Update on Measurement of Generalized Polarizabilities of the proton by VCS

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HALL A&C JOINT MEETING 07/16/2020

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- Background Theories
- VCS Experiment E12-15-001
- Analysis Progress
  - Proton Absorption
  - Elastic Data
  - Pion Data
  - Energy calibration
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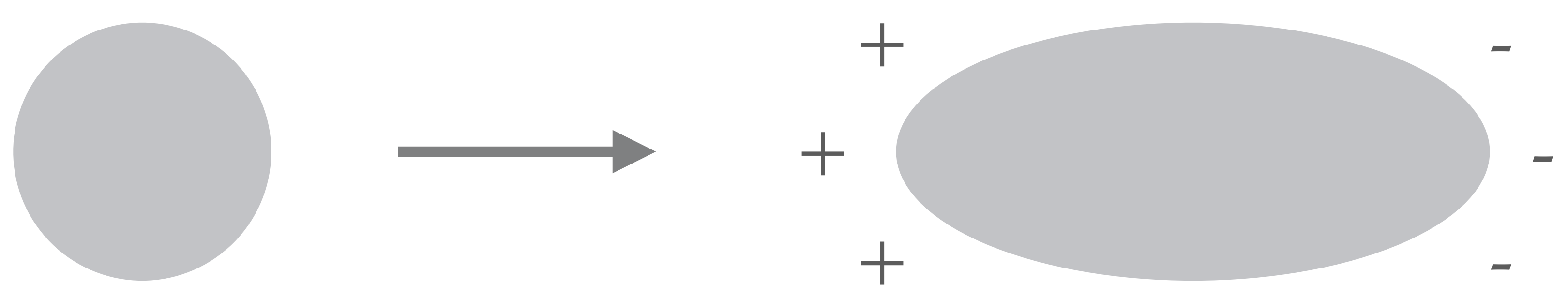
Polarizabilities

Polarizability:

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



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

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

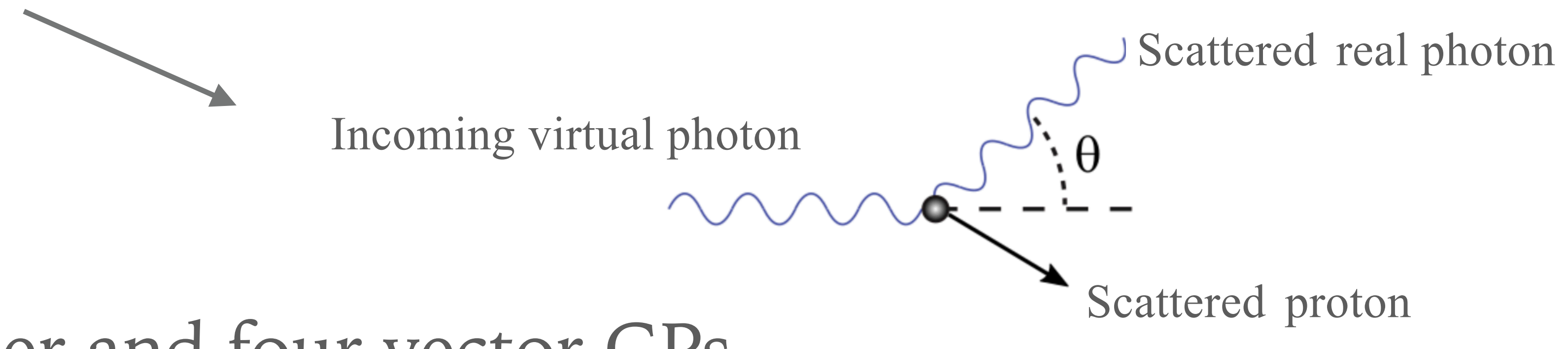
p $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.00727646688 \pm 0.00000000009$ u
Mass $m = 938.272081 \pm 0.000006$ MeV [a]
$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, 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 $\mu = 2.7928473446 \pm 0.0000000008$ 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)

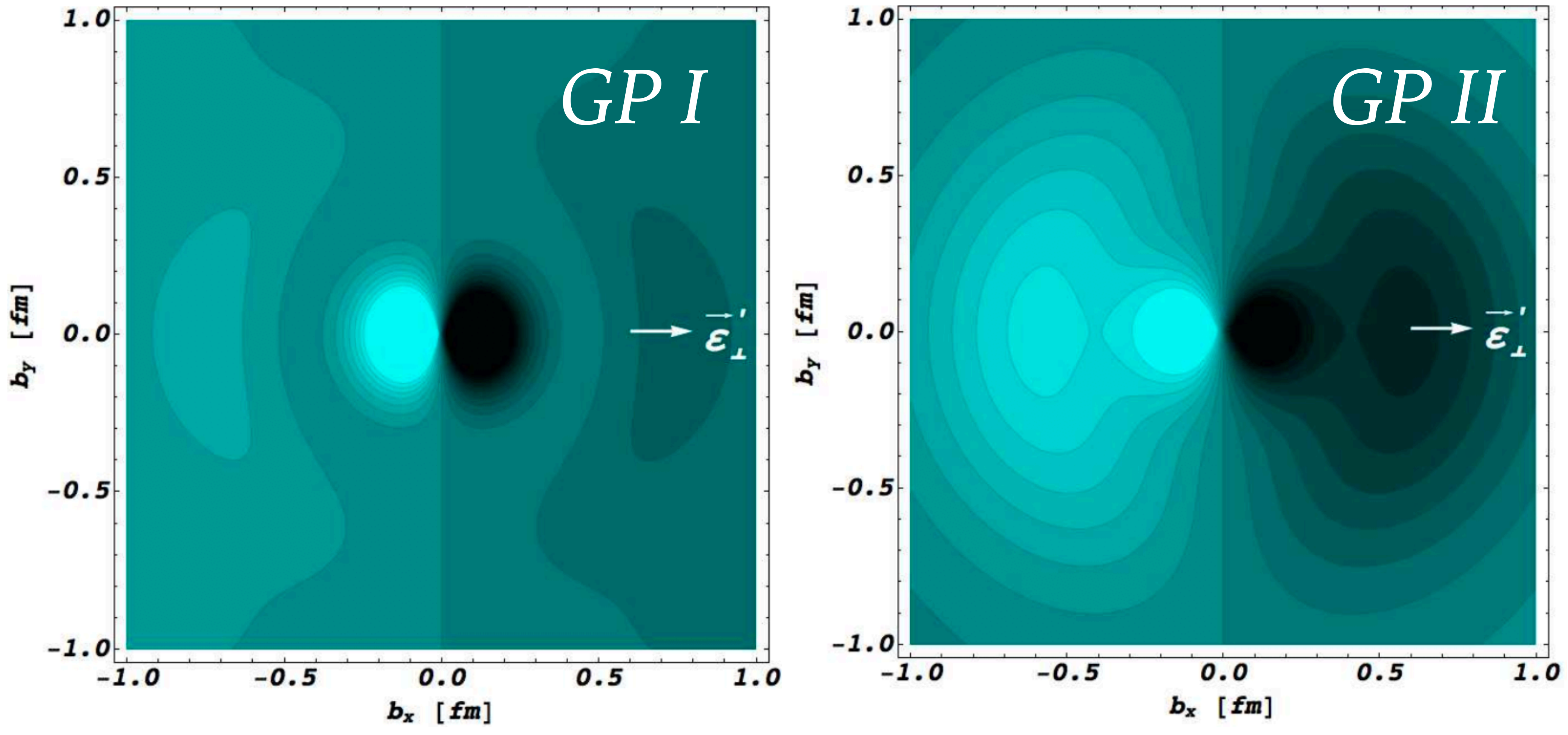
Generalized Polarizabilities

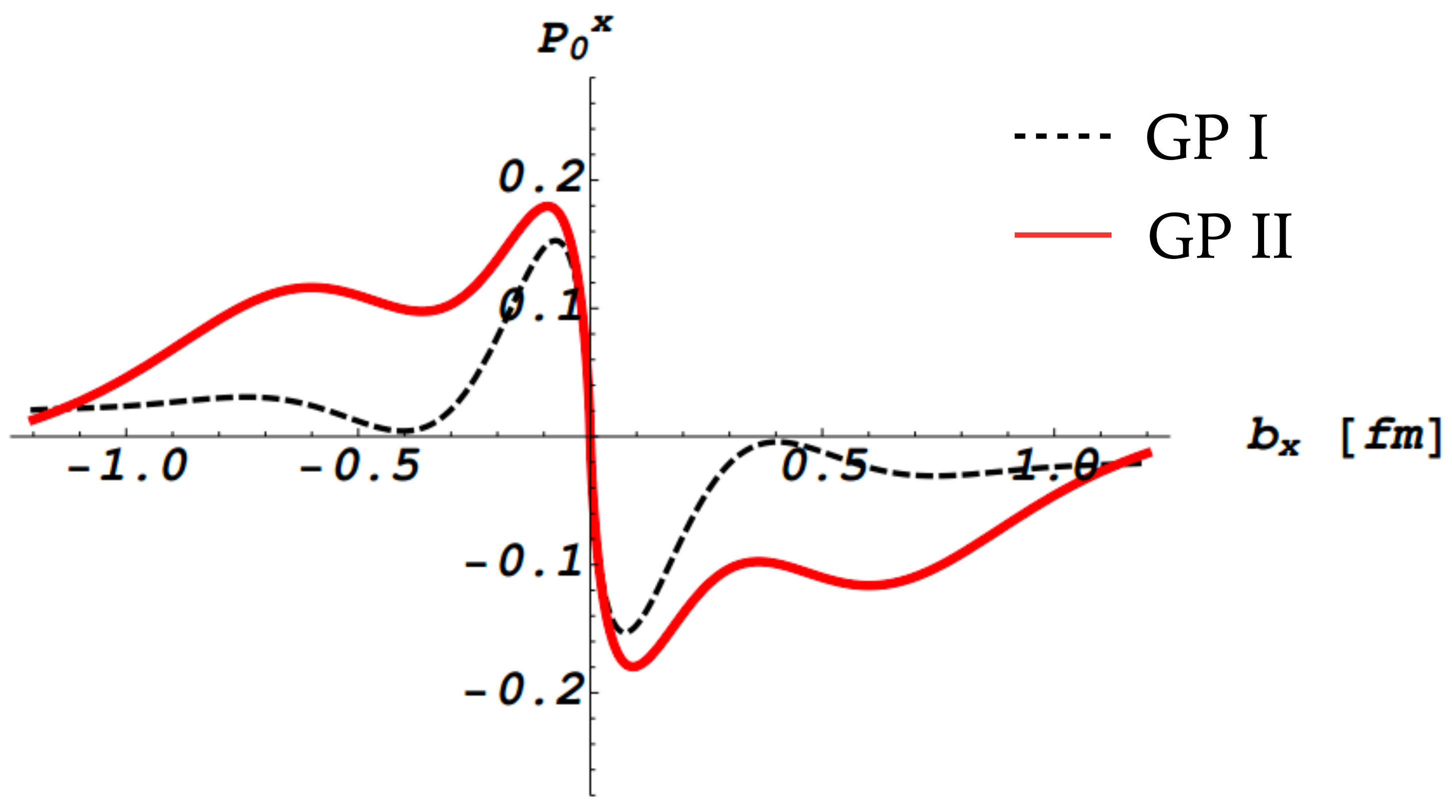
Generalized Polarizabilites (GPs):

- Access by Virtual Compton Scattering (VCS)



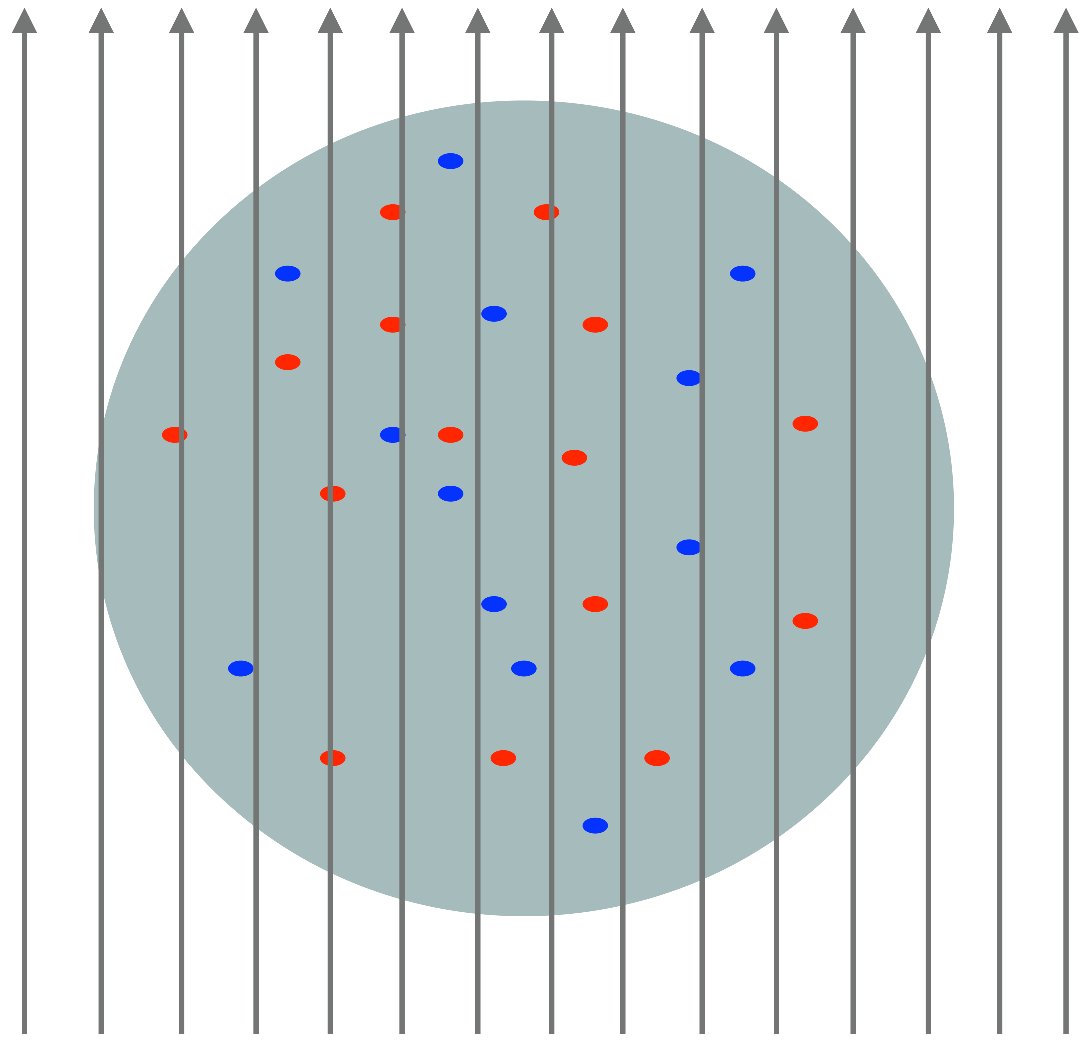
- Two scaler and four vector GPs
- Fourier transform can map out the spatial distribution density of the polarization induced by an EM field





M. Gorchtein, C. Lorce, B. Pasquini, M. Vanderhaeghen, Phys. Rev. Lett. 104, 112001 (2010)

Generalized Polarizabilities



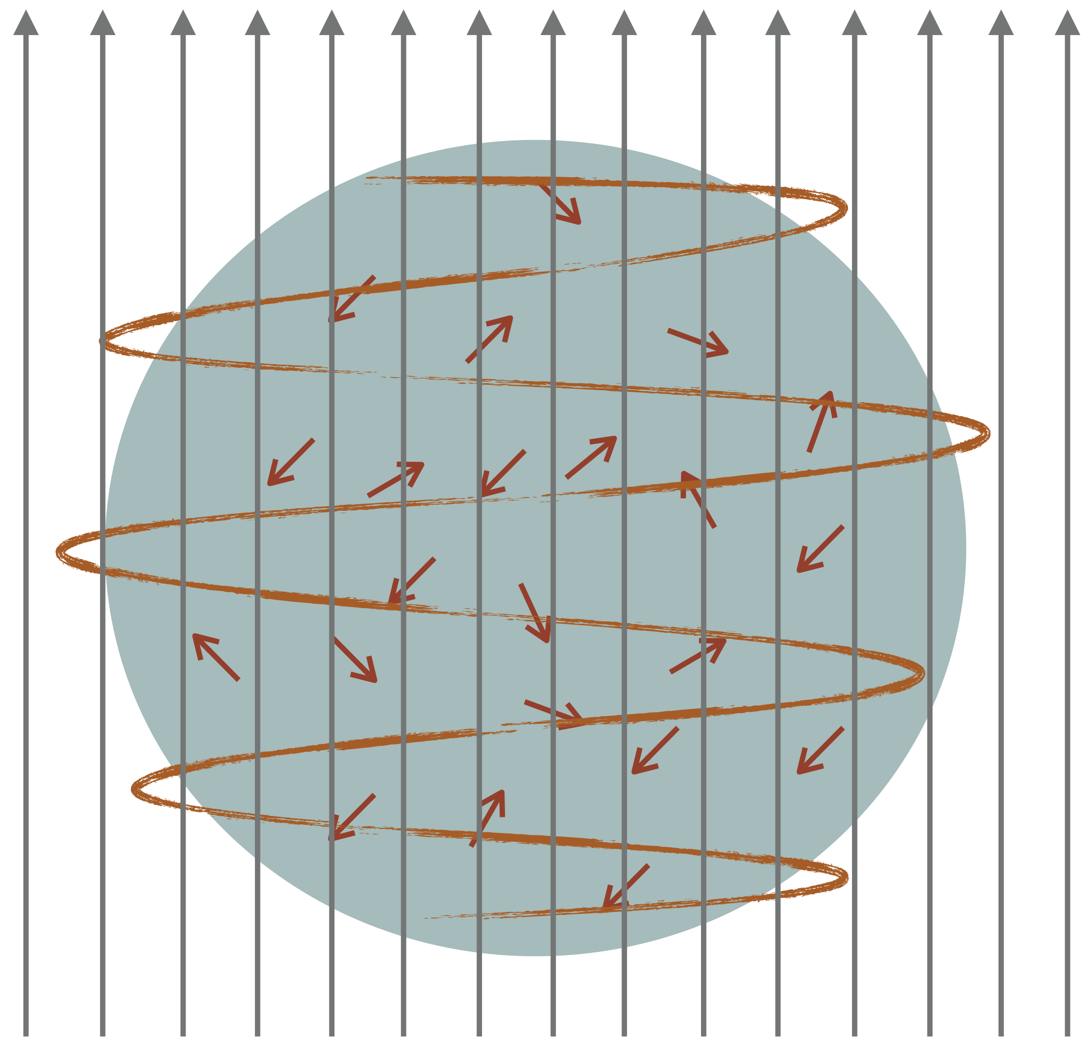
$\overrightarrow{E}$

$$\overrightarrow{p} = \alpha \overrightarrow{E}$$

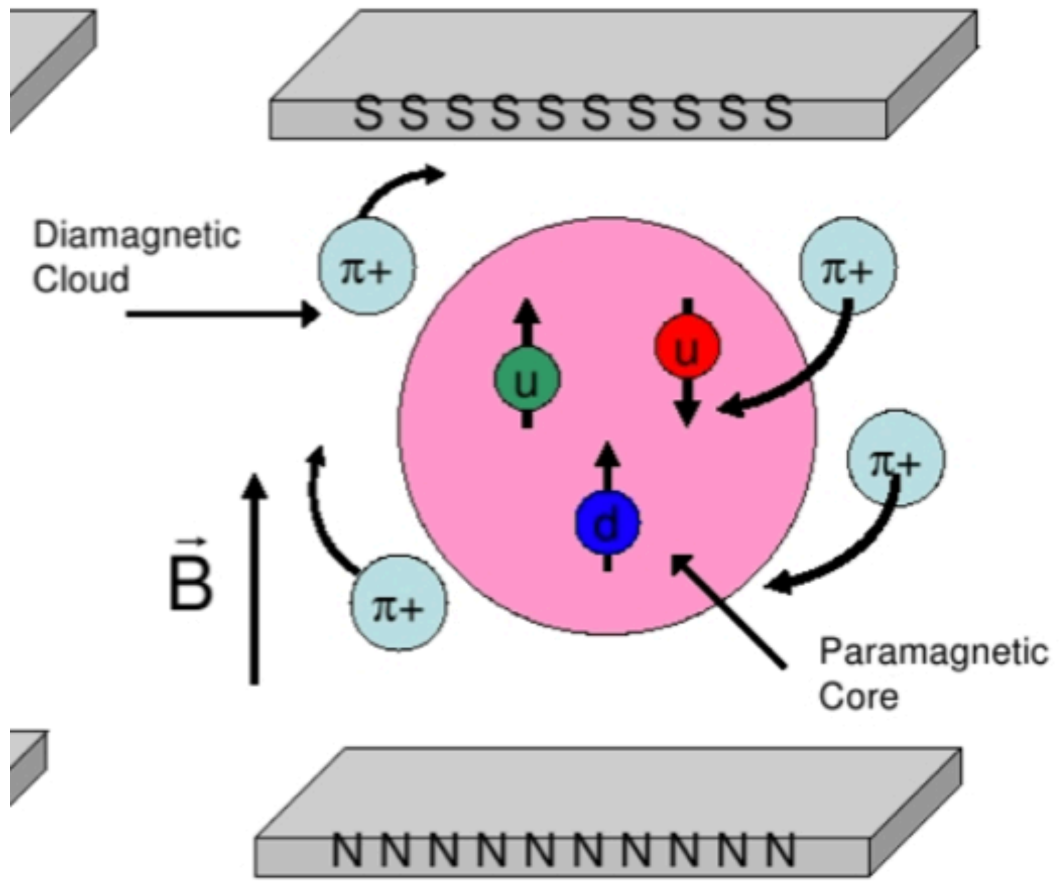
Electric polarizability α reflects the **rigidity** of proton

$\alpha_E \rightarrow$ Electric Polarizability

$\beta_M \rightarrow$ Magnetic Polarizability



$\overrightarrow{B}$



$$\overrightarrow{m} = \beta \overrightarrow{B}$$

Paramagnetic: >0, quarks align along magnetic field;

Diamagnetic: <0, pion cloud induced magnetic field in opposite direction

Partially cancels each other, makes the value small

Reaction

$e \rightarrow e\gamma^*$

$p\gamma^* \rightarrow p\gamma$

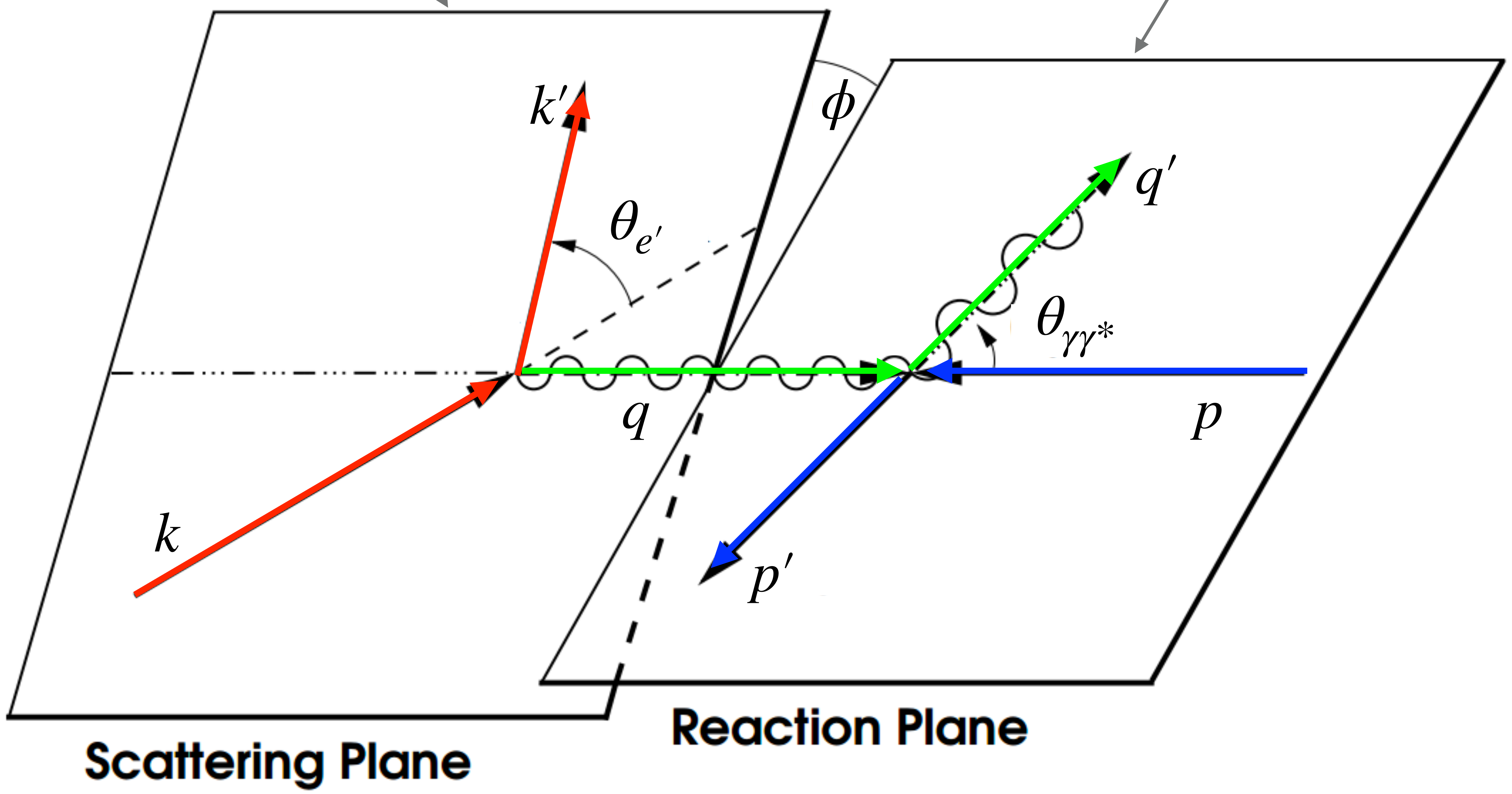


Fig.1 Kinematics of $ep \rightarrow ep\gamma$ reaction

k-incoming electron

k'-scattered electron

q-virtual photon

q'-real photon

p-initial proton

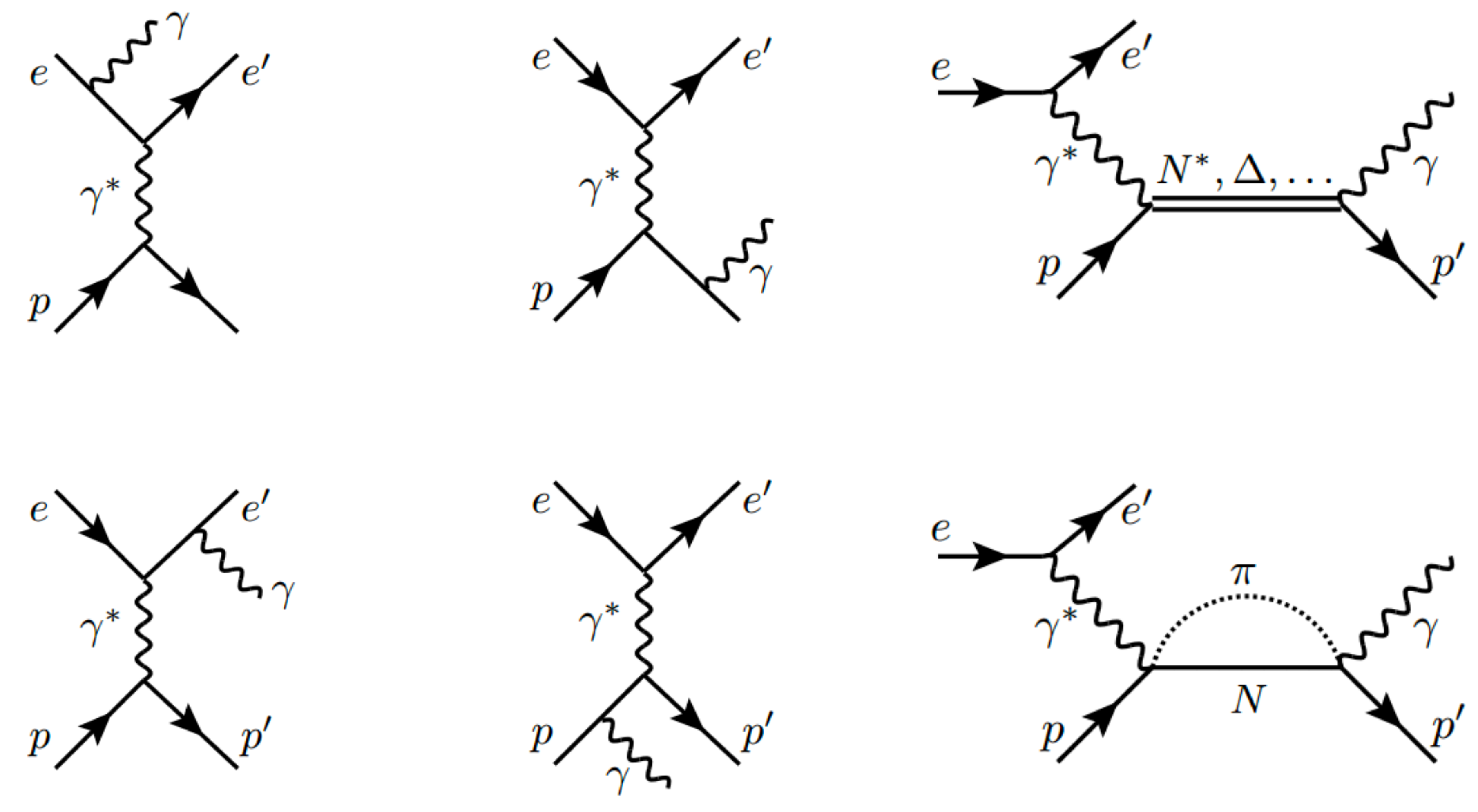
p'-final proton

VCS cross section

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

Amplitudes & GPs

VCS process → photon electro-production reaction



Bethe-Heitler   VCS Born   VCS non-Born

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

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

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

- $\rho(\rho')$,characterizes the photon longitudinal or EM nature

- $L(L')$, angular momentum

- $[S = 1,0]$, spin flip or non spin flip

Amplitudes for photon electroproduction process :

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

LEX & DR Formalism

LEX - Low Energy Expansion

Below pion threshold

Calculable with G_E and G_M

Phase-space factor

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

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

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

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

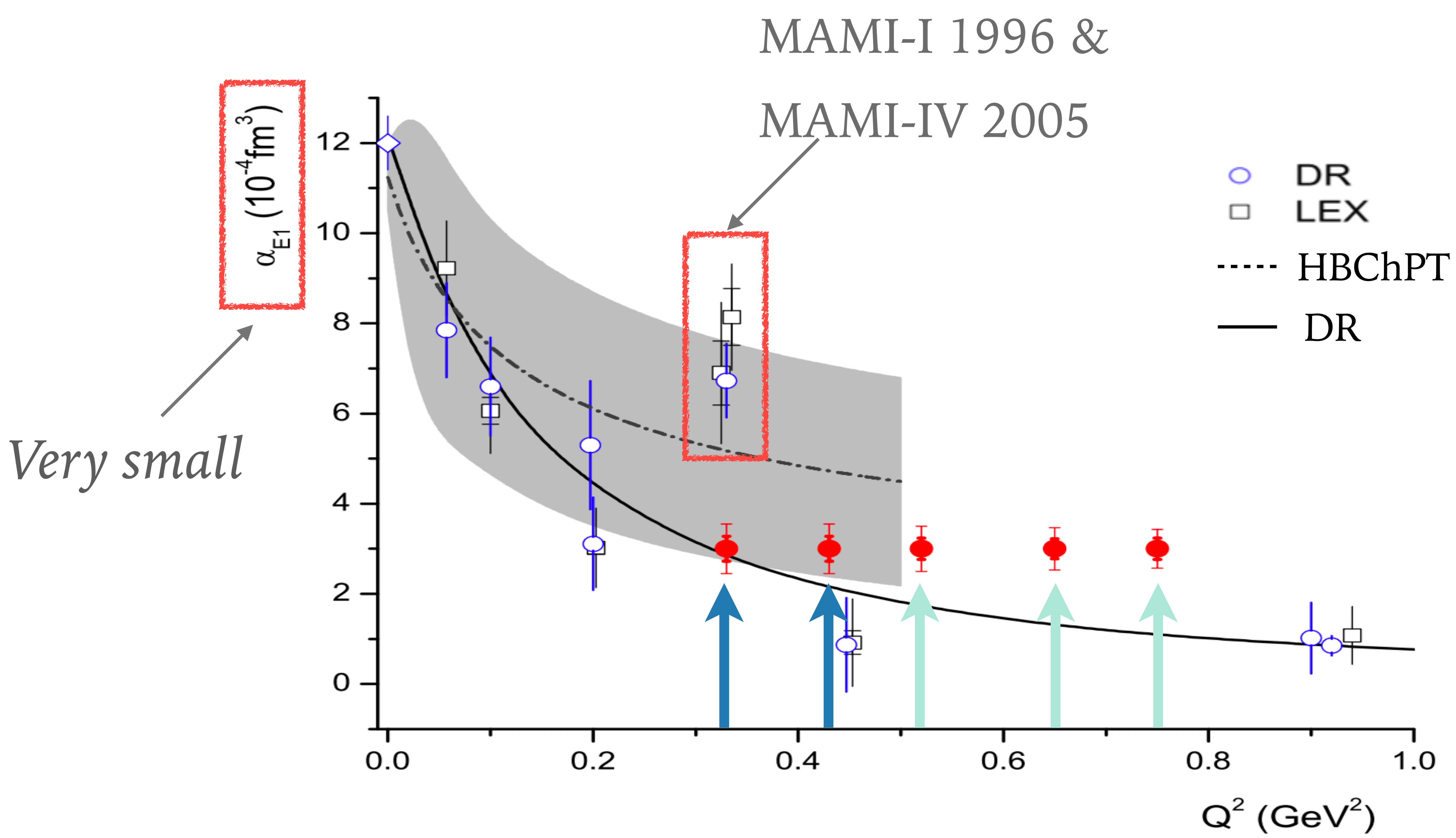
$$P_{TT} \sim (P^{(M1,M1)1}(Q^2) - \sqrt{2}\tilde{q}^0 P^{(L1,M1)1}(Q^2))$$

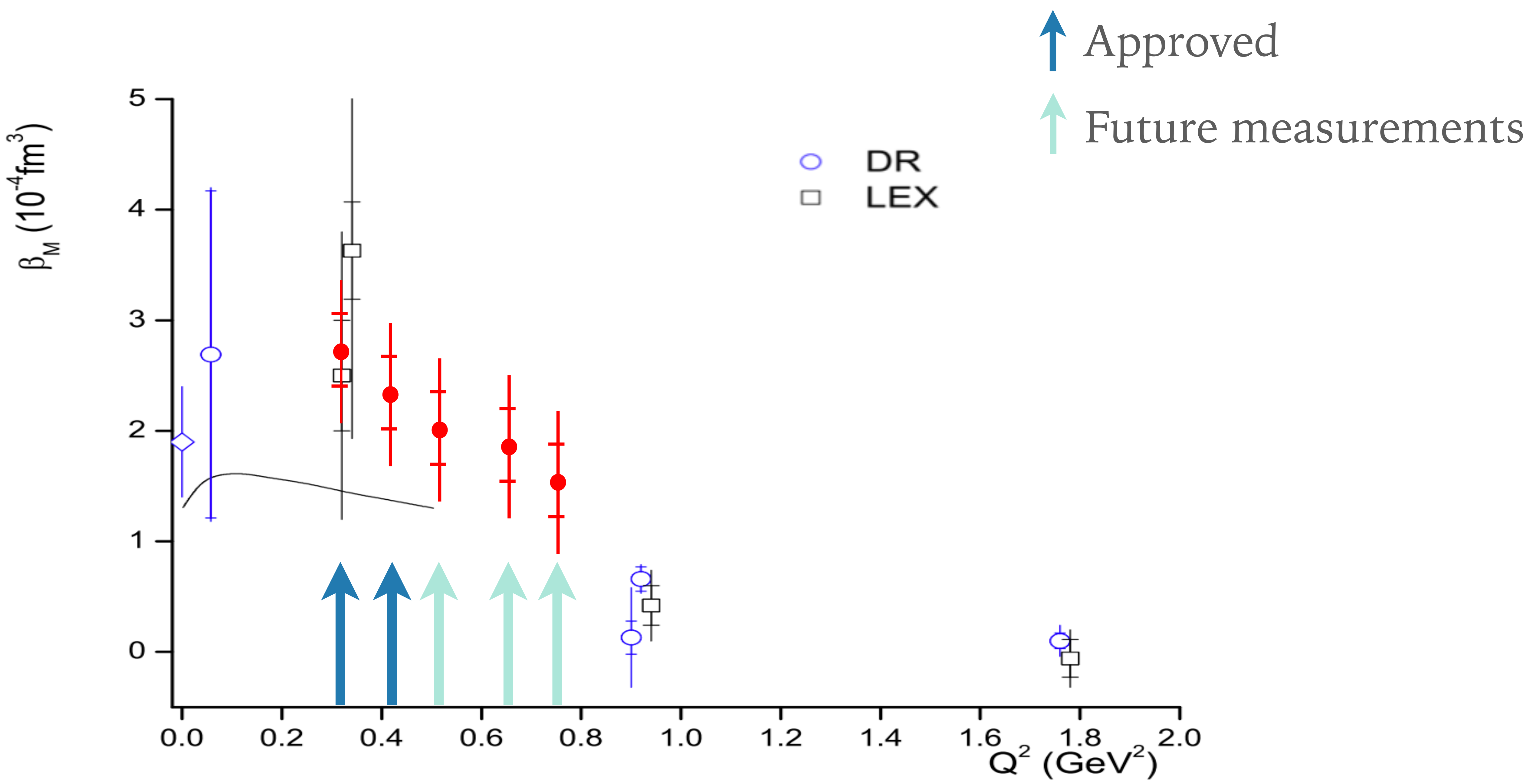
DR - Dispersion Relation Formalism

Below & Above pion threshold

- *4 spin (vector) GPs* → Predicted
- *2 scaler GPs* → Free parameters
- Fits to cross section of experimental data
- Find best χ^2
- Measurement of α_E and β_M

World Data & Motivation



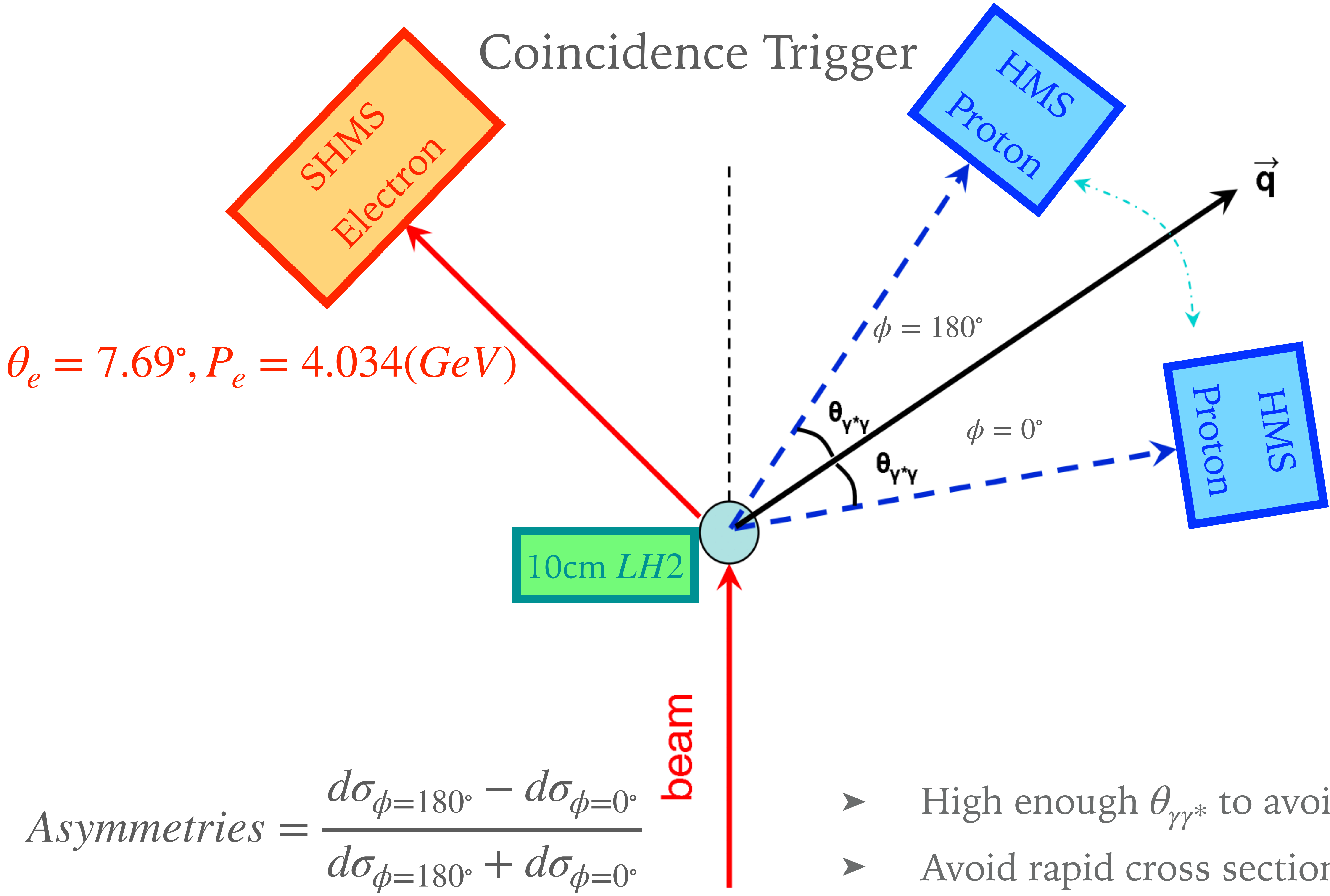


- Initial theoretical models predicted smooth fall off of α_E
  - data at $Q^2 = 0.33$ implies non-trivial structure
- New experiment can:
  - Address puzzling α_E enhancement
  - Reduce error by 2

- Small values, 1/3 ~ 1/4 of α_E
- 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

VCS Experiment



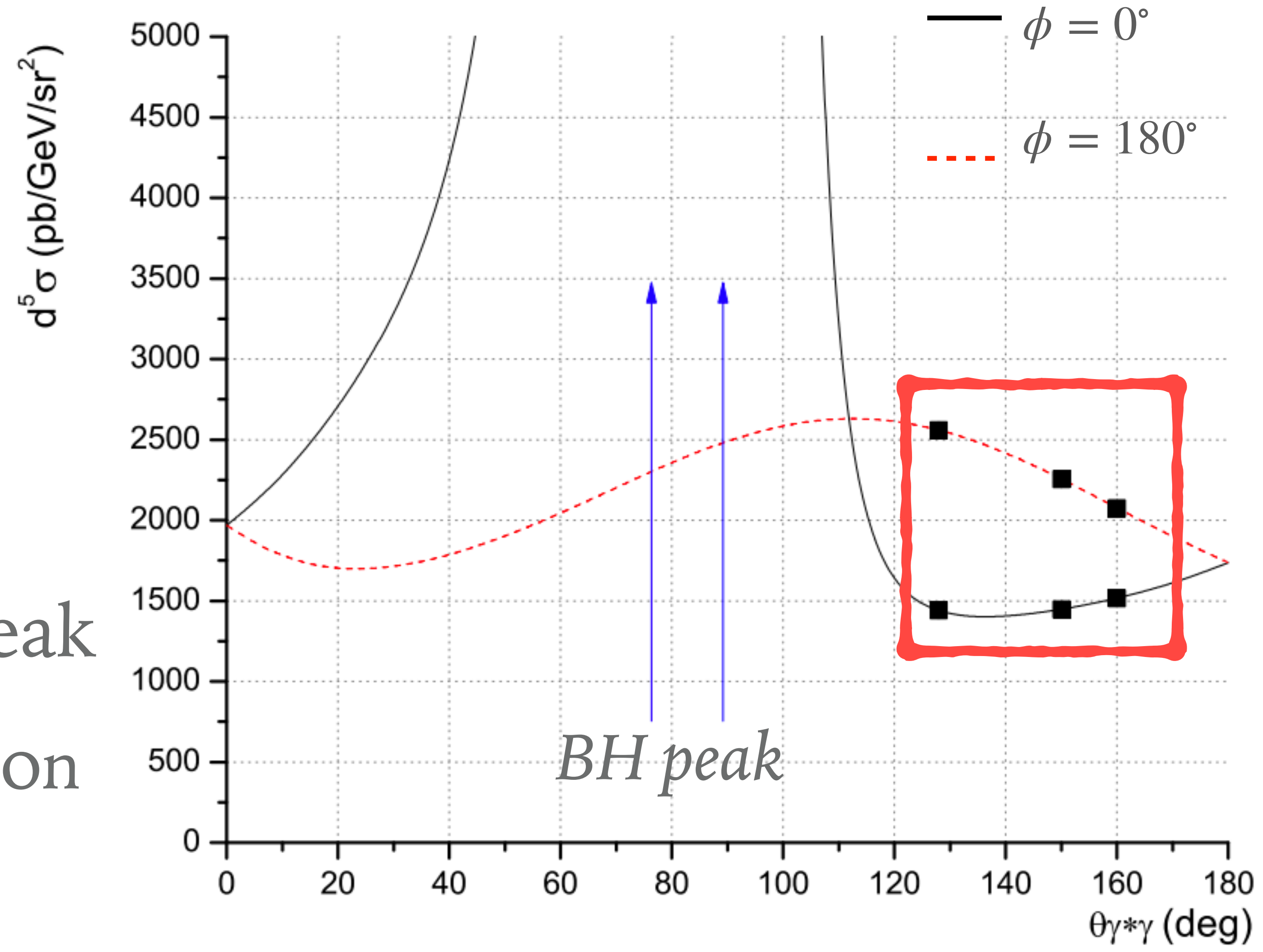
- Summer 2019: July 20 - August 5
- Beam $E = 4.56GeV$,
- $Q^2 = 0.33GeV^2$, $W = 1.232GeV$

$\theta_p = 33.73\ to\ 60.74^\circ$;

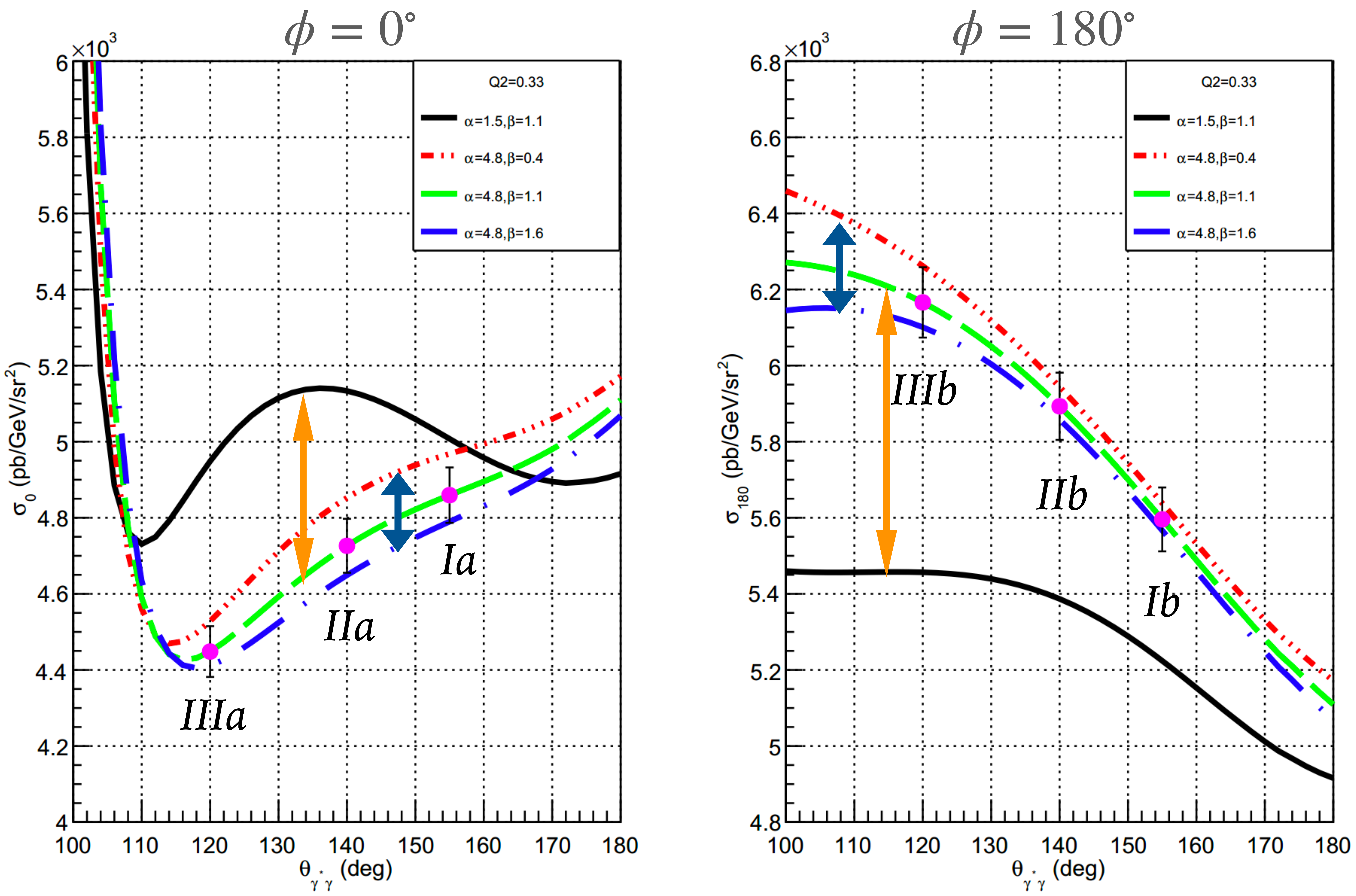
$P_p = 0.893\ to\ 0.795(GeV)$

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

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



Predicted Measurement

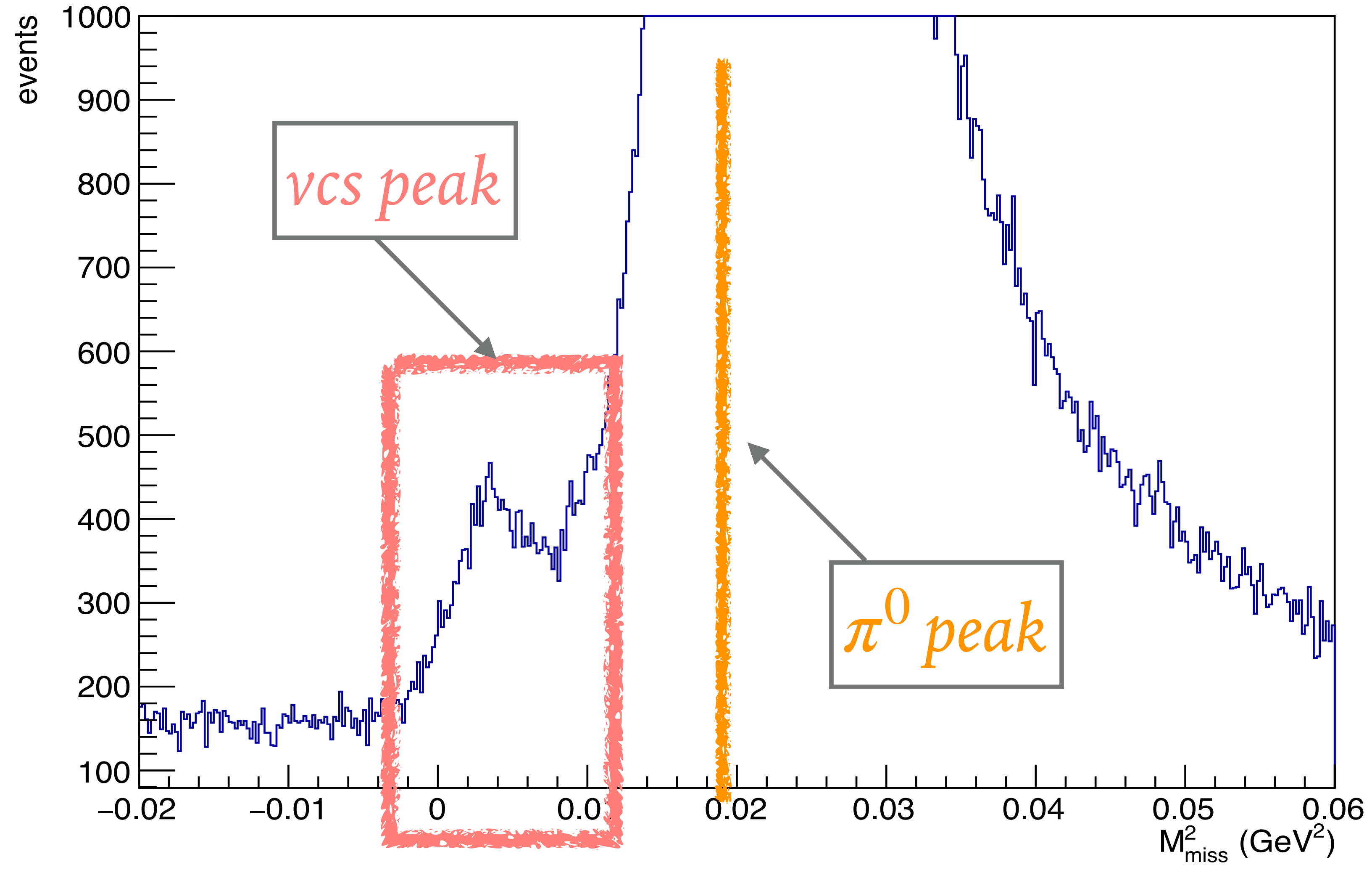


Sensitivity to α_E

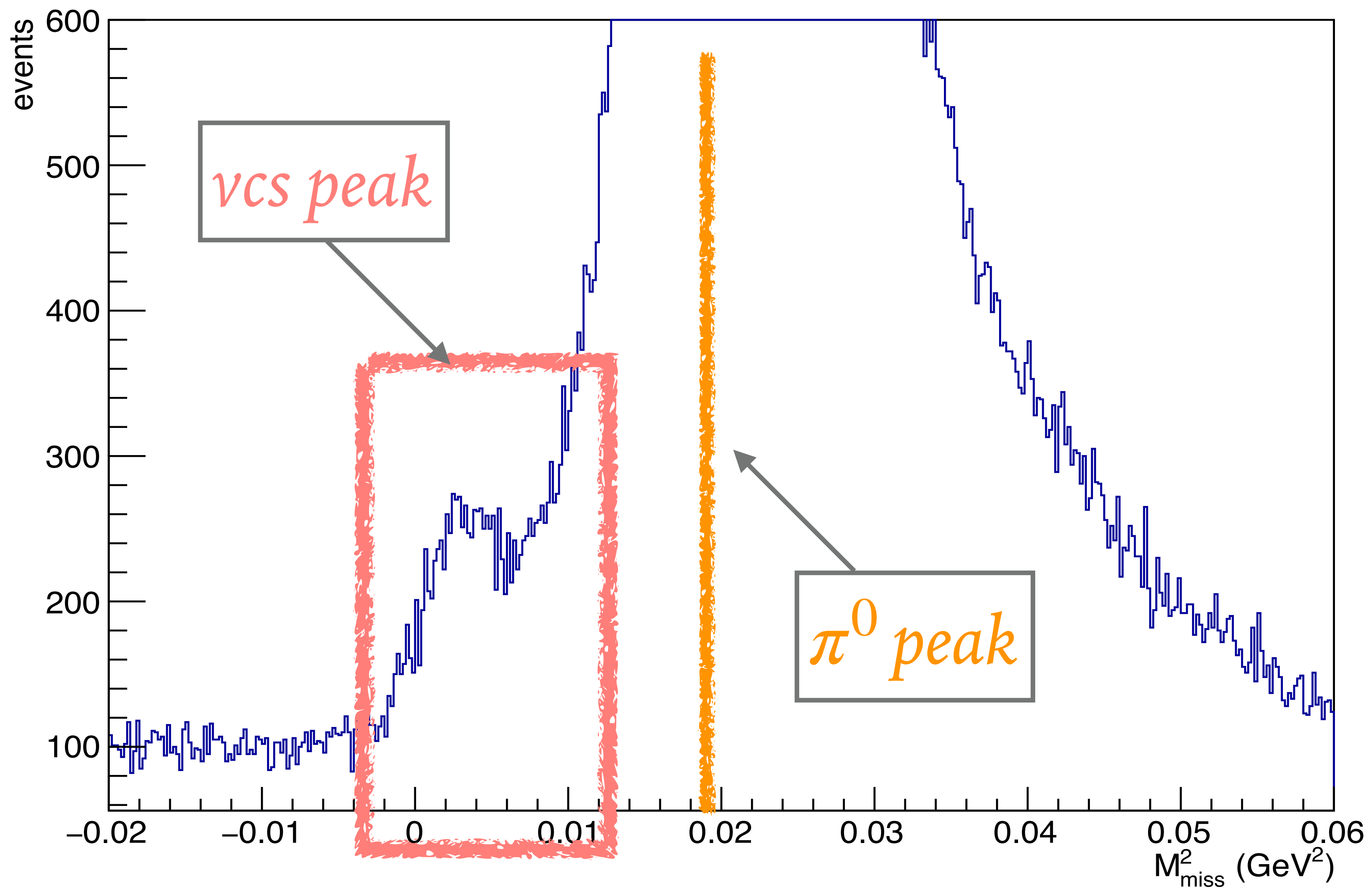
Sensitivity to β_M

VCS peak and pi0 peak

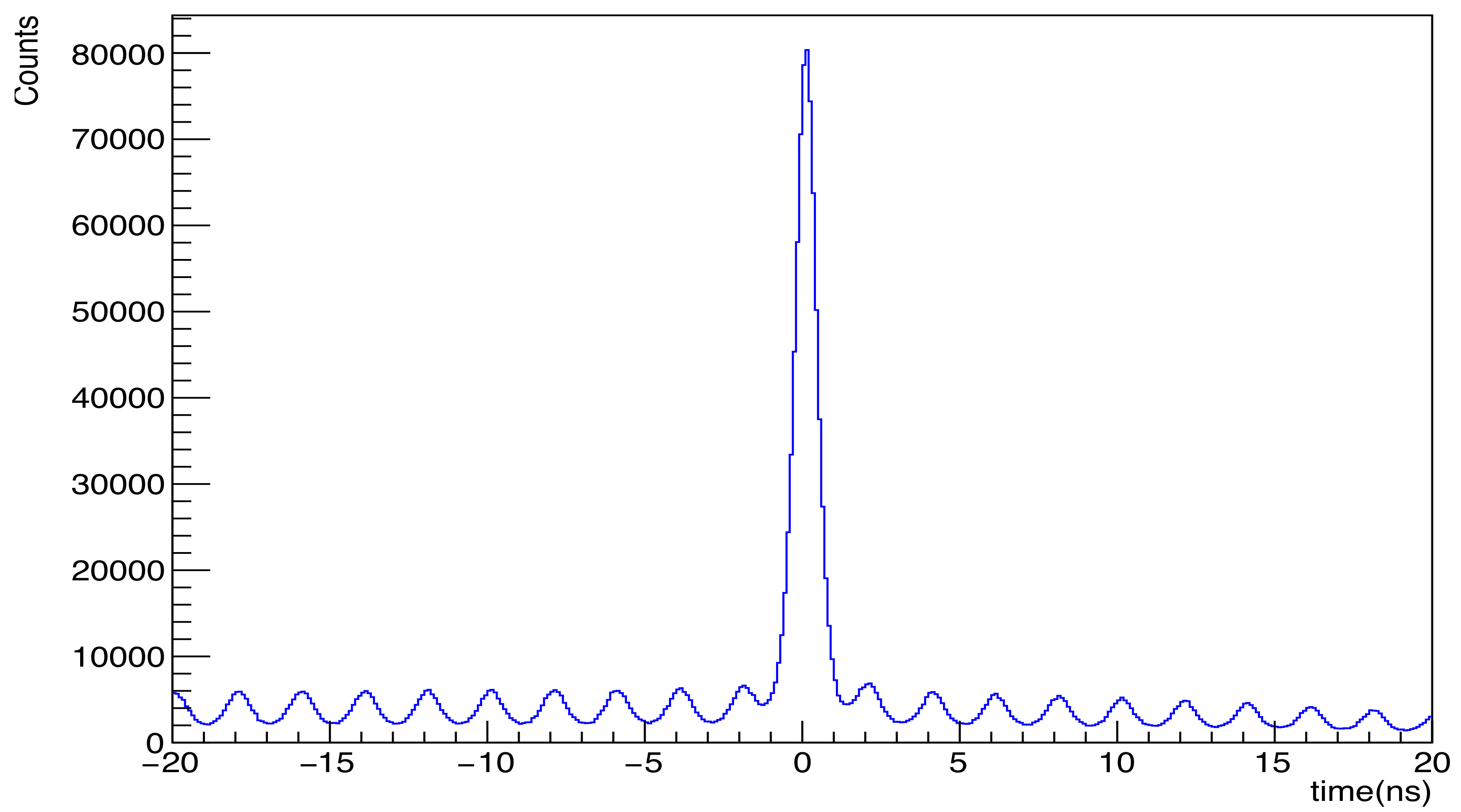
KIN Ib Run 9053



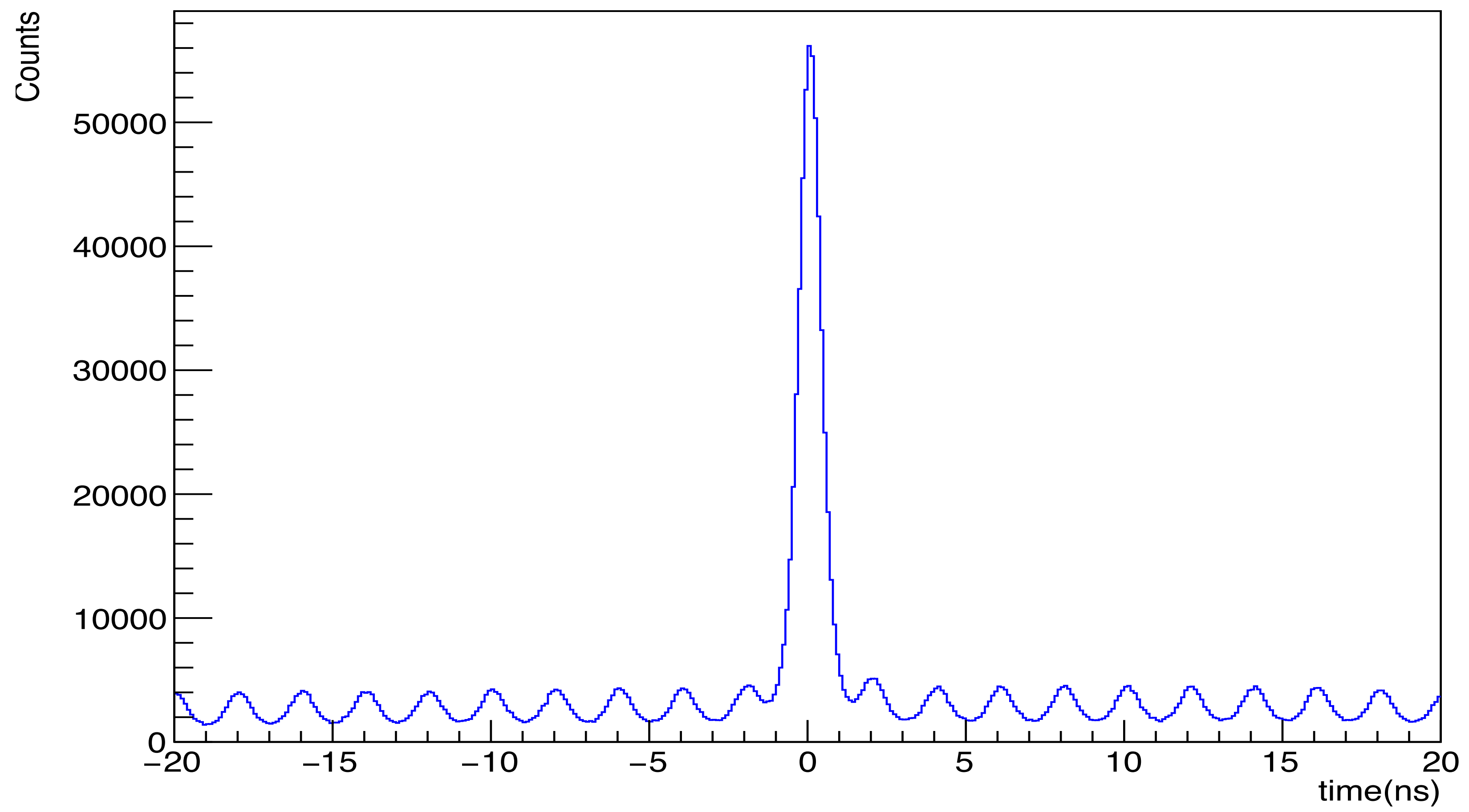
KIN IIb Run 8880



Run 9053 Coincidence ToF



Run 8880 Coincidence ToF



Cuts:

ABS(CTime.epCoinTime_ROC2 -50) < 1.2

Trigger g.evtyp ==4

HMS:

dp = +/-8,

theta = +/- 0.08,

phi = +/- 0.04

SHMS:

dp = +/-8,

theta = +/- 0.045,

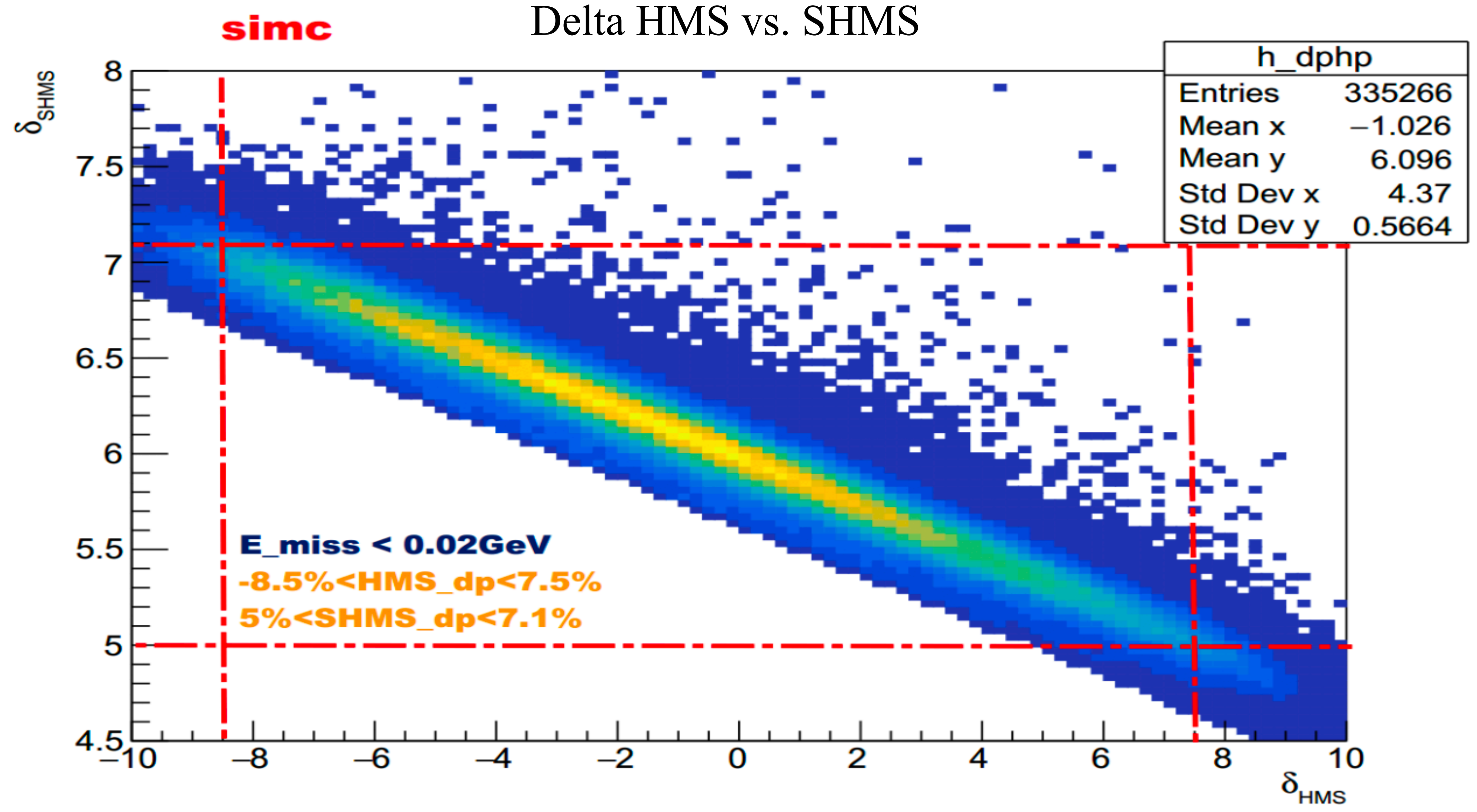
phi = +/- 0.04

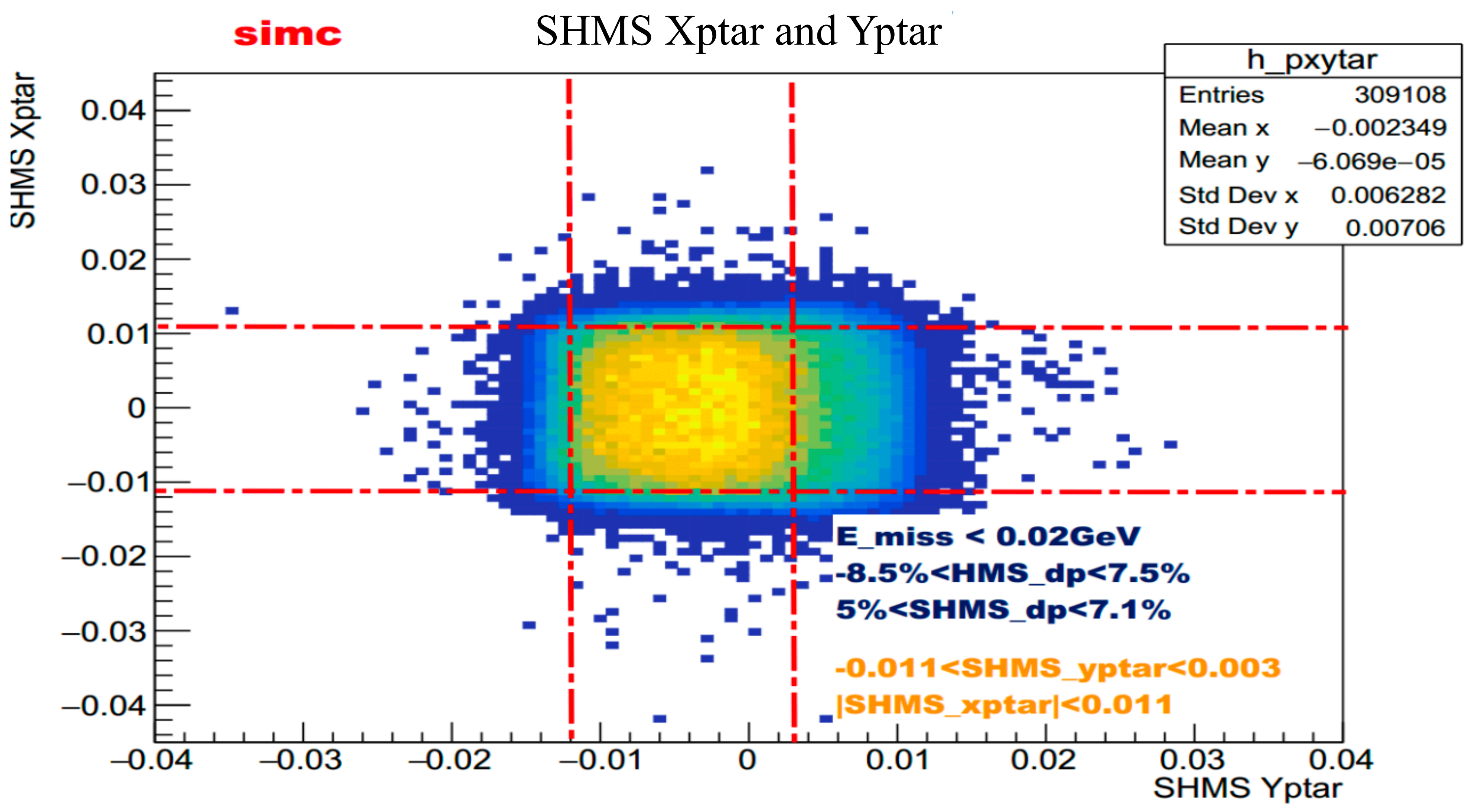
H.gtr.beta < 0.9

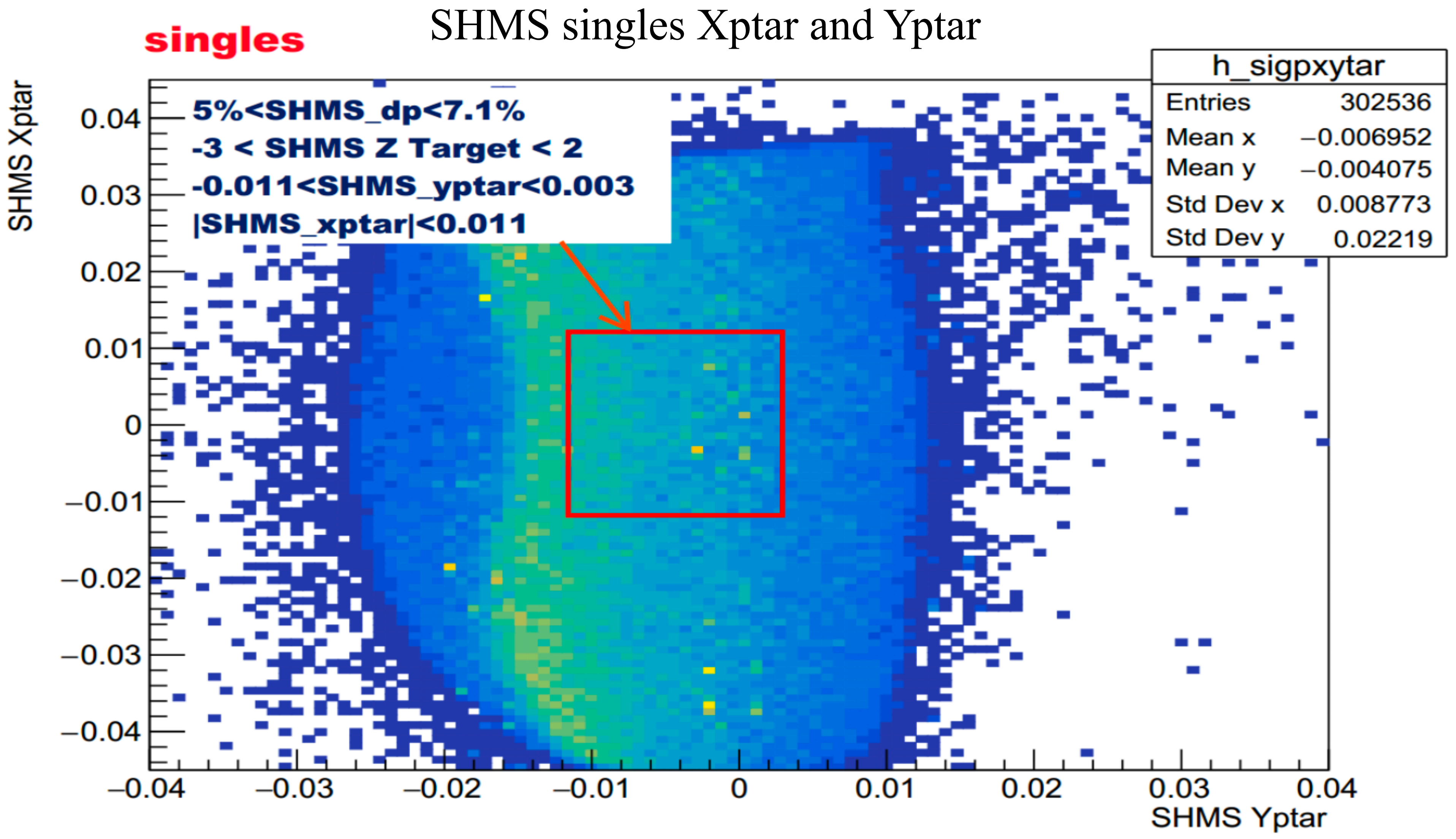
P.cal.etottracknorm > 0.8

W > 1.1

Proton Absorption



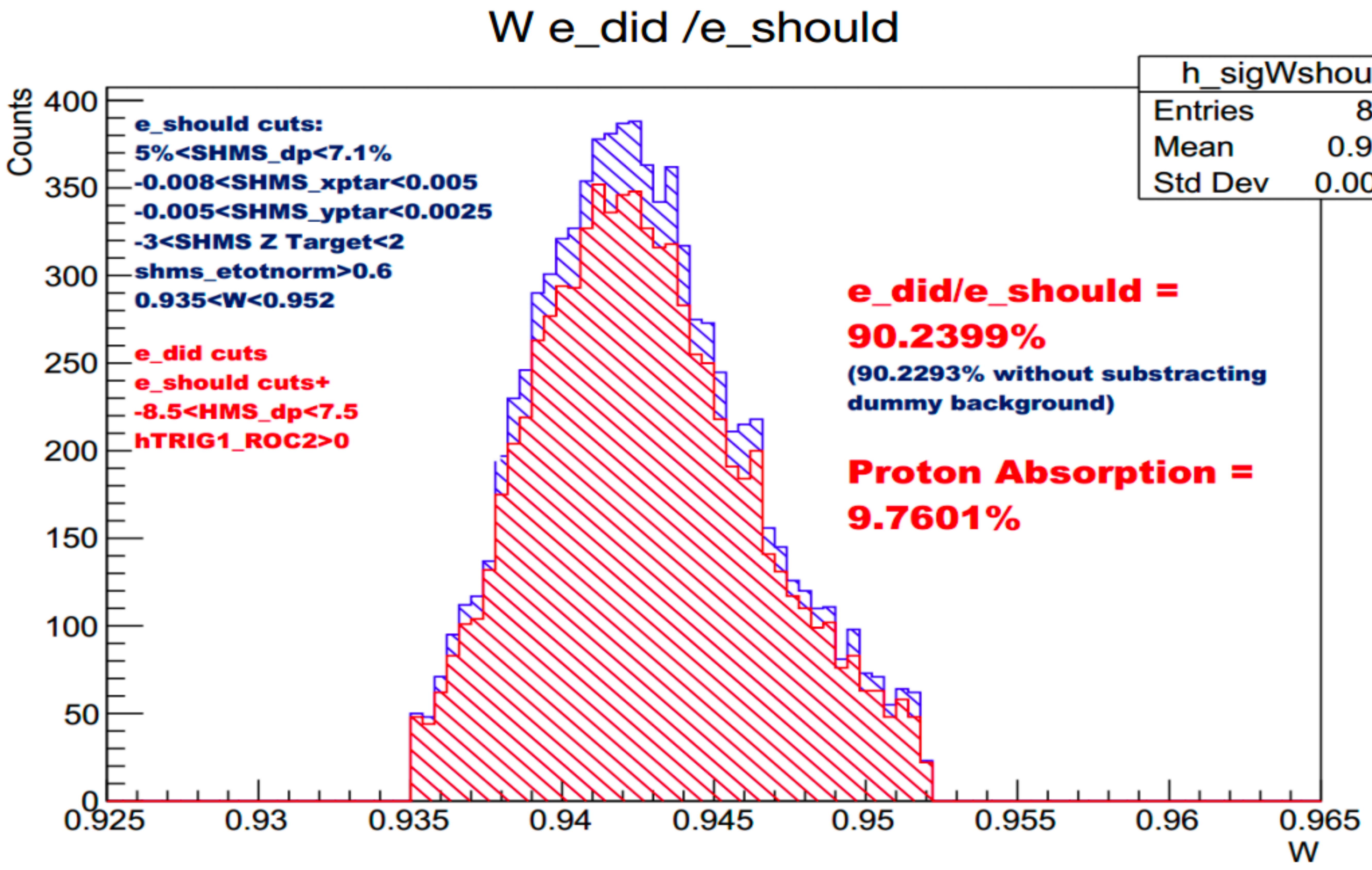




- Select ep-elastic acceptance region (coindence)
- Find number of electrons should be detected (SHMS singles)
- Find number of electrons did be detected (SHMS acceptance cuts + hTRIG1>0)

$$Proton\ absorption = 1 - \frac{e^-_{did}}{e^-_{should}}$$

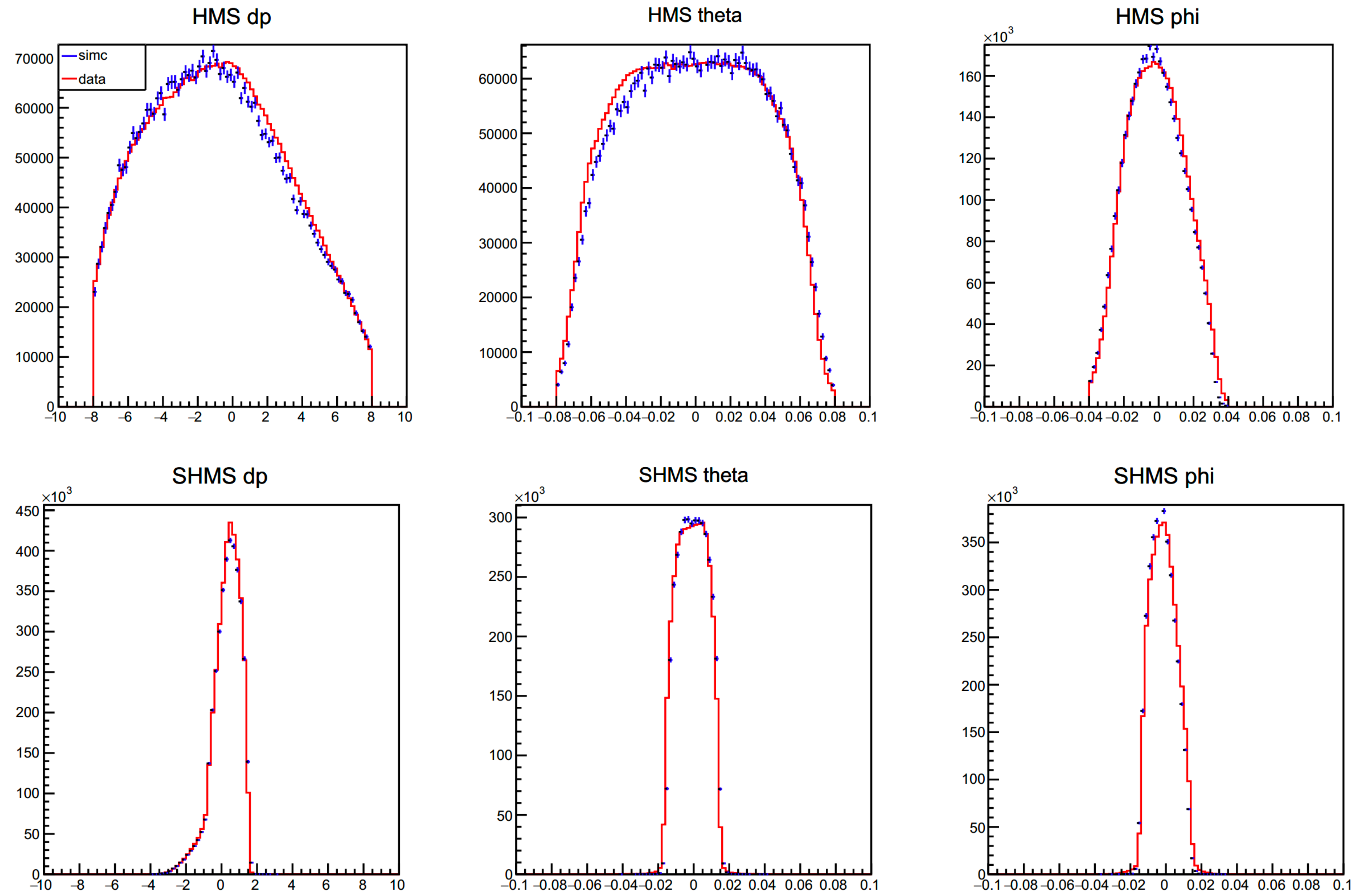
Proton Absorption



9.7601% Proton did NOT make it to form a trigger

Elastic

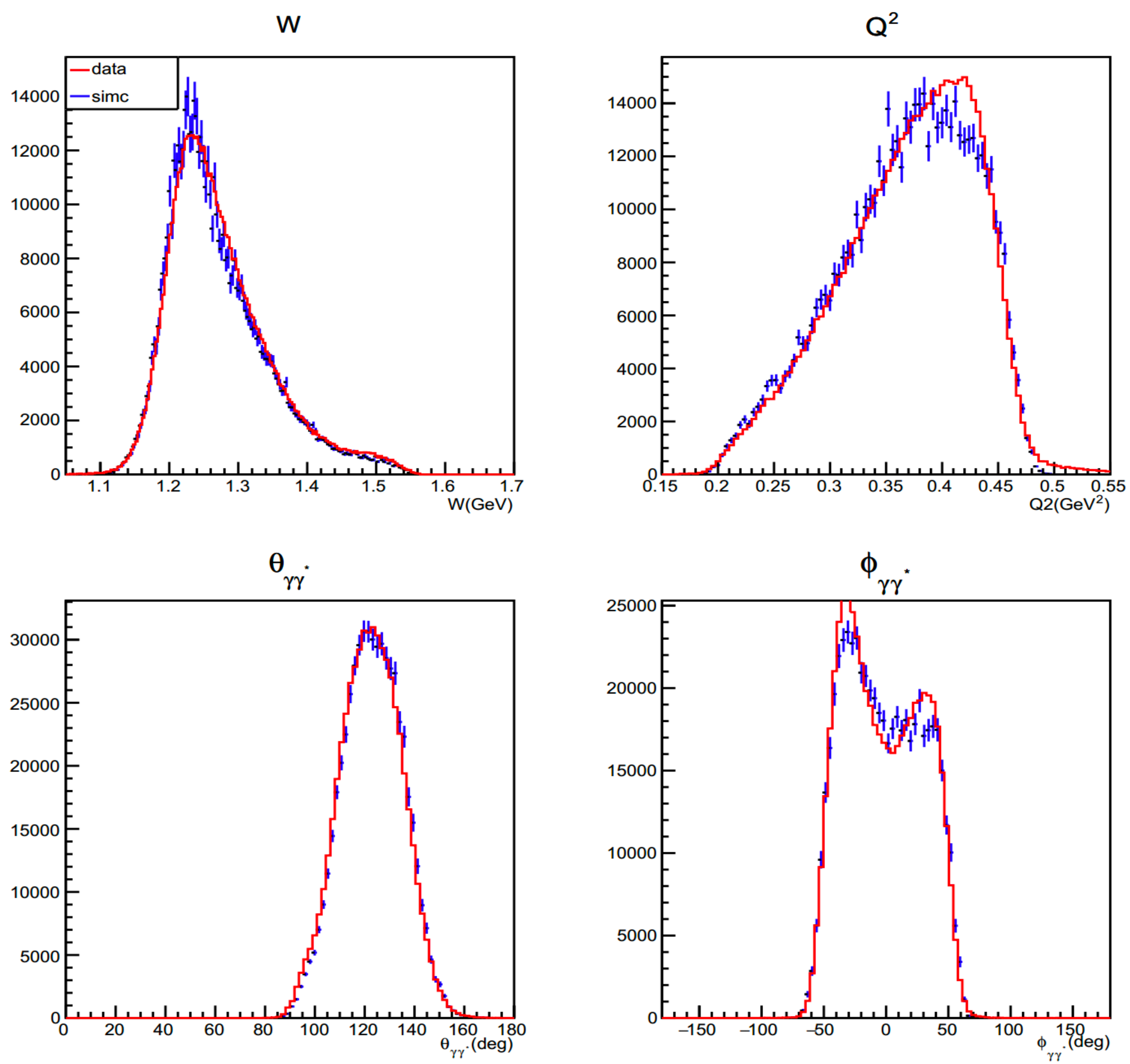
Elastic I data vs. simc



Agreement in 1~2 %

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

Pion Data



Cuts:

ABS(CTime.epCoinTime_ROC2 -50) < 3

Trigger g.evtyp ==4

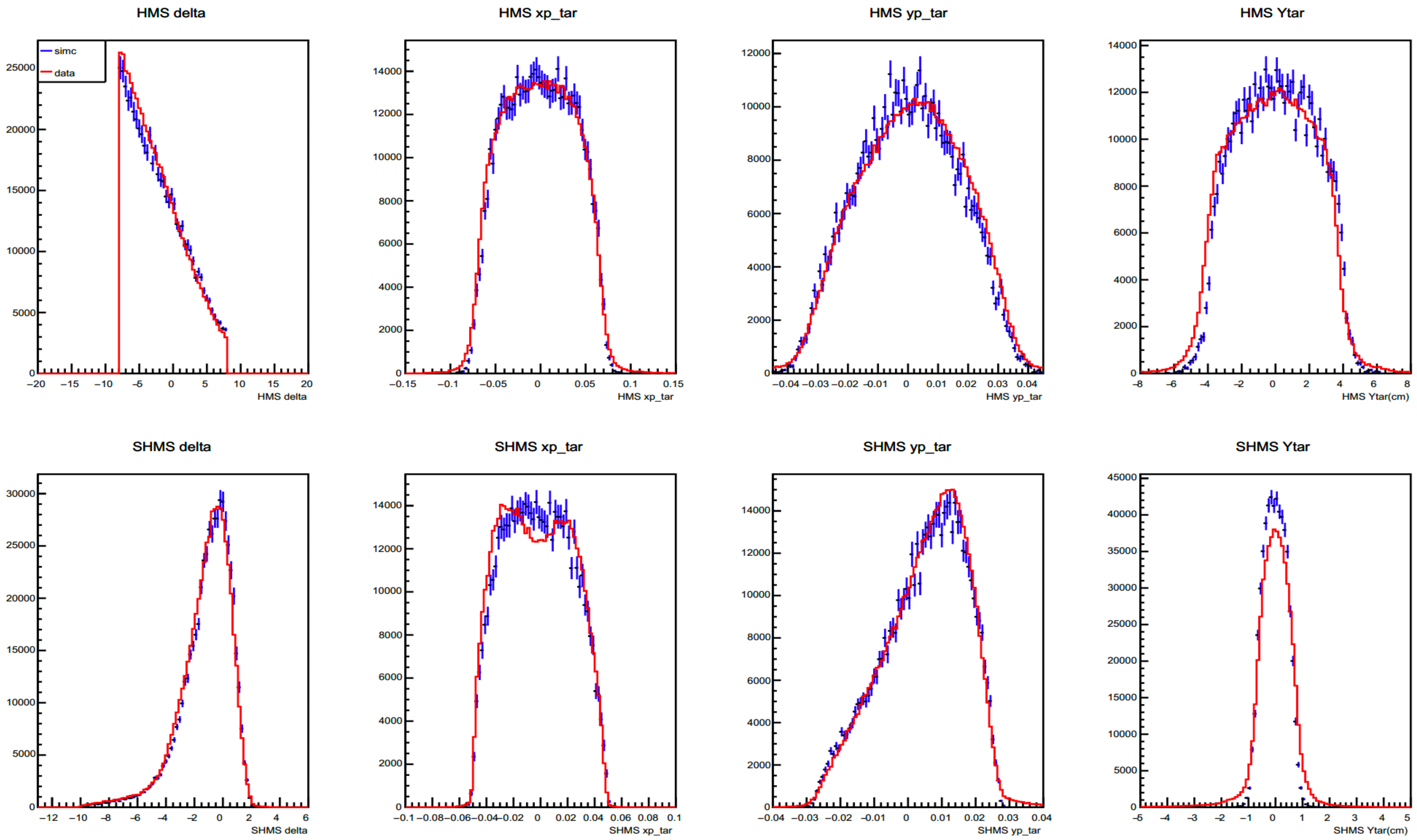
HMS_dp = +/-8

SHMS_dp > -10

0.0025 < mm2 < 0.06

Agreement in 4 %

Pion Data


HMS delta
simc
data
HMS xp_tar
HMS yp_tar
HMS Ytar
HMS Ytar(cm)
SHMS delta
SHMS xp_tar
SHMS yp_tar
SHMS Ytar
SHMS Ytar(cm)

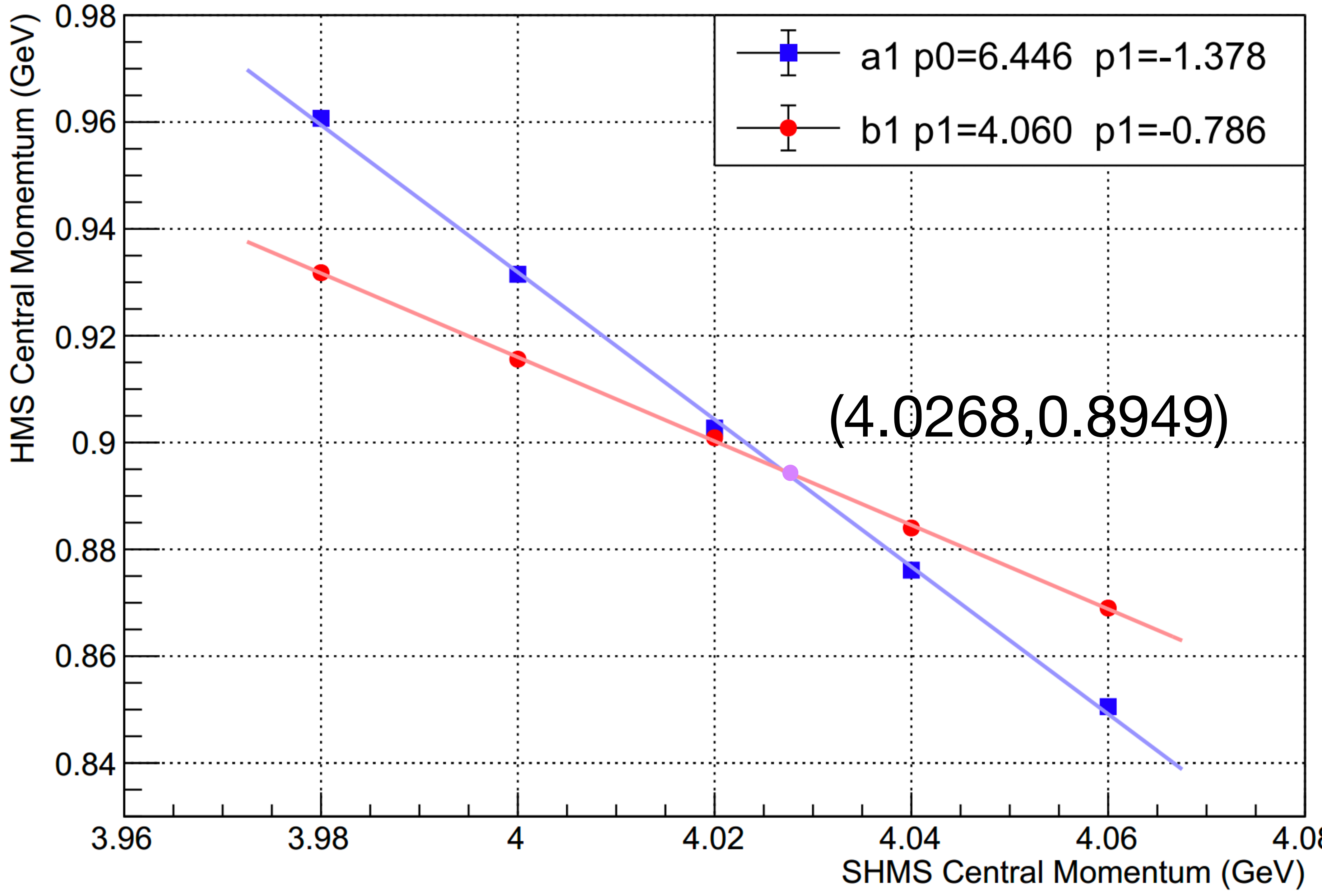
Energy Calibration

Spectrometer:
Same P
Different Theta

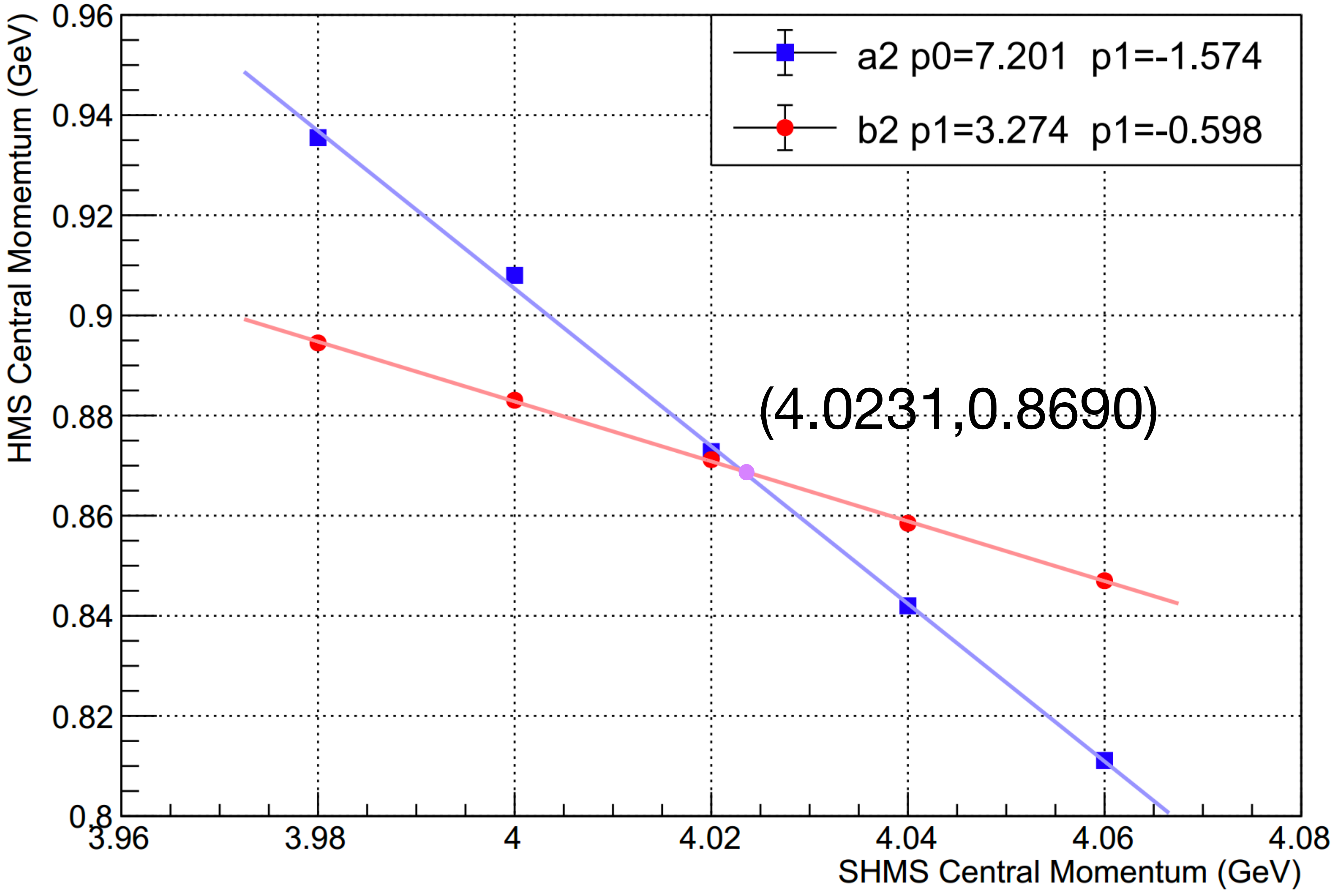
	SHMS_p	SHMS_th	HMS_p	HMS_th
Kin1a	4.034	7.69	0.893	37.33
Kin1b	4.034	7.69	0.893	51.40

	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

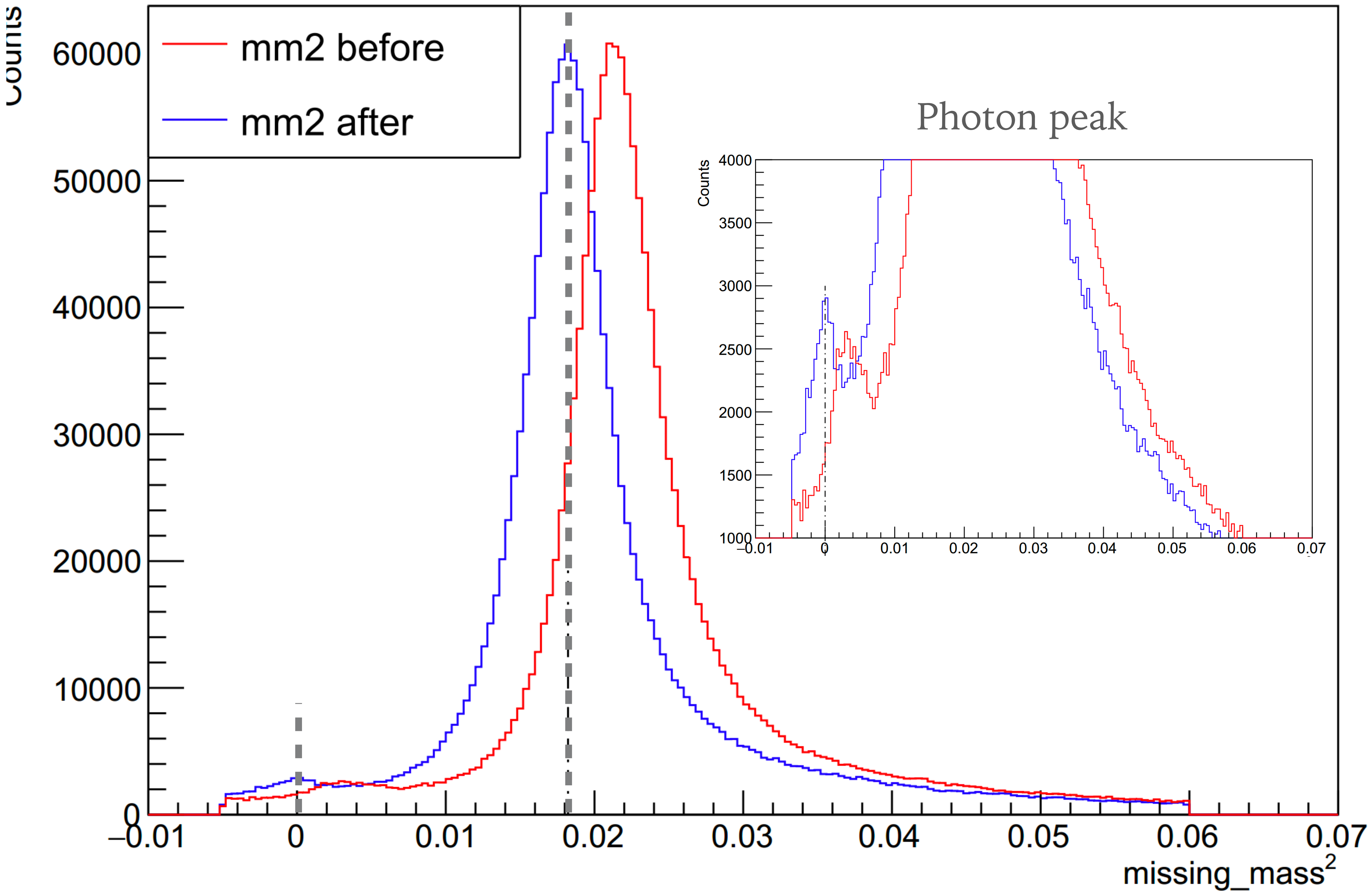


Kin 2a & Kin 2b



Energy Calibration

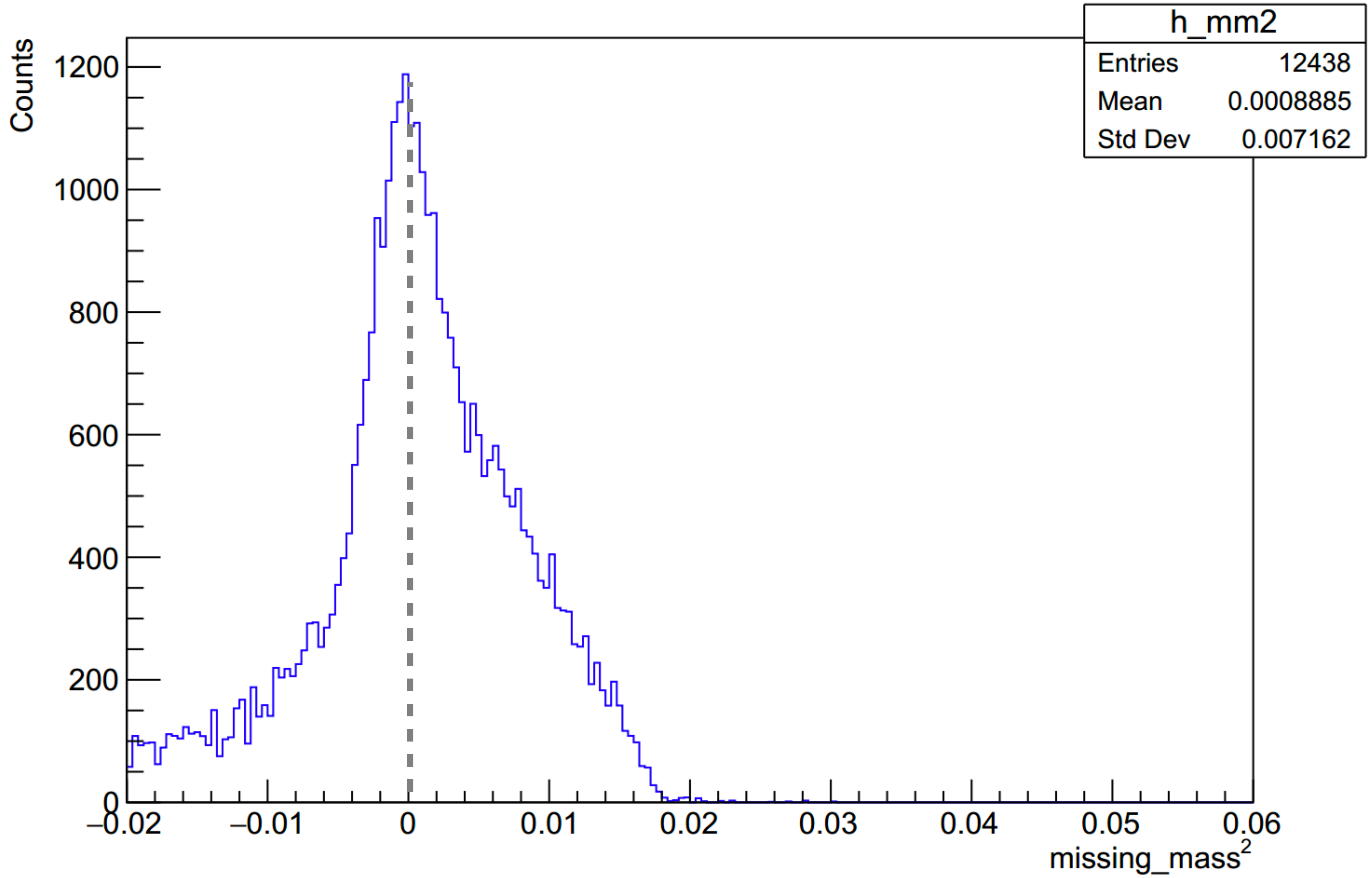
Kin2b



	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

VCS Data

Kin2b



Cuts:

ABS(CTime.epCoinTime_ROC2 -50) < 3

Trigger g.evtyp ==4

HMS_dp = +/-8

SHMS_dp > -10

mm2 < 0.06

ABS(theta_gg-140) < 6

ABS(W-1.232) < 0.01

ABS(Q2-0.33) < 0.05

VCS data vs. SIMC comparison

ONGOING…

Future Work

- Detector Calibration
- Acceptance Study
- Radiative Corrections
- Extracting Cross-Sections and Asymmetries
- Extracting the Electric and Magnetic Generalized Polarizabilities

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

Backup Slides

Backup Slides