Timelike Compton Scattering
and J/ψ photoproduction at JLab 12 GeV

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Outline

Introduction to Timelike Compton Scattering

Approved JLab 12 GeV TCS experiments

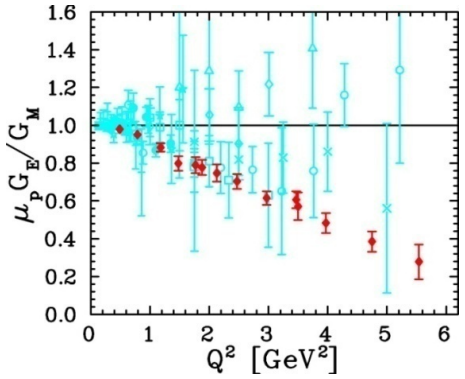
- CLAS experiment E12-12-001

  Also first measurement of J/ψ near threshold and search for LHCb pentaquark

- SoLID experiment E12-12-006A

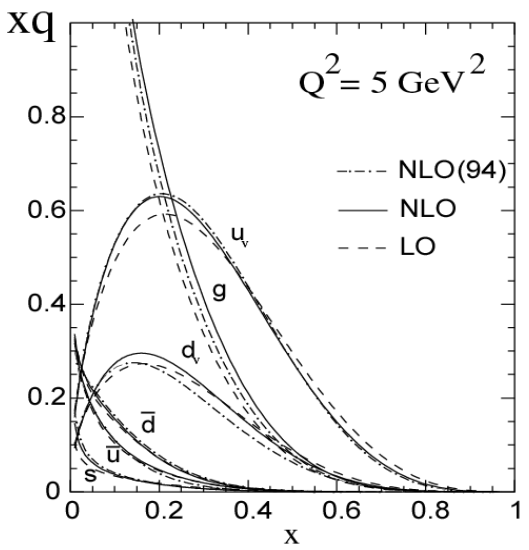
Future TCS measurements at JLab 12 GeV

Partons in the nucleon

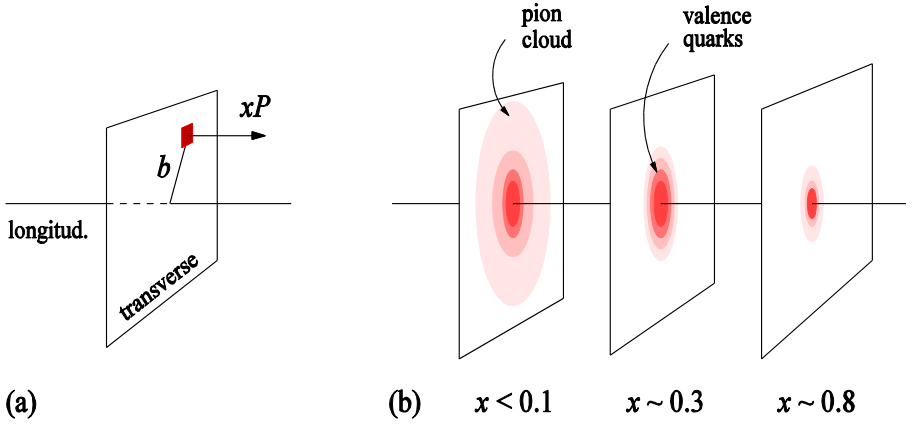


Elastic form factors

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



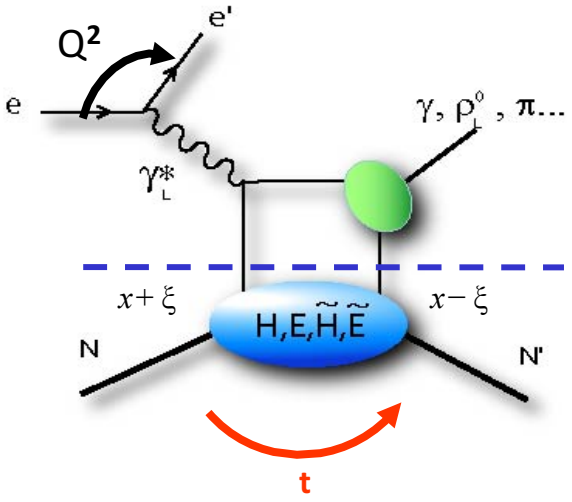
Parton Distribution Functions
Longitudinal momentum distributions

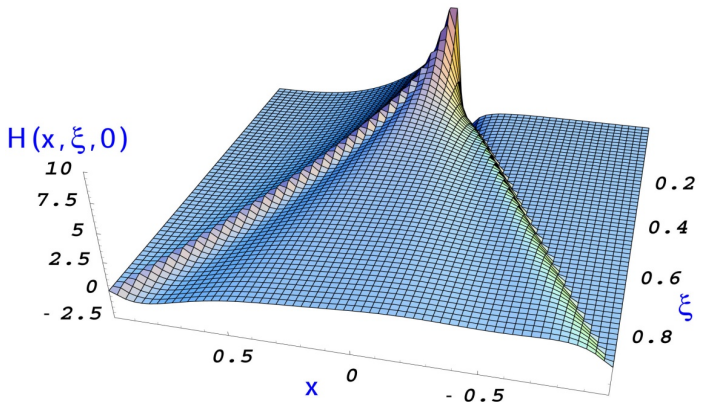


Generalized Parton Distributions

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)

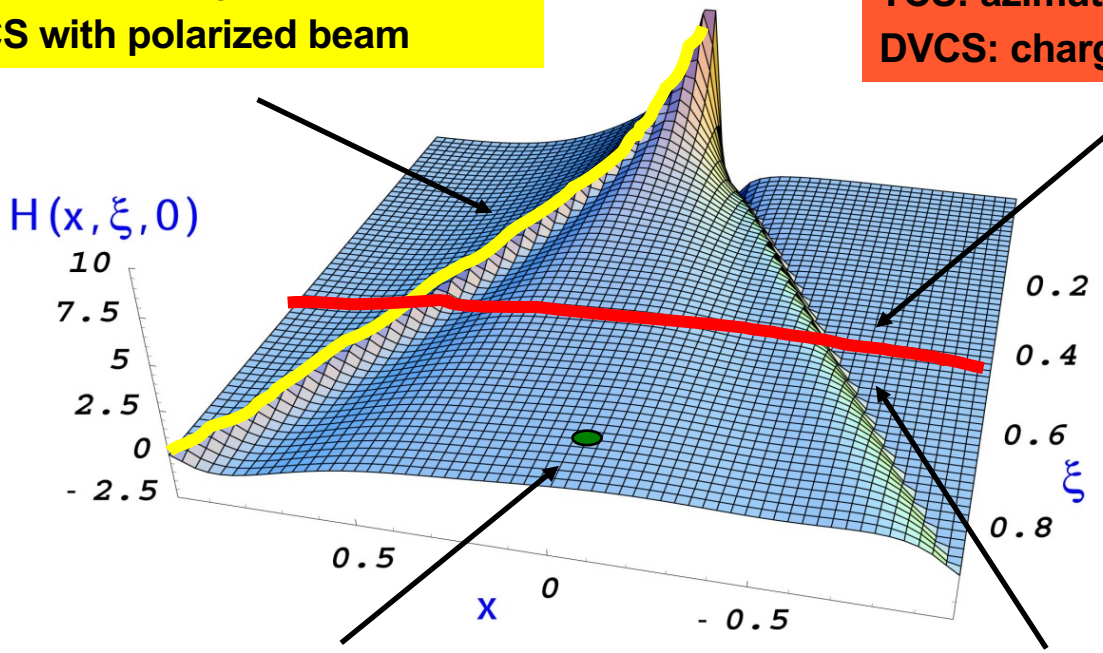
$$H(x,\xi=0,t=0) = q(x)$$
$$H(x,\xi=0,t=0) = \Delta q(x)$$

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

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

Timelike Compton Scattering (TCS)

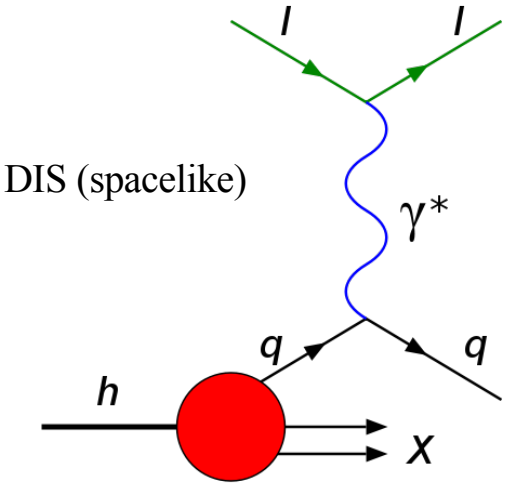
Timelike-spacelike correspondence and the universality of GPDs

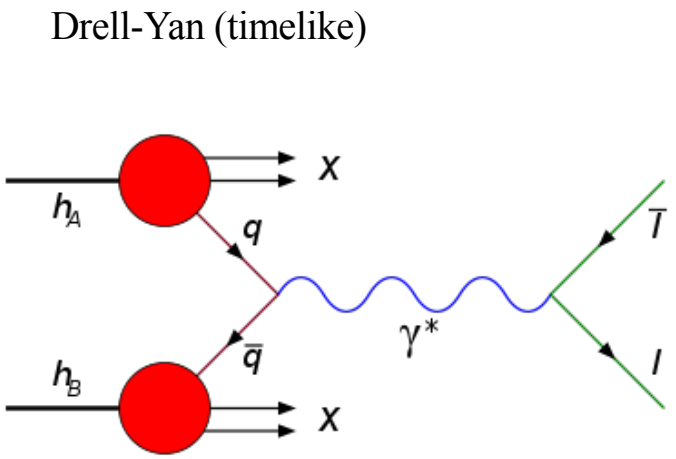
- Of fundamental importance for the GPD program

Real (and imaginary) part of Compton amplitude

- Straightforward access through azimuthal asymmetry of lepton pair
- Input for fits of Compton Form Factors

Deep Inelastic Scattering (DIS) and Drell-Yan

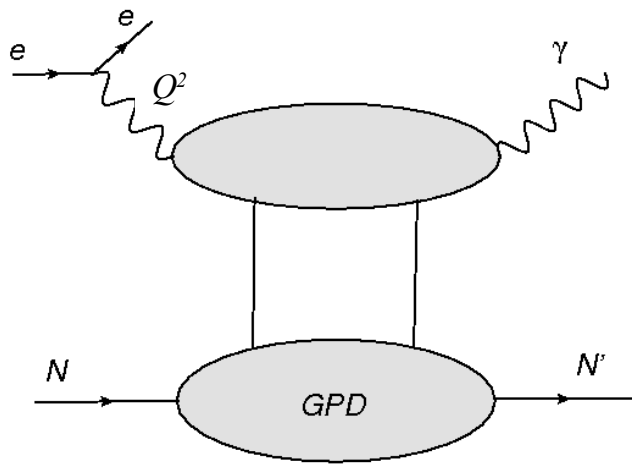




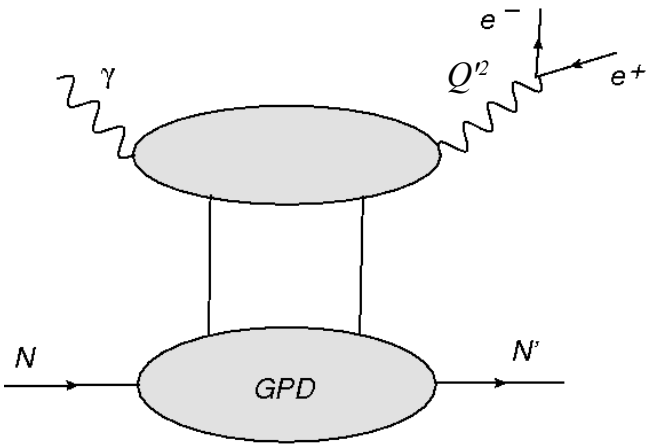
- The spacelike DIS and timelike Drell-Yan processes both factorize into a partonic cross section and a Parton Distribution Function (PDF)
  - Measurements of both demonstrated the universality of PDFs

DVCS and TCS

(spacelike) Deeply Virtual Compton Scattering

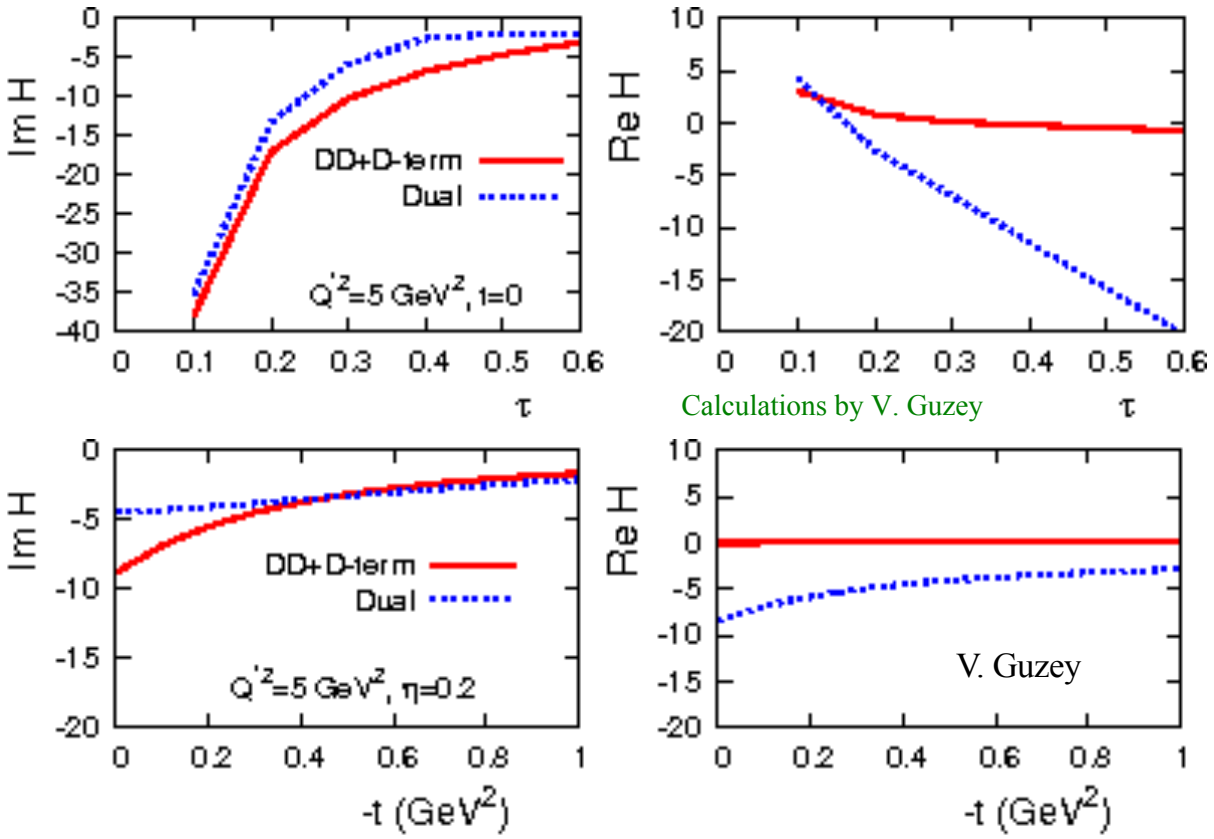


Timelike Compton Scattering



- 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



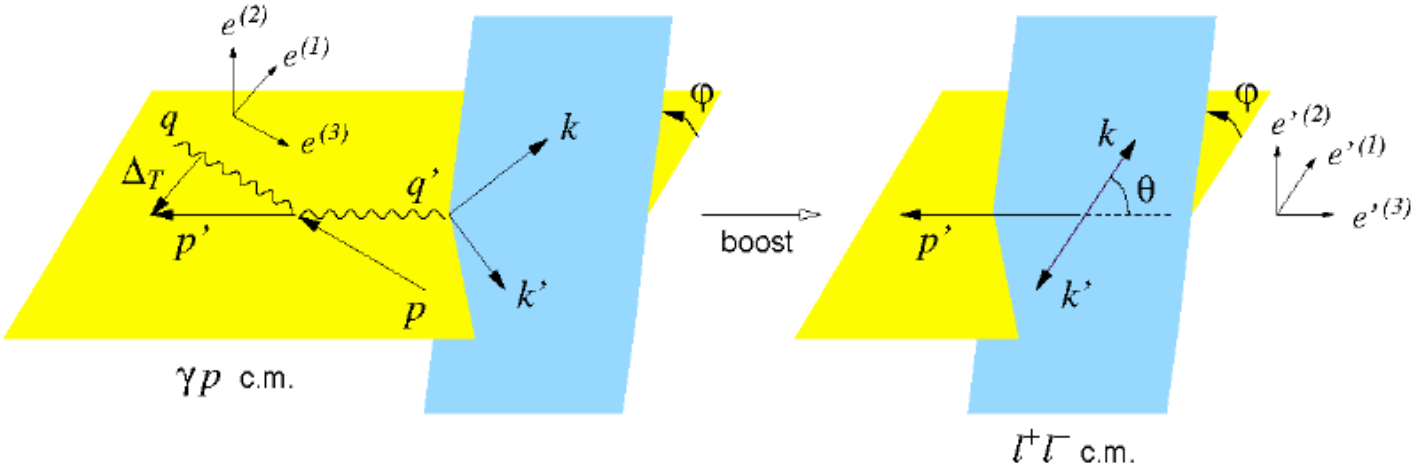
$$\tau = \frac{Q'^2}{s - M_p^2}$$

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

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

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

TCS kinematics

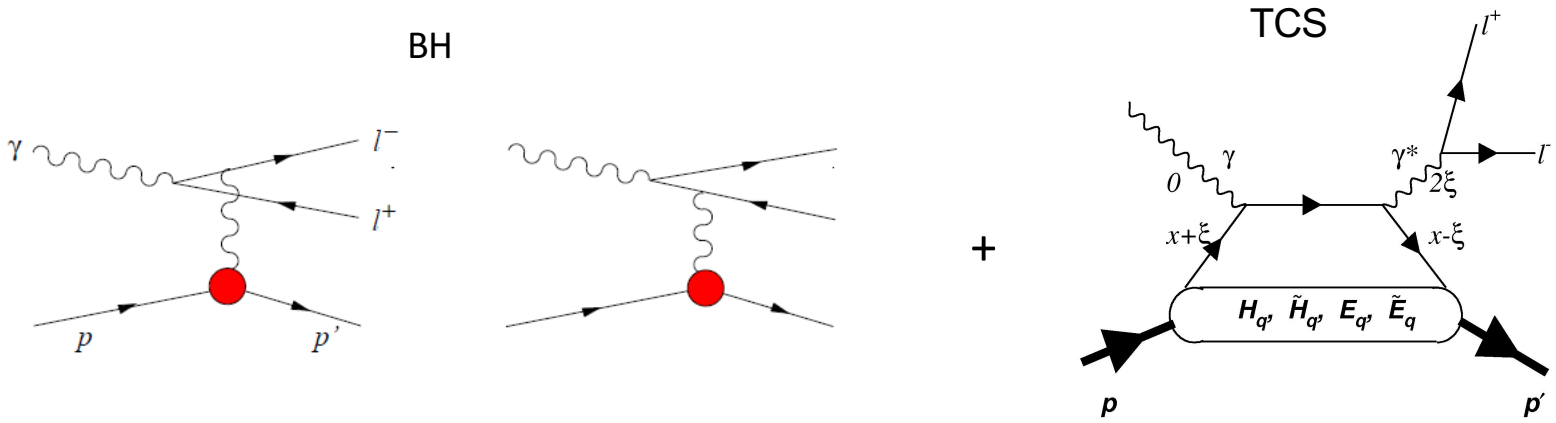


- k,k' = momentum of e^-, e^+
- θ = angle between the scattered proton and the electron
- φ = angle between lepton scattering- and reaction planes

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

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

TCS-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

TCS cross section and the interference term

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

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

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

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

First measurements at 6 GeV

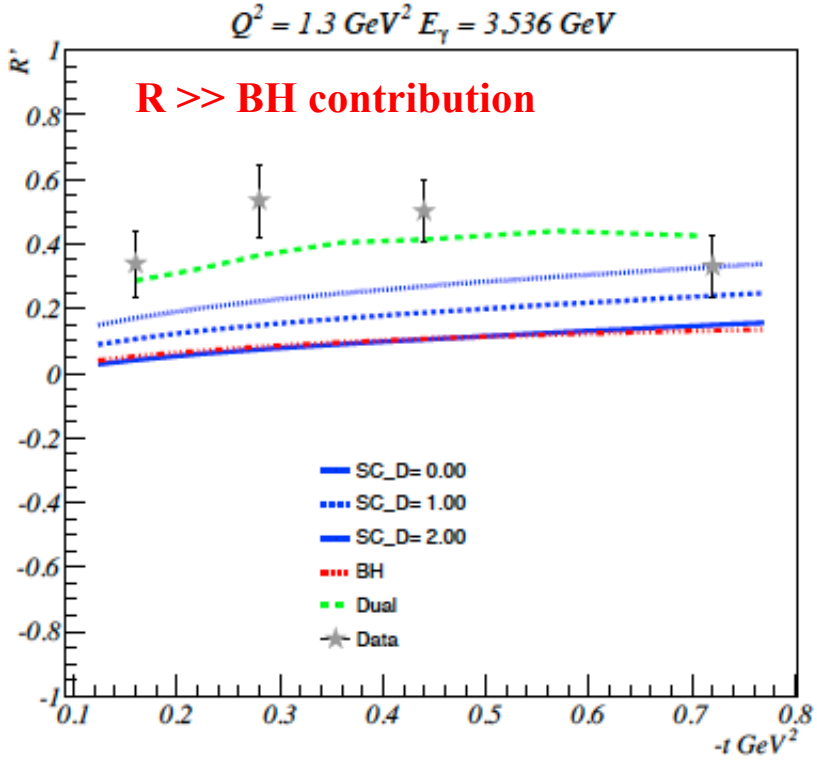
- Cosine moment of weighted cross sections

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

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

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

- R can be compared directly with GPD models



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

Imaginary part accessed through circular polarization

To leading order, in terms of helicity amplitudes:

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

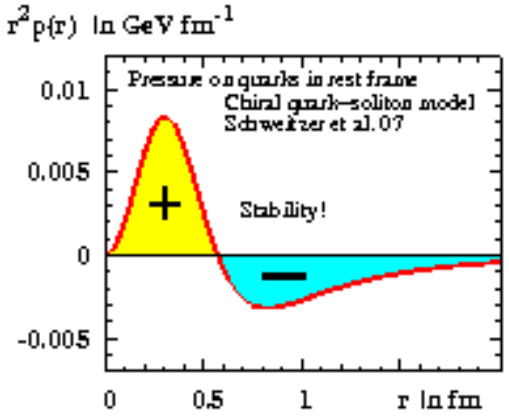
$$-\nu\,\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\Big[\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\,\tilde{M}^{--} - \sin 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Im}\,\tilde{M}^{0-} + \sin 3\varphi\,\sin\theta\,\mathrm{Im}\,\tilde{M}^{+-}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

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

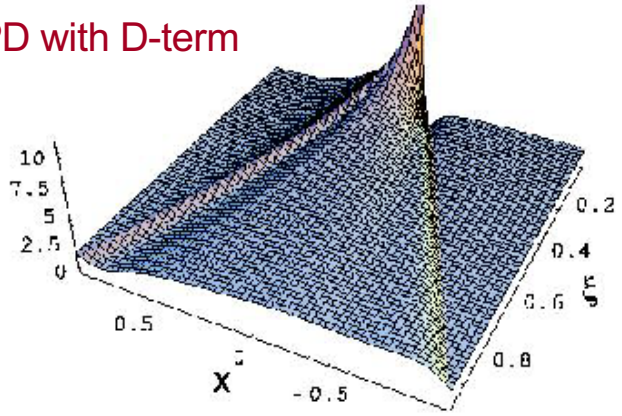
$$\frac{1}{2}\sum_{\lambda,\lambda'}|M^{\lambda'-,\lambda-}|^2 = (1-\eta^2)\Big(|\mathcal{H}_1|^2 + |\tilde{\mathcal{H}}_1|^2\Big) - 2\eta^2\,\mathrm{Re}\Big(\mathcal{H}_1^*\,\mathcal{E}_1 + \tilde{\mathcal{H}}_1^*\,\tilde{\mathcal{E}}_1\Big) - \Big(\eta^2 + \frac{t}{4M^2}\Big)|\mathcal{E}_1|^2 - \eta^2\frac{t}{4M^2}|\tilde{\mathcal{E}}_1|^2,$$

The D-term and the pressure balance in the nucleon

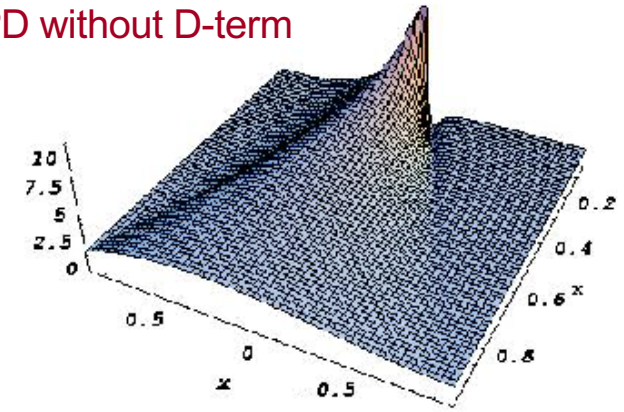
$$H(x,\xi) = H_{DD}(x,\xi) + \theta(\xi - |x|)\frac{1}{N_f} D\left(\frac{x}{\xi}\right)$$



GPD with D-term

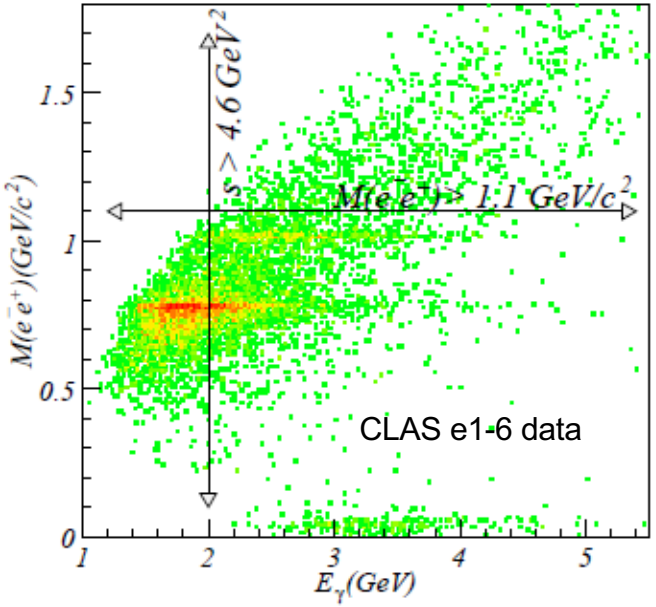


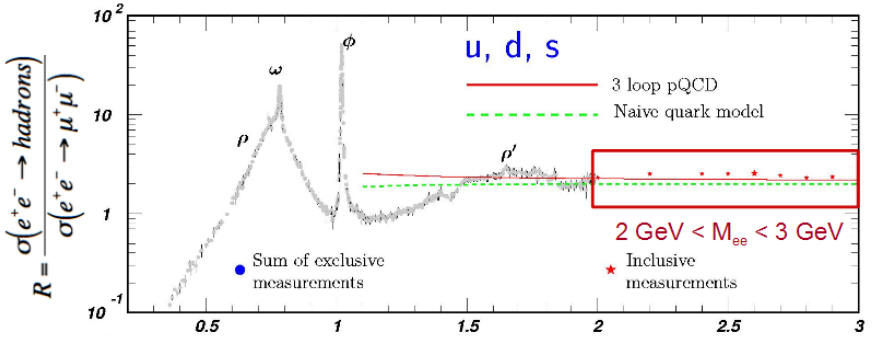
GPD without D-term



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

From 6 to 12 GeV

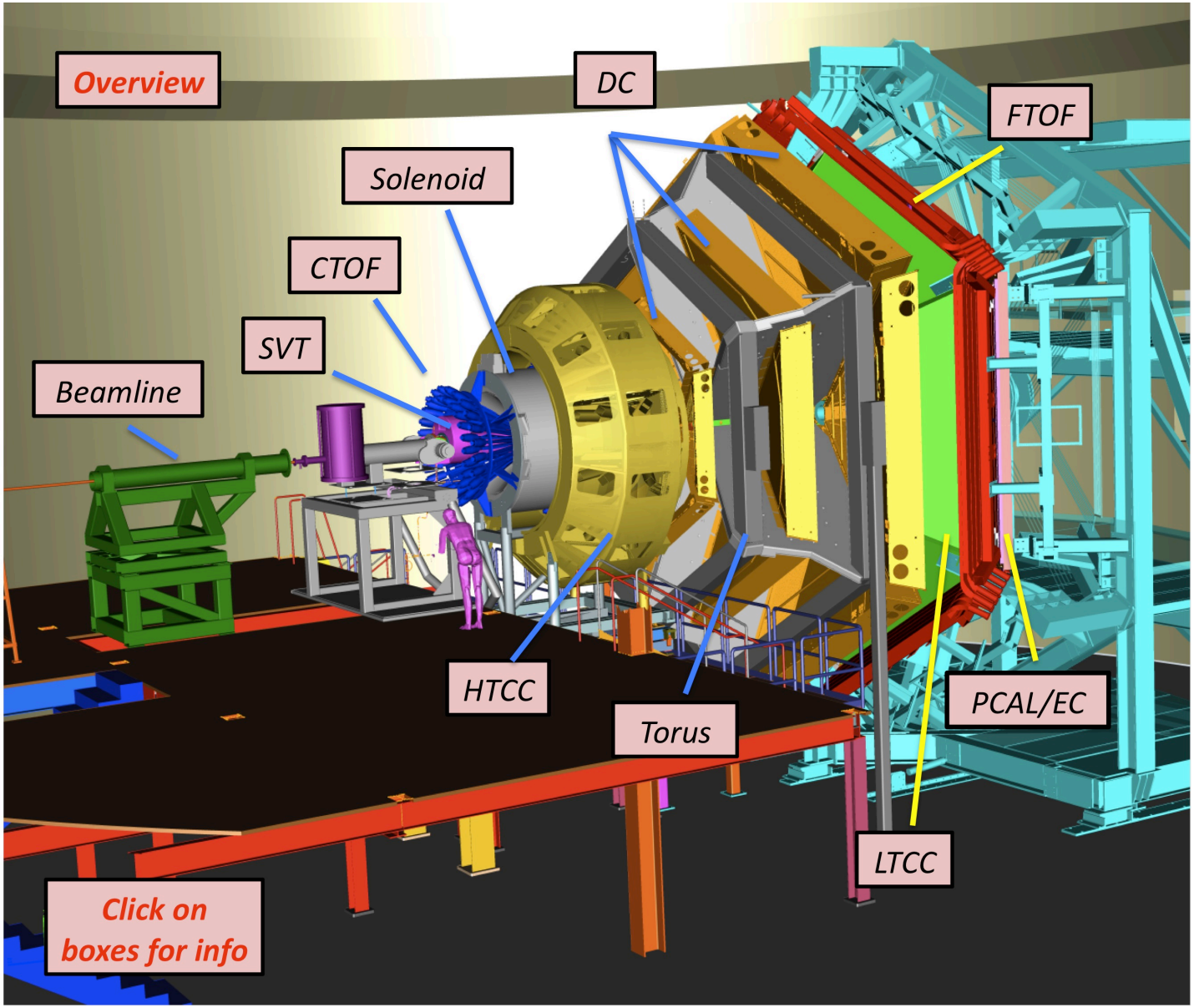




- 6 GeV kinematics are limited to $M_{e^+e^-} < 2$ GeV.
- 12 GeV extends this mass (Q') range up to 3 GeV

- 6 GeV data were important for developing methods
- 12 GeV will provide
  - 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

TCS and J/ψ photoproduction with CLAS12 in Hall B



Approved CLAS12 experiments

Proposal	Physics	Contact	Rating	Days	Group	New equipment	Energy	Run Group	Target
E12-06-108	Hard exclusive electro-production of π^0, η	Stoler	B	80	139	RICH (1 sector) Forward tagger	11	A F. Sabatié	liquid H_2
E12-06-112	Proton's quark dynamics in SIDIS pion production	Avakian	A	60					
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	A	80					
E12-09-003	Excitation of nucleon resonances at high Q^2	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-	120					
E12-12-007	Exclusive φ meson electroproduction with CLAS12	Stoler, Weiss	B+	60					
PR12-12-008	Photoproduction of the very strangest baryon	Guo	--	80					
E12-07-104	Neutron magnetic form factor	Gilfoyle	A-	30	90	Neutron detector RICH (1 sector) Forward tagger	11	B K. Hafidi	liquid D_2 target
PR12-11-109 (a)	Dihadron DIS production	Avakian	-	-					
E12-09-007a	Study of partonic distributions in SIDIS kaon production	Hafidi	A-	56					
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	170	Polarized target RICH (1 sector) Forward tagger	11	C S. Kuhn	NH_3 ND_3
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	-	-					
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	D	Nuclear
E12-06-117	Quark propagation and hadron formation	Brooks	A-	60	60		11	E	Nuclear
E12-10-102	Free Neutron structure at large x	Bueltman	A	40	40	Radial TPC	11	F	Gas D_2
TOTAL approved run time (PAC days)				1491	559				

E12-12-001

Approved for 100 PAC days as part of Run Group A, plus an additional 20 days with reverse torus polarity

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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The CLAS12 detector

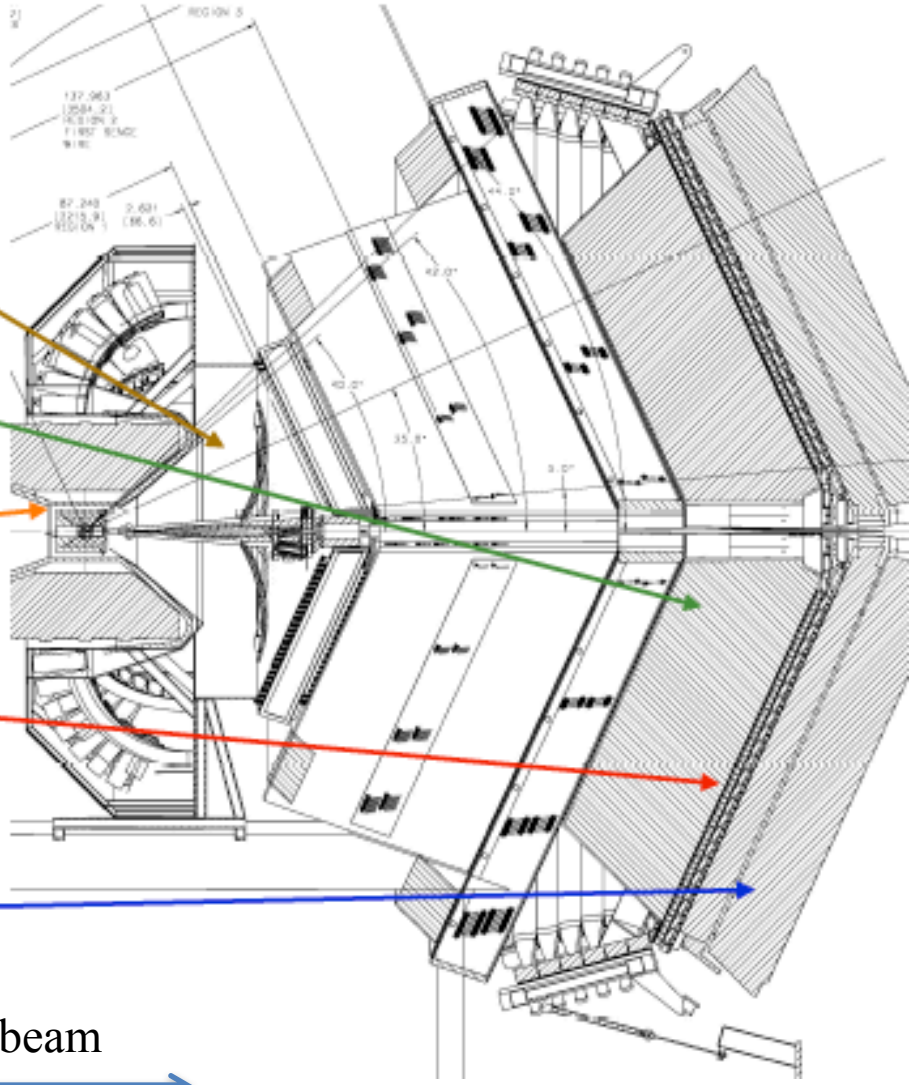
High Threshold Cherenkov Counter (HTCC) for e/π separation, $P_{th}^{\pi} > 4.7\ GeV/c$

Low Threshold Cherenkov Counter (LTCC) for e/π separation, $P_{th}^{\pi} > 2.7\ GeV/c$

Scintillator counters (cTOF) @ 50 cm from the target, time resolution of 60ps

Scintillator counters (fTOF) @ ~650cm from the target, time resolution of 80ps

Electromagnetic calorimeters (PCAL&EC), 54 layers of lead and scintillators, 22 r.l.

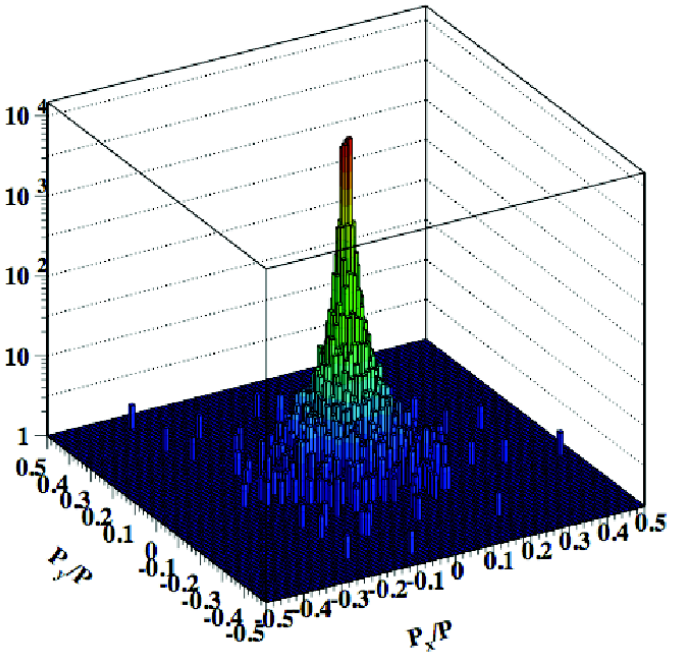


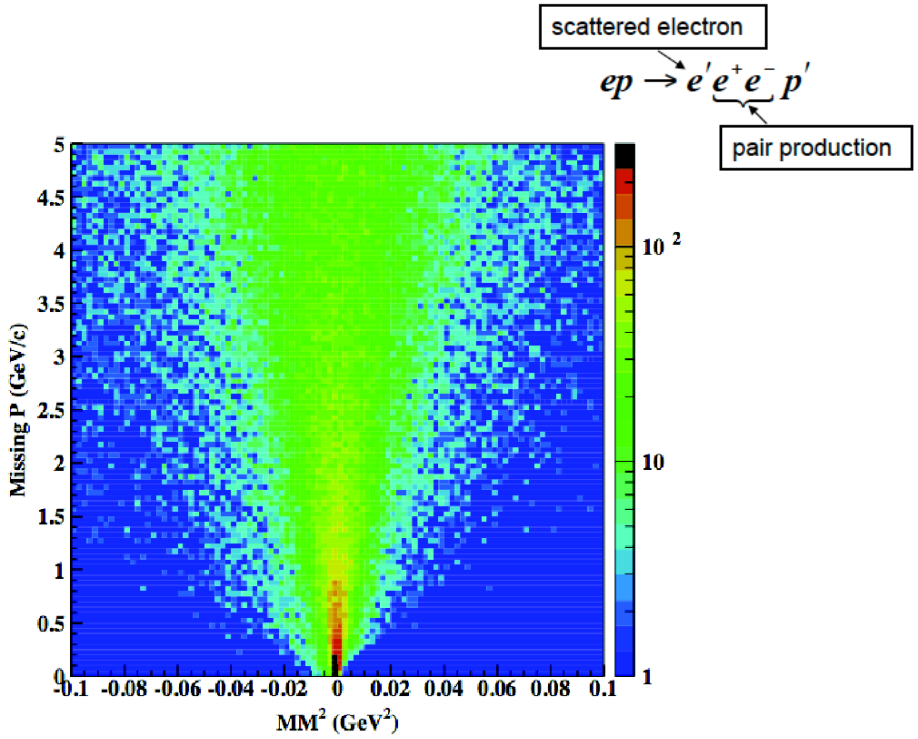
CLAS12 parameters (at max torus field)

Parameters	Forward Detector	Central Detector
Charged tracks:		
polar angular range (θ)	5° to 35°	35° to 125°
resolution:		
polar angle ($\delta\theta$)	< 1 mr	< 10 mr to 20 mr
azimuthal angle ($\delta\phi$)	< 4 mr	< 5 mr
momentum (δp/p)	$< 1\%$ at 5 GeV/c	$< 5\%$ at 1.5 GeV/c
Neutral particles:		
angular range (θ)	5° to 40°	40° to 125° (neutrons)
angular resolution ($\delta\theta$)	< 4 mr	< 10 mr
Energy resolution	$< 0.1/\sqrt{(E)}$	$< 5\%$
PID:		
e/π	full momentum range	NA
π/p	full momentum range	< 1.25 GeV/c
K/π	< 3 GeV/c	< 0.65 GeV/c
K/p	< 4 GeV/c	< 1 GeV/c

Luminosity: 10^{35} cm^{-2}s^{-1}

Exclusive quasi-real photoproduction in CLAS12

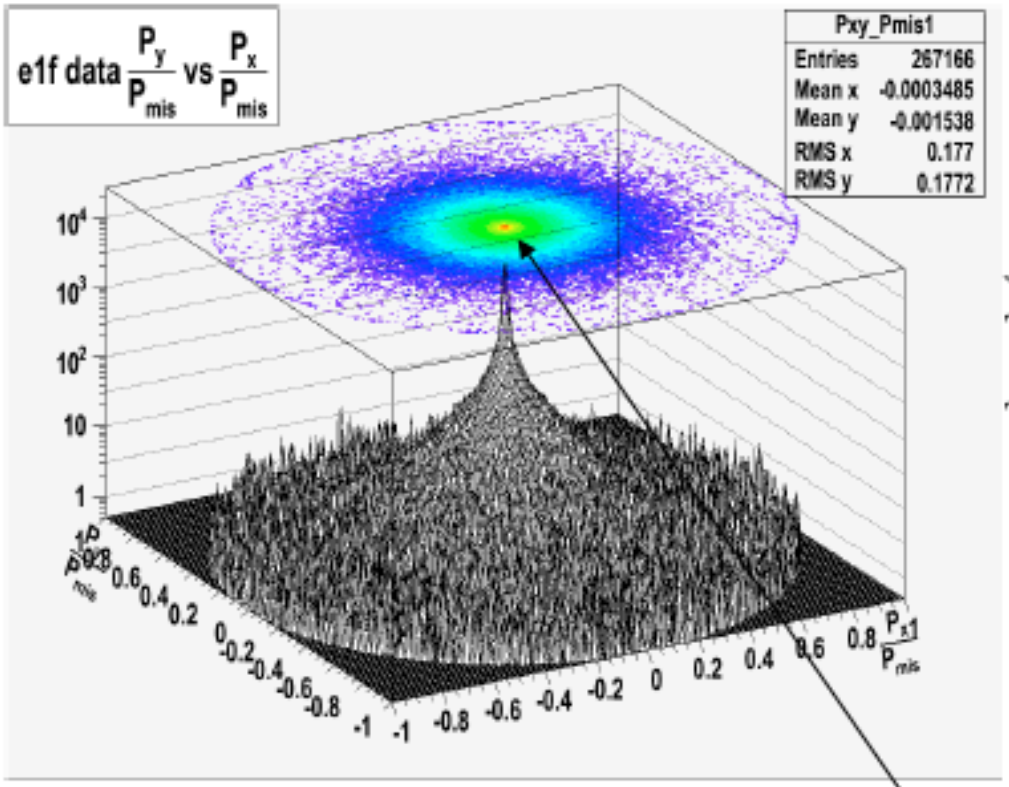


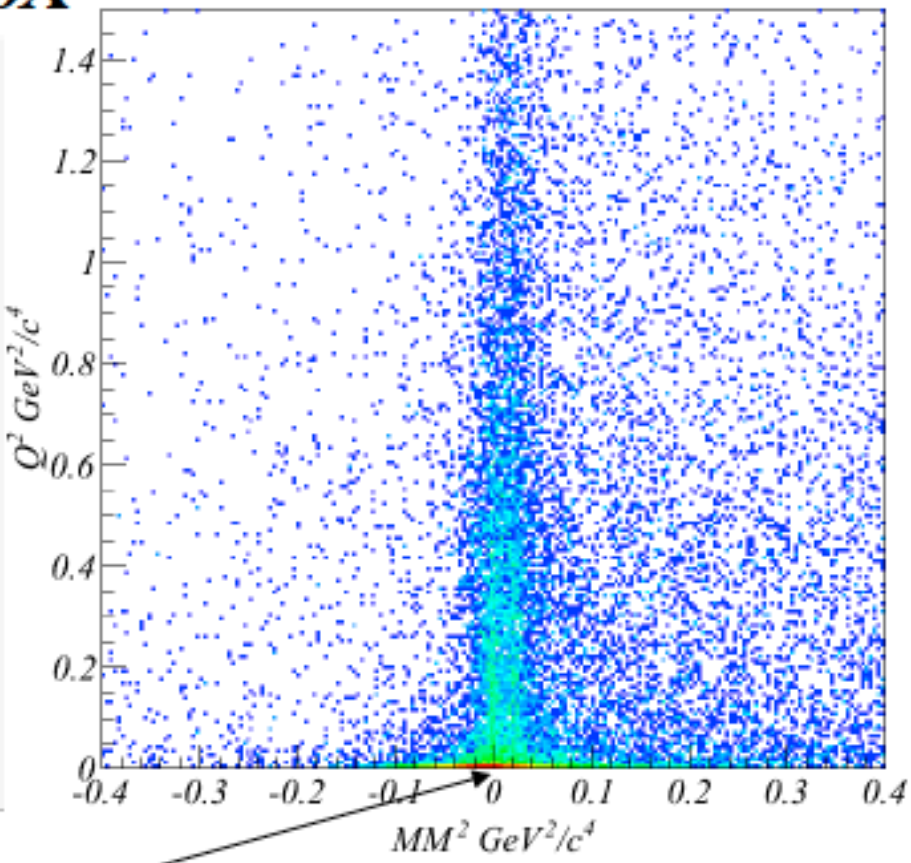


- Low-Q^2 events are reconstructed by applying cuts on the transverse momentum of the missing beam electron.
- Exclusivity is ensured by detection of all produced final-state particles, and application of an additional missing mass cut.

Exclusive quasi-real photoproduction in CLAS (data)

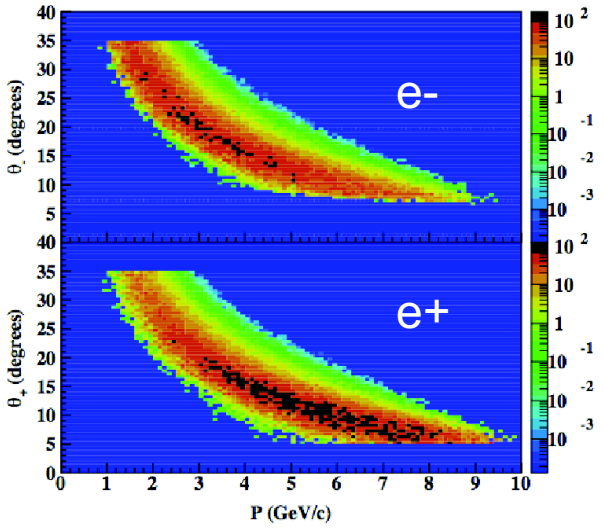
$$ep \rightarrow e^+e^-pX$$

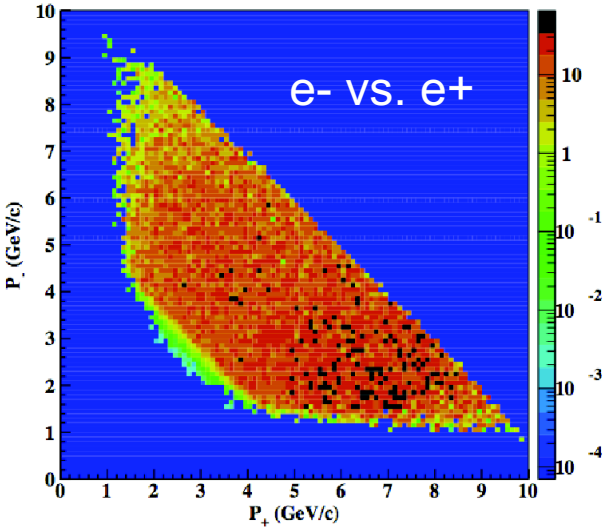


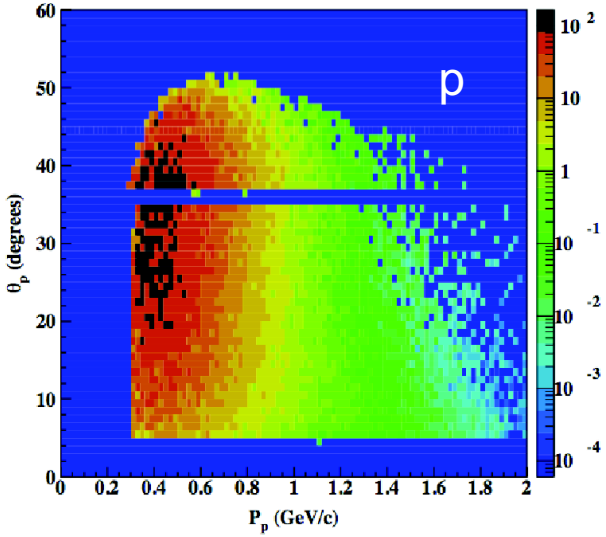


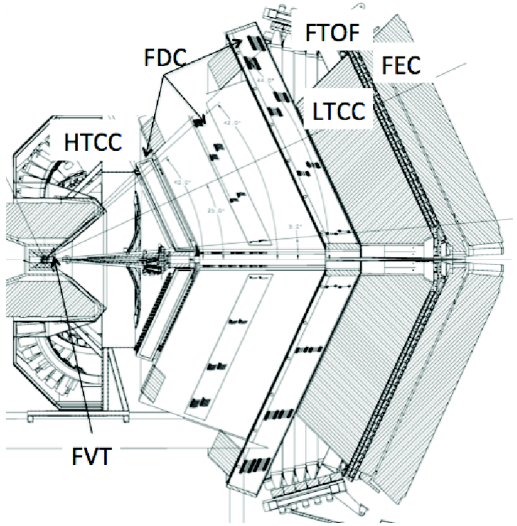
X – is identified as an electron scattered at 0 degrees, $Q^2<0.01$ (GeV/c)^2 and $|M_X^2|<0.1$ (GeV)^2

Detection of the exclusive final state in CLAS12



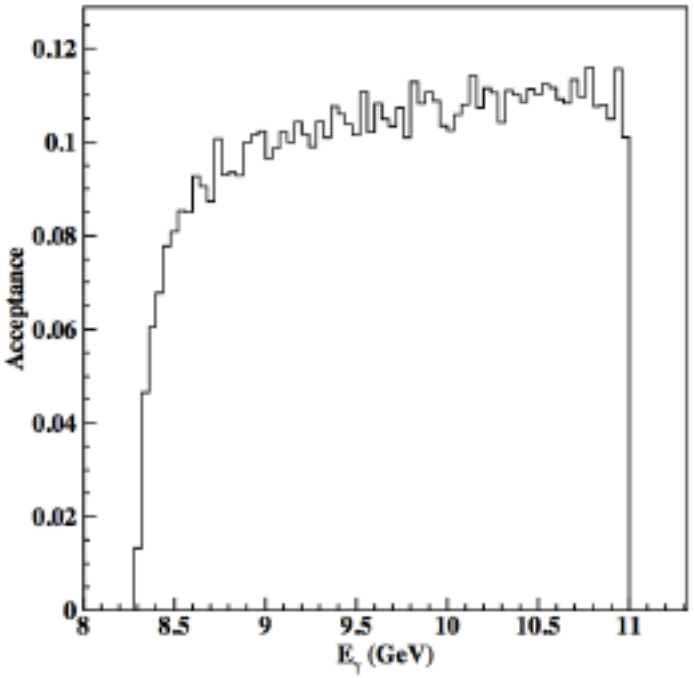


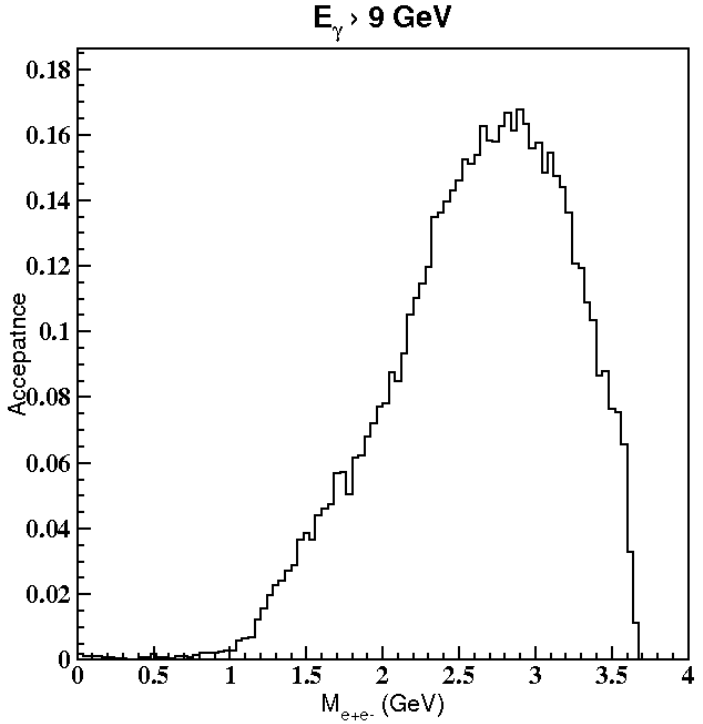




- The leptons pairs are detected and identified using the High-Threshold Cherenkov Counter (HTCC) and the Forward Electromagnetic Calorimeter (FEC).
- Pairs with one lepton below the HTCC pion threshold of 4.9 GeV/c will have a pion pair rejection factor of $2 \cdot 10^7$.
- Proton kinematics and acceptance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

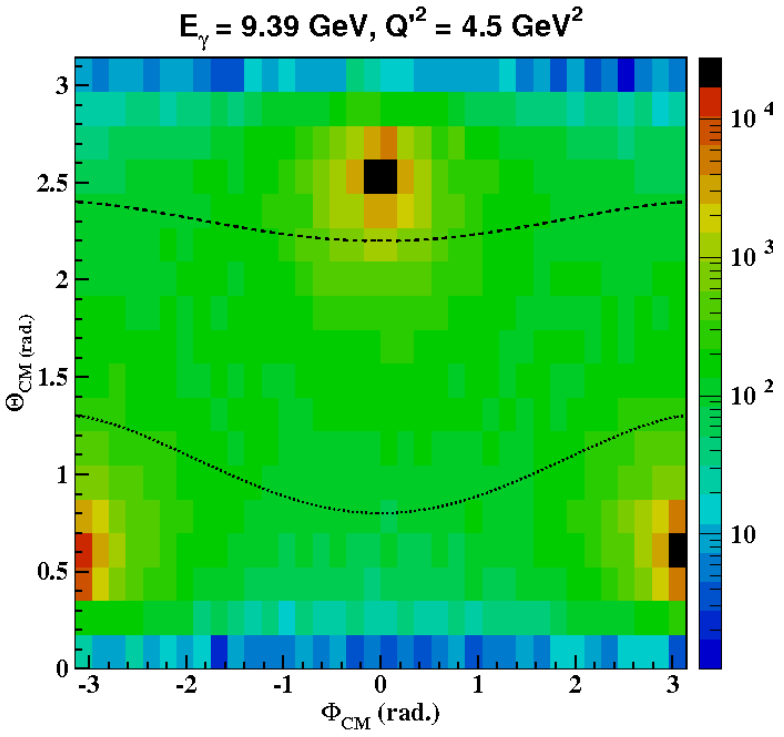
CLAS12 acceptance for pe^+e^- final states



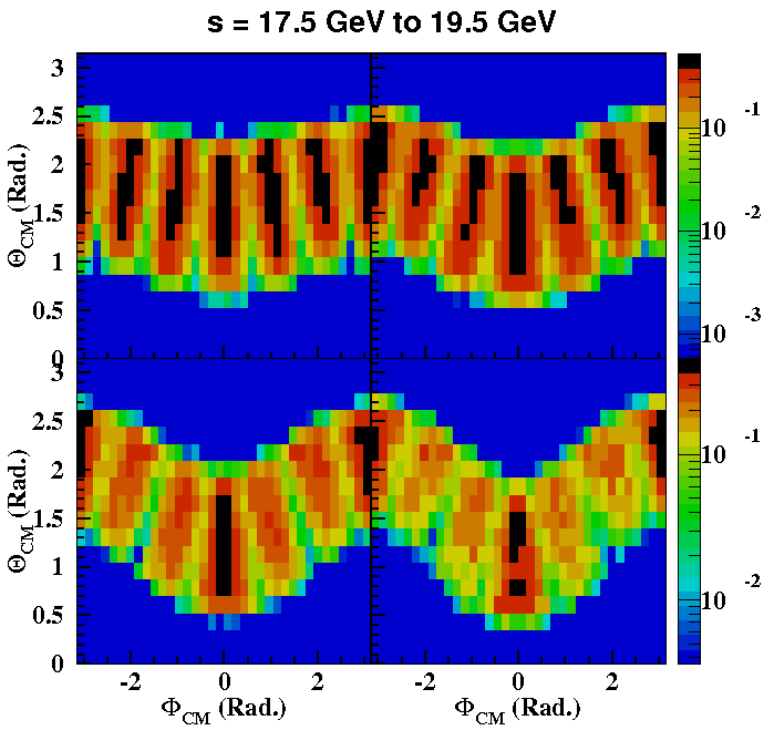


- CLAS12 has good acceptance for exclusive photoproduction of lepton pairs with a large invariant mass over a wide range of photon energies.

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



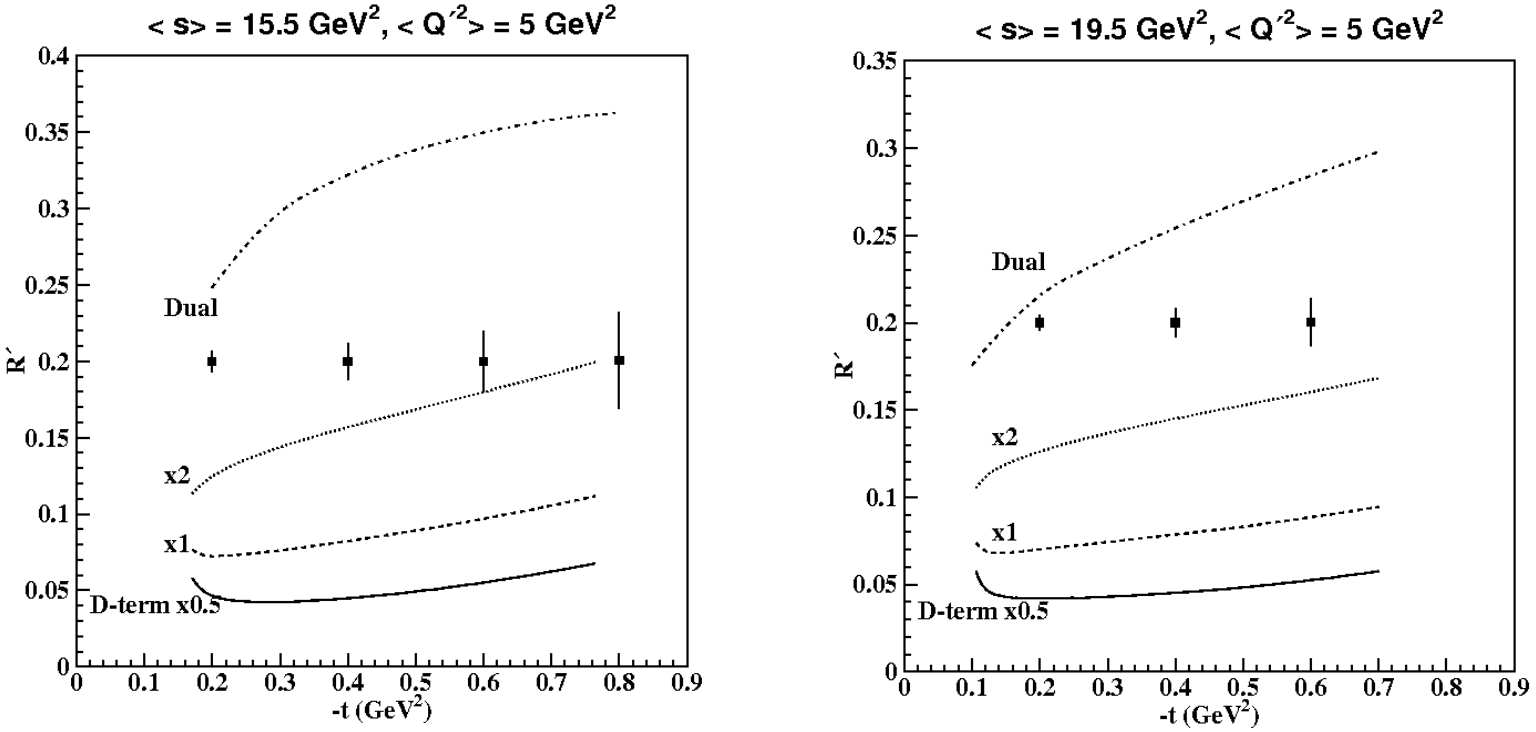
Generated events. Regions dominated by BH fall outside of the contour indicating the CLAS acceptance.



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} $cm^{-2}s^{-1}$

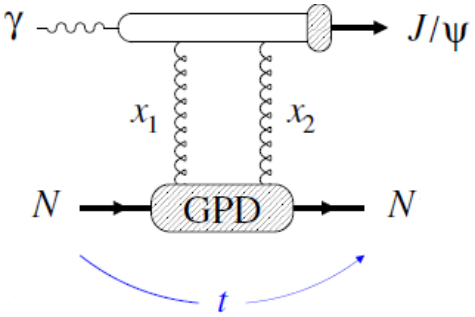


- Uncertainties for R', integrated over the CLAS12 acceptance, for two bins in photon energy, for the lowest Q'^2 bin above the ρ' resonance.
- Different values of the D-term are only shown for the double distribution

J/ψ photoproduction near threshold

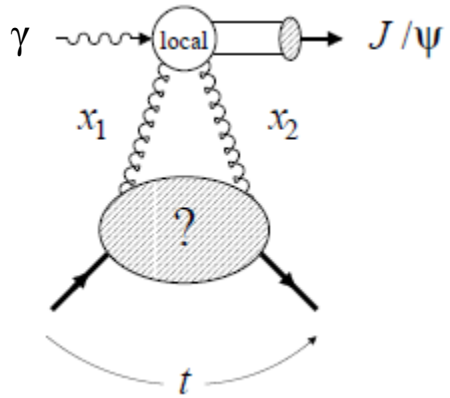
J/ψ production at high W

- 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}



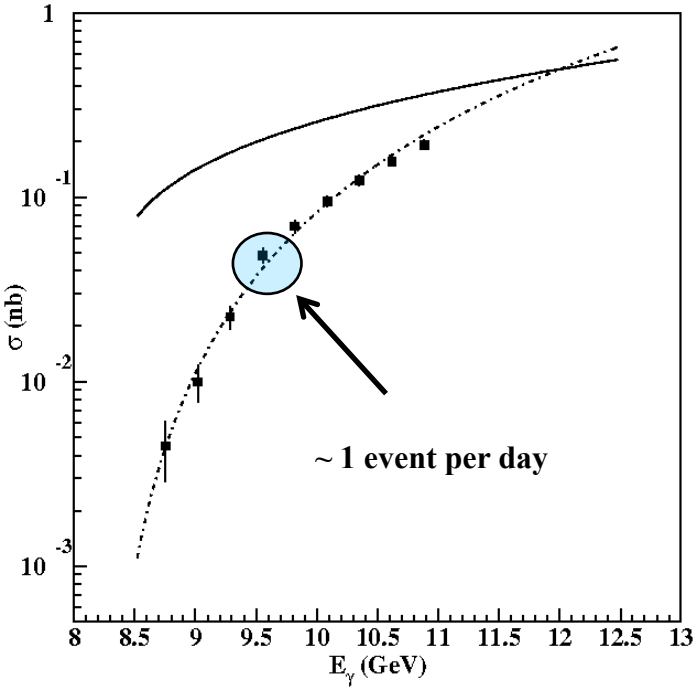
$$A(\gamma + p \to J/\psi + p) \propto F_{2g}(t)$$

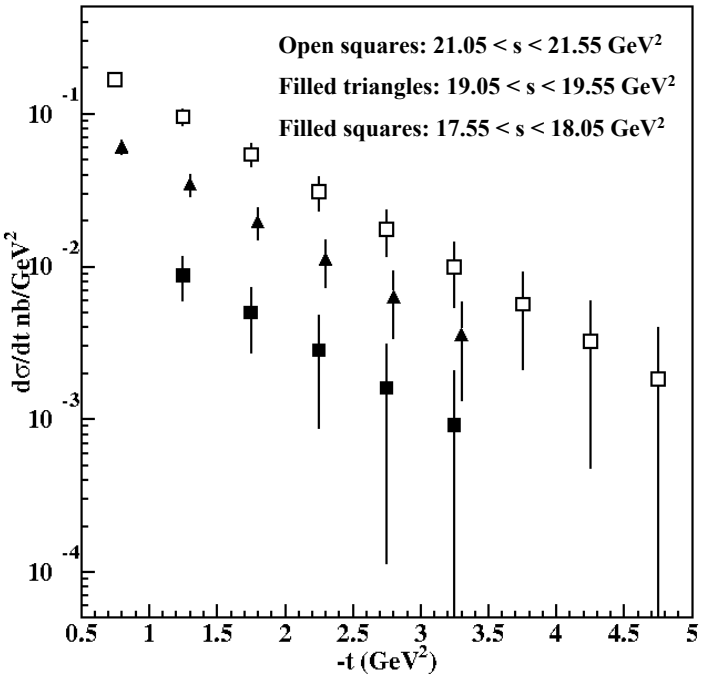
gluonic form factor

Weiss, Strikman

Projected results – exclusive J/ψ photoproduction

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



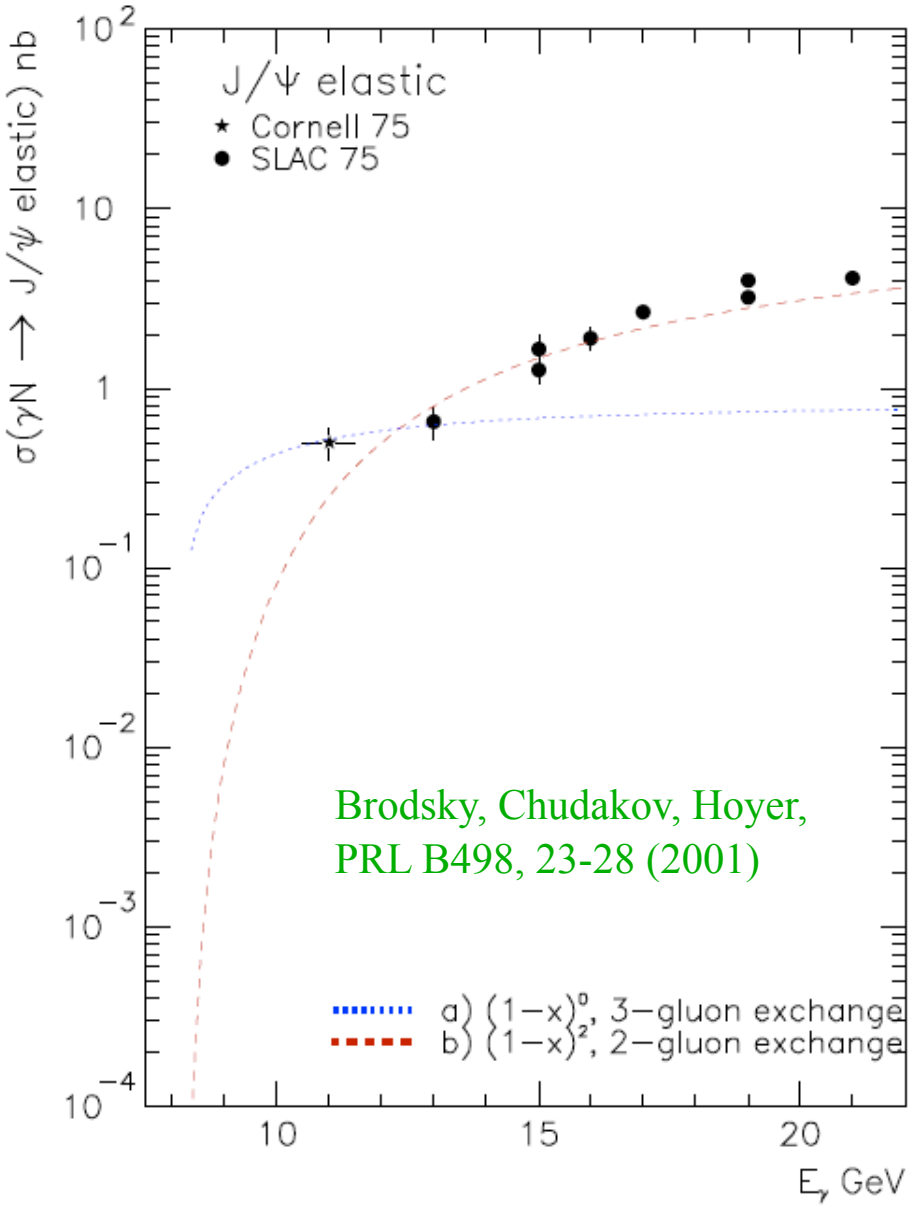


Uncertainties for the total cross section assuming the most conservative prediction

(smaller than point side except for the three lowest points)

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

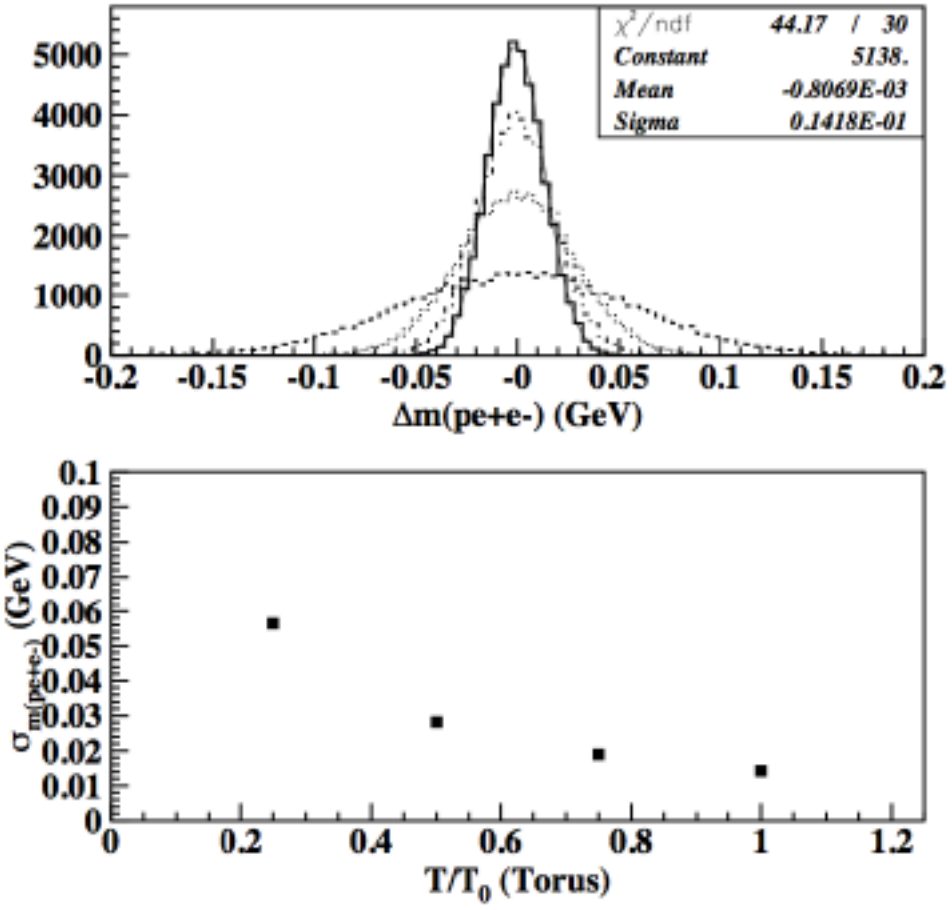
Enhancement instead of suppression near threshold?



- Cornell: should we expect an enhancement instead, despite the impact of a large t_{min}?
- LHCb charmonium pentaquark? Can be photoproduced in the s-channel with 10 GeV photons!

  Comparable statistics!

CLAS12 provides excellent mass resolution



- Mass resolution of the detected p-J/ψ system (charmonium pentaquark)

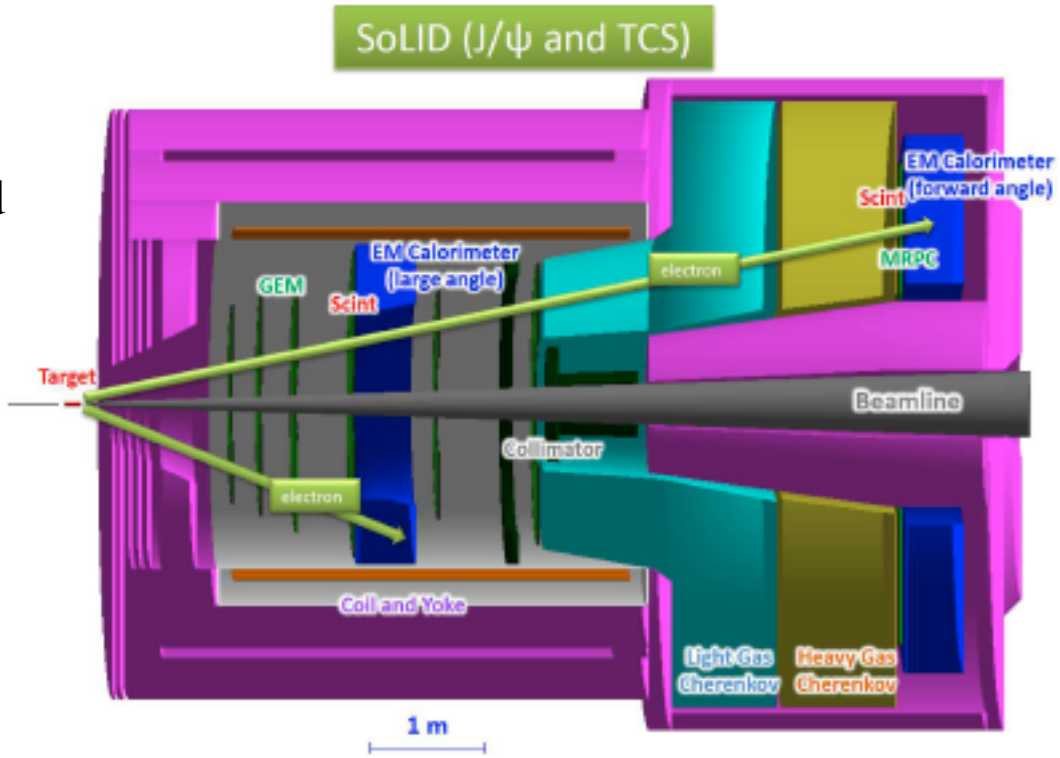
J/ψ from nuclear targets in CLAS12

Proposal	Physics	Contact	Rating	Days	Group	New equipment	Energy	Run Group	Target
E12-06-108	Hard exclusive electro-production of π^0, η	Stoler	B	80	139	RICH (1 sector) Forward tagger	11	A F. Sabatié	liquid H_2
E12-06-112	Proton's quark dynamics in SIDIS pion production	Avakian	A	60					
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	A	80					
E12-09-003	Excitation of nucleon resonances at high Q^2	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-	120					
E12-12-007	Exclusive φ meson electroproduction with CLAS12	Stoler, Weiss	B+	60					
PR12-12-008	Photoproduction of the very strangest baryon	Guo	--	80					
E12-07-104	Neutron magnetic form factor	Gilfoyle	A-	30	90	Neutron detector RICH (1 sector) Forward tagger	11	B K. Hafidi	liquid D_2 target
PR12-11-109 (a)	Dihadron DIS production	Avakian	-	-					
E12-09-007a	Study of partonic distributions in SIDIS kaon production	Hafidi	A-	56					
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	170	Polarized target RICH (1 sector) Forward tagger	11	C S. Kuhn	NH_3 ND_3
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	-	-					
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	D	Nuclear
E12-06-117	Quark propagation and hadron formation	Brooks	A-	60	60		11	E	Nuclear
E12-10-102	Free Neutron structure at large x	Buetman	A	40	40	Radial TPC	11	F	Gas D_2
TOTAL approved run time (PAC days)				1491	559				

A proposal for coherent J/ψ production on deuterium will be submitted in 2017.

TCS with the planned SoLID detector in Hall A

Luminosity: up to 10^{37} polarized and 10^{39} unpolarized



Parameters	SoLID detector
polar angular range (θ) (target at z=-315cm)	8.5° to 16° for FA and 17° to 24.5° for LA
azimuthal angular range (ϕ)	full
resolution:	
polar angle ($\delta\theta$)	< 0.6 mr
azimuthal angle ($\delta\phi$)	< 5 mr
momentum (δp/p)	$< 2\%$
PID:	
e/π by EC	full momentum range
e/π by CC	< 4.9 GeV/c at FA
p/K by TOF	< 4.4 GeV/c at FA and < 2 GeV/c at LA

E12-12-006A

Approved for 50 PAC days as part of to a run group together with experiment E12-12-001

Run Group Proposal with E12-12-006 at Jefferson Lab PAC 43
Timelike Compton Scattering on the proton in e^+e^- pair production with SoLID at 11 GeV

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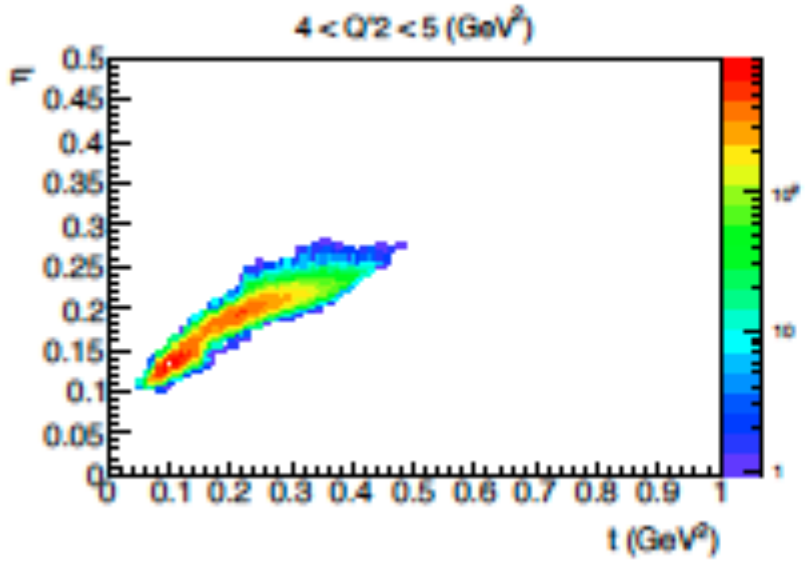
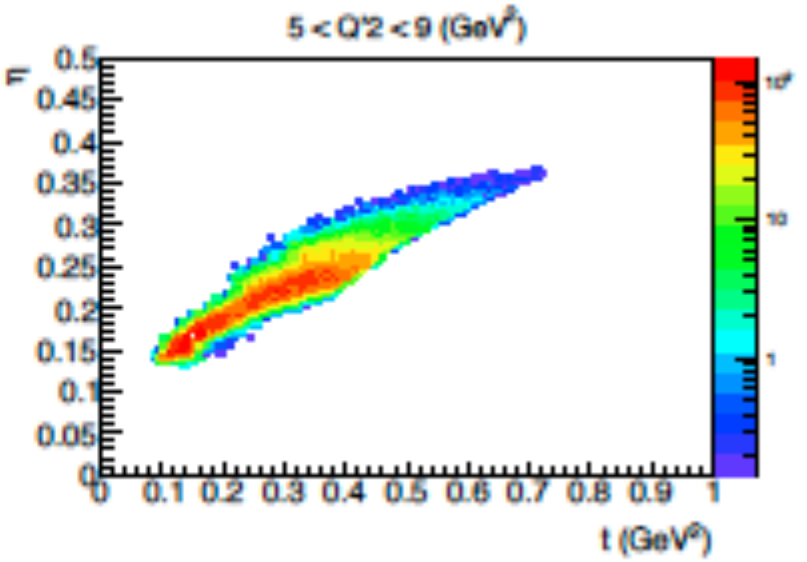
(Dated: May 18, 2015)

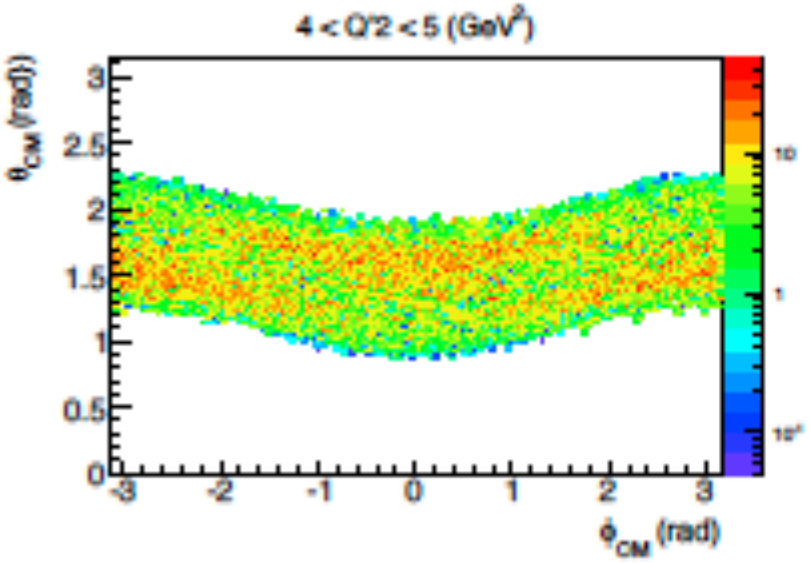
*Co-spokesperson

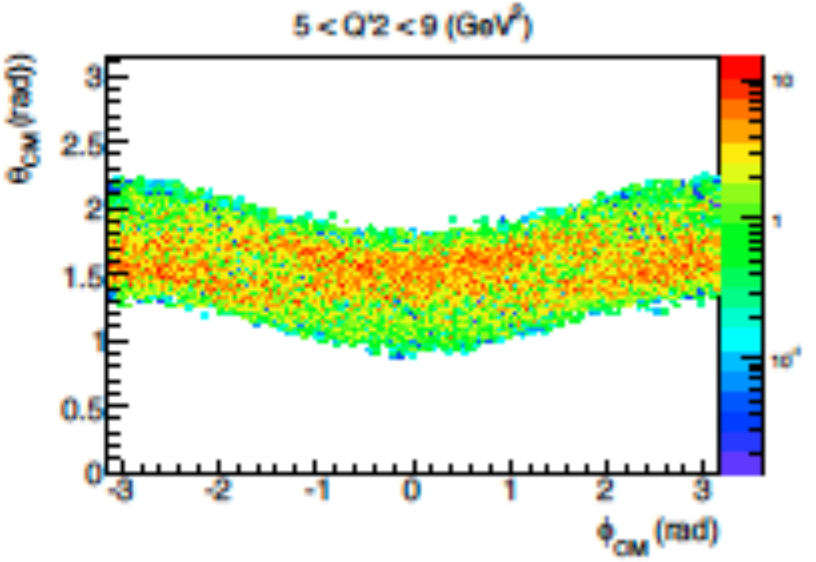
†Contact person: zwzhao@jlab.org

SoLID acceptance in two bins of Q'^{2}

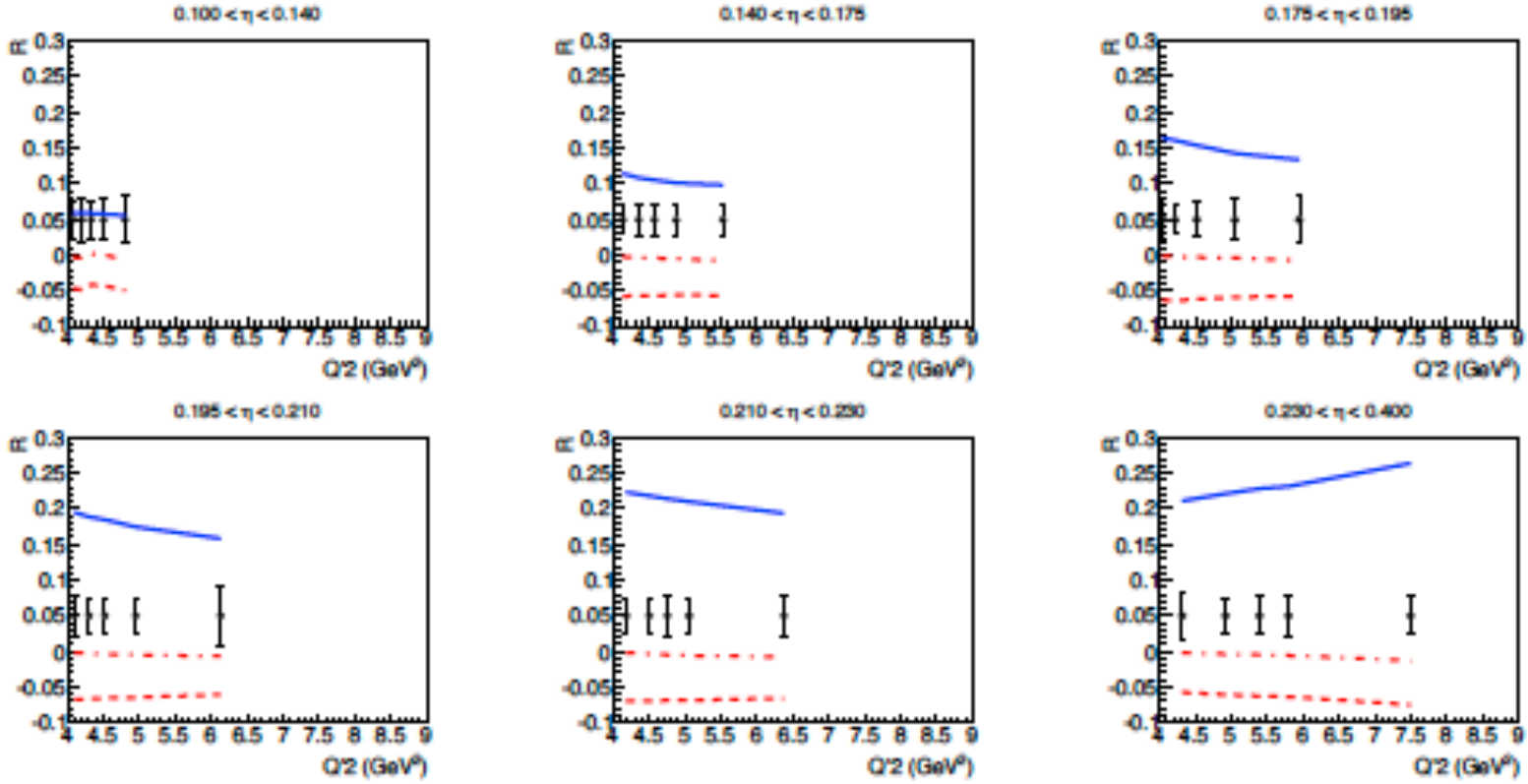








Projected results for 50 days at $5x10^{36}$ in SoLID



- Projected results in different bins of skewness for dual parametrization (blue) and double-distribution with (dash-dotted red) or without (dashed red) D-term.

Future direction – polarization!

Polarized beams and targets planned for next generation of TCS experiments

- Additional observables provide a strong constraint on GPD extraction even if TCS statistics will more limited than DVCS
- Sensitivity to the elusive GPD E with transversely polarized targets

New measurements

- Linearly polarized photons and target in CLAS12
- Transversely polarized target in Hall A (SoLID) and Hall C (NPS)

Summary

- Charmonium pentaquark?

TCS is an essential part of the GPD program

- Universality of GPDs
- Combined fits of CFFs with DVCS

More than a year of (calendar) beam time has been approved for TCS at JLab 12 GeV for CLAS12 in Hall B and SoLID in Hall A

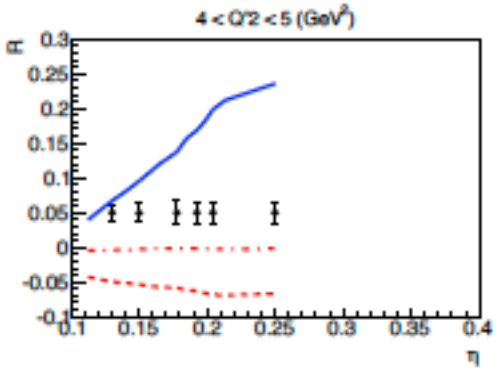
- Extensions to linearly polarized beams (Hall B) and targets (Hall C)

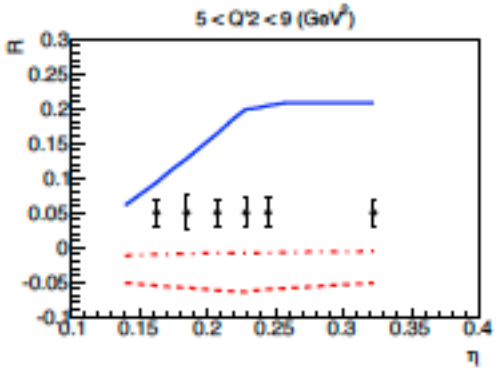
J/ψ photoproduction near threshold offers unique opportunties

- LHCb charmonium pentaquark
- Extension to nuclear targets

Backup

Projected results for 50 days of SoLID sunning

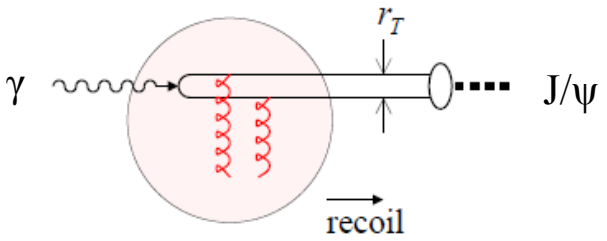




Charmonium is a probe of the nucleon's color field

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

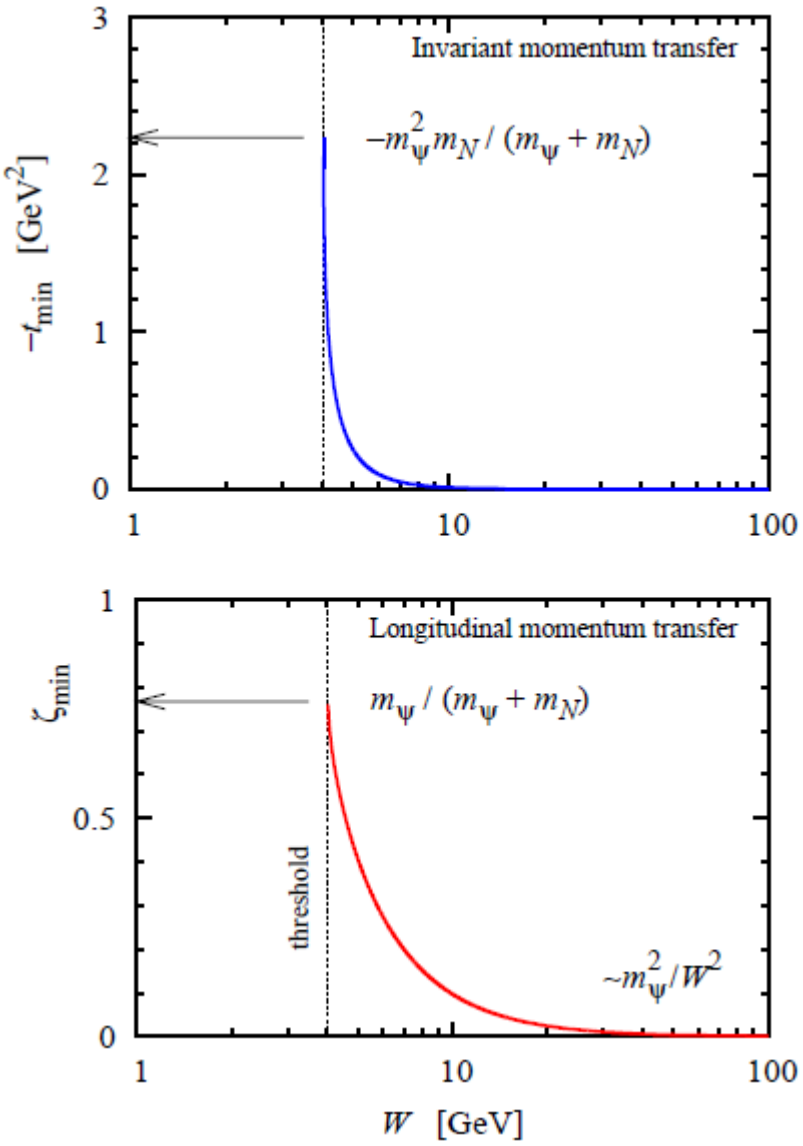
- *c.f.* color transparency
- Local probe of color field



J/ψ photoproduction

- Probes distances $\approx 1/\sqrt{Q^2 + M^2_{J/\psi}} \approx 1/M_{J/\psi}$
- J/ψ radius still smaller than nucleon: $r_{J/\psi} \sim 0.2 - 0.3$ fm $<<$ 1 fm

Exclusive J/ψ kinematics near threshold



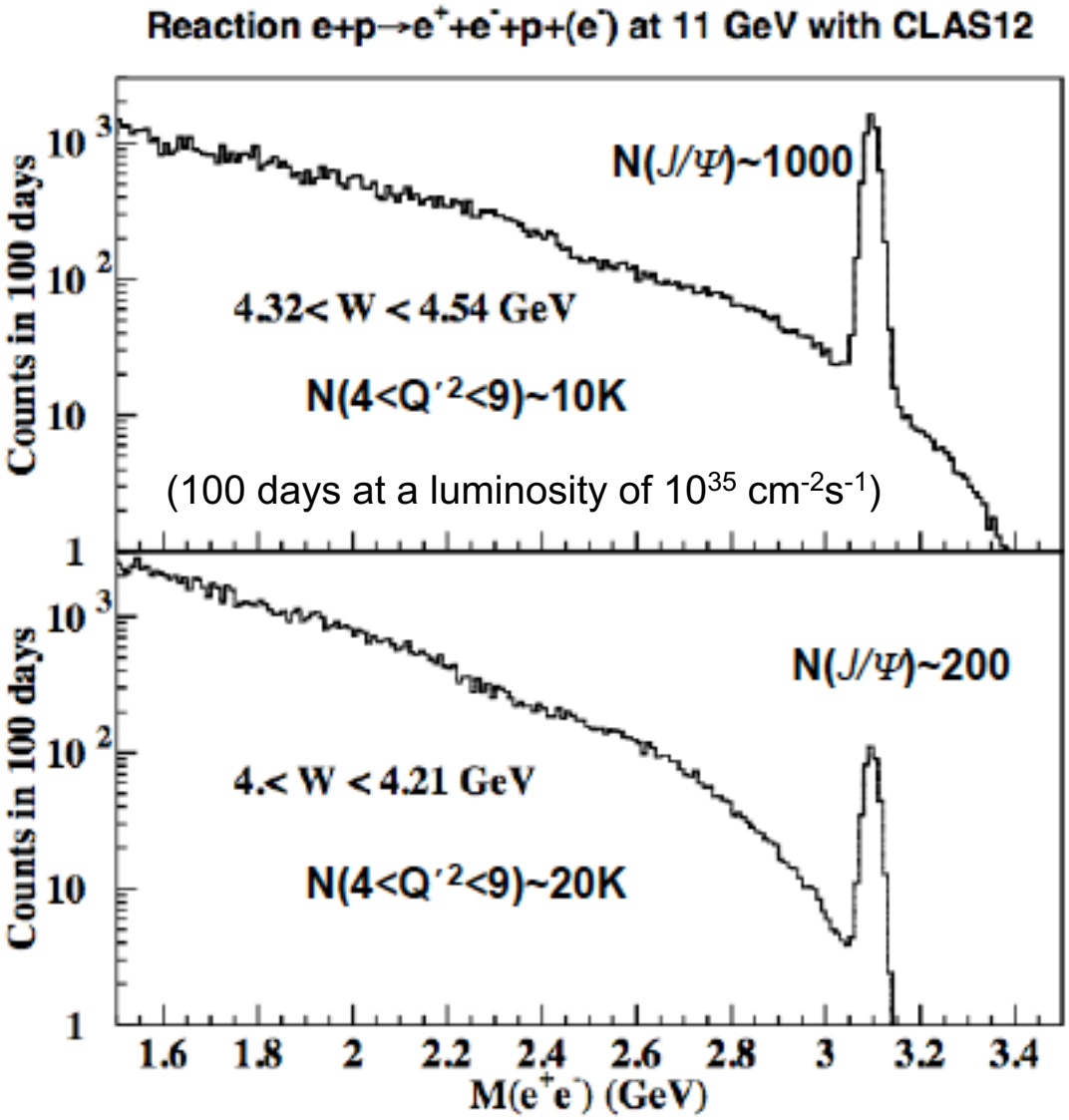
Four-momentum transfer to the nucleon

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

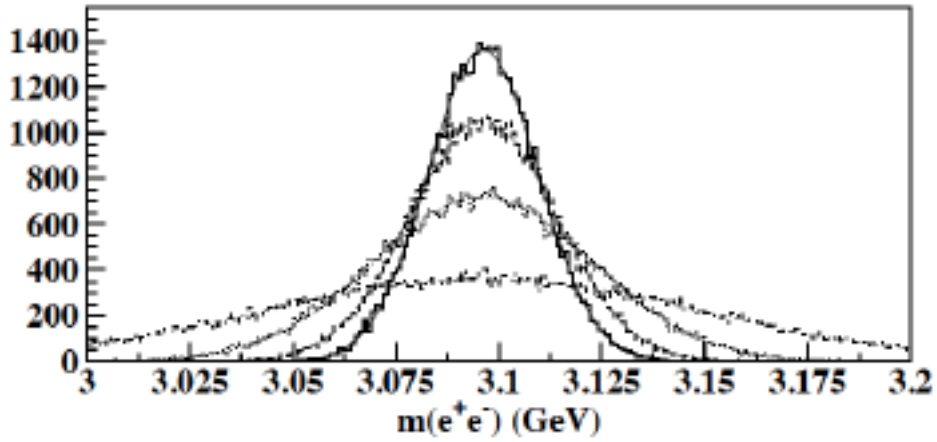
- ζ is the „plus“ momentum transfer
  - light cone variables
- Δ_T is the transverse momentum transfer
- t_{min} at threshold is 2.2 GeV^2

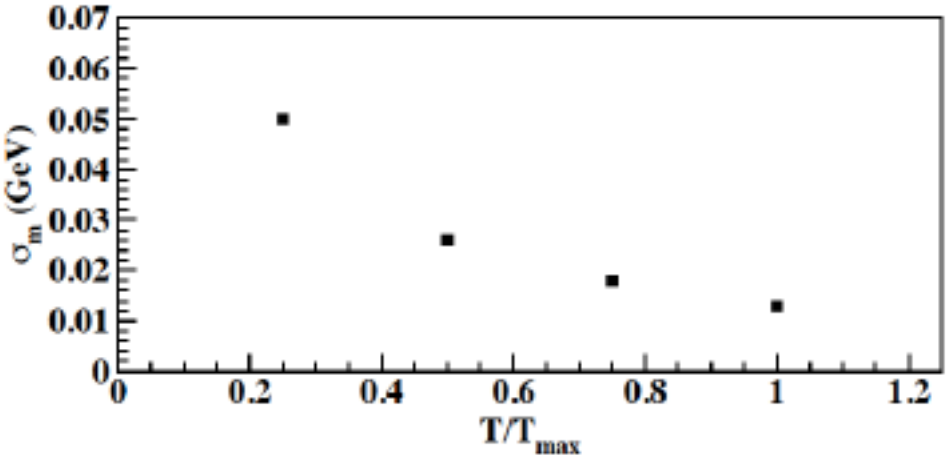
C. Weiss, Non-perturbative forces in QCD, Temple U., 26-28 March 2012

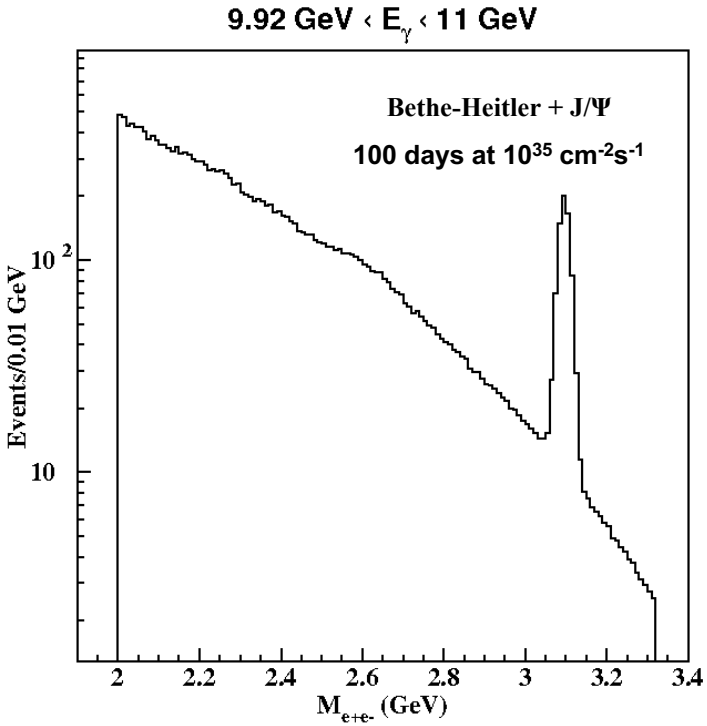
Conservative (J/ψ) yield projections in two sample bins



J/ψ mass resolution in CLAS12







- J/ψ + Bethe-Heitler at max field

- The CLAS12 resolution is good for J/ψ for fields at half field or above.