Muons in FGT

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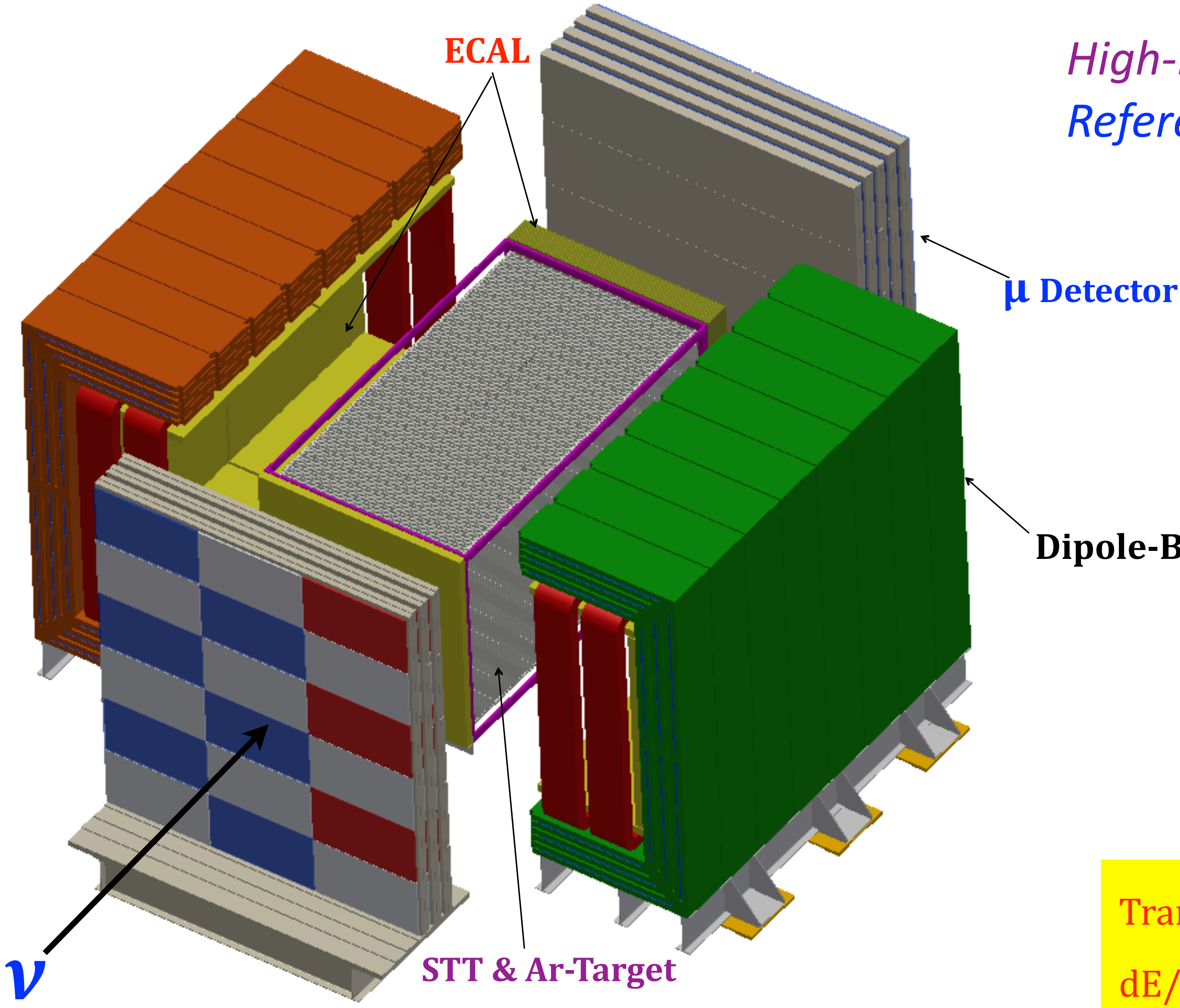


High-Resolution Fine Grain Tracker: Reference ND of DUNE

- ~3.5m x 3.5m x 6.5m STT ($\rho \simeq 0.1 gm/cm^3$)
- 4π-ECAL in a Dipole-B-Field (0.4T)
- 4π-μ-Detector (RPC) in Dipole and Downstream
- Pressurized Ar-target ($\simeq$x5 FD-Stat) ⇛ *LAr-FD*

Transition Radiation ⤔ $e^{+/-}$ ID ⇒ γ

dE/dx ⤔ Proton, $\pi^{+/-}$, $K^{+/-}$

Magnet/Muon Detector ⤔ $\mu^{+/-}$ $e^{+/-}$

(⇒ ***Absolute Flux measurement***)

$1X_0$ ~ 600 cm / 1 λ ~ 1200 cm

Muon Measurement in FGT

✳ $\nu_\mu \leftrightarrow \mu^-$;   anti-$\nu_\mu \leftrightarrow \mu^+$;

✳ μ-Momentum Measurement:

Track-reconstruction in STT:

Curvature ⇒ $|\mathbf{p}|$ & "-" or "+"

Direction-cosines ⇒ STT Track-fit extrapolated to the vertex including dE/dx

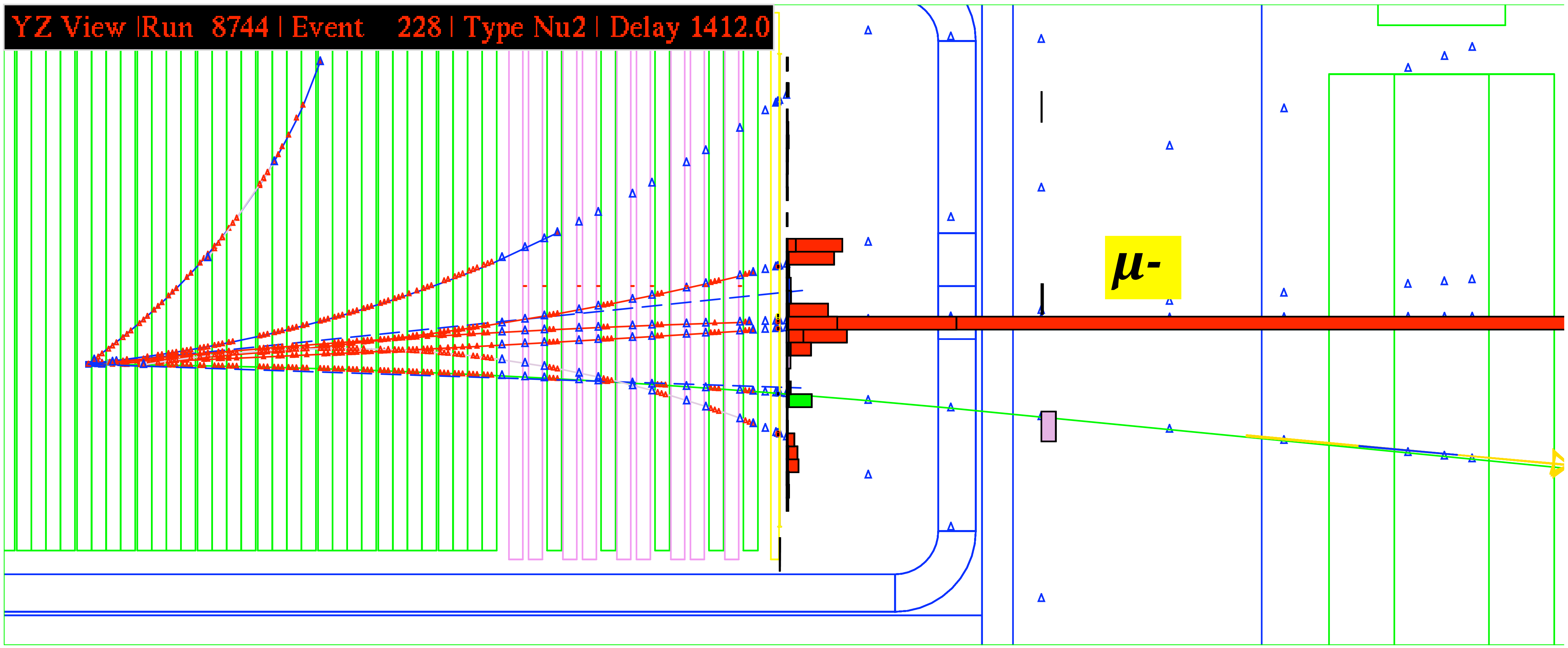
✳ μ-ID Measurement:

Track-reconstruction in the μ-Detector (RPC)

μ-*ID* Detector (RPC) will have a 4**π**-coverage ⟹ $\boldsymbol{\mu}^+$ .vs. $\boldsymbol{\mu}^-$ separation & Large-angle $\boldsymbol{\mu}$

Match the RPC-Track with the STT-Track

A ν_μ CC candidate in NOMAD



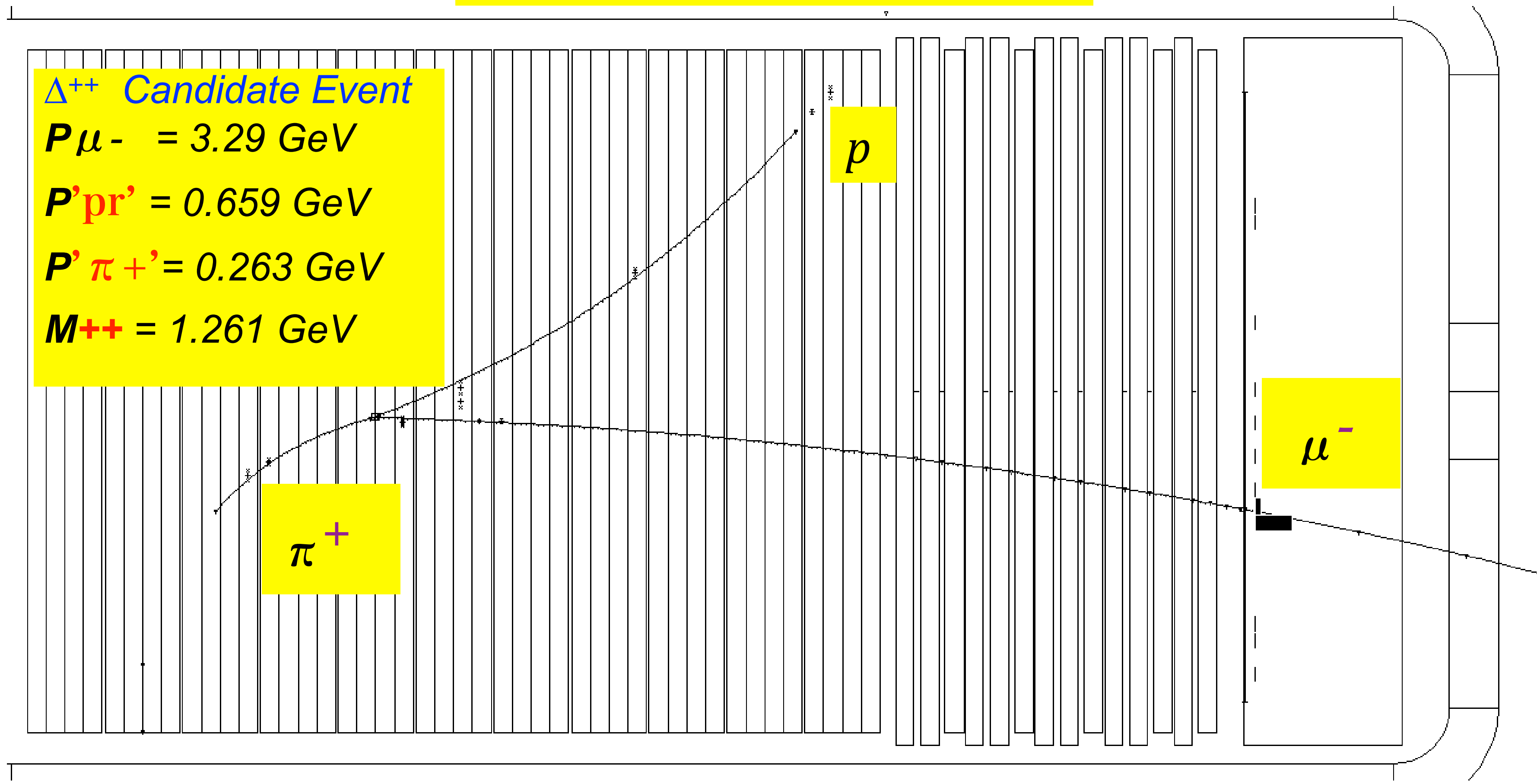
Observation ⇛

(1) Hadrons are tracks, enabling the momentum vector measurement

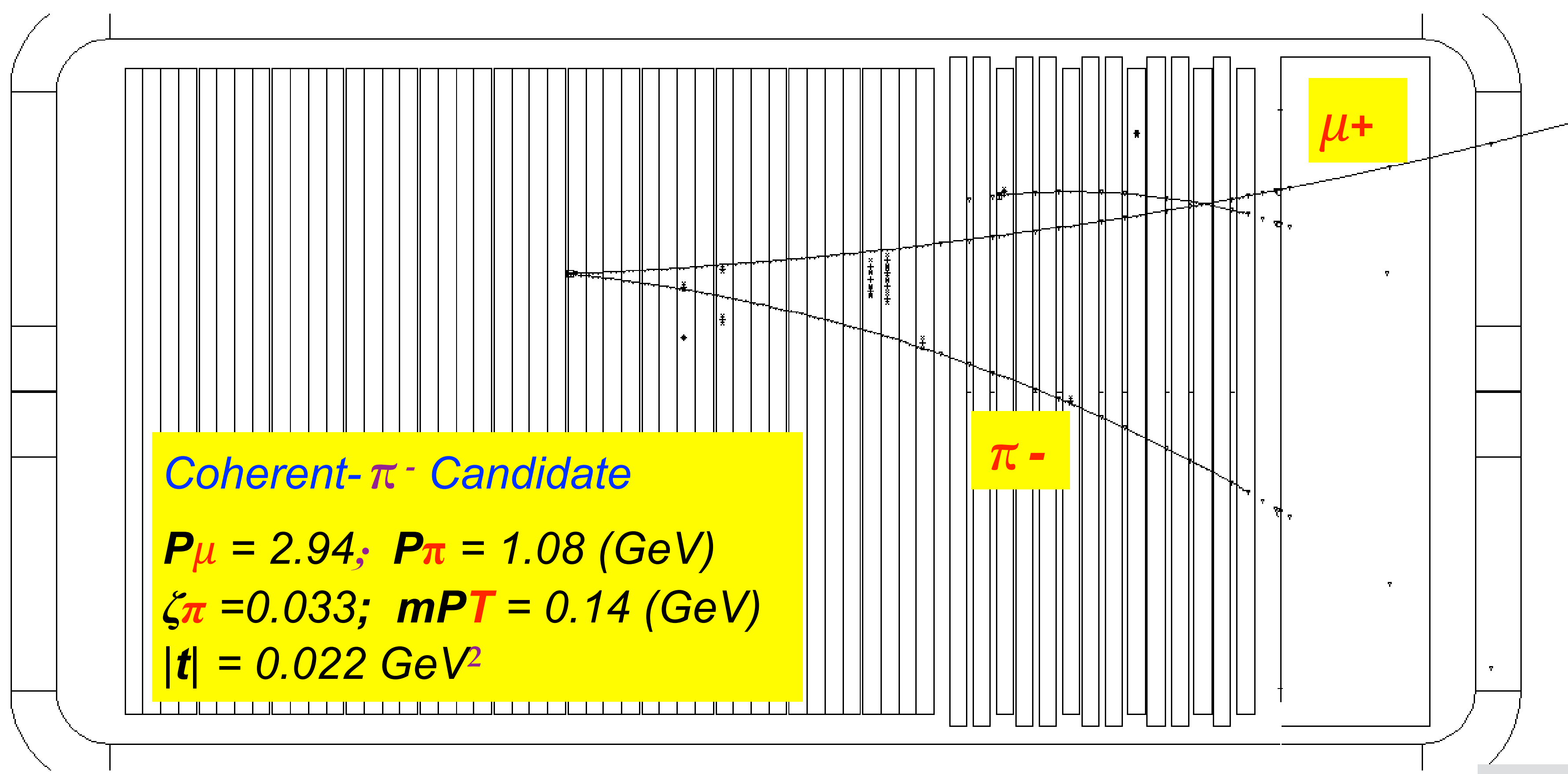
(2) μ is kinematically separated from Hardon-vector ⇒ Miss-PT Measurement

(3) FGT offers ~x5 higher tracking-points for hadronic tracks

μ-CC Events in NOMAD



In FGT
- x3 higher track-points in μ
- ~x10 higher track-points in p/pi



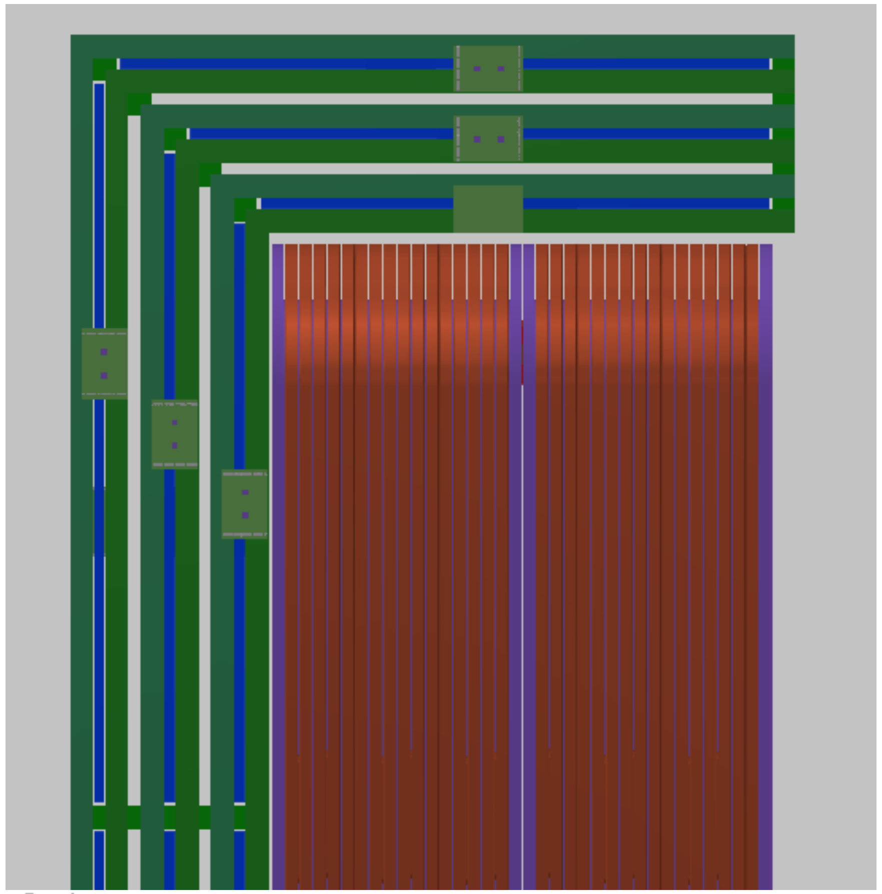
THE MUON DETECTOR

- ✦ Glo-Sci-51 *measure absolute and relative ν_μ and $\bar{\nu}_\mu$ spectra separately.*
  Glo-Sci-52 *measure NC and CC cross-sections separately vs. hadronic energy*

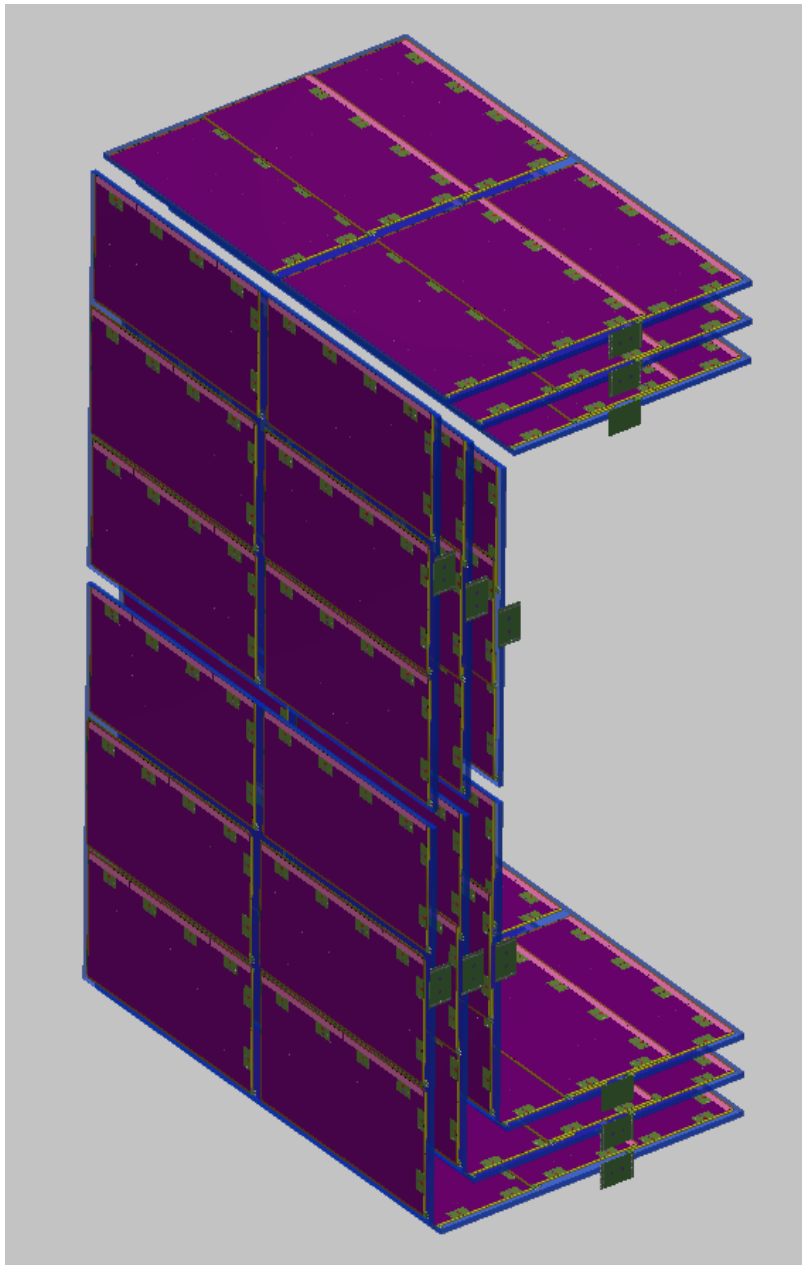
  $\Longrightarrow$ *identify muons exiting the tracking volume* NDC-L2-34,35
  $\Longrightarrow$ *4π muon detector with < 1 mm space resolution*

- ✦ *Instrument magnet yoke (3 planes), and downstream (5 planes) and upstream (3 planes) stations*

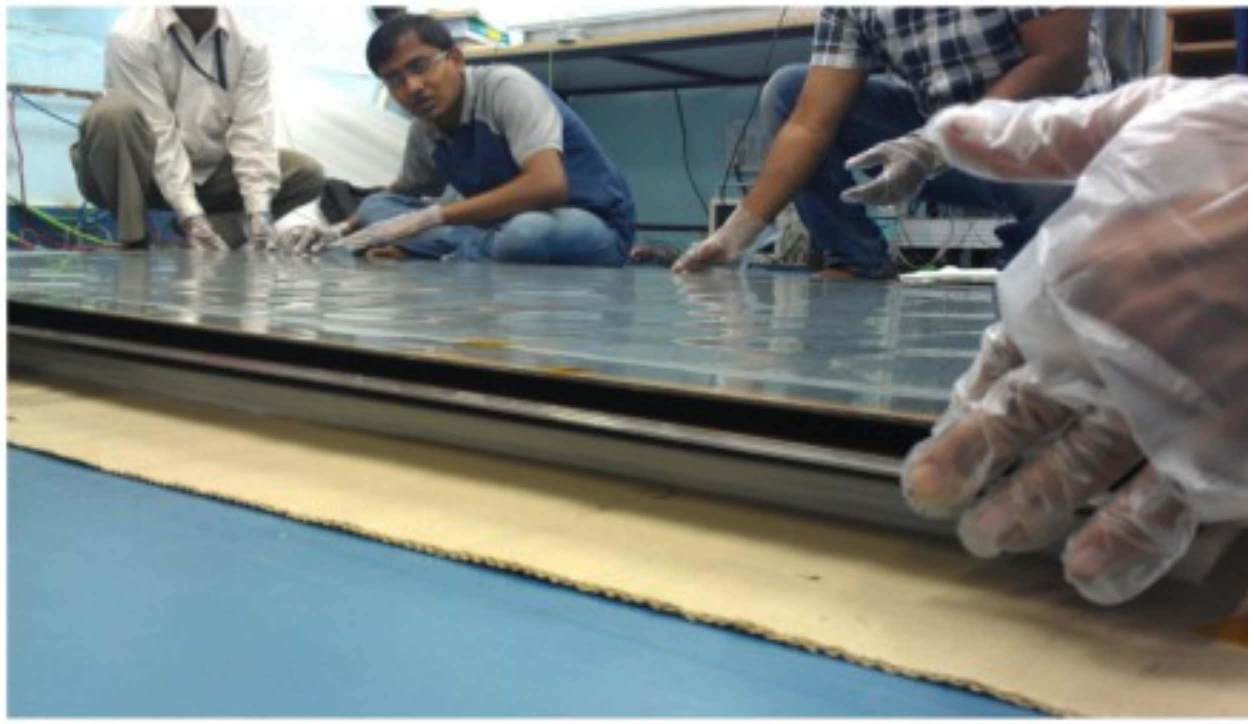
- ✦ *Bakelite RPC chambers 2m $\times$ 1m (432 in total) with 7.65 (7.5) mm X (Y) strips in avalanche or streamer mode*

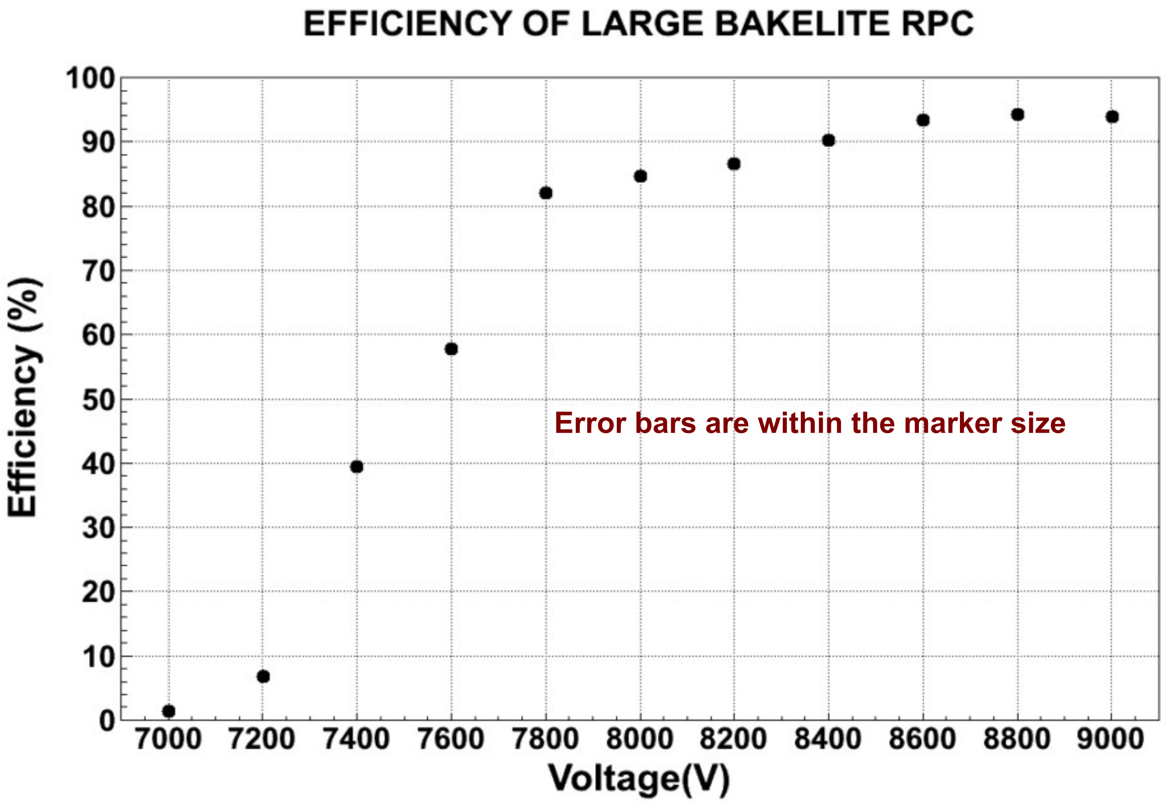


✴ *166k Channels*



Full-scale RPC Prototype @ VECC (Subhsish, Zybayer)

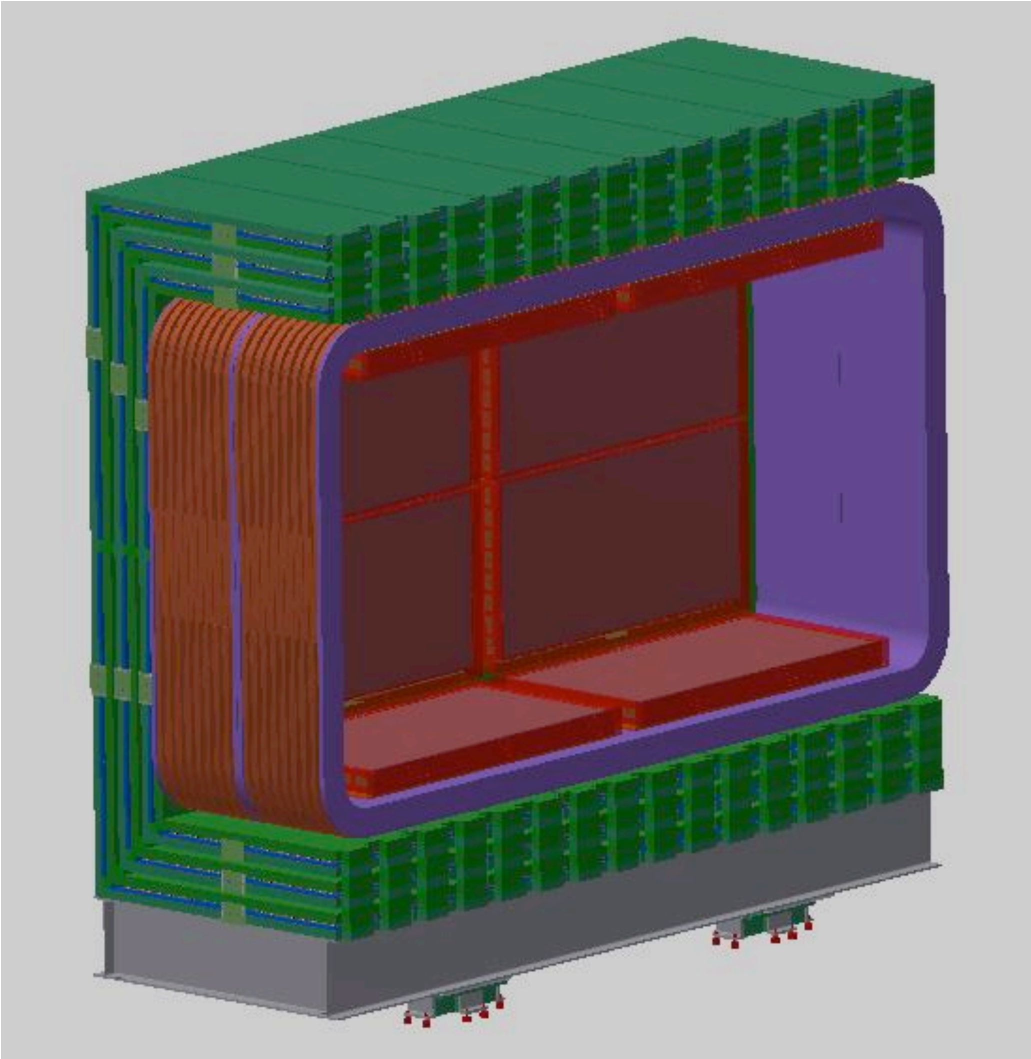


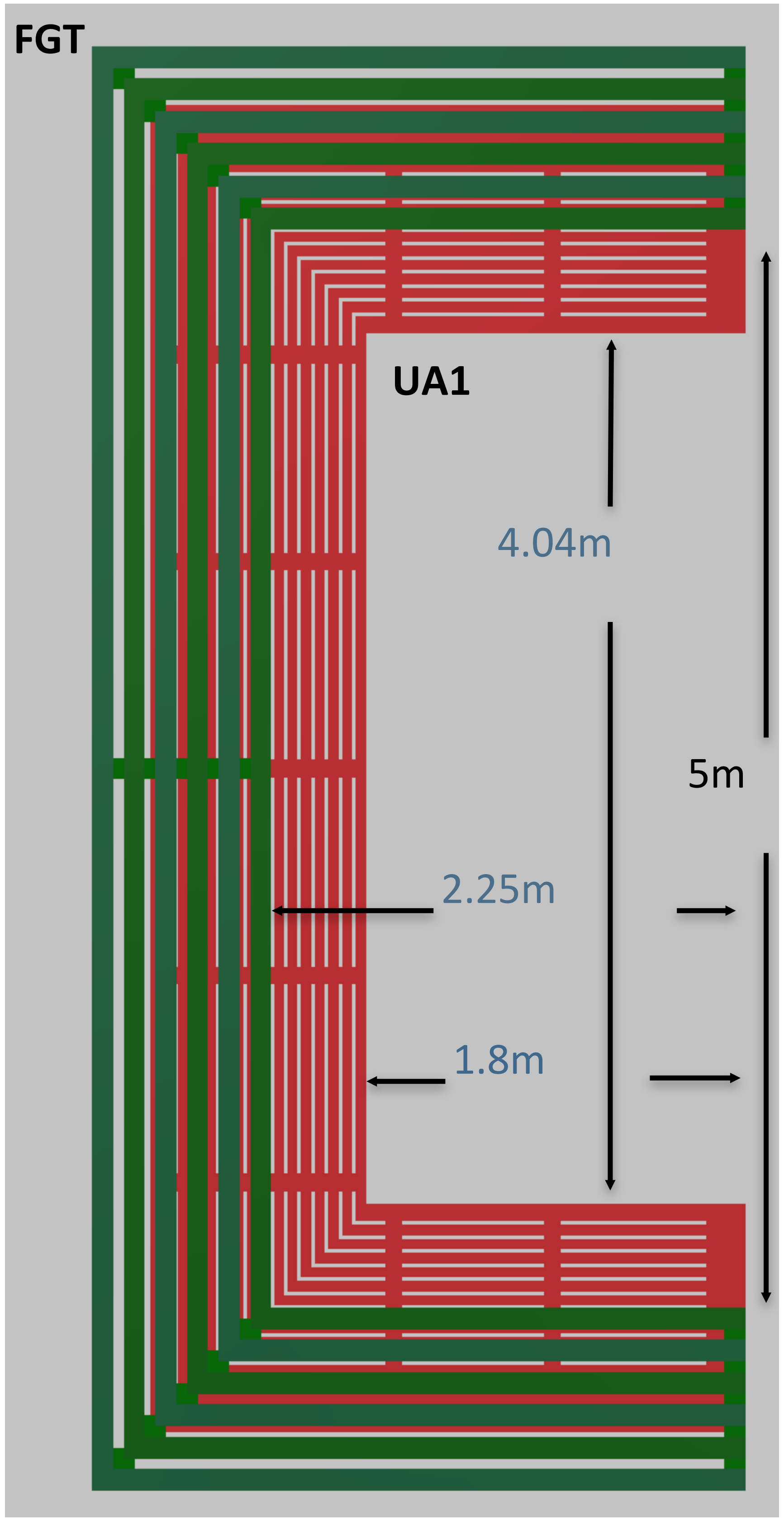


- *Built $2.4m \times 1.2m \times 2cm$ prototype (full scale) at VECC in India*
- *Operated in streamer mode, $\varepsilon \sim 95\%$, noise < 1 Hz/cm^2*

THE DIPOLE MAGNET *Design by BARC: Sanjay Malhotra & team*

- *Design based on established UA1/NOMAD/T2K magnet*
- *Magnetic volume $4.5m \times 4.5m \times 8.1m$, nominal B=0.4 T*
- *Return yoke with 8+8 "C" sections:*
  6 $\times$ 100 mm steel plates, 50 mm gaps (960 tons)
- *4 vertical Cu coils (150 tons) made of 8 double pancake*
- *Power requirement for nominal field 2.43 MW,*
  water flow for coil cooling 20 l/s





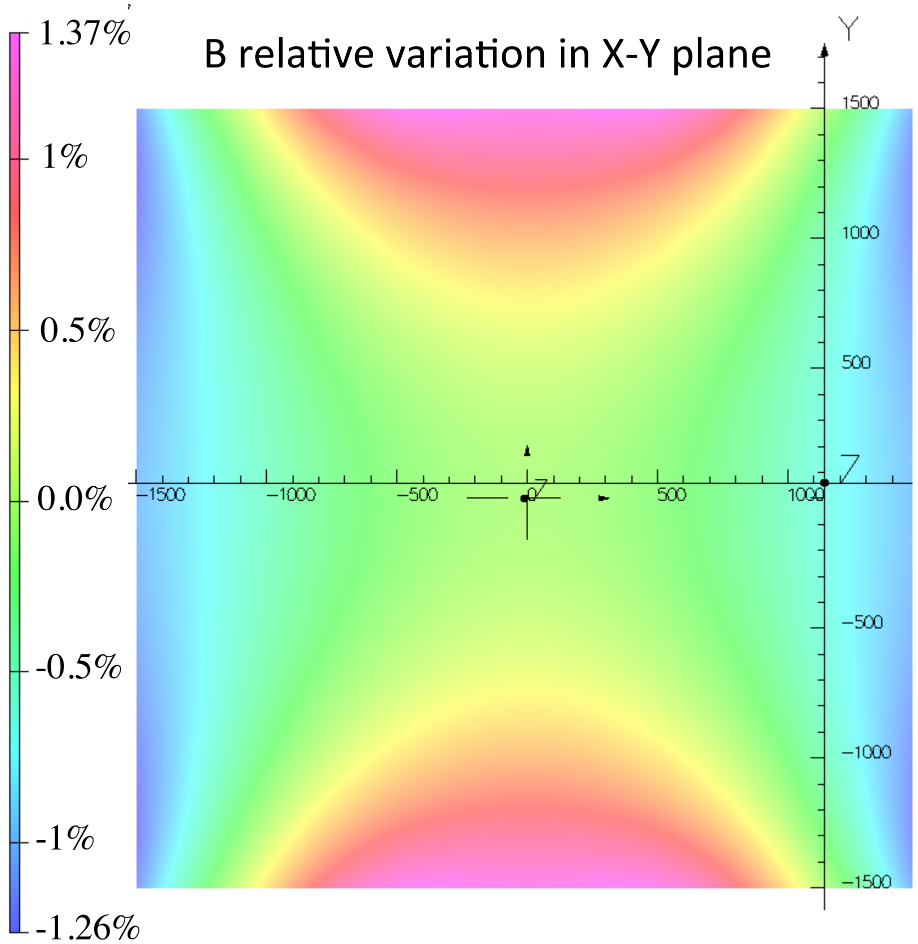
Muon Momentum Reconstruction using Curvature in the B-Field

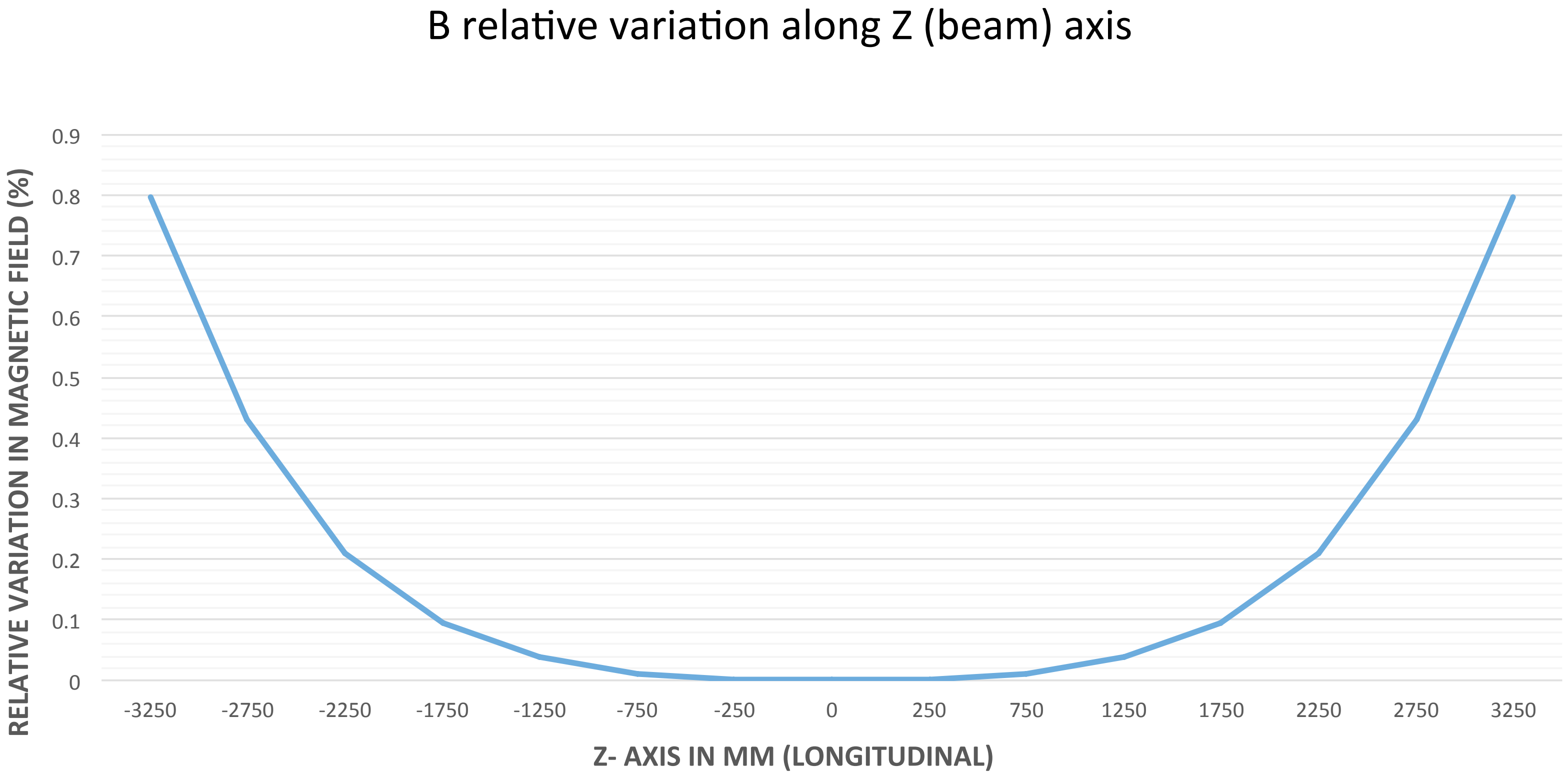
- ✴ Need a uniform B-Field with
  Good design uniformity (~*1% variation over the volume of 3.5m* x *3.5m* x *6.5m*)

- ✴ Detailed B-Field map-varations measured with ≤*10% precision*
  ⟹ B-Field known to *~0.1%* precision

- ✴ Continual monitoring of the B-Field during operation
  ⟹ Built in instrumentation in the field volume, especially the edges & yokes

Design by BARC: Sanjay Malhotra & team





BARC, India

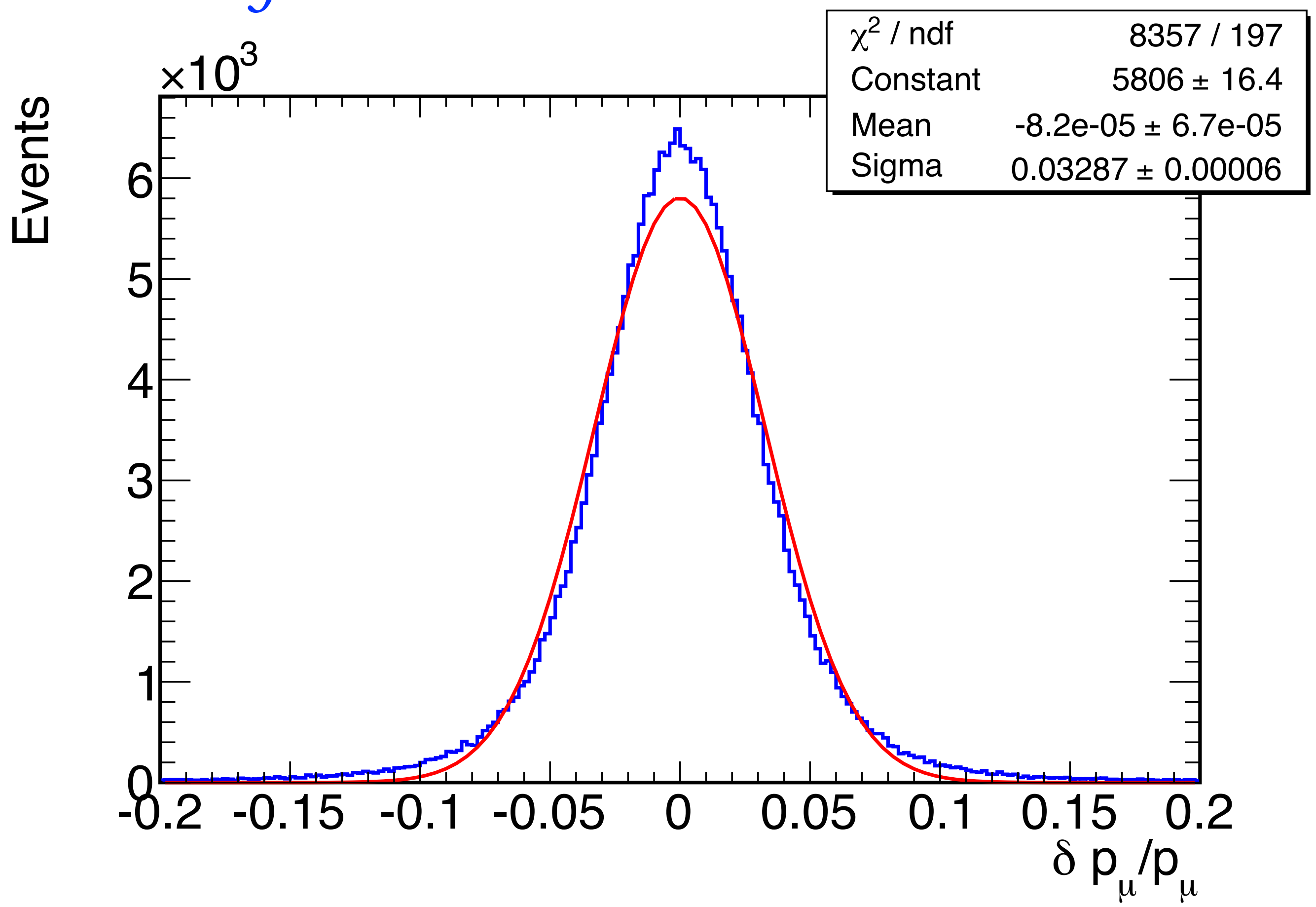
- *B uniformity in $3.5m \times 3.5m \times 7m$ tracking volume better than 2% (field simulations)*
- *Maximal deformation of C yoke 1.16 mm, maximal buckling of bobbin 1 mm*
- Glo-Sci-51,23 *measure absolute and relative ν_μ, ν_e and $\bar{\nu}_\mu, \bar{\nu}_e$ spectra separately.*

$\Longrightarrow$ *Low-ν technique for relative fluxes requires muon energy scale to $< 0.2\%$*

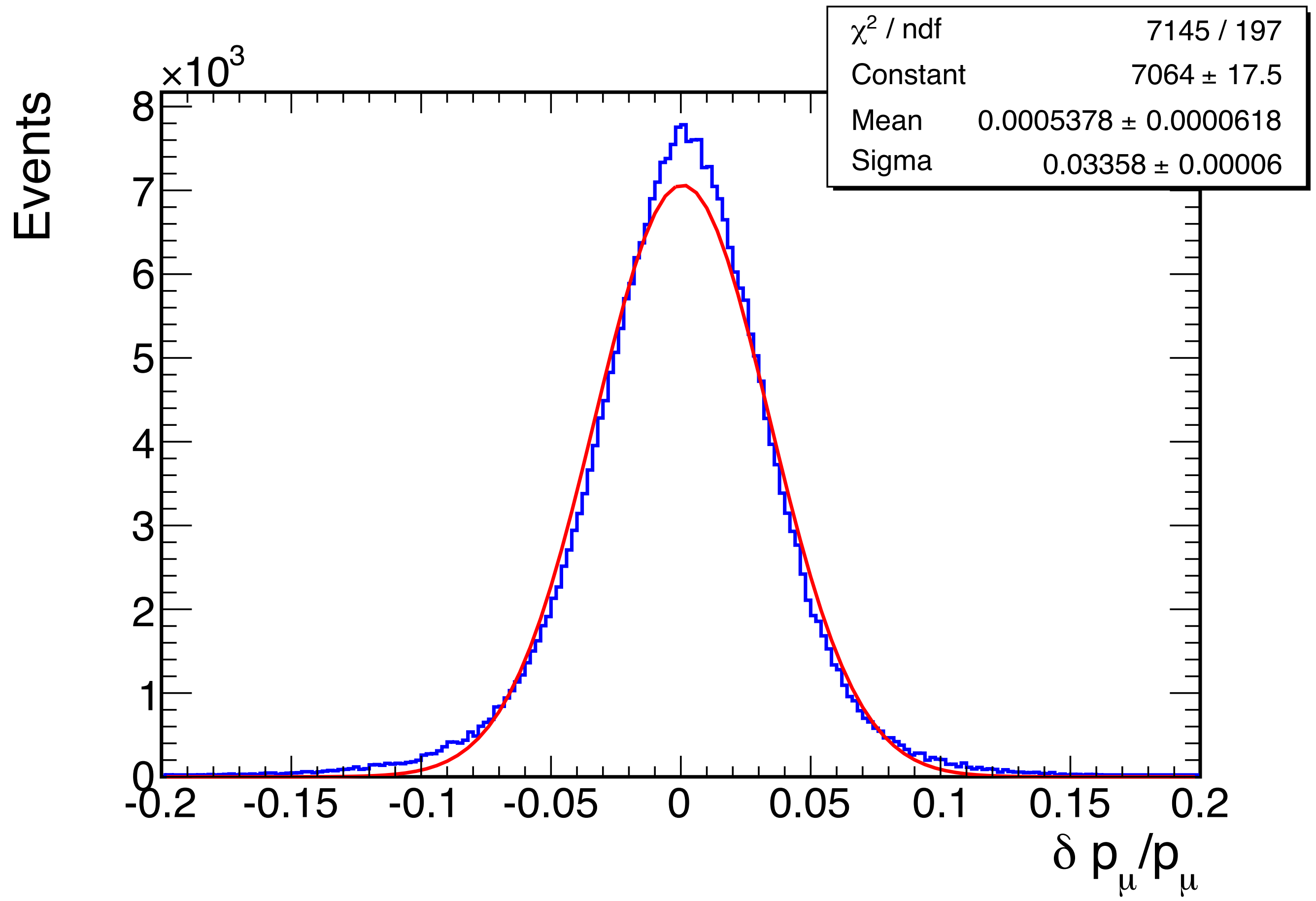
$\Longrightarrow$ *B field mapping to better than 1% matches the requirement*

Muon Momentum Resolution in FGT

FGT

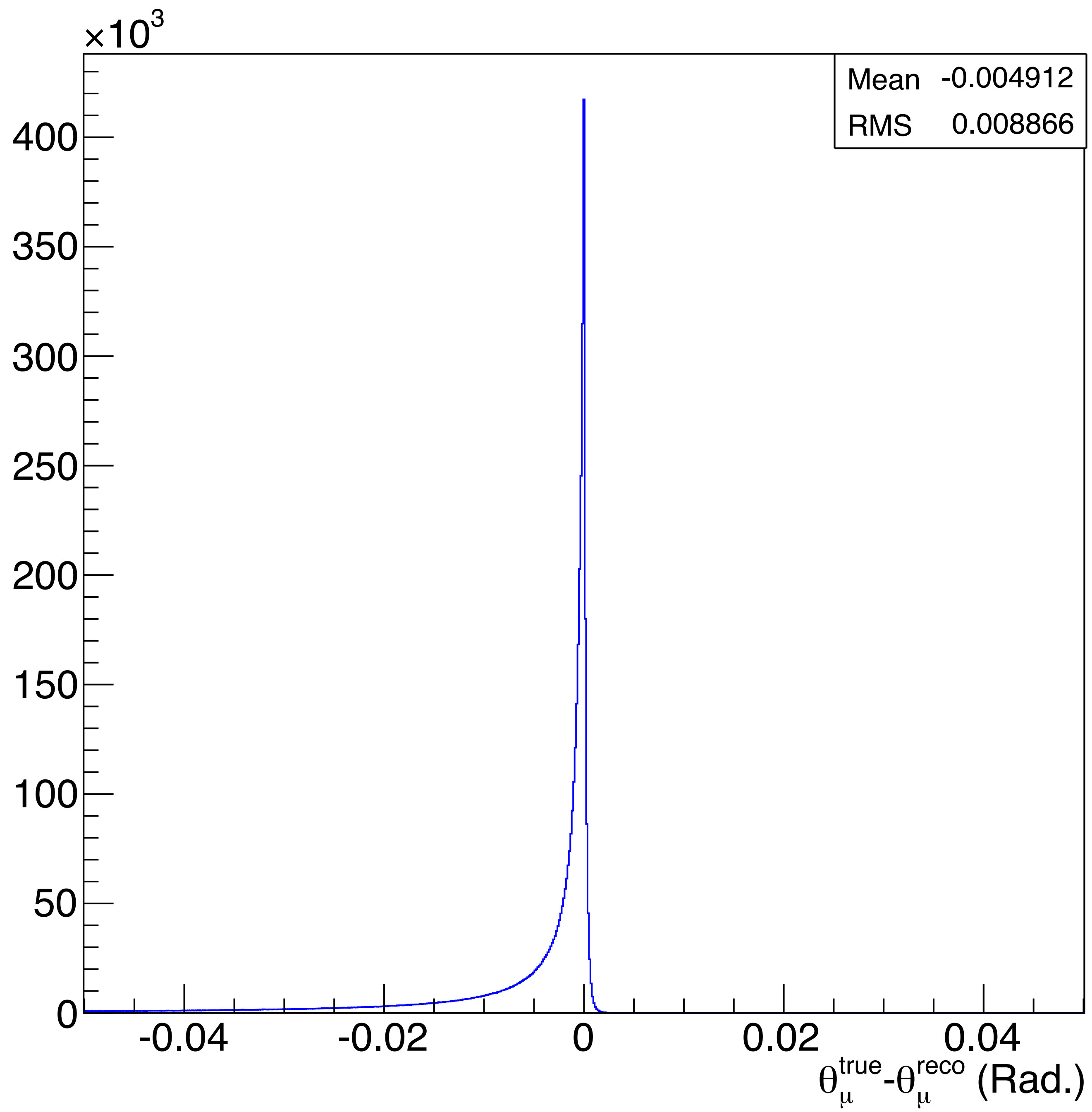


NOMAD



Muon Angular (θ) Resolution in FGT

- Resolution depend on "p"
  *< **Δθ**> ~ 1 mad for the LBNF-spectrum [Fig. will be updated]*



Measurement of Muons, μ^+ & μ^-, at Large Angles

- Need to measure muons emitted at large angles

- At the 1st oscillation maximum (2—3 GeV):

θ-Cut	% ν_μ-CC
$>60^0$	~11%

- At the 2nd oscillation maximum (0.5—1 GeV):

θ-Cut	% ν_μ-CC
$>60^0$	~37%

⇛ *Imperative to measure muons at large angles*

- With 4π *μ-ID* coverage, FGT will measure large-angle muons without any discernible loss of efficiency compared to, say, $\theta < 60^0$

Muon Efficiency in FGT (Prelim.)

Efficiencies from Fast-MC; cross-checked against NOMAD
Purity, in P<1 GeV, estimated from Fast-MC (prelim.)

- P > *1* GeV: Efficiency ~ *~95%; Purity >99%*
- P ∈ [*0.6, 1*] GeV: Efficiency ~ *~80%; Purity ~80%*
- P ∈ [*0.3, 0.6*] GeV: Efficiency ~ *~60%; Purity ~70%*

in situ Constraint on the Eμ-scale

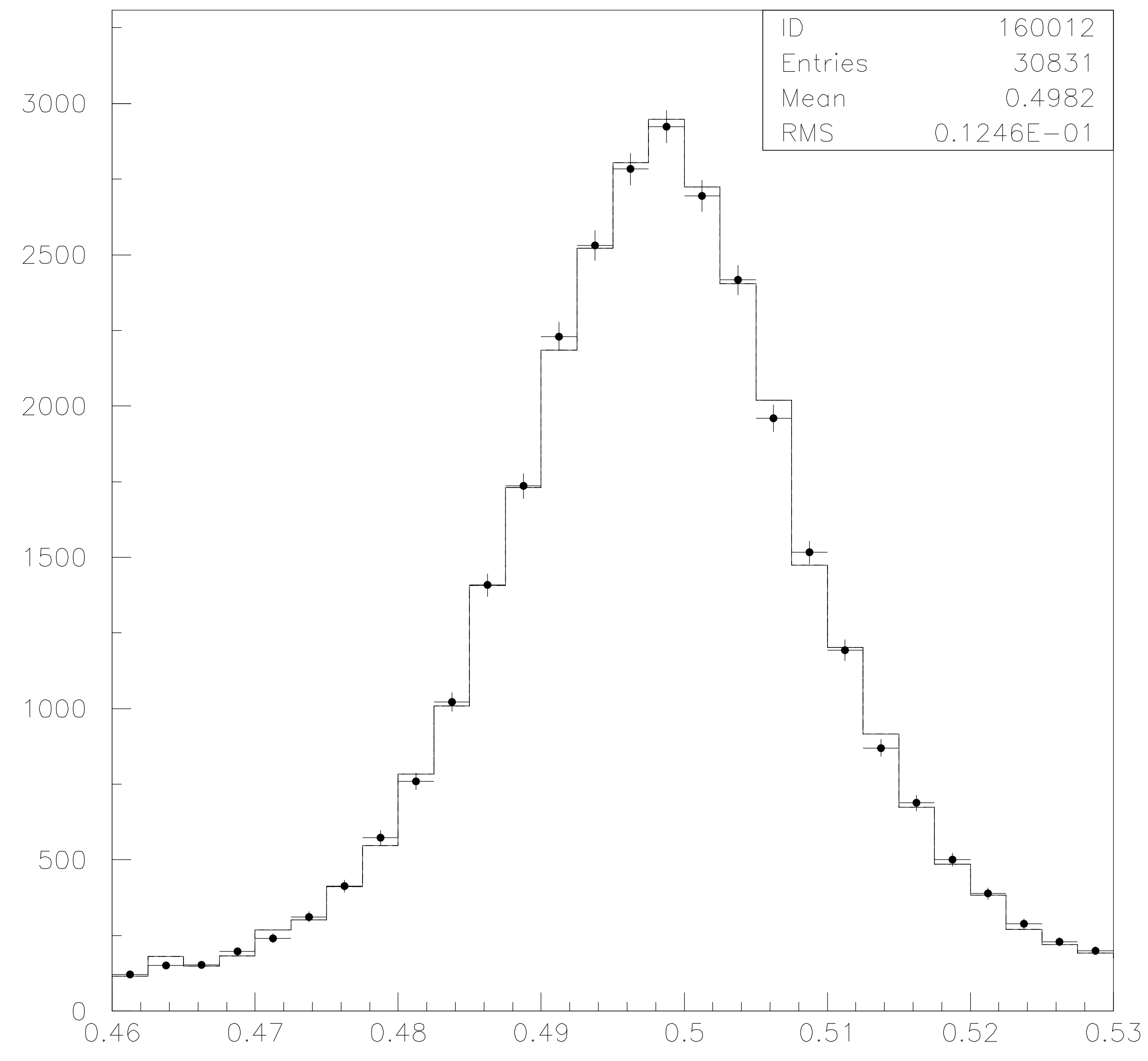
- Measure K^0_s produced in the ν-interactions

  Expect > 750,000 reconstructed K^0_s

- Constrain the error on the |p|-from-curvature

  Expect an error <0.1% on the momentum energy scale

* Measurement of the Mass-K^0_s ⟹ in situ constraint on the ***Energy-scale***
* NOMAD, 32k K^0_s ⟹ error on the $|p|$-scale $< 0.2\%$



Mass-K^0_s

in situ Constraint on the $E\mu$-efficiency

✴ Measure the beam Muons

(1) Using the Up-stream Mu-ID module & Up-Stream ECAL module with Barrel, or Down-stream ECAL -&- RPC-in-Yoke or RPC-in-Down-stream
$\Longrightarrow$ Define the muon entering the detector (Denominator)

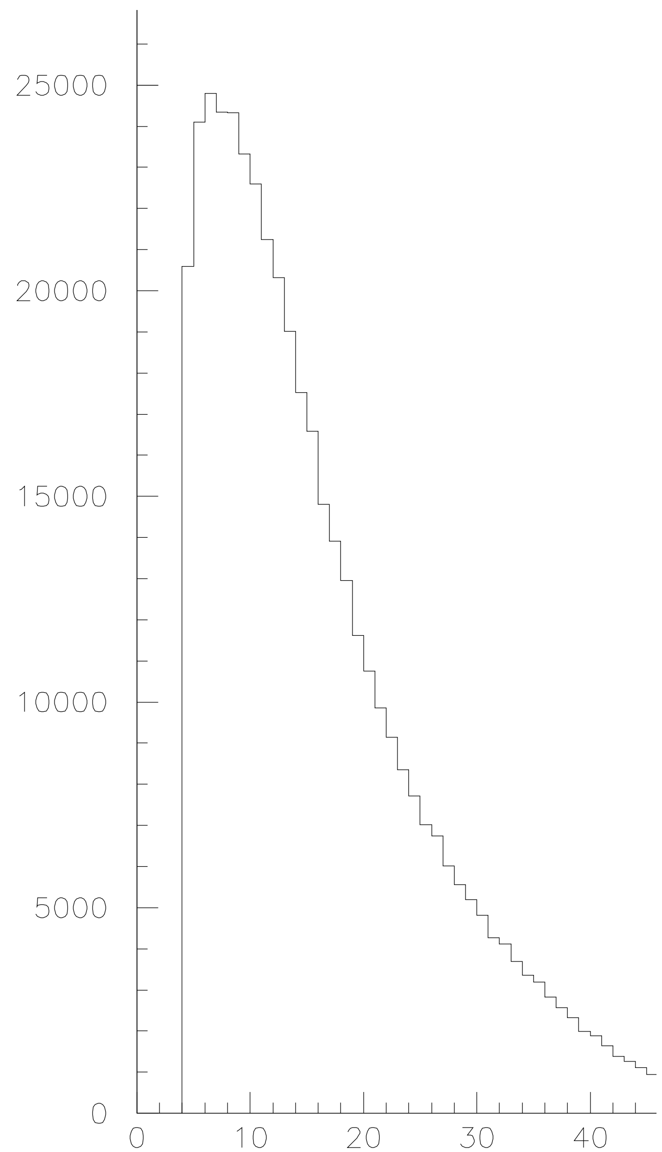
(2) Reconstruct these muons using STT and mu-ID (Numerator)

(3) Compute the Efficiency = Numerator/Denominator as a function of $E\mu$

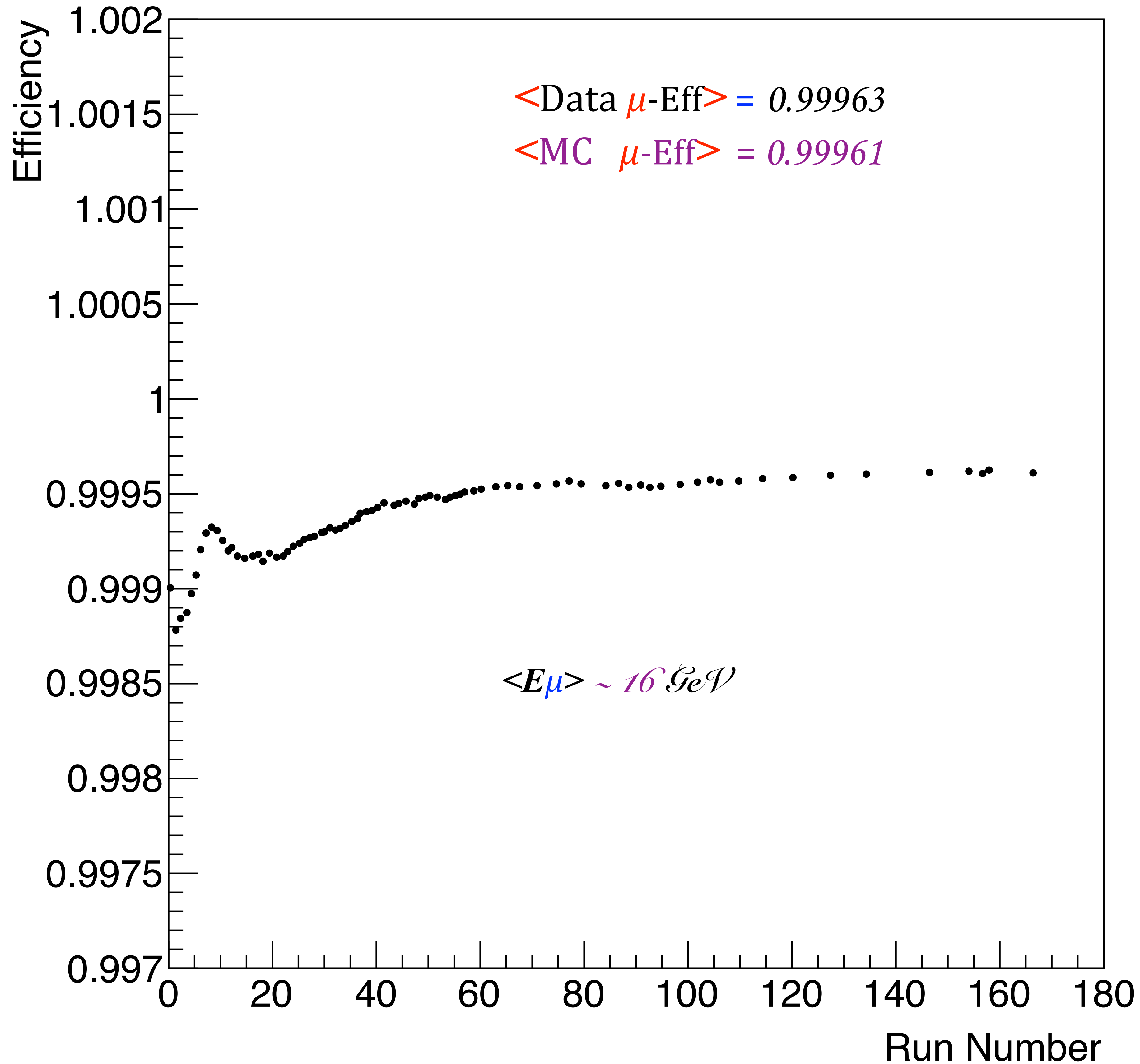
(4) Repeat this with the corresponding MC-Simulation

(5) Compare *(3)* with *(4)* : Check on the absolute $E\mu$-*efficiency*

Checking the Eμ-efficiency in NOMAD using the "Flattop" Muons



*4 ≤ **Eμ** ≤ 40 GeV*



. . . *in order of increasing **Eμ***

A final separation of $\nu\mu \Rightarrow \mu$ *from the non-prompt* $\pi^{+-}/K^{+-} \Rightarrow \mu$

- Use the Lepton-Hadron isolation to reduce the remaining impurity (later)

Outlook

(1) Measure $E\mu$ with ~ *3.5%* resolution

(2) *100%* distinction between μ^- .vs. μ^+ in *~0.3 - 50 GeV*

(3) B-field design allows the $|E\mu|$-scale to be measured to ~ 0.1% precision

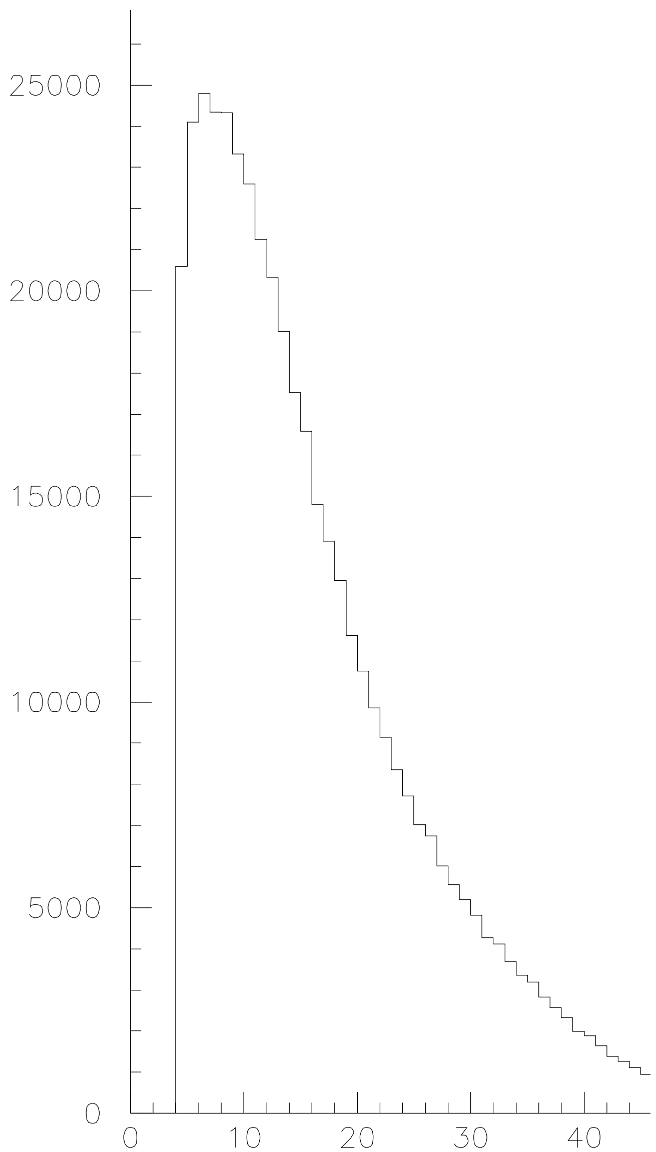
(4) in situ measurement of 0.75M K^0s checks the $|E\mu|$-scale to ~ 0.1% precision

(5) Absolute efficiency of the μ-reconstruction will be checked using the Beam-μ using the built-in redundancy offered by the 4π coverage by ECAL & RPC with < 0.1% precision

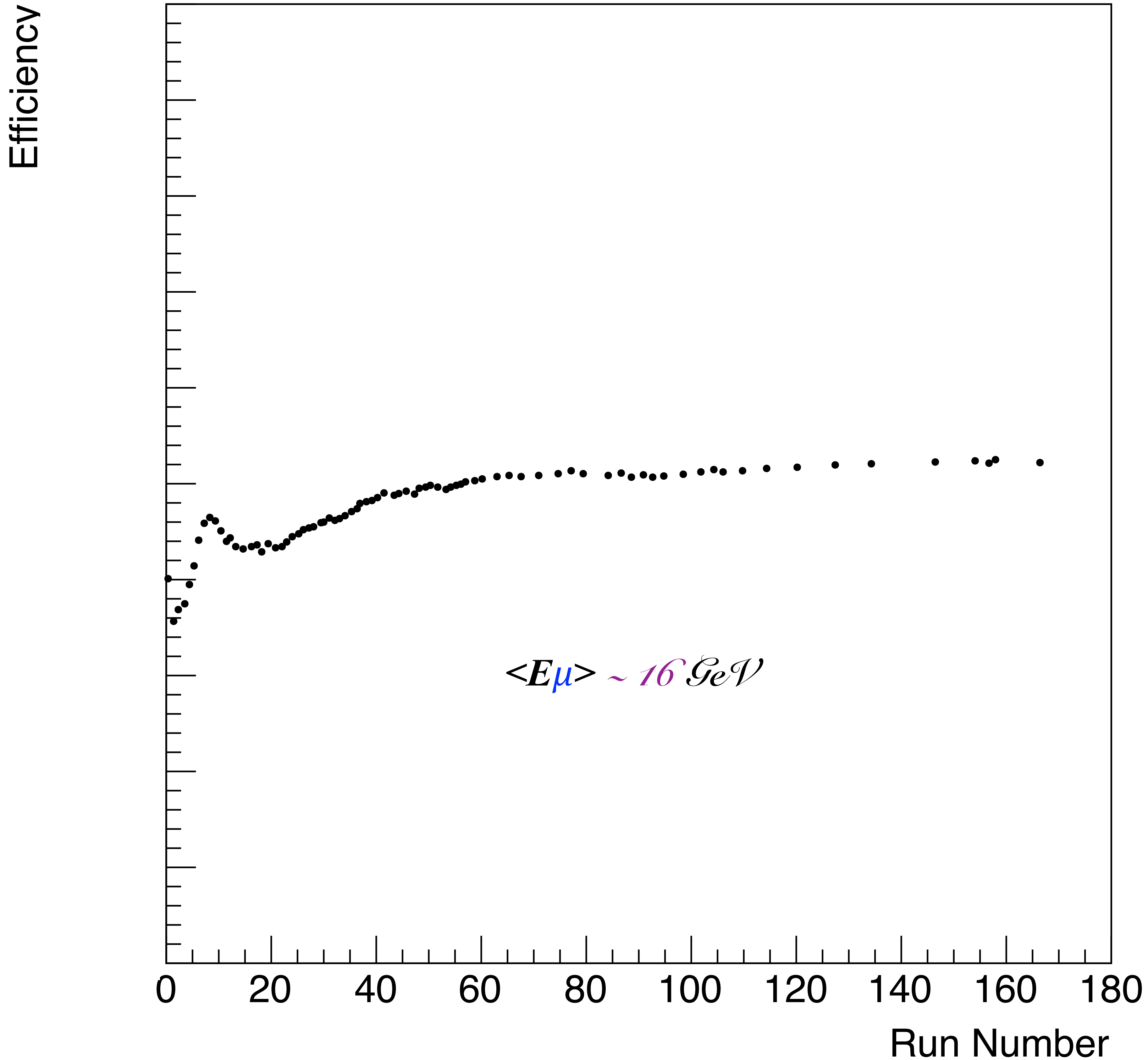
(6) Measure large-angle muons, e.g. $\theta > 60^0$, without loss of efficiency/bias compared to low-angle muons ⟸ Important for the 2nd oscillation maximum

Backup

Checking the Eμ-efficiency in NOMAD using the "Flattop" Muons



$4 \leq E\mu \leq 40$ GeV



. . . *depend on* **E**μ, **θ**μ ⇛