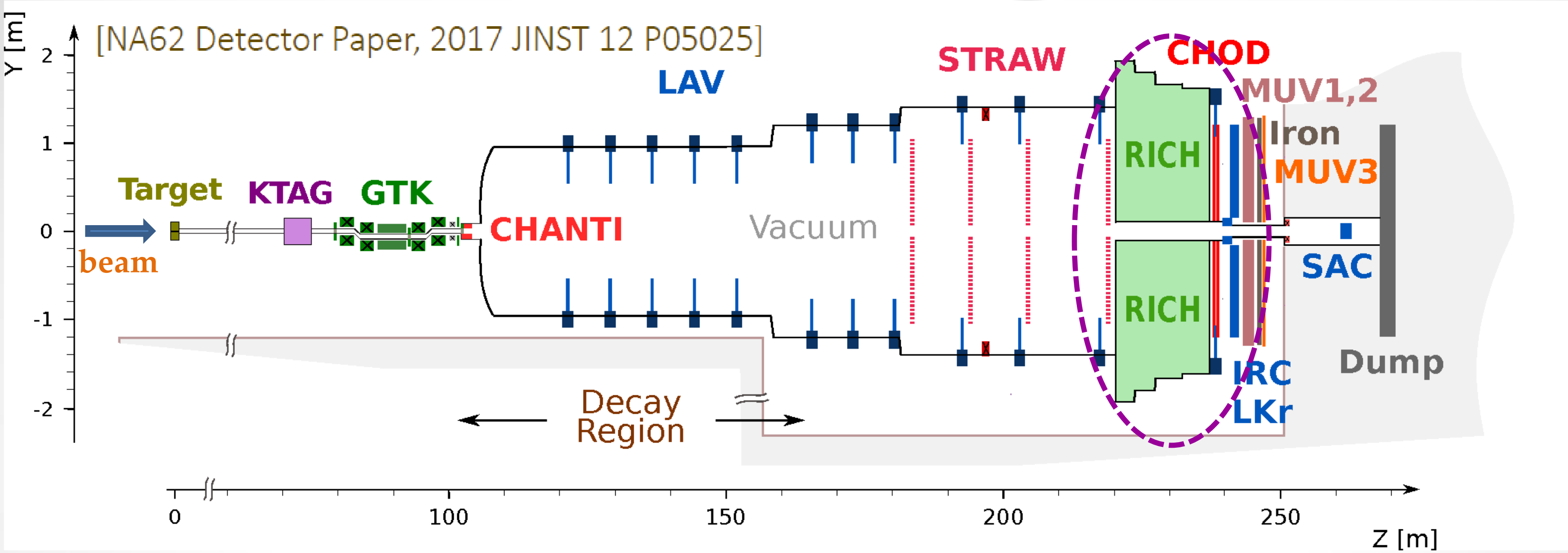
NA62 RICH performance: measurement and optimization

Viacheslav Duk
on behalf of the NA62 RICH working group

Outline

- NA62 and RICH
- Precise mirror alignment
- RICH performance:
  - Electron selection
  - Single ring iterative fit
  - Single hit time resolution
  - Number of hits
  - Ring radius resolution
  - Ring centre (track slope) resolution
  - Single hit resolution
- Conclusions

NA62 setup



Secondary positive beam	
Momentum	75 GeV/c, 1% bite
Divergence (RMS)	100 µrad
Transverse Size	$60 \times 30\text{mm}^2$
Composition	$K^+(6\%)/\pi^+(70\%)/p(24\%)$
Nominal Intensity	33×10^{11} ppp (750 MHz at GTK3)

Decay region and Detectors	
Fiducial region	60 m
K^+ decay rate	~ 5 MHz
Vacuum	$\mathcal{O}(10^{-6})$ mbar

- **Main goal**: BR($K^+ \to \pi^+ \nu\nu$) measurement
- Other: search for New Physics in rare decays

See the talk by Patrizia Cenci for details

NA62 and RICH requirements

NA62 requirements:
- 10^{13} kaon decays in the fiducial volume
- O(100) signal events
- ~10% precision

See the talk by Patrizia Cenci for details

O(10^{12}) background rejection

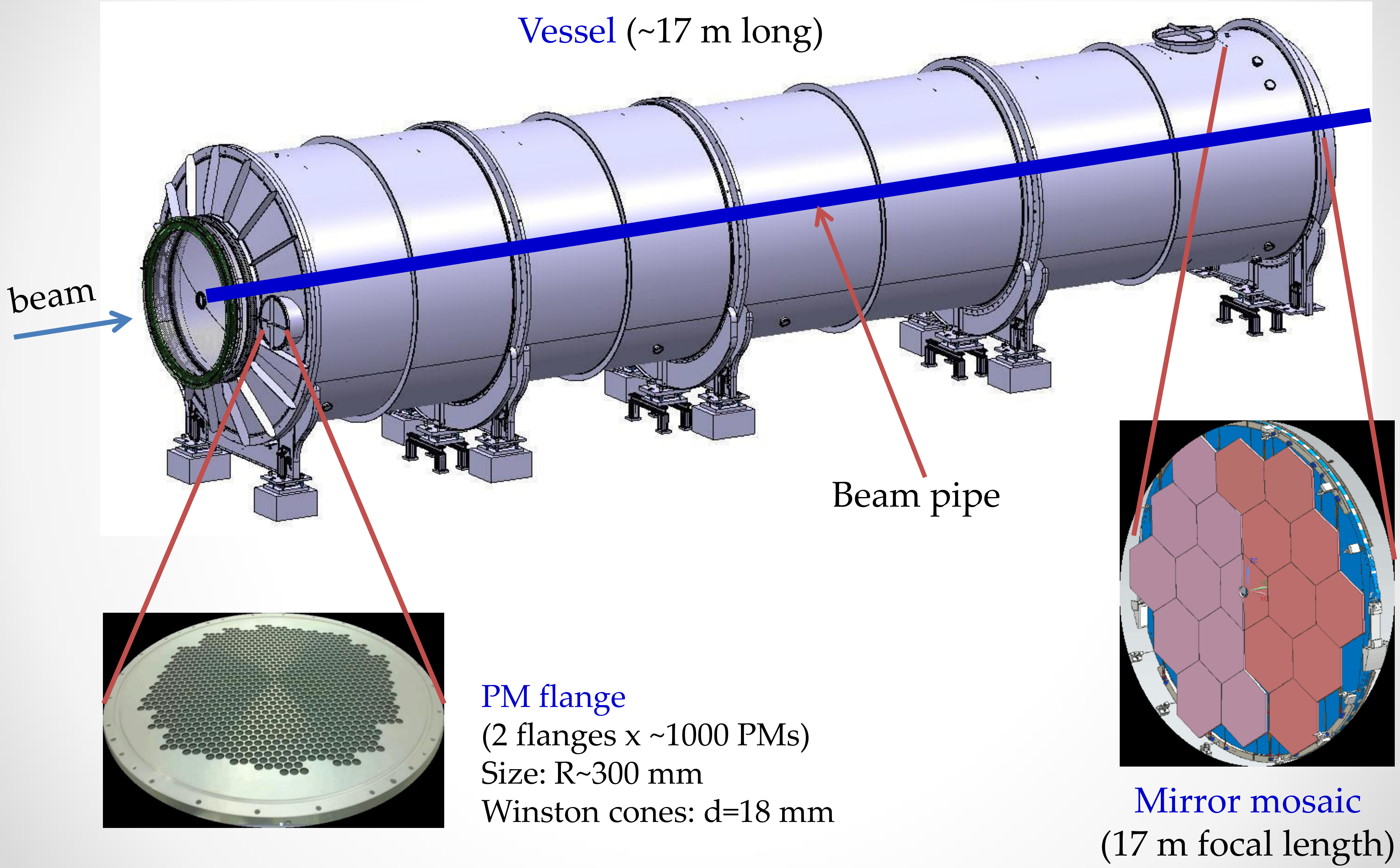
Main kaon decay modes

decay	BR
$K^+ \to \mu^+ \nu_\mu$	63.6%
$K^+ \to \pi^+ \pi^0$	20.7%

Rejection of $K^+ \to \mu^+ \nu_\mu$:
- Kinematics: O(10^4)
- PID in calorimeters: >10^5
- PID in **RICH:** >10^2

RICH requirements:
- Muon misID probability at the ~10^{-2} level in 15 GeV/c < p < 35 GeV/c
- Measure the pion crossing time with ~100 ps resolution
- Provide L0 trigger for charged tracks

RICH layout

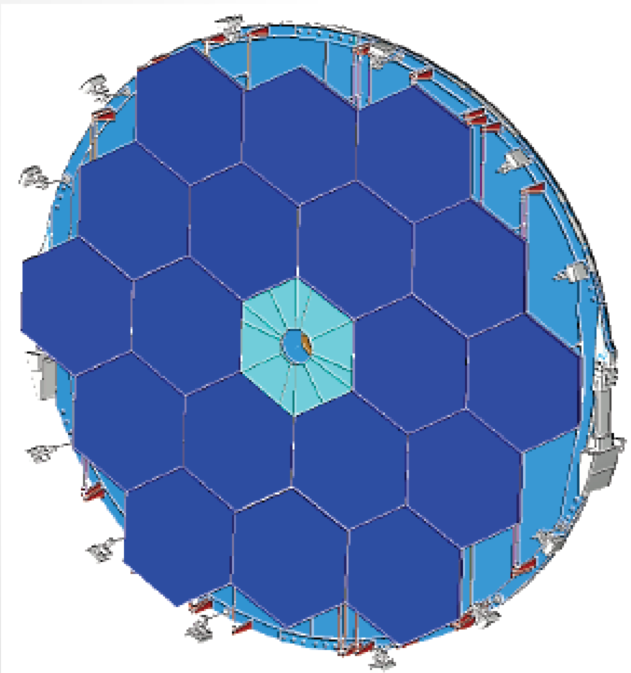


Vessel (~17 m long)
beam
Beam pipe
PM flange
(2 flanges x ~1000 PMs)
Size: R~300 mm
Winston cones: d=18 mm
Mirror mosaic
(17 m focal length)

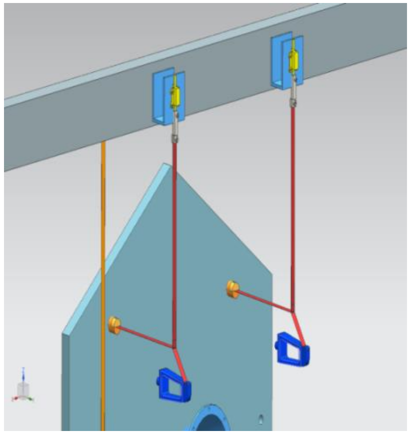
RICH mirrors

RICH mirrors:

- 18 hexagonal mirrors (35 cm side), 2 semi-hexagonal (central part)
- Made of 2.5 cm thick glass (~20% X_0)
- Al coating
- Thin dielectric film to improve reflectivity



Mirror mosaic



Al ribbons and piezo motors

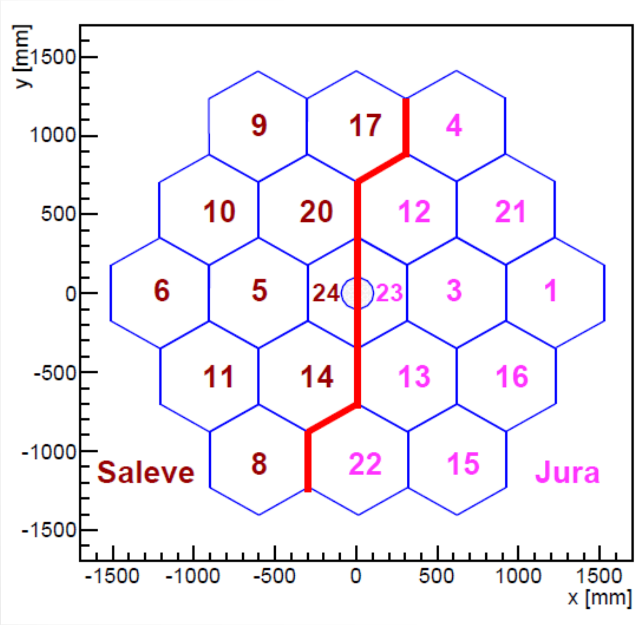
Mirror support system:

- 5 cm thick honeycomb panel
- Mirrors are supported by the dowel connected to the support panel
- two Al ribbons allow for the mirror orientation
- One Al ribbon to prevent mirror rotation
- Two piezo motors to rotate mirrors remotely

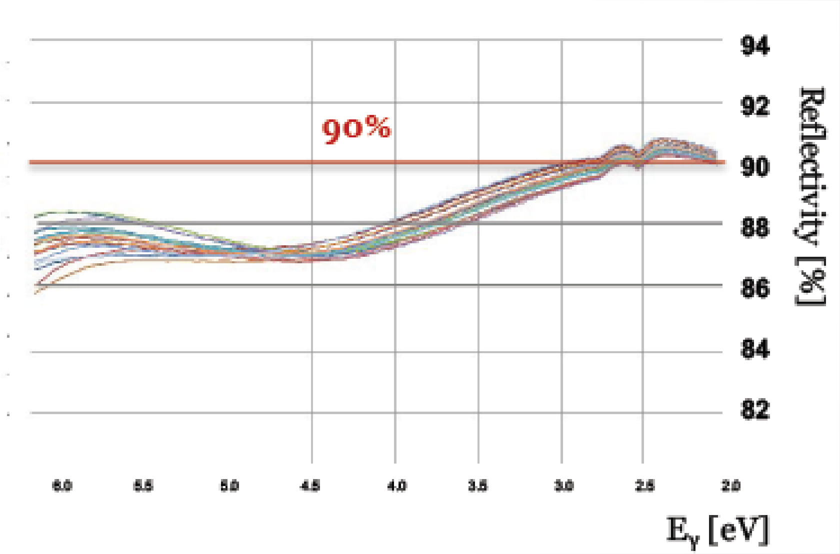
RICH mirrors

2 mirror groups (Jura, Saleve):
- Each group is oriented towards a corresponding PM flange

Mirror optical properties:
- R = 34 m
- Reflectivity ~88% (λ = 195-650 nm)
- $D_0 \leq 4$ mm



Mirror numbering

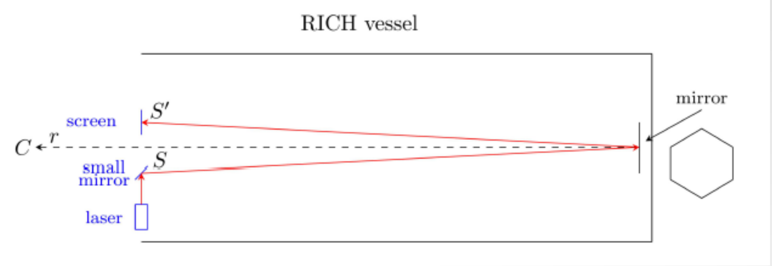


Reflectivity measurement: one curve per mirror

RICH mirror alignment

Preliminary laser alignment:

- Measured before closing the vessel
- Setup with ~10 m lever arm (R=34 m)
- **Precision O(500) μrad** in terms of mirror orientation



Precise alignment with data:

- Measured during data taking
- Use reconstructed tracks
- Iterative procedure
- **Precision O(30) μrad** in terms of mirror orientation

Mirror alignment: procedure

Event selection:
- single track in the mirror acceptance
- Area illuminated by the cherenkov light in the acceptance of a single mirror (steps 1, 2) or a single group (step 3)
- single ring 100% in PM acceptance (>80% for lateral mirrors)

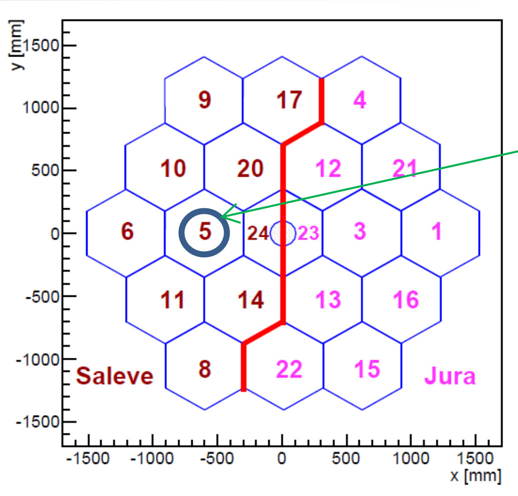
Step 1:
- Measure the **absolute misalignment AM** for 20 mirrors
- AM = Real – Predicted
- Real ring centre: ring fit
- Predicted ring centre: track extrapolation to the PM plane (nominal orientation assumed)

↳ **Step 2:**
- Calculate the **relative misalignment** for 18 hexagonal mirrors
- Reference (one per group): semihex mirror
- Calculate **piezo motor movements** needed to compensate the relative misalignment
- Rotate mirrors

↳ **Step 3:**
- Calculate a **global offset GO** (average absolute misalignment) for each group
- Calculate **residual misalignment RM** (RM = AM – GO) for each mirror

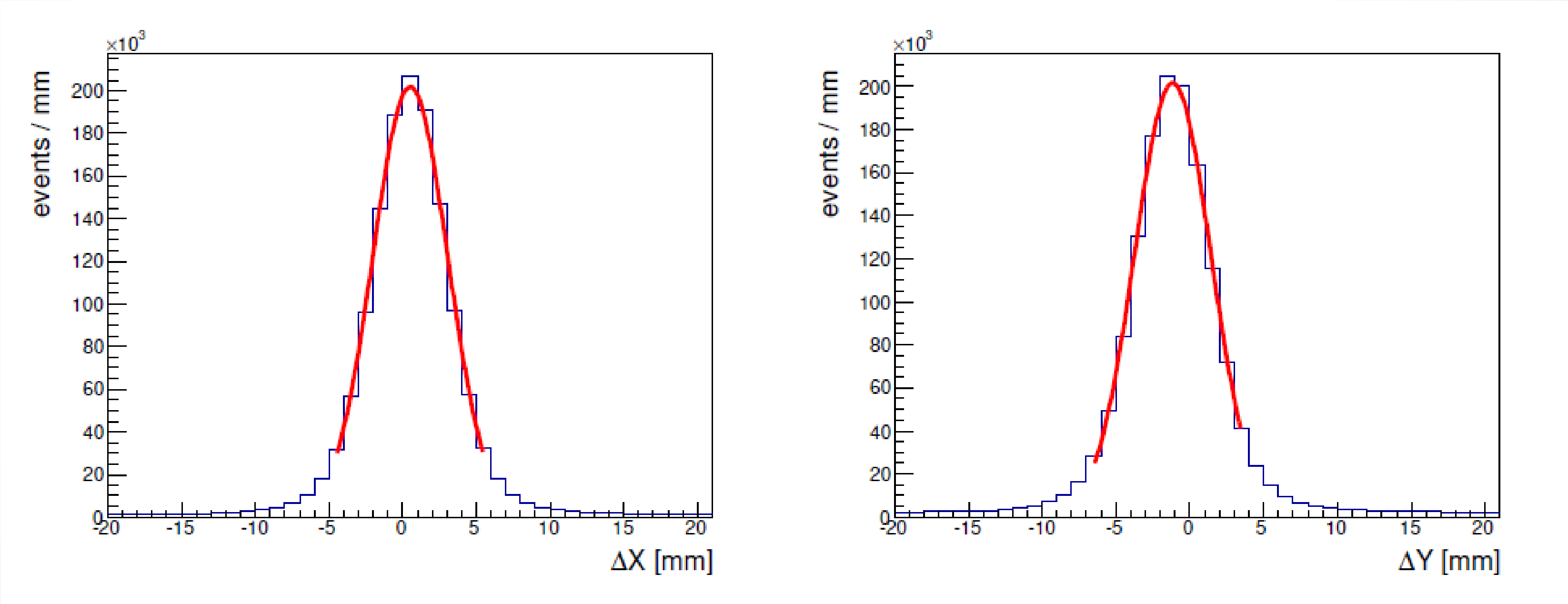
End of the iteration procedure:
- Residual misalignment O(1) mm (i.e. 30 μrad)

Mirror alignment: example



Alignment in 2016, step 1:

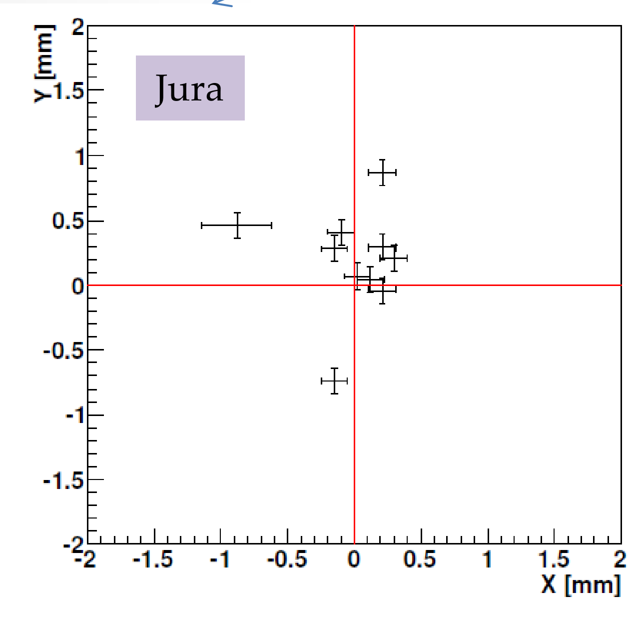
- Mirror #5
- Global offsets of the previous iteration subtracted
- Gaussian fit performed
- Absolute misalignment is the gaussian mean

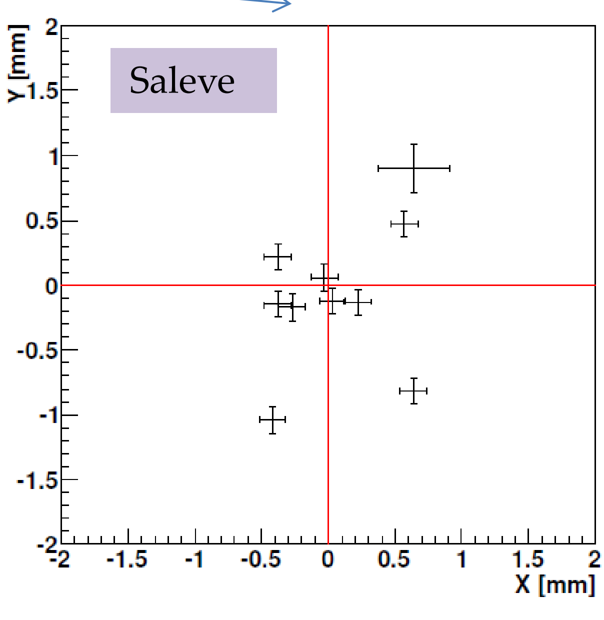


Mirror alignment: results

Alignment in 2016, step 3:

- Global offsets ~O(20) mm
- Residual misalignment (one point = one mirror)





Performance optimization:

- ✓ Misalignment measurement on a monthly basis
- ✓ Global offsets and residual misalignment stored in a database

RICH performance

RICH performance depends a lot on the event selection

"basic" performance:

- Dedicated event selection
- Resolution of "low-level" variables
- Can be compared with other RICHes

"real" performance:

- Analysis-driven event selection (e.g. $K^+ \rightarrow \pi^+ \nu\nu$)
- "high-level" variables (PID)

Measurement:

- Electron sample from $K^+ \rightarrow e^+ \nu_e \pi^0$
- Rings fully in acceptance

This talk

Measurement (π/μ PID):

- $\pi\nu\nu$-like selection
- Pion sample from $K^+ \rightarrow \pi^+ \pi^0$
- Muon sample from $K^+ \rightarrow \mu^+ \nu_\mu$

See the talk by Roberta Volpe for details

RICH measurements and performance

RICH measurement	Where used	Performance parameter
Time		
Ring radius		
Ring centre		
N_{hits}*		

* : $N_{hits} \approx N_{photons}$ (one photon per PM)

RICH measurements and performance

RICH measurement	Where used	Performance parameter
Time	L0 trigger	
Ring radius	PID	
Ring centre	Complementary track slope measurement	
N_{hits}*	Specific event selection, PID	

* : $N_{hits} \approx N_{photons}$ (one photon per PM)

RICH measurements and performance

RICH measurement	Where used	Performance parameter
Time	L0 trigger	• Single hit time resolution • event time resolution
Ring radius	PID	• Ring radius resolution • single hit resolution
Ring centre	Complementary track slope measurement	• Ring centre resolution
N_{hits}*	Specific event selection, PID	• $\langle N_{hits} \rangle$ • Figure of Merit

* : $N_{hits} \approx N_{photons}$ (one photon per PM)

Iterative single ring fit

Standalone single ring fit:

- No track information
- $\Sigma|r_i - r_0 - R|^2 / \sigma_{hit}^2$ is minimized (r_i : hit position, σ_{hit} : single hit resolution)
- Fit result: ring centre r_0 , ring radius R
- $NDF = N_{hits} - 3$

Iterative single ring fit (to remove noisy hits):

- Perform the standard single ring fit
- Calculate $\chi 2(iter) = (r_i - r_0 - R)/\sigma_{hit}^2 + (t_i - \langle t \rangle)^2/\sigma_t^2$ for each hit

  (<t> : average hit time, σ_t=0.28 ns)
- A hit with the largest $\chi 2$(iter) is removed

Conditions to stop the iterative procedure (OR):

- $\chi 2(iter) < 4$ for each hit
- $N_{hits} = 4$
- $N_{iter} > 5$

Performance optimization:

✓ Fit procedure can be tuned for single-track analyses (standalone, track seeded, combination)

Single hit time resolution

($t_{hit} - t_{ref}$) distribution: non-gaussian due to delayed hits (known issue)

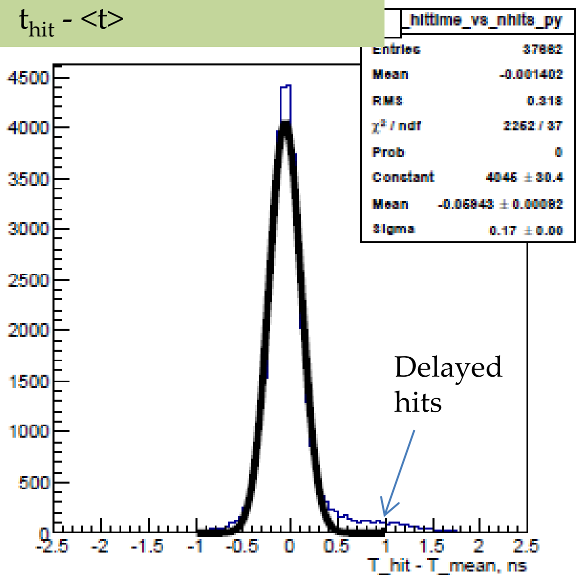
Gaussian part:

- plot (t_{hit} - <t>)
- Fit the central part

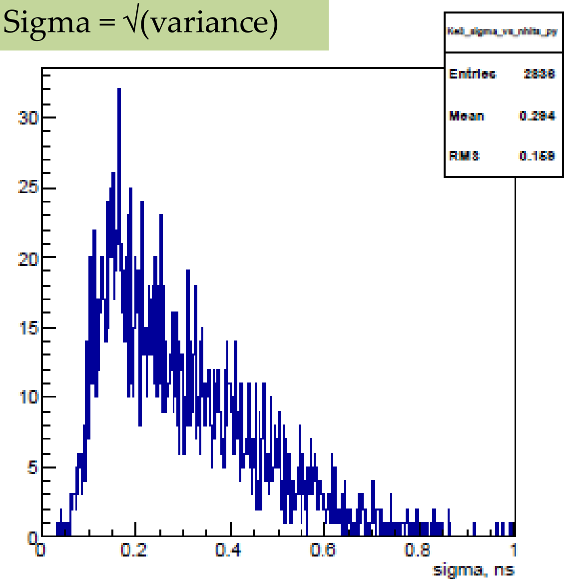
RMS:

- Calculate variance of hit times
- Plot $\sqrt{(\text{variance})}$
- RMS is the histogram mean

t_{hit} - <t>



Sigma = $\sqrt{(\text{variance})}$



Gaussian part: 0.17 ns
RMS: ~0.28 ns

Event time resolution: see the talk by Roberta Volpe

Number of hits

Poissonian fit:
$\langle N_{hits} \rangle = 13.8$

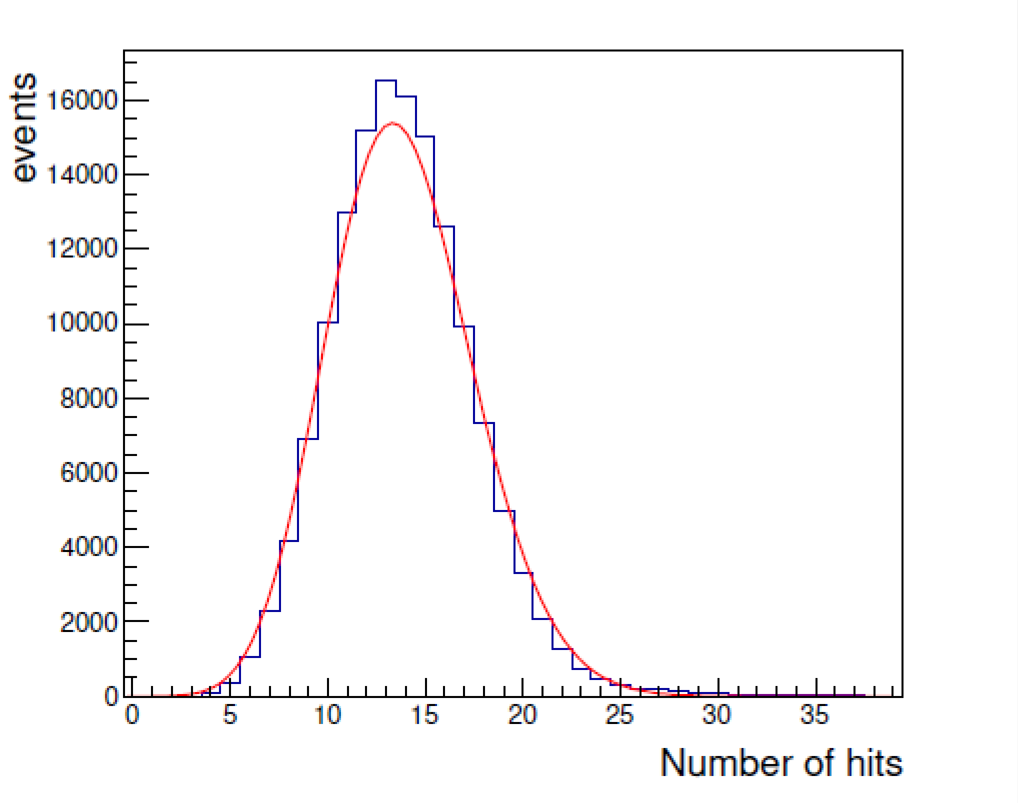


Figure of Merit N_0:
$N_{hits} = N_0 * L * \sin^2\theta$

$N_0 = 65\ cm^{-1}$

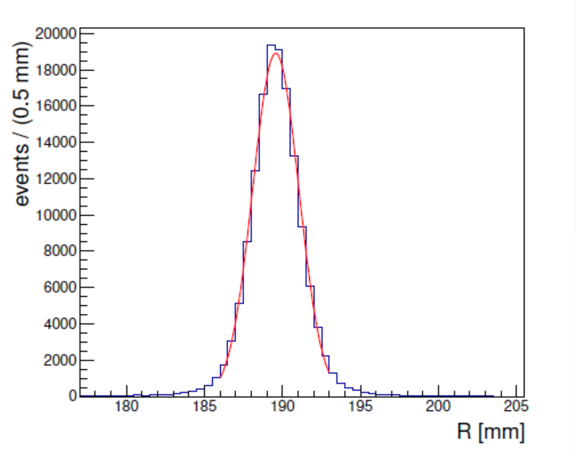
Performance optimization:
- ✓ $\langle N_{hits} \rangle$ is measured on a run-by-run basis
- ✓ Values are stored in a database

Ring radius and ring centre resolution

Ring radius:
- <R> = 189.6 mm (θ = 11.2 mrad)
- σ (R) = 1.47 mm (90 µrad)

→ Ring radius resolution

Ring radius distribution

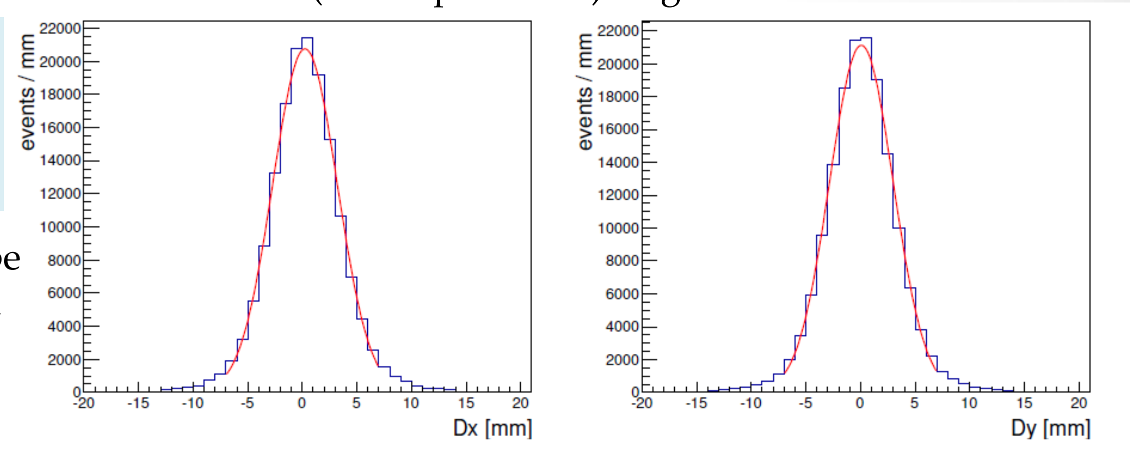


Ring centre (track slope) :
- σ (Dx) = 2.96 mm (170 µrad)
- σ (Dy) = 2.92 mm (170 µrad)

Ring centre resolution

Track slope resolution

(Real – predicted) ring centre



→ Spectrometer contribution: < 0.6 mm (< 35 µrad)

Performance optimization:
- ✓ <R> is measured on a run-by-run basis
- ✓ Values are stored in a database

Single hit (space) resolution

Single hit resolution σ_{hit}:

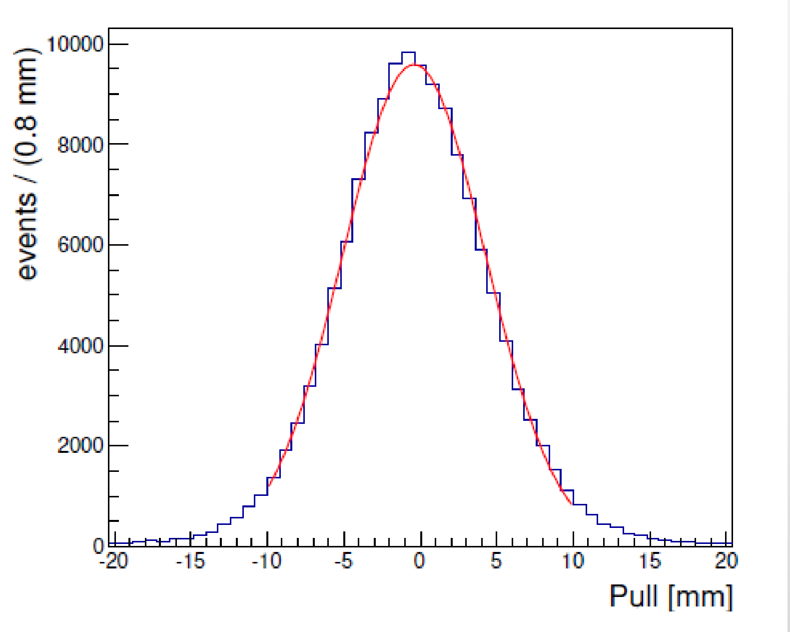
- "Normalized" (per hit) ring radius resolution
- Must be synchronized with the ring fit method
- $Pull = (R - \langle R \rangle)\sqrt{(N_{hits} - 3)}$ used for σ_{hit} determination

→ Classical approach: hit-ring centre distance

Single hit resolution:

- σ_{hit} = 4.66 mm (270 μrad)

Pull distribution



Resolution key factors

factor	Impact	Contribution to the resolution	How to measure
Mirror misalignment			
Multiple scattering (entrance window)			
Multiple scattering (Ne)			
Cone geometry			
Ne dispersion			

Resolution key factors

factor	Impact	Contribution to the resolution	How to measure
Mirror misalignment	• Hit position		
Multiple scattering (entrance window)	• Track slope		
Multiple scattering (Ne)	• Photon emission angle		
Cone geometry	• Hit position • N_{hits}		
Ne dispersion	• Cherenkov angle		

Resolution key factors

factor	Impact	Contribution to the resolution	How to measure
Mirror misalignment	• Hit position	▪ σ_{hit} ▪ $\sigma(Dx/Dy)$	
Multiple scattering (entrance window)	• Track slope	▪ $\sigma(Dx/Dy)$	
Multiple scattering (Ne)	• Photon emission angle	▪ σ_{hit} ▪ $\sigma(Dx/Dy)$	
Cone geometry	• Hit position • N_{hits}	▪ σ_{hit} ▪ $\sigma(Dx/Dy)$	
Ne dispersion	• Cherenkov angle	▪ σ_{hit} ▪ $\sigma(Dx/Dy)$	

Resolution key factors

factor	Impact	Contribution to the resolution	How to measure
Mirror misalignment	• Hit position	▪ σ_{hit} ▪ $\sigma(Dx/Dy)$	Data
Multiple scattering (entrance window)	• Track slope	▪ $\sigma(Dx/Dy)$	Analytical calculation
Multiple scattering (Ne)	• Photon emission angle	▪ σ_{hit} ▪ $\sigma(Dx/Dy)$	Toy MC
Cone geometry	• Hit position • N_{hits}	▪ σ_{hit} ▪ $\sigma(Dx/Dy)$	Toy MC
Ne dispersion	• Cherenkov angle	▪ σ_{hit} ▪ $\sigma(Dx/Dy)$	Analytical calculation

Mirror misalignment contribution

Measure resolutions for two event selection:
- All
- Single mirror

Mirror misalignment contribution is the quadratic difference (All – Single mirror)

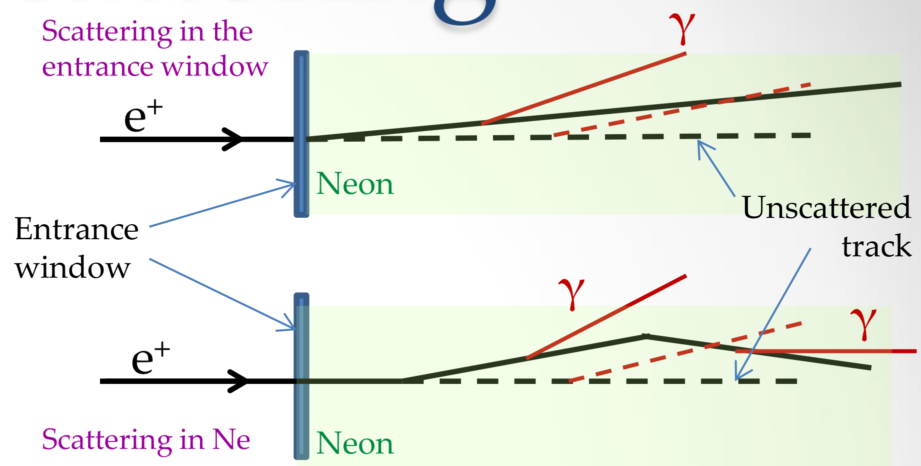
resolution	all	Single mirror	Misalignment contribution
$\sigma(R)$, mm	1.47	1.31	0.7
$\sigma(Dx)$, mm	2.96	2.82	0.9
$\sigma(Dy)$, mm	2.92	2.83	0.7
σ_{hit} , mm	4.66	4.18	2.1

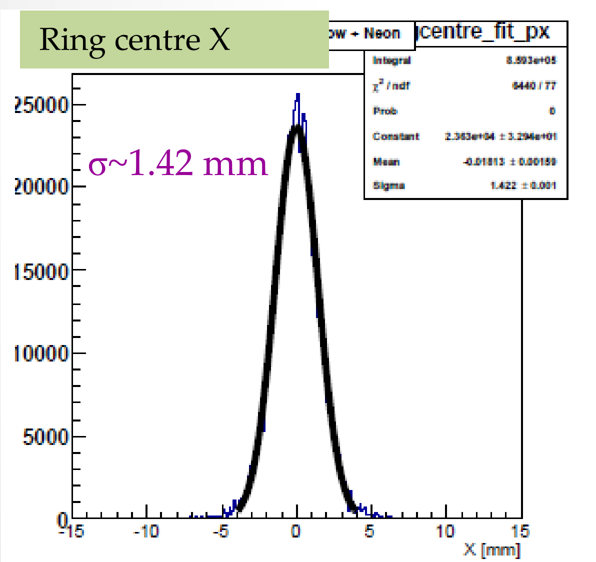
Performance optimization:
- ✓ Misalignment contribution is not dominant
- ✓ Mirror alignment is optimized

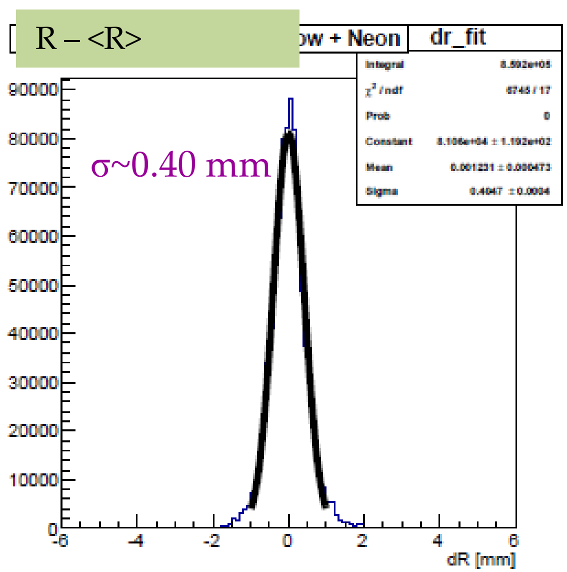
Multiple scattering

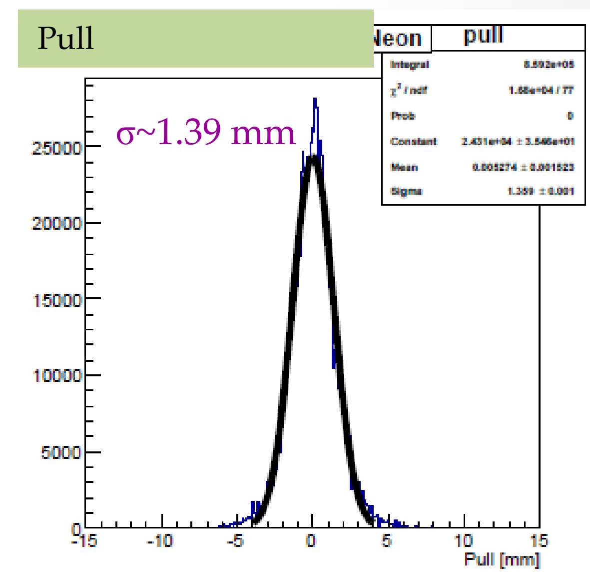
Toy MC:

- Entrance window (2 mm Al, 2.2% X_0)
- Ne (17 m, 5.6% X_0)
- Photon emission points



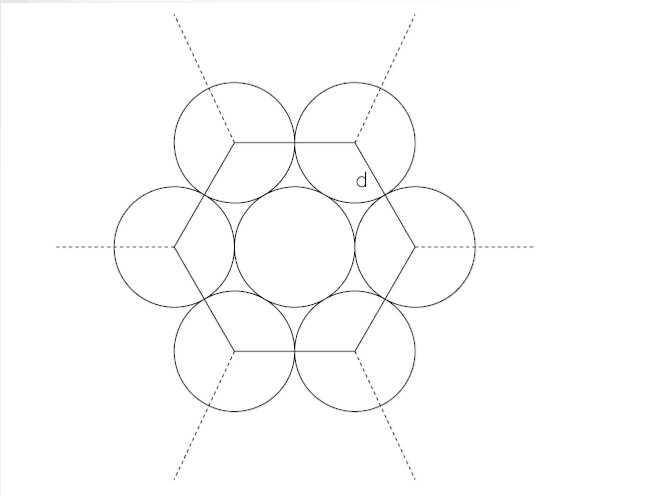






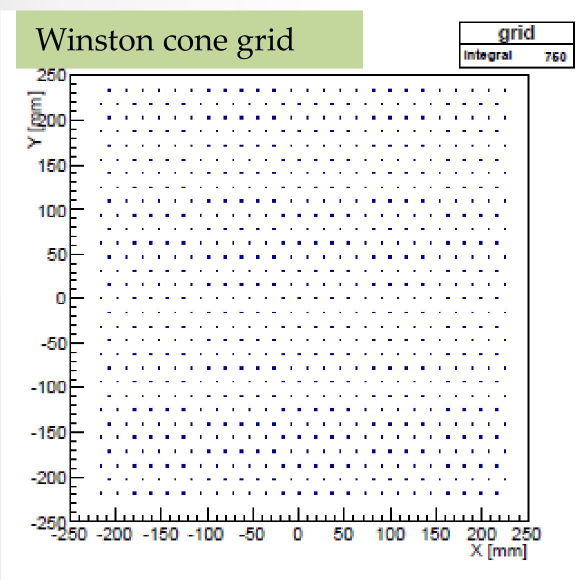
Cone geometry

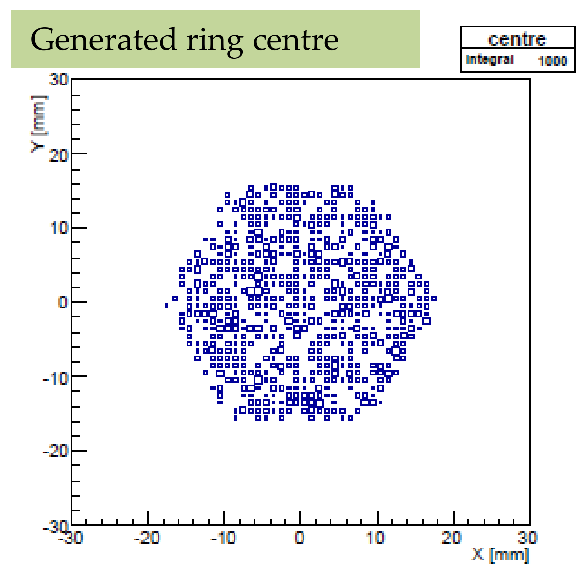
Hexagonal packing of Winston cones

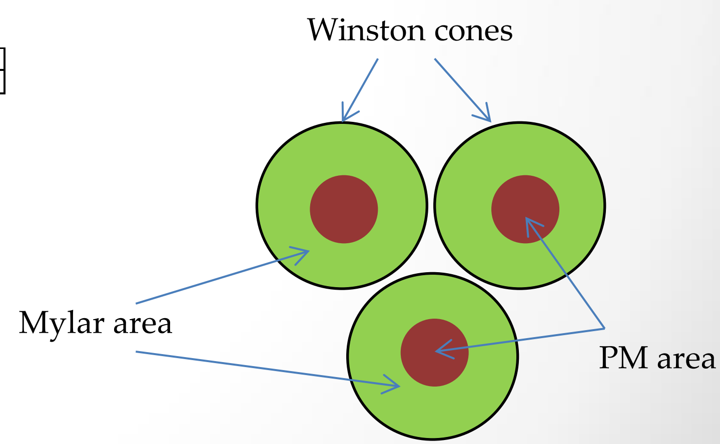


Toy MC:

- 2D grid of Winston cones
- Generate real ring centre, uniformly in the central hexagon
- Shift all hits by the real centre coordinates
- Assign closest cone centre to the hit position
- Reject hits between cones
- Cone reflectivity: reject 5% hits in the mylar area ($3.75 < r < 9$ mm)

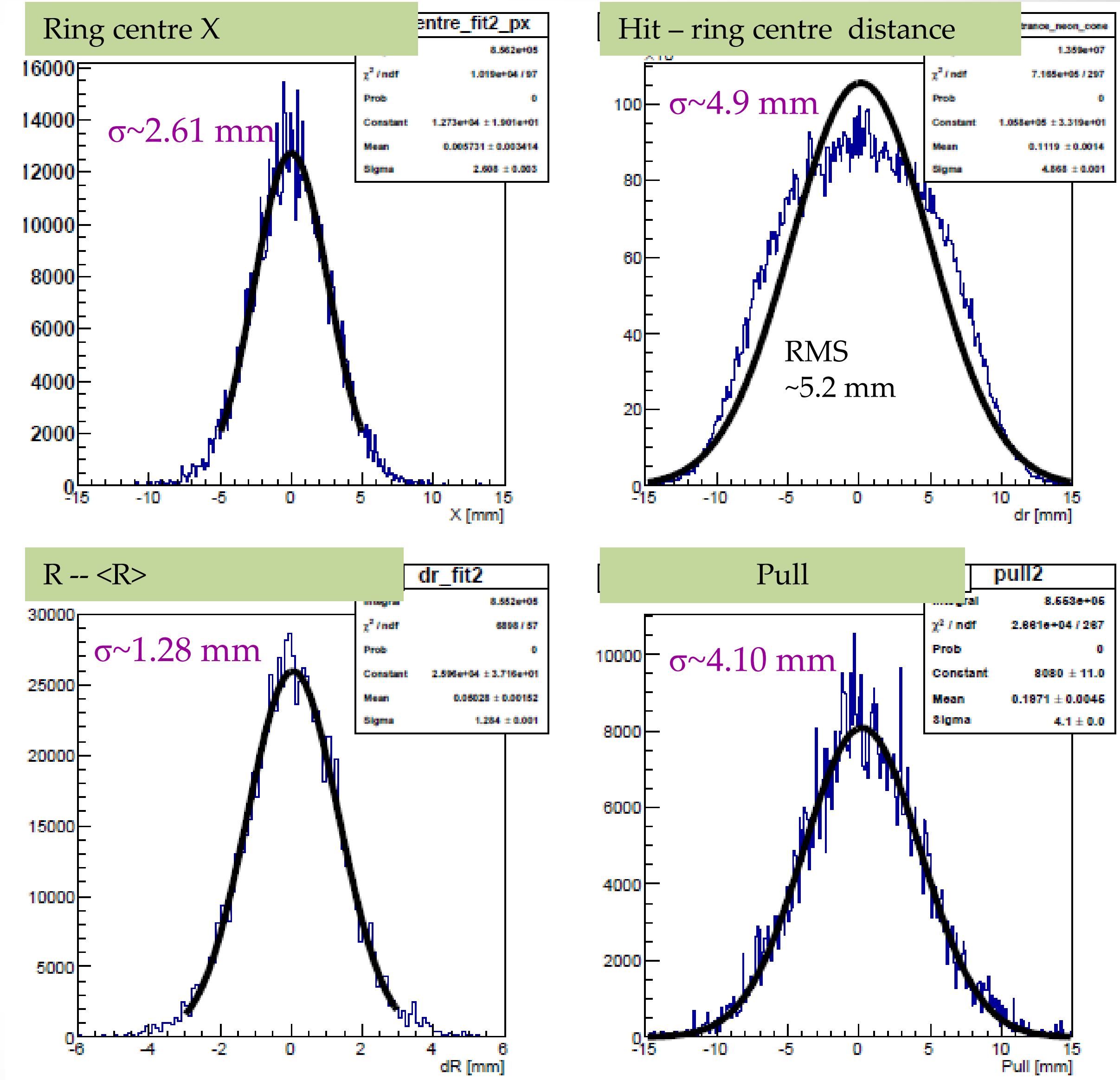






Toy MC: combined effect

Effects simulated:
- track angular resolution
- Multiple scattering
- Cone geometry



Non-gaussian shape of the hit-ring distance:
- observed in data
- reproduced by the toy MC
- Due to the cone geometry

Toy MC vs data

	Multiple scattering (toy MC)	Cone geometry (toy MC)	Total (toy MC)	Data (single mirror)
Ring radius resolution [mm]	0.40	1.2	1.28	1.31
Single hit resolution [mm]	1.39	3.9	4.10	4.18
Ring centre X resolution [mm]	1.42	2.2	2.61	2.82

- Reasonable agreement between toy MC and data
- Some discrepancy in the ring centre resolution (~1.1 mm) could be explained by a larger effective thickness of the entrance window

Neon dispersion

Contribution to the single hit resolution:

$\sigma_{hit,\ \Delta n} \simeq f \Delta\theta_n \simeq f \Delta n/\theta$, where θ is the Cherenkov angle, $\theta \simeq R/f$

$$\Delta n = \sqrt{< (n-1)^2 > - < (n-1) >^2}$$

Averaging over the "real" photon spectrum:

$$<(n-1)> = \int [(n(\lambda)-1) * \varepsilon_{tot}(\lambda) * dN(\lambda)] / \int [\varepsilon_{tot}(\lambda) * dN(\lambda)]$$

$$<(n-1)^2> = \int [(n(\lambda)-1)^2 * \varepsilon_{tot}(\lambda) * dN(\lambda)] / \int [\varepsilon_{tot}(\lambda) * dN(\lambda)]$$

$$\varepsilon_{tot}(\lambda) = \varepsilon_{mirror}(\lambda) * \varepsilon_{cone}(\lambda) * \varepsilon_{quartz}(\lambda) * \varepsilon_{packing} * \varepsilon_{PM}(\lambda)$$

$\sigma_{hit,\ \Delta n} = 0.6$ mm (small)

Resolution budget

Ring radius	[mm]	[μrad]
Mirror misalignment	0.7	40
Multiple scattering	0.4	20
geometry	1.2	70
Total (measured)	1.5	90

Single hit	[mm]	[μrad]
Mirror misalignment	2.1	120
Multiple scattering	1.4	80
geometry	3.9	230
Total (measured)	4.7	270

Ring centre / Track slope (X)	[mm]	[μrad]
Mirror misalignment	0.9	50
Multiple scattering	1.4	110
geometry	2.2	260
Total (measured)	3.0	350

Conclusions

- Precise mirror alignment procedure has been developed and implemented
- RICH performance has been measured using the electron sample
- Contributions to the resolutions have been investigated in detail
- Performance optimization has been discussed

Performance parameter	[mm]	[μrad]
Residual mirror misalignment	O(1)	O(30)
Ring radius	1.5	80
Ring centre / track slope (X)	3.0	170
Single hit (space)	4.7	270

Performance parameter	Value
Single hit (time), RMS	0.28 ns
$\langle N_{hits} \rangle$	13.8

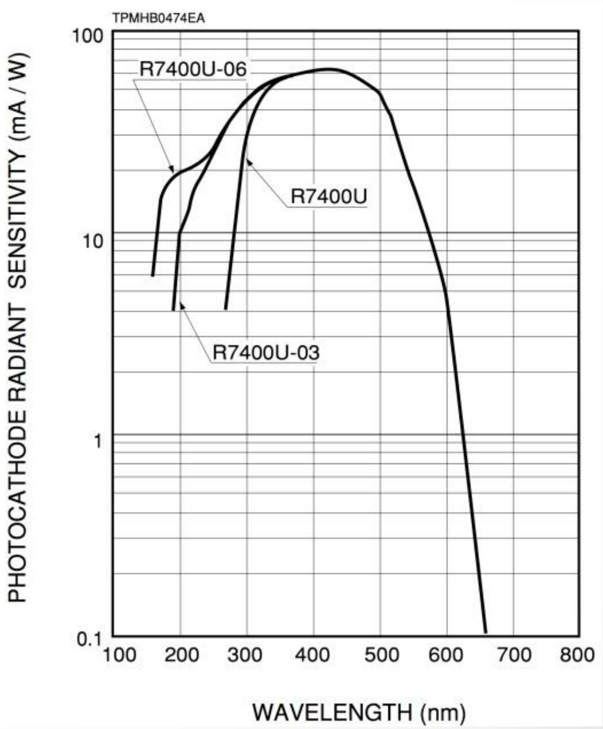
Thank you!

Spare

Light detection

Hamamatsu R7400 U03 PMs:

- External diameter 16mm
- Active diameter 7.5 mm
- UV glass window
- Custom-made HV divider
- 185-650 nm sensitive range
- Peak sensitivity @ 420 nm
- Gain 1.5*10^6 (HV = 900 V)
- **QE ~20% (@ 420 nm)**
- Transit time spread 0.28 ns (FWHM)



σ_{hit}: classical vs NA62 approach

	classical	NA62
NDF for σ(R) determination	N_{hits} - 1 OK	N_{hits} - 3
Spectrometer contribution to σ_{hit}	yes	no OK
Track slope measurement	no	yes OK
σ_{hit} affected by the multiple scattering in the entrance window	yes	no OK
Non-gaussian shape of the σ_{hit} determination distribution	yes	no OK

OK : better performance

Toy MC

Toy MC salgorithm:

- Simulate an event
- Perform the standalone ring fit
- look at $\sigma(R)$, $\sigma(Dx/Dy)$, σ_{hit}

quantity	Simulation recipe
P	e^+ spectrum known from data
N_{hits}	Poissonian p.d.f., $\langle N_{hits} \rangle$ tuned to have 13.8 at the final step
track angular uncertainty (Spectrometer)	Known from data
multiple scattering (RICH entrance)	Analytical calculation
multiple scattering (Ne)	Analytical calculation
Cone geometry	Size known, reflectivity ~95%

Multiple scattering

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\ z\ \sqrt{x/X_0}\left[1 + 0.038\ln(x/X_0)\right]$$

NB plane case (i.e. one coordinate: X or Y)

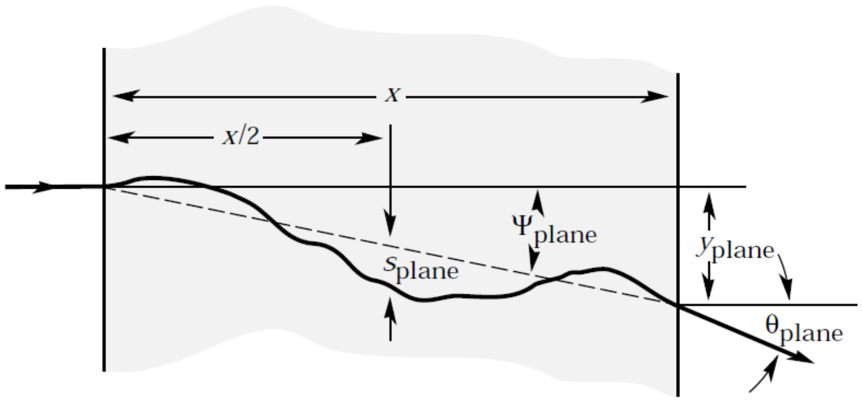


Figure 27.8: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

$$\theta^2_{\mathrm{space}} \approx (\theta^2_{\mathrm{plane},x} + \theta^2_{\mathrm{plane},y})$$

Multiple scattering simulation:

- Calculate θ_0
- Generate γ_1, γ_2: normally distributed with (0, 1)
- $\theta_X = \theta_0\ \gamma_1$
- $\theta_Y = \theta_0\ \gamma_2$
- PM (focal) plane: $dX = \theta_X f$; $dY = \theta_Y f$