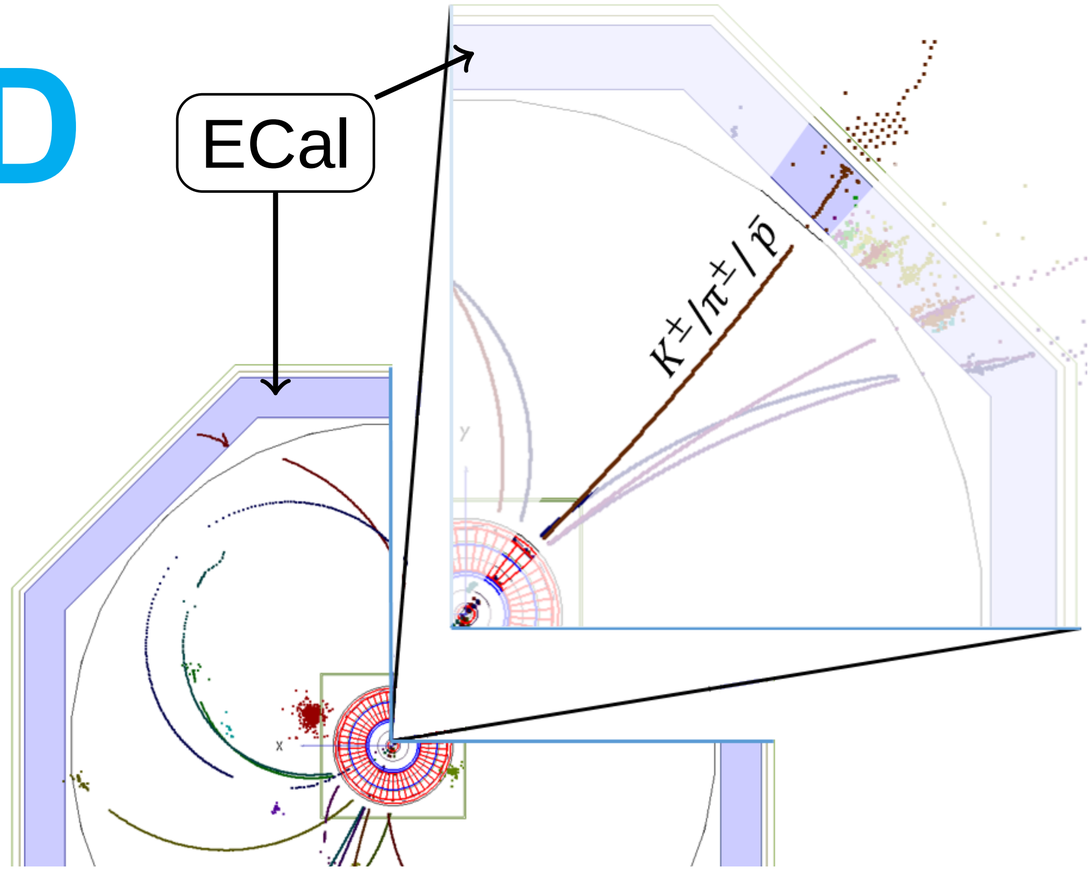
Fast Timing for PID



LCWS 2024
Tokyo University
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[1] Deutsches Elektronen-Synchrotron DESY
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[3] Georg-August-Universität Göttingen

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Introduction

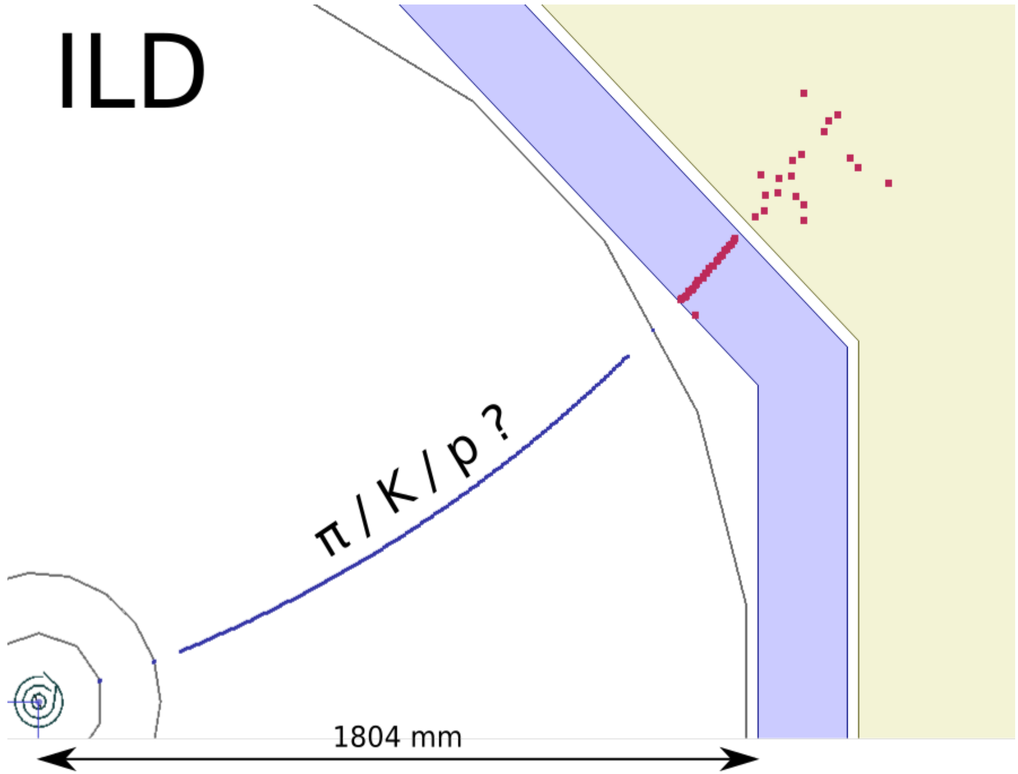
Fast time measurements for Higgs Factory detectors?

- ToF traditionally widely used eg in heavy ion experiments (STAR, NA61/SHINE, ALICE)
- significant hardware progress: 10ps timing and better in reach, e.g. LGADs & Co
- HL-LHC: ATLAS & CMS implement fast timing layers for pile-up mitigation, LGADs and crystals with SiPMs (30-40ps)
- Can Higgs Factories profit?
  - reject hits from other BX or backscatter ~ O(ns) sufficient, foreseen already (eg CLICdp)
  - integrate time information into ParticleFlow(5D) => work starting, probably O(100ps) can already achieve a lot
  - **This talk: ToF for Kaon and proton identification (PID)?**
- What can we gain?
  - with TPC, i.e. dE/dx
  - without TPC
- Today:
  - State-of-the-Art ToF reconstruction in ILD
  - Benefit for PID

State-of-the-Art ToF

Working principle

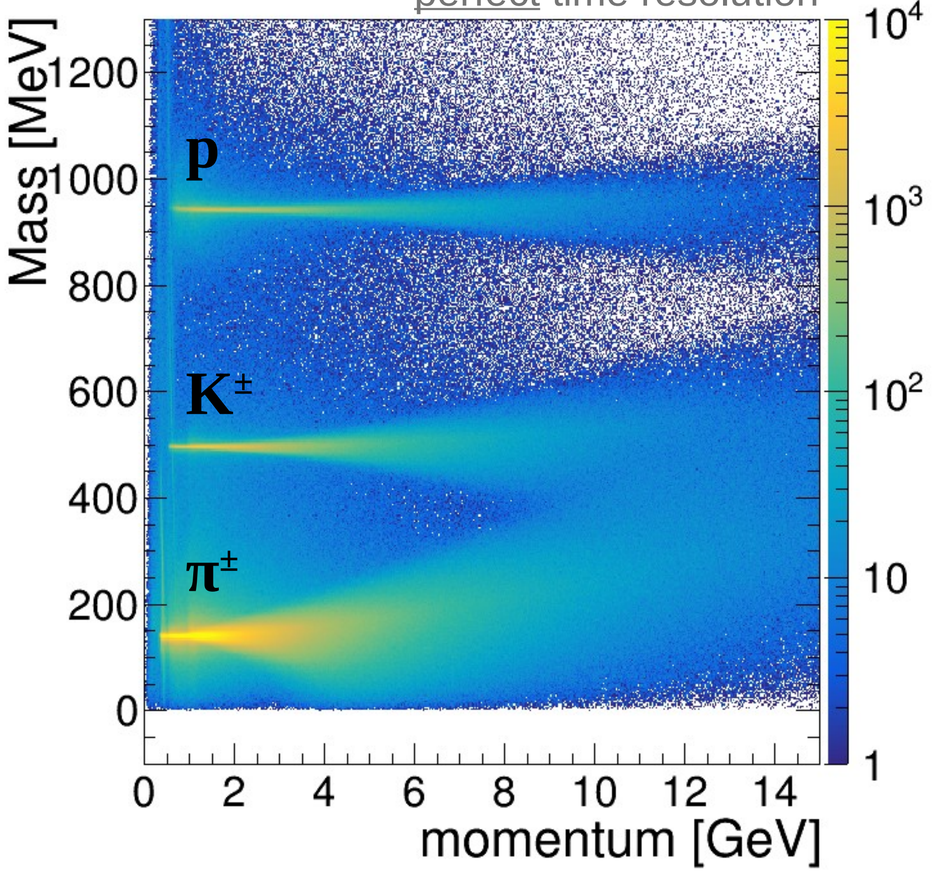
The basic ingredients



the master formula:

$$m = p\sqrt{\frac{c^2T^2}{L^2} - 1}$$

ILD full reconstruction
perfect time resolution



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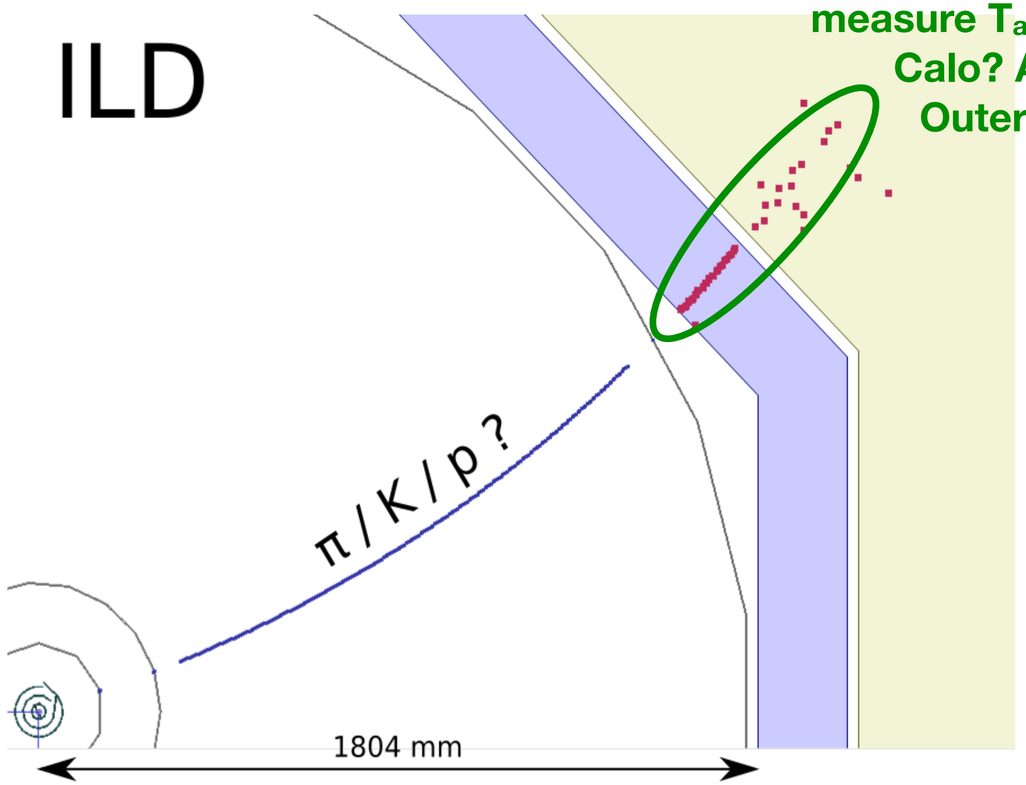

measure $T_{arrival}$ of particle:
Calo? Algorithm?
Outer tracker?

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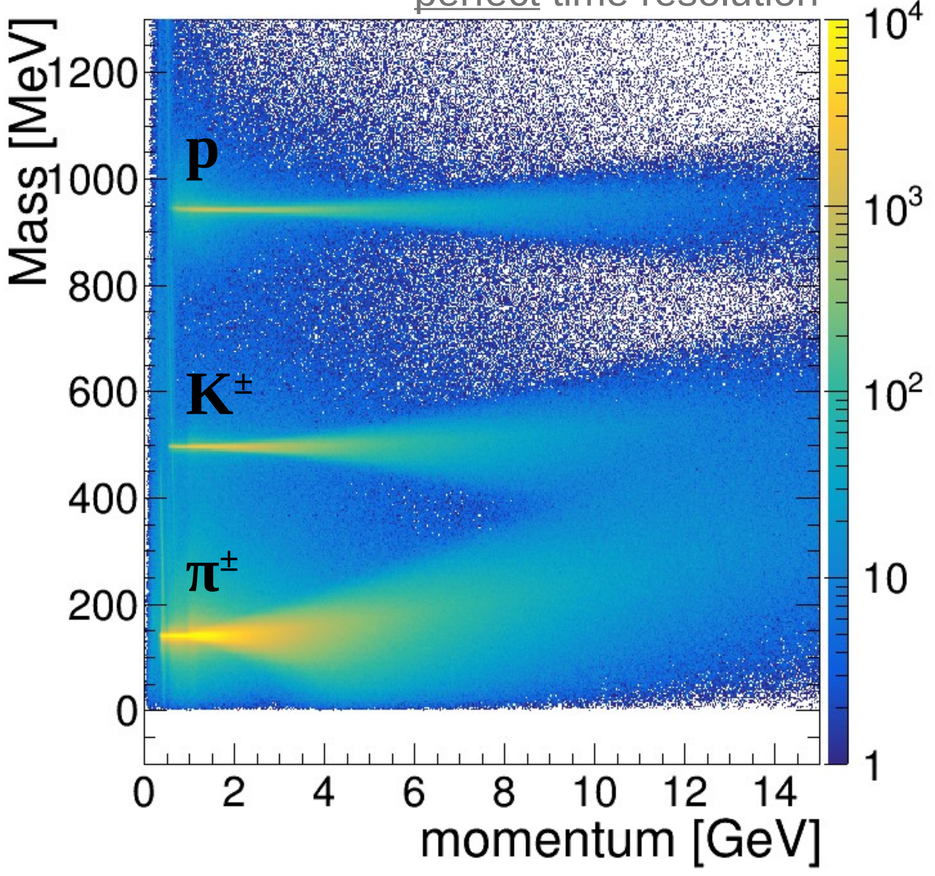

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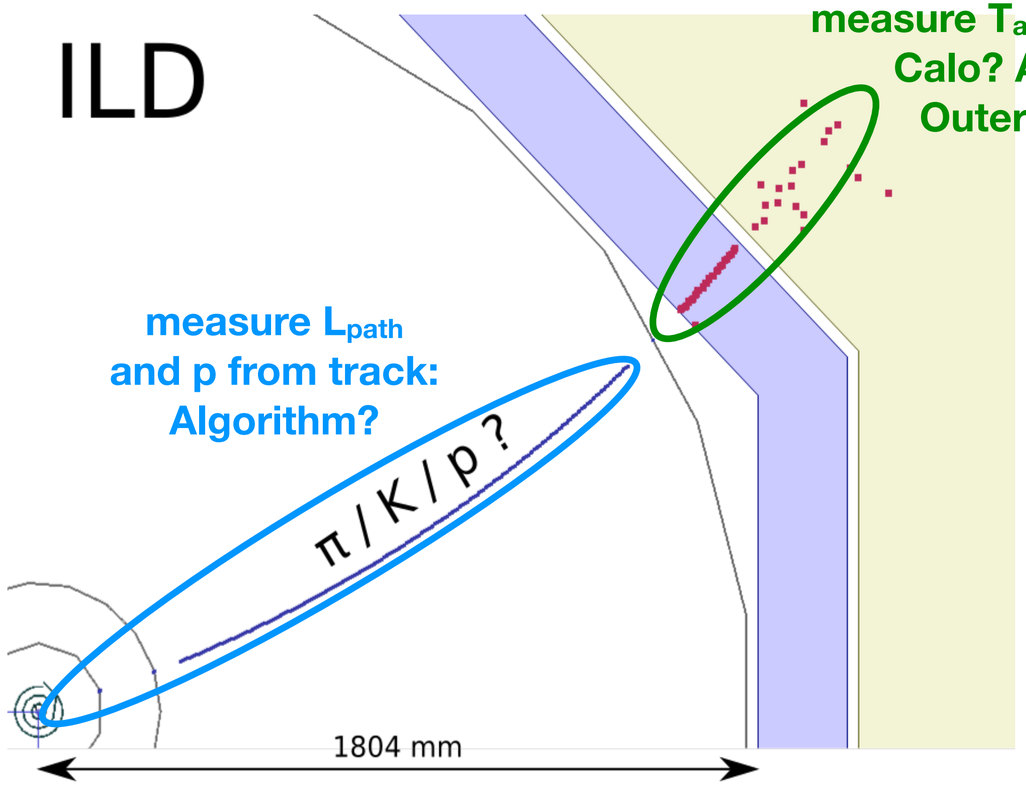

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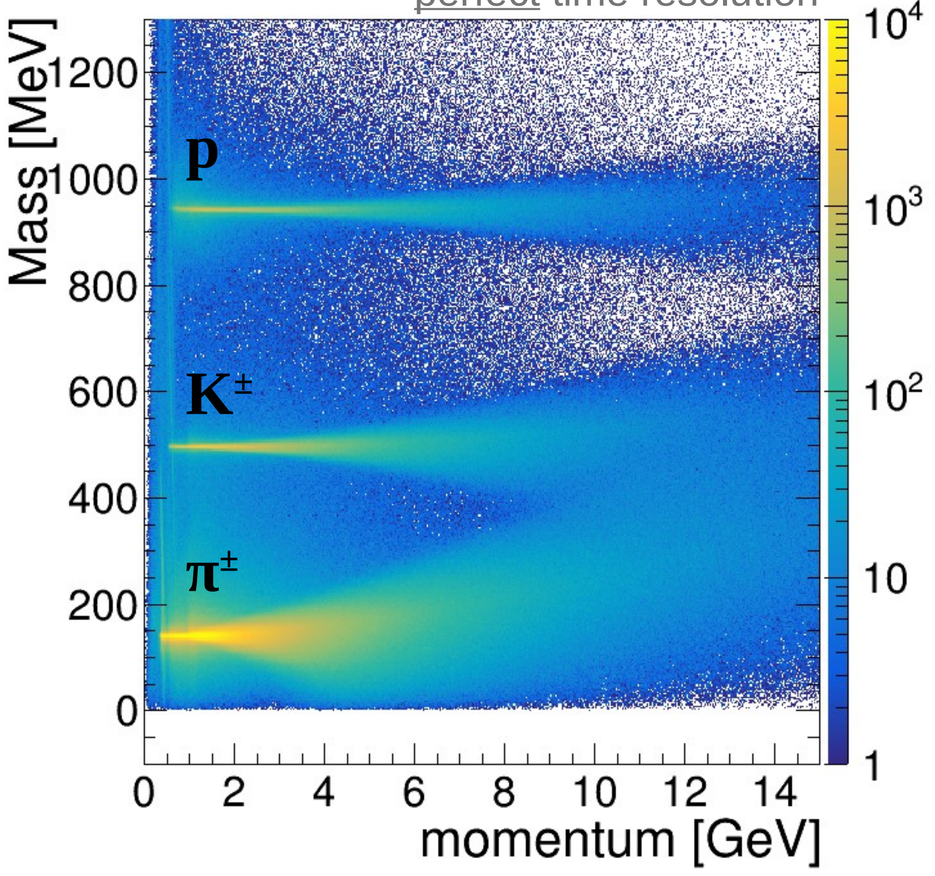
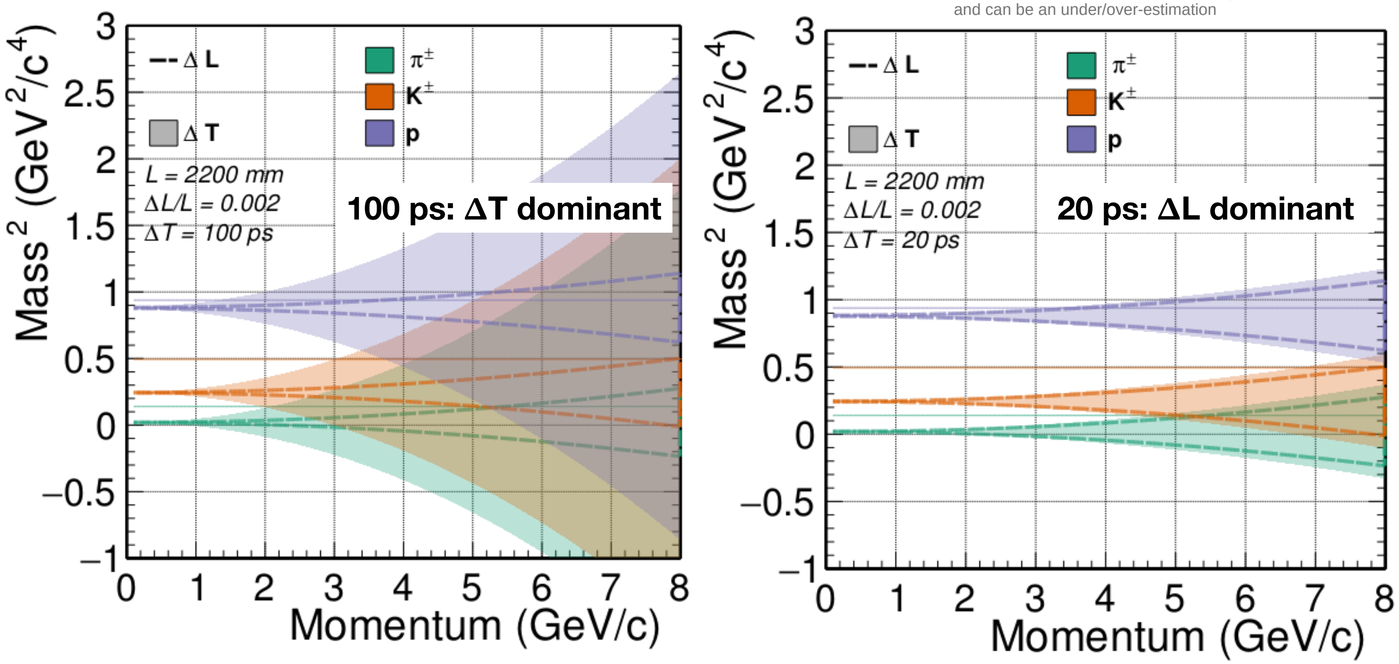


Track Length

The first surprise….

- precise track length very important for $\Delta T < 100$ps!
- rule of thumb: ΔT=10 ps ~ ΔL = 3 mm
  - which track parameters?
  - from which track state?

Note: ΔL/L = 0.002 serves as an example and can be an under/over-estimation



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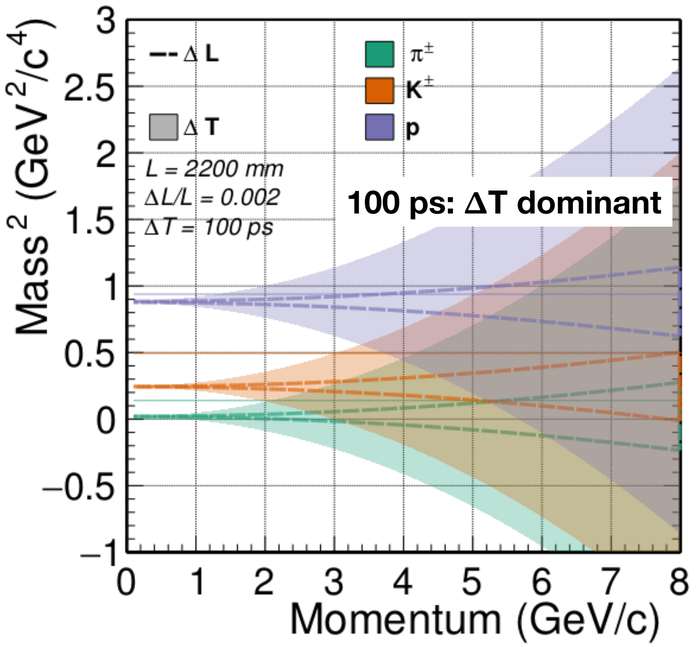

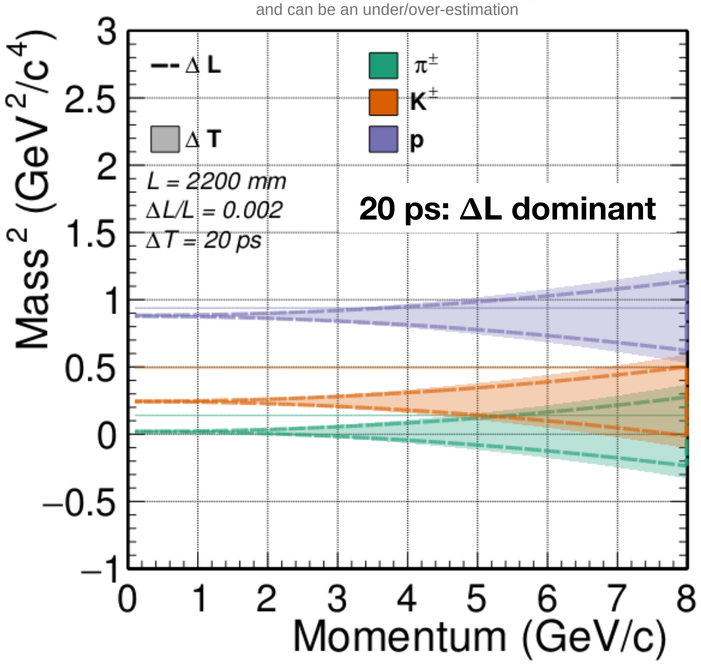

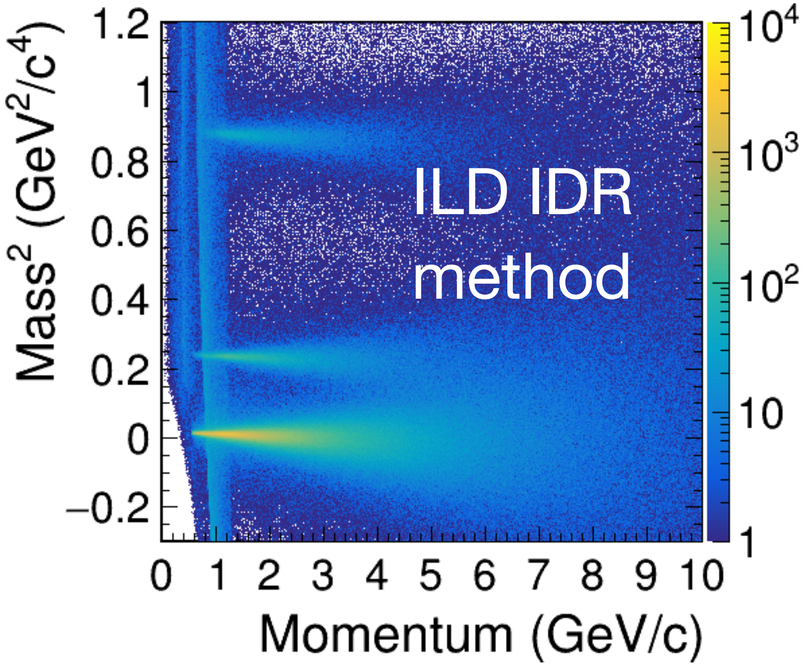

$$L = \frac{\varphi_{\mathrm{IP}} - \varphi_{\mathrm{ECAL}}}{\Omega_{\mathrm{IP}}} \sqrt{1 + \tan^2 \lambda_{\mathrm{IP}}}$$

$$m^2c^4 = (pc)^2_{\mathrm{IP}} \cdot \left(\frac{c^2 T^2}{L^2} - 1 \right)$$

with perfect ΔT

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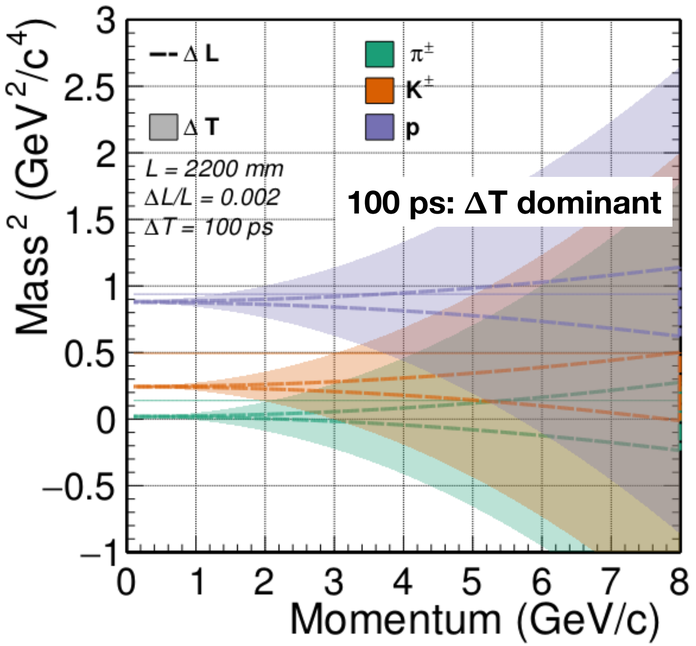

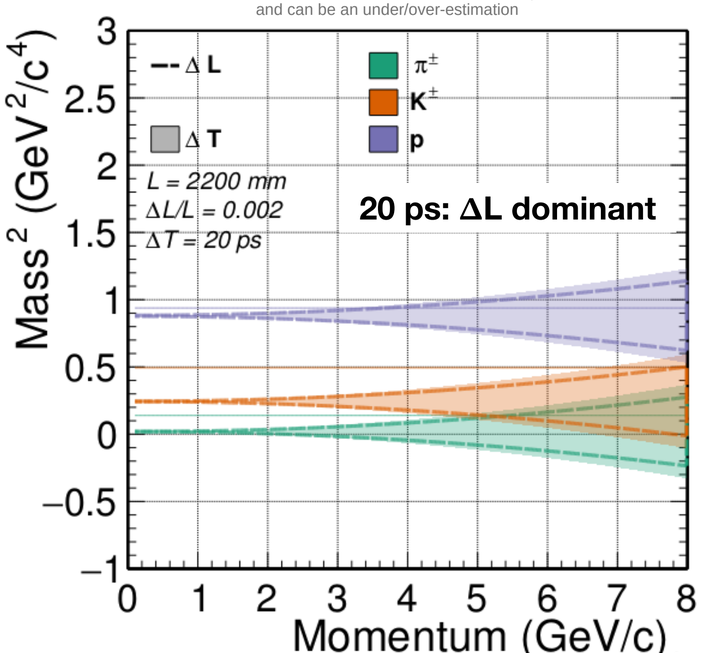

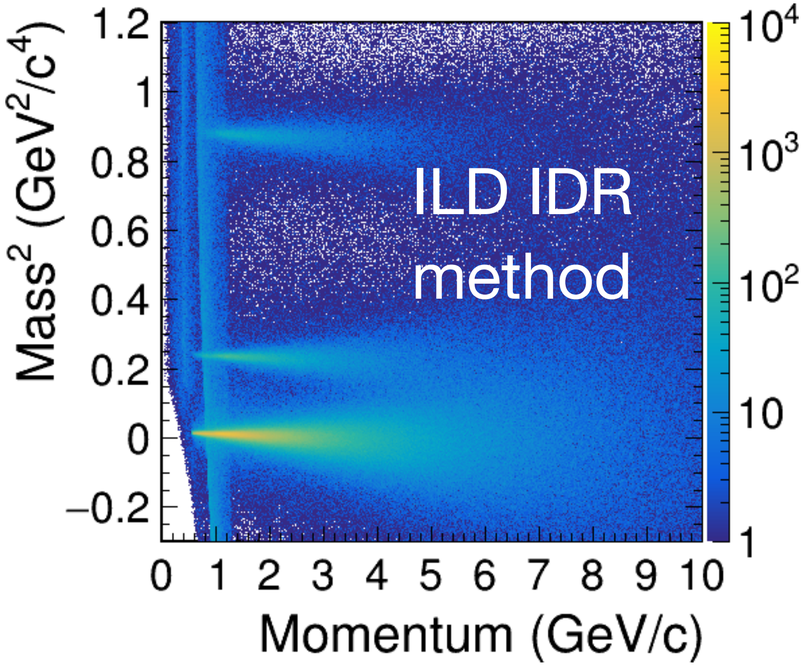

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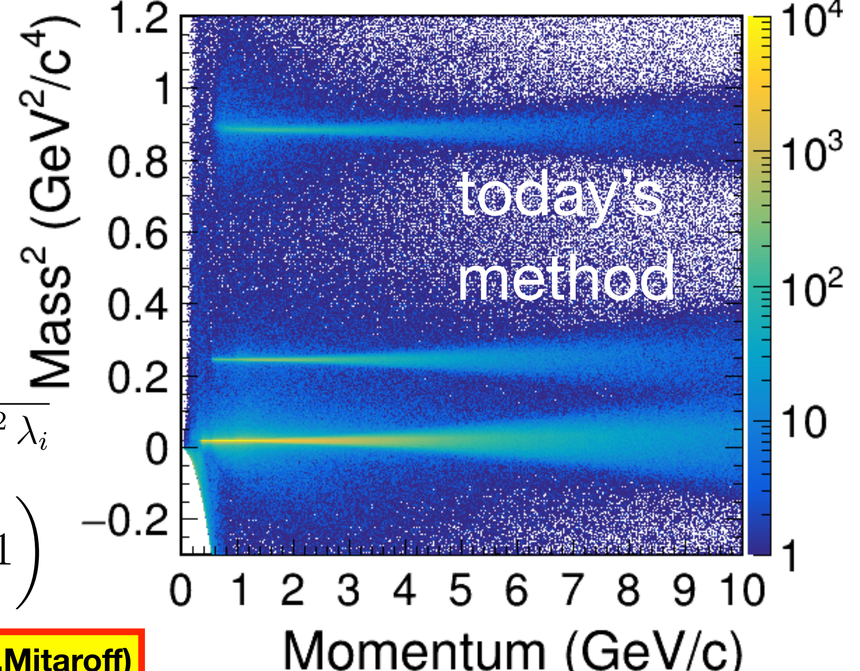
$$L = \sum_{i=1}^{N_{\mathrm{hits}}-1} L_i = \sum_{i=1}^{N_{\mathrm{hits}}-1} \left| \frac{z_{i+1} - z_i}{\tan \lambda_i} \right| \sqrt{1 + \tan^2 \lambda_i}$$

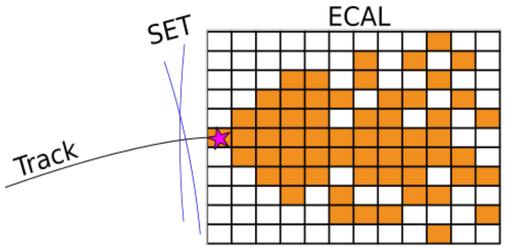
$$m^2c^4 = \left\langle (pc)^2 \right\rangle_{HM} \cdot \left(\frac{c^2T^2}{L^2} - 1 \right)$$

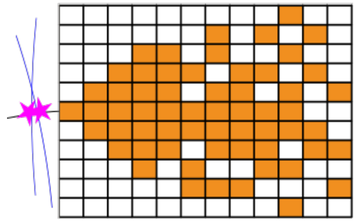


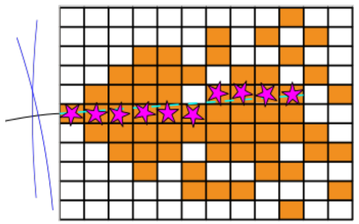
c.f. also arXiv: 2107.02031 (W.Mitaroff)

ToF Implementation

Overview







	First ECAL layer dedicated for timing	Two external tracker layers	10 ECAL layers (conservative timing)
Placement:			
Assumed hit time resolution:	~ 30 ps	~ 50 ps	~ 100 ps
Expected TOF resolution:	~ 30 ps	$\sim \frac{50}{\sqrt{2}}$ ps	$\sim \frac{100}{\sqrt{10}}$ ps

- Hit time reconstruction is very simplified
  (no digitization effects, only Gaussian smear of MC true time)
- Central question: what is the best way for TOF reconstruction?

Fast timing in the whole ECAL is likely not feasible:
→ high power consumption
→ requires active cooling
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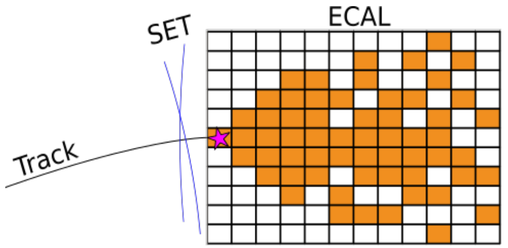

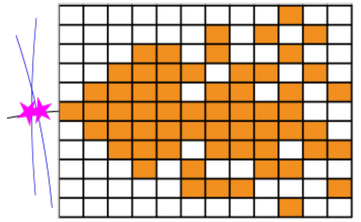

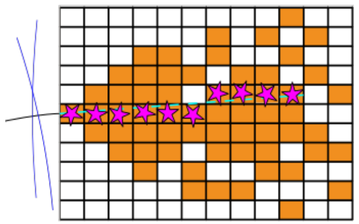

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- clock jitter
- dependence on size of signal
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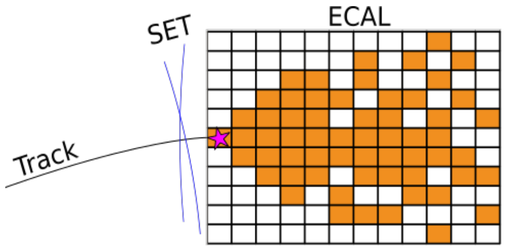

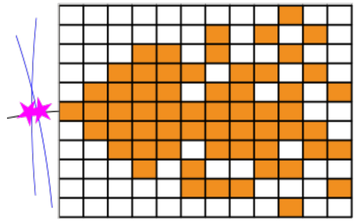

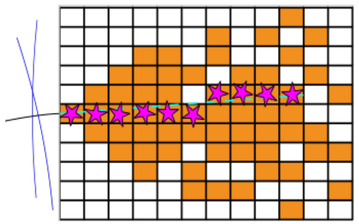

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- **Is 1/sqrt(N_{hit}) achievable in pratice?**

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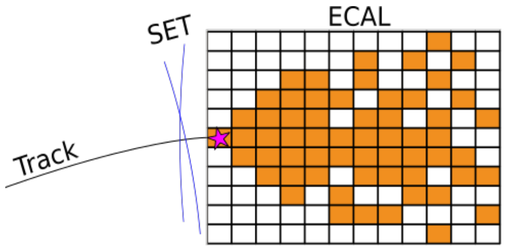

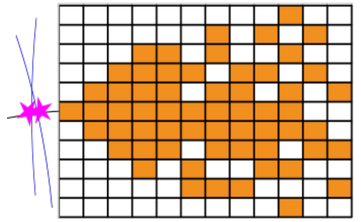

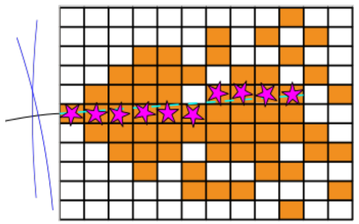

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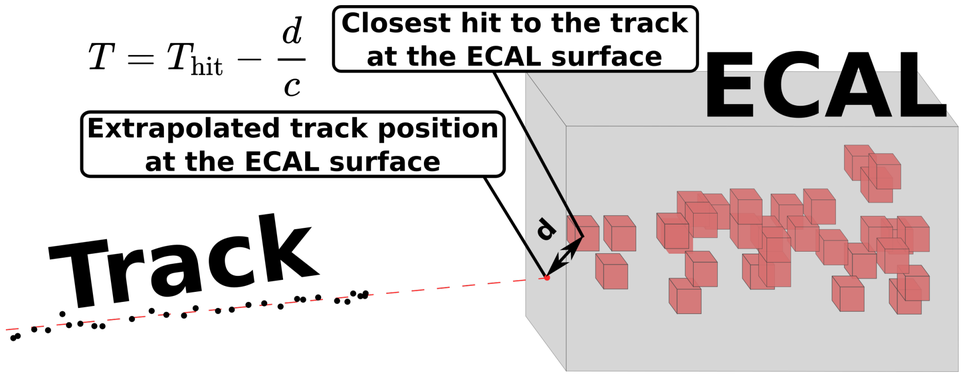
$$T = T_{\text{hit}} - \frac{d}{c}$$



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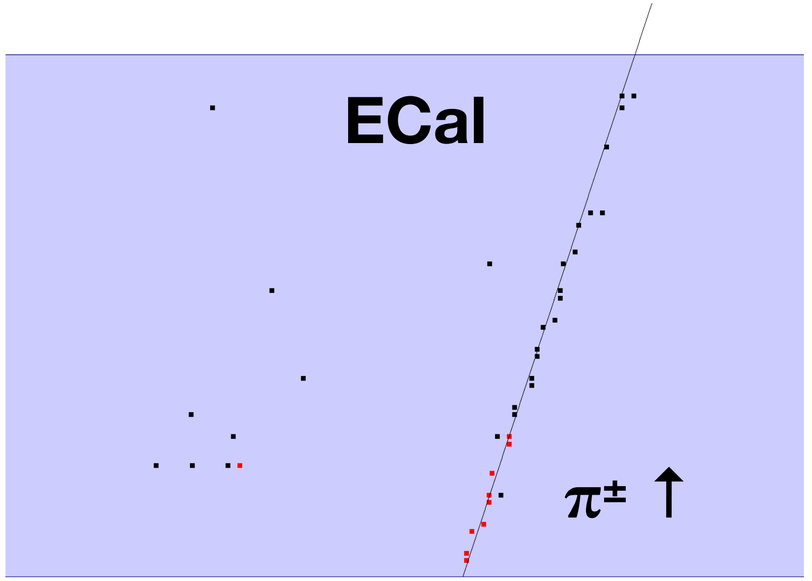
Methods for Calo ToF Reconstruction I

Cylinder Method

- Baseline ILD IDR: take closest hit to extrapolated track in each layer
- New: “Cylinder” - optimised outlier rejection in terms of
  - radius from track
  - median hit time
- for 50 ps hit time resolution achieve ΔT = 17 ps ToF



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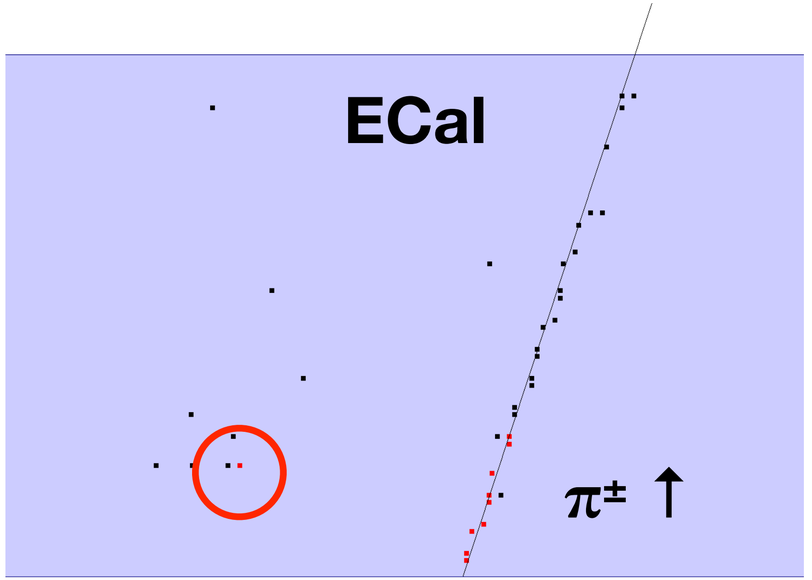

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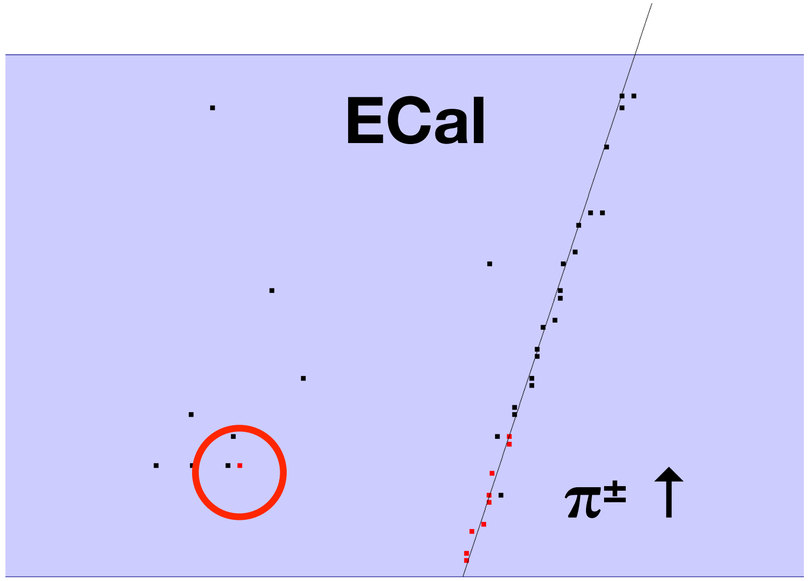

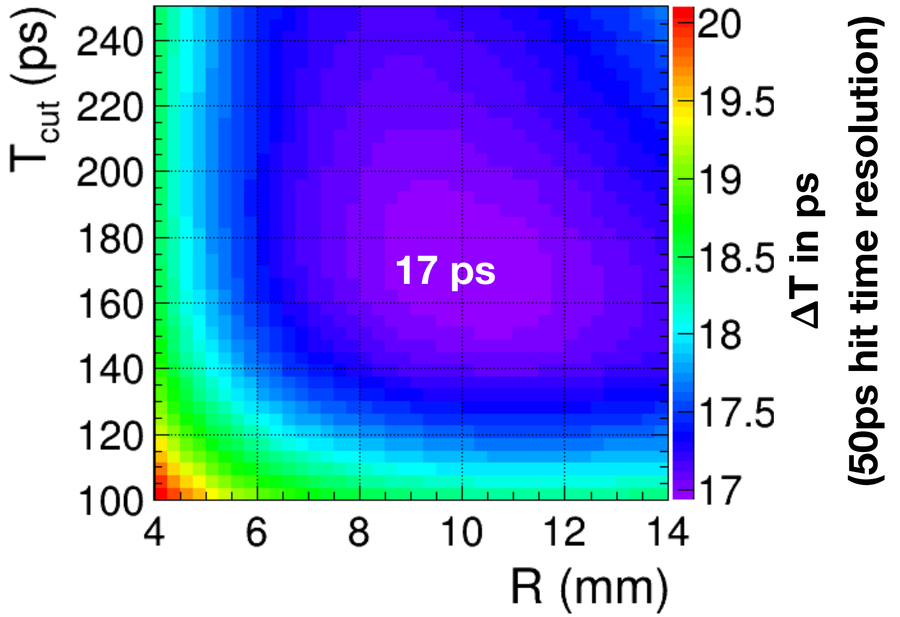

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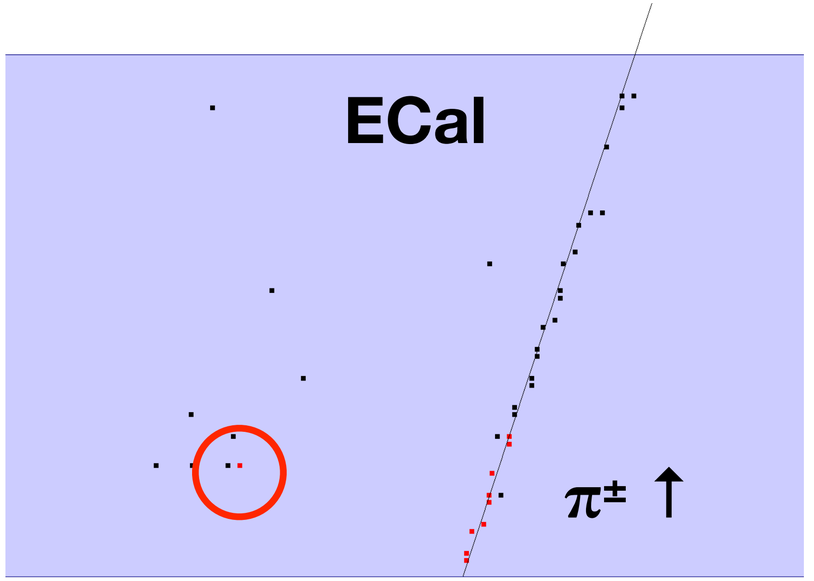

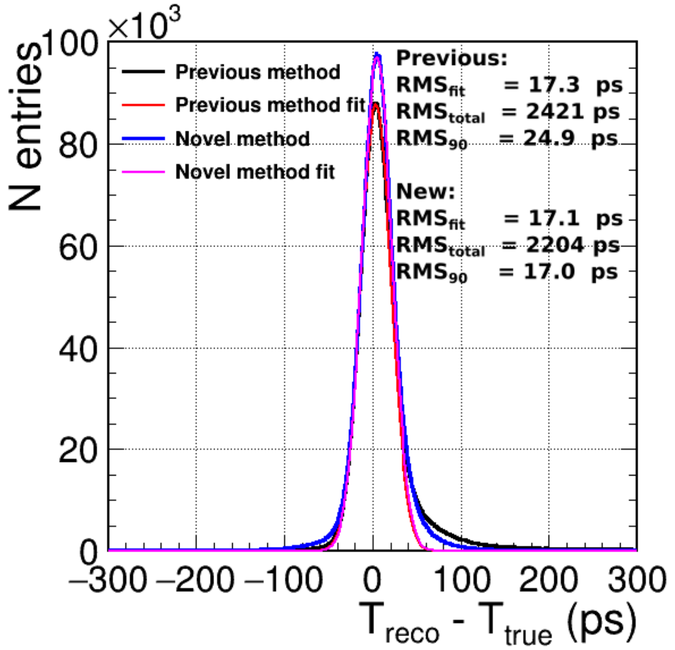

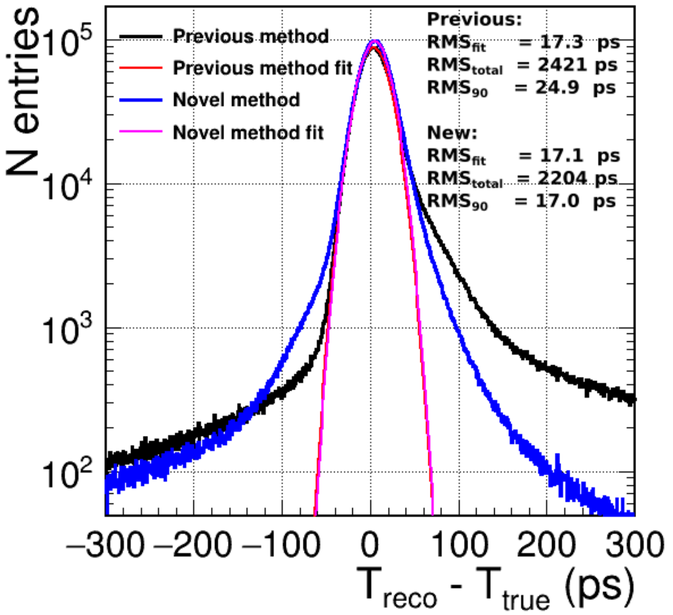

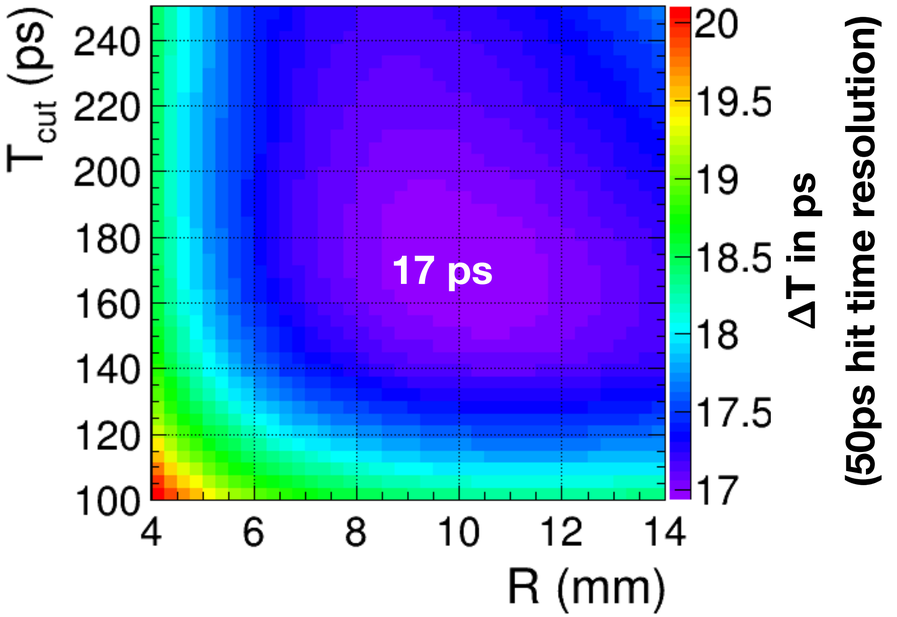

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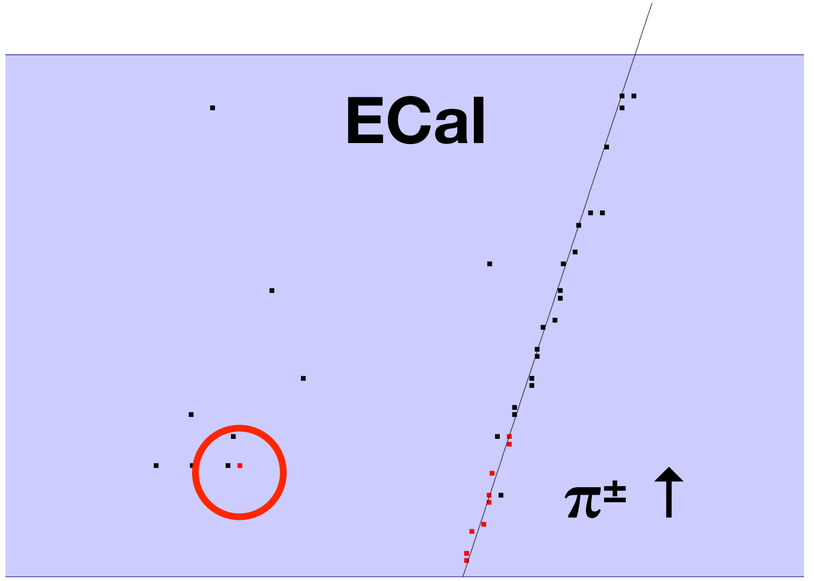
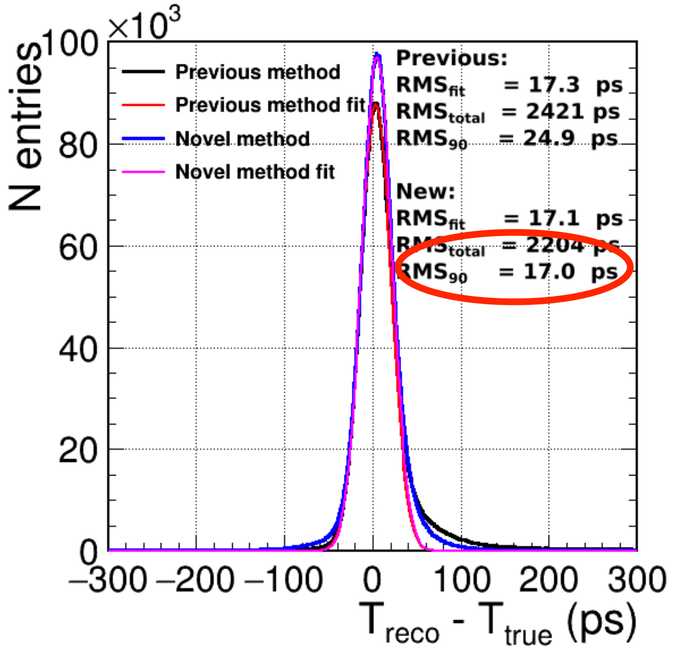
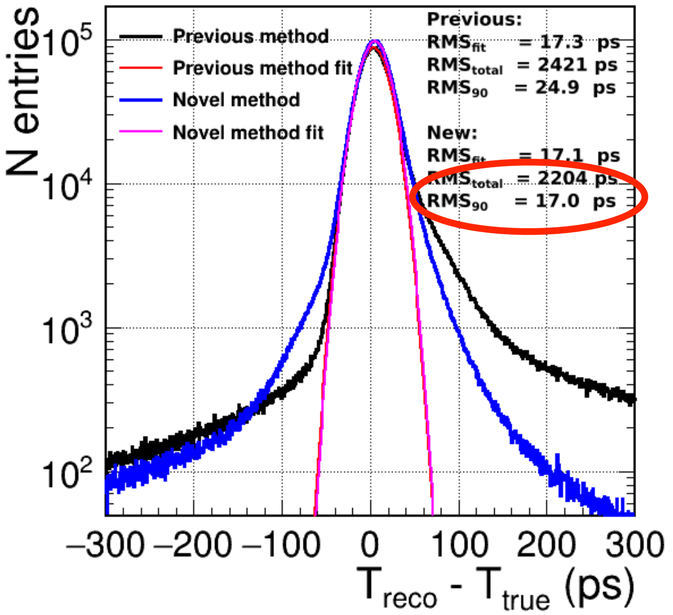
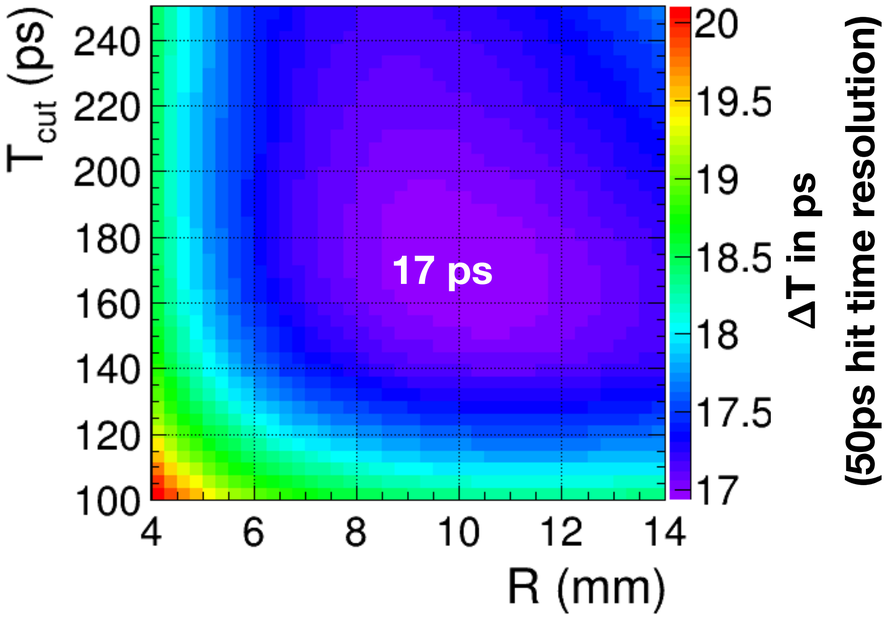


ΔT(ToF) ≈ ΔT(hit) / √ (N_{hit}) holds !







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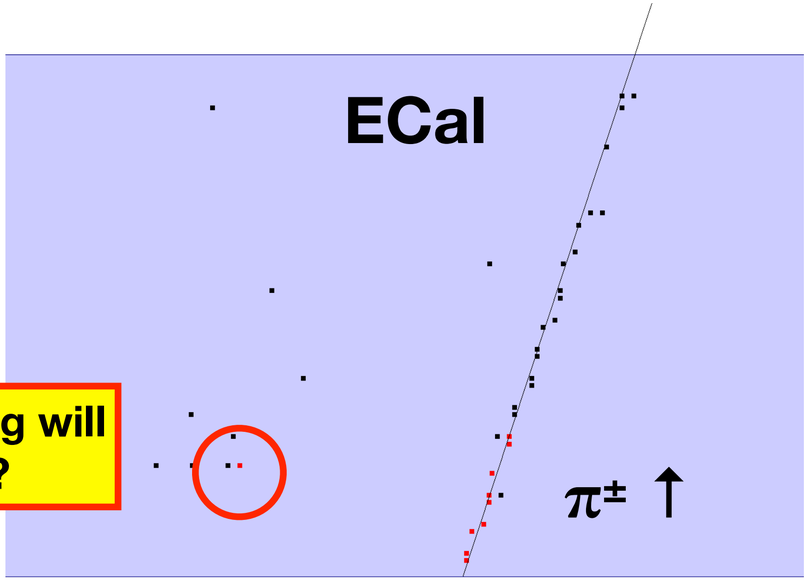
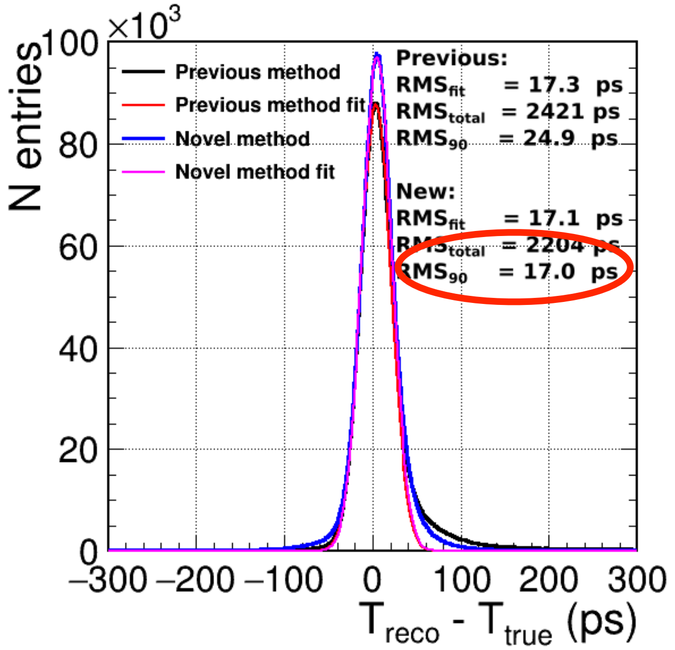
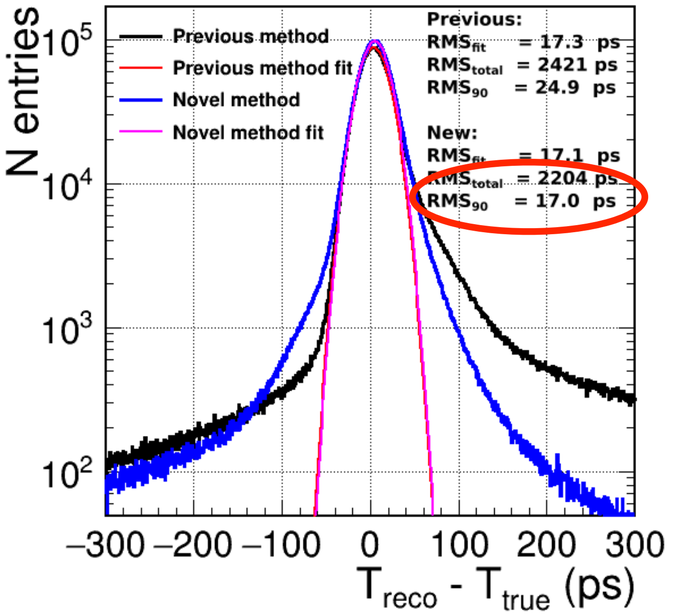
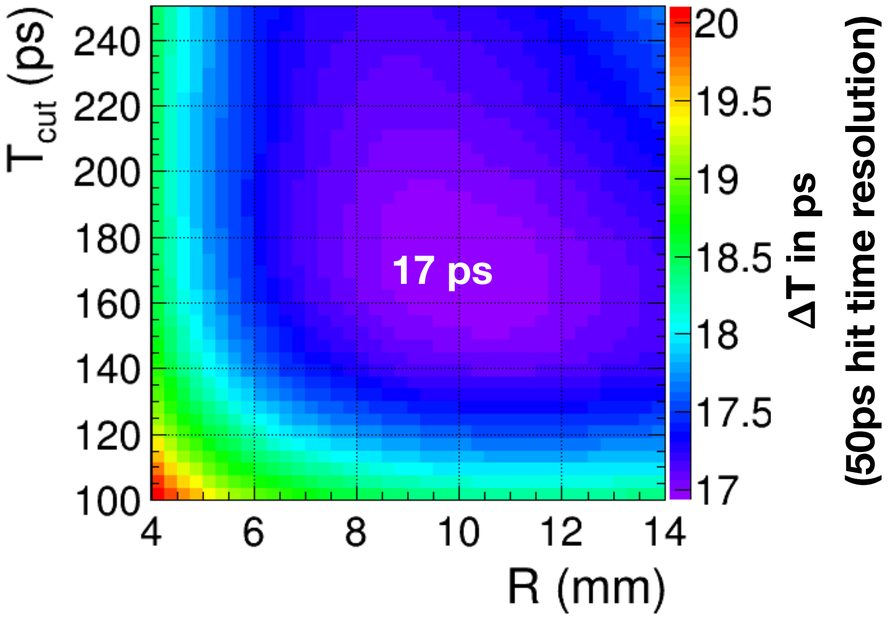


Strong hint that timing will also help PFlow?

ΔT(ToF) ≈ ΔT(hit) / √ (N_{hit}) holds !







Methods for Calo ToF Reconstruction II

Machine-Learning!

Transformer Network

- hit position (3D)
- hit time
- hit energy
- dist(3D) to ECal entry point
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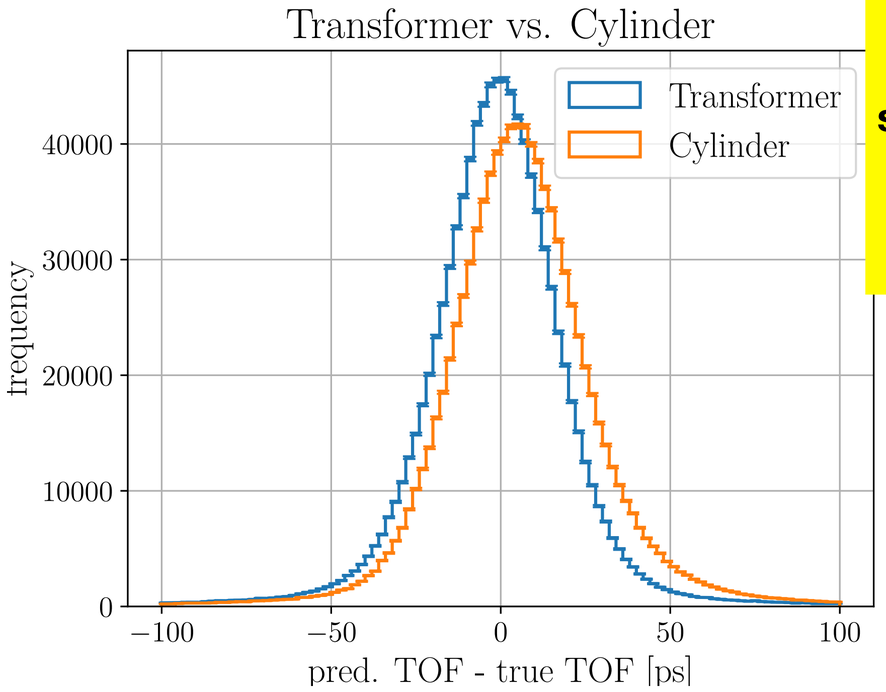

π,K,p mix:
transformer slightly better resolution, much less bias!

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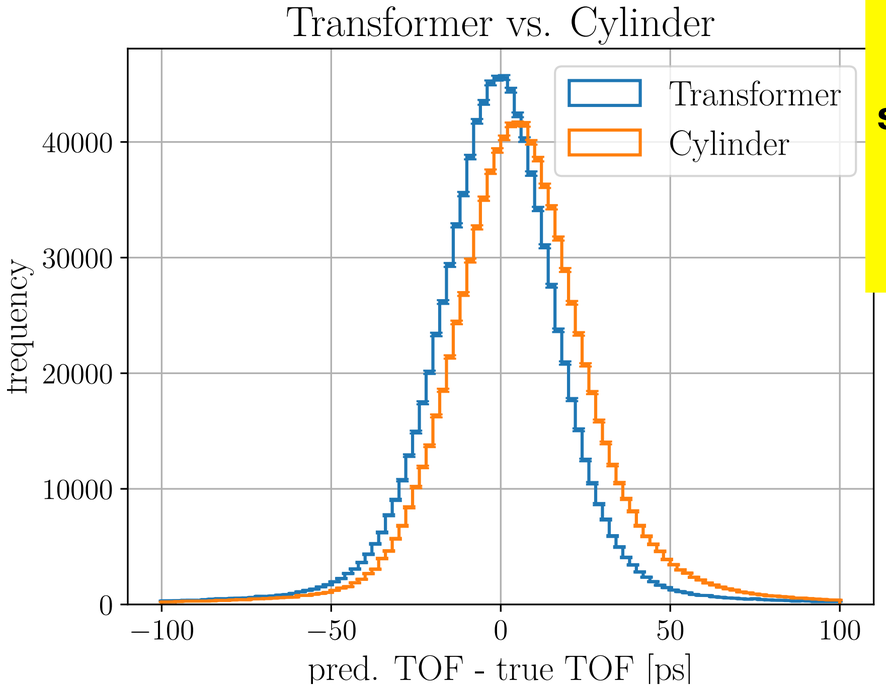

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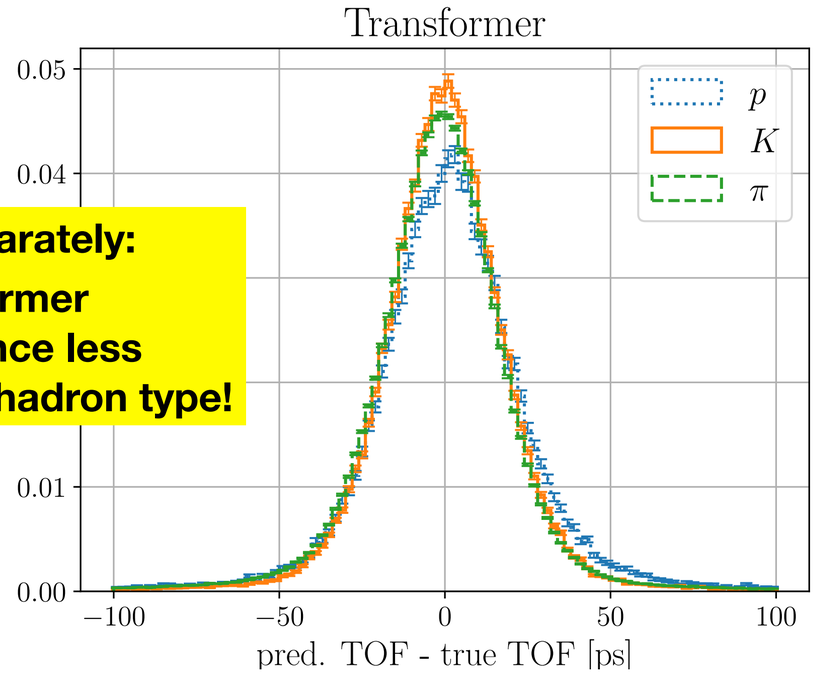
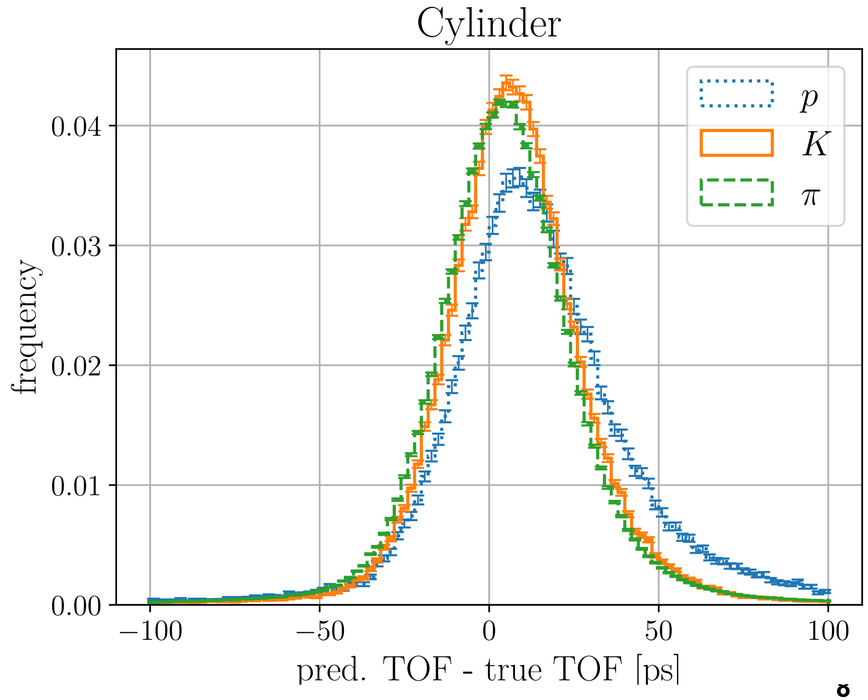
π,K,p separately: transformer performance less dependent on hadron type!





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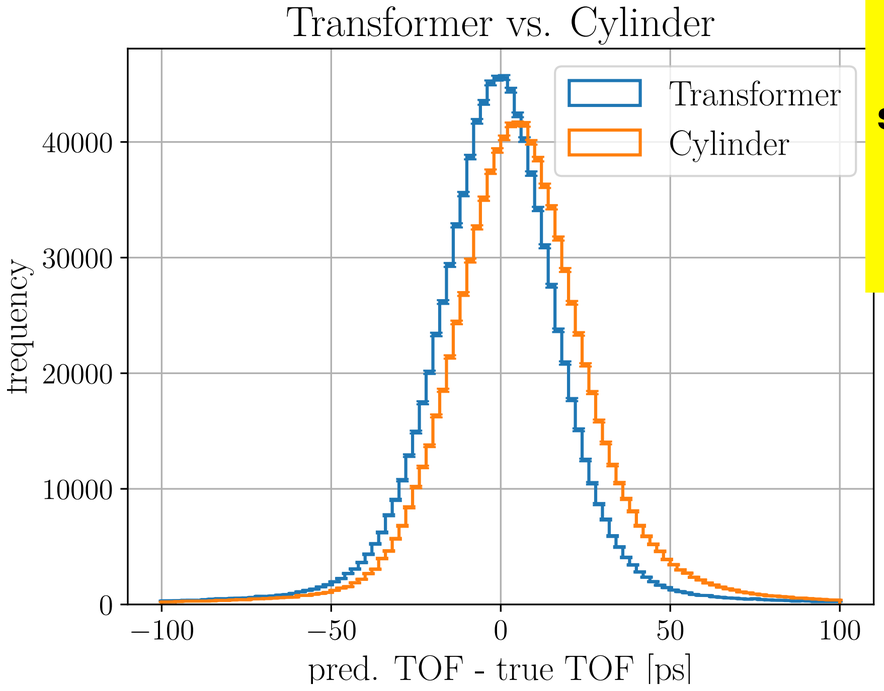

π,K,p mix: transformer slightly better resolution, much less bias!

reminder: time resolution dependence on hit energy currently not simulated, probably transformer would easily learn to correct since it uses E_{hit}

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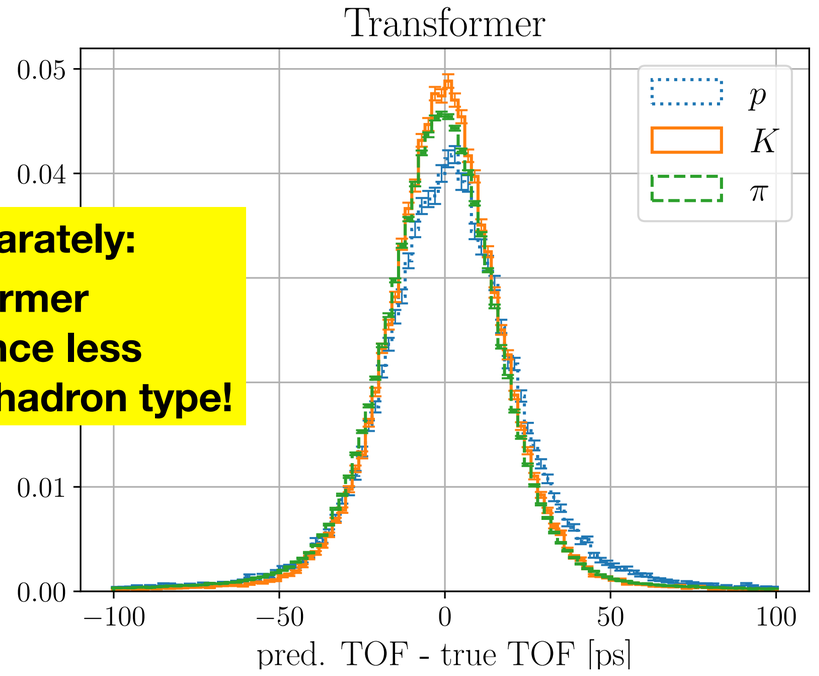

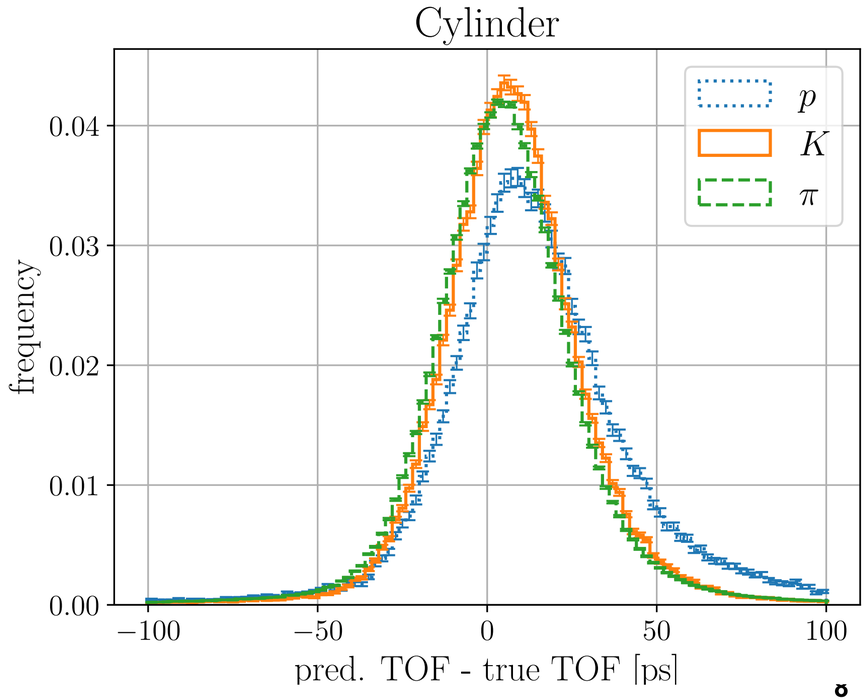

Impact on pi/K/p ID

Definition of Separation Power

between different particle species

- thin slices in p
- define

$$\varepsilon = \text{efficiency} = \frac{S}{S_0} = \frac{\text{correctly identified signals}}{\text{all signal events}}$$

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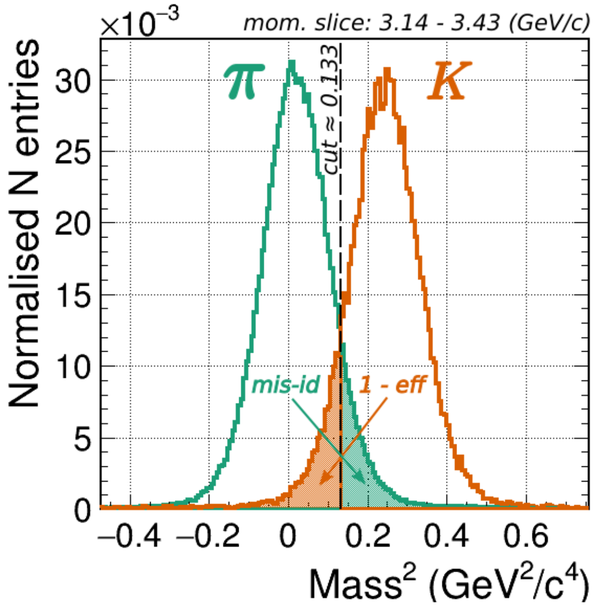

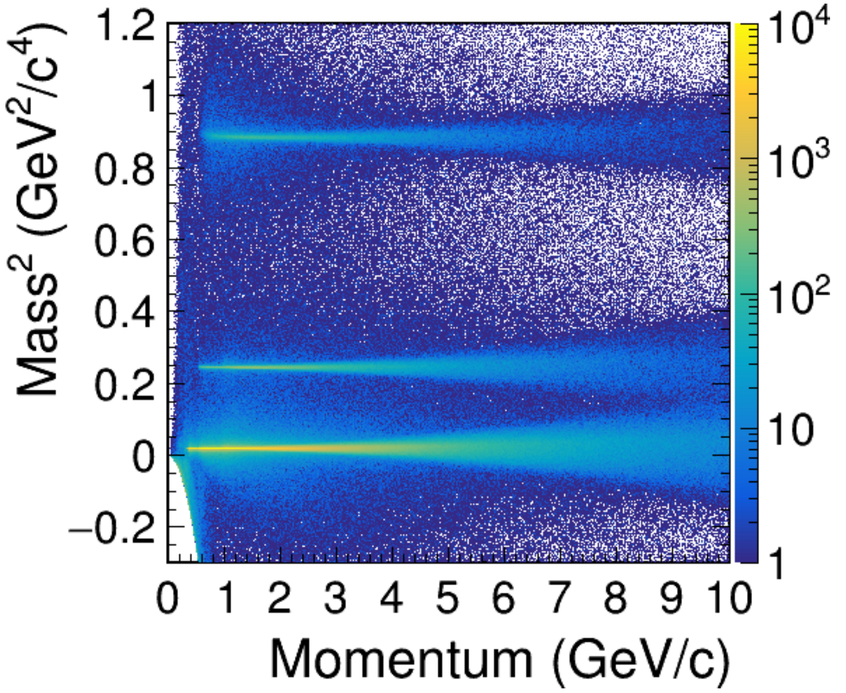

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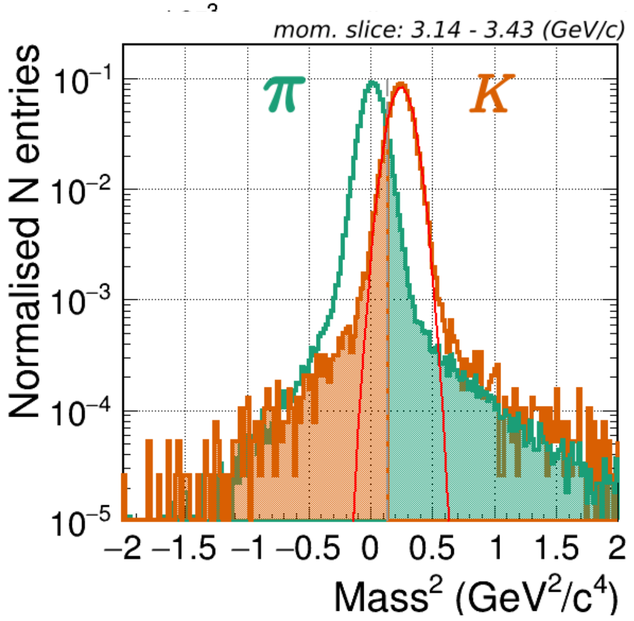

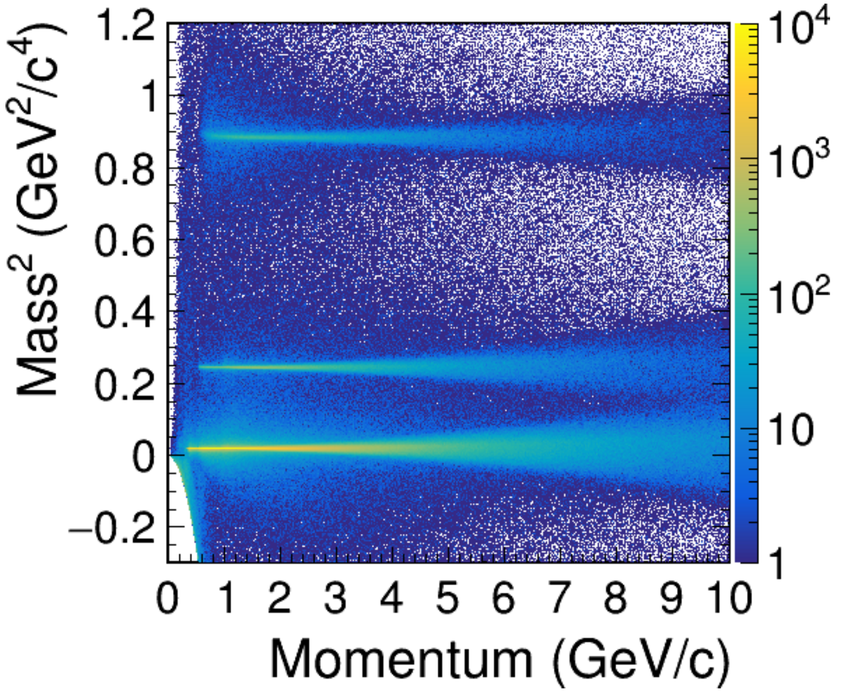

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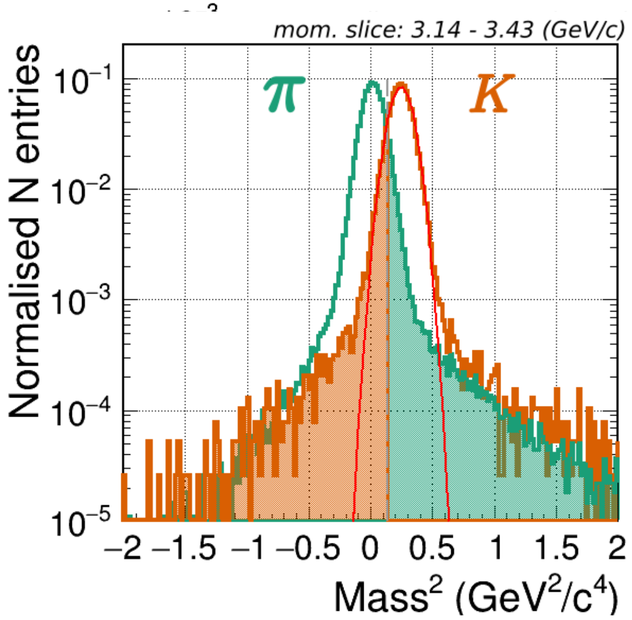

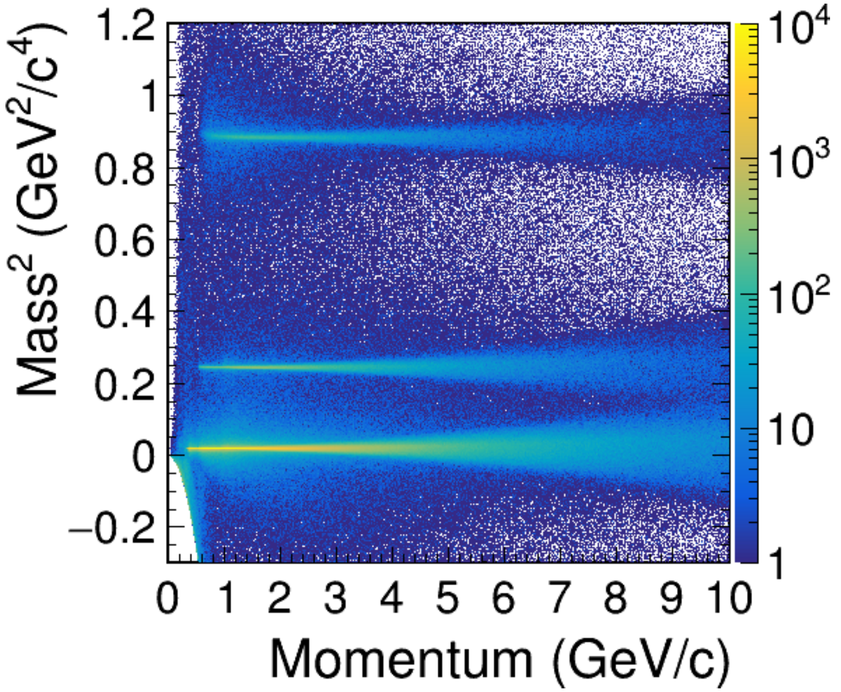

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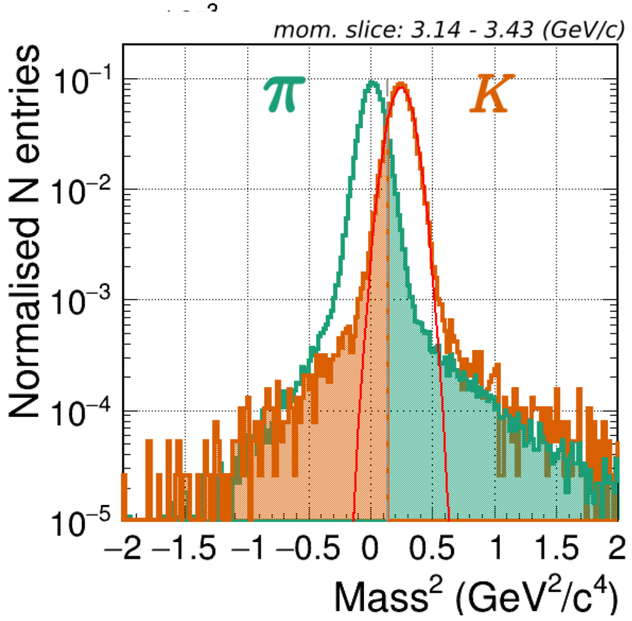
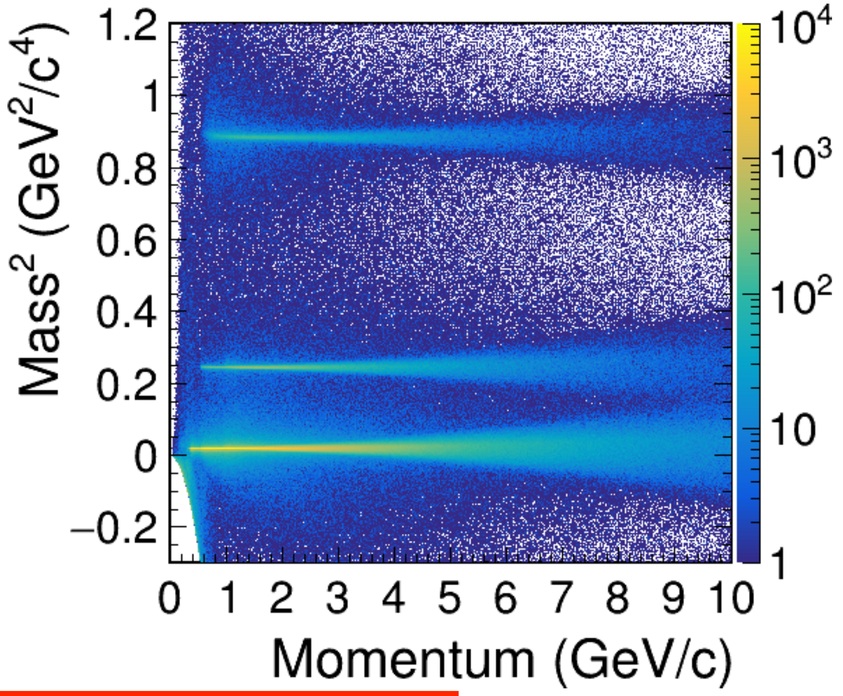
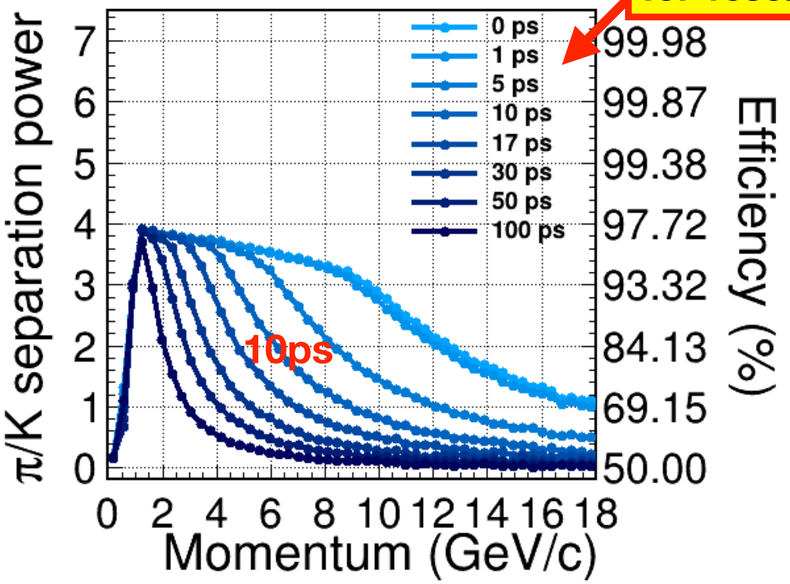
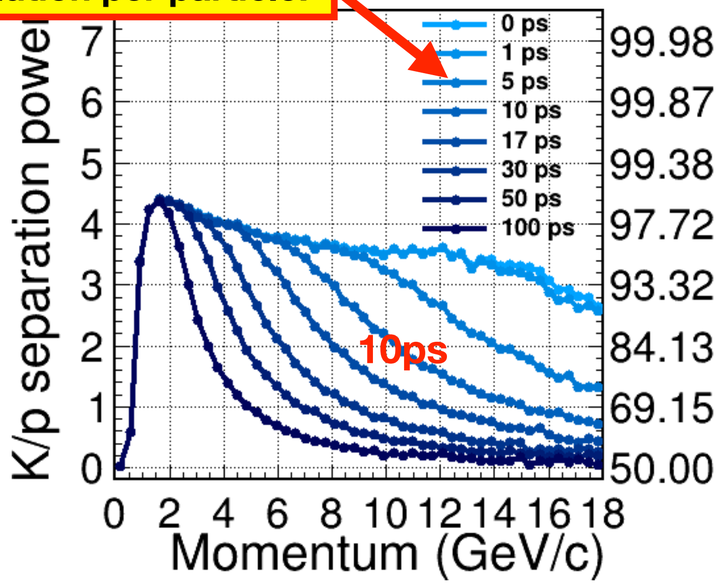




ToF resolution per particle!





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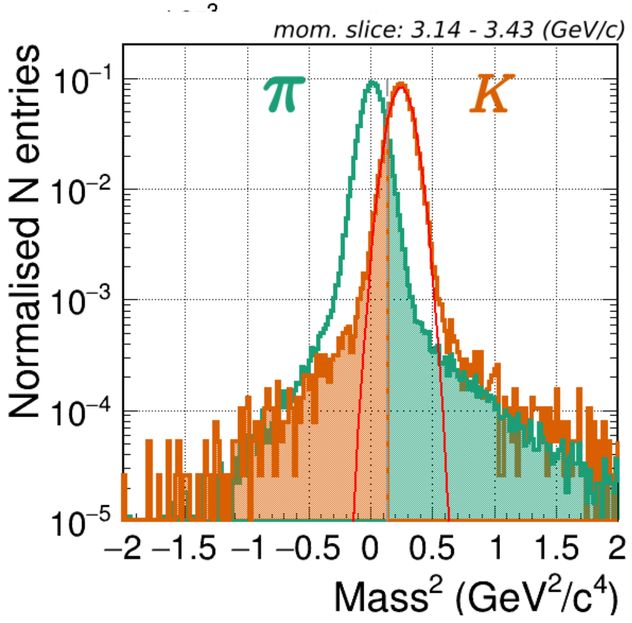

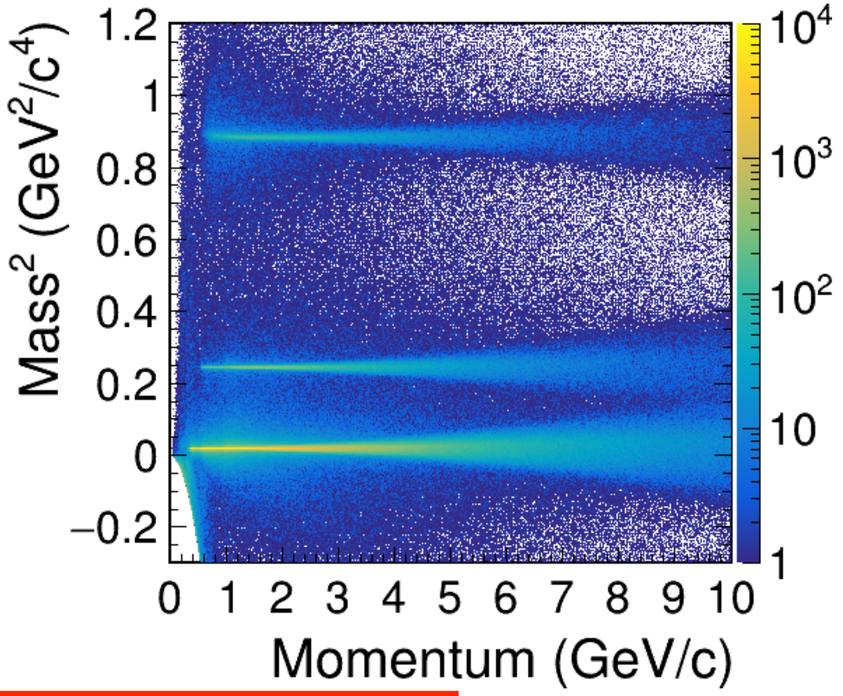

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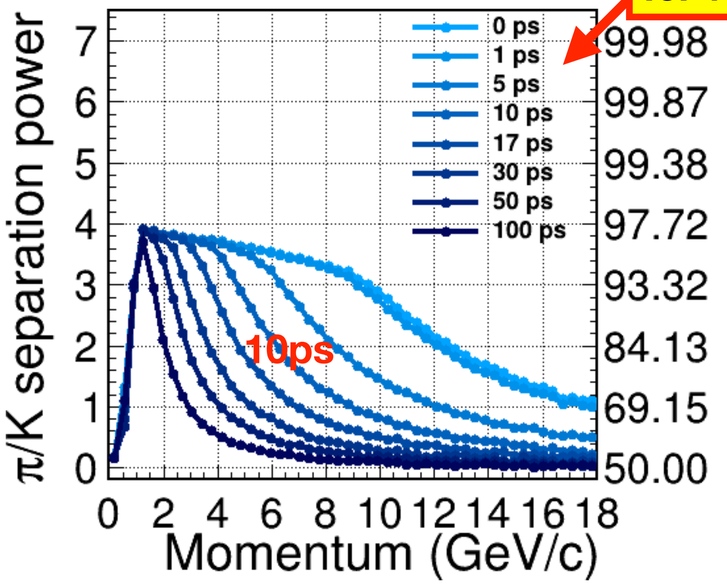
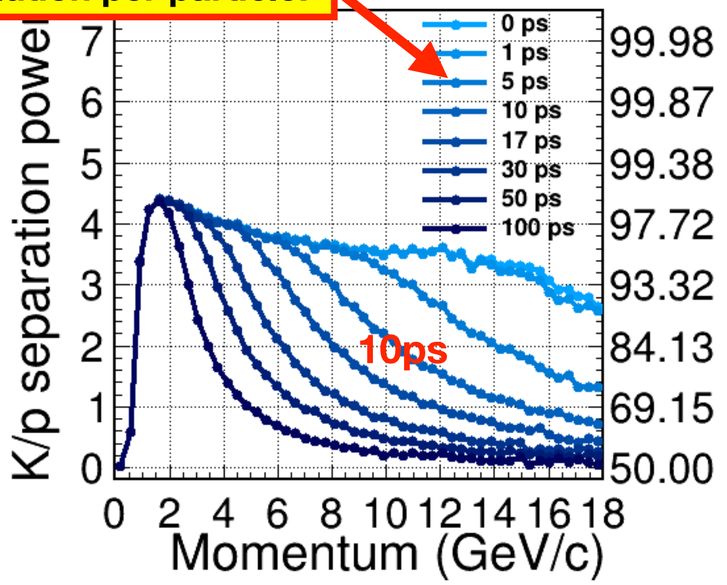




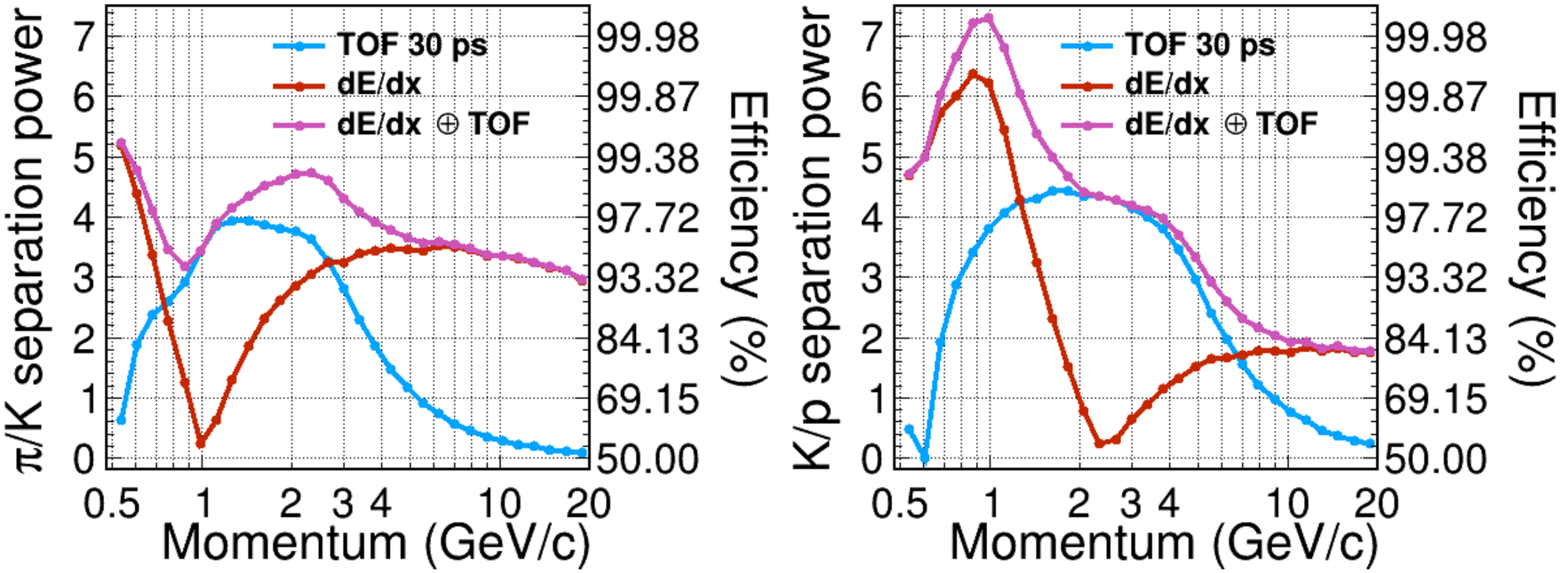
ToF & dE/dx Separation Power

ILD can combine the two

- 30 ps / particle
  ≙ 100 ps / hit for 10 ECal layers
- dE/dx res. ~4.5%

=> > 3σ for 0.5-18 GeV π / K

> 3σ for 0.5-5 GeV K / p



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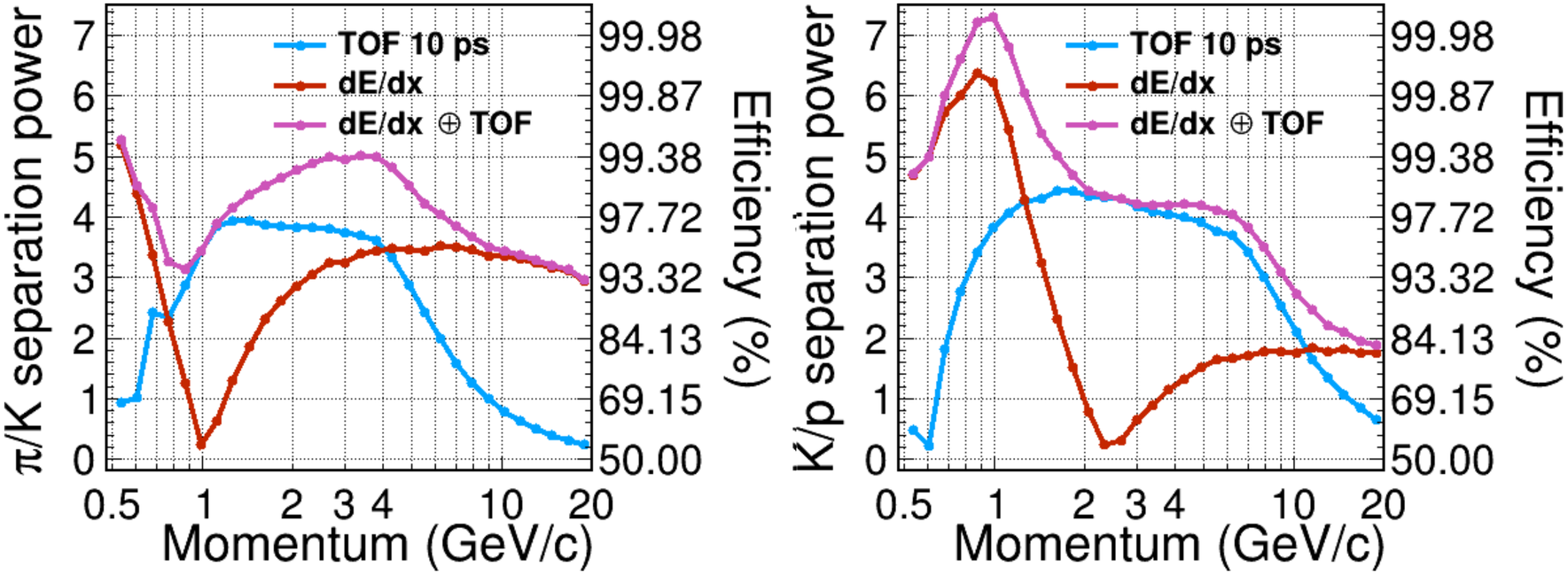

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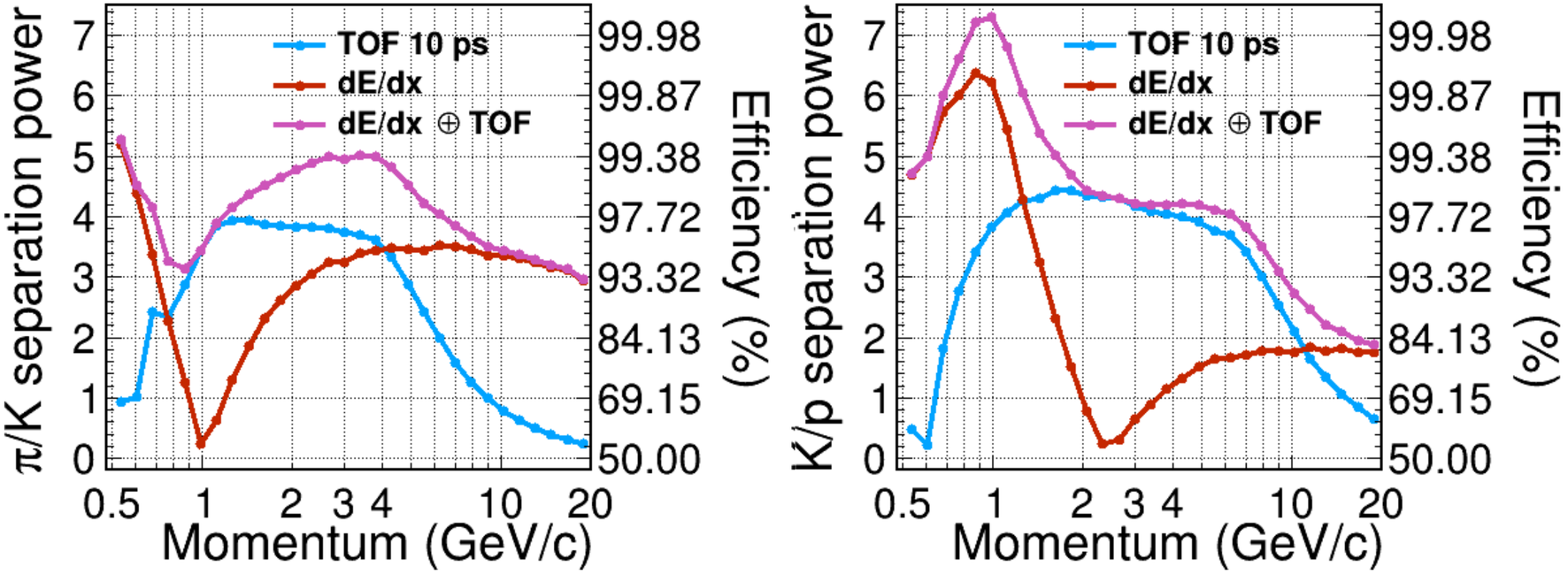
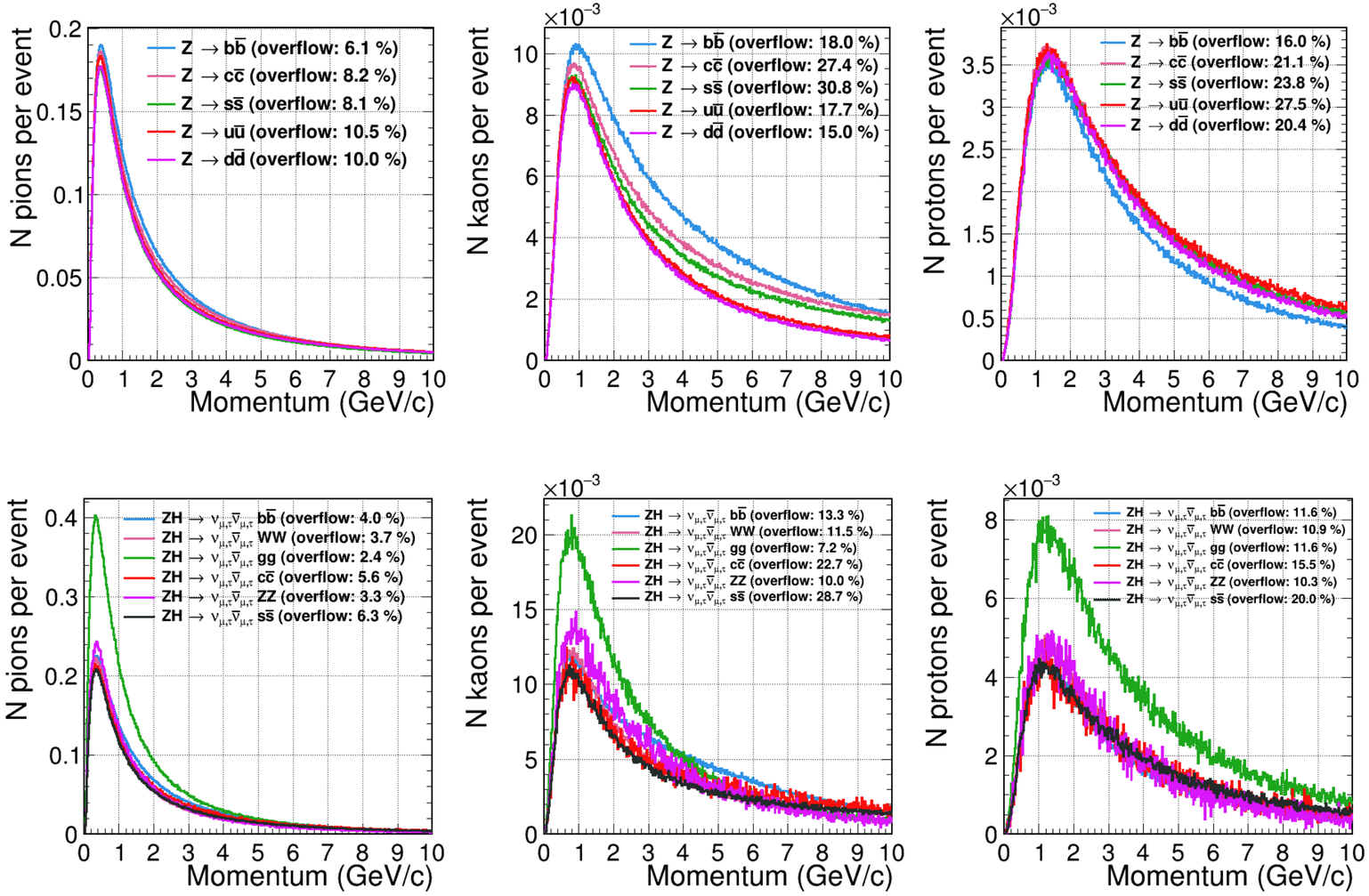


- ToF covers low-momentum dips in dE/dx at > 3σ level
- large part of the momentum range even > 4σ
- contributes up to ~10 GeV (K/p even up to 20 GeV)
- superseeds IDR plot!

pi/K/p momentum spectra

Generator-level and after reconstruction

- most particles actually are ToF-relevant momentum range
- but often not the leading K, p etc => ML-based taggers use PID infor for alll particles
- many π / K with p <1 GeV decay in tracker => if kink is identified in TPC, could still do ToF with more complex algorithm



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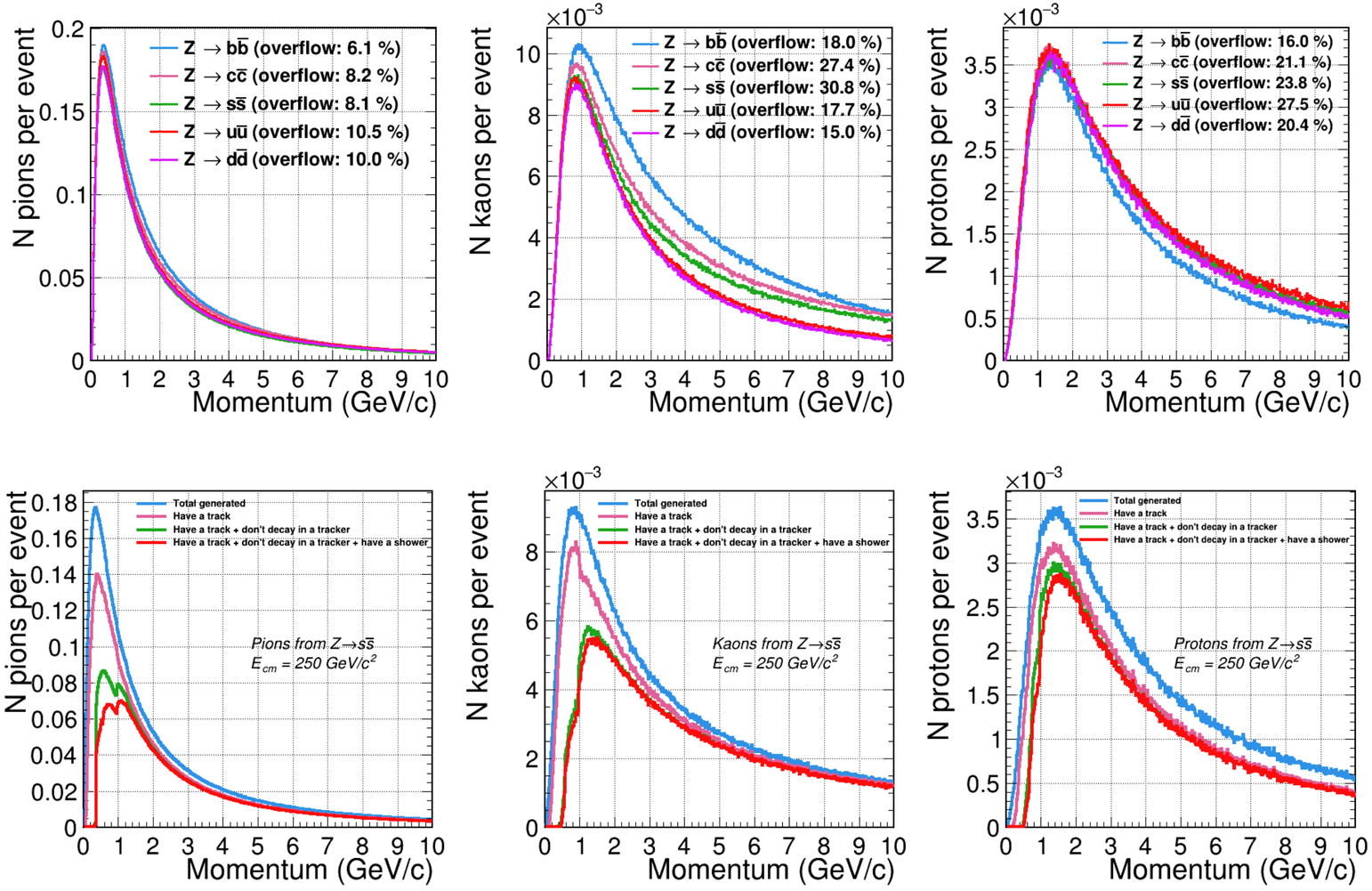

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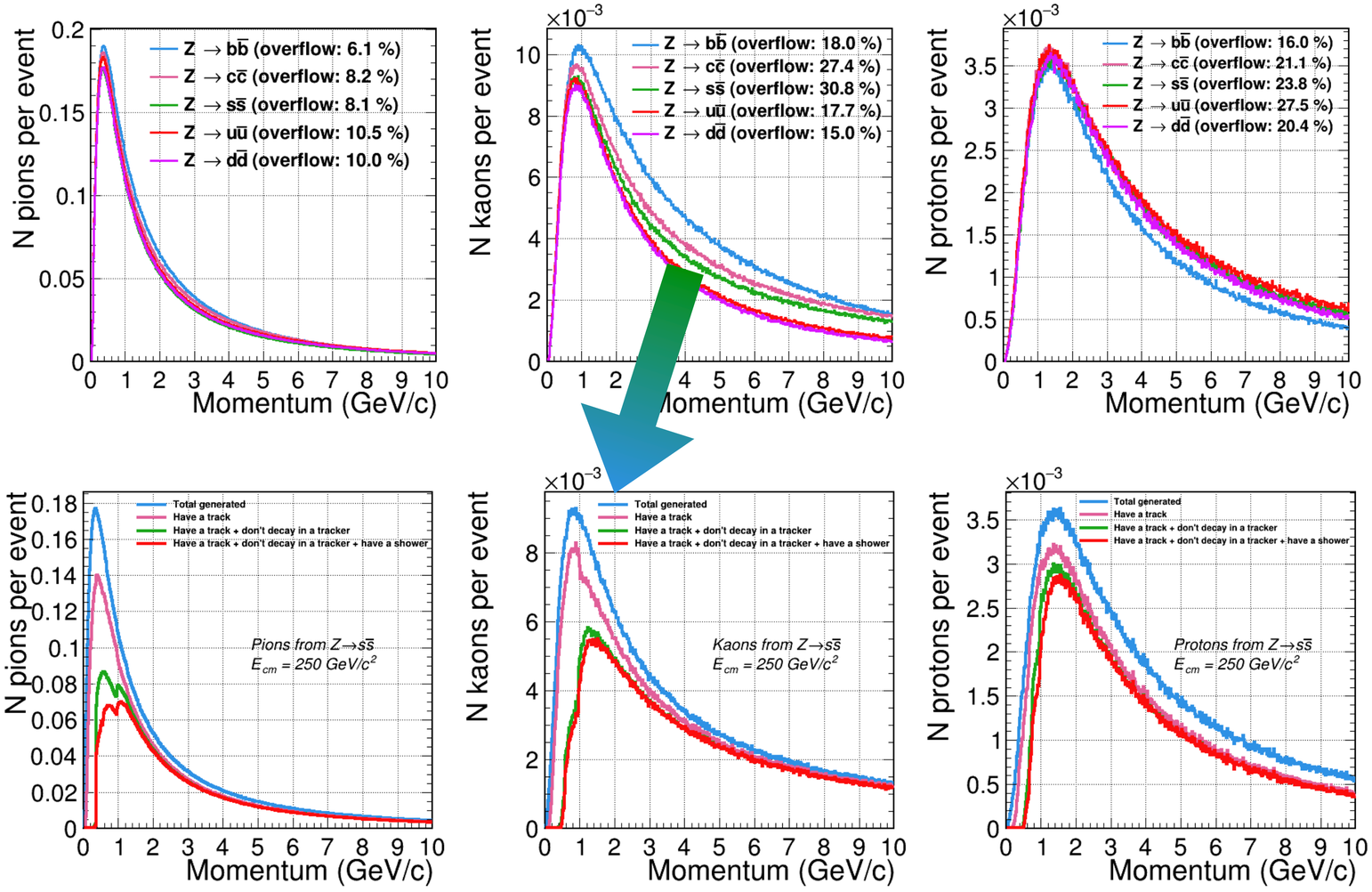

Kaon purity

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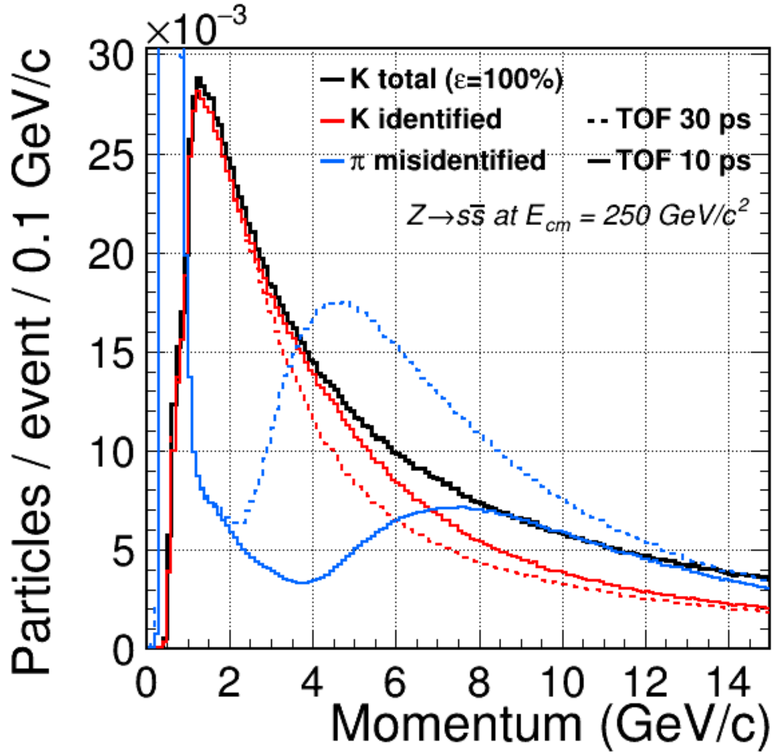

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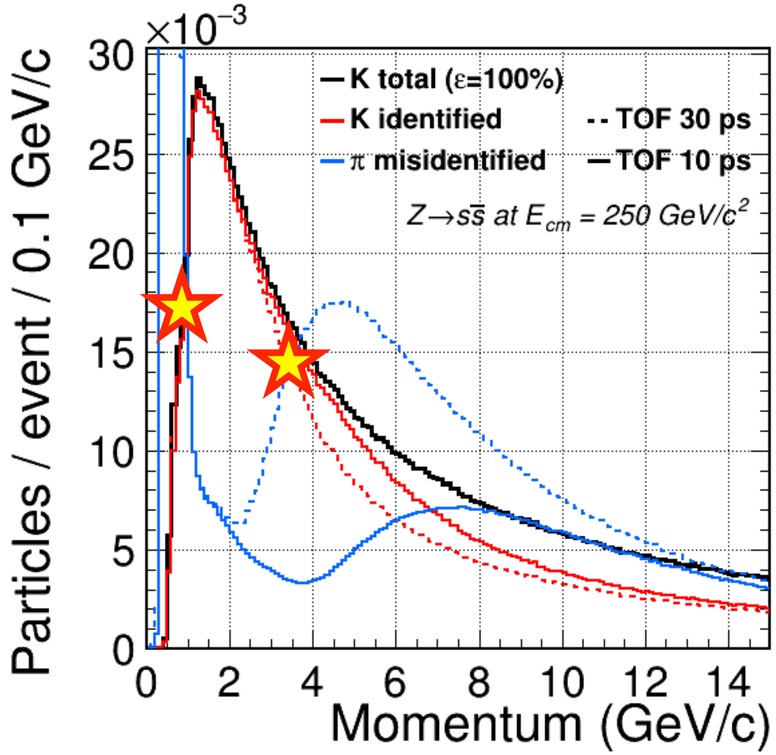

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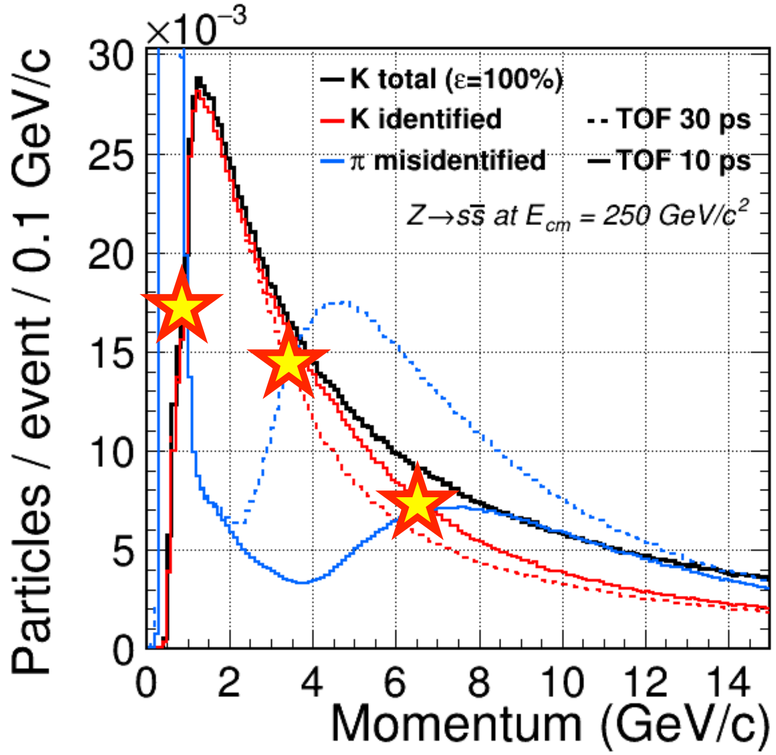

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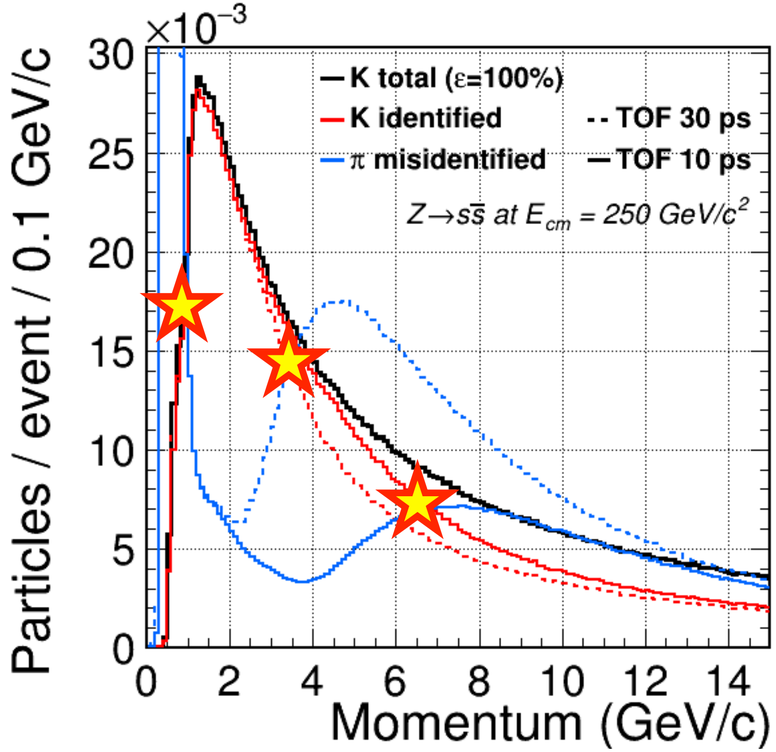

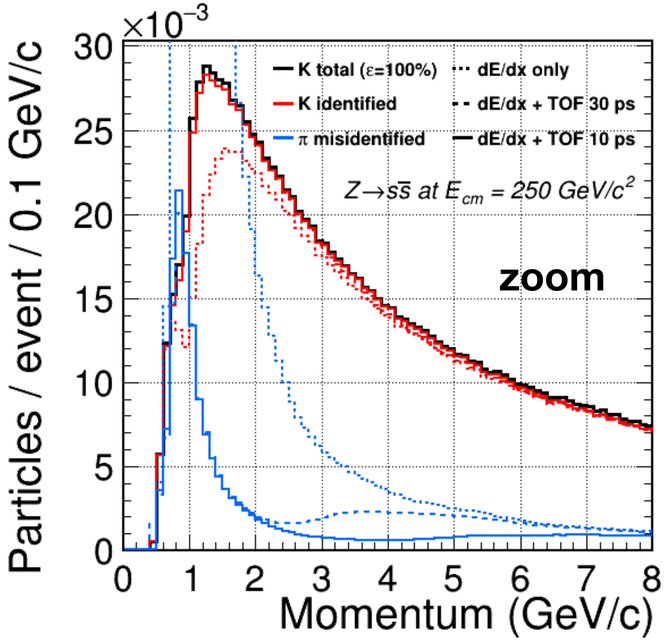

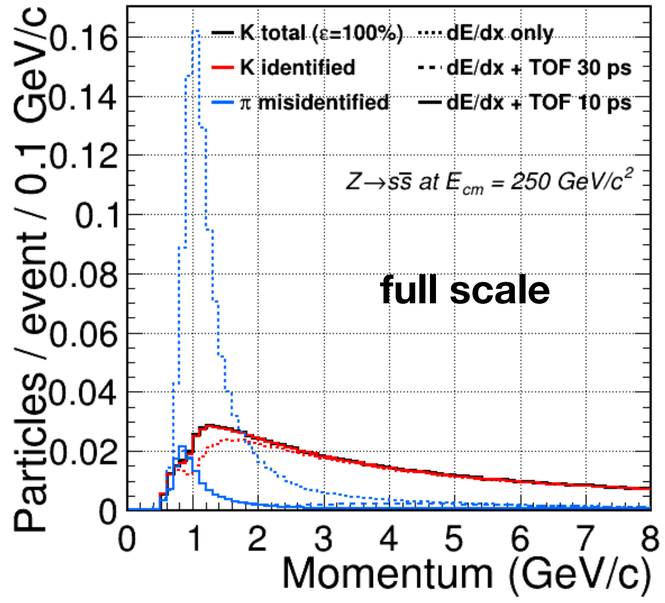

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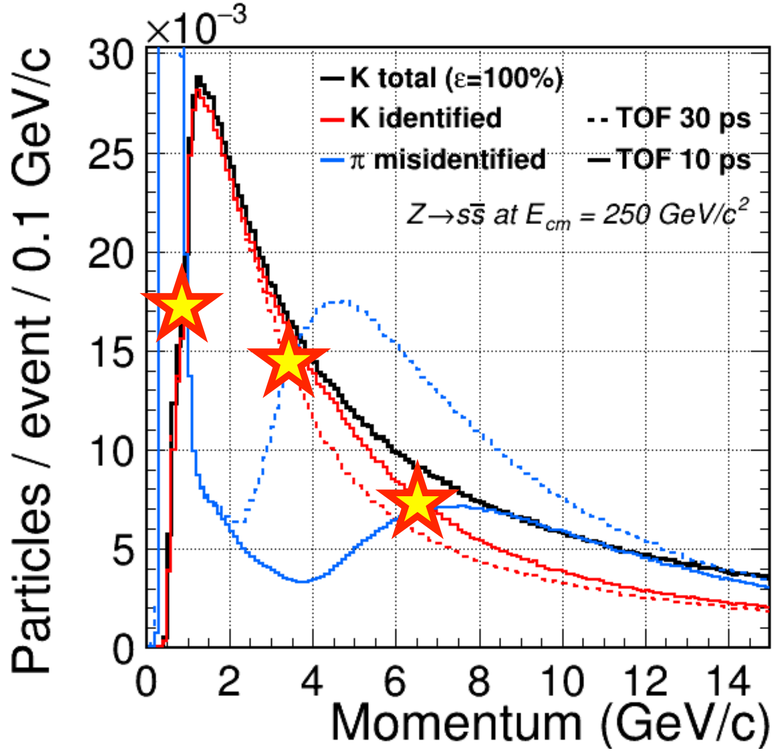

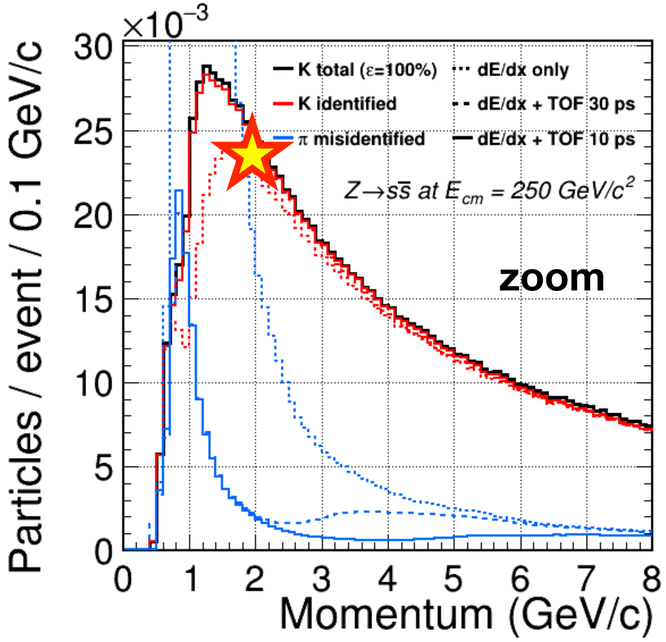

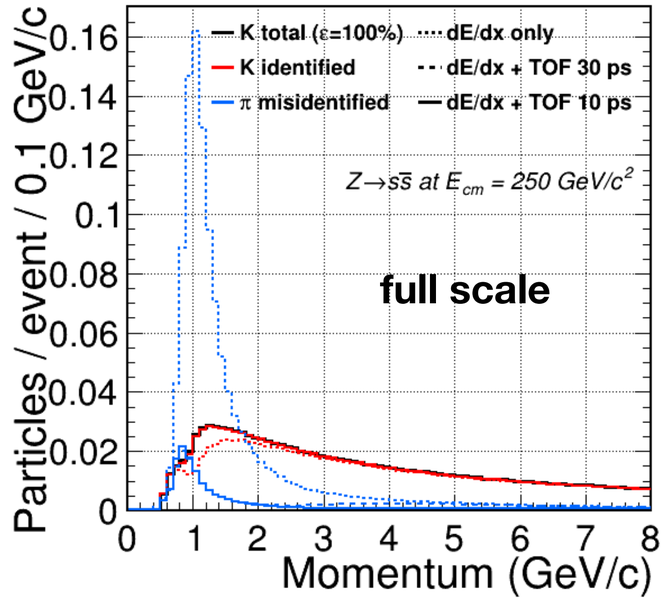

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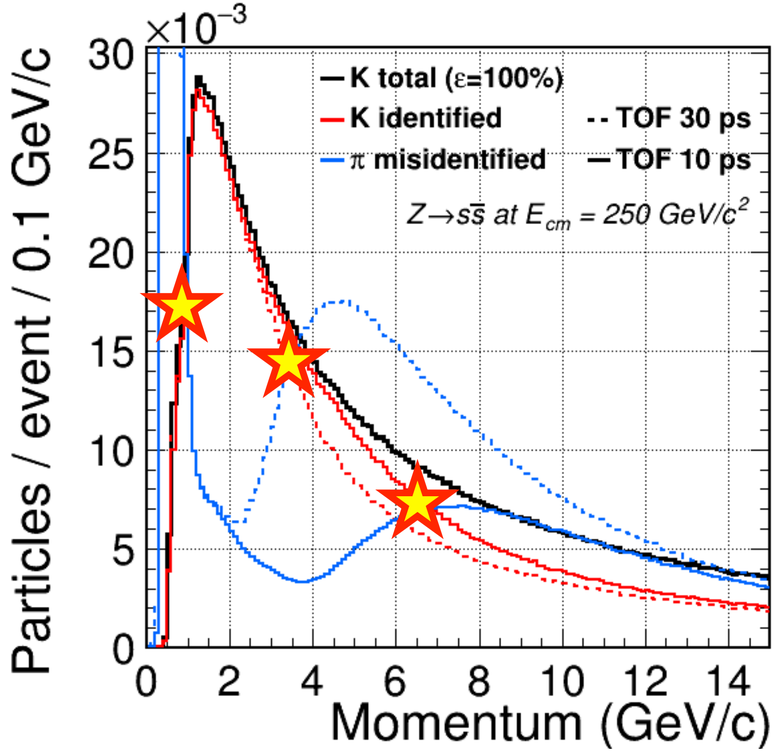

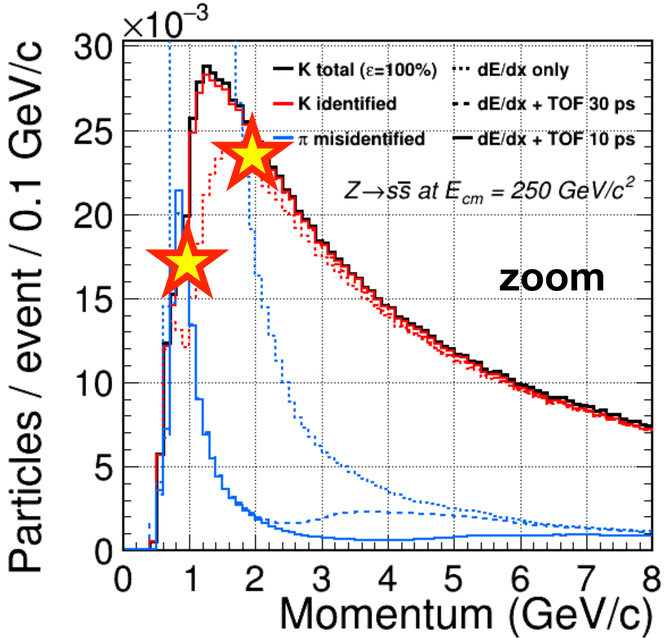

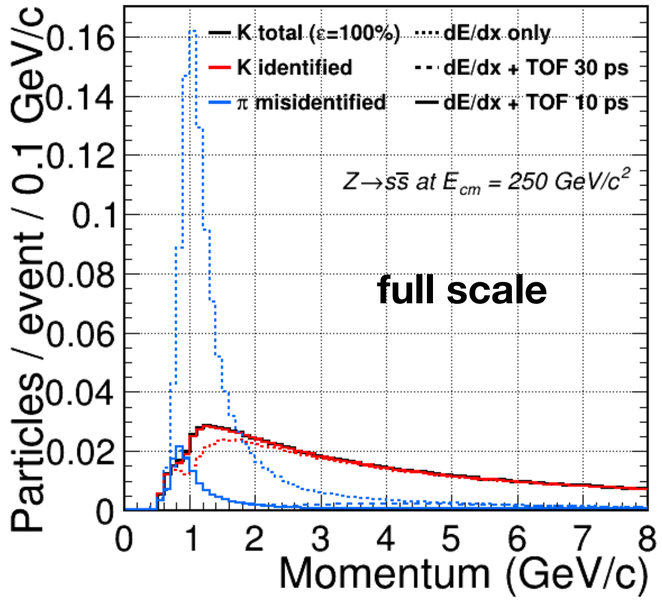

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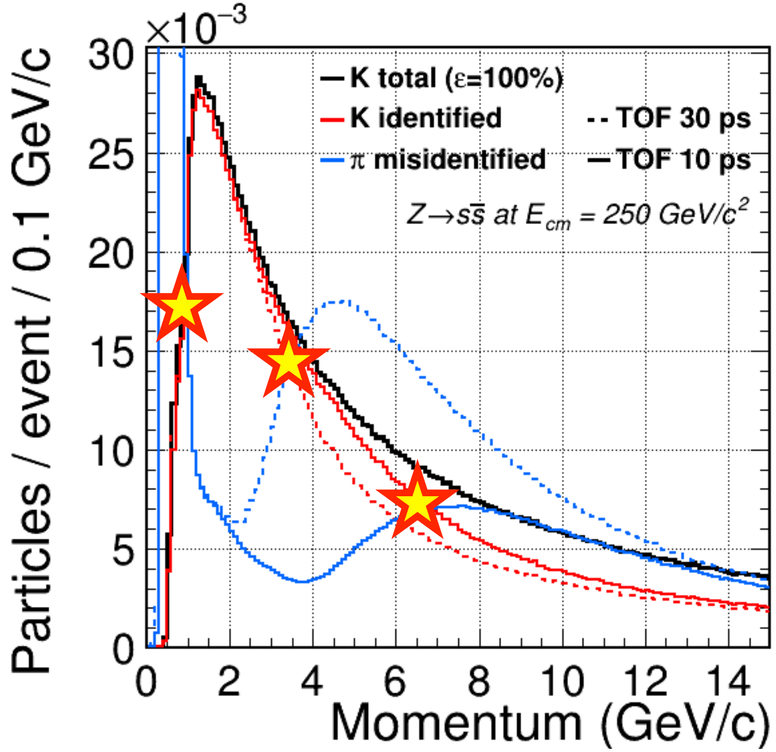
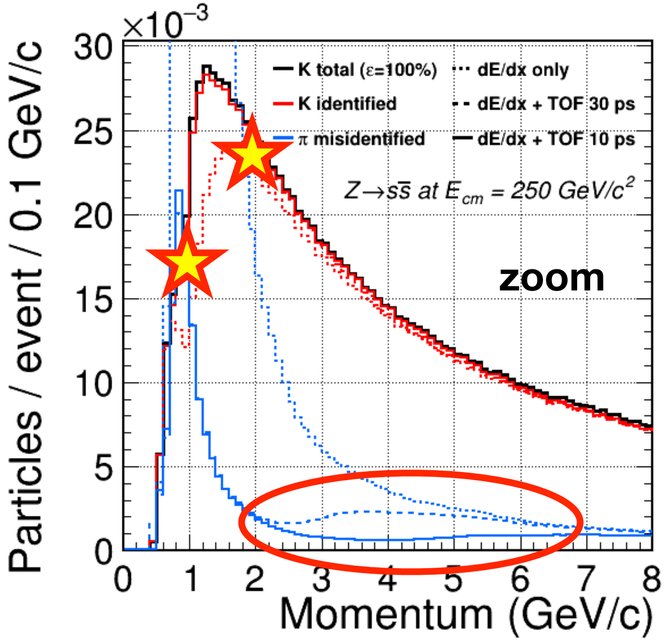
- with ToF-10ps, improve to 1-6 GeV

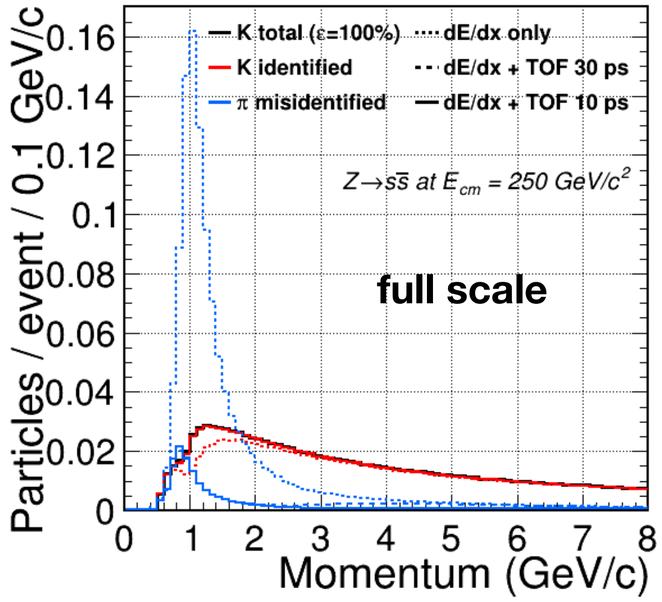
=> without TPC, 10ps or better required to make ToF useful for Kaon ID

- with dE/dx only, overwhelmed by π below 2 GeV
- adding ToF-30ps, K useful down to 1 GeV
- ToF-10ps improves purity a lot in 2-7 GeV!

=> with TPC, 30ps is enough to cover "hole" at low momenta, however 10ps significantly improves purity at higher momenta!







Kaon purity

in Z->ss

- for same working point as before, i.e. effi = 1-misID (actual analyses might use other choice!)
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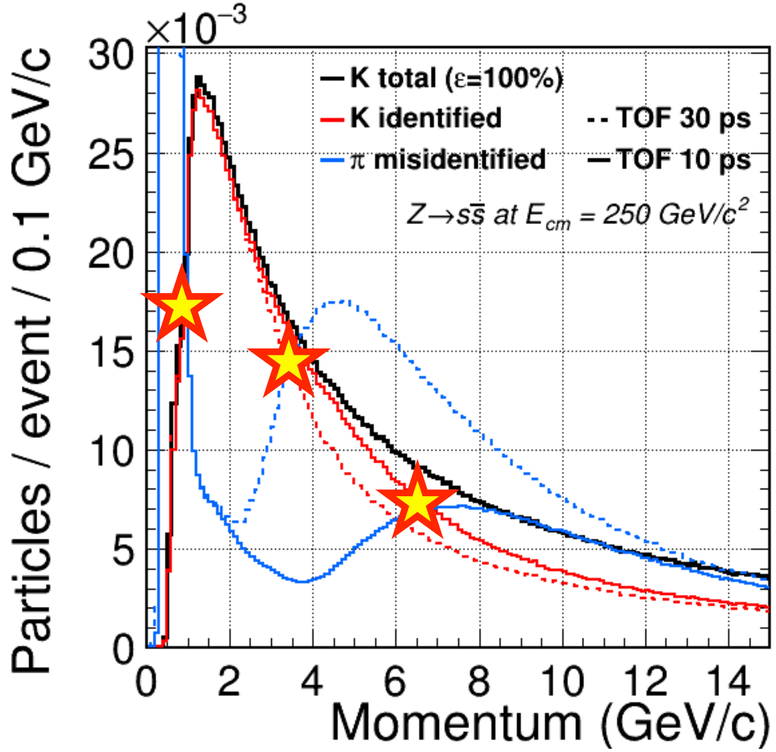
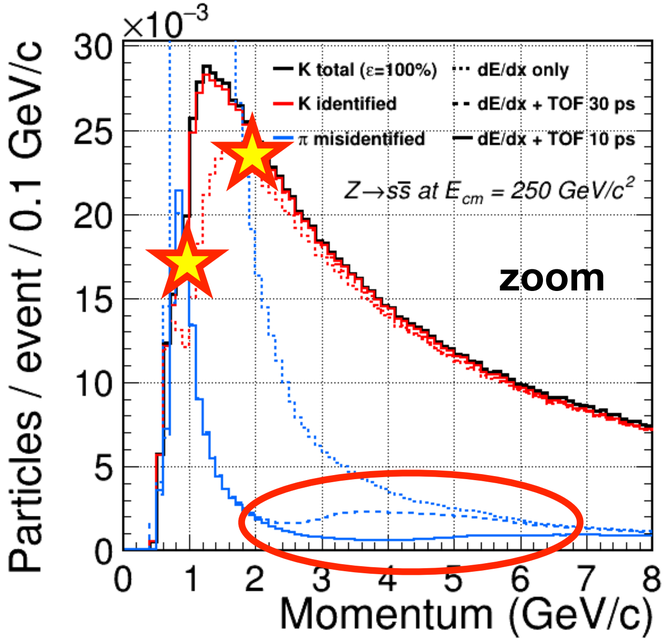
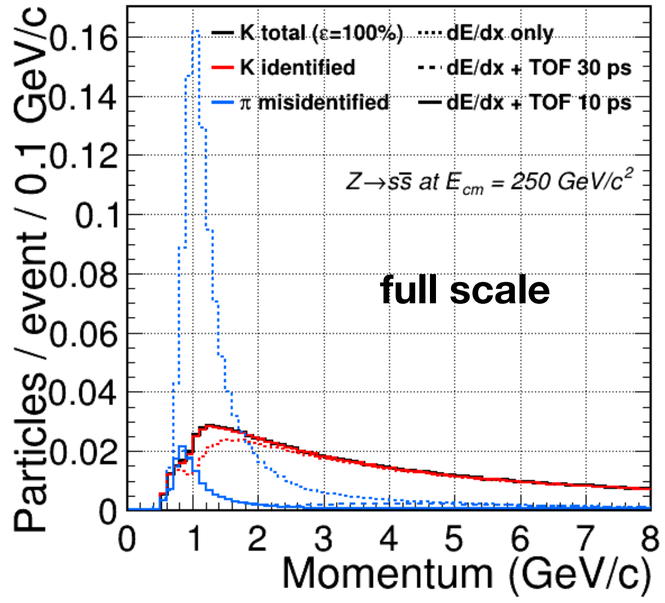
10ps vs 30ps makes a difference!

10 ps ≙ 2 outer tracker 2 hits with 15ps — or 10 layers ECal with 30ps

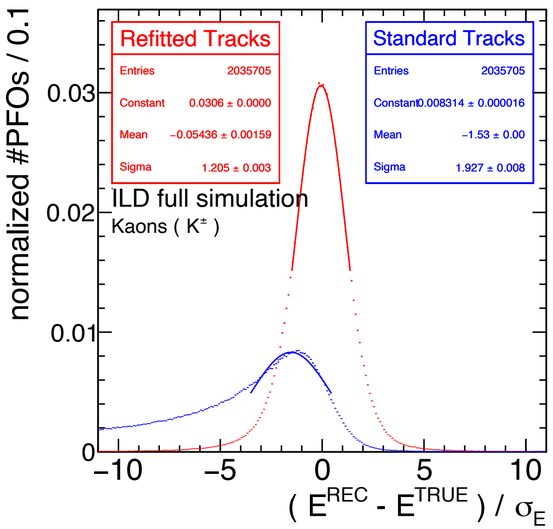


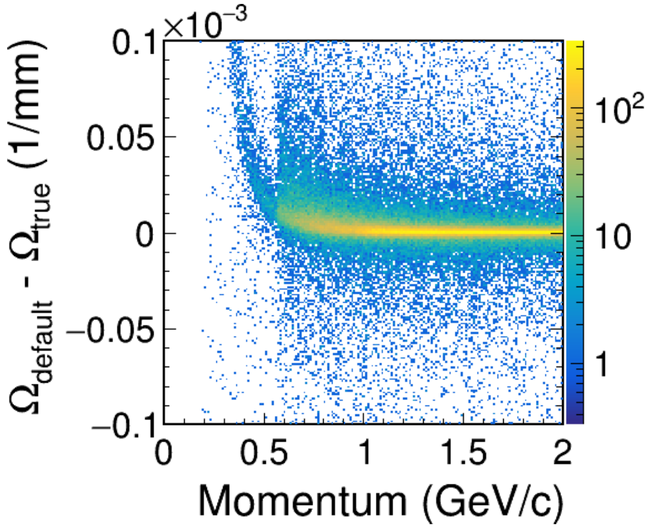


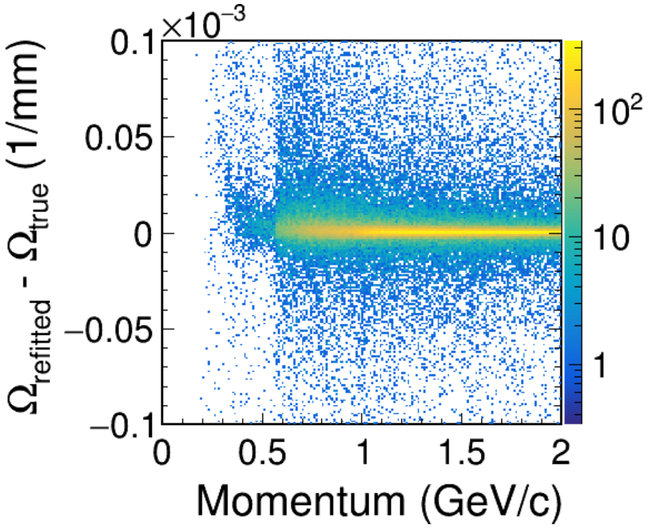


Overview on Applications

Just a few brief comments







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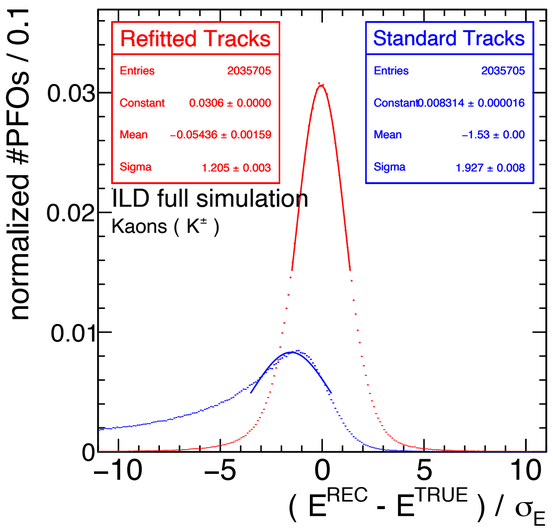
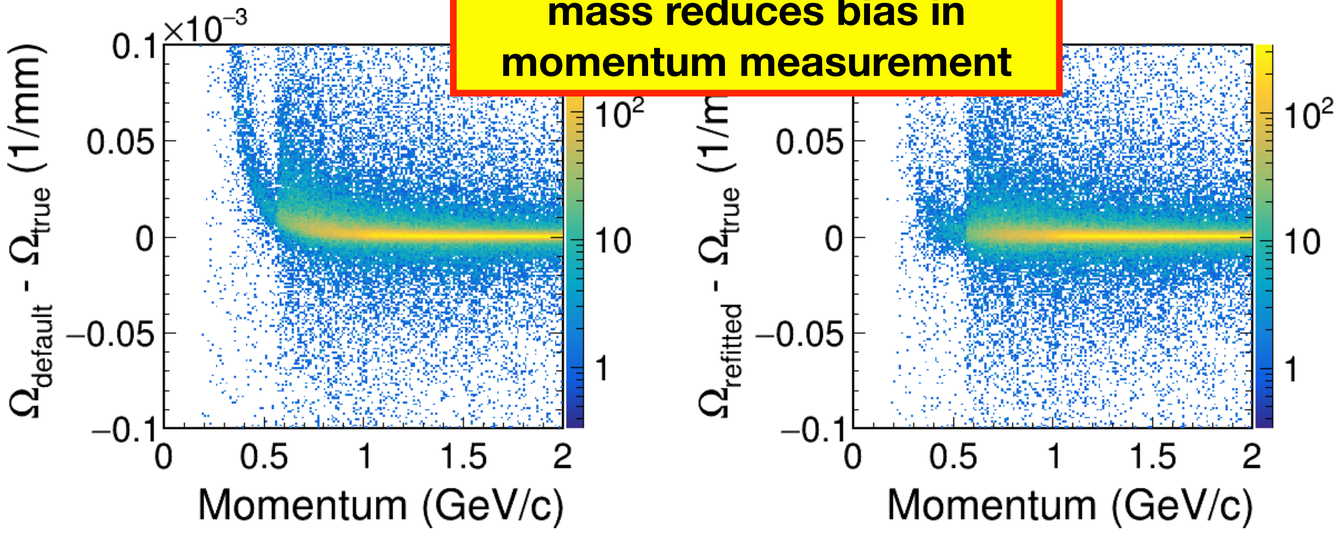


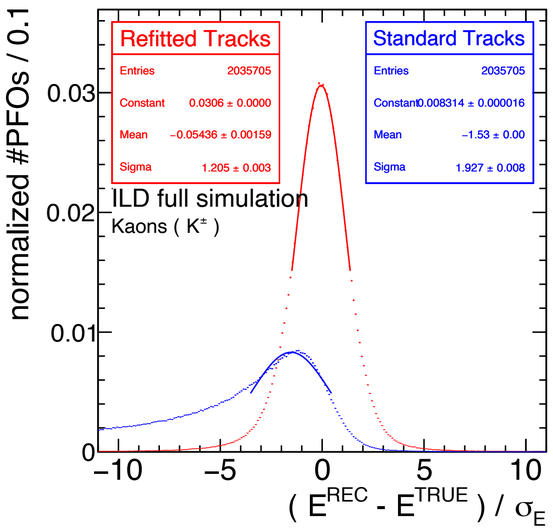
track refitting with correct mass reduces bias in momentum measurement



Overview on Applications

Just a few brief comments

correct mass drastically improves PFO-level covariance matrix (Y.Radkhorrami), propagates to jet-level covariance matrix



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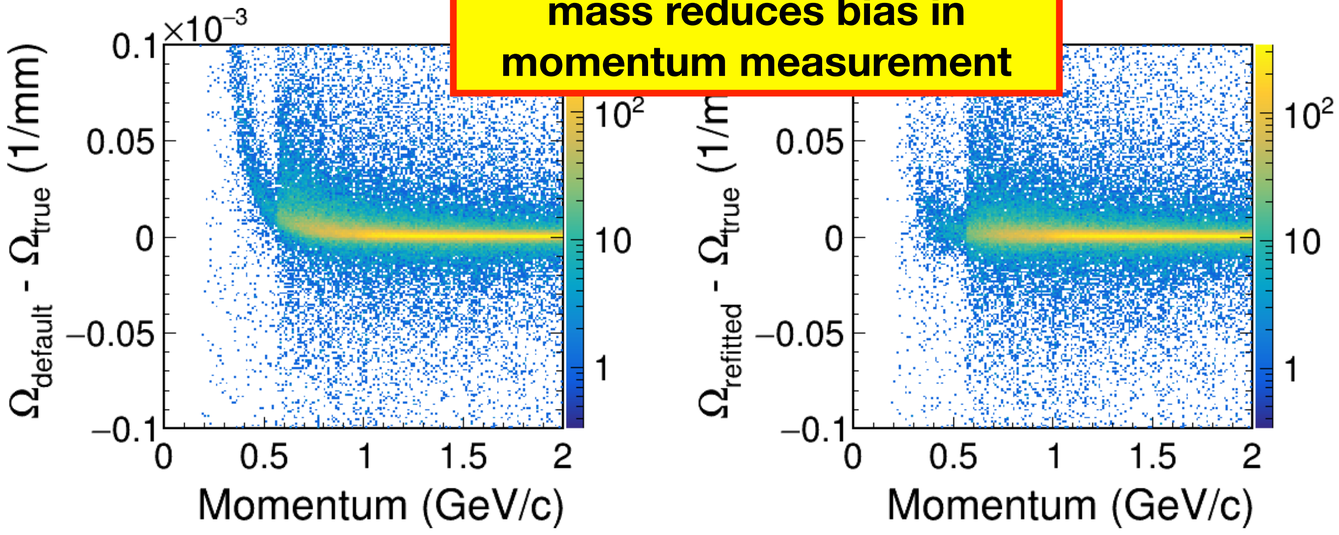

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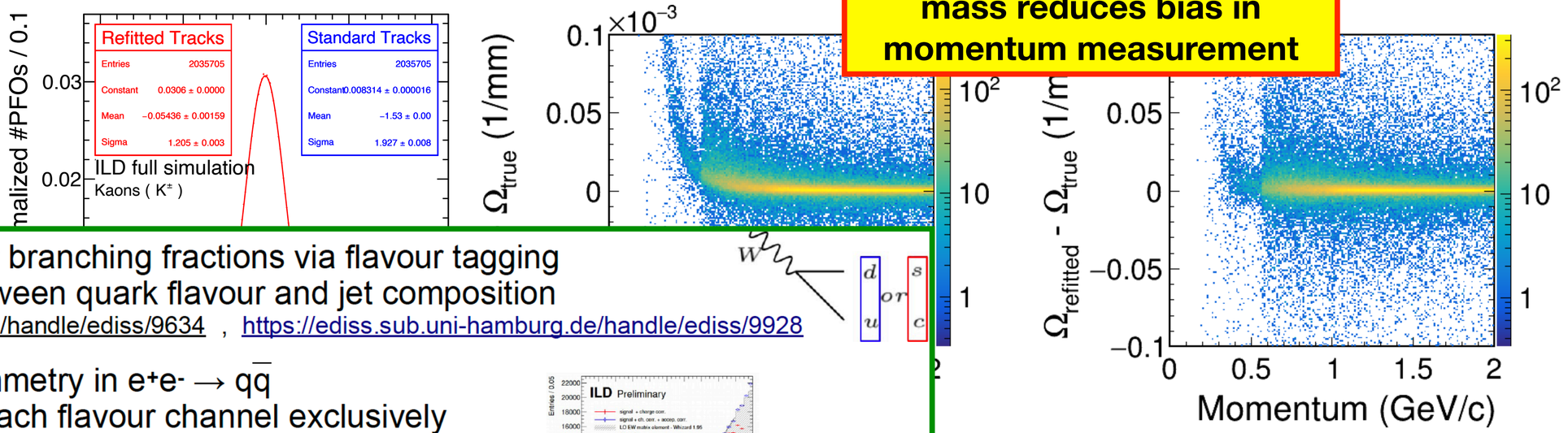
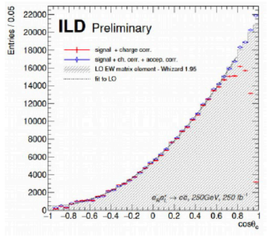
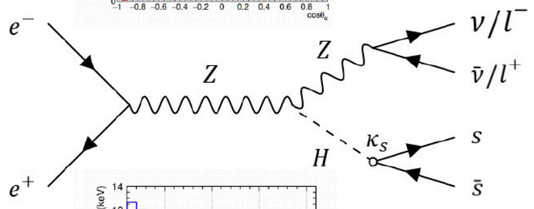


correct mass drastically improves PFO-level covariance matrix (Y.Radkhorrami),

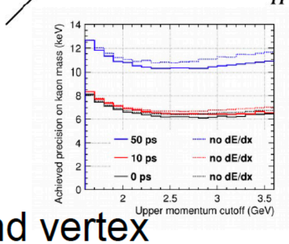
- Z and W hadronic decay branching fractions via flavour tagging
  → make connection between quark flavour and jet composition
  https://ediss.sub.uni-hamburg.de/handle/ediss/9634 , https://ediss.sub.uni-hamburg.de/handle/ediss/9928

- Forward-backward asymmetry in $e^+e^- \to q\bar{q}$
  → study asymmetry in each flavour channel exclusively
  overview: https://tel.archives-ouvertes.fr/tel-01826535
  $e^+e^- \to t\bar{t}$, $b\bar{b}$: https://agenda.linearcollider.org/event/8147
  $e^+e^- \to b\bar{b}/c\bar{c}$: https://arxiv.org/abs/2002.05805 ,
  https://agenda.linearcollider.org/event/9211/contributions/49358/
  $e^+e^- \to b\bar{b}/c\bar{c}$, $s\bar{s}$: https://agenda.linearcollider.org/event/9440 ,
  https://agenda.linearcollider.org/event/9285





- $H \to s\bar{s}$ with s-tagging
  → identify high-momentum kaons to tag $s\bar{s}$ events
  https://arxiv.org/abs/2203.07535



- Kaon mass with TOF
  https://pos.sissa.it/380/115/
- Track refit with correct particle mass for better momentum and vertex
  https://agenda.linearcollider.org/event/8498/

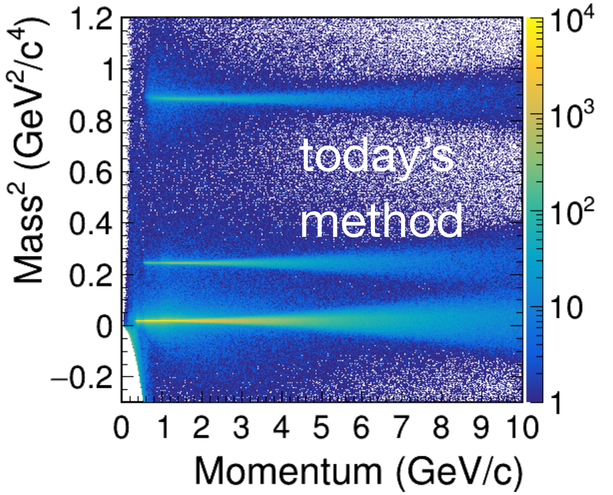
Many ILD analyses use Kaon-ID => all would profit from ToF —in particular in combination with advanced flavour taggers using PID for all PFOs, not only the leading PFO

Towards application in analysis

CPID

- state-of-the-art ToF requires
  - new track length calculation => tracker hits!
  - new hit time -> PFO time method => ECal hits!

=> this cannot be post-fixed on DST, REC saved for only few % of data



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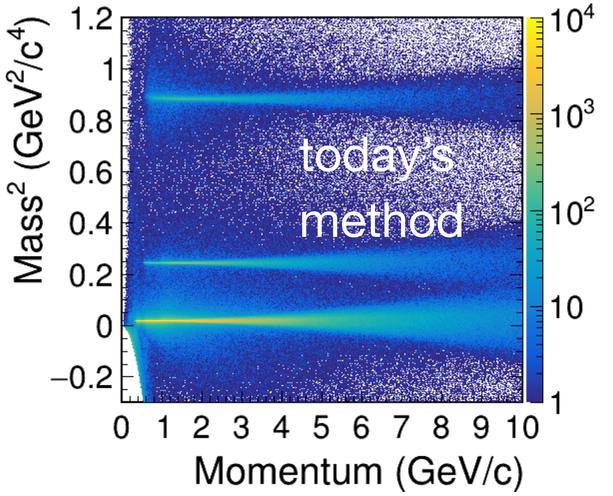
All this not available on mc-2020 250GeV ILD DST mass production – can only use IDR ToF



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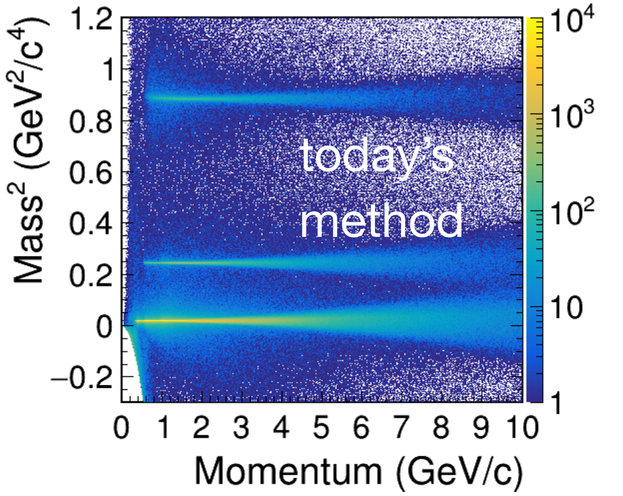

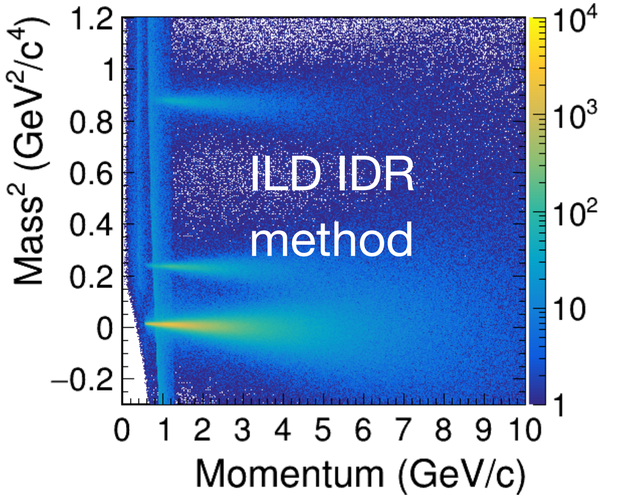

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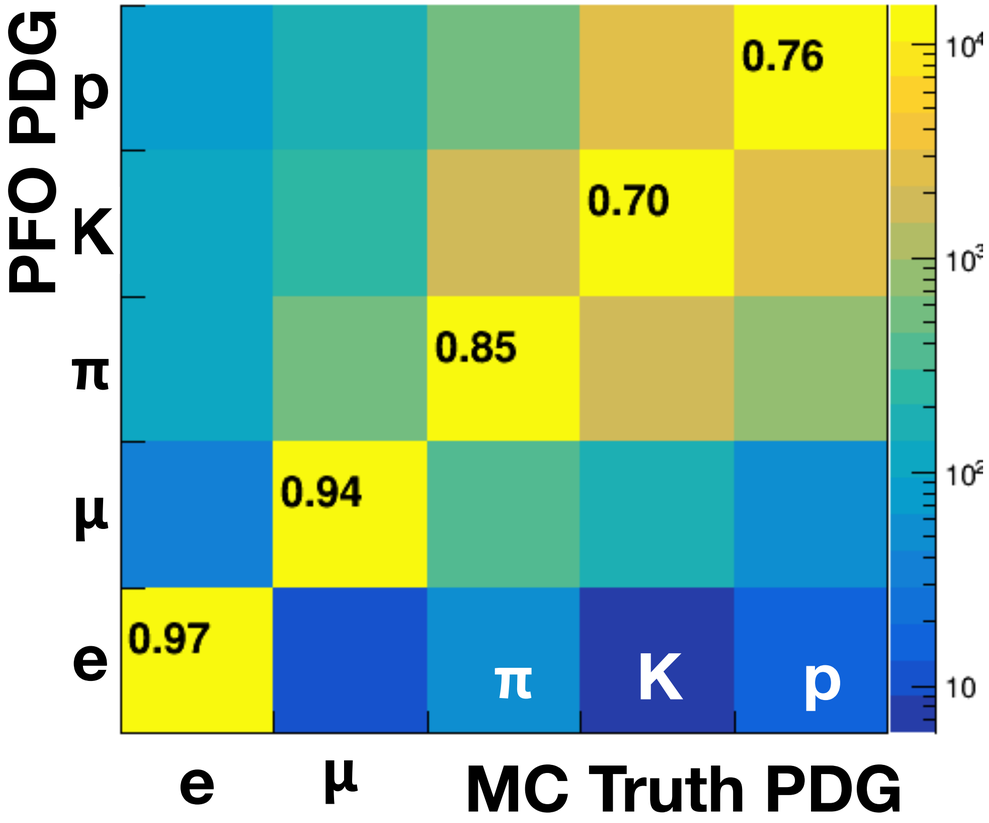

er hits!
ECal hits!
ed for

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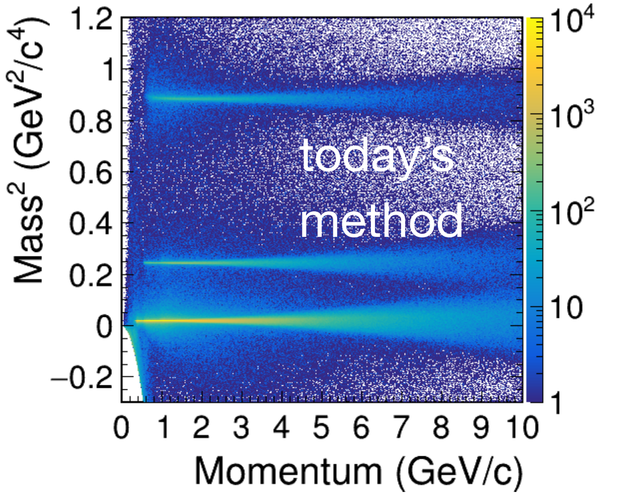
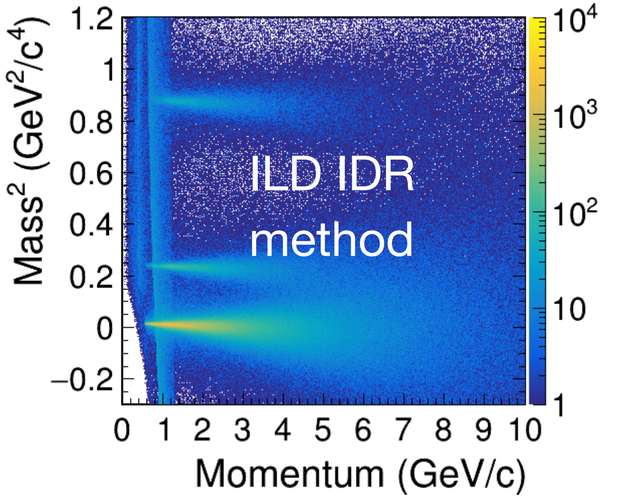
CPID on single particles, 1-100 GeV, with

- **dE/dx 4.5%**
- **IDR ToF, 50ps /hit**
- **Pandora PID**
- **LeptonID in jets**





Towards application in analysis

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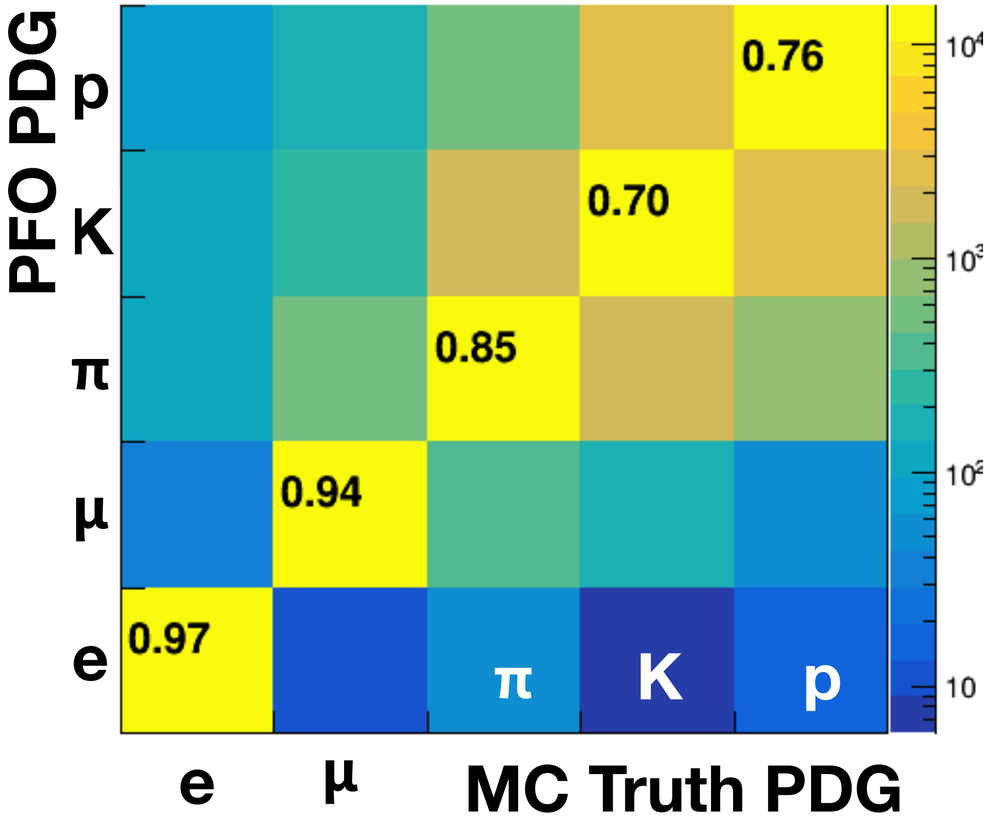

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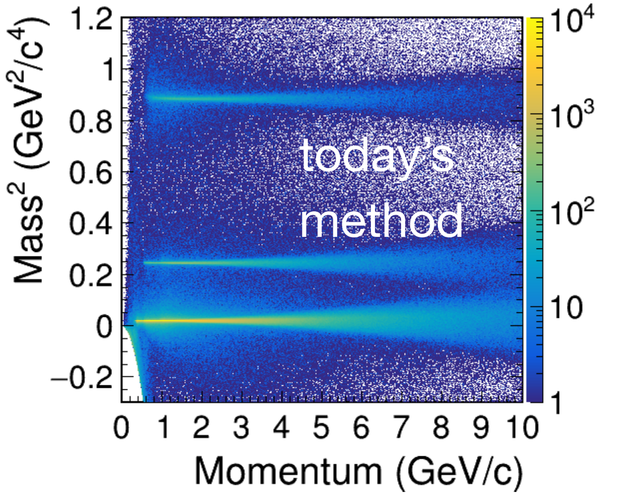

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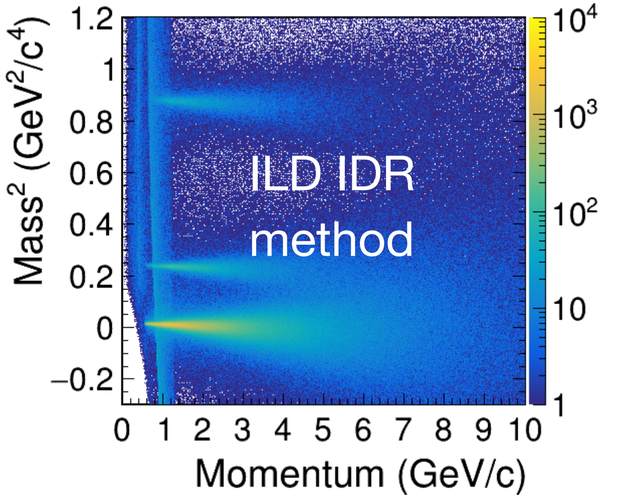
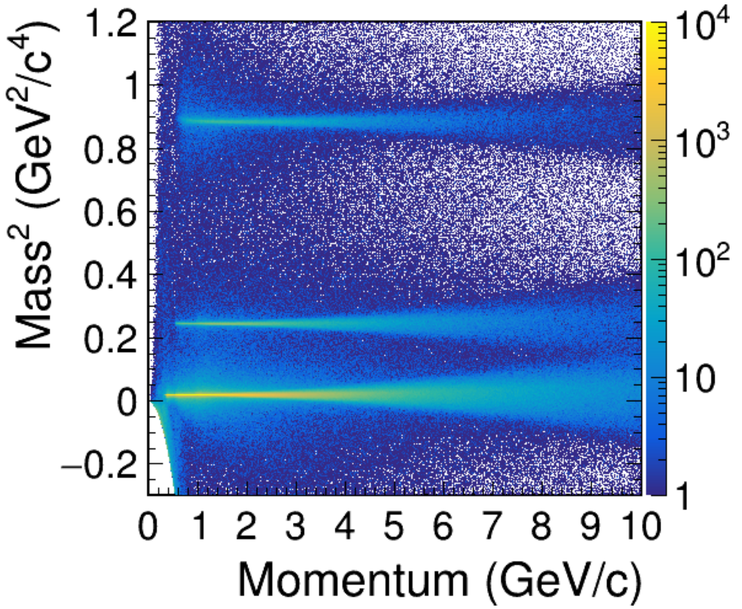


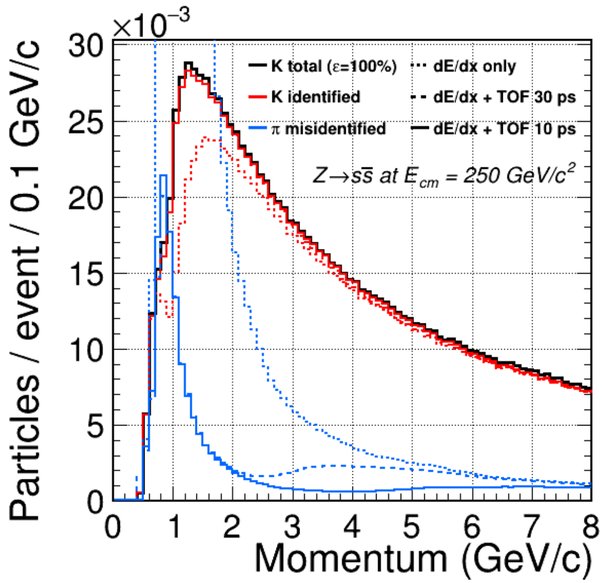
- outlook:
  - new track length in master, could be used in a next ILD MC production
  - hit -> PFO time algorithms not yet committed, but could live with effective smearing of true Geant time

Conclusions

and Outlook

- **over the last years lot of progress on reconstructing ToF for PID**
  - track length => 220 TPC hits ✔ —all Si tracker ?
  - including endcaps (multiple turns!)
  - how to estimate ToF from ECal hits => $\Delta T(ToF) \approx \Delta T(hit) / \sqrt{(N_{hit})}$ holds
- **detector optimisation**
  - 30 ps / particle — 100ps / ECal hit ~ 50ps / SET hit:
    - all Si tracker: not very useful..?
    - with TPC: enough to cover dE/dx “gaps” at low momentum
  - 10 ps/ particle — 30ps / ECal hit ~ 15ps / SET hit:
    - all Si tracker: Kaon ID ~1-6 GeV
    - with TPC: significant improvement of Kaon purity 2-7 GeV!
  - real-life problems not yet evaluated: synchronisation, clock jitter, power budget…. **=> needs ECal experts’ input!**
- **physics applications:**
  - many…
  - **full exploitation of PID information only starting**
  - stay tuned for ongoing ML flavour tagging





BACKUP