PID with Gaseous Tracking and Timing in ILD

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Particle Identification in ILD

Likelihood PID

π^0, τ, J/Ψ, etc. finders

Shower shapes

μ/π separation at low p

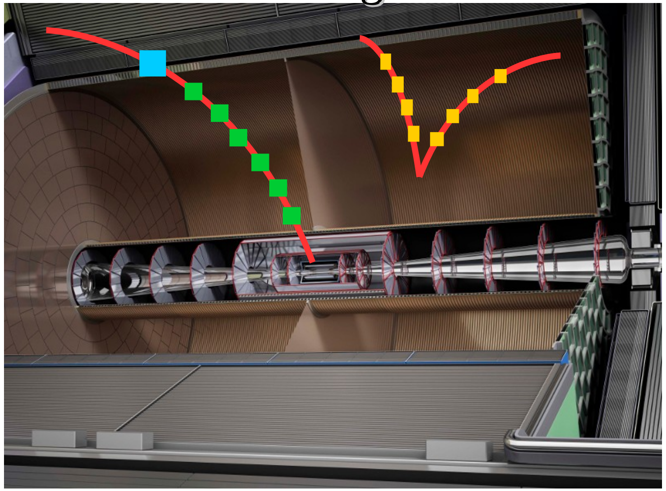
V_0 finder — K^0_S, Λ^0, $\gamma \rightarrow e^+e^-$

Time of Flight — π, $K^\pm$, p

TPC dE/dx — μ, e, π, $K^\pm$, p

Pandora particle flow — μ, e, γ, π $K^\pm$ p, n K^0_L

International Large Detector



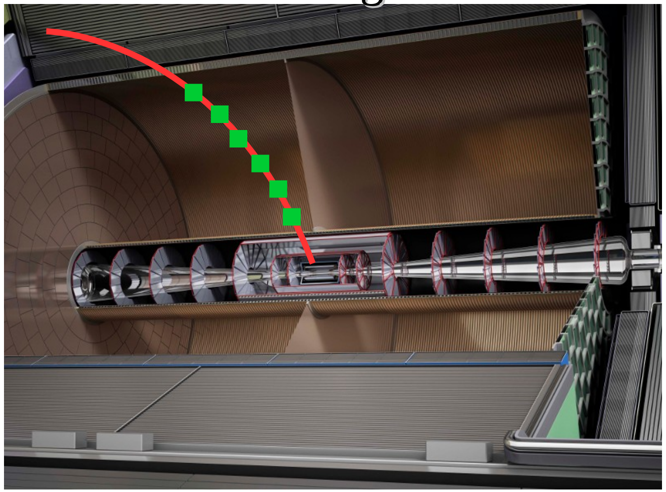
dE/dx reconstruction inside TPC

TPC in the ILD Geant4 simulation:

Gas: Ar-CH_4-CO_2 mixture (93%/5%/2%)

Segmentation: 220 radial hits with a 6 mm step

International Large Detector



Compute_dEdxProcessor

1. Calculates dE/dx per hit

$$\left(\frac{\mathrm{dE}}{\mathrm{dx}}\right)_{\mathrm{hit}} = \frac{\text{sum(gas ionisation from Geant4)}}{\text{distance to the previous hit}}$$

2. Calculates truncated mean <dE/dx> per track

$$< \frac{\mathrm{dE}}{\mathrm{dx}} >_{\mathrm{track}} = \begin{array}{c} \text{take all hits associated with a track} \\ \text{reject 30\% hits with the highest dE/dx} \\ \text{reject 8\% hits with the lowest dE/dx} \end{array}$$

3. Smears $<dE/dx>_{track}$ to match LCTPC test beam results

https://arxiv.org/abs/1801.04499

note[1]: currently, not all track hits are used, but only hits from the first half circle

note[2]: smearing accounts for N_{hits} and θ_{track} correlations

note[3]: for overlapping tracks hits are merged

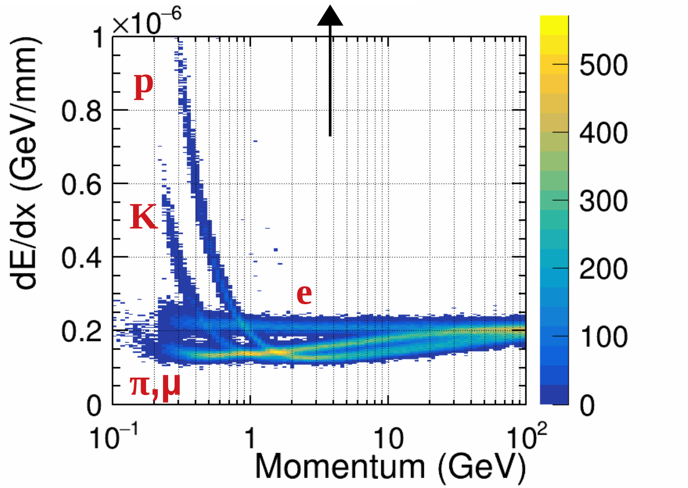
dE/dx particle ID performance

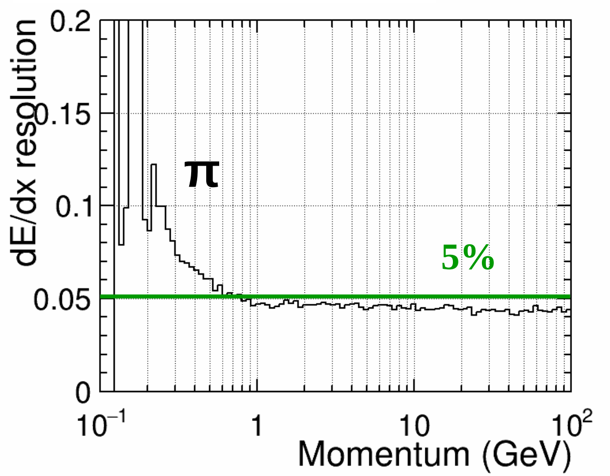
dEdxAnalyser

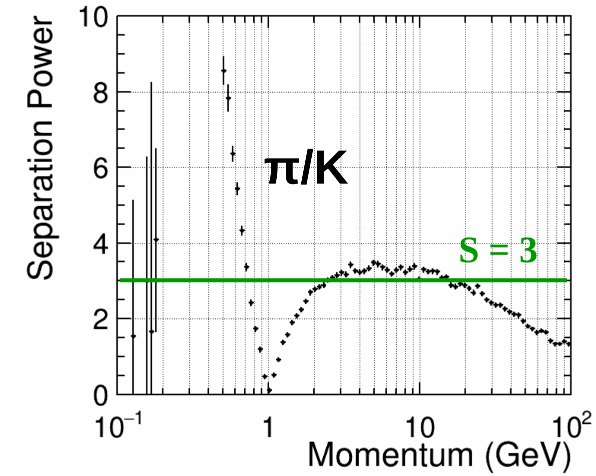
Estimate particle ID performance with dE/dx resolution and separation power

$$\sigma(p), \mu(p) \rightarrow \frac{\sigma_{dE/dx}}{\langle dE/dx \rangle} = \frac{\sigma(p)}{\mu(p)}$$

$$S = \frac{|\mu_A - \mu_B|}{\sqrt{\frac{1}{2}(\sigma_A^2 + \sigma_B^2)}}$$



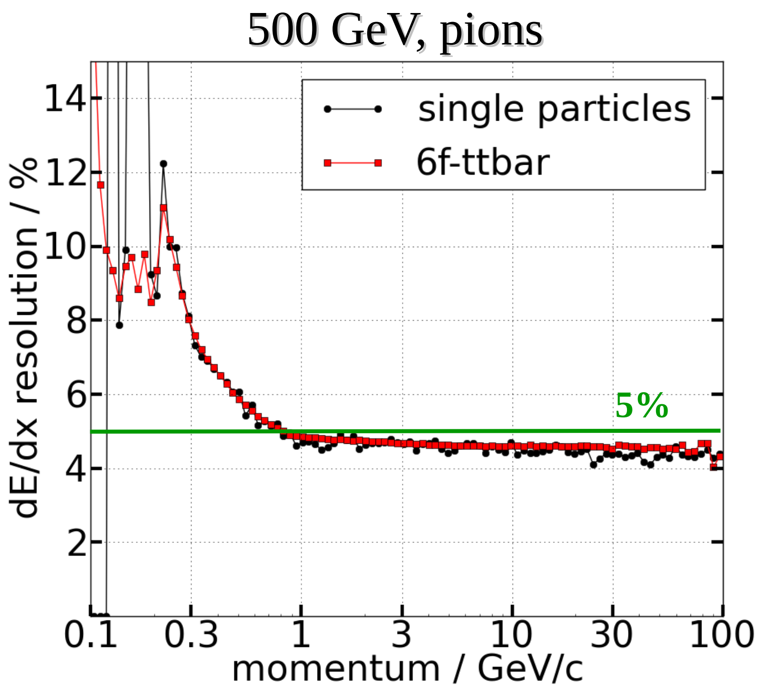




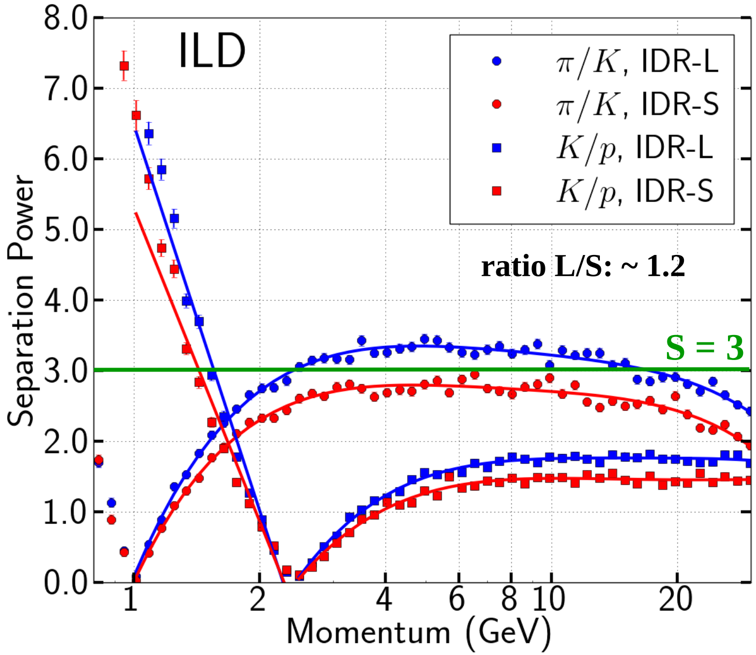
courtesy of Ulrich Einhaus

dE/dx particle ID performance examples

dE/dx resolution does not degrade in a dense jet environment



Smaller TPC radius negatively impacts dE/dx separation power



TPC-large (r_{out} – 177 cm; N_{hits} – 220)

vs

TPC-small (r_{out} – 143 cm; N_{hits} – 163)

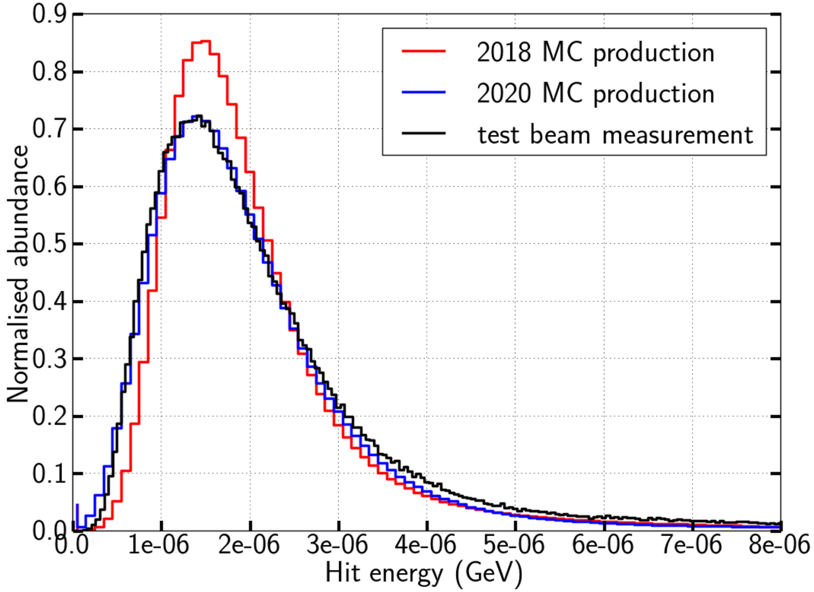
courtesy of Ulrich Einhaus

dE/dx validation with a test beam data

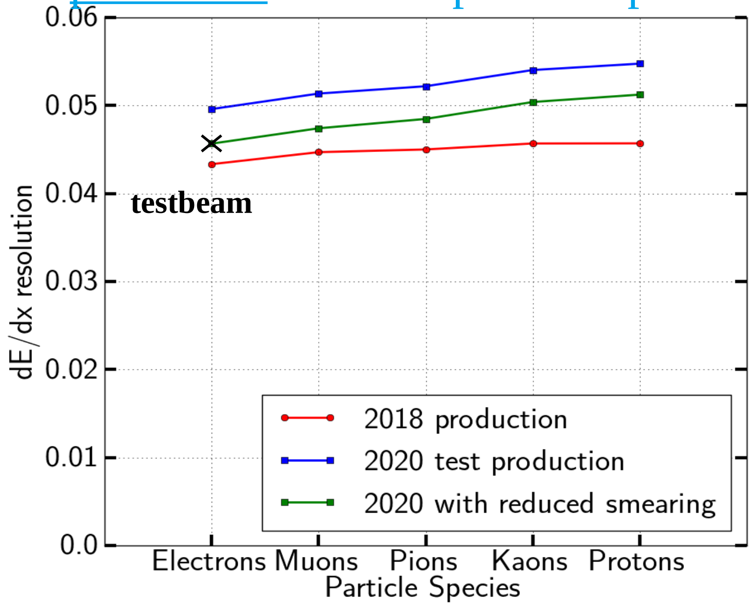
We transited to a newer Geant4 version for the ILD 2020 MC production

- The effective resolution was overestimated in the past. Now it is substantially more realistic
- Now smearing factor has to be smaller to match test beam data.
- Calibration parameters were re-adjusted

Hit energy spectrum is <u>more realistic</u> and wider in the new Geant4 version



dE/dx resolution difference <u>became more prominent</u> between particle species



courtesy of Ulrich Einhaus

Cluster Counting / Charge summation / Granularity

A separate detailed simulation using MarlinTPC has been made to study pad granularity effects on dE/dx resolution

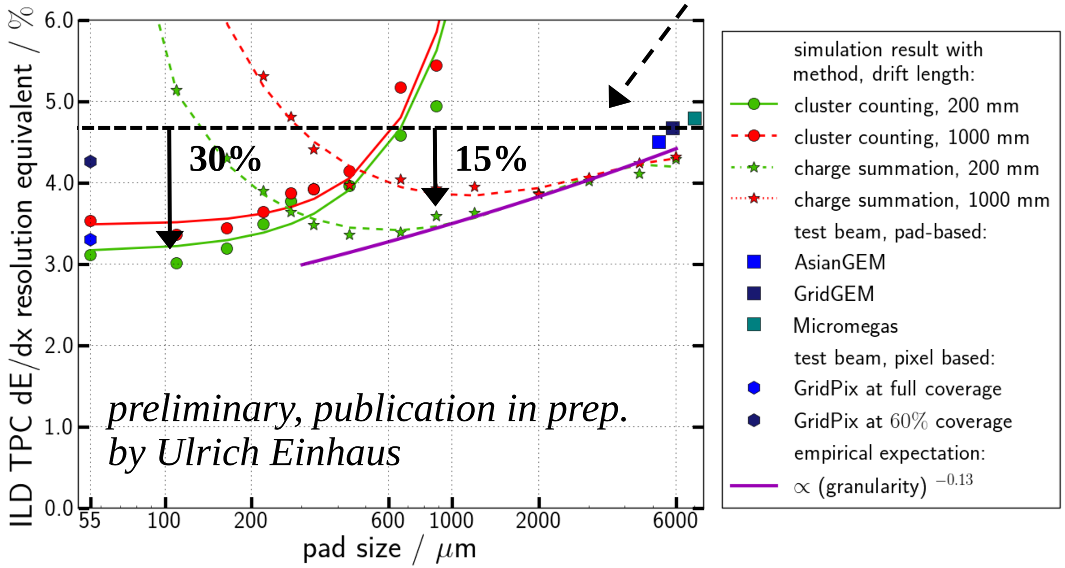
- Current full ILD reconstruction: 6 mm pads → ~4.6 % dE/dx resolution
- 6 mm → 1 mm: 15% improved resolution via charge summation (dE/dx)
- 6 mm → 0.1 mm: 30% improved resolution via cluster counting (dN/dx)

current resolution in the full ILD reco assuming 6 mm pads

We can achieve a better dE/dx resolution than currently implemented in the simulation

Yet, it is not trivial to implement small granularity inside simulation

Changing granularity might stop working at very low pad sizes, due to a very distorted pad geometry.



Time of Flight particle ID

TOFEstimators and TrackLength processors

Calculate track length and harmonic mean of squared momentum during Kalman Filter fit procedure hit-by-hit

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

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

https://arxiv.org/abs/2107.02031

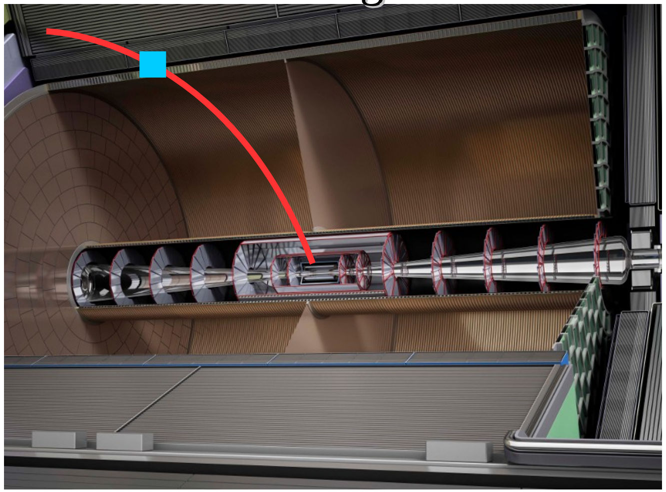
Use closest ECAL hit to the track to calculate TOF and then smear it with σ to simulate effective TOF resolution (per particle!)

$$\text{TOF} = \text{RandGauss}\left(t_{\text{hit}} - \frac{|\vec{r}_{hit} - \vec{r}_{track}|}{c}, \sigma\right)$$

Reconstruct mass of a particle, using p, l_{track}, TOF

$$m = \frac{p}{\beta}\sqrt{1 - \beta^2} \qquad \beta = \frac{\ell_{\text{track}}}{c \cdot \text{TOF}}$$

International Large Detector

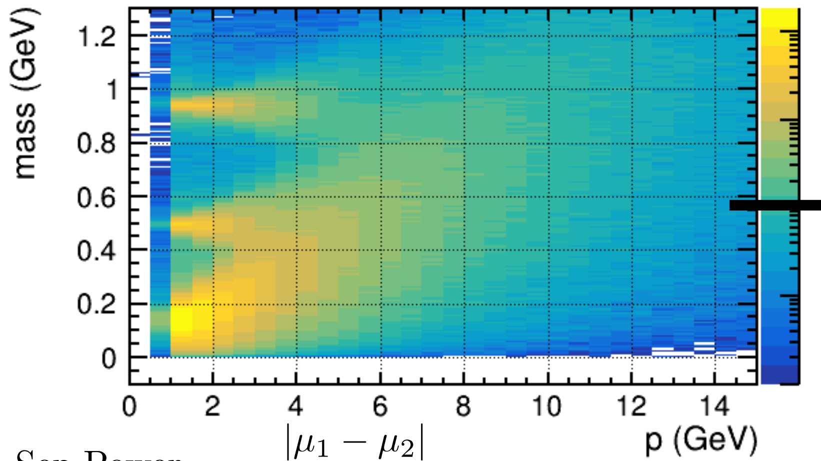


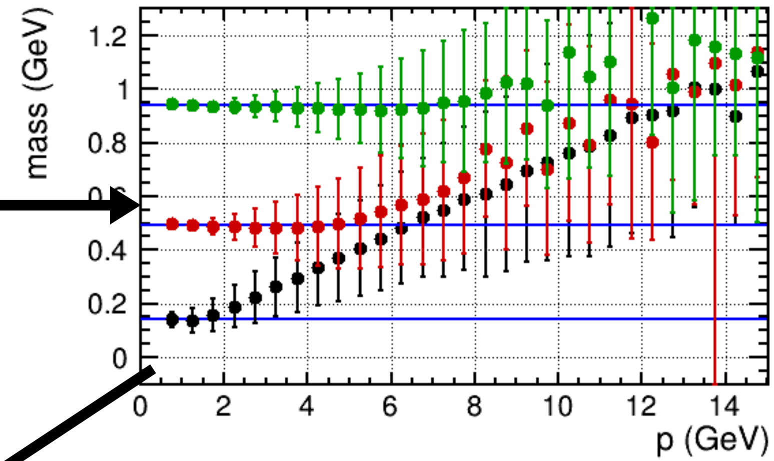
My latest in-depth talk on TOF

note[1]: current Si sensor developments show 20 – 100 ps time resolution (per hit!) is possible to achieve
note[2]: event time always assumed t_0=0. It is always can be absorbed in the effective TOF resolution
note[3]: fast timing sensors can be placed in the inner-most ECAL layers or as an additional outer Si tracker layer

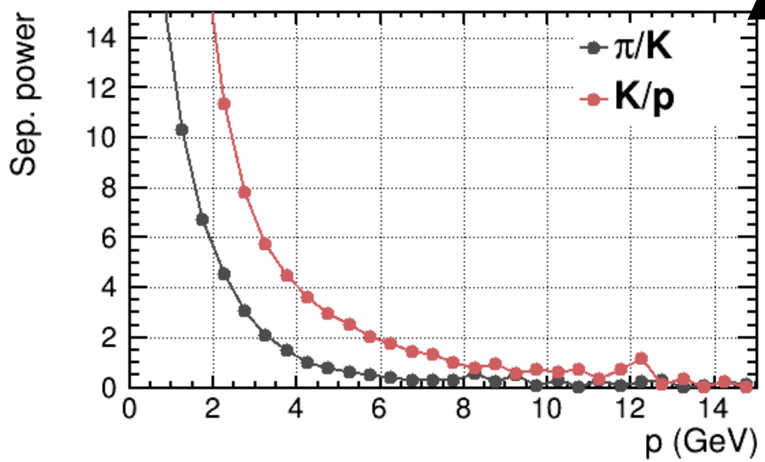
TOF particle ID performance

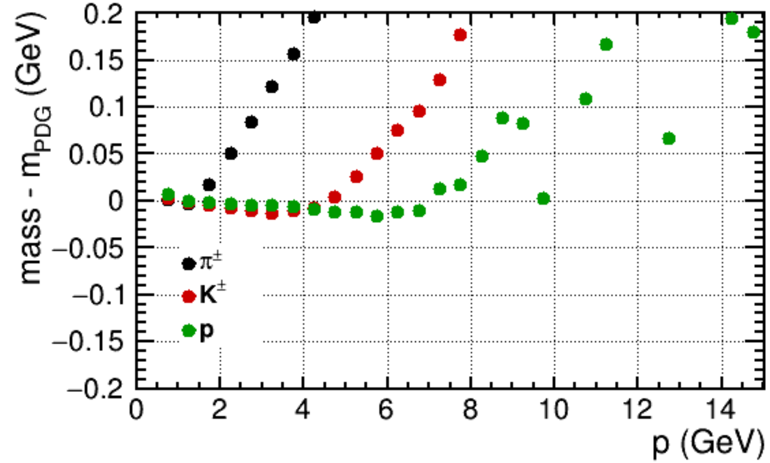
only barrel / 30 ps TOF resolution / (Z→qq 250 GeV)





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

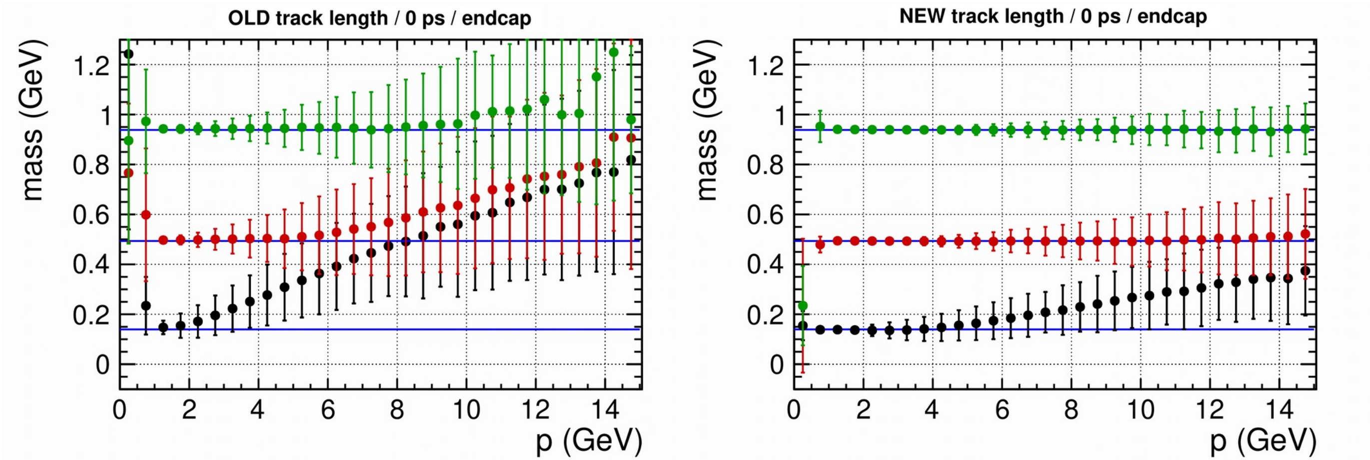




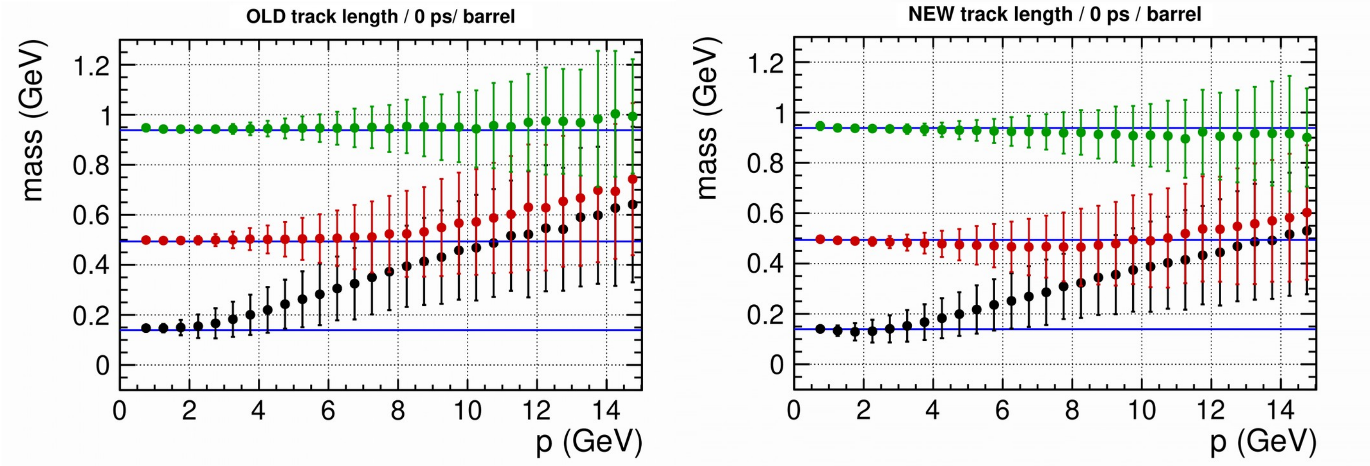
note[1]: using m(p) shows better results than β(p) because slice distribution is more Gaussian (back up)

Impact of the track length on time of flight particle ID

Track length hit-by-hit gives huge improvement in the endcap compared to the helix approximation

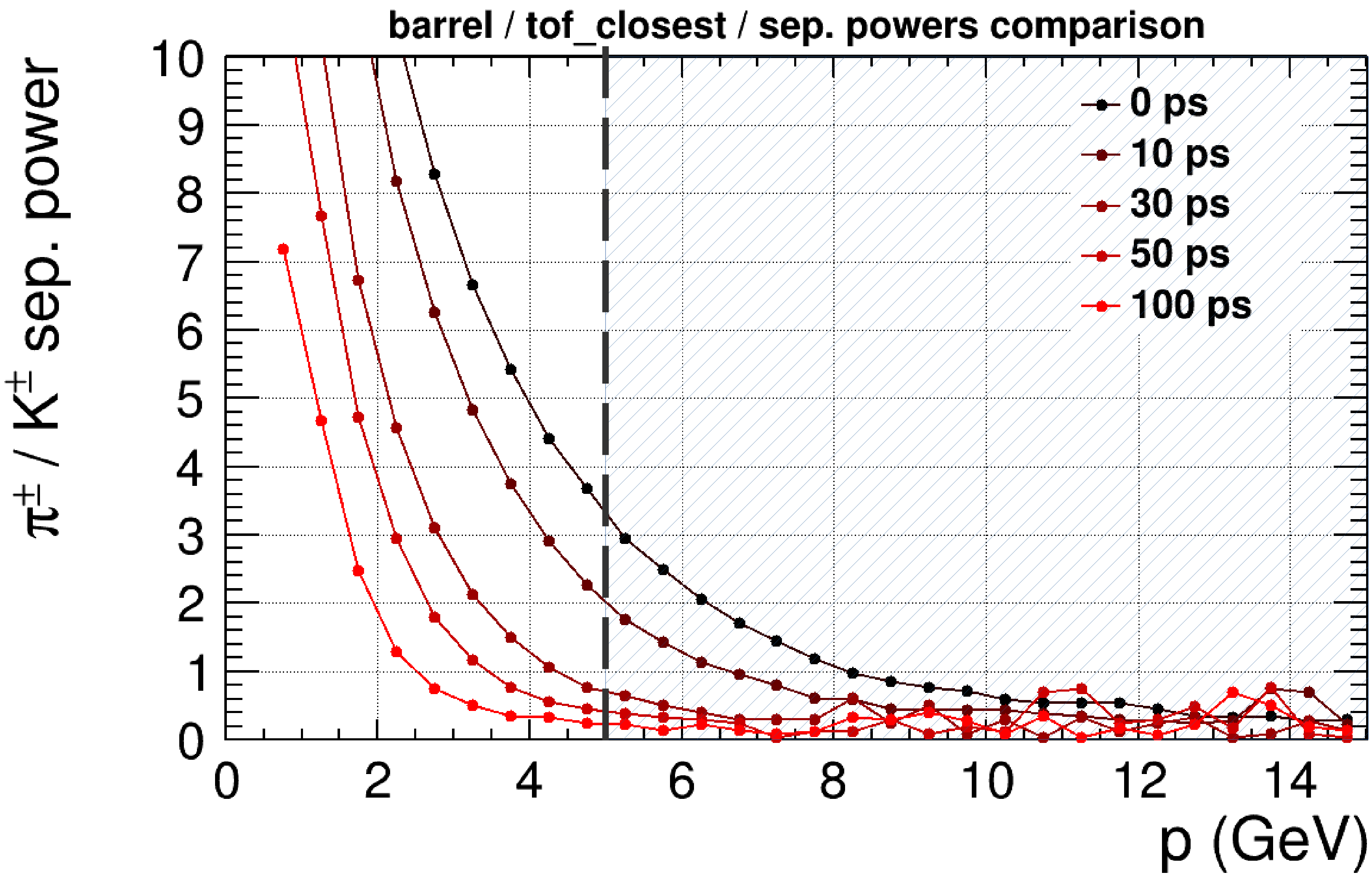


Track length hit-by-hit gives mild improvement in the barel compared to the helix approximation



note[1]: these plots assume perfect TOF resolution

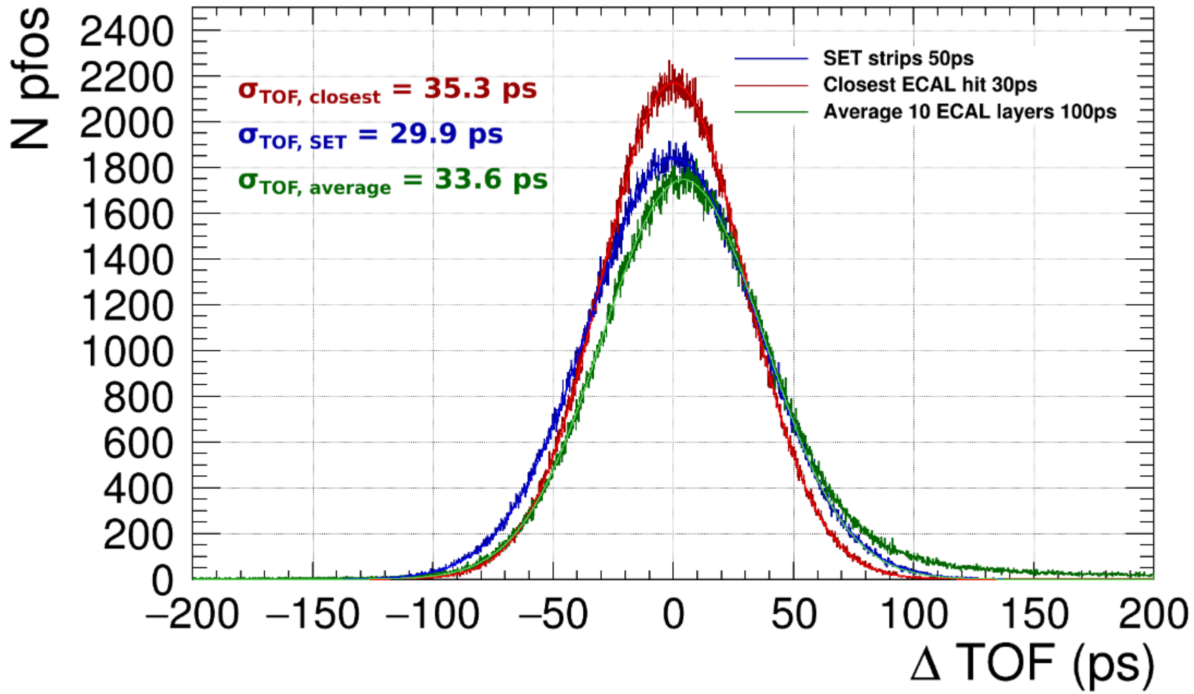
Separation power versus TOF resolution



Potential technological implementation of time of flight measurement

- 1 ECAL timing layer with cutting-edge 30 ps hit time resolution (e.g. LGAD)
- 2 Si strips (e.g. between TPC and Ecal) with moderate 50 ps hit time resolution
- 10 ECal timing laters with decent 100 ps hit time resolution

All result in roughly ~30 ps final TOF resolution.
Many technological options are still viable



V0 finder

V0 finder

Cut-based processor, checks all track combinations:

- To be consistent with a common non-IP vertex
- To actually be a prong of that vertex
- To have an invariant mass consistent with the V_0 hypothesis

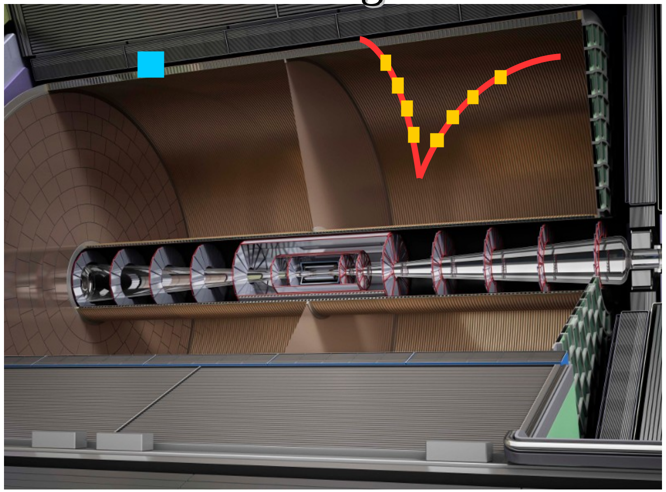
Requires min. distance to IP to not interfere with later vertexing (LCFIPlus)

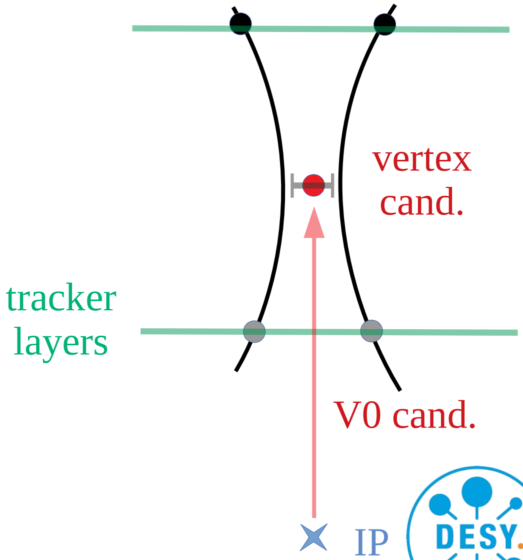
Most common V_0s:

- $K^0_S \rightarrow \pi^+\pi^-$ (69%)
- $\Lambda^0 \rightarrow p^+\pi^-$ (64%)
- $\gamma \rightarrow e^+e^-$

Written as a separate collection and the PID is attached to PFOs

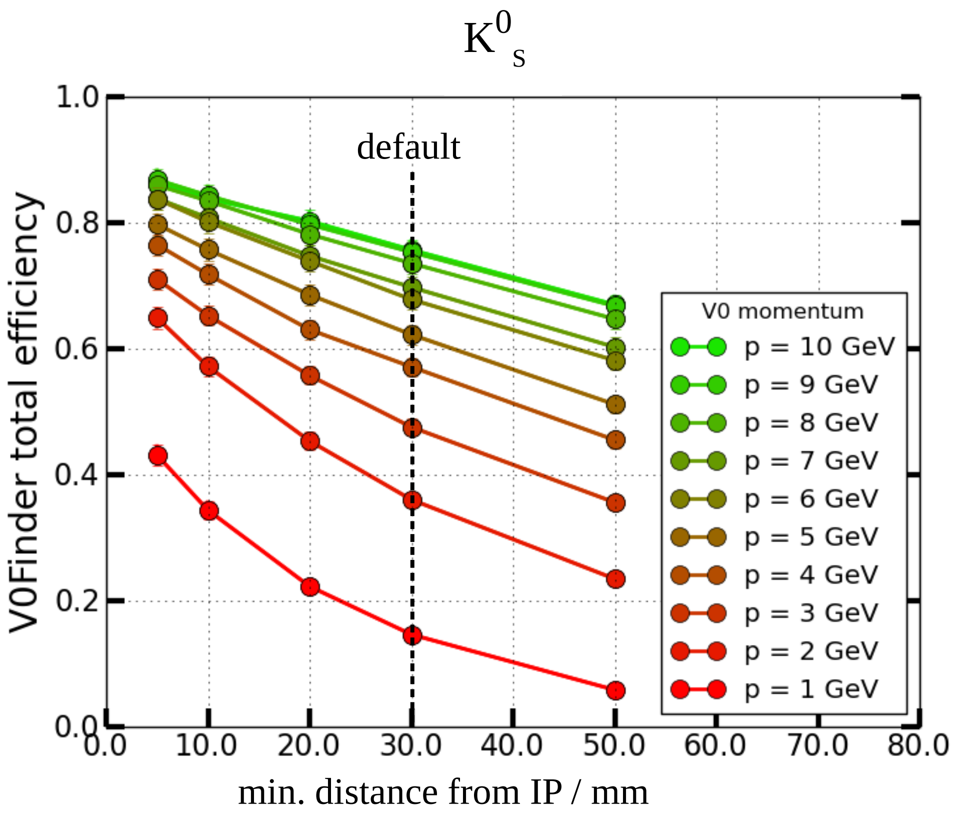
International Large Detector

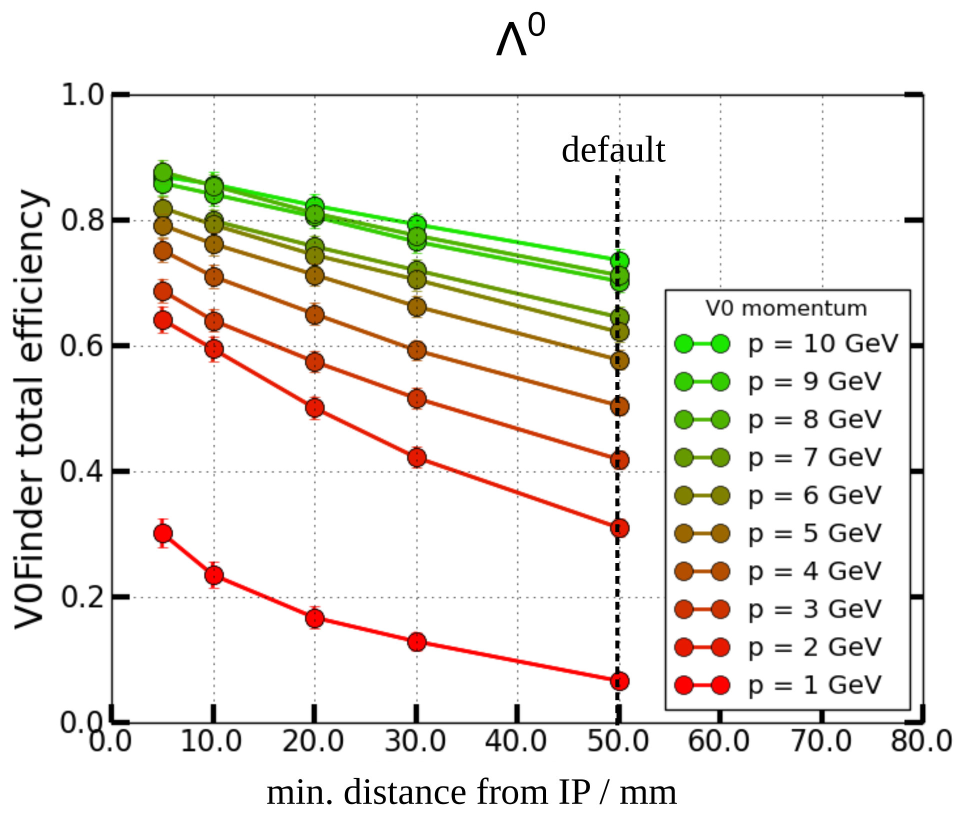




V_0 finder performance

Basic assessment of efficiency, depending on momentum and radial cut shows room for improvement





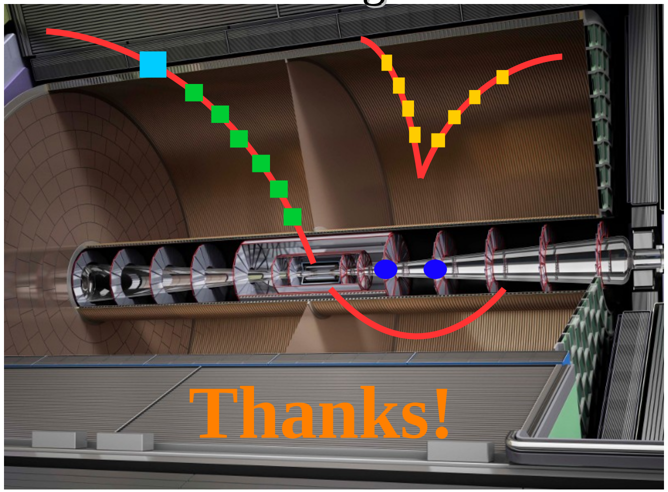
Summary and Future plans

- Many active developments have happened over the recent years (despite Covid) showing a great TPC particle ID capabilities
- dE/dx PID is already very robust, but still has a room to improve resolution beyond current 4.6%
- TOF PID is very recent and develops very fast, showing excellent PID below 5 GeV complementing dE/dx in a dip

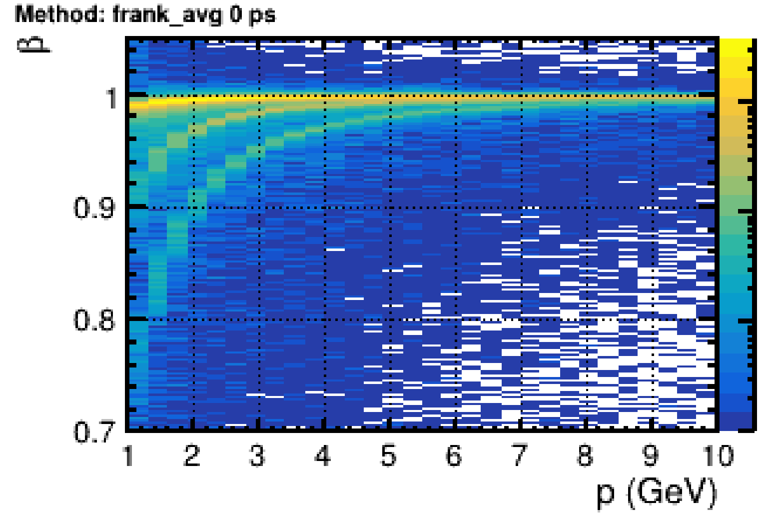
Still many things are planned and ongoing:

- Make fully robust likelihood PID processor: dE/dx+TOF+shower shapes+etc.
- Simulate realistic digitizer in the ECAL for TOF measurement, not only earliest MC contribution, but full threshold behaviour.
- Explicitly show TOF particle ID benefits for physics analyses
- Full assessment of V_0 finder and its relation to LCFIPlus vertexing/V_0s planned for this year

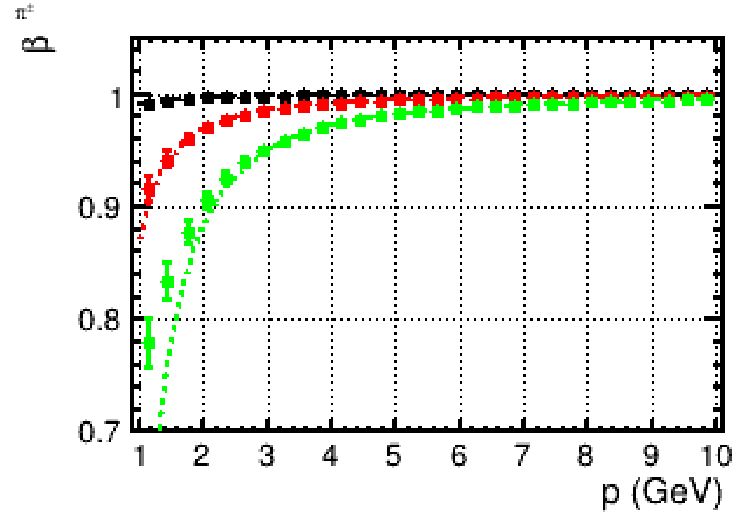
International Large Detector



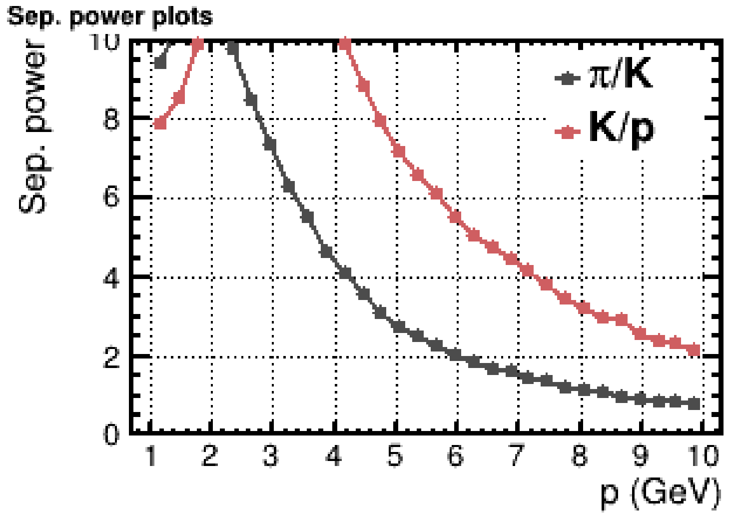
Back up



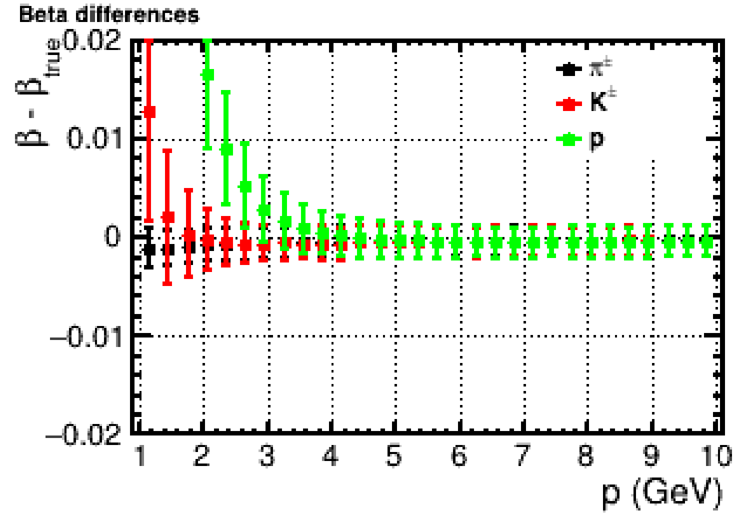
Method: frank_avg 0 ps
β
p (GeV)



β
p (GeV)

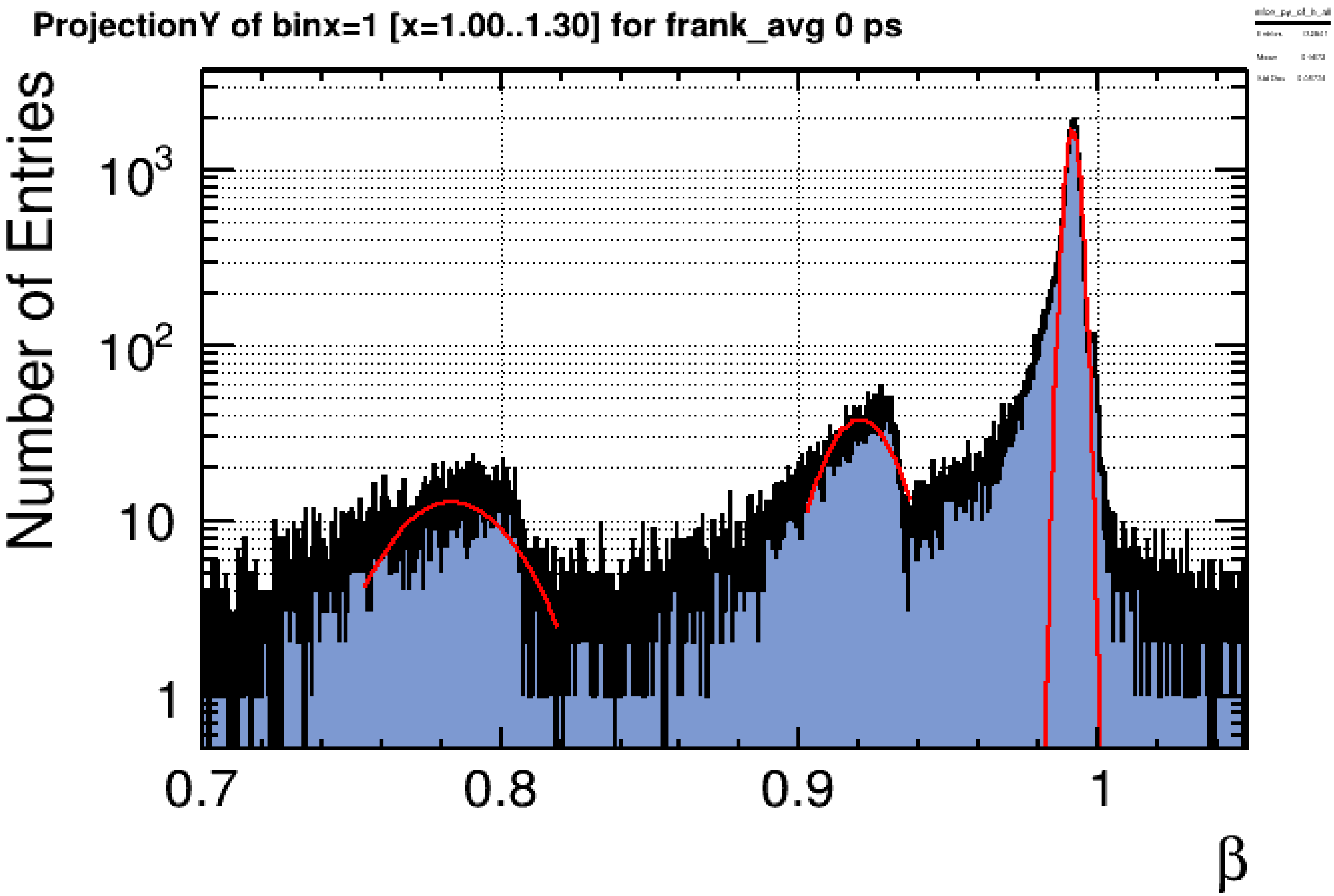


Sep. power plots
Sep. power
π/K
K/p
p (GeV)



Beta differences
$\beta - \beta_{true}$
$\pi^{\pm}$
$K^{\pm}$
p
p (GeV)

Back up



ProjectionY of binx=1 [x=1.00..1.30] for frank_avg 0 ps
Number of Entries
1
10
10^2
10^3
0.7
0.8
0.9
1
β