LHCb future upgrade: RICH software status

LHCb workshop: Annecy

Many people in RICH group including
Chris Jones, Floris Keizer, Steve Wotton, Michele Blago, Sajan Easo, Carmelo D'Ambrosio et.al.

Science & Technology Facilities Council

S.Easo
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Challenges in LHCb-RICH upgrade

➢ Improve single photon resolutions and yield

$$\sigma_p = \sigma_{\text{chromatic}} \oplus \sigma_{\text{emission point}} \oplus \sigma_{\text{pixel}}$$

$$\sigma_t = \frac{\sigma_p}{\sqrt{N}} + \text{Const.}$$

➢ Cope with high occupancy expected in Phase2

- *Phase 1a and 1b: nominal ν=7.6*
- *phase2 onwards : nominal ν=35 : RICH1 > 100 % occupancy*

➢ Upgrade the coverage at low and high momenta

- *No signal from Kaons < 9.3 GeV/c and Protons < 18 GeV/c : Many charged tracks in this range*
- *Above ~ 70 GeV/c close to saturation from all particle types*

Approaches to improve LHCb-RICH

- **Mitigate occupancy:**
  - Use the space and time coordinates of hits : *status report*
    - ❑ *Separate out hits from multiple PV*
    - ❑ *Reduce background in RICH*
  - Needs new photon detectors and readout with fast timing

- **Improve resolutions and yield :** *status report*

- **Extend the momentum coverage :**
  - Develop novel radiators *status report*
  - Improve conventional radiators ?
  - TORCH

➢ *This presentation: Three status reports listed above*

Technical Issues

Chris,
Marco Adinolfi et.al.

- Using SiPM means having much more channels compared to MaPMT.
  To label all of them needs a 64-bit word (for RichSmartID).
  Using dedicated 'branches' of LHCb software and databases and running on the grid

- The 64-bit RichSmartID is also used to store and access the RICH Time information , for now.

- RICH needs a tracking detector to go with it, for simulation and reconstruction.
  Possibility to re-install 'cheated tracking' in reconstruction, to predict phase2 RICH performance ?

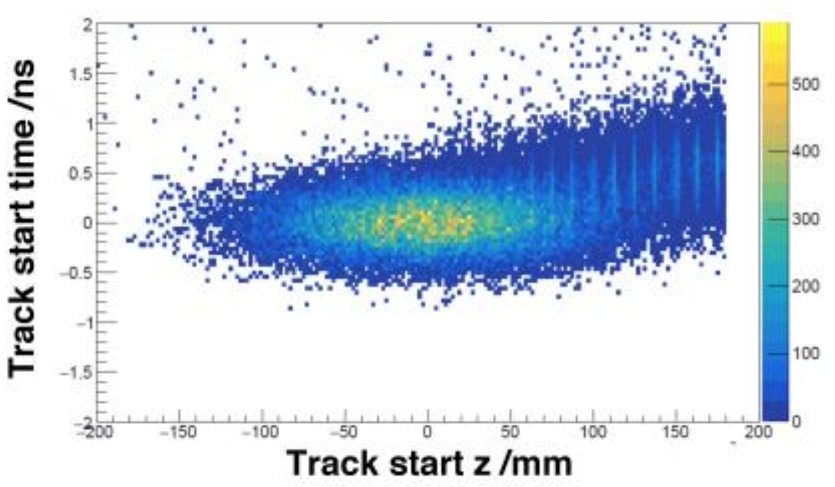
- RICH PID reconstruction is optimized for the standard configurations.
  Non-standard inputs normally seem to require detailed review.

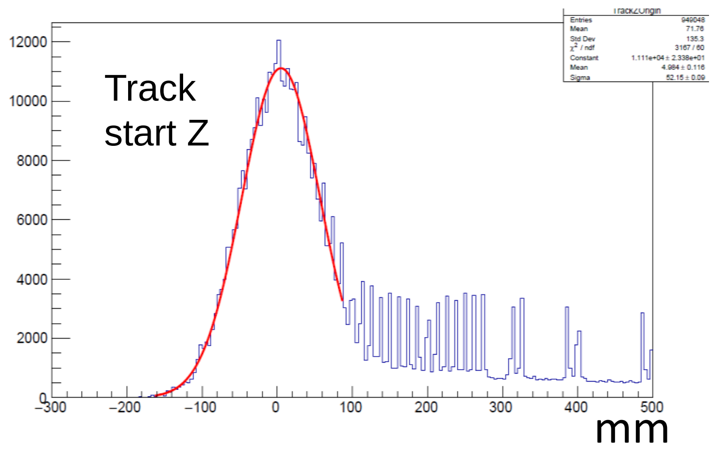
Audi V6

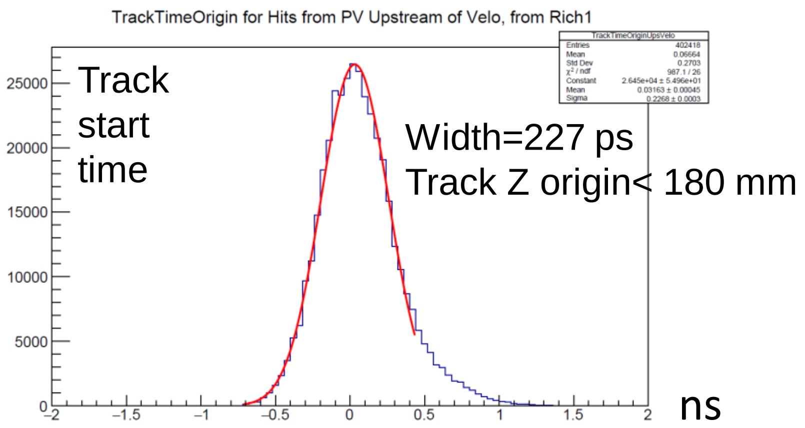
Opel Mokka 1.4 turbo

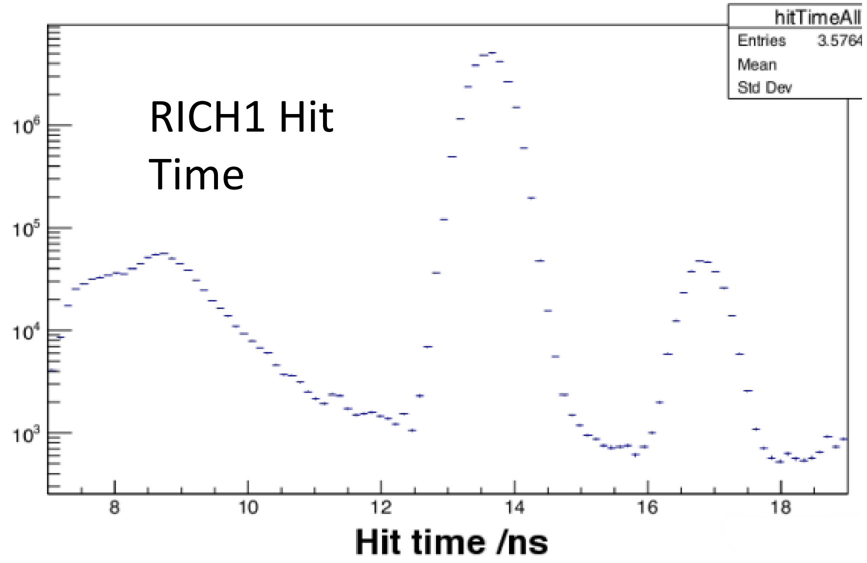
RICH Hit Time: Earlier status

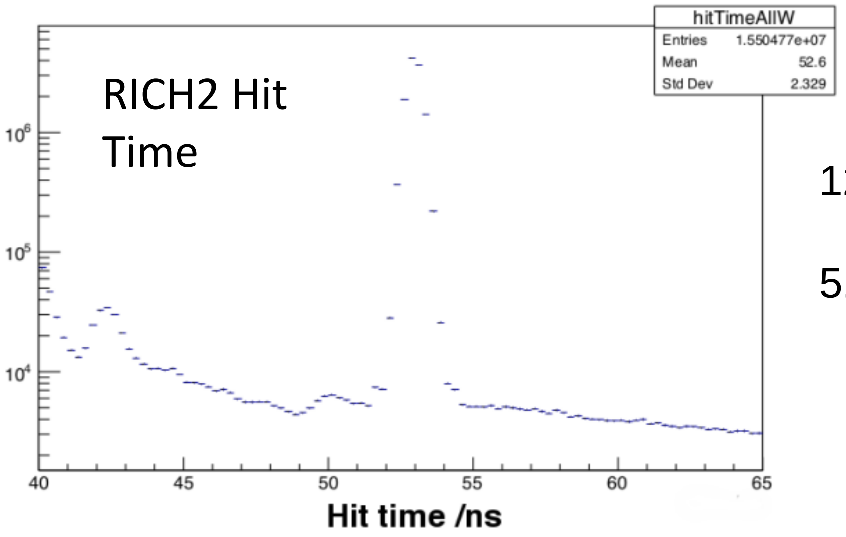
- PV Time simulated in Gauss using a Markov chain sampler











12 ns < RICH1 Signal< 15 ns

51.5 ns < RICH2 Signal < 54.5 ns

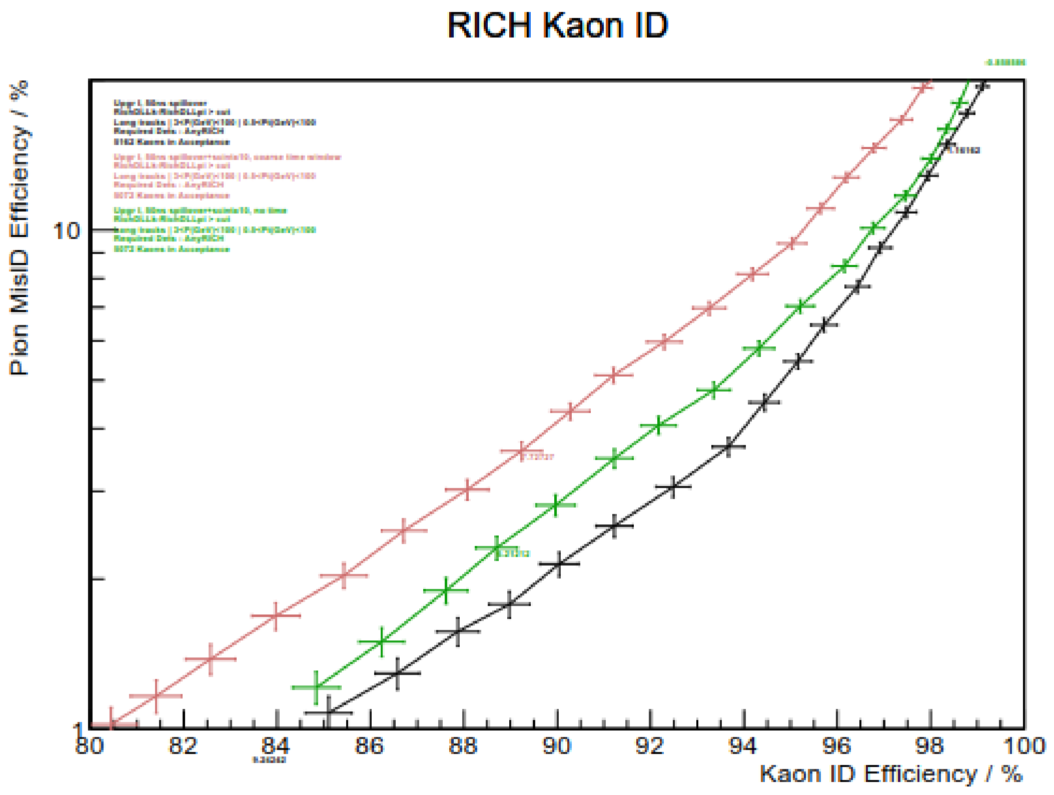
Chris, Floris

RICH Hit Time Window

- Nominal background from out of 'time window' hits : RICH2 ~ 10% and RICH1 ~ few percent
- For test, artificially increase RICH2 background 10 times.

Black: standard phase1a

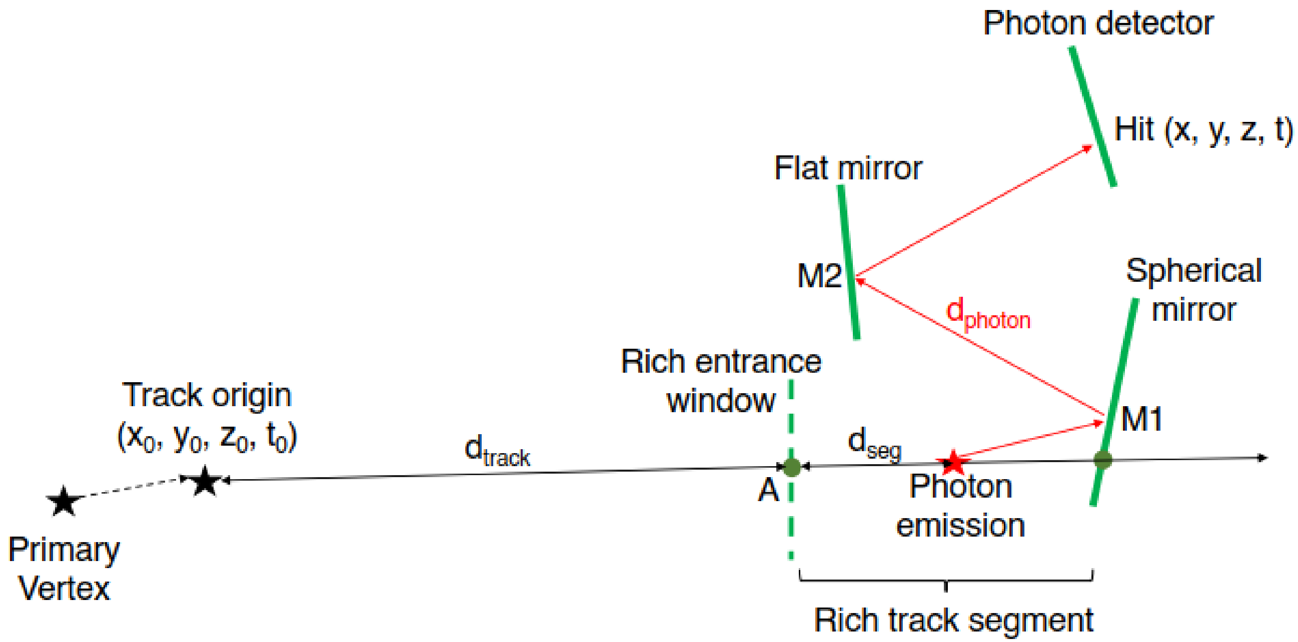
Red: Increased background , Green: Increased background+ Time Window



- Other similar tests underway also
- Superpose 5 RICH events to study the effect of pile-up at high luminosity

Towards RICH PID with Time

Chris, Floris



$$t = t_0 - z_{origin}/\beta c + C$$

$$\text{Nominally,}\quad C = d_{track}/\beta c + d_{seg}\frac{n\cos\theta_c}{c} + d_{photon}\frac{n}{c}$$

$$= 13.6 \text{ ns for RICH1}, \quad 52.95 \text{ ns for RICH2}$$

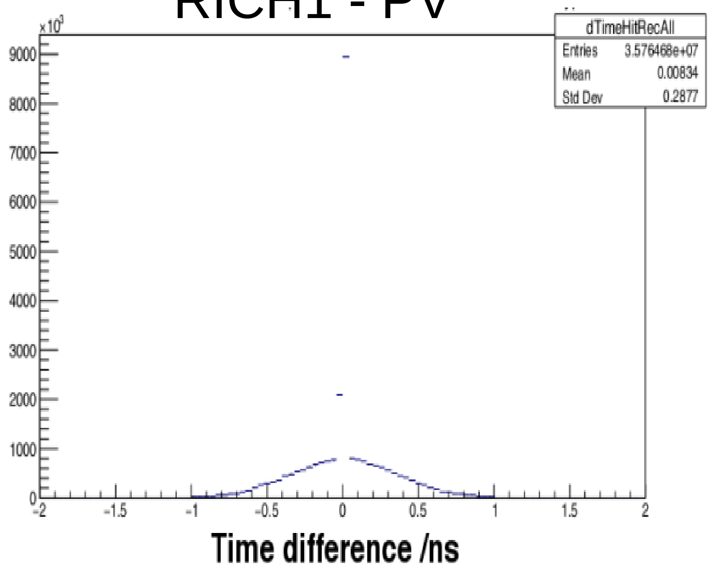
$$\beta = \frac{p}{\sqrt{p^2 + m^2}}$$

Towards RICH PID with Time

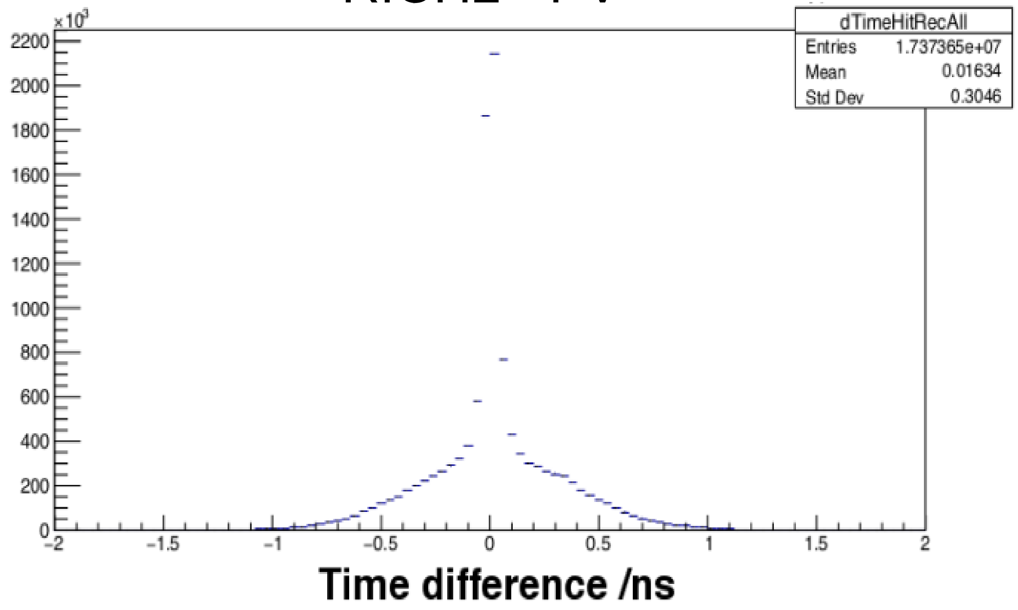
Chris, Floris

- Obtain Time and Z shifts of PV from MC. Subtract this from RICH Time

RICH1 - PV



RICH2 - PV



- Peak at zero from signal (Correct combinations of Track and RICH hit)
- Gaussian backgrounds (from all other combinations)
- Next step : Extend the likelihood algorithm to include the time information

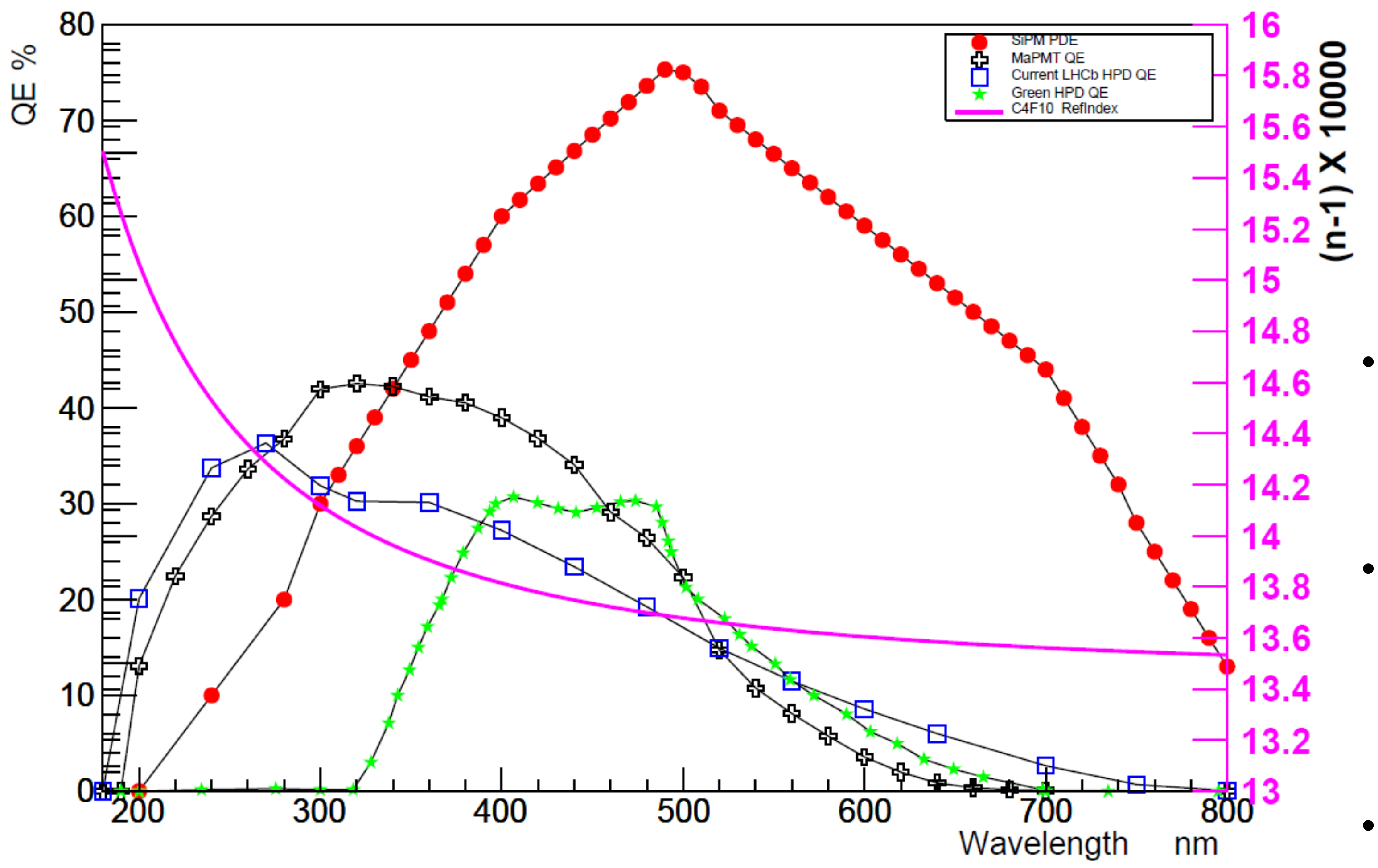
Probability distribution function : Eqn 18 of LHCb/98-040 RICH

$$f_{h_j}(\theta) \propto \frac{1}{\sigma(\theta)} \exp\left[-\frac{(\theta-\theta_c(h_j))^2}{2\sigma^2(\theta)}\right] \quad \text{(current)}$$

$$f_{h_j}(\theta) \propto \frac{1}{\sigma(\theta)}\frac{1}{\sigma(t)} \exp\left[-\frac{(\theta-\theta_c(h_j))^2}{2\sigma^2(\theta)} - \frac{(t-t_{exp})^2}{2\sigma^2(t)}\right] \quad \text{(incl. time)}$$

- *Work in progress to implement and evaluate this from Brunel*

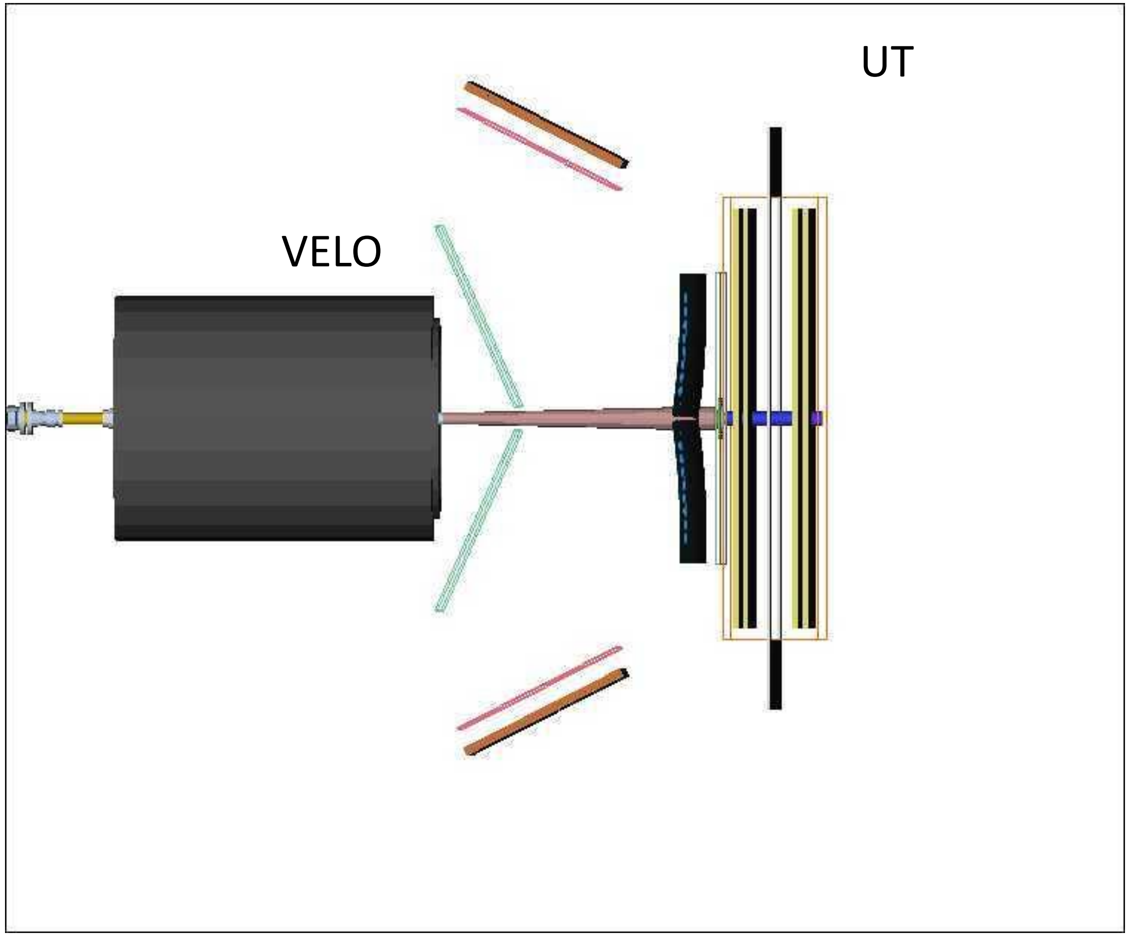
Improve resolutions and yields



- *Slightly improved "green MaPMTs" available now from Hamamatsu*
- *SiPM-PDE with realistic "fill factor" under review. This may potentially affect the height of the red plot.*
- *SiPM gives better PDE than the QE of MaPMT photocathodes*

Phase-Ia upgrade : *Black*: *Typical MaPMT*
Future upgrade options : *Red : SiPM*
Green: Photonics HPD prototype

RICH1 : A geometry option



Sph.Mirror ROC=3800 mm
tilt ~ 140 mrad
Flat mirror in acceptance

Phase-1a Upgrade: Sph. Mirror ROC=3650 mm
tilt ~ 258 mrad

- Uses of light weight flat mirrors, which are more expensive than glass mirrrors

- The proposed geometry may require changing the magnetic shielding structure to get enough space inside the shielding.

- With SiPM, the shielding requirements are less stringent than those of MaPMTS

Resolutions, yields : RICH1

RICH1	Overall mrad	Chromatic mrad	Emis. Pt. mrad	Pixel mrad	Yield
Current	1.60	0.84	0.76	1.04	32
Phase-1 upgrade Reference	0.78	0.57	0.36	0.45	41.2
QE of SiPM	0.59	0.13	0.35	0.45	41.4
QE of SiPM + Geometry modif.	0.44	0.12	0.10	0.43	30
SiPM (QE+ pixel) + Geometry modif	0.22	0.12	0.10	0.15	35
QE of Green HPD	0.61	0.18	0.34	0.46	19.4

ν	RICH1 Peak Occupancy
7.6	SiPM: 3.1 %
35	SiPM : 14.3 %

SiPM with 1 mm pixel size used

- Resolutions from particle gun events, for illustration
- A cut-off at 400 nm when using SiPM QE

Const. ~0.4 mrad
New RICH related σ < Const

Resolutions, yields : RICH2

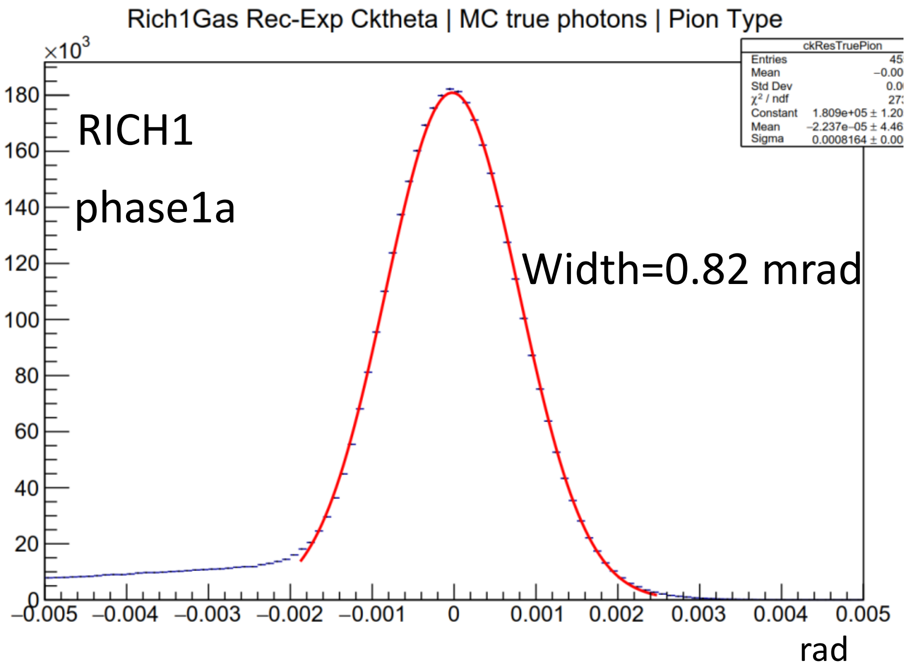
RICH2	Overall mrad	Chromatic mrad	Emis. Pt. mrad	Pixel mrad	Yield
Current	0.65	0.48	0.27	0.35	24
Phase-1 upgrade Reference	0.45	0.31	0.26	0.20	23
QE of SiPM	0.36	0.16	0.22	0.20	21
SiPM (QE+ pixel)	0.28	0.16	0.22	0.07	24
QE of Green HPD	0.37	0.18	0.24	0.20	10

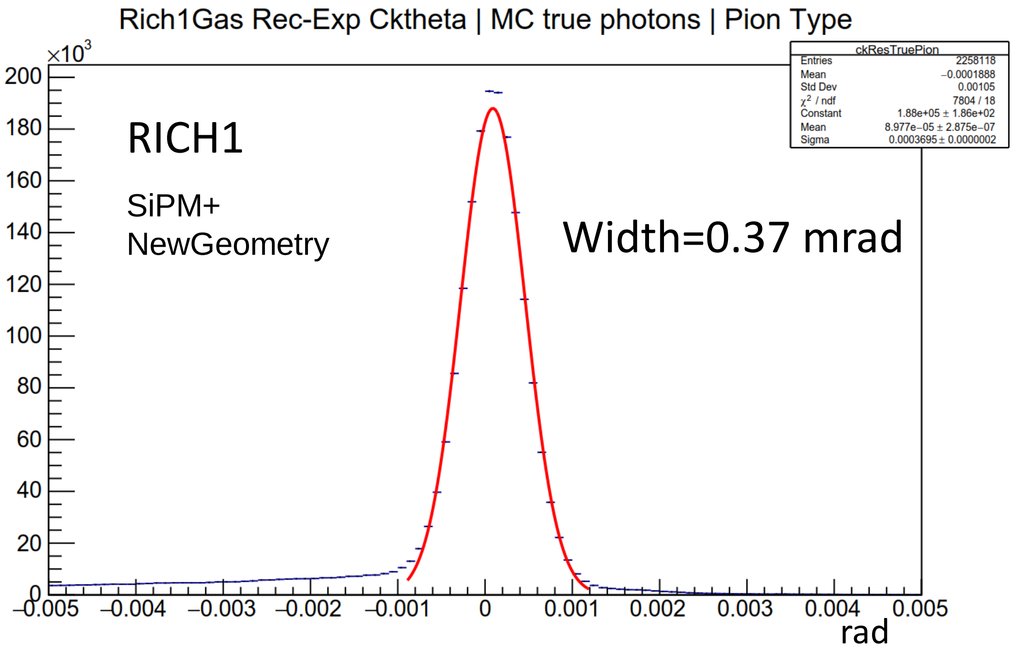
- Resolutions from particle gun events, for illustration
- Quoting the values for small MaPMT (*R13742*), as an example here for the SiPM options
- A cut-off at 400 nm when using SiPM QE

- *Plan to improve the geometry of RICH2 also so that New RICH2 σ < New RICH1 σ*

Resolutions: Brunel

- B-events in Brunel:





RICH2:

Phase 1a	SiPM
0.54 mrad	0.37 mrad

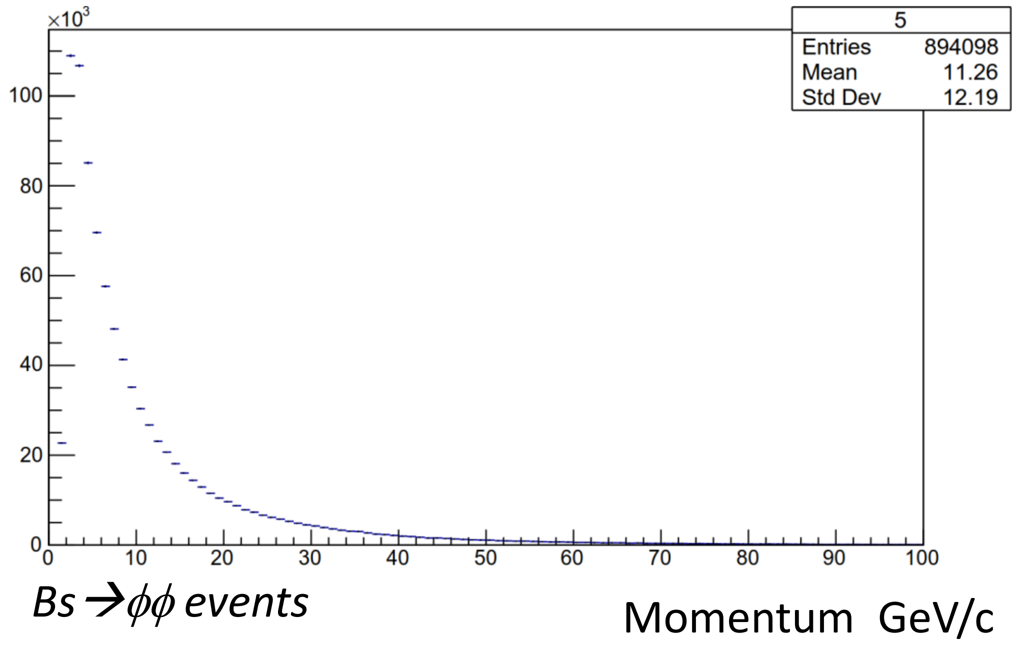
Tracking contribution: approx. 0.34 mrad

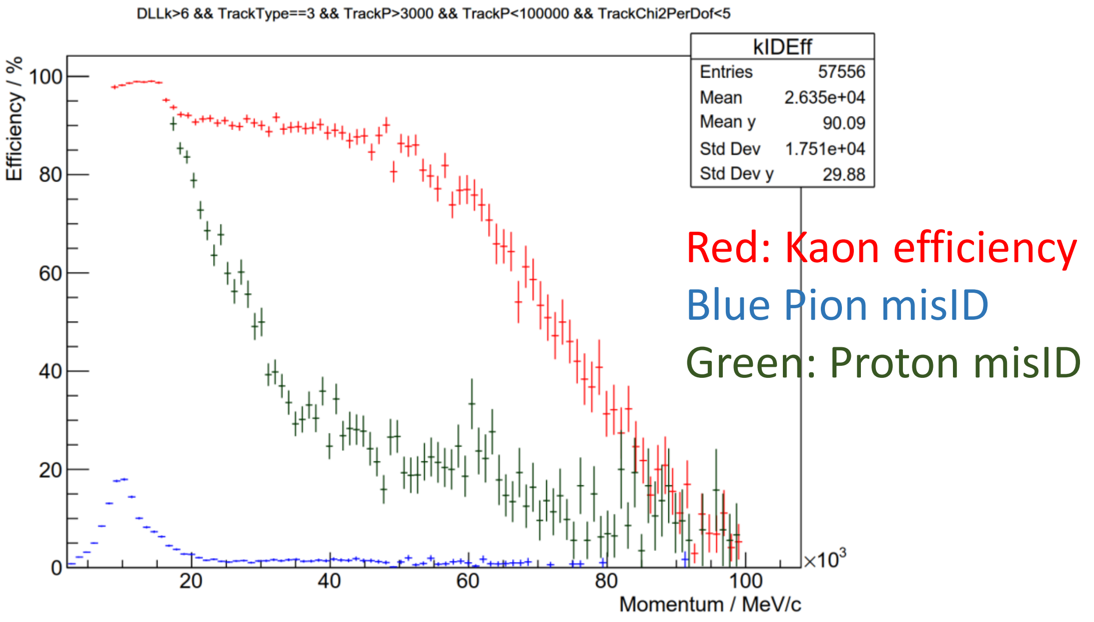
- Overall resolution dominated by tracking resolution in RICH1 and RICH2, when using SiPM
- Work in progress to upgrade PID algorithm to use SiPM+Geometry in Brunel

Limitations of current radiators

- No good material to cover the full momentum range 1 - 10   GeV/c

- No Cherenkov photons produced by kaons below 9.3 GeV/c and protons below 17.7 GeV/c. Lot of the LHCb charged tracks are in this momentum range.

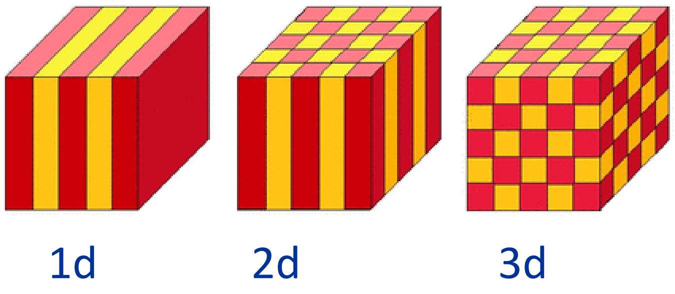




- Above 10 GeV/c   we use large gas radiators which take up lot of valuable detector space.   It would be desirable to have thin radiators
- Electron identification essentially impossible above a few GeV/c

Potential solutions

- Various solutions being discussed and pursued
- The approach discussed here is expected to be complementary to other solutions
- General idea:
    - Assemble materials to produce desired ‘*effective refractive index*’
    - Design photonic crystals from transparent dielectrics



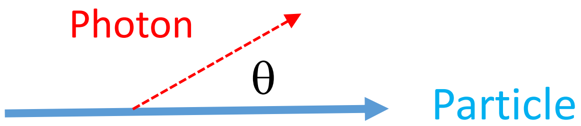
- Salient Features:
    - Thickness of each layer is similar in magnitude to photon wavelengths.
    - The 1d crystals with layer thickness of few hundred nanometers can be made on large scale.
    - The production of Cherenkov photons from these crystals already shown in theory and experiments
    - Simulations using FDTD (Finite Difference Time Domain) method and COMSOL framework available

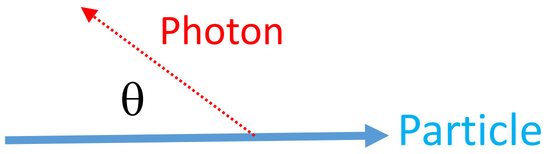
Ref: backup slides

Simulations

X.Lin, I.Kaminer

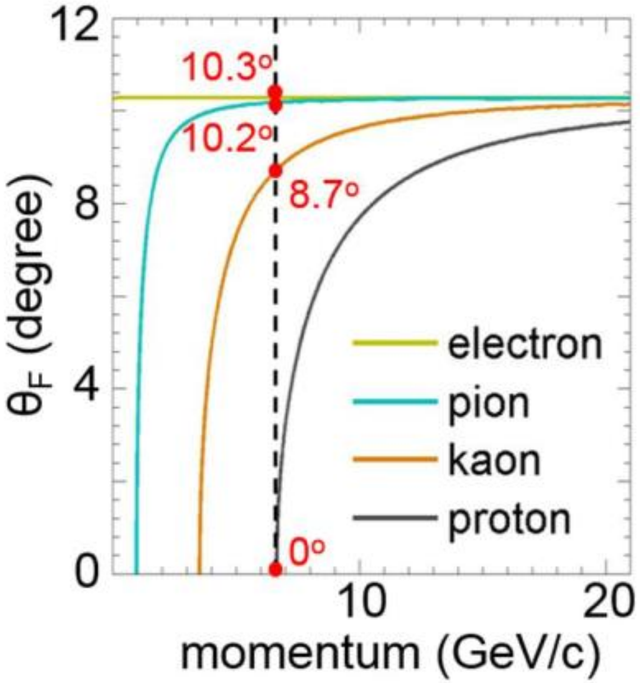
- FDTD: Solve Maxwell's equations for 1d system in example configurations

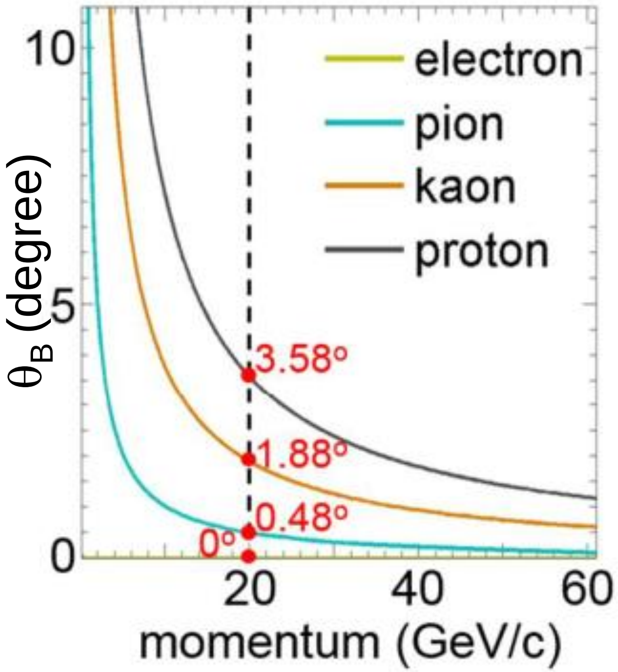




Forward θ : Same as in conventional radiator
Forward θ increase with particle velocity

Backward $\theta = 180^o$ – Forward θ
Backward θ decrease with particle velocity





Overall thickness = 2 mm, ε_1 = 10.6 (GaP), ε_2=2.1 (SiO2)
Forward setup: 2800 periods with (214.3 nm+ 500nm)

Backward setup: 10200 periods with (117.3nm+78.1nm)

R&D start up with prototypes

I.Kaminer, X.Lin

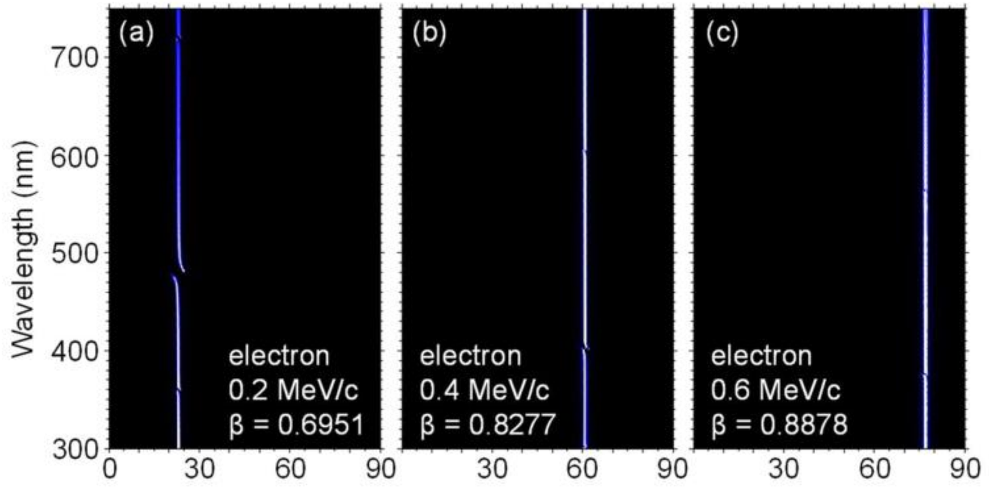
- Goal: To verify the simulations of ‘effective Cherenkov radiation”

- R&D work in very early stages:
  - Few 1d samples obtained from industry

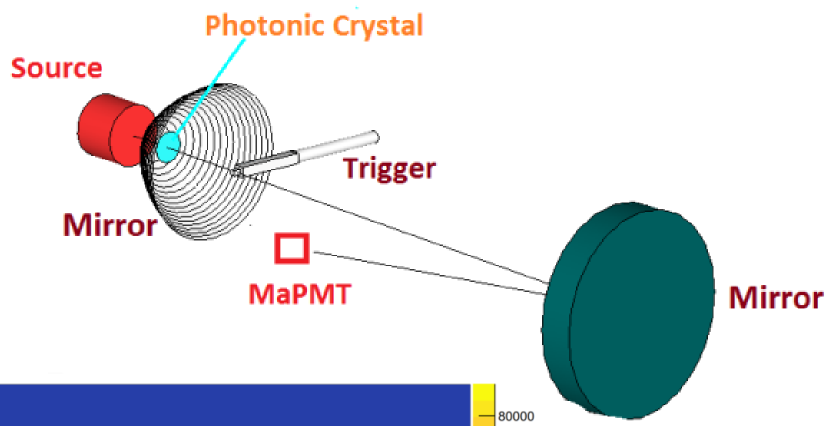
    PVDF $n_1=1.414$ + *PET* $n_2=1.567$

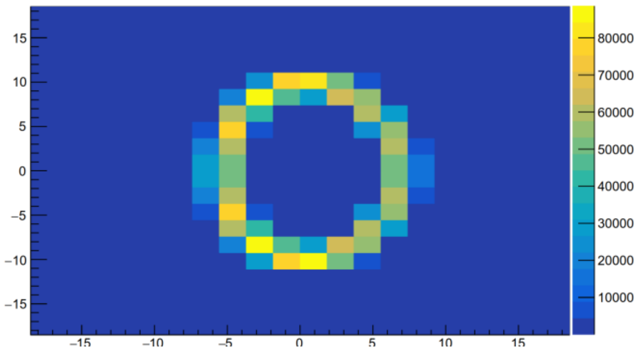
    1024 layers, each with 250 nm thickness

Photon energy density

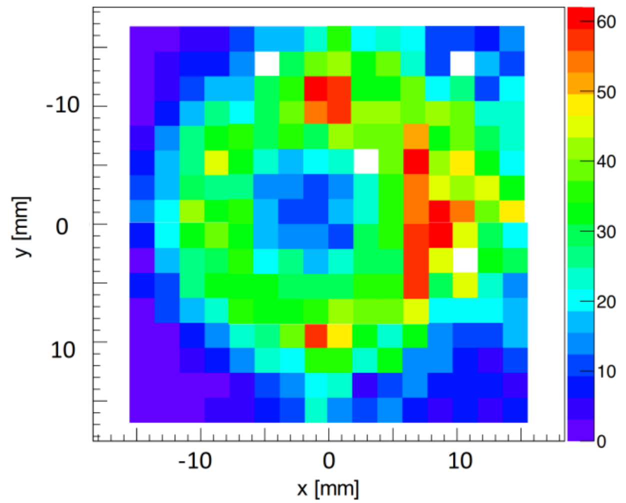


FDTD Simulation: wavelength vs Forward angle





Optics Simulation for 0.5 MeV/c



Michele

Real Data

0.2 → 0.7 MeV/c

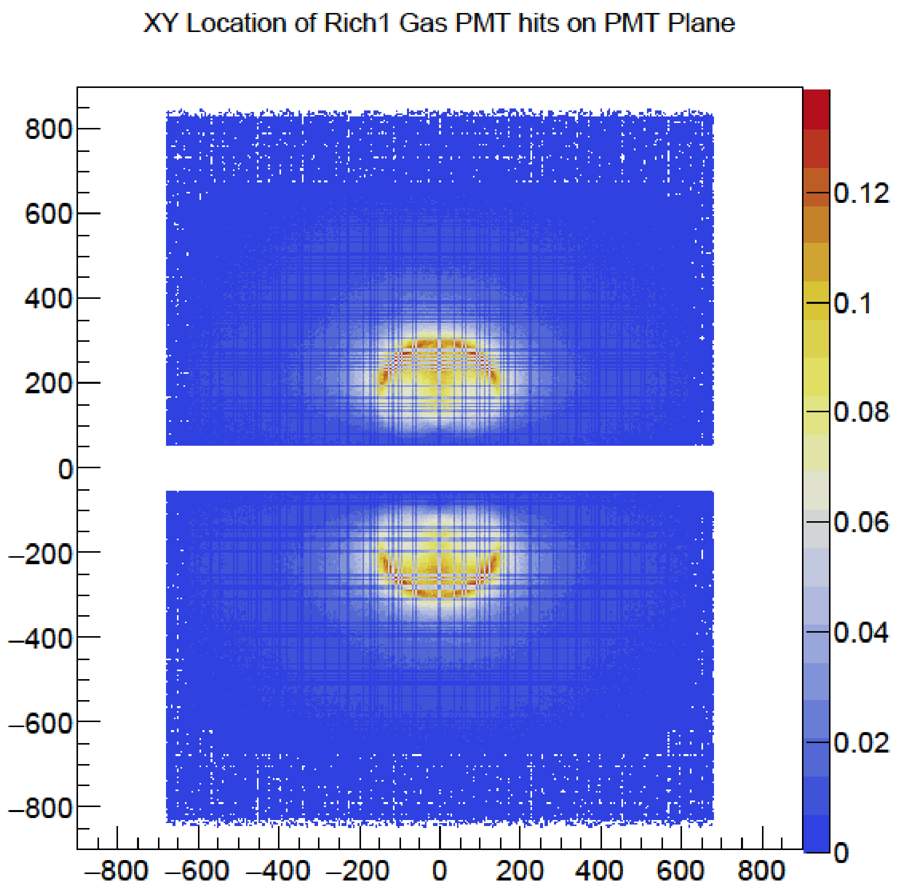
Summary

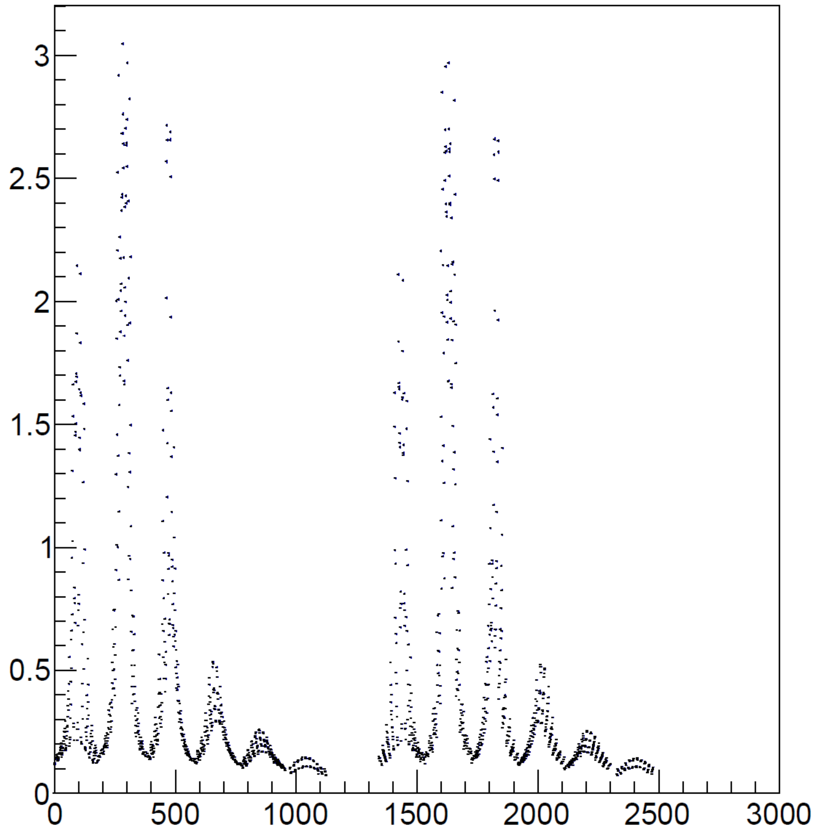
- Several technical issues being worked through, to use our software framework for future upgrade
- Work in progress to use the RICH Hit Time information in Brunel and upgrade the PID algorithm
- Using an SiPM based RICH detector with geometry upgrade, the RICH resolutions can be improved. Work on progress to evaluate the corresponding PID improvements
- Current radiators have known limitations. One option overcome this limitation, is to develop new radiators. Work started towards this goal.

BACKUP SLIDES

RICH1 Occupancy

SiPM (Pixel + QE)+ new geometry





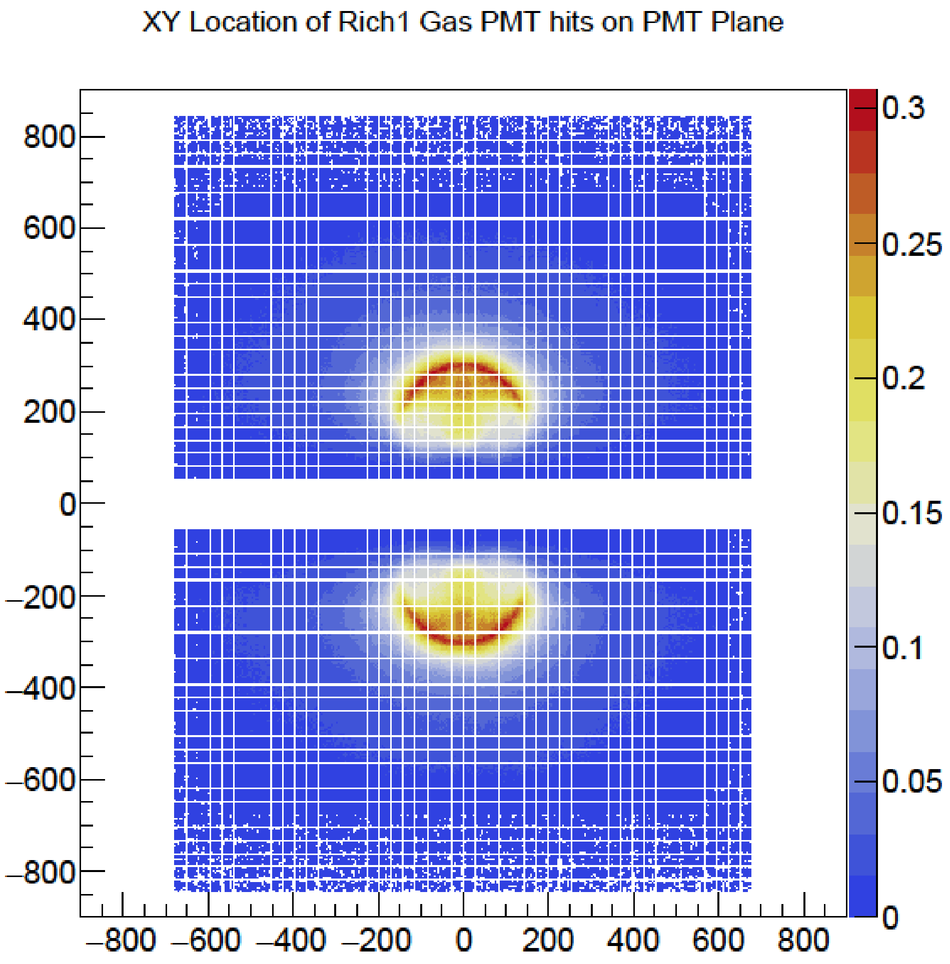
- Number of hits in SiPM X (100/ (25 x25))

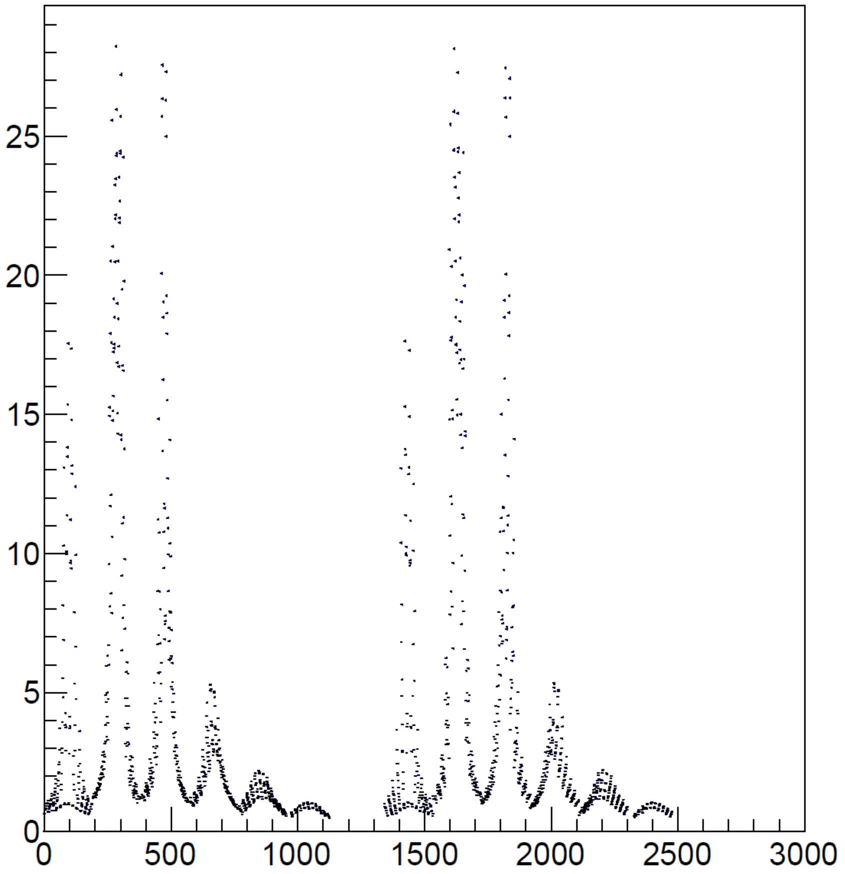
Luminosity : phase -1 upgrade : peak SiPM occupancy ~ 3.1 %

At phase-2 upgrade: assuming ν=35 and linear scaling : peak SiPM occupancy ~ 14.3 %

RICH1 Occupancy

MaPMT + phase I upgrade geometry





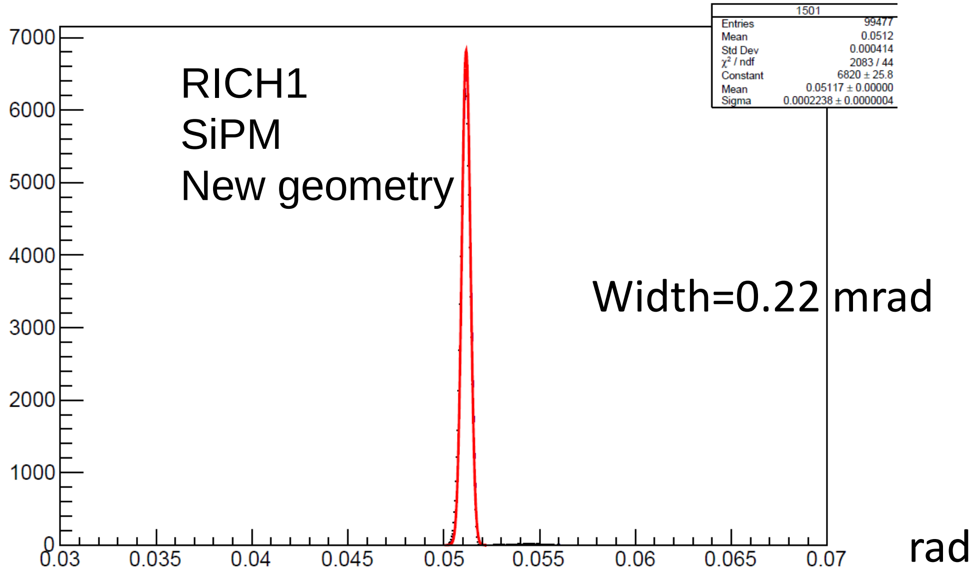
Number of hits in MaPMT X (100 /64)

Luminosity: phase -1 upgrade : peak occupancy ~ 28 %

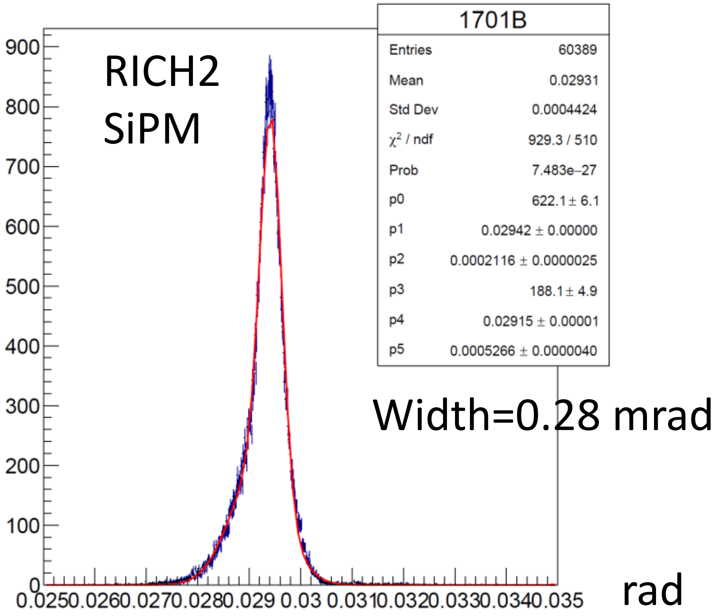
At phase-II upgrade: assuming ν=35 and linear scaling : peak occupancy ~ 129 %

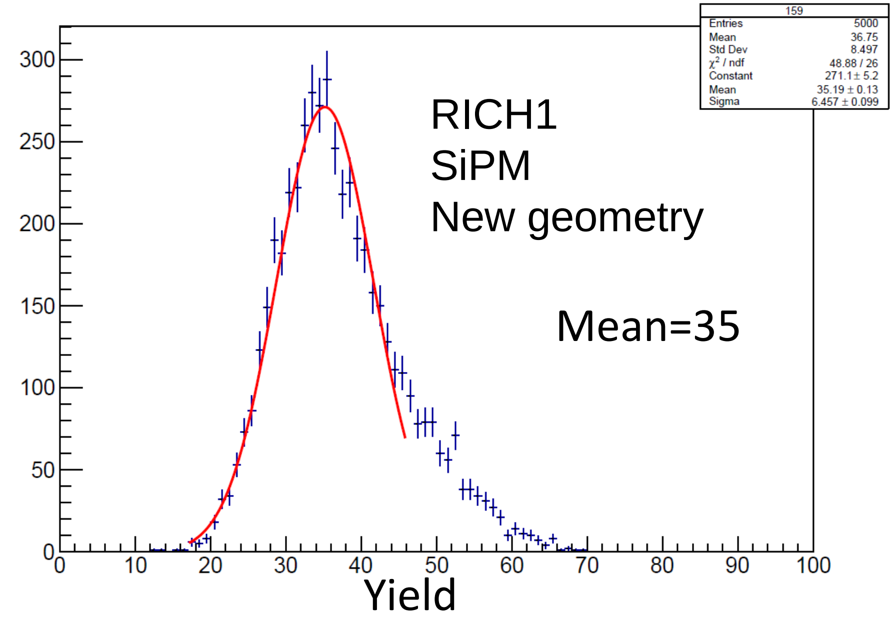
Typical resolutions and yields

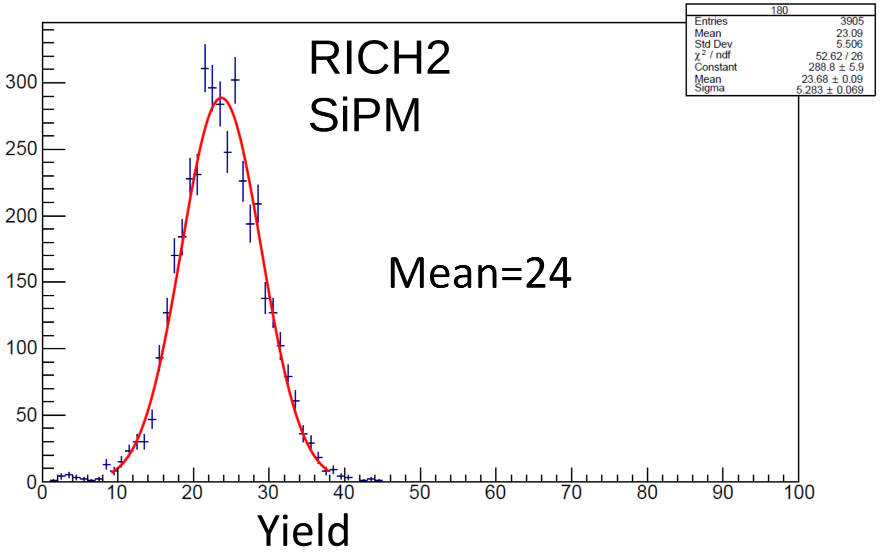
Reconstructed Cherenkov angle



Reconstructed Cherenkov angle



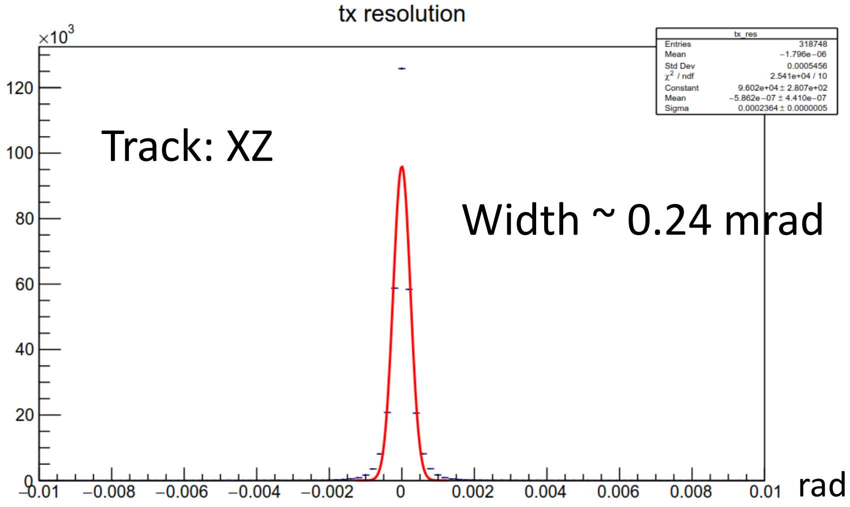


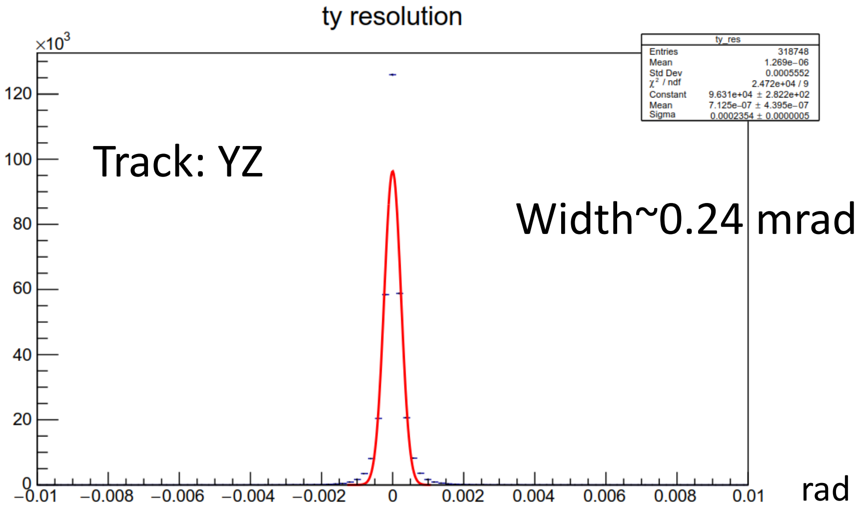


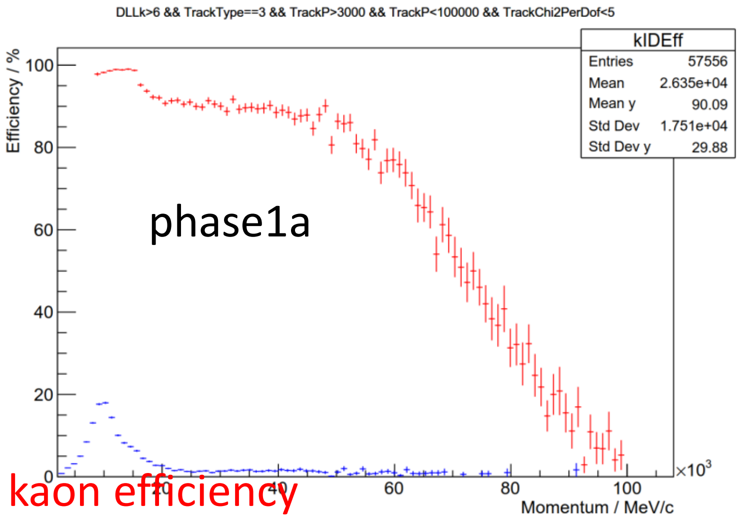
Improving resolutions, yields and occupancy

$$\sigma_{\text{p}} = \sigma_{\text{chromatic}} \oplus \sigma_{\text{emission point}} \oplus \sigma_{\text{pixel}}$$

Use new photodetectors : **QE augmented and shifted to larger λ**	➢ *Improve chromatic error and yield* ➢ *Potential candidates: SiPM and MCP*
Improve optics geometry	➢ *Improve emission point error and occupancy* ➢ *Use new light weight mirrors* ➢ *Address the space constraints around the RICH system , costs for detector plane area etc.*
Improve pixel granularity	➢ *1 mm pixel size as may be achieved in SiPM*
Improve readout	➢ *Binary readout → 'two bits' readout in high occupancy regions (apply two thresholds)*

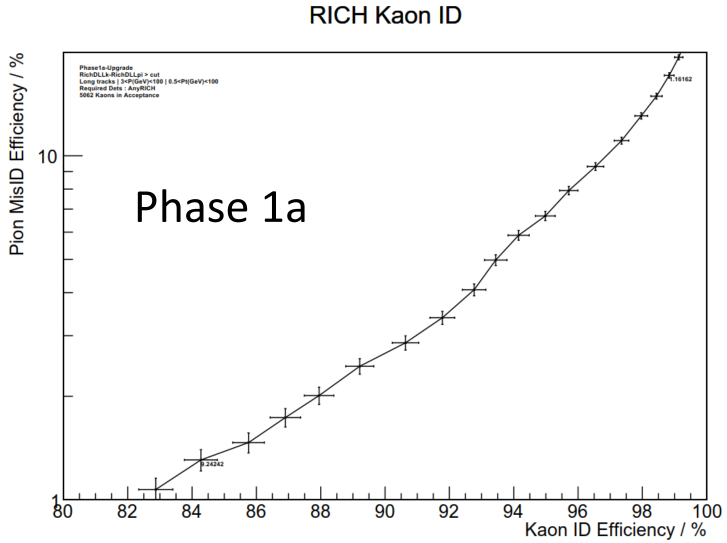






Red: kaon efficiency

Blue: Pion misID



References:

1. *V.Ginis et.al. , "Controlling Cherenkov Radiation with Transformation-Optical Metamaterials",* PRL 113 , 167402 (2014)
2. C. Luo et.al. , "*Cerenkov Radiation in Photonic Crystals*" Science Vol. 299, Issue 5605 page 368-371 (2003)
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