The Beam-Helicity Asymmetry for $\gamma p \to p K^+ K^-$ and $\gamma p \to p \pi^+ \pi^-$

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Jefferson Lab EXPLORING THE NATURE OF MATTER

CEBAF Large Acceptance Spectrometer

g12 HyCLAS SUPER-G

Purpose and Status

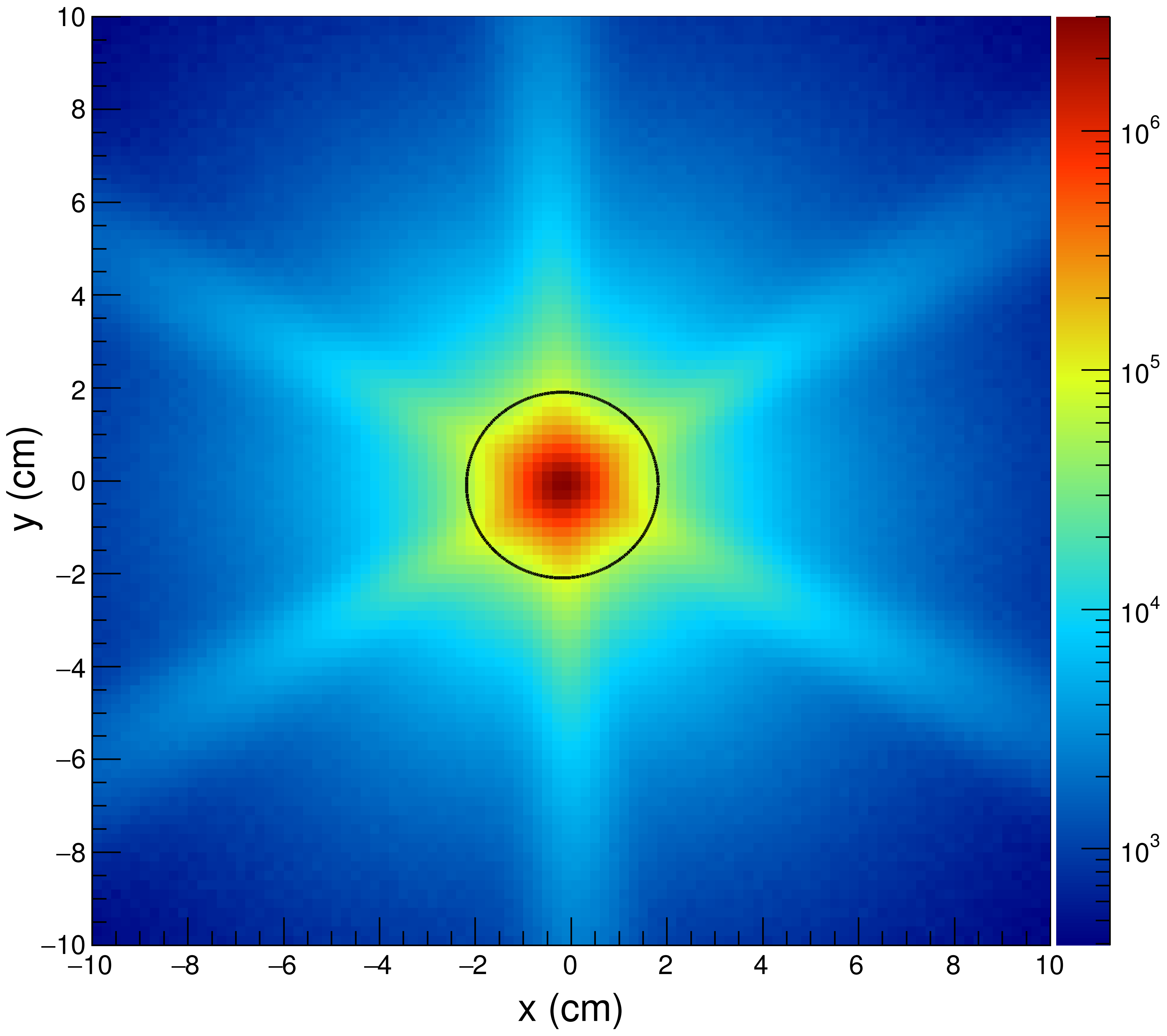
- Purpose is to demonstrate details of analysis and receive feedback
- Emphasis on procedures
- Currently writing draft of paper and analysis note

g12 Experiment

- Analysis of $\gamma p \to pK^+K^-$ and $\gamma p \to p\pi^+\pi^-$ using data collected from the g12 experiment
- All final state particles were required to be detected
- Photoproduction experiment on proton target with luminosity 68pb^{-1}
- Photon beam was circularly polarized (max polarization $\approx 80\%$) with an energy range $1.1 - 5.5$ GeV
- Proton target was not polarized

Event Selection

- No detached vertices for either reaction
- Reconstructed vertex required to lie inside target cylinder
  - $r < 2.0$ cm
  - $-110 < z < -70$ cm



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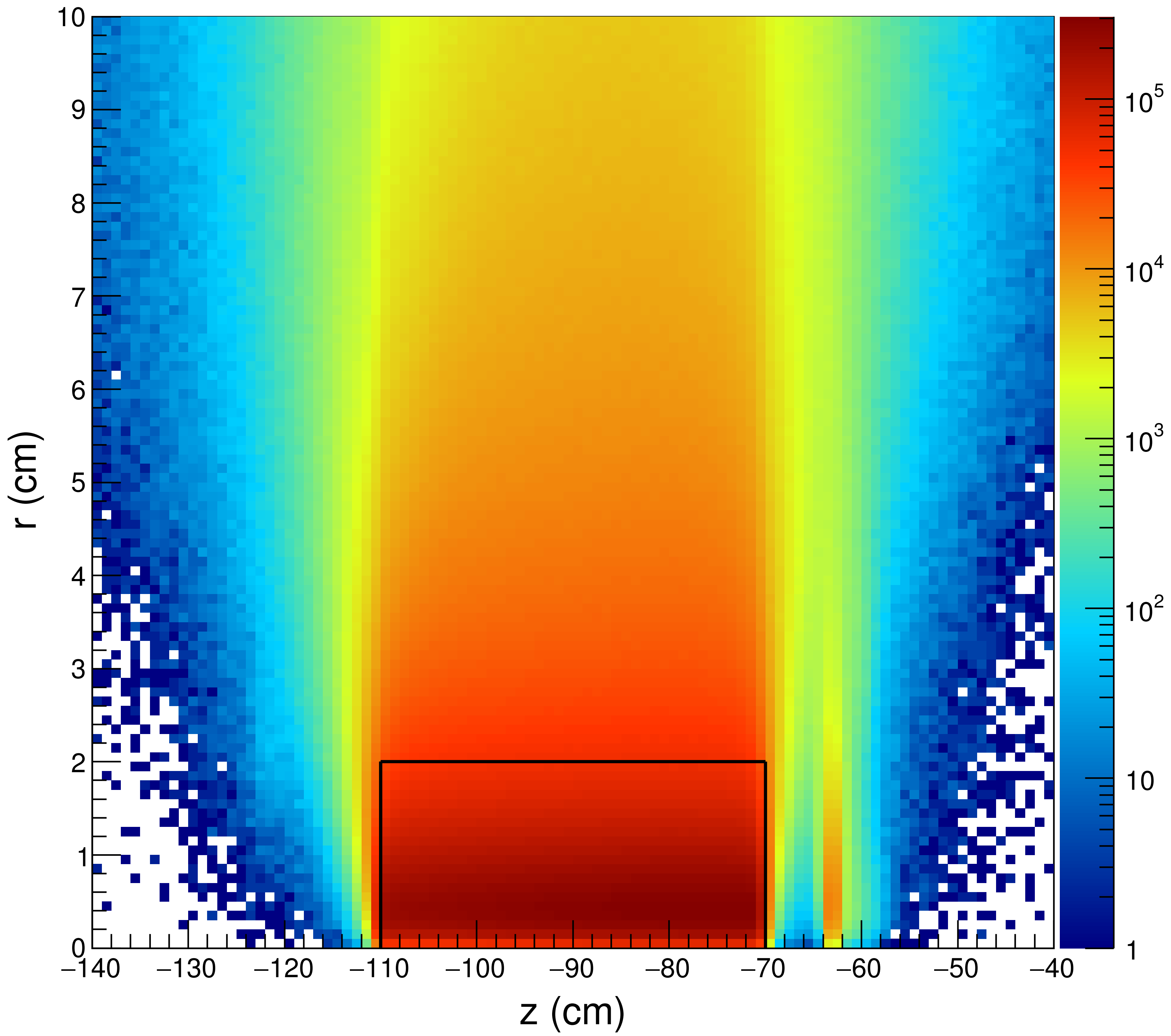

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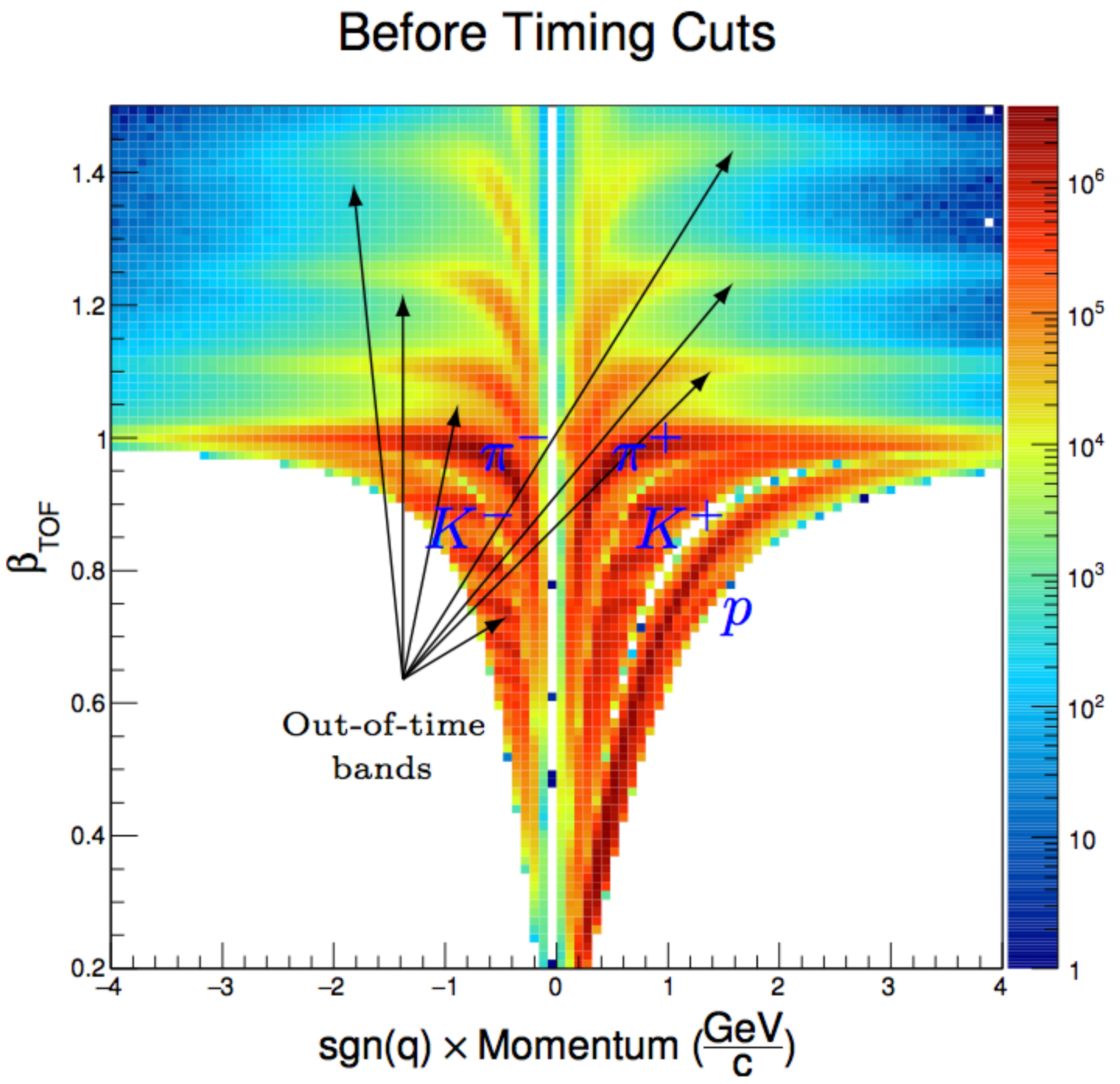
- Vertex time as determined by RF and TOF were required to be 1 ns from each other



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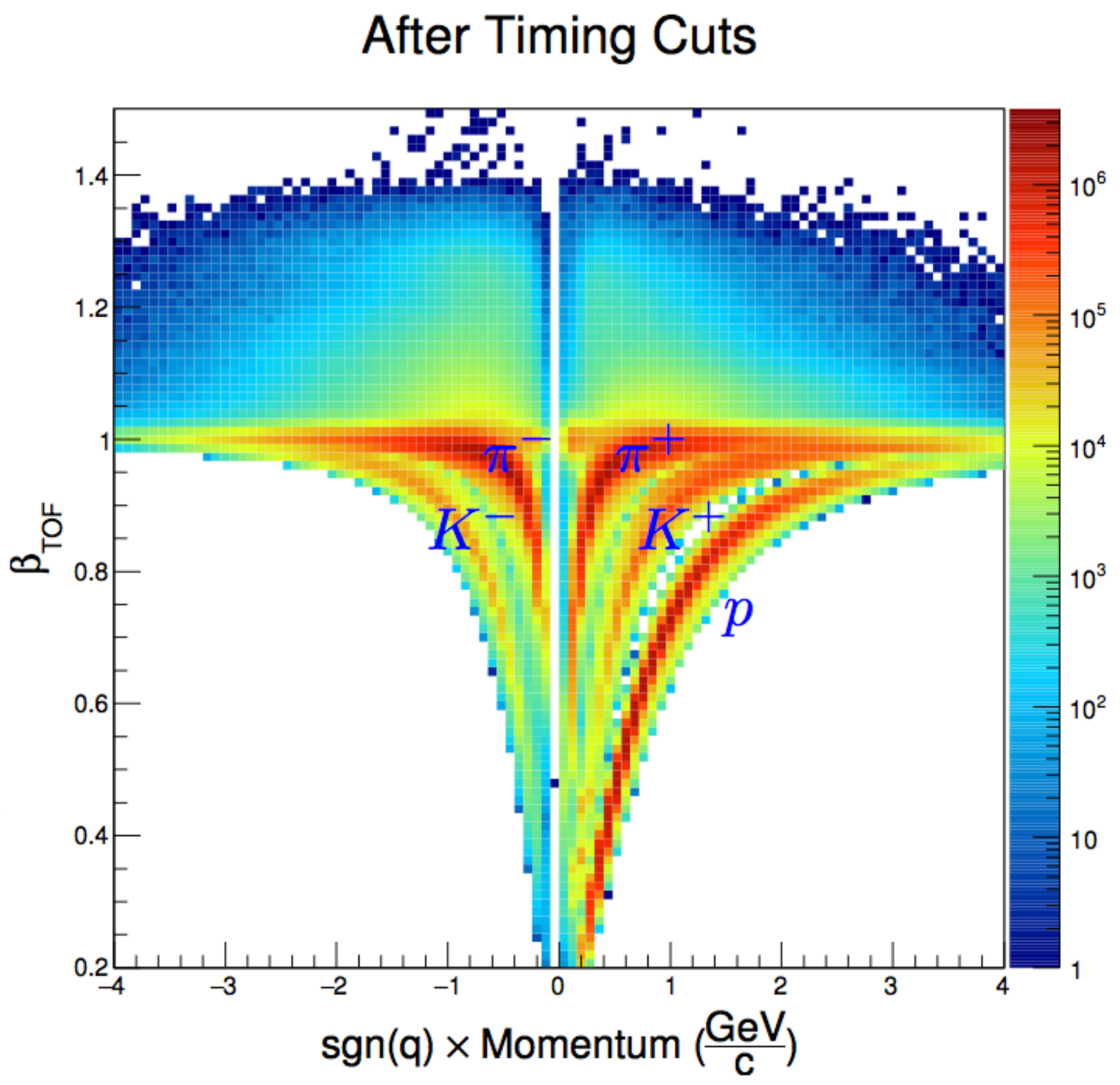
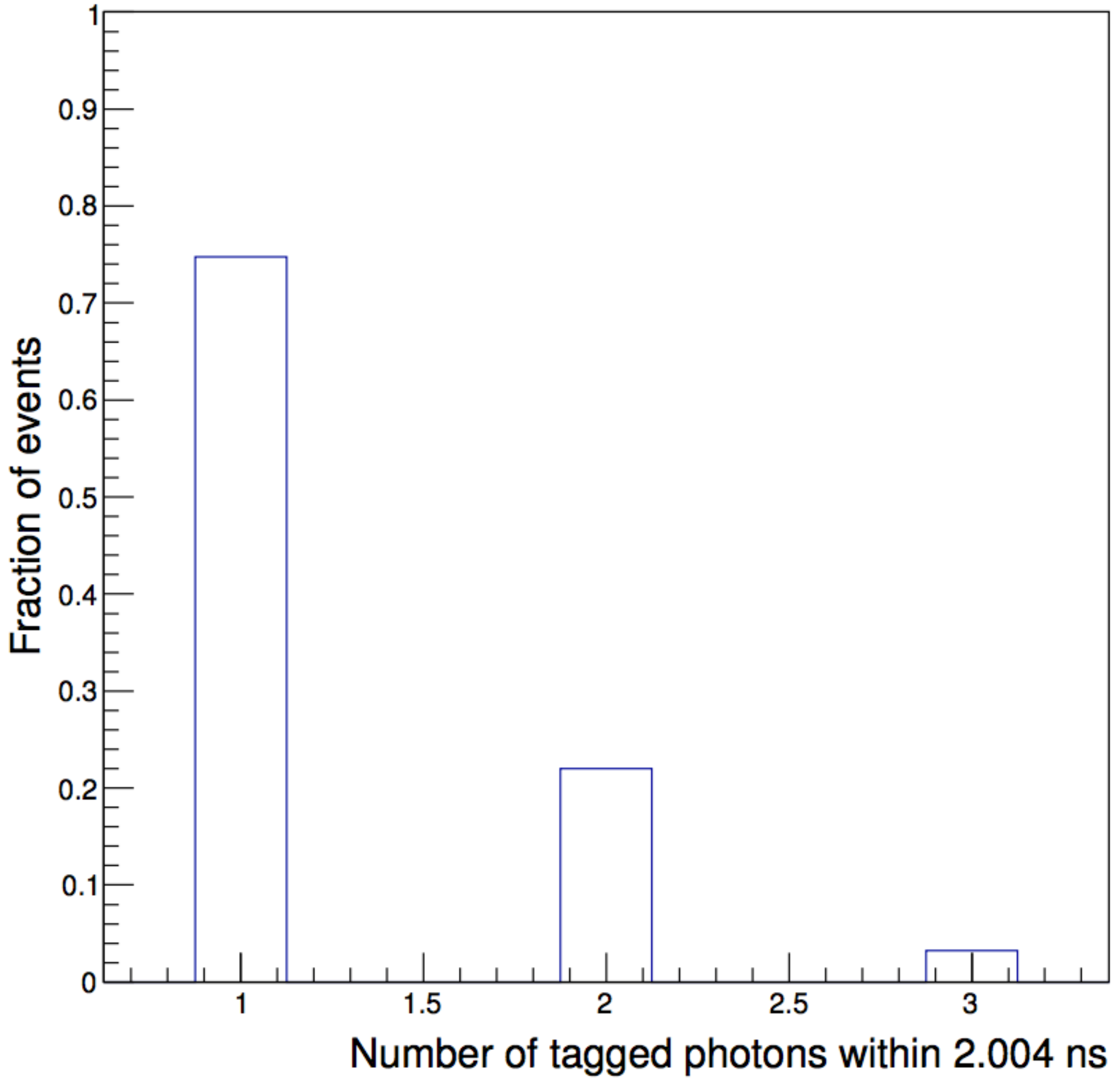


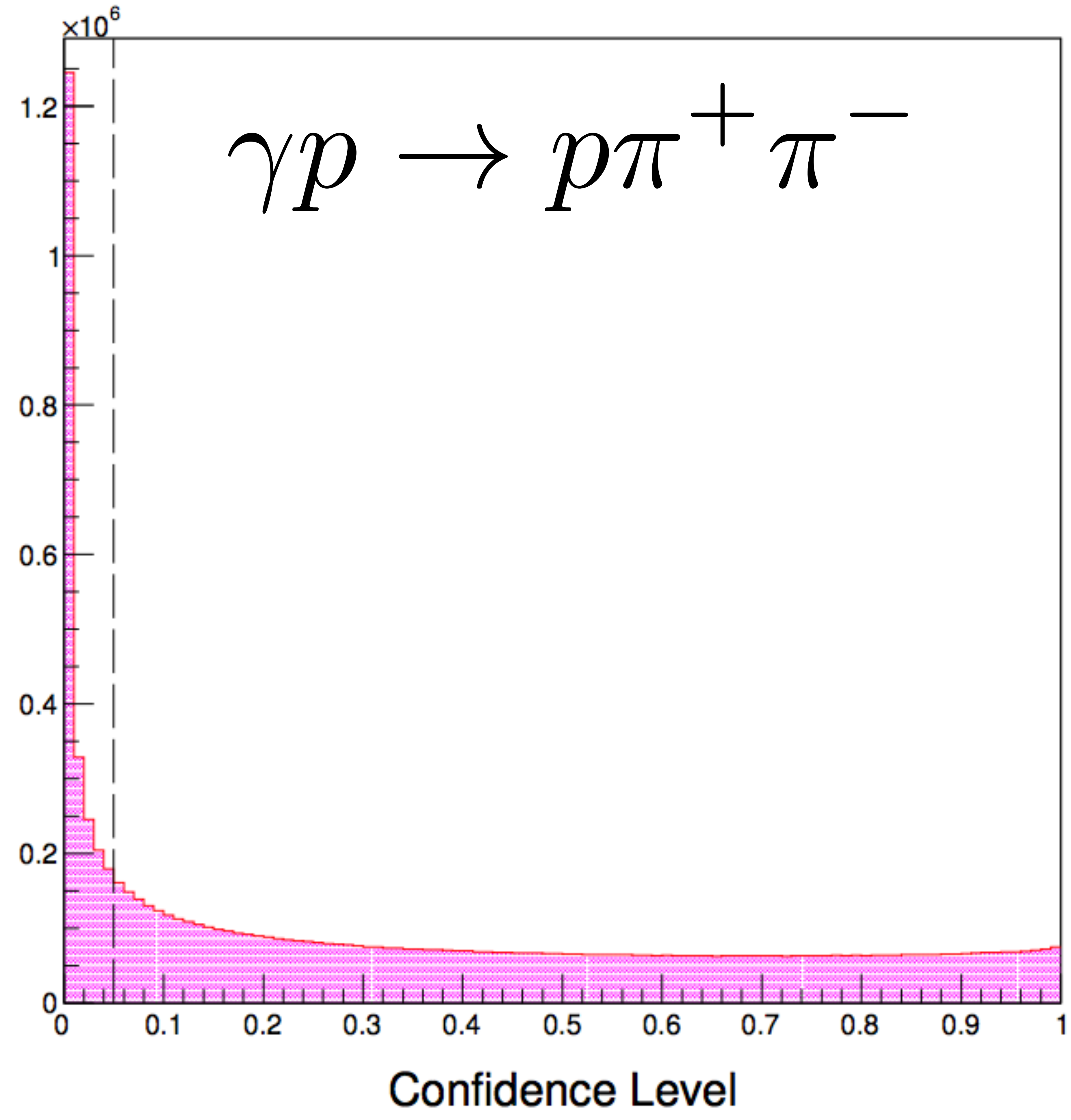
Event Selection

- Multiple photons were sometimes tagged
- Several algorithms were considered
    - Select random photon
    - Select more energetic photon
    - Select photon with larger probability from kinematic fitting
    - Remove events with multiple tagged photons
- Analysis simply removed events with multiple tagged photons



g12 Corrections Applied

- Beam Energy Corrections
- Energy Loss
- Momentum Corrections
- Kinematic Fitting



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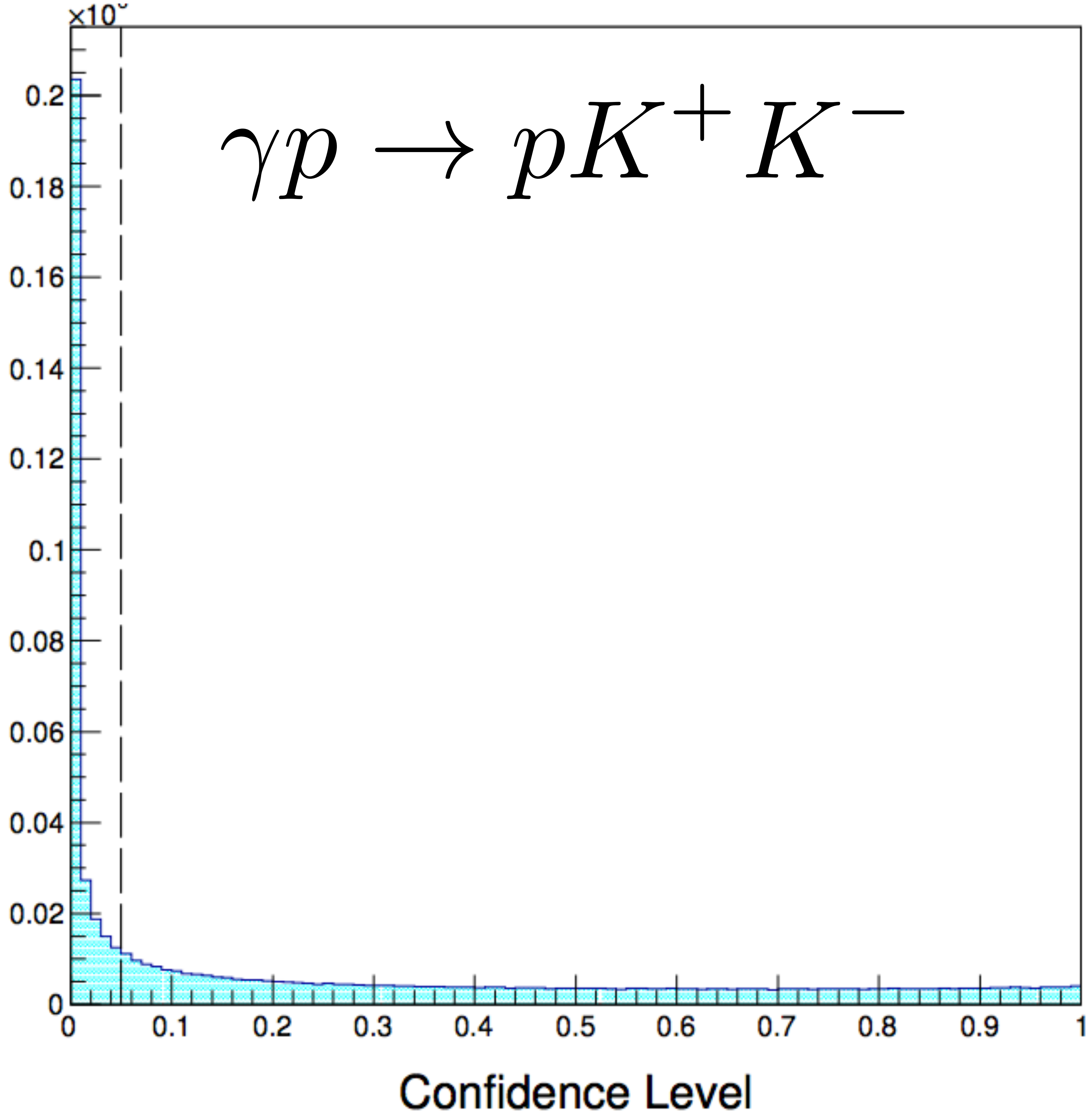
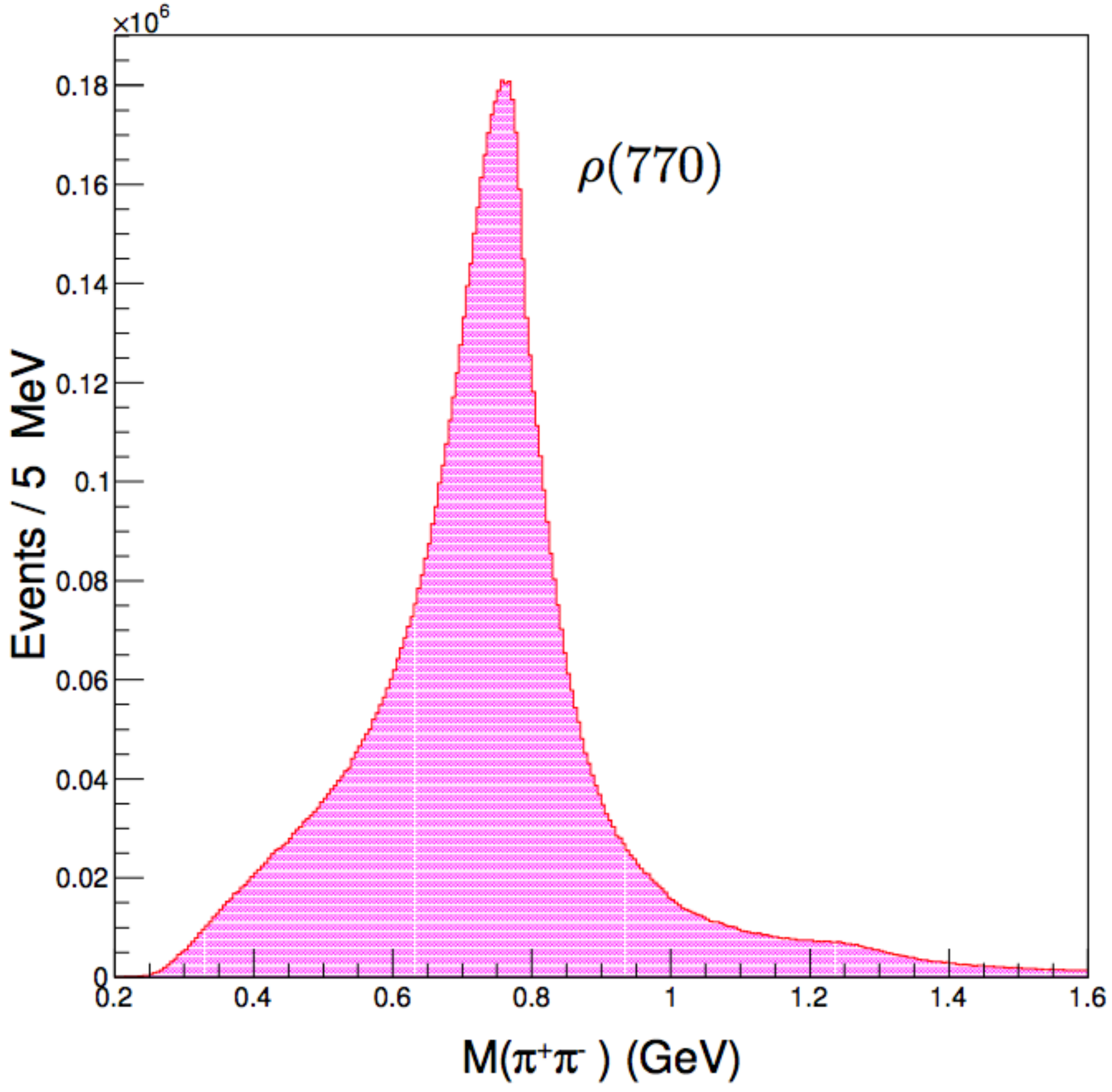
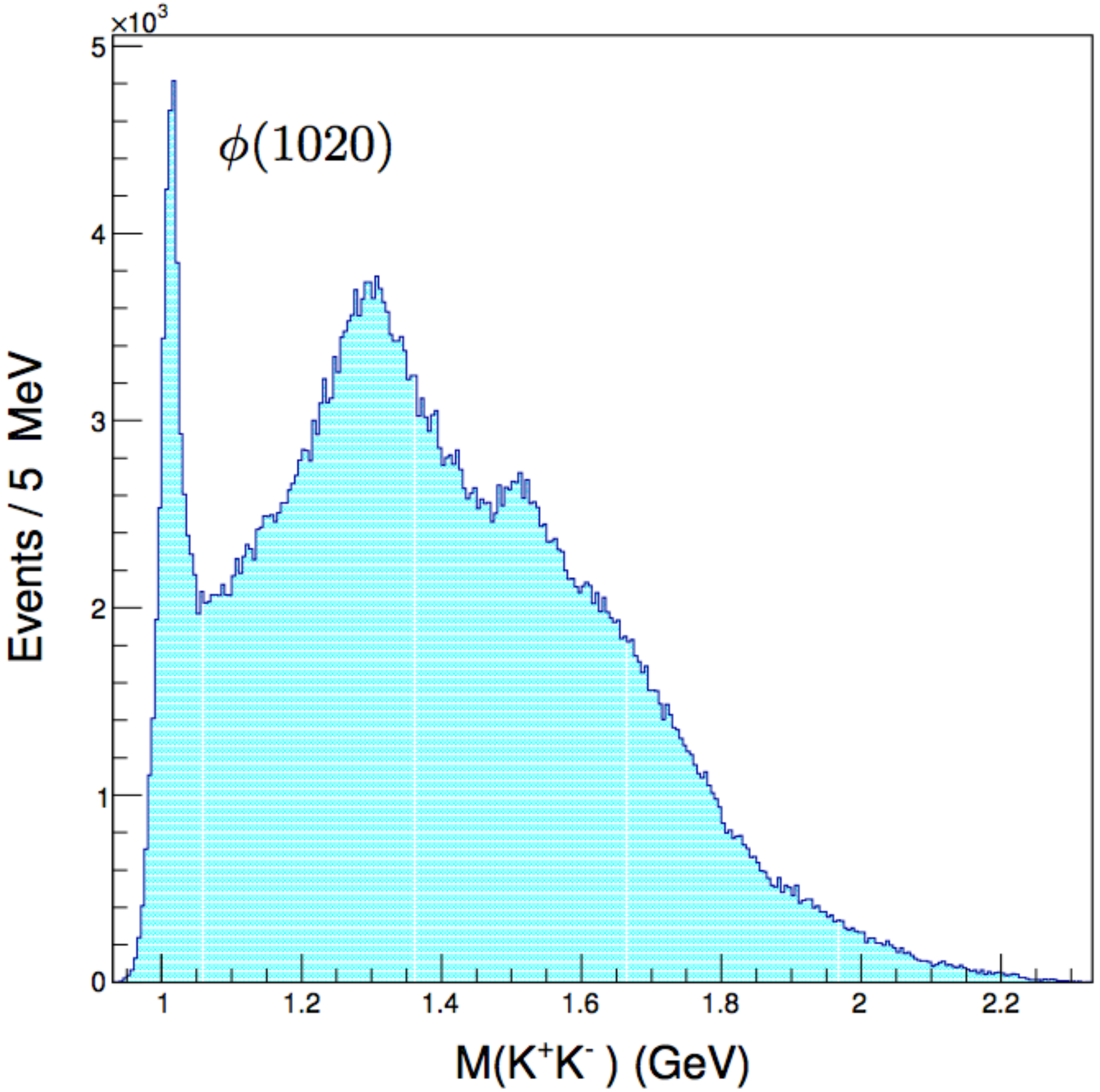


Invariant Mass Plots





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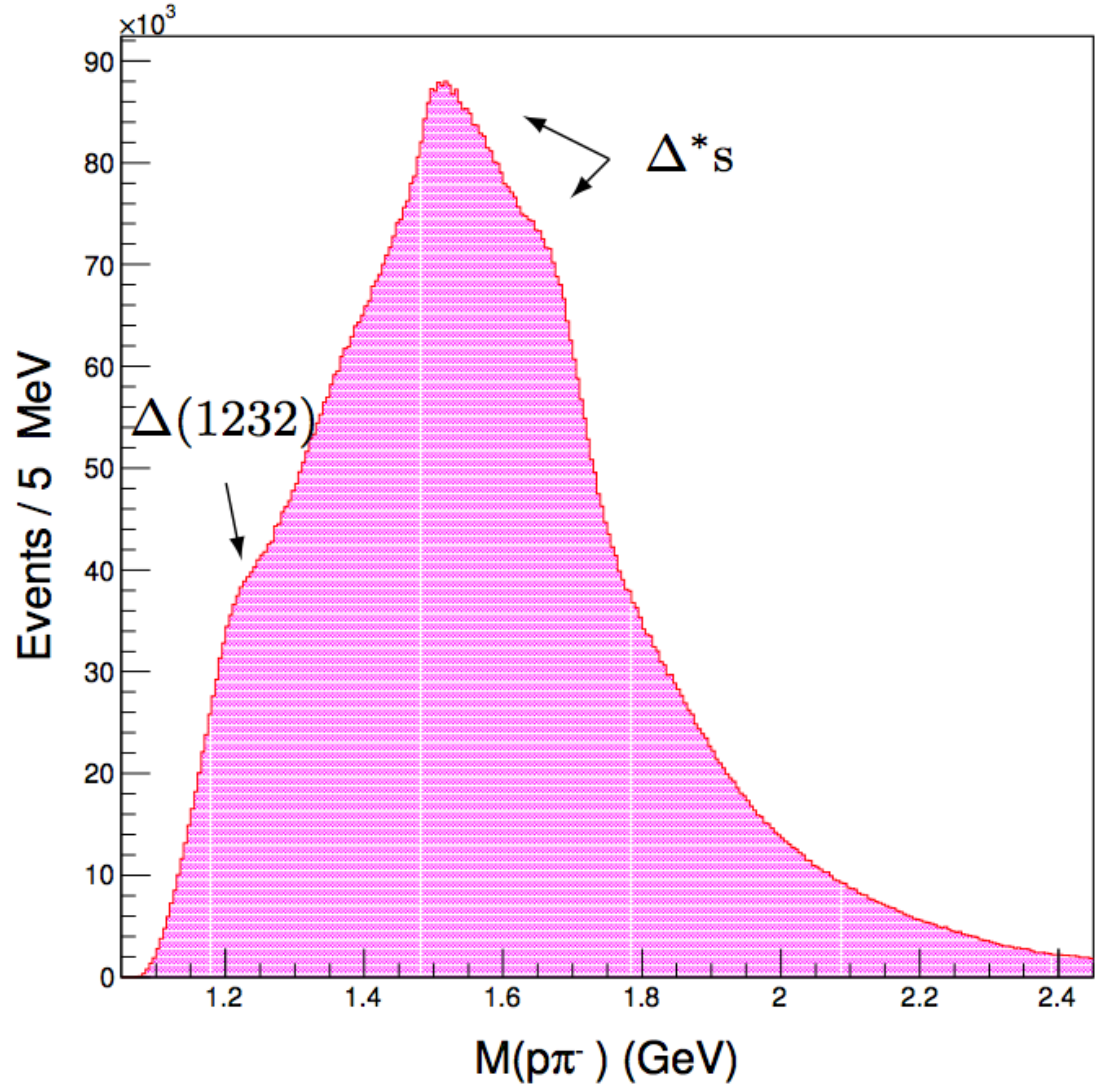

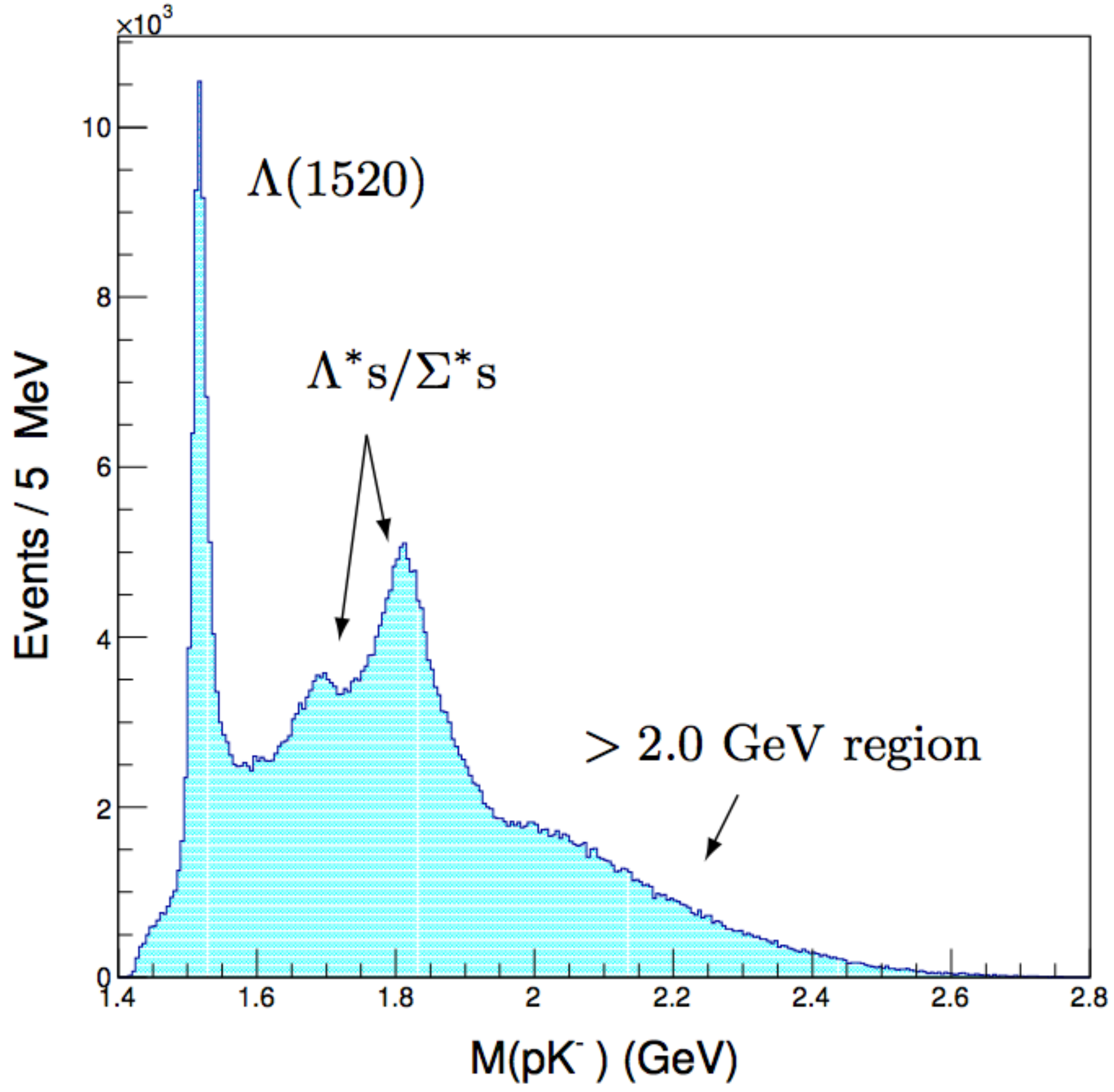

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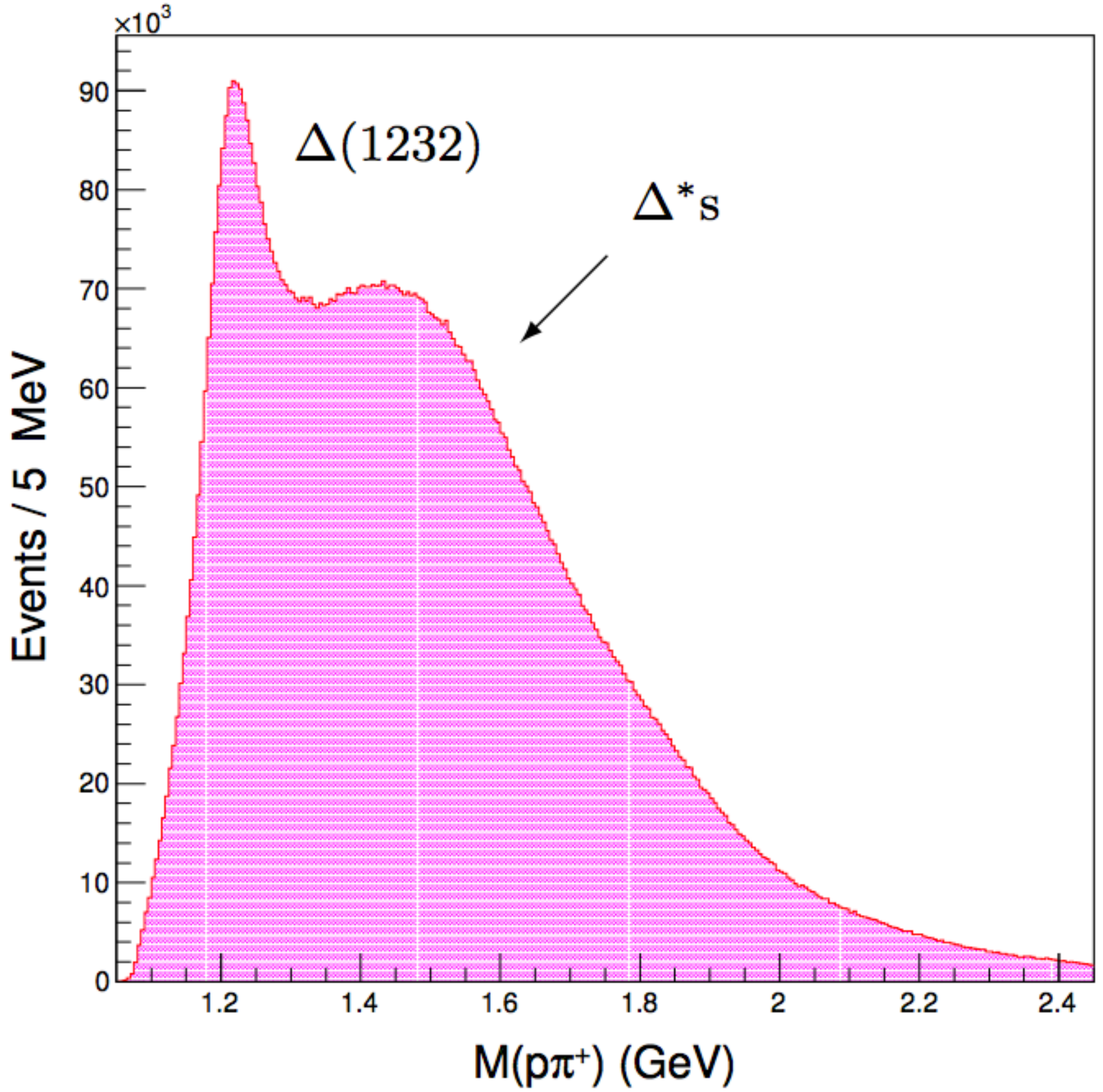
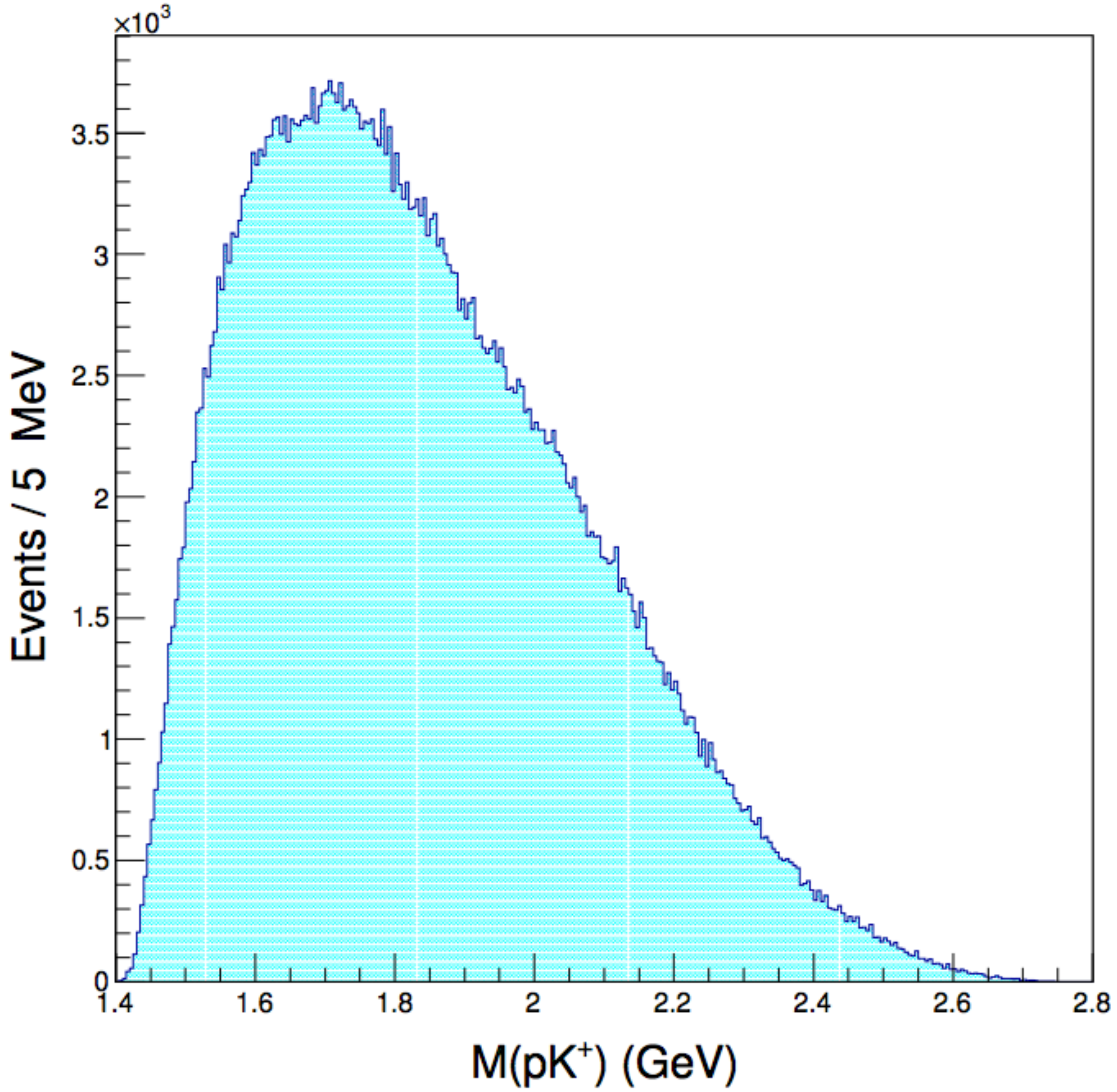




Beam-Helicity Asymmetry

- In a given kinematic bin, τ, the beam-helicity asymmetry is defined as

$$I^{\odot}(\tau) = \frac{1}{P_\gamma(\tau)} \frac{\sigma^+(\tau) - \sigma^-(\tau)}{\sigma^+(\tau) + \sigma^-(\tau)}$$

- It is measured experimentally as

$$I^{\odot}_{\mathrm{exp}}(\tau) = \frac{\frac{Y^+(\tau)}{\alpha^+} - \frac{Y^-(\tau)}{\alpha^-}}{\frac{N^+(\tau)}{\alpha^+} + \frac{N^-(\tau)}{\alpha^-}}$$

Beam-Helicity Asymmetry

$$I^{\odot}_{\exp}(\tau) = \frac{\frac{Y^{+}(\tau)}{\alpha^{+}} - \frac{Y^{-}(\tau)}{\alpha^{-}}}{\frac{N^{+}(\tau)}{\alpha^{+}} + \frac{N^{-}(\tau)}{\alpha^{-}}}$$

- $N^{\pm}(\tau)$ number of events in τ coming from a $\pm$ photon helicity
- $\alpha^{\pm} = \frac{1}{2}(1 \pm \bar{a}_c)$
- $\bar{a}_c = \frac{N_\pi^{+} - N_\pi^{-}}{N_\pi^{+} + N_\pi^{-}} = 0.0028 \pm 0.0008$ is the beam-charge asymmetry
  - Beam-charge asymmetry was measured using the reactions $\gamma p \to p\pi^0$ and $\gamma p \to n\pi^+$

Beam-Helicity Asymmetry

$$I^{\odot}_{\exp}(\tau) = \frac{\frac{Y^{+}(\tau)}{\alpha^{+}} - \frac{Y^{-}(\tau)}{\alpha^{-}}}{\frac{N^{+}(\tau)}{\alpha^{+}} + \frac{N^{-}(\tau)}{\alpha^{-}}}$$

$$Y^{\pm}(\tau) = \sum_{i=1}^{N^{\pm}(\tau)} \frac{1}{P^{\pm}_{\gamma,i}}$$

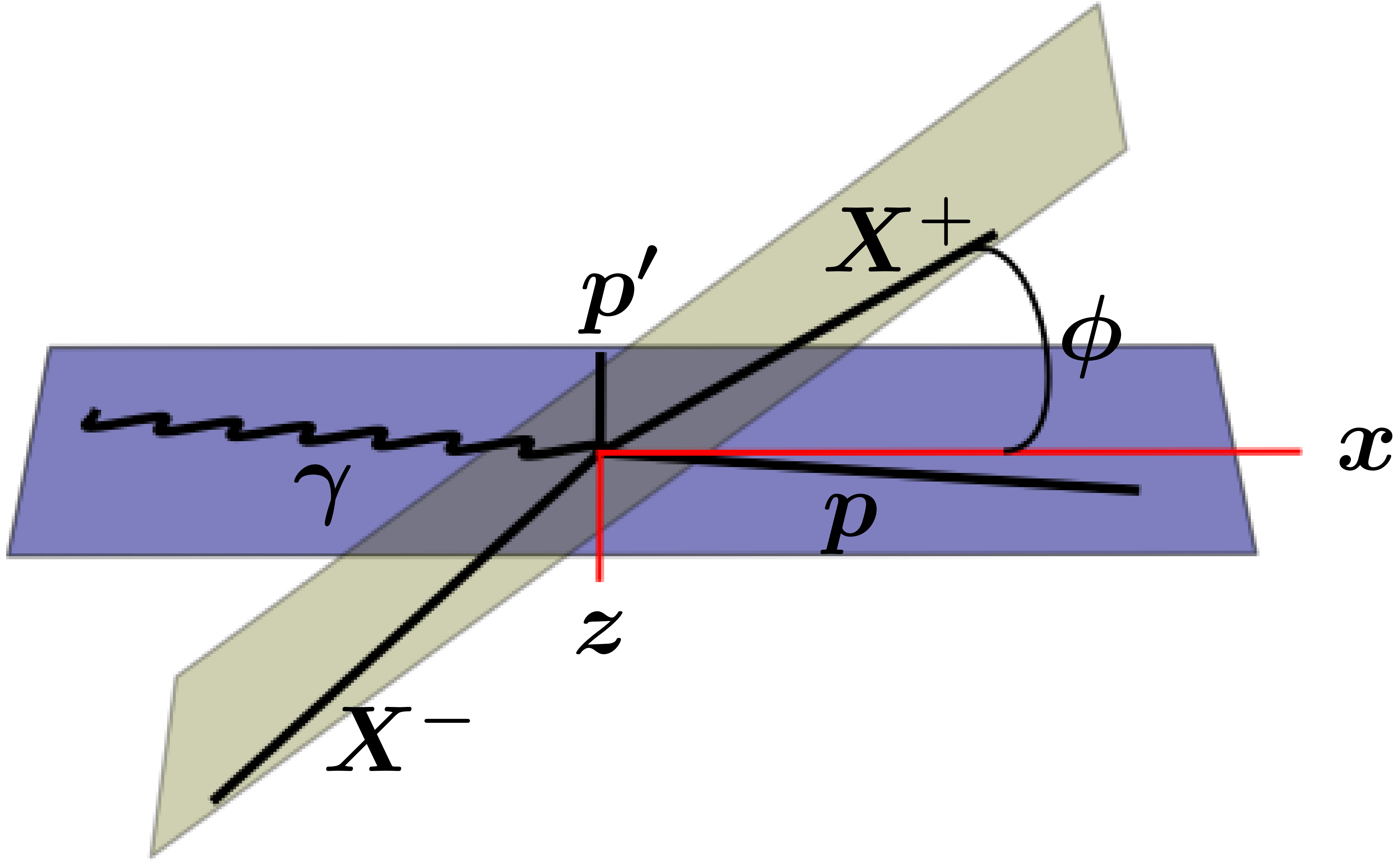
Each event is weighted by inverse polarization

$$P_{\gamma} = \frac{E_{\gamma}(E_e + \frac{E_e - E_{\gamma}}{3})}{E_e^2 + (E_e - E_{\gamma})^2 - \frac{2}{3}E_e(E_e - E_{\gamma})} P_e$$

Electron beam polarization measured by Moller polarimeter

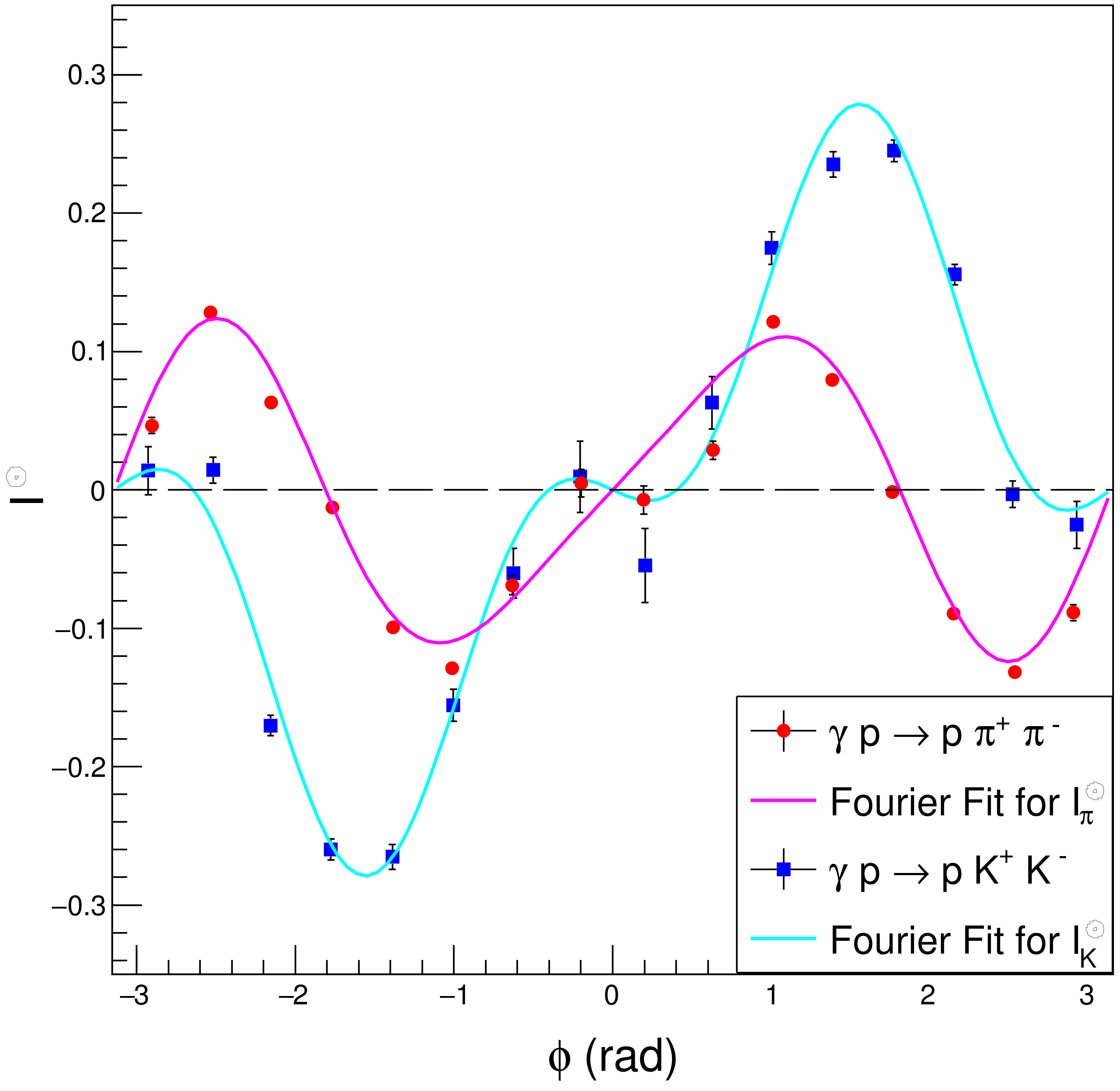
Beam-Helicity Asymmetry

- Beam-Helicity asymmetry was measured with respect to the angle between two predefined planes
- Figure on right defines the "Meson-Meson Plane Configuration"



Beam-Helicity Asymmetry

- Comparison of $I^{\odot}$ between kaon and pion channels in Meson-Meson Plane Configuration as function of ϕ
- Kaon channel has larger asymmetry amplitude and dominated by $\sin(2\phi)$

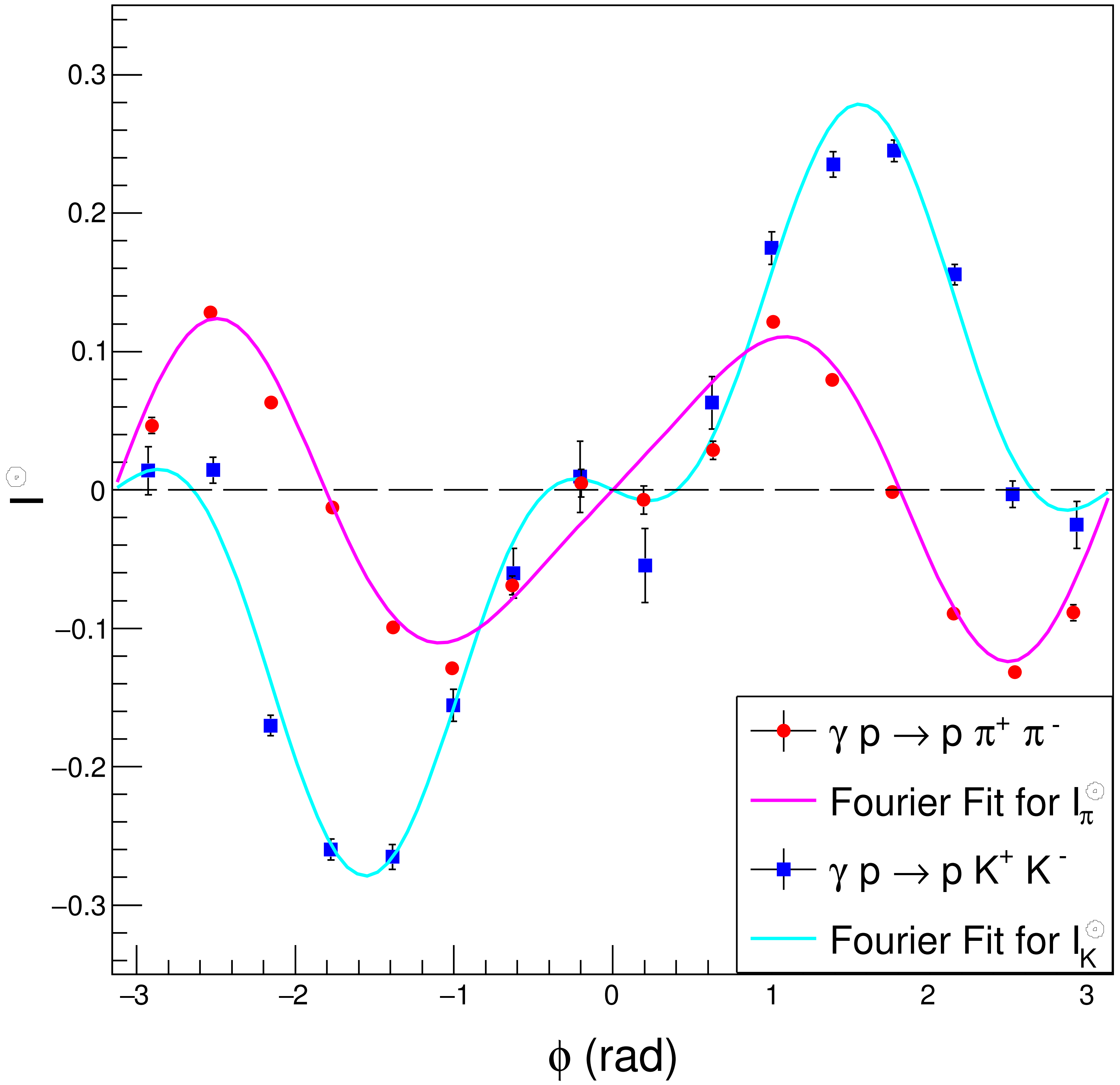


Beam-Helicity Asymmetry

- Fourier fit is to

$$I^{\odot}(\phi) = \sum_{n=1}^{3} c_n \sin(n\phi)$$

- Coefficients stopped at 3 after significance testing
  - Hypothesis Tests
  - LASSO

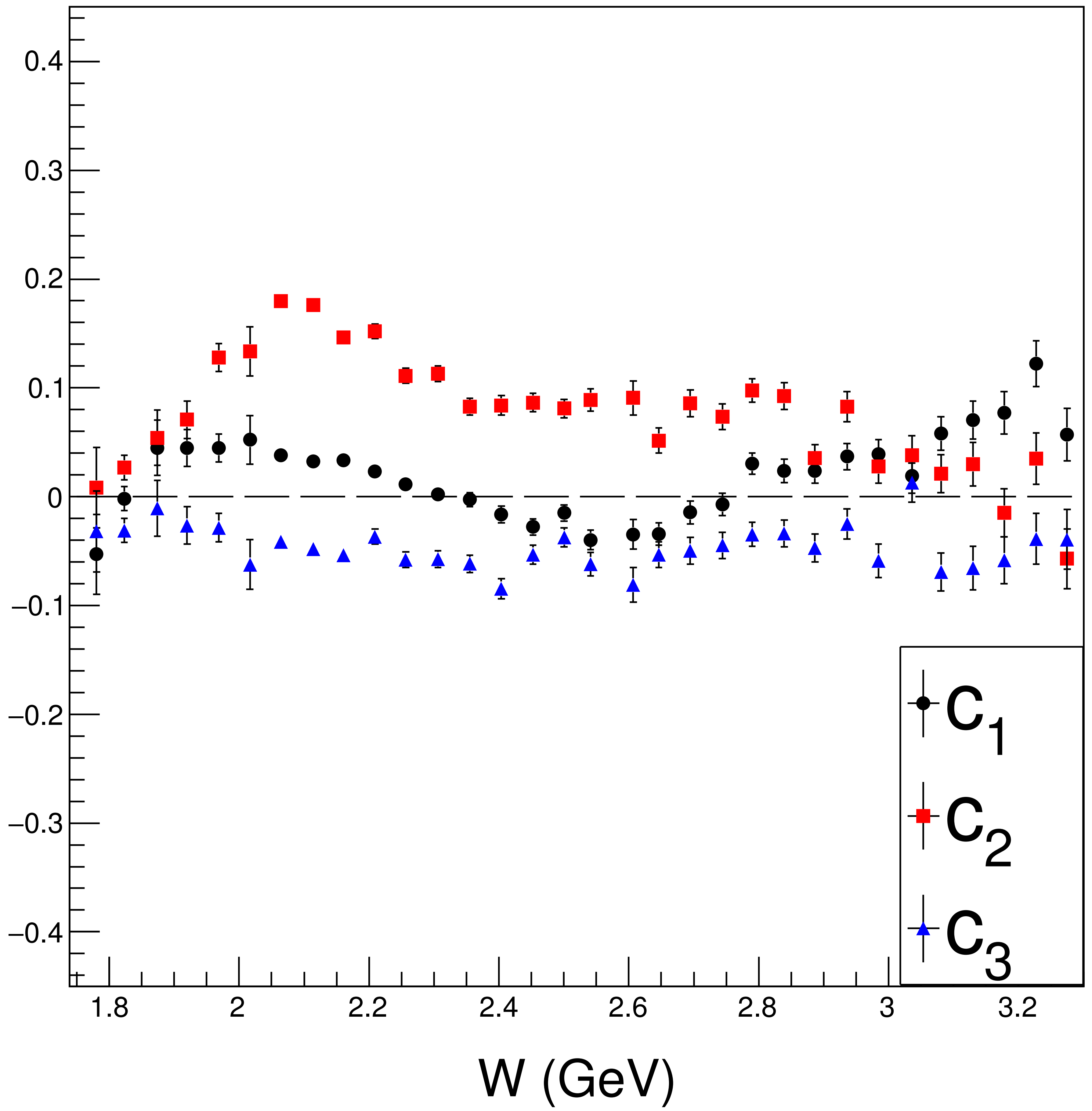


Beam-Helicity Asymmetry

- Investigated Fourier coefficients as function of different kinematics

$$I_\pi^{\odot}(\phi; W) = \sum_{n=1}^{3} c_n(W)\sin(n\phi)$$

- Pion asymmetry dominated by $\sin(2\phi)$ for most of the energy range

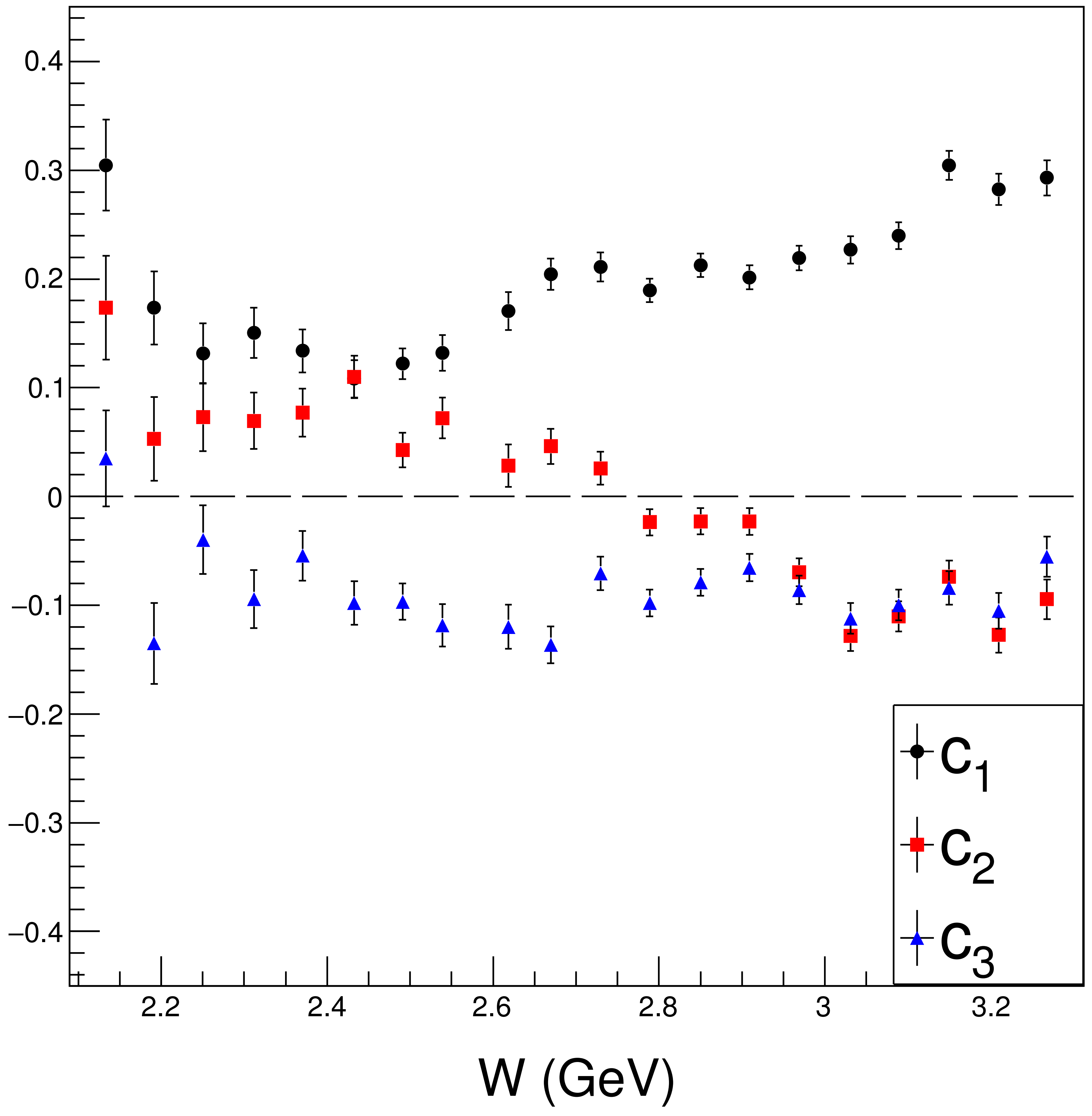


Beam-Helicity Asymmetry

- Investigated Fourier coefficients as function of different kinematics

$$I_K^{\odot}(\phi; W) = \sum_{n=1}^{3} c_n(W)\sin(n\phi)$$

- Kaon asymmetry dominated by $\sin(\phi)$ for most of the energy range

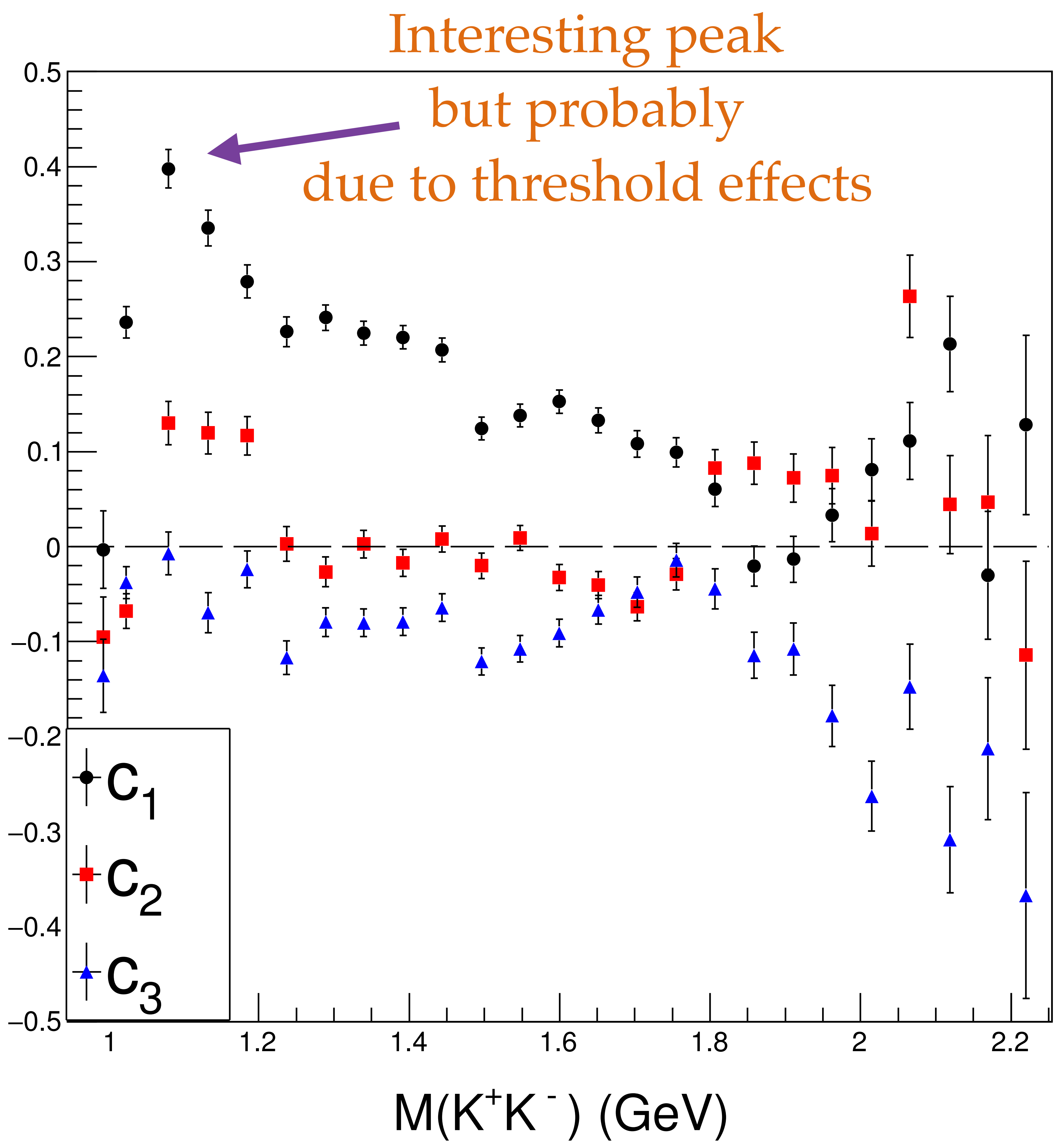


Beam-Helicity Asymmetry

- Investigated Fourier coefficients as function of different kinematics

$$I_K^{\odot}(\phi; M(K^+K^-)) = \sum_{n=1}^{3} c_n(M)\sin(n\phi)$$

- Overall amplitude decreases as $M(K^+K^-)$ increases



Beam-Helicity Asymmetry

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$$I_K^{\odot}(\phi; M(pK^-)) = \sum_{n=1}^{3} c_n(M)\sin(n\phi)$$

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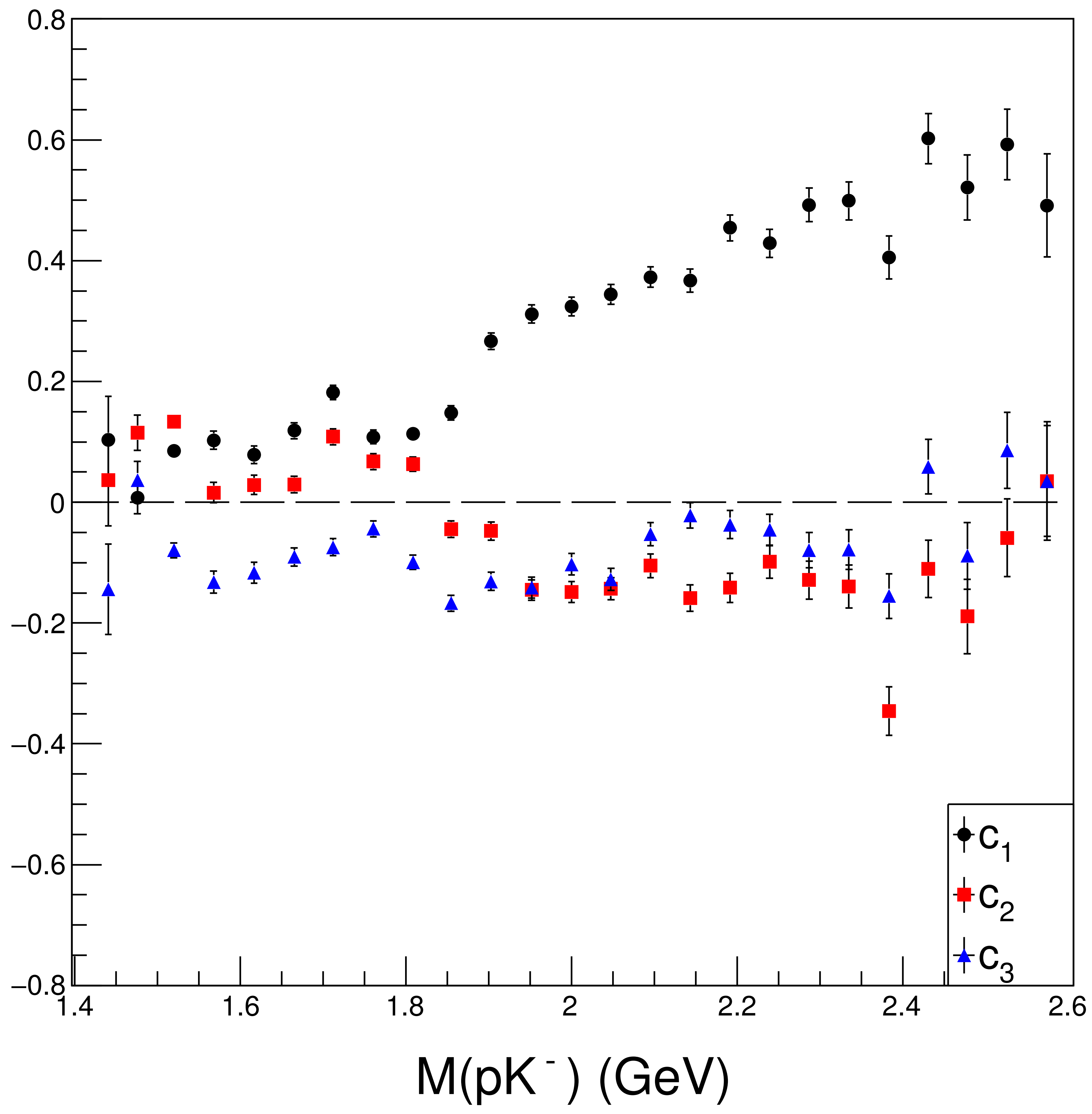
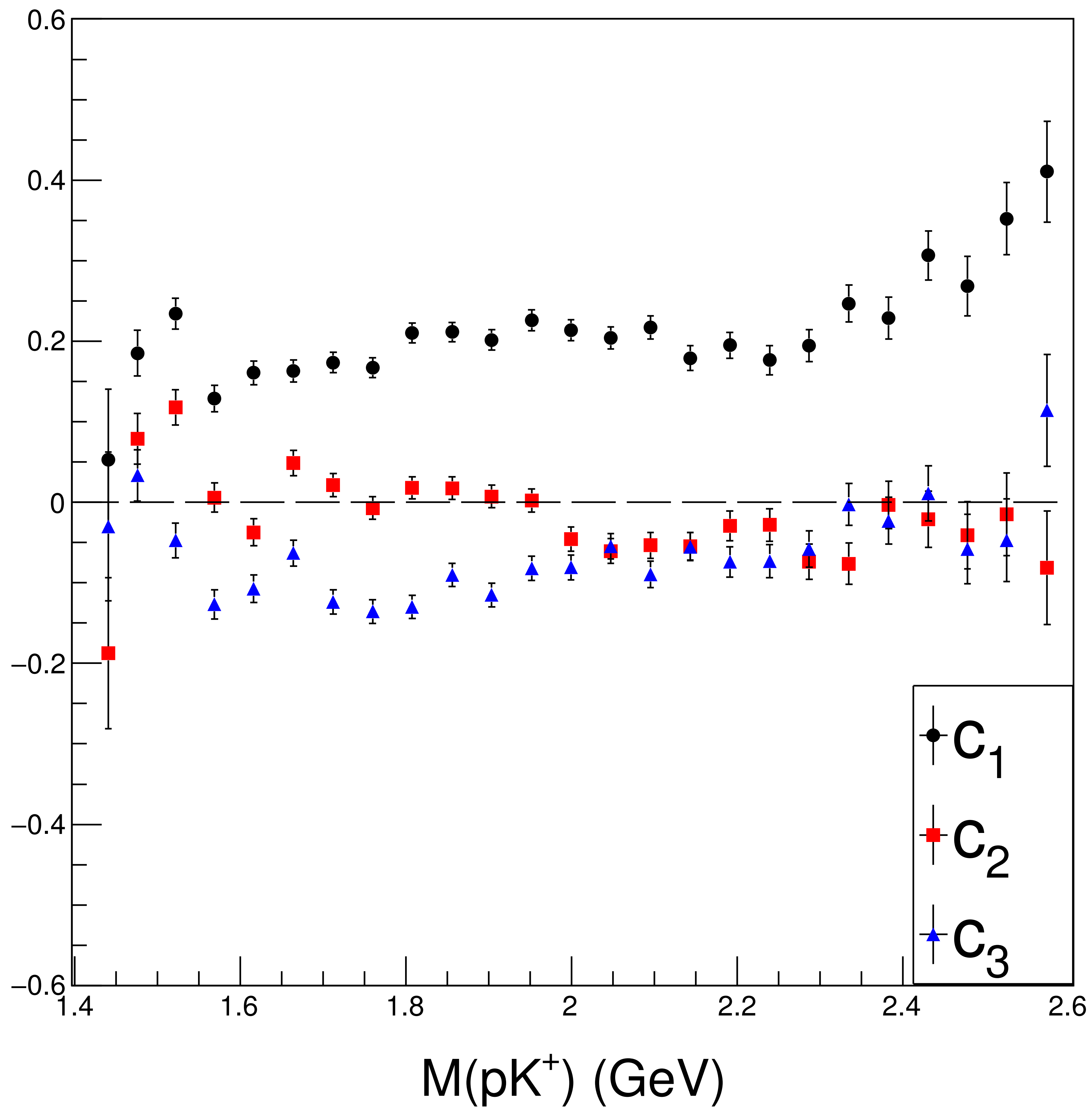


Beam-Helicity Asymmetry

- Investigated Fourier coefficients as function of different kinematics

$$I_K^{\odot}(\phi; M(pK^+)) = \sum_{n=1}^{3} c_n(M)\sin(n\phi)$$

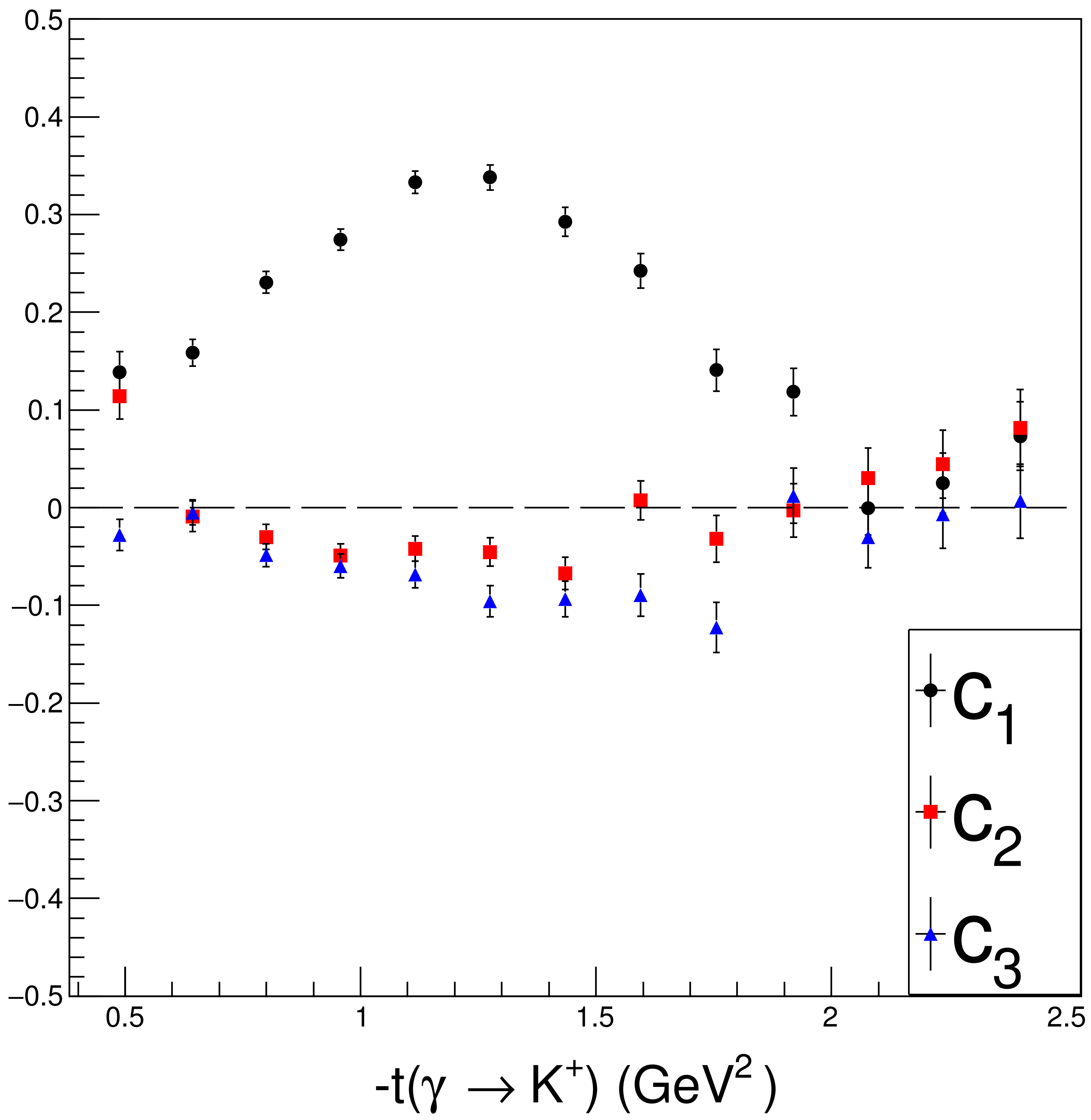
- Overall amplitude increases as $M(pK^+)$ increases



Beam-Helicity Asymmetry

- Investigated Fourier coefficients as function of different kinematics

$$I_K^{\odot}(\phi; t_{\gamma\to K^+}) = \sum_{n=1}^{3} c_n(-t)\sin(n\phi)$$



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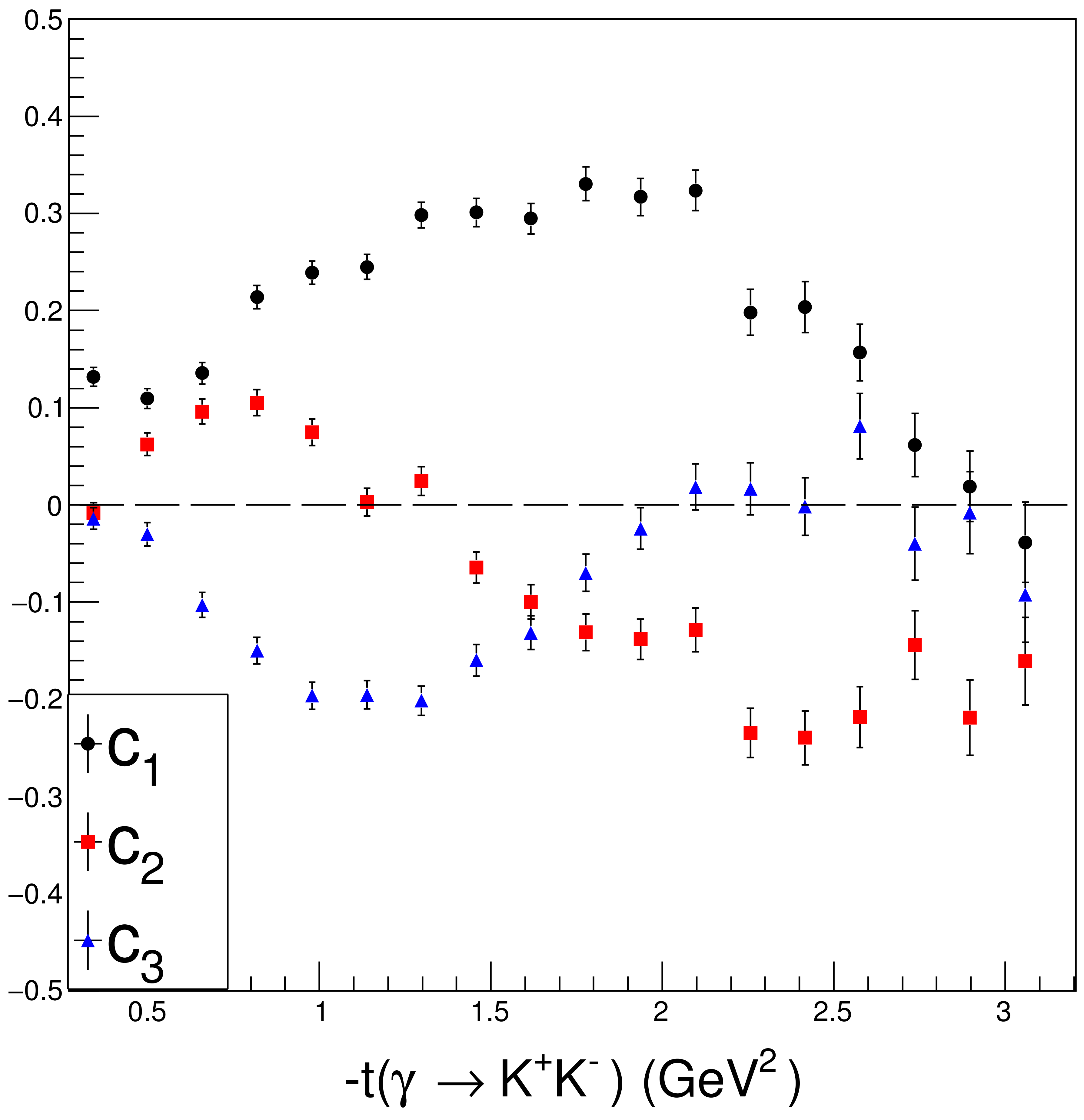
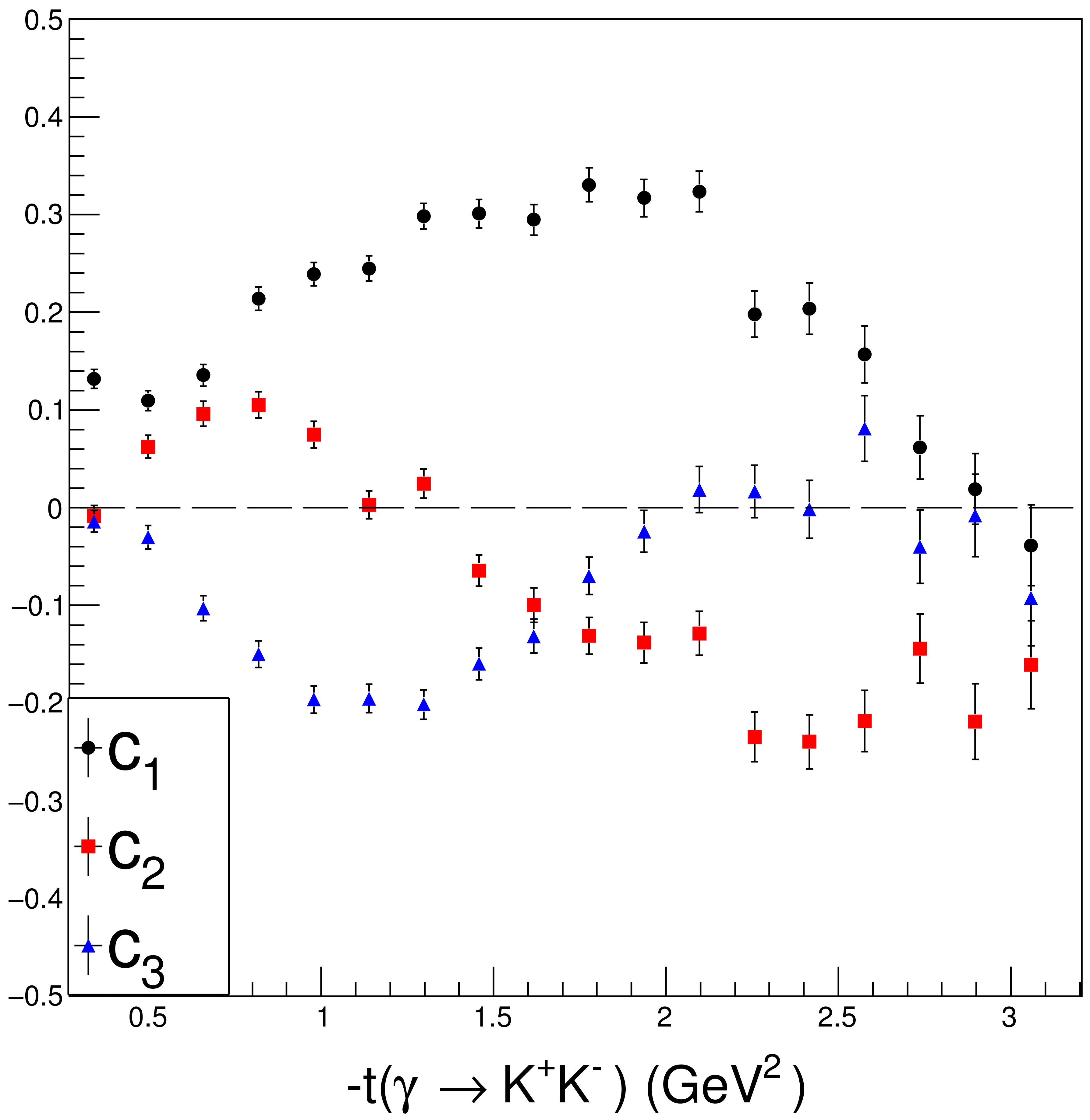


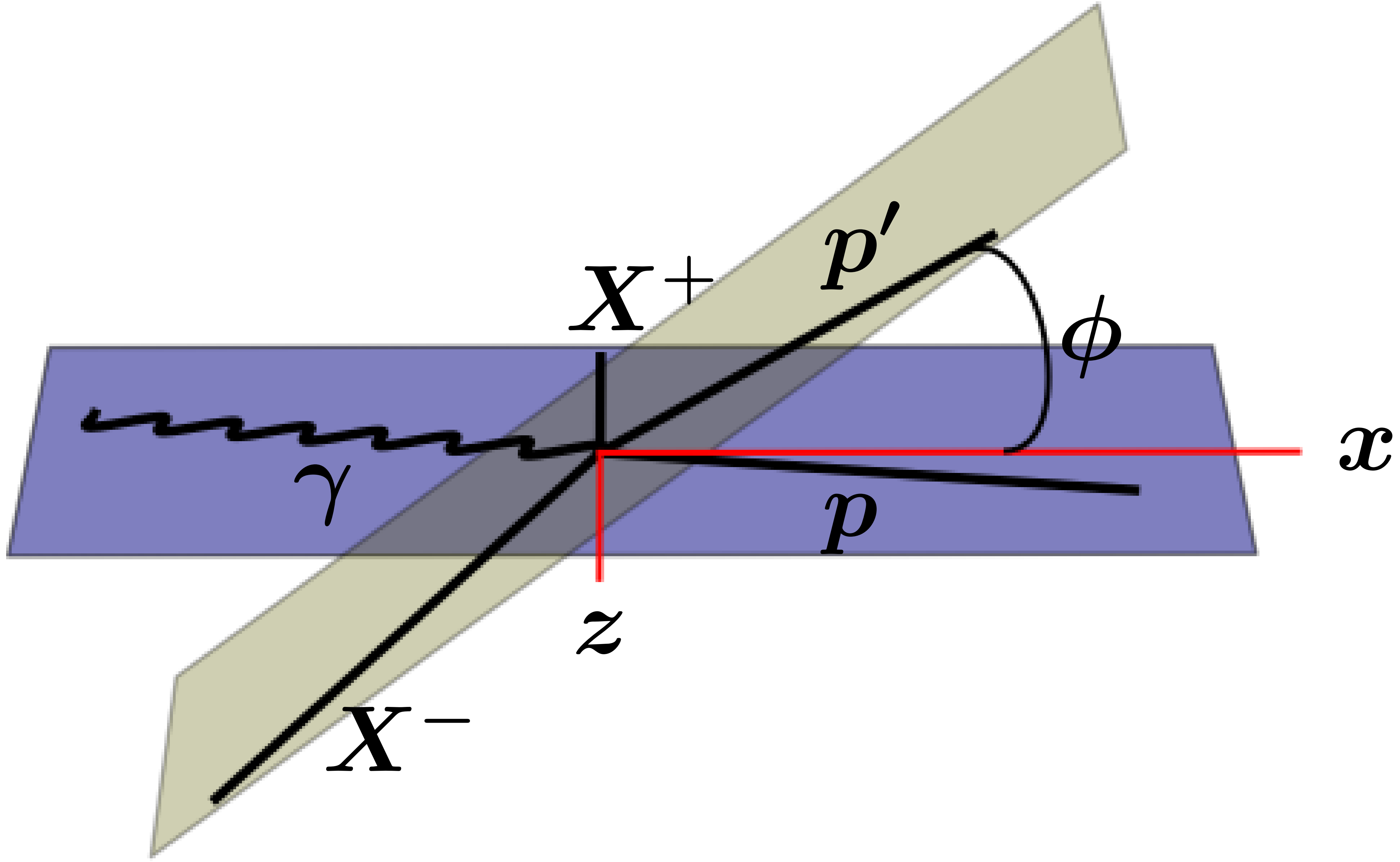
Beam-Helicity Asymmetry

- Investigated Fourier coefficients as function of different kinematics
- Thorough study
- Repeated for other plane configurations



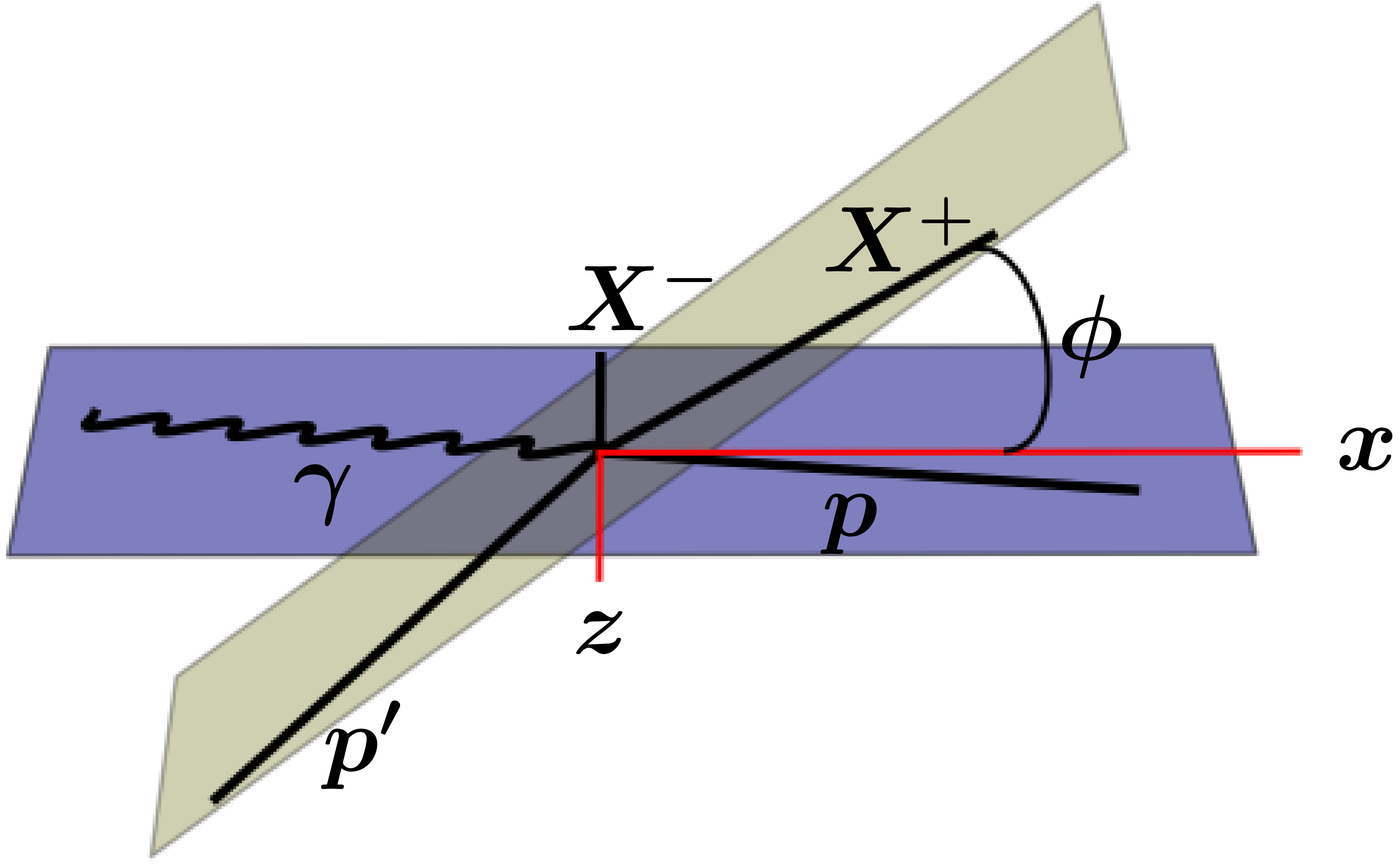
Beam-Helicity Asymmetry

- Figure on right defines the “Neutral Baryon Plane Configuration”



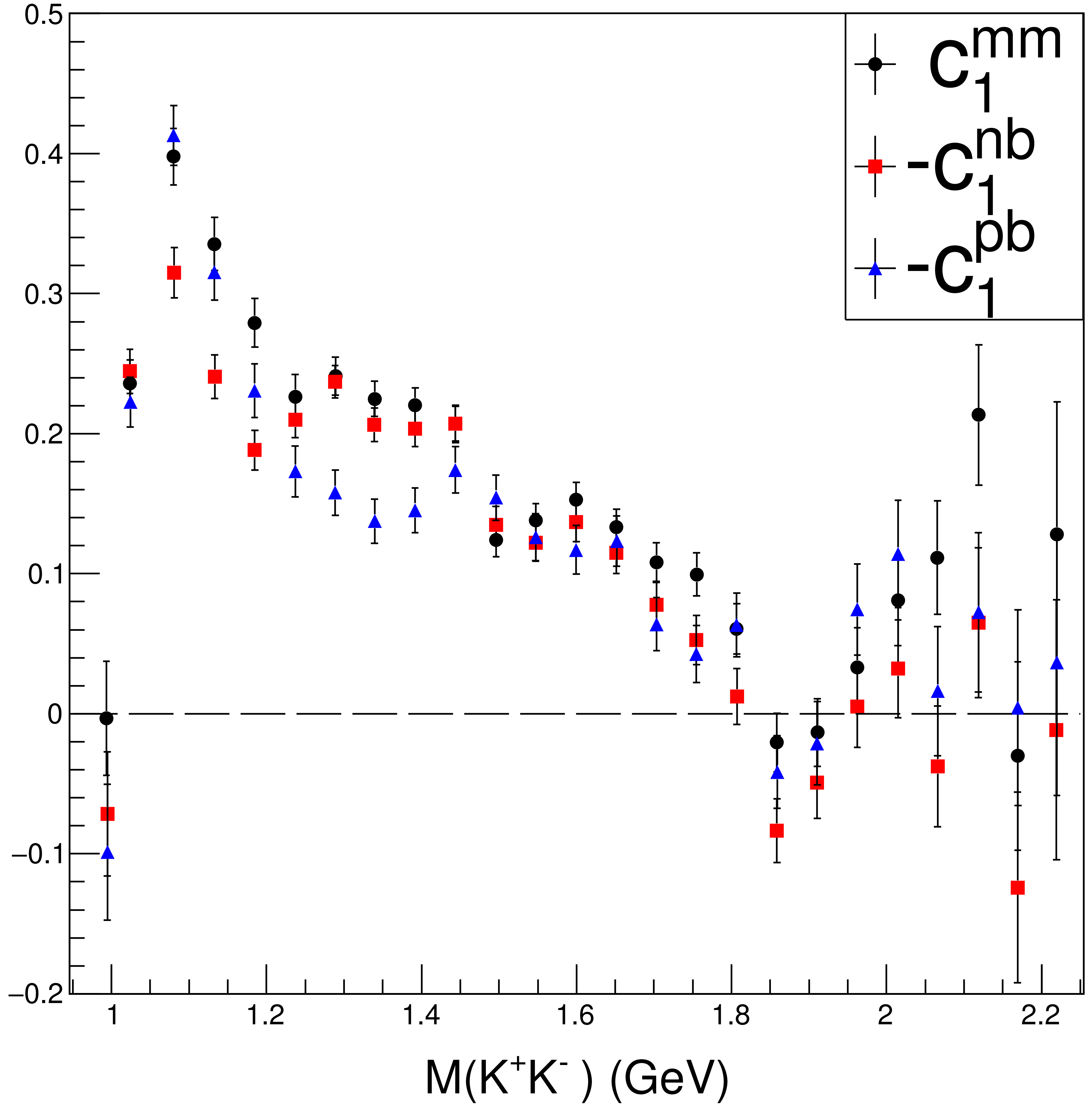
Beam-Helicity Asymmetry

- Figure on right defines the “Positive Baryon Plane Configuration”



Beam-Helicity Asymmetry

- Apparent agreement among leading coefficients for different plane/angle configurations across all kinematics (up to sign of the permutation)
- Also true for pion channel
- Not true for other coefficients



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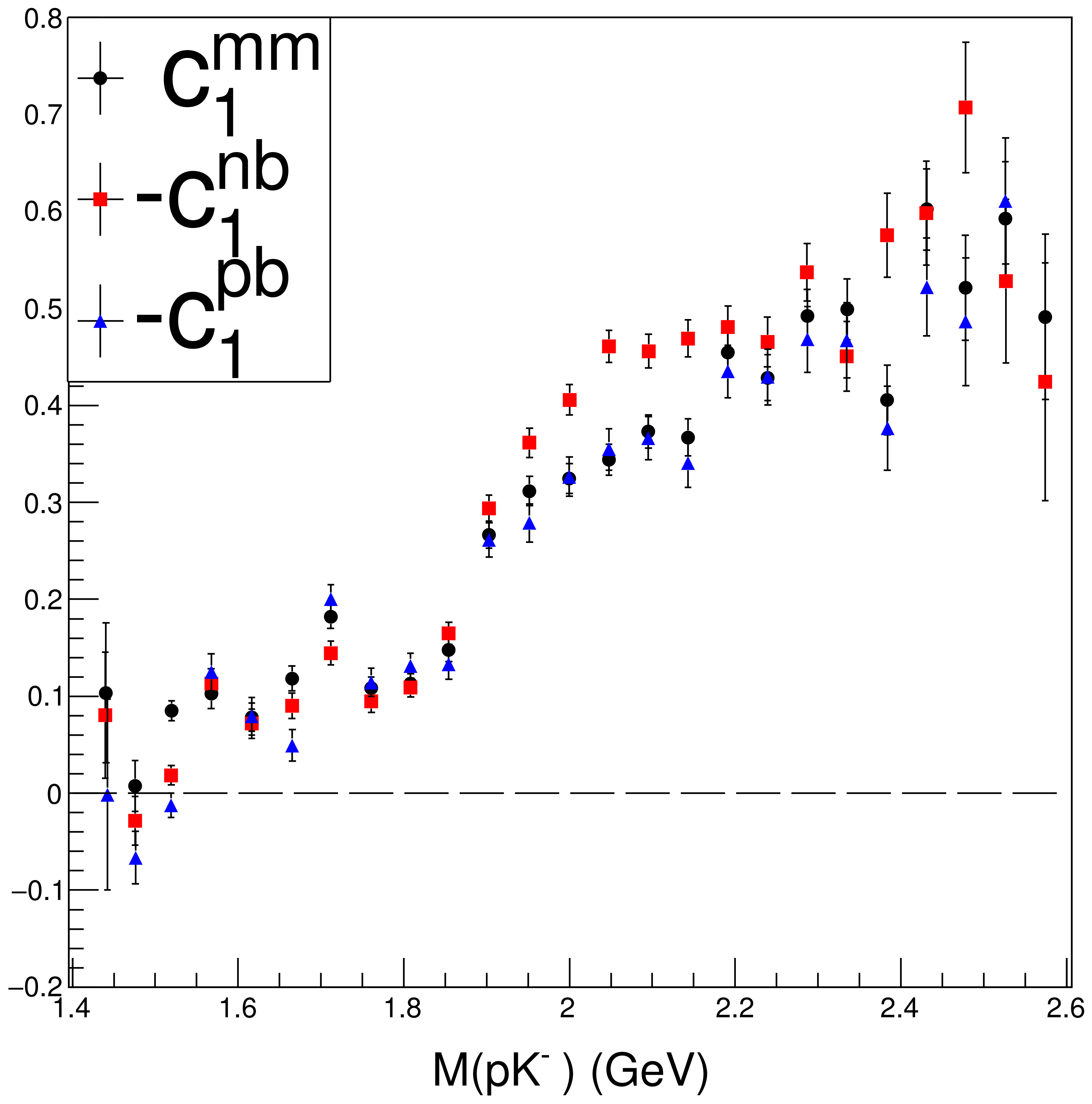

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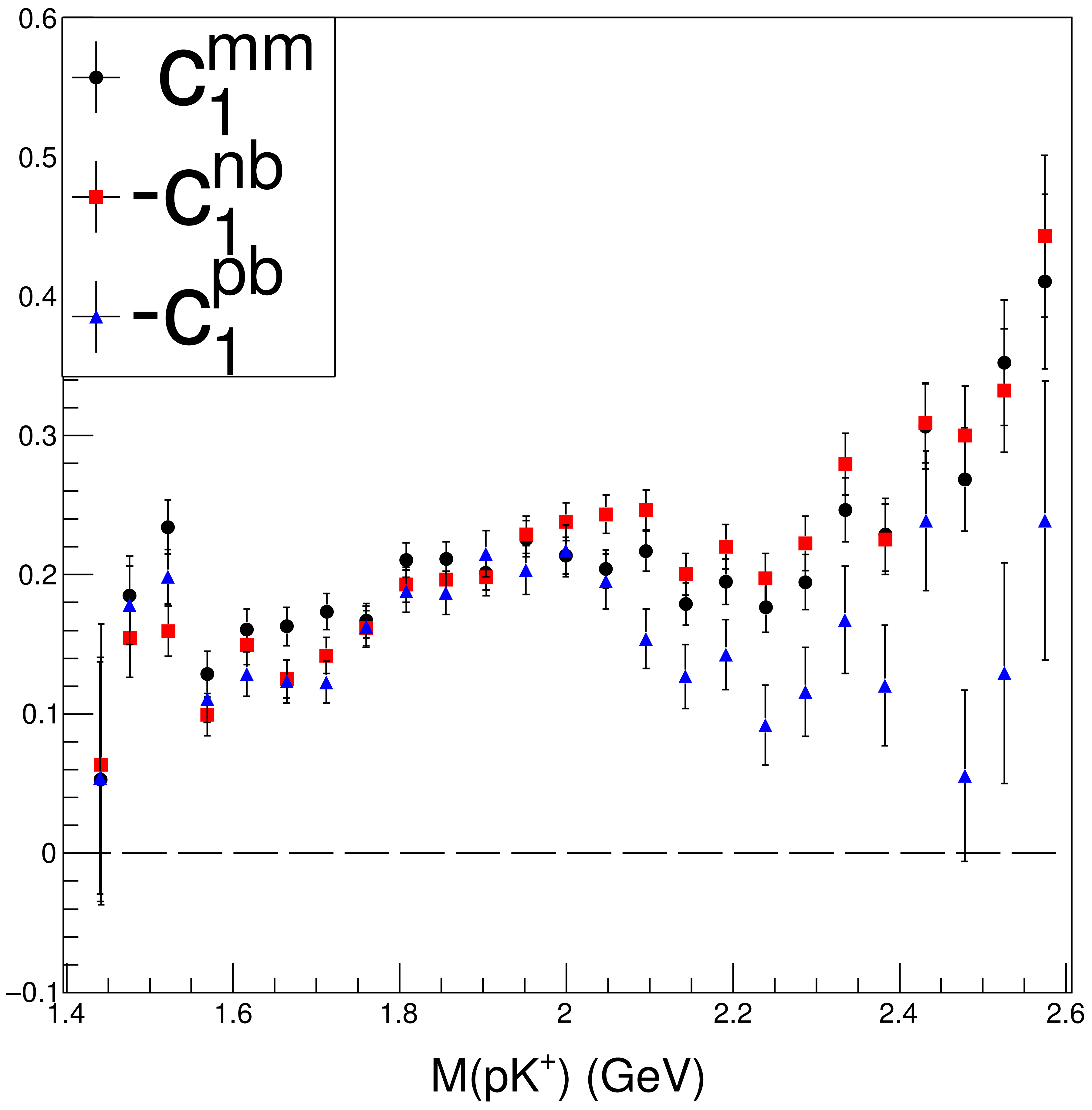

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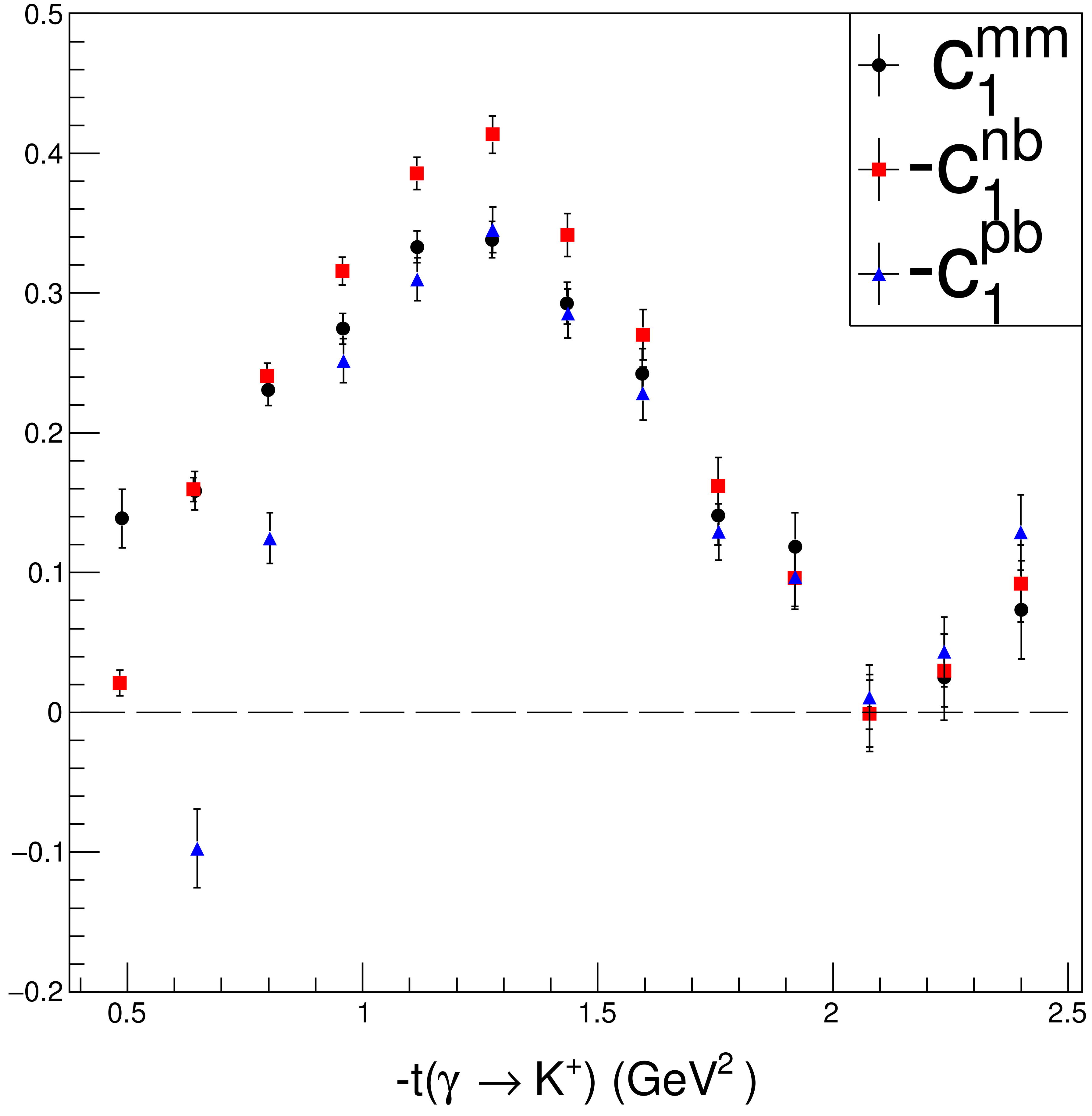

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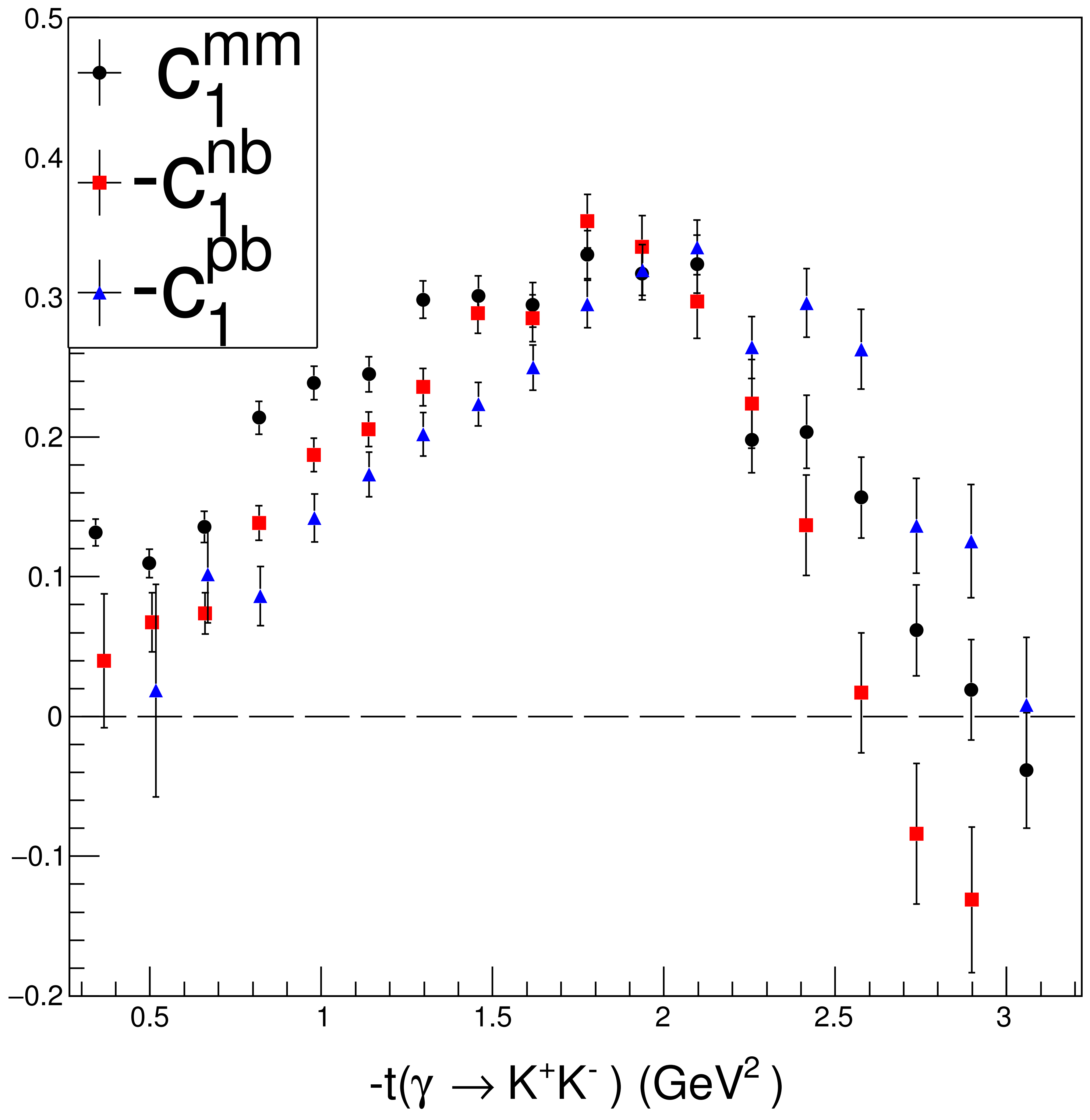

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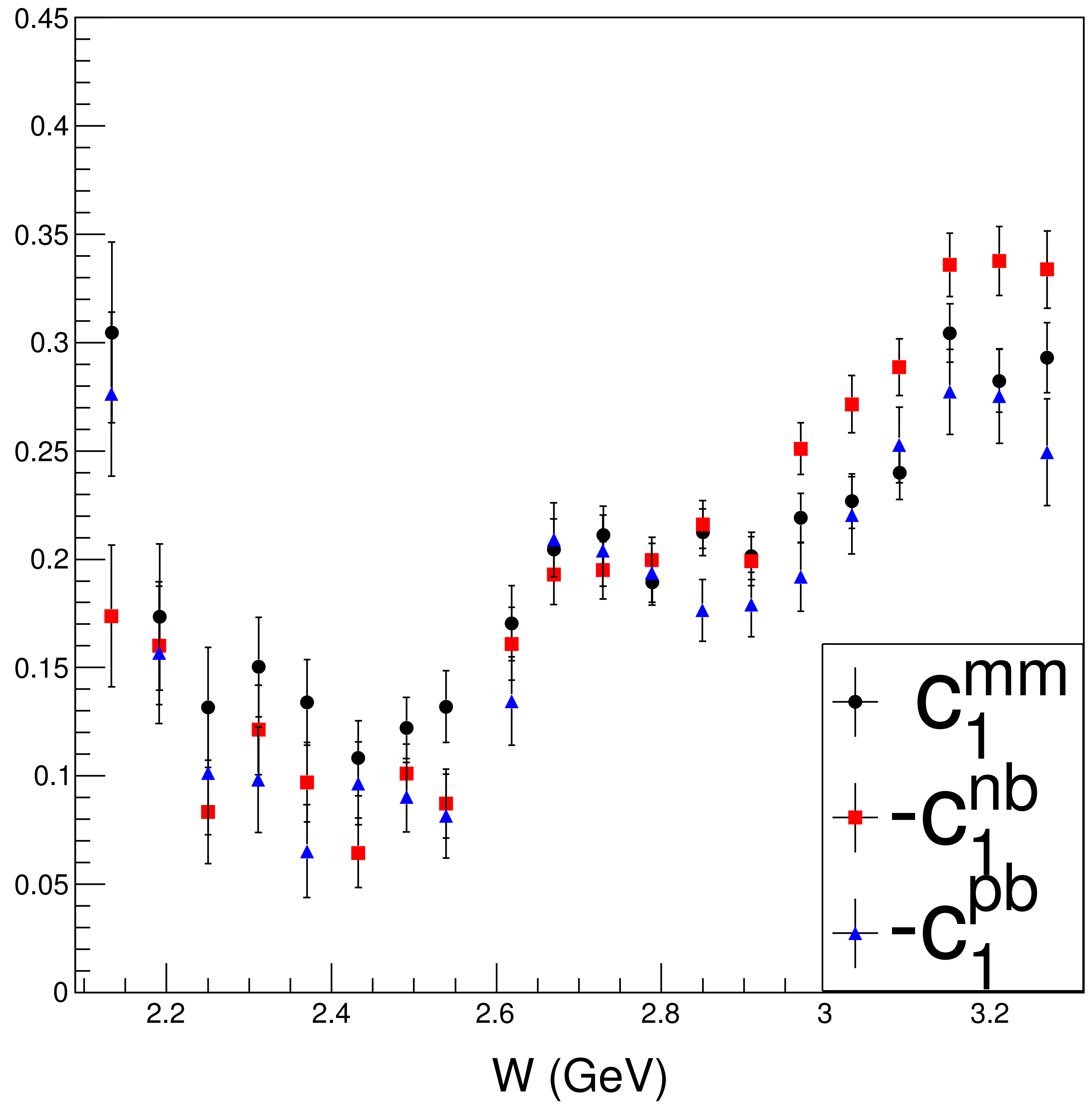

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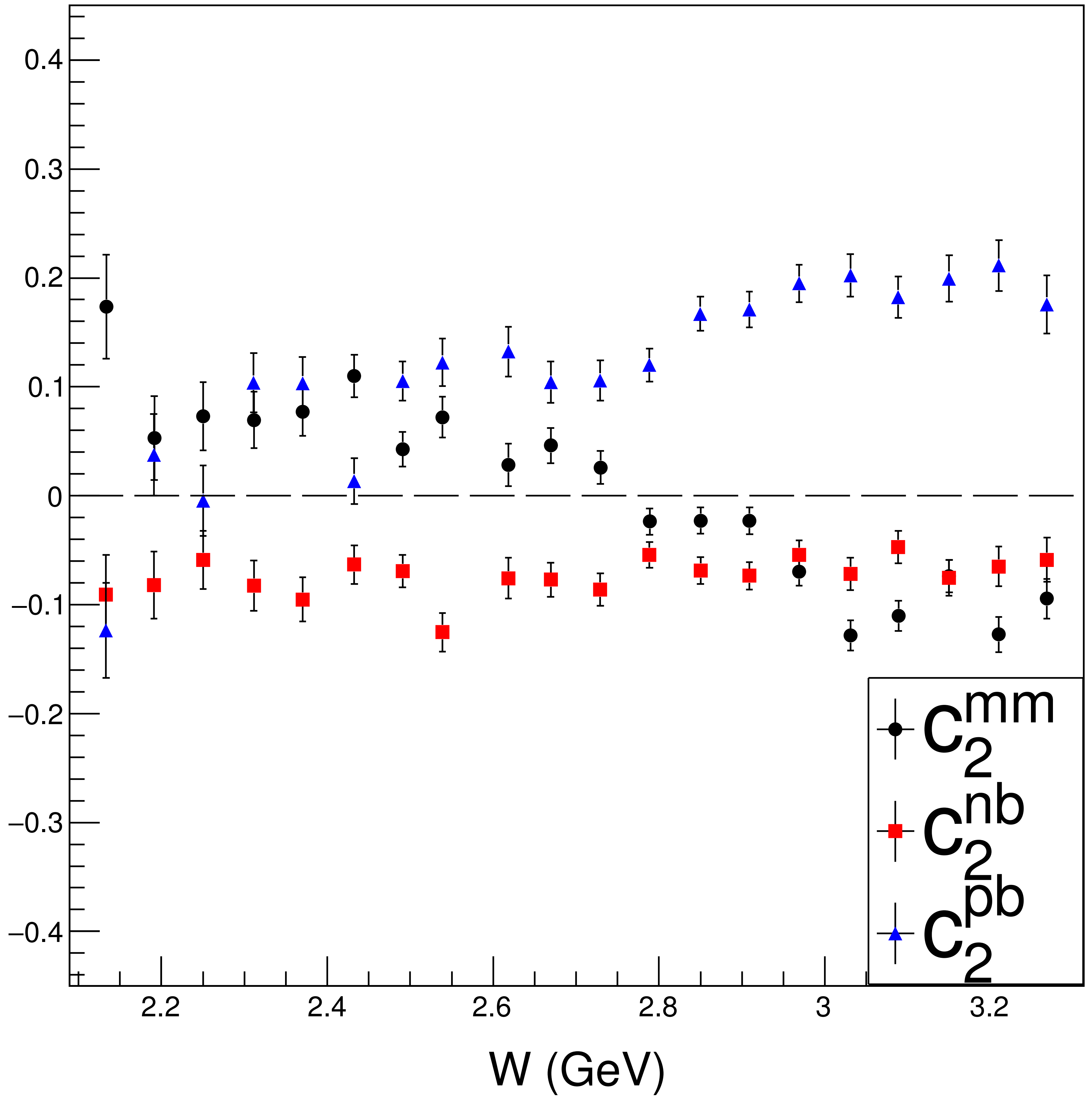

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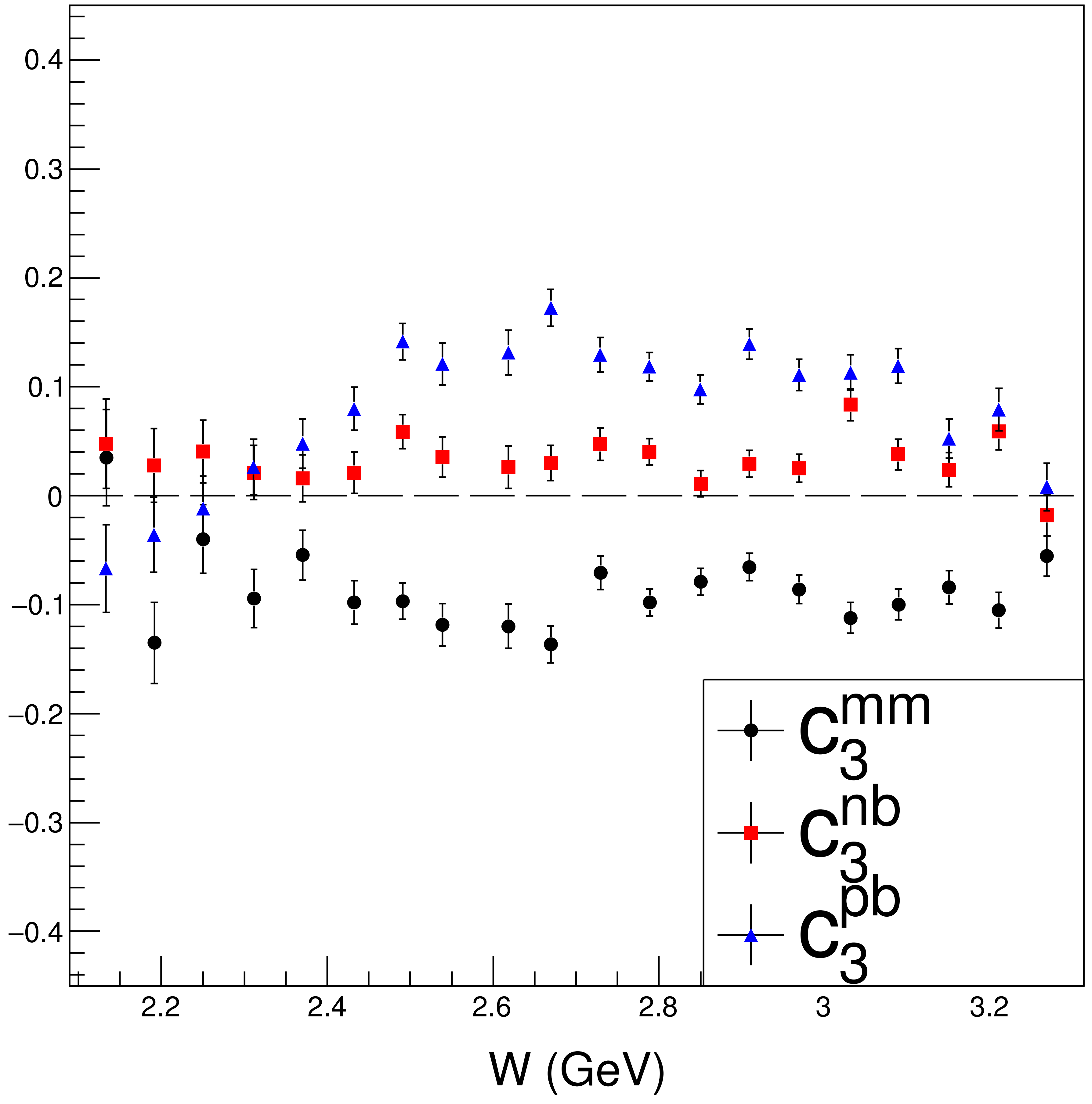

Statistical Uncertainties

- Statistical uncertainties treated each event following a Bernoulli-type distribution, weighted by inverse polarization and adjusted by the beam-charge asymmetry

- For N Bernoulli trials (trial can yield either ± 1), the standard error on the average number of successes (defining $+1$ to be a success) is given by

$$\sigma\left(\frac{N(+1)}{N}\right) = \frac{2\sqrt{N(+1)N(-1)}}{N^{\frac{3}{2}}}$$

Statistical Uncertainties

- In this study, $N(\pm 1)$ is replaced by $\frac{N^{\pm}}{\alpha^{\pm}} = \bar{N}^{\pm}$
- Due to each event weighted by the inverse polarization, the standard error is multiplied by the root-mean-square of the inverse polarization over all events
- The standard error on $I^{\odot}$ is given by

$$\sigma_{\text{stat}}(I^{\odot}) = \frac{2\sqrt{\bar{N}^{+}\bar{N}^{-}}}{\bar{N}^{\frac{3}{2}}} \left\langle \frac{1}{P^2} \right\rangle^{\frac{1}{2}}$$

Systematic Uncertainties

- The systematic uncertainties were estimated by varying each cut used in the event selection process
- The cuts were varied by 10% in each direction
- Radial Vertex Cut
  - $r < 2.0$ cm $\rightarrow r < 2.2$ cm
  - $r < 2.0$ cm $\rightarrow r < 1.8$ cm

Systematic Uncertainties

- The systematic uncertainties were estimated by varying each cut used in the event selection process
- The cuts were varied by 10% in each direction
- Longitudinal Vertex Cut
  - $|z - 90| < 20.0$ cm $\rightarrow |z - 90| < 22.0$ cm
  - $|z - 90| < 20.0$ cm $\rightarrow |z - 90| < 18.0$ cm

Systematic Uncertainties

- The systematic uncertainties were estimated by varying each cut used in the event selection process
- The cuts were varied by 10% in each direction
- Timing Cut
  - $|\Delta t| < 1.0$ ns $\rightarrow |\Delta t| < 1.1$ ns
  - $|\Delta t| < 1.0$ ns $\rightarrow |\Delta t| < 0.9$ ns

Systematic Uncertainties

- The systematic uncertainties were estimated by varying each cut used in the event selection process
- Multiple Photon Cut
    - Multiple photon cut $\rightarrow$ no multiple photon cut

Systematic Uncertainties

- The systematic uncertainties were estimated by varying each cut used in the event selection process
- Binning
  - 16 ϕ bins $\rightarrow$ 17 ϕ bins
  - 16 ϕ bins $\rightarrow$ 15 ϕ bins

Systematic Uncertainties

- The systematic uncertainties were estimated by varying each cut used in the event selection process
- The systematic uncertainty from an arbitrary source is estimated by

$$\delta_{\text{sys}} = \sqrt{\frac{\sum_i \left(\frac{I^{\odot}_{\text{nom}}(\phi_i) - I^{\odot}_{\text{alt}}(\phi_i)}{\delta I^{\odot}_{\text{nom}}(\phi_i)} \right)^2}{\sum_i \left(\frac{1}{\delta I^{\odot}_{\text{nom}}(\phi_i)} \right)^2}}$$

Systematic Uncertainties

- The systematic uncertainties were estimated by varying each cut used in the event selection process
- The total systematic uncertainty was obtained by adding the uncertainties from the different sources in quadrature

$$\delta_{\mathrm{sys,tot}} = \sqrt{\sum_{\mathrm{src}} \delta^2_{\mathrm{sys,src}}}$$

Systematic Uncertainties

- Systematic uncertainties for pion channel in the meson-meson plane configuration

Source	$\delta I^{\odot}$
Vertex Position	1.57×10^{-3}
Timing Cuts	1.89×10^{-3}
Multiple Photon	2.92×10^{-3}
Confidence Level	3.06×10^{-3}
$\cos(\theta_{\pi^+\pi^-})$	6.09×10^{-4}
Number of Bins	7.35×10^{-3}
Total Systematic	8.85×10^{-3}

Systematic Uncertainties

- Systematic uncertainties for kaon channel in the meson-meson plane configuration

Source	$\delta I^{\odot}$
Vertex Position	2.19×10^{-3}
Timing Cuts	3.82×10^{-3}
Multiple Photon	7.10×10^{-3}
Confidence Level	7.94×10^{-3}
$\cos(\theta_{K^+K^-})$	2.18×10^{-3}
Number of Bins	1.06×10^{-2}
Total Systematic	1.58×10^{-2}

Systematic Uncertainties

- Systematic uncertainties for kaon channel in the neutral baryon plane configuration

Source	$\delta I^{\odot}$
Vertex Position	2.73×10^{-3}
Timing Cuts	2.49×10^{-3}
Multiple Photon	6.75×10^{-3}
Confidence Level	6.36×10^{-3}
$\cos(\theta_{pK^-})$	3.46×10^{-3}
Number of Bins	9.07×10^{-3}
Total Systematic	1.39×10^{-2}

Systematic Uncertainties

- Systematic uncertainties for kaon channel in the positive baryon plane configuration

Source	$\delta I^{\odot}$
Vertex Position	1.53×10^{-3}
Timing Cuts	3.07×10^{-3}
Multiple Photon	8.51×10^{-3}
Confidence Level	8.13×10^{-3}
$\cos(\theta_{pK^+})$	1.84×10^{-3}
Number of Bins	1.19×10^{-2}
Total Systematic	1.71×10^{-2}

Systematic Uncertainties

- Compared to $I^{\odot}_{\mathrm{rms}}$, the systematic uncertainty is $\approx 10\%$

$$I^{\odot}_{\mathrm{rms}} = \sqrt{\frac{\sum_i \left(\frac{I^{\odot}(\phi_i)}{\delta I^{\odot}(\phi_i)}\right)^2}{\sum_i \left(\frac{1}{\delta I^{\odot}(\phi_i)}\right)^2}}$$

Conclusions

- Thorough study on the beam-helicity asymmetry
- Its angular dependence was studied
- Fourier coefficients studied as functions of key kinematic variables
- Procedures, results, and uncertainty estimation presented
- Systematic uncertainties on fiducial cuts and TOF knockouts to be conducted