12 GeV Upgrade
Future Science at Jefferson Lab

Dilepton Production with SoLID (TCS and DDVCS)

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INT Program INT–17–3
Spatial and Momentum Tomography of Hadrons and Nuclei
August 28 – September 29, 2017

Jefferson Lab
EXPLORING THE NATURE OF MATTER

Duke
UNIVERSITY

Nuclear and Nucleon Structure Through Dileptons Production

October 24-28, 2016, ECT Trento, Italy

http://www.ectstar.eu/node/1667

Introduction

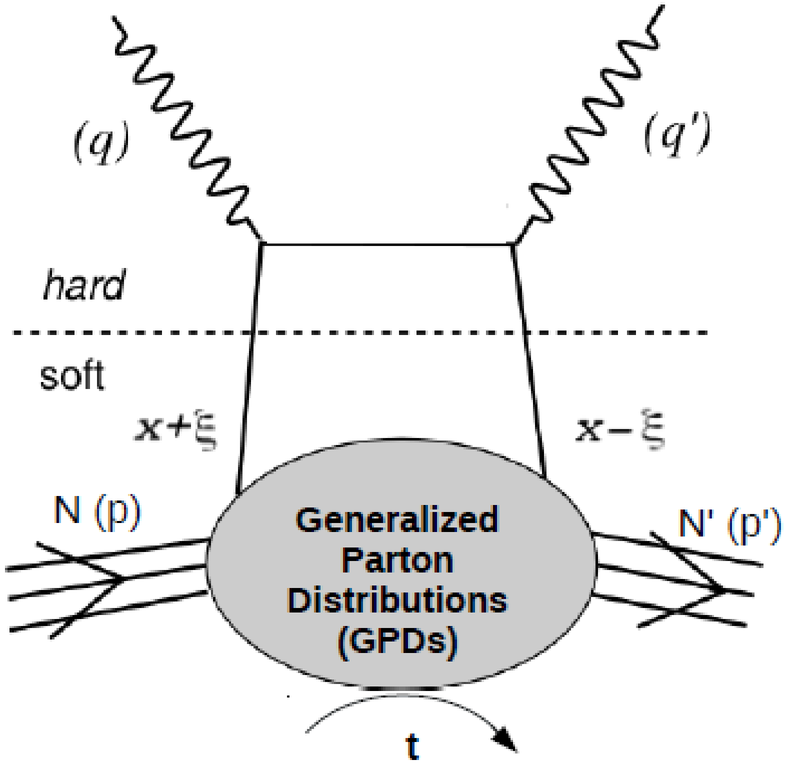
Exclusive dilepton production at JLab 12GeV

$$\gamma^* \, p \rightarrow l^- \, l^+ \, p'$$

- Access GPDs *(Marie Boer at week1 on theory, this talk on exp)*
  Timelike Compton Scattering (TCS) $\Gamma \, p \rightarrow \gamma^*(l^- \, l^+) \, p'$
  Double Deeply Virtual Compton Scattering (DDVCS) $\gamma^* \, p \rightarrow \gamma^*(l^- \, l^+) \, p'$

- Study gluon and proton mass *(Sylvester Joosten at week1)*
  J/ψ threshold production $\gamma^* \, p \rightarrow J/\psi(l^- \, l^+) \, p'$

Generalized Parton Distributions with exclusive Compton processes



γ (*) N → γ(*) N' → e+ e- N'

- outgoing photon is real :
<u>spacelike</u> **Deeply Virtual Compton Scattering**
DVCS = e N → e' γ N'

- incoming photon is real :
<u>Timelike</u> **Compton Scattering (TCS)**
TCS = γ N → e^+e^- N'

- both photons are virtual :
<u>Double</u> **Deeply Virtual Compton Scattering**
DDVCS = e N → e' e^+e^- N'

(e stands for any lepton)

x : average longitudinal momentum fraction of the struck quark
ξ : longitudinal momentum transfer
t : momentum transfer squared
$Q^2 = -q^2$; $Q'^2 = +q'^2$: hard scale, photon's virtuality

General Compton Process accessing GPDs in different ways

(Im, $x=\xi$)

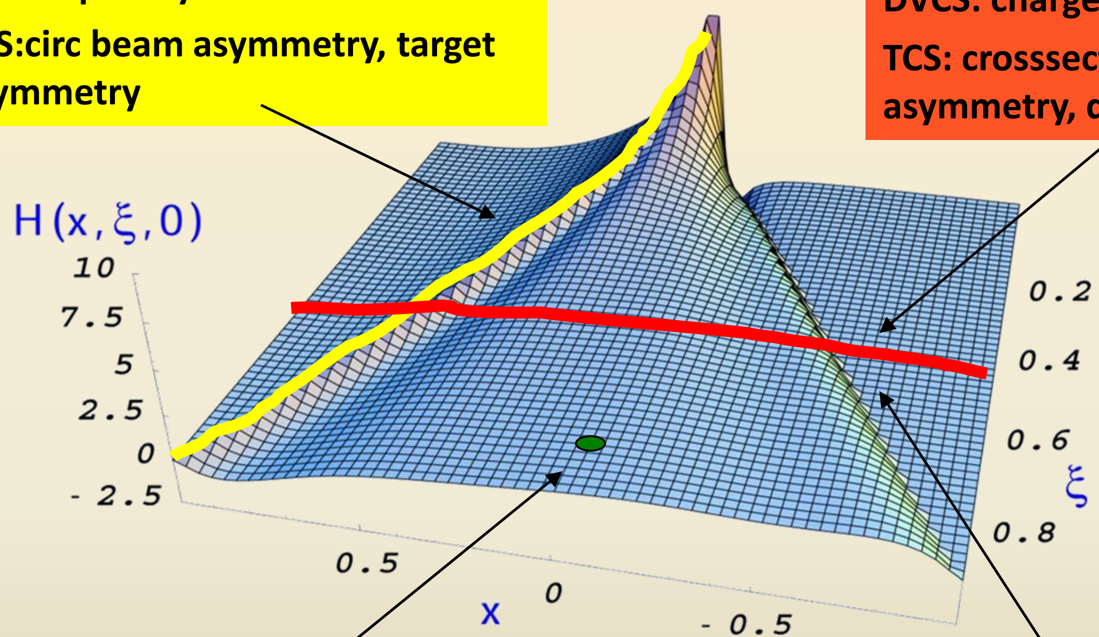
DVCS: spin asymmetries

TCS:circ beam asymmetry, target asymmetry

(Re)

DVCS: charge asymmetry

TCS: crosssection, lin beam asymmetry, double asymmetry



(Im, $x \neq \xi$, $x < |\xi|$)

Double DVCS

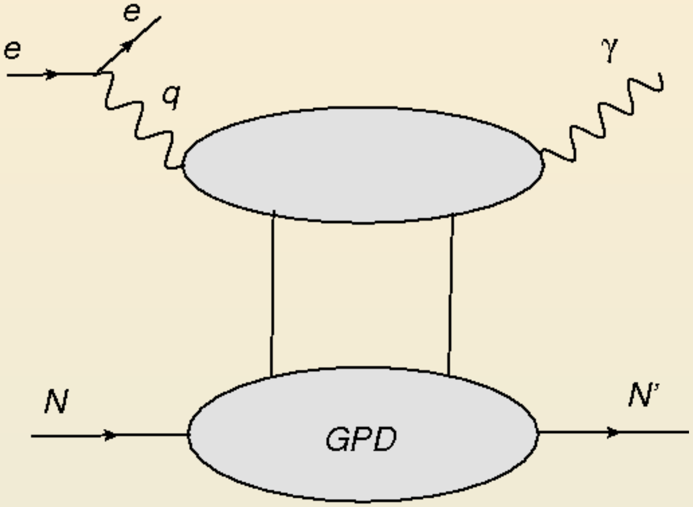
($|Im|^2+|Re|^2$)

DVCS: cross section

DVCS and TCS access the same GPDs

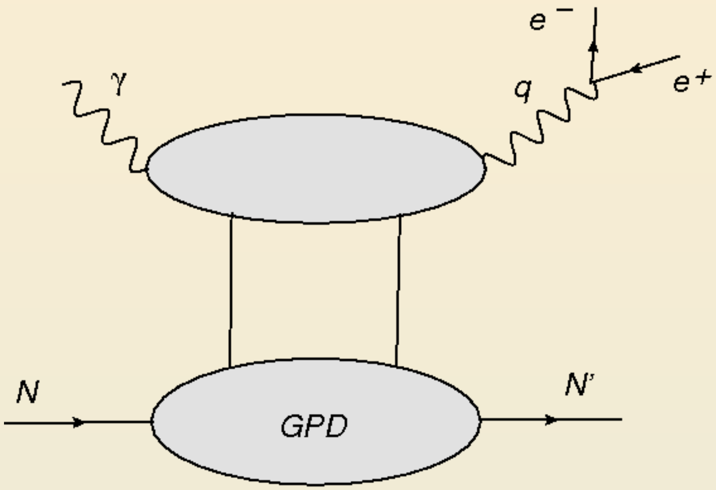
Spacelike Deeply Virtual Compton Scattering

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



Timelike Compton Scattering

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

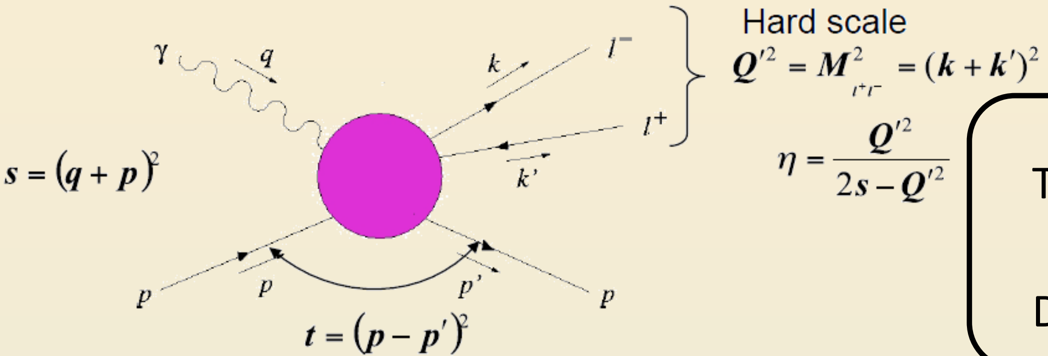


- "The amplitudes of these two reactions are related at Born order by a simple complex conjugation but they significantly differ at next to leading order (NLO)"
- " The Born amplitudes get sizeable $O(\alpha_s)$ corrections and, even at moderate energies, the gluonic contributions are by no means negligible.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

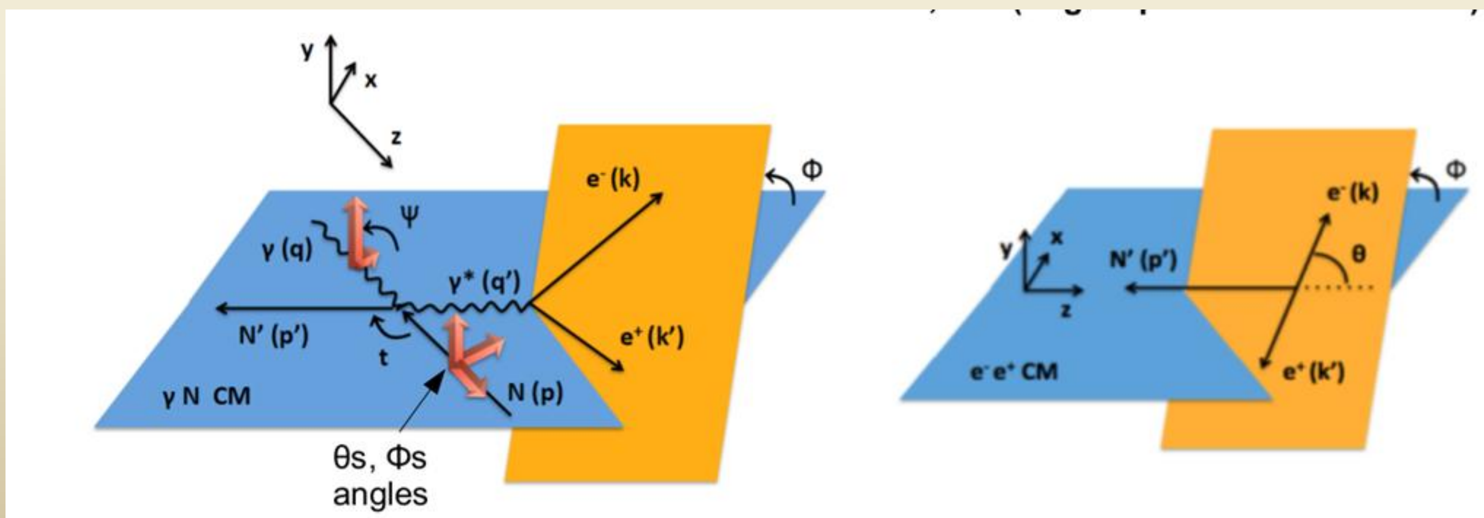
H. Moutarde et al. Phys. Rev. D 87, 054029 2013 arXiv:1301.3819

TCS

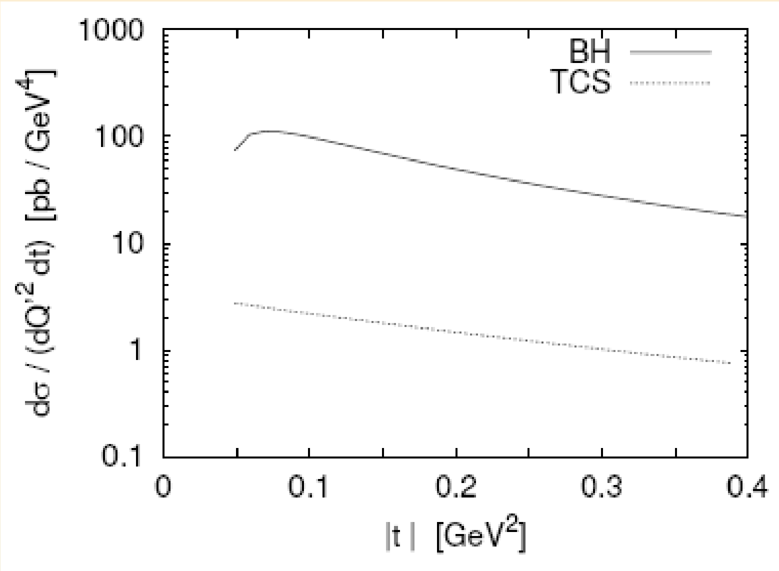
- 5 independent variables
- Q'^2 invariant mass of lepton pair instead of Q^2



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

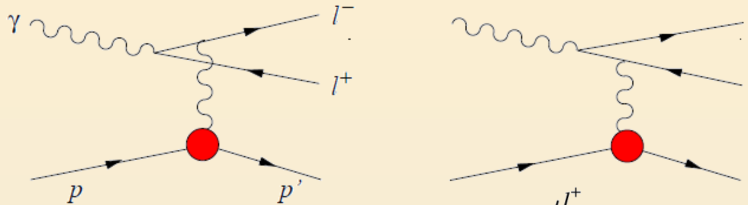


TCS and Bethe-Heitler (BH) Interference

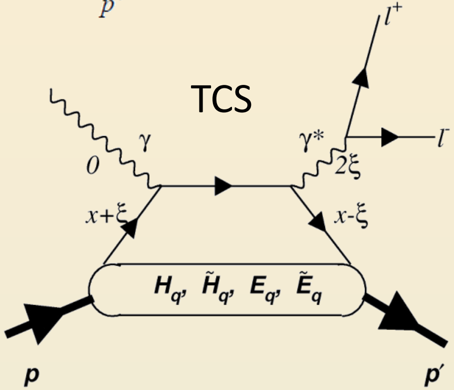


E. Berger *et al.*, Eur. Phys. J. C23, 675 (2002)

BH



TCS



Unpolarized Crosssection

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

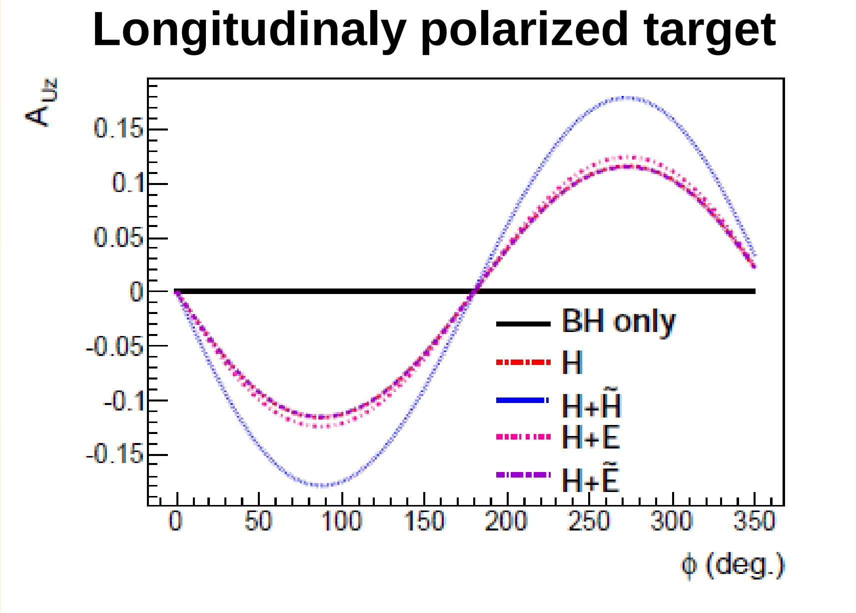
- For lepton charge conjugation, TCS and BH amplitudes are ***even***, while the interference term is ***odd***
- Direct access to interference term through angular distribution of the lepton pair (cosine and sine moments)

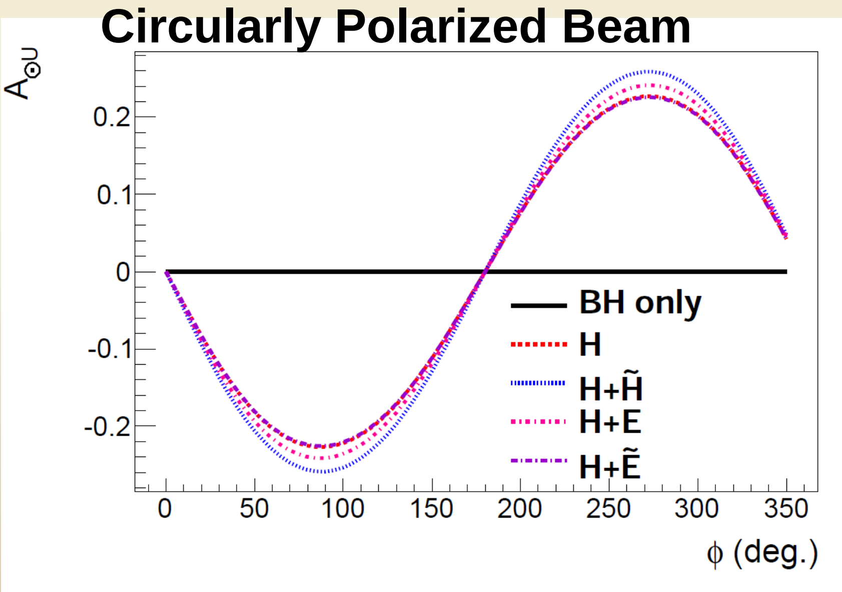
$$R = \frac{2\int_0^{2\pi} d\varphi \cos\varphi \frac{dS}{dQ^2\, dt\, d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ^2\, dt\, d\varphi}}$$

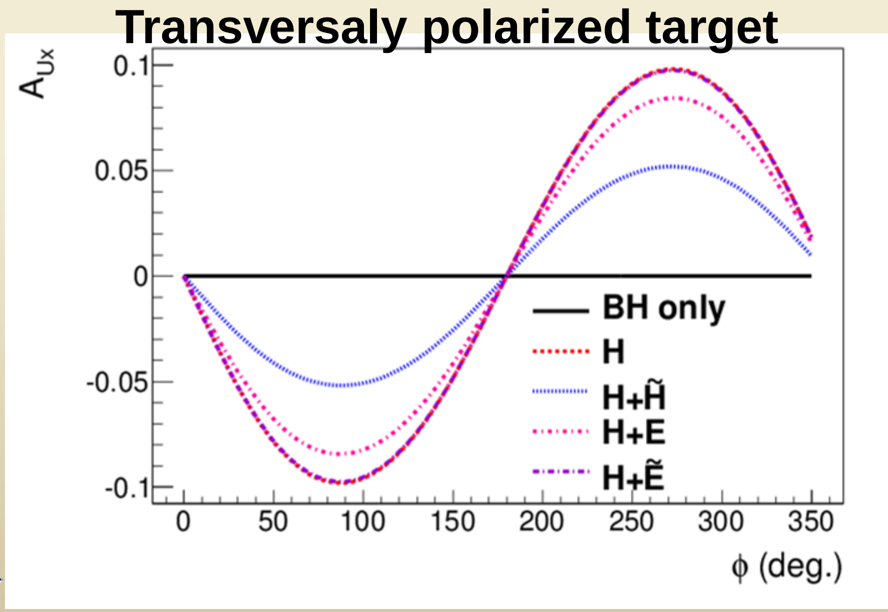
$$\frac{dS}{dQ^2\, dt\, d\varphi} = \int \frac{L(\theta,\varphi)}{L_0(\theta)} \frac{d\sigma}{dQ^2\, dt\, d\varphi\, d\theta}\, d\theta$$

TCS Spin Asymmetry

- BH cancels
- Measurable imaginary part
- Sensitive to H and Ĥ







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

TCS at JLab 6GeV

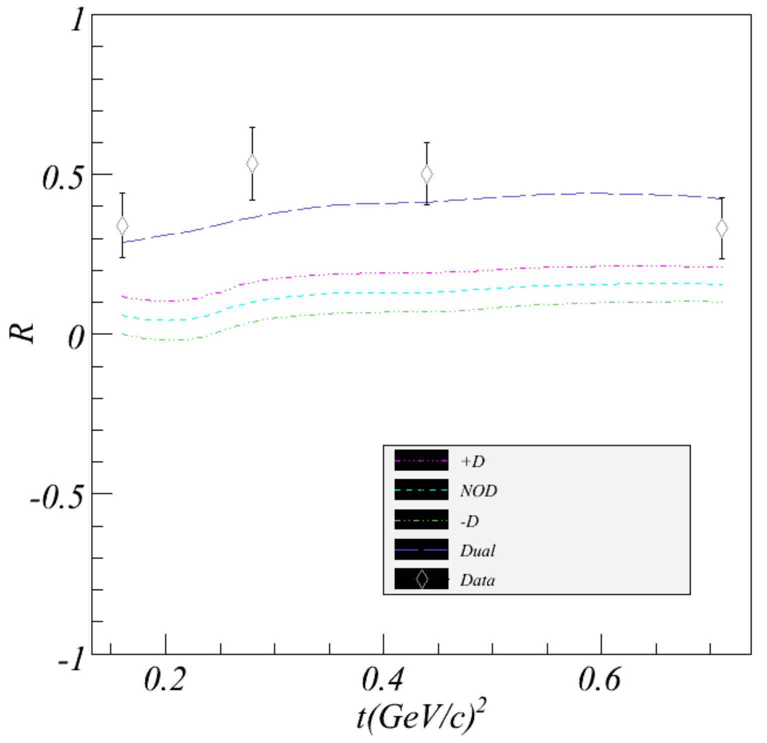
Cosine moment of weighted cross sections

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

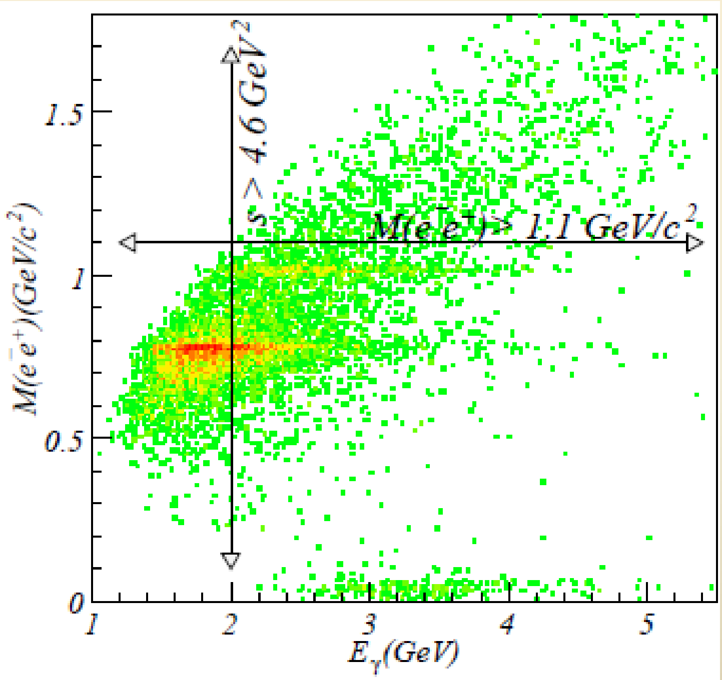
$$R=\frac{2\int_0^{2\pi} d\varphi \cos\varphi \frac{dS}{dQ^2\,dt\,d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ^2\,dt\,d\varphi}}$$

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

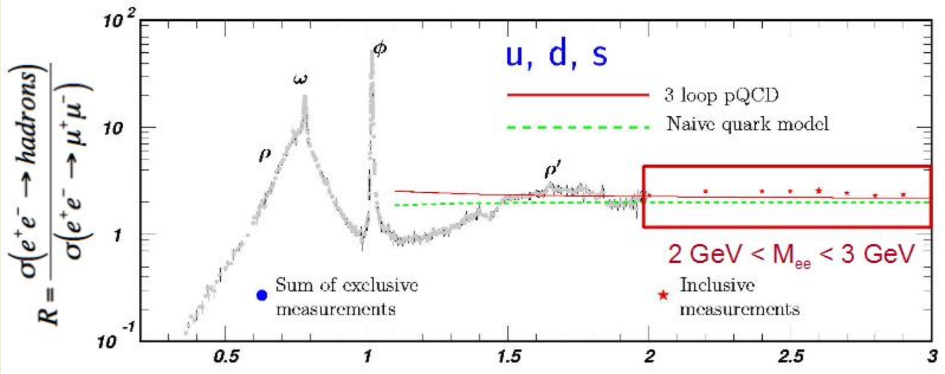


Comparison of results by R. Paremuzyan *et al* from CLAS e1-6/e1f with calculations by V. Guzey.

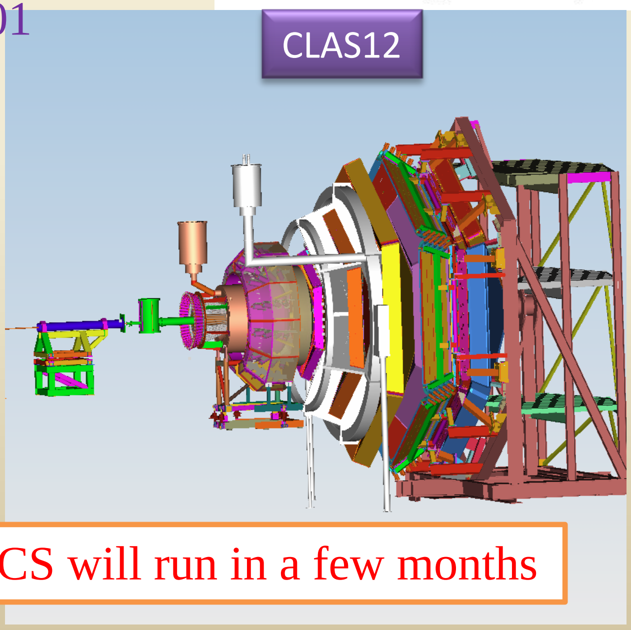


TCS at JLab 12GeV

- 11 GeV beam extends s to $20 GeV^2$
- 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, η reaches from 0.1 to 0.45
- Higher luminosity and thus more statistics for multi-dimensional binning

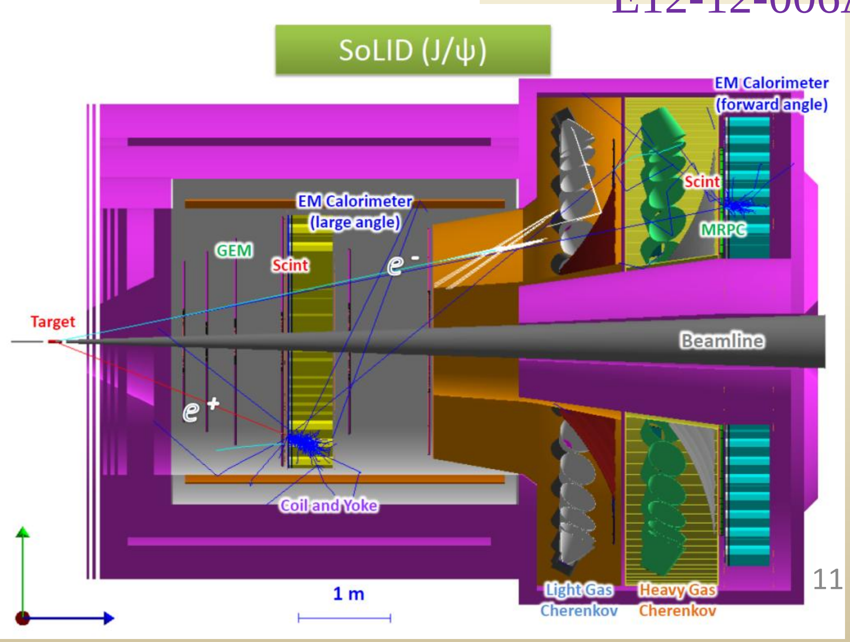


E12-12-001



CLAS12 TCS will run in a few months

E12-12-006A



CLAS12 and SoLID: 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 (δp/p)	< 1% at 5 GeV/c	< 5% at 1.5 GeV/c

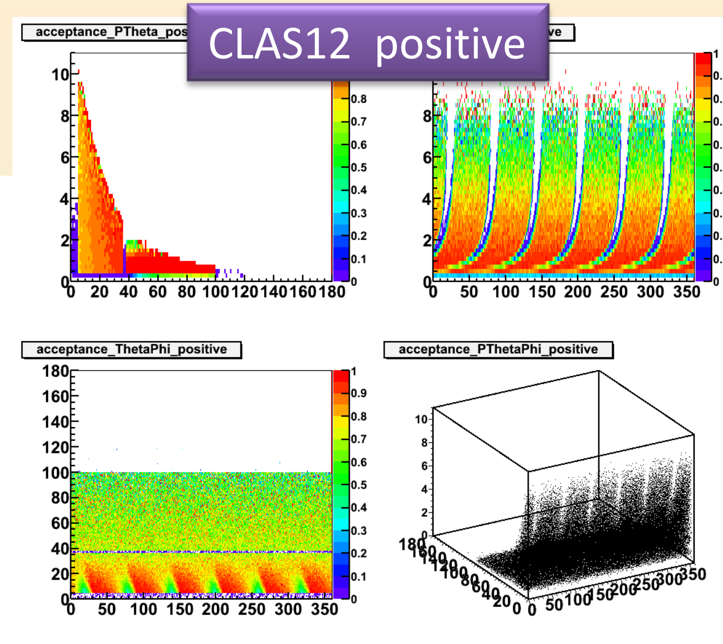
- Resolution is important for exclusivity
- Both are good enough

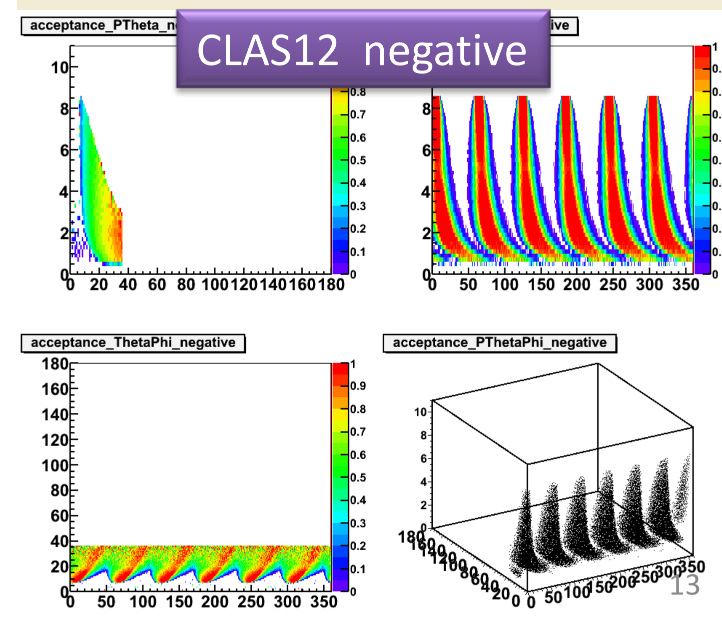
SoLID

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

CLAS12 and SoLID: Acceptance

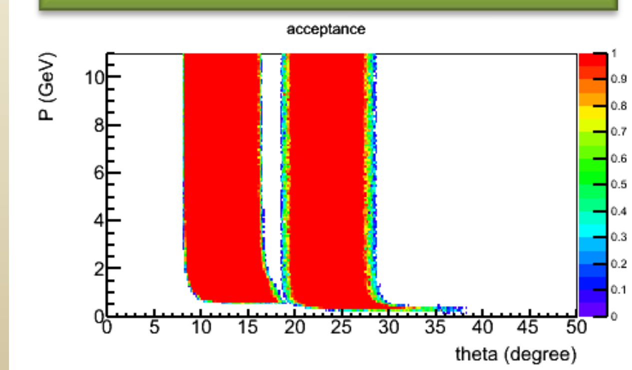
	CLAS12	SoLID
e^- and e^+ coverage	θ(5° – 36°) ϕ (~ 80% full) Asymmetric	θ(8° – 17°) θ(18° – 28°) ϕ(full) Symmetric
proton coverage	θ(5° – 36°) Θ(38° – 125°) ϕ (~ 80% full)	θ(8° – 17°) θ(18° – 28°) ϕ(full)
Luminosity	$10^{35}/cm^2/s$	$10^{37}/cm^2/s$





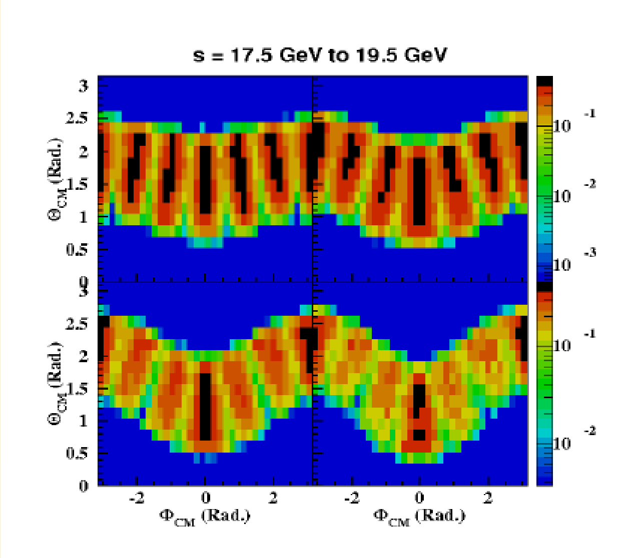
- Acceptance correction is important for crosssection
- Different acceptance in theta and phi

SoLID positive and negative



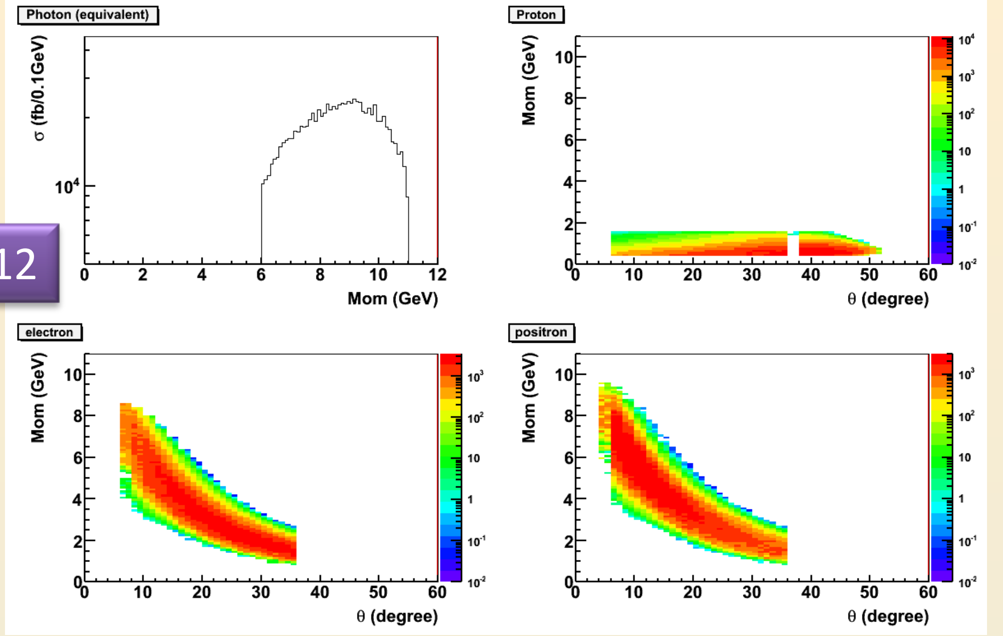
CLAS12 and SoLID: Overall

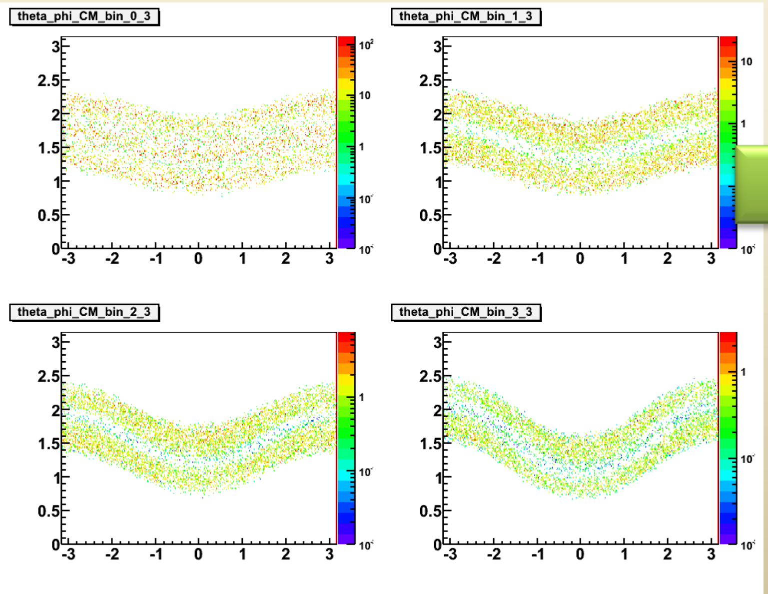
Complimentary



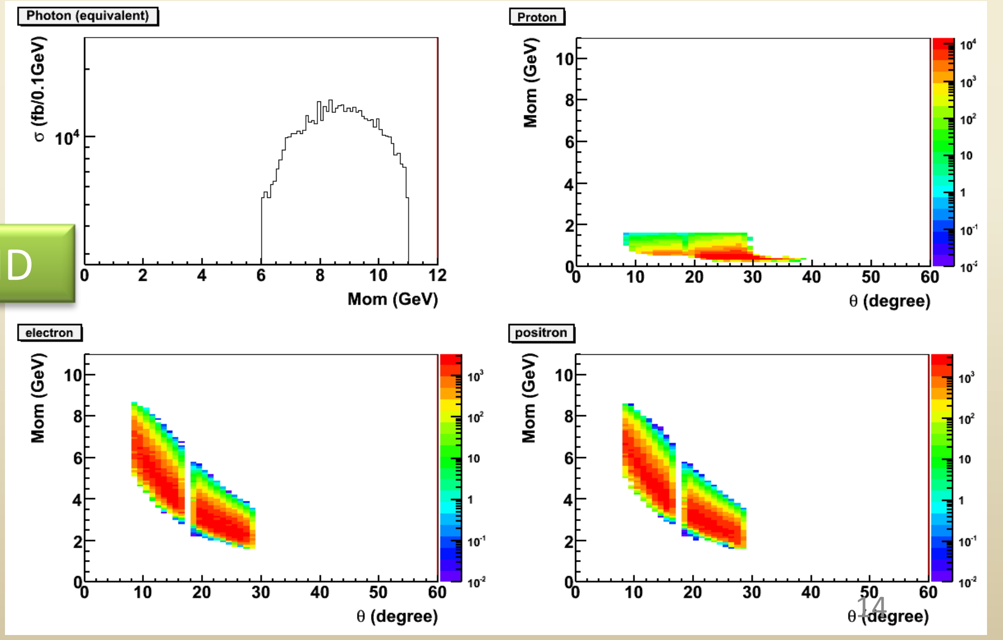
Accepted events for four t-bins. The observable R' is integrated over the CLAS acceptance

CLAS12



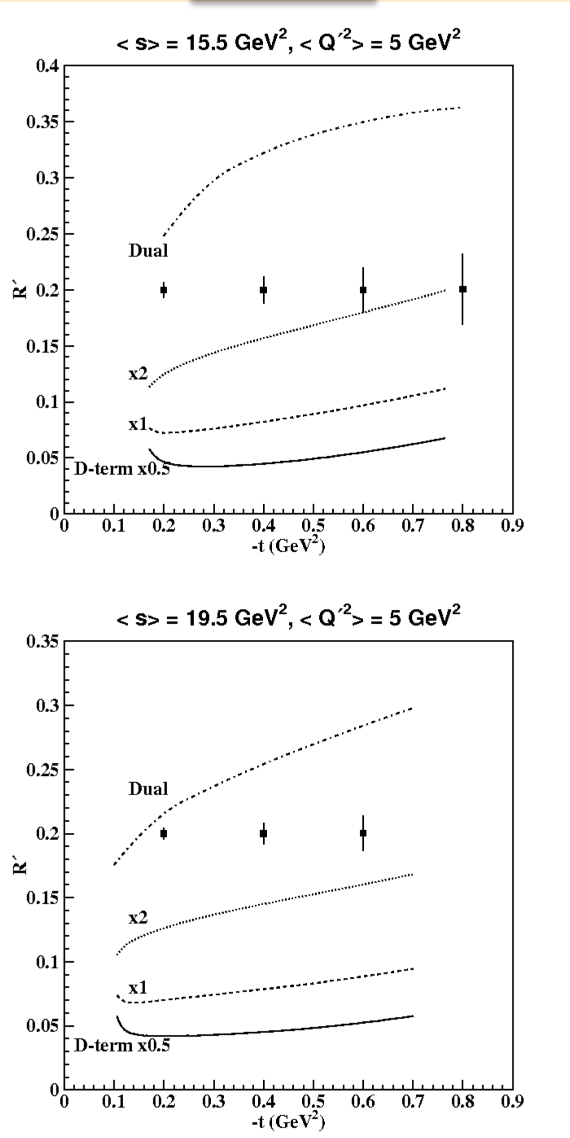


SoLID

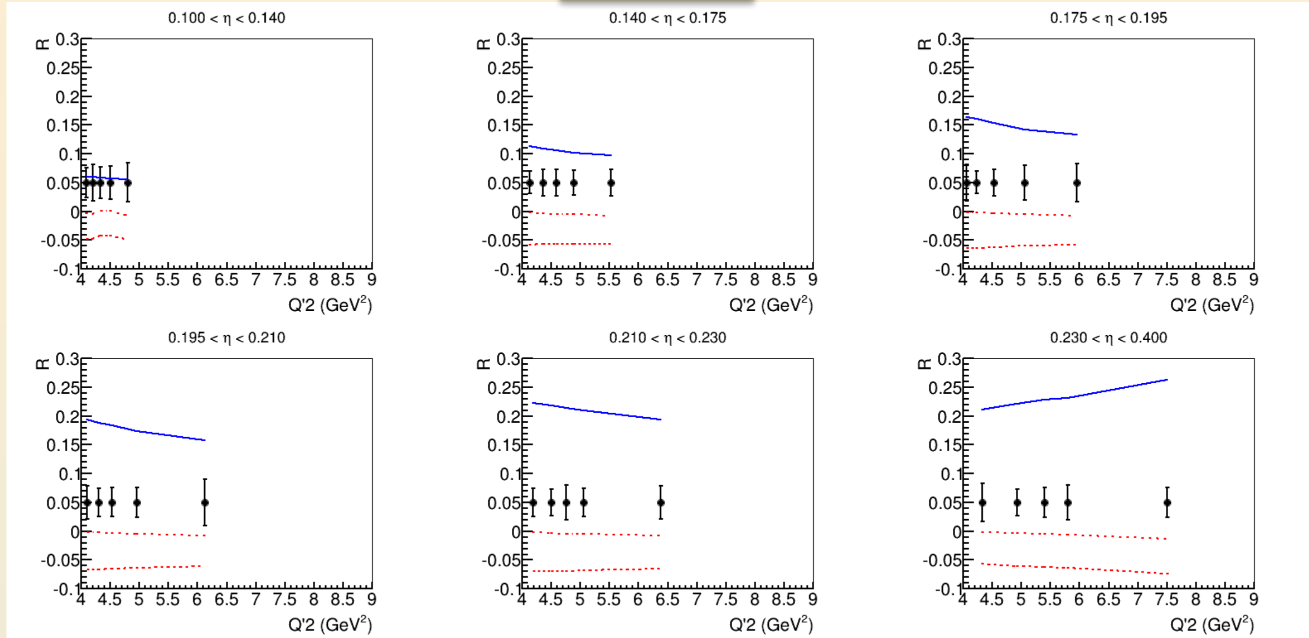


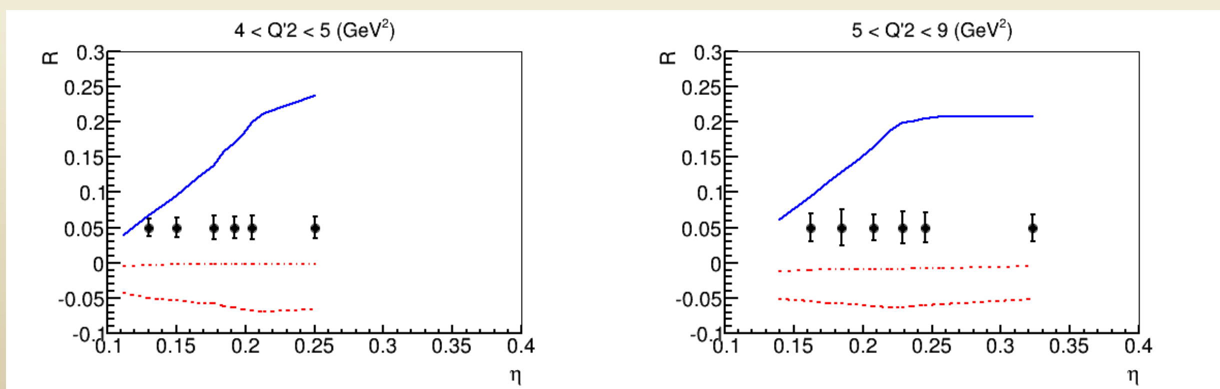
CLAS12 and SoLID: TCS R projection

CLAS12



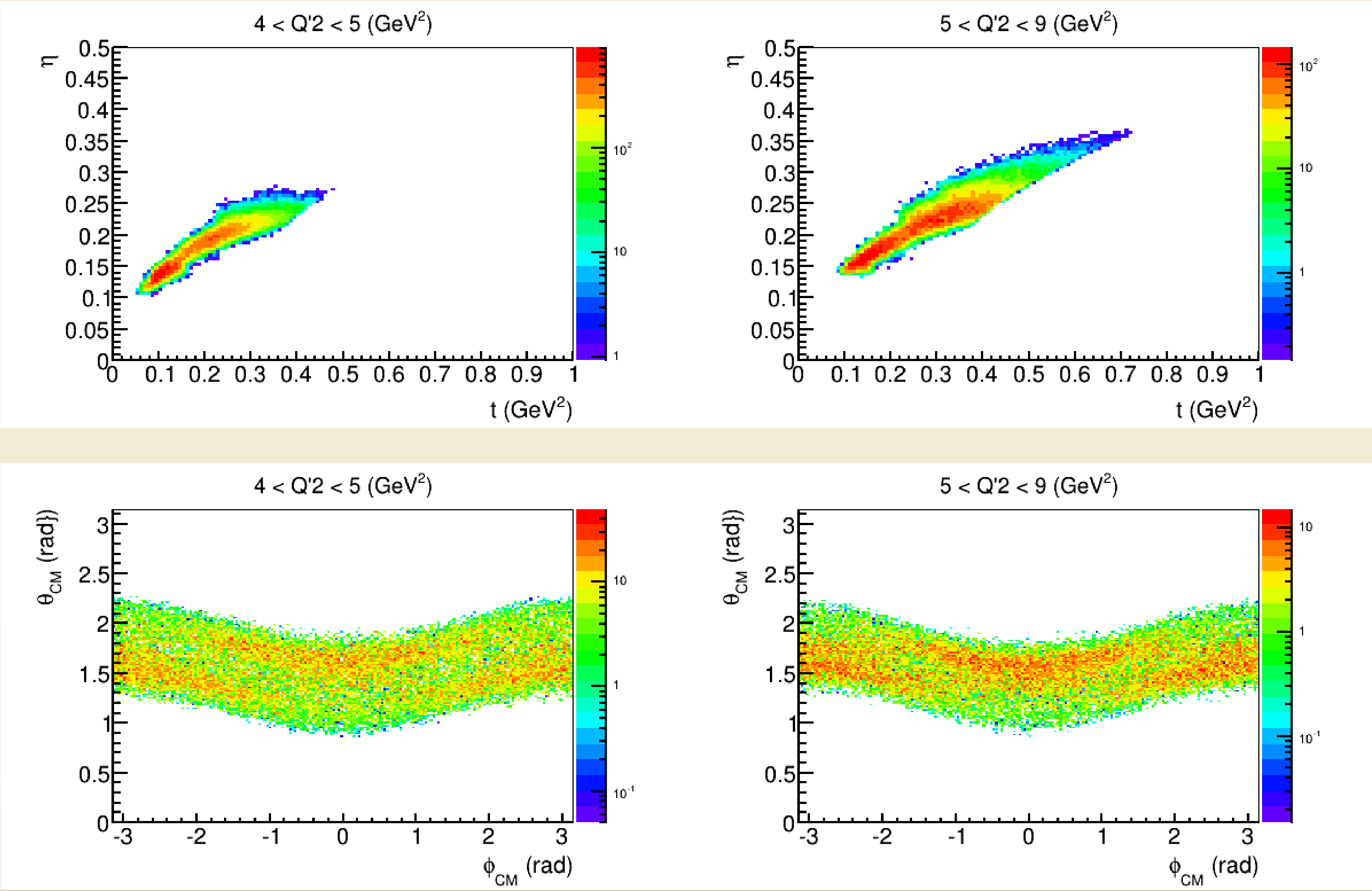
SoLID



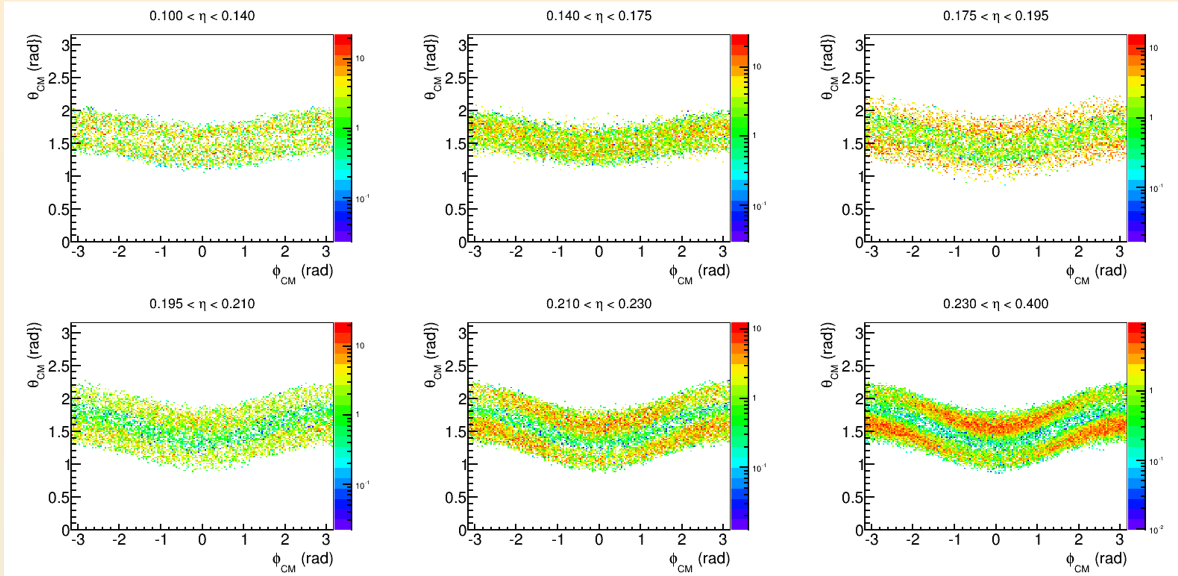


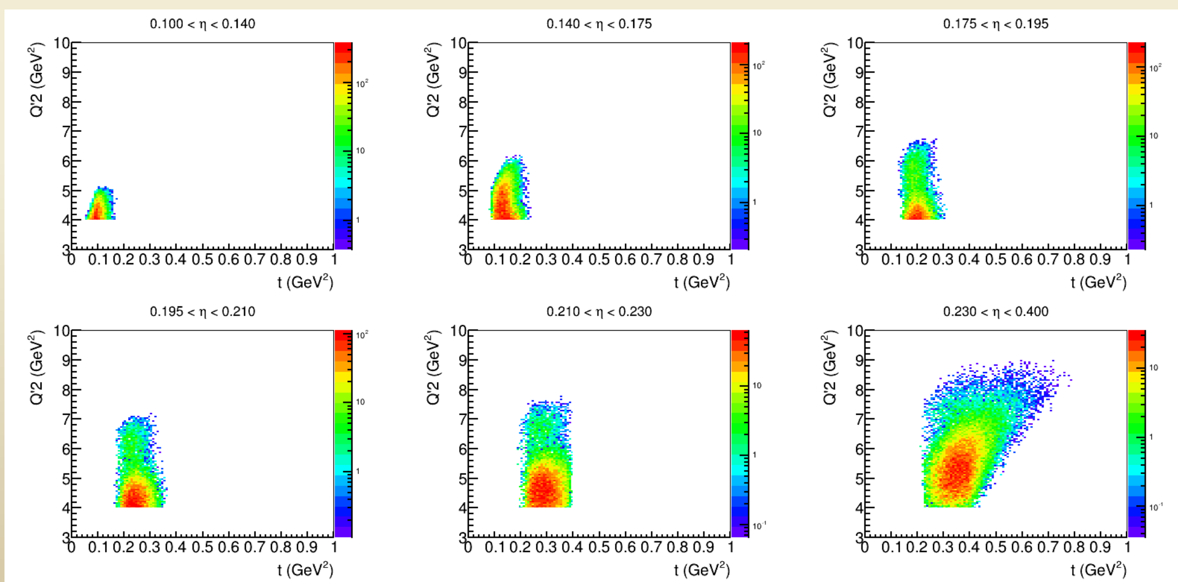
SoLID with near x10 data allows kinematic exploring

SoLID TCS Kinematic Coverage in Q'²



SoLID TCS Kinematic Coverage in η





GPD fit

Marie Boer

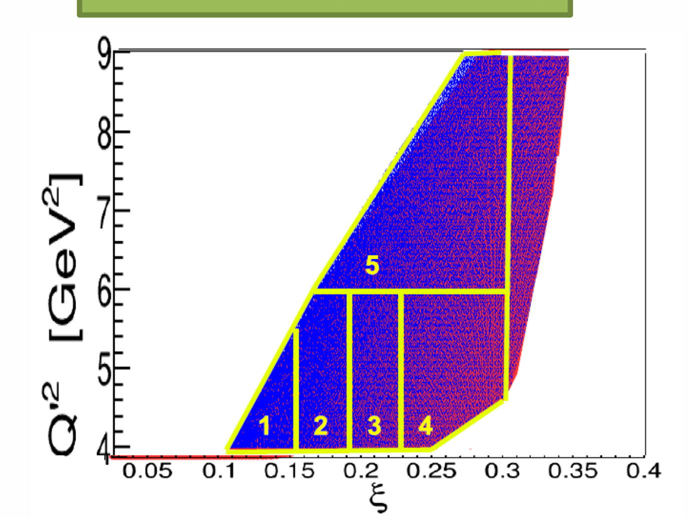
- TCS circular beam asymmetry helps constrain Im{H} in fitting
- Need more data to improve fitting

Fit exercise (general)

	$(\sigma, \Delta\sigma_{LU})$ 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

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

Fit exercise (SoLID TCS)



	$(\sigma, \Delta\sigma_{LU})$ 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

TCS Summary

- SoLID TCS will provide higher statistics and different acceptance than CLAS12 TCS, and thus provide better fit to CFF and explore kinematic space with more details to help constrain on GPD models
- CLAS12 (E12-12-001, 130 days) and SoLID (E12-12-006A, 60 days) form nice complementary programs both in detector and in timeline
- SoLID TCS can be a run group with SoLID JPsi and will provide help on background study and normalization crosscheck

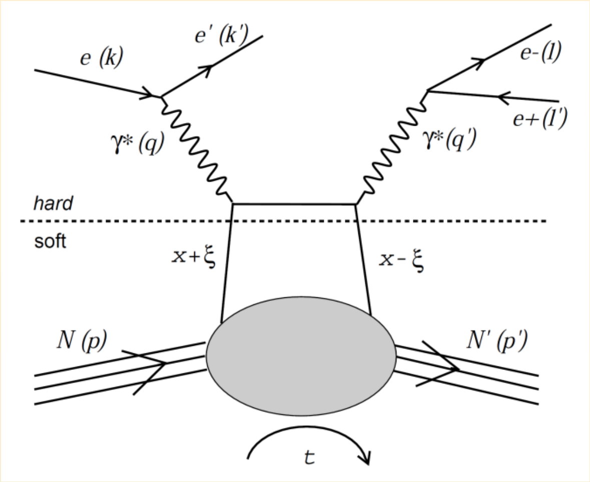
- Other exp ideas under work
  - LOI in Hall C: dedicated measurement with a transversely polarized target
  - studies in Hall D with a real linearly polarized photon beam

TCS related questions to theorists

- What other observables can be used?
- How to improve overall GPD study with TCS data available in two stages (less stat soon and more stat in a few years)?

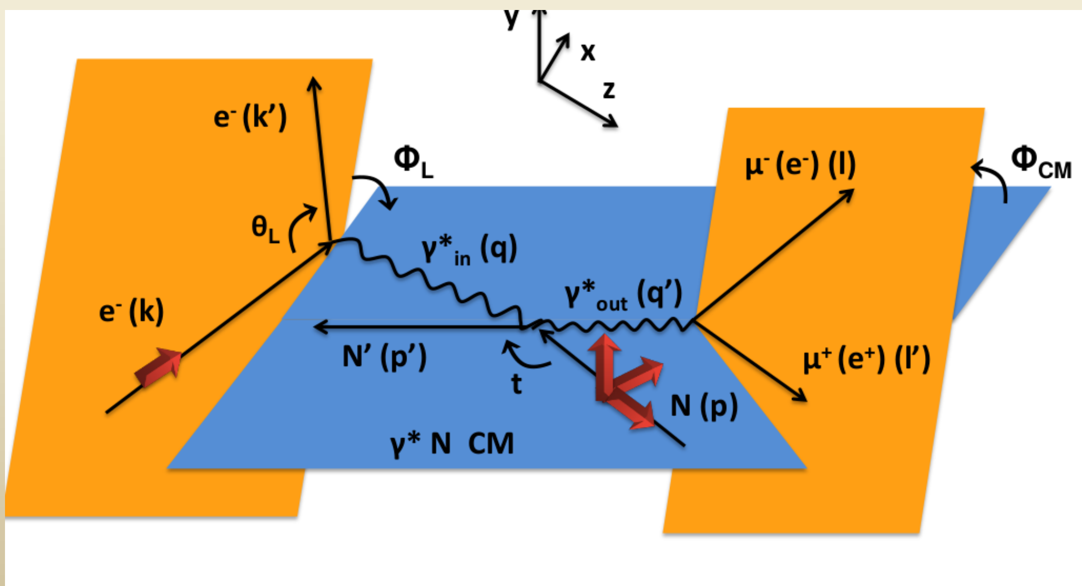
DDVCS

- 7 independent variables
- Both Q^2 and Q'^2 are at play to access $x \neq \xi$ region

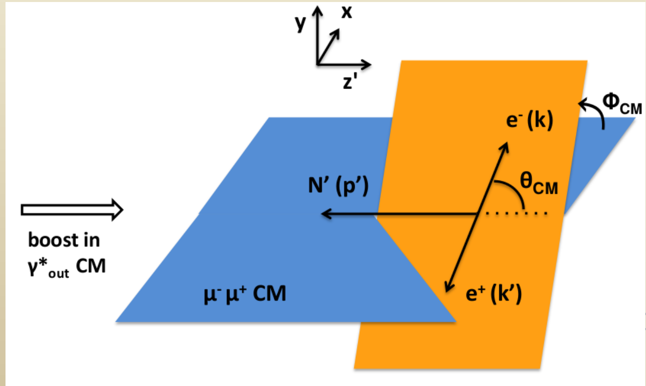


$$T^{DDVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x-(2\xi'-\xi)+i\varepsilon}\,dx + \ldots \sim \quad P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x-(2\xi'-\xi)}\,dx - i\pi H(2\xi'-\xi,\xi,t) + \ldots$$

$$\xi' = \frac{x_B}{2-x_B} \qquad \xi = \xi' . \frac{Q^2+Q'^2}{Q^2}$$



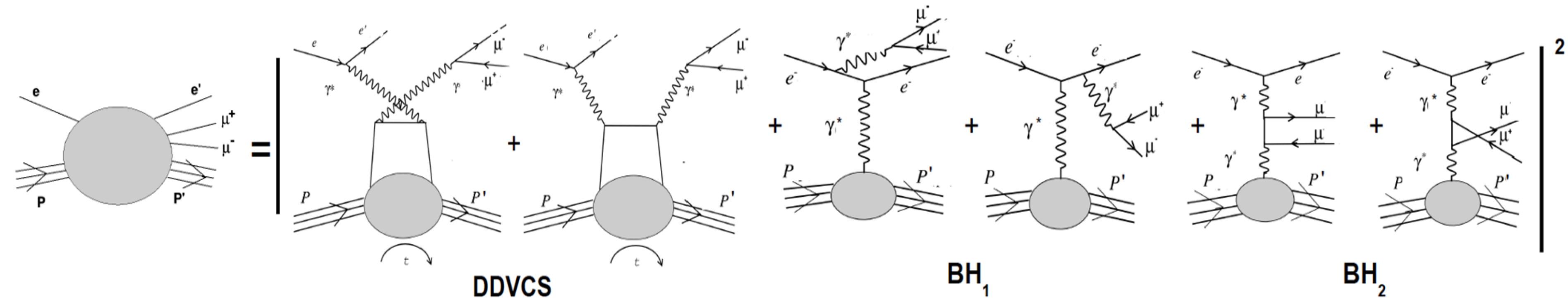
Michel Guidal



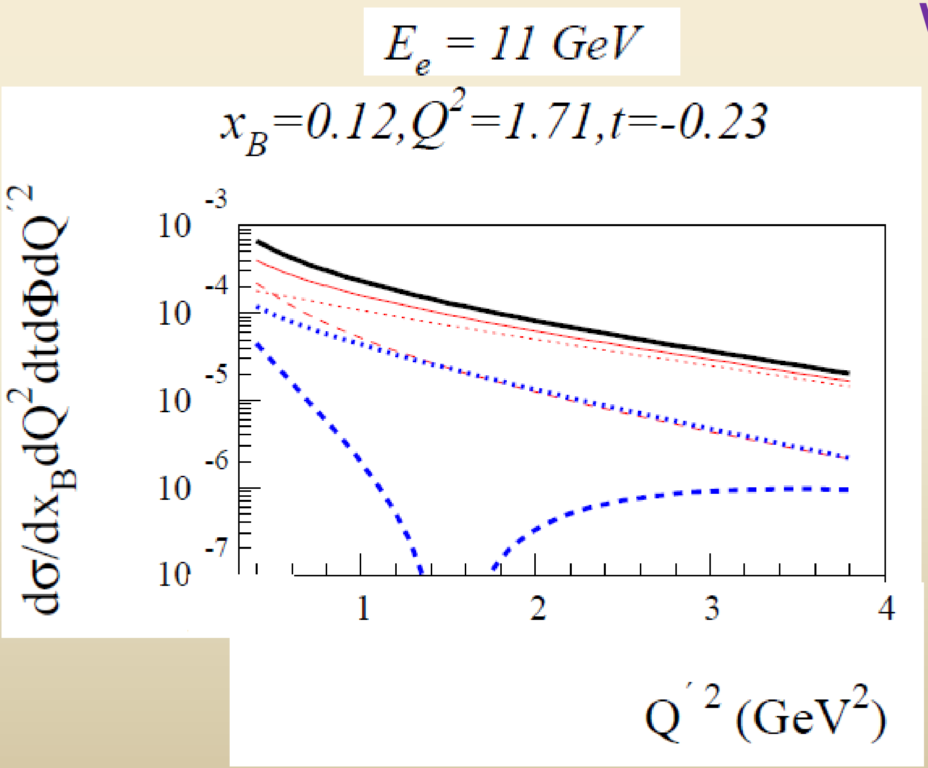
Unpolarized Crosssection

muon

Interference with BH



What observable can be used?



Im (DDVCS) drop when $Q'^2 \rightarrow Q^2$

no GPD interpretation in this region?

cross section Q^2 scan

- **DDVCS+BH**
- **BH (BHt + BHs)**
- **BHs**
- **BHt**
- **Re(DDVCS)**
- **Im(DDVCS)**

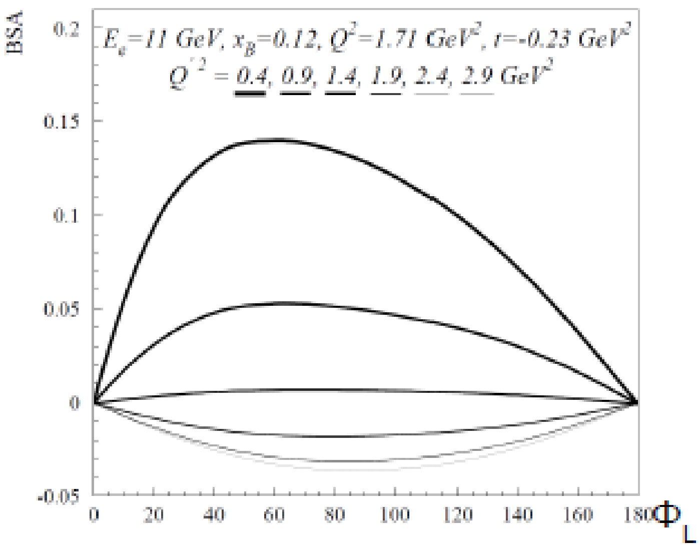
Nucleon tomography and sign change in DDVCS beam spin asymmetry

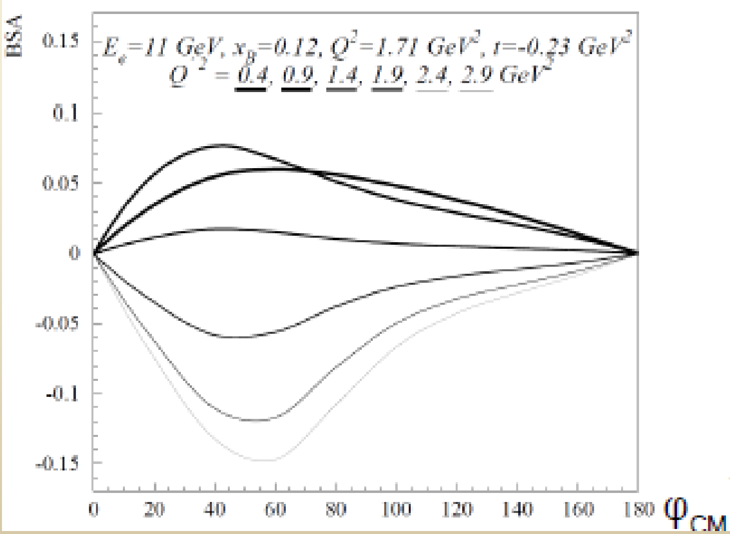
muon

Calculations and figures from M. Guidal

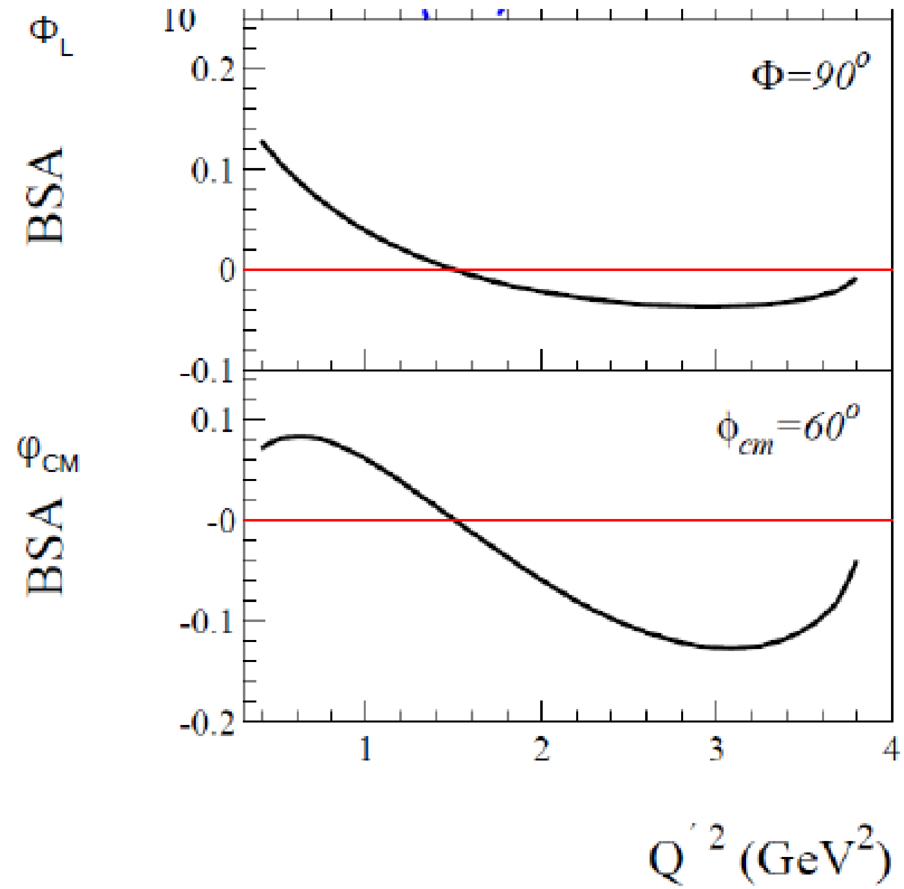
→ scan of BSA in Q'^2 at fixed Q^2

→ sign change in BSA vs Φ_L and vs φ_{CM} when $Q'^2 \approx Q^2$





asymmetry Q^2 scan



- Expectation of sign change for observables sensitive to Im (DDVCS) when moving from « spacelike » to « timelike » region 33

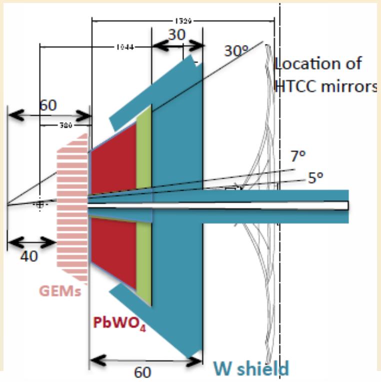
→ this reaction is unique for probing effects between these 2 regions.

CLAS12 LOI at PAC 44

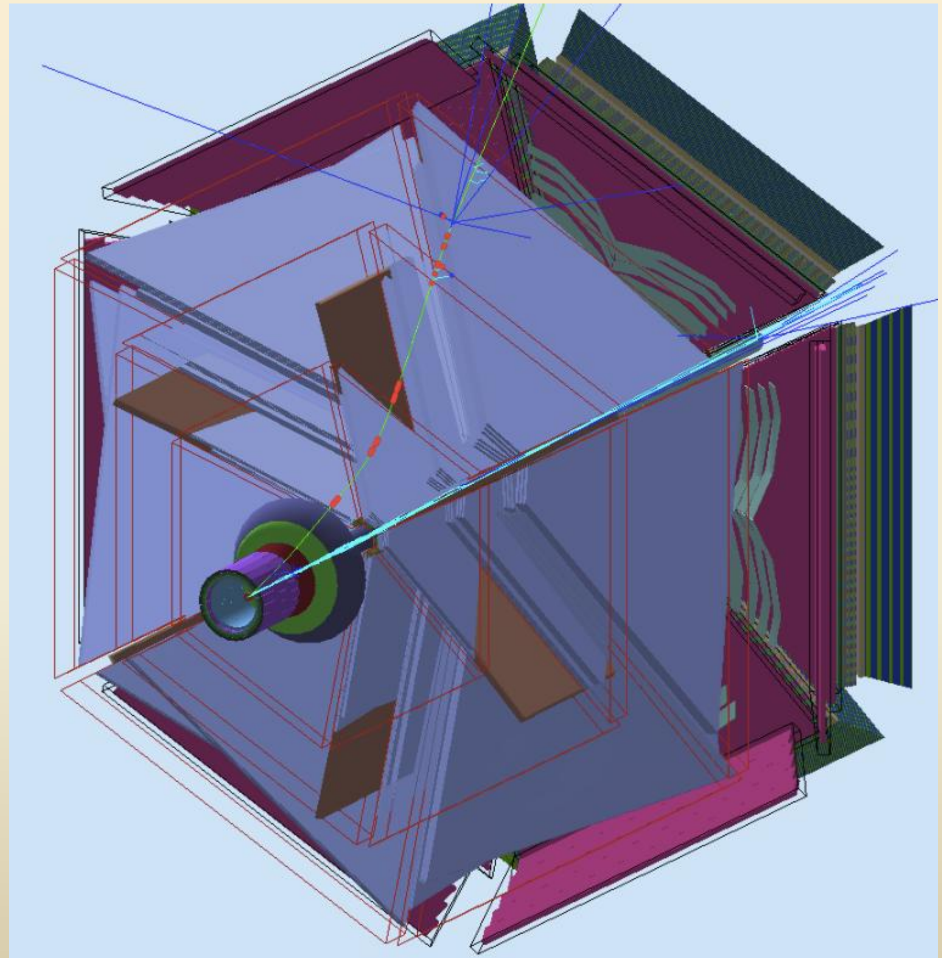
"Electroproduction of muon pairs with CLAS12 Double DVCS and J/ψ electroproduction" (Boer,Guidal,Stepanyan,Paremuzyan)

10^{35} */cm²/s* -> 10^{37} */cm²/s* Modified CLAS12 for higher luminosity

New EC and GEM

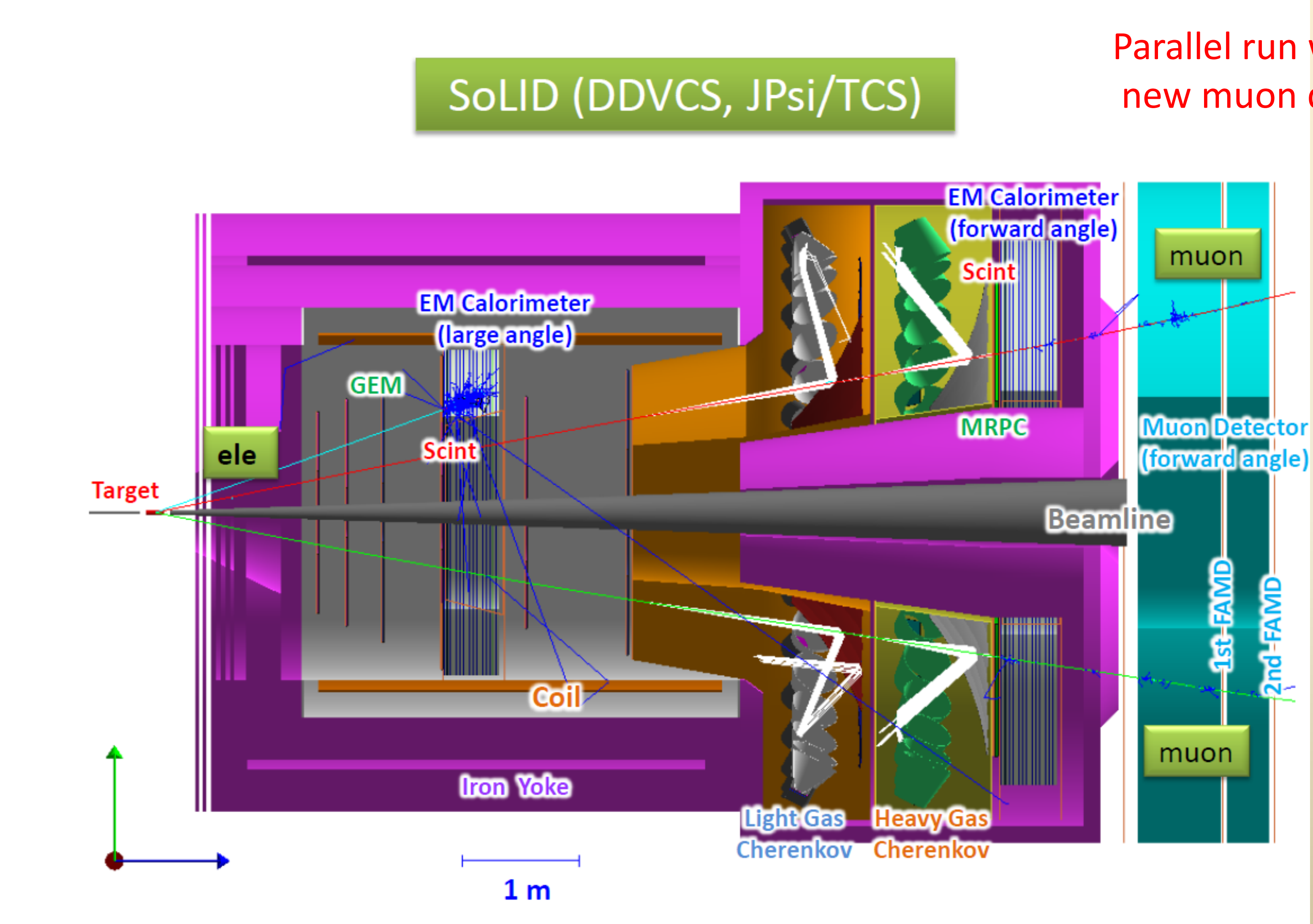


- Calorimeter/shield configuration serves as absorber for the muon detector (CLAS12 FD)
  - and fully protects the forward drift chambers from electromagnetic and hadronic background
- Scattered electron detected in the new calorimeter
- GEM based tracking detectors aid reconstruction of charged particle vertex (momentum and angles)



SoLID LOI at PAC43

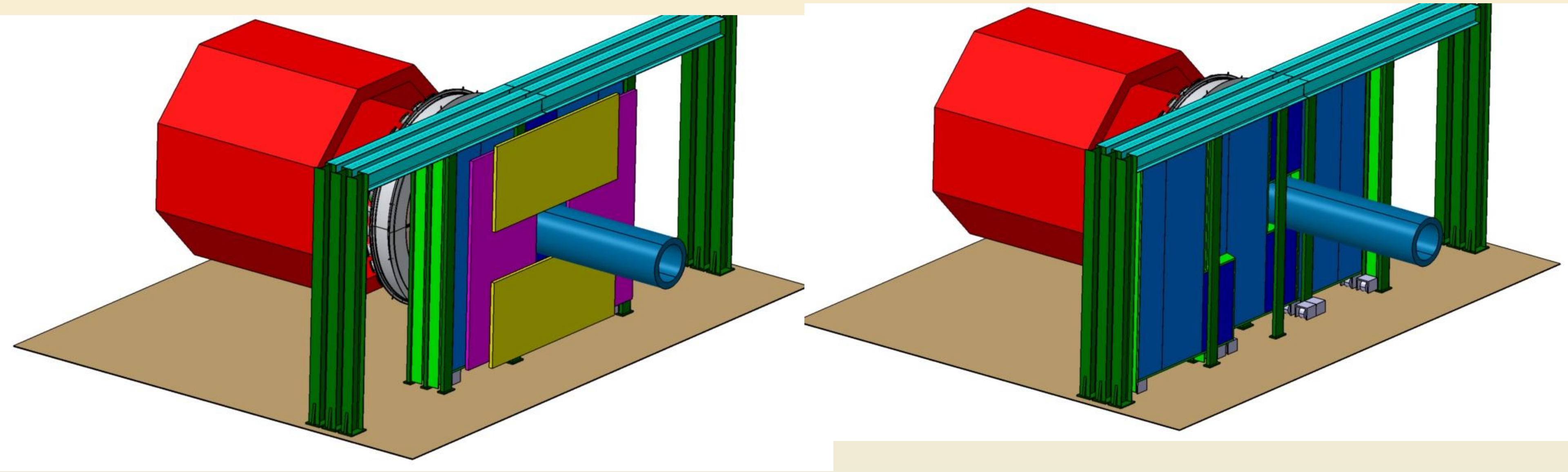
"Measurement of Double Deeply Virtual Compton Scattering (DDVCS) in the di-muon channel with the SoLID spectrometer"
(Boer,Camsonne,Gnanvo,Sparveris,Voutier,Zhao)



Parallel run with
new muon detector

SoLID muon detector

Iron from CLEO and Micro Pattern Gaseous Detectors

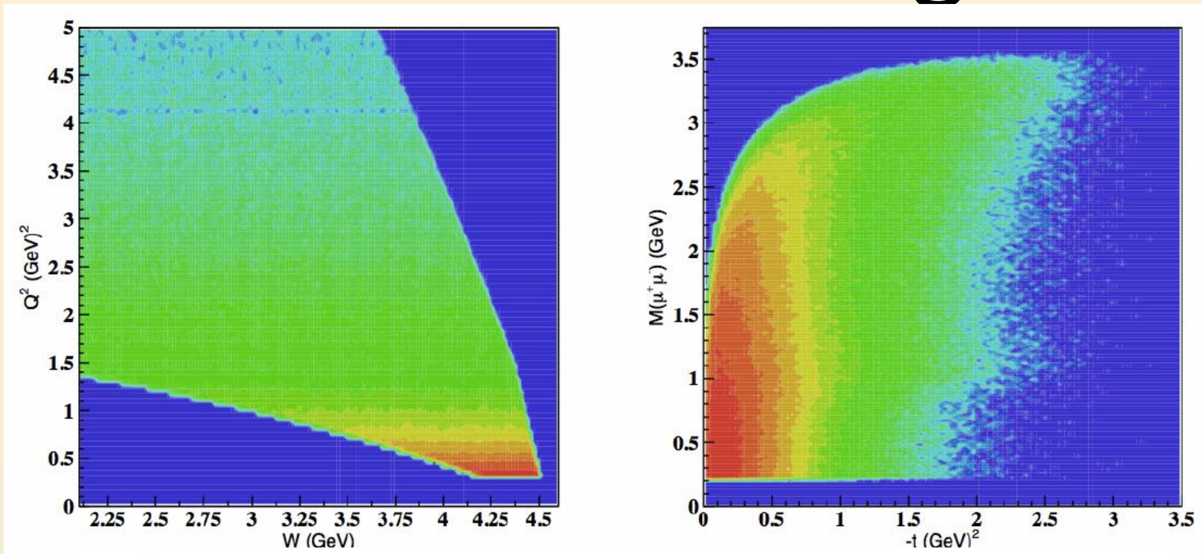


Preliminary design from IPNO :
Christine Legalliard / Dominique Marchand /Eric Voutier
Will have more accurate design if approved

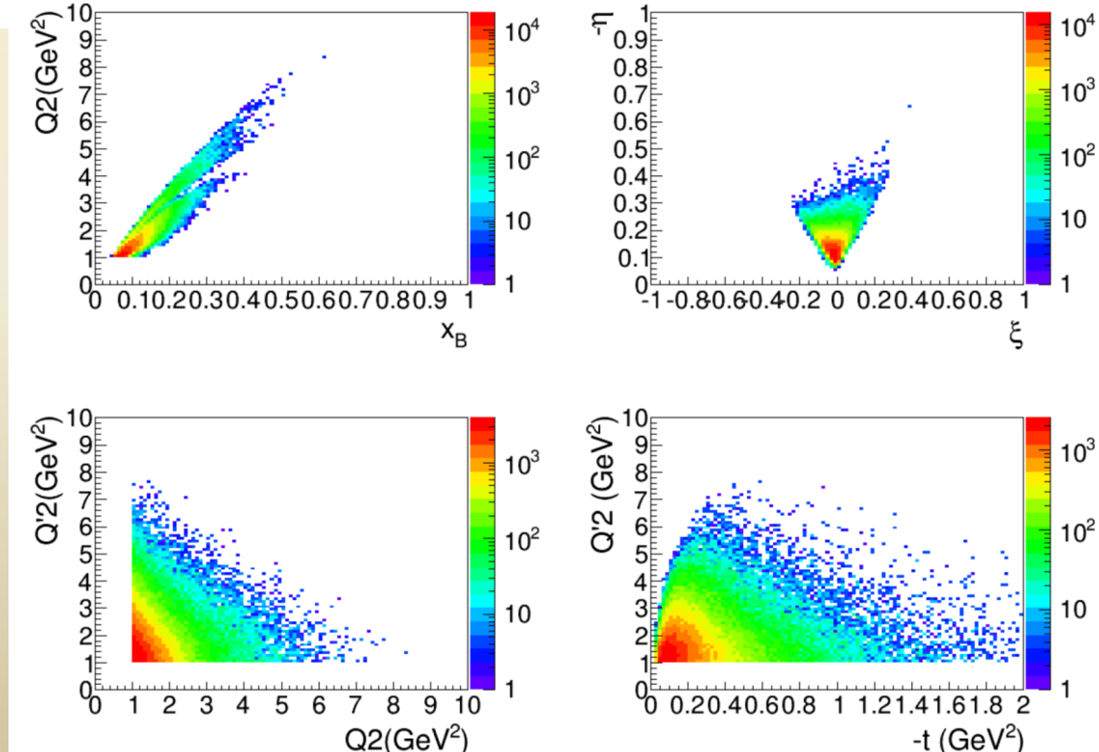
DDVCS Coverage

muon

CLAS12



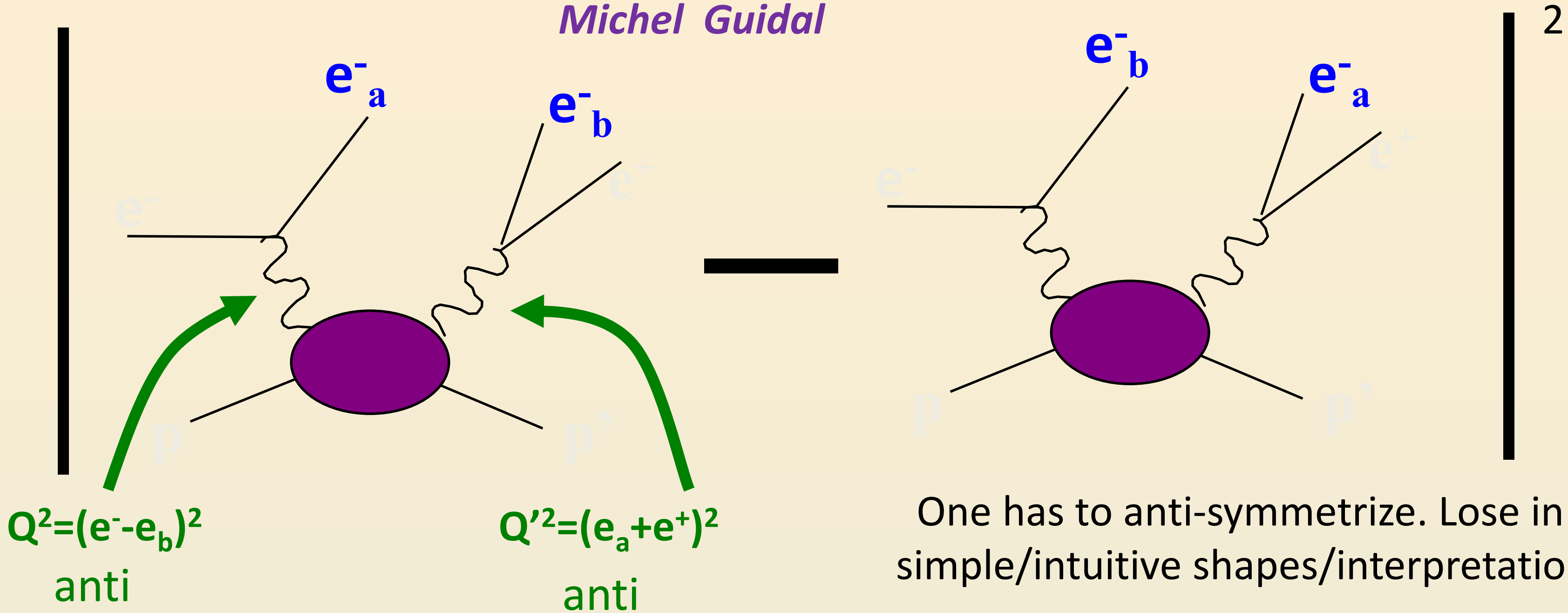
SoLID



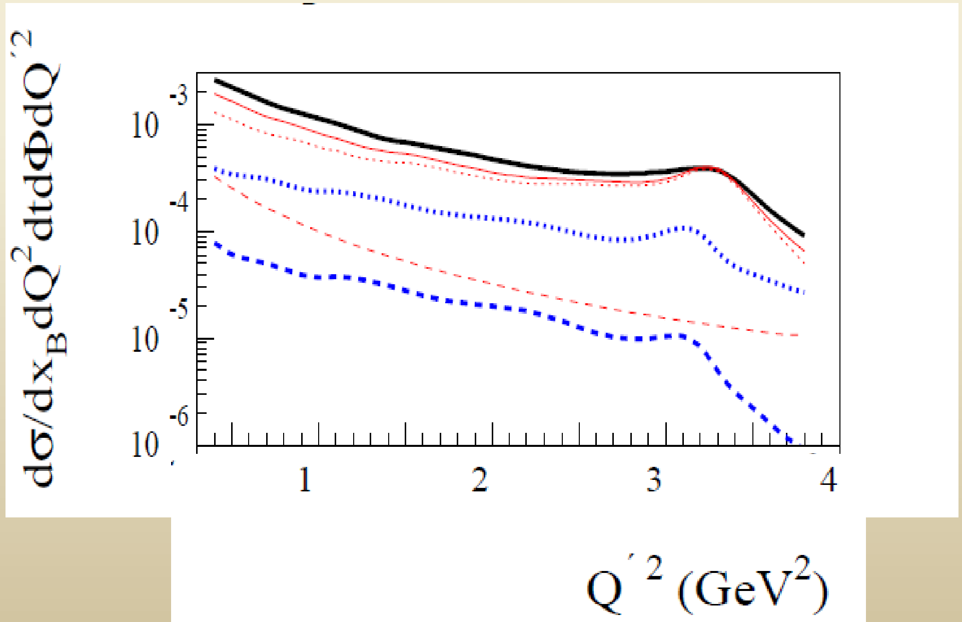
The particular case of e-/e+ pairs

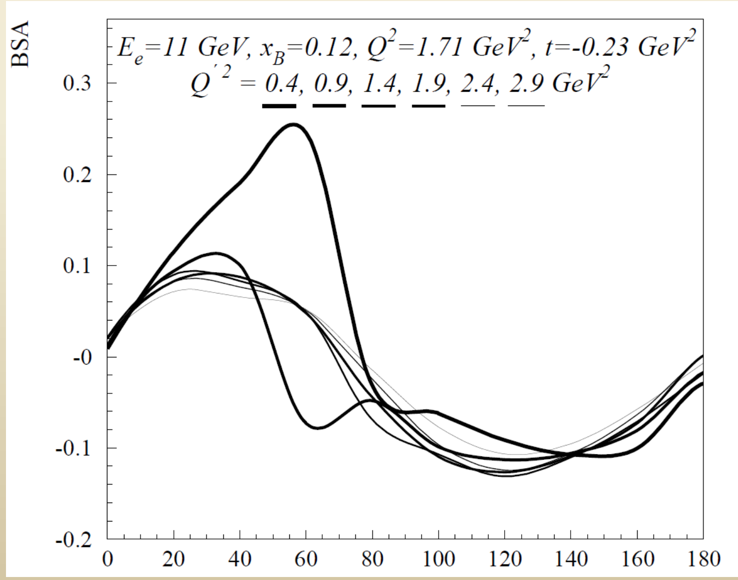
electron

Michel Guidal



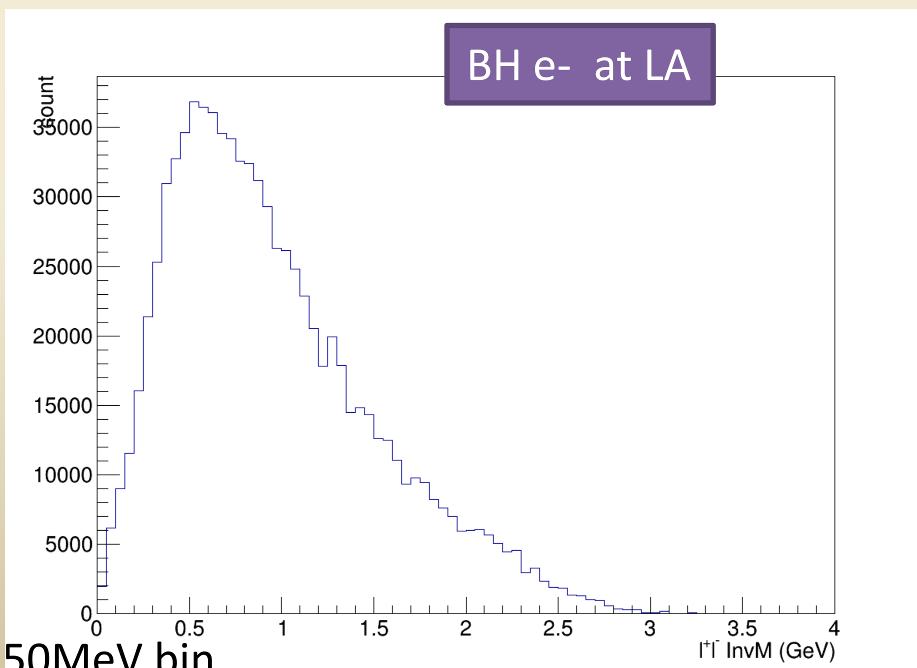
One has to anti-symmetrize. Lose in general simple/intuitive shapes/interpretations

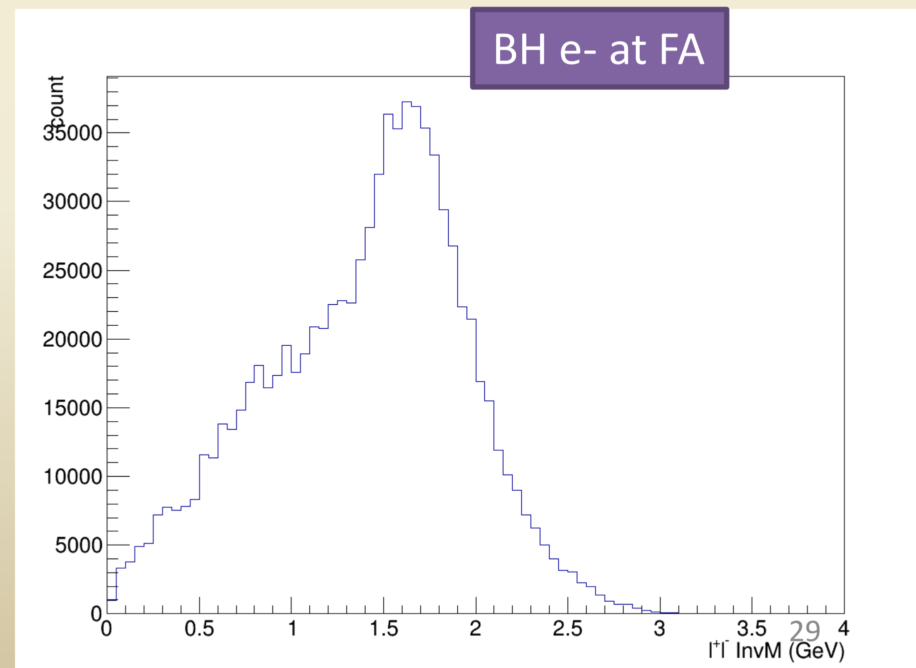




How to interpret the electron DDVCS data which will be available anyway?

- SoLID detection as example
  - 1 e+ detected at both Forward Angle (FA) and Large Angle (LA)
  - 1 e- at LA and 1 e- at FA
- Can this separate high and low Q2 events to minimize interference?





DDVCS Summary

- CLAS12 DDVCS needs new electron detectors, modification to existing ones, and new beam time
- SoLID DDVCS needs new muon detectors, no modification to existing ones, and no new beam time
- There may be some muon detection with existing detectors

DDVCS related questions to theorists

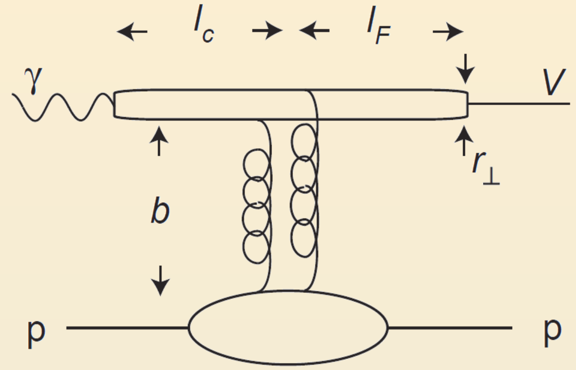
- What observables can be used?
- How to improve overall GPD study with DDVCS muon data?
- How to interpret the DDVCS electron data which will be available in two stages (less stat soon and more stat in a few years)?

Backup

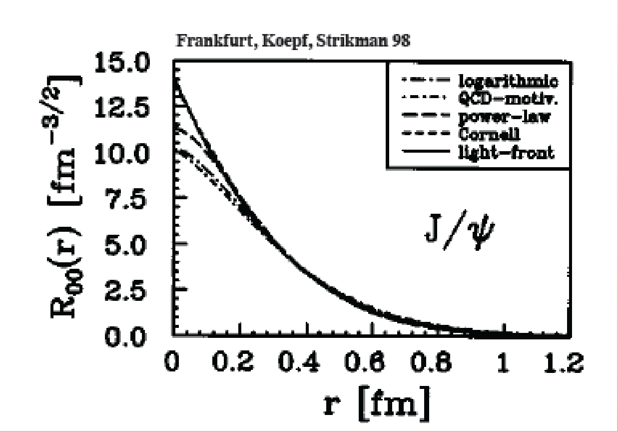
J/ψ Production on Neuclon

$J/\psi(1S): I^G\left(J^{PC}\right) = 0^-\left(1^{--}\right)$ $M_{J/\psi} \approx 3.097 GeV$ Width: 93 KeV

Probe strong color field in nucleon



- **J/ψ is a *charm-anti-charm* system**
  - Little (if not zero) common valence quark between J/ψ and nucleon
  - Quark exchange interactions are strongly suppressed
  - Pure gluonic interactions are dominant
- **Charm quark is heavy** $\gg \Lambda_{QCD}$
  - Typical size of J/ψ is 0.2-0.3 fm
  - Impact distance b ~ $1/m_c$ ~ 0.1fm



Interaction between J/ψ-N

New scale provided by the charm quark mass and size of the J/ψ

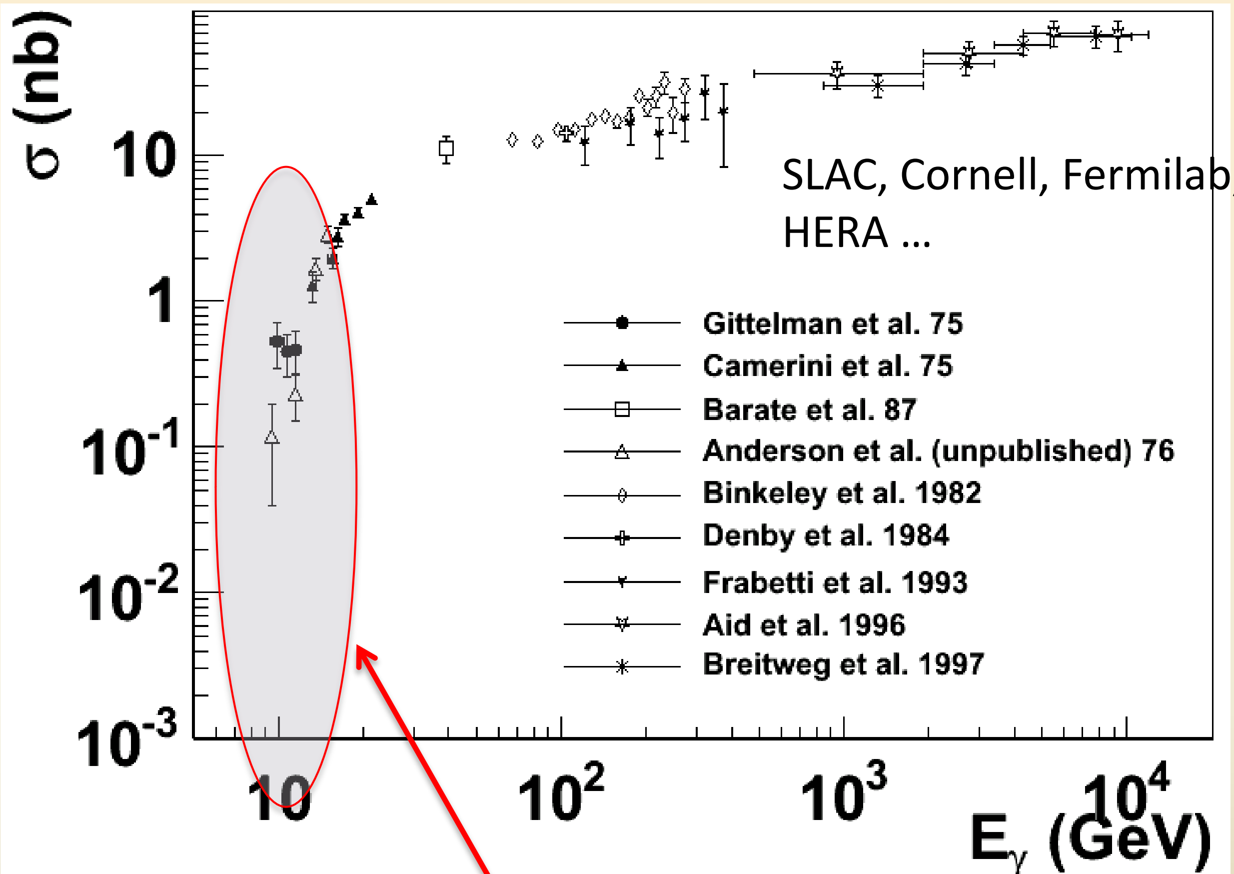
- OPE, Phenomenology, Lattice QCD ...

- High Energy region: Pomeron picture …
- Medium/Low Energy: 2-gluon exchange
- Very low energy: QCD color Van der Waals force
  - Prediction of J/ψ-Nuclei bound state
    - Brodsky et al. ….

- Experimentally no free J/ψ are available
  - Challenging to produce close to threshold!
  - **Photo/electro-production of J/ψ at JLab is an opportunity**

Experimental status

$\gamma(\gamma^*) + N \rightarrow N + J/\Psi$



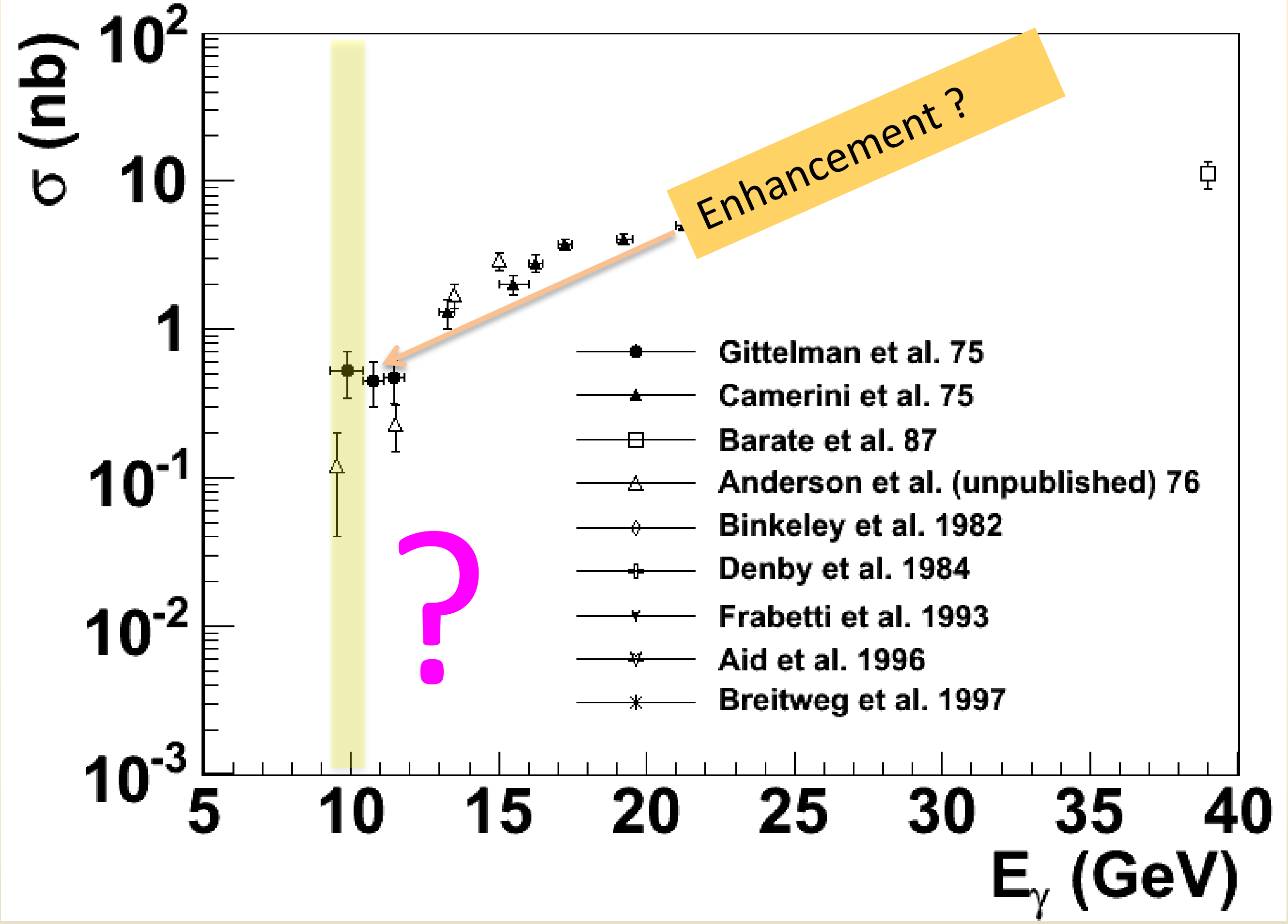
SLAC, Cornell, Fermilab, HERA …

More data exist with inelastic scattering on nuclei, such as A-dependence.

Not included are the most recent results from HERA H1/ZEUS at large momentum transfers and diffractive production with electro-production

The physics focus is at threshold region

Near Threshold

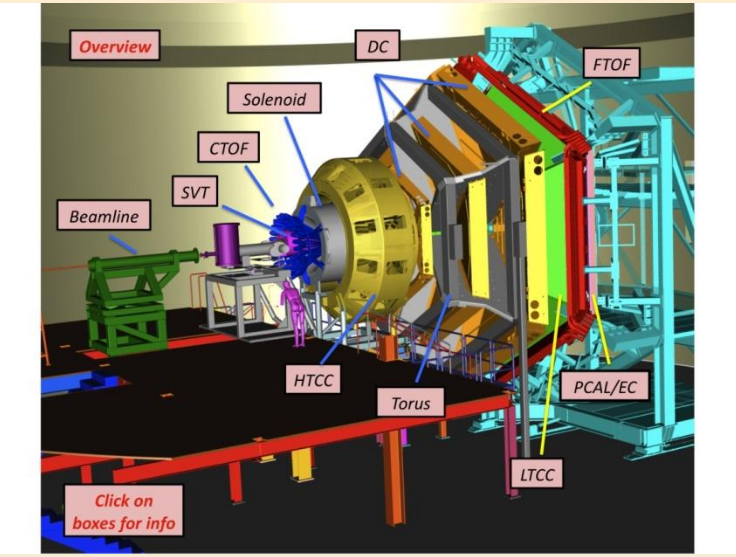


Intense experimental effort (SLAC, Cornell …) shortly after the discovery of J/ψ

But near threshold not much data since (**~40 years till now**)

J/ψ @ CLAS12

- E12-12-001 approved together with TCS
- 1e35 /cm2/s Lumi, 120 days on LH2, Single particle trigger
- Photoproduction, photon energy not directly measured



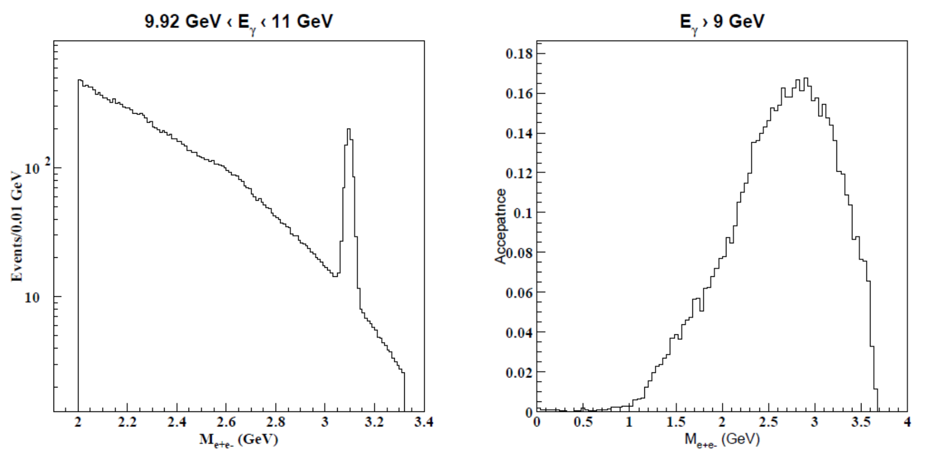


FIG. 26: *Left panel:* Exclusive J/ψ yield on a BH background as a function of the e^+e^- invariant mass for an incoming photon energy bin between 10 and 11 GeV. The J/ψ peak is clearly visible. *Right panel:* CLAS12 acceptance for the exclusive reaction $ep \to e^+e^-p(e')$ for photon energies between 9 and 11 GeV. In high-energy e^+e^- photoproduction, the CLAS12 acceptance for the $\phi(1020)$ is small.

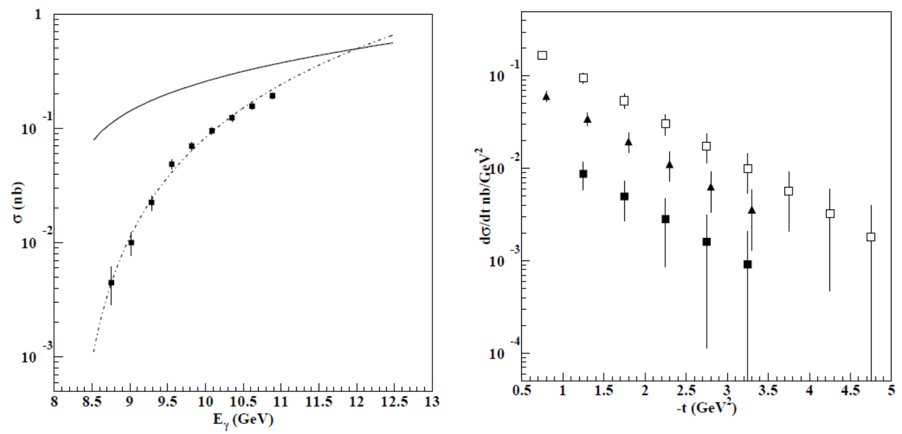
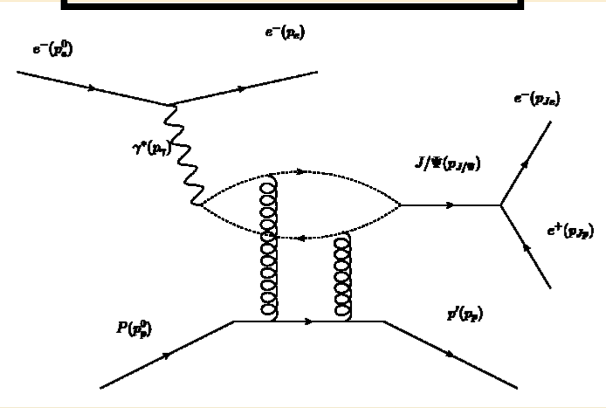


FIG. 27: Statistical uncertainties for exclusive J/ψ photoproduction in 100 days of running. *Left panel:* Total cross section as a function of incoming photon energy. The curves are calculated according to cross section formulas in Ref. [67]. *Right panel:* Differential cross section as a function of the four-momentum transfer $-t$ for three bins of s. The dashed line and the filled squares are for $s = 17.55$ to 18.05 GeV^2, the dotted line and the inverted filled triangles are for $s = 19.05$ to 19.55 GeV^2, and the dashed-dotted line and the open squares are for $s = 21.05$ to 21.55 GeV^2.

J/ψ @ SoLID

$$\gamma^* + N \rightarrow N + J/\psi$$

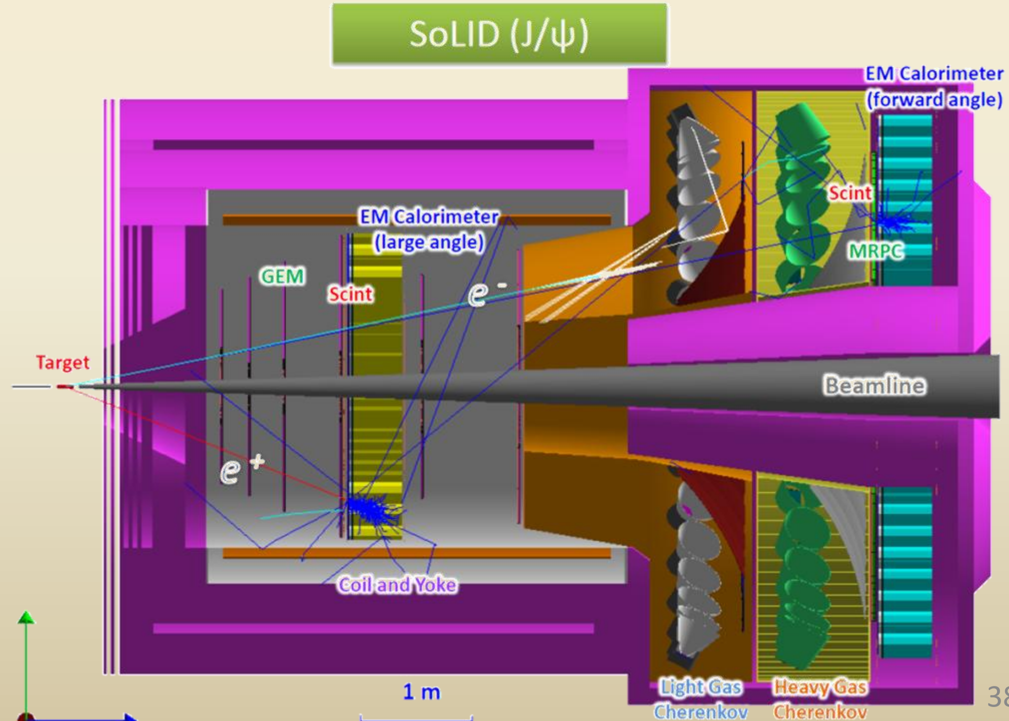


- E12-12-006

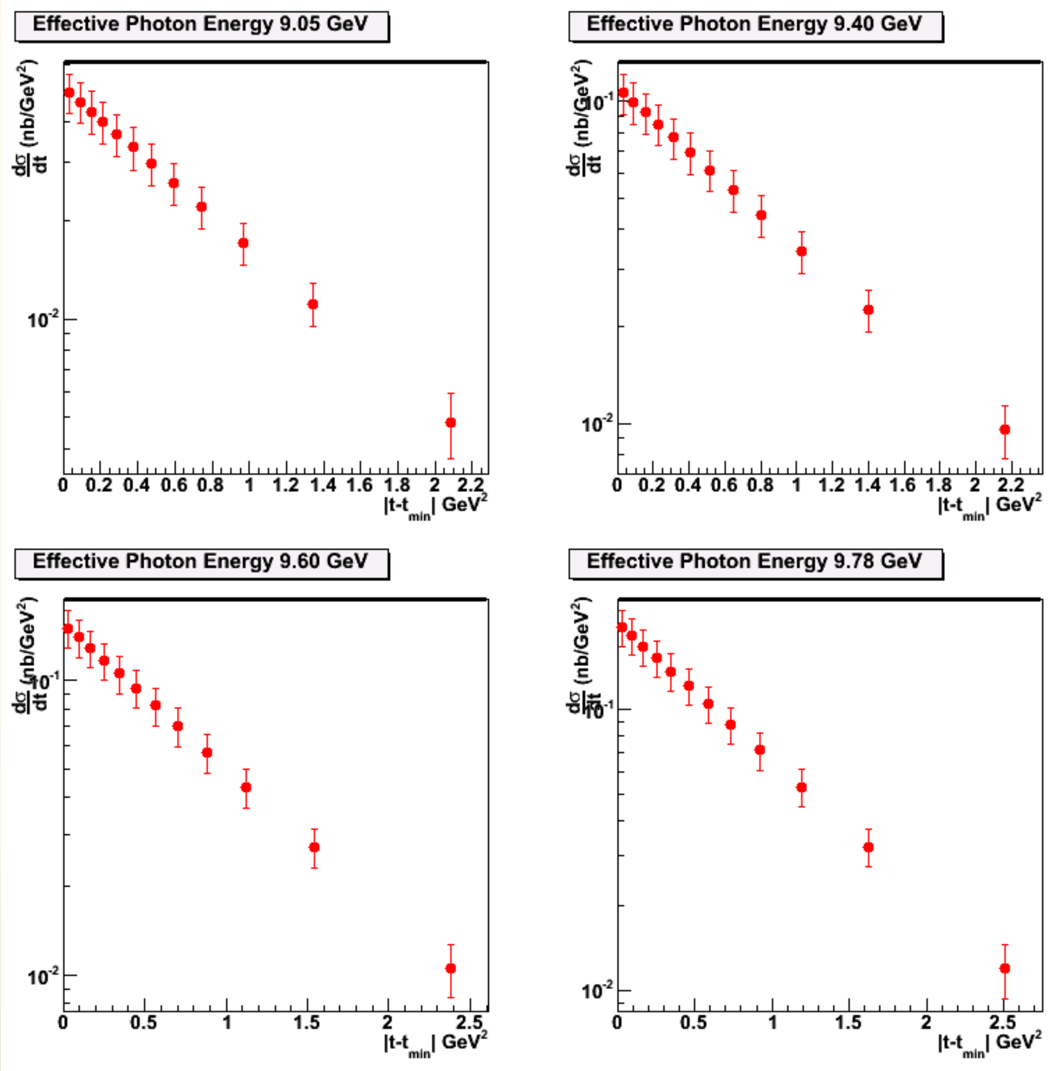
$e\ p \rightarrow e'\ p'\ J/\psi(e^-\ e^+)$

$\gamma\ p \rightarrow p'\ J/\psi(e^-\ e^+)$

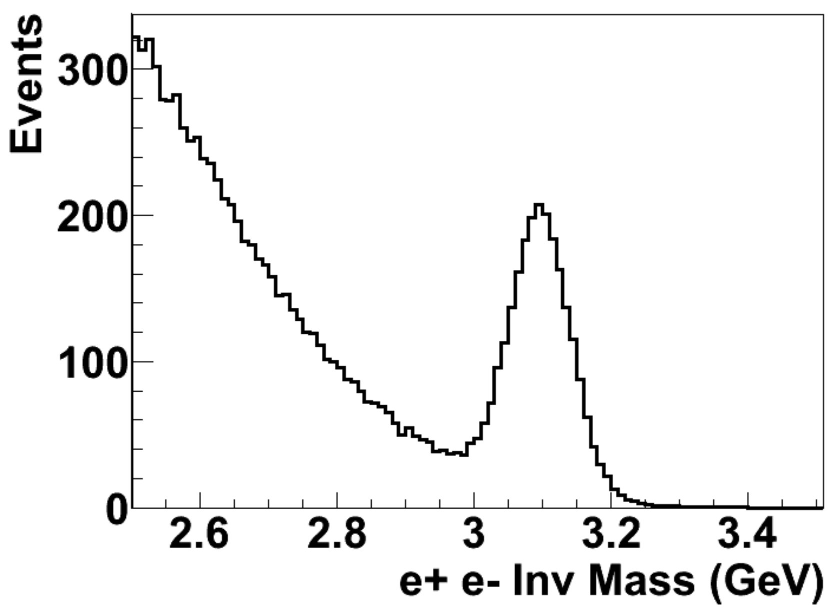
- Detect decay $e^-\ e^+$ pair
- Detect (or not) scattering e for electroproduction (or photoproduction)
- Detect recoil p to be exclusive



Projections of crosssection with 2-g model

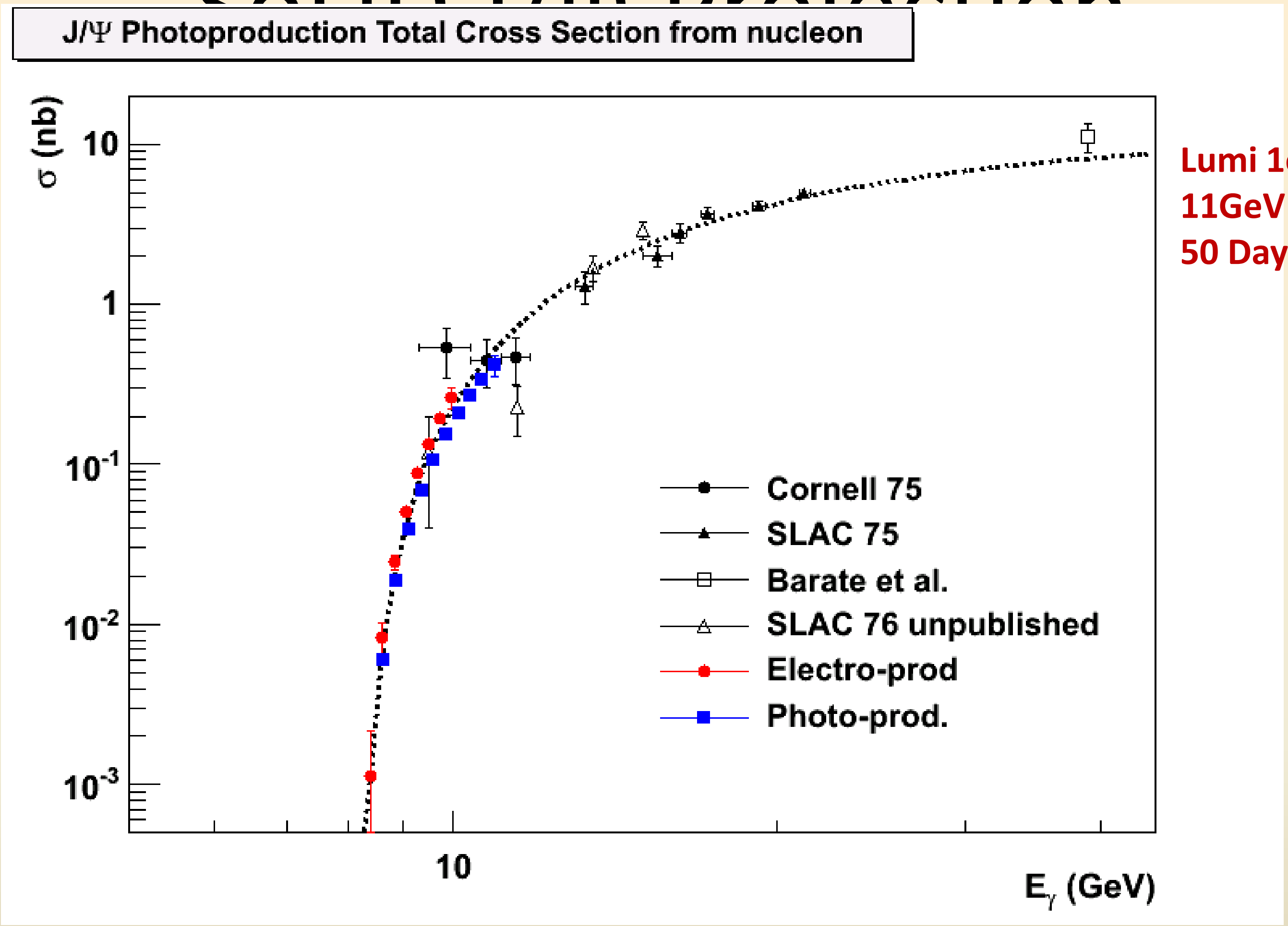


- Data will be first binned in *t* at different *W* (or effective photon energy) to study the t-dependence of the differential cross section



$$E_\gamma^{eff} = \frac{W^2 - M_p^2}{2M_p}$$

SoLID J/ψ Projection



Lumi 1e37/cm^2/s
11GeV e on 15cm LH2
50 Days

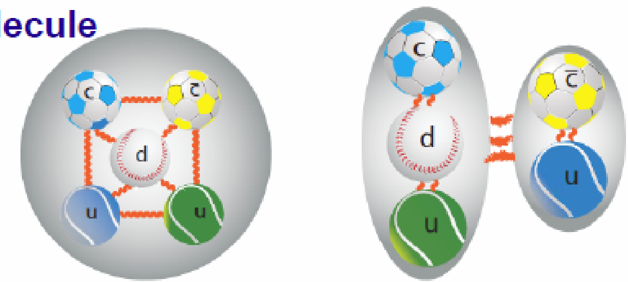
With < 0.01 GeV energy resolution and small binning to study the threshold behavior of cross section

Search for *hidden charmed pentaquarks* and study of *gluonic structure* of the nucleon

What is the exact nature of *charmed pentaquark* states discovered by LHCb collaboration at CERN

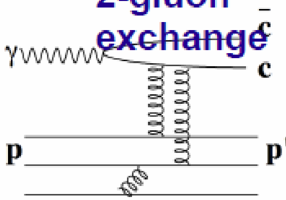
$$P_c \Rightarrow J/\psi\, p$$

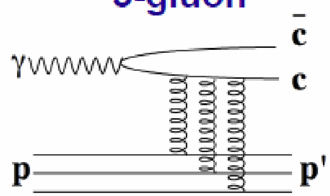
5-quark bound state **or** **Hadronic molecule**

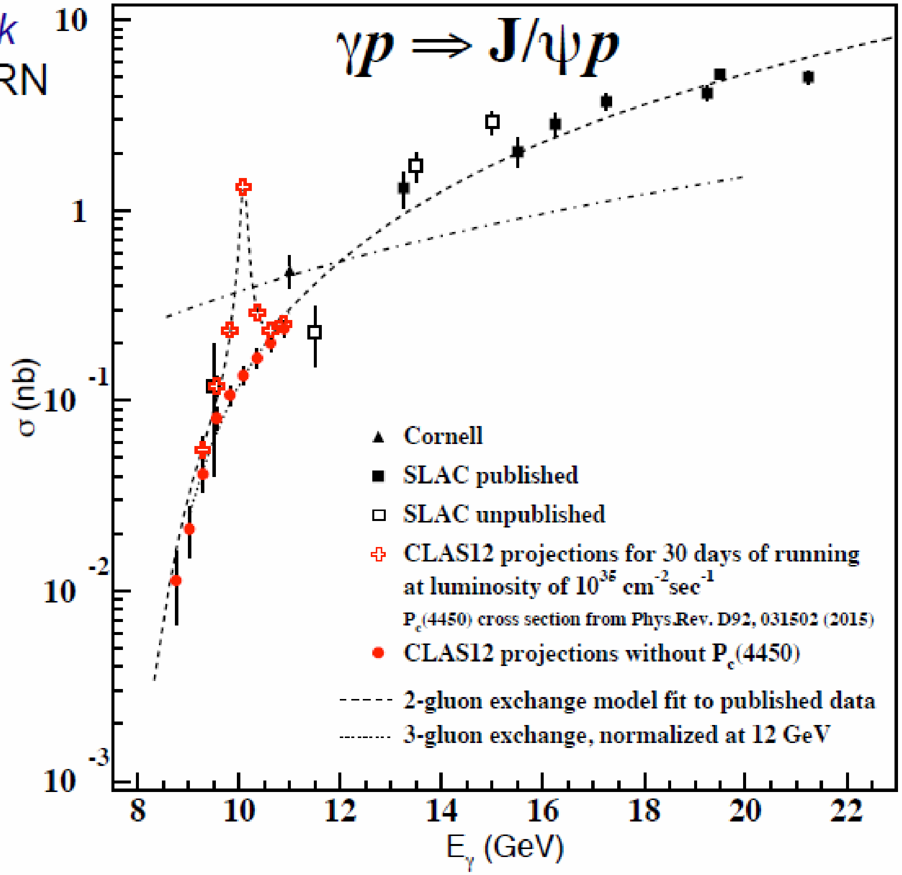


What is the mechanism of charmonium production at the threshold

2-gluon exchange **or** **3-gluon**







Experiment E12-12-001 measures J/ψ production on the proton near threshold – will verify existence of the ***charmed pentaquarks*** and will study ***the gluon field of the nucleon***

J/ψ Summary

- SoLID J/ψ will provide higher statistics and different acceptance than CLAS12 J/ψ, where precision is needed near the threhold
- CLAS12 (E12-12-001, 130 days) and SoLID (E12-12-006, 60 days) form a nice complementary program both in detector and in timeline
- TCS and J/ψ can be both detected for trigger on decay lepton pair only

Others at JLab

- J/ψ
  - E12-16-007 A Search for the LHCb Charmed "Pentaquark" using Photoproduction of J/psi at Threshold in Hall C at Jefferson Lab *https://arxiv.org/pdf/1609.00676.pdf*
  - E12-07-106, production on nuclei target
  - Work in progress to have parallel run with deuteron target at LCAS12

- TCS
  - LOI in Hall C: dedicated measurement with NPS with a transversely polarized target for asymmetry and "quasi real“ photon beam
  - studies of feasibility in Hall D with a real linearly polarized photon beam

Activity

- Non-Perturbative Color Forces in QCD workshop

  March 2012 at Temple

  http://quarks.temple.edu/~npcfiqcd
- The Proton Mass workshop

  March 2016 at Temple, https://phys.cst.temple.edu/~meziani/proton-mass-workshop-2016/
- Nuclear and Nucleon Structure Through Dileptons Production workshop

  Oct 2016 at ECT

  https://www.jlab.org/conferences/ECT2016/

Cut on quasi-real and real photon

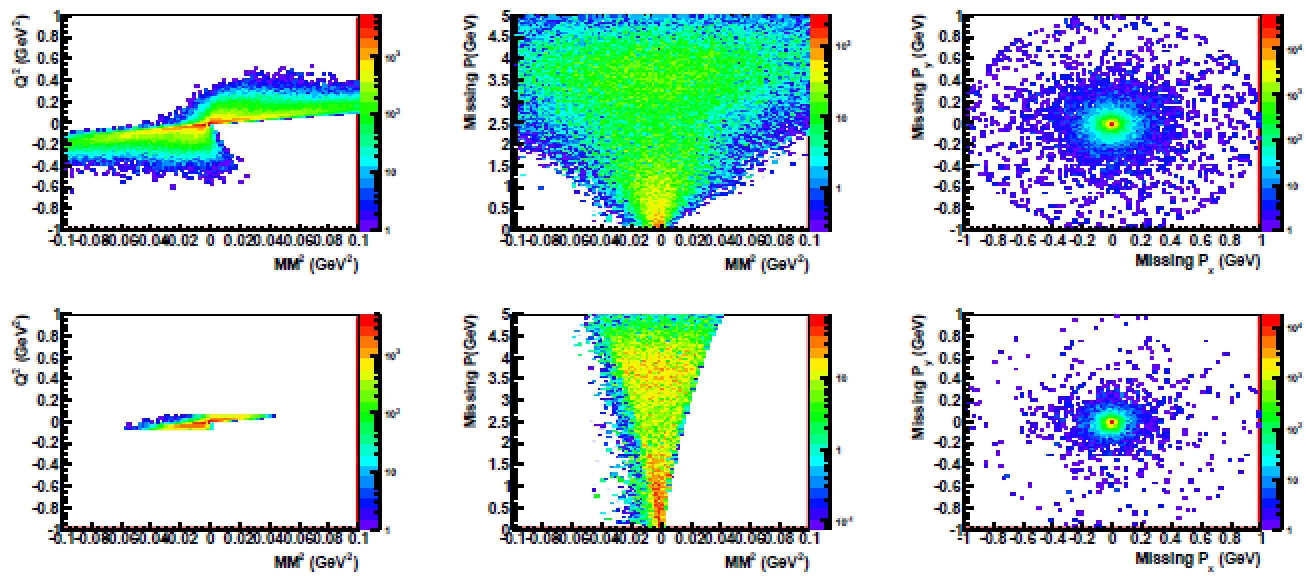
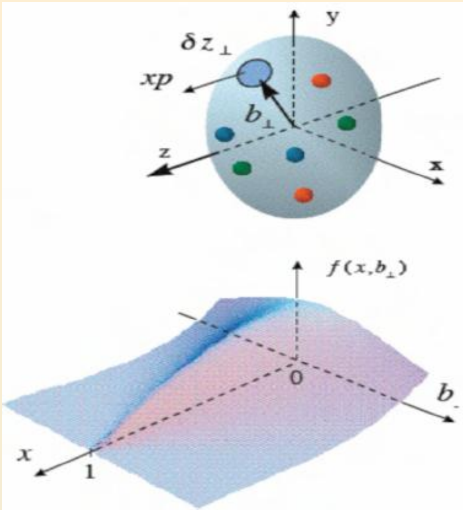
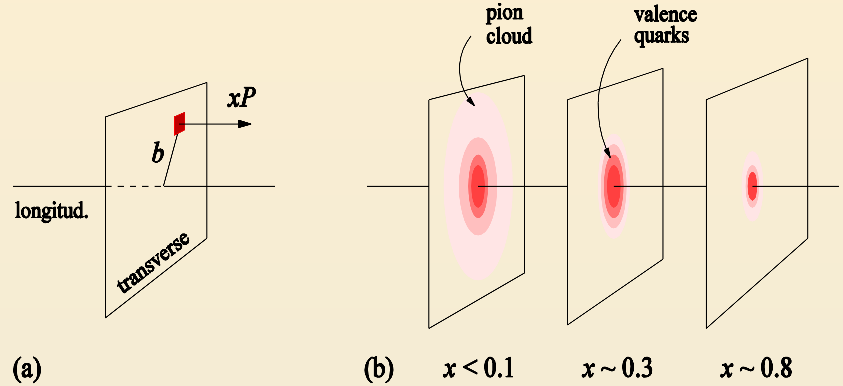


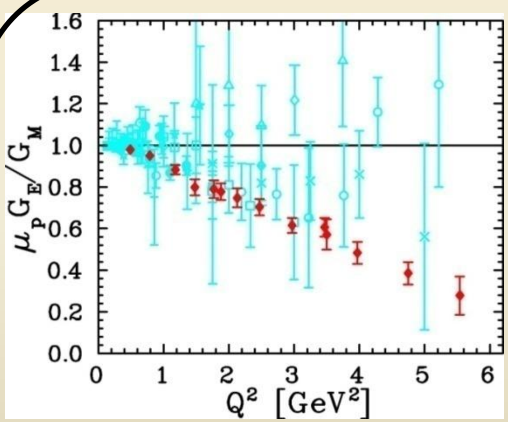
FIG. 23: Missing-particle kinematics before and after the cut $Q^2 < 0.05$ GeV^2 *Left panels:* Q^2 versus missing mass squared MM^2. *Middle panels:* Missing momentum versus missing mass squared MM^2. *Right panels:* Missing momentum P_x versus missing momentum P_y. *Top row:* before the Q^2 cut *Bottom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

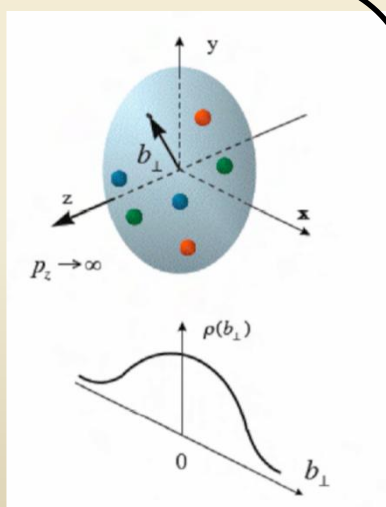
Generalized Parton Distribution (GPD)



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

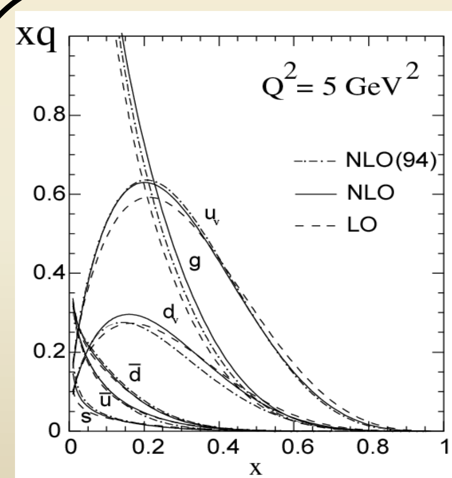


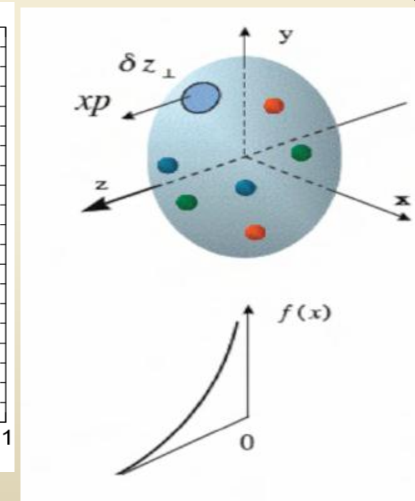




Elastic form factors

Transverse spatial distributions





Parton Distribution Functions

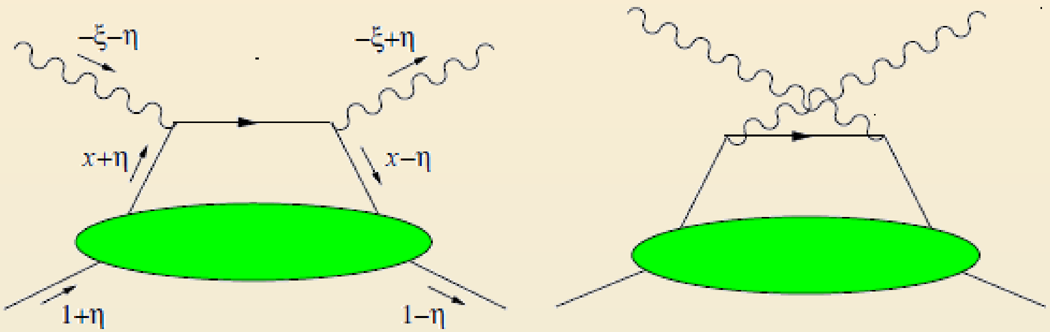
Longitudinal momentum distributions

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)

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

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

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

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

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

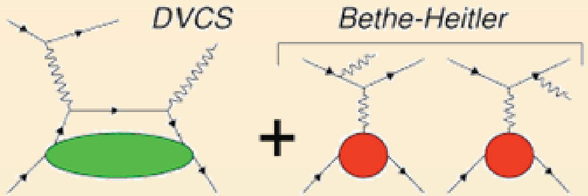
$$\eta = -\frac{(q-q')\cdot(q+q')}{(p+p')\cdot(q+q')} \approx \frac{Q^2 + Q'^2}{2s + Q^2 - Q'^2},$$

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

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

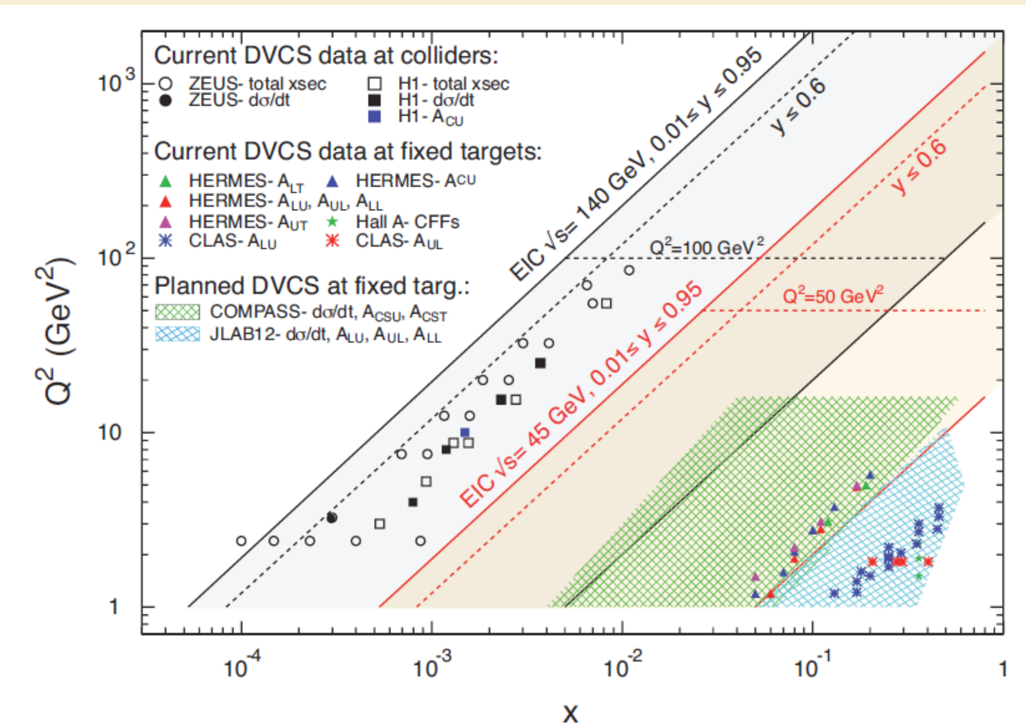
DVCS

ep' epγ =

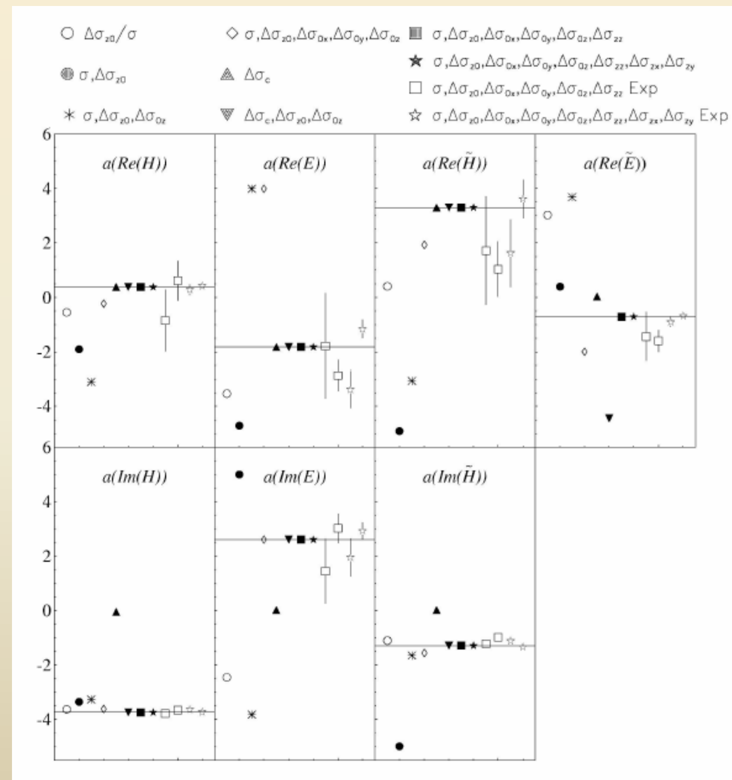


$$\mathcal{T} = |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}$$

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



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)

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

- 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

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

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

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

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

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

Interference term

In terms of helicity amplitudes:

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

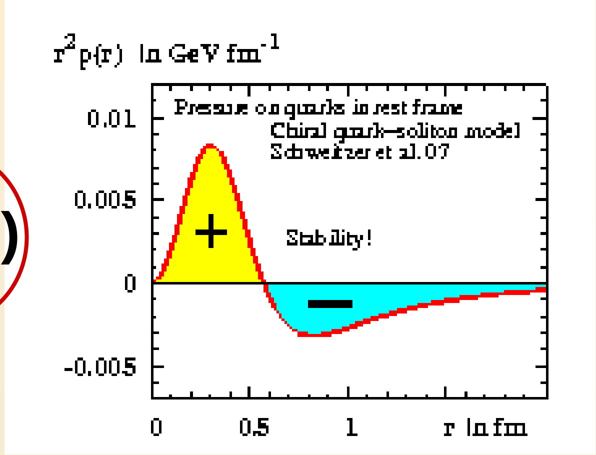
$$-\nu\,\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\left[\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\,\tilde{M}^{--} - \sin 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Im}\,\tilde{M}^{0-} + \sin 3\varphi\,\sin\theta\,\mathrm{Im}\,\tilde{M}^{+-}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

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

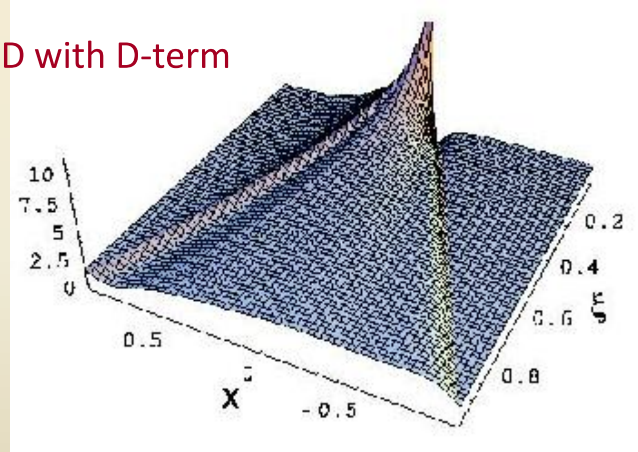
$$\frac{1}{2}\sum_{\lambda,\lambda'}|M^{\lambda'-,\lambda-}|^2 = (1-\eta^2)\left(|\mathcal{H}_1|^2 + |\tilde{\mathcal{H}}_1|^2\right) - 2\eta^2\,\mathrm{Re}\left(\mathcal{H}_1^*\,\mathcal{E}_1 + \tilde{\mathcal{H}}_1^*\,\tilde{\mathcal{E}}_1\right) - \left(\eta^2 + \frac{t}{4M^2}\right)|\mathcal{E}_1|^2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

The D-term and the pressure balance in the nucleon

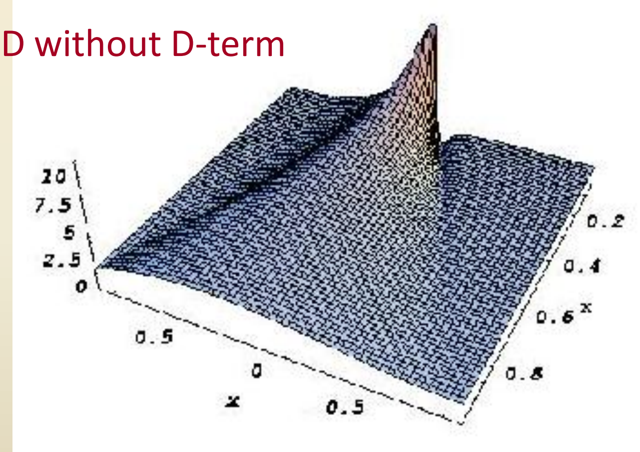
$$H(x,\xi) = H_{DD}(x,\xi) + \theta(\xi - |x|)\frac{1}{N_f} D\left(\frac{x}{\xi}\right)$$



GPD with D-term



GPD without D-term



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

TCS NLO

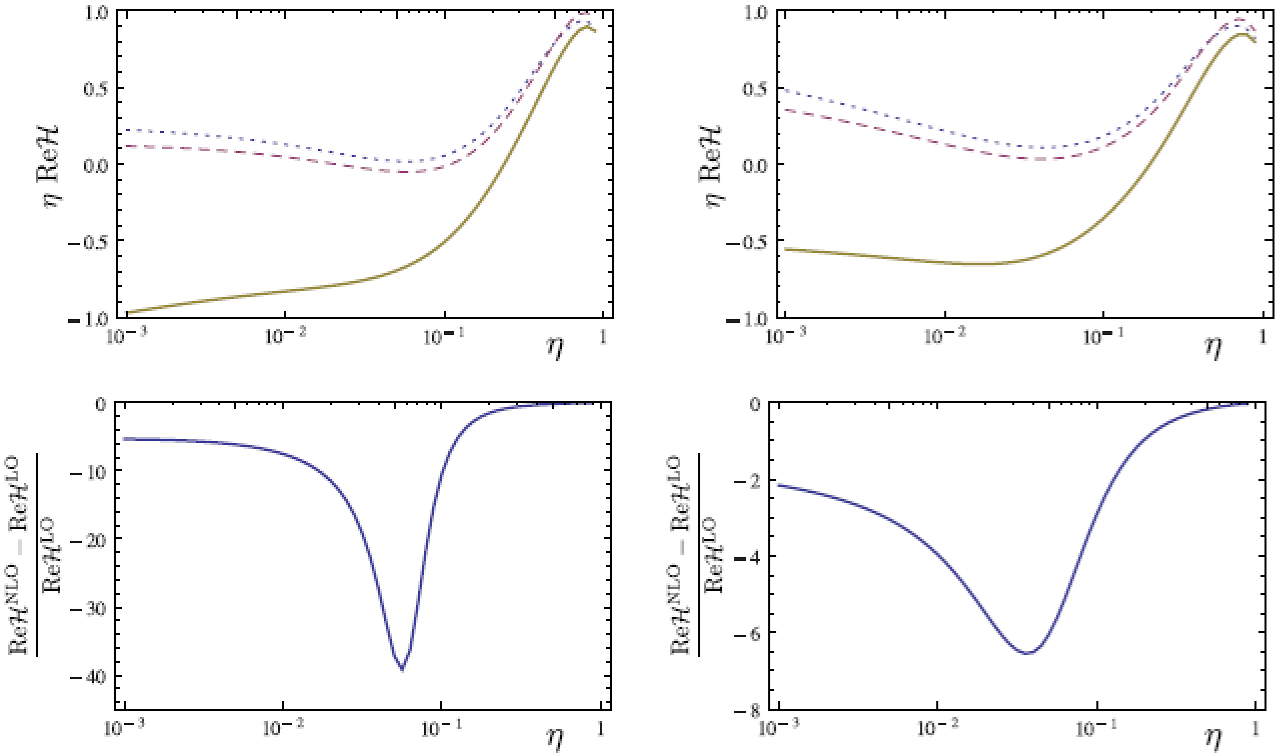


Figure 4: The real part of the *timelike* Compton Form Factor $\mathcal{H}$ multiplied by η, as a function of η in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.1$ GeV^2. Below the ratios of the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

DVCS NLO

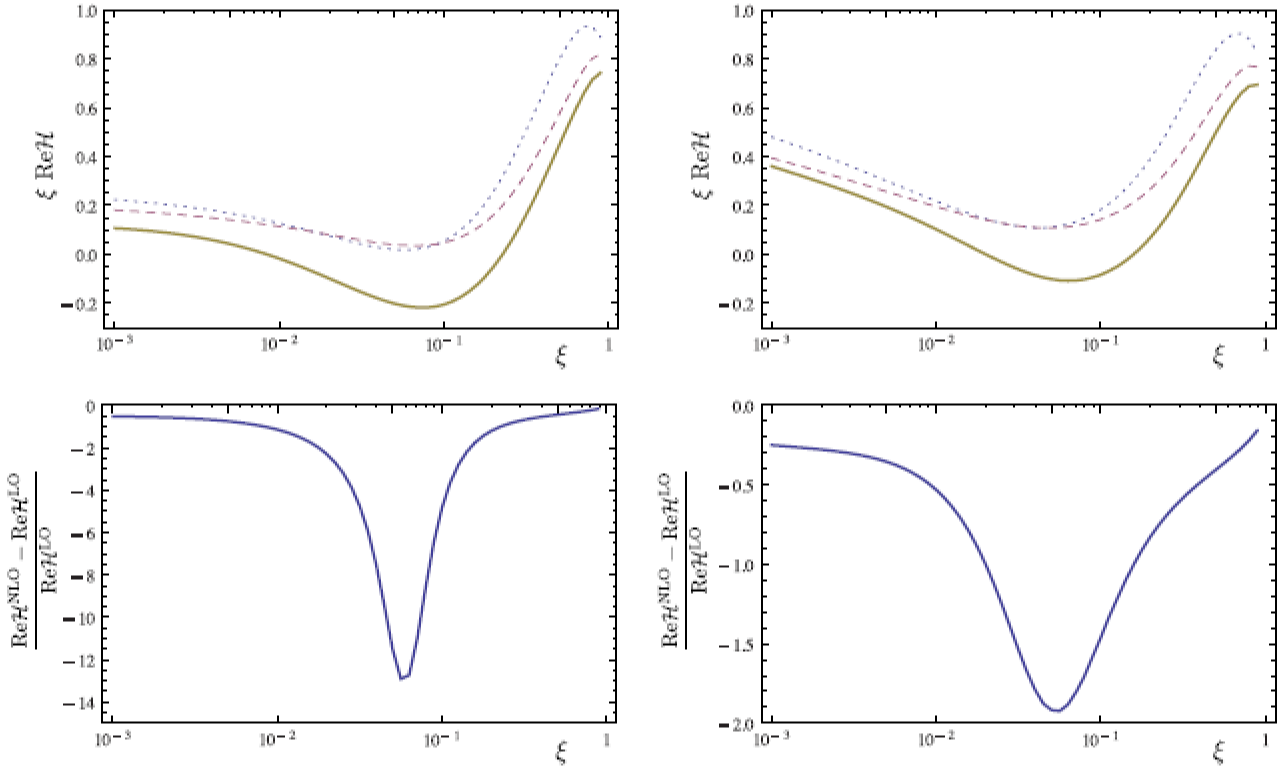


Figure 1: The real part of the *spacelike* Compton Form Factor $\mathcal{H}(\xi)$ multiplied by ξ, as a function of ξ in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4\,\mathrm{GeV}^2$ and $t = -0.1\,\mathrm{GeV}^2$, 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.

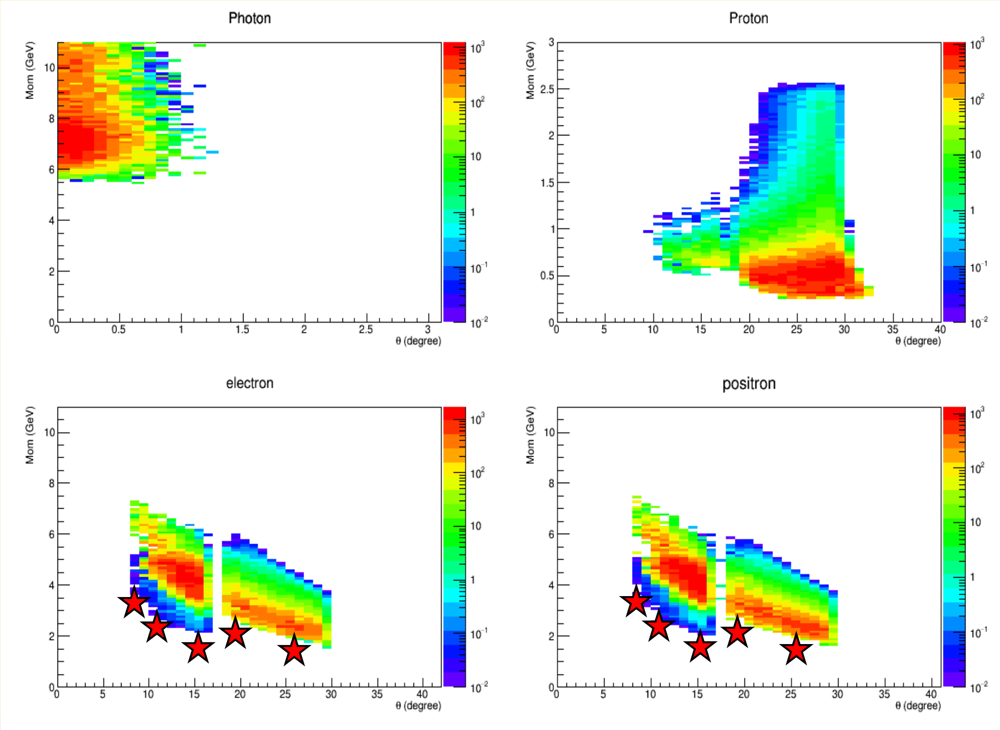
Acceptance and Trigger

- 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 (1.2e37/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

Random coincidence of two electron trigger within 30ns time window is 1.13e6*1.13e6*30e-9 = 40kHz

SIDIS event as background is estimated to be 3kHz by using same trigger and assuming ~10 total pion rejection

Total ~50kHz, which is below 100kHz SIDIS Setup limit

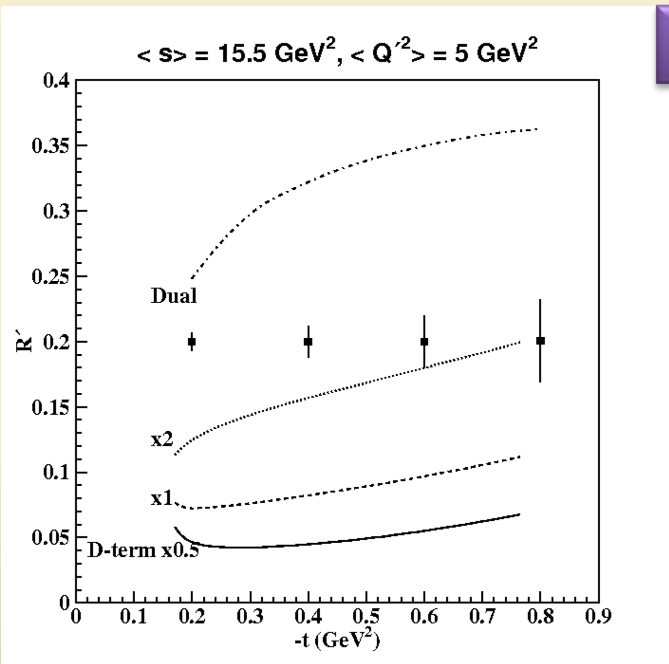
Approved ep → e'pe^{+}e- program for CLAS12

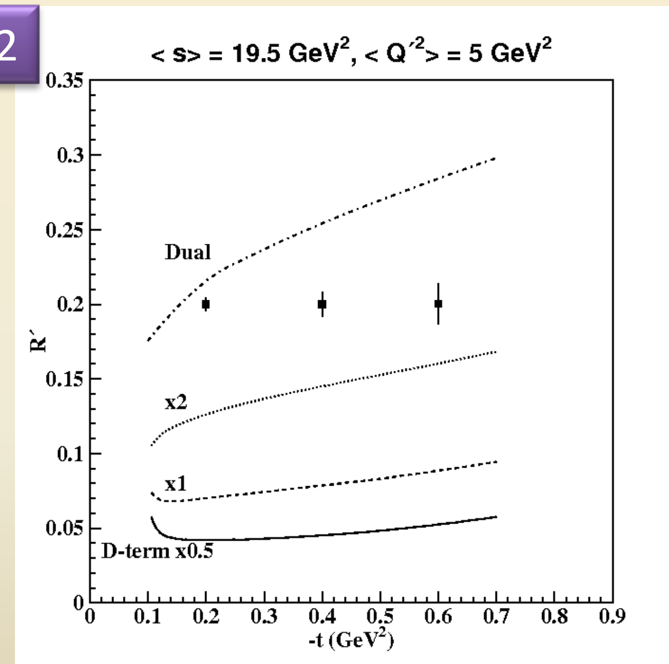
Proposal	Physics	Contact	Rating	Days	Group	Energy	Target
E12-06-108	Hard exclusive electro-production of π0, η	Stoler	B	80			
E12-06-112	Proton's quark dynamics in SIDIS pion production	Avakian	A	60			
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	A	80	119 days + 20 days with reversed torus field	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

CLAS12 TCS Projected Result

CLAS12

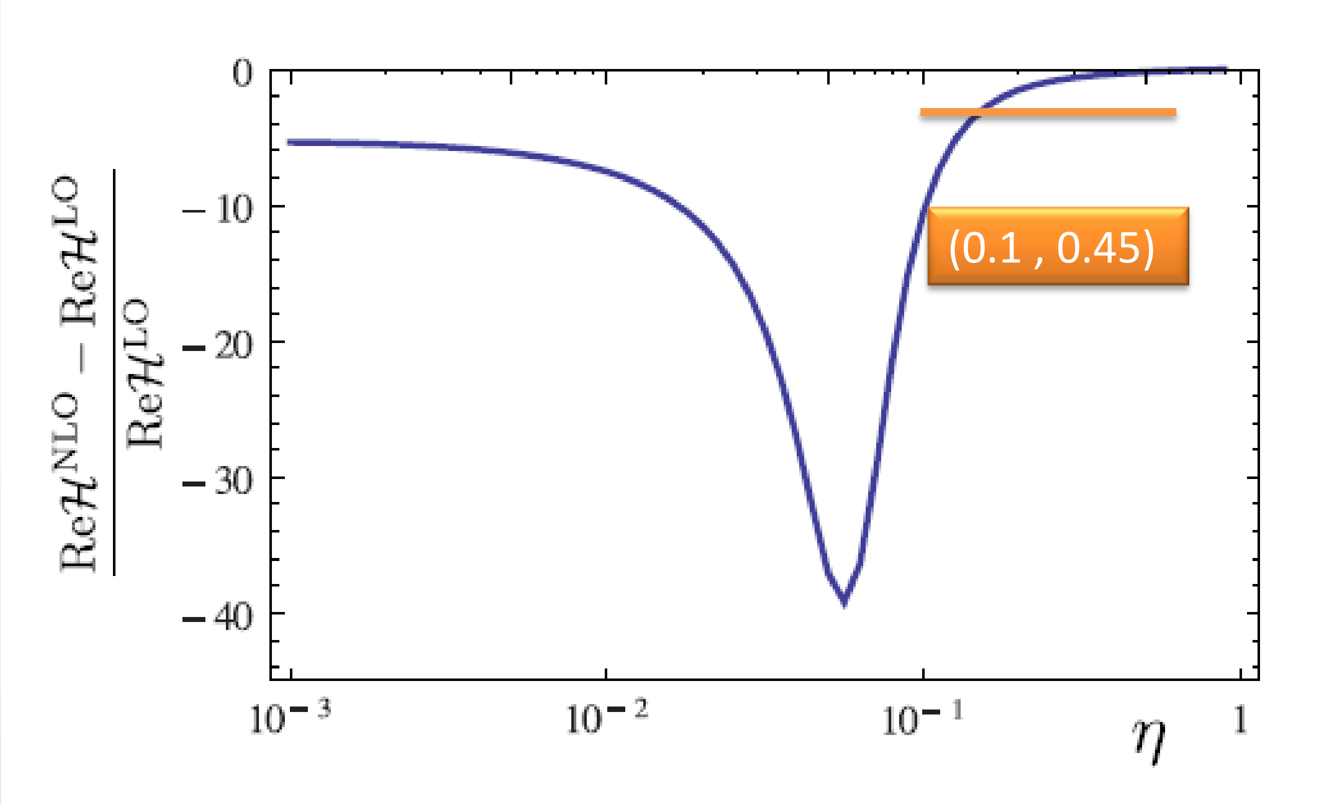




- Statistical uncertainties for 100 days at a luminosity of 10^{35} $cm^{-2}s^{-1}$
- Uncertainties for cosine moment R', integrated over the CLAS12 acceptance, for two bins in photon energy, for the lowest Q'^2 bin above the ρ' resonance.
- Different values of the D-term are only shown for the double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

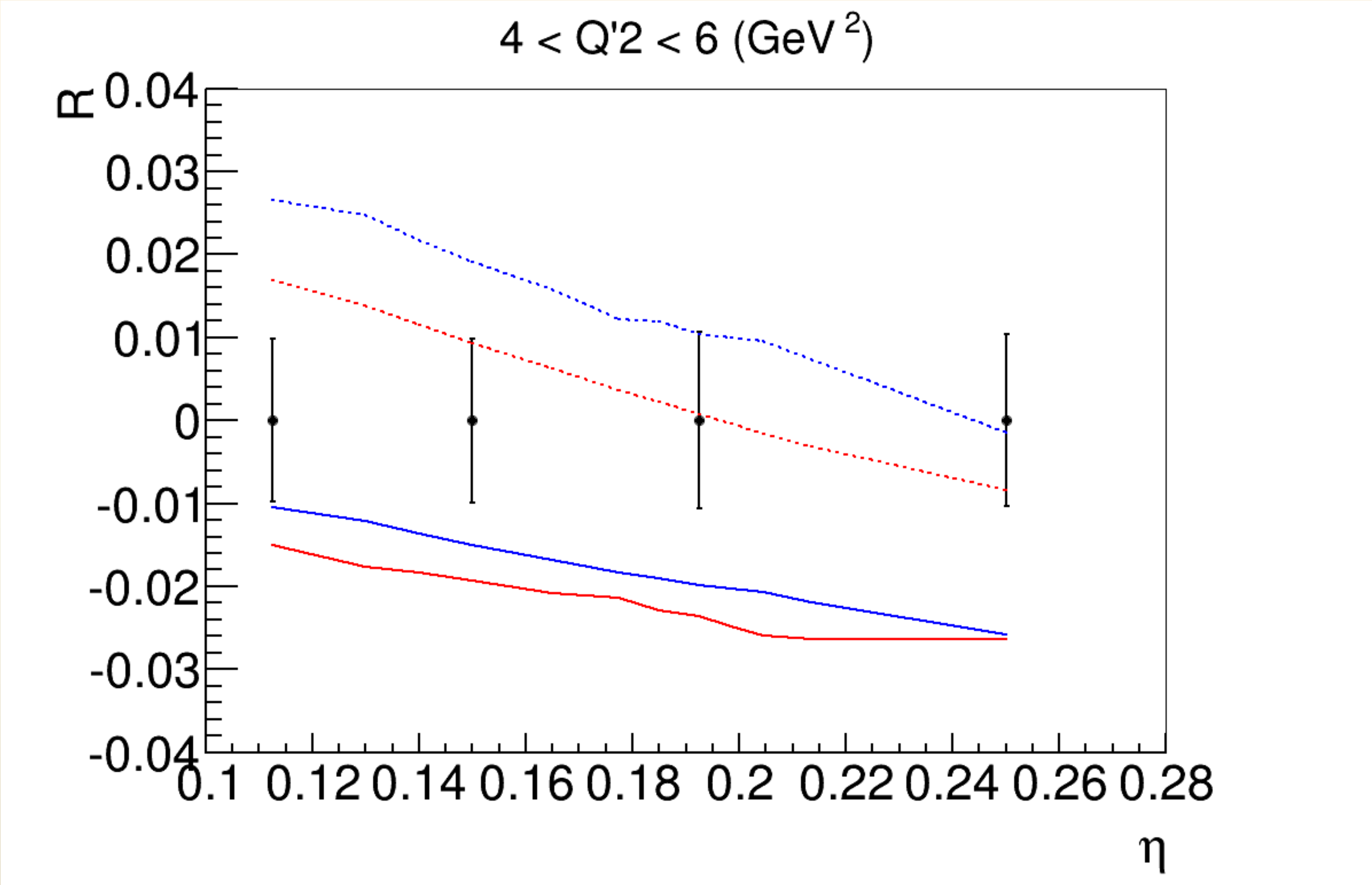
SoLID TCS

- estimated **100k** 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)



SoLID TCS projection

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



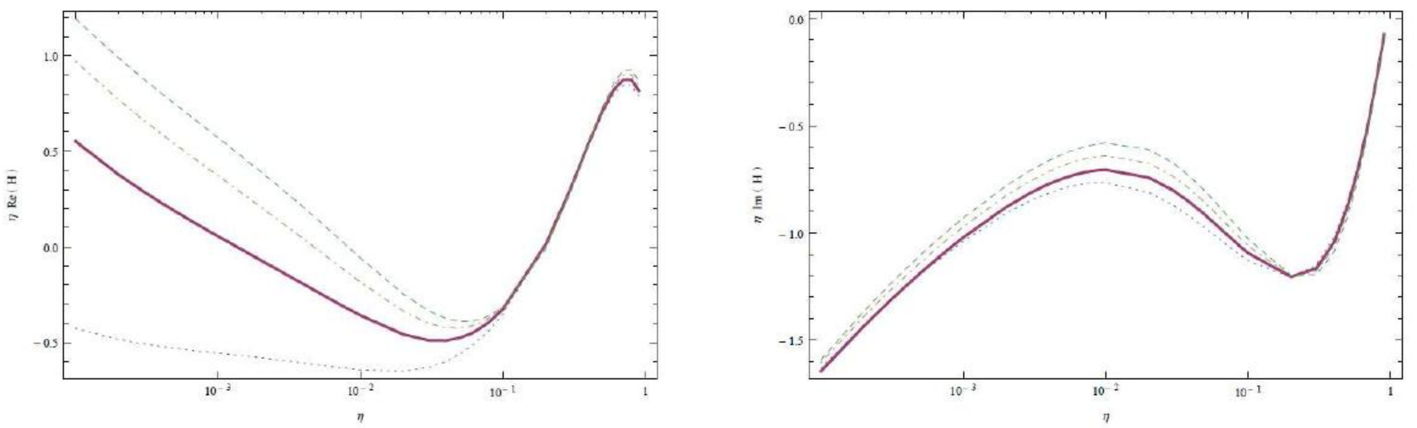
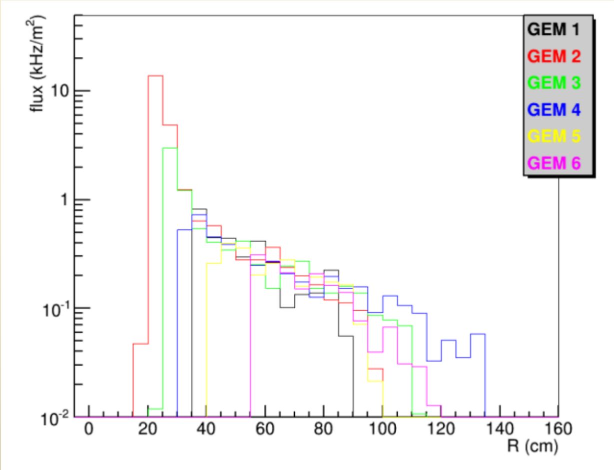


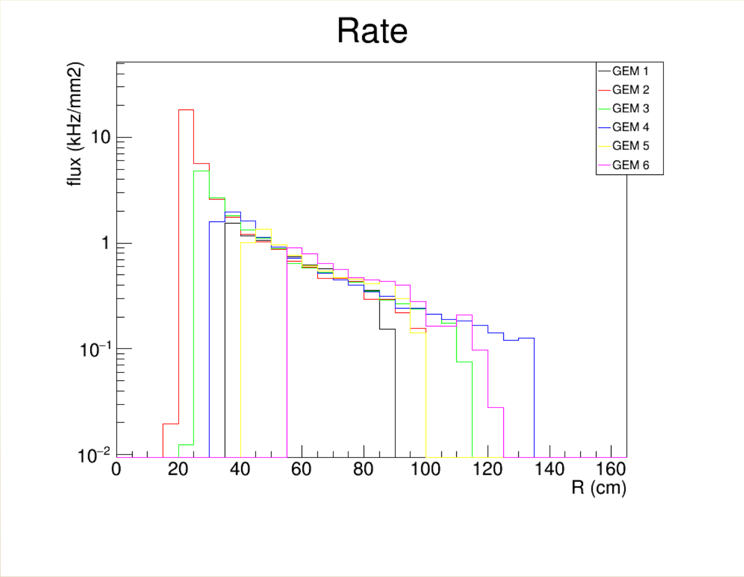
FIG. 18: Full NLO result for real(left) and imaginary(right) part of the CFF $\mathcal{H}$ multiplied by skewness η for the $Q^2 = 4Gev^2$, $t = -0.1Gev^2$ and various choices of the factorization scale $\frac{Q^2}{\mu_F^2} = \{1, 2, 3, 4\}$. We see that for JLab kinematics result is very stable.

GEM rate

SIDIS He3, 7e36/cm2/s, target at -350cm



Jpsi, 1.2e37/cm2/s, target at -315cm



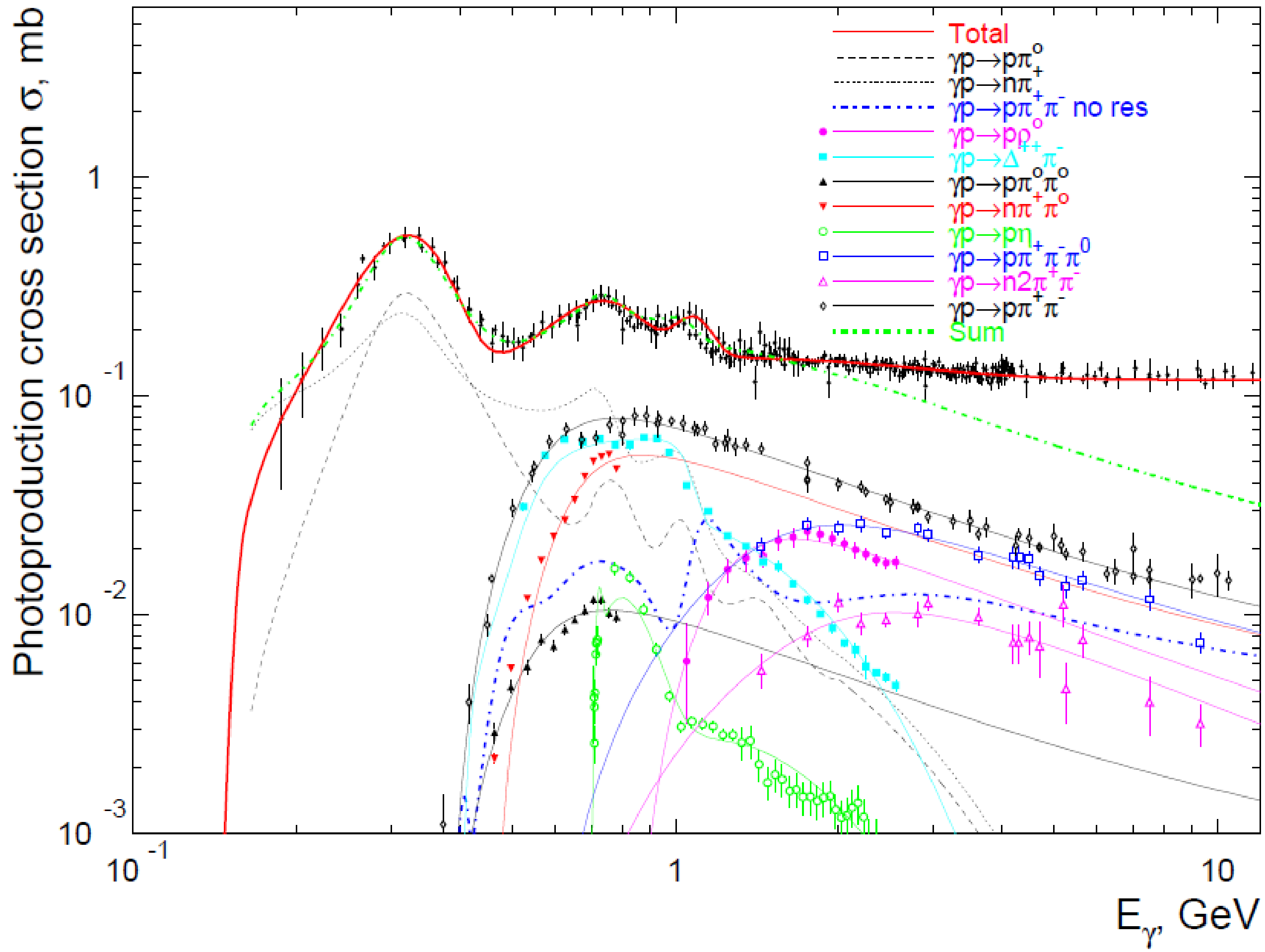
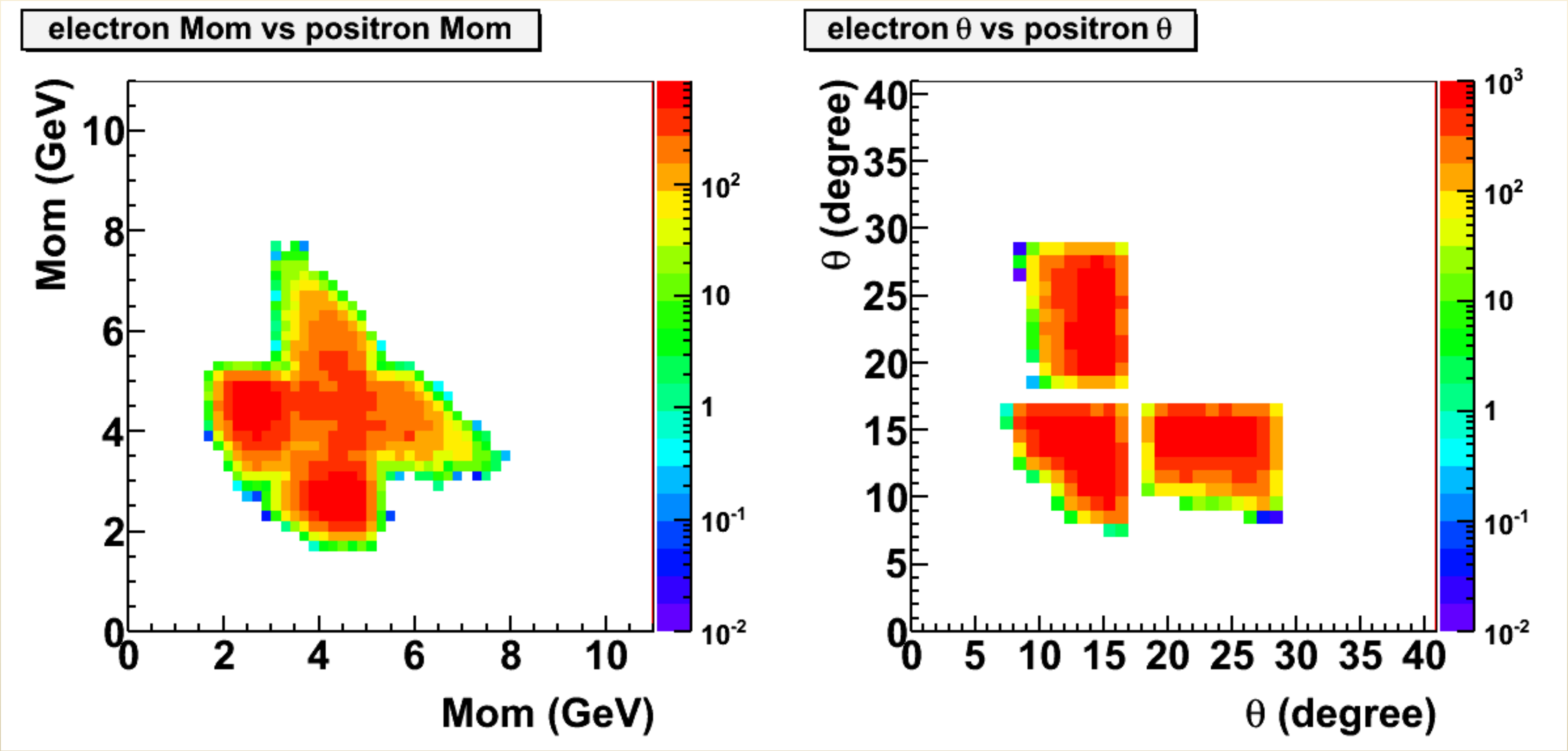


Figure 2: The total photoproduction cross section (the red solid curve) and the partial cross sections for the reactions used at the energies below 3 GeV. The sum of all these partial cross sections (the green dotted curve) matches the total cross section very well, below 2 GeV. At 3 GeV the sum is about 30% smaller than the total cross section. For the simulation, all the partial cross sections were normalized to keep their sum equal to the total cross section.

Electron PID

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



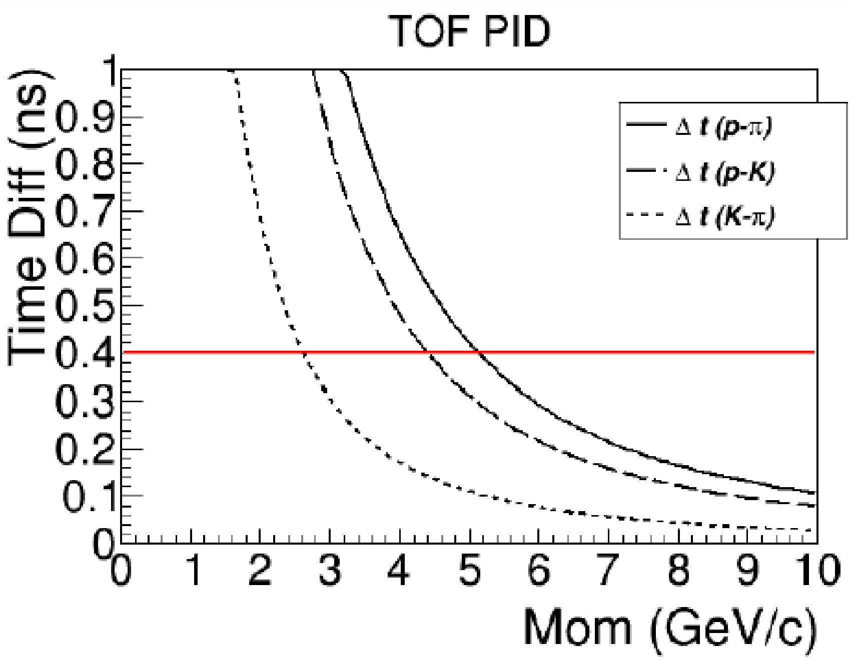
Proton PID

Recoil p:

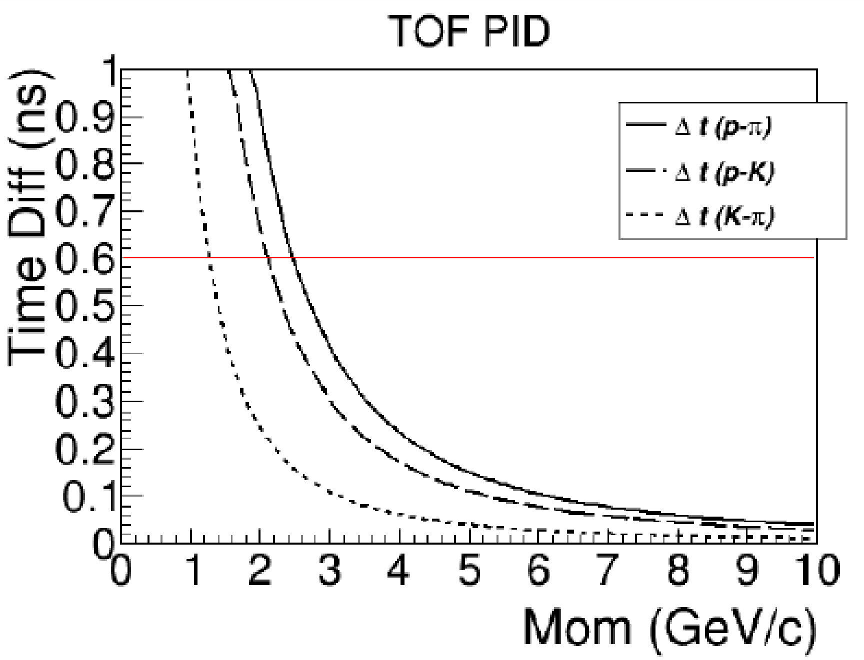
100 ps TOF(MRPC): 4 σ separation p/K up to 4.4 GeV and p/pi up to 5GeV @ forward angle

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

FA



LA



CLAS 6, missing particle cut

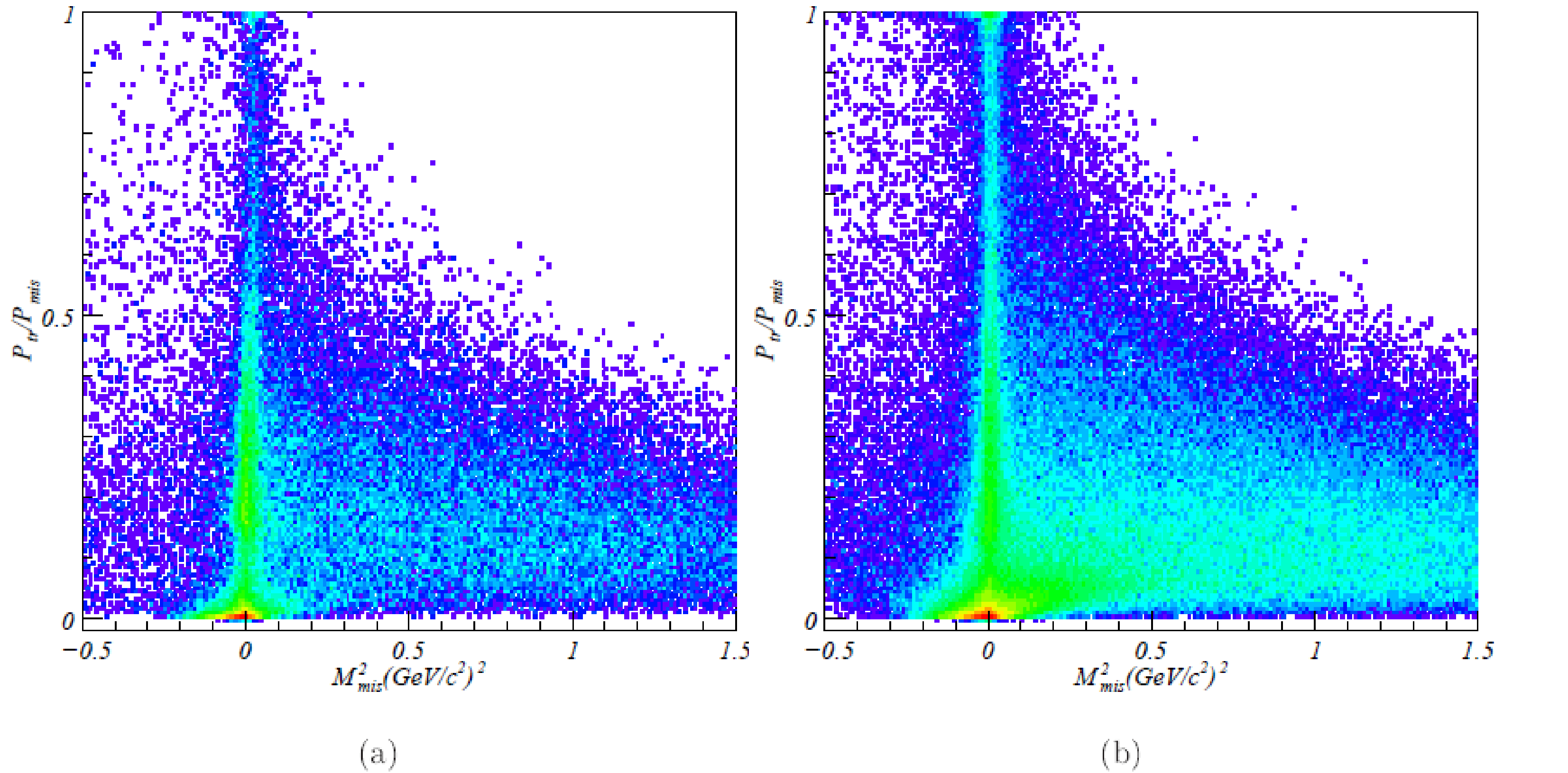
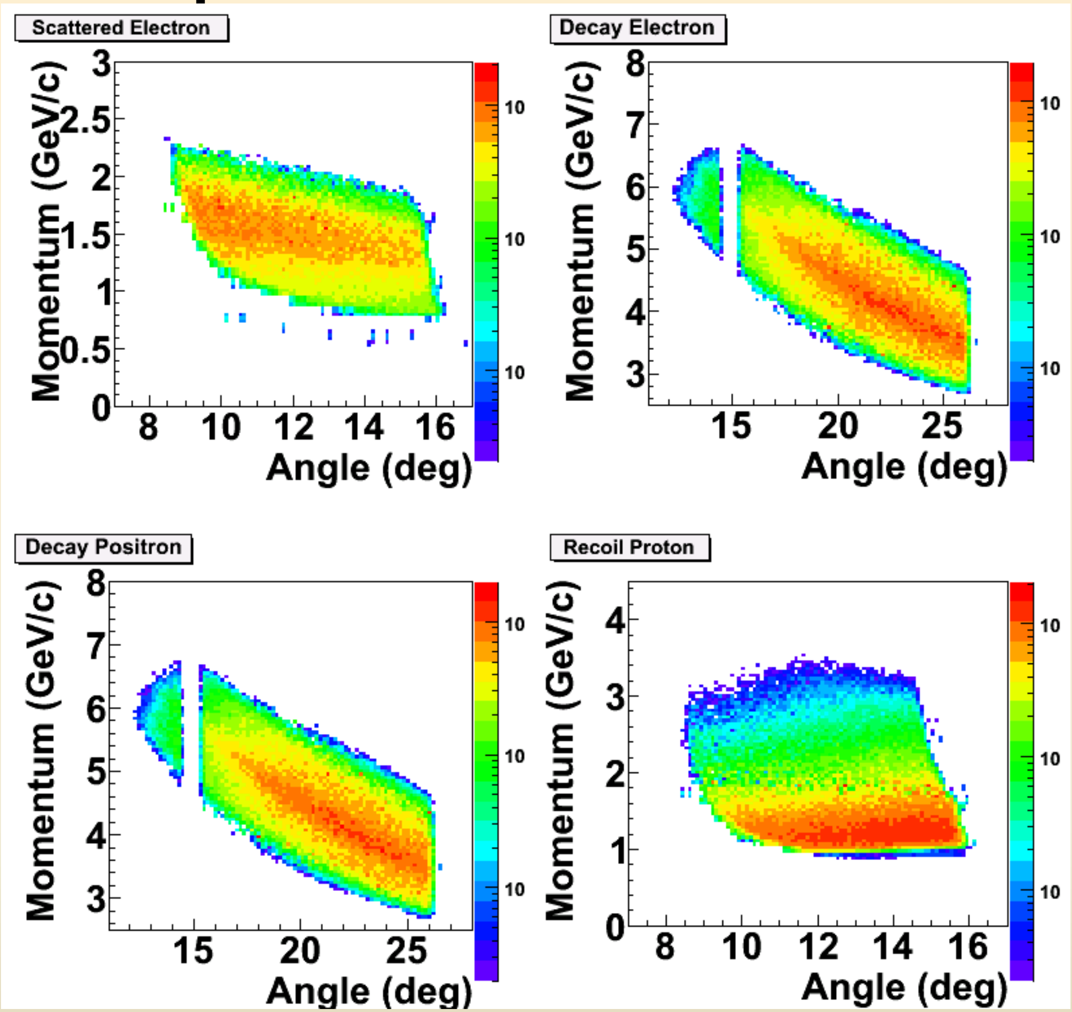


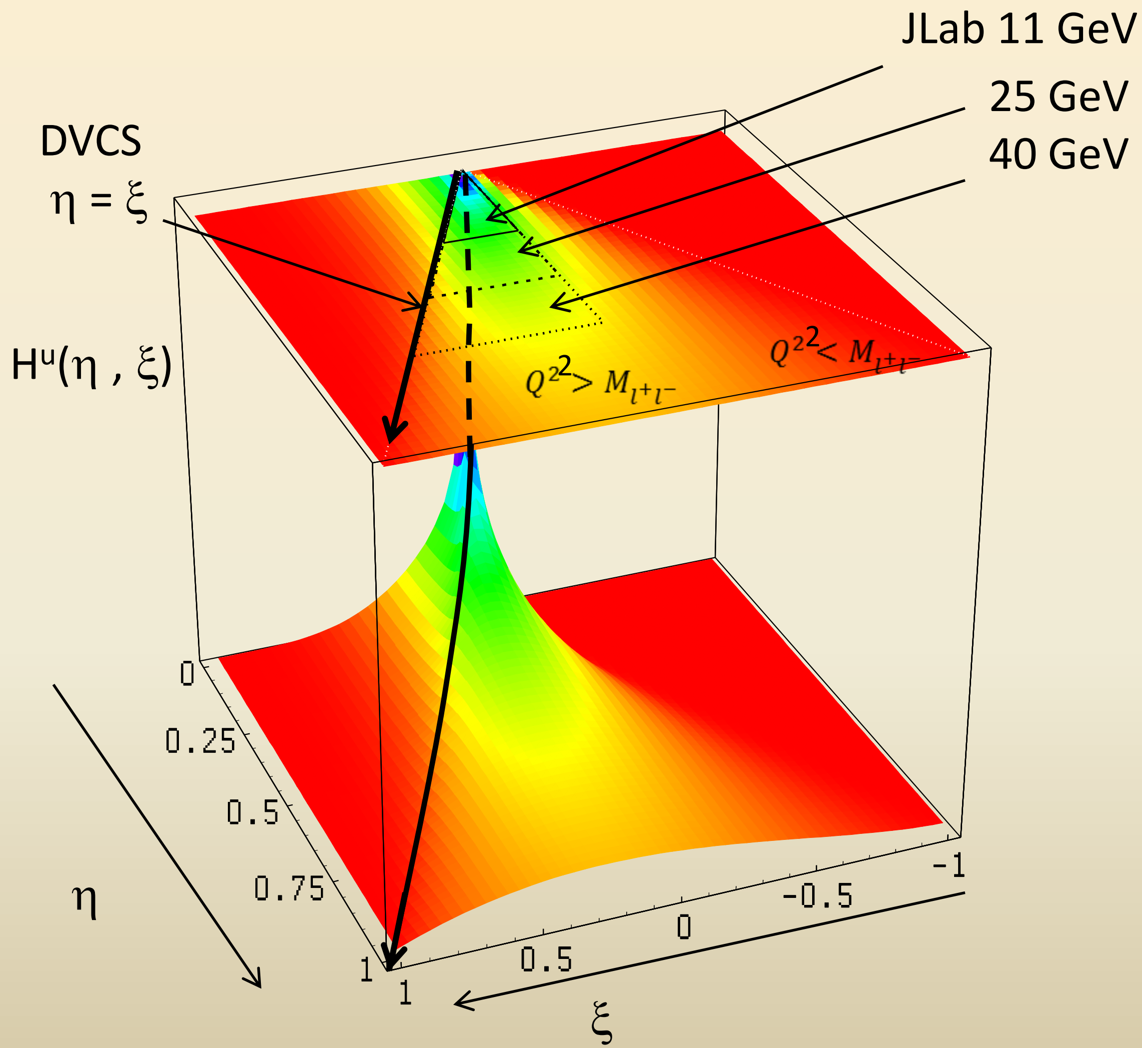
Figure 4.2: Distribution of the perpendicular missing momentum fractions vs. missinag mass squared for the selectrd e^-e^+p events. a) e1-6 data, b) e1f data

PID and Acceptance

- Scattered electron:
  - GC + Calorimeter @ forward angle
- Decay electron/Positron:
  - Calorimeter only at large angle
  - GC+Calorimeter at forward angle
- Recoil proton:
  - 100 ps TOF: 2 ns separation between p/K @ 2 GeV/c
  - ~8m flight path



DDVCS JLab12GeV
Kinematical coverage



The continuously varying virtuality of the incoming and outgoing photon allows to "tune" the kinematical point at which the GPDs are sampled

- DVCS only probes η = ξ line
- Example with model of GPD H for up quark
- Kinematical range increases with beam energy (larger dilepton mass)