The Generalized Polarizabilities of the Proton

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On behalf of JLAB E12-15-001 Collaboration

HALL C COLLABORATION MEETING 02/18/2022

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- Theoretical background
- VCS Experiment E12-15-001
- Analysis Progress
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Polarizabilities

Polarizability:

- A fundamental characteristic of the proton
- Characterizes the nucleon dynamical response to an external electromagnetic field

N BARYONS
$(S = 0, I = 1/2)$

$p, N^+ = uud; \quad n, N^0 = udd$

p

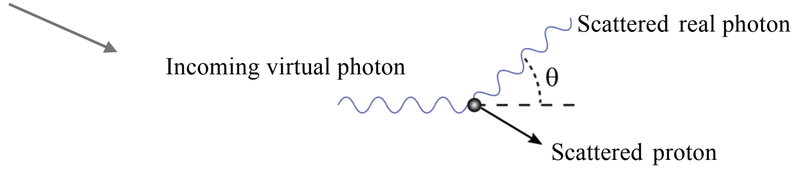
$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.00727646688 \pm 0.00000000009$ u
Mass $m = 938.272081 \pm 0.000006$ MeV [a]
$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 1.00000000000 \pm 0.00000000007$
$|q_p + q_{\overline{p}}|/e < 7 \times 10^{-10}$, CL = 90% [b]
$|q_p + q_e|/e < 1 \times 10^{-21}$ [c]
Magnetic moment $\mu = 2.7928473446 \pm 0.0000000008\ \mu_N$
$(\mu_p + \mu_{\overline{p}}) / \mu_p = (0.3 \pm 0.8) \times 10^{-6}$
Electric dipole moment $d < 0.021 \times 10^{-23}$ e cm
Electric polarizability $\alpha = (11.2 \pm 0.4) \times 10^{-4}$ fm^3
Magnetic polarizability $\beta = (2.5 \pm 0.4) \times 10^{-4}$ fm^3 (S = 1.2)
Charge radius, μp Lamb shift = 0.84087 ± 0.00039 fm [d]
Charge radius, ep CODATA value = 0.8751 ± 0.0061 fm [d]
Magnetic radius = 0.78 ± 0.04 fm [e]
Mean life $\tau > 2.1 \times 10^{29}$ years, CL = 90% [f] ($p \rightarrow$ invisible mode)
Mean life $\tau > 10^{31}$ to 10^{33} years [f] (mode dependent)

→ Scaler GP at the four-momentum transferred squared Q^2=0 (RCS limit)

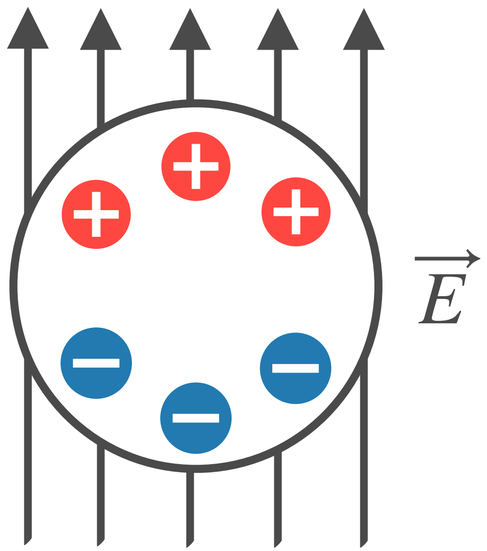
Generalized Polarizabilites (GPs):

- Access by Virtual Compton Scattering (VCS)



- Two scaler and four vector GPs
- Fourier transform can map out the spatial distribution density of the polarization induced by an EM field

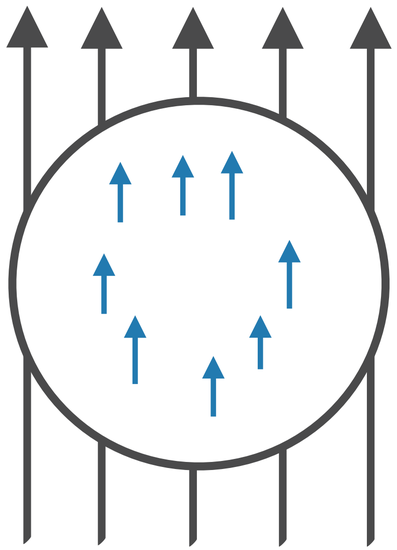
Generalized Polarizabilities

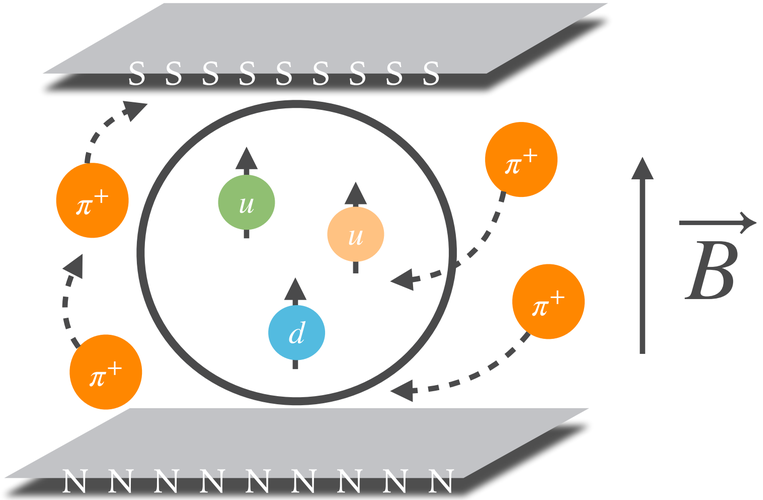


$$\vec{p} = \alpha_E \vec{E}$$

Electric Polarizability

- Electric polarizability α_E reflects the rigidity of proton





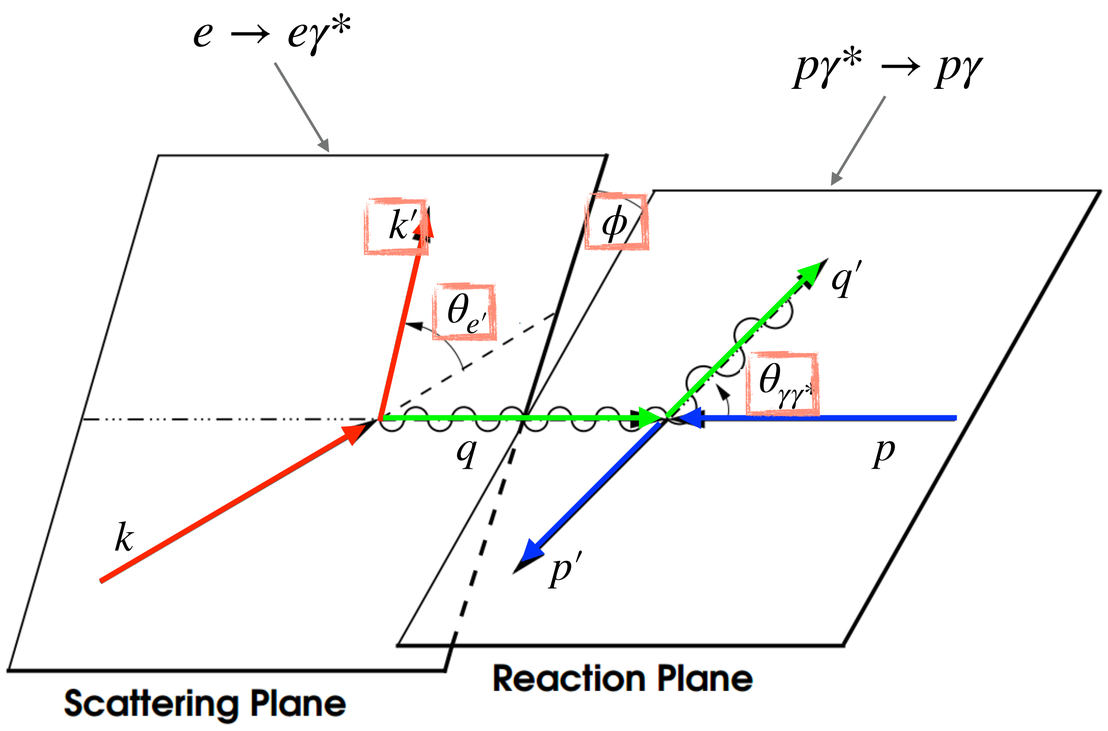
Magnetic Polarizability

$$\vec{m} = \beta_M \vec{B}$$

- Paramagnetic: >0, quarks align along magnetic field;
- Diamagnetic: <0, pion cloud induced magnetic field in opposite direction
- Partially cancels each other, makes β_M value small

Reaction & Amplitudes

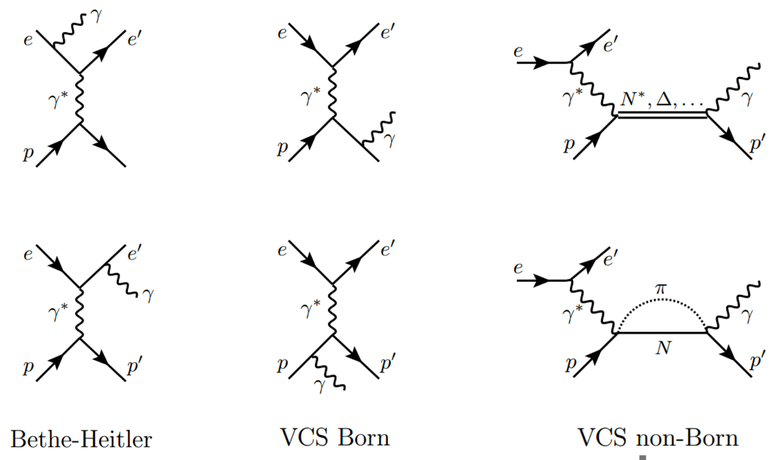
k-incoming electron q-virtual photon p-initial proton
k'-scattered electron q'-real photon p'-final proton



Kinematics of $ep \to ep\gamma$ reaction

$$\text{VCS cross-section} = d^5\sigma/(dk'_{lab}d\Omega'_{elab}d\Omega_{p_{cm}})$$

VCS process → photon electro-production reaction



$$\alpha_{E1}(Q^2) = -\frac{e^2}{4\pi}\cdot\sqrt{\frac{3}{2}}\cdot P^{(L1,L1)0}(Q^2) \qquad \beta_{M1}(Q^2) = -\frac{e^2}{4\pi}\cdot\sqrt{\frac{3}{8}}\cdot P^{(M1,M1)0}(Q^2)$$

Electric Scaler GP

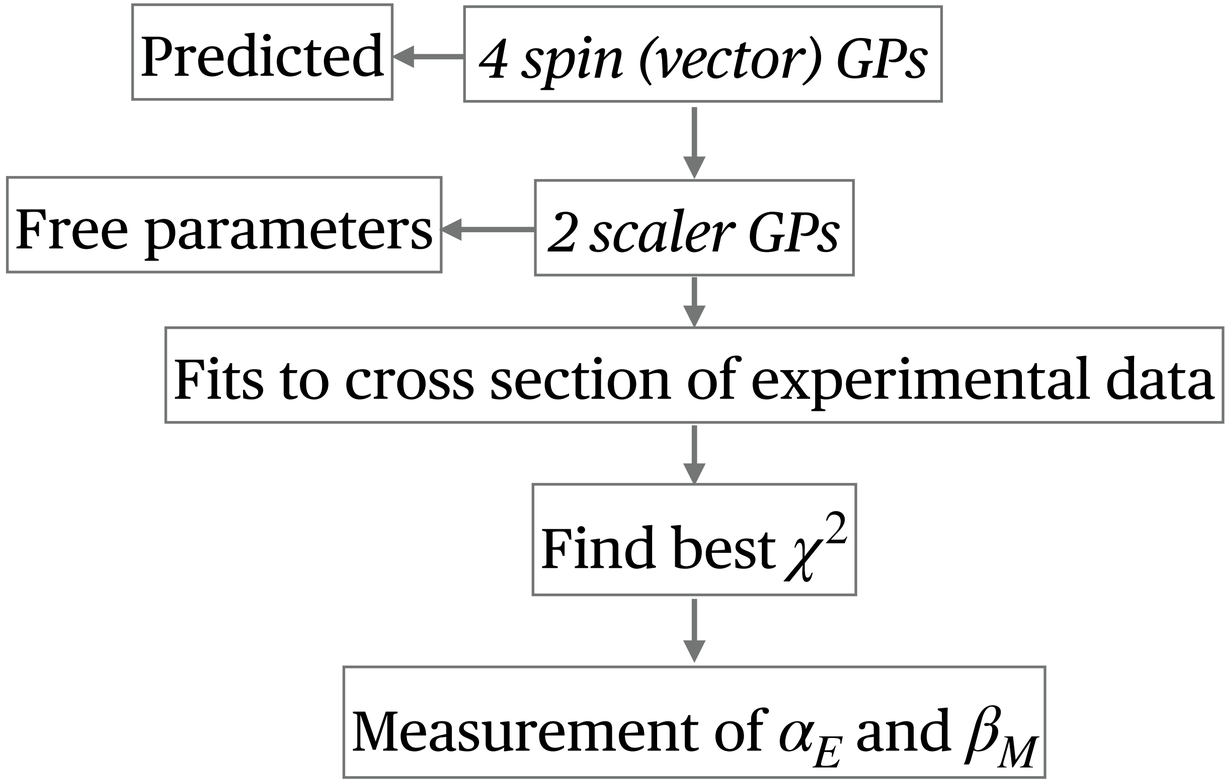
Magnetic Scaler GP

$P^{(\rho' L',\rho L)S}(Q^2)$

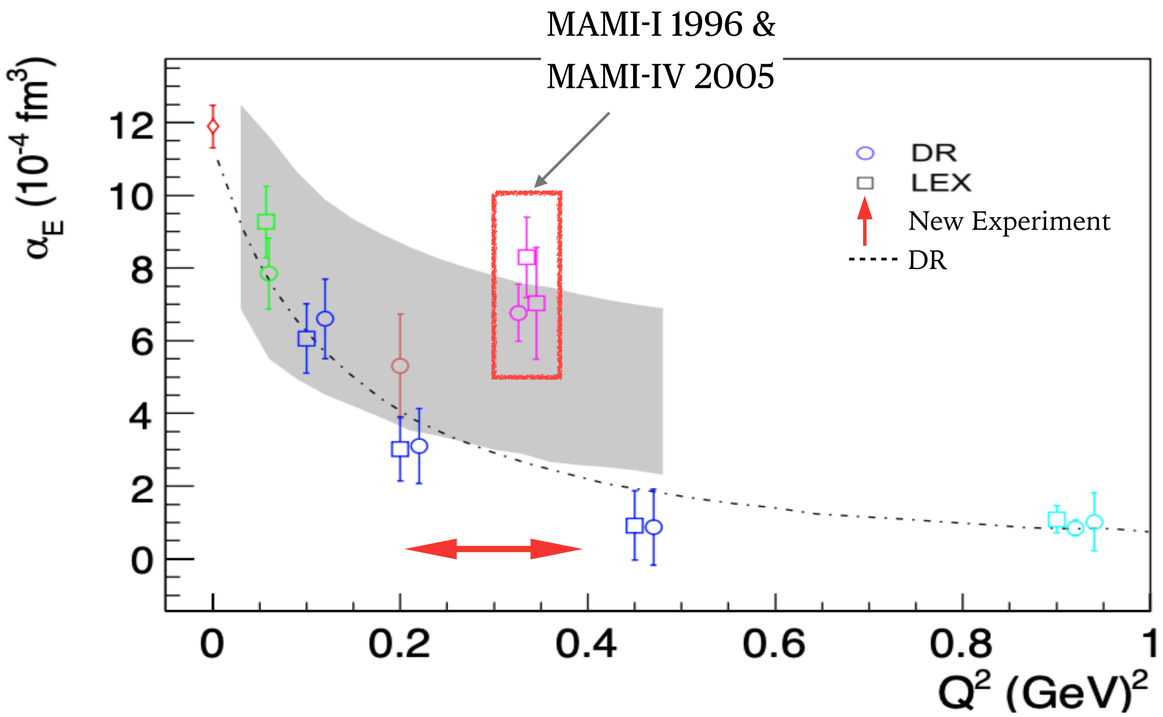
- $\rho(\rho')$ photon longitudinal or EM nature
- $L(L')$ angular momentum
- $[S = 1,0]$ spin flip or non spin flip

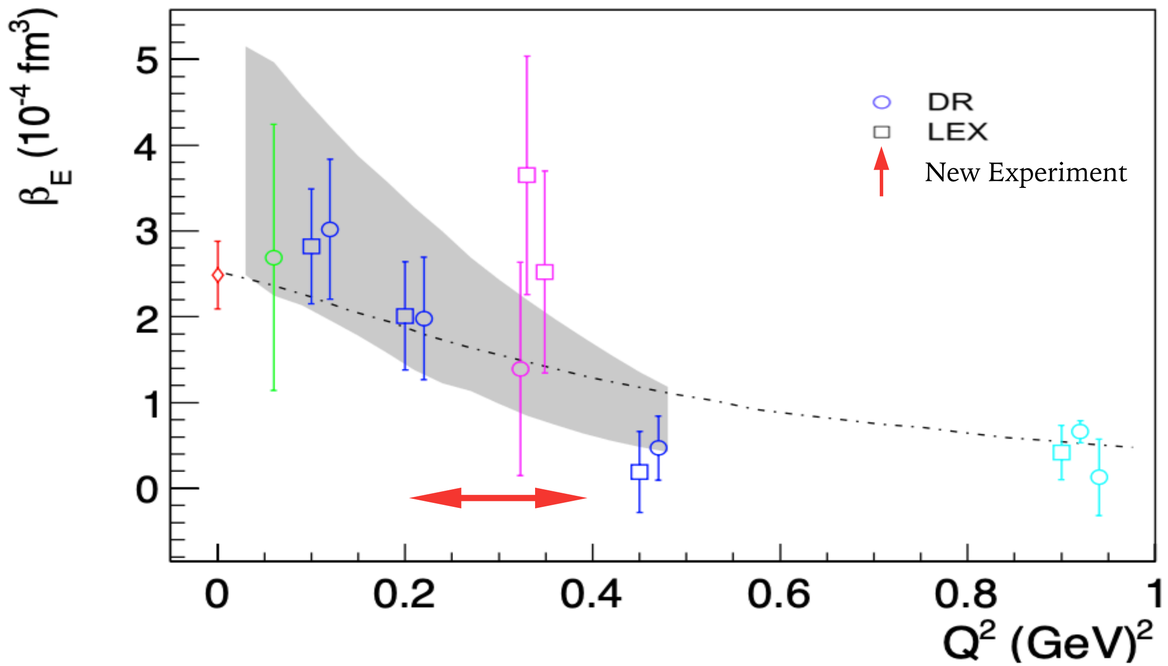
LEX & DR Formalism

- **LEX - Low Energy Expansion** *Below pion threshold*
- **DR - Dispersion Relation Formalism** *Below & Above pion threshold*



World Data & Motivation



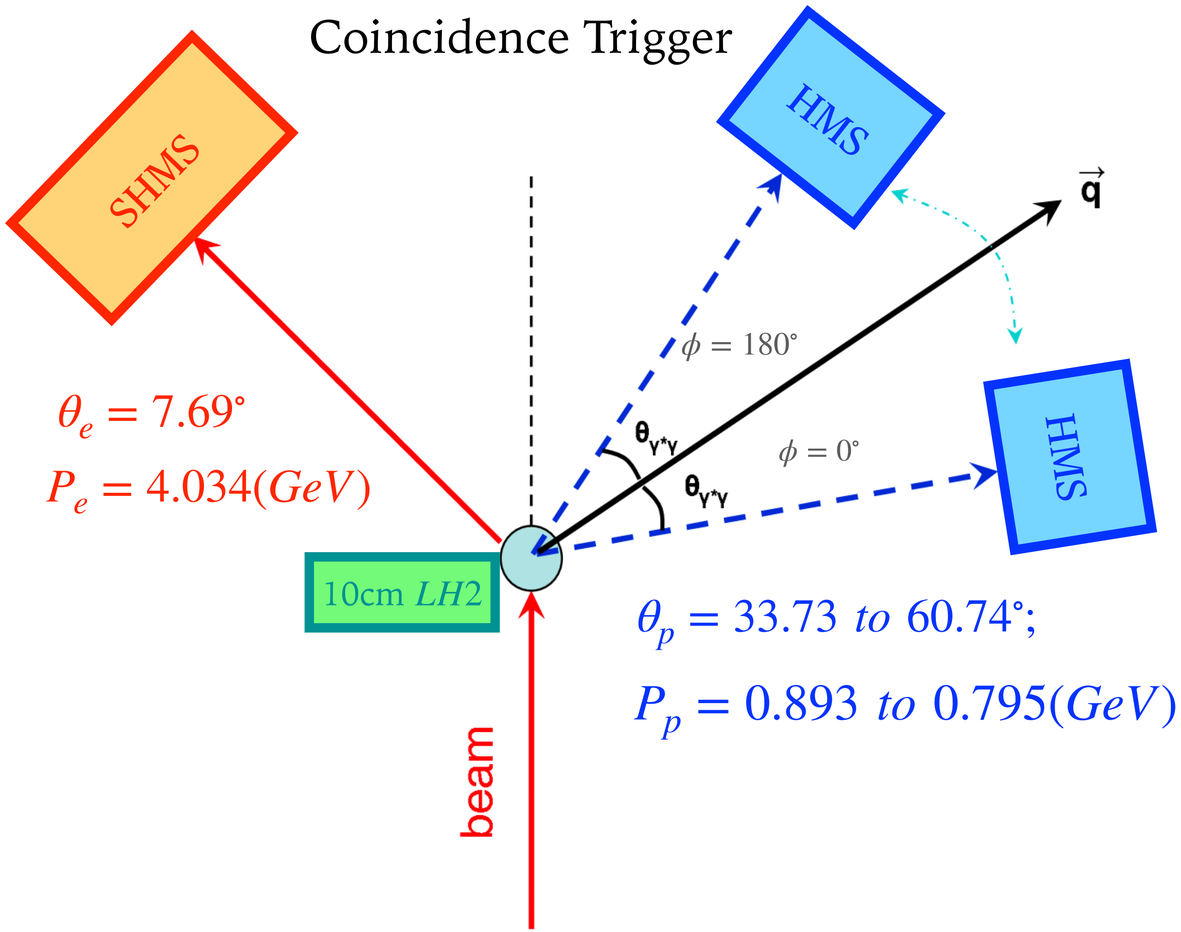


- Initial theoretical models predicted smooth fall off of α_E
  - data at $Q^2 = 0.33$ implies non-trivial structure
- New experiment can:
  - Address puzzling α_E enhancement
  - Reduce error by 2

- Small values, 1/3 ~ 1/4 of α_E
- Large uncertainties
- New experiment can:
  - Improve precision
  - Explore para-& dia-magnetic mechanism inside nucleon

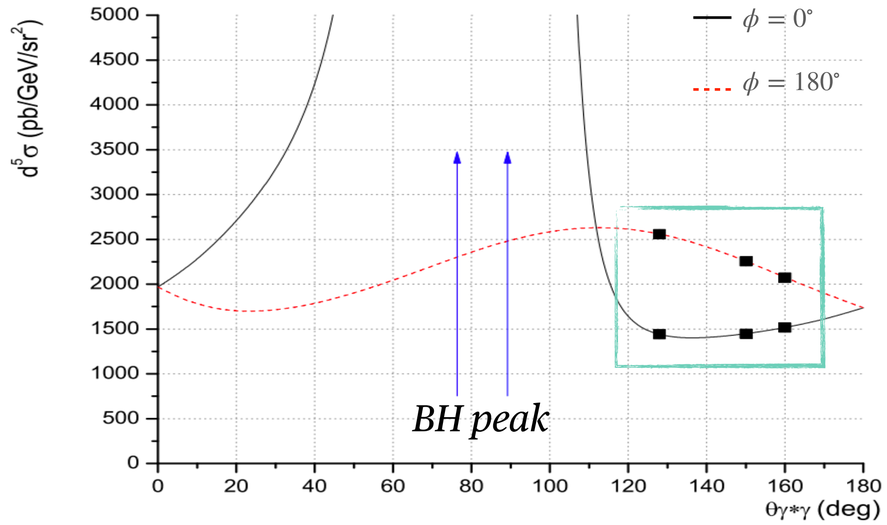
*J. Roche, et al., Phys. Rev. Lett. 85 (2000) 708-711; P. Janssens, et al., Eur. Phys. J. A37 (2008) 1-8; G. Laveissiere, et al., Phys. Rev. Lett. 93 (2004) 122001; H. Fonvieille, et al., Phys. Rev. C86 (2012) 015210;P. Bourgeois, et al., Phys. Rev. Lett. 97 (2006) 212001; Eur.Phys.J.A55(2019)no. 10,182; Phy.Rev.Lett. 123(2019)no.19,192302;Phys.Rev.C 103, 025205(2021) *Figure Credit: Hamza Atac*

JLab E12-15-001 Experiment



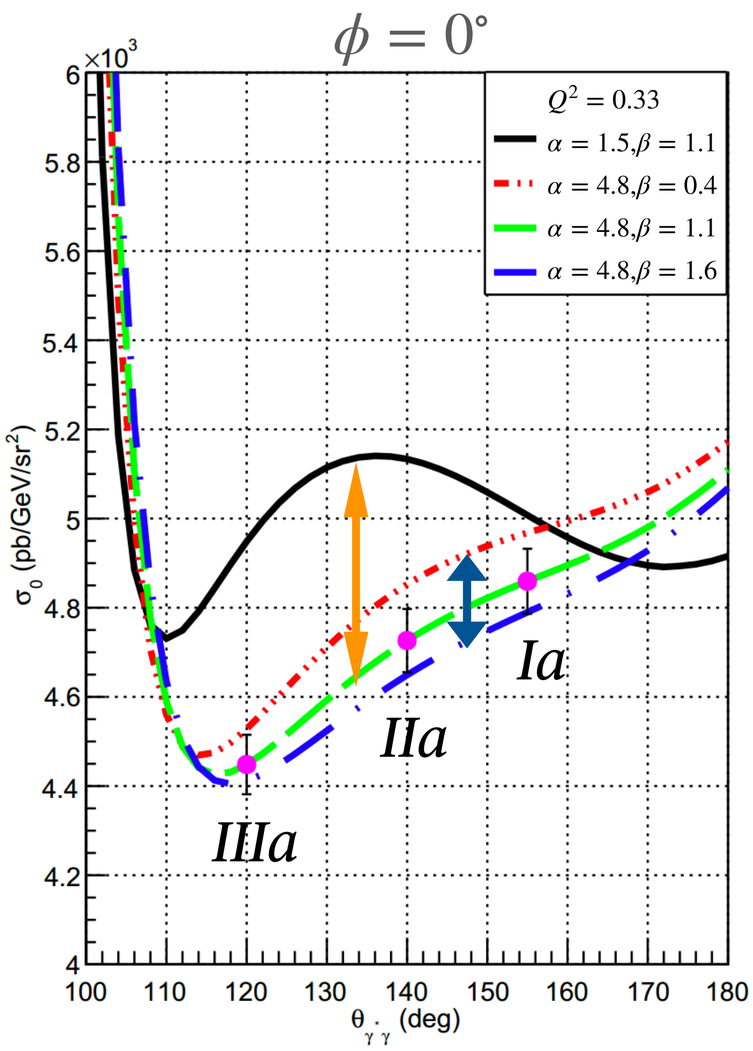
$$Asymmetries = \frac{d\sigma_{\phi=180^\circ} - d\sigma_{\phi=0^\circ}}{d\sigma_{\phi=180^\circ} + d\sigma_{\phi=0^\circ}}$$

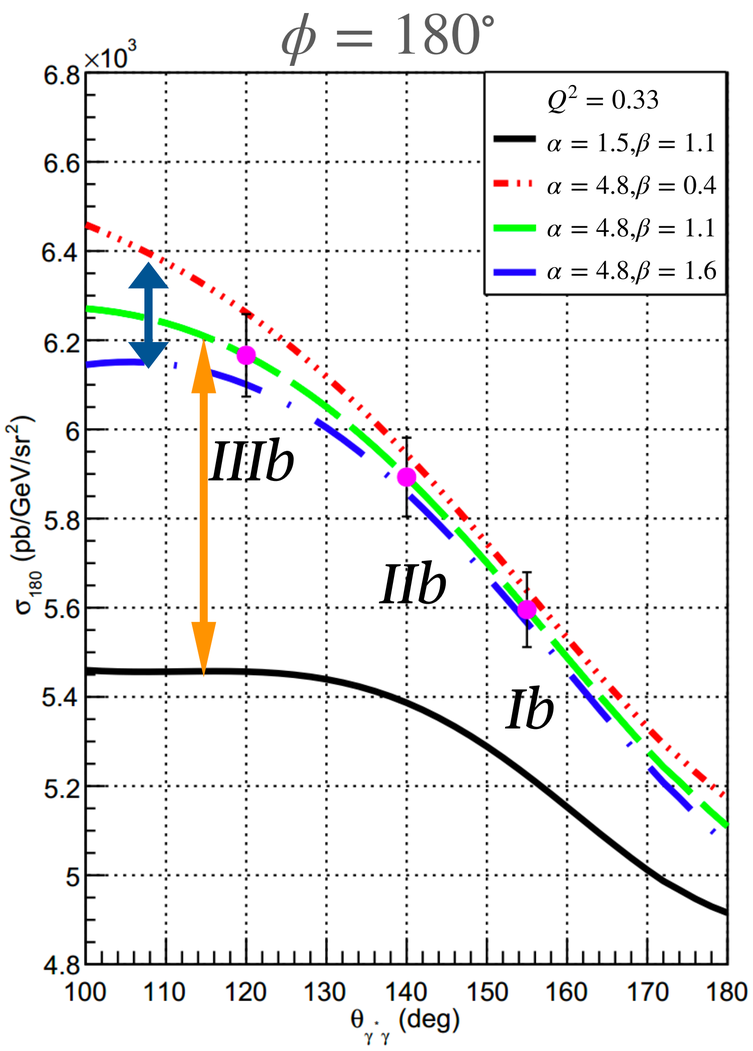
- Summer 2019: July 20 - August 5
- Beam $E = 4.56GeV$
- $Q^2 = 0.33GeV^2$, $W = 1.232GeV$



- ➤ High enough $\theta_{\gamma\gamma^*}$ to avoid BH peak
- ➤ Avoid rapid cross section variation

Predicted Measurement



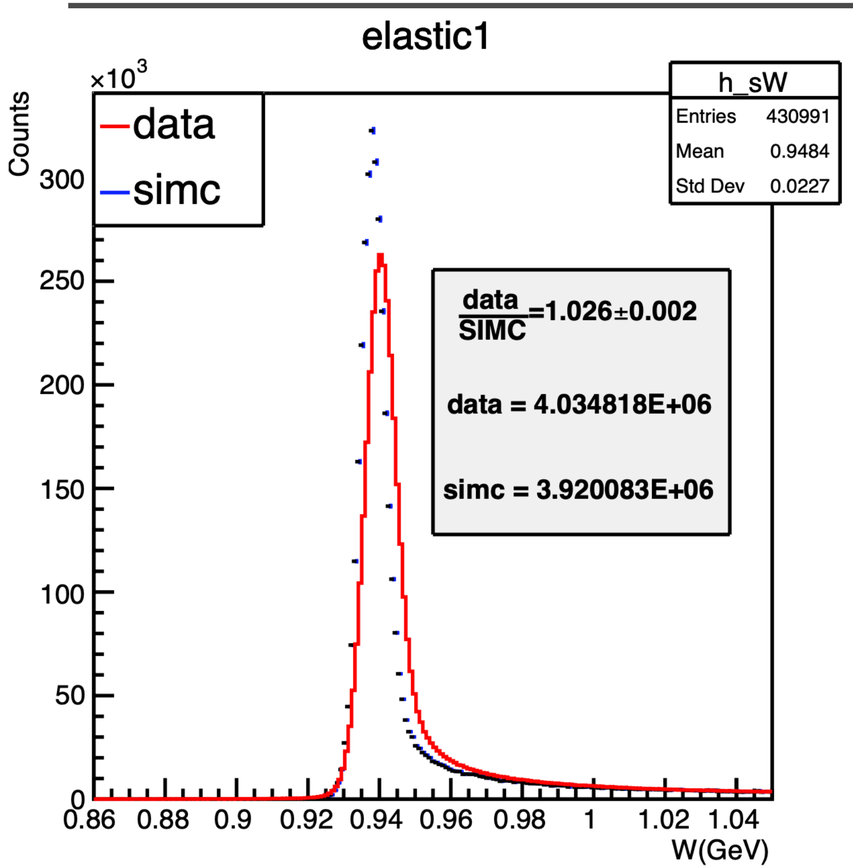


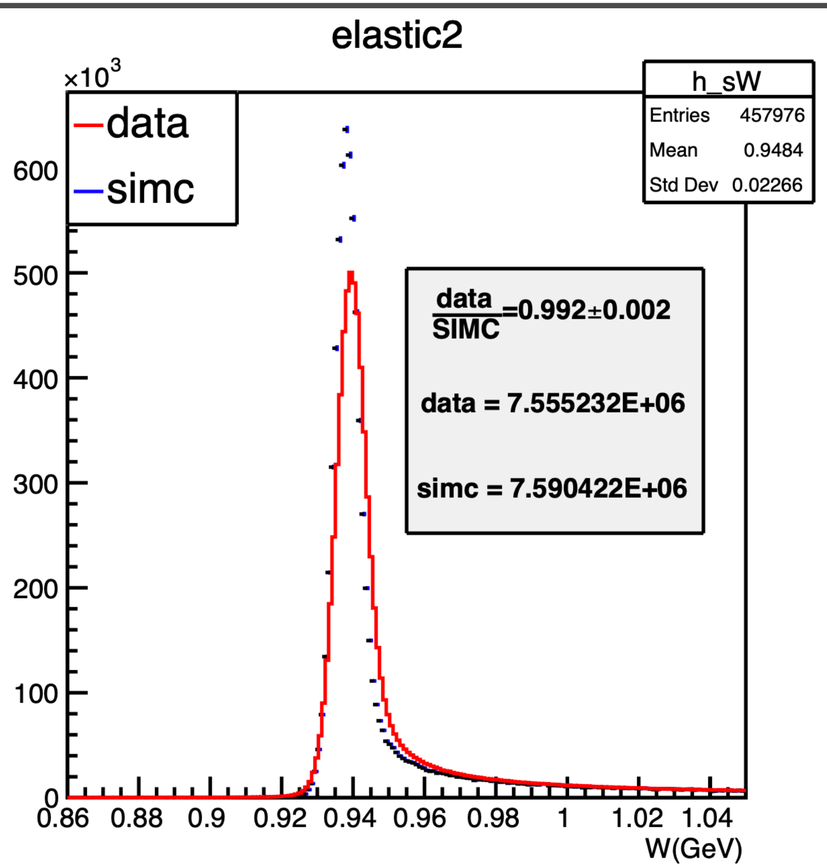
Sensitivity to α_E

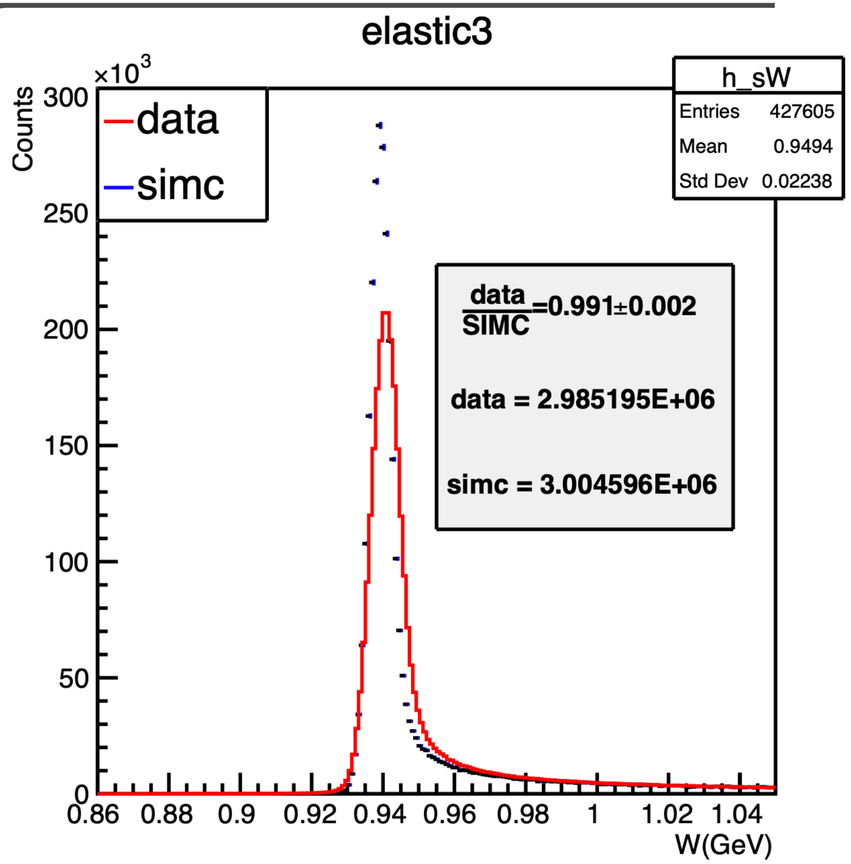
Sensitivity to β_M

- ϵ increase to 0.98
- Doubles the sensitivity to the GPs

Elastic







Kinematic	θ_e°	$P_e(GeV/c)$	θ_p°	$P_p(GeV/c)$
Elastic I	10.76	4.193	61.16	0.893
Elastic II	10.41	4.214	61.95	0.863
Elastic III	9.64	4.259	63.76	0.795

Cuts:

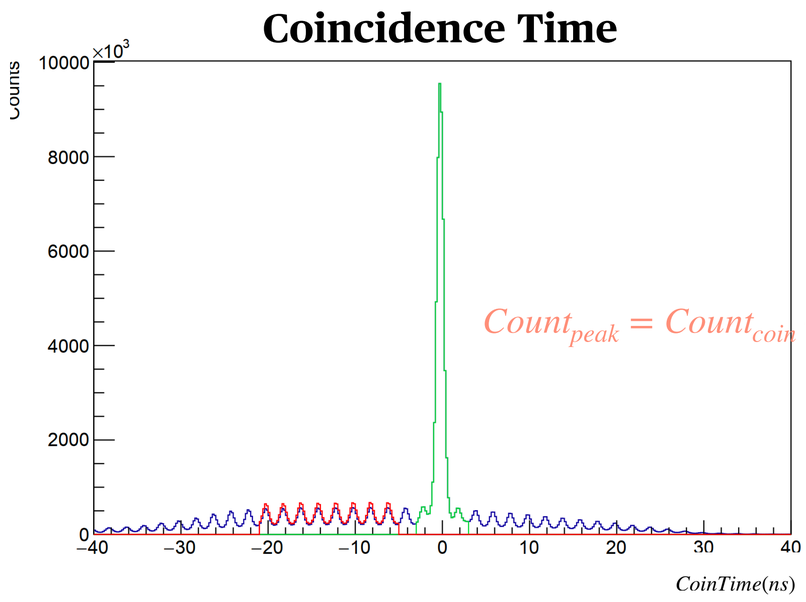
abs(HMS_dp)<8

-10<SHMS_dp<22

g.evtyp==4

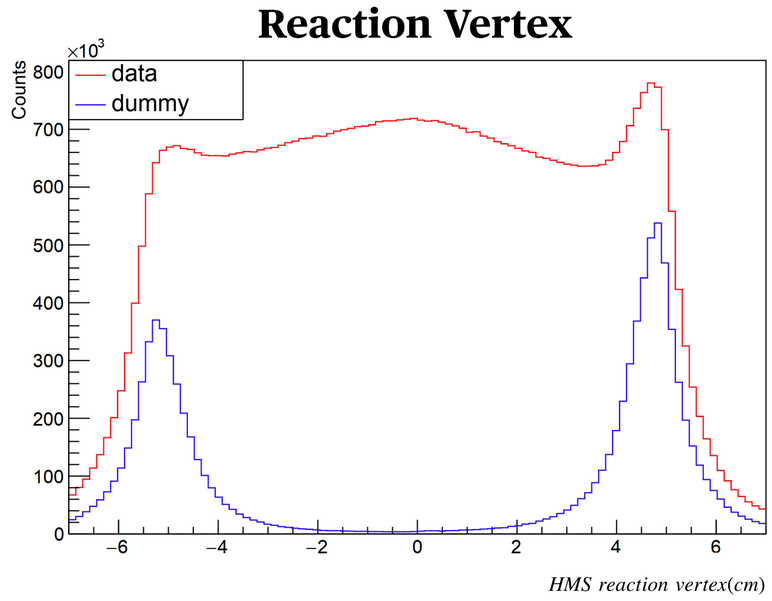
0.85 < W < 1.05

VCS peak and pi0 peak

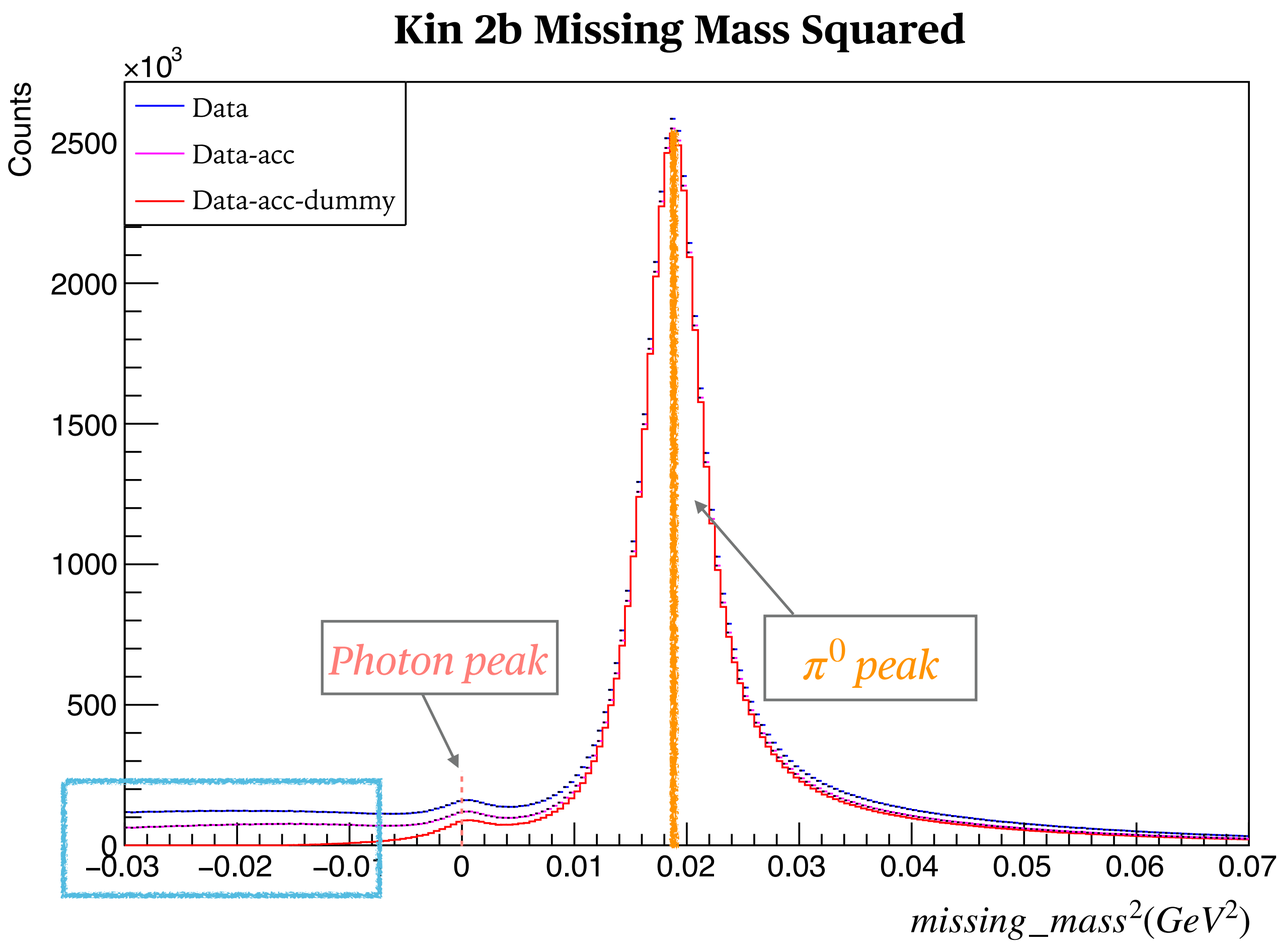


$$Count_{peak} = Count_{coin} - \frac{3}{8} Count_{acc}$$

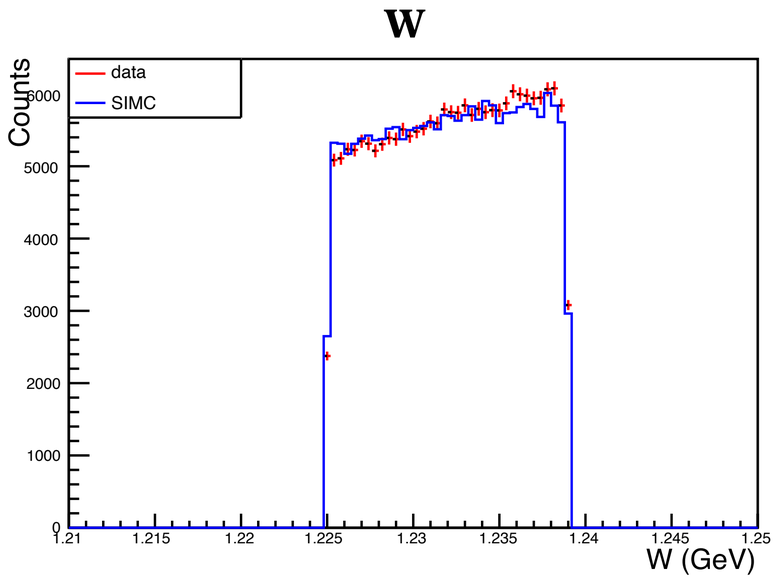
Accidentals subtraction

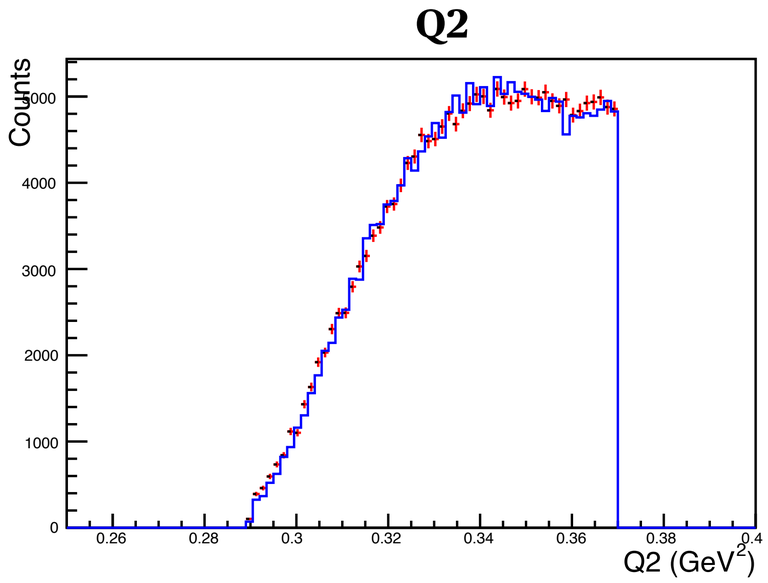


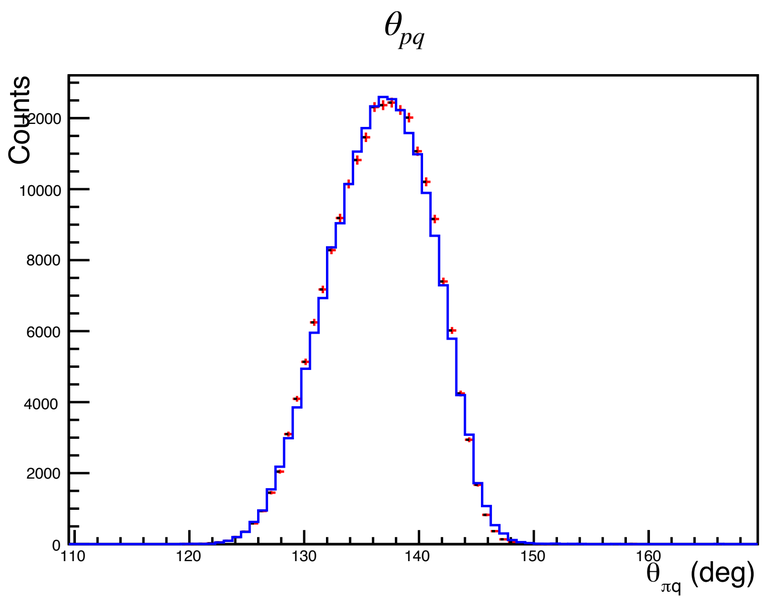
Dummy subtraction

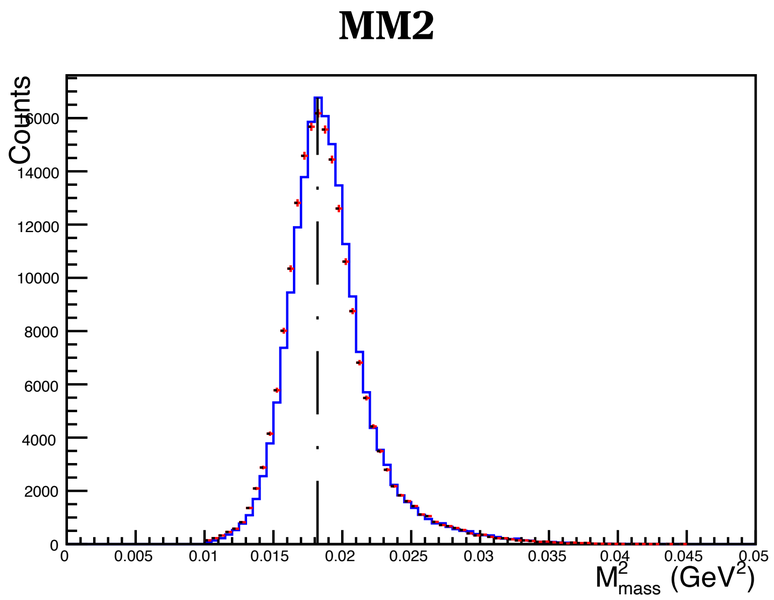


Pion Preliminary Analysis









Kin2b

data vs. MAID

Cuts:

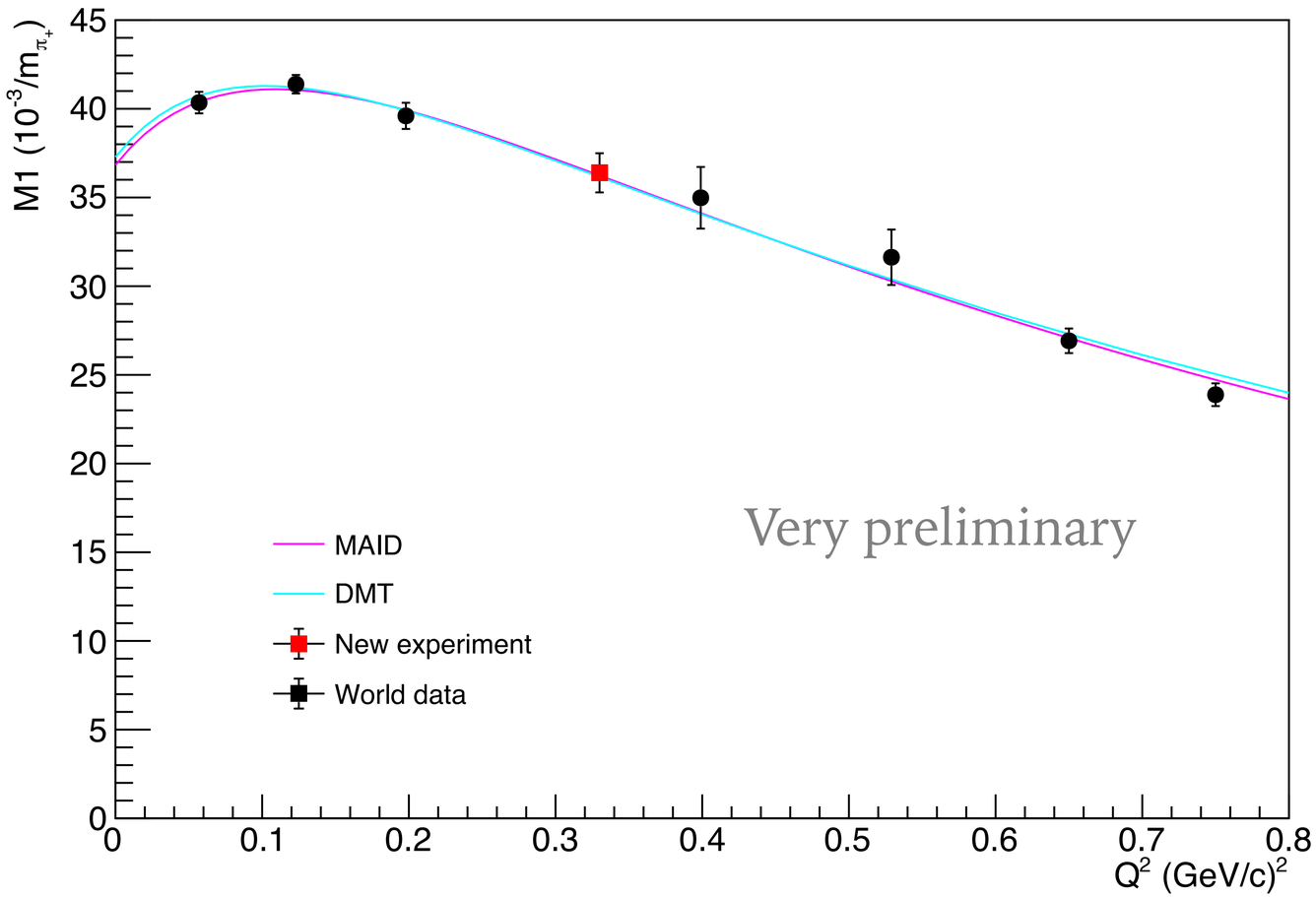
$0.01 < mm2 < 0.05\ (GeV^2)$

$abs(W - 1.232) < 0.007\ (GeV)$

$abs(Q2\text{-}0.33) < 0.04\ (GeV^2)$

$abs(\phi_{pq} - \phi_{center}) < 25\ (deg)$

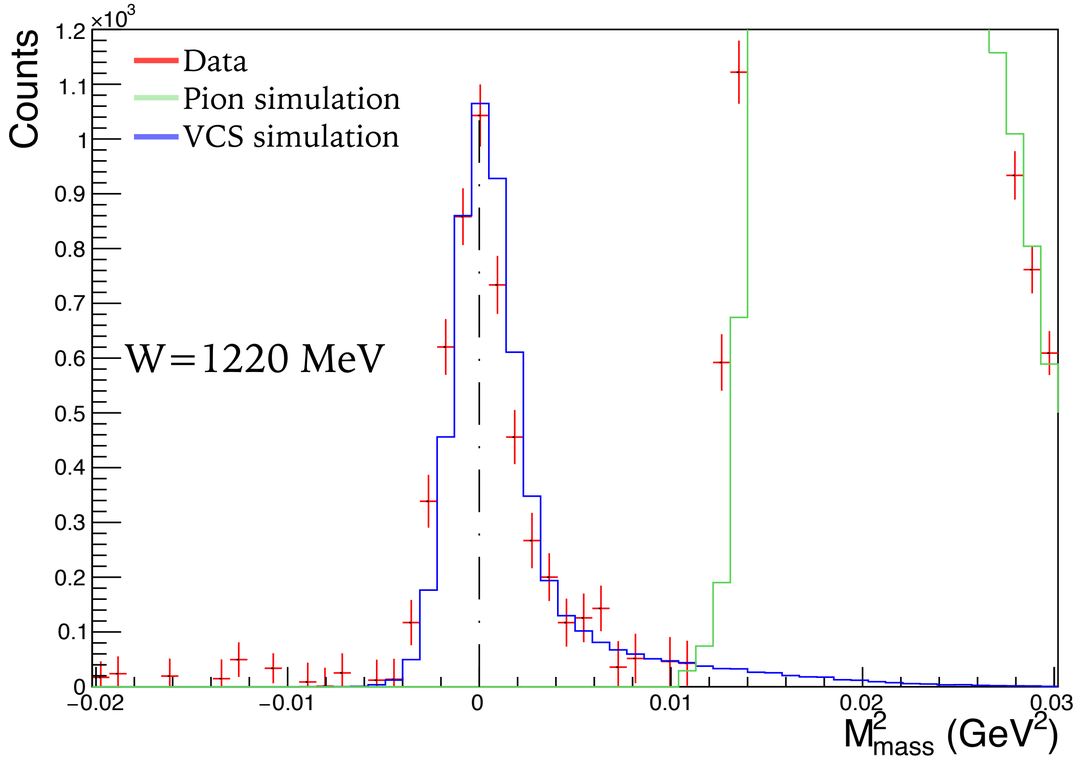
Pion Preliminary Analysis

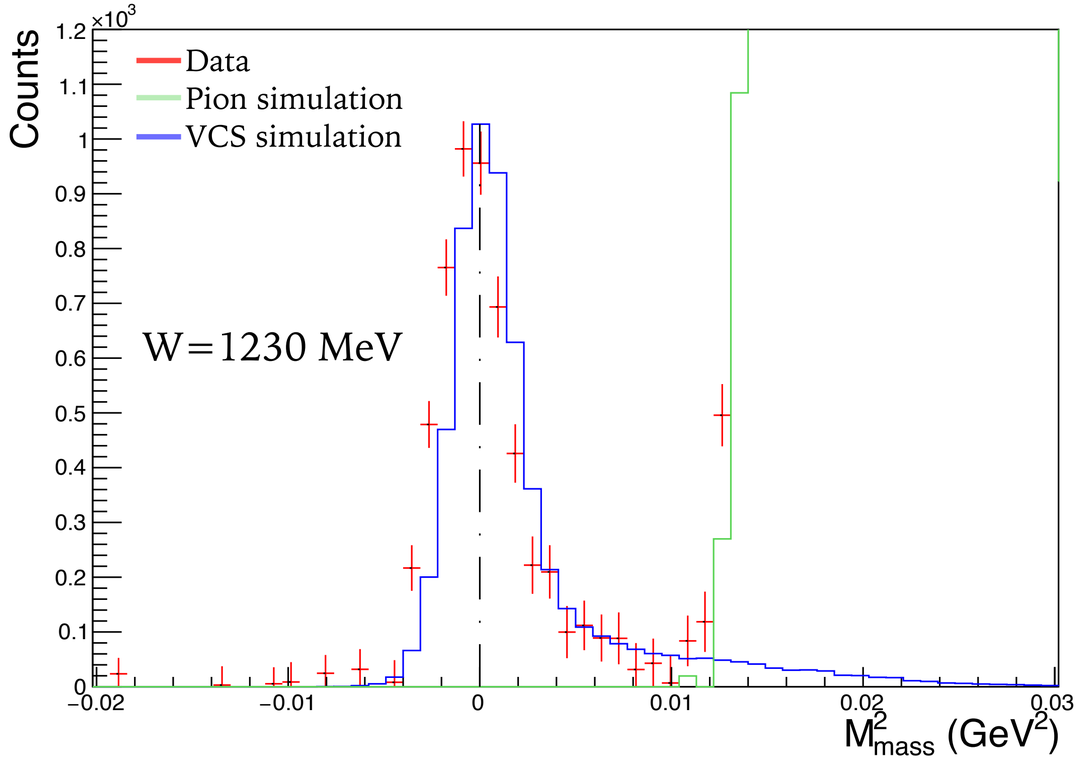


M1 - Magnetic dipole amplitude

Normalization wise good

VCS Preliminary Analysis





Cuts:

$abs(mm2) < 0.01\ (GeV^2)$

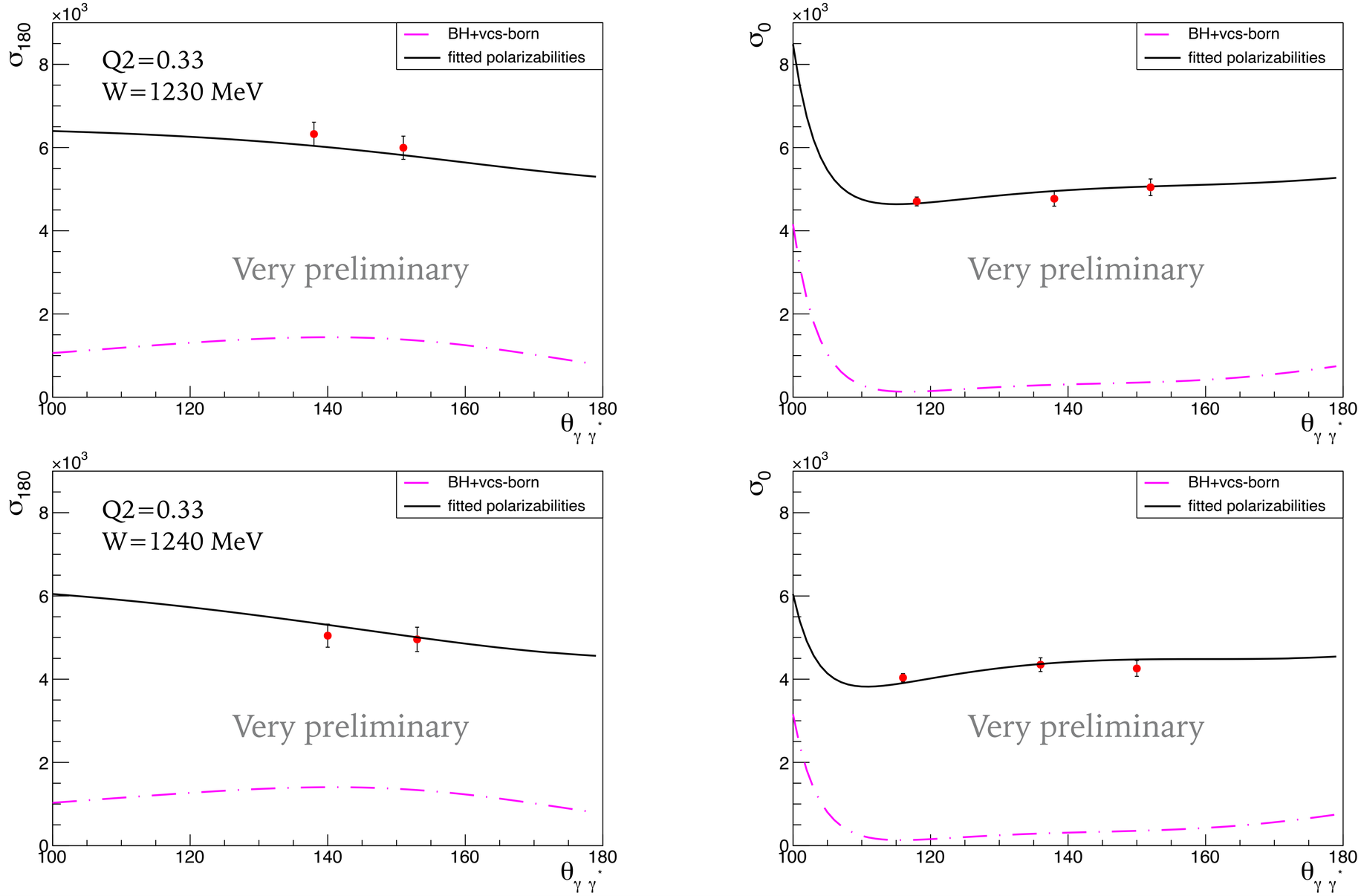
$abs(W - W_{center}) < 0.007\ (GeV)$

$abs(Q2\text{-}0.33) < 0.035\ (GeV^2)$

$abs(\theta_{pq} - \theta_{center}) < 4\ (deg)$

$abs(\phi_{pq} - \phi_{center}) < 25\ (deg)$

VCS Preliminary Analysis



Fitted polarizabilities are based on full data set for both in-plane and out-of-plane

VCS Preliminary Analysis

- Results will be extracted at Q2=0.28 , 0.33 and 0.4 GeV^2
- Preliminary results show an alphaE enhancement at Q2 region showed in previous slide
- Final results will be presented in the next few weeks

Ongoing effort: finalizing systematic uncertainties

Summary

- **GPs are fundamental structure constants**
- **Data at $Q^2 = 0.33$ implies non-trivial structure**
- **JLab E12-15-001 experiment focus on exploring the mechanism of the non-trivial $Q2$ dependence of α_E**
- **Analysis status**
  - **Detector calibration and timing cuts – completed**
  - **Elastic $H(e, e')p$ data cross section comparison at same HMS central momentum – completed**
  - **Determination spectrometer central angle and momentum offsets – completed**
  - **π^0 production cross section extraction – preliminary results**
  - **Determination of VCS cross section and extraction of α_E and β_M – preliminary results**
  - **Systematic uncertainty study - ongoing**

People

Zulkaida Akbar, Hamza Atac, Vladimir Berdnikov, Deepak Bhetuwal, Debaditya Biswas, Marie Boer, Alexandre Camsonne, Jian-Ping Chen, Eric Christy, Arthur Conover, Markus Diefenthaler, Burcu Duran, Dipangkar Dutta, Rolf Ent, Dave Gaskell, Carlos Ayerbe Gayoso, Ole Hansen,Florian Hauenstein, Nathan Heinrich, William Henry, Tanja Horn, Joshua Hoskins, Garth Huber, Shuo Jia, Mark Jones, Sylvester Joosten, Abishek Karki, Stephen Kay, Vijay Kumar, Ruonan Li, Xiaqing Li, Wenliang Li,Anusha Habarakada Liyanage, Dave Mack, Simona Malace, Pete Markowitz, Mike McCaughan, Hamlet Mkrtchyan, Casey Morean, Mireille Muhoza, Amrendra Narayan, Michael Paolone, Melanie Rehfuss, Brad Sawatzky, Andrew Smith, Greg Smith, Nikolaos Sparveris, Richard Trotta, Carlos Yero, Xiaochao Zheng, Jingyi Zhou

Spokespersons Run Coordinators Post-docs Graduate student

Thank You & Question Time

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On behalf of JLAB E12-15-001 Collaboration

Backup Slides

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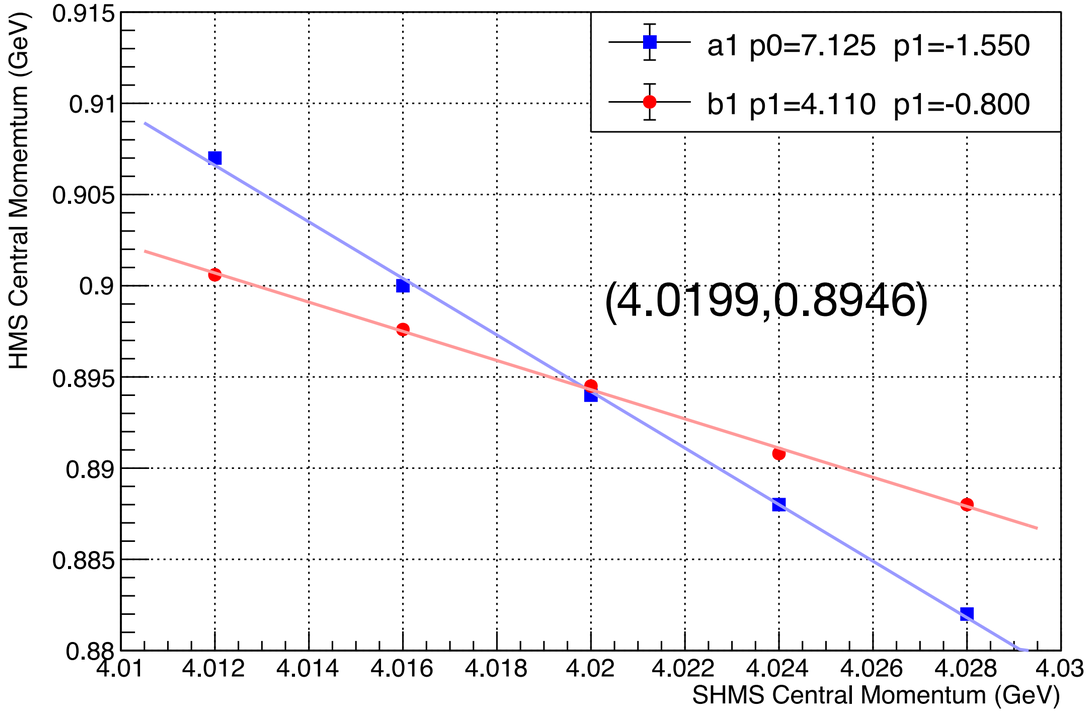
Energy Calibration

Spectrometer: Same momentum,Different HMS theta

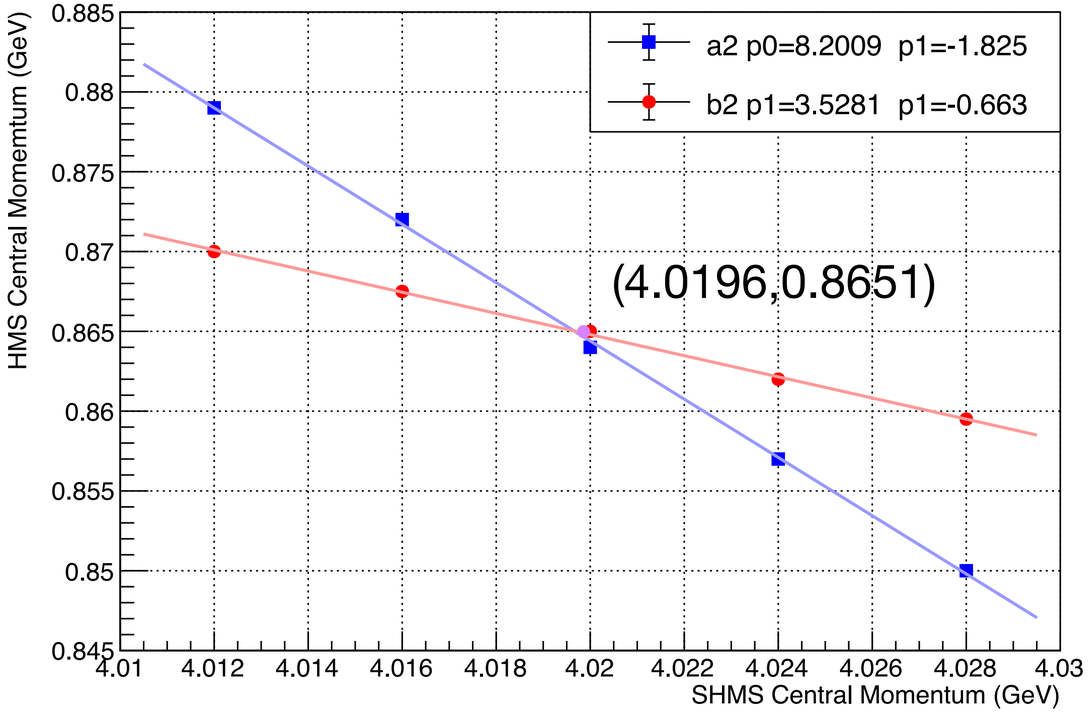
	SHMS_p	SHMS_th	HMS_p	HMS_th
Kin1a	4.034	7.69	0.893	37.33
Kin1b	4.034	7.69	0.893	51.40

	SHMS_p	SHMS_th	HMS_p	HMS_th
Kin2a	4.034	7.69	0.863	33.52
Kin2b	4.034	7.69	0.863	55.22

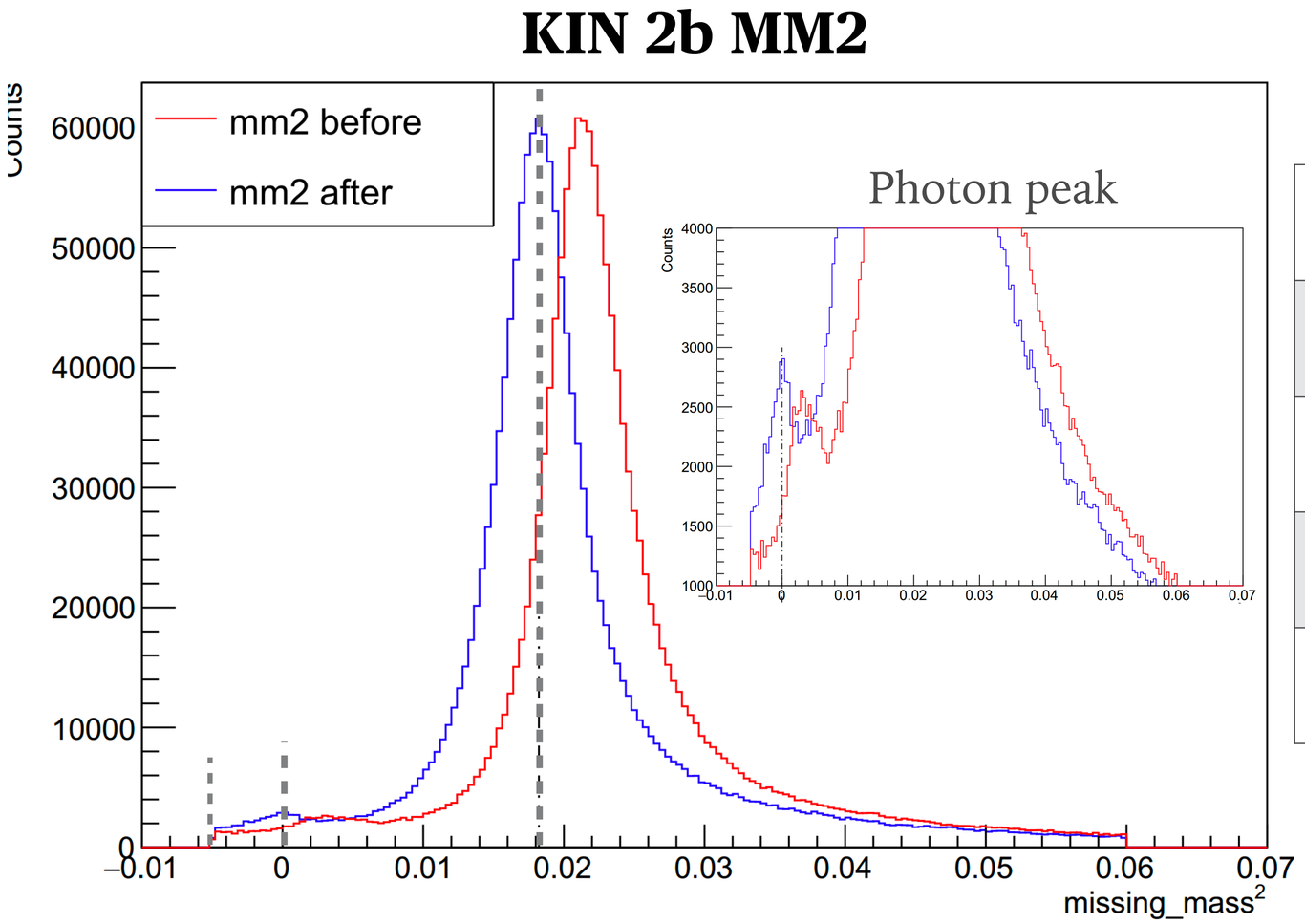
Kin 1a & Kin 1b



Kin 2a & Kin 2b



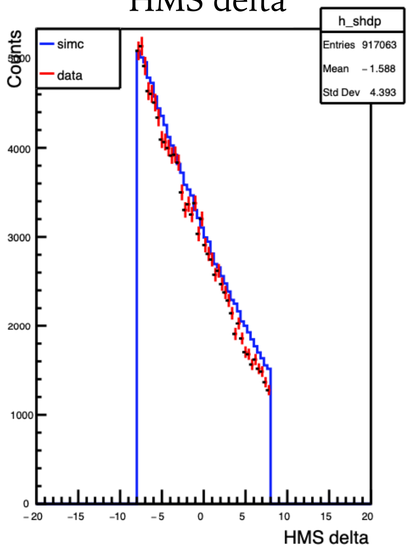
Energy Calibration



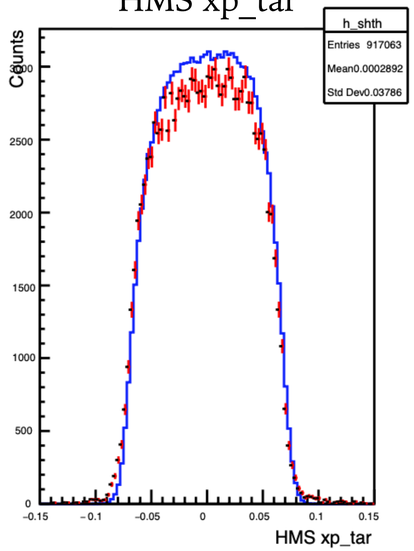
	SHMS_p Cal	SHMS_p Exp	Offset	HMS_p Cal	HMS_p Exp	Offset
Kin1a	4.0199	4.034	0.003	0.8946	0.893	0.002
Kin1b	4.0199	4.034	0.003	0.8946	0.893	0.002
Kin2a	4.0196	4.034	0.004	0.8651	0.863	0.002
Kin2b	4.0196	4.034	0.004	0.8651	0.863	0.002

Pion Preliminary Analysis

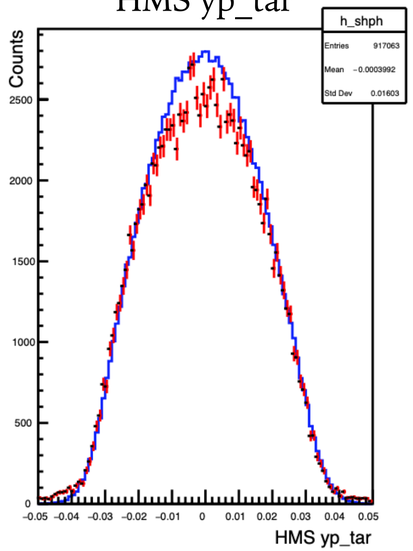
HMS delta



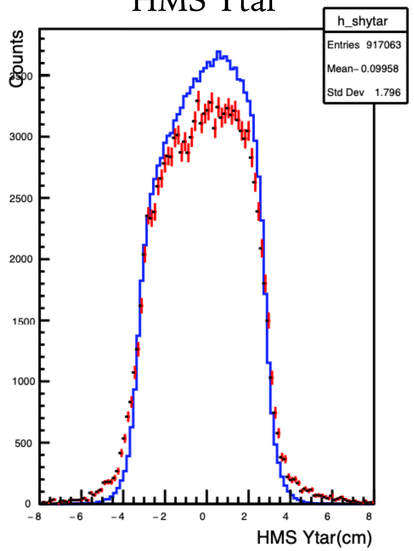
HMS xp_tar



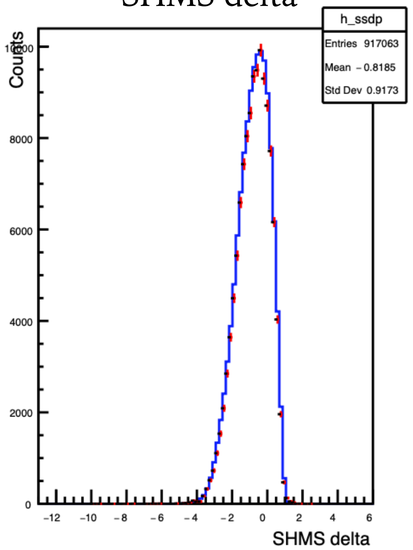
HMS yp_tar



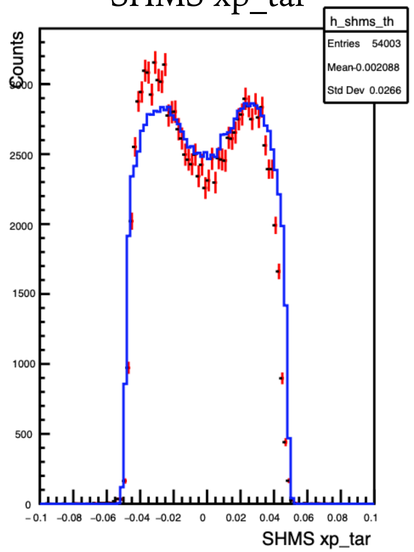
HMS Ytar



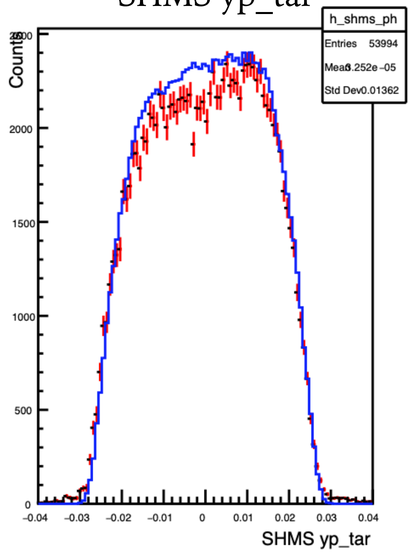
SHMS delta



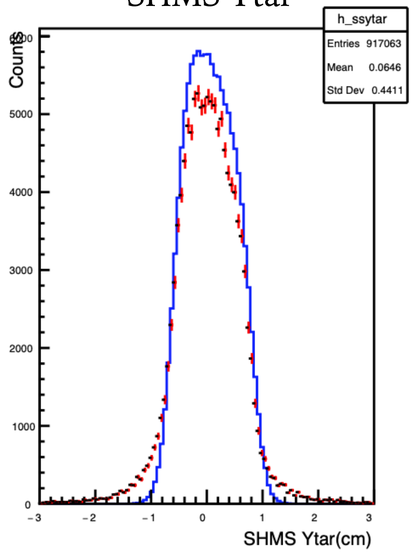
SHMS xp_tar



SHMS yp_tar

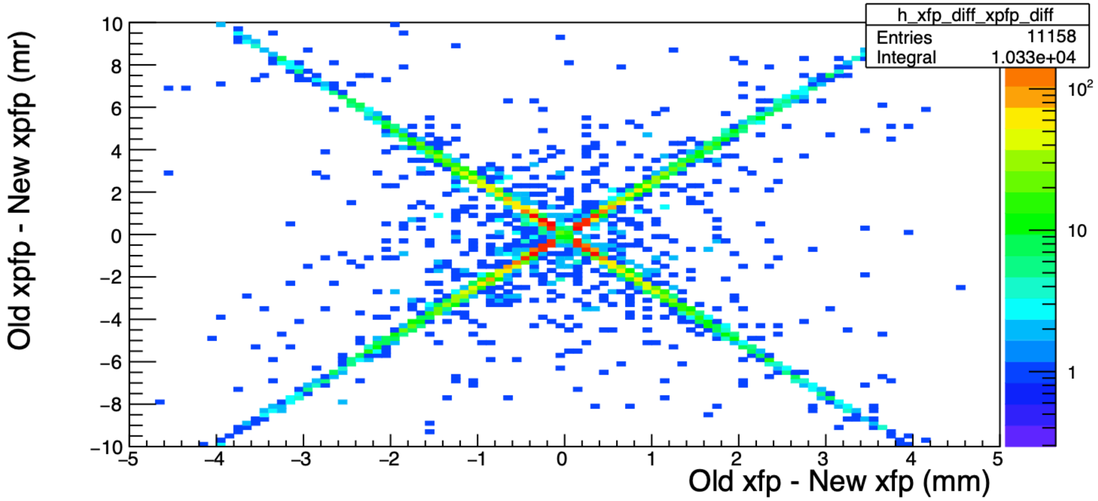


SHMS Ytar

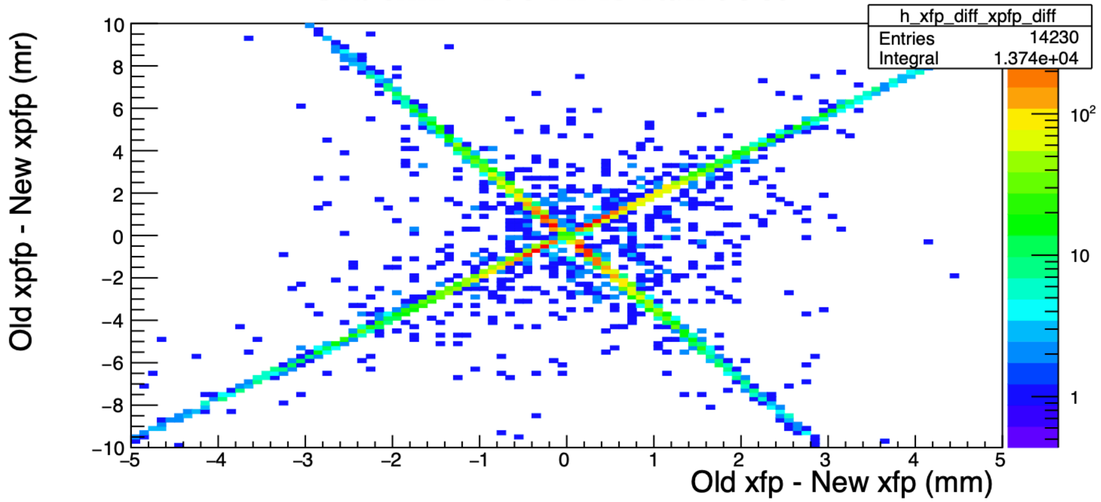


HCANA UPDATE

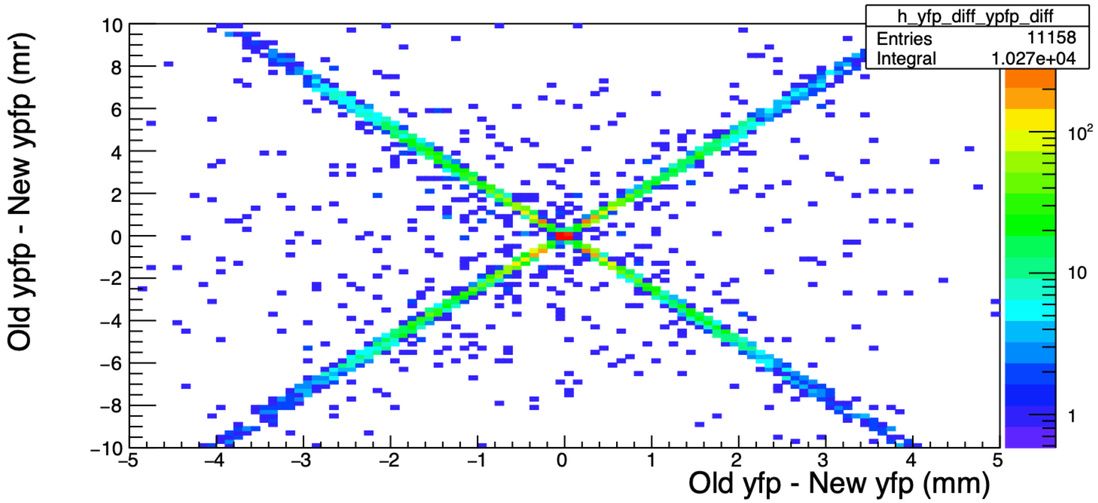
Old chi2>100 SHMS Run 9369



Old chi2>100 HMS Run 9369



Old chi2>100 SHMS Run 9369



Old chi2>100 HMS Run 9369

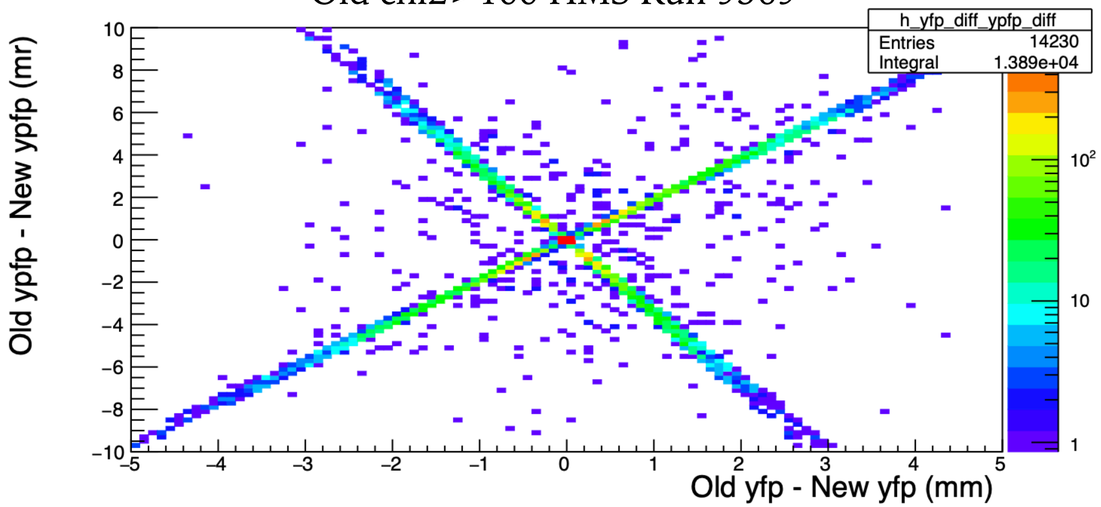


Figure Credit: Mark Jones