Particle identification with the time of flight at the ILD

CALICE Collaboration Meeting
10 September 2021, IJCLab

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Before we start… It is <u>inspiring</u> to see many talks on timing!

Update on LGAD-APD tests — *Taikan Suehara*
Auditorium Pierre Lehmann, Building 200, IJCLab — 16:25 - 16:45

Measurement of the time resolution of the Klaus ASIC — *Konrad Briggl*
Auditorium Pierre Lehmann, Building 200, IJCLab — 11:40 - 12:00

SDHCAL Timing — *Qiu-Ping SHEN*
Auditorium Pierre Lehmann, Building 200, IJCLab — 15:25 - 15:45

Time resolution measurements with AHCAL scintillator tiles - test beam results — *Lorenz Emberger*
Auditorium Pierre Lehmann, Building 200, IJCLab — 16:50 - 17:10

Time resolution measurements with AHCAL scintillator tiles - simulations & laser measurements — *Fabian Hummer*
Auditorium Pierre Lehmann, Building 200, IJCLab — 17:10 - 17:35

Analysis of LGAD test beam at Tohoku in February 2021 — *Shusaku Tsumura*
Auditorium Pierre Lehmann, Building 200, IJCLab — 09:00 - 09:20

Two main questions of this talk:

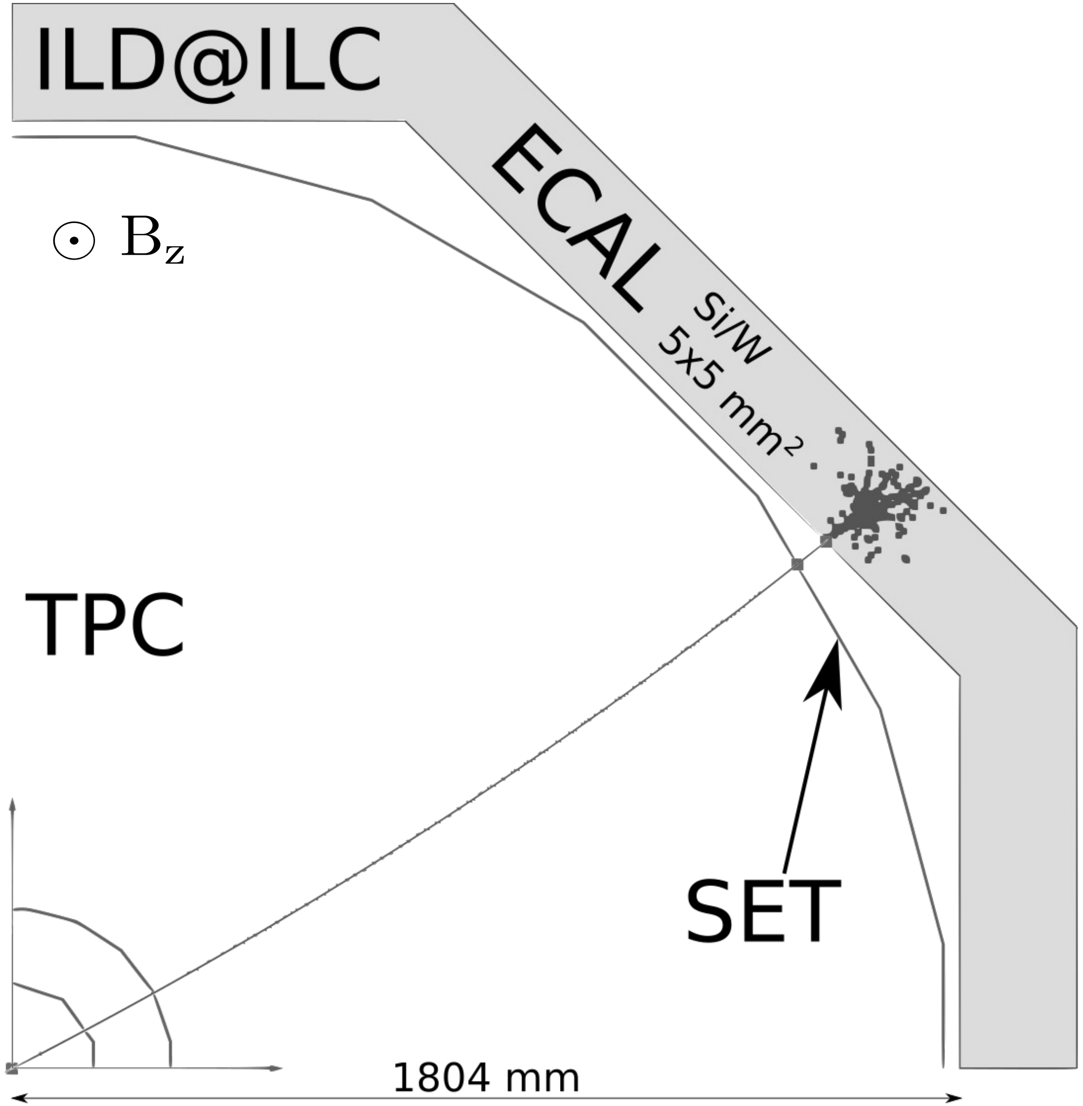
1) How do we use time information for particle ID?

2) How does time resolution affects particle ID?

The same subject as in the talk by Mami Kuhara
at the CALICE Collaboration Meeting in March 2021

Basic principle of the particle identification with TOF

We have a track. How to identify what particle it is?

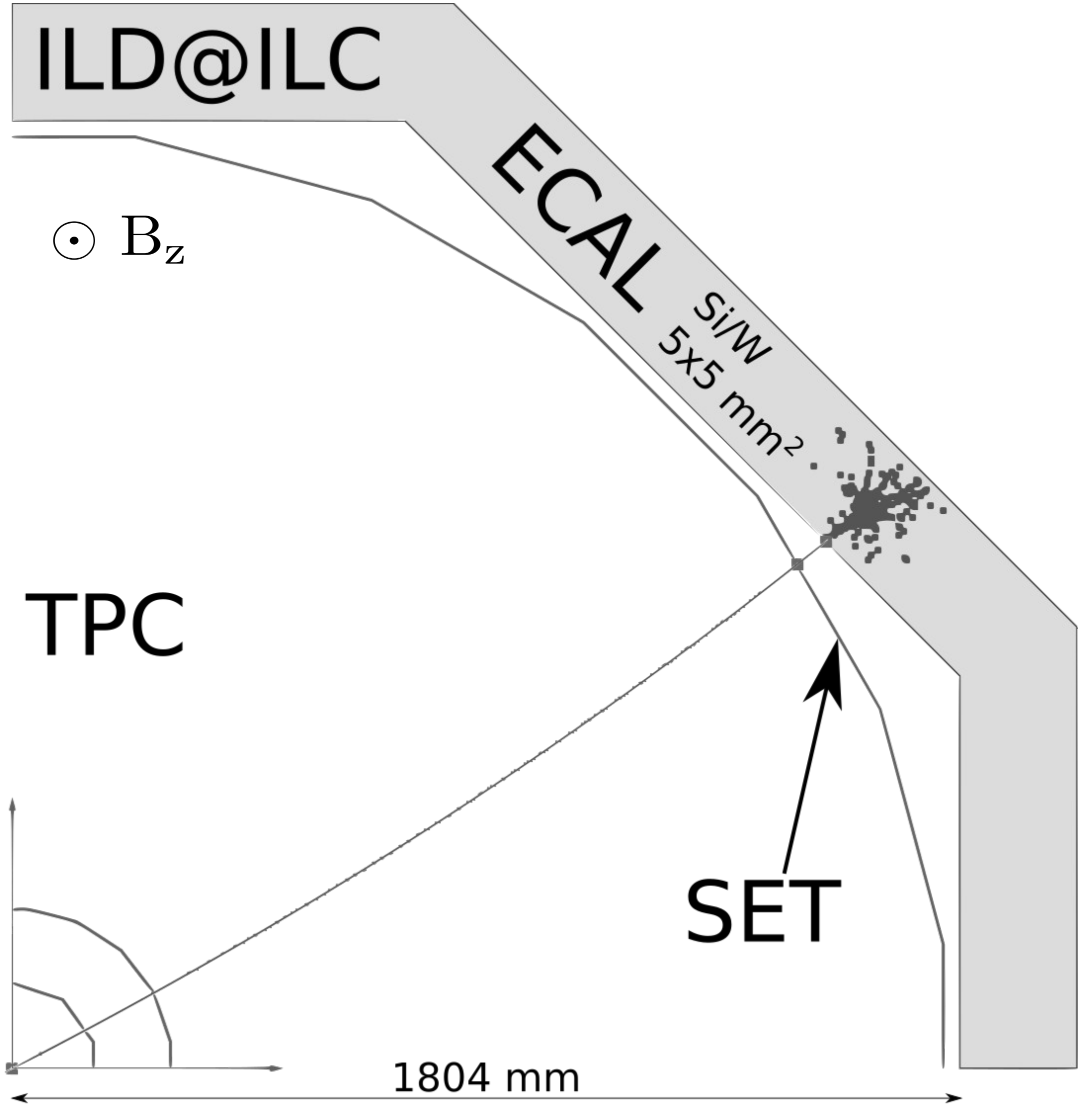


Let's use formula for the relativistic momentum to find out the mass of the particle

$$m = \frac{p}{\beta}\sqrt{1-\beta^2}$$

Basic principle of the particle identification with TOF

We have a track. How to identify what particle it is?



Let's use formula for the relativistic momentum to find out the mass of the particle

$$m = \frac{p}{\beta}\sqrt{1-\beta^2}$$

$$p = e\frac{|B_z|}{|\Omega|}\sqrt{1+\tan^2\lambda} \qquad \beta = \frac{\ell_{\text{track}}}{c \cdot \text{TOF}}$$

$$\ell_{\text{track}} = \sum_{i=0}^{n} \ell_i = \sqrt{\left(\frac{\varphi_{i+1}-\varphi_i}{\Omega}\right)^2 + (z_{i+1}-z_i)^2}$$

$$\text{TOF} = \text{measure at the ECal / SET}$$

Recent developments on the track length

Recently we **significantly improved** track length estimator and pID in general:

- Fixed φ coordinate flip bug that caused wrong estimation of the track length
- Using track states at **all TPC hits** now! Allows to measure the track length for curly tracks in the endcap!
- Use harmonic mean momentum for mass reconstruction as proposed by Winfried A. Mitaroff in his paper

Full and detailed description of all technicalities in my recent talk at the ILD S&A meeting

something remains unclear? Don’t hesitate to contact via email :)

Potential TOF estimators

TOF estimators

easy	closest ECal hit
	fastest ECal hit
	SET hit

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medium	average all or a subset of ECal hits
	(linear) fit of all or a subset of ECal hits

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🔥**Hardcore**🔥	“tracking” inside shower (see Taikan talk on Wed.)
	3D vector field “shower flow”
	Hit selection using shower starter

Potential TOF estimators

TOF estimators

null	Let the machine learning do the job for us
easy	closest ECal hit
	fastest ECal hit
	SET hit
medium	average all or a subset of ECal hits
	(linear) fit of all or a subset of ECal hits
🔥**Hardcore**🔥	“tracking” inside shower (see Taikan talk on Wed.)
	3D vector field “shower flow”
	Hit selection using shower starter

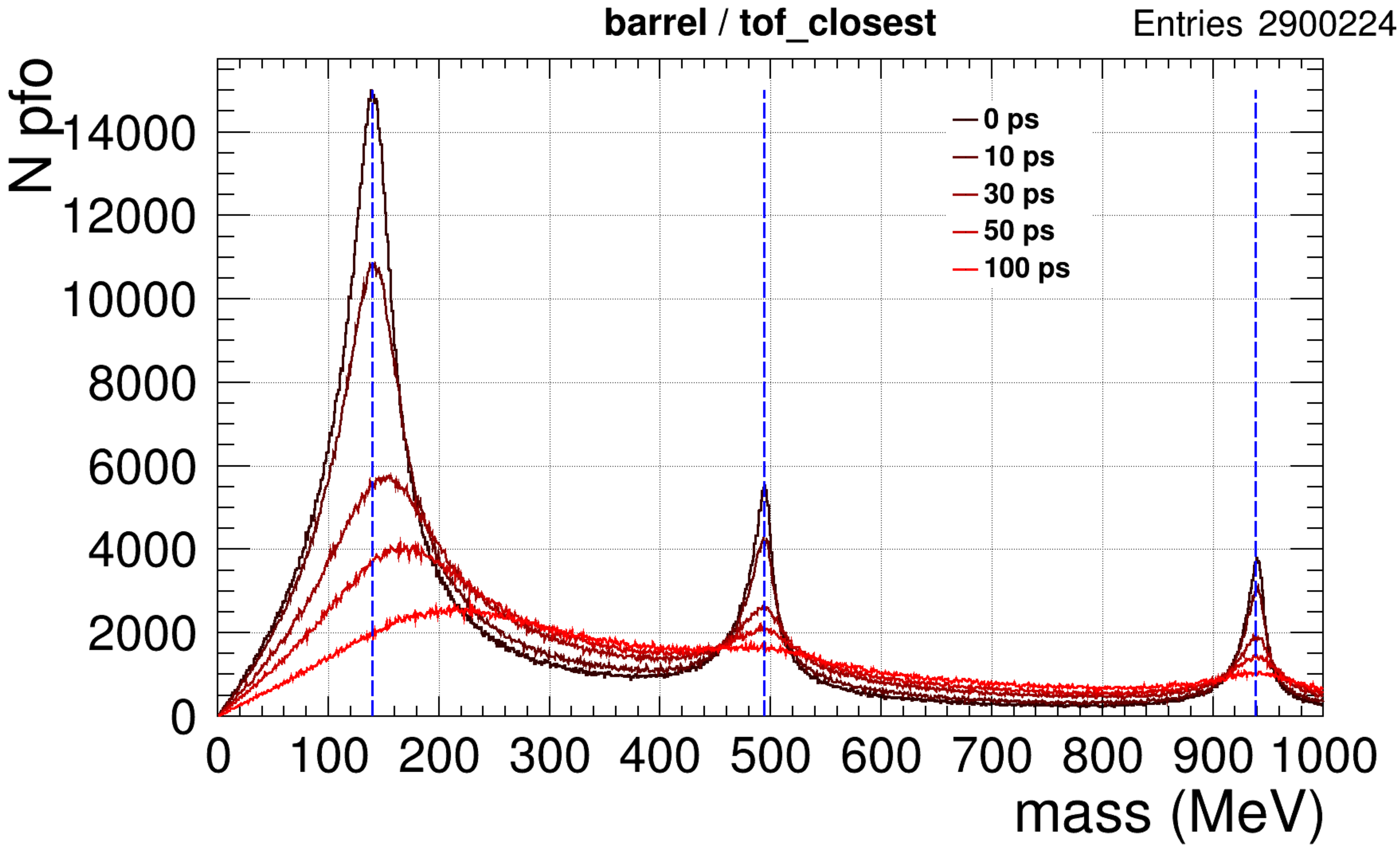
TOF estimators

For further plots I will use “**TOF closest**” estimator

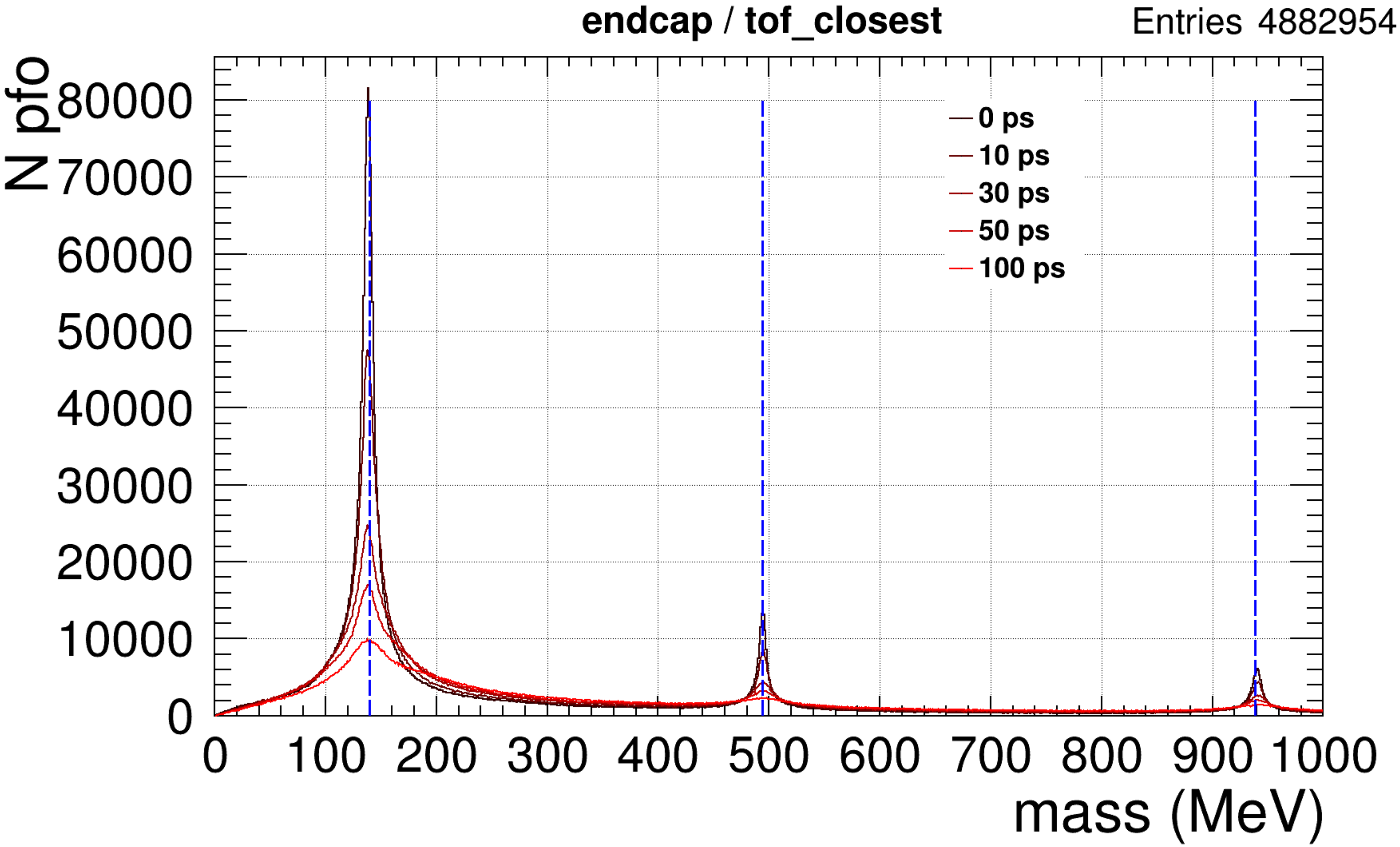
- Straightforward and simple logic. No shower or algorithmic effects – no additional errors or biases

- Using single hit we get: $\Delta TOF = \Delta t_{hit}$
  The “worst” case scenario benchmark which we can try to improve with any algorithm described above

Mass bias


barrel / tof_closest
Entries 2900224
N pfo
14000
12000
10000
8000
6000
4000
2000
0
0 ps
10 ps
30 ps
50 ps
100 ps
0
100
200
300
400
500
600
700
800
900
1000
mass (MeV)

Mass bias



endcap / tof_closest
Entries 4882954
N pfo
80000
70000
60000
50000
40000
30000
20000
10000
0
0
100
200
300
400
500
600
700
800
900
1000
mass (MeV)
0 ps
10 ps
30 ps
50 ps
100 ps

Mathematical explanation

$$p(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\frac{(t-t_0)^2}{\sigma^2}}$$

$$m(t) = \frac{p}{\beta}\sqrt{1-\beta^2} = p\sqrt{\frac{t^2c^2}{l_{trk}^2} - 1}$$

Left formula:
- p(t) – probability distribution of measured time
- t_0 – true TOF
- σ – TOF resolution

Right formula:
- m(t) – relation between mass and time
- p – true momentum
- c – speed of light
- l_{trk} – track length

Given:

t – random variable with p(t) distribution
m – random variable with m=m(t) relation

Find:

$$p(m) = |\frac{dt}{dm}| p(t(m))$$

We can analytically calculate mass distribution based on the resolution

Mathematical details

$$t = \frac{l_{trk}}{pc}\sqrt{m^2 + p^2}$$

$$\frac{dt}{dm} = \frac{l_{trk}}{pc}\frac{m}{\sqrt{m^2 + p^2}}$$

$$p(m) = \frac{l_{trk}}{pc}\frac{m}{\sqrt{m^2 + p^2}}\frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{(\frac{l_{trk}}{pc}\sqrt{m^2+p^2}-t_0)^2}{2\sigma^2}}$$

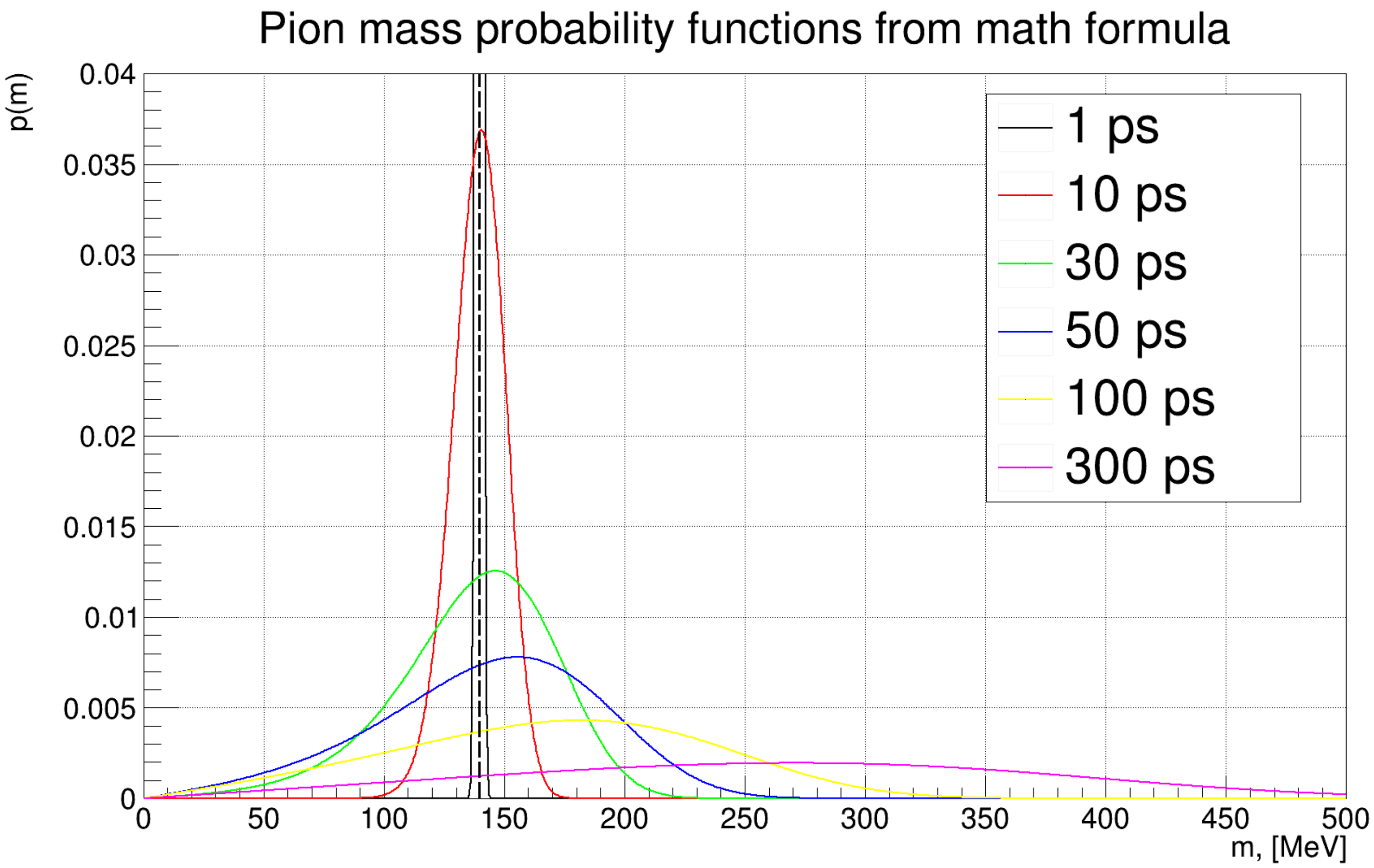
Mass probability distribution not a pure Gaussian

Example mass distributions

Let's consider:

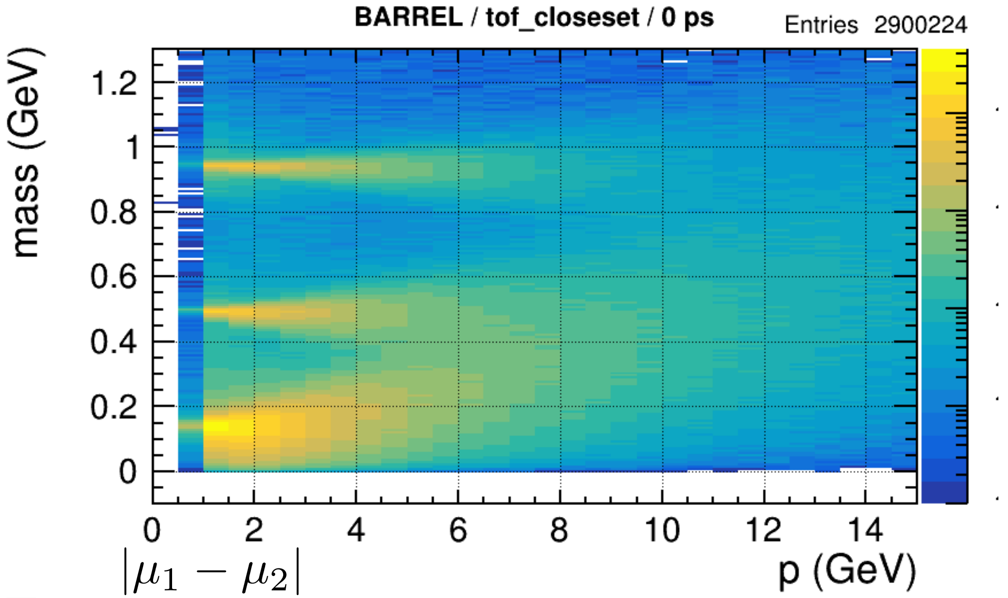
m = 139.57018(35) MeV ($\pi^{\pm}$)
p = 1 GeV
l_{trk} = 2 m
$t_0(m, p, l_{trk})$ = 6.7359462 ns

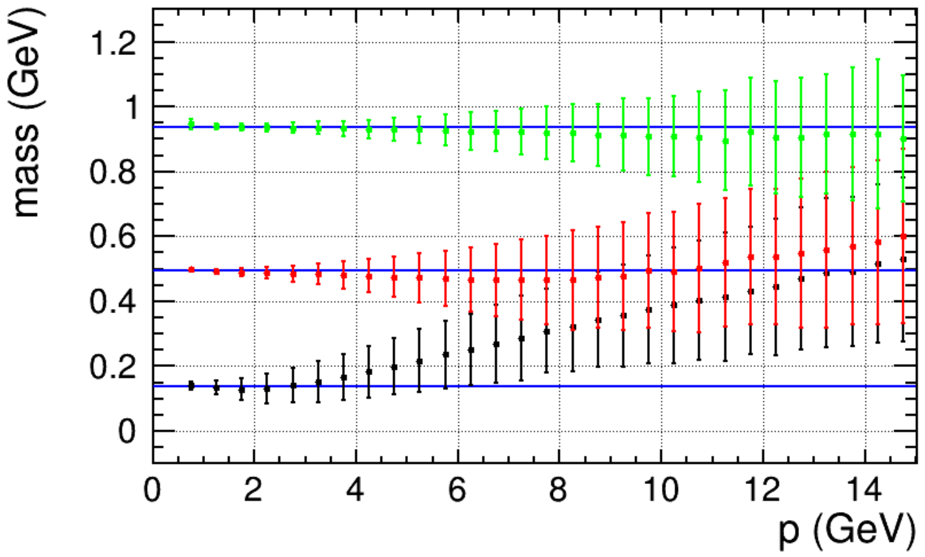
σ = 1, 10, 30, 50, 100, 300 ps



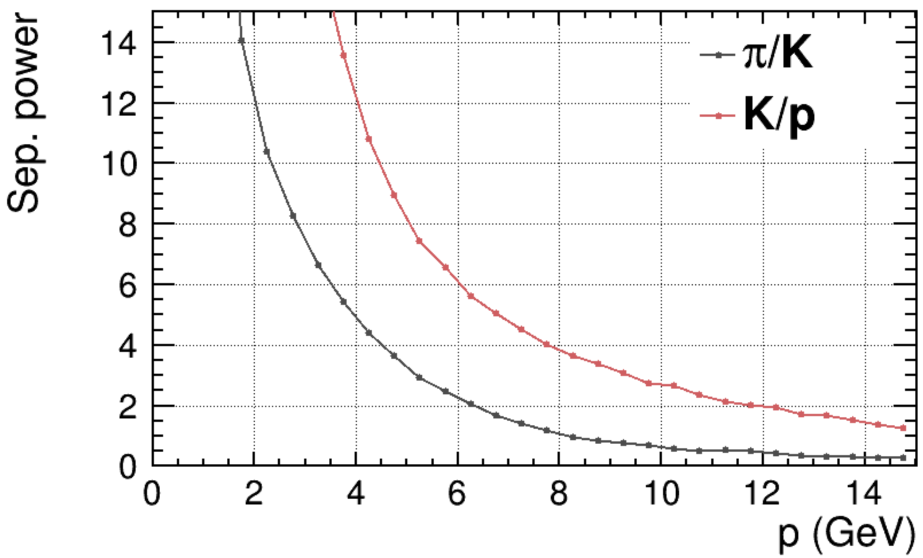
Mathematical functions repeat observed bias from MC simulations

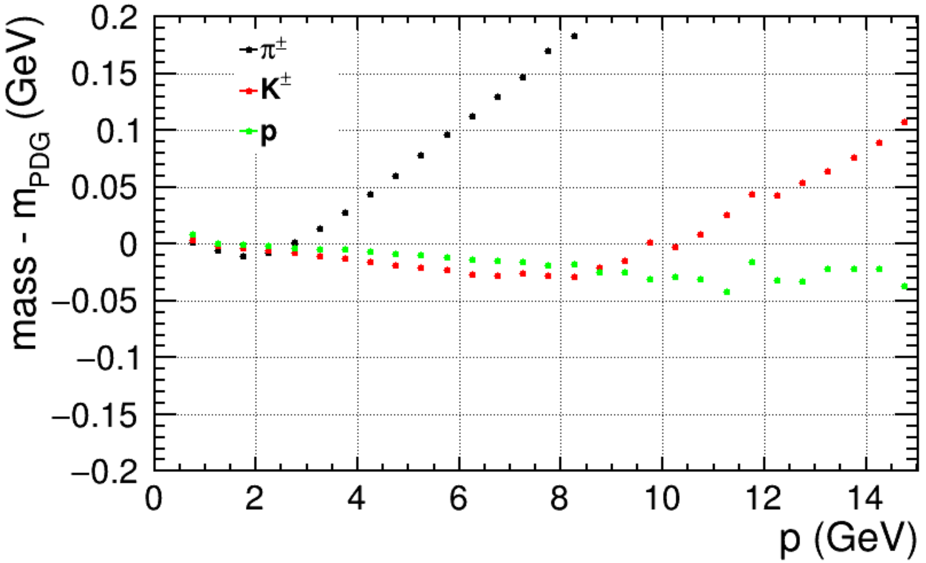
Extraction of separation power (0 ps)



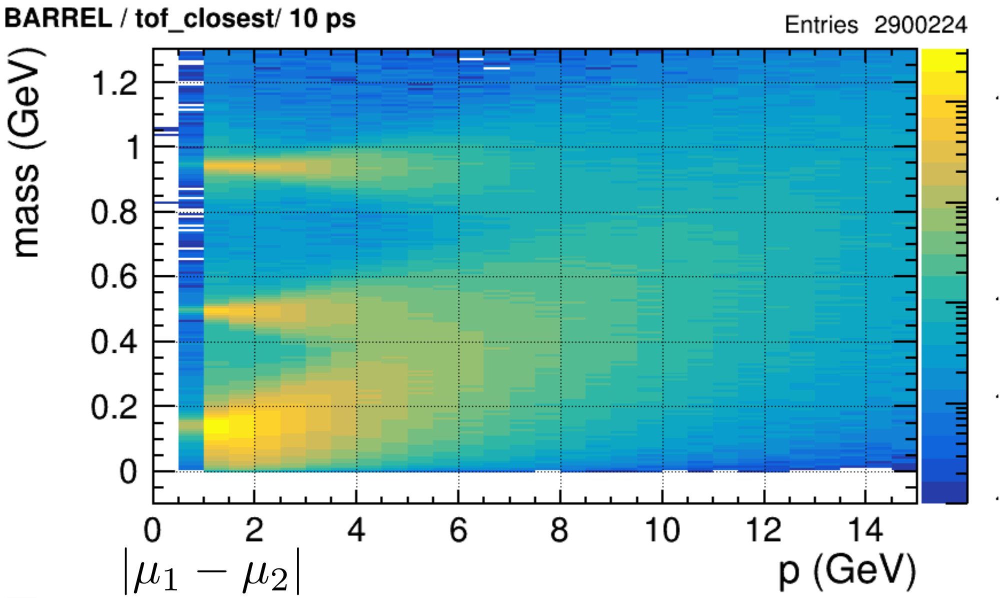


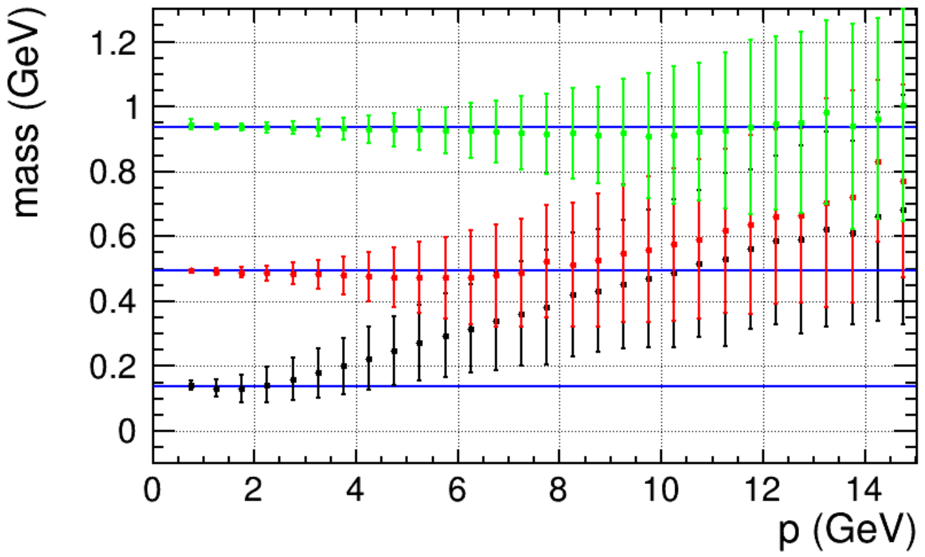
$$\mathrm{Sep.Power} = \frac{|\mu_1 - \mu_2|}{\sqrt{0.5(\sigma_1^2 + \sigma_2^2)}}$$





Extraction of separation power (10 ps)





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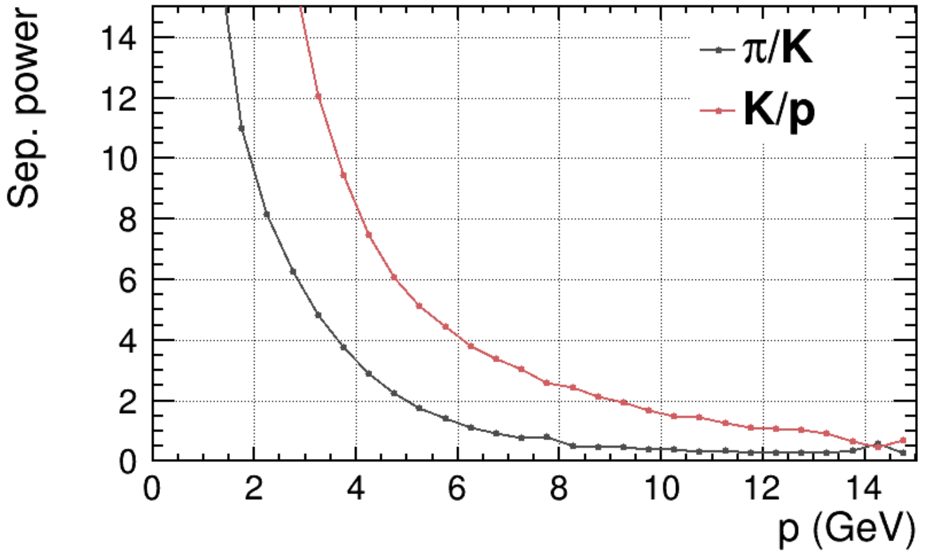
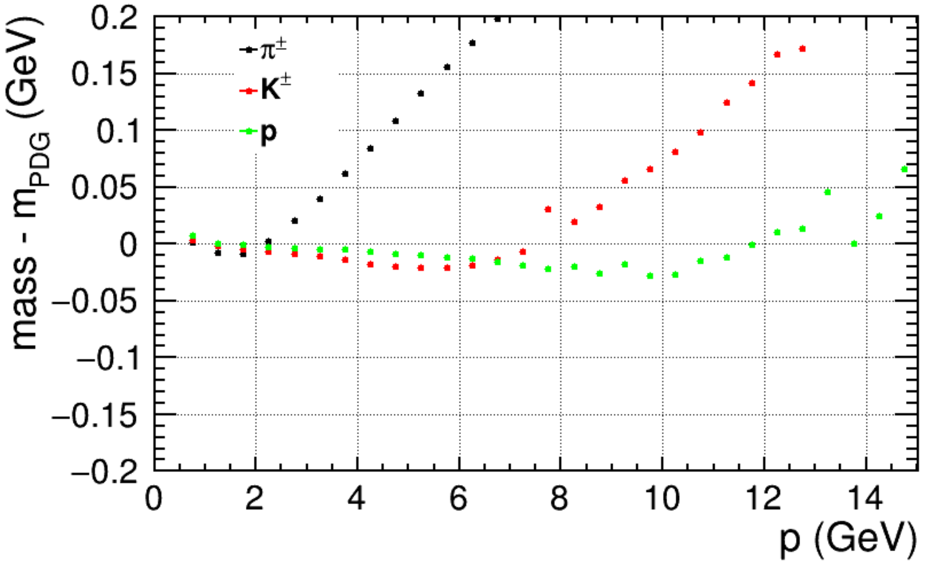
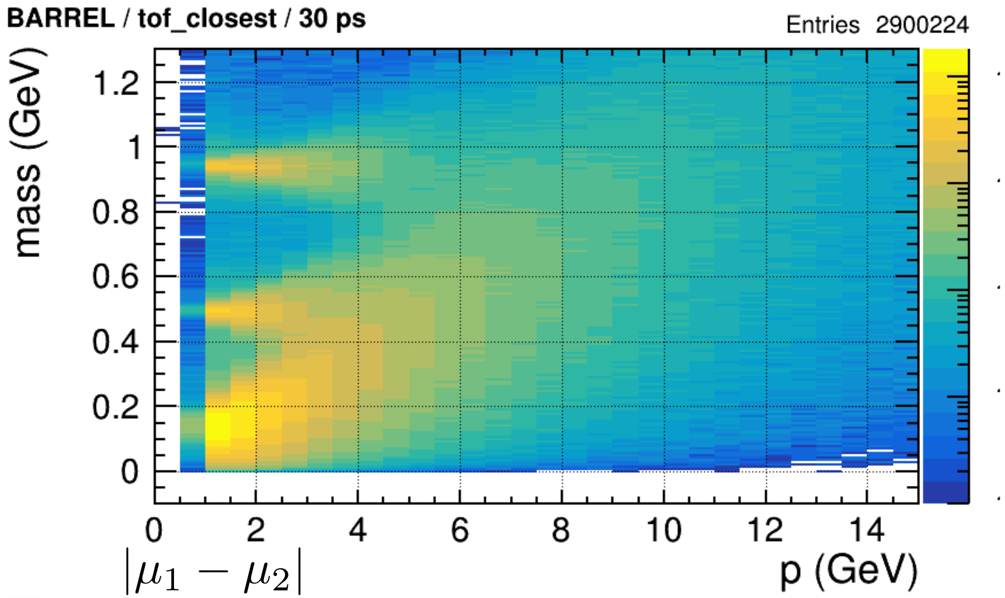
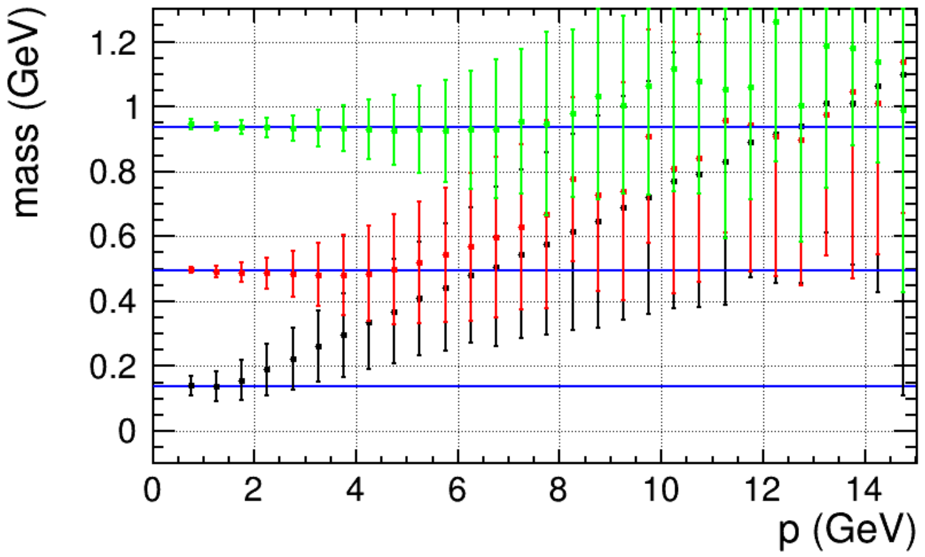




Extraction of separation power (30 ps)





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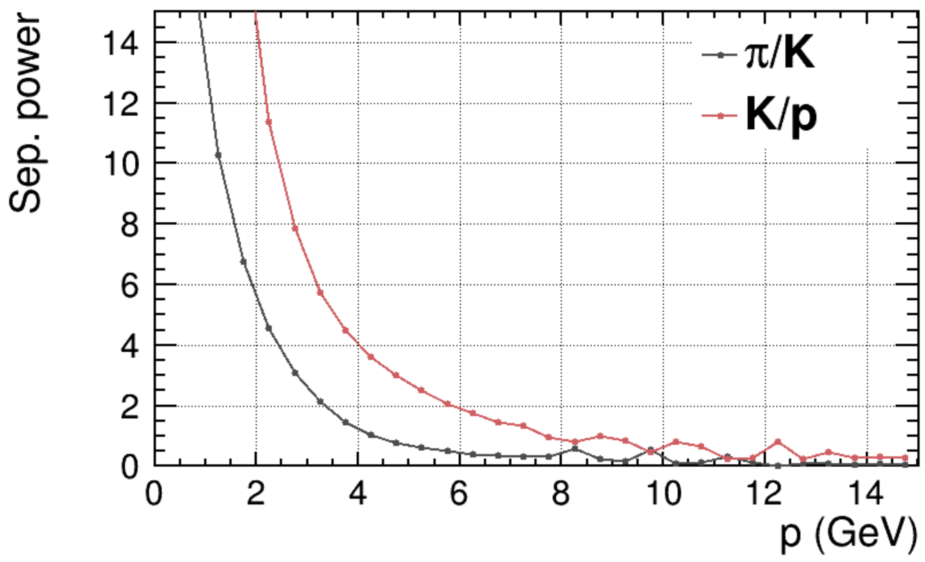
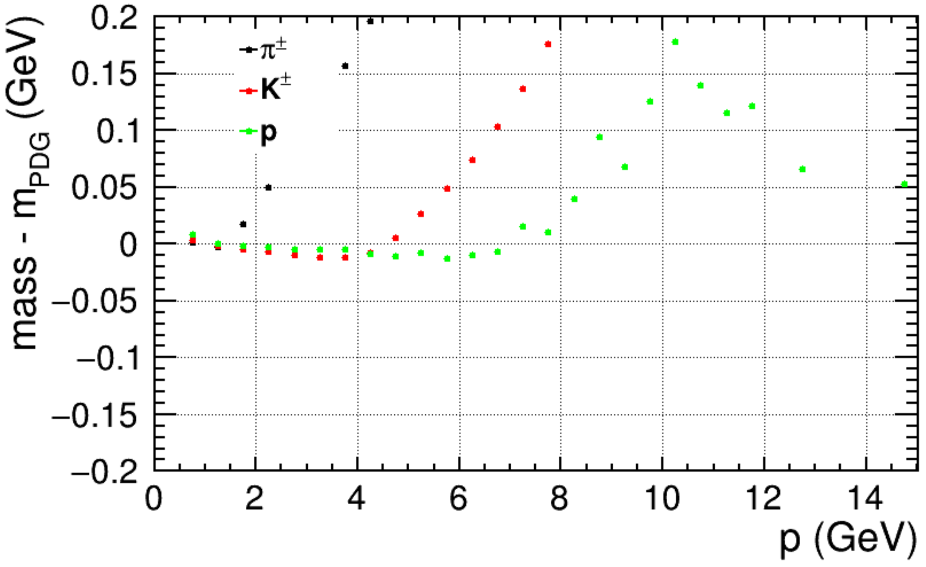
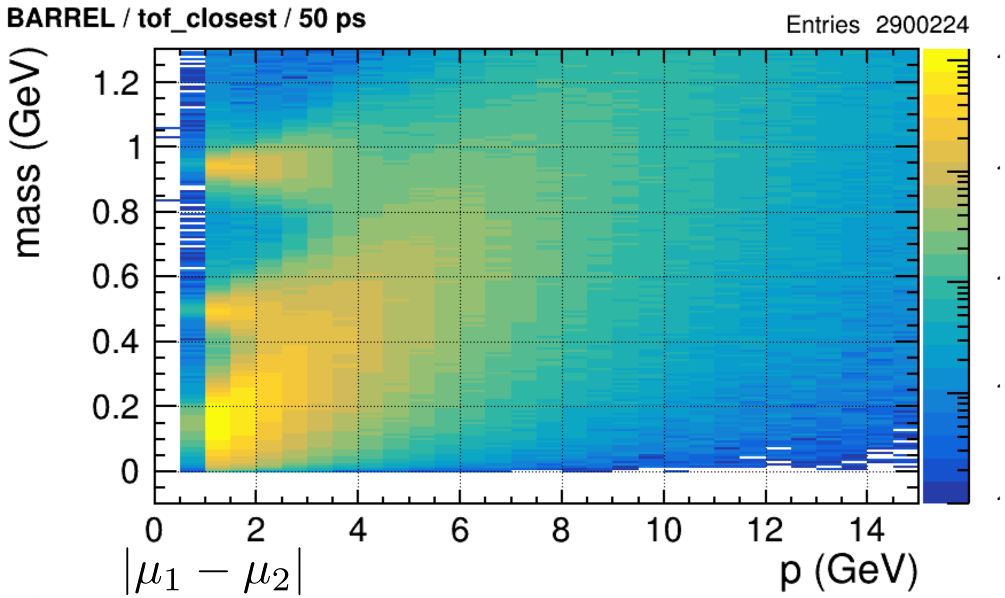
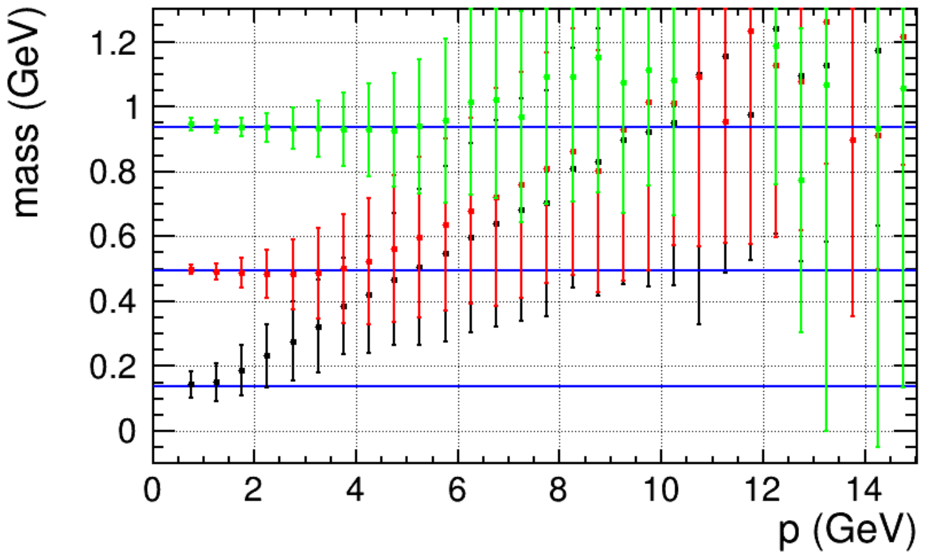




Extraction of separation power (50 ps)





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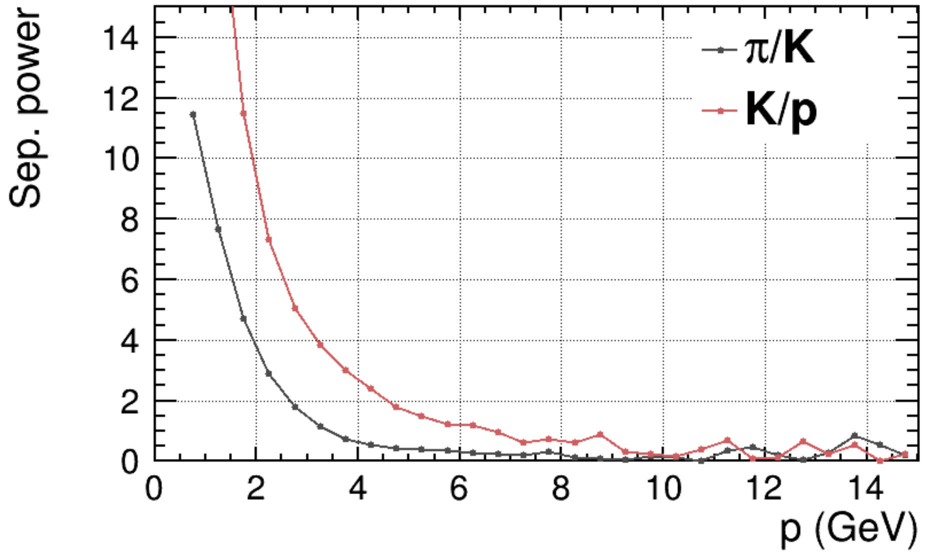
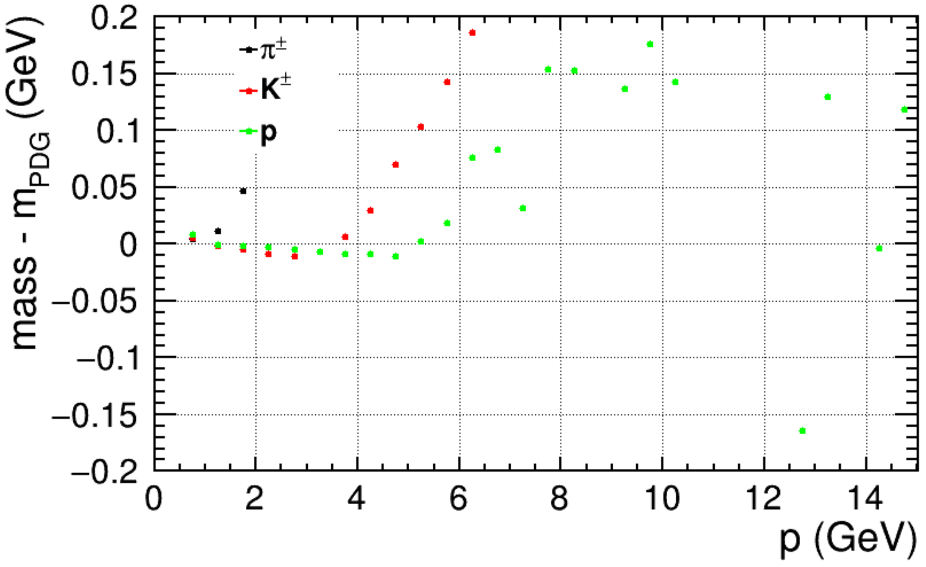
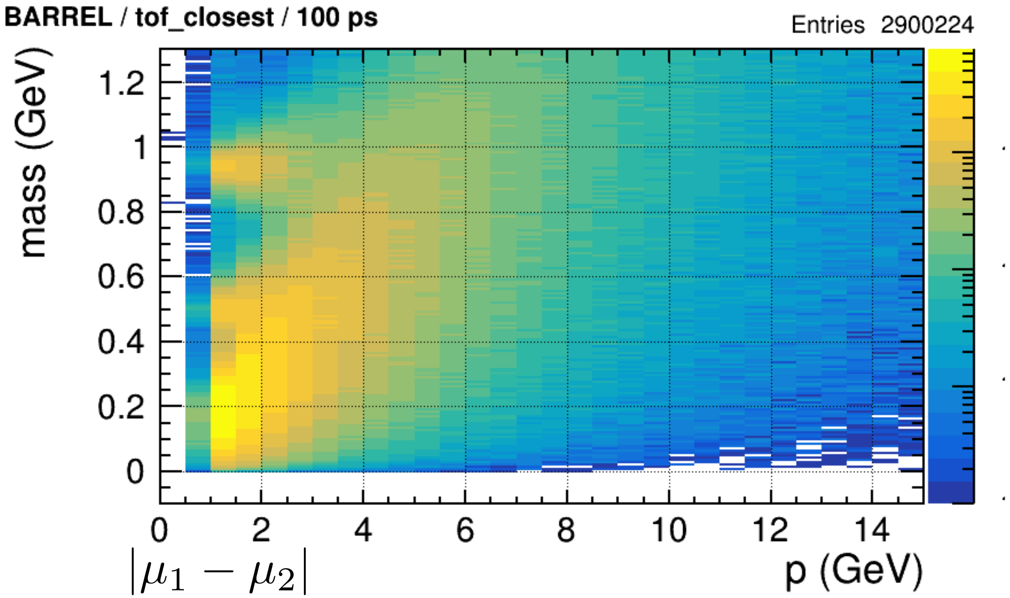
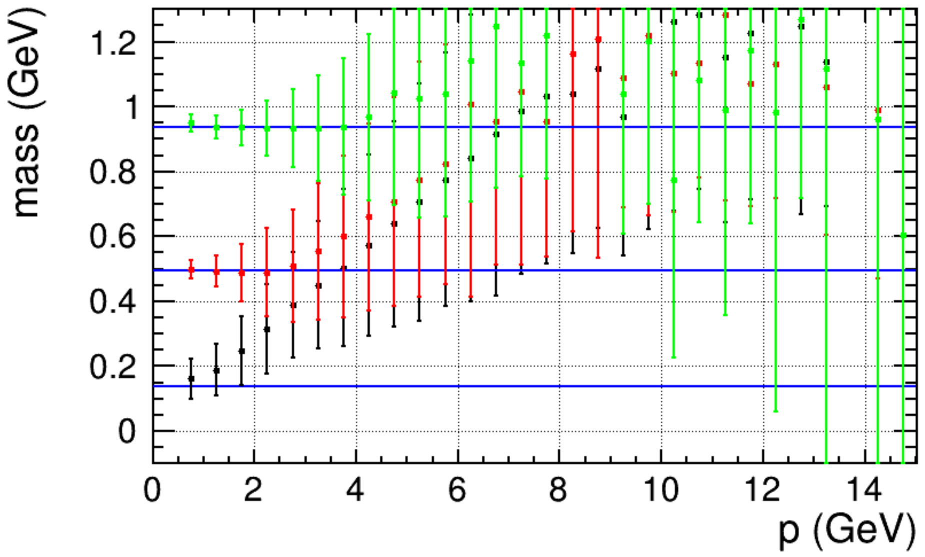




Extraction of separation power (100 ps)





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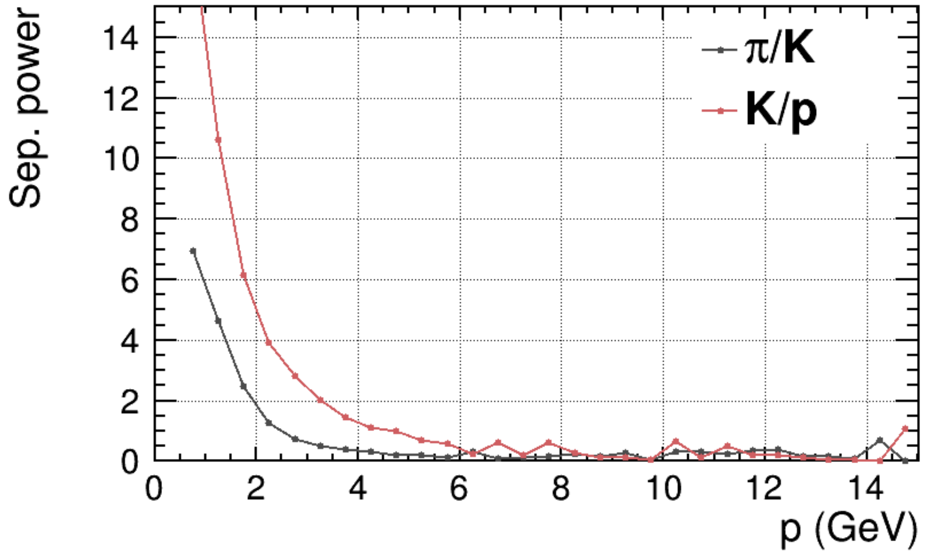
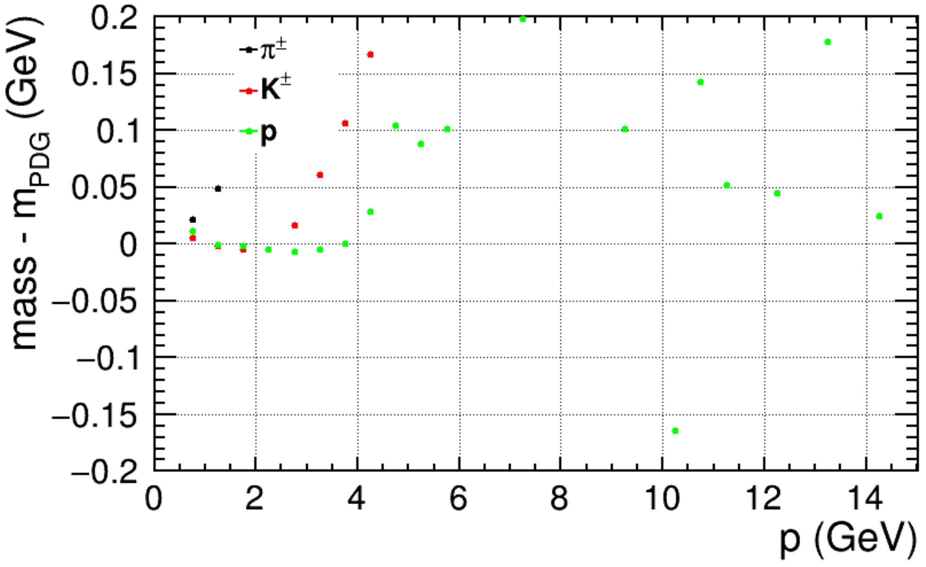
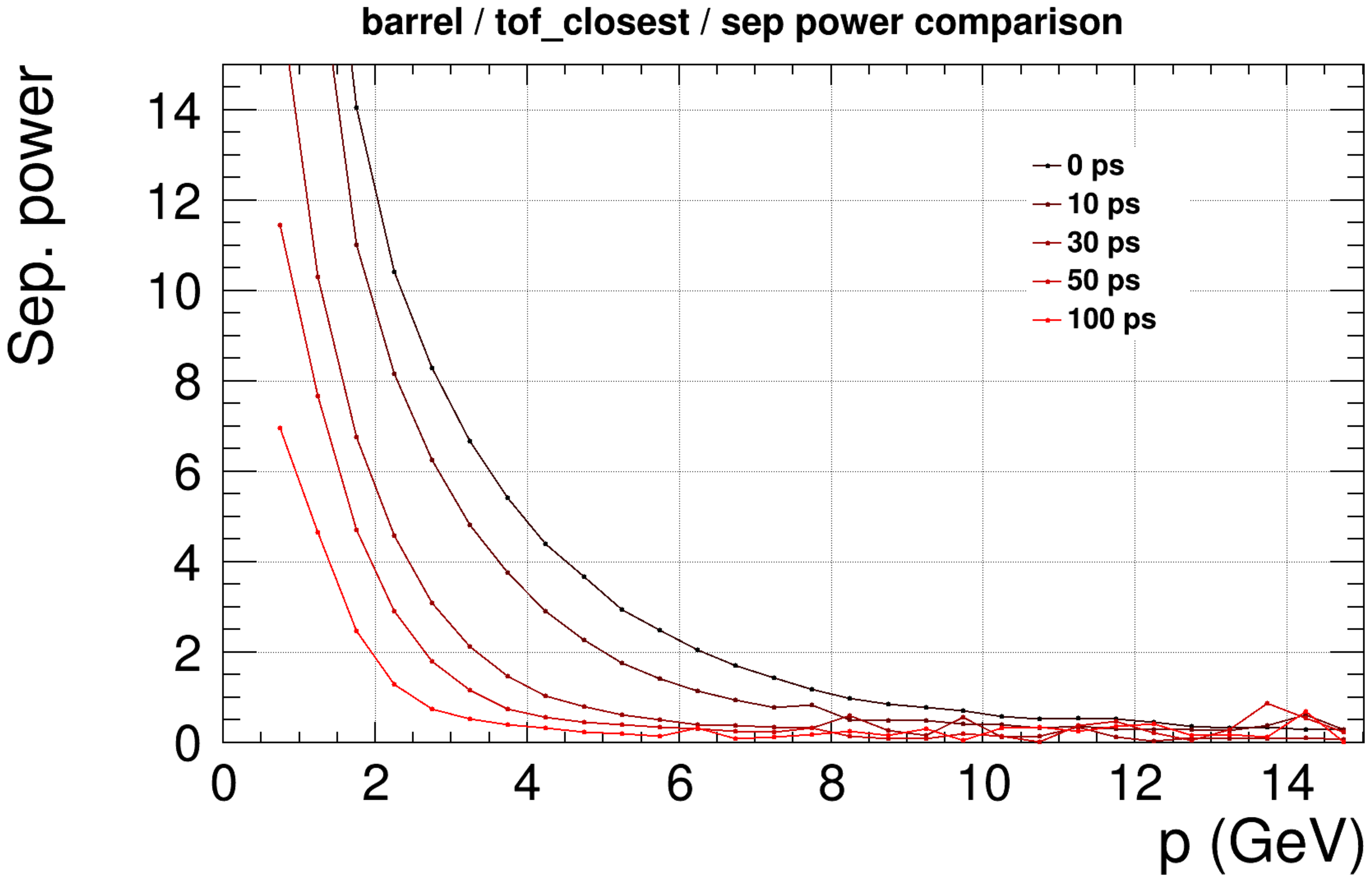
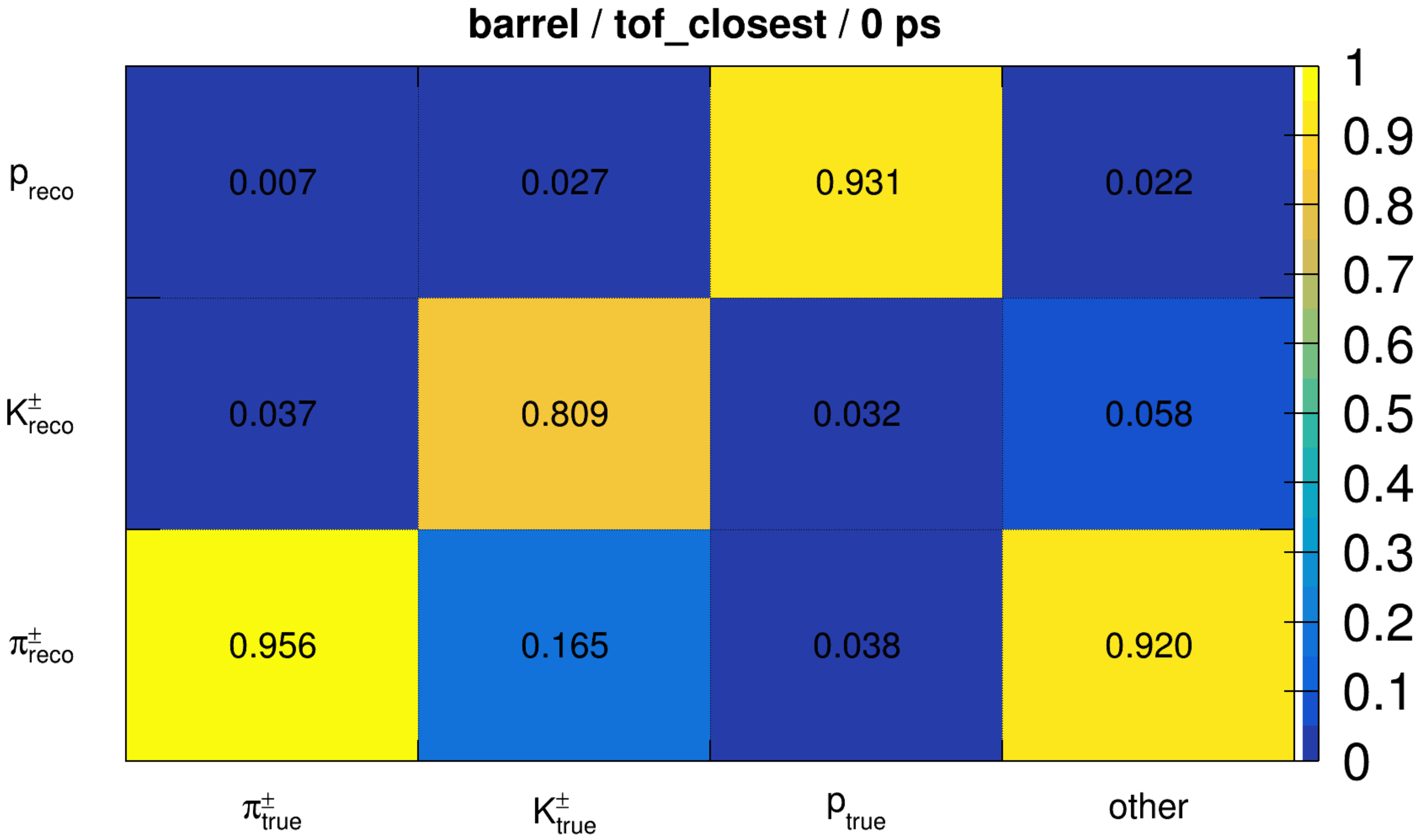




Comparison of sep. power



Confusion matrix (0 – 15 GeV mom range)



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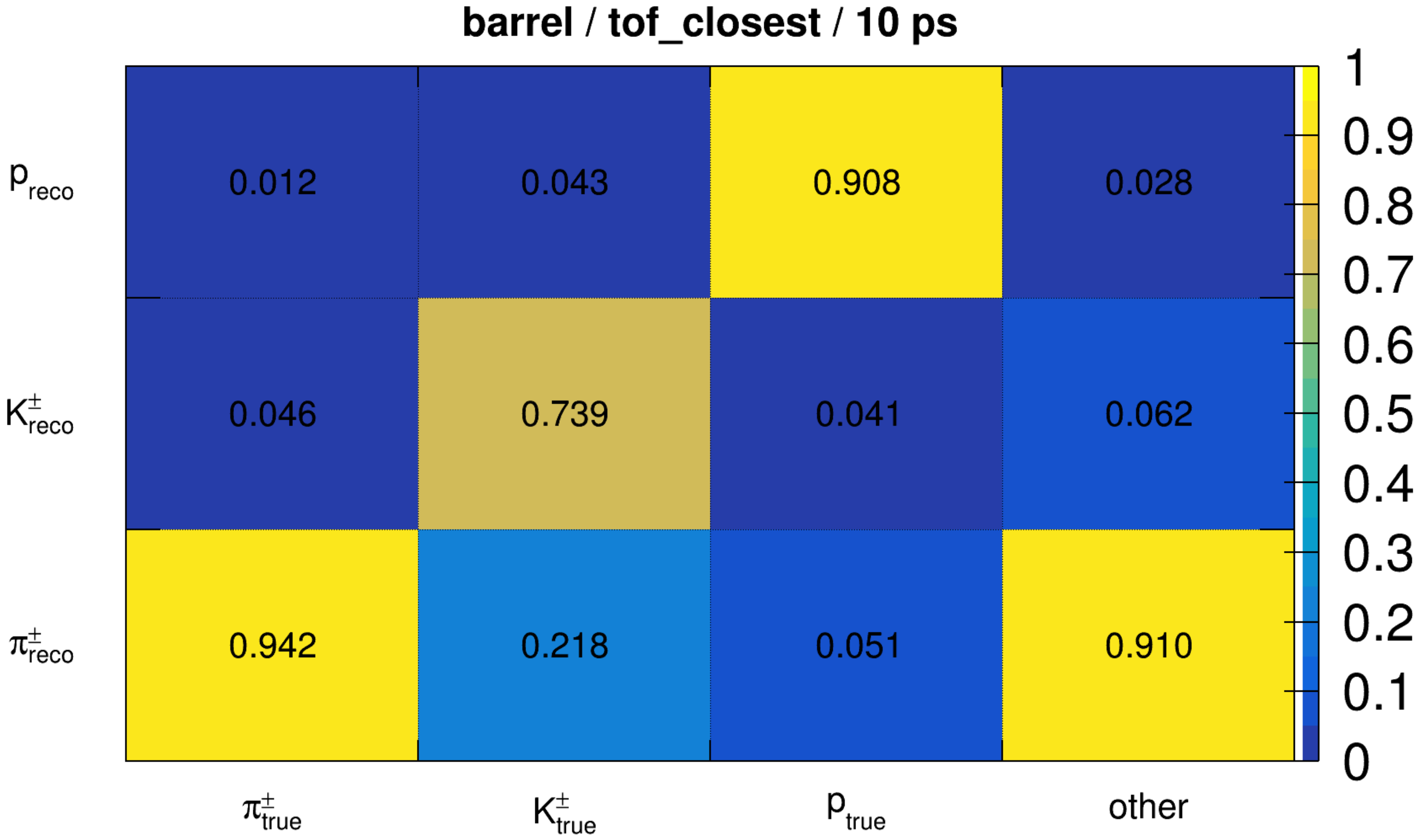

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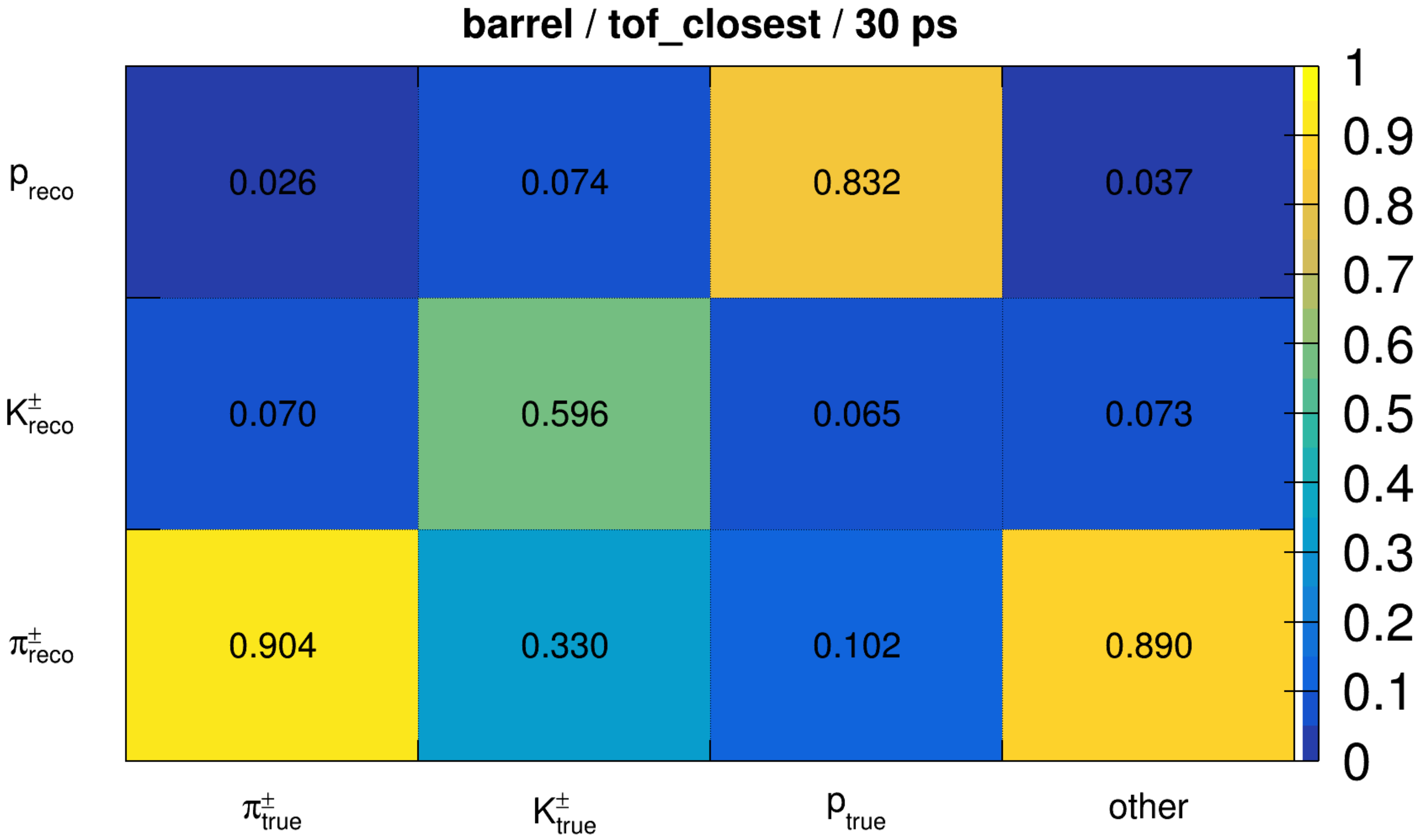

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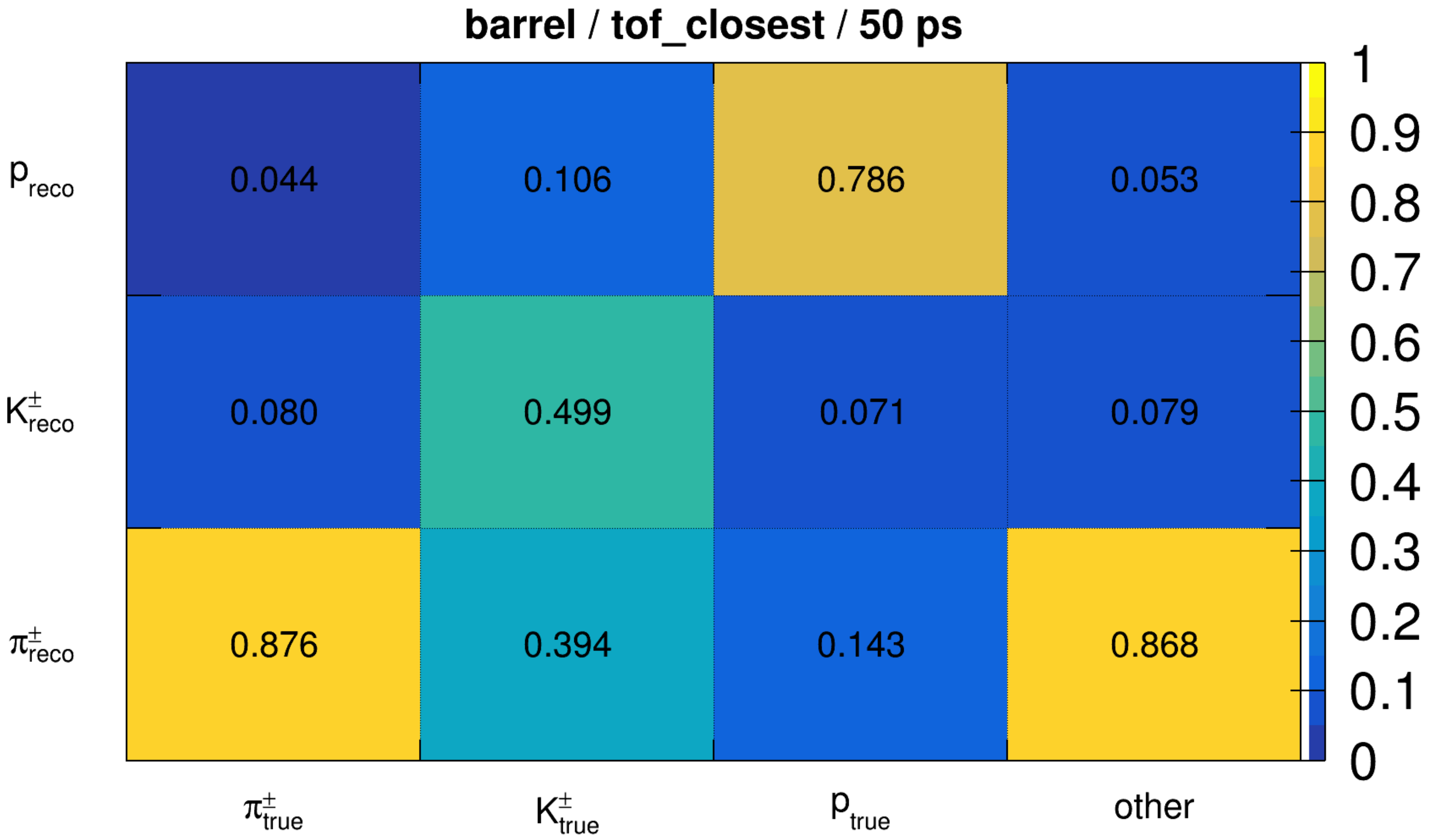

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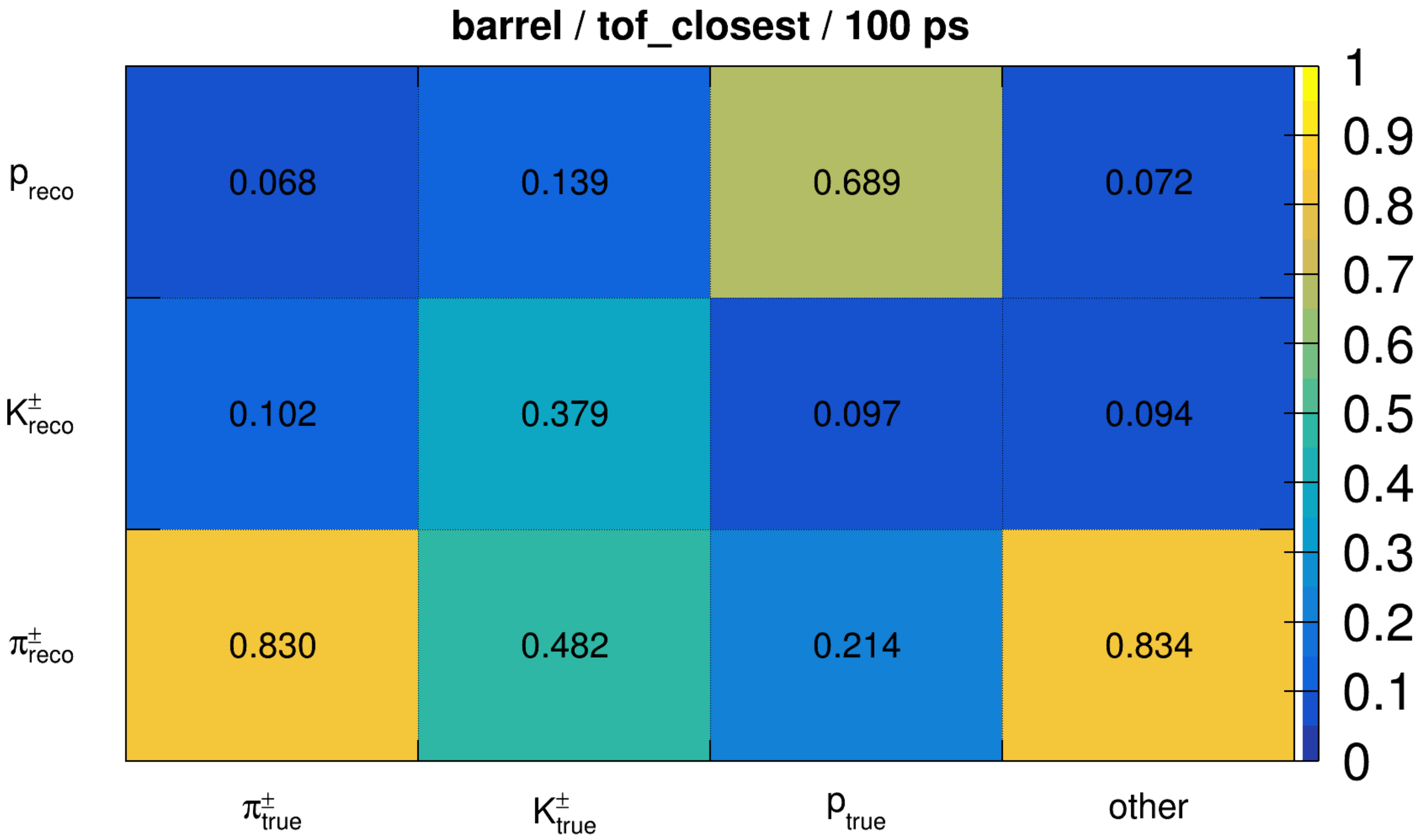
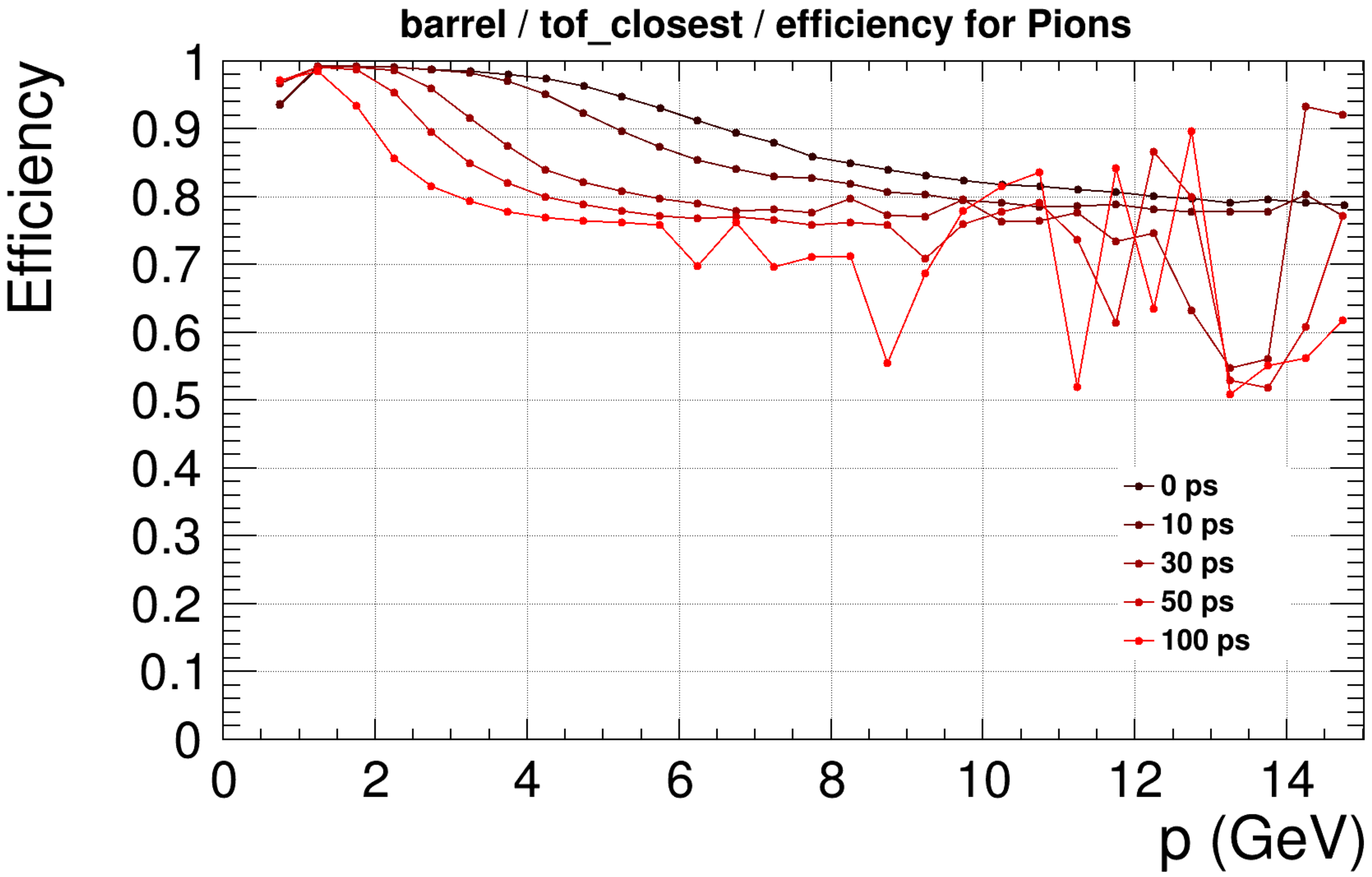


Efficiency for pions vs TOF resolution



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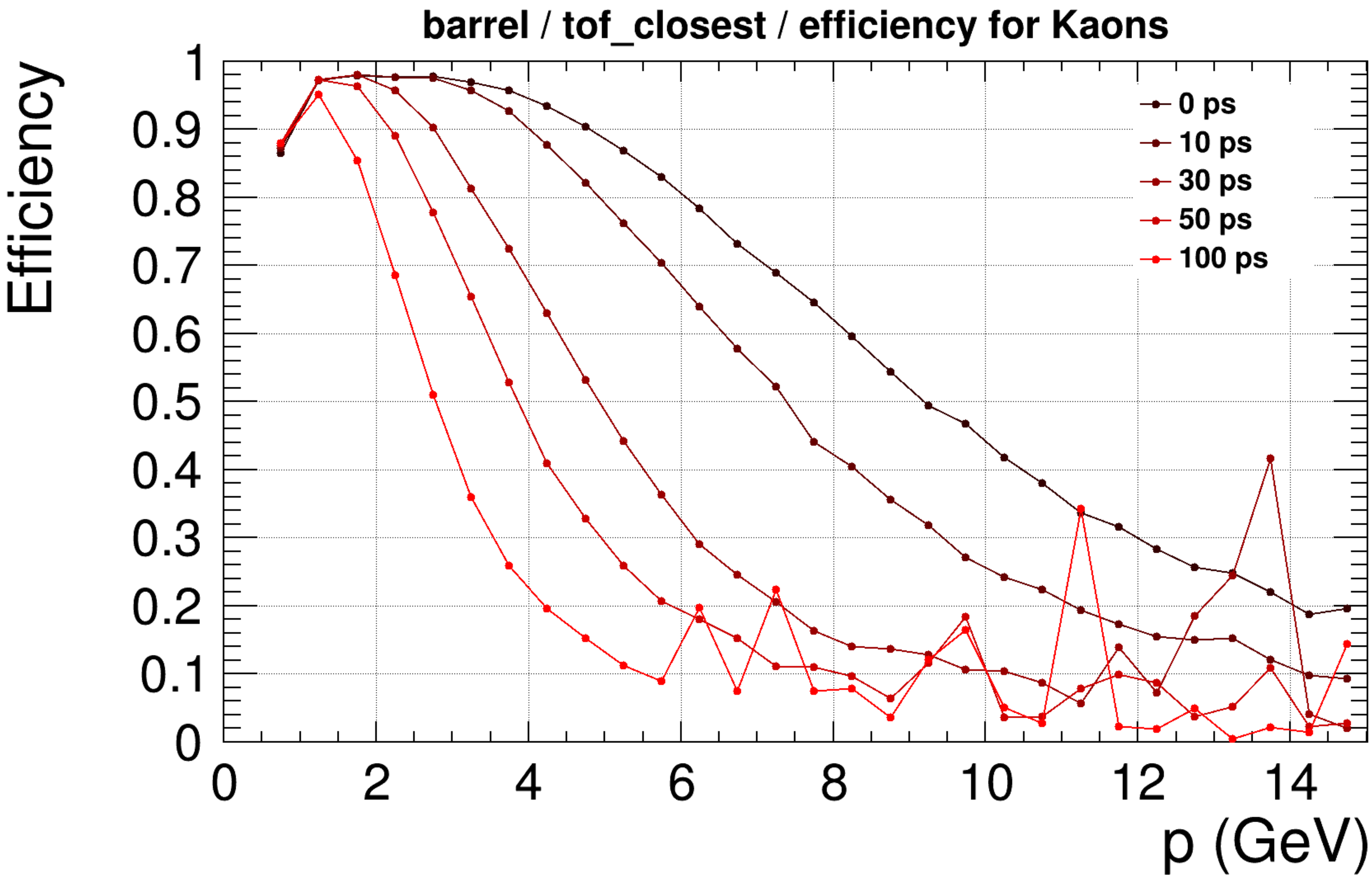

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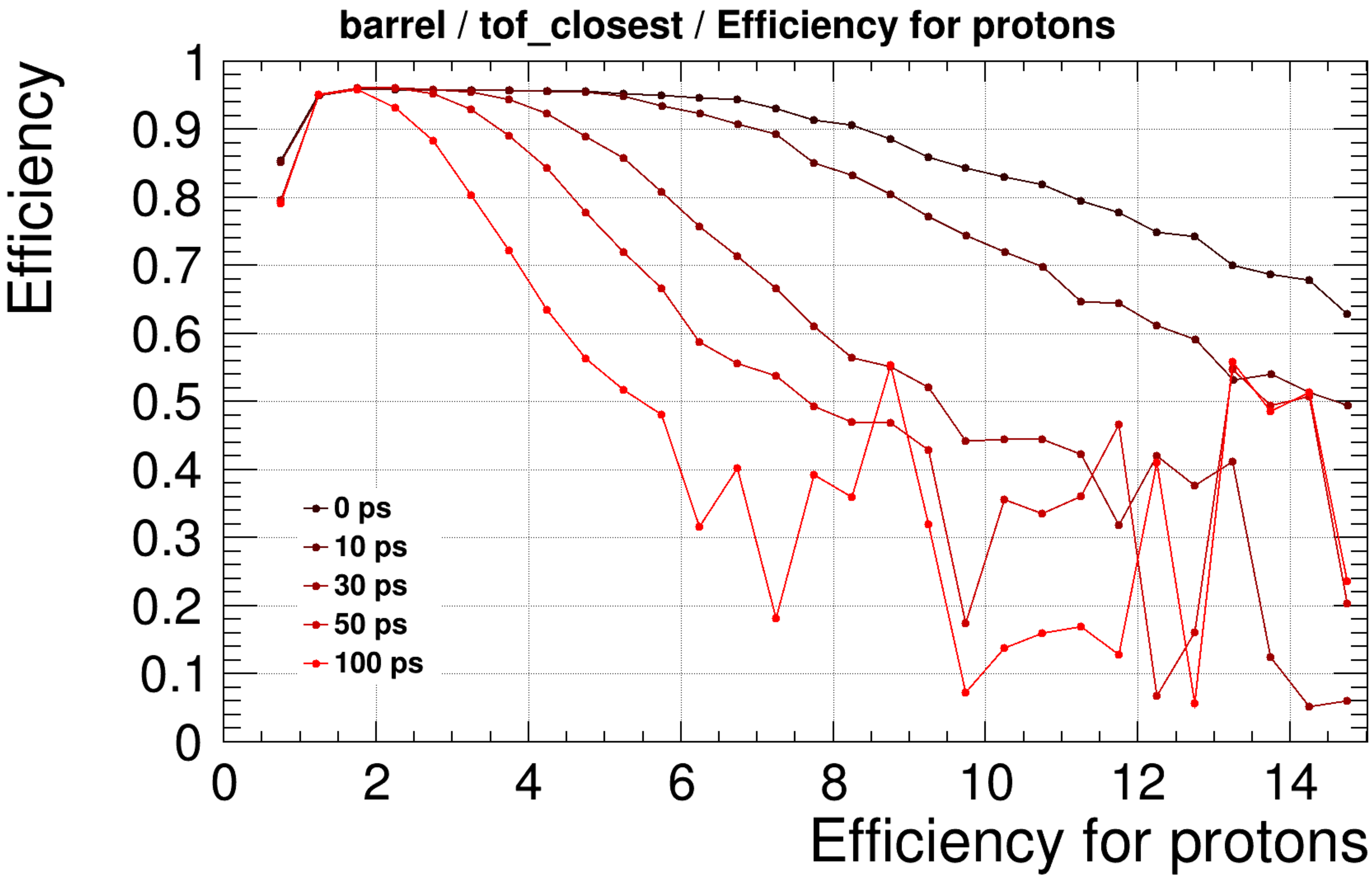

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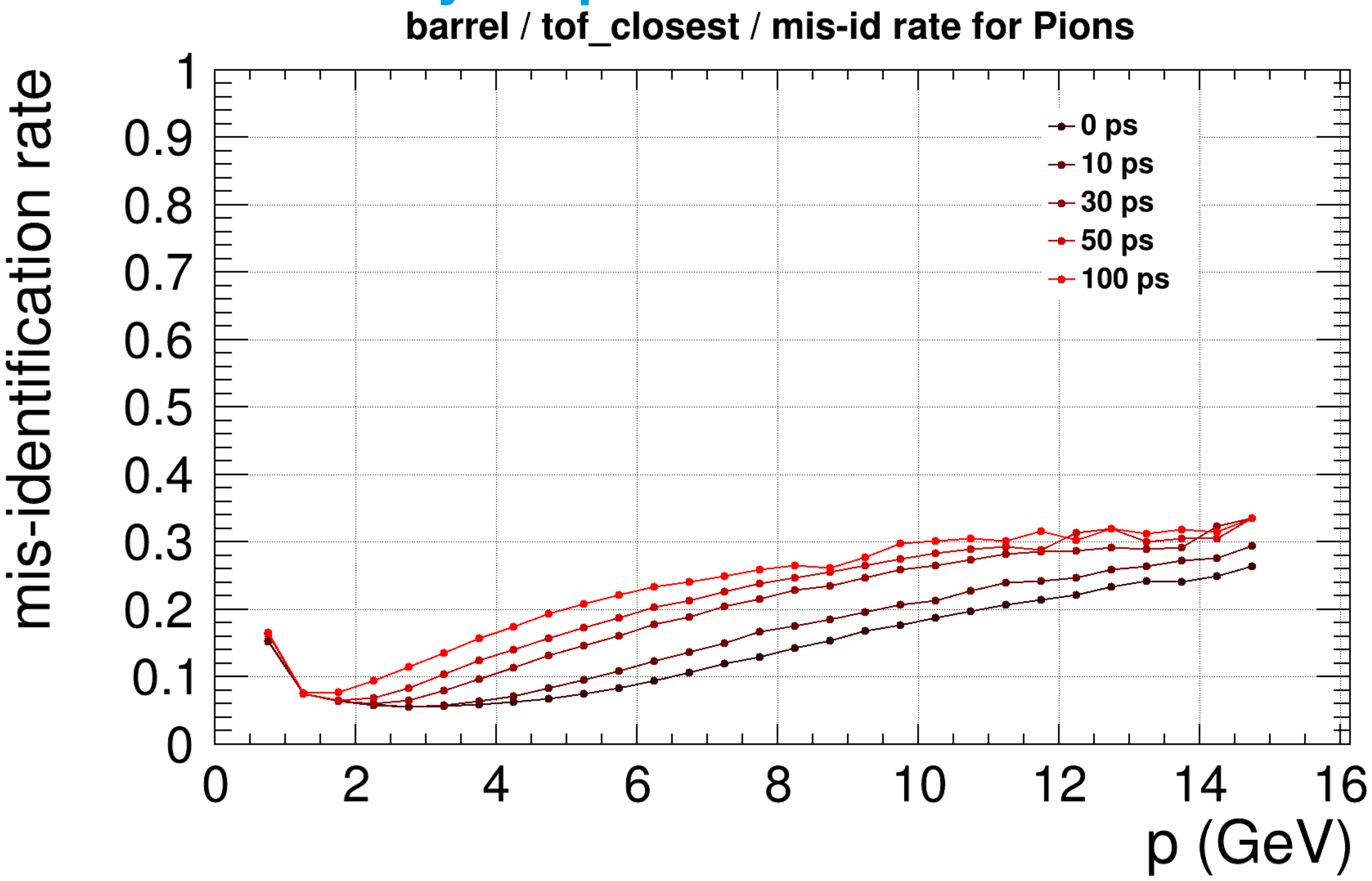

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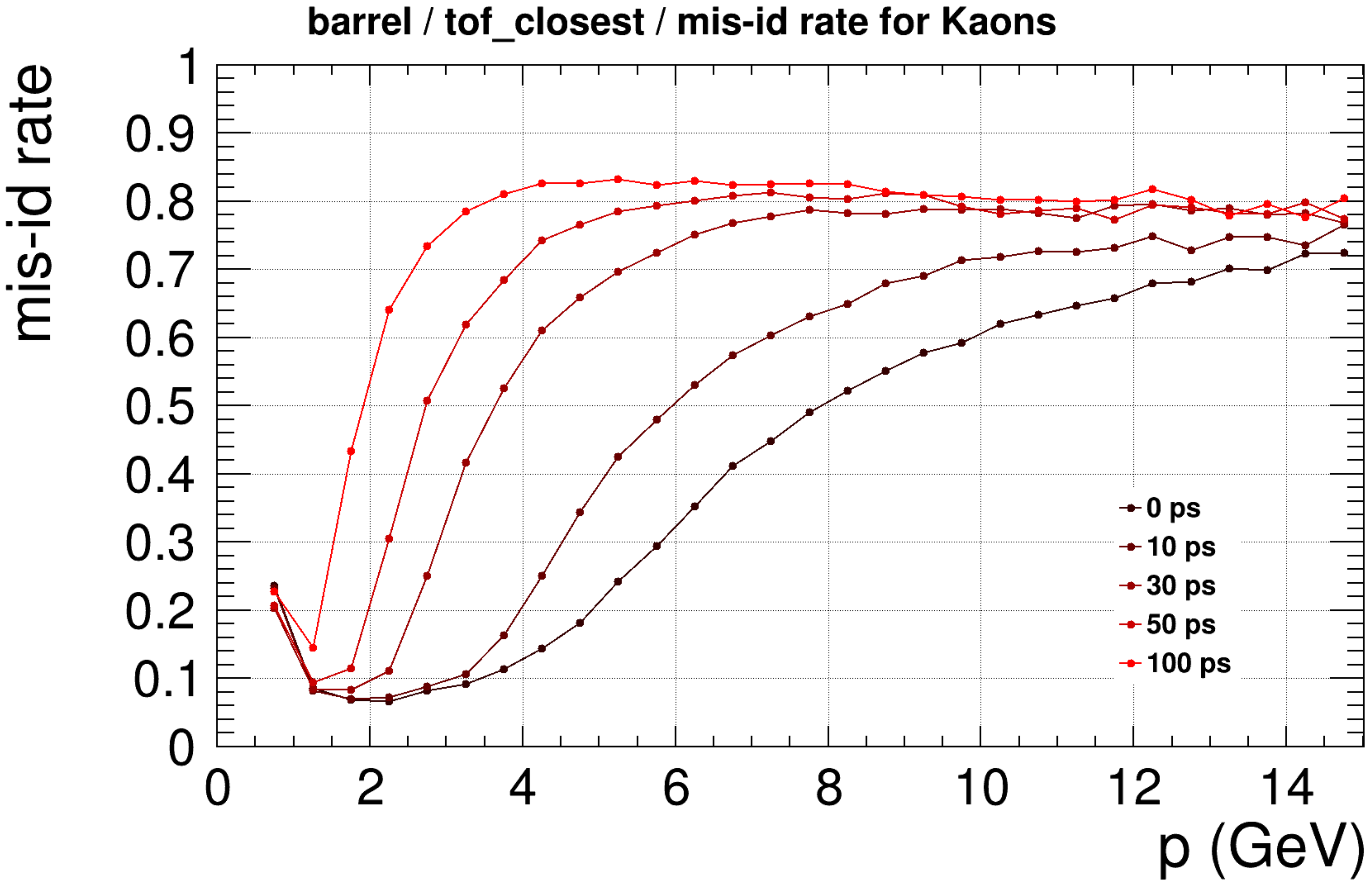

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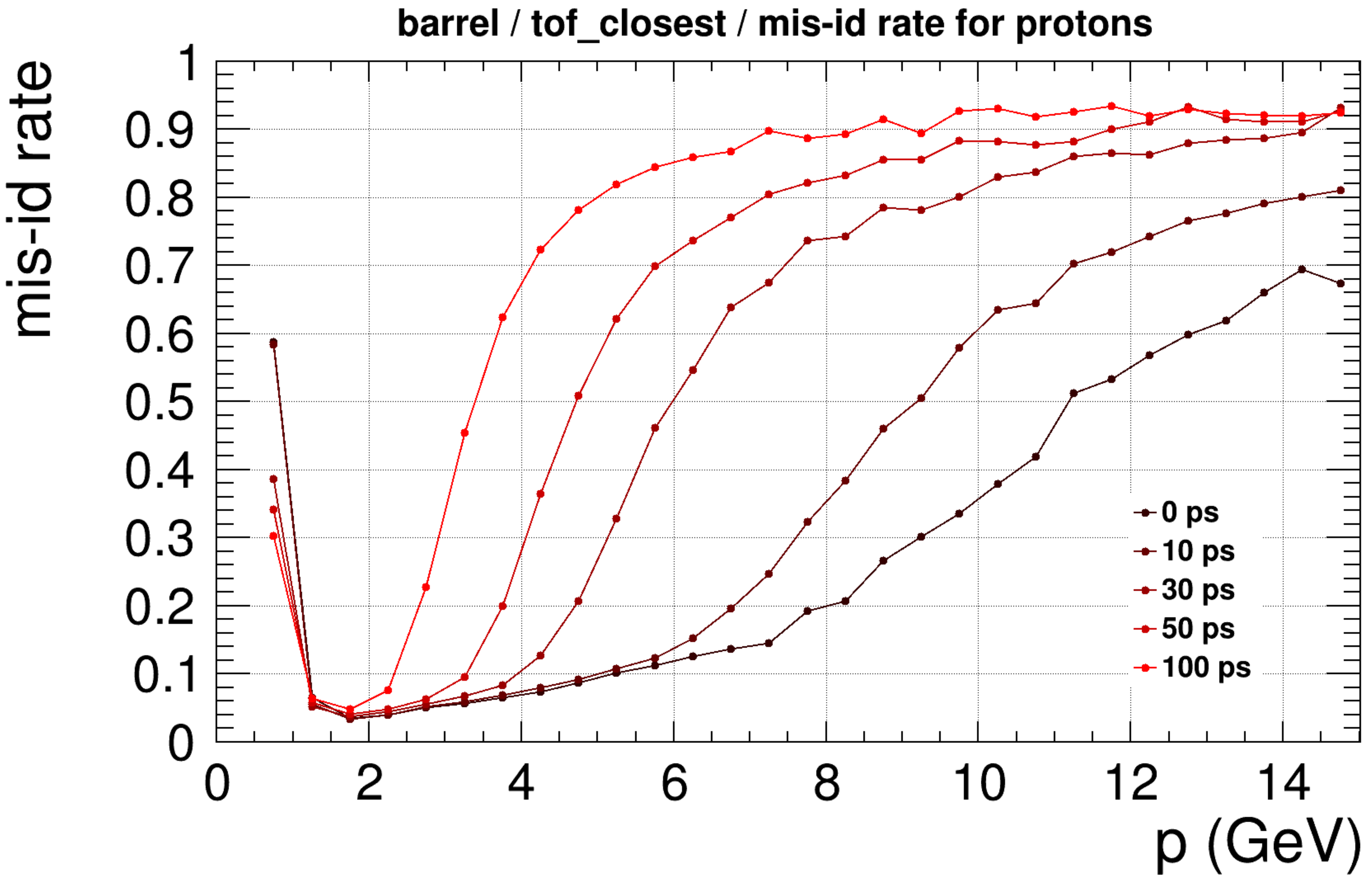


Conclusions

- Track length estimation has been tested and improved compared to the previous version
  Now we have more confidence for particle ID in the endcaps

- Current TOFestimators processor in the iLCSoft is under major revision and soon will be updated probably breaking backwards compatibility.
  New version will include the latest developments presented here and beyond

- Eliminating major negative effects from the track length estimator shifts limiting factor for particle ID on time resolution

Future plans for pID

- Use combined information (dE/dx + ToF) for particle identification
  (very promising coverage of a broad momentum range with high efficiency)

- Study timing more in depth, e.g.: digitization, different time estimators, etc. effects on pID

- Show how relevant timing for actual physics analysis (affects mostly everything with b/c quarks)

Back up

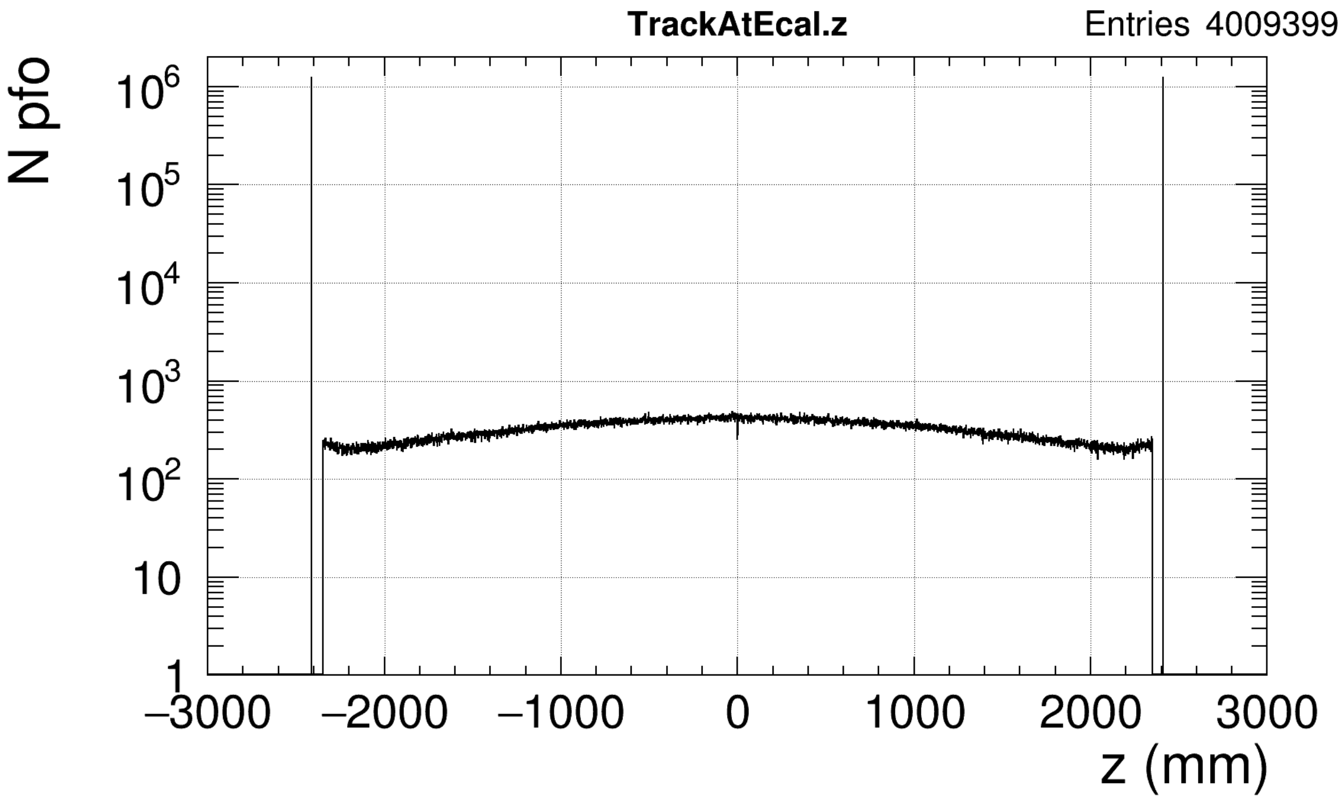
MC samples	
Energy	250 GeV
Process	Z → 2f → hadronic
Detector	ILD_l5_o1_v02
ILCSoft	02-02-02

Selection	
N clusters	1
N tracks	1
(tsAtECal – closestHit).r()	< 4000 m
N Ecal hits	>0

Back up

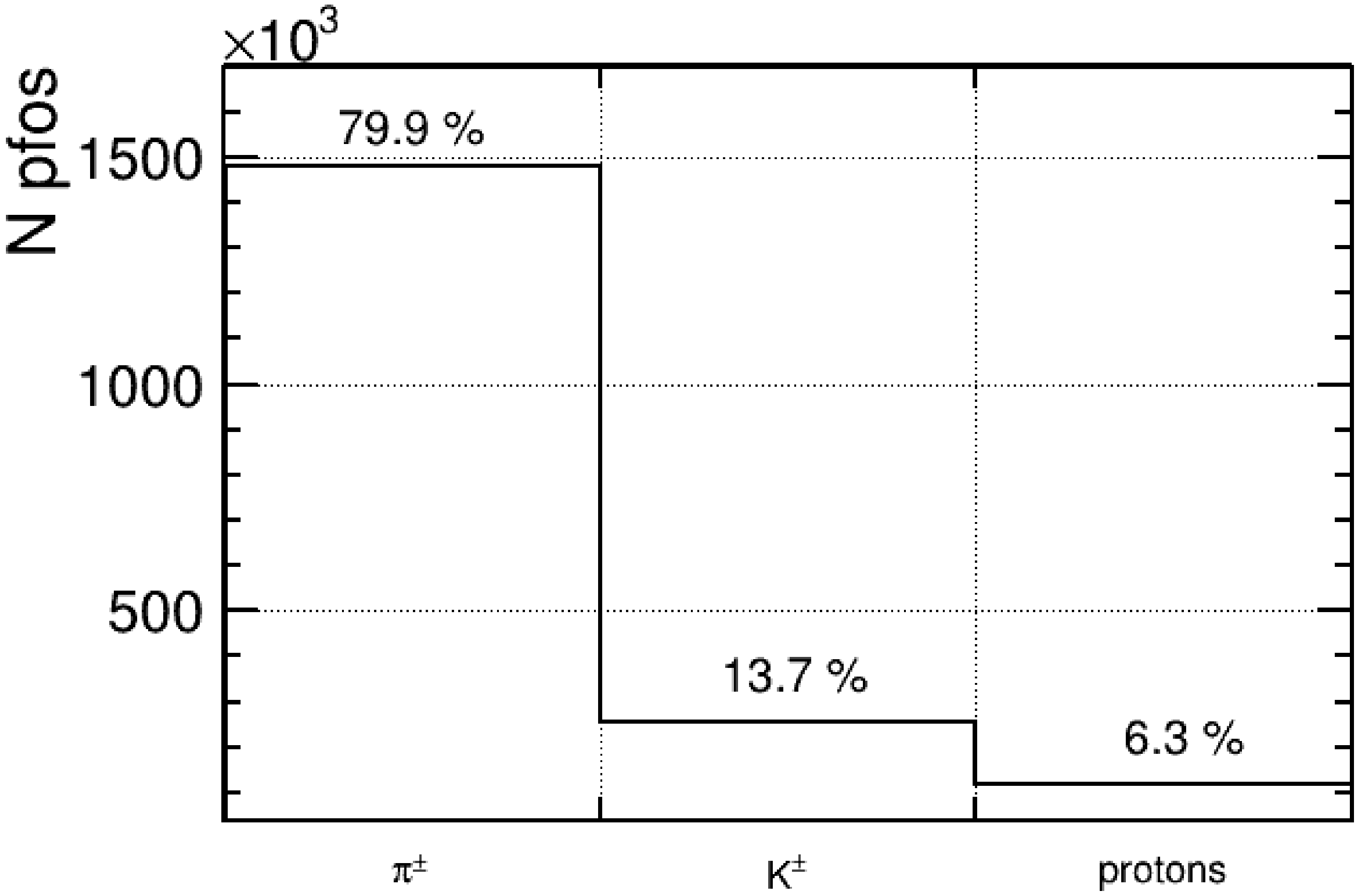
Distinction between barrel/endcap in this analysis is made with the cut on trackState position at the ECal:

|z| < 2385 mm – barrel
|z| > 2385 mm – endcap



Back up

Particle abundance in the analyzed MC samples:



Back up

Binning to extract exactly the same separation plots

// 30 bins over 0 – 15 GeV momentum range
// 200 bins from -0.1 – 1.3 GeV mass range
Histo2D binning = (30, 0., 15., 200, -0.1, 1.3)

Fit details:
// fit each particle band selecting it with MC PDG value
// set starting and limit fit parameters based on max_bin
// max_bin - x position (mass) of the bin with maximum entries in the current momentum slice
// if slice has less than 100 entries, don't fit and don't add the point to the final graphs

```
hp = h.ProjectionY("hp", bin, bin)
if hp.GetEntries() < 100:
        continue
func = ROOT.TF1("func", "gaus", max_bin-0.5, max_bin+0.5)
func.SetParameter(1, max_bin)
func.SetParLimits(1, max_bin-0.1, max_bin+0.1)
func.SetParameter(2, 0.03)
```

$$\mathrm{Sep.Power} = \frac{|\mu_1 - \mu_2|}{\sqrt{0.5(\sigma_1^2 + \sigma_2^2)}}$$

BACK UP: Confusion matrix information from ILD talk:

Simple algorithm to assign particle types:

1) Get the difference between m_{reco} and m(p) graph mean in sigma units for each particle type assumption.

$$d_{\pi,K,p} = \frac{|m_{\mathrm{reco}} - \mu_{\pi,K,p}(p_{\mathrm{reco}})|}{\sigma_{\pi,K,p}(p_{\mathrm{reco}})}$$

2) Assign particle type which has minimal distance

3) If β_{reco}>1 and we can't calculate m_{reco} we assume it is a $\pi^{\pm}$.

momentum is limited to 0 – 15 GeV

This is a <u>very first</u> raw estimate
Numbers are dependent on the implementation:

- Binning of the initial histogram
- Fit success / constraints, etc.
- Momentum range

Both methods show similar performance in the barrel. With novel approach being slightly better