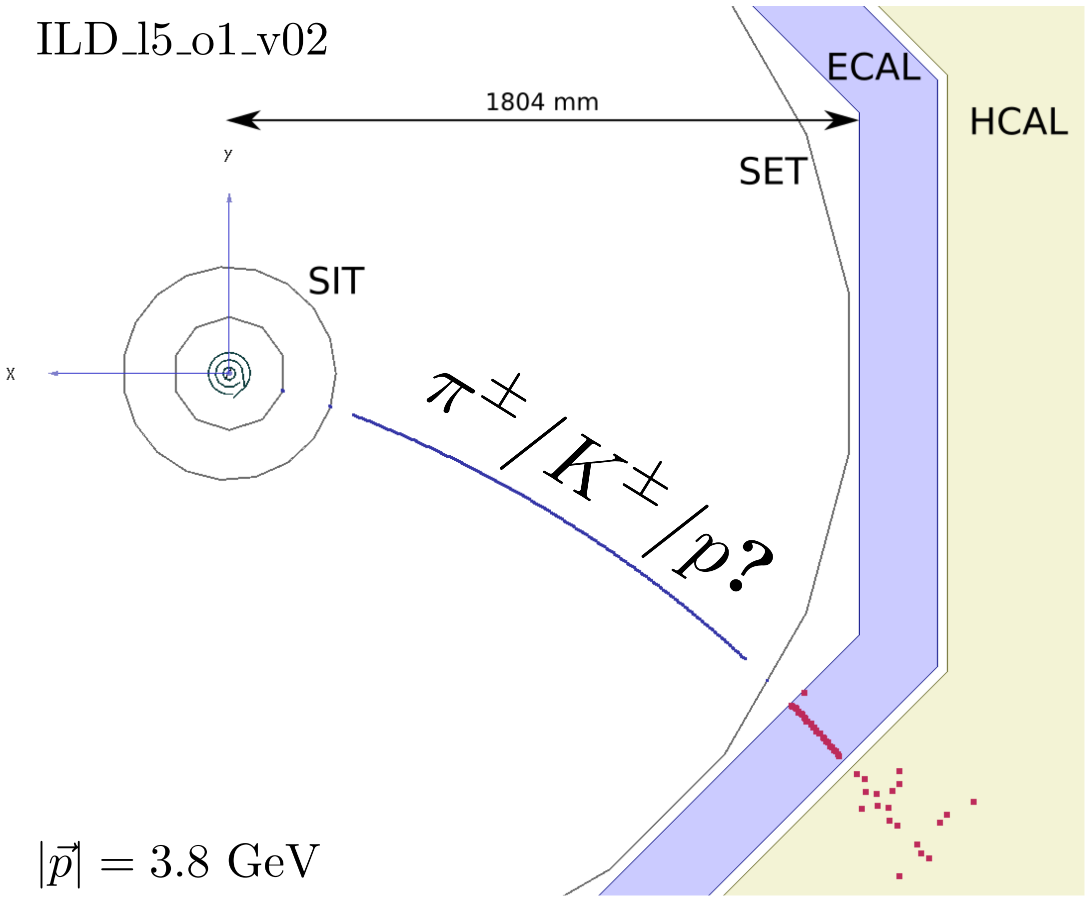
Overview of physics applications of time-of-flight particle ID at a future Higgs factory

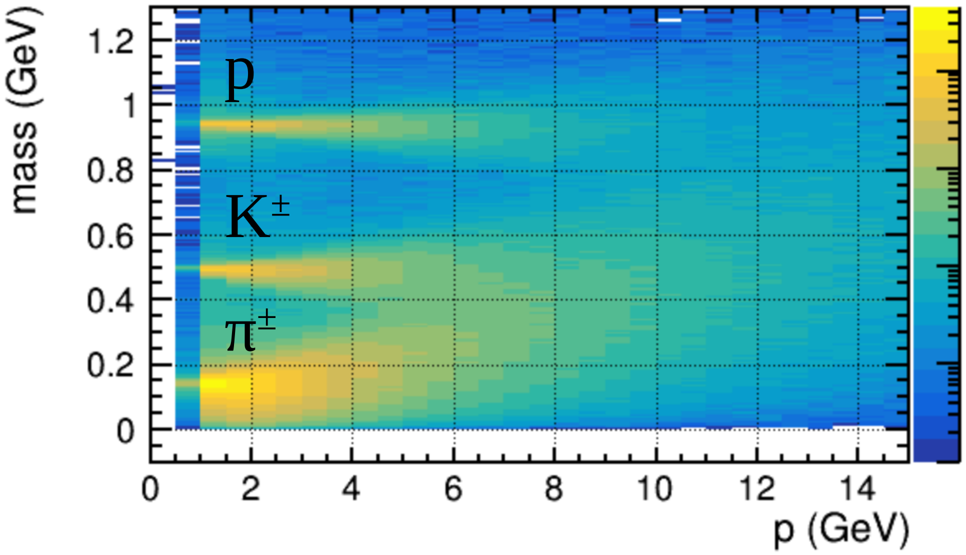
ILD Analysis/Software Meeting
23 November 2022

Bohdan Dudar
bohdan.dudar@desy.de

Reminder: time-of-flight particle identification



$$m = p\sqrt{\frac{c^2 \mathrm{TOF}^2}{\ell_{\mathrm{track}}^2} - 1}$$

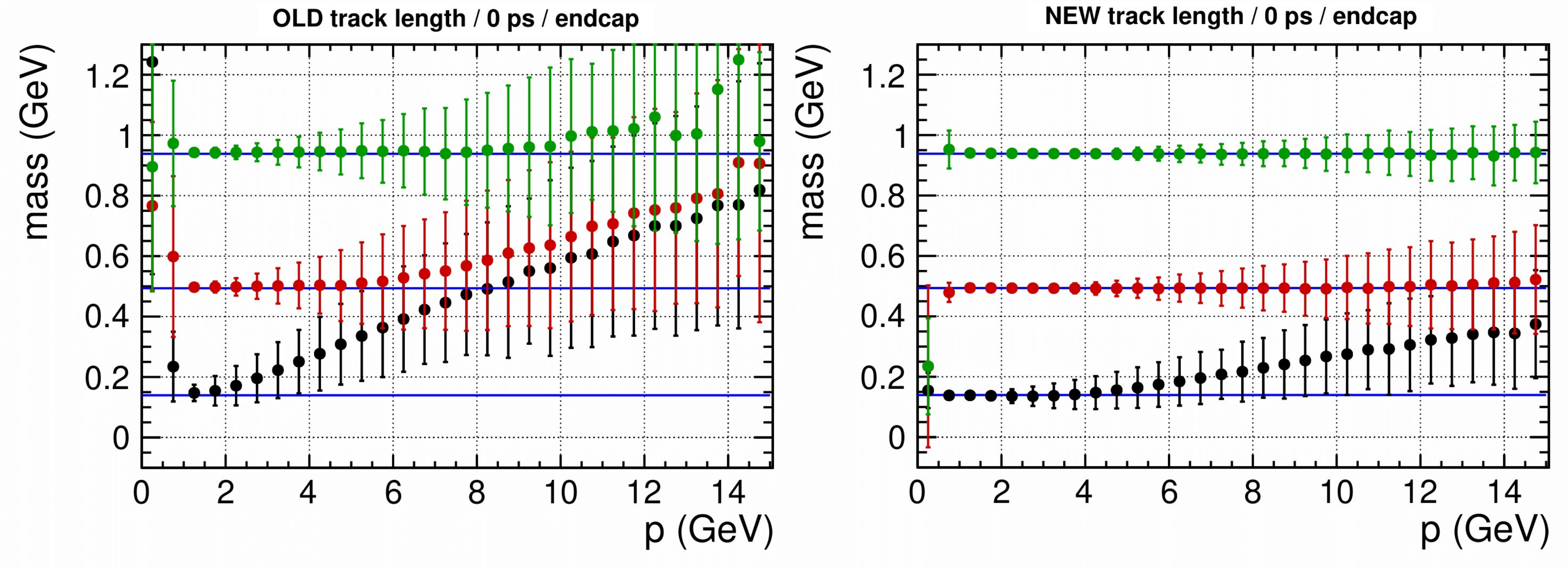


Our understanding has significantly improved over the last two years: track length impact on mass

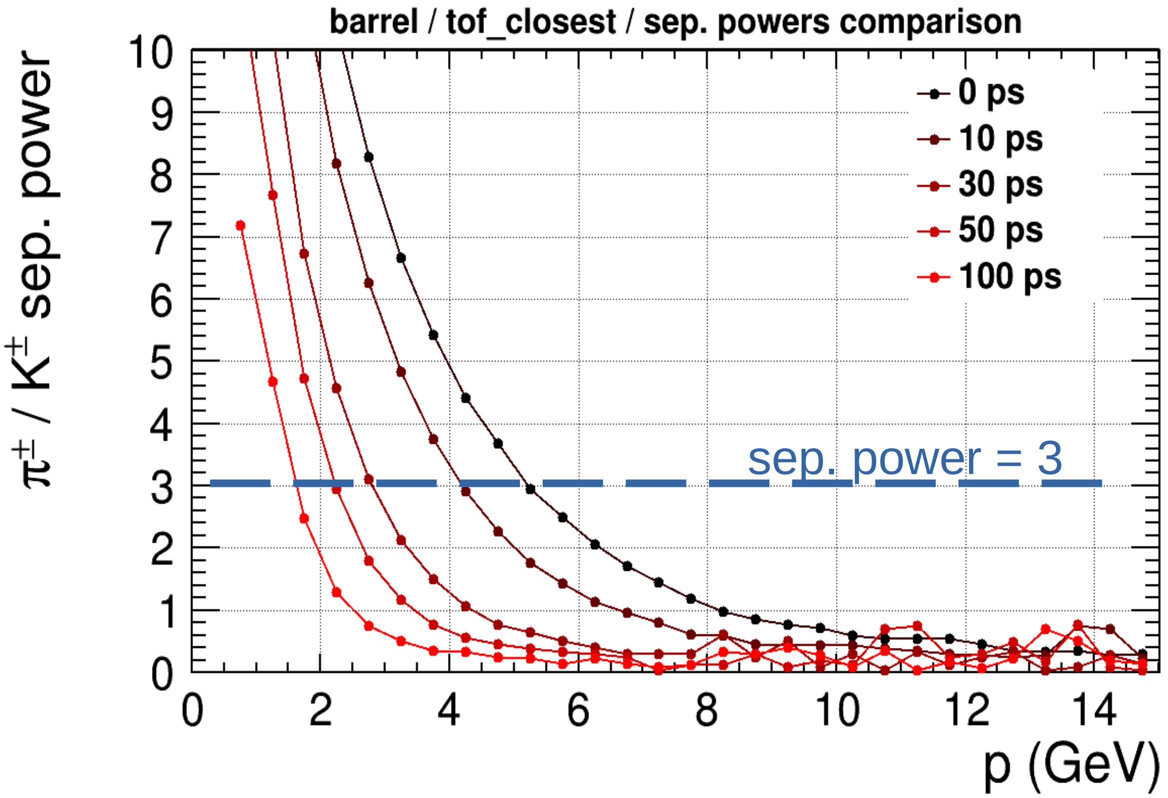
Winfried A. Mitaroff

$$p = \sqrt{\langle p^2 \rangle_{HM}} = \sqrt{\sum_{i=0}^{n} \ell_i \Big/ \sum_{i=0}^{n} \frac{\ell_i}{p_i^2}}$$

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

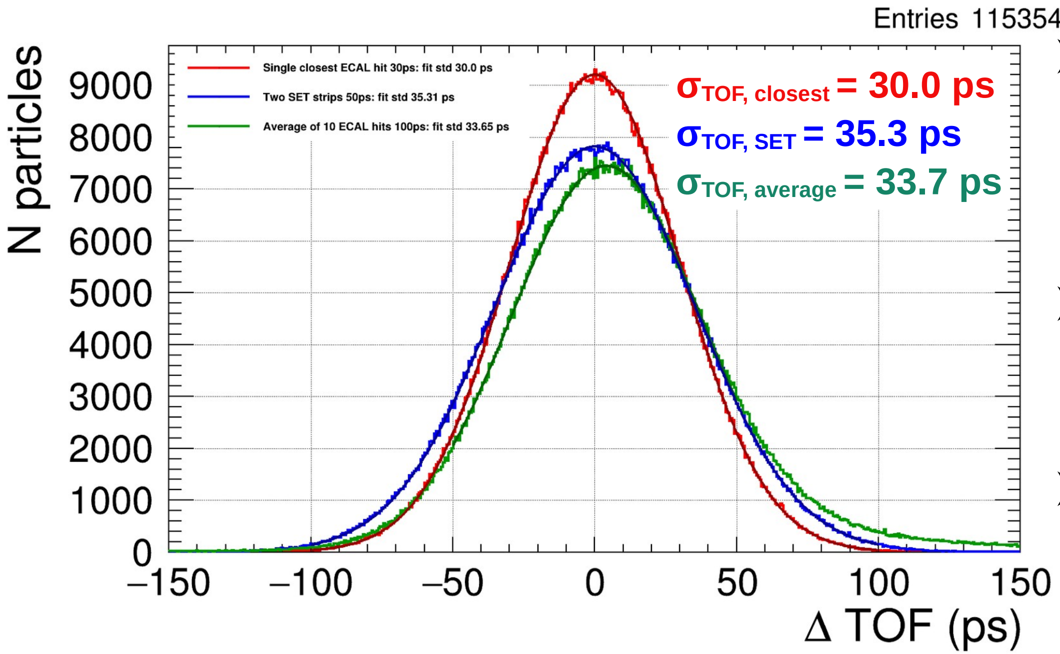


Our understanding has significantly improved over the last two years: time resolution impact on sep. power



- Even with a perfect time res. (0 ps) we are limited by other factors (track length)

Our understanding has significantly improved over the last two years: realistic implementations



- Combining multiple time measurements we can improve TOF resolution: $\sigma_{\mathrm{TOF}} \sim \frac{\sigma_{\mathrm{hit}}}{\sqrt{n}}$
- However, we used simplified digitization: MC truth hit time → smear with a Gaussian
- Further communication with calorimeter people is needed for realistic implementation of ECAL hit signal processing

The goal of this presentation: overview of physics applications

Goal #1

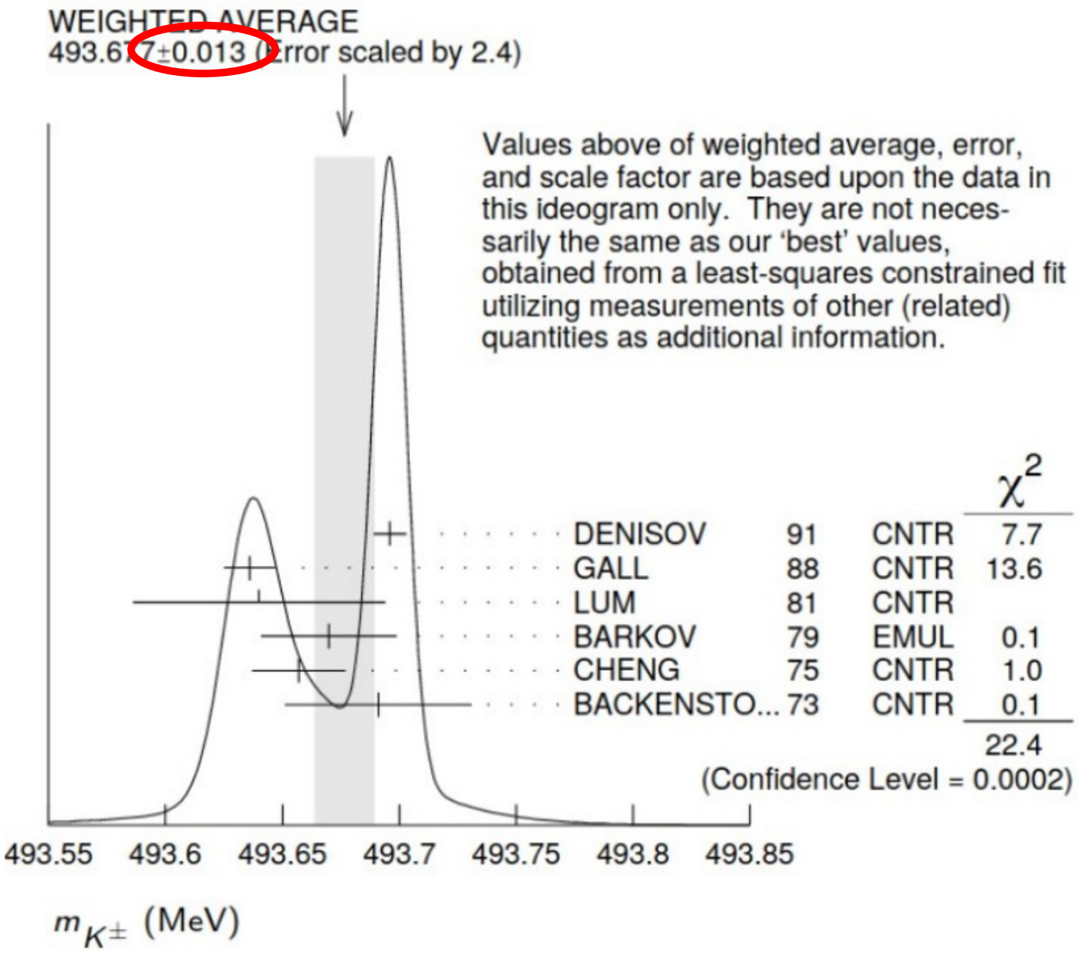
Share accumulated experience of two years:
potential physics applications of TOF pID we have studied so far

Goal #2

Collect feedback from expert audience:
what have we missed?

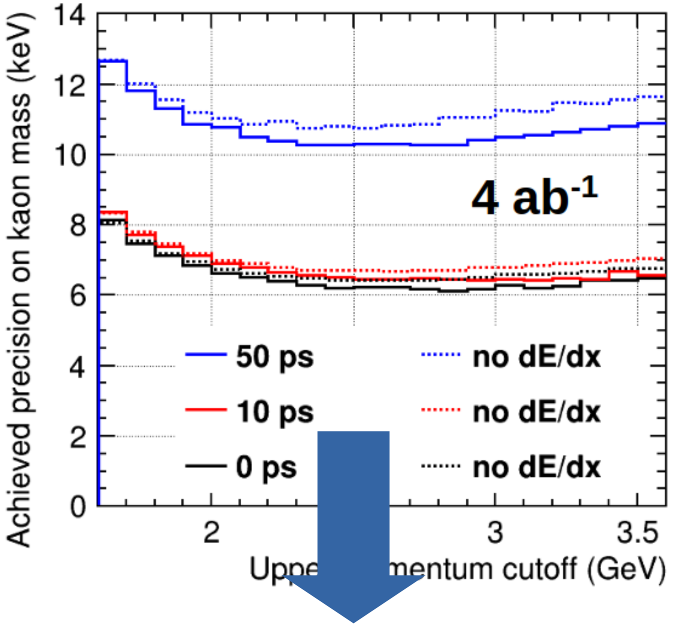
Contribution to the Kaon mass measurement

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)



Contribution to the Kaon mass measurement

Status on September 2020 by Uli Einhaus



$$\Delta m_{K,\mathrm{stat}} \approx 10\ \mathrm{keV}$$

$$\Delta \mathrm{TOF} \approx 17\ \mathrm{ps\ (per\ particle)}$$

$$\mathrm{PDG:}\ m_K = 493.677 \pm 0.013\ \mathrm{MeV}$$

Contribution to the Kaon mass measurement

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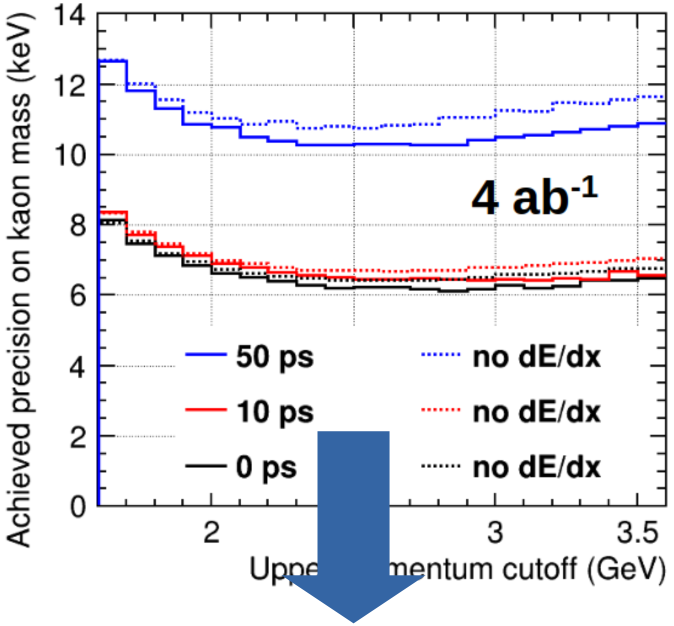
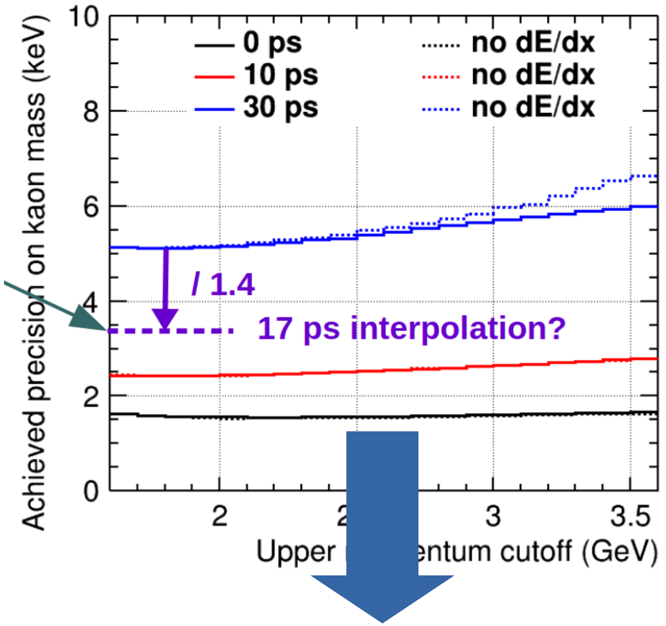


$\Delta m_{K,\mathrm{stat}} \approx 10$ keV

$\Delta \mathrm{TOF} \approx 17$ ps (per particle)

Status on April 2022 by Uli Einhaus



$\Delta m_{K,\mathrm{stat}} \approx 3.5$ keV

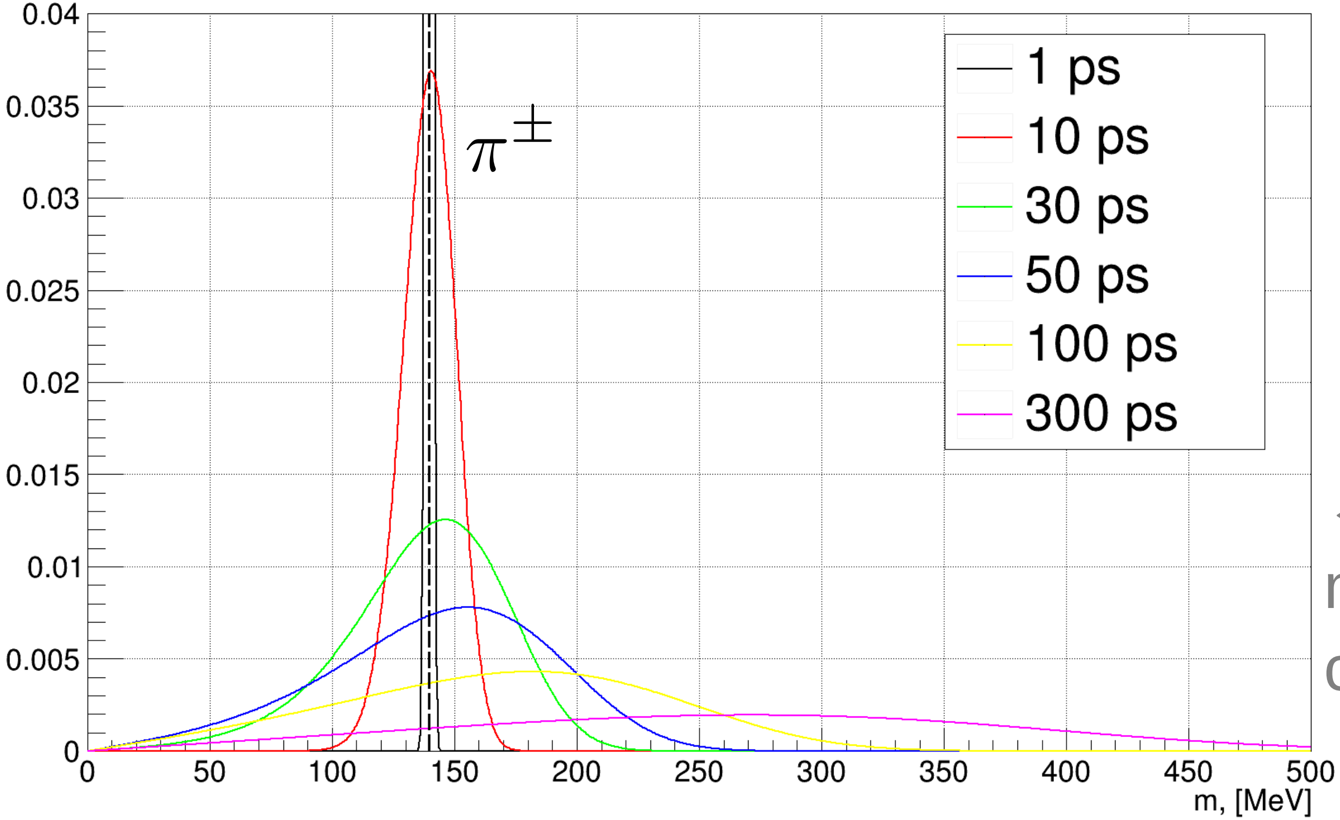
$\Delta \mathrm{TOF} \approx 17$ ps (per particle)

$$\mathrm{PDG:}\ m_K = 493.677 \pm 0.013\ \mathrm{MeV}$$

Contribution to the Kaon mass measurement: systematic bias

$$m = p\sqrt{\frac{c^2\mathrm{TOF}^2}{\ell^2_{\mathrm{track}}} - 1}$$

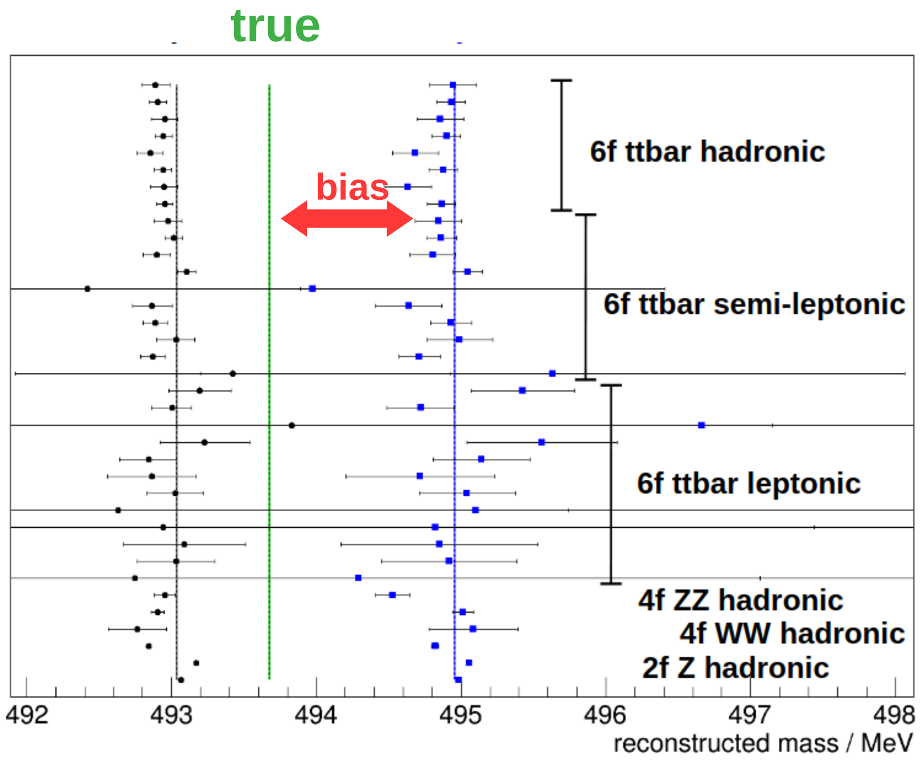
$$\begin{array}{c}\underline{\text{not}}\\ \text{perfect}\\ \text{Gauss}\end{array} = p\sqrt{\left(\begin{array}{c}\text{perfect}\\ \text{Gauss}\end{array}\right)^2 - 1}$$



← purely mathematical calculation

Contribution to the Kaon mass measurement: systematic bias

Status on September 2020 by Uli Einhaus



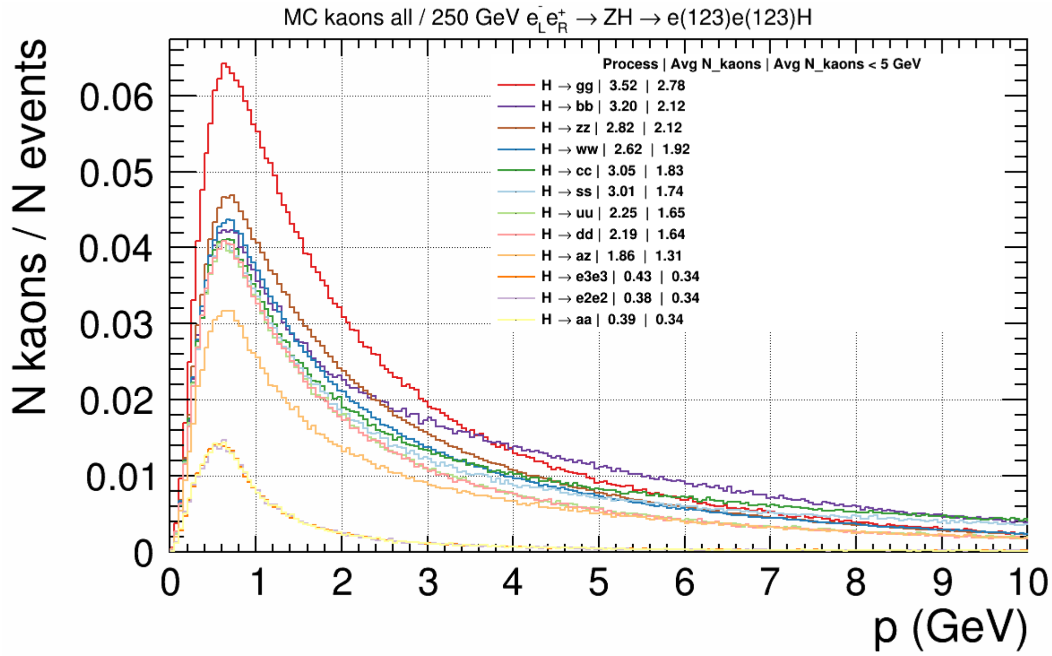
Unfolding of the true Kaon mass:

- requires good understanding of the behaviour of
  - track length and its uncert.
  - time resolution and its uncert.
  - momentum and its uncert.
- realistic simulation of time resolution

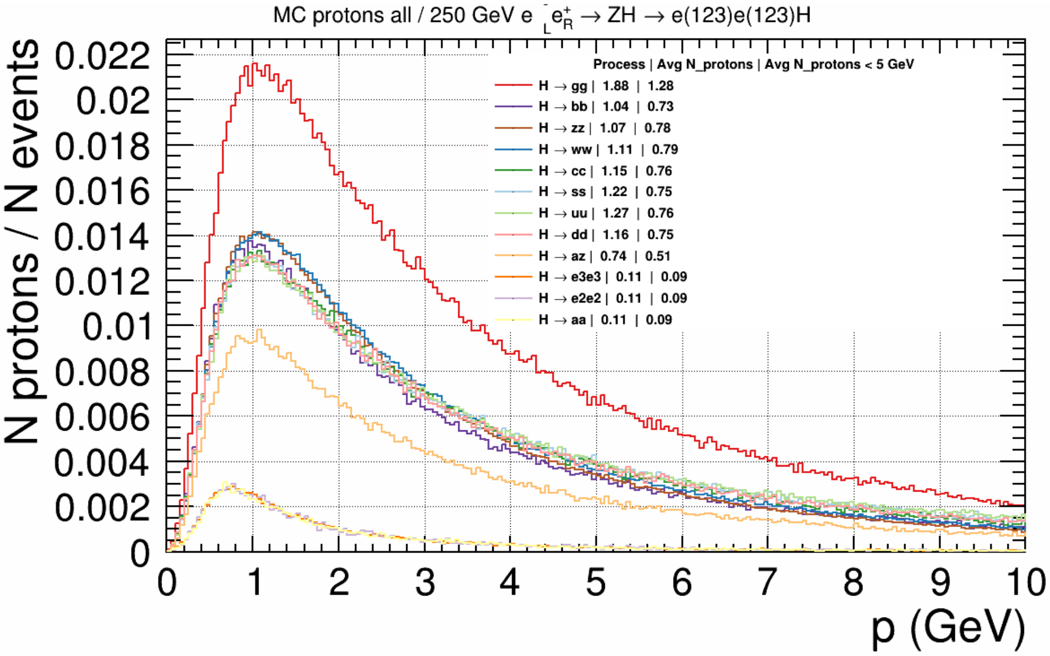
Doable, but requires a quite involved study and significant time investment

Momentum distribution of charged hadrons in $e^+e^- \rightarrow ZH@250$ GeV

kaons



protons



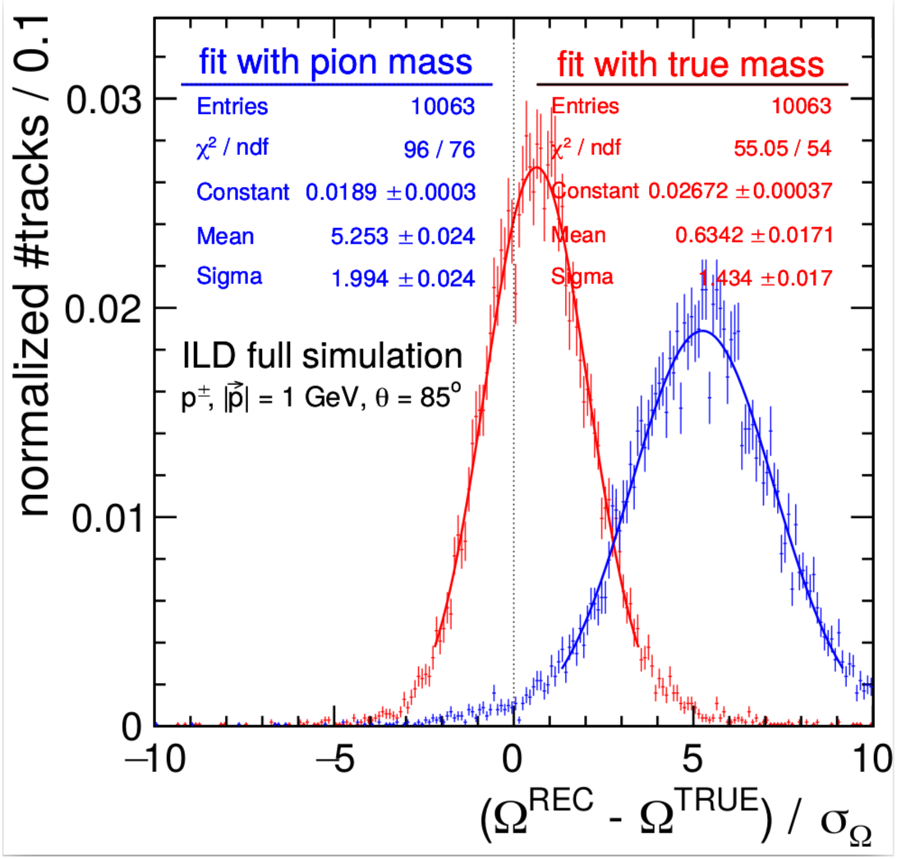
- Majority of $\pi^{\pm}/K^{\pm}/p$ are produced at low-momenta, which is covered by TOF pID

- Improve tracks with TOF pID:
  fit tracks with true mass instead of default $\pi^{\pm}$ mass

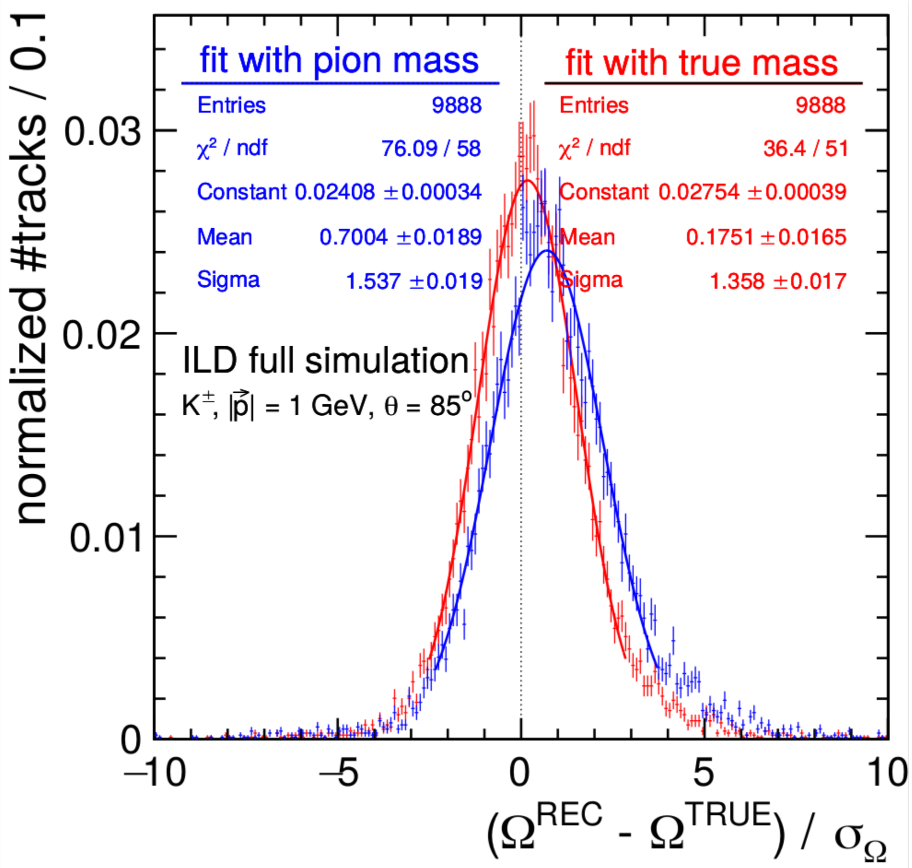
Track fit with a proper mass (default $m_{\pi\pm}$) hypothesis using pID

Study by Yasser (PhD thesis)

protons curvature pull



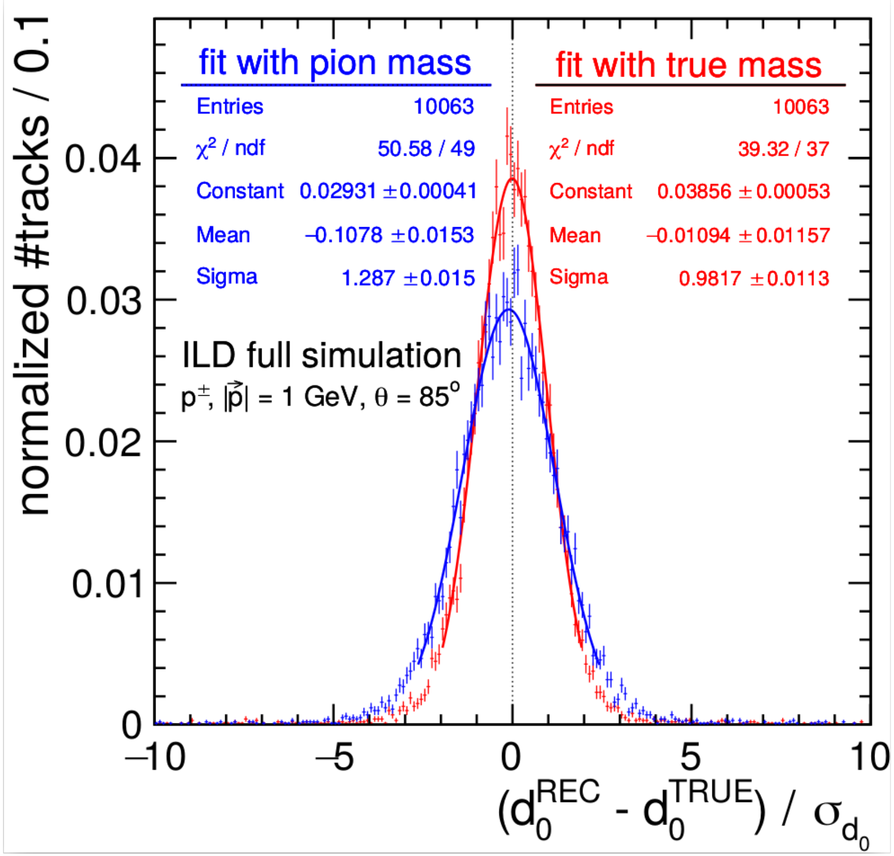
kaons curvature pull



Track fit with a proper mass (default $m_{\pi\pm}$) hypothesis using pID

Study by Yasser (PhD thesis)

protons d_0 pull



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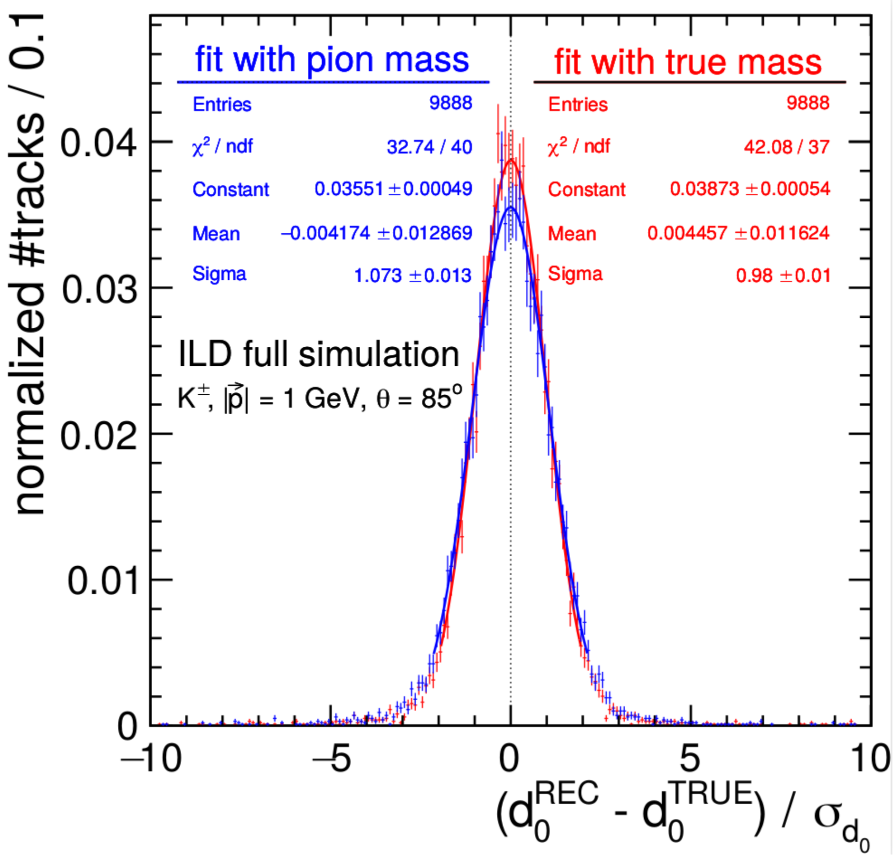
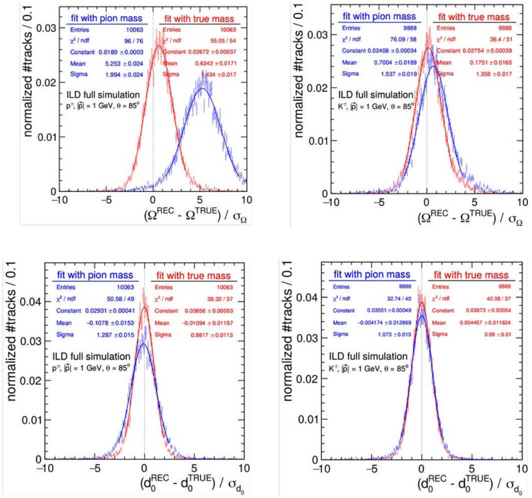


Track fit with a proper mass (default $m_{\pi\pm}$) hypothesis using pID



- Very well established positive effect:
  - better track parameters
  - and their uncertainties

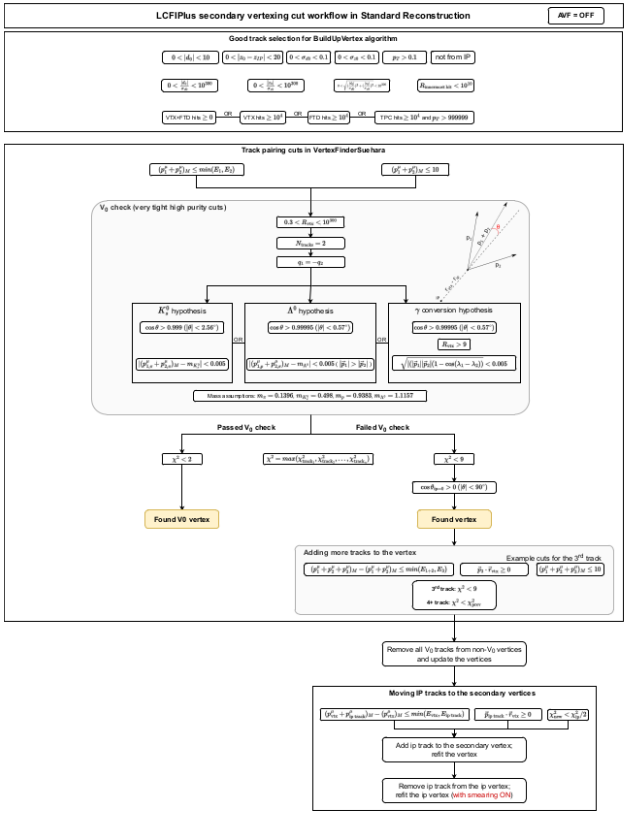
but ...

- Ideal → TOF pID transition still has to be made
- Relevant only in the limited momentum (< 2 GeV)
- Definitely nice for reconstruction, but how does it translate to high-level physics studies?

Better track parameters → better 2nd vertex reconstruction?

We are using LCFIPlus for vertex reconstruction

Detour into LCFIPlus 2nd vertex reconstruction



Detour into LCFIPlus 2nd vertex reconstruction

Good track selection

LCFIPlus secondary vertexing cut workflow in Standard Reconstruction — AVF = OFF

Good track selection for BuildUpVertex algorithm

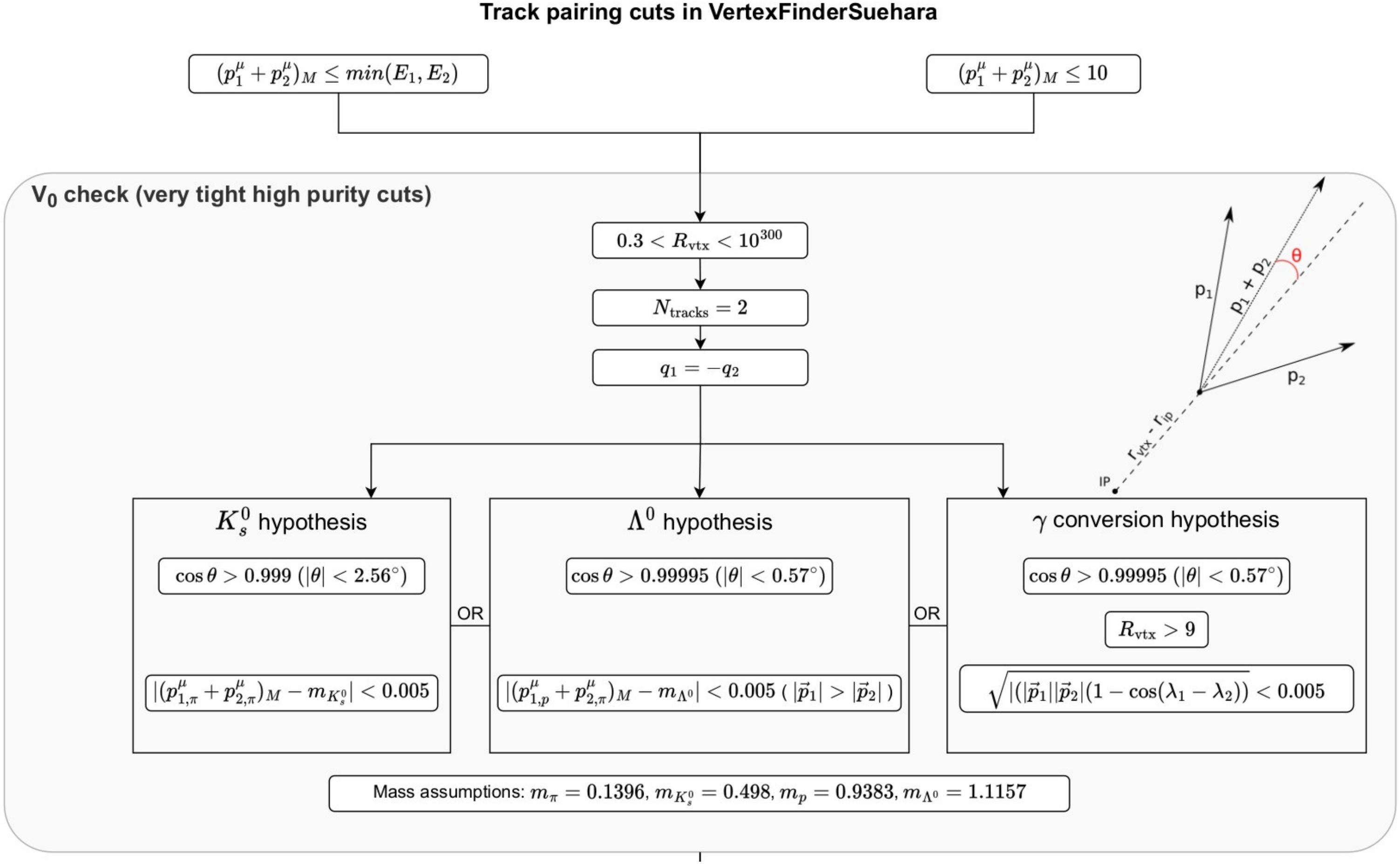
$0 < |d_0| < 10$ | $0 < |z_0 - z_{IP}| < 20$ | $0 < \sigma_{d0} < 0.1$ | $0 < \sigma_{z0} < 0.1$ | $p_T > 0.1$ | not from IP

$0 < \frac{|d_0|}{\sigma_{d0}} < 10^{300}$ | $0 < \frac{|z_0|}{\sigma_{z0}} < 10^{300}$ | $0 < \sqrt{(\frac{|d_0|}{\sigma_{d0}})^2 + (\frac{|z_0|}{\sigma_{z0}})^2} < 10^{300}$ | $R_{\text{innermost hit}} < 10^{10}$

VTX+FTD hits ≥ 0 OR VTX hits $\geq 10^4$ OR FTD hits $\geq 10^4$ OR TPC hits $\geq 10^4$ and $p_T > 999999$

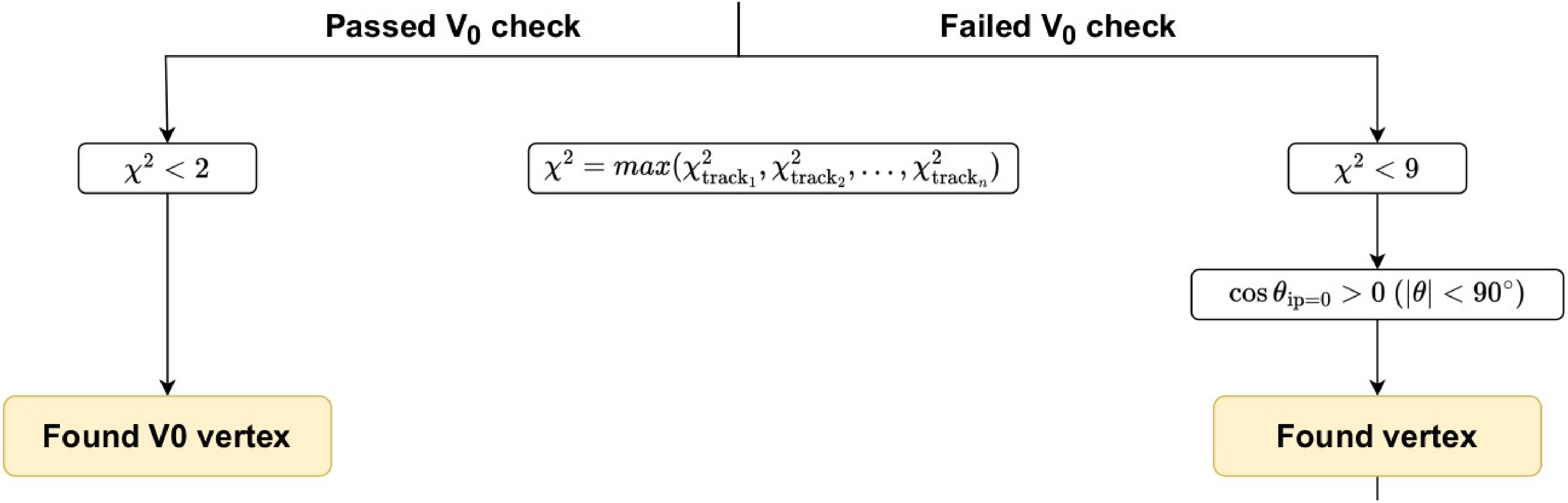
Detour into LCFIPlus 2nd vertex reconstruction

Matching tracks and V_0 check



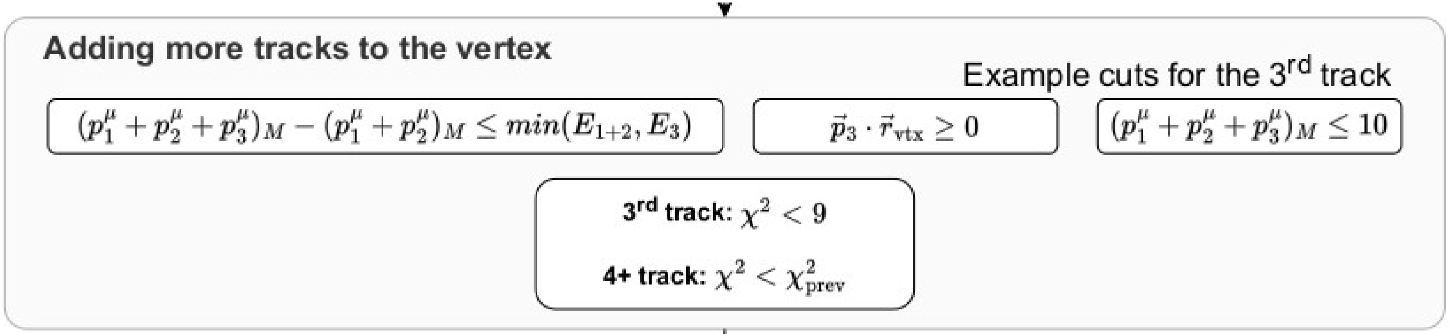
Detour into LCFIPlus 2nd vertex reconstruction

Vertex fit of the pair of tracks



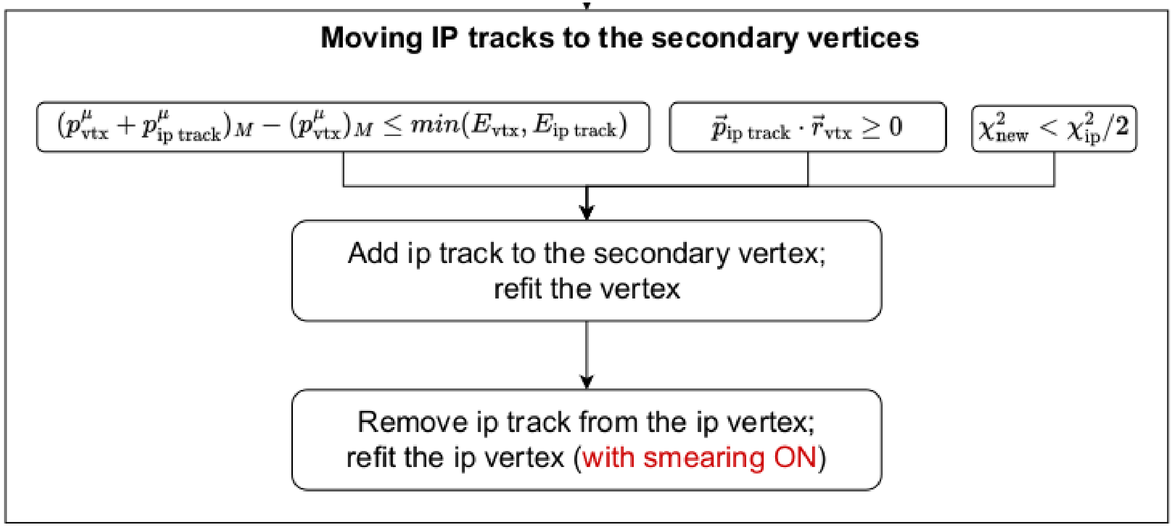
Detour into LCFIPlus 2nd vertex reconstruction

<u>Testing 3+ tracks per vertex scenario</u>



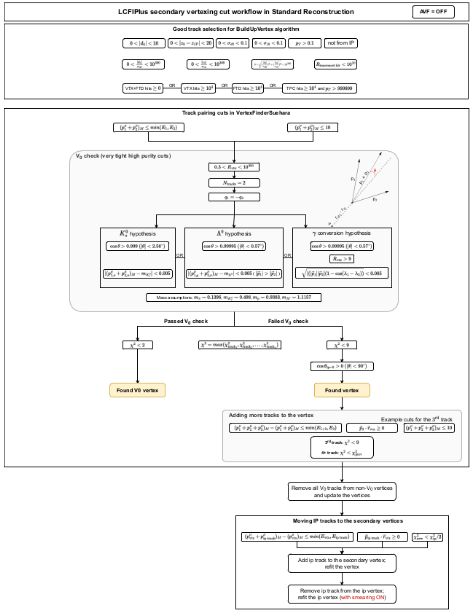
. . .

<u>Testing IP tracks as 2nd vertex tracks</u>



Better track parameters → better 2nd vertex reconstruction?

Using LCFIPlus

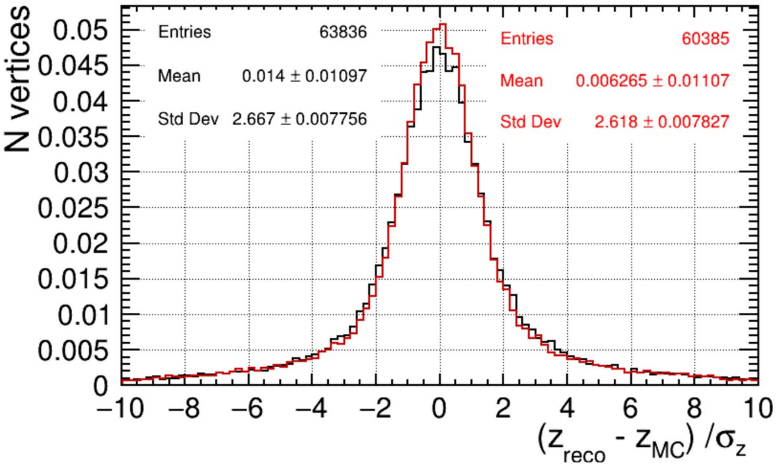


More realistic track parameter uncertainties

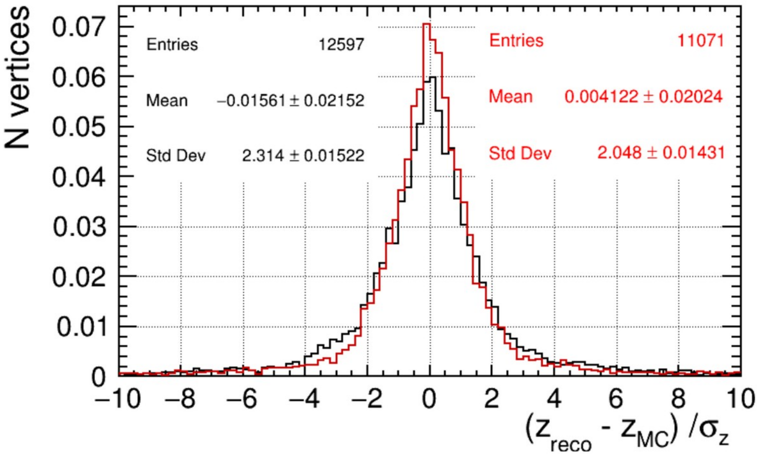
→

more realistic vertex position uncertainties

Reco Vertices with <1 GeV $K^{\pm}$

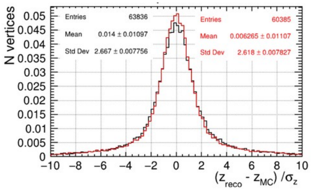


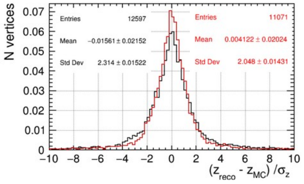
Reco Vertices with <1 GeV $p^{\pm}$



Slightly better vertex position reconstruction ✓

Better track parameters → better 2^{nd} vertex reconstruction?





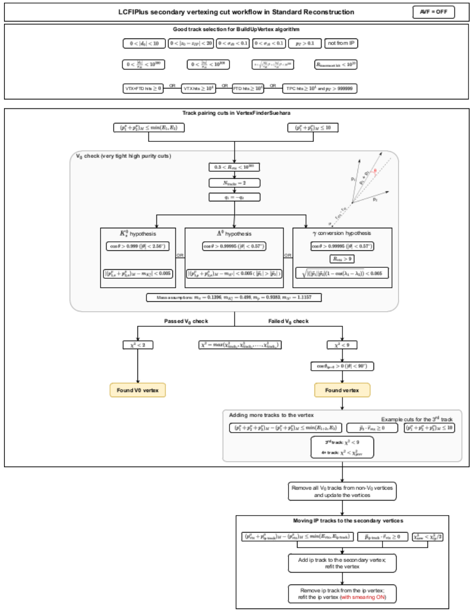
- Very well established positive effect:
  - Slightly better vertex position reconstruction
  - Slightly better vertex position uncertainties

very similar buts ...

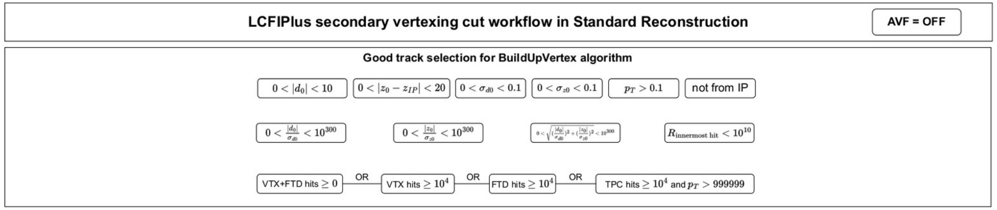
- Ideal → TOF pID transition still has to be made
- Relevant only for vertices with at least one $\pi^{\pm}/K^{\pm}/p$ ($p < 1$ GeV)
- Definitely nice for reconstruction, but how does it translate to high-level physics studies?

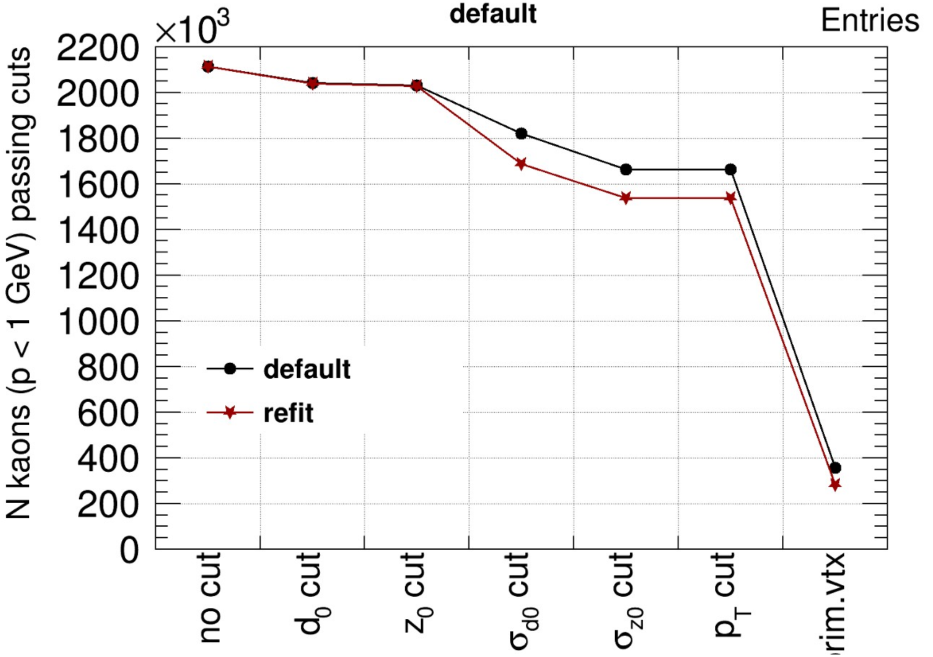
Better track parameters → better 2nd vertex reconstruction

Using LCFIPlus



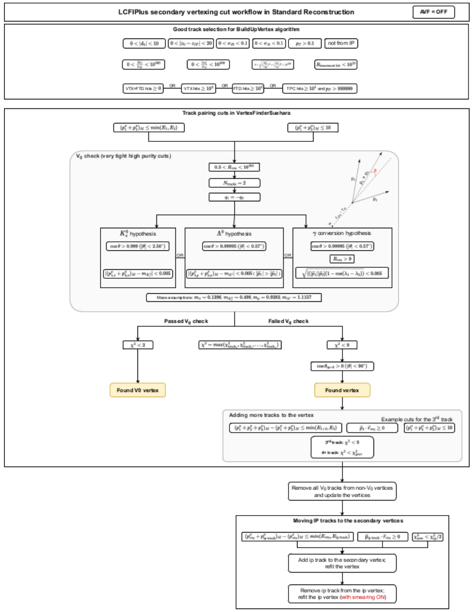
More realistic track parameter uncertainties→
Less missed/fake vertices? *(direct impact on flavour tag!)*





Better track parameters → better 2nd vertex reconstruction

Using LCFIPlus



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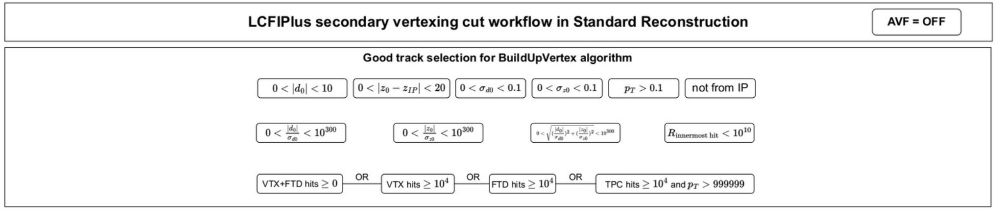

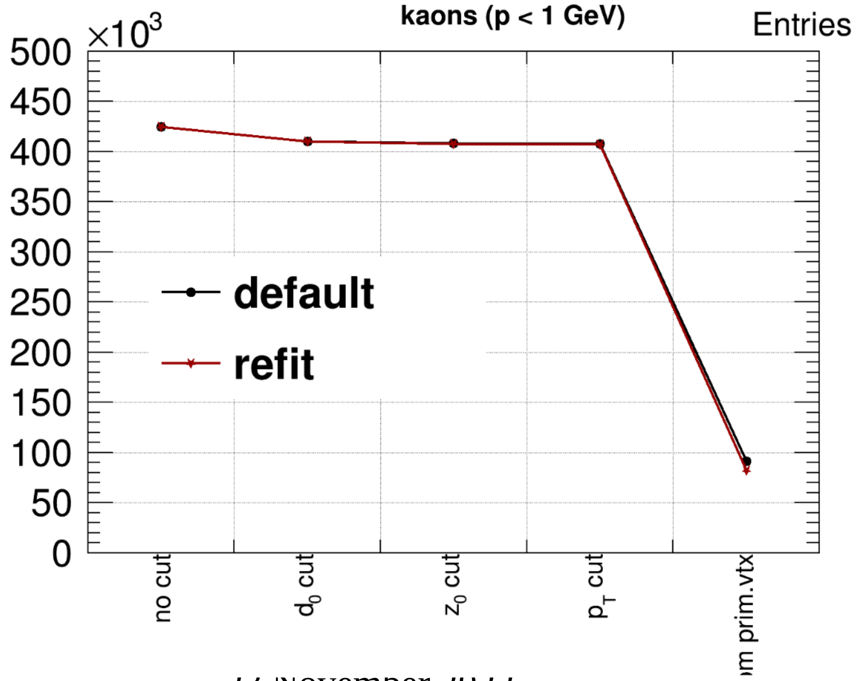

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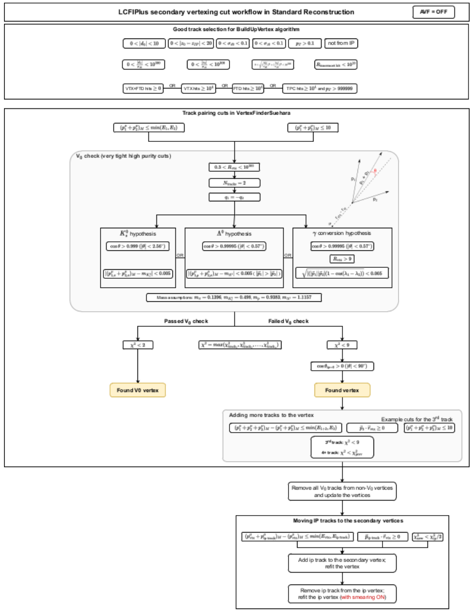
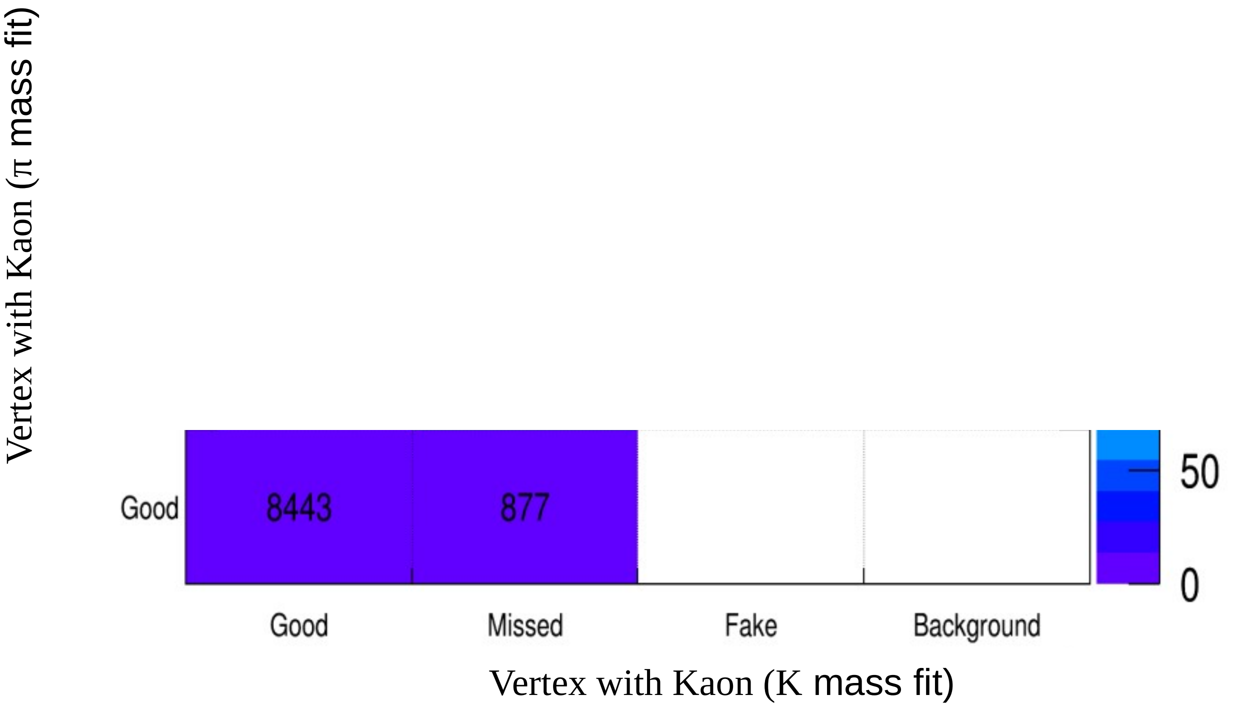


More realistic track parameter uncertainties→
Less missed/fake vertices? *(direct impact on flavour tag!)*

2nd vertices with kaons (< 1 GeV), no d0/z0 error cuts



Better track parameters → better 2nd vertex reconstruction

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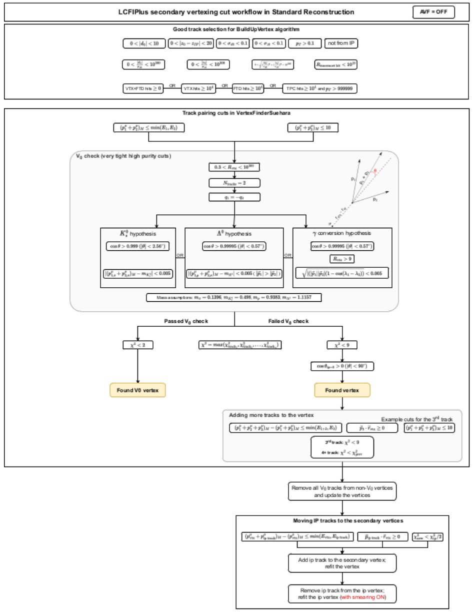

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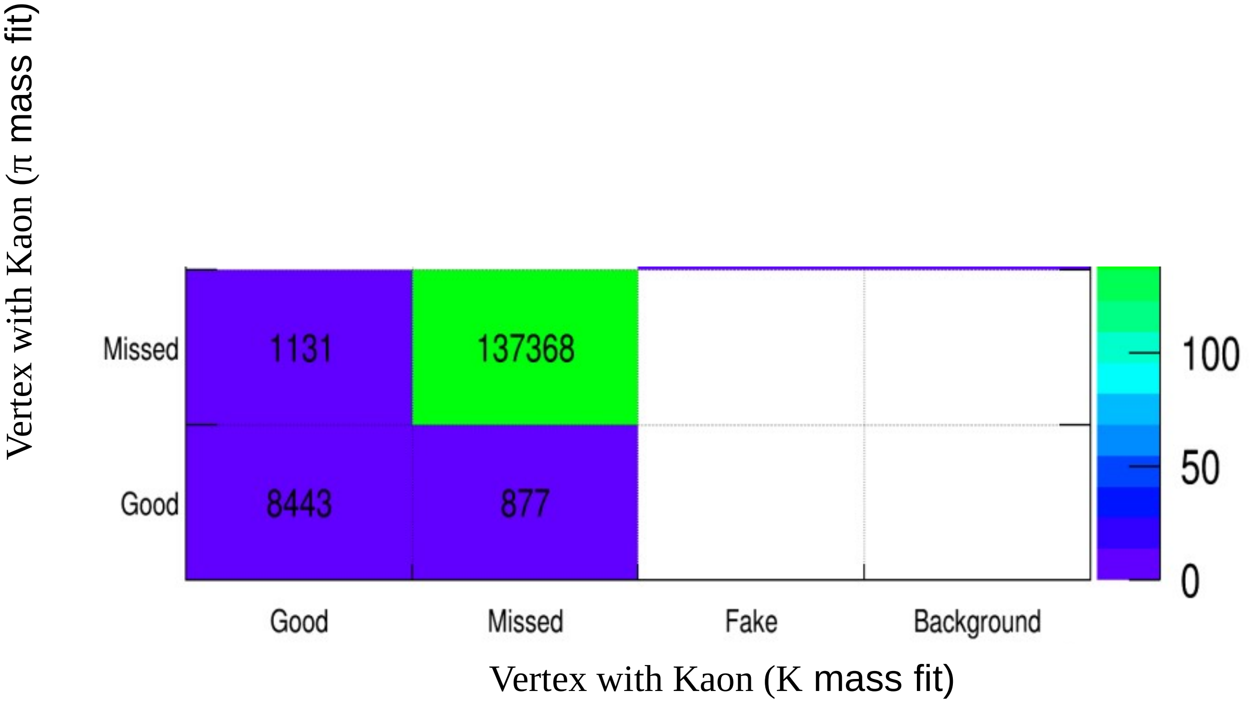
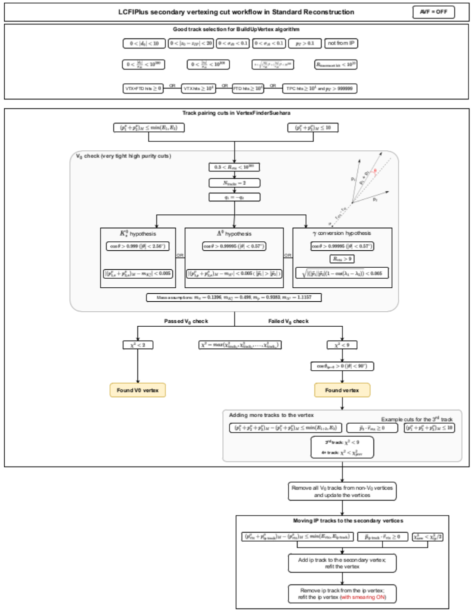


Better track parameters → better 2nd vertex reconstruction

Using LCFIPlus



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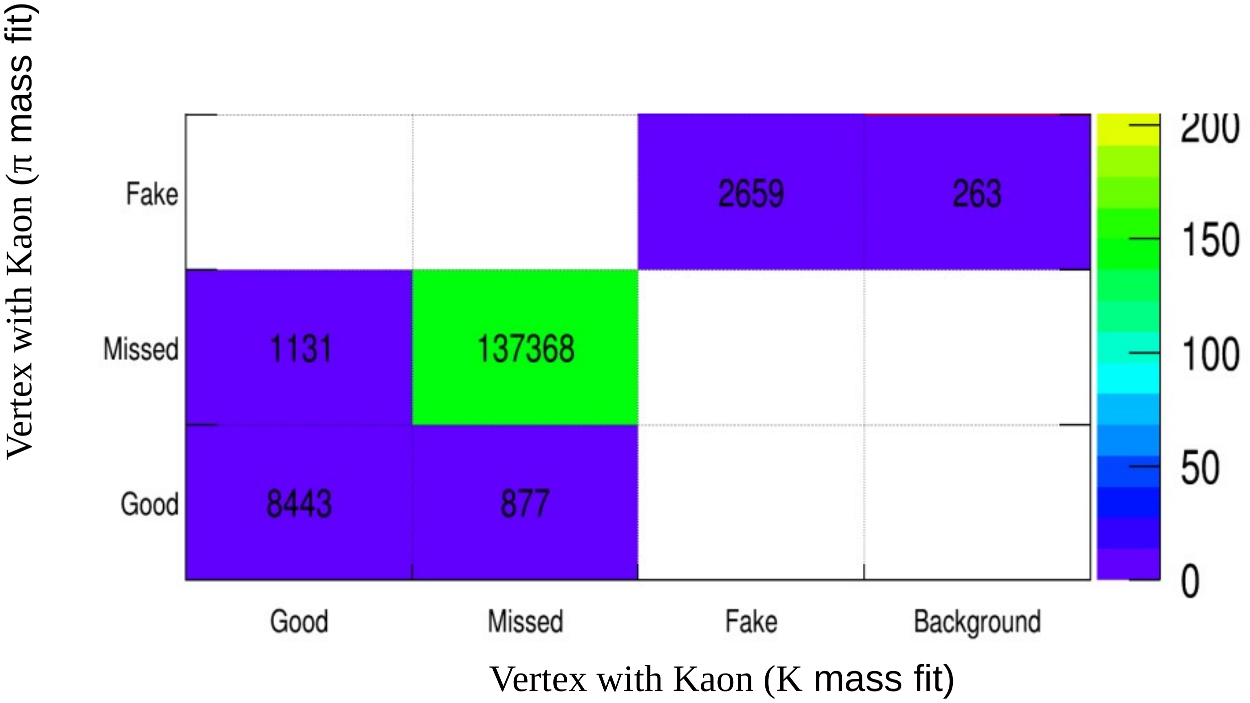

Better track parameters → better 2nd vertex reconstruction

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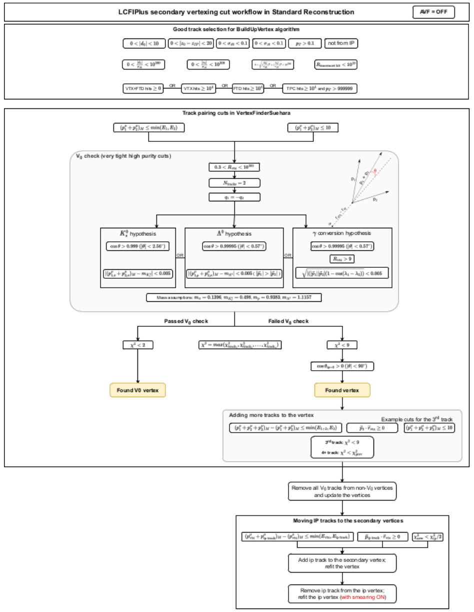

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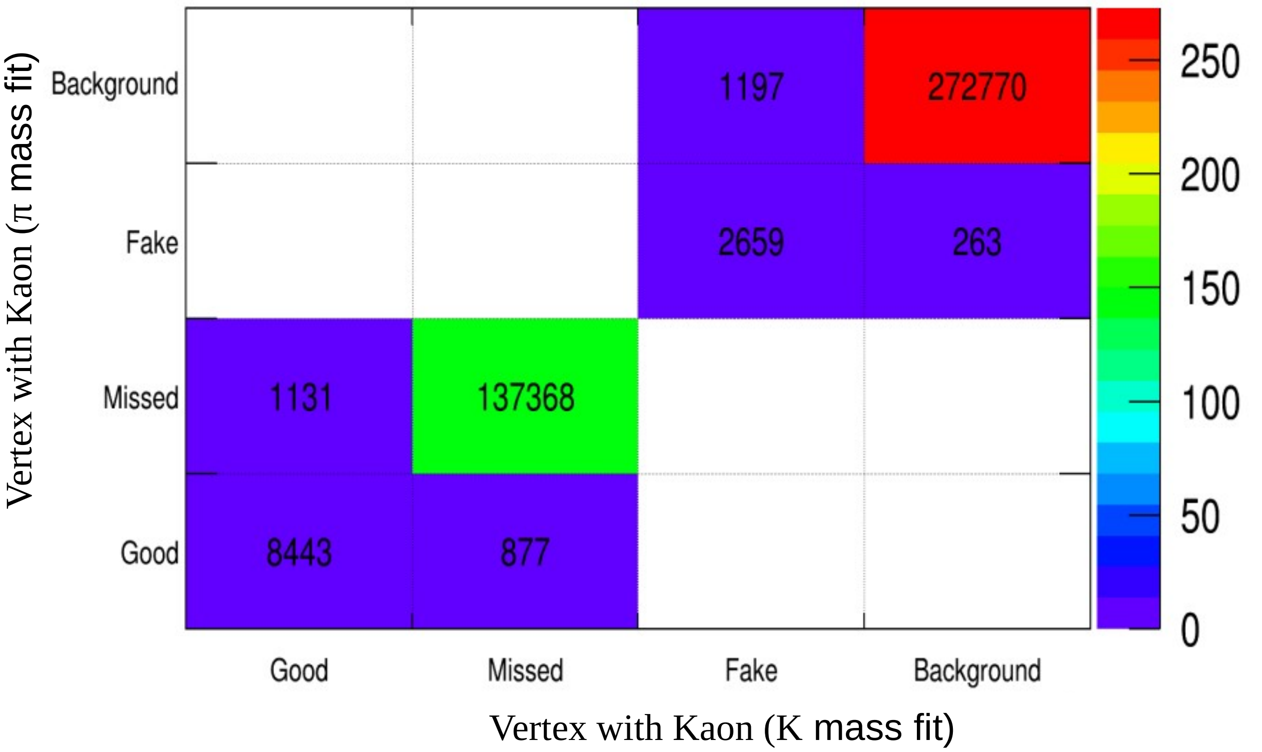
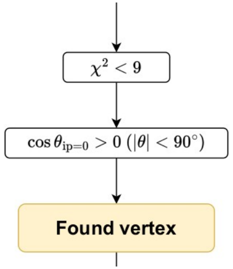


Better track parameters → better 2nd vertex reconstruction

$$\chi^2 = max(\chi^2_{\text{track}_1}, \chi^2_{\text{track}_2}, \cdots, \chi^2_{\text{track}_n})$$



More realistic track parameter uncertainties →
Less missed/fake vertices? *(direct impact on flavour tag!)*

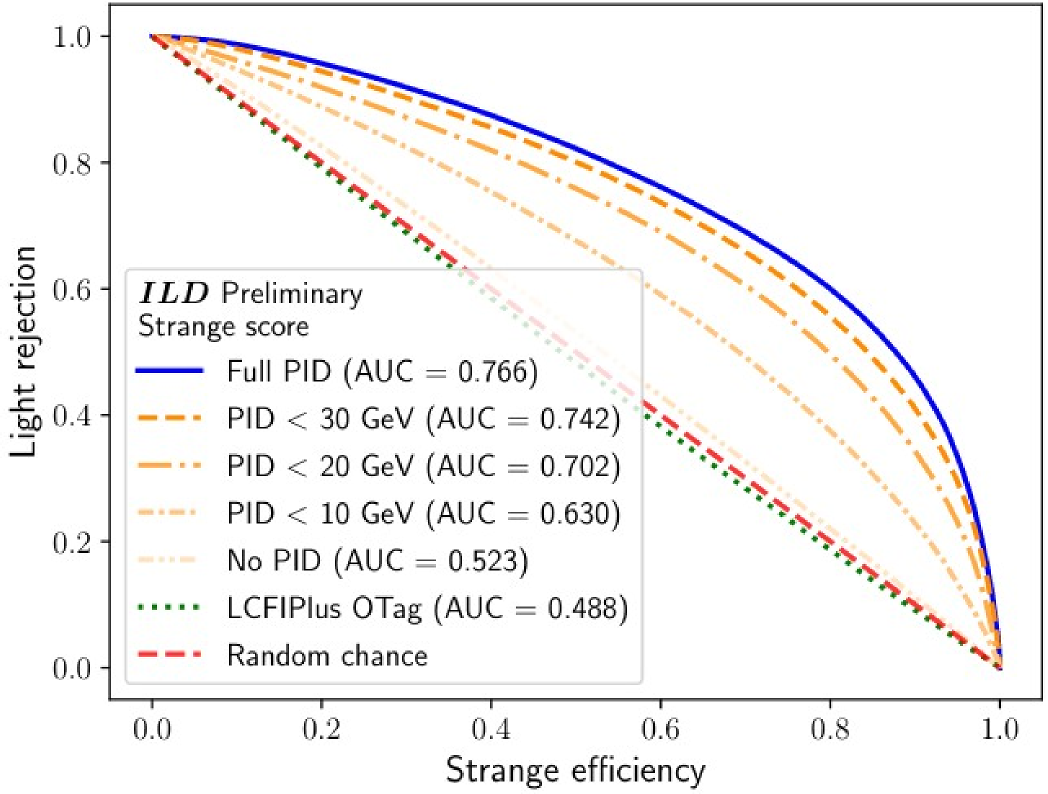
- Larger track parameter uncertainties → looser cut on vertex fit (doesn't matter if it is more realistic, its just smaller χ^2)
- With the current LCFIPlus algorithm we don't get "better" results we just get different results.

Looking into the future:

- If we will have pID based vertex fit we might achive improved vertex reconstruction using TOF pID. But this requires tedious and detailed development
- At the moment, few cutting-edge DNN flavour tags are in development (Mareike, Taikan). Might also benefit from pID

Higgs studies: H → ss

Study by Matthew Basso, Valentina Cairo, et.al. [2203.07535]



(c) Strange vs. light, using s-jet score

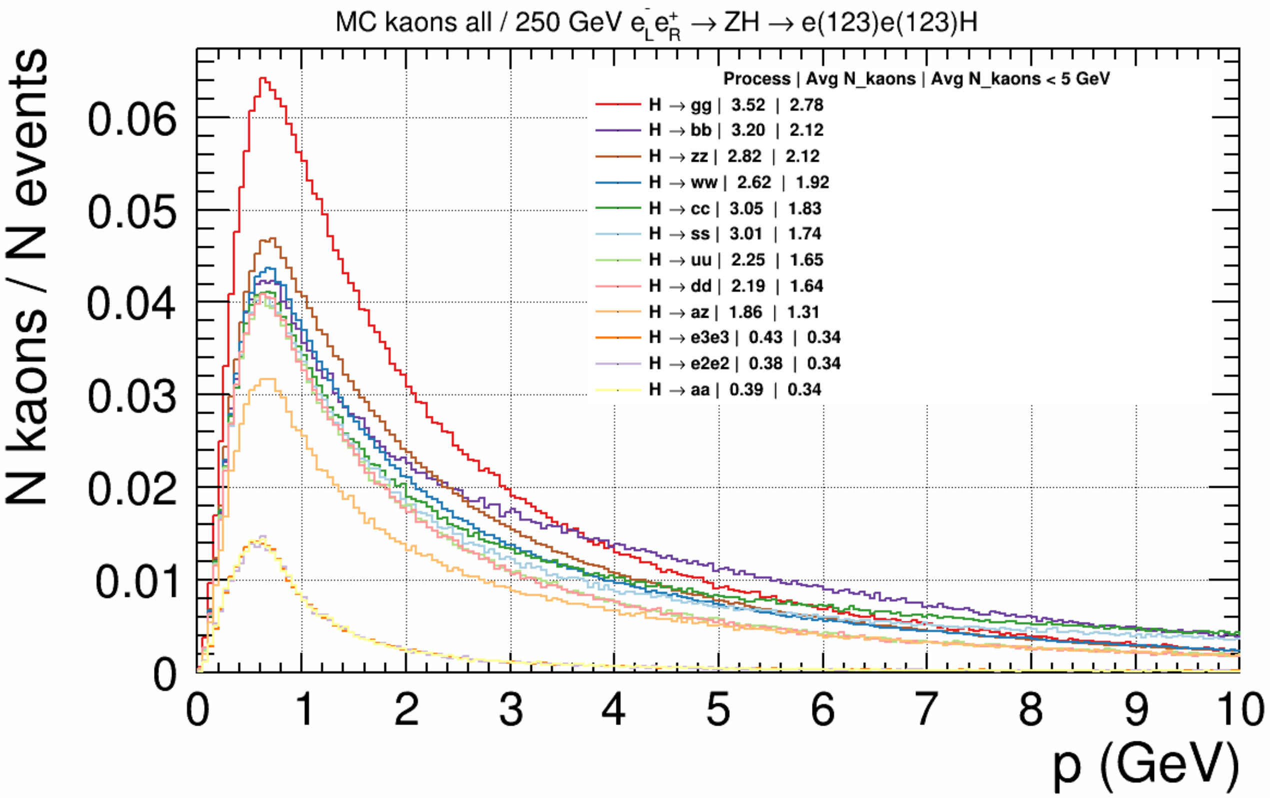
Including PID < 10 GeV:
AUC: 0.523 → 0.630

interpolating

Including TOF pID (< 5 GeV):
AUC: 0.523 → 0.577

- TOF pID might bring slight enhancement, but definitely is not a game-changer here.
- H → ss heavily relies on pID at high momenta

Higgs studies: H → gg



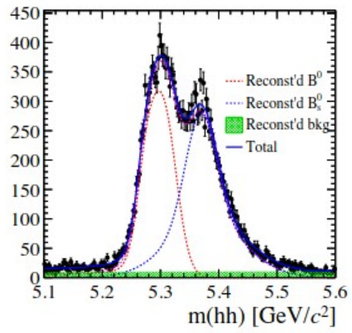
- Potential TOF use: tag H → gg?
- H → gg has larger production of low-momentum $K^{\pm}$ compared to other decay modes

Rare B_s decays at FCC/CEPC

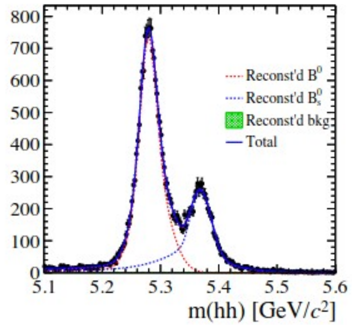
Study by Shanzhen Chen (CEPC2021):

Impact of $\pi^{\pm}/K^{\pm}$ pID information studied with $B_{(s)}^0$->hh

50% eff. pID



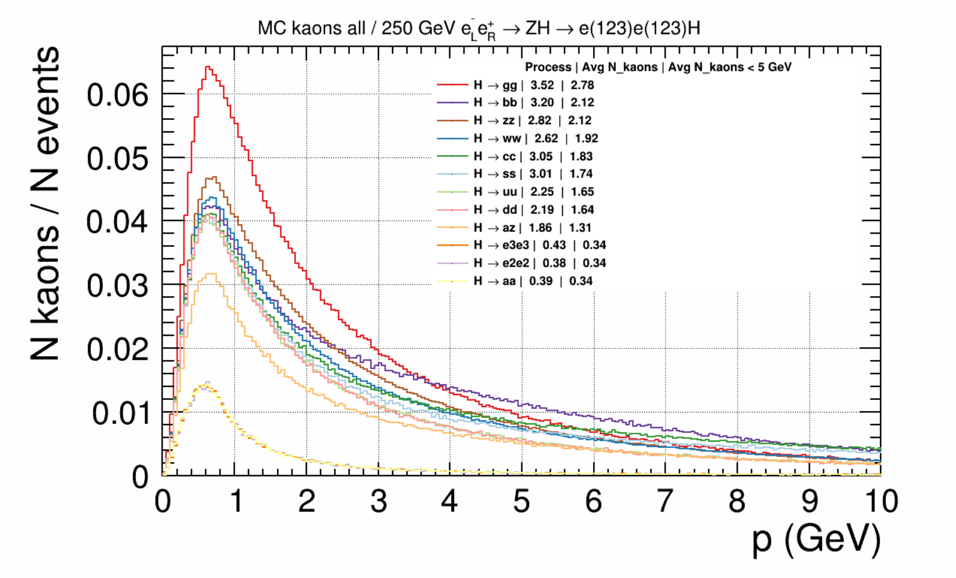
100% eff. pID



- So far study assumed no backgrounds at all – very preliminary
- Very rare decays → relevant only at TeraZ → FCC-ee/CEPC

- Momentum distribution of $K^{\pm}$ at TeraZ?
  (TOF vs dN/dx) pID impact

Measuring hadrons yield for generator tuning?



- Most $\pi^{\pm}/K^{\pm}/p$ are produced in the momentum range covered by TOF
- Use TOF to improve precision measurement of $\pi^{\pm}/K^{\pm}/p$ yields for generator tuning?
- Many generators tuning still rely on LEP data

- Momentum spectrum at Z-pole?

Summary

Potentially few applications for TOF pID:

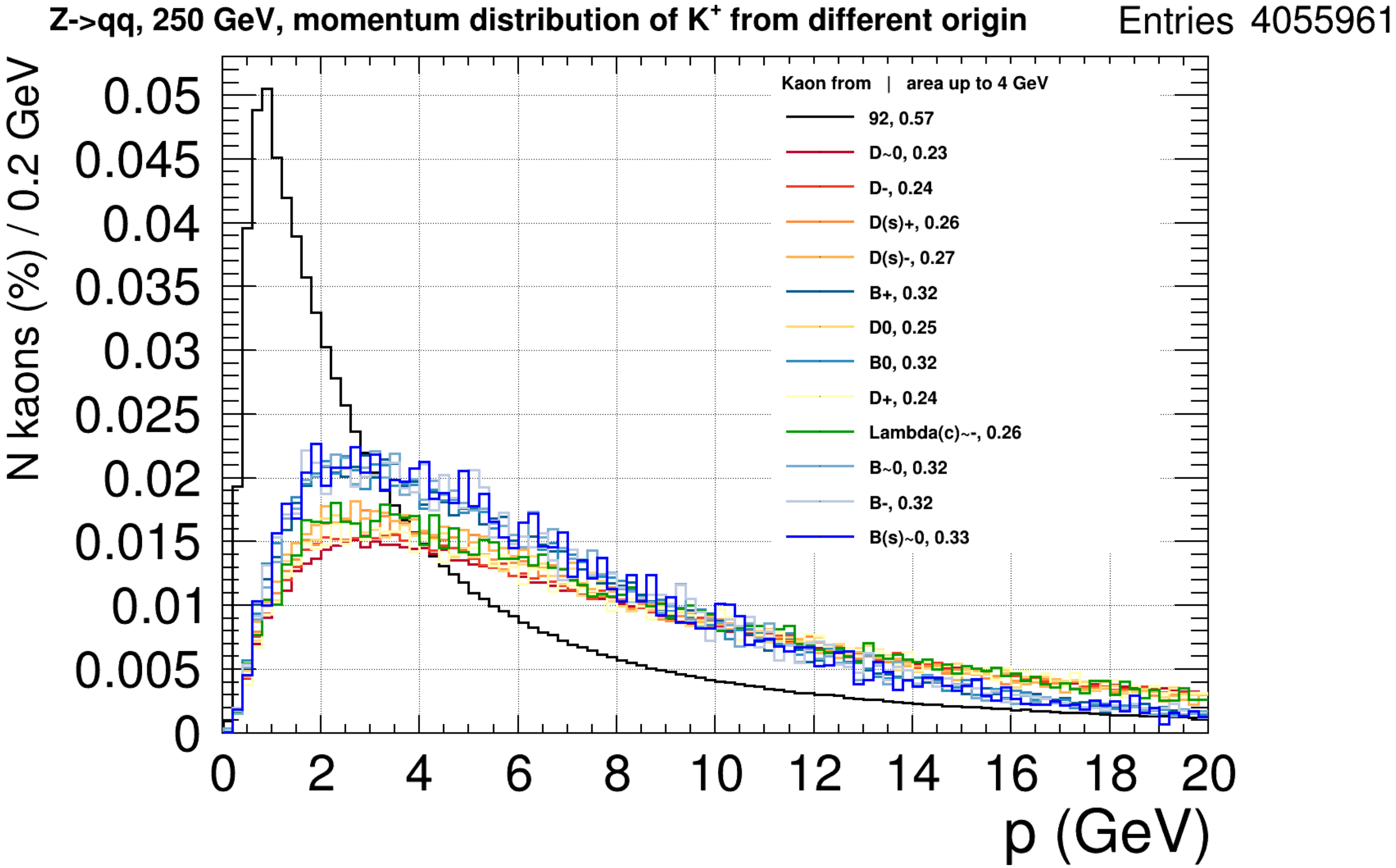
- kaon mass → achievable, requires involved study
- track reconstruction → no clear transition to physics
- Vertex reconstruction → requires involved study
- Higgs studies (H → gg) → requires involved study
- Flavour physics → not clear so far
- Generator tuning → not clear so far

but…

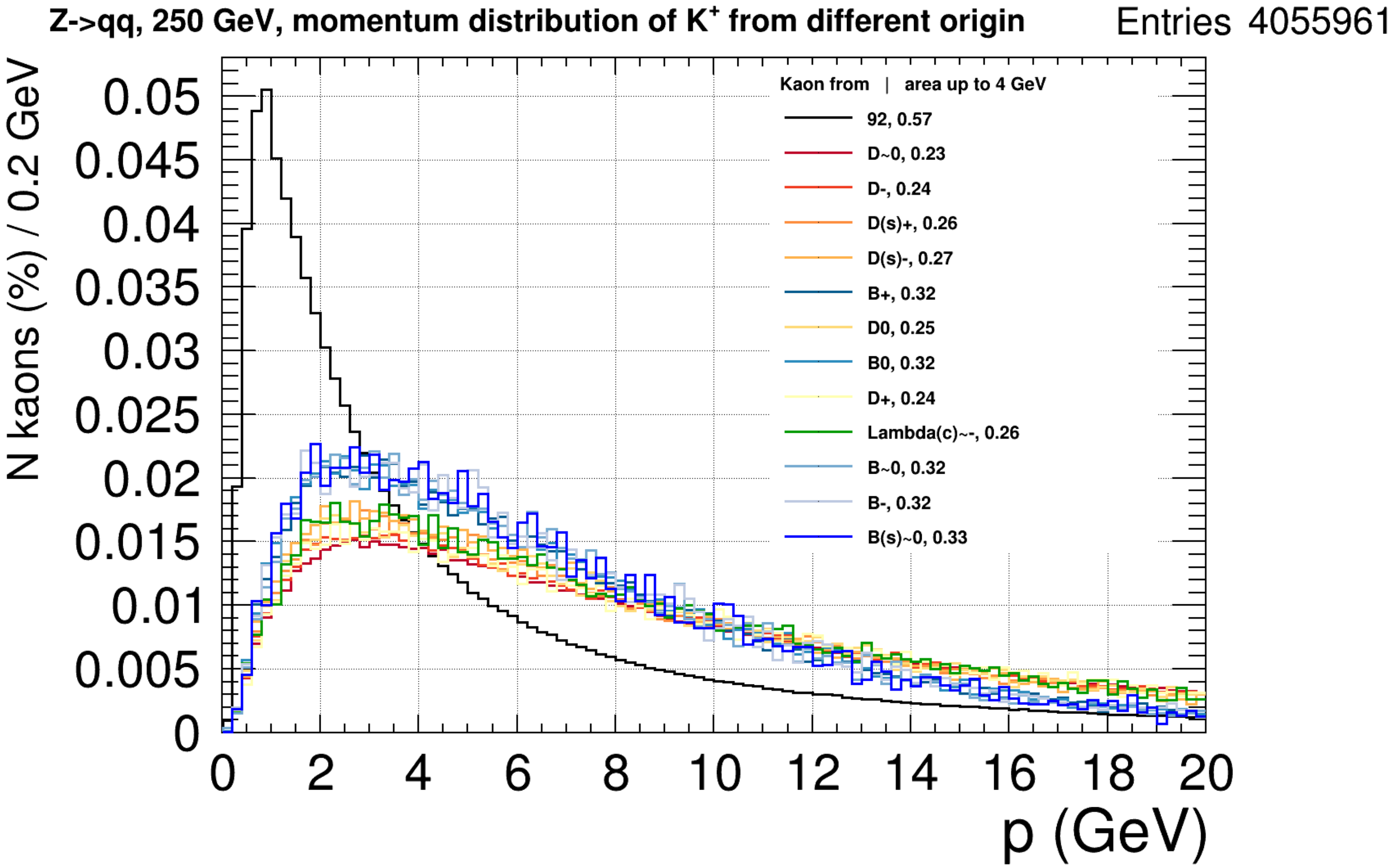
- TOF doesn’t have “a smoking gun” use case so far
- dE/dx in the ILD already covers a good momentum range
- Invest more into TOF detailed developments for ILD?

Any follow up ideas from the audience?

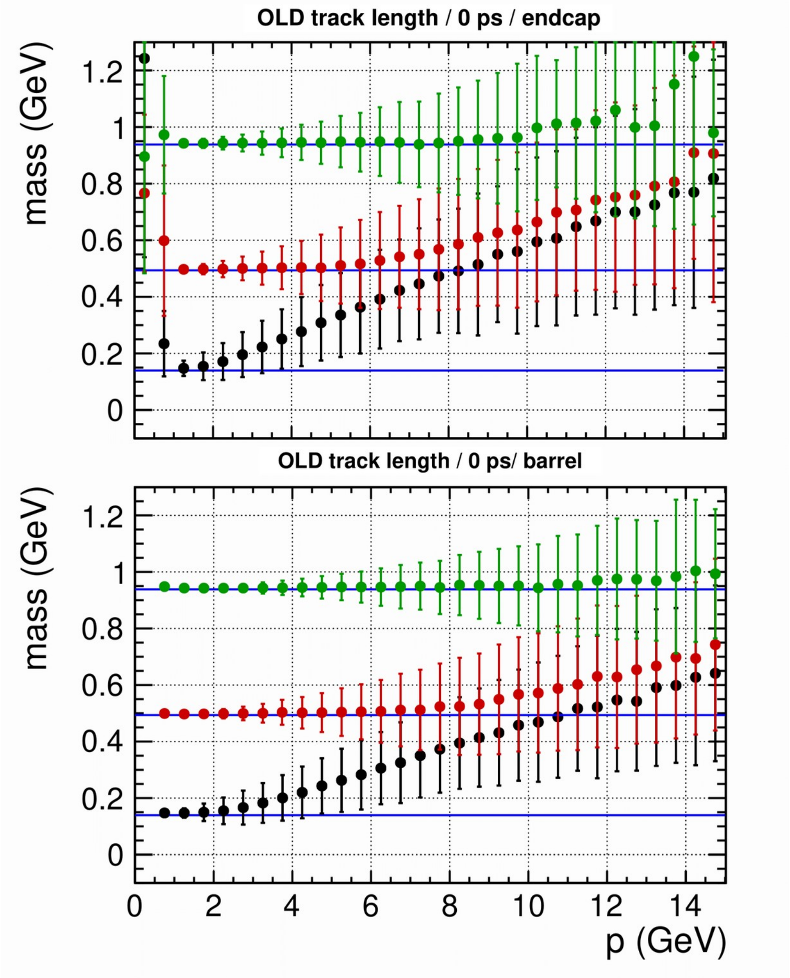
BACK UP: kaon production from different decay modes



BACK UP: kaon production from different decay modes

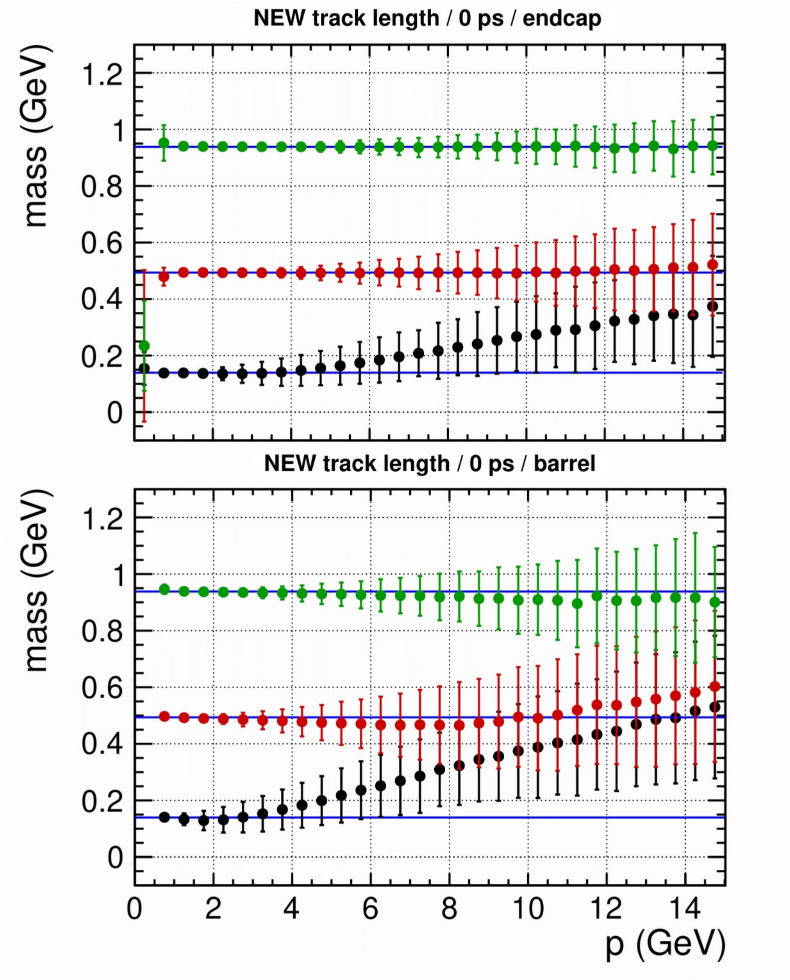


Back up: new track length results for the barrel

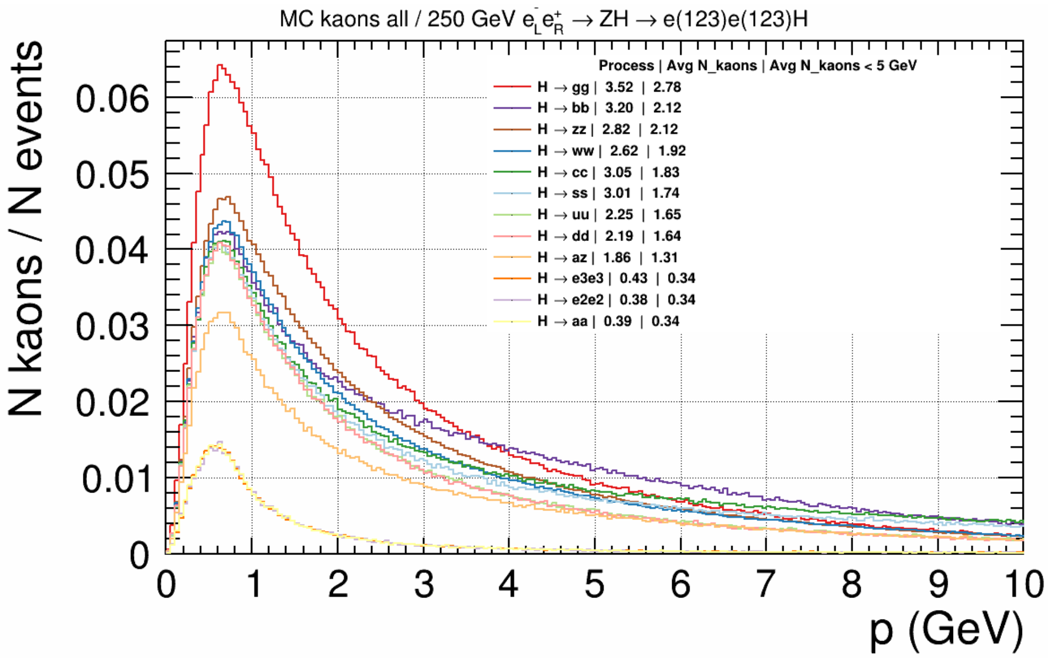


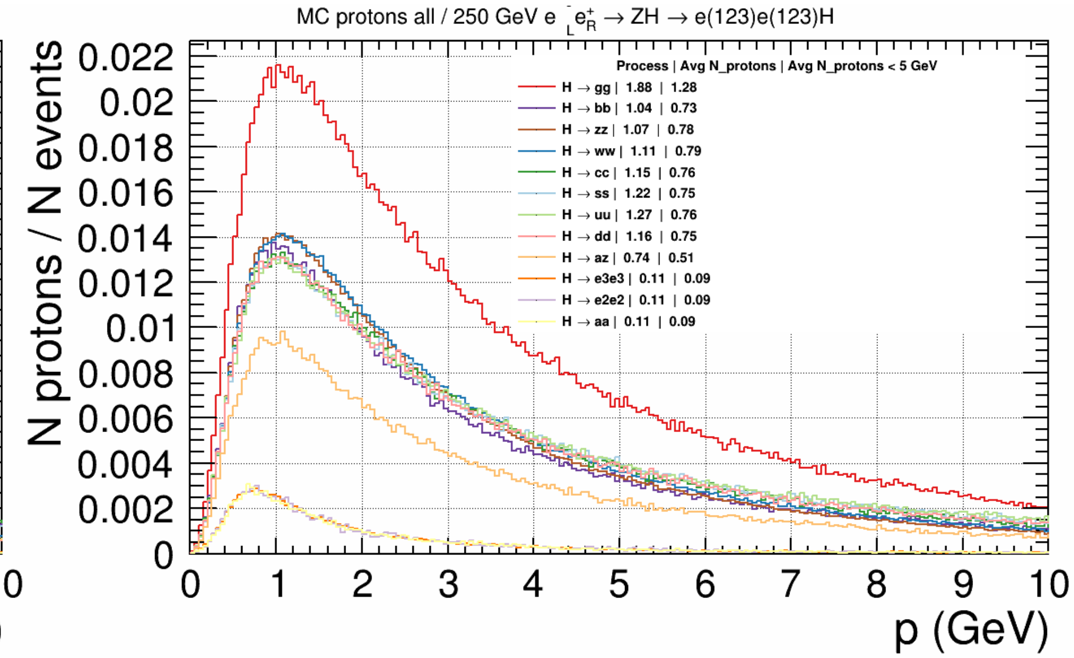
ENDCAP

BARREL

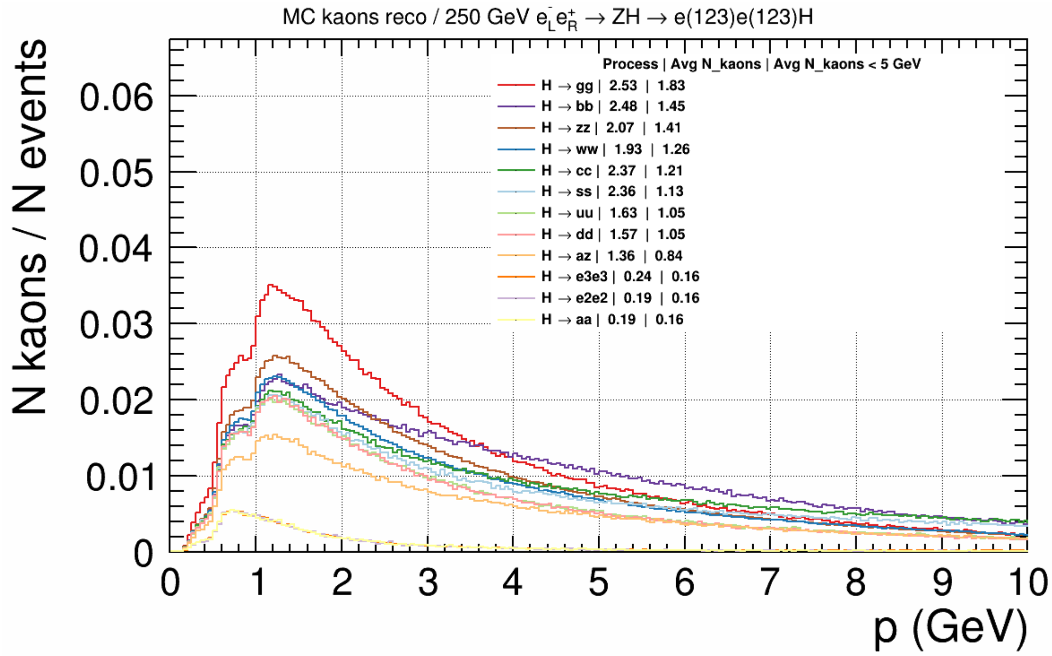


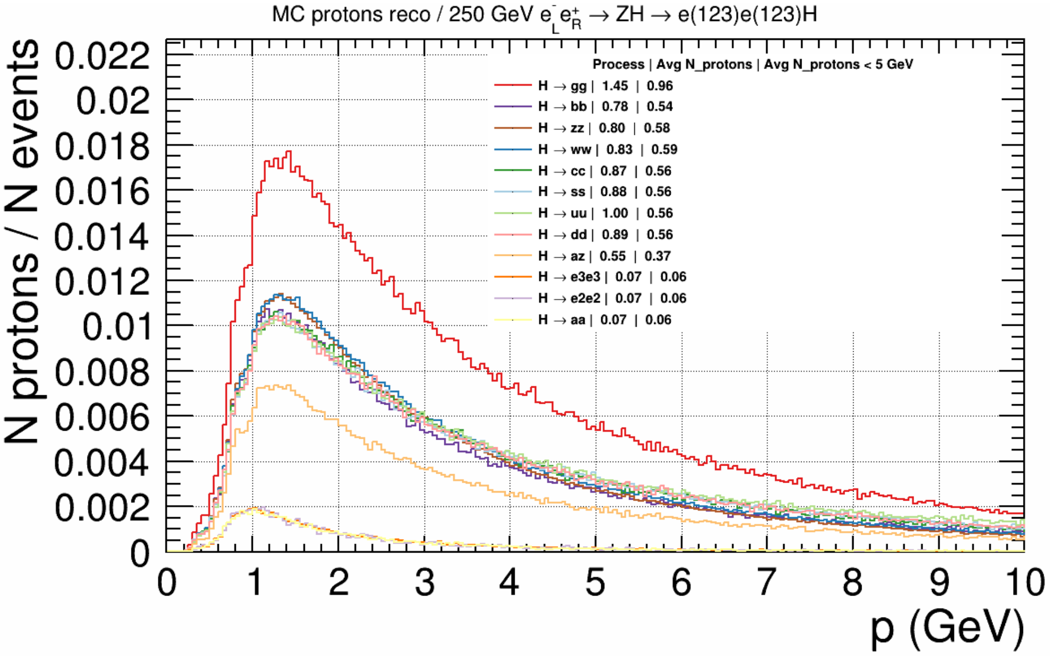
Back up: momentum spectrum of pions/kaons/protons



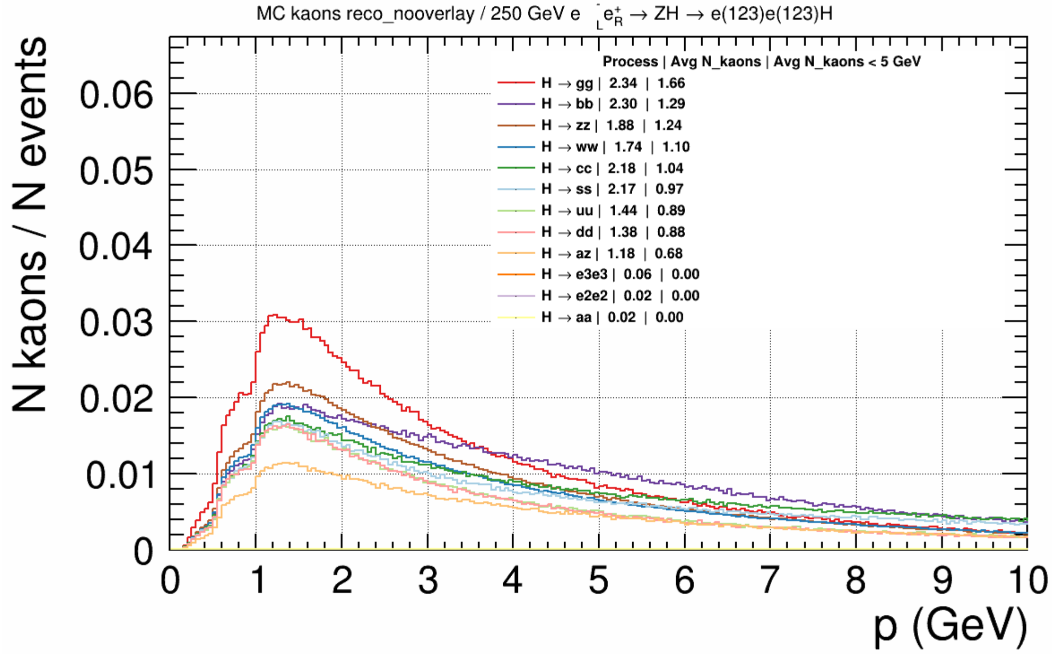


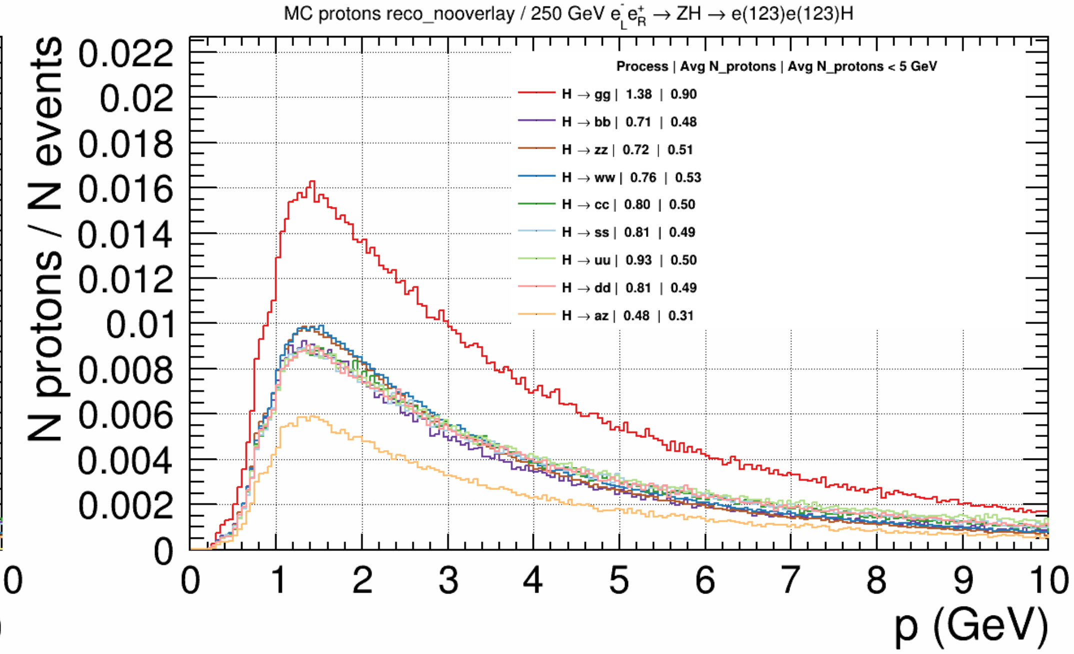
Back up: momentum spectrum of pions/kaons/protons



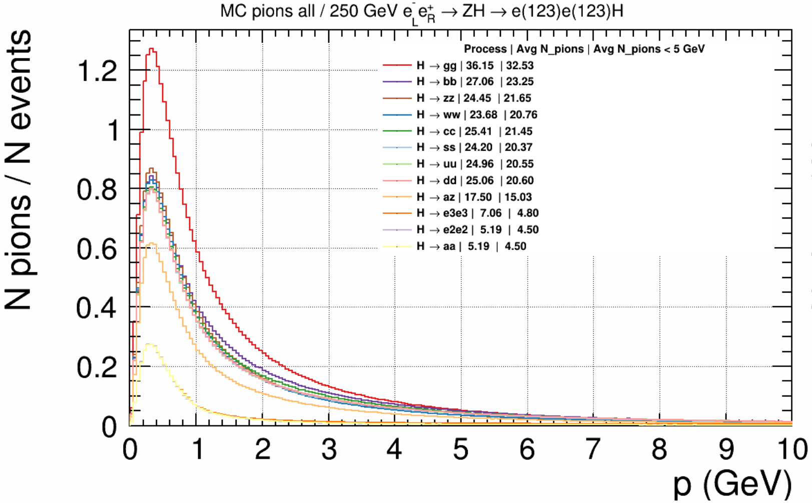


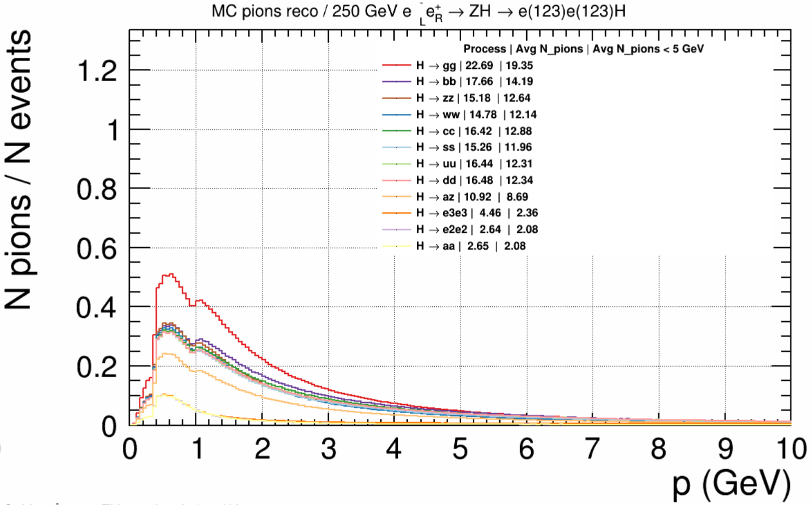
Back up: momentum spectrum of pions/kaons/protons

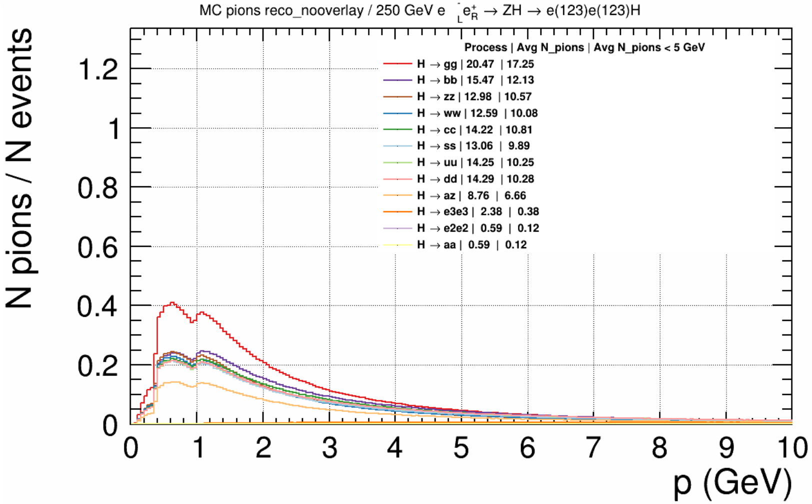




Back up: momentum spectrum of pions/kaons/protons

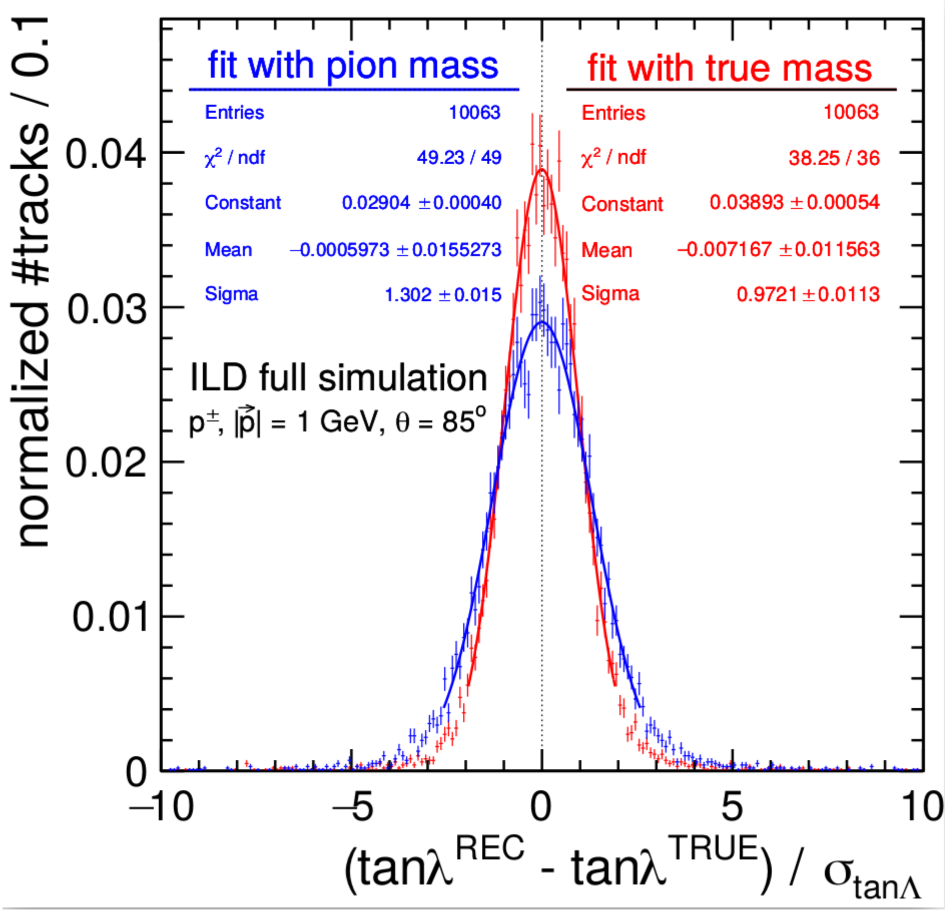




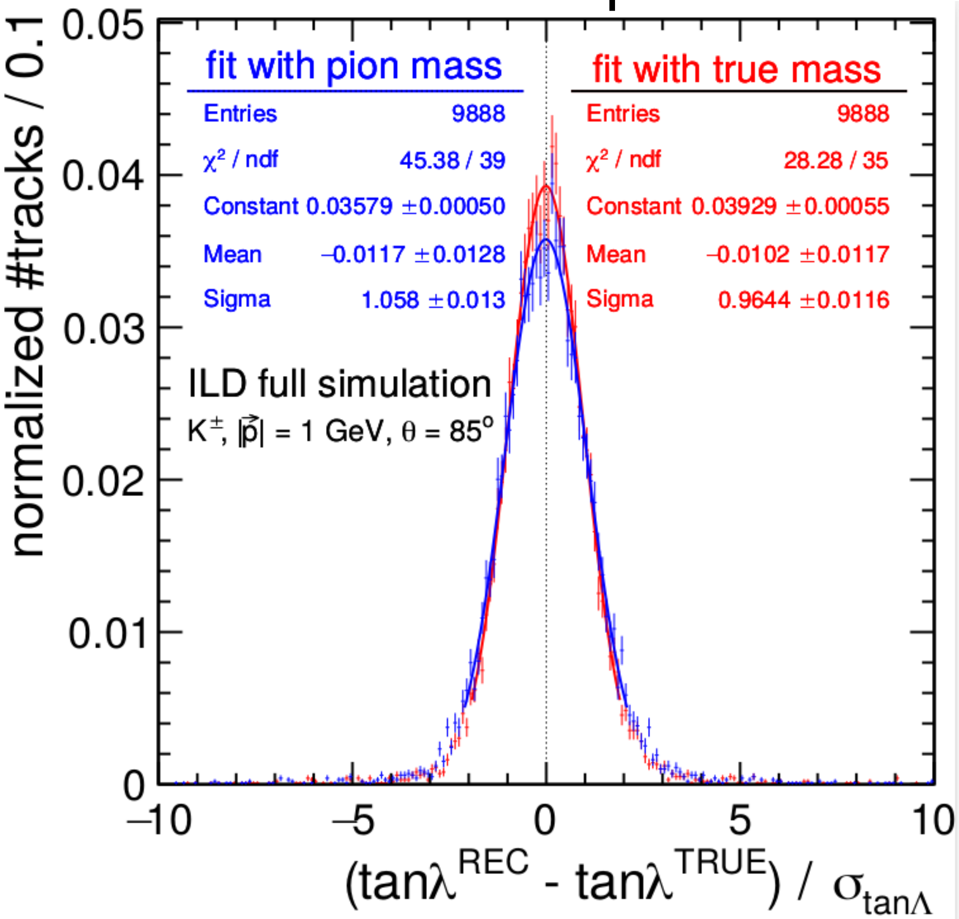


Back up: refit impact on track parameters

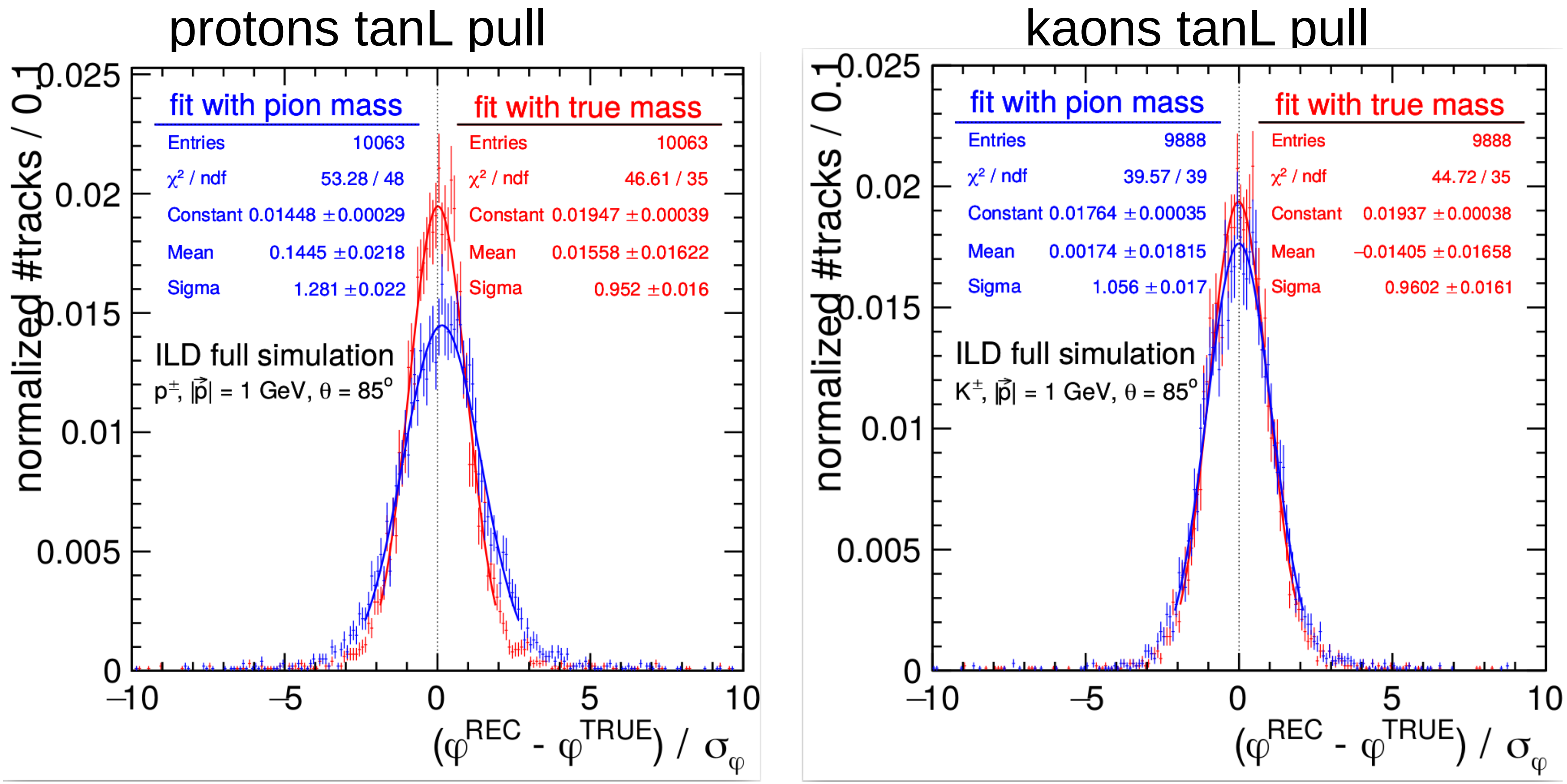
protons tanL pull



kaons tanL pull



Back up: refit impact on track parameters



Back up: My definition of a true* (reconstructable) vertex

Particle (Hadron) has a **true*** (reconstructable) vertex if:

- Hadron MCParticle has the reconstructed track
  and origin at a point further than 3 μm from the IP.

- True* vertex must have >1 tracks coming from 3 μm proximity
  (requirement of being reconstructable in principle even with ideal [3μm] precision)

P.S. I didn't do any requirements on opposite track signs (+- not required)

Back up: Classification of particles based on vertex info

Iterate over K/p with the reconstructed track

? ?

	True* vertex	Reconstructed** vertex
Good	✓	✓
Missed	✓	✗
Fake	✗	✓
Background	✗	✗

(**) Reconstructed vertex = particle is attached to any vertex by LCFIPlus
no any spacial constrains

Back up: Classification of particles based on vertex info

Note[1]: so this classification of particles, not vertices

Note[2]: This means, for each "vertex" I will have 2+ entries in the histogram.
Which is not the problem, as most of the vertices consist of only 2 tracks.
And I think I limit my plots only for vertices with 2 tracks

Note[3]: I don't require any spacial agreement, but looking at the pull position distribution, it is not necessary → position agrees