E12-06-114

Deeply Virtual Compton Scattering (DVCS) in Hall A

Hall A collaboration meeting

24 January 2018

Bishnu Karki

Ohio University, Athens, Ohio

On behalf of DVCS collaboration

Award 1614479

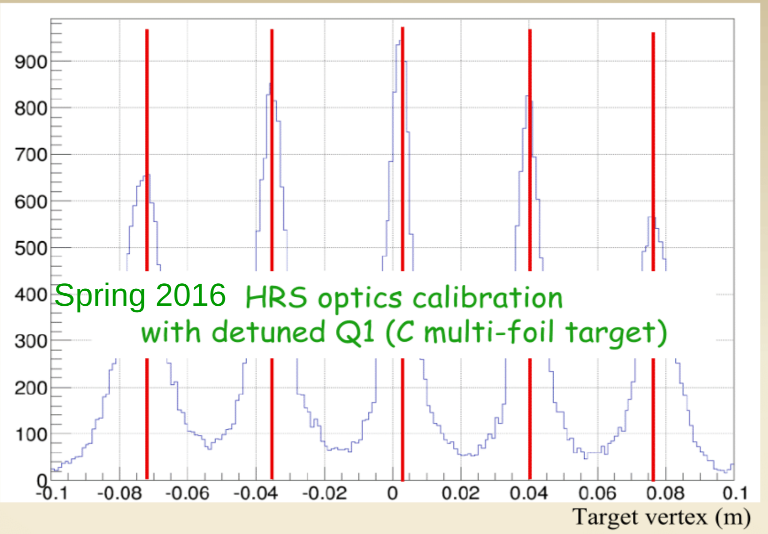
Overview

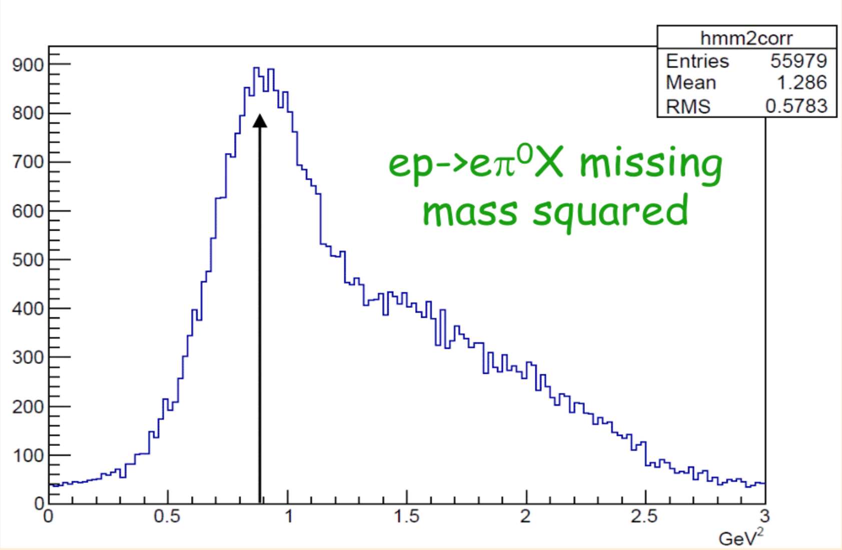
E12-06-114 DVCS/Hall A Experiment at 11 GeV

100 PAC days approved:

- **High impact experiment for nucleon 3D imaging program**
- High precision scaling tests of the DVCS cross section at constant x_B
- CEBAF12 will allow to explore for the first time the high x_B region

50% of experiment planned & completed in 2014-2016





All calibrations (beamline+HRS+calo) completed
DVCS & π^0 cross section analyses well underway

Analysis path:

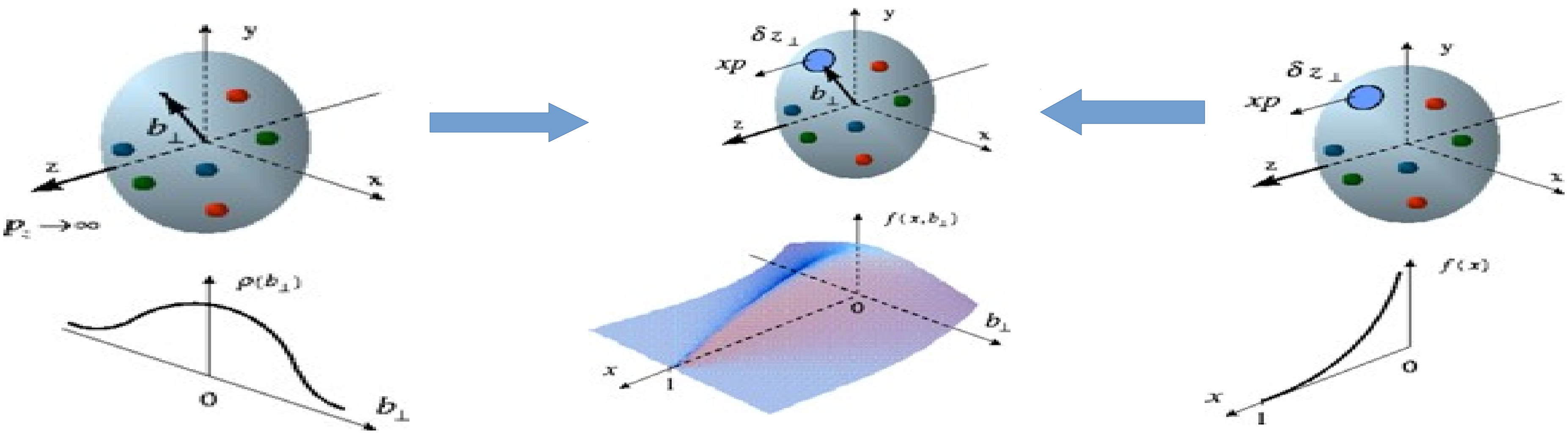
- **Jun'18:** Preliminary results on π^0 at x_B=0.36
- **Oct'18:** Preliminary results on DVCS
- **Nov'18:** Short paper submitted to PRL on π^0
- **Jan'19:** Letter to PRL on DVCS
- **Jul'19:** Long paper to PRC (DVCS & pi0)

Slide from C. Camacho

Generalized Parton Distributions (GPDs):

Elastic Scattering

Deep Inelastic Scattering



- **Form Factors (FFs)**
  - ✩ Spatial distribution
  - ✩ Momentum distribution

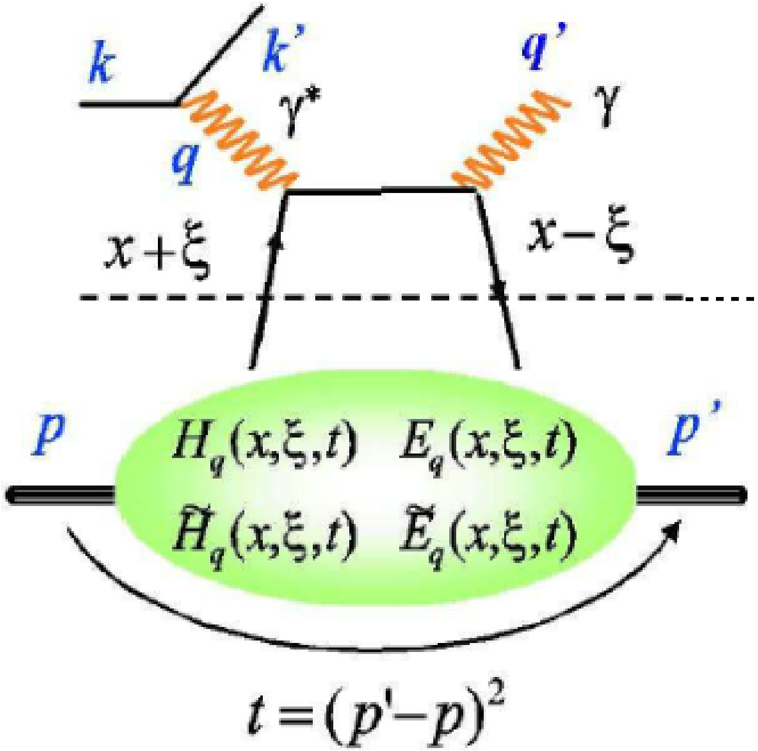
- **Generalized Parton distribution (GPDs)**
  - ✩ Spatial distribution
  - ✩ Longitudinal momentum distribution

- **P**atron **D**istribution **F**unctions **(PDFs)**
  - ✩ Longitudinal momentum distribution
  - ✩ Spatial distribution

GPDs allows to access the 3D parton structure of Nucleon

Factorization

In Bjorken limit: $\left.\begin{array}{r} Q^2 = -q^2 \to \infty \\ \nu \to \infty \end{array}\right\}$ At fixed $x_B = Q^2 / 2M\nu$



M. Mazouz PhD Thesis 2006

Handbag diagram for DVCS

Hard/perturbative Part:

Calculable

Soft/non-perturbative Part:
Nucleon structure is Parametrized by GPDs

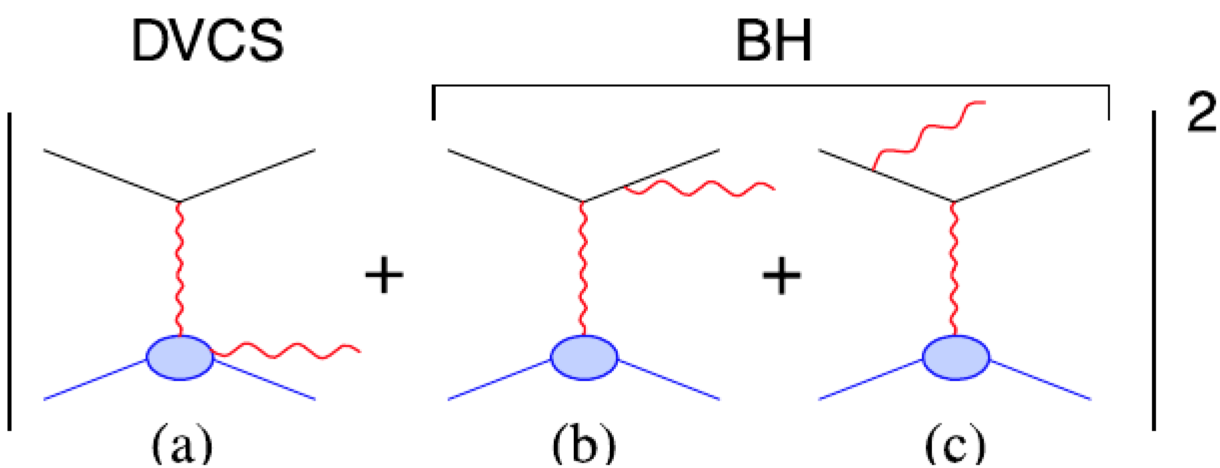
Minimal Q^2 at which factorization holds must be tested

Definition of variables:
x: longitudinal momentum fraction carried by struck quark.
ξ: longtitudinal momentum transfer ≈ x_B / (2- x_B).
t: four momentum transfer related to $b_\perp$ via Fourier transform.

DVCS x-section → GPDs → Description of internal structure

DVCS and Bethe-Heitler (BH):

ep ⟶ epγ =



C.M. Camacho PhD Thesis 2005

$$\frac{d^5\sigma}{dQ^2 dt dx_B d\phi_e d\phi} \propto |\, \mathcal{T}_{DVCS} + \mathcal{T}_{BH} \,|^2$$
$$= |\, \mathcal{T}_{DVCS} \,|^2 + |\, \mathcal{T}_{BH} \,|^2 + \mathcal{I}$$

At leading twist

$$d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma} = \Im m\,(T^{BH} \cdot T^{DVCS})$$
$$d^5\overrightarrow{\sigma} + d^5\overleftarrow{\sigma} = |BH|^2 + \Re e\,(T^{BH} \cdot T^{DVCS}) + |DVCS|^2$$

Known to 1%

Bilinear combinations of GPDS

Linear combinations of GPDs

Interference with BH gives access to Re and Im part of DVCS amplitude.

DVCS in Hall A

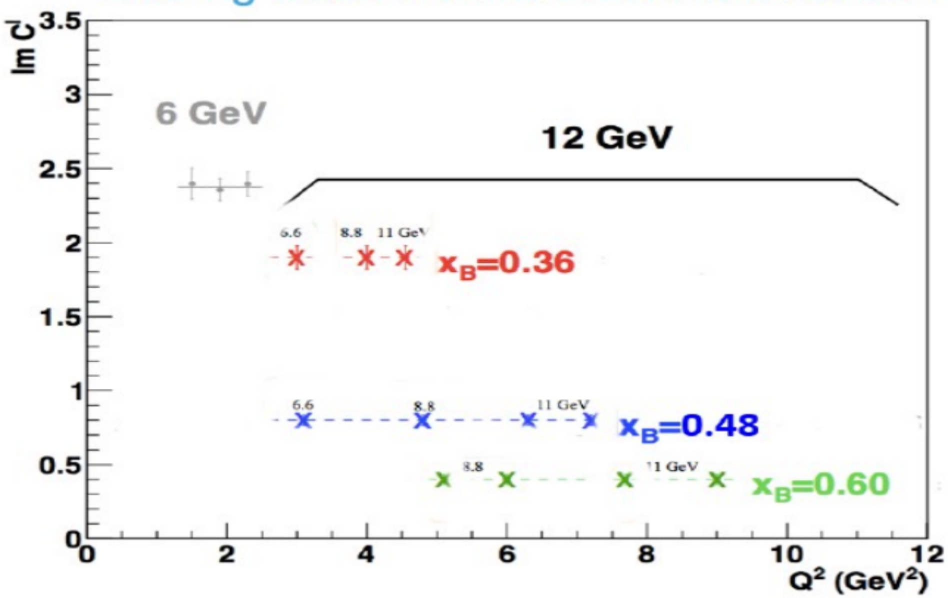
3 Generation of experiments so far

1st Gen (2004)
- Q^2 dependence study

2nd Generation (2010)
- Q^2 + beam energy dependence

3rd Generation (2014-2016)
- **High impact experiment for nucleon 3D imaging program**
- High precision scaling tests of the DVCS cross section at constant x_B
- CEBAF12 will allow to explore for the first time the high x_B region

Scaling tests of the DVCS cross section



Pushing to high Q^2 and x_B

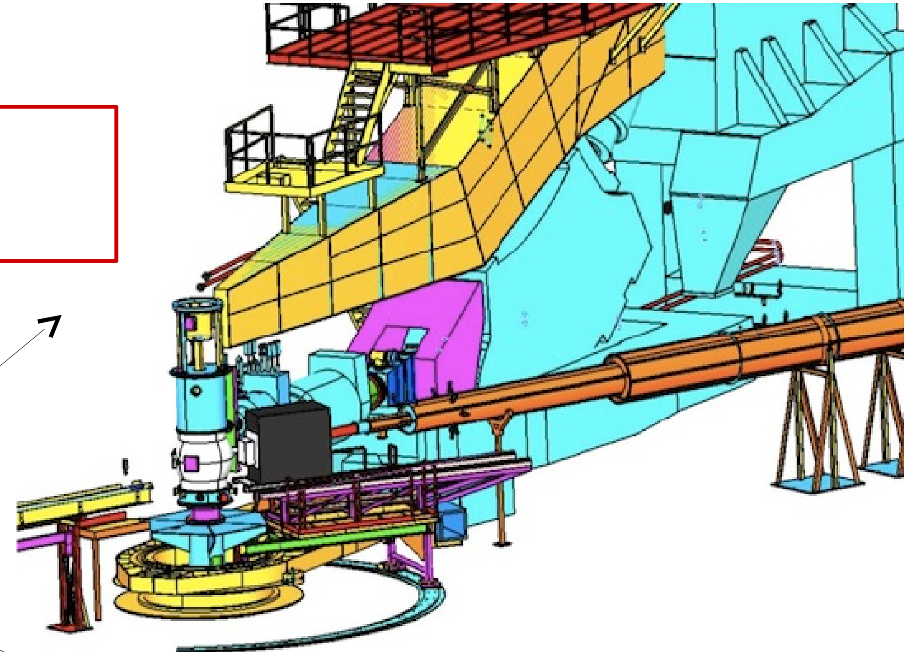
Period	Kinematic	Q^2	x_B	% target Charge
F '14	361	3.20	0.36	100.0
F '16	362	3.60	0.36	100.0
F '16	363	4.47	0.36	100.0
Sp '16	481	2.7	0.48	100.0
Sp '16	482	4.37	0.48	56.6
Sp '16	483	5.33	0.48	76.4
Sp '16	484	6.90	0.48	53.0
F '16	601	5.54	0.60	100.0
~~F '16~~	~~**602**~~	~~**6.10**~~	~~**0.60**~~	~~**0.0**~~
F '16	603	8.40	0.60	100.0
~~F '16~~	~~**604**~~	~~**9.00**~~	~~**0.60**~~	~~**0.0**~~

F– Fall Sp– Spring Q^2 – in GeV^2

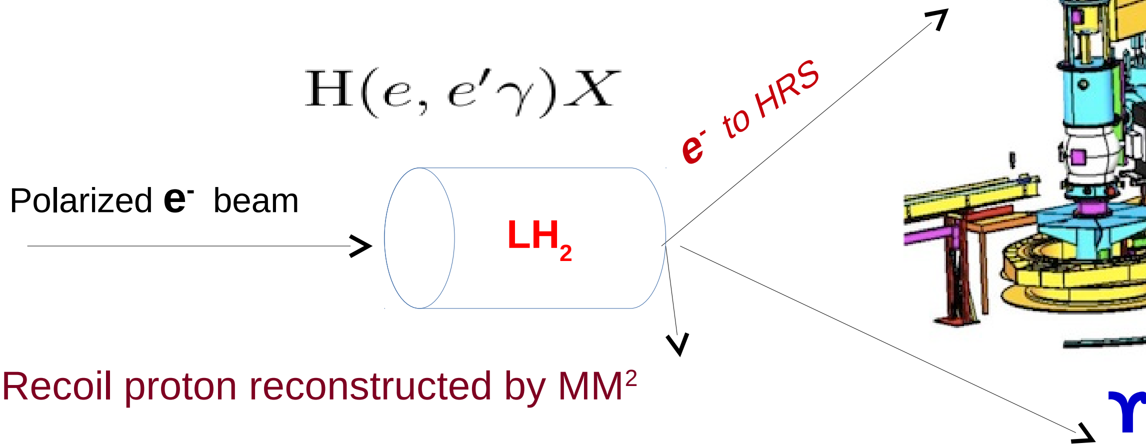
~50% of allocated 100 PAC days from Fall 2014, Spring 2016, and Fall 2016

E12-06-114 (DVCS3)

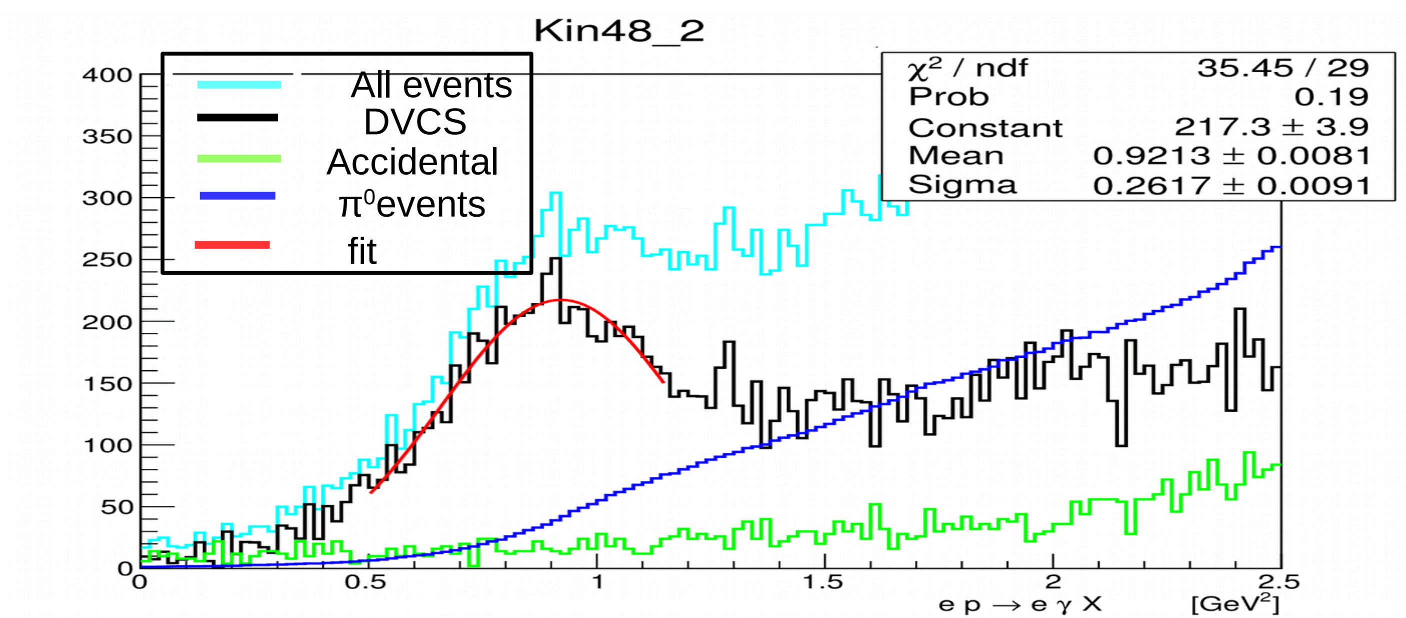
Exclusive DVCS: $ep \rightarrow ep\gamma$

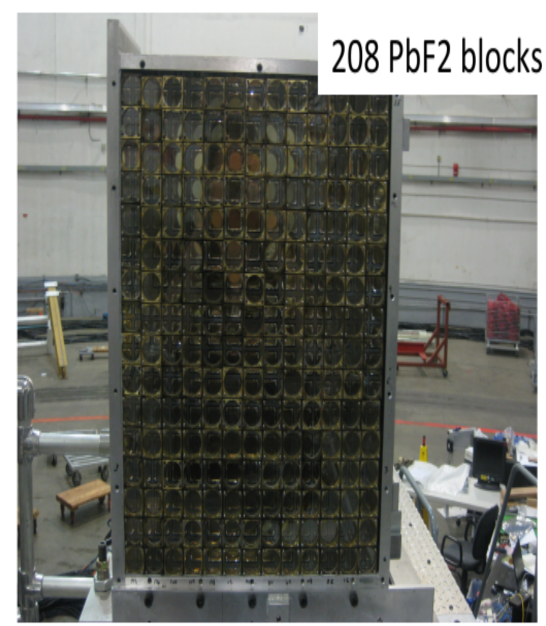


$$\mathrm{H}(e, e'\gamma)X$$



Recoil proton reconstructed by MM²

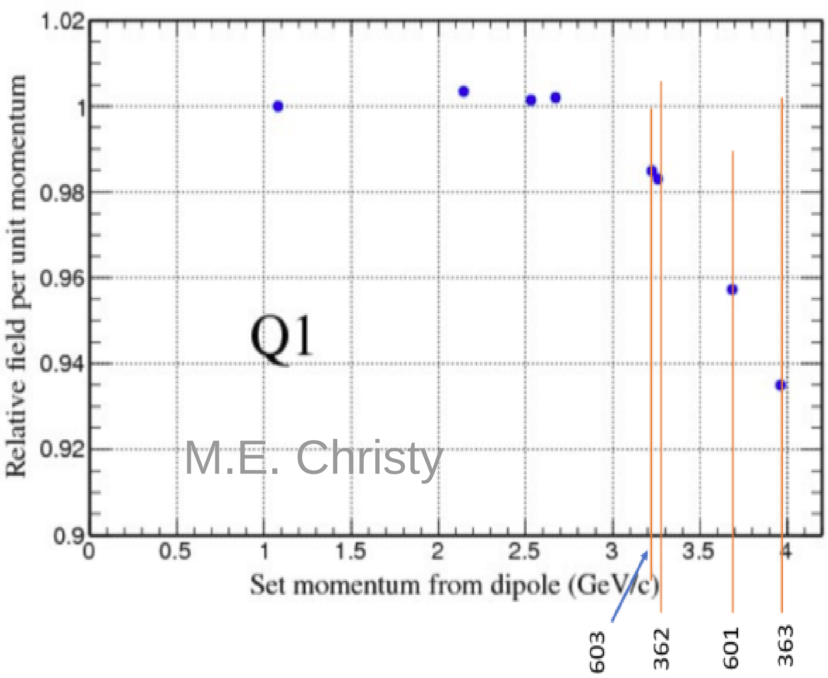




$$M^2_{ep\rightarrow e'\gamma X} = (k + p - k' - q_\gamma)^2$$

Analysis status

Beam Studies
- Beam energy measurement
- Polarization measurement
- Raster calibration
- BCM/BPM calibration



High Resolution Spectrometer
- Trigger Efficiency
- Particle Identification
- Optics calibration
- Tracking Efficiency
- Acceptance Studies
- DIS x-section

Calorimeter
- Coincidence time correction
- Waveform analysis
- Elastic and π^0 calibration
- π^0 electroproduction (in progress)

- DVCS Simulation

Q1 Status

Fall 2014 : Old Q1 at full field

Spring 2016: Maximum current was limited to 2.8 GeV setting (detuned)

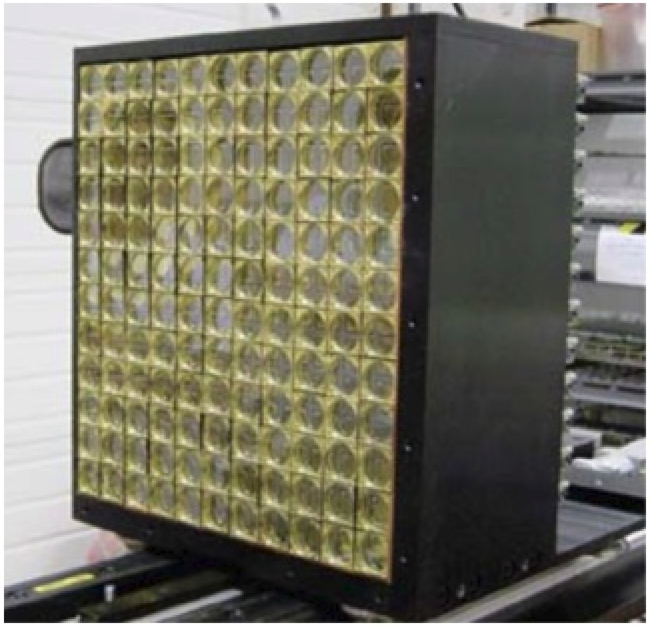
Fall 2016: Q1 saturated

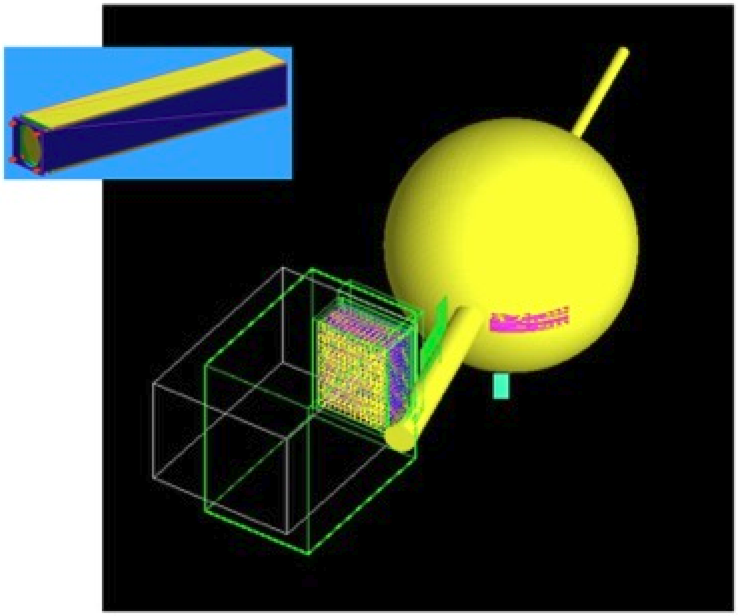
Geant4 Simulation (W.P. Henry)

- Method developed to simulate one production run (~400,00 DVCS events) in about 2 hours using Auger

- R-Function, calorimeter energy smearing, and photon reconstruction has been implemented

- Simulation is moving towards the version control and will be on Git

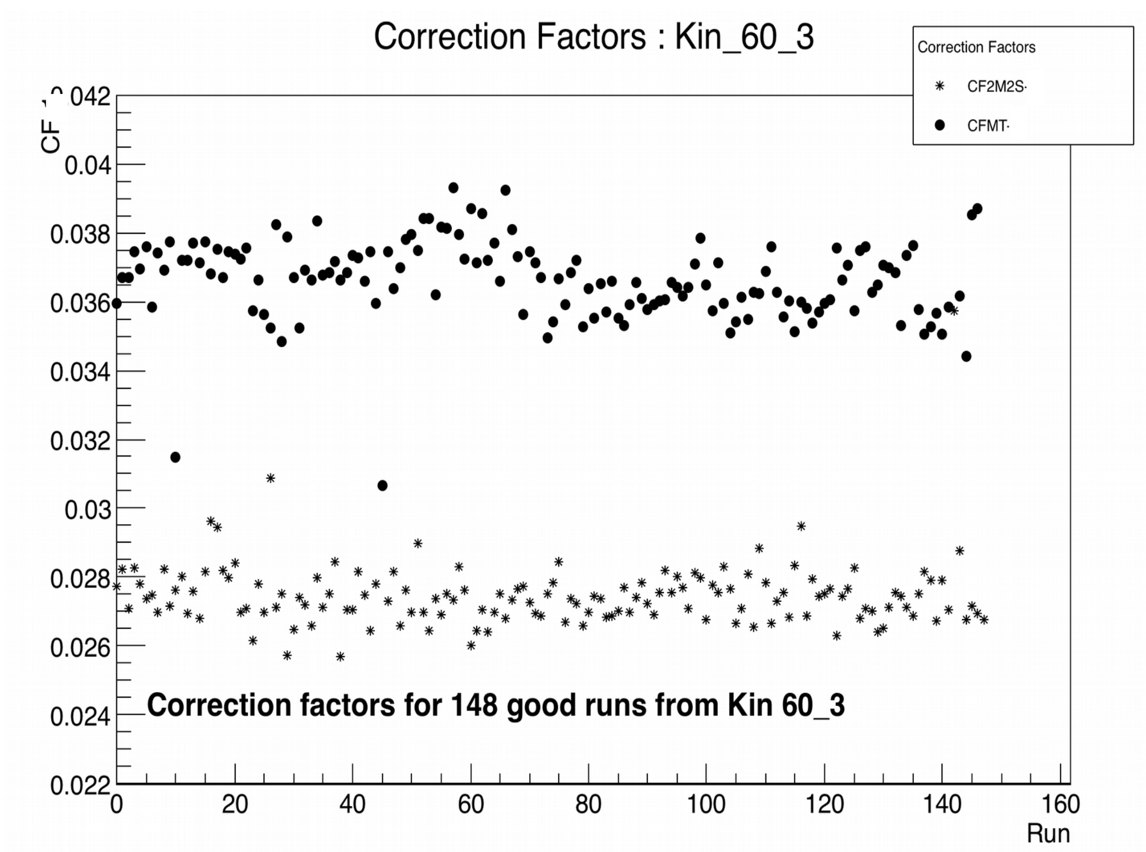




Tracking efficiency (H. Rashad)

$$\eta_{MultiCluster} = \frac{N_{2M2S\ \mathrm{Electrons}}}{N_{(0M4S+1M3S)\ \mathrm{Electrons}}}$$

$$\eta_{MultiTrack} = \frac{N_{MultiTrack\ Electrons}}{N_{(0M4S+1M3S)\ Electrons}}$$



- Analyzer 1.5 has issues with reconstructing tracks for events with more than one cluster in any given VDC wire planes
- 3 cases: 0M4S, 1M3S, and 2M2S events yields single track reconstruction.
  Keep 0M4S and 1M3S exclude 2M2S
- ~5-10% events are reconstructed with more than one track and are excluded

Multi-cluster and Multi-track correction factors are mutually exclusive

$\eta_{Final} = \eta_{MultiCluster} + \eta_{MultiTrack}$

Major correction

Deadtime (S. Ali/ M. Dlamini)

$$\text{Dead time} = 1 - \text{live time}$$

$$\text{Live time} = \frac{\text{live scaler rate}}{\text{raw scaler rate}}$$

DIS : **S2 + Cer**

DVCS : **S2 + Cer**
(coincidence with Calo)

- Scalers to compute deadtime
- Dedicated runs to check the dead time correction
- Normalized DIS rates corrected by deadtime OK
- Normalized DVCS rates corrected by deadtime shows beam current dependence
  - Accidental coincidences (calorimeter-HRS)
  - Study in progress..

I (μA)	Livetime (LT)	DIS rate /3.45 (Hz/μA)	DVCS rate /5.62 (Hz/μA)
10.61	0.985	0.992	0.93
15.32	0.976	1.0	1.0
20.53	0.965	0.999	1.06

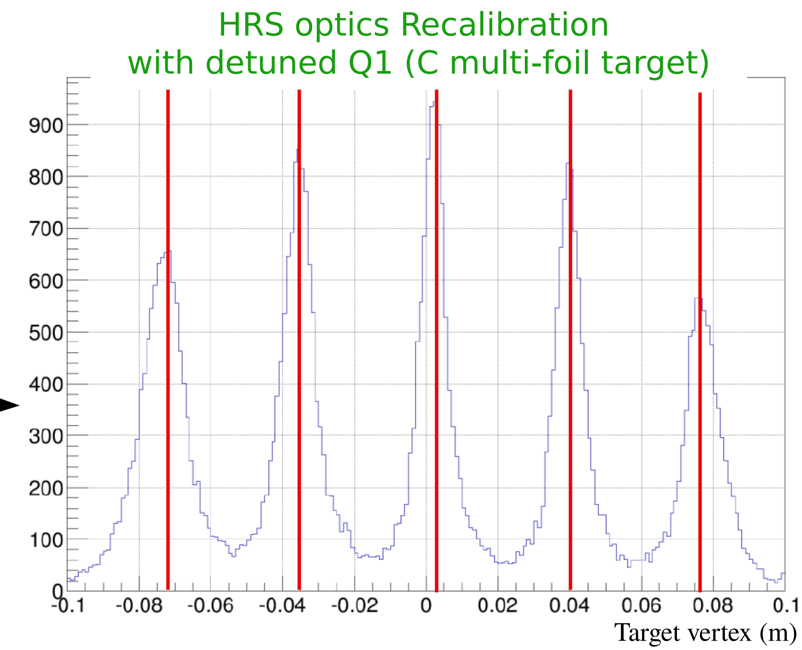
Optics re-calibration Spring 2016 (F. Georges)

3 out of 4 kinematics were detuned (Q1)

LHRS optics calibration 16^0 → poor illumination → Poor reconstruction of target vertex

Kin48_2 (Q1 at 62%, kscatt = 3.996 GeV)			
Calibration method	Everything at order of 5 (reference)	Vertex& phi at order 2 and set higher terms to 0	Vertex-phi rotated and vertex rescaled
Run number	13006	13006	13006
Run type	pointing	pointing	pointing
Target length	14.19	14.38	15.00
1st foil sigma (mm)	3.44 (mm)	8.31	5.85
5th foil sigma (mm)	4.76 (mm)	6.41	4.91
Distance foils 1-2 (cm)	3.18	3.65	3.74
Distance foils 2-3 (cm)	3.64	3.58	3.76
Distance foils 3-4 (cm)	3.70	3.60	3.78
Distance foils 4-5 (cm)	3.64	3.60	3.72

►Expected value 15 cm

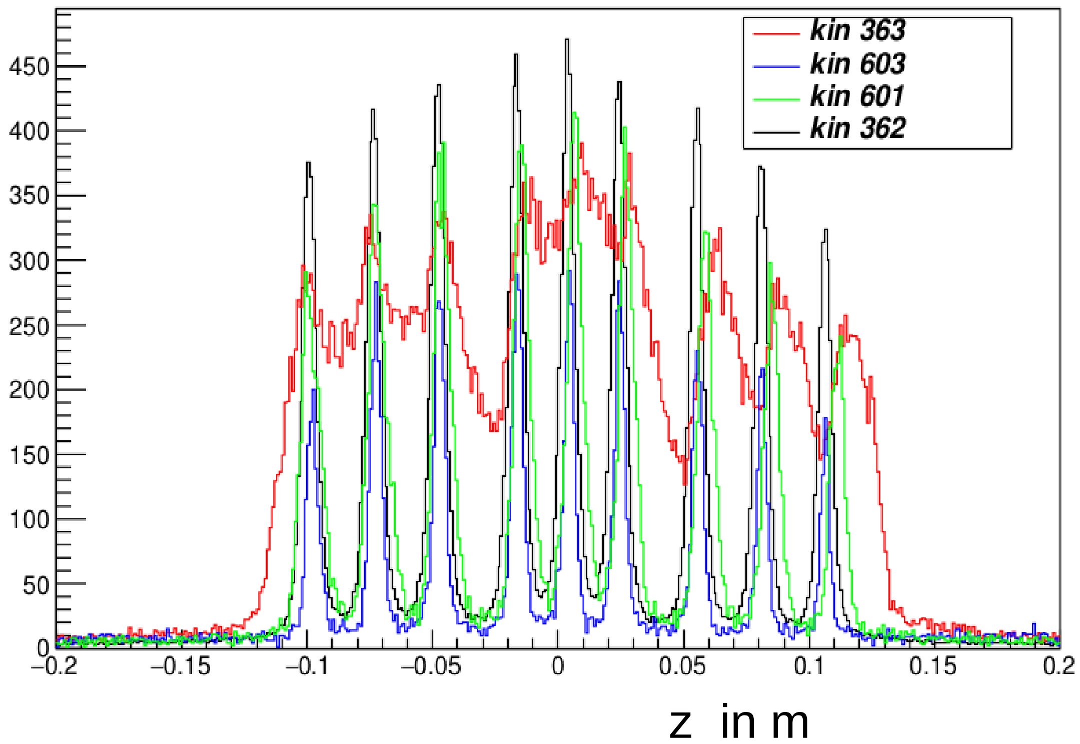


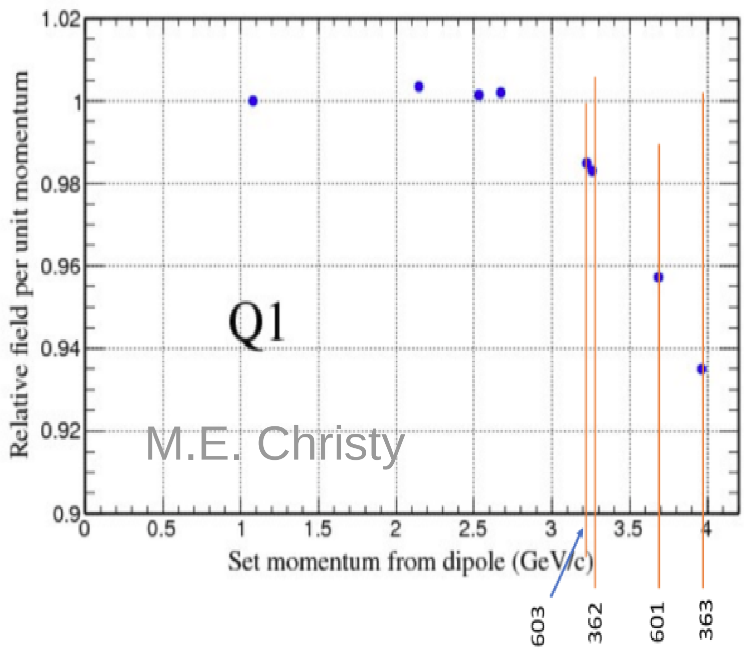
►Expected value 3.75 cm

Rotation of the vertex-phi plane to correct vertex-phi dependence

Multiplication of the vertex by a scaling factor to reach ~15cm target length

Z vertex reconstruction for Fall 2016 kinematics



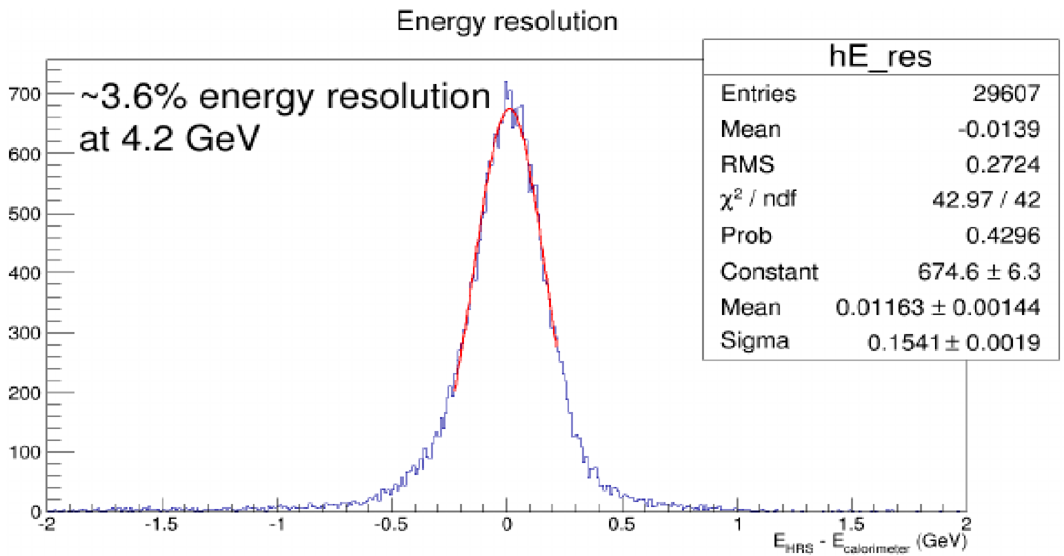


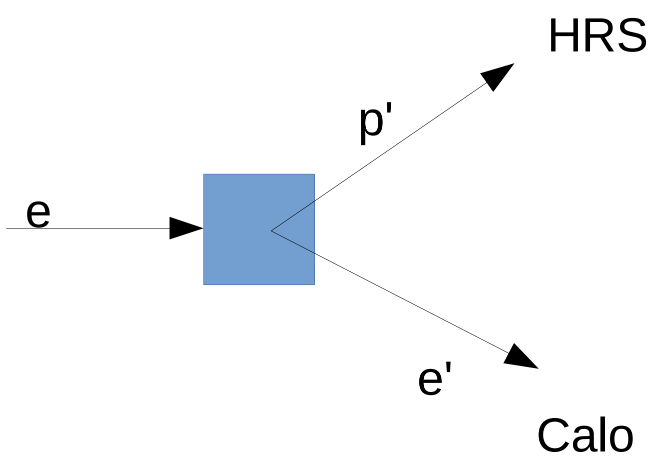
Work in progress for optimization of optics matrix for Fall 2016

Calorimeter energy calibration (M. Dlamini)

Elastic calibration (Invasive)

- Compute scattered electron energy, $\mathbf{E_{e'}}$ (from detected p)
- Adjust calorimeter blocks' gain so that measured e' energy = $\mathbf{E_{e'}}$

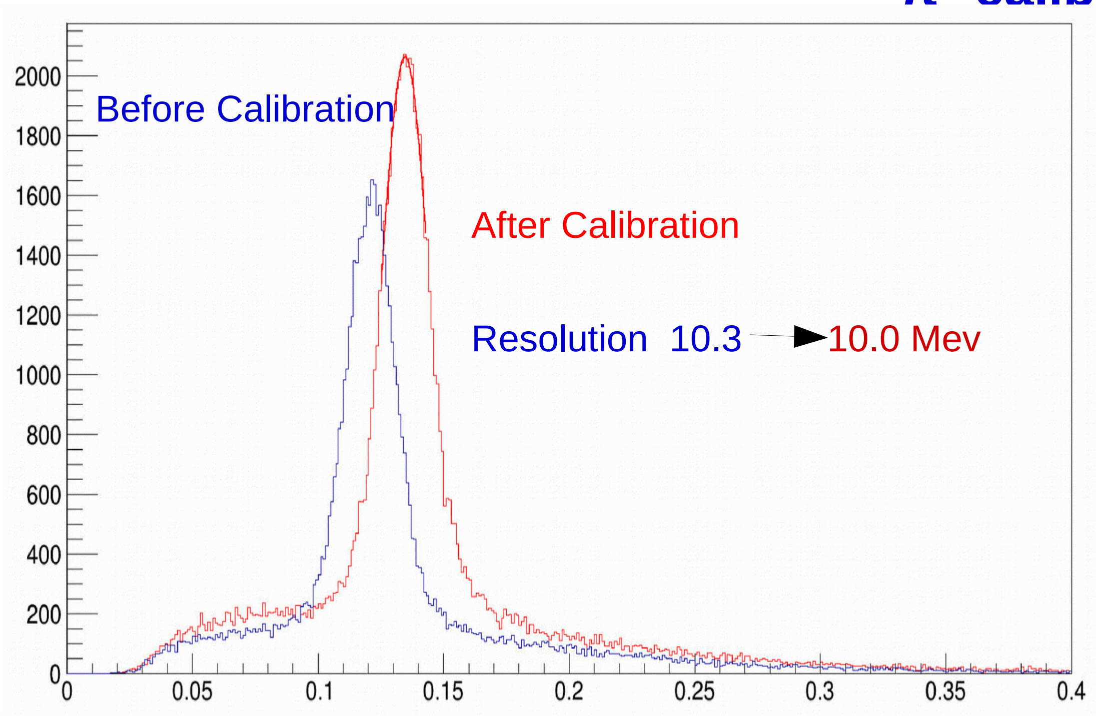




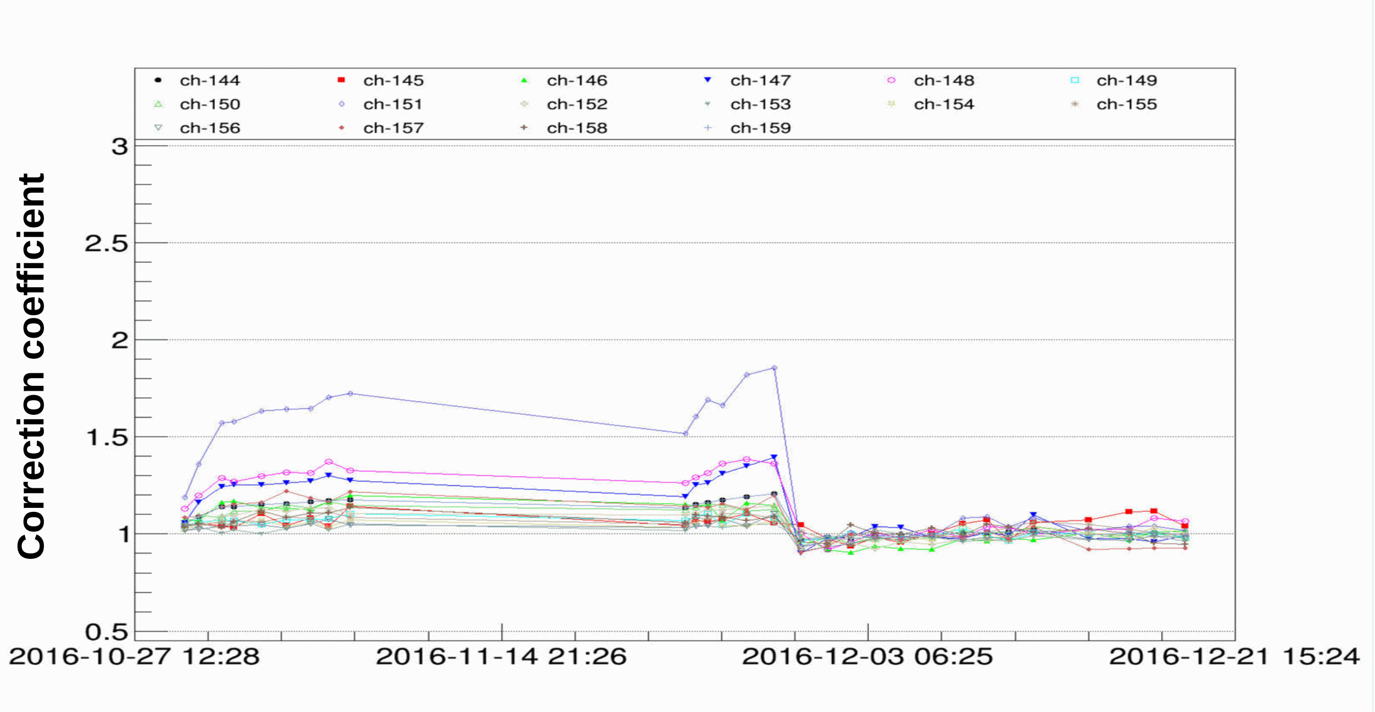
- Calorimeter blocks gain is lost due to radiation damage
- Correct calorimeter blocks gain with π^0 calibration

Calorimeter energy calibration (F. Georges)

π^0 calibration

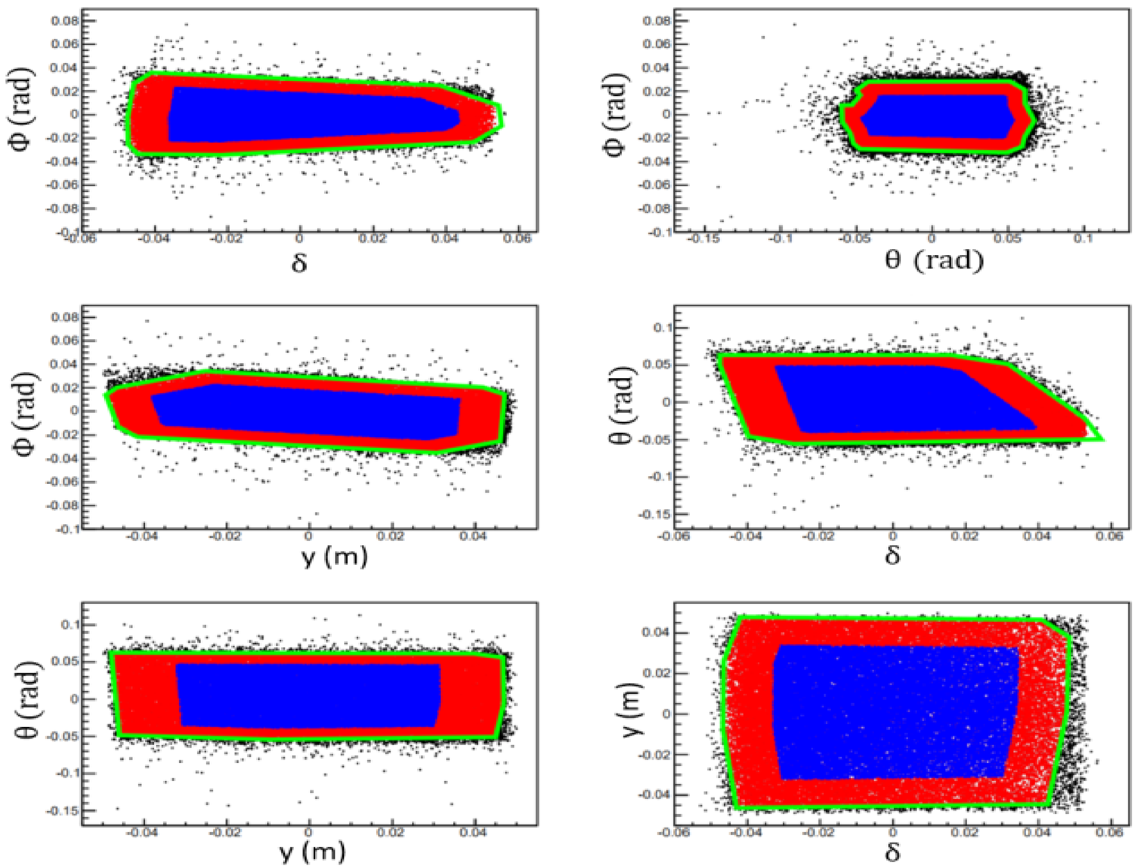


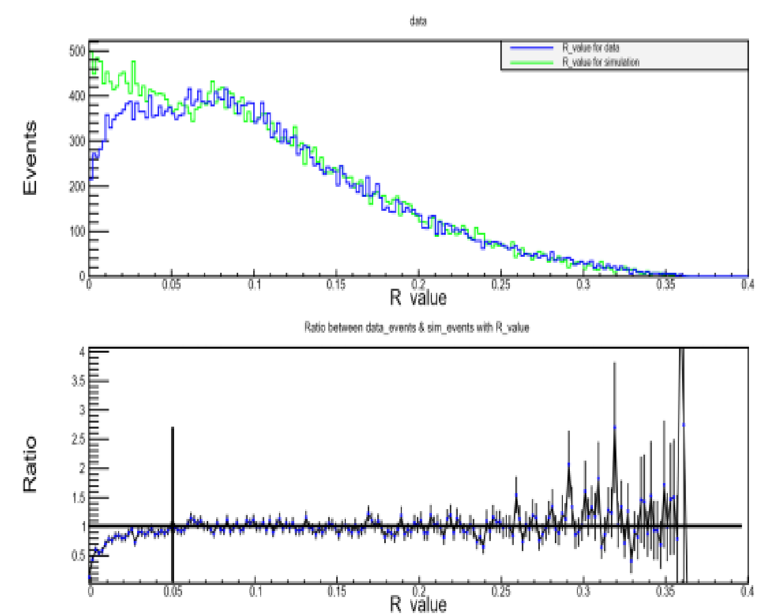
- Compute correction coefficient by reconstructing π^0 invariant mass
- Optimize π^0 invariant mass mean value and resolution



Spectrometer Acceptance Study (G. Hamad and A. Johnson)

R-Function





- R-Function: computes Min. distance (R-value) of an event from edge of spectrometer
- **More efficient cut than multiple 1D cut due to correlations**
- Single R-cut value defines spectrometer acceptance

- Data and MC event distribution must agree for R-value > R-cut
- MC uses the R-cut to compute the spectrometer acceptance

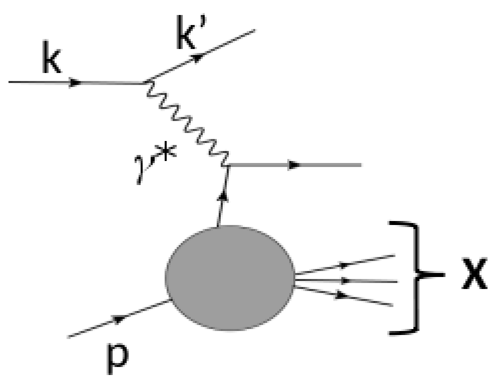
DIS x-section (B. Karki/ G. Hamad)

- **Reproducing DIS cross section ensure our understanding of luminosity and e detection by HRS**

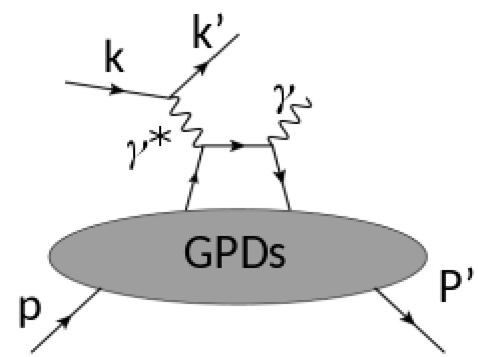
$$\frac{d^2\sigma}{dx dQ^2} = \frac{N_c}{\mathcal{L}} \times \left(\frac{1}{\alpha \times \eta_{virt} \times \eta_{exp} \times \Gamma_{DIS}}\right)$$

$\mathcal{L}$ Integrated luminosity
α term to modify phase space due to radiative effects
η_{virt} term correcting virtual radiative effects
η_{exp} term correcting detectors inefficiencies
Γ_{DIS} phase space covered by LHRS
N_c no. of event passing analysis cut (PID, vertex, track...)

DIS



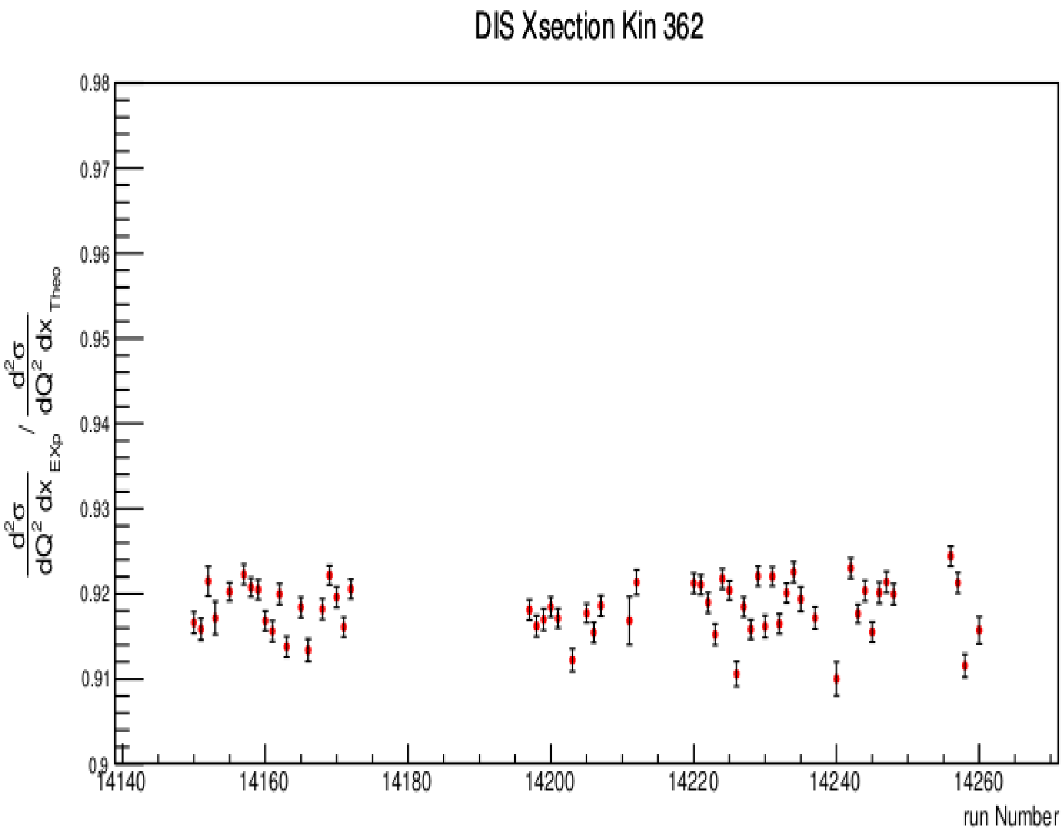
DVCS



DIS x-section

- E12-06-114 DIS cross section compared to world data from
  M. E. Christy et al. Phys. Rev. **C81**, 055213 (2010)

- Upto 5% uncertainty in reference cross-section



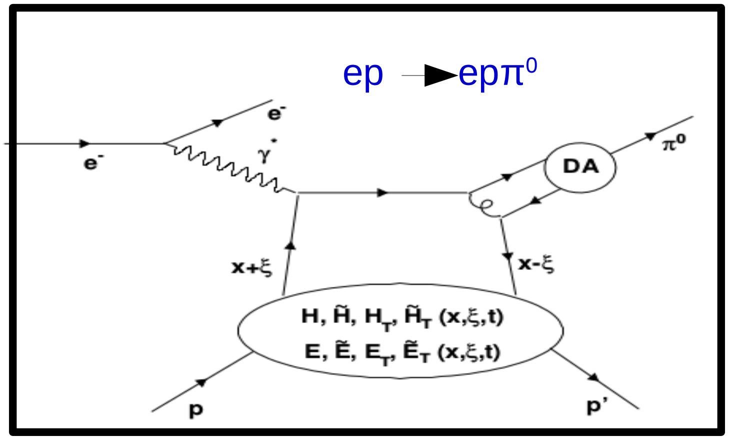
Period	Kinematic	Relative difference(%)
Fall 2014	361	-2
Fall 2016	362	-8
Fall 2016	363*	-15
Spring 2016	481**	-2
Spring 2016	482	-7
Spring 2016	483	-5
Spring 2016	484	-6
Fall 2016	601**	-5
Fall 2016	603	+3

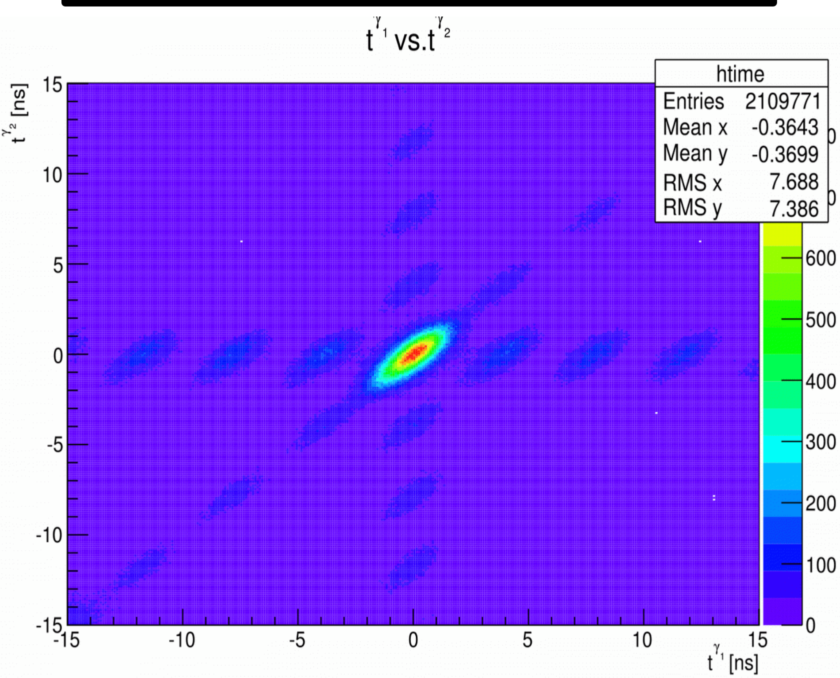
* Q1 saturation effect
** atypical run to run stability

Work in progress..

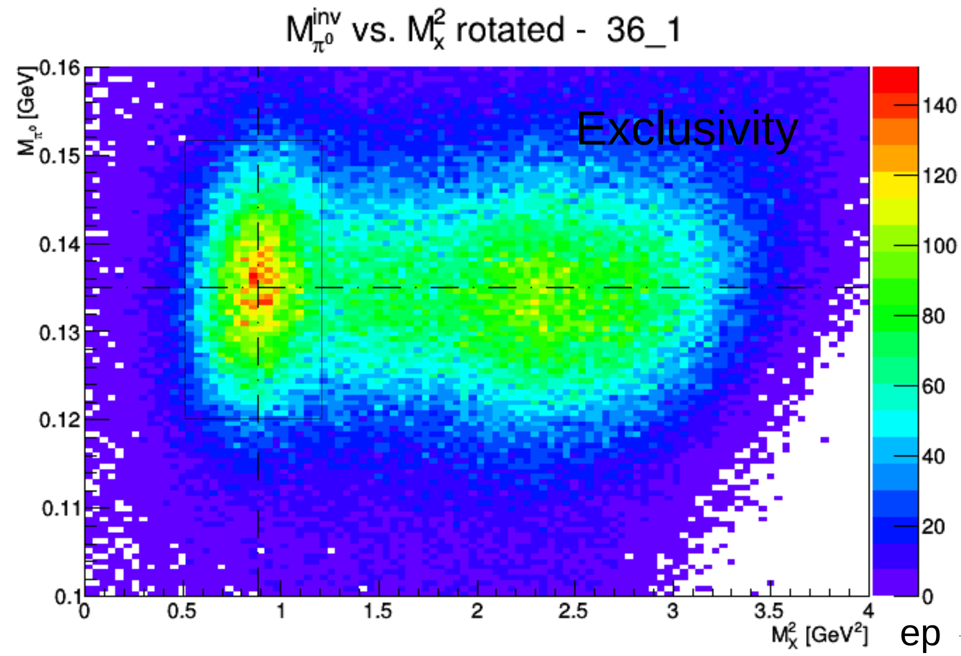
π^0 electroproduction (M. Dlamini)

- **Experimental setup allows exclusive π^0 events**
- **Provides interesting and complementary insight into GPDs of nucleon**





[-2, 2] ns window cut



ep → eπ0X

Other cuts:

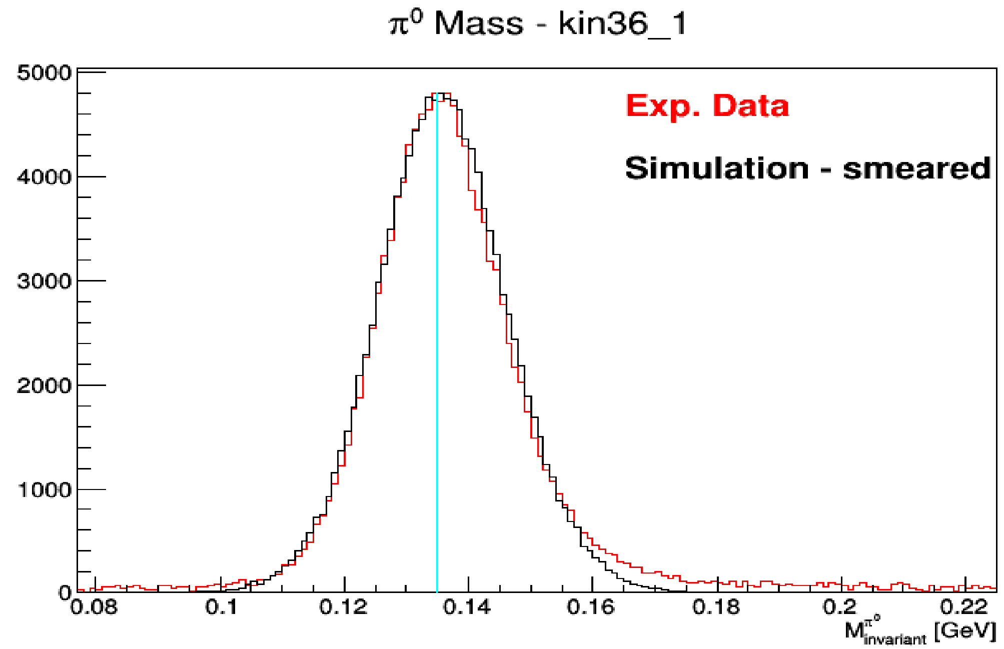
→ **Electron PID (same as DIS)**

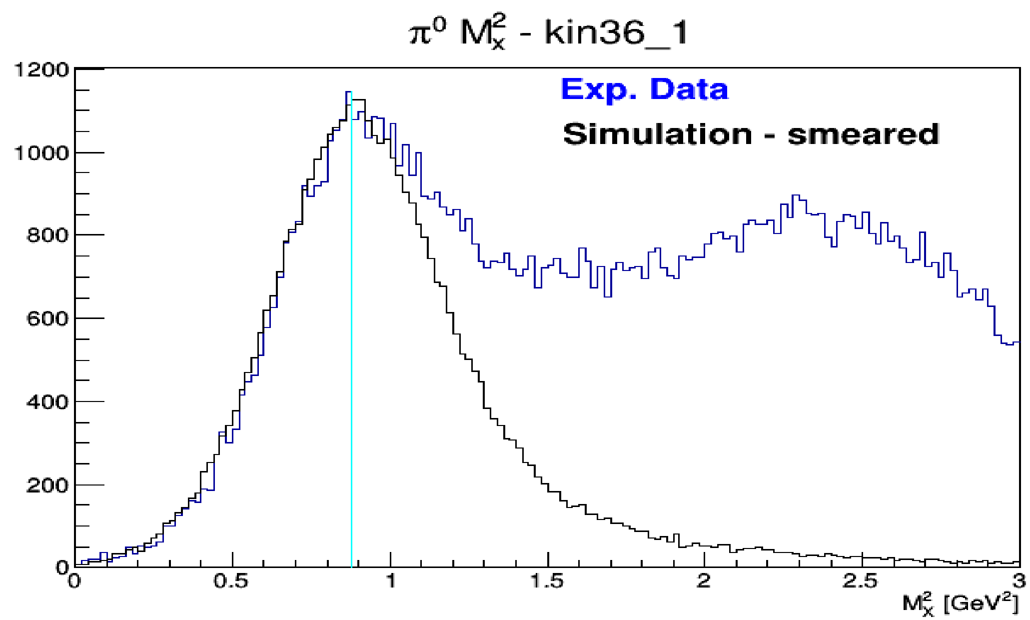
→ **Cut on photon energy, E_γ>1.2 GeV**

→ **Accidental subtraction**

π^0 electroproduction (M. Dlamini)

simulation–data

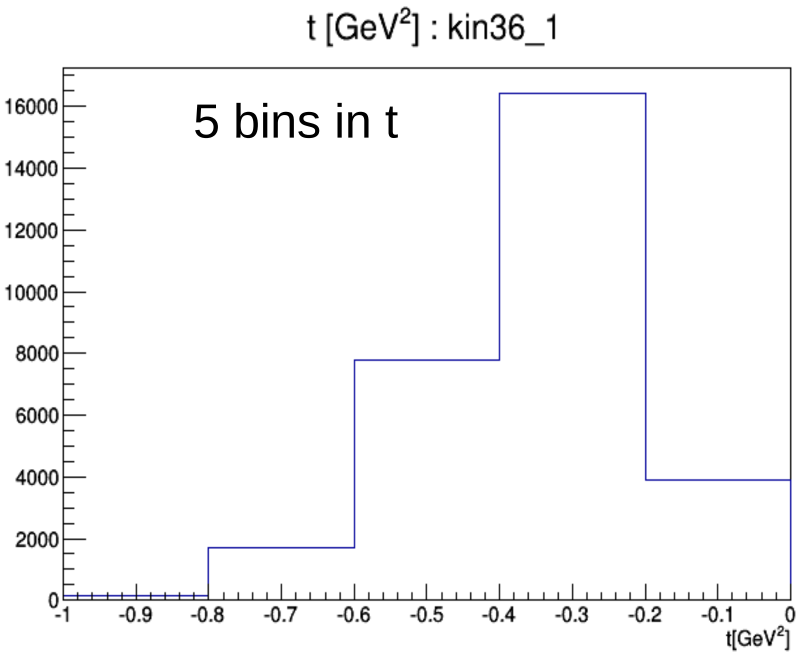


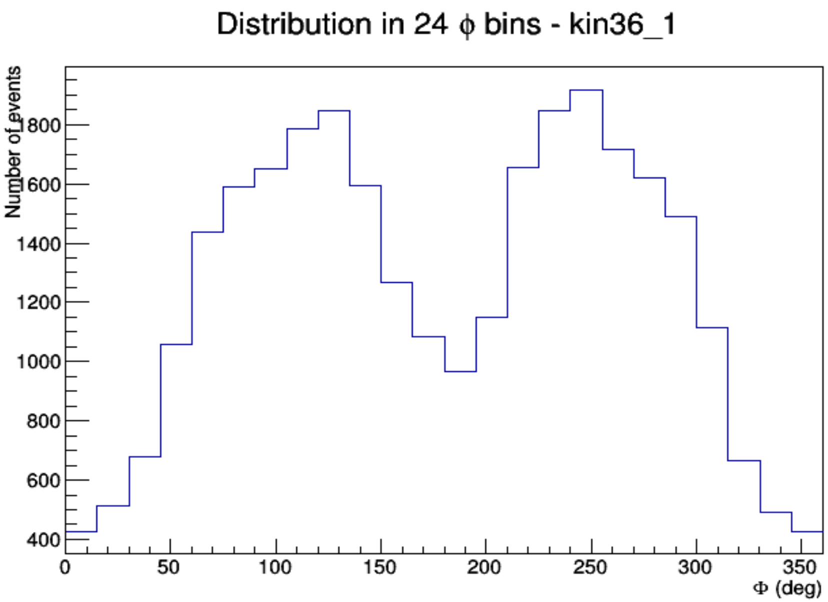


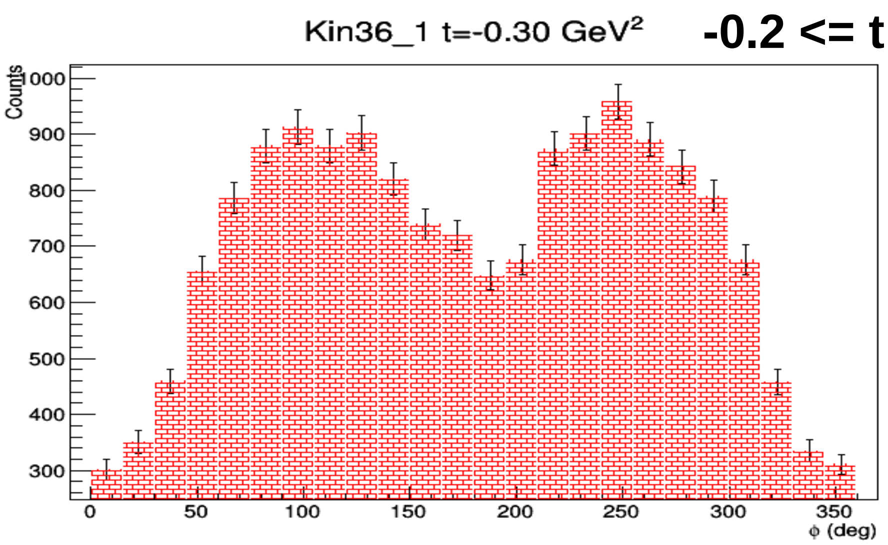
Data in good agreement with simulation

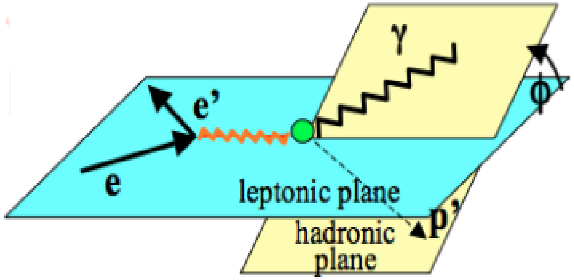
π^0 electroproduction (M. Dlamini)

(π^0 data sample)









Working on total and helicity-dependent cross sections for all x_B=0.36 points.

Summary and outlook

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100 PAC days approved:

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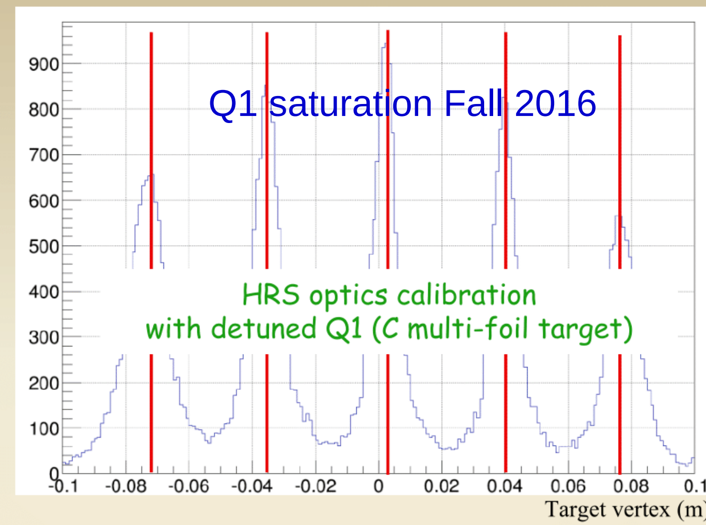
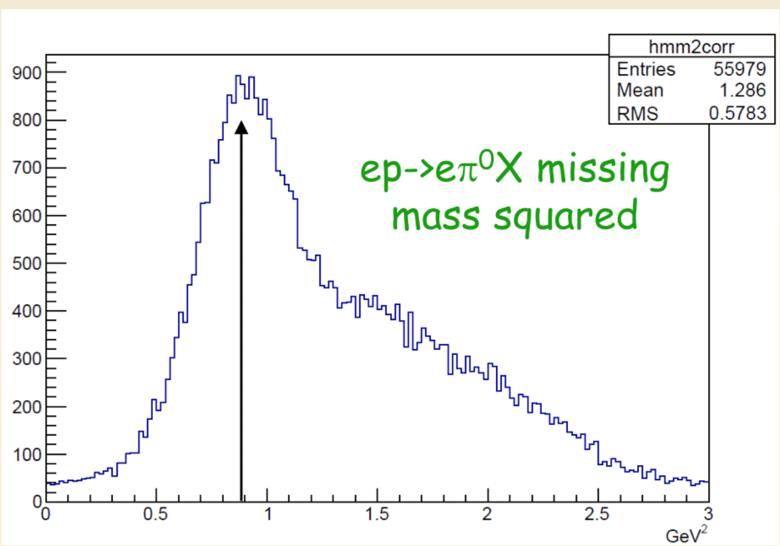
- CEBAF12 will allow to explore for the first time the high x_B region

50% of experiment planned & completed in 2014-2016





All calibrations (beamline+HRS+calo) completed
DVCS & π^0 cross section analyses well underway

Analysis path:

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- **Jan'19:** Letter to PRL on DVCS
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U.S. DEPARTMENT OF ENERGY | Office of Science | JSA   Jefferson Lab

Slide from C. Camacho

Acknowledgments:

Hall A DVCS Collaboration

Hall A Collaboration

Hall A technical staff

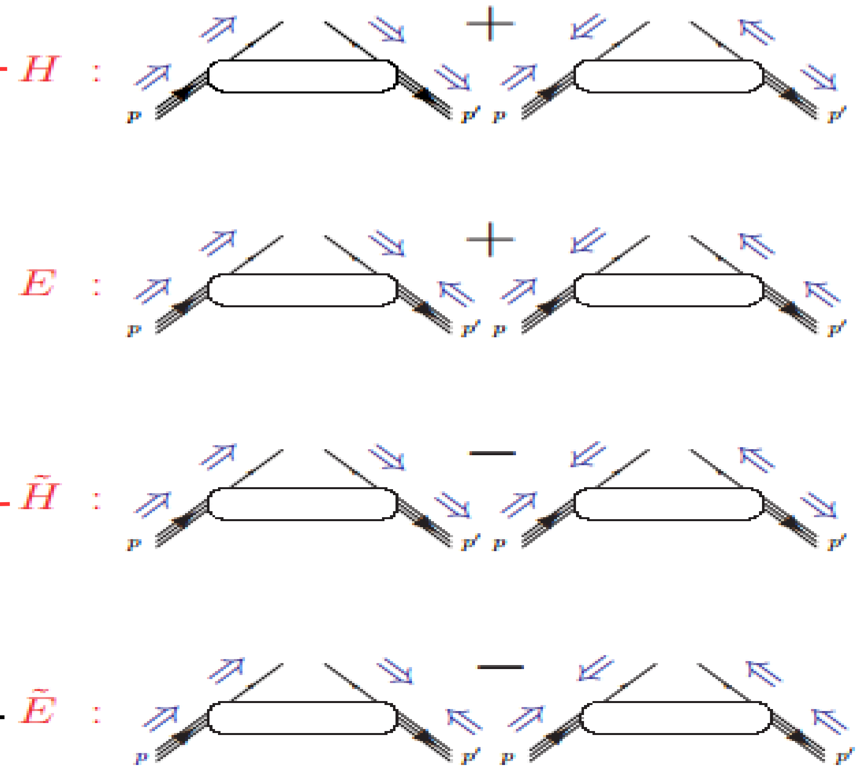
Accelerator staff

THANK YOU !

GPDs: Quarks helicity and nucleon spin orientation:

Nucleon helicity conserving

Nucleon helicity non-conserving

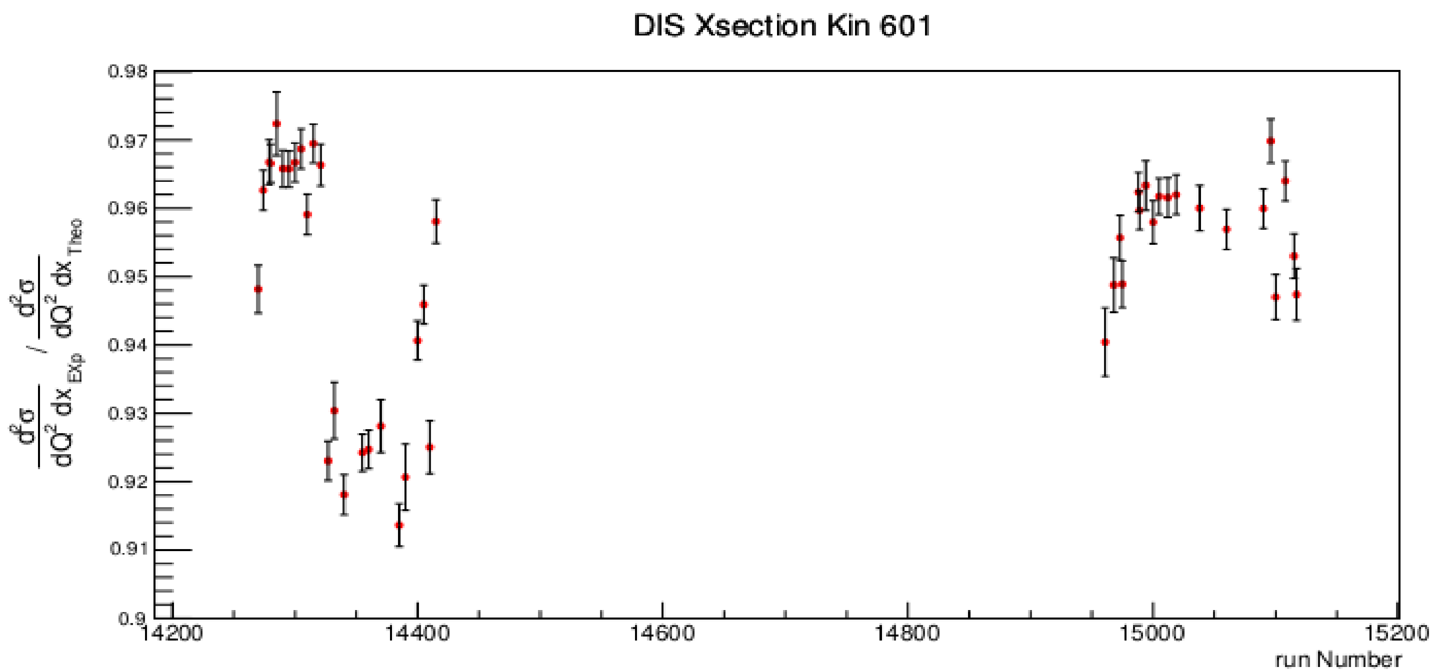


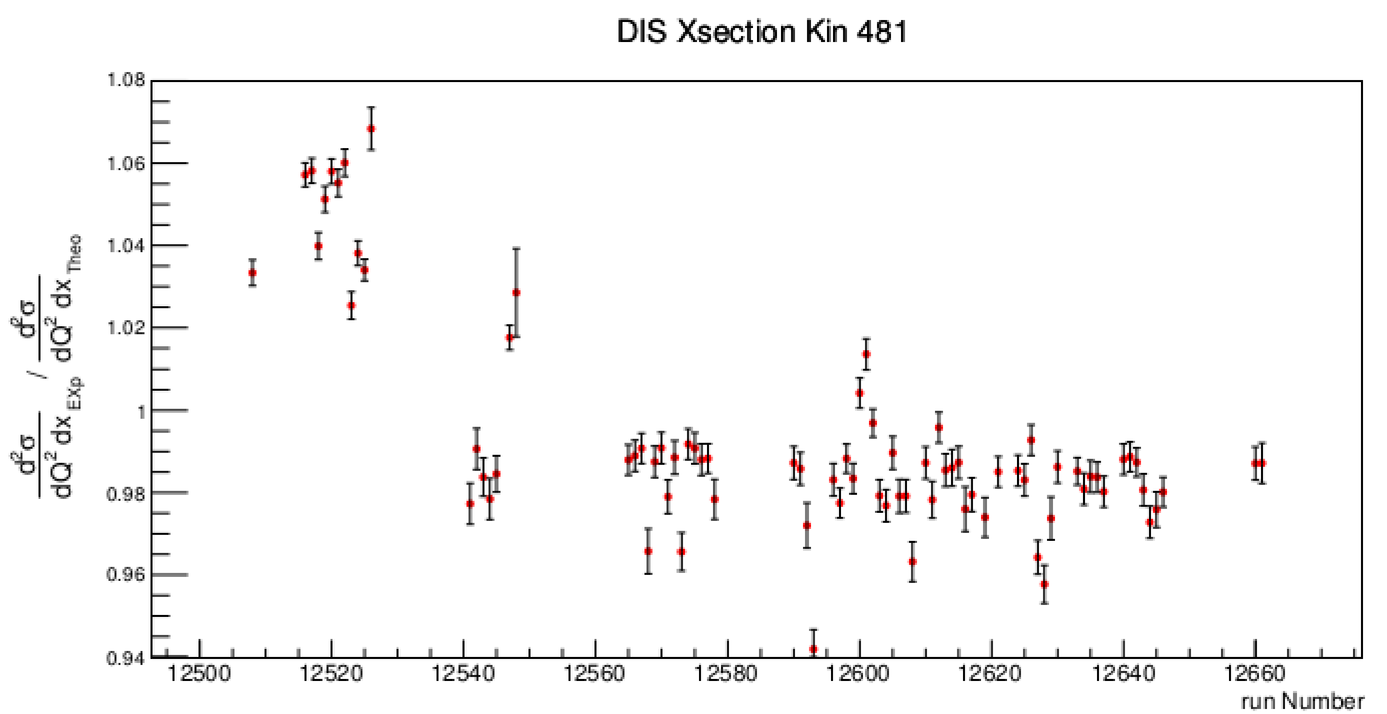
Average over quark helicity
Unpolarized

Difference of quark helicity
Polarized

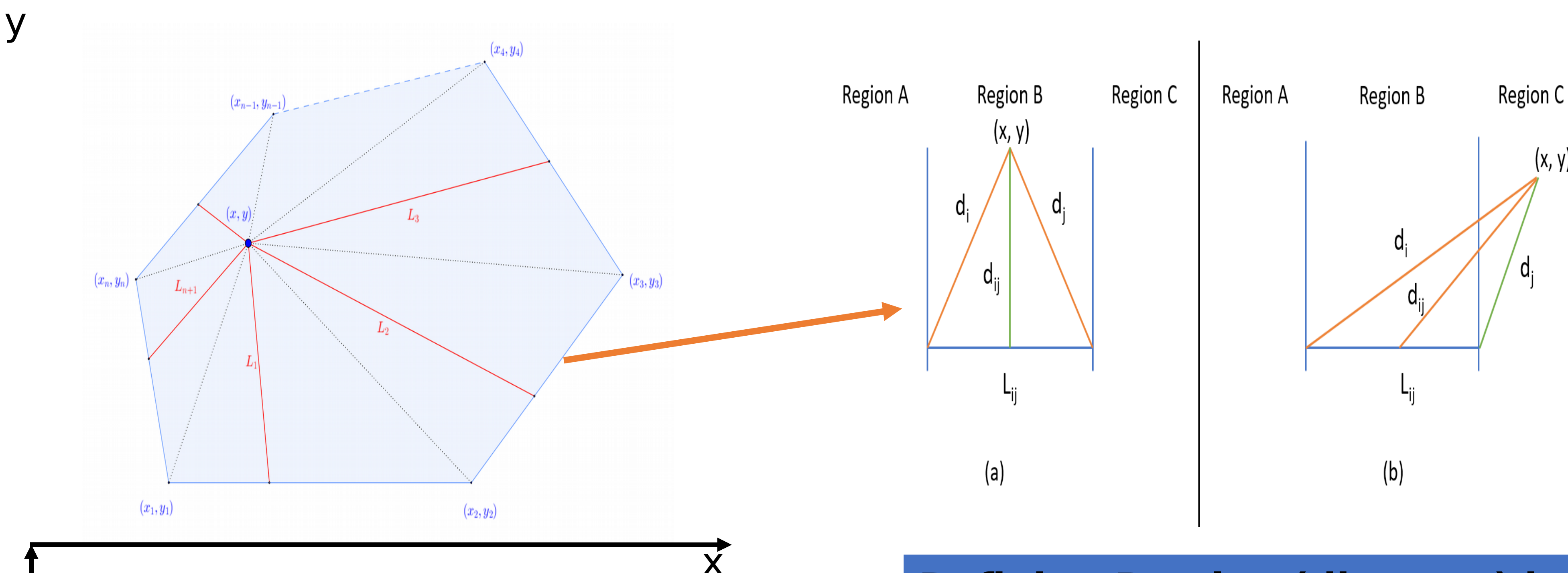
M. Guidal et al 2013 Rep. Prog. Phys. **76** 066202

- Q^2 = 1.5, 1.9, 1.75 GeV2, x_B = 0.36


DIS Xsection Kin 601
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.9
14200
14400
14600
14800
15000
15200
run Number


DIS Xsection Kin 481
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
12500
12520
12540
12560
12580
12600
12620
12640
12660
run Number

Definition of R-value



Defining a polygon in xy-plane

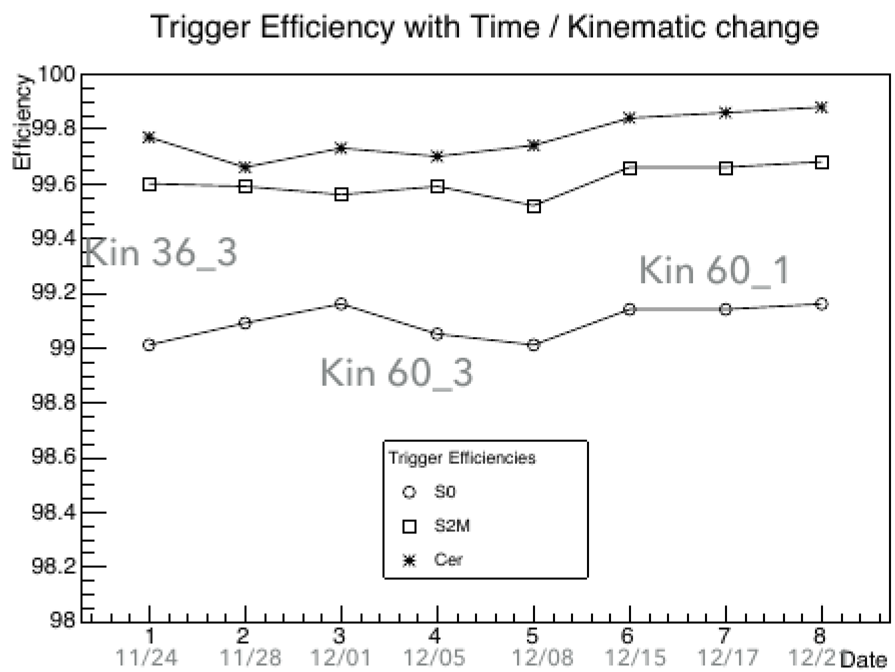
the test point is inside the polygon R-value > 0
the test point is outside the polygon R-value <0
the test point is on the boundary of the polygon

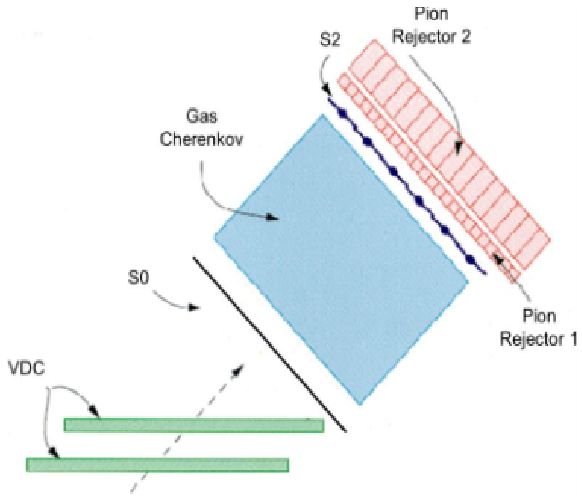
Defining R-value (distance) in one segment of a plane

Case	Condition	$d_{xy,ij}$
a	$L^2_{ij} + d^2_i - d^2_j > 0$ and $L^2_{ij} + d^2_j - d^2_i > 0$	d_{ij}
b	$L^2_{ij} + d^2_i - d^2_j \leq 0$ or $L^2_{ij} + d^2_j - d^2_i \leq 0$	Min(d_i, d_j)

Z. Chai PHD thesis (2003)

Trigger efficiency studies (H. Rashad)





- DVCS production is triggered by S2M && Cherenkov in coincidence with DVCS calorimeter
- S0, S2M, and Cherenkov all have > 99% efficiency