Performance study of the RICH counter in hadron identification for SIDIS physics at COMPASS

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COMPASS

CERN

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Outline

1. Introduction to SIDIS physics in COMPASS
2. Particle Identification in COMPASS
3. Characterization of new Photon detectors of COMPASS RICH
4. Tuning of COMPASS RICH
5. Improvements
6. Consistency Checks
7. PID performance
8. Conclusion

1/8 Introduction to SIDIS physics in COMPASS

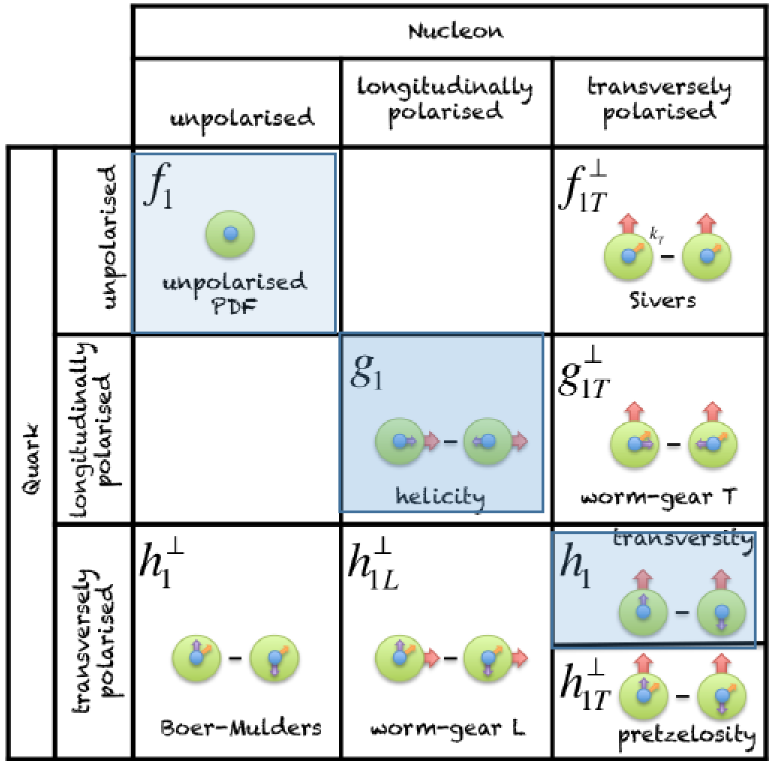
The proton, a century on

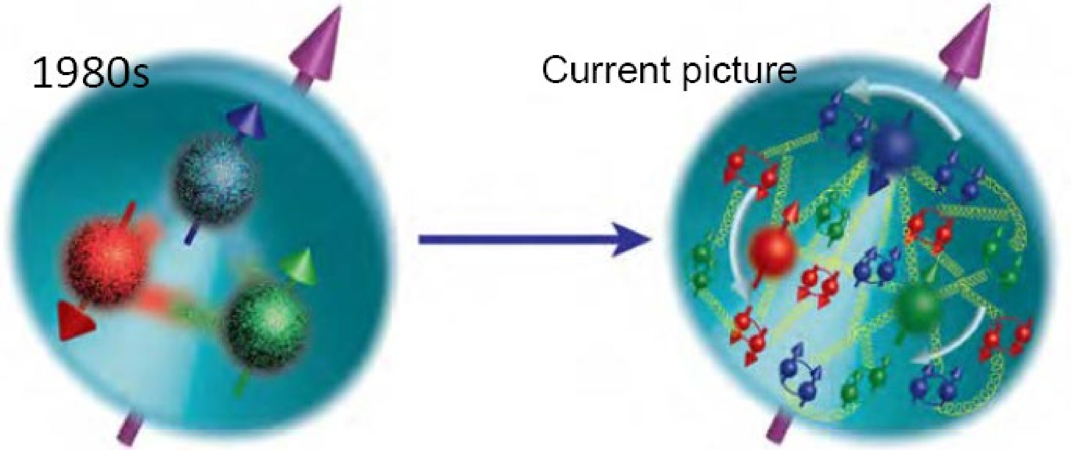
A century after physicist Ernest Rutherford published work proving the existence of the proton, much remains to be learnt about this ubiquitous particle

12 JUNE, 2019

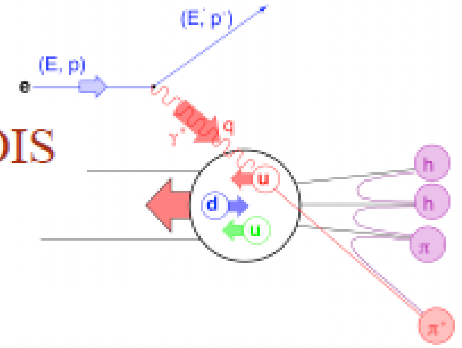
"… leading to Ernest Rutherford's discovery of the proton, published in 1919, …how a deeper understanding may be key to the search for new physics phenomena, and what remains to be learnt – including the origin of the proton's spin, whether or not the proton decays on long timescales, and the puzzling, although soon-to-be resolved, value of its radius…."

CERN COURIER 12 June 2019



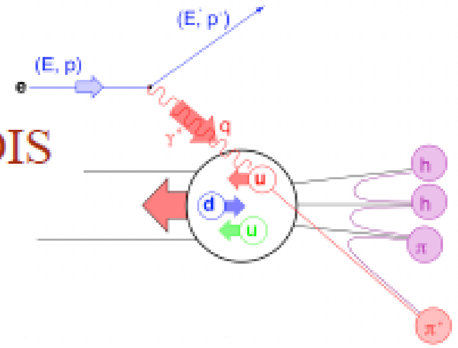


Semi-Inclusive DIS



Physics motivation to use a RICH

Semi-Inclusive DIS



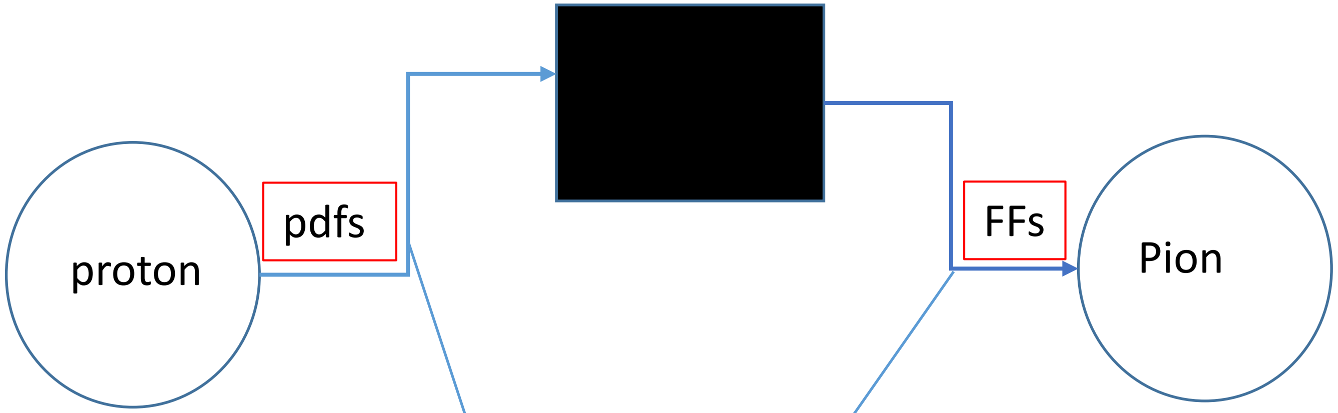
Simply, **identification** of **at least one hadron in coincidence** with the scattered muon is mandatory in SIDIS. In order to tag the struck quark of the nucleon via virtual gamma interaction.

$$Q^2 = -(p' - p)^2$$ How fine we can scan!

$$x_{Bj} = \frac{Q^2}{2P.q}$$ How much of the protons momenta the parton is carrying!

$$z = \frac{P.p_h}{P.q}$$ Fractional energy of the virtual photon the hadron took away!

Partons
(black box: we can not detect them)



$$\frac{dM^i(x,Q^2,z)}{d(x,Q^2,z)} = \frac{\sum_q e_q^2 q(x,Q^2) D_q^i(z,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$$

Pdfs and FFs should not depend on interaction → universality
They appear in the cross-section as products → Factorization

SIDIS cross-section of hadron type h

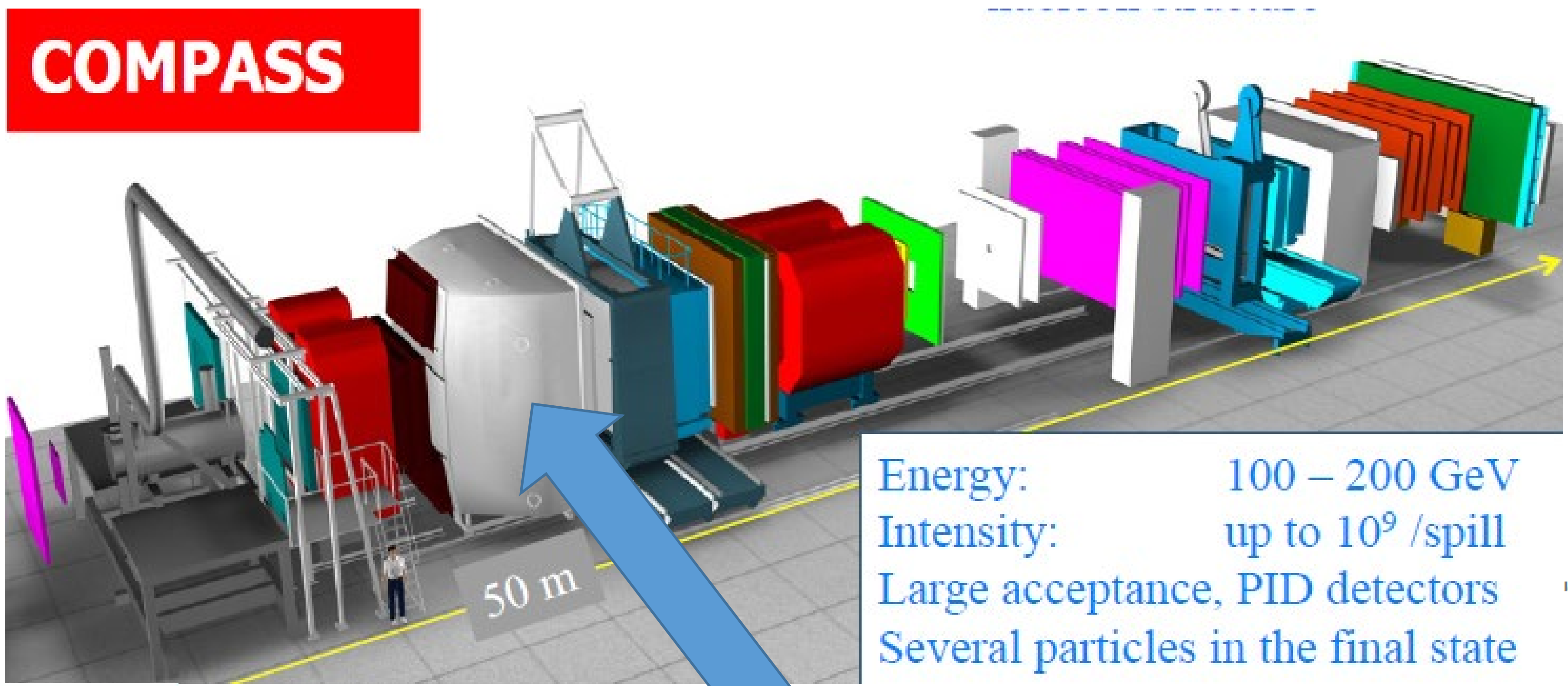
$$\frac{dM^h(x,Q^2,z)}{dz} = \frac{d^3\sigma^h(x,Q^2,z)/dx dQ^2 dz}{d^2\sigma^{DIS}(x,Q^2)/dx dQ^2}.$$

CERN-EP-2018-012

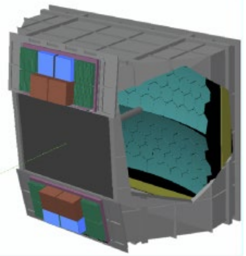
Inclusive DIS cross-section

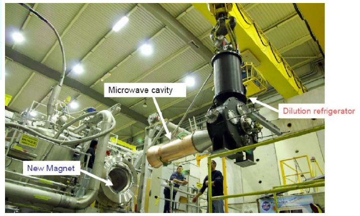
COMPASS spectrometer

COMPASS



2002	nucleon structure with	160 GeV μ	L&T	polarised deuteron target
2003	nucleon structure with	160 GeV μ	L&T	polarised deuteron target
2004	nucleon structure with	160 GeV μ	L&T	polarised deuteron target
2005	*CERN accelerators shut down*			
2006	nucleon structure with	160 GeV μ	L	polarised deuteron target
2007	nucleon structure with	160 GeV μ	L&T	polarised proton target
2008	*hadron spectroscopy*			
2009	*hadron spectroscopy*			
2010	nucleon structure with	160 GeV μ	T	polarised proton target
2011	nucleon structure with	190 GeV μ	L	polarised proton target
2012	Primakoff & DVCS / SIDIS test			
2013	*CERN accelerators shut down*			
2014	Test beam Drell-Yan process with π beam and T polarised proton target			
2015	Drell-Yan process with π beam and T polarised proton target			
2016	DVCS / SIDIS with μ beam and unpolarised proton target			
2017	DVCS / SIDIS with μ beam and unpolarised proton target			
2018	Drell-Yan process with π beam and T polarised proton target			





hadron PID from 3 to 60 GeV/c

acceptance: H: 500 mrad V: 400 mrad

trigger rates: up to ~50 KHz, beam rates up to ~10^8 Hz,

Detector designed in 1996 In operation since 2002
MAPMT based upgrade in 2006 A new upgrade with Hybrid MPGD is done in 2016

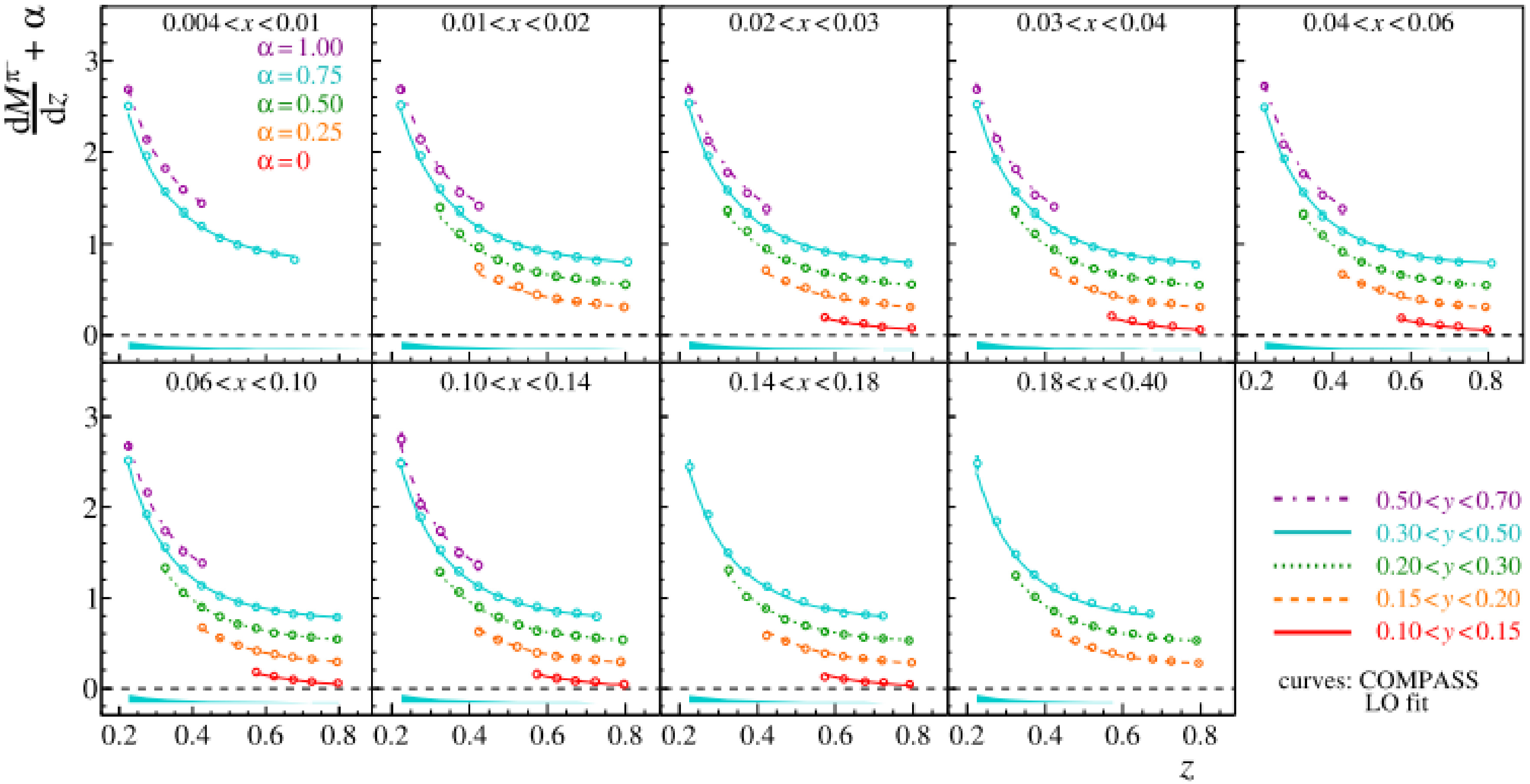
Fixed target experiment @ CERN SPS
2 stage spectrometer.
Naturally polarized muon beam and unique polarized target.
300 layers of trackers, Calorimeters,
3m long RICH with radiator of C_4F_{10}

Pioneered GEMS, MicroMegas (for tracking) & THGEM-Micromegas based hybrids for single photon detection.

Physics motivation to use a RICH

Negative pion multiplicities versus z for x bins and y bins. The bands correspond to the total systematic uncertainties for the range 0.30 < y < 0.50. The curves correspond to the COMPASS LO fit

Physics Letters B 764 (2017) 1–10



Corrections for raw multiplicities: spectrometer acceptance, **the particle identification efficiency and particle misidentification probability**, the contribution from decay products of diffractive mesons, radiative corrections.

Efficient particle identification is MANDATORY.

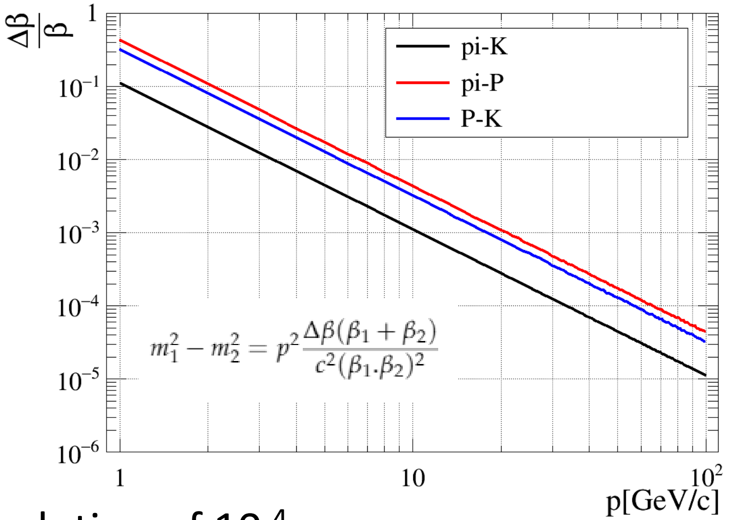
2/8 Particle Identification in COMPASS

Particle identification and RICH

Identification of the mass of the particle.

$$m = \frac{p}{c\beta\gamma} \rightarrow \left(\frac{dm}{m}\right)^2 = \left(\gamma^2\frac{d\beta}{\beta}\right)^2 + \left(\frac{dp}{p}\right)^2$$

to be more uncompromising in the accuracy of velocity determination at a higher momentum.



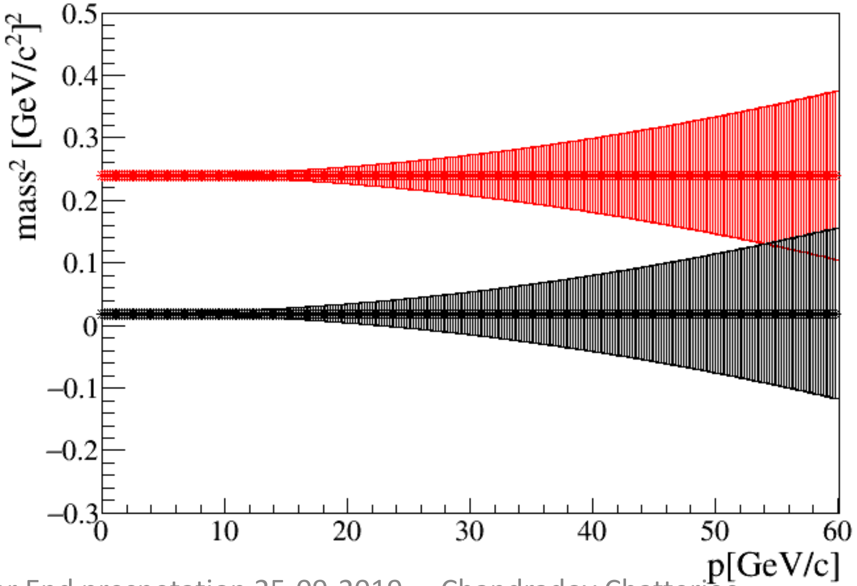
RICH is obvious choice for Beta resolution of 10^{-4}

RICH → Cherenkov Imaging → $\cos\theta = \frac{1}{n\beta}$

$$\cos\theta = \frac{1}{n\beta}$$

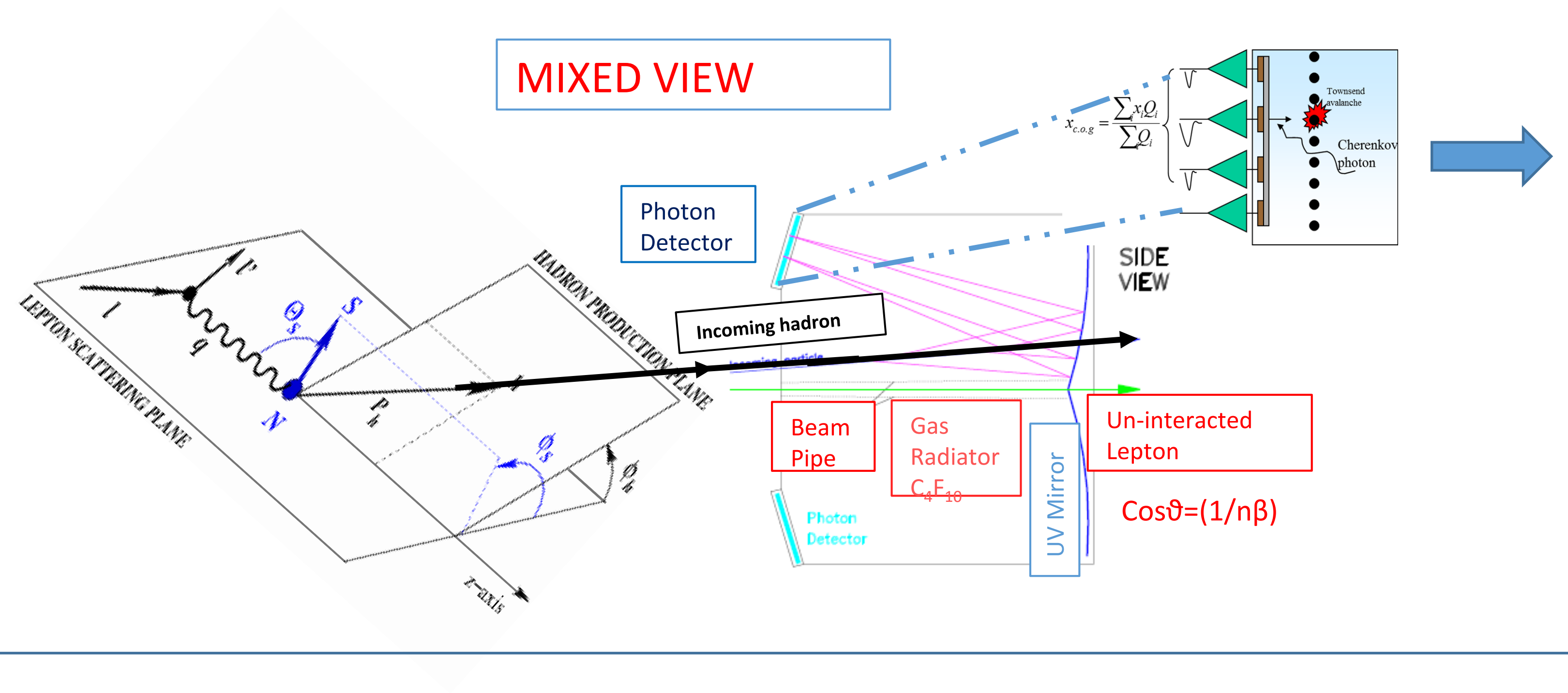
$$(1-\theta^2/2) = (1-(n-1))(1+1/2\frac{m^2}{p^2})$$

$$m^2 = p^2\left[\frac{2(n-1)-\theta^2}{1-(n-1)}\right]$$



Efficient performance of RICH :
Precision in RICH-1 Geometry (input for **θ** reconstruction algorithm),
Knowledge of Radiator gas (refractive index),
reconstruction algorithm (determination of **θ** value),
RICH data analysis framework
photon detection techniques.

Photon detection of COMPASS RICH-1



COMPASS RICH-1 Photon detection
→ Two Methodologies:
a. MAPMTs
b. Gaseous detectors
→ Two generations
i. MWPCs
ii. MPGD based hybrids

Readout
MAPMTs → CMAD Chip
Gaseous dets→ APV Chip

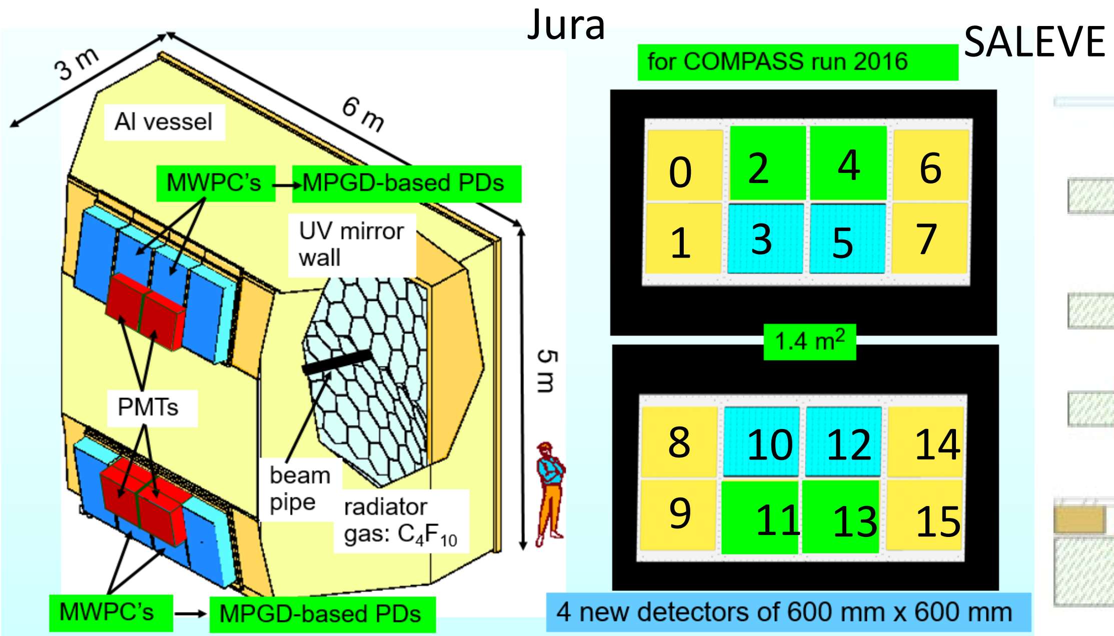
- central region (25% of the active surface) : highly populated (up to 1MHz/ch) by uncorrelated background. Multi-Anode PhotoMultiplier Tubes (MAPMTs) are used (~0.4 ns time res)
- peripheral regions(75% of the active area): gaseous detectors employed (large surface at affordable cost). Readout by APV25chips.

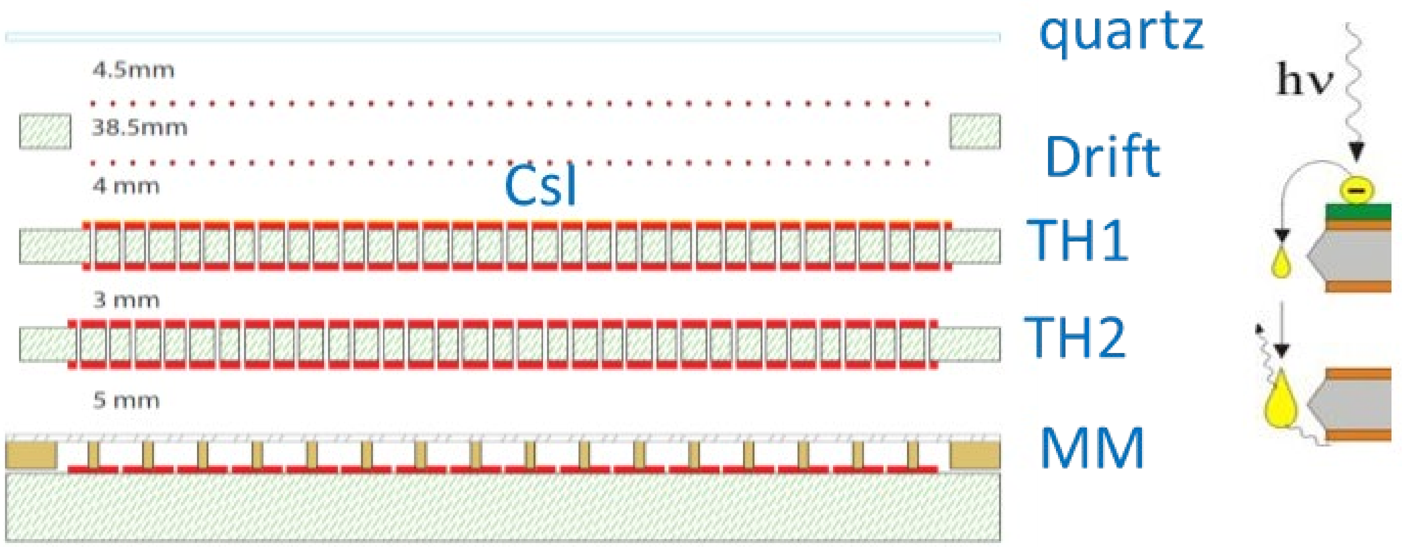
MWPCs + CsI: successful but with important performance limitations, in particular in the case of the 4 central chambers.

Decreased number of photons.
Aging due to ion-back flow.
Long recovery time after discharge.

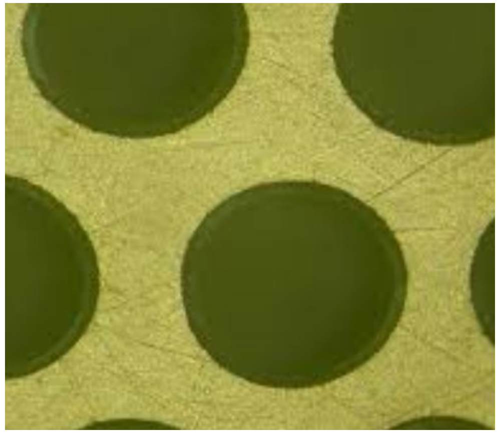
→ 1/3 area upgraded to MPGD based hybrids

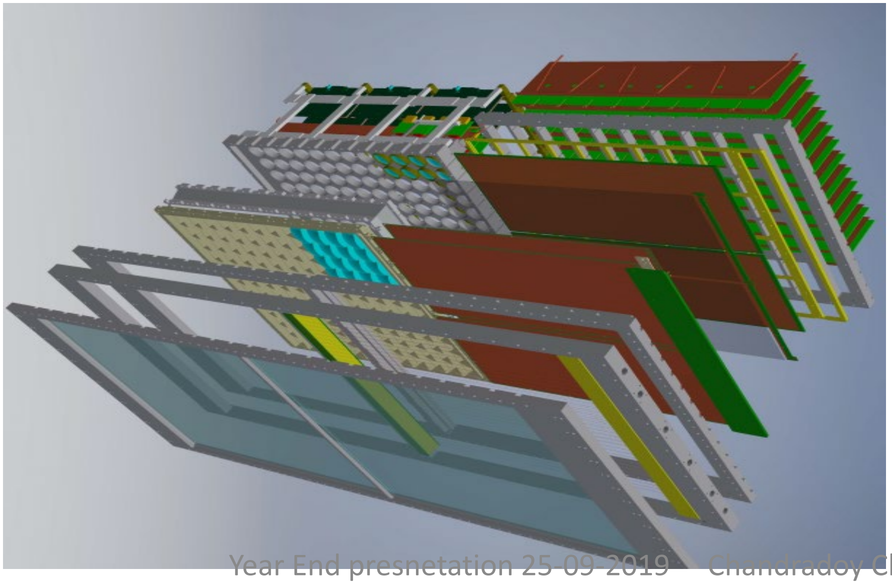
RICH-1 upgrade

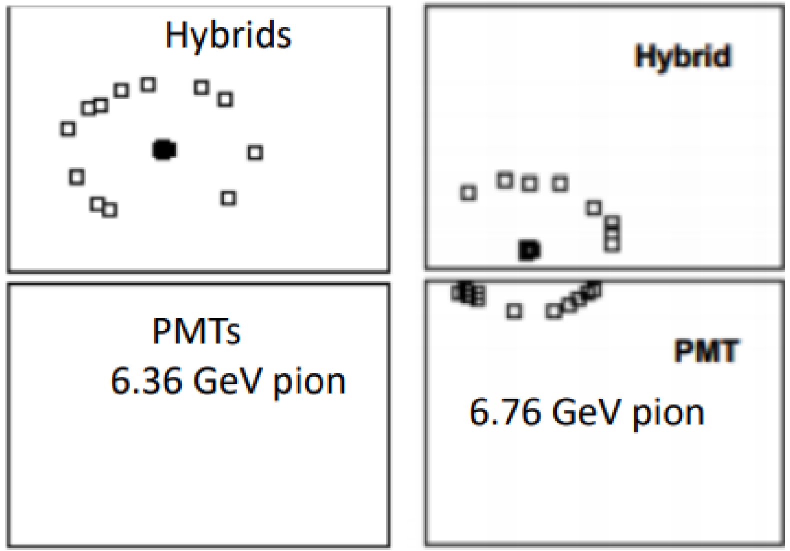




After 2016

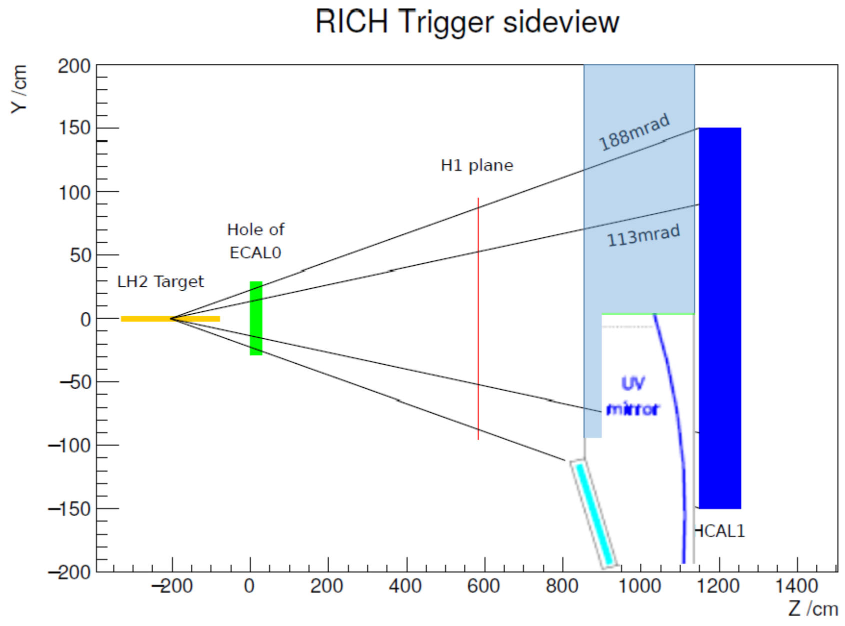


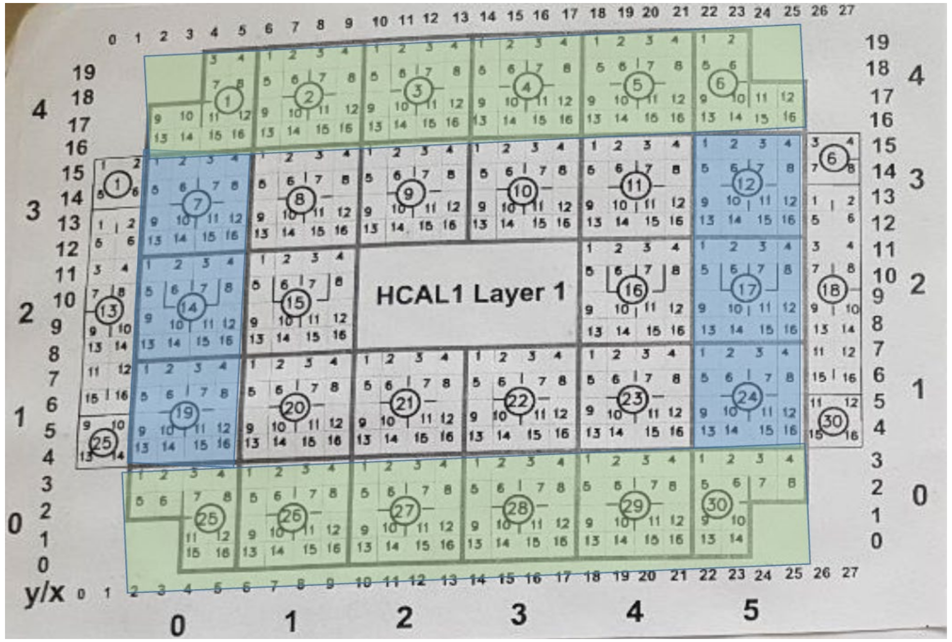




3/8 Characterization of new Photon detectors of COMPASS RICH

Dedicated trigger setup for 2017 pion data

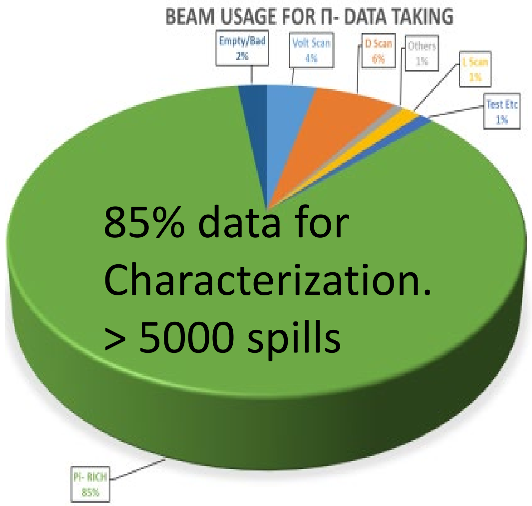




Interaction rate: $6.5*10^5$ events/spill.
The trigger could select ~5% of interactions on the bases of output hadron angle.
→ 30 k triggers / spill

- **dedicated trigger** was set up for large
angle coverage in RICH detector
- Negative Pion beam energy = 160 GeV

Trigger: HCAL1 & beam & (!beam Killer). 4 GeV threshold for colored blocks. Very high threshold for other blocks



Thanks to the collaboration.

Gain Studies

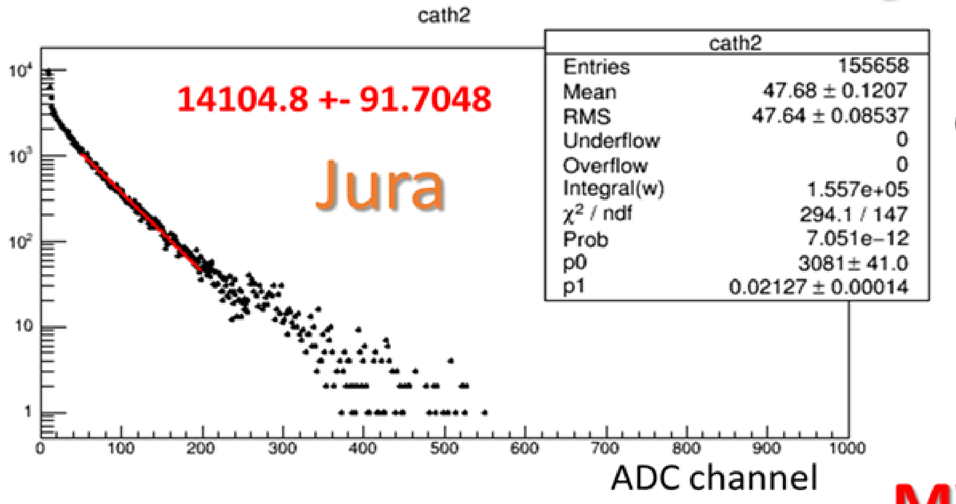
Hybrids

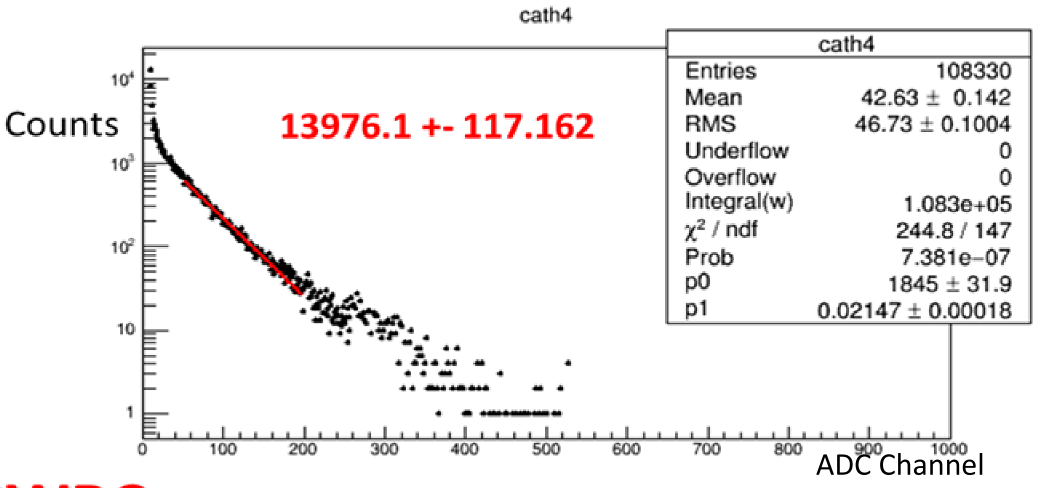
Cherenkov photon is converted to single photo electron as signal.

signal amplitude is exponentially distributed.

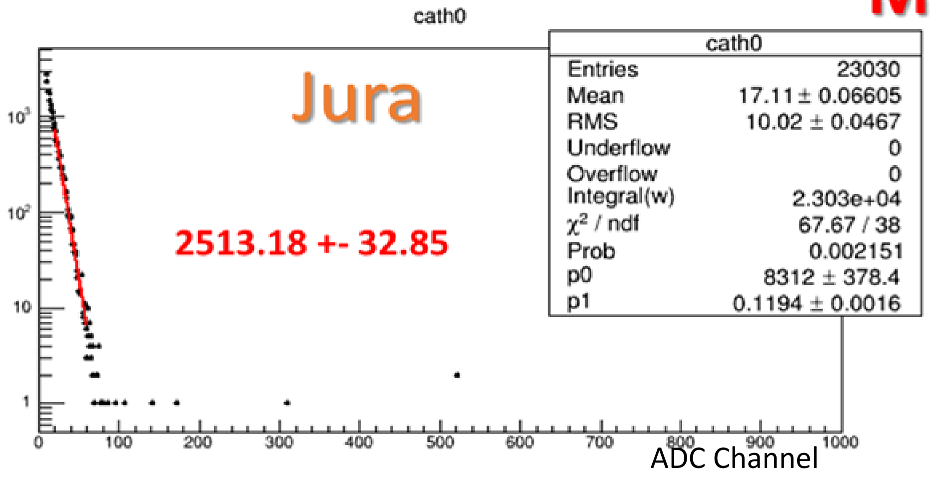
The slope gives an estimation of effective gain. (roughly,1 e→ N e . Effective Gain = N)

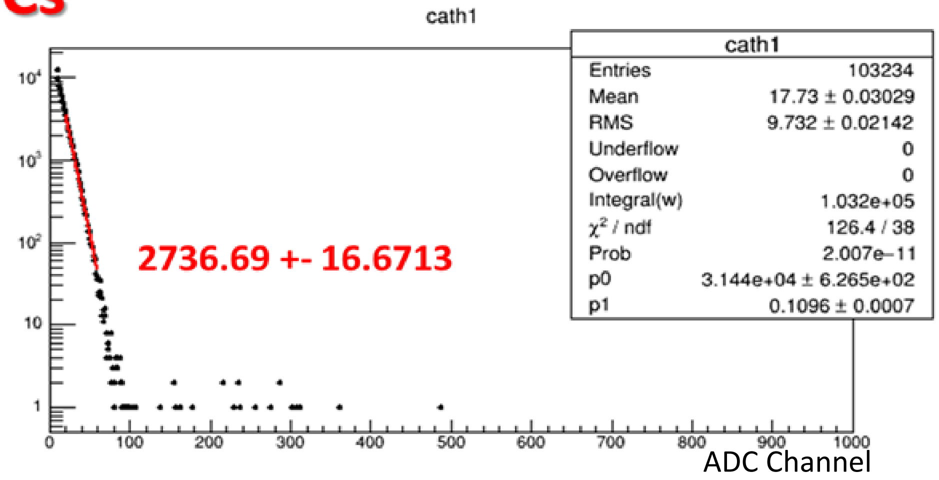
Signal and background has exactly same size.



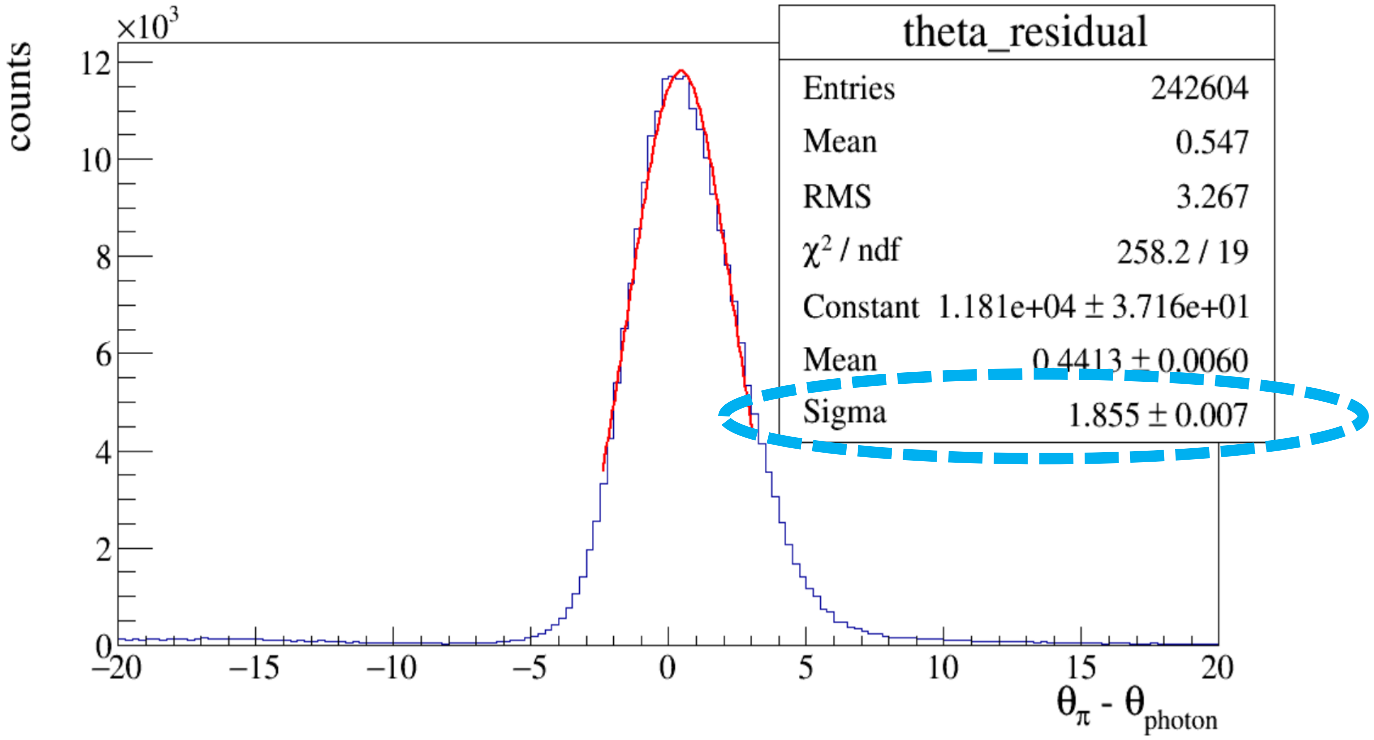


MWPCs





Photon angle reconstruction residual---Hybrid combined

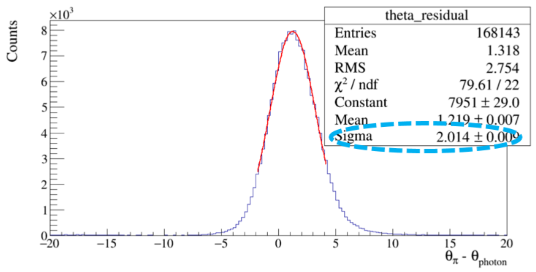


$$\vartheta = arccosine\left(\frac{1}{n\beta}\right)$$

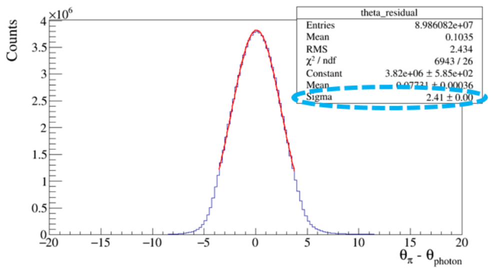
Estimate ϑ_π and take differences of each photon

Pion track selection:
pion likelihood > 1.2 * Second likelihood.

Photon angle reconstruction residual MWPC combined



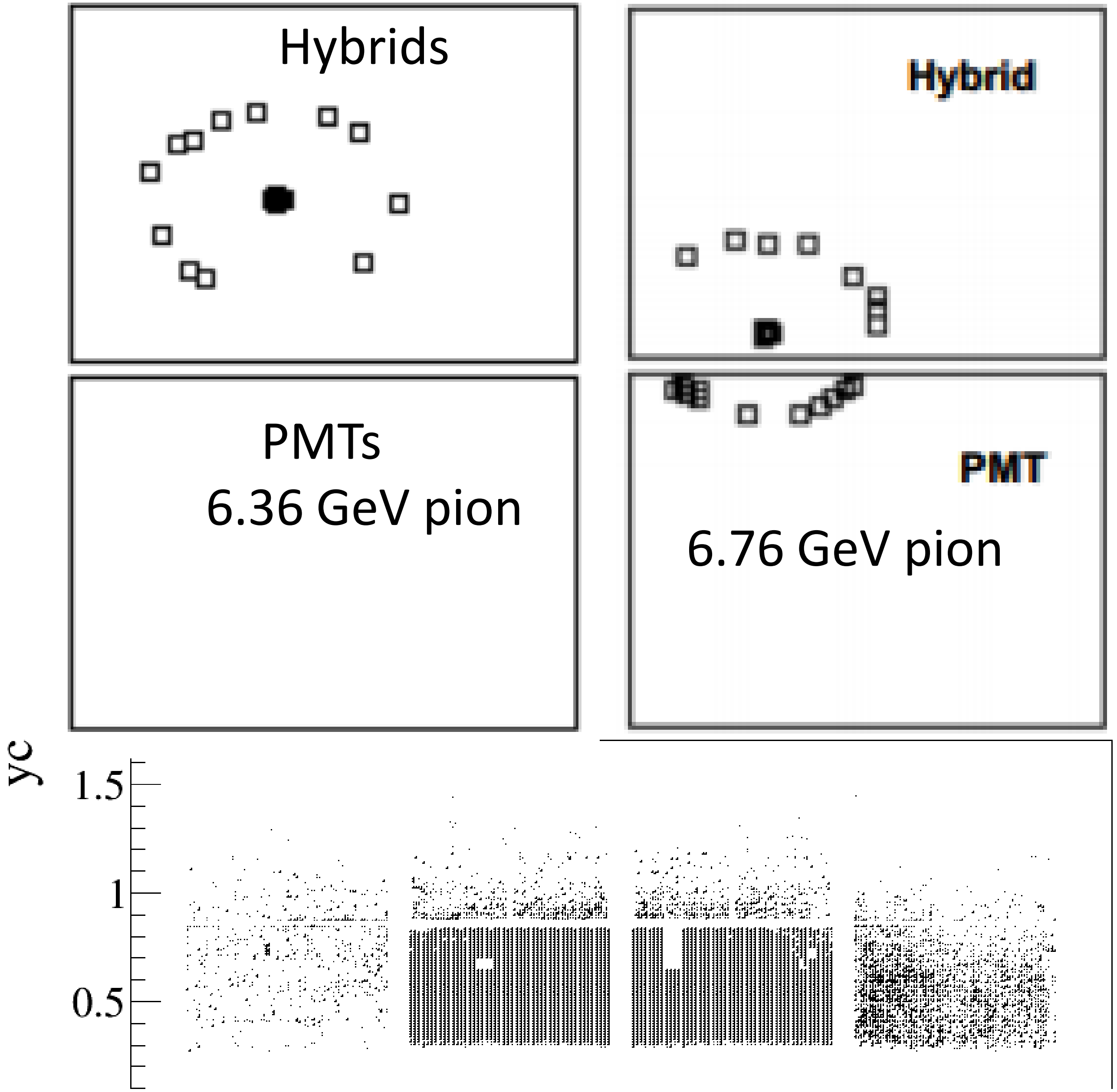
Photon angle reconstruction residual PMT combined



Summary of Angular Resolution :
Hybrids ~ 1.85 mrad
MWPCs ~ 2.0 mrad
MAPMTS ~2.41 mrad

Number of photons

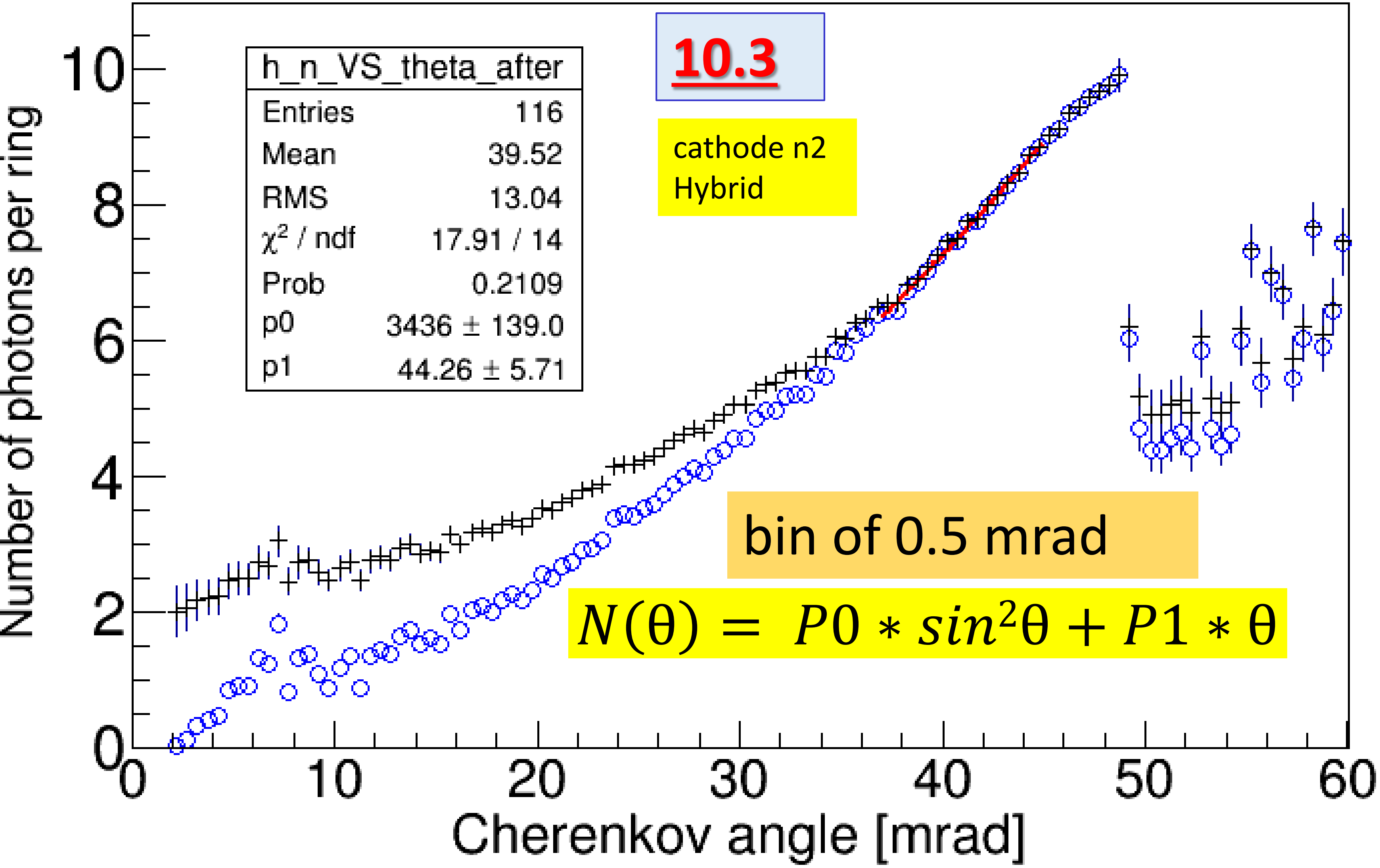
- ✓ Algorithm selects rings in the hybrid which contain 95% of arc length of a half ring within the active are.
- ✓ For the hybrids the standard Poisson correction has been modified to Poisson + Binomial.
- ✓ pion likelihood > 1.2 * second likelihood.



Number of photons

Number of detected photons are related to the Cherenkov angle by Frank-Tamm relation

$$N_{\mathrm{pe}} = N_0 L \sin^2 \theta_c$$



Extrapolate to pion saturation angle → 55.2 mrad, no of detected photo electrons = 12.9. First part of the function = 10.3 +/- 0.4; second part of the function= 2.6 +/- 0.3

4/8 Tuning of COMPASS RICH

RICH tuning: refractive index estimation

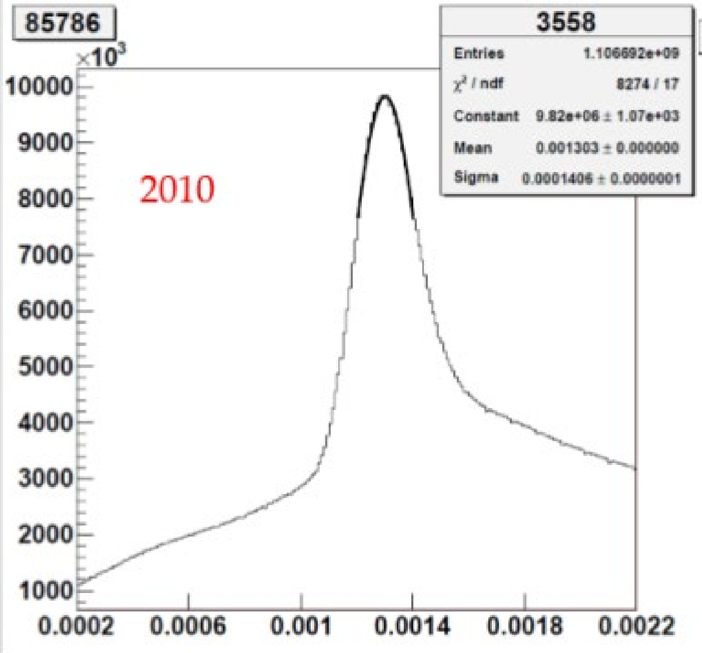
To efficiently perform hadron identification the RICH needs a delicate tuning:
In particular the refractive index n needs to be known very precisely.

$$cos\theta = \frac{1}{n}\sqrt{1+\frac{m^2}{p^2}}$$

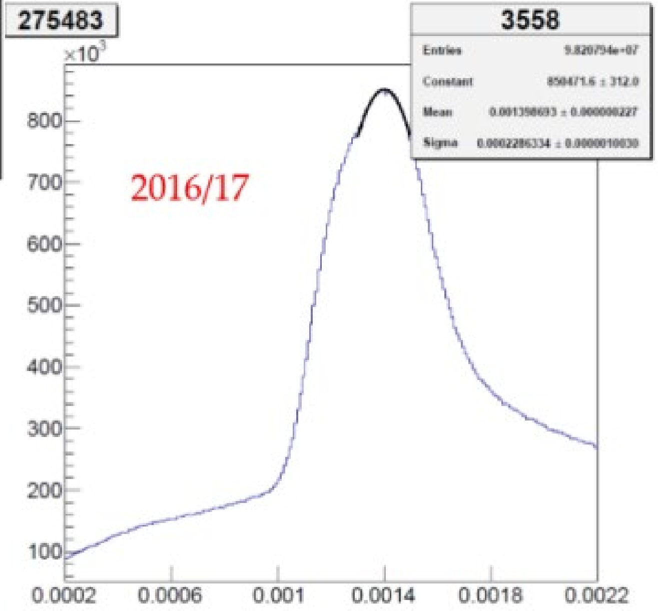
PID: n and p known, θ measured → m

Tuning: m and p known, θ measured → n

$$n_e = n_\pi \sqrt{\frac{p^2 + m_e^2}{p^2 + m_\pi^2}}$$



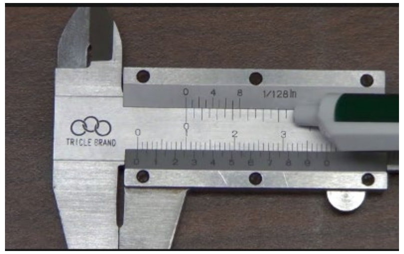
n-1



n-1

Technically we use n-1 in the units of 10^{-6}

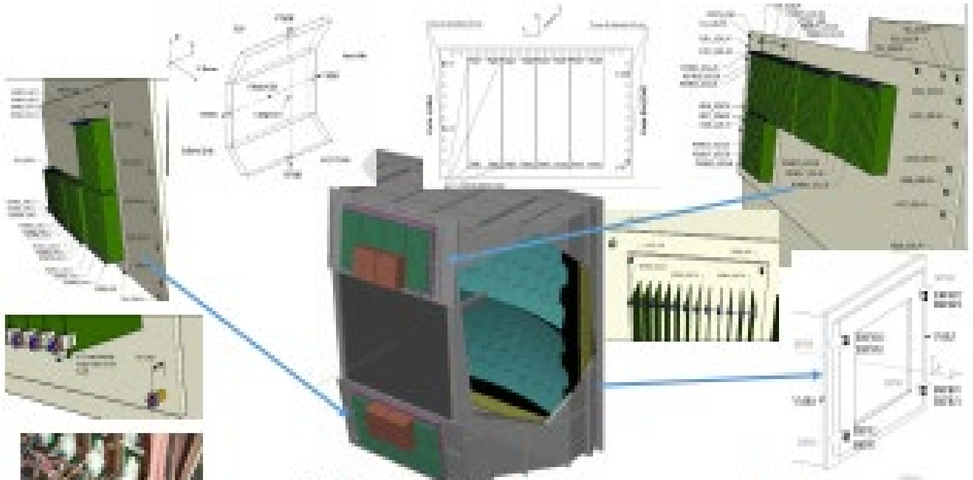
Large statistics in the MAPMTs



Solution achieved.
Three remedies

1. **New detector positions**
2. **Global Mirror alignment**
3. **New momentum range for extraction (from upto 30 Gev/c to 40-100 GeV/c)**

Detector Position Survey



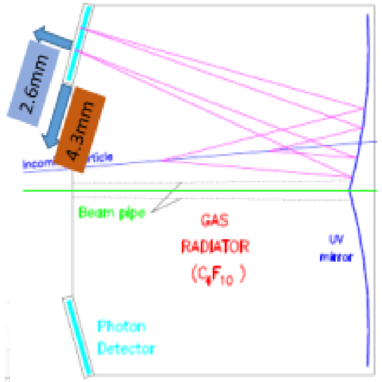
174 data points measured all over the RICH (Front and rear sides)

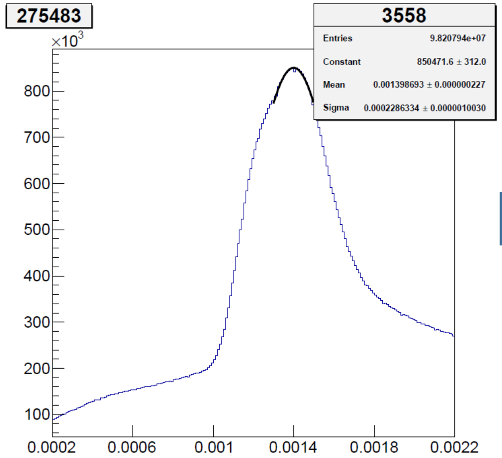
3 survey campaigns. 174 data points collected allover the RICH surface.
Data points have stability in different years within 1 mm .
Suggested data and CAD drawing Consistency within 1 mm.
Survey precision is 0.5 mm

No significant displacement has been found w.r.t 2009 and 2006 data. No significant tilt has been observed. Nice agreement of data and nominal CAD drawings.

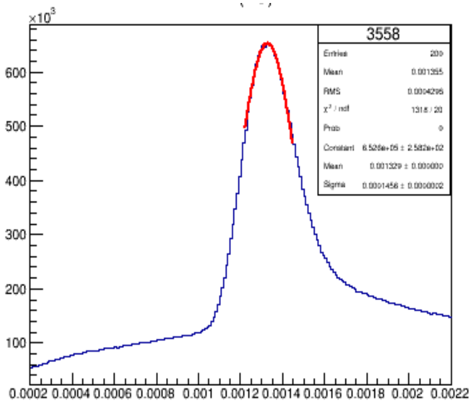
BUT ALSO SUGGESTED:

MAPMTS are displaced 4.3 mm toward beam axis, 2.6 mm upstream (outside vessel).





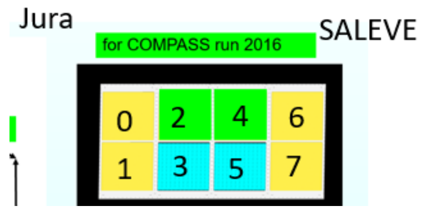
Mean: 1398 ppm Sigma: 228 ppm



Mean 1329 ppm Sigma 142 ppm

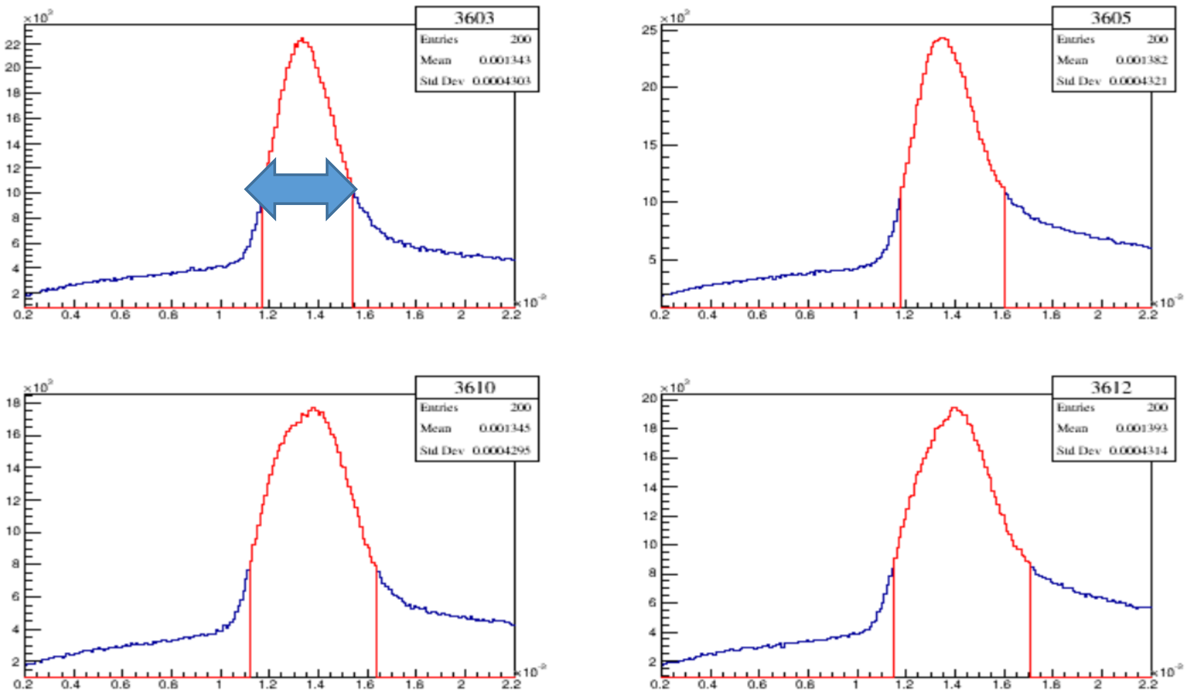
Still inconsistencies existing: particularly cathode-wise

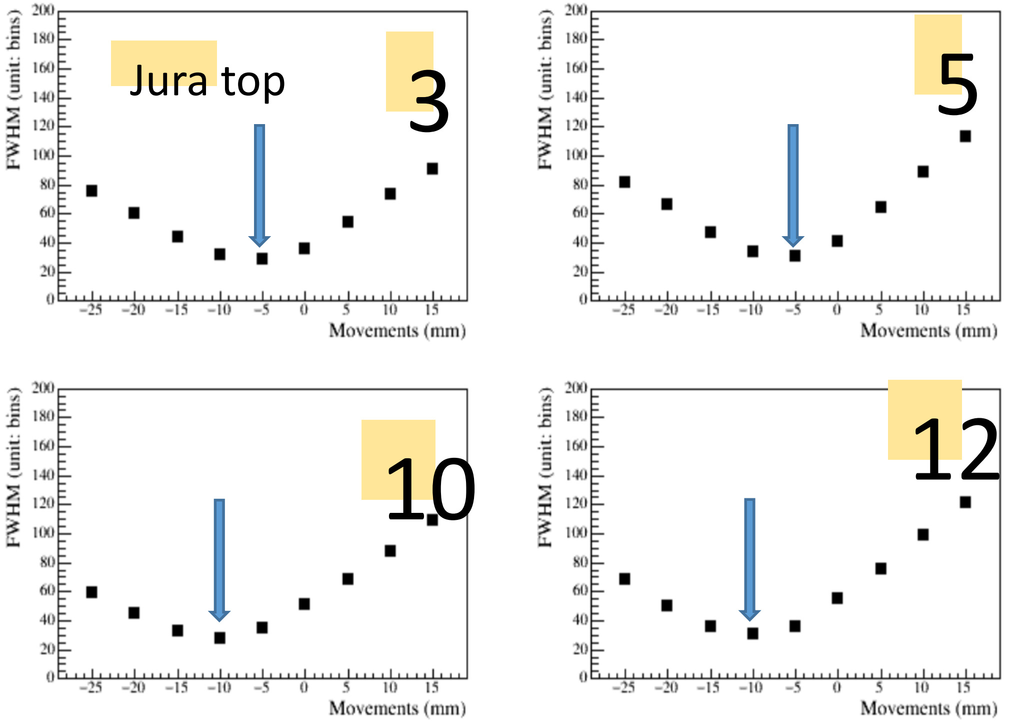
Defined as FWHM



+z mm = **move top two MaPMT up** AND **move bottom two MaPMT down**

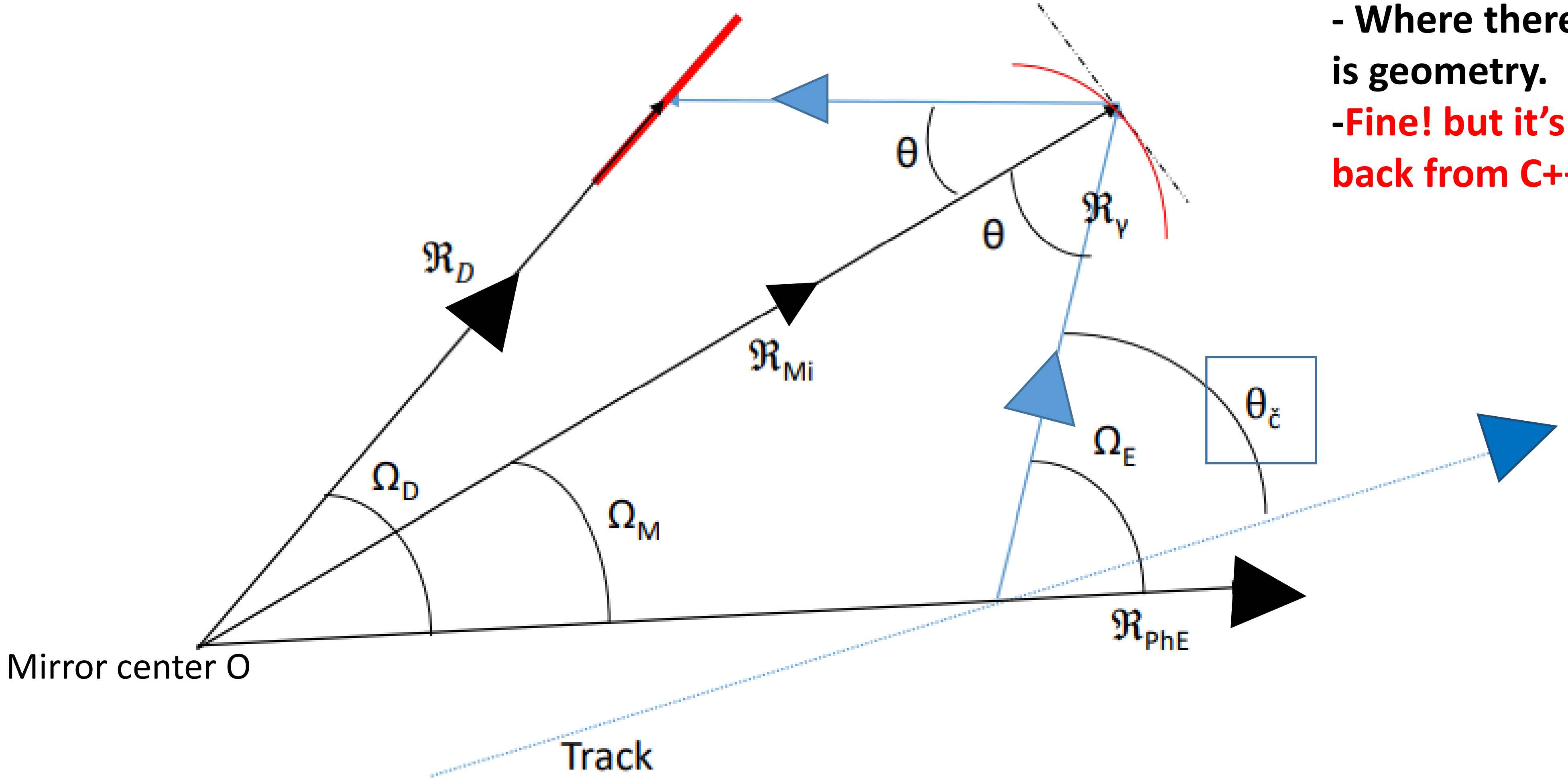
-z mm = **move top two MaPMT down** AND **move bottom two MaPMT up**



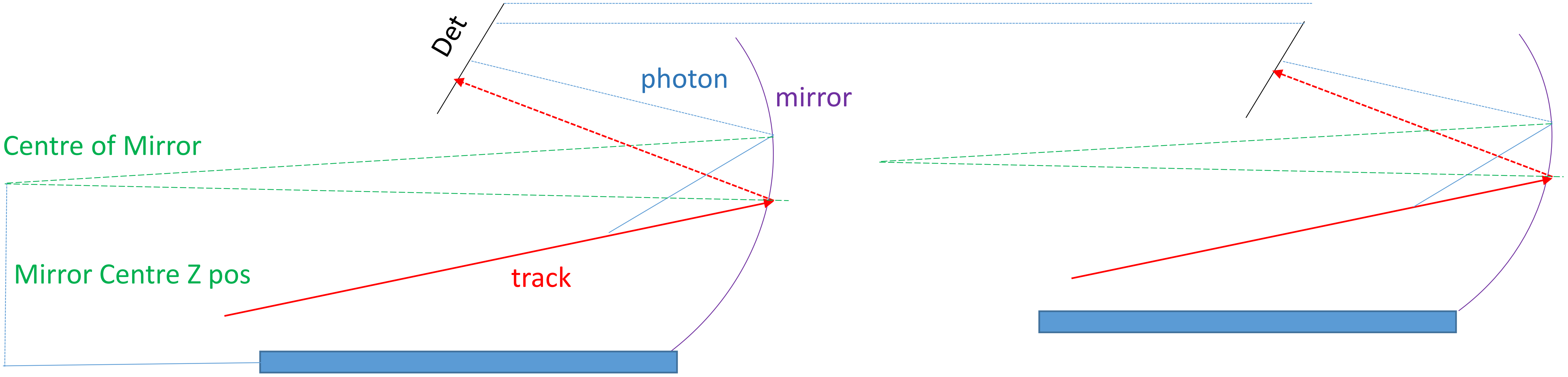


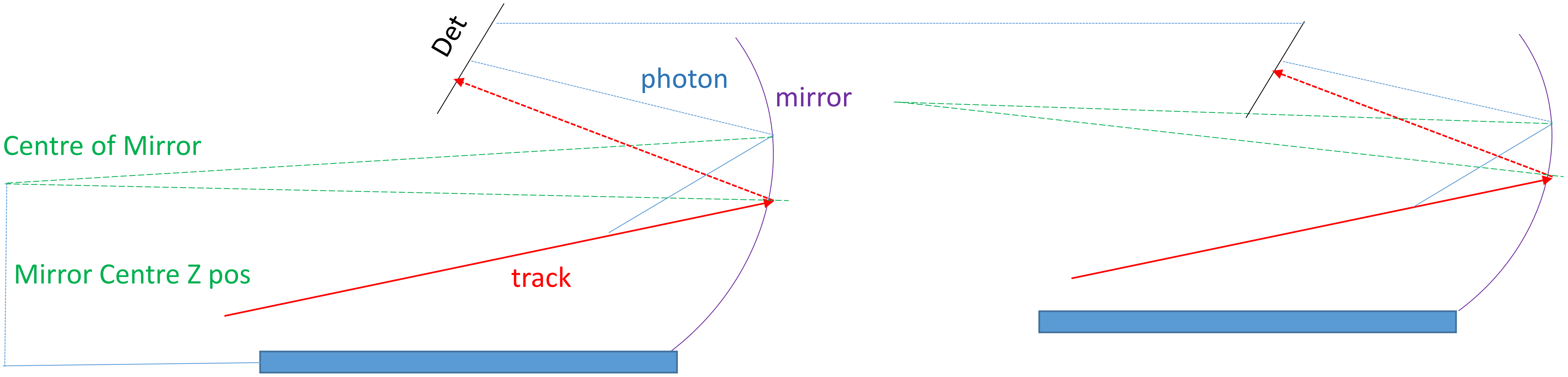
Inconsistent with survey data

Critical Geometry of Cherenkov angle reconstruction for focusing RICH



- **Where there is matter, there is geometry.**
- **Fine! but it's painful to get it back from C++ codes.**


Det
photon
mirror
Centre of Mirror
Mirror Centre Z pos
track



The Z position of the mirror has opposite effect of the detector Z position!

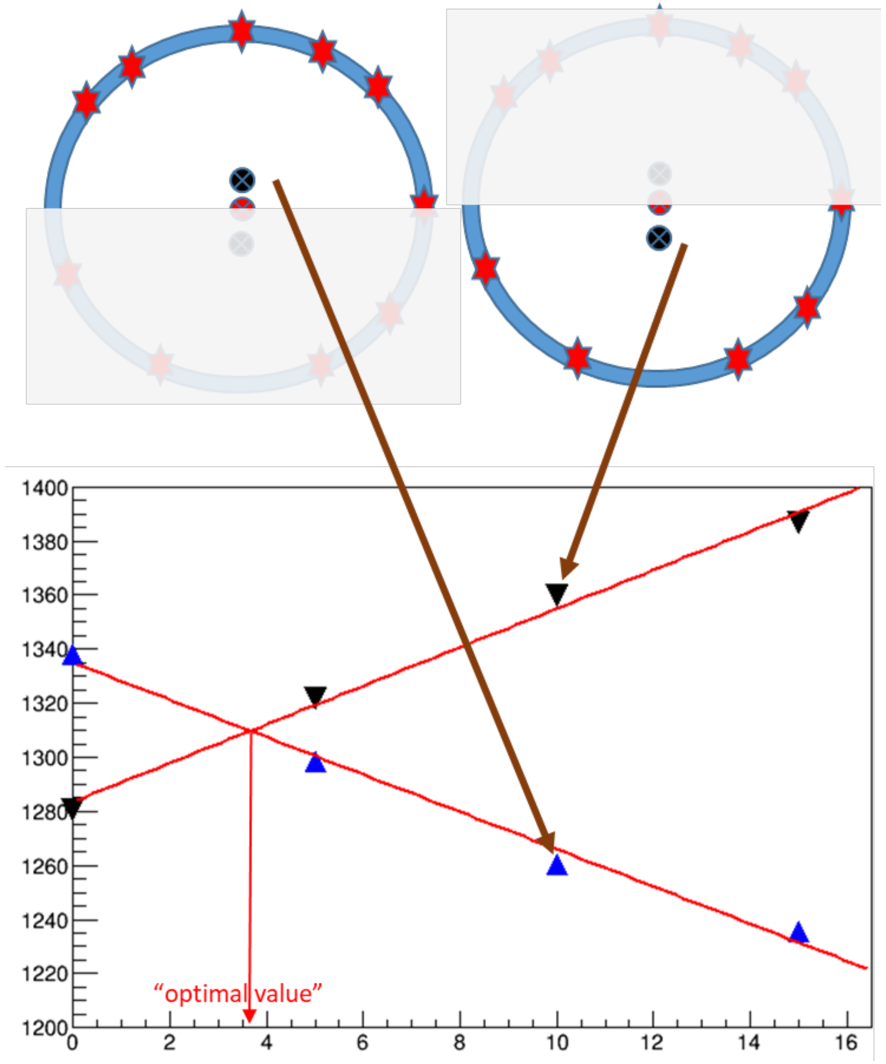
The detector position has been constrained by survey with a precision of <0.5 mm

The half ring analysis:

At the correct position of the optical system, the detected photons belonging to the upper part of the ring will point to the same n-1 as compared to the lower photons.

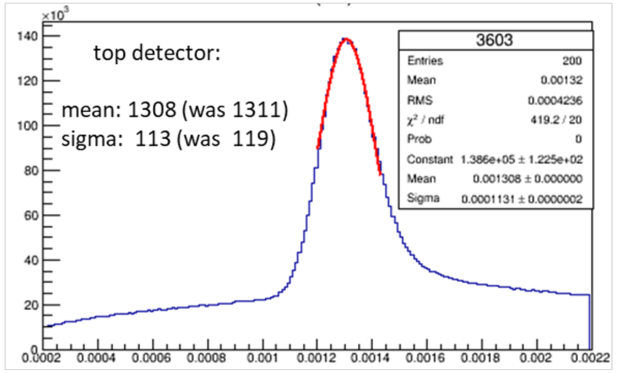
Algorithm we have used:

1. Search track cathode containing full rings in each cathode.
2. Estimate the refractive index contributed by the upper half and lower half of the ring.

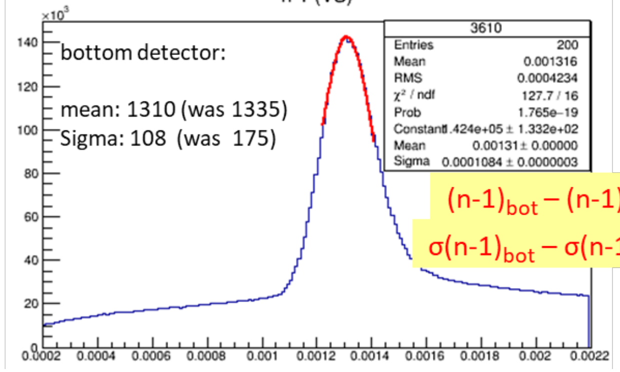


Study of half-rings suggested a further modification of the RICH geometry

→ a mirror orientation correction has been found which removes the TOP - BOTTOM discrepancy

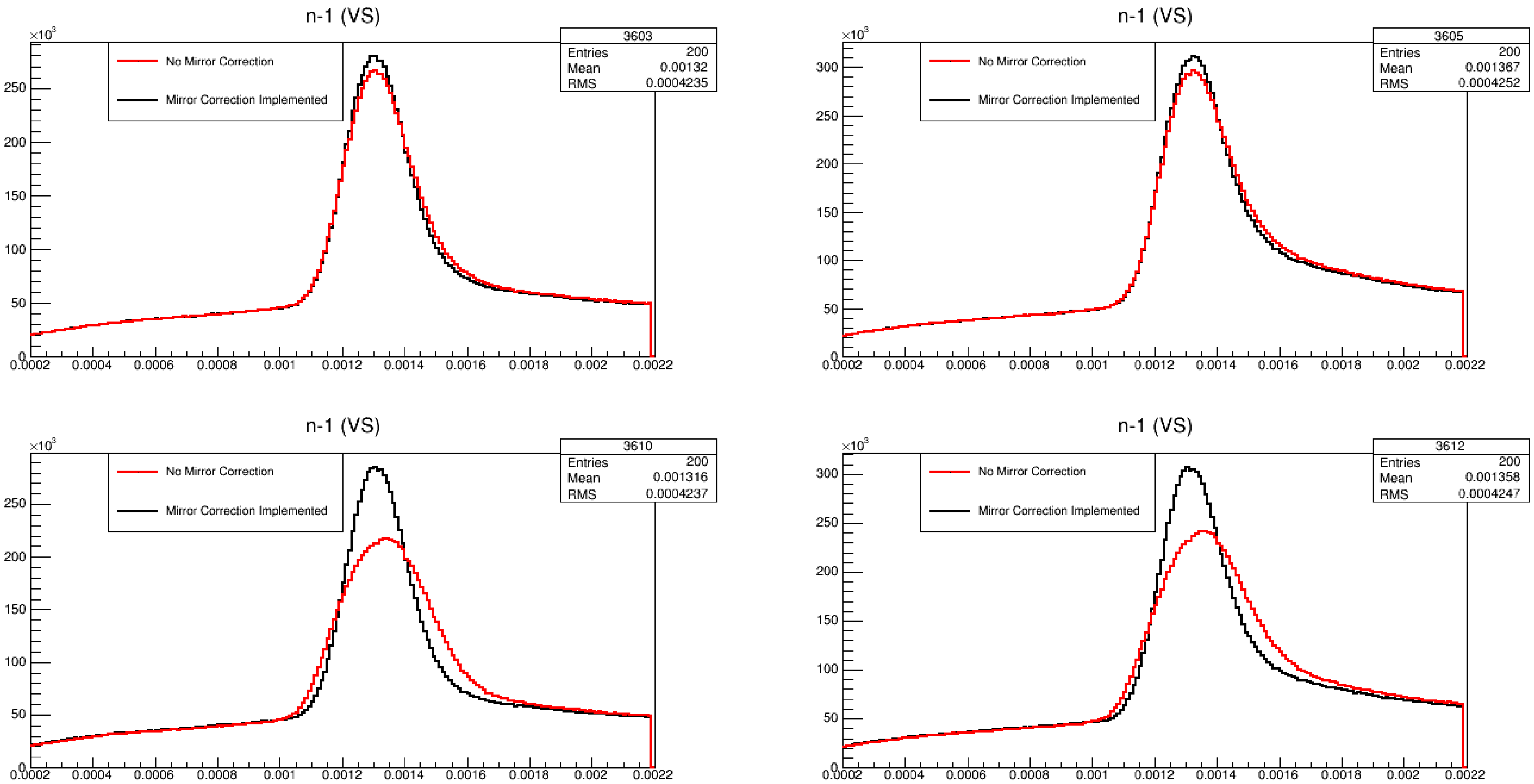


n-1 (VS)



$(n\text{-}1)_{bot} - (n\text{-}1)_{top}$ = -2 ppm

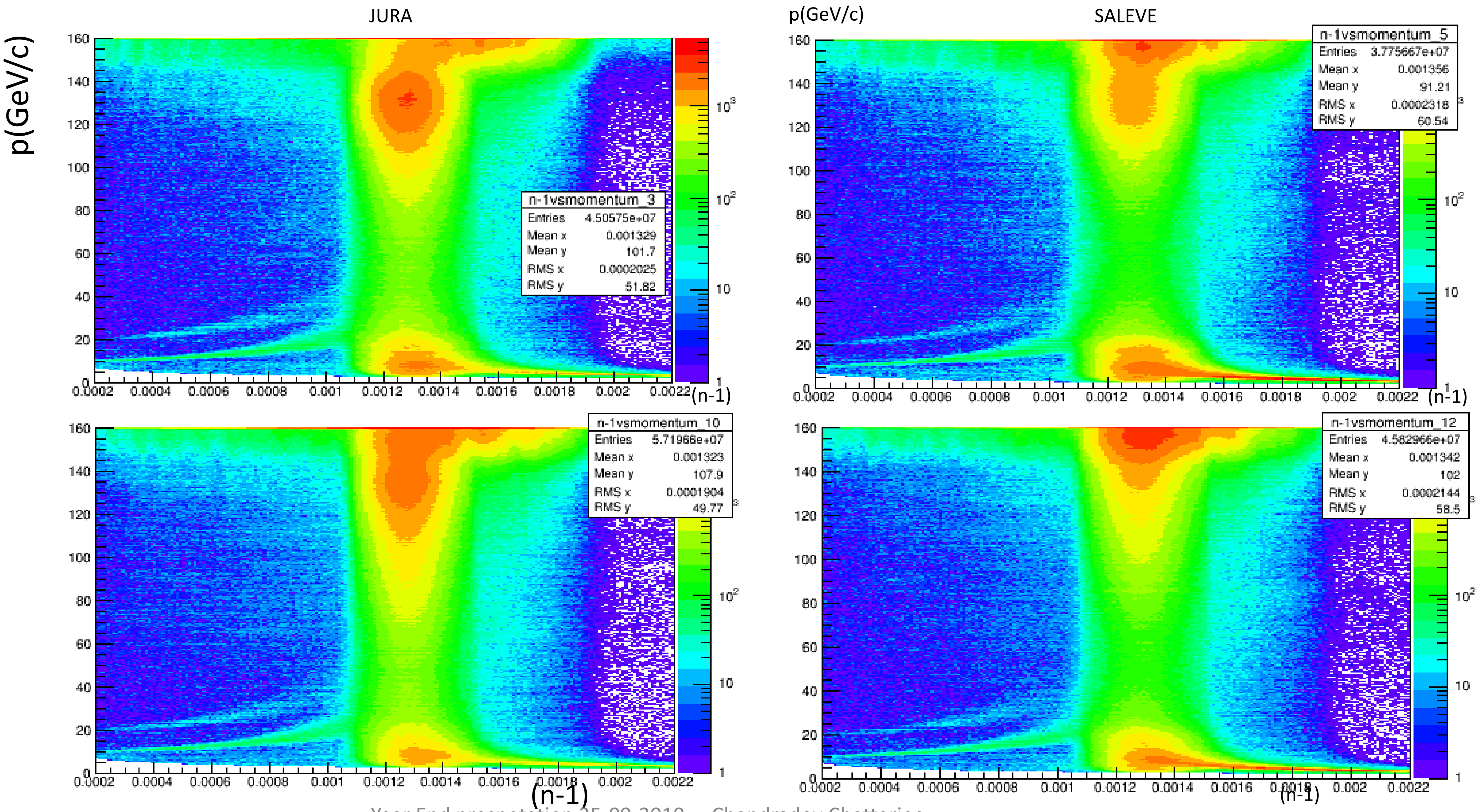
$\sigma(n\text{-}1)_{bot} - \sigma(n\text{-}1)_{top}$ = -5 ppm



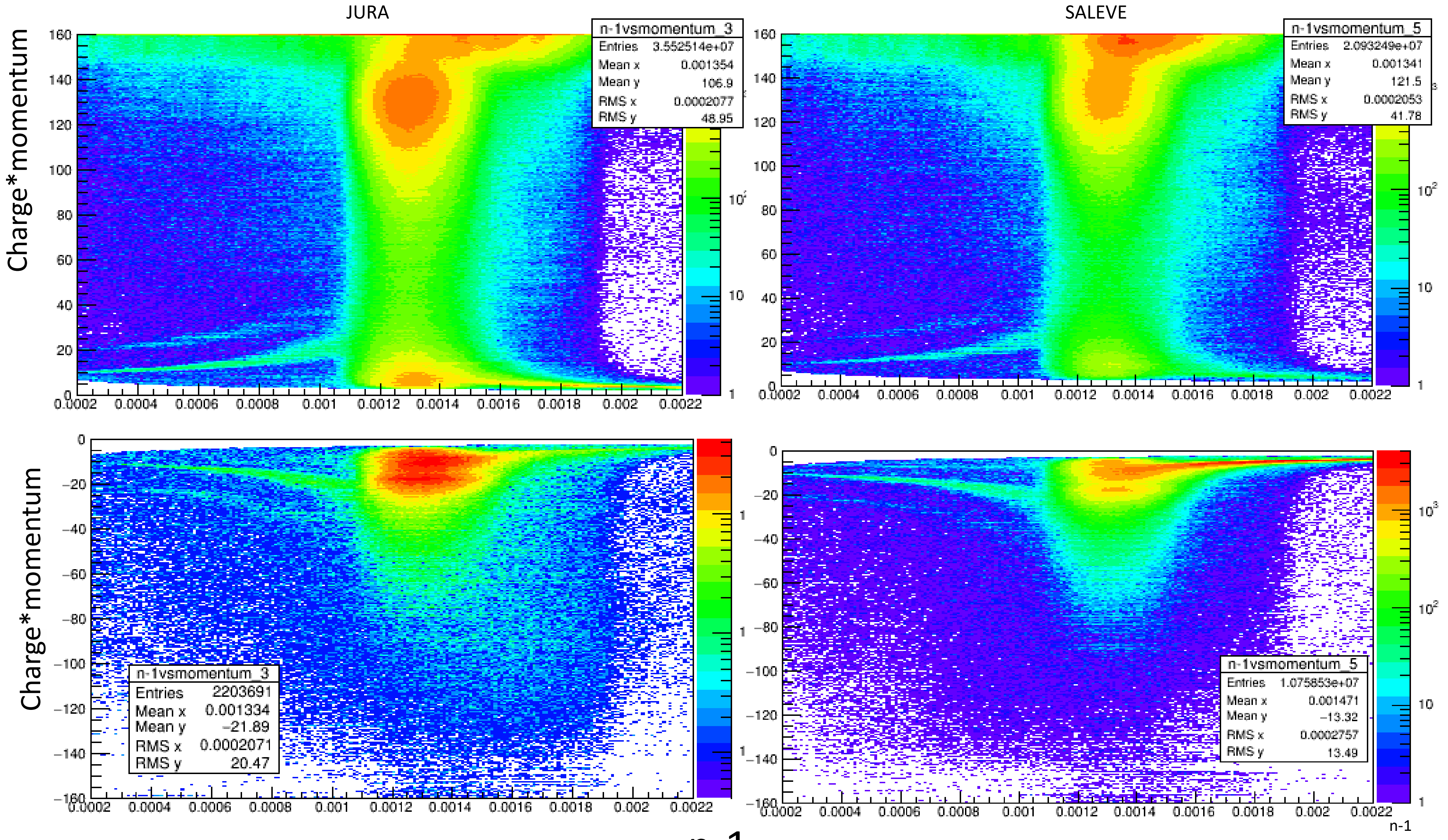
How does it depends momentum? Do we have similar situations for different charged tracks?

(n-1) estimate vs track mom.

beam: μ+,   mass: π

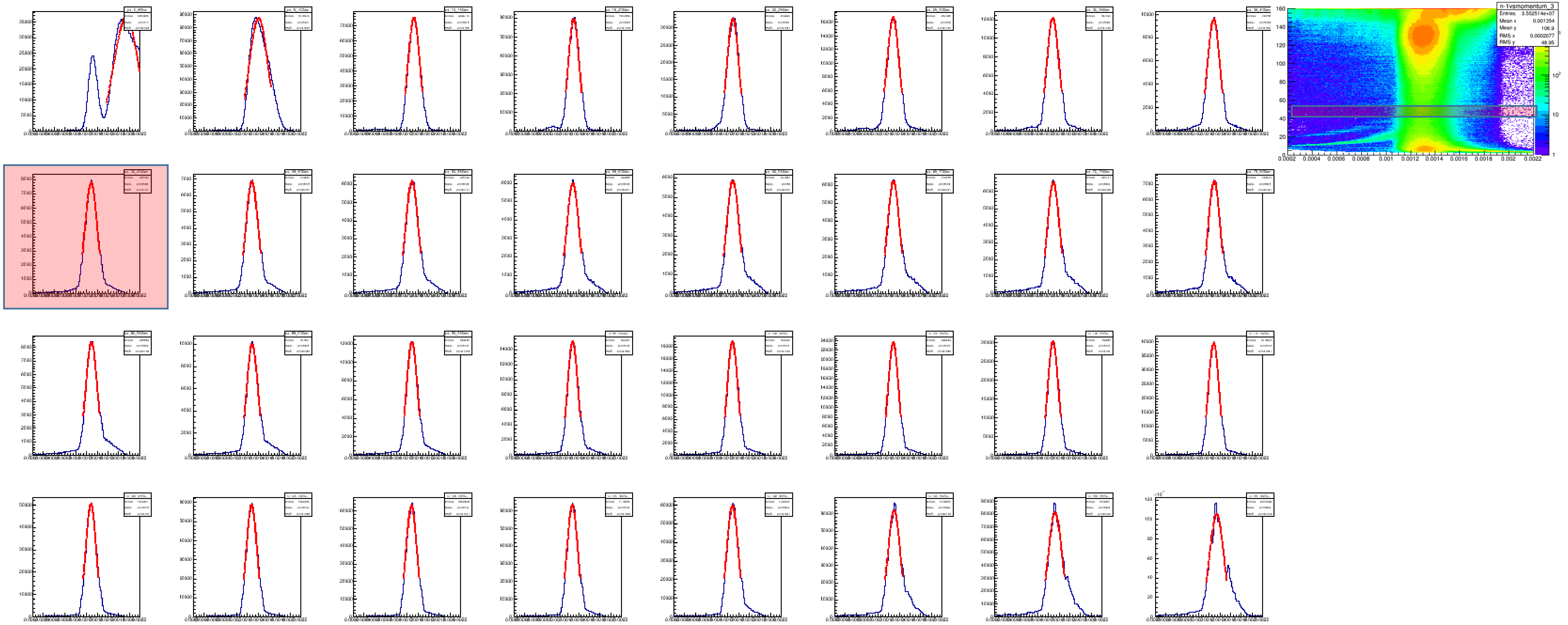


(n-1) estimate vs track mom for top 2 MAPMTs

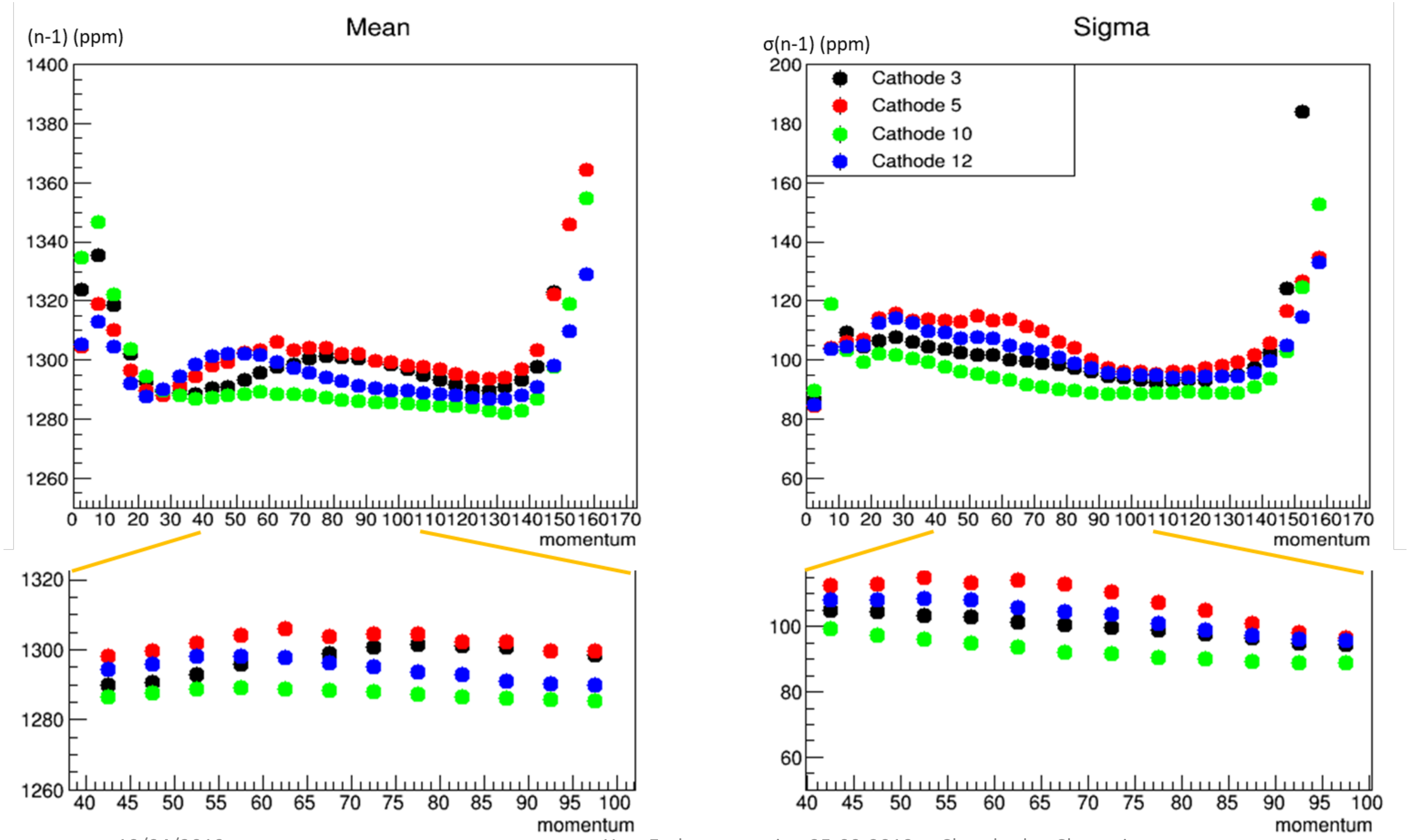


n-1

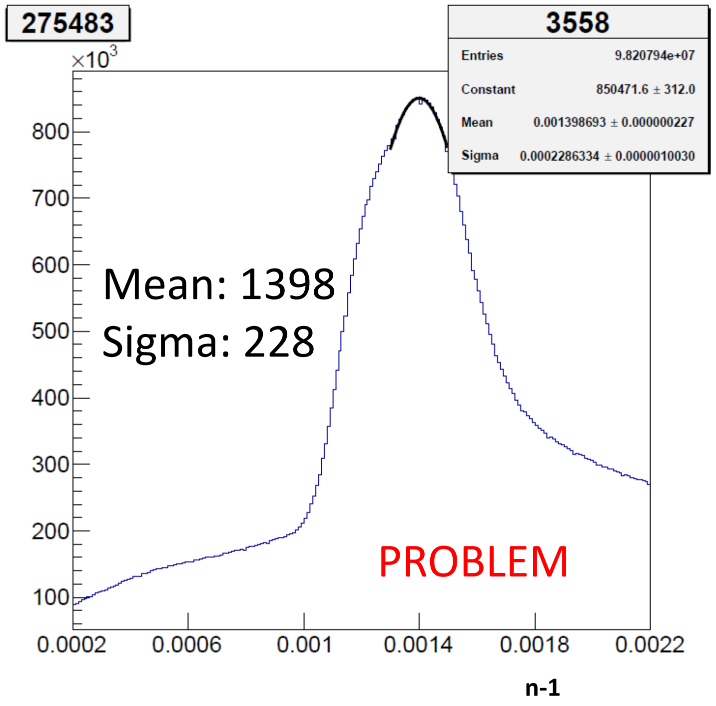
Example of n-1 projection in mom. 5 GeV Bins. all track. Saleve Cathode



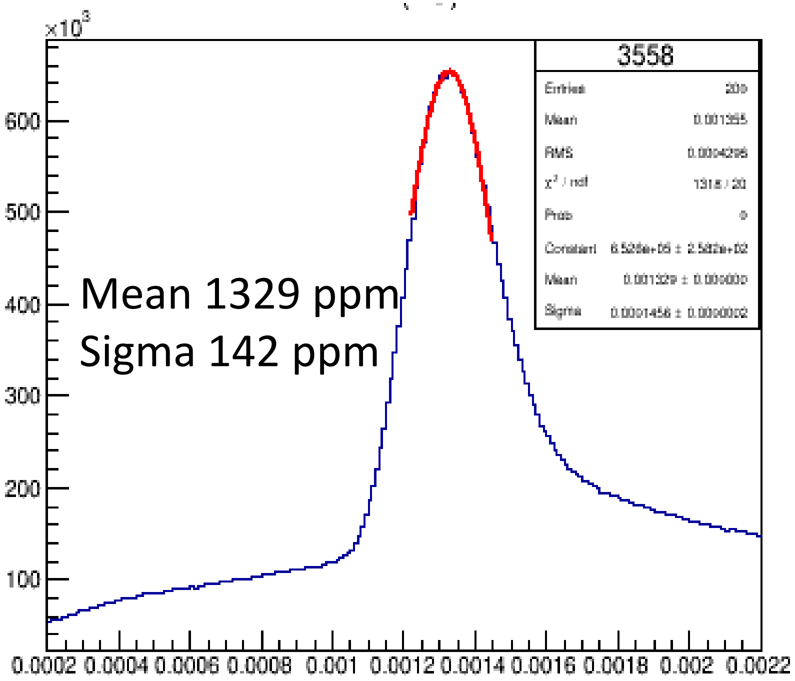
(n-1) mean and σ vs track mom.



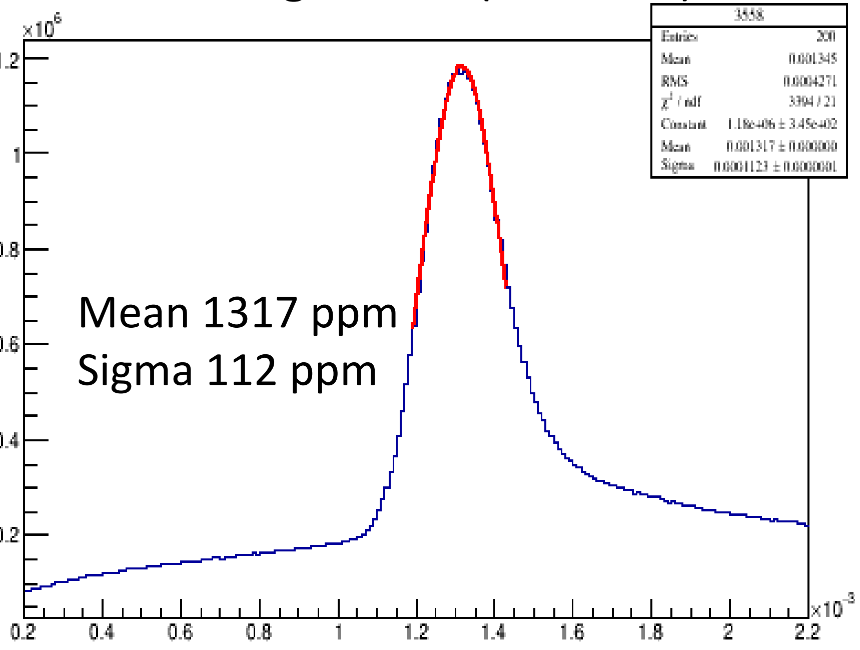
Before Detector Survey and Mirror alignment. (0-30GeV)

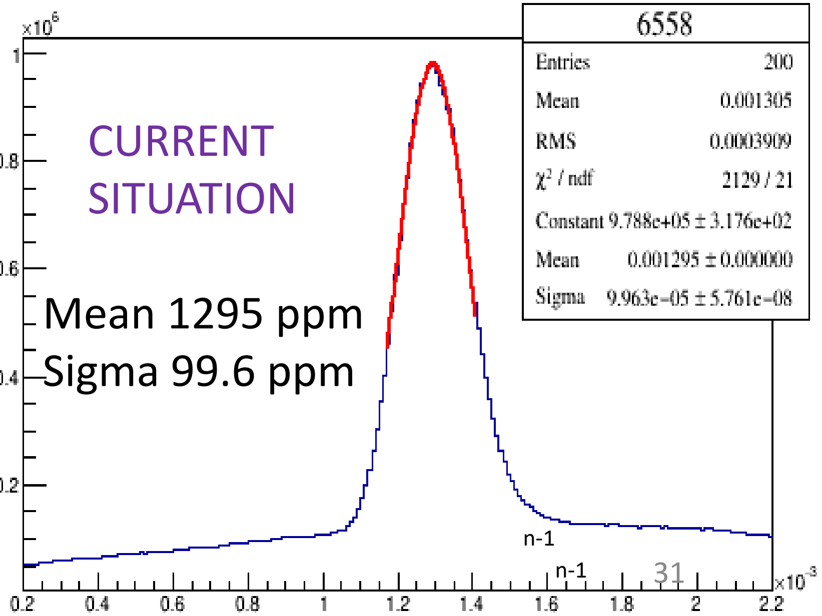


After Detector Survey and No Mirror alignment. (0-30GeV)



After Detector Survey and Mirror alignment. (0-30GeV)





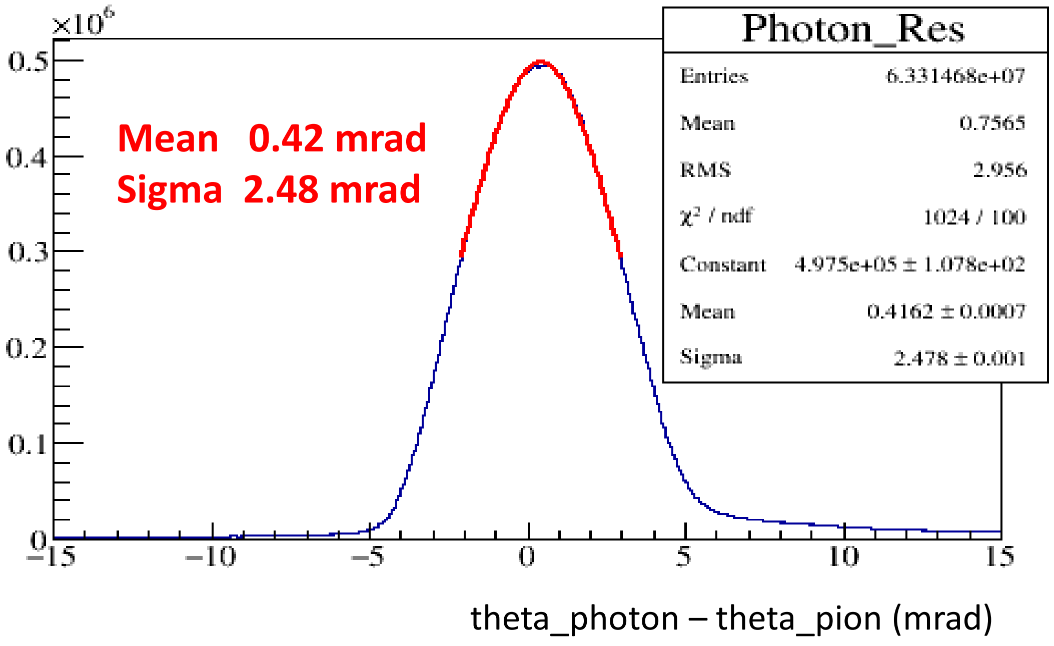
After Detector Survey and Mirror alignment. (40-100GeV)

5/8 Improvements

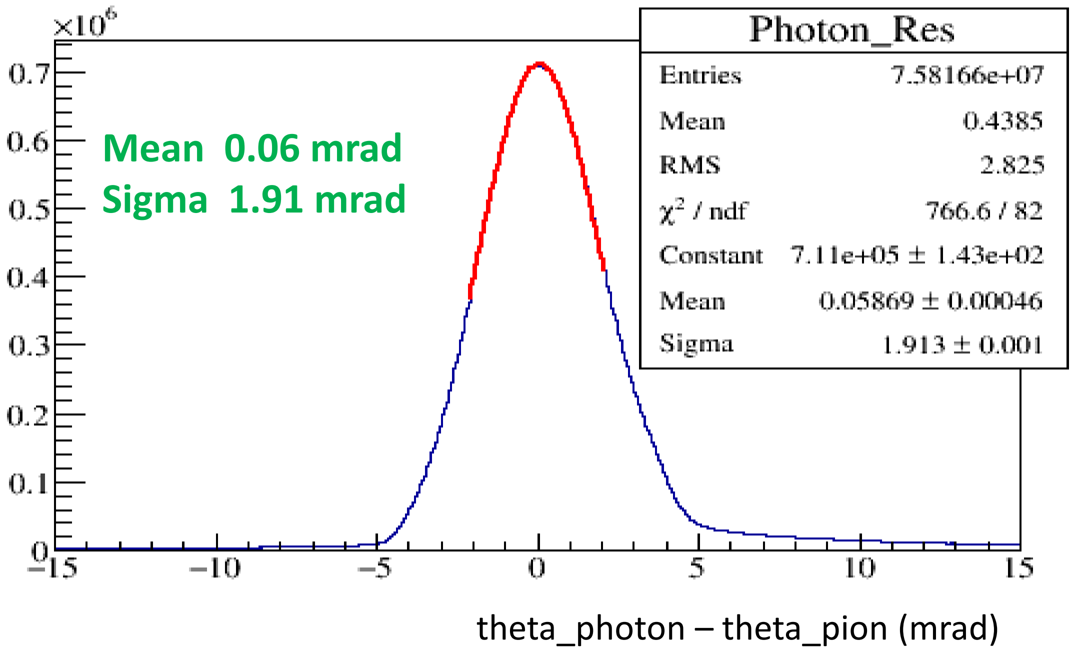
Photon Angle Resolution

No likelihood cut applied.

Before mirror correction and new n-1 algo

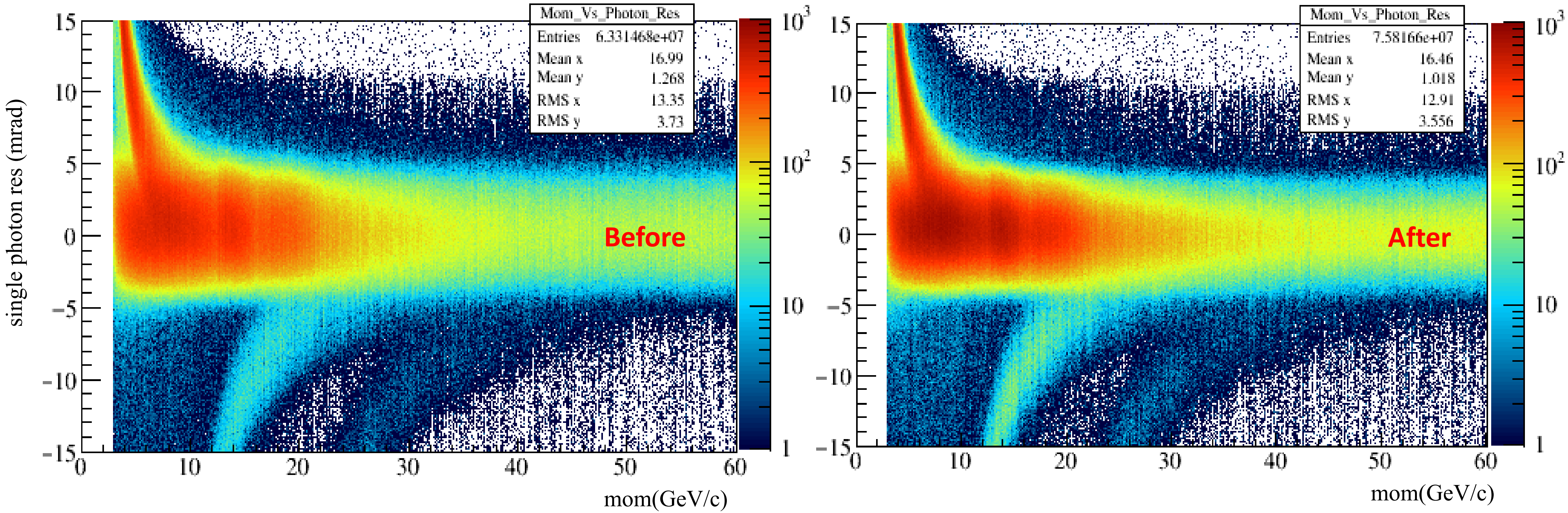


After mirror correction and new n-1 algo



Improvement in photon resolution 2.5 mrad → 1.9 mrad

Photon residual vs momentum

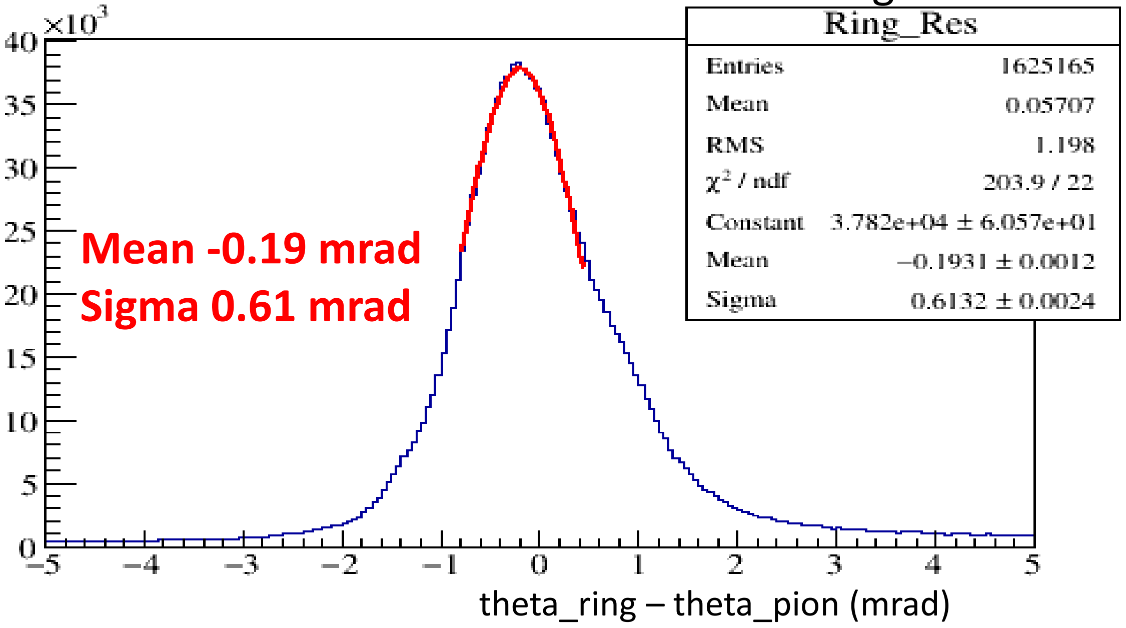


Photon residual = photon theta – pion theta

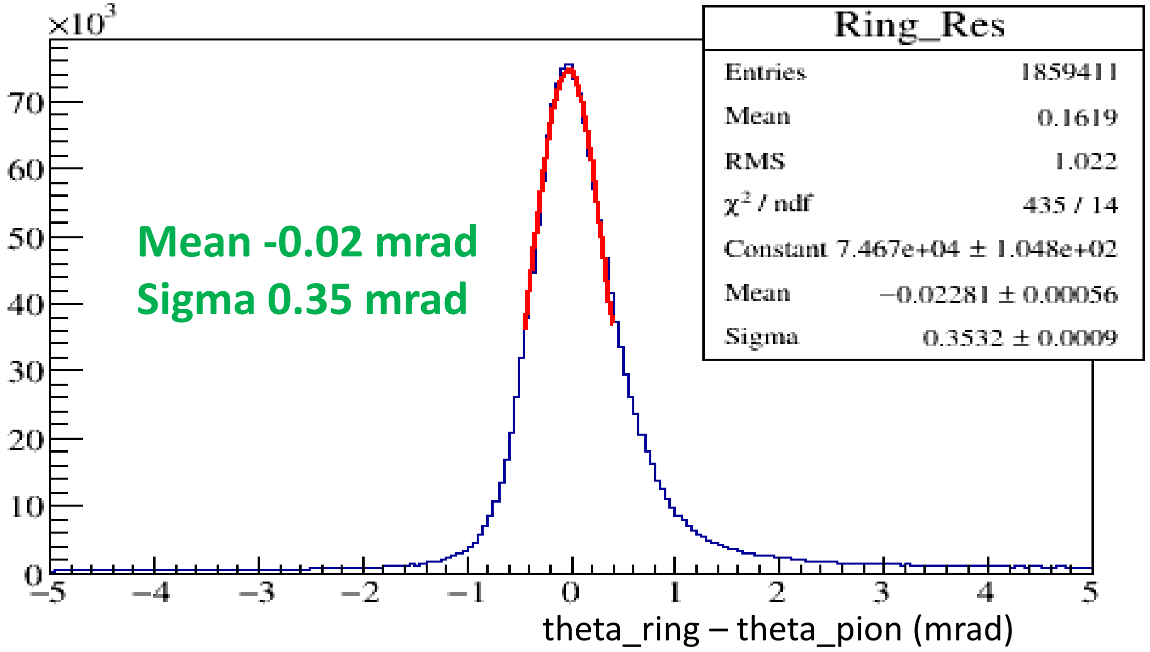
Ring Angle Resolution

No likelihood cut applied.

Before mirror correction and new n-1 algo

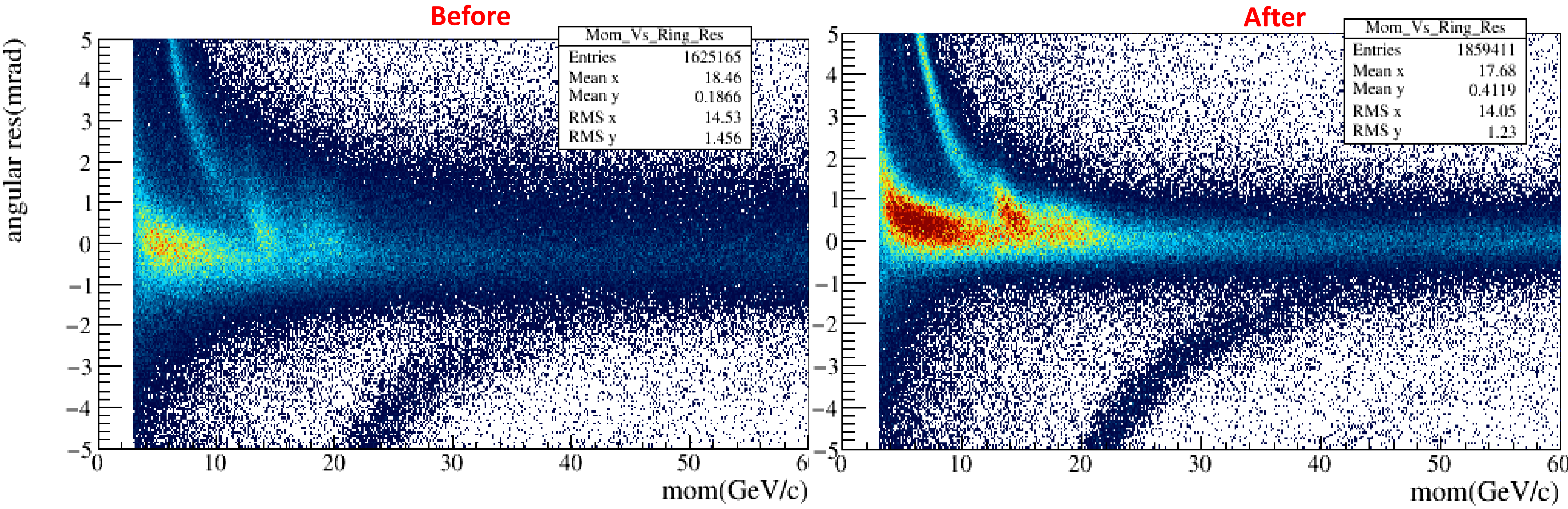


After mirror correction and new n-1 algo



Improvement in ring resolution 0.6 mrad → 0.35 mrad

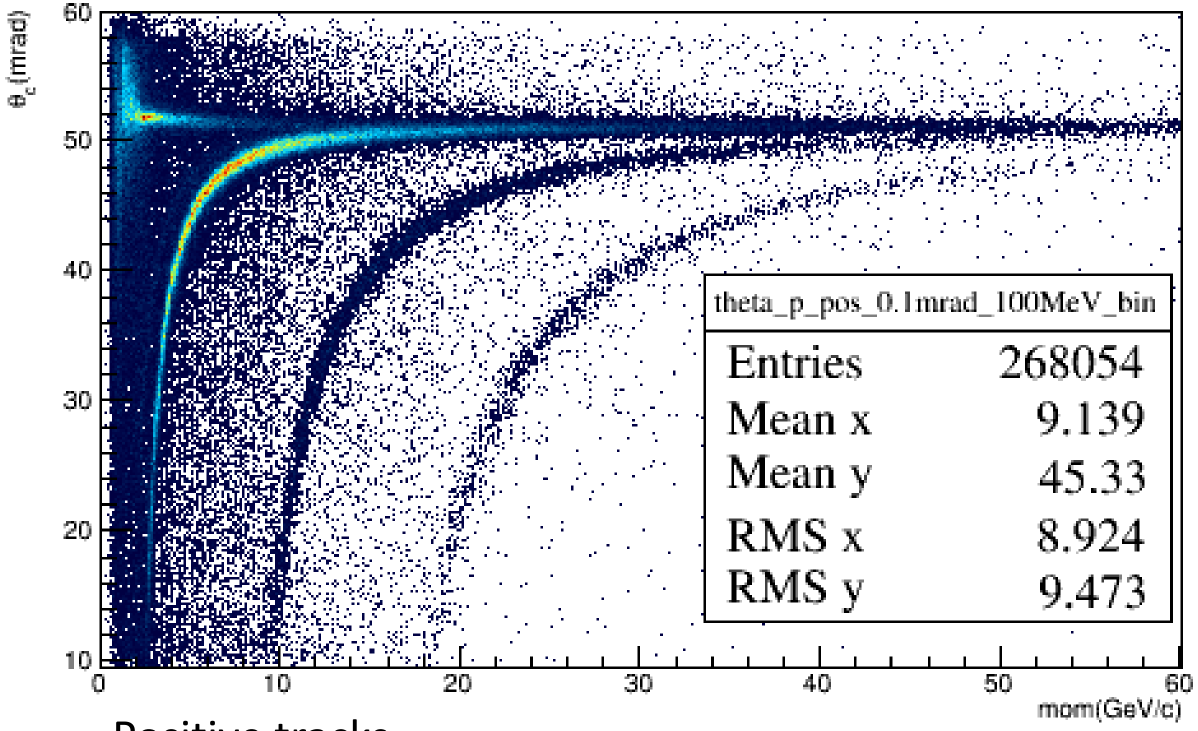
Ring residual vs momentum



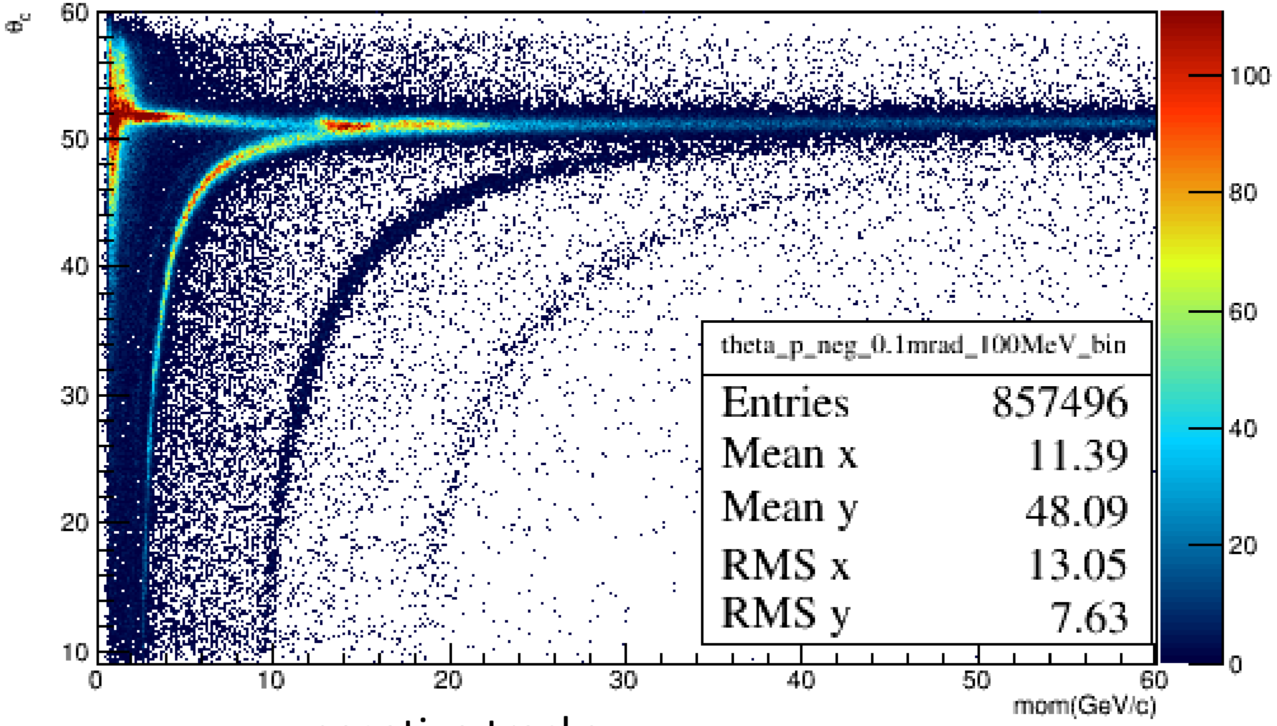
ring residual = ring theta – pion theta

Enhanced Kaon band. Good separation

Ring theta versus momentum

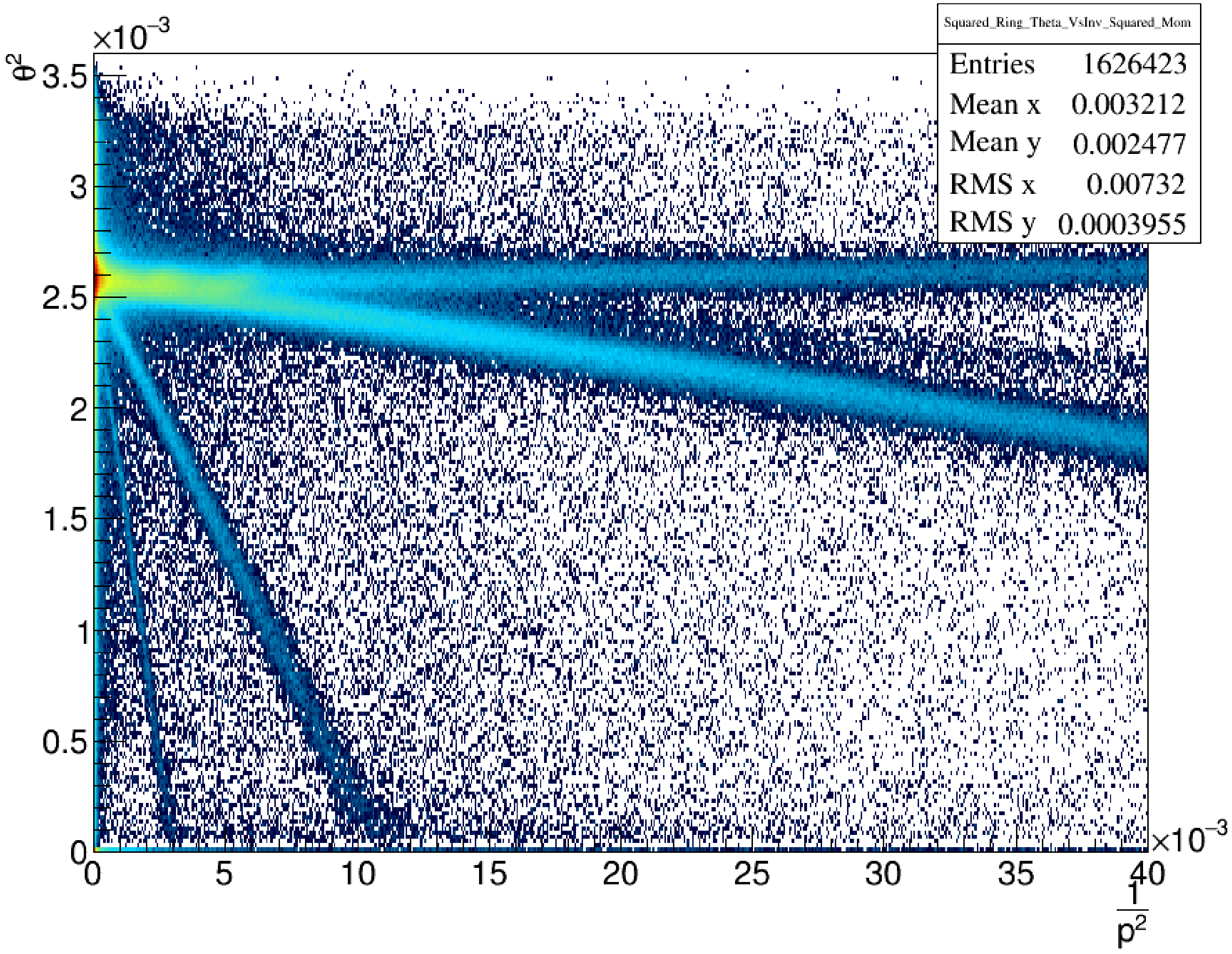


Positive tracks



negative tracks

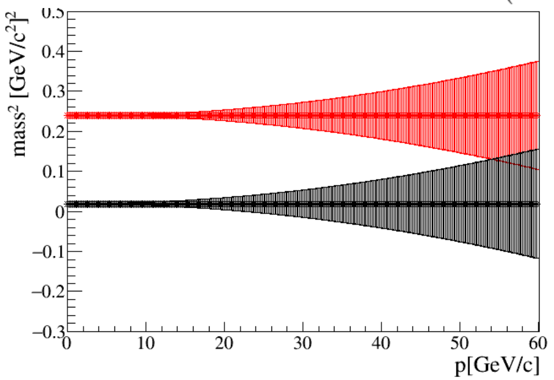
Ring theta versus momentum



- **Theoretically theta vs momentum plots based on measurement by RICH and spectrometer. No Refractive index comes into the plot.**
- **This plot can be mapped into a squared mass plot.**
- **Theoretically we expect straight lines at correct values of squared mass.**

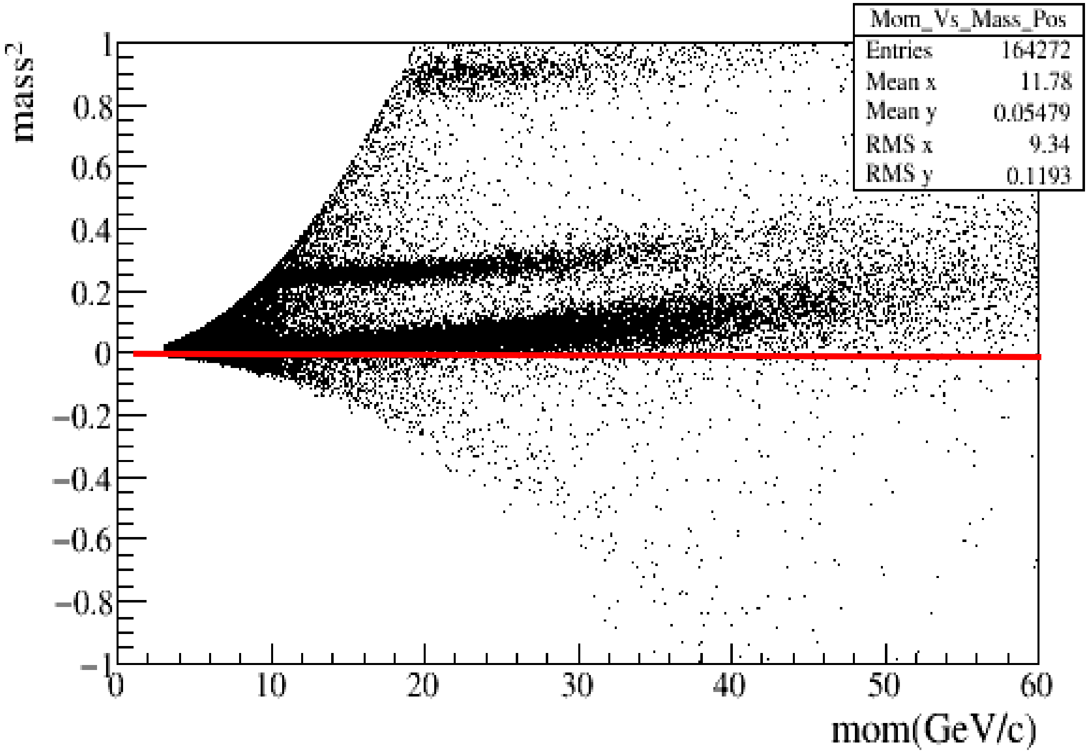
$$\left(\frac{\sigma_{m^2}}{m^2}\right)^2 = \left(2m^2\frac{\sigma p}{p}\right)^2 + \left(p^2\frac{2\theta\sigma_\theta}{(n-1)-1}\right)^2 + \left([2p^2-(p\theta)^2]\frac{\sigma_{(n-1)}}{[(n-1)-1]^2}\right)^2 \quad (3.14)$$

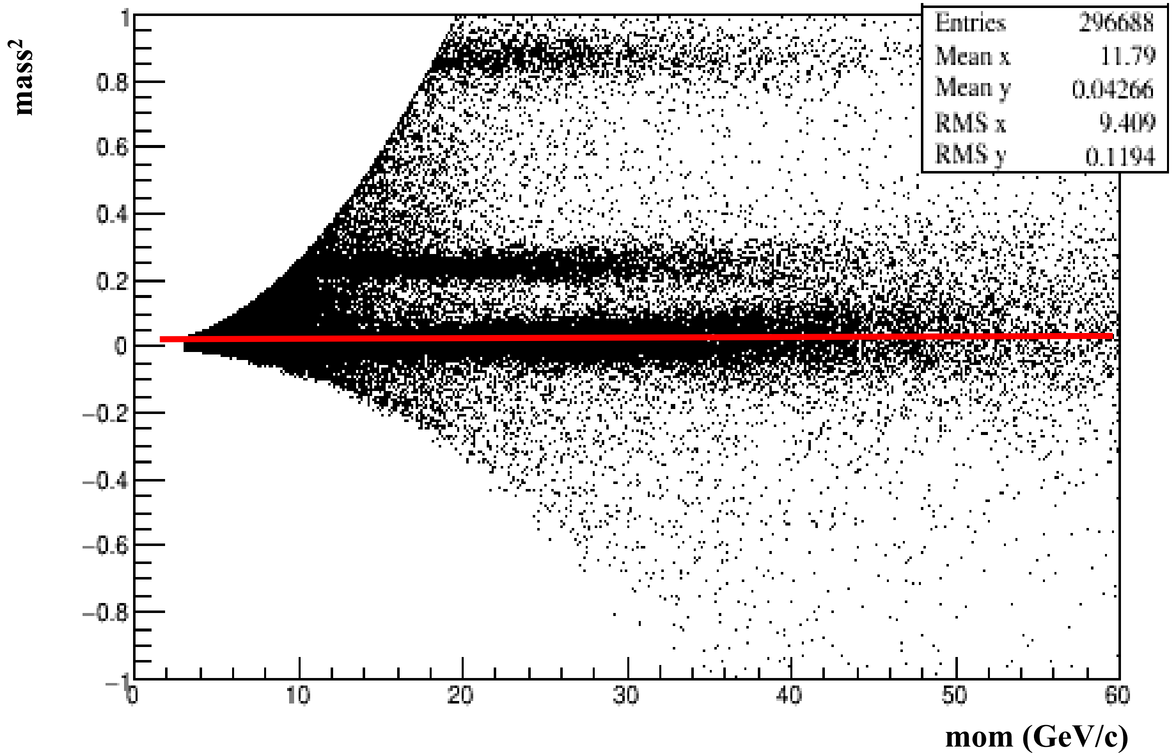
delta p/p = 0.5 %
sigma_theta = 0.35 mrad
sigma_n-1 = 0.4%



Mass^2 estimation by RICH

Near Saturation 2(n-1)~ squared theta. Gaussian nature of measured theta distribution suggests squared theta can be greater than 2(n-1). Giving negative mass squared. Using mass will loose half of the information.

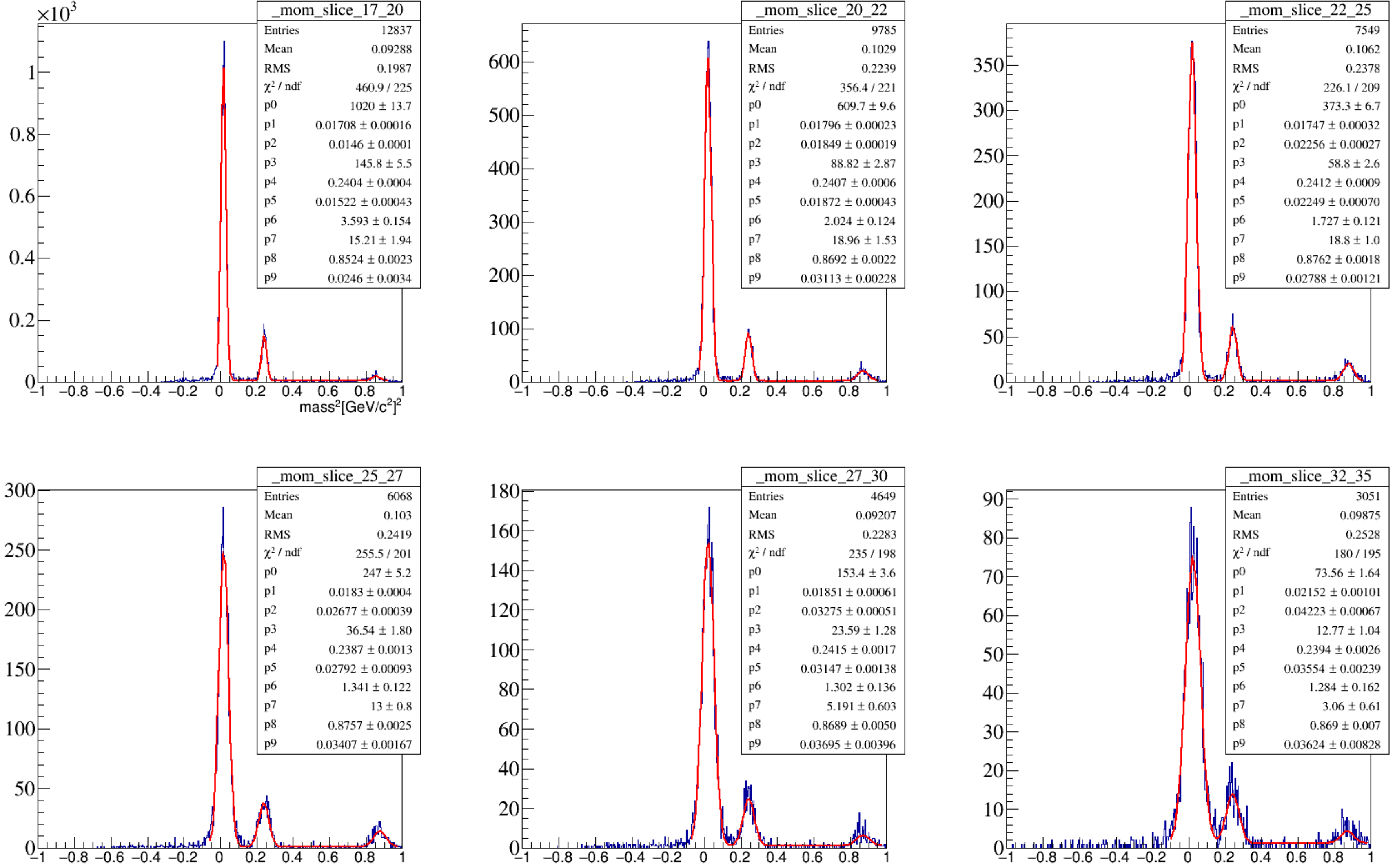




Refractive index NOT rightly set (electron contamination present)

Refractive index **rightly** set (No electron contamination)

Mass^2 estimation by RICH



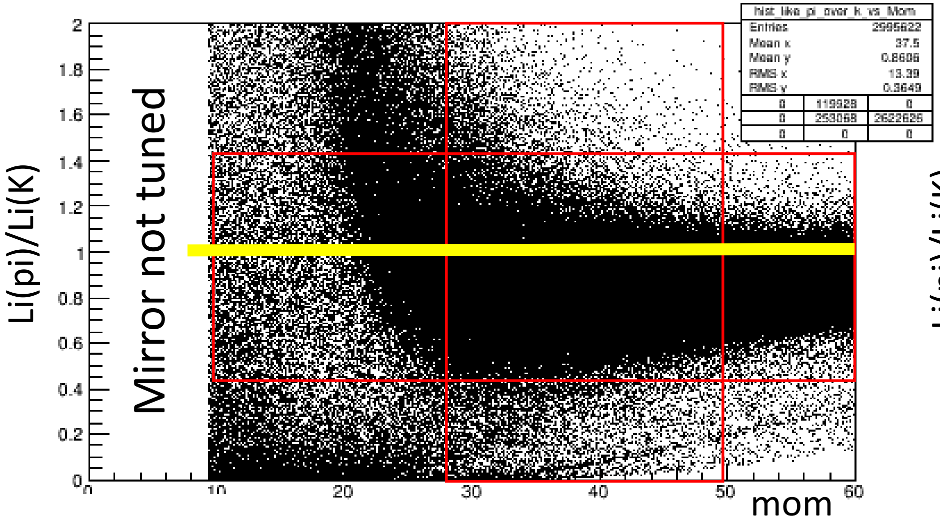
Example: Estimated mass

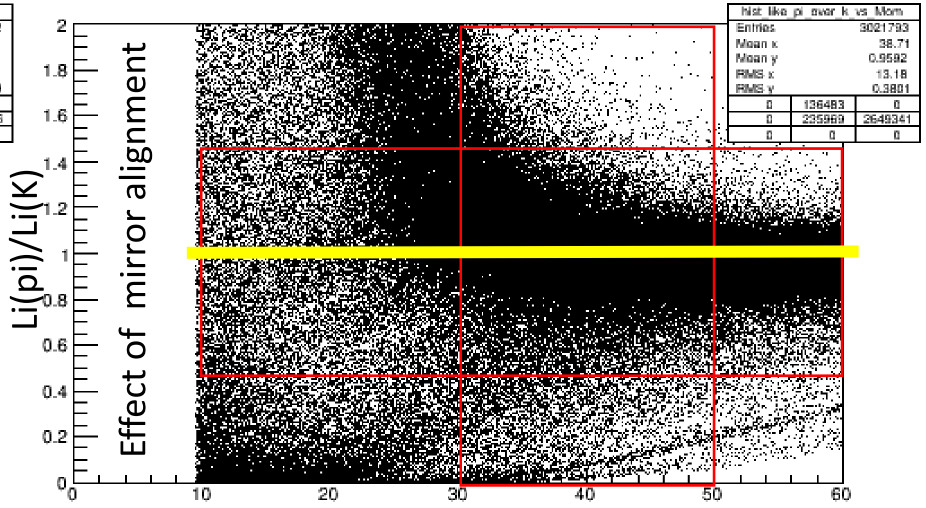
PDG:	**COMPASS RICH:**	
π mass: 0.13957 GeV/c^2	π mass: 0.138 GeV/c^2	= PDG value – ~2 MeV/c^2
K mass: 0.49368 GeV/c^2	K mass: 0.490 GeV/c^2	= PDG value – ~4 MeV/c^2
p mass: 0.93827 GeV/c^2	p mass: 0.932 GeV/c^2	= PDG value – ~6 MeV/c^2

→ ***Reasonable tuning; Good internal consistency***

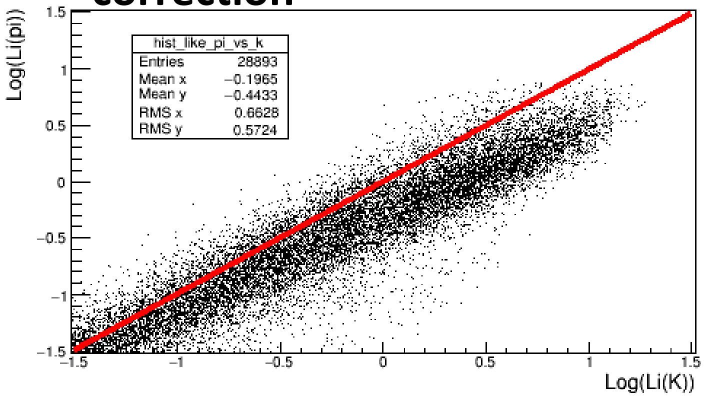
effect of the corrections on the likelihood values

Given tuned ref. index and measured theta, each photon of a track is used in an extended likelihood algorithm. Values with pion, Kaon, proton, electron, muon and bkg hypothesis computed.

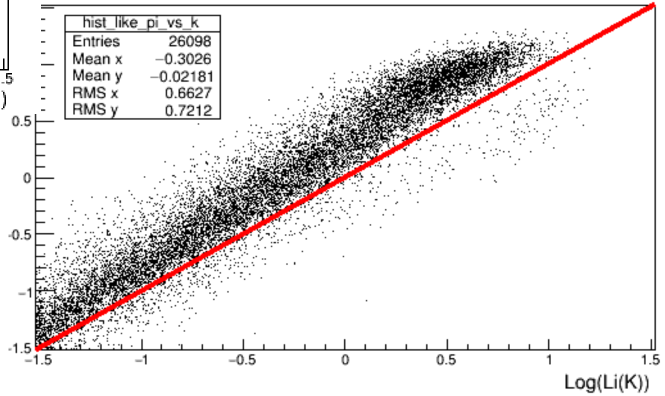


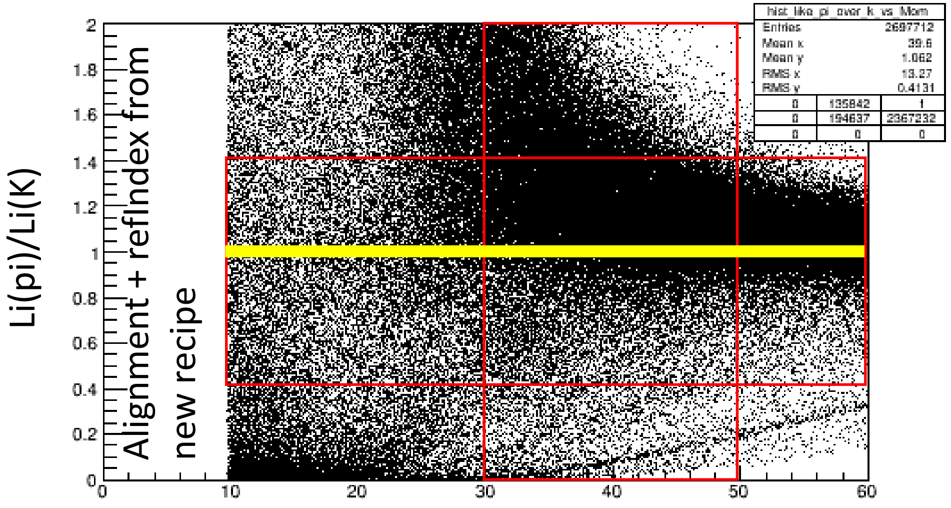


before correction



after mirror correction and new refractive Index



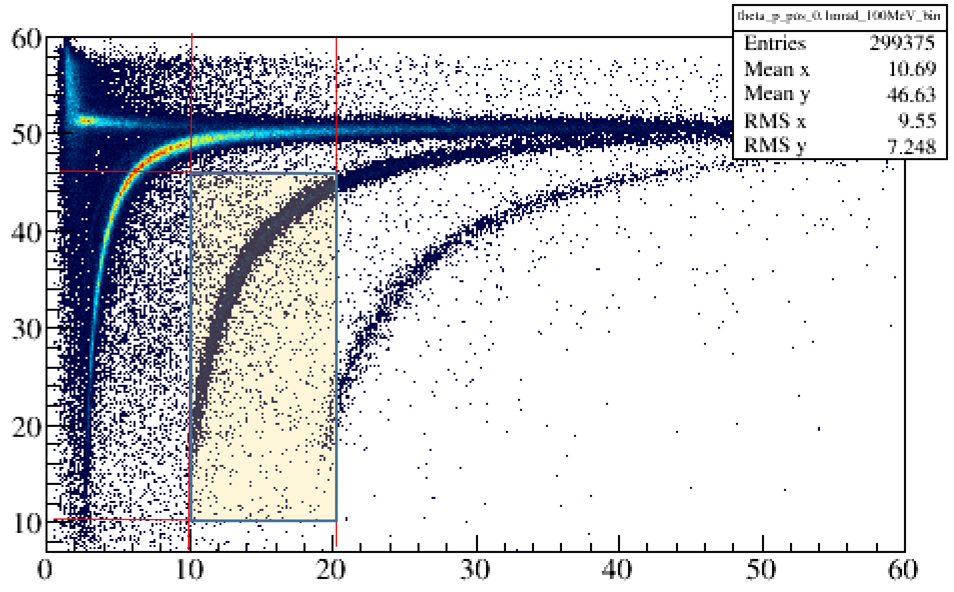


The ratio of likelihood of pion over kaon is supposed to be >1.

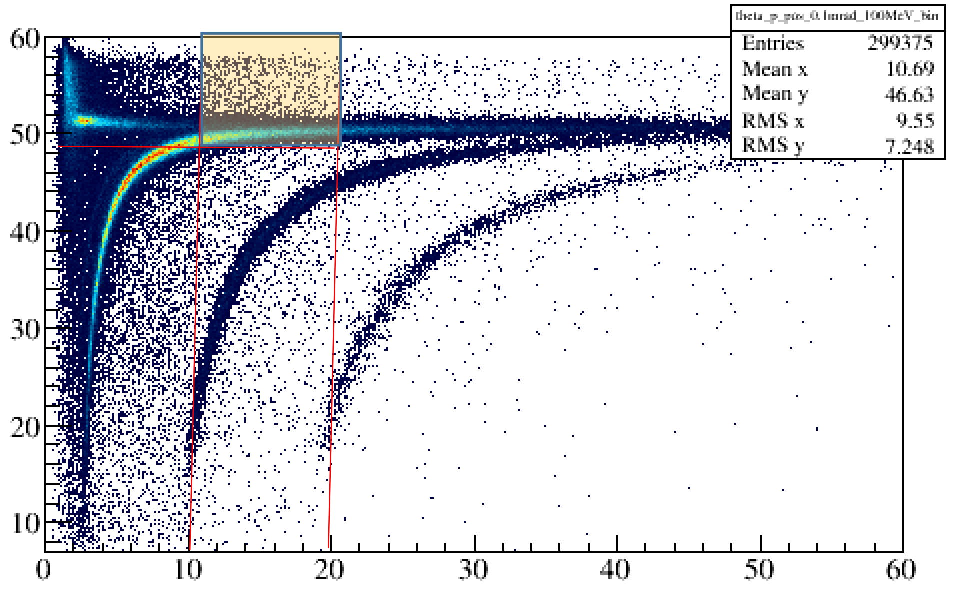
6/8 Consistency Checks

Consistency Check with likelihood and ring theta

Negative muon beam& +ve charged tracks, beam region excluded. Ring angle vs momentum. Selected regions (Shaded) with 1) Kaon dominated. 2) pion dominated.



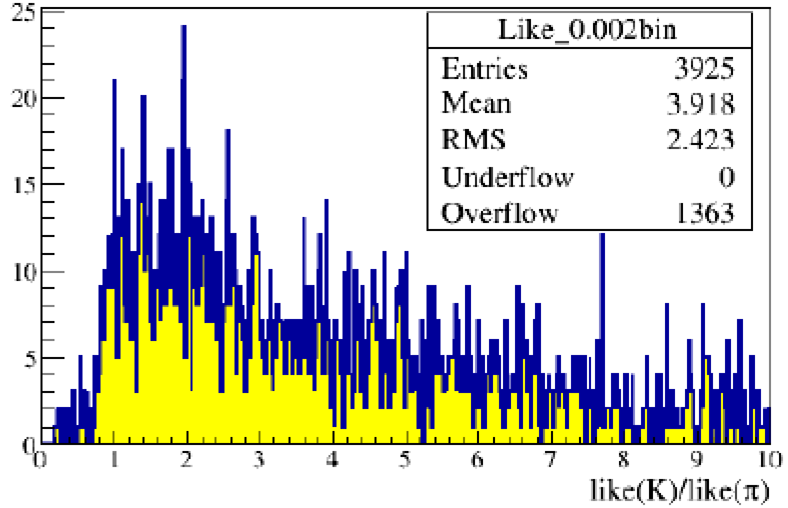
1



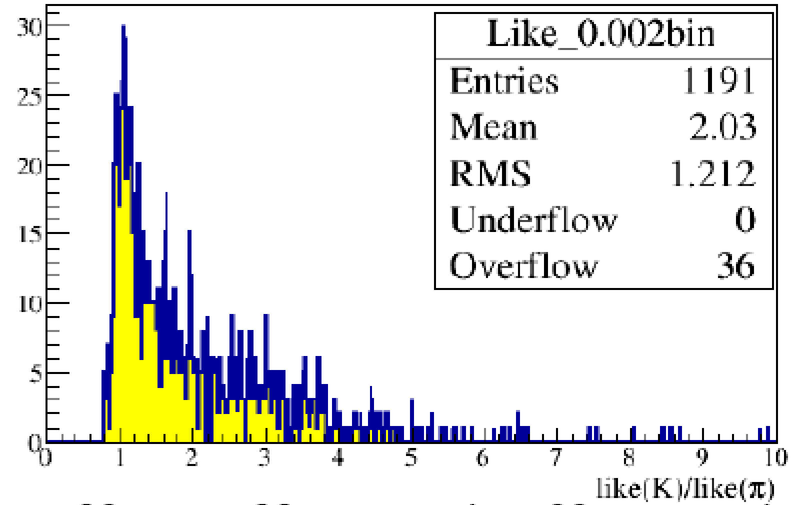
2

Consistency Check with likelihood and ring theta

If(mom>20 && mom<30 && VS_ring_angle>40 && VS_ring_angle<47)



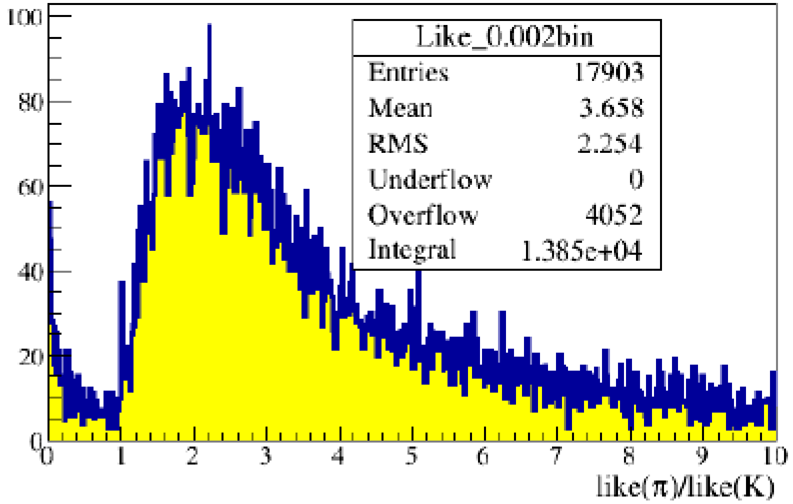
If(mom>30 && mom<35 && VS_ring_angle>47 && VS_ring_angle<50)



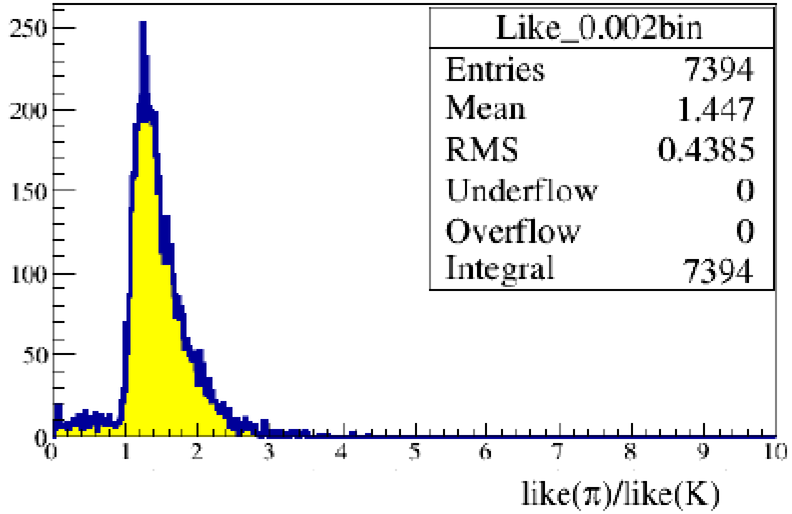
1

Like(K)/Like(pi)

If(mom>20 && mom<30 && VS_ring_angle>50 && VS_ring_angle<60)



If(mom>30 && mom<40 && VS_ring_angle>50 && VS_ring_angle<60)



Like(pi)/Like(K)

2

7/8 PID performance

RICH Performance on kinematically selected tracks

K^0 and Λ selection

Selection of good secondary vertex
- Loop over all vertices
- Vertex is not a primary one
- Exactly two oppositely charged outgoing particles
- The tracks should not be connected to any other primary vertex
- Primary and secondary vertex separated by more than 2σ

Select good hadron tracks
- Both particles should not have crossed more than 10 radiation length
- Last measured position (ZLast) behind SM1
- Transverse momentum with respect to the mother particle larger than 23MeV to suppress electrons
- Check that the decaying particle is connected to the primary vertex (angle<< 0.01)

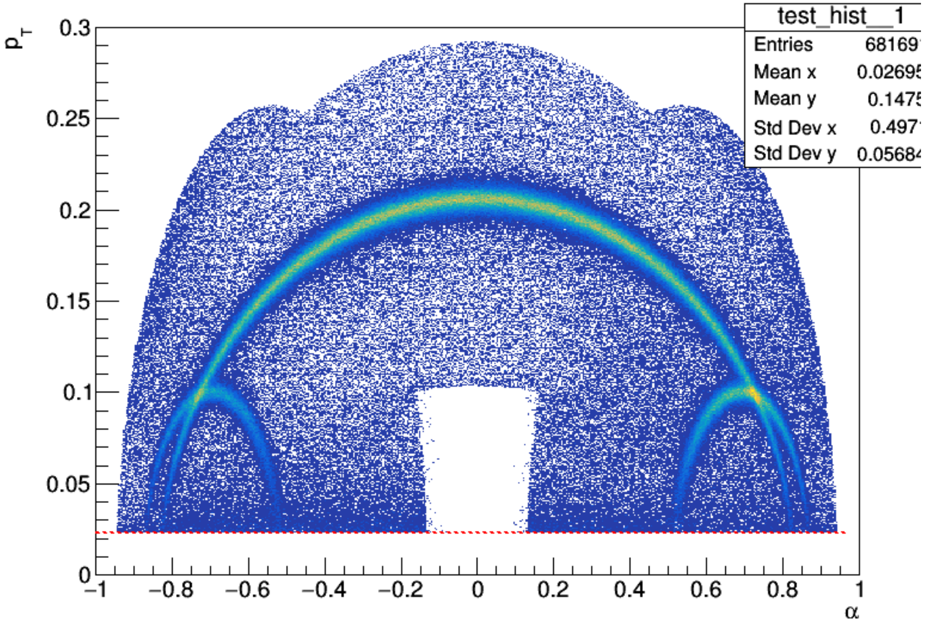
Additional cuts
- p_h > 1 GeV/c
- Mass difference smaller than 150MeV/c2 between the K^0/Λ mass and the invariant mass of the two decay hadrons assuming the correct masses

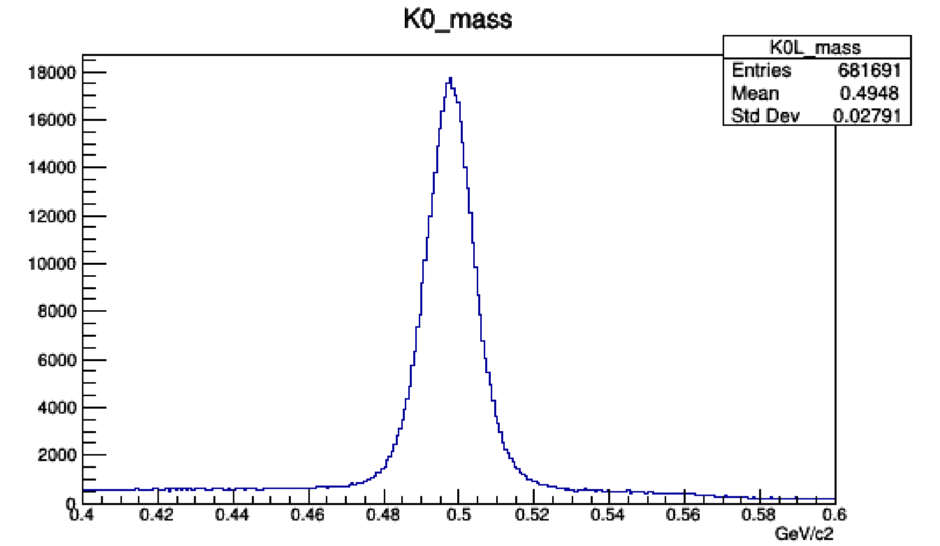
Φ Selection

Select possible event with Φ mesons
- At least 3 outgoing particles (includes scattered muon)
- Loop over all outgoing particles
- Oppositely charged pairs of hadrons (none is a muon)

Select good hadron tracks
- Last measured position behind SM1
- Transverse momentum with respect to the mother particle larger than 23MeV to suppress electrons

3. Additional cuts
- 9 GeV/c < p < 55 GeV/c
- Mass difference between mass and the invariant mass of the two hadrons smaller than 120MeV/c^2 assuming the kaon mass





Efficiency and purity

$$M_{RICH} = \begin{pmatrix} \epsilon(\pi \to \pi) & \epsilon(\pi \to K) & \epsilon(\pi \to p) & \epsilon(\pi \to noID) \\ \epsilon(K \to \pi) & \epsilon(K \to K) & \epsilon(K \to p) & \epsilon(K \to noID) \\ \epsilon(p \to \pi) & \epsilon(p \to K) & \epsilon(p \to p) & \epsilon(p \to noID) \end{pmatrix}$$

For positive pion identification, events from K^0 are used where the negative arm has been identified as a pion.
Histograms are booked

1. ALL Events (No RICH info)
2. pi+ → pi+
3. pi+ → K+
4. pi+ → P
5. pi+ → Bkg

Simultaneous fitting of all these histograms with the following function

$$f(x) = N_{sig}*f_{sig}+N_{Bg}*f_{Bg}$$

SAMPLE	SIGNAL	BACKGROUND
K^0	$\delta G(\mu, \sigma_1) + (1-\delta)G(\mu, \sigma_2)$	$1 + ax + b(2x^2 - 1) + c(4x^3 - 3x)$
ϕ	$BW(\mu, \sigma_1) \otimes G(\mu, \sigma_2)$	$(x-t)^n \cdot \exp(-a(x-t))$ with $t = 2 \cdot m_K$
Λ	$\delta G(\mu, \sigma_1) + (1-\delta)G(\mu, \sigma_2)$	$(x-t)^n \cdot \exp(-a(x-t))$ with $t = m_p + m_\pi$

	PION	KAON	PROTON	
Momentum	$p > p_{\pi,thr}$	$p > p_{K,thr}$	$p \leqslant p_{p,thr}$	$p > p_{p,thr}$
Likelihood type i	π	K	bg	p
LH(i)/LH(π)	—	> 1.08	> 1.0	> 1.0
LH(i)/LH(K)	> 1.0	—	> 1.0	> 1.0
LH(i)/LH(p)	> 1.0	> 1.00	—	—
LH(i)/LH(bg)	> 1.0	> 1.24	—	> 1.0

$$M_{RICH} = \begin{pmatrix} \epsilon(\pi \to \pi) & \epsilon(\pi \to K) & \epsilon(\pi \to p) & \epsilon(\pi \to noID) \\ \epsilon(K \to \pi) & \epsilon(K \to K) & \epsilon(K \to p) & \epsilon(K \to noID) \\ \epsilon(p \to \pi) & \epsilon(p \to K) & \epsilon(p \to p) & \epsilon(p \to noID) \end{pmatrix}$$

	PION	KAON	PROTON	
Momentum	$p > p_{\pi,thr}$	$p > p_{K,thr}$	$p \leqslant p_{p,thr}$	$p > p_{p,thr}$
Likelihood type i	π	K	bg	p
$LH(i)/LH(\pi)$	—	> 1.08	> 1.0	> 1.0
$LH(i)/LH(K)$	> 1.0	—	> 1.0	> 1.0
$LH(i)/LH(p)$	> 1.0	> 1.00	—	—
$LH(i)/LH(bg)$	> 1.0	> 1.24	—	> 1.0

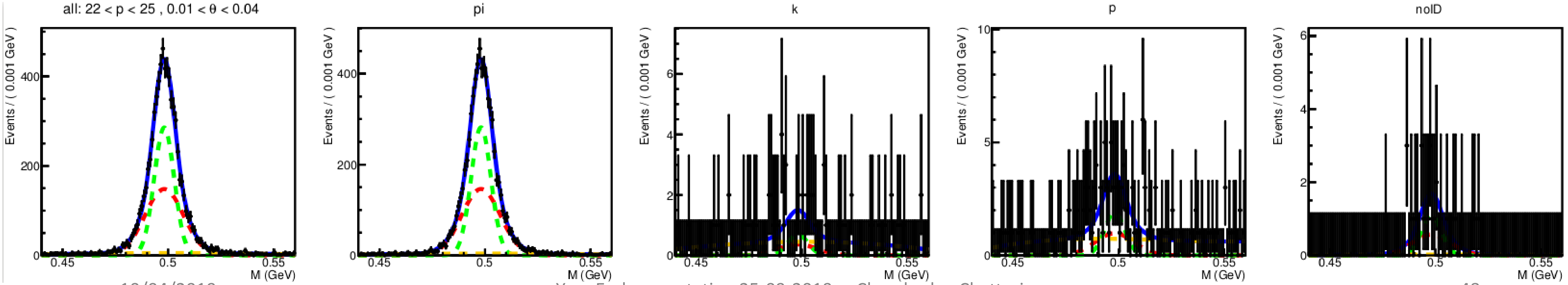
For positive pion identification, events from K^0 are used where the negative arm has been identified as a pion.
Histograms are booked

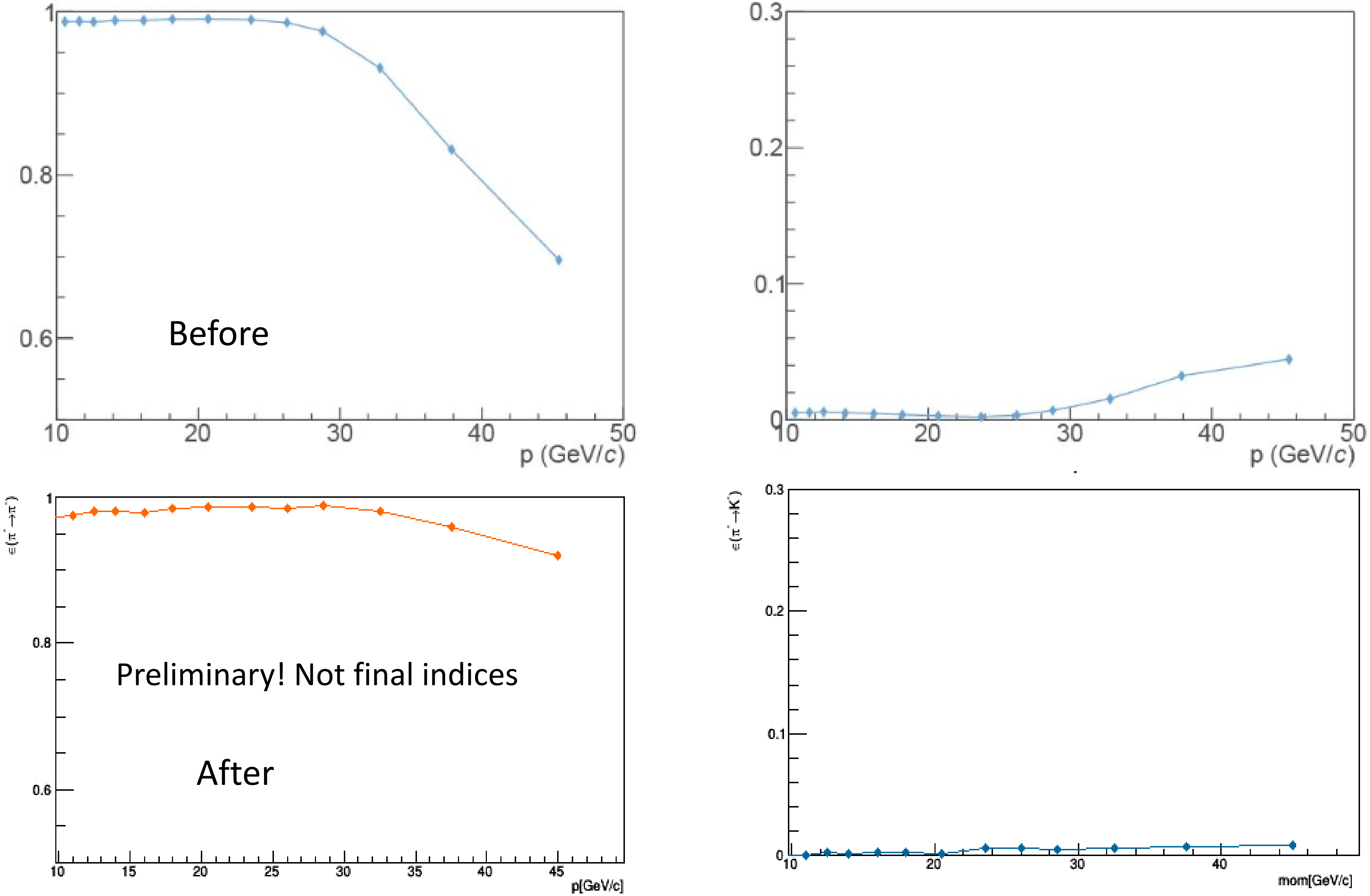
1. ALL Events (No RICH info)
2. pi+ → pi+
3. pi+ → K+
4. pi+ → P
5. pi+ → Bkg

Simultaneous fitting of all these histograms with the following function

$$f(x) = N_{sig} * f_{sig} + N_{Bg} * f_{Bg}$$

Ratio of the signals are the matrices elements Preliminary! Not final




Before
p (GeV/c)
p (GeV/c)
Preliminary! Not final indices
After
p[GeV/c]
mom[GeV/c]

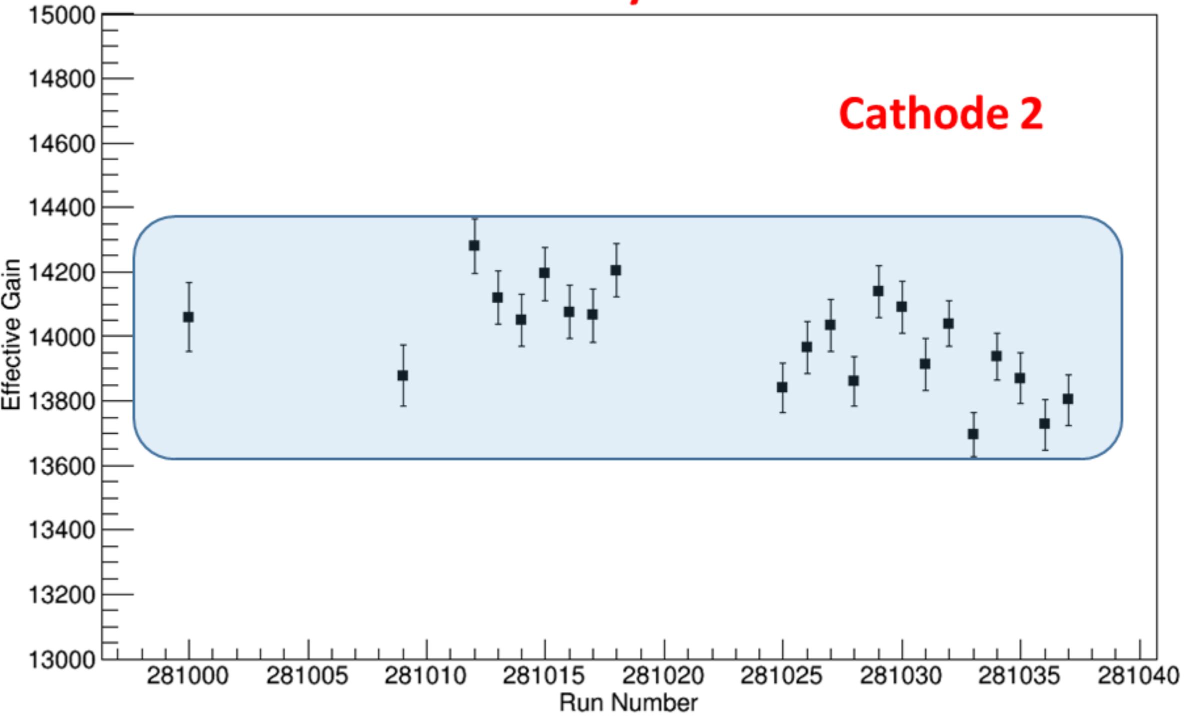
8/8 Conclusion

Conclusion

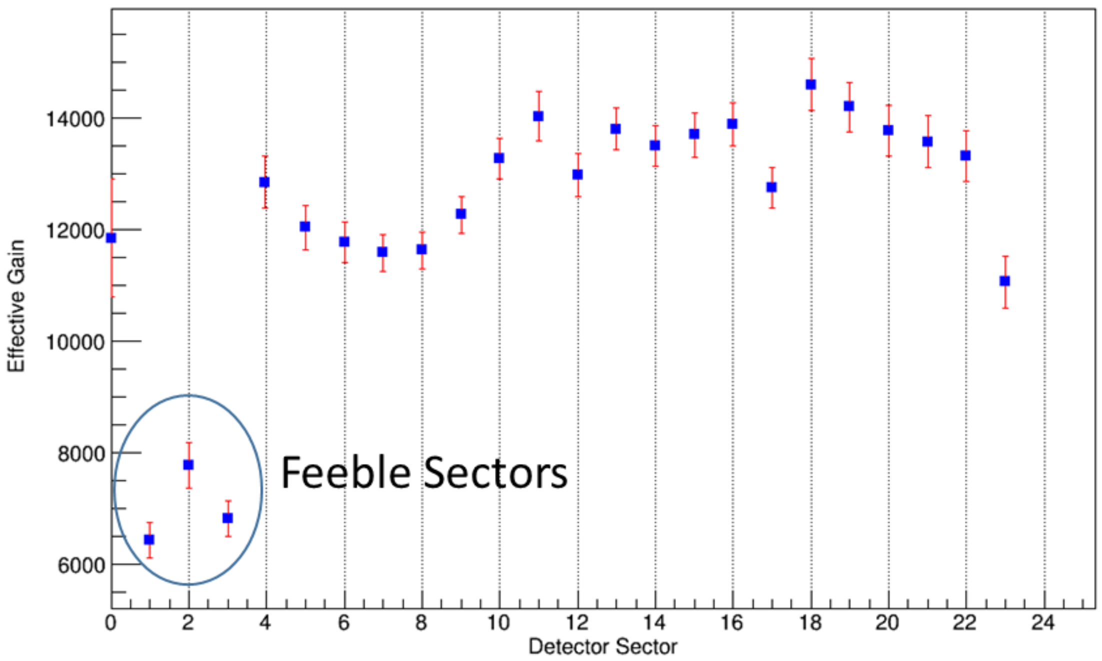
- COMPASS RICH has been upgraded with New photon detectors based on MPGD technologies. I have Characterized them.
- The number of photons per ring is satisfactory with large gain and good single photon resolution.
- I have tuned the RICH reasonably with upgraded Detector and Mirror position. The RICH geometry and reconstruction algorithm is well under control.
- Preliminary PID performance is promising after the tuning.
- Full chain for RICH studies is under control.

Back ups

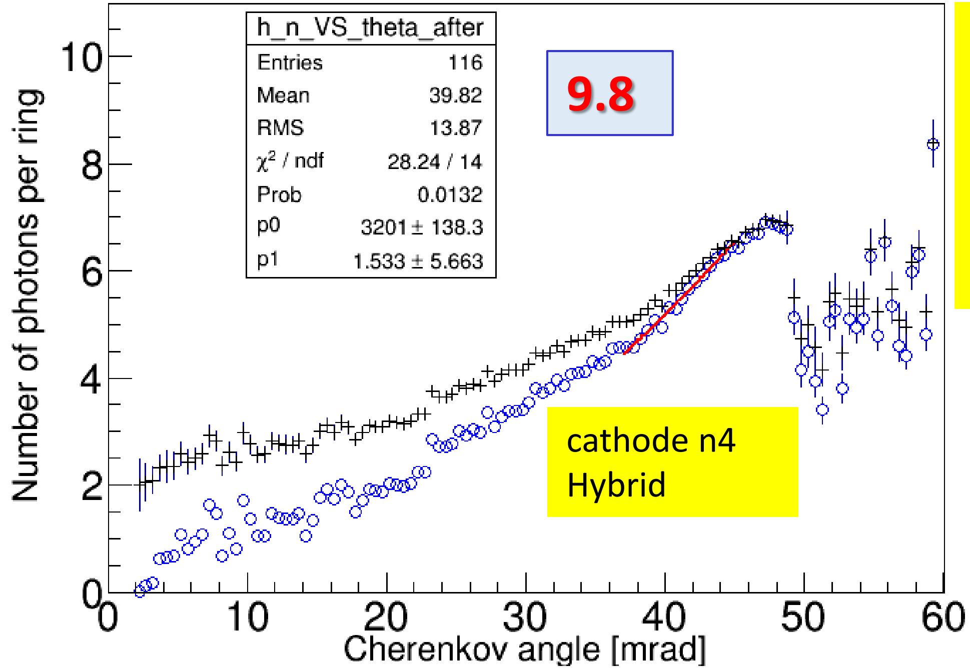
Run By Run



Sector by Sector



Number of photons : other cathodes

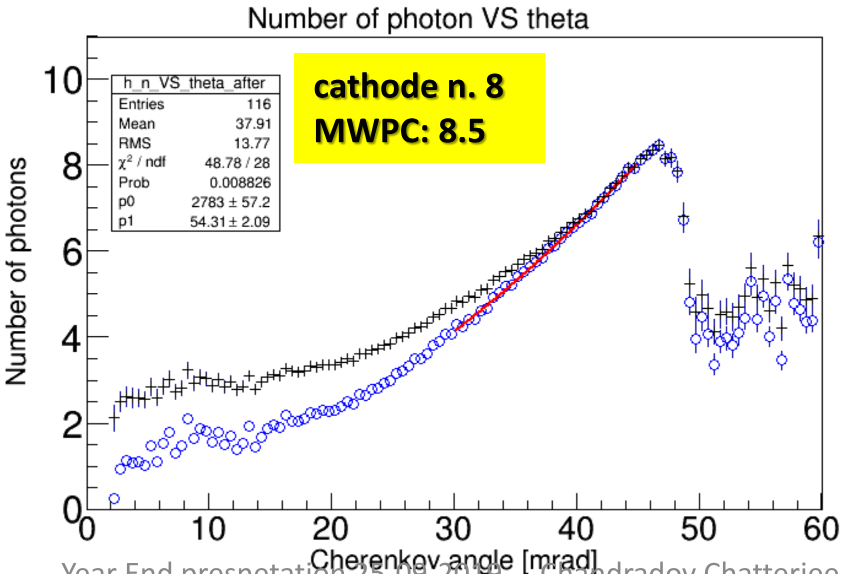


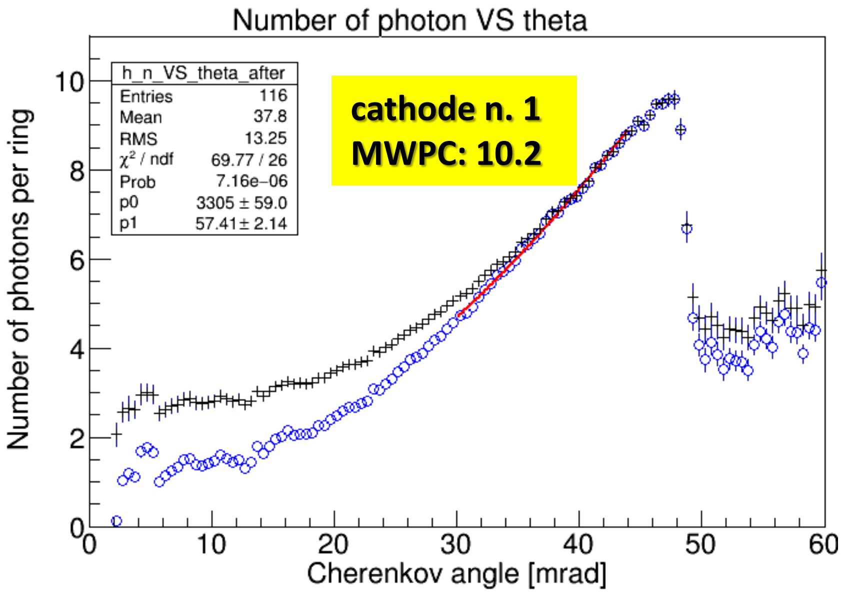
$QE_2/QE_4 = 1.10$

$\frac{\text{No of photon}_{Cath2}}{\text{No of photon}_{Cath4}}$ =1.05

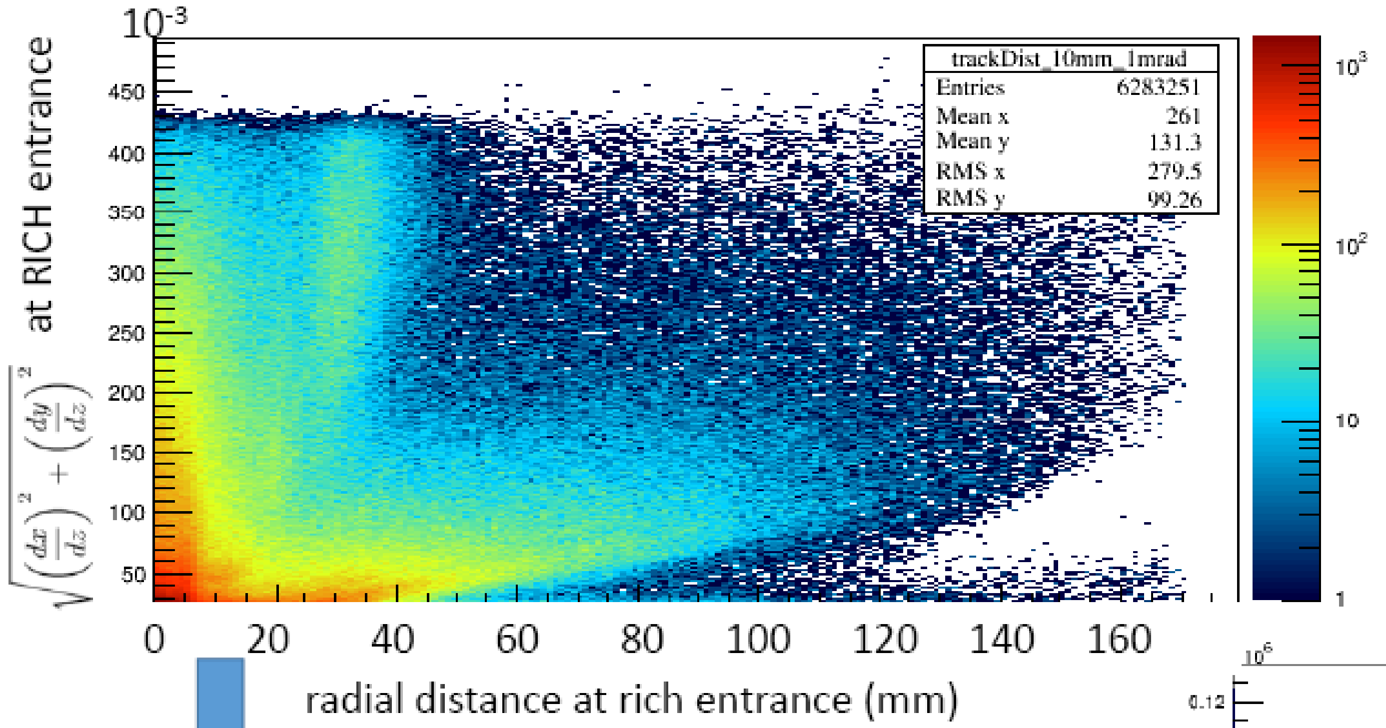
For the Saleve side MWPCs, we have not observed many events. The statistics were to low for doing this analysis.

Extrapolate to 55.2 mrad, n. of det. ph.e.= 9.83. First part of the function = 9.74 +/- 0.4; second part of the function= 0.08 +/- 0.3

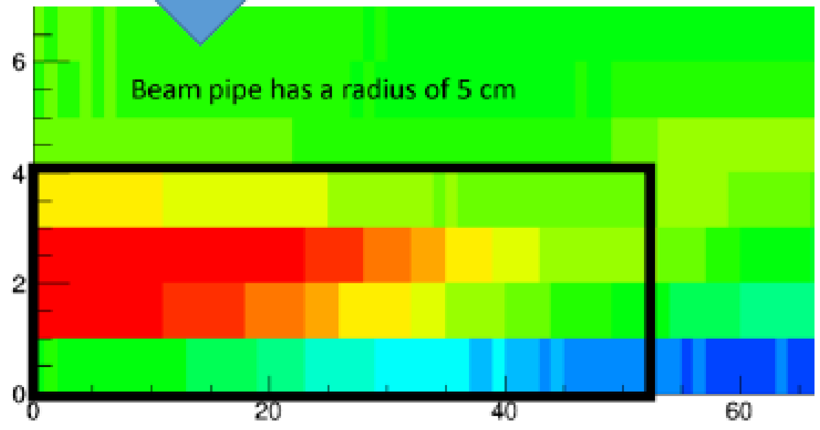


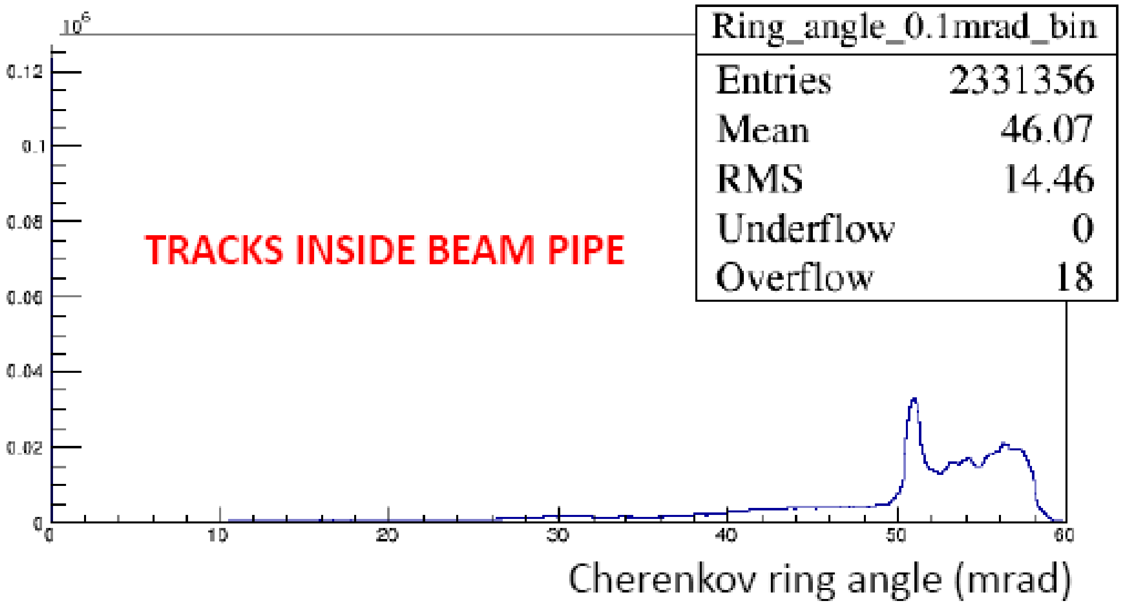


Effect of Beam

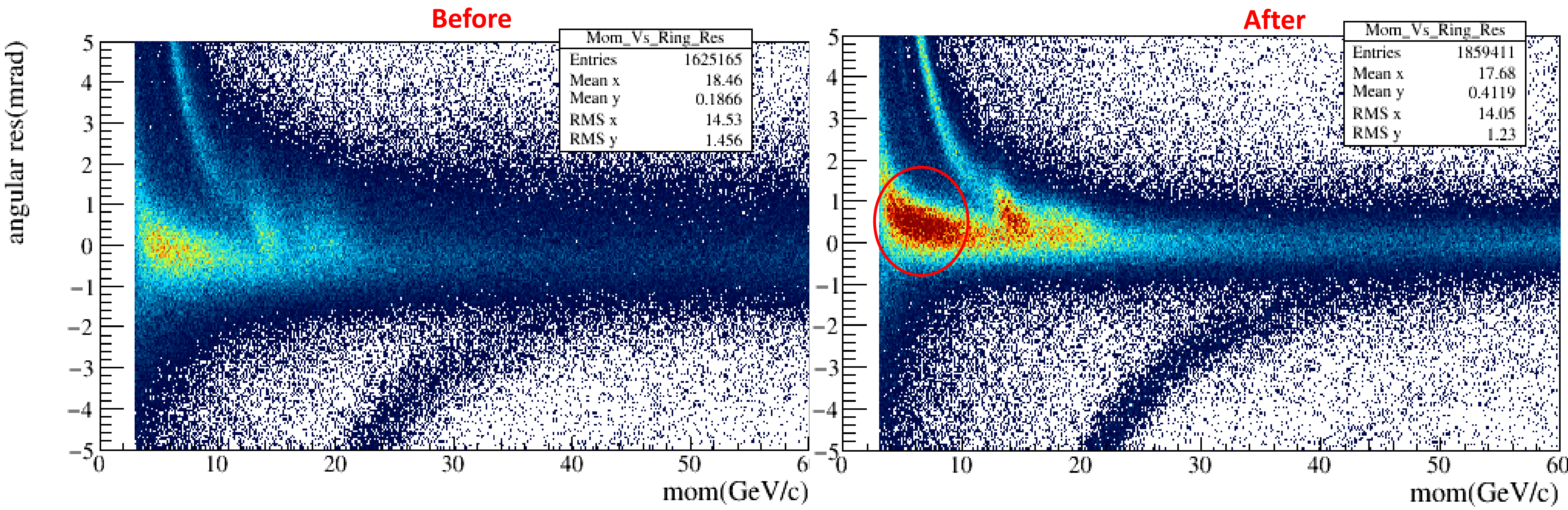


For further studies we cut out the beam region, 5 cm in spatial and 4 mrad in angular





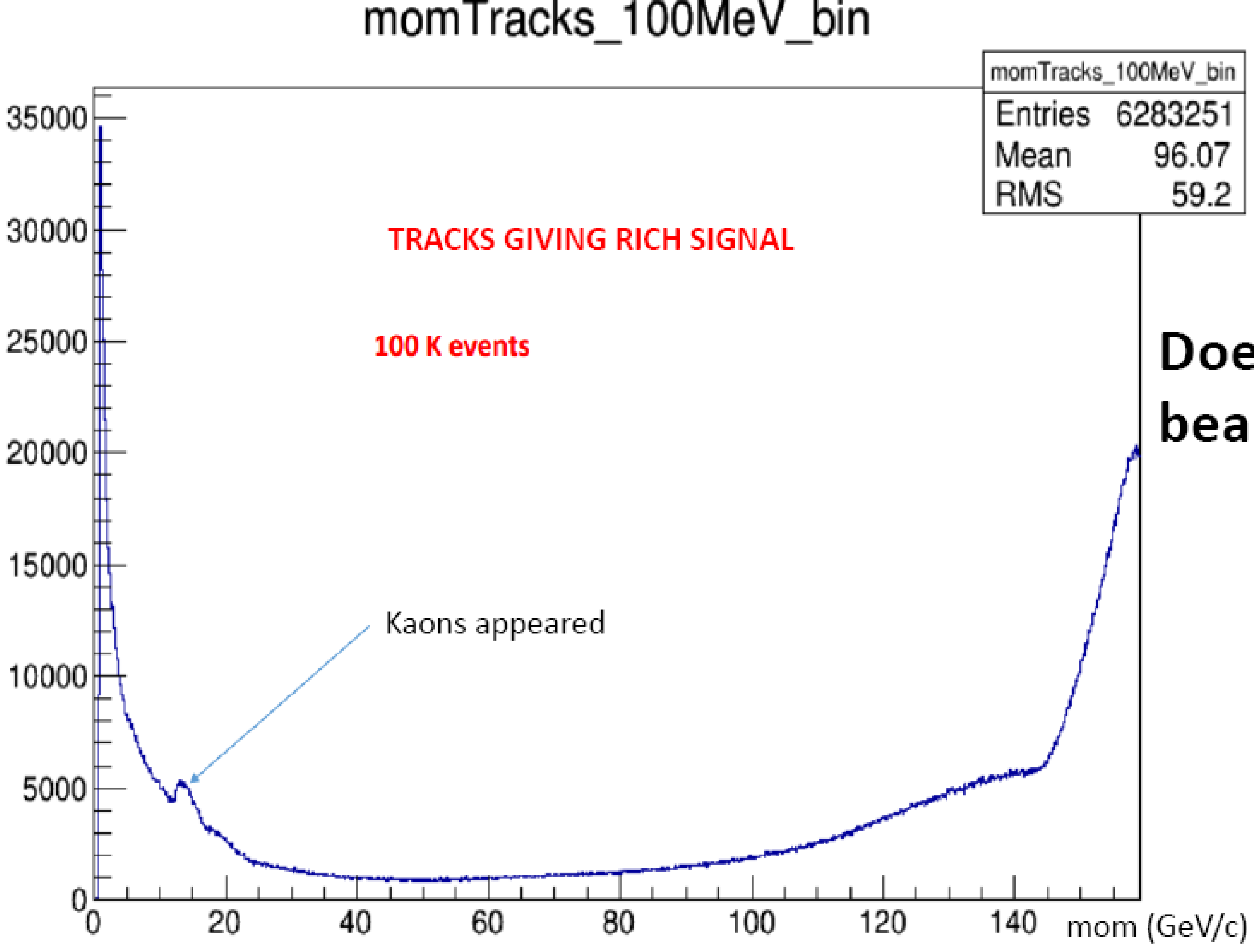
Ring residual vs momentum



ring residual = ring theta – pion theta

$$\theta_{ms} = \frac{13.6MeV}{p} q\sqrt{x/X0}$$

XX0 of the radiator 1/10 ; X0 of C_4F_{10} = 33 gcm^{-2}
multiple scattering : 5 GeV/c electrons ~ 0.6 mrad



momTracks_100MeV_bin
momTracks_100MeV_bin
Entries 6283251
Mean 96.07
RMS 59.2
TRACKS GIVING RICH SIGNAL
100 K events
Kaons appeared
35000
30000
25000
20000
15000
10000
5000
0
0
20
40
60
80
100
120
140
mom (GeV/c)

Doe
bea

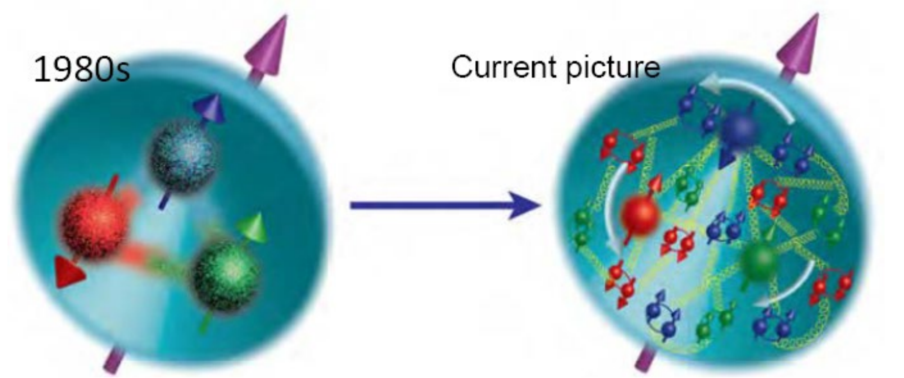
Fundamental physics goals of COMPASS

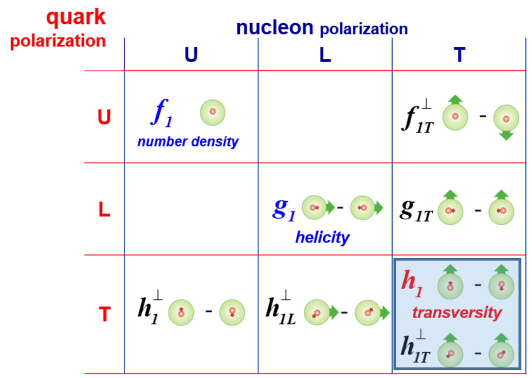
With a collaboration of 250 Physicists:24 institutes:13 countries
COMPASS addresses many fundamental questions of particle physics.

Measurements with muon beam:	Measurements with hadron beams:
COMPASS - I (2002 – 2011)	
Spin Structure, Gluon Polarization	Pion Polarizability
Flavor Decomposition	Diffractive and Central Production
Transversity	Light Meson Spectroscopy
Transverse Momentum Dependent PDFs	Baryon Spectroscopy
COMPASS - II (2012 – 2018)	
DVCS and DVMP	Pion and Kaon Polarizabilities
Unpolarized SIDIS and TMDs	Drell-Yan Studies

Approval of one more year running (2021) with deuteron target for SIDIS physics.
Proposal for measuring proton radius by muon-proton scattering.

Evolution of our understanding of nucleon structure





The **un-polarized** quark density in **un-polarized** nucleon and **longitudinally** polarized quark density in **longitudinally** polarized nucleon **are not sufficient!!**
TRANSVERSITY is a fundamental quantity of nucleons.
Semi Inclusive DIS is applied to extract the distribution functions.

Nominal thickness of MWPC is 79.5 mm, the measured vales are 79.9mm and 79.6 mm (bottom and top). **Δ bottom = 0.4 mm, Δ top = 0.1 mm.**
Nominal MWPC + FE thickness is 219.3 mm. Bottom measured 219.6 mm and top 218.9 mm**.** **Δ bottom = 0.3 mm, Δ top = -0.4 mm.**
Nominal Hybrid+ FE thickness 245.9mm, bottom measured 246.1mm and top 245.7 **Δ bottom = 0.2 mm, Δ top = -0.2mm.**
Measured Hybrid to MWPC including frontend thickness difference is 26.6mm. Nominal is 27mm.
CsI_Hy to frame distance -67.1 mm : Nominal -67.5 mm
CsI_MWPC = - 52mm Δ**(CsI_Hy – CsI_MWPC) = -15.1mm**