Improvement of particle identification method for the Aerogel RICH of the Belle II spectrometer

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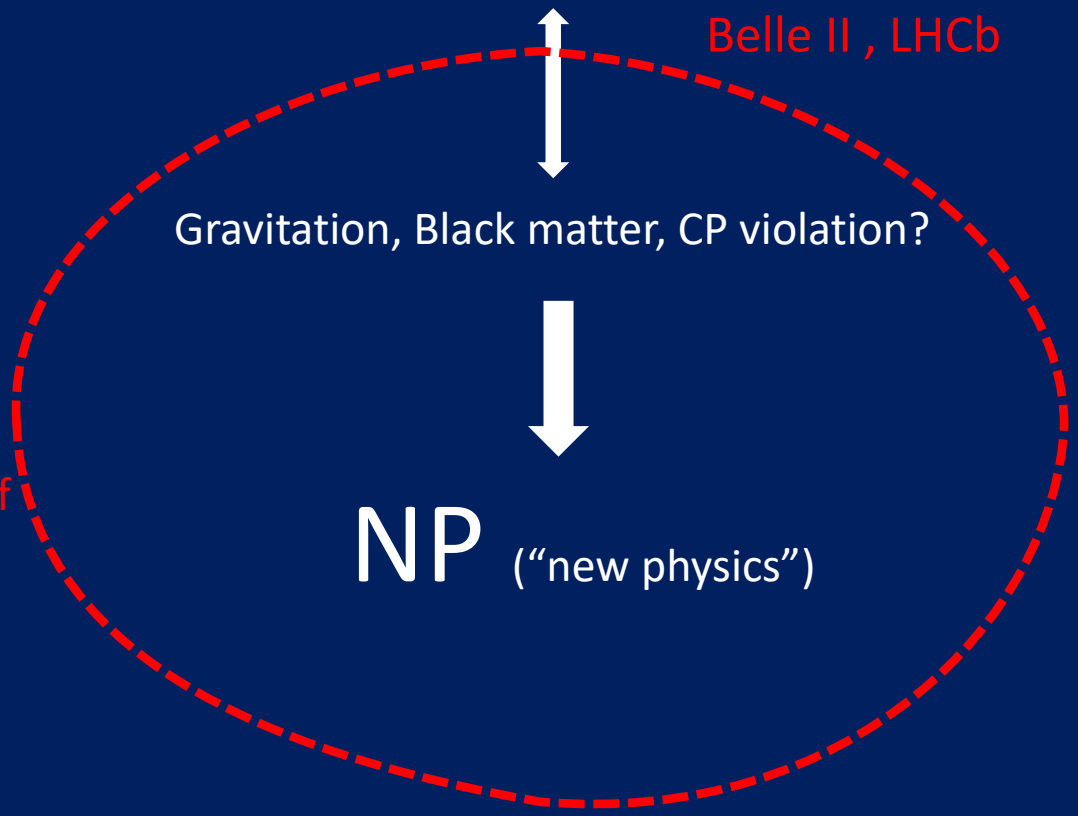
Motivation

- ATLAS, CMS (High-energy collisions) ⟷ In accord with SM (Standard model)

  (Higgs, CKM, …)



Experiments hinting at existence of NP :

- Lepton Flavor Universality (LFU) Violation

Motivation

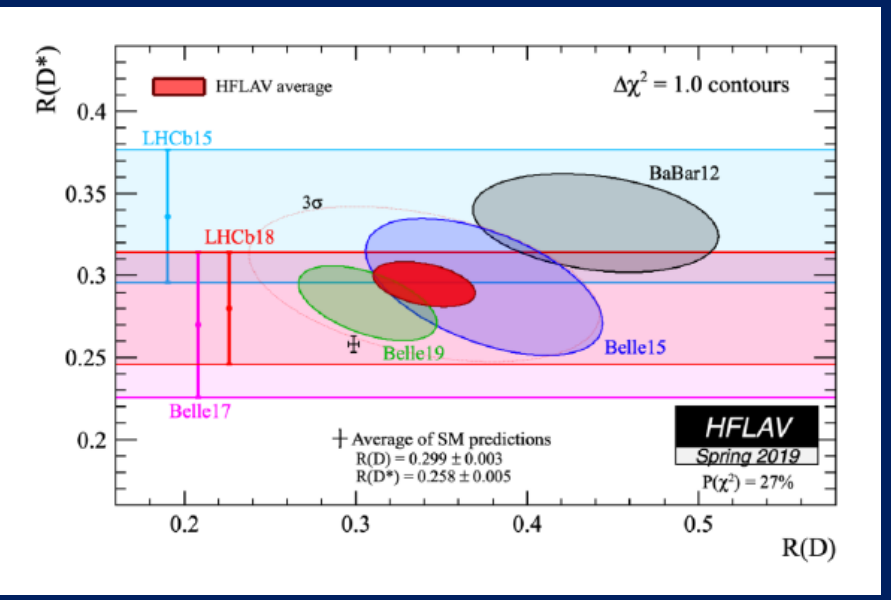
- ATLAS, CMS (High-energy collisions) ⟷ In accord with SM (Standard model)

  (Higgs, CKM, …)

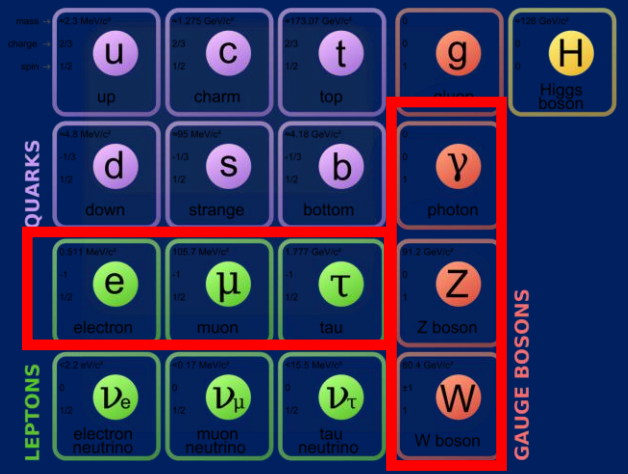
  Belle II , LHCb

- Lepton Flavor Universality (LFU) violation

$$R(D^*) = \frac{\mathrm{R}(B \to D^* \tau \bar{\nu}_\tau)}{\mathrm{R}(B \to D^* \mu \bar{\nu}_\mu)}$$



3 lepton generations (flavors)



SU(2)xU(1) Electro-weak int.

$$R(D) = \frac{\mathrm{R}(B \to D \tau \bar{\nu}_\tau)}{\mathrm{R}(B \to D \mu \bar{\nu}_\mu)}$$

Motivation

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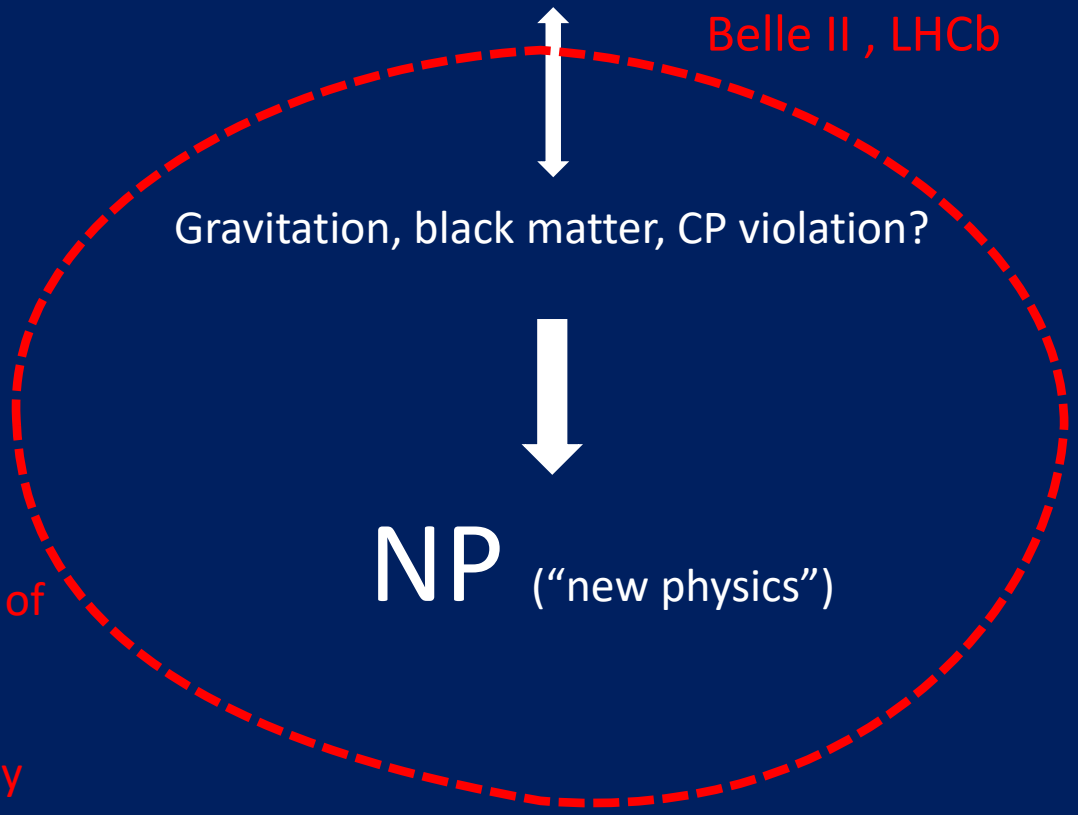


(To) low statistical significance

Need more measurements!

Experiments hinting at existence of NP :

- Lepton Flavor Universality (LFU) violation

SuperKEKB particle collider and Belle II detector

Belle II detector :

- Precise measurements of rare B,D meson and lepton τ particle decays
- Magnet spectrometer
- Detection of charged particle tracks and subsequent trajectory curvature measurement allow for momentum determination.

Decay reconstruction

(CDC, ARICH, TOP, KLM,ECL)

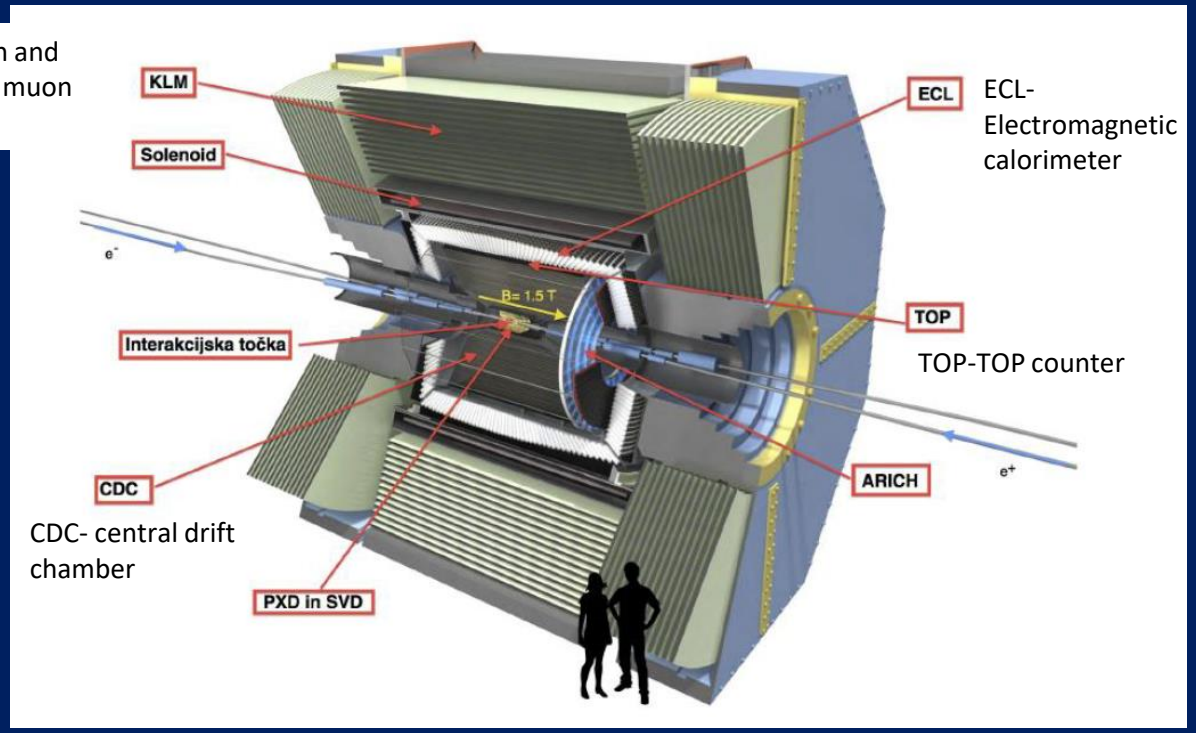
e, μ, π, K, p

+

Energy: γ + K_L^0

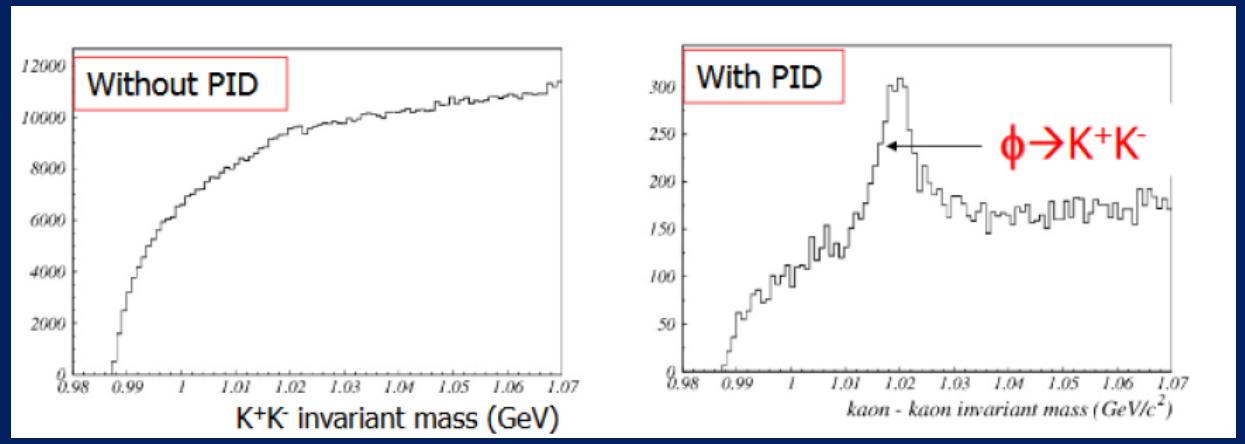
- More subdetector components, crucial for ID: TOP and ARICH

KLM- Kaon and long-lived muon detector



Particle ID

- Vital for High-Energy experiments – Belle II
- Reduction of combinatorial background, B meson flavor tagging
- Example: $\phi \rightarrow K^+K^-$

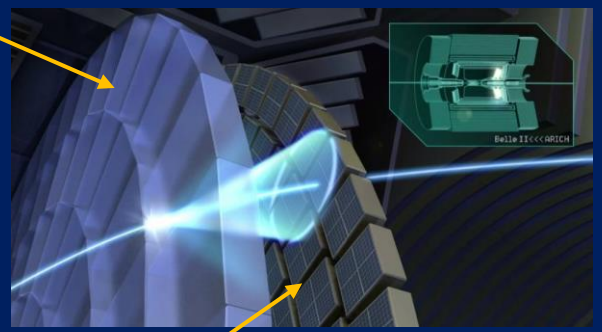


- B meson decay endstates ⟶ $K + \pi$ (Mostly at ARICH)

SuperKEKB particle collider and Belle II detector

ARICH (**A**erogel **R**ing **I**maging **Cherenkov** counter):

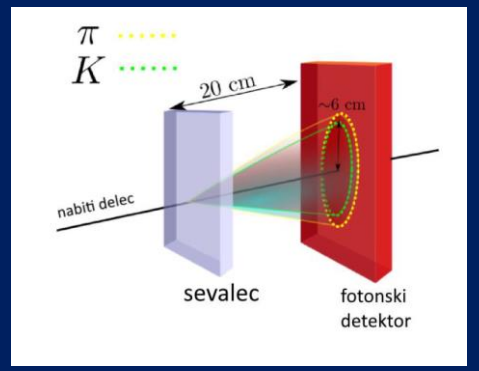
Aerogel radiator



HAPD photodetectors

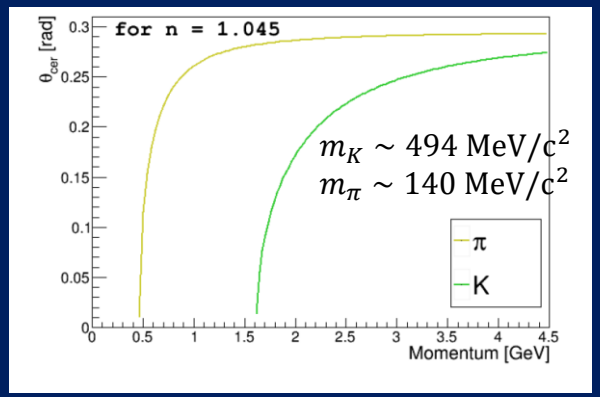
Hamamatsu HAPD detektorji

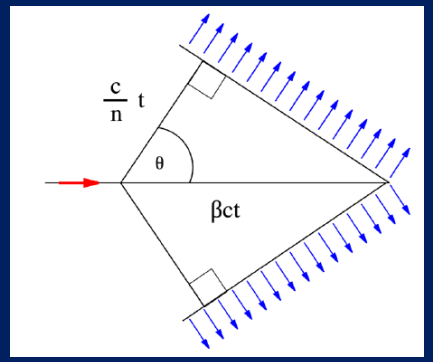
Charged particles emit Cherenkov photons when traversing the radiator layers



Different velocity ⟺ Different Cherenkov angle

$\left[\cos\theta_c = 1/\beta n\right]$





Different velocity + known track momentum $\xrightarrow{p = \gamma m v}$ m

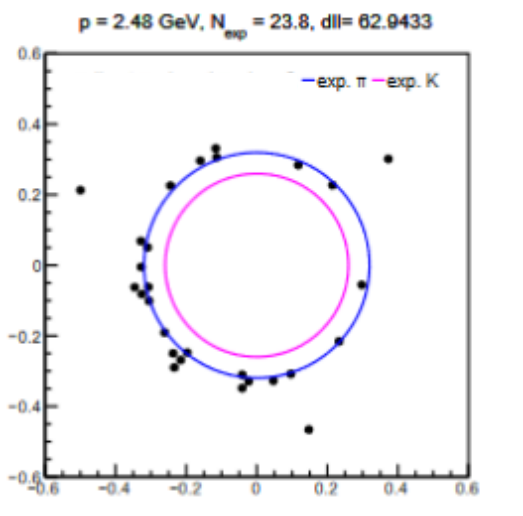
Particle ID at ARICH

Concretely (ARICH): Calculate **expected** photon hit distribution, for each mass hypothesis, compared it with **measured** hit distribution.

Measured detector response ⟷ Expected detector response (for each mass hypothesis: e, μ, π, K, p)

Depends on detector

Control samples, simulation, theoretical predictions



- Formally: Calculate likelihood function $\mathcal{L}(\boldsymbol{x}|H)$ → Probabilty, that particle type H produces detector response $\boldsymbol{x}$.
- "Global" likelihood:

$$\mathcal{L}_i = \mathcal{L}(\boldsymbol{x}|H_i) = \prod_{det}^{det=\{SVD,CDC,ARICH,\dots\}} \mathcal{L}^{det}(\boldsymbol{x}|H_i), \quad i = \{e, \mu, \pi, K, p\}$$

Independent detector measurements

- π/K separation, R_{ij} ration:

$$R_{K\pi} = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi},$$

Particle ID at ARICH

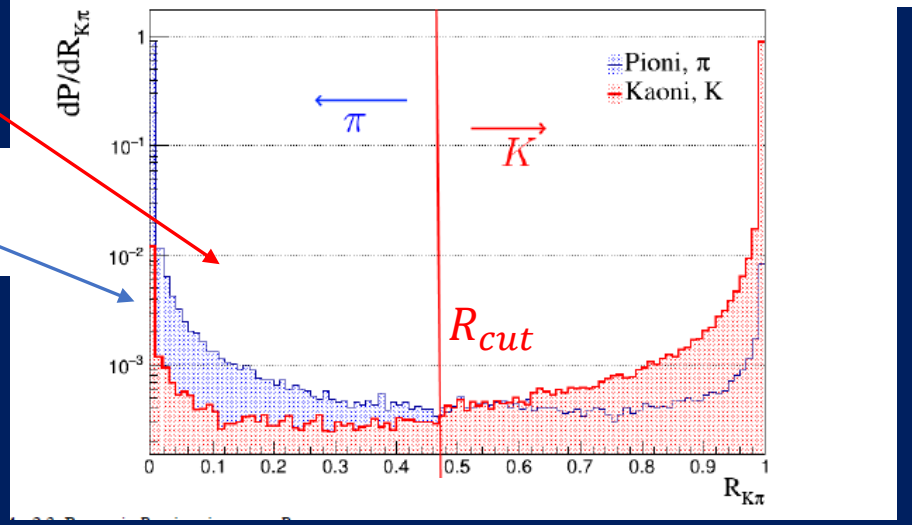
Example: (Separation based on $R_{K\pi}$ value)

$$\pi\text{-fake rate}\ (R_{cut}) = \int_{R_{cut}}^{1} \frac{dP}{dR_{K\pi}}(\pi)\, dR_{K\pi}$$

$$K\text{-efficiency}\ (R_{cut}) = \int_{R_{cut}}^{1} \frac{dP}{dR_{K\pi}}(K)\, dR_{K\pi}$$

$R_{K\pi} = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$ (kaon tracks)

$R_{K\pi} = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$ (pion tracks)



Efficiency measure:

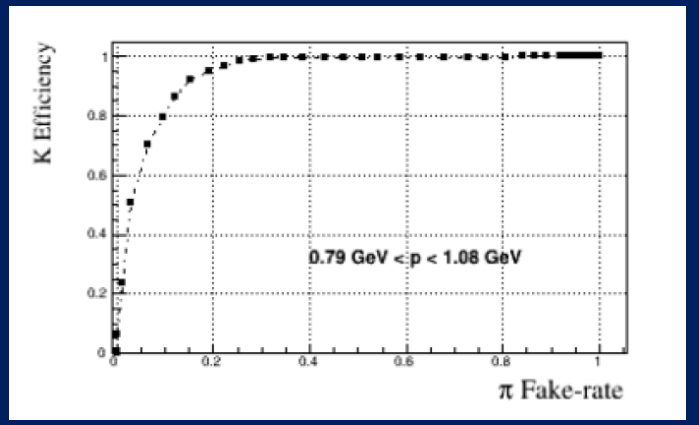
$$K - \text{efficiency} = \frac{\text{number of kaon tracks, (properly) identified as kaon}}{\text{number of all kaon tracks}}$$

$$\pi\text{-fake rate} = \frac{\text{number of pion tracks (}\mathbf{wrongly}\text{) identified as kaons}}{\text{number of all pion tracks}}$$

Determined from *simulation, where data on real particle identity, scattering, … is known.

*or control samples

Get a set of points

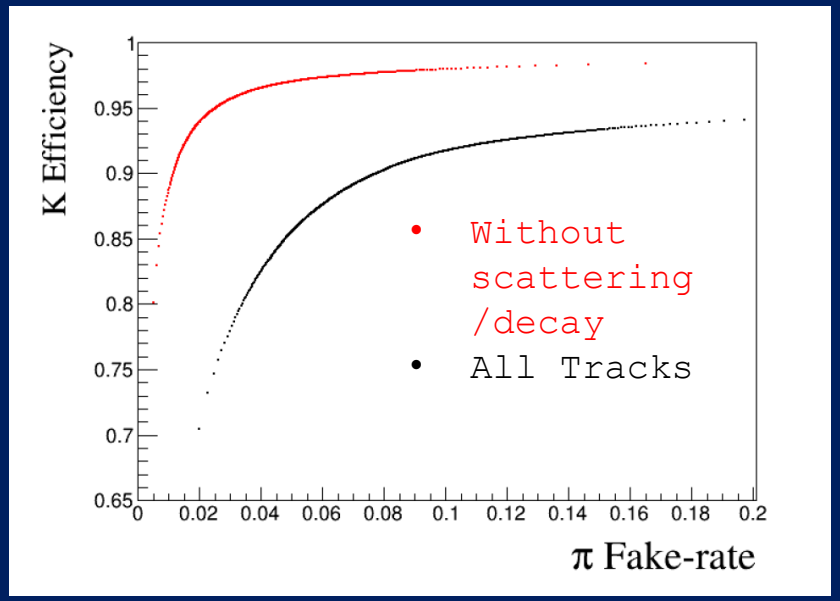


Purpose:

- Efficiency measure
- Determination of optimal R_{cut}

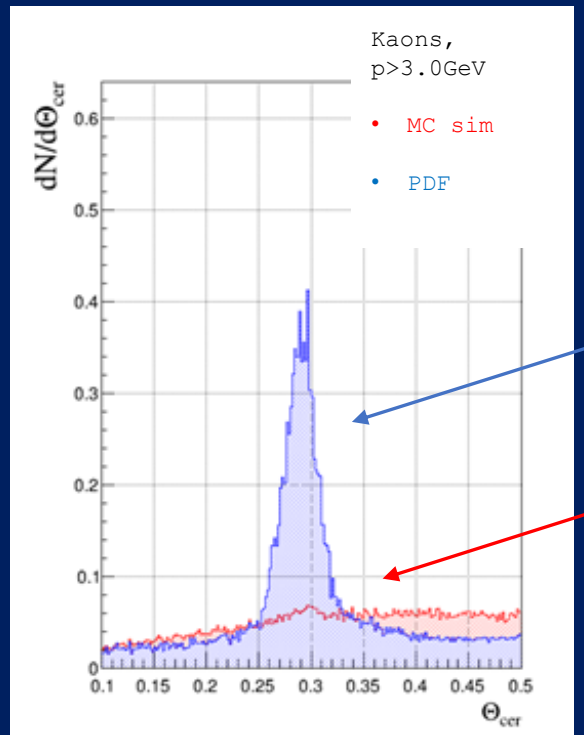
Improvement of the particle ID method at ARICH

- Scattering/decay of particles drastically decreases K/π separation efficiency
- For construction of the Likelihood function $\mathcal{L}_{ARICH}$ a PDF of photon hits by Cherenkov angle is used.



Background: $\mathcal{L}_{ARICH}$ is calculated for all tracks, but not all actually reach the detector.

Problem: Current method does not discriminate between scattered/decayed particle tracks and non – scattered/decayed tracks.

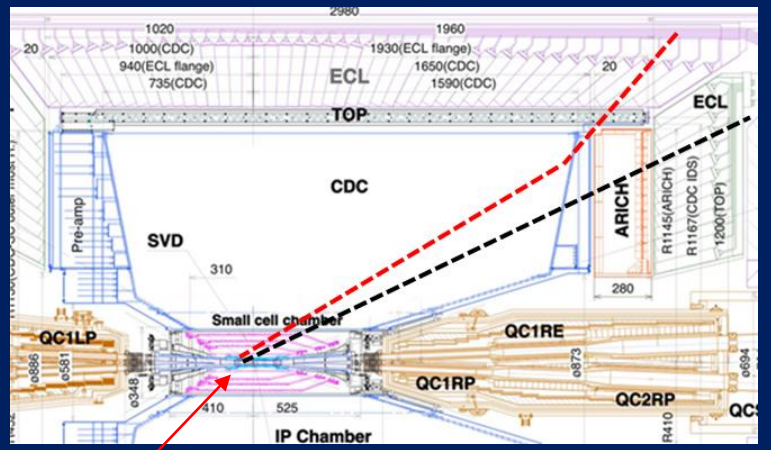


PDF currently in use

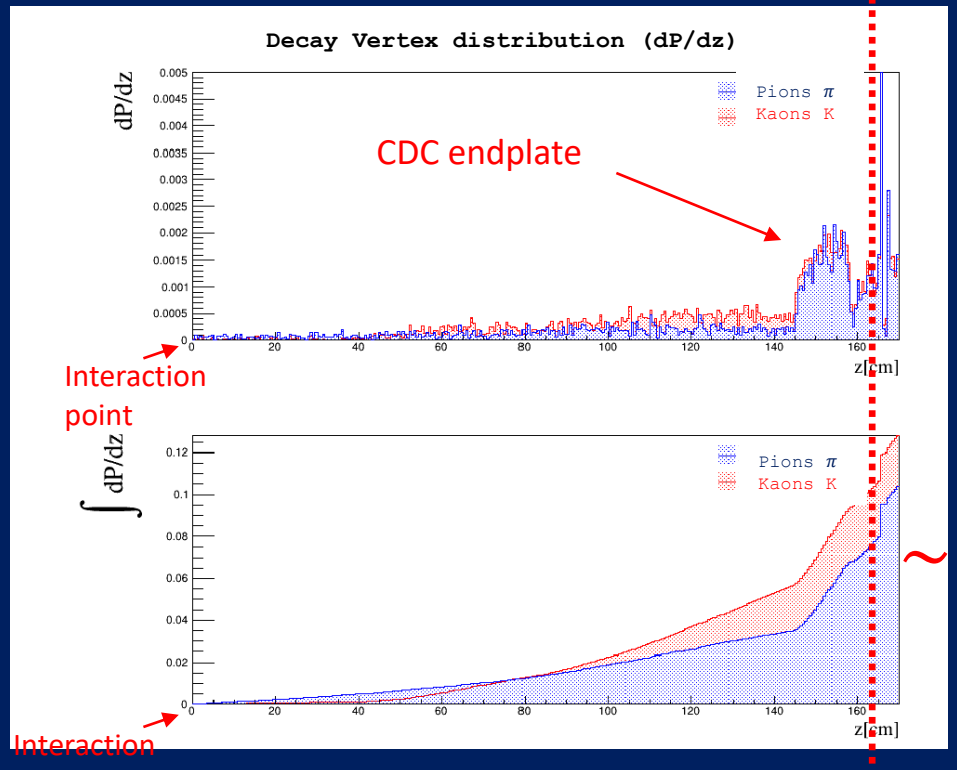
Observed distribution in MC for scattered/decayed particles

Notice: Immense difference !

- Problem: Scattering + “in flight” decays of particles before reaching the ARICH



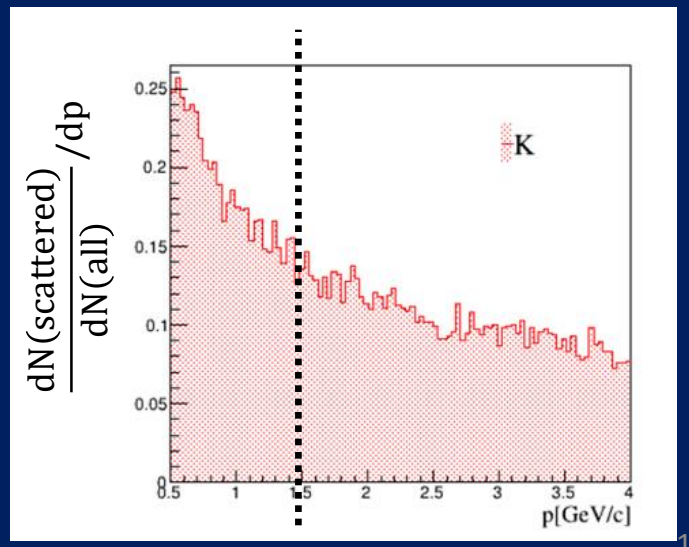
ARICH: $z \sim 164$ cm



MC simulation

$\sim 10\% \ \pi, K$

More evident at lower momenta (decay time, scattering crossection,..)



Idea: Write PDF as a sum of two contributions: $PDF_{scatt.}$ (scattered) + $PDF_{nscatt.}$ (non-scattered)

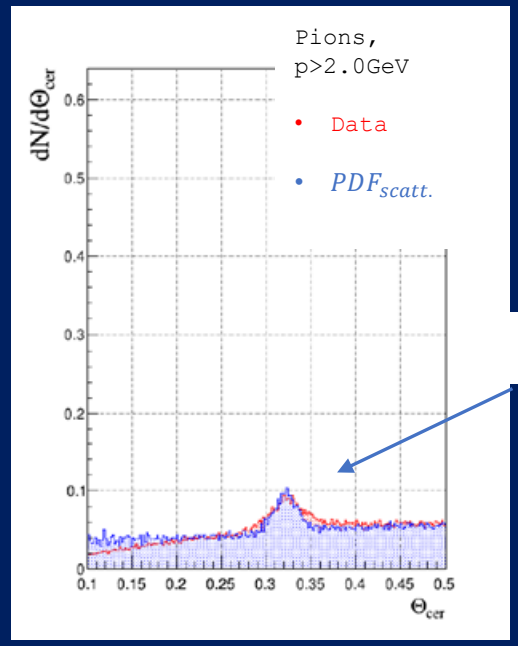
+ Scattering/decay probability weights (for each track)

$$PDF = p_{scatt.} \times PDF_{scatt.} + p_{nscatt.} \times PDF_{nscatt.}$$

$PDF_{scatt.}$, $PDF_{nscatt.}$ determined via least squares fit using MC simulation data

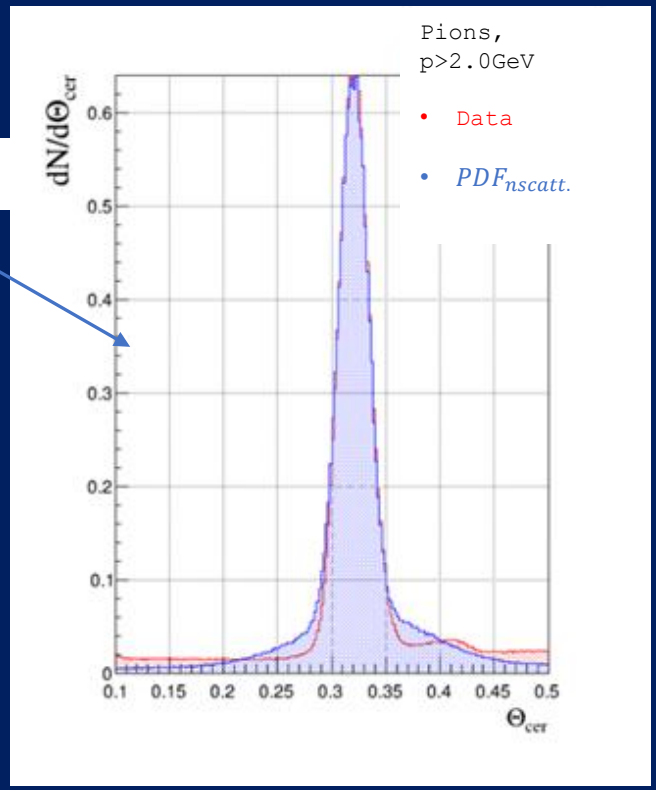
*scattered means scattered + decayed

Notice: better agreement of data and PDF



$PDF_{scatt.}$

$PDF_{nscatt.}$

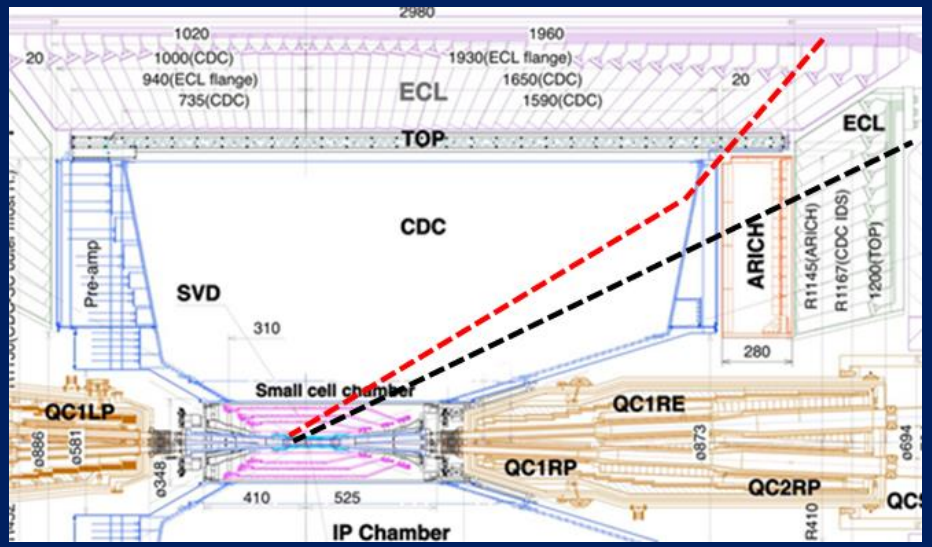


We need to determine $p_{scatt.}$ probability weights.

Based on two criteria

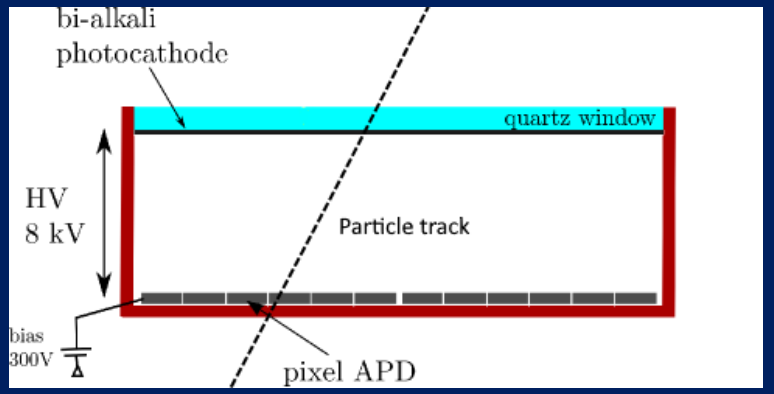
Scattered, non-Scattered?

ECL Shower criteria



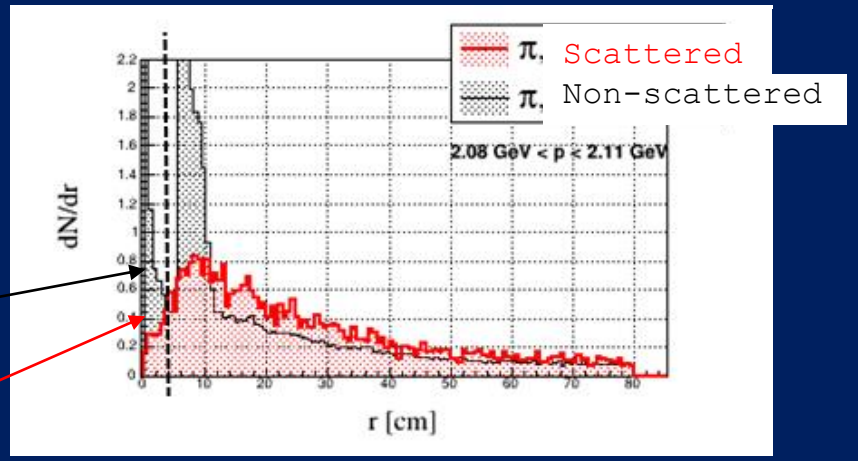
Quartz window (Cherenkov) photons criteria

Problem: Not all tracks have a recorded window hit, HAPD coverage ~ 60%



Distribution of photon hits by distance from extrapolated track hit (r) on detector plane

$$r = |\vec{r}_{Track\ Hit} - \vec{r}_{photon}|$$



More photons

Less photons

Scattered, non-Scattered?

6 categories

Tracks without a window hit (winHit=0):

- Tracks with an ECL shower (**winHit=0 + ECL=1**)
- Tracks without an ECL shower (**winHit=0 + ECL=0**)

Tracks with a window hit:

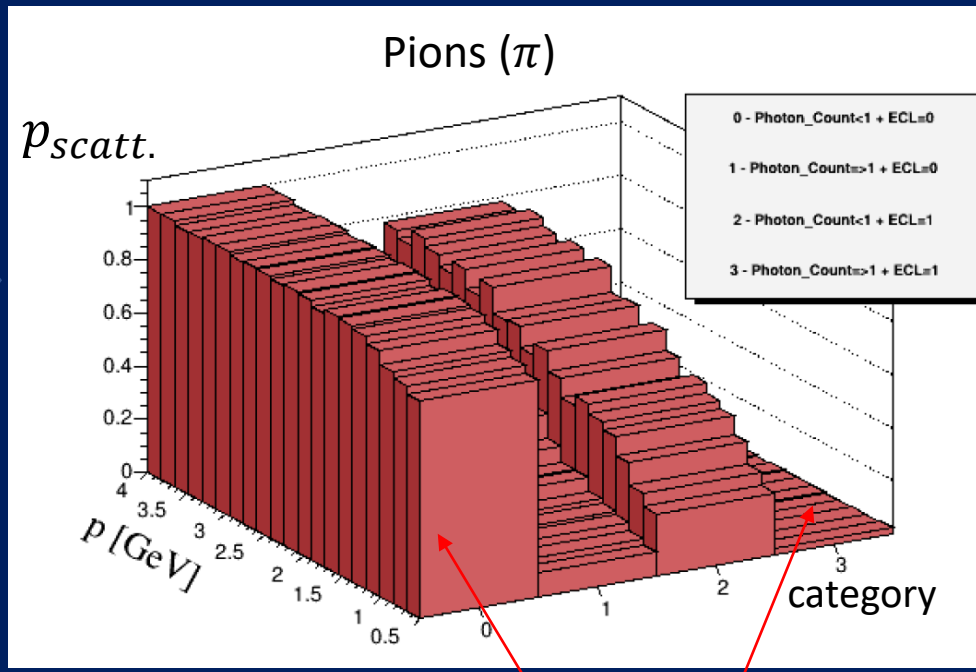
- Tracks with zero photons inside $r < 2.5$cm and without an ECL shower (**Photon_Count=0 + ECL=0**),
- Tracks with several photons inside $r < 2.5$cm and without an ECL shower (**Photon_Count!=0 + ECL=0**),
- Tracks with zero photons inside $r < 2.5$cm and with an ECL shower (**Photon_Count=0 + ECL=1**),
- Tracks with several photons inside $r < 2.5$cm and with an ECL shower (**Photon_Count!=0 + ECL=1**).

Graph category:

0
1
2
3

Simulation (determination of $p_{scatt.}$)

$$p^i_{scatt.} = \frac{\text{scattered tracks in category } i}{\text{all track in category } i}$$



Difference!

Identification:

Old method: (no discrimination between scattered and non-scattered)

PDF → $\mathcal{L}_{ARICH}$

New method:

For every track we determine the category (based on presence of recorded window hit, ECL shower, photons) → Using category determination and momentum each track is assigned a $p_{scatt.}$ value → i-category, h-mass hypothesis (K/π)

$$PDF = p^{i,h}_{scatt.}(p) \cdot PDF^h_{scatt.} + \left(1 - p^{i,h}_{scatt.}(p)\right) \cdot PDF^h_{nscatt.}$$

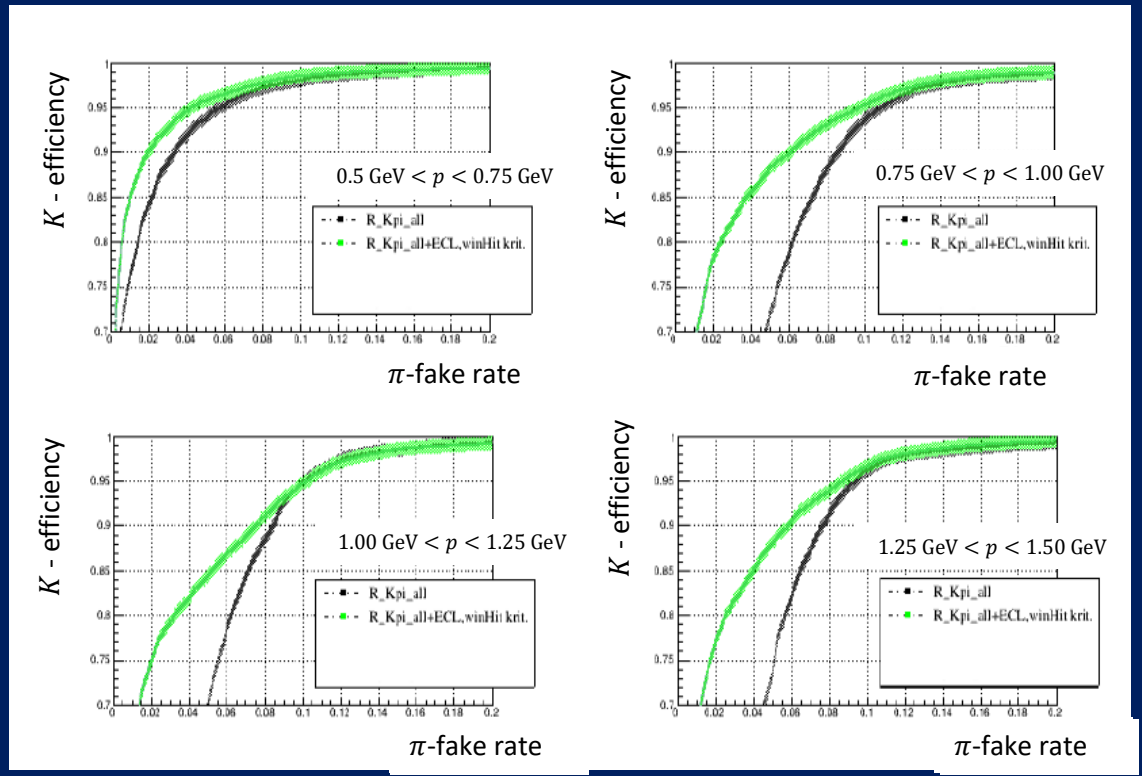
($p_{nscatt.}$)

→ $\mathcal{L}_{ARICH}$

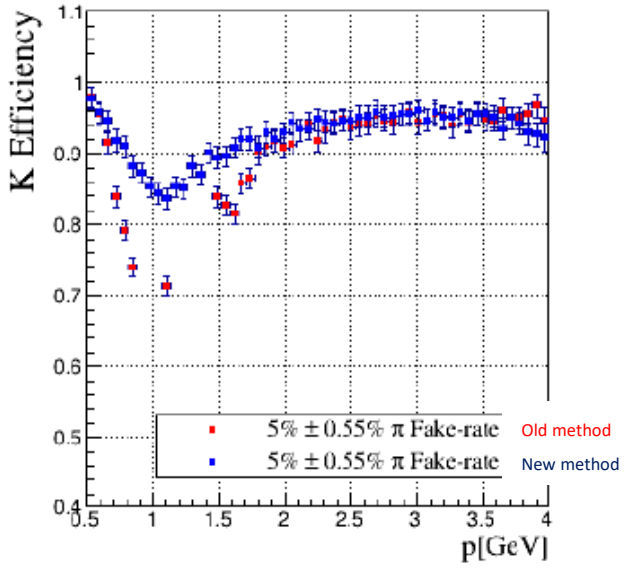
Results

Green – new method
Black – old method

Considerable improvement (up to 1.5 GeV)

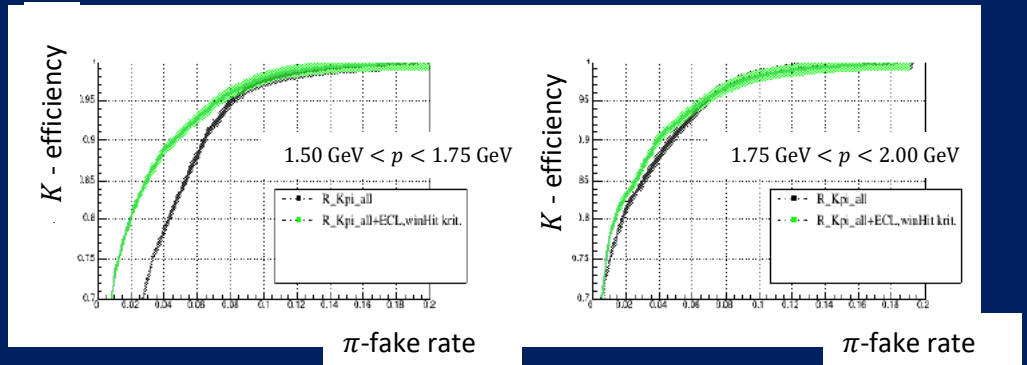


Considerable improvement at ~5% π-fake rate

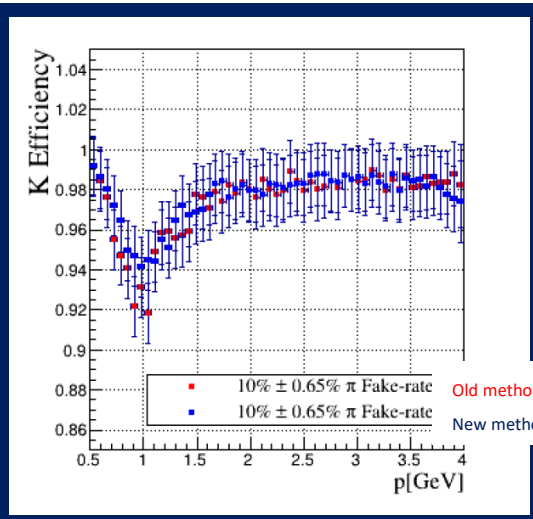


Bigger momenta (>1.5 GeV)

Less improvement



Negligible improvement at higher π-fake rates



Summary:

- Scattering of particle tracks
- Separated treatment of scattered and non-scattered particle tracks
- Probability of scattering/decay based on two criteria

Improved K/π separation efficiency

- Further testing on “real” data necessary