Plans to measure J/ψ photoproduction and TCS on the proton at CLAS12

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Int. Workshop on using Heavy Flavors to Probe New Hadron Spectroscopies/Dynamics, Busan, Korea, November 18-21, 2012

Outline

Introduction

J/ψ photoproduction near threshold

- Gluonic structure of the nucleon at large x
- Behavior of cross section near threshold is unknown
  - CLAS12 will provide the first results
- Future measurements with nuclear targets?

Timelike Compton Scattering (TCS)

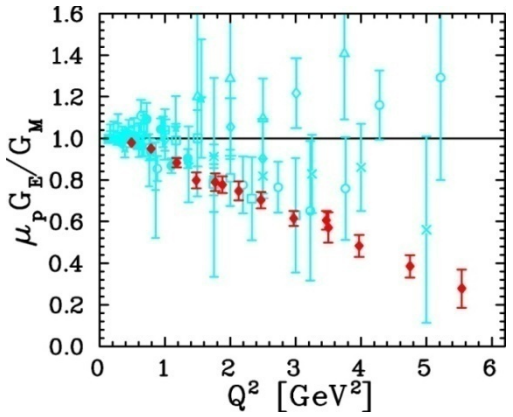
- Timelike-spacelike correspondence and universality of GPDs
- Real and imaginary parts of Compton form factors for valence quarks

Approved ep → e'pe$^+$e- program for CLAS12

Proposal	Physics	Contact	Rating	Days	Group	Energy	Target
E12-06-108	Hard exclusive electro-production of π0, η	Stoler	B	80			
E12-06-112	Proton's quark dynamics in SIDIS pion production	Avakian	A	60			
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	A	80	119 days + 20 days with reversed torus field	11 GeV	Liquid H_2
E12-09-003	Excitation of nucleon resonances at high Q2	Gothe	B+	40			
E12-11-005	**Hadron spectroscopy with forward tagger**	Battaglieri	A-	119			
E12-12-001	**Timelike Compton Scatt. & J/ψ production in e+e-**	Nadel-Turonski	A-	100 +20			
E12-12-007	Exclusive φ meson electroproduction with CLAS12	Stoler, Weiss	B+	60			

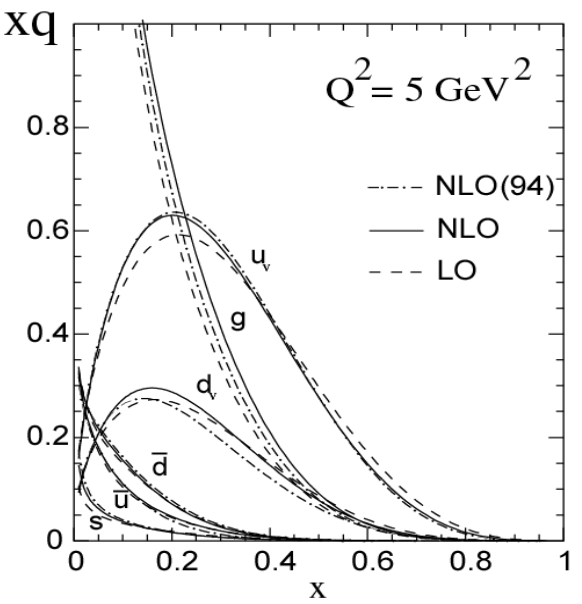
- Unpolarized proton target will be first to run
- Experiment E12-12-001 for e+e- physics was approved at the last PAC meeting
- Spectroscopy (119 PAC days) and e+e- (100+20 days) experiments drive the total beam time for proton running (119+20 days), which can be shared by all.
- Approved beam time corresponds to more than a year of actual running

Partons in the nucleon

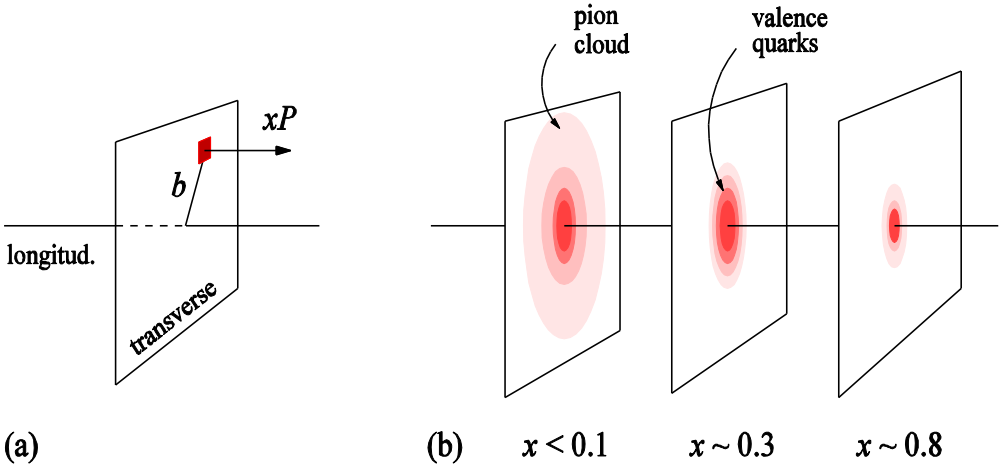


Elastic form factors

Transverse spatial distributions
(Naively Fourier transform of Q^2 or t)



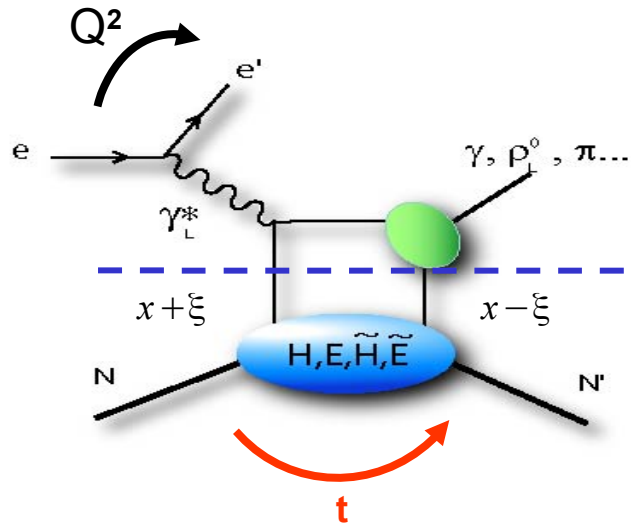
Parton Distribution Functions
Longitudinal momentum distributions

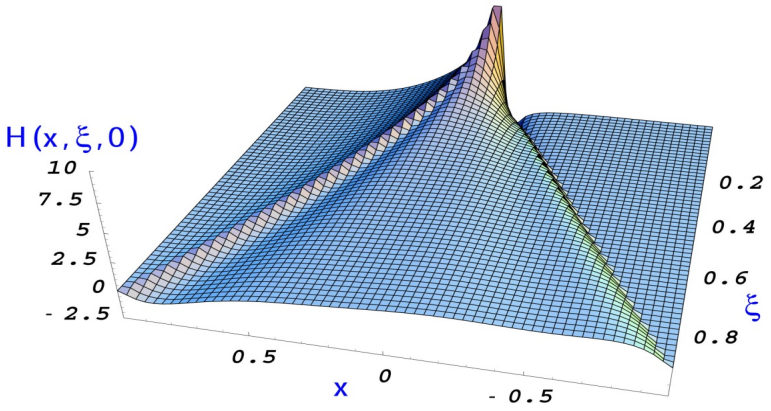


Generalized Parton Distributions

A unified descriptions of partons (quarks and gluons) in momentum and impact parameter space

Generalized Parton Distributions (GPDs)





Experimental Kinematics

- GPDs are measured in exclusive processes
- Q^2 is the momentum transfer *from* the electron
- t is the momentum transfer *to* the nucleon
- 2ξ is the difference between initial and final momentum of the struck parton

Elastic Form Factors

$$\int_{-1}^{1} dx\, H(x,\xi,t) = F_1(t) \qquad \int_{-1}^{1} dx\, \tilde{H}(x,\xi,t) = g_A(t)$$

$$\int_{-1}^{1} dx\, E(x,\xi,t) = F_2(t) \qquad \int_{-1}^{1} dx\, \tilde{E}(x,\xi,t) = h_A(t)$$

Parton Distribution Functions (PDFs)

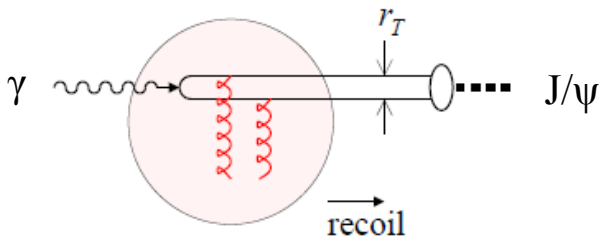
$$H(x,\xi=0,t=0) = q(x)$$
$$\tilde{H}(x,\xi=0,t=0) = \Delta q(x)$$

$E, \tilde{E}$ don't appear in DIS (*nucleon helicity flip*)

Charmonium as a probe of nucleon's color field

At high Q^2 $c\bar{c}$ is produced in small-size configurations

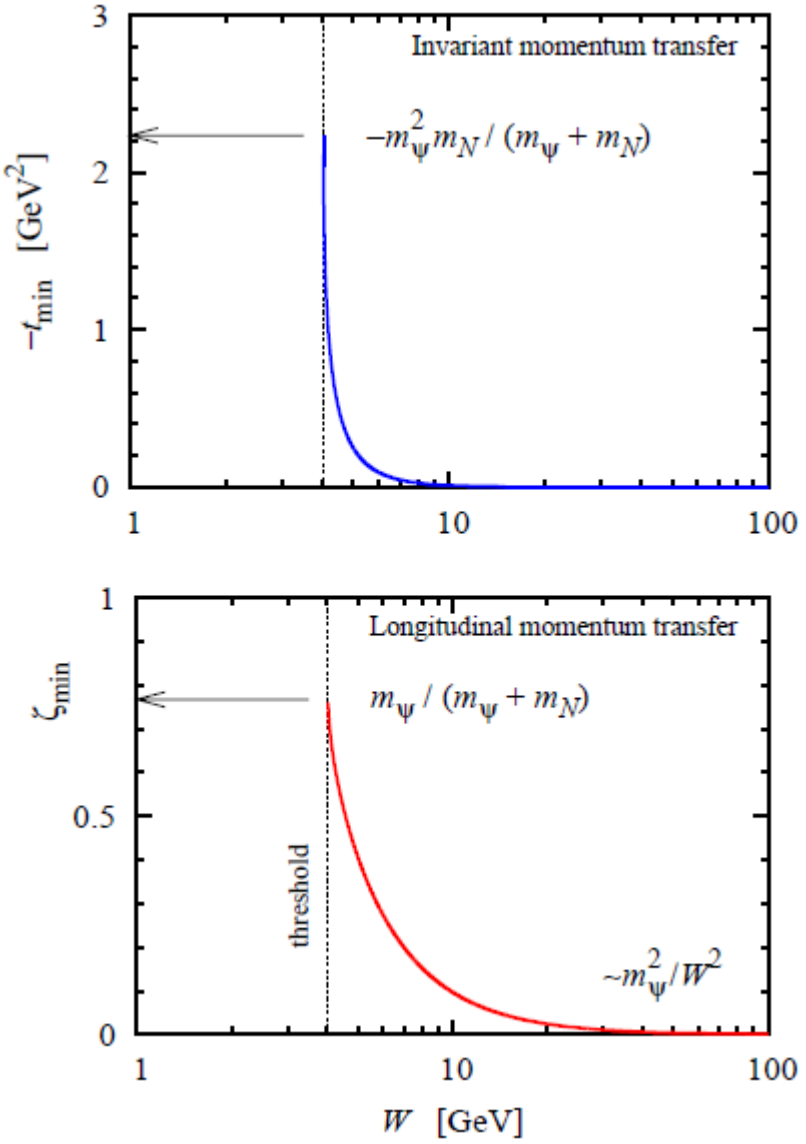
- *c.f.* color transparency
- Local probe of color field



J/ψ photoproduction

- Probes distances $\approx 1/\sqrt{Q^2+M_{J/\psi}^2} \approx 1/M_{J/\psi}$
- J/ψ radius much smaller than nucleon: $r_{J/\psi} \sim 0.2 - 0.3$ fm << 1 fm
- Transverse size in light-cone wave function: $\langle r_T^2 \rangle = 2/3 \langle r^2 \rangle$
- Small-size configurations dominate, but corrections could be important

Exclusive J/ψ kinematics near threshold



Four-momentum transfer to the nucleon

$$t = -(\zeta^2 m_N^2 + \Delta_T^2)/(1-\zeta)$$

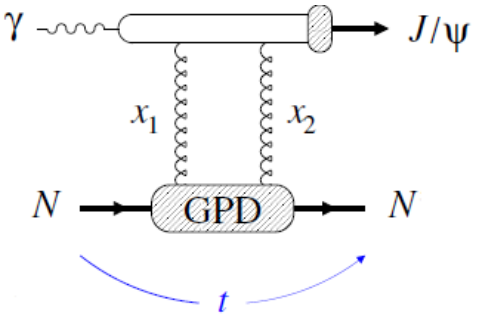
- ζ is the „plus“ momentum transfer
  - light cone variables
- Δ_T is the transverse momentum transfer
- t_{min} at threshold is 2.2 GeV

C. Weiss, Non-perturbative forces in QCD, Temple U., 26-28 March 2012

J/ψ production at high vs. low W (= √s)

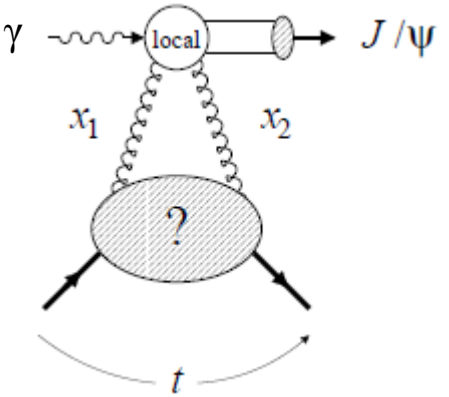
J/ψ production at high W

- Access to nucleon's gluon GPD at small x
  - t_{min} and ζ small, well understood diffractive process
  - Measurements at EIC, HERA, COMPASS, FNAL



J/ψ production near threshold

- t_{min} and ζ large, implies large skewness x_1 - x_2
- 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}

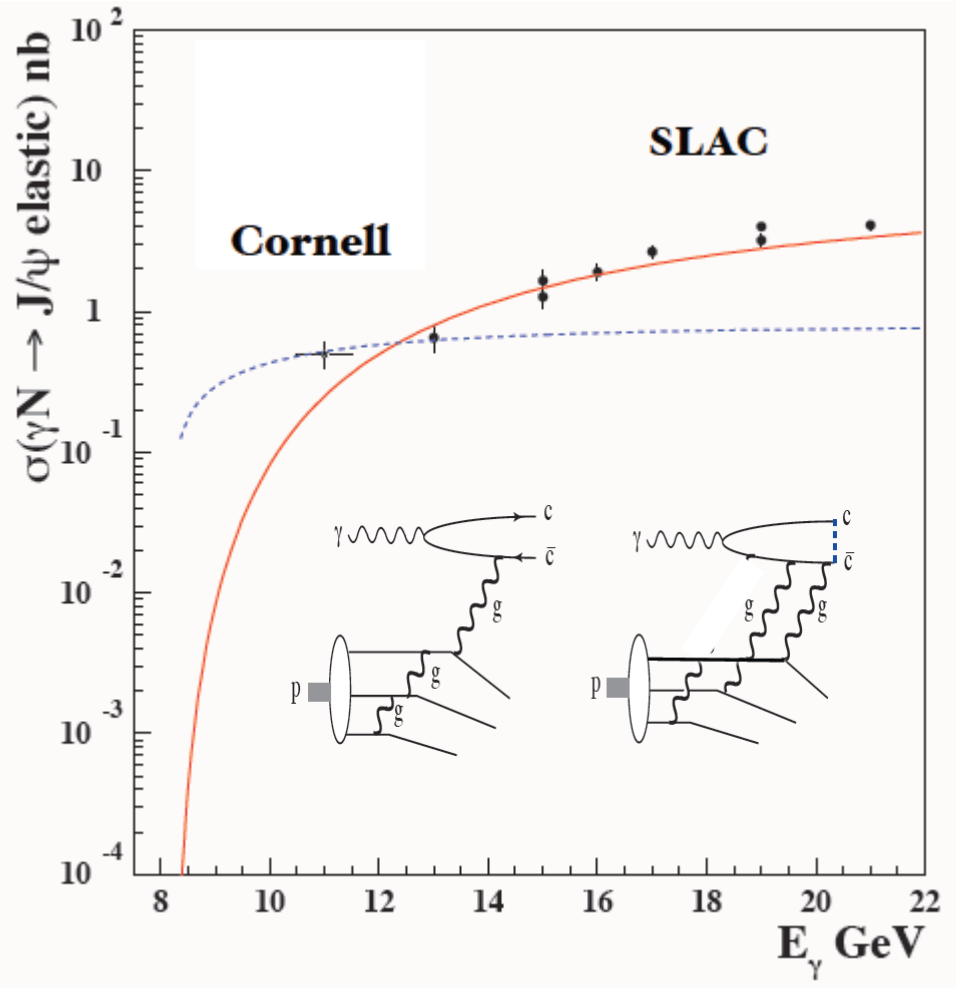


$$A(\gamma + p \to J/\psi + p) \propto F_{2g}(t)$$

gluonic form factor

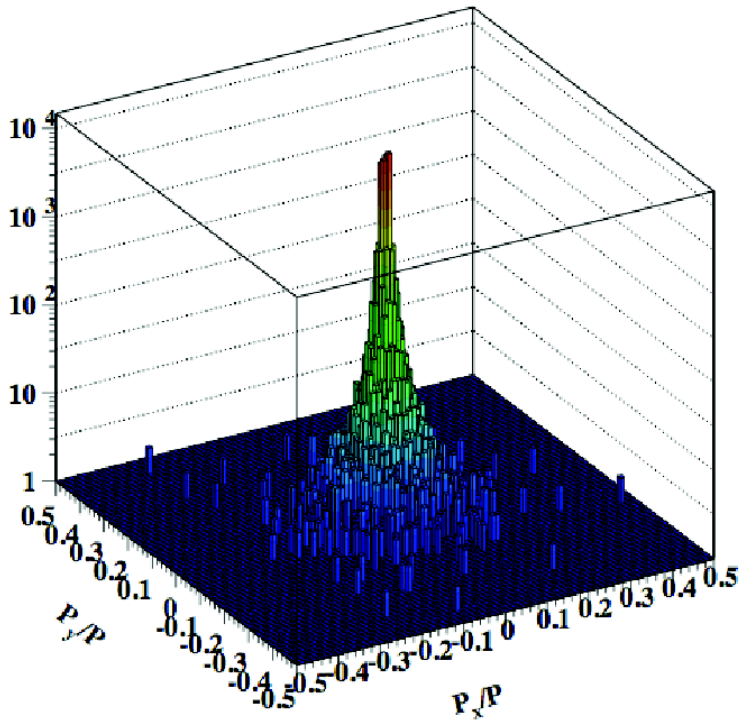
Weiss, Strikman

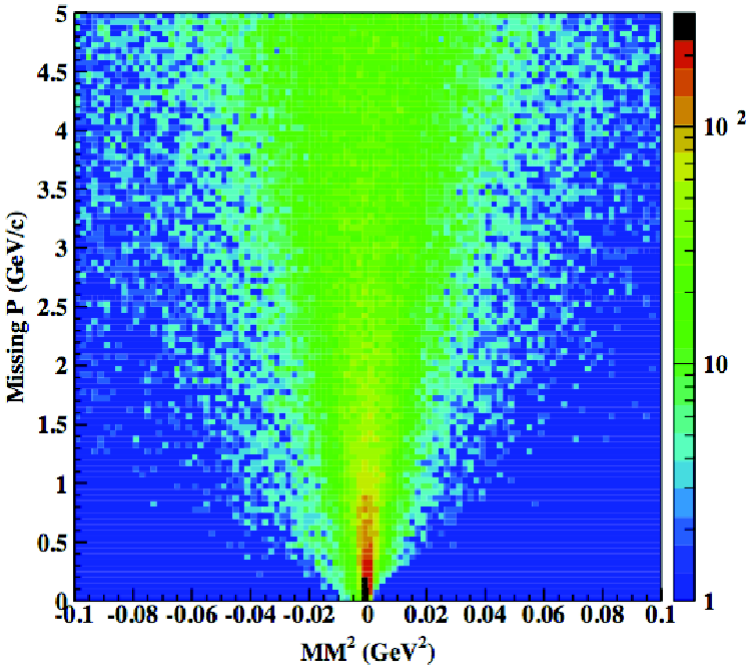
Enhancement instead of suppression near threshold?



- Based on the Cornell point, Brodsky *et al.* instead suggest a flattening out near threshold
  - diagram on the right?
- CLAS12 can easily answer this question.
- For rate predictions, a conservative estimate more akin to the red curve was used for E12-12-001.

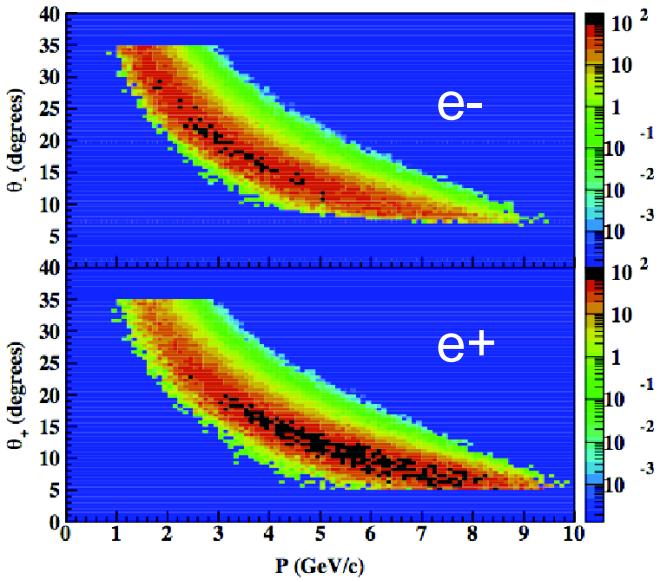
Exclusive quasi-real photoproduction in CLAS12

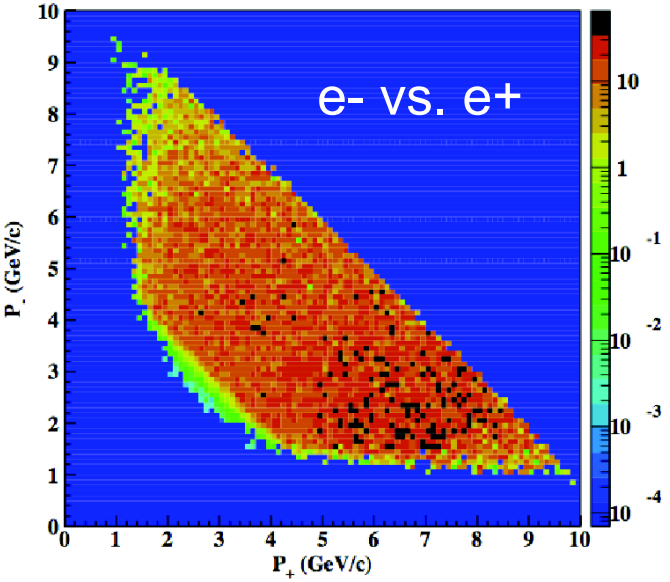


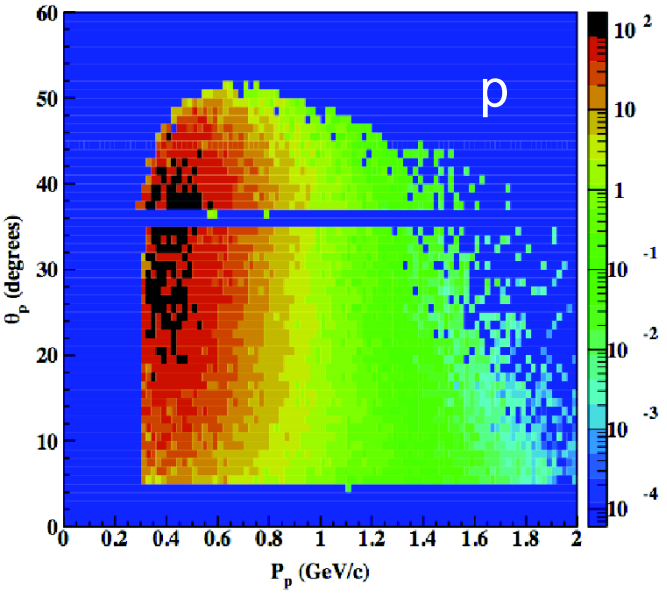


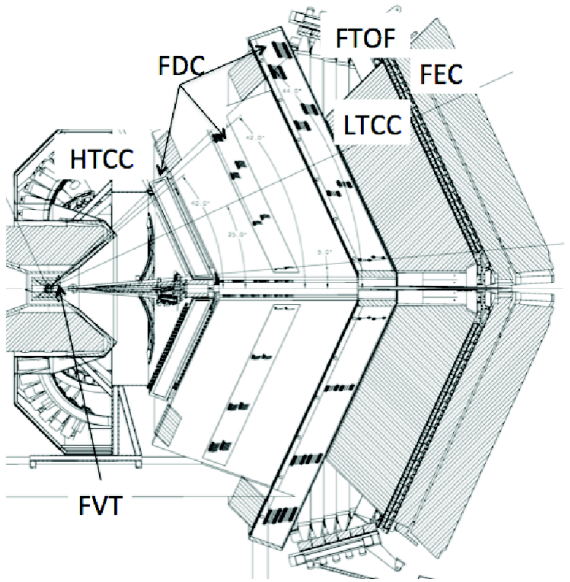
- Low-Q^2 events are reconstructed by applying cuts on the transverse momentum of the missing beam electron.
- Exclusivity is ensured by detection of all produced final-state particles, and application of a missing mass cut.

Detection of the exclusive final state in CLAS12



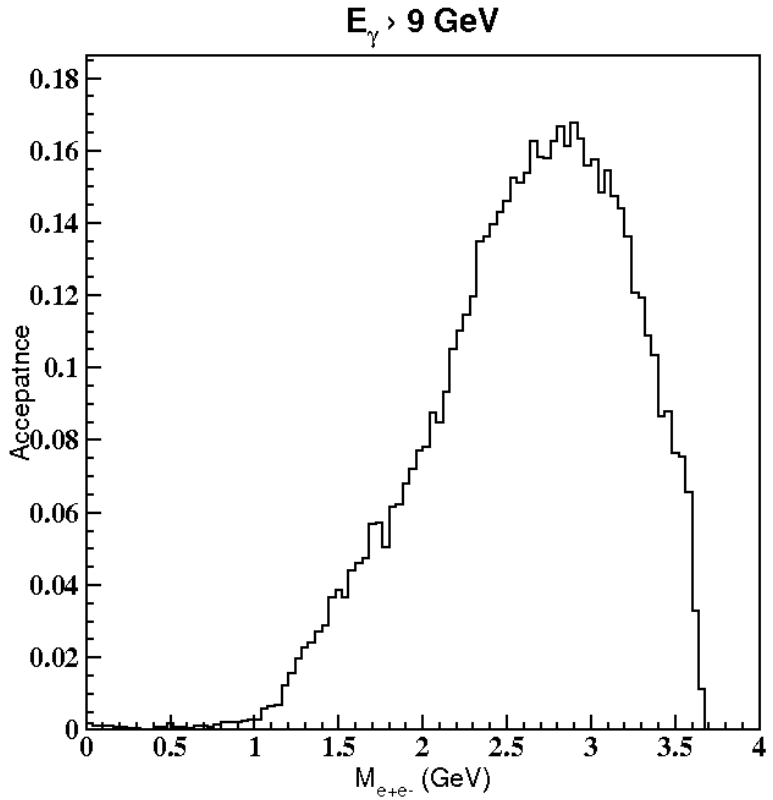


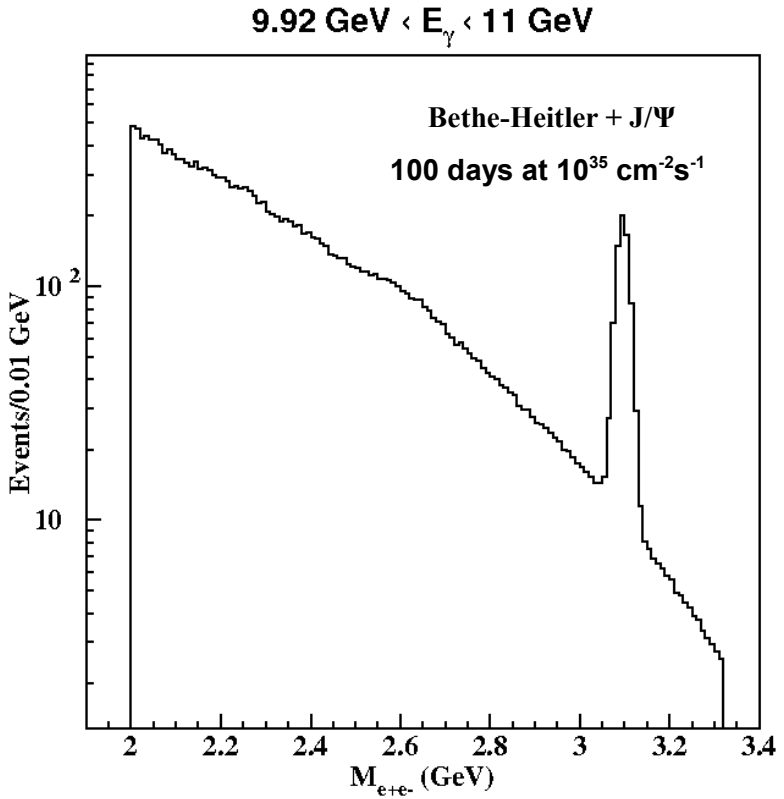




- The leptons pairs are detected and identified using the High-Threshold Cherenkov Counter (HTCC) and the Forward Electromagnetic Calorimeter (FEC).
- Pairs with one lepton below the HTCC pion threshold of 4.9 GeV/c will have a pion pair rejection factor of $2 \cdot 10^7$.
- Proton kinematics and acceptance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

Acceptance and yields for J/ψ in CLAS12

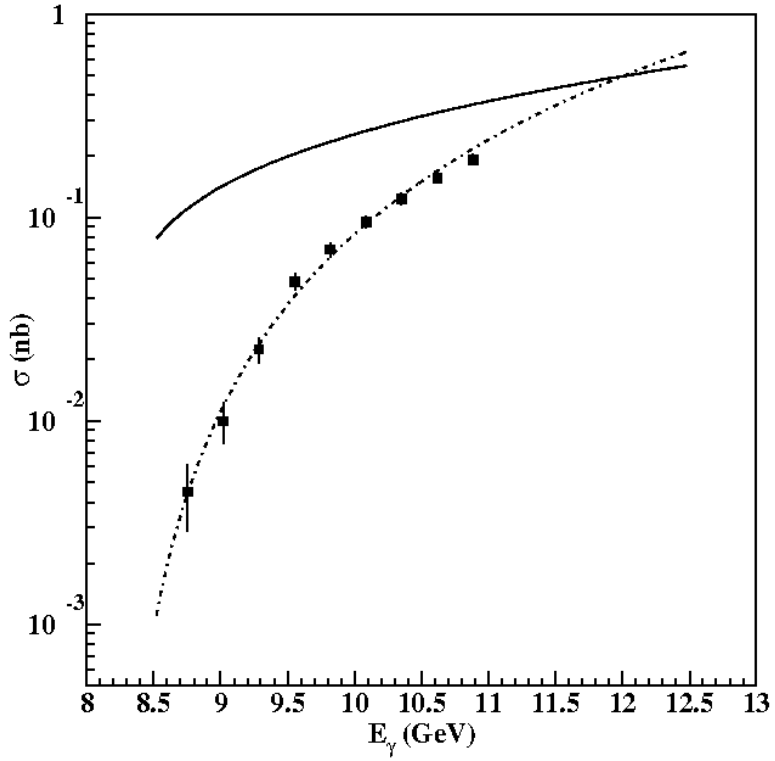




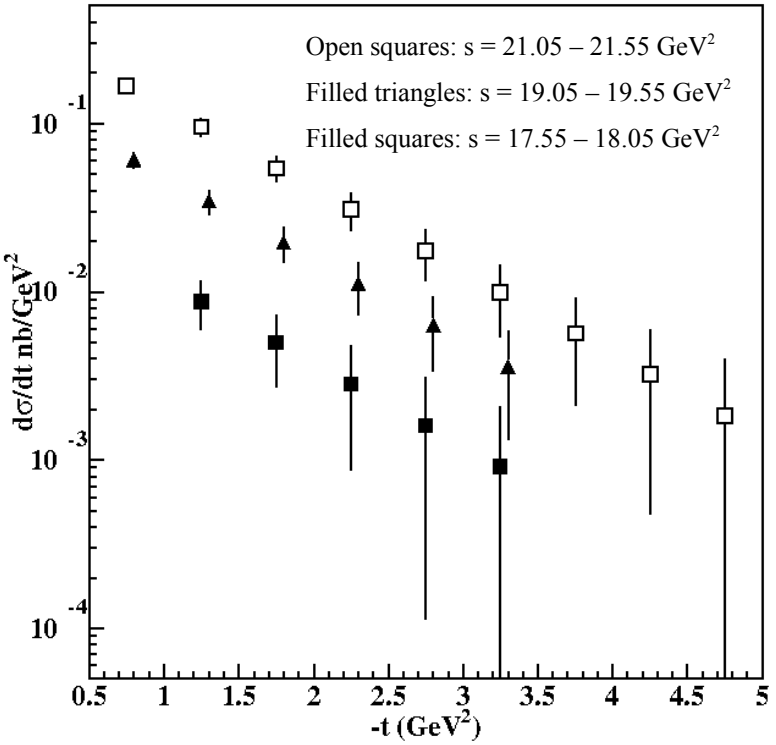
- CLAS12 has excellent acceptance for photoproduction of lepton pairs with a large invariant mass over a wide range in s and t.

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

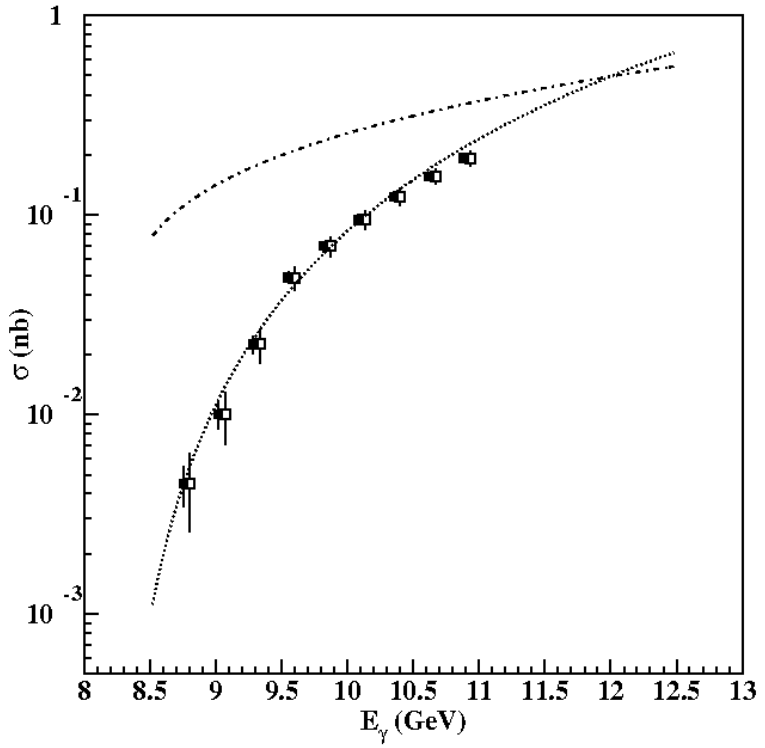


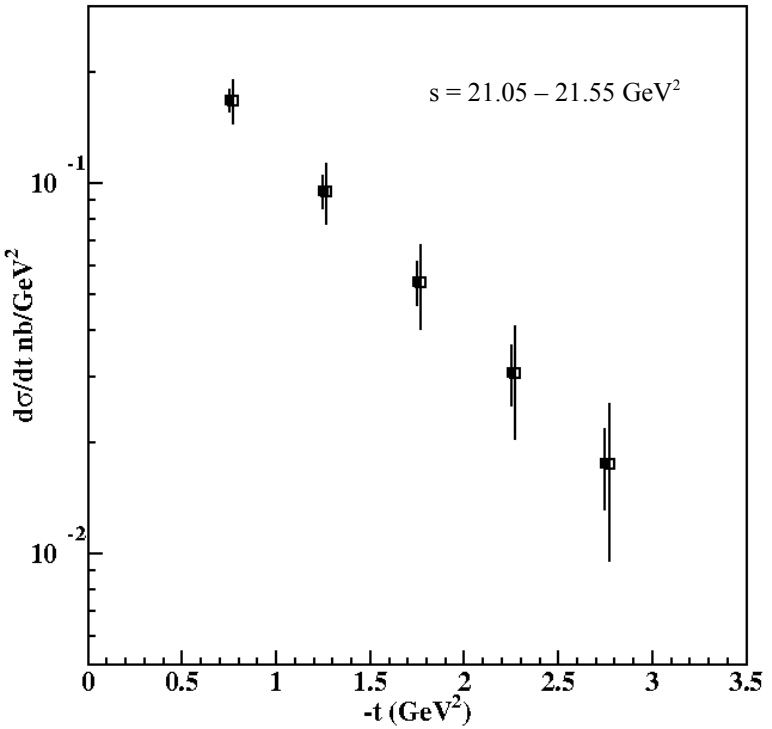
t-dependence in narrow bins of *s* for a total cross section given by the lower curve on the left

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

Approved CLAS12 beam time with nuclear targets

Proposal	Physics	Contact	Rating	Days	Group	Energy	Target
E12-07-104	Neutron magnetic form factor	Gilfoyle	A-	30			
PR12-11-109 (a)	Dihadron DIS production	Avakian	-				
E12-09-007a	Study of partonic distributions in SIDIS kaon production	Hafidi	A-	56	90	11	liquid D2 target
E12-09-008	Boer-Mulders asymmetry in K SIDIS w/ H and D targets	Contalbrigo	A-	TBA			
E12-11-003	DVCS on neutron target	Niccolai	A	90			
E12-06-109	Longitudinal Spin Structure of the Nucleon	Kuhn	A	80			
E12-06- 119(b)	DVCS on longitudinally polarized proton target	Sabatie	A	120			
E12-07-107	Spin-Orbit Correl. with Longitudinally polarized target	Avakian	A-	103			
PR12-11-109 (b)	Dihadron studies on long. polarized target	Avakian	-		170	11	NH3 ND3
E12-09-007(b)	Study of partonic distributions using SIDIS K production	Hafidi	A-	110			
E12-09-009	Spin-Orbit correlations in K production w/ pol. targets	Avakian	B+	103			
E12-06-106	Color transparency in exclusive vector meson production	Hafidi	B+	60	60	11	Nuclear
E12-06-117	Quark propagation and hadron formation	Brooks	A-	60	60	11	Nuclear
E12-10-102	Free Neutron structure at large x	Bueltman	A	40	40	11	Gas D2

Timelike Compton Scattering (TCS)

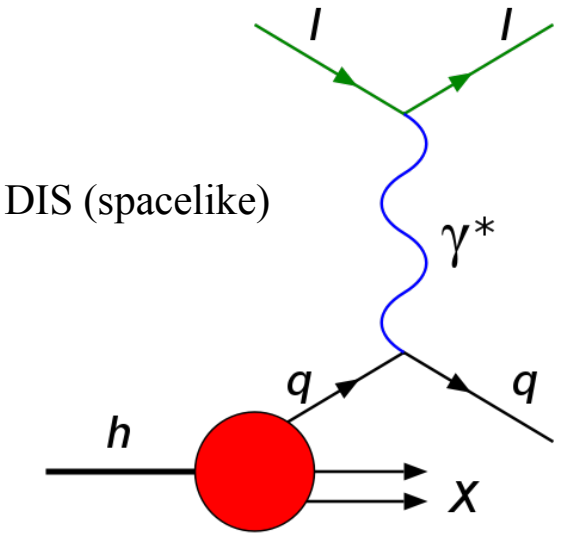
Timelike-spacelike correspondence and the universality of GPDs

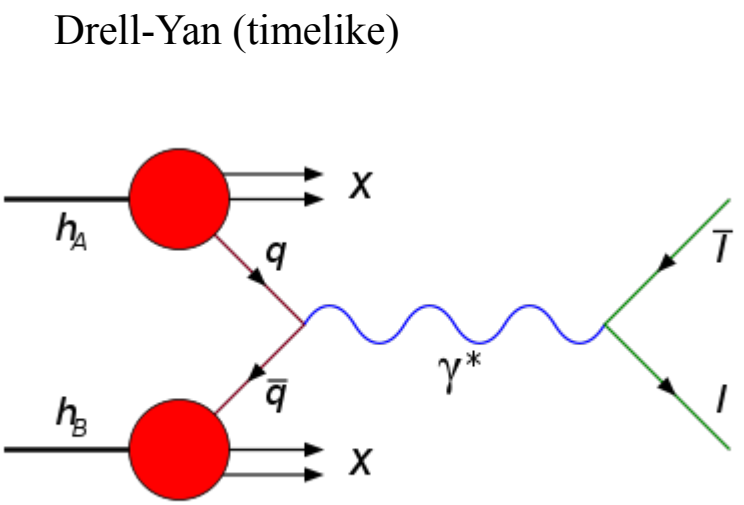
- Of fundamental importance for the GPD program

Real (and imaginary) part of Compton amplitude

- Straightforward access through azimuthal asymmetry of lepton pair
- Input for global analysis of Compton Form Factors (and GPDs)

Deep Inelastic Scattering (DIS) and Drell-Yan

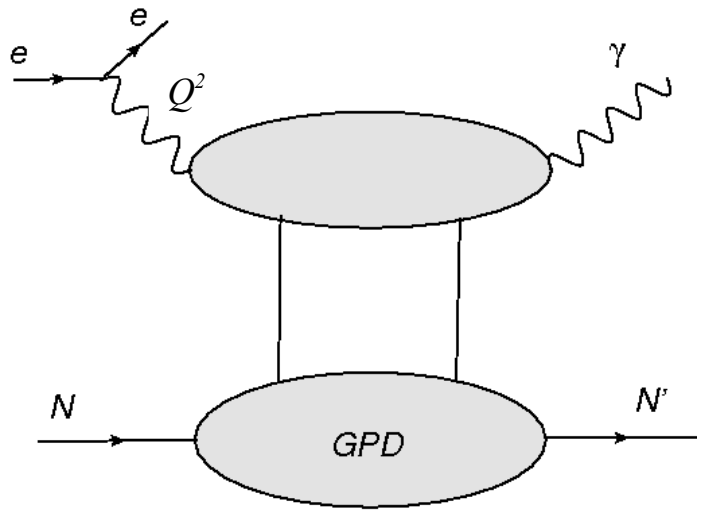




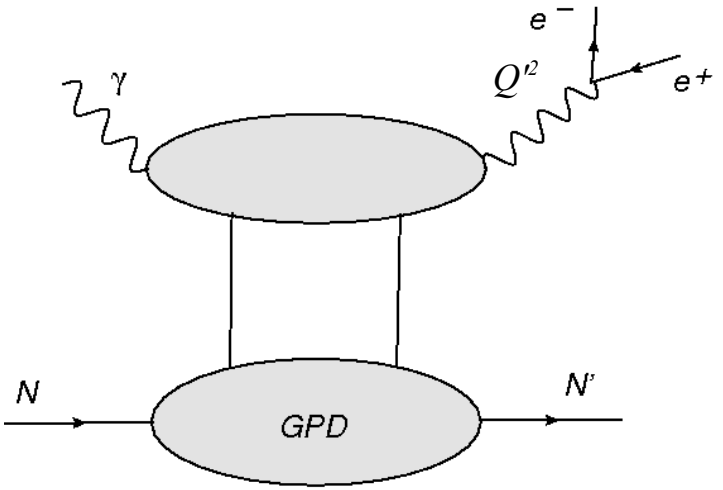
- The spacelike DIS and timelike Drell-Yan processes both factorize into a partonic cross section and a Parton Distribution Function (PDF)
  - Measurements of both demonstrated the universality of PDFs

DVCS and TCS

(spacelike) Deeply Virtual Compton Scattering

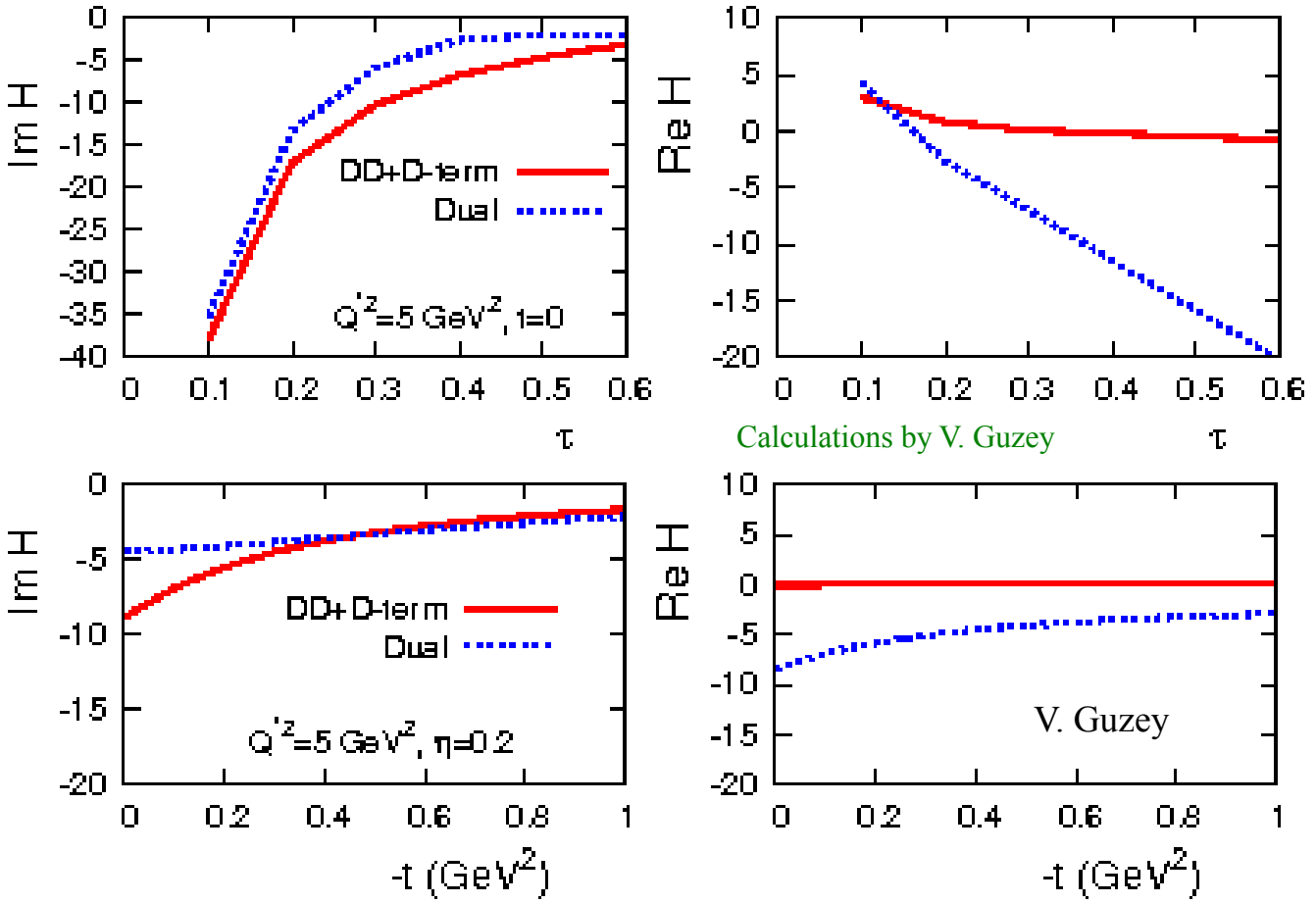


Timelike Compton Scattering



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

Real part at large x important for GPD models



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

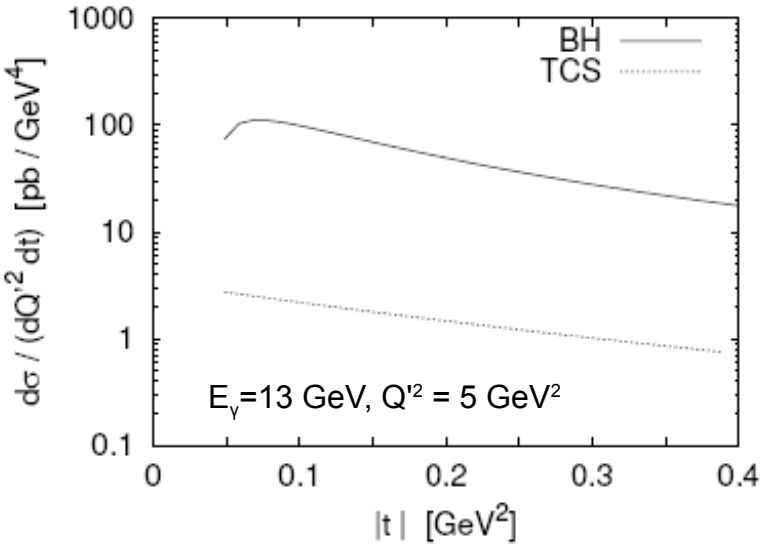
$$\eta = \frac{\tau}{2 - \tau}$$

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

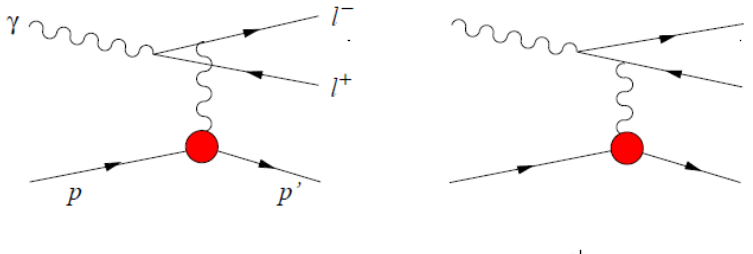
$Q'^2 = M^2_{e+e-}$ is the timelike virtuality of the outgoing photon (→ hard scale)

Photoproduction of lepton pairs

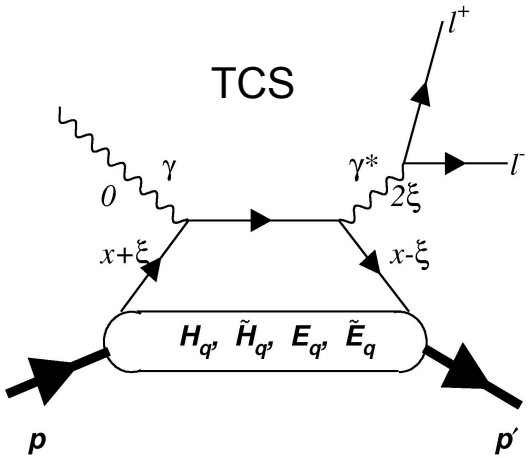
E. Berger *et al.*, Eur. Phys. J. C23, 675 (2002)



Bethe-Heitler (BH)

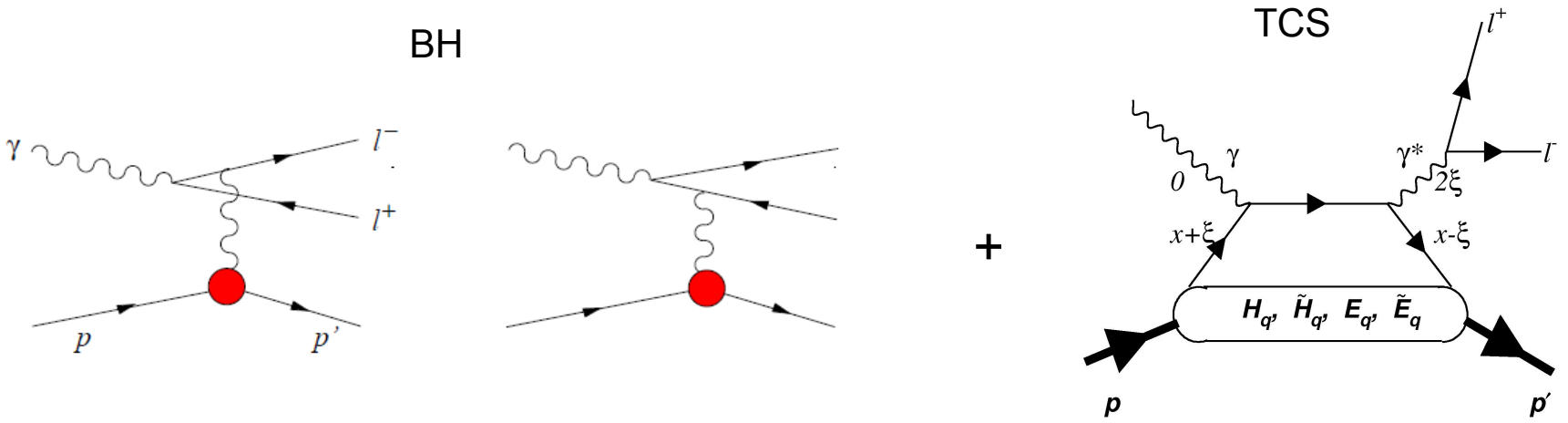


TCS



- 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



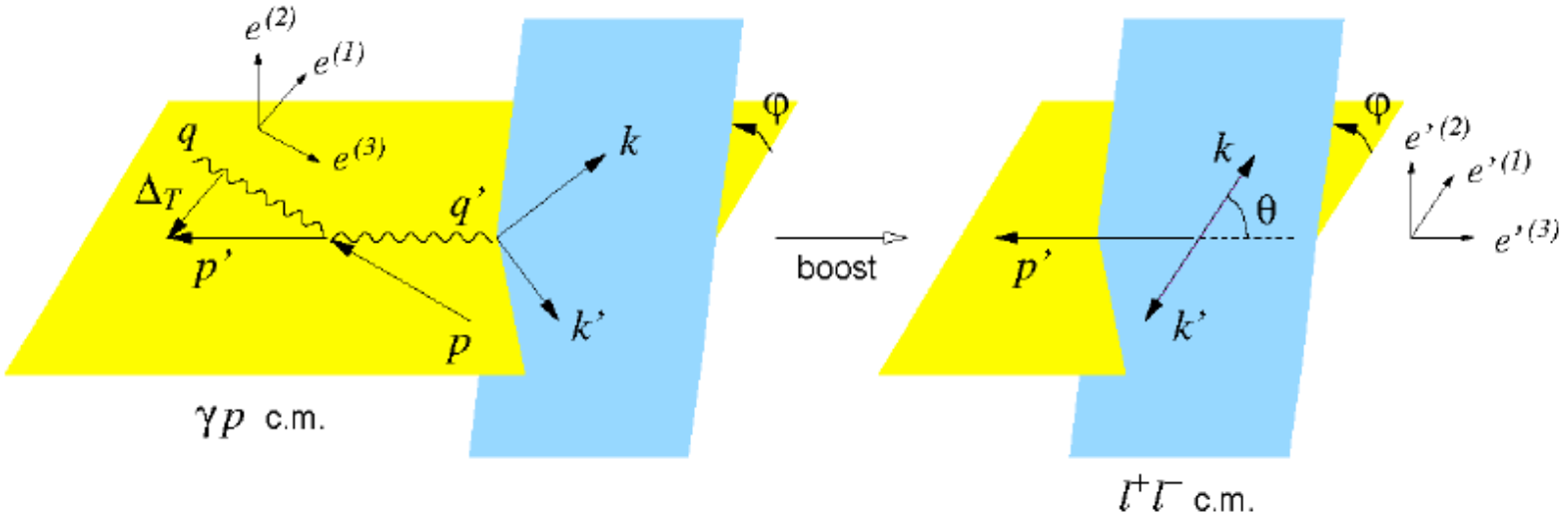
$$\frac{d\sigma^4}{dQ'^2\,dt\,d(\cos\theta)\,d\phi} = |BH|^2 + I(BH\cdot TCS) + |TCS|^2$$

- 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.

TCS cross section and the interference term

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

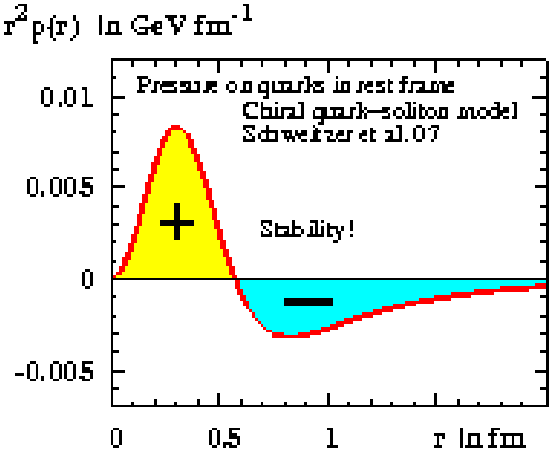
$$\frac{d\sigma_{INT}}{dQ'^2\, dt\, d\cos\theta\, d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\cos\varphi\frac{1+\cos^2\theta}{\sin\theta}\mathrm{Re}\,\tilde{M}^{--}$$

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

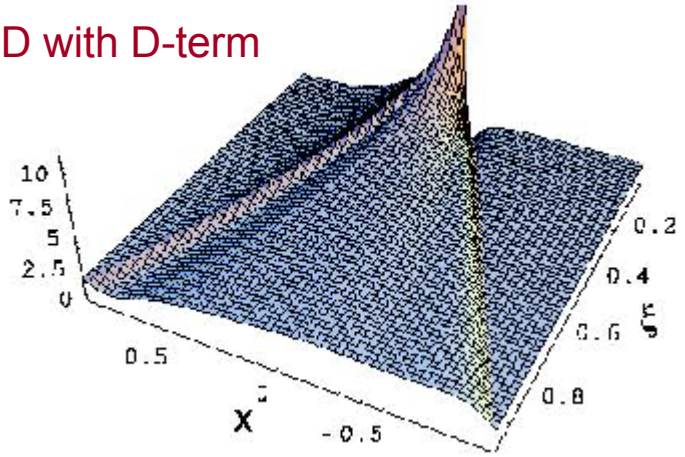
$$\mathcal{H}(\xi,t) = \sum_q e_q^2 \int_{-1}^{1} dx \left(\frac{1}{\xi-x+i\epsilon} - \frac{1}{\xi+x+i\epsilon}\right) H^q(x,\xi,t)$$

The D-term and the pressure balance in the nucleon

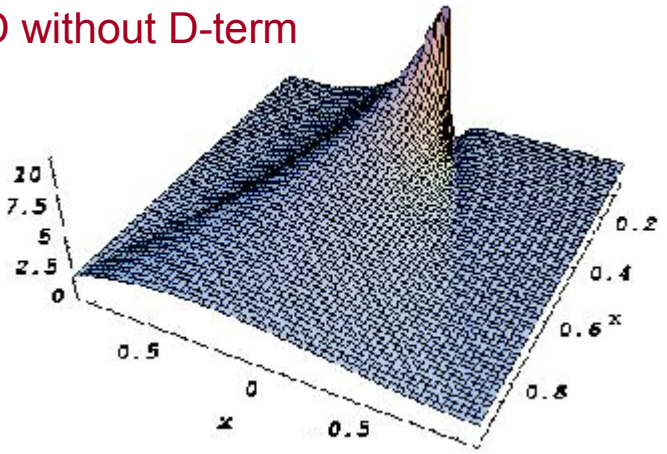
$$H(x,\xi) = H_{DD}(x,\xi) + \theta(\xi - |x|)\frac{1}{N_f} D\left(\frac{x}{\xi}\right)$$



GPD with D-term



GPD without D-term



- The D-term contributes only to the real part of the Compton amplitude

First measurements at 6 GeV

- Cosine moment of weighted cross sections

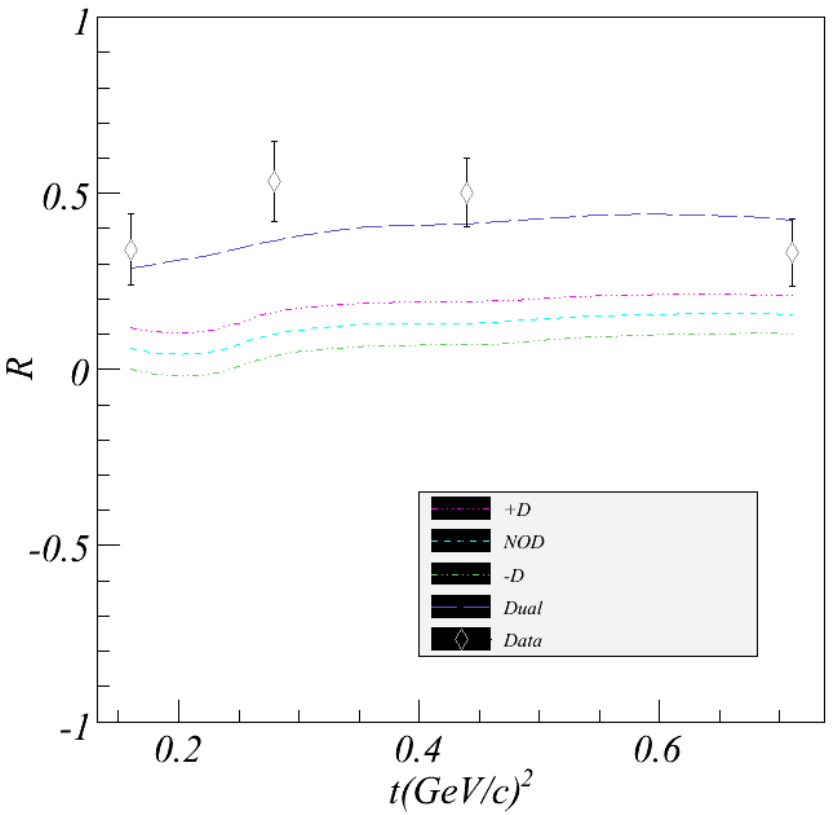
$$\frac{dS}{dQ^2\,dt\,d\varphi} = \int \frac{L(\theta,\varphi)}{L_0(\theta)} \frac{d\sigma}{dQ^2\,dt\,d\varphi\,d\theta}\, d\theta$$

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

- Numerator is proportional to $\tilde{\tilde{M}}^{--}$
  - cos φ part of interference term

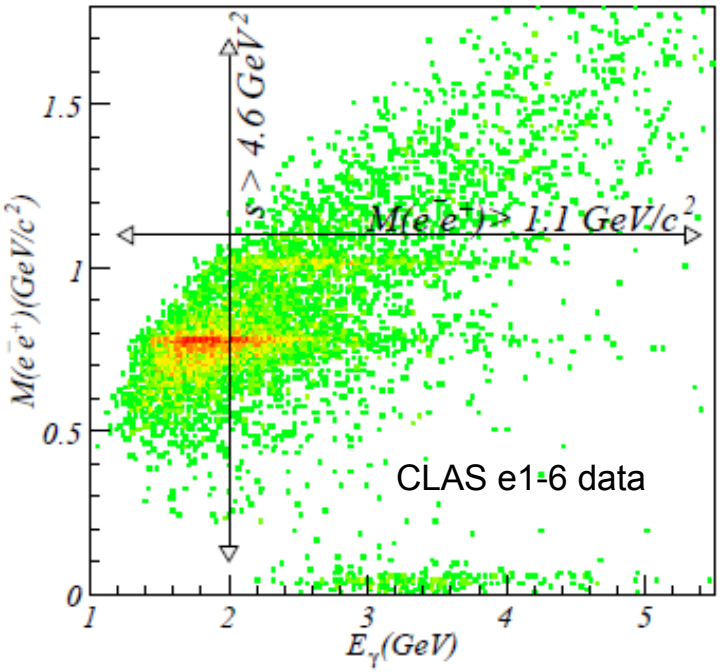
- R can be compared directly with GPD models

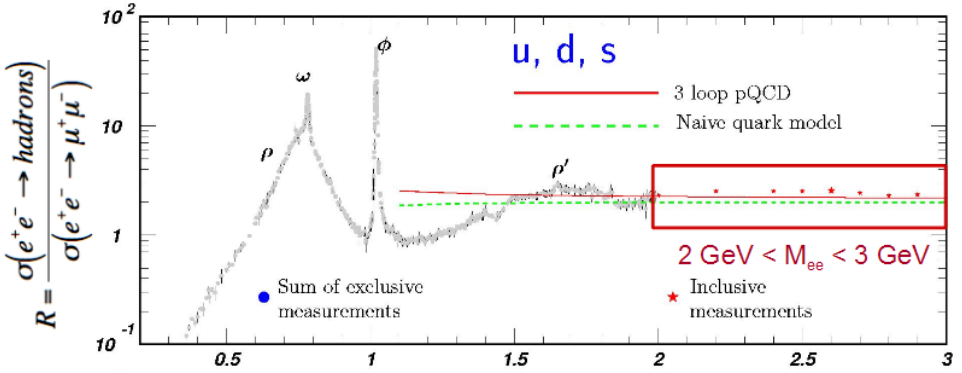
- Analysis of 6 GeV data with tagged real photons is underway



Comparison of results by R. Paremuzyan *et al* from e1-6/e1f with calculations by V. Guzey.

From 6 to 12 GeV



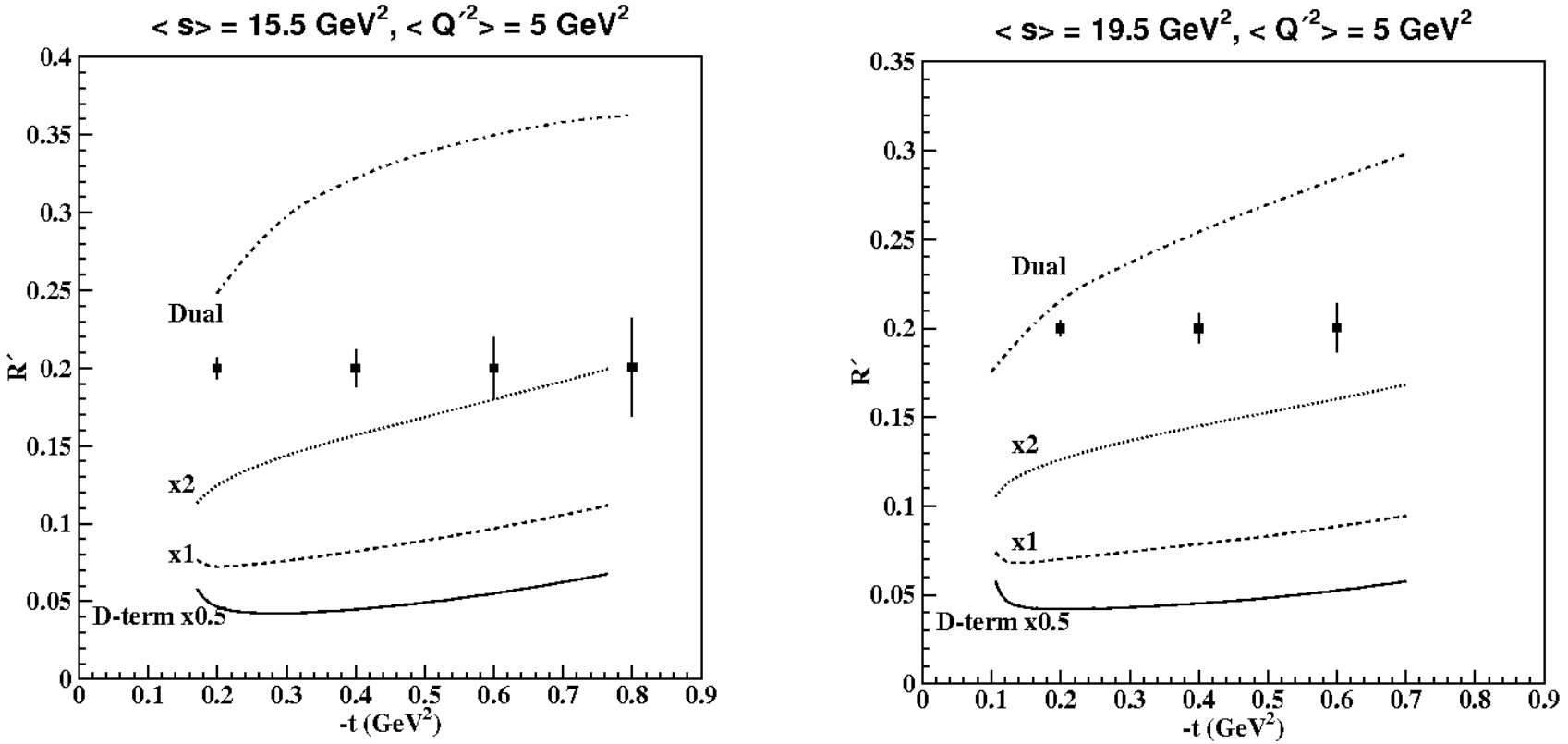


- 6 GeV kinematics are limited to $M_{e^+e^-} < 2$ GeV.
- 12 GeV extends this mass (Q') range up to 3 GeV

- 6 GeV data were important for developing 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

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 acceptance, for two bins in photon energy, for the lowest Q'^2 bin above the ρ' resonance.
- Different values of the D-term are only shown for the double distribution

Summary

CLAS12 experiment E12-12-001 will measure TCS and J/Ψ

J/Ψ photoproduction near threshold

- Establish reaction mechanism
- Access to gluonic structure of the nucleon at large x

Timelike Compton Scattering (TCS)

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

Backup

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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(Dated: May 4, 2012)

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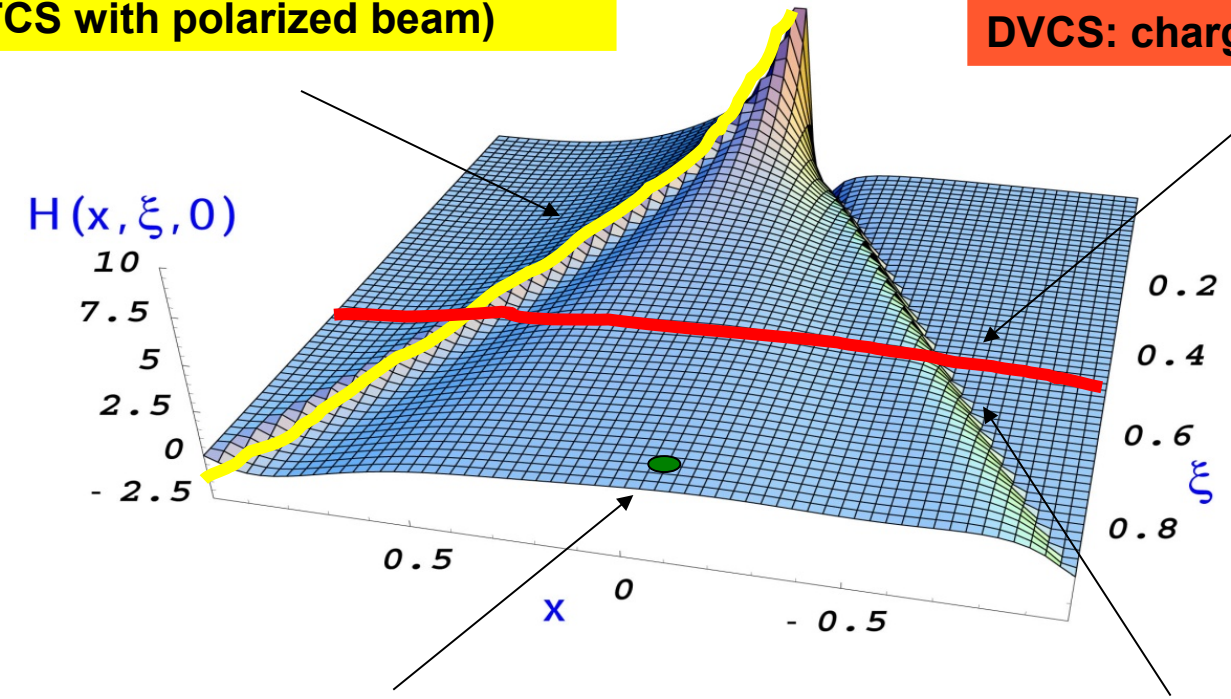
Probing GPDs through Compton scattering

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

(Re)
TCS: azimuthal asymmetry
DVCS: charge asymmetry



(Im, x ≠ ξ, x < |ξ|)
Double DVCS

(|Re|²)
DVCS: cross section

Interference term

To leading order, in terms of helicity amplitudes:

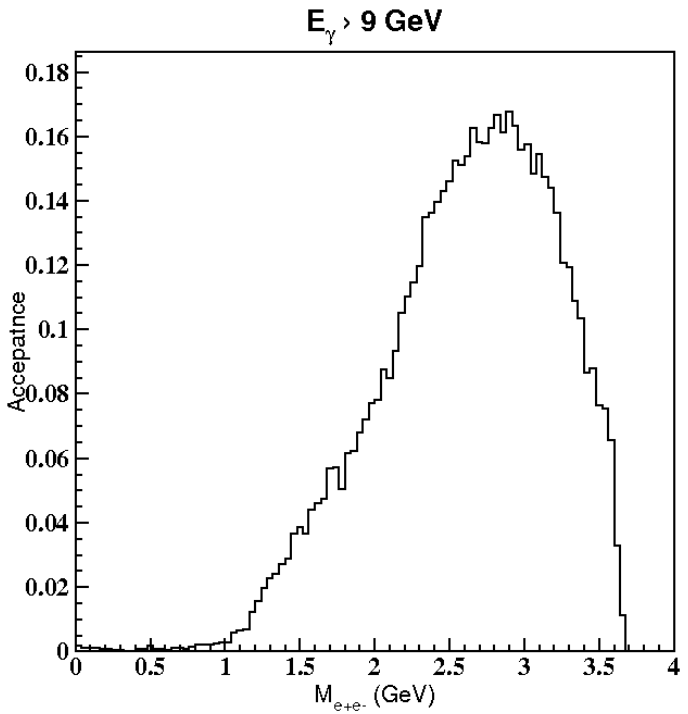
$$\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\Big[\cos\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Re}\,\tilde{M}^{--} - \cos 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Re}\,\tilde{M}^{0-}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

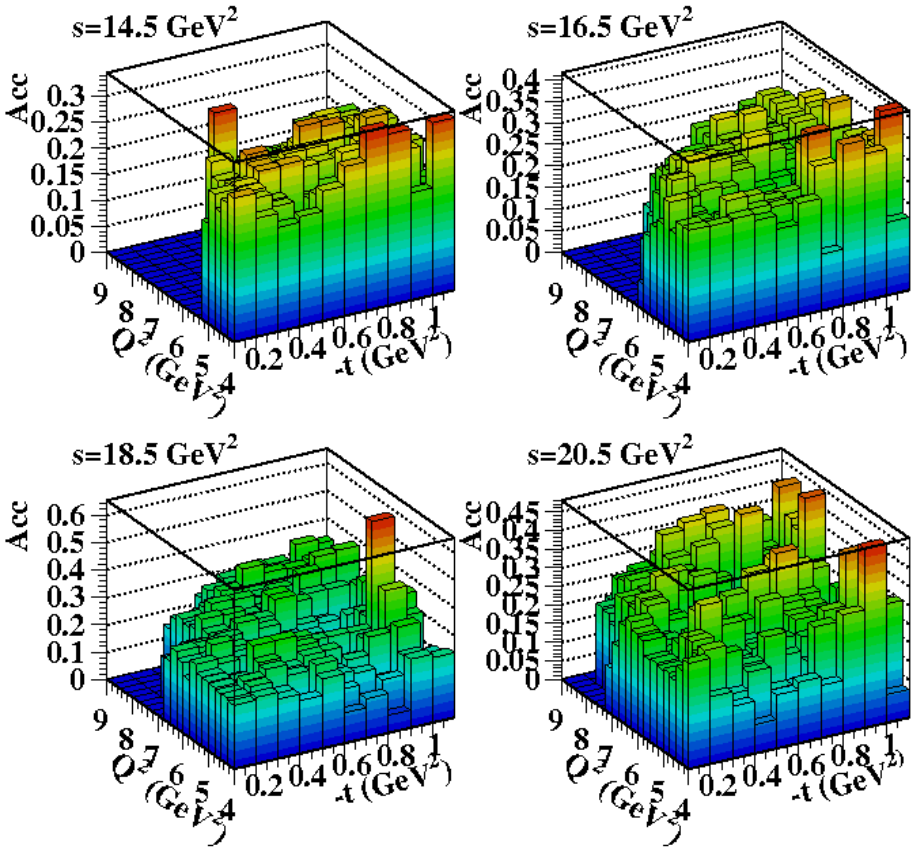
$$-\nu\,\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\Big[\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\,\tilde{M}^{--} - \sin 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Im}\,\tilde{M}^{0-} + \sin 3\varphi\,\sin\theta\,\mathrm{Im}\,\tilde{M}^{+-}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

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

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

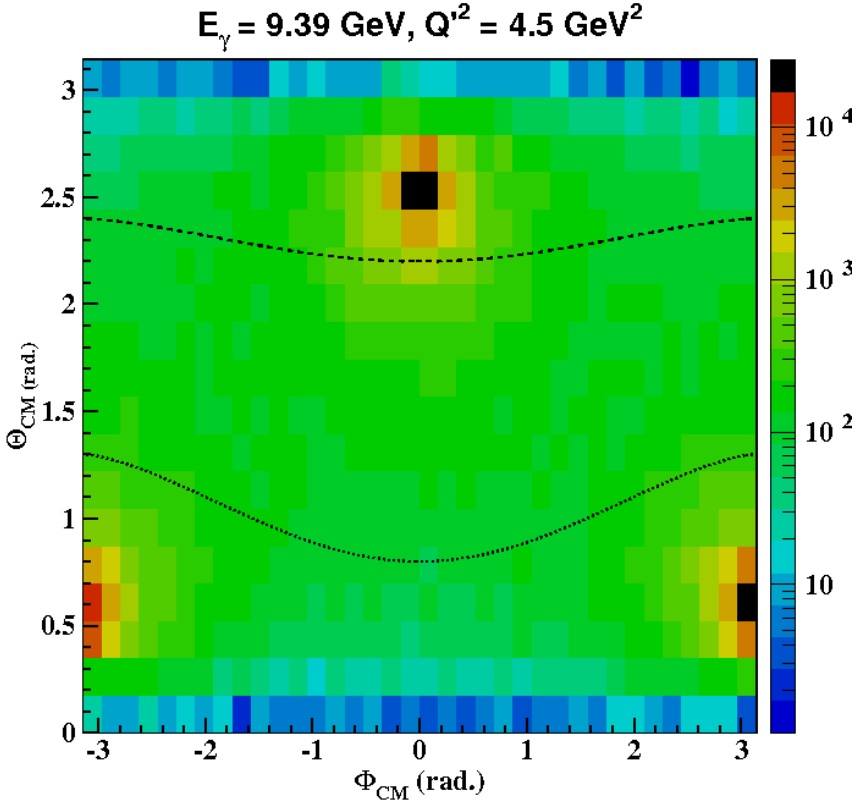
Acceptance in Q'^2, s, and t



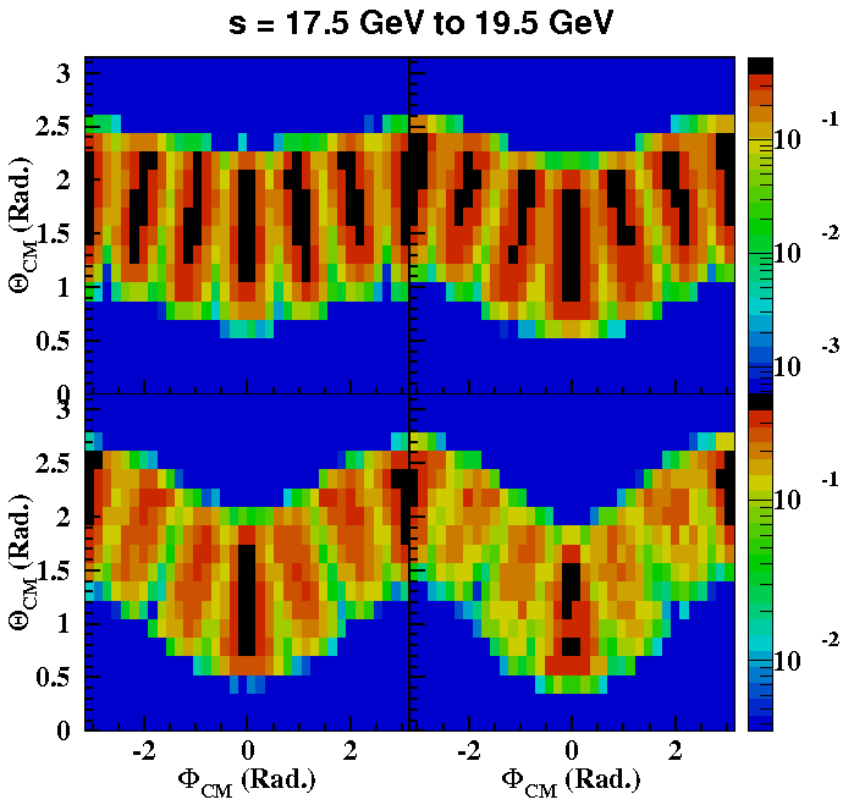


- CLAS12 has excellent acceptance for photoproduction of lepton pairs with a large invariant mass over a wide range in s and t.

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



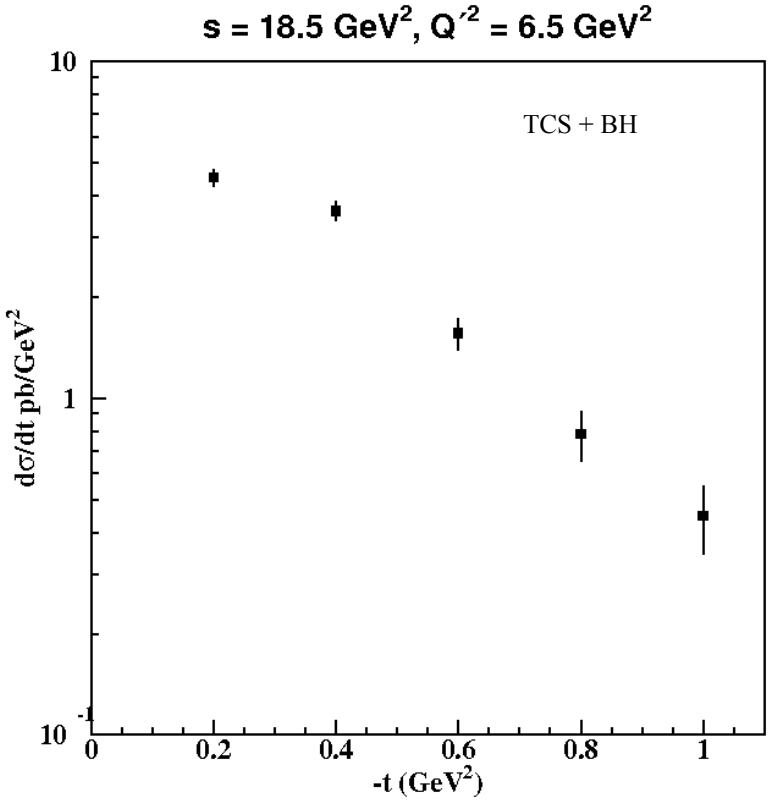
Generated events. Regions dominated by BH fall outside of the contour indicating the CLAS acceptance.

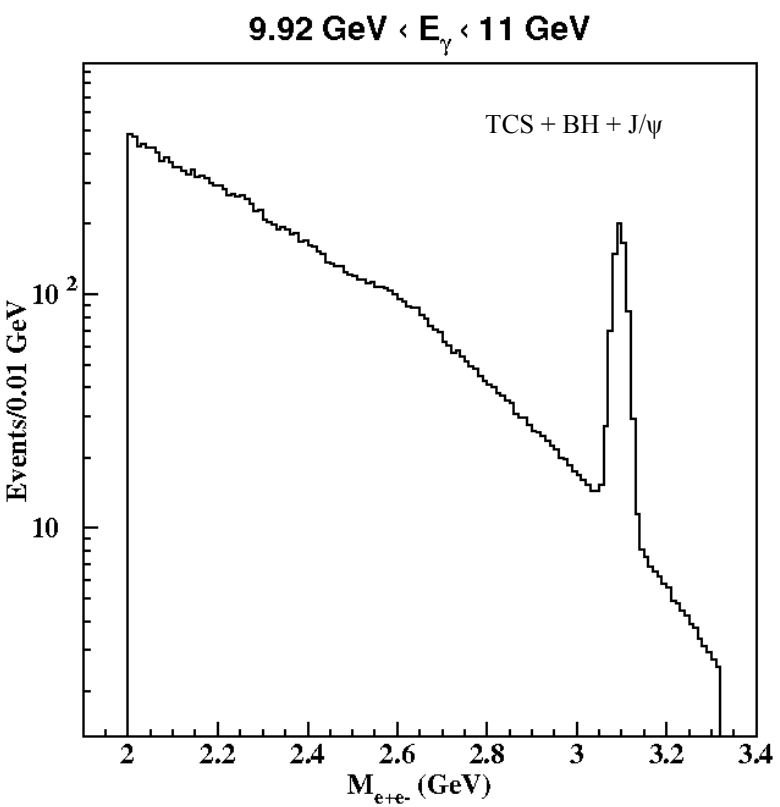


Accepted events for four t-bins. The observable R' is integrated over the CLAS acceptance

Projected results – 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.