Workshop on Photon Hadron
Physics with the Glue-X Detector
6--8 March 2008
Jefferson Lab

Exclusive Di-Lepton Production

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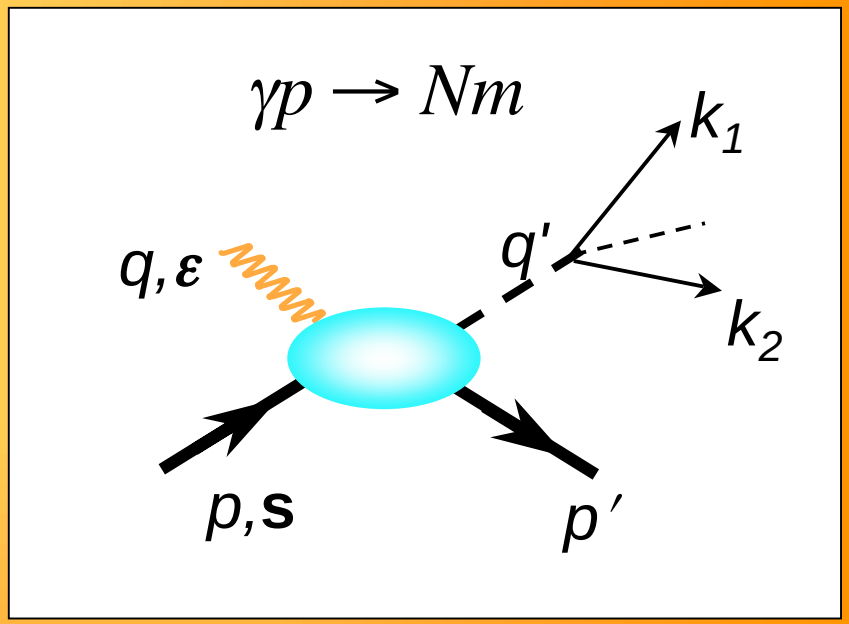
Kinematics of High Energy Exclusive Photo-Production:

2-Body & n-Body Final States

- Invariants
  - Center of Mass:
    - $W^2=(q+p)^2$
  - Momentum Transfer squared
    - $t=\Delta^2=(p'-p)^2$
  - Final State "Particle"
    - $m^2=(q')^2$
  - "Skewness" variable
    - $(q')^2/(W^2-M^2)$



- Azimuths:
  - Scattering plane $\mathbf{q}'\otimes\mathbf{p}'$ around polarization plane $\mathbf{q}\otimes\boldsymbol{\varepsilon}$
  - Decay plane $\mathbf{q}'\rightarrow\mathbf{k}_1\otimes\mathbf{k}_2$ around Scattering Plane $\mathbf{q}'\otimes\mathbf{p}'$
  - Target Polarization plane *vs.* other planes

Two-Body Final States

$\gamma p \rightarrow p\gamma$

$\gamma p \rightarrow p\pi^0$

$\gamma p \rightarrow n\pi^+ \ldots$

- Acceptance of recoil nucleon and scattered γ, or π can be matched with spectrometers/dedicated detectors.
  - Product of luminosity times acceptance favors dedicated experiments (Hall A,C)

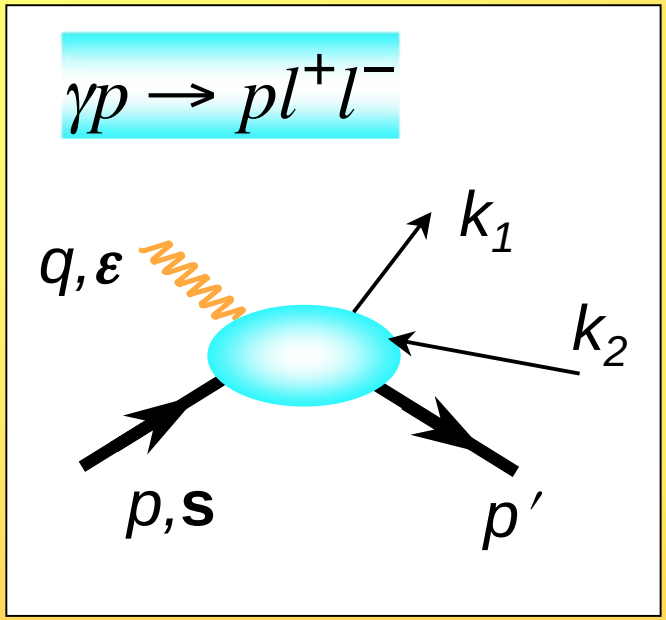
Many-body Final States

$\gamma p \rightarrow p\gamma^{*} \rightarrow pl^{+}l^{-}$ high mass

$\gamma p \rightarrow p(\rho,\omega,\phi)$

$\gamma p \rightarrow p\pi^{+}\pi^{-}$ high mass

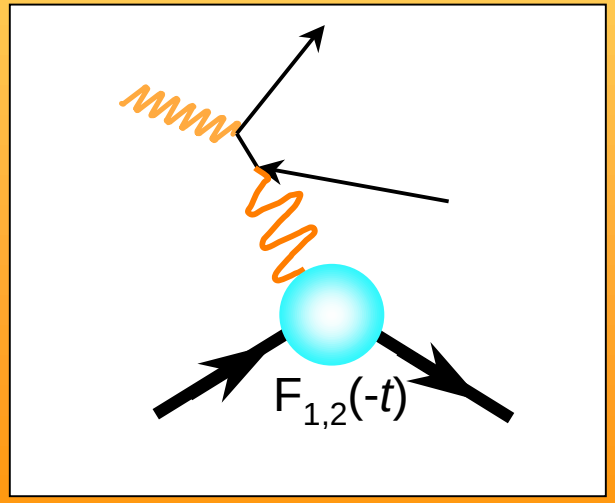
- Complicated final state favors large acceptance detector.
- Dileptons:
  - Access to Compton phase from interference with Bethe-Heitler
  - High-*t*, $m_{\pm}<m_{\pi}$: extension of Real Compton Scattering
  - Low-*t*, $m_{\pm}<m_{\pi}$: Forward Compton Amplitude, GDH Sum Rule
  - Low-t, $m_{\pm}= \rho,\omega$: ρ,ω interference
  - Low-*t*, large $m_{\pm}$: Spatial imaging of quarks and gluons



Inverse Virtual Compton Scattering (iVCS): Di-Lepton Photo-Production

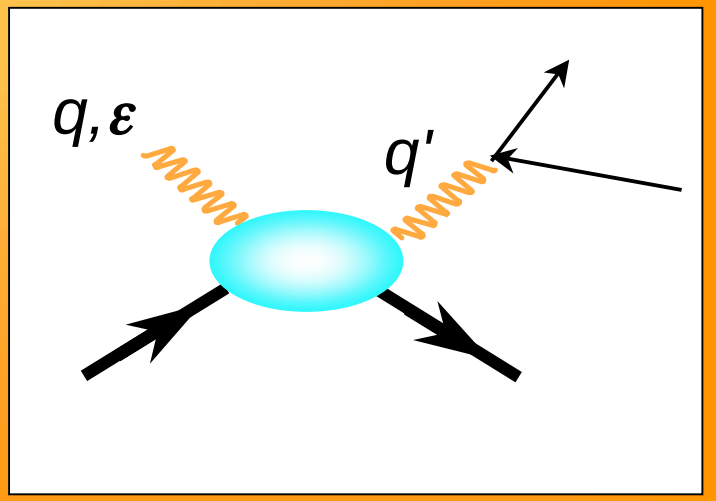
- $q' = k_1 + k_2$
- $\Delta = (q - q')$

=



Bethe-Heitler

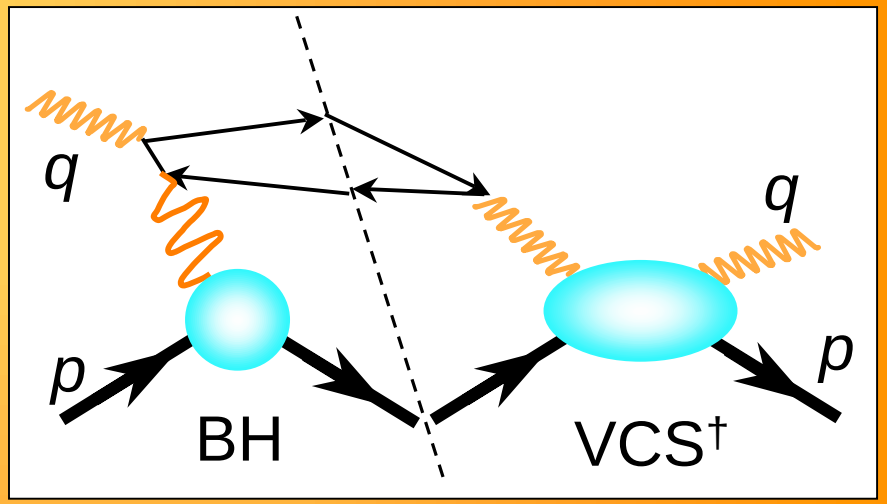
+



Virtual Compton Scattering

Charge Conjugation & the BH•VCS Interference

$$d\sigma \propto \left|T^{BH}\right|^2 + 2\Re e\left[T^{BH}T^{VCS\dagger}\right] + \left|T^{VCS}\right|^2$$

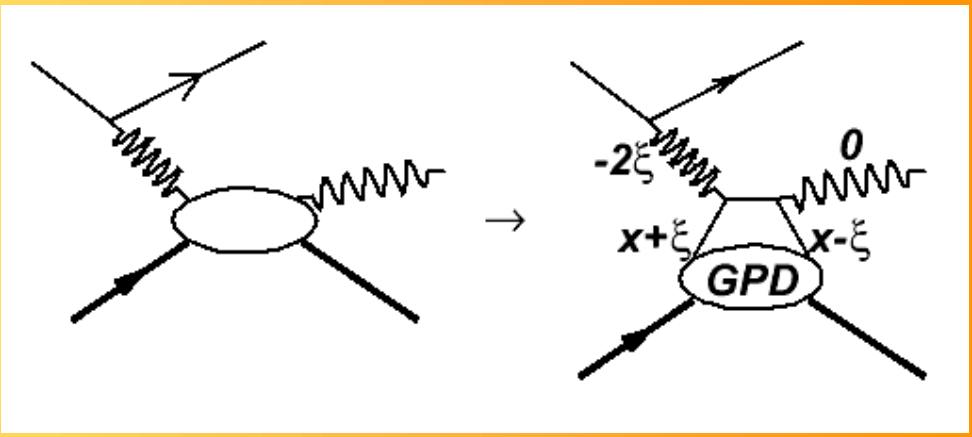


- Charge Conjugation Exchange:
  - [electron ⇔positron]
    $[k_1,k_2] \Leftrightarrow [k_2,k_1]$
  - Interference term:
    - Odd number of photon couplings to lepton line.
    - $d\sigma(k_1,k_2) - d\sigma(k_2,k_1)$ = BH•VCS Interference
- VCS:
  - $(e^{\pm}p \rightarrow e^{\pm}p\gamma)$: requires electron and positron beams; **or**
  - Multiple beam energies (E07-007 Hall-A DVCS).

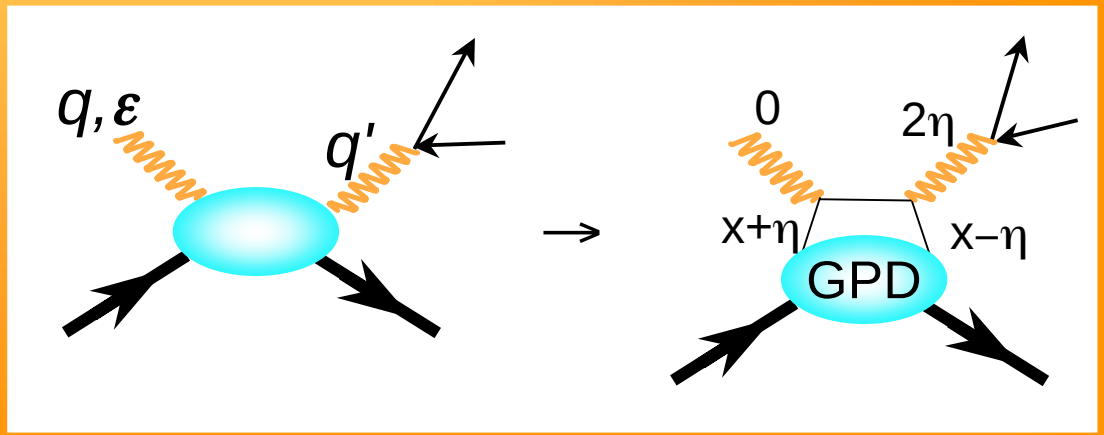
Deeply Virtual Compton Scattering

Space-Like & Time-Like: QCD factorization:

- Space-Like
  - $x_B = Q^2/(2p \bullet q)$
  - $\xi = x_B/(2-x_B)$
  - Generalized Parton Distributions (GPDs)
    - $\Delta_\perp$ is fourier conjugate to transverse spatial coordinate **b** of parton of light cone momentum fraction $x \pm \xi$.

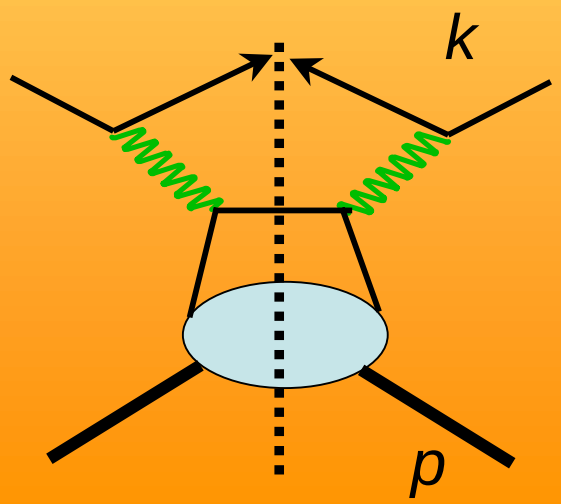


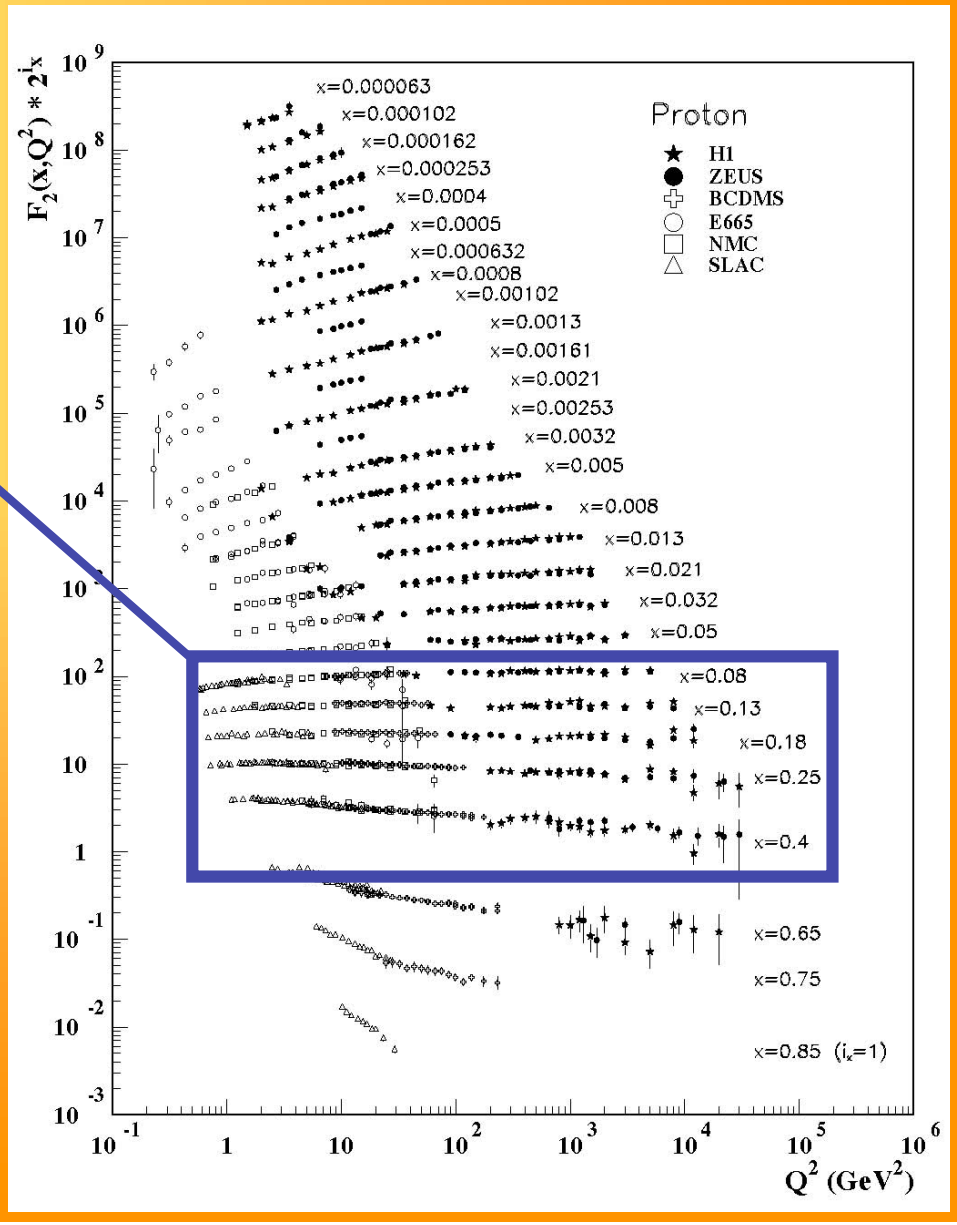
- Time-Like
- $\tau = (q')^2/(2p \bullet q)$
- $\eta = \tau/(2-\tau)$

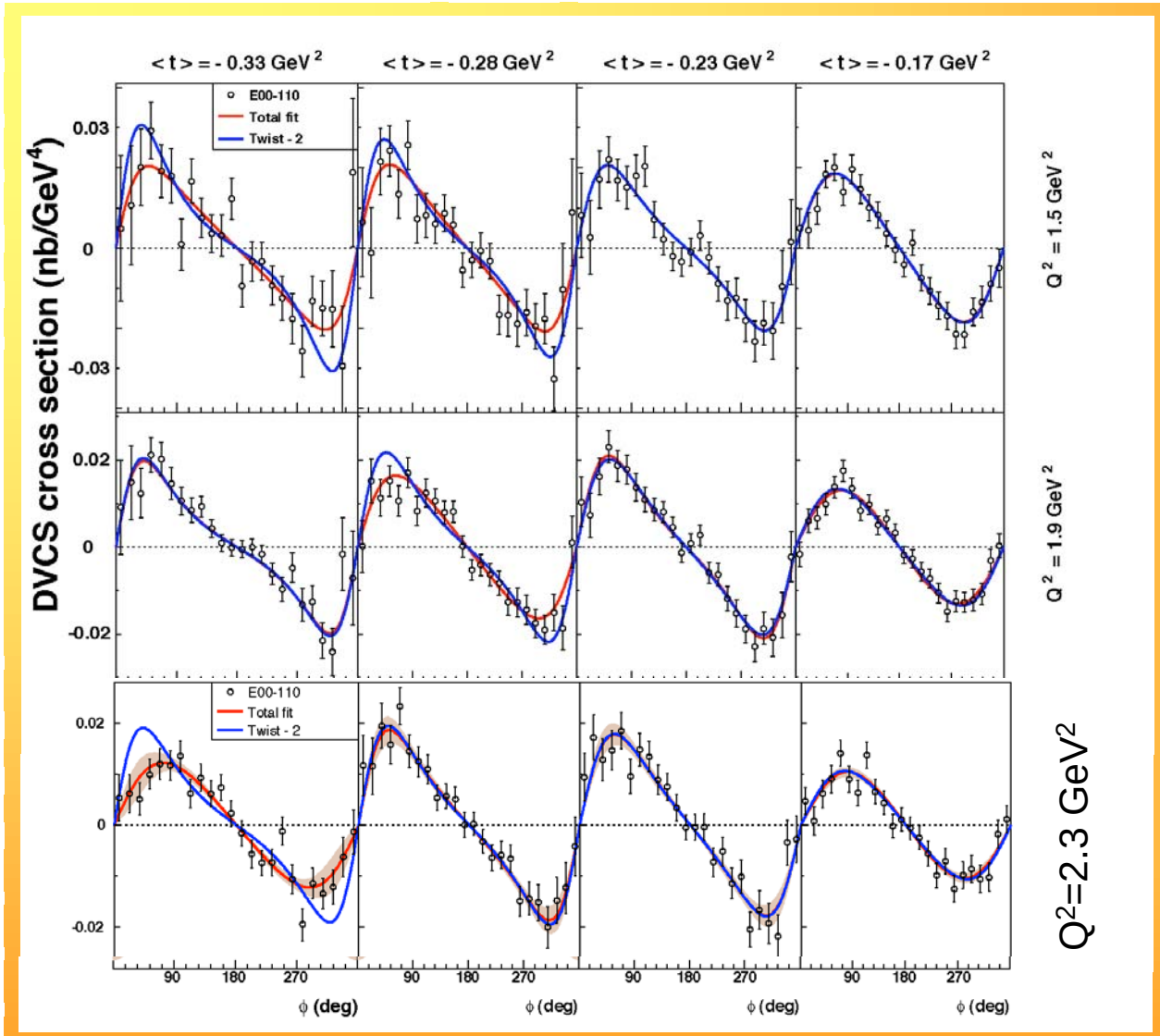


Factorization & Evolution: DIS

- DIS Factorization Scale: $Q^2 \approx$ few GeV^2
- Very gentle QCD evolution scale-breaking for $0.1 < x_B < 0.6$







Hall A
Cross section differences:

PRL**97**:262002

C. MUNOZ CAMACHO, *et al.*,

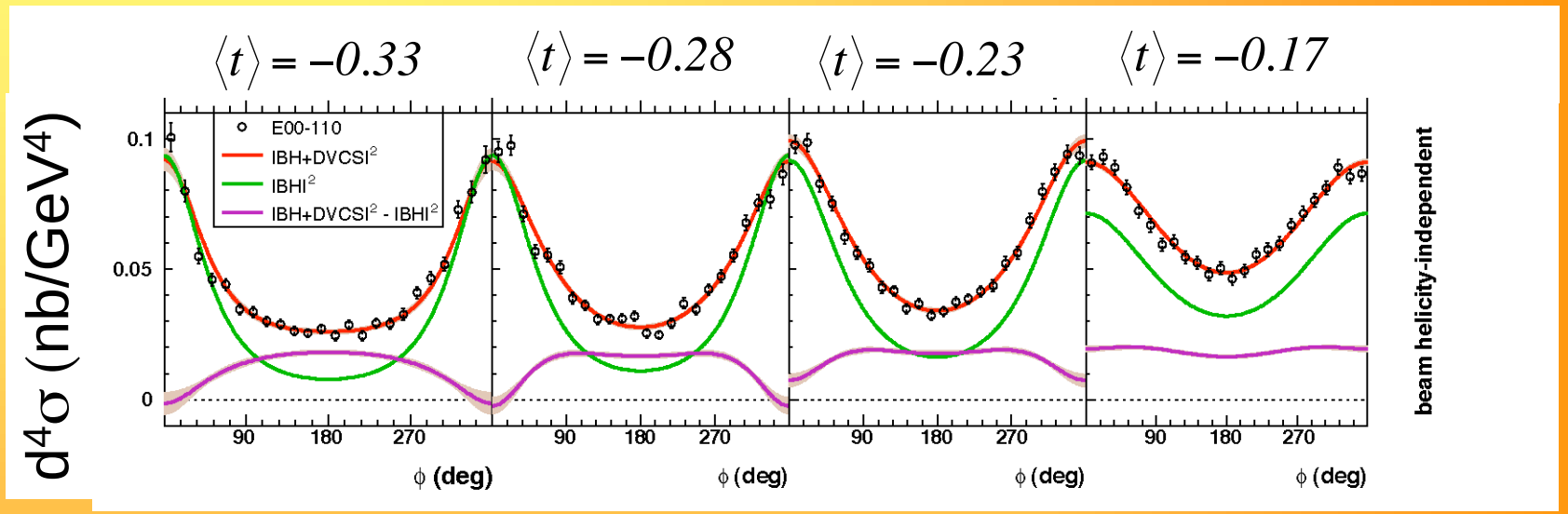
Twist-2(GPD)+…

Twist-3(qGq)+…

$\Gamma_{s1,2}$ = kinematic factors

$$\sum hd\sigma(h) = \frac{s_1 \sin(\phi_{\gamma\gamma})\Gamma_{s1} + s_2 \sin(2\phi_{\gamma\gamma})\Gamma_{s2}}{P_1(\phi_{\gamma\gamma})P_1(\phi_{\gamma\gamma})}$$

Beam helicity-independent cross sections at $Q^2=2.3$ GeV^2, $x_B=0.36$ PRL**97**:262002



$$d\sigma = d\sigma(|BH|^2) + 2\,\mathrm{Re}[DVCS^{*}\,BH] + |DVCS|^2$$

$$= d\sigma(|BH|^2) + \frac{c_0\Gamma_0 + c_1\cos(\phi_{\gamma\gamma})\Gamma_1 + c_2\cos(2\phi_{\gamma\gamma})\Gamma_2 + \ldots}{P_1(\phi_{\gamma\gamma})P_1(\phi_{\gamma\gamma})}$$

DVCS is not small!

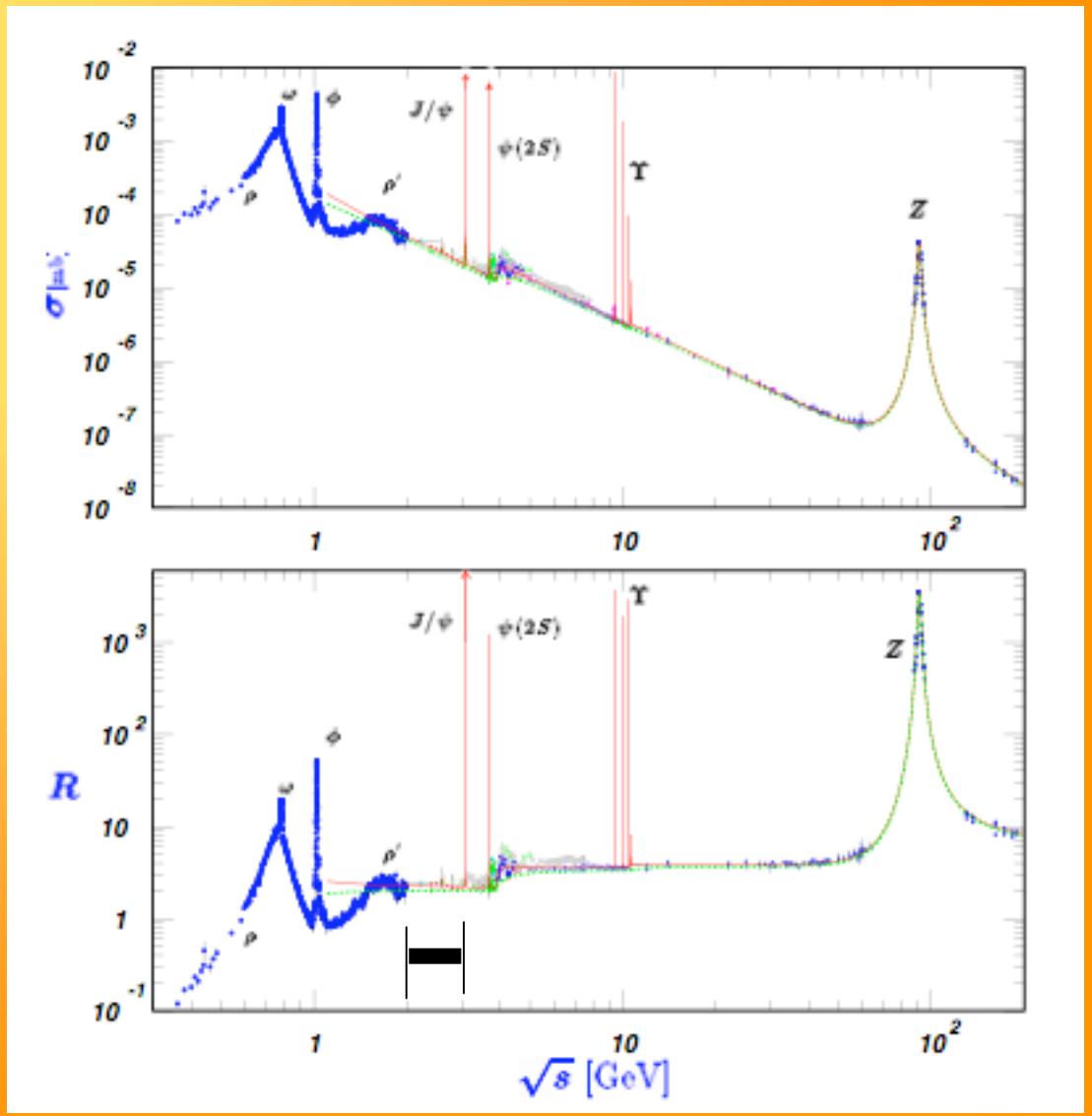
$$c_{0,1}(t) \approx \mathrm{Re}[C^{I}(GPD)] \pm C^{DVCS}\left(GPD^2\right)$$

$$c_2(t) = \mathrm{Twist}-3 = (qGq)$$

3 free parameters per bin $[Q^2, x_B, t]$

Inverse DVCS

- Factorization at large $m_{\pm}^2=(q')^2$
  - Di-Lepton mass in region of smooth R
- Hall D / Glue-X
  - q = 9 GeV; $W^2-M^2 \approx 17$ GeV^2
  - $4 \le m_{\pm}^2 \le 9$ GeV^2
  - $0.25 \le \tau \le 0.55$
    - Comparable to x_B range of DVCS at 11 GeV.
  - J/Psi measures Gluon GPDs at $\tau \ge 0.6$

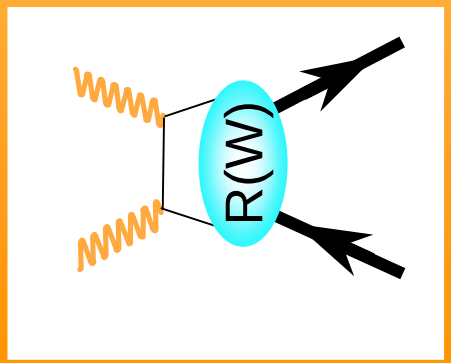


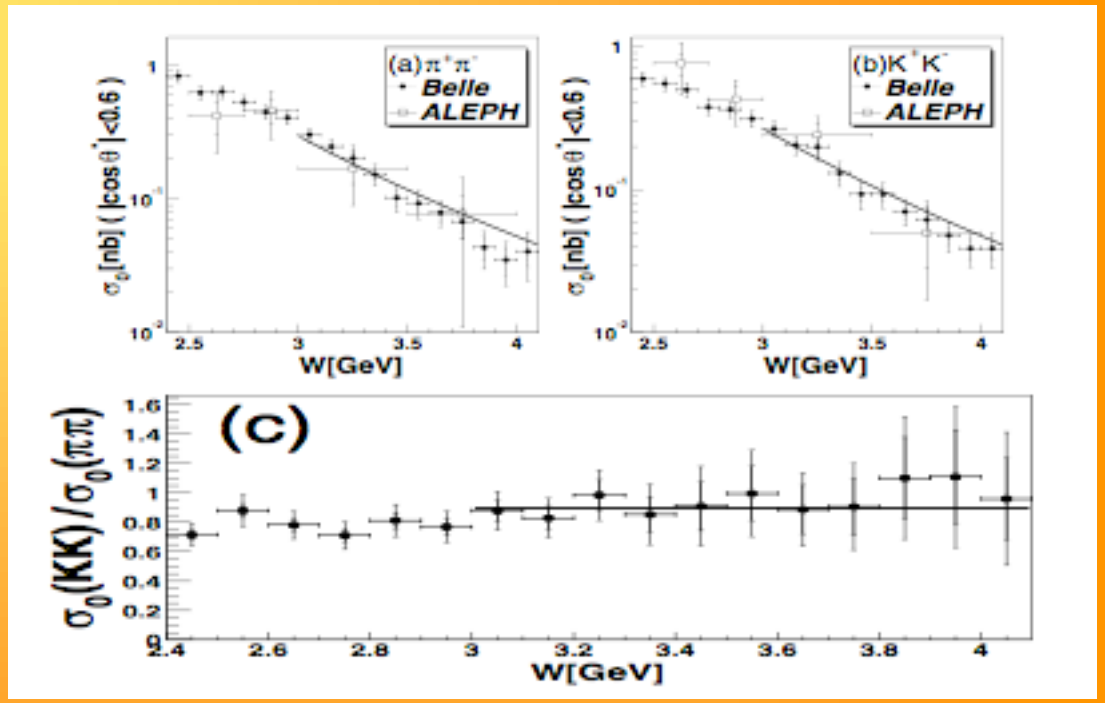
Two-Photon data from BELLE

A.E. Chen, Int J. Mod Phys A**21** (2006) 5543

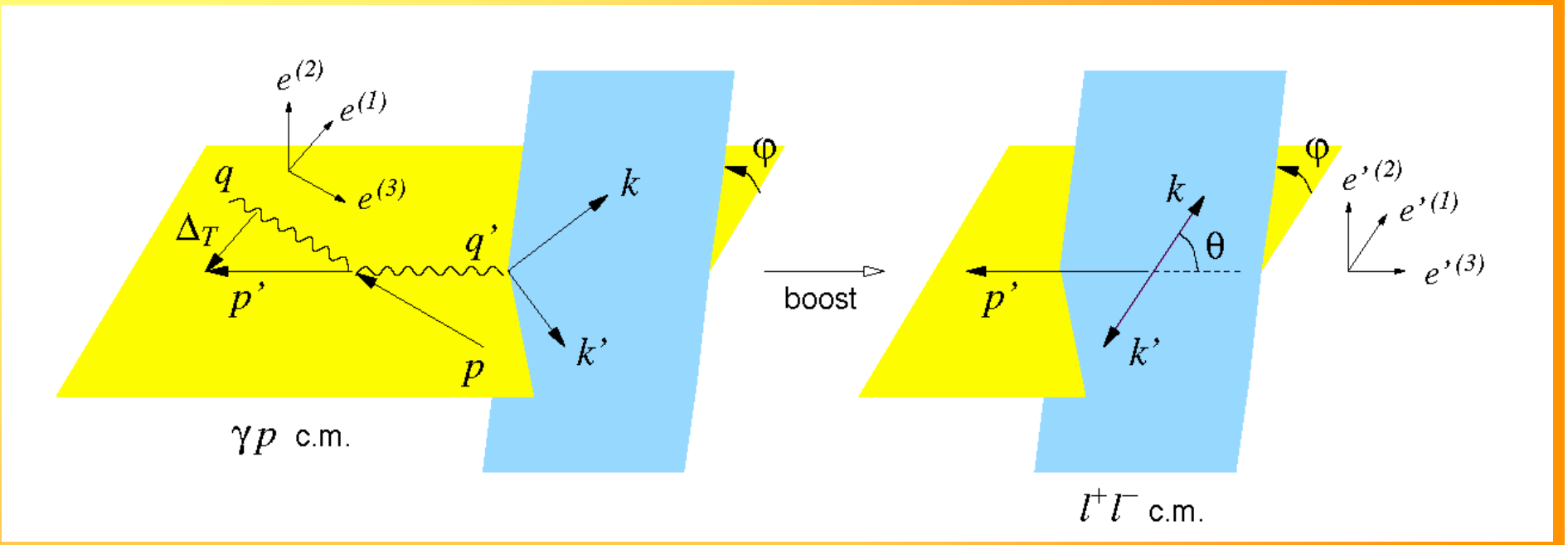
S. Uehara *et al*, PRL **96** (2006) 082003

- Compatible with "Handbag" model
  - Scaling as W^{-n}
  - All isospin/flavors equal.
  - M.Diehl, P.Kroll, C.Vogt EPJC26 (2003) 567.



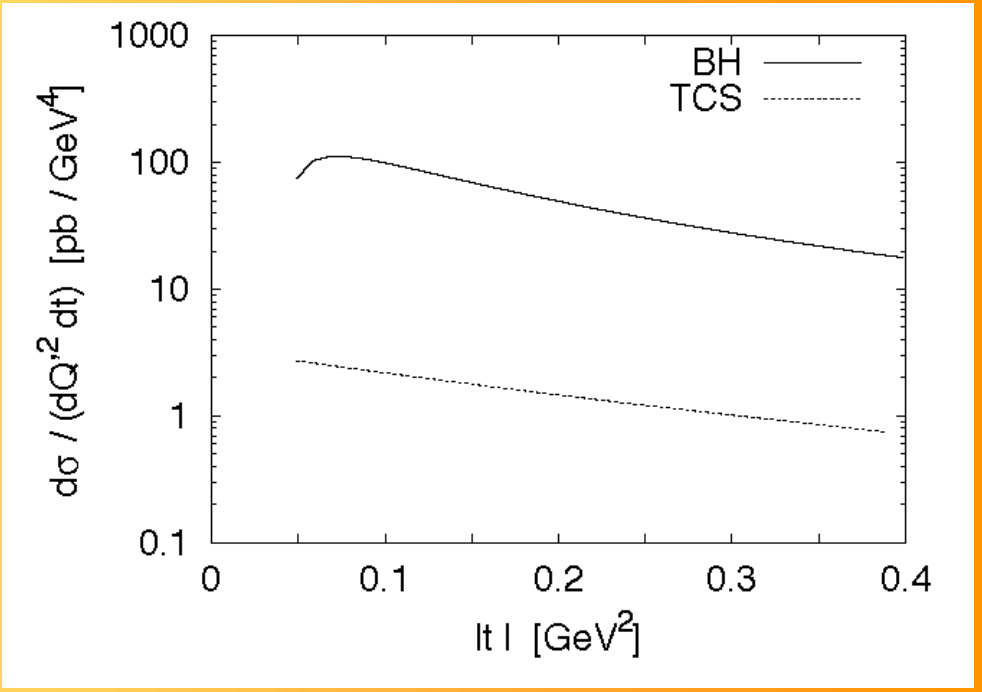


E.Berger, M.Diehl, B.Pire hep-ph/0110062



- Strong BH peak for *k* or *k'* co-linear with *q*
  - Integrate over $45° < \theta_{Rest} < 135°$.
- $|DVCS|^2 / |BH|^2$
  - $ep \rightarrow ep\gamma$: $\propto 1/y^2 = [Q^2/(2k_e M x_B)]^2$
    - BH larger at CEBAF energies, DVCS dominates at high energy
  - $\gamma p \rightarrow p l^+ l^-$: $\propto (-t)/m^2 \ll 1$: BH always dominant

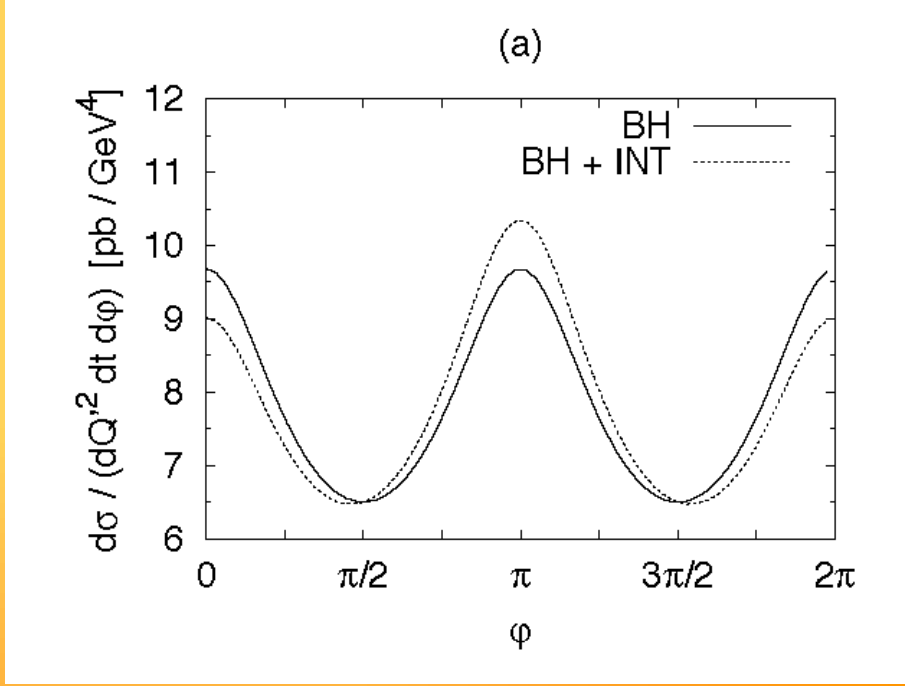
E.Berger, M.Diehl, B.Pire
hep-ph/0110062



- W^2=25 GeV^2, m^2=5 GeV^2
  - $d\sigma^{BH} \propto W^{-4}$
- Integrated over
  - $45° < \theta_{Rest} < 135°$.
  - $0 \leq \varphi \leq 360°$.
- Coherent Photon Luminosity
  - 10^8/s • 2 g/cm^2 =0.12 Hz/nb
  - 2000 hours = 800 events/pb
- 2000 hours $\otimes$ [Δm^2=1GeV^2] $\otimes$ Δt=0.15 GeV^2
  - 10 pb per bin
  - 8000 events per bin
  - 4$\otimes$4 bins in $m^2 \otimes$ t

Interference Signal

- BH background is subtracted by charge conjugation difference
- W^2=25 GeV^2, m^2=5 GeV^2
  t = –0.2 GeV^2
  Integrated over
  - $45° < \theta_{Rest} < 135°$
- $\int \cos\varphi \, d\sigma^{Int} d\varphi \approx 0.2$ pb/bin
- Inteference $\pm \sqrt{BH}$
  =160 ± 60 events



- Circularly polarized photons will generate an independent observable (Im part of Interference of comparable magnitude).
- Monte Carlo event generator with integration over ideal detector in progress.

Conclusions

- Di-Lepton measurements in DVCS regime are feasible
  - Requires maximum luminosity and several months of beam time.
    - Photon tagging may not be required, since final state is over-complete
    - Specialized trigger possible
      - ≈ 100% of beam energy in 2 EM showers.
  - Charge Conjugation access to Re part of BH•DVCS interference
    - Consistency with electroproduction is test of factorization
    - Variation of photon energy is 2nd test of factorization

Electrons or Muons?

- High energy $a+b \rightarrow \mu + X$
  - Inclusive muons swamped by inclusive pion background
- Exclusive $\gamma+p \rightarrow \mu^+ \mu^- + p$
  - Exclusive $\pi^+\pi^-$ at large mass-squared strongly suppressed
    - $q\bar{q} \rightarrow \pi^+\pi^-$ Distribution Amplitude $R_{2\pi}(s)$
    - Measured in BELLE: $\gamma\gamma \rightarrow \pi^+\pi^-$
- π/μ rejection factor r
  - $(\pi^+\pi^-)/(\mu^+\mu^-)$ rejection factor = r^2
- Even moderately good muon id makes di-muons feasible.