Studies of nucleon structure with CLAS12 at Jefferson Lab

The Central Neutron Detector and Timelike Compton Scattering

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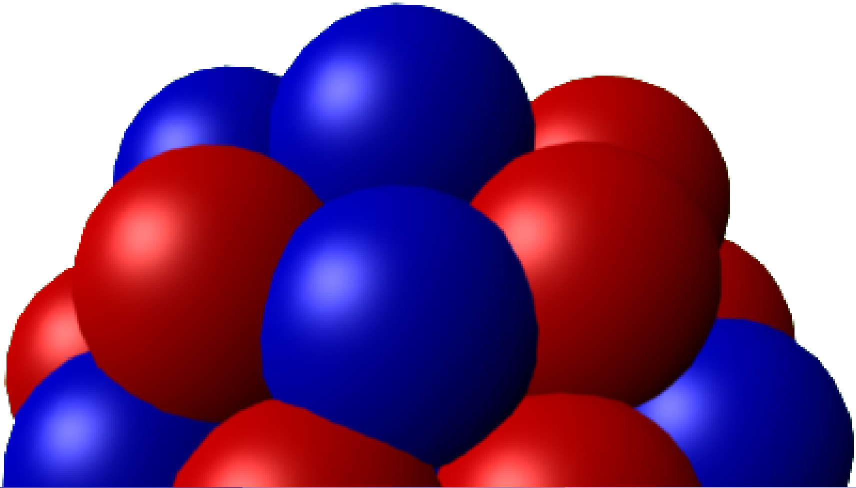
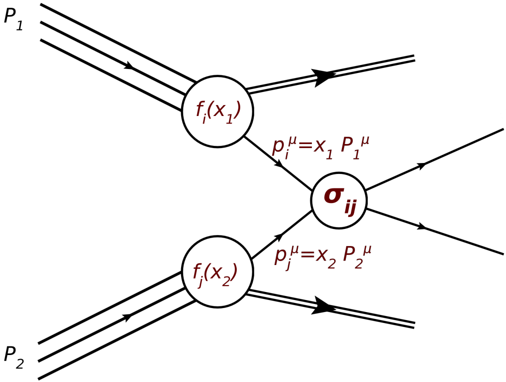
We all know what protons are...

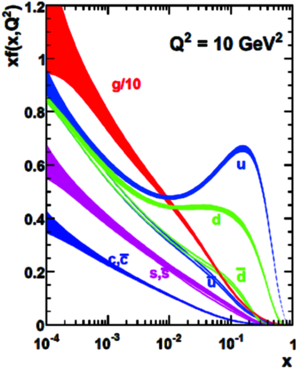
Protons in ... Nuclear Physics

$$S = \frac{1}{2} \quad I = \frac{1}{2}$$



Protons in ... Particle Physics





So do we know everything about protons
(and neutrons) ?

Still a lot more to understand

Origin of the nucleon mass, of the spin, the little explored low x region, the behaviour of nucleons in nuclei (nPDFs, EMC effect,...) and a lot more

Outline of this talk

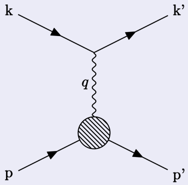
- Nucleon Structure and Generalized Parton Distributions
- Jefferson Lab and CLAS12 overview
- **Part I** The Central Neutron Detector of CLAS12
- **Part II** Extracting GPDs from Timelike Compton Scattering

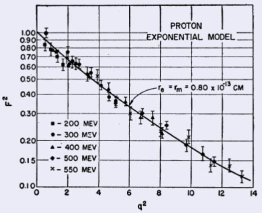
Brief history of the structure of the nucleon

Form factors

Elastic scattering

$ep \rightarrow ep$

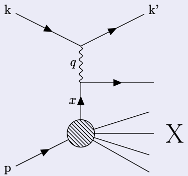


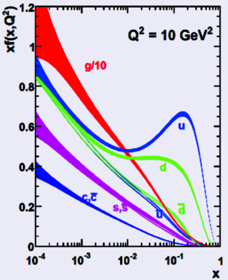


Parton distributions

Inelastic scattering

$ep \rightarrow eX$

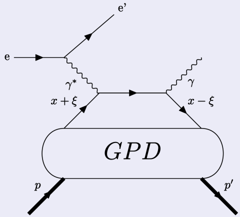


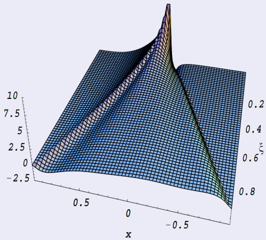


Generalized Parton Distributions

Exclusive reactions

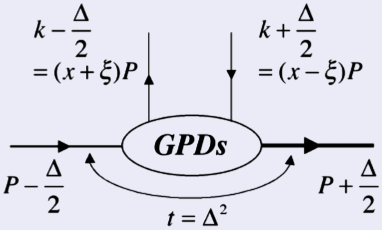
$ep \rightarrow ep\gamma$





Generalized Parton Distributions

GPDs are structure functions parametrizing the "soft" structure of the nucleon, not calculable by pertubative QCD.



- GPDs depend on x, ξ and t
- 4 helicity conserving GPDs H, $\tilde{H}$, E, $\tilde{E}$
- 4 helicity changing GPDs
- Gluon GPDs exist too...

Impact parameter interpretation

$$H(x, b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-ib_\perp \Delta_\perp} H(x, 0, -\Delta_\perp^2)$$

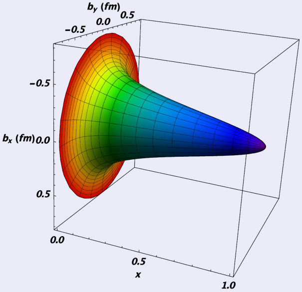
Why are GPDs interesting ?

The spin puzzle and the Ji's sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g \text{ where } \frac{1}{2}\Delta\Sigma + L_q = \frac{1}{2}\int_{-1}^{1} x(H(x,\xi,0) + E(x,\xi,0))dx$$

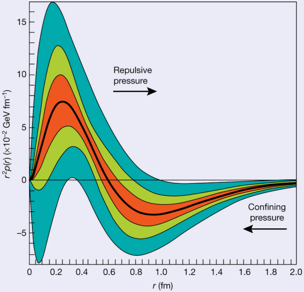
Quarks spin , Quarks angular momentum , Gluons contributions

Proton tomography



Dupré, Guidal and Vanderhaeghen (2016)

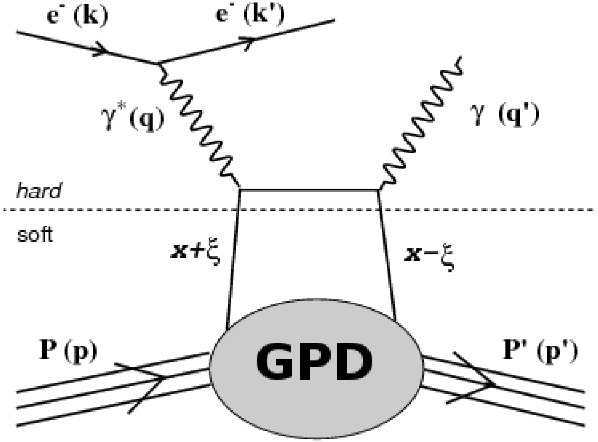
Internal pressure



Burkert, Elouadrhiri and Girod (2018)

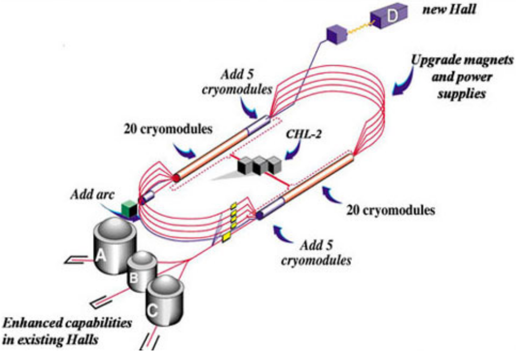
Measuring GPD

Deeply **V**irtual **C**ompton **S**cattering



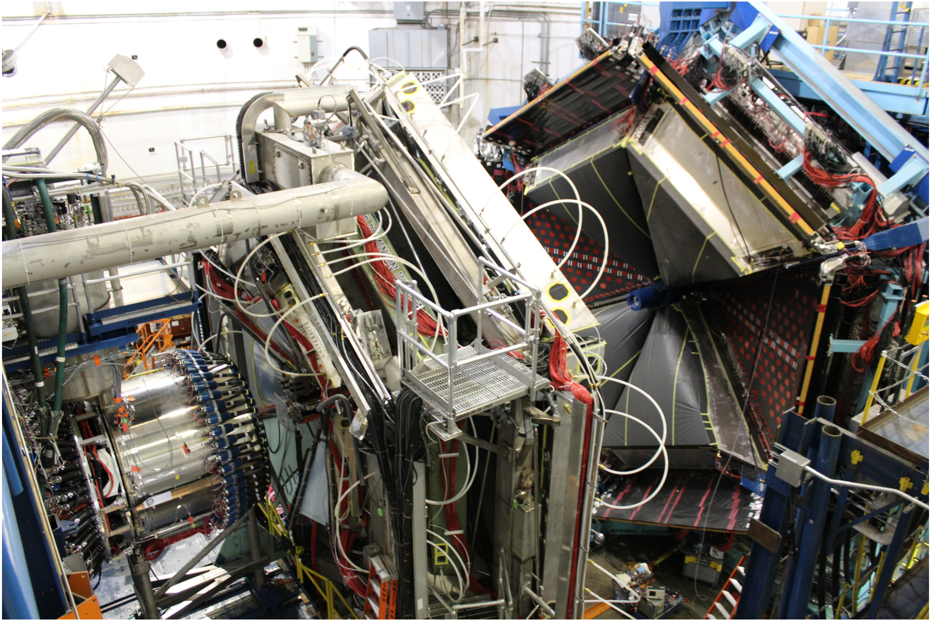
Factorisation in the Bjorken regime (large photon virtuality and energy)

Jefferson lab



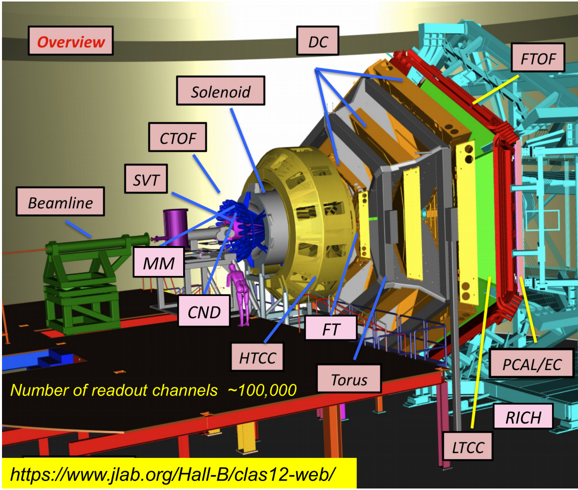
- Polarized electron beam
- Hall A and C: ↑ luminosity, ↓ phase space
- Hall B: ↑ phase space, ↓ luminosity
- Hall D: tagged photon beam dedicated to spectroscopy

CLAS12 in hall B



CLAS12 sub-detectors

- Central Detector (CD)
  - Time-of-Flight (CTOF)
  - Tracking (SVT and MM)
  - Neutron detector (CND)
- Forward Detector (FD)
  - Drift Chambers (DC)
  - Time-of-Flight (FTOF)
  - Calorimeters (PCAL/EC)
  - Cherenkov Counters (HTCC and LTCC)
  - RICH
  - Forward tagger (FT)



Part I

The **C**entral **N**eutron **D**etector of CLAS12

The Central Neutron Detector

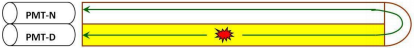
DVCS on neutron to separate GPDs flavour, using isospin symmetry

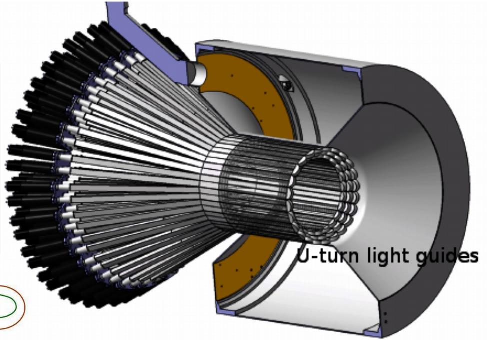
$$H^p = \frac{4}{9}H^u + \frac{1}{9}H^d \qquad H^n = \frac{4}{9}H^d + \frac{1}{9}H^u$$

Access the GPD E appearing in the Ji's sum rule

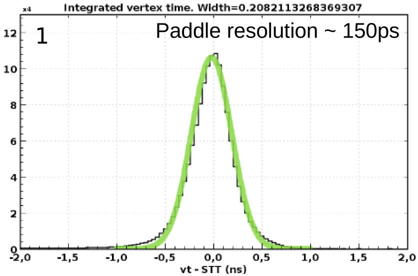
$$J_q = \frac{1}{2}\int_{-1}^{1} x(H(x,\xi,0) + E(x,\xi,0))dx$$

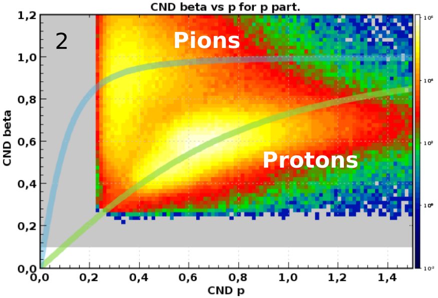
- DVCS neutrons are mainly emitted at large angle ($> 40°$)
- Measurement of time of flight and deposited energy of neutral particles

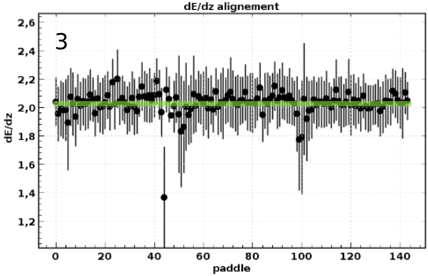


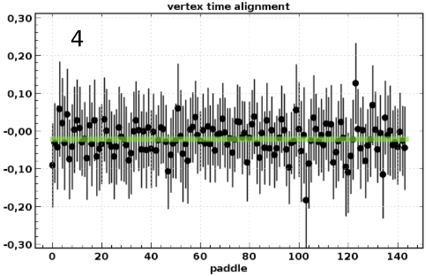


CND performances for charged particles





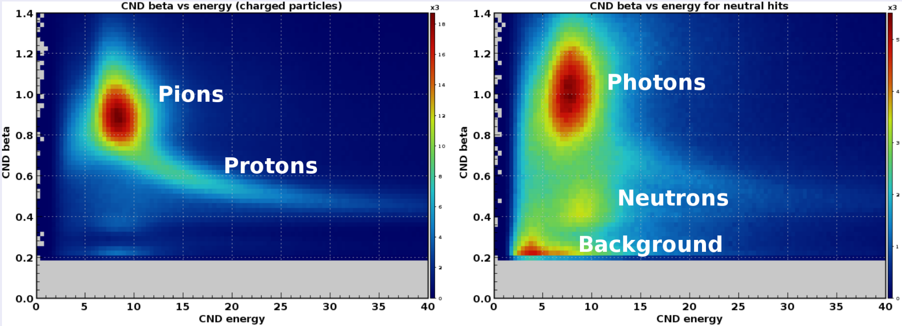




Plots 1,3 and 4 use MIP particles, selected as negative charge particles (π^-).

What about neutrons ?

Deposited energy



$$ep \rightarrow e\pi^{+}(n)$$

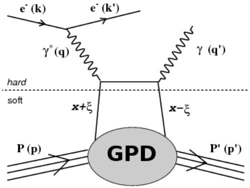
- Look for events with e and π^{+} in the forward detector
- Neutron identified with missing mass + cut on $\beta_{neutron}$ and W

$\rightarrow$ $Neutron_{efficiency} = \frac{Number\ of\ neutron\ with\ cluster\ in\ CND}{Total\ number\ of\ neutrons\ in\ the\ CD} \approx 8\%$

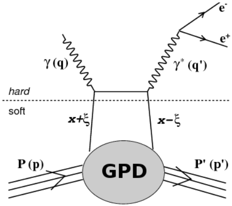
Part II
Timelike Compton Scattering

From DVCS to TCS

DVCS $(\gamma^* p \to \gamma p)$



TCS $(\gamma p \to \gamma^* p)$



Compton Form Factors

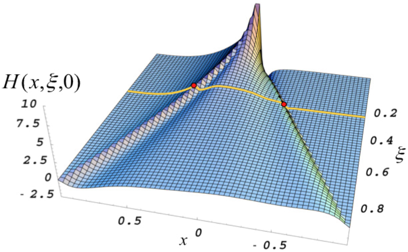
$$\mathcal{H} = \sum_q e_q^2 \left\{ \mathcal{P} \int_{-1}^{1} dx H^q(x,\xi,t) \left[\frac{1}{\xi - x} - \frac{1}{\xi + x} \right] + i\pi \left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t) \right] \right\}$$

Imaginary part

- Measured in DVCS asymmetries

Real part

- Accessible in DVCS cross section
- Accessible in TCS in cross section angular modulation



Data analysis

$$ep \rightarrow (e)\gamma p \rightarrow (e)\gamma^* p \rightarrow (e)e^+e^-p$$

Final state

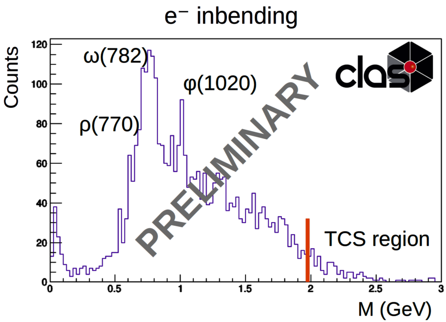
Events with e^+e^-pX selected

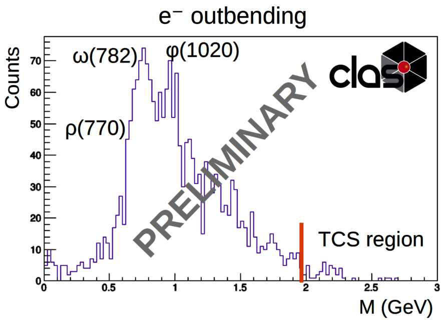
Incoming photon

Cut on $Xp \rightarrow e^+e^-p$ missing mass

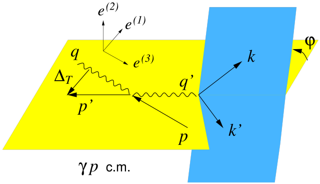
Scattered electron

Look at $ep \rightarrow e^+e^-pX$ system

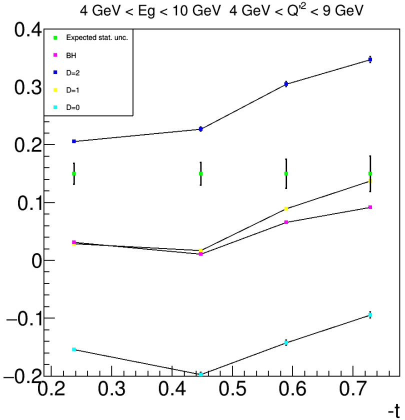




Cross section ratio



$$R(\sqrt{s}, Q'^2, t) = \frac{\int_0^{2\pi} d\phi \, \cos(\phi) \, \frac{dS}{dQ'^2 dt d\phi}}{\int_0^{2\pi} d\phi \, \frac{dS}{dQ'^2 dt d\phi}}$$



CLAS12 data will allow to differenciate CFFs parametrizations

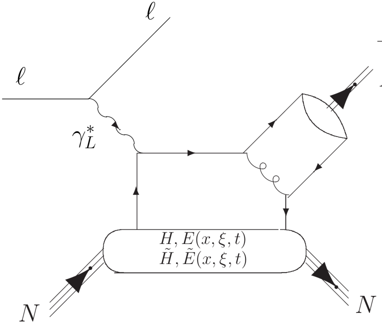
Takeaways

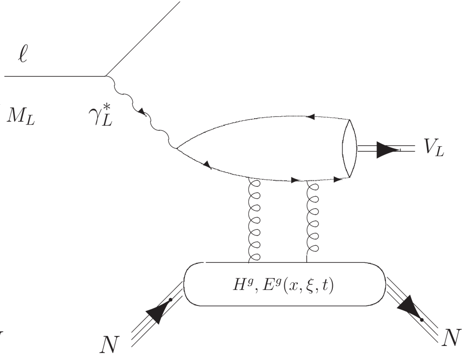
- Generalized Parton Distributions (GPDs) allow a 3D tomography of the nucleon.
- DVCS observables measurements on the neutron will be performed with the Central Neutron detector of CLAS12, toward a GPDs flavor separation.
- The CND has been taking data for one year and shows performances close to the design values.
- Timelike Compton Scattering allows to investigate the real part of CFFs which is difficult to constrain with DVCS.

Thank you !

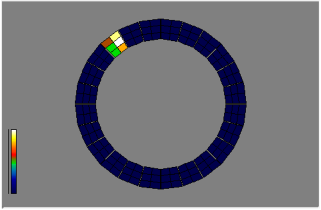
Back up

Deeply Virtual Meson Scattering

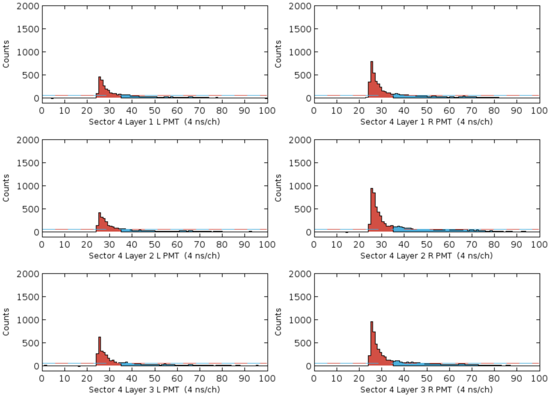




CND data chain



Event in the CND



Flash ADC signals

- Integral of the ADC peak related to the deposited energy
- Value of the TDC related to the time and position of the hits
- 1 hit $\rightarrow$ 2 ADCs (ADC_L, ADC_R) and 2 TDCs (TDC_L, TDC_R)

Time and position calibration

From TDC to time:

$$t_{L/R} = TDC_{L/R} \cdot TDC\_to\_time \tag{1}$$

For a hit in a **L**eft component:

$$t_L = t_{tof} + \frac{z}{v_{effL}} + t_{off} + t_{offL} + Stt + TDC_{jitter} \tag{2}$$

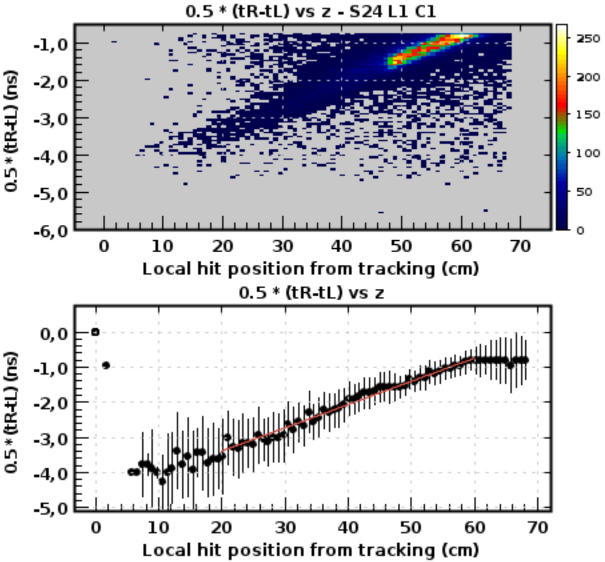
$$t_R = t_{tof} - \frac{z}{v_{effL}} + \frac{L}{v_{effL}} + \frac{L}{v_{effR}} + u_{tloss} + t_{off} + t_{offR} + Stt + TDC_{jitter} \tag{3}$$

What we want , Given by other CLAS12 sub-system , To calibrate

Example: Light effective velocity calibration

$$z = (t_L - t_R) \cdot \frac{v_{effL}}{2} + cst$$

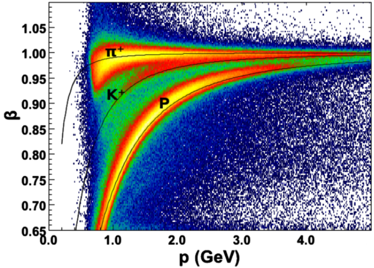
Light effective velocity calibration



- Plot $(\frac{T_L - T_R}{2})$ vs z
- z is extrapolated from track measured by CVT
- Gradient of the slice fit gives v_{eff}

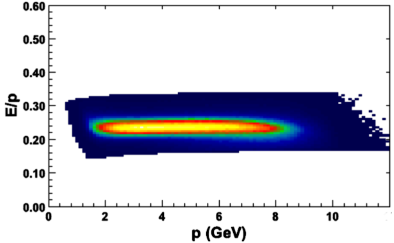
e^+e^-pX final state selection

Protons



- Matching β calculated from TOF and momentum from tracking

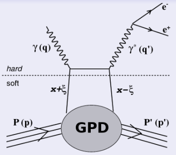
Leptons



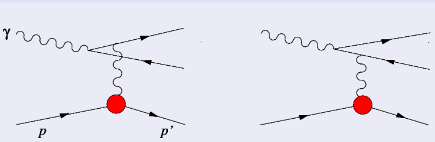
- Number of Cherenkov photons > 2
- Minimum energy deposit in the Pre-Shower Calorimeter (PCAL)
- Cuts on sampling fractions (total and PCAL)
- Fiducial cuts on position in the PCAL

TCS and Bethe-Heitler

$\gamma p \to e^+ e^- p$

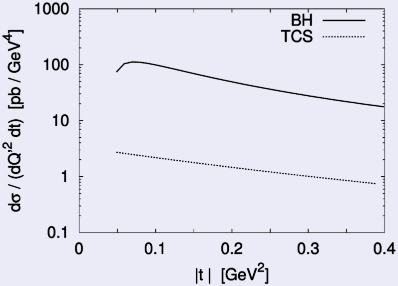


Timelike Compton Scattering



Bethe-Heitler

TCS cross section



$$\frac{d^4\sigma}{dQ'^2 dt d\Omega} = \sigma_{TCS} + \sigma_{BH} + \sigma_{INT}$$

TCS cross section not accessible directly

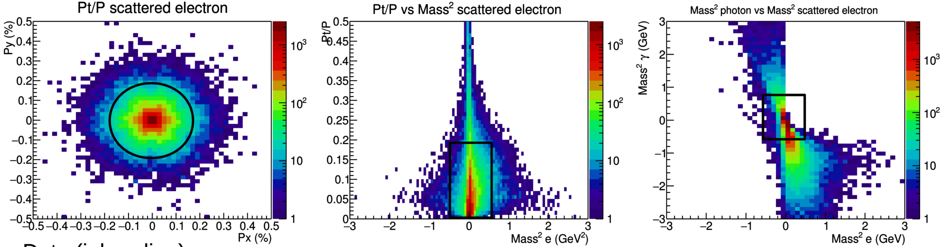
Use interference term to access GPDs

Berger, Diehl and Pire (2002)

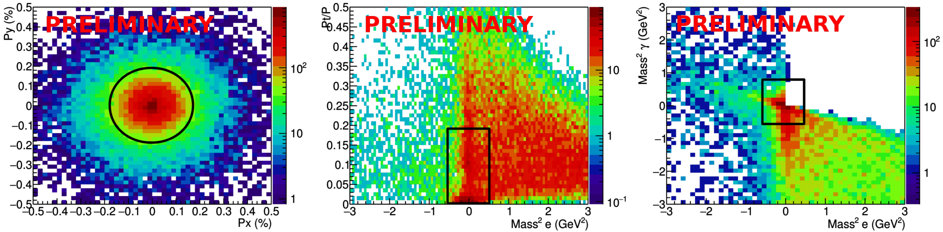
Exclusivity cuts

- Scattered electron: $p^{\mu}_{scattered\ e^-} = p^{\mu}_{beam} + p^{\mu}_{target} - p^{\mu}_{proton} - p^{\mu}_{e^+} - p^{\mu}_{e^-}$
- Mass of the real photon: $M^2_{\gamma} = (p^{\mu}_{target} - p^{\mu}_{proton} - p^{\mu}_{e^+} - p^{\mu}_{e^-})^2$

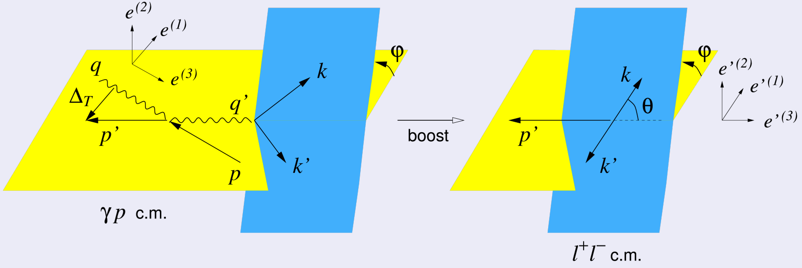
Simulation (e^+e^-p events weighted with BH+TCS cross section)



Data (inbending)



$\gamma p \to e^+ e^- p$ kinematics



$$Q'^2 = (k + k')^2 \qquad t = (p' - p)^2$$

$$L = \frac{(Q'^2 - t)^2 - b^2}{4} \qquad L_0 = \frac{Q'^4 sin^2\theta}{4} \qquad b = 2(k - k')(p - p')$$

$$\tau = \frac{Q'^2}{2p\cdot q} \qquad s = (p + q)^2 \qquad t_0 = -\frac{4\xi^2 M^2}{(1 - \xi^2)}$$

$\gamma p \to e^+e^-p$ Cross section and CFFs

Interference cross section

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{m_p}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\left[\cos(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)} Re\ \tilde{M}^{--} + ...\right]$$

$$\to \tilde{M}^{--} = \frac{2\sqrt{t_0 - t}}{M}\frac{1-\xi}{1+\xi}\left[F_1\mathcal{H} - \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right]$$

BH cross section

$$\frac{d^4\sigma_{BH}}{dQ'^2 dt d\Omega} \approx -\frac{\alpha_{em}^3}{2\pi s^2}\frac{1}{-t}\frac{1+\cos^2(\theta)}{\sin^2(\theta)}\left[(F_1^2 - \frac{t}{4M^2}F_2^2)\frac{2}{\tau^2}\frac{\Delta_T^2}{-t} + (F_1+F_2)^2\right]$$

Weighted cross section ratio

$$R(\sqrt{s}, Q'^2, t) = \frac{\int_0^{2\pi} d\phi\ \cos(\phi)\ \frac{dS}{dQ'^2 dt d\phi}}{\int_0^{2\pi} d\phi \frac{dS}{dQ'^2 dt d\phi}} \qquad \frac{dS}{dQ'^2 dt d\phi} = \int_{\pi/4}^{3\pi/4} d\theta \frac{L}{L_0}\frac{d\sigma}{dQ'^2 dt d\phi d\theta}$$