

Test beam of a real-scale prototype of the ePIC-dRICH detector

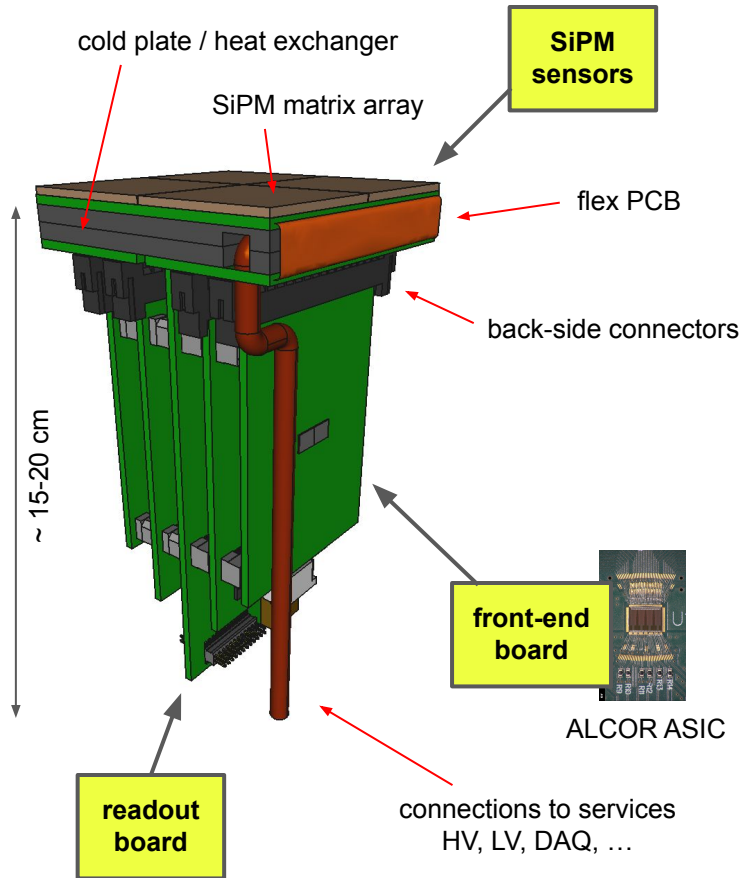
Photodetector and performance results

Roberto Preghenella
INFN Bologna

the photodetector

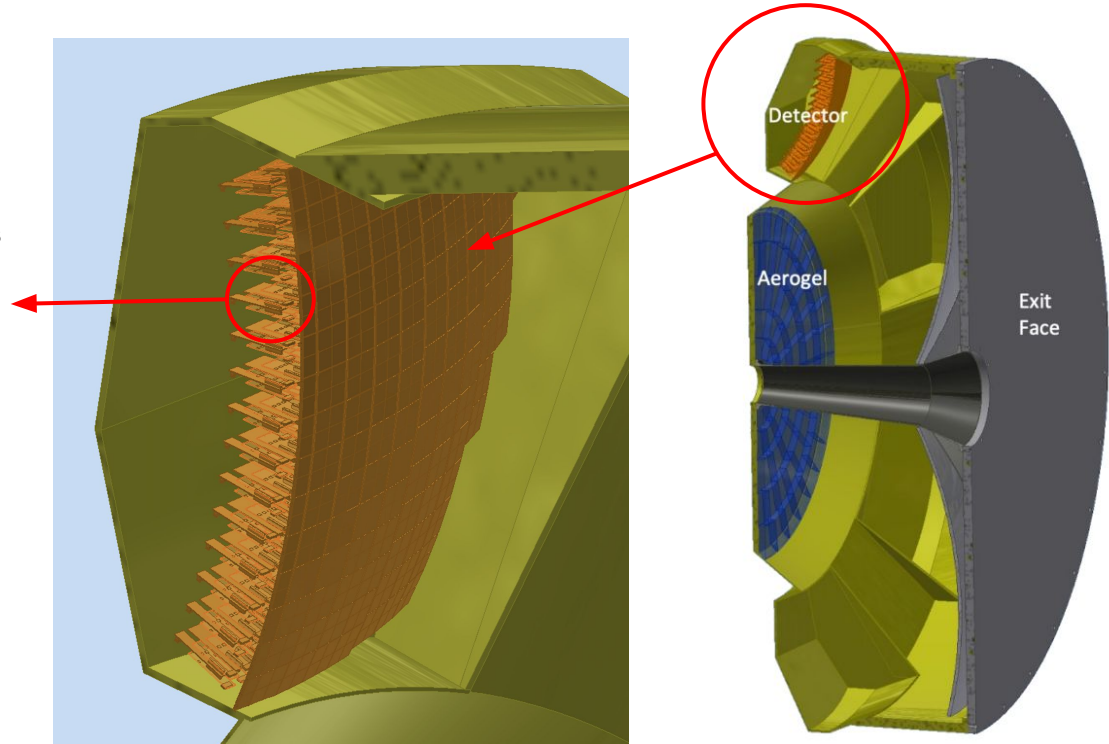
Photodetector unit

conceptual design of PDU layout

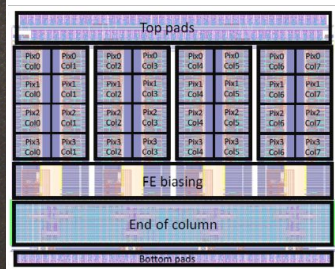
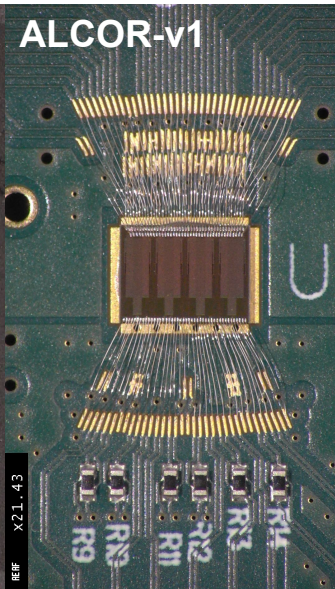
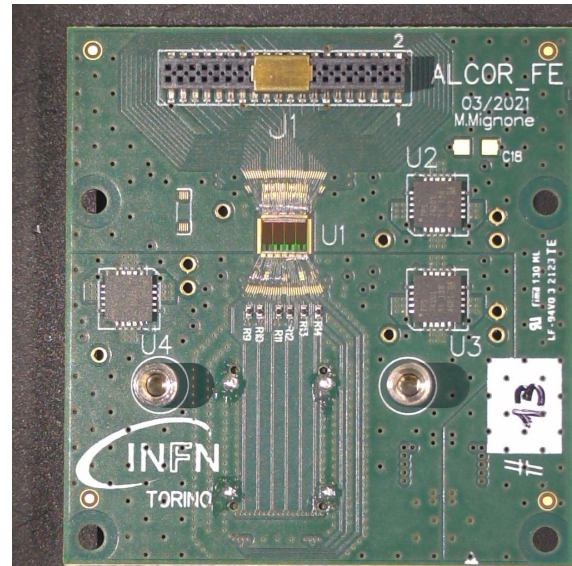


SiPM sensor matrices mounted on carrier PCB board

- 4x 64-channel SiPM array device (256 channels) for each unit
 - need modularity to realise curved readout surface
- 1248 photodetector units for full dRICH readout
 - **4992 SiPM matrix arrays (8x8)**
 - 319488 readout channels



ALCOR ASIC: integrated front-end and TDC

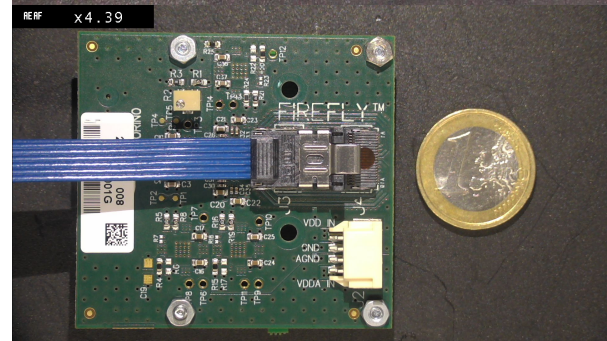


developed by INFN-TO

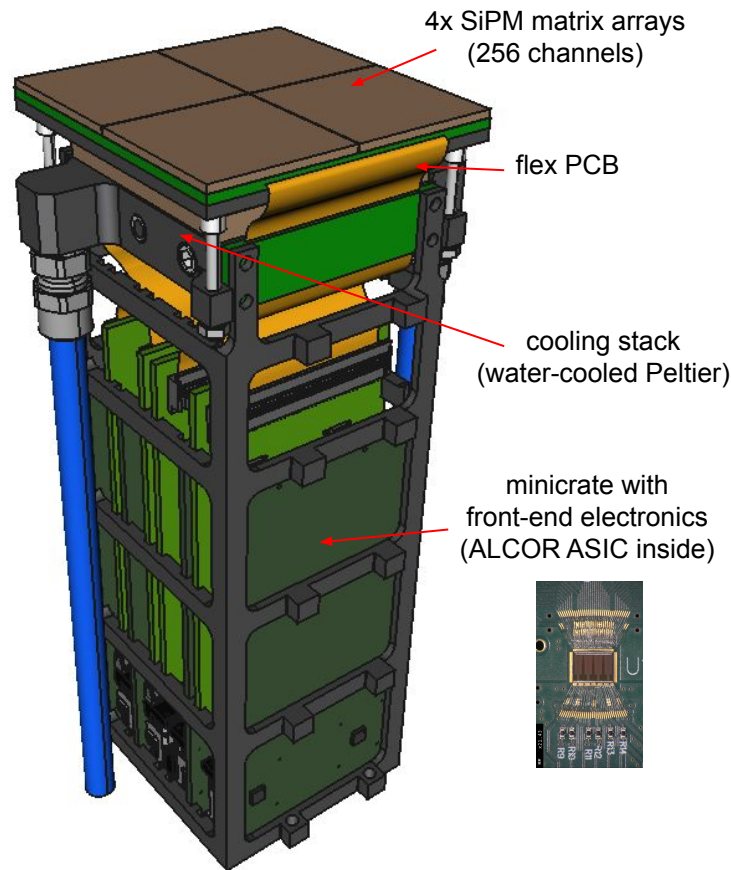
64-pixel matrix mixed-signal ASIC

current versions (v1,v2,v2.1) have 32 channels, wirebonded
final version will have 64 channels, BGA package, 394.08 MHz clock

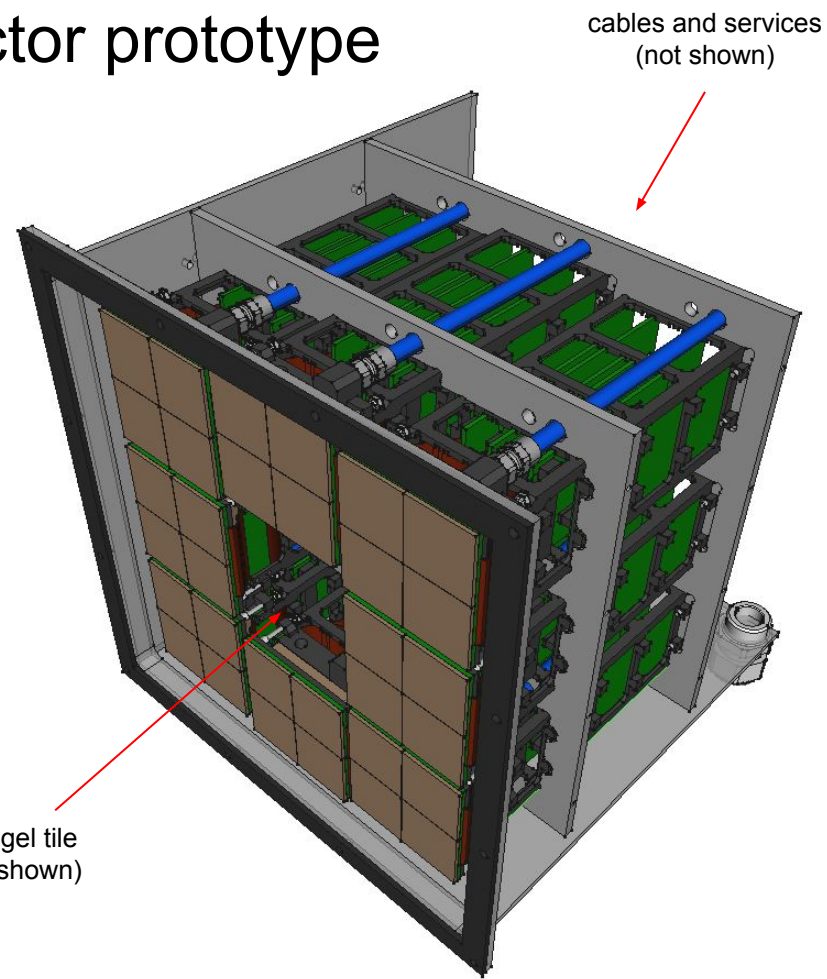
- **the chip performs**
 - signal amplification
 - conditioning and event digitisation
- **each pixel features**
 - 2 leading-edge discriminators
 - 4 TDCs based on analogue interpolation
 - 20 or 40 ps LSB (@ 394 MHz)
 - digital shutter to enable TDC digitisation
 - suppress out-of-gate DCR hits
 - 1-2 ns timing window
 - programmable delay, sub ns accuracy
- **single-photon time-tagging mode**
 - continuous readout
 - also with Time-Over-Threshold
- **fully digital output**
 - 8 LVDS TX data links



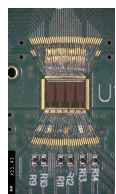
EIC ePIC-dRICH SiPM photodetector prototype



PhotoDetector Unit (PDU)



Readout Box

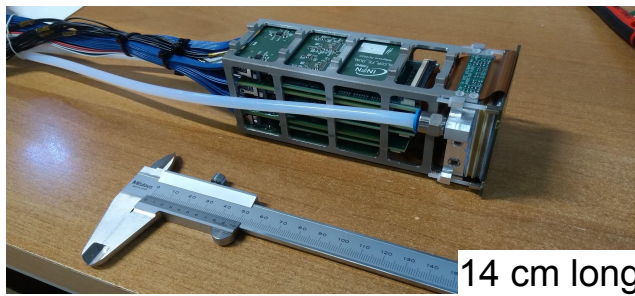
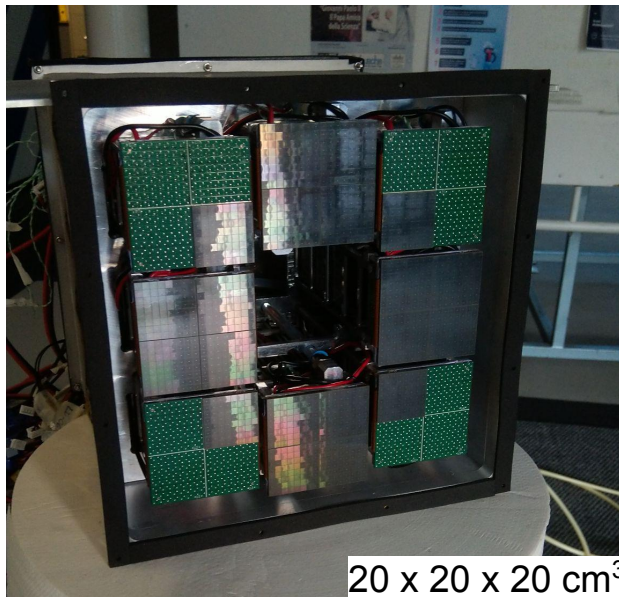
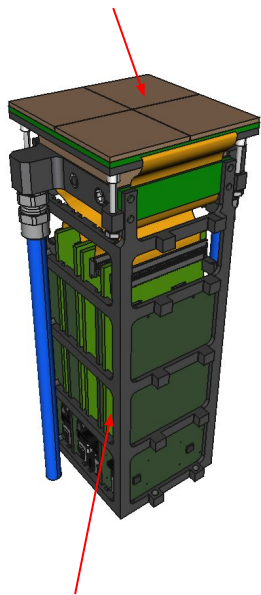


2023 test beam at CERN-PS

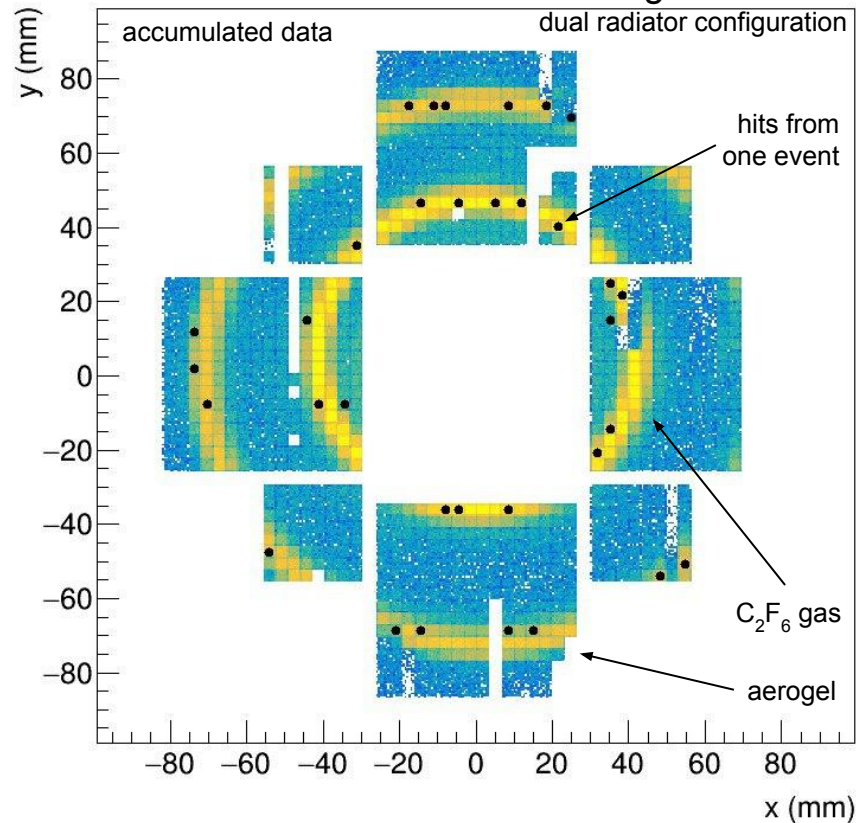
successful beam test with prototype SiPM photodetector units (CERN-PS, ended on 18th October)

PDU

4x SiPM matrix arrays
(256 channels)

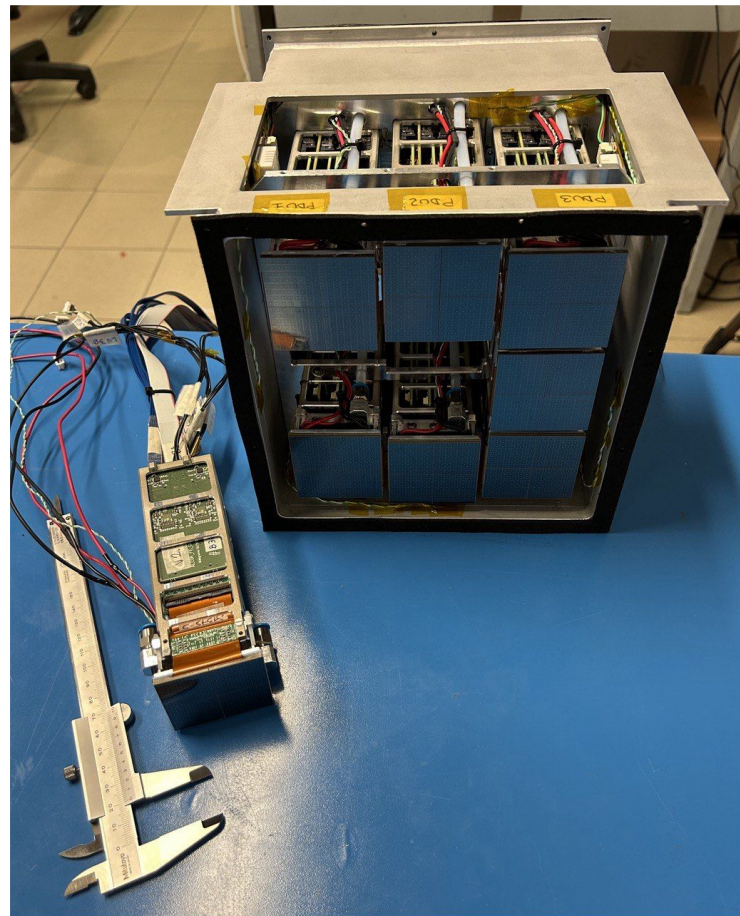
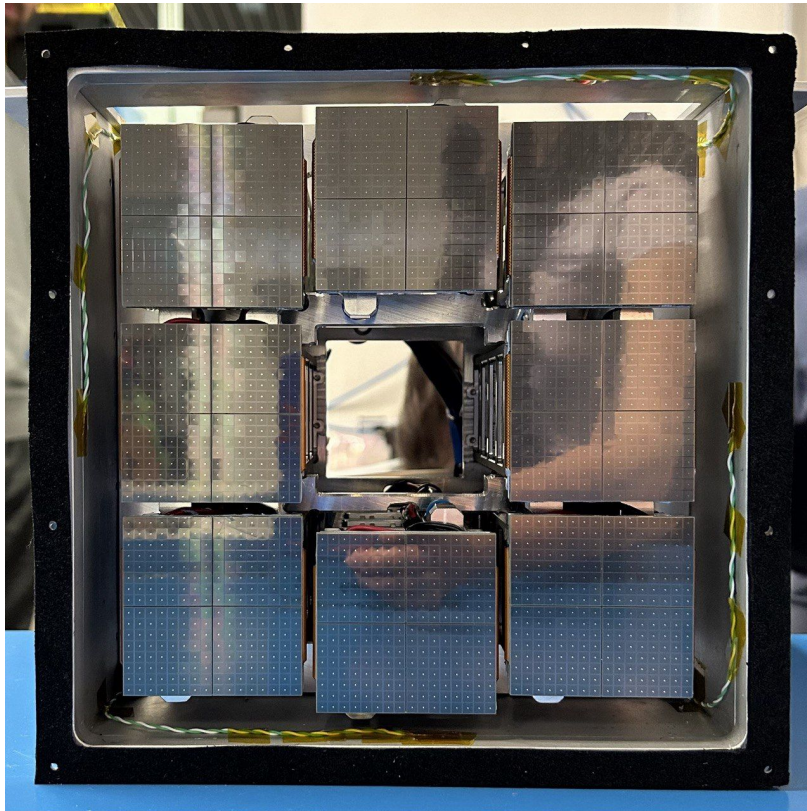


10 GeV negative beam



Upgraded in 2024 with 2k channels

Hamamatsu S13360-3050/3075 8x8 MPPC arrays



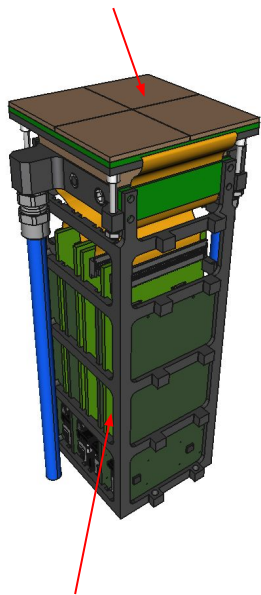
fully-equipped, **2048-channels** SiPM readout surface with cooling and TDC electronics

2024 test beam at CERN-PS

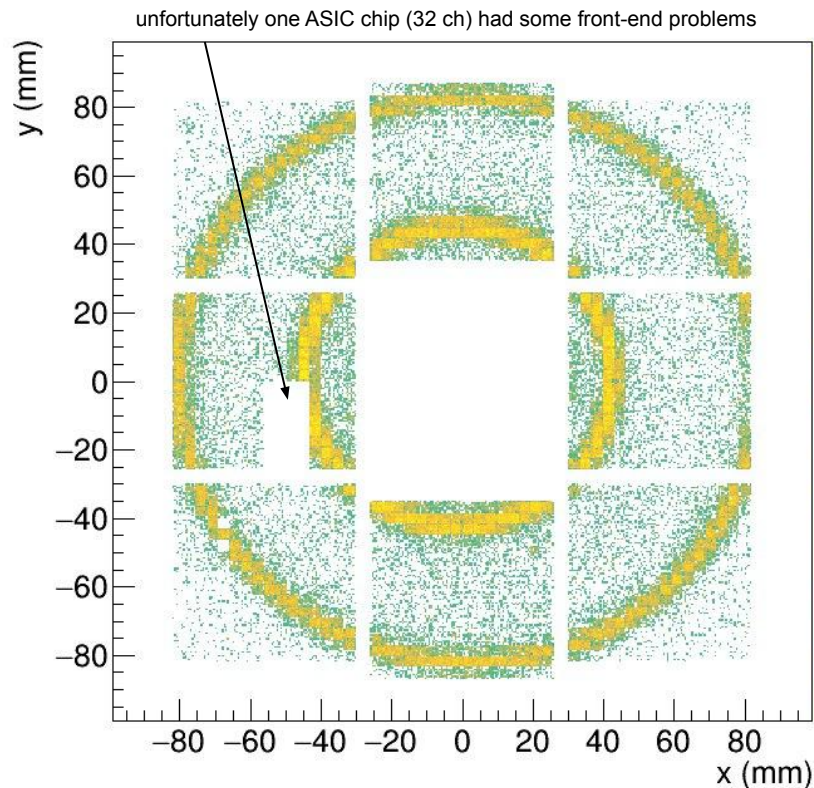
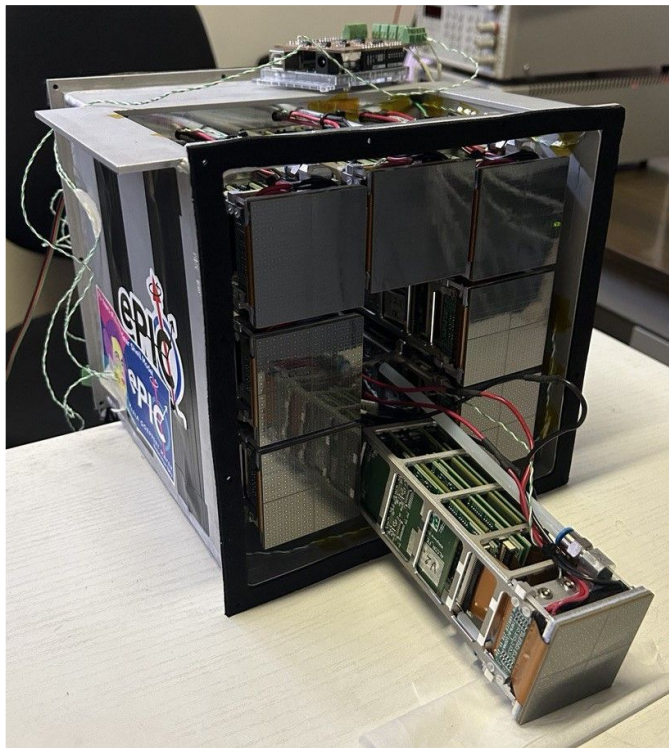
another successful beam test with prototype SiPM photodetector units (CERN-PS, ended on 5th June)

PDU

4x SiPM matrix arrays
(256 channels)

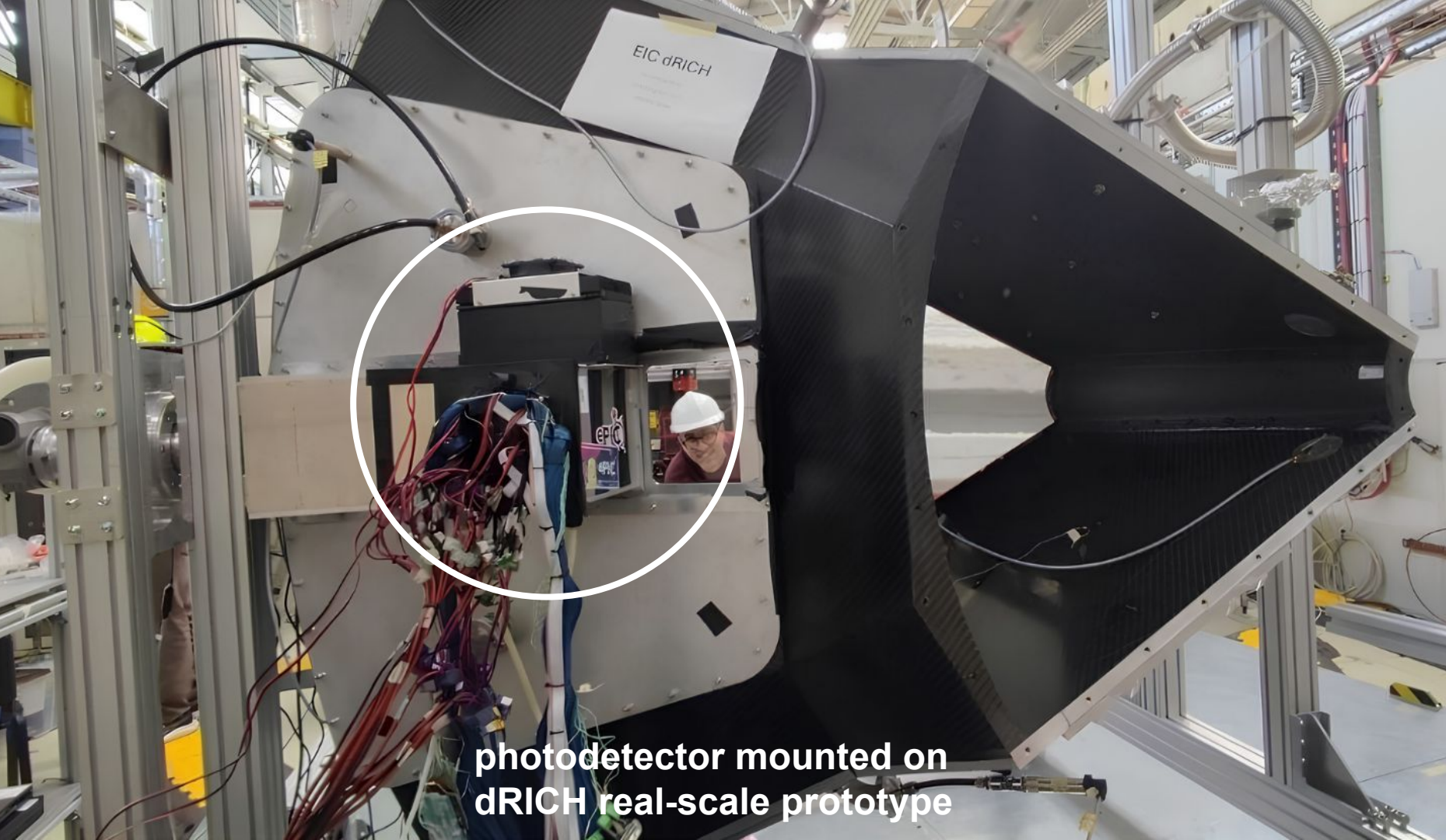


front-end electronics
(ALCOR ASIC inside)



all the rest was rather full of photons
> 2000 SiPMs with TDC readout at work

2026 test beam



**photodetector mounted on
dRICH real-scale prototype**



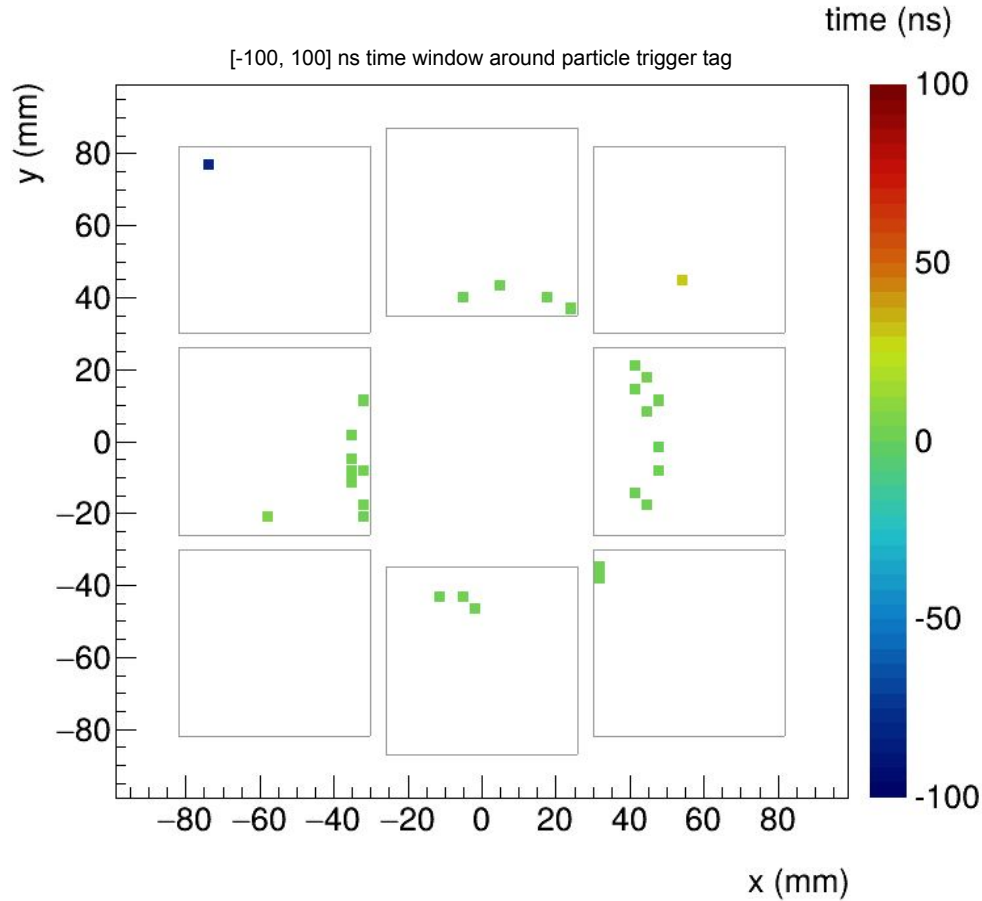
**photodetector mounted on
dRICH real-scale prototype**

Basic information

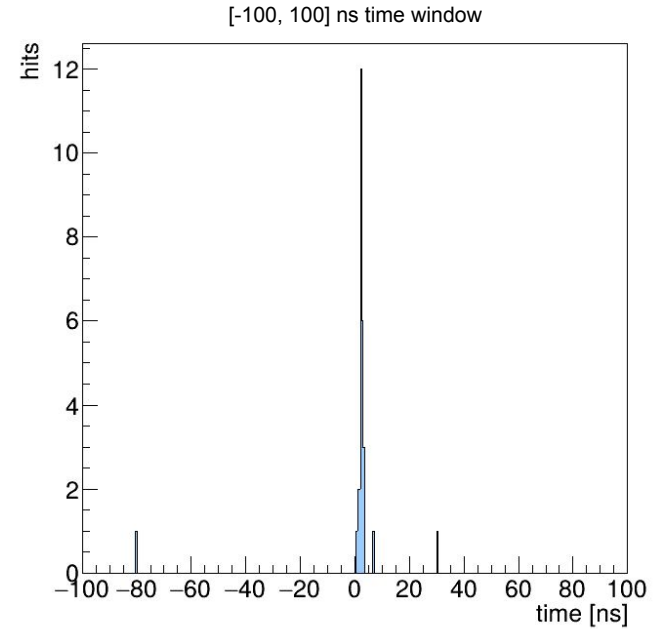
- data collected in June 2026 at the **SPS**
- beam configuration was a **180 GeV** positive beam
- this analysis focuses on a single **SiPM** operating configuration/run
- dRICH was in **C₂F₆ gas** configuration
- dRICH was rotated to the orientation corresponding to **$\eta = 3.2$**
- timing calibration not the main analysis focus, quality is adequate but not optimal
- events tagged with ALCOR-based **timing-scintillator** system
- **finger-scintillator trigger** tagging is available, but not used in this analysis

some event displays

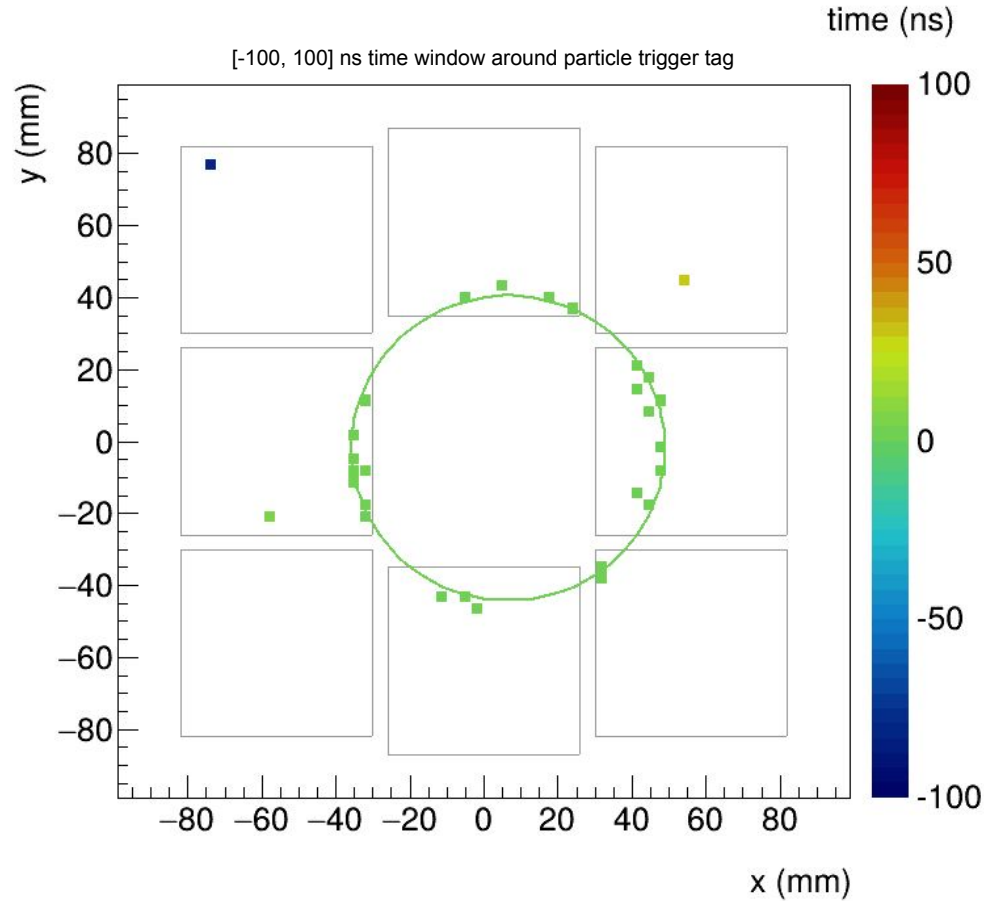
spill 0 frame 0



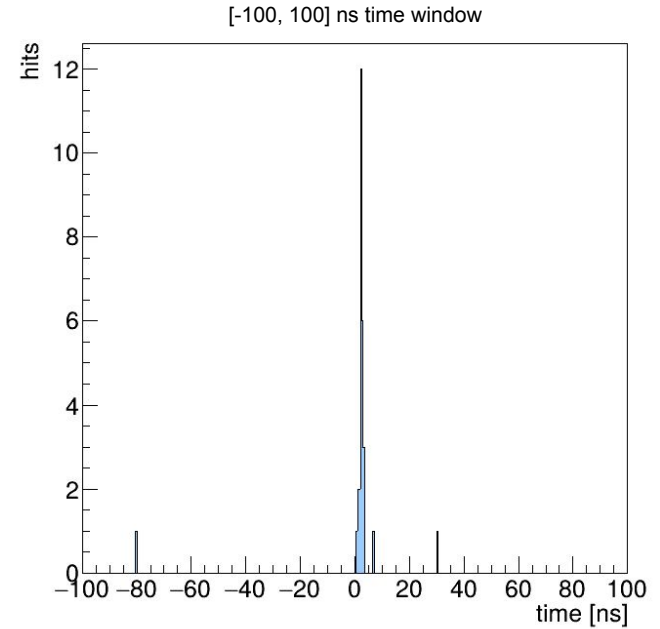
spill 0 frame 0 Cherenkov timing



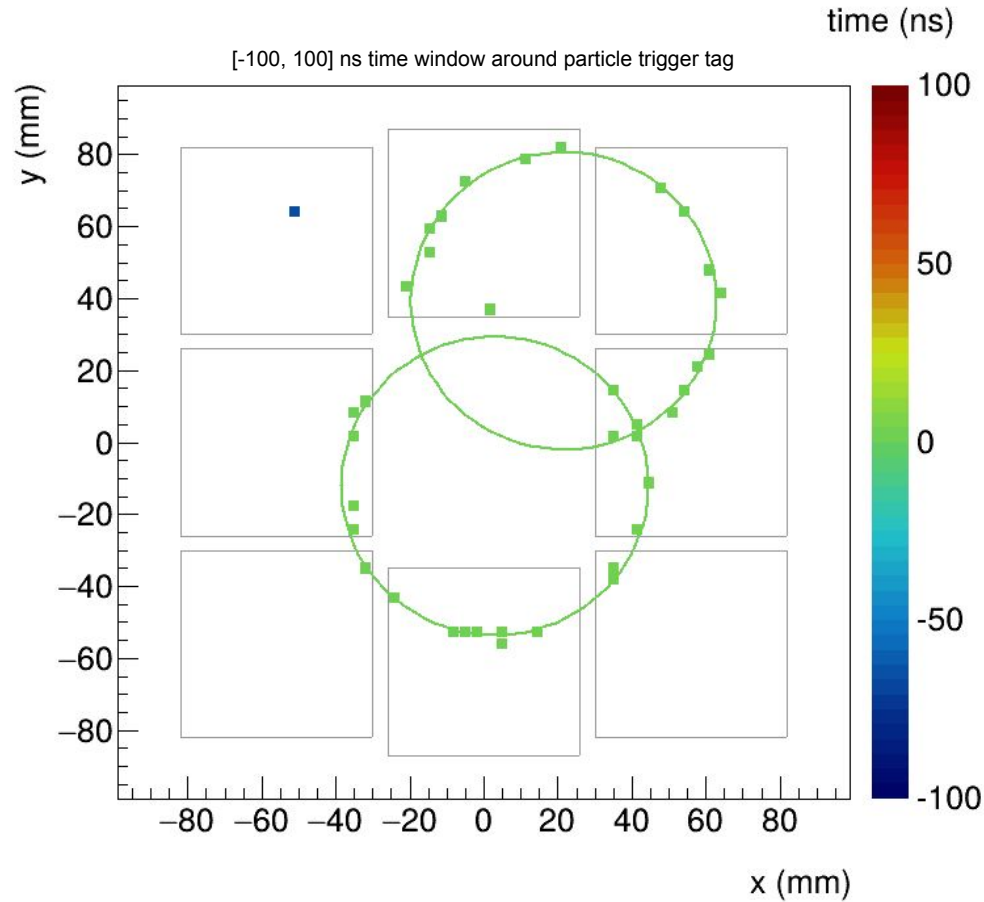
spill 0 frame 0



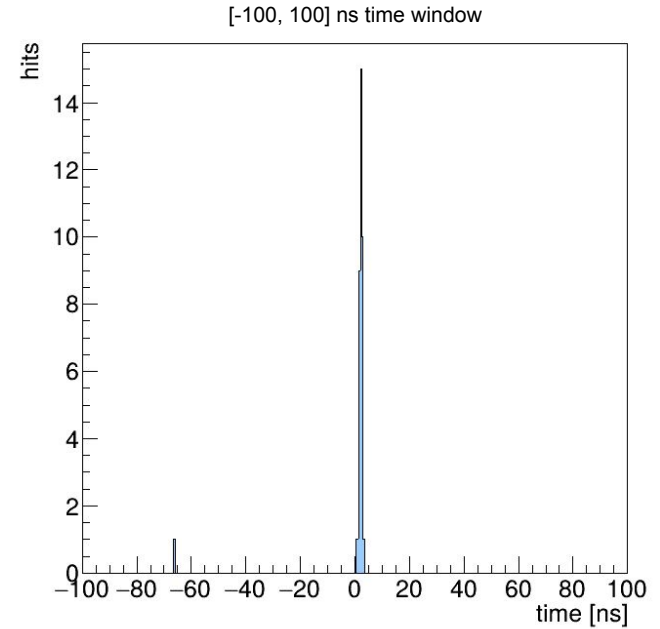
spill 0 frame 0 Cherenkov timing



spill 0 frame 239

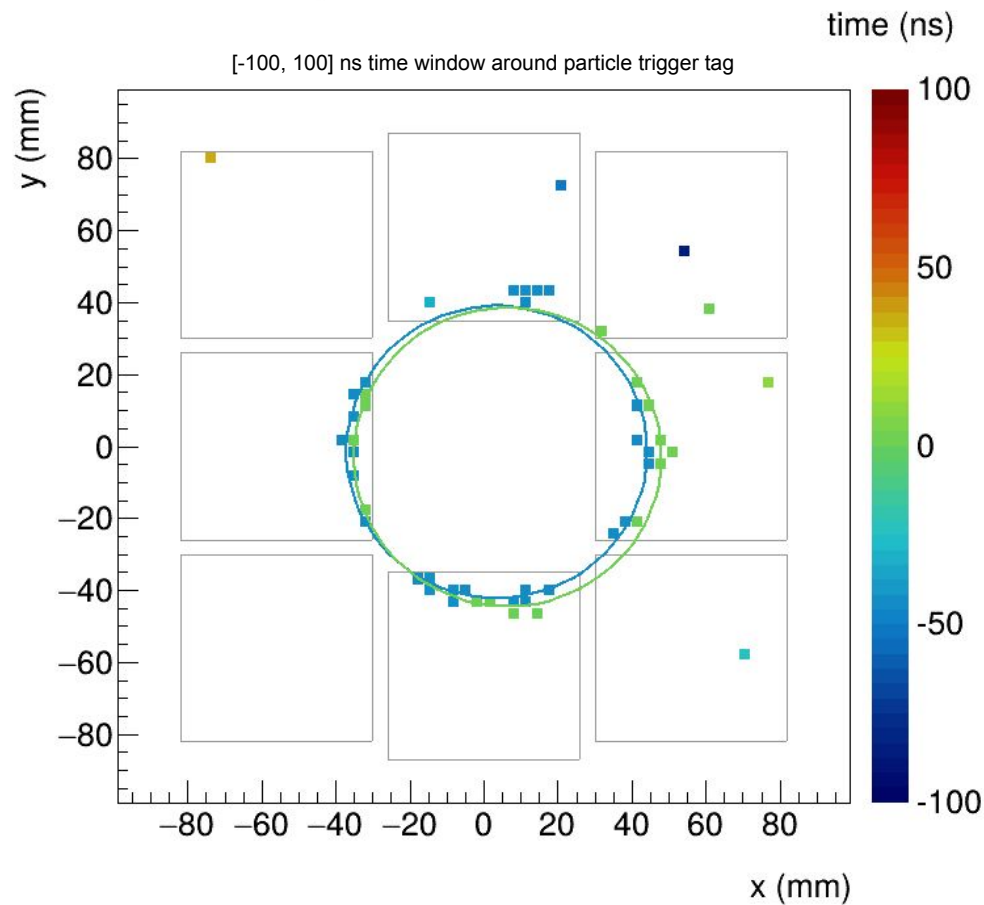


spill 0 frame 239 Cherenkov timing

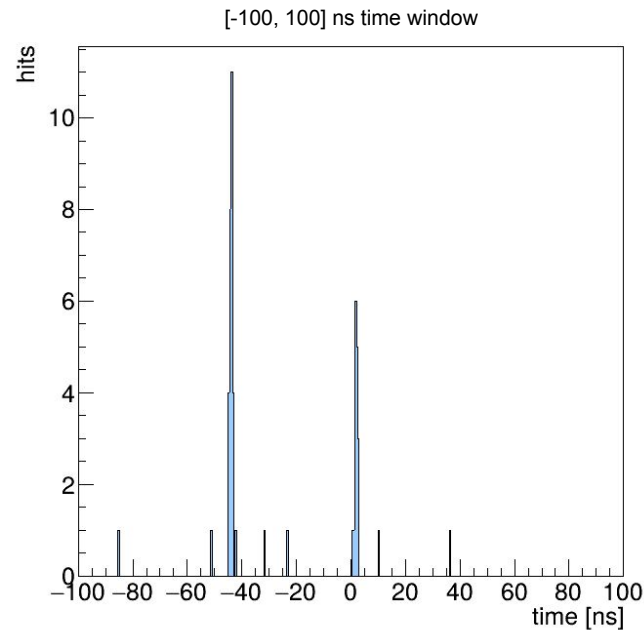


two almost simultaneous particles producing displaced "rings"

spill 0 frame 1065

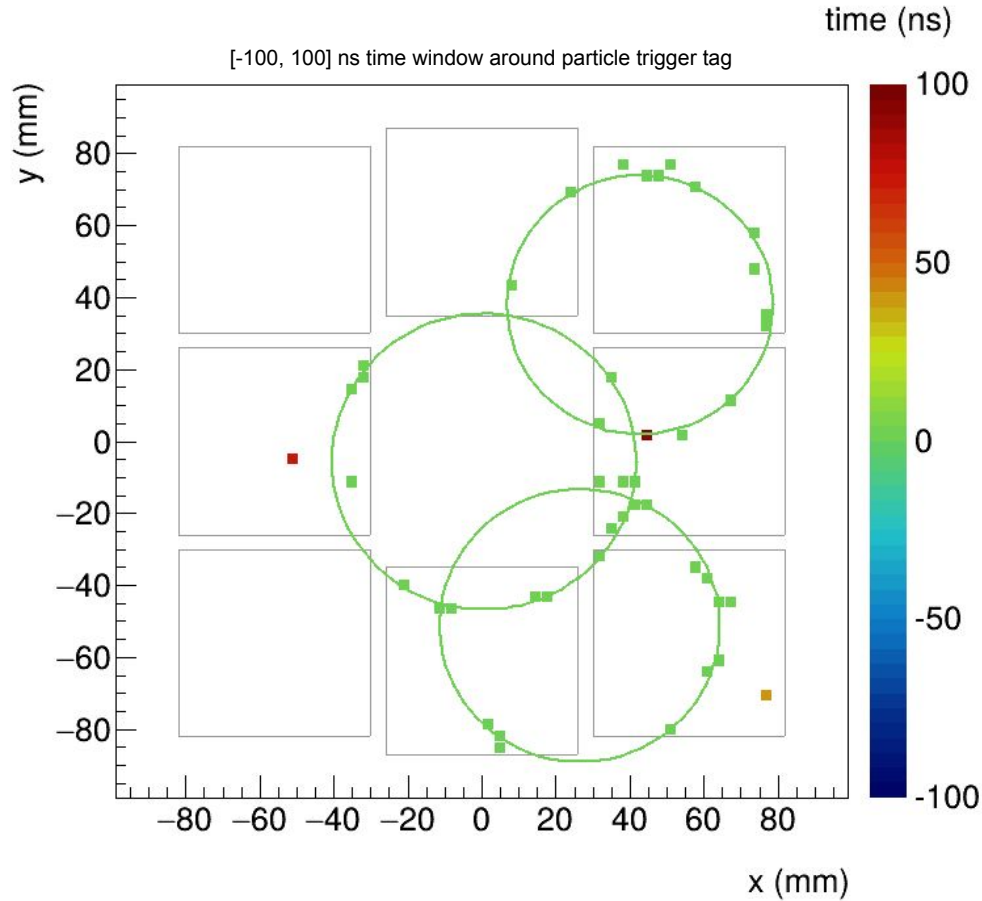


spill 0 frame 1065 Cherenkov timing

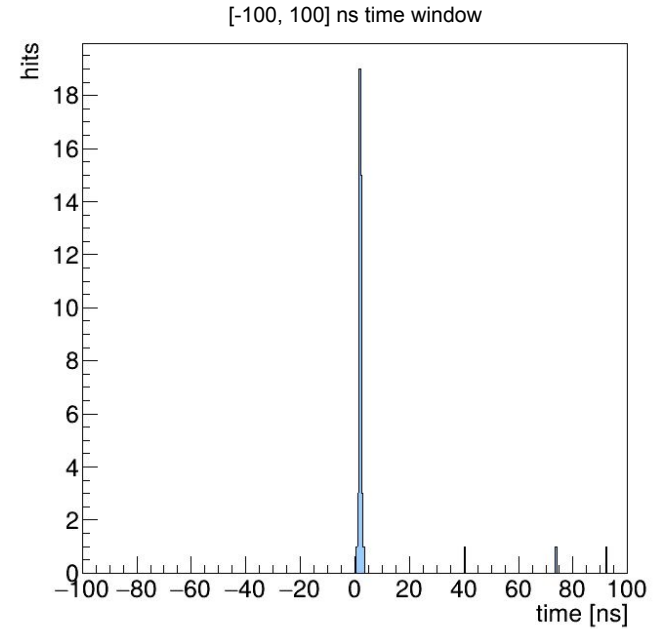


two successive particles producing almost overlapping rings

spill 0 frame 4479



spill 0 frame 4479 Cherenkov timing



inverse ray-tracing
reconstruction

IRT reconstruction: inspired by HERMES algorithm

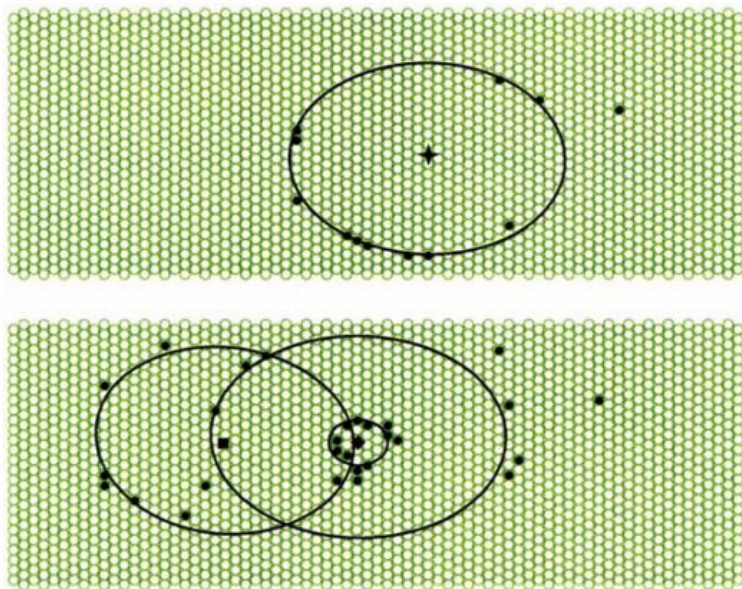


Fig. 12. HERMES RICH event display for an event with a 14.6 GeV electron (right) and a 1.5 GeV π^- (left) in the lower half and a 5.5 GeV K^+ in the upper half. See text for detailed description.

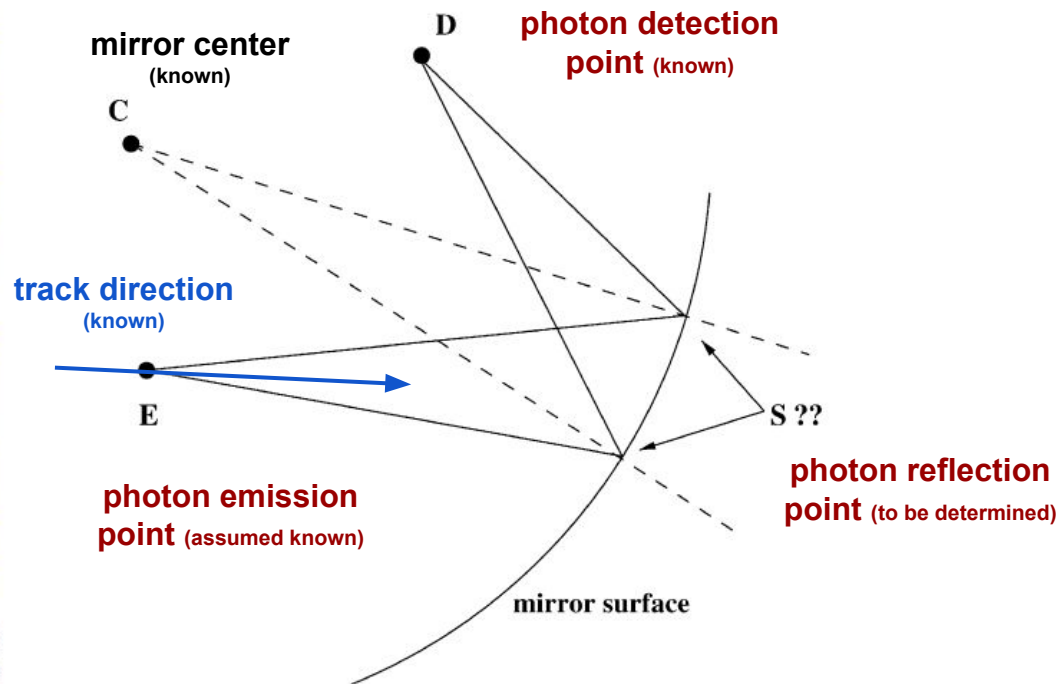


Fig. 13. The problem of inverse ray tracing.

solve the reflection point S equation → photon emission direction → angle wrt. track direction

```
# All coordinates and radii are in millimetres, angles are in radians.
# These values describe the nominal optical geometry.
# Data-derived alignment corrections belong in a separate configuration.
```

```
[mirror]
center = (1150.08, 0.0, 939.0)
radius = 2203.01
pivot_center = (327.9, 0.0, 3110.6)      # Mechanical rotation pivot of the mirror, in millimetres.
rotation_vector = (0.0, 0.0, 0.0)        # Mirror rotation about the mechanical pivot.

[detector]
sphere_center = (1834.0, 0.0, 1414.0)    # The photodetector is a tangent plane located on a nominal sphere.
sphere_radius = 1100.0
theta = -0.66041320                      # Direction from the sphere centre to the tangent-plane centre
phi = 0.0                                # plane centre = (1163.3, 0.0, 2282.6) mm.
rotation_vector = (0.0, 0.0, 0.0)        # Rotation of the detector plane about its fixed plane centre.

[track]
origin = (0.0, 0.0, 0.0)
direction = (0.0, 0.0, 1.0)              # The track goes along the z axis.
emission_z = 2534.0                      # The pseudorapidity is defined by a rotation of the whole dRICH assembly.

[assembly]
rotation_x_pivot = (0.0, 0.0, 2500.0)    # Rotation pivots and angles of the whole dRICH assembly.
rotation_x = 0.0
rotation_y_pivot = (0.0, 0.0, 0.0)
rotation_y = -0.081479300                # This corresponds to eta = 3.2
```

All coordinates and radii are in millin
 # These values describe the nominal optic
 # Data-derived alignment corrections belo

[mirror]

center = (1150.08, 0.0, 939.0)

radius = 2203.01

pivot_center = (327.9, 0.0, 3110.6)

rotation_vector = (0.0, 0.0, 0.0)

[detector]

sphere_center = (1834.0, 0.0, 1414.0)

sphere_radius = 1100.0

theta = -0.66041320

phi = 0.0

rotation_vector = (0.0, 0.0, 0.0)

[track]

origin = (0.0, 0.0, 0.0)

direction = (0.0, 0.0, 1.0)

emission_z = 2534.0

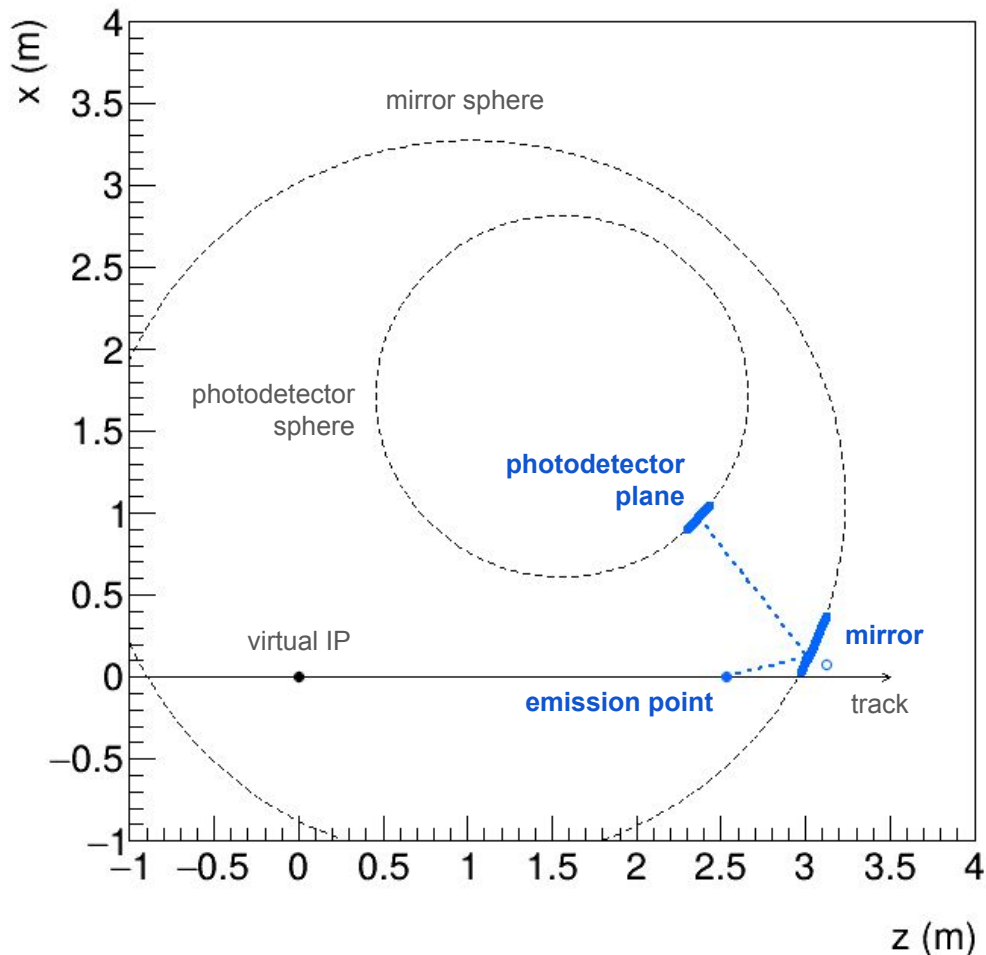
[assembly]

rotation_x_pivot = (0.0, 0.0, 2500.0)

rotation_x = 0.0

rotation_y_pivot = (0.0, 0.0, 0.0)

rotation_y = -0.081479300



Nominal prototype geometry used as the starting point for the IRT reconstruction

Accumulated hits

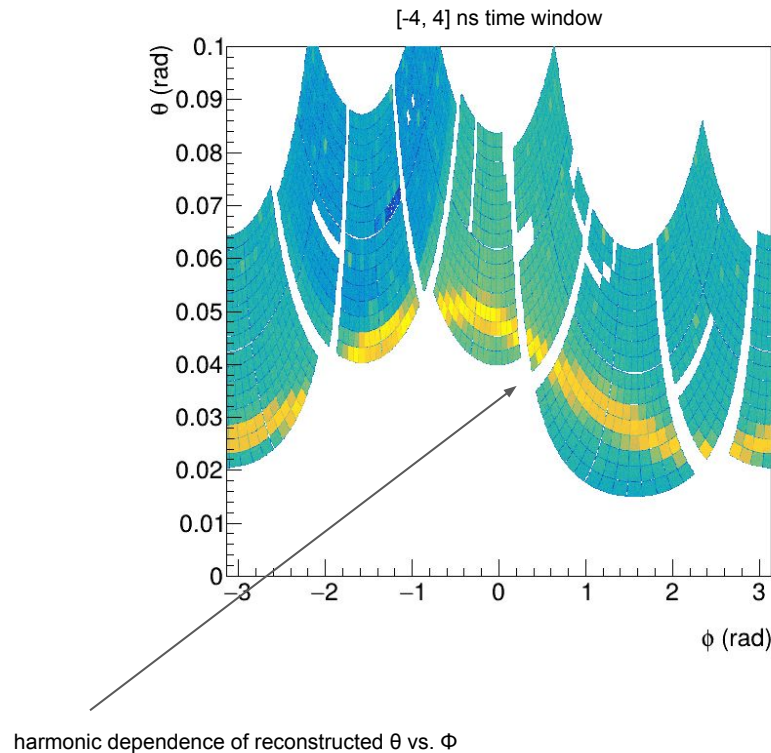
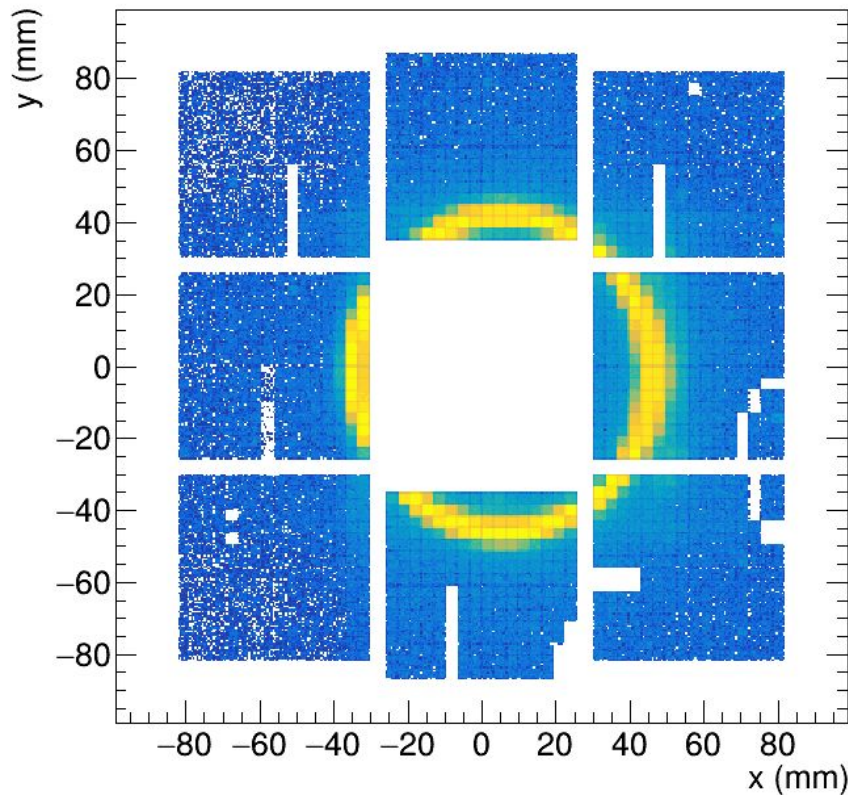
events with one ring

$1.68 < x_0 < 10.53$

$-6.93 < y_0 < 2.69$

$30.52 < r < 53.61$

[-4, 4] ns time window around particle trigger tag



IRT reconstruction: nominal geometry does not produce a constant Cherenkov angle $\rightarrow$ need to refine geometry

fitting geometry
parameters

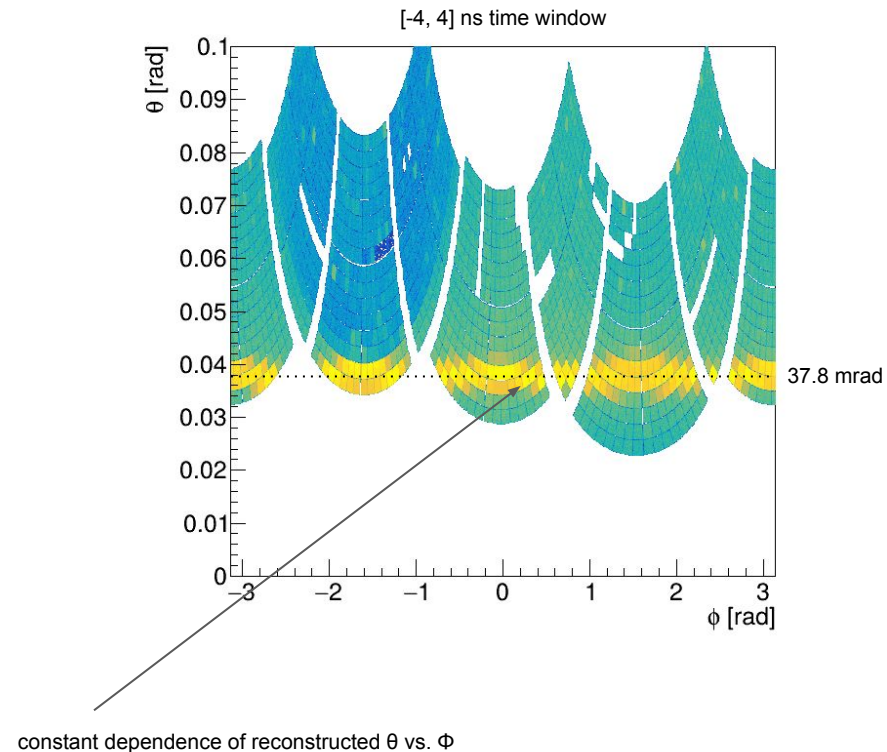
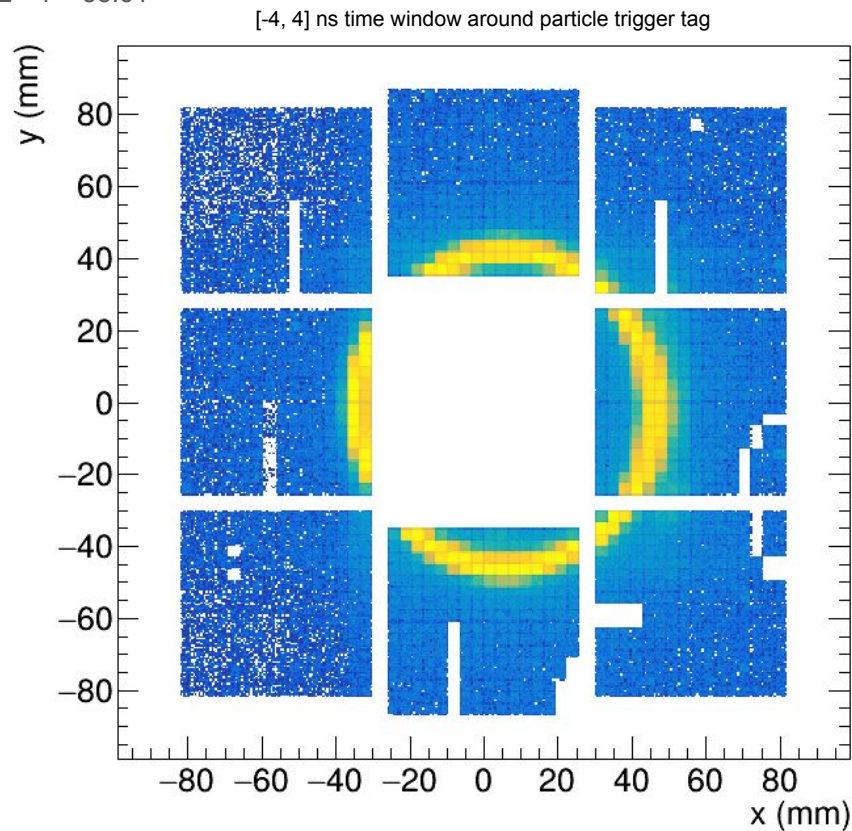
Best SPS geometry fit found with eta = 3.2 fixed.

# name	start	min	max	status
assembly_rotation_x	0.0	-0.1	0.1	fixed
assembly_rotation_y	-0.081479300	-0.2	0.2	fixed
assembly_rotation_x_pivot_y	0.0	-500.0	500.0	fixed
assembly_rotation_x_pivot_z	2500.0	1500.0	3500.0	fixed
emission_z	2534.0	2300.0	2700.0	fixed
mirror_delta_x	0.0	-100.0	100.0	fixed
mirror_delta_y	0.0	-100.0	100.0	fixed
mirror_delta_z	0.0	-100.0	100.0	fixed
mirror_delta_r	0.0	-100.0	100.0	fixed
mirror_rotation_x	0.0314381	-0.1	0.1	free
mirror_rotation_y	0.0563053	-0.1	0.1	free
mirror_rotation_z	0.0	-0.01	0.01	fixed
detector_delta_x	0.0	-100.0	100.0	fixed
detector_delta_y	0.0	-100.0	100.0	fixed
detector_delta_z	0.0	-100.0	100.0	fixed
detector_delta_theta	-0.126726	-0.2	0.2	free
detector_delta_phi	-0.0632111	-0.2	0.2	free
detector_rotation_x	0.0	-0.1	0.1	fixed
detector_rotation_y	0.0	-0.1	0.1	fixed
detector_rotation_z	0.0	-0.1	0.1	fixed
expected_cherenkov_angle	0.0378242	0.03	0.05	free

fitted detector geometry parameters, global orientation fixed to $\eta = 3.2 \rightarrow$ best fitted Cherenkov $\theta = 37.82$ mrad (close to simulation)

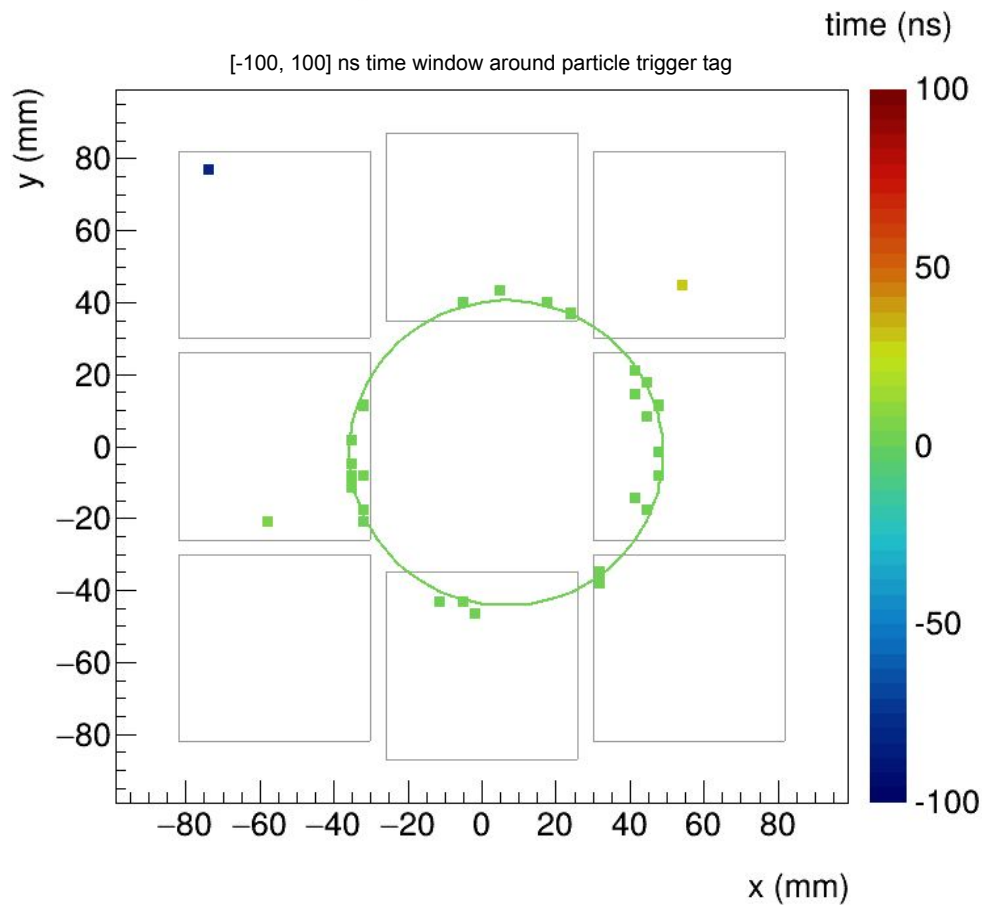
Accumulated hits

events with one ring
 $1.68 < x_0 < 10.53$
 $-6.93 < y_0 < 2.69$
 $30.52 < r < 53.61$

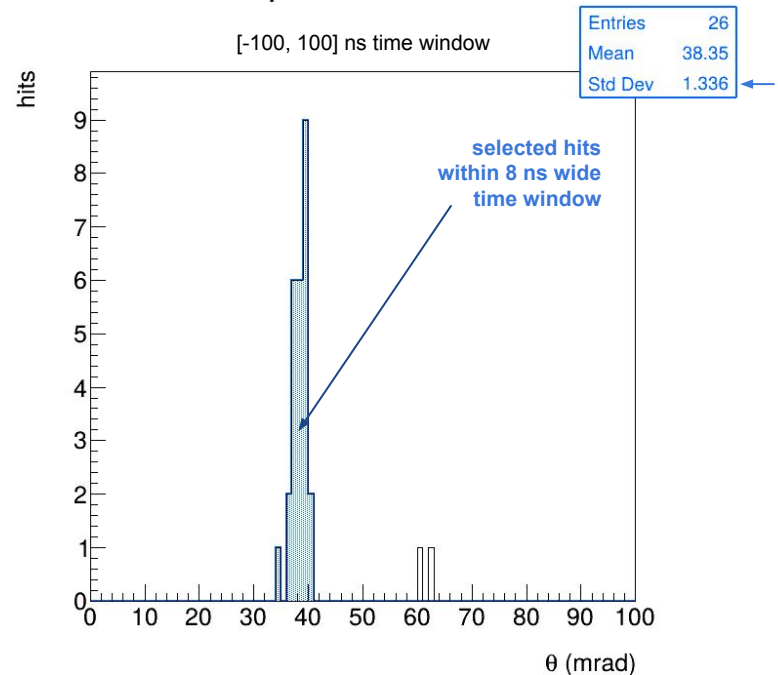


some event-display
images with IRT

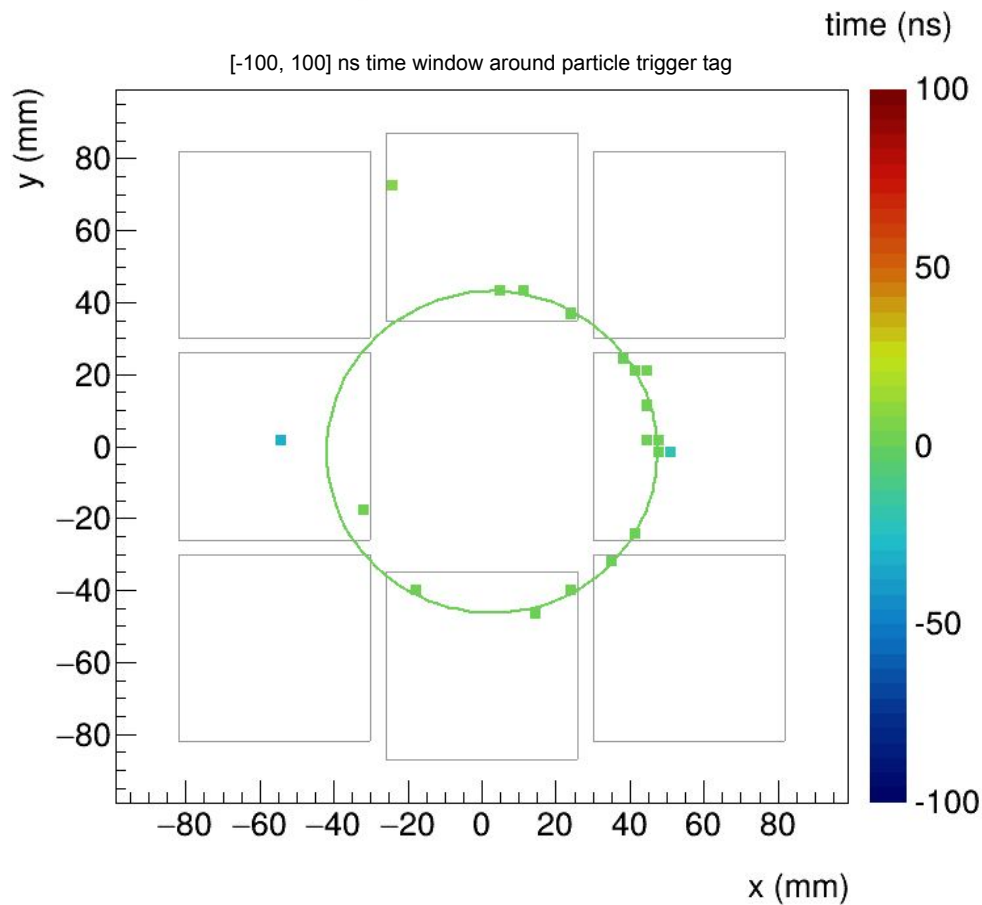
spill 0 frame 0



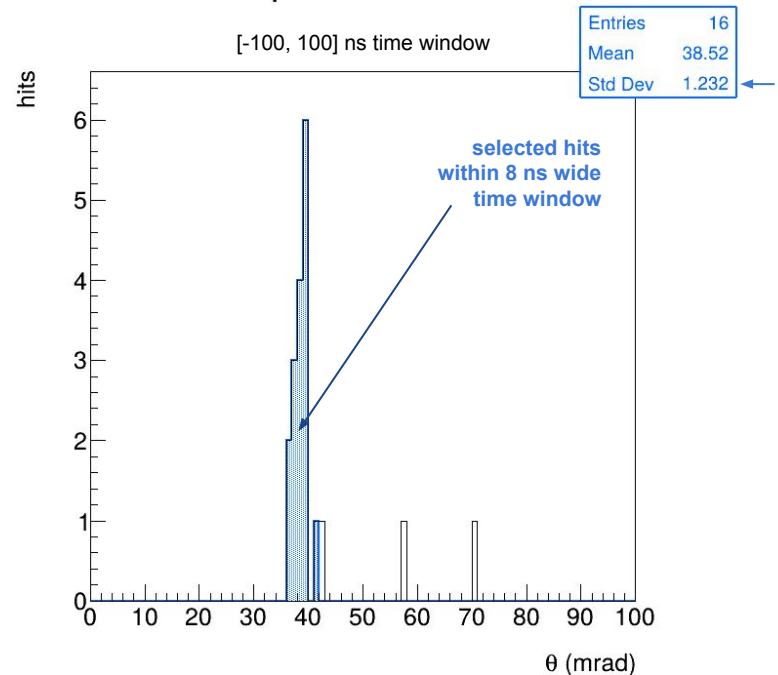
spill 0 frame 0



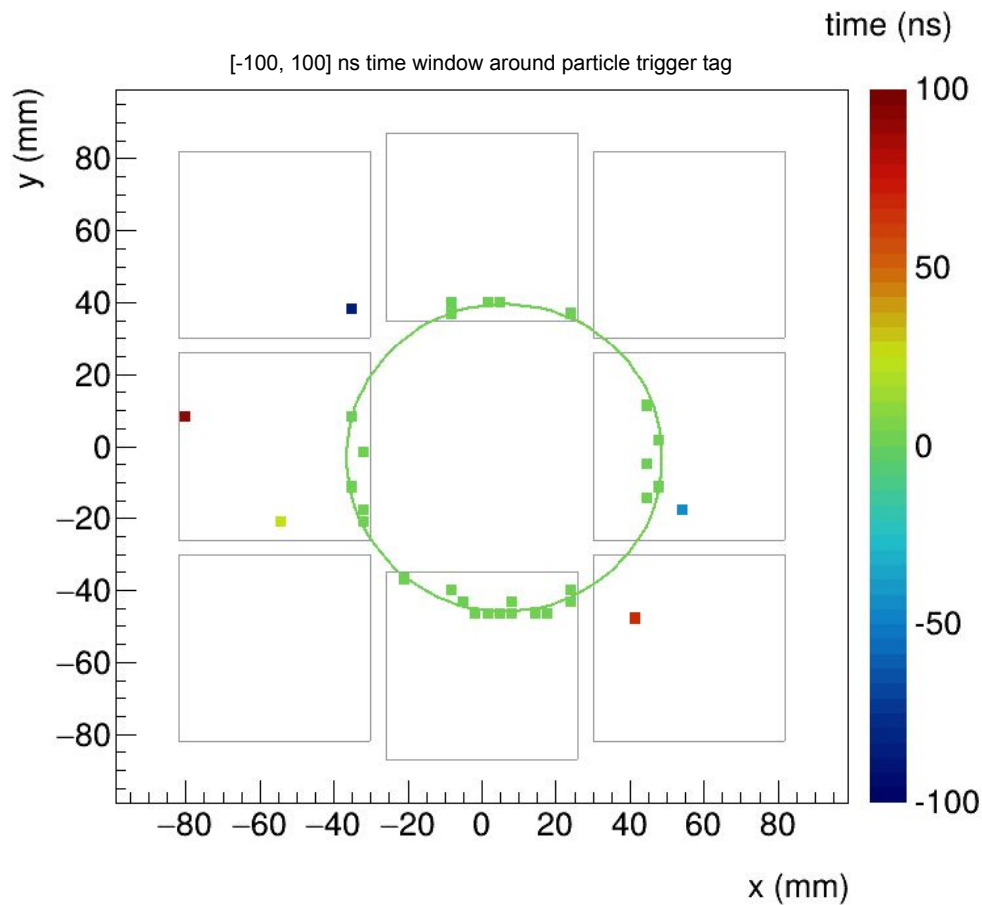
spill 0 frame 1



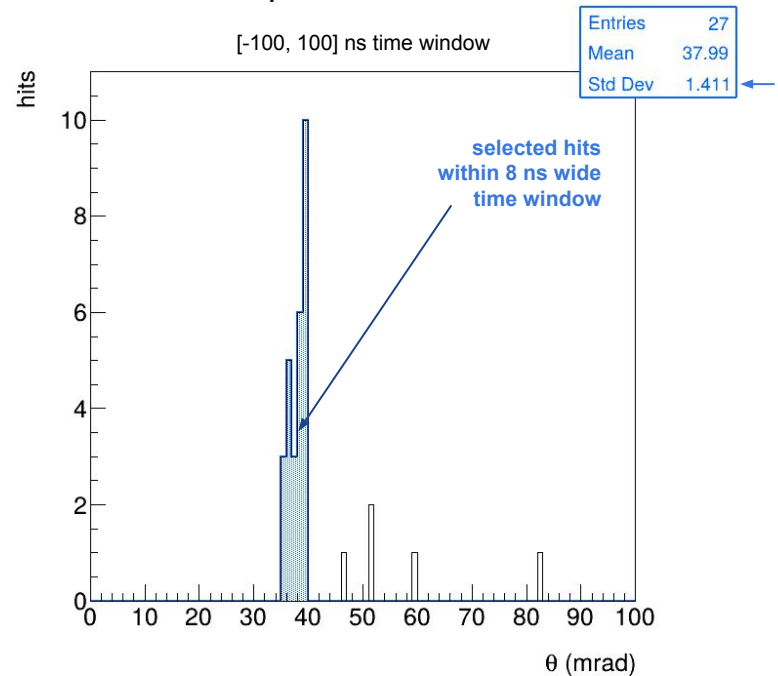
spill 0 frame 1



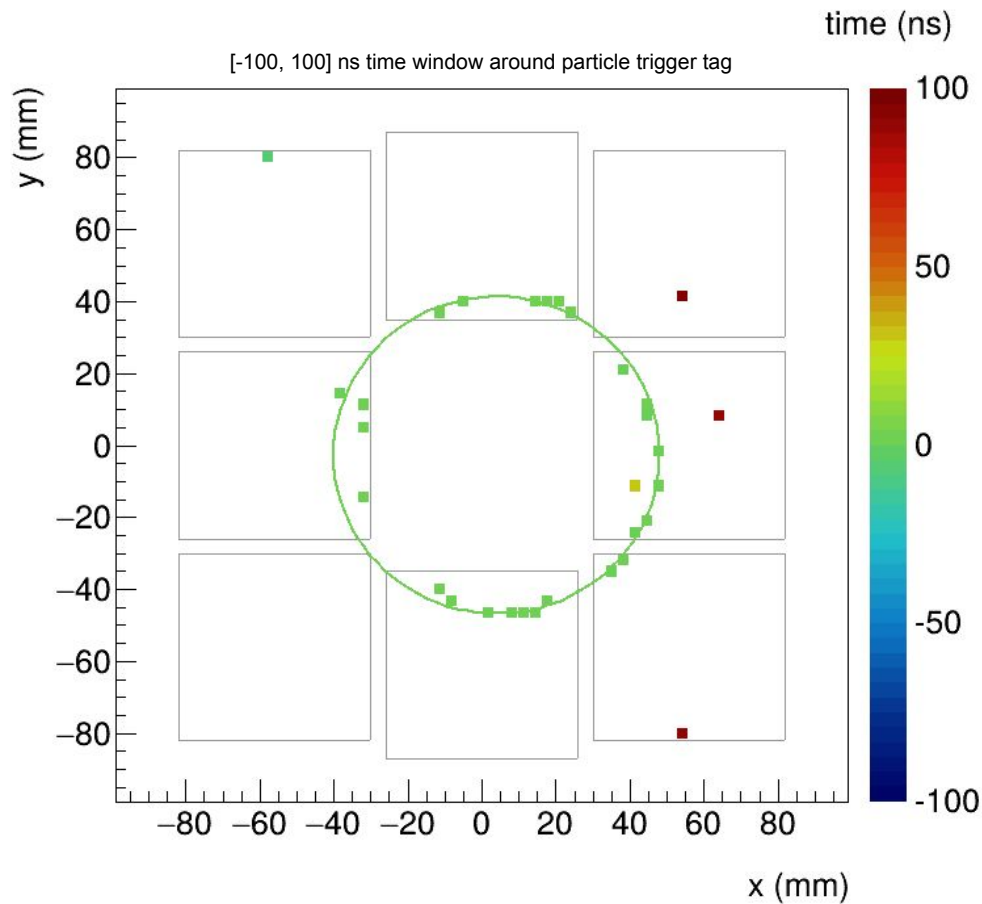
spill 0 frame 2



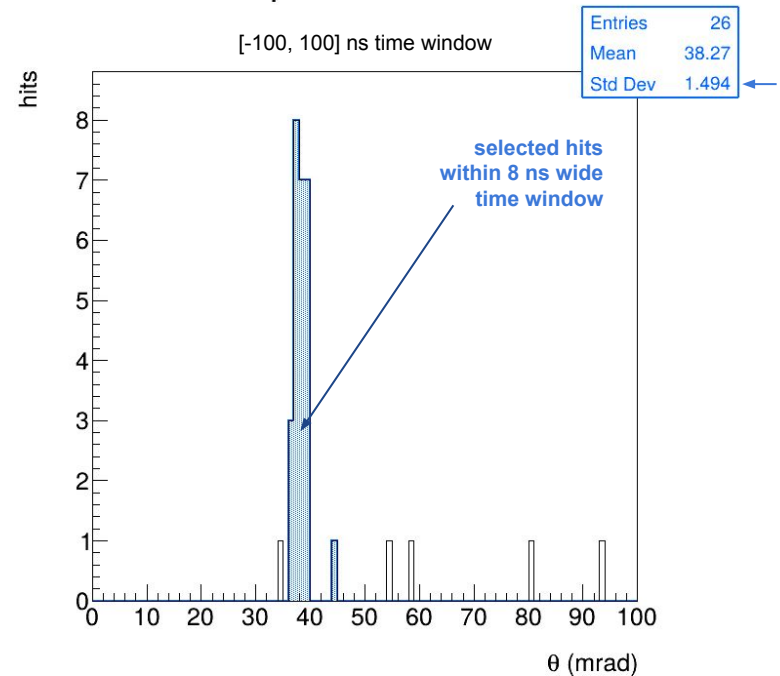
spill 0 frame 2



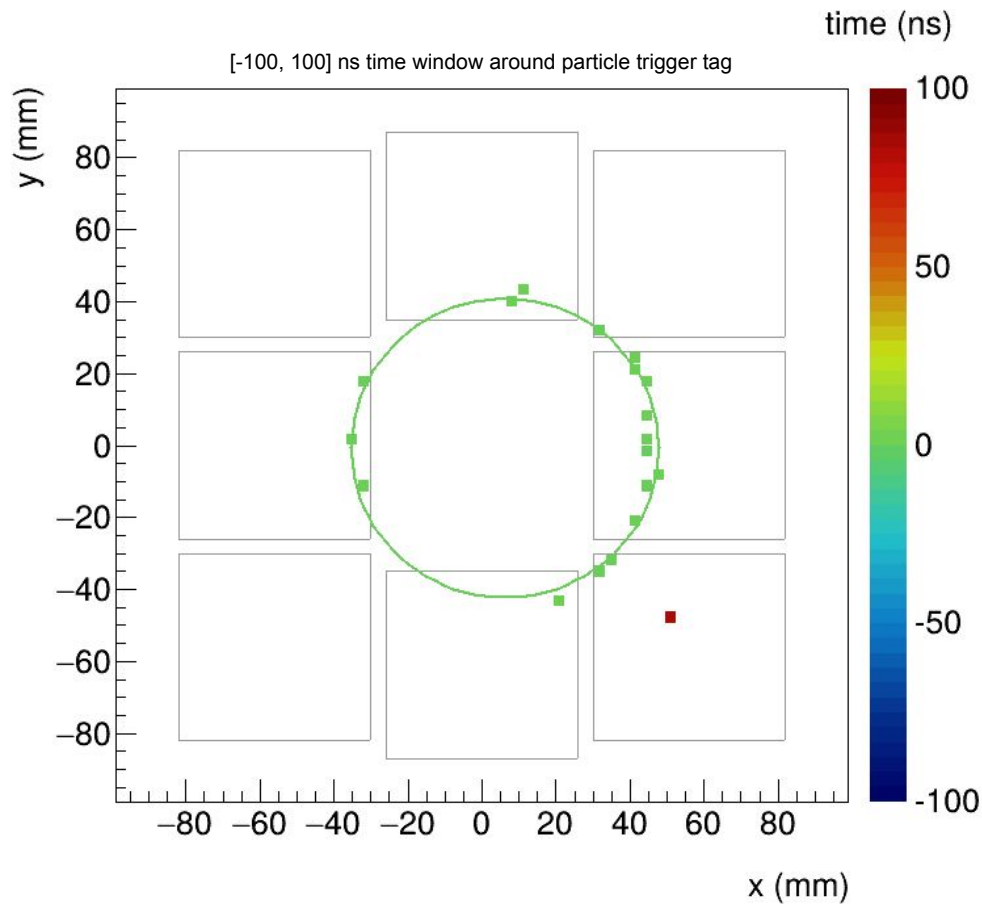
spill 0 frame 3



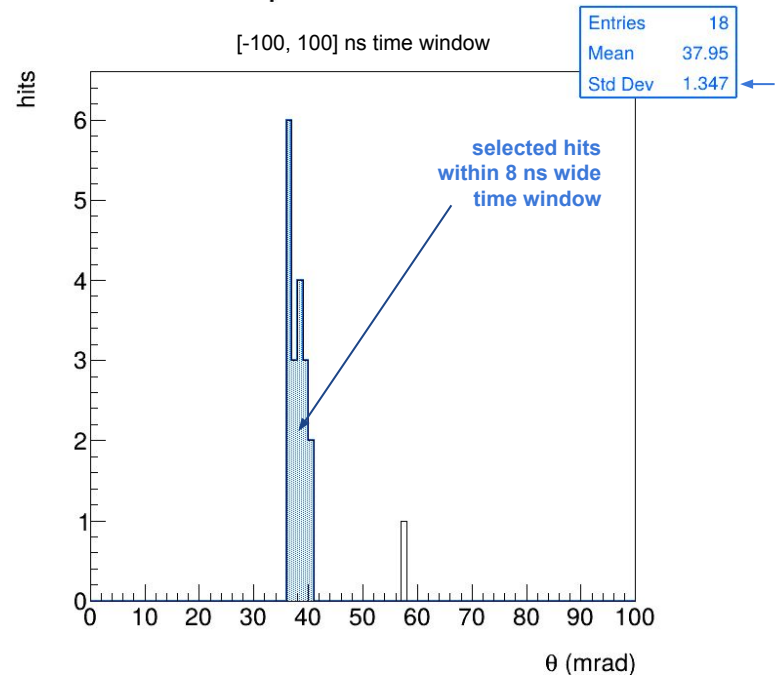
spill 0 frame 3



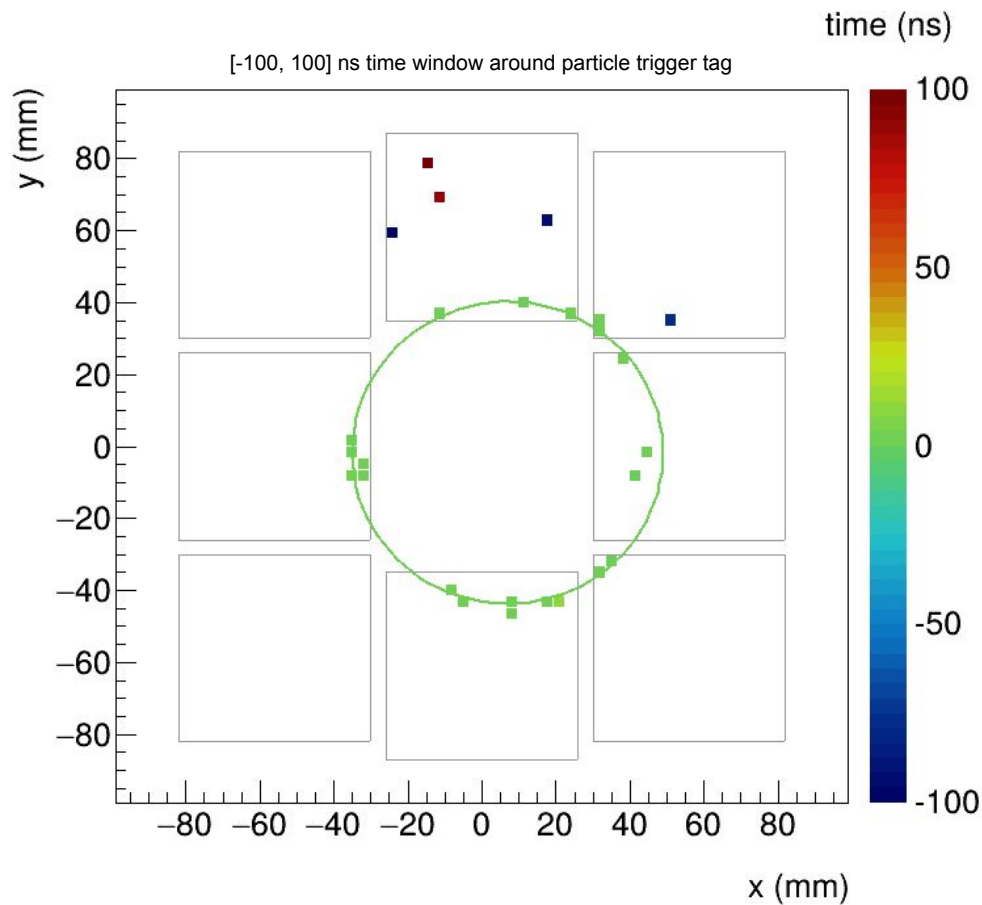
spill 0 frame 4



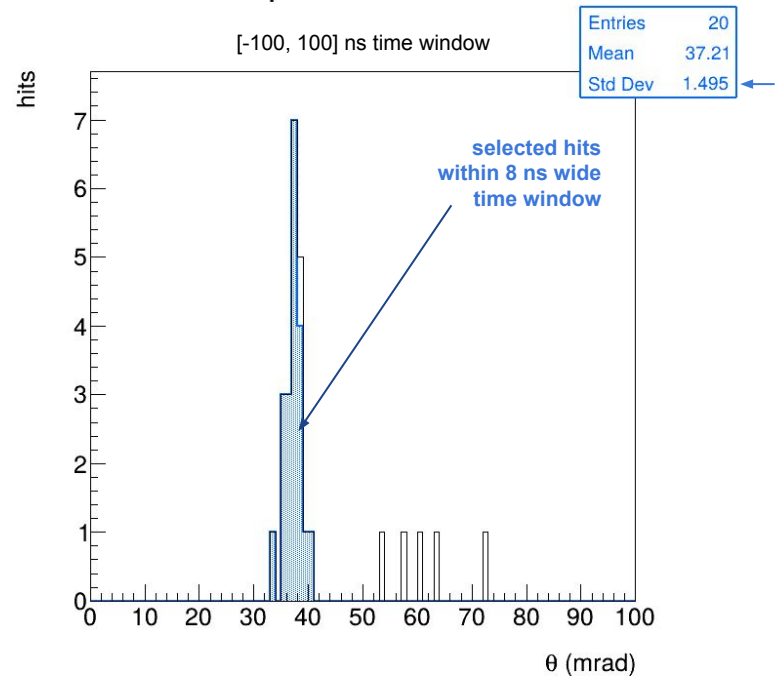
spill 0 frame 4



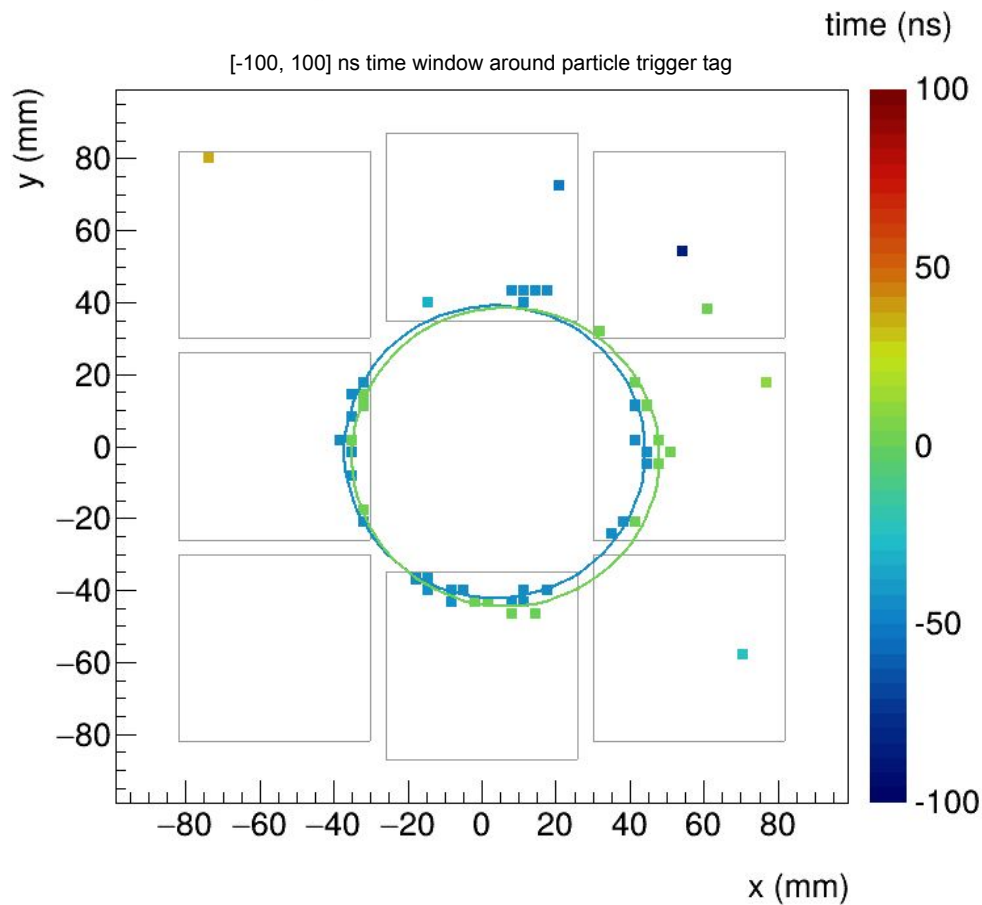
spill 0 frame 5



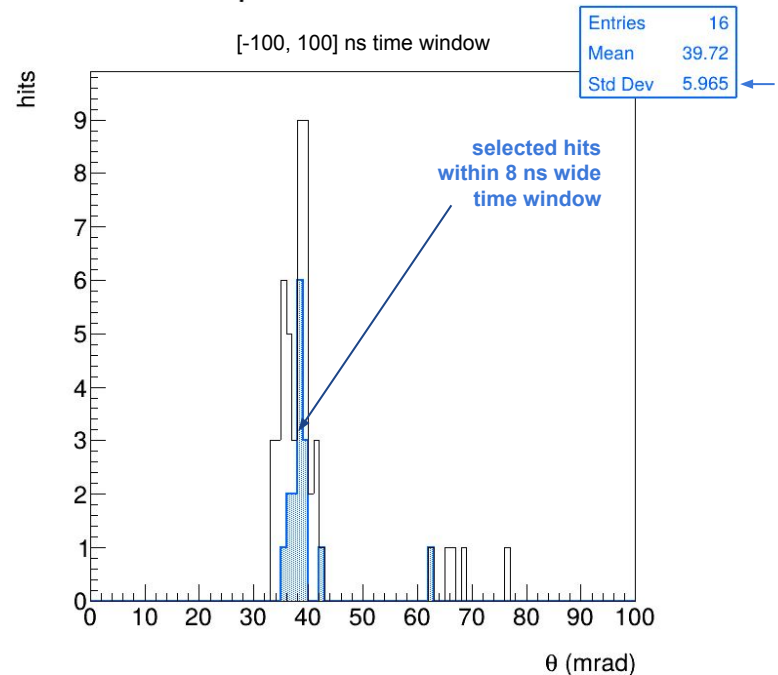
spill 0 frame 5



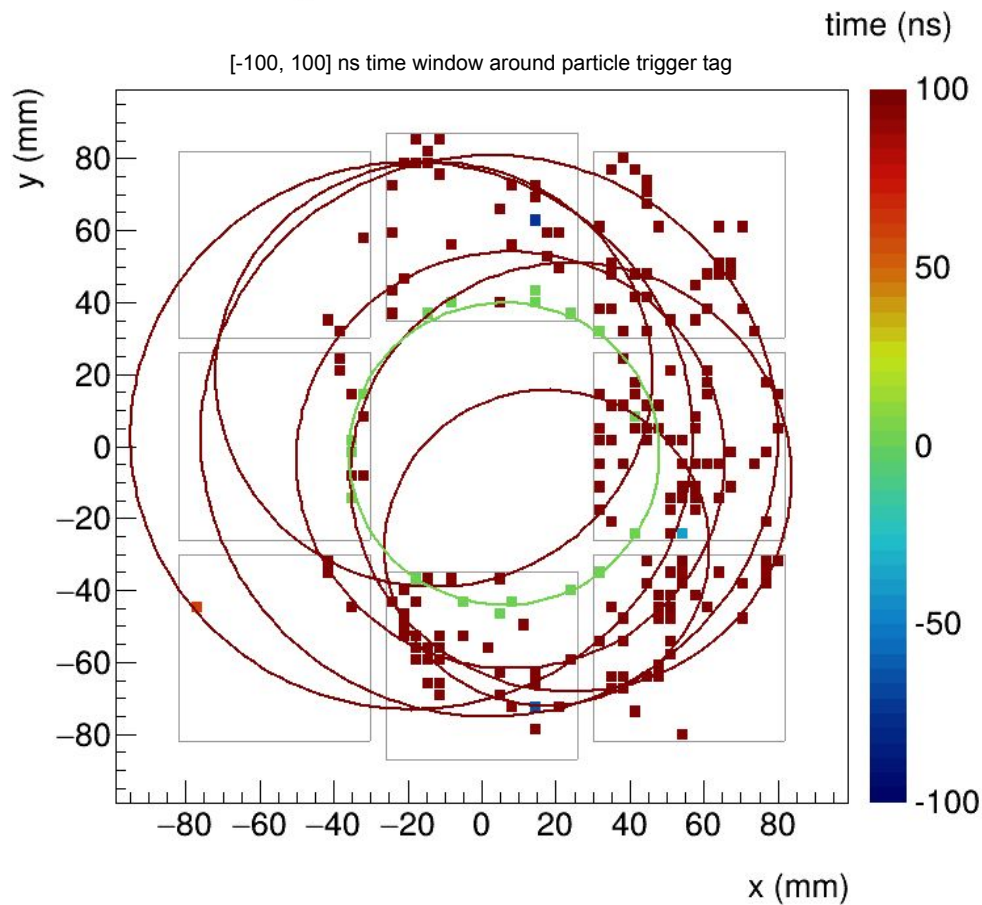
spill 0 frame 1065



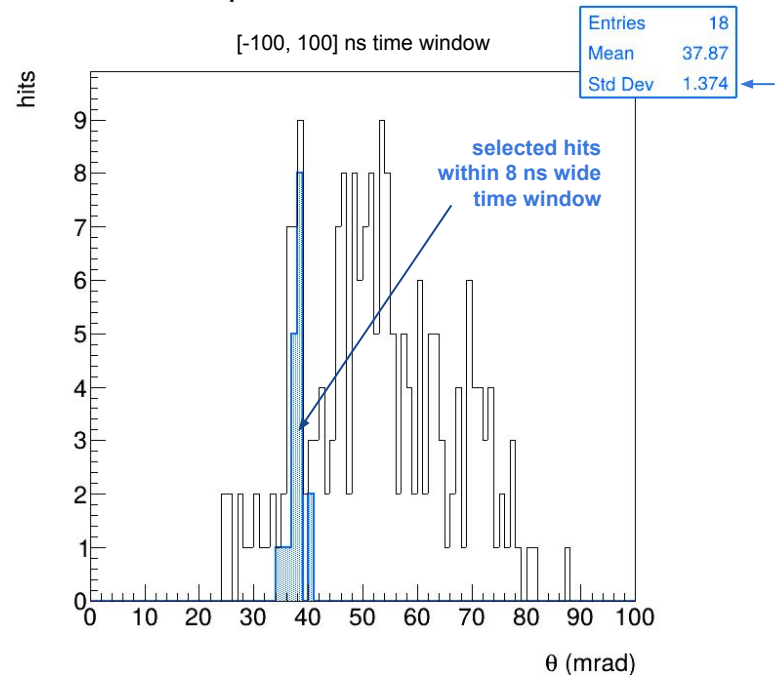
spill 0 frame 1065



spill 0 frame 21960



spill 0 frame 21960

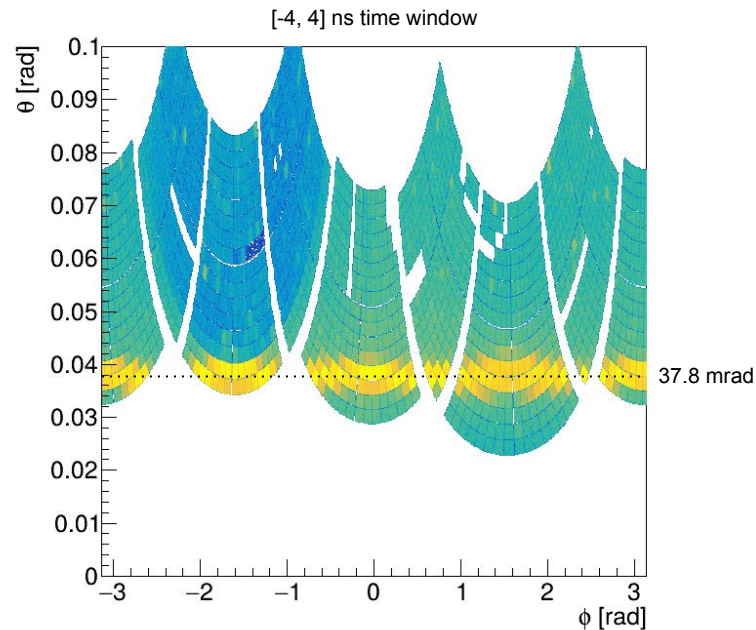
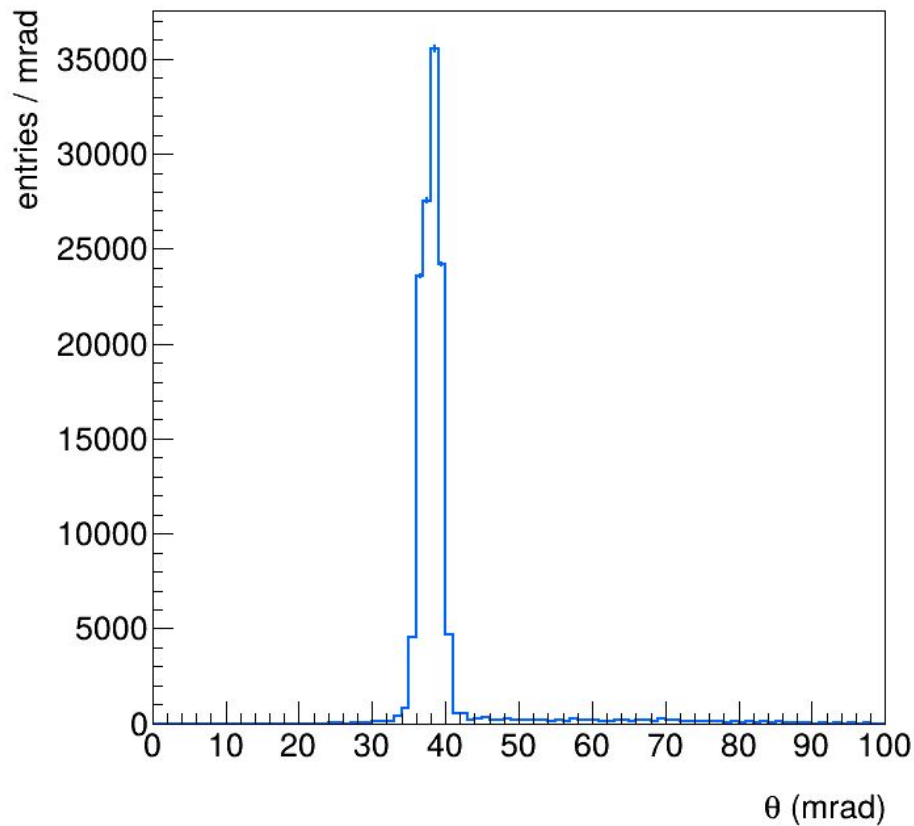


IRT-reconstructed
photon angles

Single-photon angle distribution

events with one ring
 $1.68 < x_0 < 10.53$
 $-6.93 < y_0 < 2.69$
 $30.52 < r < 53.61$

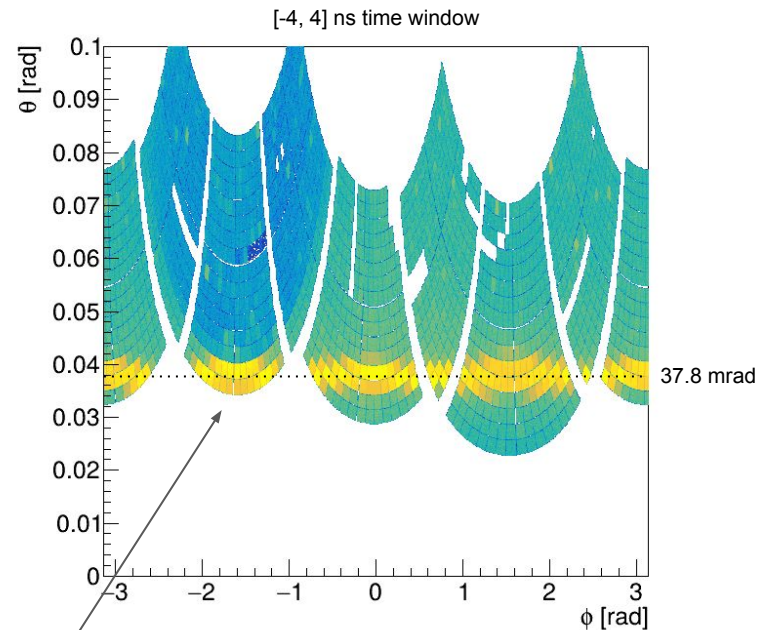
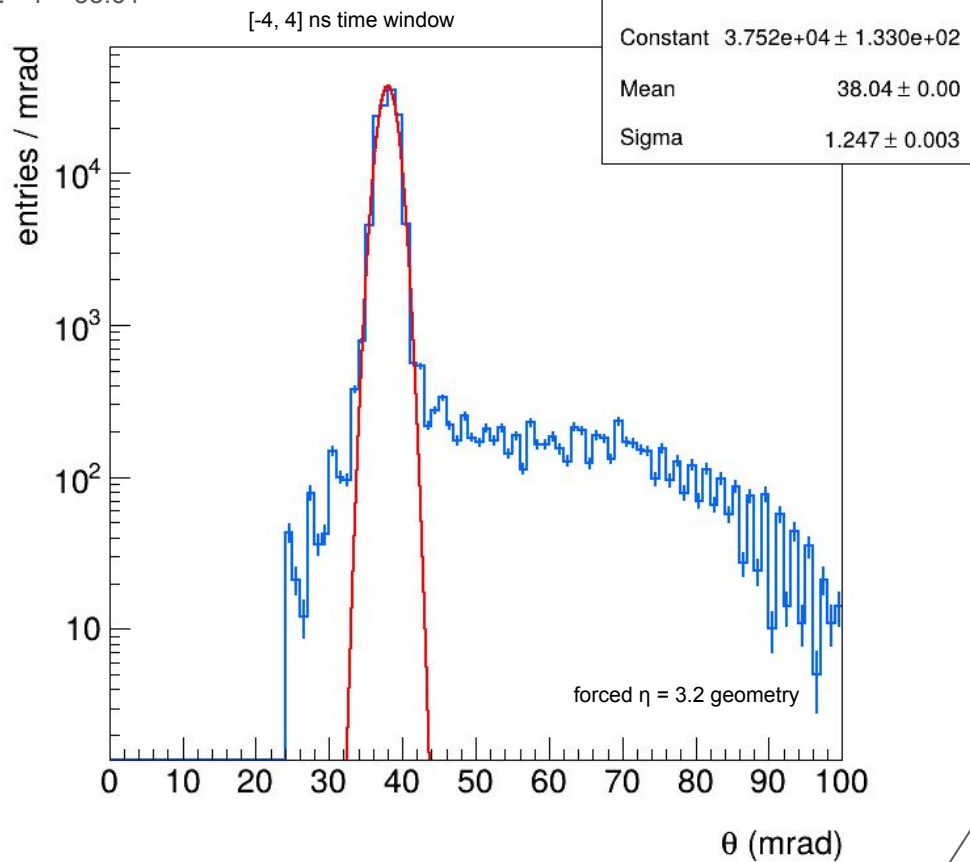
[-4, 4] ns time window around particle trigger tag



distribution of the IRT reconstructed single-photon cherenkov angle of all hits (within expected timing) in selected one-ring events

events with one ring
 $1.68 < x_0 < 10.53$
 $-6.93 < y_0 < 2.69$
 $30.52 < r < 53.61$

Single-photon angle distribution

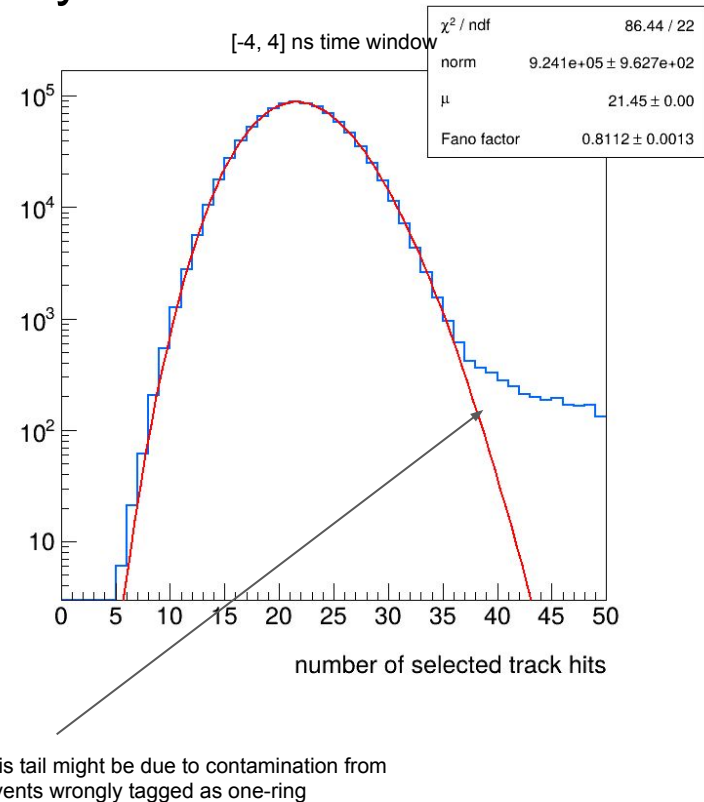
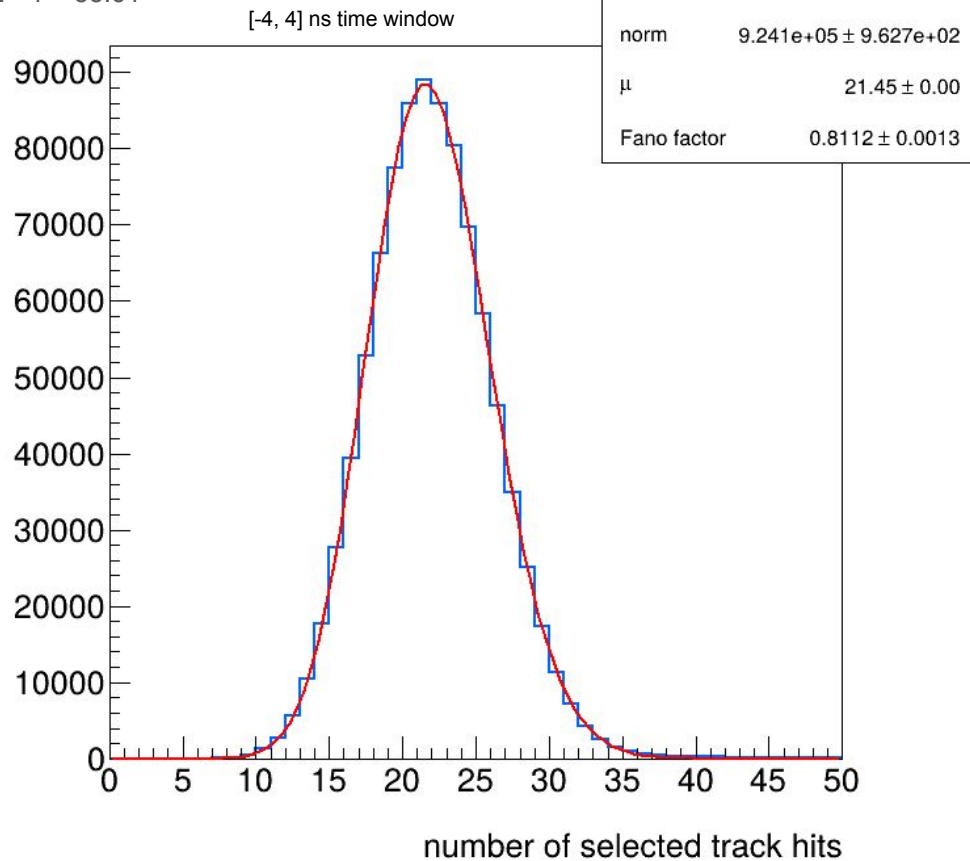


Gaussian fit yields single-photon $\sigma = 1.25$ mrad (distribution may be biased by incomplete azimuthal acceptance)

IRT-reconstructed
track angles

Track photon multiplicity

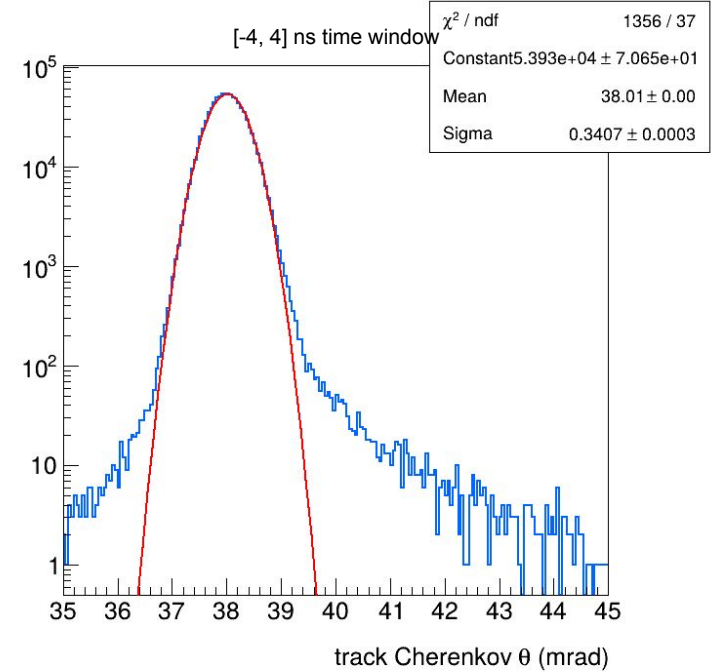
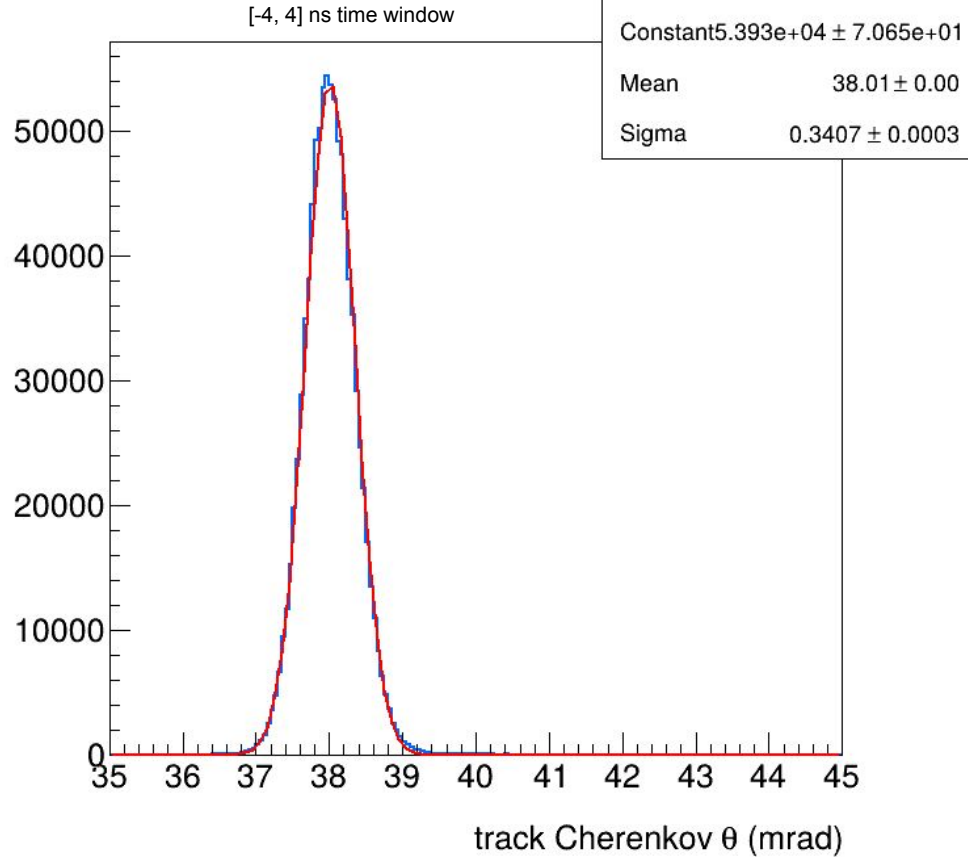
events with one ring
 $1.68 < x_0 < 10.53$
 $-6.93 < y_0 < 2.69$
 $30.52 < r < 53.61$



distribution of the number of selected track hits: large Poisson mean 21.5 hits / track, undercorrelations (Fano factor is 0.81)

Reconstructed track angle distribution

events with one ring
 $1.68 < x_0 < 10.53$
 $-6.93 < y_0 < 2.69$
 $30.52 < r < 53.61$



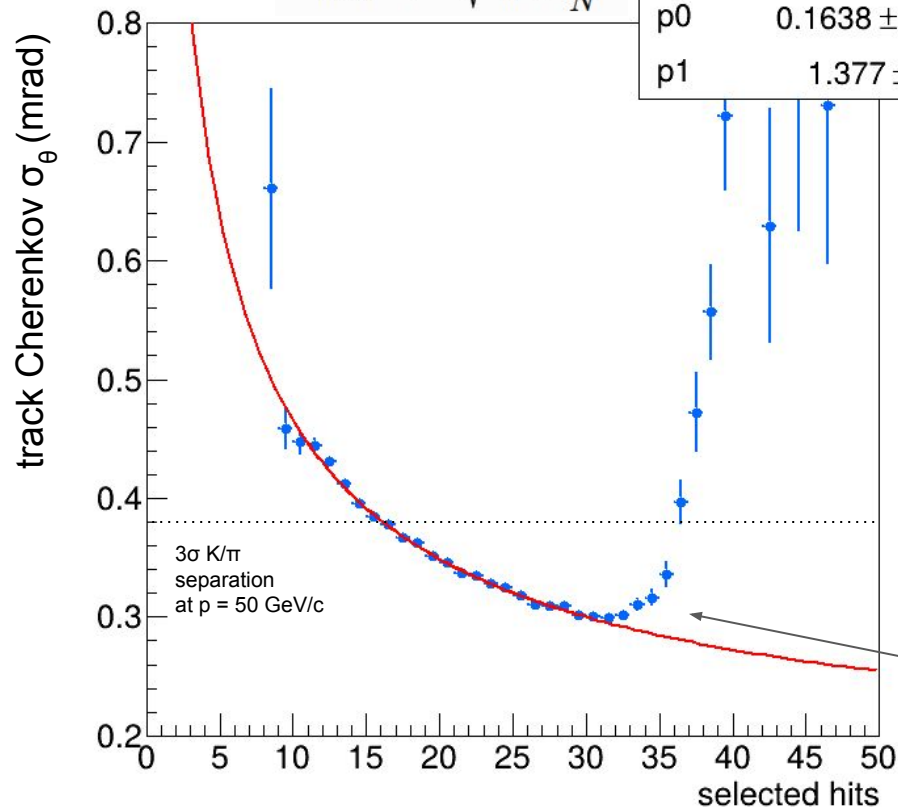
event-by-event distribution of the reconstructed track Cherenkov angle: average track Cherenkov resolution is 0.34 mrad

Resolution vs. multiplicity

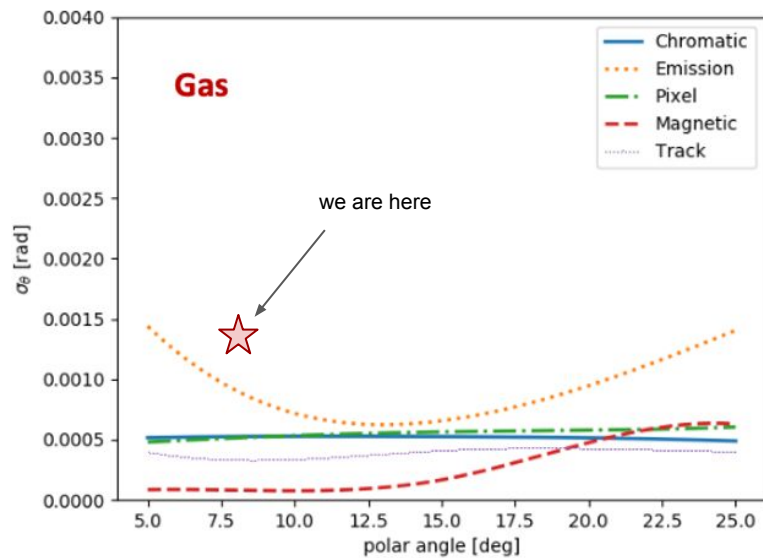
events with one ring
 $1.68 < x_0 < 10.53$
 $-6.93 < y_0 < 2.69$
 $30.52 < r < 53.61$

$$\sigma_{\text{track}}(N) = \sqrt{\sigma_0^2 + \frac{\sigma_{\text{sp}}^2}{N}}$$

χ^2 / ndf	45.19 / 18
p0	0.1638 ± 0.0031
p1	1.377 ± 0.008



Yellow Report plot: performance simulation
 estimated contributions to resolution

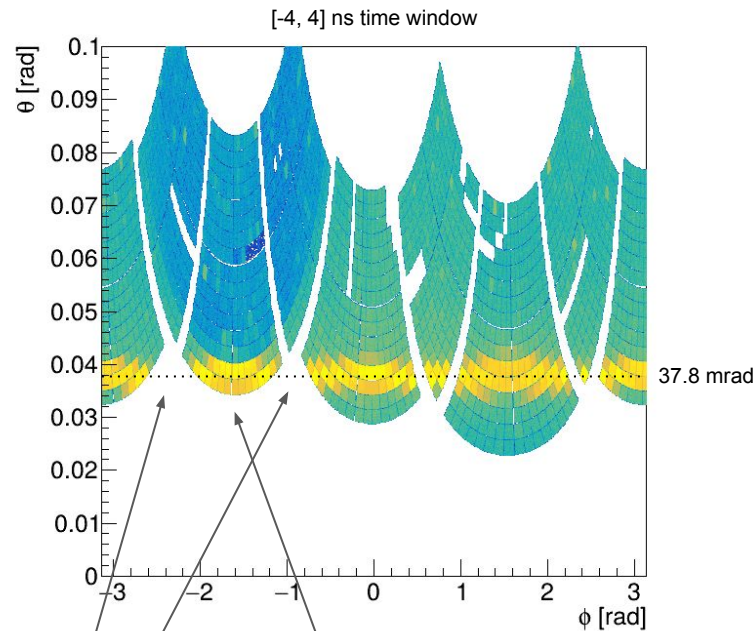
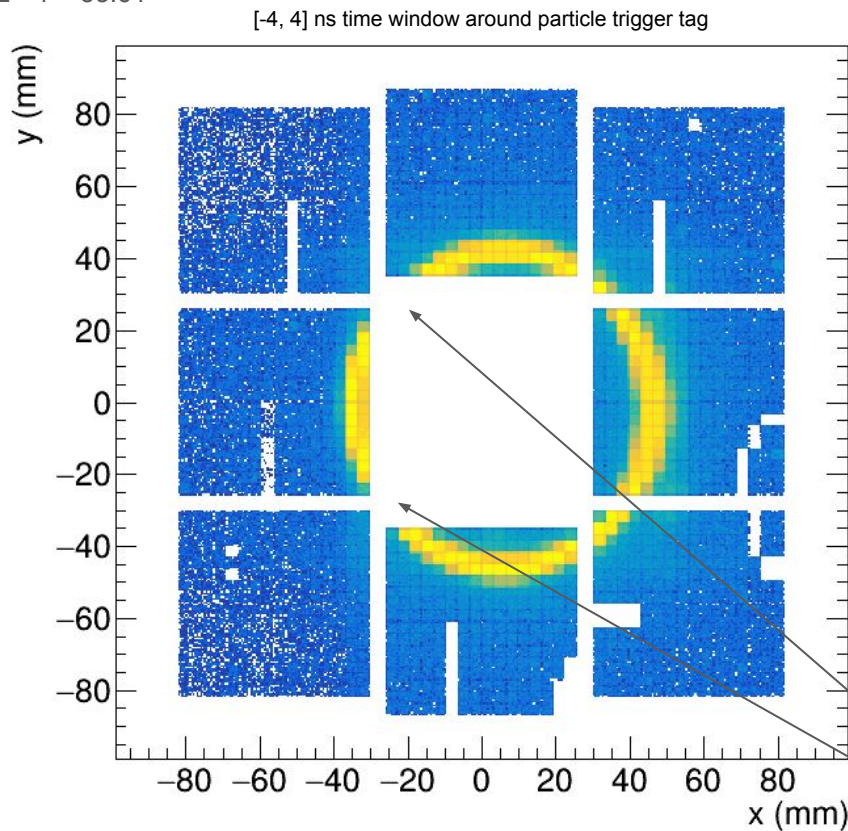


from reconstructed track rings, overall single-photon angular resolution is $\sigma_{\text{sp}} = 1.38 \text{ mrad}$, with a constant term of $\sigma_0 = 0.16 \text{ mrad}$

acceptance

Accumulated hits

events with one ring
 $1.68 < x_0 < 10.53$
 $-6.93 < y_0 < 2.69$
 $30.52 < r < 53.61$



the average 22 hits / track should be corrected by the acceptance, as we have large holes in Φ and incomplete coverage

Accumulated hits

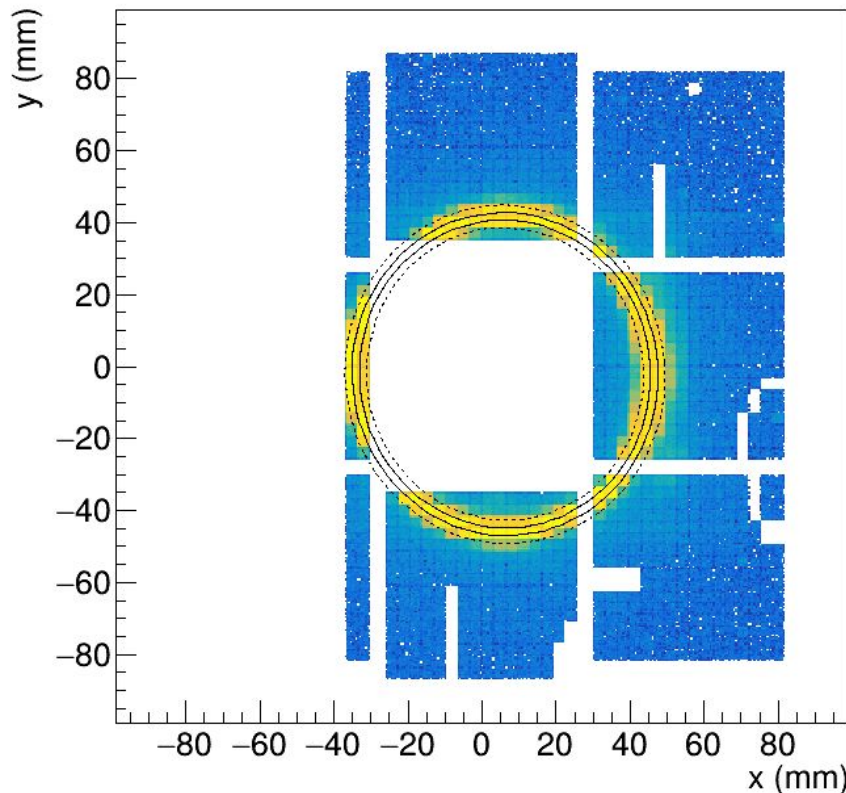
events with one ring

$$1.68 < x_0 < 10.53$$

$$-6.93 < y_0 < 2.69$$

$$30.52 < r < 53.61$$

[-4, 4] ns time window around particle trigger tag



calculations based on the fitted ellipse model

- **continuous ring**
 - 33.08 hits
- **ideal full-area pixel array**
 - with $3 \times 3 \text{ mm}^2$ pixels
 - 3.2 mm pitch
 - 29.07 hits
- **realistic full-area PDU array**
 - with 3 mm gaps between PDUs
 - 26.02 hits
- **real eight-PDU geometry**
 - 21.73 hits
 - the model matches the data

relative to the ideal full-area pixel array, the real geometry intercepts an **acceptance of ~75%**

relative to the realistic full-area PDU array, the real geometry intercepts an **acceptance of ~83.5%**

ellipse fit to the observed ring pattern, estimated acceptance: ~83.5% → average 26 photons/track (close to simulation)

Summary

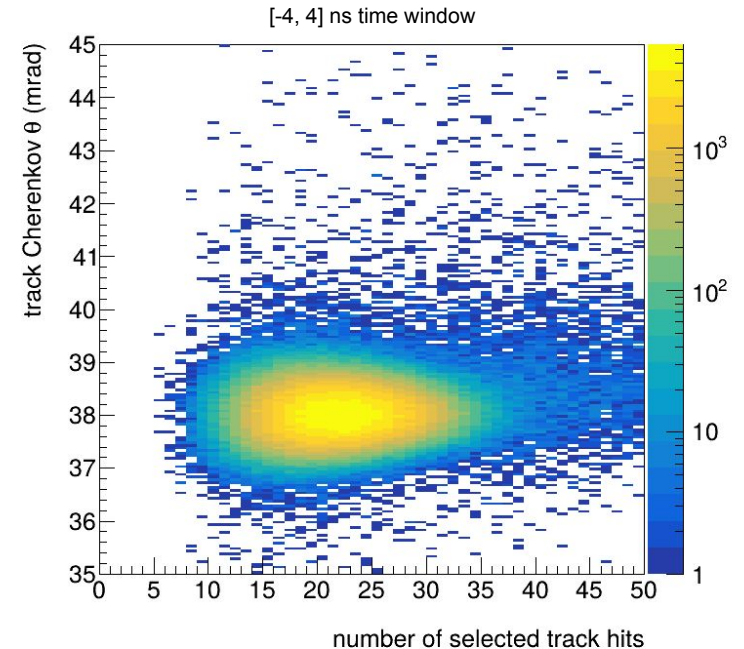
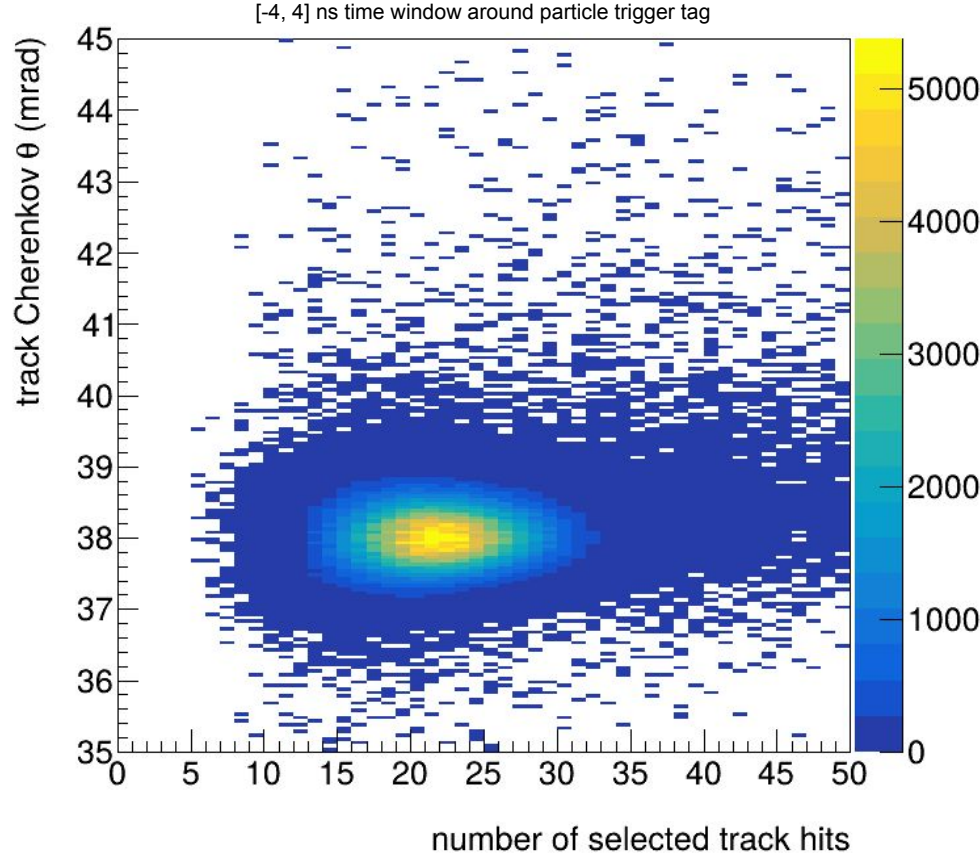
- **successful operation** of the 2048-channel SiPM photodetector on the real-scale dRICH prototype
 - clear Cherenkov-ring reconstruction with event-by-event timing selection
 - geometry aligned directly from data using inverse ray tracing
- **mean detected photon yield**
 - 21.5 photons per track in the instrumented geometry
 - 26 photons per track acceptance-corrected expectation
 - preliminarily consistent with simulations
- **track Cherenkov-angle resolution**
 - 0.34 mrad
 - fulfils requirement for 3σ K/ π separation at $p = 50$ GeV/c
- **single-photon angular resolution**
 - approximately 1.3–1.4 mrad
 - compatible with the simulated expectation within the present analysis precision

First results are consistent with the expected dRICH performance and with the requirements for forward hadron identification at the EIC
further data-analysis, selection and systematic studies are ongoing



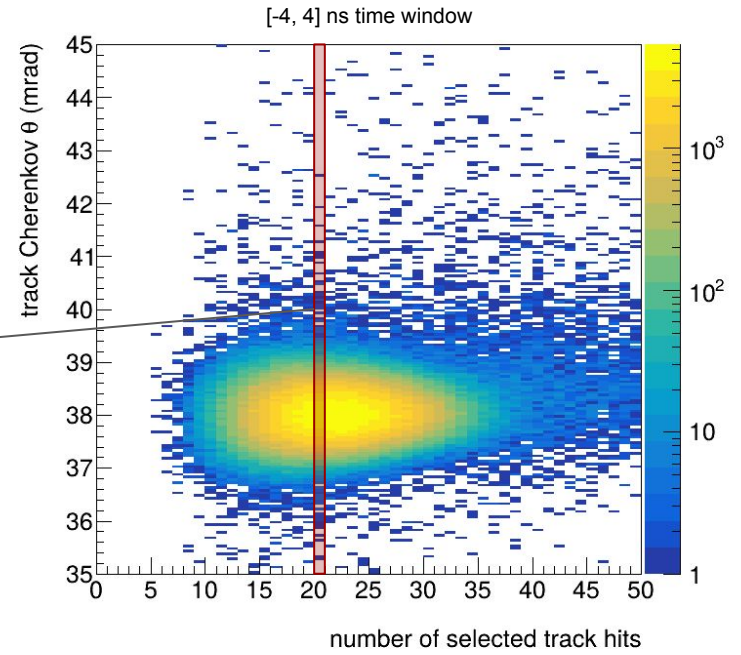
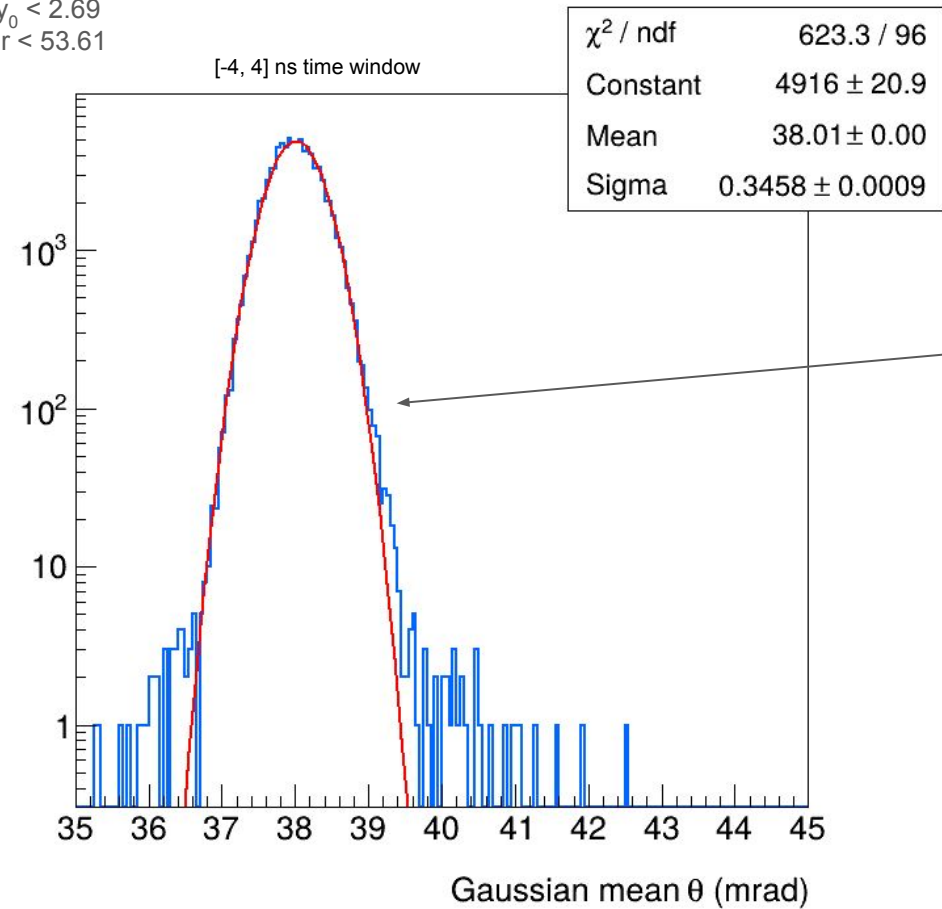
That's all Folks!

events with one ring
 $1.68 < x_0 < 10.53$
 $-6.93 < y_0 < 2.69$
 $30.52 < r < 53.61$



extract single-photon angular resolution from the gaussian fits in slices of the track hit multiplicity

events with one ring
 $1.68 < x_0 < 10.53$
 $-6.93 < y_0 < 2.69$
 $30.52 < r < 53.61$



extract single-photon angular resolution from the Gaussian fits in slices of the track hit multiplicity (here shown N = 20 slice)