12 GeV Upgrade
Future Science at Jefferson Lab

Timelike Compton Scattering at SoLID

Run Group Proposal with E12-12-006 (SoLID JPsi)

Zhiwen Zhao

Marie Boer, Pawel Nadel-Turonski ,

Jixie Zhang

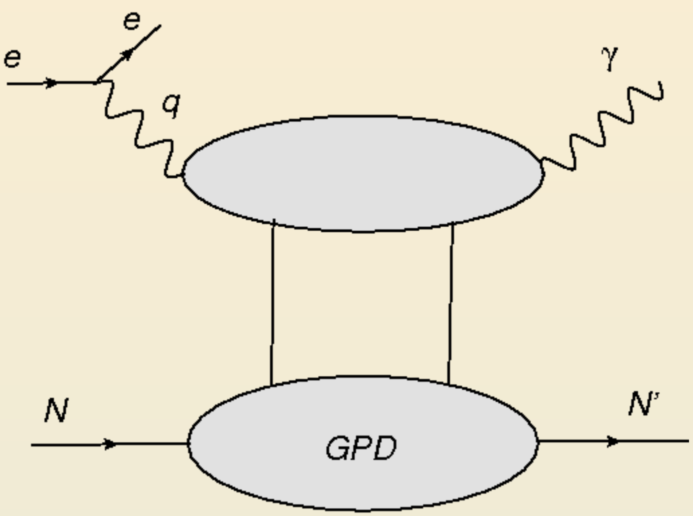
2015/5

Jefferson Lab
EXPLORING THE NATURE OF MATTER

DVCS and TCS access the same GPDs

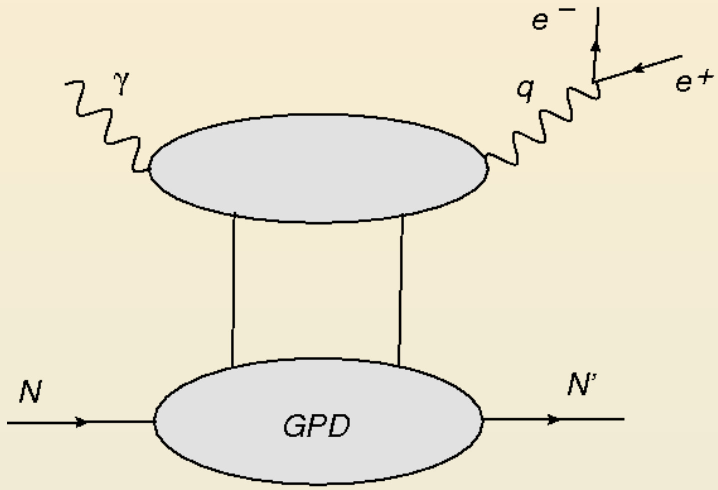
Spacelike Deeply Virtual Compton Scattering

$$\gamma^* p \rightarrow \gamma\, p'$$



Timelike Compton Scattering

$$\gamma\, p \rightarrow \gamma^*(e^- e^+)\, p'$$



- "The amplitudes of these two reactions are related at Born order by a simple complex conjugation but they significantly differ at next to leading order (NLO)"
- " The Born amplitudes get sizeable $O(\alpha_s)$ corrections and, even at moderate energies, the gluonic contributions are by no means negligible. We stress that the timelike and spacelike cases are complementary and that their difference deserves much special attention."

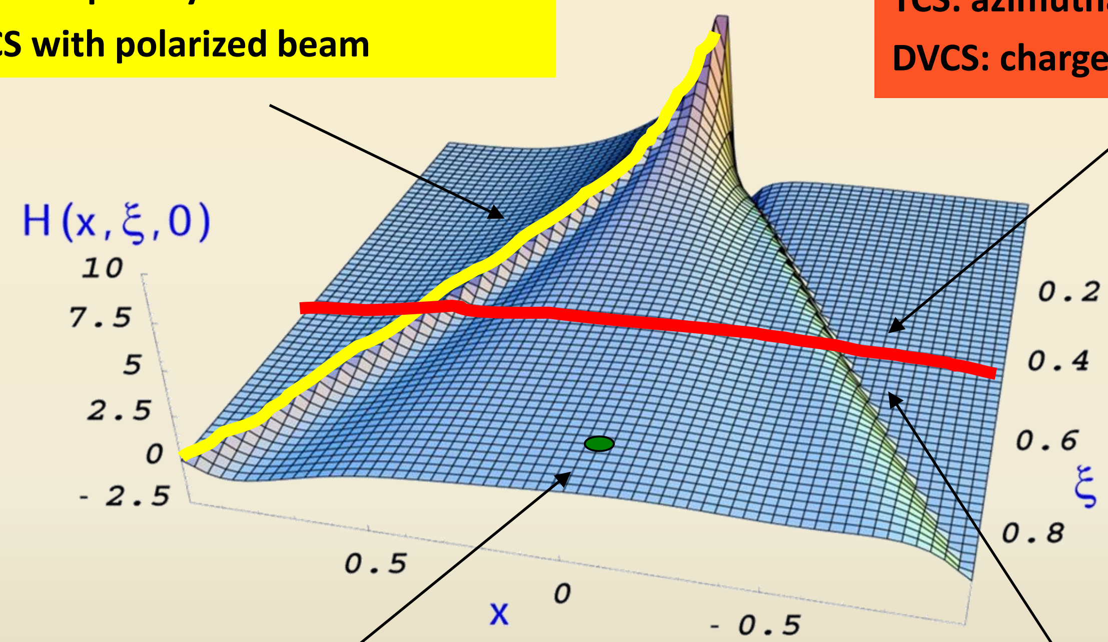
H. Moutarde et al. arXiv:1301.3819, 2013

General Compton Process

accessing GPDs

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

(Re)
TCS: azimuthal asymmetry
DVCS: charge asymmetry

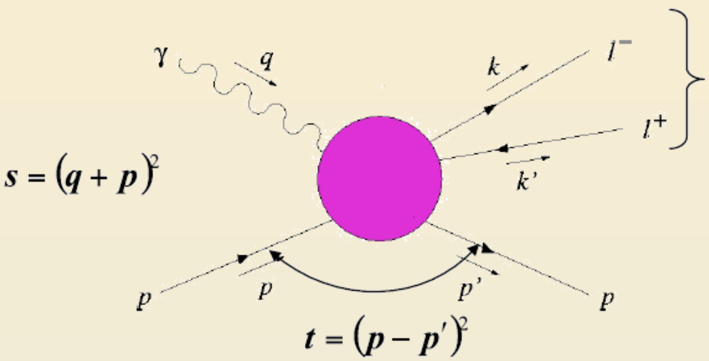


(Im, x ≠ ξ, x < |ξ|)
Double DVCS

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

TCS

Information on the real (imaginary) part of the Compton amplitude can be obtained from photoproduction of lepton pairs using unpolarized (circularly polarized) photons

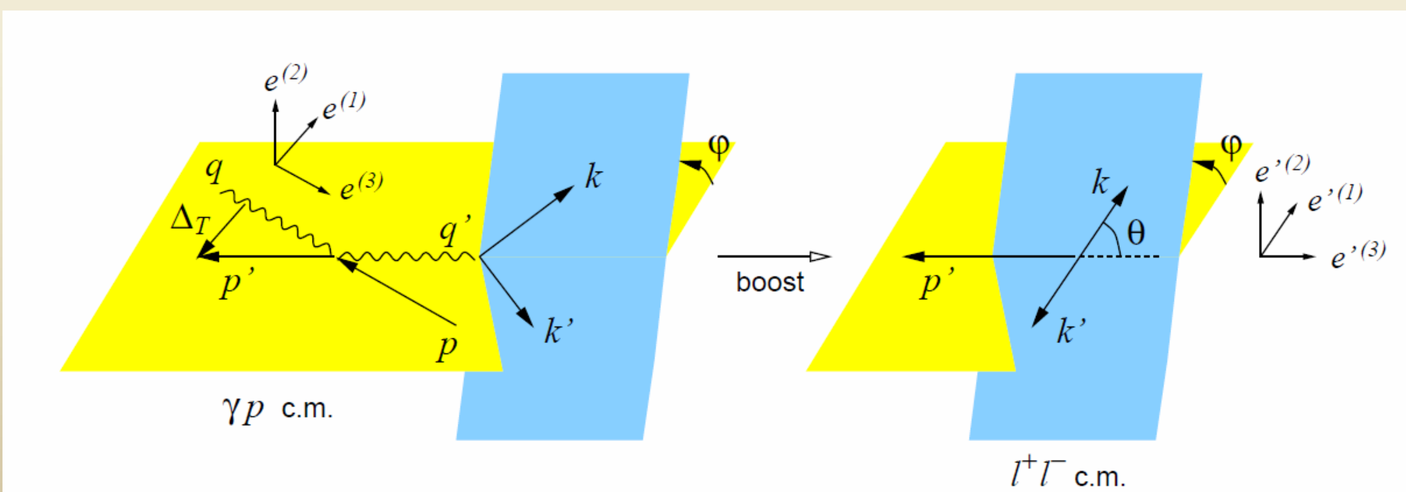


Hard scale

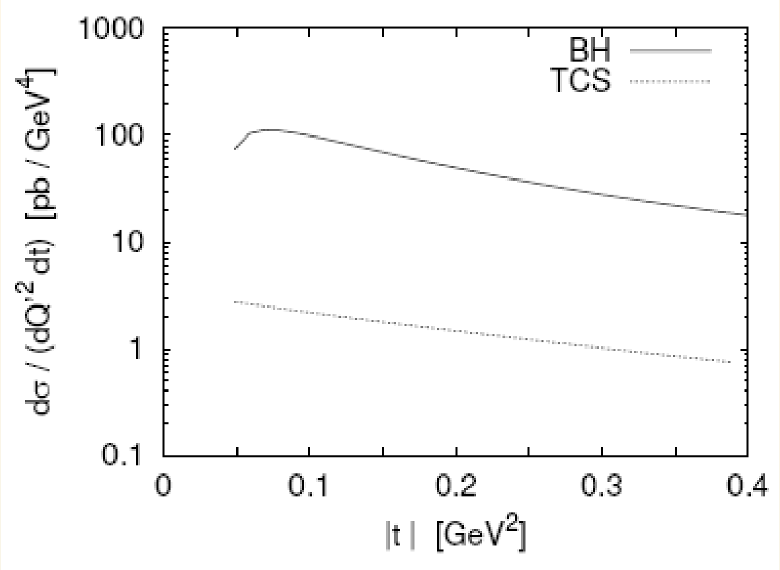
$$Q'^2 = M^2_{l^+l^-} = (k+k')^2$$

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

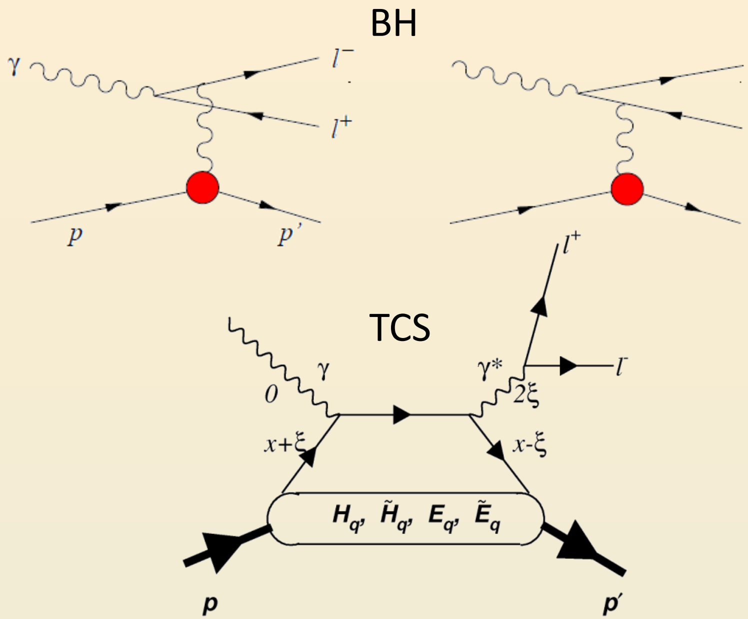
TCS	$\tau = \dfrac{Q'^2}{2p \cdot q} = \dfrac{Q'^2}{s - M^2}$	$\eta = \tau/(2-\tau)$
DVCS	$x_B = Q^2/(2p \cdot q)$	$\eta = x_B/(2-x_B)$



TCS and Bethe-Heitler (BH) Interference



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

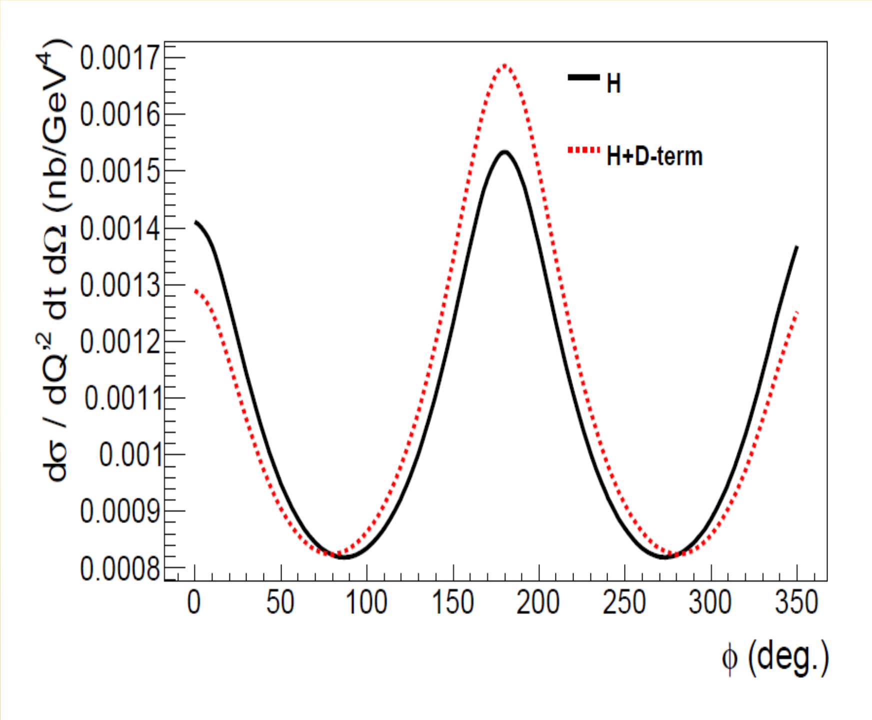


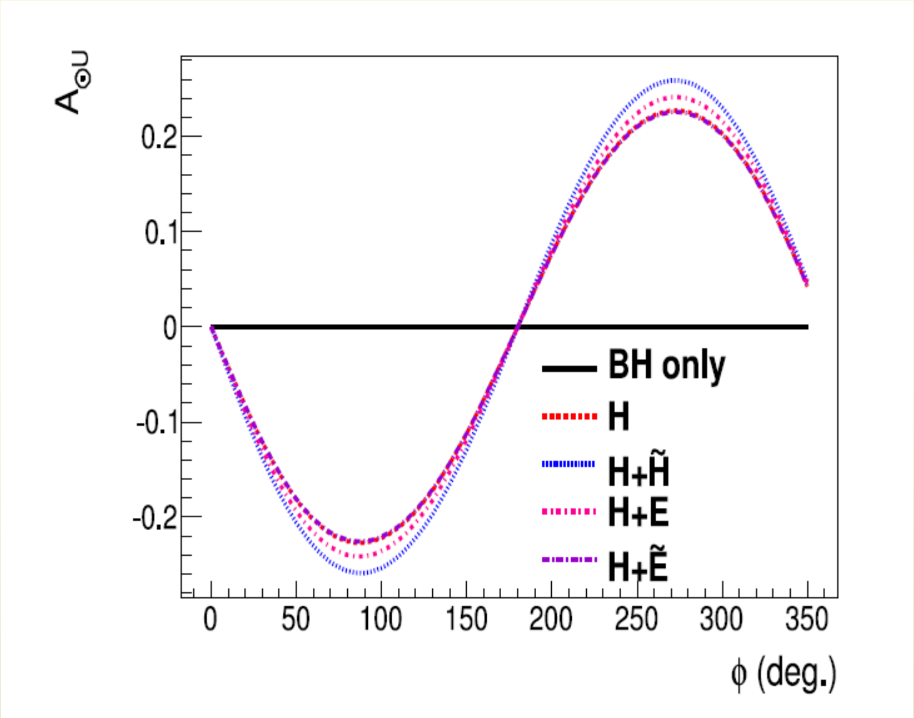
$$\frac{d\sigma^4}{dQ'^2\,dt\,d(\cos\theta)\,d\phi} = |BH|^2 + I(BH\cdot TCS) + |TCS|^2$$

- For lepton charge conjugation, TCS and BH amplitudes are ***even***, while the interference term is ***odd***
- Therefore, direct access to interference term through angular distribution of the lepton pair (cosine and sine moments)

Cross section and Asymmetry

- Access to both observables
- Sensitive to GPD





$\eta=0.2,\ -t = 0.4\ \mathrm{GeV}^2,\ Q'^2 = 7\ \mathrm{GeV}^2$

TCS at JLab 6GeV

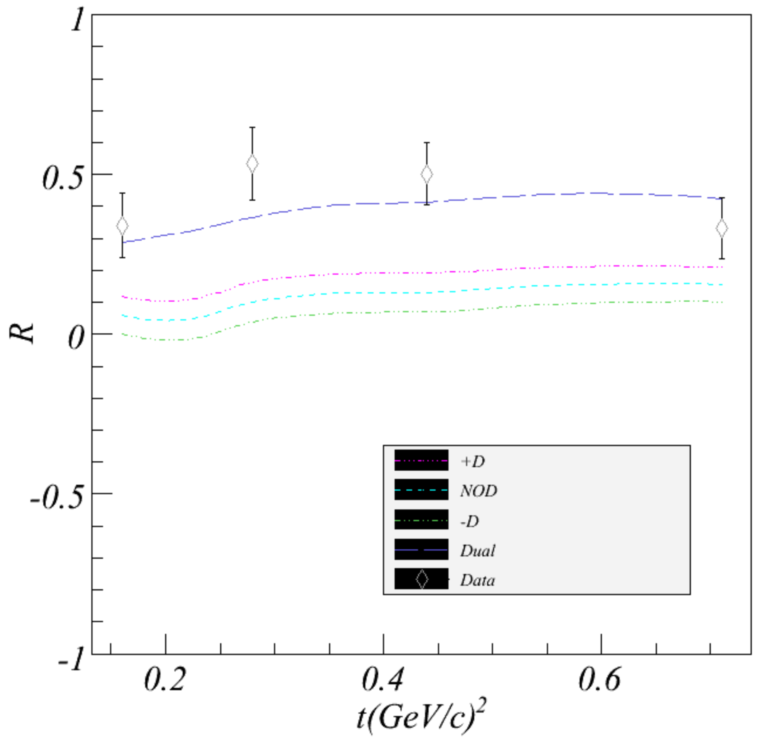
Cosine moment of weighted cross sections

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

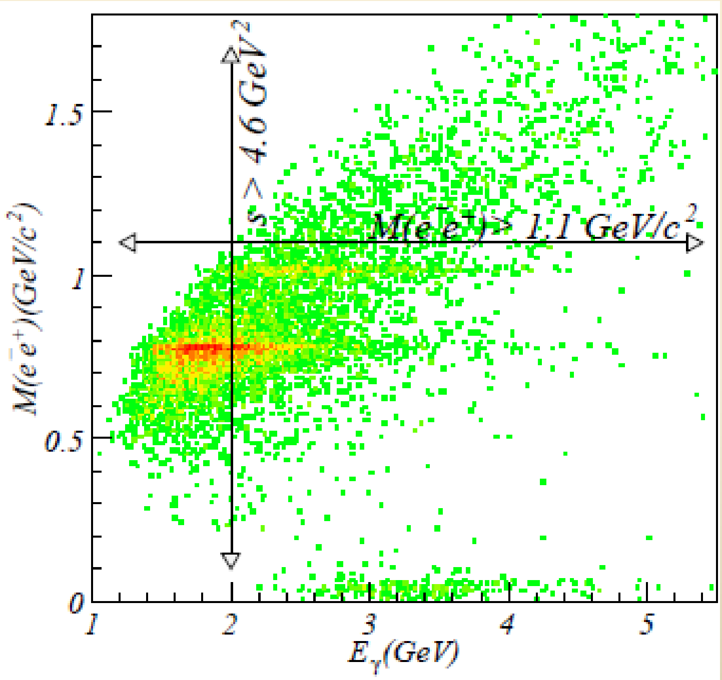
$$R = \frac{2\int_0^{2\pi} d\varphi \cos\varphi \frac{dS}{dQ^2\,dt\,d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ^2\,dt\,d\varphi}}$$

R can be compared directly with GPD models

- 6 GeV data were important for developing methods
- But its kinematics are limited to $M_{e+e-} < 2$ GeV



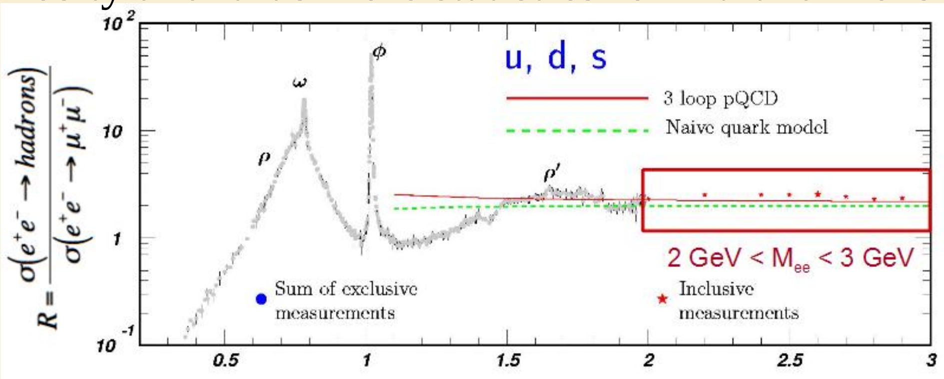
Comparison of results by R. Paremuzyan *et al* from CLAS e1-6/e1f with calculations by V. Guzev.

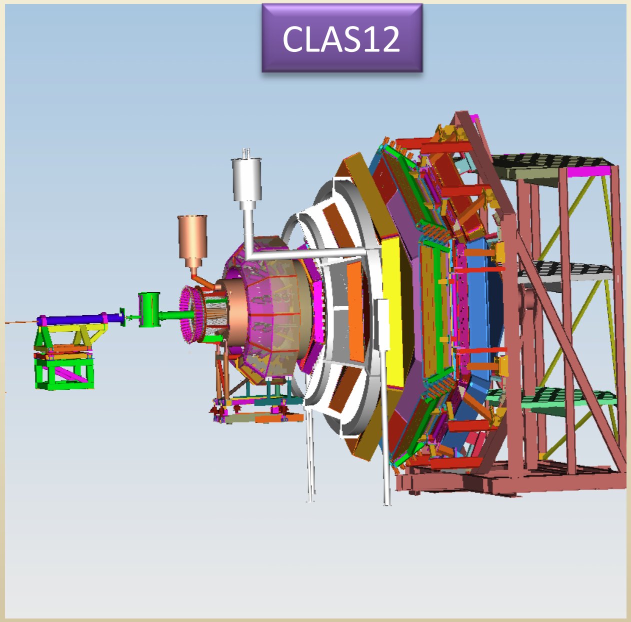


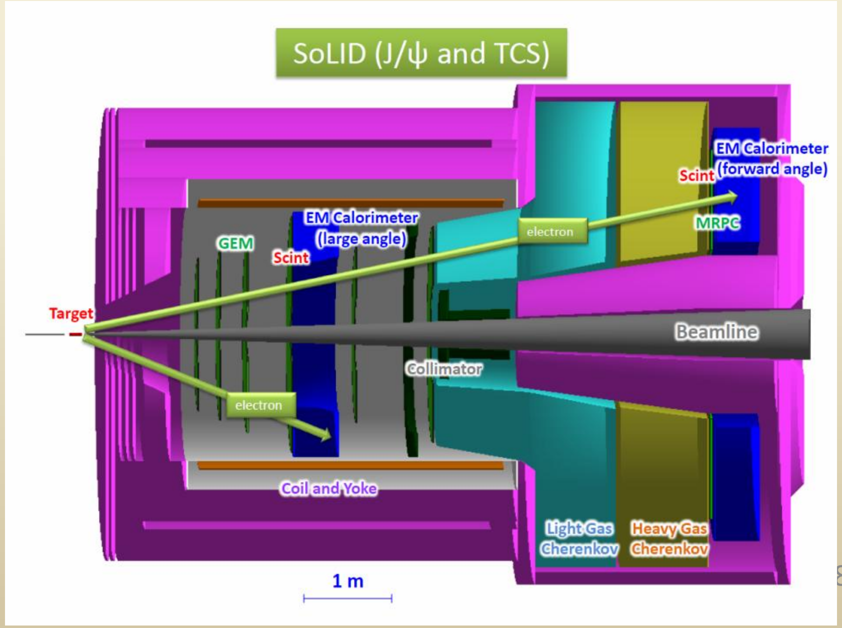
Analysis of CLAS g12 with tagged real photons is ongoing

TCS at JLab 12GeV

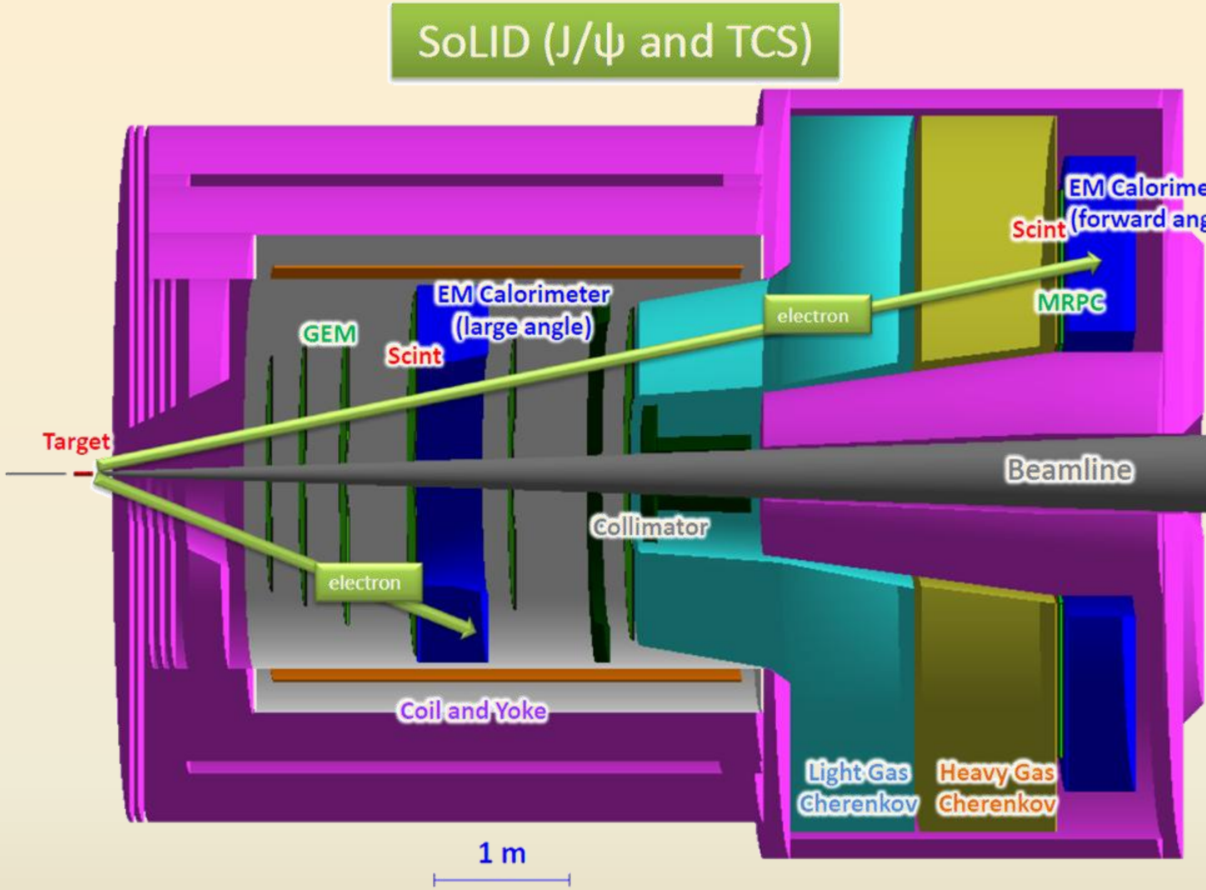
- 11 GeV beam extends s to 20GeV^2
- M_{e+e-} (Q') reaches about 3.5GeV and this allows the access to the resonance free region from 2GeV to 3GeV
- τ can reach from 0.2 to 0.6, eta reaches from 0.1 to 0.45
- Higher luminosity and thus more statistics for multi-dimensional binning







SoLID JPsi and TCS Setup



- 15cm LH2 target 315cm upstream from solenoid coil center, 35cm downstream relative to SIDIS He3 target center
- 3uA current, 1e37/cm2/s luminosity for 50+10 days
- forward angle coverage about 8.5-16 degree,
  large angle coverage about 17-24.5 degree
- Trigger on decay lepton pair

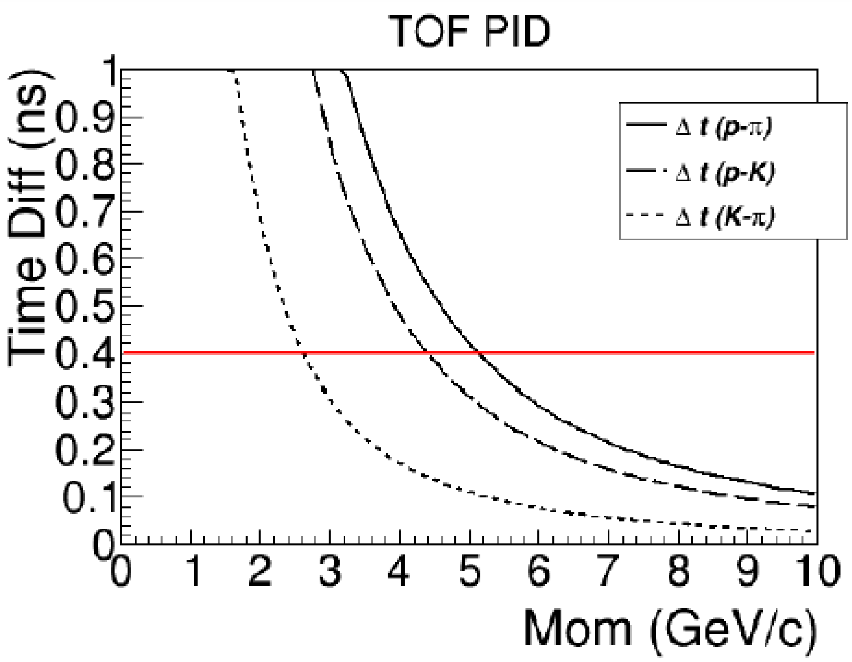
SoLID JPsi and TCS Setup

Recoil p:

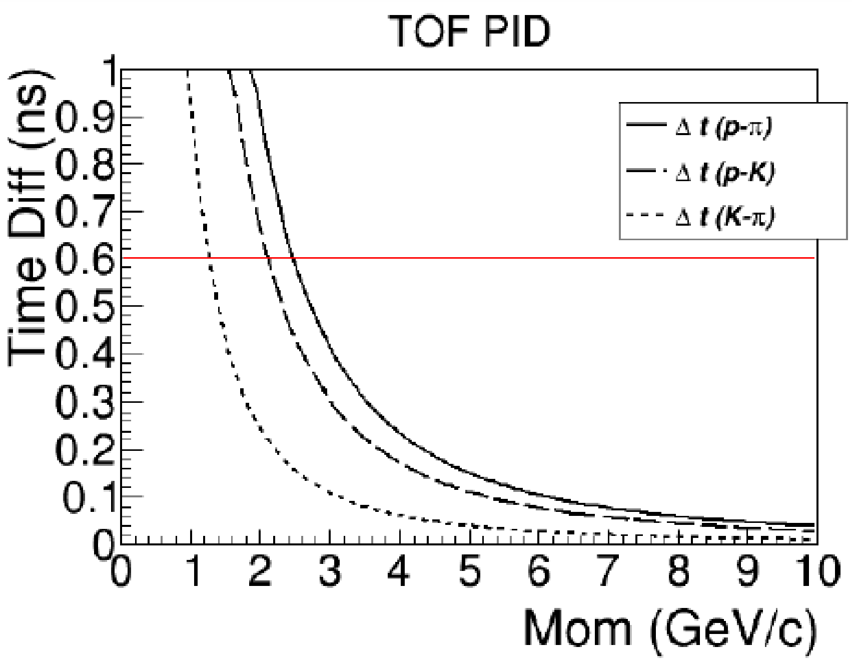
100 ps TOF(MRPC): 4 σ separation p/K up to 4.4 GeV and p/pi up to 5GeV @ forward angle

150 ps TOF(Scint): 4 σ separation p/K up to 2 GeV p/pi up to 2.7GeV @ large angle

FA

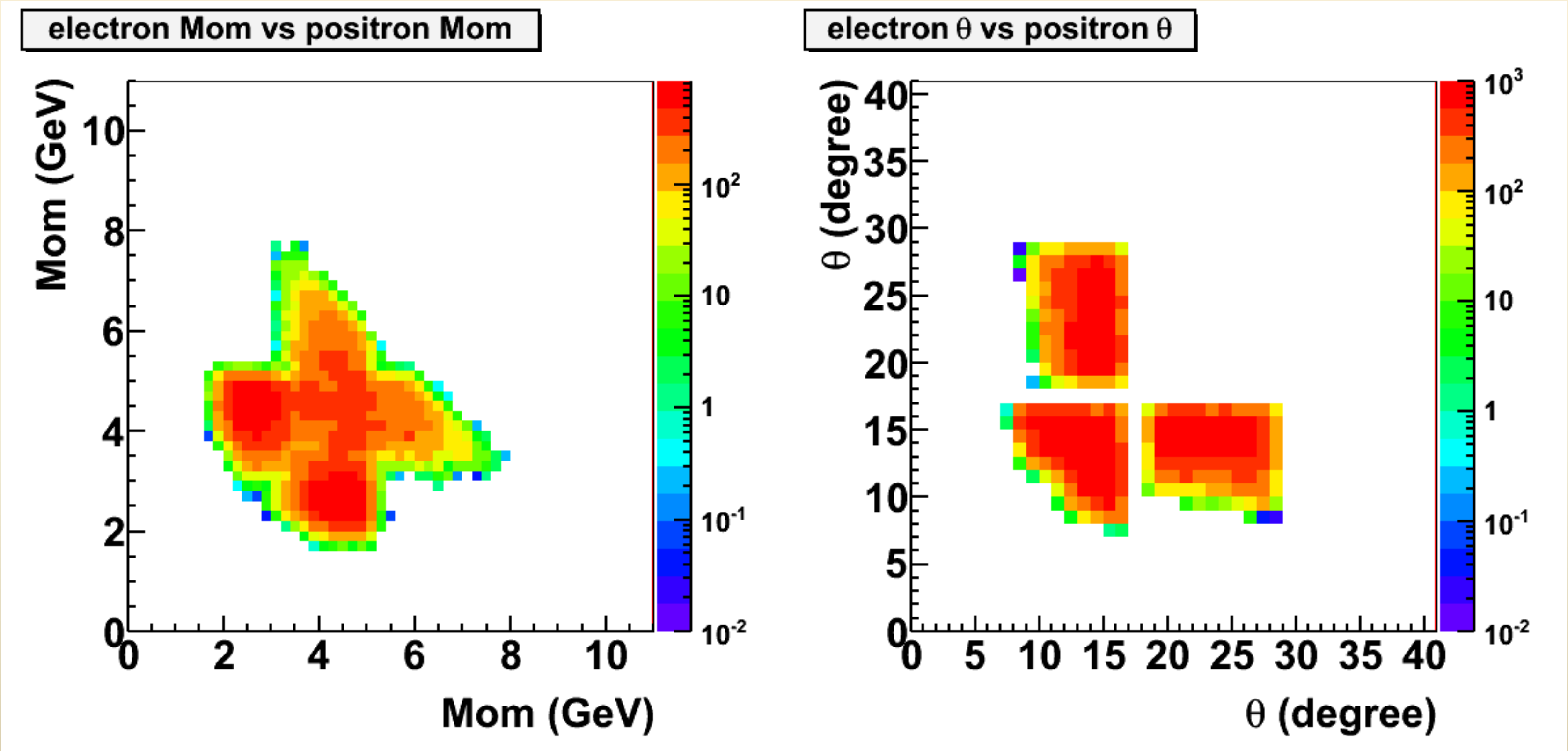


LA



Electron PID

- Require at least one electron/positron in LGCC and below 4.9GeV threshold to help reject pions



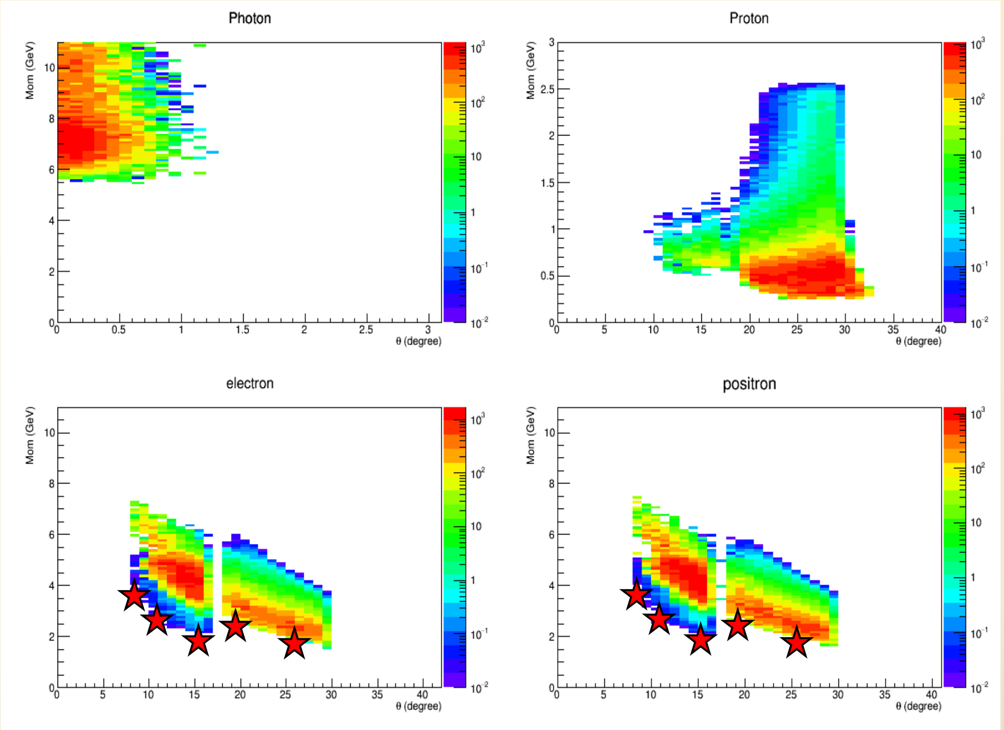
SoLID Trigger and Acceptance

- Trigger on decay electron and positron
- Allow both electroproduction and photoproduction in data
- EC has radial dependent trigger threshold from 4 – 2GeV (stars)
- LGCC, MRPC, SPD help reject other hadrons and photons
- Same trigger works for Jpsi and TCS as run group

- Study was done in the way similar to PVDIS and SIDIS trigger rate
- Using SIDIS_He3 EC trigger response for now, luminosity (1e37/cm2/s) is similar for both and background has no big effect on EC trigger for this level of luminosity)

BH (photo + quasi-photoproduction)

Require proton and decay pair



Single electron trigger including both FA (682kHz) and LA(446kHz) is about 1.13MHz

Coincidence of two electron trigger within 30ns time window is 1.13e6*1.13e6*30e-9 = 40kHz, which is below 100kHz SIDIS Setup limit

Cut on quasi-real and real photon

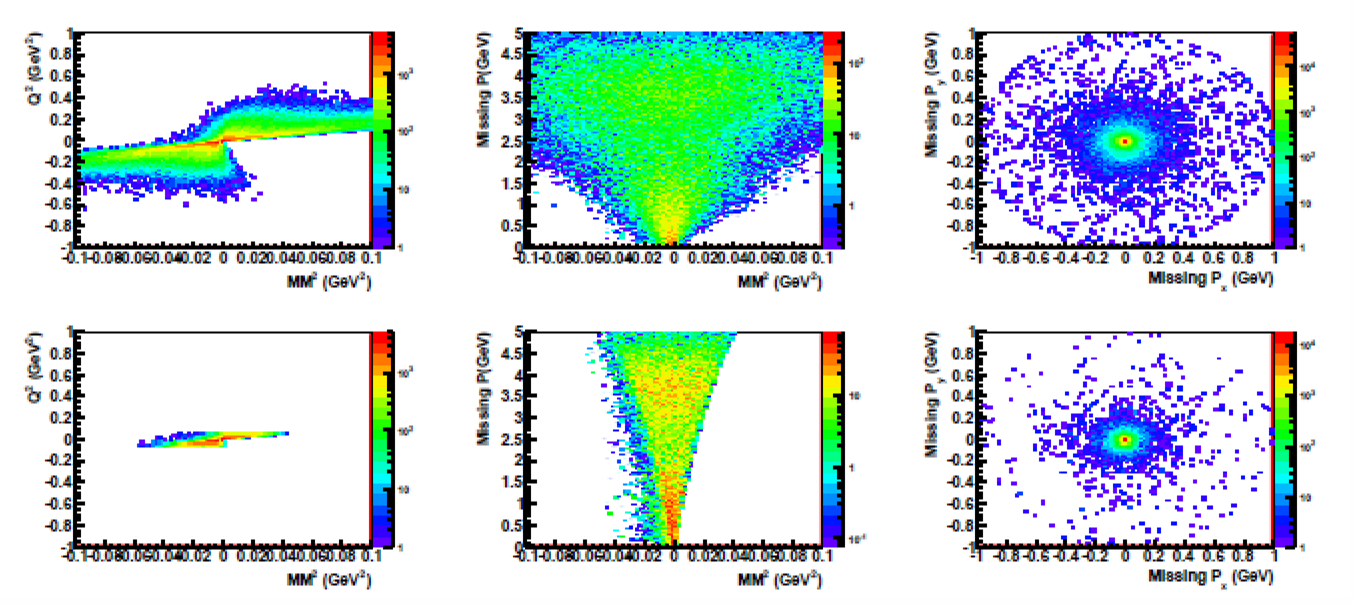
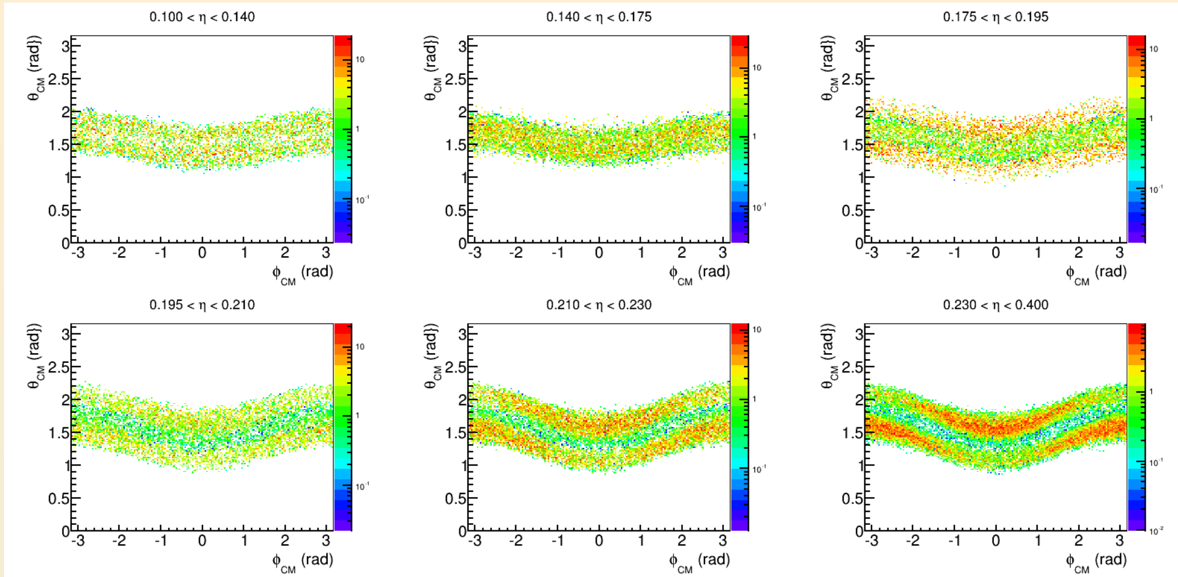
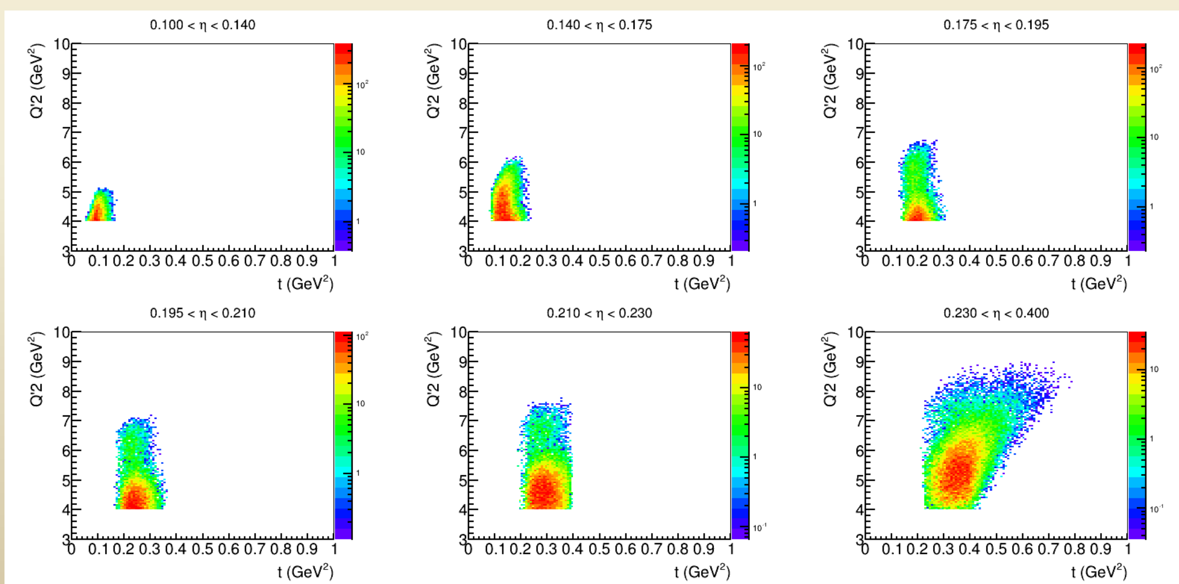


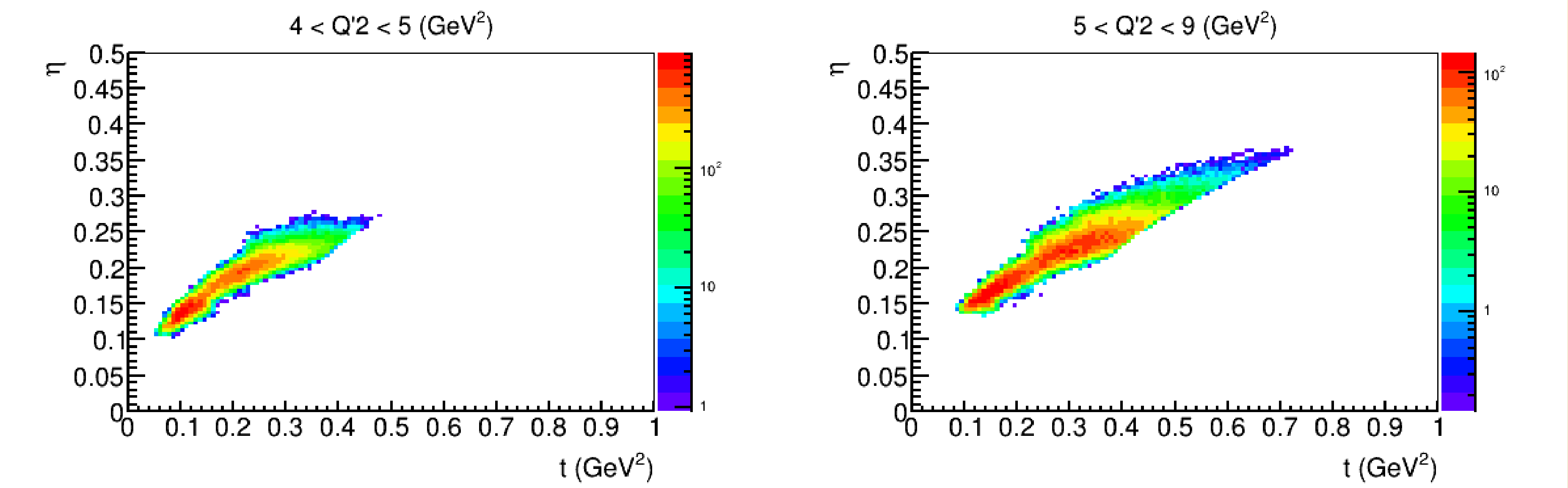
FIG. 23: Missing-particle kinematics before and after the cut $Q^2 < 0.05$ GeV^2 *Left panels:* Q^2 versus missing mass squared MM^2. *Middle panels:* Missing momentum versus missing mass squared MM^2. *Right panels:* Missing momentum P_x versus missing momentum P_y. *Top row:* before the Q^2 cut *Bottom row:* after the Q^2 cut.

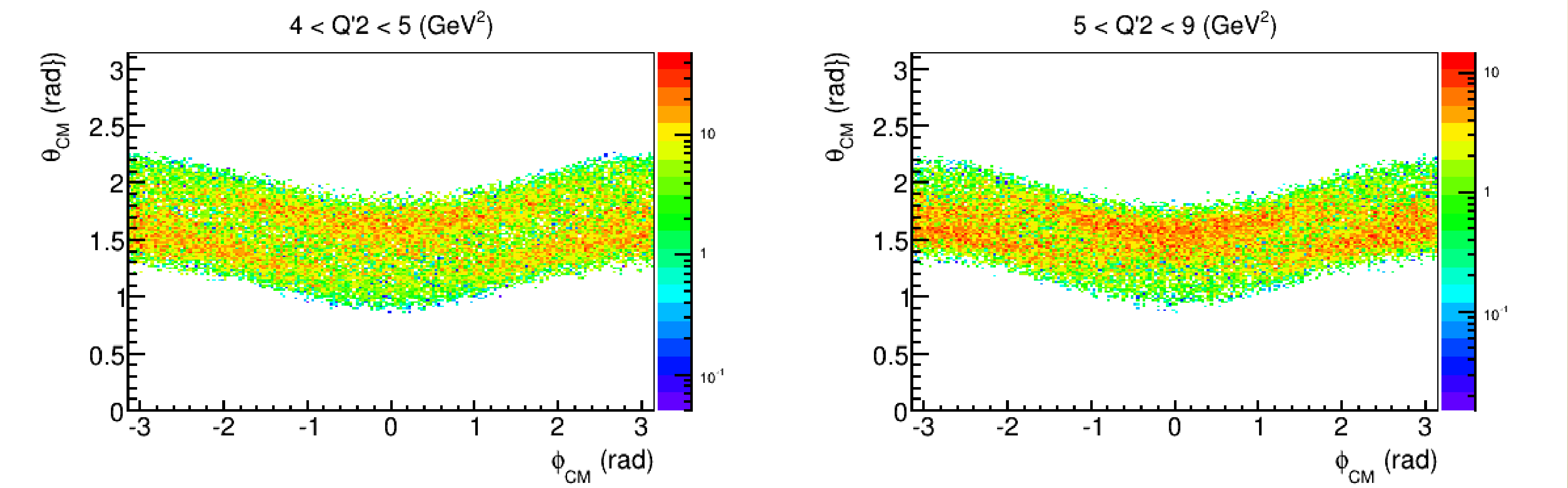
SoLID TCS projection





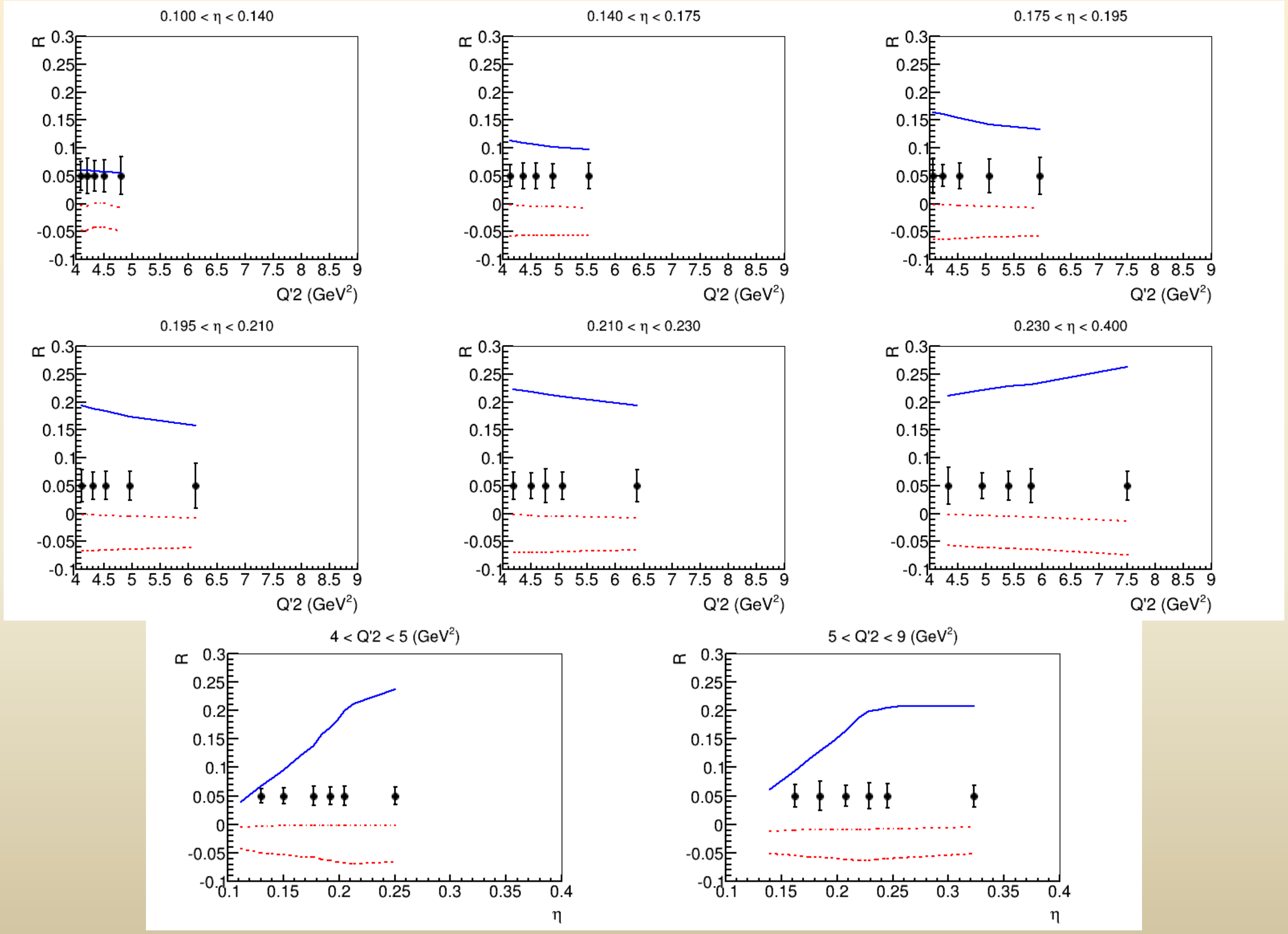
SoLID TCS projection





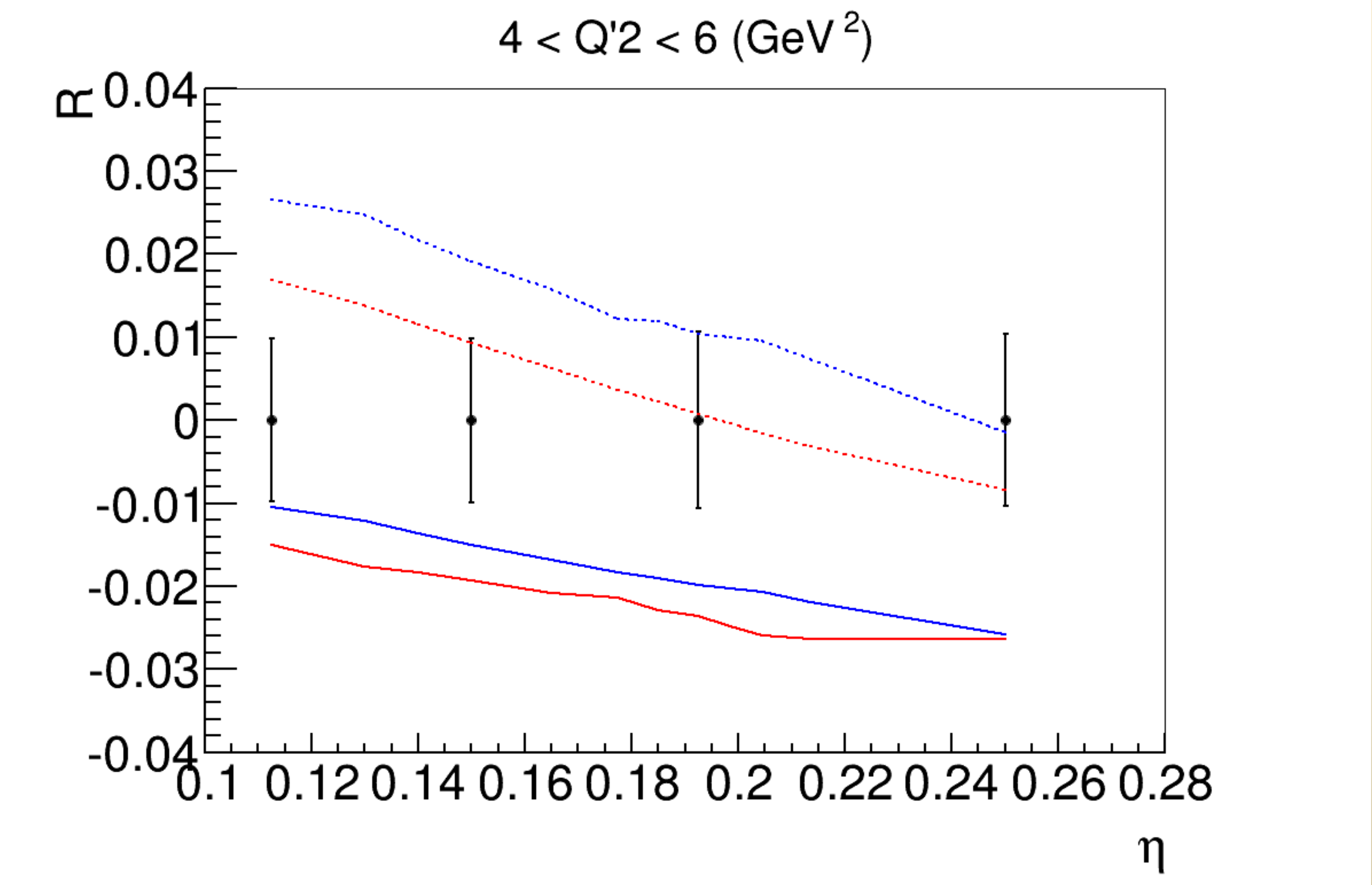
SoLID TCS projection

- Blue solid line, dual parameterization model
- Red dash-dot line, double distribution with D-term model
- Red dash line, double distribution without D-term model



SoLID TCS projection

- GK model (blue), MSTW model (red)
- Solid line, LO; dotted line, NLO



GPD fit

Fit exercise

	$(\sigma, \Delta\sigma_{LU})$ DVCS 5%	$(\sigma, \Delta\sigma_{LU})$ DVCS 5% + TCS_ℓ 15%	$(\sigma, \Delta\sigma_{LU})$ DVCS 5% + TCS_c 15%	$(\sigma, \Delta\sigma_{LU})$ DVCS 5% + TCS_ℓ 5%	$(\sigma, \Delta\sigma_{LU})$ DVCS 5% + TCS_c 5%
$\sigma^+(Re\{\mathcal{H}\})$	+1.21	+0.92	+0.80	+0.54	+0.55
$\sigma^-(Re\{\mathcal{H}\})$	-0.84	-0.79	-0.83	-0.44	-0.45
$\sigma^+(Im\{\mathcal{H}\})$	+0.23	+0.20	+0.15	+0.11	+0.12
$\sigma^-(Im\{\mathcal{H}\})$	-0.50	-0.40	-0.21	-0.27	-0.19

Fit exercise for SoLID TCS

Go through SoLID simulation to get acceptance and counts for 50 days of running, then fit it

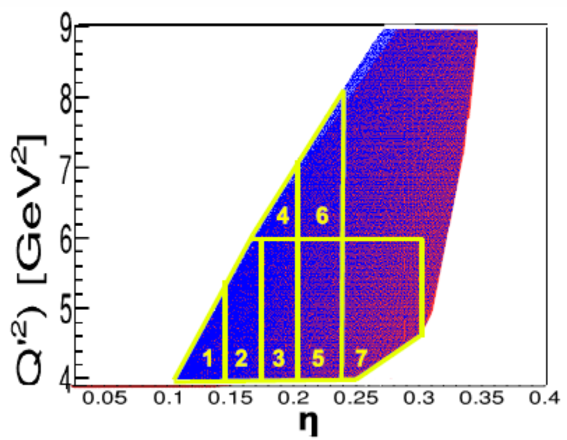


FIG. 37: Phase space for TCS as a function of Q'^2 and η with the definition of the 7 bins for Hall A SoLID data.

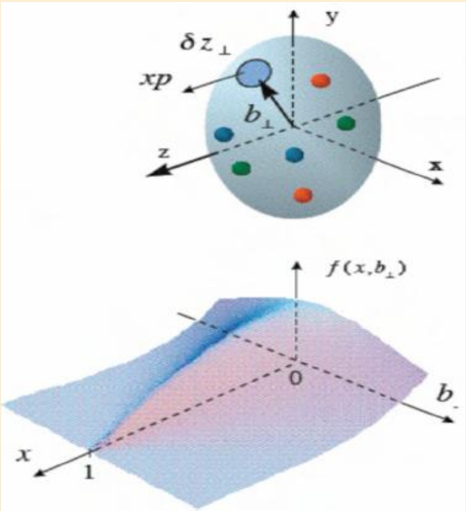
	$(\sigma, \Delta\sigma_{LU})$ DVCS + TCS_c
$\sigma^+(Re\{\mathcal{H}\})$	+0.82
$\sigma^-(Re\{\mathcal{H}\})$	-0.77
$\sigma^+(Im\{\mathcal{H}\})$	+0.16
$\sigma^-(Im\{\mathcal{H}\})$	-0.40

Summary

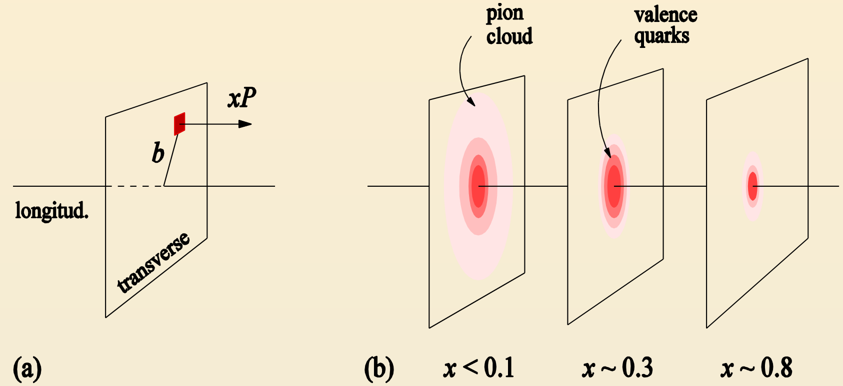
- SoLID TCS will provide higher statistics and different acceptance than CLAS12 TCS, and thus provide better fit to GPD and explore kinematic space with more details to help constrain on models
- CLAS12 and SoLID form a nice complementary program both in detectors and in timelines
- SoLID TCS can be a run group with SoLID JPsi and will provide help on background study and normalization crosscheck

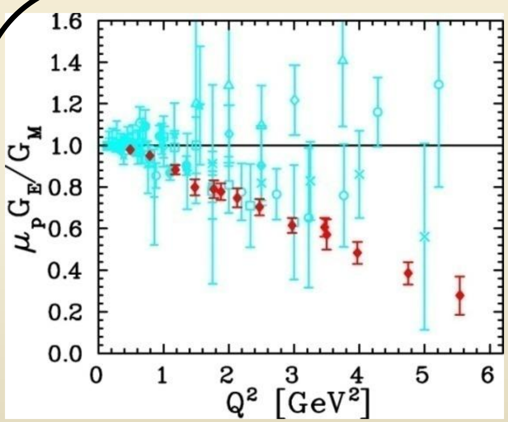
Backup

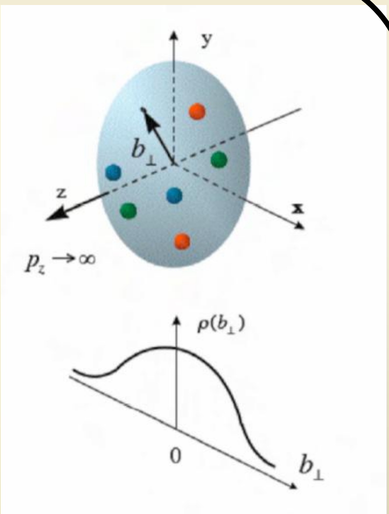
Generalized Parton Distribution (GPD)



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

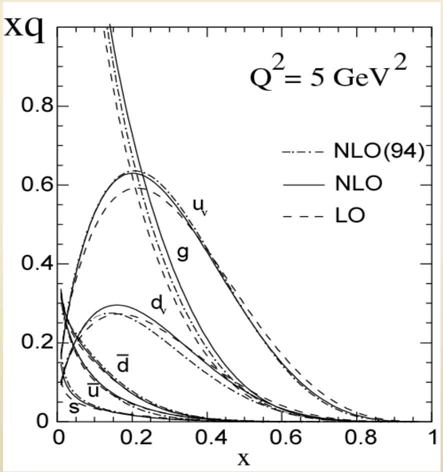


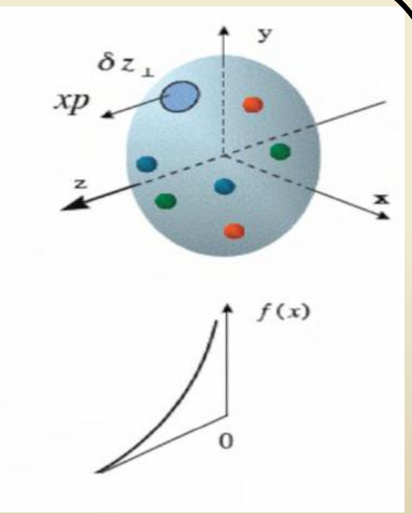




Elastic form factors

Transverse spatial distributions





Parton Distribution Functions

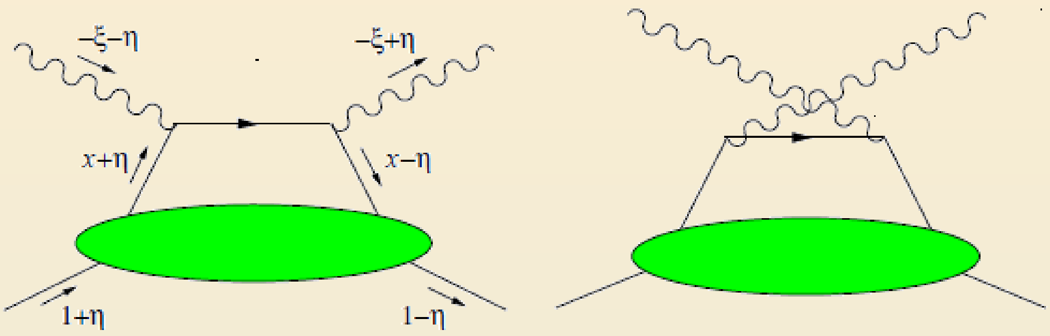
Longitudinal momentum distributions

General Compton Process

accessing GPDs

$$\gamma(q) + p(p) \to \gamma(q') + p(p')$$

$$Q^2 = -q^2, \quad Q'^2 = q'^2, \quad s = (p+q)^2, \quad t = \Delta^2,$$



Compton Form Factor (CFF)

$$\mathcal{H}_1(\xi,\eta,t) = \sum_q e_q^2 \int_{-1}^{1} \mathrm{d}x \left(\frac{H^q(x,\eta,t)}{\xi - x - \mathrm{i}\epsilon} - \frac{H^q(x,\eta,t)}{\xi + x - \mathrm{i}\epsilon} \right),$$

$$\mathcal{E}_1(\xi,\eta,t) = \sum_q e_q^2 \int_{-1}^{1} \mathrm{d}x \left(\frac{E^q(x,\eta,t)}{\xi - x - \mathrm{i}\epsilon} - \frac{E^q(x,\eta,t)}{\xi + x - \mathrm{i}\epsilon} \right),$$

$$\tilde{\mathcal{H}}_1(\xi,\eta,t) = \sum_q e_q^2 \int_{-1}^{1} \mathrm{d}x \left(\frac{\tilde{H}^q(x,\eta,t)}{\xi - x - \mathrm{i}\epsilon} + \frac{\tilde{H}^q(x,\eta,t)}{\xi + x - \mathrm{i}\epsilon} \right),$$

$$\tilde{\mathcal{E}}_1(\xi,\eta,t) = \sum_q e_q^2 \int_{-1}^{1} \mathrm{d}x \left(\frac{\tilde{E}^q(x,\eta,t)}{\xi - x - \mathrm{i}\epsilon} + \frac{\tilde{E}^q(x,\eta,t)}{\xi + x - \mathrm{i}\epsilon} \right)$$

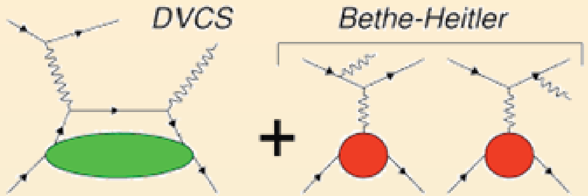
$$\xi = -\frac{(q+q')^2}{2(p+p')\cdot(q+q')} \approx \frac{Q^2 - Q'^2}{2s + Q^2 - Q'^2},$$

$$\eta = -\frac{(q-q')\cdot(q+q')}{(p+p')\cdot(q+q')} \approx \frac{Q^2 + Q'^2}{2s + Q^2 - Q'^2},$$

$$x = \frac{(k+k')^+}{(p+p')^+}, \quad \xi \approx -\frac{(q+q')^+}{(p+p')^+}, \quad \eta \approx \frac{(p-p')^+}{(p+p')^+}.$$

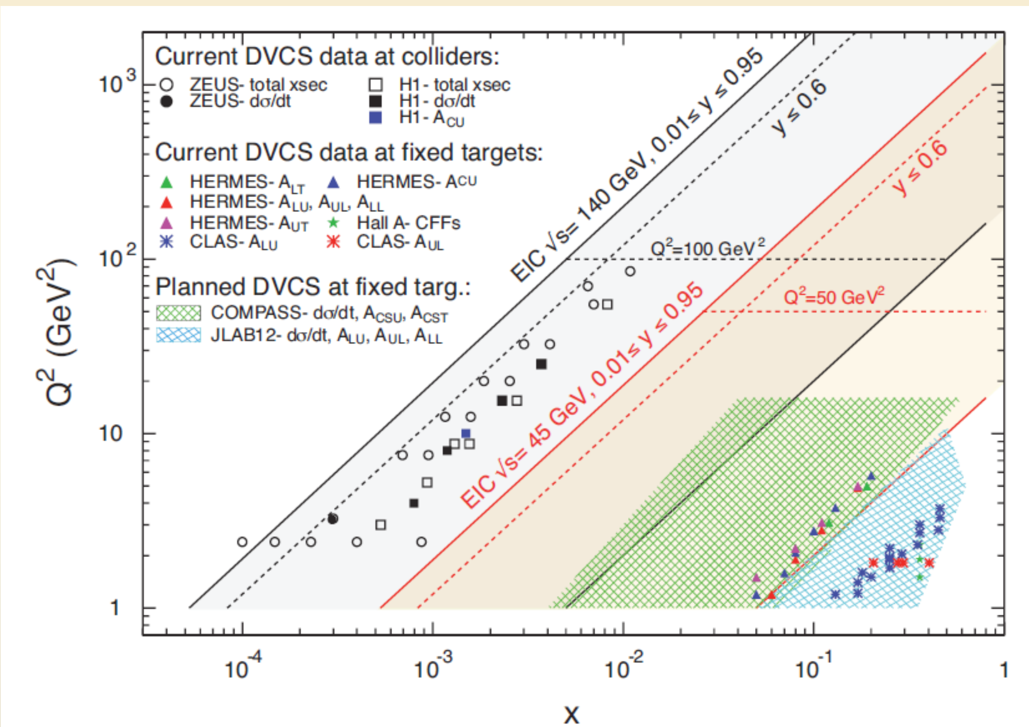
E.R. Berger et al. Eur. Phys. J. C 23, 675–689 (2002)

DVCS

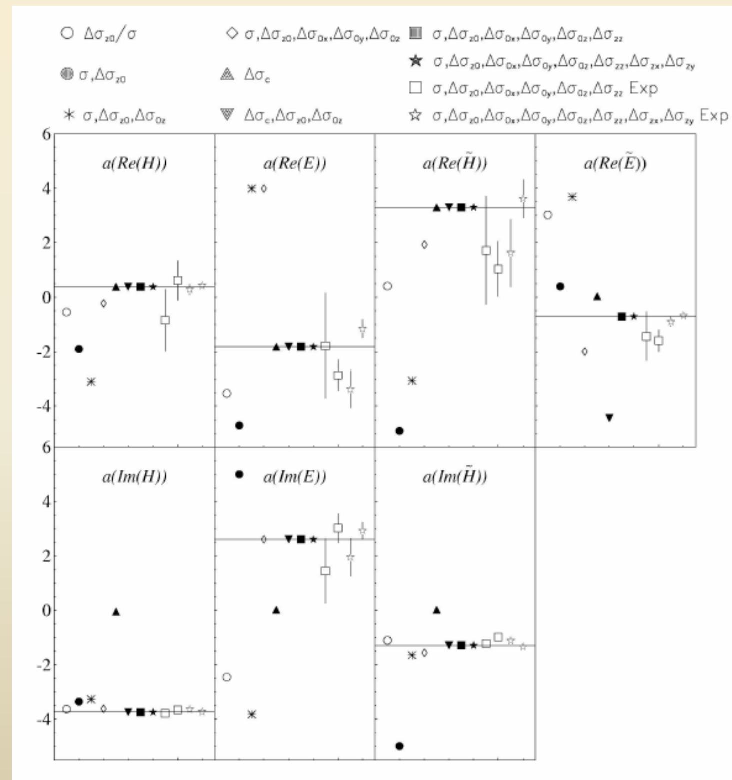
ep' epγ = 

$$\mathcal{T}=\left|\mathcal{T}_{BH}\right|^2+\left|\mathcal{T}_{DVCS}\right|^2+\mathcal{T}^*_{DVCS}\mathcal{T}_{BH}+\mathcal{T}^*_{BH}\mathcal{T}_{DVCS}$$

$$\mathcal{H}(\xi,t)=\underbrace{i\pi\left[H(\xi,\xi,t)-H(-\xi,\xi,t)\right]}_{\mathrm{Im}}+\underbrace{\mathrm{P}\int_{-1}^{+1}dx\left(\frac{1}{\xi-x}\pm\frac{1}{\xi+x}\right)\left[H(x,\xi,t)\mp H(-x,\xi,t)\right]}_{\mathrm{Re}}$$



An overview of existing and planned measurements of DVCS



Global fit to the DVCS data

M. Guidal, Eur.Phys.J. A37, p319 (2008)

Timelike Compton Scattering (TCS)

$$\gamma\, p \to p'\, \gamma^*(e^-\, e^+)$$

- Test spacelike-timelike correspondence and the universality of GPDs
  - Input for global analysis of Compton Form Factors
  - access through azimuthal asymmetry of lepton pair
- Explore GPDs of quarks and gluons at different kinematics

TCS crosssection

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

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

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

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

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

Interference term

In terms of helicity amplitudes:

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

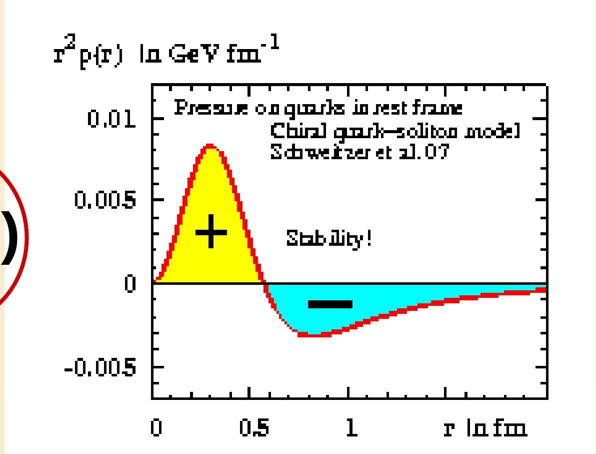
$$-\nu\,\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\Big[\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\,\tilde{M}^{--} - \sin 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Im}\,\tilde{M}^{0-} + \sin 3\varphi\,\sin\theta\,\mathrm{Im}\,\tilde{M}^{+-}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

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

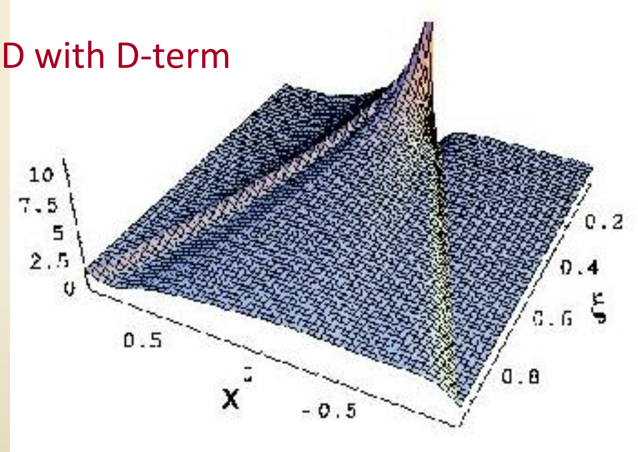
$$\frac{1}{2}\sum_{\lambda,\lambda'}|M^{\lambda'-,\lambda-}|^2 = (1-\eta^2)\big(|\mathcal{H}_1|^2+|\tilde{\mathcal{H}}_1|^2\big) - 2\eta^2\,\mathrm{Re}\big(\mathcal{H}_1^*\,\mathcal{E}_1+\tilde{\mathcal{H}}_1^*\,\tilde{\mathcal{E}}_1\big) - \Big(\eta^2+\frac{t}{4M^2}\Big)|\mathcal{E}_1|^2 - \eta^2\frac{t}{4M^2}|\tilde{\mathcal{E}}_1|^2,$$

The D-term and the pressure balance in the nucleon

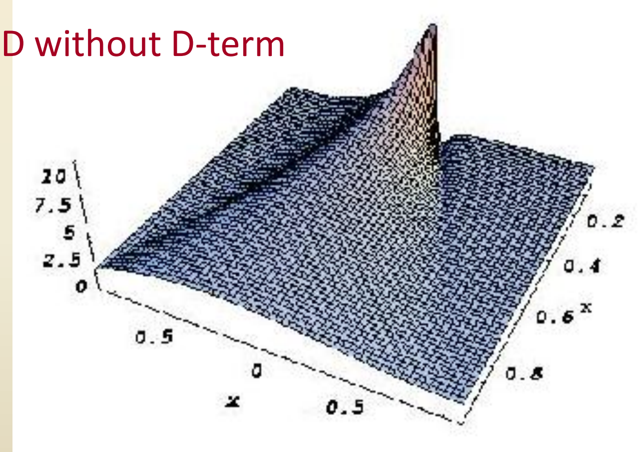
$$H(x,\xi) = H_{DD}(x,\xi) + \theta(\xi - |x|)\frac{1}{N_f} D\left(\frac{x}{\xi}\right)$$



GPD with D-term



GPD without D-term



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

TCS NLO

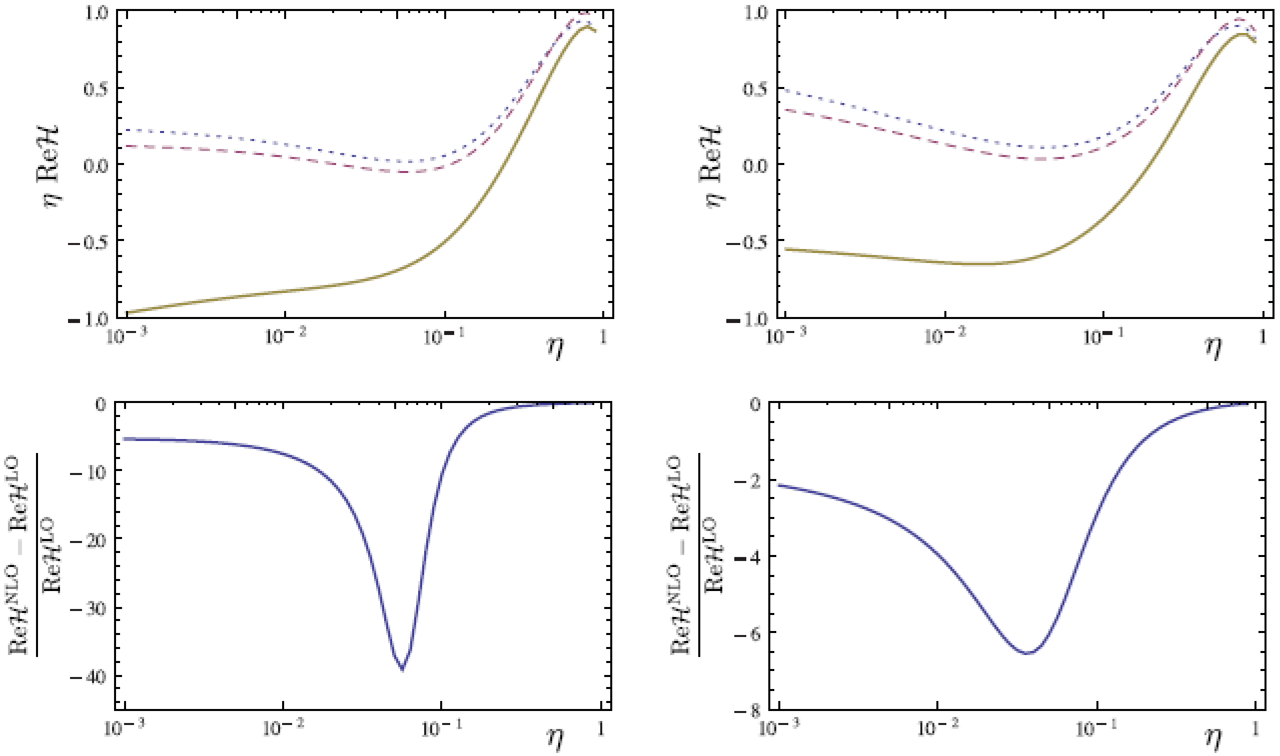


Figure 4: The real part of the *timelike* Compton Form Factor $\mathcal{H}$ multiplied by η, as a function of η in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.1$ GeV^2. Below the ratios of the NLO correction to LO result of the corresponding models.

DVCS NLO

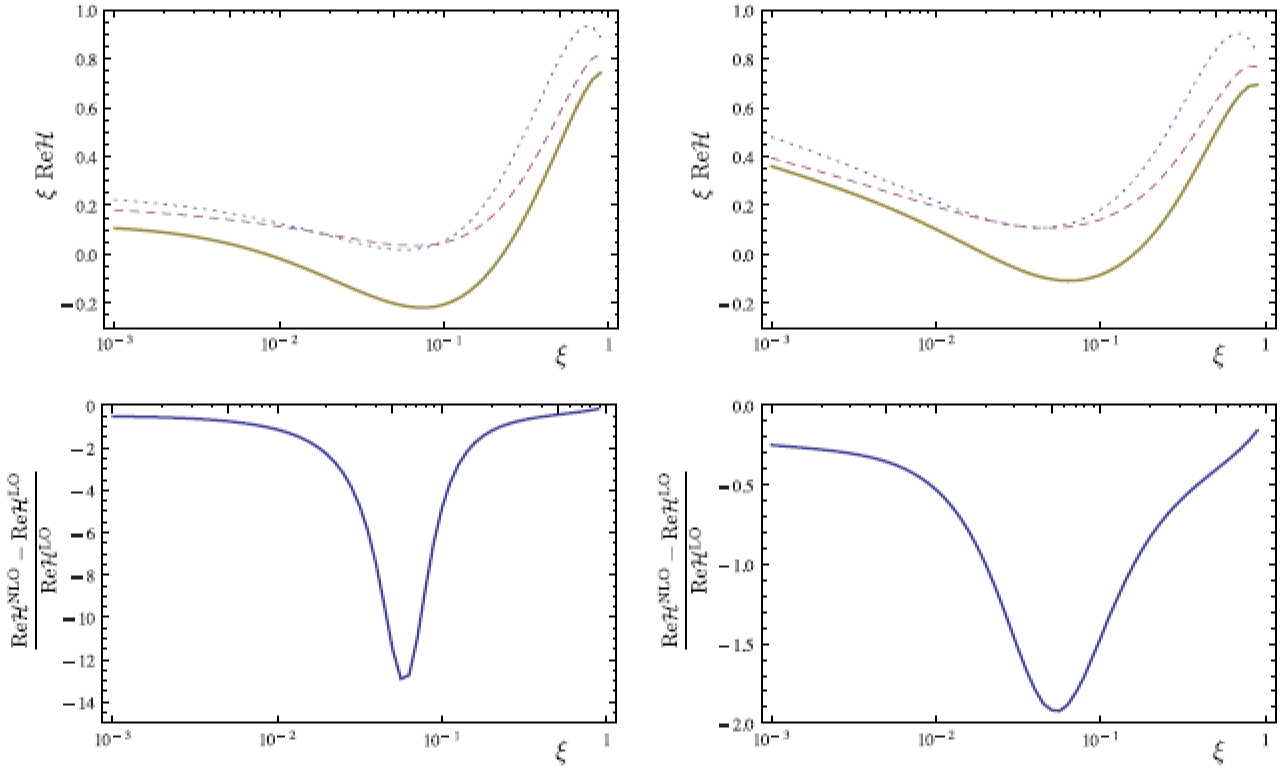
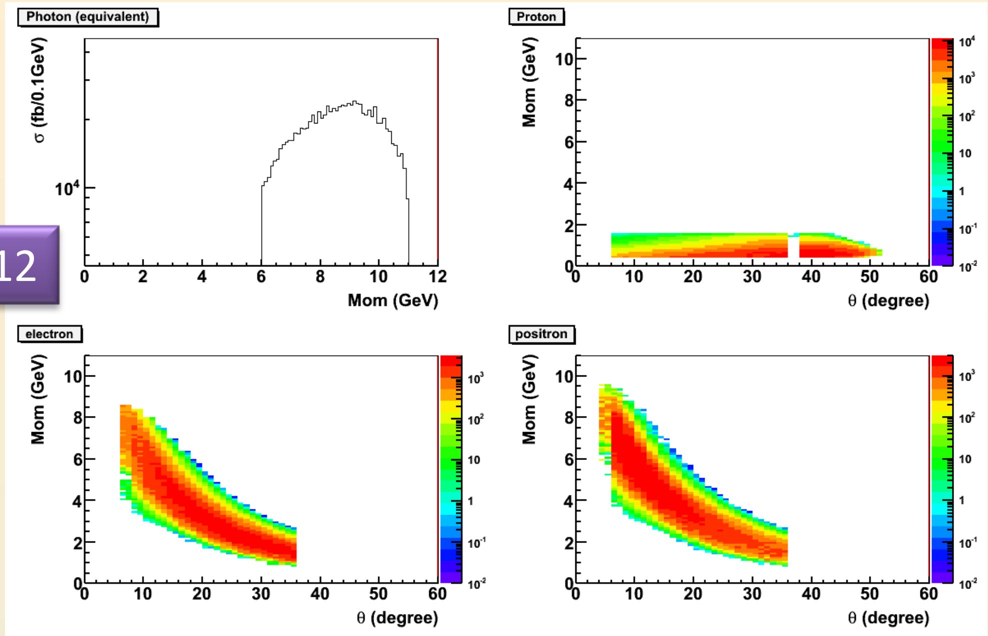


Figure 1: The real part of the *spacelike* Compton Form Factor $\mathcal{H}(\xi)$ multiplied by ξ, as a function of ξ in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4\,\mathrm{GeV}^2$ and $t = -0.1\,\mathrm{GeV}^2$, at the Born order (dotted line), including the NLO quark corrections (dashed line) and including both quark and gluon NLO corrections (solid line). Below the ratios of the NLO correction to LO result in the corresponding models.

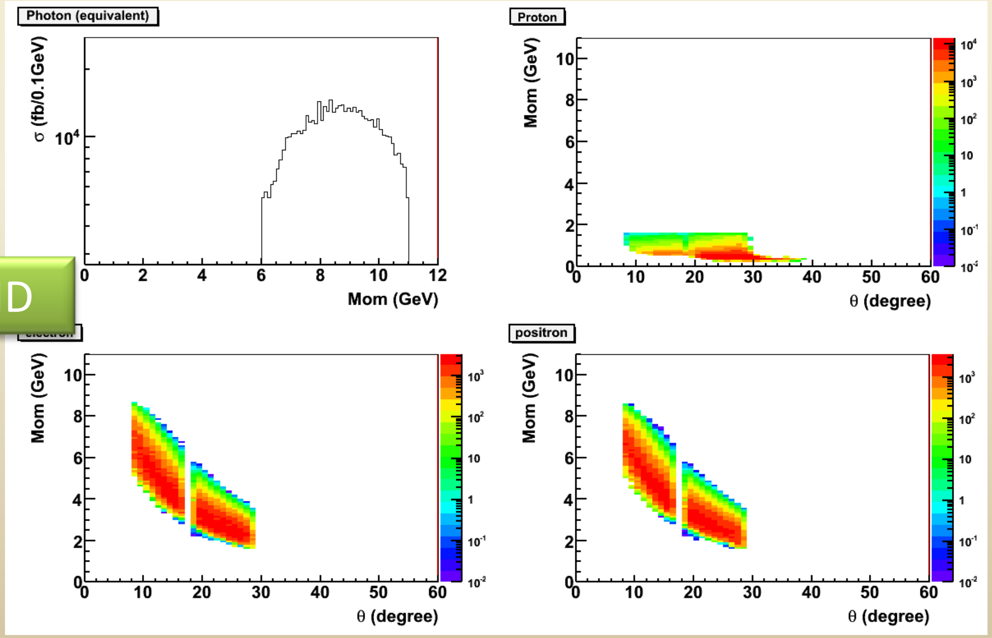
CLAS12 and SoLID: BH Detection (Lab Frame)

- BH events in the resonance free region are used for simulation
- CLAS12 and SoLID have similar overall coverage
- CLAS12 acceptance is slightly larger SoLID, but within a factor of 2

CLAS12



SoLID

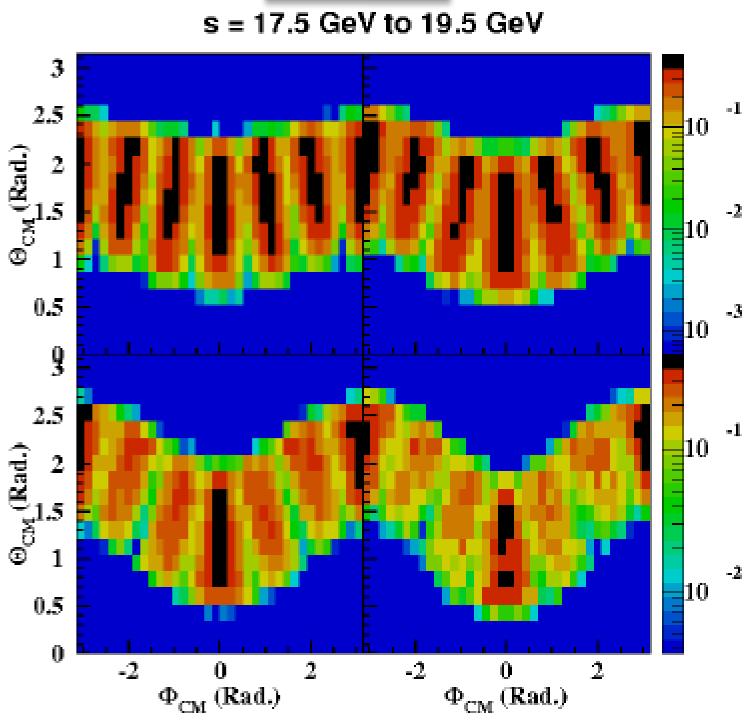


CLAS12 and SoLID: BH Detection (γ^* CM Frame)

$4GeV^2 < Q'2 < 9GeV^2$
$17.5GeV^2 < s < 19.5GeV^2$
4 t-bins within $0.1GeV^2 < t < 0.9GeV^2$

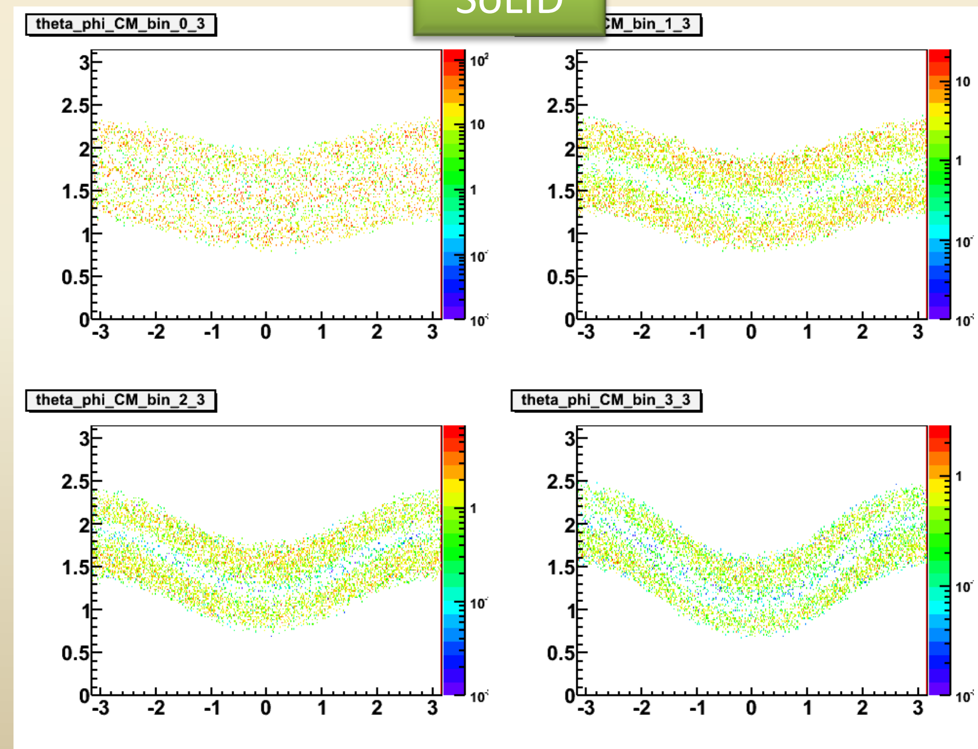
- CLAS12 has ϕ structure which has to be corrected by acceptance
- SoLID is smooth over ϕ, but has θ gap

CLAS12



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

SoLID



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

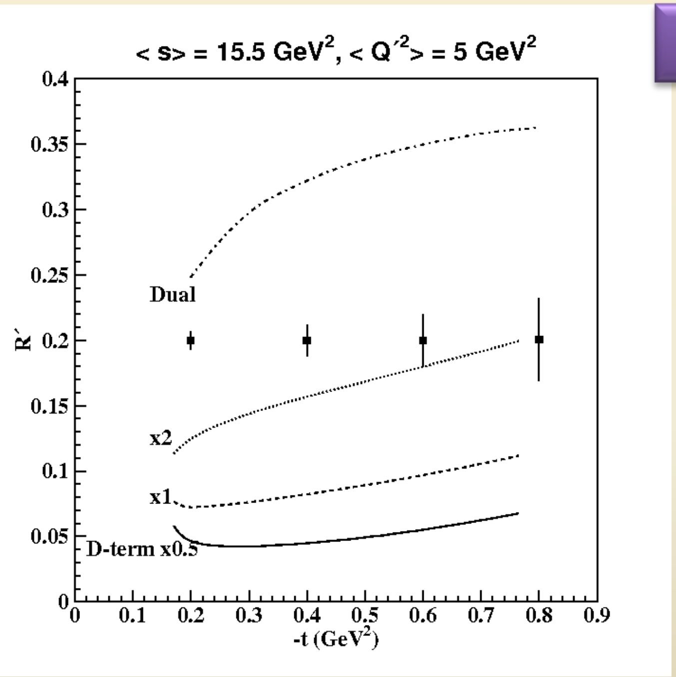
Proposal	Physics	Contact	Rating	Days	Group	Energy	Target
E12-06-108	Hard exclusive electro-production of $\pi0$, η	Stoler	B	80			
E12-06-112	Proton's quark dynamics in SIDIS pion production	Avakian	A	60			
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	A	80	119 days + 20 days with reversed torus 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			

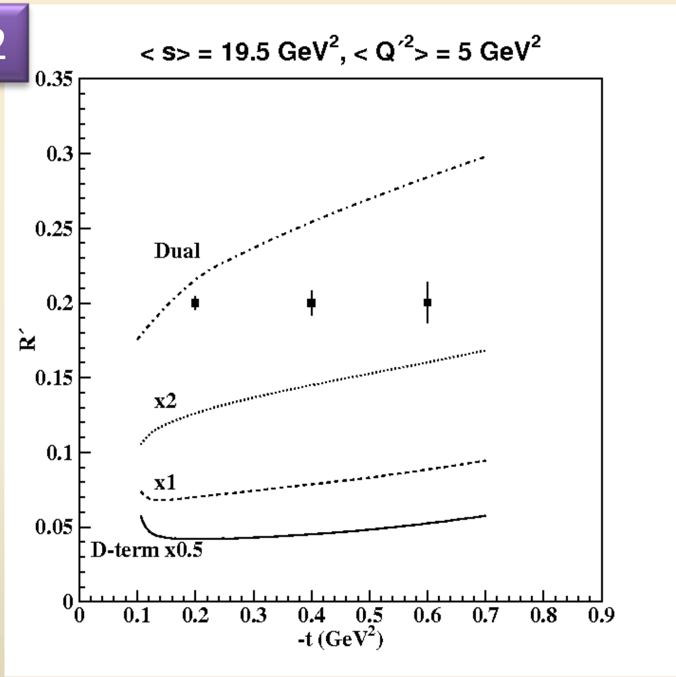
- Unpolarized proton target will be first to run
- Experiment E12-12-001 for e+e- physics was approved at the last PAC meeting
- Spectroscopy (119 PAC days) and e+e- (100+20 days) experiments drive the total beam time for proton running (119+20 days), which can be shared by all.
- Approved beam time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

TCS at JLab 12GeV Projected Result

- SoLID, with 100 time more luminosity, should have about factor of 50 more events than CLAS12 under same running time
- ***CLAS12 and SoLID will run at different time and be well complementary***

CLAS12

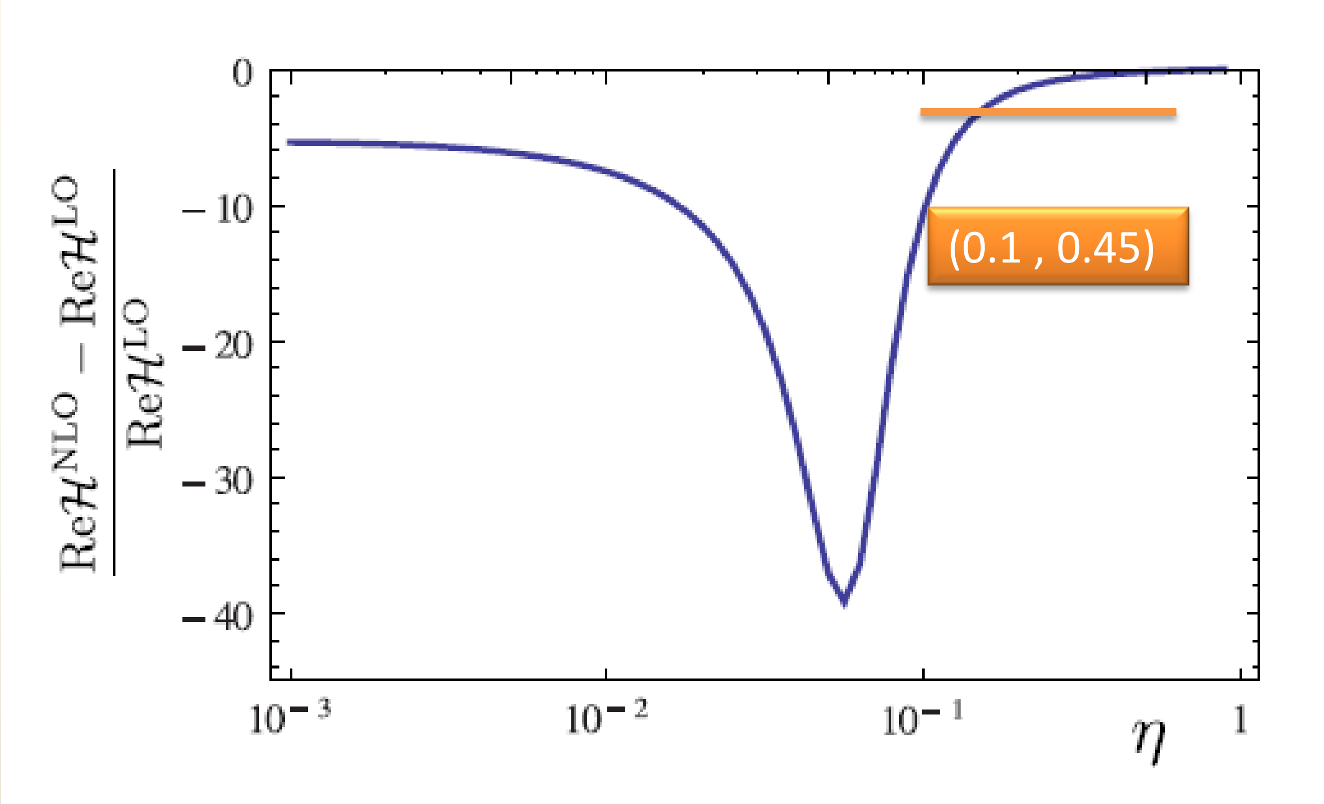




- Statistical uncertainties for 100 days at a luminosity of 10^{35} $cm^{-2}s^{-1}$
- Uncertainties for cosine moment R', integrated over the CLAS12 acceptance, for two bins in photon energy, for the lowest Q'^2 bin above the ρ' resonance.
- Different values of the D-term are only shown for the double distribution

SoLID TCS

- (preliminary) estimated **500k** events for 1e37cm^{-2}s^{-1} lumi and 50 days
- Higher statistics enables multi-dimension binning (Q2, s, t , eta…)
  - e.g. study the change over eta and search for NLO (gluonic)

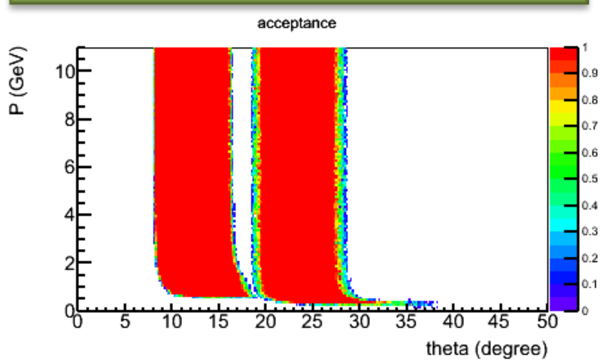


CLAS12 and SoLID: Acceptance

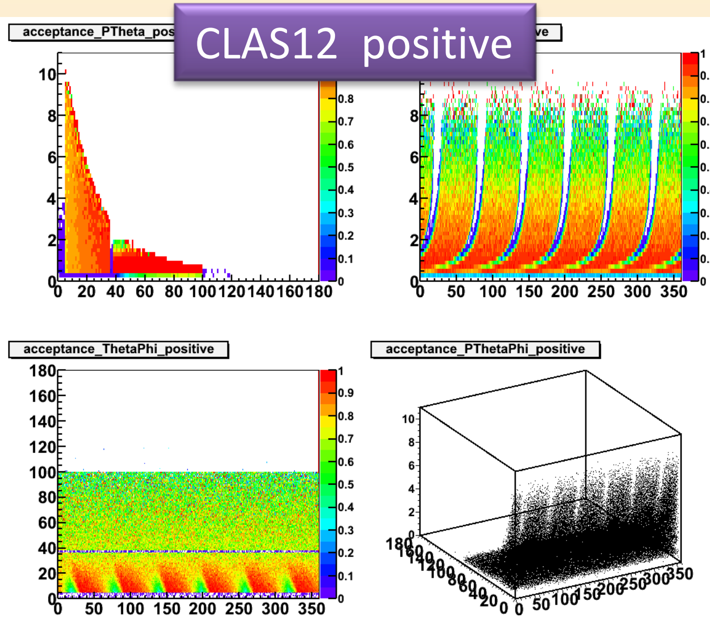
	CLAS12	SoLID
e^- and e^+ coverage	θ(5° – 36°) ϕ (~ 80% full) Asymmetric	θ(8° – 17°) θ(18° – 28°) ϕ(full) Symmetric
proton coverage	θ(5° – 36°) Θ(38° – 125°) ϕ (~ 80% full)	θ(8° – 17°) θ(18° – 28°) ϕ(full)
Luminosity	10^{35}/cm²/s	10^{37}/cm²/s

- CLAS12 larger CC coverage
- CLAS12 large TOF (proton PID) coverage

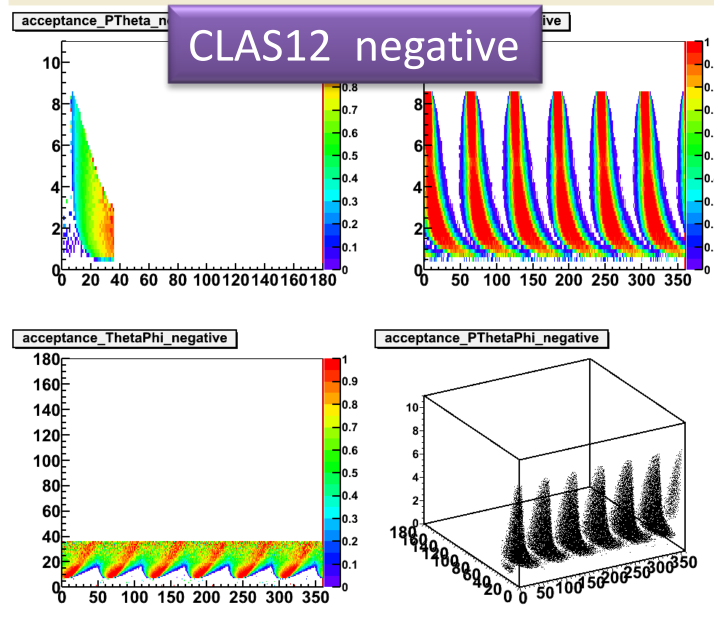
SoLID positive and negative



CLAS12 positive



CLAS12 negative



CLAS12 and SoLID: Resolution

- CLAS12 better resolution

CLAS12

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 ($\delta p/p$)	$< 1\%$ at 5 GeV/c	$< 5\%$ at 1.5 GeV/c

SoLID

Parameters	So ctor
polar angular range (θ)	8° to 17° and 18° to 28°
azimuthal angular range (ϕ)	full
resolution:	
polar angle ($\delta\theta$)	< 0.6 mr
azimuthal angle ($\delta\phi$)	< 5 mr
momentum ($\delta p/p$)	$< 2\%$
PID:	
e/π by EC	full momentum range
e/π by CC	< 5 GeV/c at $8^\circ < \theta < 17^\circ$
p/K by TOF	< 4.5 GeV/c at $8^\circ < \theta < 17^\circ$ and < 2.5 GeV/c at $18^\circ < \theta < 28^\circ$

TABLE II: SoLID design characteristics.

SoLID TCS

- SoLID/CLAS12 luminosity 100
- CLAS12 has 6 times better selection power for TCS physics than SoLID
- SoLID JPsi approved for 50 days
- CLAS12 TCS approved for 120 days
- SoLID 100k events, CLAS12 14k events
- SoLID/CLAS12 statistics about a factor of 7