The Generalized Polarizabilities of the Proton

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On behalf of JLAB E12-15-001 Collaboration

JLAB HALLC COLLABORATION MEETING 1/29/2021

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- VCS Experiment E12-15-001
- Analysis Progress
  - Elastic Data
  - Pion Preliminary Analysis
  - VCS Preliminary Analysis
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Polarizabilities

Polarizability:

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

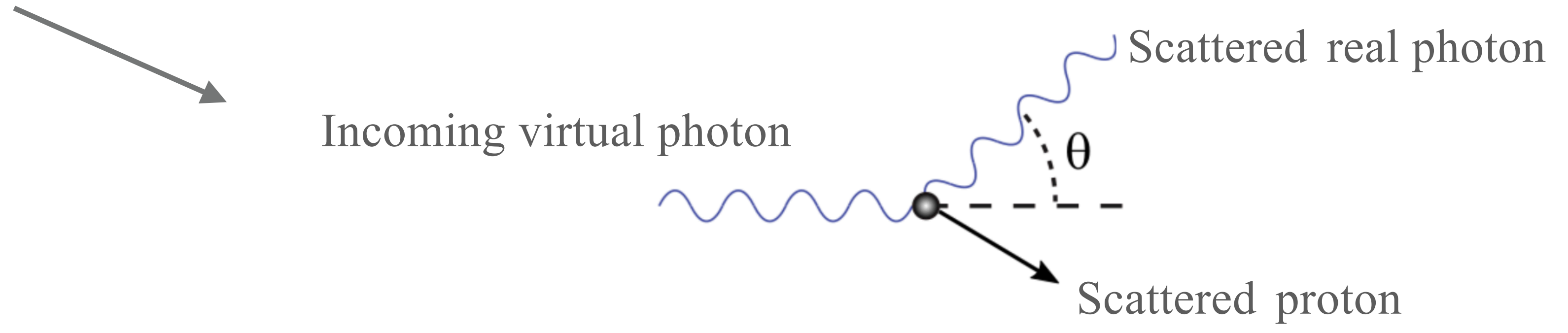
N BARYONS
($S = 0$, $I = 1/2$)
p, $N^+ = uud$; n, $N^0 = udd$

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]
$\left|m_p - m_{\overline{p}}\right|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$\left|\frac{q_{\overline{p}}}{m_{\overline{p}}}\right|/(\frac{q_p}{m_p}) = 1.00000000000 \pm 0.00000000007$
$\left|q_p + q_{\overline{p}}\right|/e < 7 \times 10^{-10}$, CL = 90% [b]
$\left|q_p + q_e\right|/e < 1 \times 10^{-21}$ [c]
Magnetic moment $\mu = 2.7928473446 \pm 0.0000000008$ μ_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 $= 0.84087 \pm 0.00039$ fm [d]
Charge radius, ep CODATA value $= 0.8751 \pm 0.0061$ fm [d]
Magnetic radius $= 0.78 \pm 0.04$ 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)

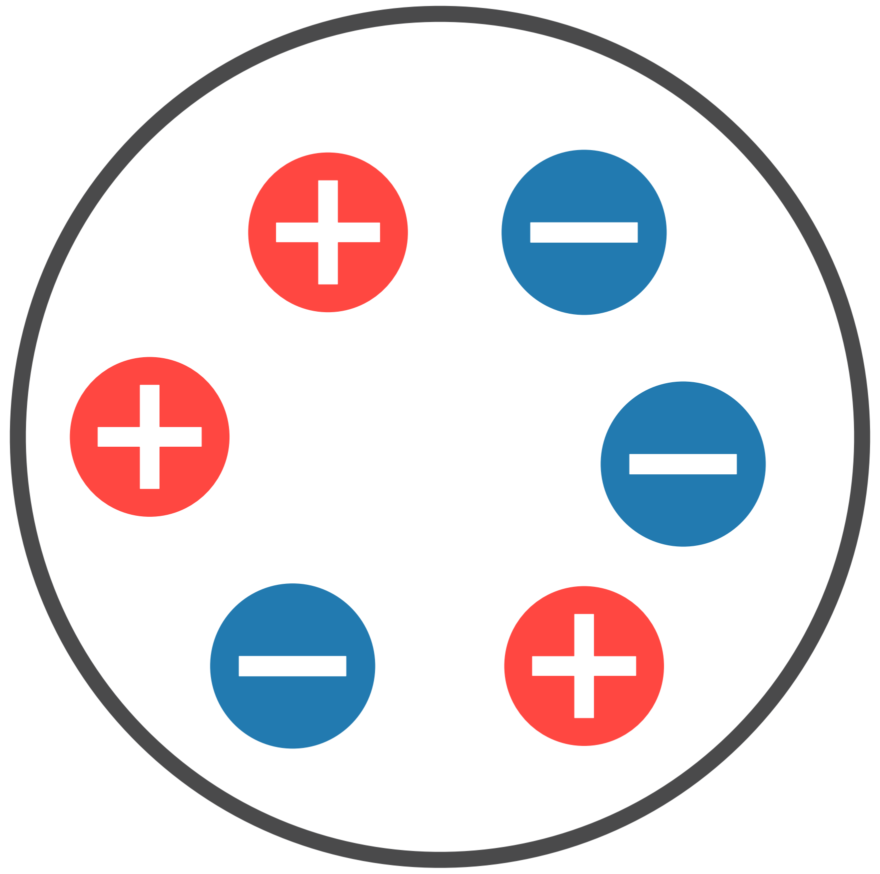
Generalized Polarizabilites (GPs):

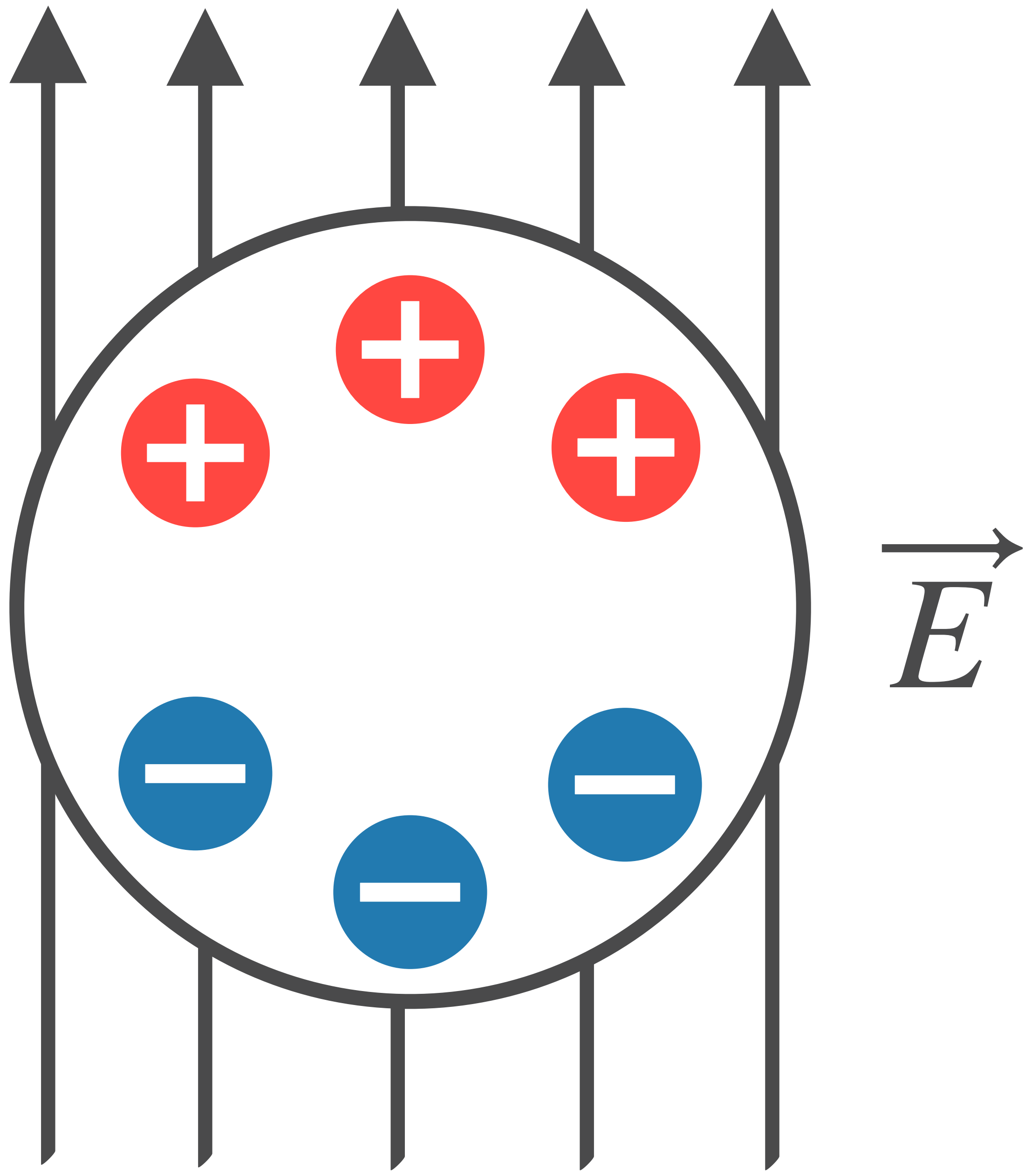
- Access by Virtual Compton Scattering (VCS)



- 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



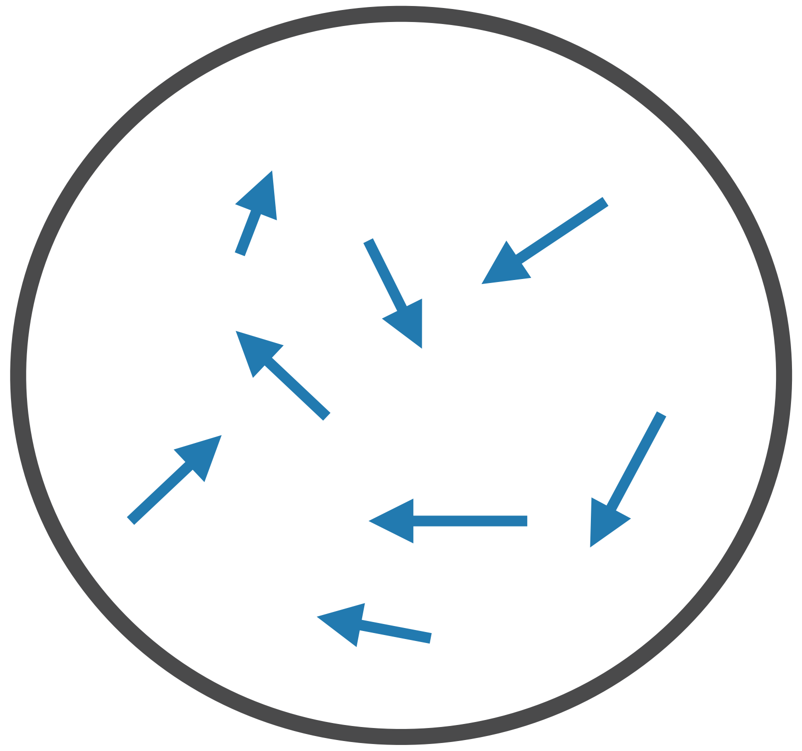


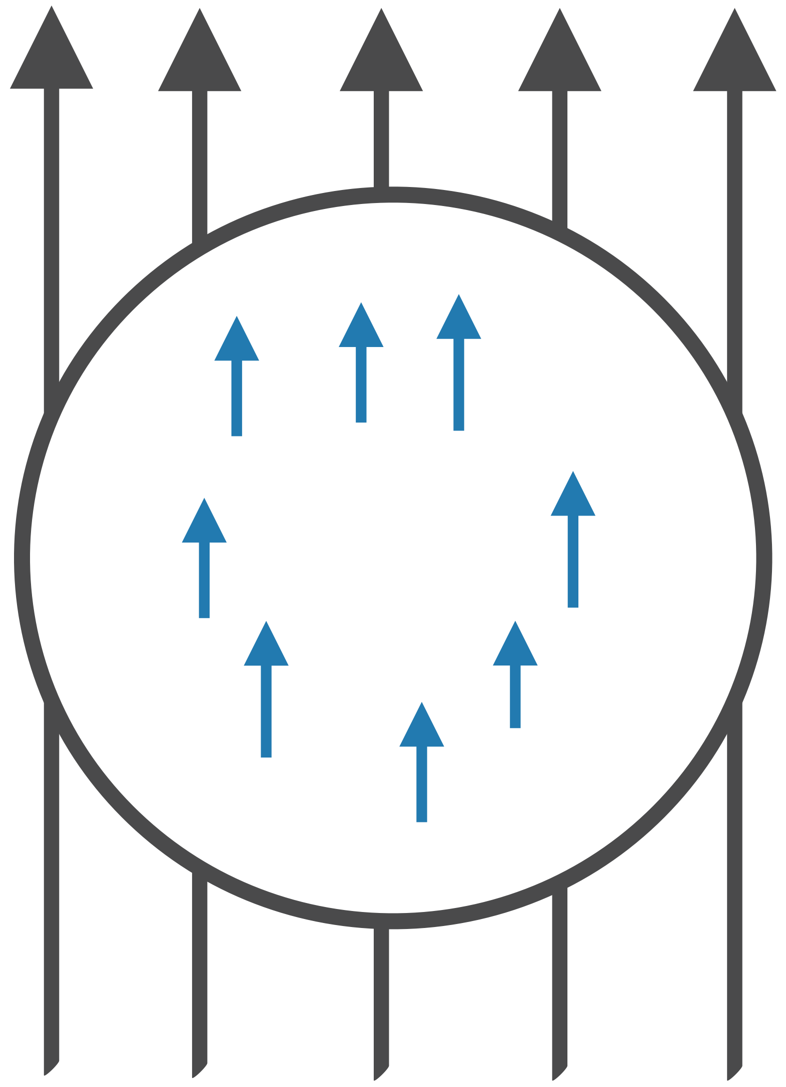
$$\vec{p} = \alpha_E \vec{E}$$

Electric Polarizability

- Electric polarizability α_E reflects the **rigidity** of proton

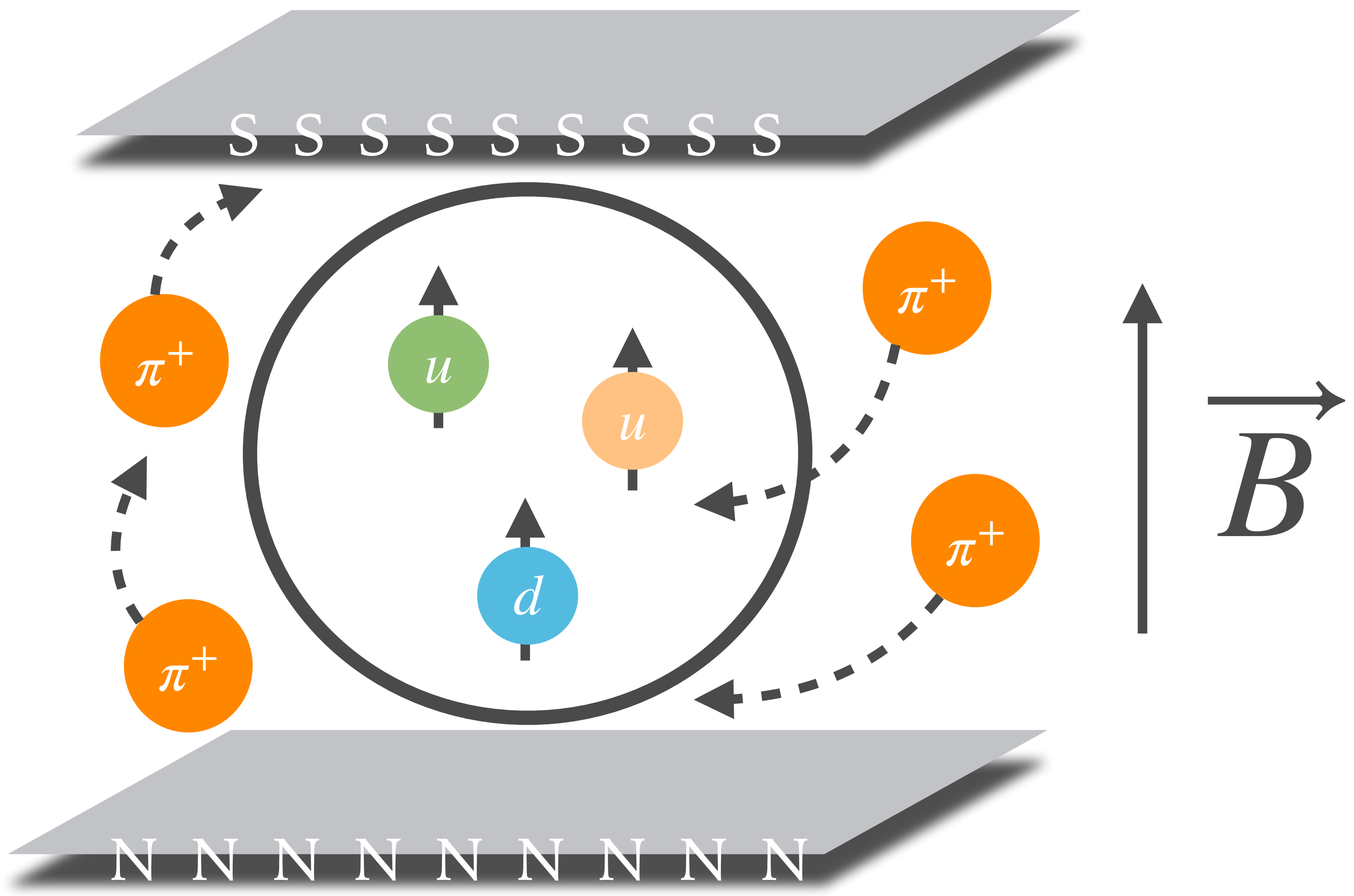
Generalized Polarizabilities





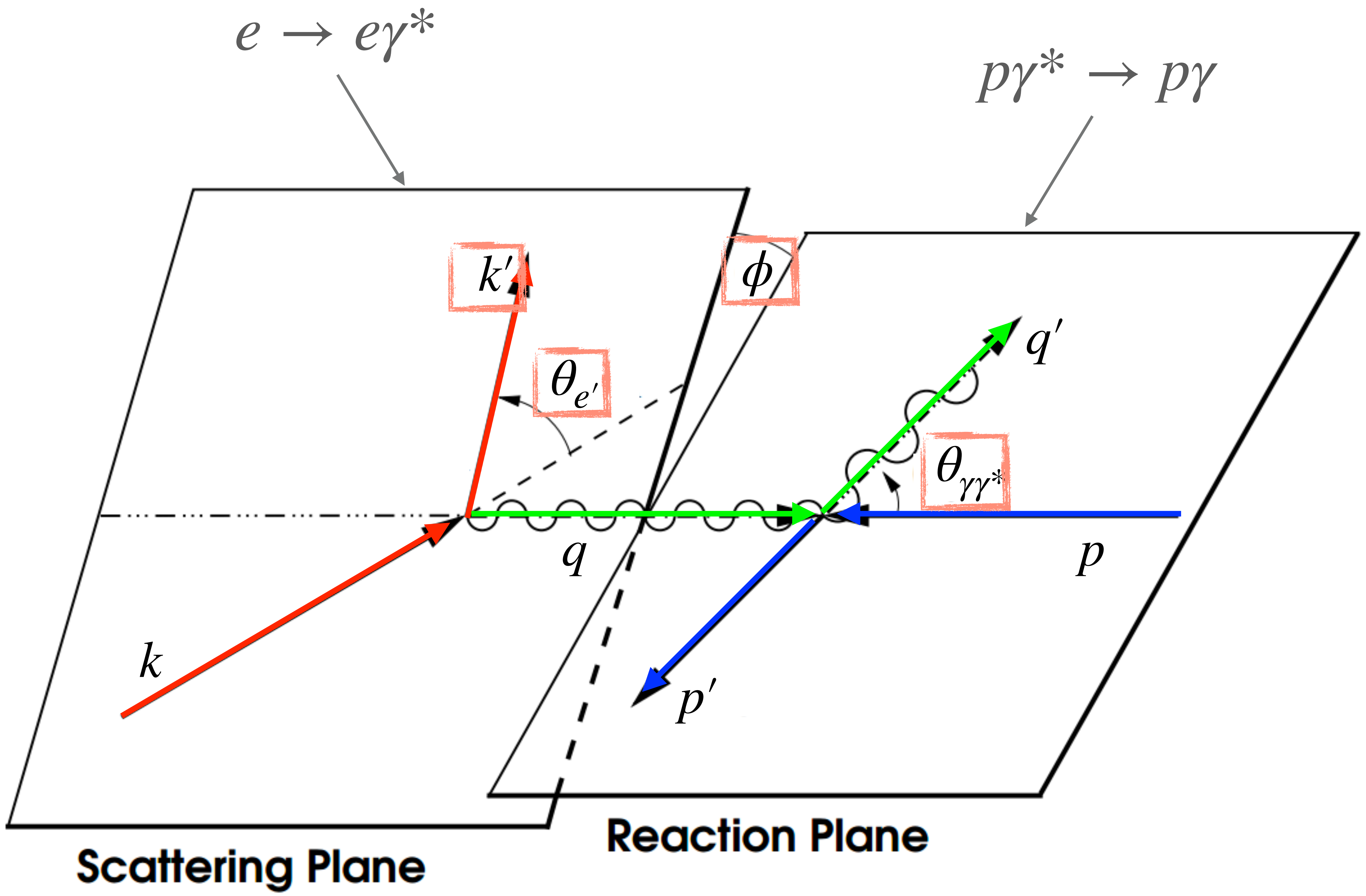
Magnetic Polarizability

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



- **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



Kinematics of $ep \to ep\gamma$ reaction

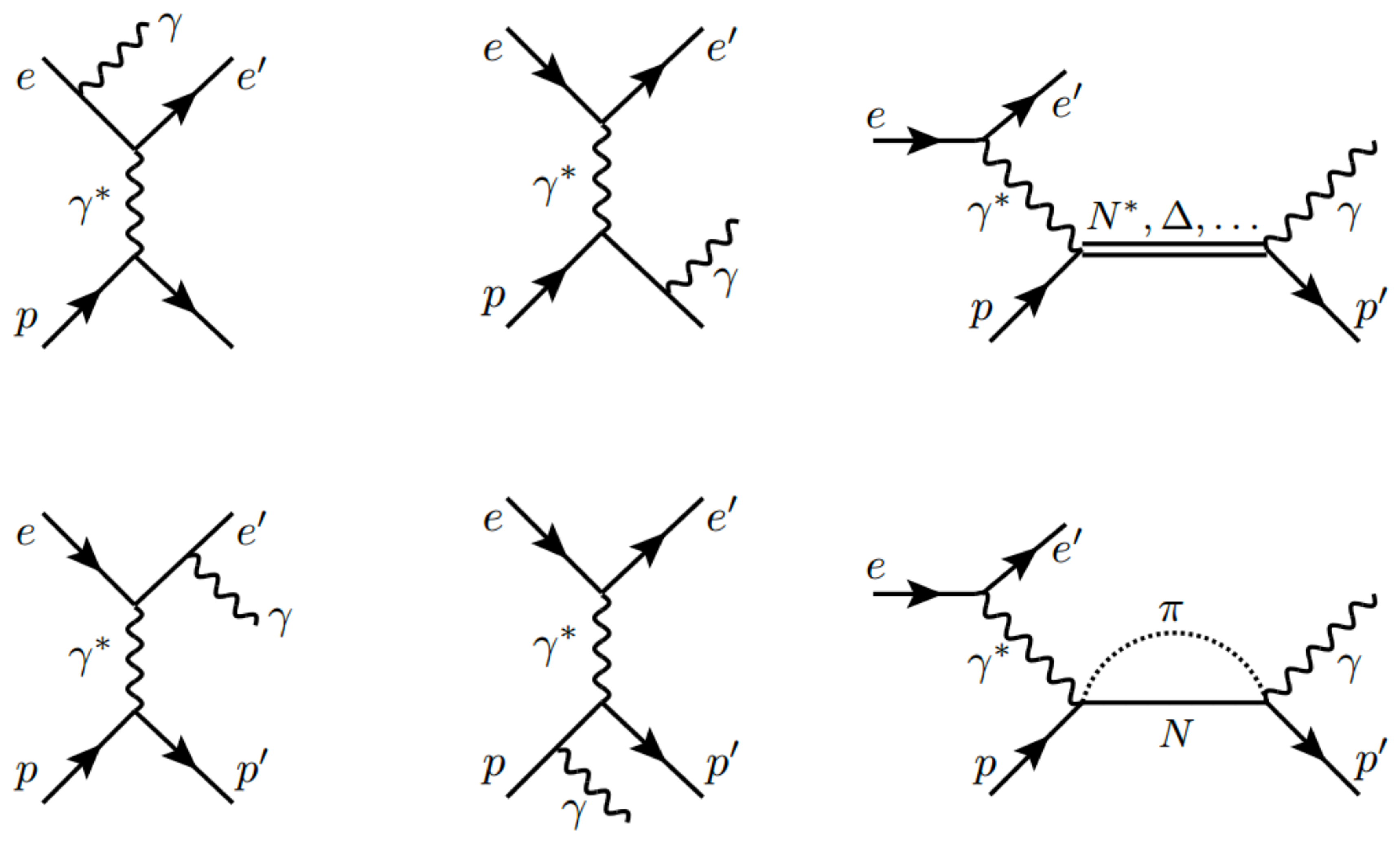
k-incoming electron
q-virtual photon
p-initial proton
k'-scattered electron
q'-real photon
p'-final proton

VCS cross section =

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

Amplitudes

VCS process → photon electro-production reaction



Bethe-Heitler | VCS Born | VCS non-Born

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

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

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

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

Amplitudes for photon electroproduction process :

$$T^{ep\to ep\gamma} = T^{BH} + T^{Born} + T^{NB} = T^{BH} + T^{VCS}$$

LEX & DR Formalism

LEX - Low Energy Expansion

Below pion threshold

$$d\sigma = d\sigma_{BH+Born} + (\Phi \cdot q'_{cm}) \cdot \Psi_0 + O(q'^2_{cm})$$

$$\Psi_0 = V_{LL} \cdot (P_{LL} - P_{TT}/\epsilon) + V_{LT} \cdot P_{LT}$$

$P_{LL} \sim P^{(L1,L1)0}(Q^2)$

$P_{TT} \sim (P^{(M1,M1)1}(Q^2) - \sqrt{2}\tilde{q}^0 P^{(L1,M1)1}(Q^2))$

$P_{LT} \sim P^{(M1,M1)0}(Q^2) + P^{(L1,L1)1}(Q^2)$

DR - Dispersion Relation Formalism

Below & Above pion threshold

Predicted ← *4 spin (vector) GPs*

↓

Free parameters ← *2 scaler GPs*

↓

Fits to cross section of experimental data

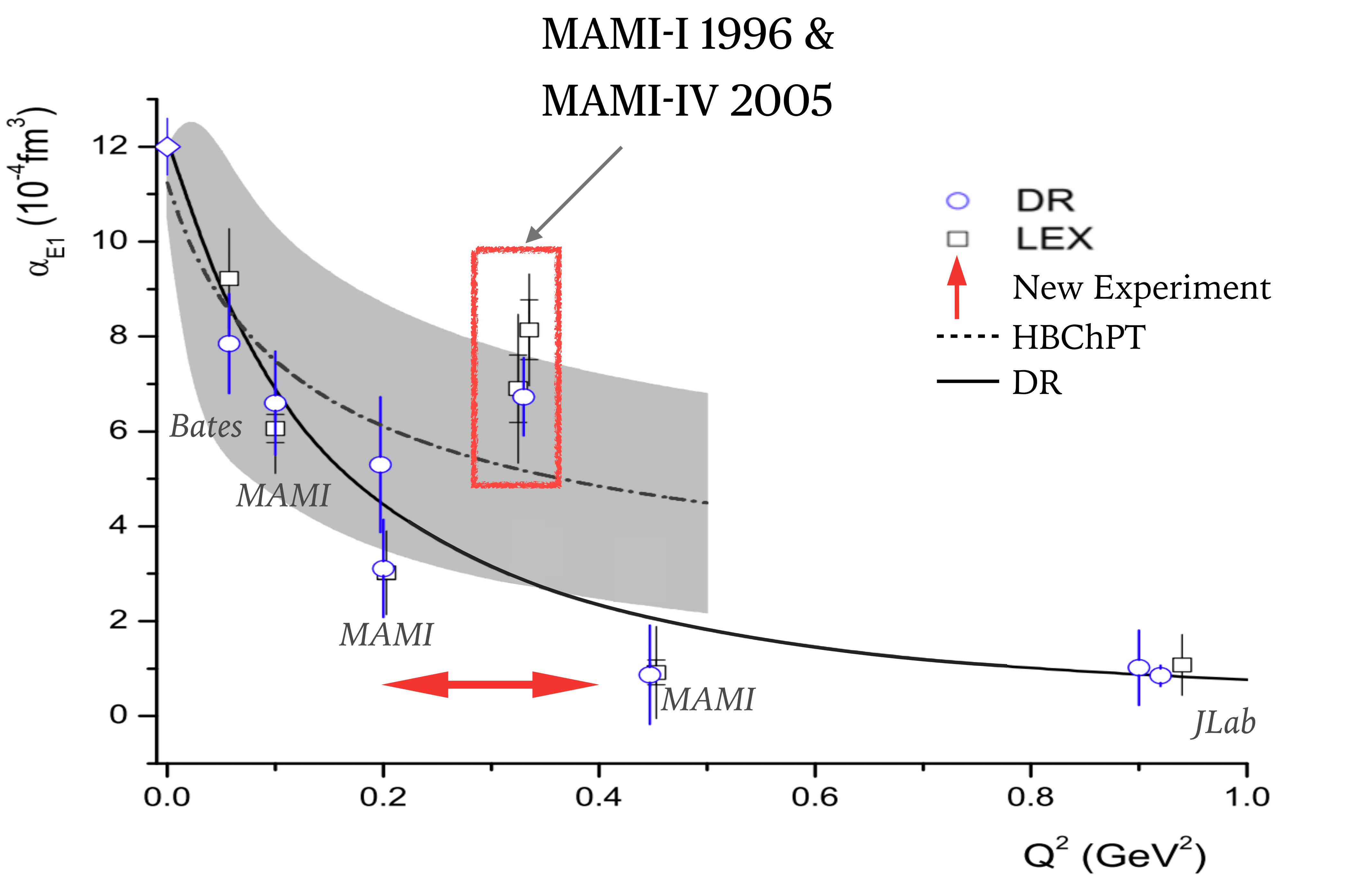
↓

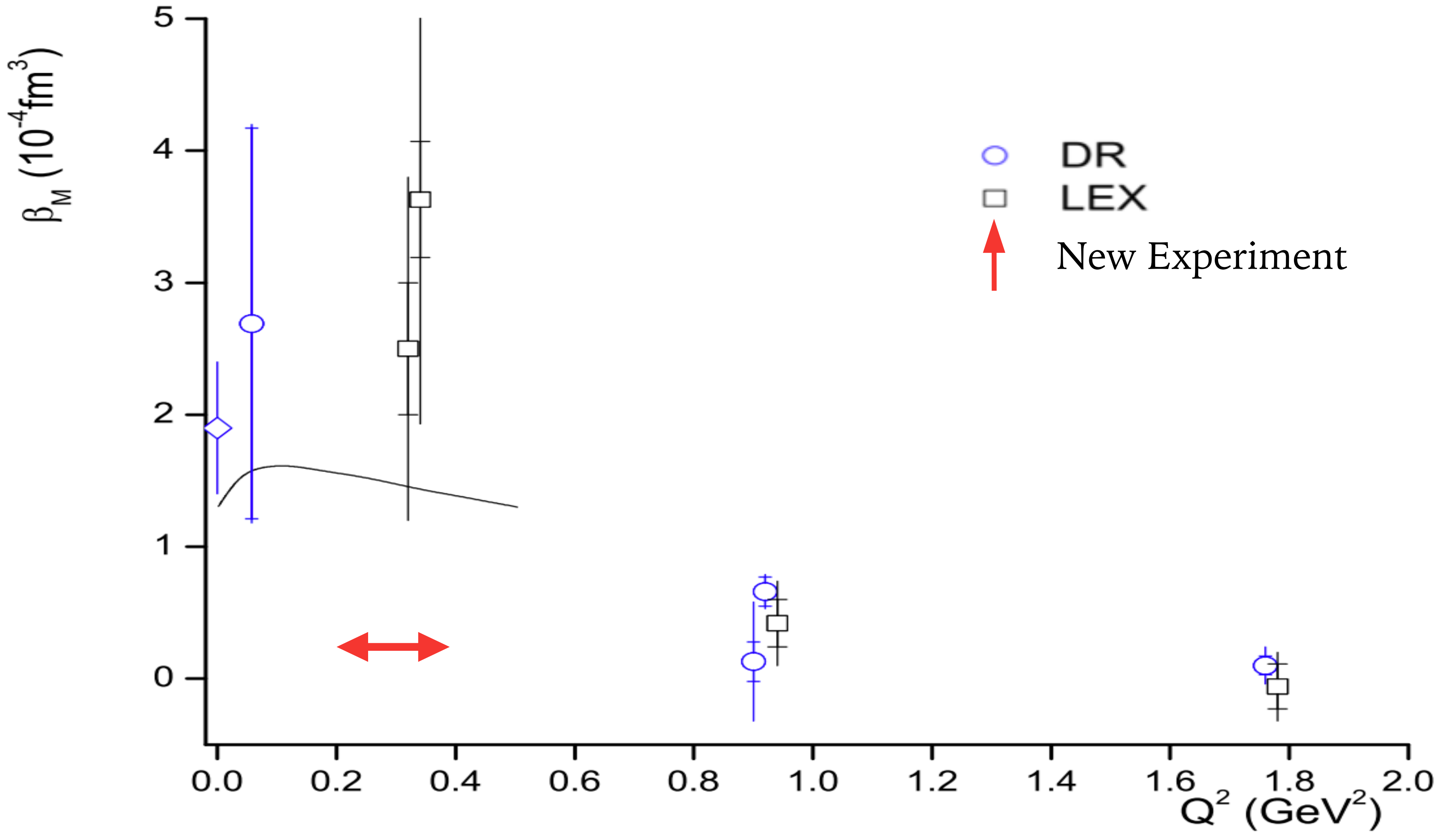
Find best χ^2

↓

Measurement of α_E and β_M

World Data & Motivation



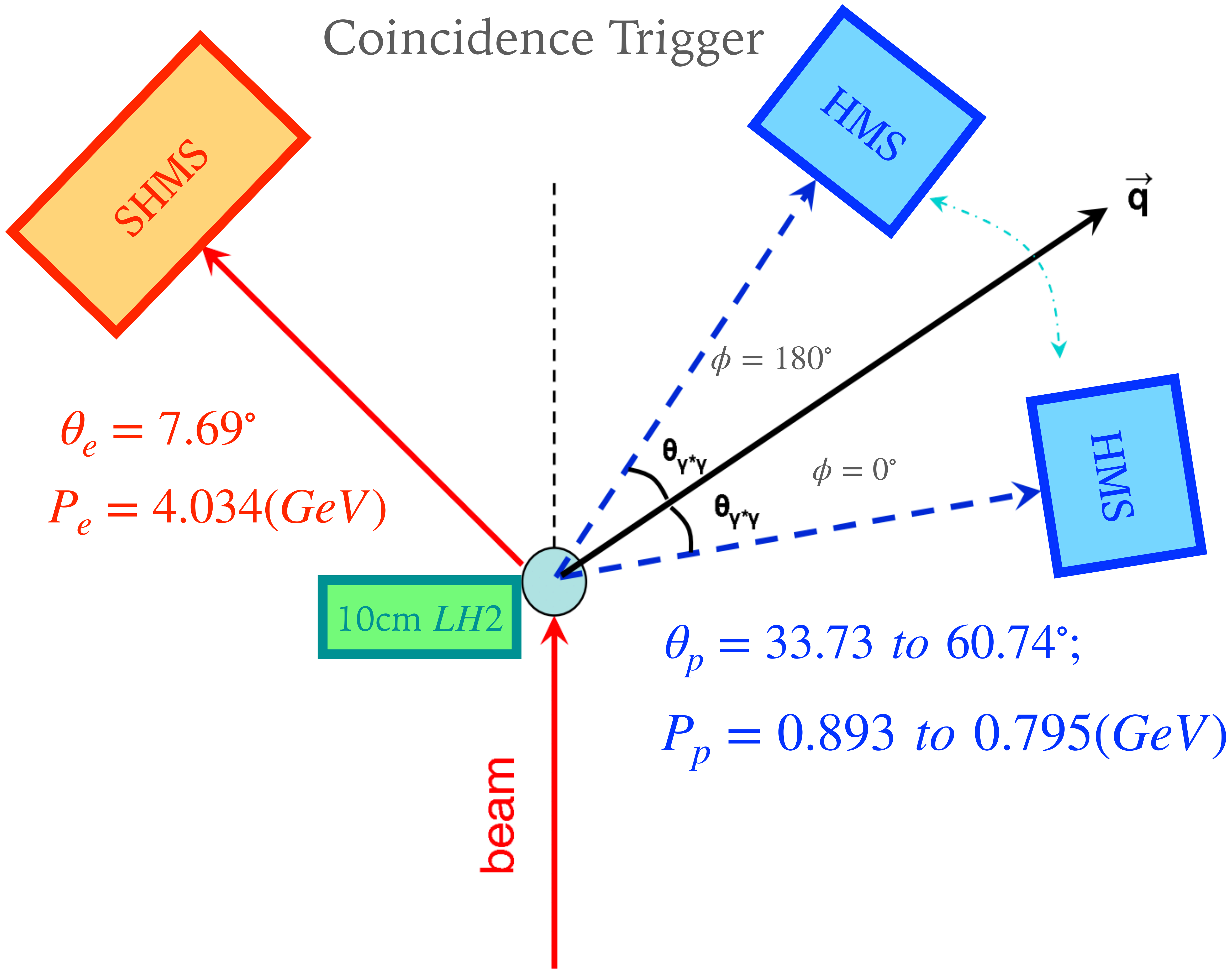


- Initial theoretical models predicted smooth fall off of α_E
  - data at $Q^2 = 0.33$ implies non-trivial structure
- New experiment can:
  - Address puzzling α_E enhancement
  - Reduce error by 2

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

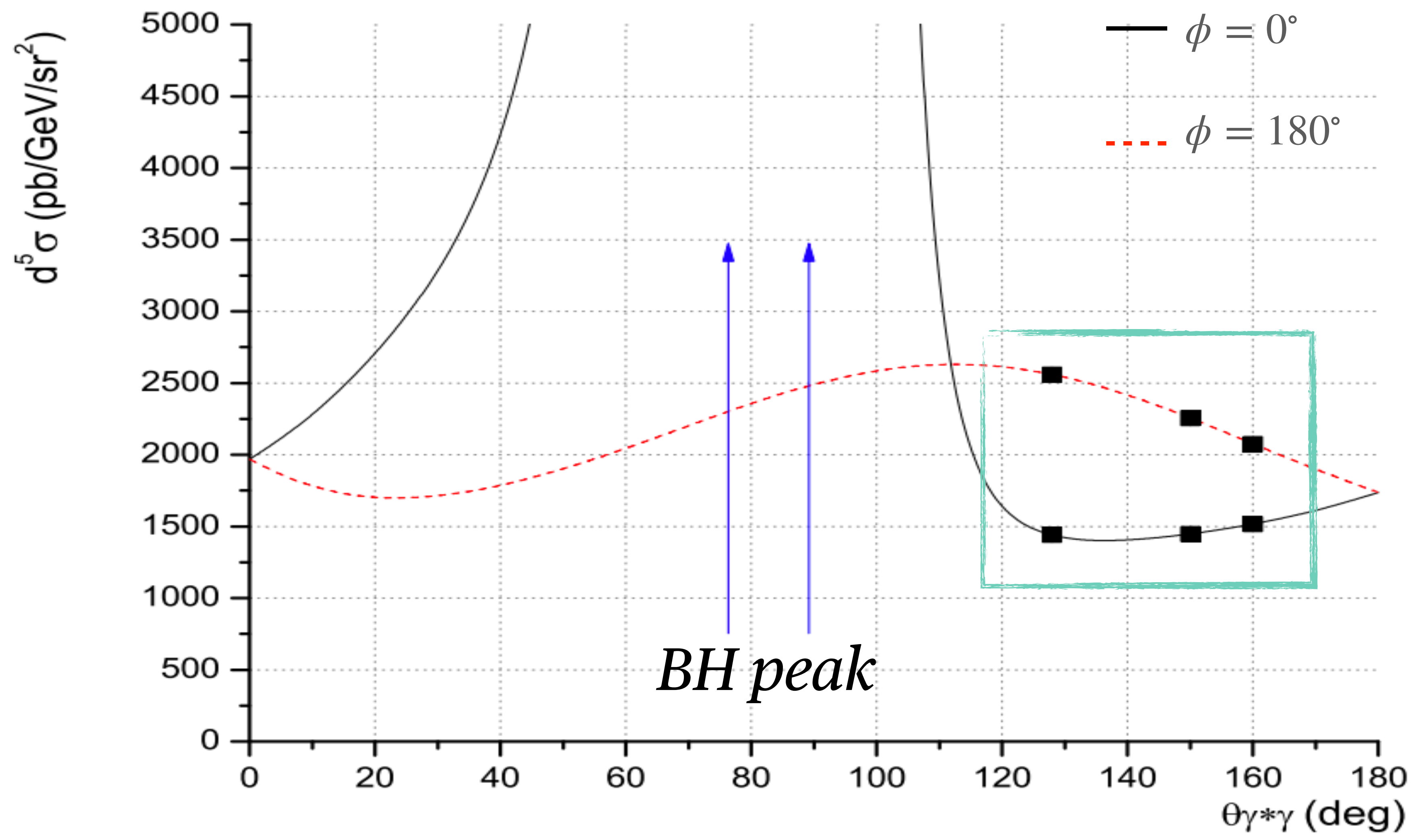
J. Roche, et al., Phys. Rev. Lett. 85 (2000) 708-711; P. Janssens, et al., Eur. Phys. J. A37 (2008) 1-8; G. Laveissiere, et al., Phys. Rev. Lett. 93 (2004) 122001; H. Fonvieille, et al., Phys. Rev. C86 (2012) 015210;P. Bourgeois, et al., Phys. Rev. Lett. 97 (2006) 212001; Eur.Phys.J.A55(2019)no. 10,182;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

JLab E12-15-001 Experiment



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

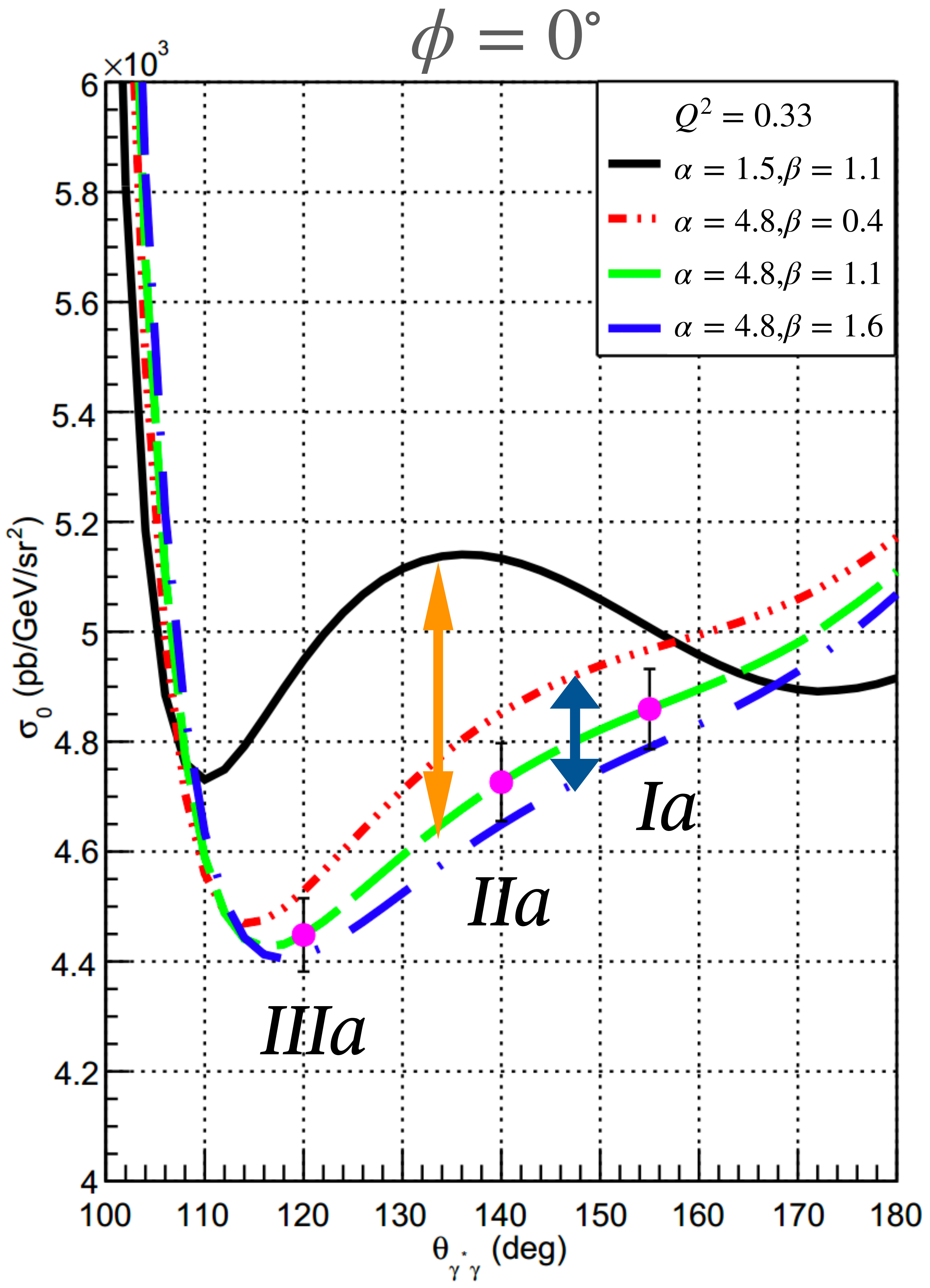
- Summer 2019: July 20 - August 5
- Beam $E = 4.56GeV$
- $Q^2 = 0.33GeV^2$, $W = 1.232GeV$

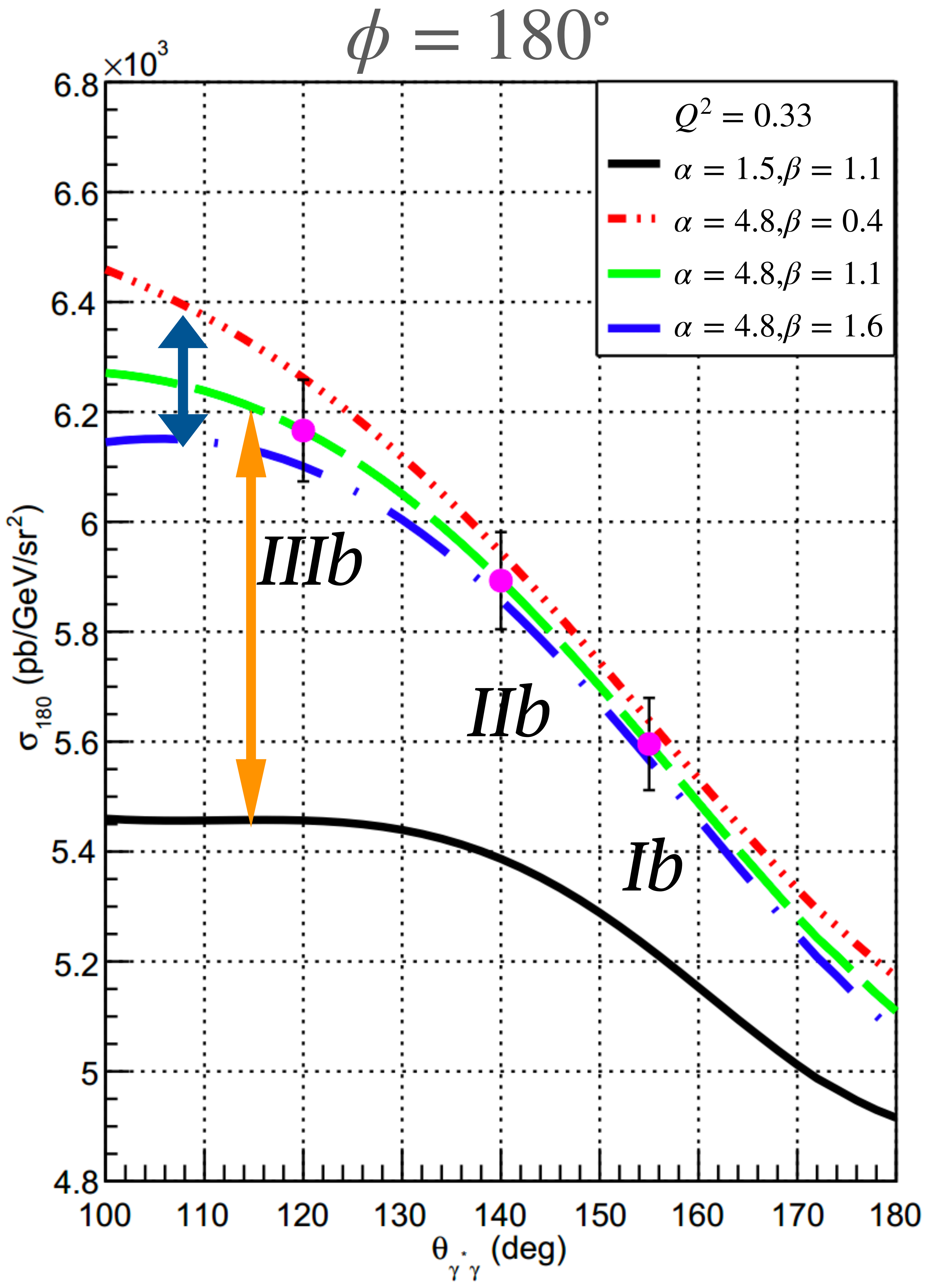


➤ High enough $\theta_{\gamma\gamma^*}$ to avoid BH peak

➤ Avoid rapid cross section variation

Predicted Measurement





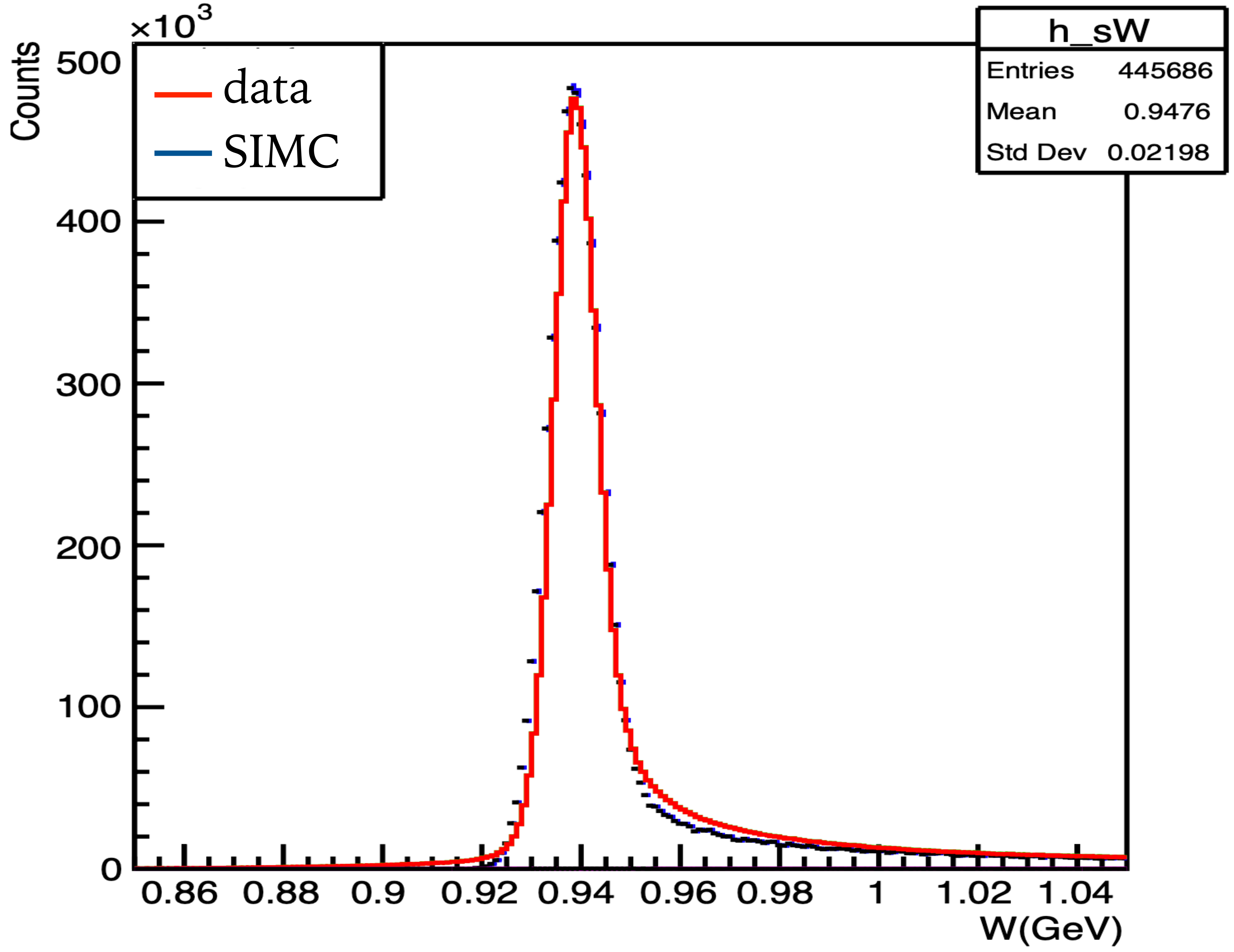
Sensitivity to α_E

Sensitivity to β_M

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

Elastic

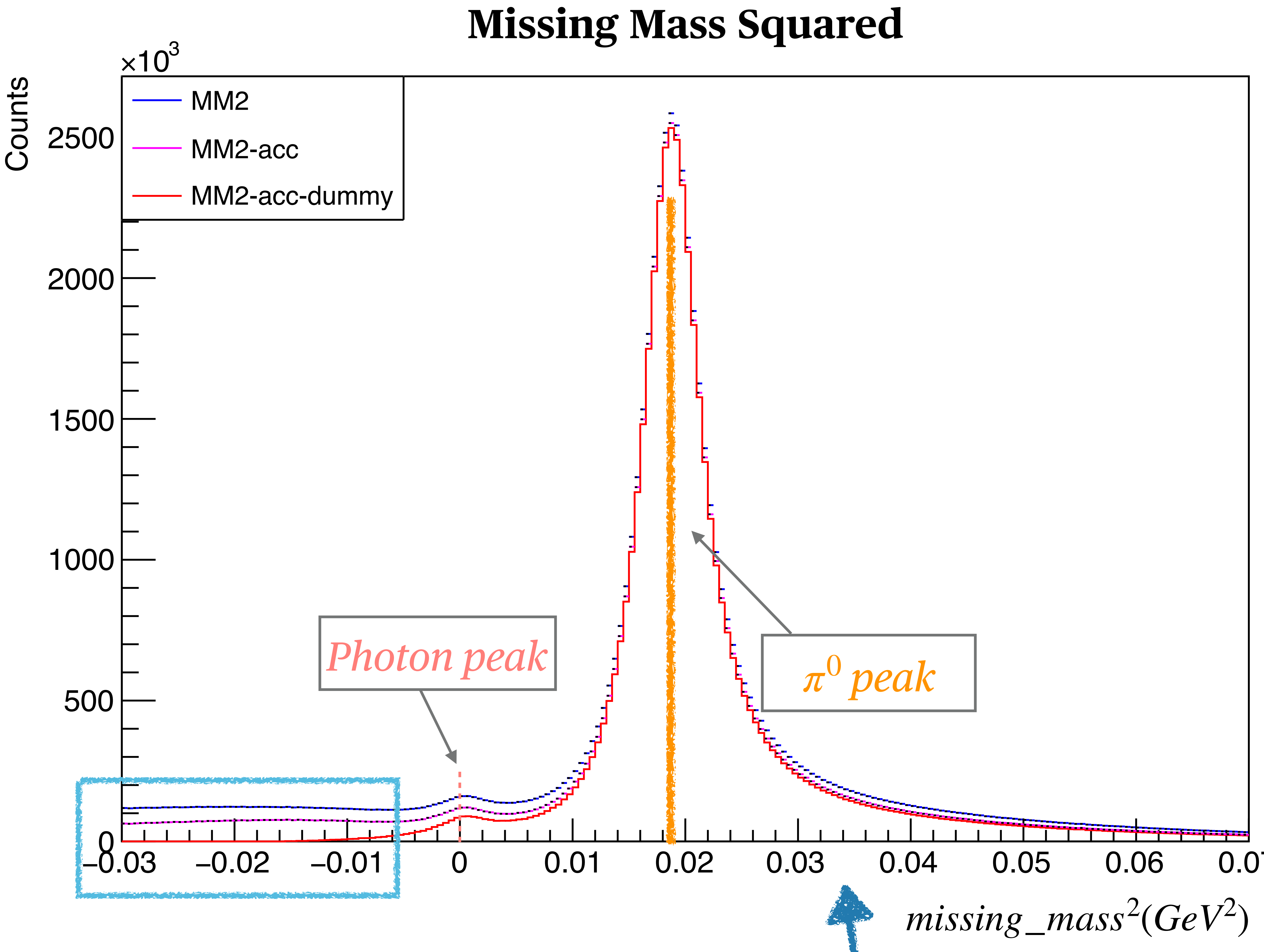
Elastic II data vs. simulation

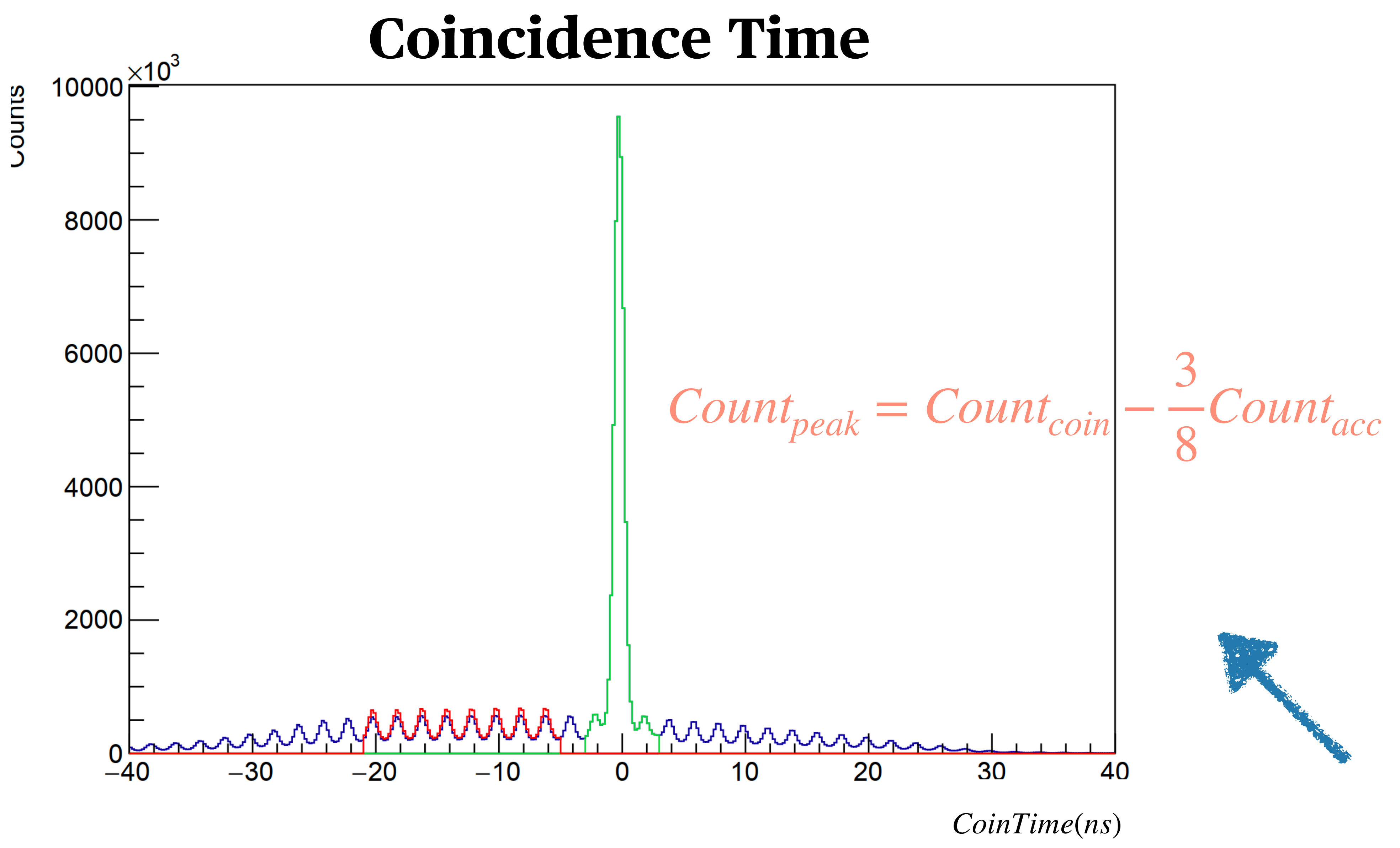


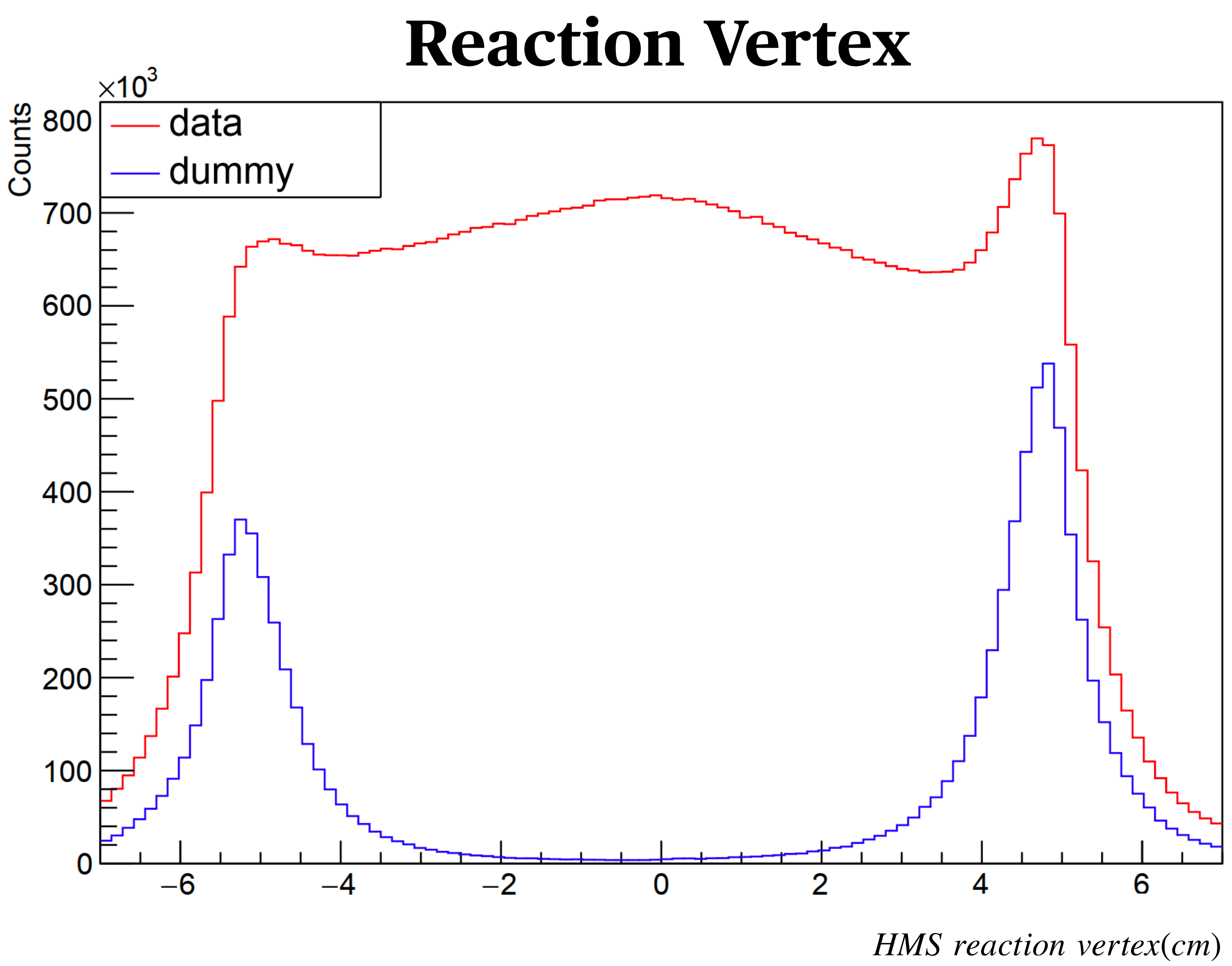
Kinematic	θ_e°	$P_e(GeV/c)$	θ_p°	$P_p(GeV/c)$
Elastic I	10.76	4.193	61.16	0.893
Elastic II	10.41	4.214	61.95	0.863
Elastic III	9.64	4.259	63.76	0.795

Agreement in 3 %

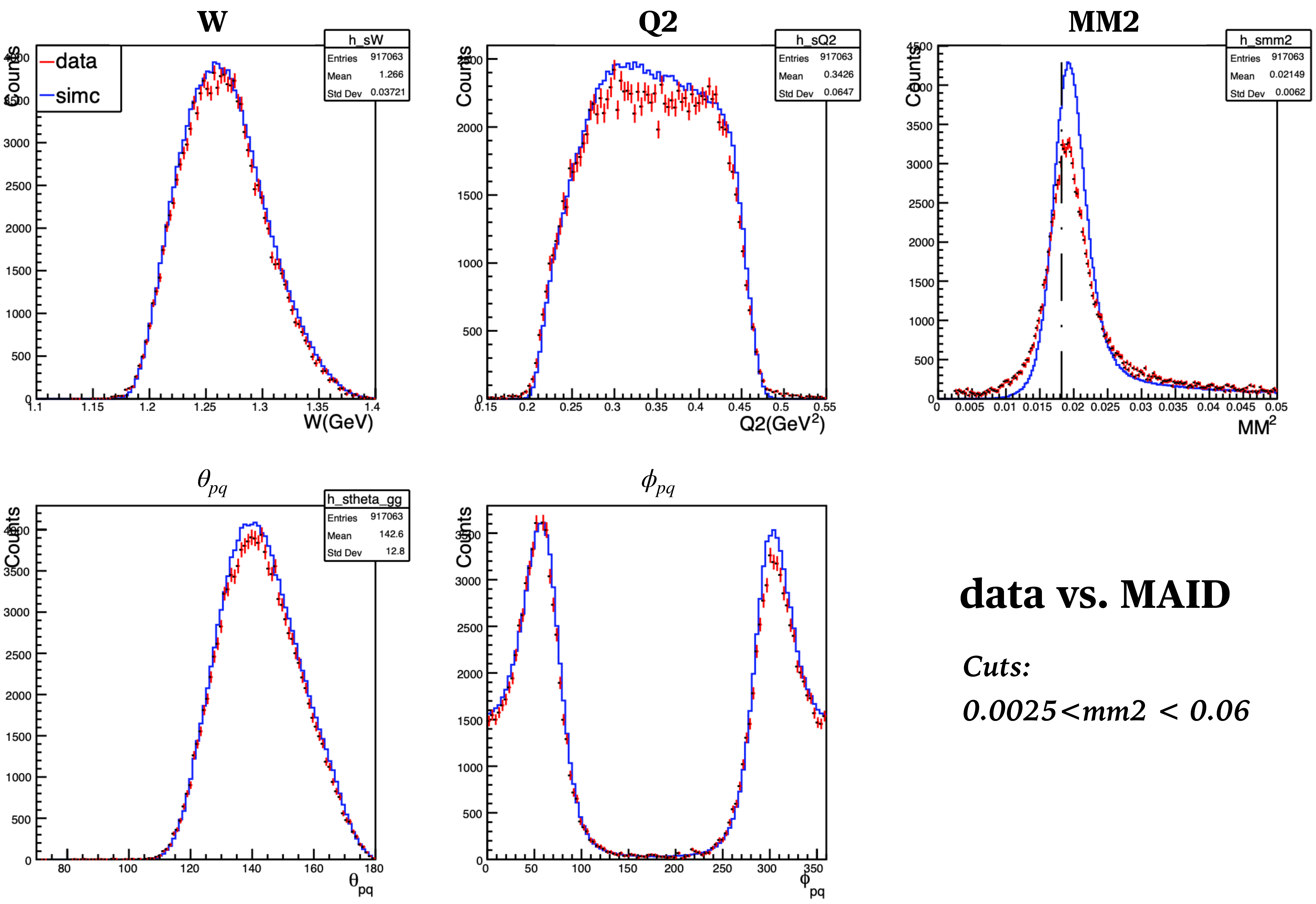
VCS peak and pi0 peak







Pion Preliminary Analysis

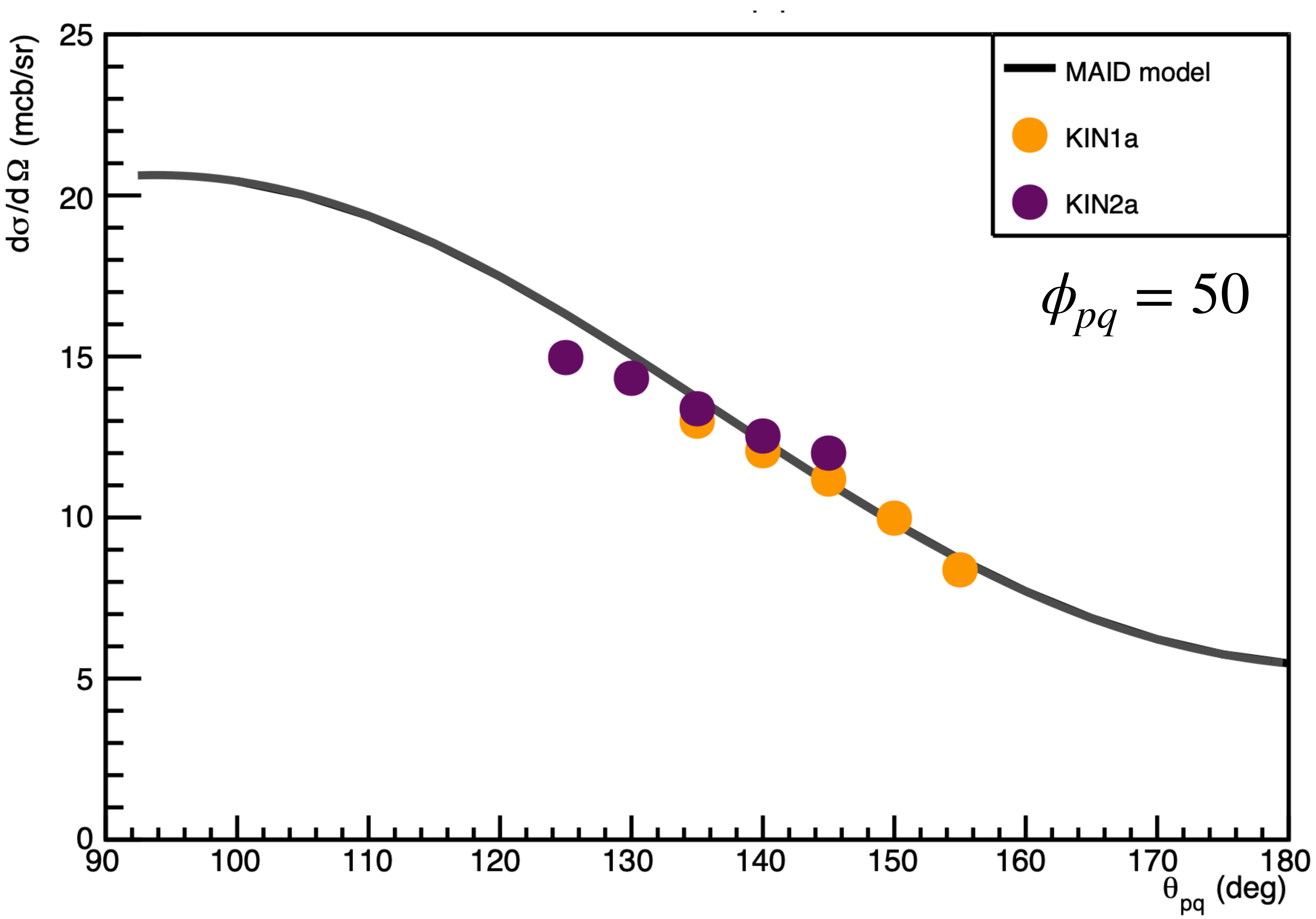


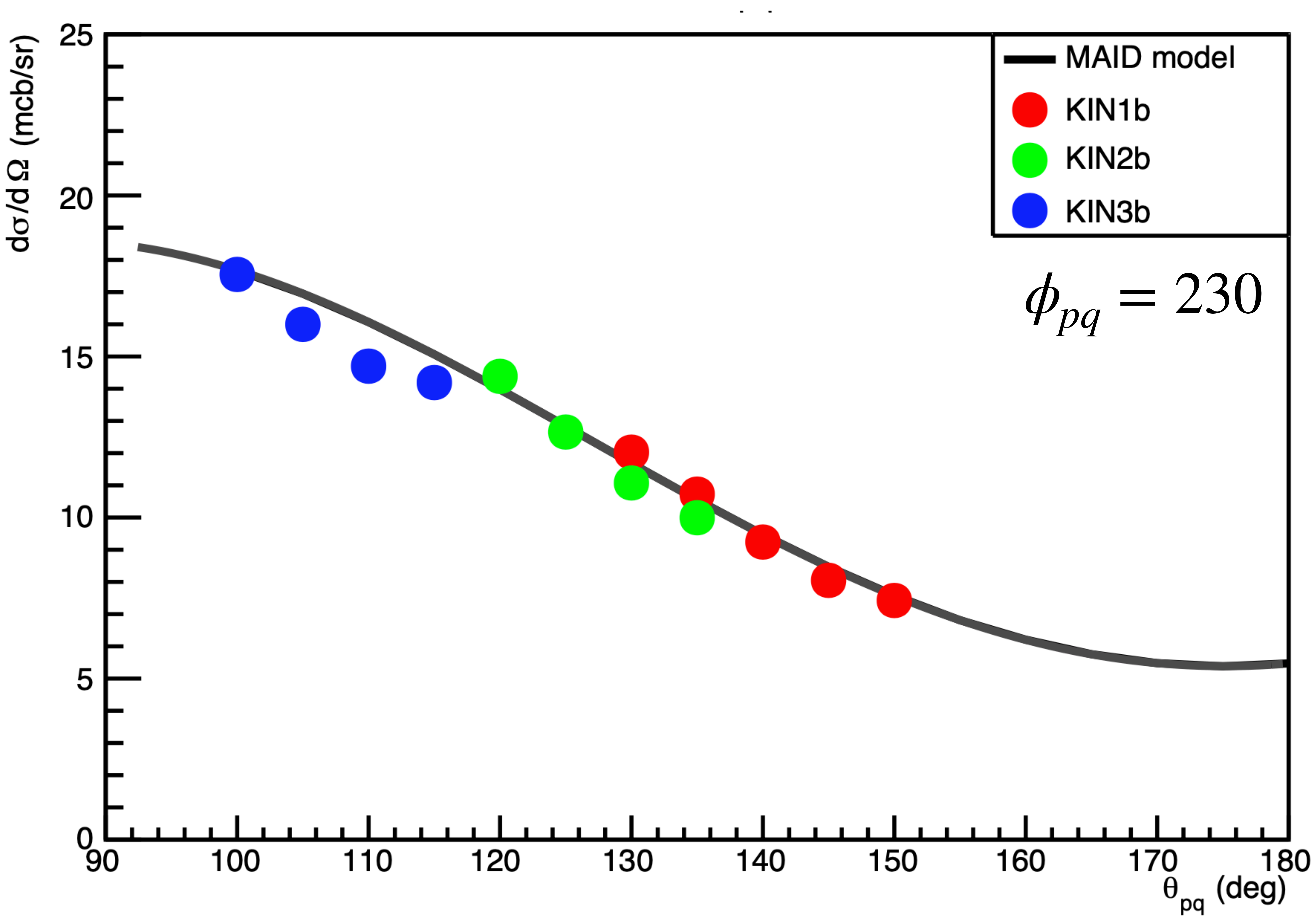
data vs. MAID

Cuts:

$0.0025 < mm2 < 0.06$

Pion Preliminary Analysis





Cuts:

0.0025<mm2 < 0.06

abs(W-1.260)<0.01

abs(W-0.33)<0.05

abs $(\theta_{pq} - \theta_{center}) < 5$

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

Pion Preliminary Analysis

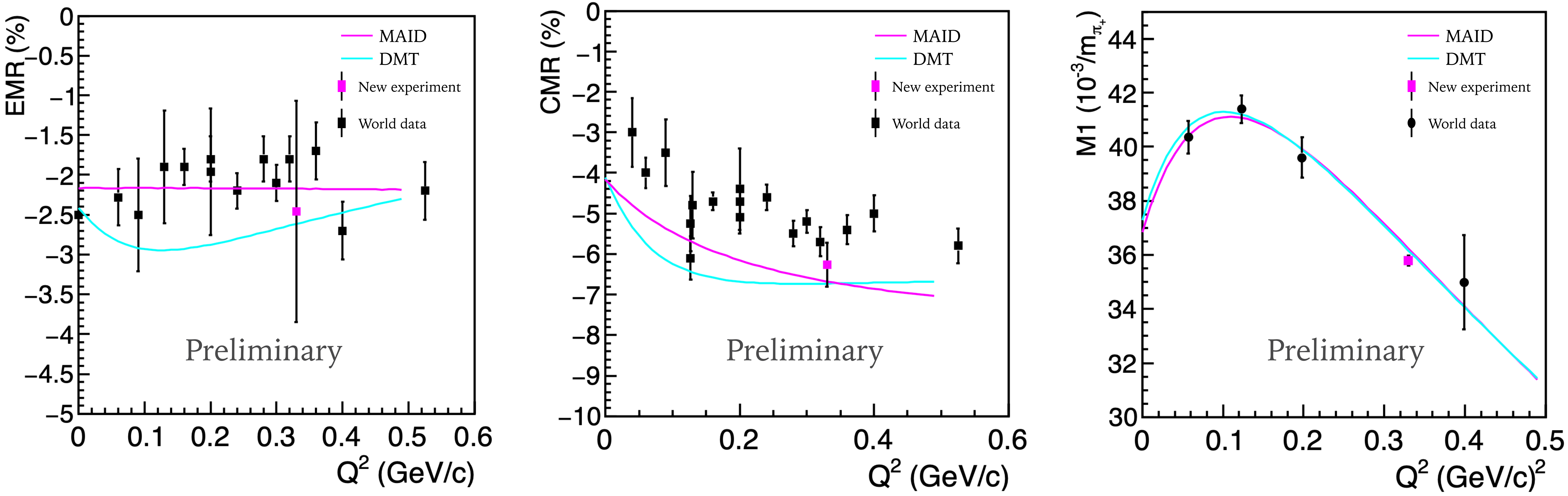
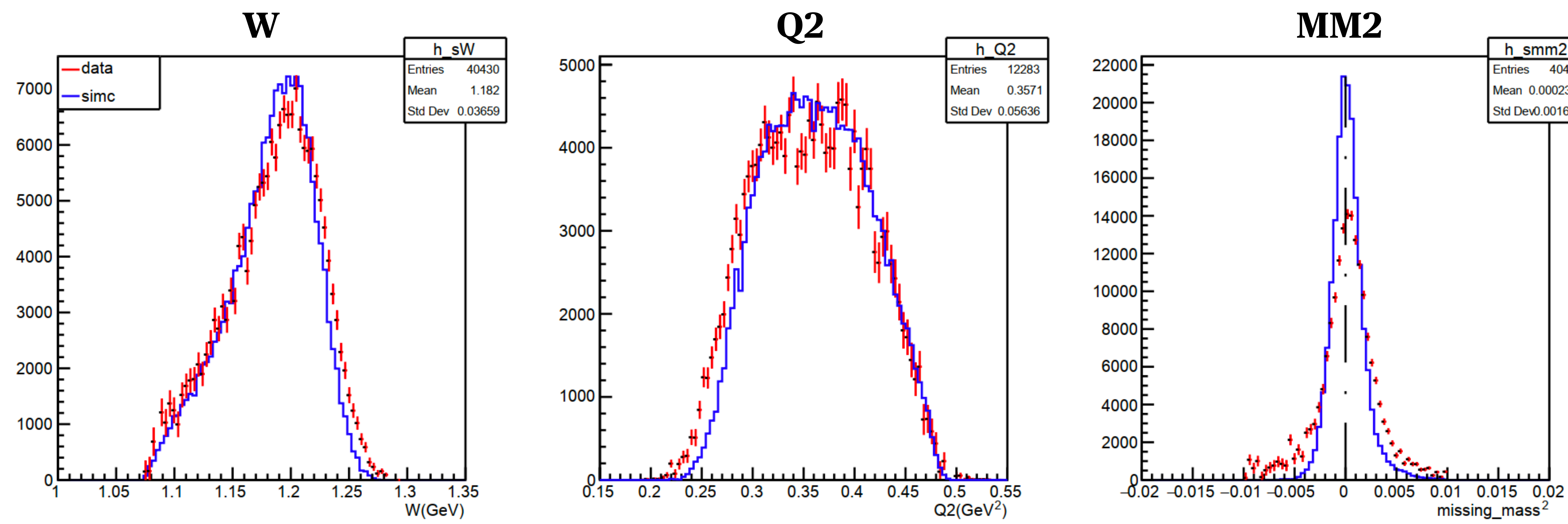
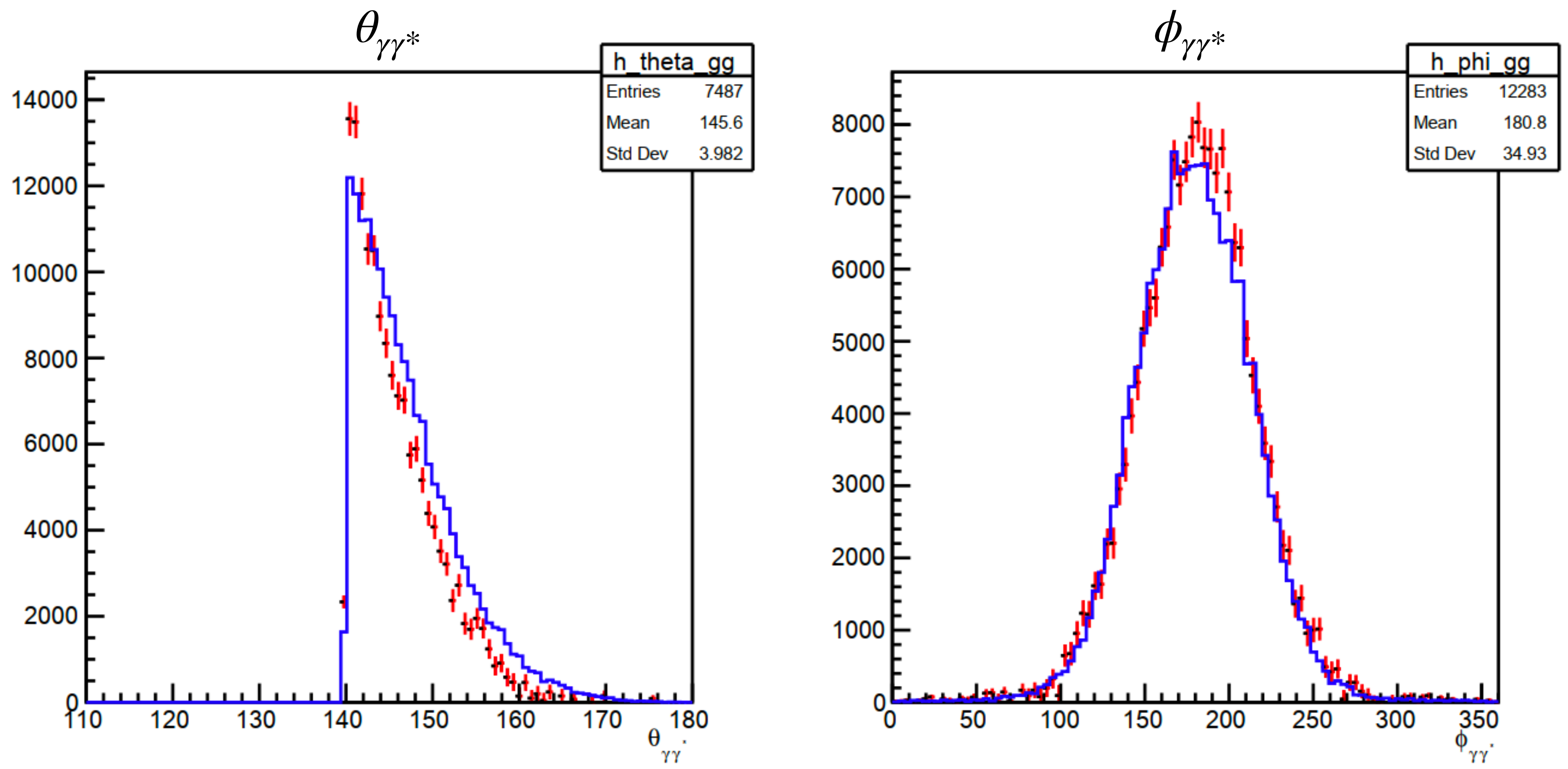


Figure Credit: Hamza Atac

VCS Preliminary Analysis





data vs. DR

$Q^2 = 0.33(GeV^2)$

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

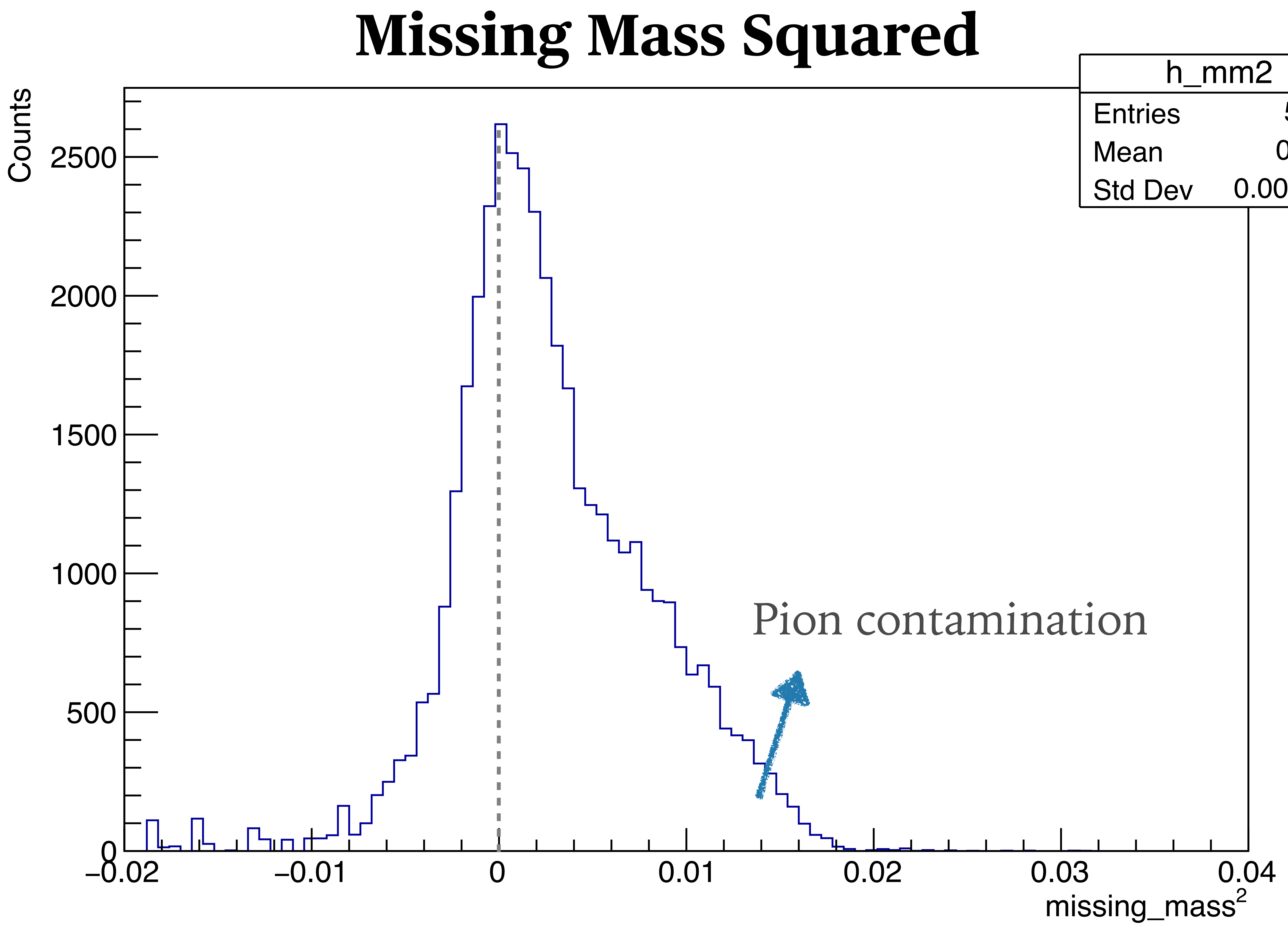
Cuts:

-0.01<mm2 < 0.01

theta_gg > 140

1.075 < W < 1.3

VCS Preliminary Analysis



Cuts:

mm2 < 0.06

ABS(theta_gg-140) < 6

ABS(W-1.232) < 0.008

ABS(Q2-0.33) < 0.05

VCS data vs. DR comparison

ONGOING…

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**
    - **Agreement with world data at 3% level**
  - **Determination spectrometer central angle and momentum offsets** – **nearly complete**
  - **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

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Backup Slides

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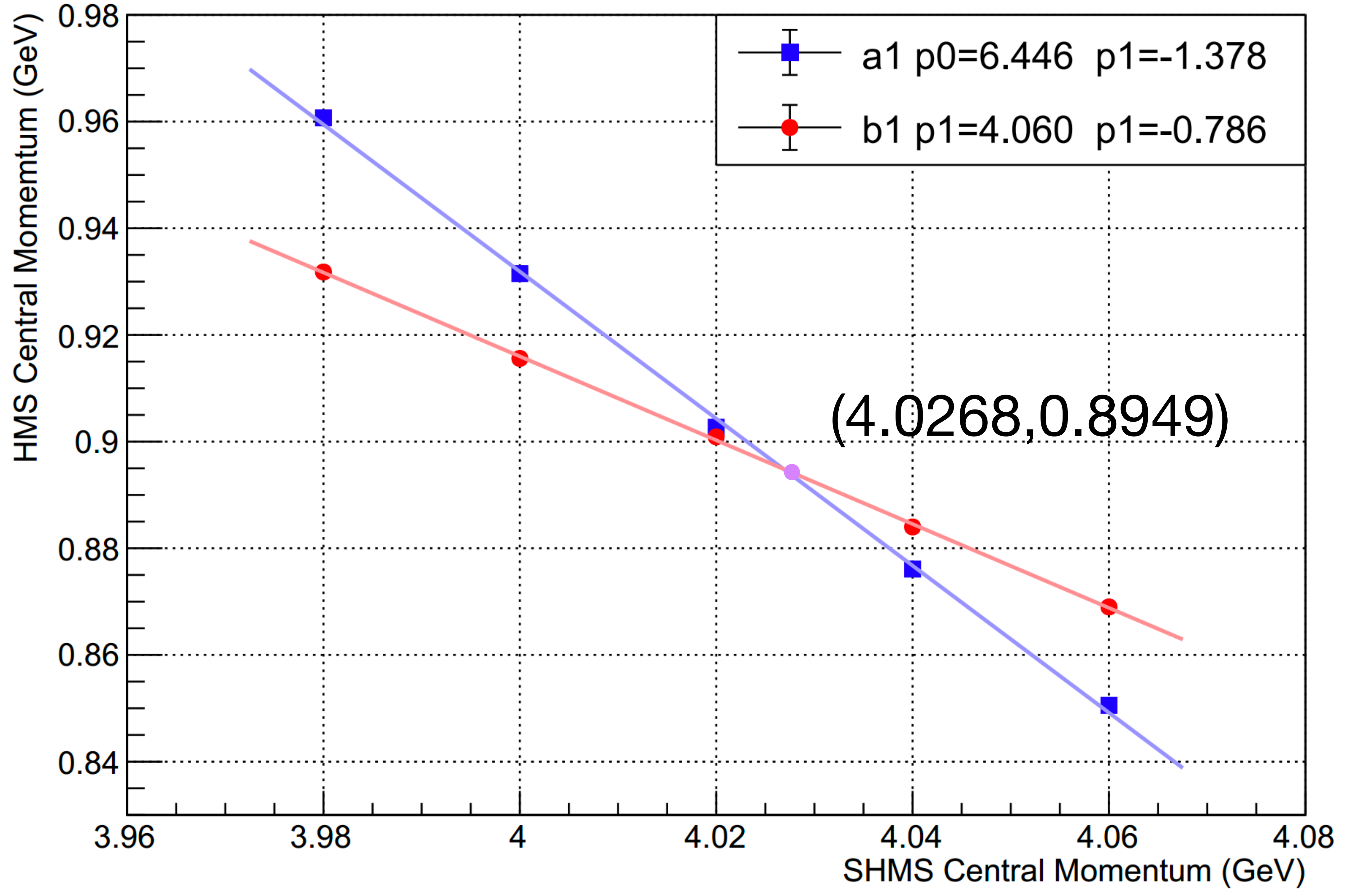
Energy Calibration

Spectrometer: Same momentum,Different HMS theta

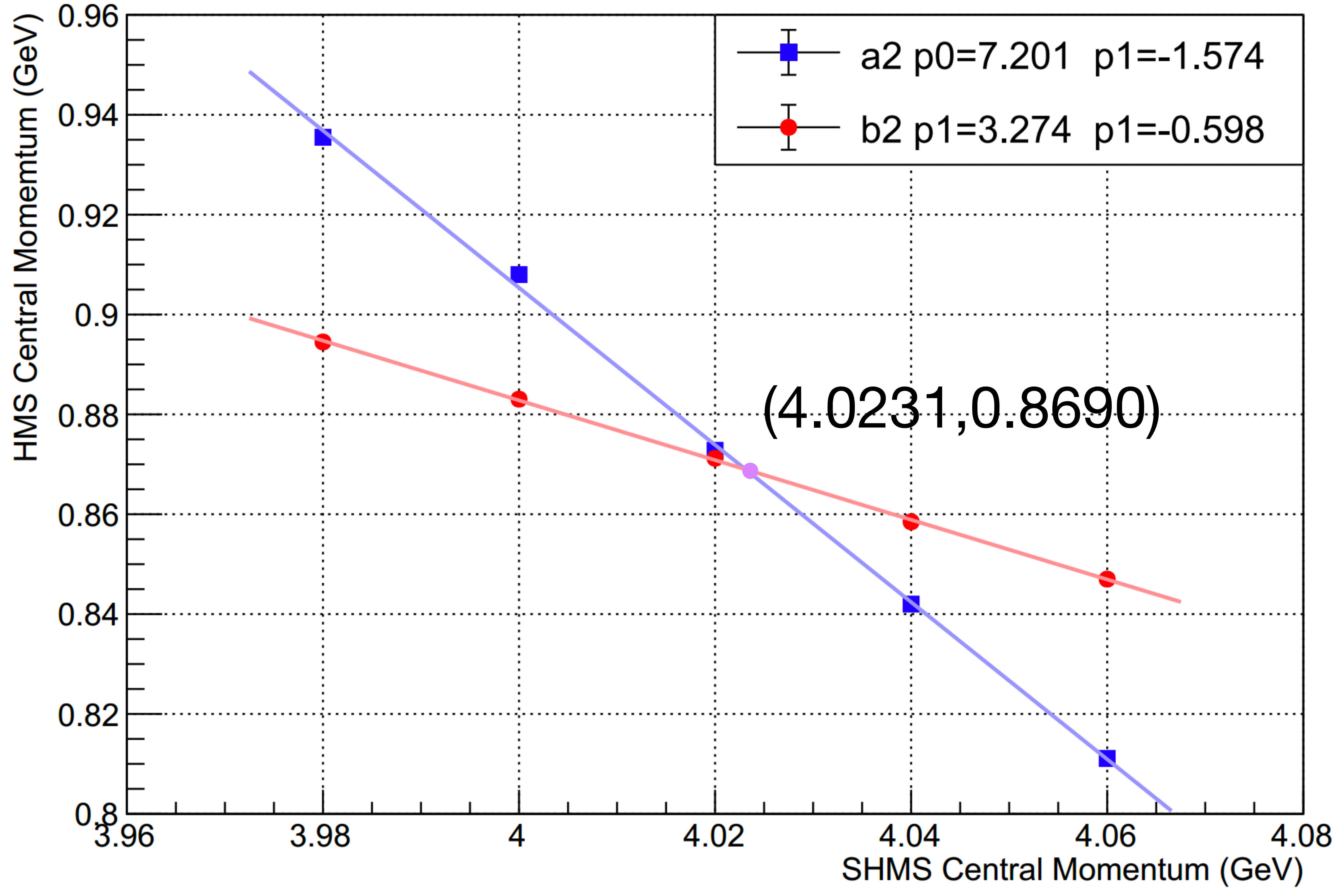
	SHMS_p	SHMS_th	HMS_p	HMS_th
Kin1a	4.034	7.69	0.893	37.33
Kin1b	4.034	7.69	0.893	51.40

	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

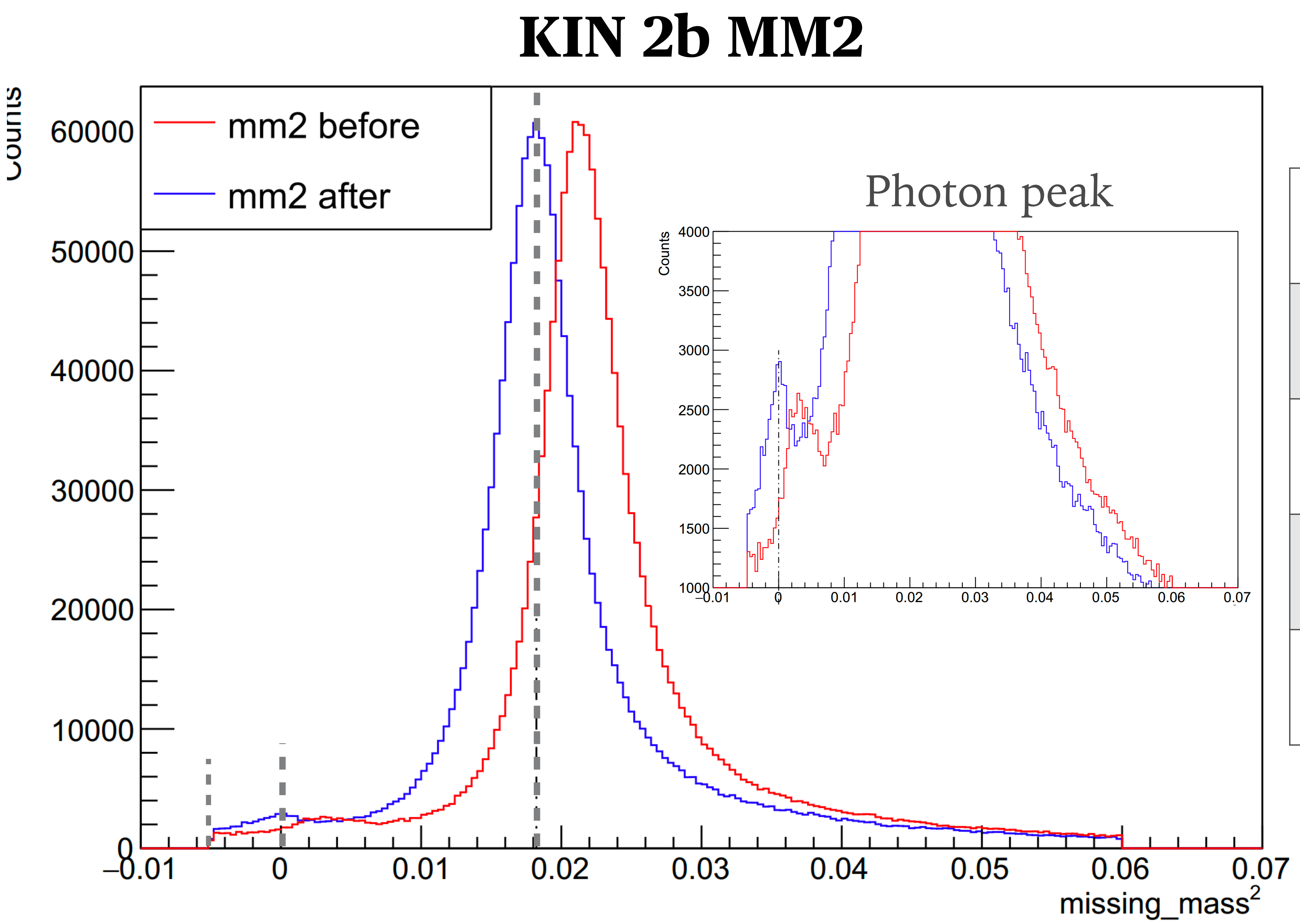
Kin 1a & Kin 1b



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