# LHCb RICH : Future upgrades

*LHCb: Elba workshop*

Science & Technology
Facilities Council

S.Easo
29-05-2017

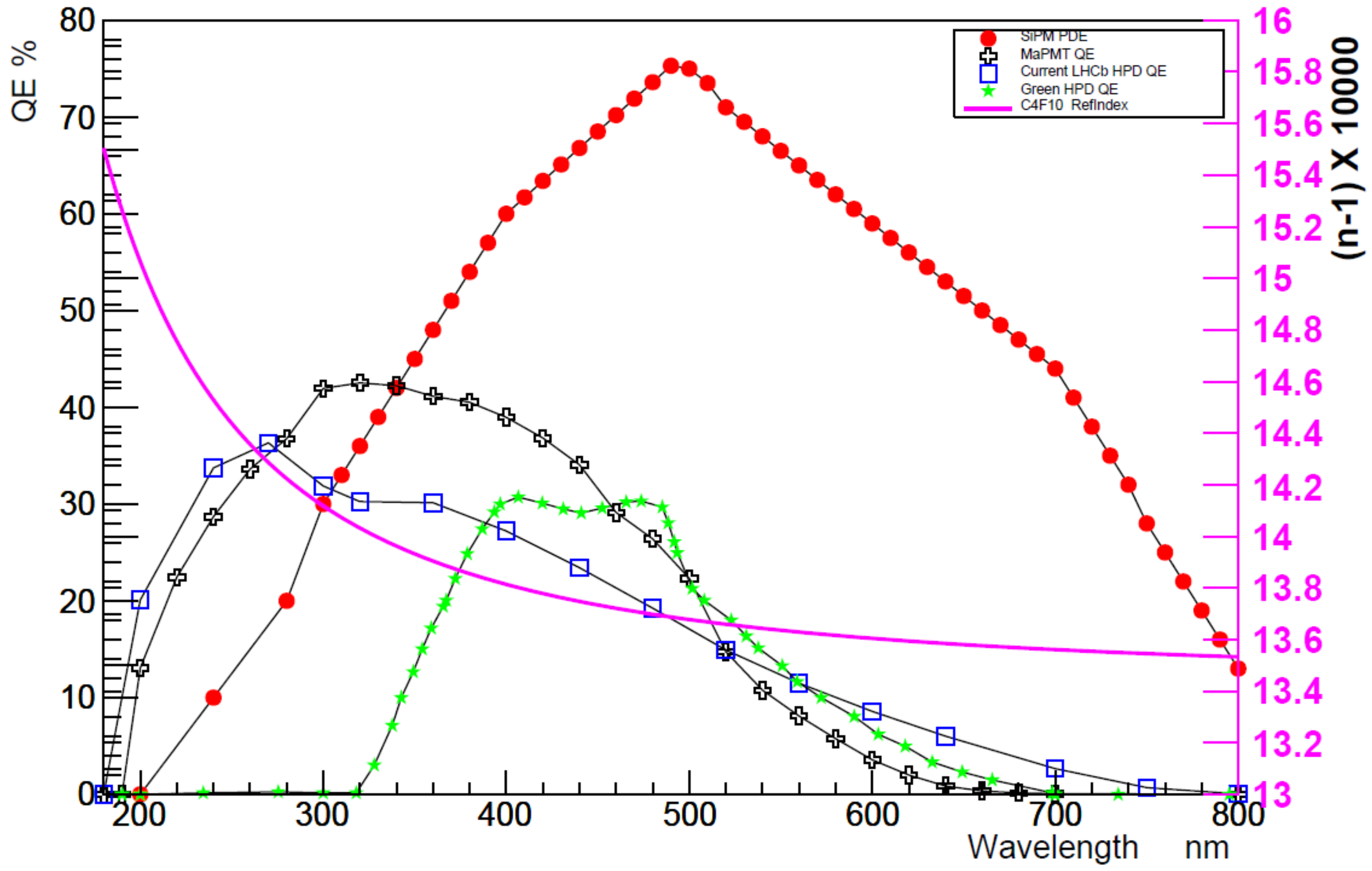
# Preamble

- Hadron PID at HL-LHC / Phase-II upgrade calls for major changes in the design of the RICH system

- Some of the ideas pursued
  - Improve the resolutions and yields from RICH : Natural evolution using latest technology
  - Use the "Hit Time" information as a new input : Introduce fast-timing detectors
  - Develop novel radiators which could overcome some of the basic limitations in the RICH system

- This presentation:
  - Current status and plans for R&D in the coming years
  - Resulting from various discussions with Carmelo and other colleagues in the RICH group
  - Using contributions from many colleagues in LHCb

# Improve resolutions and yields




Yield (N): Number of photon (p) hits per track (t)

Resolution:

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

Phase-I upgrade : *Black*: *Typical MaPMT*

Future upgrade options : *Red : SiPM*

*Green: Photonics HPD prototype*

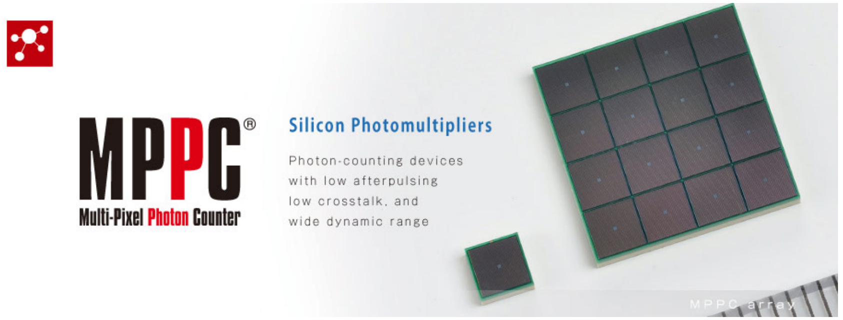
# Improving resolutions, yields and occupancy

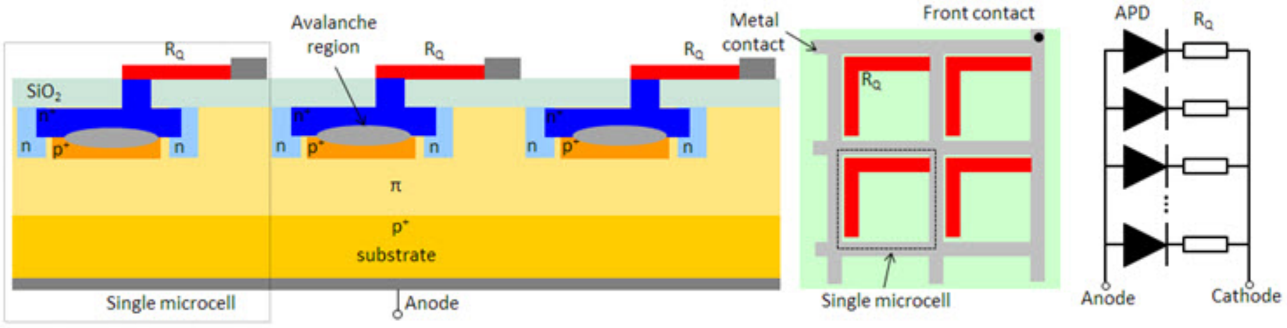
$$\sigma_{p} = \sigma_{chromatic} \oplus \sigma_{emission\ point} \oplus \sigma_{pixel}$$

| | |
|---|---|
| **Use new photodetectors :**<br>**QE augmented and shifted to larger λ** | ➢ *Improve chromatic error and yield*<br>➢ *Potential candidates: SiPM and MCP* |
| **Improve optics geometry** | ➢ *Improve emission point error and occupancy*<br>➢ *Use new light weight mirrors*<br>➢ *Address the space constraints around the RICH system , costs for detector plane area etc.* |
| **Improve pixel granularity** | ➢ *Potential candidate: SiPM with 1 mm pixel size (cf. MaPMT ~2.85 mm )* |
| **Improve readout** | ➢ *Binary readout → 'two bits' readout in high occupancy regions ( apply two thresholds)* |

# Photon detectors

- Usage  of SiPM (Silicon Photomultiplier) is being discussed as  an option



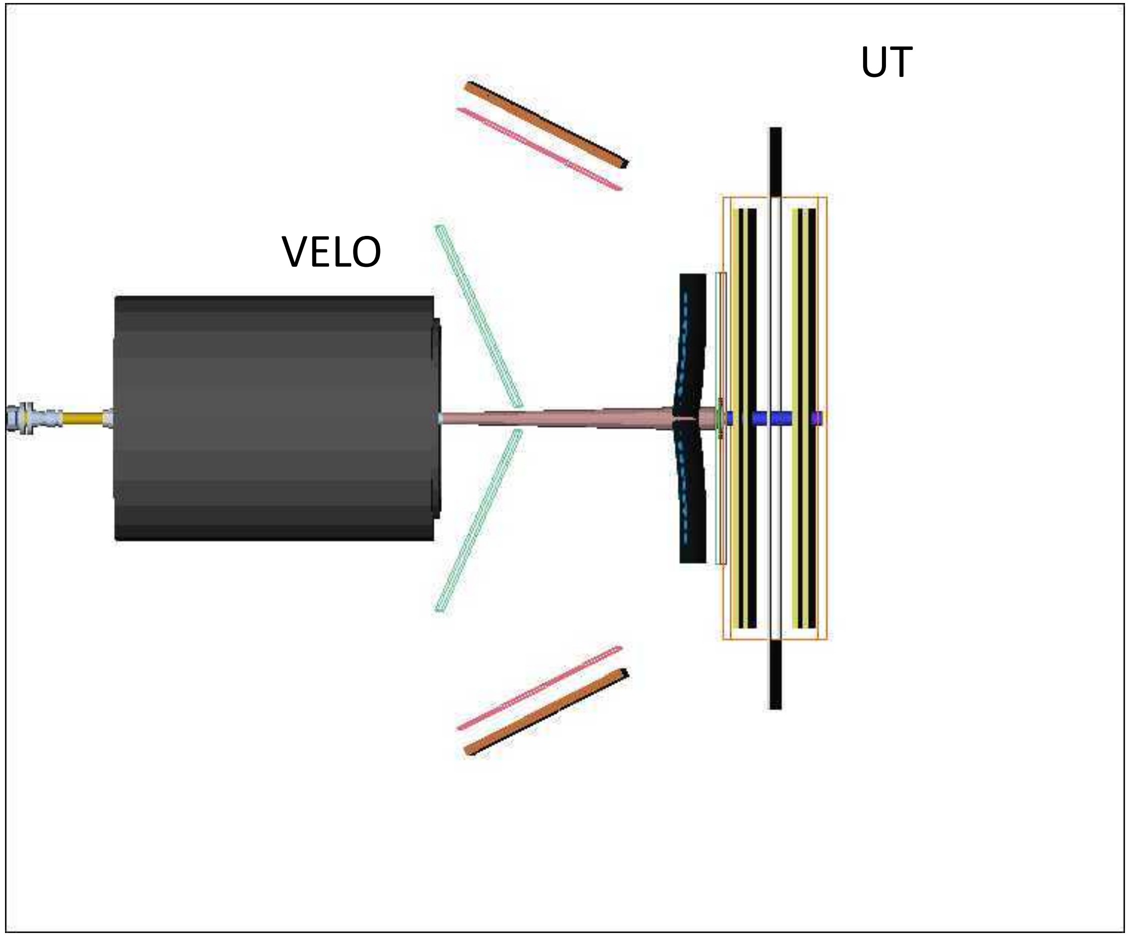

- For now considering, 1 mm X 1 mm  pixel size.
  Issues related to noise, especially due to such an area,   to be addressed in the future.

- Using MCP is another option, but its QE compared to that of  SiPM, may be an issue

- More information in the following presentations

# RICH1 : A geometry option

- Assuming we keep the general structure of the current “two RICH” system




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

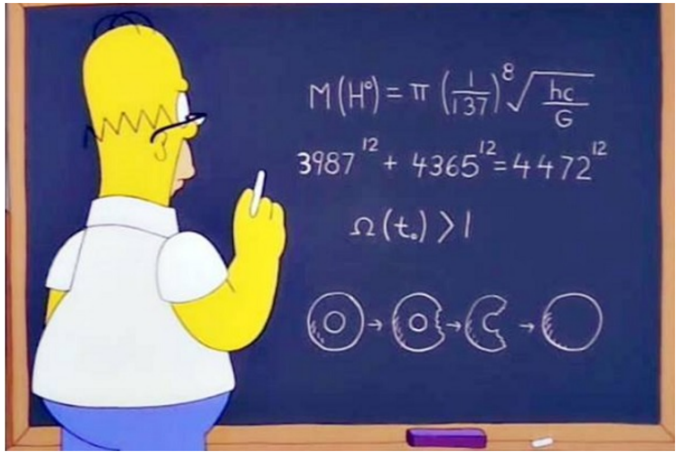
*Phase-1 Upgrade: Sph. Mirror ROC=3650 mm*
*tilt ~ 258 mrad*

- 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

# Configurations for simulation study



- Standard LHCb software simulation

- Phase-I upgrade setup to study the effects of different options

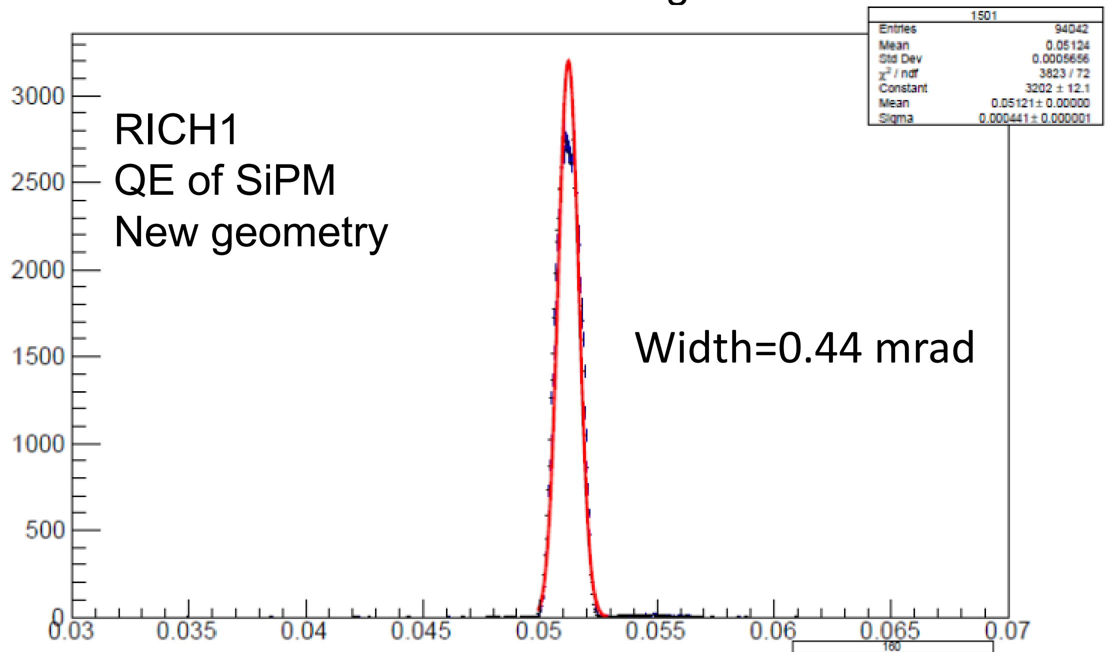
| Luminosity $cm^{-2}$ $s^{-1}$ | # bunches | Beam Energy (TeV) | ν |
|---|---|---|---|
| $2 \times 10^{33}$ | 2400 | 7 | 7.6 |

- RICH options

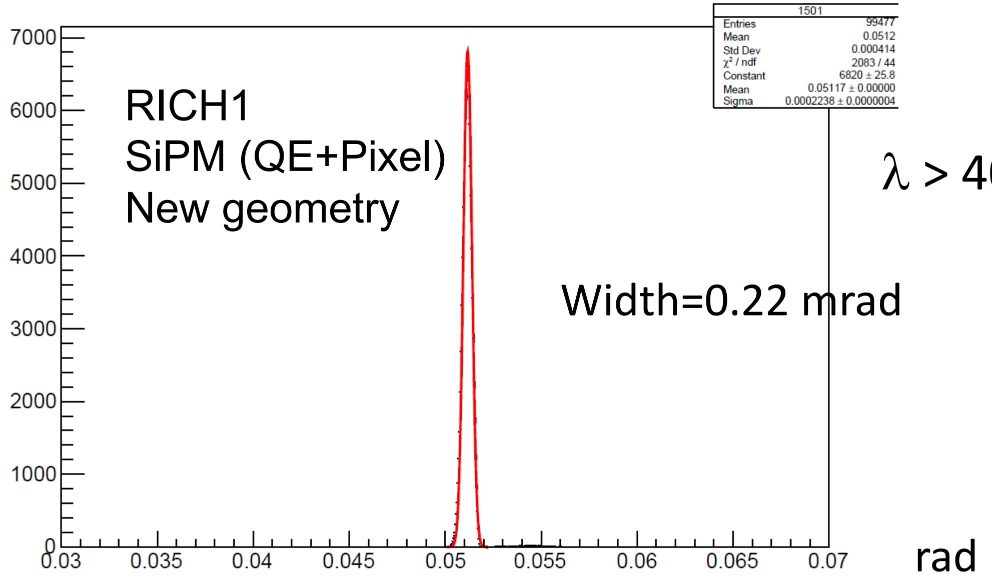
| | Option | Description |
|---|---|---|
| (a) | Phase -1 Upgrade | Reference |
| (b) | QE of SiPM | QE →PDE of SiPM wrt. (a) |
| (c) | RICH1 modification | New RICH1 geometry option wrt. (b) |
| (d) | SiPM Pixel | Use a pixel size of 1 mm wrt. (c) |
| (e) | Green photocathode | Use QE of Photonics Green HPD wrt. (a) |

# Typical resolutions and yields

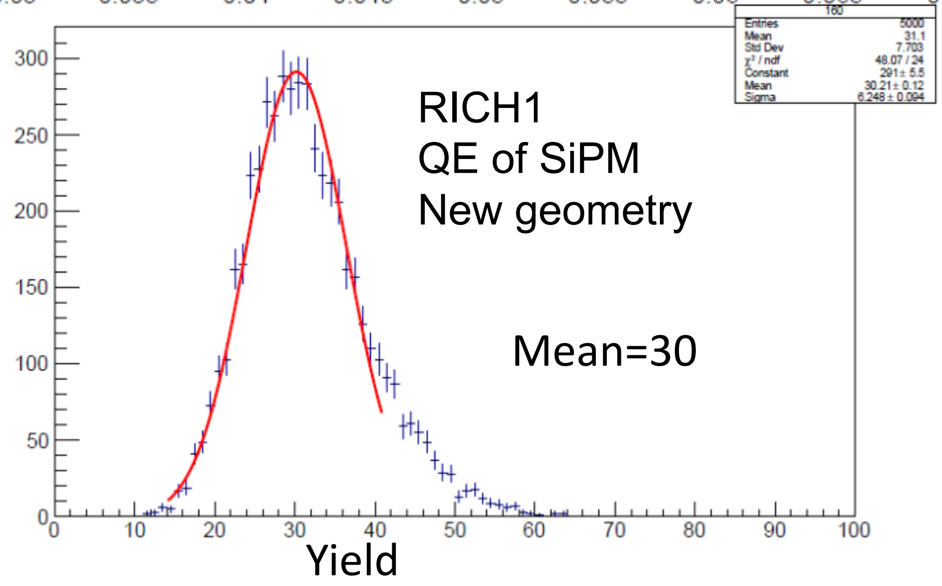
Reconstructed Cherenkov angle

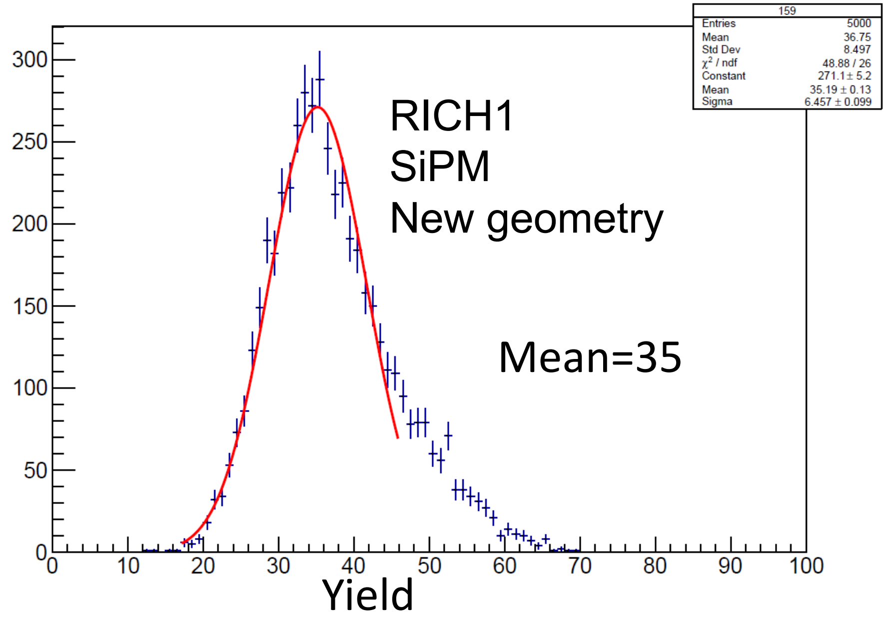



Reconstructed Cherenkov angle




$\lambda > 400$ nm



# 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 |

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

*Const. ~0.4 mrad*
*New RICH related $\sigma$ < Const*

# Resolutions, yields : RICH2

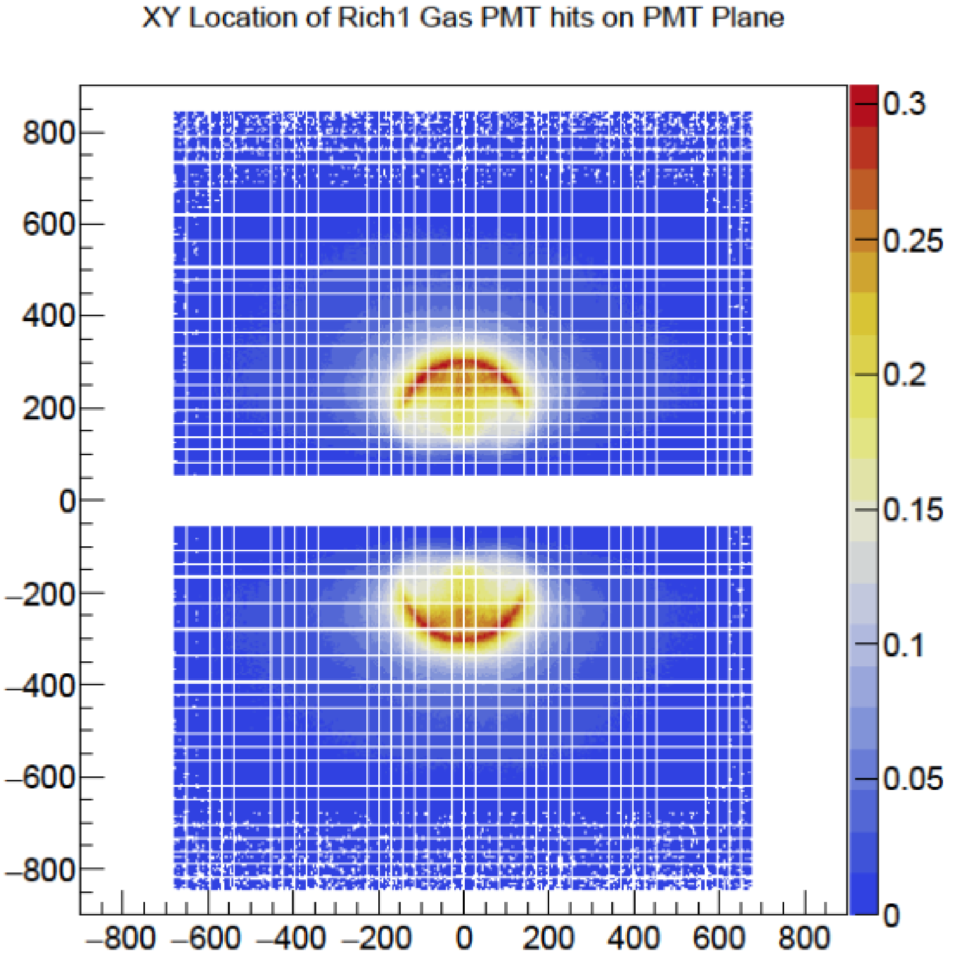
| RICH2 | Overall mrad | Chromatic mrad | Emis. Pt. mrad | Pixel mrad | Yield |
|---|---|---|---|---|---|
| Current | 0.65 | 0.48 | 0.27 | 0.35 | 24 |
| Phase-1 upgrade Reference | 0.45 | 0.31 | 0.26 | 0.20 | 23 |
| QE of SiPM | 0.36 | 0.16 | 0.22 | 0.20 | 21 |
| SiPM (QE+ pixel) | 0.28 | 0.16 | 0.22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

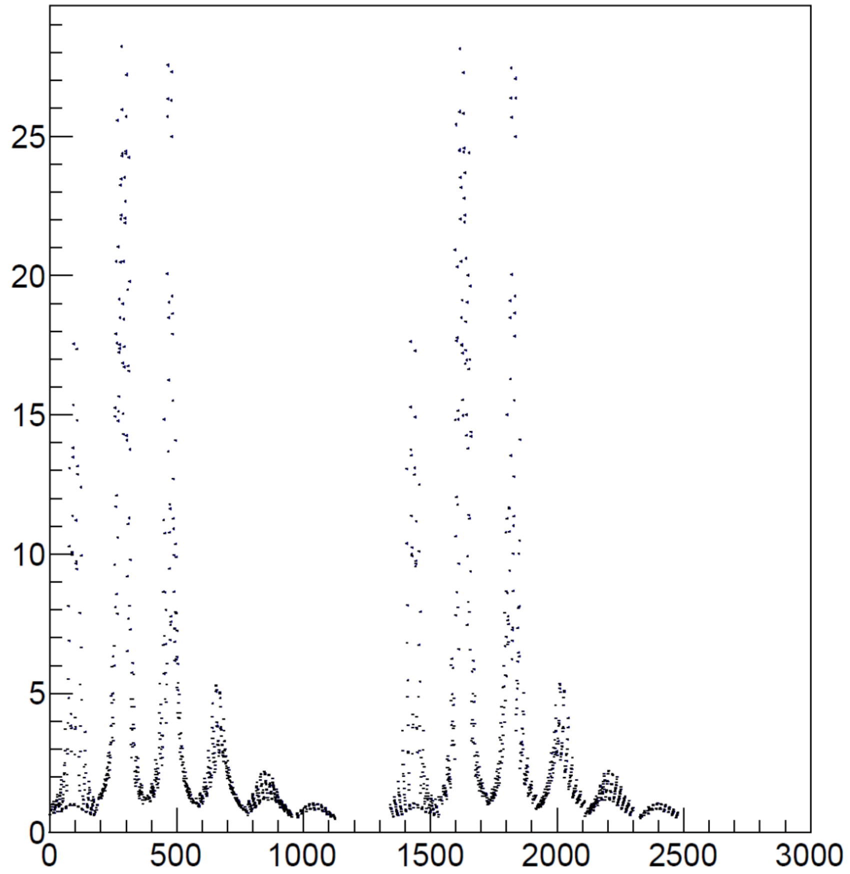
- Resolutions from particle gun events, for illustration
- Quoting the values for small MaPMT (*R13742*), as an example here for the SiPM options
- A cut-off at 400 nm when using SiPM QE

- *Plan to improve the geometry of RICH2 also so that New RICH2 $\sigma$ < New RICH1 $\sigma$*

# RICH1  Occupancy

MaPMT + phase I  upgrade geometry



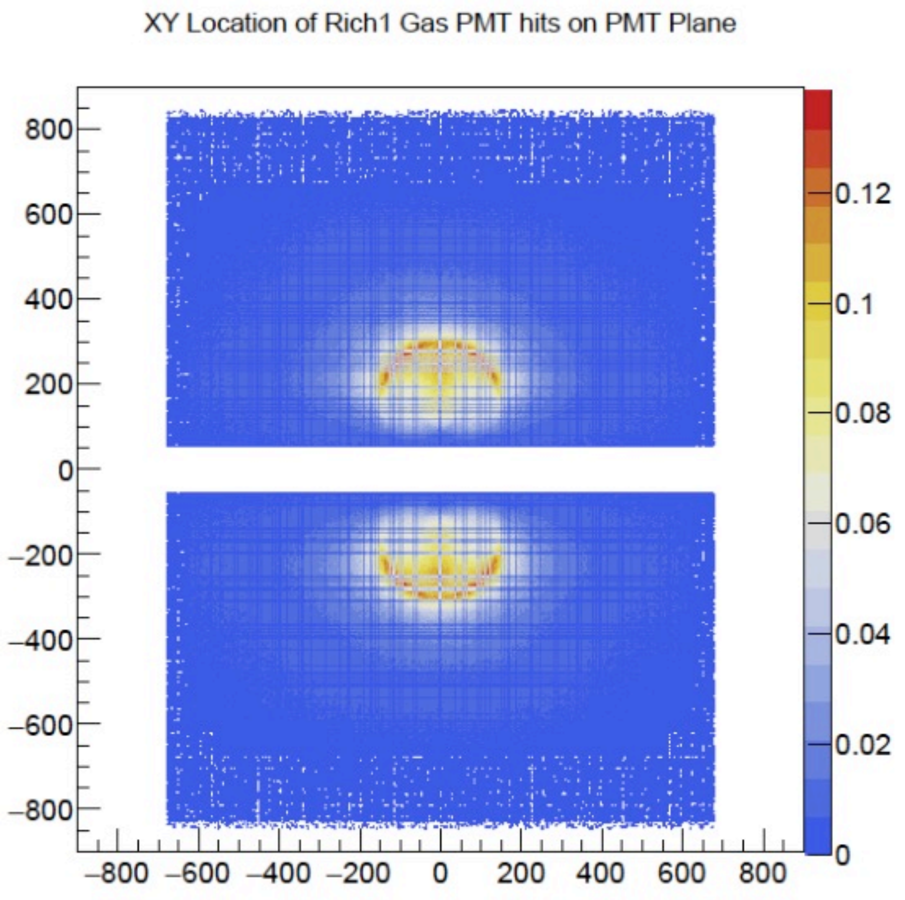

Number of hits  in MaPMT X (100 /64)

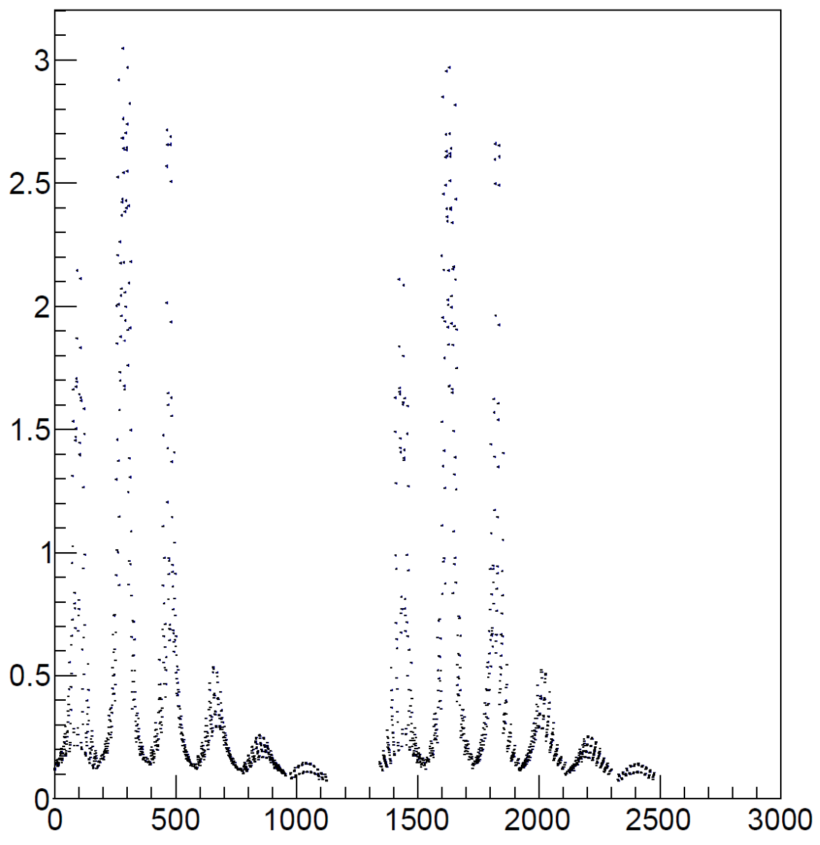
Luminosity: phase -1 upgrade :  peak occupancy ~ 28 %

At phase-II upgrade: assuming ν=38 and linear scaling   :  peak occupancy ~ 140 %

# 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-II upgrade: assuming ν=38 and linear scaling   : peak SiPM occupancy ~ 15.5 %

# RICH with Time

- Potential uses of "Hit Time" Info:

  - Multiple interactions within 25 ns at $1X10^{34}$ $cm^{-2}s^{-1}$ : *Prohibitively large occupancies in RICH1*
    *Peak occupancy exceeding 100 %*

    Separating these PV using the "Hit Time" info would be desirable

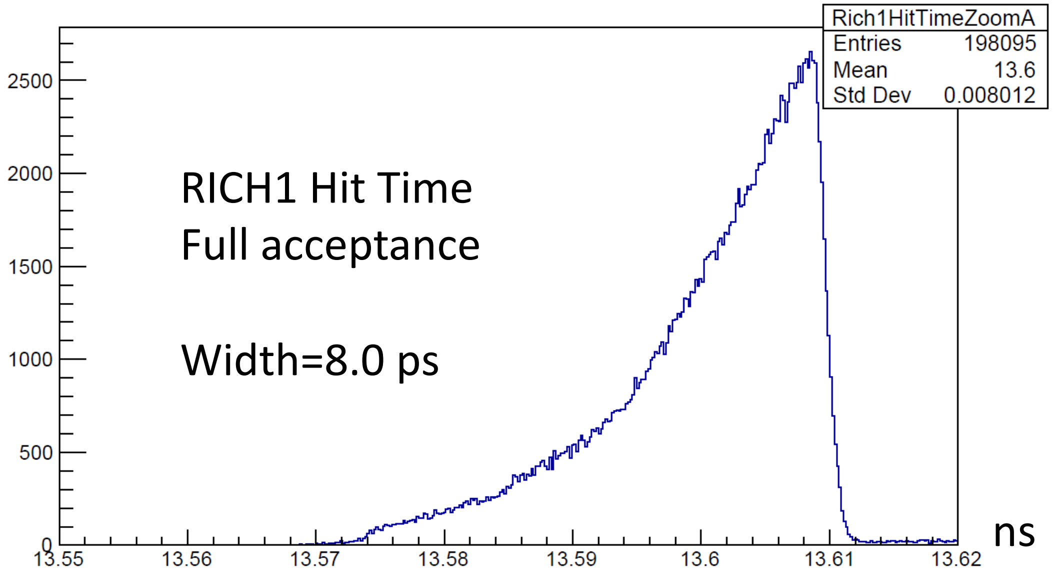
  - Adding the "HitTime" info to improve PID algorithm , for tracks above Cherenkov threshold

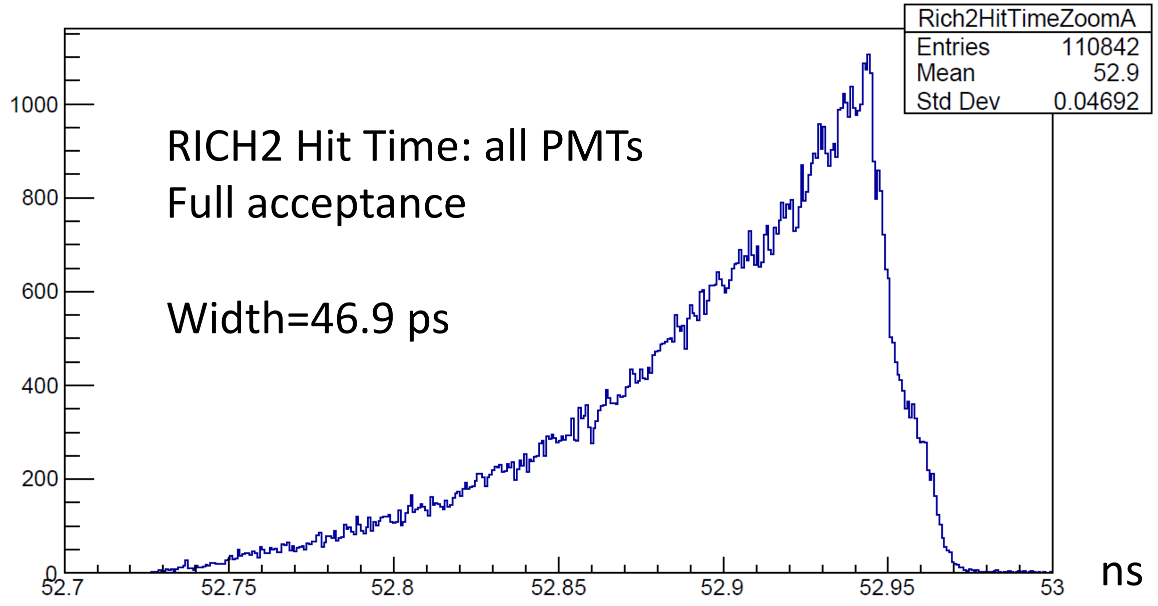
  - Reduce the background from 'out of time' Hits

- Recent progress:

  - Simulation of PV time : Floris Keizer, Chris Jones

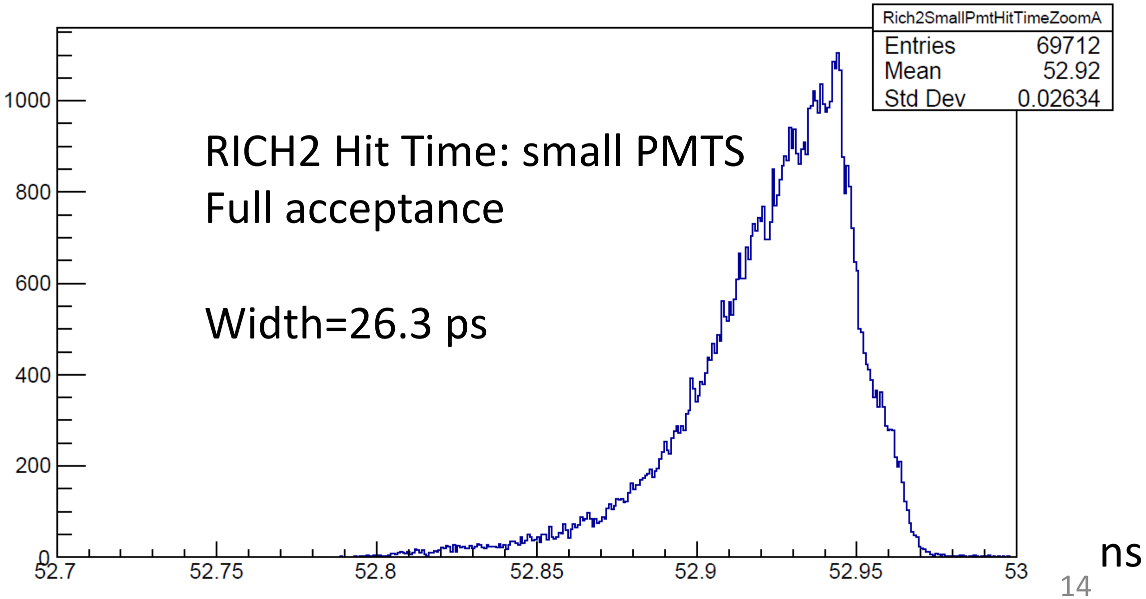
# RICH Hit Time : particle gun




- Intrinsic width of RICH hits in time
- Long tails due to the finite size of 'flat detector plane' (part of 'emission point error').

- For the central region, the widths reduce to
  RICH1: 4.5 ps,
  RICH2 : 35.6 ps (all PMT) , 19.6 ps (small PMTs)



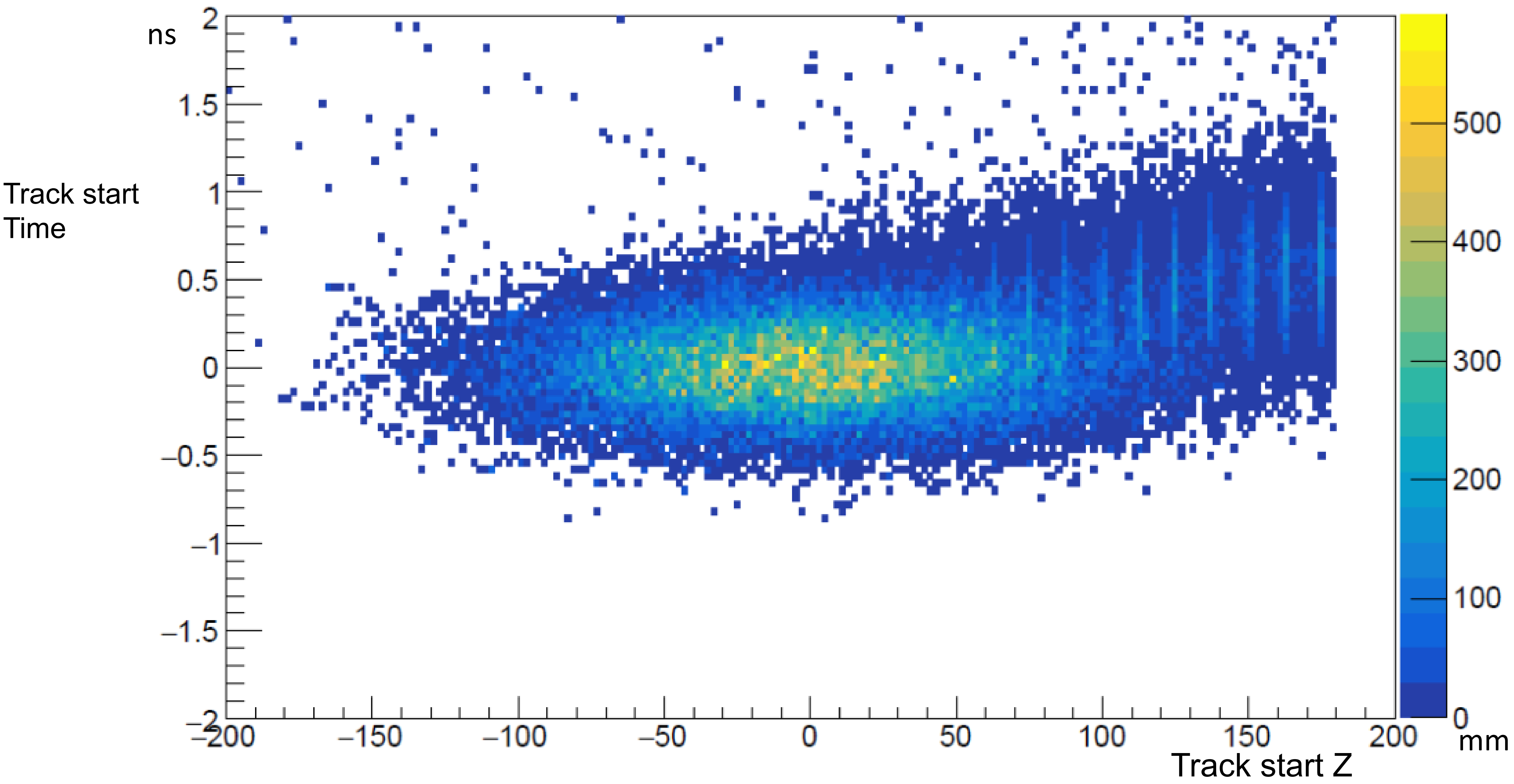
# Introducing the TIME of PV

*Floris Keizer*
*Chris Jones*

- The primary vertex generator in the LHCb simulation is updated to model the bunches as 4D-Gaussians (x, y, z, <u>time</u>).
- The Probability Distribution Function is calculated when the bunches travel towards the collision point at the beam crossing angles.
- A Markov Chain sampler is used to sample from the 4D PDF.
- The generator called "BeamSpotMarkovChainSampleVertex" has been released as an option from Gaussv49r6 onwards.

*Ref: Talk by Floris at Gauss meeting on 18-10-2016*

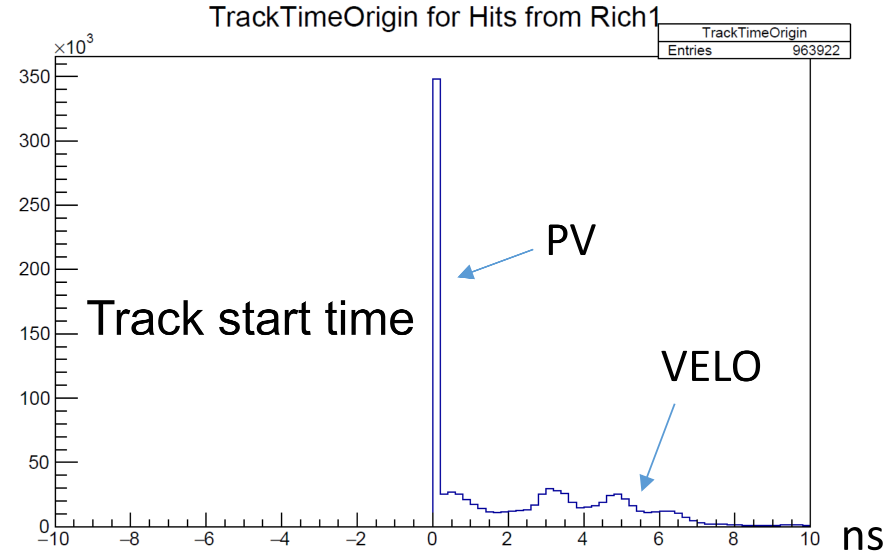
# PV : Time vs Z

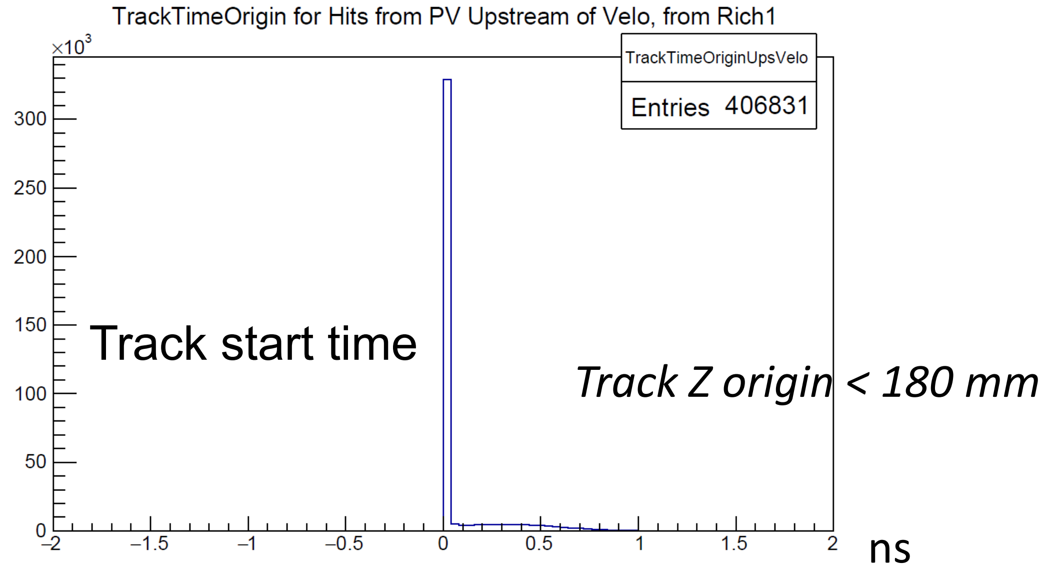


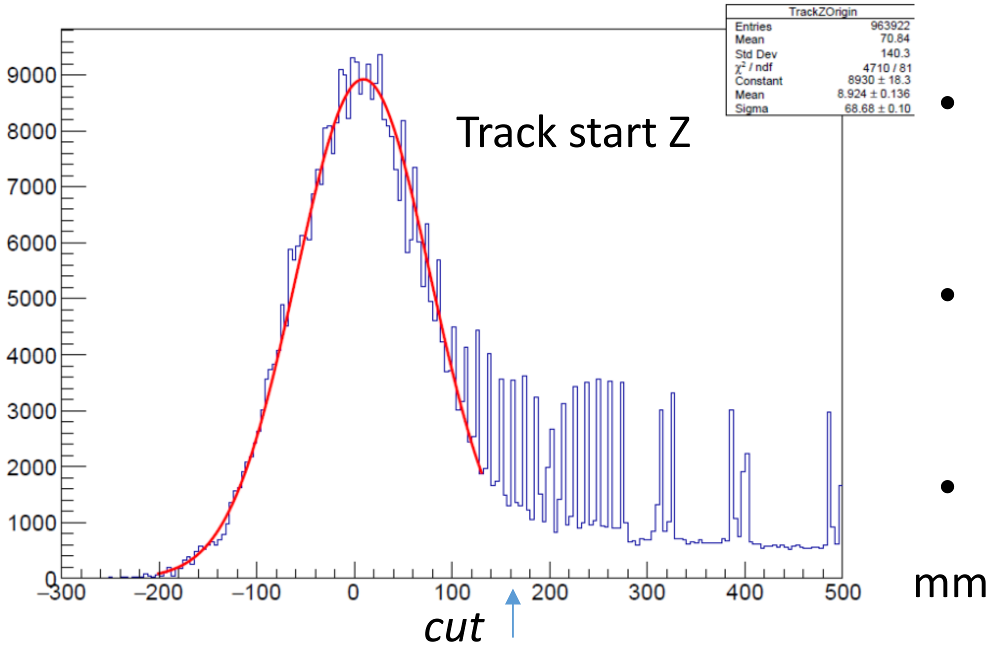

- Tracks which created hits in RICH1 used for illustration

# Track Origin : B-events

No simulation of PV time (old version)



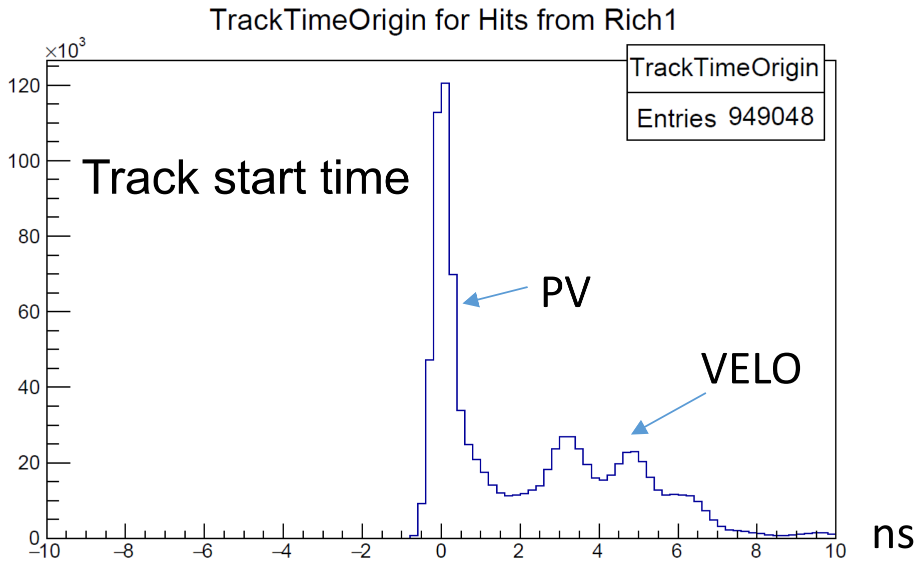



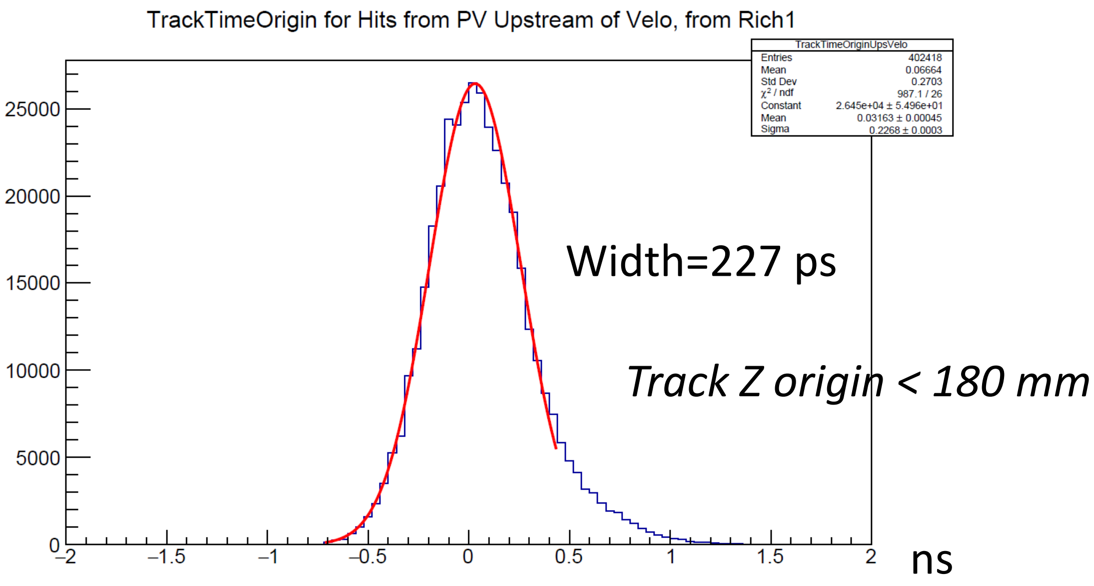



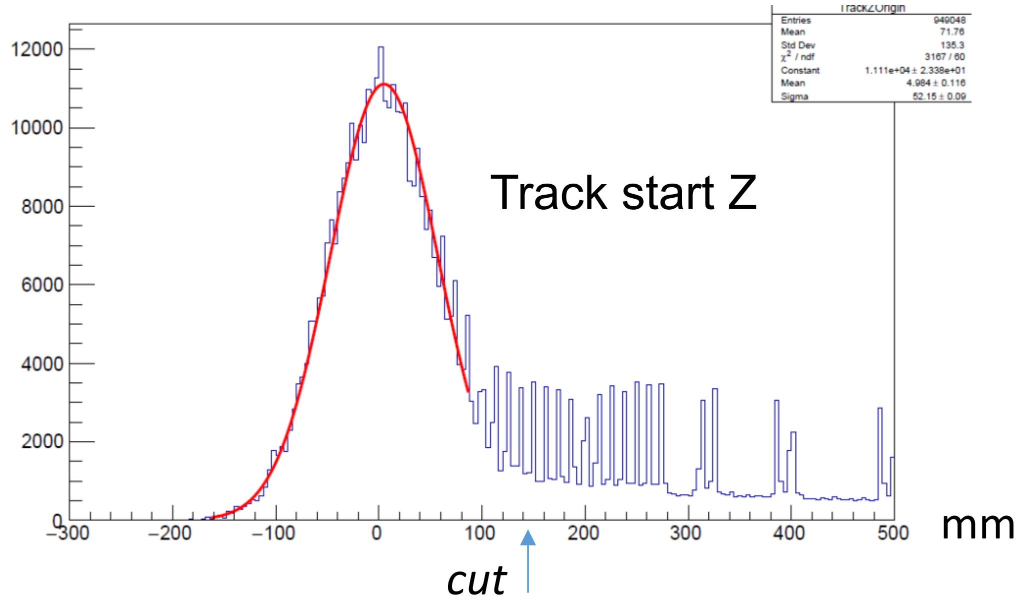

- In this case, tracks start at zero time, when originating from PV.
- Some (secondary) tracks start from VELO structures and locations further downstream, at non-zero time.
- Tracks which created hits in RICH1, used here for illustration

# Track Origin: B-events

## With simulation of PV time

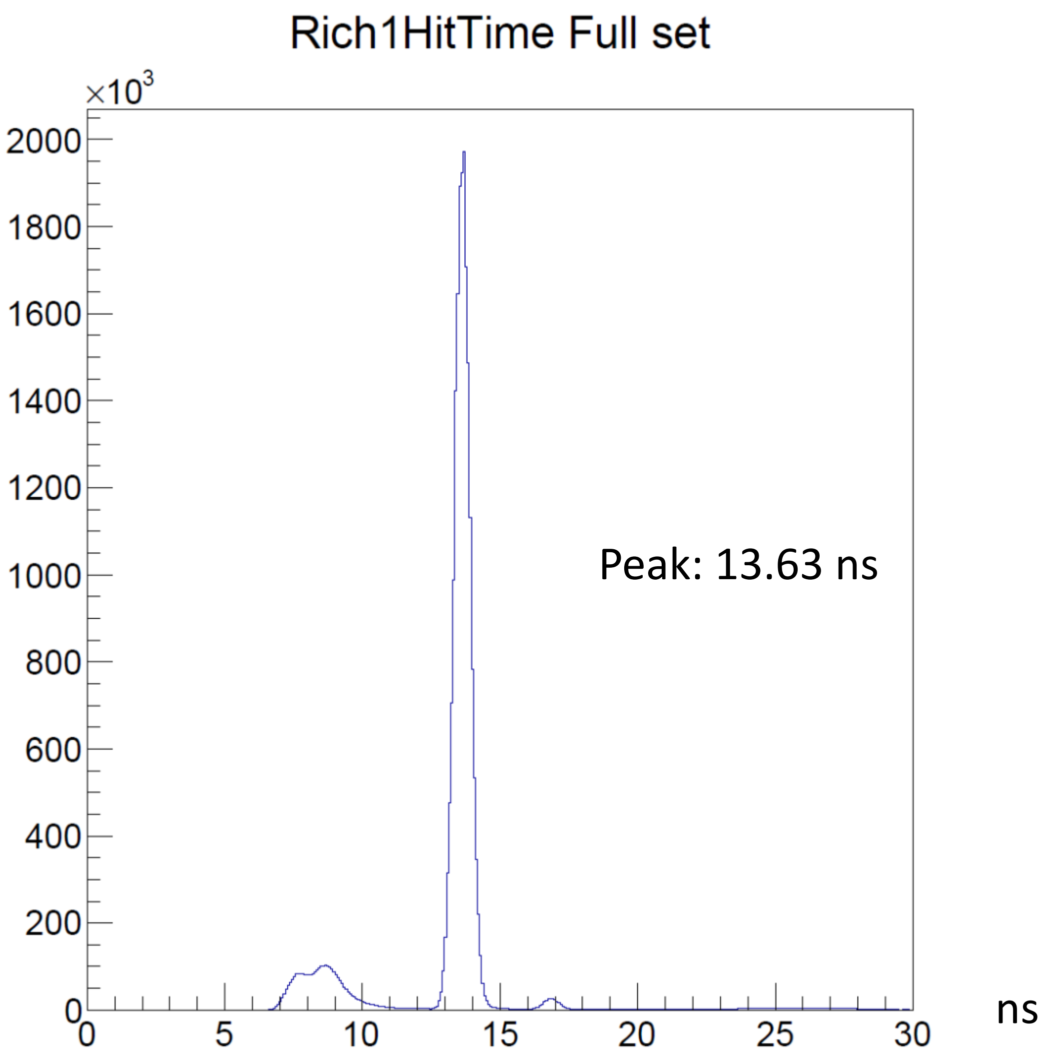


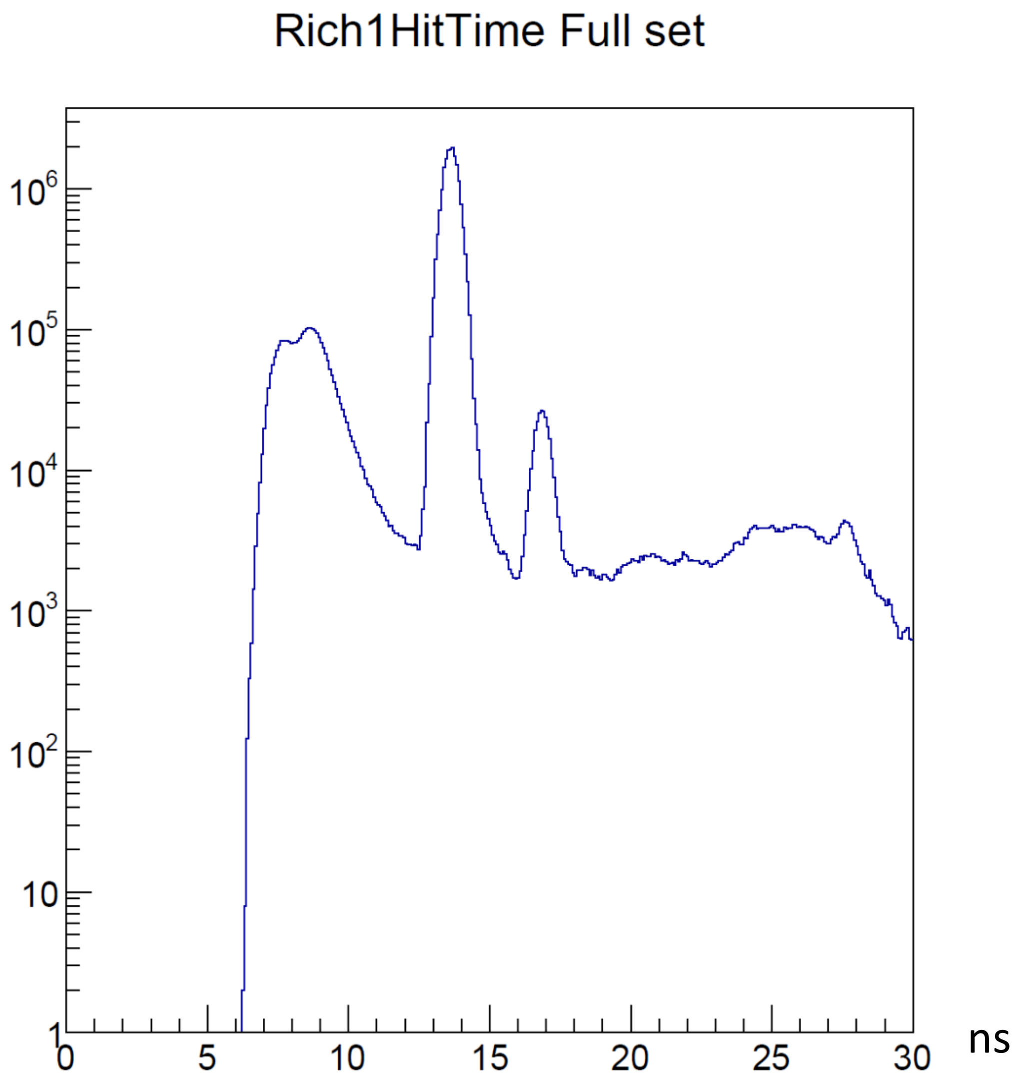




- In this case tracks start at different times , when originating from PV
- Tracks which created hits in RICH1, used here for illustration

# RICH1 Hit Time

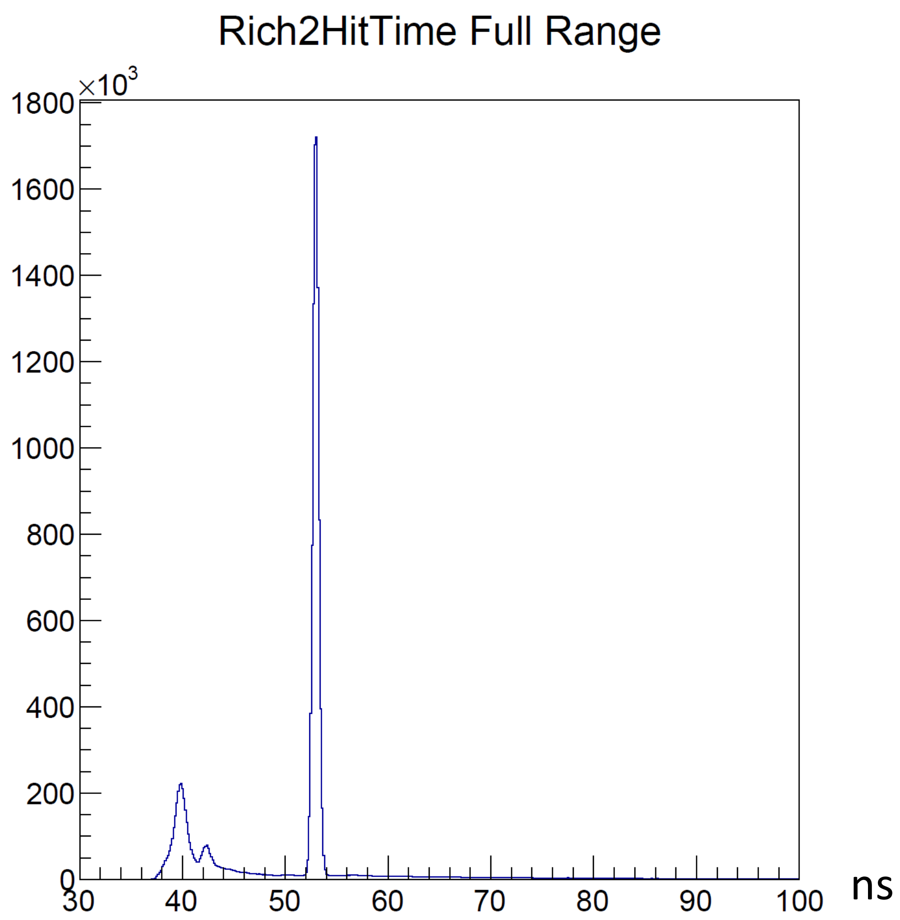


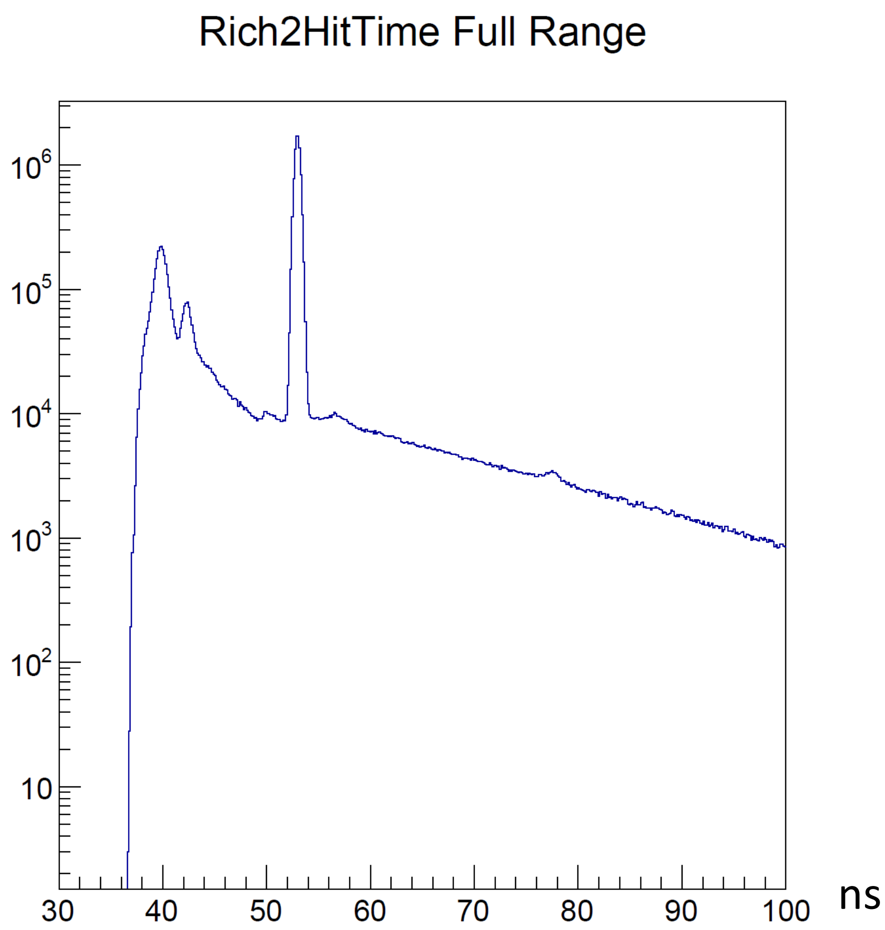




- RICH1 Hit Time in linear and log scales
- Using PV time simulation in B-events

- *Small peaks from multiple reflections, photons taking a shortcut to detector plane etc.*

# RICH2 Hit Time

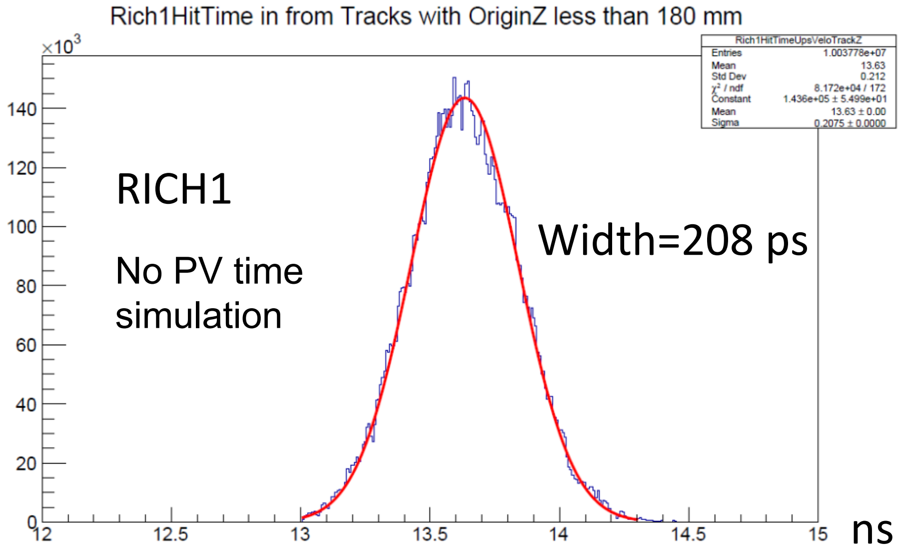


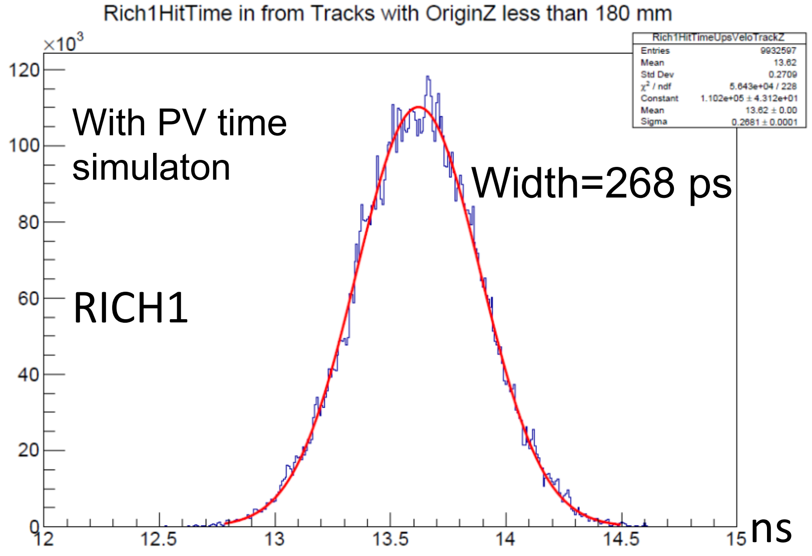



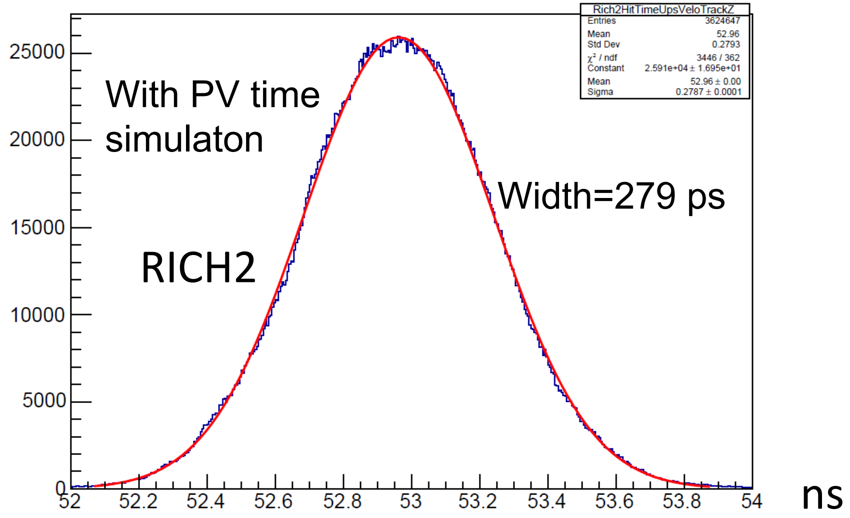

- RICH2 Hit Time in linear and log scales
- Using PV time simulation in B-events

- *Small peaks from multiple reflections, photons taking a shortcut to detector plane, hits from different bunch-crossing etc.*

# RICH  Hit Time



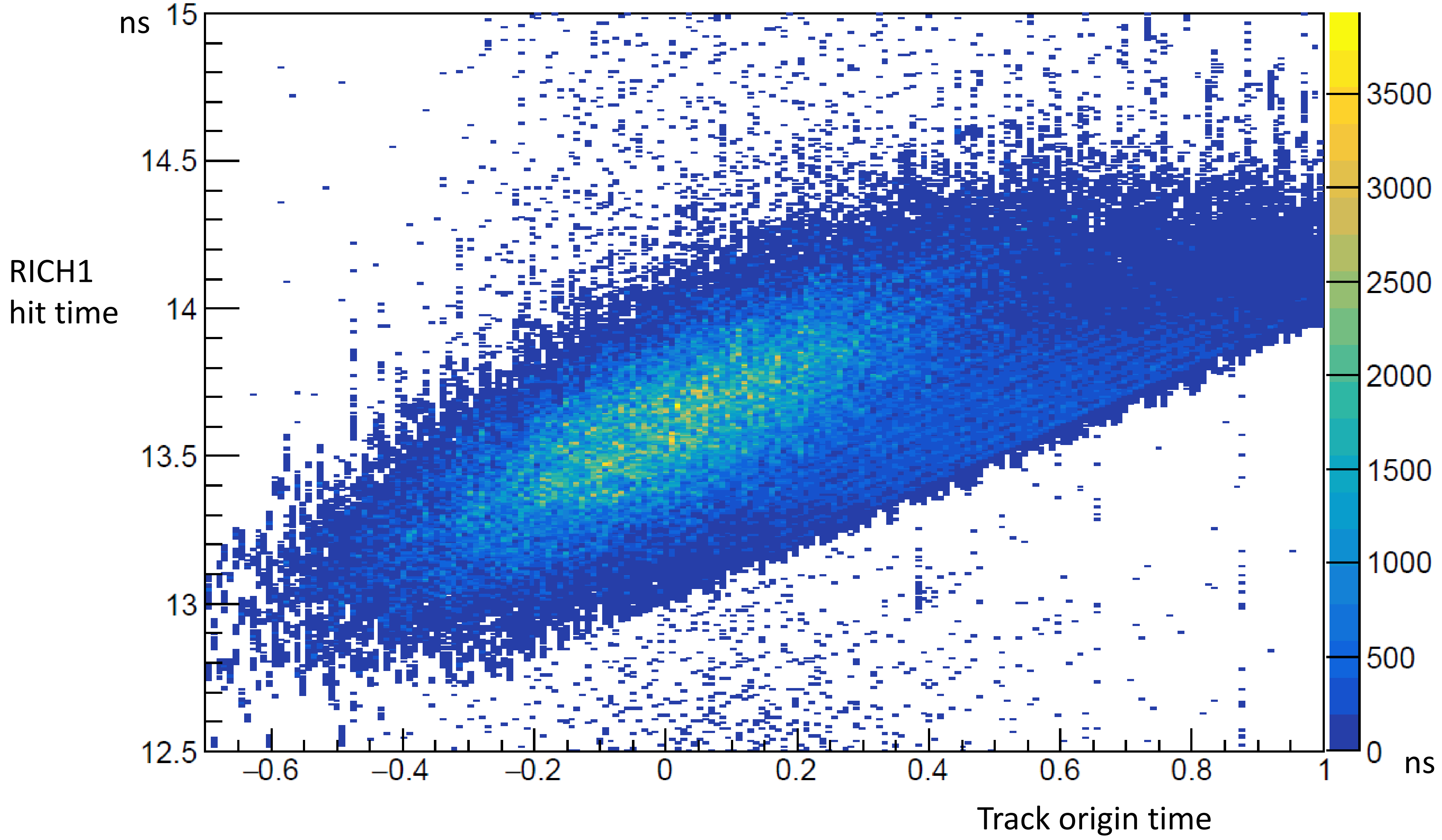

- Using B-events

- Using Tracks with origin Z < 180 mm.

- *Width of PV Time distribution =  227 ps    (from an earlier page)*

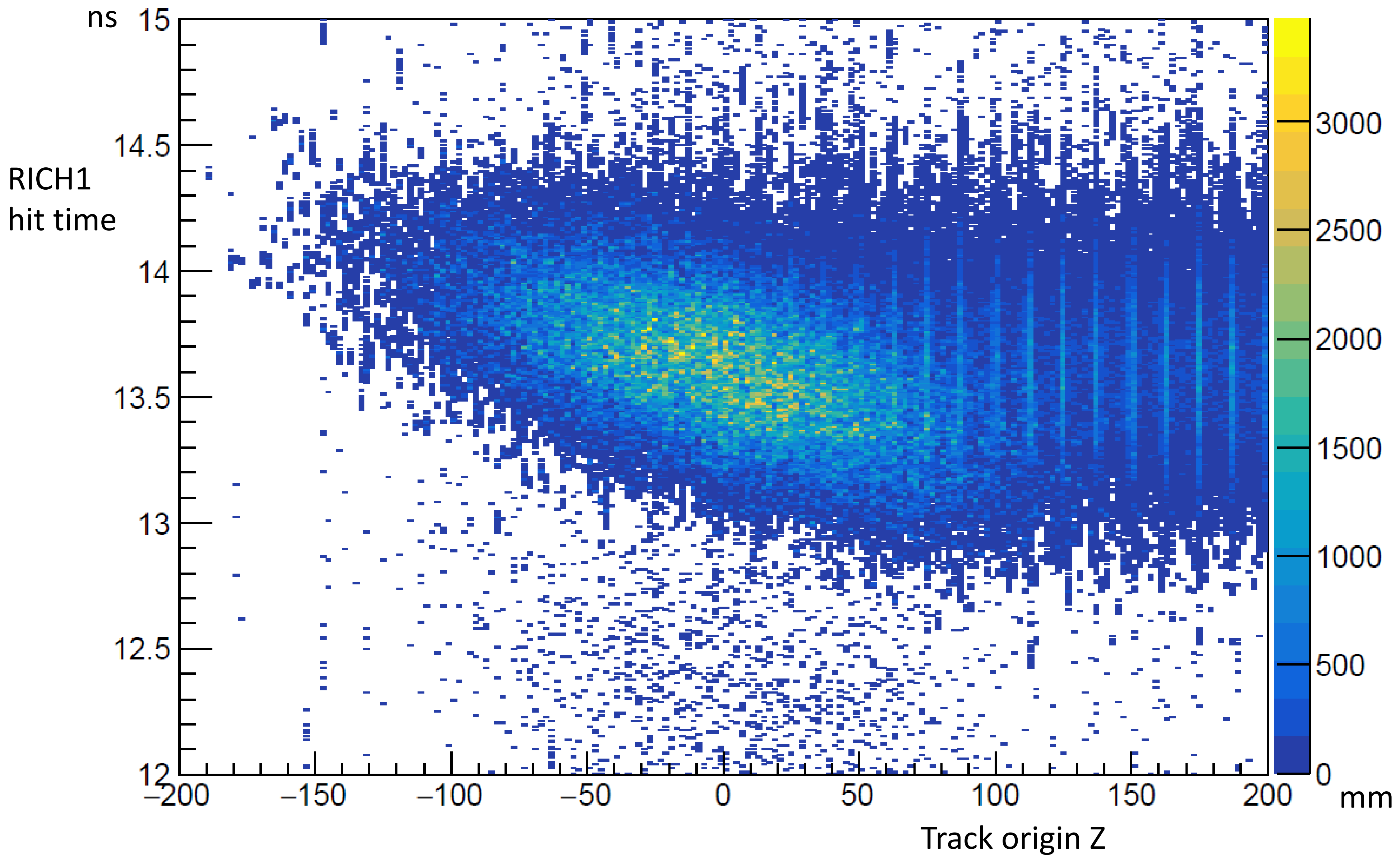
- *The hit times for the different hits from the same track are correlated.*

# RICH1 hit time vs PV time

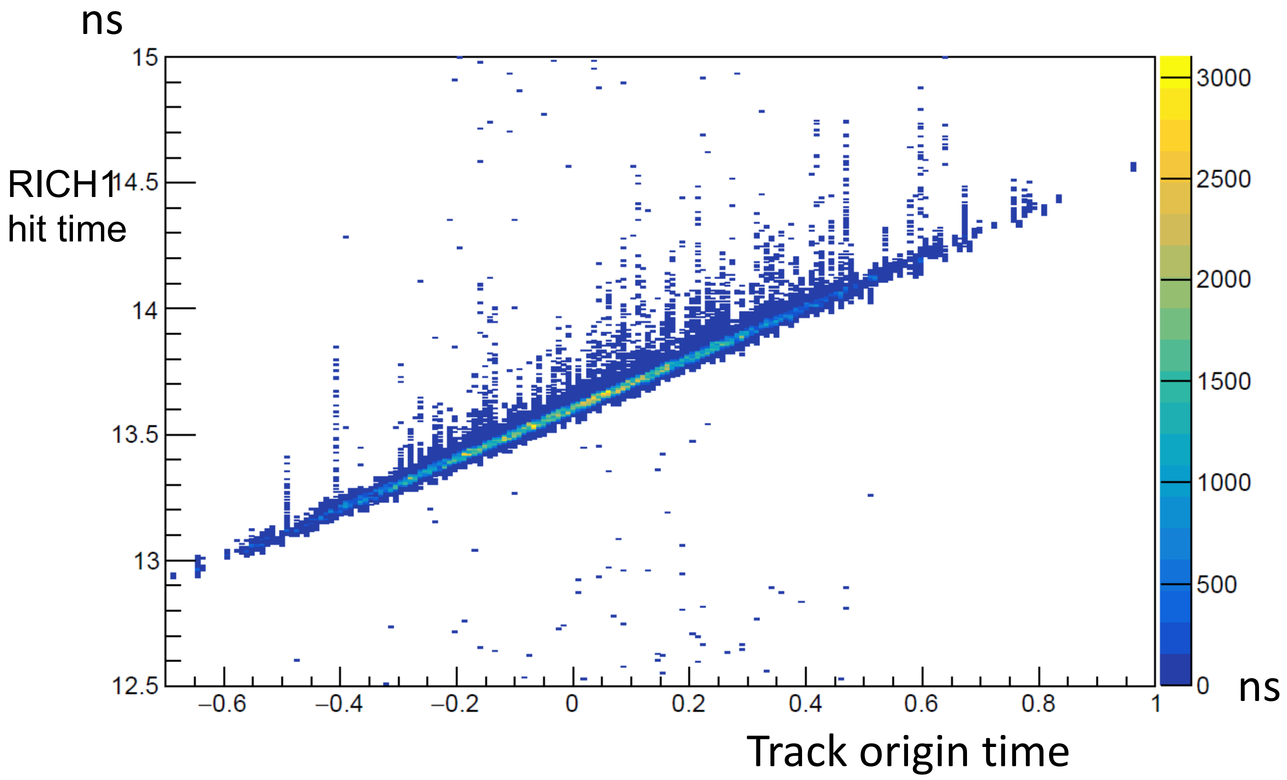


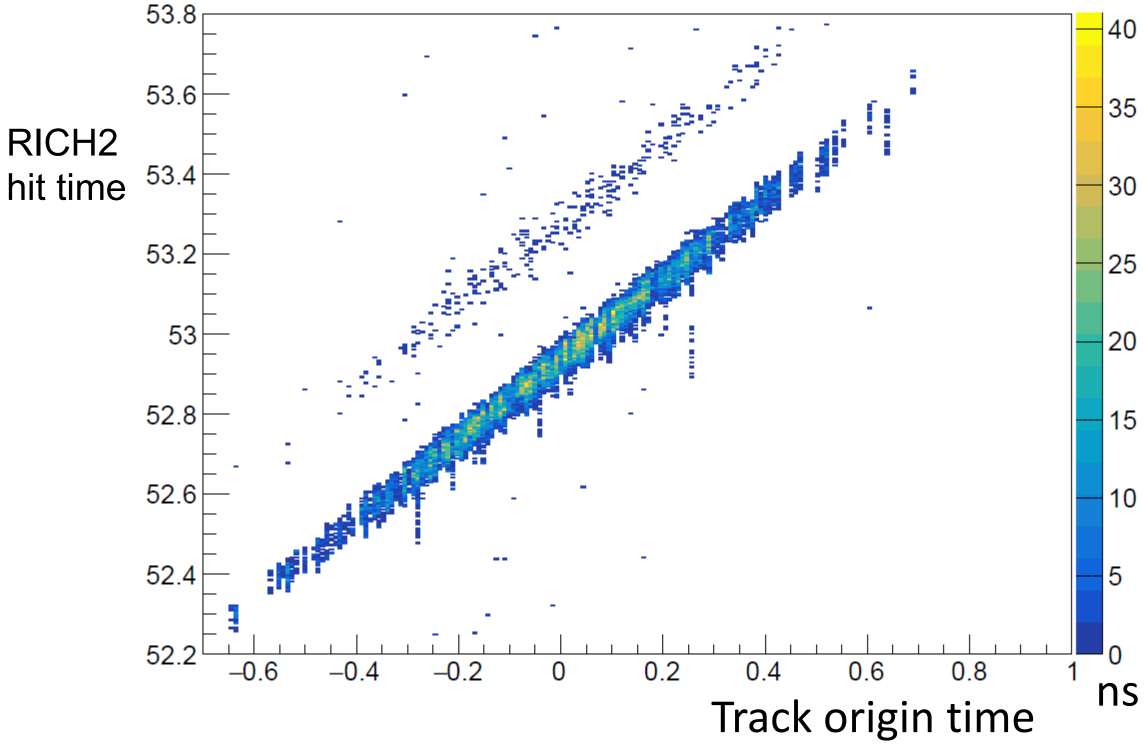

- RICH1 Hit Time correlated to the PV time
- Using the tracks whose Origin Z < 180 mm

# RICH1 hit time vs PV Z



# RICH hit time vs PV time

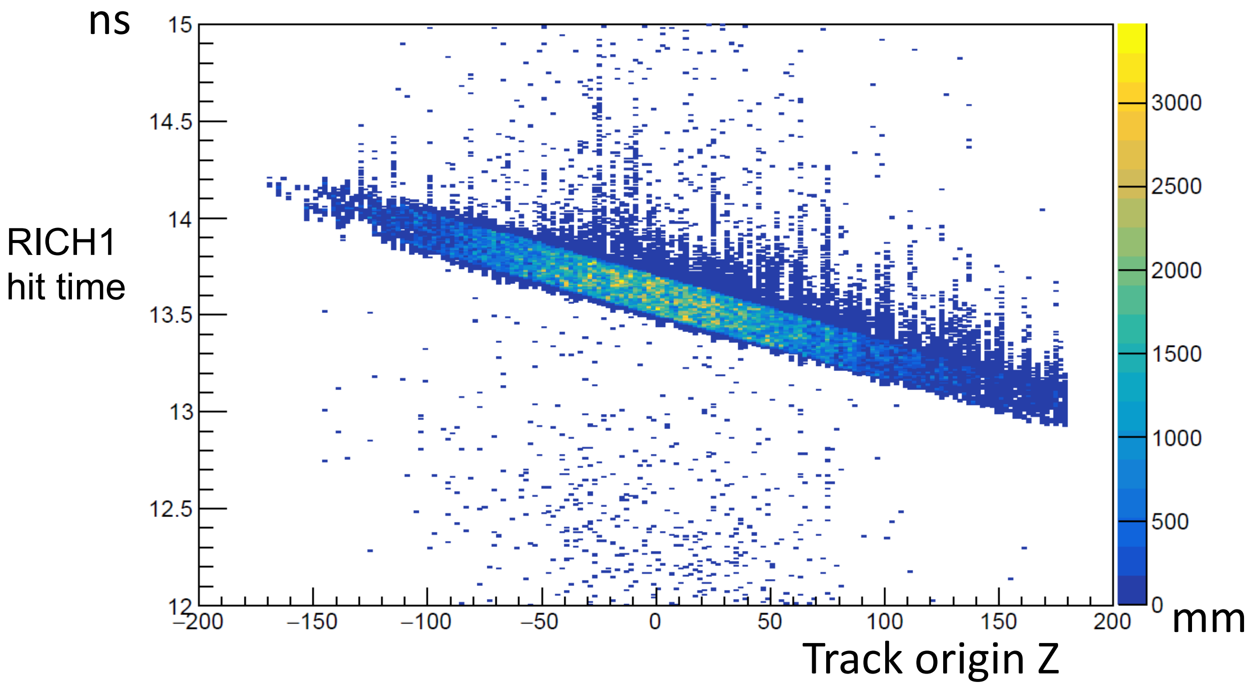


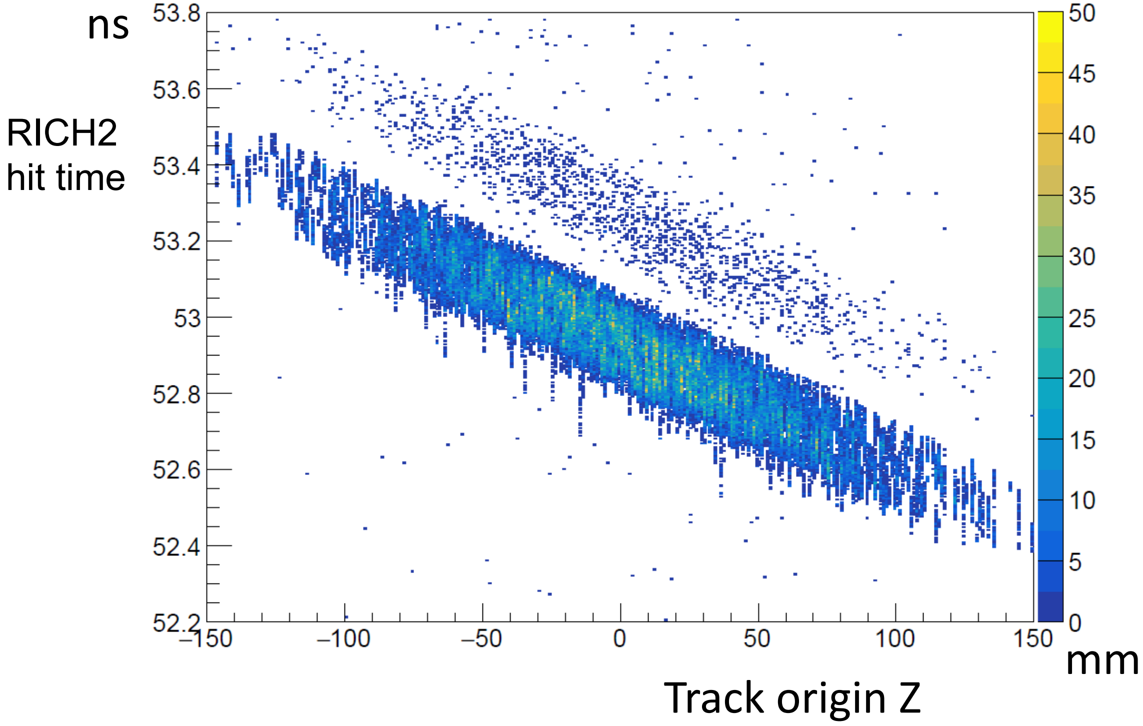




*For RICH2, Tracks with momentum > 50 GeV/c used for illustration*

- *Using the slice -5.0 mm< Track Origin Z < 5 mm*
- *Correlation seen between RICH hit time and PV time within a PV Z slice*

# RICH hit time vs PV Z




*For RICH2, Tracks with momentum > 50 GeV/c used for illustration*

- Using the PV slice -0.1 ns < PV Time < 0.1 ns

- *Correlation seen between RICH hit time and PV Z within a PV time slice*

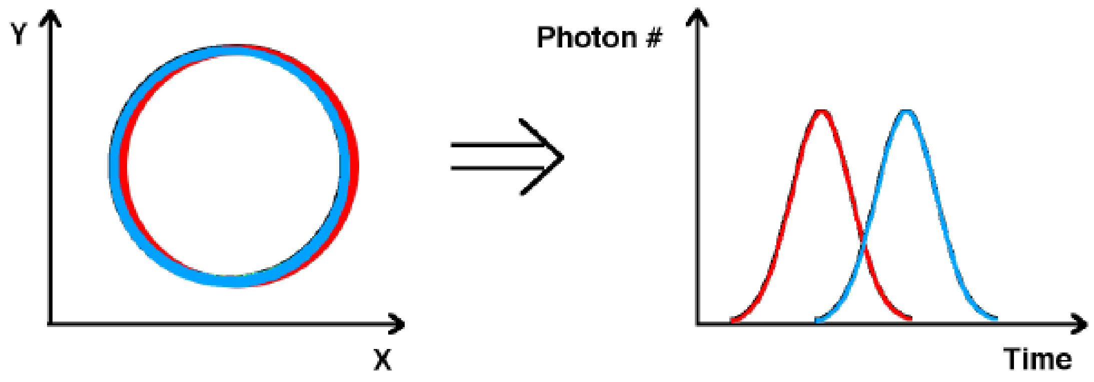
# Plans for using RICH Time

*Floris Keizer*
*Chris Jones et.al.*

- Currently a 'global likelihood algorithm' is used to determine the likelihood of each track to be of each particle type.

- Option 1:
  - *Add the predicted RICH time coordinate in the 'expected photon' distribution*
  - *However this needs the 'track time' , with the help of upgraded VELO for example.*
  - *If this proves to be difficult, we may re-visit the idea of storing these from full simulations.*

- Option2:
  - *Improve the algorithm by using the 'relative' hit time.*
    *(Rings overlapping in spatial coordinates can be distinguished in time.*
    *This is useful in high occupancy regions)*



# Plans for using RICH Time

- Proof-of-principle measurements with SiPM + CLARO in laboratory setup:

  *Cambridge, Edinburgh, Milano, CERN, RAL, Genova et.al.*

  *Previous tests : C.Gotti et. al. JINST 8 C01029 (2013)*

*Stephen Wotton ,*
*Floris Keizer et.al.*

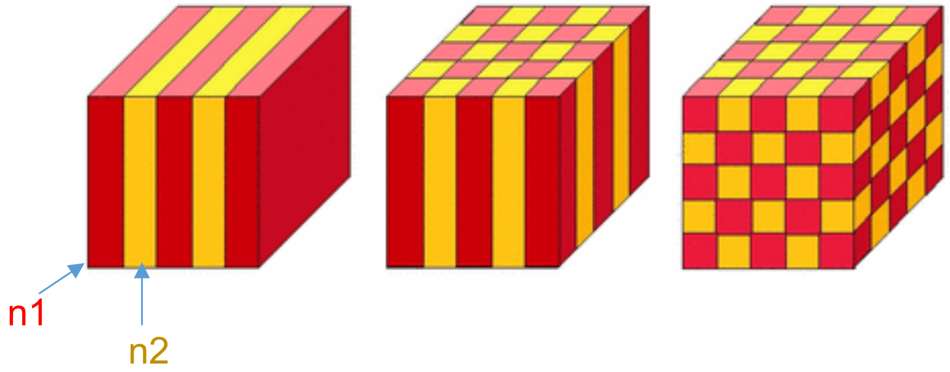
- A time resolution down to 1 ns can be achieved by
  FPGA based RICH upgrade digital boards. (Kintex 7 FPGA)
  This can help to reject hits outside a narrow window around the signal

- It is planned to use dedicated firmware with improved time resolution, at Cambridge.
  This is to allow the optimization of up to 8 channels on the digital boards to
  sample with a 150-200 ps time resolution

- Future upgrade will require redesign of the digital readout, with the implementation of
  an ASIC or FPGA with TDC.

# Using novel radiators

- Starting from two media with ref. index n1 and n2, create a new effective ref index n3
- Design an effective  ref. index from thin layers of materials.
    - *This can overcome some of the basic limitations related to chromatic and  emission point errors*
    - *Thin radiator would free up large amount of space taken up  by  the gas radiators.*
- Using photonic crystals for this, is being  investigated
    - *RICH-2016 conference : September 2016*

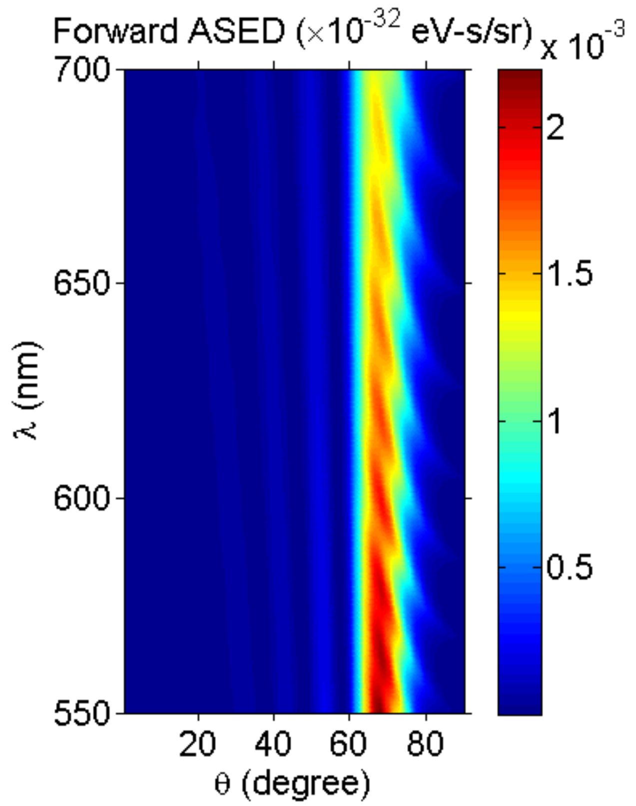


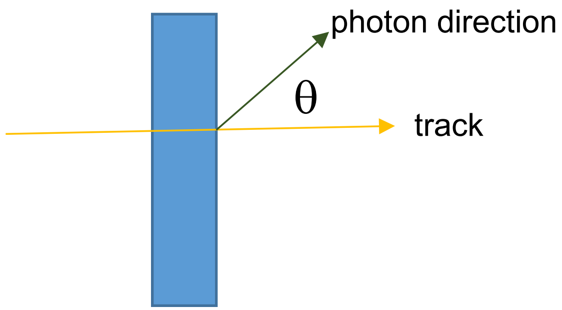

- Technology to produce them exists in the industry
    - *It is already  used  in some smart phone displays*

# Using novel radiators

- R&D in progress at CERN:
  - Few samples obtained from industry
  - Work in progress towards testing them in the lab and in test beams
  - Results from these tests to help design custom made samples.

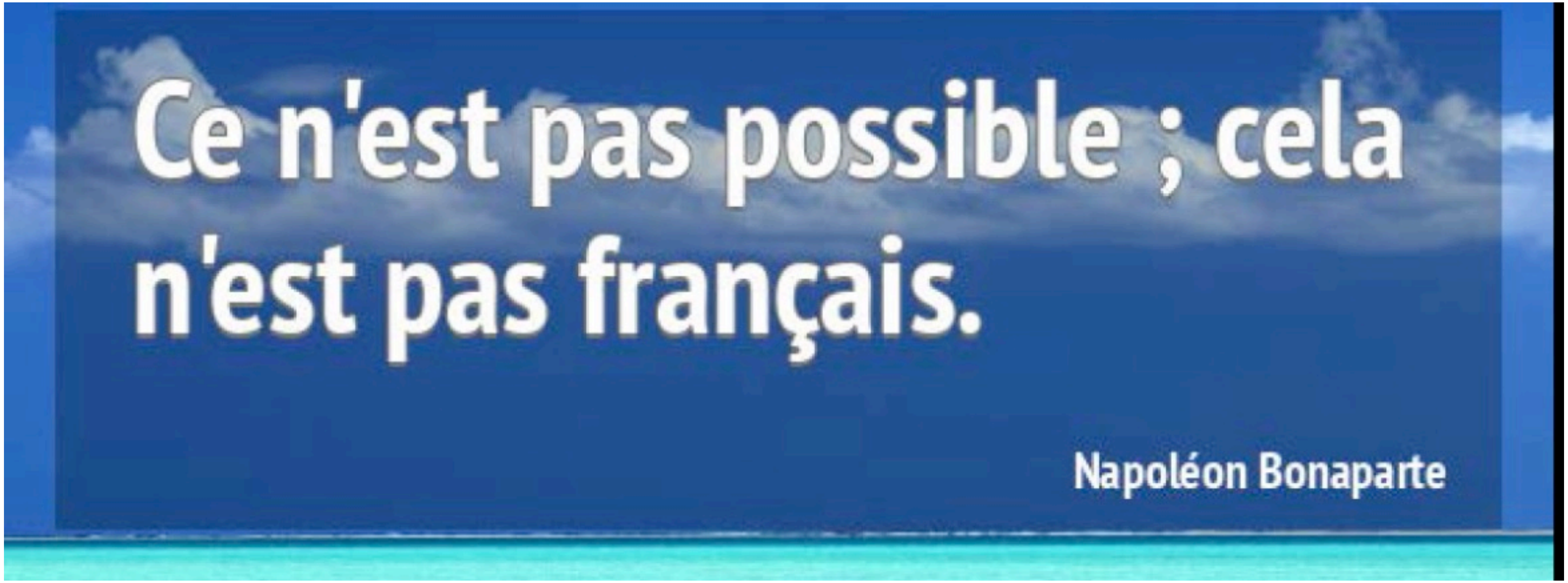
- Properties of an early prototype (1D crystal):
  - Single sheet thickness : 250 nm X 16 layers = 4 micron
  - Expected 'effective' Cherenkov angle ~ 65 degrees



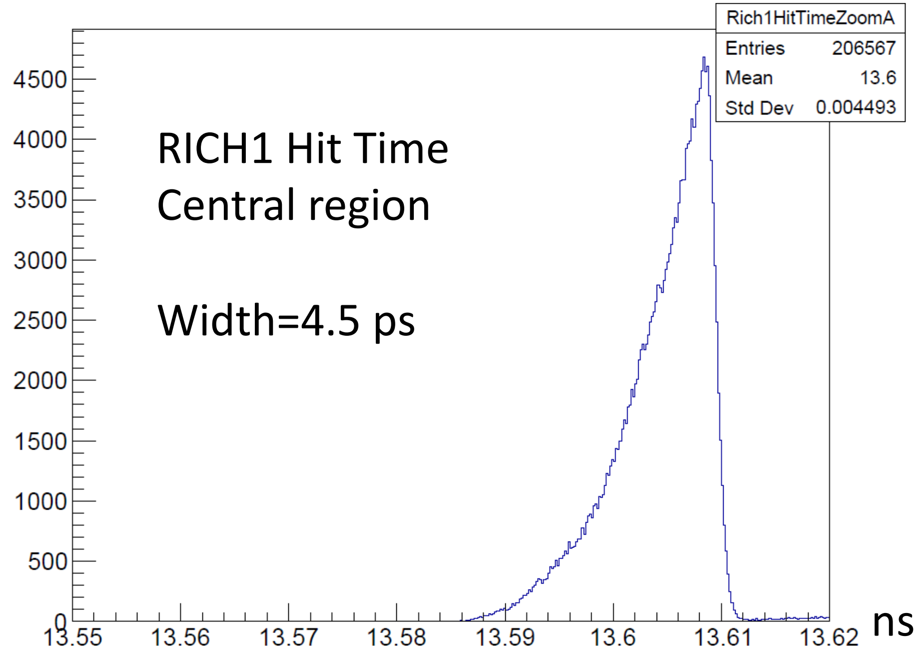
# SUMMARY

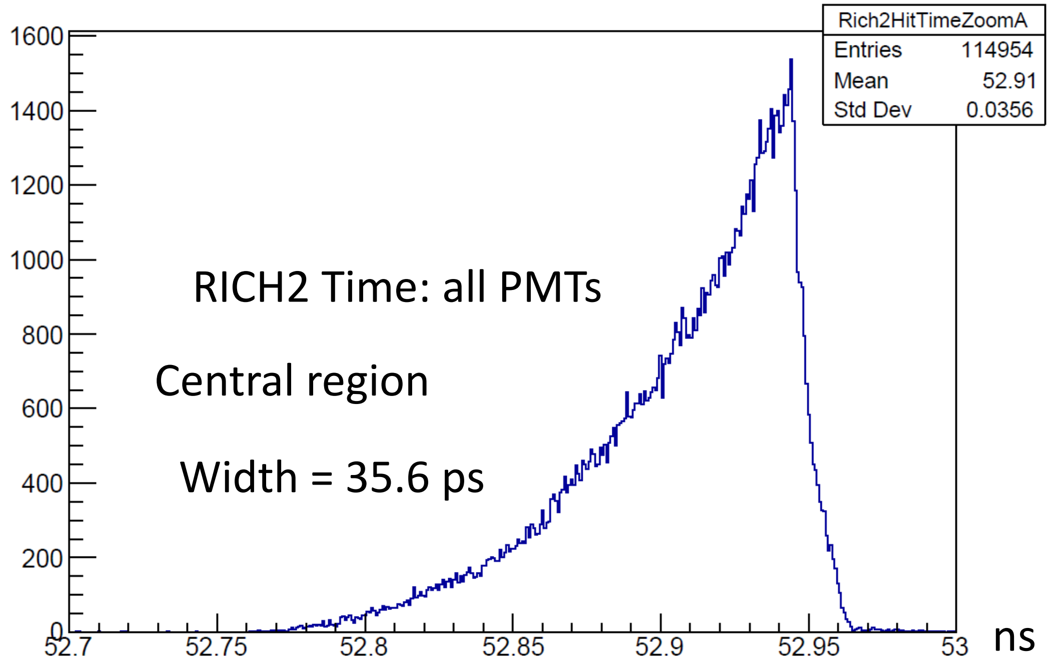
- R&D is in progress towards improving the  performance of the RICH system
- Using SiPM as photodetector is one of the ideas under consideration
- Feasibility studies started towards geometry modifications
- Using  RICH time information is a promising avenue. R&D to test this are being planned
- Work started in preparing the tests with prototypes of novel radiators

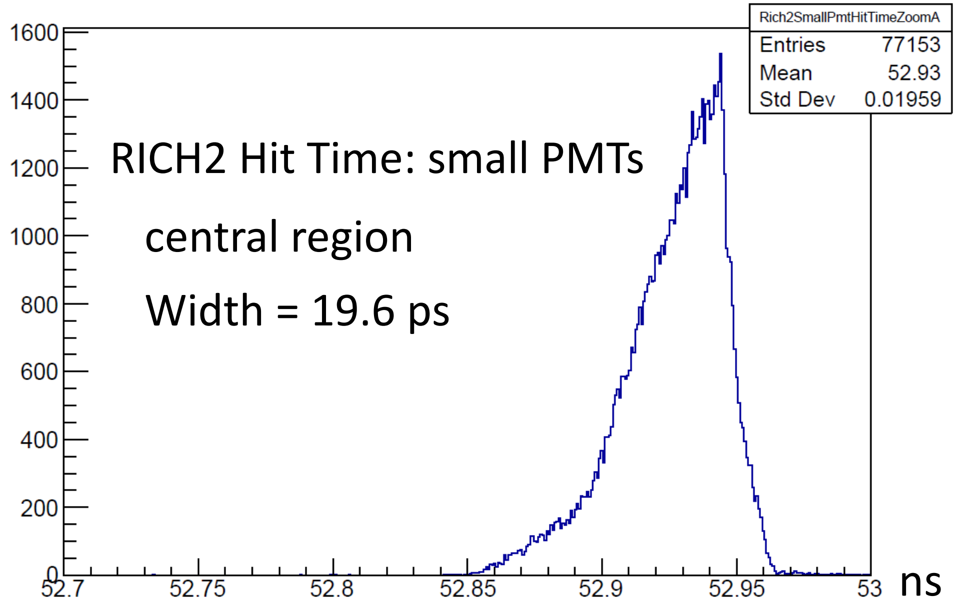

Ce n'est pas possible ; cela n'est pas français.
Napoléon Bonaparte

# EXTRA SLIDES

# RICH Hit Time : particle gun

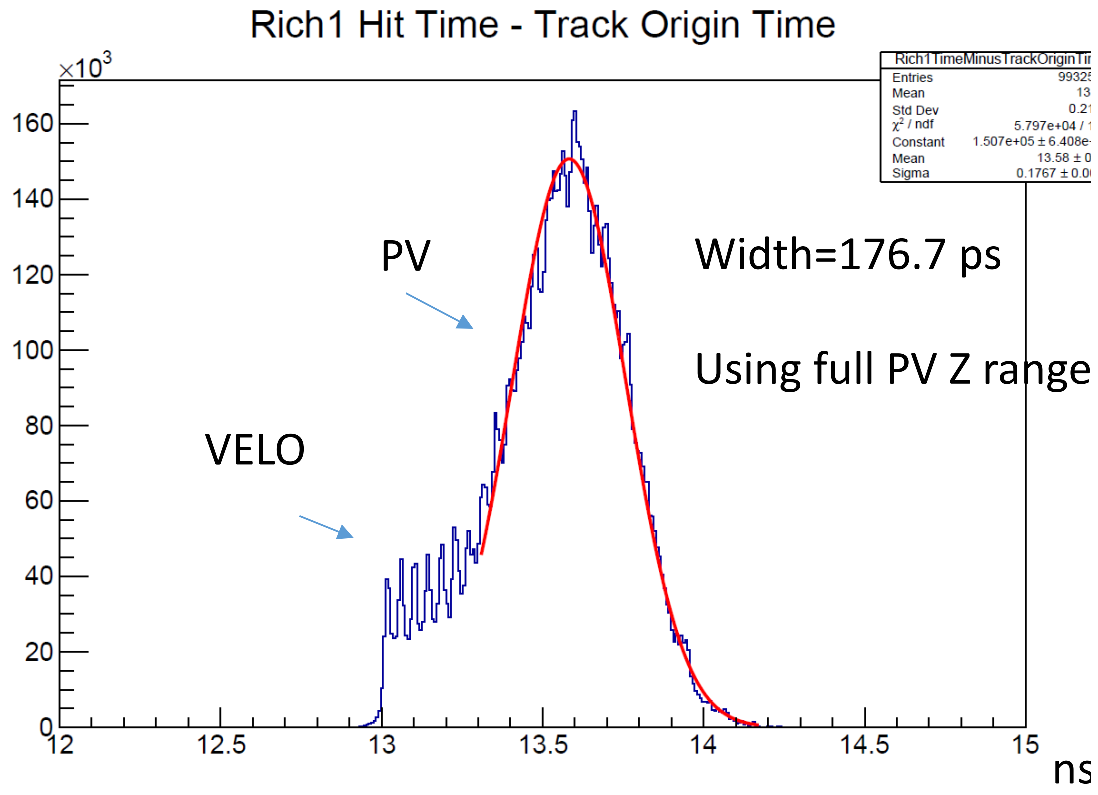


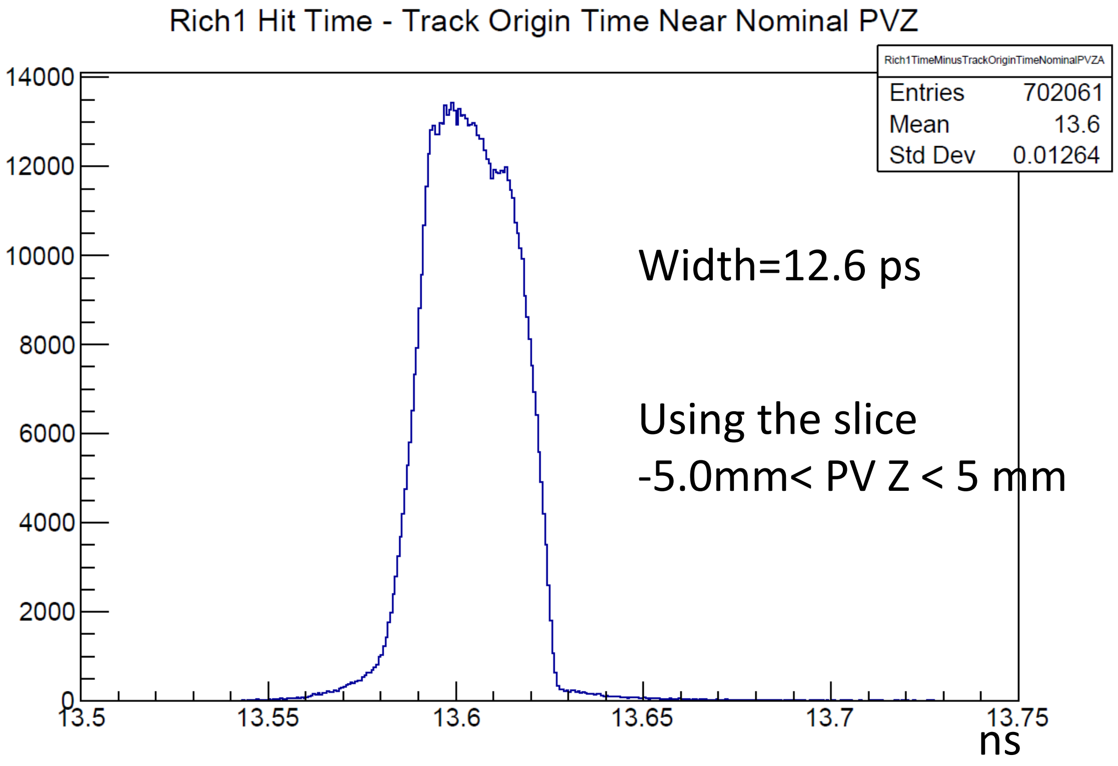




- Intrinsic width of RICH hits in time in its central region of each RICH
- Tails due to the finite size of ‘flat detector plane’ considered (part of ‘emission point error’).

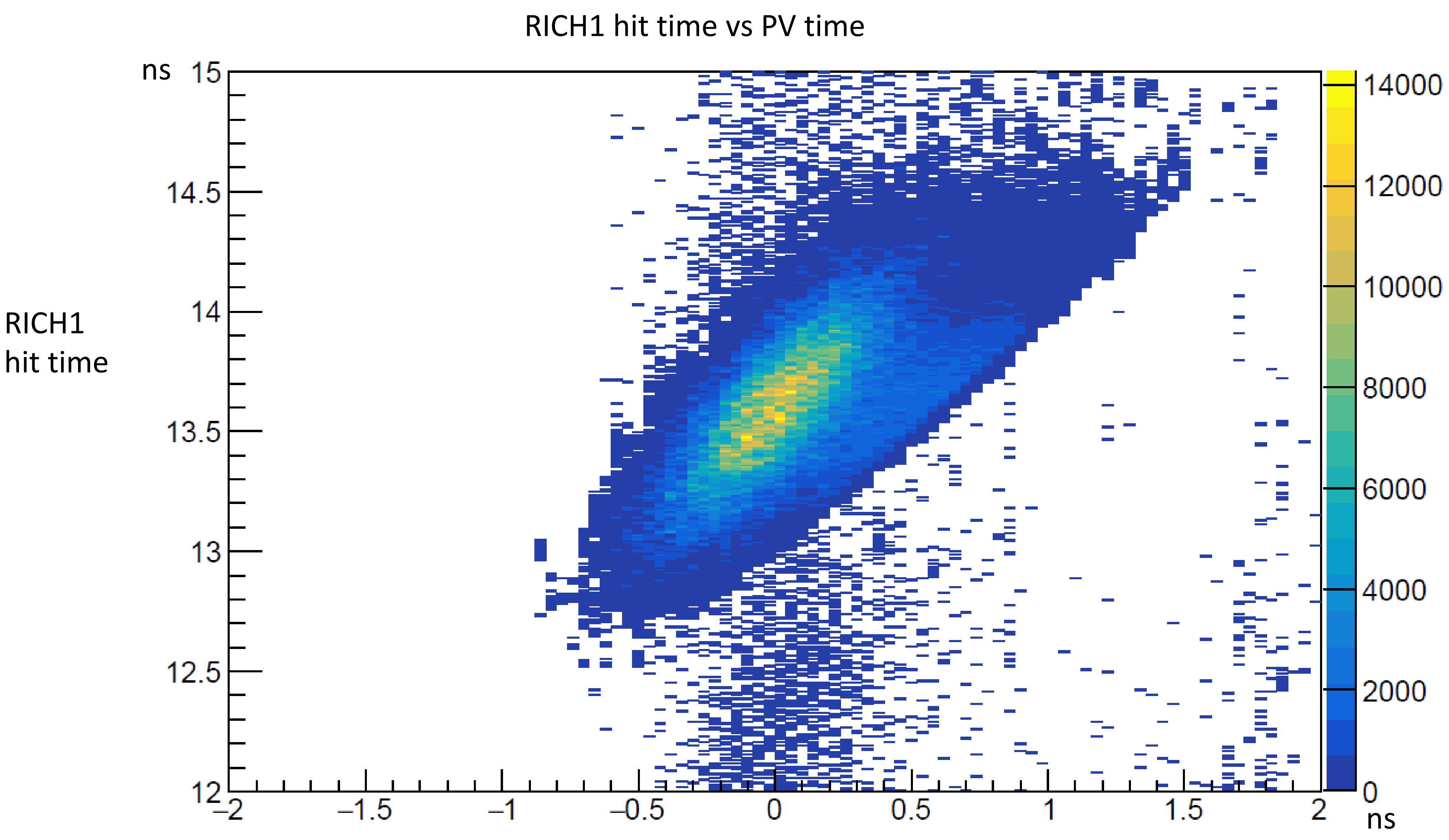
# Using Slices of PV



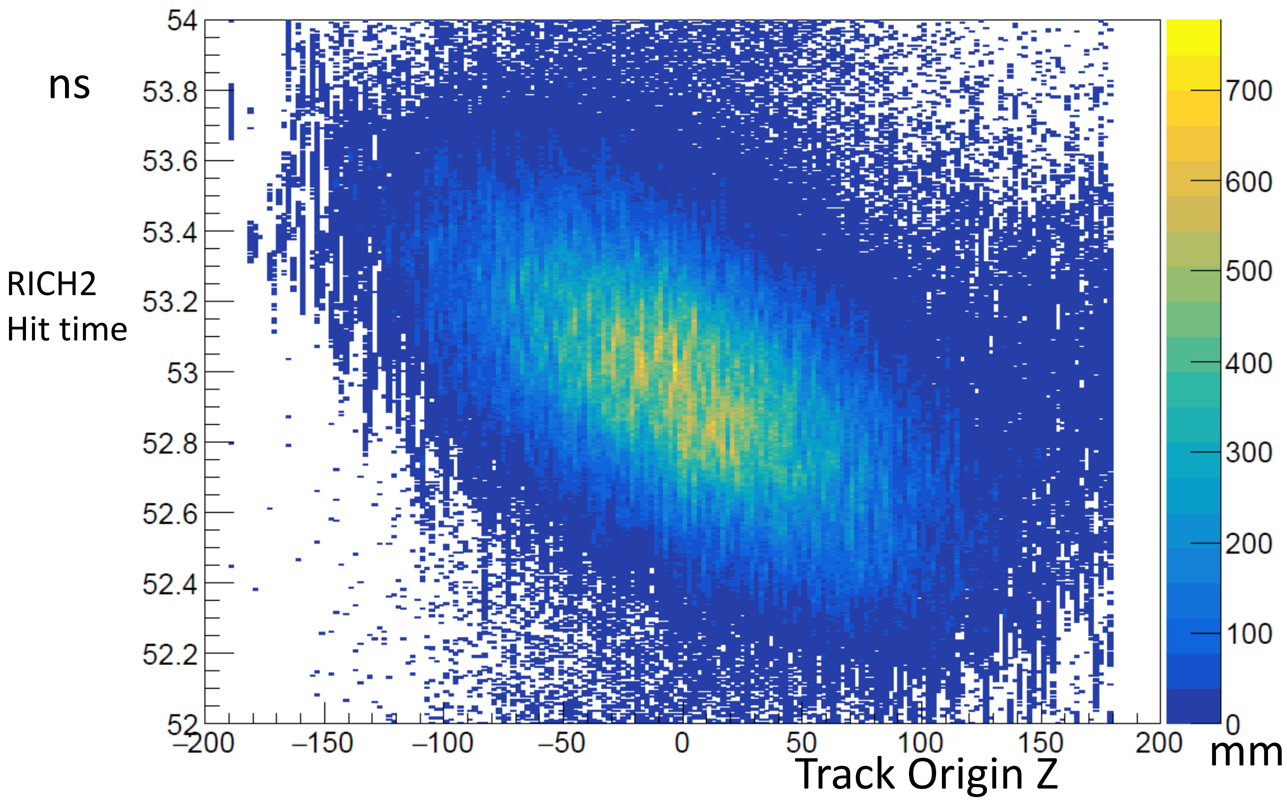

Left Plot: Width dominated by width of PV Z

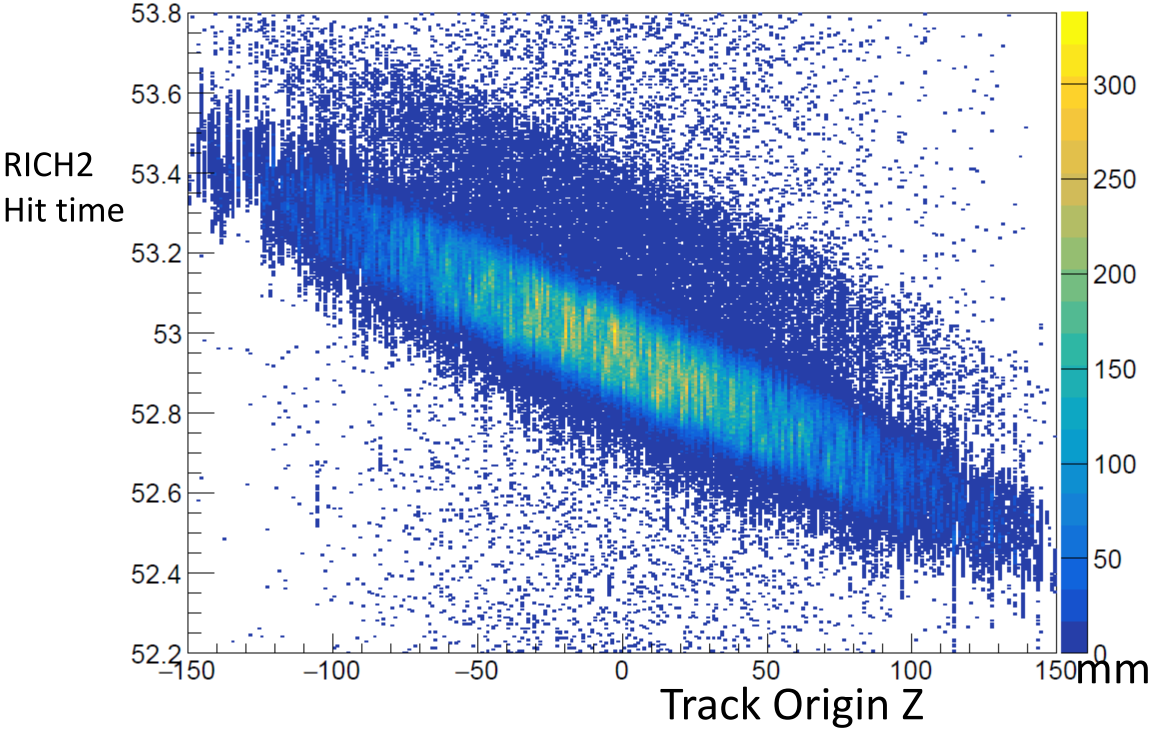
Right Plot: Width dominated by intrinsic RICH1 Time resolution




- RICH1 Hit Time correlated to the PV time
- Using the tracks whose Origin Z < 180 mm

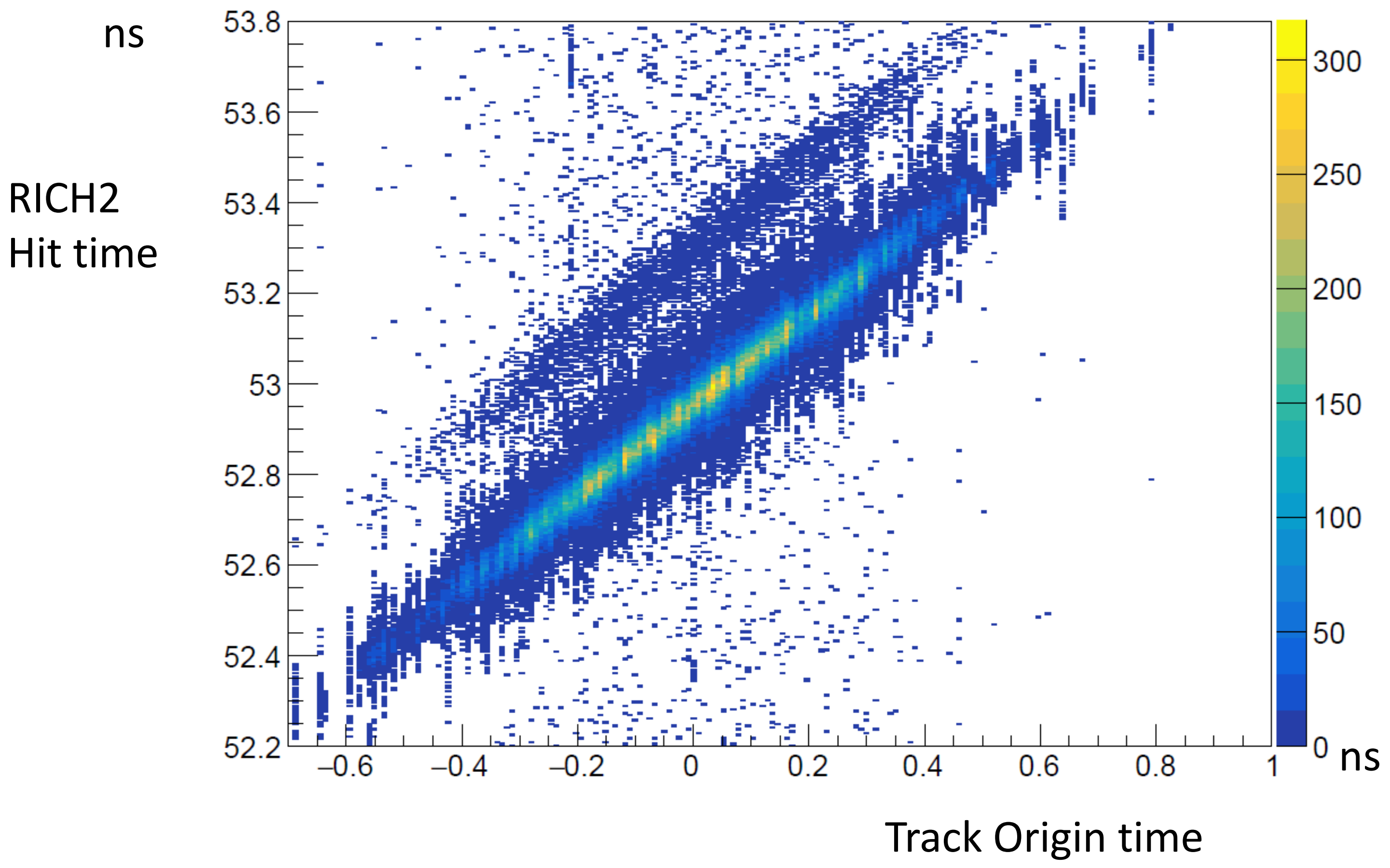
RICH2 Hit time vs PV Z



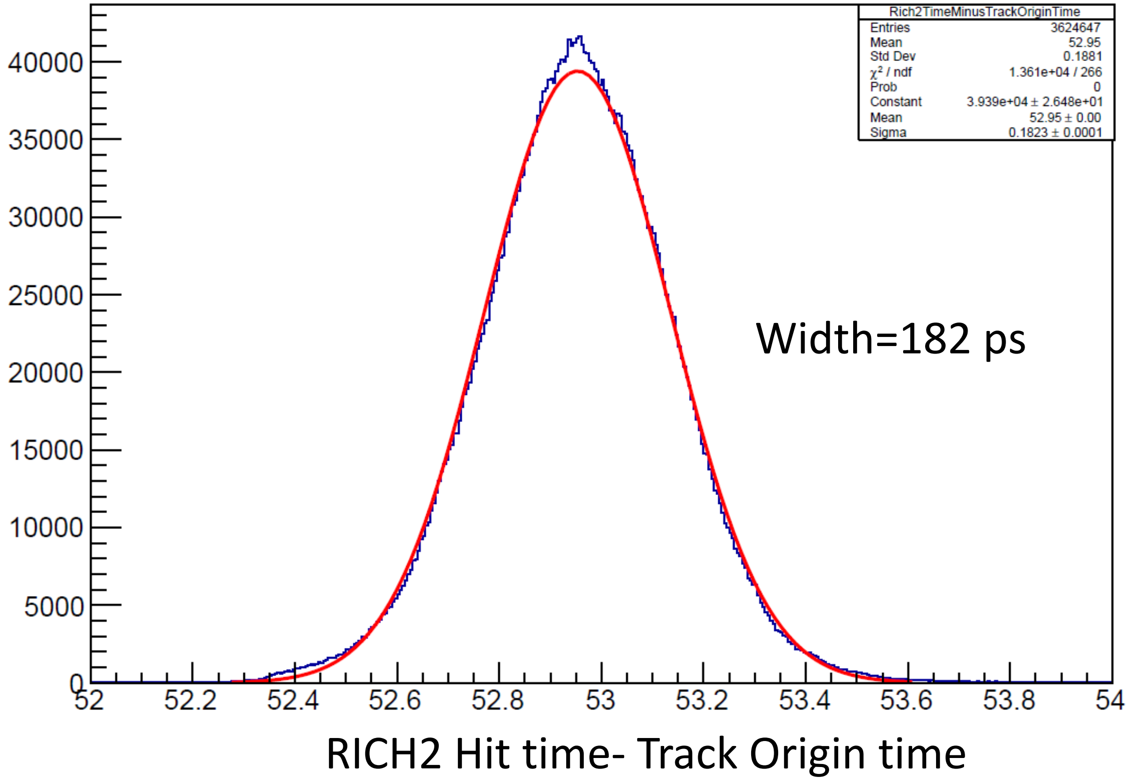

- Using all PV
- Using the PV slice -0.1 ns < PV Time < 0.1 ns

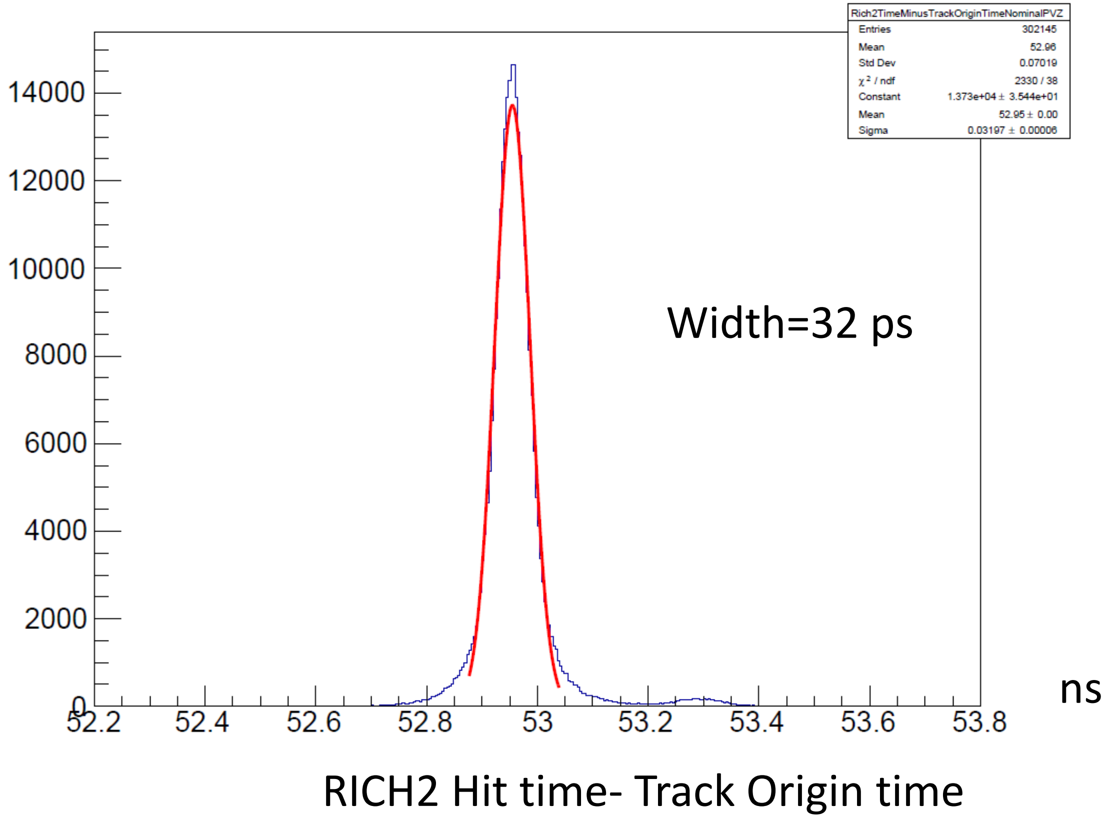
# RICH2 Hit time vs PV Time




- *Using the slice -5.0 mm< Track Origin Z < 5 mm*

# RICH2 Hit Time:  B-Events



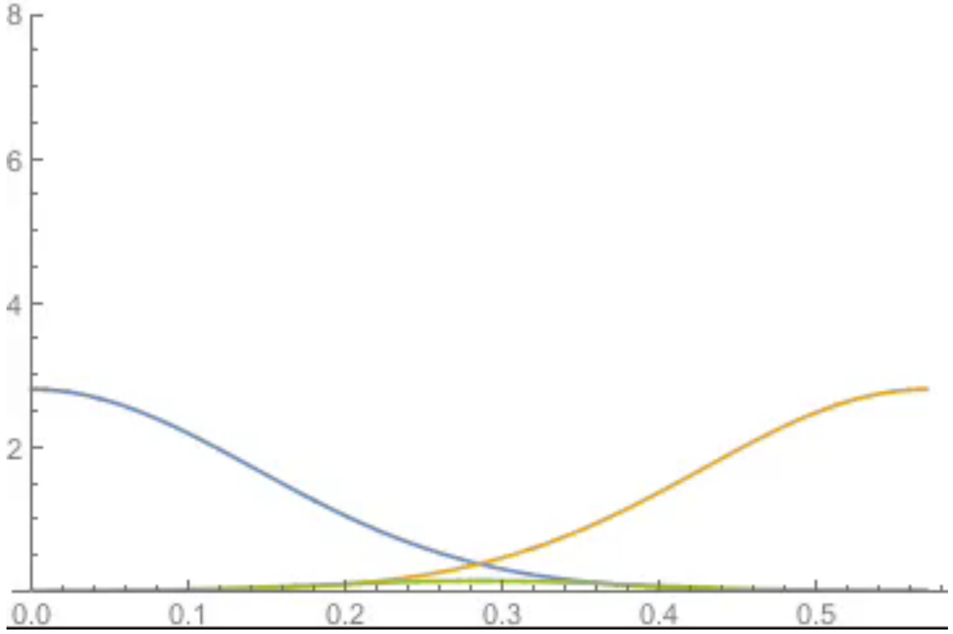

- Using all tracks   with OriginZ < 180 mm

- For the -0.5 mm< Track Origin Z < 0.5 mm
- The width dominated by intrinsic RICH2 time resolution

# New version: product of Gaussian bunches

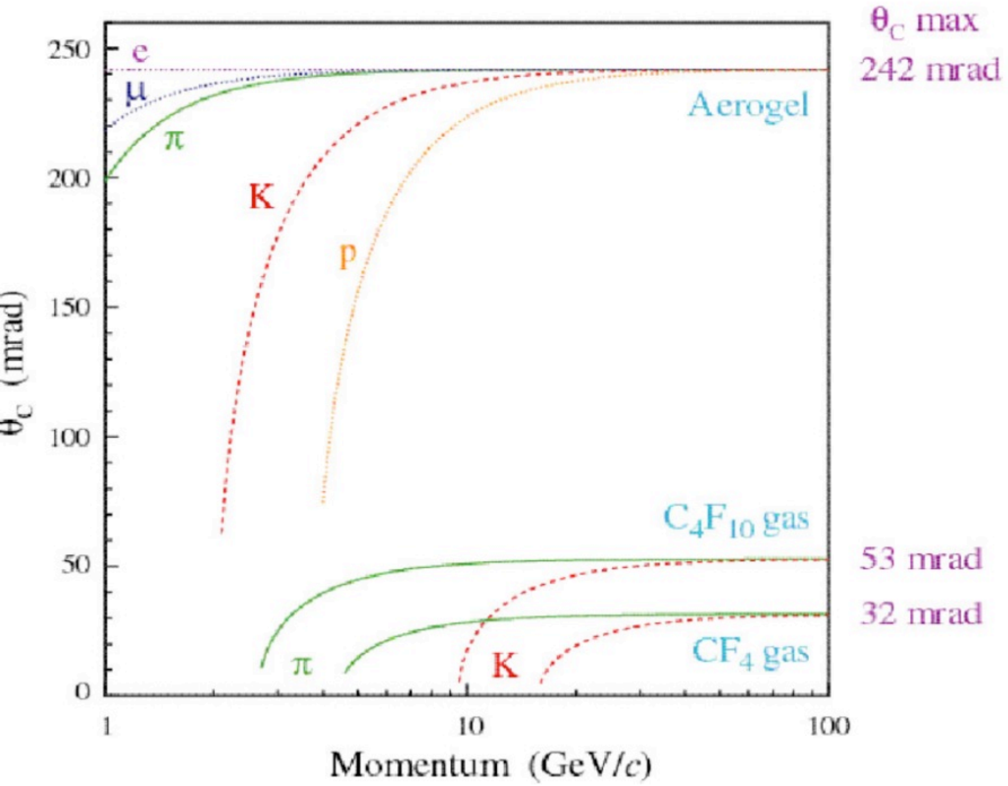
1. 4D PDF for primary vertex: product of two *moving* 3D Gaussians.
2. Sample from the 4D distribution using a Markov chain.

The 1D case looks like:

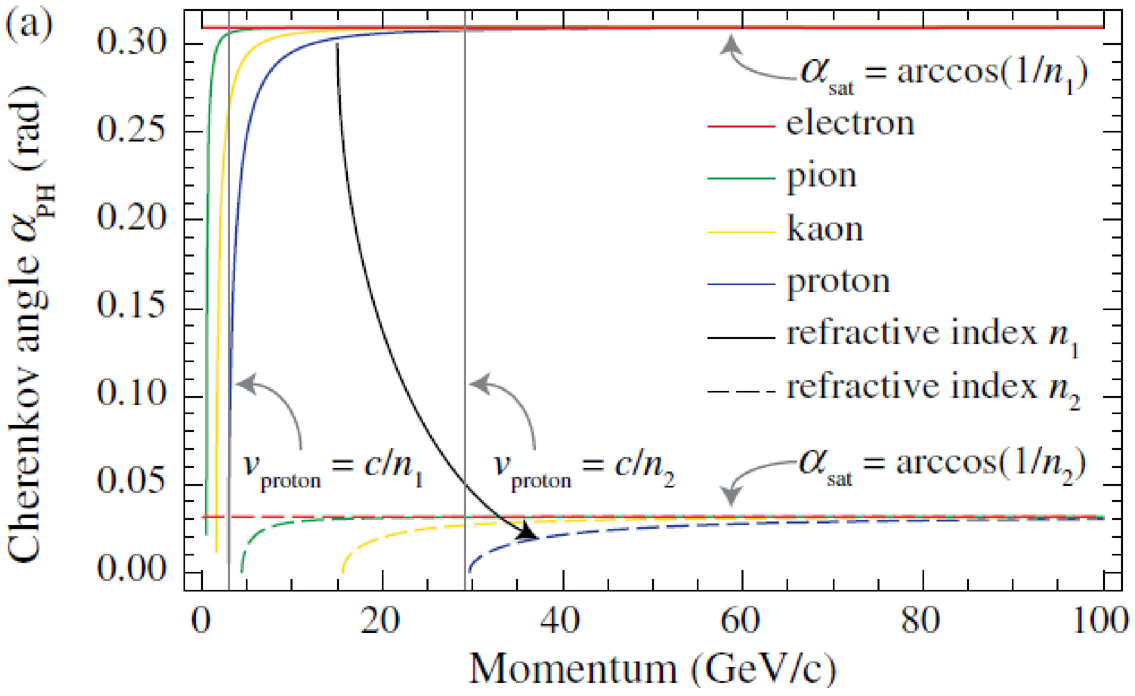


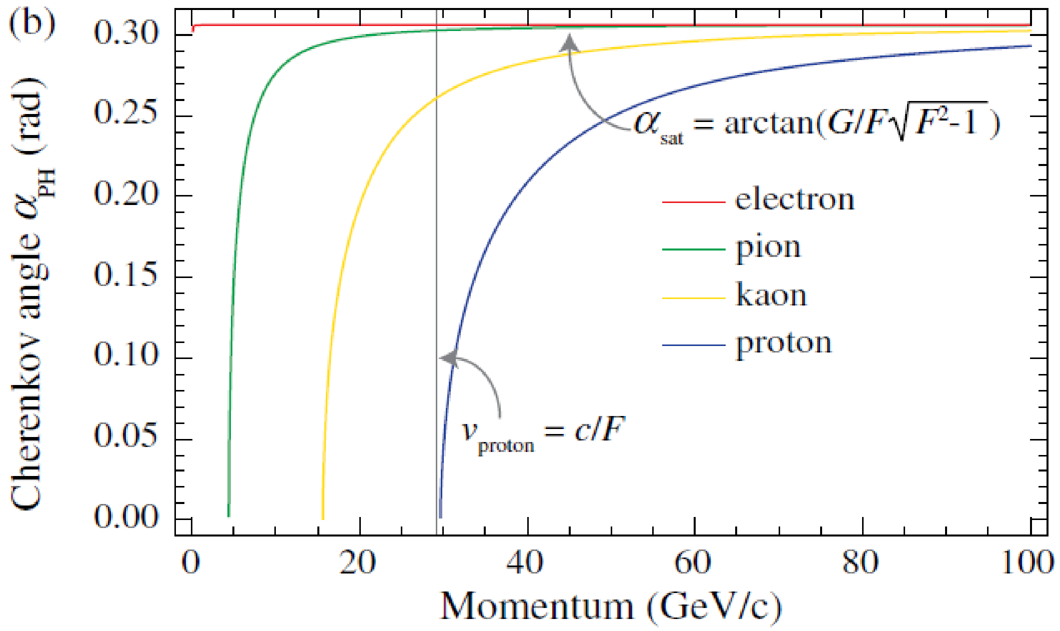
# Particle Identification

*PRL 113, 167402 (2014)*




*RICH1 EDR: LHCb-2004-121*




Sensitivity= $\theta_{\text{eletron}} - \theta_{\text{proton}}$

Transformation optics:

Longitudinal stretching=F=1.005 : Shift curves to right
Transverse stretching = G=10 : Increase $\theta$