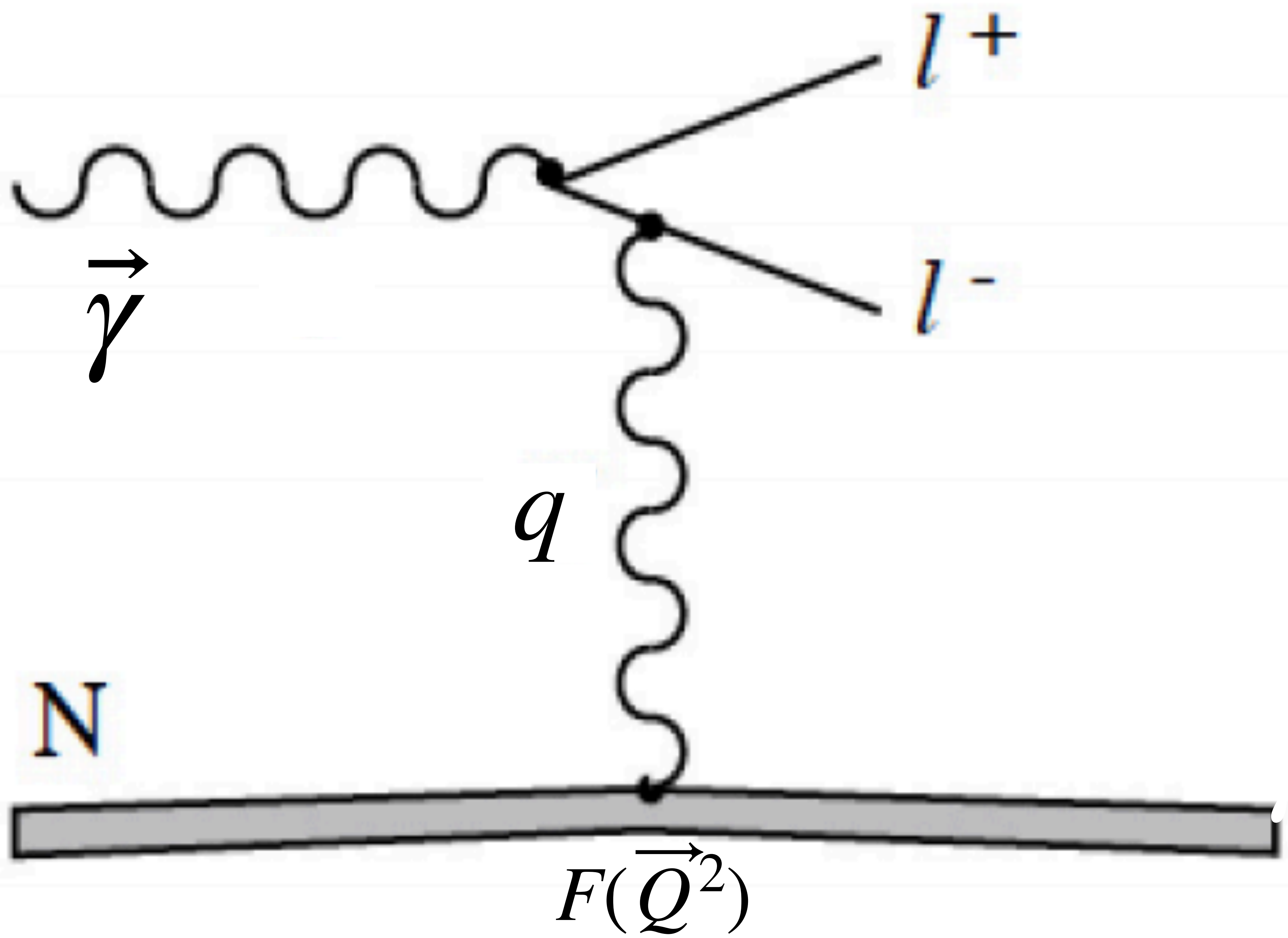
Using Bethe Heitler Pairs as a Polarimeter in GlueX

University of Massachusetts Amherst
MENP



Andrew Schick

BLTWG Meeting, Tuesday, March 30 2021

Jefferson Lab

Use Bethe-Heitler pairs to measure linear photon polarization.

$$
\begin{aligned}
d\sigma &= \left(\frac{1+\mathcal{P}}{2}\right) d\sigma_{||} + \left(\frac{1-\mathcal{P}}{2}\right) d\sigma_{\perp} \\
&= \underbrace{\left(\frac{d\sigma_{||}+d\sigma_{\perp}}{2}\right)}_{d\sigma_0} + \mathcal{P}\underbrace{\left(\frac{d\sigma_{||}-d\sigma_{\perp}}{2}\right)}_{d\sigma_1}
\end{aligned}
$$

$d\sigma_0$ Unpolarized

$d\sigma_1$ Polarized

Use Bethe-Heitler pairs to measure linear photon polarization.

$$\mathrm{d}\sigma = \left(\frac{1+\mathcal{P}}{2}\right)\mathrm{d}\sigma_{\|} + \left(\frac{1-\mathcal{P}}{2}\right)\mathrm{d}\sigma_{\perp}$$
$$= \underbrace{\left(\frac{\mathrm{d}\sigma_{\|}+\mathrm{d}\sigma_{\perp}}{2}\right)}_{\mathrm{d}\sigma_0} + \mathcal{P}\underbrace{\left(\frac{\mathrm{d}\sigma_{\|}-\mathrm{d}\sigma_{\perp}}{2}\right)}_{\mathrm{d}\sigma_1}$$

Unpolarized

Polarized

$$\mathrm{d}\sigma_1 \sim P_\gamma |\vec{J}_T|^2 \cos(2\phi_{J_T})$$

(Bakmaev, 2008)

Use Bethe-Heitler pairs to measure linear photon polarization.

$$\begin{aligned} d\sigma &= \left(\frac{1+\mathcal{P}}{2}\right) d\sigma_{\parallel} + \left(\frac{1-\mathcal{P}}{2}\right) d\sigma_{\perp} \\ &= \underbrace{\left(\frac{d\sigma_{\parallel} + d\sigma_{\perp}}{2}\right)}_{d\sigma_0} + \mathcal{P} \underbrace{\left(\frac{d\sigma_{\parallel} - d\sigma_{\perp}}{2}\right)}_{d\sigma_1} \end{aligned}$$

$d\sigma_0$ Unpolarized

$d\sigma_1$ Polarized

$$d\sigma_1 \sim P_\gamma |\vec{J}_T|^2 \cos(2\phi_{J_T})$$ (Bakmaev, 2008)

$$\vec{J}_T = \frac{\vec{p_1}}{p_1^2 + m^2} + \frac{\vec{p_2}}{p_2^2 + m^2} = \frac{\vec{p_1}}{c_1} + \frac{\vec{p_2}}{c_2}$$

$\vec{p_1}$, $\vec{p_2}$ are the lepton's transverse momenta

Use Bethe-Heitler pairs to measure linear photon polarization.

$$\mathrm{d}\sigma = \left(\frac{1+\mathcal{P}}{2}\right)\mathrm{d}\sigma_{\parallel} + \left(\frac{1-\mathcal{P}}{2}\right)\mathrm{d}\sigma_{\perp}$$
$$= \underbrace{\left(\frac{\mathrm{d}\sigma_{\parallel}+\mathrm{d}\sigma_{\perp}}{2}\right)}_{\mathrm{d}\sigma_0} + \mathcal{P}\underbrace{\left(\frac{\mathrm{d}\sigma_{\parallel}-\mathrm{d}\sigma_{\perp}}{2}\right)}_{\mathrm{d}\sigma_1}$$

$\mathrm{d}\sigma_0$ Unpolarized

$\mathrm{d}\sigma_1$ Polarized

$$\mathrm{d}\sigma_1 \sim P_\gamma |\vec{J}_T|^2 \cos(2\phi_{J_T})$$ (Bakmaev, 2008)

$$\vec{J}_T = \frac{\vec{p_1}}{p_1^2+m^2} + \frac{\vec{p_2}}{p_2^2+m^2} = \frac{\vec{p_1}}{c_1} + \frac{\vec{p_2}}{c_2}$$

$\vec{p_1}, \vec{p_2}$ are the lepton's transverse momenta

Bakmaev's formulation is really only valid at very large t

Can we find a similar reduction in Heitler's born approximation formulation?

$$d\sigma=\frac{Z^2}{137}\frac{e^4}{4\pi^2}\frac{p_+p_-dE_+d\Omega_+d\Omega_-}{k^3q^4}\left\{\frac{(\boldsymbol{\varepsilon}\cdot\mathbf{p}_+)^2(q^2-4E_-^2)}{(E_+-p_+\cos\theta_+)^2}+\frac{(\boldsymbol{\varepsilon}\cdot\mathbf{p}_-)^2(q^2-4E_+^2)}{(E_--p_-\cos\theta_-)^2}-\frac{2(\boldsymbol{\varepsilon}\cdot\mathbf{p}_+)(\boldsymbol{\varepsilon}\cdot\mathbf{p}_-)(q^2+4E_+E_-)}{(E_+-p_+\cos\theta_+)(E_--p_-\cos\theta_-)}+\frac{k^2[p_+^2\sin^2\theta_++p_-^2\sin^2\theta_-+2p_+p_-\sin\theta_+\sin\theta_-\cos(\varphi_+-\varphi_-)]}{(E_+-p_+\cos\theta_+)(E_--p_-\cos\theta_-)}\right\}.$$

T.H. Berlin and L. Madansky (1950)

$\boldsymbol{\varepsilon}$ is a unit vector in the direction of polarization of the incident photon.

Can we find a similar reduction in Heitler's born approximation formulation?

$$d\sigma = \frac{Z^2}{137}\frac{e^4}{4\pi^2}\frac{p_+p_-dE_+d\Omega_+d\Omega_-}{k^3q^4}\left\{\frac{(\boldsymbol{\varepsilon}\cdot\mathbf{p}_+)^2(q^2-4E_-^2)}{(E_+-p_+\cos\theta_+)^2}\right.$$
$$+\frac{(\boldsymbol{\varepsilon}\cdot\mathbf{p}_-)^2(q^2-4E_+^2)}{(E_--p_-\cos\theta_-)^2}-\frac{2(\boldsymbol{\varepsilon}\cdot\mathbf{p}_+)(\boldsymbol{\varepsilon}\cdot\mathbf{p}_-)(q^2+4E_+E_-)}{(E_+-p_+\cos\theta_+)(E_--p_-\cos\theta_-)}$$
$$\left.+\frac{k^2[p_+^2\sin^2\theta_++p_-^2\sin^2\theta_-+2p_+p_-\sin\theta_+\sin\theta_-\cos(\varphi_+-\varphi_-)]}{(E_+-p_+\cos\theta_+)(E_--p_-\cos\theta_-)}\right\}.$$

$\boldsymbol{\varepsilon}$ is a unit vector in the direction of polarization of the incident photon.

T.H. Berlin and L. Madansky (1950)

$$d\sigma_1 \sim |\vec{J}_T|^2\cos(2\phi_{J_T}), \qquad \vec{J}_T = f_1\vec{p_1} + f_2\vec{p_2}$$

Can we find a similar reduction in Heitler's born approximation formulation?

⟶ **Yes! If we write:**

$$\vec{J}_T = \frac{2E_2}{E_1 - p_1\cos\theta_1}\vec{p}_{1T} + \frac{2E_2}{E_2 - p_2\cos\theta_2}\vec{p}_{2T}$$

$$\vec{K}_T = \frac{\sqrt{q^2}}{E_1 - p_1\cos\theta_1}\vec{p}_{1T} - \frac{\sqrt{q^2}}{E_2 - p_2\cos\theta_2}\vec{p}_{2T}$$

$$d\sigma = \frac{Z^2}{137}\frac{e^4}{4\pi^2}\frac{p_+p_-dE_+d\Omega_+d\Omega_-}{k^3q^4}\left\{\frac{(\boldsymbol{\varepsilon}\cdot\mathbf{p}_+)^2(q^2-4E_-^2)}{(E_+-p_+\cos\theta_+)^2}+\frac{(\boldsymbol{\varepsilon}\cdot\mathbf{p}_-)^2(q^2-4E_+^2)}{(E_--p_-\cos\theta_-)^2}-\frac{2(\boldsymbol{\varepsilon}\cdot\mathbf{p}_+)(\boldsymbol{\varepsilon}\cdot\mathbf{p}_-)(q^2+4E_+E_-)}{(E_+-p_+\cos\theta_+)(E_--p_-\cos\theta_-)}+\frac{k^2[p_+^2\sin^2\theta_++p_-^2\sin^2\theta_-+2p_+p_-\sin\theta_+\sin\theta_-\cos(\varphi_+-\varphi_-)]}{(E_+-p_+\cos\theta_+)(E_--p_-\cos\theta_-)}\right\}.$$

$\boldsymbol{\varepsilon}$ is a unit vector in the direction of polarization of the incident photon.

Can we find a similar reduction in Heitler's born approximation formulation?

$\longrightarrow$ **Yes! If we write:**

$$d\sigma = \frac{Z^2}{137}\frac{e^4}{4\pi^2}\frac{p_+ p_- dE_+ d\Omega_+ d\Omega_-}{k^3 q^4}\left\{\frac{(\boldsymbol{\varepsilon}\cdot\mathbf{p}_+)^2(q^2-4E_-^2)}{(E_+-p_+\cos\theta_+)^2} + \frac{(\boldsymbol{\varepsilon}\cdot\mathbf{p}_-)^2(q^2-4E_+^2)}{(E_--p_-\cos\theta_-)^2} - \frac{2(\boldsymbol{\varepsilon}\cdot\mathbf{p}_+)(\boldsymbol{\varepsilon}\cdot\mathbf{p}_-)(q^2+4E_+E_-)}{(E_+-p_+\cos\theta_+)(E_--p_-\cos\theta_-)} + \frac{k^2[p_+^2\sin^2\theta_+ + p_-^2\sin^2\theta_- + 2p_+p_-\sin\theta_+\sin\theta_-\cos(\varphi_+-\varphi_-)]}{(E_+-p_+\cos\theta_+)(E_--p_-\cos\theta_-)}\right\}.$$

$\boldsymbol{\varepsilon}$ is a unit vector in the direction of polarization of the incident photon.

$$\vec{J}_T = \frac{2E_2}{E_1 - p_1\cos\theta_1}\vec{p_1}_T + \frac{2E_2}{E_2 - p_2\cos\theta_2}\vec{p_2}_T$$

$$\vec{K}_T = \frac{\sqrt{q^2}}{E_1 - p_1\cos\theta_1}\vec{p_1}_T - \frac{\sqrt{q^2}}{E_2 - p_2\cos\theta_2}\vec{p_2}_T$$

$$\mathrm{d}\sigma = \mathrm{d}\sigma_0 + P_\gamma \mathrm{d}\sigma_1$$

$$\mathrm{d}\sigma_0 = \frac{\mathrm{d}\sigma_\parallel + \mathrm{d}\sigma_\perp}{2} = k\left[-\left|\vec{J}_T\right|^2 + \left|\vec{K}_T\right|^2 + 2E_0^2\frac{\left|\vec{p_1}_T + \vec{p_2}_T\right|^2}{\left(E_1 - p_1\cos\theta_1\right)\left(E_2 - p_2\cos\theta_2\right)}\right]$$

$$\mathrm{d}\sigma_1 = \frac{\mathrm{d}\sigma_\parallel - \mathrm{d}\sigma_\perp}{2} = k\left[-\left|\vec{J}_T\right|^2\cos 2\phi_{J_T} + \left|\vec{K}_T\right|^2\cos 2\phi_{J_T}\right]$$

Can we find a similar reduction in Heitler's born approximation formulation?

⟶ **Yes! If we write:**

$$\vec{J}_T = \frac{2E_2}{E_1 - p_1 \cos\theta_1}\vec{p}_{1T} + \frac{2E_2}{E_2 - p_2 \cos\theta_2}\vec{p}_{2T}$$

$$\vec{K}_T = \frac{\sqrt{q^2}}{E_1 - p_1 \cos\theta_1}\vec{p}_{1T} - \frac{\sqrt{q^2}}{E_2 - p_2 \cos\theta_2}\vec{p}_{2T}$$

$$d\sigma = \frac{Z^2}{137}\frac{e^4}{4\pi^2}\frac{p_+ p_- dE_+ d\Omega_+ d\Omega_-}{k^3 q^4}\left\{\frac{(\boldsymbol{\varepsilon}\cdot\mathbf{p}_+)^2(q^2-4E_-^2)}{(E_+-p_+\cos\theta_+)^2} + \frac{(\boldsymbol{\varepsilon}\cdot\mathbf{p}_-)^2(q^2-4E_+^2)}{(E_--p_-\cos\theta_-)^2} - \frac{2(\boldsymbol{\varepsilon}\cdot\mathbf{p}_+)(\boldsymbol{\varepsilon}\cdot\mathbf{p}_-)(q^2+4E_+E_-)}{(E_+-p_+\cos\theta_+)(E_--p_-\cos\theta_-)} + \frac{k^2[p_+^2\sin^2\theta_+ + p_-^2\sin^2\theta_- + 2p_+p_-\sin\theta_+\sin\theta_-\cos(\varphi_+-\varphi_-)]}{(E_+-p_+\cos\theta_+)(E_--p_-\cos\theta_-)}\right\}.$$

$\boldsymbol{\varepsilon}$ is a unit vector in the direction of polarization of the incident photon.

$$\mathrm{d}\sigma = \mathrm{d}\sigma_0 + P_\gamma \mathrm{d}\sigma_1$$

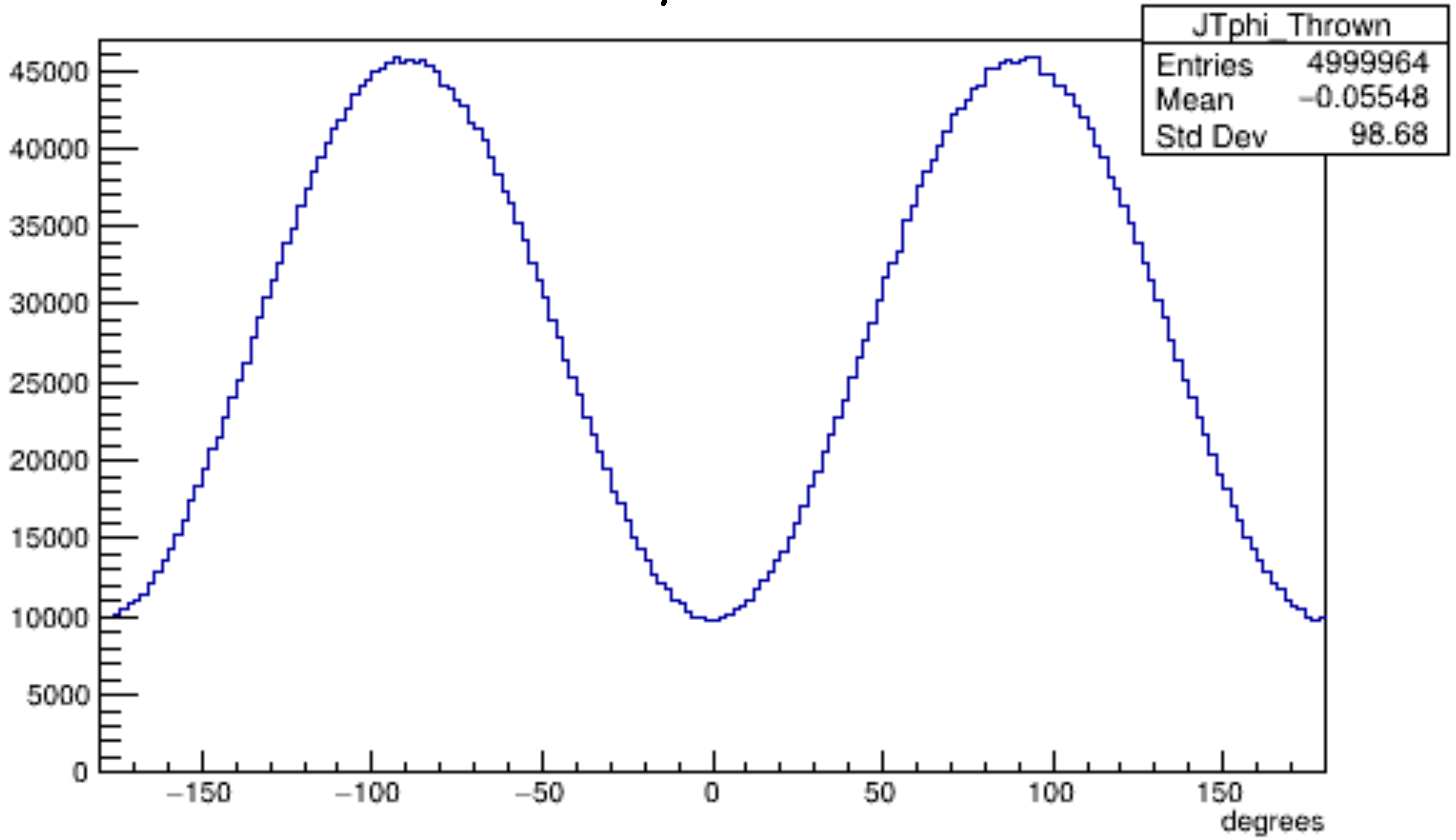
$$\mathrm{d}\sigma_0 = \frac{\mathrm{d}\sigma_\parallel + \mathrm{d}\sigma_\perp}{2} = k\left[-\left|\vec{J}_T\right|^2 + \left|\vec{K}_T\right|^2 + 2E_0^2\frac{\left|\vec{p}_{1T}+\vec{p}_{2T}\right|^2}{\left(E_1 - p_1\cos\theta_1\right)\left(E_2 - p_2\cos\theta_2\right)}\right]$$

$$\mathrm{d}\sigma_1 = \frac{\mathrm{d}\sigma_\parallel - \mathrm{d}\sigma_\perp}{2} = k\left[-\left|\vec{J}_T\right|^2\cos 2\phi_{J_T} + \left|\vec{K}_T\right|^2\cos 2\phi_{J_T}\right]$$

Generally, $\left|\vec{J}_T\right|^2 \gg \left|\vec{K}_T\right|^2$

$$d\sigma = d\sigma_0 + P_\gamma d\sigma_1 \qquad d\sigma_1 = \sim \left|\vec{J}_T\right|^2 \cos 2\phi_{J_T}$$

$$P_\gamma = 1$$



MC with BH Cross-Section

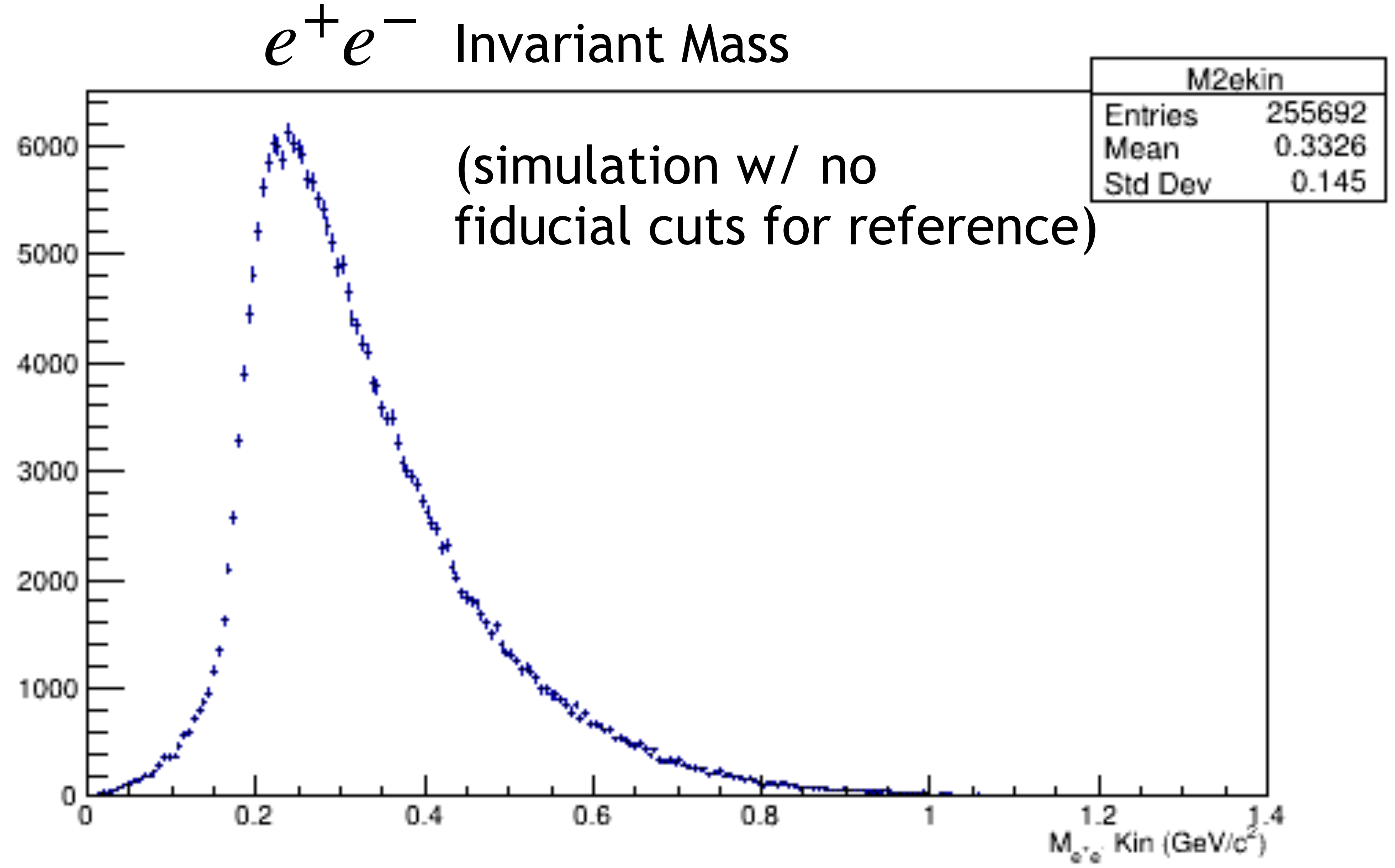
$$d\sigma = \frac{Z^2}{137}\frac{e^4}{4\pi^2}\frac{p_+p_-dE_+d\Omega_+d\Omega_-}{k^3q^4}\left\{\frac{(\boldsymbol{\varepsilon}\cdot\mathbf{p}_+)^2(q^2-4E_-^2)}{(E_+-p_+\cos\theta_+)^2} + \frac{(\boldsymbol{\varepsilon}\cdot\mathbf{p}_-)^2(q^2-4E_+^2)}{(E_--p_-\cos\theta_-)^2} - \frac{2(\boldsymbol{\varepsilon}\cdot\mathbf{p}_+)(\boldsymbol{\varepsilon}\cdot\mathbf{p}_-)(q^2+4E_+E_-)}{(E_+-p_+\cos\theta_+)(E_--p_-\cos\theta_-)} + \frac{k^2[p_+^2\sin^2\theta_+ + p_-^2\sin^2\theta_- + 2p_+p_-\sin\theta_+\sin\theta_-\cos(\varphi_+-\varphi_-)]}{(E_+-p_+\cos\theta_+)(E_--p_-\cos\theta_-)}\right\}.$$

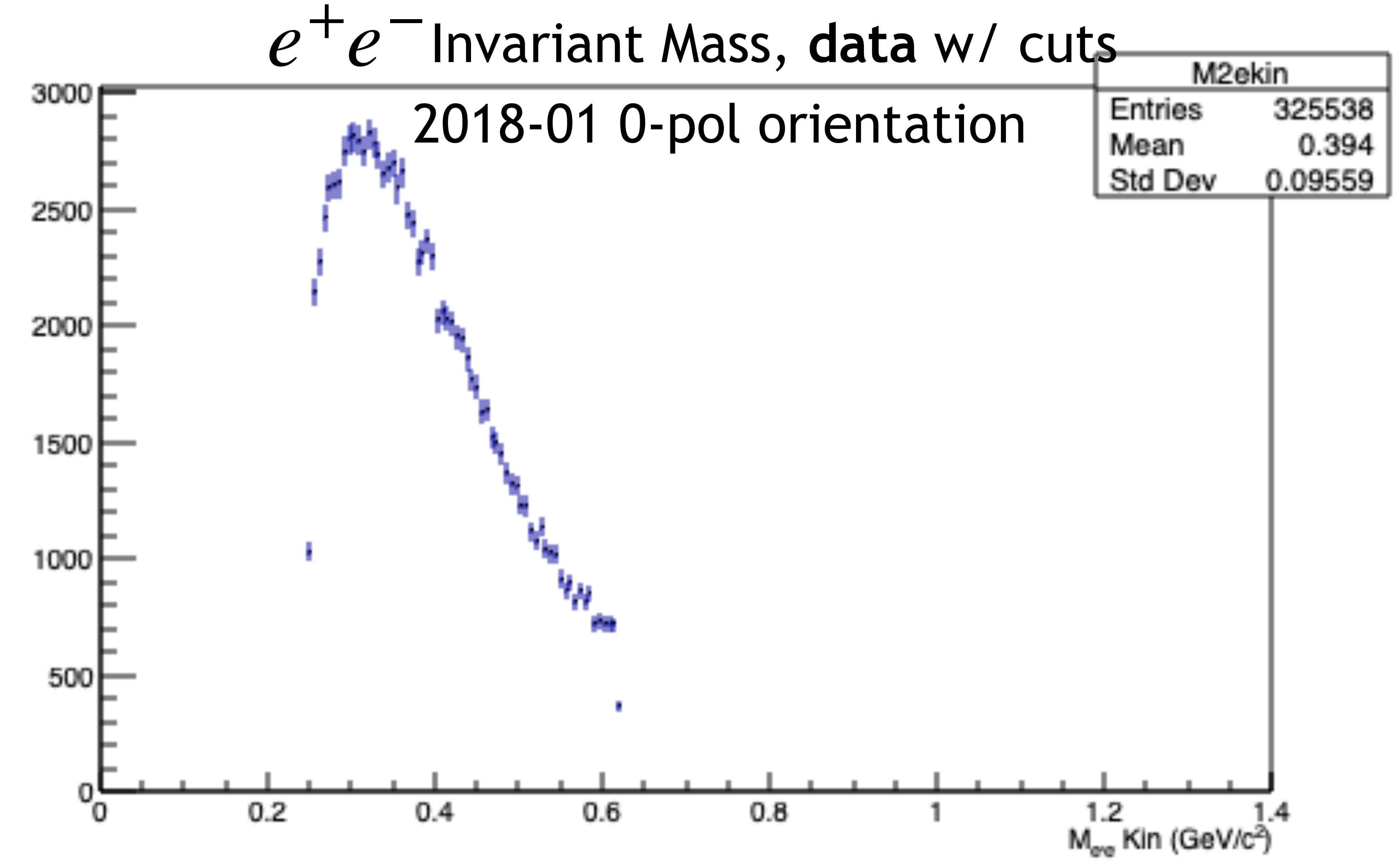
1. Generate e+e- 4 vectors using this cross section

2. Plot ϕ_{J_T} from the 4 vectors

3. Measuring ϕ_{J_T} allows you to infer the beam polarization

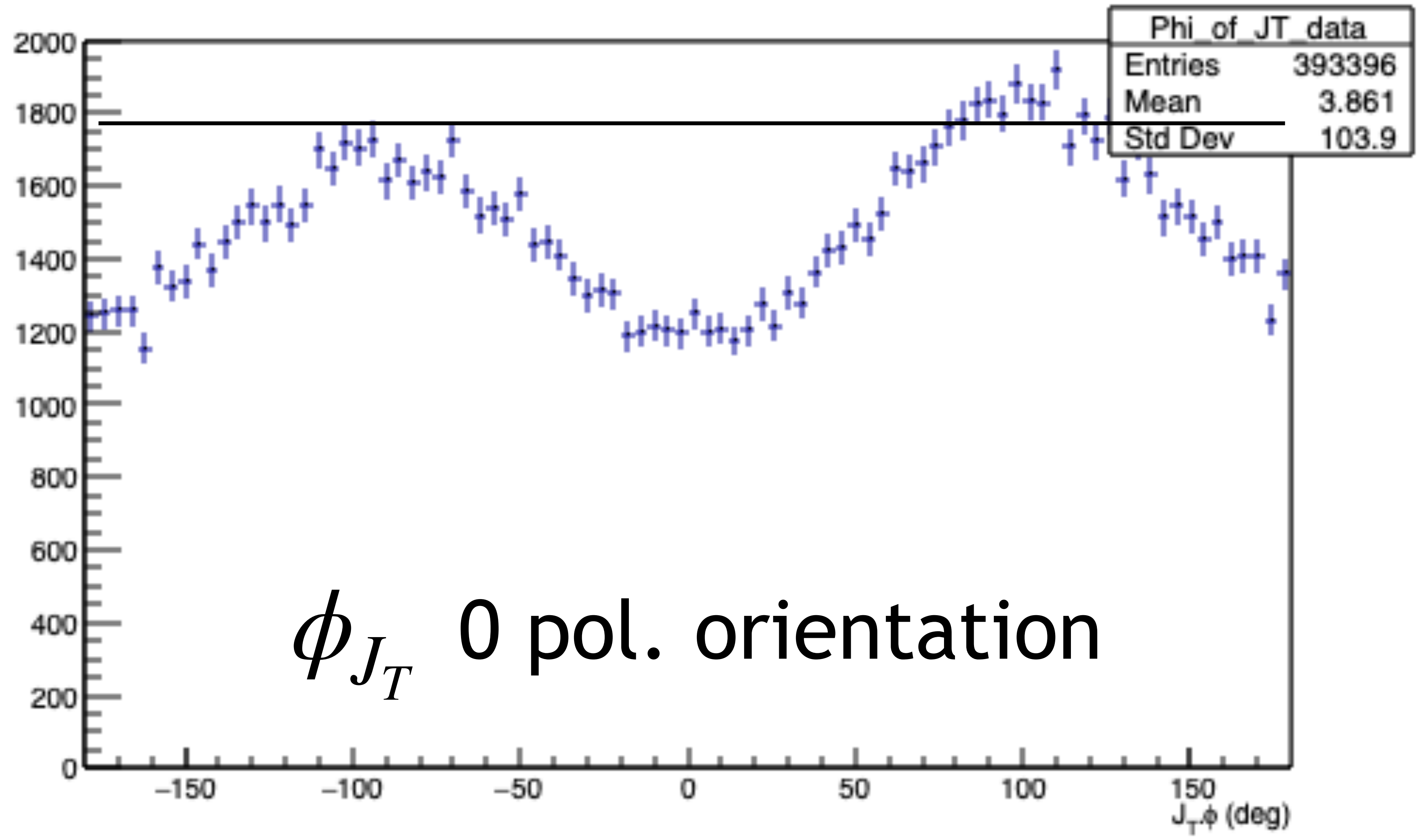
2018-01 GlueX data
$\gamma p \rightarrow e^+e^-(p)$ Reaction Filter

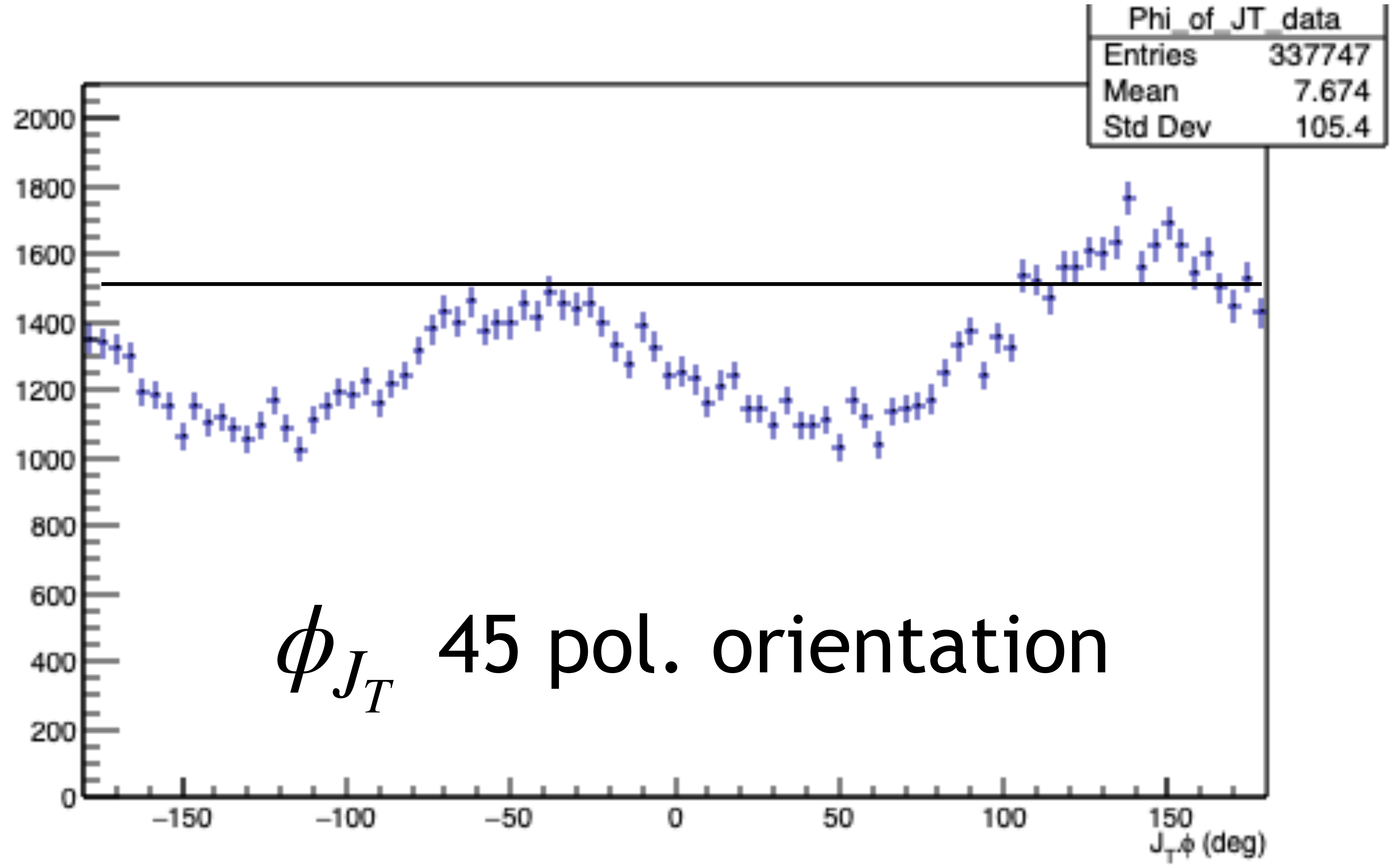


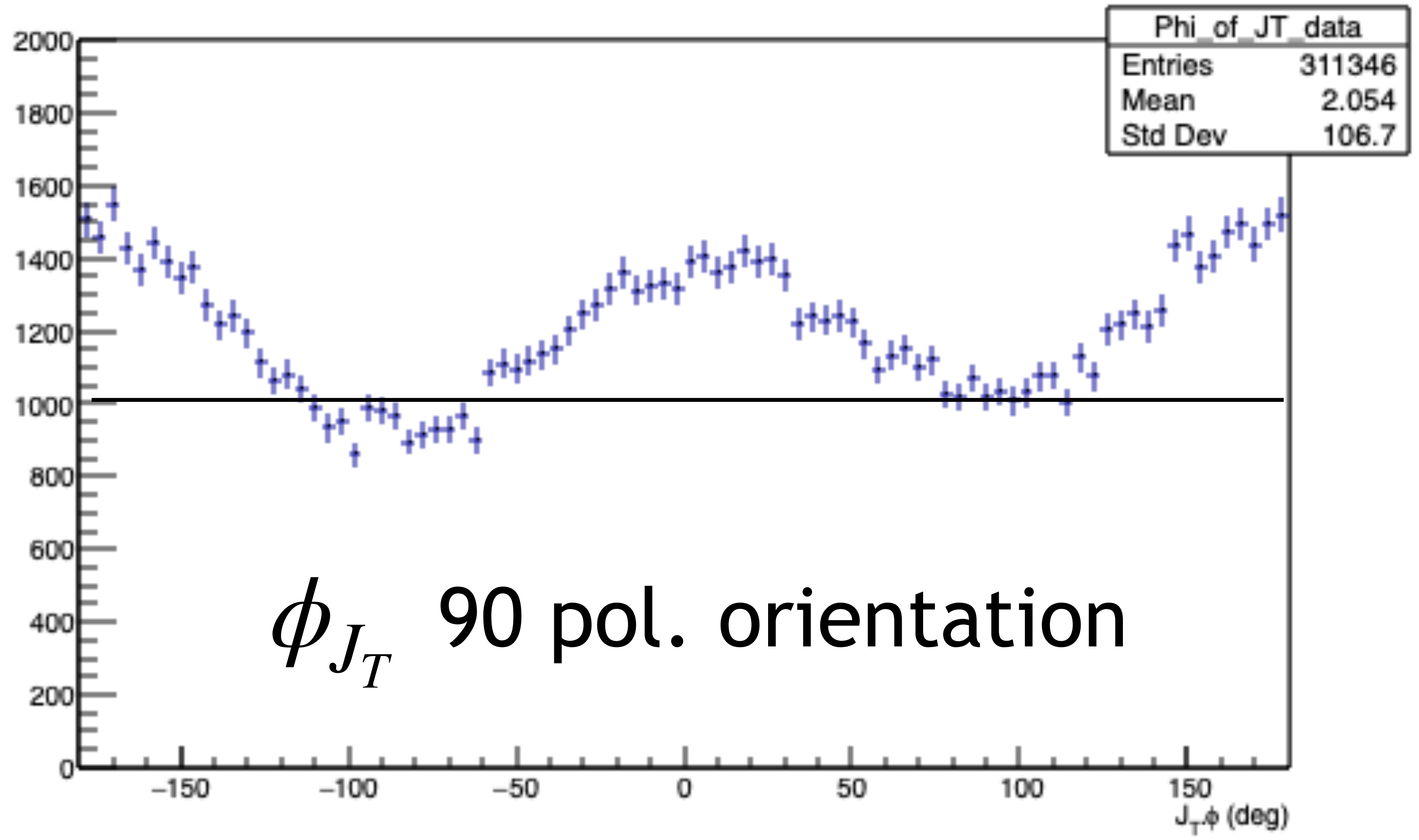


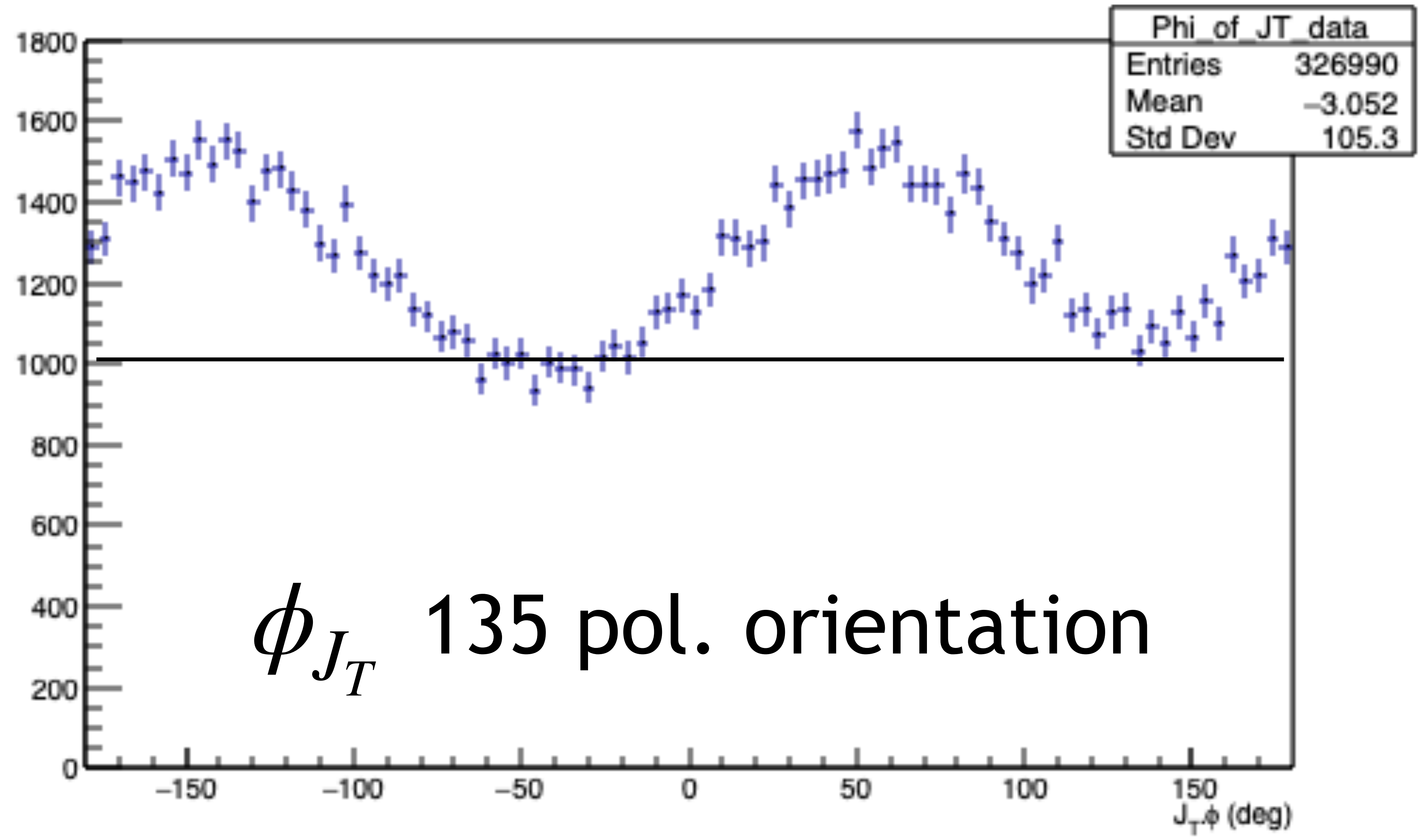
Neural Net Cuts:
Neural Net Classification Cuts (NN1, NN2 < 0.2)
Fiducial Cuts:
$8.2\,\text{GeV} < E_\gamma < 8.8\,\text{GeV}$
$0.25\,\text{GeV} < W_{ee} < 0.621\,\text{GeV}$
Both tracks have hits in the TOF
$\theta_1, \theta_2 > 1.5\,\text{deg}$
FCAL Elasticity > 0.9
Vertex cut (Window free): 52 < z < 78 cm

$\gamma p \rightarrow e^+e^-(p)$ 2018-01 GlueX data, w/ fiducial+N.N. cuts









$$\frac{Y_\perp(\phi) - \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)}{Y_\perp + \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)} = \frac{\Sigma \cos 2\phi (P_\perp + P_\parallel)}{2 + \Sigma \cos 2\phi (P_\perp - P_\parallel)}$$

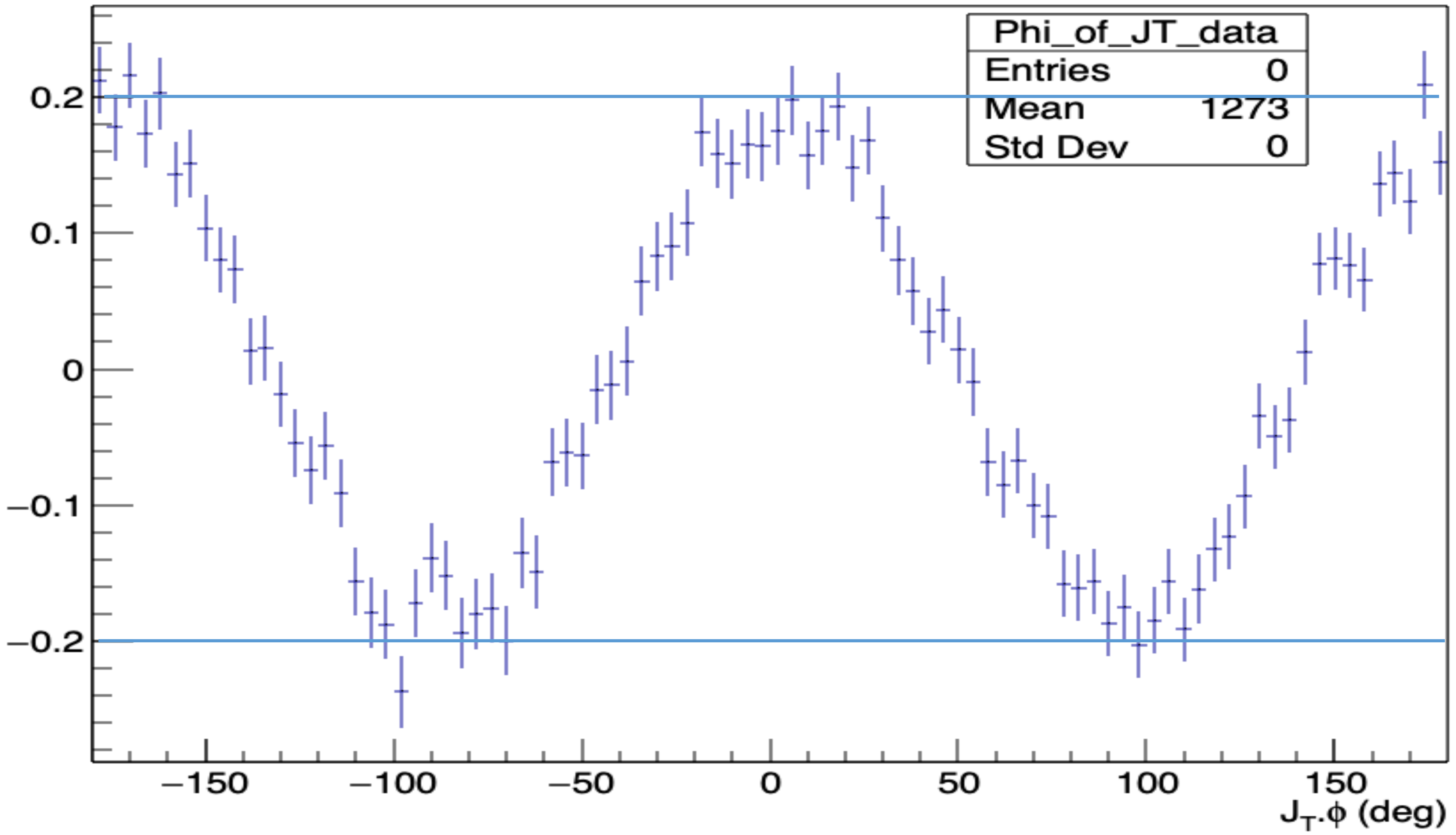
$$N_\perp = 311346 \qquad \frac{N_\perp}{N_\parallel} = 0.9564$$

$$N_\parallel = 325538$$

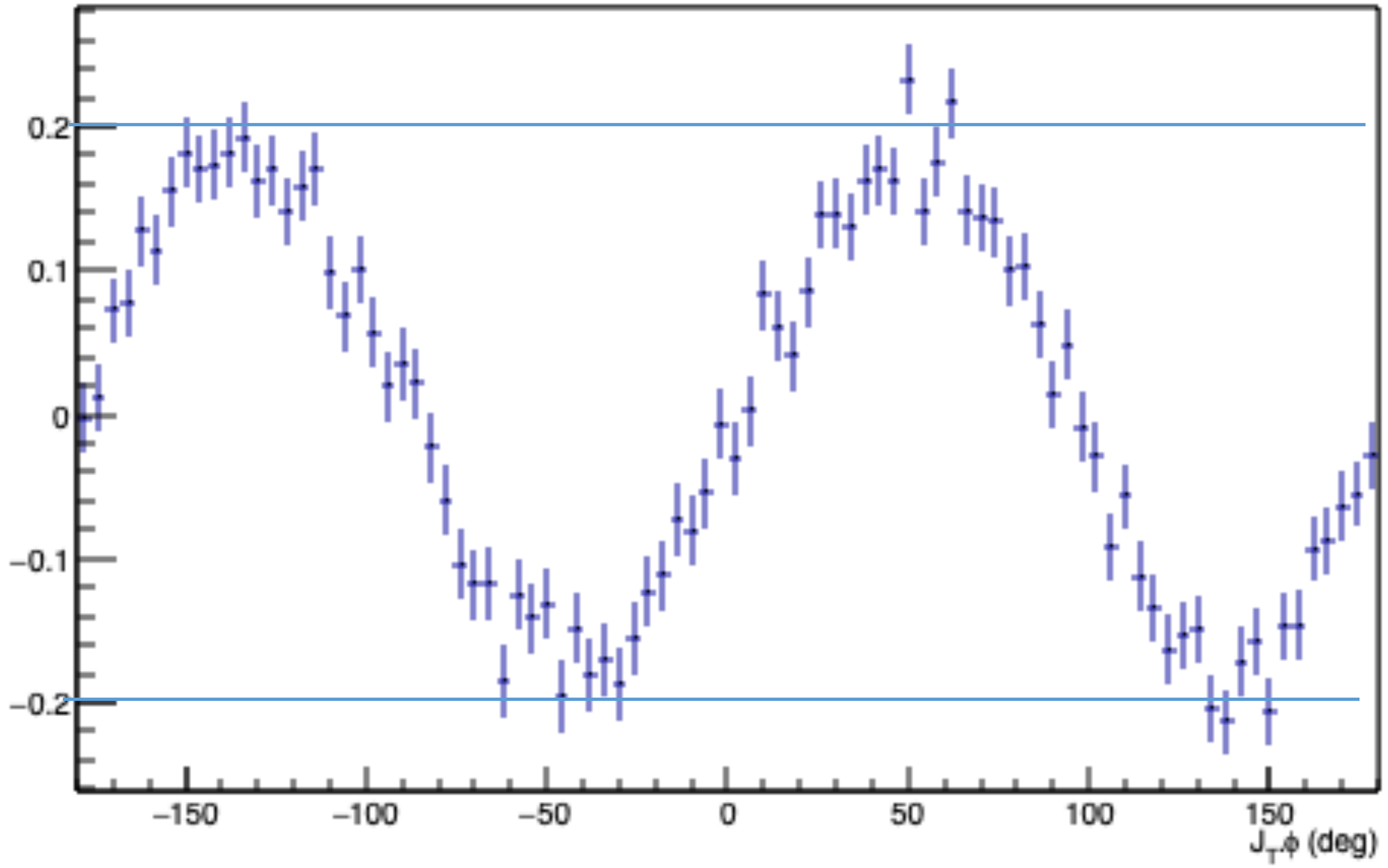
2018-01 GlueX data, $\gamma p \rightarrow e^+ e^- (p)$

Yield Asymmetry

0/90 runs



45/135 runs

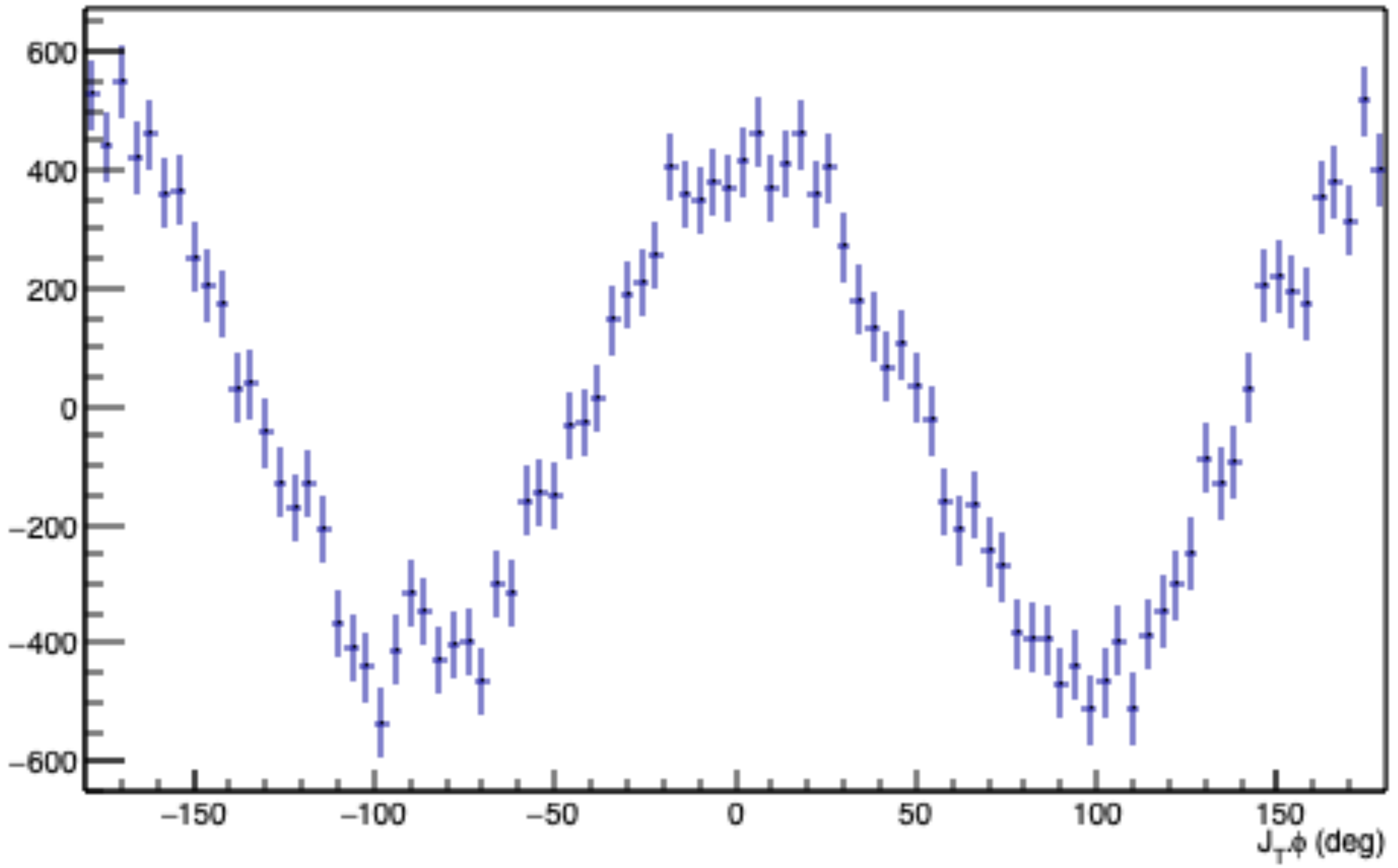


2018-01 GlueX data, $\gamma p \to e^+e^-(p)$

0/90 pol. Orientation

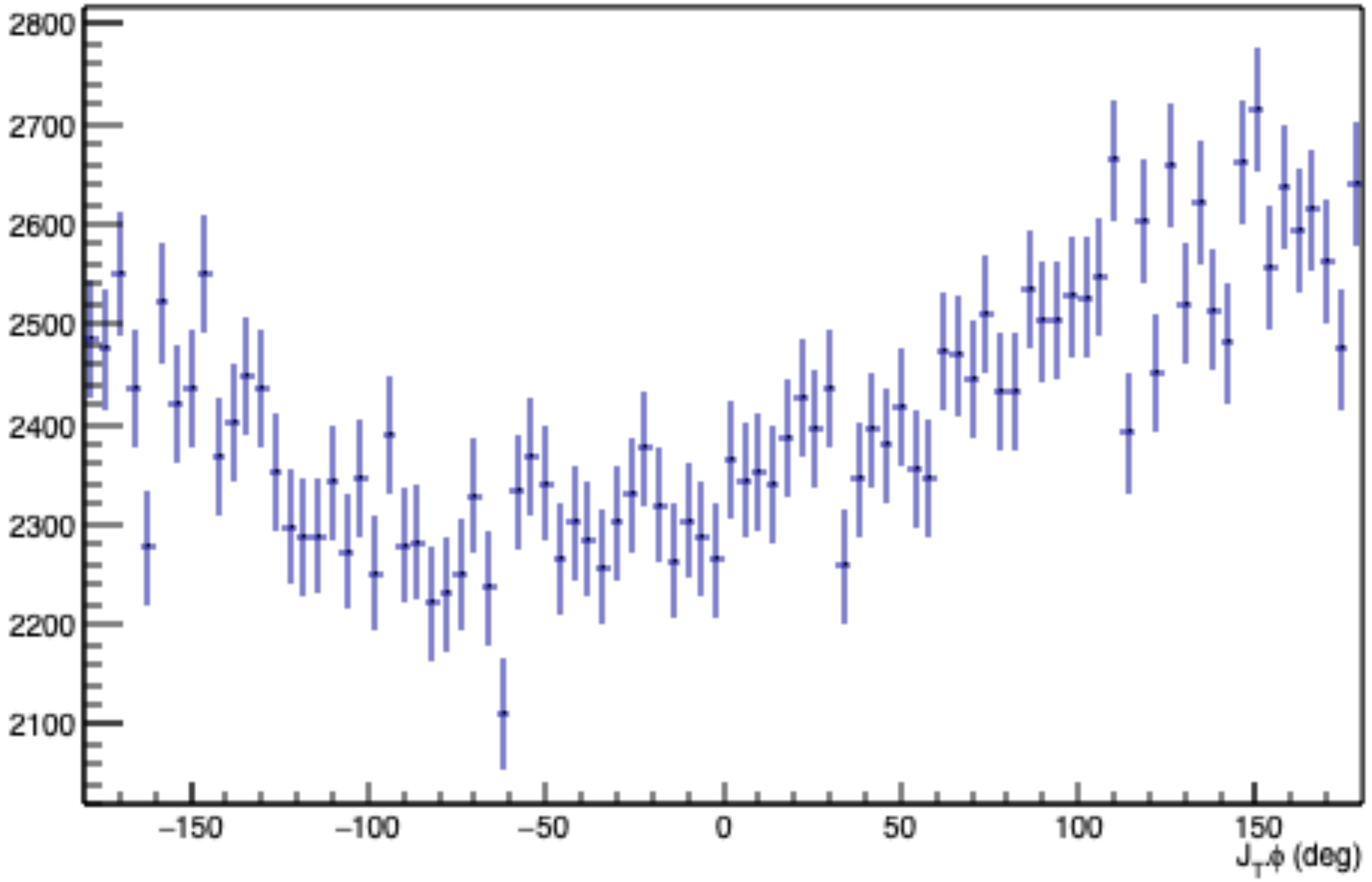
Just Numerator

$$Y_\perp(\phi) - \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)$$



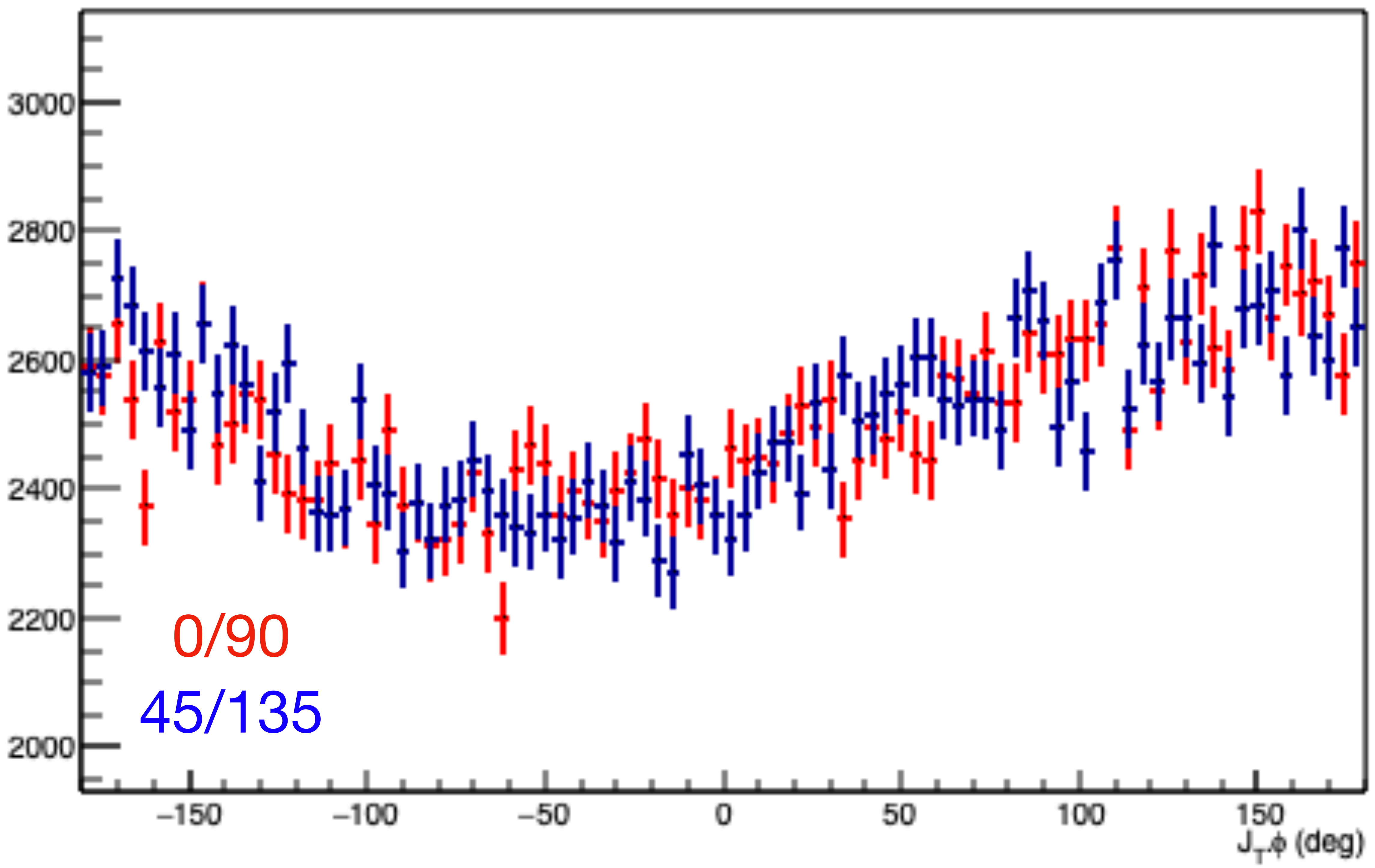
Just Denominator

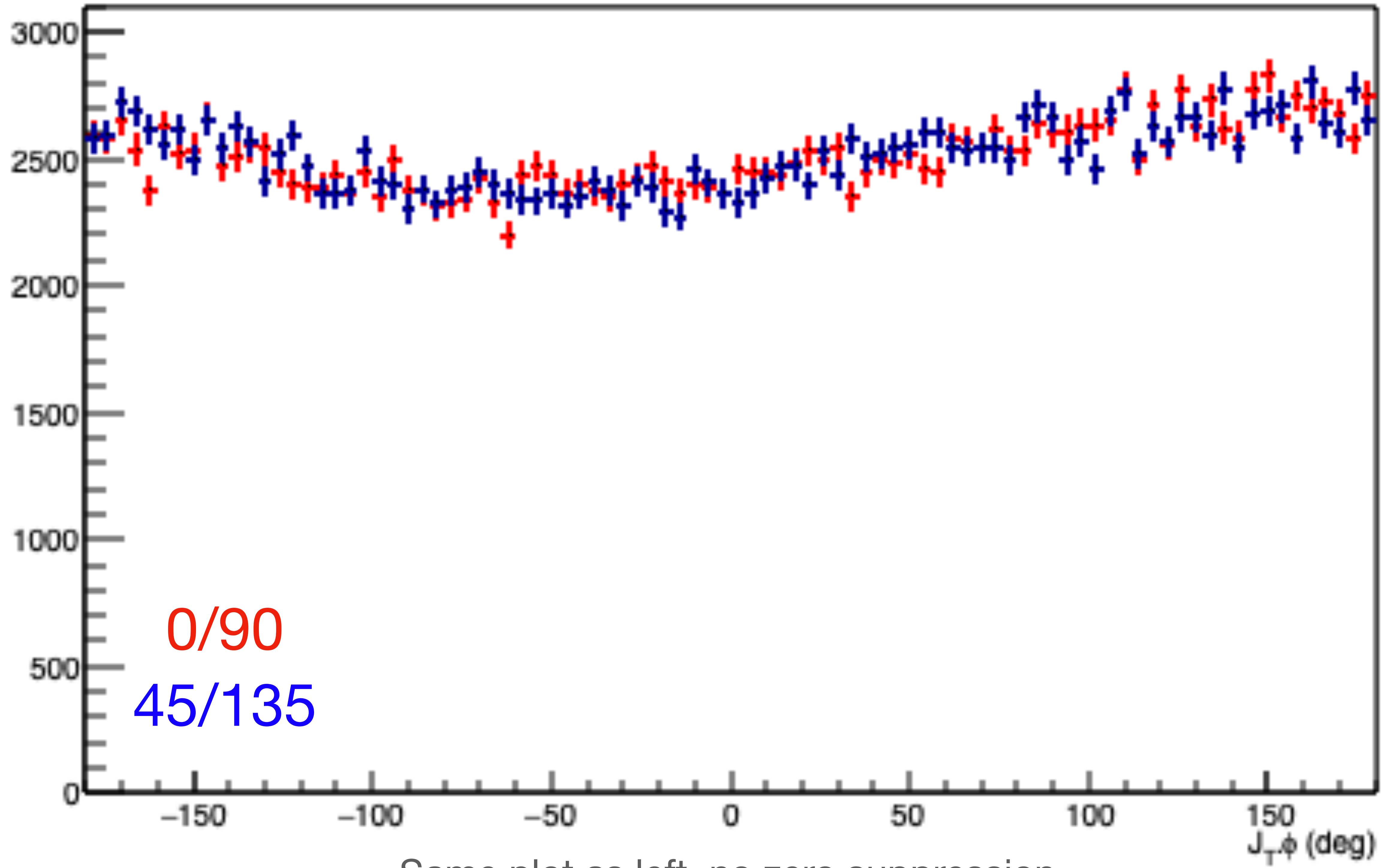
$$Y_\perp(\phi) + \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)$$



Just Denominator

$$Y_{\perp}(\phi) + \frac{N_{\perp}}{N_{\parallel}} Y_{\parallel}(\phi)$$



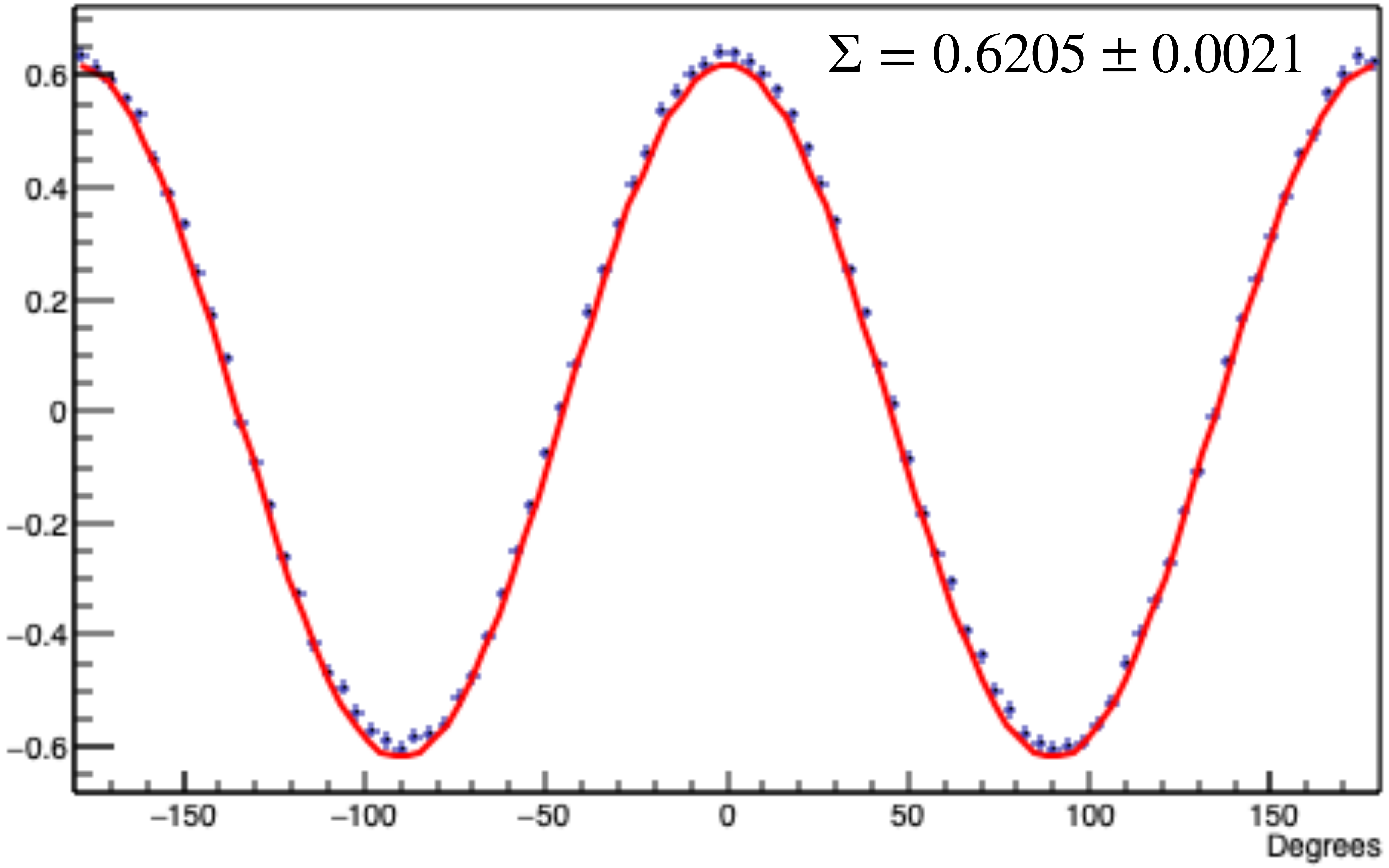


Same plot as left, no zero suppression

$$\frac{Y_\perp(\phi) - Y_\parallel(\phi)}{Y_\perp + Y_\parallel(\phi)} = \Sigma \cos 2\phi$$

$$\frac{Y_\perp(\phi) - \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)}{Y_\perp + \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)} = \frac{\Sigma \cos 2\phi (P_\perp + P_\parallel)}{2}$$

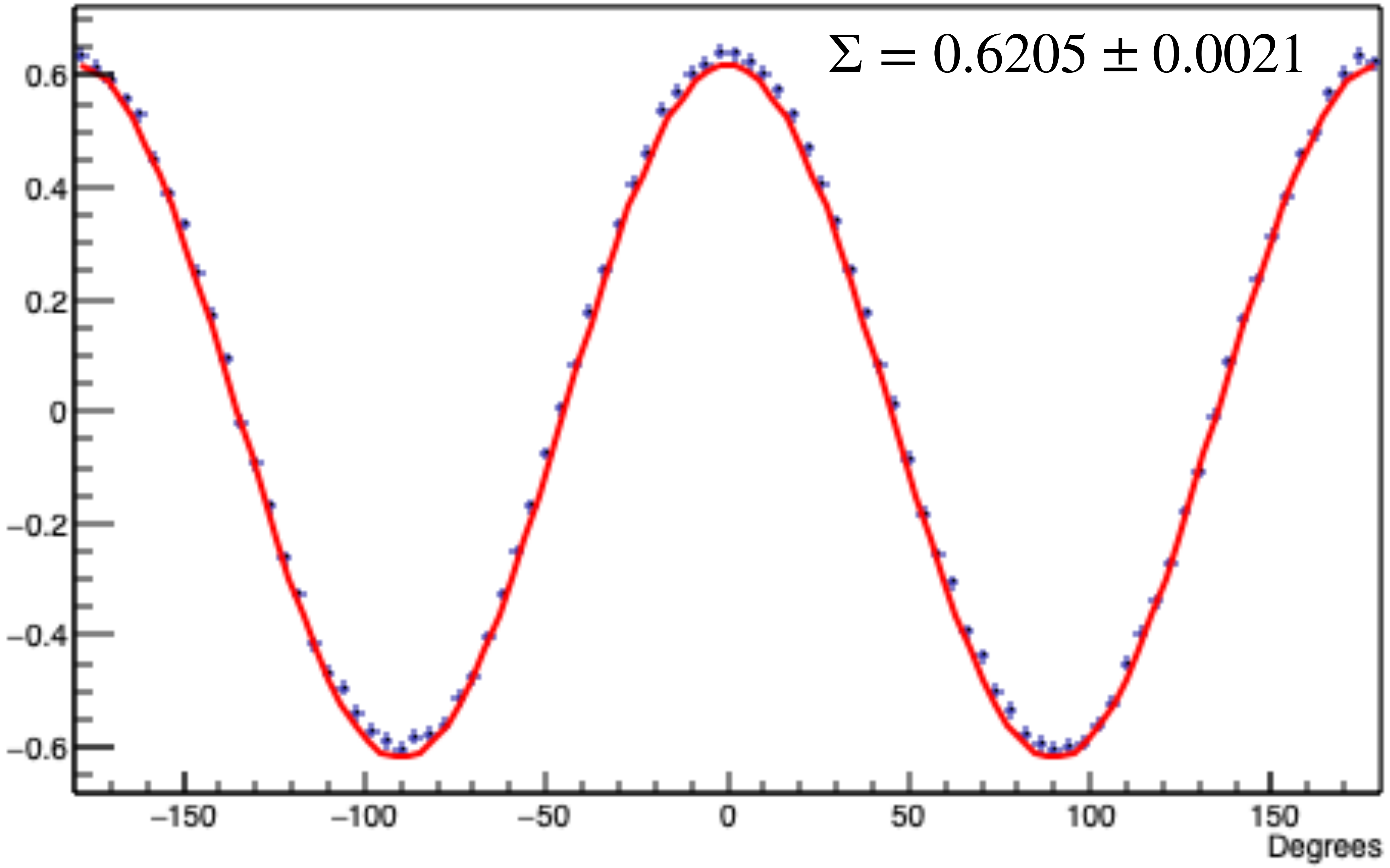
Simulated Yield Asymmetry



$$\frac{Y_\perp(\phi) - Y_\parallel(\phi)}{Y_\perp + Y_\parallel(\phi)} = \Sigma \cos 2\phi$$

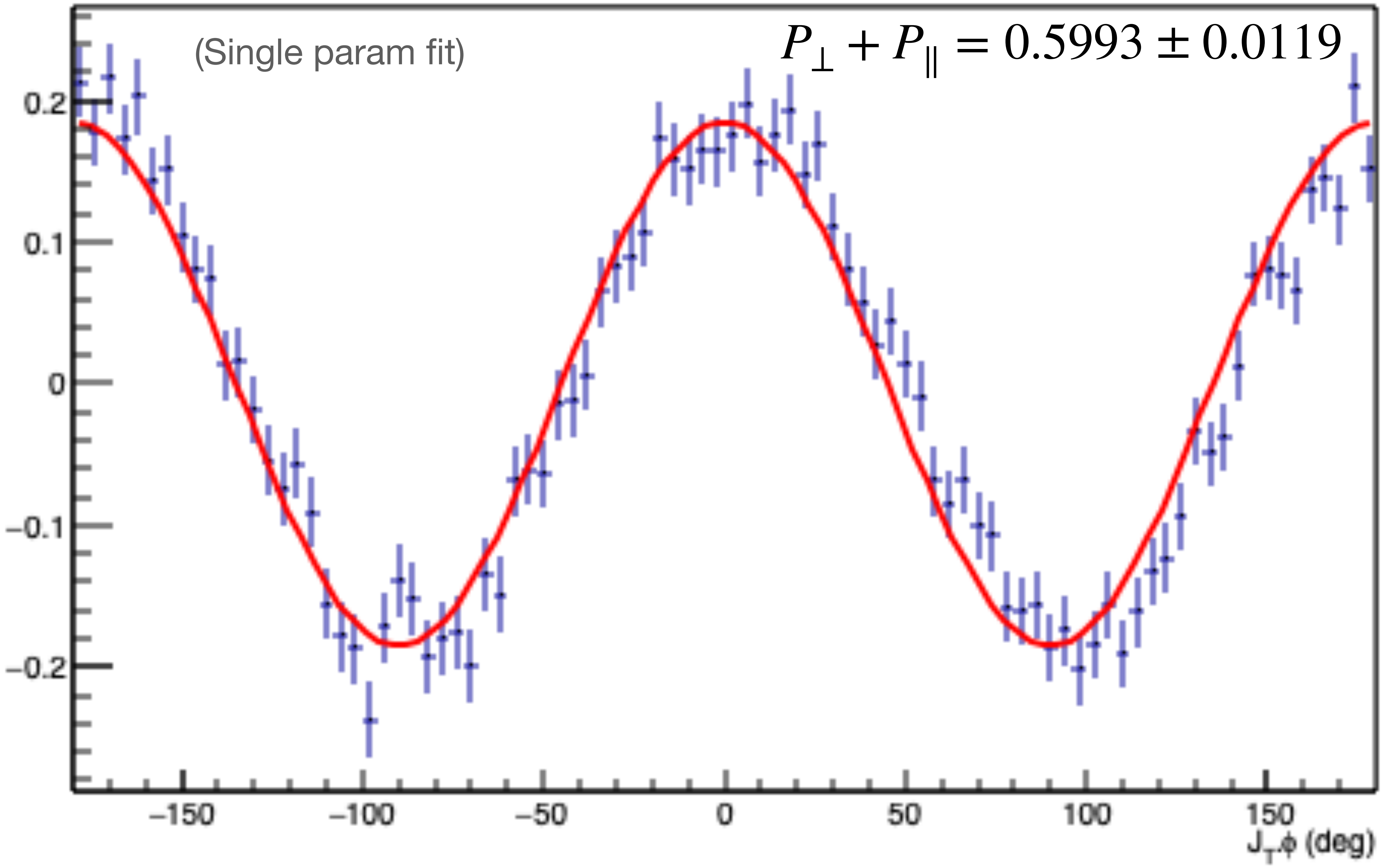
$$\frac{Y_\perp(\phi) - \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)}{Y_\perp + \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)} = \frac{\Sigma \cos 2\phi (P_\perp + P_\parallel)}{2}$$

Simulated Yield Asymmetry



2018-01 Pol = 0 and 90 runs

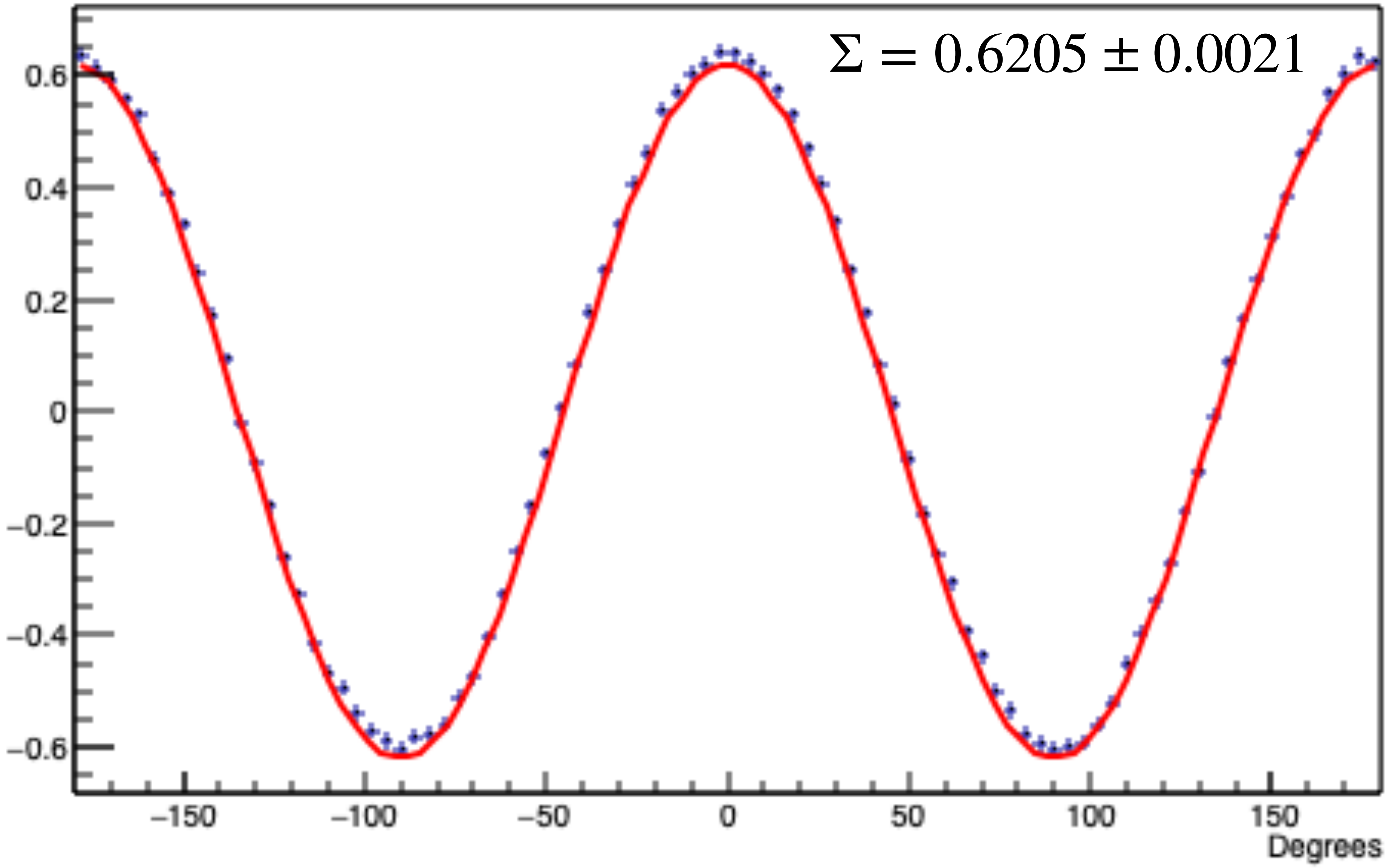
Data Yield Asymmetry



$$\frac{Y_\perp(\phi) - Y_\parallel(\phi)}{Y_\perp + Y_\parallel(\phi)} = \Sigma \cos 2\phi$$

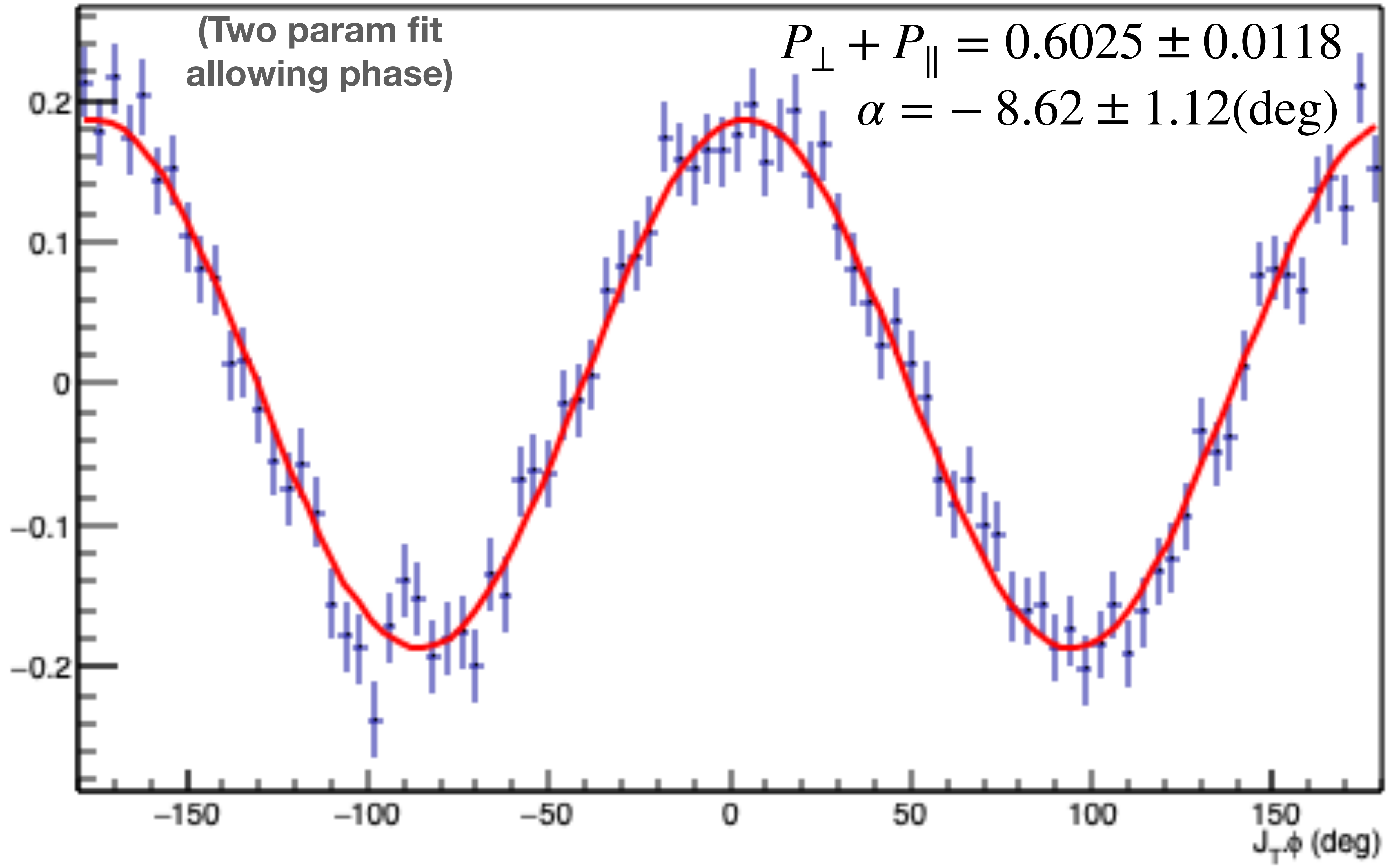
$$\frac{Y_\perp(\phi) - \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)}{Y_\perp + \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)} = \frac{\Sigma \cos(2\phi + \alpha)(P_\perp + P_\parallel)}{2}$$

Simulated Yield Asymmetry



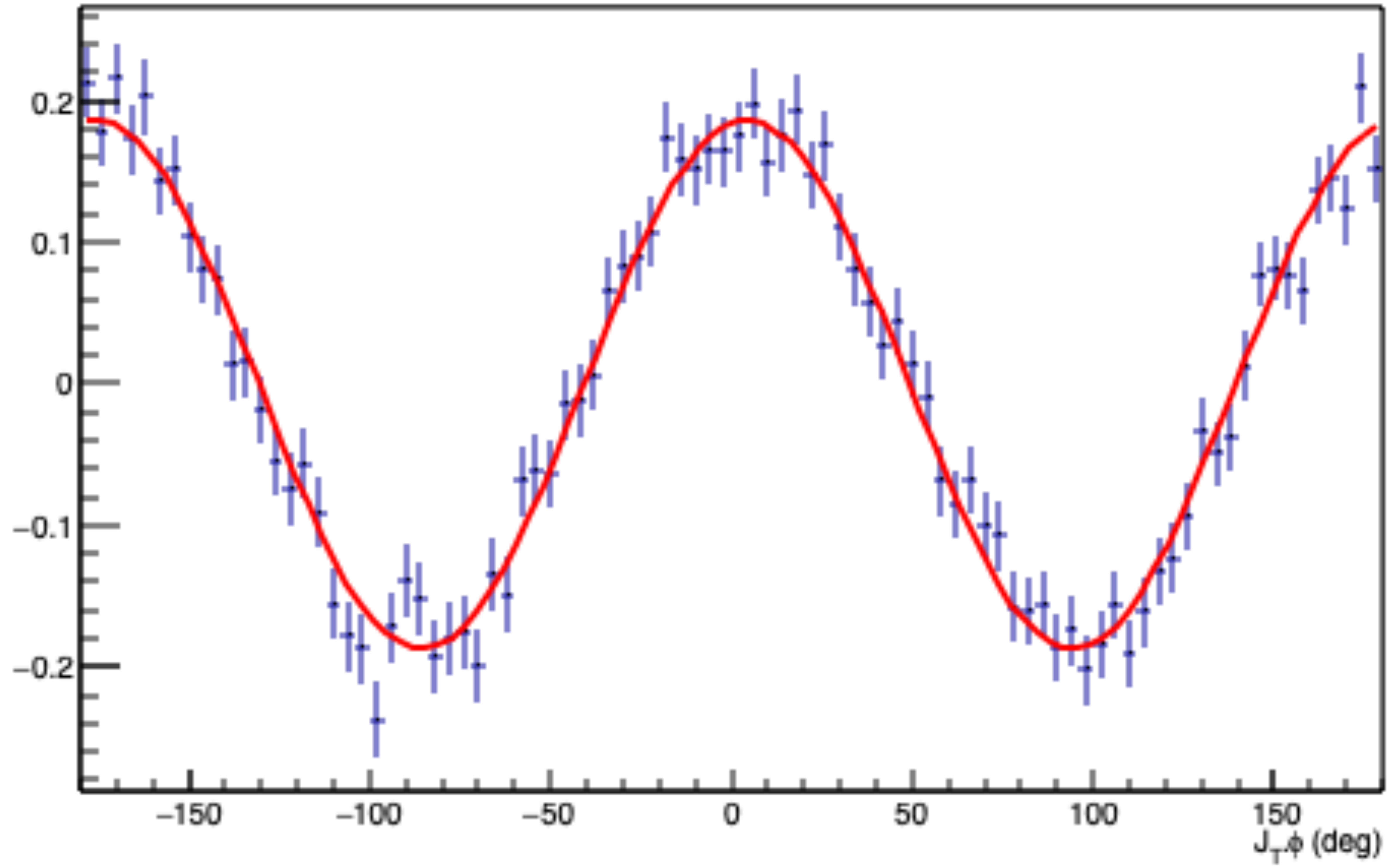
2018-01 Pol = 0 and 90 runs

Data Yield Asymmetry



$$\frac{Y_\perp(\phi) - \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)}{Y_\perp + \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)} = \frac{\Sigma \cos(2\phi + \alpha)(P_\perp + P_\parallel)}{2 + \Sigma \cos(2\phi + \alpha)(P_\perp - P_\parallel)}$$

0 and 90 Yield Asymmetry



$P_\perp + P_\parallel = 0.6025 \pm 0.011$ $\quad \alpha = -8.62 \pm 1.12(\text{deg})$

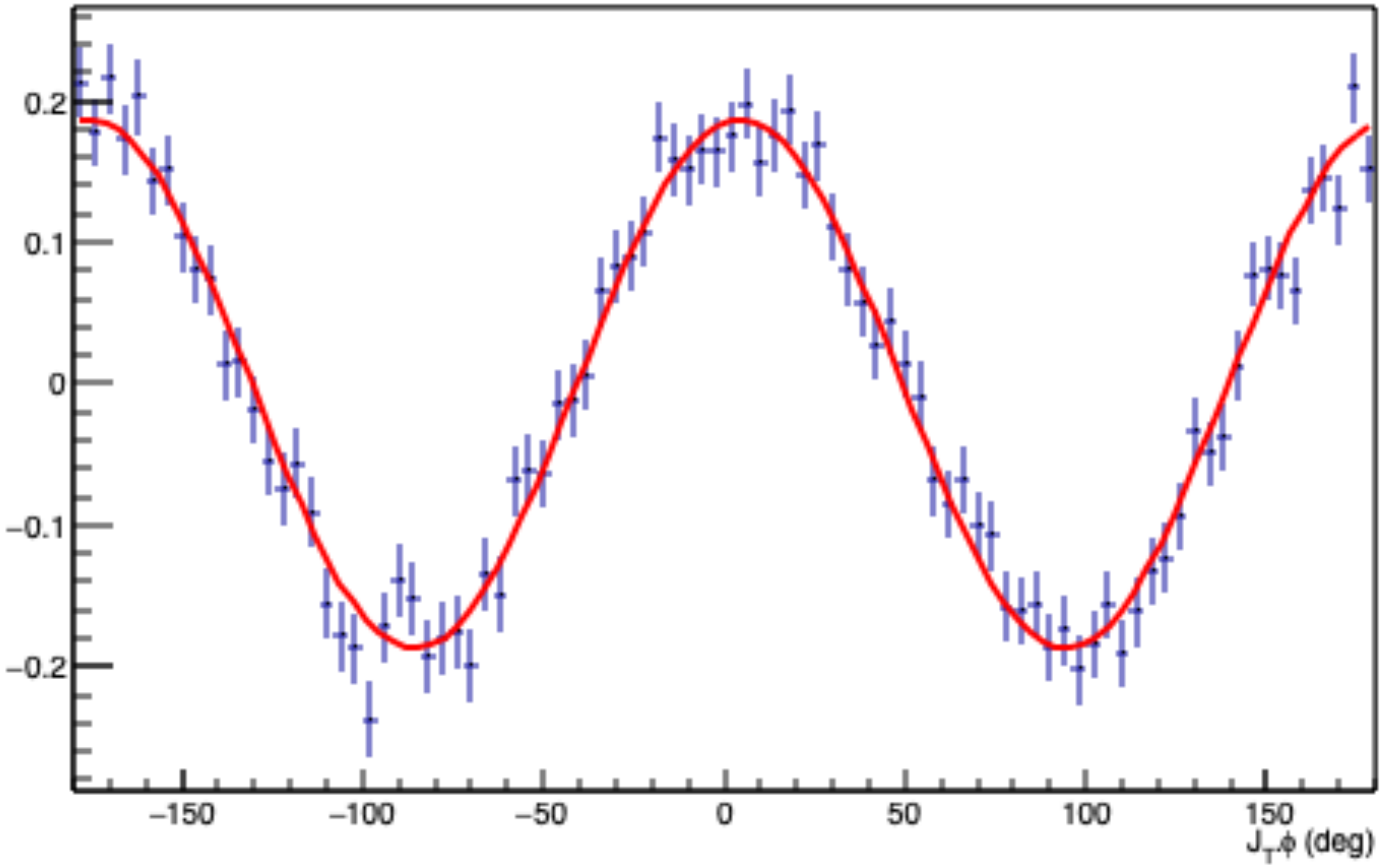
$P_\perp - P_\parallel = 0.0091 \pm 0.0737$

Nothing to be gained from trying to fit $(P_\perp - P_\parallel)$. It is effectively 0.

2018-01 GlueX data, $\gamma p \to e^+e^-(p)$, ϕ_{J_T} Yield Asymmetry

$$\frac{Y_\perp(\phi) - \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)}{Y_\perp + \frac{N_\perp}{N_\parallel} Y_\parallel(\phi)} = \frac{\Sigma \cos(2\phi + \alpha)(P_\perp + P_\parallel)}{2}$$

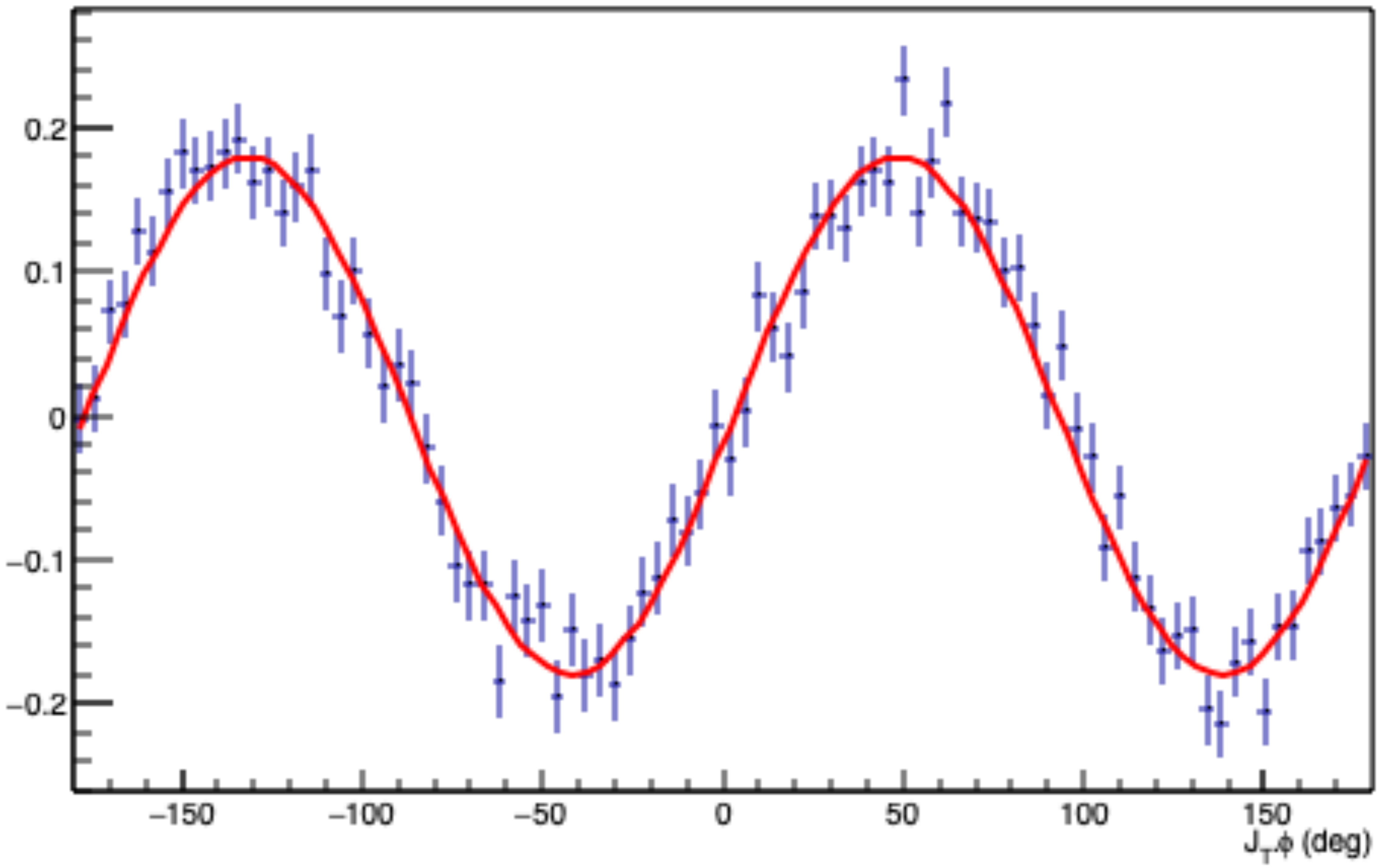
0/90



$P_\perp + P_\parallel = 0.6025 \pm 0.0118$

$\alpha = -8.62 \pm 1.12$(deg)

45/135



$P_\perp + P_\parallel = 0.5789 \pm 0.0116$

$\alpha = 83.53 \pm 1.14$(deg)

SUMMARY SO FAR

TPOL expected polarization for energy range $8.2 < E_\gamma < 8.8$ $\bar{\mathscr{P}}_\gamma = 0.3399 \pm 0.0125$

Chisq method: Measured with ϕ of J_T, pol 0 config runs $\mathscr{P}_\gamma = 0.2860 \pm 0.0016$

Yield asymmetry method: Average polarization between 0 and 90 runs: $\frac{\mathscr{P}_\perp + \mathscr{P}_\parallel}{2} = 0.0301 \pm 0.0060$

Yield asymmetry method: Average polarization between 45 and 135 runs: $\frac{\mathscr{P}_\perp + \mathscr{P}_\parallel}{2} = 0.2895 \pm 0.0058$

Backup Slides

TPOL Value for the BH events

```
*************************************************************
 Polarization values for E_gamma between 8.2 and 8.8 GeV
-------------------------------------------------------------
        Beam orientation           Polarization
          0 degrees:            0.3420 +/- 0.0063
         45 degrees:            0.3474 +/- 0.0065
         90 degrees:            0.3478 +/- 0.0063
        135 degrees:            0.3517 +/- 0.0065
```

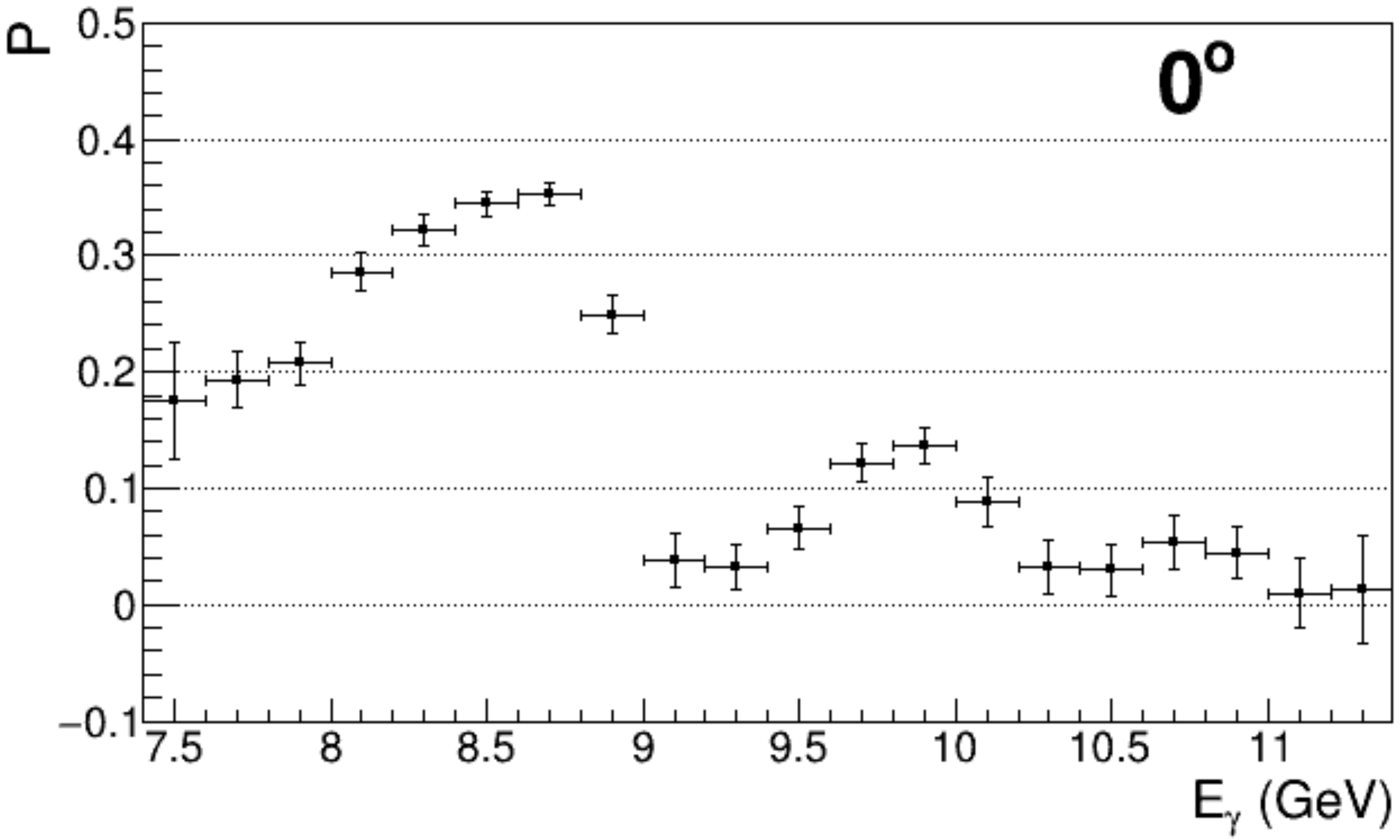
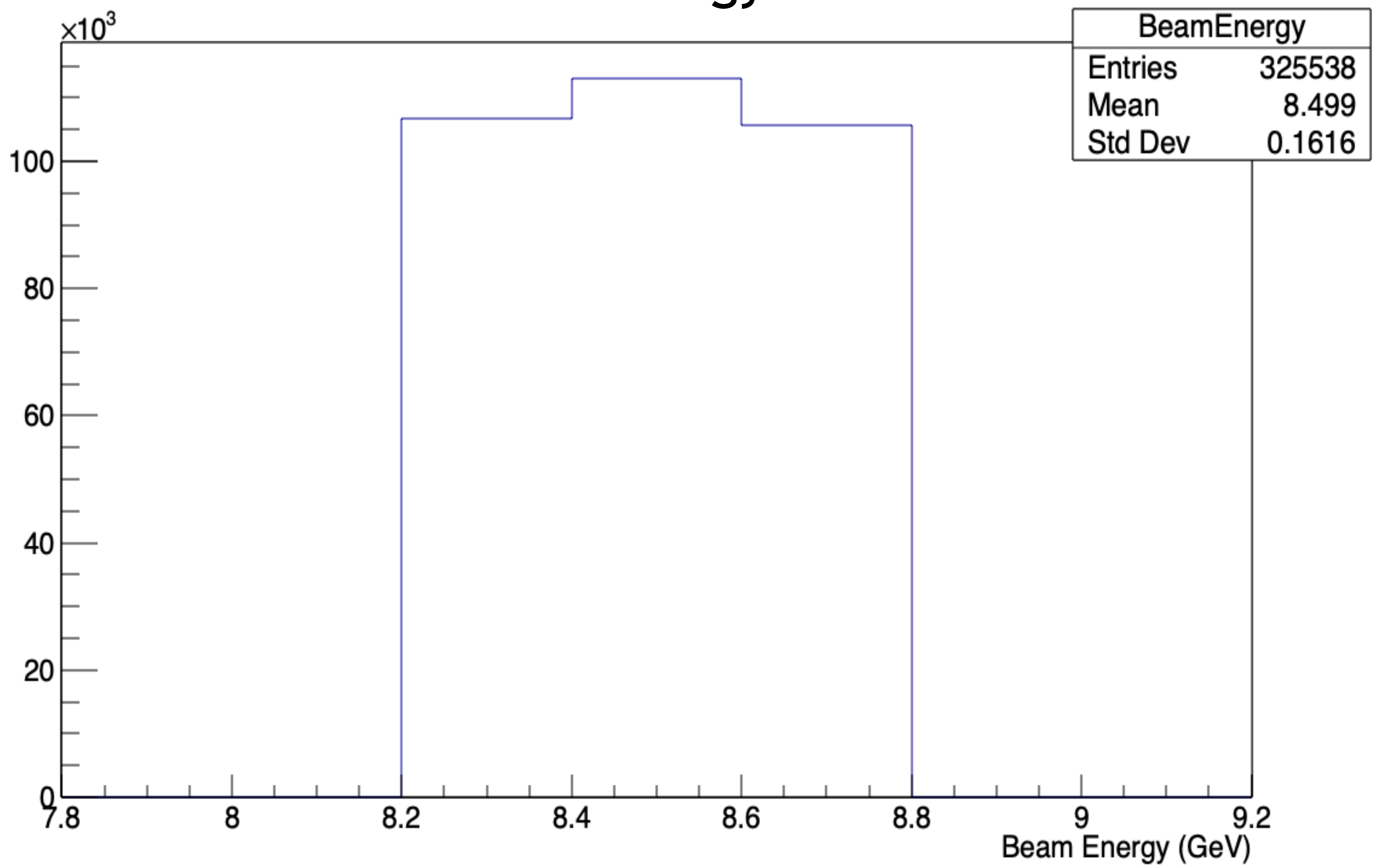


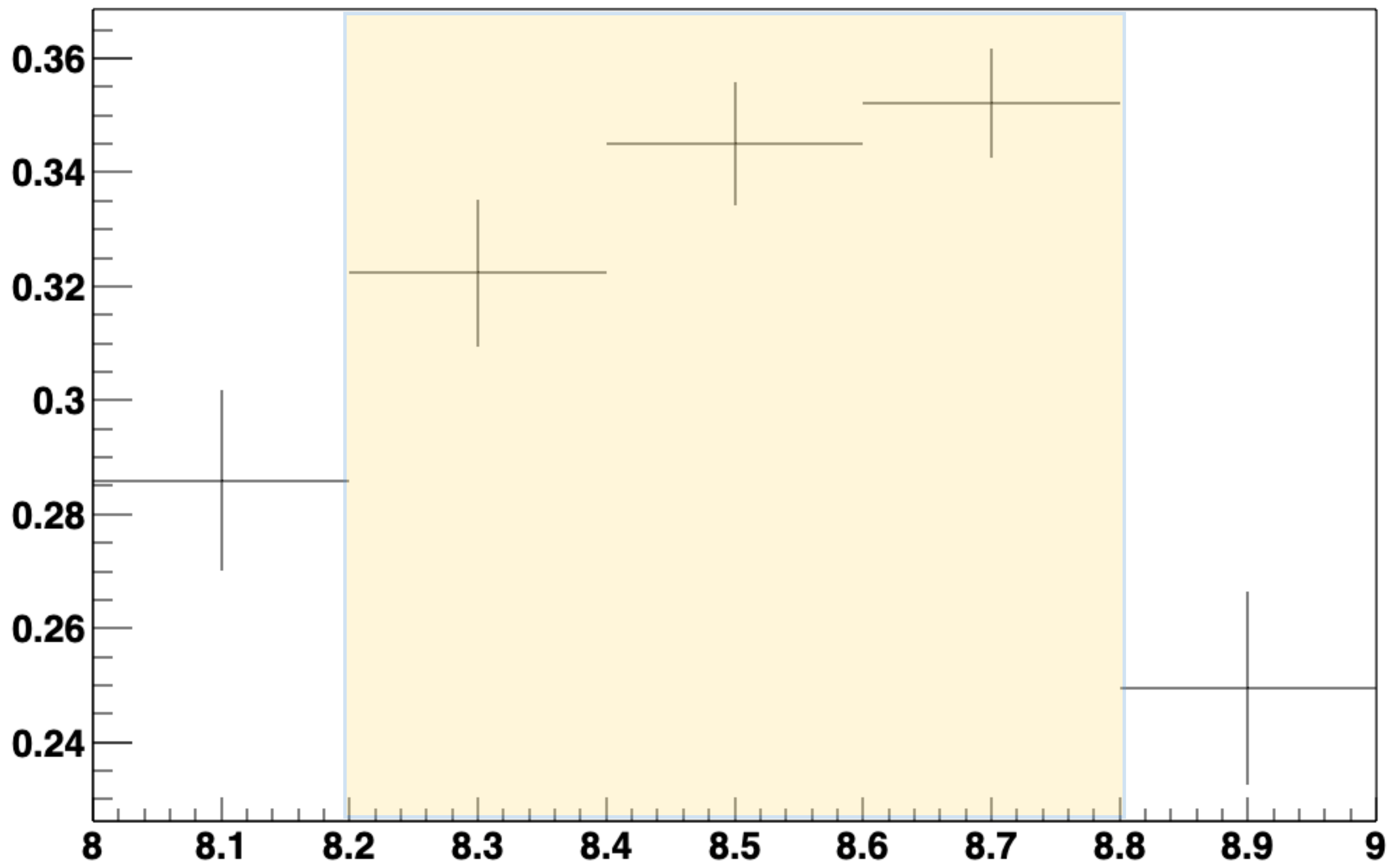
Table 1

8.3	106740
8.5	113046
8.7	105752

Bethe-Heitler Data
Beam Energy



8.2 to 8.8 Energy range

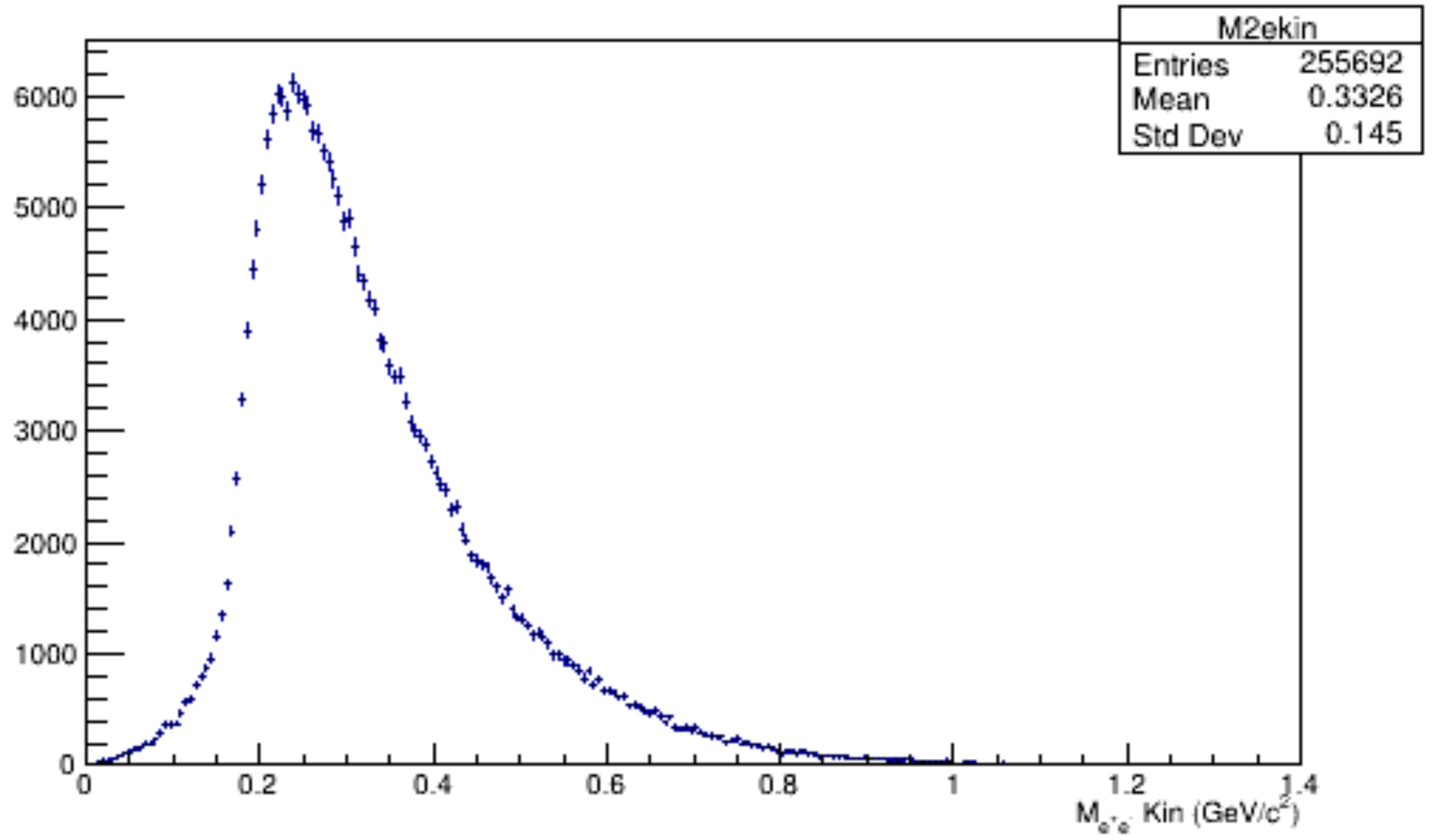


$$8.2 < E_\gamma < 8.8 \qquad \bar{\mathscr{P}}_\gamma = 0.3399 \pm 0.0125$$

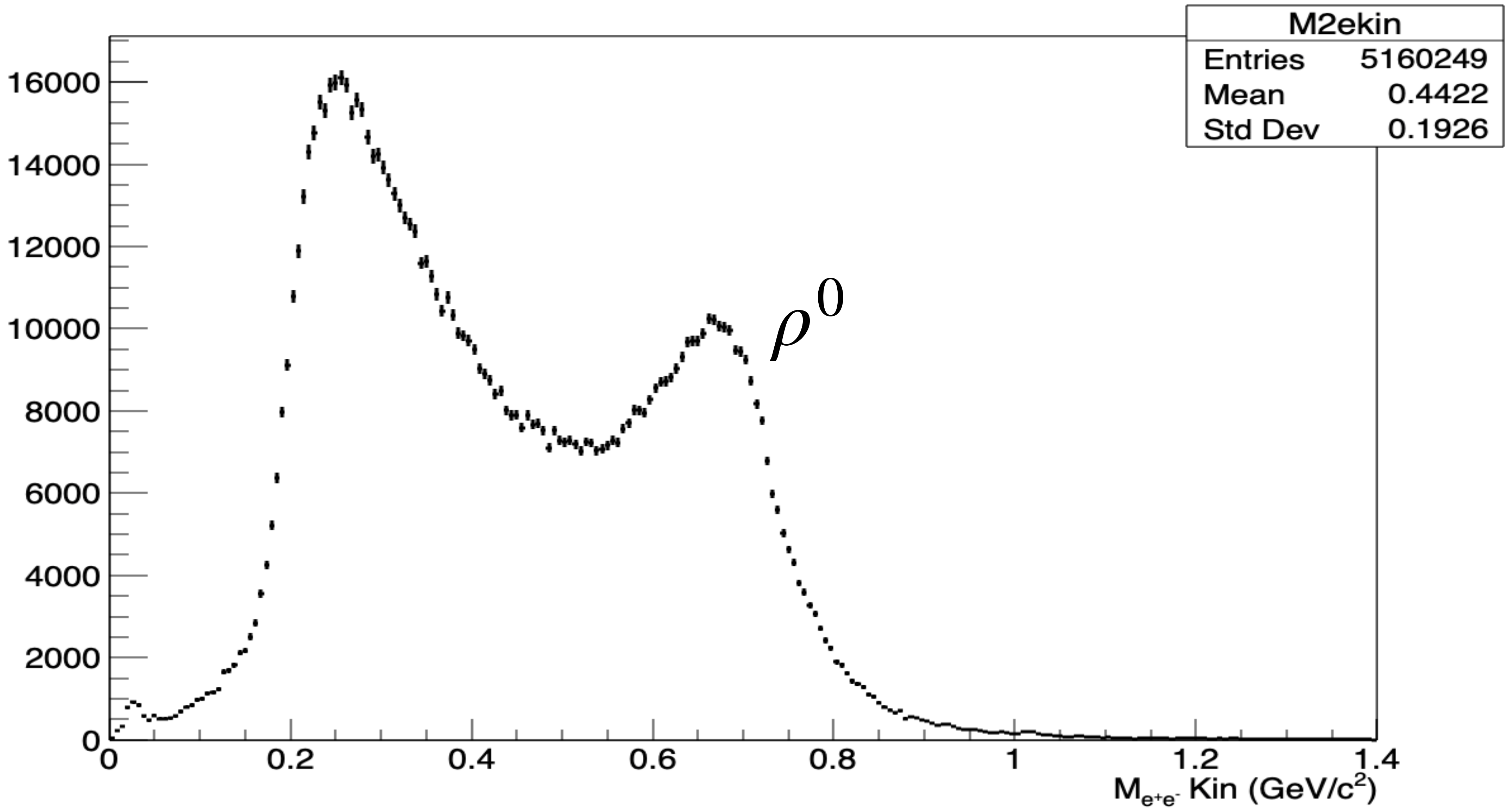
BH Event Selection w/ Neural Nets

Analyzing data

e^+e^- Invariant Mass (simulation)



e^+e^- Invariant Mass (data)



e/π separation using Machine Learning

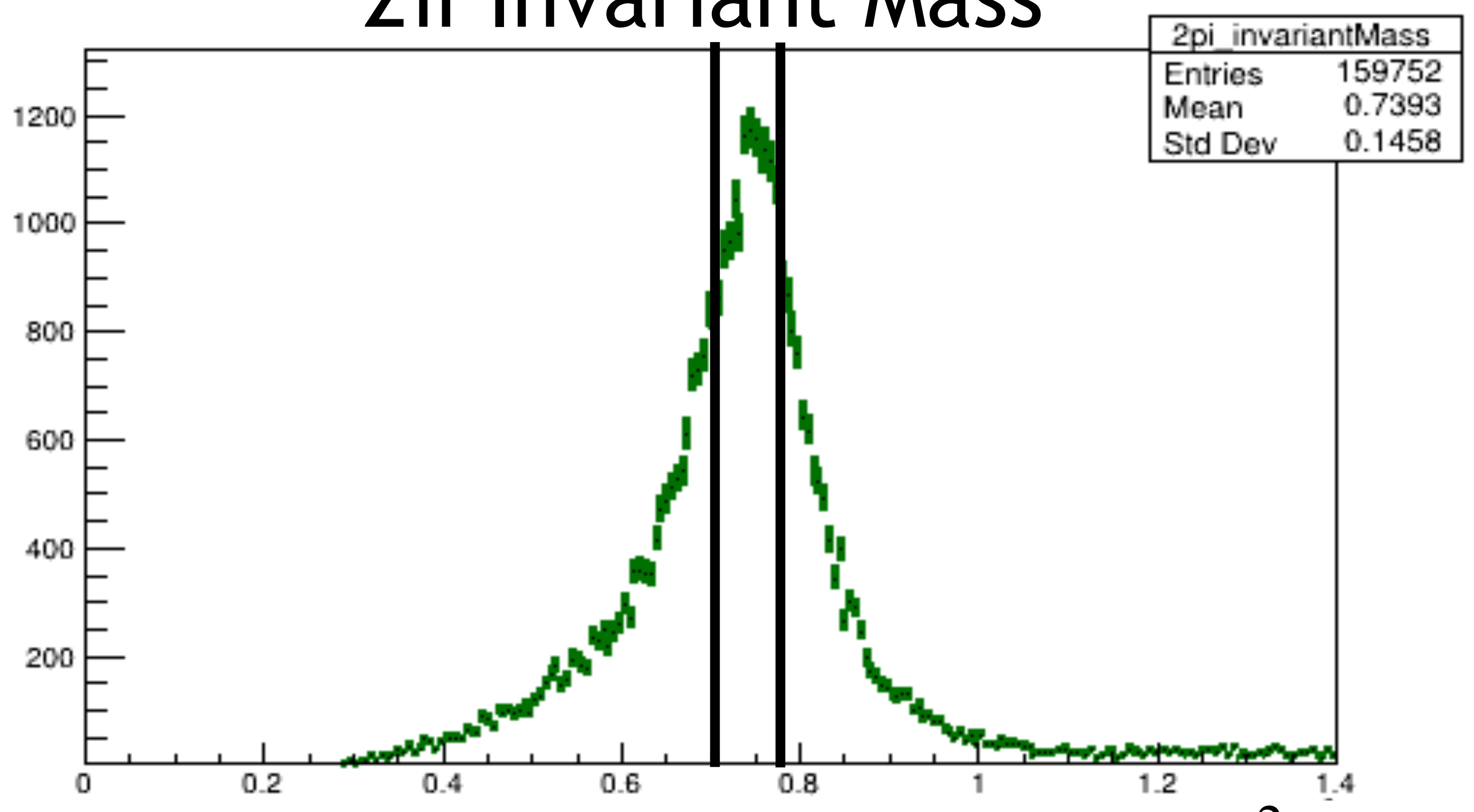
- ROOT's TMVA package
- Two multi-layer perceptron neural nets—one for e+/π+ separation, and one for e-/π-
  - Classify single tracks as e± or π±, but only keep for analysis events where *both* tracks pass as e+/e-, or π+/π-
- π+/π- signal training using GlueX 2018-01 ρ^0 data with $\gamma p \to \pi^+\pi^- p$ reaction filter, $700\text{ MeV} < W_{\pi\pi} < 770\text{ MeV}$
- e+/e- background training using Bethe-Heitler Monte Carlo, $\gamma p \to e^+e^-(p)$ reaction filter

Cuts for Training Samples

ρ^0 DATA, $\gamma p \to \pi^+\pi^- p$ (signal)

- Default GlueX analysis launch cuts
- 8.11 GeV $< E_\gamma < 8.88$ GeV
- TOF $dE/dx > 0$ for both tracks
- 700 MeV $< W_{\pi\pi} < 770$ MeV

2π Invariant Mass

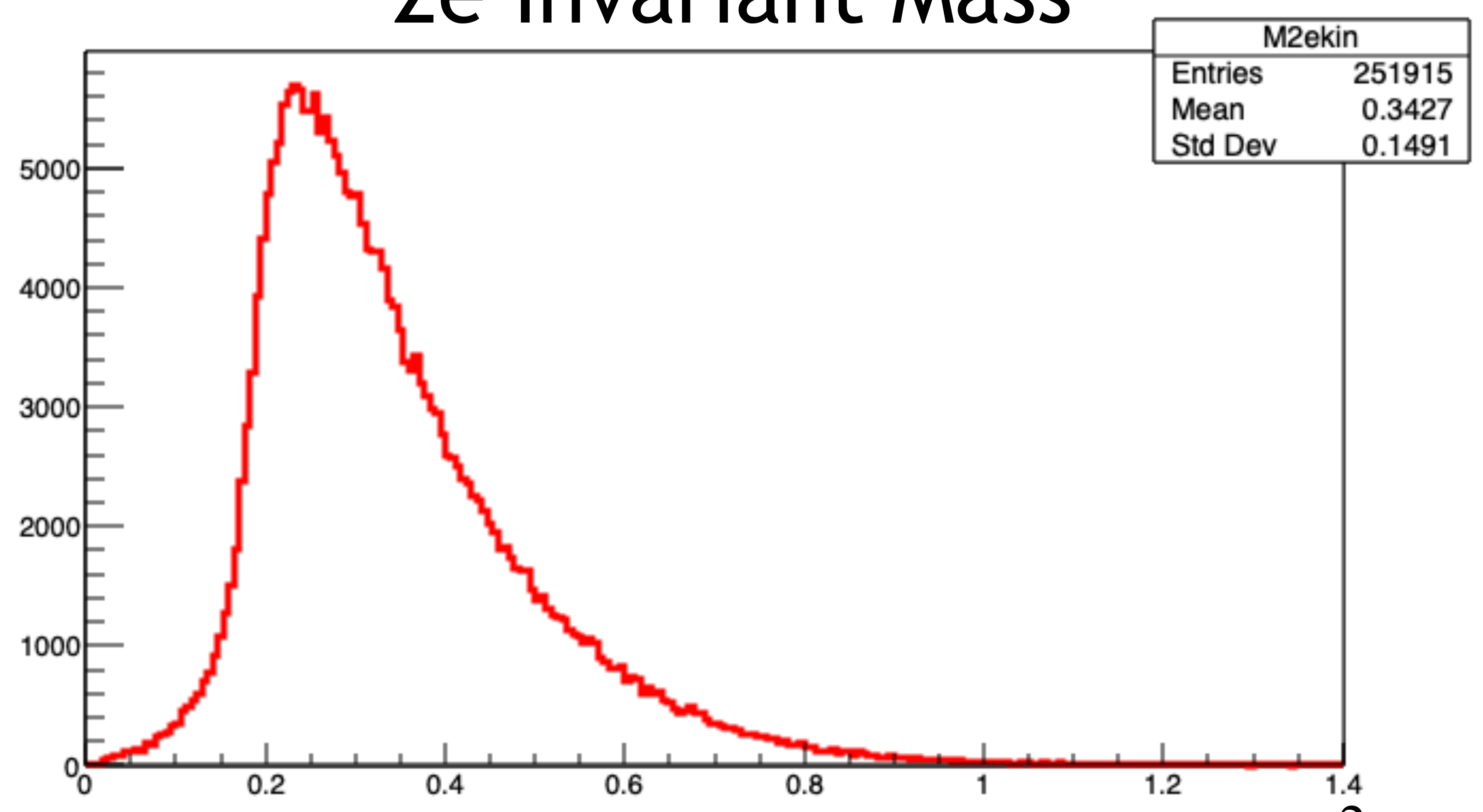


$W_{\pi\pi}$ (GeV/c^2)

BH MC, $\gamma p \to e^+e^-(p)$ (bkgnd)

- Default GlueX analysis launch cuts
- 8.11 GeV $< E_\gamma < 8.88$ GeV
- TOF $dE/dx > 0$ for both tracks

2e Invariant Mass



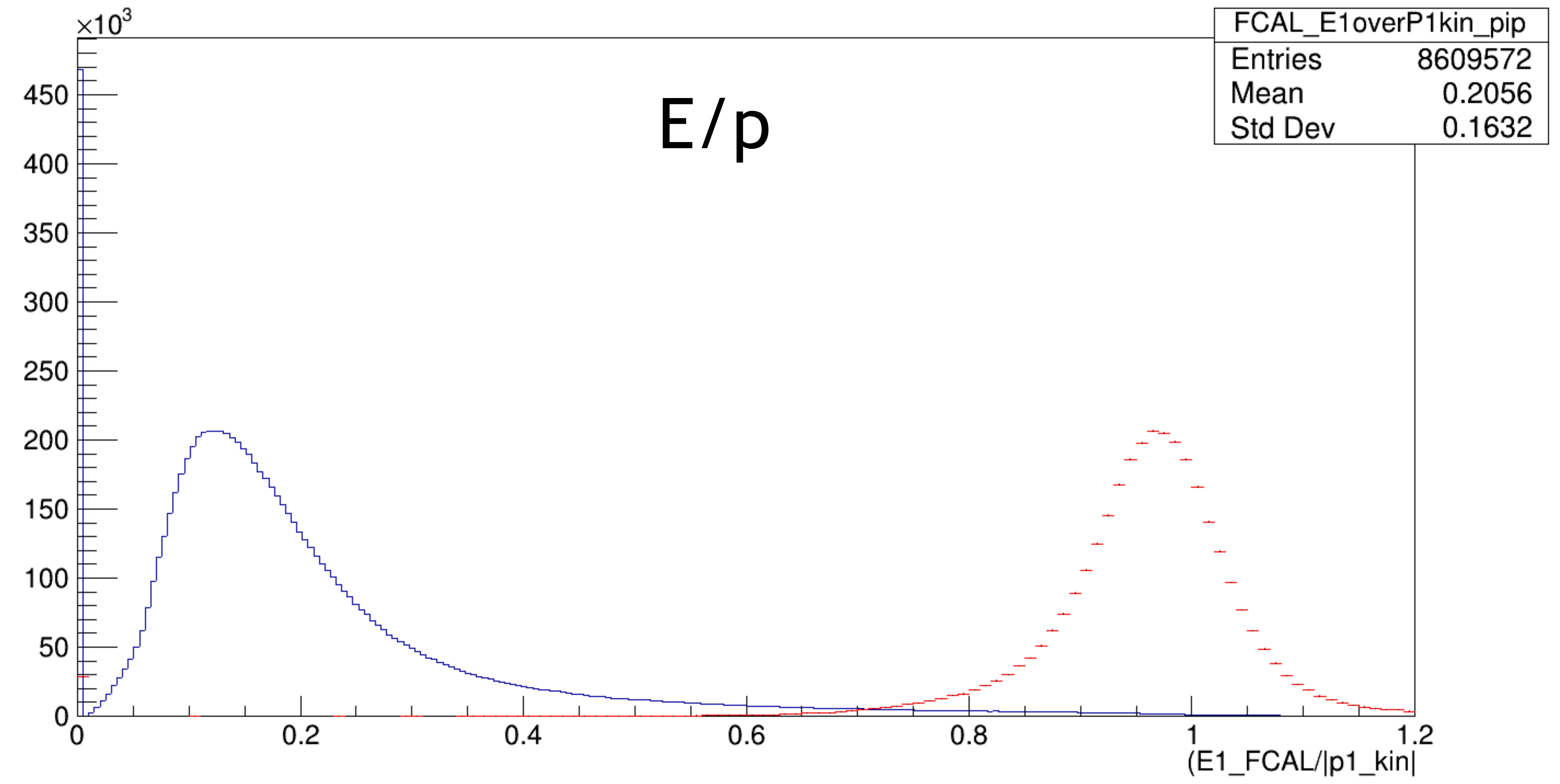
W_{ee} (GeV/c^2)

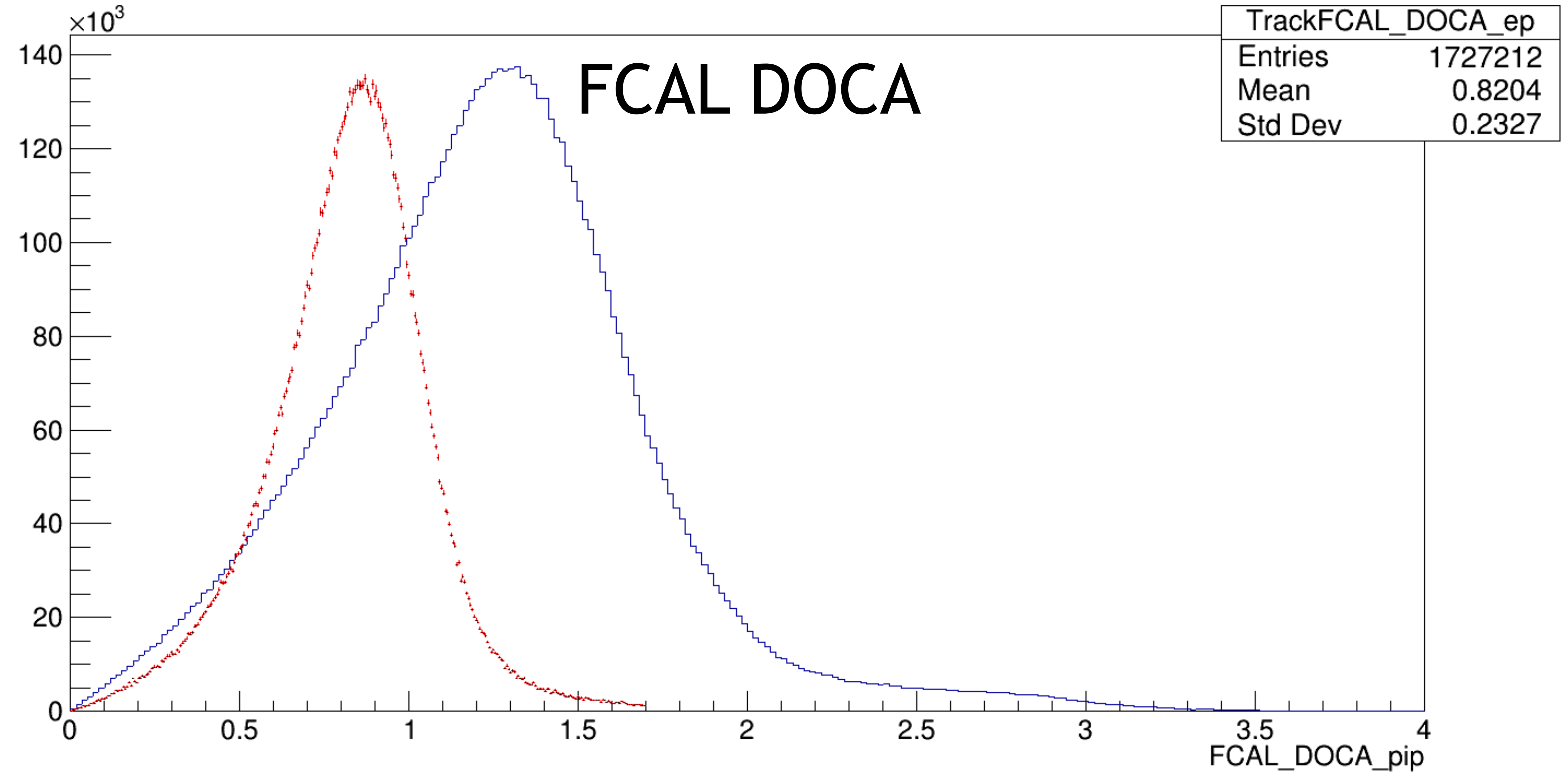
3 Training Variables

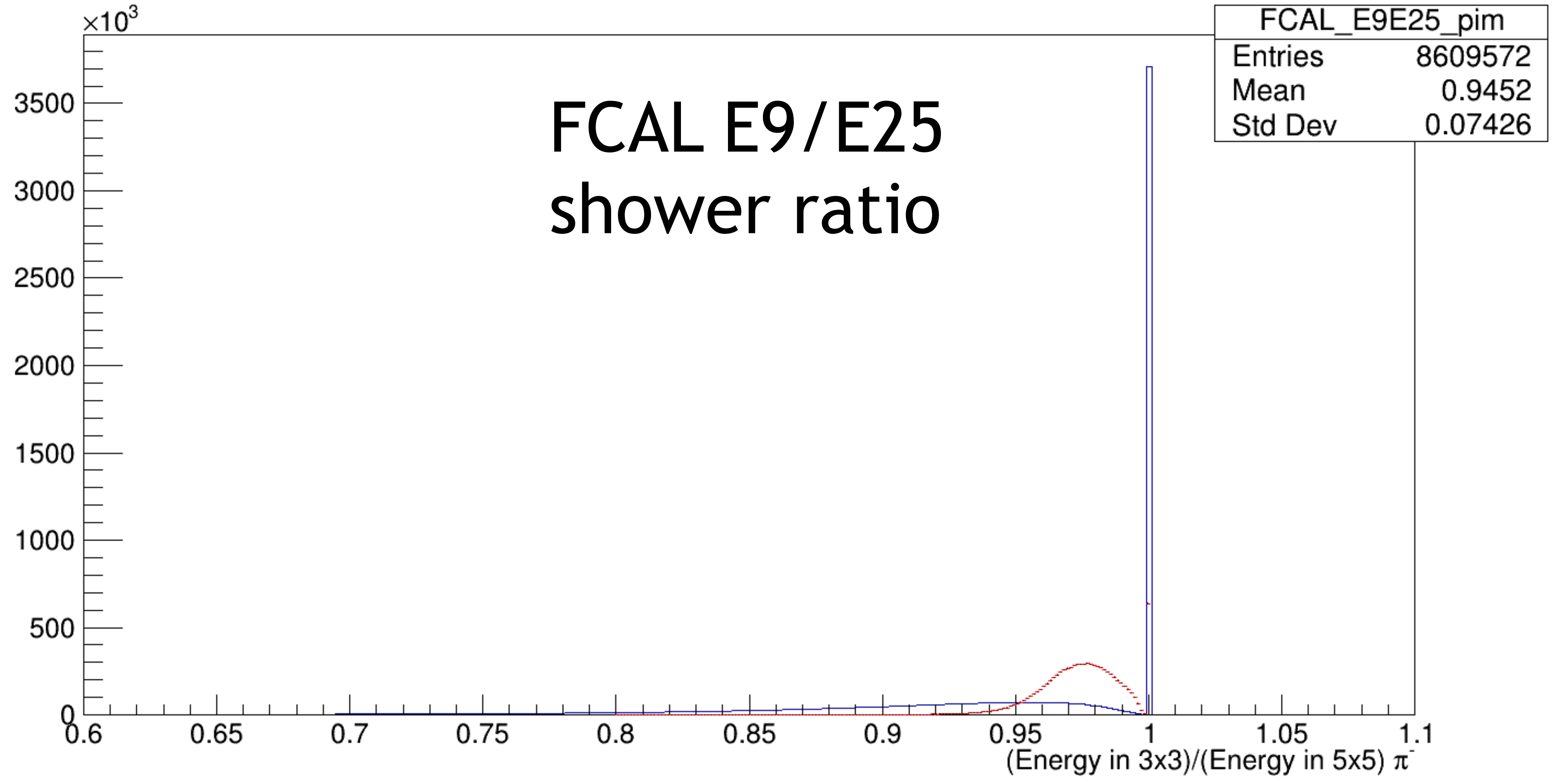
Energy deposited by track in FCAL/tracks momentum

DOCA: Distance between shower centroid and track projection.

E9/E25: Sum of energy deposited in 3x3 grid of FCAL blocks, divided by the sum of energy in a 5x5 grid





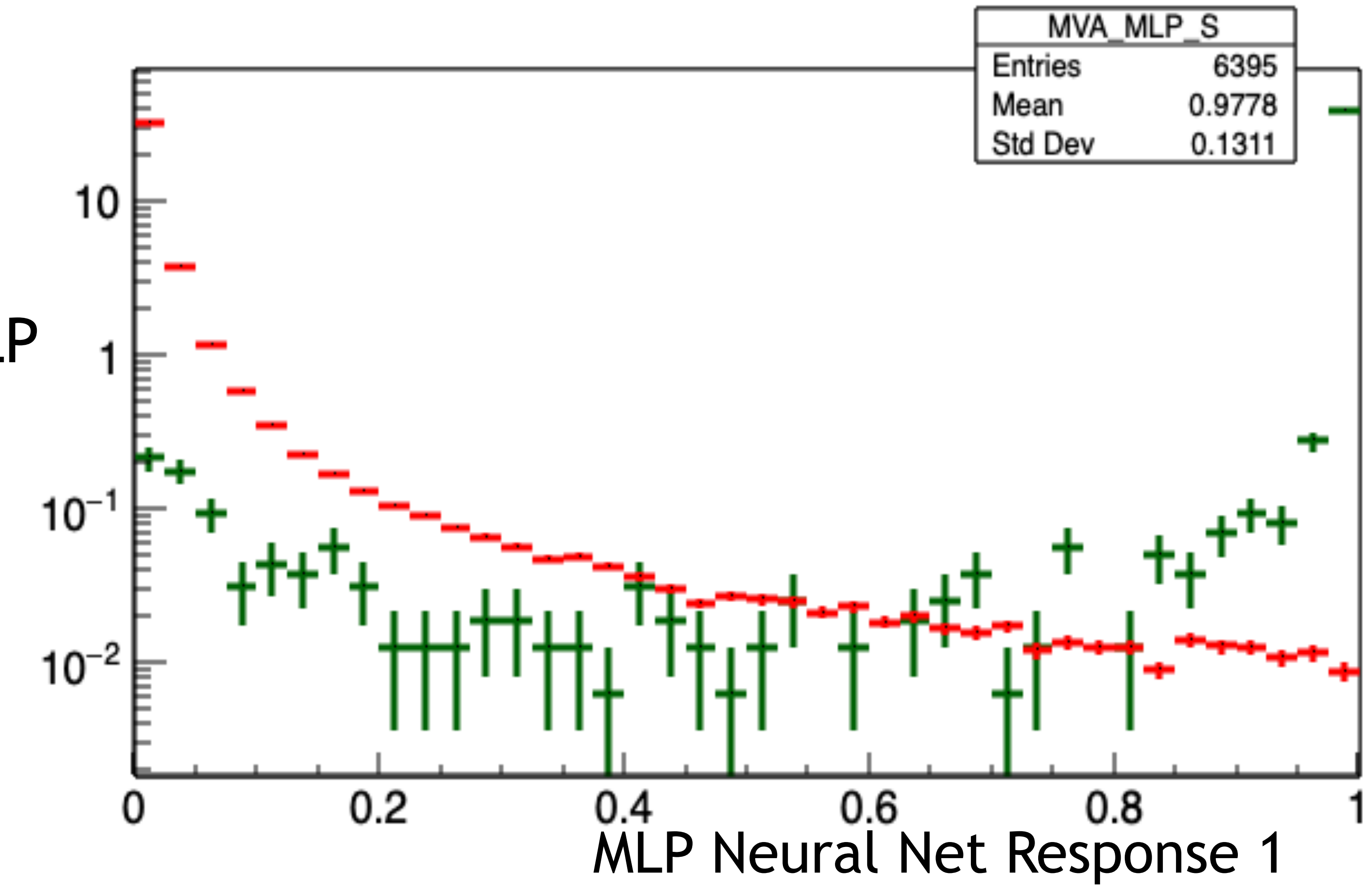


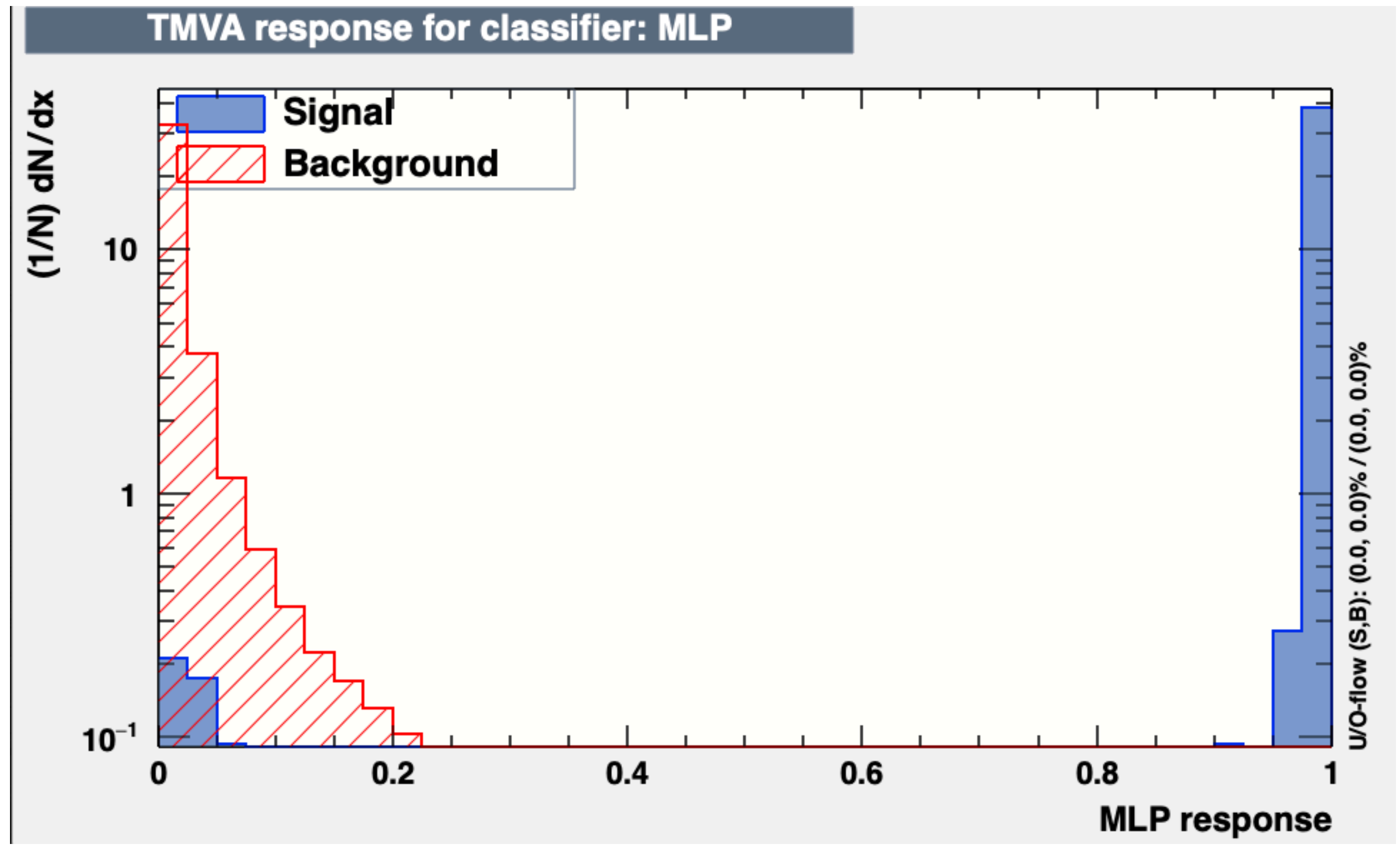
Neural Net Responses from ρ^0 data/BH MC training

TOP: User created plot of MLP response on log Y scale to better show 0.2 < NNR < 0.9 range.

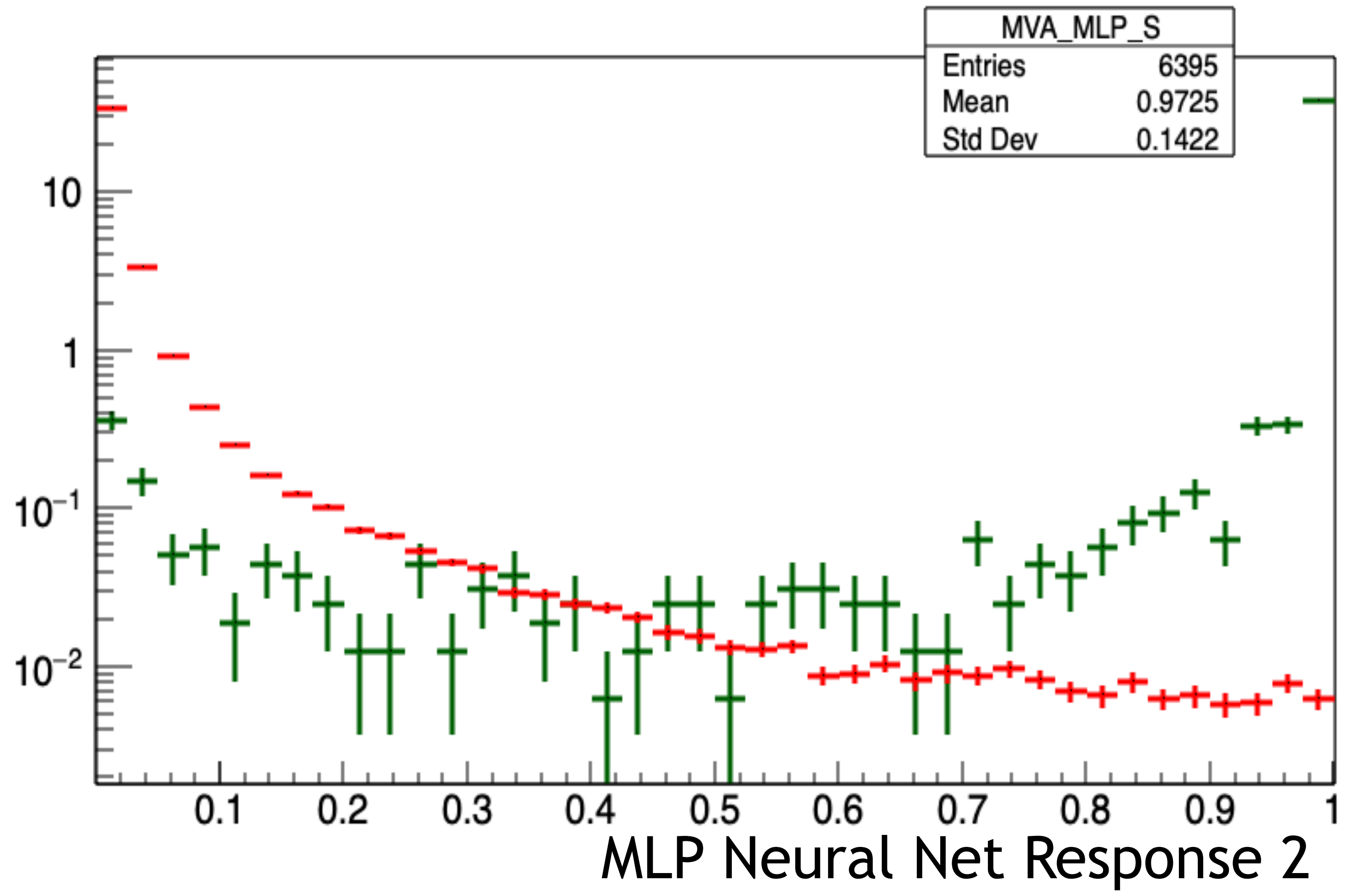
BOT: TMVA default plot of MLP response on log Y scale

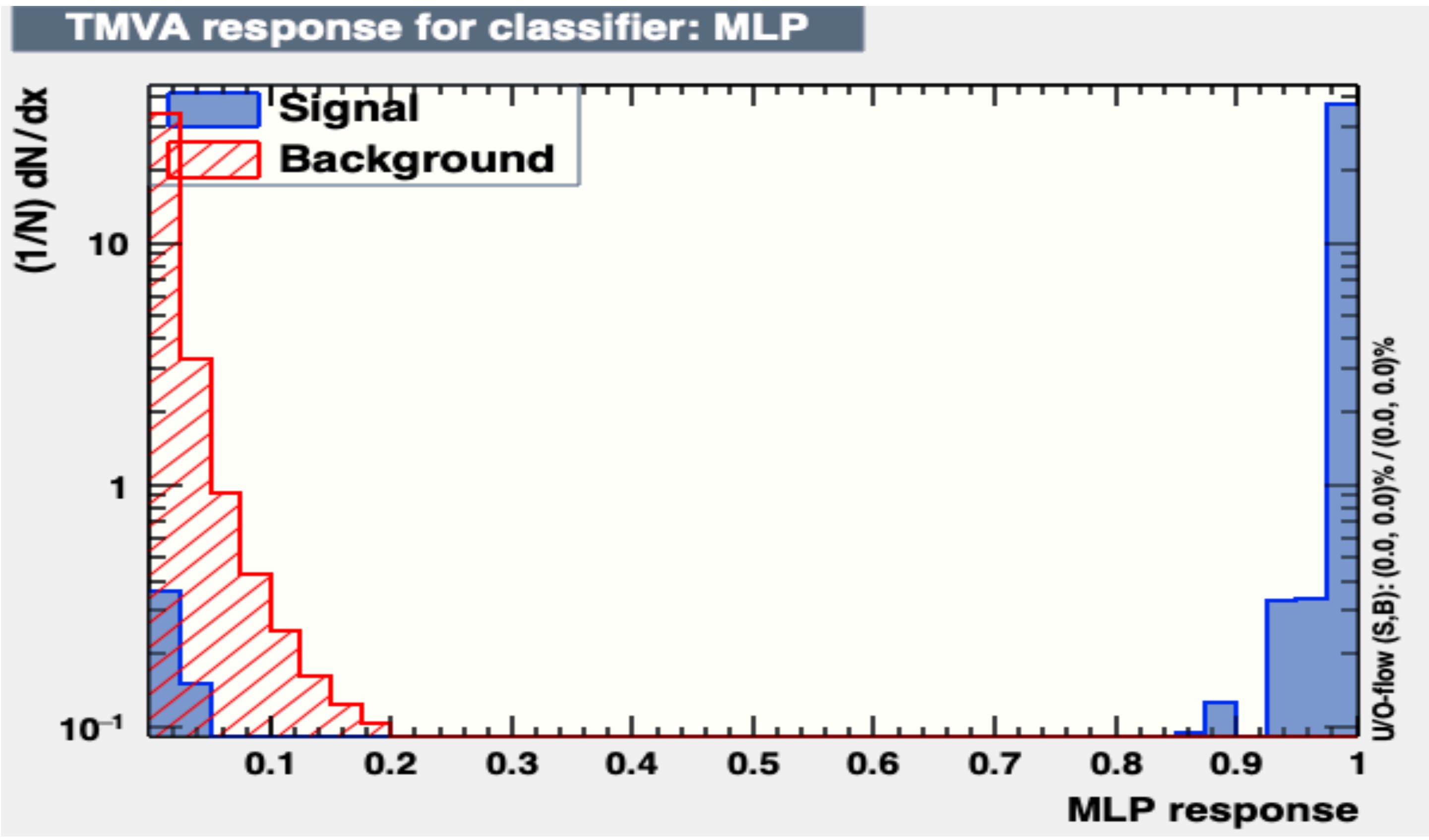
Training: π-/e- classifier output





Training: π+/e+ classifier output





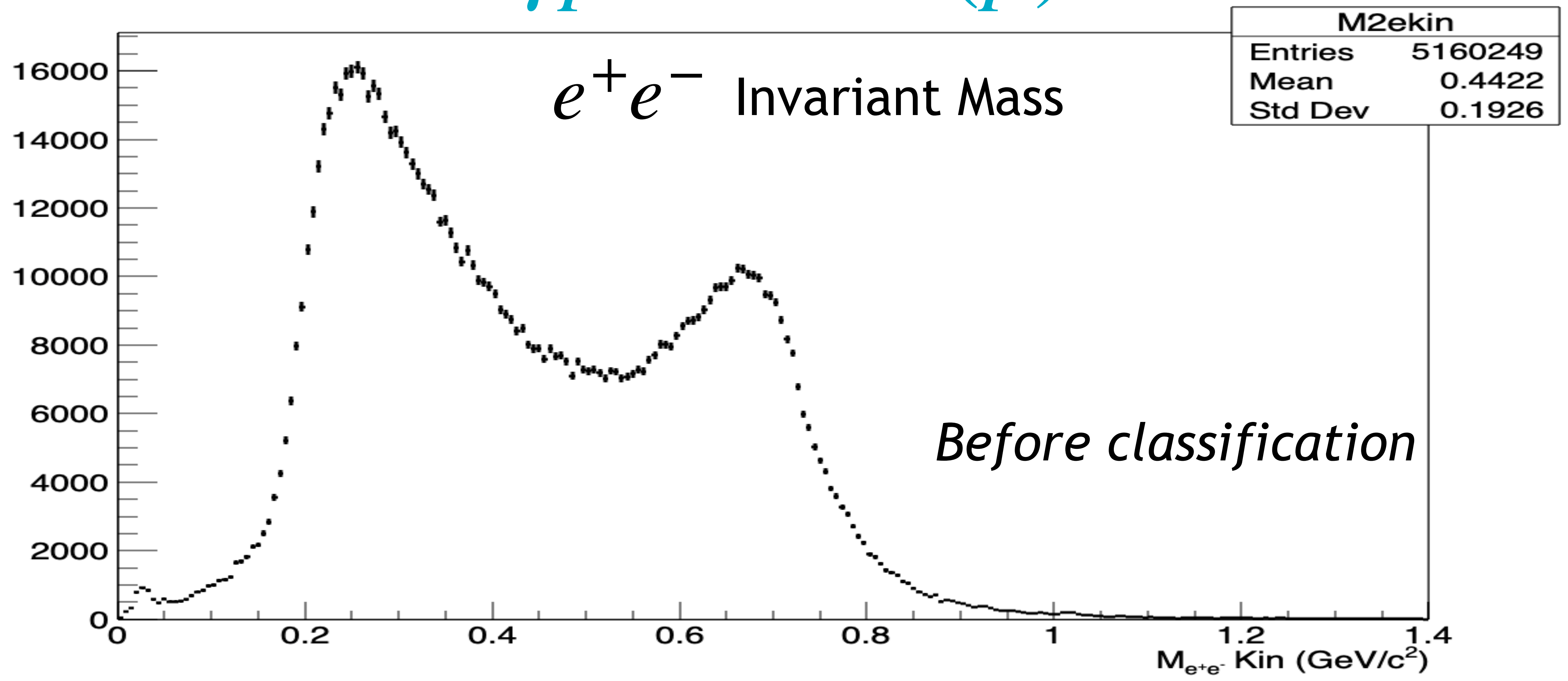
Benchmark Studies

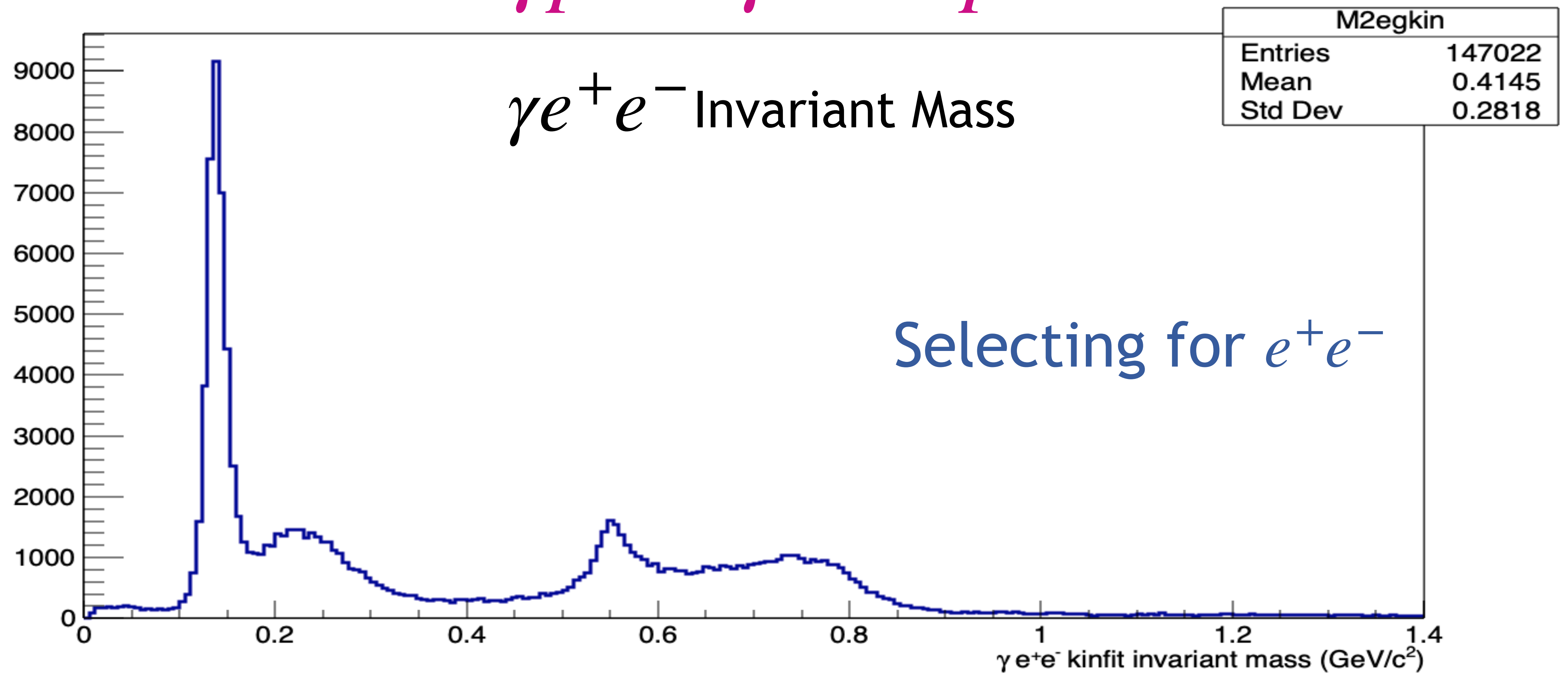
LEFT: 2018 GlueX data containing BH pairs and ρ^0. Use NN to classify and separate.

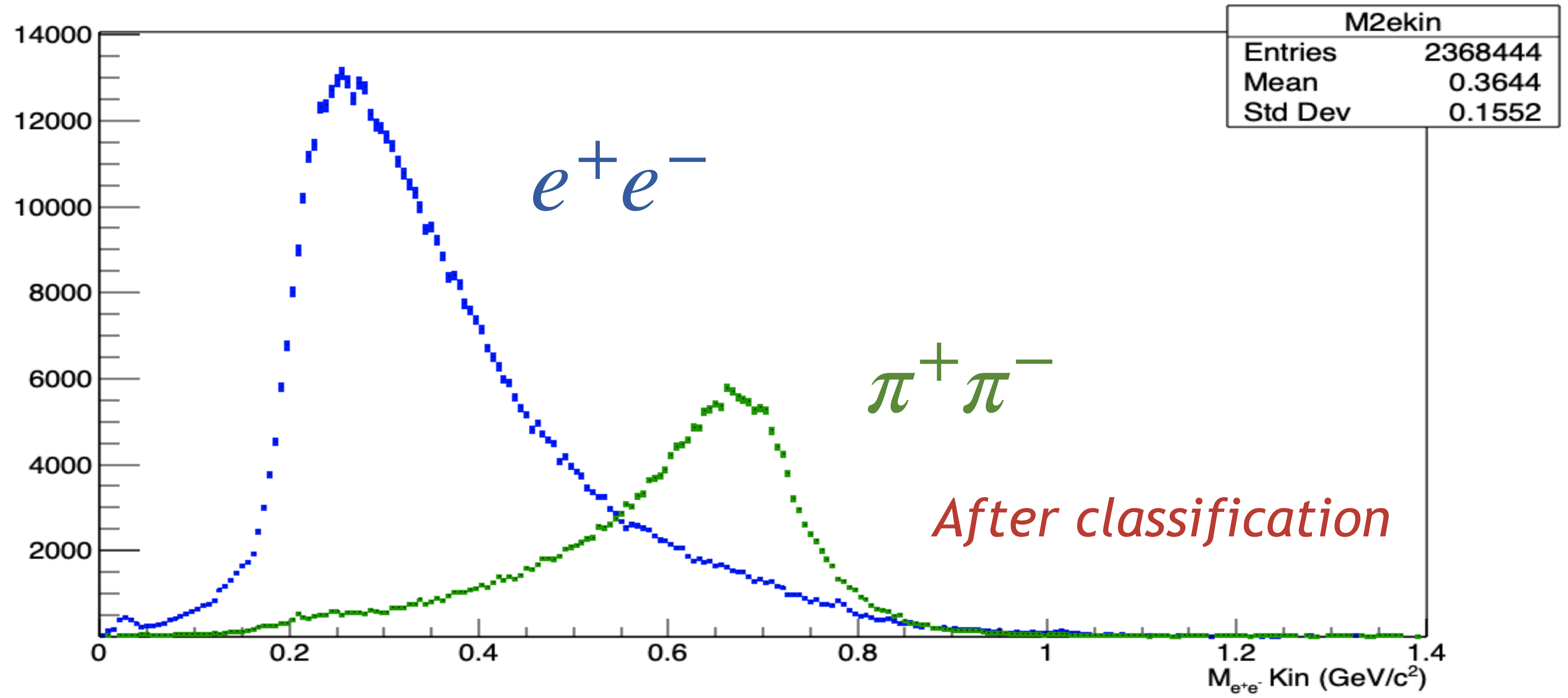
RIGHT: 2018 GlueX data containing π^0 Dalitz decay. Select for pions and see how many e+e- pairs from π^0 get through.

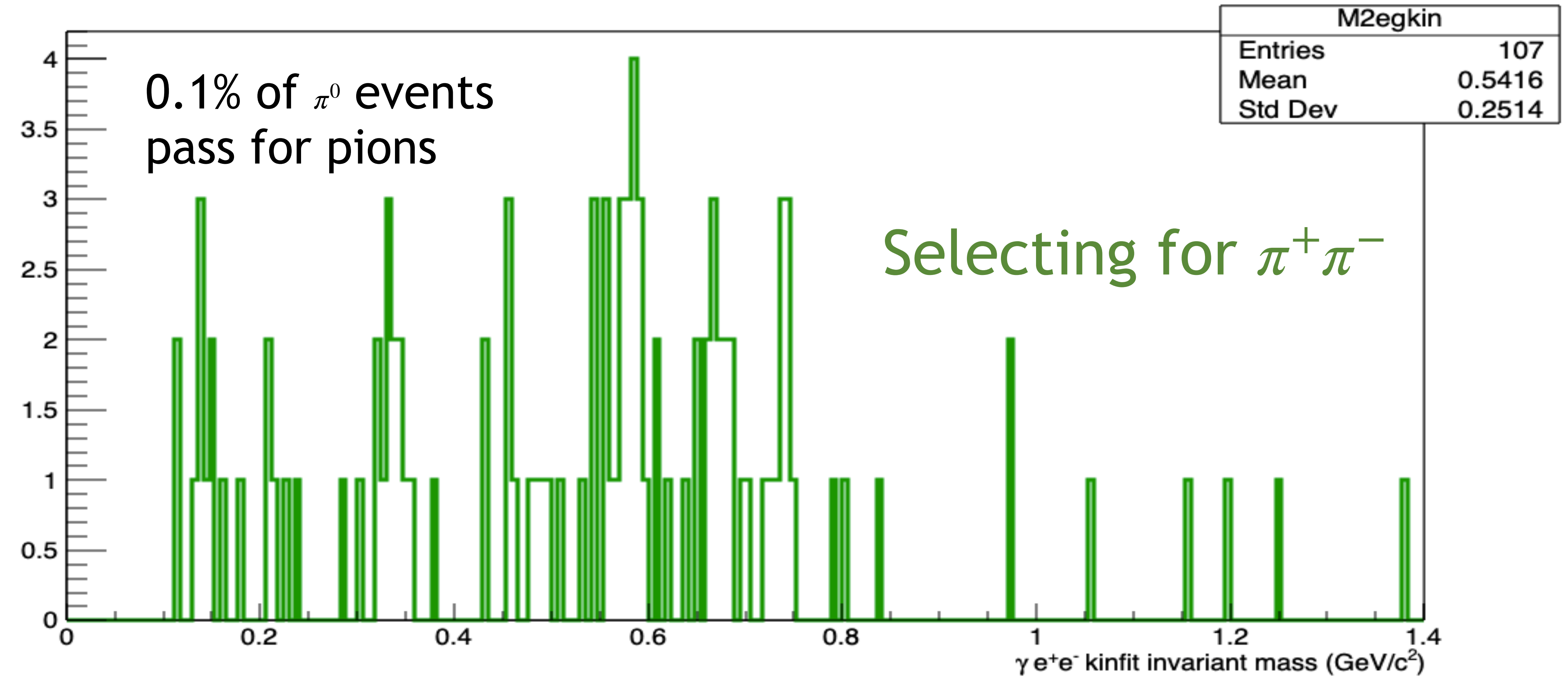
$\gamma p \rightarrow e^+e^-(p)$

$\gamma p \rightarrow \gamma e^+e^- p$



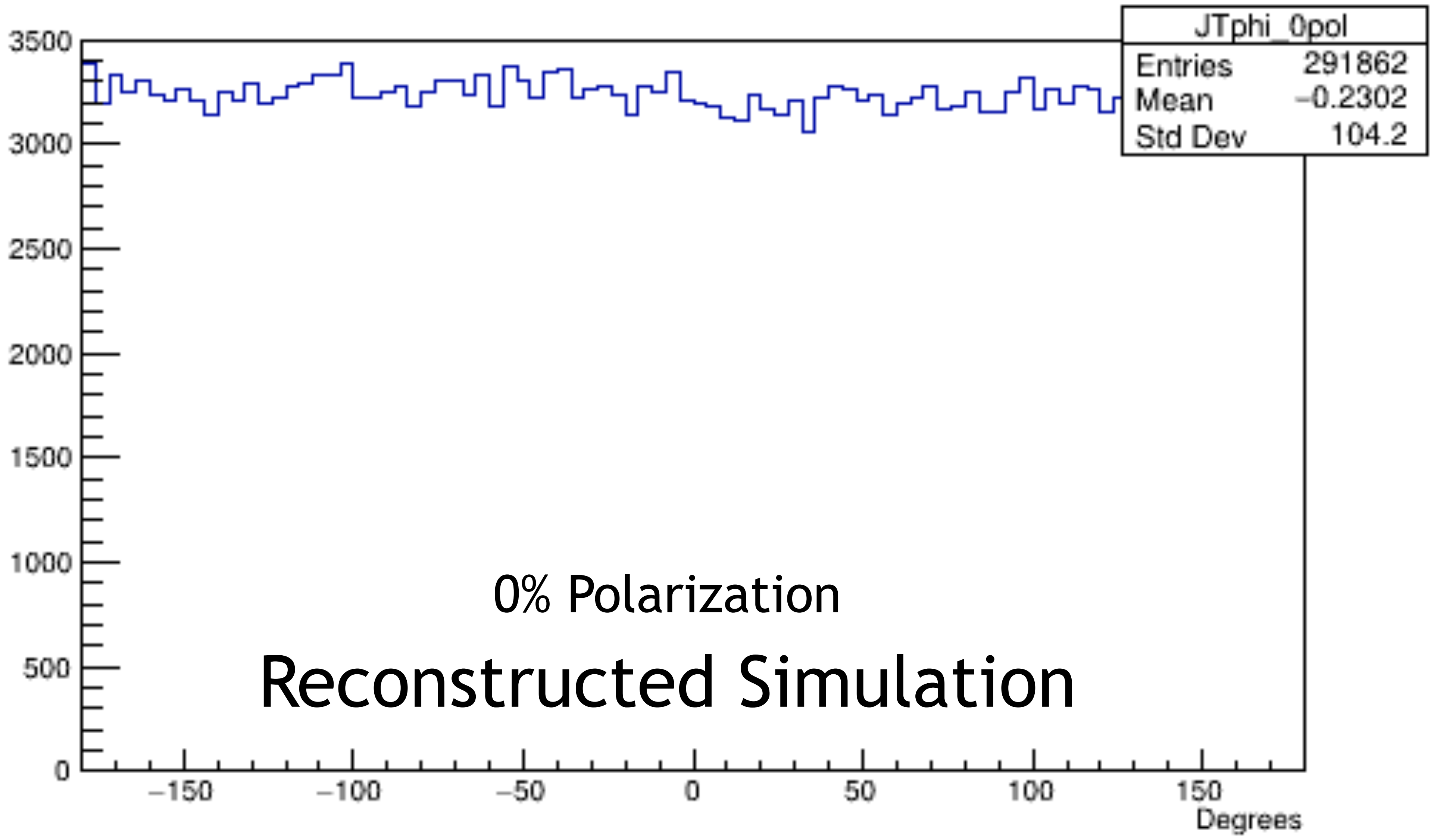


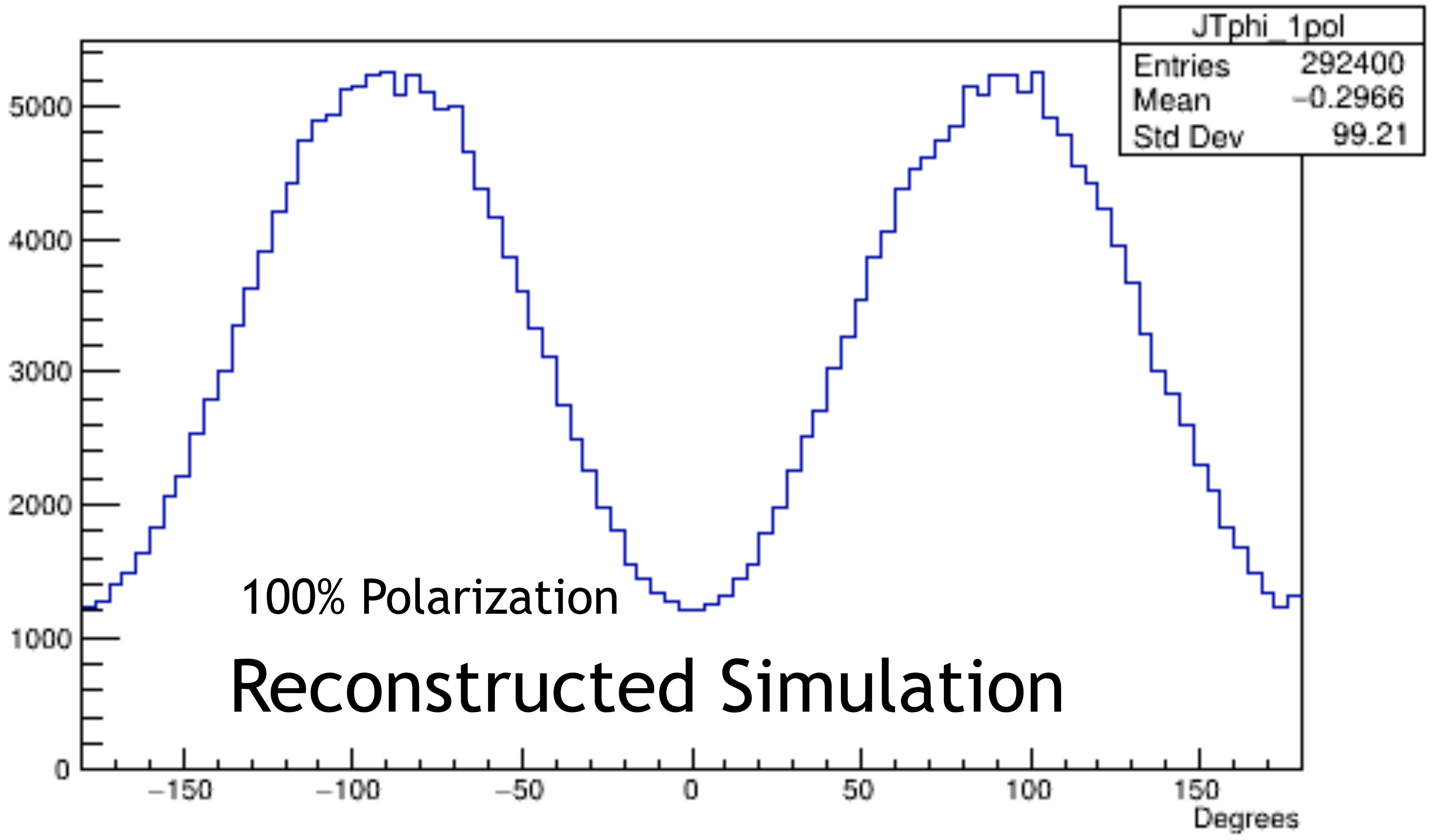


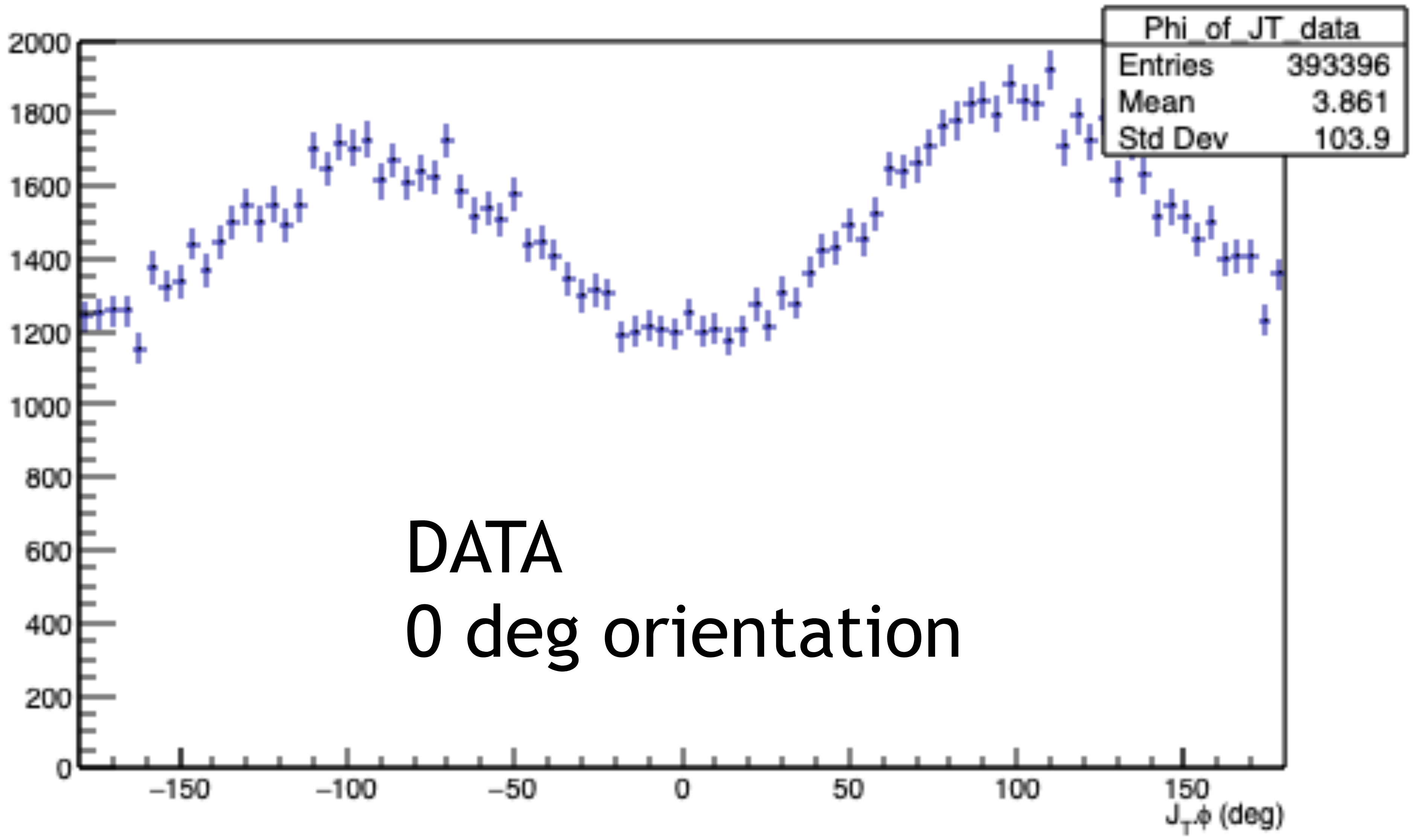


Same neural net and cut on NN response used in both studies

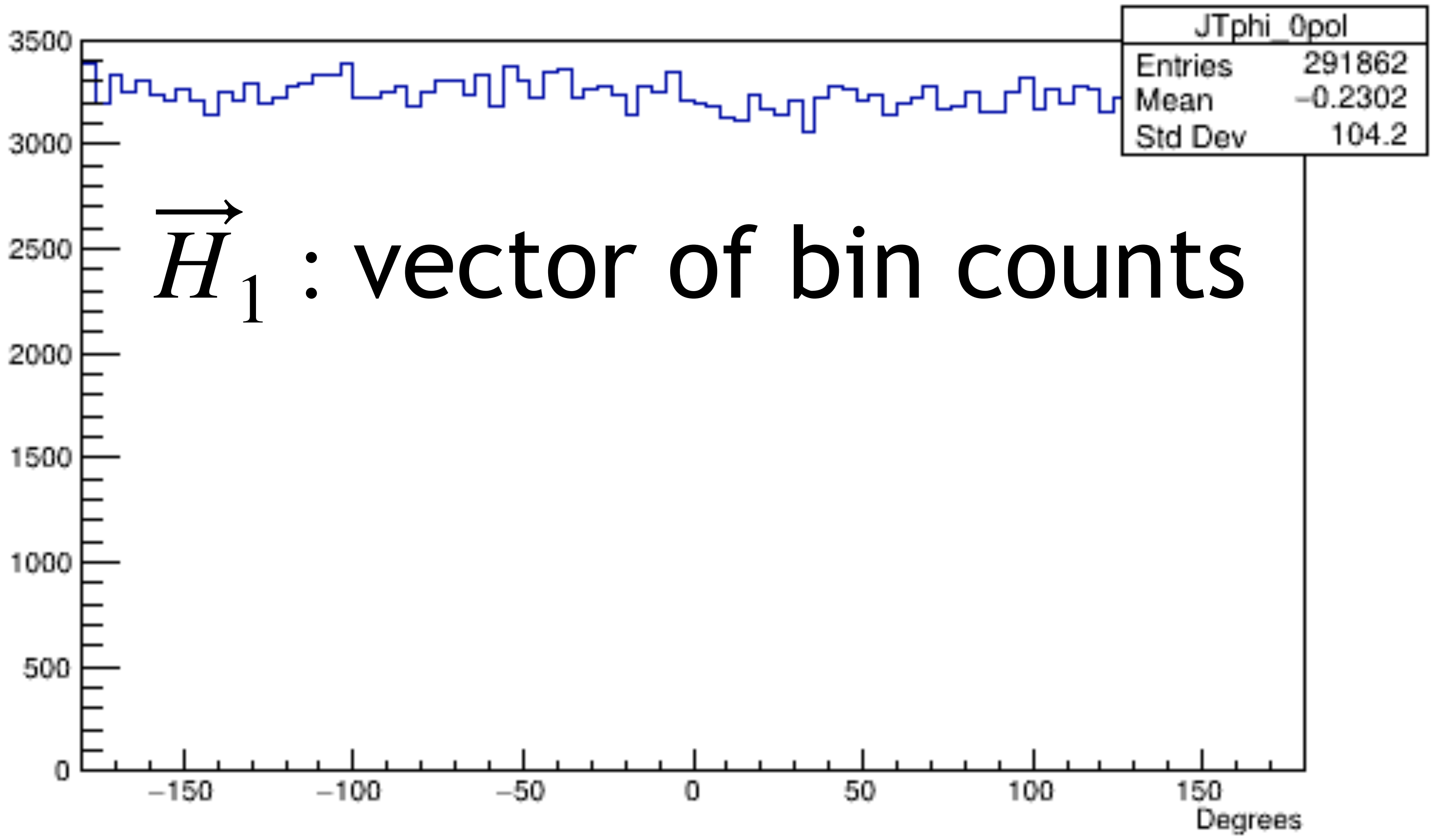
Early Attempts to measure the polarization (January 2021)

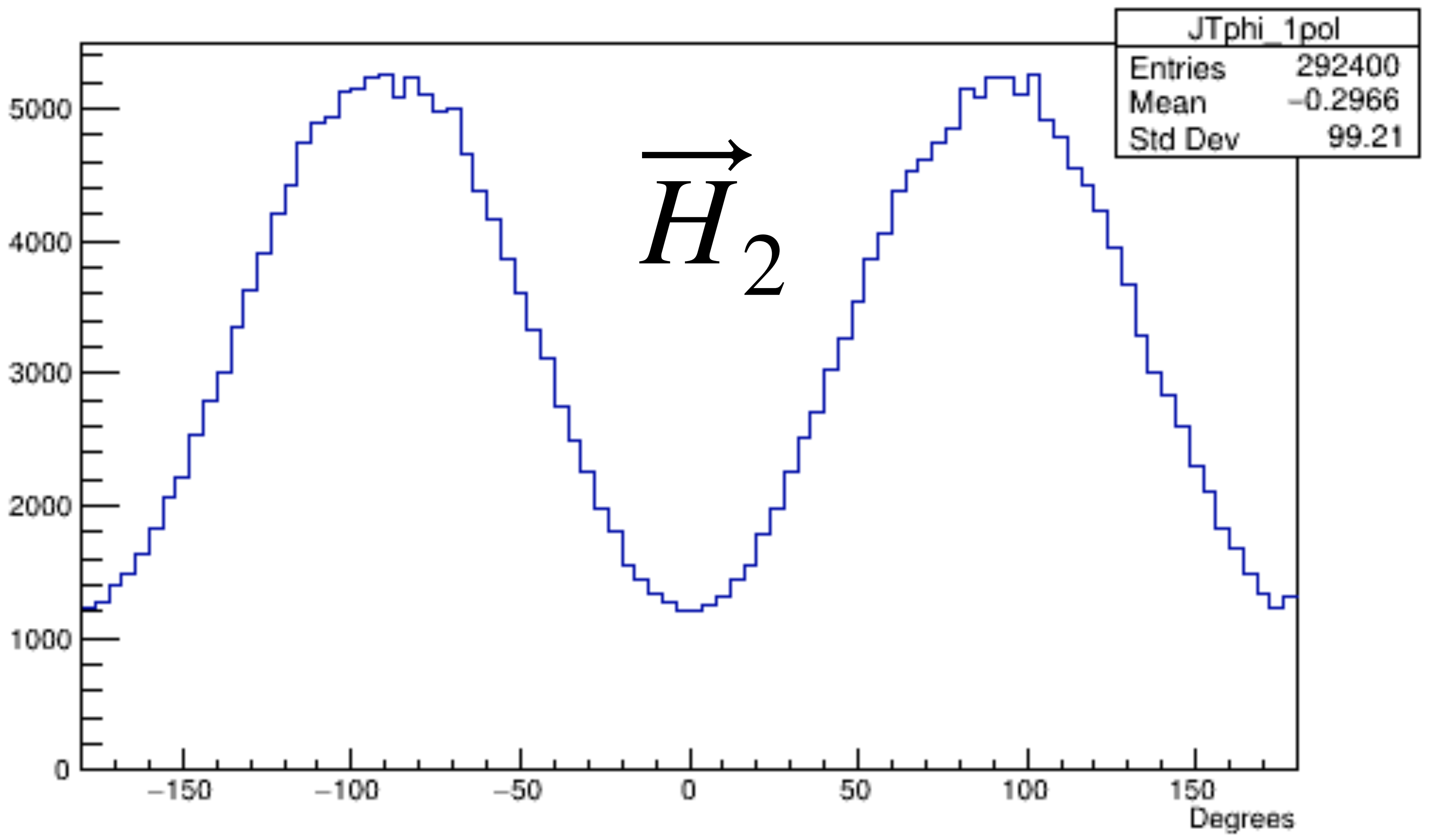


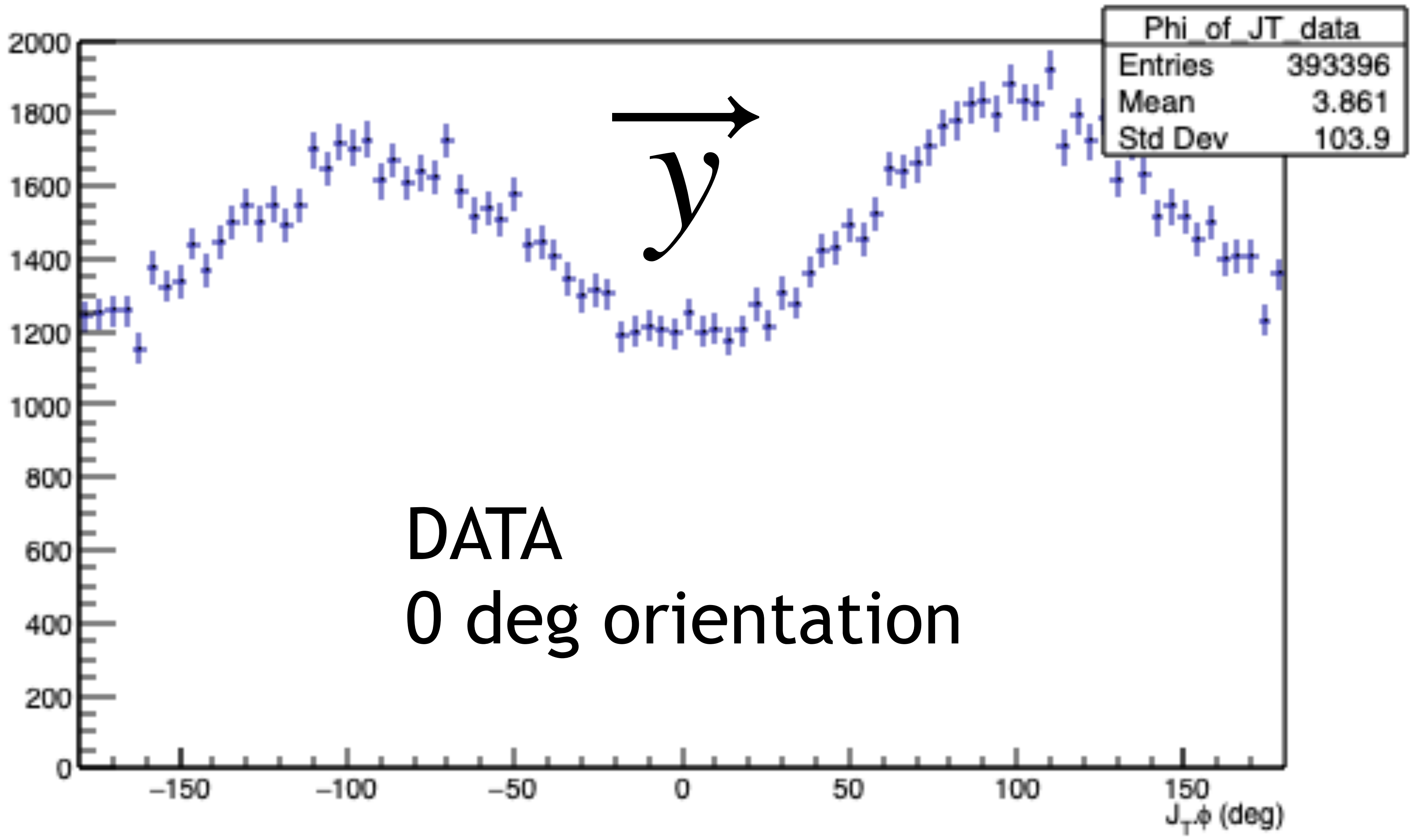




Neural Net Cut:
NN1,NN2 < 0.2
Fiducial Cuts Require:
$8.12 < E_\gamma < 8.88$ GeV
FCAL Elasticity > 0.9
Theta1,Theta2 > 1.5 deg
0.25 GeV < W < 0.621 GeV





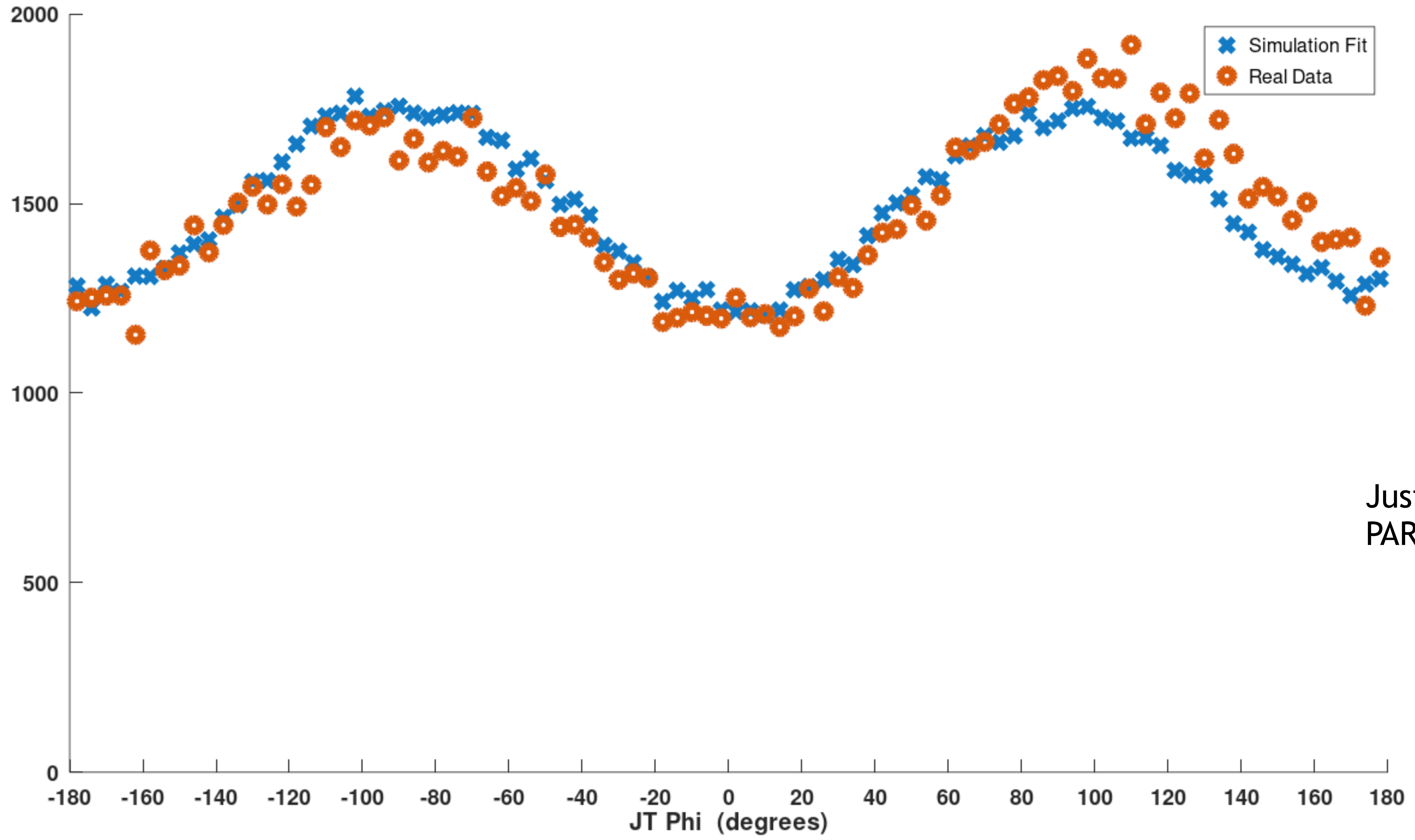


$$J(\overrightarrow{\theta}) = \frac{1}{2}(\theta_1 \overrightarrow{H}_1 + \theta_2 \overrightarrow{H}_2 - \overrightarrow{y})^2$$

find $\overrightarrow{\theta}$ such that $J(\overrightarrow{\theta})$ is minimized

(gradient descent)

$$\min[J(\overrightarrow{\theta})] = \min[\frac{1}{2}(\theta_0\overrightarrow{H}_0 + \theta_1\overrightarrow{H}_1 - \overrightarrow{y})^2] \Rightarrow \overrightarrow{\theta} = [0.2773, \quad 0.1111]$$



Odeg Pol: orientation

$$P_\gamma = \frac{\theta_1}{\theta_0 + \theta_1} = \frac{0.1111}{0.3883} = 0.2860$$

Justin's Paper: PERP: 0.382 ± 0.008(stat.) ± 0.006(syst.)
PARA: 0.440 ± 0.009(stat.) ± 0.007(syst.)

```
0.2773
0.1111
```

$$\sigma^2_{\theta_0} = \frac{1}{\sum_i H_i^0 H_i^0 / J_i} \qquad \sigma^2_{\theta_1} = \frac{1}{\sum_i H_i^1 H_i^1 / J_i}$$

$$P_\gamma = \frac{\theta_1}{\theta_0 + \theta_1} = \frac{0.1111}{0.3883} = 0.2860$$

$$\sigma_0^2 = 1.3053 \times 10^{-6} \qquad \sigma_1^2 = 1.2014 \times 10^{-6}$$

Denominator first: $f = A + B$ $\qquad \sigma_f = \sqrt{\sigma_A^2 + \sigma_B^2 + 2\sigma_{AB}}$

$$\sigma_d^2 = \sigma_0^2 + \sigma_1^2 = 1.3053 \times 10^{-6} + 1.2014 \times 10^{-6} = 2.5067 \times 10^{-6}$$

Numerator is just: $\sigma_n = \sigma_1$

$$f = \frac{A}{B} \qquad \sigma_f \approx |f| \sqrt{\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2 - 2\frac{\sigma_{AB}}{AB}}$$

$$\sigma \approx \left|\frac{\theta_1}{\theta_0 + \theta_1}\right| \sqrt{\left(\frac{\sigma_1}{\theta_1}\right)^2 + \left(\frac{\sigma_d}{\theta_0 + \theta_1}\right)^2} = \left|0.2860\right| \sqrt{\frac{1.2014 \times 10^{-6}}{0.2773^2} + \frac{2.5067 \times 10^{-6}}{0.3883^2}} = 0.0016241$$

$$P_\gamma = 0.2860 \pm 0.0016$$

$$P_\gamma = \frac{\theta_1}{\theta_0 + \theta_1} = \frac{0.1111}{0.3883} = 0.2860$$

Error associated with P_γ is given by $$\sigma^2_{P_\gamma} = \left[\frac{\partial P_\gamma}{\partial \theta_0}\sigma_{\theta_0}\right]^2 + \left[\frac{\partial P_\gamma}{\partial \theta_1}\sigma_{\theta_1}\right]^2$$

$$\sigma^2_{\theta_0} = \frac{1}{\sum_i H_0^{(i)} H_0^{(i)} / y^{(i)}} = 1.3053 \times 10^{-6} \qquad \sigma^2_{\theta_1} = \frac{1}{\sum_i H_1^{(i)} H_1^{(i)} / y^{(i)}} = 1.2014 \times 10^{-6}$$

$$\frac{\partial P_\gamma}{\partial \theta_0} = -\frac{\theta_1}{(\theta_0 + \theta_1)^2} = -\frac{0.1111}{(0.3883)^2} = -0.7369 \qquad \left(\frac{\partial P_\gamma}{\partial \theta_0}\right)^2 = 0.5430$$

$$\frac{\partial P_\gamma}{\partial \theta_1} = \frac{1}{\theta_0 + \theta_1} - \frac{\theta_1}{(\theta_0 + \theta_1)^2} = \frac{1}{0.3883} - 0.7369 = 1.8384 \qquad \left(\frac{\partial P_\gamma}{\partial \theta_1}\right)^2 = 3.3797$$

$$\sigma^2_{P_\gamma} = \left[\frac{\partial P_\gamma}{\partial \theta_0}\sigma_{\theta_0}\right]^2 + \left[\frac{\partial P_\gamma}{\partial \theta_1}\sigma_{\theta_1}\right]^2 = (0.5430) \cdot (1.3053 \times 10^{-6}) + (3.3797) \cdot (1.2014 \times 10^{-6}) = 4.7691 \times 10^{-6}$$

$$\sigma_{P_\gamma} = 0.0021$$

```
**********************************************************
 Polarization values for E_gamma between 8.2 and 8.8 GeV
----------------------------------------------------------
        Beam orientation         Polarization
          0 degrees:          0.3420 +/- 0.0063
         45 degrees:          0.3474 +/- 0.0065
         90 degrees:          0.3478 +/- 0.0063
        135 degrees:          0.3517 +/- 0.0065
```

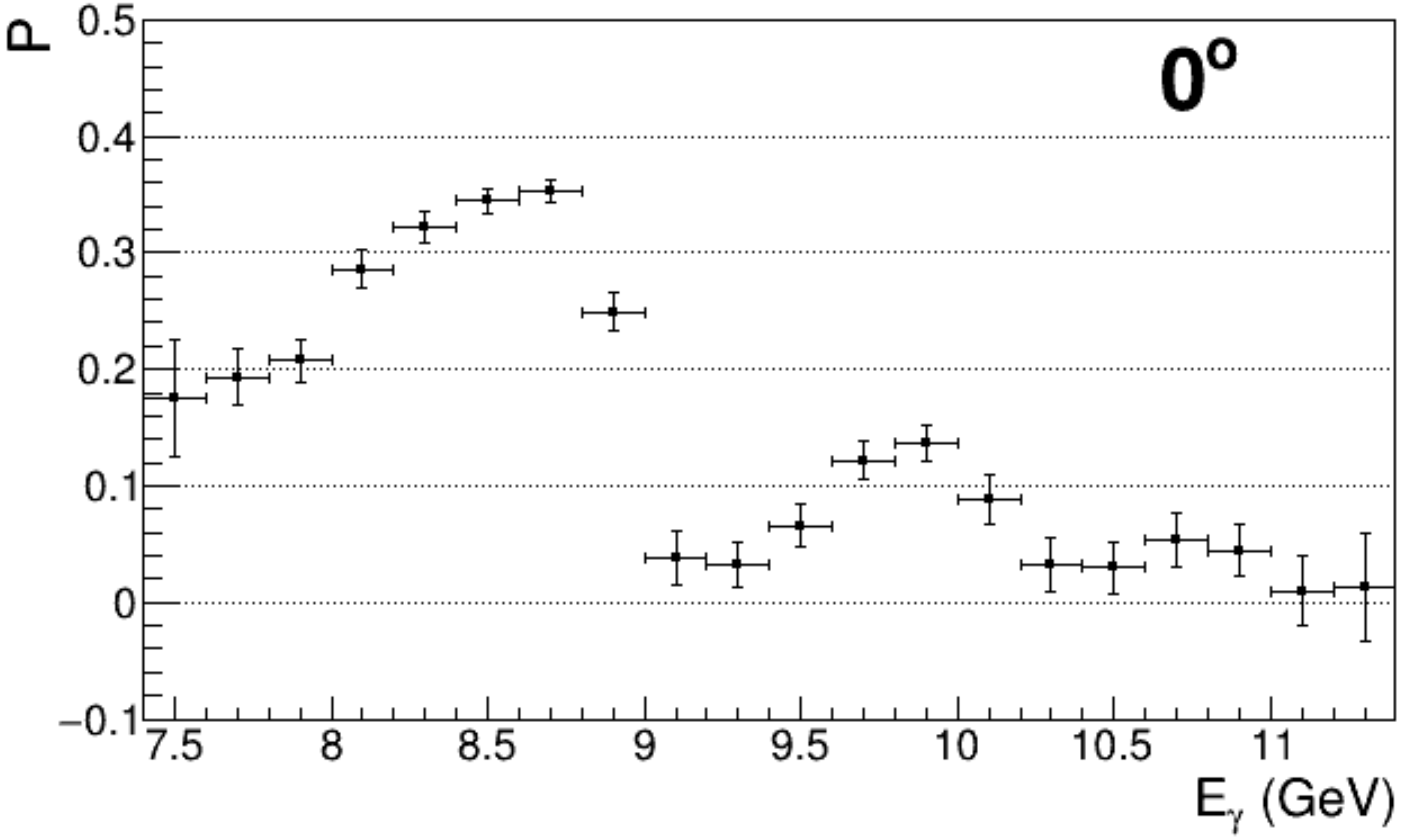
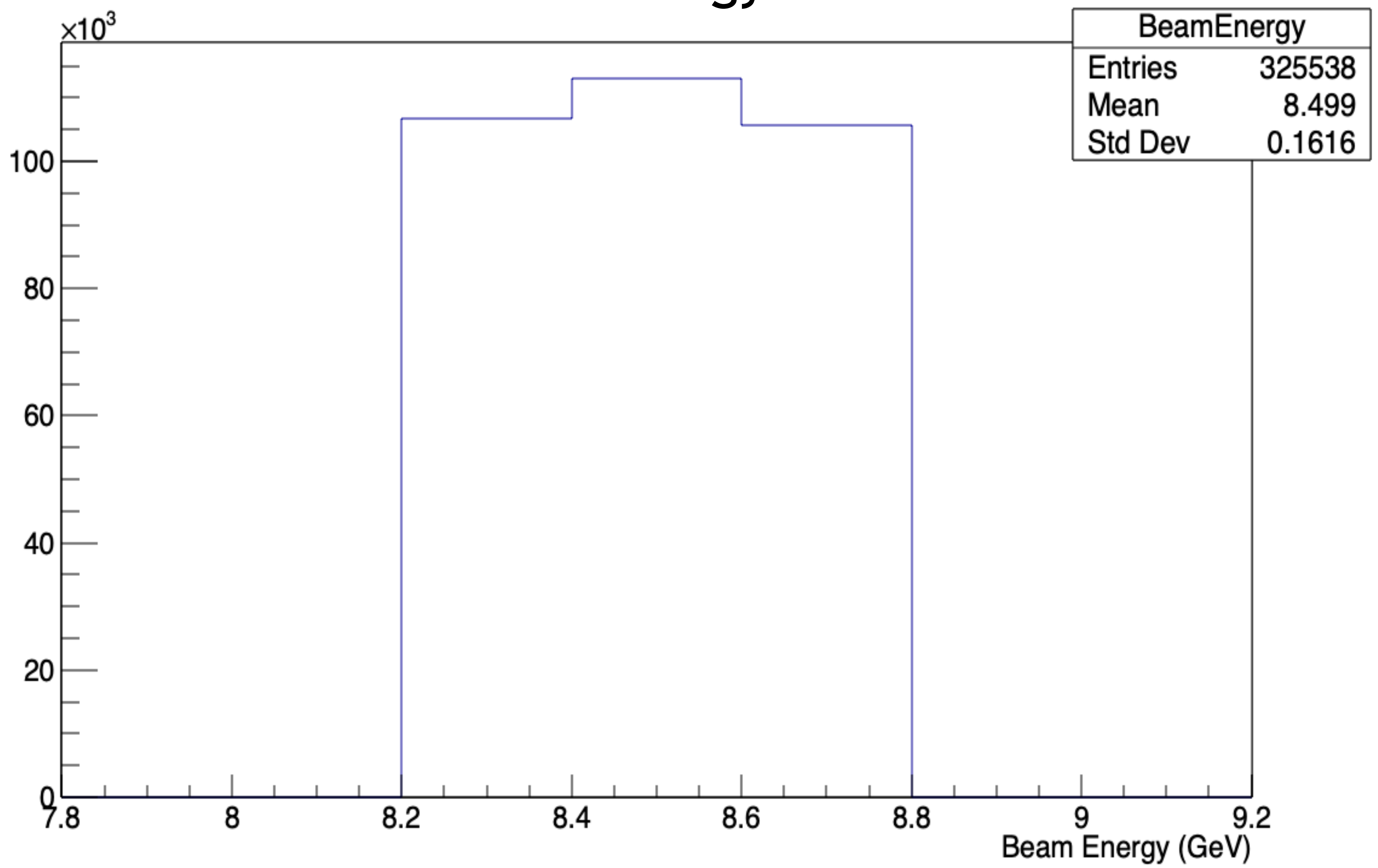


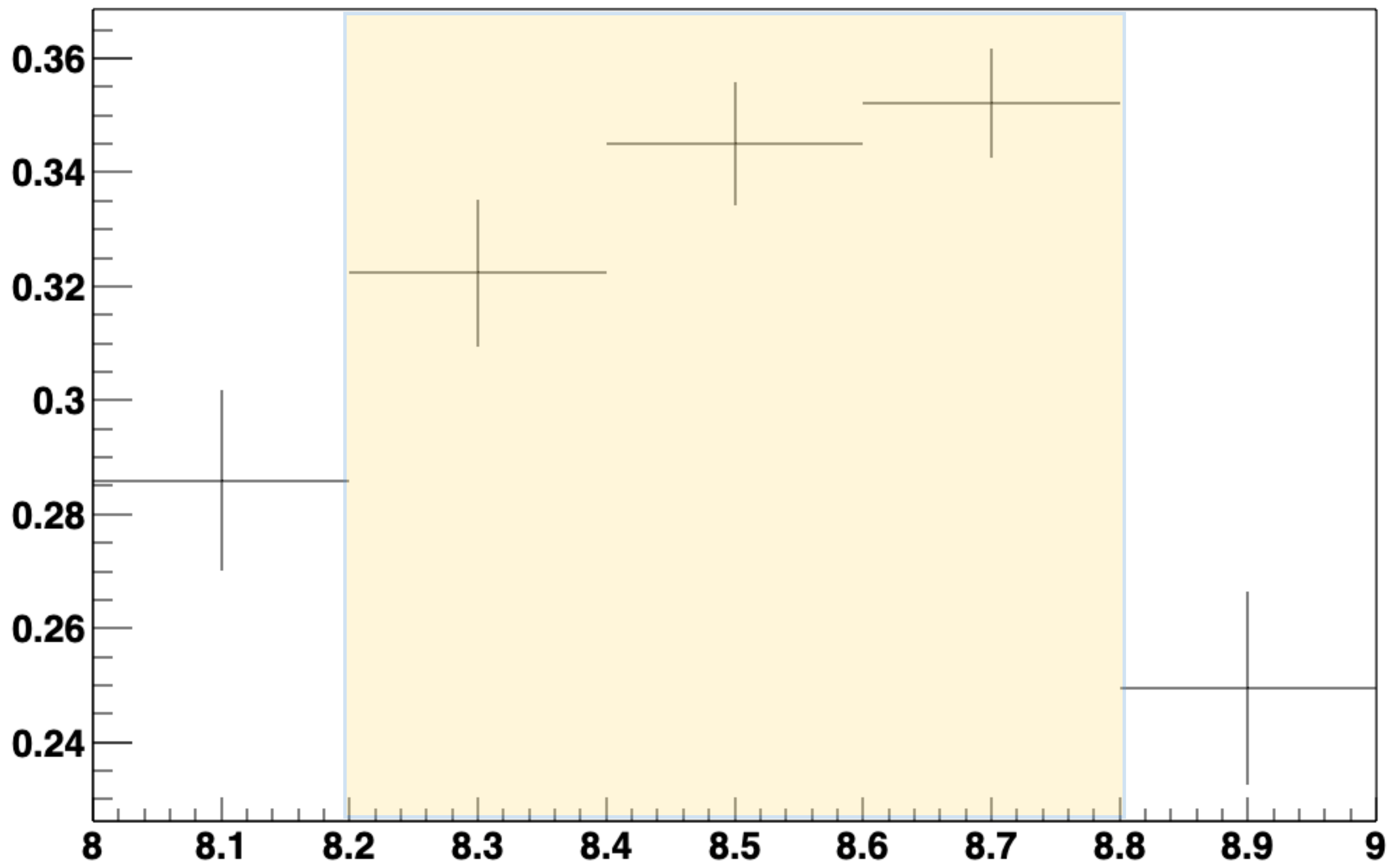
Table 1

8.3	106740
8.5	113046
8.7	105752

Bethe-Heitler Data
Beam Energy



8.2 to 8.8 Energy range



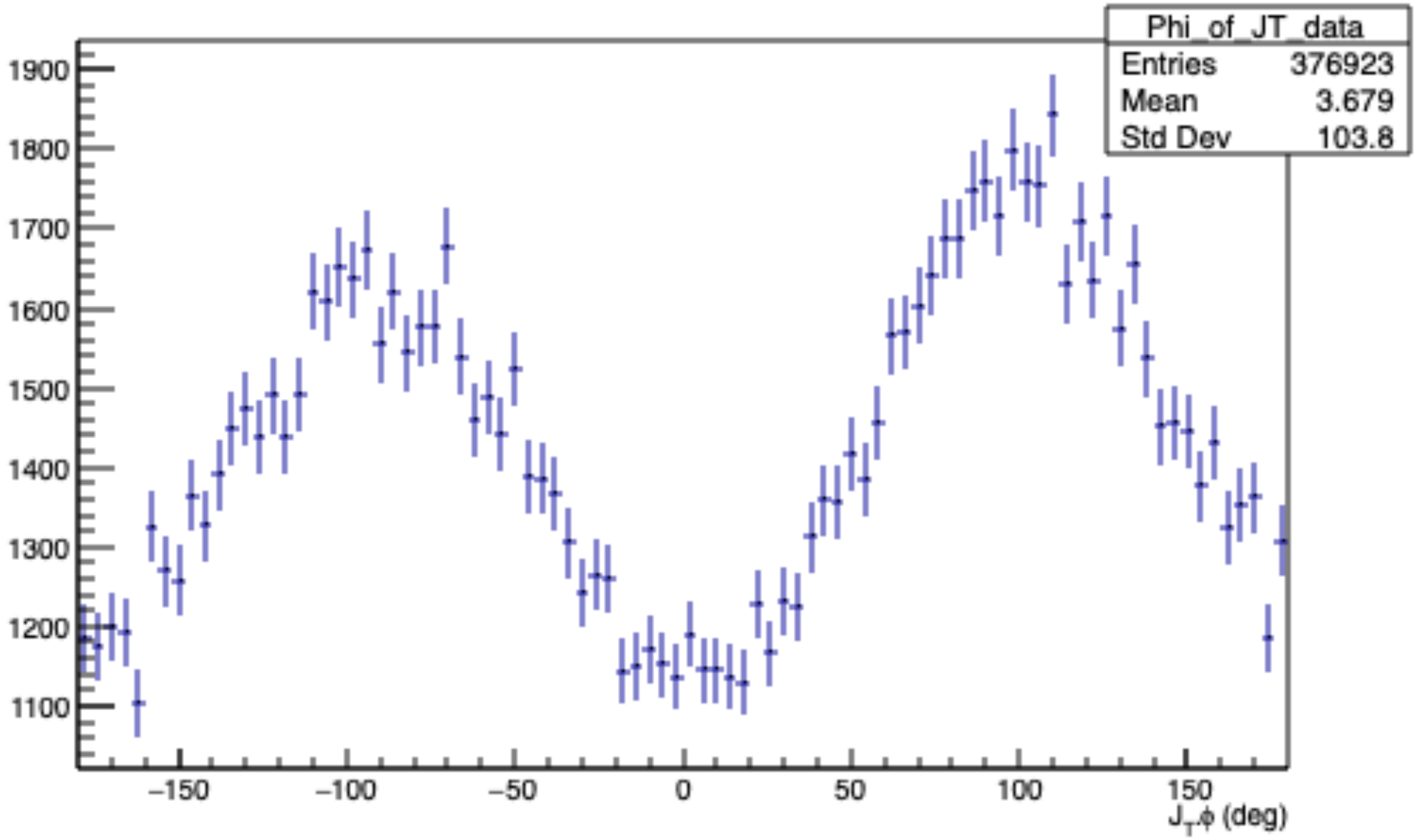
$$8.2 < E_\gamma < 8.8 \qquad \bar{\mathcal{P}}_\gamma = 0.3399 \pm 0.0125$$

SUMMARY SO FAR

TPOL expected polarization for energy range $8.2 < E_\gamma < 8.8$ $\bar{\mathscr{P}}_\gamma = 0.3399 \pm 0.0125$

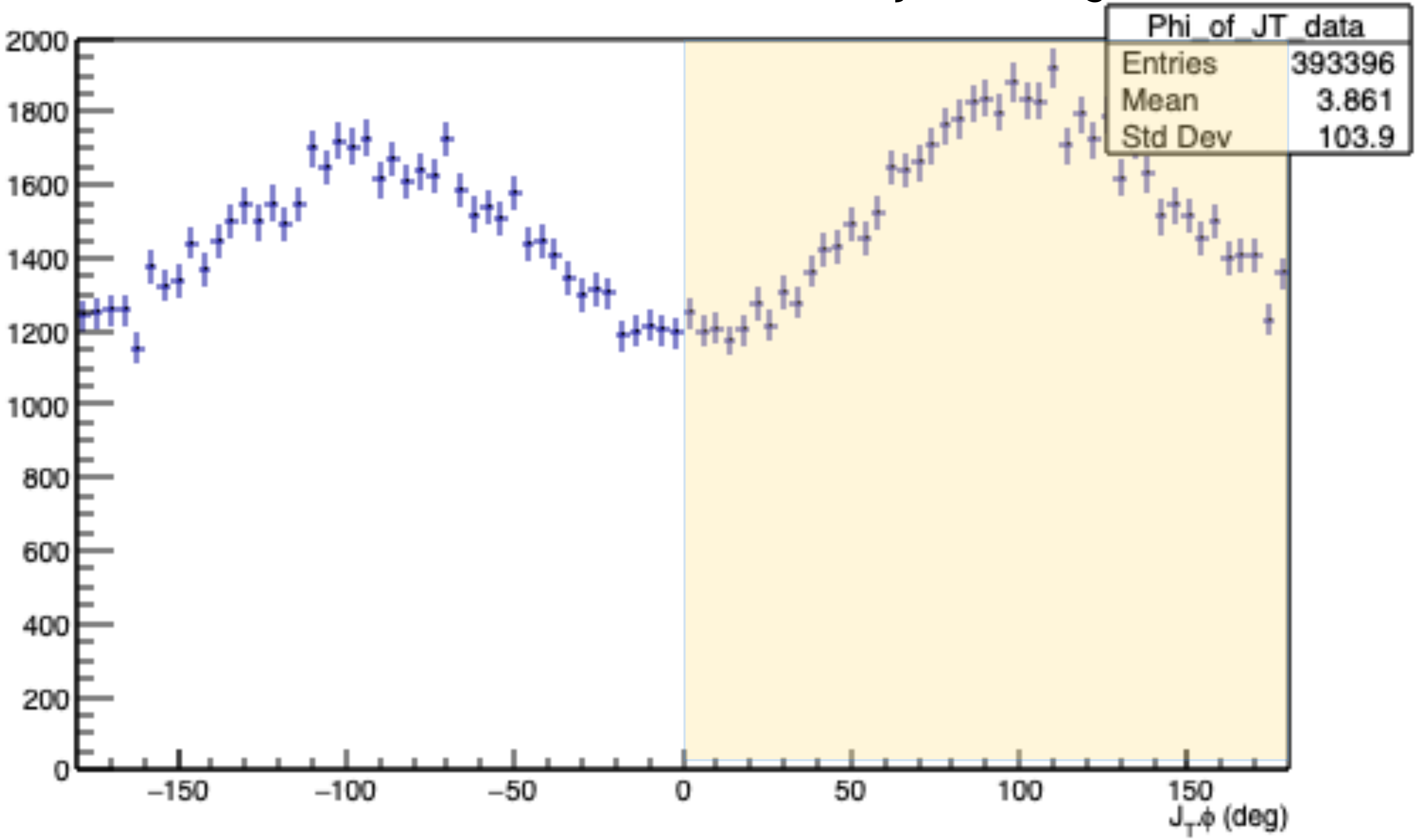
Chisq method: Measured with ϕ of J_T, pol 0 config runs $\mathscr{P}_\gamma = 0.2860 \pm 0.0016$

Yield asymmetry method: Average polarization between 0 and 90 runs: $\frac{\mathscr{P}_\perp + \mathscr{P}_\parallel}{2} = 0.2996 \pm .0060$



Tighter cut on invariant mass (300 MeV < W 500 MeV) does not fix asymmetry. This is likely due to calibration. Jobs to test this are running now but may be statistics limited. Will submit for new reconstruction of 2018-01 data set.

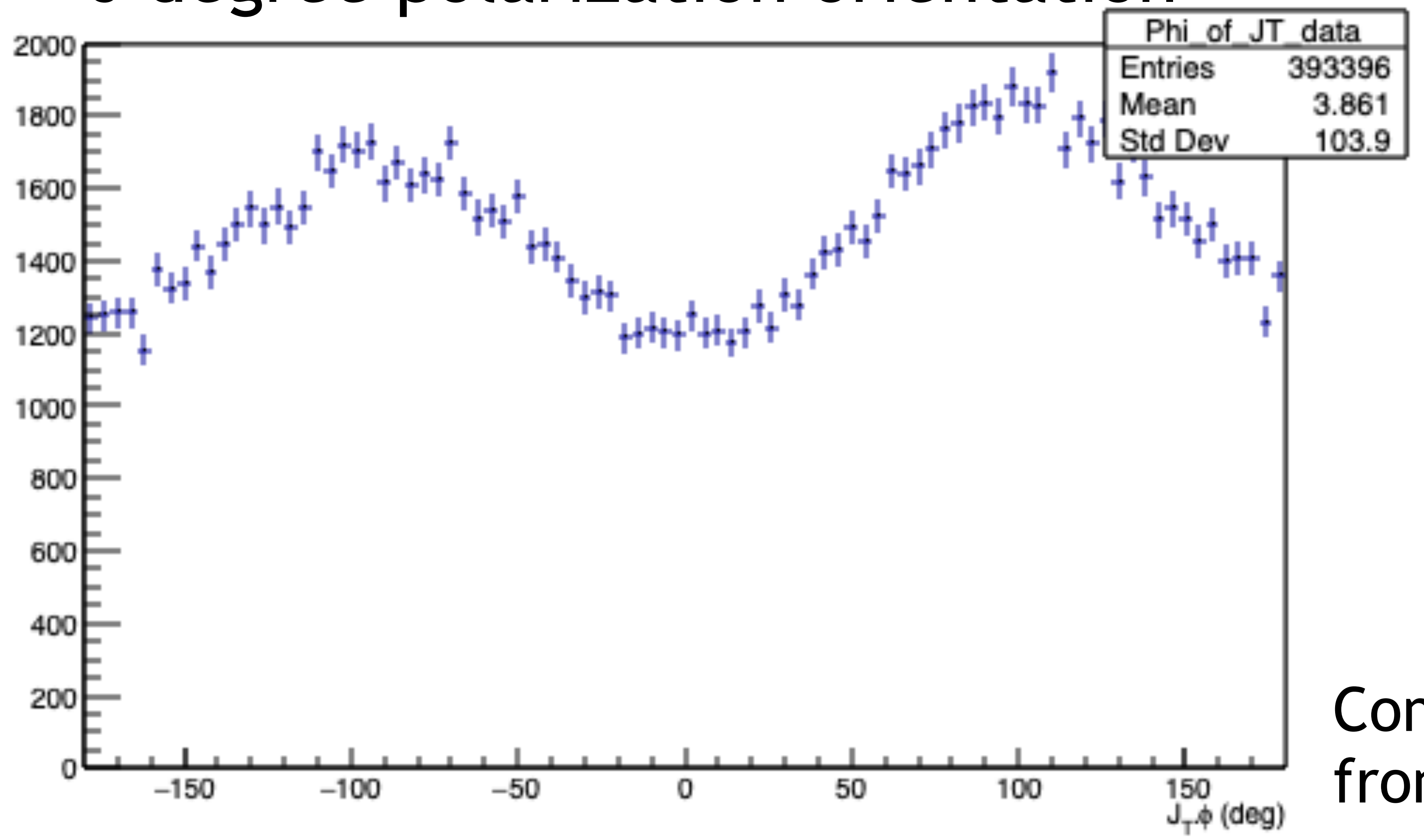
What if I just take right side?



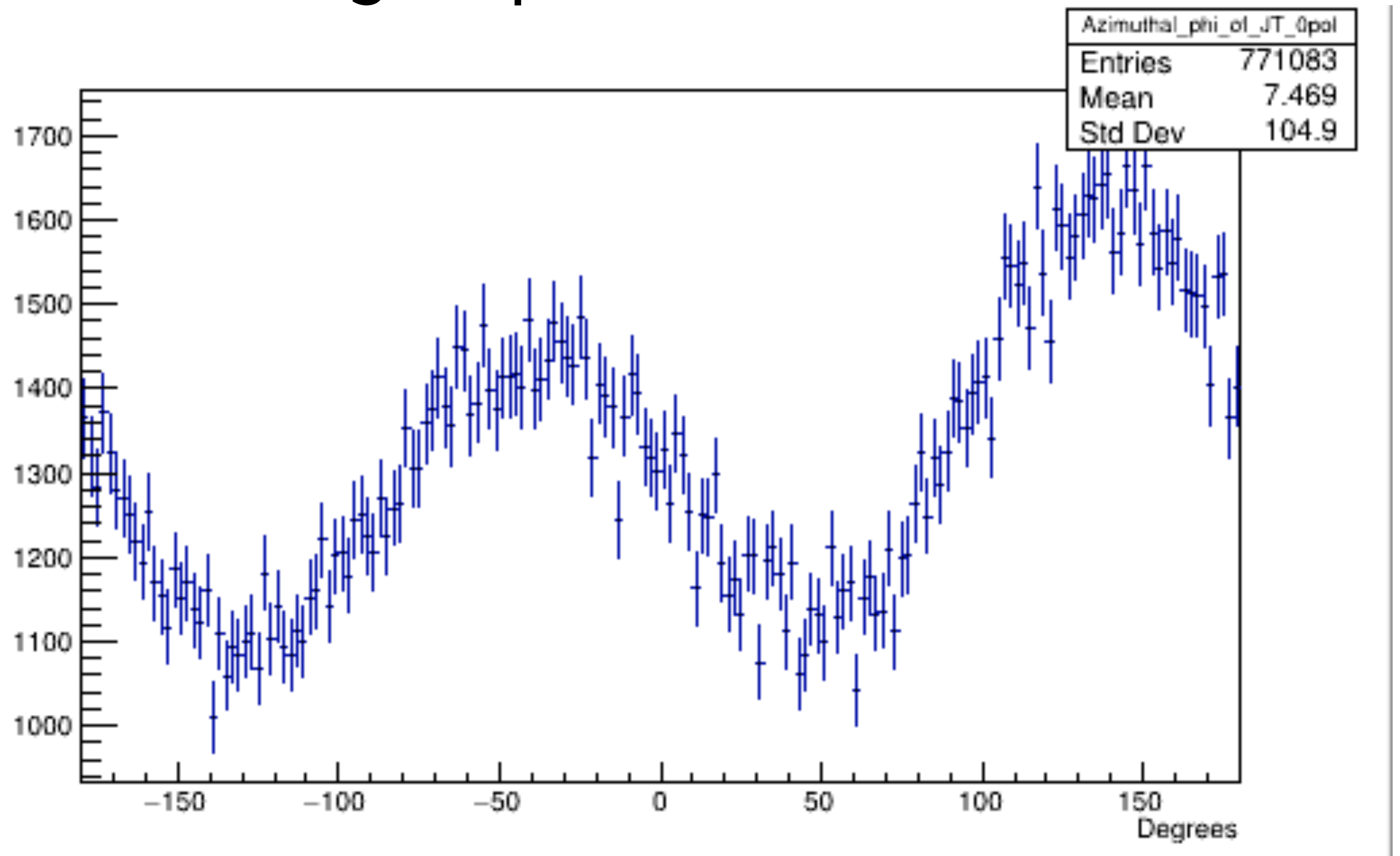
Then I get .30449 for a polarization.

Asymmetric peaks maybe are part of the problem, but not enough to get results to agree with tpol.

0 degree polarization orientation



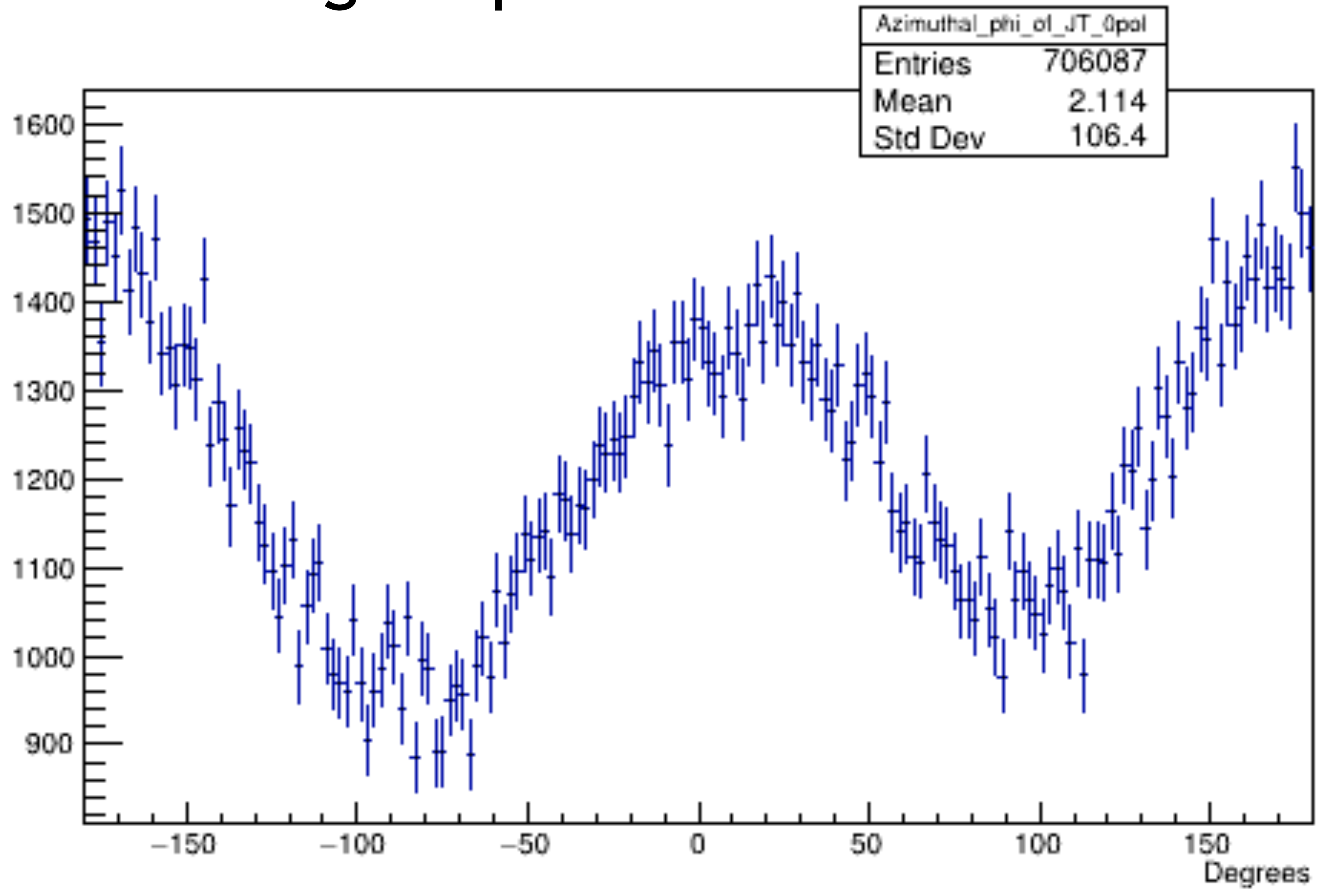
45 degree polarization orientation



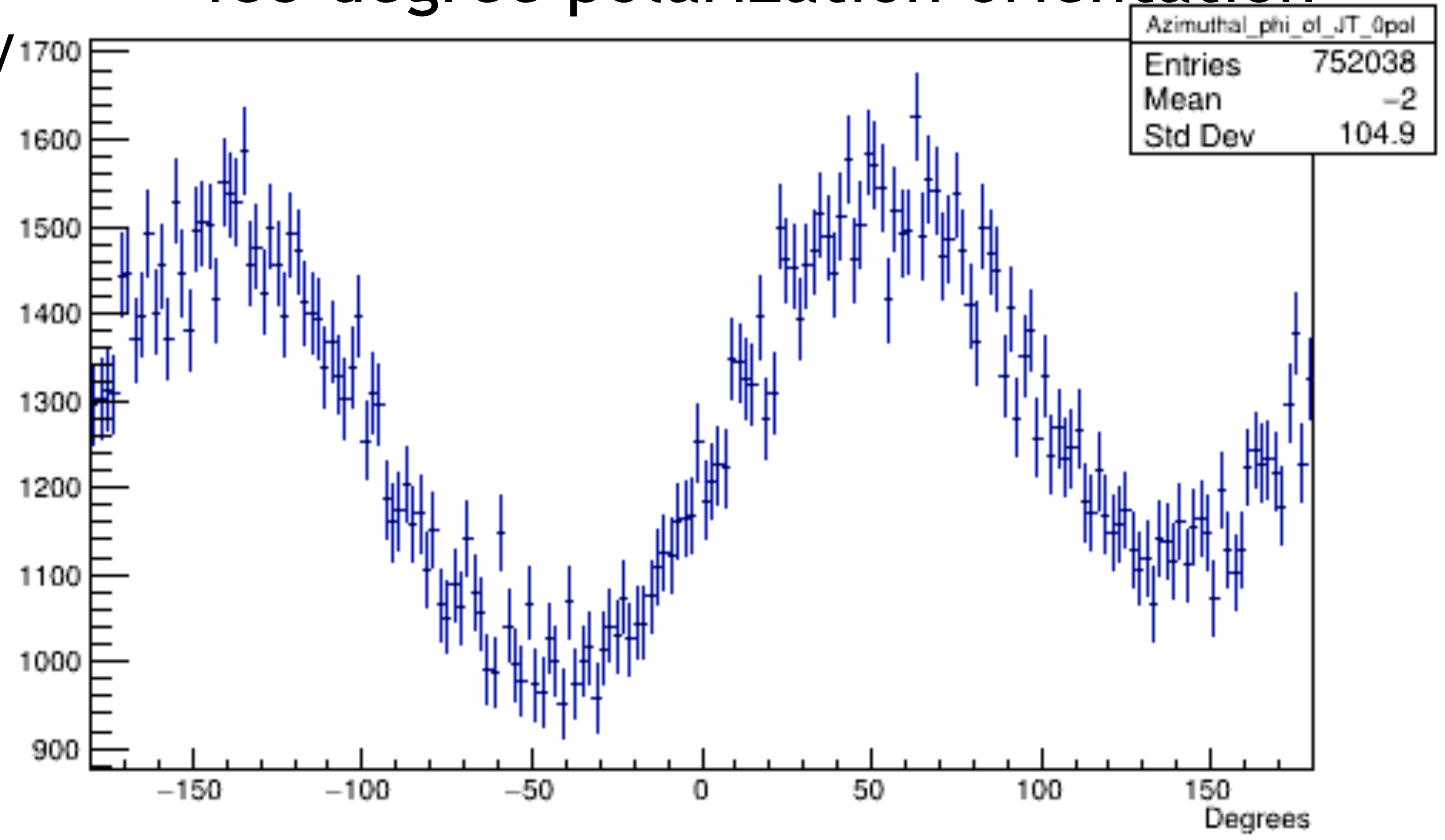
Comparing data from separate pol. runs:

All exhibit asymmetry

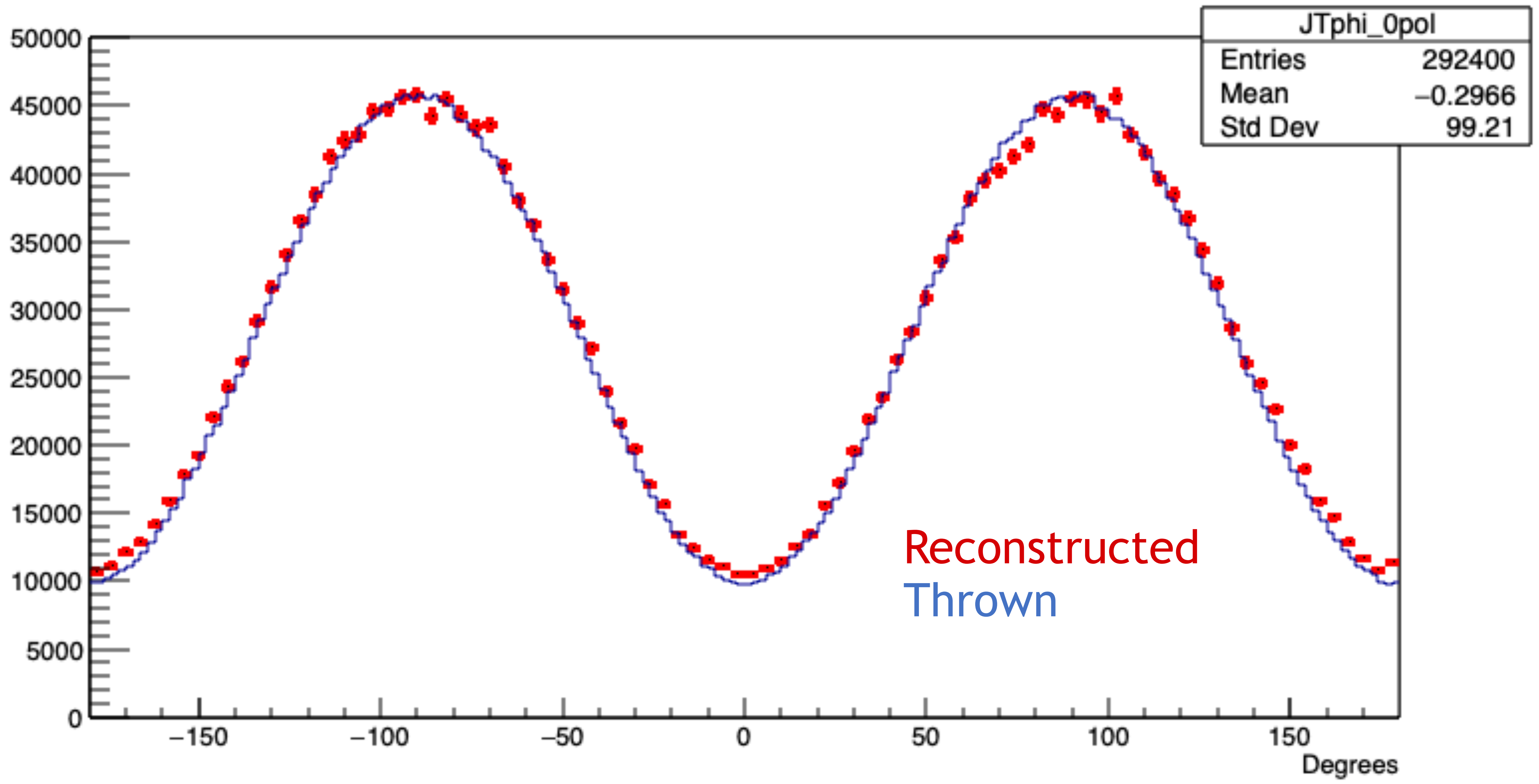
90 degree polarization orientation



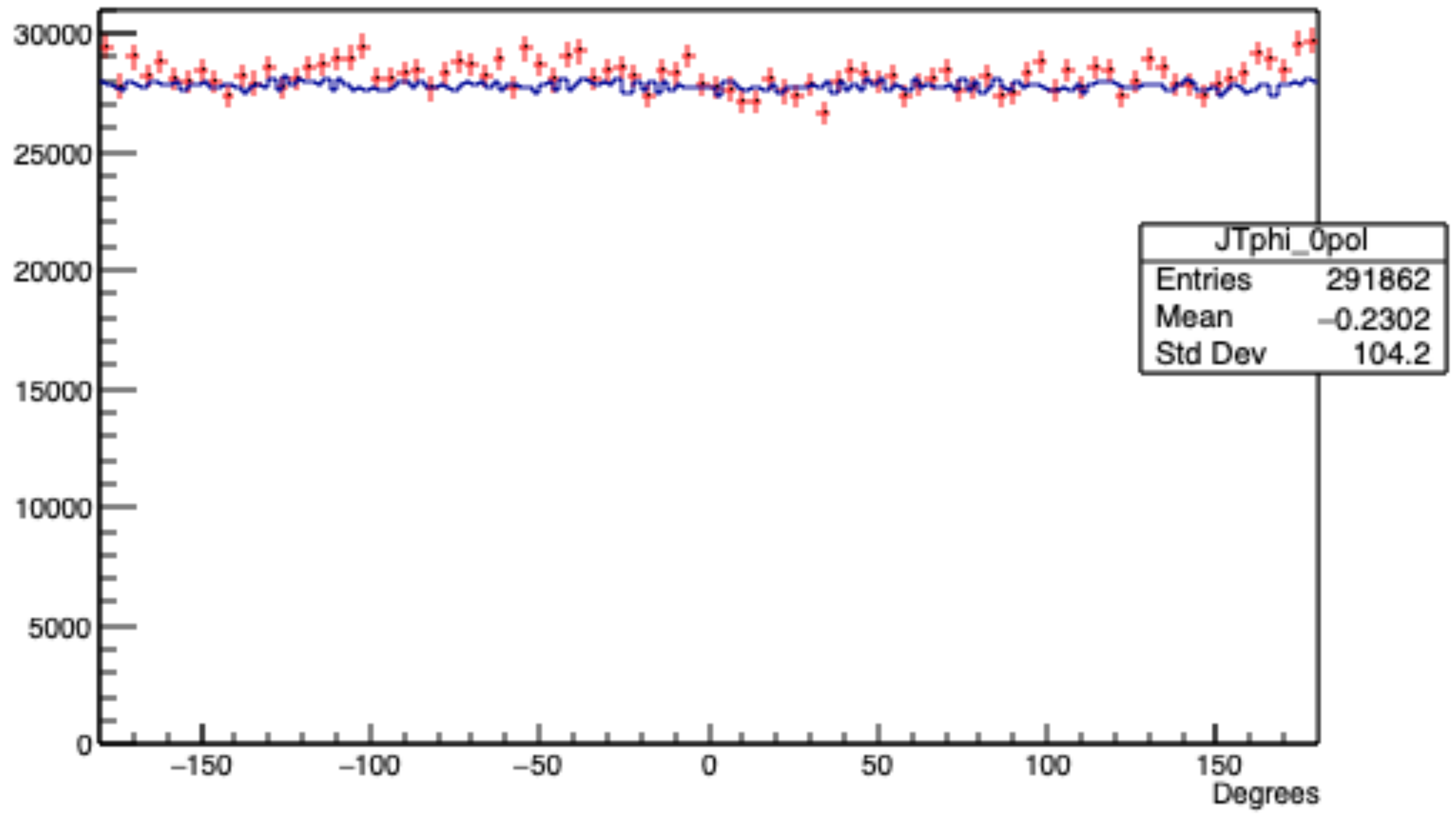
135 degree polarization orientation

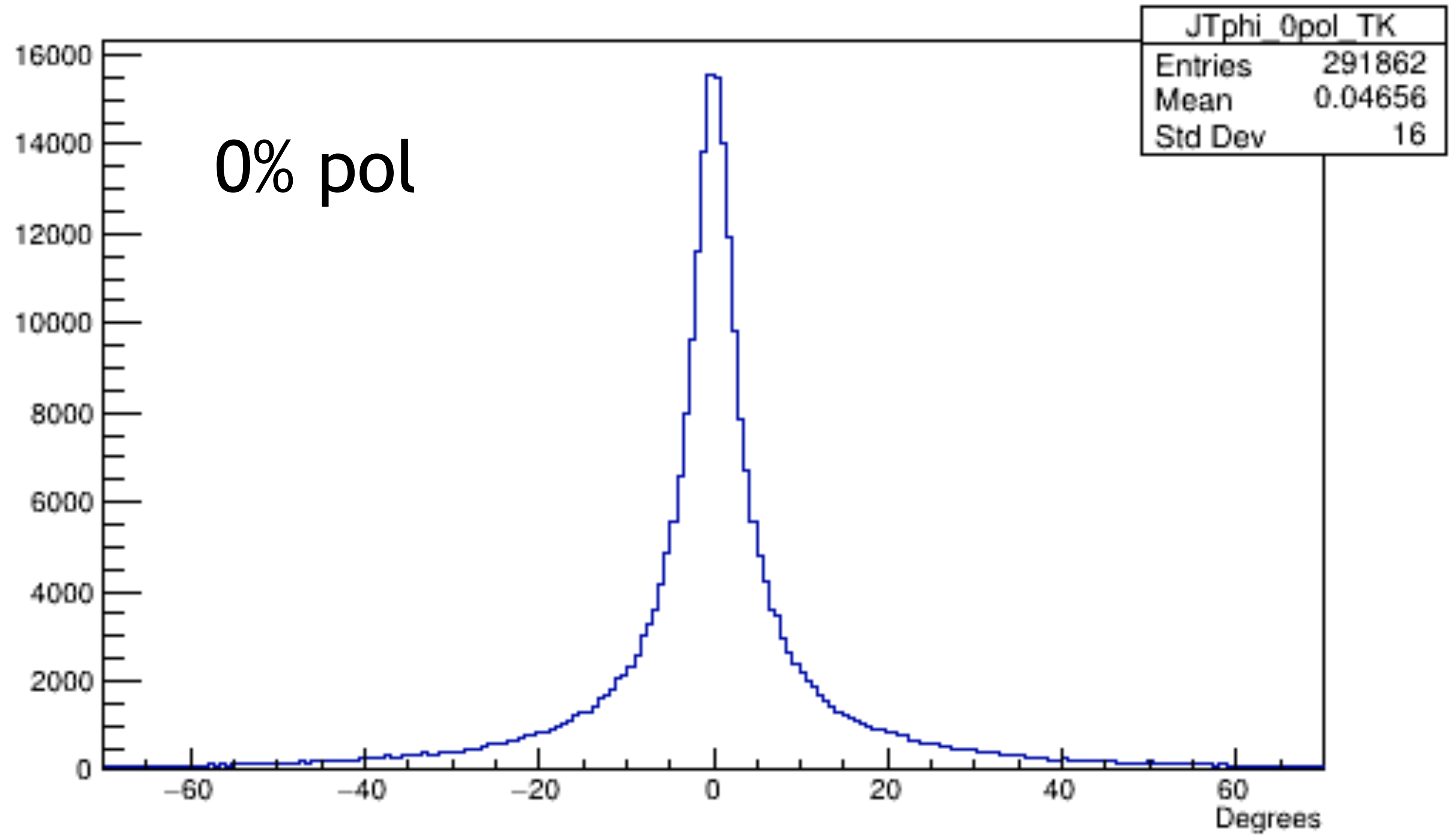


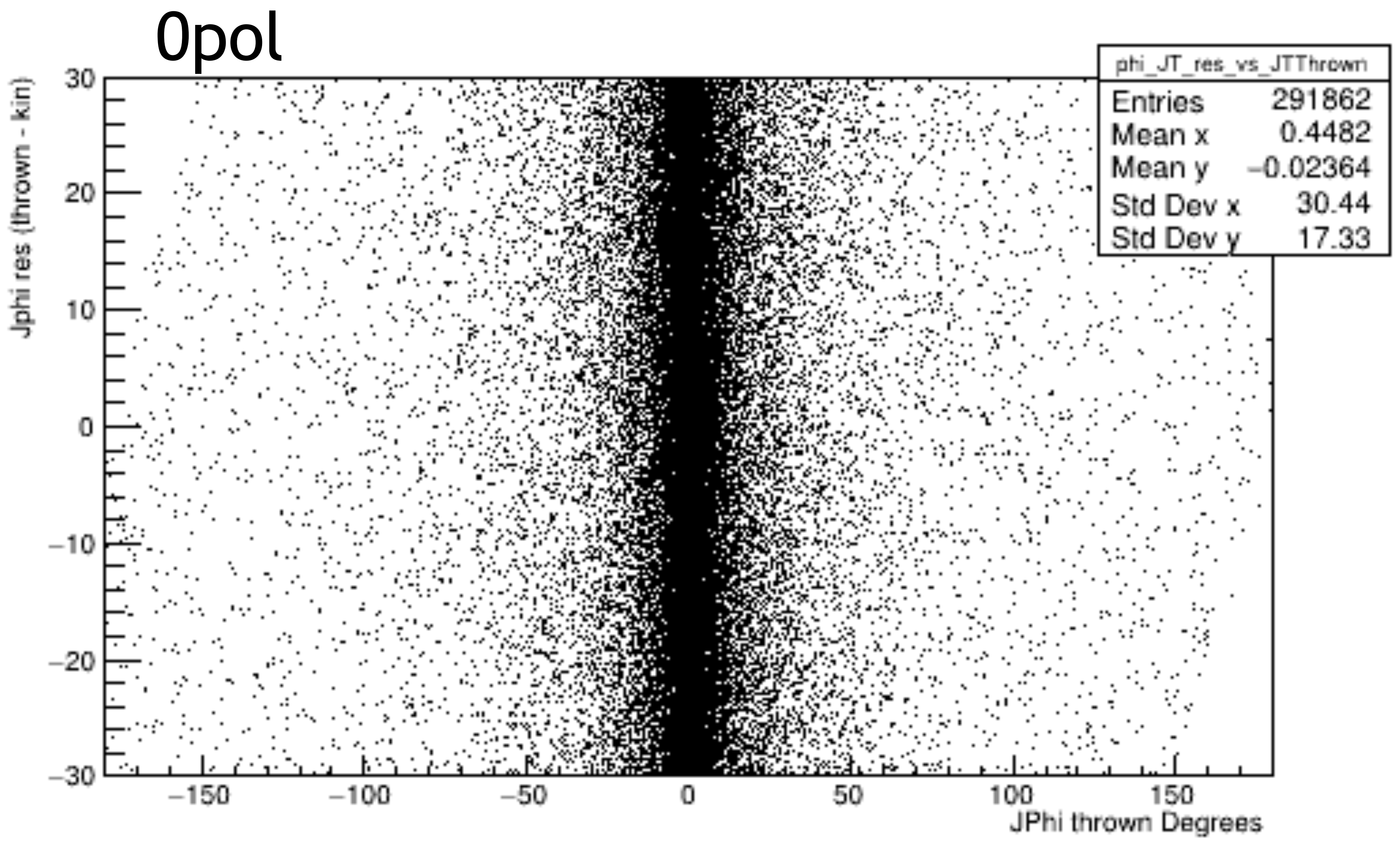
100% pol
phi of JT

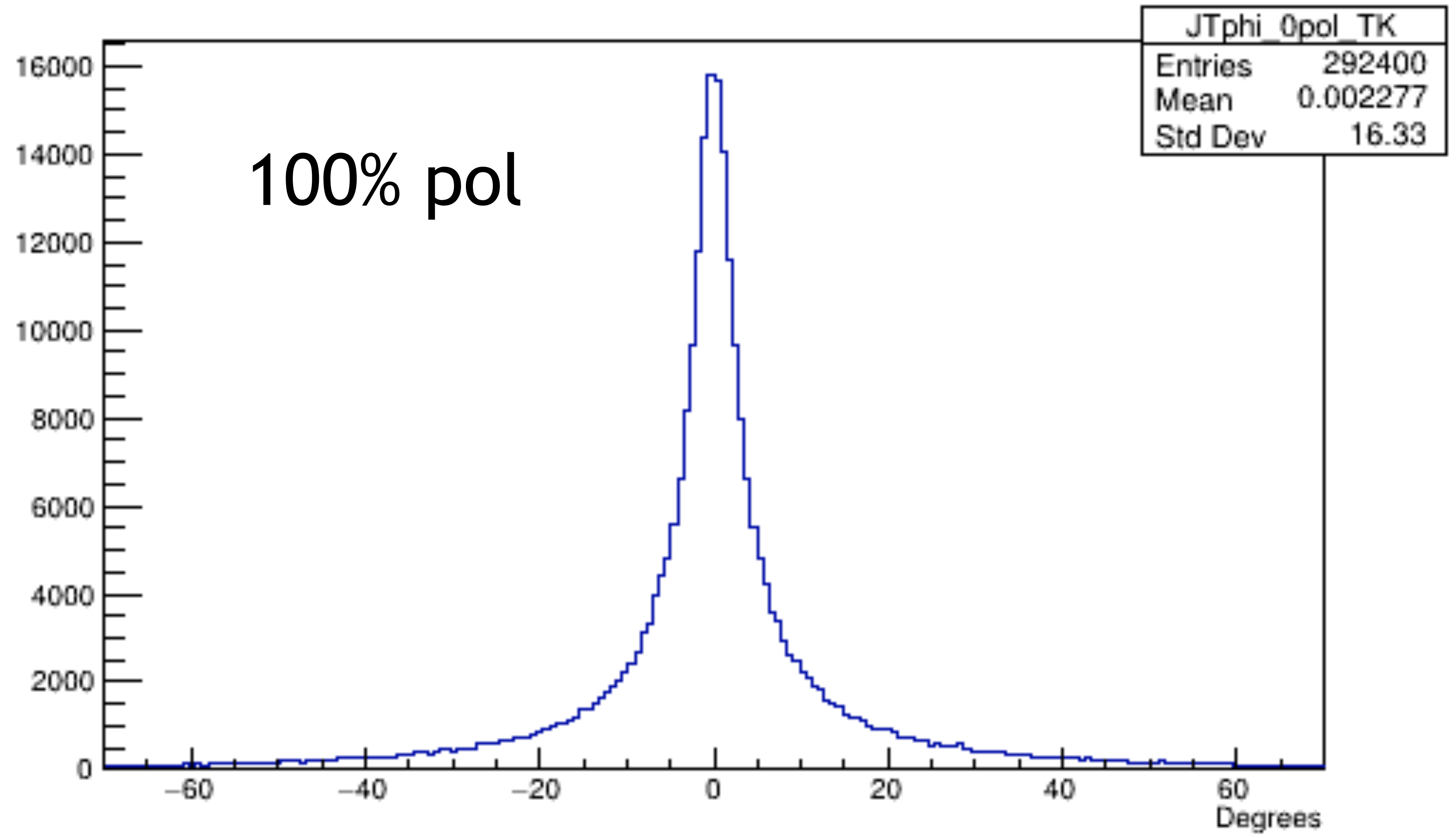


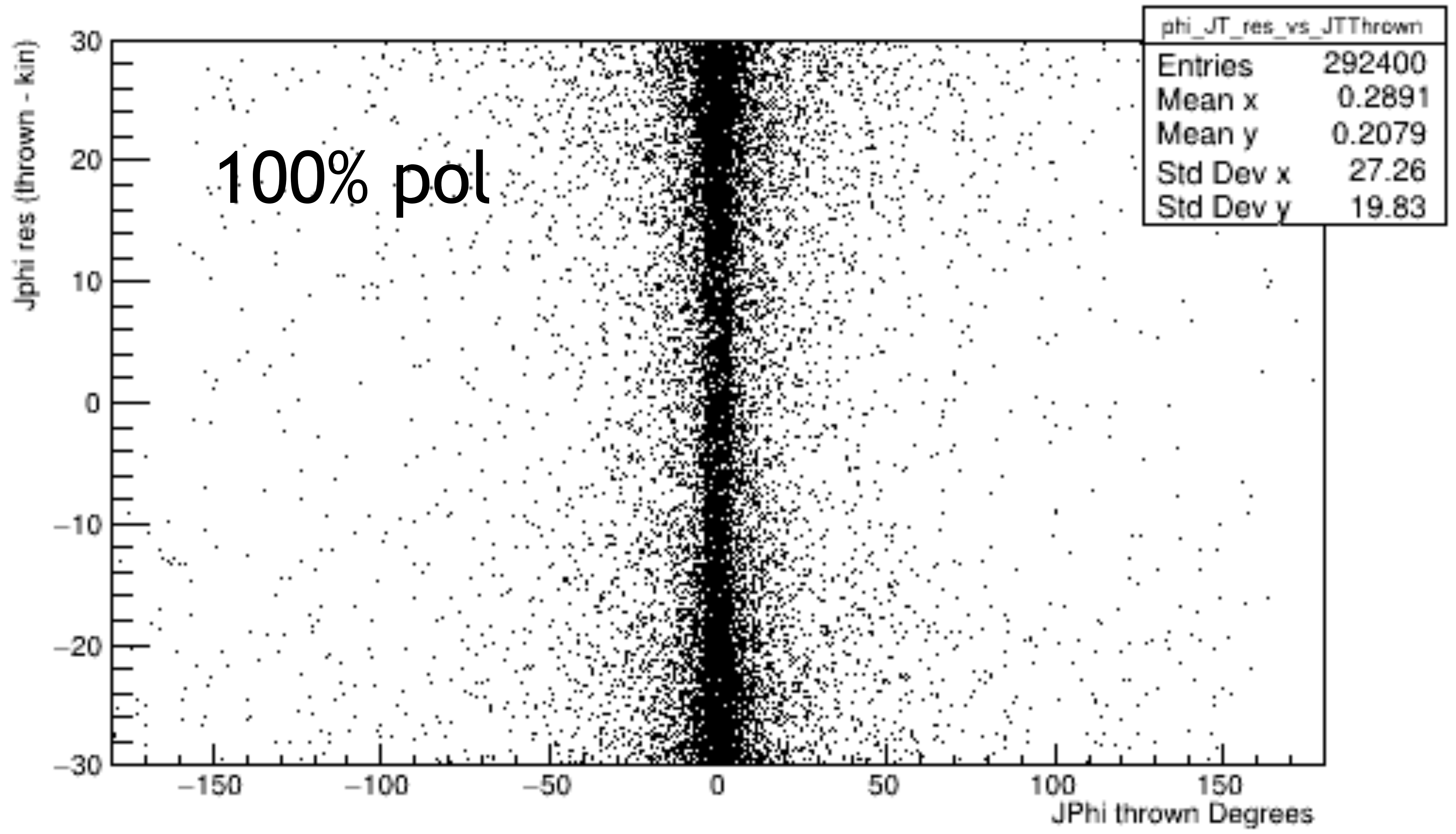
0% pol
phi of JT

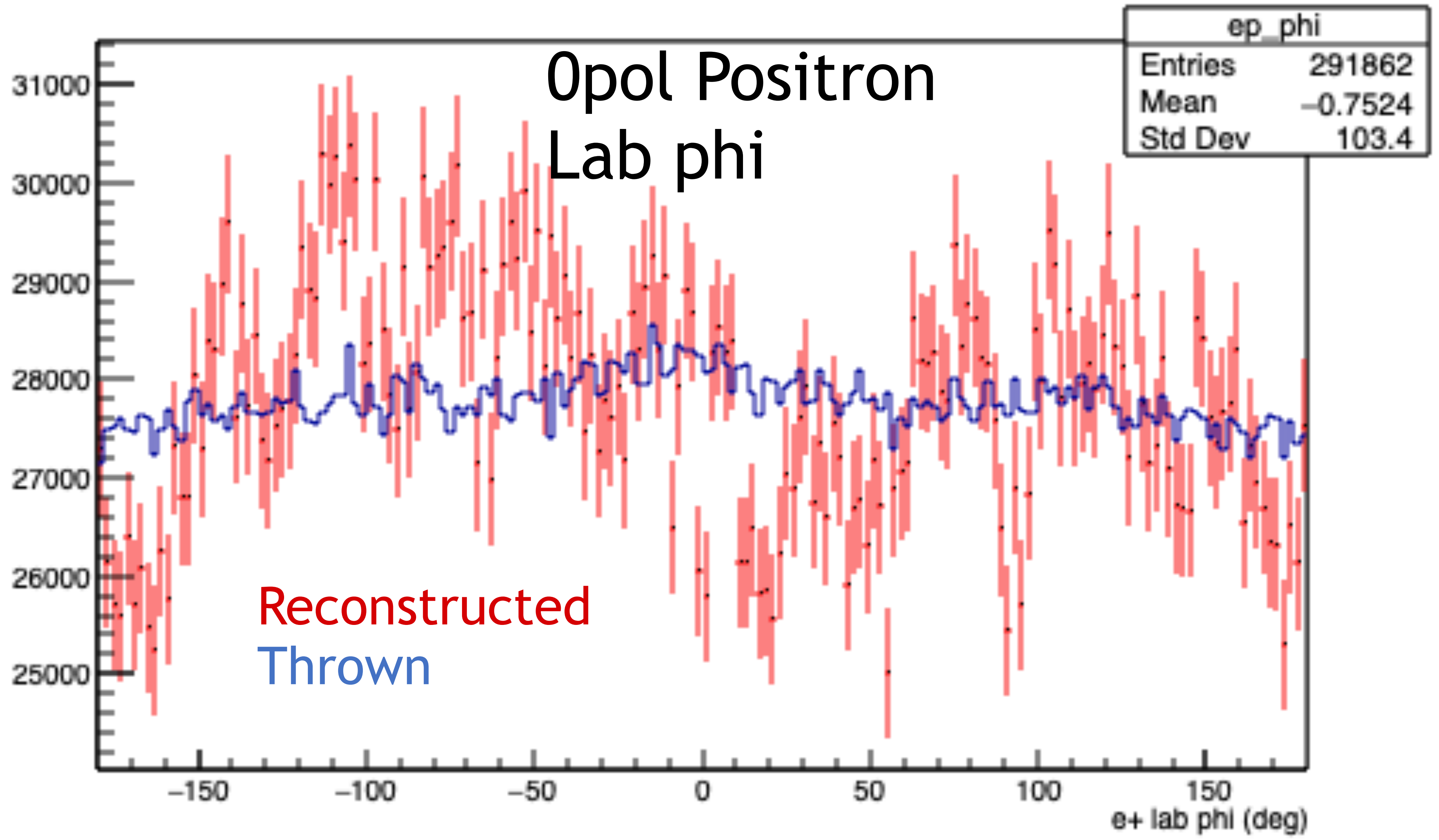


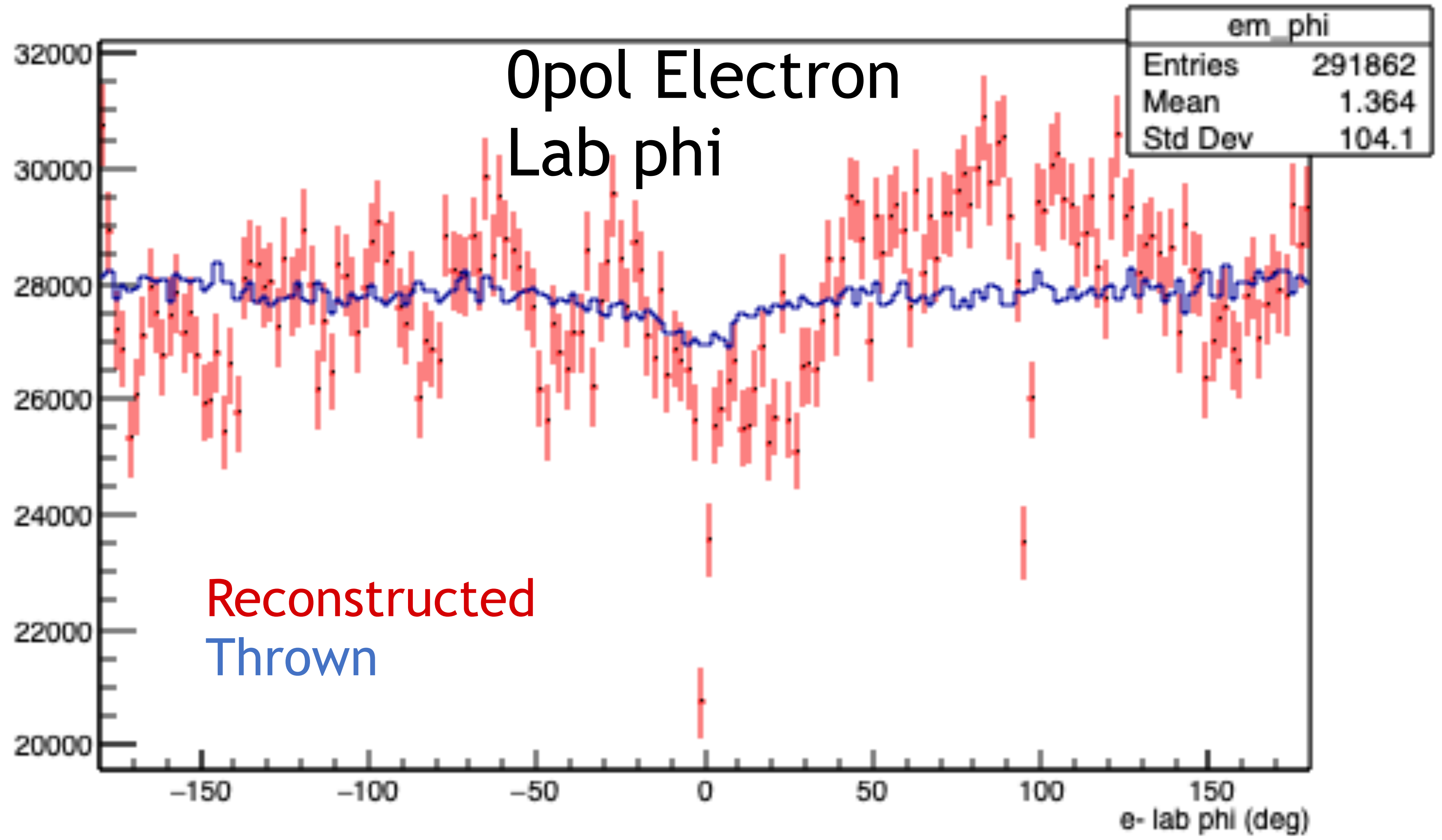

JTphi_0pol_TK
Entries 291862
Mean 0.04656
Std Dev 16
0% pol
Degrees

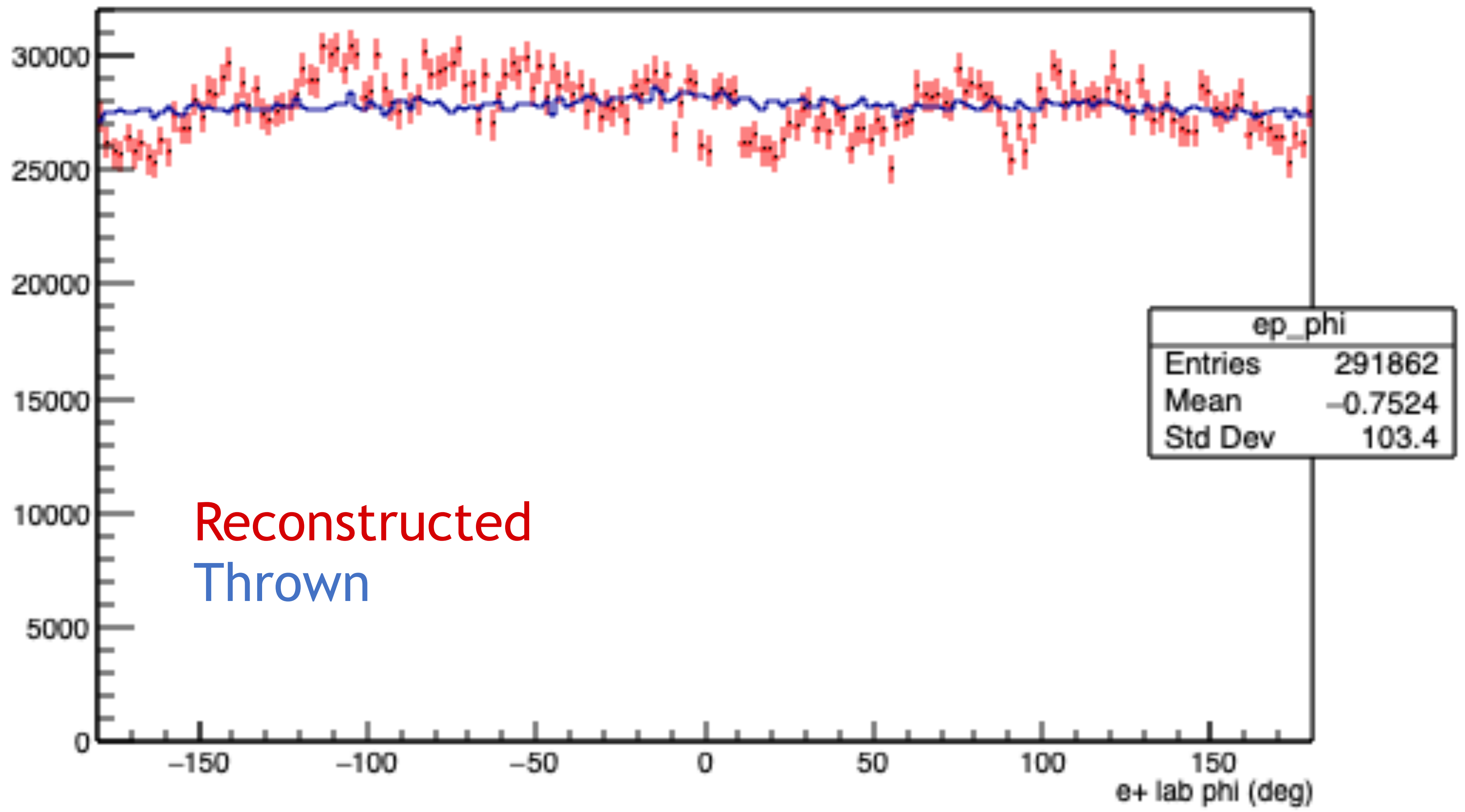

0pol
phi_JT_res_vs_JTThrown
Entries 291862
Mean x 0.4482
Mean y −0.02364
Std Dev x 30.44
Std Dev y 17.33
Jphi res (thrown - kin)
JPhi thrown Degrees

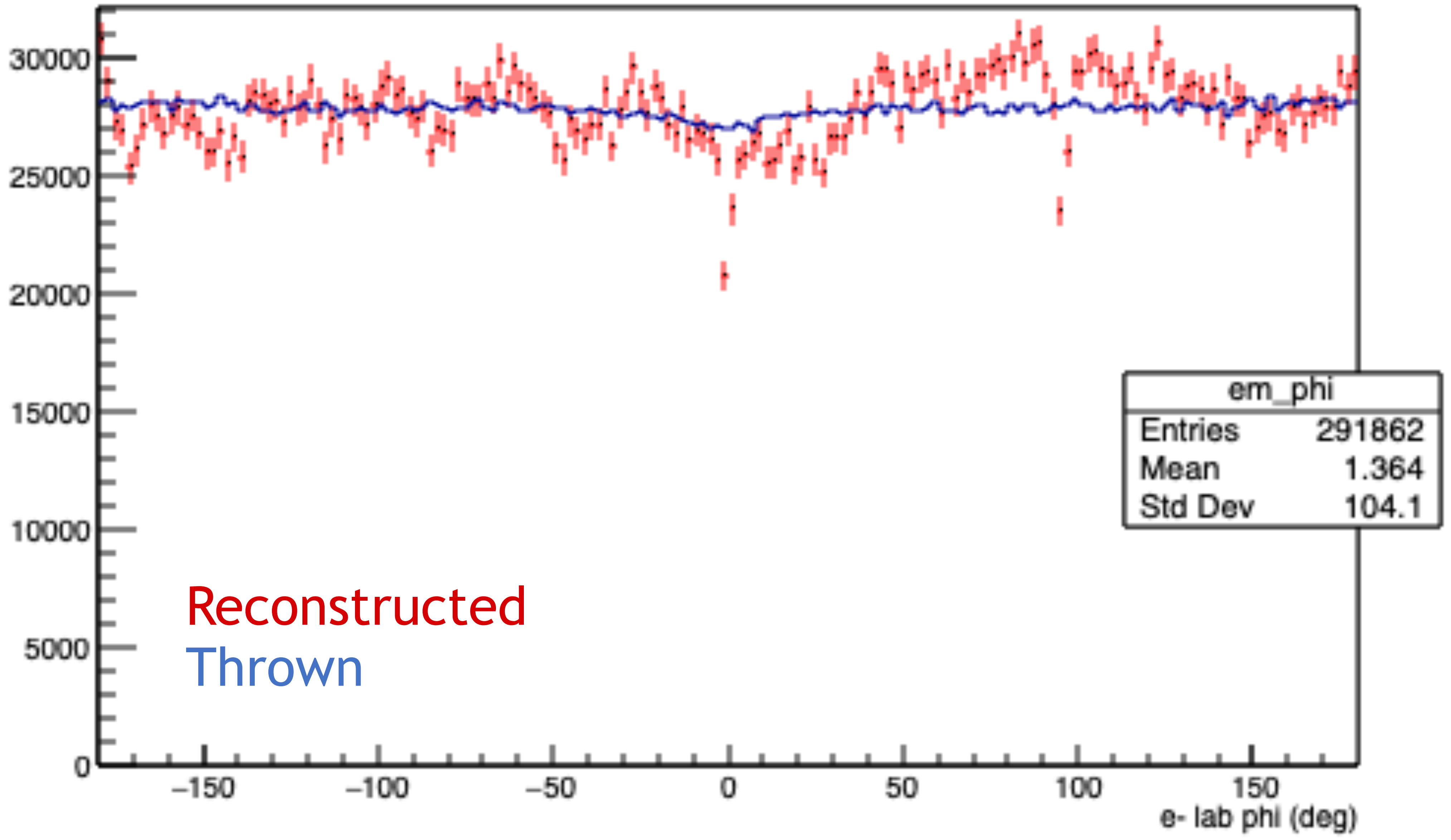

JTphi_0pol_TK
Entries 292400
Mean 0.002277
Std Dev 16.33
100% pol
Degrees


phi_JT_res_vs_JTThrown
Entries 292400
Mean x 0.2891
Mean y 0.2079
Std Dev x 27.26
Std Dev y 19.83
100% pol
Jphi res (thrown - kin)
JPhi thrown Degrees

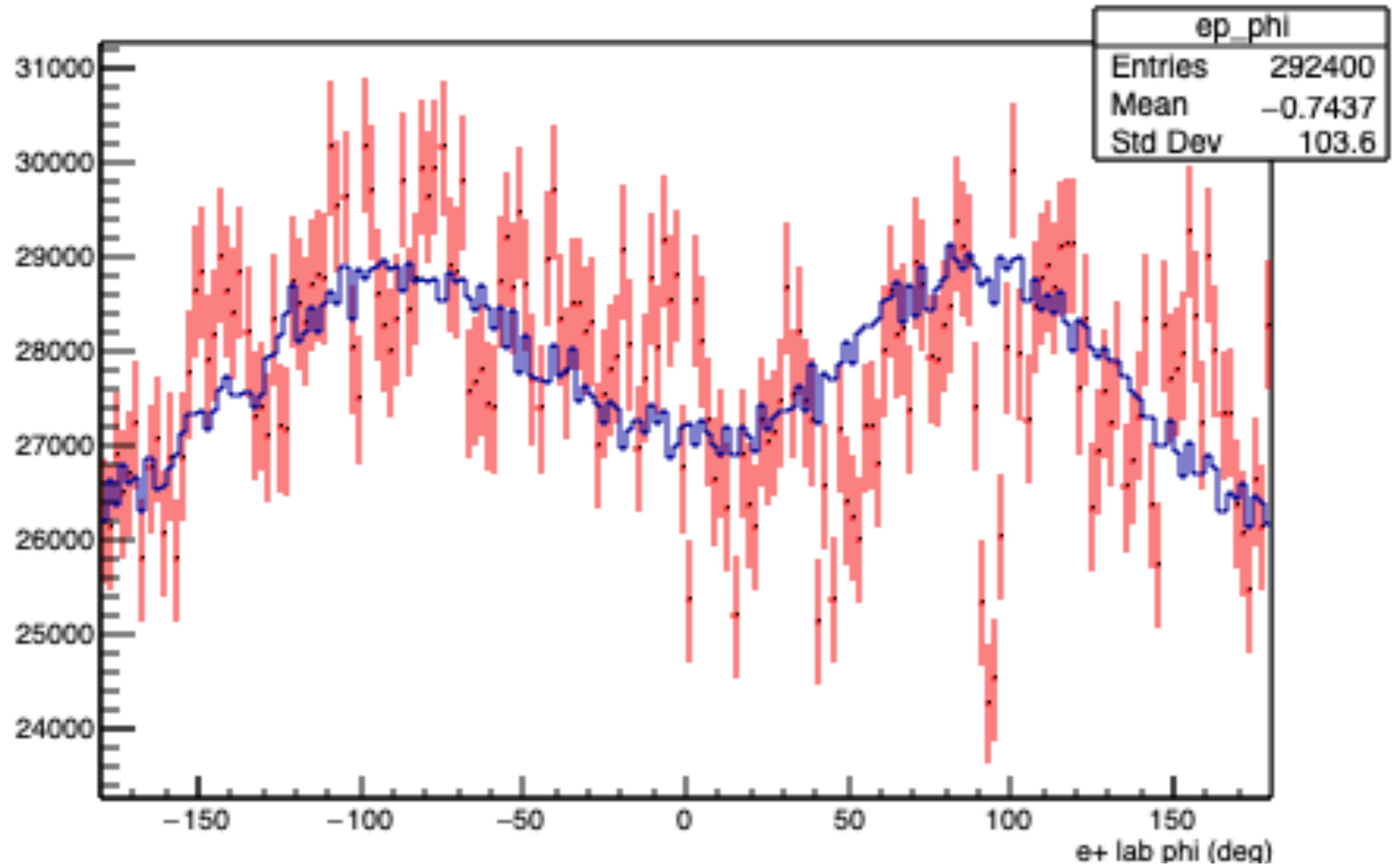

ep_phi
Entries 291862
Mean −0.7524
Std Dev 103.4
0pol Positron
Lab phi
Reconstructed
Thrown
e+ lab phi (deg)


em_phi
Entries 291862
Mean 1.364
Std Dev 104.1
0pol Electron
Lab phi
Reconstructed
Thrown
e- lab phi (deg)

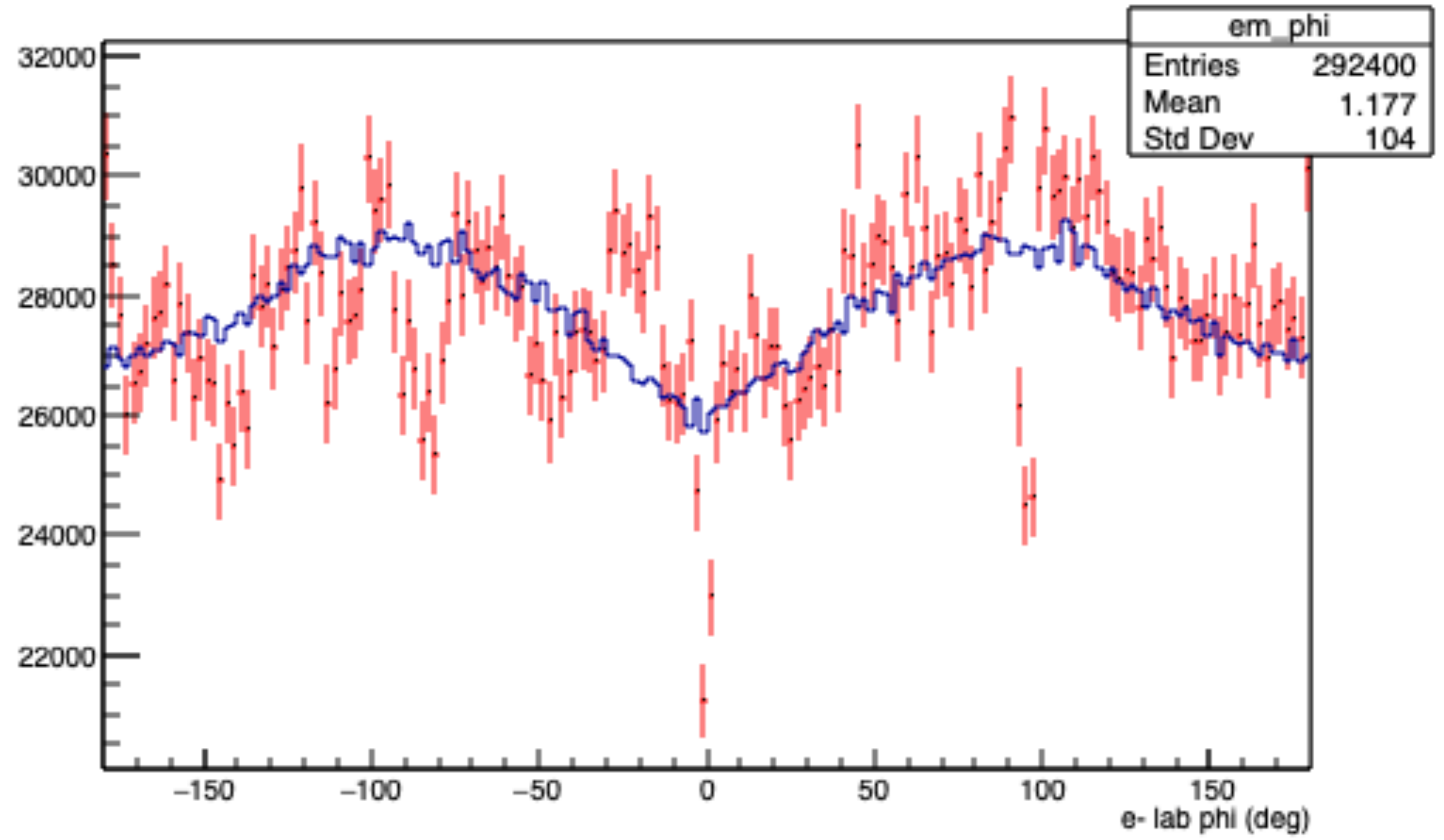

ep_phi
Entries 291862
Mean −0.7524
Std Dev 103.4
Reconstructed
Thrown
e+ lab phi (deg)

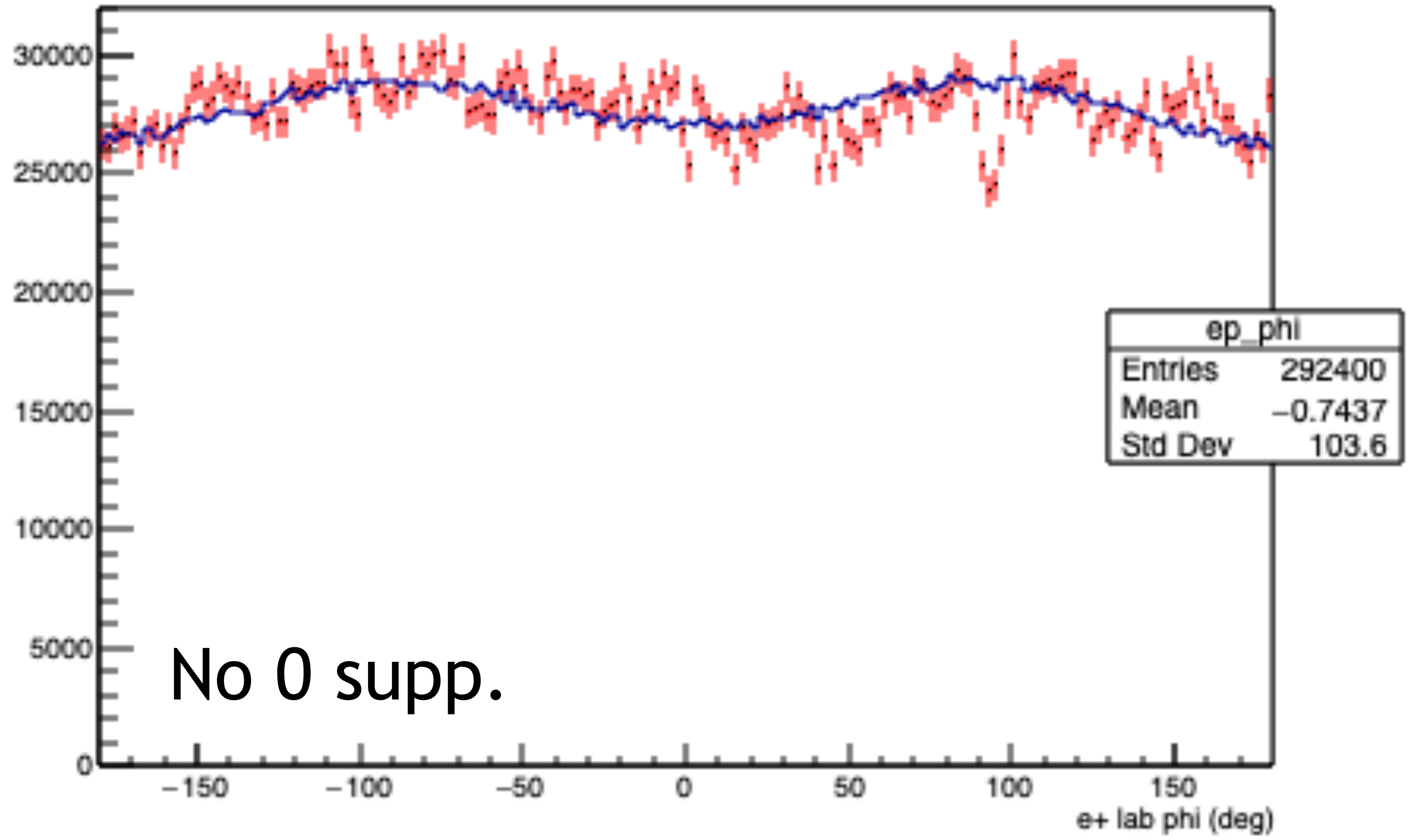

em_phi
Entries 291862
Mean 1.364
Std Dev 104.1
Reconstructed
Thrown
e- lab phi (deg)

100% pol positron

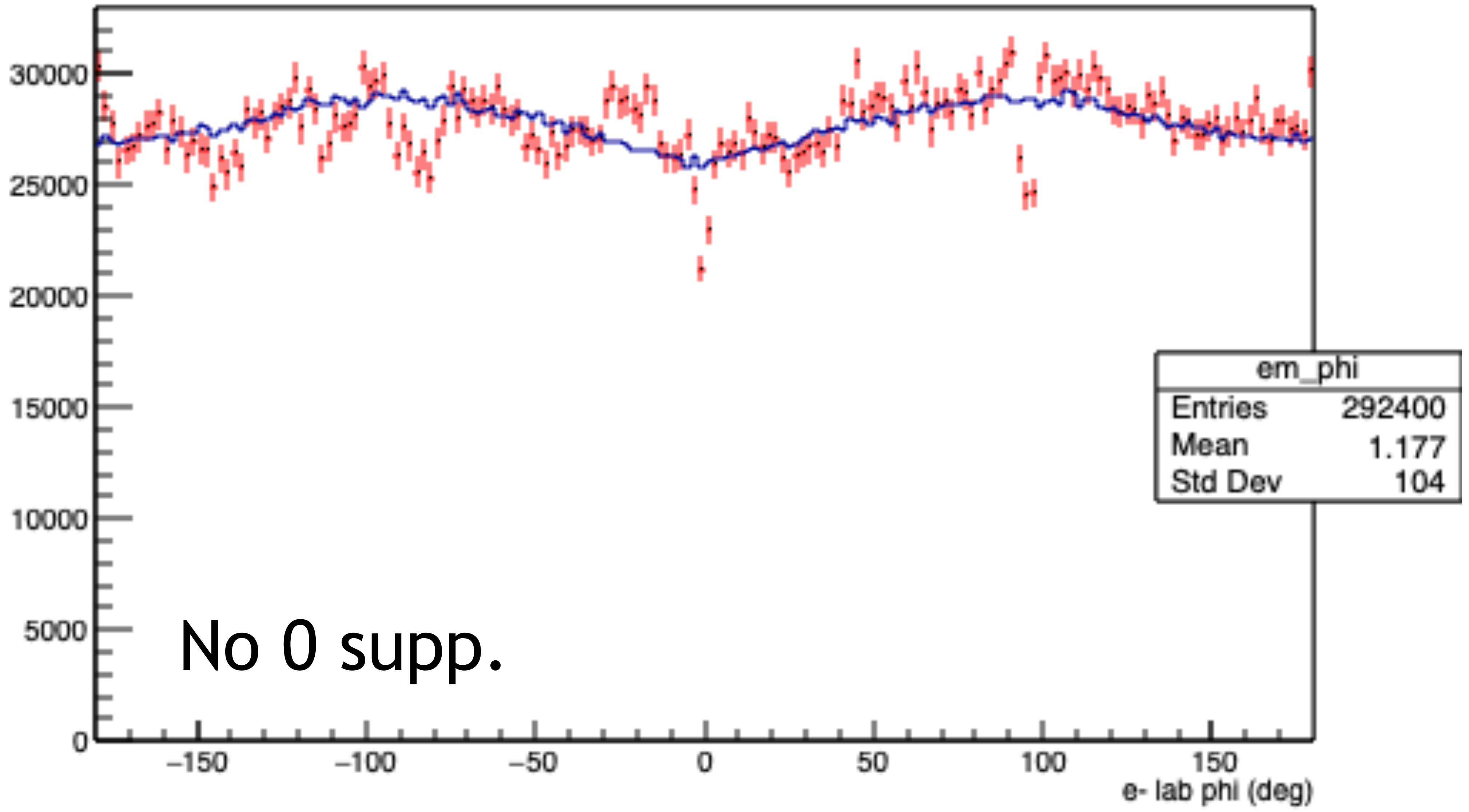


100% pol electron

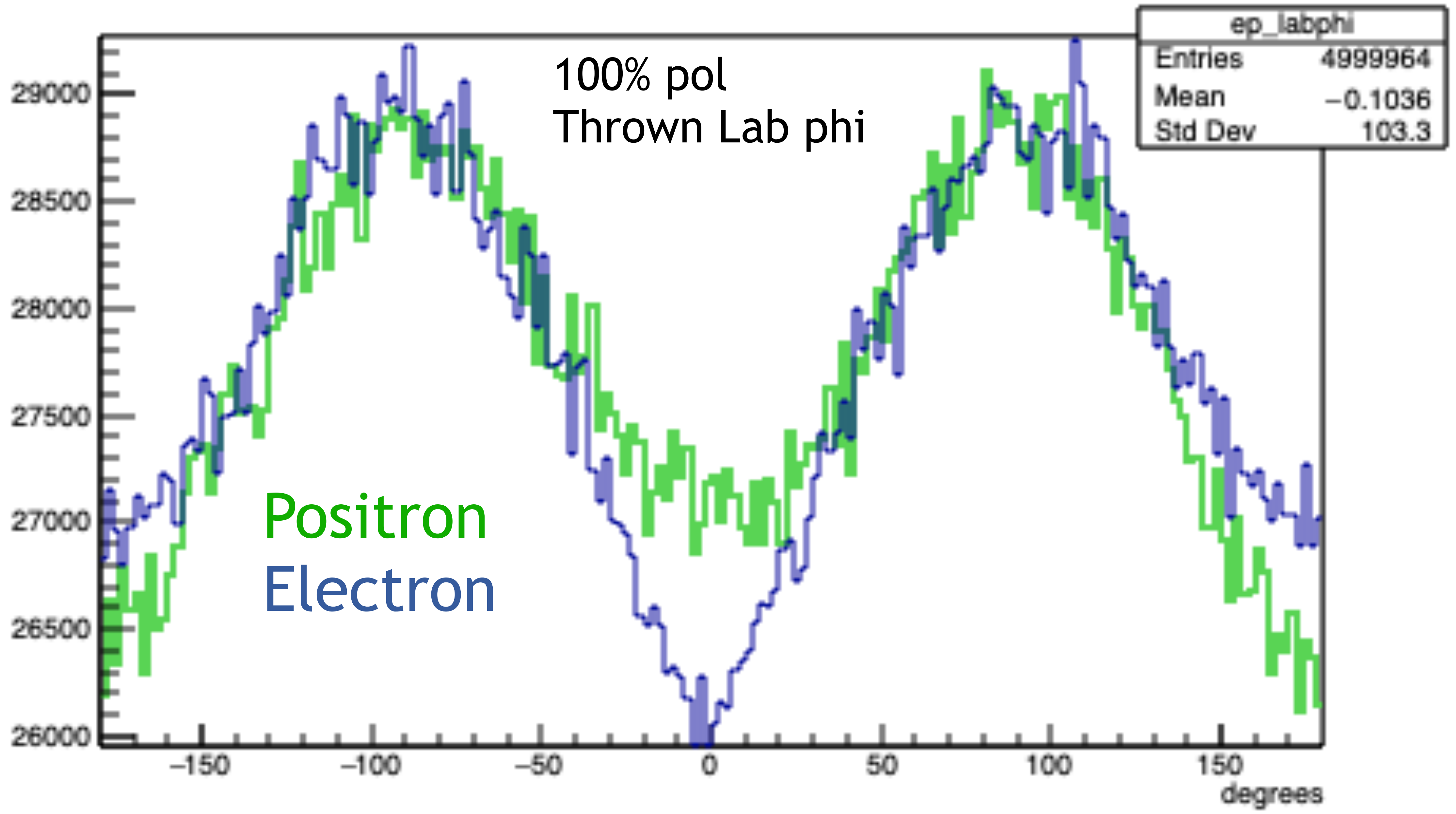




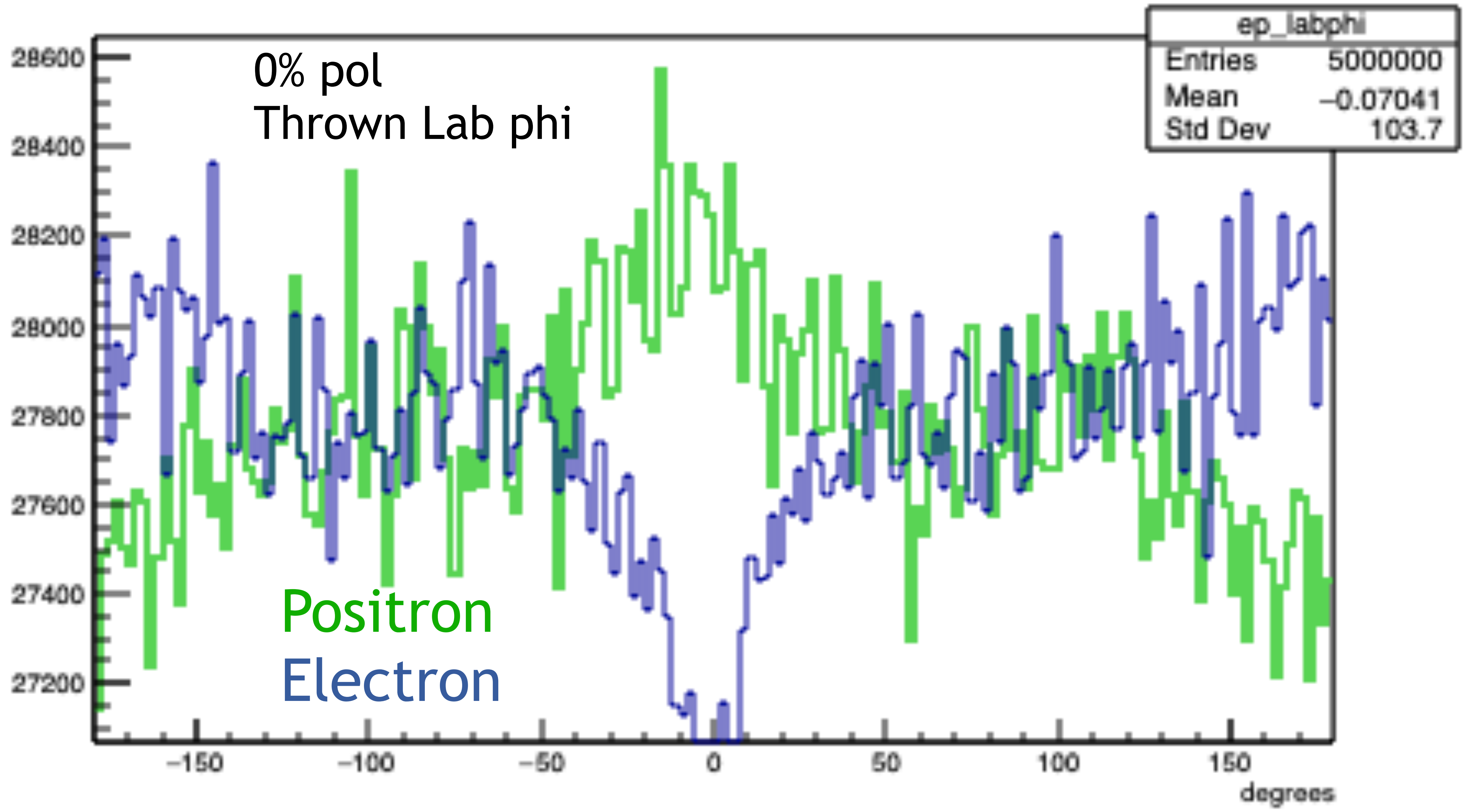
No 0 supp.



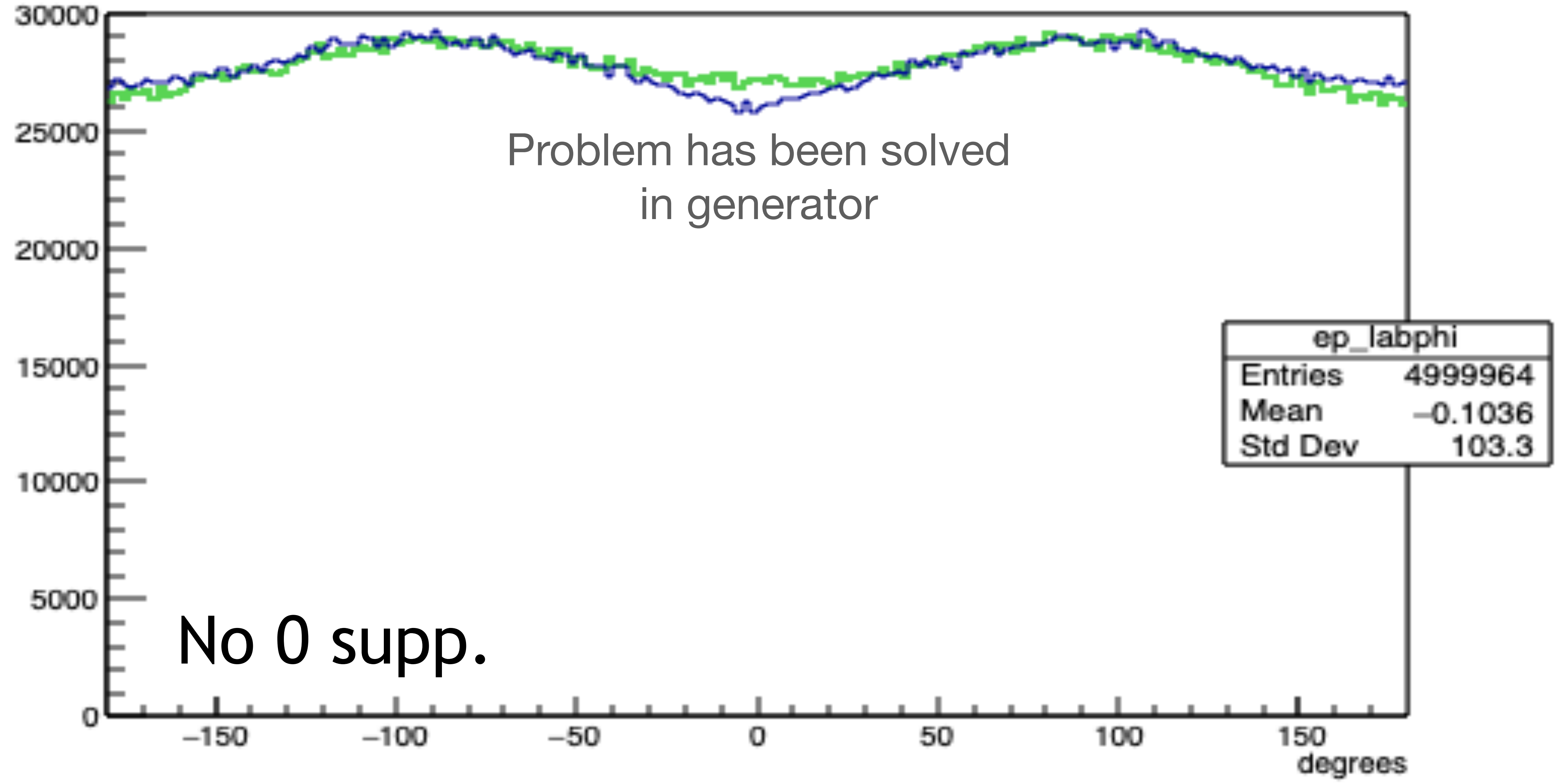
No 0 supp.



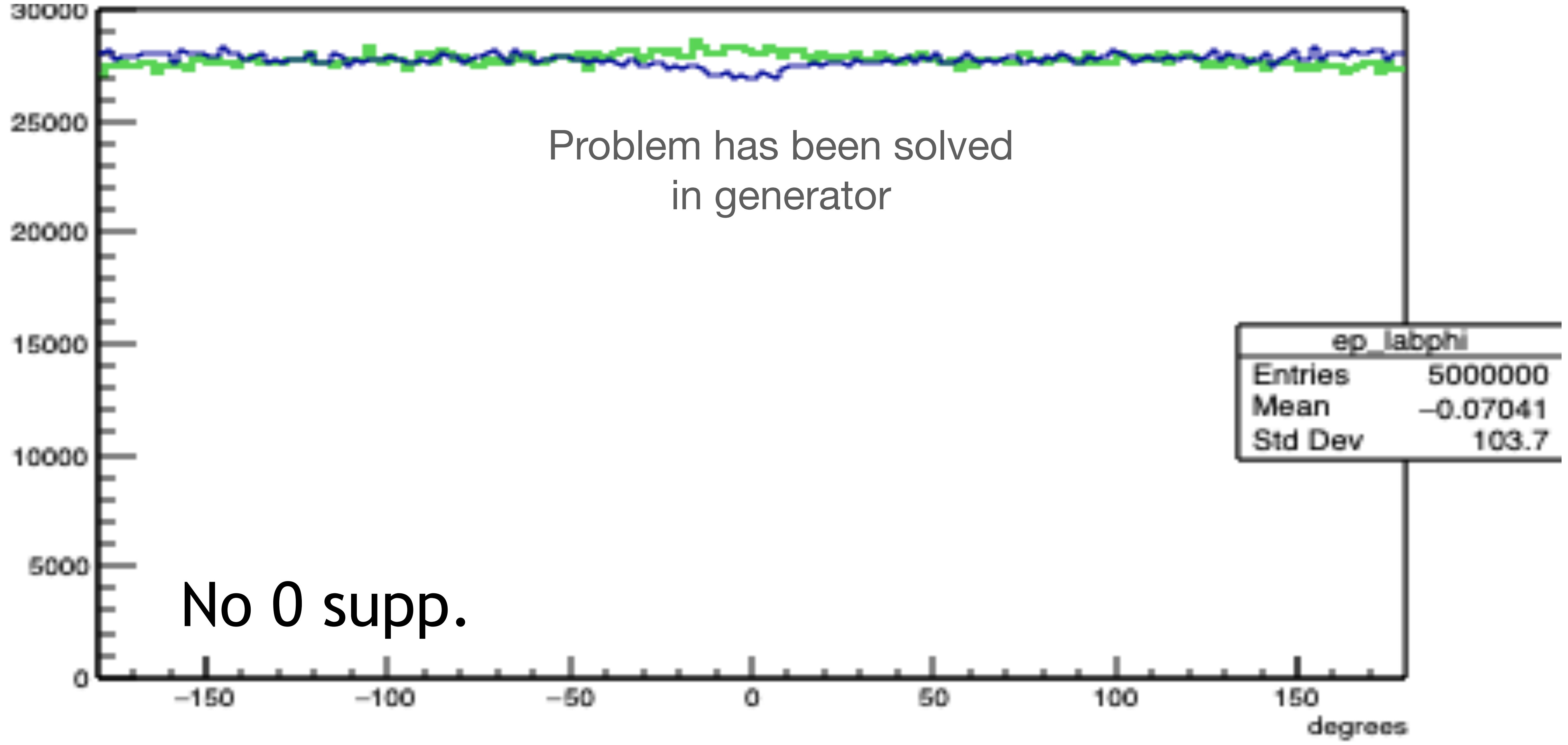
ep_labphi
Entries 4999964
Mean −0.1036
Std Dev 103.3
100% pol
Thrown Lab phi
Positron
Electron
degrees



ep_labphi
Entries 5000000
Mean −0.07041
Std Dev 103.7
0% pol
Thrown Lab phi
Positron
Electron
degrees

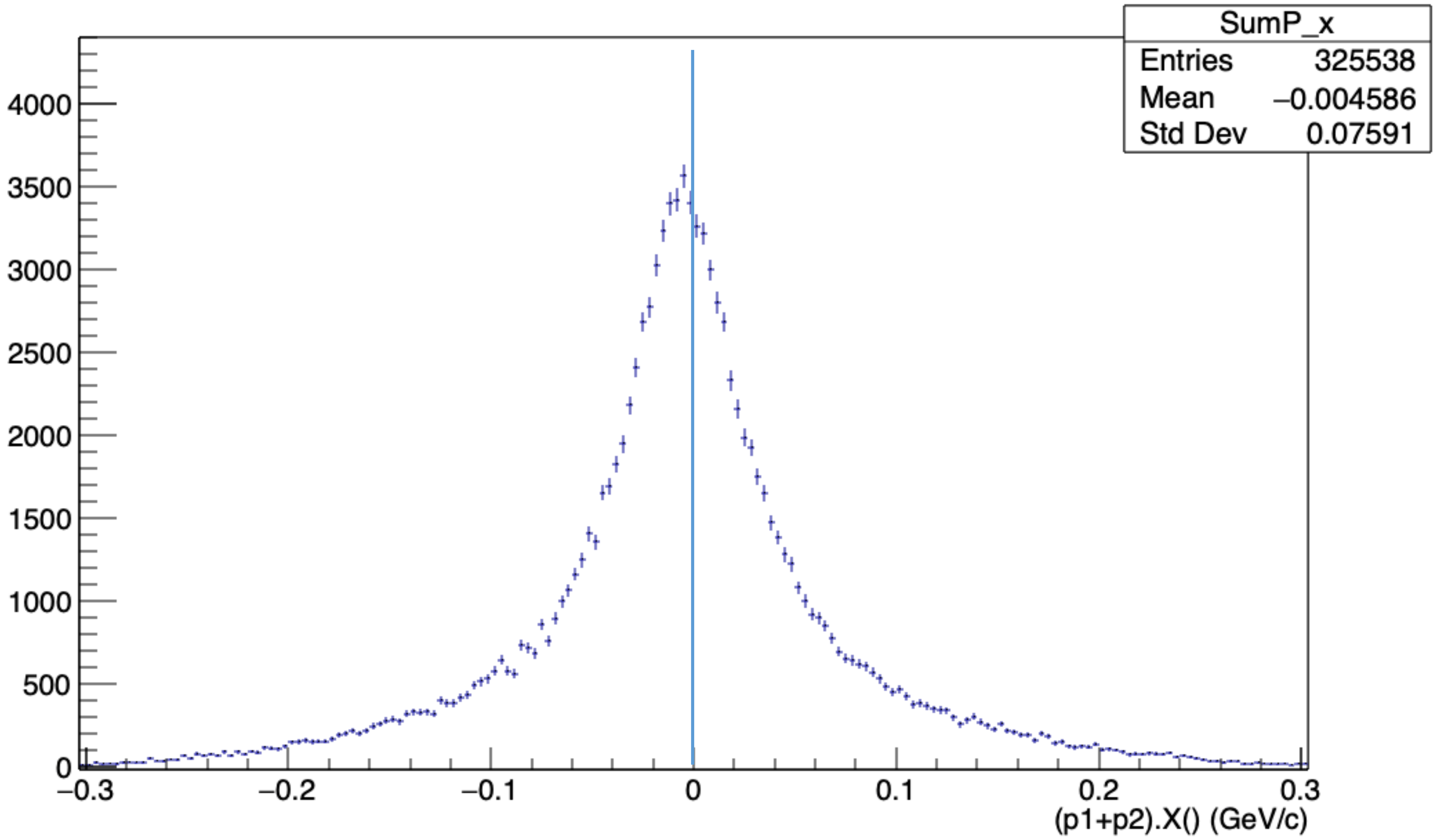


Problem has been solved
in generator
ep_labphi
Entries 4999964
Mean −0.1036
Std Dev 103.3
No 0 supp.
degrees

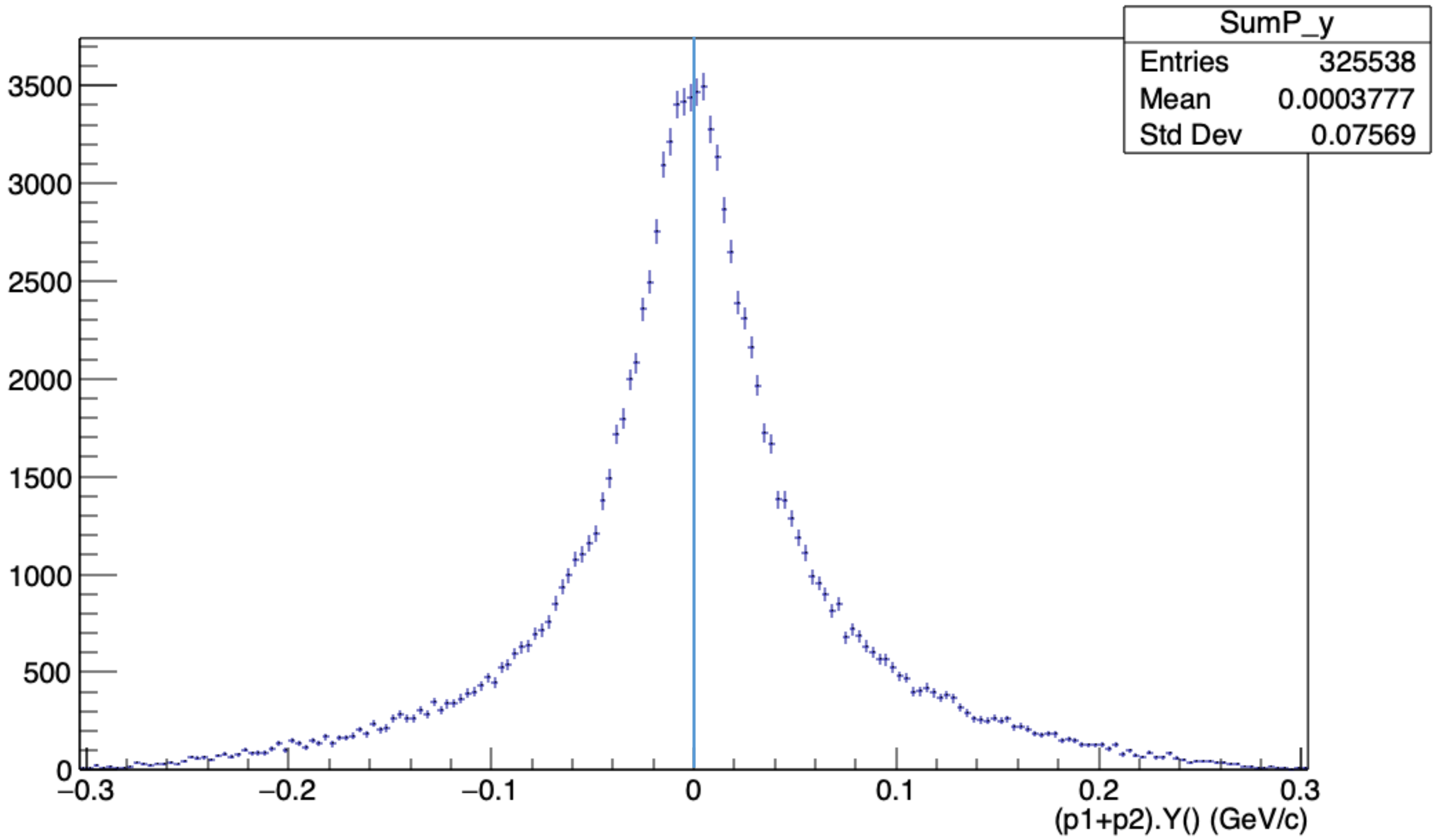


Problem has been solved
in generator
ep_labphi
Entries 5000000
Mean −0.07041
Std Dev 103.7
No 0 supp.
degrees

P1 + P2, x component
2018-01 GlueX data



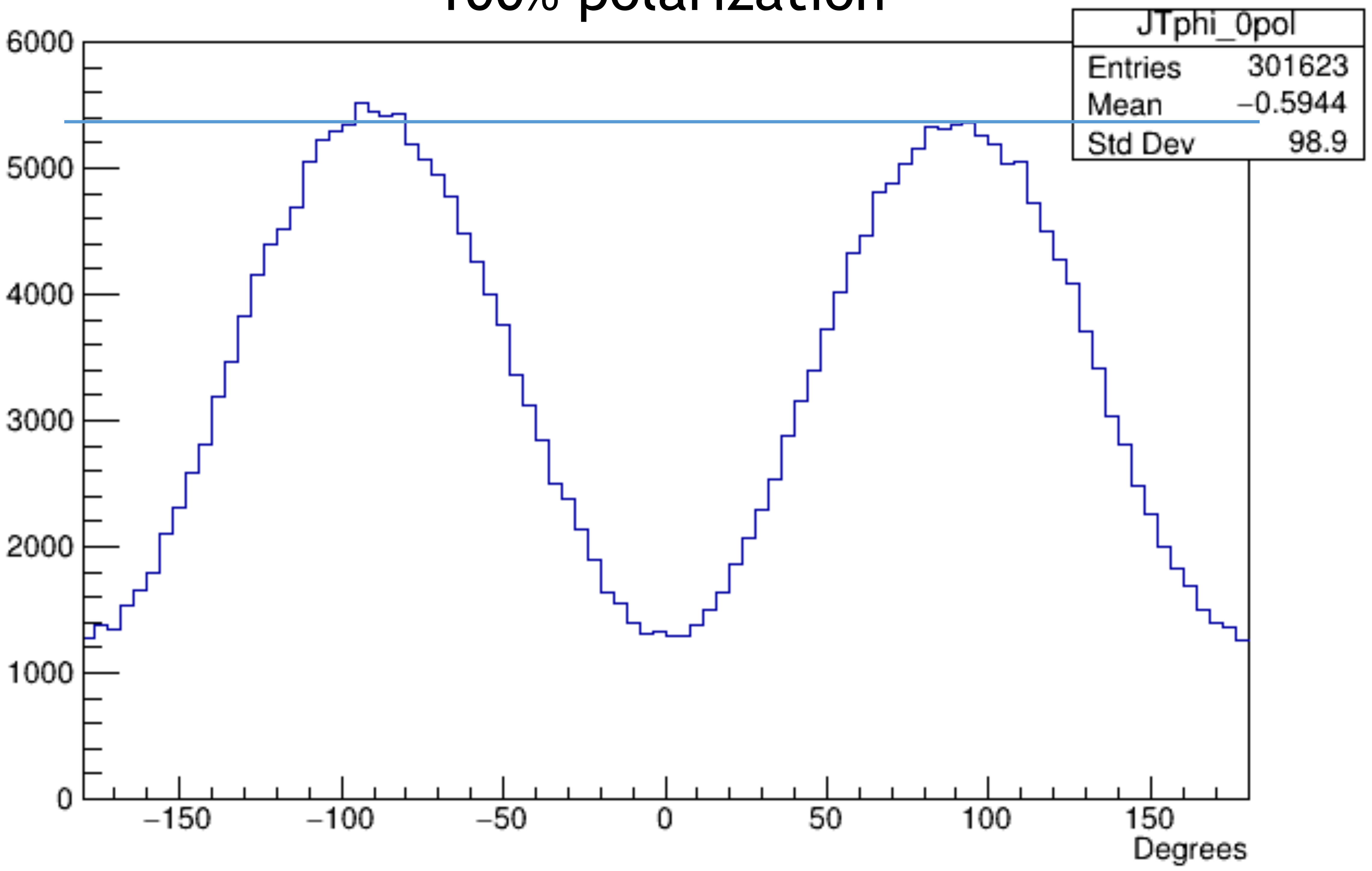
P1 + P2, y component
2018-01 GlueX data



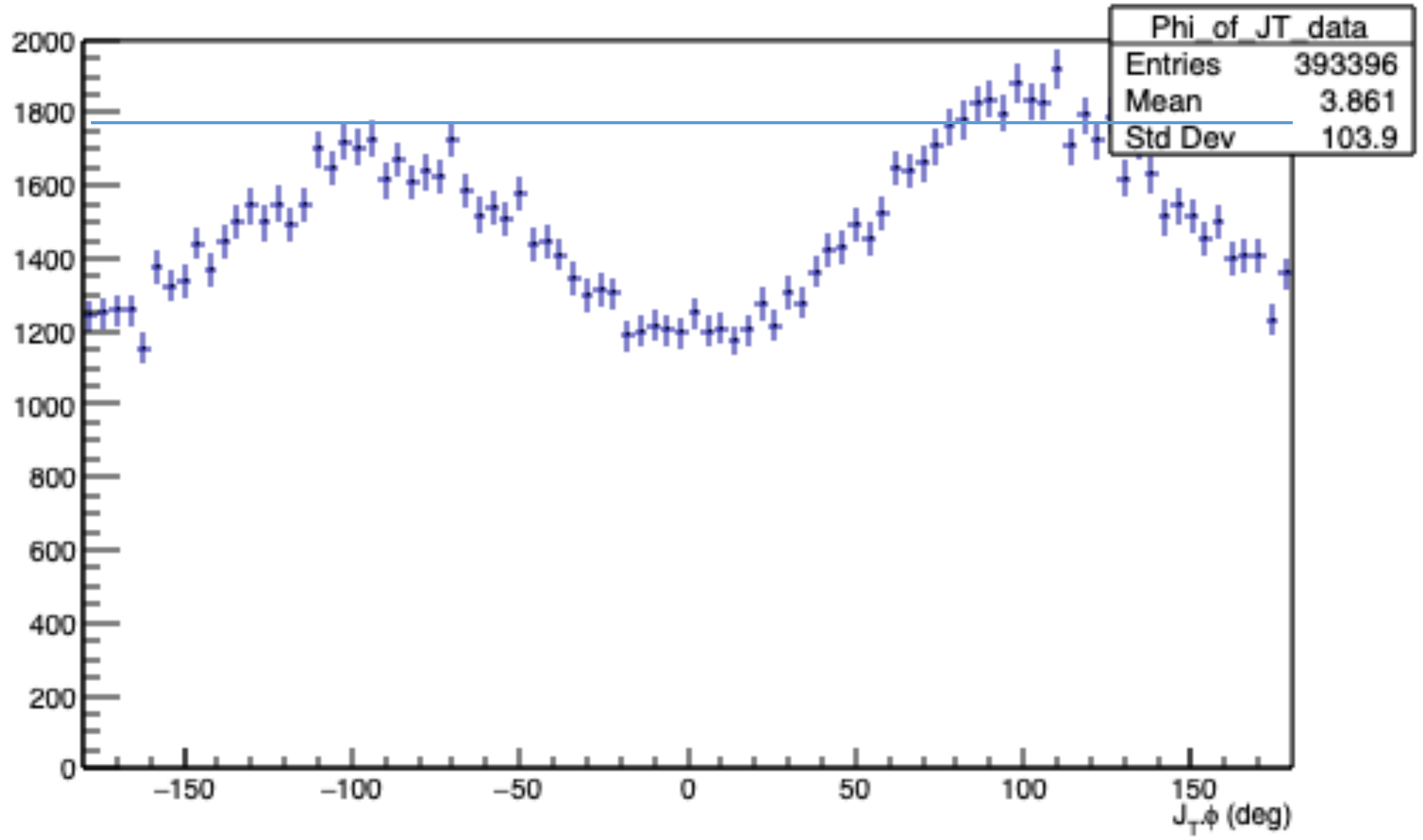
RUNNING SIMULATION WITH THE ELECTRON BEAM OFFSET ON THE COLLIMATOR

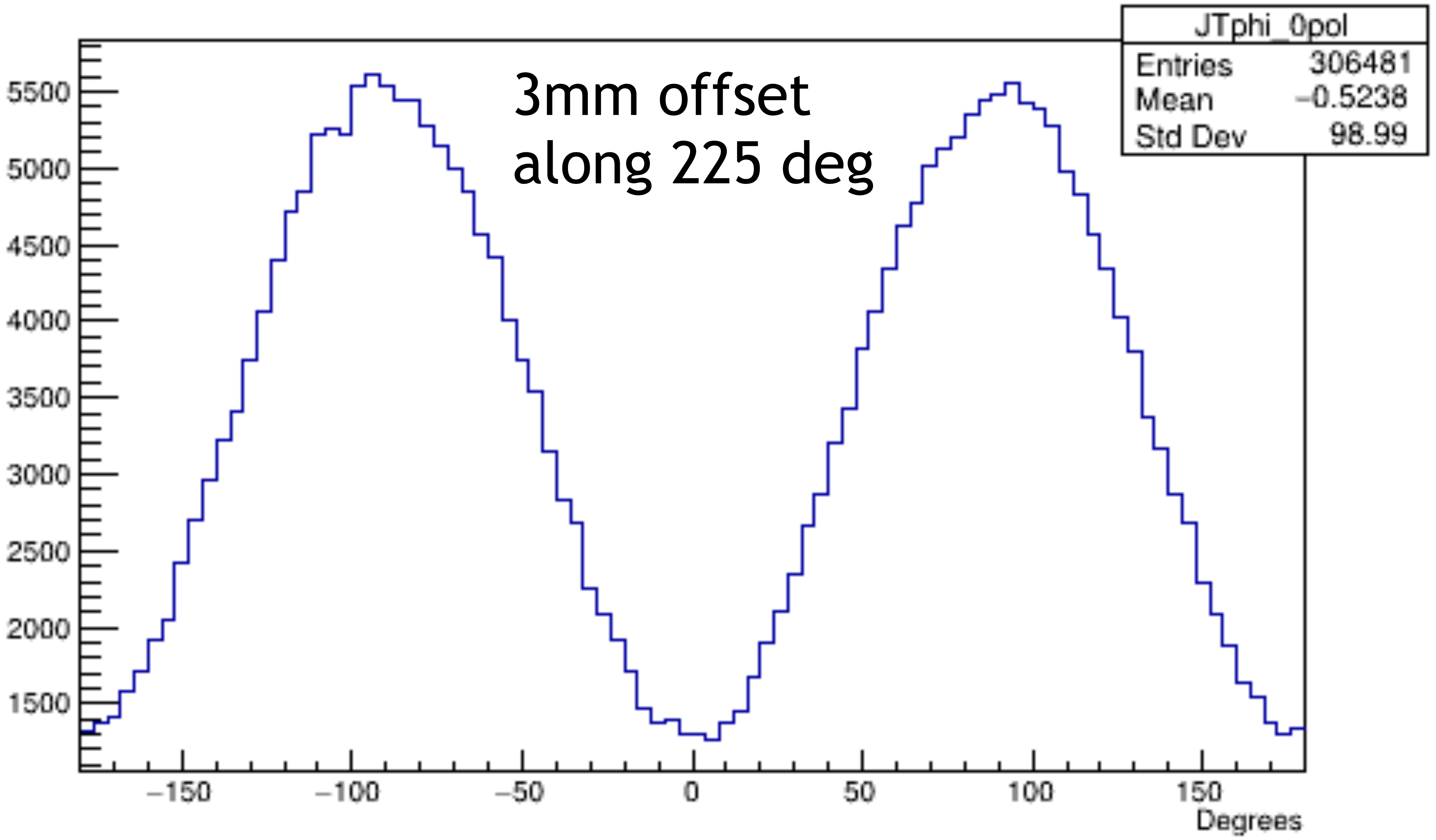
$\gamma p \rightarrow e^+e^-(p)$ reaction filter.

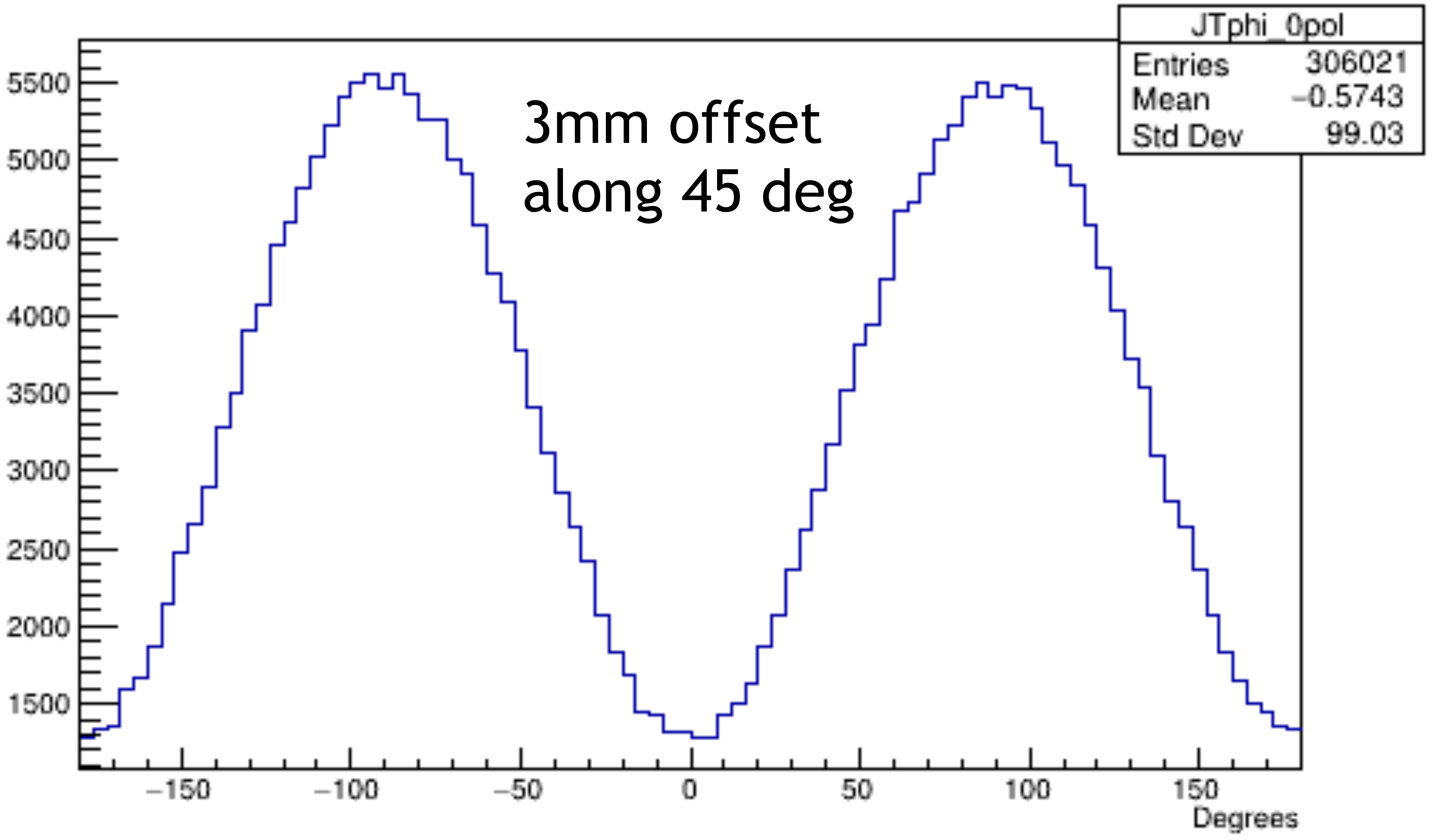
SIMULATION WITH ELECTRON BEAM OFFSET
ON COLLIMATOR 1mm along 45 deg
100% polarization



2018-01 DATA
0 deg orientation runs







Does not produce an asymmetry