

Physics with positron beams

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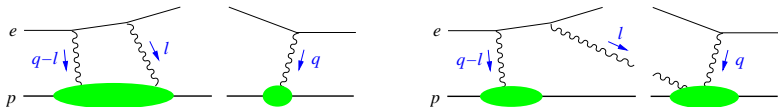
1. Two photon exchange in elastic scattering
2. Deeply virtual Compton scattering
3. Conclusions

Elastic nucleon form factors

- ▶ basic quantities describing nucleon structure
depend on single variable Q^2
- ▶ intuitive interpretation as Fourier transformed spatial densities
- ▶ elastic scattering archetype of exclusive reaction
↪ validate dynamical approaches
- ▶ at large Q^2 (several GeV^2) few if any other observables
measuring GPDs hardly possible for large invariant nucleon
momentum transfer

high precision desirable

- ▶ be able to see subtle trends
- ▶ may want to transform $G_{E,M}^{p,n} \rightarrow F_{1,2}^{u,d}$
↪ error propagation

Two photon exchange in elastic ep and en scattering

+ graph with photon lines crossed

- ▶ at order α_{em} interference of one- and two-photon exchange
- ▶ loop integral $\int d^4l \rightarrow$ all photon virtualities $(q-l)^2, l^2$
typical scale set by Q^2
 \rightsquigarrow doubly virtual Compton amplitude $\mathcal{A}(\gamma^*p \rightarrow \gamma^*p)$
- ▶ contributes with opposite sign to e^+p and e^-p
- ▶ IR divergence for $l \rightarrow 0$ cancelled by soft bremsstrahlung
in following always understood that this is included

Two photon exchange affects

- ▶ unpolarized cross section \rightsquigarrow Rosenbluth separation
- ▶ double spin asymmetries:
 - P_L, P_S : polarization of recoil proton for positive-helicity e beam
longitudinal and transverse in scattering plane (sideways)
 - A_L, A_S : corresponding asymmetries for polarized beam and target
time reversal symmetry $\rightsquigarrow A_L = -P_L$ and $A_S = P_S$
 - these go with $\text{Re } \mathcal{A}(\gamma^* p \rightarrow \gamma^* p)$
- ▶ single spin asymmetries:
 - $P_N = A_N$: proton polarization normal to scattering plane
 - goes with $\text{Im } \mathcal{A}(\gamma^* p \rightarrow \gamma^* p)$

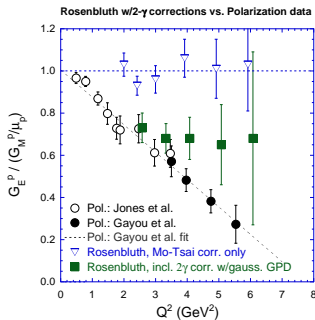
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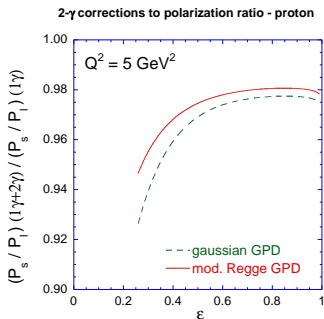


- ▶ candidate for explaining discrepancy of G_E/G_M extracted by Rosenbluth separation and recoil method (P_S/P_L)
- ▶ theory: effects on Rosenbluth sep. can be large and increase with Q^2

← A.Afanasev et al., hep-ph/0502013

Two photon exchange affects

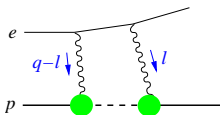
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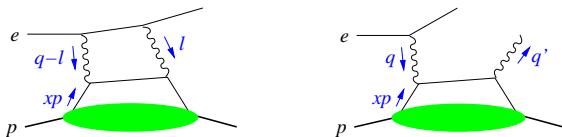
- ▶ effects on P_S/P_L expected small but not negligible if aim at precision
- ▶ find effects of similar size for **neutron** target

← A.Afanasev et al., hep-ph/0502013

Dynamics



- ▶ no calculation of two-photon amplitude from first principles
is more complicated than form factors themselves
- ▶ for low Q^2 : hadronic intermediate states
 nucleon, Δ , ... P.G.Blunden et al., S.Kondratyuk et al. '03-'07
- ▶ for large $Q^2 \rightsquigarrow$ large $\hat{s} = (p + q - l)^2$
 need more and more resonances
 \rightsquigarrow partonic description more efficient A.Afanasev et al. '04, '05



- ▶ factorized into quark-level process $eq \rightarrow eq$ and $1/x$ moment of generalized parton distributions
- ▶ large $Q^2 \rightsquigarrow$ struck quark carries most of nucleon momentum $x \rightarrow 1$, Feynman mechanism
- ▶ analogous description for wide-angle Compton scattering
A.Radyushkin '98; M.D., Th.Feldmann, R.Jakob, P.Kroll '98, '04; ...
 - ▶ no factorization proof as for DVCS
 - ▶ promising phenomenology for $\gamma p \rightarrow \gamma p$ data
- ▶ possible strategy (my assessment):
 - ▶ use factorized approach to estimate two-photon exchange
 - ▶ use experimental information on two-photon exchange to further test/constrain approach

A closer look at observables

- ▶ parameterize $\mathcal{A}(ep \rightarrow ep)$ for conserved lepton helicity by three generalized form factors $\tilde{G}_M, \tilde{G}_E, \tilde{F}_3$

P.Guichon, M.Vanderhaeghen'03

$$\tilde{G}_M = G_M(Q^2) + \delta\tilde{G}_M(Q^2, \epsilon)$$

$$\tilde{G}_E = G_E(Q^2) + \delta\tilde{G}_E(Q^2, \epsilon)$$

$$\tilde{F}_3 = \delta\tilde{F}_3(Q^2, \epsilon)$$

where $\delta\tilde{G}_M, \delta\tilde{G}_E, \delta\tilde{F}_3 \propto \alpha_{\text{em}} \mathcal{A}(\gamma^*p \rightarrow \gamma^*p)$

- are complex-valued
- change sign when replace e^- with e^+

► find

C. Carlson, M. Vanderhaeghen '07

$$\sigma_R = G_M^2 + \frac{\epsilon}{\tau} G_E^2 + 2G_M \operatorname{Re}[\delta\tilde{G}_M + \dots \delta\tilde{F}_3] + G_E \operatorname{Re}[\delta\tilde{G}_E + \dots \delta\tilde{F}_3]$$

$$P_S = -\frac{1}{\sigma_R} \dots \left\{ G_E G_M + G_M \operatorname{Re}[\delta\tilde{G}_E + \dots \delta\tilde{F}_3] + G_E \operatorname{Re} \delta\tilde{G}_M \right\}$$

$$P_L = \frac{1}{\sigma_R} \dots \left\{ G_M^2 + 2G_M \operatorname{Re}[\delta\tilde{G}_M + \dots \delta\tilde{F}_3] \right\}$$

$$\text{with } \tau = \frac{Q^2}{4m^2} \quad \text{and} \quad \sigma_R = \frac{\epsilon(1+\tau)}{\tau} \frac{d\sigma}{dQ^2} / \frac{d\sigma_{\text{Mott}}}{dQ^2}$$

► two-photon exchange modifies ϵ dependence at given Q^2 ► two-photon terms in P_S , P_L differ from those in σ_R

↪ cannot obtain from measuring charge asymmetry $A_C =$

$$\frac{\sigma_R(e^+) - \sigma_R(e^-)}{\sigma_R(e^+) + \sigma_R(e^-)}$$

► with $\sigma_R(e^+) + \sigma_R(e^-)$ can do usual Rosenbluth separation► with polarized e^+ and e^- have 6 observables for 5 unknowns

$$(G_M, G_E, \delta\tilde{G}_M, \delta\tilde{G}_E, \delta\tilde{F}_3)$$

⇒ full model indep't extraction

Planned or proposed measurements in near future

- ▶ beam charge asymmetry for $ep \rightarrow ep$

experiment	$Q^2 [GeV^2]$
VEPP-3 (Novosibirsk)	up to 1.76
JLAB E-04-116 (CLAS)	0.5 to 2.1
OLYMPUS (DESY)	0.6 to 2.2

- ▶ ϵ dependence of P_L, P_S and measurement of P_N
JLAB E-04-019 (Hall C): four points in ϵ at $Q^2 = 3.2 \text{ GeV}^2$

Planned form factor measurements for 12 GeV upgrade

experiment	measurement	$Q^2 [GeV^2]$
E12-07-108 (Hall A)	G_M^p from σ_R	7 to 17.5
E12-07-109 (Hall A)	G_E^p/G_M^p from P_S/P_L	13, 15
PR12-09-001 (Hall C)	G_E^p/G_M^p from P_S/P_L	6, 10.5, 13

neutron form factors: G_M^n (CLAS)

G_E^n (Hall C, neutron recoil polarization)

Conclusions (first part)

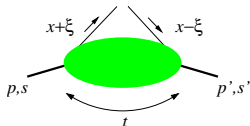
- ▶ elastic nucleon form factors = backbone observables for nucleon structure
- ▶ JLAB12 upgrade offers possibilities to significantly extend precision data to high Q^2
- ▶ two-photon exchange
 - ▶ affect precision of obtained results (σ_R or polarization method)
 - ▶ interest in itself: factorized partonic description
complementary to wide-angle Compton scattering program
- ▶ possibilities with unpolarized e^+ :
 - ▶ charge asymmetry: exhibit two-photon effects
and validate dynamical calculations
 - ▶ $\sigma(e^+) + \sigma(e^-)$: Rosenbluth separation
 with polarized e^+ and recoil or target polarization:
 - ▶ full model-independent extraction of form factors and two-photon exchange amplitudes approx. $m_e = 0$

Generalized parton distributions: some brief reminders

- ▶ defined from matrix elements $\langle p' | \mathcal{O} | p \rangle$

\mathcal{O} = operator with quark or gluon fields along light cone

same as for usual parton densities



- ▶ depend on two mom. fractions x, ξ and $t = (p' - p)^2$ and on factorization scale
- ▶ spin structure for conserved parton helicity:

	nucleon helicity	
	conserved	flipped
partons unpolarized	H	E
long. polarized	\tilde{H}	\tilde{E}

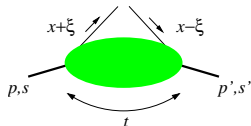
- ▶ lowest Mellin moments in $x \leftrightarrow$ electromagnetic form factors

Generalized parton distributions: some brief reminders

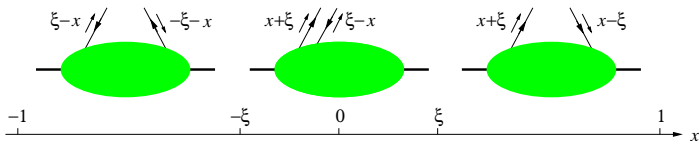
- ▶ defined from matrix elements $\langle p' | \mathcal{O} | p \rangle$

\mathcal{O} = operator with quark or gluon fields along light cone

same as for usual parton densities



- ▶ depend on two mom. fractions x, ξ and $t = (p' - p)^2$ and on factorization scale
- ▶ partonic interpretation depending on x :



Key processes (with factorization theorems)

- ▶ deeply virtual Compton scattering:
 - ▶ NLO and NNLO corrections known and typically small
D. Müller et al. '05–'07
 - ▶ large number of observables accessible to GPD approach
both twist-two and twist-three amplitudes
 - ▶ separate Im and Re of Compton amplitude
↔ most direct connection with GPDs
- ▶ meson electroproduction: → talk P.Kroll
 - ▶ quantitative theoretical analysis more difficult
important radiative and power corrections
 - ▶ information on aspects difficult to study in DVCS:
gluon distributions, quark flavor structure

Different roles of real and imaginary part

amplitudes for DVCS and vector meson production at LO in α_s :

$$\text{Im } \mathcal{H}(\xi, t) = \pi [H(\xi, \xi, t) - H(-\xi, \xi, t)]$$

simple and direct relation, similar to inclusive DIS

two representations for real part:

$$\begin{aligned} \text{Re } \mathcal{H}(\xi, t) &= \text{PV} \int_{-1}^1 dx H(x, \xi, t) \left[\frac{1}{\xi - x} - \frac{1}{\xi + x} \right] \\ &= \text{PV} \int_{-1}^1 dx H(x, x, t) \left[\frac{1}{\xi - x} - \frac{1}{\xi + x} \right] + C(t) \end{aligned}$$

access to x values different from measured $\xi = x_B/(2 - x_B)$

$C(t)$ related with Polyakov-Weiss D -term

for brevity suppress quark flavor labels
analogous eq's for mesons with other quantum numbers

► at leading order in α_s

$\text{Im } \mathcal{H}(\xi, t, Q^2)$ from $H(\xi, \xi, t; Q^2)$

$\text{Re } \mathcal{H}(\xi, t, Q^2)$ from $H(x, x, t; Q^2)$ at all x and $C(t)$

- amplitude determined by $\text{GPD}(x, x)$ and subtraction constant
- Re sensitive to x range around measured ξ

O.V. Teryaev '05, I.V. Anikin and O.V. Teryaev '07
K. Passek-Kumerički et al. '07; M.D. and D.Yu. Ivanov '07

- ▶ at leading order in α_s

$\text{Im } \mathcal{H}(\xi, t, Q^2)$ from $H(\xi, \xi, t; Q^2)$

$\text{Re } \mathcal{H}(\xi, t, Q^2)$ from $H(x, x, t; Q^2)$ at all x and $C(t)$

- amplitude determined by GPD(x, x) and subtraction constant
- Re sensitive to x range around measured ξ

- ▶ Q^2 dependence from evolution:

$$\frac{d}{d \ln Q^2} H(\xi, \xi, t; Q^2) = \text{kernel} \otimes \{H(x, \xi, t; Q^2) \text{ for } |x| \geq \xi\}$$

- sensitive to GPD in region $|x| \geq \xi$

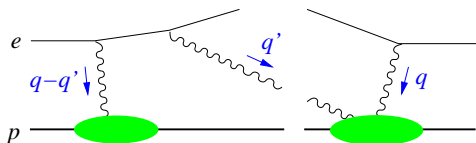
- ▶ beyond leading order in α_s find

- amplitude determined by GPD in region $|x| \geq \xi$
and more complicated subtraction constant

O.V. Teryaev '05, I.V. Anikin and O.V. Teryaev '07
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Making the most of DVCS

- ▶ use interference with Bethe-Heitler process:



- ▶ cross section for $ep \rightarrow e\gamma p$

$$\frac{d\sigma_{\text{VCS}}}{dx_B dQ^2 dt} : \frac{d\sigma_{\text{BH}}}{dx_B dQ^2 dt} \sim \frac{1}{y^2} \frac{1}{Q^2} : \frac{1}{t} \quad y = \frac{Q^2}{x_B s_{ep}}$$

- ▶ interference term visible unless y is very small
- ▶ key variable: azimuth ϕ between lepton and hadron planes
- ▶ following slides:
 - ▶ how to extract the interference, relevance of e^+ beam
 - ▶ possibilities with lepton and nucleon polarization

GPD combinations in interference term made simple

$$\text{target pol.} \quad \text{interference} \propto \quad \tau = \frac{-t}{4m^2}, \quad \tau' = \frac{t_0 - t}{4m^2}$$

$$\begin{aligned} \text{Unpolarized} & \quad \sqrt{\tau'} [F_1 \mathbf{H} + \xi(F_1 + F_2) \tilde{\mathbf{H}} + \tau F_2 \mathbf{E}] \\ \text{Longitudinal} & \quad \sqrt{\tau'} [F_1 \tilde{\mathbf{H}} + \xi(F_1 + F_2) \mathbf{H} + (\tau F_2 - \xi F_1) \xi \tilde{\mathbf{E}}] + \sqrt{\tau'} \xi^2 \mathcal{O}(\mathbf{E}, \xi \tilde{\mathbf{E}}) \\ \text{Normal} & \quad \tau [F_2 \mathbf{H} - F_1 \mathbf{E} + \xi(F_1 + F_2) \xi \tilde{\mathbf{E}}] + \xi^2 \mathcal{O}(\mathbf{H}, \mathbf{E}, \tilde{\mathbf{H}}) \\ \text{Sideways} & \quad \tau [F_2 \tilde{\mathbf{H}} + \xi(F_1 + F_2) \mathbf{E} - (F_1 + \xi F_2) \xi \tilde{\mathbf{E}}] + \xi^2 \mathcal{O}(\mathbf{H}, \mathbf{E}, \tilde{\mathbf{H}}, \xi \tilde{\mathbf{E}}) \end{aligned}$$

count $\xi \tilde{\mathbf{E}}$ since pion exchange gives $\tilde{\mathbf{E}} \propto 1/\xi$

- with long. and transv. target pol. can separate all four GPDs

Structure of differential cross section (unpolarized target)

$$\sigma_{ep \rightarrow e\gamma p} = \sigma_{\text{BH}} + e_{\ell} \sigma_{\text{INT}} + P_{\ell} e_{\ell} \tilde{\sigma}_{\text{INT}} + \sigma_{\text{VCS}} + P_{\ell} \tilde{\sigma}_{\text{VCS}}$$

where σ even in ϕ $\sigma_{\text{INT}} \propto \text{Re } \mathcal{A}_{\gamma^* N \rightarrow \gamma N}$
 $\tilde{\sigma}$ odd in ϕ $\tilde{\sigma}_{\text{INT}} \propto \text{Im } \mathcal{A}_{\gamma^* N \rightarrow \gamma N}$

beam charge	beam pol.	combination
e^{-}	difference	$-\tilde{\sigma}_{\text{INT}} + \tilde{\sigma}_{\text{VCS}}$
difference	none	σ_{INT}
difference	fixed	$P_{\ell} \tilde{\sigma}_{\text{INT}} + \sigma_{\text{INT}}$

so that with

only pol. e^{-}

need Rosenbluth to separate $\tilde{\sigma}_{\text{INT}}$ from $\tilde{\sigma}_{\text{VCS}}$
(different y at same x_B and Q^2)

unpol. e^{-} and e^{+}

get σ_{INT}

pol. e^{-} and pol. e^{+}

get σ_{INT} and separate $\tilde{\sigma}_{\text{INT}}$ from $\tilde{\sigma}_{\text{VCS}}$

Structure of differential cross section (polarized target)

$$\sigma_{ep \rightarrow e\gamma p} = \sigma_{\text{BH}} + e_l \sigma_{\text{INT}} + P_{\ell} e_l \tilde{\sigma}_{\text{INT}} + \sigma_{\text{VCS}} + P_{\ell} \tilde{\sigma}_{\text{VCS}}$$

$$+ S [P_{\ell} \Delta\sigma_{\text{BH}} + e_l \Delta\tilde{\sigma}_{\text{INT}} + P_{\ell} e_l \Delta\sigma_{\text{INT}} + \Delta\tilde{\sigma}_{\text{VCS}} + P_{\ell} \Delta\sigma_{\text{VCS}}]$$

where polarization S can be longitudinal or transverse

beam charge	beam pol.	target pol.	combination
e^-	difference	none	$-\tilde{\sigma}_{\text{INT}} + \tilde{\sigma}_{\text{VCS}}$
difference	none	none	σ_{INT}
difference	fixed	none	$P_{\ell} \tilde{\sigma}_{\text{INT}} + \sigma_{\text{INT}}$
e^-	none	difference	$-\Delta\tilde{\sigma}_{\text{INT}} + \Delta\tilde{\sigma}_{\text{VCS}}$
difference	none	fixed	$S \Delta\tilde{\sigma}_{\text{INT}} + \sigma_{\text{INT}}$
difference	fixed	fixed	$S \Delta\tilde{\sigma}_{\text{INT}} + S P_{\ell} \Delta\sigma_{\text{INT}} + P_{\ell} \tilde{\sigma}_{\text{INT}} + \sigma_{\text{INT}}$

so that with pol. target and

only pol. e^-

unpol. e^- and e^+

pol. e^- and pol. e^+

need Rosenbluth to separate $\Delta\tilde{\sigma}_{\text{INT}}$ from $\Delta\tilde{\sigma}_{\text{VCS}}$

can separate $\Delta\tilde{\sigma}_{\text{INT}}$ from $\Delta\tilde{\sigma}_{\text{VCS}}$

can separate $\Delta\tilde{\sigma}_{\text{INT}}$ from $\Delta\tilde{\sigma}_{\text{VCS}}$ and get $\Delta\sigma_{\text{INT}}$

Conclusions (second part)

- ▶ DVCS is key process to access generalized parton distributions
 - ▶ most direct access to GPDs from **Im** part of amplitude
sensitivity to wider x range from **Re** part
 - ▶ two benefits of e^+ beams:
 - ▶ separate **Im** part of interference from pure DVCS contribution
in principle can do Rosenbluth separation instead
but requires feasibility study (**lever arm, control of errors**)
 - ▶ give **Re** part of interference
- a part of this separation requires e^+ **polarization**