PR12-12-001

Jefferson Lab PAC 39 Proposal
Timelike Compton Scattering and J/ψ photoproduction on the proton in e^+e^- pair production with CLAS12 at 11 GeV

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LOI11-106: e^+e^- pair production with CLAS12 at 11 GeV

Physics objectives:

- Timelike Compton Scattering ($\gamma p \rightarrow \gamma^* p \rightarrow e^+e^-p$)
- J/ψ production on nuclei nucleon and nuclei

PAC recommendation

"The physics addressed in this proposal is very relevant for the JLab 12 GeV program. The PAC encourages the development of a full proposal."

Main goals of proposal

Timelike-spacelike correspondence and the universality of GPDs

- Of fundamental importance for the GPD program

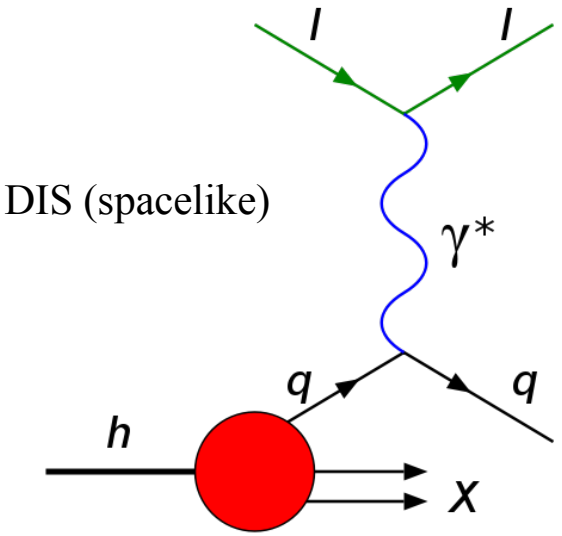
Real (and imaginary) part of Compton amplitude

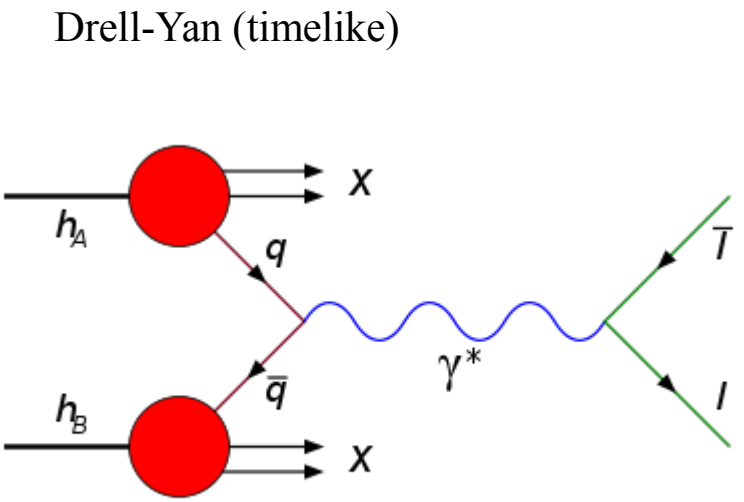
- Straightforward access through azimuthal asymmetry of lepton pair
- Input for global analysis of Compton Form Factors
  - Model independent fits
  - Dispersion relations

First measurement of J/ψ production near threshold

- Establish reaction mechanism
- Access to gluonic structure of the nucleon
- Important benchmark for TCS systematics

Deep Inelastic Scattering and Drell-Yan

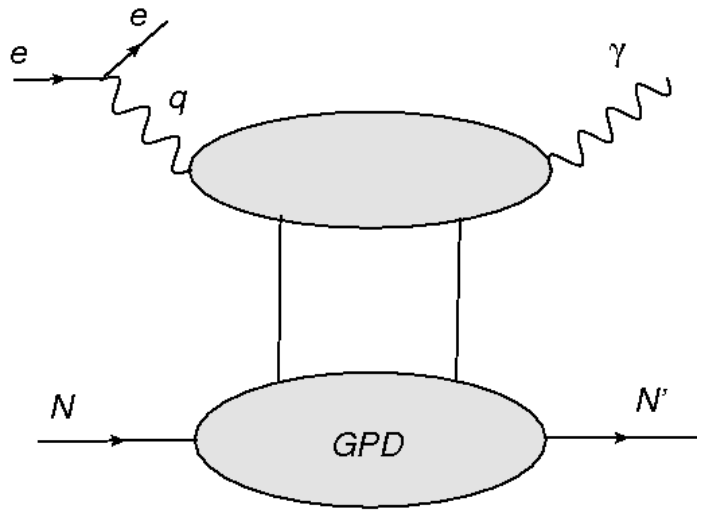




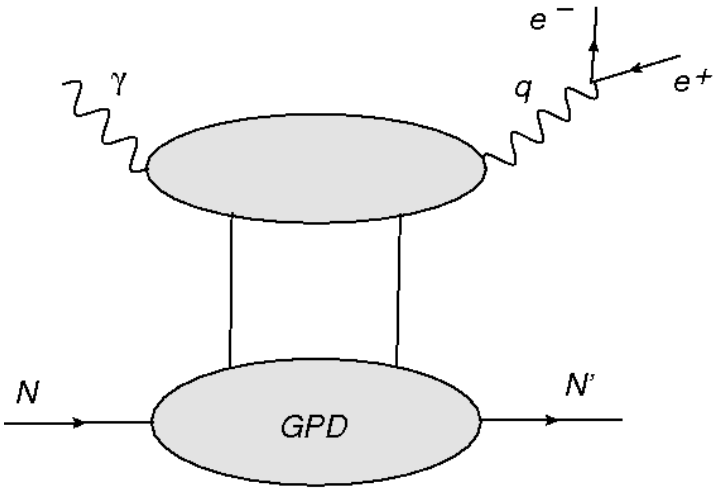
- The spacelike DIS and timelike Drell-Yan processes both factorize into a partonic cross section and a Parton Distribution Function (PDF)
  - Measurements of both demonstrated the universality of PDFs

DVCS and TCS

(spacelike) Deeply Virtual Compton Scattering



Timelike Compton Scattering

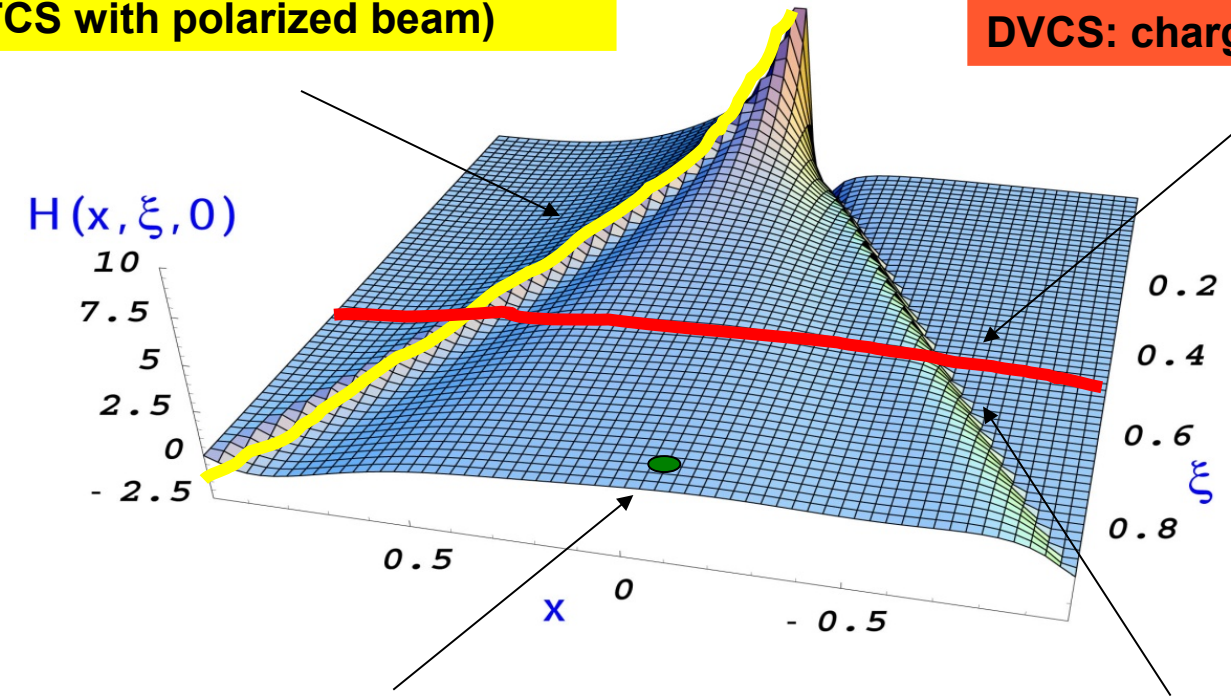


- In DVCS there is a similar factorization at the amplitude level into a partonic amplitude and a Generalized Parton Distribution (GPD)
  - Measurement of both spacelike DVCS and Timelike Compton Scattering (TCS) can test the universality of GPDs

Probing GPDs through Compton scattering

(Im, x=ξ)
DVCS: spin asymmetries
(TCS with polarized beam)

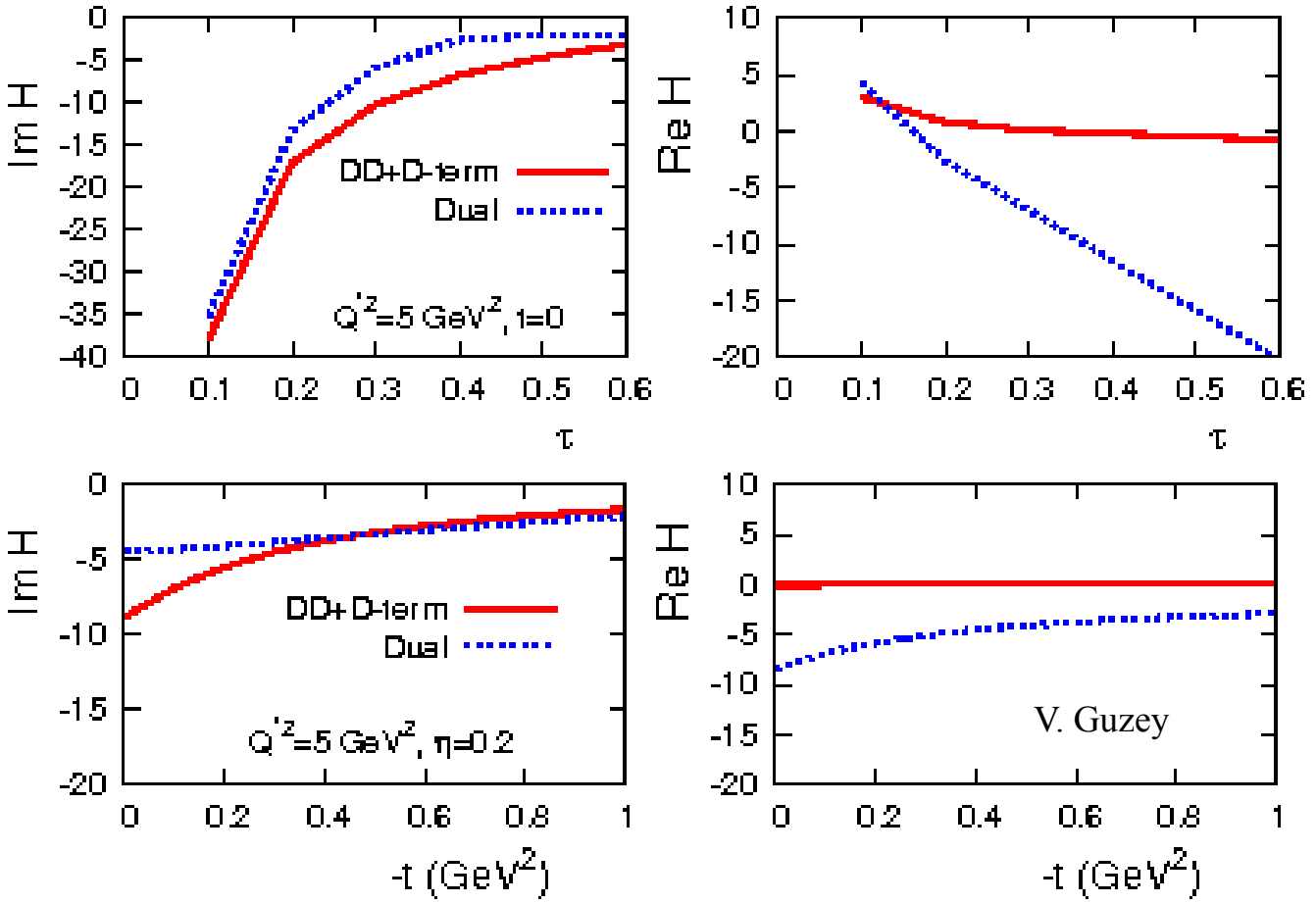
(Re)
TCS: azimuthal asymmetry
DVCS: charge asymmetry



(Im, x ≠ ξ, x < |ξ|)
Double DVCS

($|Im|^2+|Re|^2$)
DVCS: cross section

Real part at large x important for GPD models



$$\tau = \frac{Q'^2}{s - M_p^2}$$

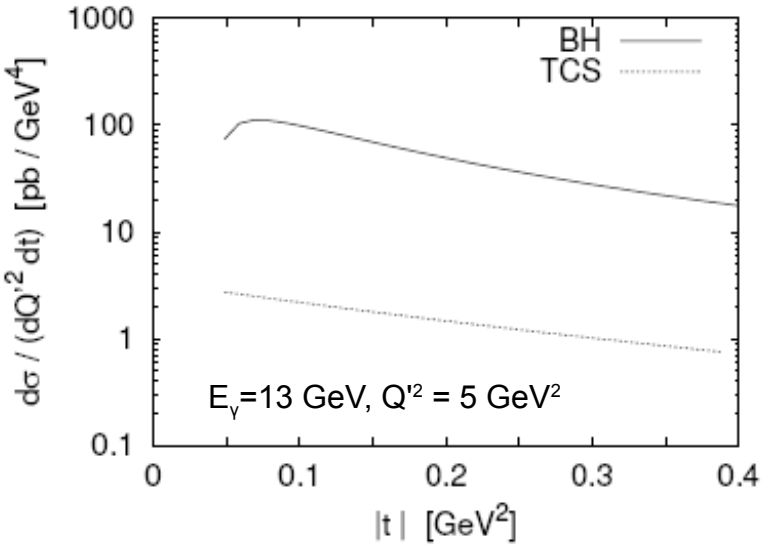
$$\eta = \frac{\tau}{2 - \tau}$$

τ and η are the TCS equivalents of Bjorken *x* and the skewness ξ

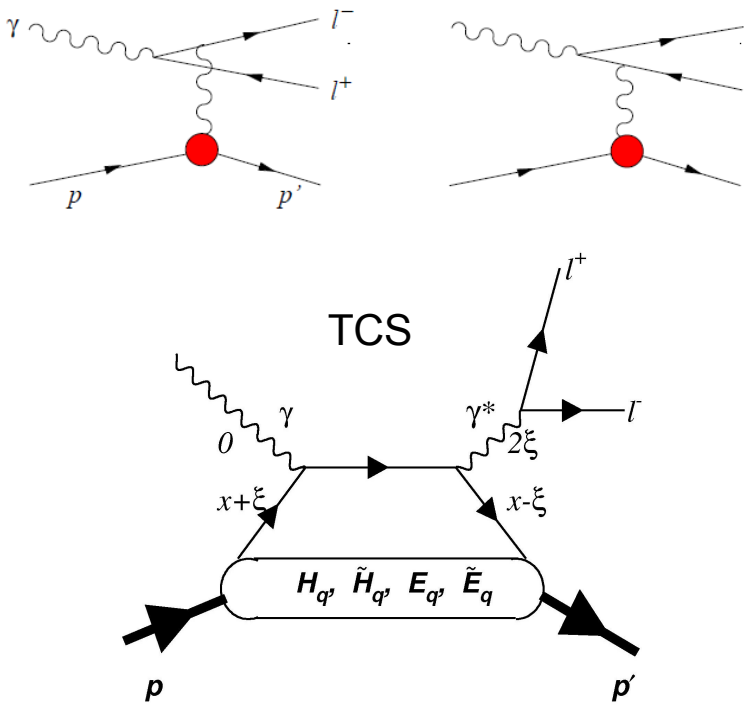
$Q'^2 = M^2_{e+e-}$ is the timelike virtuality of the outgoing photon (→ hard scale)

Photoproduction of lepton pairs

E. Berger *et al.*, Eur. Phys. J. C23, 675 (2002)

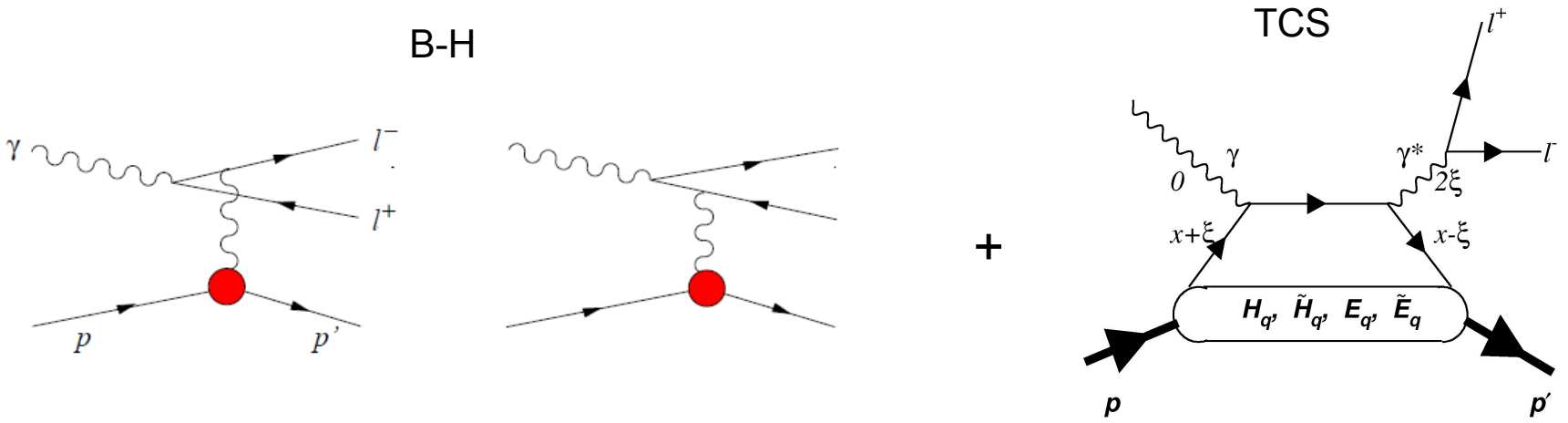


Bethe-Heitler (BH)



- TCS and Bethe-Heitler (BH) processes contribute
- TCS cross section is smaller than BH in JLab 12 GeV kinematics
- The interference term is enhanced by the BH and easy to isolate

TCS-BH interference



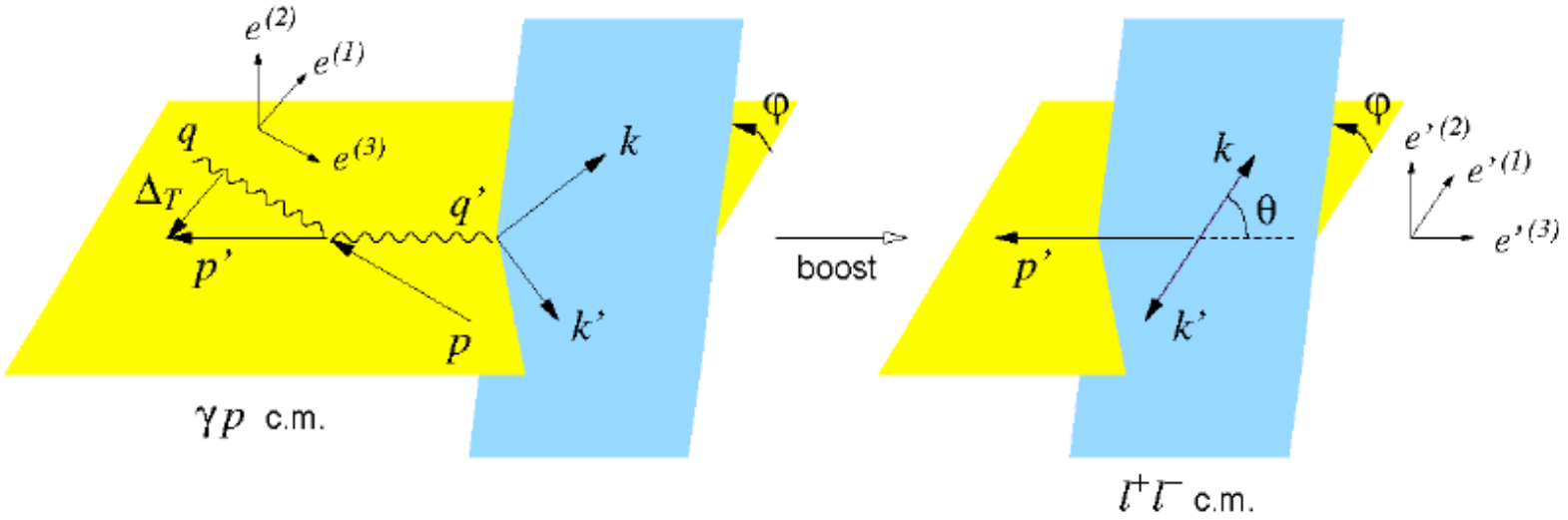
$$\frac{d\sigma^4}{dQ'^2\,dt\,d(\cos\theta)\,d\phi} = |BH|^2 + I(BH\cdot TCS) + |TCS|^2$$

- Under lepton charge conjugation:
  - Compton and BH amplitudes are *even*
  - Interference term is *odd*

  } Easy to project out *only* the interference term

- Direct access to interference term through angular distribution of the lepton pair
  - cosine and sine moments

Kinematics



- k,k' = momentum of e^-, e^+
- θ = angle between the scattered proton and the electron
- φ = angle between lepton scattering- and reaction planes

$$\frac{d\sigma_{BH}}{dQ'^2 dt d\cos\theta} \approx 2\alpha^3 \frac{1}{-tQ'^4} \frac{1+\cos^2\theta}{1-\cos^2\theta} \left(F_1(t)^2 - \frac{t}{4M_p^2} F_2(t)^2 \right)$$

- For θ close to 0 and π, BH becomes large. A cut is usually applied.

Interference term

In terms of helicity amplitudes:

$$\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\Big[\cos\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Re}\,\tilde{M}^{--} - \cos 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Re}\,\tilde{M}^{0-} + \cos 3\varphi\,\sin\theta\,\mathrm{Re}\,\tilde{M}^{+-} + O\Big(\frac{1}{Q'}\Big)\Big],$$

$$-\nu\,\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\Big[\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\,\tilde{M}^{--} - \sin 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Im}\,\tilde{M}^{0-} + \sin 3\varphi\,\sin\theta\,\mathrm{Im}\,\tilde{M}^{+-} + O\Big(\frac{1}{Q'}\Big)\Big]$$

ν: circular polarization of incoming photon also gives access to imaginary part

$$\frac{1}{2}\sum_{\lambda,\lambda'}|M^{\lambda'-,\lambda-}|^2 = (1-\eta^2)\Big(|\mathcal{H}_1|^2 + |\tilde{\mathcal{H}}_1|^2\Big) - 2\eta^2\,\mathrm{Re}\Big(\mathcal{H}_1^*\,\mathcal{E}_1 + \tilde{\mathcal{H}}_1^*\,\tilde{\mathcal{E}}_1\Big) - \Big(\eta^2 + \frac{t}{4M^2}\Big)|\mathcal{E}_1|^2 - \eta^2\frac{t}{4M^2}|\tilde{\mathcal{E}}_1|^2,$$

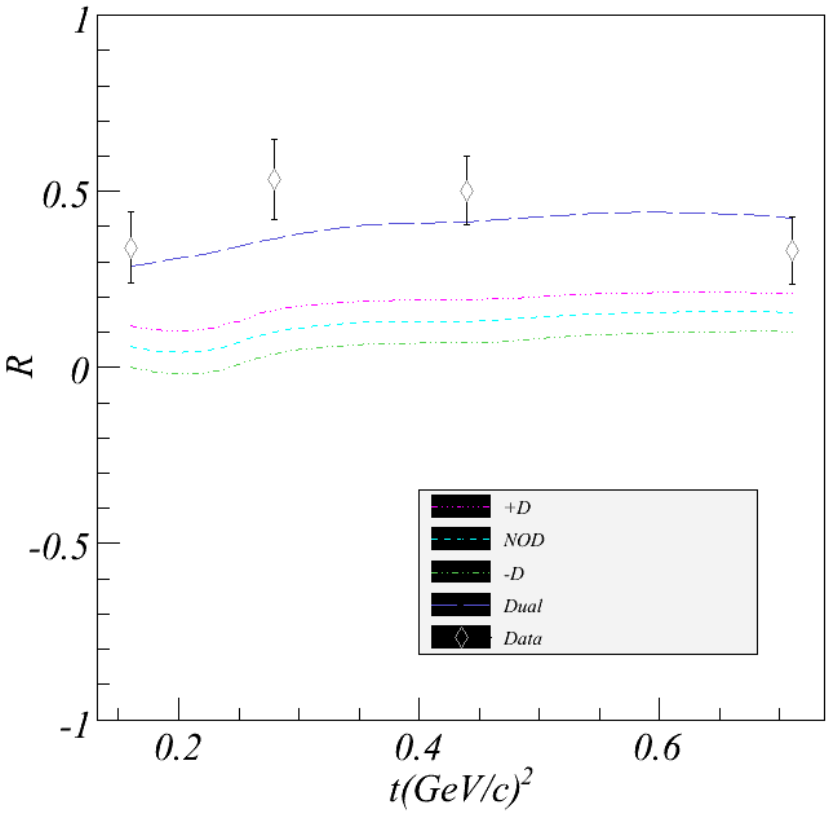
First measurements at 6 GeV

- Cosine moment of weighted cross sections

$$\frac{dS}{dQ'^2\,dt\,d\varphi} = \int \frac{L(\theta,\varphi)}{L_0(\theta)} \frac{d\sigma}{dQ'^2\,dt\,d\varphi\,d\theta} d\theta$$

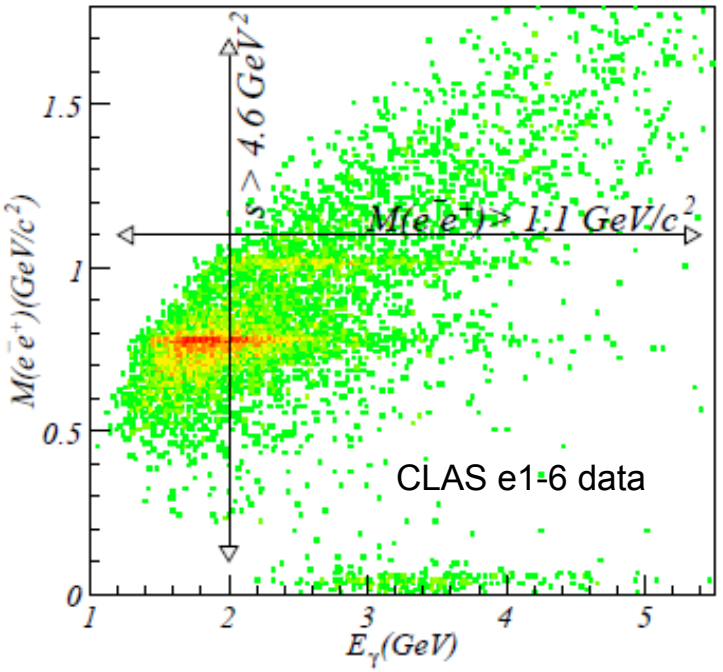
$$R = \frac{2\int_0^{2\pi} d\varphi \cos\varphi \frac{dS}{dQ'^2 dt d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ'^2 dt d\varphi}}$$

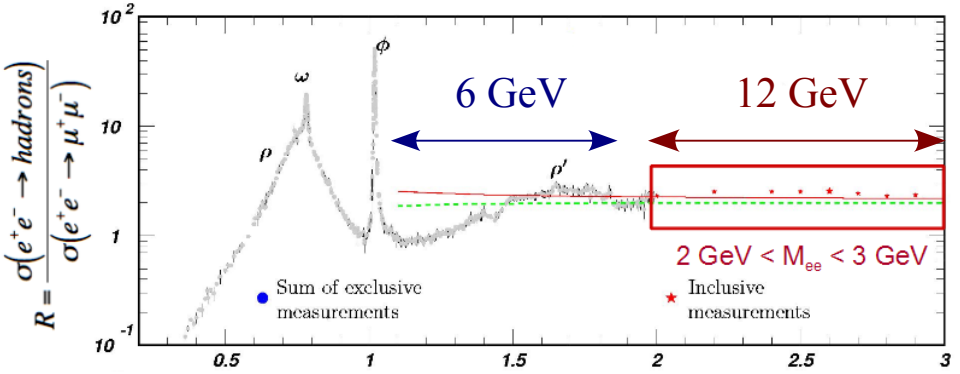
- Numerator is proportional to Re M^{--}
  - cos φ part of interference term
- R can be compared directly with GPD models
- Polyakov-Weiss D-term in double distribution?



Comparison of results from e1-6/e1f with calculations by V. Guzey.

From 6 to 12 GeV

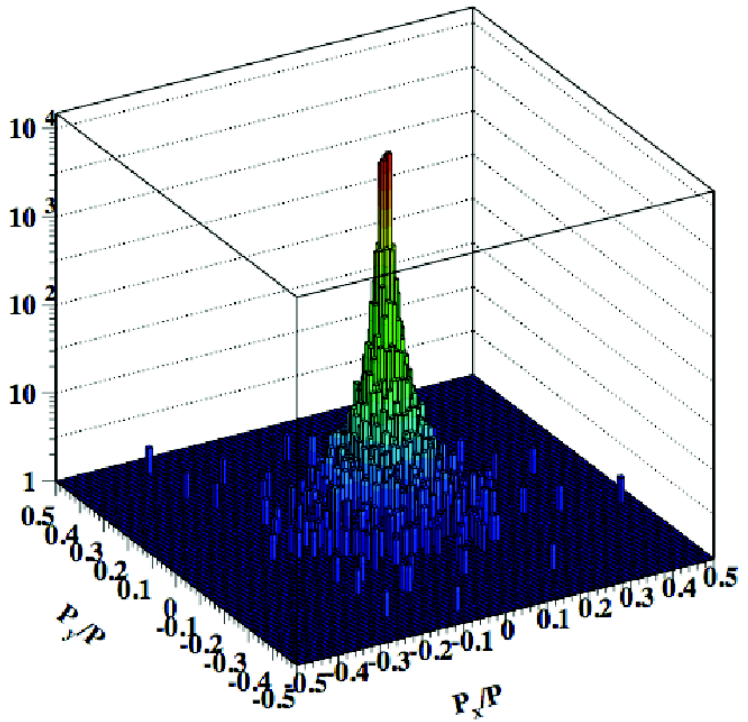


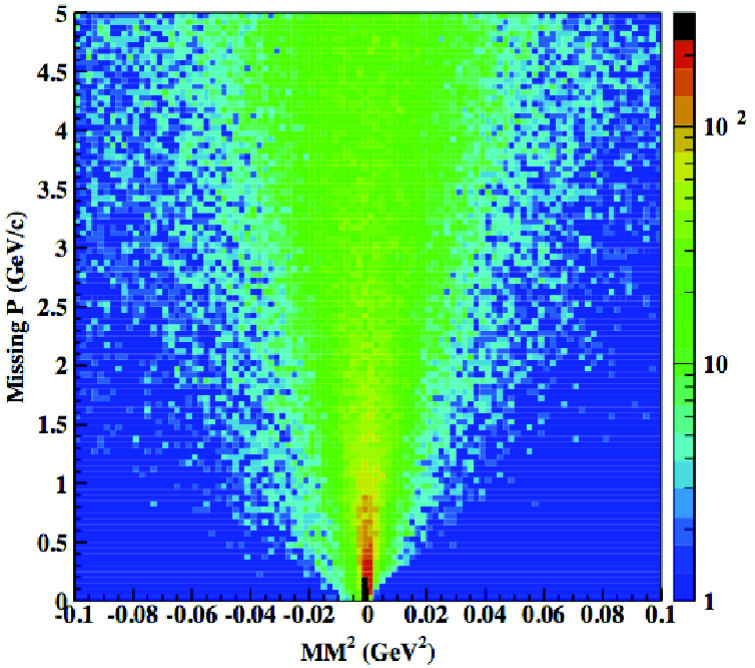


- 6 GeV kinematics are limited to $M_{e^+e^-} < 2$ GeV
- 12 GeV extends this mass (Q') range up to 3 GeV

- 6 GeV data were important for developing analysis methods
- 12 GeV will provide
  - A much larger reach in s and Q'^2
  - Higher luminosity and more statistics for multi-dimensional binning
  - A possibility to avoid meson resonances in the e^+e^- final state
    - Data can be taken in the resonance-free region between the ρ' and J/ψ

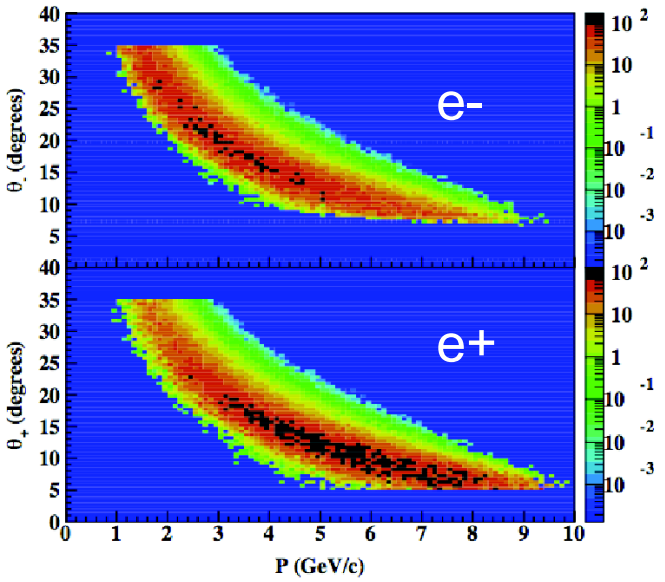
Exclusive quasi-real photoproduction in CLAS12

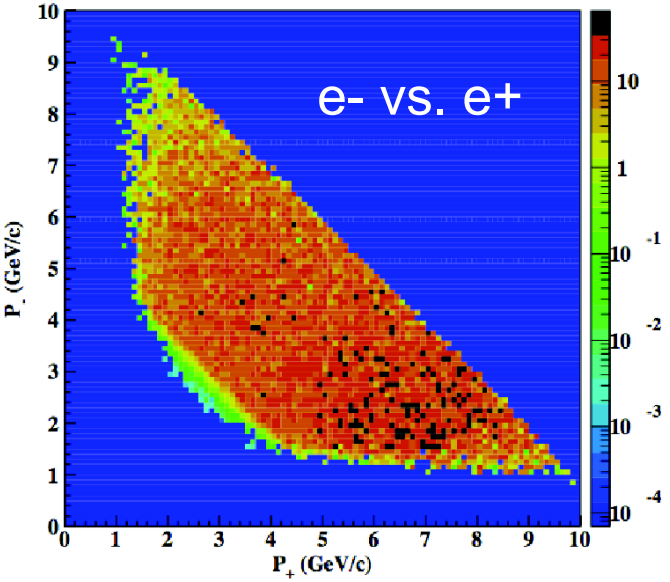


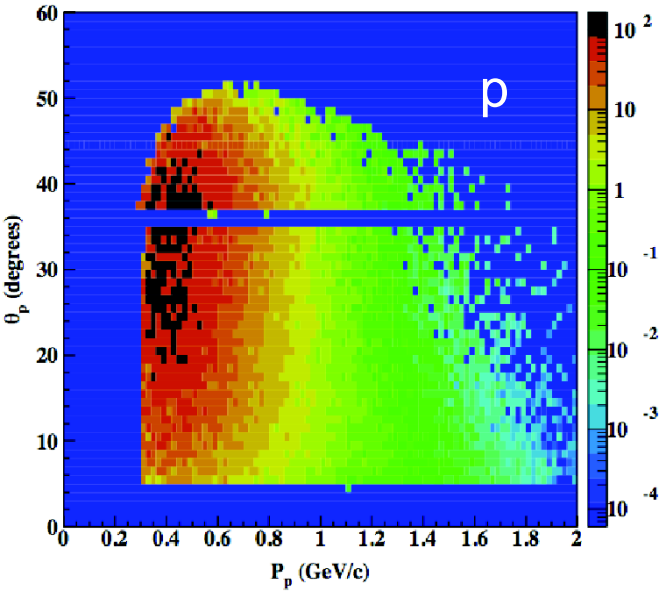


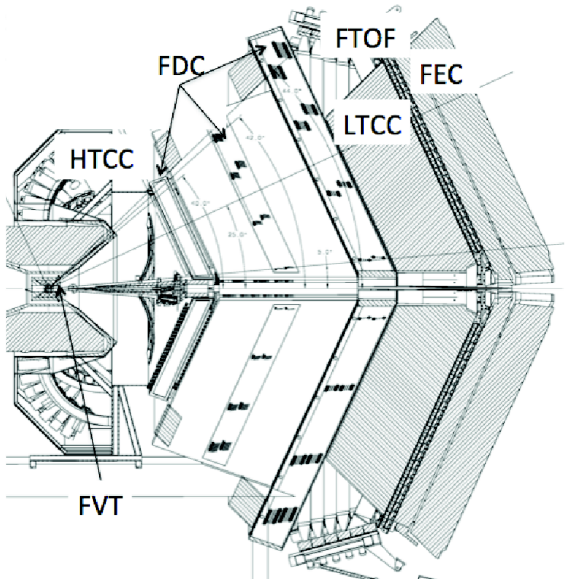
- Low-Q^2 events are reconstructed by applying cuts on the transverse momentum of the missing beam electron.
- Exclusivity is ensured by detection of all produced final-state particles, and application of a missing mass cut.

Detection of the exclusive final state in CLAS12



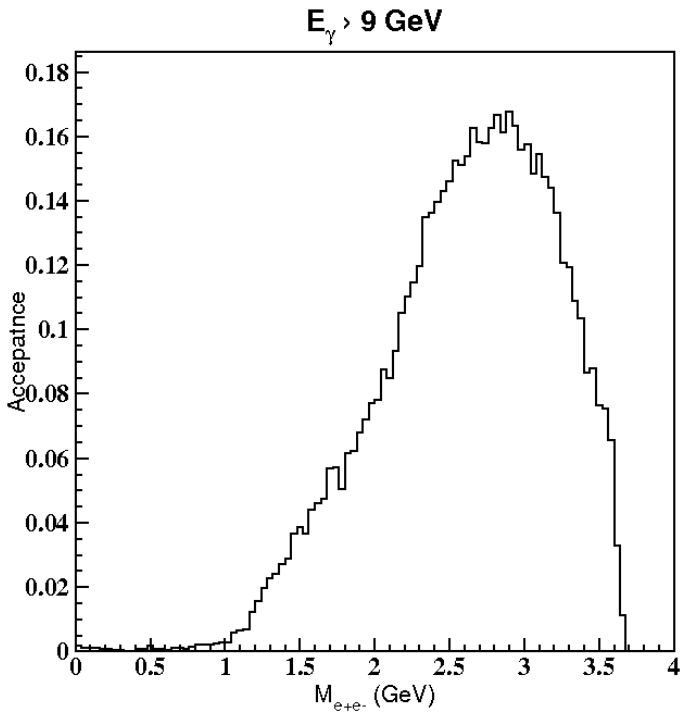


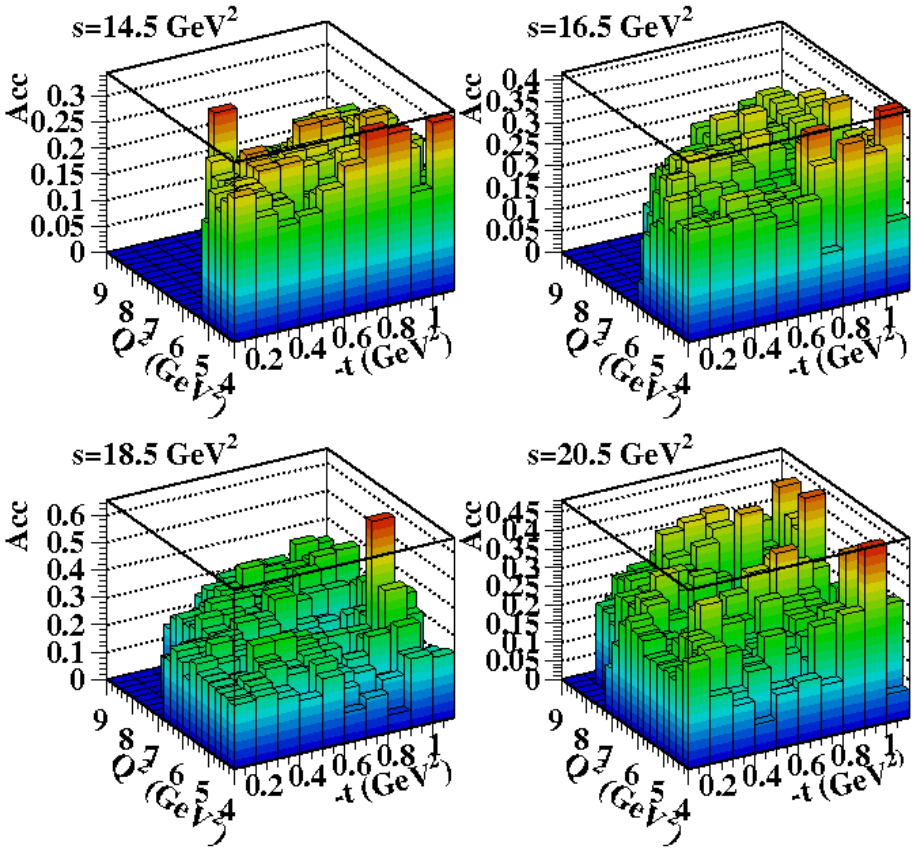




- The leptons pairs are detected and identified using the High-Threshold Cherenkov Counter (HTCC) and the Forward Electromagnetic Calorimeter (FEC).
- Pairs with one lepton below the HTCC pion threshold of 4.9 GeV/c will have a pion pair rejection factor of $2 \cdot 10^7$.
- Proton kinematics and acceptance are shown on the right.

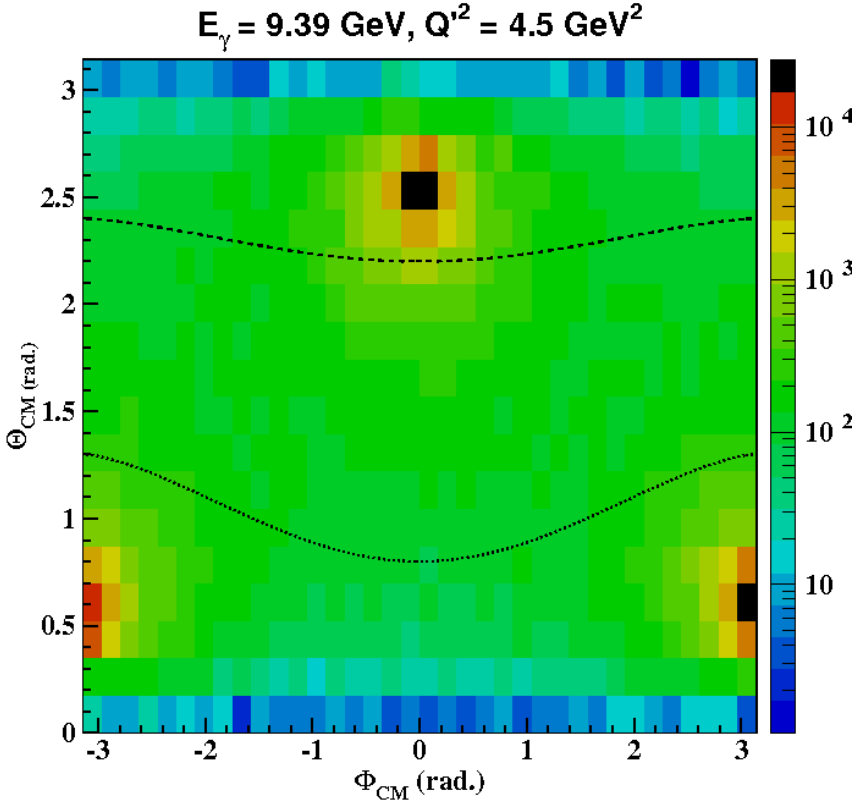
Acceptance in Q'^2, s, and t



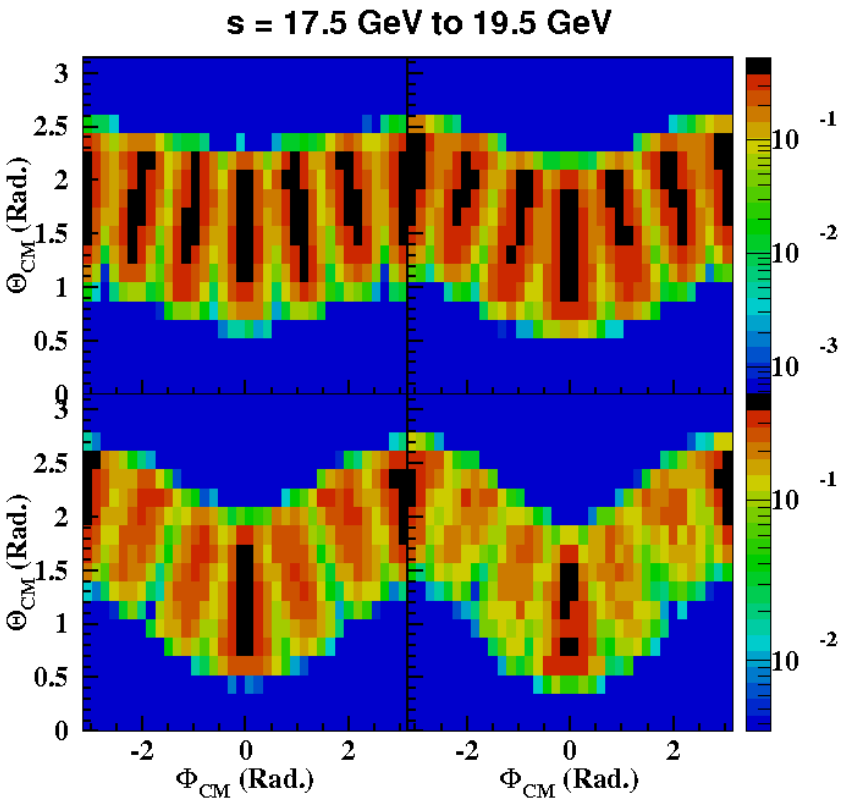


- CLAS12 has excellent acceptance for photoproduction of lepton pairs with a large invariant mass over a wide range in s and t.

Acceptance in the TCS angles θ_{CM} and φ_{CM}



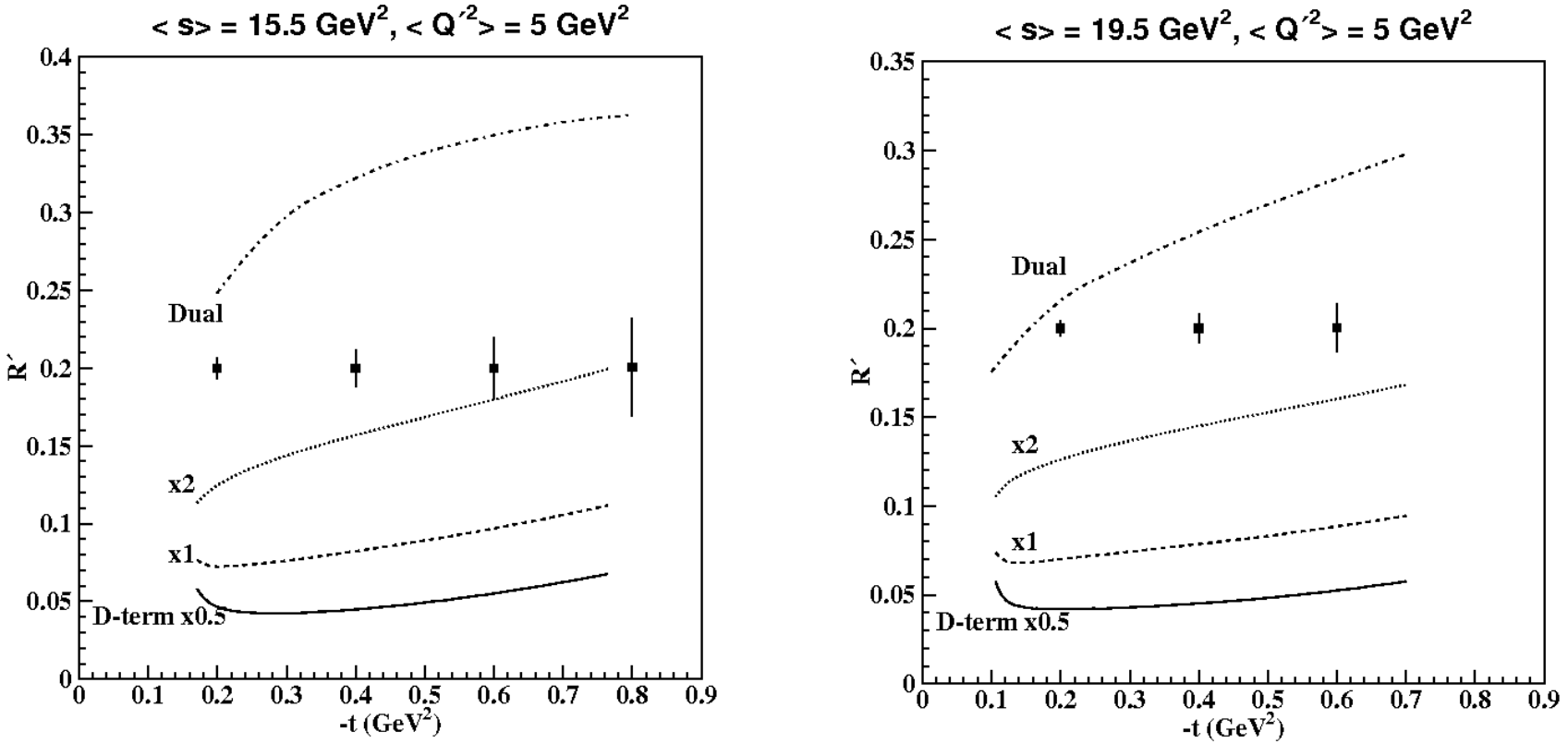
Generated events. Regions dominated by BH fall outside of the contour indicating the CLAS acceptance.



Accepted events for four t-bins. The observable R' is integrated over the CLAS acceptance.

Projected results – cosine moment R'

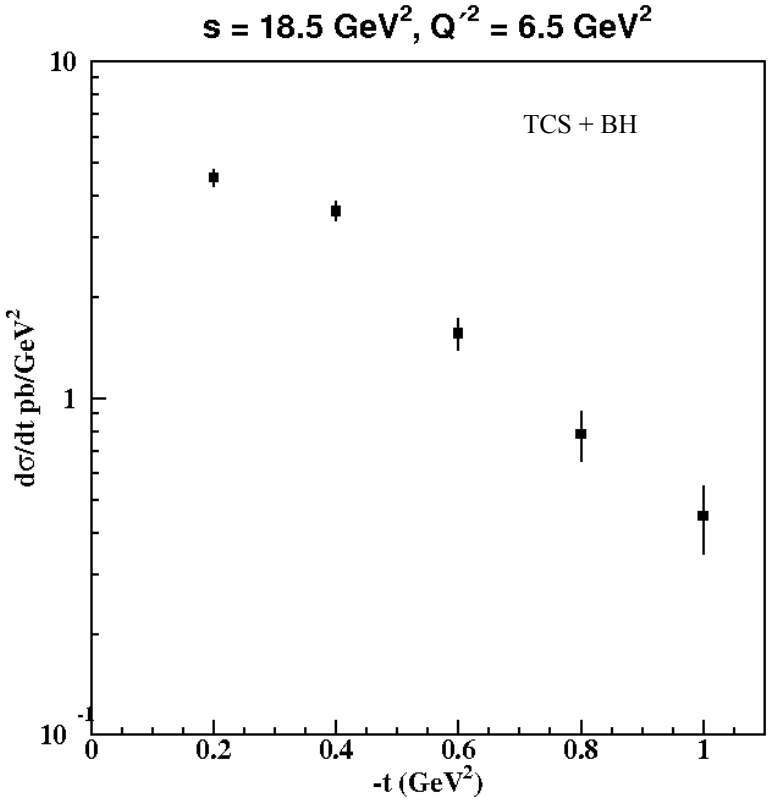
Statistical uncertainties for 100 days at a luminosity of 10^{35} $cm^{-2}s^{-1}$

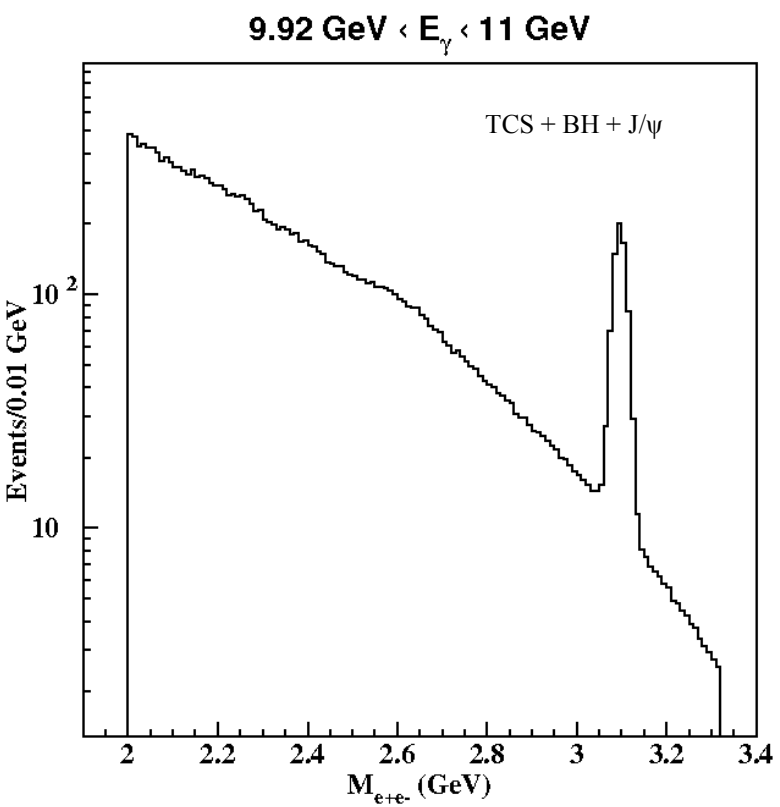


- Uncertainties for R', integrated over the CLAS12 θ_{CM} — φ_{CM} acceptance, for two photon energy bins, for the lowest Q'^2 bin above the ρ' resonance.
- Different values of the D-term are only shown for the double distribution.

Projected results – cross section

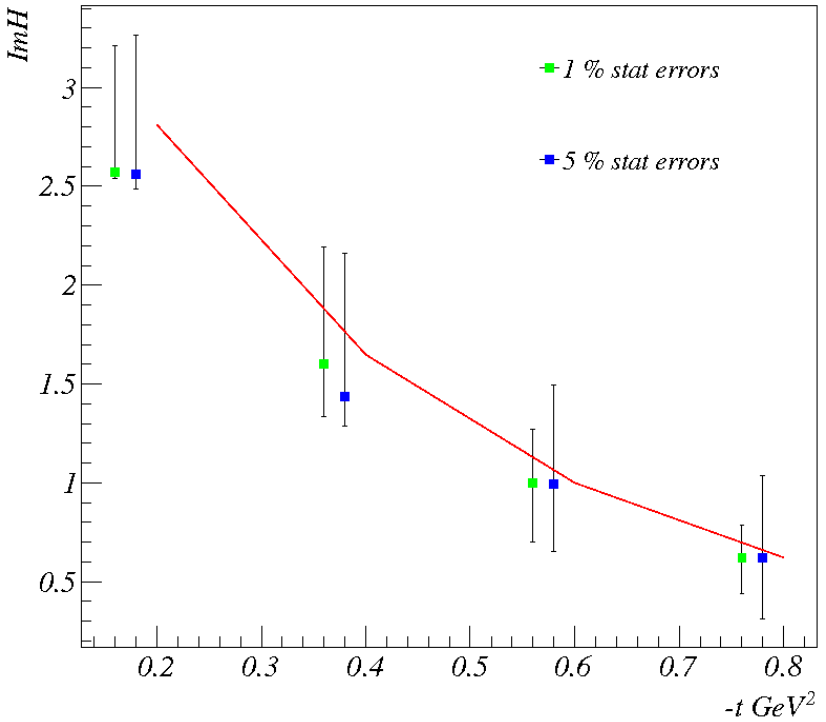
Statistical uncertainties for 100 days at a luminosity of 10^{35} $cm^{-2}s^{-1}$

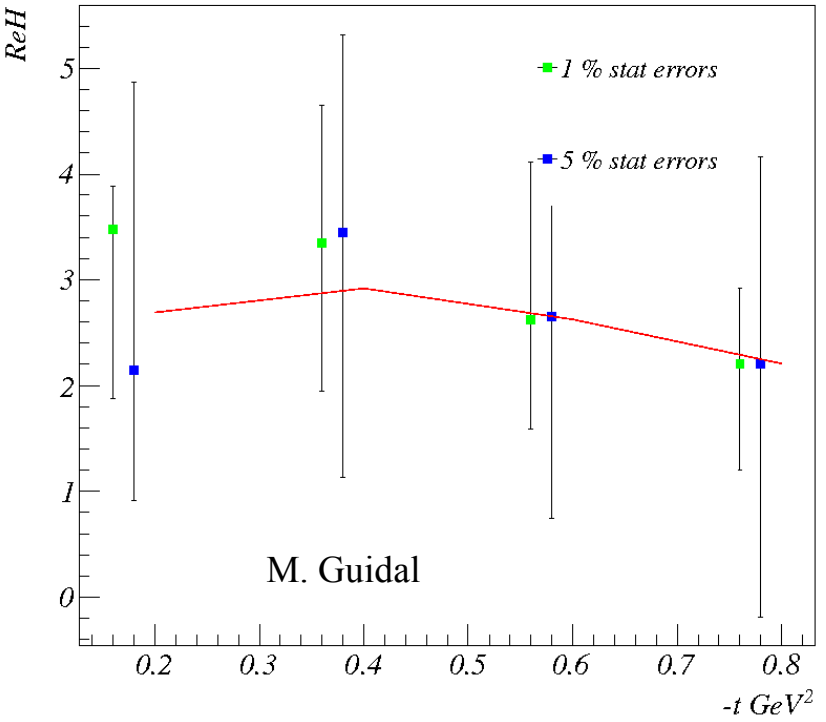




- The unpolarized and polarized four-fold differential TCS+BH cross sections will provide input for global analysis of Compton Form Factors.
- The narrow J/ψ peak on the right is very prominent.

Global analysis of Compton Form Factors



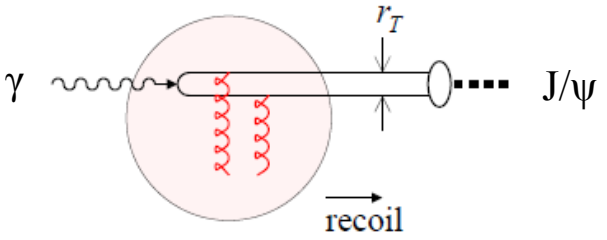


- TCS pseudodata, based on VGG CFFs, were successfully fitted and the original values recovered, demonstrating the feasibility of the procedure.
- Absolute values of shown uncertainties reflect the model-independent fit of all CFFs using only two observables, not the uncertainty in the data. Uncertainties can be reduced through combined fits, adding theory constraints, or measuring additional observables – polarized targets?

J/ψ photoproduction near threshold

First measurement in CLAS12

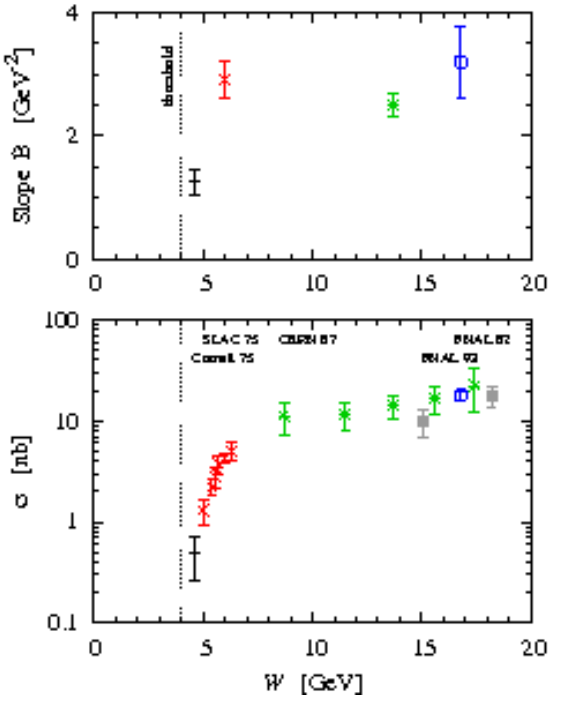
- Preliminary results on the proton in 2016?



Will establish reaction mechanism

- Great theoretical interest but data are needed
  - Dedicated workshop: Non-perturbative forces in QCD, Temple U., 26-28 March 2012
- Predictions differ by orders of magnitude

  Specific models: Non-relativistic QCD (Butenschoen 12); Hard-scattering mechanism (Brodsky *et al*. 02); others in progress

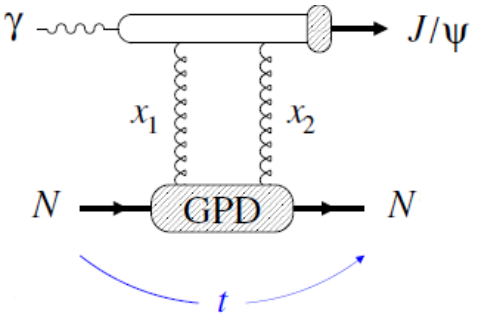


Important cross check for TCS

- Benchmark for acceptance and PID studies
  - Normal and reversed CLAS12 torus field

Probing the gluonic structure of the nucleon

- $c\bar{c}$ produced in small-size configurations
  - Probes distances ~ $1/\sqrt{(Q^2+M^2_{J/\psi})} \sim 1/M_{J/\psi}$

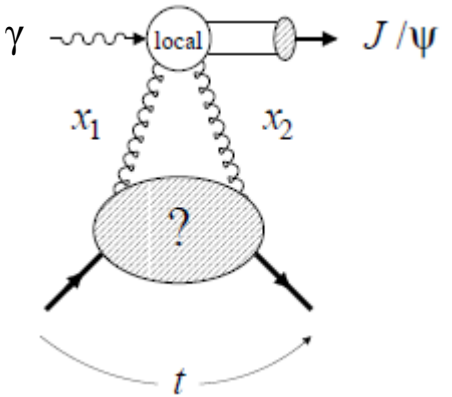


J/ψ production at high W

- Access to nucleon's gluon GPD at small x
  - EIC, HERA, COMPASS, FNAL

J/ψ production near threshold

- Large t_{min} implies large skewness x_1 - x_2
- More natural interpretation in terms of a gluonic form factor sensitive to non-perturbative gluon field
  - analogous to high-t elastic eN scattering
- Amplitude constant but cross section near threshold suppressed by large t_{min}?

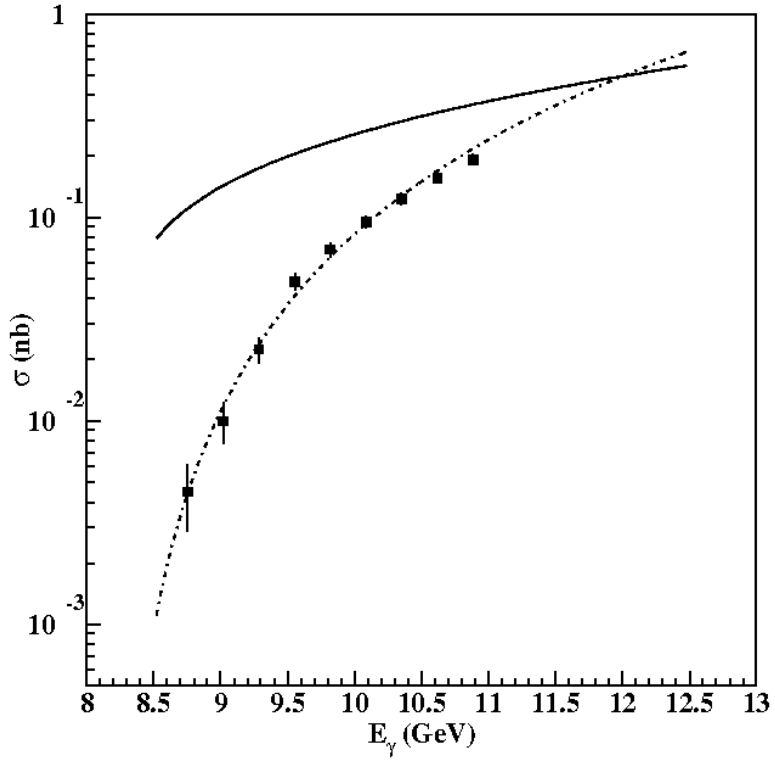


$$A(\gamma + p \to J/\psi + p) \propto F_{2g}(t)$$

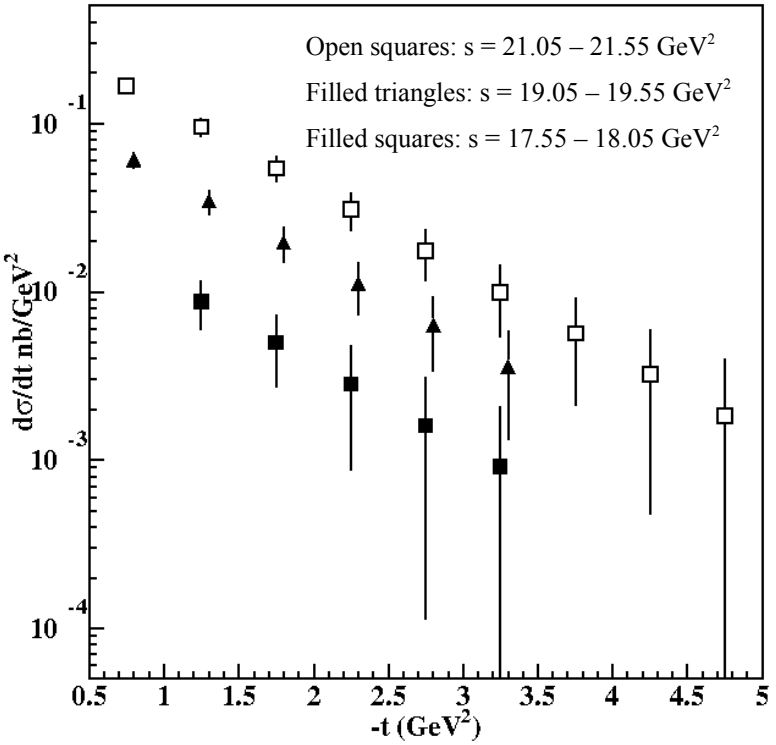
gluonic form factor

Projected results – exclusive J/ψ production

Statistical uncertainties for 100 days at a luminosity of 10^{35} $cm^{-2}s^{-1}$



Uncertainties for the total cross section assuming the most conservative prediction

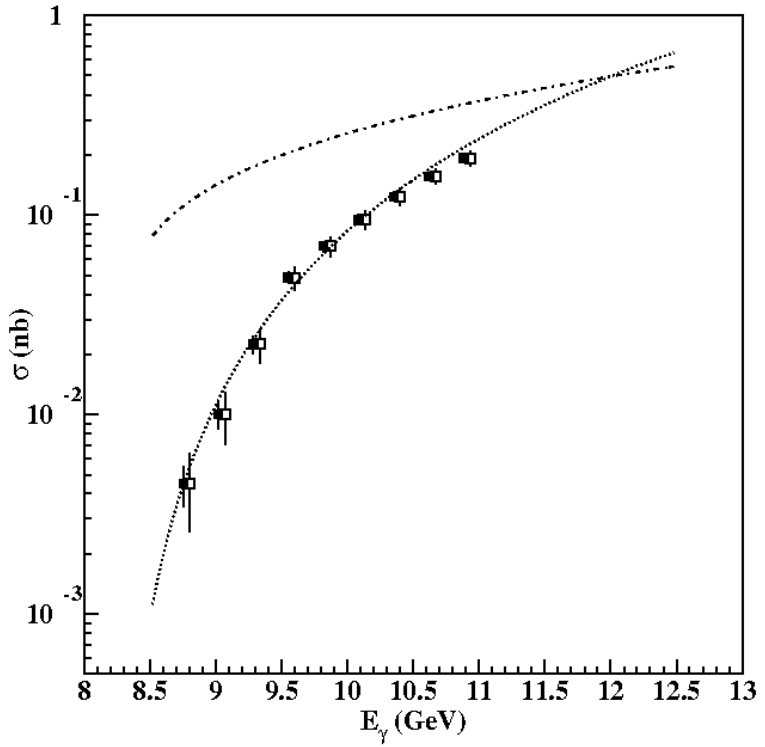


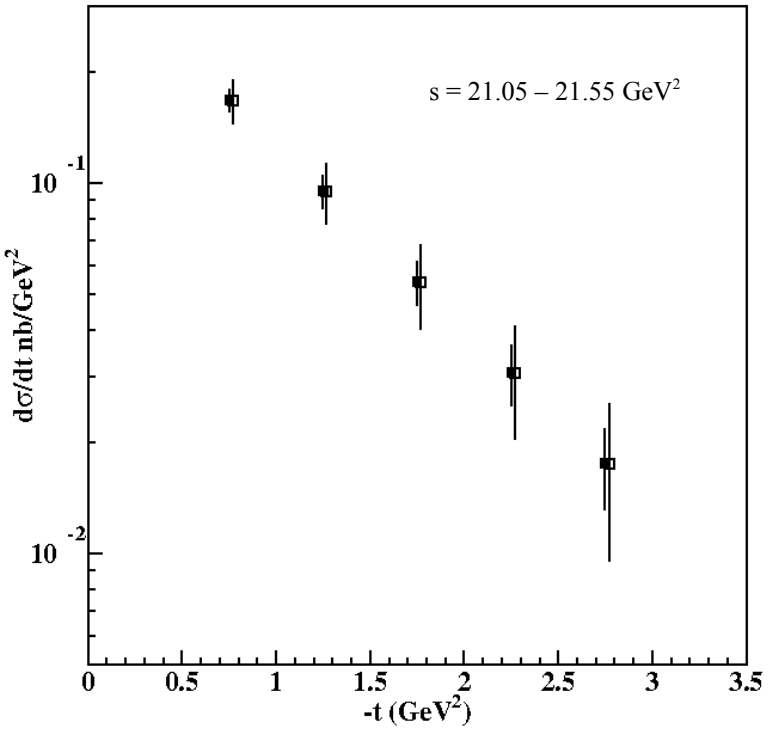
t-dependence in narrow bins of *s* for a total cross section given by the lower curve on the left

Projected results – "inclusive" J/ψ production

Statistical uncertainties at a luminosity of 10^{35} $cm^{-2}s^{-1}$

Filled squares: 100 days Open squares: 30 days





- Excellent benchmark for studies of detector efficiency
  - Nominal acceptance for e^+ e^- final state identical for both torus polarities
  - Essential for understanding uncertainties due to acceptance in TCS
- 100 days with normal and 30 with reversed torus field will allow a comparison over a wide range in E_γ and t.

Running conditions and beam time request

Running conditions

- We request a longitudinally polarized 11 GeV electron beam and a LH_2 target.

Beam time request

- We request the equivalent of 100 days at full luminosity with normal torus field polarity, and 30 days with reversed field setting.
  - Part with normal torus field can run in parallel with approved experiments

PR12-12-001 summary

Proposed CLAS12 measurement of TCS and J/ψ

- Proton target first to run

Timelike Compton Scattering (TCS)

- Test universality of GPDs
- Straightforward access to real part of Compton form factors

J/ψ photoproduction near threshold

- Establish reaction mechanism
- Access to gluonic structure of the nucleon
- Important benchmark for TCS

Backup

TCS cross section and the interference term

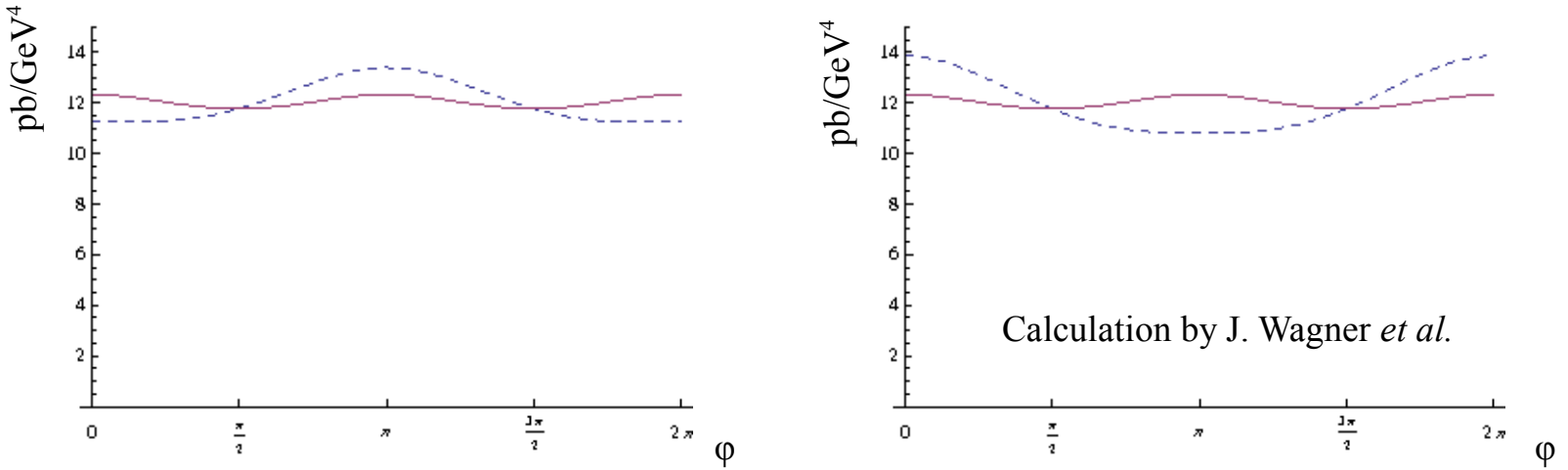
$$\frac{d\sigma_{TCS}}{dQ'^2 d\Omega dt} \approx \frac{\alpha^3}{8\pi}\frac{1}{s^2}\frac{1}{Q'^2}\left(\frac{1+\cos^2\theta}{4}\right) 2(1-\xi^2)\,|\mathcal{H}(\xi,t)|^2$$

$$\frac{d\sigma_{INT}}{dQ'^2\, dt\, d\cos\theta\, d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\cos\varphi\frac{1+\cos^2\theta}{\sin\theta}\mathrm{Re}\,\tilde{M}^{--}$$

$$\tilde{M}^{--} \approx \frac{2\sqrt{t_0-t}}{M}\frac{1-\xi}{1+\xi}\,[F_1(t)\mathcal{H}(\xi,t)]$$

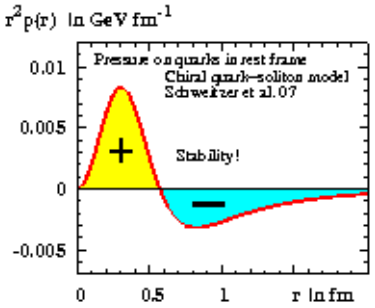
$$\mathcal{H}(\xi,t) = \sum_q e_q^2 \int_{-1}^{1} dx \left(\frac{1}{\xi-x+i\epsilon} - \frac{1}{\xi+x+i\epsilon}\right) H^q(x,\xi,t)$$

NLO corrections



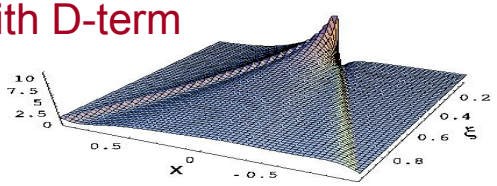
LO (left) and NLO (right) differential cross sections for B-H (solid) and B-H + INT (dashed) for Eγ = 11 GeV, Q'^2 = 5 GeV^2, and t = -0.1 GeV^2.

D-term in DD-parametrization of GPDs

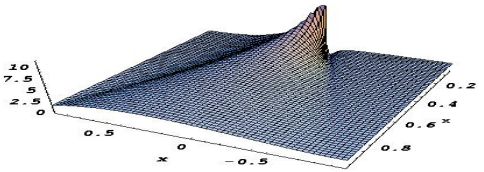


$$H^q(x,\xi) = H^q_{DD}(x,\xi) + \theta(\xi - |x|)\frac{1}{N_f} D\left(\frac{x}{\xi}\right)$$

GPD with D-term



GPD without D-term



Real part of the Compton amplitude is sensitive to the D-term