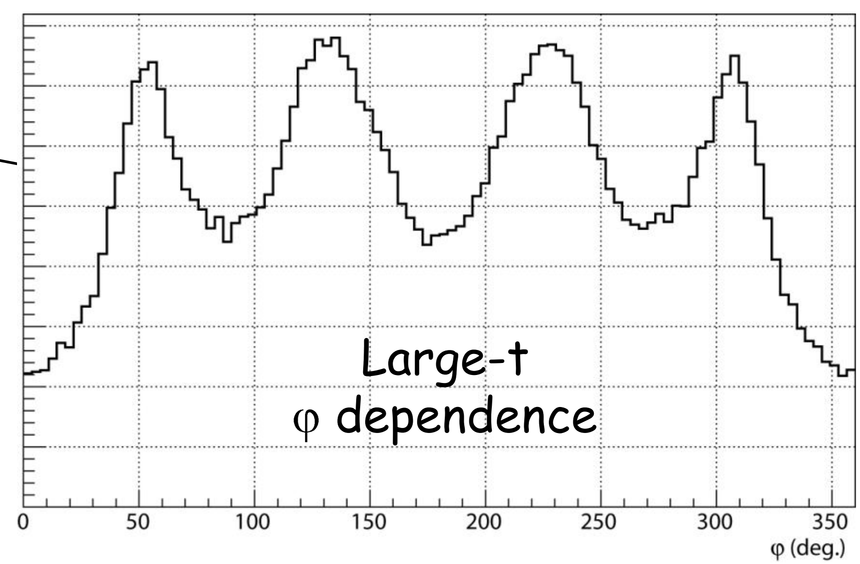
Analysis – Calorimeter acceptance

The t-acceptance of the calorimeter is uniform at low $t_{min}-t$:

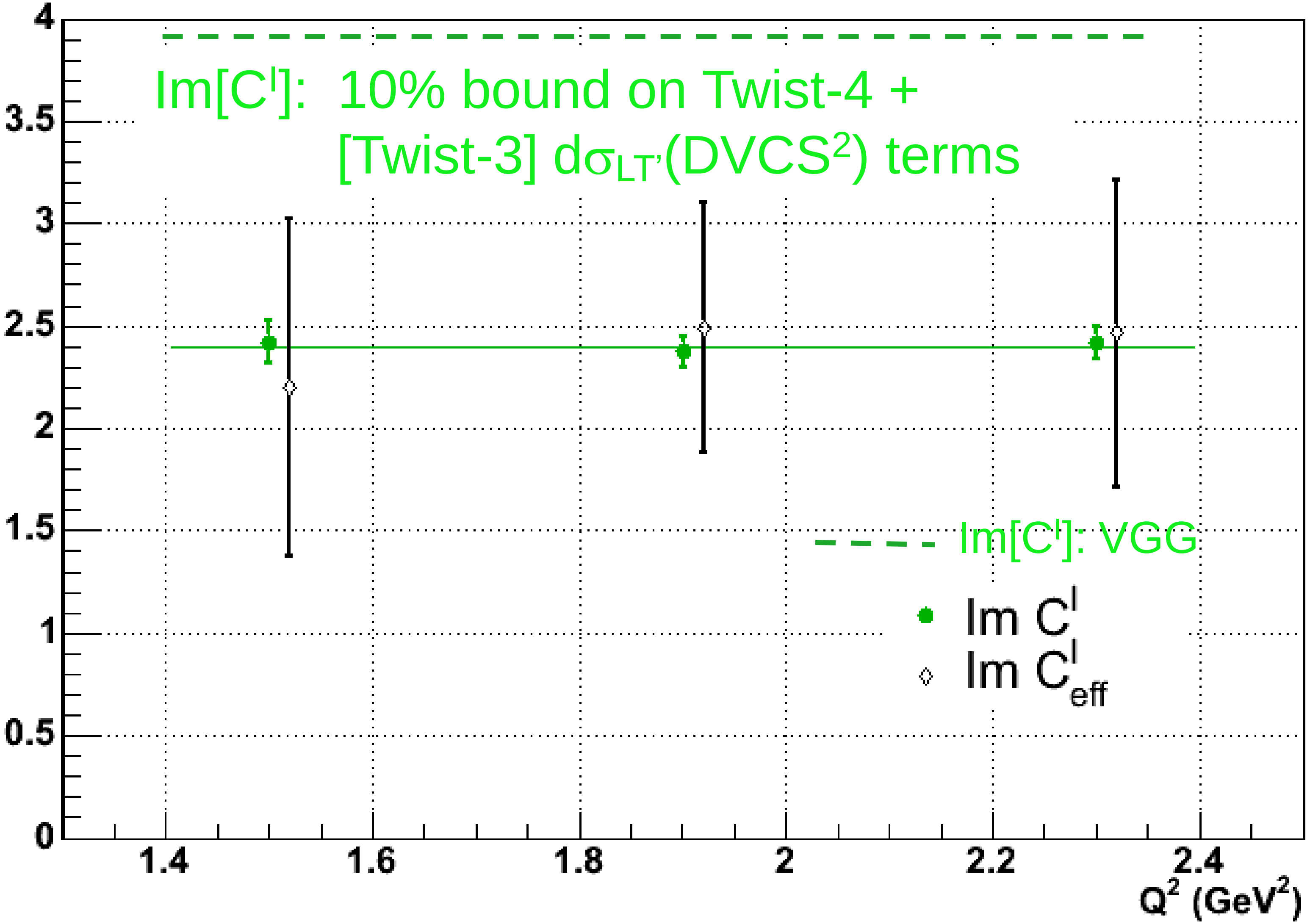


5 bins in t:

Min	Max	Avg
-0.40	-0.35	-0.37
-0.35	-0.30	-0.33
-0.30	-0.26	-0.28
-0.26	-0.21	-0.23
-0.21	-0.12	-0.17



Q^2-dependence: averaged over t: <t>=-0.23 GeV^2



Im[C^I_{eff}]: Twist-3 suppression in $(t_{min}-t)/Q^2$ kinematic coefficient, not in magnitude of <qGq> matrix element