The Generalized Polarizabilities of the Proton

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On behalf of E12-15-001 Collaboration

HALL A/C COLLABORATION MEETING 06/16/2022

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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

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

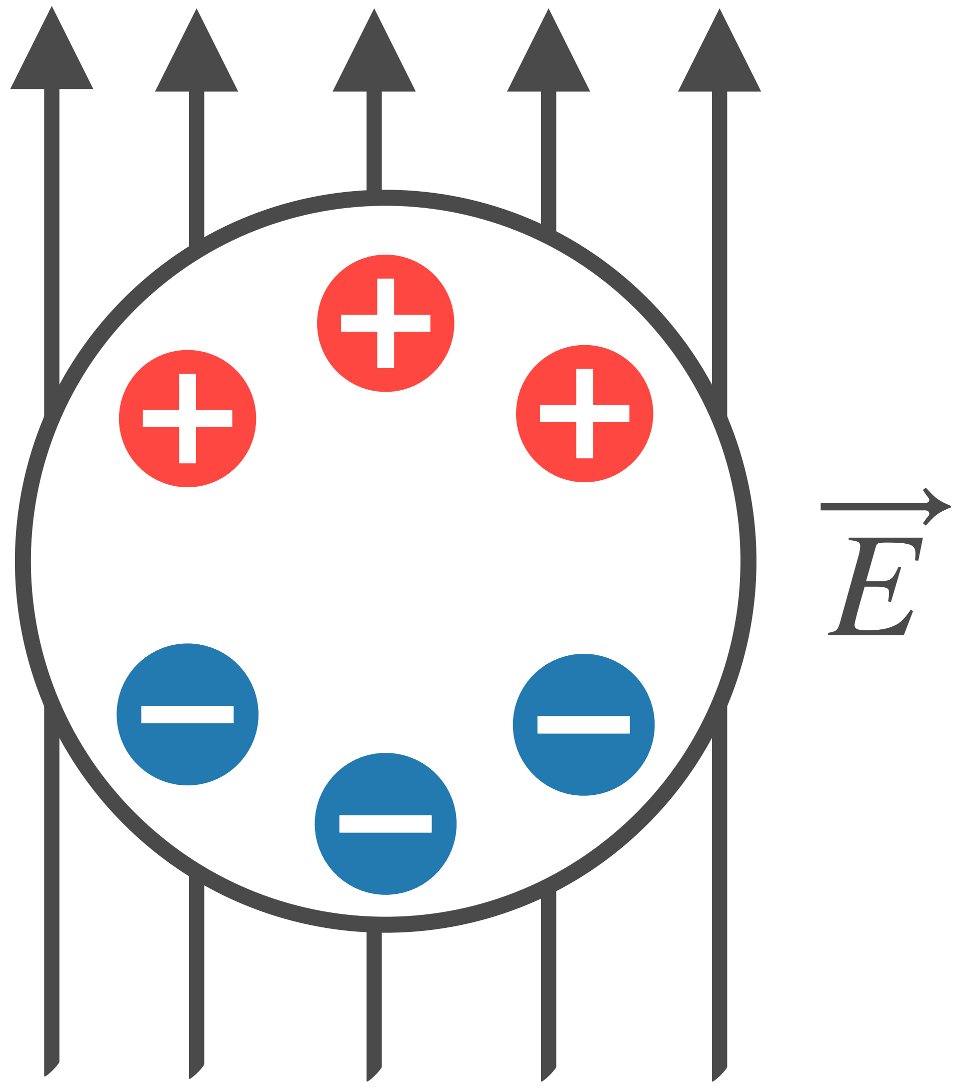
Mass $m = 1.00727646688 \pm 0.00000000009$ u
Mass $m = 938.272081 \pm 0.000006$ MeV [a]
$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 1.00000000000 \pm 0.00000000007$
$|q_p + q_{\overline{p}}|/e < 7 \times 10^{-10}$, 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):

- Generalization at finite Q^2 of the polarizability
- Access by Virtual Compton Scattering (VCS)
- 2 scaler and 4 vector GPs
- Fourier transform can map out the spatial distribution density of the polarization induced by an EM field

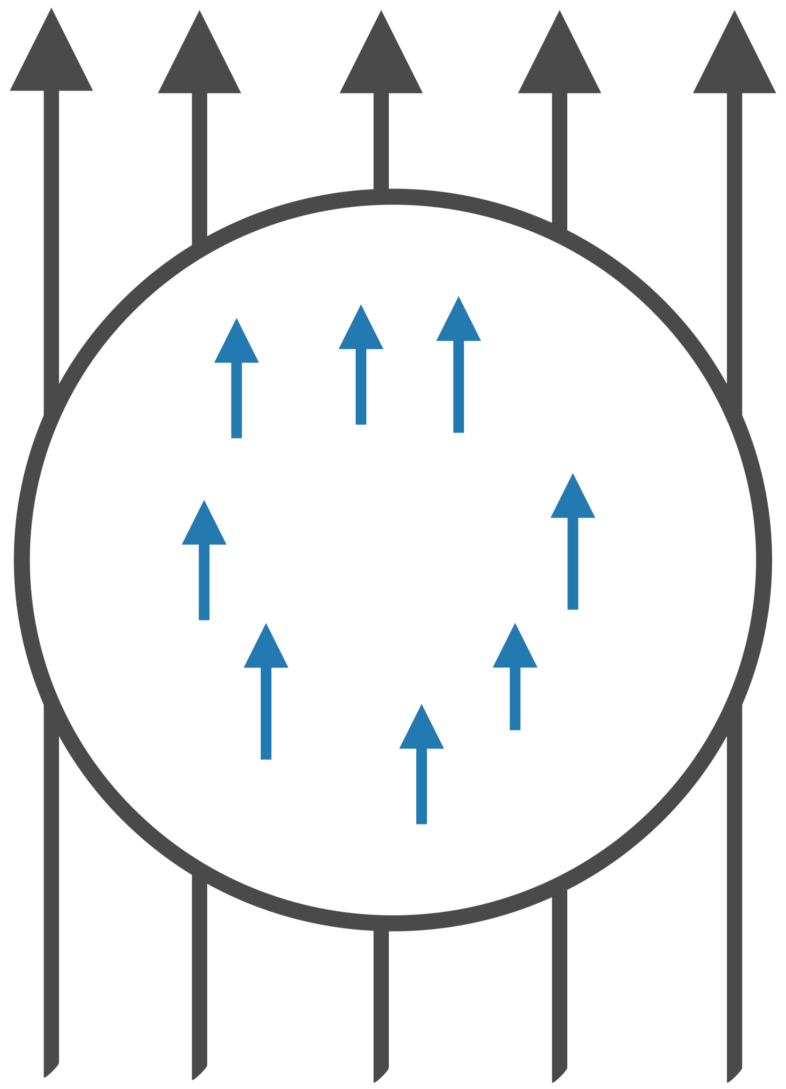
Generalized Polarizabilities

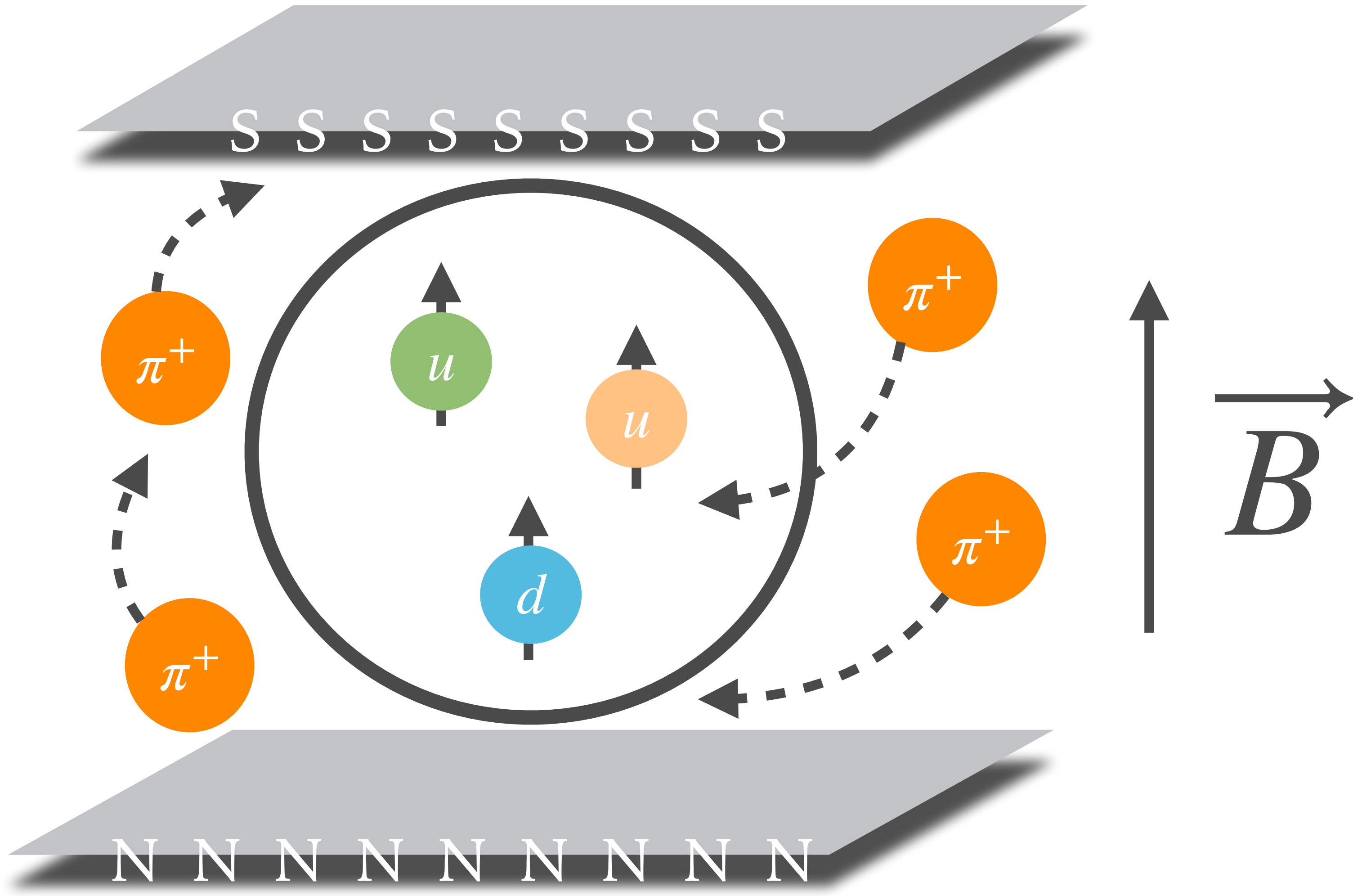


$$\vec{p} = \alpha_E \vec{E}$$

Electric Polarizability

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





Magnetic Polarizability

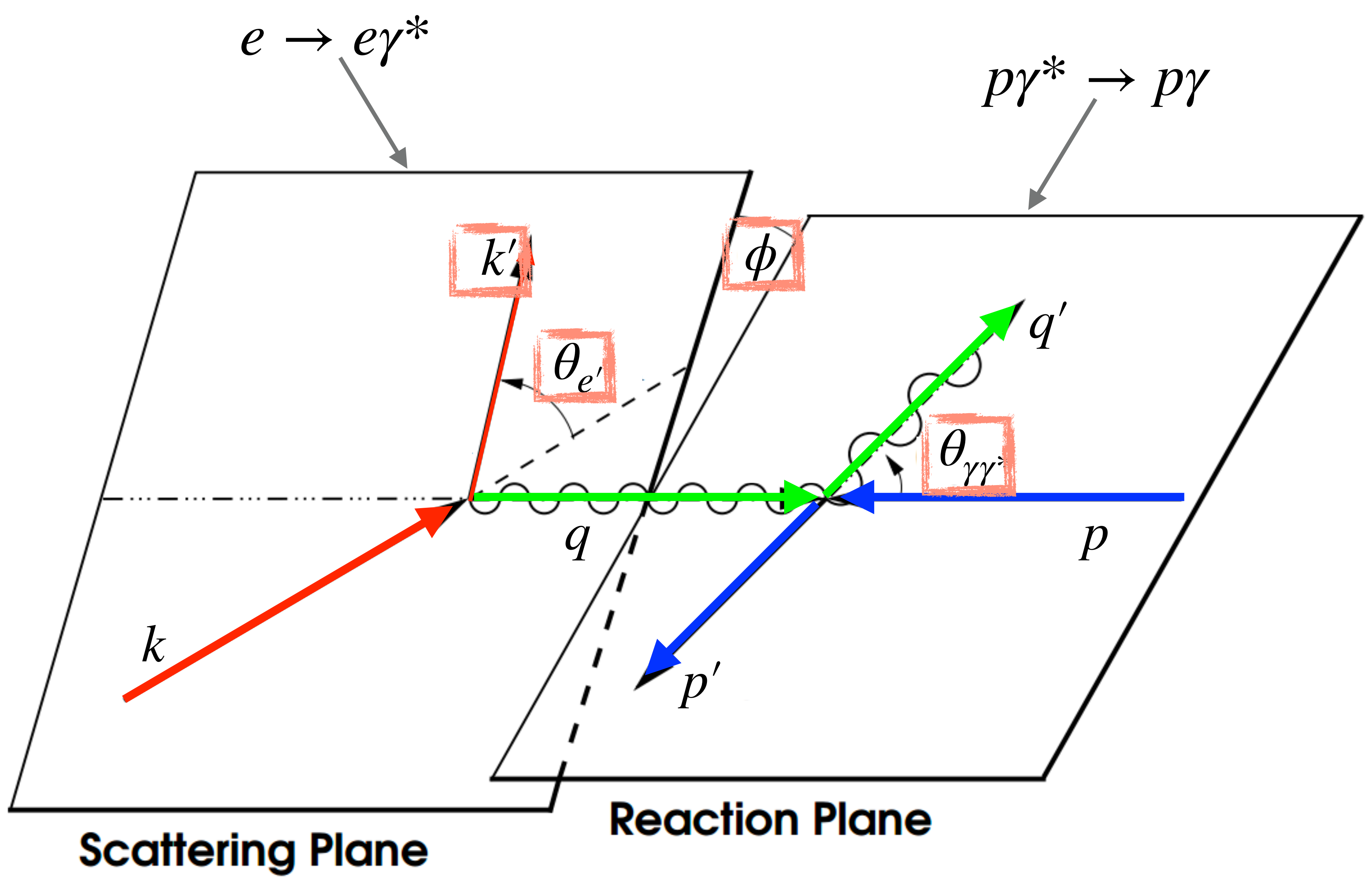
$$\vec{m} = \beta_M \vec{B}$$

- **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

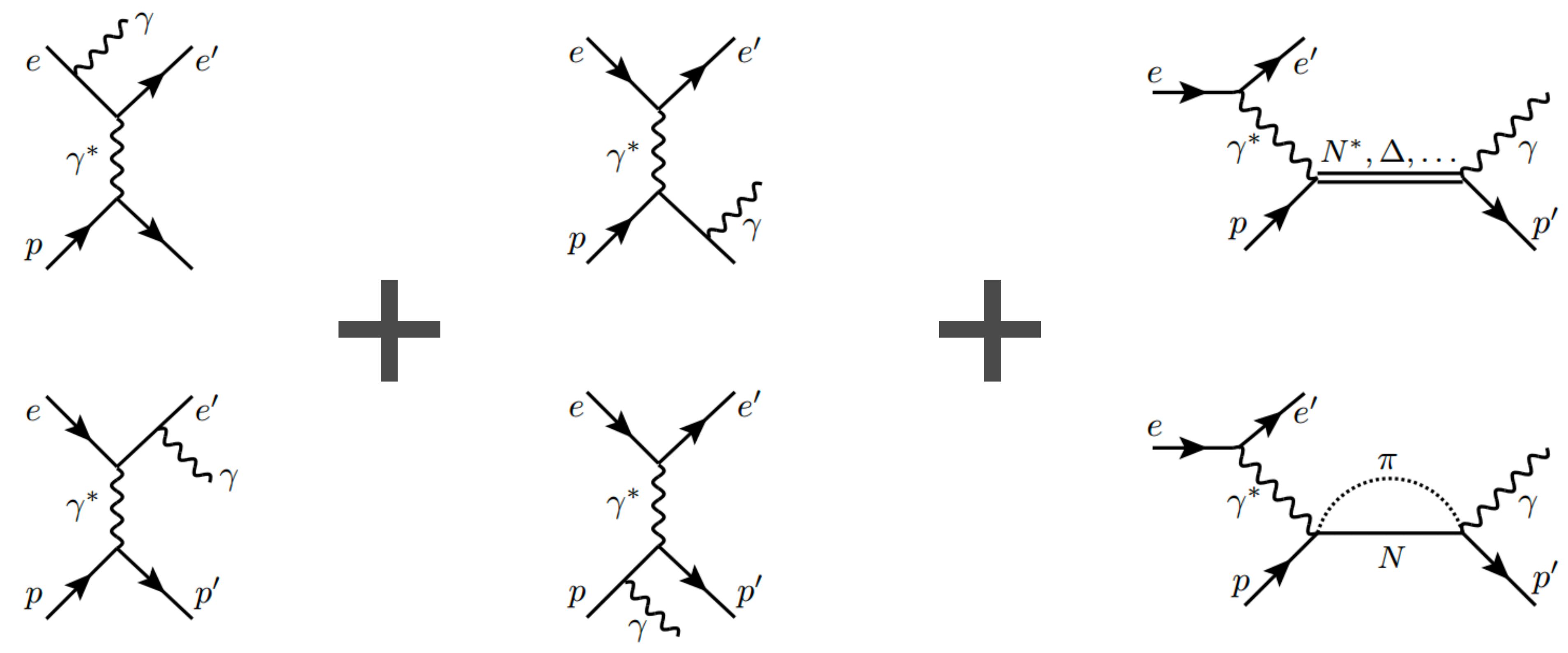
k'-scattered electron q'-real photon p'-final proton



Kinematics of $ep \to ep\gamma$

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

VCS process → photon electro-production reaction



Bethe-Heitler + VCS Born + VCS non-Born

Calculable with nucleon form factors G_E, G_M

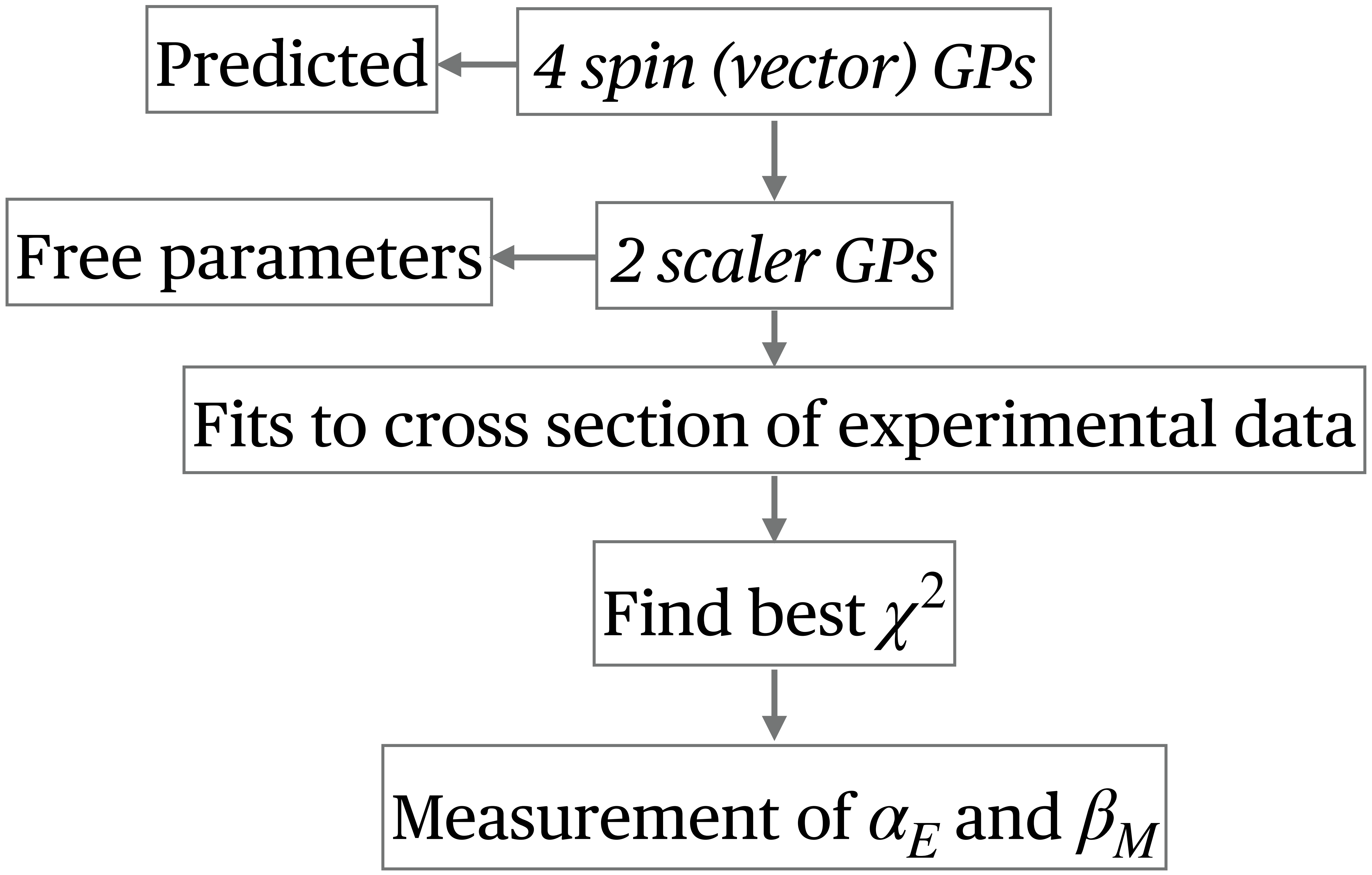
$$\alpha_{E1}(Q^2) = -\frac{e^2}{4\pi} \cdot \sqrt{\frac{3}{2}} \cdot P^{(L1,L1)0}(Q^2)$$

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

Electric & Magnetic Scaler GP

LEX & DR Formalism

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



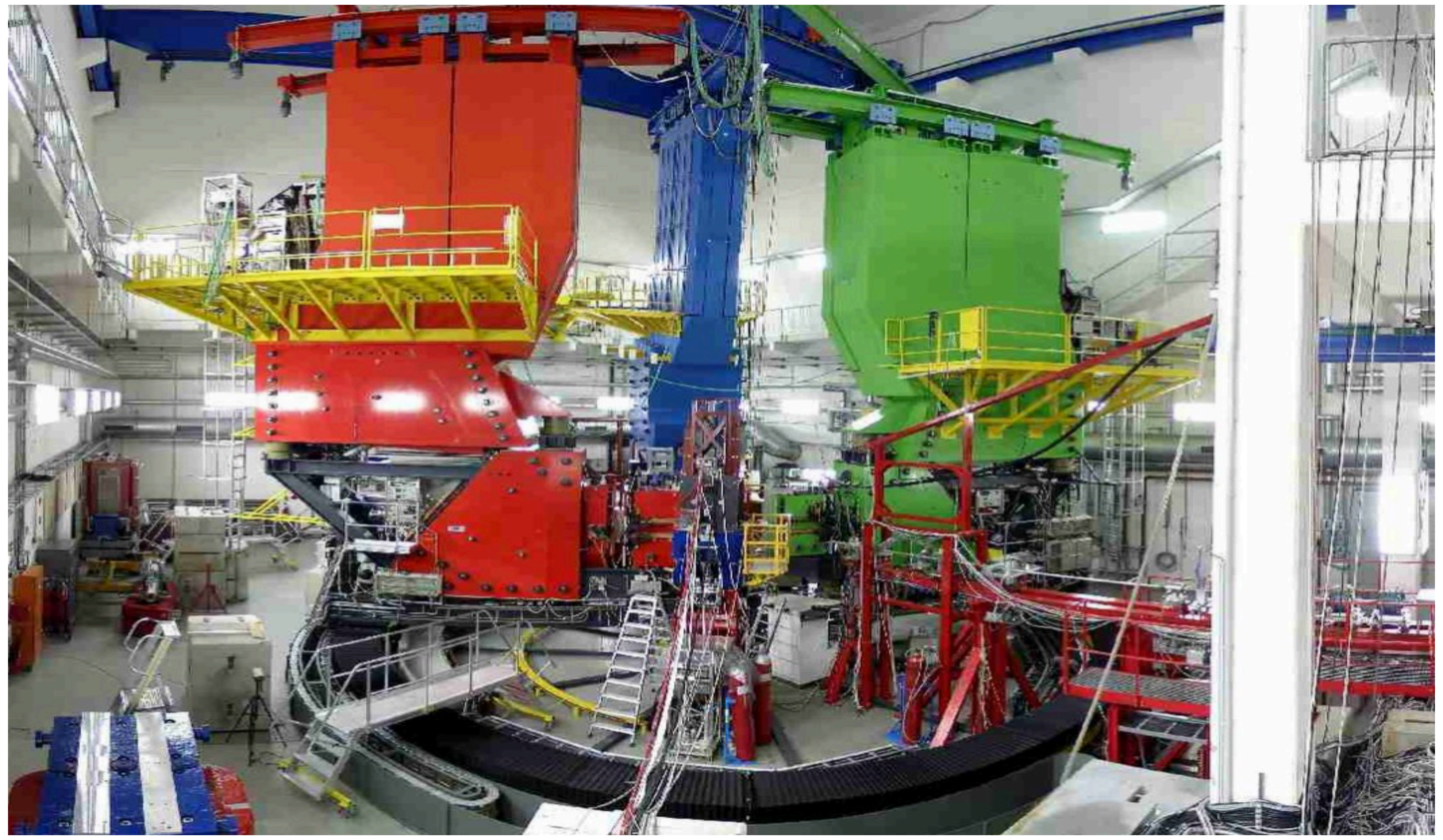
"The effect of the GPs in the photon electroproduction cross-section roughly scales with the outgoing photon energy."

Phys. Rev C 86, 015210 (2012)
Phys. Rev Lett. 93, 122001 (2004)

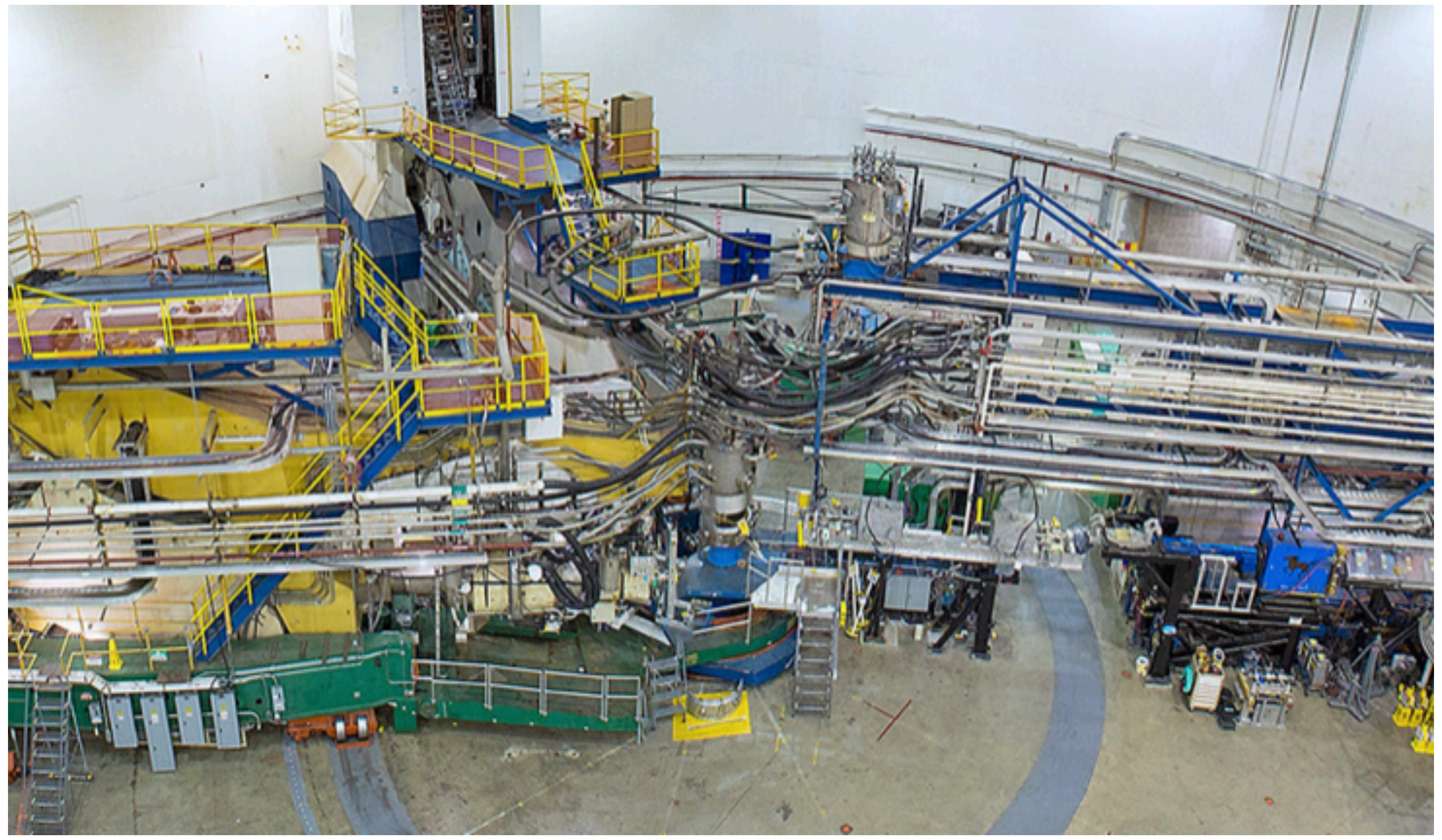
High sensitivity to the GPs

World Data & Motivation

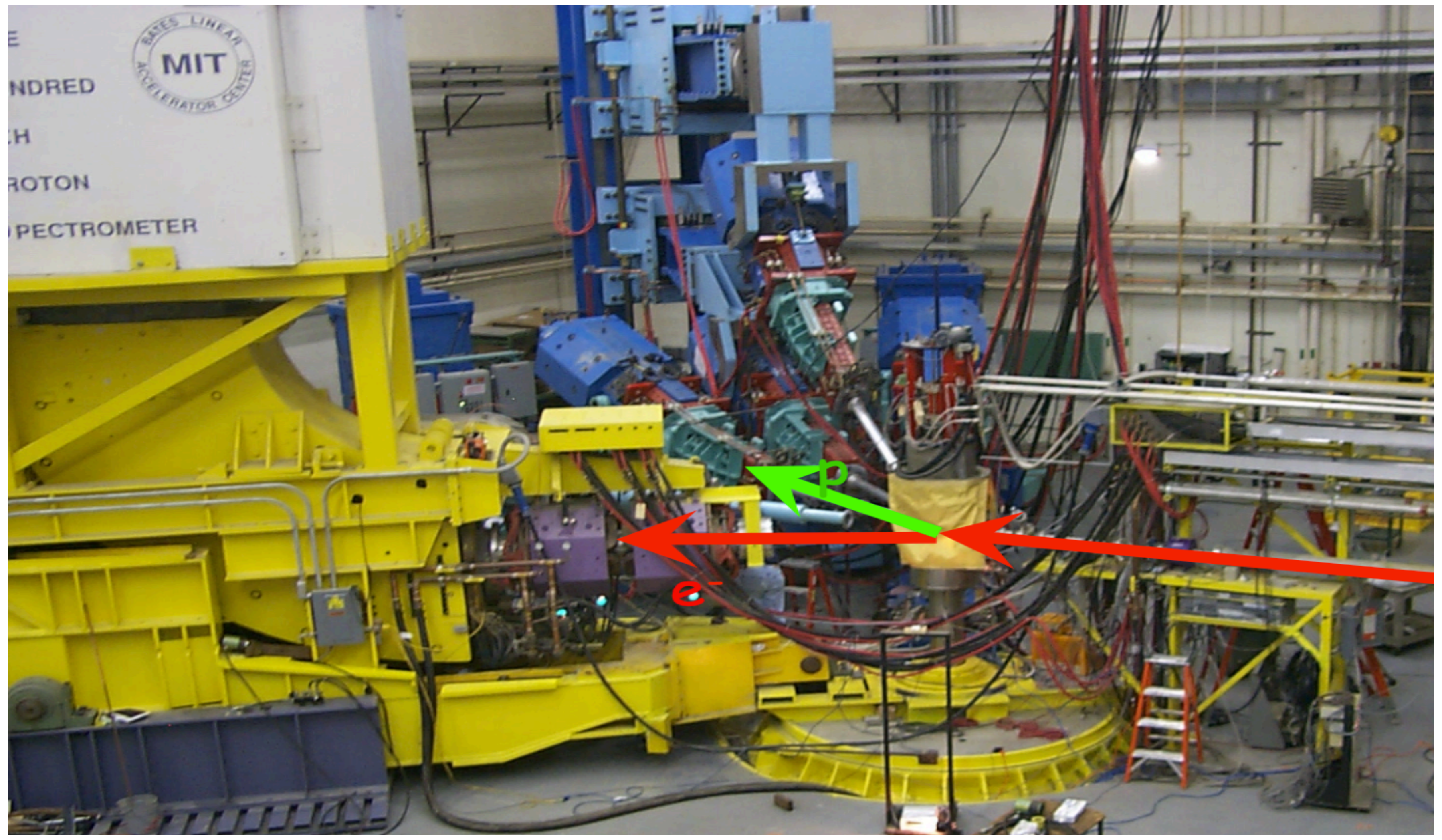
MAMI at $Q^2 = 0.1$ & 0.2 & 0.33 & $0.45\ GeV^2$



JLAB Hall A at $Q^2 = 0.92$ & $1.76\ GeV^2$

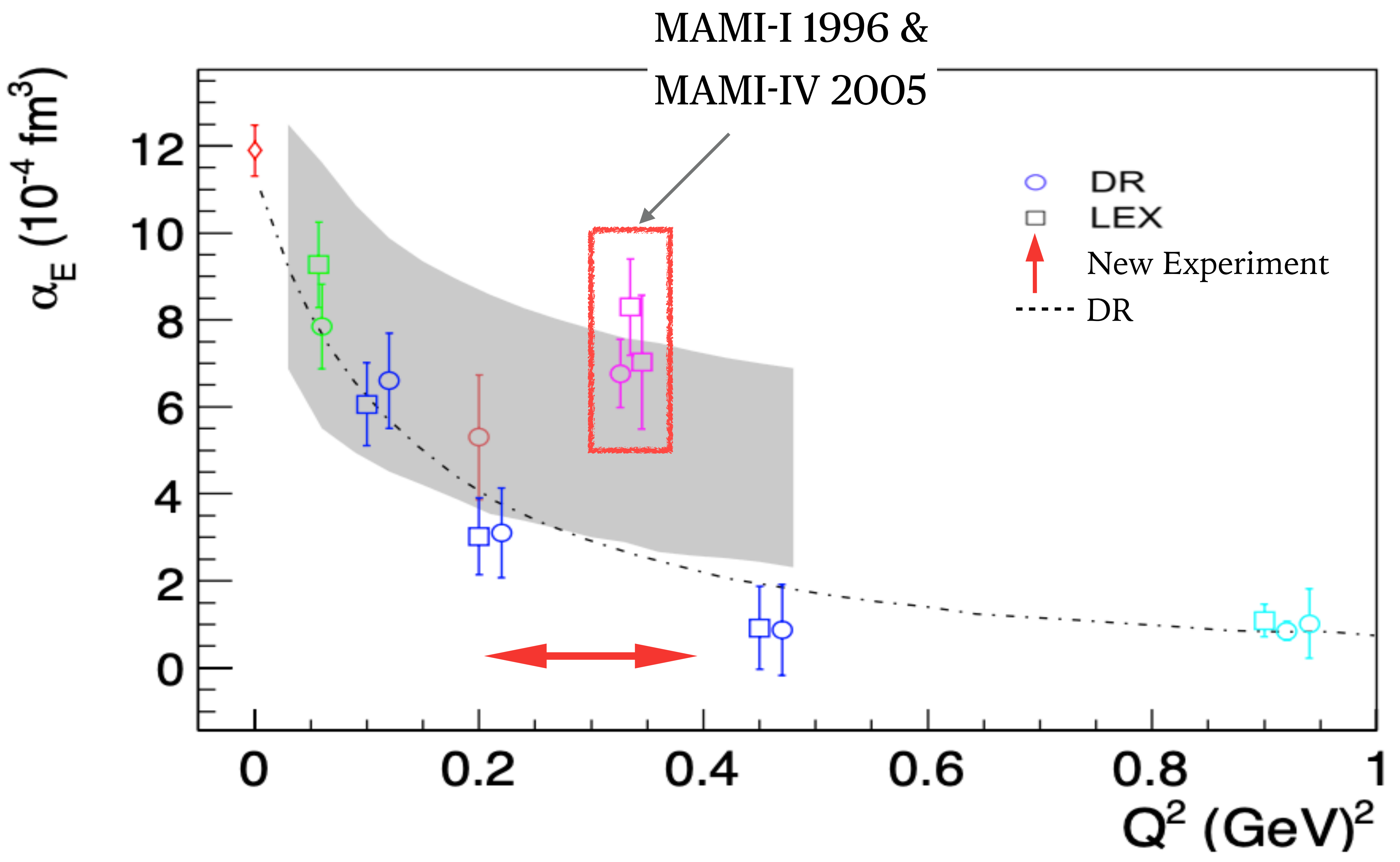


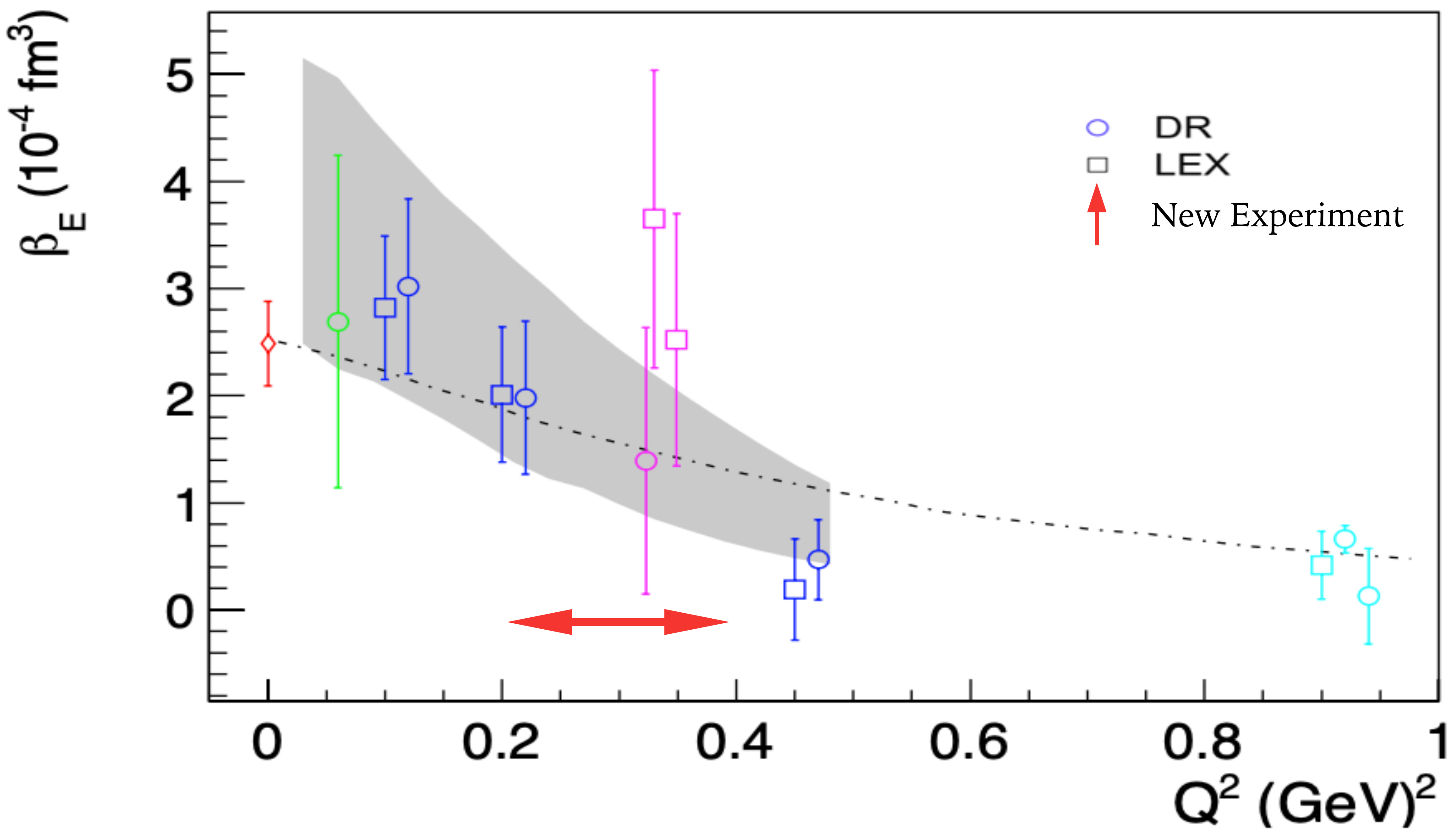
MIT-Bates at $Q^2 = 0.057\ GeV^2$



JLAB Hall C at $Q^2 = 0.33\ GeV^2$

World Data & Motivation



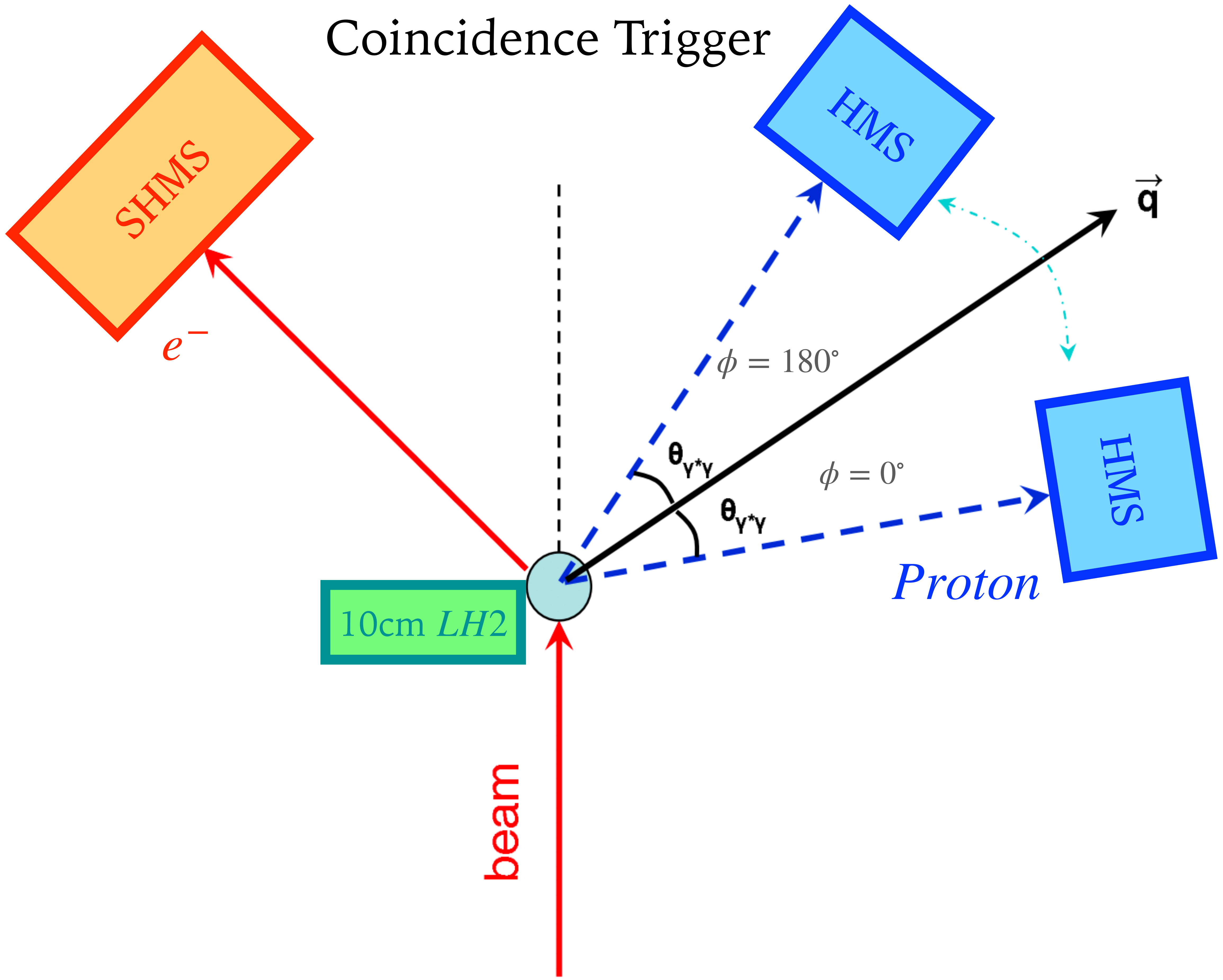


- Initial theoretical models predicted smooth fall off of α_E
  - data at $Q^2 = 0.33$ implies a non-trivial structure
- New experiment can:
  - Address puzzling α_E enhancement
  - Reduce error by 2

- 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



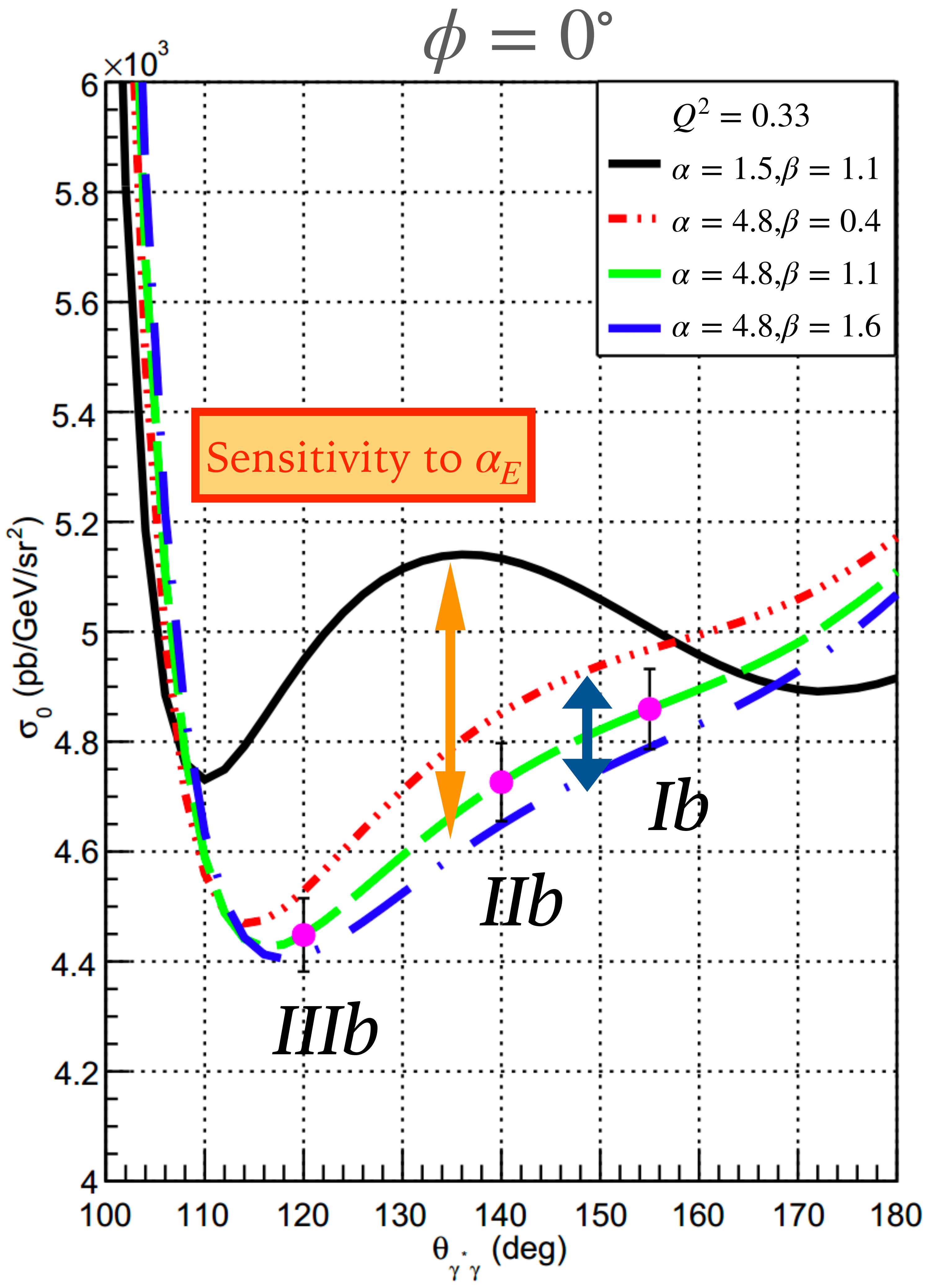
- In-plane azimuthal asymmetries to suppress systematic uncertainties:

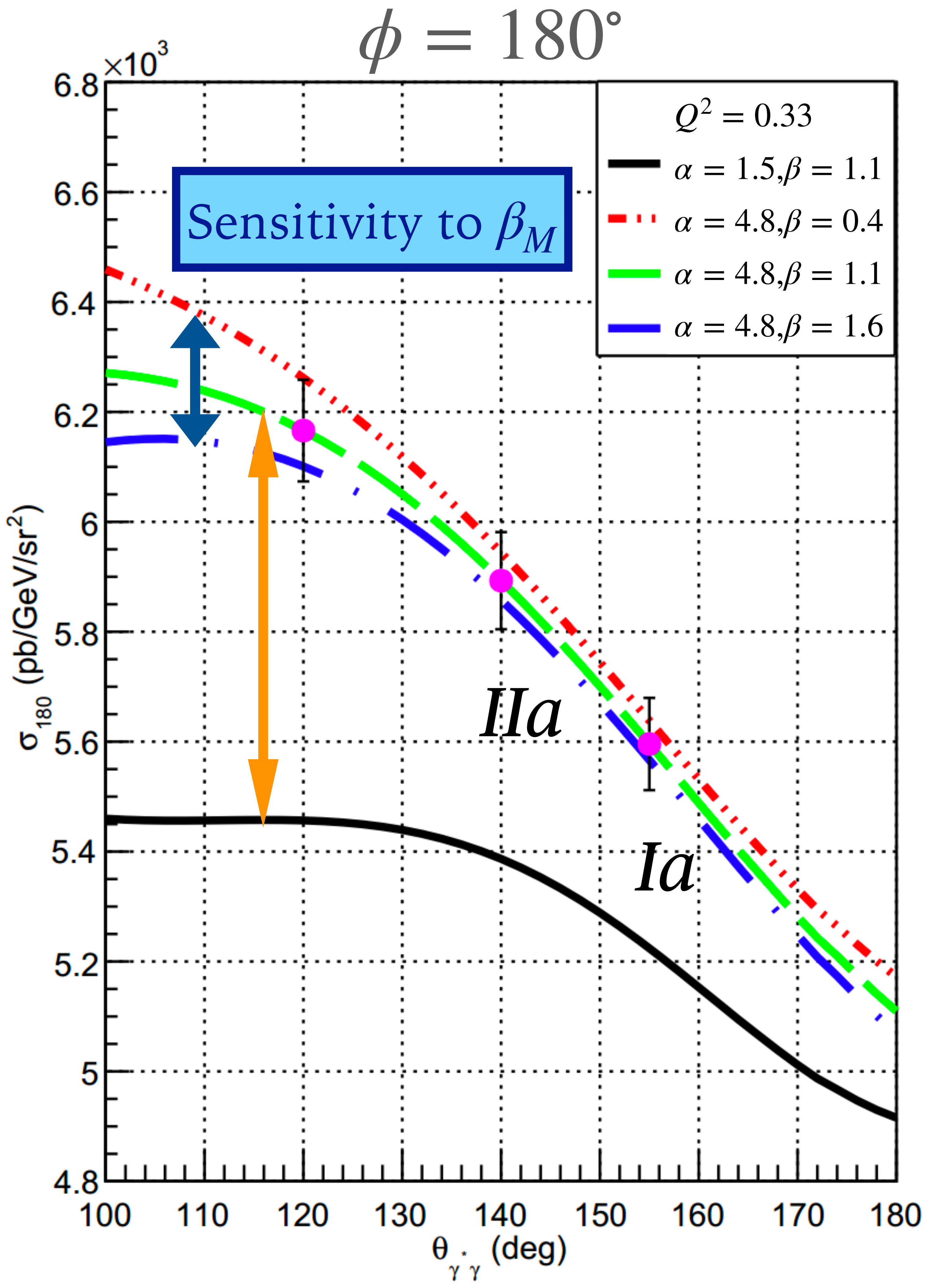
$$\frac{d\sigma_{\phi=180^\circ} - d\sigma_{\phi=0^\circ}}{d\sigma_{\phi=180^\circ} + d\sigma_{\phi=0^\circ}}$$

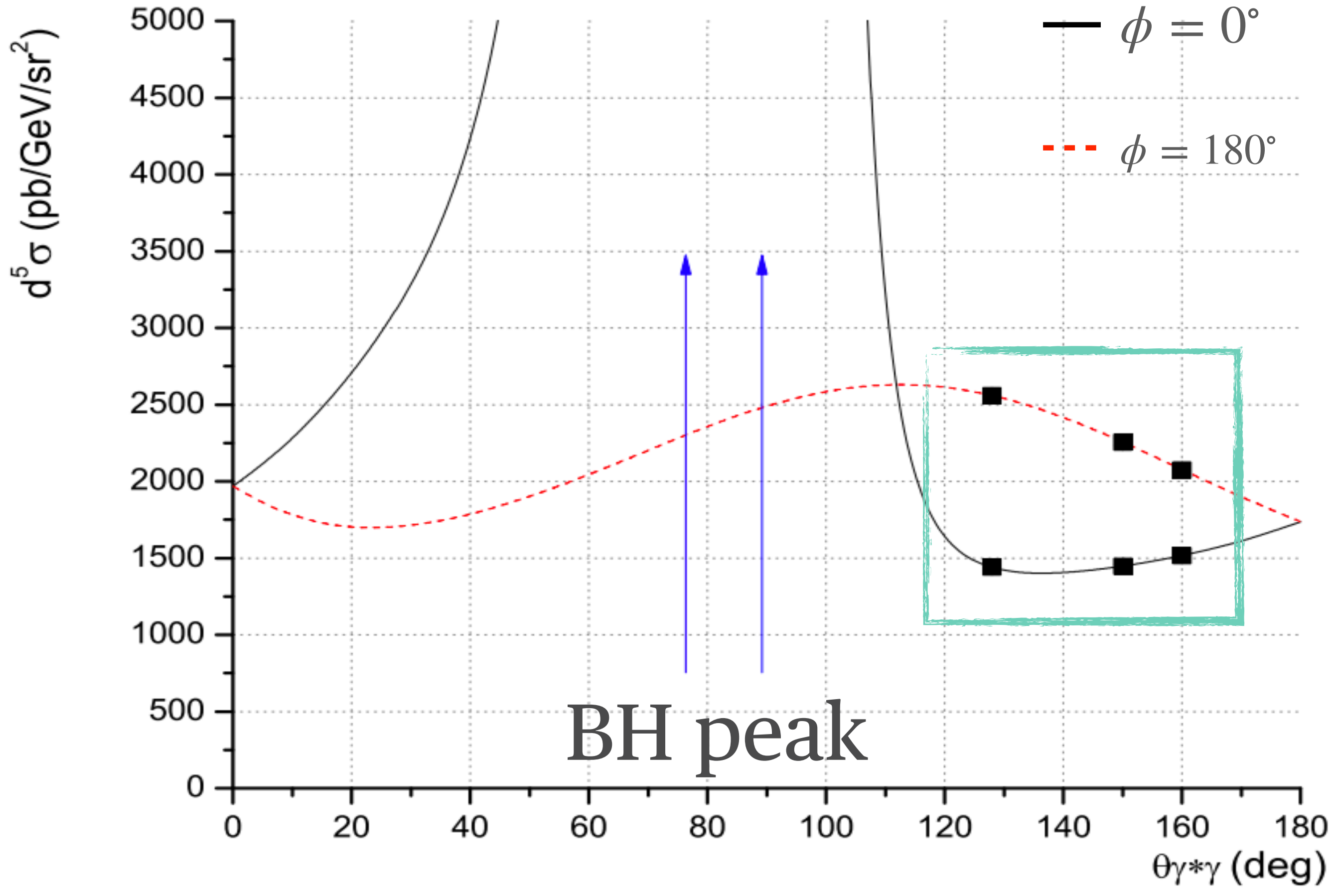
- Summer 2019: July 20 - August 5
- Beam $E = 4.56GeV$
- $Q^2 = 0.33GeV^2$, $W = 1.232GeV$

Kinematics	θ_e°	$P_e(GeV/c)$	θ_p°	$P_p(GeV/c)$
Kin 1a	7.69	4.034	37.33	0.893
Kin 1b	7.69	4.034	51.40	0.893
Kin 2a	7.69	4.034	33.53	0.863
Kin 2b	7.69	4.034	55.22	0.863
Kin 3b	7.69	4.034	60.74	0.795

Predicted Measurement



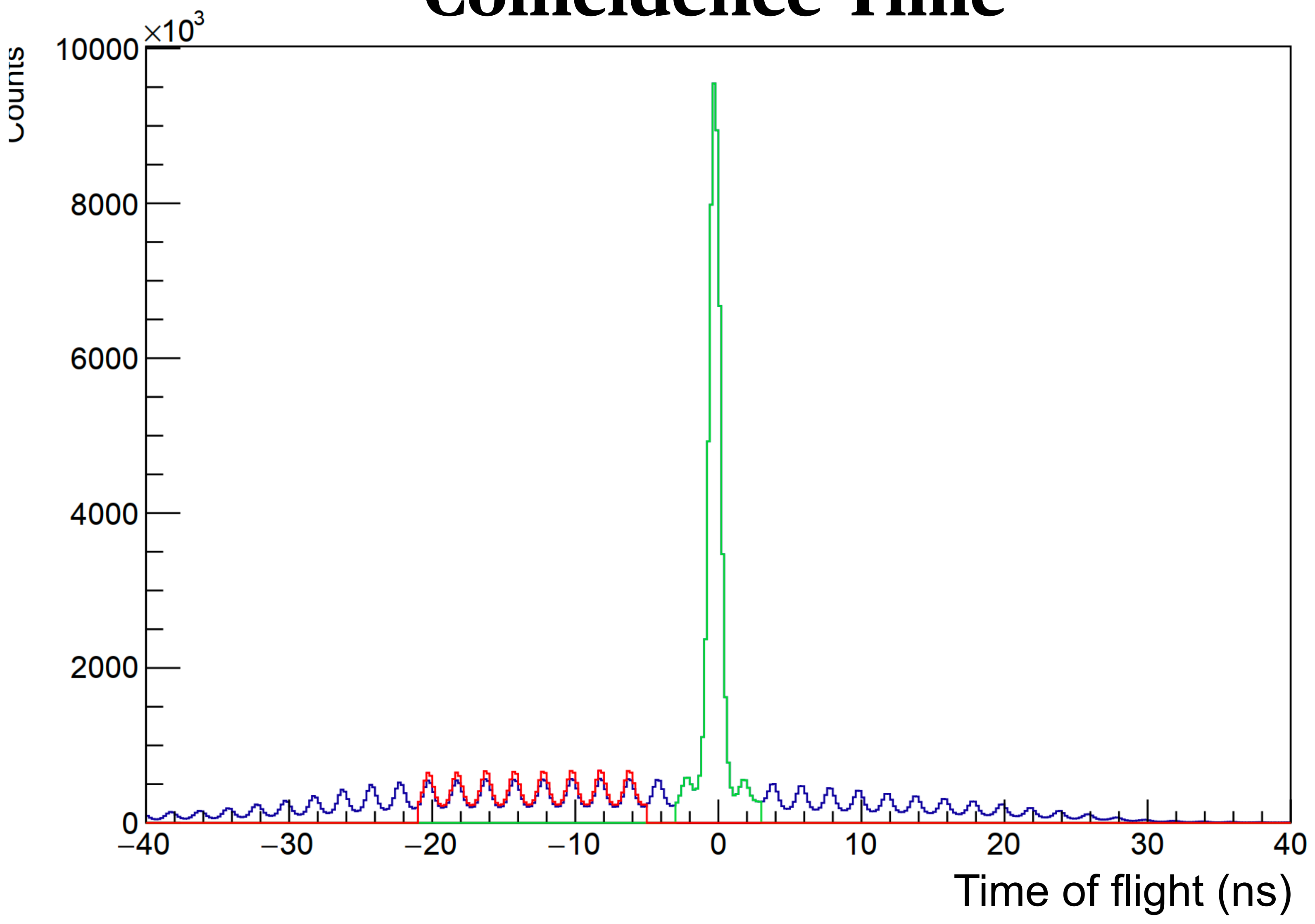


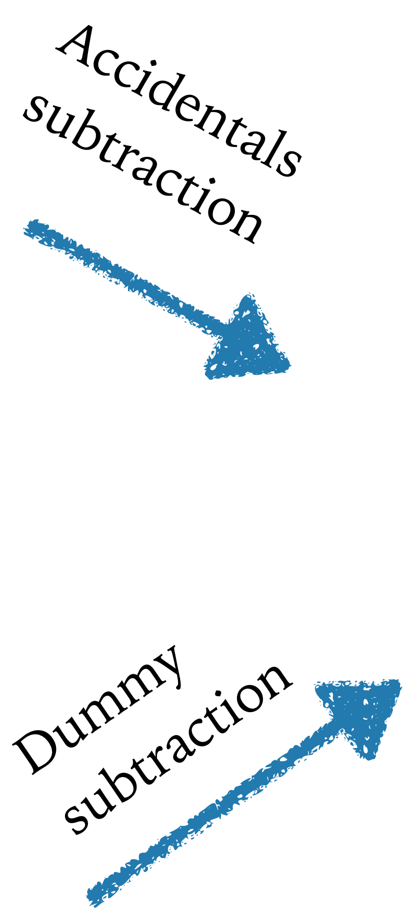


- High enough $\theta_{\gamma\gamma^*}$ to avoid BH peak
- Avoid rapid cross-section variation
- ϵ increases from 0.6 to 0.98 – doubles the sensitivity to GPs

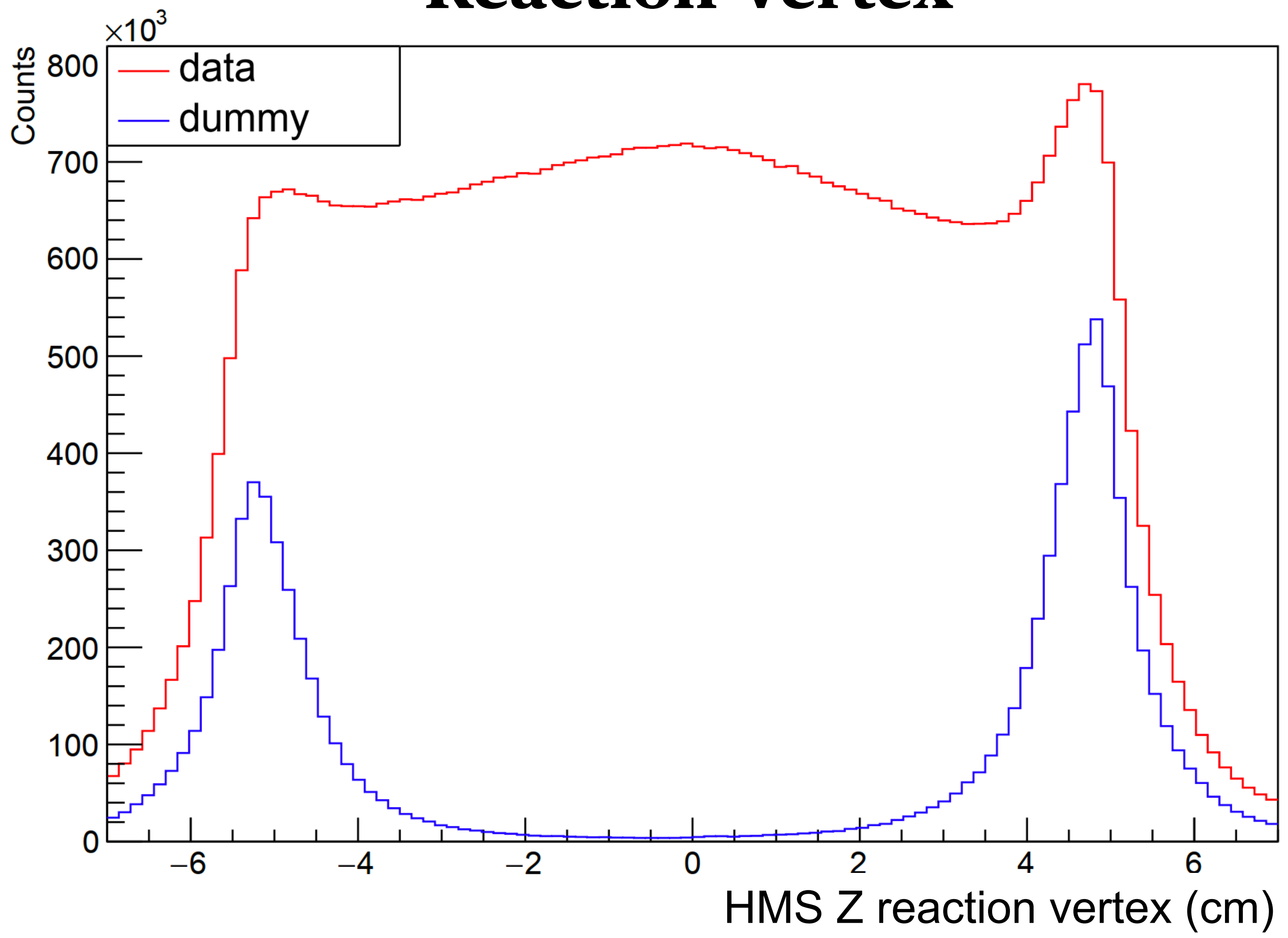
VCS Peak and piO Peak

Coincidence Time

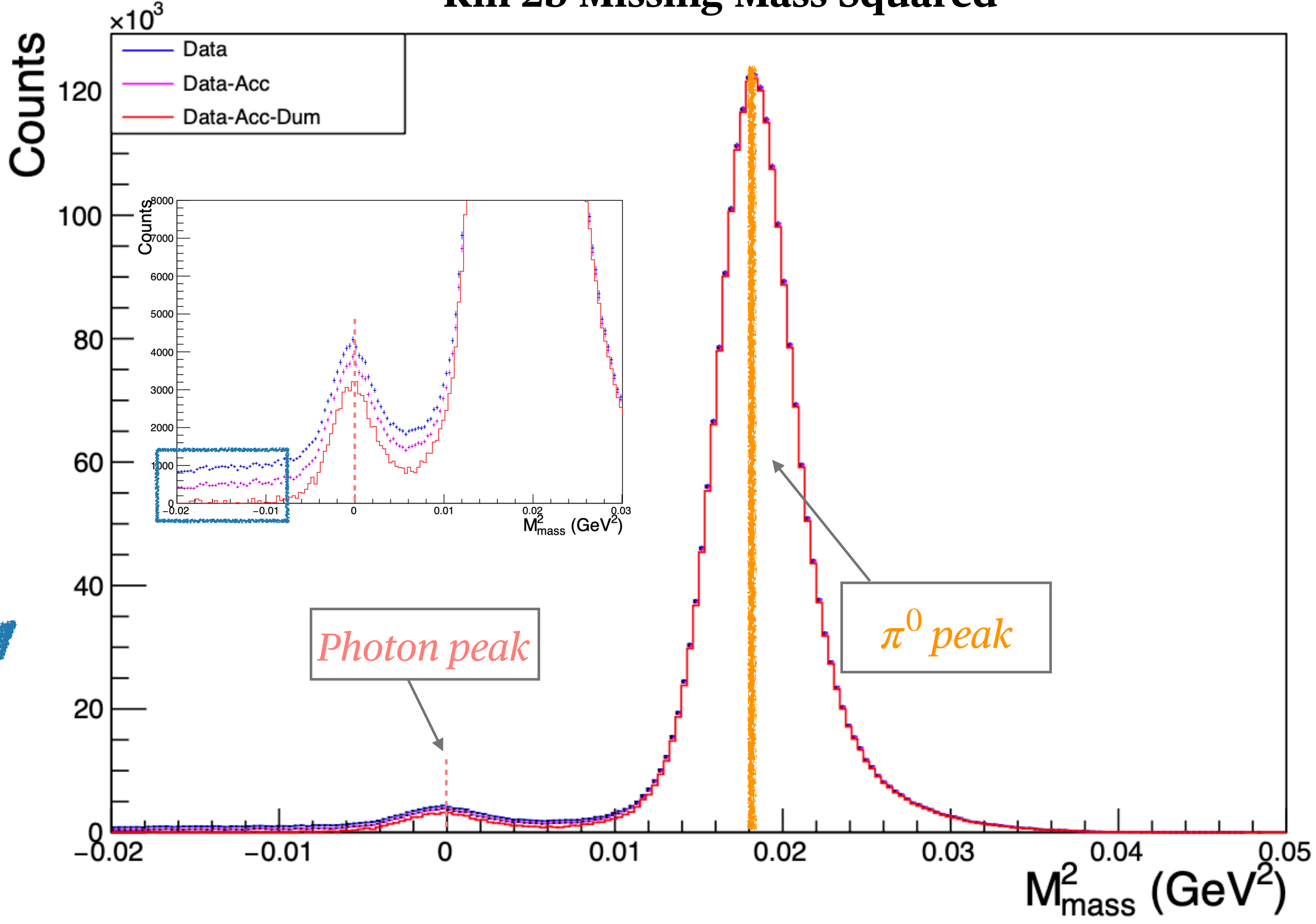




Reaction Vertex

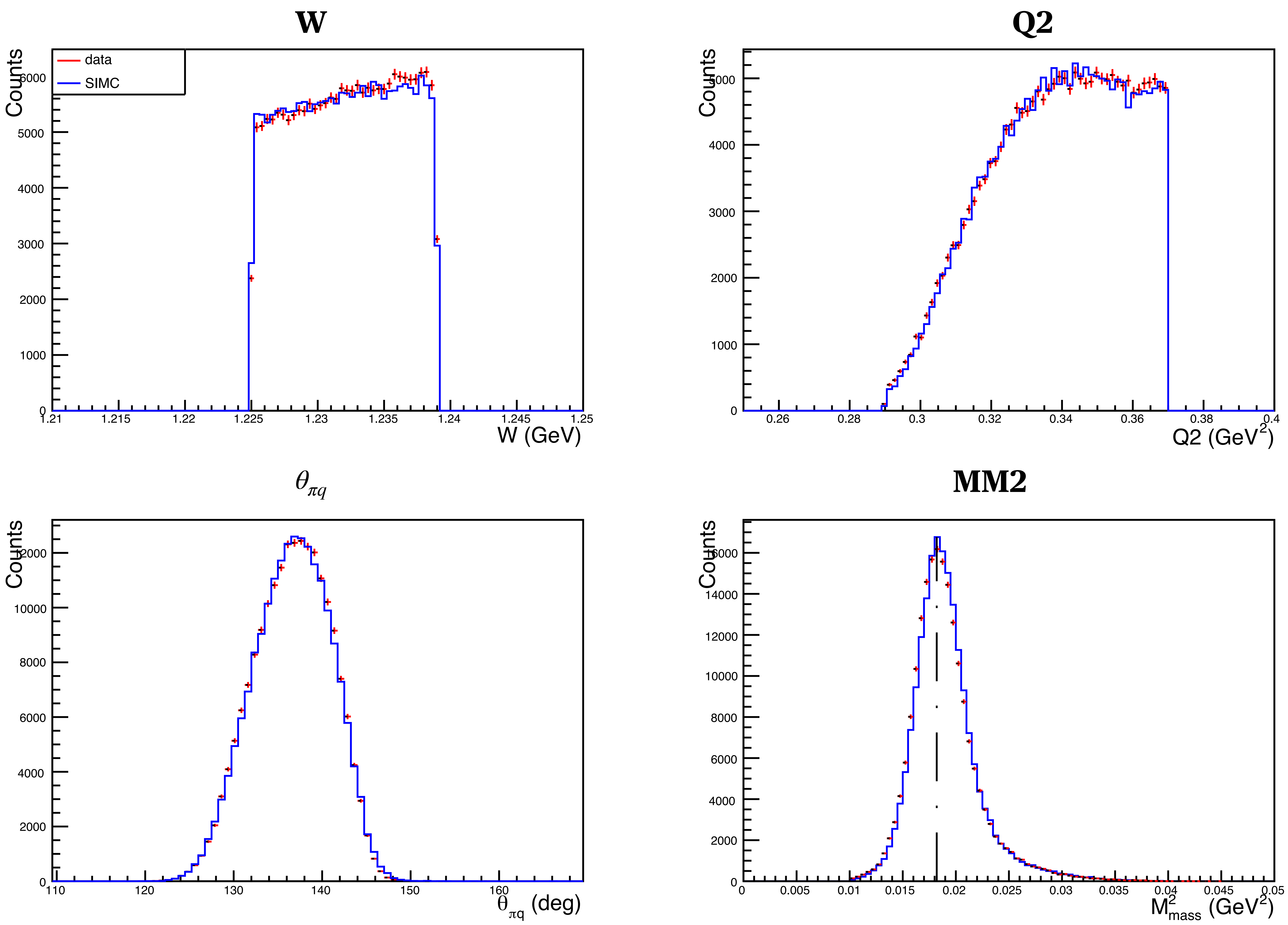


Kin 2b Missing Mass Squared



- *The missing mass technique is used to identify photons*

Pion Preliminary Analysis



Kin2b

data vs. MAID

Cuts:

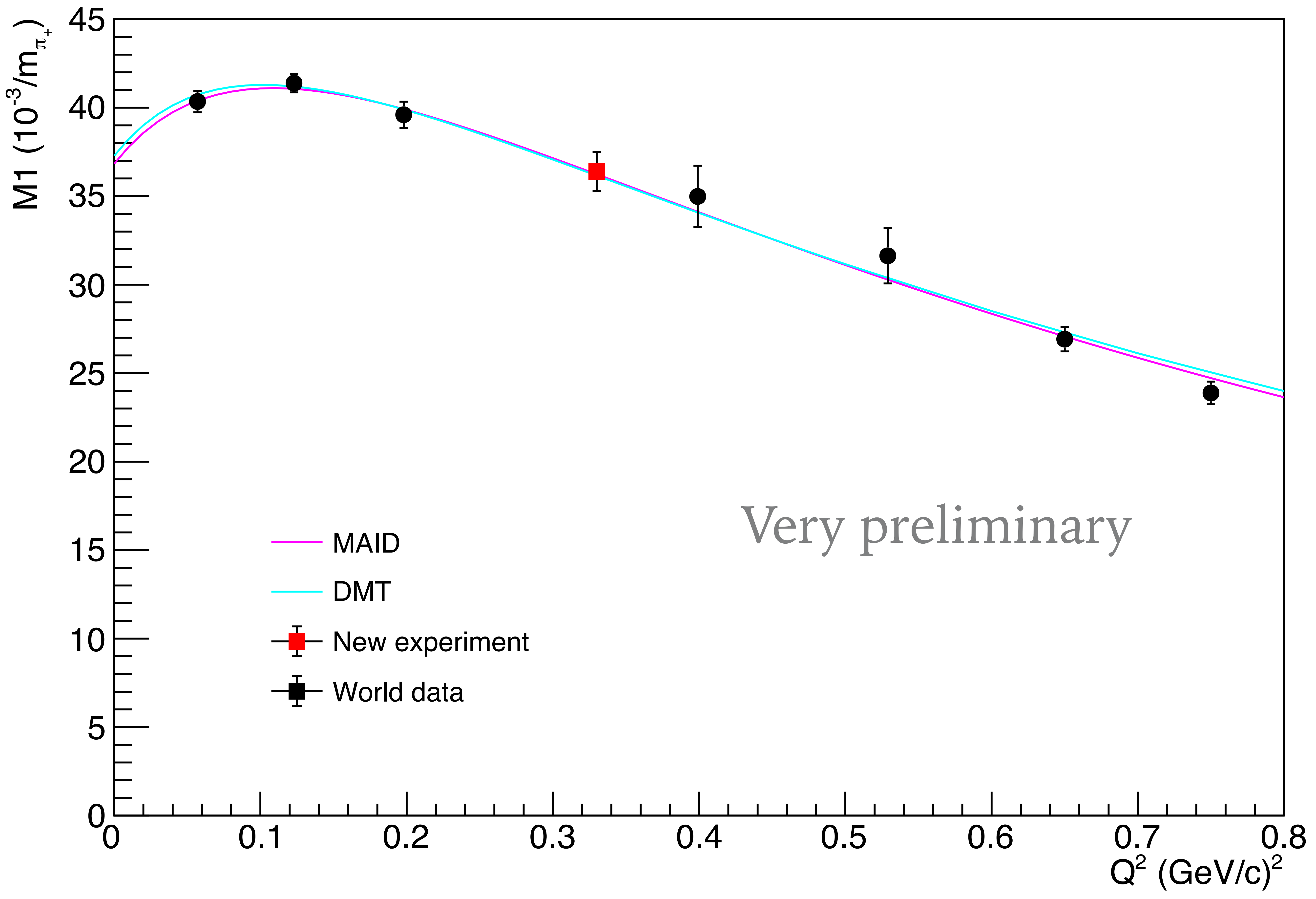
$0.01 < mm2 < 0.05$ (GeV^2)

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

$abs(Q2-0.33) < 0.04$ (GeV^2)

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

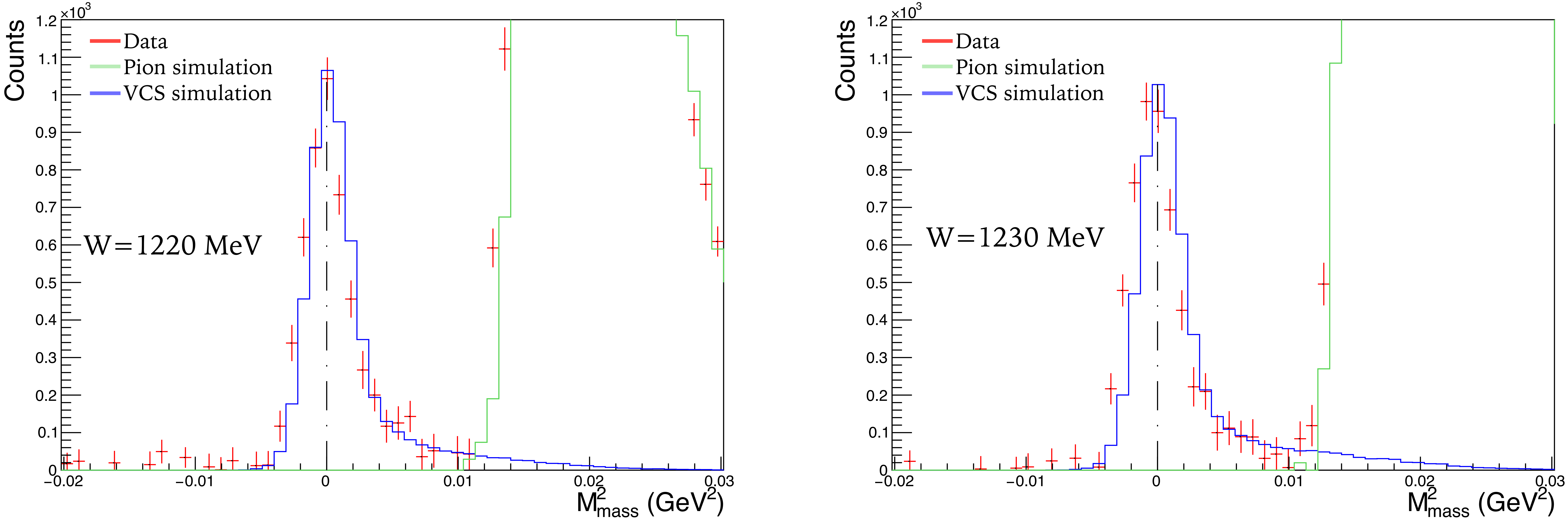
Pion Preliminary Analysis



M1 - Magnetic dipole amplitude

Normalization wise good

VCS Analysis



Cuts:

abs(mm2)<0.01 (GeV^2)

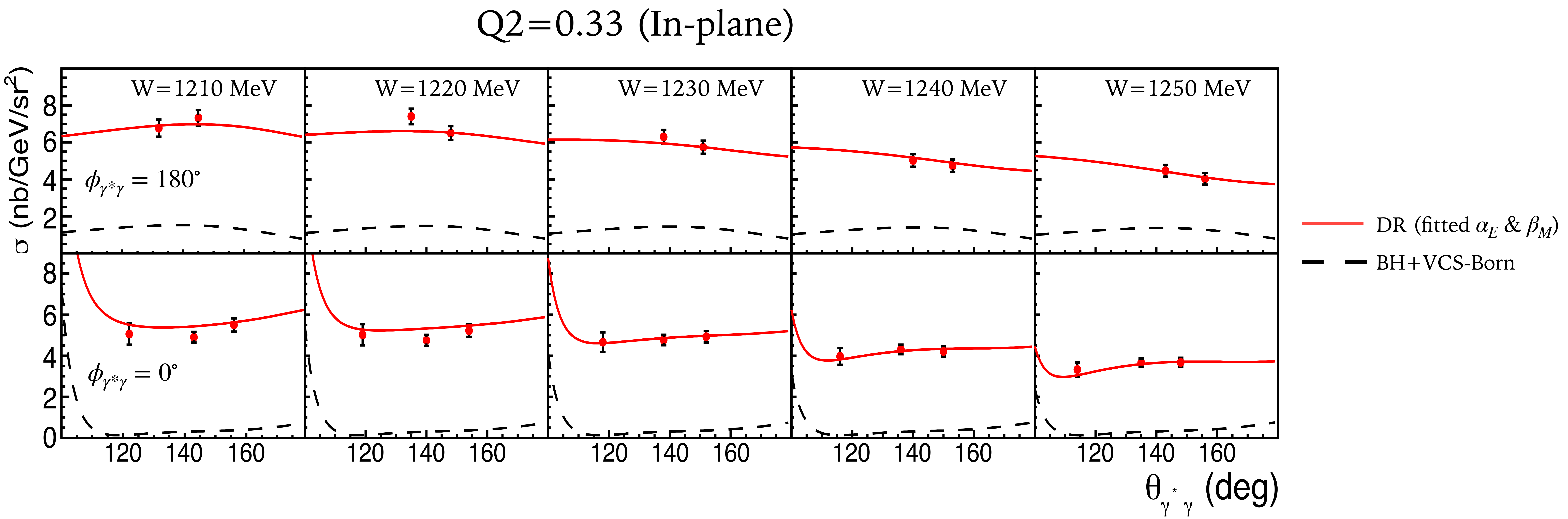
abs($W - W_{center}$)<0.007 (GeV)

abs(Q2-0.33)<0.035 (GeV^2)

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

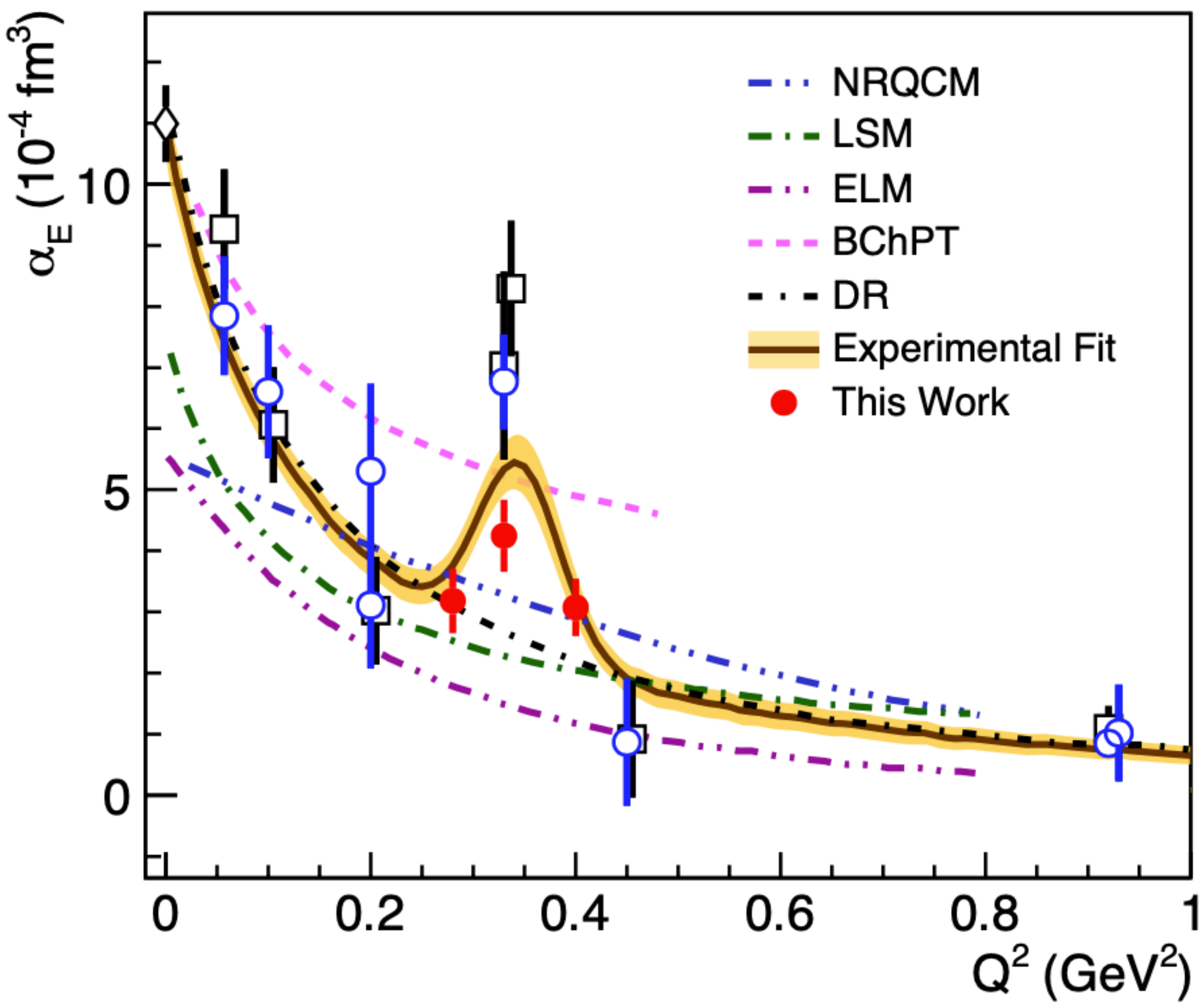
abs($\phi_{pq} - \phi_{center}$)<25 (deg)

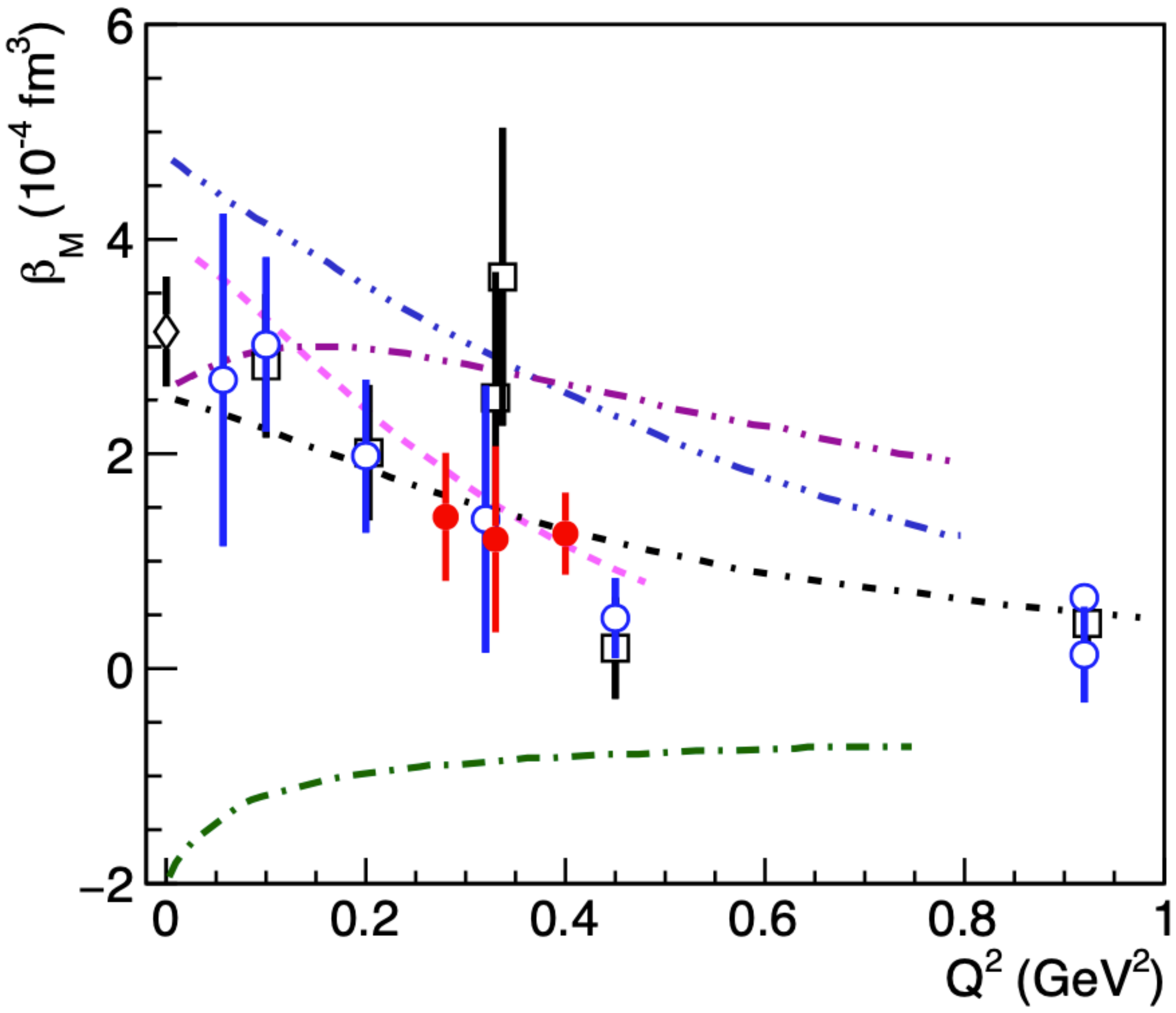
VCS Analysis



- **Example of VCS in-plane cross-sections at $Q^2 = 0.33$ for different W bins**
- **Fitted final α_E & β_M are based on full data set for both in-plane and out-of-plane**

VCS Analysis

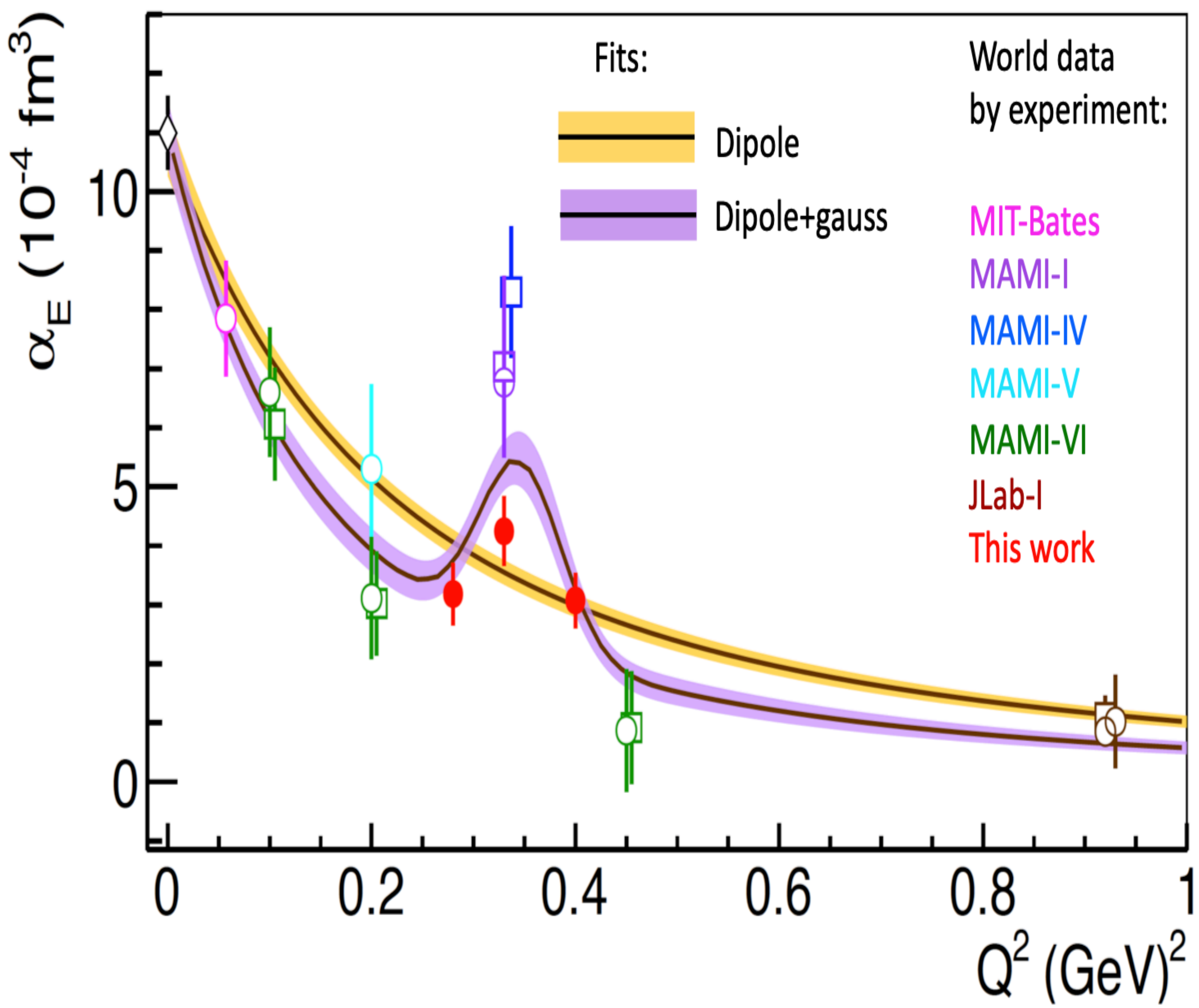




- **Local α_E enhancement in the measured region**
- **A smaller α_E magnitude with improved precision**

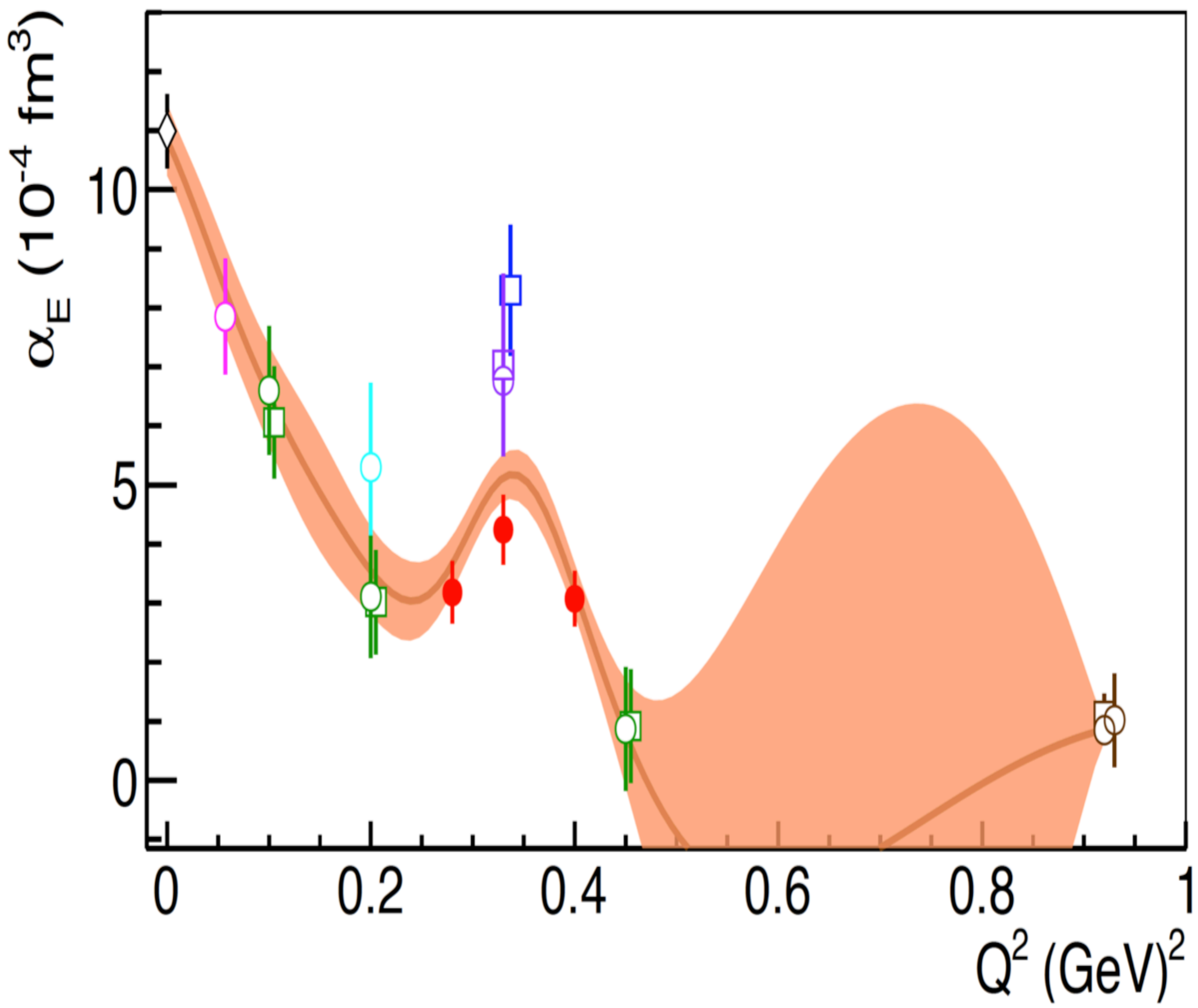
- **β_M has a smooth Q^2-dependence**
- **Near cancellation because of dia- and para-magnetic effects**

VCS Analysis



- Fits to the data using predefined functional form
  - Dipole fit – $\chi^2_\nu = 3.7$
  - Dipole+gauss fit – $\chi^2_\nu = 1.9$

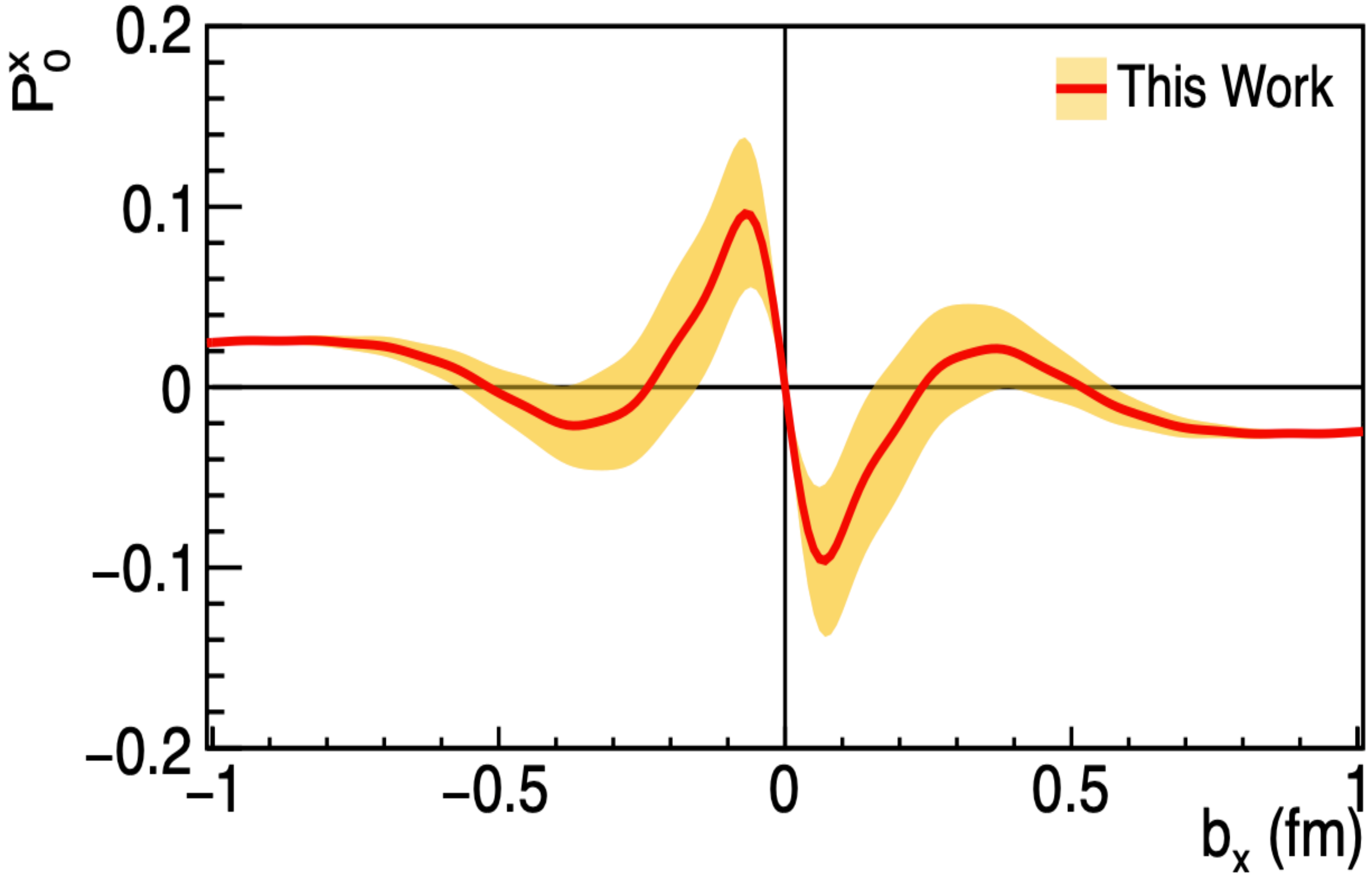
Figure credit: Hamza Atac



- Fits are based on a data-driven technique that assumes no direct underlying functional form
- The error bands correspond to the total uncertainty at 1σ level

Figure credit: Michael Paolone

Induced Polarization in the Proton



Induced polarization P_0^x in the proton versus the transverse position b_x when subject to an EM field with *photon polarization along the x-axis for* $b_y = 0$

$$\vec{P}_0(\vec{b}) = \hat{b} \int_0^\infty \frac{dQ}{(2\pi)} Q\, J_1(b\, Q)\, A(Q^2)$$

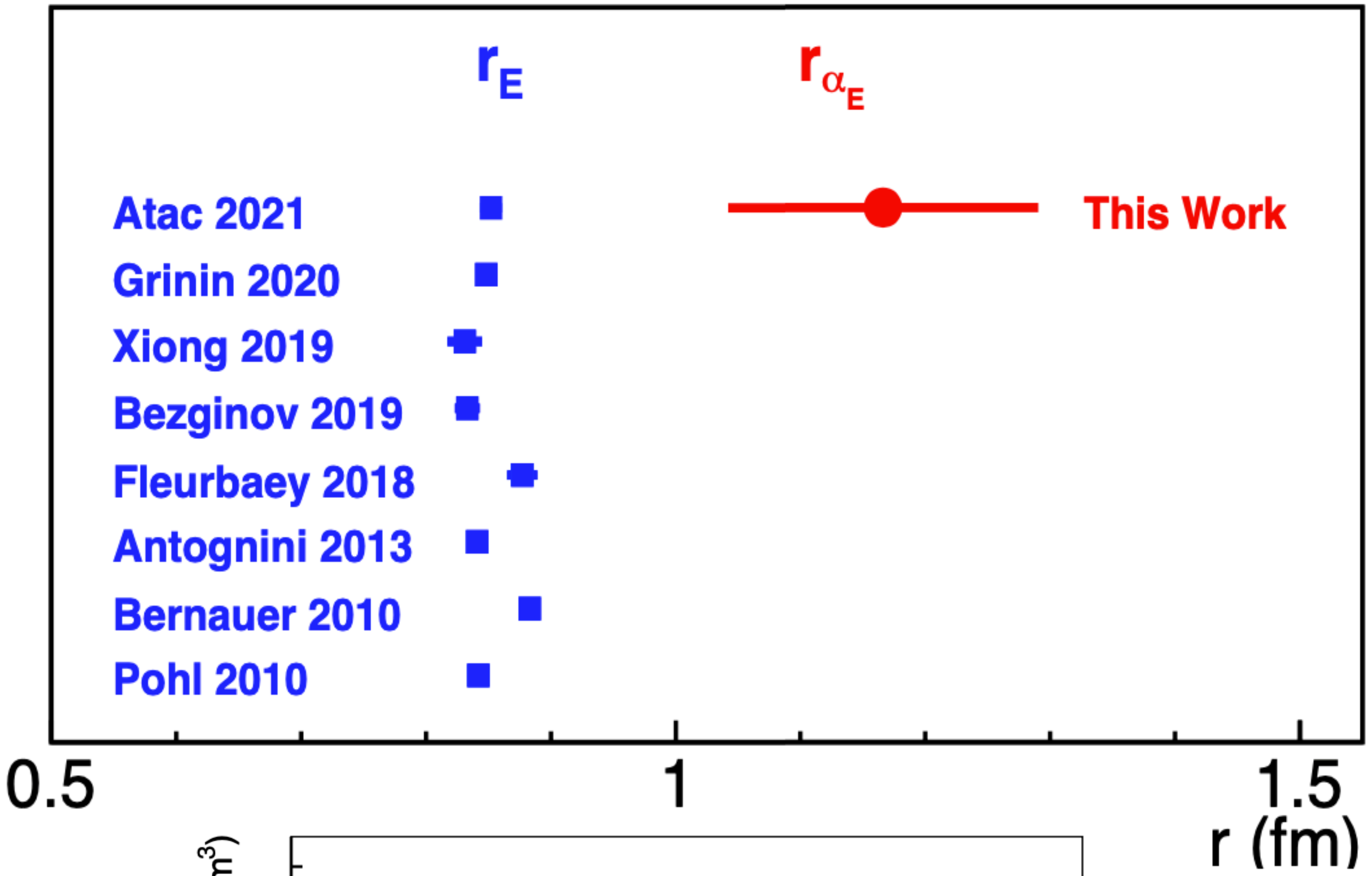
– $\vec{b}$ is the transverse position, $\hat{b} = \vec{b}/|b|$

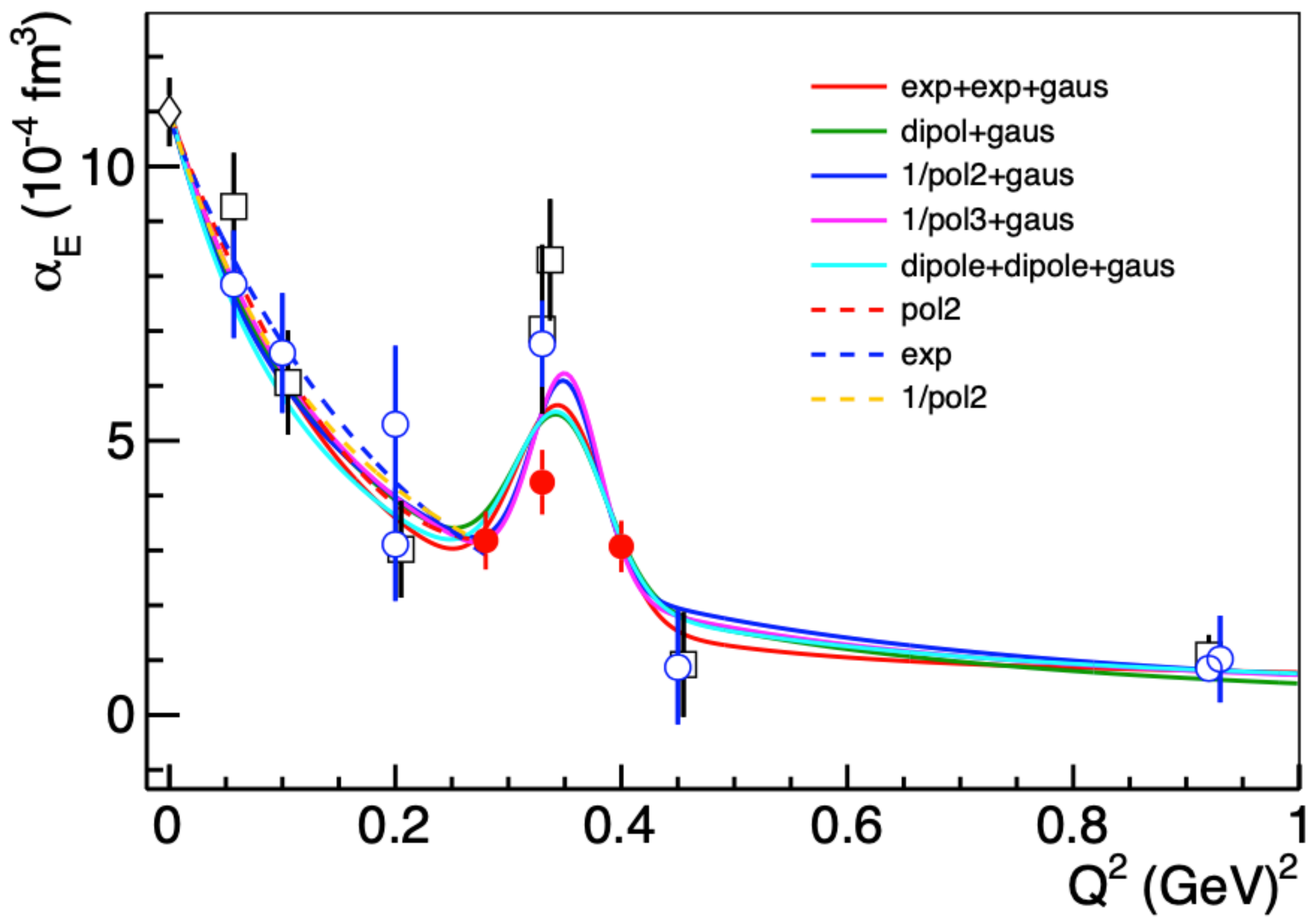
– J_1 is the 1st order Bessel function

– $A(Q^2)$ is a a function of the GPs

- **Spatial distribution of P_0^x has distinct structure:**
  - **First change of sign — ~ 0.25 fm**
  - **A secondary maximum — ~0.35 fm**

Proton Mean Square Electric Polarizability radius





The proton mean square electric polarizability radius:

$$\langle r^2_{\alpha_E} \rangle = \frac{-6}{\alpha_E(0)} \cdot \frac{d}{dQ^2} \alpha_E(Q^2) \Big|_{Q^2=0}$$

- **The slope of α_E at $Q^2 = 0$ determined from fits of world data**
  - Multiple functional forms were used to provide a reliable fit
  - $\alpha_E(0)$ from the most recent measurement – *Phys.Rev.Lett.* 128 (2022) 13, 132503
- $\langle r^2_{\alpha_E} \rangle = 1.36 \pm 0.29\ fm^2$
- **Larger than the proton mean square charge radius**

Figure credit: Hamza Atac

Summary

- **GPs are fundamental structure constants**
- **Data at** $Q^2 = 0.33\ GeV^2$ **implies a non-trivial structure**
- **New JLab E12-15-001 experiment measured** α_E **and** β_M **with improved precision at** $Q^2 = 0.28\ \&\ 0.33\ \&\ 0.40\ GeV^2$
- **A local enhancement of** α_E **is observed which is currently not accounted for in the theory**
- **More data points at** $Q^2 > 0.4\ GeV^2$ **will be proposed and measured**

The VCS paper is submitted to Nature and currently under review

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
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On behalf of JLAB E12-15-001 Collaboration

HALL A/C COLLABORATION MEETING 06/16/2022

Backup Slides

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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:

$0.85 < W < 1.05$

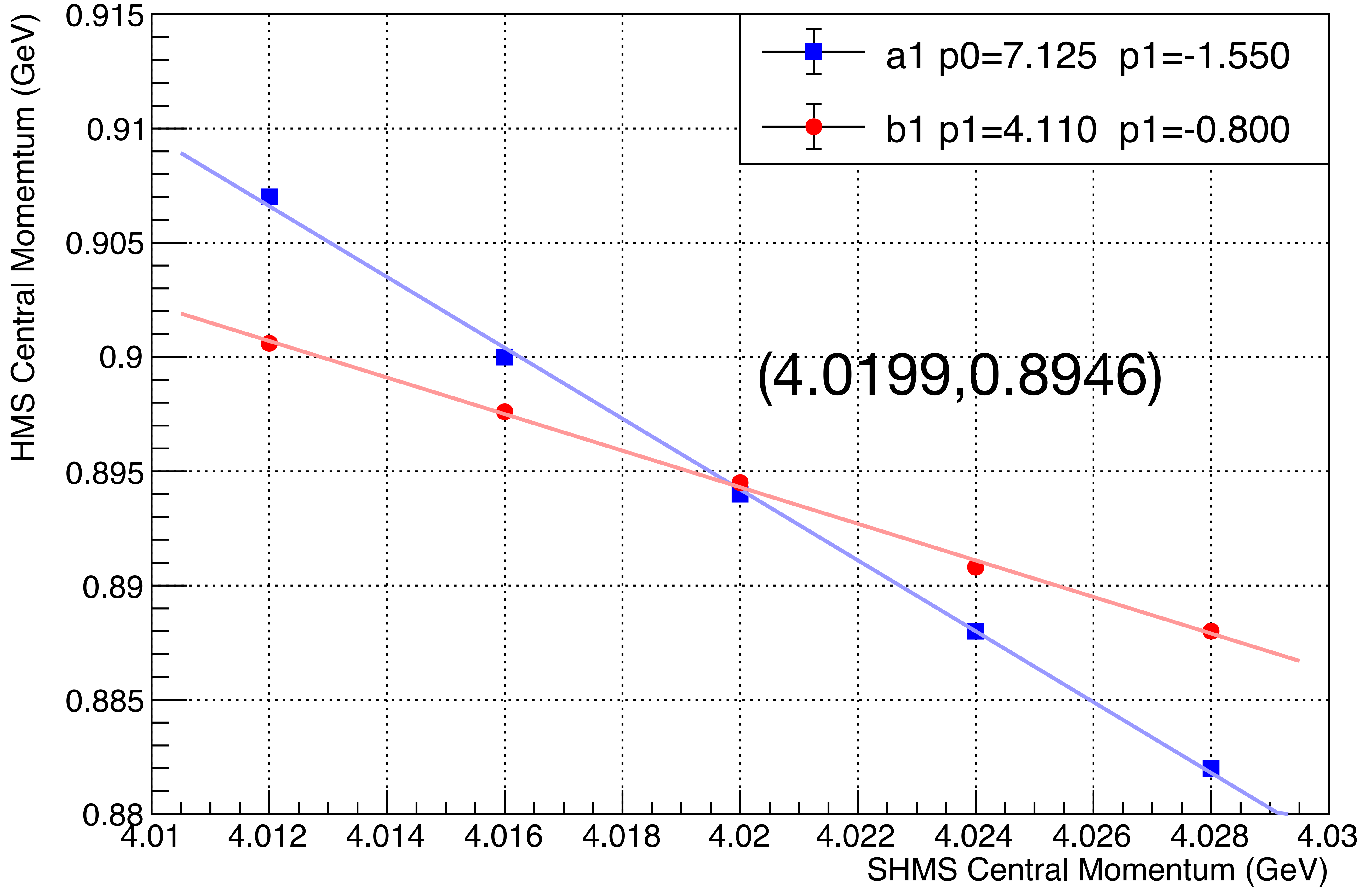
Energy Calibration

Spectrometer: Same momentum,Different HMS theta

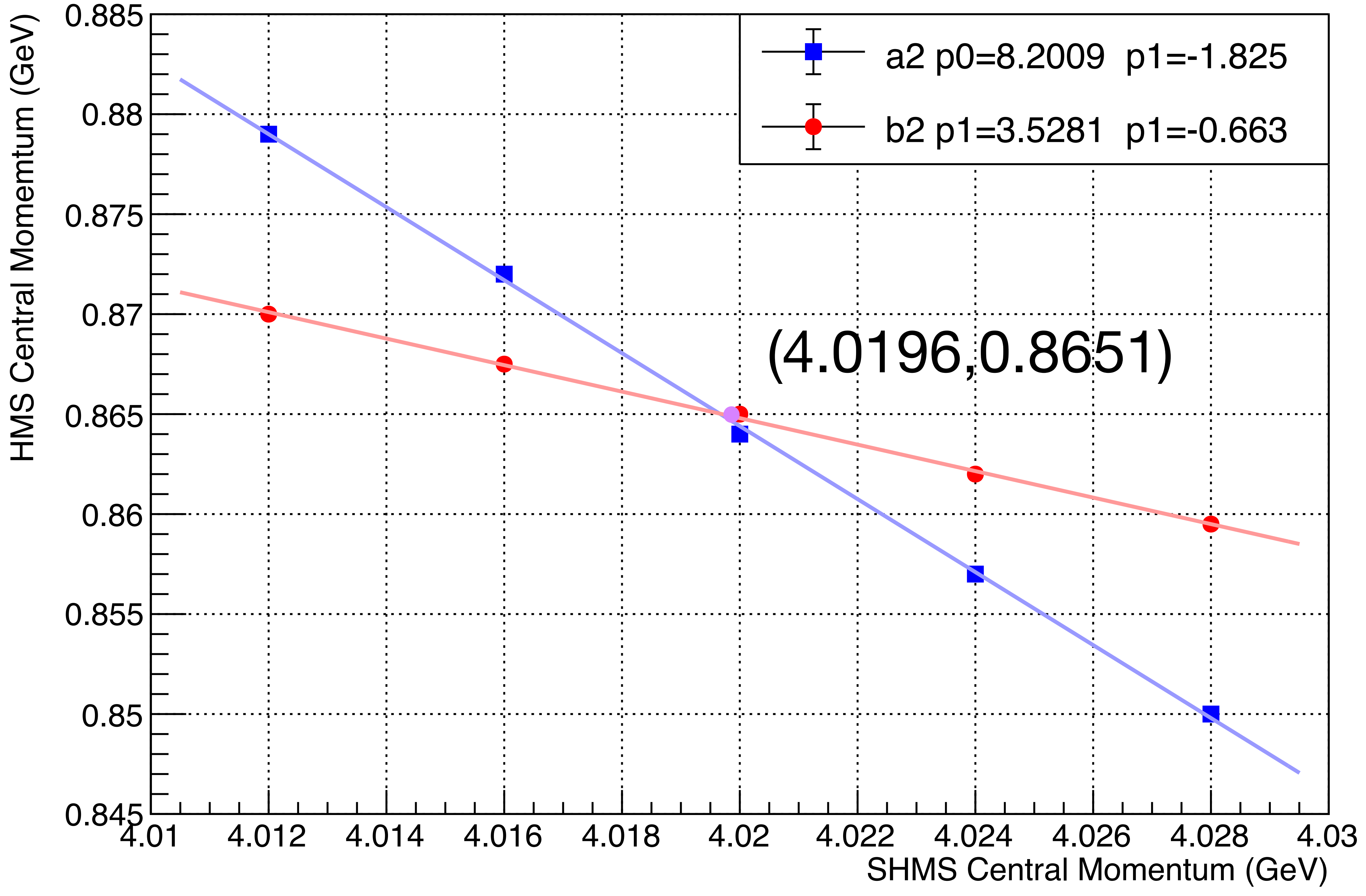
	SHMS_p	SHMS_th	HMS_p	HMS_th
Kin1a	4.034	7.69	0.893	37.33
Kin1b	4.034	7.69	0.893	51.40

	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

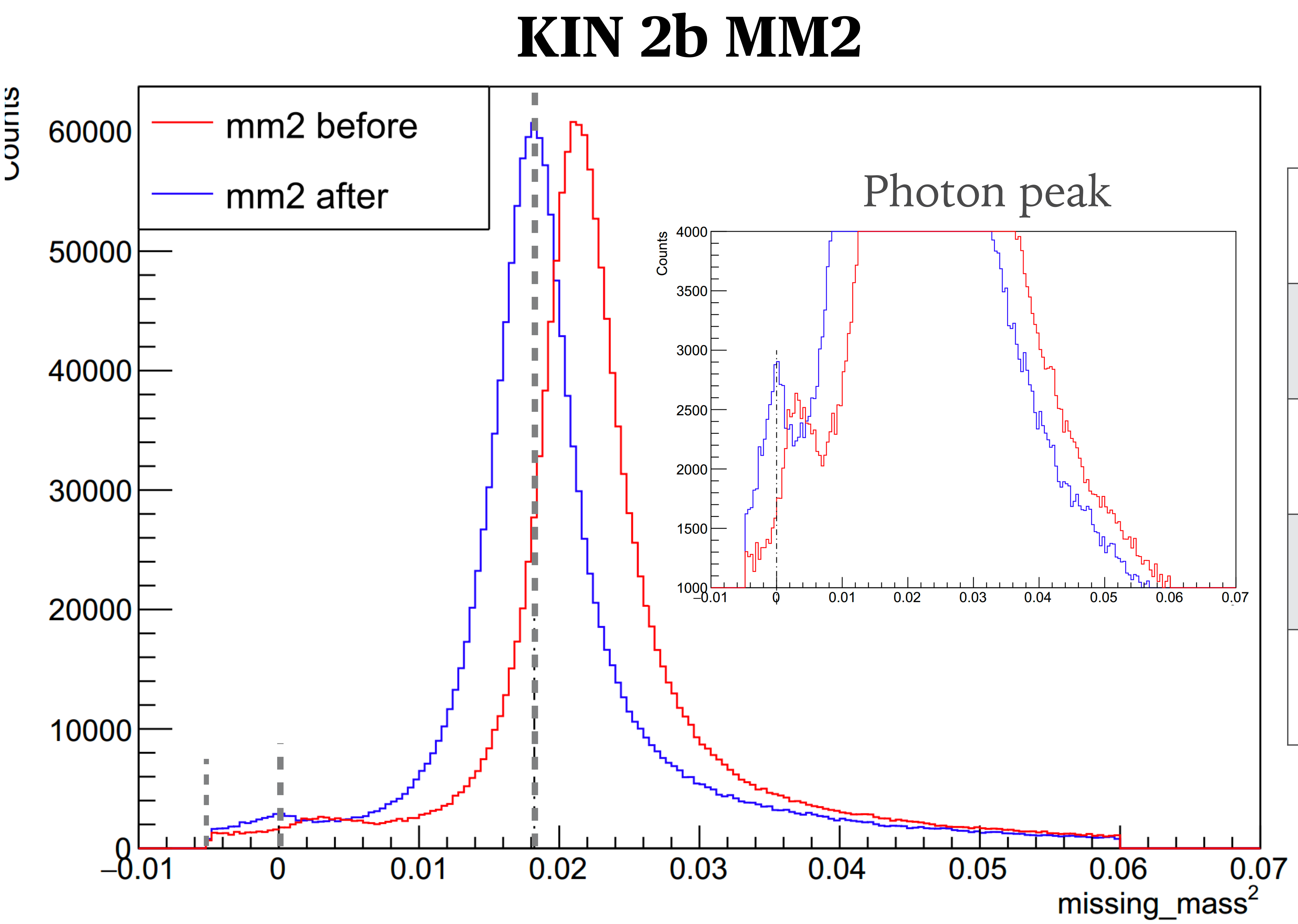
Kin 1a & Kin 1b



Kin 2a & Kin 2b

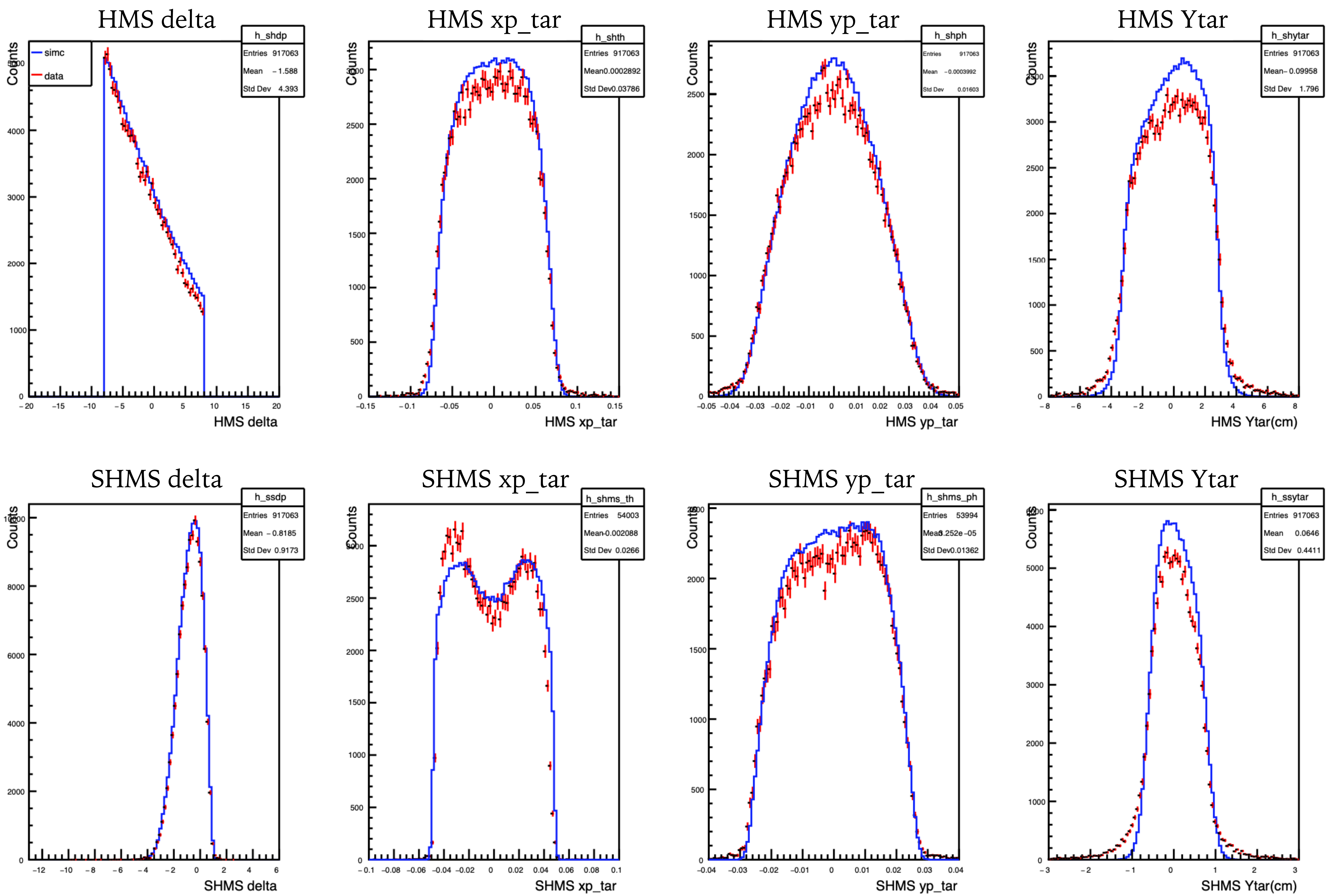


Energy Calibration



	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



HCANA UPDATE

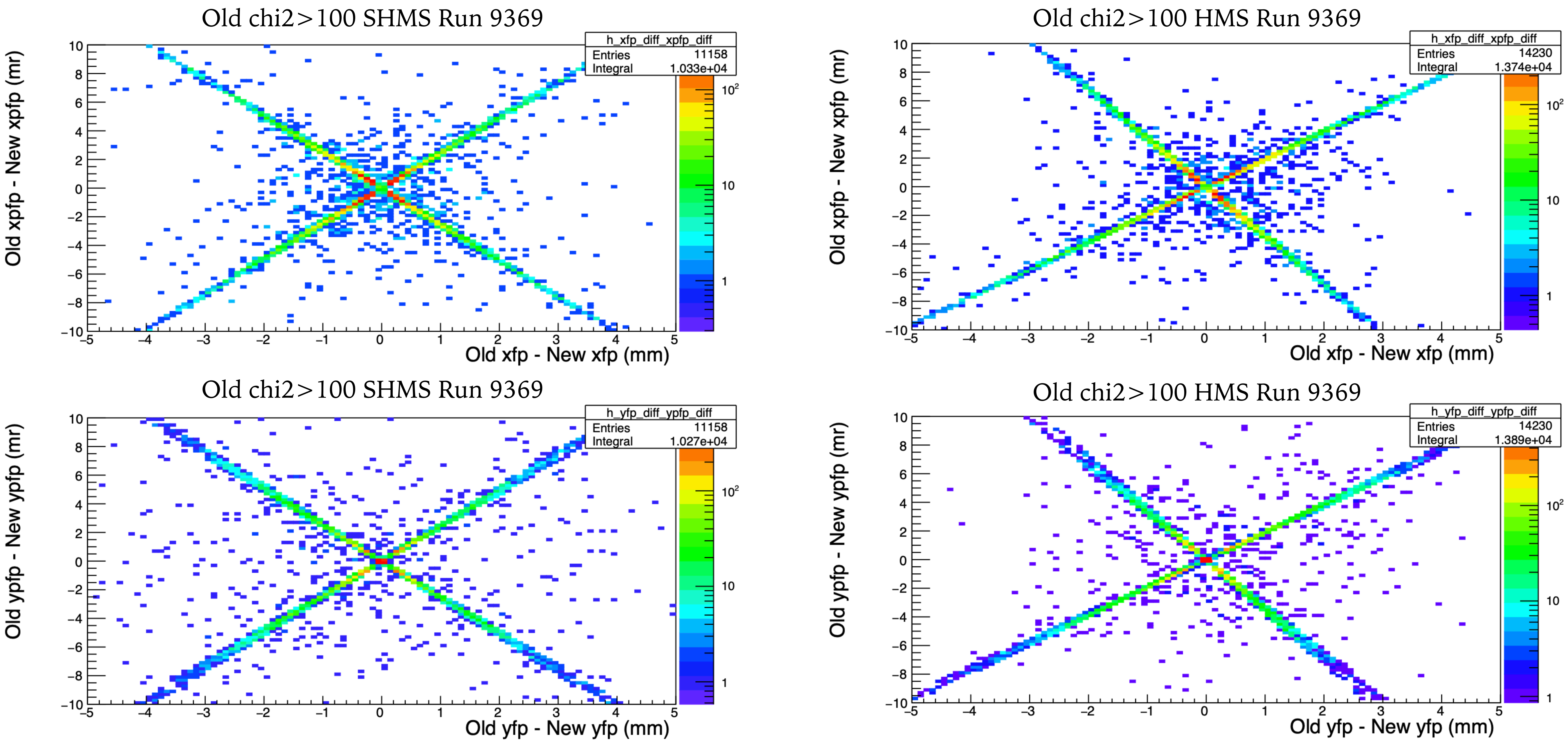


Figure Credit: Mark Jones