Oscar下超子半轻衰变过程$\Lambda \to pe^-\bar{\nu}_e$的研究进展

报告人：周俊贤

复旦大学

STCF物理模拟和探测器联合讨论会

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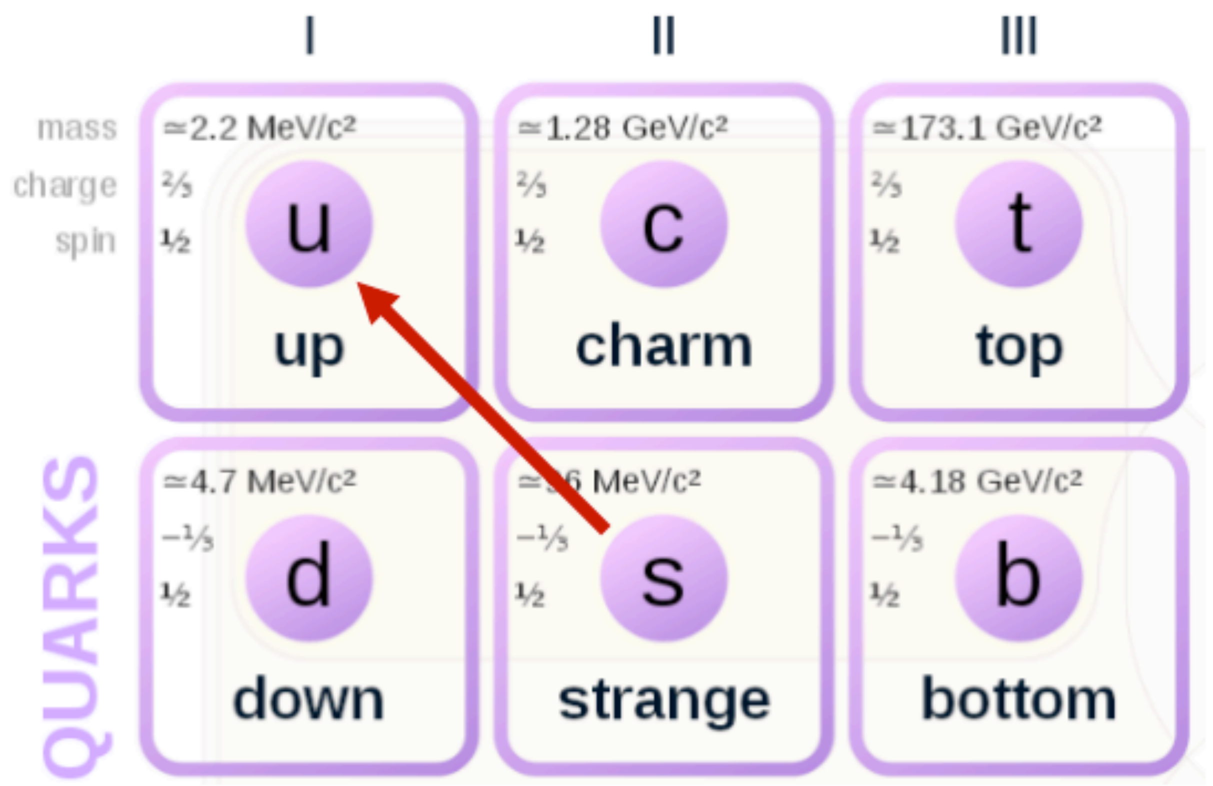
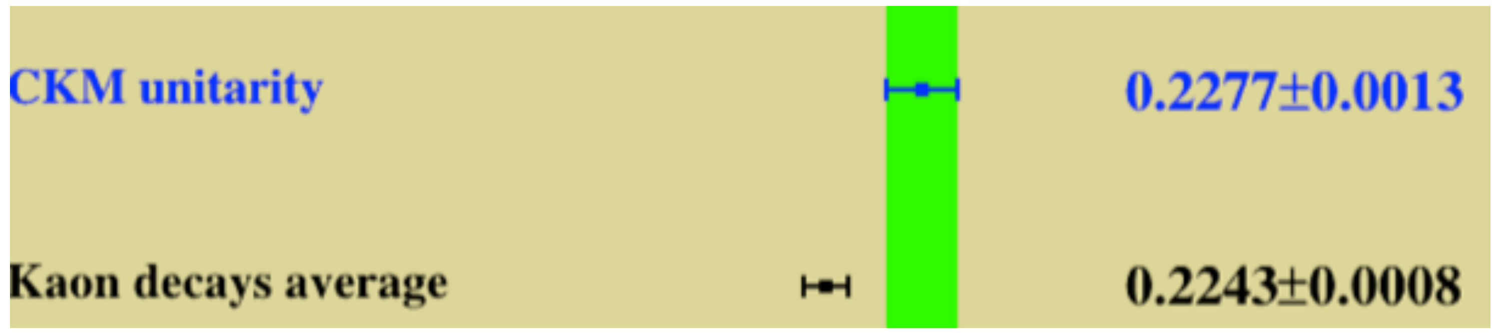
Motivation: Extract the solid CKM matrix element $|V_{us}|$



- $|V_{us}|$ describes the transition between s and a u quark
- Results from kaon decays indicate a 2.3σ deviation from CKM matrix unitary



Phys. Rev. D 70, 114036

$$\Gamma_{SM} = \frac{\mathscr{B}_{\Lambda\to pe^-\bar{\nu}_e}}{\tau_\Lambda} = \frac{G_F^2|V_{us}|^2 f_1(0)^2\Delta^5}{60\pi^3}[(1-\frac{3}{2}\delta+\frac{6}{7}\delta^2)+\frac{4}{7}\delta^2 g_w^2 + (3-\frac{9}{2}\delta+\frac{12}{7}\delta^2)g_{av}^2+\frac{12}{7}\delta^2 g_{av2}^2+\frac{6}{7}\delta^2 g_w+(-4\delta+6\delta^2)g_{av}g_{av2}]$$

$$\Delta \equiv M_\Lambda - M_p \qquad \delta \equiv \frac{M_\Lambda - M_p}{M_\Lambda}$$

- Extracting $|V_{us}|$ requires $\mathscr{B}_{\Lambda\to pe^-\bar{\nu}_e}$, $f_1(0)$, $g_{av} \equiv \frac{g_1(0)}{f_1(0)}$, $g_w \equiv \frac{f_2(0)}{f_1(0)}$, and $g_{av2} \equiv \frac{g_2(0)}{f_1(0)}$,

- $\mathscr{B}_{\Lambda\to pe^-\bar{\nu}_e}$, $g_{av} \equiv \frac{g_1(0)}{f_1(0)}$, $g_w \equiv \frac{f_2(0)}{f_1(0)}$ from experimental measurement
- Assume $g_{av2} \equiv \frac{g_2(0)}{f_1(0)}=0$
- Get $f_1(0)$ through g_{av} measurement and LQCD input $g_1(0)$

Current research of the $|V_{us}|$ from different decays

PDG(2024): from independent measurements

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984 \pm 0.0007$$

2.3 σ tension ⟺

Through CKM unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$|V_{ud}|$: Most precise; results from different decays are consistent at $O(10^{-4})$

$|V_{us}|$: there are different results from different decays as shown below.

$|V_{ub}|$: Small （$|V_{ub}|^2 \cong 1.7 \times 10^{-5}$） $\rightarrow$ The effect could be ignored in current precision.

Most precise

Kaon: 2.3 σ tension from unitarity

$$|V_{us}| = 0.22431 \pm 0.00085$$

Cited in PDG 2024

Second most precise

Tau: 3.7 σ tension from unitarity

$$|V_{us}| = 0.2207 \pm 0.0014$$

HFLAV 2022

Our target decay

Hyperon: consist with CKM unitarity

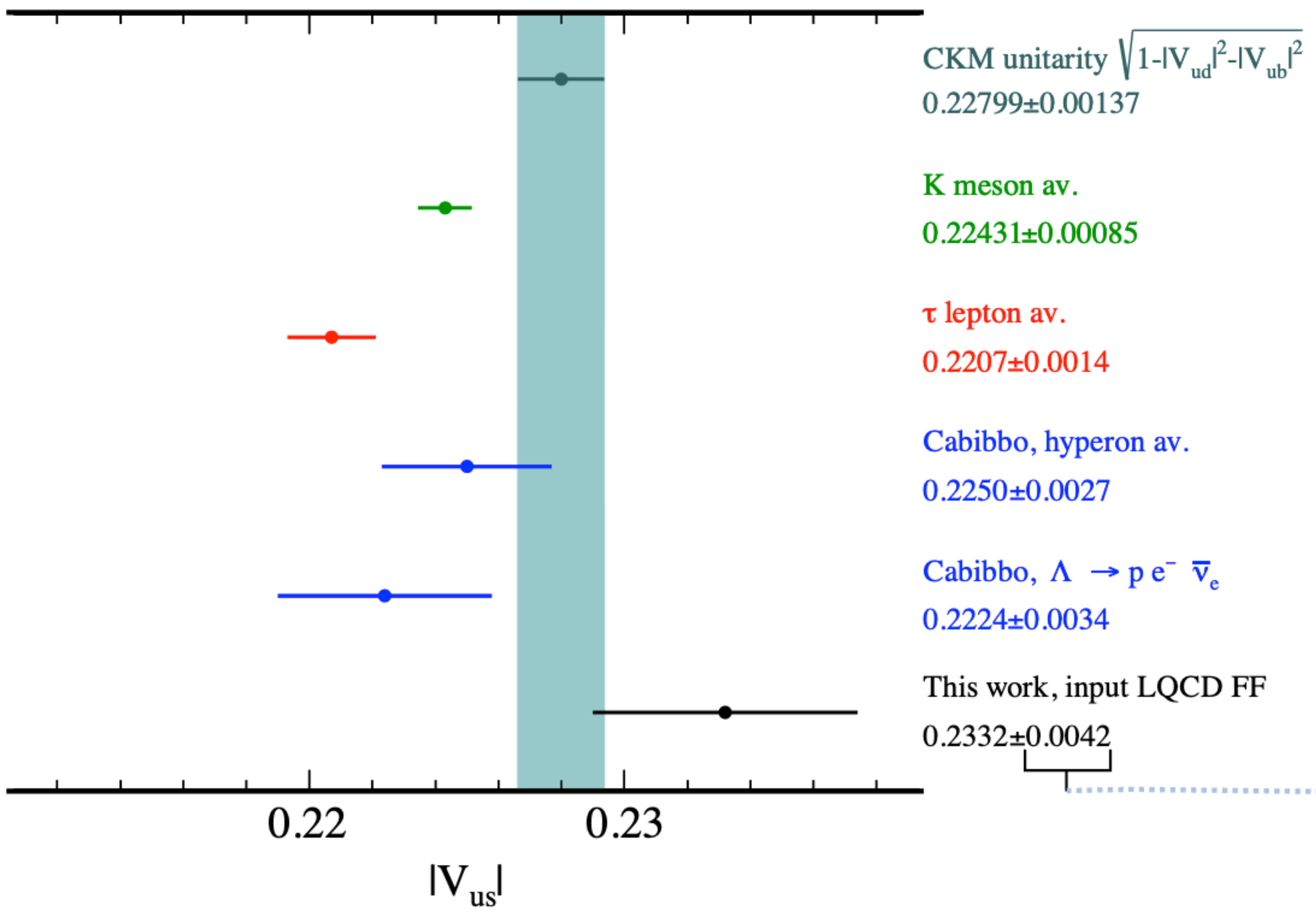
$$|V_{us}| = 0.2250 \pm 0.0027$$

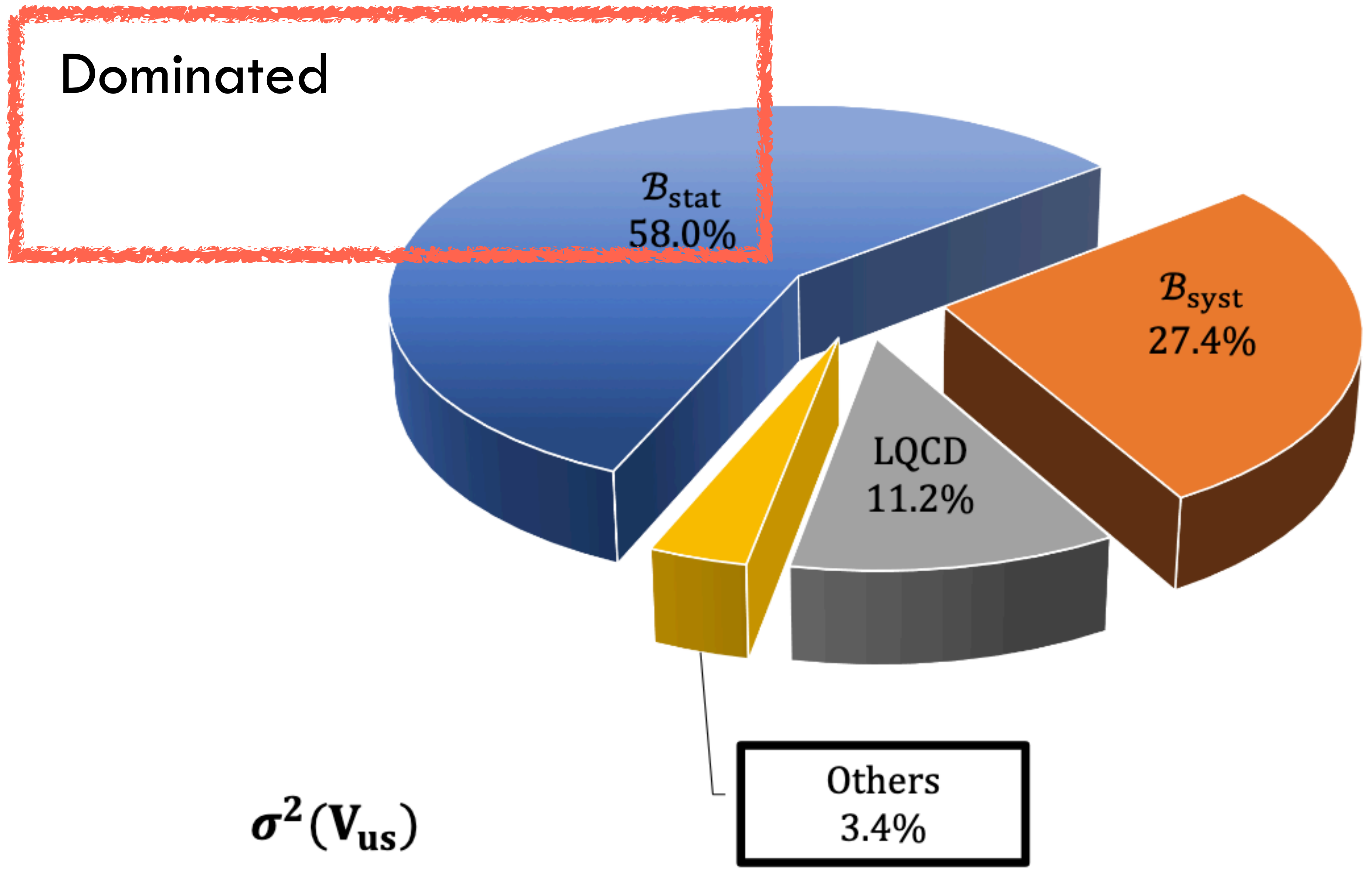
PRL 92.251803(2004)

Dominated by the $\Lambda \rightarrow p e^- \bar{\nu}_e$,

but show large uncertainty.

Recent results at BESIII

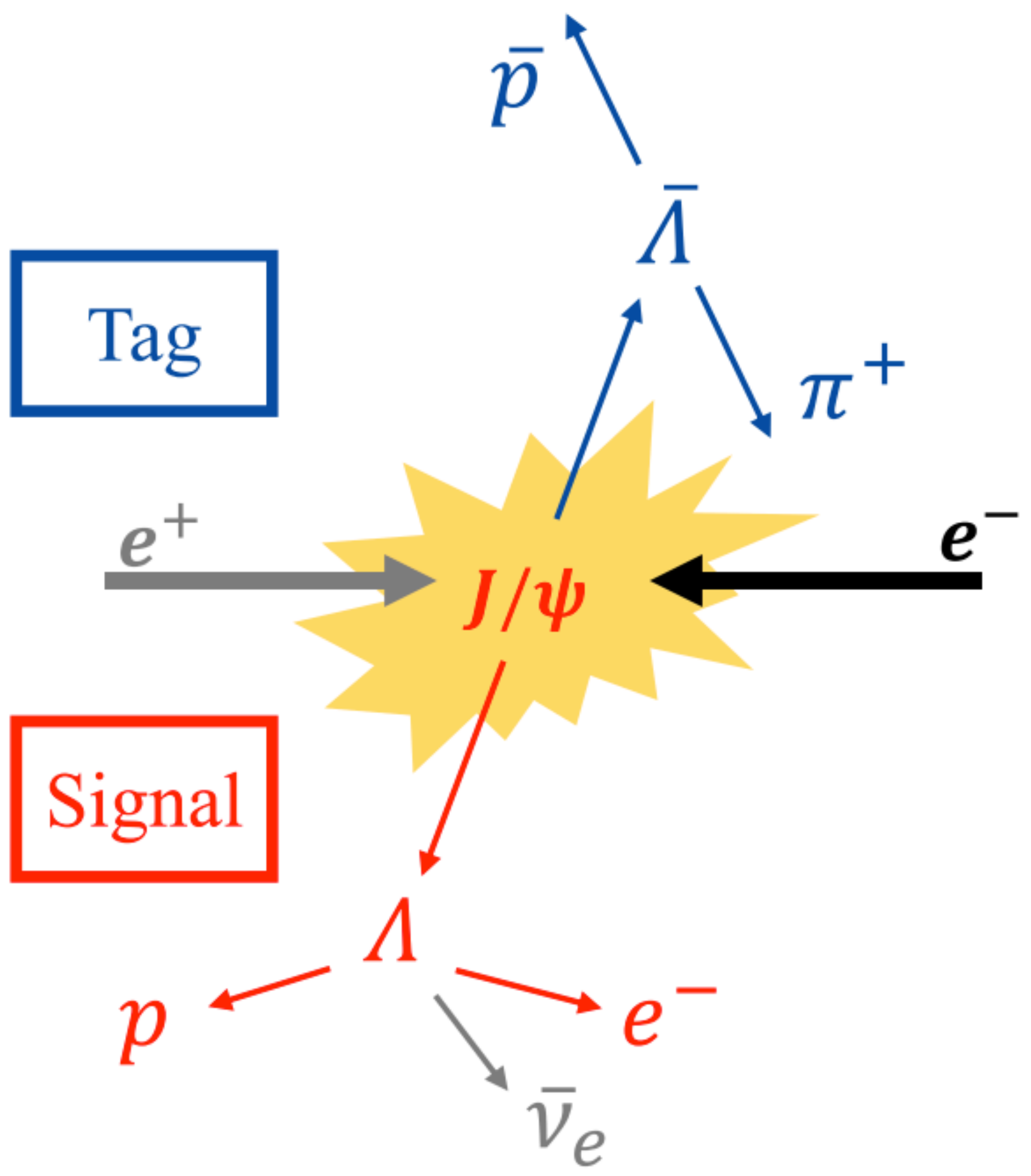




http://arxiv.org/abs/2509.09266

Analysis

Double tag method



$$N_{tag} = 2N_{\Lambda\bar{\Lambda}}\mathscr{B}_{tag}\epsilon_{tag}$$

$$N_{sig} = 2N_{\Lambda\bar{\Lambda}}\mathscr{B}_{tag}\mathscr{B}_{sig}\epsilon_{tag,sig}$$

$$\mathscr{B}_{sig} = \frac{N_{sig}/\epsilon_{tag,sig}}{N_{tag}/\epsilon_{tag}}$$

Get the absolute branching faction

$N_{\Lambda\bar{\Lambda}}$: the number of $\Lambda\bar{\Lambda}$ Paris

$\mathscr{B}_{tag}$: Branching faction of $\bar{\Lambda} \to \bar{p}\pi^+$

$\mathscr{B}_{sig}$: Branching faction of $\Lambda \to pe^-\bar{\nu}_e$

N_{tag} : ST yield	N_{sig} : DT yield
ϵ_{tag} : ST efficiency	$\epsilon_{tag,sig}$: ST efficiency

Can be obtained in our analysis

Decay channel: $J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to pe^-\bar{\nu}_e, \bar{\Lambda} \to \bar{p}\pi$

Software: Oscar 2.6.2 (update 6.25)

Analysis

Selection criteria at single tag

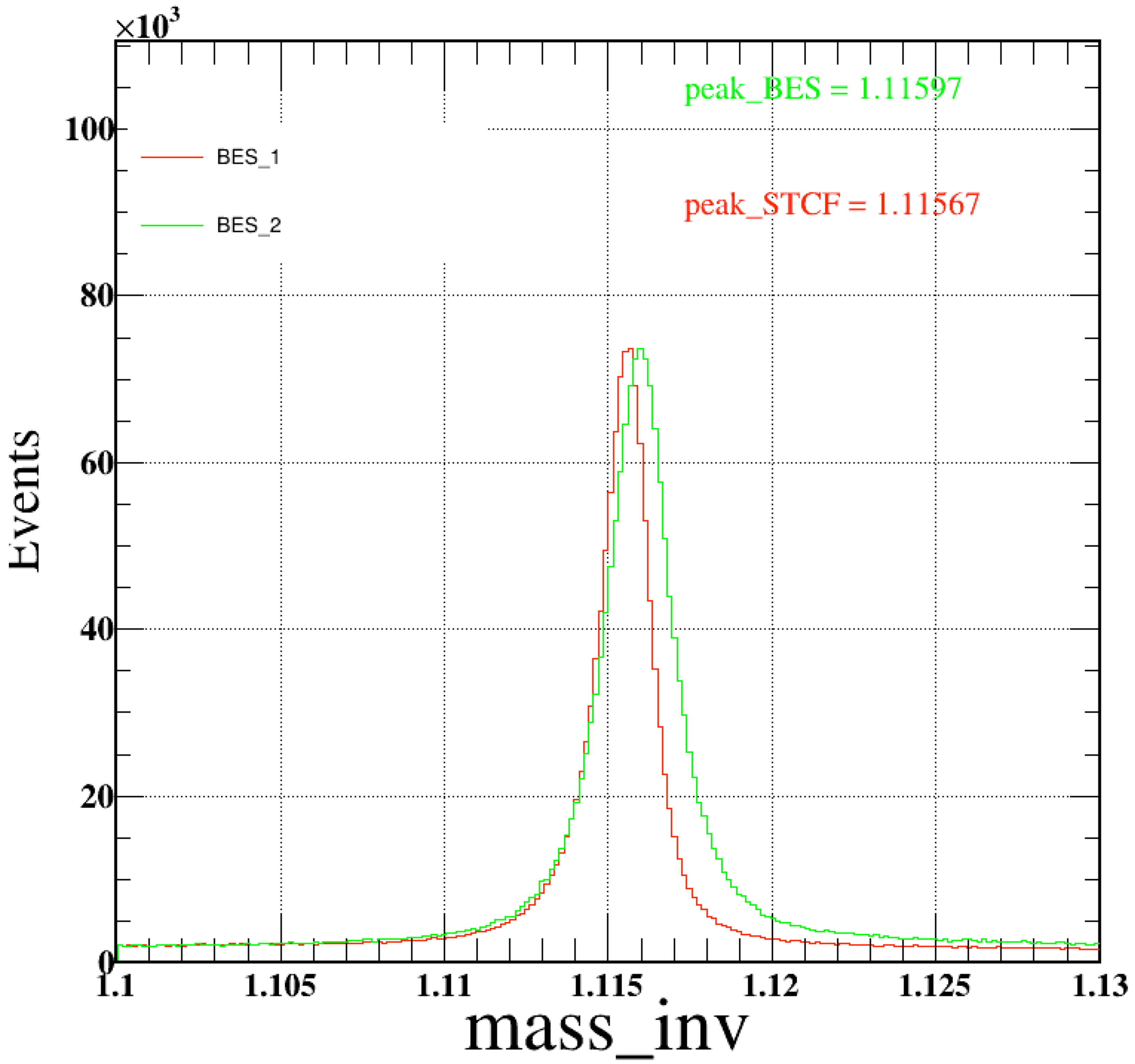
PhysRevLett.127.121802

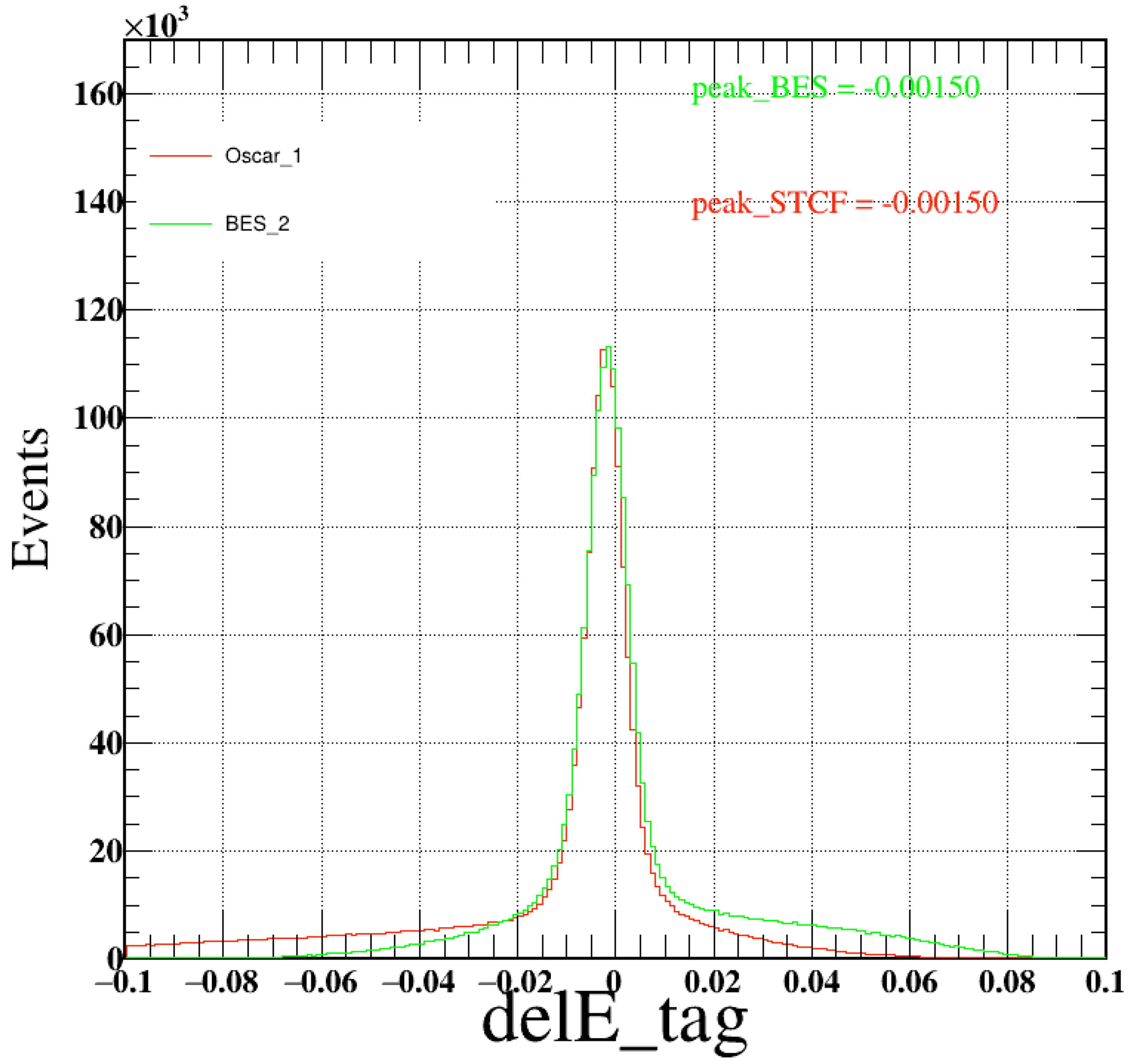
- Good charged tracks
  - ✔ At least 2 oppositely-charged tracks
  - ✔ No vertex requirement due to existence of $\bar{\Lambda}$
  - ✔ $|cos\theta| < 0.93$

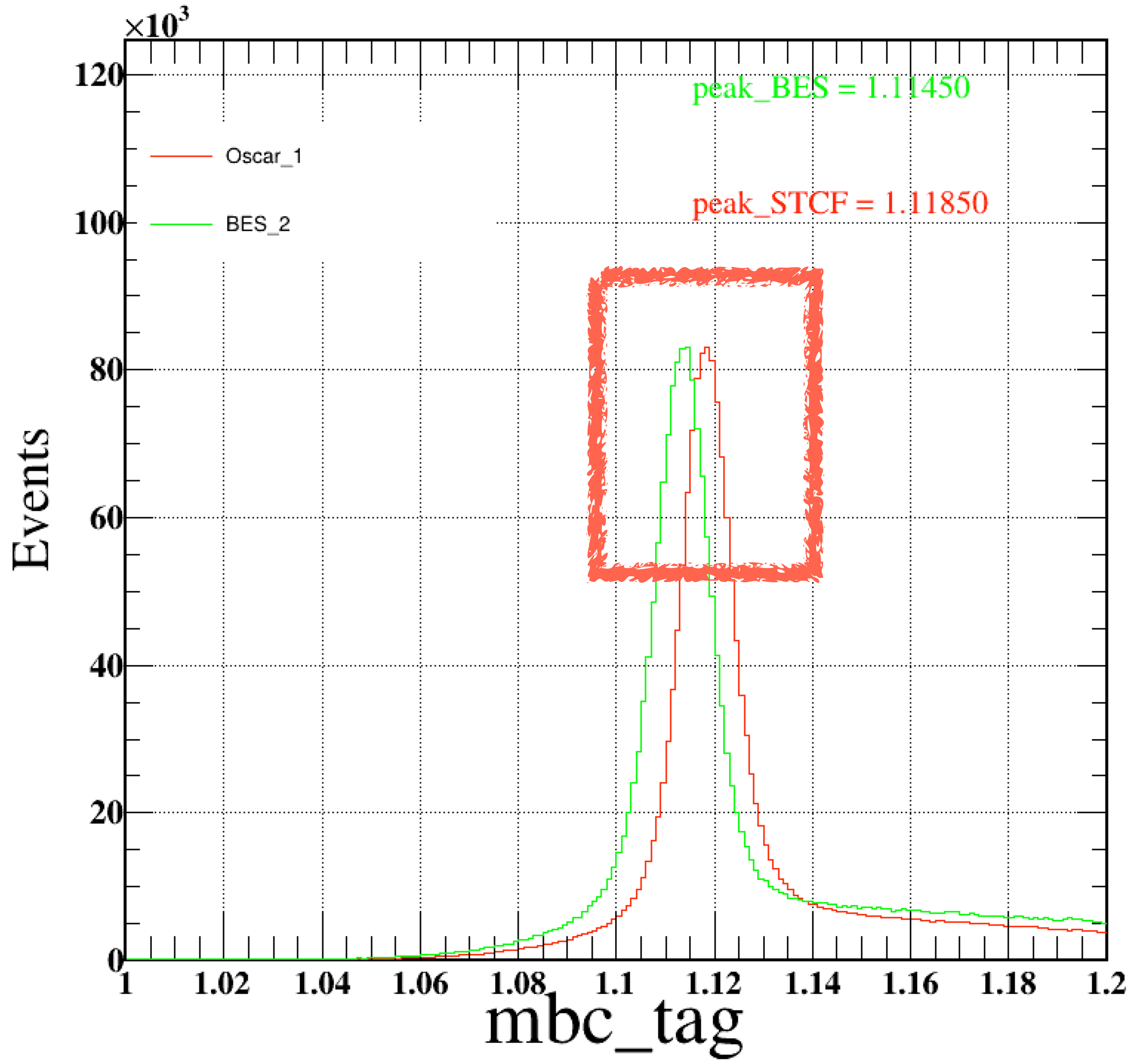
- Reconstruction of $\bar{\Lambda}$
  - ✔ Looping over all combinations with positive and negative charged tracks
  - ✔ Vertex and Second Vertex Fit for $\bar{\Lambda}$ based on $\bar{p}\pi^+$ hypothesis
  - ✔ The candidates are selected from combinations with the minimum $\Delta E = E_{beam} - E_{singletag}$
  - ✔ Vertex/second vertex fit: $\chi^2 < 100$, $L/\sigma > 2$

Analysis

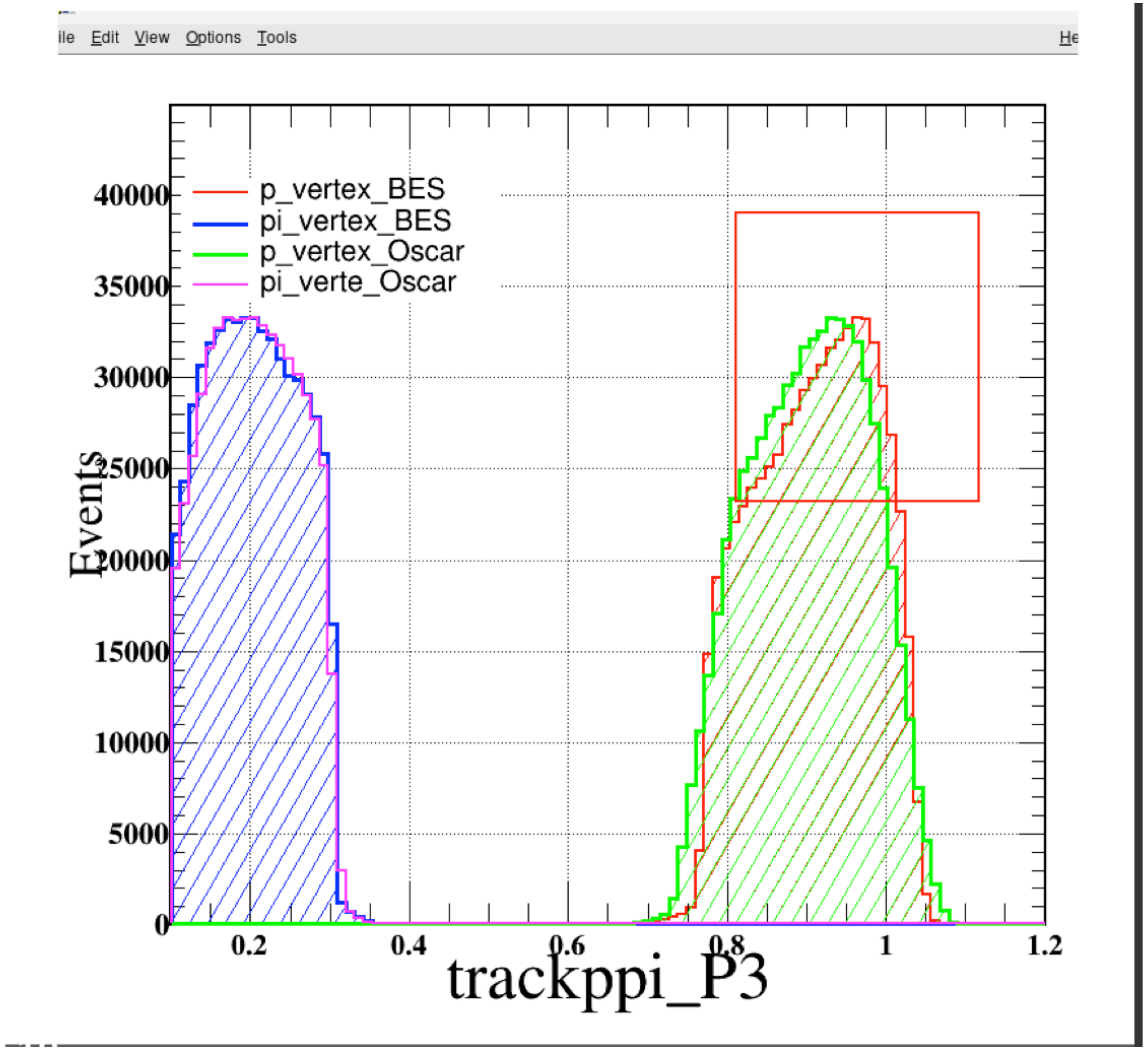
$\bar{\Lambda}$

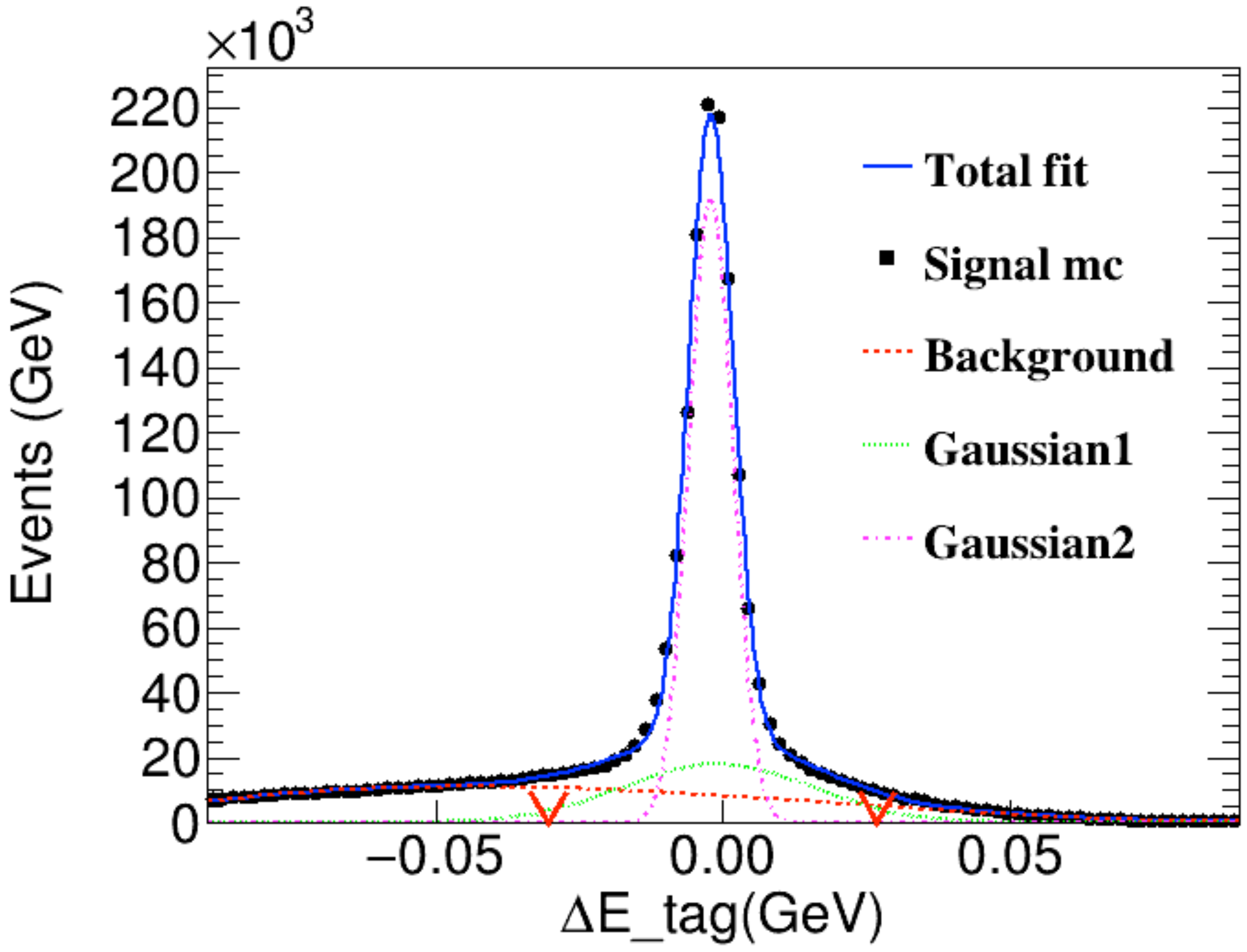






Selection criteria at single tag





ΔE window

Analysis

Table 1: Cut flow at Oscar single tag

entries, nocut	1995994
entries, Goodtracks	2586630
entries, ΔE cut	1524035
entries, lam_chi_tag<200	1513869
entries, length/lengtherr>2	1358343
ϵ_{tag}	0.525

Table 2: Cut flow at BESIII single tag

entries, nocut	10000
entries, Goodtracks	10043
entries, ΔE cut	7062
entries, lam_chi_tag<200	6695
entries, length/lengtherr>2	6110
ϵ_{tag}	0.611

Selection criteria at double tag

- Good charged tracks
  - ✔ 4 good tracks(another 2 tracks based on single tag)
  - ✔ No vertex requirement due to existence of Λ
  - ✔ $|cos\theta| < 0.93$
  - ✔ $\Sigma_i^4 Q_i = 0$
- Reconstruction of Λ
  - ✔ Vertex and second vertex Fit for Λ
  - ✔ Decay length >0
  - ✔ $\chi^2 < 100$
- Particle identification
  - ✔ Require one track to be electron strictly

    The other track is assumed to be a proton

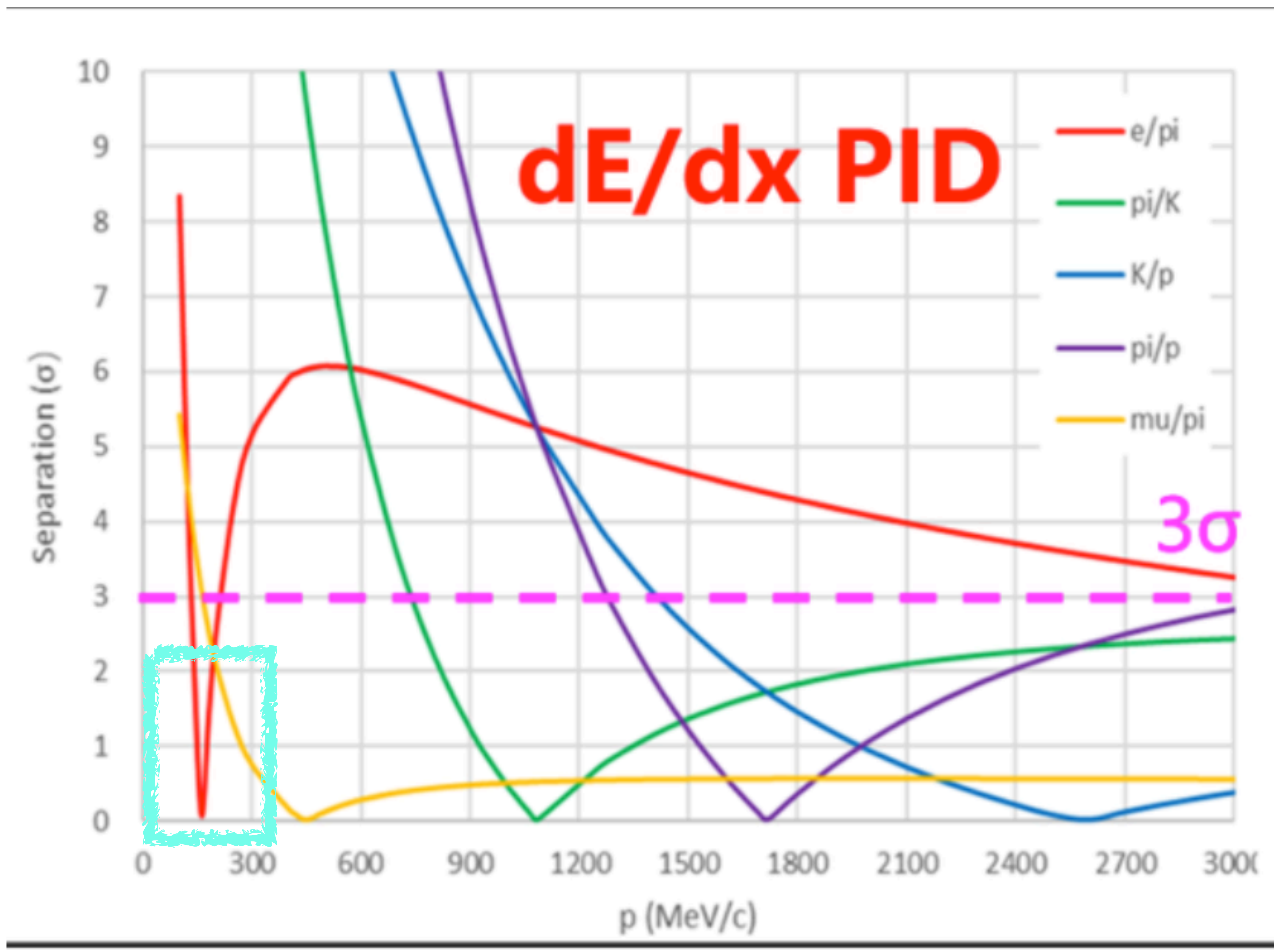
Cut flow of double tag

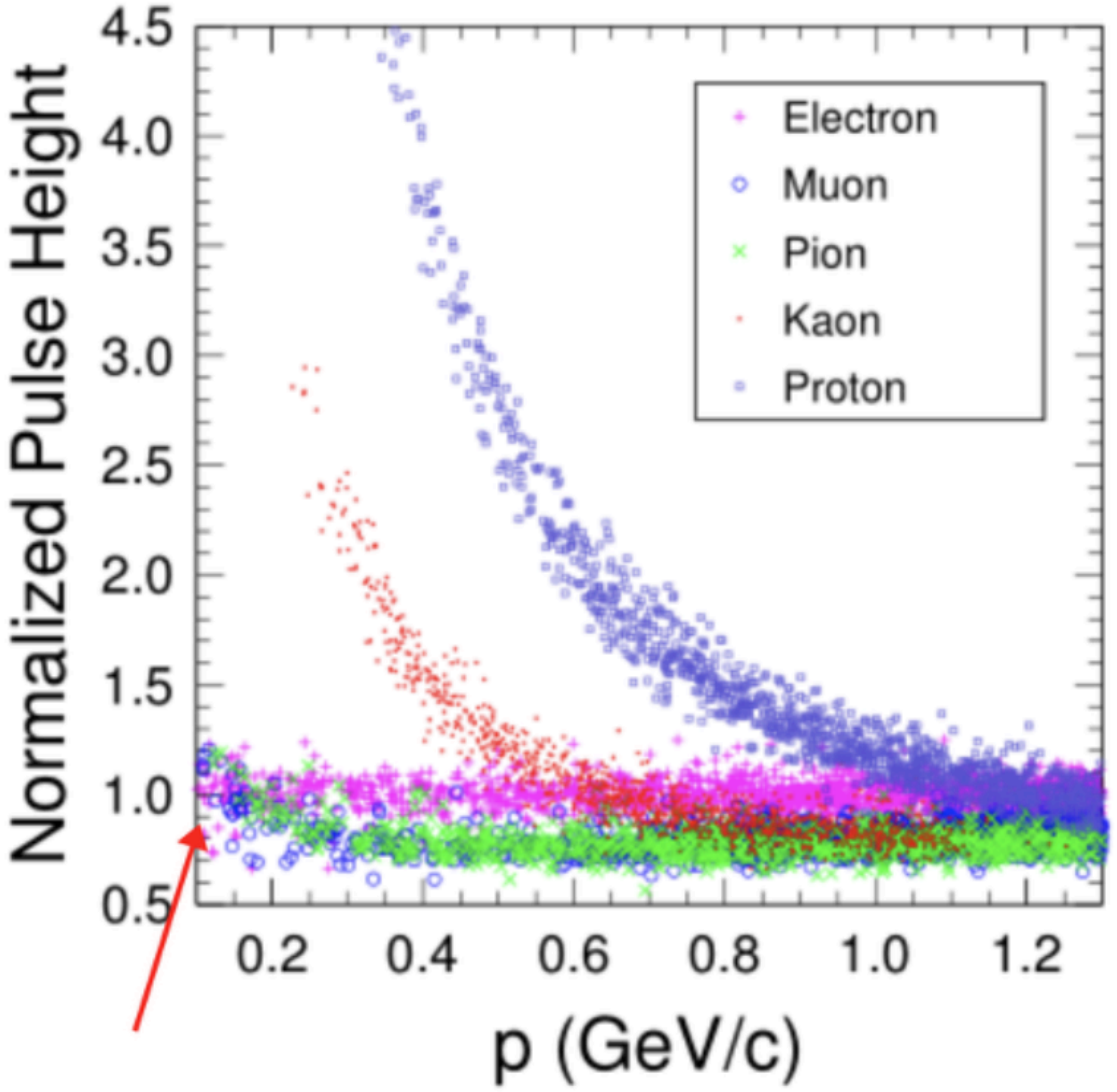
Table 1: Cut flow

	Events	Efficiency(%)	Relative Efficiency
Total number	**1997996**	100	
Good tracks	**1581149**	61.59	61.59
ΔE cut	**973336**	48.71	61.55
lam_chi_tag<200	**937279**	47.41	97.32
length/lengtherr>2	**853987**	42.74	**90.15**
mbc_tag	**710725**	35.47	**82.21**
lam_chi_sig<200	**684798**	34.27	**96.37**
lam_sig_len>0	**684798**	23.95	100
prob(e)>prob(other)	**478580**	17.95	**62.07**
prob(e)>0.987	**254693**	**12.35**	**59.95**
χ_{4c} cut	**238678**	**11.74**	**93.71**
p_sig_e>0.12	**151151**	7.57	**63.32**
U_{miss} cut	**140877**	7.05	**93.2**

Cut research

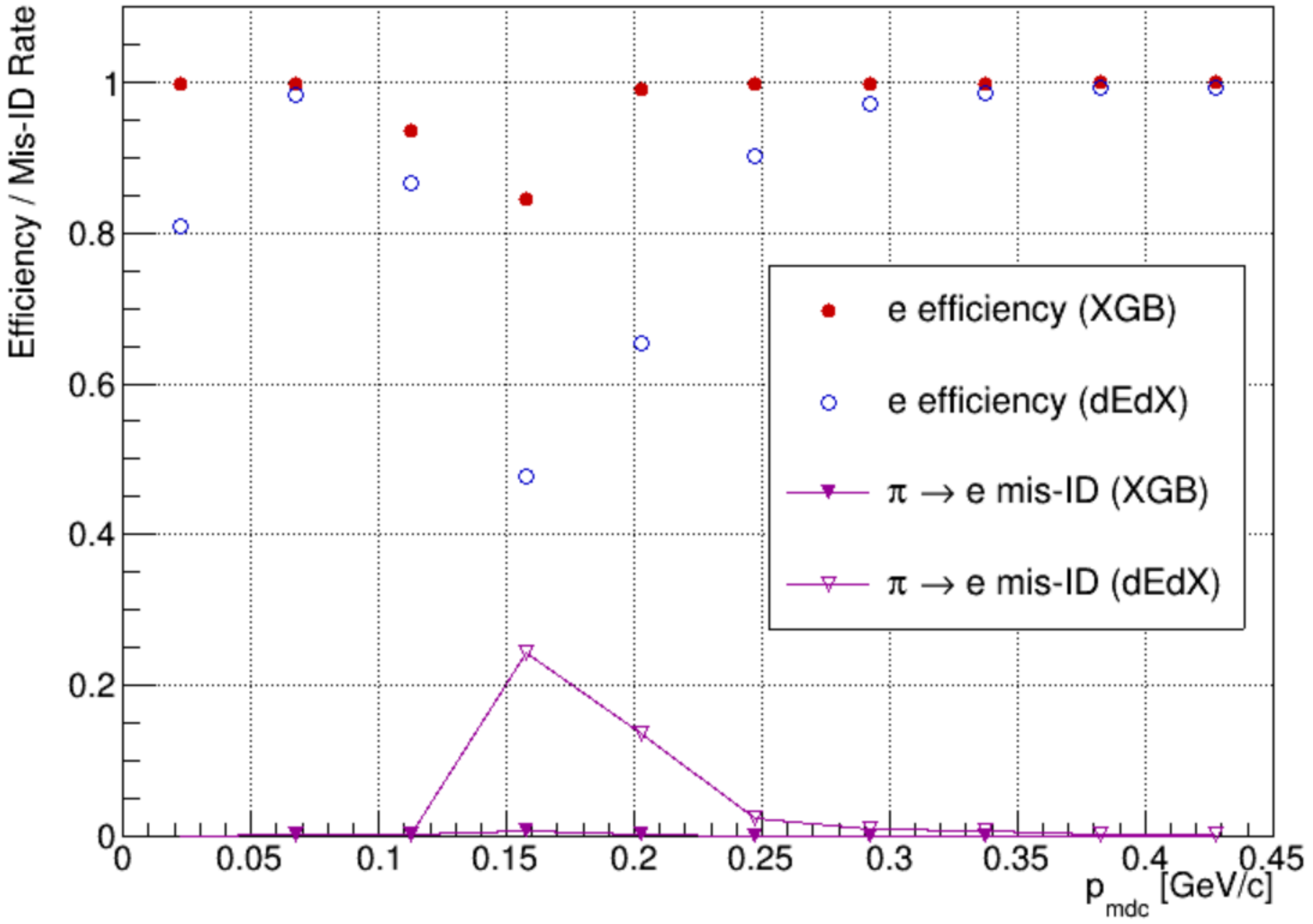
mis-ID of e/π with global PID

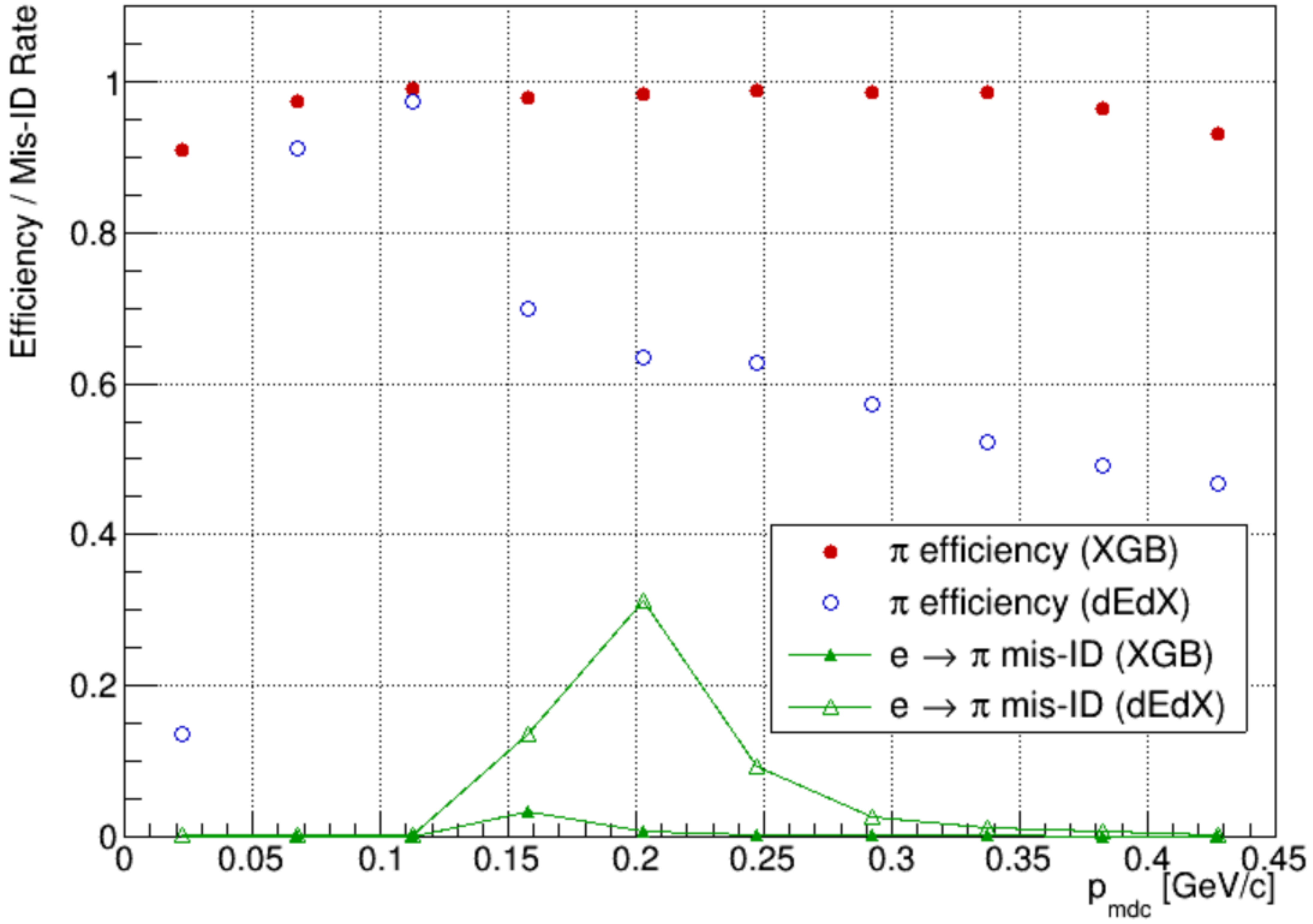




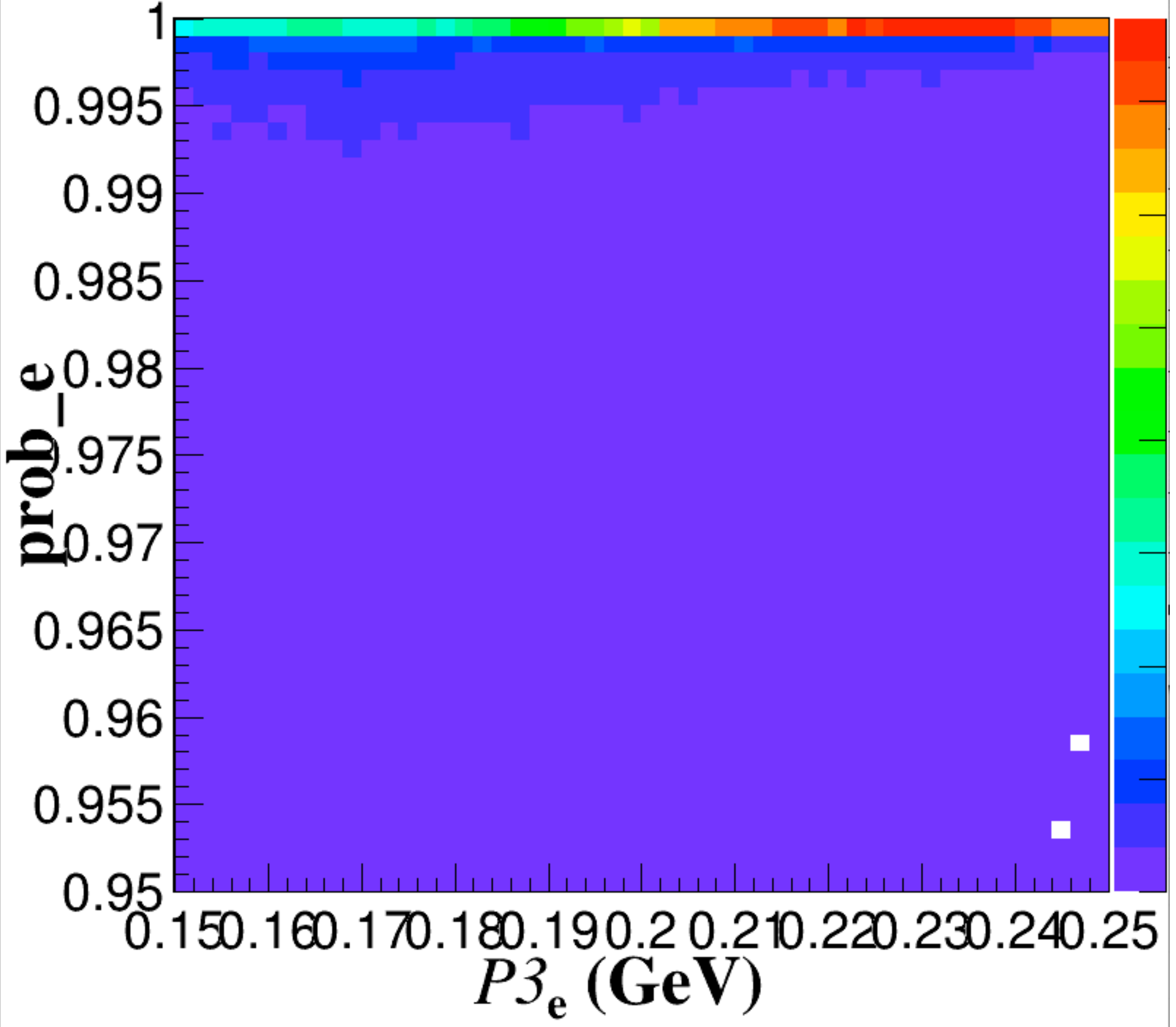
Cut research

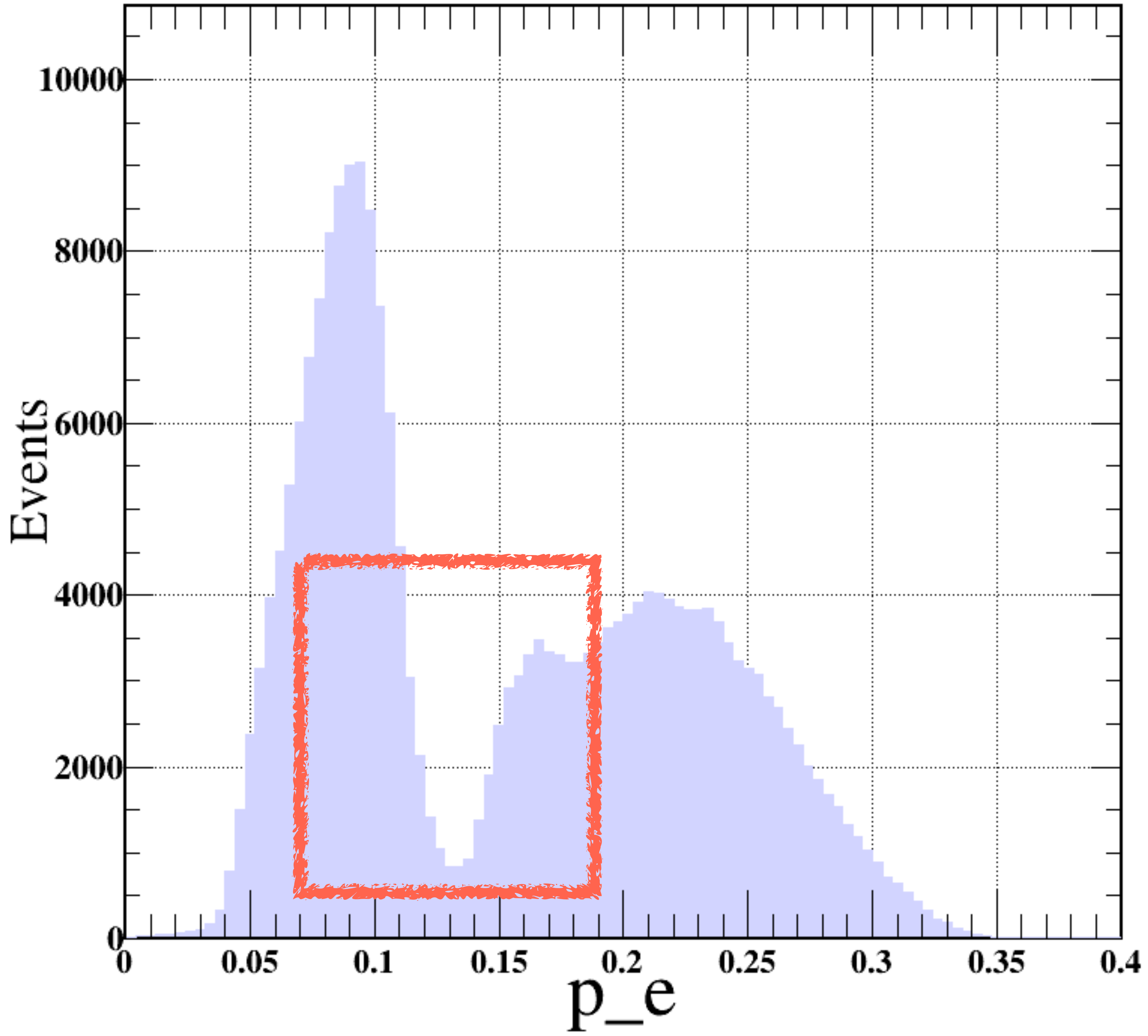
mis-ID of e/π with global PID





Cut research



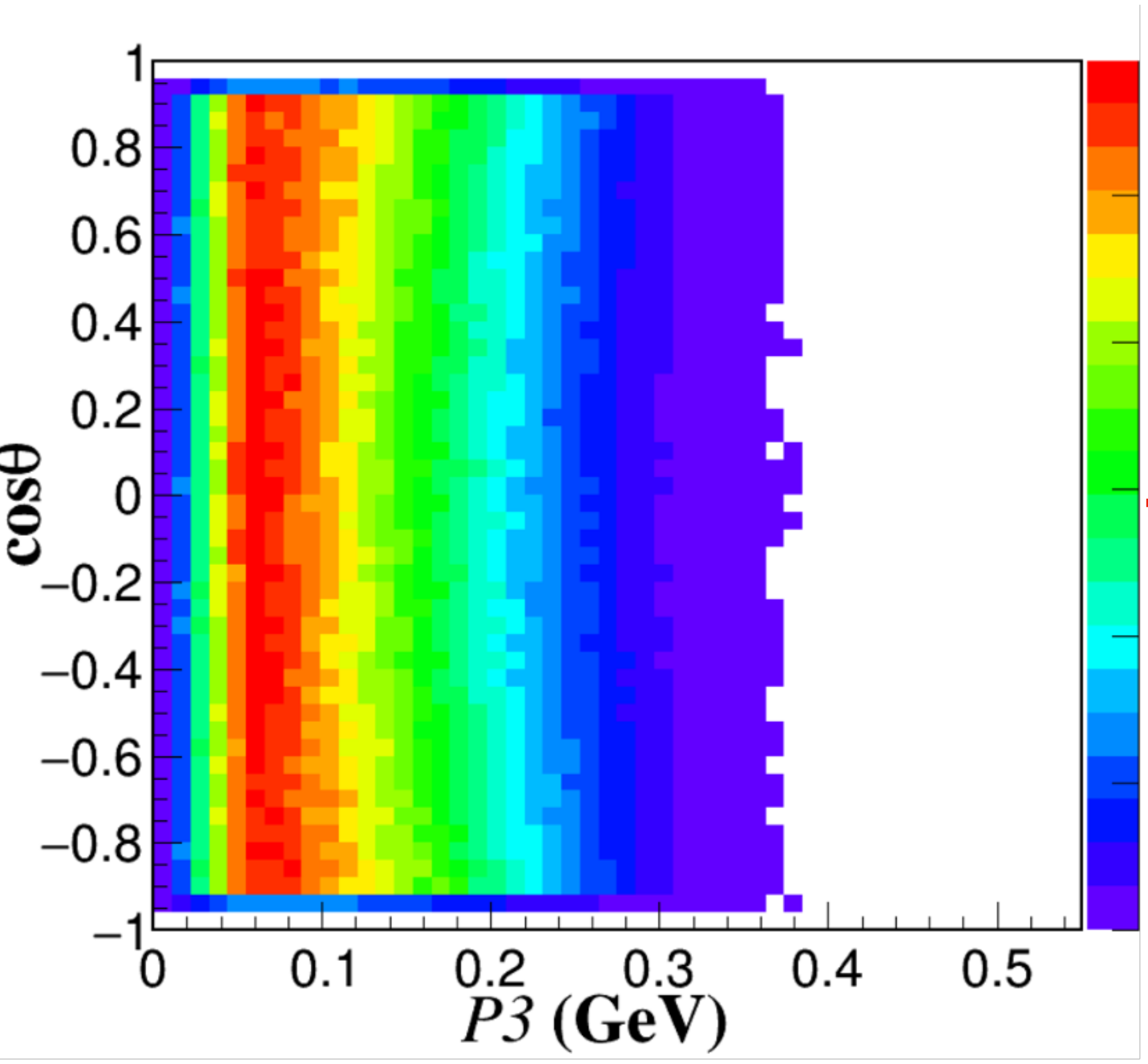


Poor reconstruction quality at low momentum

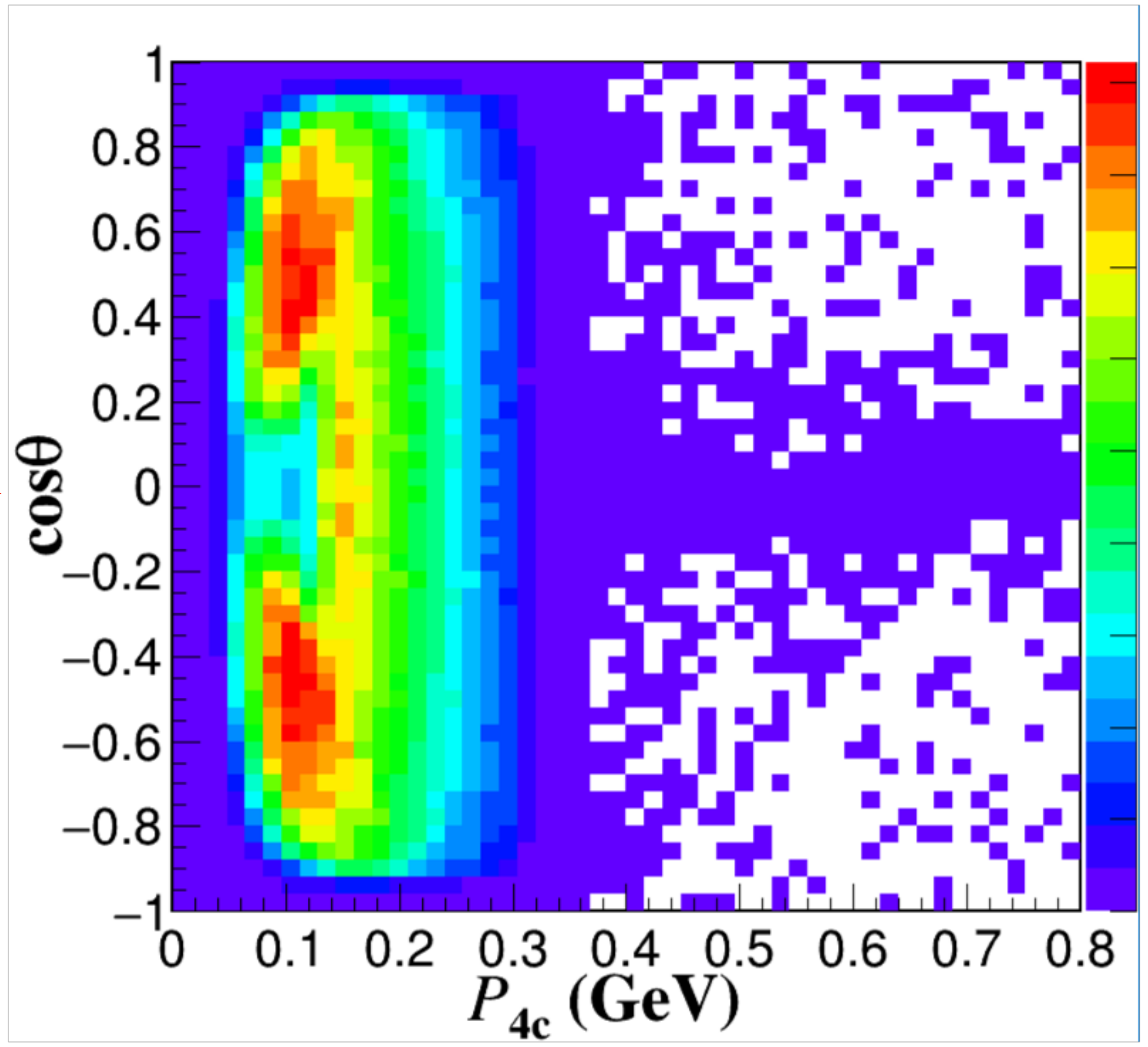
Cut research

PID of e track at Oscar

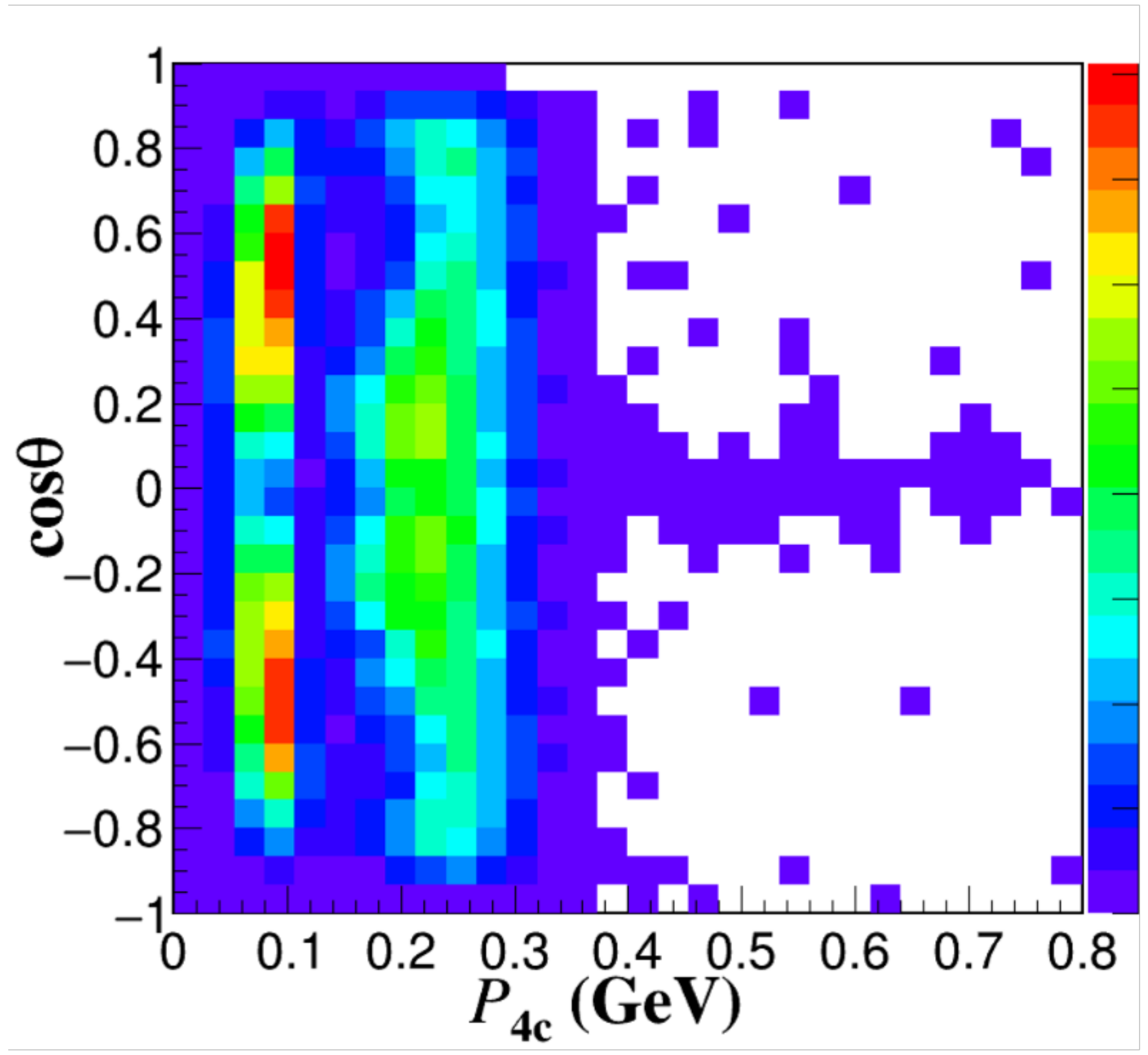
Truth



Rec (before PID)

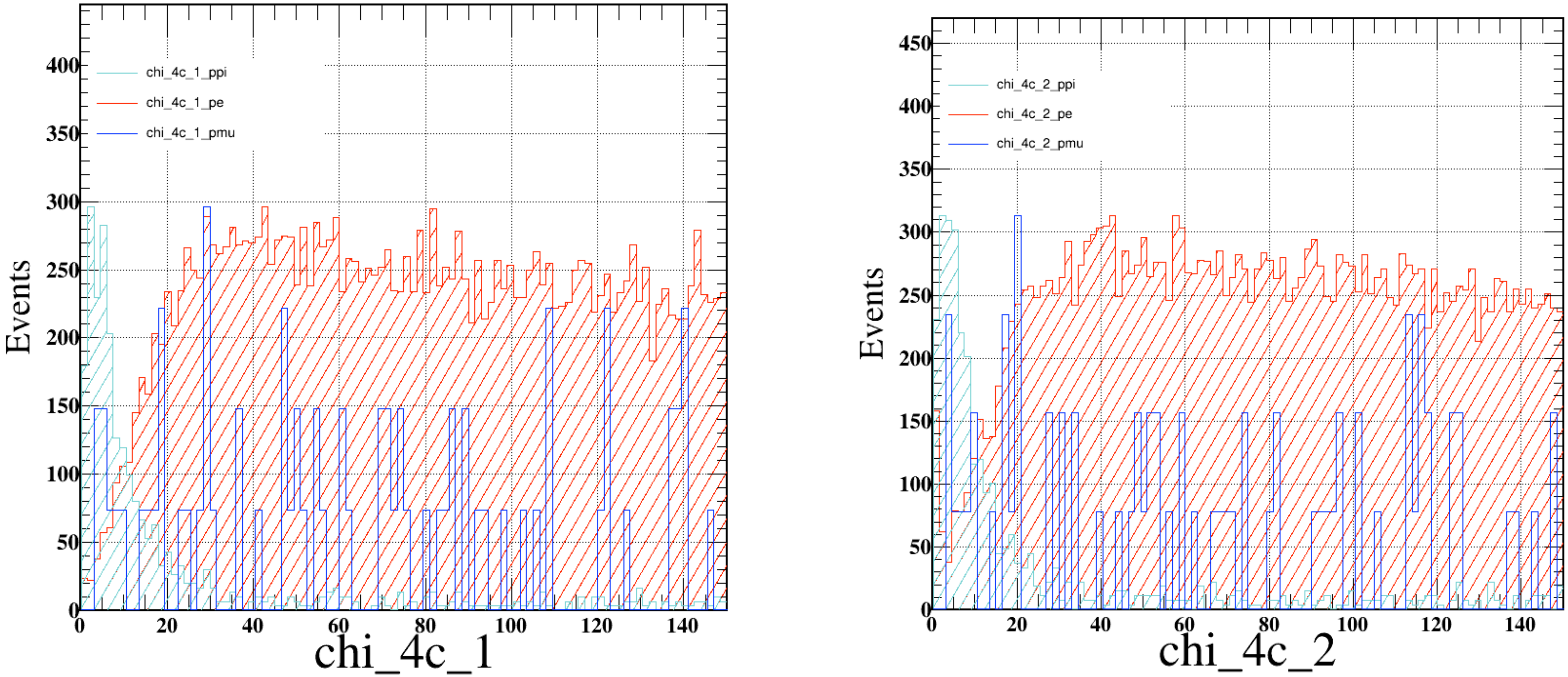


Rec (after PID)



Cut research

Kinematic fit performed under the background hypothesis, $e \rightarrow \pi$

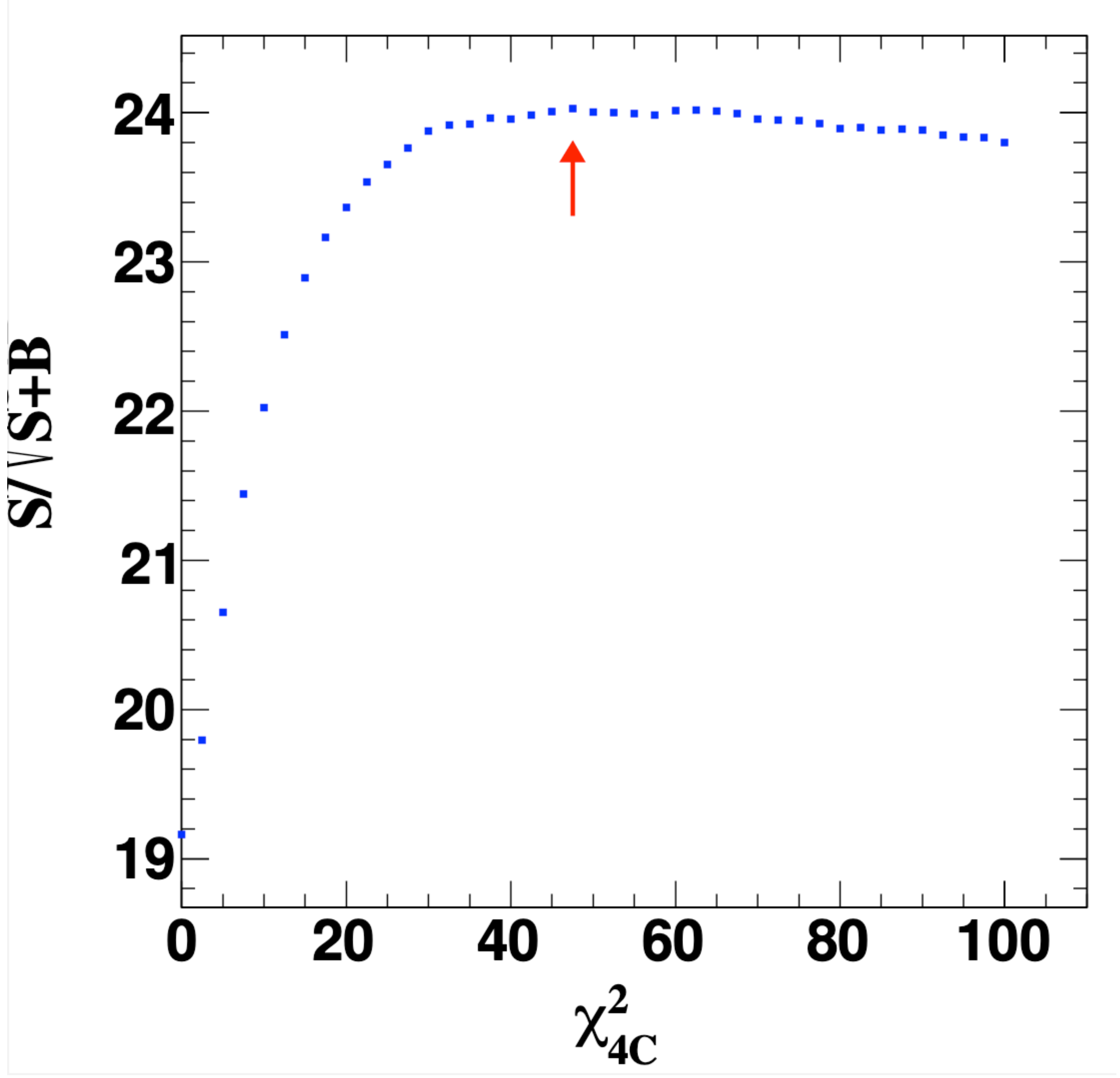


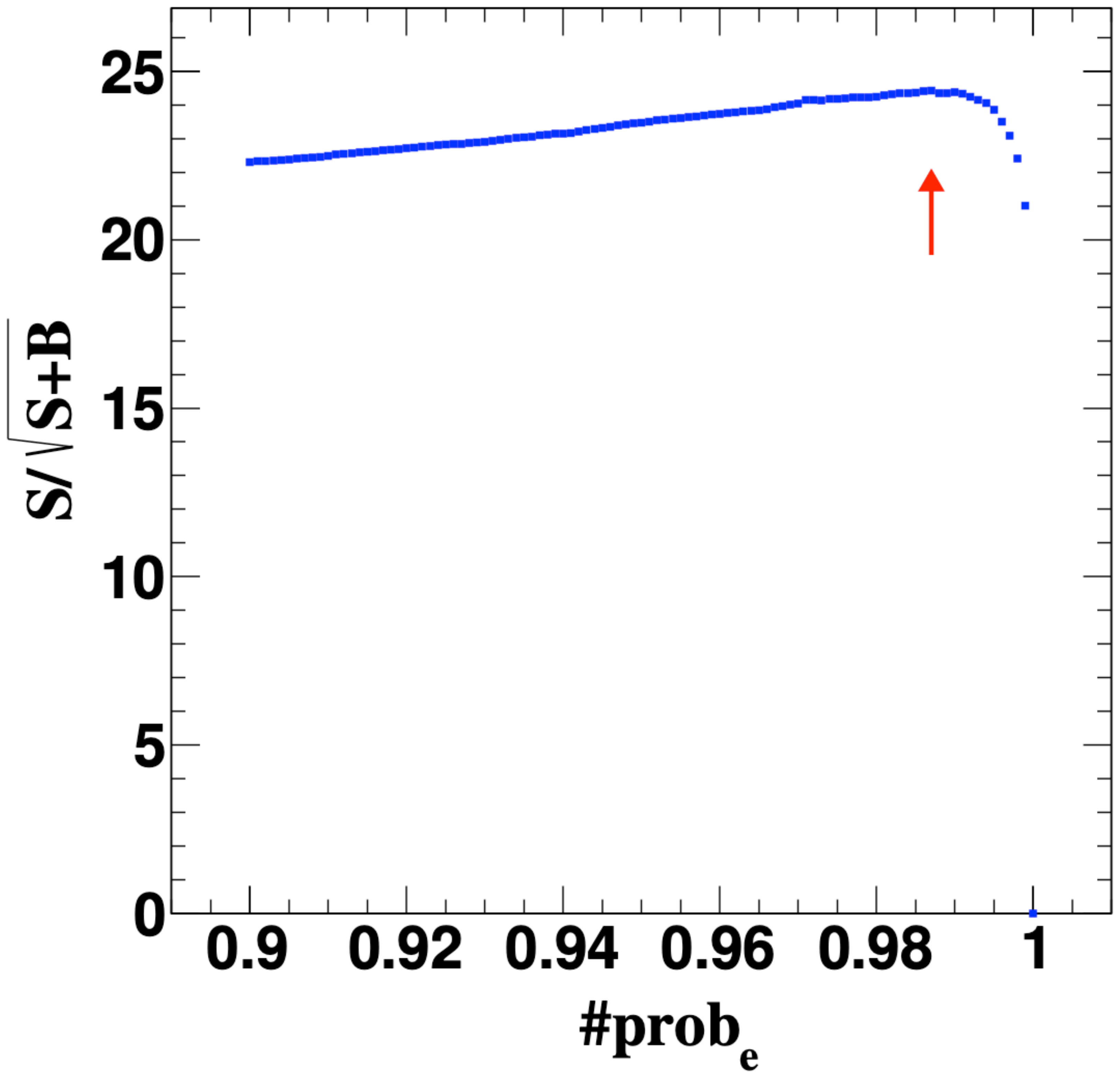
Cut research

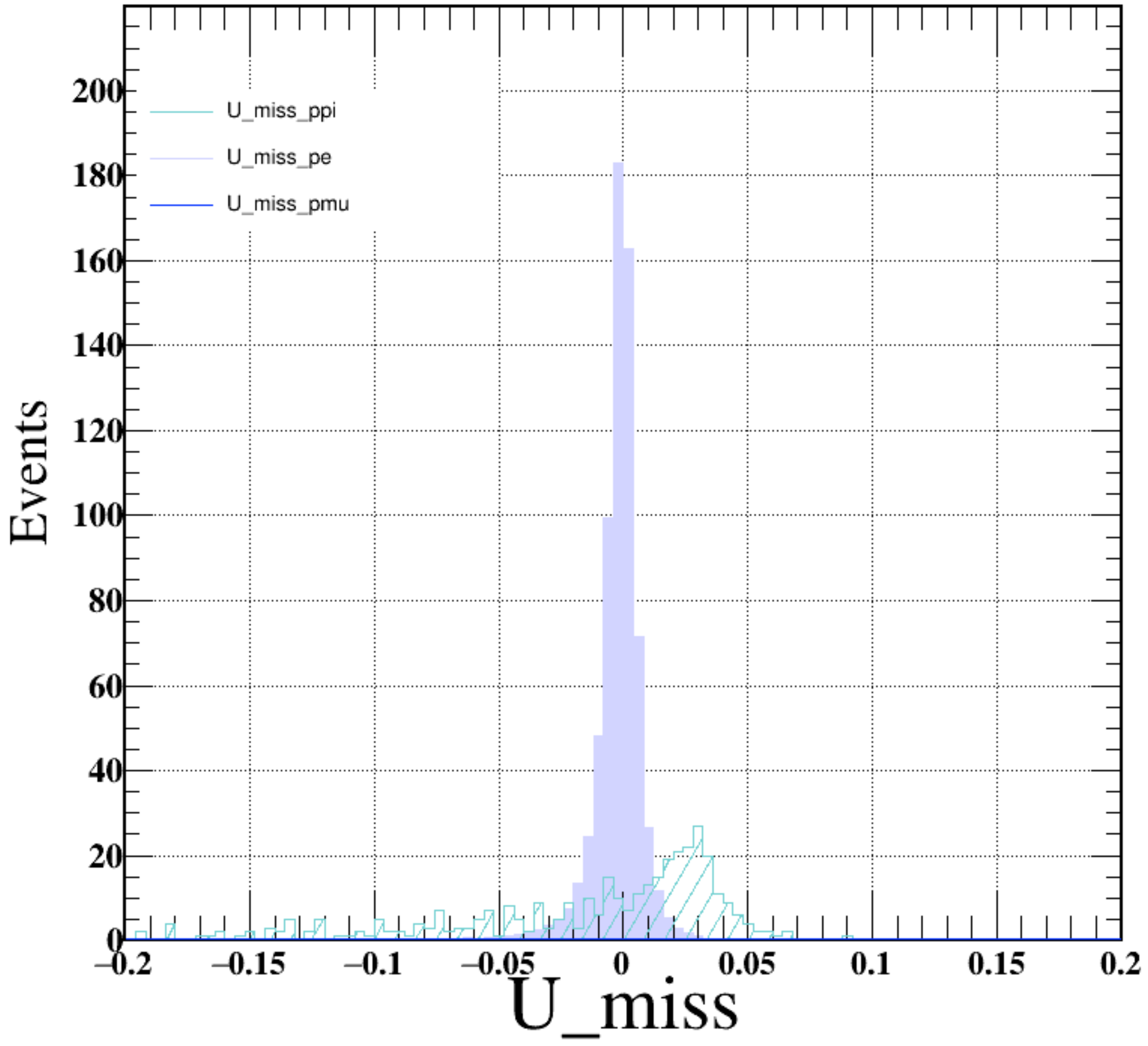
$$U_{miss} \equiv E_{miss} - c|\vec{P}_{miss}|$$

E_{miss}: The energy of the missing neutrino

P_{miss}: The momentum of the missing neutrino







Analysis

Estimation of systematic uncertainty

10^7 $\Lambda\bar{\Lambda}$ pairs at BES

↕

10^9 $\Lambda\bar{\Lambda}$ pairs at STCF

Table 12: Relative systematic uncertainties (in %) in the measurement of the BF for $\Lambda \to pe^-\bar{\nu}_e$.

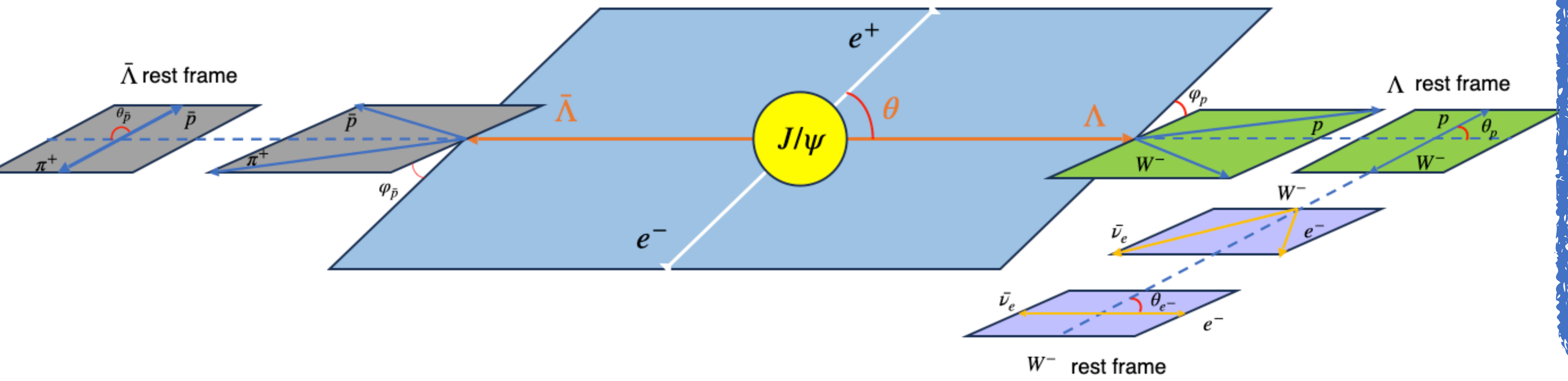
Sources	Uncertainties
Fitting M_{bc}	0.37
Fitting U_{miss}	0.80
$N_{Trk} = 4$	0.03
Λ reconstruction through vertex fit	0.20
Tracking of p	0.26
Electron detection	1.55
Kinematic fit	0.22
Total	1.83

↕

Category	Source	relative uncertainty(%)
$\delta_{red.}$	proton tracking	0.01
	e PID	0.08
	Kinematic fit	0.01
	Λ reconstruction through vertex fit	0.01
	$N_{track} = 4$	negligible
$\delta_{irred.}$	Fitting M_{bc}	0.37
	Fitting U_{miss}	0.80
Sum		0.88

Measure the Form Factor

The Formalism for this decay



Definition of the helicity angles

[Phys. Rev. D 108, 016011]

$$d\Gamma \propto \mathscr{W}(\boldsymbol{\xi}; \alpha_\psi, \Delta\Phi, g_{av}^\Lambda, g_w^\Lambda, \alpha_\Lambda) \quad \Omega = (\alpha_\psi, \Delta\Phi, g_{av}, g_w, \alpha_\Lambda)$$

$$\sigma_\Lambda^{sl}(\boldsymbol{\xi}'')\Big[\mathscr{F}_0(\boldsymbol{\xi}') + \alpha_\psi \mathscr{F}_1(\boldsymbol{\xi}')$$

$$+a_\Lambda^{sl}(\xi'')\alpha_{\bar{\Lambda}}\left(\mathscr{F}_2(\xi') + \alpha_\psi \mathscr{F}_3(\xi') + \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\mathscr{F}_4(\xi')\right)$$

$$+I_\Lambda^{sl}(\boldsymbol{\xi}'')\alpha_{\bar{\Lambda}}\left(\mathscr{F}_2'(\boldsymbol{\xi}') + \alpha_\psi \mathscr{F}_3'(\boldsymbol{\xi}') + \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\mathscr{F}_4'(\boldsymbol{\xi}')\right)$$

$$+\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\left(a_\Lambda^{sl}(\xi'')\mathscr{F}_5(\xi') + I_\Lambda^{sl}(\xi'')\mathscr{F}_5'(\xi') + \alpha_{\bar{\Lambda}}\mathscr{F}_6(\xi')\right)\Big]$$

$$\xi' = (\theta_\Lambda, \theta_p, \phi_p, \theta_{\bar{p}}, \phi_{\bar{p}}), \xi = (\theta_\Lambda, \theta_p, \phi_p, \theta_e, q^2, \theta_{\bar{p}}, \phi_{\bar{p}}), \xi'' = (\theta_e, q^2).$$

We assume the $\alpha_\Lambda = \alpha_{\bar{\Lambda}}$,$g_2(0)$=0

Parameters input

Mode $\Lambda \to pe^-\bar{\nu}_e$	$\boldsymbol{\alpha_\psi}$	$\Delta\Phi$	$\boldsymbol{\alpha_\Lambda/\alpha_{\bar{\Lambda}}}$	$g_w^\Lambda/g_w^{\bar{\Lambda}}$	$g_{av}^\Lambda/g_{av}^{\bar{\Lambda}}$
	0.4748	0.7521	0.4748	1.066	0.719

The $g_{av}^\Lambda/g_{av}^{\bar{\Lambda}}$ value input was the most precise measurement from experiments.

The $g_w^\Lambda/g_w^{\bar{\Lambda}}$ value input is from Cabibbo theory.

Results of our fit

$$-\ln \mathscr{L} = -\sum_{i=1}^{N} \ln \frac{\mathscr{W}(\xi_i;\Omega)}{\mathscr{N}(\Omega)}$$

$$-\ln \mathcal{L}_{sig} = -\ln \mathcal{L}_{data} + \ln \mathcal{L}_{bkg-p\pi}$$

$$\Omega = (\alpha_\psi, \Delta\Phi, g_{av}, g_w, \alpha_\Lambda)$$

$g_{av}^{\Lambda}/g_{av}^{\bar{\Lambda}}$, $g_w^{\Lambda}/g_w^{\Lambda}$ are floating.

The other 3 parameters are fixed.

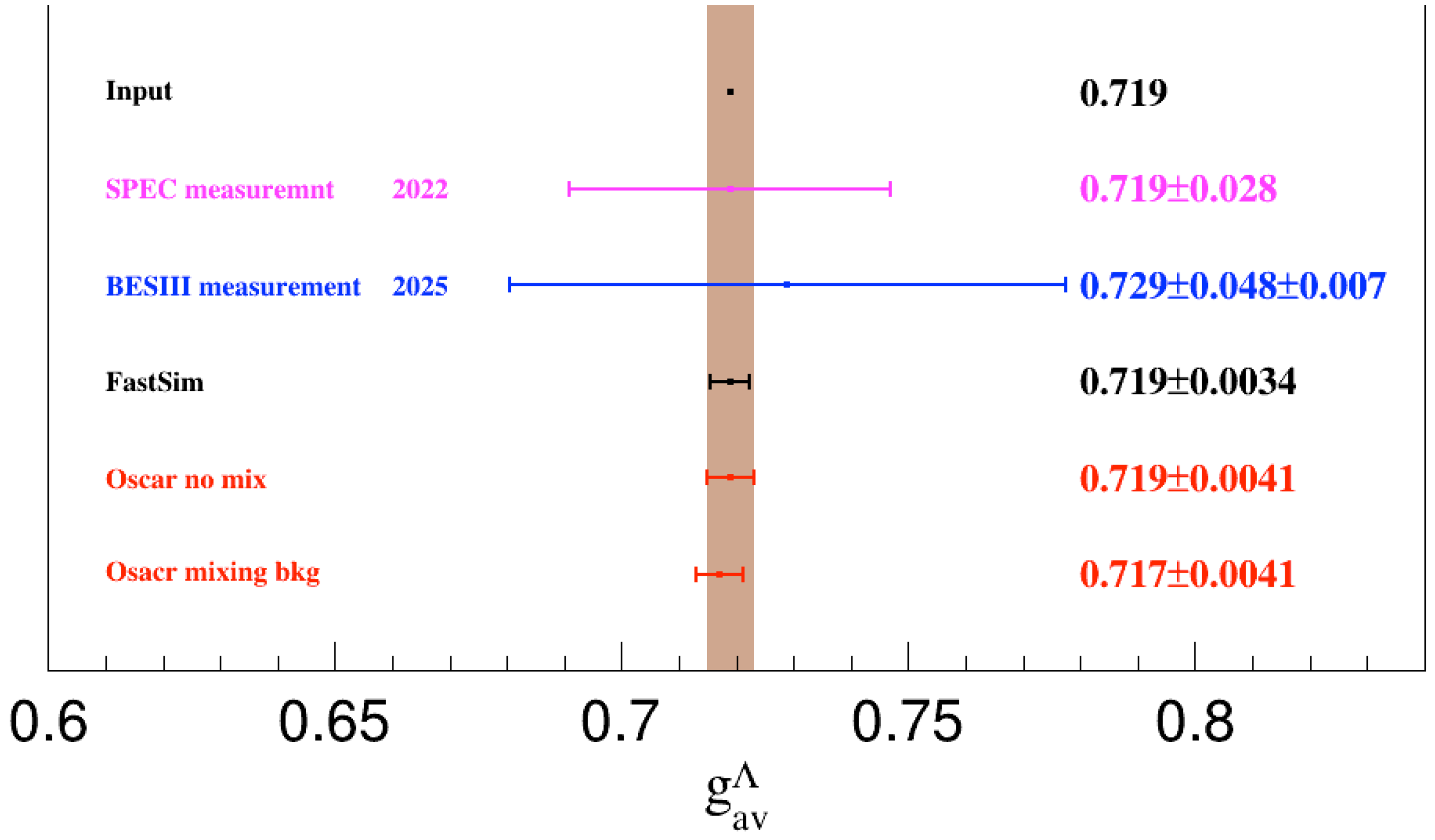
Normalization factor is got using mDIY MC

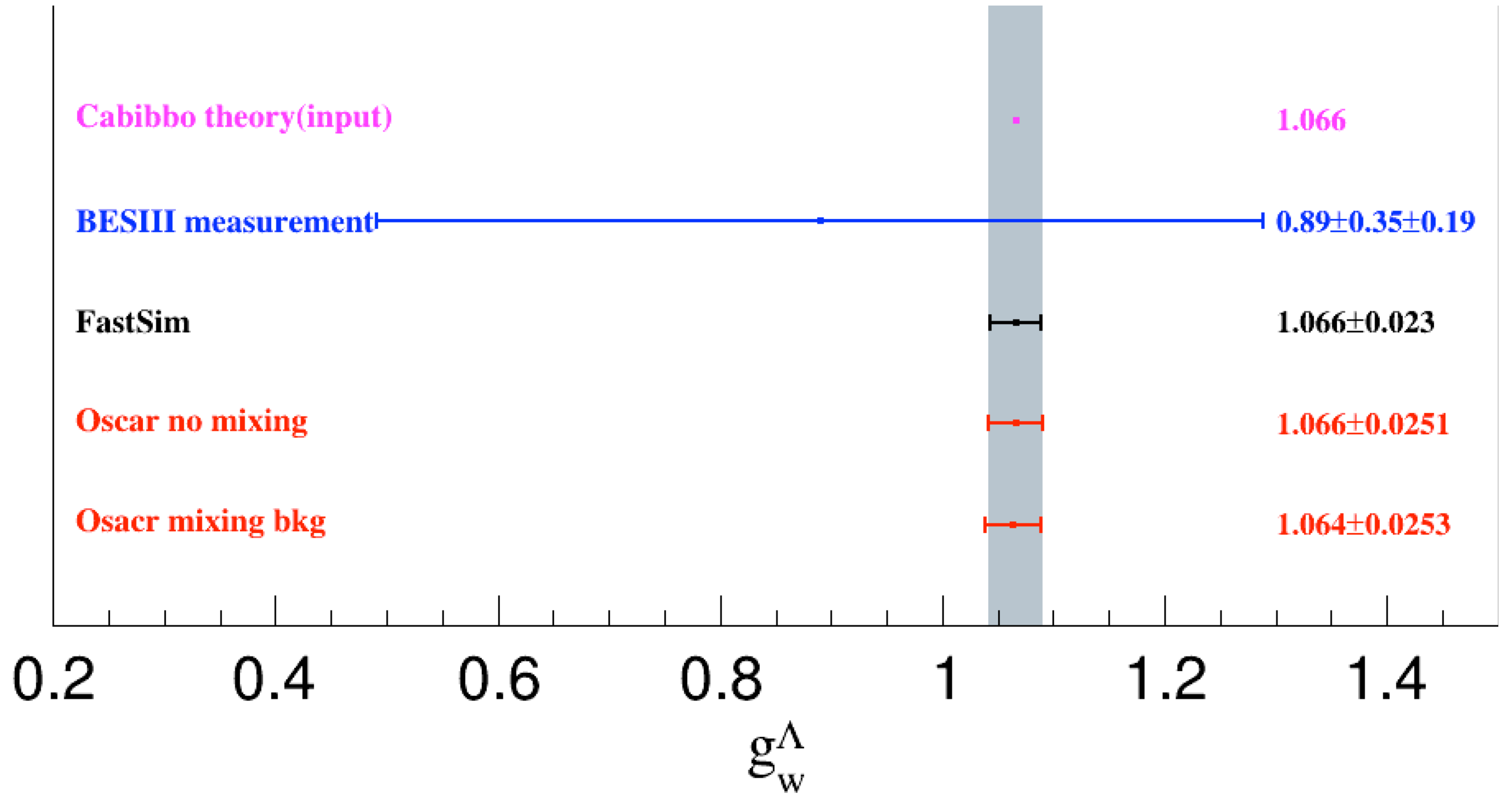
Contributions from backgrounds can be subtracted

The dominated contributions from $p\pi$ is considered

Selection criteria is similar to measuring $\mathscr{B}$ besides U_{miss} cut.

Results of our fit with Oscar



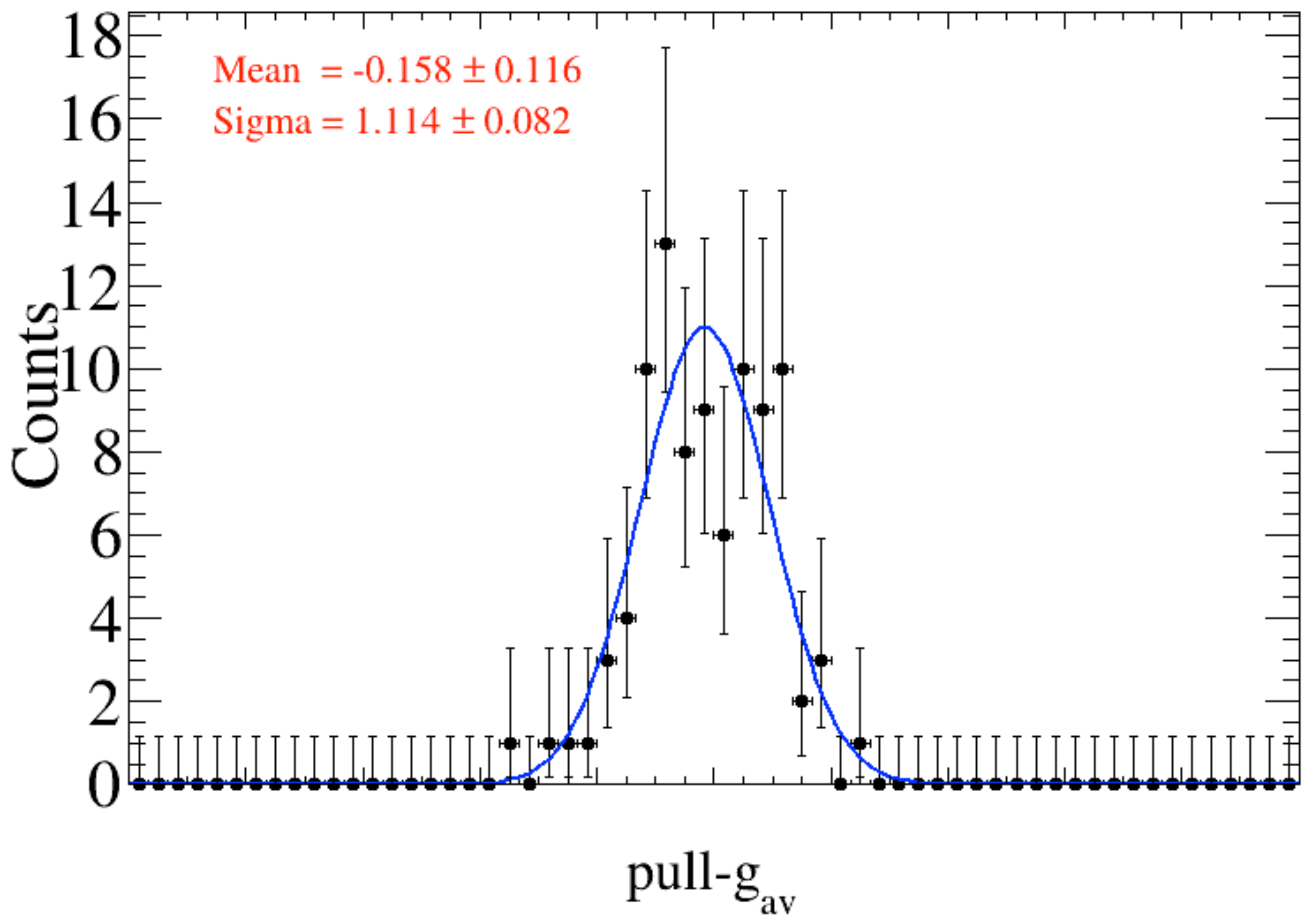


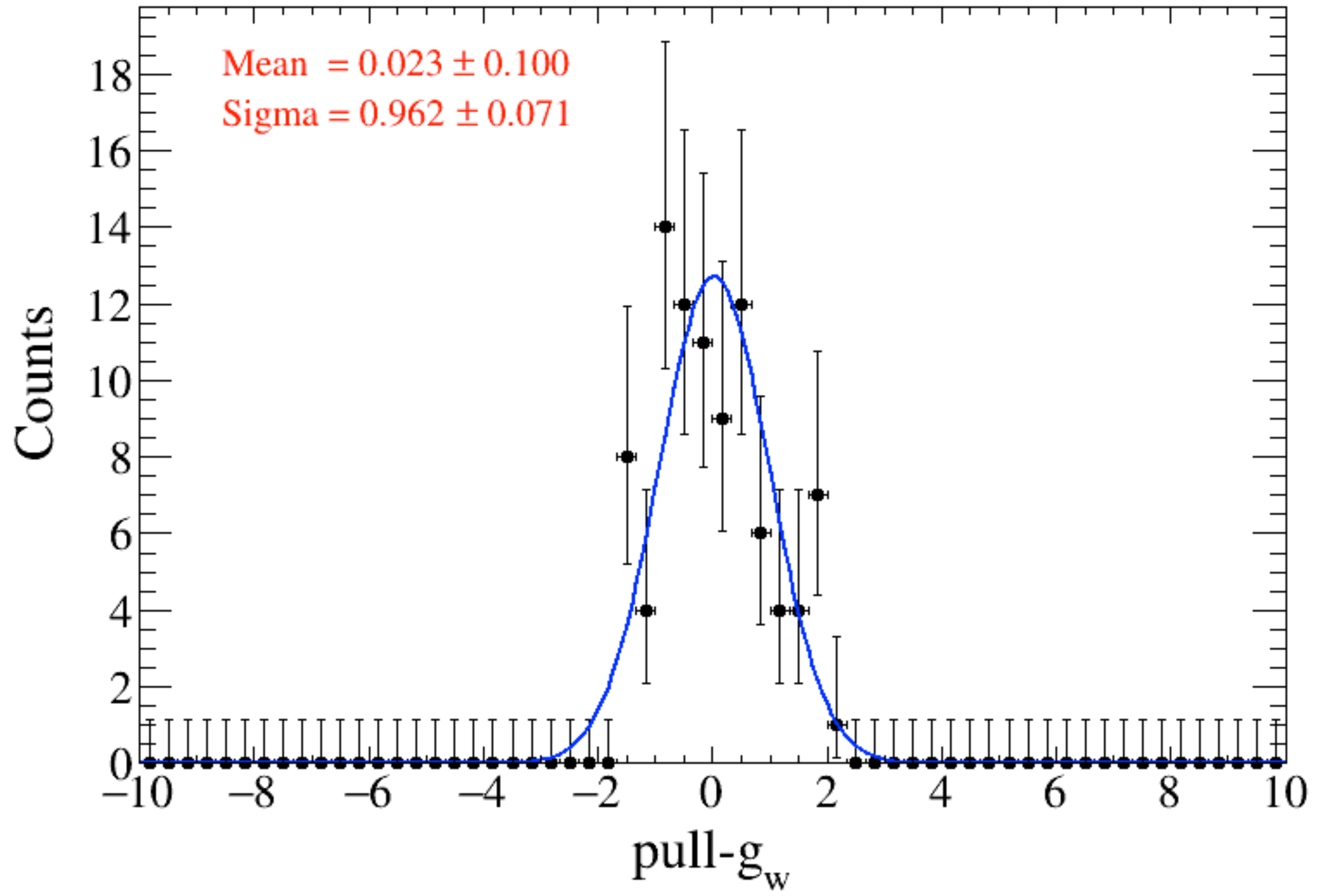
a prospect of the statistical uncertainty through sampling method bootstrap same as measuring BF.

Measure the Form Factor

IO check of our fit

Only signal MC check with Oscar





a prospect of the statistical uncertainty through sampling method bootstrap same as measuring BF.

Calculation of $|V_{us}|$ and uncertainty

Calculation of $|V_{us}|$ prospect results with FastSim

$$\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\Gamma_{e,\,\rm SM}}{dq^2}dq^2 = \frac{\mathcal{B}_{B_1\to B_2+\ell+\overline{\nu}_l}}{\tau_{B_1}},$$

$$\frac{\Gamma_{e,\,\rm SM}}{dq^2} = \frac{G_F^2\,|V_{us}|^2\,\Delta^5}{60\pi^3}[(1-\frac{3}{2}\delta+\frac{6}{7}\delta^2)f_1(q^2)^2 + \frac{4}{7}\delta^2 f_2(q^2)^2 + (3-\frac{9}{2}\delta+\frac{12}{7}\delta^2)g_1(q^2)^2 + \frac{6}{7}\delta^2 f_1(q^2)f_2(q^2)],$$

$$f_1(q^2) = f_1(0)\times[1+q^2(\frac{1}{m_V^2}+\frac{1}{m_V^2+\alpha_R^{-1}})],$$

$$f_2(q^2) = f_2(0)\times[1+q^2(\frac{1}{m_V^2}+\frac{1}{m_V^2+\alpha_R^{-1}}+\frac{1}{m_V^2+2\alpha_R^{-1}})],$$

$$g_1(q^2) = g_1(0)\times[1+q^2(\frac{1}{m_A^2}+\frac{1}{m_A^2+\alpha_R^{-1}})],$$

Through $g_{av} \equiv \frac{g_1(0)}{f_1(0)}, g_{av} \equiv \frac{f_2(0)}{f_1(0)}, g_1(0) = -0.8263 \pm 0.0070$(From LQCD)

https://arxiv.org/pdf/2507.09970

We can get the result of $|V_{us}|$

Uncertainties from Fastsim and PDG

From BF(prospect):0.0002;

From LQCD:0.0019;

From PDG:0.0007;

From FF(prospect):0.0004;

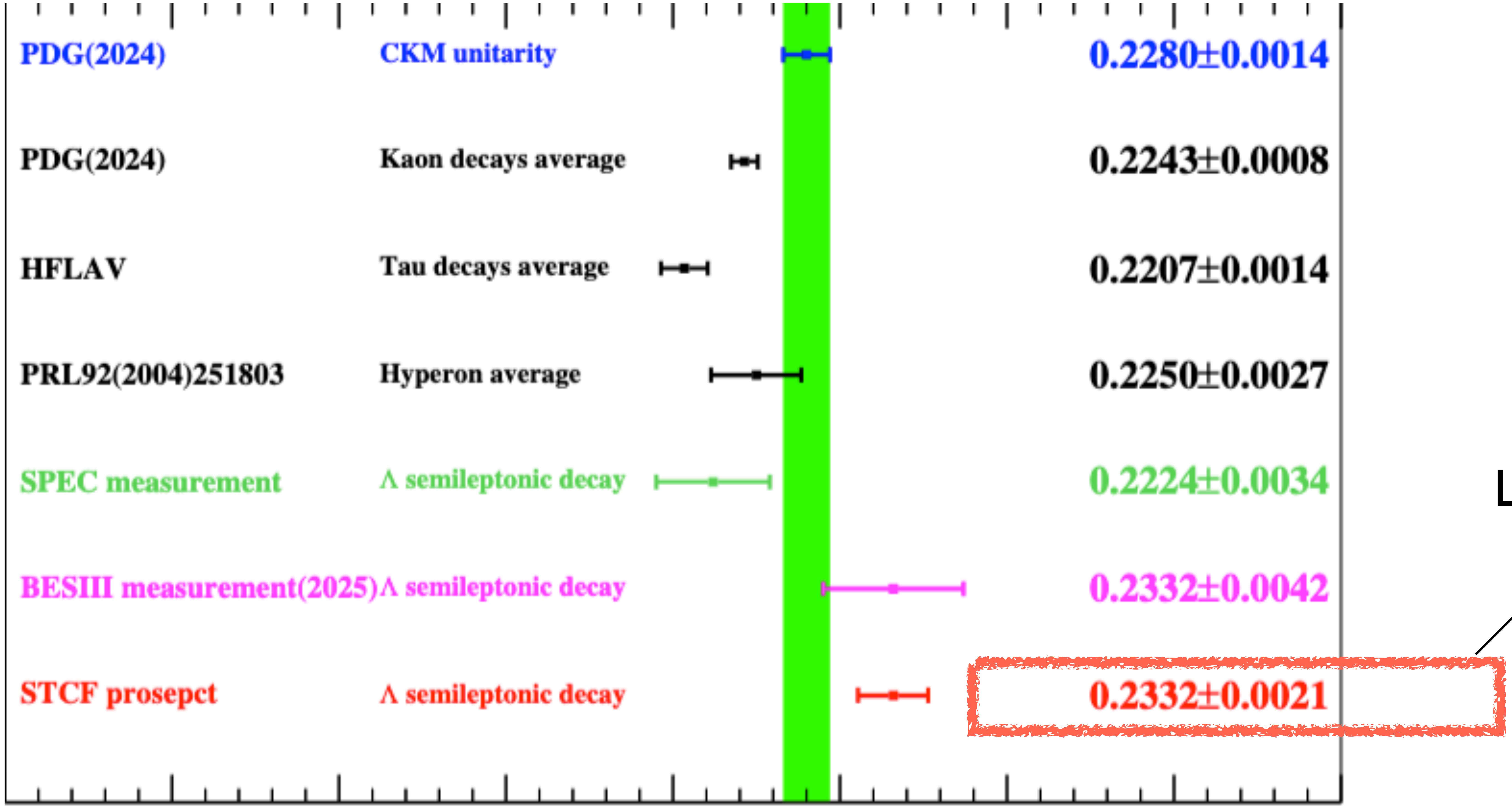
Through MC method

$|V_{us}| = 0.2335 \pm 0.0021$

The uncertainties of BF and FF contribution mainly come from statistical uncertainty

Comparison of $|V_{us}|$ and uncertainty

prospect results with FastSim



LQCD input accounts for 90%

Summary

Have studied

1. As prospect, give a prospect of the $|V_{us}|$ measurement with its uncertainty at STCF with Fastsim.
2. The results will test the CKM matrix unitarity with higher precision in Hyperon decay.

Next to do

1. There are many mis-combinatorial backgrounds on the tag side.
2. the IO check with mixing background is not fully studied at **OSCAR**.
3. Currently, the LQCD input value has high uncertainty , wait for more precise input.
4. Use ECAL information to separate e/π if possible.

Thank you!

Back up

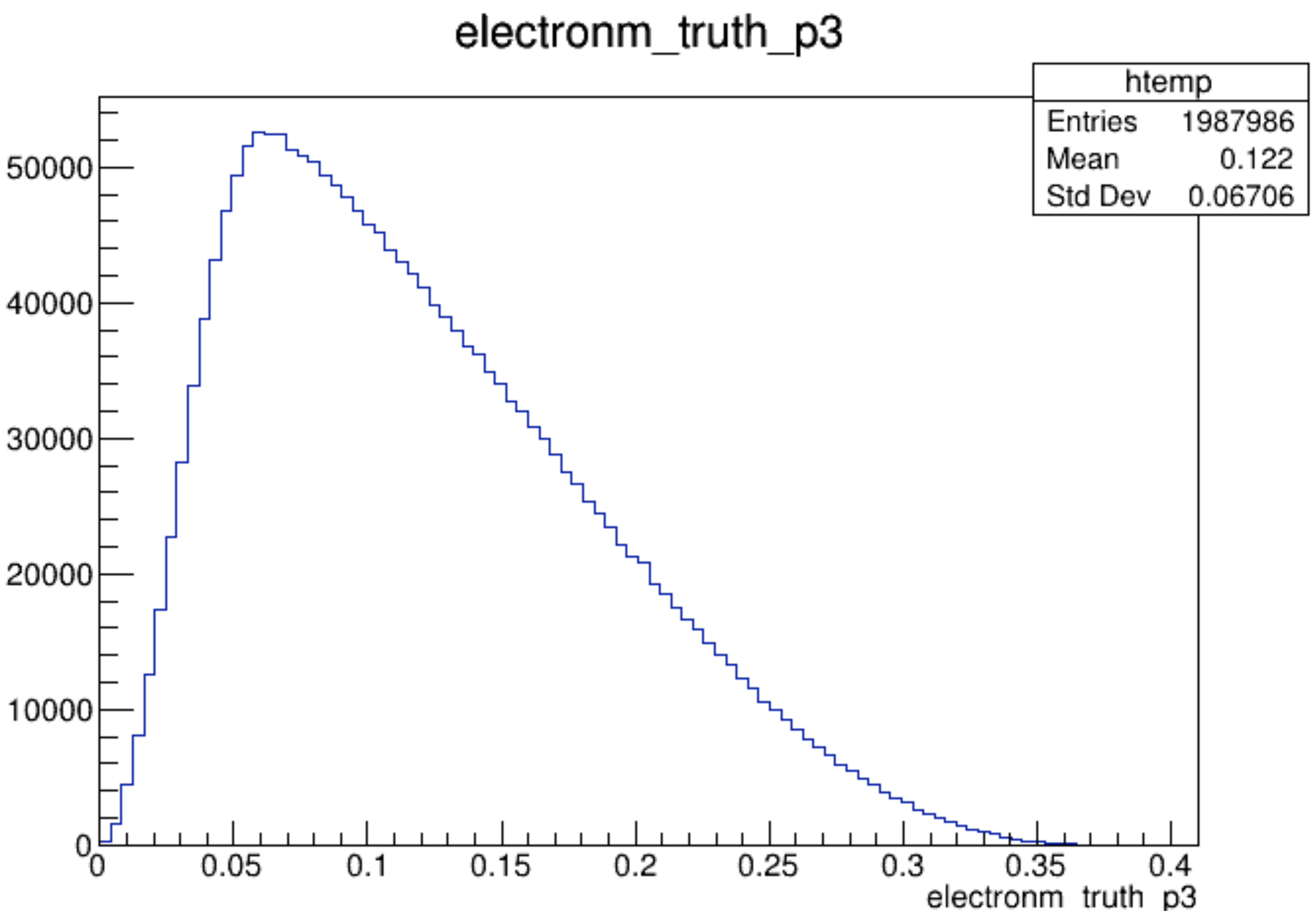
Table 1: Cut flow at Oscar

	Events	Efficiency(%)	Relative Efficiency
Total number	**1997996**	100	
Good tracks	**1581149**	61.59	61.59
ΔE cut	**973336**	48.71	61.55
lam_chi_tag<200	**937279**	47.41	97.32
length/lengtherr>2	**853987**	42.74	**90.15**
mbc_tag	**710725**	35.47	**82.21**
lam_chi_sig<200	**684798**	34.27	**96.37**
lam_sig_len>0	**684798**	23.95	100
prob(e)>prob(other)	**478580**	17.95	**62.07**
prob(e)>0.987	**254693**	**12.35**	**59.95**
χ_{4c} cut	**238678**	**11.74**	**93.71**
p_sig_e>0.12	**151151**	7.57	**63.32**
U_{miss} cut	**140877**	7.05	**93.2**

Table 2: Cut flow at BESIII

	Events	Efficiency(%)	Relative Efficiency
Total number	450 000	100	
Good tracks	246 0537	54.67	84.29
ΔE	**167 622**	37.24	68.12
lam_chi_tag<200	160 2914	35.62	95.62
L/σ	147 0345	32.67	91.72
mbc_tag	137 8986	30.64	93.78
lam_chi_sig<200	**128 514**	28.55	93.19
lam_sig_len	**1219667**	27.08	95.12
prob(e)>0.001	998872	22.17	81.9
R>0.999	583096	12.95	58.4
chi_4c	563765	12.52	96.68
p_sig_e>0.1	401 954	8.93	
U_miss	383 199	8.51	

Back up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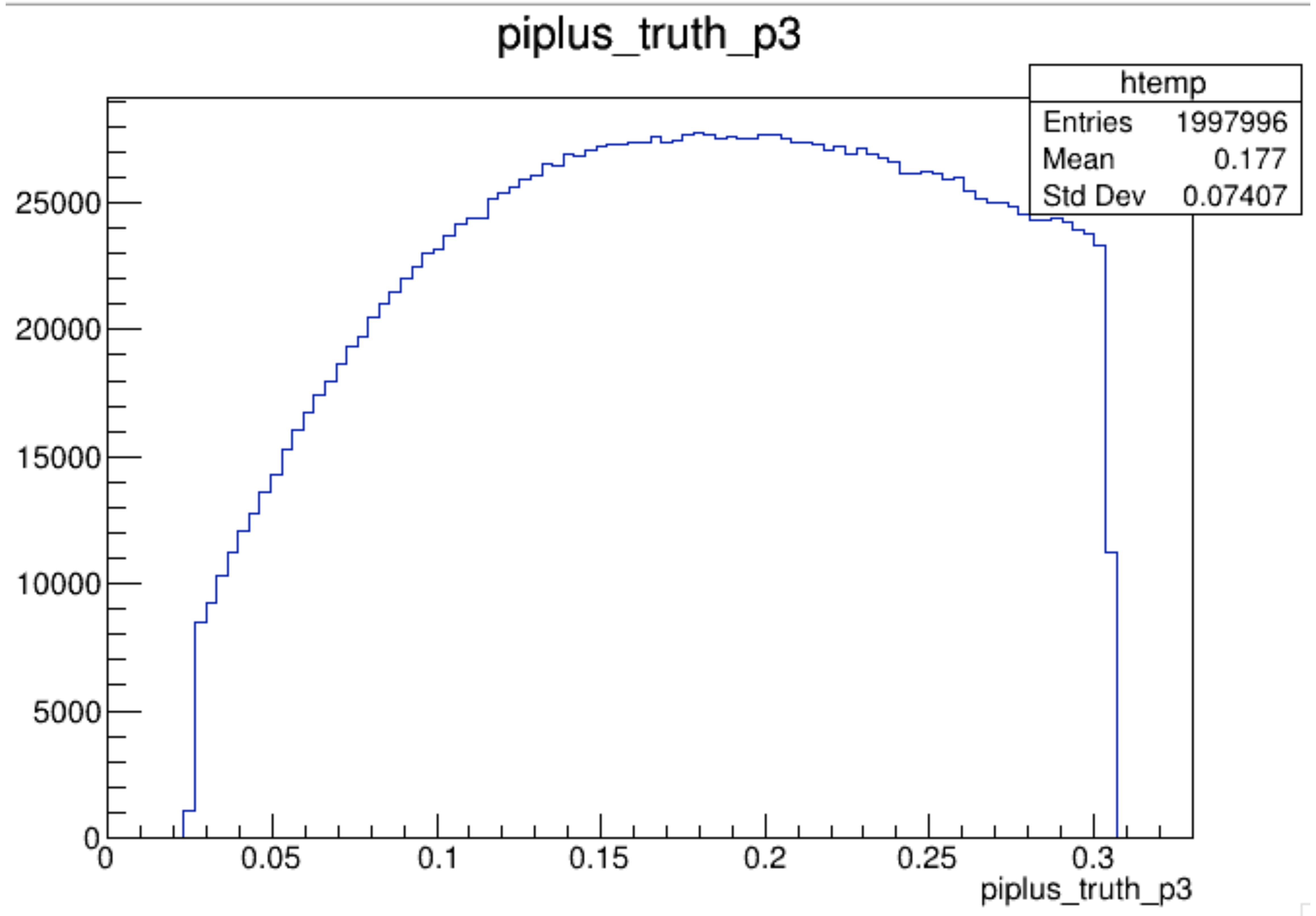
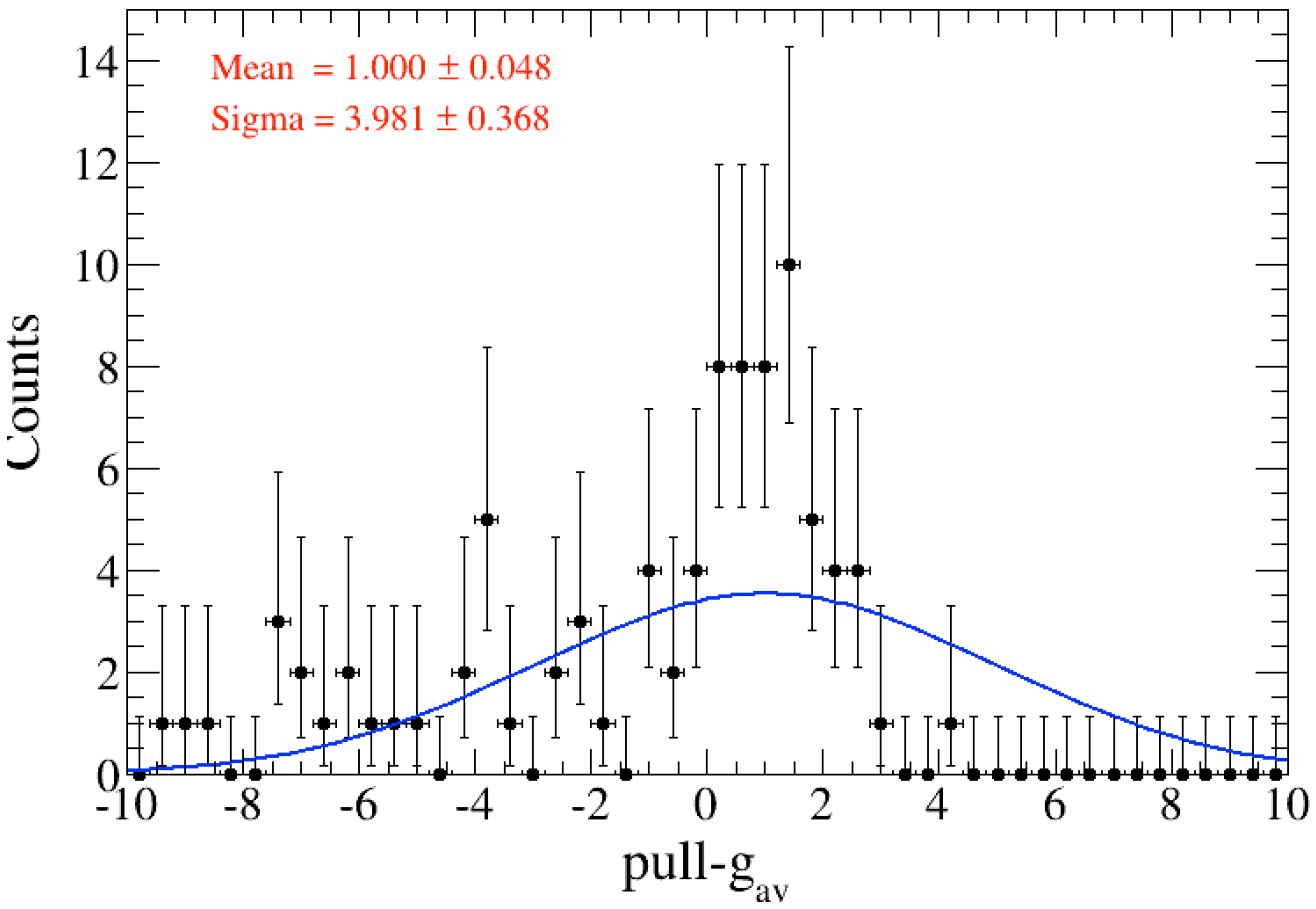
htemp
Entries 1987986
Mean 0.122
Std Dev 0.06706
50000
40000
30000
20000
10000
0
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4
electronm_truth_p3

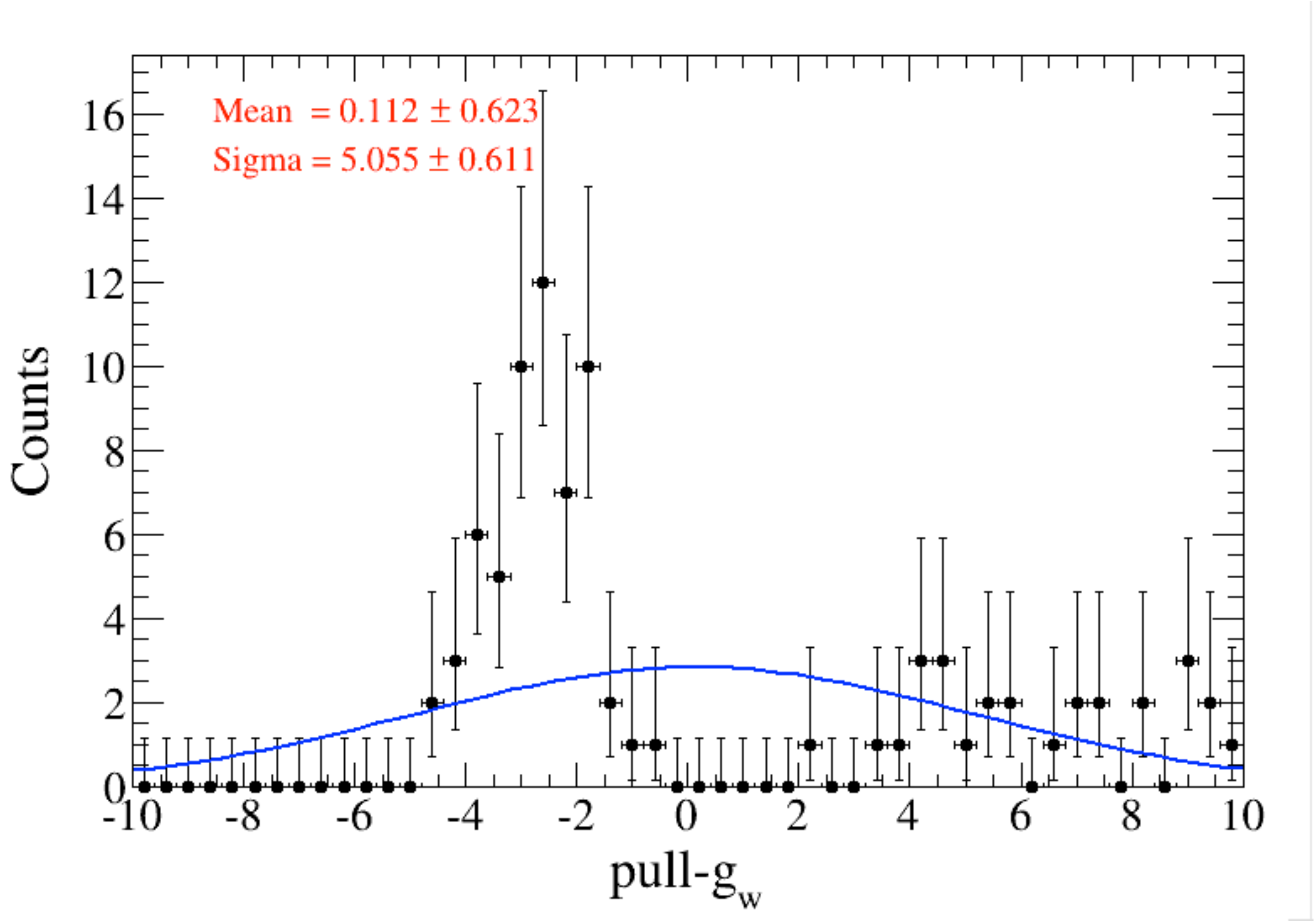

piplus_truth_p3
htemp
Entries 1997996
Mean 0.177
Std Dev 0.07407
25000
20000
15000
10000
5000
0
0 0.05 0.1 0.15 0.2 0.25 0.3
piplus_truth_p3

Measure the Form Factor

IO check of our fit

Mix ppl bkg and beam bkg with Oscar



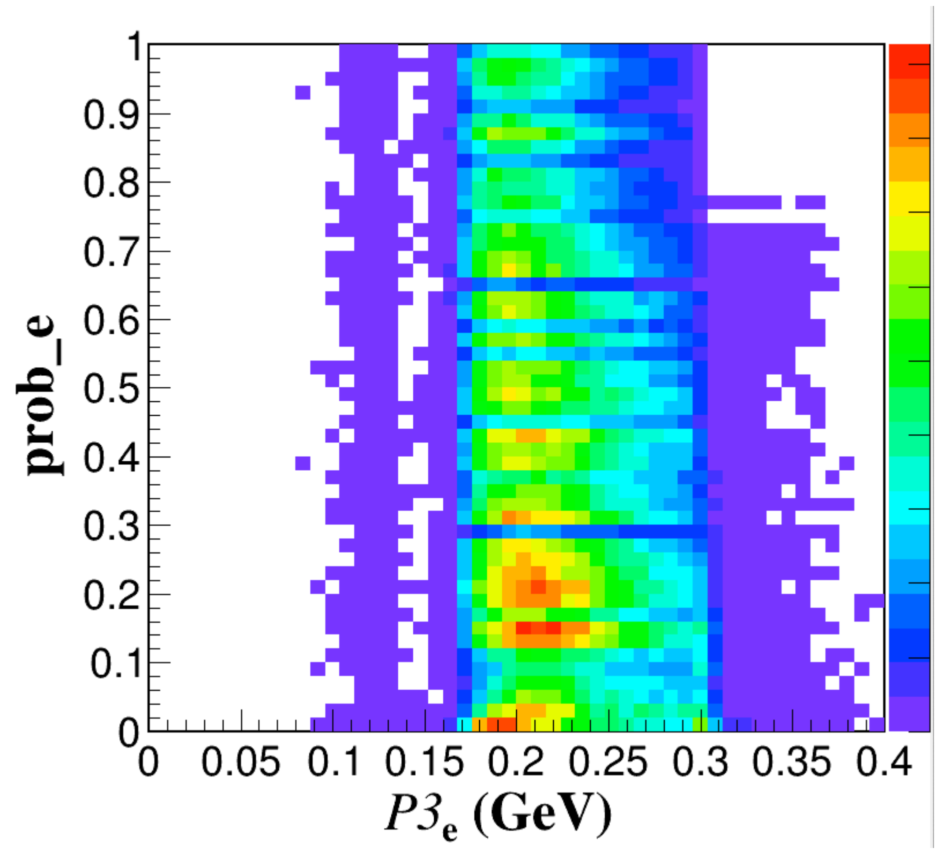


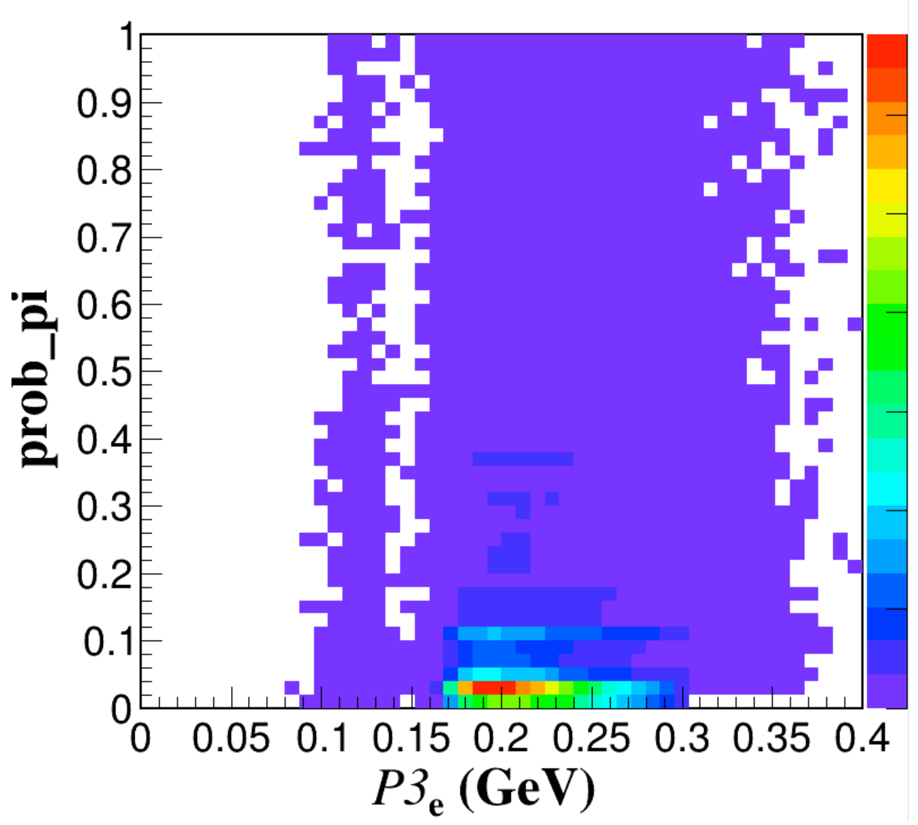
a prospect of the statistical uncertainty through sampling method bootstrap same as measuring BF.

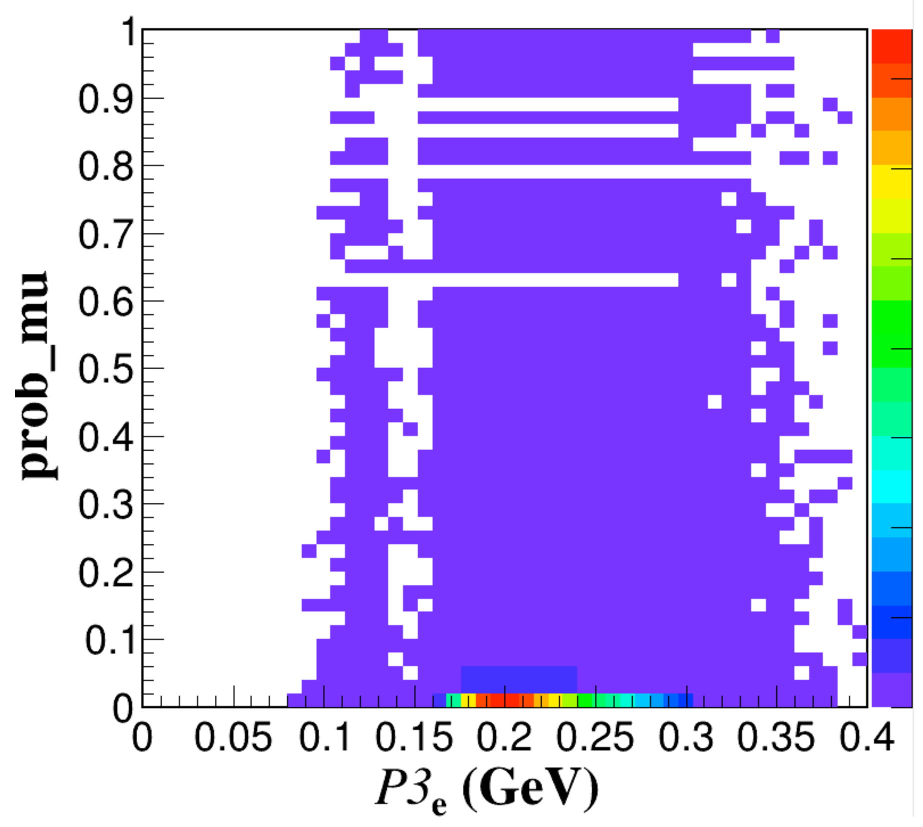
Back up

BES prob

Different prob







只画了0.15GeV-0.25GeV这个区间的