The Generalized Polarizabilities of the Proton

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On behalf of JLAB E12-15-001 Collaboration

JOINT HALL A & C SUMMER COLLABORATION MEETING 07/08/2021

Content

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- VCS Experiment E12-15-001
- Analysis Progress
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  - Pion Preliminary Analysis
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- Summary

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

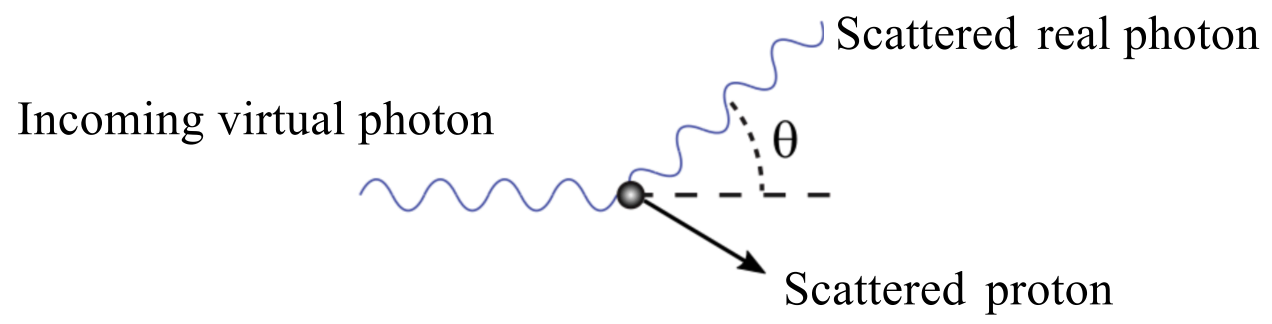
p $\qquad I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

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] ($p \to$ 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)

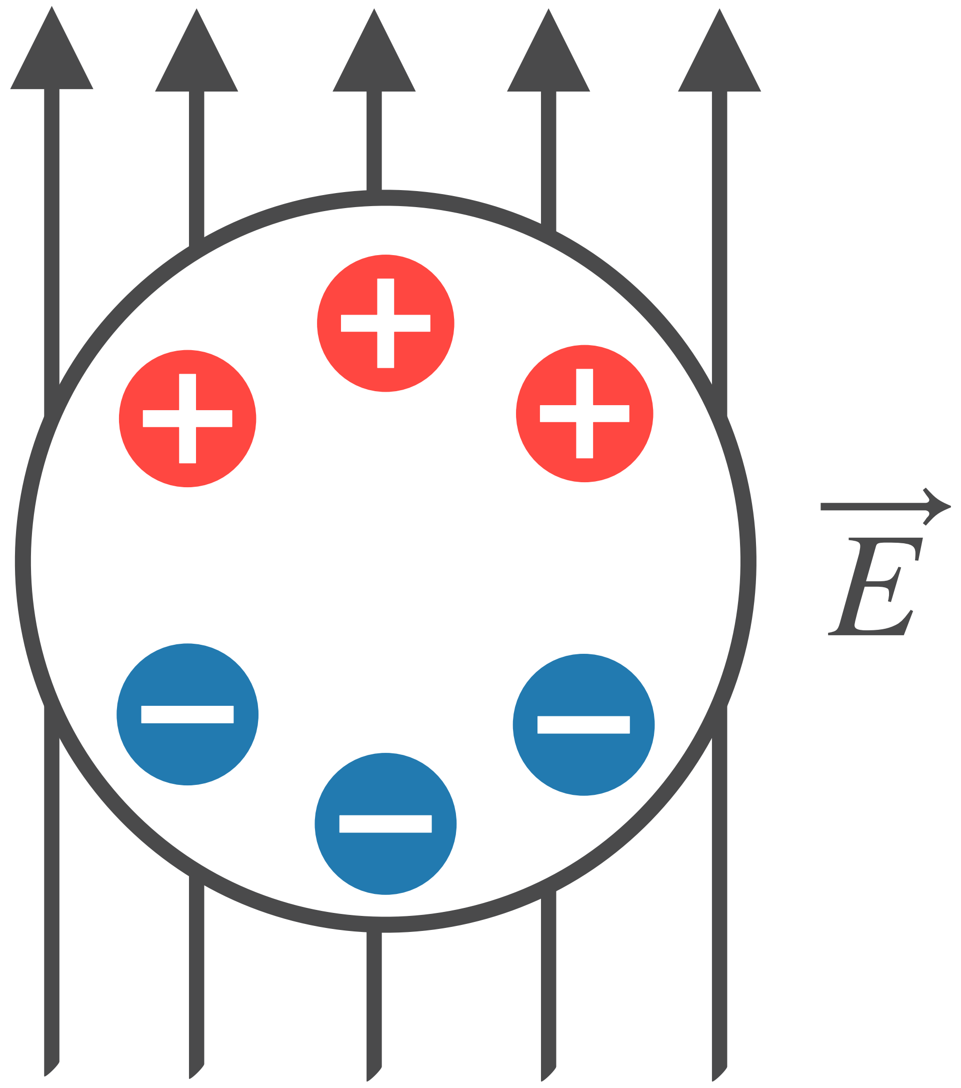
Generalized Polarizabilites (GPs):

- 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

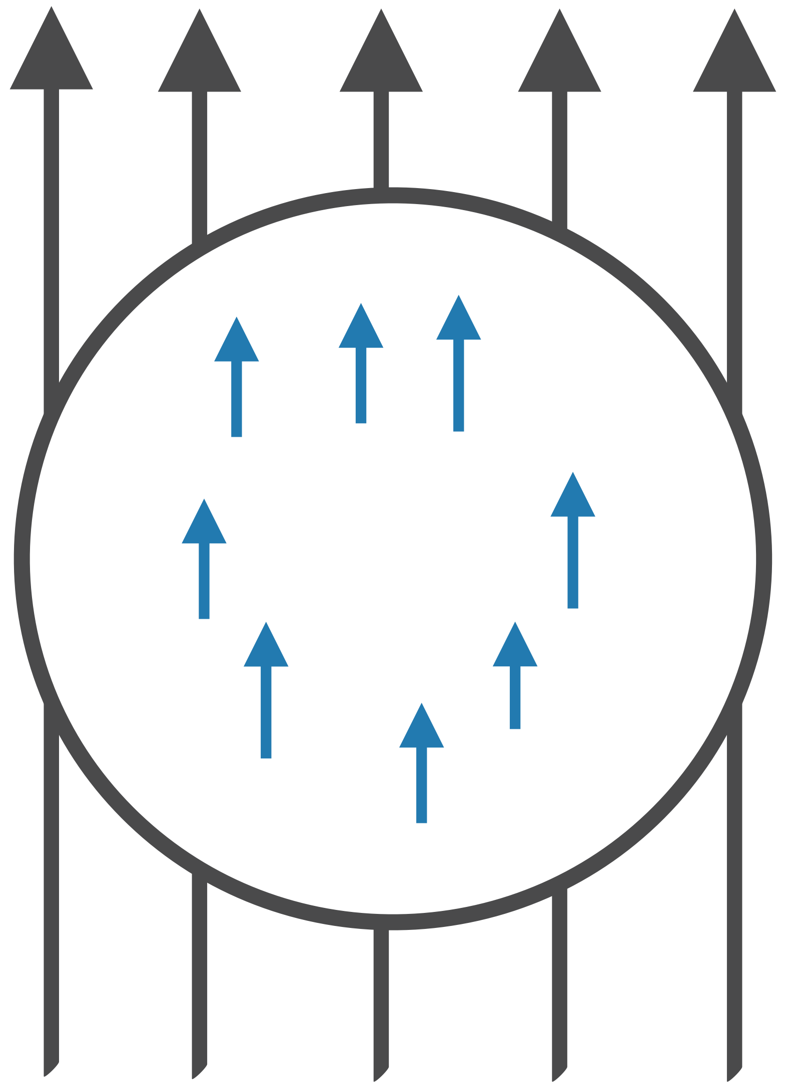
Generalized Polarizabilities

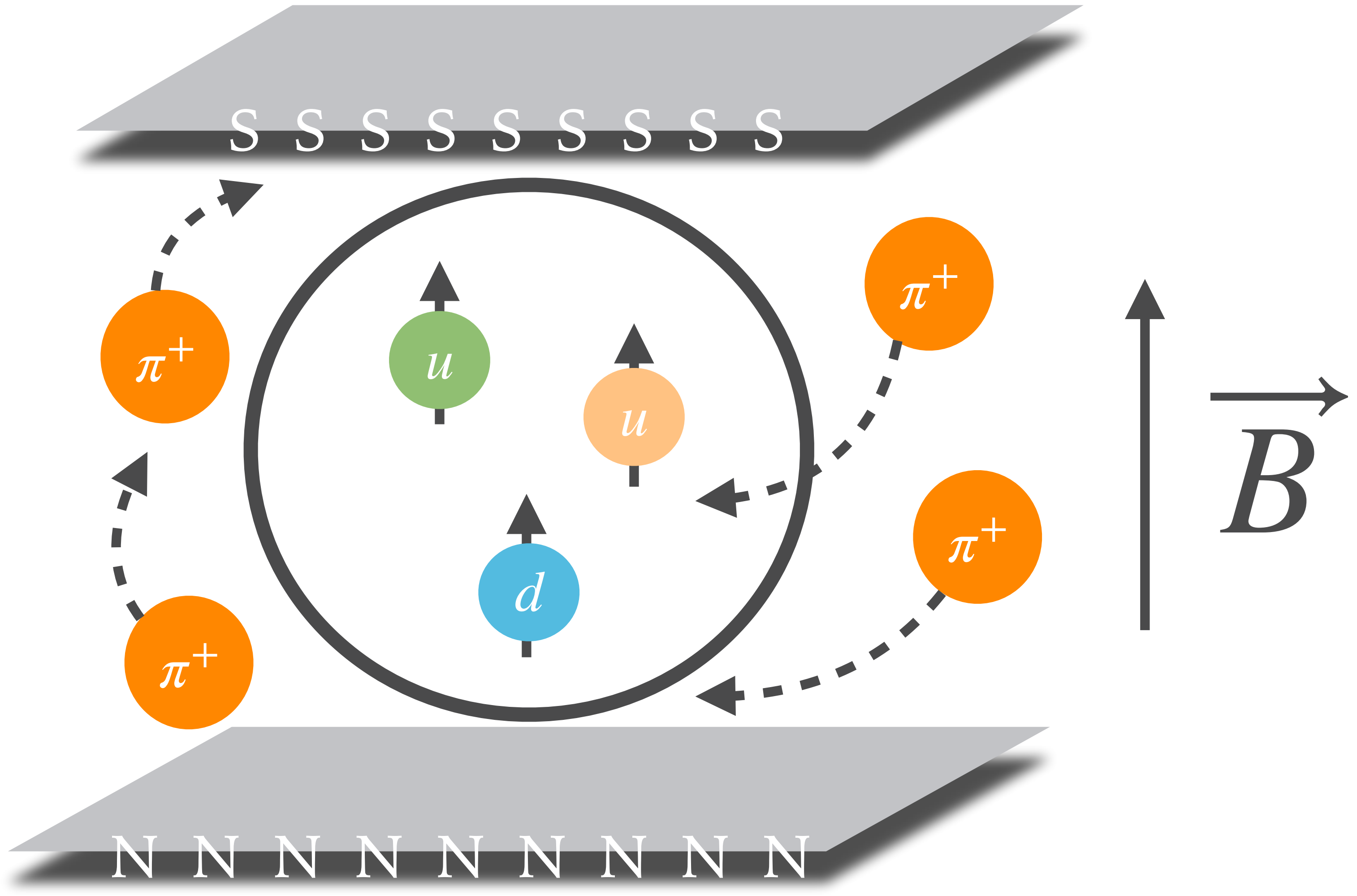


$$\vec{p} = \alpha_E \vec{E}$$

Electric Polarizability

- Electric polarizability α_E reflects the rigidity of proton





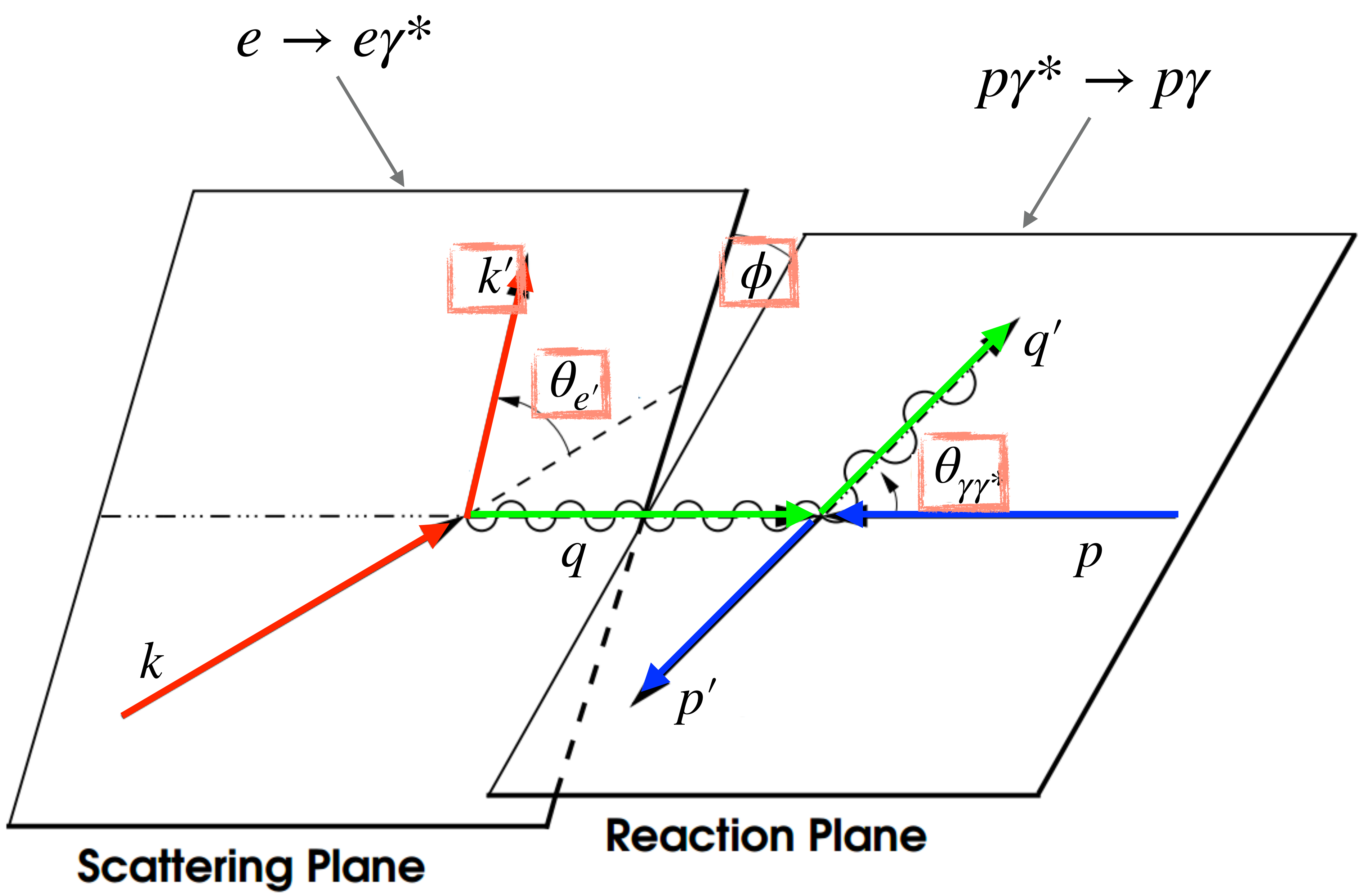
Magnetic Polarizability

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

- 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

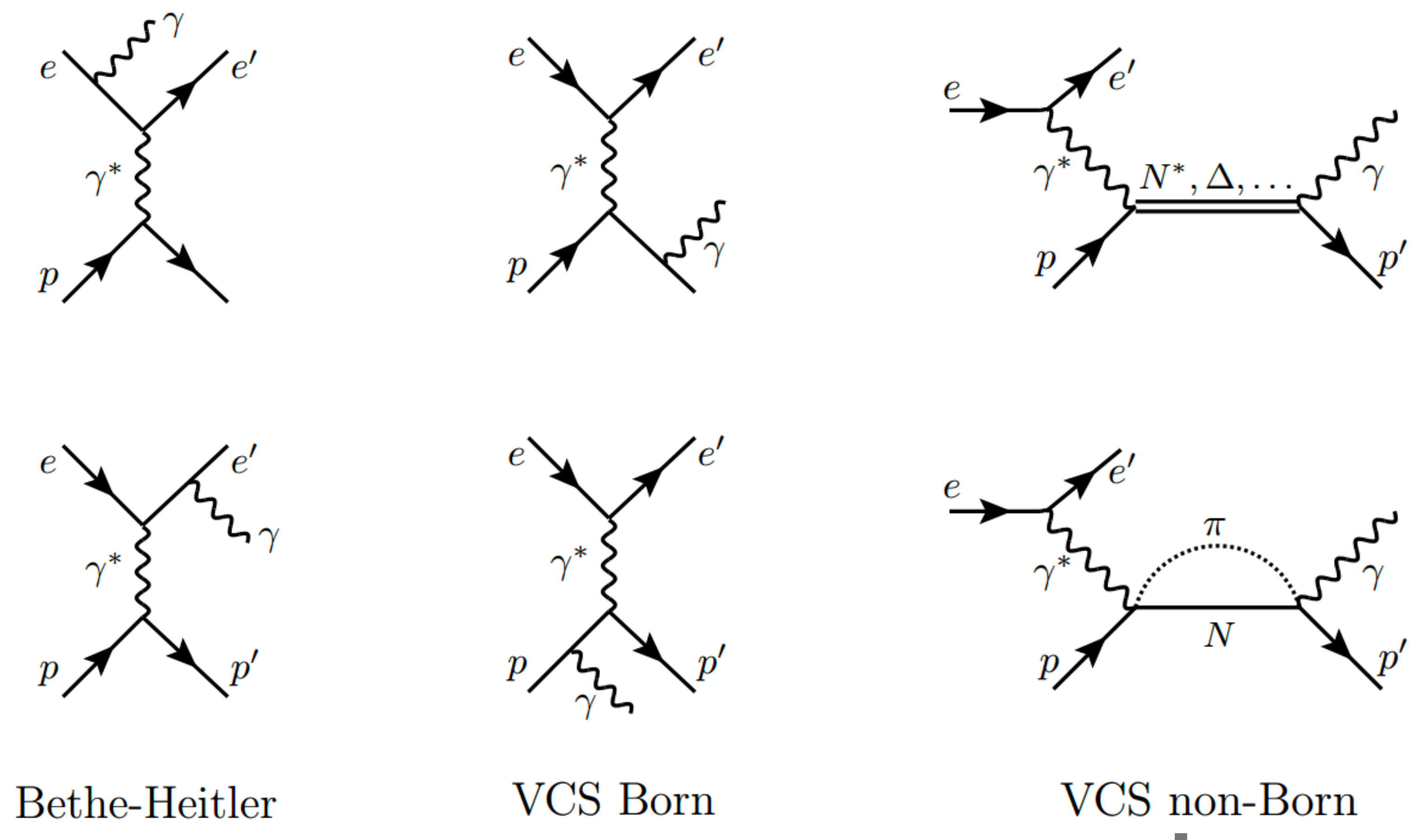
k-incoming electron q-virtual photon p-initial proton
k'-scattered electron q'-real photon p'-final proton



Kinematics of $ep \rightarrow ep\gamma$ reaction

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

VCS process → photon electro-production reaction



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

Electric Scaler GP

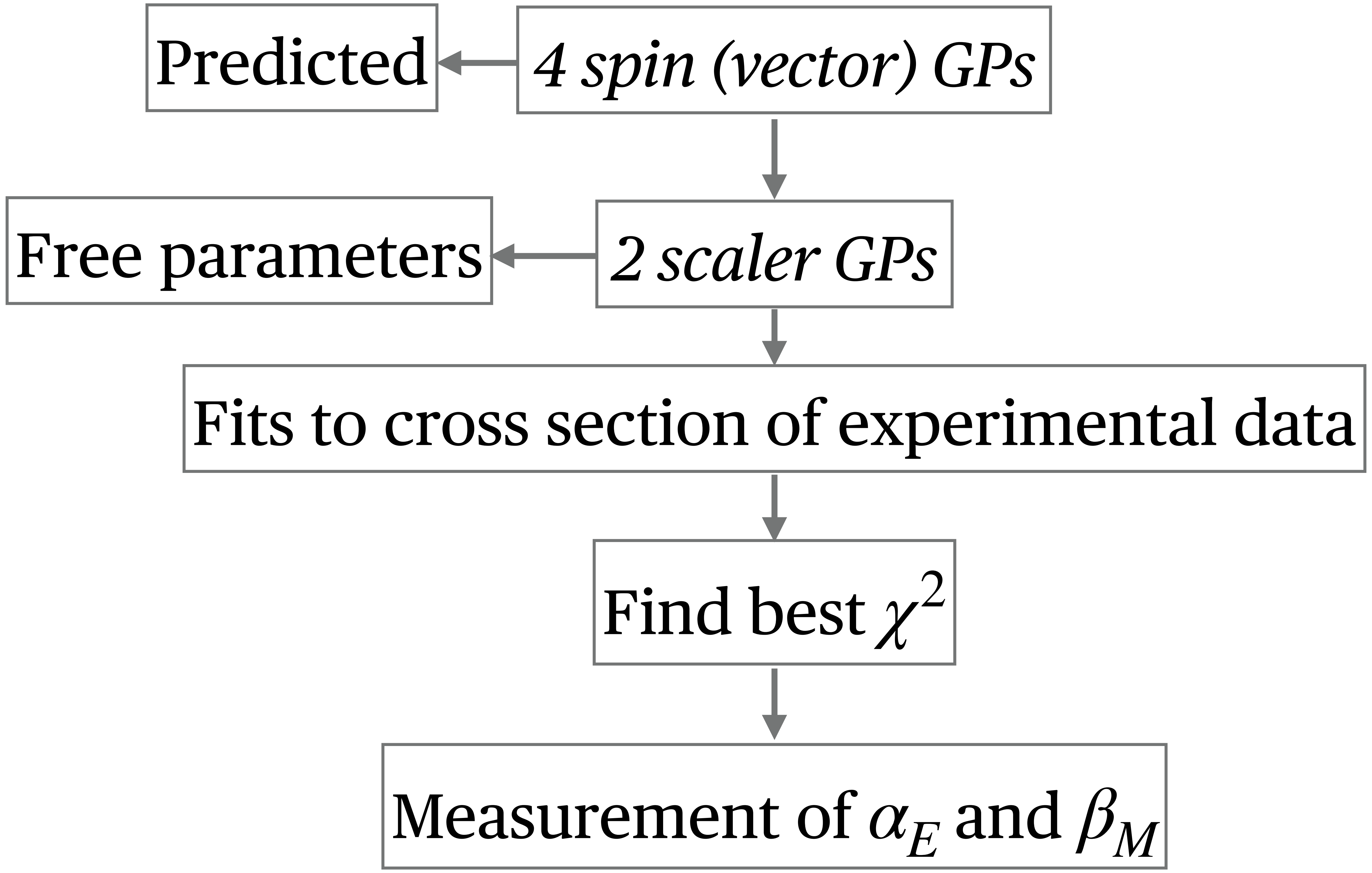
Magnetic Scaler GP

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

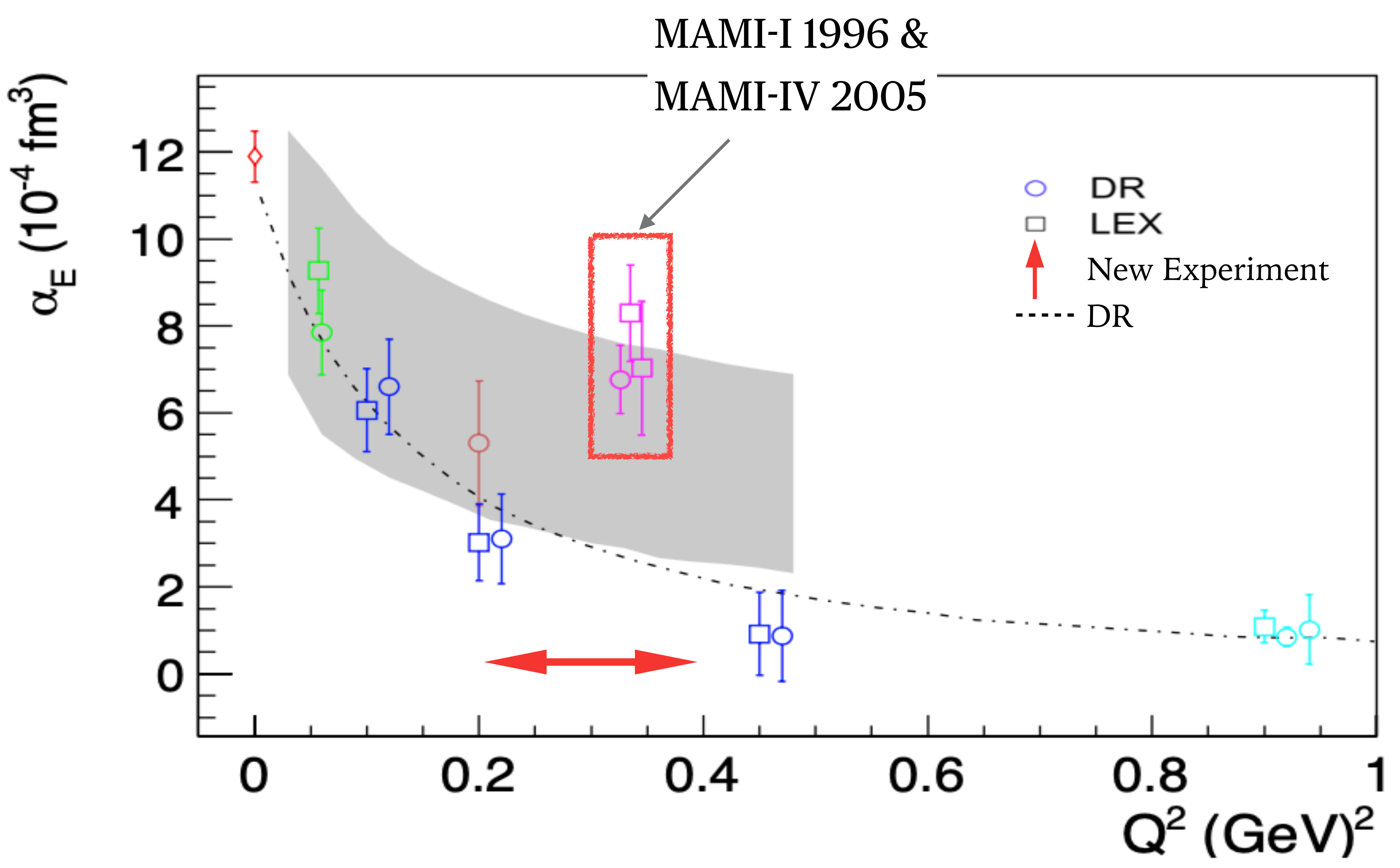
- $\rho(\rho')$ photon longitudinal or EM nature
- $L(L')$ angular momentum
- $[S = 1,0]$ spin flip or non spin flip

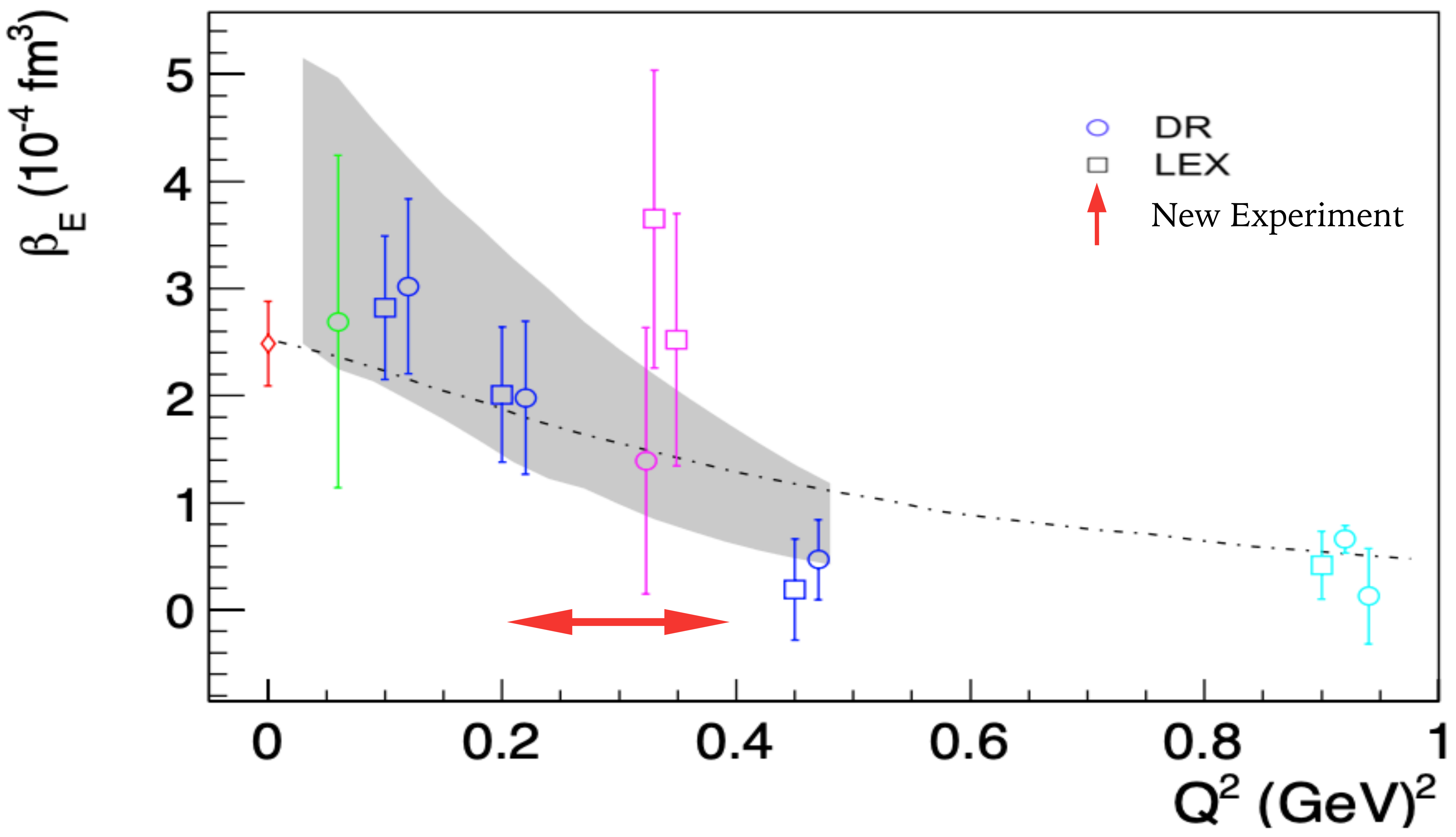
LEX & DR Formalism

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



World Data & Motivation



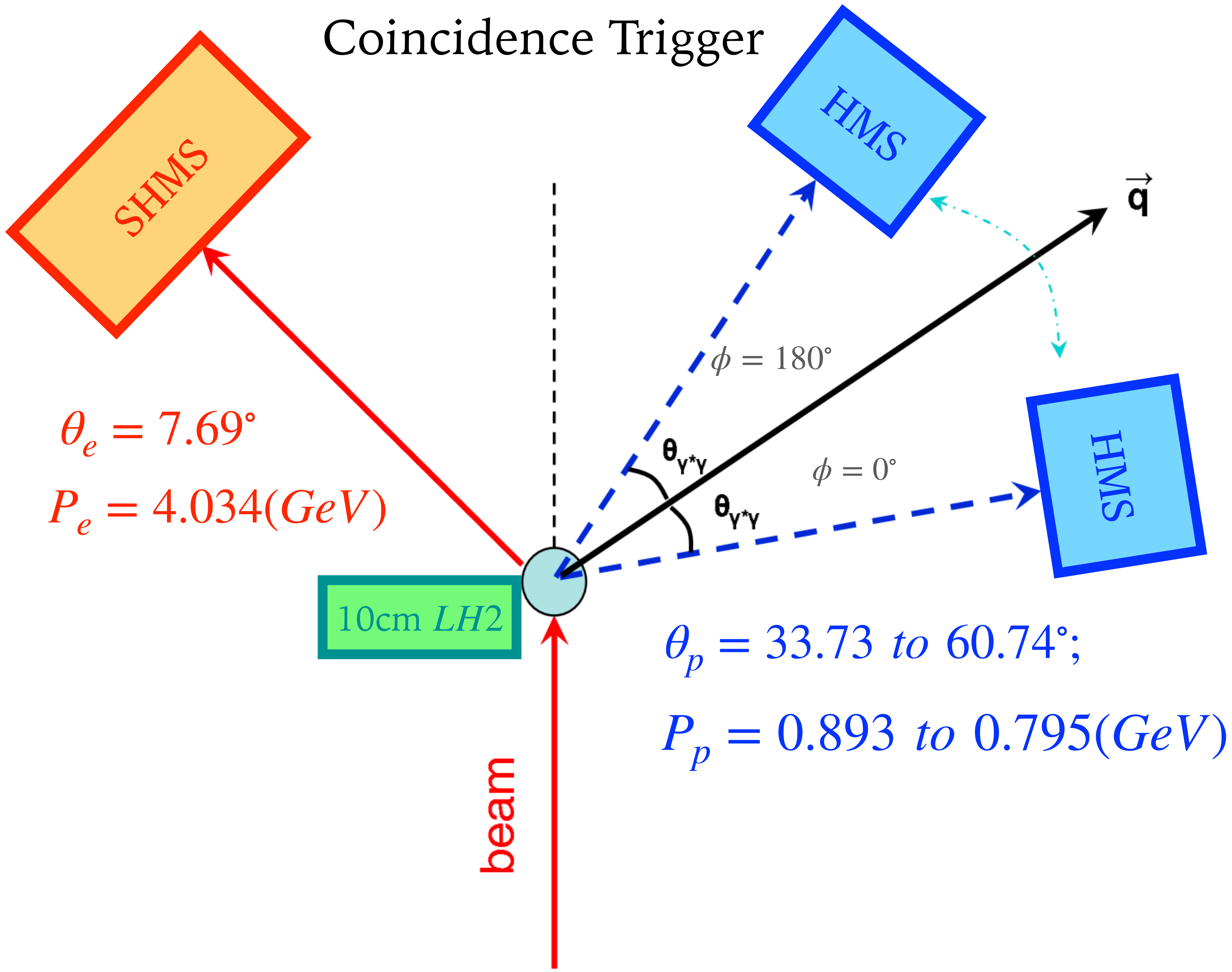


- Initial theoretical models predicted smooth fall off of α_E
  - data at $Q^2 = 0.33$ implies non-trivial structure
- New experiment can:
  - Address puzzling α_E enhancement
  - Reduce error by 2

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

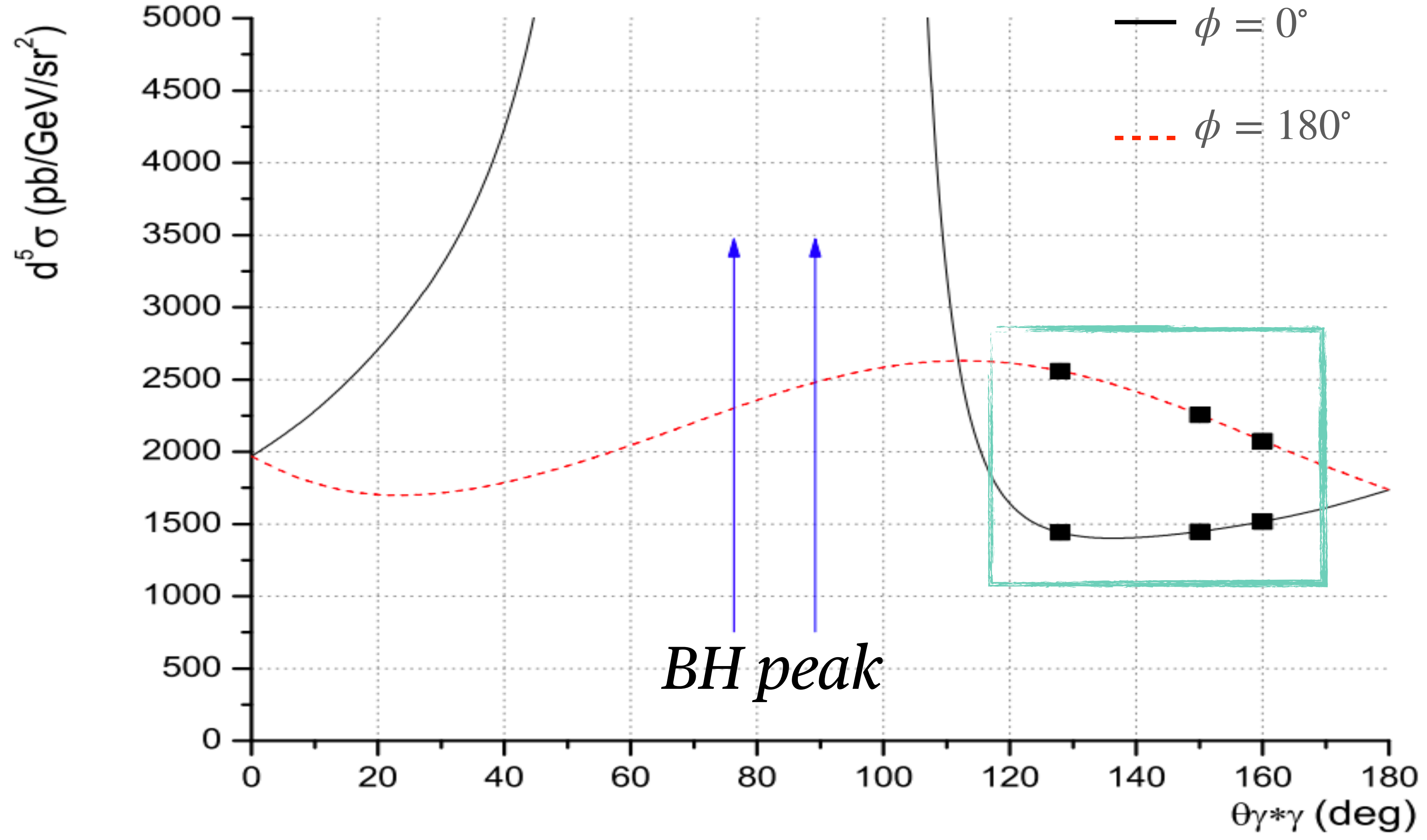
*J. Roche, et al., Phys. Rev. Lett. 85 (2000) 708-711; P. Janssens, et al., Eur. Phys. J. A37 (2008) 1-8; G. Laveissiere, et al., Phys. Rev. Lett. 93 (2004) 122001; H. Fonvieille, et al., Phys. Rev. C86 (2012) 015210;P. Bourgeois, et al., Phys. Rev. Lett. 97 (2006) 212001; Eur.Phys.J.A55(2019)no. 10,182;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

JLab E12-15-001 Experiment



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

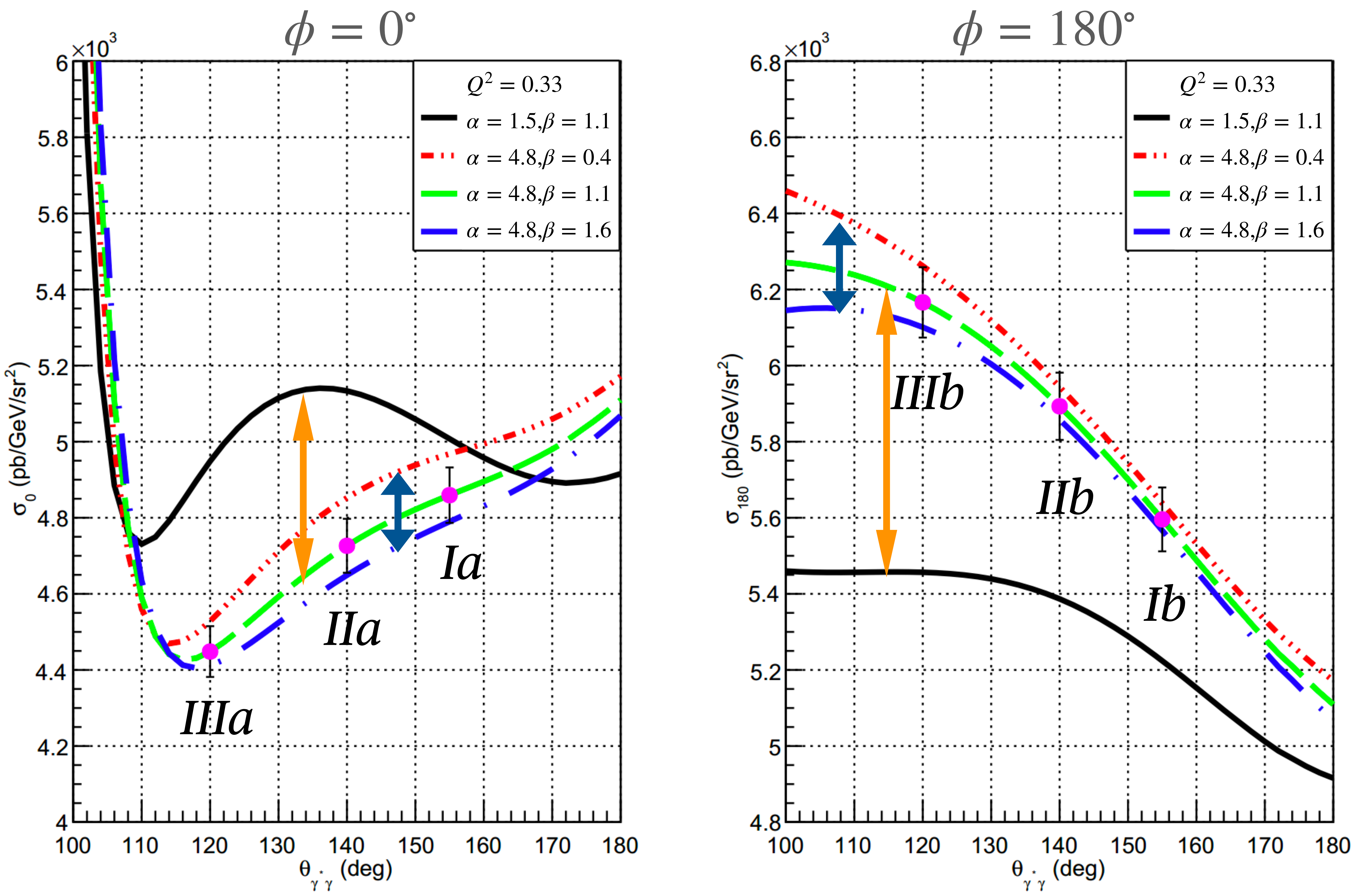
- Summer 2019: July 20 - August 5
- Beam $E = 4.56GeV$
- $Q^2 = 0.33GeV^2$, $W = 1.232GeV$



➤ 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

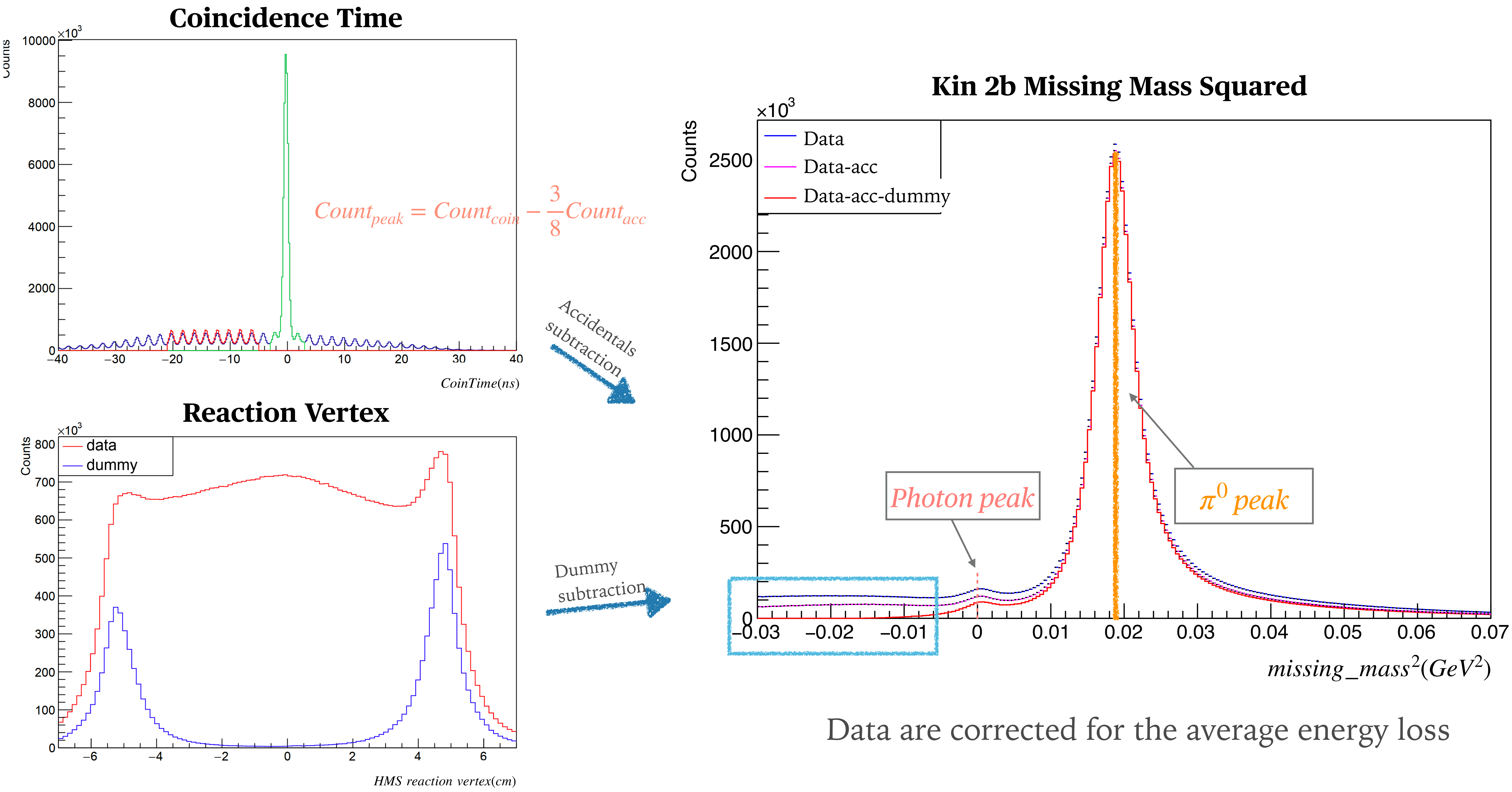
-10<SHMS_dp<22

g.evtyp==4

0.85 < W < 1.05

- Revisit SHMS/HMS moment and angle offset
  - changes to SIMC energy loss needed for low momentum proton

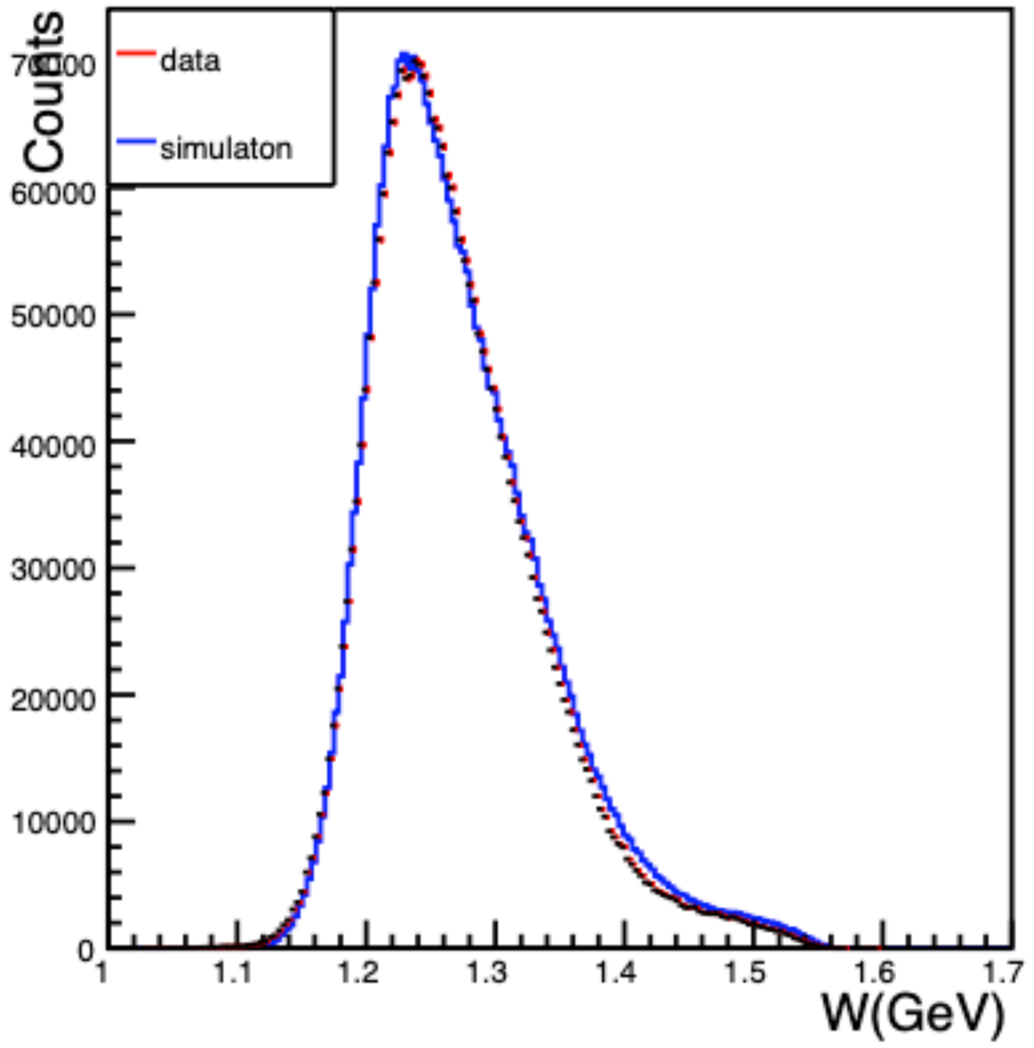
VCS peak and pi0 peak



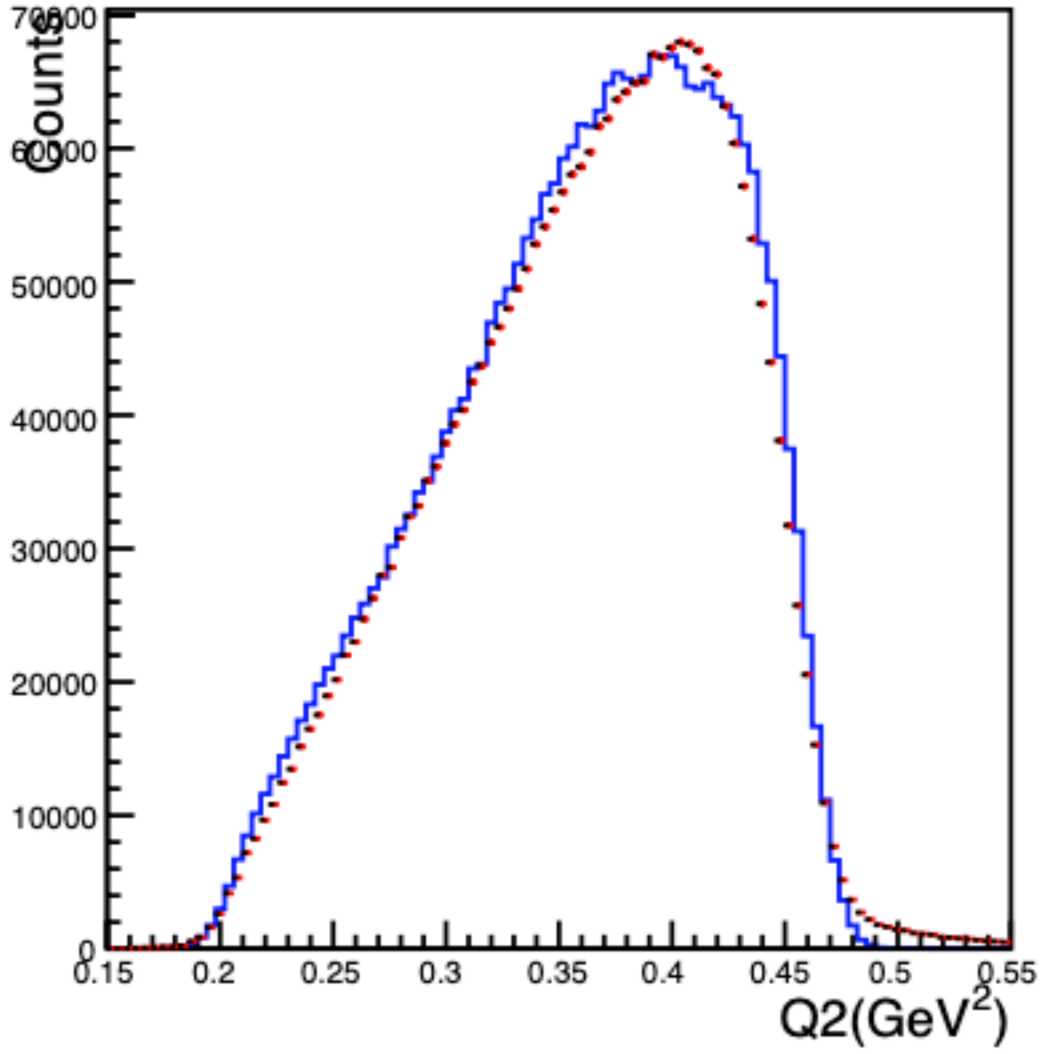
Data are corrected for the average energy loss

Pion Preliminary Analysis

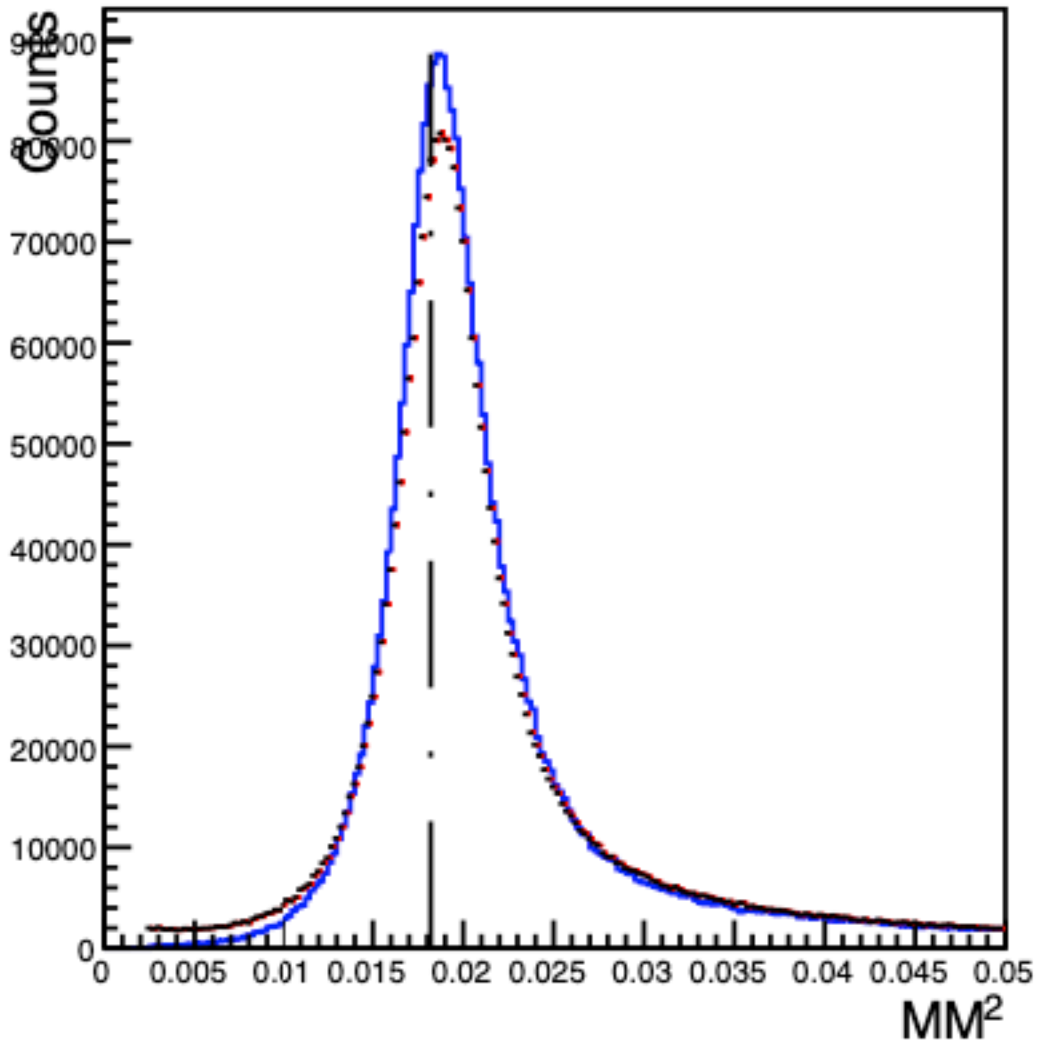
W



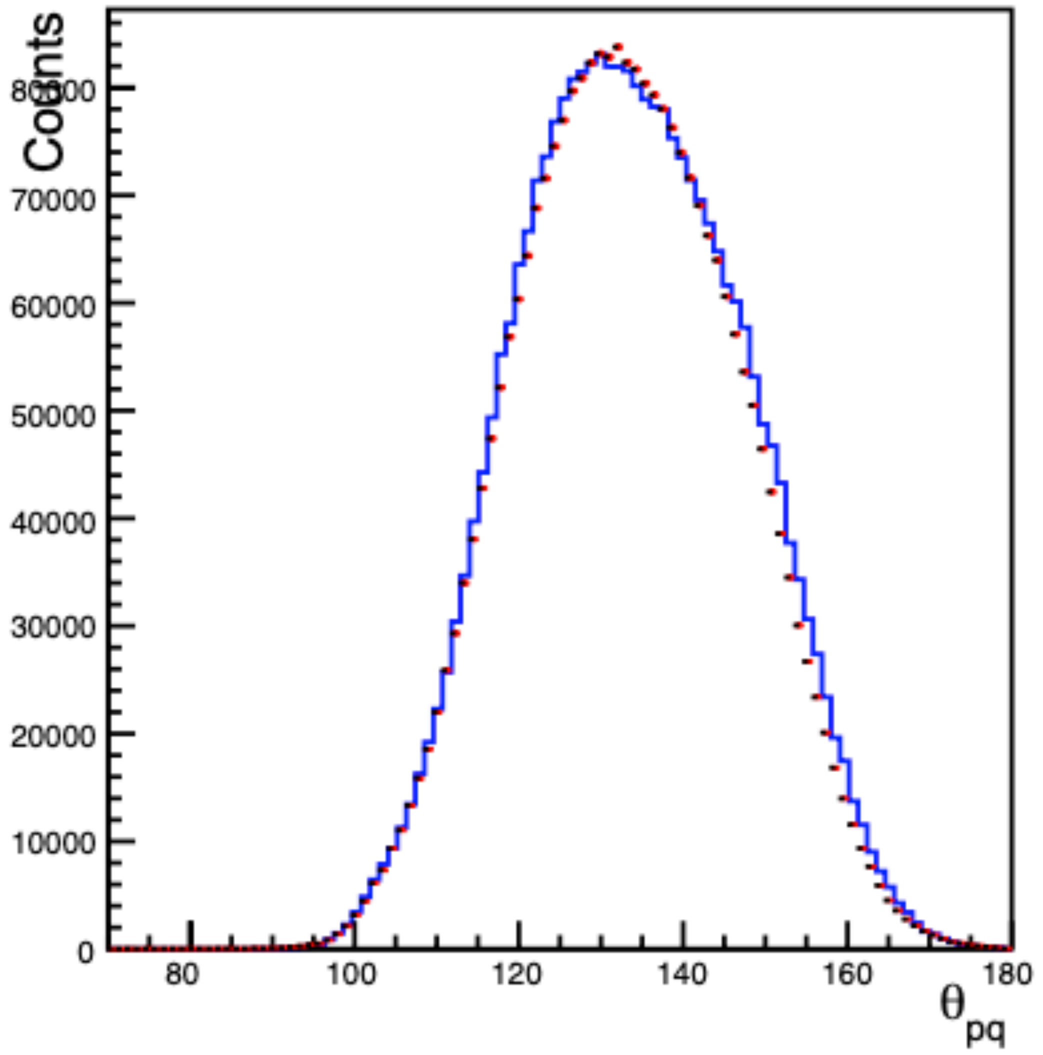
Q2



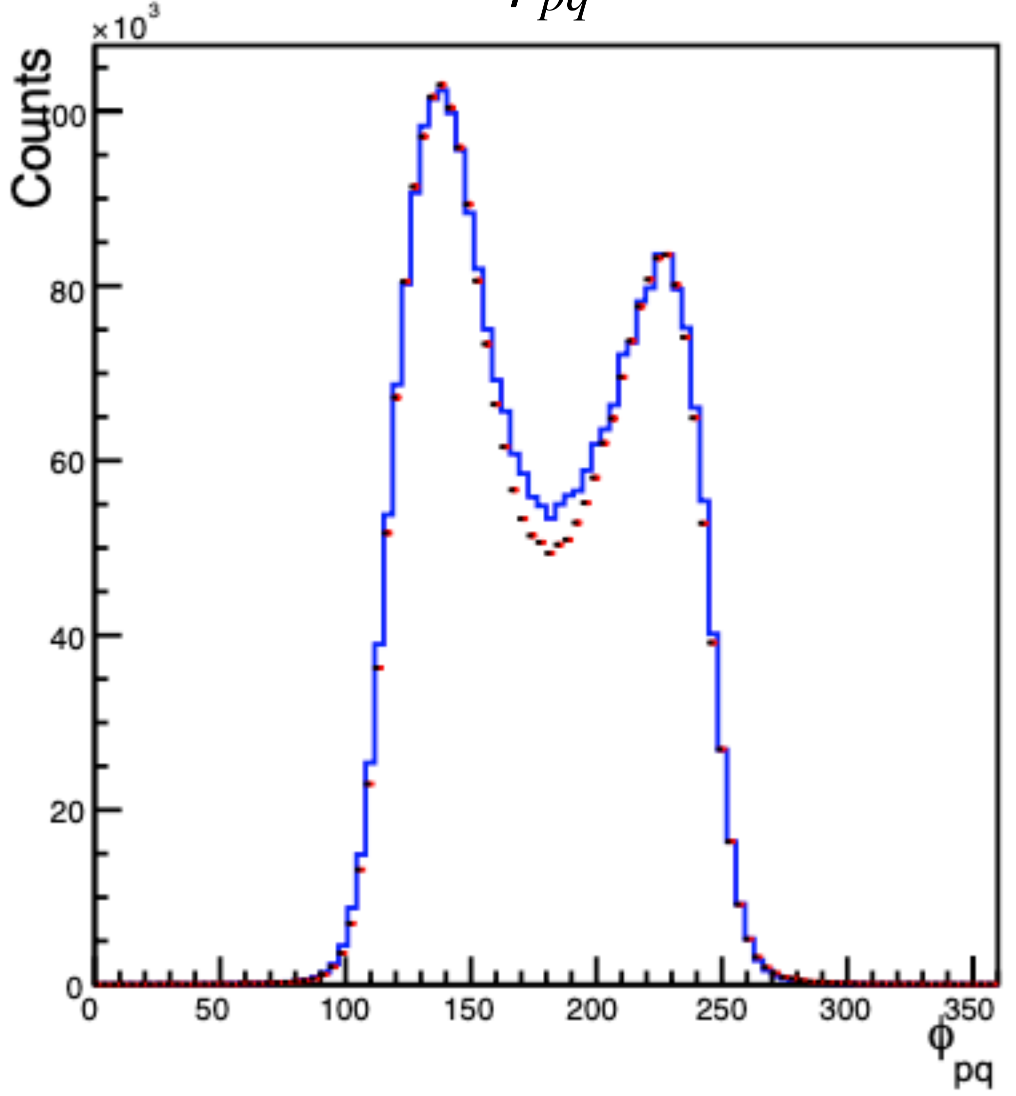
MM2



θ_{pq}



ϕ_{pq}



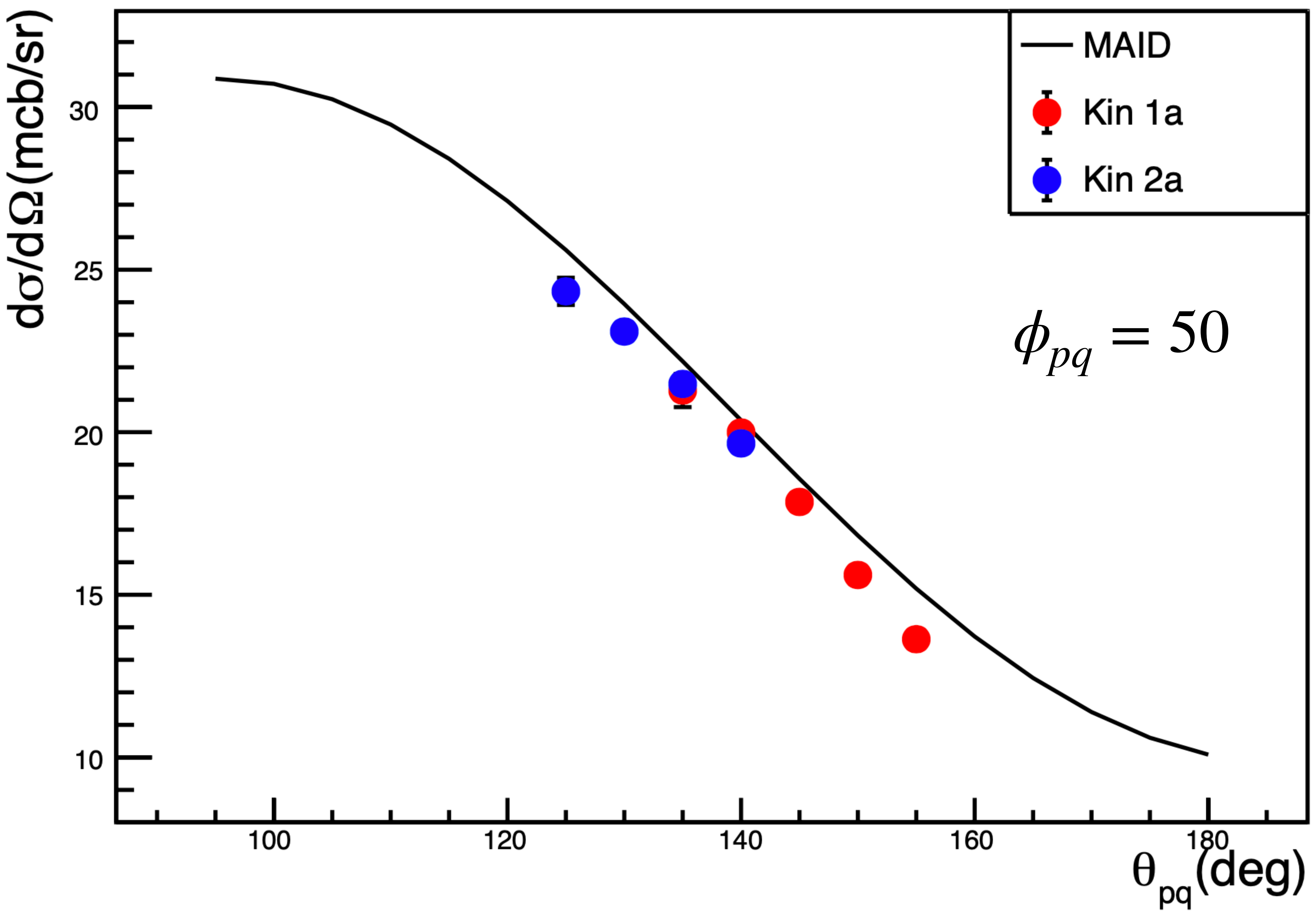
Kin1b

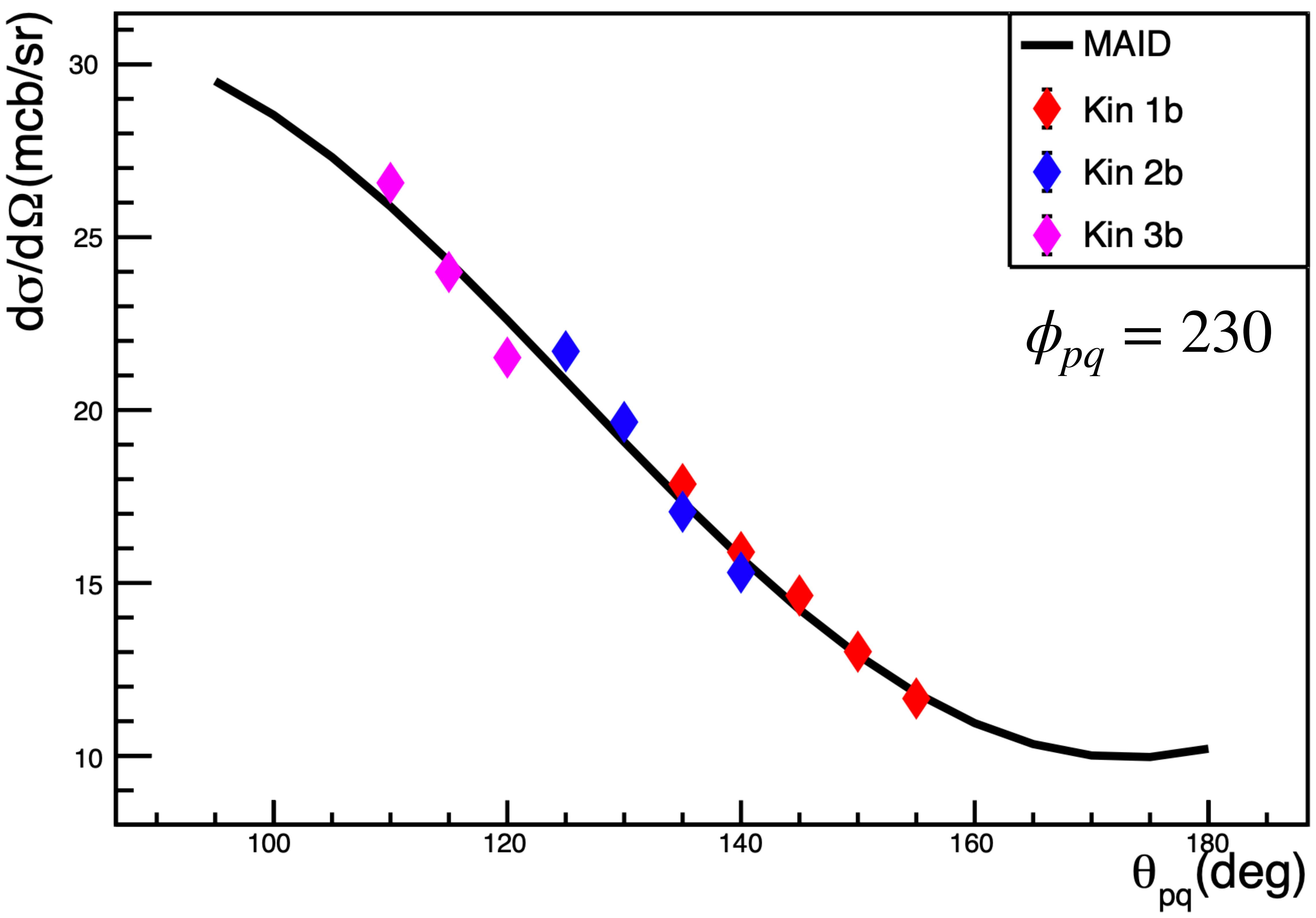
data vs. MAID

Cuts:

0.0025<mm2 < 0.06

Pion Preliminary Analysis





Cuts:

mm2>0.01

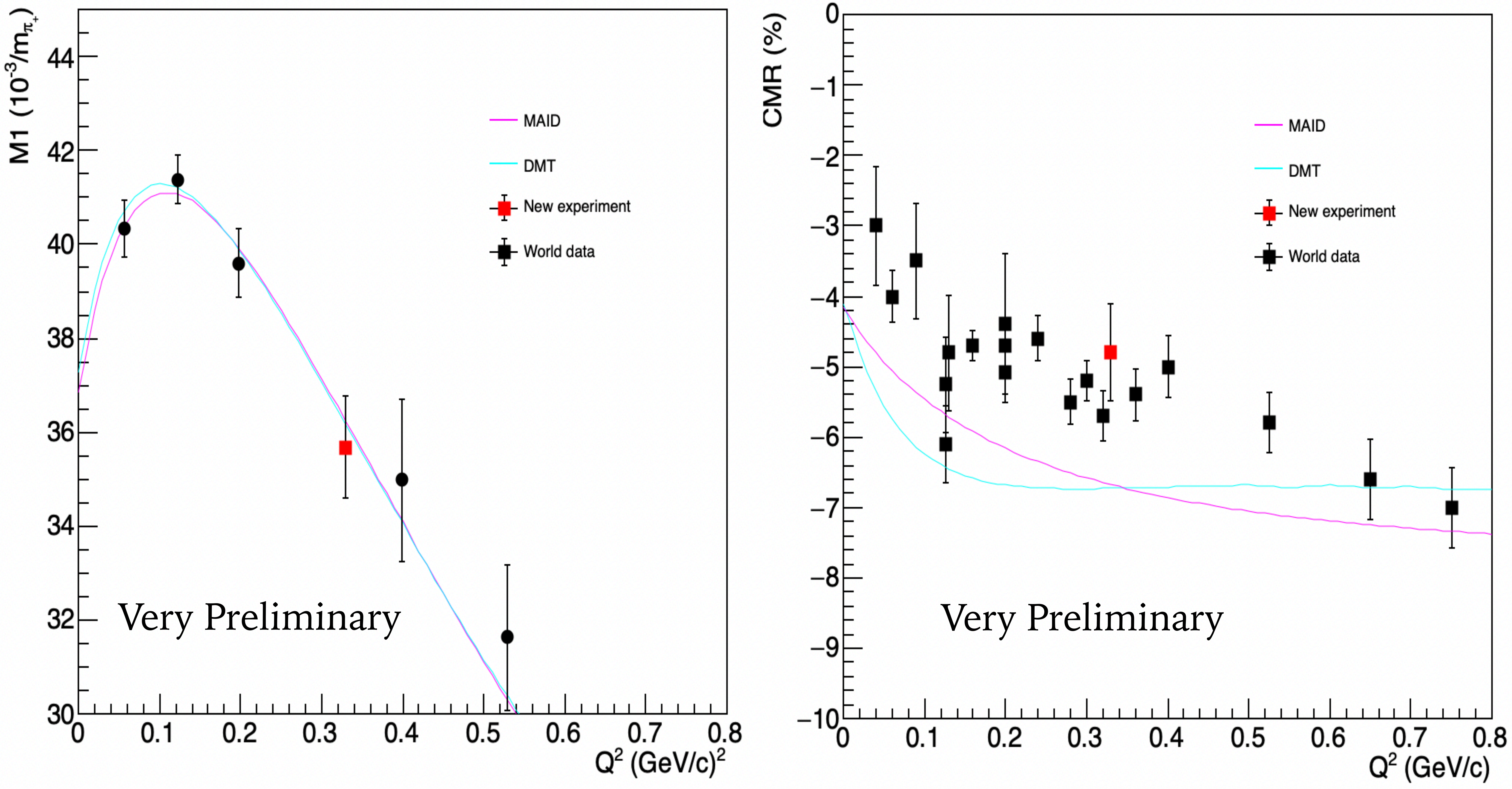
abs(W-1.232)<0.01

abs(Q2-0.33)<0.05

abs $(\theta_{pq} - \theta_{center})$ ***<3***

abs $(\phi_{pq} - \phi_{center})$ ***<70***

Pion Preliminary Analysis



M1 - Magnetic dipole amplitude

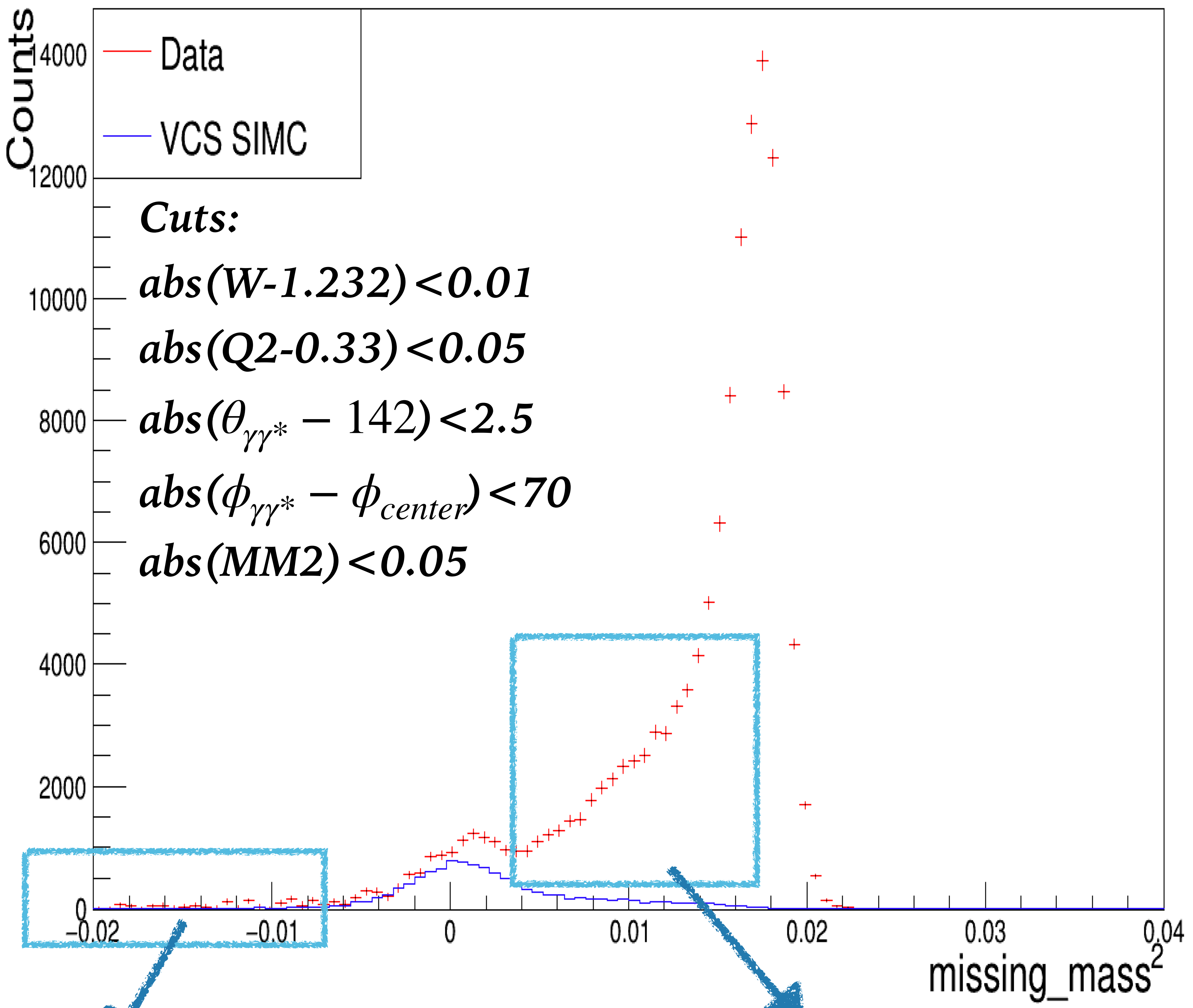
CMR = C2/M1

C2 - Coulomb quadrupole amplitude

Figure Credit: Hamza Atac

HCANA UPDATE

Kin1b OLD HCANA

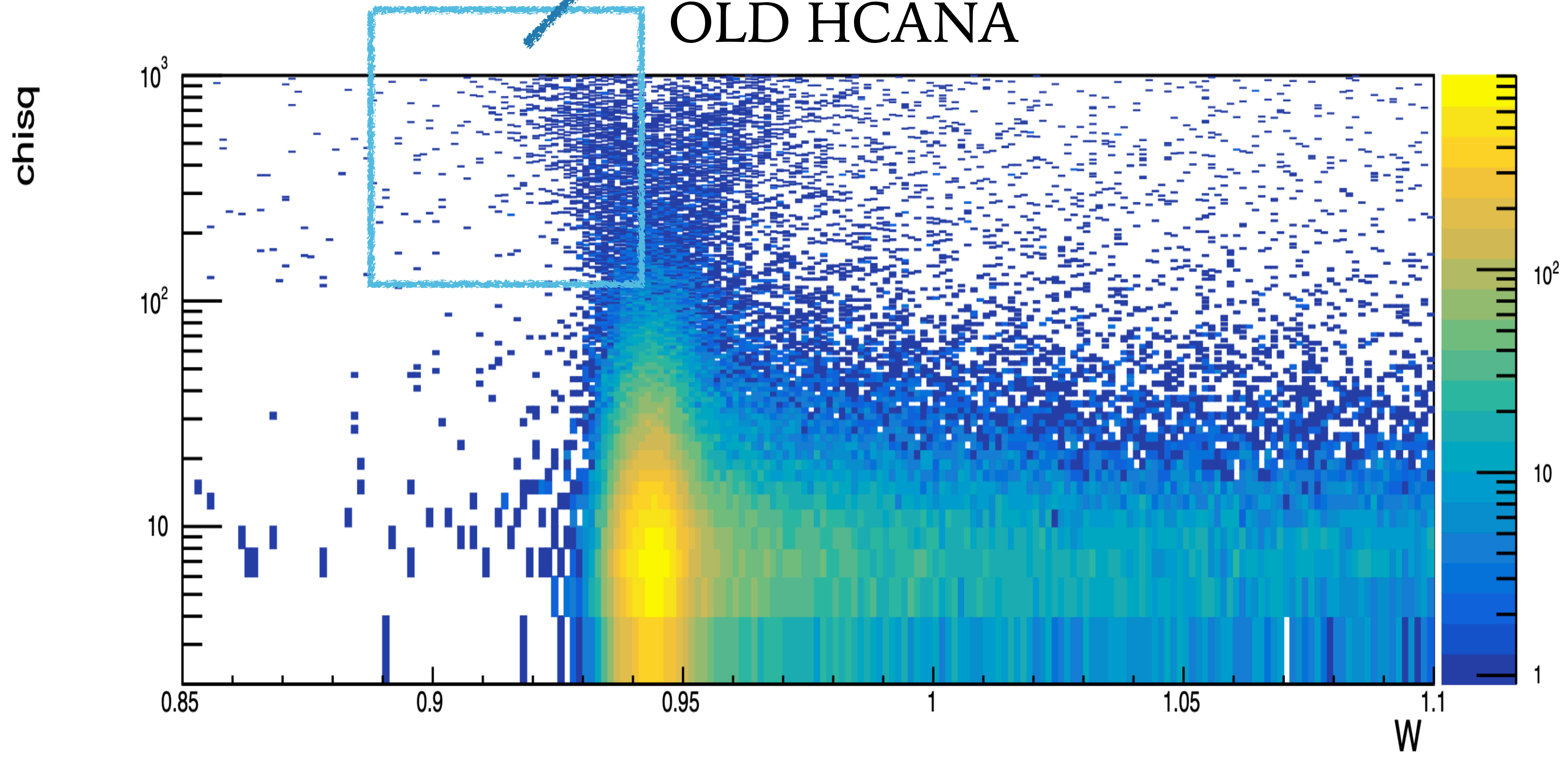


Events above zero

Unclear separation between pi0 and photon

Events below elastic peak when chisq>100

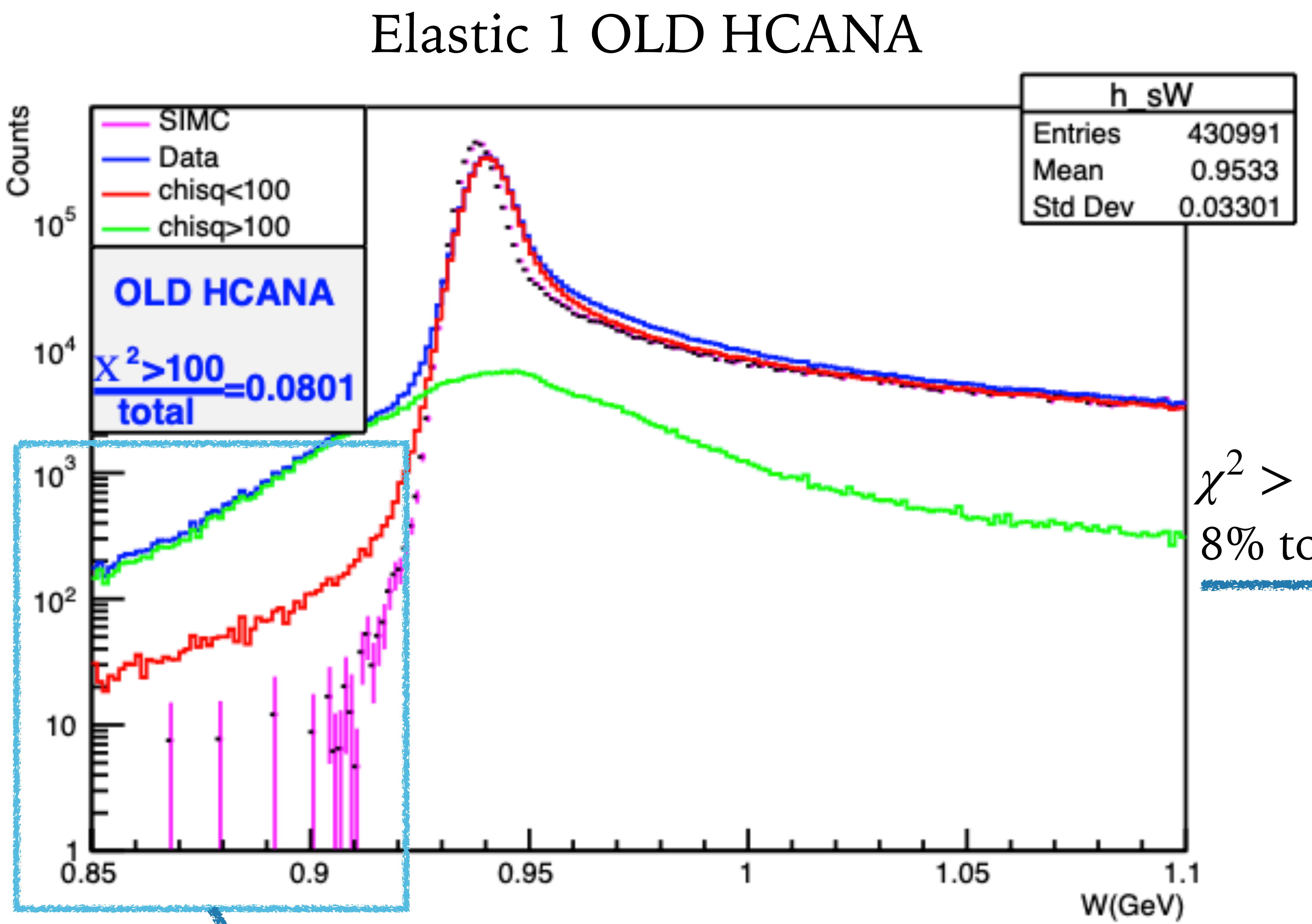
OLD HCANA



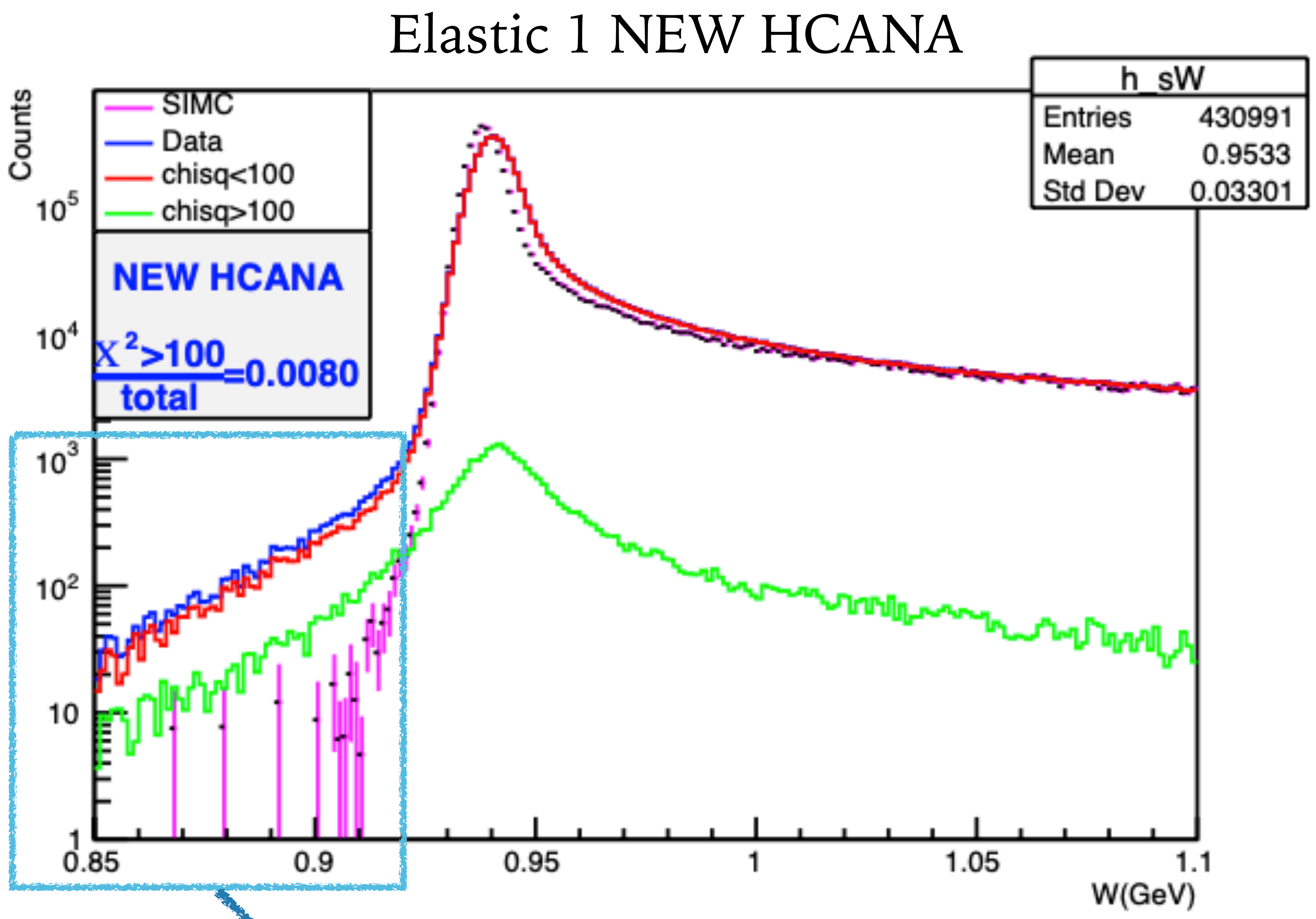
Elastic data has the same problem

Figure Credit: Mark Jones

HCANA UPDATE



$\chi^2 > 100$ from 8% to <1%

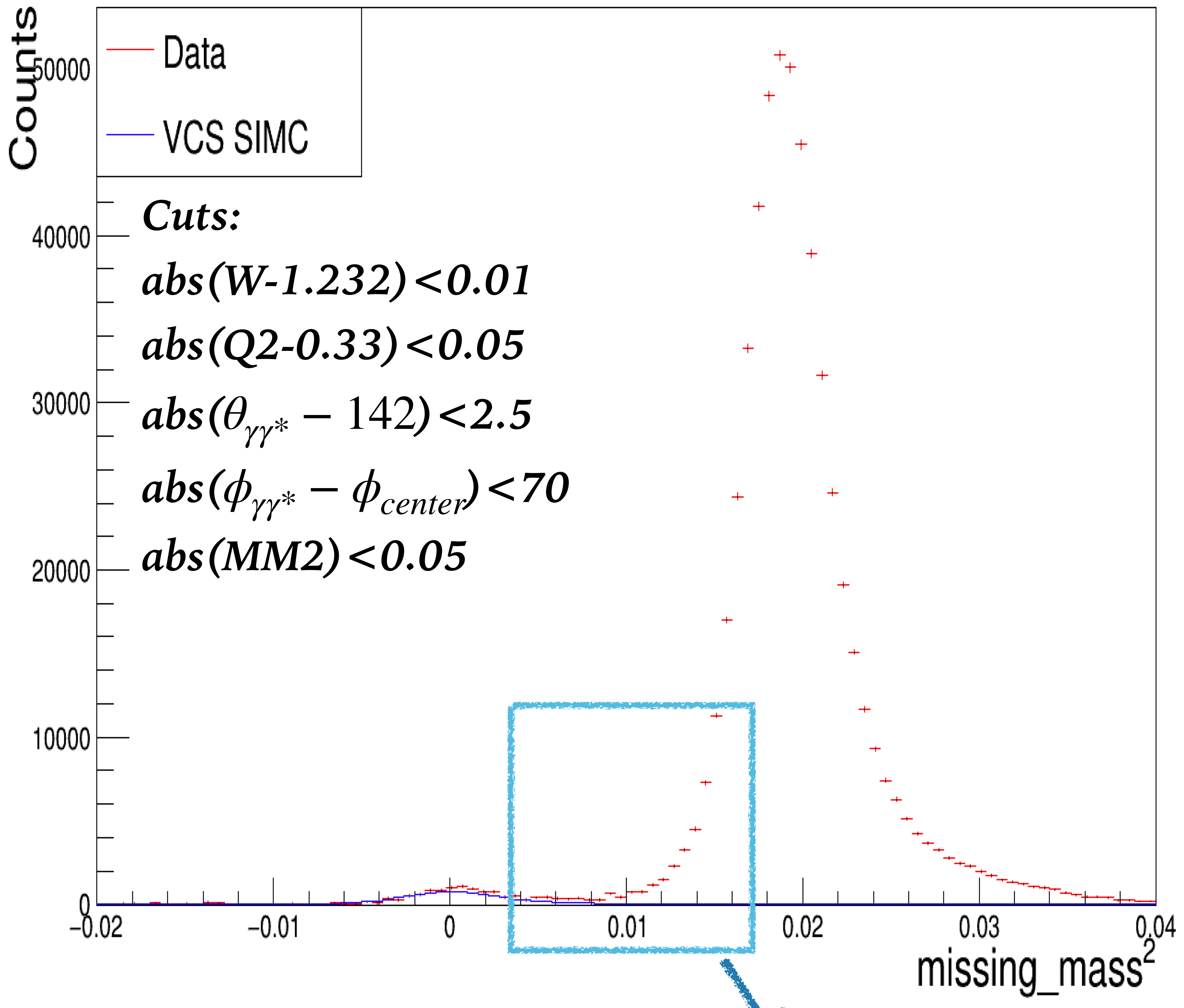


~90% of events with W<0.92 have chisq>100

- ~10% of events with W<0.92 have chisq>100
- Better resolution than old HCANA with chisq>100

HCANA UPDATE

Kin1b NEW HCANA



Cuts:

$abs(W\text{-}1.232)<0.01$

$abs(Q2\text{-}0.33)<0.05$

$abs(\theta_{\gamma\gamma*} - 142)<2.5$

$abs(\phi_{\gamma\gamma*} - \phi_{center})<70$

$abs(MM2)<0.05$

Clear pi0 tail

Almost no events below elastic peak

NEW HCANA

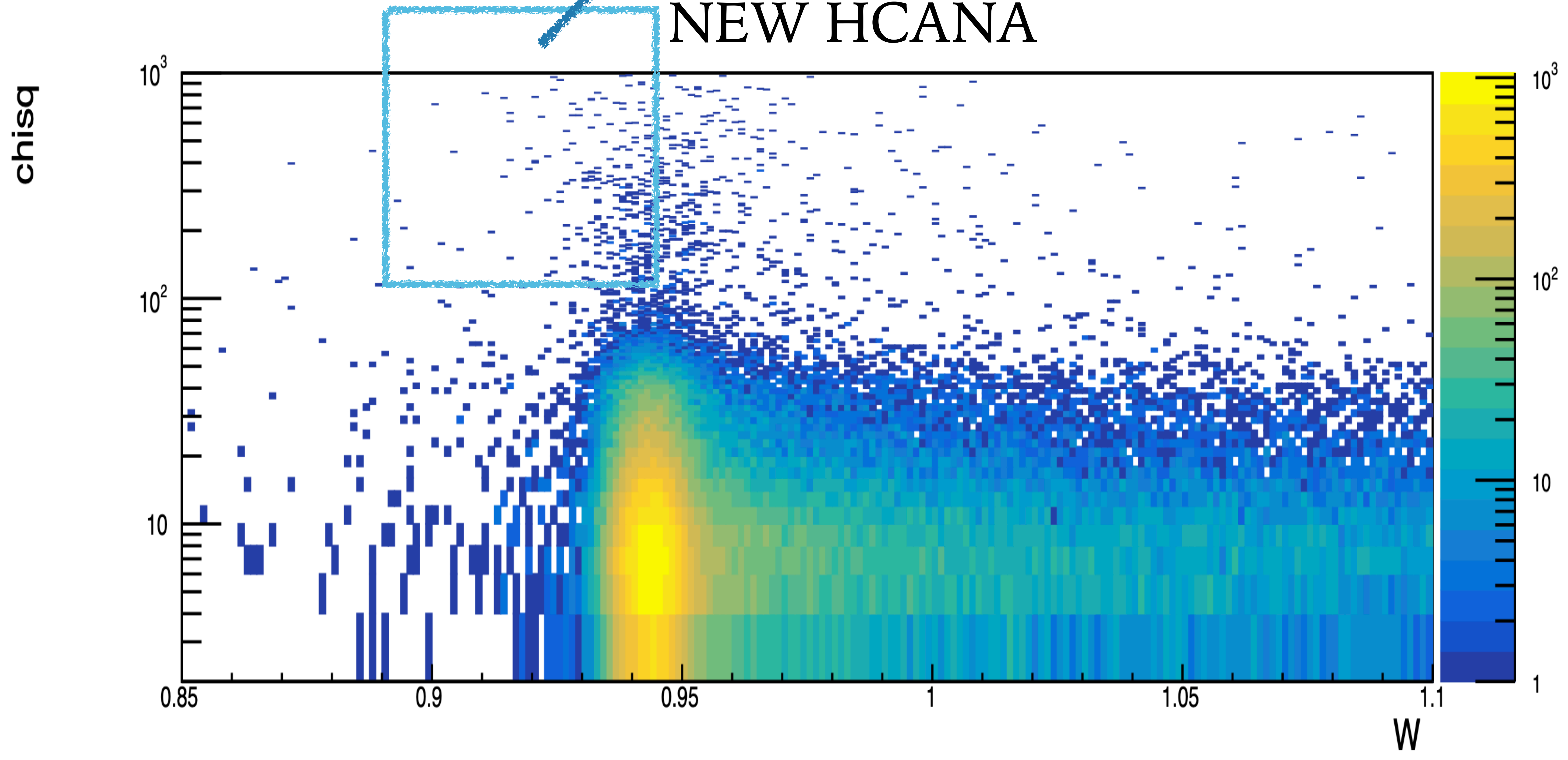
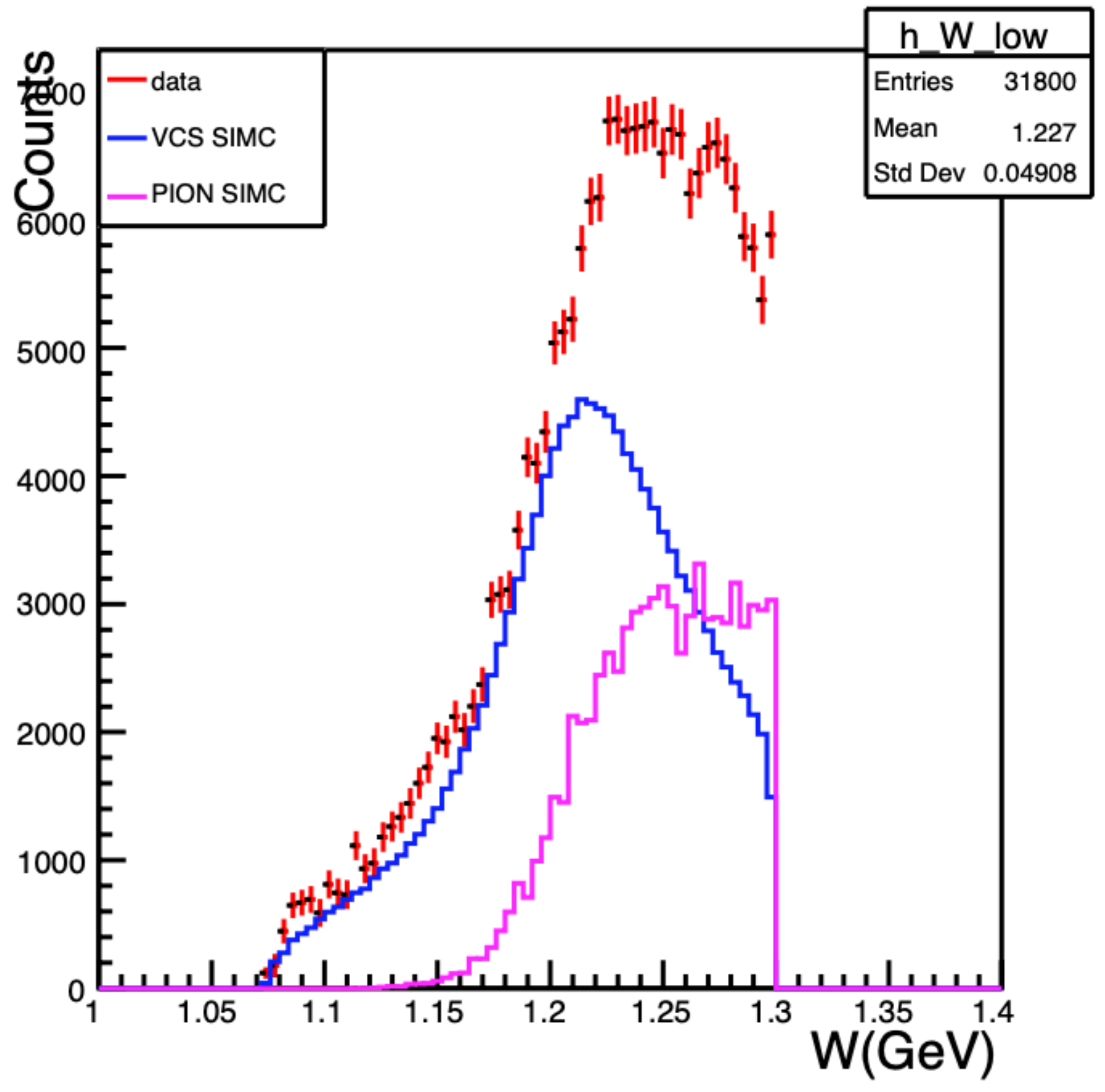


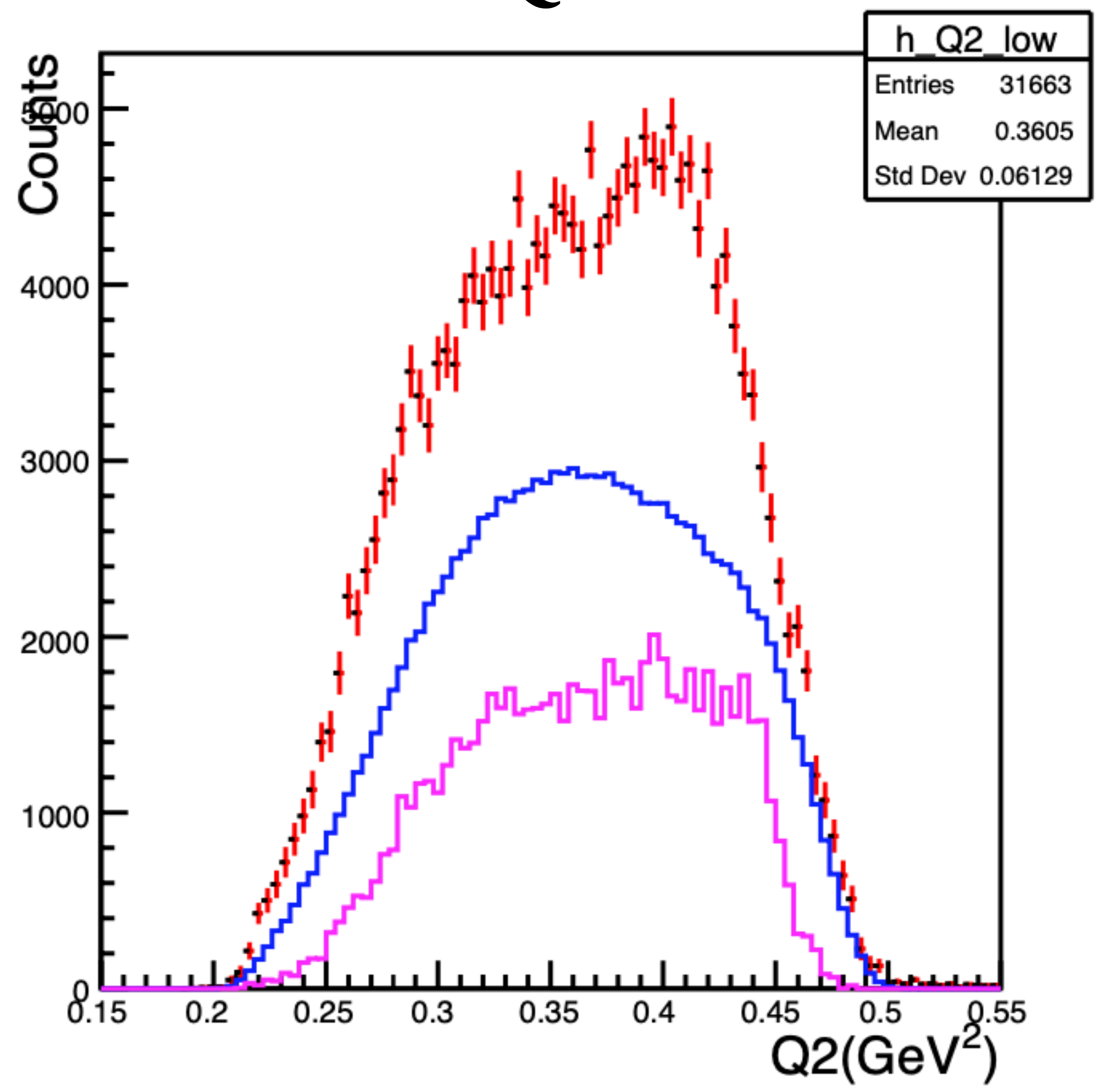
Figure Credit: Mark Jones

VCS Preliminary Analysis

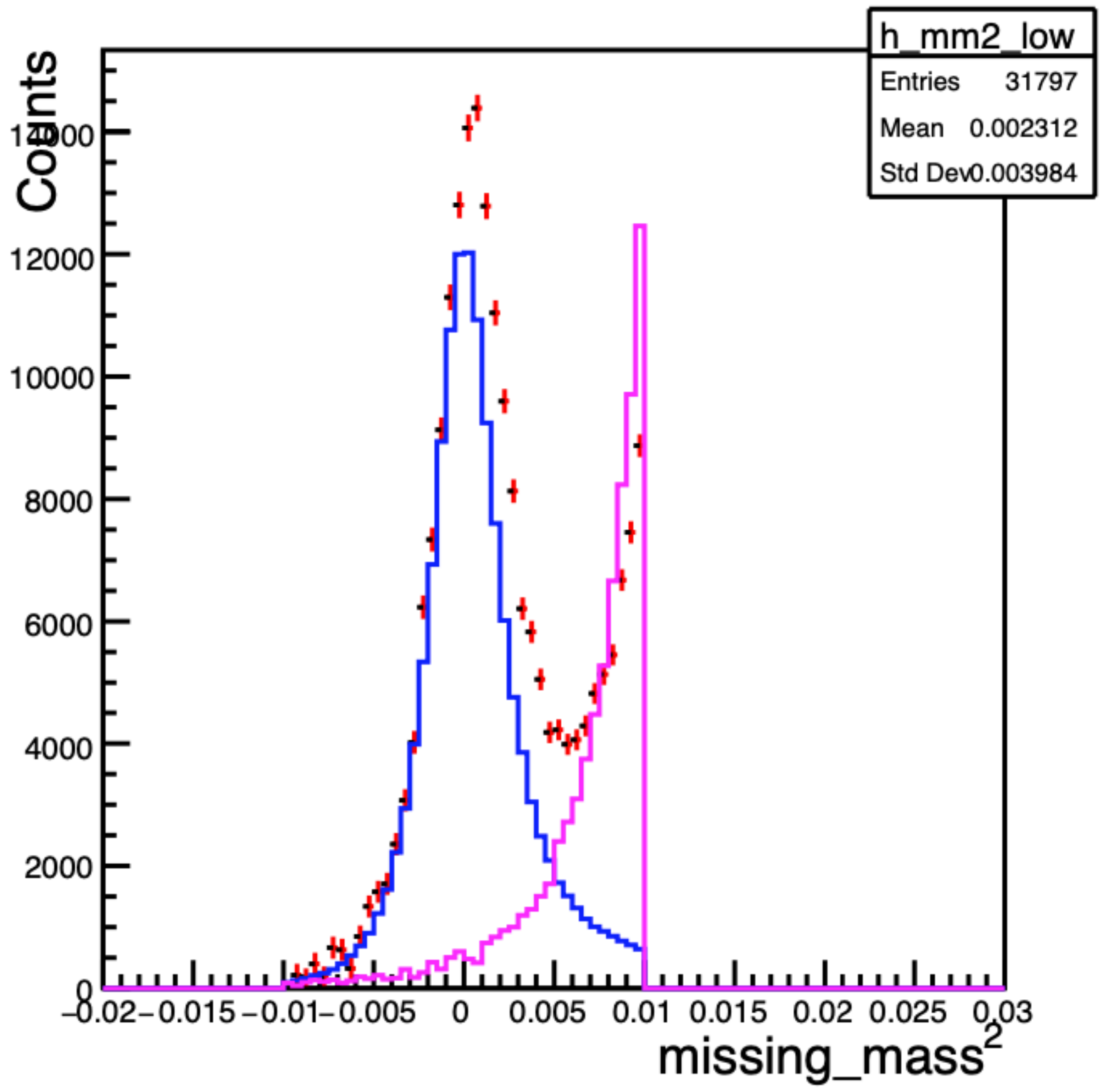
W



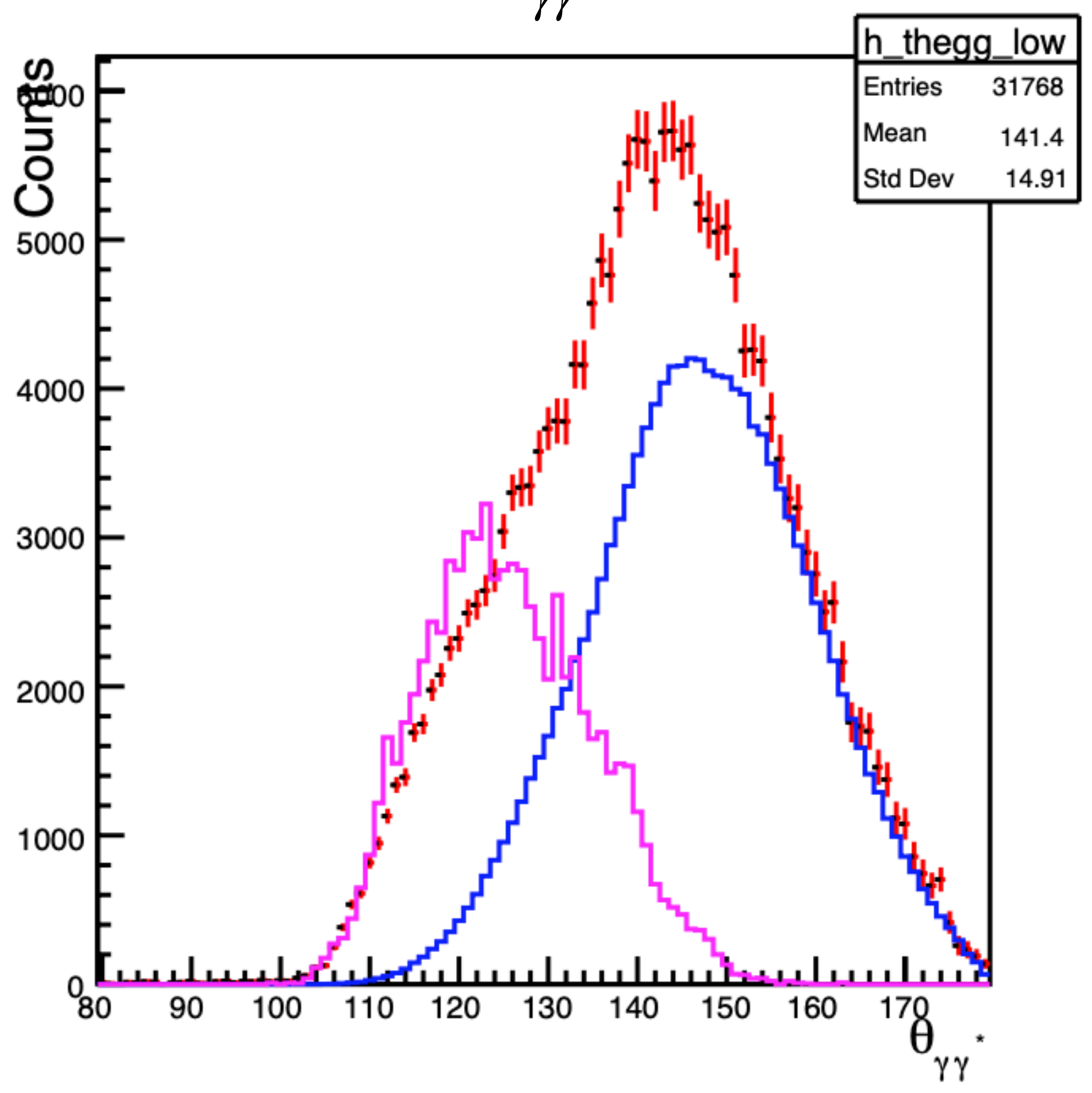
Q2



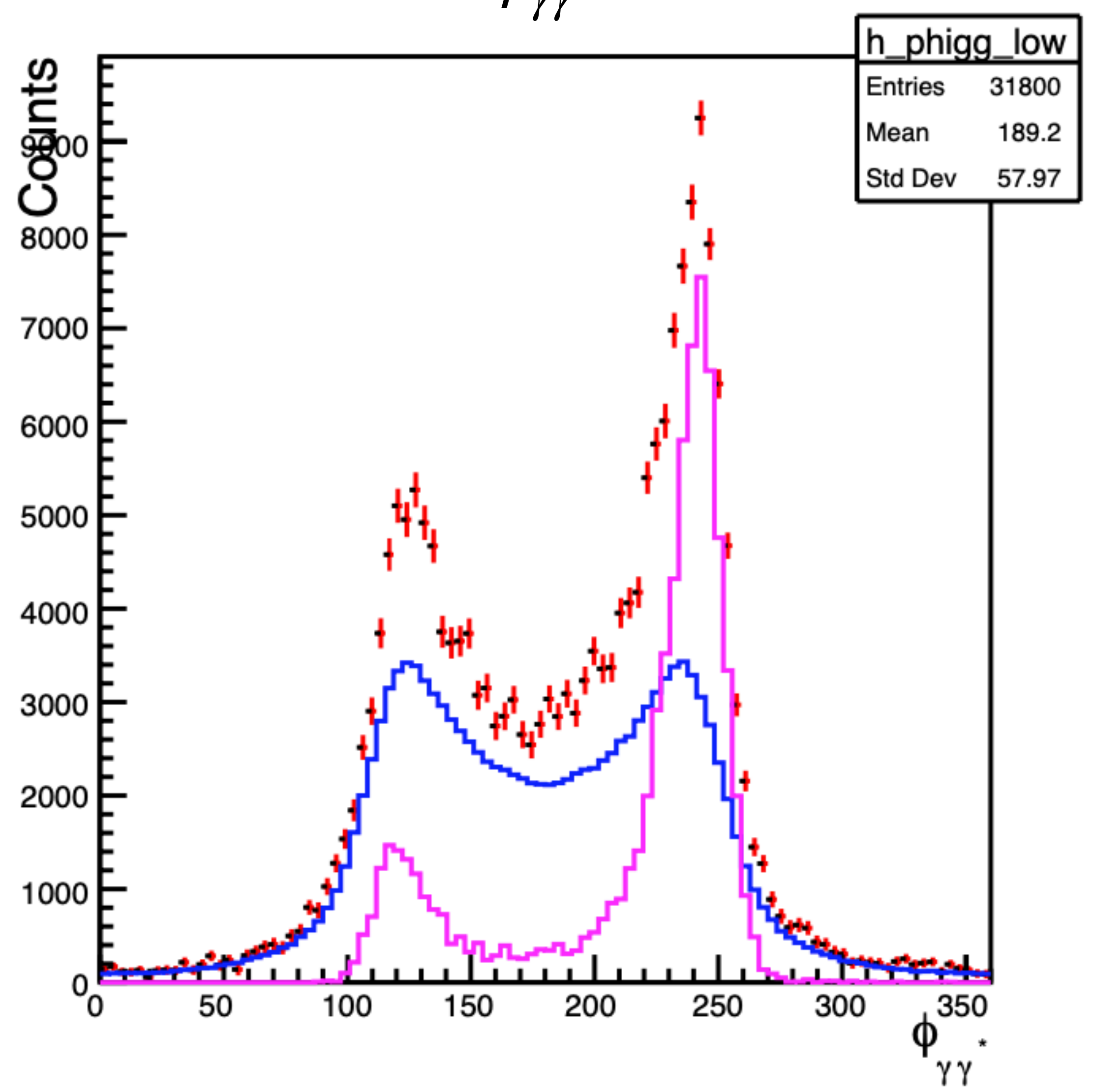
MM2



$\theta_{\gamma\gamma^*}$



$\phi_{\gamma\gamma^*}$



Kin 1b

data vs. DR & MAID

$Q^2 = 0.33(GeV^2)$ Dipole fall-off

$\lambda_\alpha = 0.7(GeV), \lambda_\beta = 0.5(GeV)$

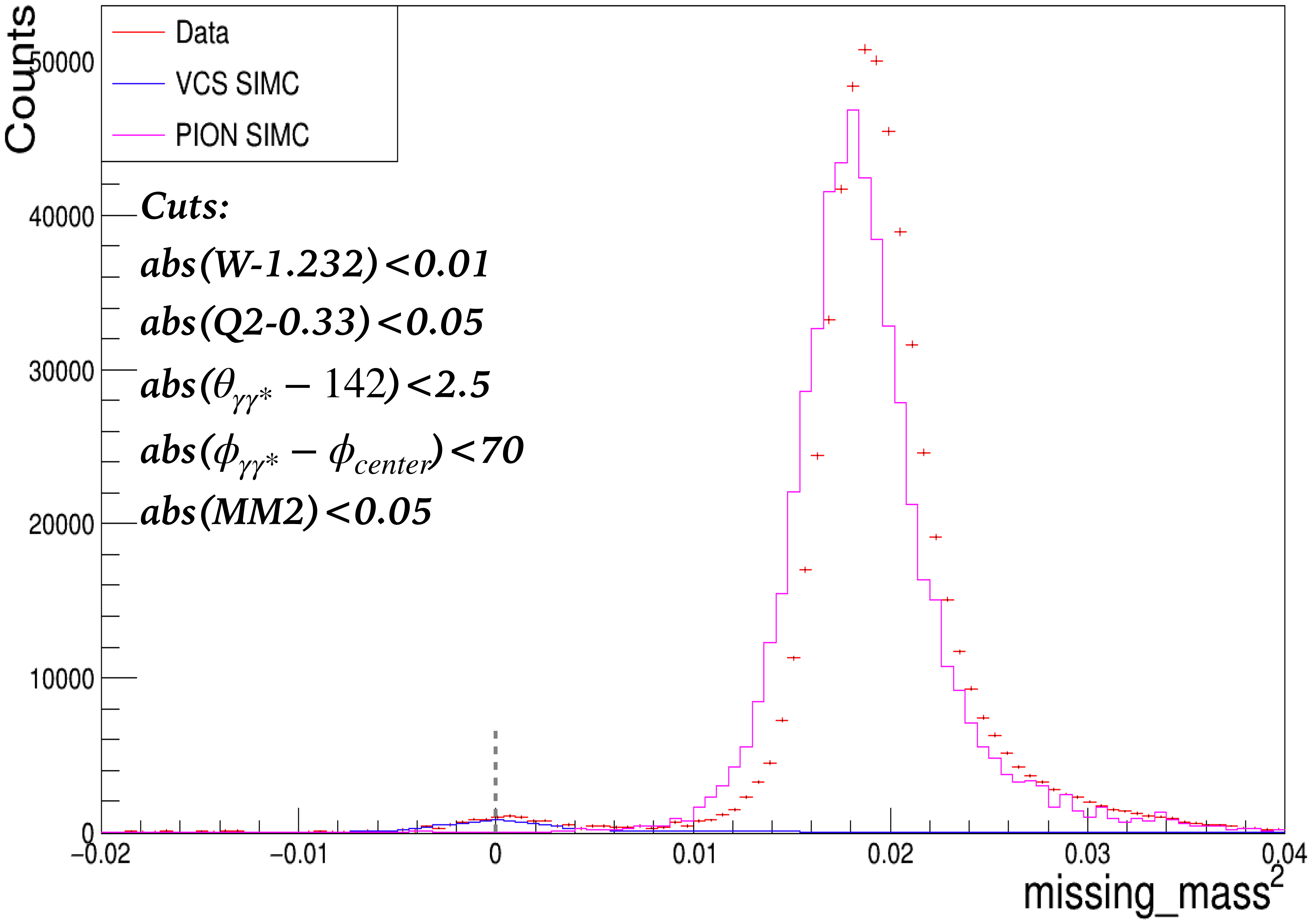
Cuts:

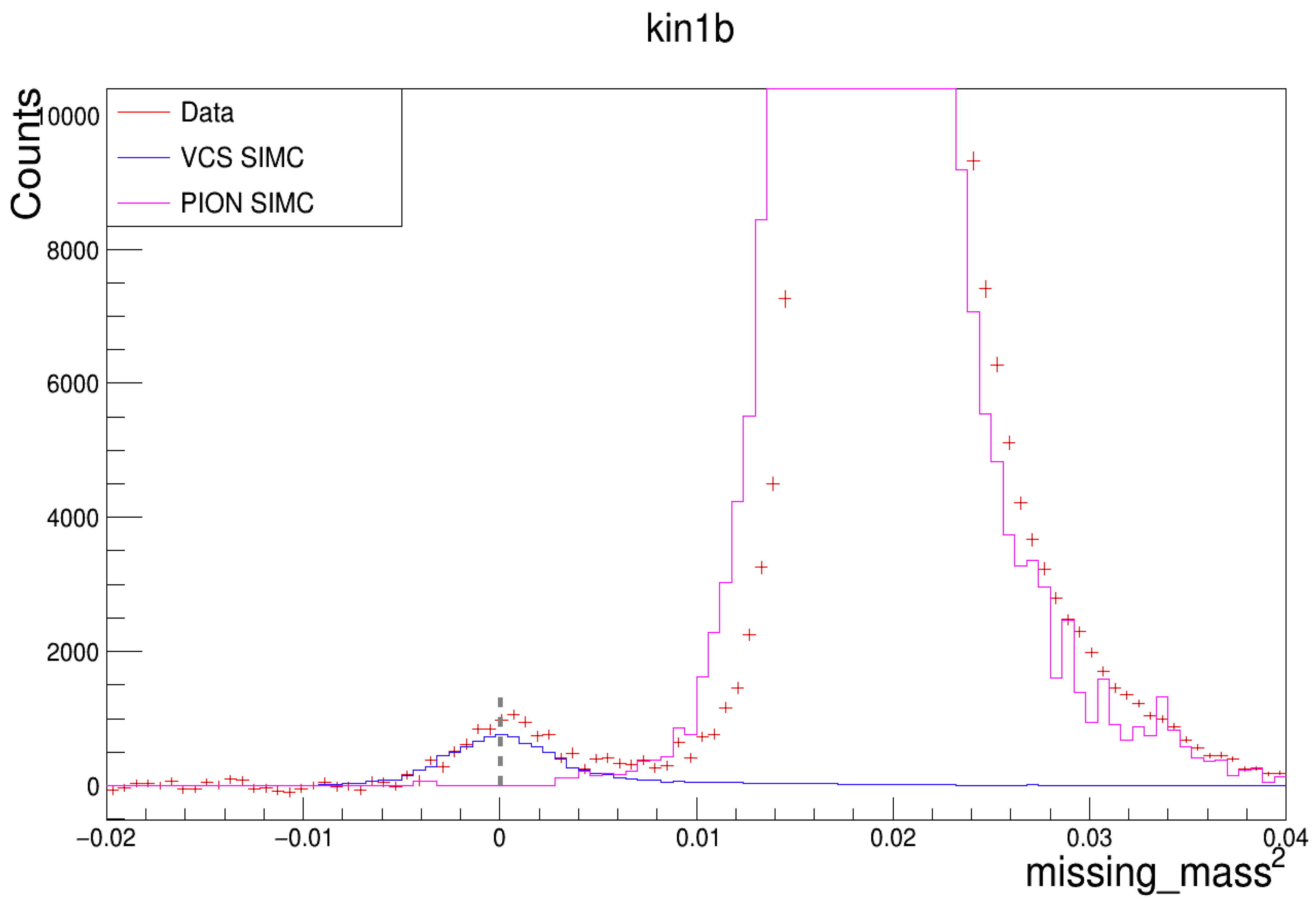
-0.01<mm2 < 0.01

1.075<W<1.3

VCS Preliminary Analysis

Kin 1b Missing Mass Squared





VCS data vs. DR comparison ONGOING…

Revisit SHMS/HMS moment and angle offset
To get a better match with pi0 peak

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(revisit)**
  - **π^0 production cross section extraction** – **preliminary results**
  - **Determination of VCS cross section and extraction of α_E and β_M** – **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

Temple University
Ruonan Li

On behalf of JLAB E12-15-001 Collaboration

Backup Slides

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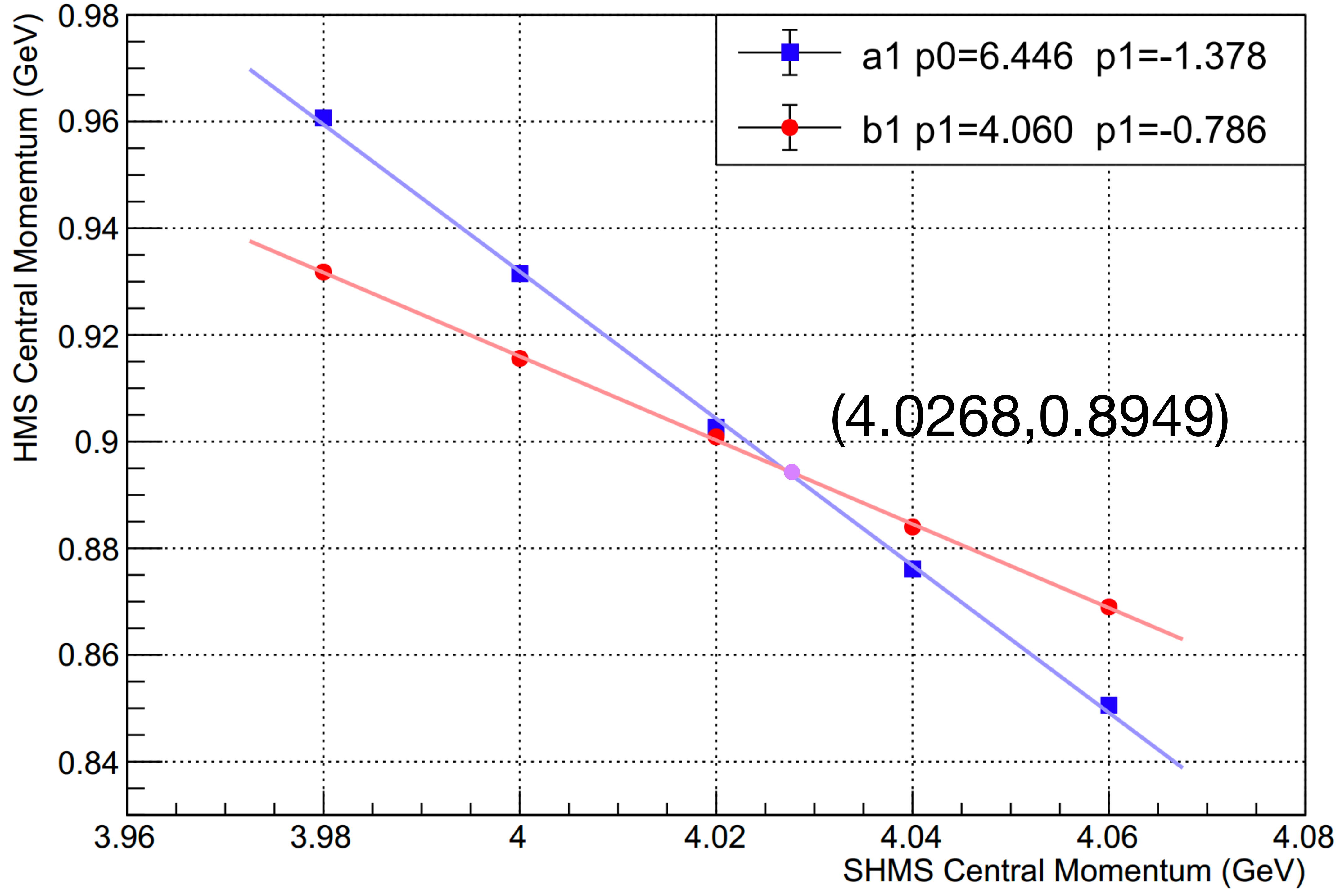
Energy Calibration

Spectrometer: Same momentum,Different HMS theta

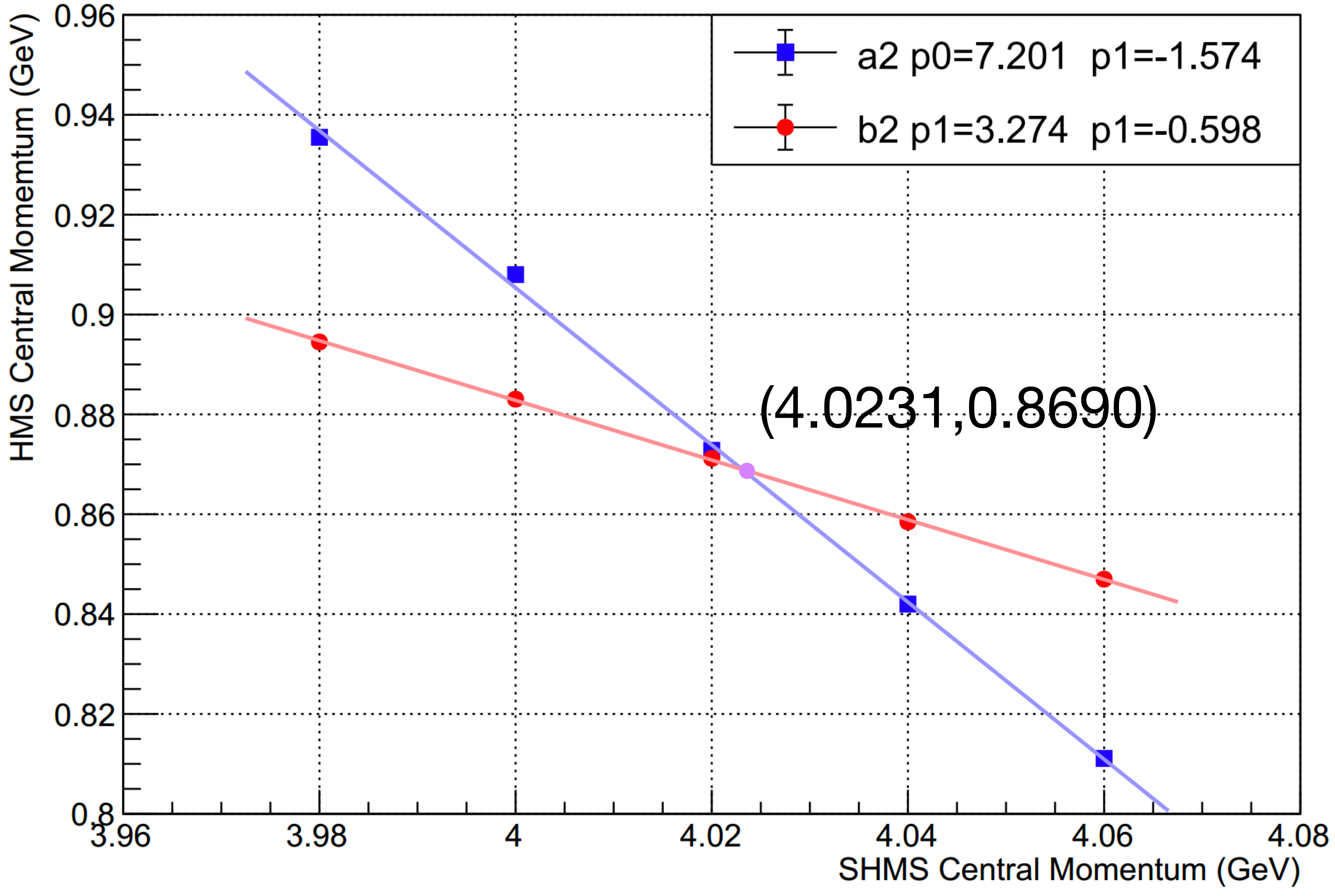
	SHMS_p	SHMS_th	HMS_p	HMS_th
Kin1a	4.034	7.69	0.893	37.33
Kin1b	4.034	7.69	0.893	51.40

	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

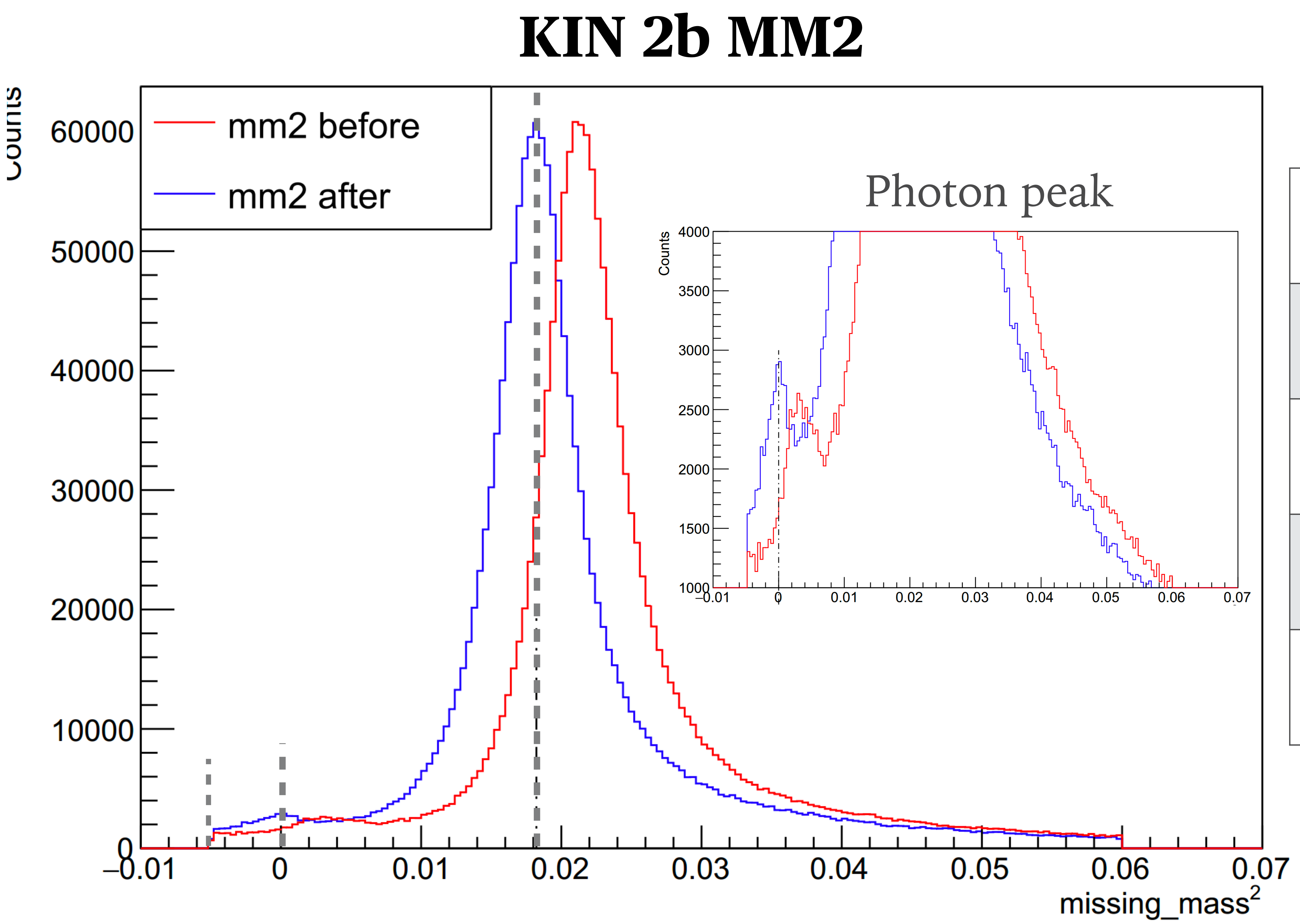
Kin 1a & Kin 1b



Kin 2a & Kin 2b

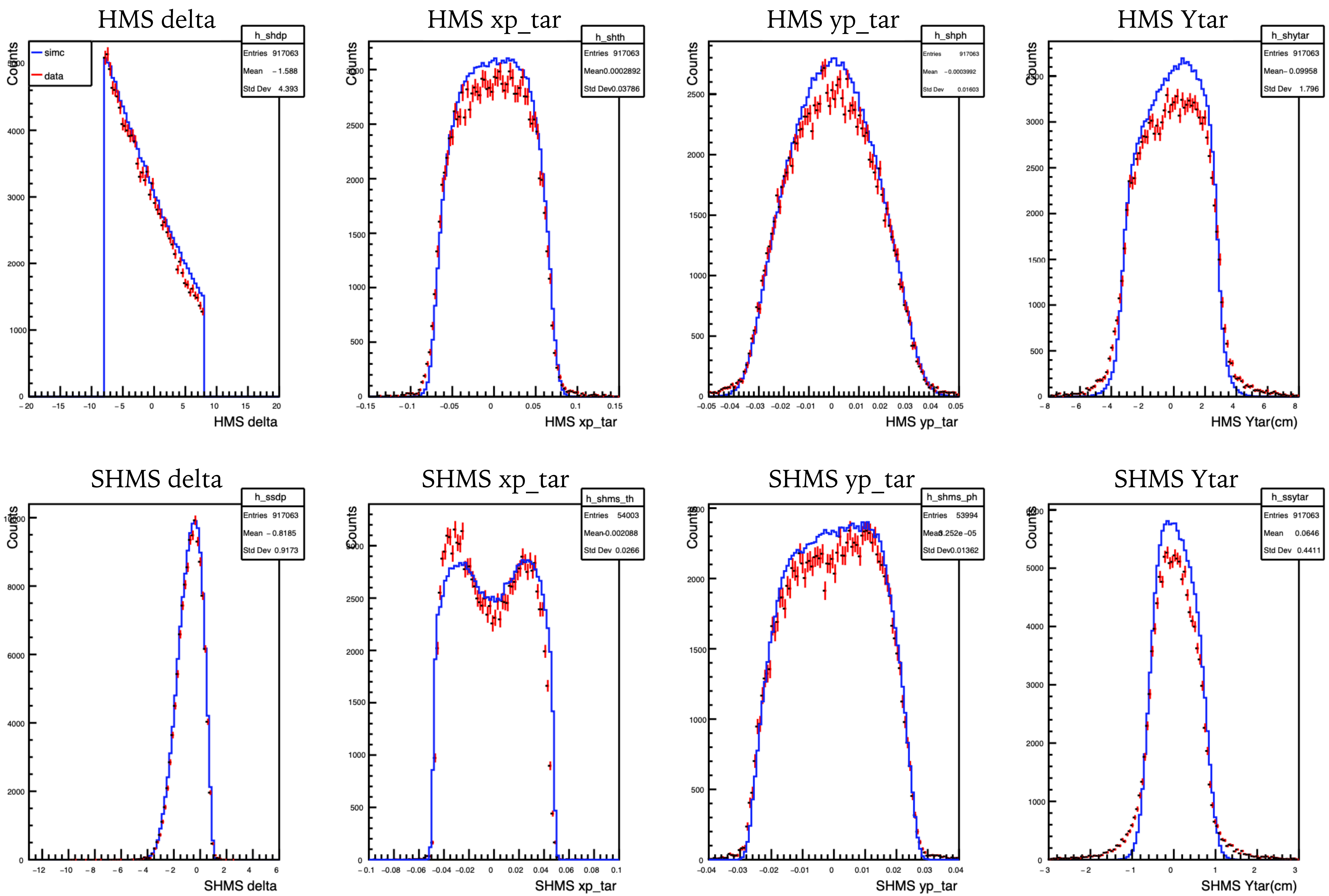


Energy Calibration



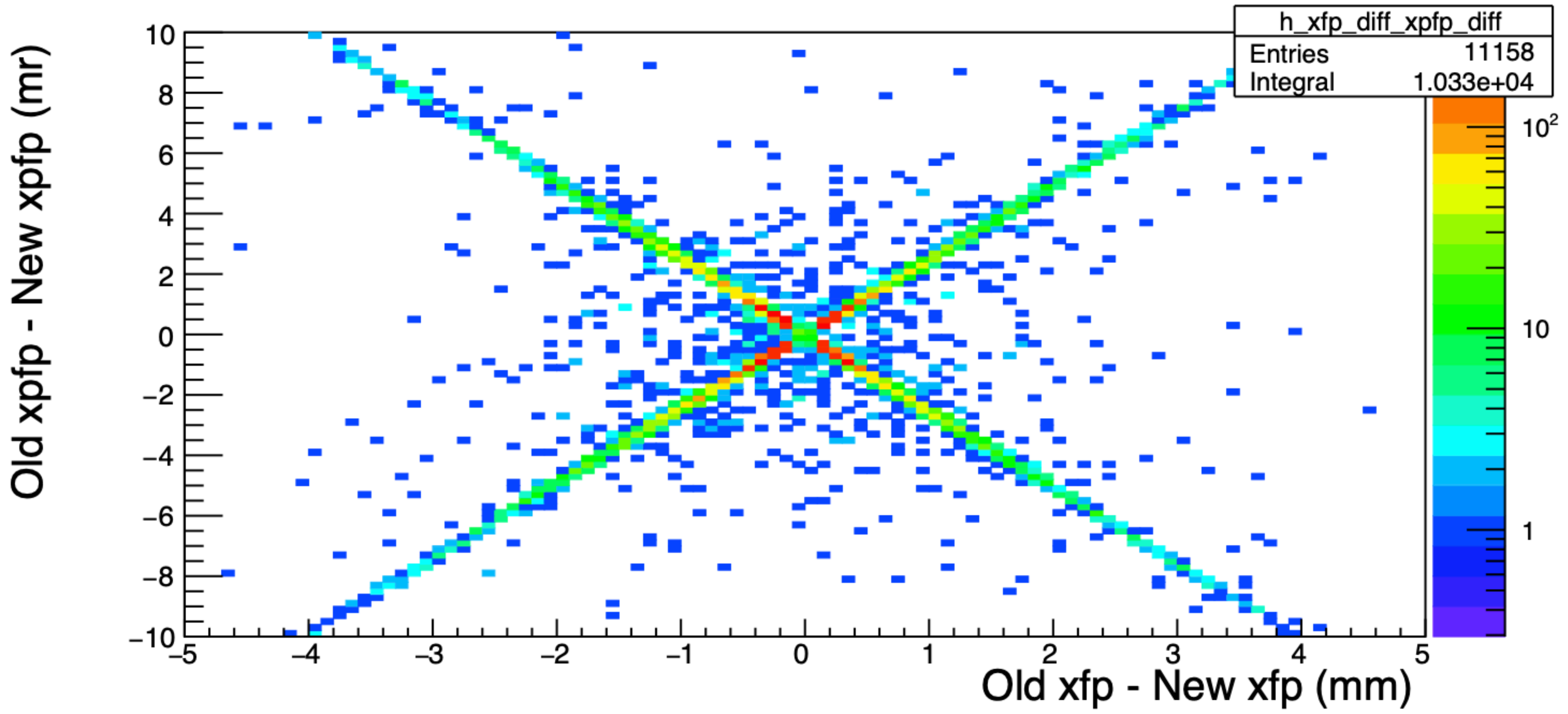
	SHMS_p Cal	SHMS_p Exp	Offset	HMS_p Cal	HMS_p Exp	Offset
Kin1a	4.0268	4.034	0.002	0.8949	0.893	0.002
Kin1b	4.0268	4.034	0.002	0.8949	0.893	0.002
Kin2a	4.0231	4.034	0.003	0.869	0.863	0.007
Kin2b	4.0231	4.034	0.003	0.869	0.863	0.007

Pion Preliminary Analysis

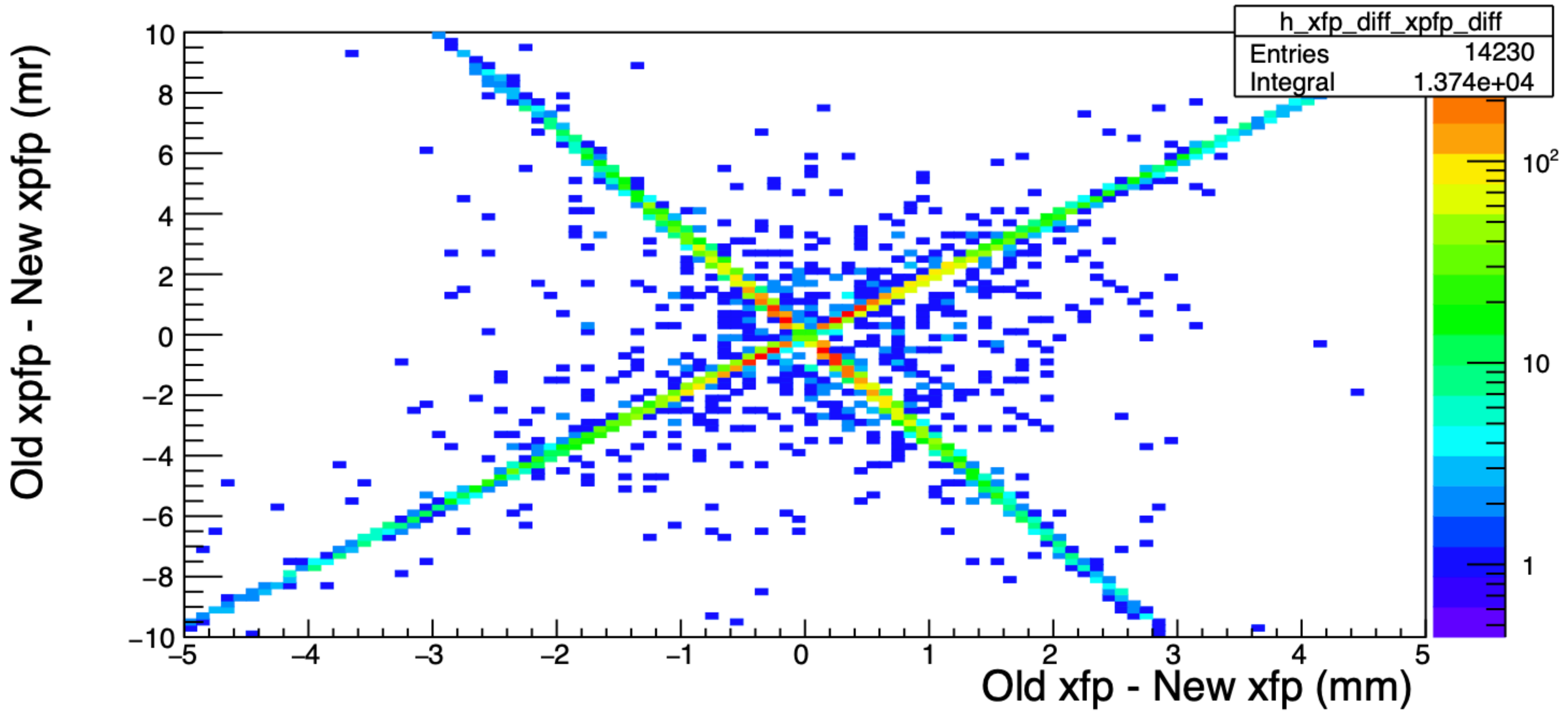


HCANA UPDATE

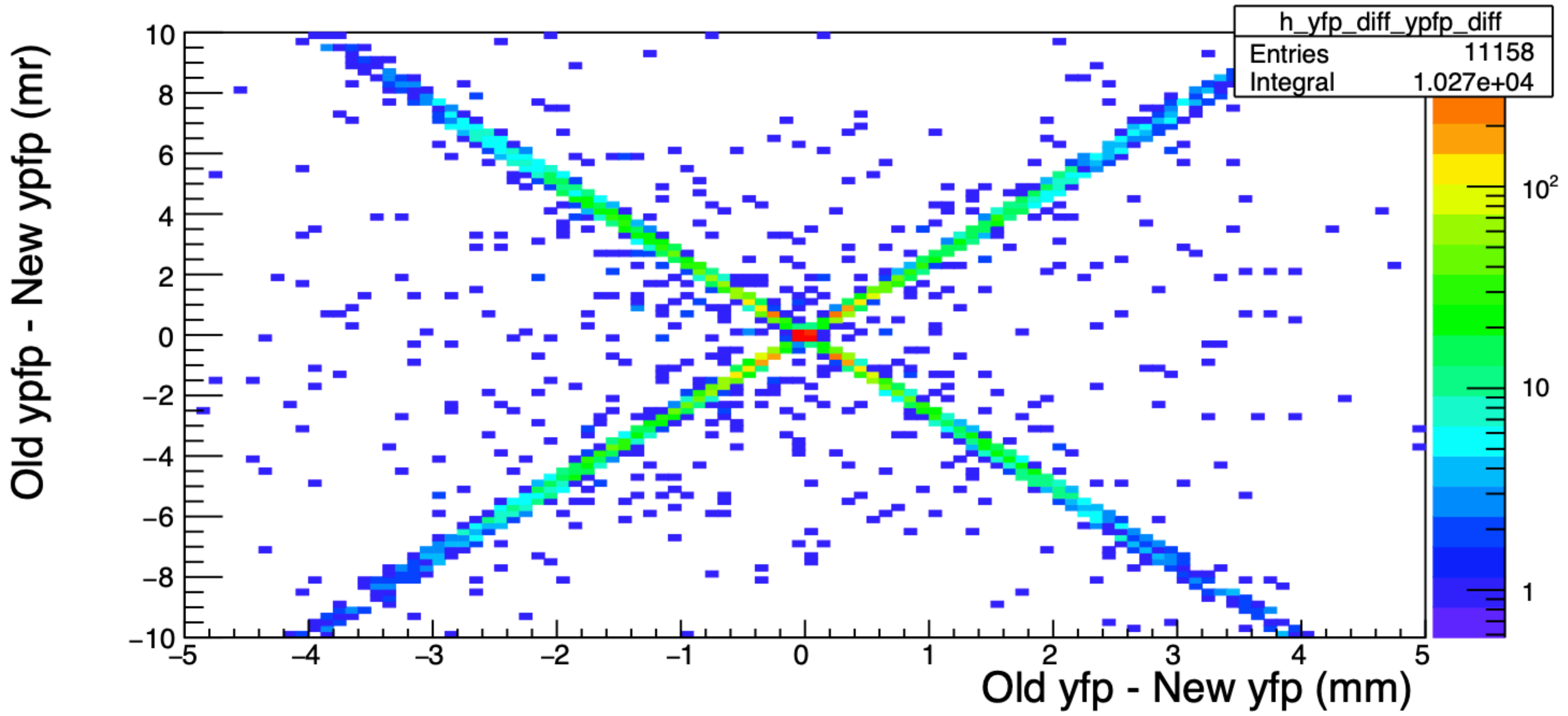
Old chi2>100 SHMS Run 9369



Old chi2>100 HMS Run 9369



Old chi2>100 SHMS Run 9369



Old chi2>100 HMS Run 9369

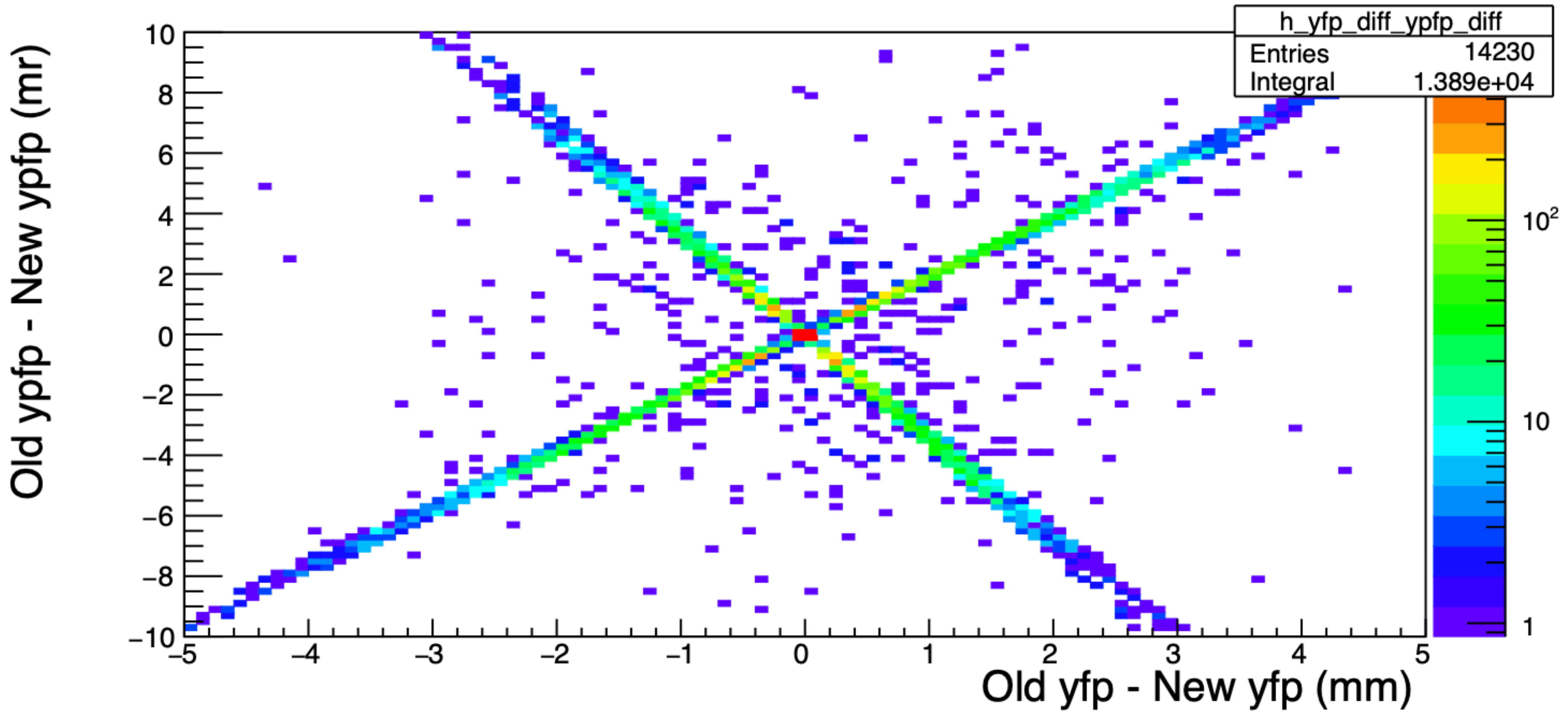


Figure Credit: Mark Jones