Novel Mass Measurement Methods using the LHCb RICH Detectors

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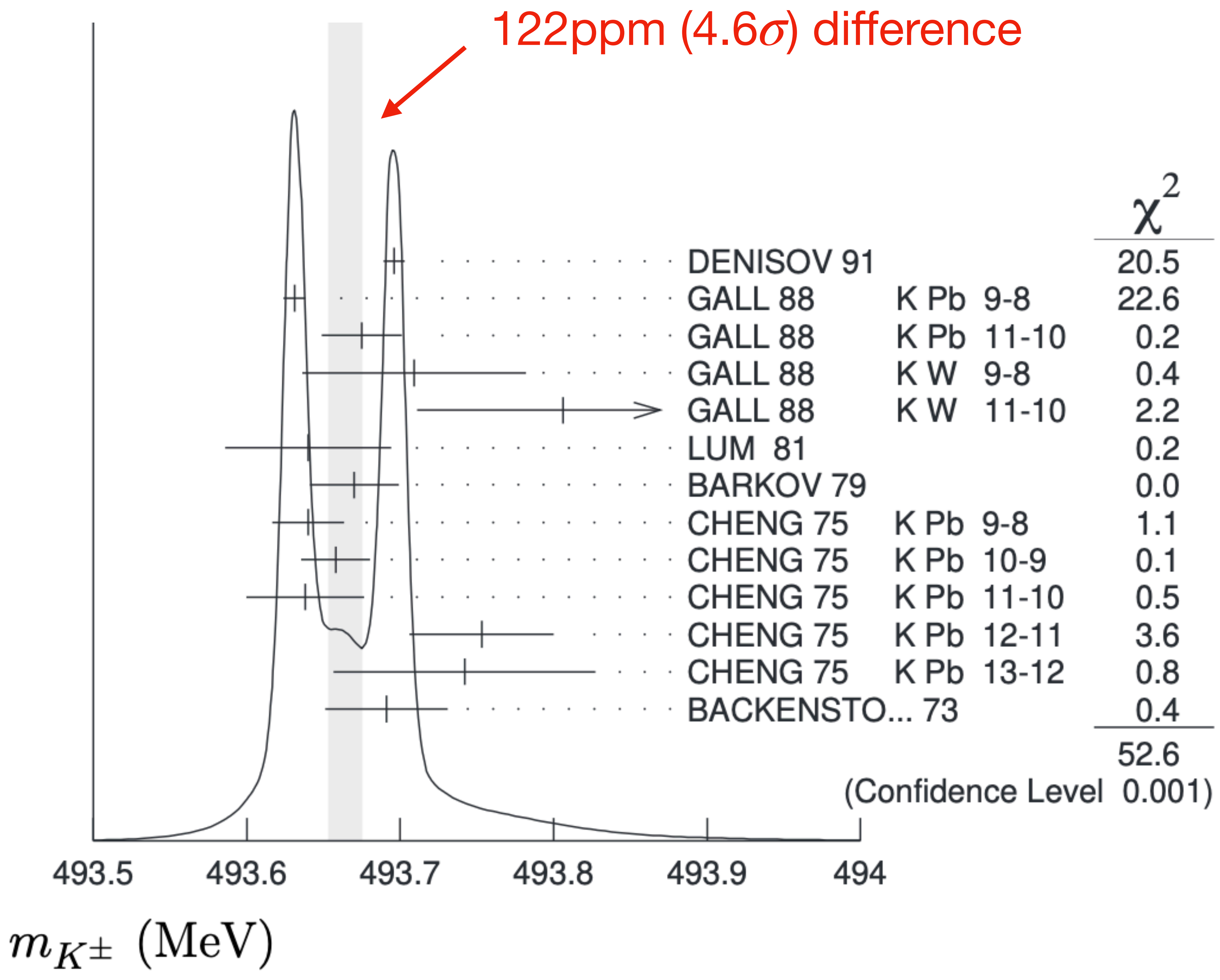
Uncertainty Around the Kaon



- PDG average kaon mass:

$$m_{K^\pm} = 493.677 \pm 0.013 \text{ MeV } \textbf{(26ppm)}$$

- **Error scaled by 2.4** to account for differences in the leading measurements.
- Reducing $\Delta m_{K^\pm}$ would benefit precision measurements, e.g:
  - $|V_{us}|$ uncertainty.
  - Very rare kaon decay uncertainties.
  - $m(\chi_{c1}(3872)) - m(D^0\bar{D}^{*0}) = -0.12 \pm 0.13$ MeV where $\Delta m_{K^\pm}$ dominates.

Uncertainty Around the Kaon

- The leading $m_{K^\pm}$ contributions are from X-ray energy measurements of kaonic atoms.
- The PDG comments that discrepancies are likely due to unresolved systematics from different transitions within GALL88.

> While we suspect that the GALL 88 K^-Pb $(9 \rightarrow 8)$ measurements could be the problem, we are unable to find clear grounds for rejecting it. Therefore, we retain their measurement in the average and accept the large scale factor until further information can be obtained from new measurements and/or from reanalysis of GALL 88 and CHENG 75 data.
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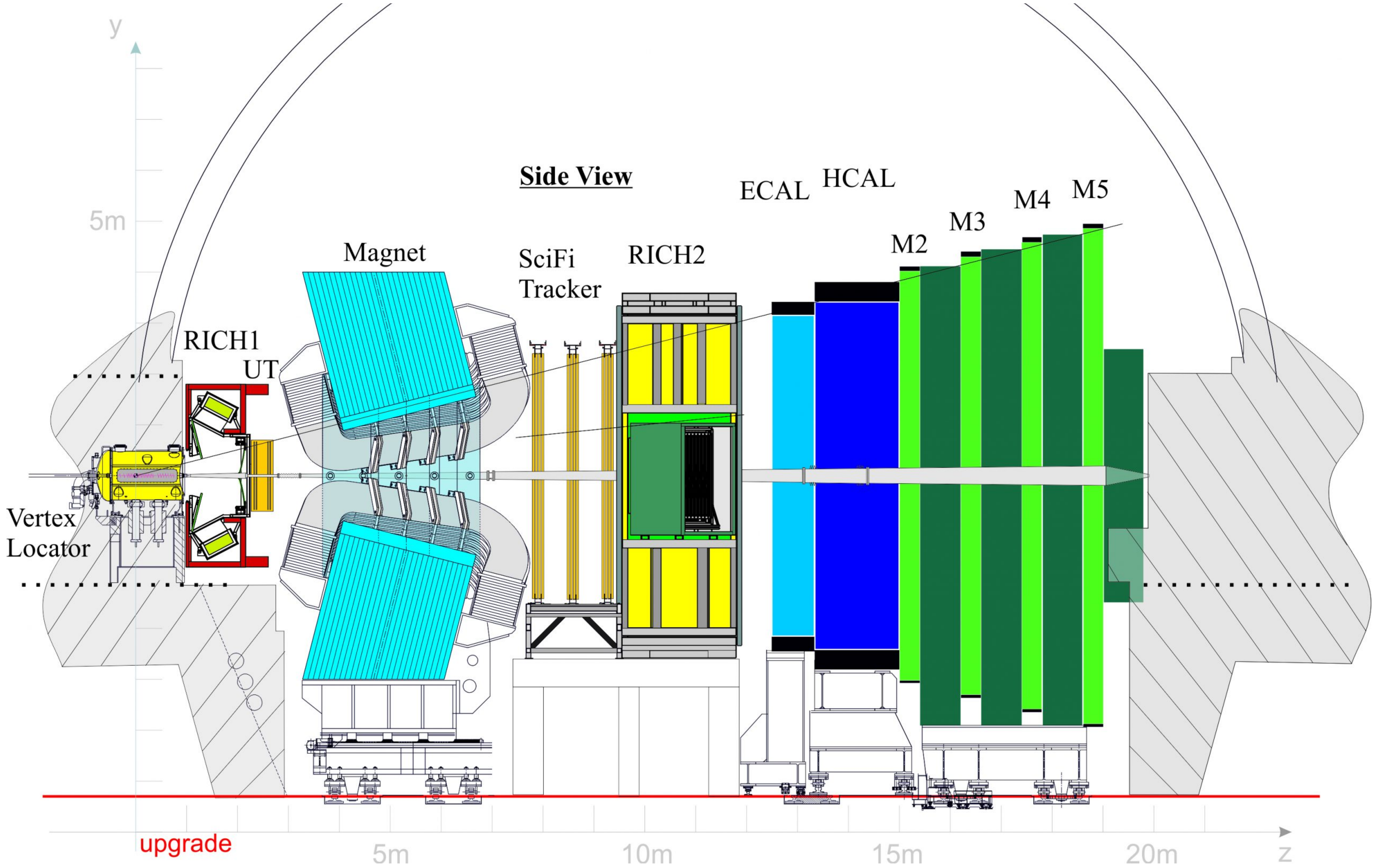
- ***A new precision measurement of $m_{K^\pm}$ could resolve the discrepancy.***

The LHCb Detector

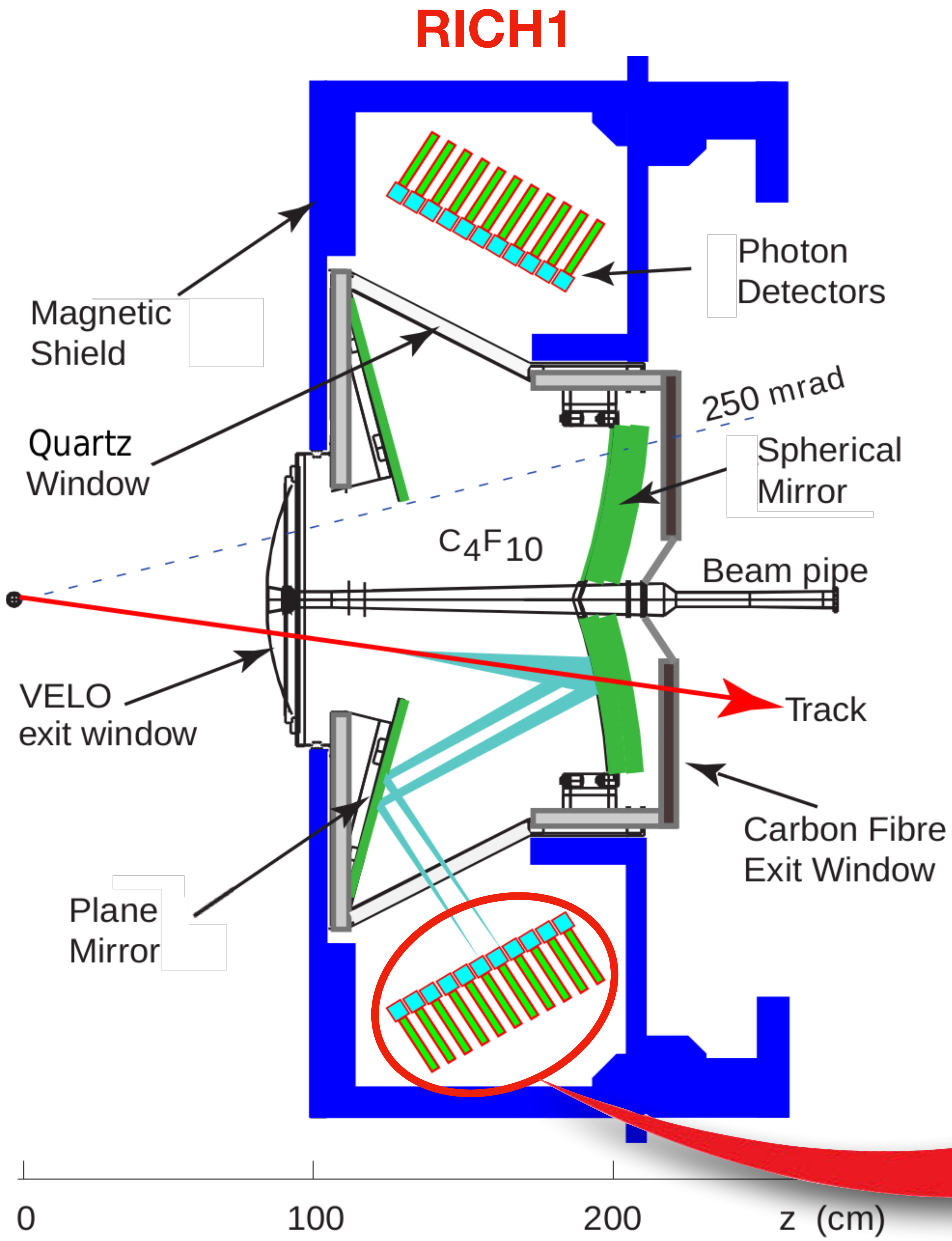


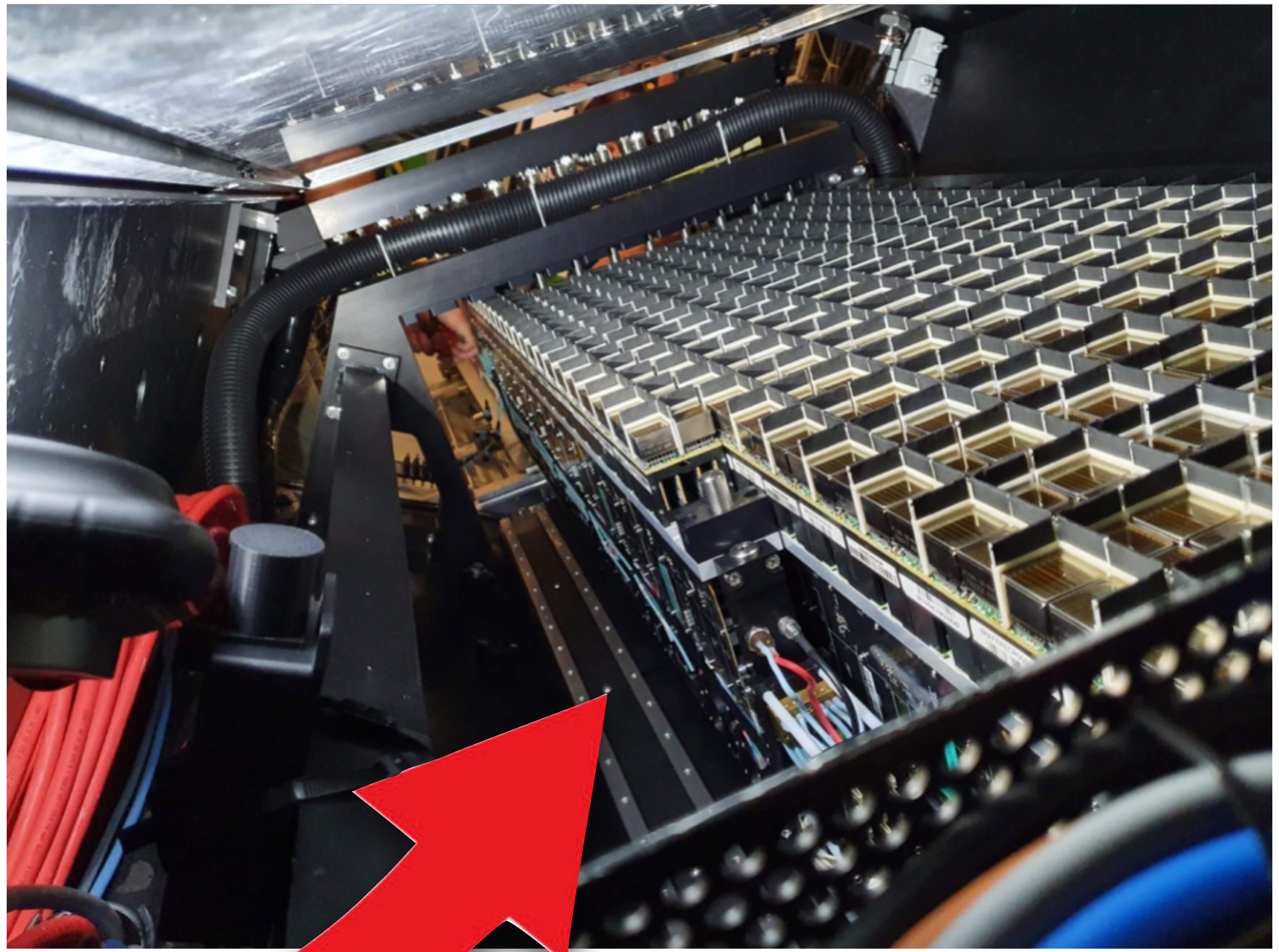
The RICH System

- RICH1 & 2 provide charged hadron discrimination between 2-60 and 15-100 GeV respectively.
- Measures Cherenkov radiation emitted by high momentum π, K or p particles.

$$\cos\theta_C = \sqrt{1 + (m/p)^2}/n$$

Characteristic Equation





Feasibility Studies

- The RICH was ***NOT*** designed to make mass measurements.
- ***But could it theoretically compete with 26ppm?***
- Propagate uncertainties with Cherenkov formula:

$$\cos\theta_C = \sqrt{1 + (m/p)^2}/n$$

$$m = p\sqrt{(n\cos\theta_C)^2 - 1}$$

$$\Delta m = \sqrt{\frac{\Delta\theta_C\, n^4 p^4 \sin^2\theta_C}{m^2} + \frac{\Delta p^2 m^2}{p^2}}$$

Refractive index calibrated online

Momentum resolution comes from tracking

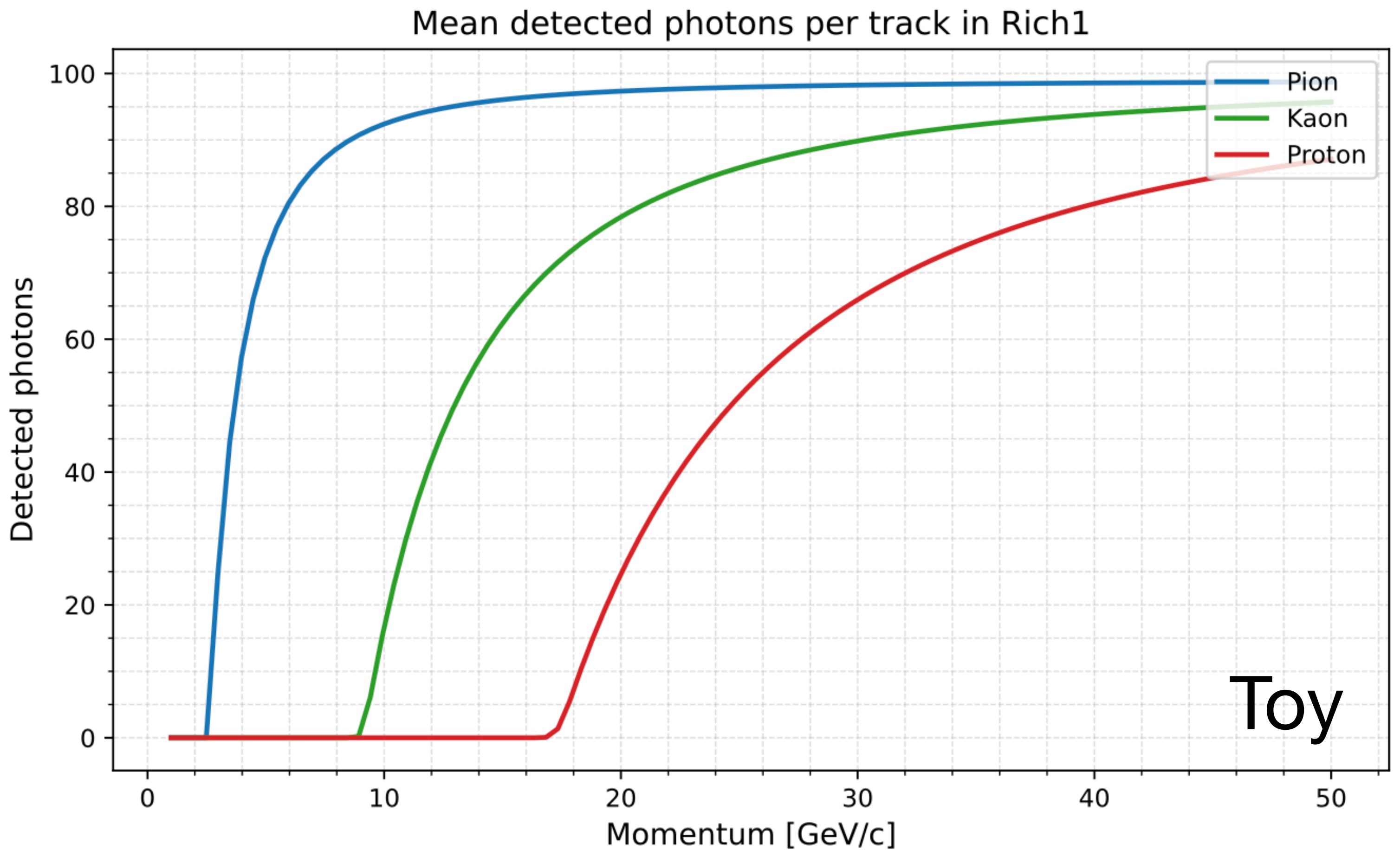
$$\Delta\theta_C = \sqrt{\frac{\sigma(\theta_C)^2}{N_{ph}^{det}} + \sigma_{trk}^2}$$

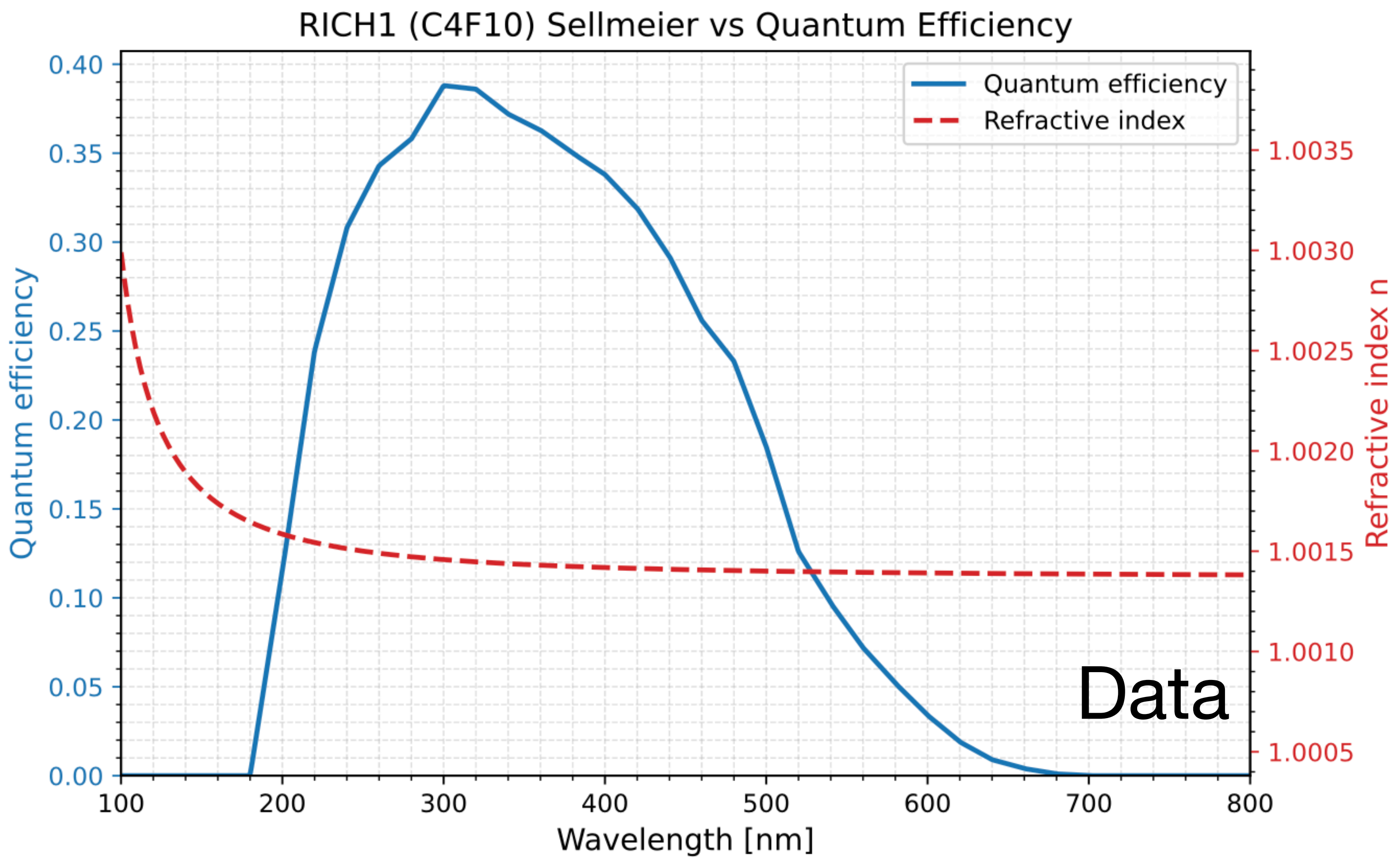
1. $\Delta\theta_C$ Cherenkov angle resolution
2. $\sigma(\theta_C)$ Single photon resolution
3. N_{ph}^{det} Detected number of photons
4. σ_{trk} Tracking contributions

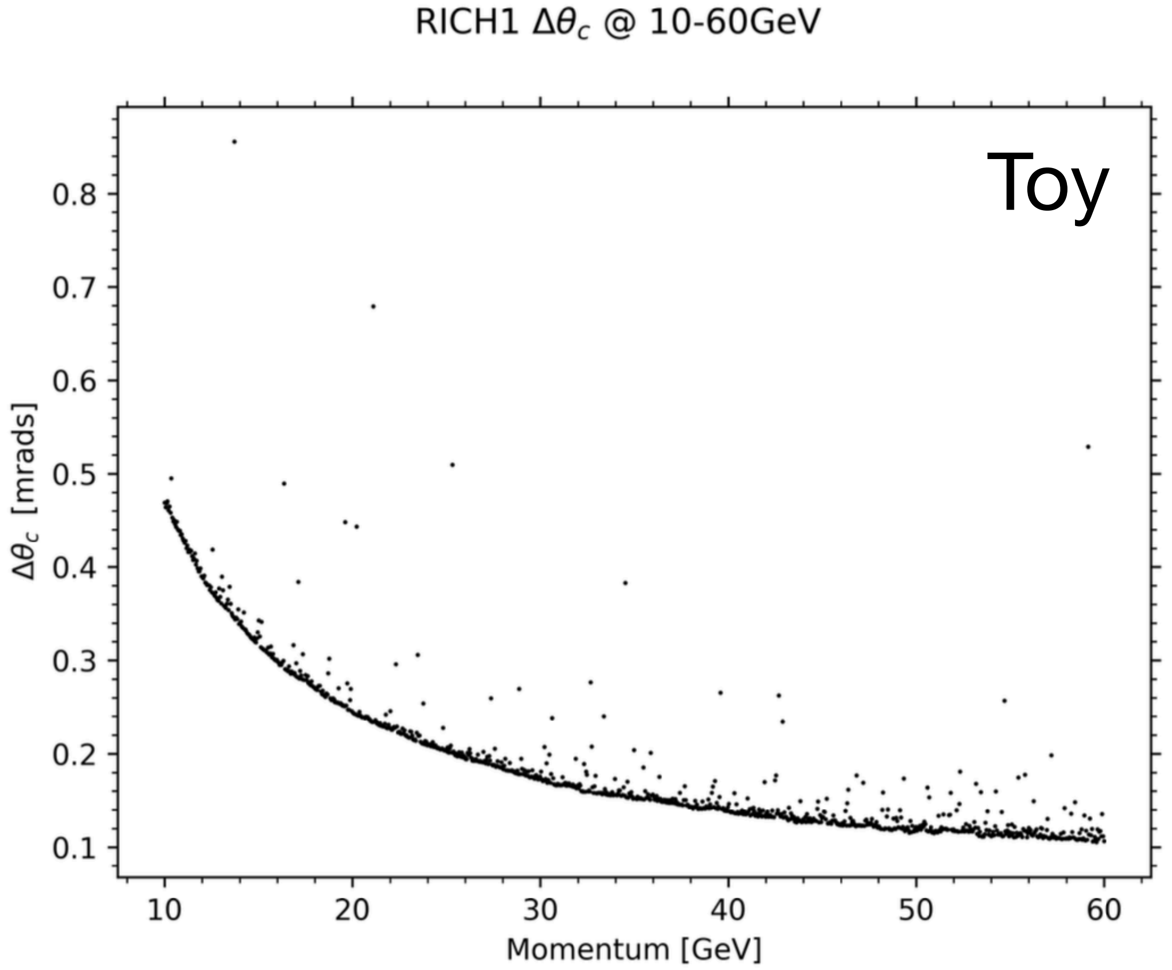
Feasibility Studies

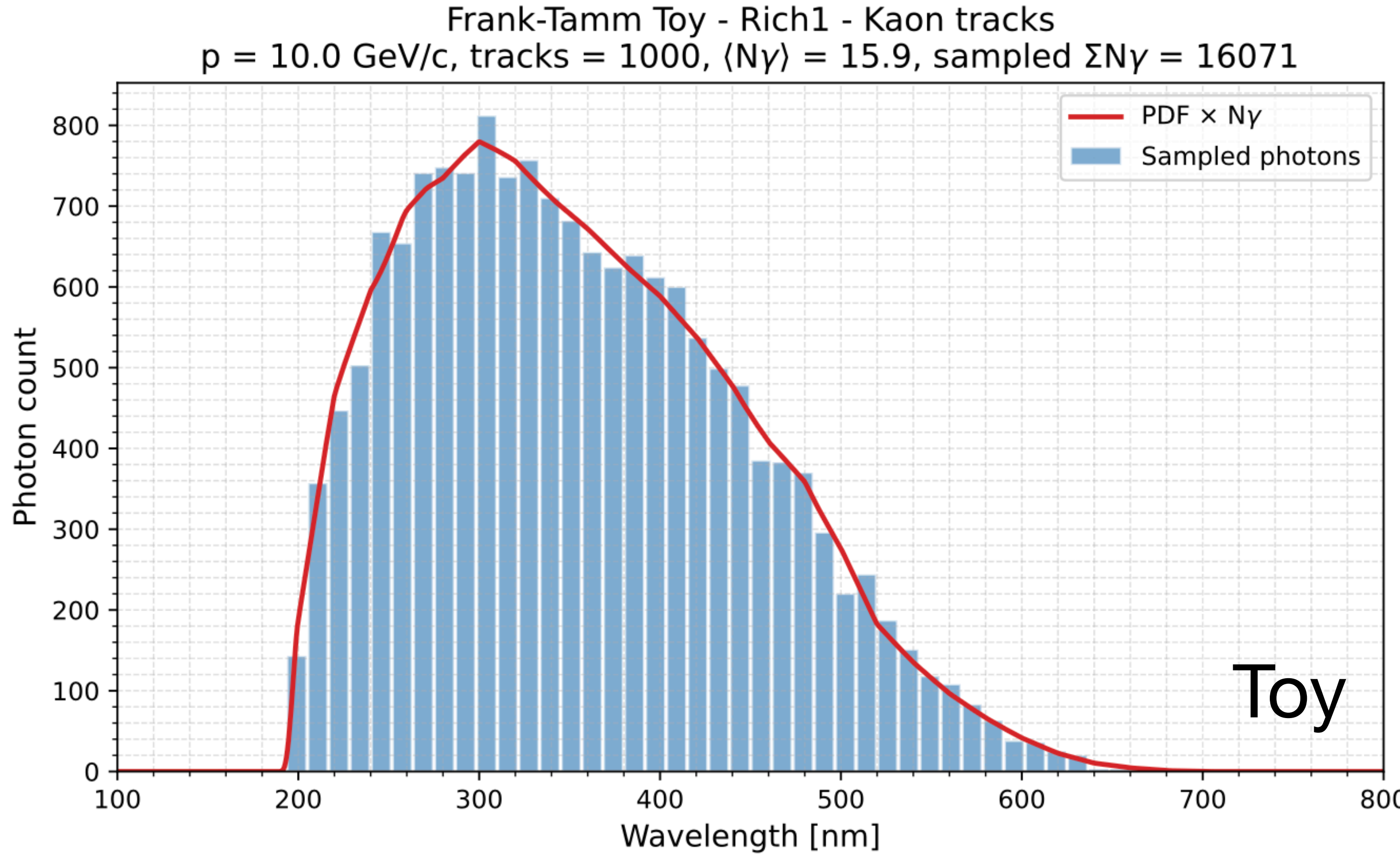
$$\Delta m = \sqrt{\frac{\Delta\theta_C\, n^4\, p^4 \sin^2\theta_C}{m^2} + \frac{\Delta p^2\, m^2}{p^2}}$$

- Must model:
  1. Mirrors and quartz reflectivity and transmissivity.
  2. Radiator refractive index.
  3. MaPMT quantum efficiency.
  4. Cherenkov photon production.
  5. Single photon resolution.
  6. Tracking effects in RICH.
  7. Momentum resolution.



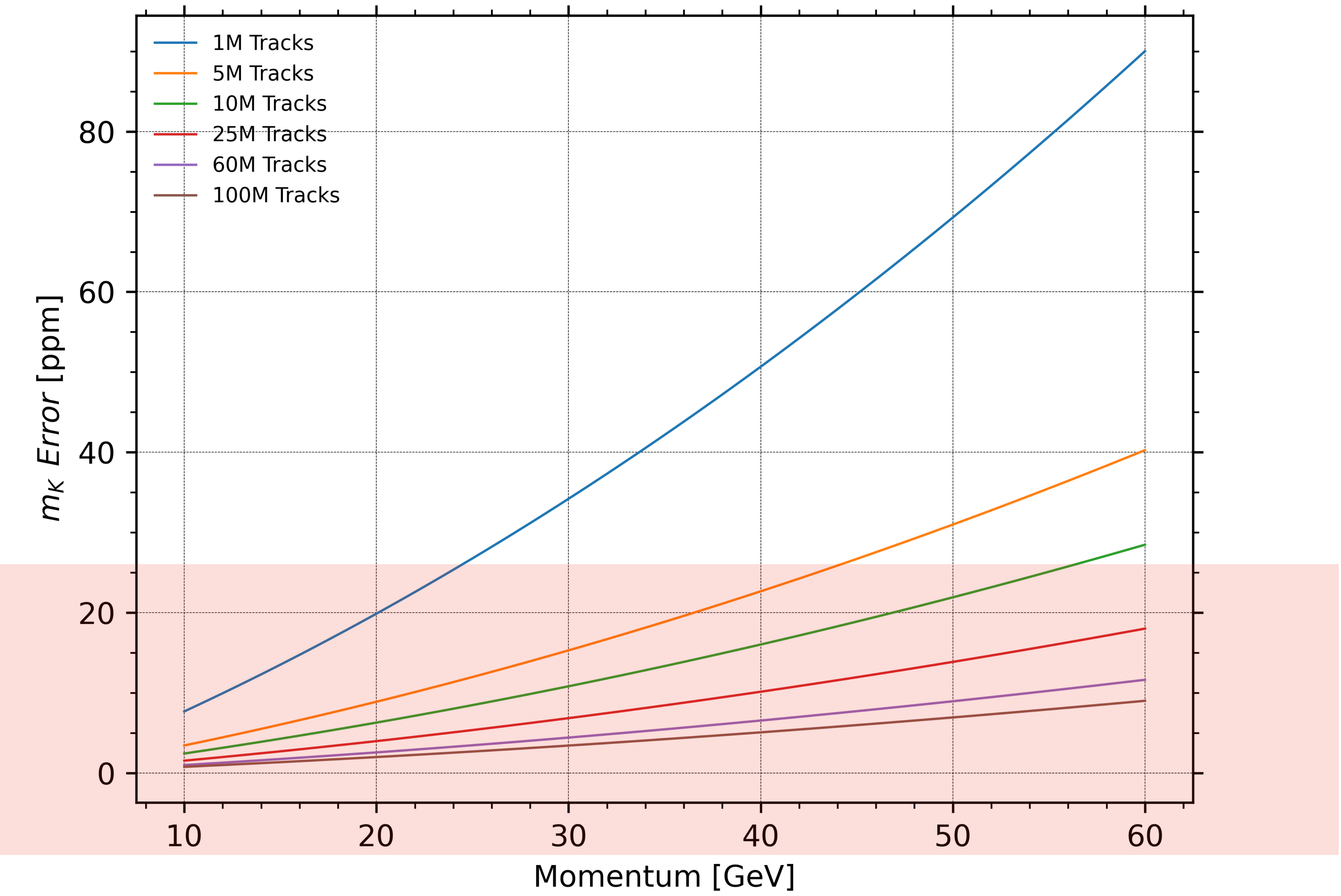




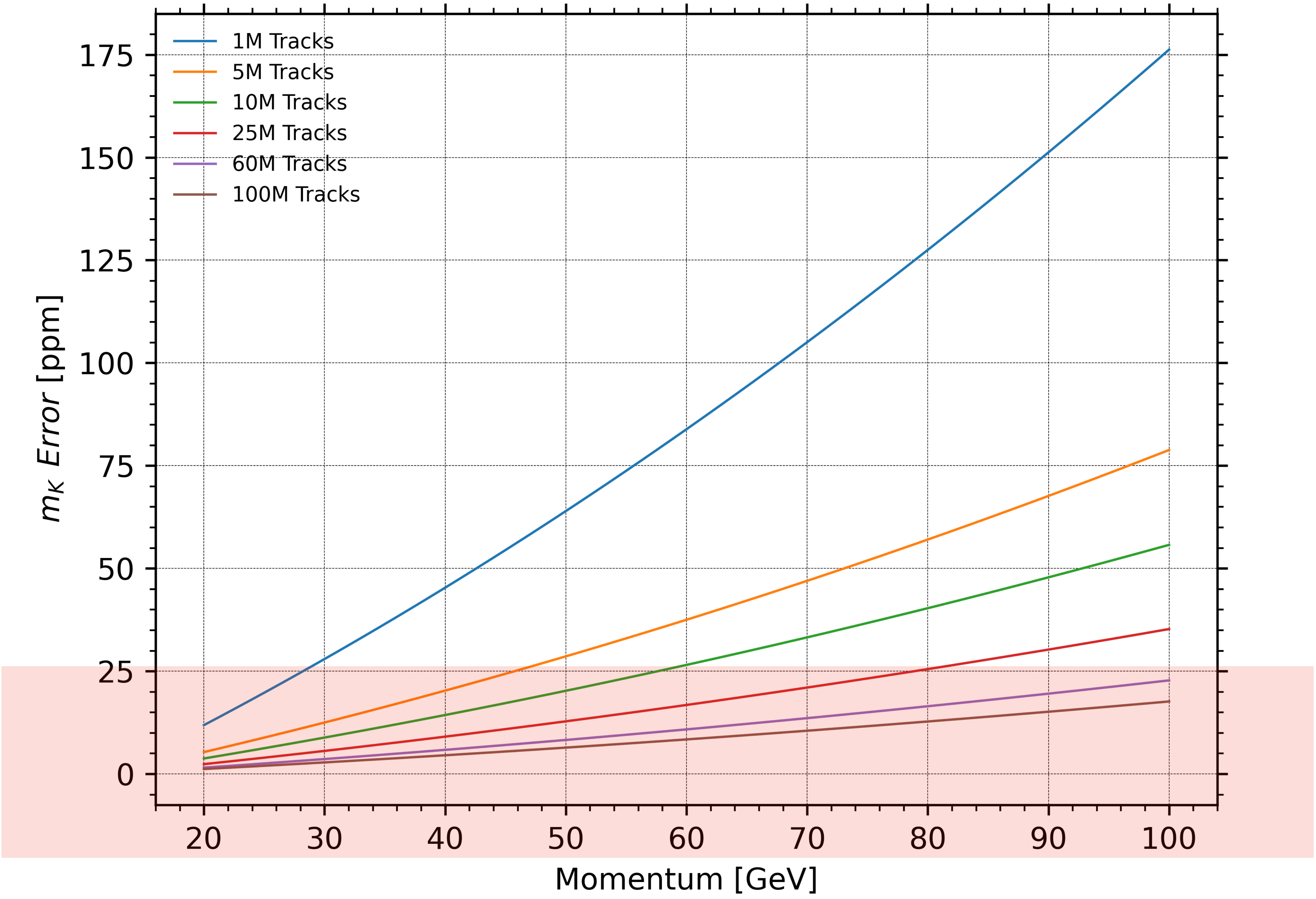


Feasibility Studies

RICH1 Statistical Unc. on m_K in ppm @ 10-60GeV



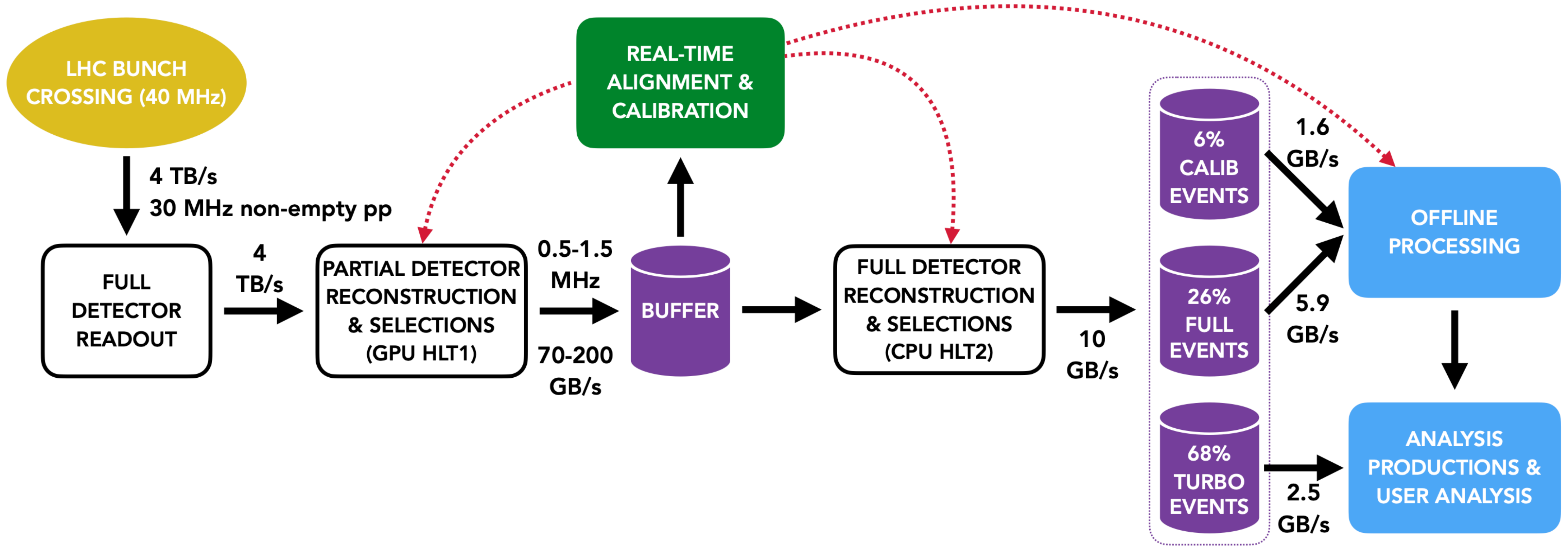
RICH2 Statistical Unc. on m_K in ppm @ 20-100GeV

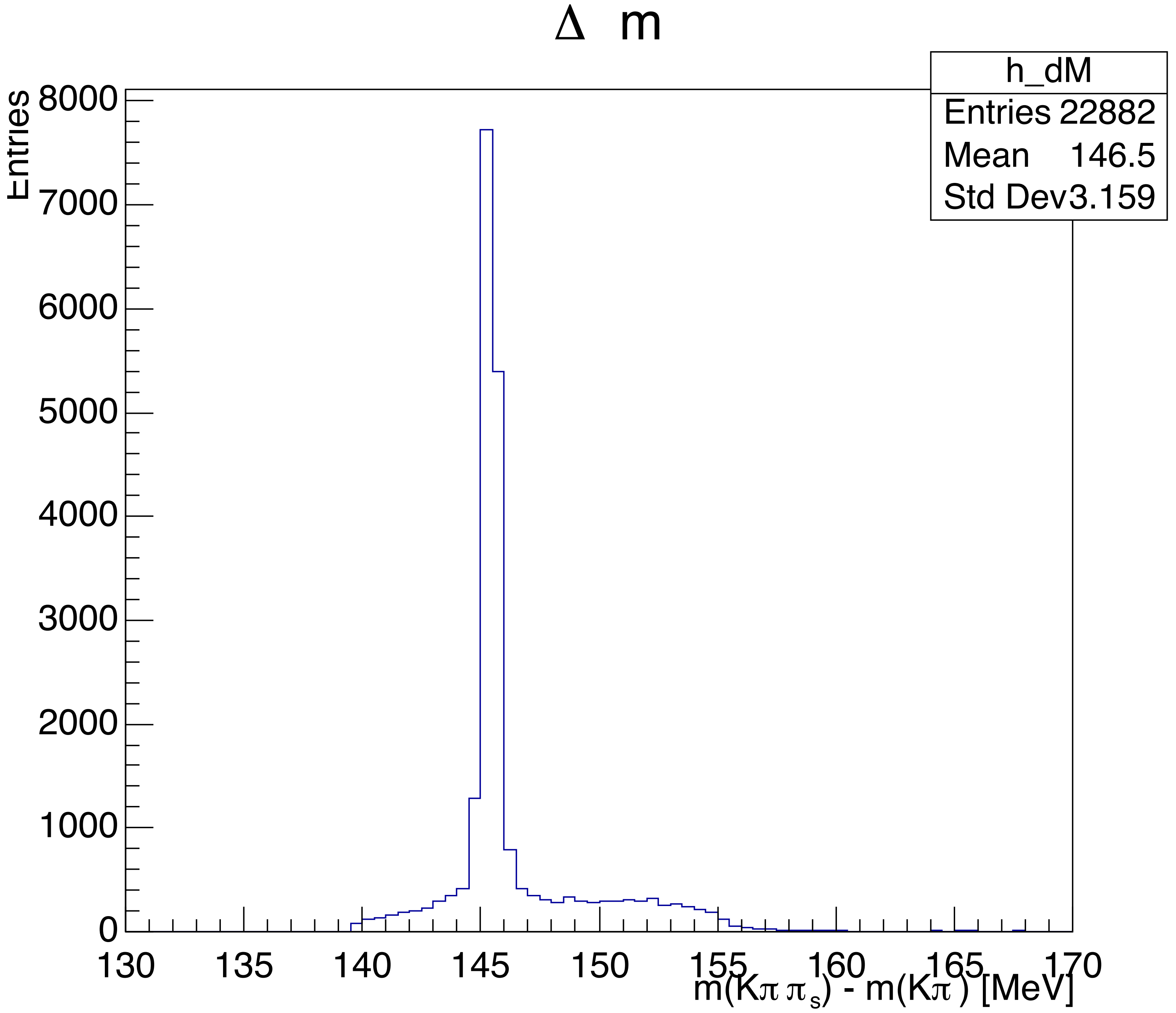


- $\Delta m_{K^\pm}[\text{ppm}] = \dfrac{\Delta m_{K^\pm} \times 10^6}{m_{K^\pm}} / \sqrt{N_{track}}$
- ***RICH1 and RICH2 could compete, especially at lower momenta!***

Kinematic Candidate Selection

- LHCb reads out at 40MHz using a 2-stage, full software trigger.
- Dedicated calibration streams (TURCAL) are used to validate detector performance.
- These provide high purity samples via tight kinematic selections.





$$\Delta m^{PDG} = m^{PDG}_{D^*} - m^{PDG}_{D^0} = 145.425 \text{ MeV}$$

- TURCAL lines of importance:

$$D^{*\pm} \rightarrow D^0\,(\rightarrow K^{\mp}\pi^{\pm})\,\pi^{\pm}$$

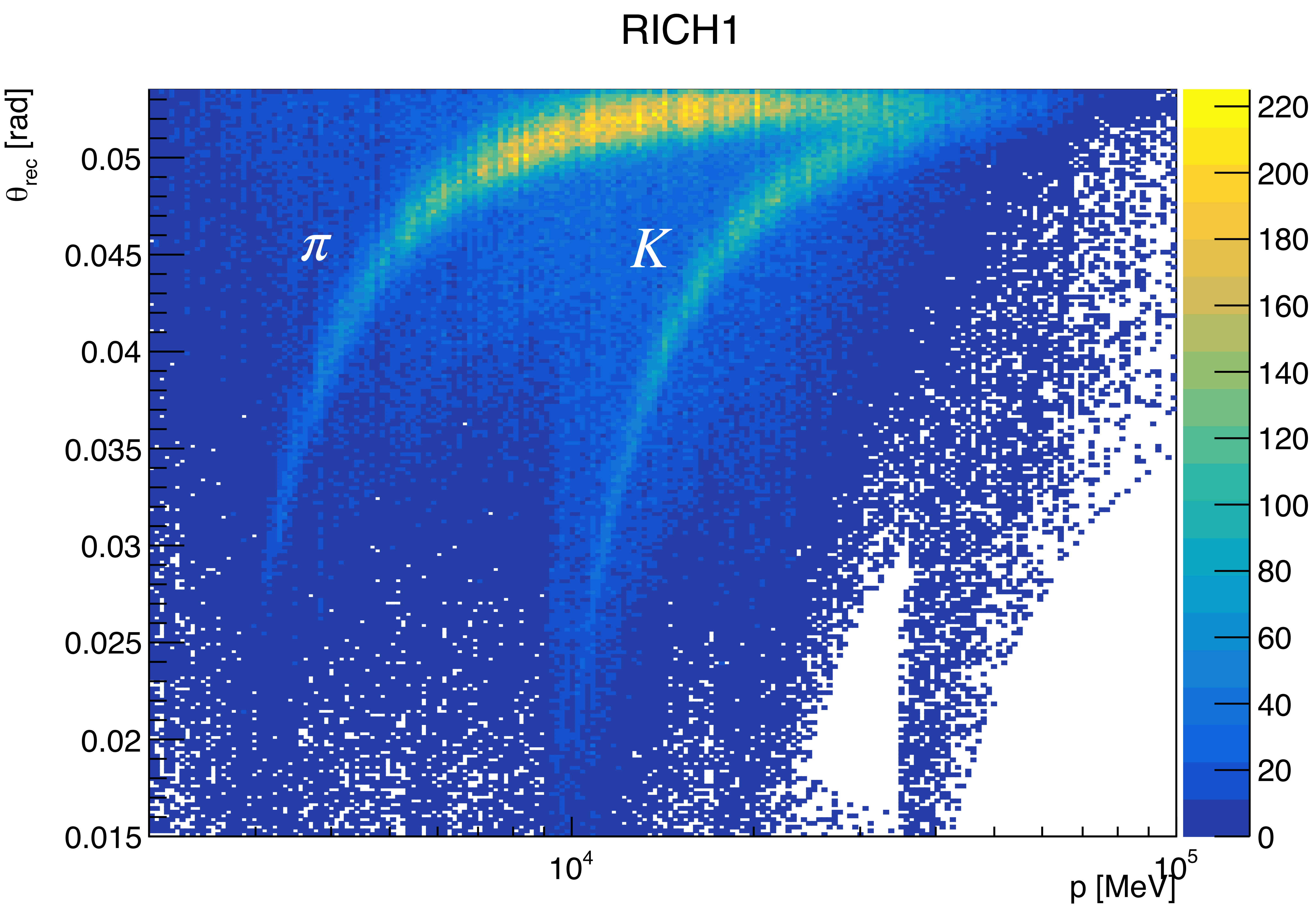
$$\Lambda \rightarrow p\,\pi^-$$

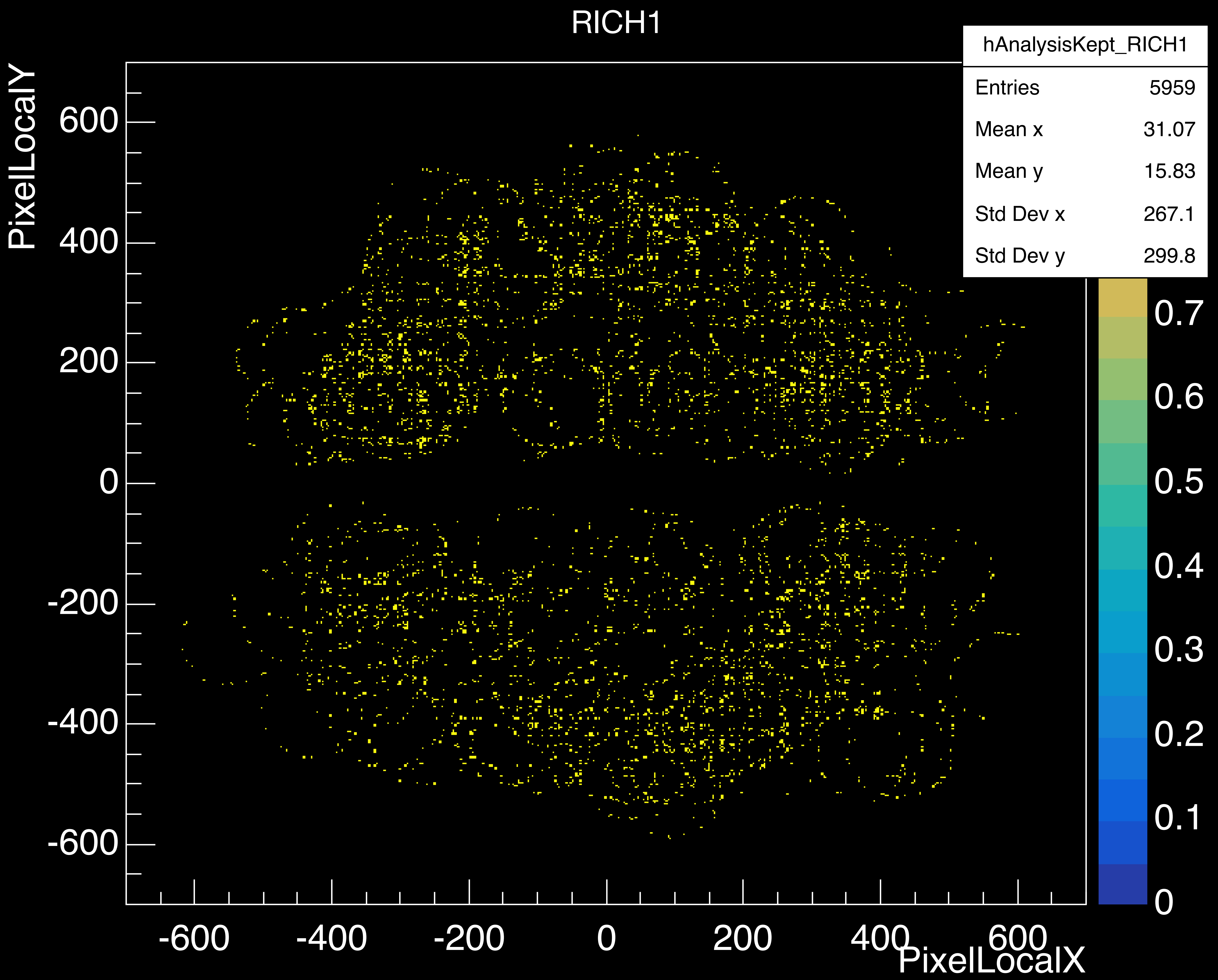
- *We can reconstruct these very well* ***without RICH PID.***
- Estimated $\sim 65M\ D^*$ and $\sim 400M\ \Lambda$ between 2024-25.

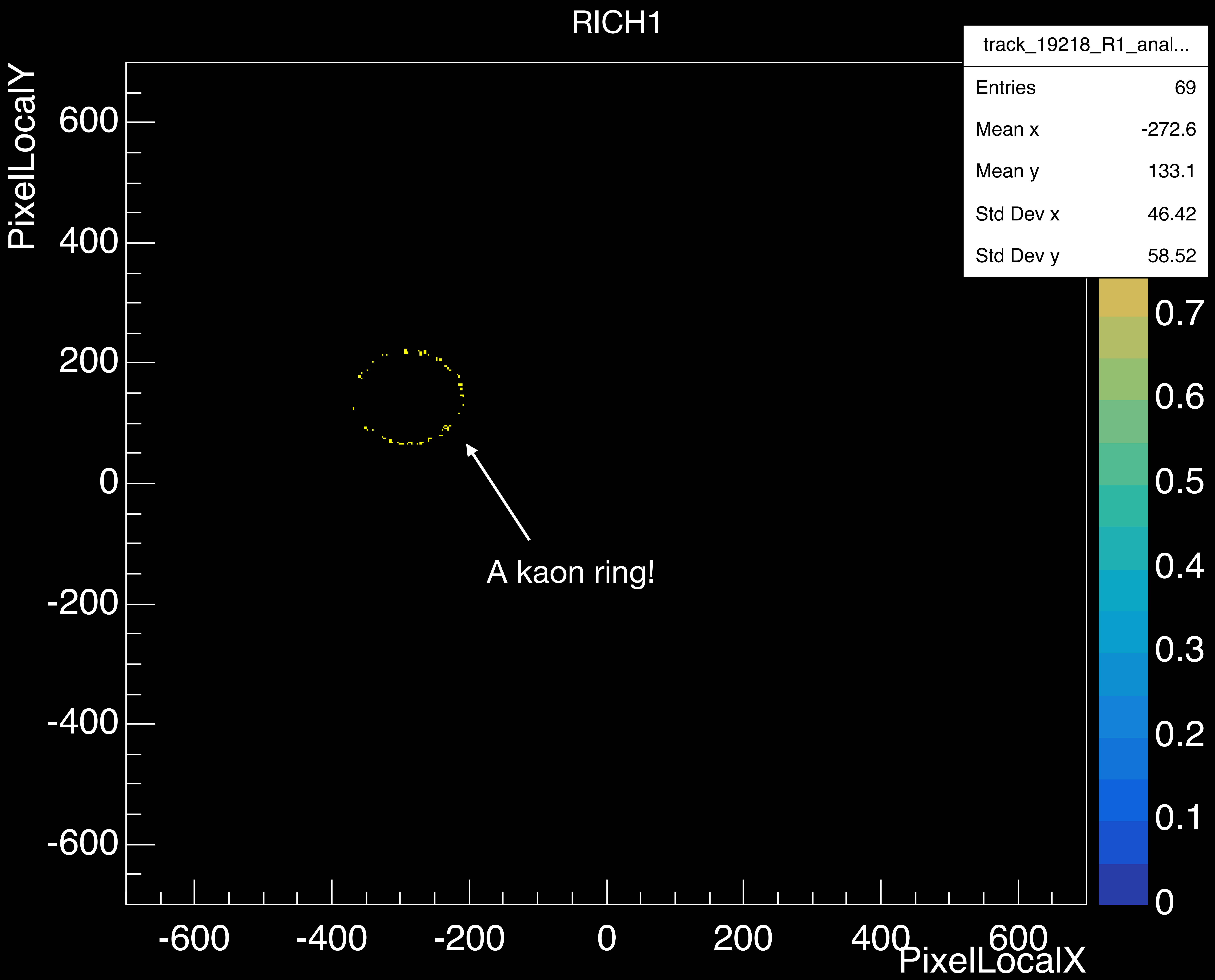
→ ***Massive statistics available.***

RICH Reconstruction

- The RICH consumes:
  1. Detected photon positions.
  2. Track momentum and direction.
- It produces:
  1. Photon-to-track association.
  2. Cherenkov angles θ_C for each photon.
  3. RICH PID probabilities.
- ***TURCAL lines coupled with reconstruction provide θ_C information for tracks known to be either π, K or p.***




RICH1
hAnalysisKept_RICH1
Entries 5959
Mean x 31.07
Mean y 15.83
Std Dev x 267.1
Std Dev y 299.8
PixelLocalY
PixelLocalX
600
400
200
0
-200
-400
-600
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0



RICH1
track_19218_R1_anal...
Entries 69
Mean x -272.6
Mean y 133.1
Std Dev x 46.42
Std Dev y 58.52
PixelLocalY
600
400
200
0
-200
-400
-600
PixelLocalX
-600
-400
-200
0
200
400
600
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
A kaon ring!

Cherenkov Mass Extraction

- ***How can we make a mass measurement?***
- For track j, we have:
    1. Species information.
    2. Momentum information.
    3. Photon-level θ_C information.
- Construct a probability density describing how well the observed θ_C information matches what is expected.

$$\mathrm{P}_j = \frac{1}{(2\pi^{3/2})\Delta\theta_j} \exp\left[-\frac{1}{2}\left(\frac{\theta_j^{\mathrm{rec}} - \theta(p_j, m)}{\Delta\theta_j}\right)^2\right]$$

θ_j^{rec} is the average θ_C over all photons.

$\theta(p_j, m) = \arccos\left(\sqrt{1 + (m/p_j)^2}/n\right)$

$\Delta\theta_j$ is the θ_C resolution.

- The product of P_j over all tracks defines the "likelihood".

$$\mathscr{L} = \prod_j^{N^{\mathrm{tracks}}} P_j$$

Cherenkov Mass Extraction

- Build the log-likelihood and rearrange:

$$-2\log\mathscr{L} = \sum_{j}^{N^{\text{tracks}}}\left[\left(\frac{\theta_j^{\text{rec}} - \theta(p_j, m)}{\Delta\theta_j}\right)^2 + \log(2\,\pi\,\Delta\theta_j^2)\right]$$

- Define χ^2 as where the mass dependence lives:

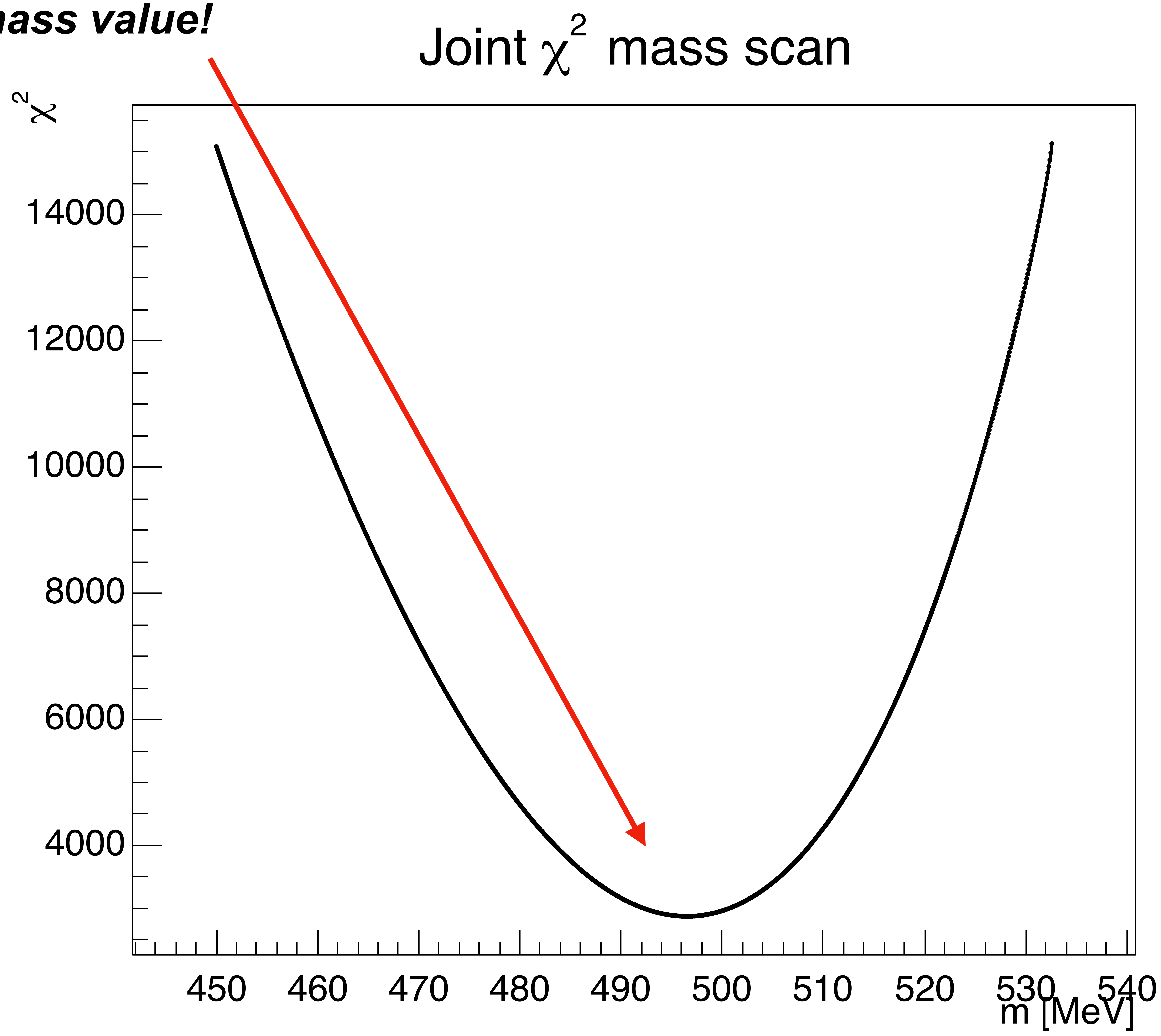
$$\chi^2 = \sum_{j}^{N^{\text{tracks}}}\left(\frac{\theta_j^{\text{rec}} - \theta(p_j, m)}{\Delta\theta_j}\right)^2$$

- We can statistically infer a ***best fit mass per species*** by choosing one which minimises the χ^2.
- Extract using a minimisation scheme e.g. ROOT's native Minuit2/MIGRAD.

χ^2 Profiles

- We can visualise the extracted value by profiling the χ^2.

→ ***Our extracted mass value!***



RICH1 Kaon MC

Conclusions

- **The method is still under development.** We have given it a name, Mass Inference via Ring Angles… MIRA!
- Demonstrates that the RICH is capable of making mass measurements!
- Still much work to be done, things are in constant motion.
- ***What's new:***
    1. A novel mass measurement technique for RICH detectors.
    2. The formalism and framework permitting this.
- ***What's promising:***
    1. **MIRA can be used to measure any charged hadron mass, not just the kaon!**
    2. Large statistics promise small statistical uncertainties.
- ***Next steps:***
    1. Move from MC → collision data.
    2. Toy studies to ascertain systematic uncertainties.
    3. Systematic studies of the effects of momentum binning.
    4. Explore possible systematics cancellation strategies.

Backup Slides

Single photon resolution $\sigma(\theta_c)$

- $\sigma(\theta_c) = \sqrt{\sigma_{chr}^2 + \sigma_{EP}^2 + \sigma_{pixel}^2}$
- $\sigma_{chr} = \dfrac{\sigma(n)}{\tan\theta_C}$ accounts for chromatic effects.
- σ_{EP} accounts for emission point error.
- σ_{pixel} accounts for finite detector pixelation.

	N	chromatic	emission	pixel	σ_p[mrad]	$\Delta\theta_C$ [mrad]	control sum (σ_p)
R1 (before input updates)	43	0.41	0.36	0.50	0.73	0.37	0.74
R1 (current)	63	0.52	0.36	0.50	0.80	0.36	0.81

	N	chromatic	emission	pixel	σ_p[mrad]	$\Delta\theta_C$ [mrad]	control sum (σ_p)
R2 (before input updates)	24	0.26	0.32	0.22	0.44	0.36	0.47
R2 (current)	34	0.34	0.32	0.22	0.50	0.36	0.51
R2 (CO2)	33	0.53	0.31	0.21	0.66	0.37	0.65

- Please ask for the slides where these can be found and I can send them to you.

RICH reconstruction

$$h = \{\mathrm{tk}_1, \mathrm{tk}_2, \mathrm{tk}_3\}$$

- Reconstruction is initialised with all tracks assigned π.

$$h_1 = \{\pi, \pi, \pi\}$$

- Given h_1, expected Cherenkov angle distributions are compared with detected photons to form a probability density $P_i(h_1)$.
- Calculate global likelihood as the product over photons i.

$$L_{h_1} = \prod_i P_i(h_1)$$

- Test likelihood with track 1 as K and p → infer identities via delta log-likelihoods.

Start with track 1

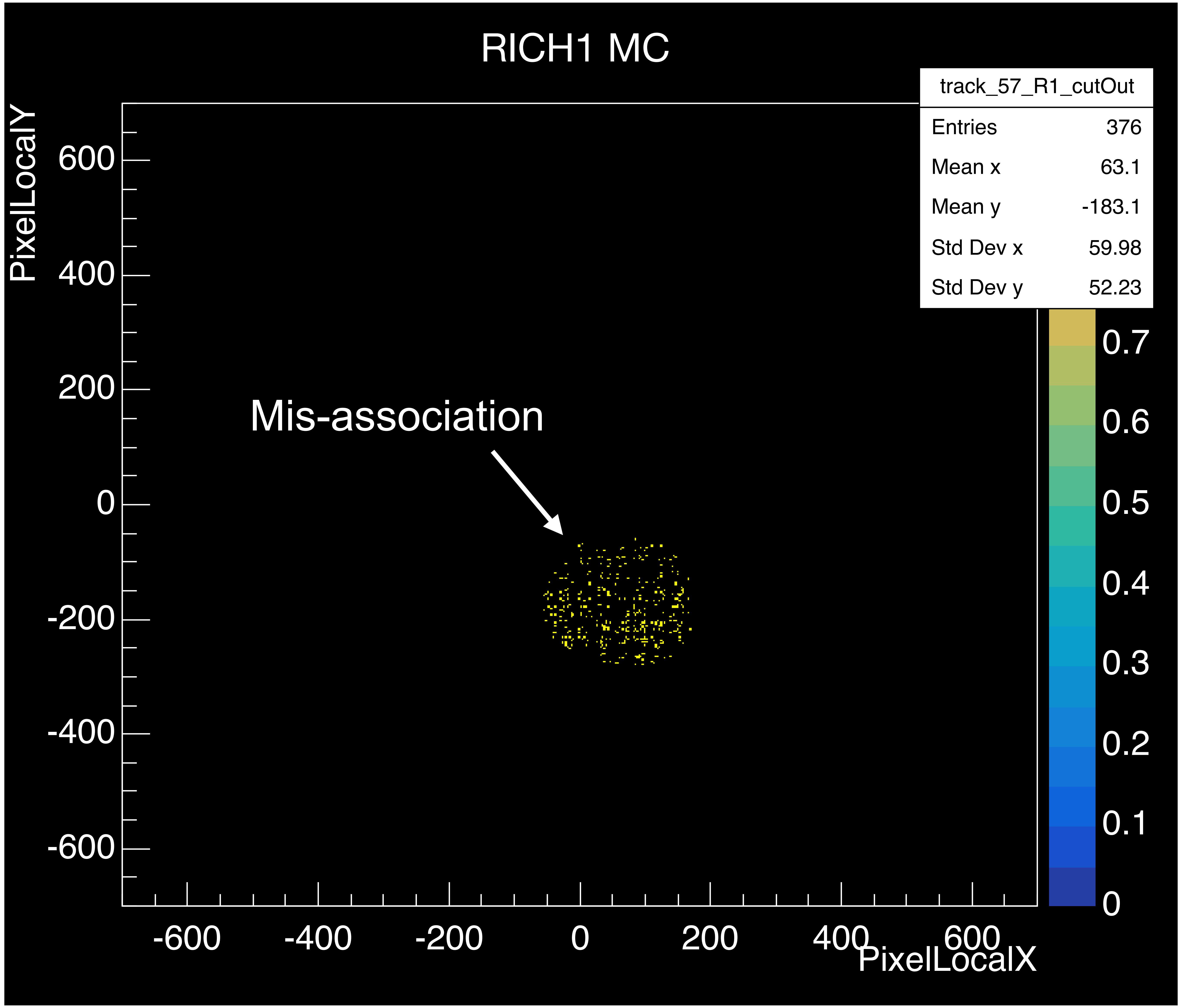
$$h_1 = \{\pi, \pi, \pi\},\ h_2 = \{K, \pi, \pi\},\ h_3 = \{p, \pi, \pi\}$$

1. $DLL(h_1 - h_1) = L_{h_1} - L_{h_1} = 0$ ← **No change since comparing π to π**
2. $DLL(h_2 - h_1) = L_{h_2} - L_{h_1} = 10$ ← **Increase! Set global track hypothesis $h_1 \rightarrow h_2$**
3. $DLL(h_3 - h_1) = L_{h_3} - L_{h_2} = -5$ ← **Decrease! h_2 remains and track 1 set to K**

Start from h_2, iterate and compute for track 2…

Photon Mis-association

- The RICH was not built for this form of measurement.
- Typical photon association assumes rings with gaussian cross sections leading to clusters of photons associated to a track.
- This is ***poor*** for ring fitting.
- Stringent particle level and photon level cuts have to be emplaced.



How Fitting Actually Works…

- It is to be determined whether we should let an additional nuisance parameter $\delta\theta$ float within the minimisation scheme.
- In principle, $\delta\theta$ would absorb systematic angular shifts from geometry, misalignment etc. This ***might*** be accounted for during online calibration steps already (LHCb does real-time alignment → refractive index calibration).
- $\delta\theta$ would be fixed per radiator (1 per RICH), enforcing a ***joint fit.***
- The minimisation scheme complicates to a simultaneous species mass fit with a shared nuisance…

$$\chi^2 = \sum_{j\in\pi} \frac{\left(\theta_j - \theta(p_j, m_\pi) - \delta_\theta\right)^2}{\Delta\theta_j^2} + \sum_{j\in K} \frac{\left(\theta_j - \theta(p_j, m_K) - \delta_\theta\right)^2}{\Delta\theta_j^2} + \sum_{j\in p} \frac{\left(\theta_j - \theta(p_j, m_p) - \delta_\theta\right)^2}{\Delta\theta_j^2}$$

Overlapping Momentum

- Cherenkov saturation limits the regions which are valuable to the mass fit.
- We can quantify this using Fisher information, calculated after extraction. Quantifies how much each entry contributes to the fit.

$$\mathrm{I}(\mu) = \mathrm{Var}\left(\left(\frac{\partial}{\partial\mu}\log\mathscr{L}(\mu\,|\,\mathrm{X})\right)^2\right)$$

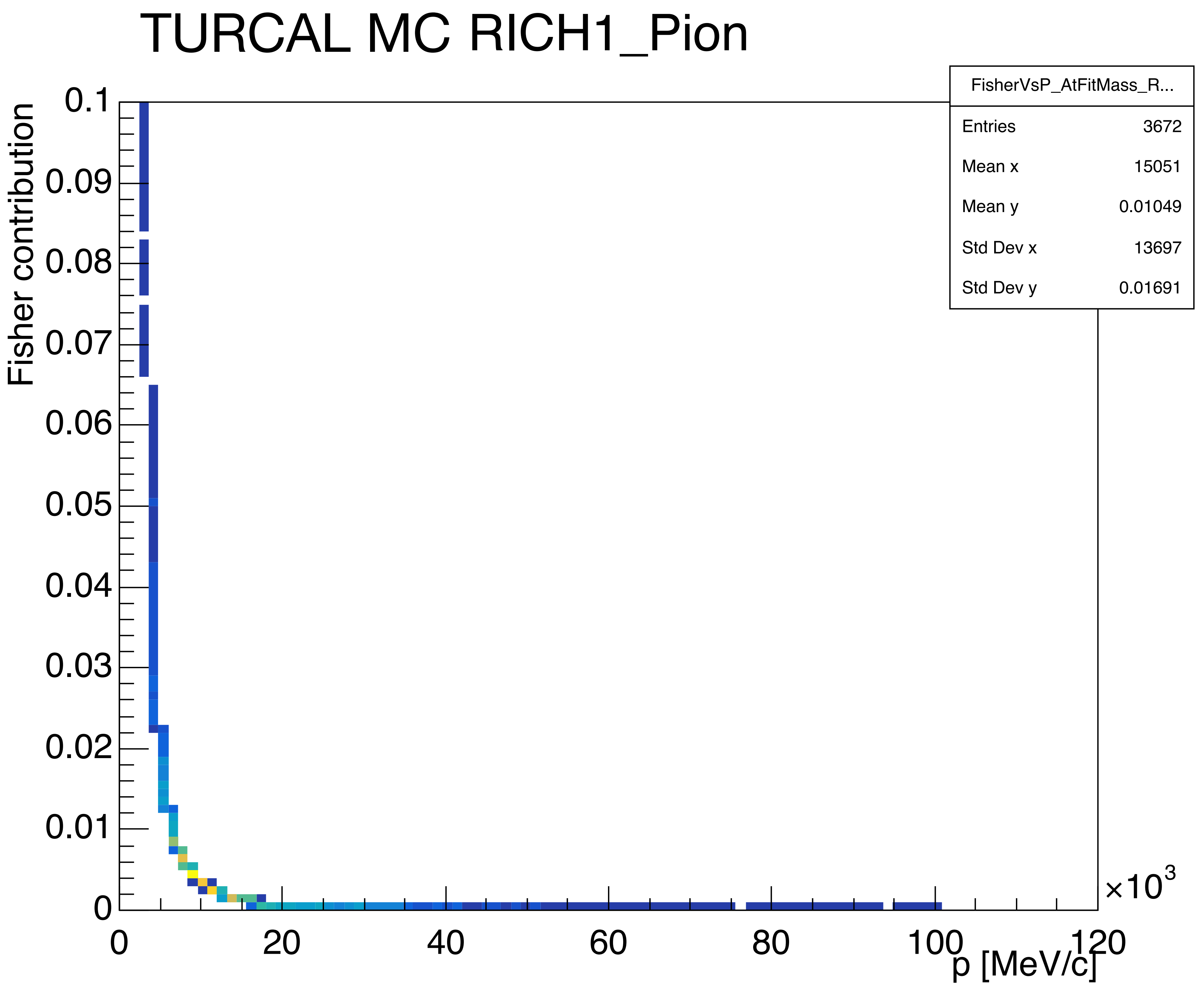
$$\mathrm{I}_j(m) = \frac{1}{\Delta\theta_j^2}\left(\frac{\partial\theta(p_j, m)}{\partial m}\right)^2$$

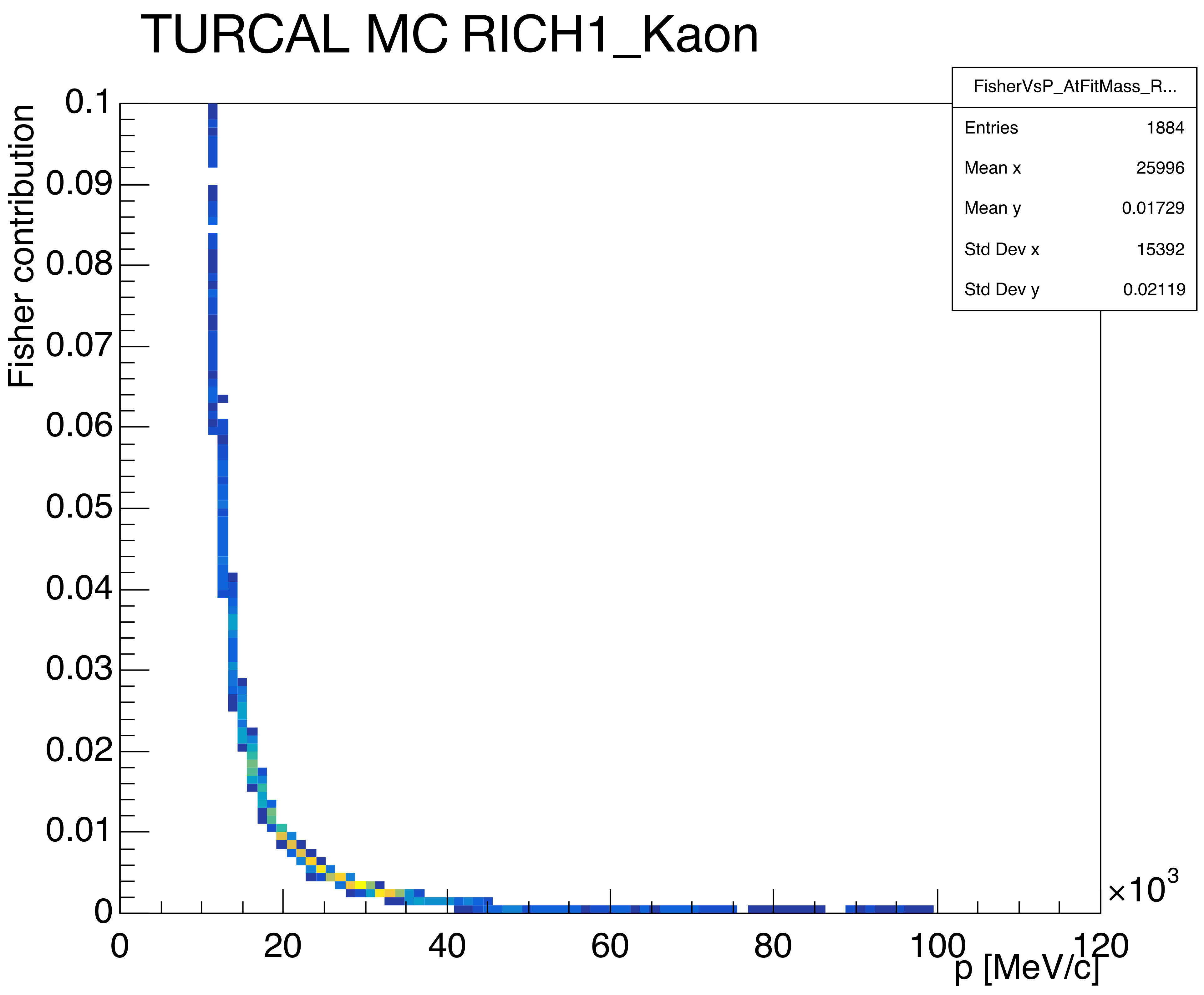
- $I_j(m) \to 0$ indicates entries not valuable to the extracted mass.

Overlapping Momentum

$$I_j(m) = \frac{1}{\Delta\theta_j^2}\left(\frac{\partial\theta(p_j, m)}{\partial m}\right)^2$$

- Examining per species identifies small, overlapping windows of non-zero $I_j(m)$ between species where we can ***potentially*** do equal momenta mass fits!



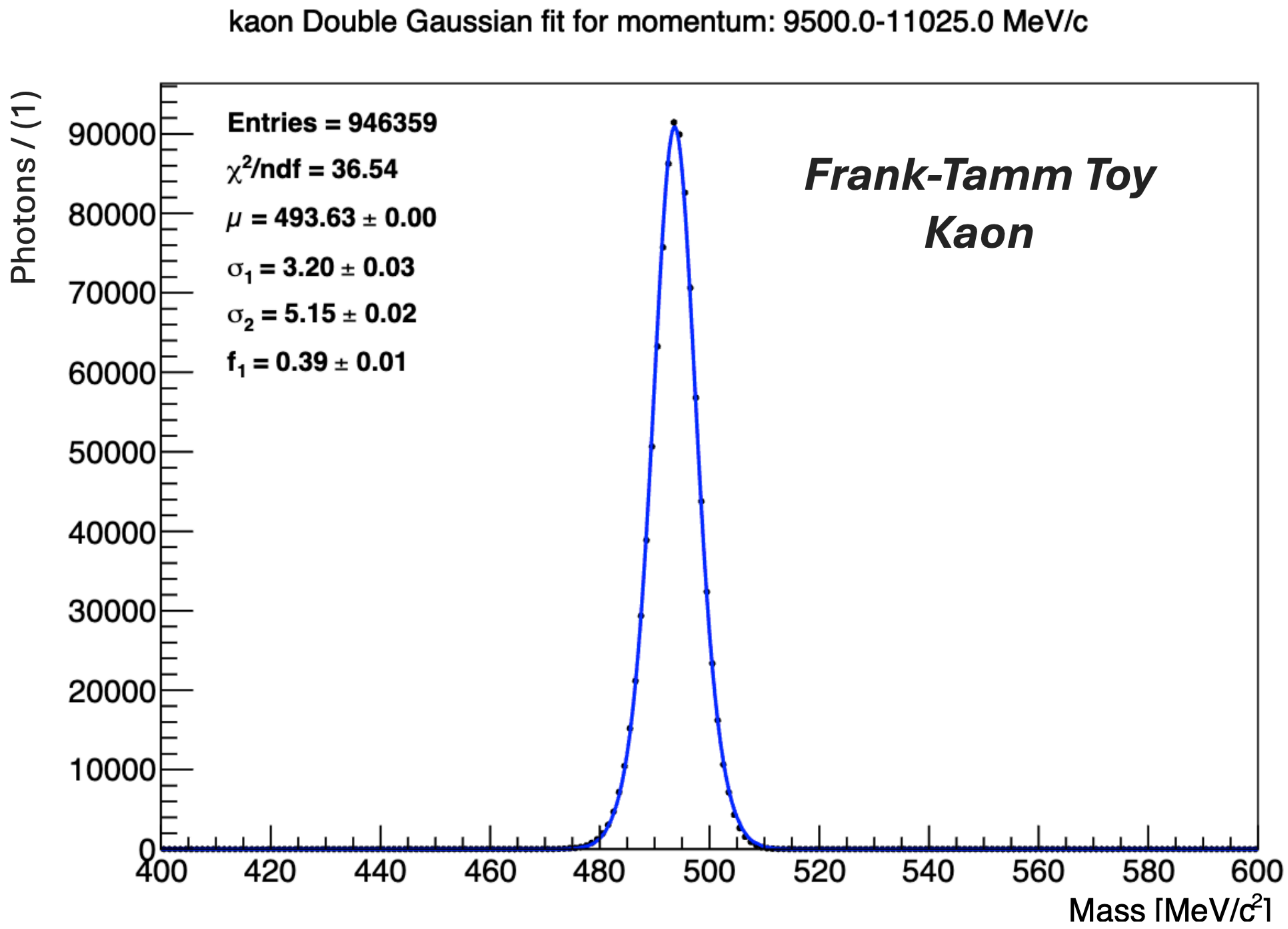


MIRA Toy - Mass Reconstruction

- Toy studies of per photon $m_{K^\pm}$ show promise!
- Based on Frank-Tamm equation for Cherenkov production.

$$\frac{dE}{dx} = \frac{q^2}{4\pi}\int_{\beta>1/n} \mu(\omega)\omega\left(1 - \frac{1}{v^2 n(\omega)^2}\right) d\omega$$

- Limited model, includes most resolution effects but no background modelling.
- ***Proof of concept.***



Reconstructed Mass Space

$$m = p\sqrt{(n\cos\theta_C)^2 - 1}$$

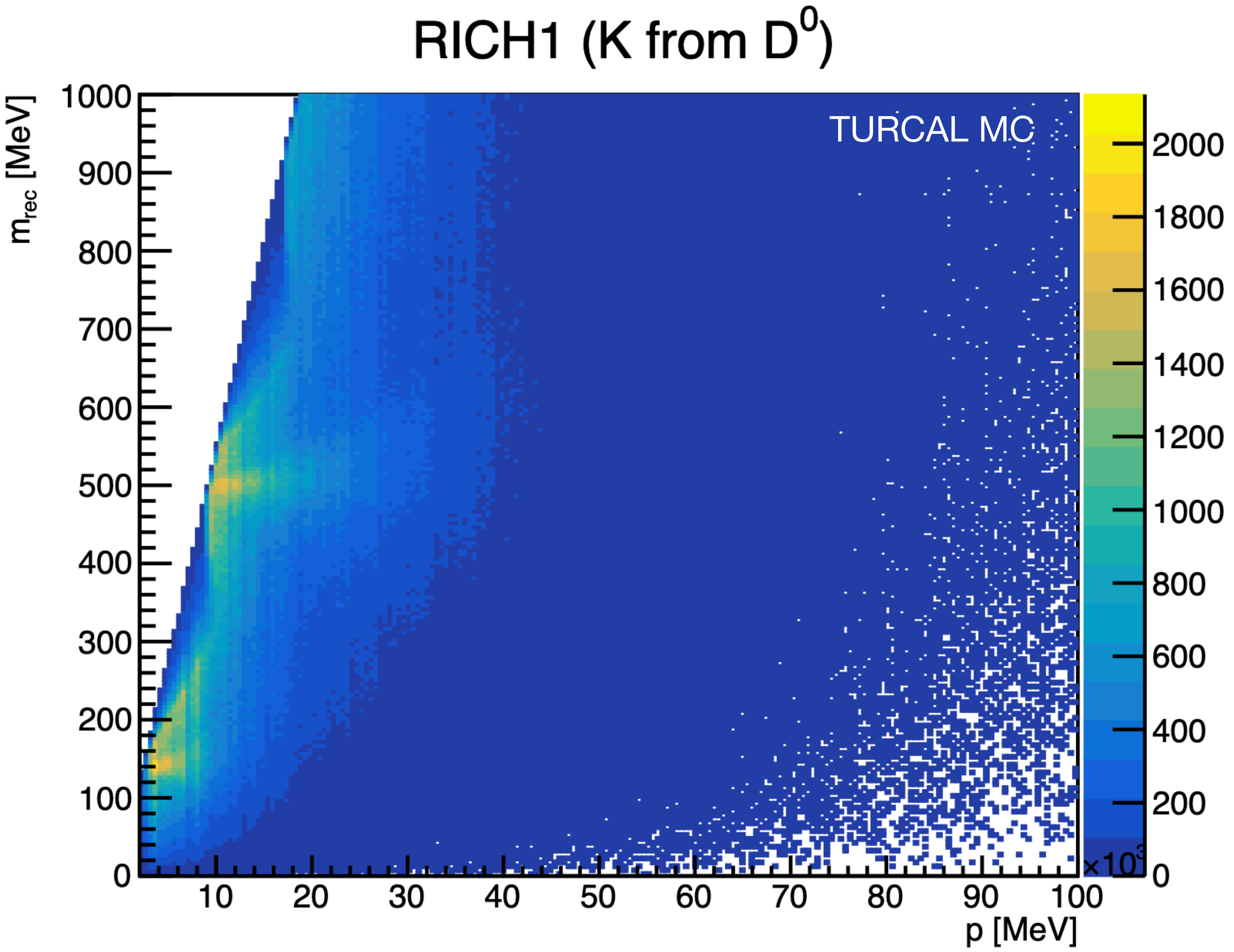
- Per photon estimation → reconstructed mass space across all momenta.

$$\Delta m = \sqrt{\frac{\Delta\theta_C\, n^4\, p^4 \sin^2\theta_C}{m^2} + \frac{\Delta p^2\, m^2}{p^2}}$$

$$\Delta\theta_C = \sqrt{\frac{\sigma(\theta_C)^2}{\underbrace{N_{ph}^{det}}_{=1}} + \sigma_{trk}^2}$$

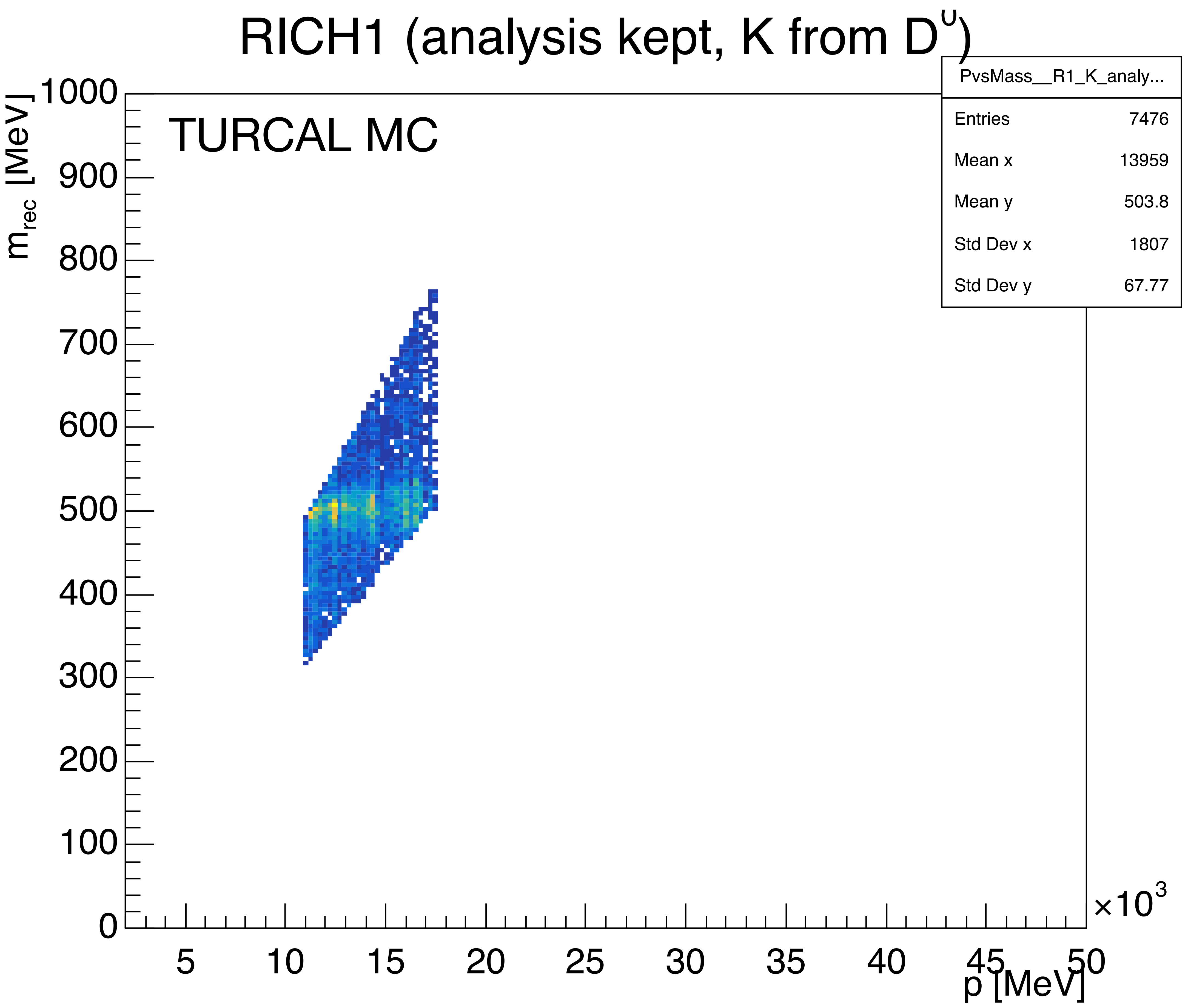
- $\Delta\theta_C$ loss offset by $\propto 1/\sqrt{N_{photons}}$.

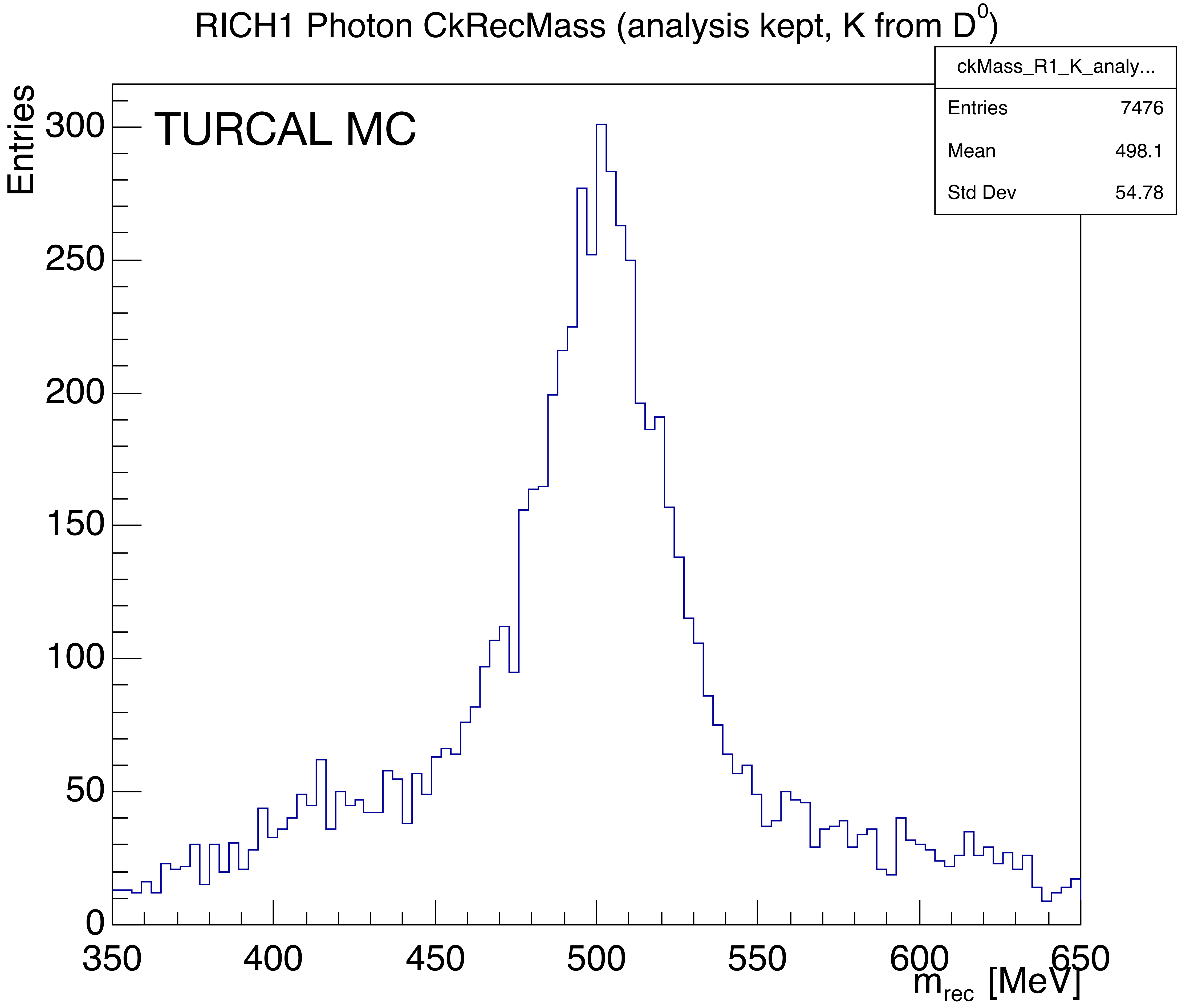
$$\Delta m_{K^\pm}[\text{ppm}] = \frac{\Delta m_{K^\pm} \times 10^6}{m_{K^\pm}} / \sqrt{N_{photons}}$$



Reconstructed $m_{K^\pm}$

- After particle and photon level selections.





θ_C Saturation

- At high momentum, θ_C saturates:

$$\lim_{\beta\to 1}(\cos\theta_C) = \lim_{\beta\to 1}\left(\frac{1}{\beta n}\right) = \frac{1}{n}$$

$$\theta_C \approx \cos^{-1} n$$

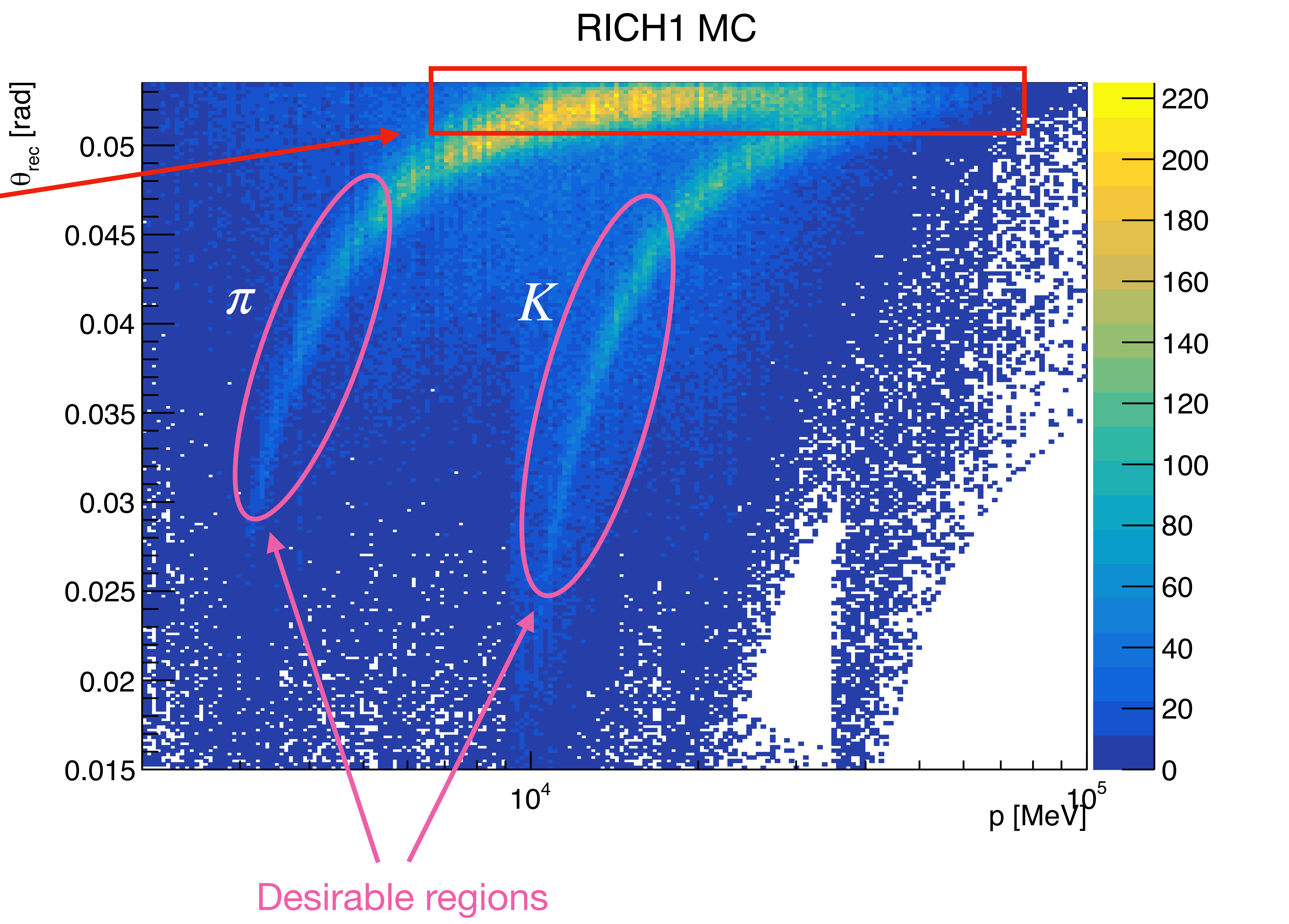
Constant

- This trickles down into mass calculations:

$$m = p\sqrt{(n\cos\theta_C)^2 - 1}$$

m: $\propto P$ — p: Increases — $(n\cos\theta_C)^2$: Constant

- Rightward shift in mass value $\propto p$!



How much D^* and Λ data is there?

- Assuming 2022 efficiencies:

  1. ~30k D^* and ~200k Λ saved to disk per pb^{-1}.
  2. 10% of events have rawbanks required for custom reconstruction.
  3. ***~$65m$ clean D^* and ~$400m$ clean Λ decays recorded between 2024-25.***