GPDs in MC and DVCS

Carlos Muñoz Camacho

Institut de Physique Nucléaire, CNRS/IN2P3 (France)

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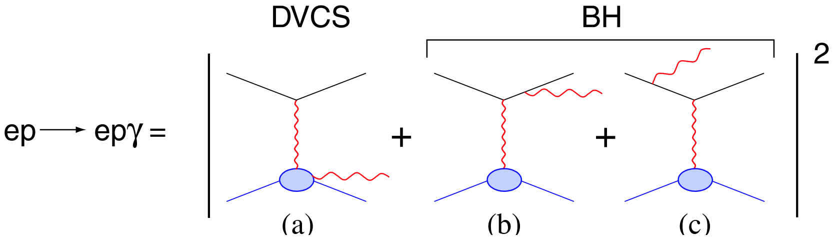
Studies of 3D Structure of Nucleon, INT-14-55W

Outline

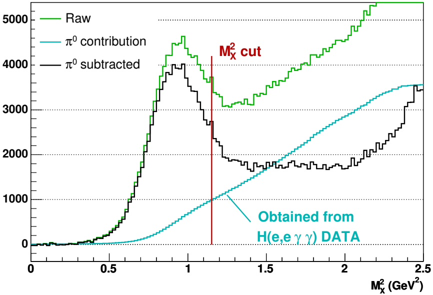
- Exclusive channel: MC much easier...
- Background carefully substracted (model-independently)
- Detector acceptance: radiative corrections + resolution effects

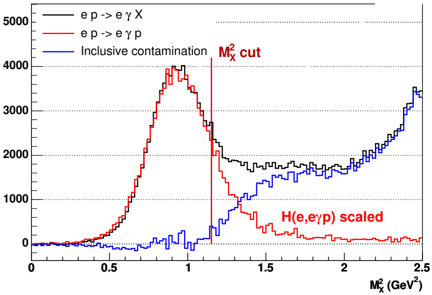
DVCS process

$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to } \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$



Missing mass squared $e\ p \to e\ \gamma\ X$

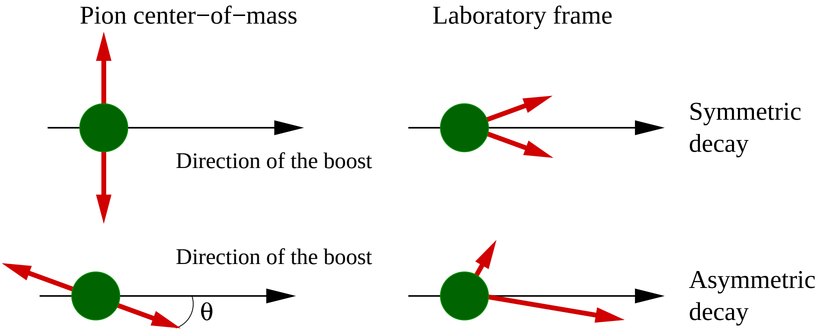




Competing channels:

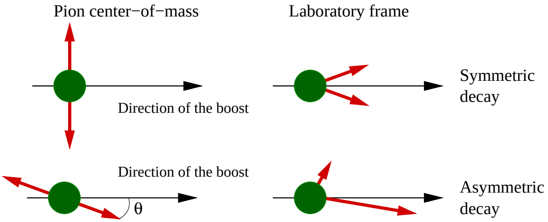
- π^0 electroproduction: $e\ p \to e\ p\ \pi^0 \to e\ p\ \gamma\ \gamma$
- Associated DVCS: $e\ p \to e\ N\ \pi\ \gamma$
  - Non-resonant: $e\ p \to e\ N\ \pi\ \gamma$ $\quad M_X^2 > (M + m_{\pi^0})^2$
  - Resonant: $e\ p \to e\ (\Delta$ or $N^*)\gamma$ $\quad m_\Delta^2 = 1.52\,\text{GeV}^2$

π^0 substraction ($\pi^0 \to \gamma\gamma$)



- Symmetric decay: minimum angle in lab of 4.4° for $E_{\pi^0}^{\text{max}} = 3.5\,\text{GeV}$
  $\Rightarrow$ **Clusters separation**
- Asymmetric decay: sometimes only 1-cluster
  $\Rightarrow$ **Mistaken for DVCS event**

π^0 substraction ($\pi^0 \to \gamma\gamma$)



Substraction procedure:

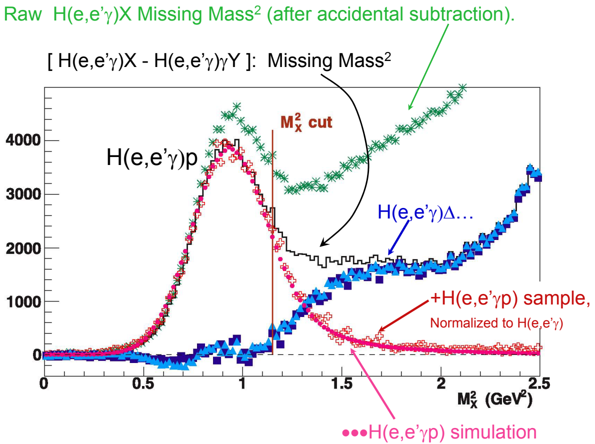
1. Compute kinematics of each *detected* π^0 (2 clusters in calorimeter).
2. Randomize the decay : sample $\cos\theta$ randomly between [-1,1] a big number of times (~ 5000).
3. Compute the ratio of 2-cluster/1-cluster events generated by this π^0 ($\sim$30% in average).

Repeating this procedure for *each* detected π^0 provides an automatic normalization of the contamination as a function of Q^2, t, φ, ...

Missing mass

Missing mass squared $ep \to e'\gamma X$

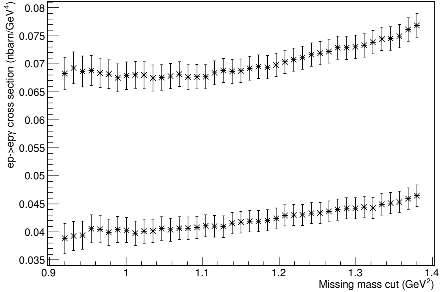
$$M_X^2 = (e + p - e' - \gamma)^2 \qquad M_X^2 \text{ cut} = (M + m_\pi)^2$$

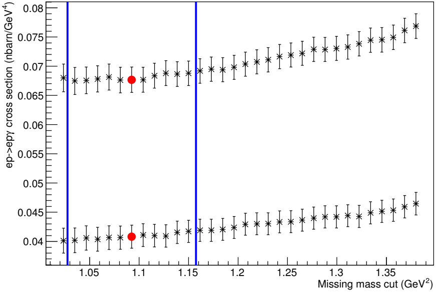


Exclusivity ensured by missing mass technique

Associated systematic error

Varying the M_X^2 cut below the π-production threshold gives an estimate of syst. uncertainty





Systematic error due to the missing mass cut $\lesssim 2\%$

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Calculations for DVCS

- M. Vanderhaeghen, et al., Phys Rev C62, 025501 (2000)

  Used for data analysis so far

- I. Akushevich and A. Ilyich, Phys Rev D85, 053008 (2012)

  Work in progress, only available for BH so far

Radiative corrections (RC)

Not small: $\sim \alpha \log\left(Q^2/m_e^2\right) \sim 10 - 20\%$

- External RC:

$$I_{\text{ext}}(E_0, \Delta E, t) = \frac{bt}{\Gamma(1+bt)}\left(\frac{\Delta E}{E_0}\right)^{bt}\left[\frac{1}{\Delta E}\left(1 - \frac{\Delta E}{E_0} + \frac{3}{4}\left(\frac{\Delta E}{E_0}\right)^2\right)\right]$$

- Internal real RC:

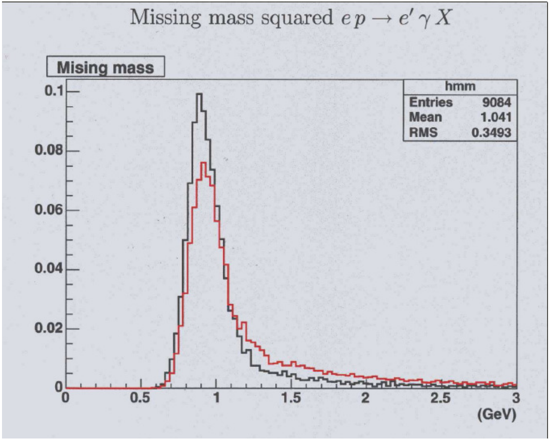
$$I_{\text{int}}(E_0, E, \nu) = \frac{\nu}{\Delta E}\left(\frac{\Delta E}{E_0}\right)^{\nu}, \qquad \nu = \frac{\alpha}{\pi}\left[\ln\left(\frac{Q^2}{m_e^2}\right) - 1\right]$$

- Internal virtual RC:

Applied as a global factor depending on the kinematics: $\mathcal{O}(10\%)$

	E GeV	E' GeV	θ_e deg	Q^2 GeV^2	δ_{Vertex}	δ_{Vacuum}	$\delta_{\text{Real},0}$	δ_S	$\delta_{\text{Real},1}(\Delta E)$
DVCS-1	5.75	3.529	15.6	1.5	-0.228	0.022	0.277	0.068	-0.295
DVCS-2	5.75	2.937	19.3	1.9	-0.236	0.022	0.286	0.069	-0.294
DVCS-3	5.75	2.344	23.8	2.3	-0.242	0.022	0.293	0.070	-0.290

Effect in missing mass distribution



- MC takes into account the radiative lineshape
- Significant effect via the M_X^2 cut

DVCS cross section

$$\frac{d^5\sigma}{d^5\Phi} = \underbrace{\frac{d^5\sigma(|BH|^2)}{d^5\Phi}}_{\text{Known from FF}} + \underbrace{\Gamma\,\eta\,\mathcal{C}^{\text{DVCS}}(\mathcal{F},\mathcal{F}^*)}_{|\text{DVCS}|^2\text{ (twist-2)}} +$$

$$\underbrace{(\Gamma_0^{\Re} - \cos(\phi_{\gamma\gamma})\Gamma_1^{\Re})\Re\text{e}\left[\mathcal{C}^I(\mathcal{F})\right] + \Gamma_{0,\Delta}^{\Re}\Re\text{e}\left[\mathcal{C}^I + \Delta\mathcal{C}^I\right](\mathcal{F}) + \cos(2\phi_{\gamma\gamma})\Gamma_2^{\Re}\Re\text{e}\left[\mathcal{C}^I(\mathcal{F}^{\text{eff}})\right]}_{\text{Interference BH-DVCS}}$$

BMK-2002:

Belitsky, Müller, Kirchner, Nucl. Phys. **B629**, 323 (2002)

DVCS cross section: data analysis

Challenge:

Very rapid variation with kinematics (mostly due to BH propagators)

Experimental issues:

- Integration of cross section within experimental bins
- Bin migration

Variables: $\mathbf{x}_v = \{k, x_B, Q^2, t, \varphi_e, \varphi, v_z\}_v$ $\quad \mathbf{x}_e = \{k, x_B, Q^2, t, \varphi_e, \varphi, v_z\}_e$
Exp. bins: $\mathbf{j}_v = \{j_{x_B}, j_{Q^2}, j_t, j_\varphi\}_v$ $\quad \mathbf{i}_e = \{i_{x_B}, i_{Q^2}, i_t, i_\varphi\}_e$

$$K(\mathbf{x}_e|\mathbf{x}_v)$$

$$\frac{d\sigma}{d\Omega}(\mathbf{x}_v) = \Gamma^{BH}(\mathbf{x}_v) + \sum_{\Lambda=1}^{3} \Gamma^{\Lambda}(\mathbf{x}_v) X^{\Lambda}_{\mathbf{j}_v} \equiv \sum_{\Lambda=0}^{3} \Gamma^{\Lambda}(\mathbf{x}_v) X^{\Lambda}_{\mathbf{j}_v}$$

Experimental number of counts

$$N(\mathbf{j}_v) = \mathcal{L} \int_{\mathbf{x}_v \in \text{Bin}(\mathbf{j}_v)} \sum_{\Lambda=0}^{3} \Gamma^{\Lambda}(\mathbf{x}_v) X^{\Lambda}_{\mathbf{j}_v} d\mathbf{x}_v =$$

$$= \mathcal{L} \sum_{\Lambda=0}^{3} X^{\Lambda}_{\mathbf{j}_v} \int_{\mathbf{x}_v \in \text{Bin}(\mathbf{j}_v)} \Gamma^{\Lambda}(\mathbf{x}_v) d\mathbf{x}_v$$

$$N(\mathbf{i}_e) = \int_{\mathbf{x}_e \in \text{Bin}(\mathbf{i}_e)} d\mathbf{x}_e \sum_{\mathbf{j}_v} N(\mathbf{i}_v) K(\mathbf{x}_e | \mathbf{x}_v) =$$

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We define a bin mapping function:

$$K^{\Lambda}_{\mathbf{i}_e, \mathbf{j}_v} = \int_{\mathbf{x}_e \in \text{Bin}(\mathbf{i}_e)} \int_{\mathbf{x}_v \in \text{Bin}(\mathbf{j}_v)} d\mathbf{x}_e \, d\mathbf{x}_v \; K(\mathbf{x}_e | \mathbf{x}_v) \Gamma^{\Lambda}(\mathbf{x}_v)$$

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$$\begin{aligned} N(\mathbf{i}_e) &= \int_{\mathbf{x}_e \in \mathsf{Bin}(\mathbf{i}_e)} d\mathbf{x}_e \sum_{\mathbf{j}_v} N(\mathbf{i}_v) K(\mathbf{x}_e|\mathbf{x}_v) = \\ &= \mathcal{L} \sum_{\mathbf{j}_v} \sum_{\Lambda=0}^{3} X^{\Lambda}_{\mathbf{j}_v} \int_{\mathbf{x}_e \in \mathsf{Bin}(\mathbf{i}_e)} d\mathbf{x}_e \int_{\mathbf{x}_v \in \mathsf{Bin}(\mathbf{j}_v)} d\mathbf{x}_v \Gamma^{\Lambda}(\mathbf{x}_v) K(\mathbf{x}_e|\mathbf{x}_v) \end{aligned}$$

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Fit of experimental counts: linear system

$$N^{\mathsf{MC}}(\mathbf{i}_e) = \mathcal{L} \sum_{\mathbf{j}_v, \Lambda} K^{\Lambda}_{\mathbf{i}_e, \mathbf{j}_v} X^{\Lambda}_{\mathbf{j}_v} \,.$$

$$\chi^2 = \sum_{\mathbf{i}_e} \frac{[N^{\mathsf{Exp}}(\mathbf{i}_e) - N^{\mathsf{MC}}(\mathbf{i}_e)]^2}{[\sigma^{\mathsf{Exp}}(\mathbf{i}_e)]^2} \,,$$

$$0 = -\frac{1}{2} \frac{\partial \chi^2}{\partial X^{\Lambda}_{\mathbf{j}_v}} \bigg|_{\overline{\mathbf{X}}_{\mathbf{j}_v}} = \sum_{\mathbf{i}_e} \mathcal{L} K^{\Lambda}_{\mathbf{i}_e, \mathbf{j}_v} \frac{\mathcal{L} \sum_{\mathbf{j}'_v, \Lambda'} K^{\Lambda'}_{\mathbf{i}_e, \mathbf{j}'_v} \overline{X}^{\Lambda'}_{\mathbf{j}'_v} - N^{\mathsf{Exp}}(\mathbf{i}_e)}{[\sigma^{\mathsf{Exp}}(\mathbf{i}_e)]^2}$$

$$0 = \sum_{\mathbf{j}'_v, \Lambda'} \alpha^{\Lambda, \Lambda'}_{\mathbf{j}_v, \mathbf{j}'_v} \overline{X}^{\Lambda'}_{\mathbf{j}'_v} - \beta^{\Lambda}_{\mathbf{j}_v} \qquad \forall\ \mathbf{j}_v,\ \Lambda \,.$$

The linear system is defined by:

$$\alpha^{\Lambda, \Lambda'}_{\mathbf{j}_v, \mathbf{j}'_v} = \sum_{\mathbf{i}_e} \mathcal{L} \frac{K^{\Lambda}_{\mathbf{i}_e, \mathbf{j}_v} K^{\Lambda'}_{\mathbf{i}_e, \mathbf{j}'_v}}{[\sigma^{\mathsf{Exp}}(\mathbf{i}_e)]^2} \qquad \beta^{\Lambda}_{\mathbf{j}_v} = \sum_{\mathbf{i}_e} \frac{N^{\mathsf{Exp}}(\mathbf{i}_e)\, K^{\Lambda}_{\mathbf{i}_e, \mathbf{j}_v}}{[\sigma^{\mathsf{Exp}}(\mathbf{i}_e)]^2}$$

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Cross-section results

The fit parameters are:

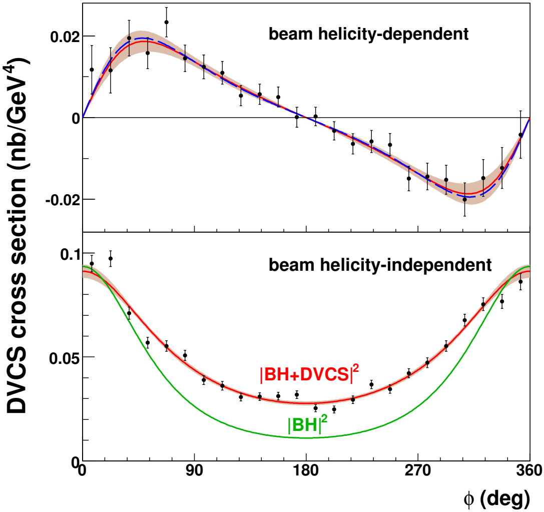
$$\overline{X}_{\mathbf{j}_v}^{\Lambda} = \sum_{\mathbf{j}'_v,\,\Lambda'} [\alpha^{-1}]_{\mathbf{j}_v,\mathbf{j}'_v}^{\Lambda,\,\Lambda'} \, \beta_{\mathbf{j}'_v}^{\Lambda'} \,.$$

The covariance matrix of the fitted parameters is:

$$V_{\mathbf{j}_v,\mathbf{j}'_v}^{\Lambda,\,\Lambda'} = [\alpha^{-1}]_{\mathbf{j}_v,\mathbf{j}'_v}^{\Lambda,\,\Lambda'} \,.$$

$$\frac{d^5\sigma^{\mathrm{Exp}}(i)}{d^5\Phi} = \frac{d^5\sigma^{\mathrm{Fit}}(i)}{d^5\Phi} N_i^{\mathrm{Exp}}/N_i^{\mathrm{Fit}},$$

Experimental results



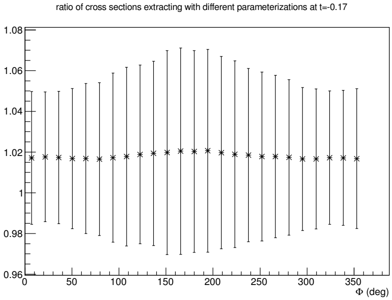
Analysis with BMK-2002:

Belitsky, Müller, Kirchner, Nucl. Phys. **B629**, 323 (2002)

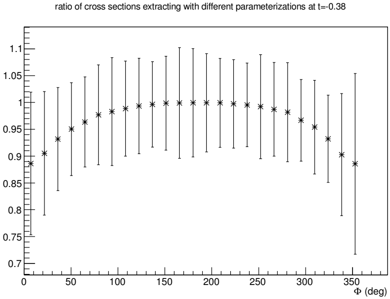
Results with different parametrizations

- Reanalysis with BMK-2010 and comparison

Low $-t$



High $-t$



- Stable within statistical uncertainties
- Especially at low $-t$ where the acceptance is best known

M. Defurne

Conclusions

- MC for exclusive reactions is required for detector acceptance:
    - Bin migration
    - Resolution effects
    - Rapid variation of the cross section within experimental bins
- Background is usually under control is exclusivity is good enough
- Radiative corrections is necessarily part of the MC simulation
- Fast GPD and RC event generators can improve the systematic uncertainties of DVCS cross section results