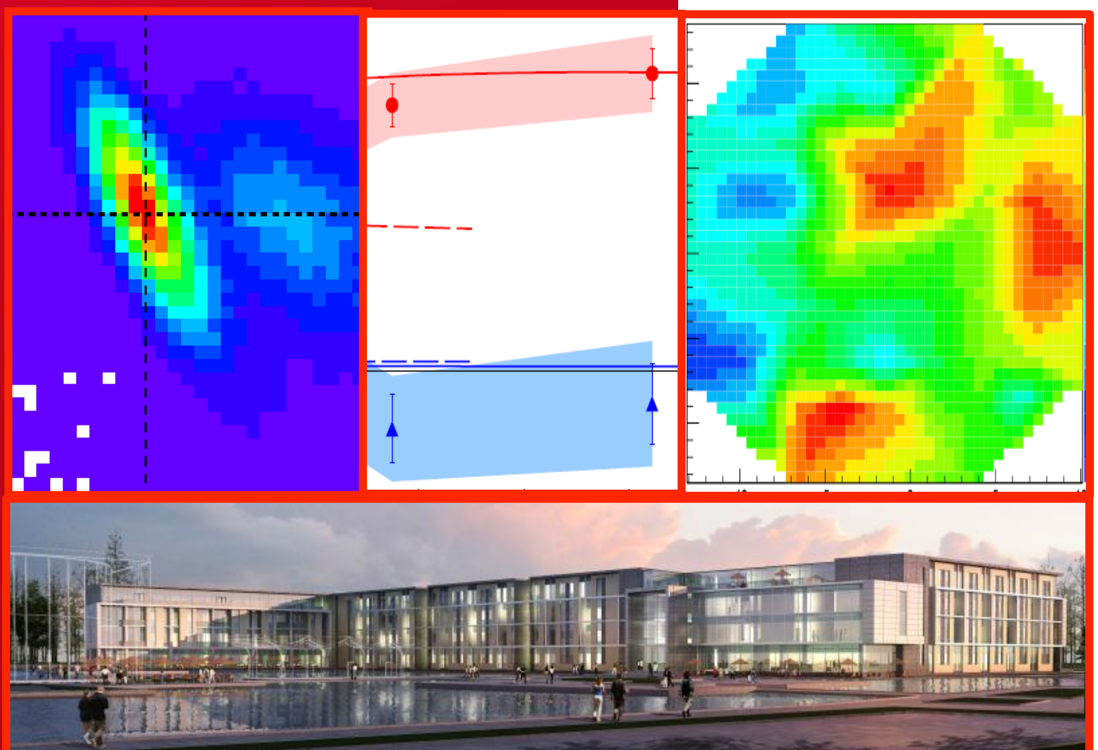
Jefferson Lab's **G**eneralized **P**arton **D**istributions program & **new γ / π^0 results !**

F. Sabatié – CEA Saclay

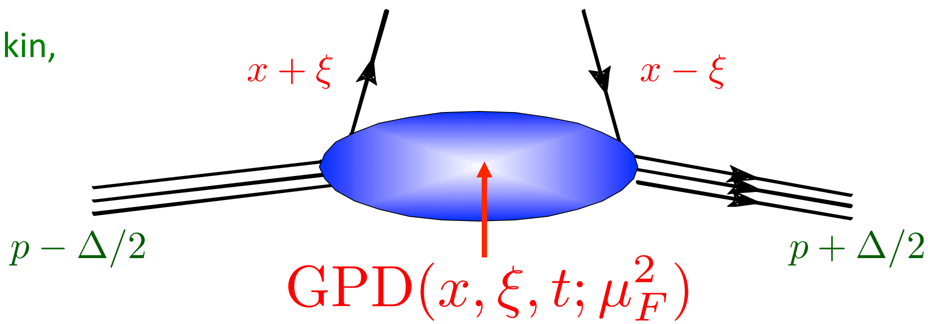
DE LA RECHERCHE À L'INDUSTRIE



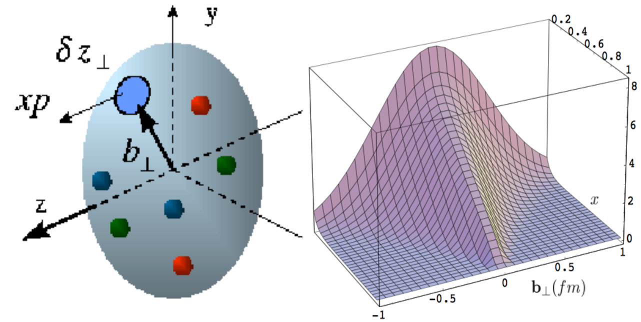
- Introduction
- Generalized Parton Distributions
- $ep \to ep(\gamma/\pi^0)$ to access GPDs
- **New** DVCS analysis & results
- **New** π^0 analysis & results
- The JLab GPD program at 12 GeV
- Summary & Conclusion

Generalized Parton Distributions

Ji, Radyushkin, Müller



$(x+\xi)$ and $(x-\xi)$: longitudinal momentum fractions of quarks



Impact parameter space Interpretation

Burkardt, Diehl, …

The structure of the nucleon can be described at leading-twist by

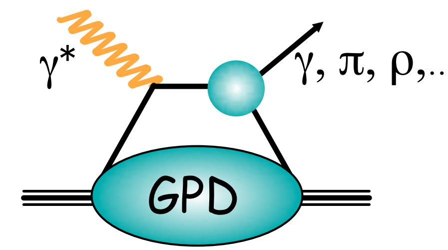
4 chiral-even **Generalized Parton Distributions** :

$$H, \widetilde{H}, E, \widetilde{E}(x,\xi,t;\mu_F^2)$$

4 chiral-odd $H_T, \widetilde{H}_T, E_T, \widetilde{E}_T(x,\xi,t;\mu_F^2)$

> They enter the $\gamma^* p \to (\gamma \text{ or } M)\ p$ amplitude

as convolution integrals : no direct access



Deep Exclusive Processes

Parton distributions in both coordinate and momentum space

> Forward limit $(t=\xi=0)$ of H and $\widetilde{H}$: PDFs

> First moment in x : Form Factors

> Second moment of $(H+E)$ when $t \to 0$: total angular momentum (Ji's sum rule)

Deeply Virtual Compton Scattering

- Theory is under control : up to α_S^2 , twist-3, target mass corrections, etc.
- Sensitive to the quark combination : $\frac{4}{9}u + \frac{1}{9}d + \frac{1}{9}s$

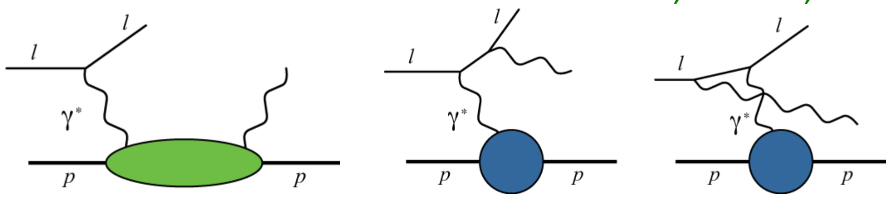
Müller et al,
Braun et al, ...

- At Jefferson Lab energies, *mostly* sensitive to valence quarks
- Actually sensitive to *gluon* GPDs at NLO or beyond (even at somewhat large x)
- At LO, direct access the GPDs on the line $x = \xi$ through Beam Spin Asymmetries

  sensitive to the interference with known Bethe-Heitler process

Moutarde, Pire,
F.S. , Wagner, ...

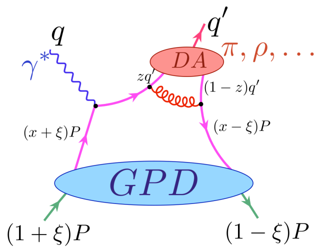
Diehl, Gousset,
Pire, Ralston, ...



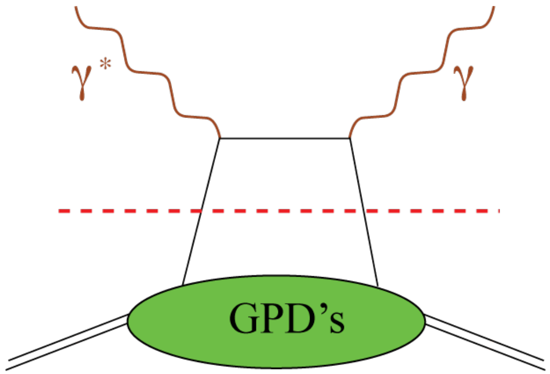
Hard Meson Electroproduction

- Many channels available for flavor separation (ρ^0, ρ^+, π^0, π^+, ϕ, ...)
- J/Ψ and ϕ access gluon GPDs. Surprises with the π^0 (later in this talk)
- Theory less under control : convolution with (unknown) meson WF,

  potentially slow scaling, large power and NLO corrections



The DVCS Amplitude : Compton Form Factors



GPD's

$$\mathcal{F}(\xi, t, Q^2) = \int_{-1}^{+1} dx\, C\left(x, \xi, \alpha_S(\mu_R), \frac{Q}{\mu_F}\right) F(x, \xi, t, \mu_F)$$

Factorization scale dependence through evolution equations

Compton Form Factor (CFF)
CFF are *complex* functions !

Integration Kernel has been worked out up to NLO

Müller et al
Pire, F.S. et al
…

$$\xi \simeq \frac{x_B}{2 - x_B}$$

DVCS observables

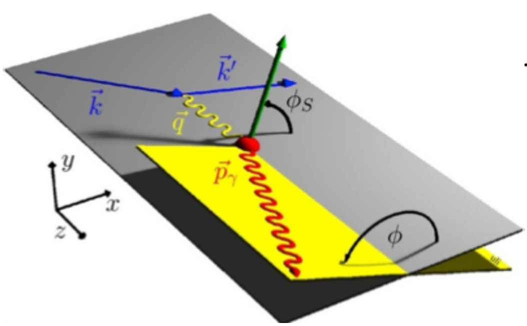
In the one-photon exchange approximation of QED,
the BH, DVCS and interference parts of the ***ep*** $\rightarrow$ ***ep***γ cross section read :

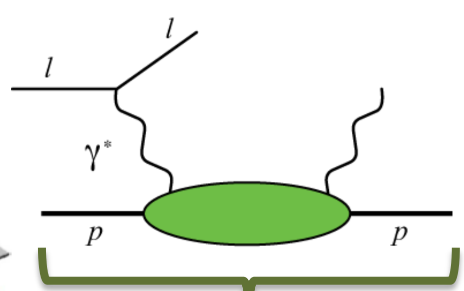
Diehl et al

$$|\mathcal{M}_{\rm BH}|^2 \propto \frac{1}{|t|}\frac{1}{P(\cos\phi)}\sum_{n=0}^{3}\left[c_n^{\rm BH}\cos(n\phi)+s_n^{\rm BH}\sin(n\phi)\right]$$

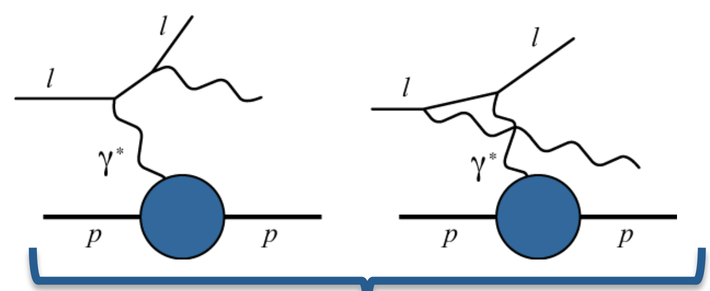
$$|\mathcal{M}_{\rm DVCS}|^2 \propto \sum_{n=0}^{3}\left[c_n^{\rm DVCS}\cos(n\phi)+s_n^{\rm DVCS}\sin(n\phi)\right]$$

$$\mathcal{M}_{\rm I} \propto \frac{1}{|t|}\frac{1}{P(\cos\phi)}\sum_{n=0}^{3}\left[c_n^{\rm I}\cos(n\phi)+s_n^{\rm I}\sin(n\phi)\right]$$





DVCS



Bethe-Heitler

DVCS observables at Jefferson Lab

Experiment	Observable	Normalized CFF dependence
CLAS	$A_{\mathrm{LU}}^{-,\sin\phi}$	$\mathrm{Im}\mathcal{H} + 0.06\mathrm{Im}\mathcal{E} + 0.21\mathrm{Im}\widetilde{\mathcal{H}}$
	$A_{\mathrm{UL}}^{-,\sin\phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} + 0.12\mathrm{Im}\mathcal{H} + 0.04\mathrm{Im}\mathcal{E}$
	$A_{\mathrm{UL}}^{-,\sin 2\phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} - 0.79\mathrm{Im}\mathcal{H} + 0.30\mathrm{Im}\mathcal{E} - 0.05\mathrm{Im}\widetilde{\mathcal{E}}$
HALL A	$\Delta\sigma^{\sin\phi}$	$\mathrm{Im}\mathcal{H} + 0.07\mathrm{Im}\mathcal{E} + 0.47\mathrm{Im}\widetilde{\mathcal{H}}$
	$\sigma^{\cos 0\phi}$	$1 + 0.05\mathrm{Re}\mathcal{H} + 0.007\mathcal{H}\mathcal{H}^*$
	$\sigma^{\cos\phi}$	$1 + 0.12\mathrm{Re}\mathcal{H} + 0.05\mathrm{Re}\widetilde{\mathcal{H}}$

Kroll, Moutarde, F.S., EPJC73 2278 (2013)

Cross sections at JLab mostly sensitive to CFF $\mathcal{H}$

Experiment	Observable	Normalized CF…
CLAS	$A_{\mathrm{LU}}^{-,\sin\phi}$	$\mathrm{Im}\mathcal{H}$…
	$A_{\mathrm{UL}}^{-,\sin\phi}$	
	$A_{\mathrm{UL}}^{-,\sin 2\phi}$	… $- 0.05\mathrm{Im}\widetilde{\mathcal{E}}$
HALL A	A…	…$\mathrm{Im}\mathcal{E} + 0.47\mathrm{Im}\widetilde{\mathcal{H}}$
		…$0.05\mathrm{Re}\mathcal{H} + 0.007\mathcal{H}\mathcal{H}^*$
		$1 + 0.12\mathrm{Re}\mathcal{H} + 0.05\mathrm{Re}\widetilde{\mathcal{H}}$

NEW 2015 DVCS analysies
from Halls A & CLAS

Kroll, Moutarde, F.S., EPJC73 2278 (2013)

Hard π^0 electroproduction: a puzzle

$$\frac{d^4\sigma}{dt d\phi dQ^2 dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi)\right]$$

$$\Gamma_{\gamma^*}(Q^2, x_B, E_e) = \frac{\alpha}{8\pi}\frac{Q^2}{M^2E_e^2}\frac{1-x_B}{x_B^3}\frac{1}{1-\epsilon}$$

$$\epsilon = \frac{1-y-\frac{Q^2}{4E_e^2}}{1-y+\frac{y^2}{2}+\frac{Q^2}{4E_e^2}}$$

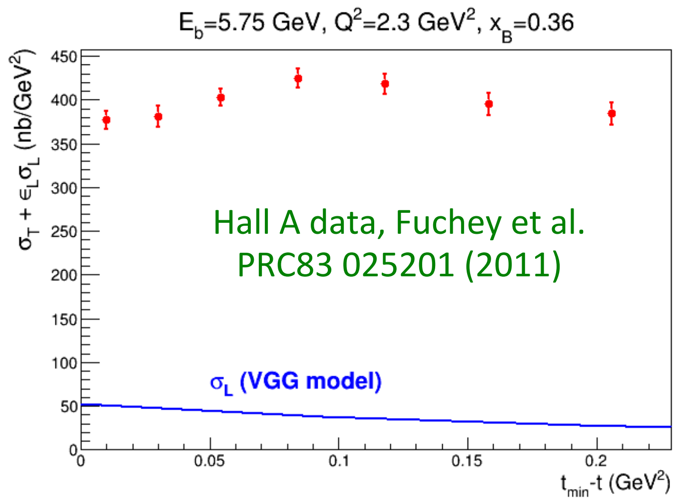
Factorization proven for L cross section only. $\frac{d\sigma_L}{dt}$ is mostly sensitive to $\widetilde{H}$:

$$\frac{d\sigma_L}{dt} \propto \frac{1}{Q^6}\left[(1-\xi^2)\left|\left\langle\widetilde{H}\right\rangle\right|^2 + \ldots\right]$$

However, exciting results in the last few years

- Hall A and CLAS π^0 un-separated cross section data overshoot chiral-even GPD models by a factor ~10 (Figure: Hall A data, similar findings at CLAS)

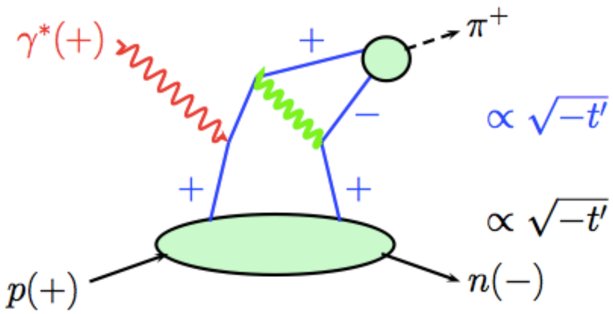
- Q^2 dependence is too large for γ_L-π transition and actually compatible with a γ_T-π transition (Hall A)



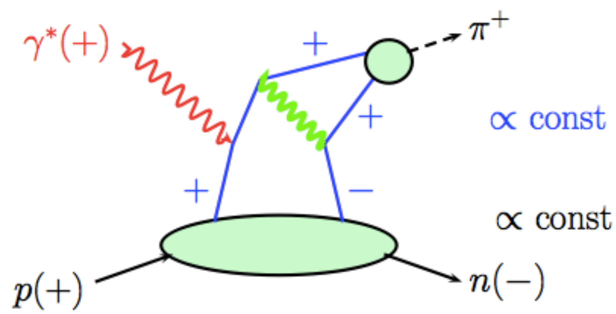
Hard π^0 electroproduction: higher-twist trick?

Goloskokov, Kroll, EPJA, 47:112 (2011)
See also: Ahmad, Goldstein, Liuti, PRD79 054014 (2009)

Explanation: chiral-odd GPD may contribute to transverse part

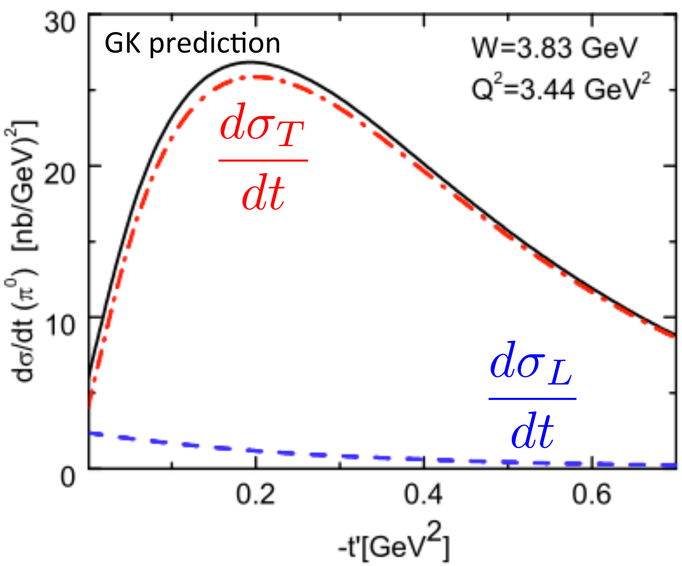


Full leading-twist diagram



This diagram requires a Twist-3 pion w.f.
Suppressed by μ_π/Q wrt leading twist, BUT

$$\mu_\pi = \frac{m_\pi^2}{m_u + m_d} \simeq 2.5 \text{ GeV}$$



In this approach :

$$\frac{d\sigma_T}{dt} \propto \frac{1}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - (t'/8m^2)\left|\langle \bar{E}_T\rangle\right|^2\right]$$

with $\bar{E}_T = 2\widetilde{H}_T + E_T$

Low-t' behavior results from interplay between $H_T, \bar{E}_T$

Hard π^0 electroproduction: higher-twist trick?

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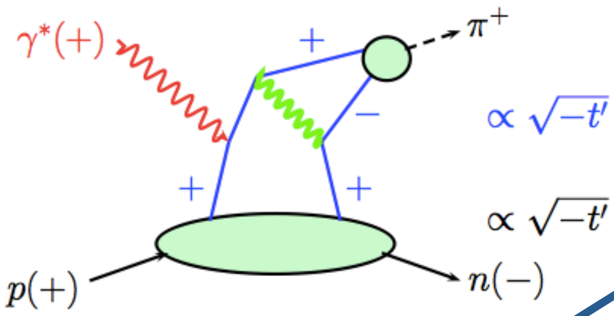
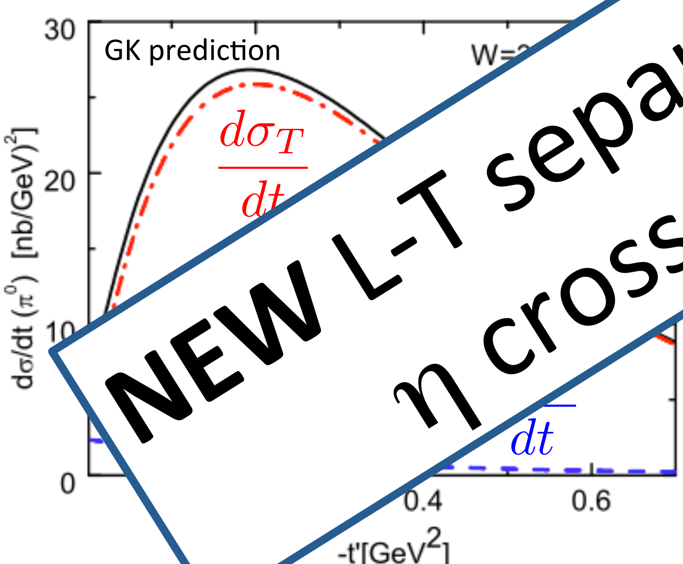


Full leading-twist diagram…

… a Twist-3 pion w.f.

… Q wrt leading twist, BUT

$$\ldots = \frac{m_\pi^2}{m_u + m_d} \simeq 2.5\ \mathrm{GeV}$$



…pproach :

$$\frac{d\sigma_T}{dt} \propto \frac{1}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - (t'/8m^2)\left|\langle \bar{E}_T\rangle\right|^2\right]$$

with $\bar{E}_T = 2\widetilde{H}_T + E_T$

Low-*t'* behavior results from interplay between $H_T, \bar{E}_T$

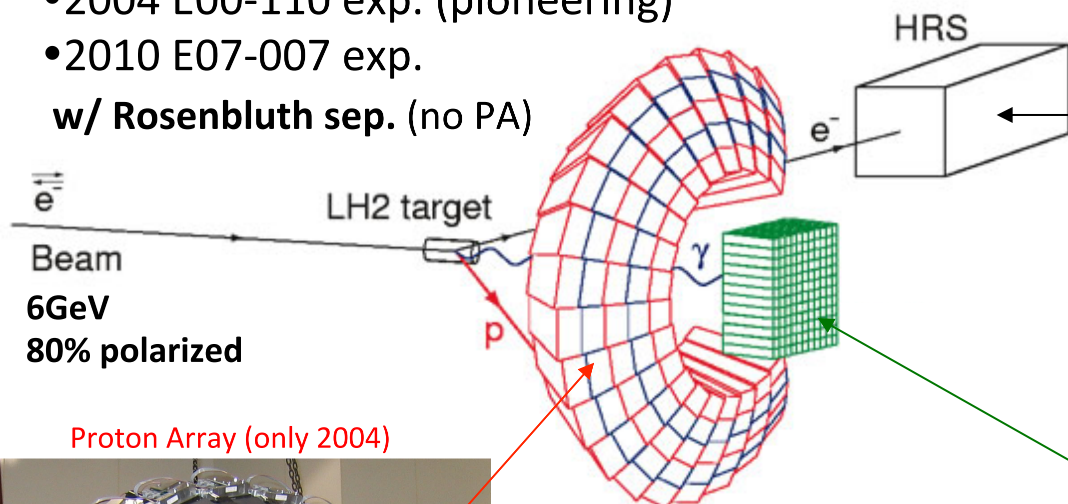
NEW L-T separation of π^0 from Hall A
η cross sections from CLAS

Jefferson Lab Hall A DVCS/π^0 experiment

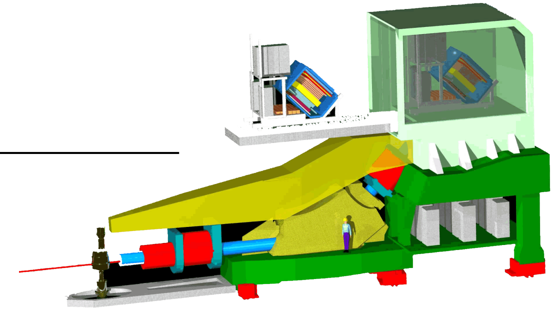
Two run periods:

- 2004 E00-110 exp. (pioneering)
- 2010 E07-007 exp.

w/ Rosenbluth sep. (no PA)

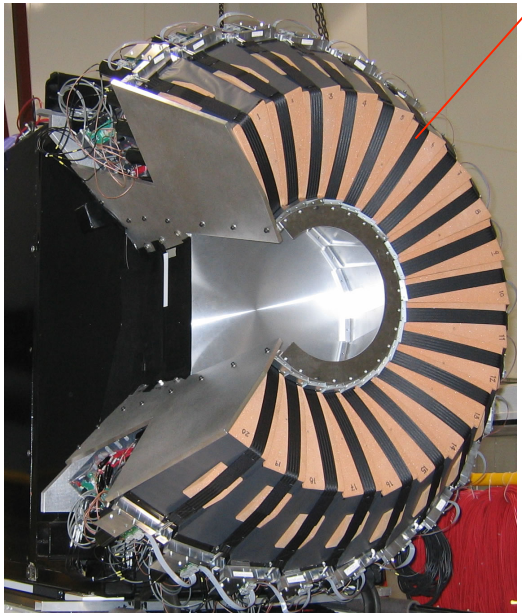


6GeV
80% polarized



HRS spectrometer in Hall A

Proton Array (only 2004)



100 scintillator blocks

E_e=5.75 GeV

2004

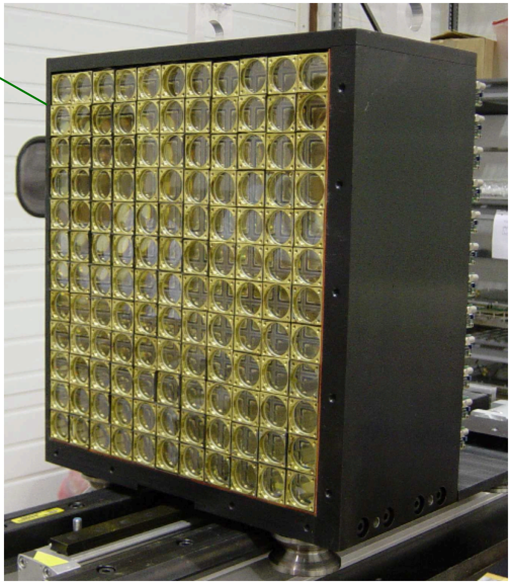
0.36	1.5
0.36	1.9
0.36	2.3

E_e=3.45, 4.55, 5.55 GeV

2010

0.36	1.5	0.52 , 0.84
0.36	1.75	0.65 , 0.79
0.36	2	0.53 , 0.72

Electromagnetic Calorimeter



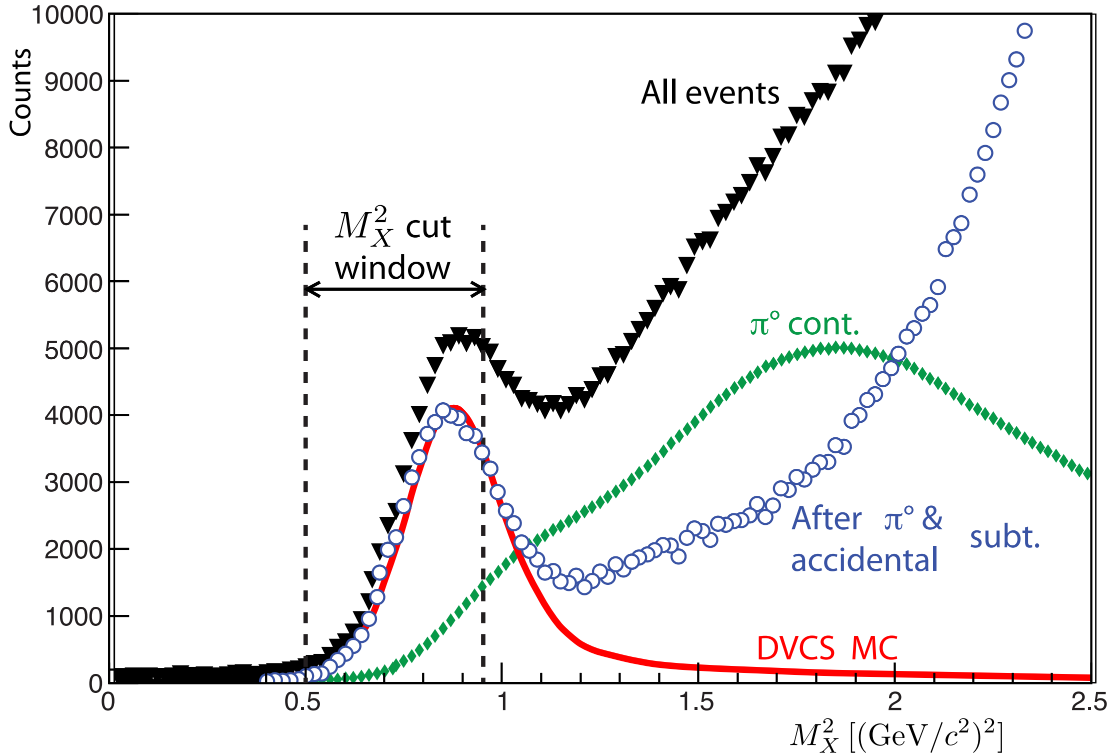
132 PbF_2 blocks
(208 in 2010)

DVCS analysis principle

Trigger formed by 1 electron in Hall A Left HRS (99% pure) + 1 cluster above 1GeV in calo

$ep \to ep\gamma$ process selected by a cut on the missing mass of the $e\gamma X$ system

Significant π^0 background subtracted using π^0 data of the very same experiment (not MC !)
Some accidentals to subtract as well (out-of-time events)



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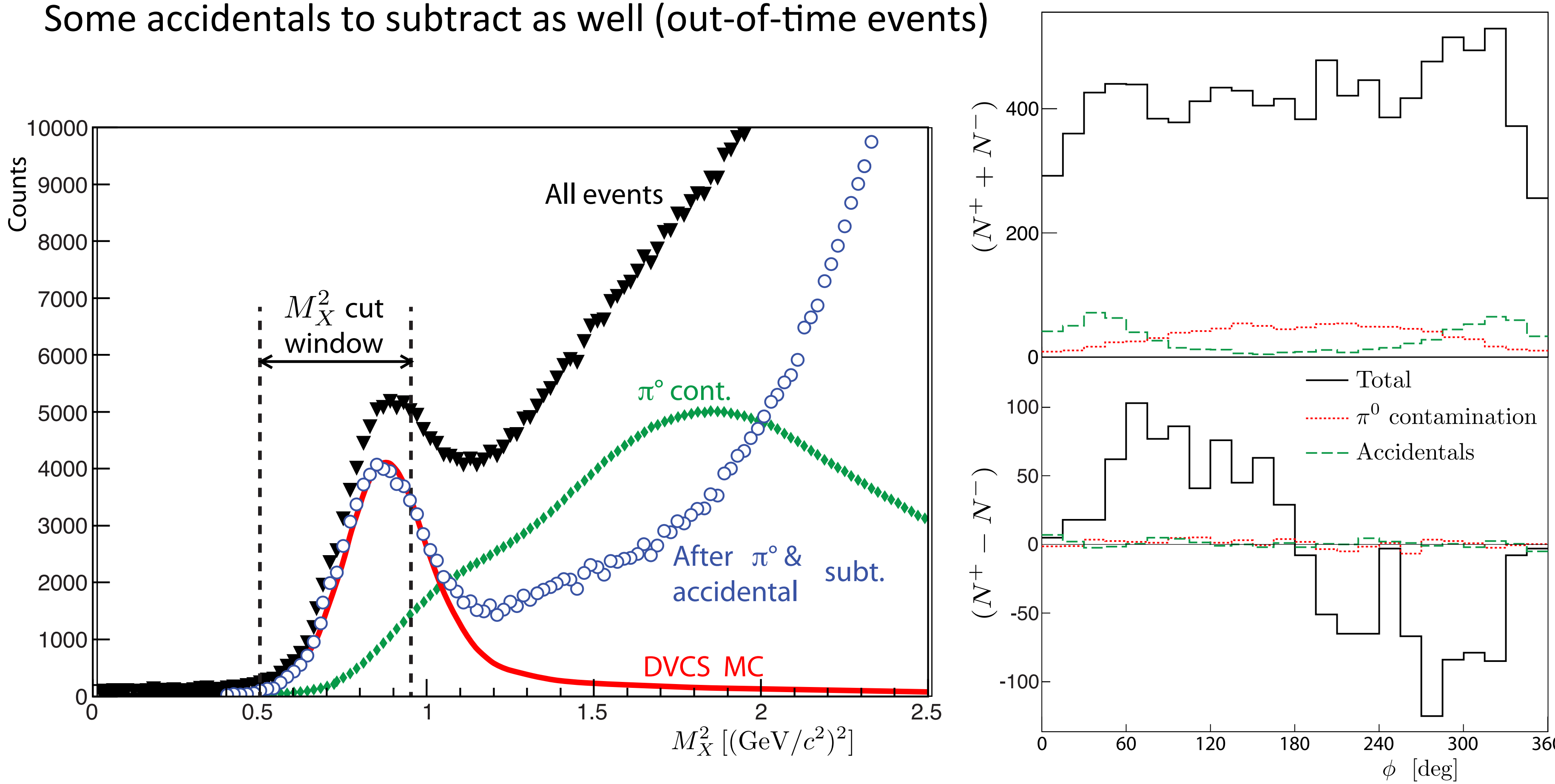
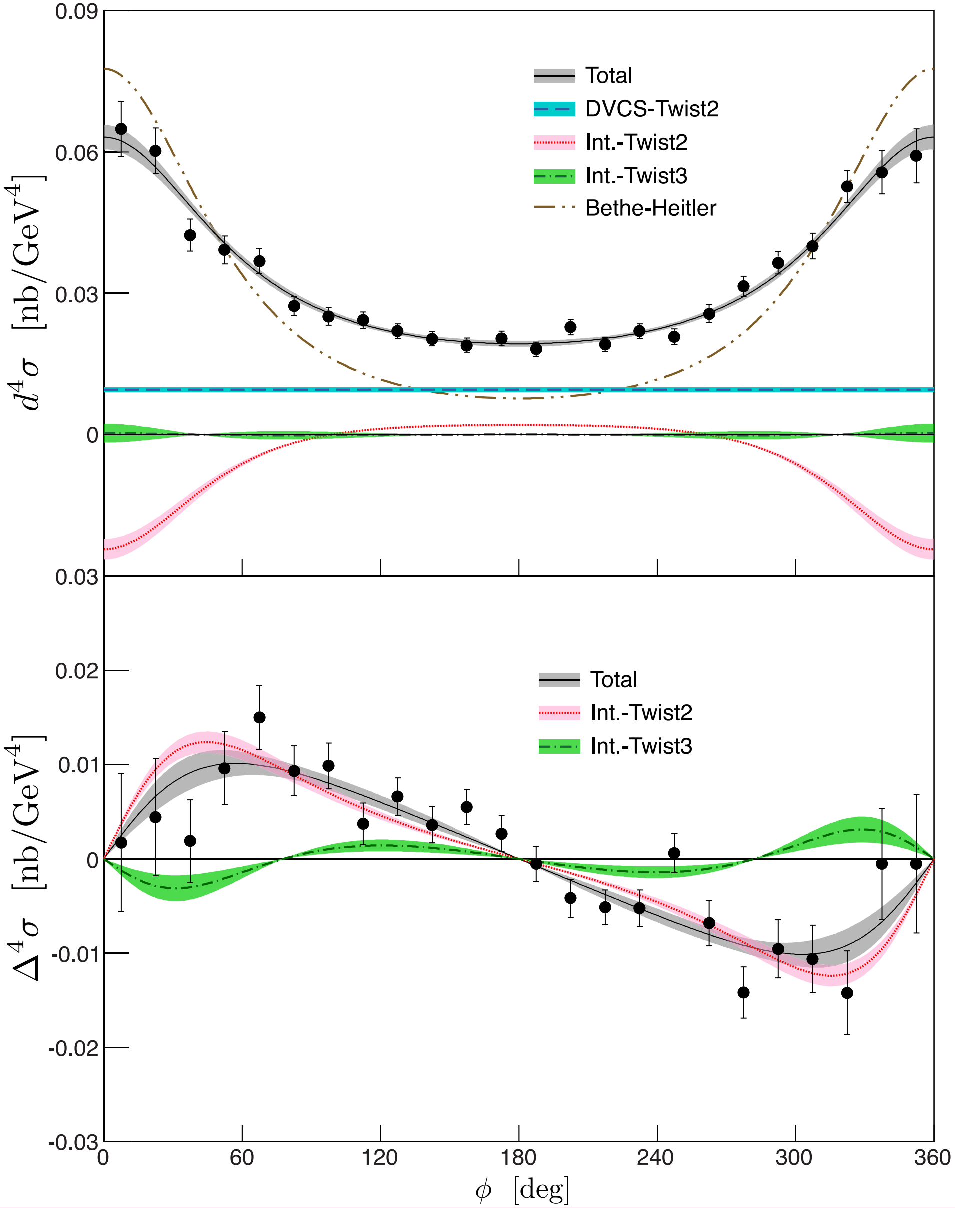


DVCS cross section extraction

$x_B = 0.37, \quad Q^2 = 2.36\ \mathrm{GeV}^2, \quad t = -0.32\ \mathrm{GeV}^2$



Extraction of CFF and cross sections :

Fit of the the harmonic structure including kinematic dep., convoluted with MC acceptance to the data (parameters = a choice of CFFs)

$$d^4\sigma = \mathcal{T}_{\mathrm{BH}}^2 + \mathcal{T}_{\mathrm{BH}}\mathcal{R}e(\mathcal{T}_{\mathrm{DVCS}}) + \mathcal{T}_{\mathrm{DVCS}}^2$$

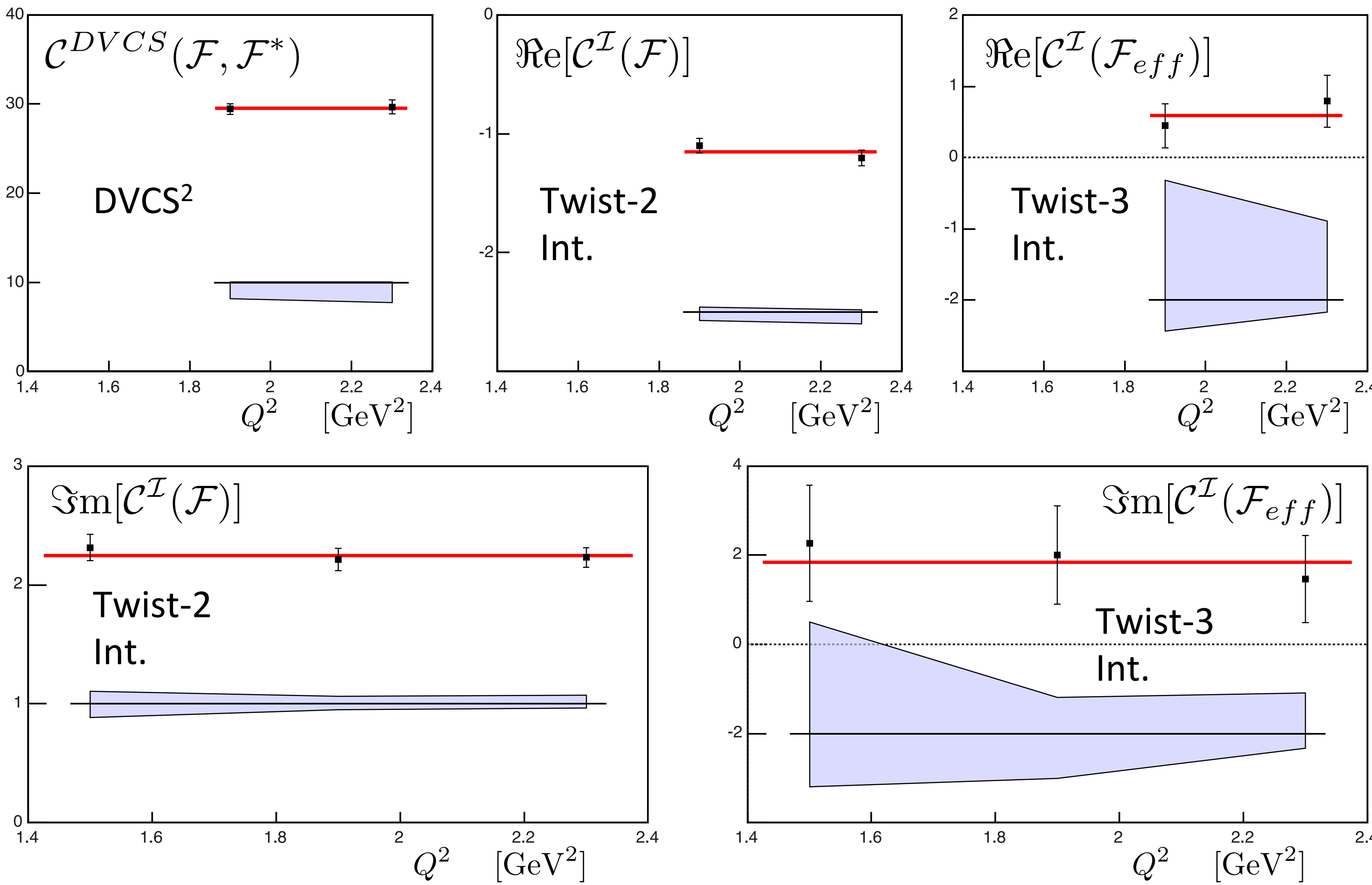
$$\mathcal{R}e(\mathcal{T}_{\mathrm{DVCS}}) \sim c_0^{\mathcal{I}} + c_1^{\mathcal{I}} \cos\phi + c_2^{\mathcal{I}} \cos 2\phi$$

$$\mathcal{T}_{\mathrm{DVCS}}^2 \sim c_0^{\mathrm{DVCS}} + c_1^{\mathrm{DVCS}} \cos\phi$$

$$\Delta^4\sigma = \frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{2} = \mathcal{I}m(\mathcal{T}_{\mathrm{DVCS}})$$

$$\mathcal{I}m(\mathcal{T}_{\mathrm{DVCS}}) \sim s_1^{\mathcal{I}} \sin\phi + s_2^{\mathcal{I}} \sin 2\phi$$

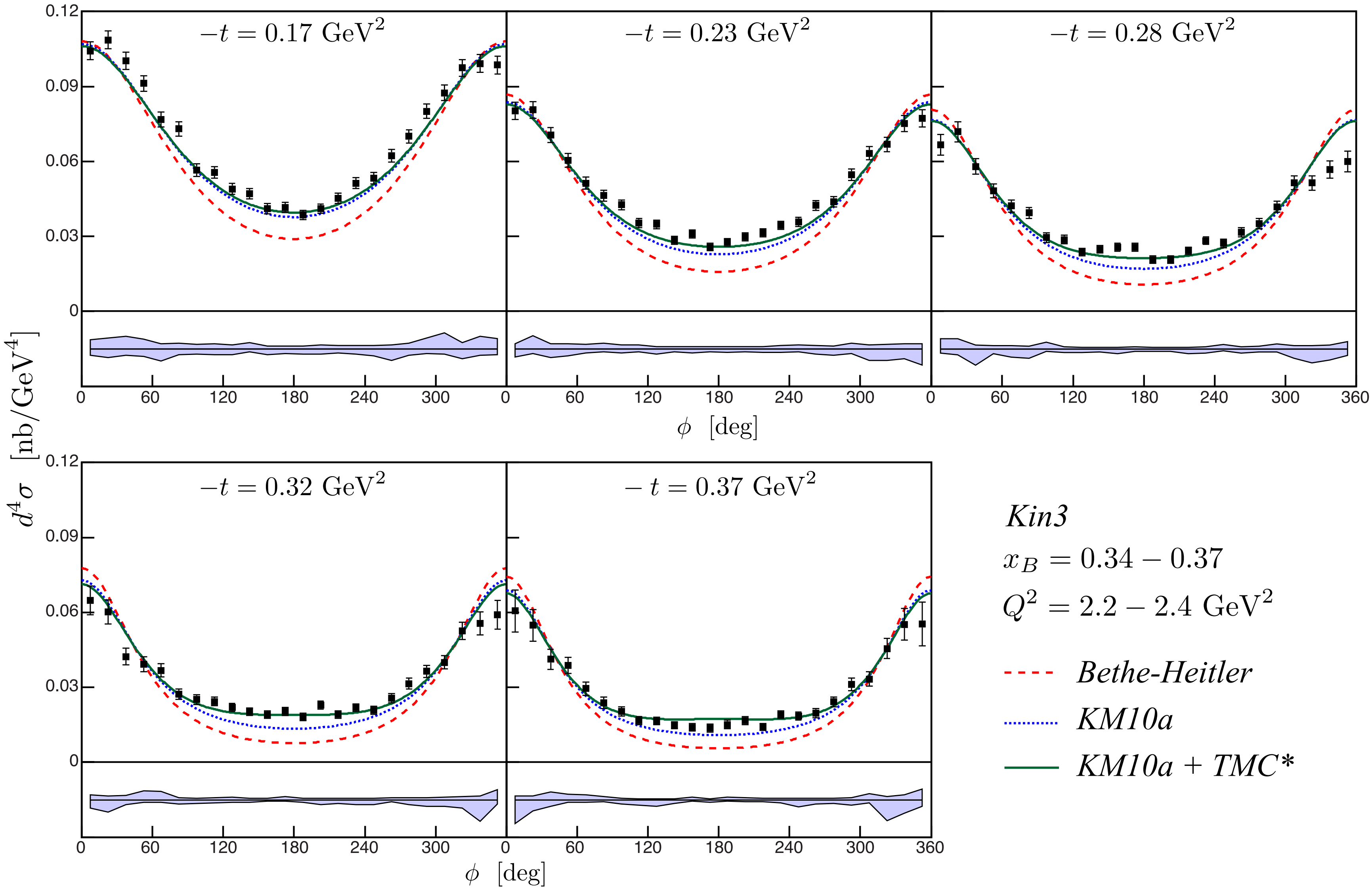
Extracted CFF versus Q^2 : scaling test



No deviation from expected Q^2-scaling observed within errors

Fit parameters from: Belitski, Mueller PRD82 074010 (2010)

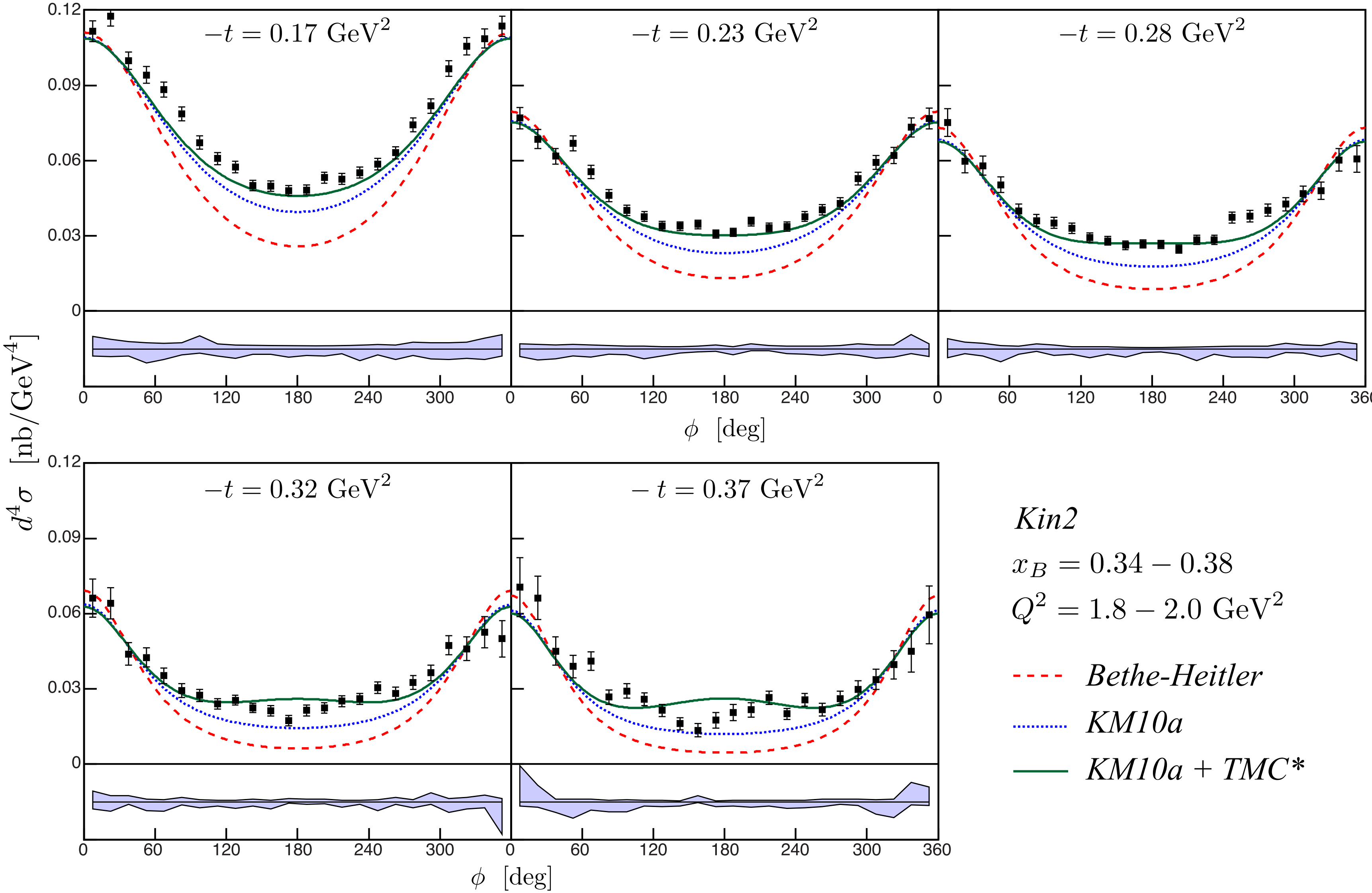
Cross sections at Q^2=2.3 GeV^2



KM10a: parametrization adjusted on HERA & CLAS asymmetries (Kumericki, Mueller, 2010)

TMC: Target-Mass Corrections (up to Twist-4) (Braun, Pirnay, Manashov, Mueller, 2014)

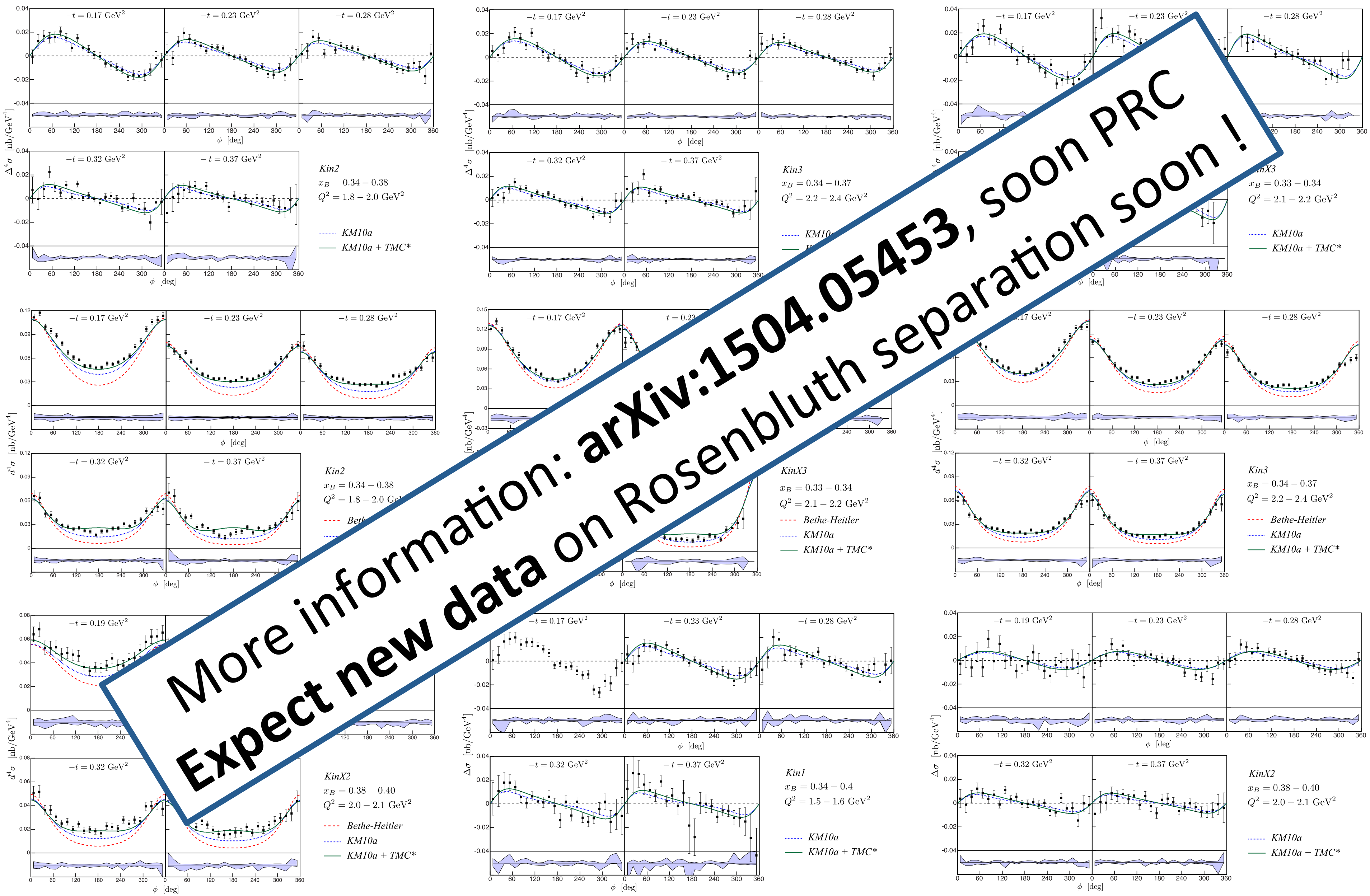
Cross sections at Q^2=1.9 GeV^2



Significant deviation from BH, significant deviation from pure Leading-Twist models

STRONG HINTS: **DVCS^2 is large**, and **higher-twists** are at play at Jefferson Lab

Most accurate DVCS cross section data set available



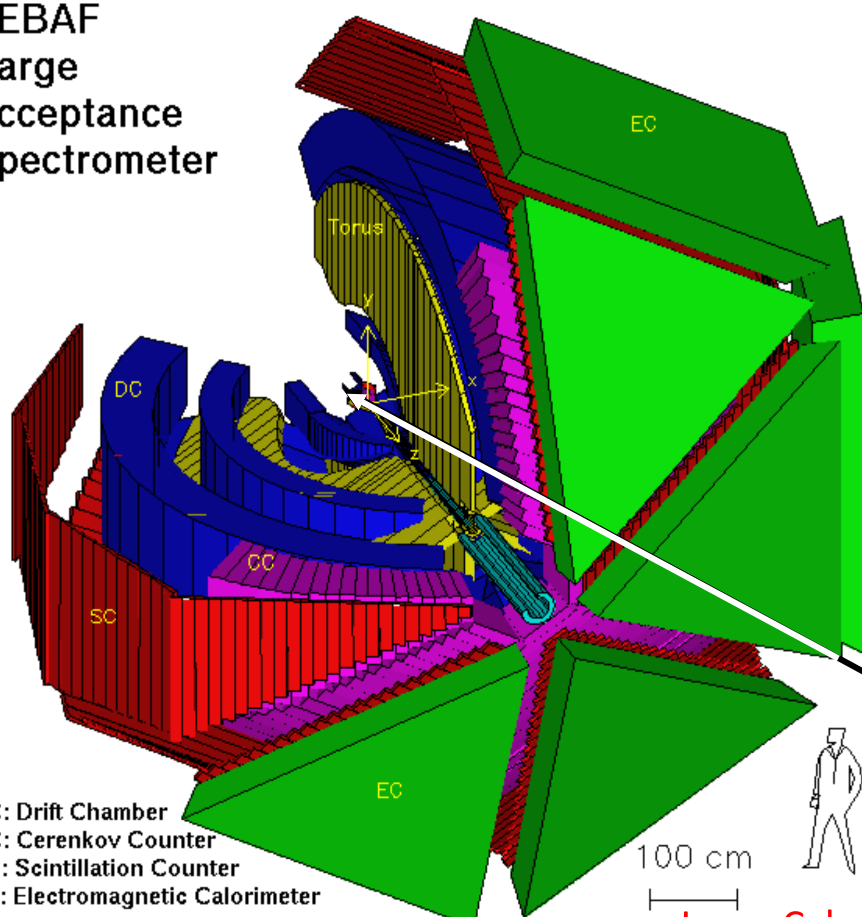
More information: **arXiv:1504.05453**, soon PRC

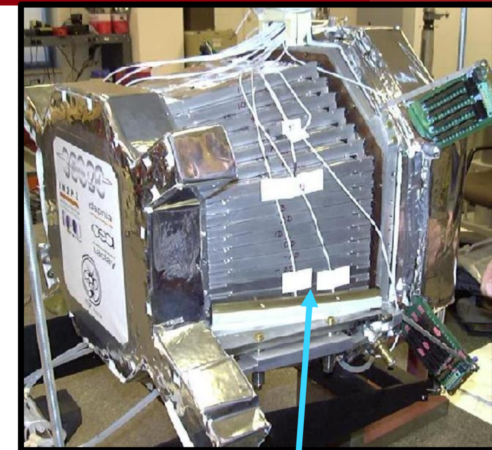
Expect new data on Rosenbluth separation soon !

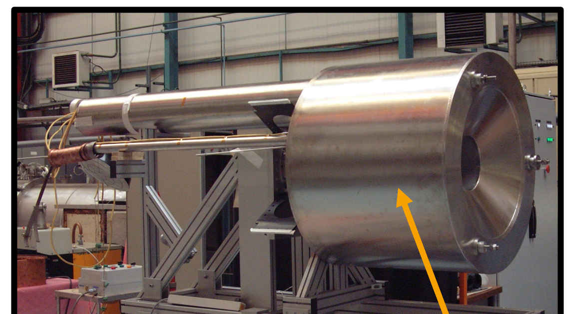
CLAS DVCS cross section analysis

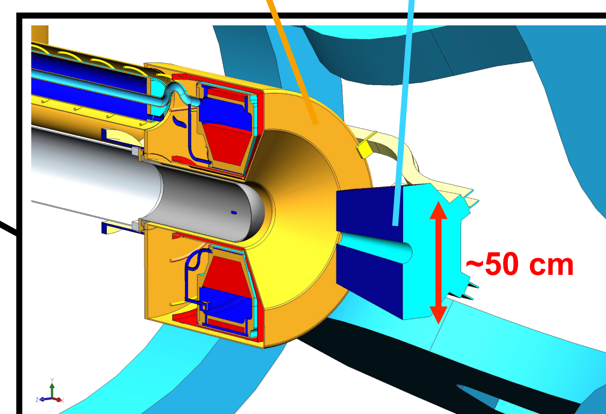
Beam energy: 5.8 GeV
Beam Polarization: 75-85%
Integ. Luminosity: 45 fb^{-1}
2nd half of data under analysis

CEBAF
Large
Acceptance
Spectrometer







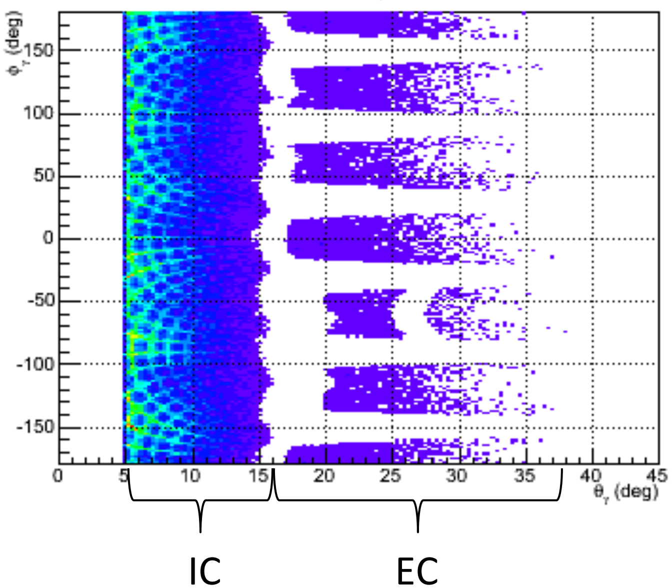


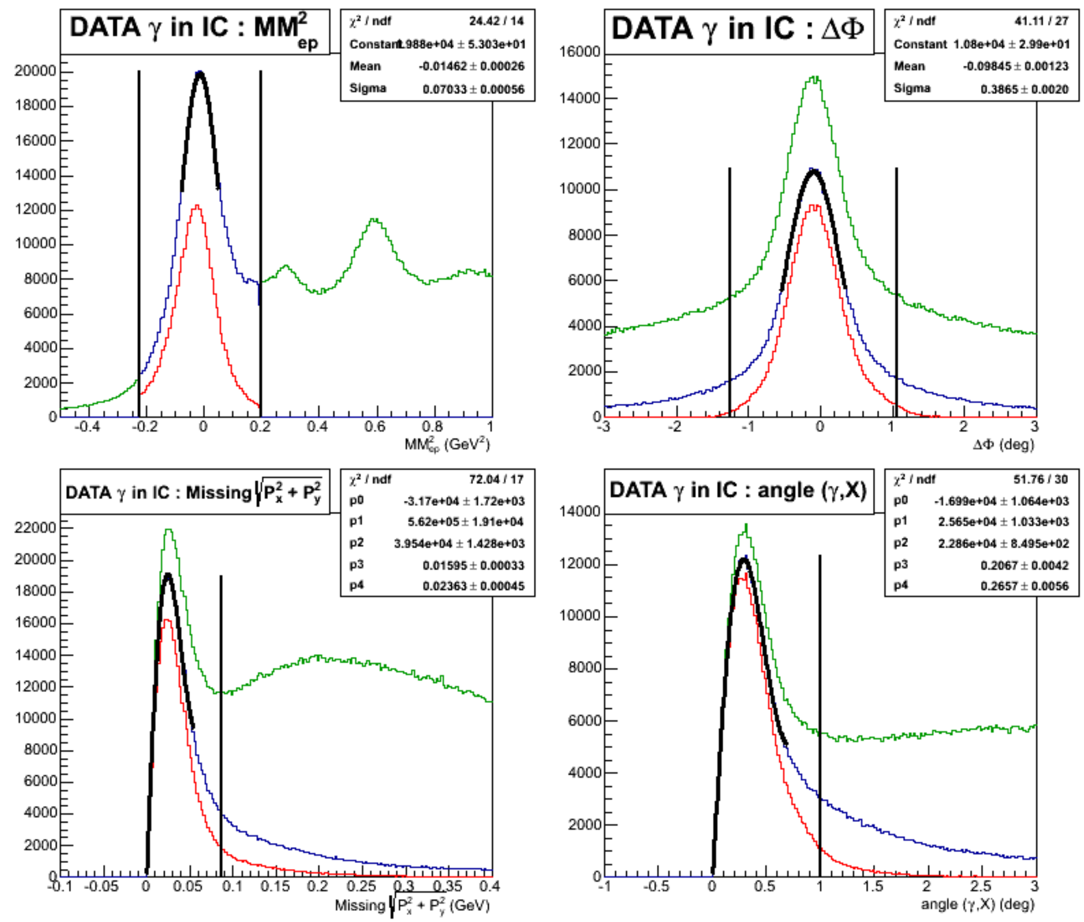
Inner Calorimeter
+ Moller shielding solenoid

CLAS DVCS cross section analysis

Trigger: 1 good electron (TOF, CC, EC)
Fully Exclusive Analysis: add 1 good proton (TOF) + 1 photon in IC or EC (no track, β≈1)

Photon : θ vs φ



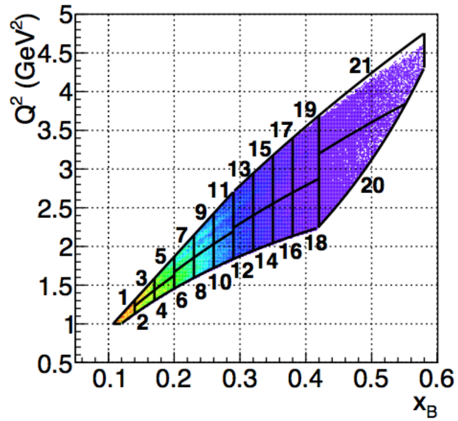


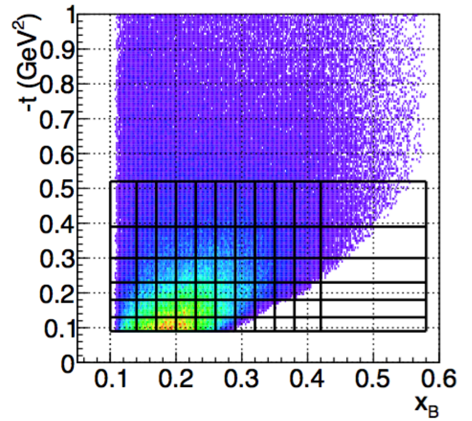
ep→epγ exclusivity cuts in the case where
the photon is detected in the IC

CLAS DVCS cross section results

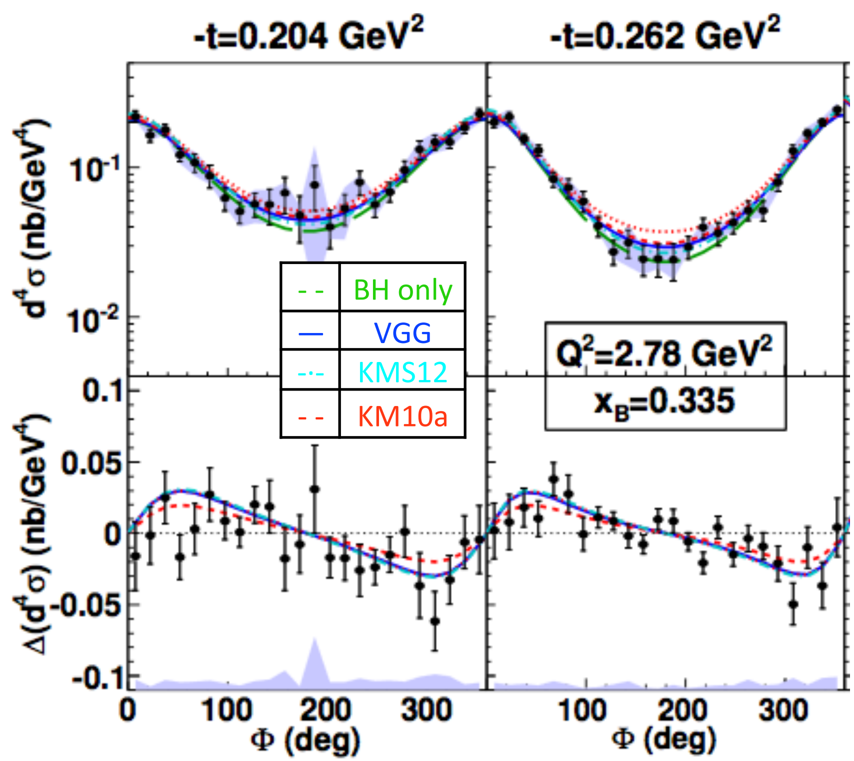
arXiv:1504.02009

110 bins !
Q^2=1 - 4.6 GeV^2
x_B = 0.1 - 0.58
-t = 0.09 - 0.52 GeV^2

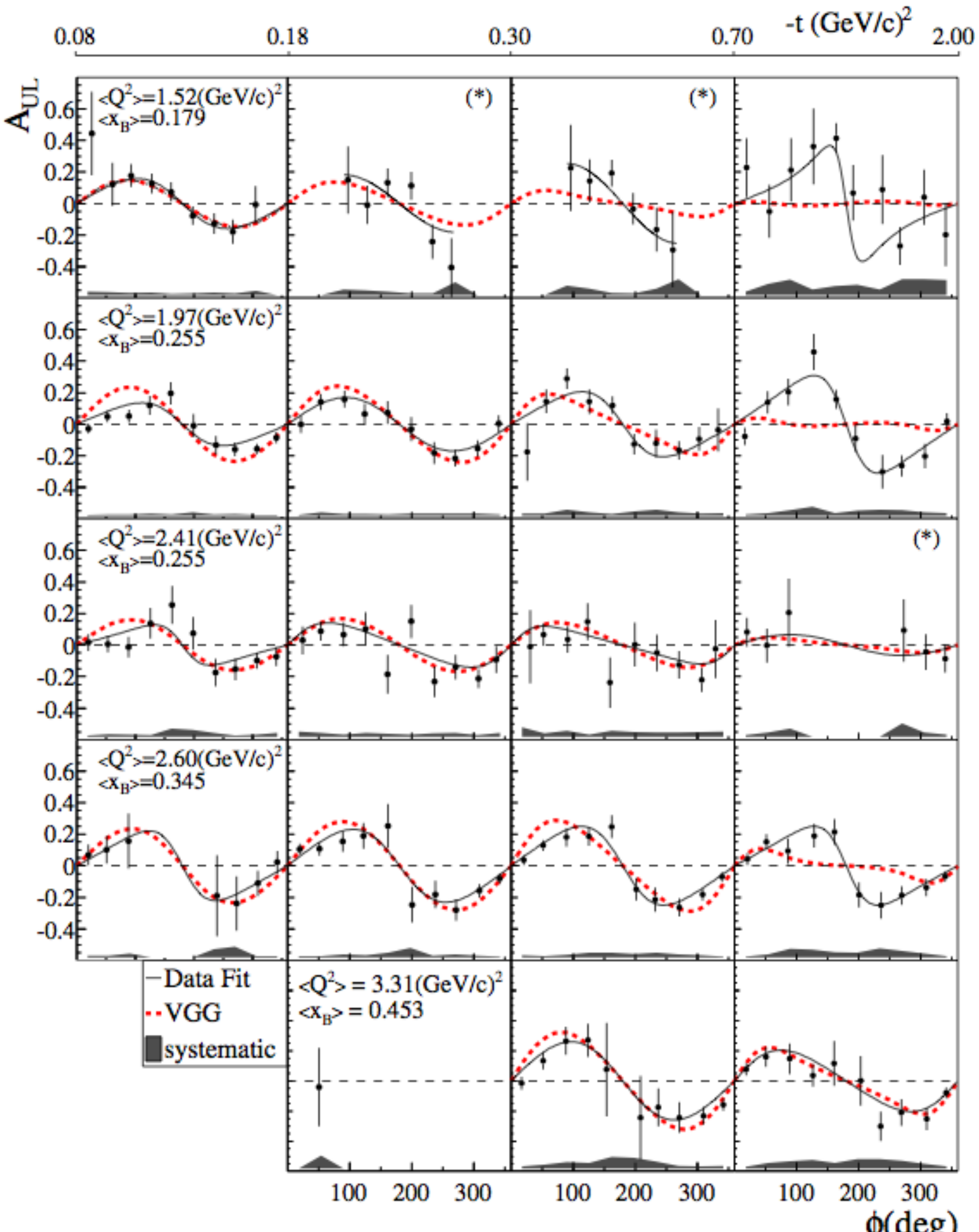




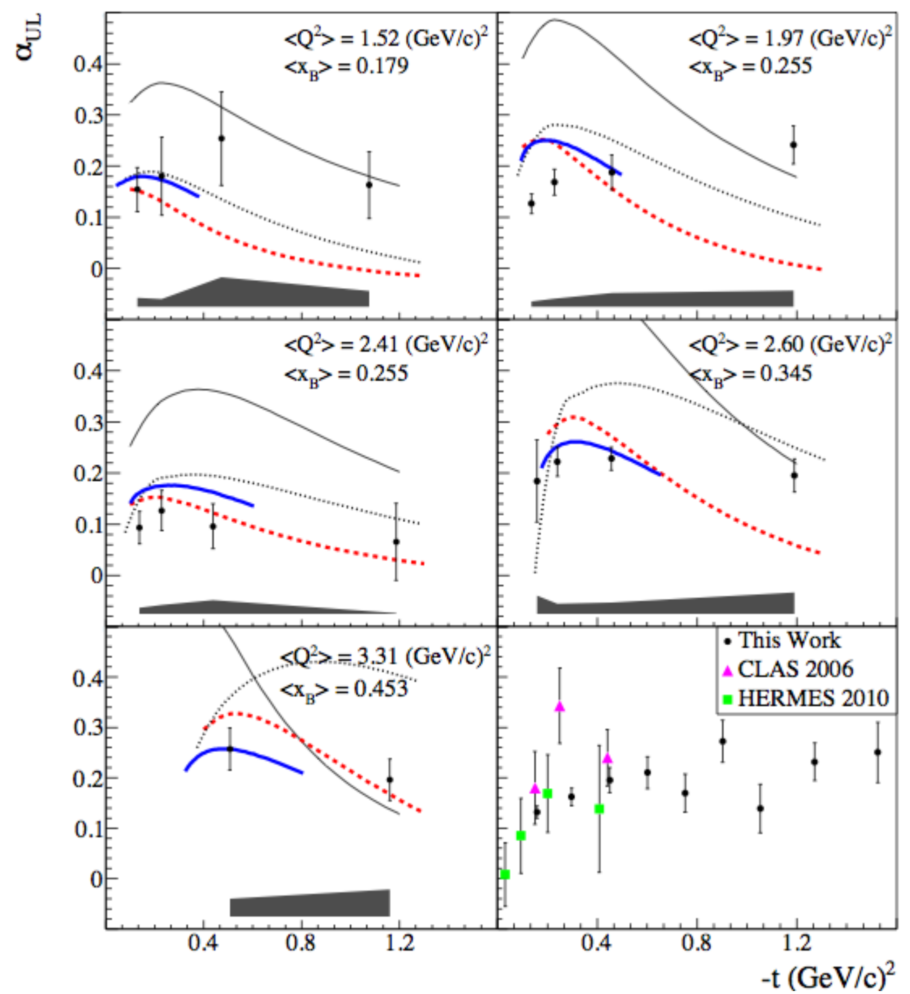
- Large kinematic domain
- Data compatible with most models
- Another ½ data set being analyzed



CLAS Target Spin Asymmetry A_{UL}



Phys. Rev. Lett. 114 (2015) 032001



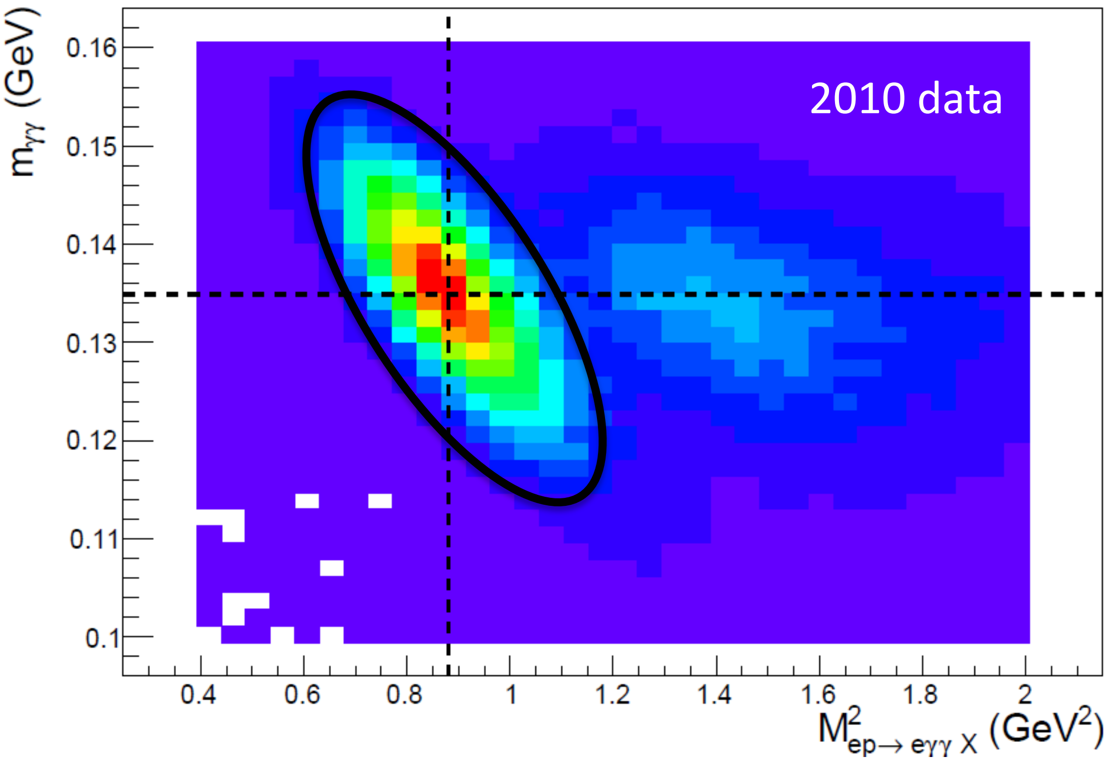
- Fair agreement with older data and DD models

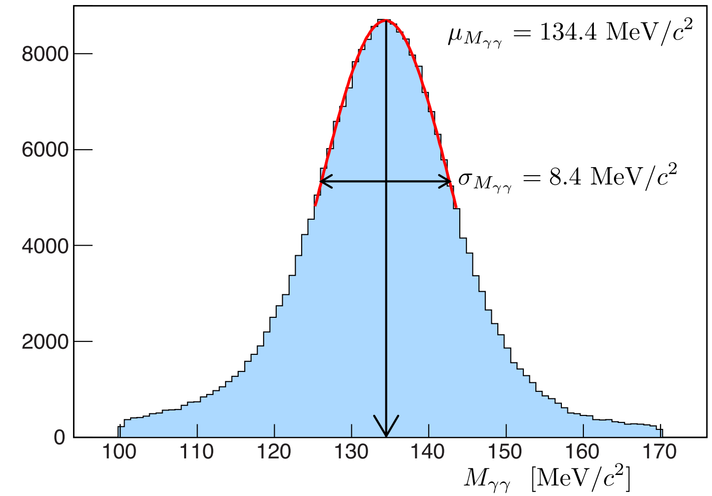
- - VGG
.... KMS12
— KMM12
— GGL

π^0 analysis principle

Inclusive electron trigger (99% pure) using Hall A Left HRS
Require two clusters in the calorimeter

$ep \to ep\pi^0$ process cleanly selected by dual cut on $\gamma\gamma$ invariant mass and *p* missing mass





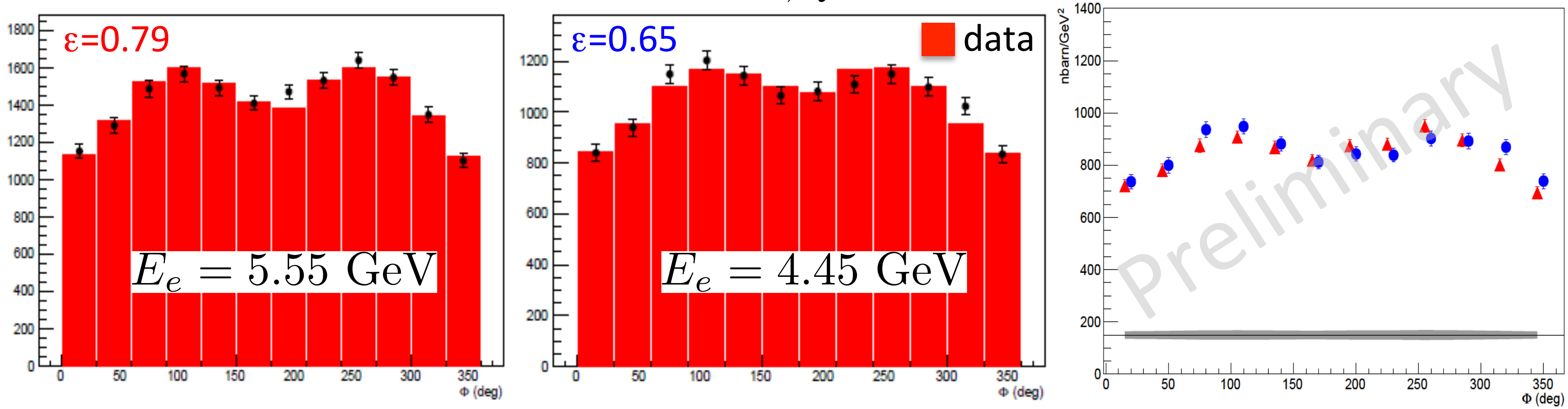
Matching of Monte-Carlo and data resolutions of utmost importance to reduce systematic uncertainties from the cuts

π^0 electroproduction cross section extraction

Extraction of all the (unpolarized) responses by a simultaneous fit to the 2 beam energies

$$\frac{d^4\sigma}{dt\,d\phi\,dQ^2\,dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi)\right]$$

$$t = -0.02\ \mathrm{GeV}^2, Q^2 = 1.75\ \mathrm{GeV}^2$$



π^0 electroproduction cross section extraction

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$$\frac{d^4\sigma}{dt d\phi dQ^2 dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi)\right]$$

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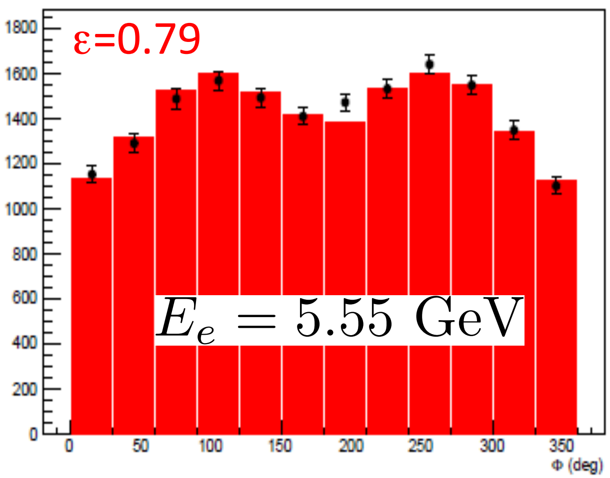
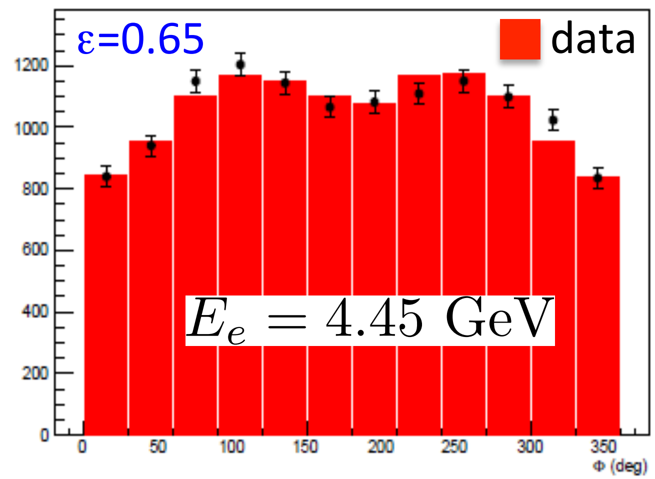
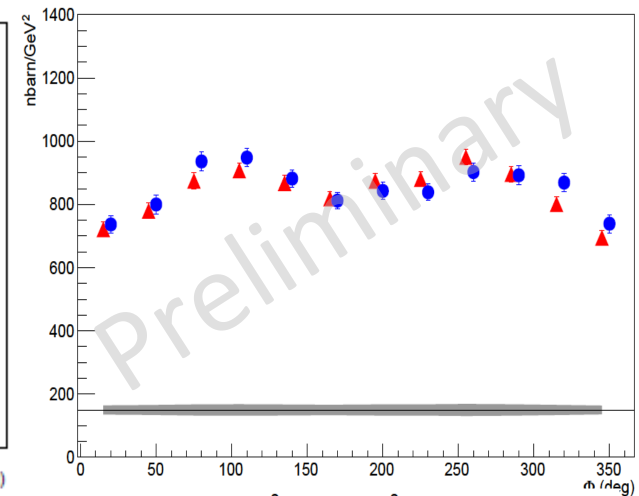
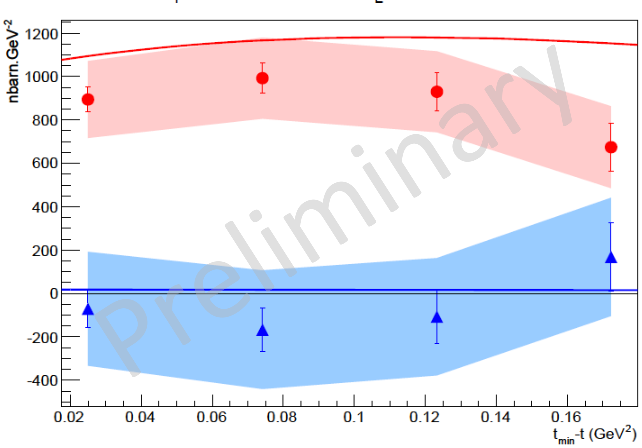


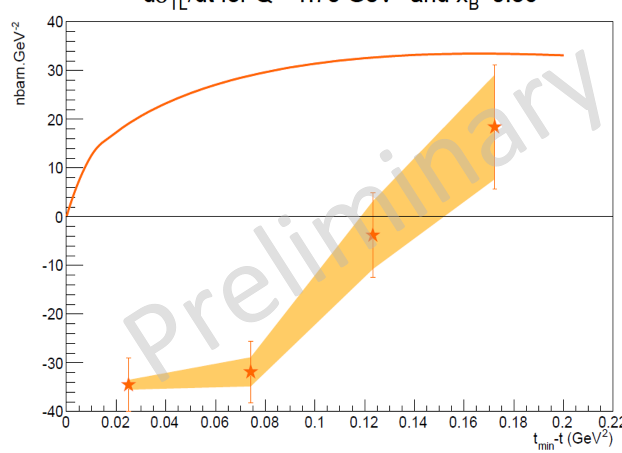




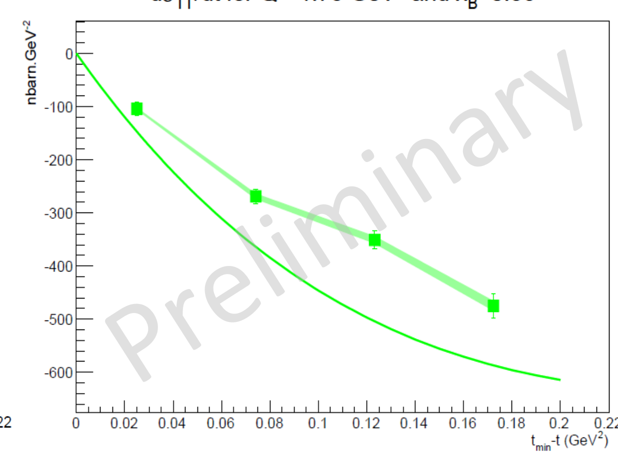
σ_T (red circle) and σ_L (blue triangle)



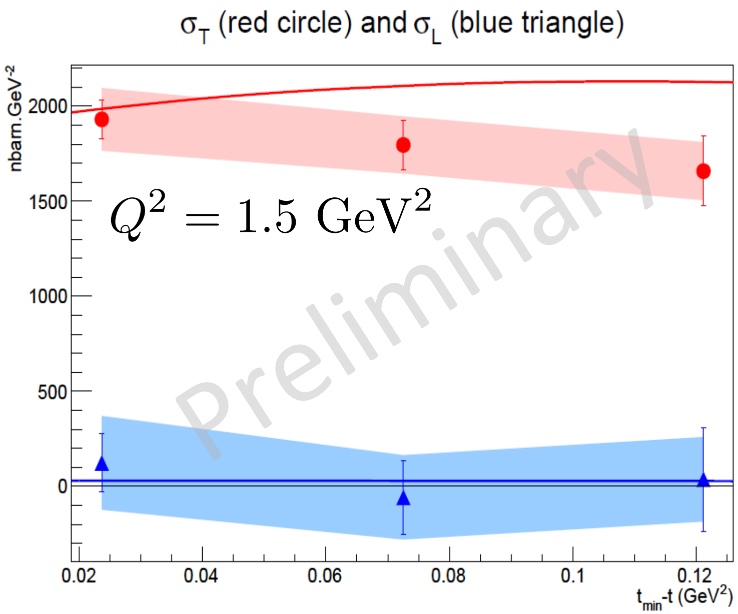
$d\sigma_{TL}/dt$ for Q^2=1.75 GeV^2 and x_B=0.36

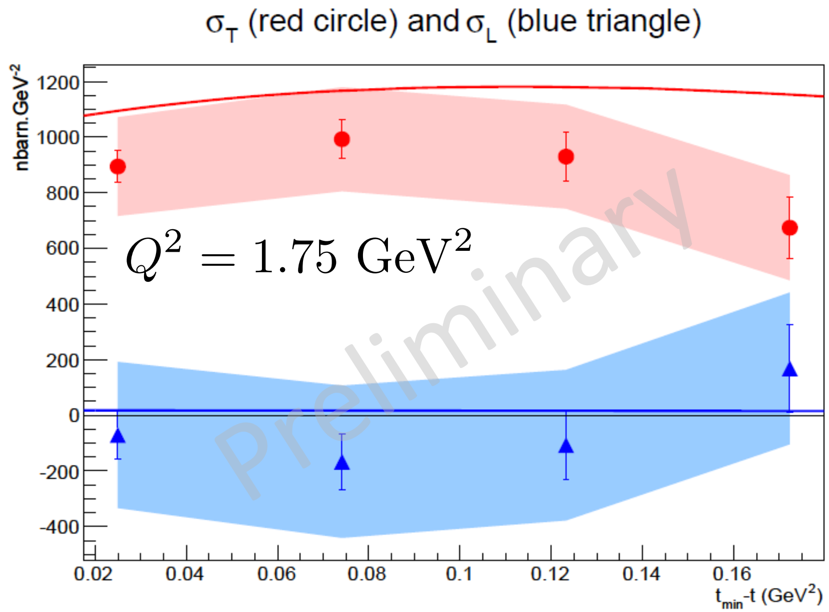


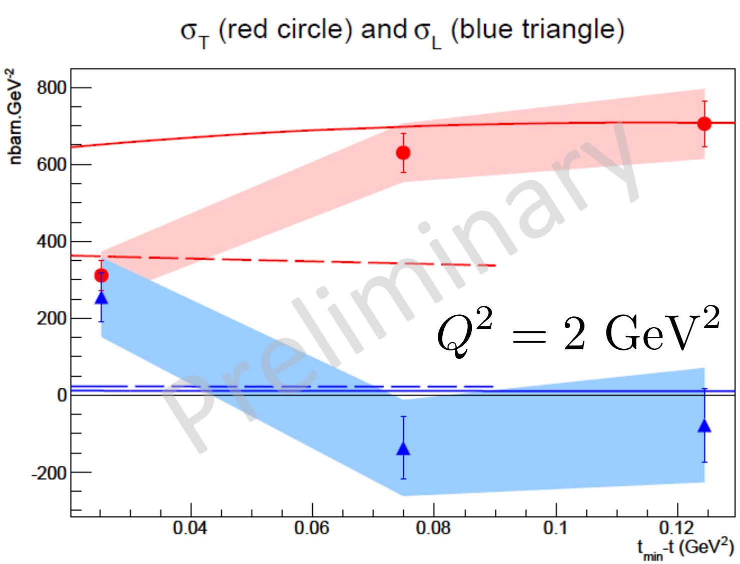
$d\sigma_{TT}/dt$ for Q^2=1.75 GeV^2 and x_B=0.36



Large dominance of transverse cross section







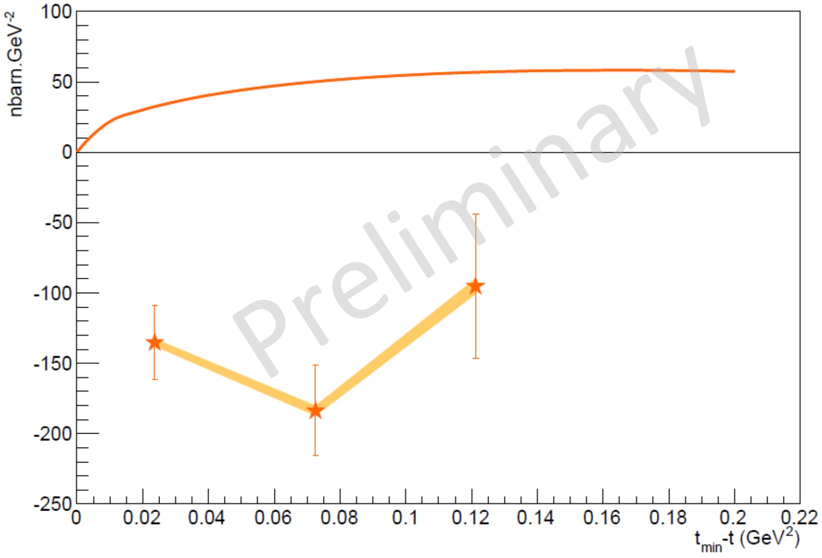
Shaded area: 2% normalization uncertainty

Solid line: GK11 model (described earlier)

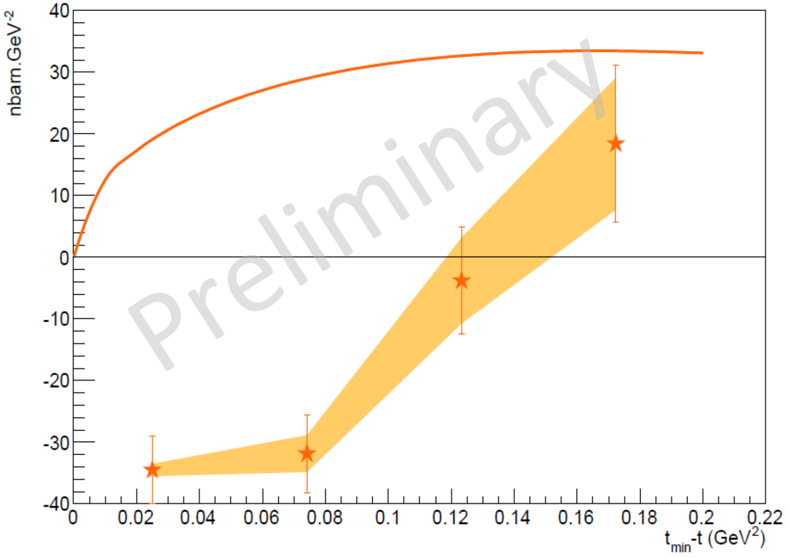
Dashed line: Goldstein-Liuti model
(waiting for updated values)

TL-interference term found with opposite sign !?

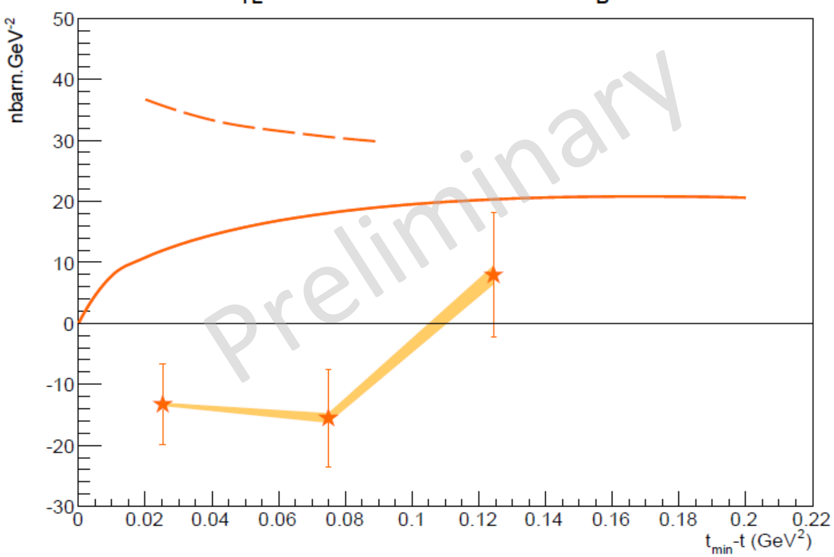
$d\sigma_{TL}/dt$ for Q^2=1.5 GeV^2 and x_B=0.36



$d\sigma_{TL}/dt$ for Q^2=1.75 GeV^2 and x_B=0.36



$d\sigma_{TL}/dt$ for Q^2=2 GeV^2 and x_B=0.36

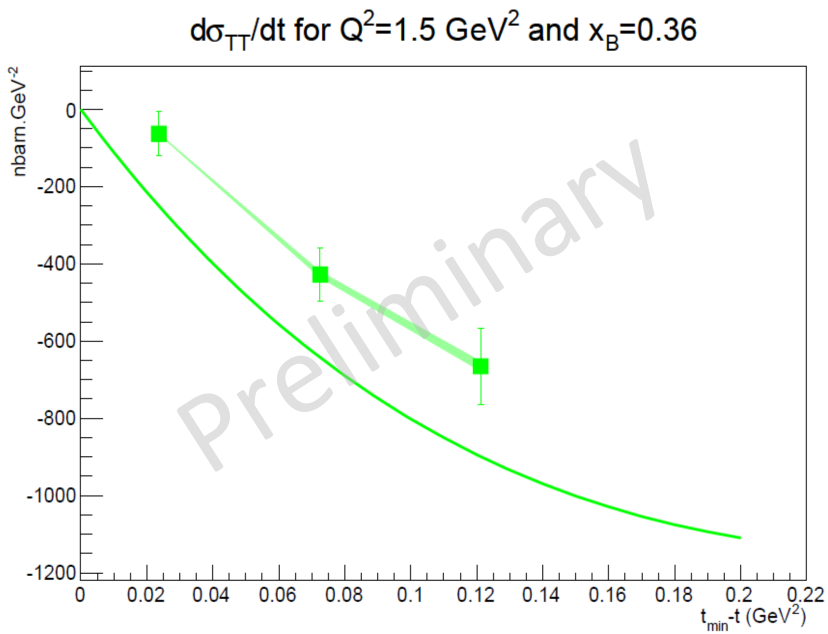


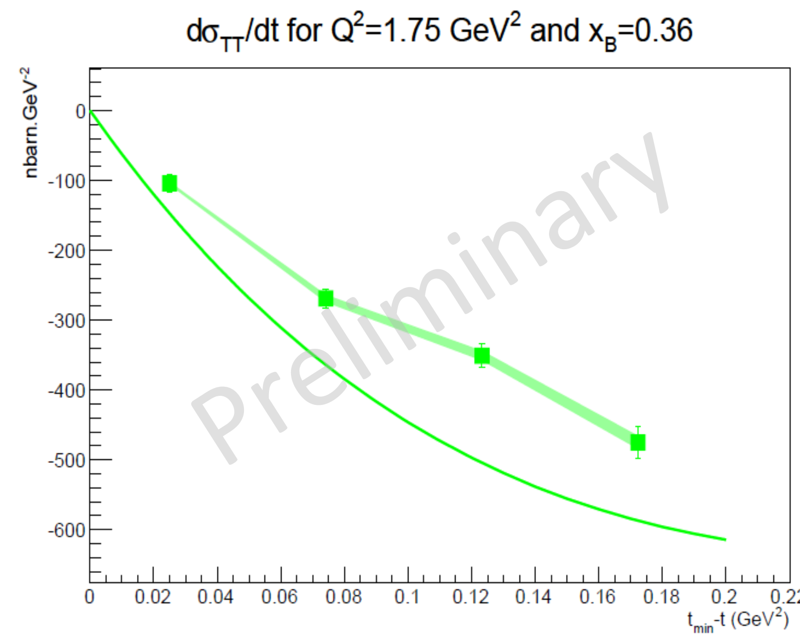
Shaded area: 2% normalization uncertainty

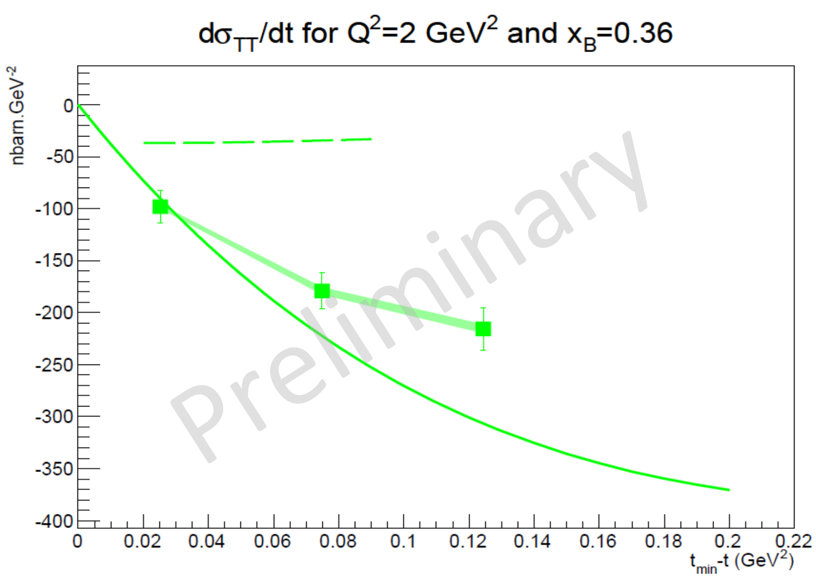
Solid line: GK11 model (described earlier)

Dashed line: Goldstein-Liuti model
(waiting for updated values)

TT-interference term found large







Shaded area: 2% normalization uncertainty

Solid line: GK11 model (described earlier)

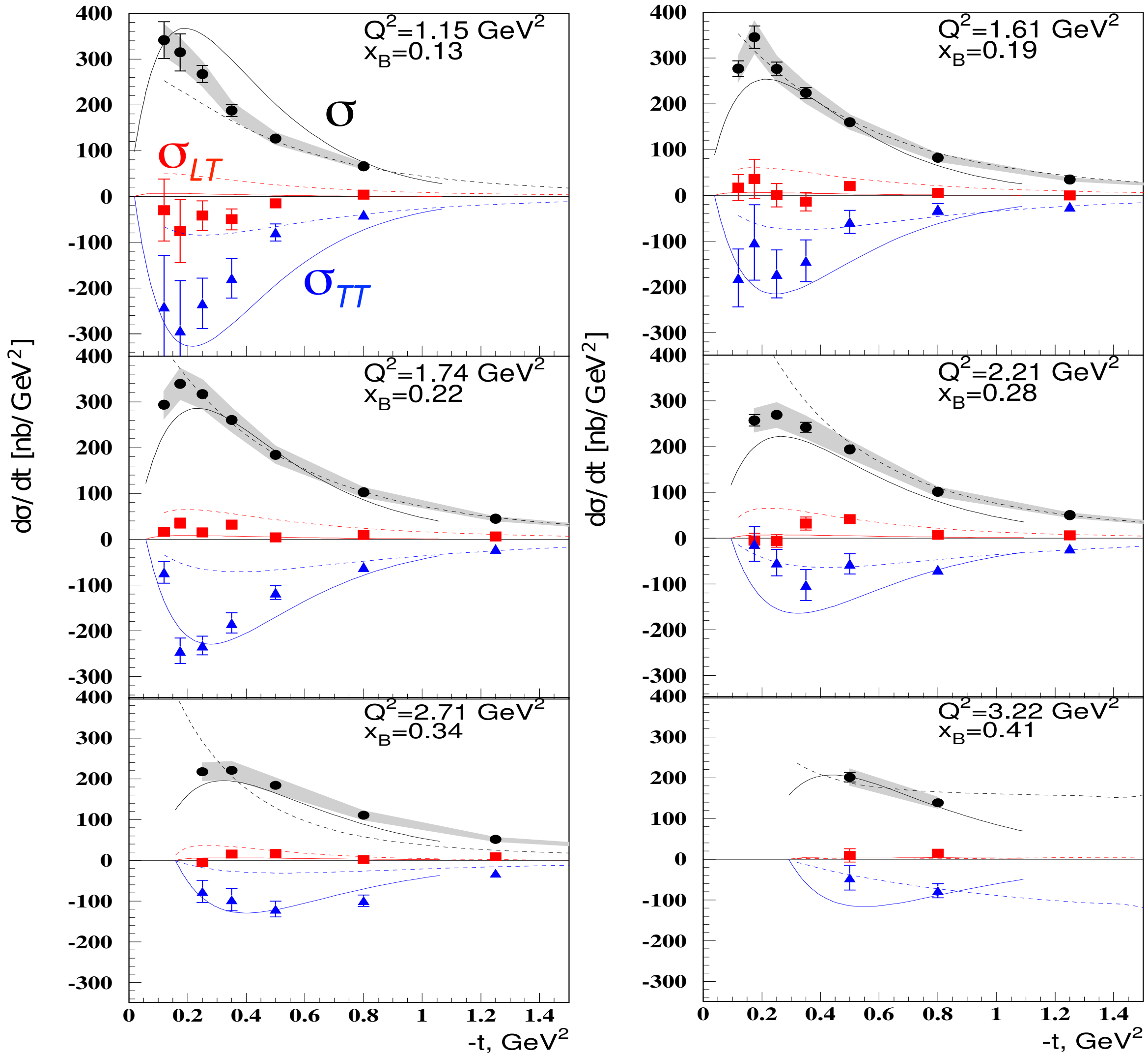
Dashed line: Goldstein-Liuti model
(waiting for updated values)

CLAS π^0 electroproduction results (un-separated)

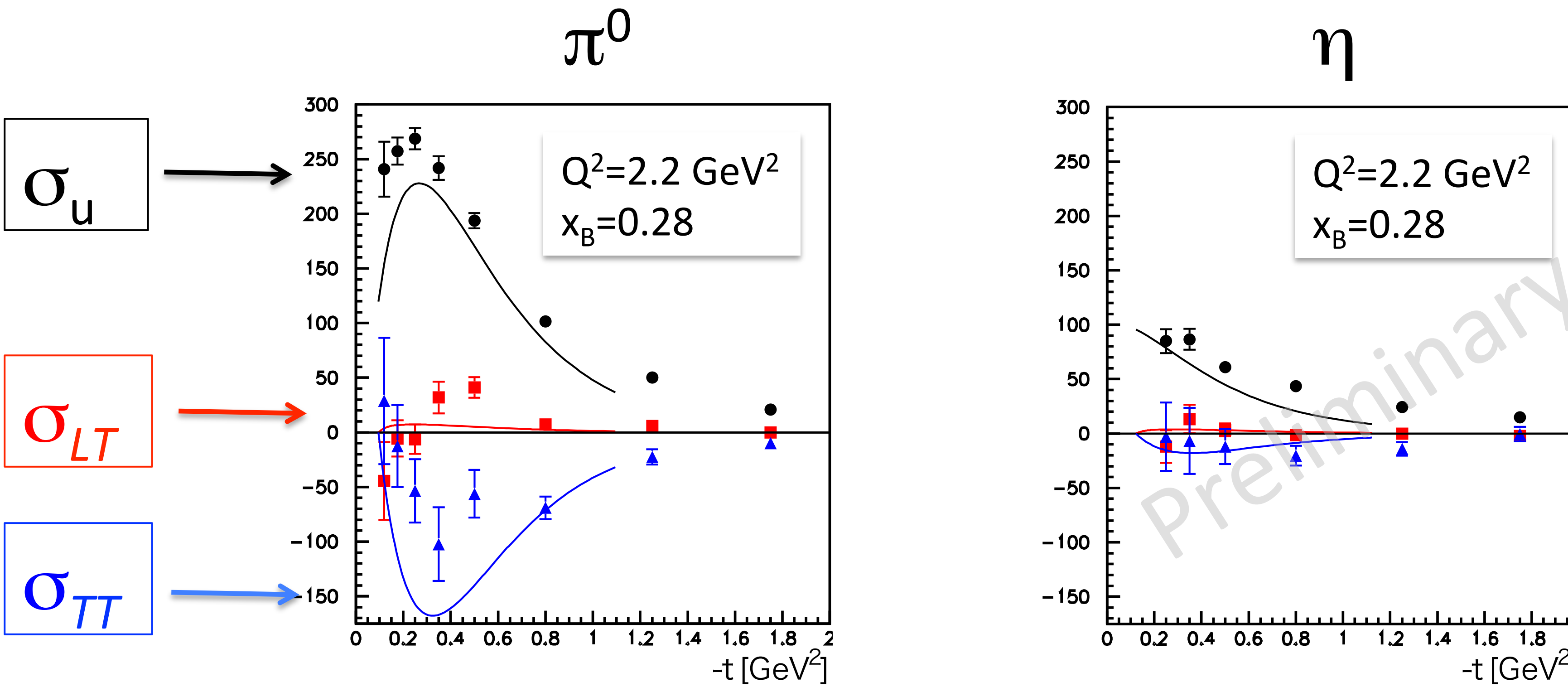
> Data set in large kinematical domain

> Large cross section,
  Large TT interference term

> Compatible with Hall A results



CLAS Preliminary η electroproduction results

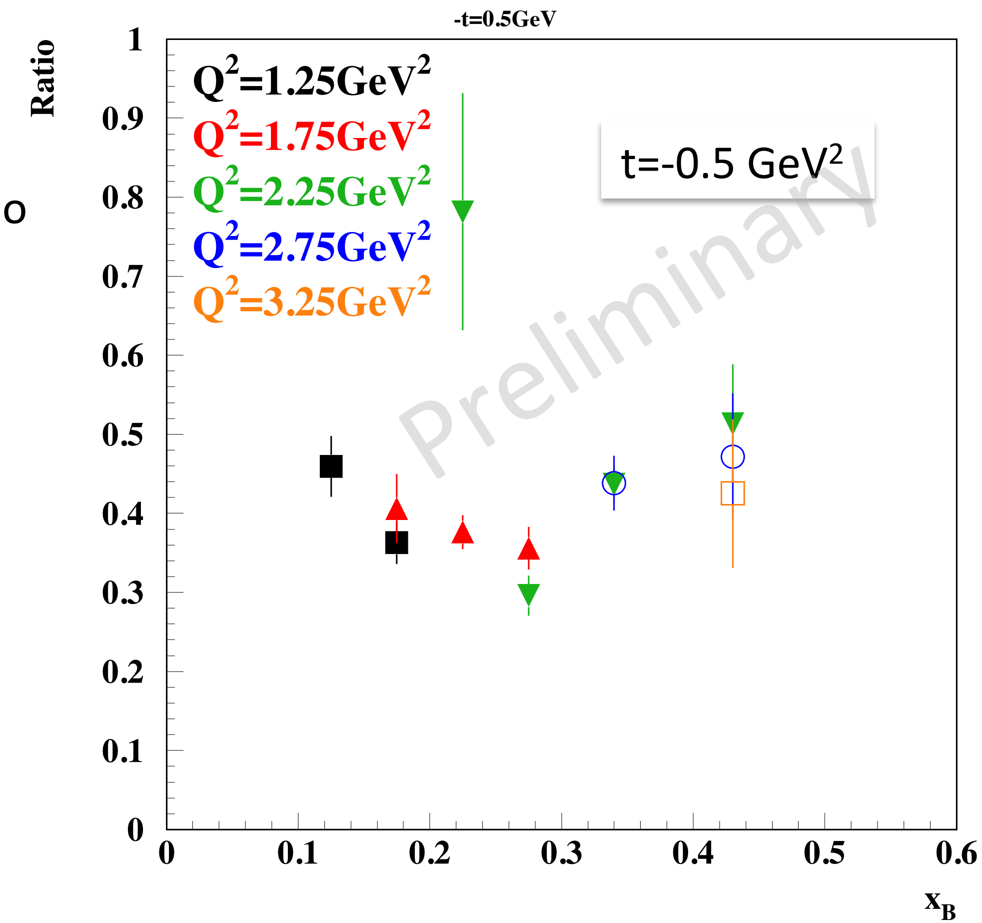


- $\sigma_U=\sigma_T+\varepsilon\sigma_L$ drops by a factor of 2.5 for η
- σ_{TT} drops by a factor of 10
- The GK GPD model (curves) follows the experimental data
- Global consistency with π^0 and η results very satisfying

CLAS Preliminary η/π^0 ratio

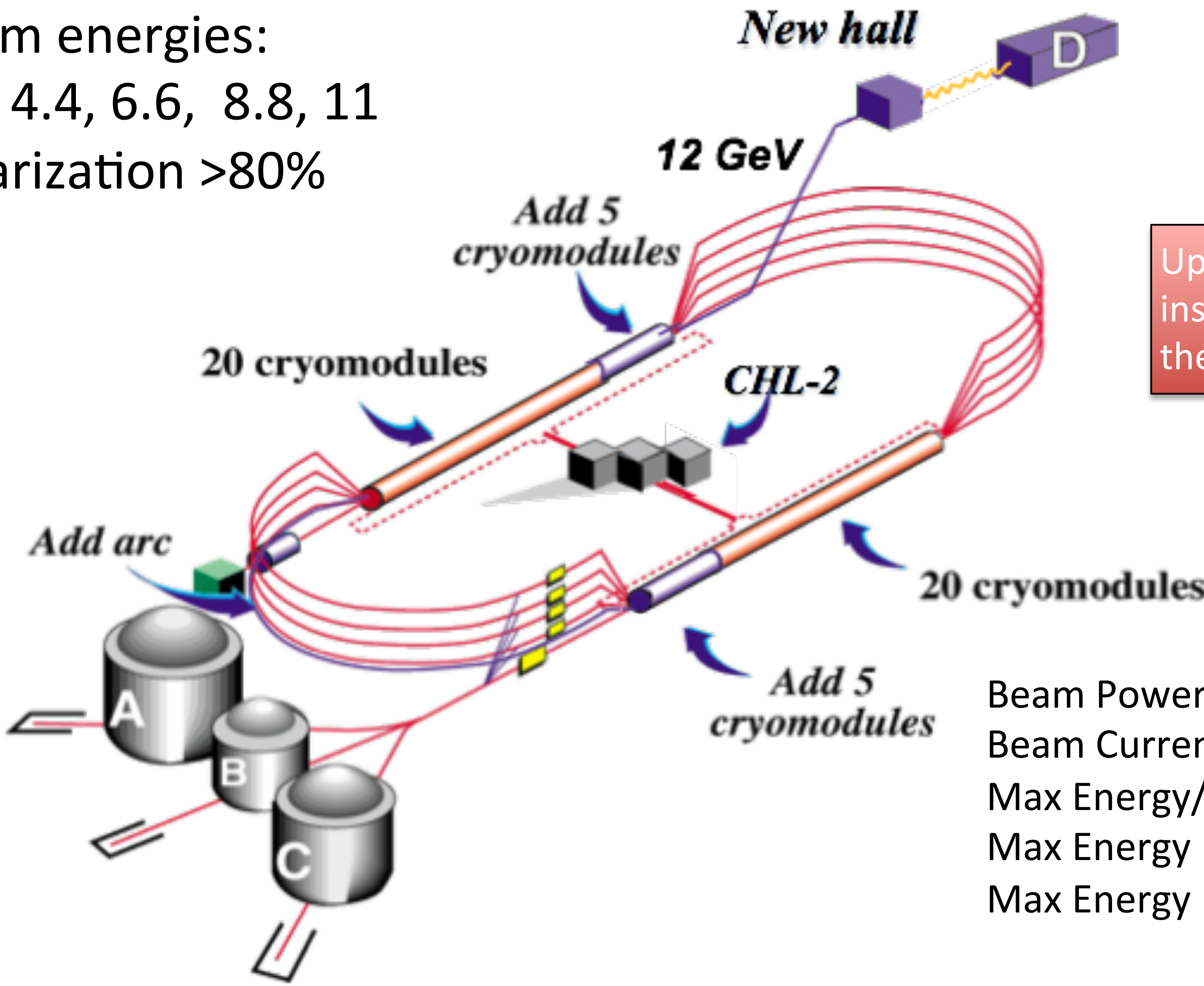
$$\frac{\sigma(ep \to ep\eta)}{\sigma(ep \to ep\pi^0)}$$

- The dependence on x_B and Q^2 is very weak.
- Chiral odd GPD models predict this ratio to be ~1/3 at CLAS kinematics
- Chiral even GPD models predict this ratio to be around 1 (at low $-t$).



Jefferson Lab upgrade to 12GeV

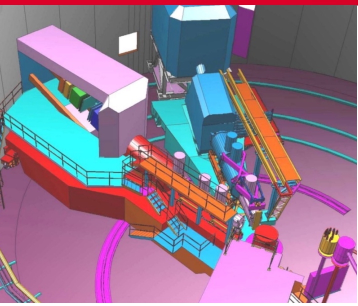
Beam energies:
2.2, 4.4, 6.6, 8.8, 11
Polarization >80%



Upgrade of the instrumentation in the three Halls

Beam Power: 1MW
Beam Current: 90 µA
Max Energy/pass: 2.2 GeV
Max Energy Hall A-B-C: 11 GeV
Max Energy Hall D: 12 GeV

Pinning down the valence GPDs at JLab12

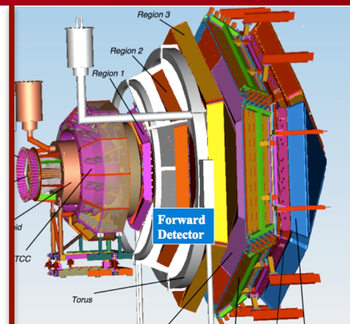


Halls A & C

Precision measurements

Very high Q^2 and x_B

Rosenbluth separation

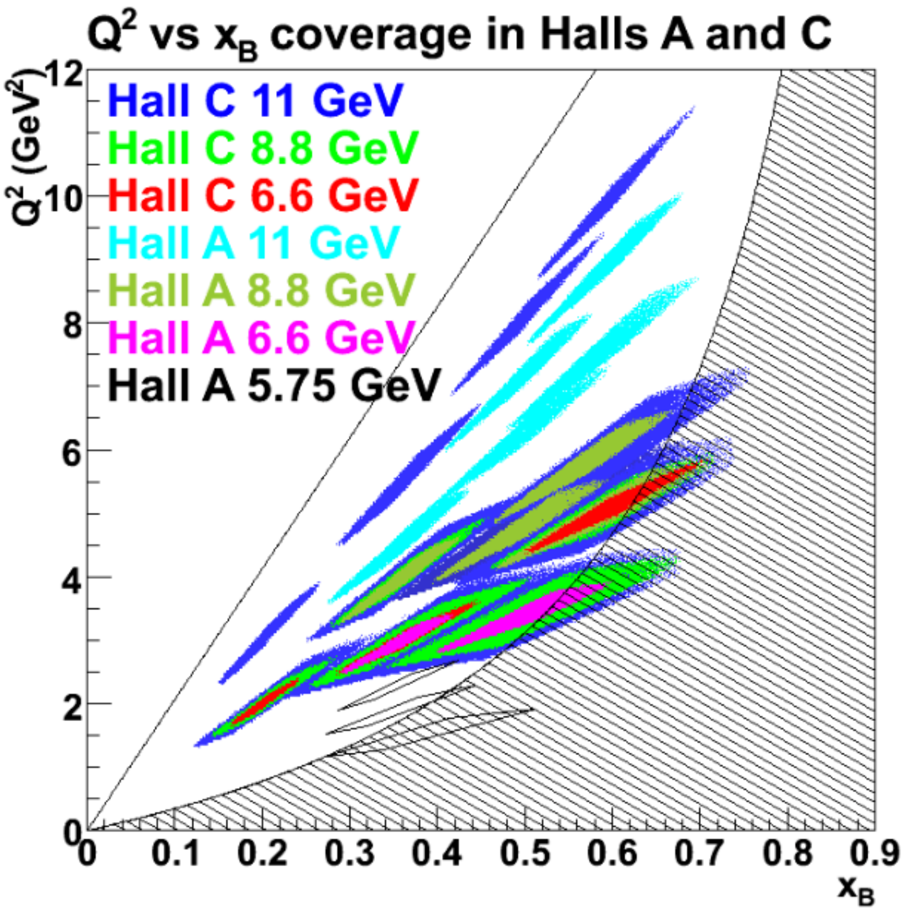


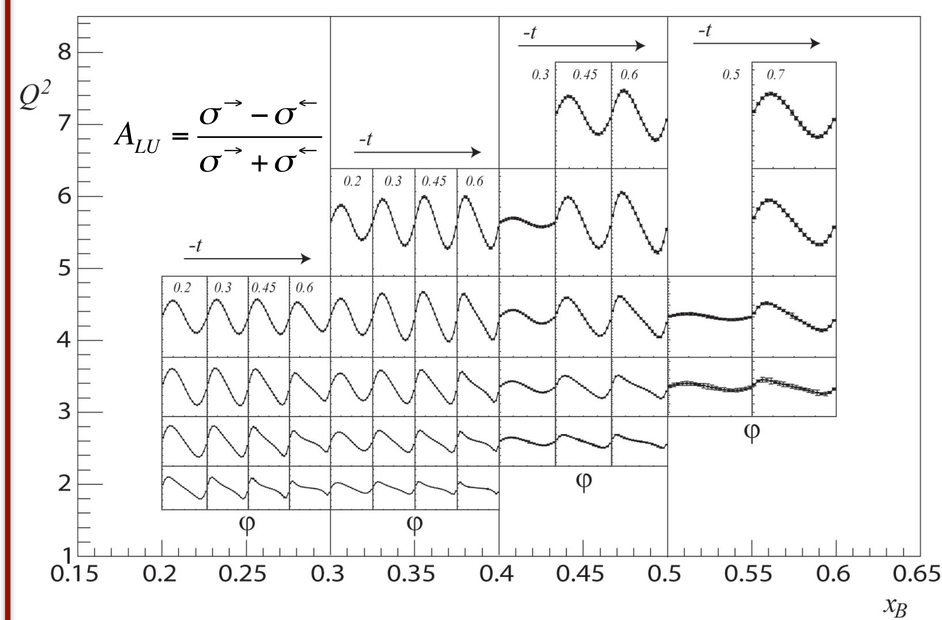
Hall B CLAS12

Large kinematical range

Polarized targets (L/T)

Nuclear targets





Summary and Conclusion

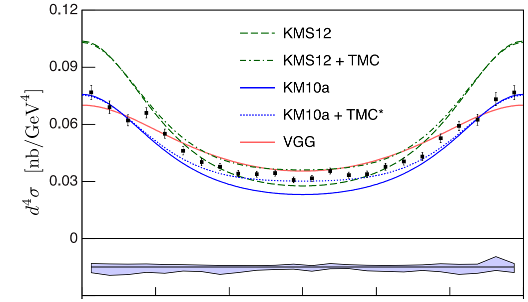
- Exciting times for DVCS in the valence region :

  New analysis of 2004 Hall A DVCS data

  → Strong hint of a significant DVCS² and *Higher-Twist* contributions

  New DVCS cross section data from CLAS

  All these data will have a **huge** impact on global fits



- More data expected **soon** from Hall A 2010 data:

  Rosenbluth study to confirm large DVCS²

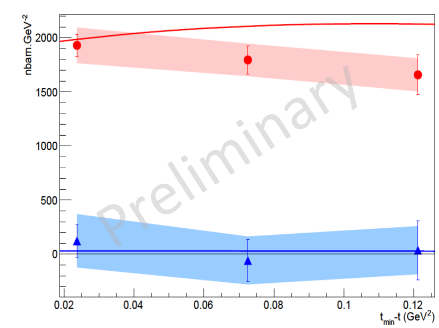
- Finally, Hall A gave **proof** that transverse π^0 cross section is dominant

  Consistent π^0 data from Hall A and CLAS (+ η)

  Cross sections are well described by GK model using

  Transversity GPDs and *Twist-3* pion wave function

  → Direct access to the elusive chiral-odd GPDs



- An **exciting future** ahead

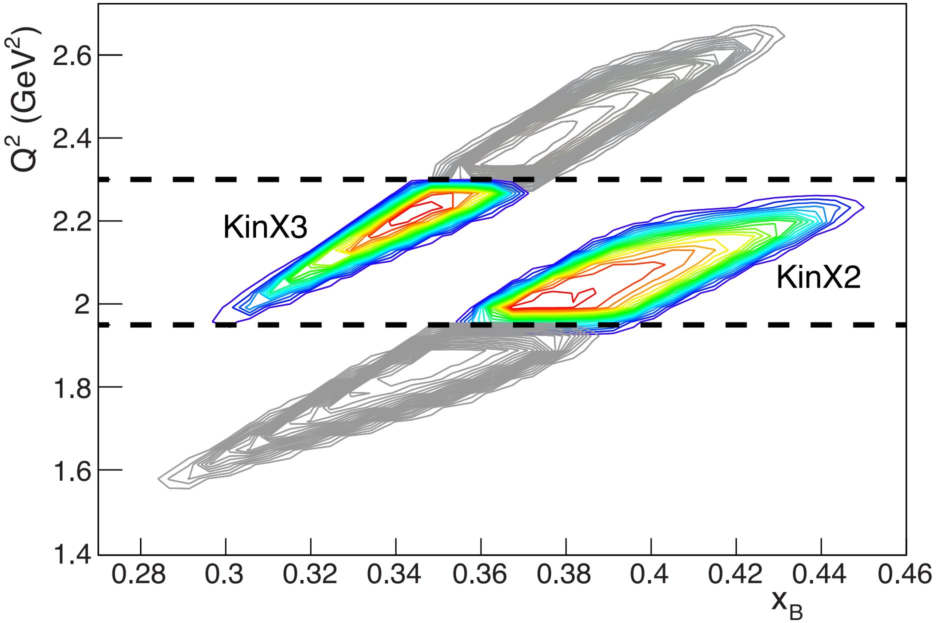
  12 GeV experiments at JLab A/B/C (Hall A experiment already started)

  and then an exciting program at EIC to pin down gluon/sea quark GPDs

Backup

New analysis of 2004 data

PhD Student : Maxime Defurne (CEA Saclay)



2004 analysis kinematics

Kin	Q^2 (GeV^2)	x_B
1	**1.5**	0.36
2	**1.9**	0.36
3	**2.3**	0.36

Additional kinematics

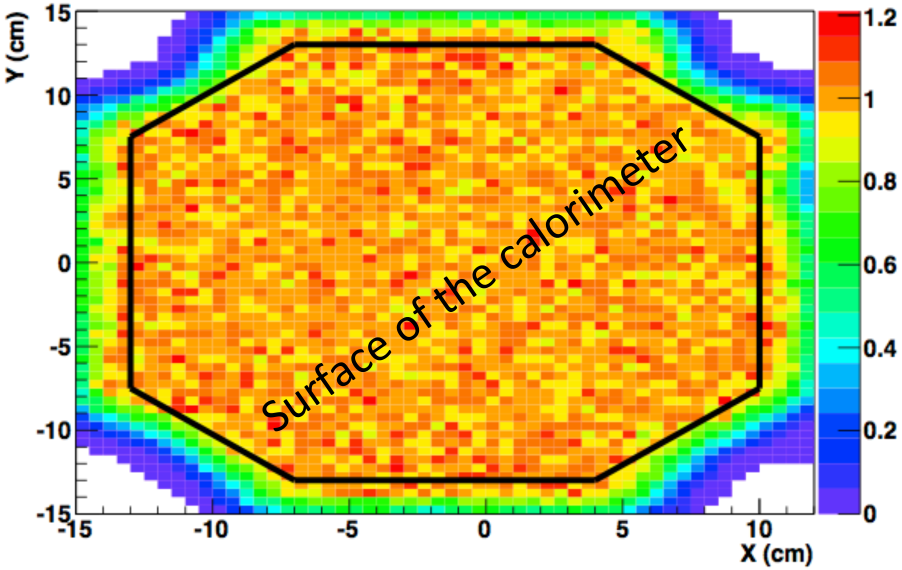
Name	Q^2 (GeV^2)	x_B
KinX2	2.1	0.4
KinX3	2.1	0.34

What's new :

- Improved Monte Carlo simulation
- Improved treatment of Radiative Corrections
- Improved understanding of normalization (inclusive trigger)
- Improved understanding of π^0 data for subtraction
- Improved systematic studies

Re-analysis of *full* data set, but in addition :

- Analysis of Q^2=1.9 GeV^2 unpolarized cross section (only 2.3 GeV^2 in 2004)
- Analysis of x_B-dependence of cross section (only Q^2 dependence in 2004)

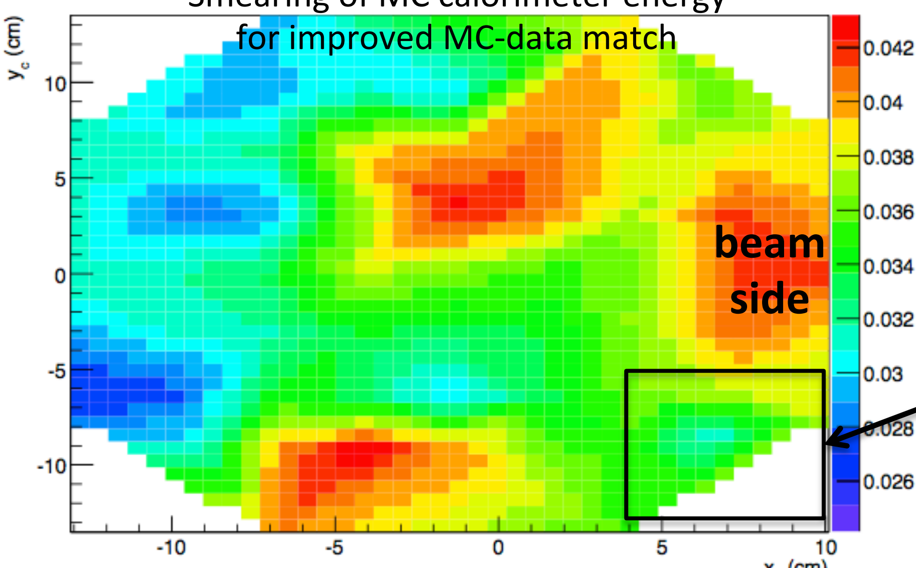


Building on π^0 analysis published in
Fuchey et al., Phys.Rev. C83 025201 (2011)

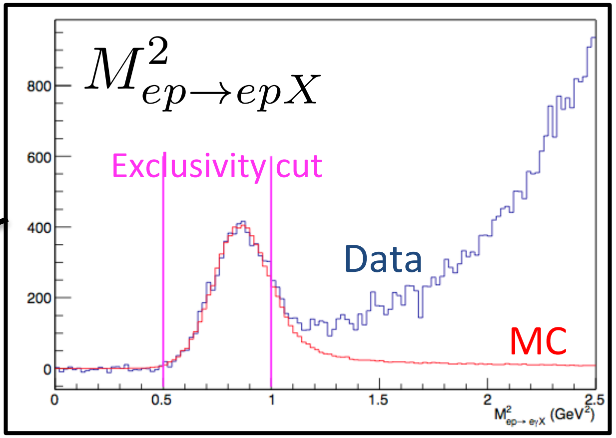
Efficient π^0 subtraction zone defined by *fiducial cut* at the surface of the calorimeter

Correction of Kin2 cross section is now possible !

Smearing of MC calorimeter energy for improved MC-data match



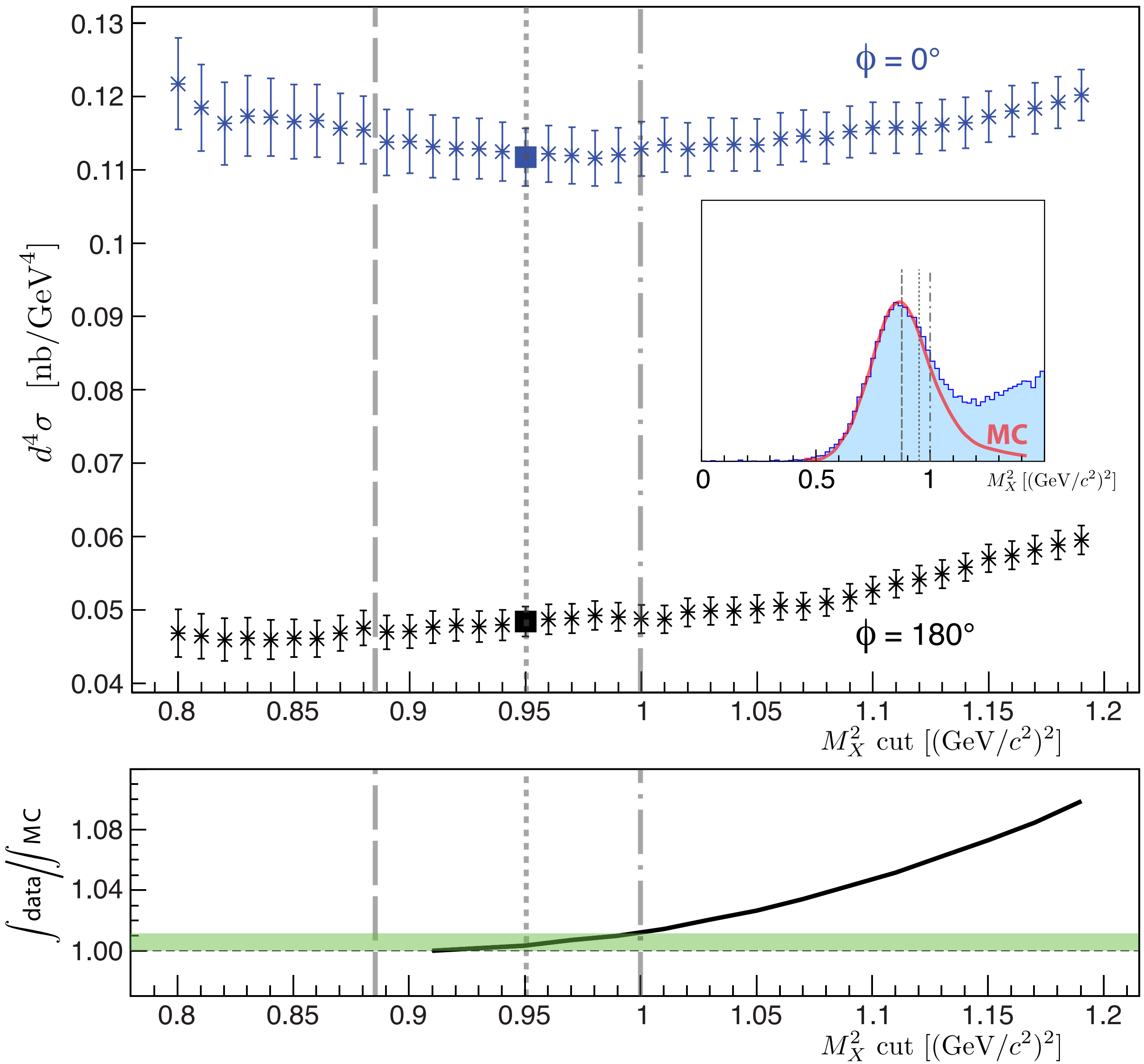
Upgraded Monte-Carlo techniques :
Improved agreement in the fiducial area between data and MC



Correlated Systematic Uncertainties

Systematic uncertainty	Value
HRS acceptance cut	1%
Electron ID	0.5%
HRS multitrack	0.5%
Multi-cluster	0.4%
Corrected luminosity	1%
Fit parameters	1%
Radiative corrections	2%
Beam polarization	2%
Total (helicity-independent)	2.8%
Total (helicity-dependent)	3.4%

Systematic Uncertainties : Exclusivity



Comparison with models : Q^2=1.9 GeV^2, t=-0.23 GeV^2