The 8th International Conference on Particle Physics and Astrophysics
(ICPPA-2026)

TPC Particle Identification Performance and Systematic Uncertainties in the T2K Near Detector Before and After the Upgrade

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T2K experiment ("Tokai to Kamioka")

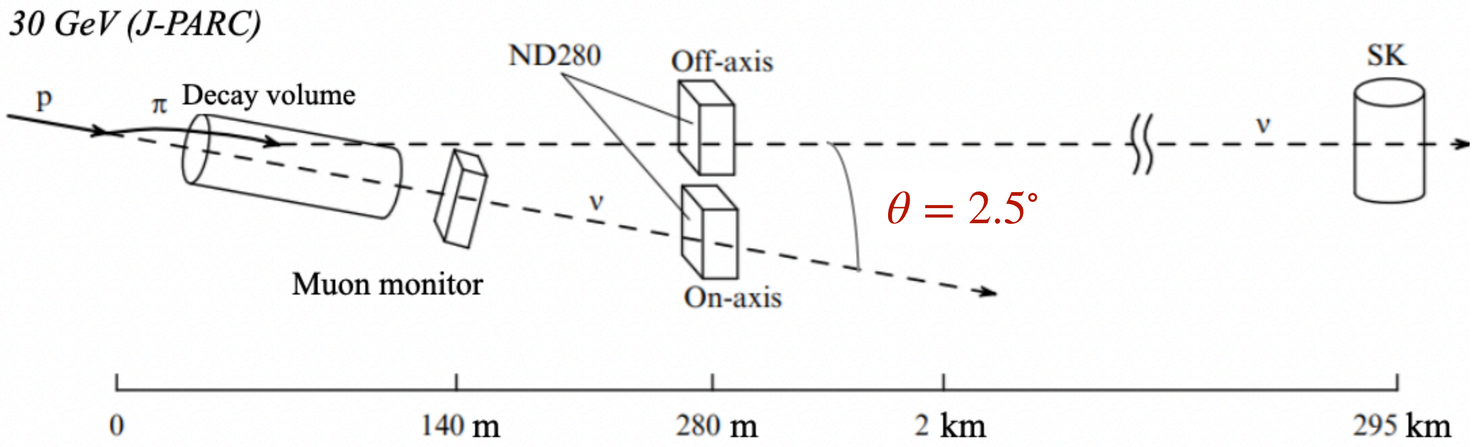
The main goals of T2K:

- *Precision measurements of neutrino oscillation parameters via:*

  $\nu_\mu/\bar{\nu}_\mu$ - *disappearance* $\longrightarrow$ $\sin^2\theta_{23}, \left|\Delta m^2_{32}\right|$

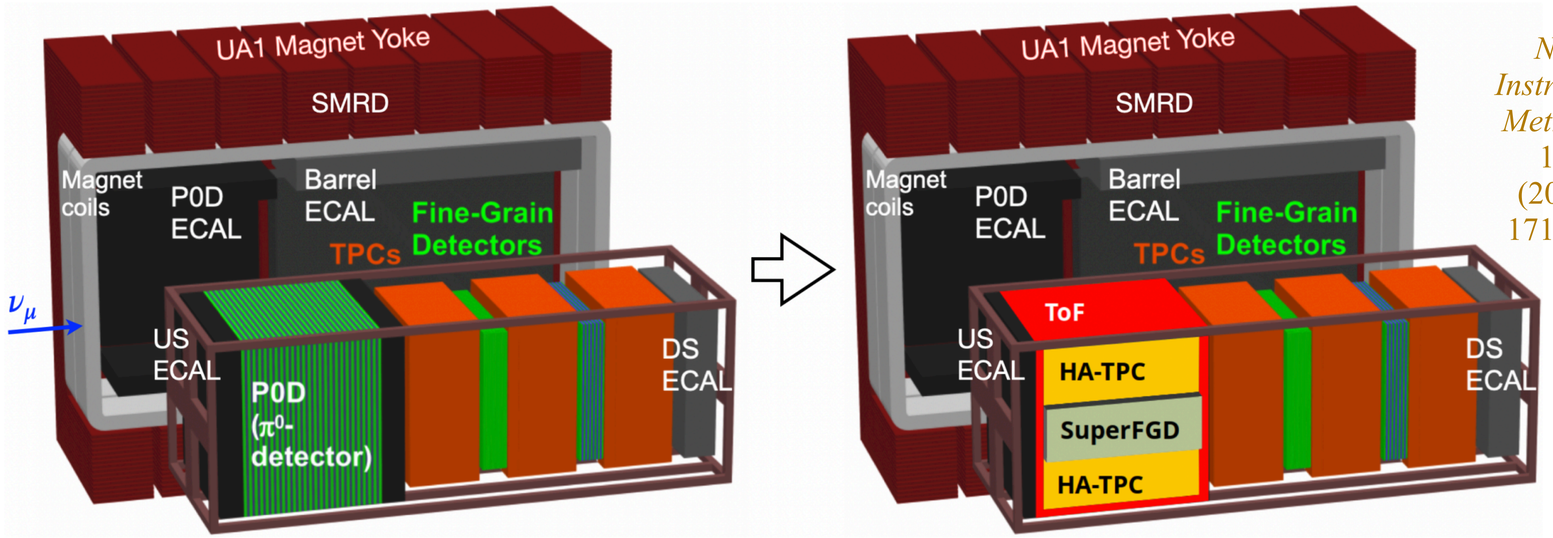
  $\nu_e/\bar{\nu}_e$ - *appearance* $\longrightarrow$ $\delta_{CP}, \theta_{13}, \theta_{23}$ *octant, mass ordering*

- *Search for CP violation in the neutrino sector*



To improve T2K's sensitivity to δ_{CP} :

Reduce systematic uncertainties in the predicted number of events at the Super-Kamiokande from 6-7% to 3-4%



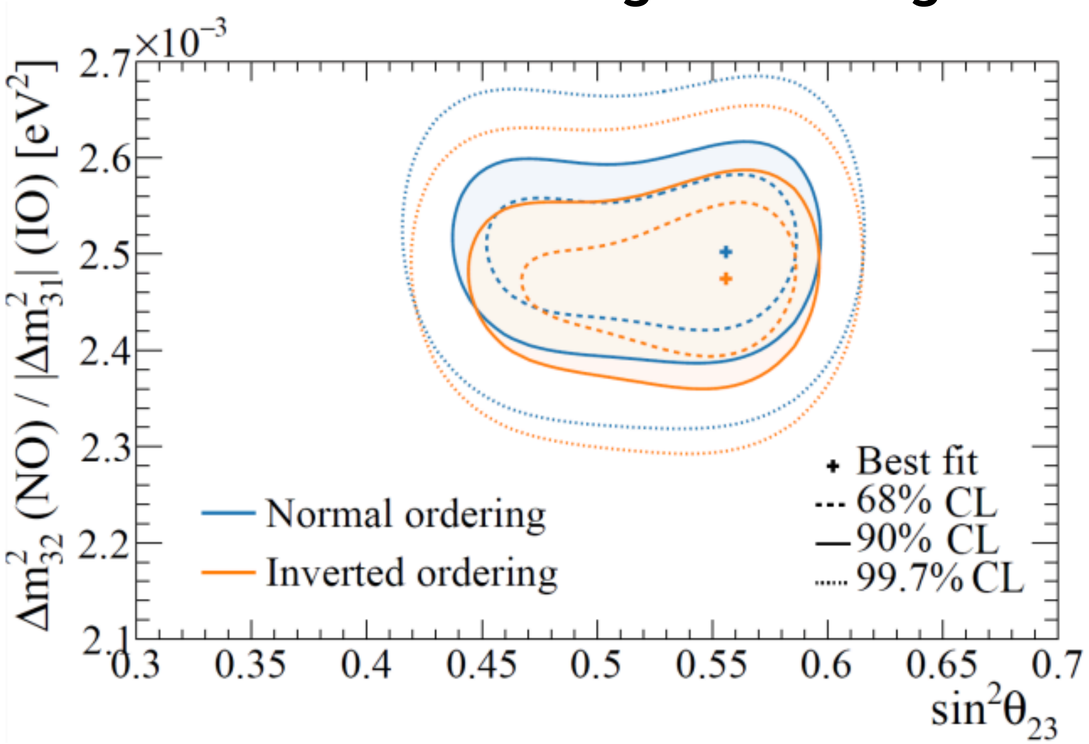
Off-axis ND280 Before the Upgrade

Off-axis ND280 After the Upgrade

Nucl. Instrum. Meth. A 1092 (2026) 171882

Recent T2K oscillation results

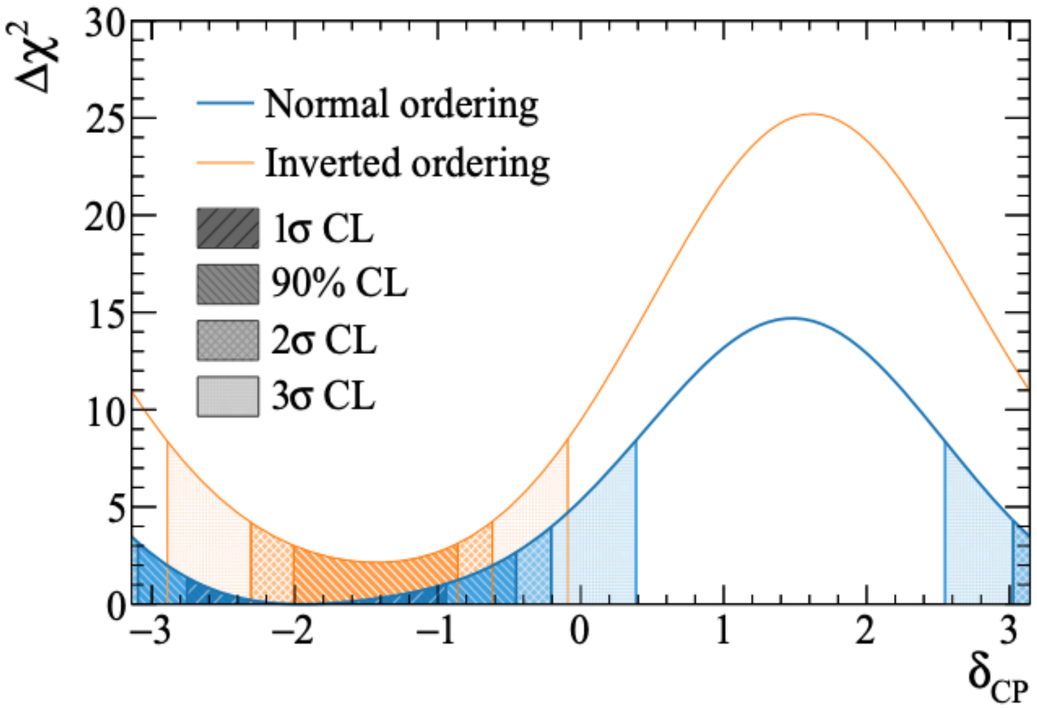
Mass ordering and mixing



- Weak preference for **normal mass ordering** (NO) and **upper θ_{23} octant**
- **Best-fit** values (NO): $\sin^2\theta_{23} = 0.559^{+0.018}_{-0.078}$

$$\Delta m^2_{32} = (2.506^{+0.039}_{-0.052}) \times 10^{-3}\text{eV}^2$$

CP violation



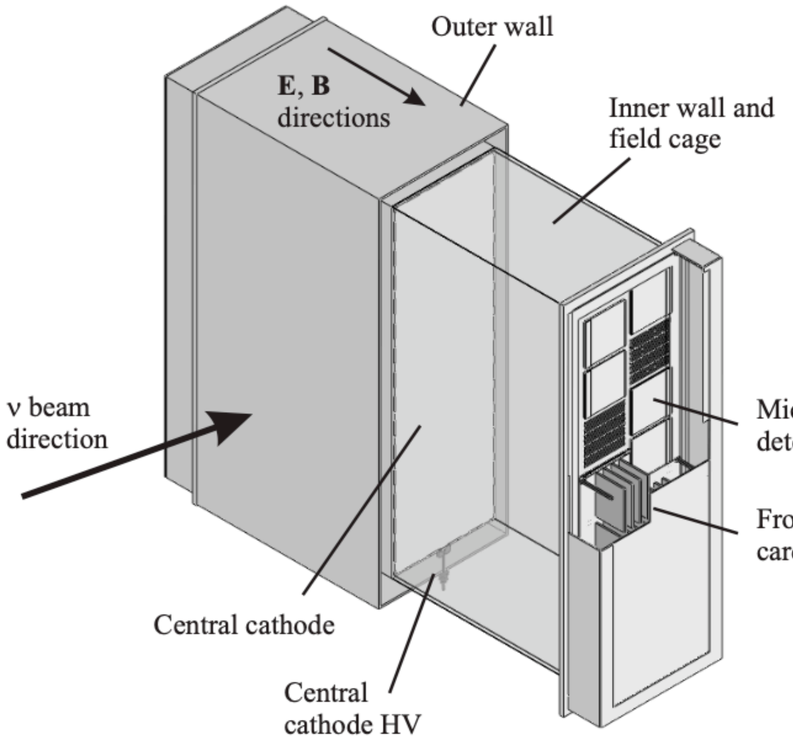
- Preference for **near-maximal CP-violation** ($\delta_{CP} \sim -\pi/2$)
- δ_{CP} = 0 is **excluded at 90% CL (NO)**
- **Best-fit** value (NO): $\delta_{CP} = -2.18^{+1.22}_{-0.47}$ rad

Results obtained with a reactor constraint on $\sin^2\theta_{13}$

Phys. Rev. Lett. 135, 261801 (2025)

TPC PID as a Systematic Source

Systematic error source	*Model*	*PDF*	*Nominal weight correction*	*Status of Prod-8 inputs*
V-TPC related				
B Field distortions	Variation	Flat	–	–
V-TPC momentum scale	Variation	Gaus	–	No update
V-TPC momentum resolution	Variation	Gaus	–	Updated
V-TPC PID	Variation	Gaus	–	Updated
V-TPC clustering	Weight	Gaus	yes	Updated
V-TPC tracking	Weight	Gaus	yes	Updated
V-TPC charge ID	Weight	Gaus	yes	Updated
HAT related				
B Field distortions	Variation	Flat	–	–
HA-TPC momentum scale	Variation	Gaus	–	New syst
HA-TPC momentum resolution	Variation	Gaus	–	New syst
HA-TPC PID	Variation	Gaus	–	New syst
HA-TPC clustering	Weight	Gaus	yes	New syst
HA-TPC tracking	Weight	Gaus	yes	New syst
HA-TPC charge ID	Weight	Gaus	yes	New syst
SFG related				
SFGD tracking	Weight	Gaus	yes	New syst
TOF related				
TOF tracking	Weight	Gaus	yes	New syst
SFGD–TPC1 related				
TPC1–SFGD matching	Weight	Gaus	yes	New syst
SFGD–HA-TPC related				
HA-TPC–SFGD matching	Weight	Gaus	yes	New syst
HA-TPC–TPC1 related				
HA-TPC–TPC1 matching	Weight	Gaus	yes	New syst
SFGD-HA-TPC–TOF related				
SFGD-HA-TPC–TOF matching	Weight	Gaus	yes	New syst
Background related				
OOFV background	Weight	Gaus	no	New syst
Sand muon background	Weight	Gaus	no	Updated
Pile-up	Weight	Gaus	yes	New syst
MC modeling related				
Momentum bias due to SFGD geometry modeling	Variation	Gaus	–	New syst
Pion secondary interactions	Weight	Gaus	yes	No update
Proton secondary interactions	Weight	Gaus	no	No update
SFGD mass	Weight	Gaus	no	New syst
Inter-detector and detector timing				
$\Delta_t(SFG - TOF)$	Variation	Gaus	–	New syst



12 Micromegas modules in total

36 columns x 48 rows

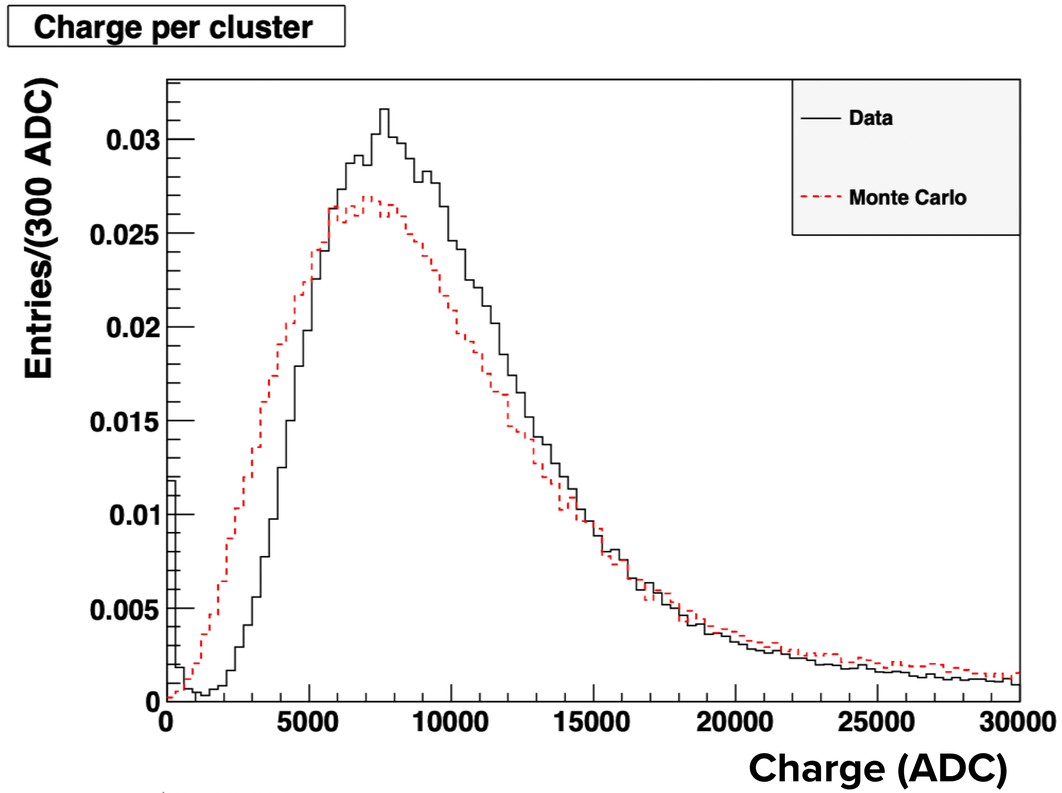
Horizontal tracks: ≤ 72 clusters
Vertical tracks: ≤ 288 clusters

Cluster — a group of hits close together in space and time within a Micromegas row or column.

TPC Particle Identification Method

Idea: Particle identification is based on the measurement of energy loss (dE/dx) of charged particles traversing the TPC gas

Measured dE/dx is estimated using the truncated mean of the lowest 70% of cluster charges.



Pull:

$$\delta_i = \frac{dE/dx^{\text{meas}} - dE/dx_i^{\text{exp}}}{\sigma_i^{\text{exp}}}$$

i — the i-th particle hypothesis (muon/electron/proton)

$dEdx^{meas}$ — the measured truncated mean of energy loss

$dEdx_i^{exp}$ — the expected value of energy loss for a given particle hypothesis i (muon/electron/proton)

σ_i^{exp} — the expected resolution, obtained from simulation

Measured dE/dx calibration in Data

- **Run-dependent calibration** performed separately for each TPC
- **Control samples:** through-going muons crossing all three TPCs
- **Reference:** mean dE/dx measured in MC for TPC2
- **TPC momentum:** 700 MeV/c < p_μ < 1000 MeV/c

Correction factor:

$$\mathrm{corr}(i,j) = \frac{\langle dE/dx \rangle^{\mathrm{Data}}(i, \mathrm{TPC}_j)}{\langle dE/dx \rangle^{\mathrm{MC}}(\mathrm{TPC}_2)}$$

i – Run index, j – TPC index

Application to Data:

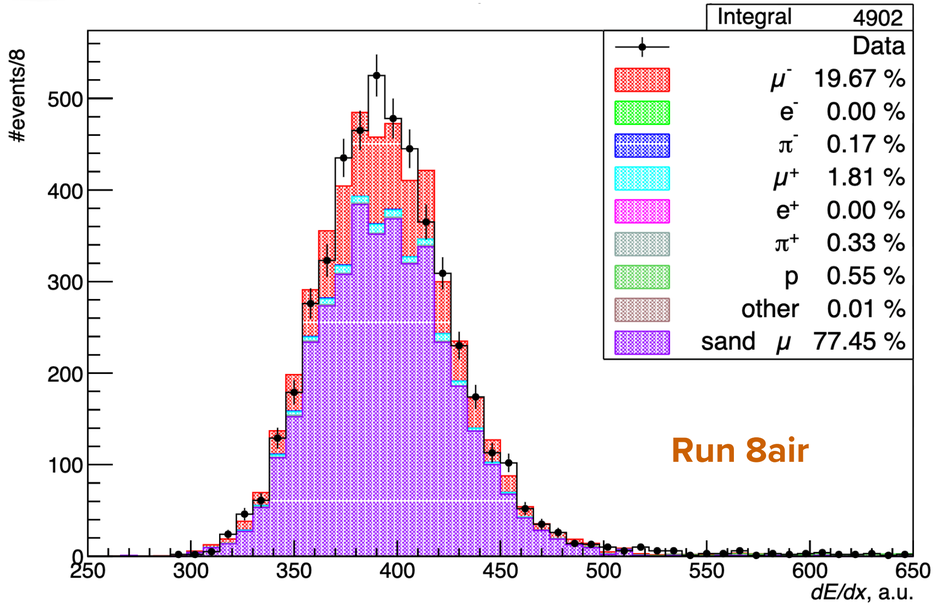
$$(dE/dx)^{\mathrm{Data}}_{\mathrm{corr}}(i, \mathrm{TPC}_j) = \frac{(dE/dx)^{\mathrm{Data}}(i, \mathrm{TPC}_j)}{\mathrm{corr}(i,j)}$$

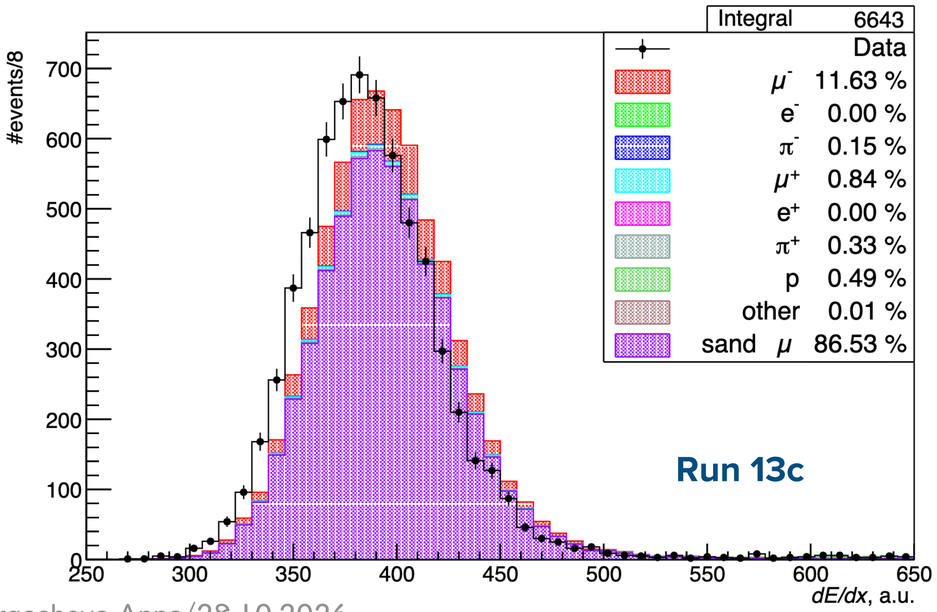
Track-by-track correction

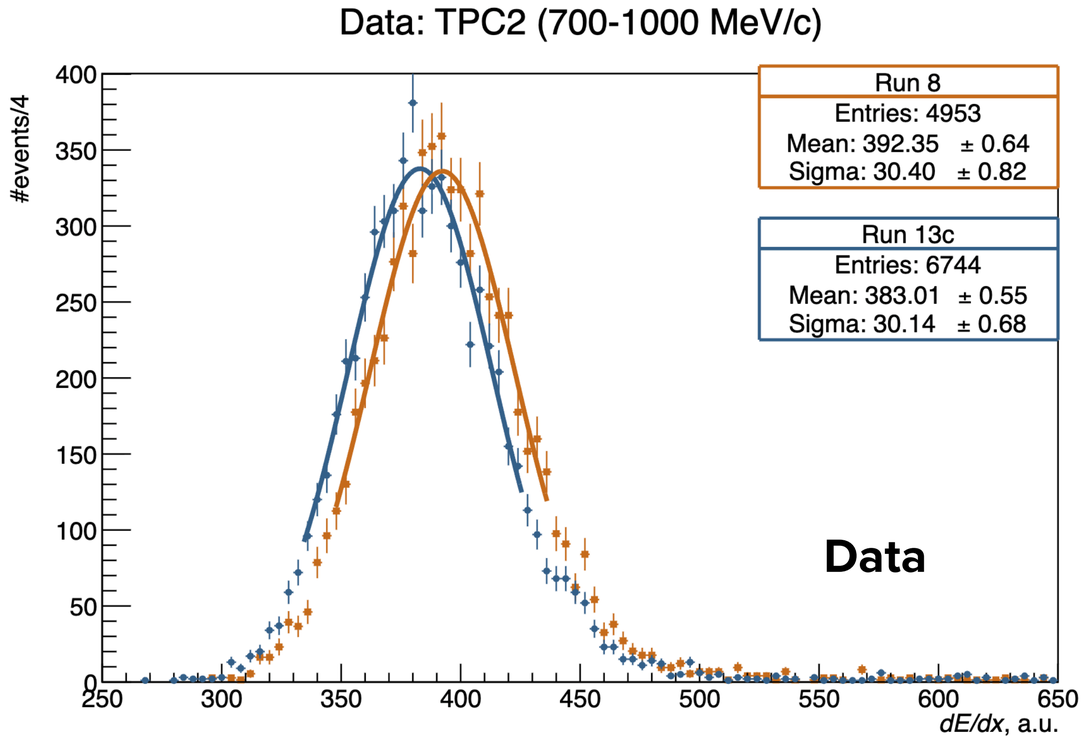
Run configurations:

Parameter	Run 8	Run 13c
Configuration	Pre-upgrade	Post-upgrade
Beam mode	FHC (ν-mode)	FHC (ν-mode)
Horn current	+250 kA	+320 kA

Measured dE/dx calibration — **TPC2**

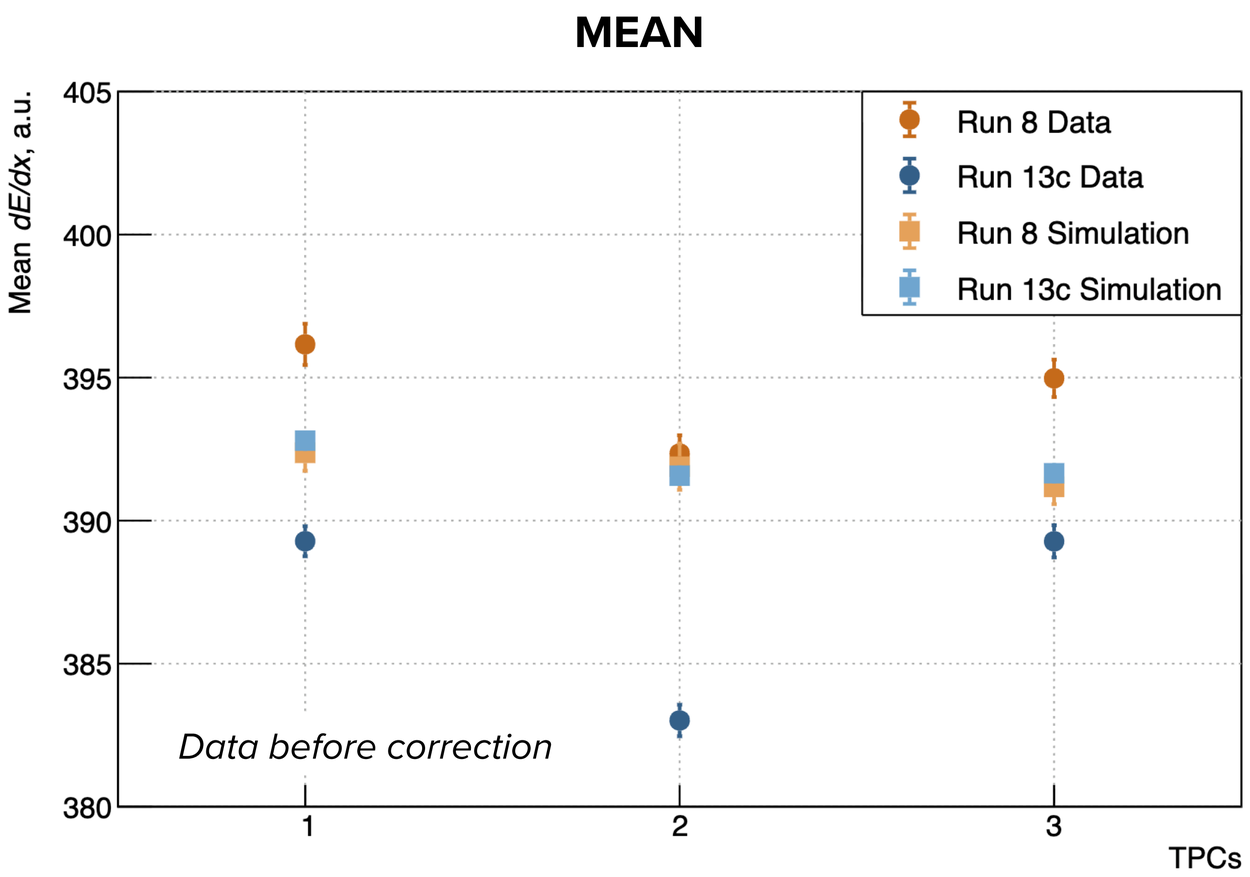


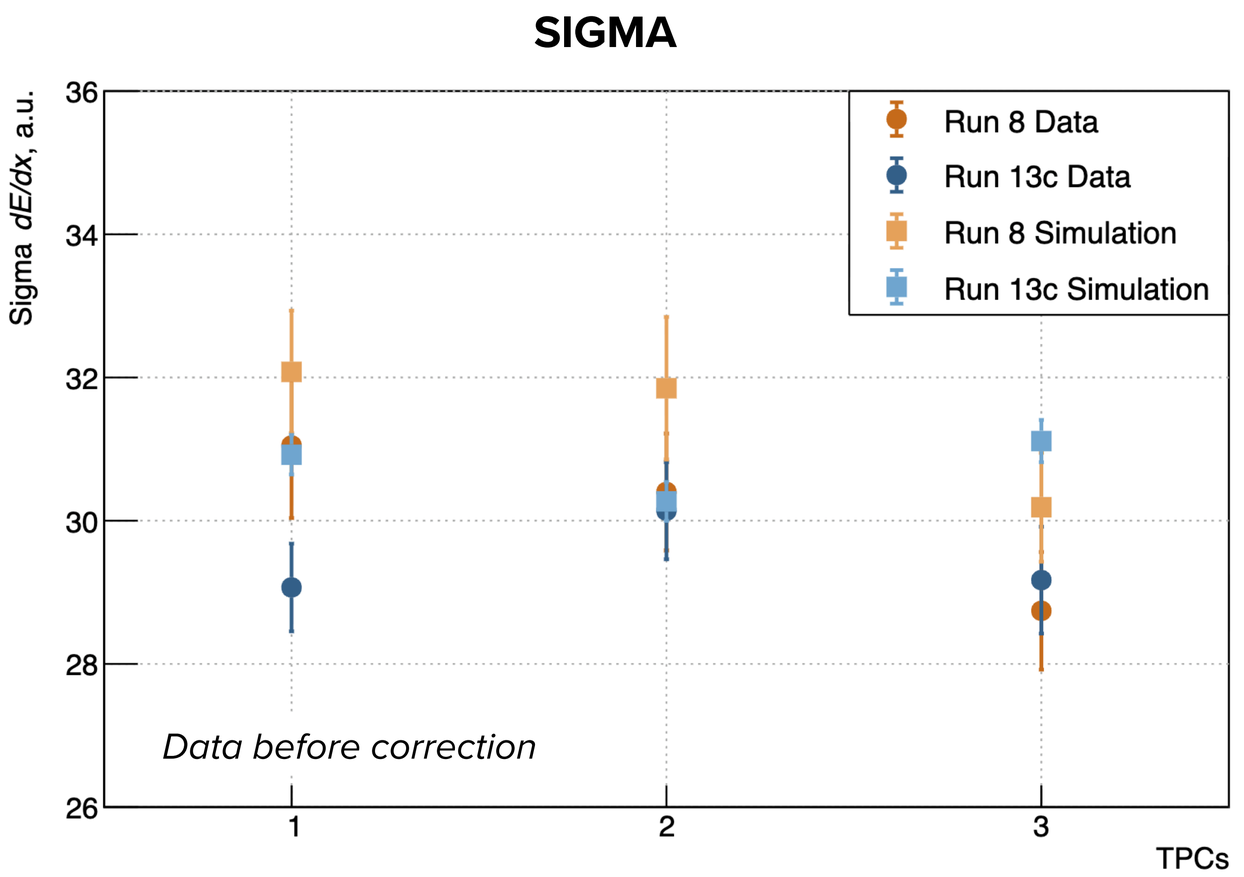




Mean dE/dx (a.u.)	Run 8	Run 13c
Data: before Correction	392,35 ± 0,64	383,01 ± 0,55
Data: after Correction	391,94 ± 0,64	391,52 ± 0,58
MC - reference value	**391,89 ± 0,81**	391,57 ± 0,24

Measured dE/dx Calibration in Data — **Mean / Sigma**





The largest offsets in mean values:

Run 13c · TPC2

— 2.19 %

383.01 Data vs 391.57 Simulation

Run 8 · TPC1

+ 1.09 %

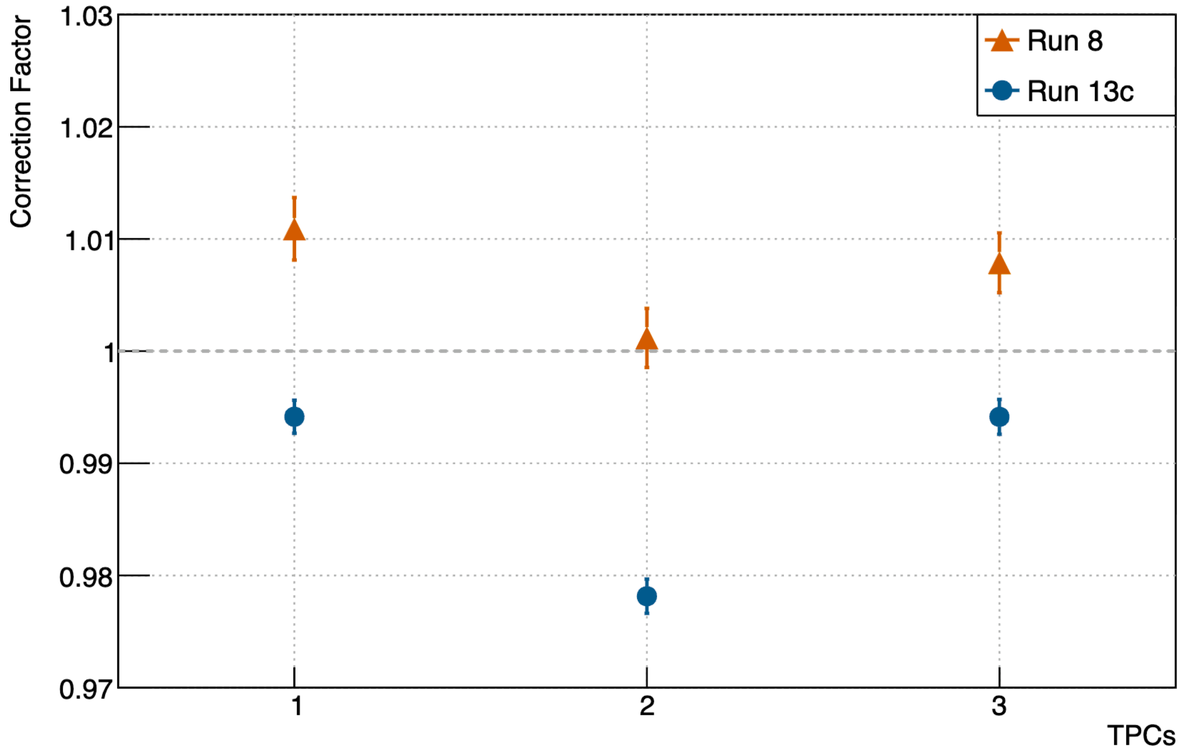
396.16 Data vs 391.89 TPC2 ref.

Measured dE/dx calibration in Data

Correction factor:

$$\mathrm{corr}(i,j) = \frac{\langle dE/dx \rangle^{\mathrm{Data}}(i, \mathrm{TPC}_j)}{\langle dE/dx \rangle^{\mathrm{MC}}(\mathrm{TPC}_2)}$$

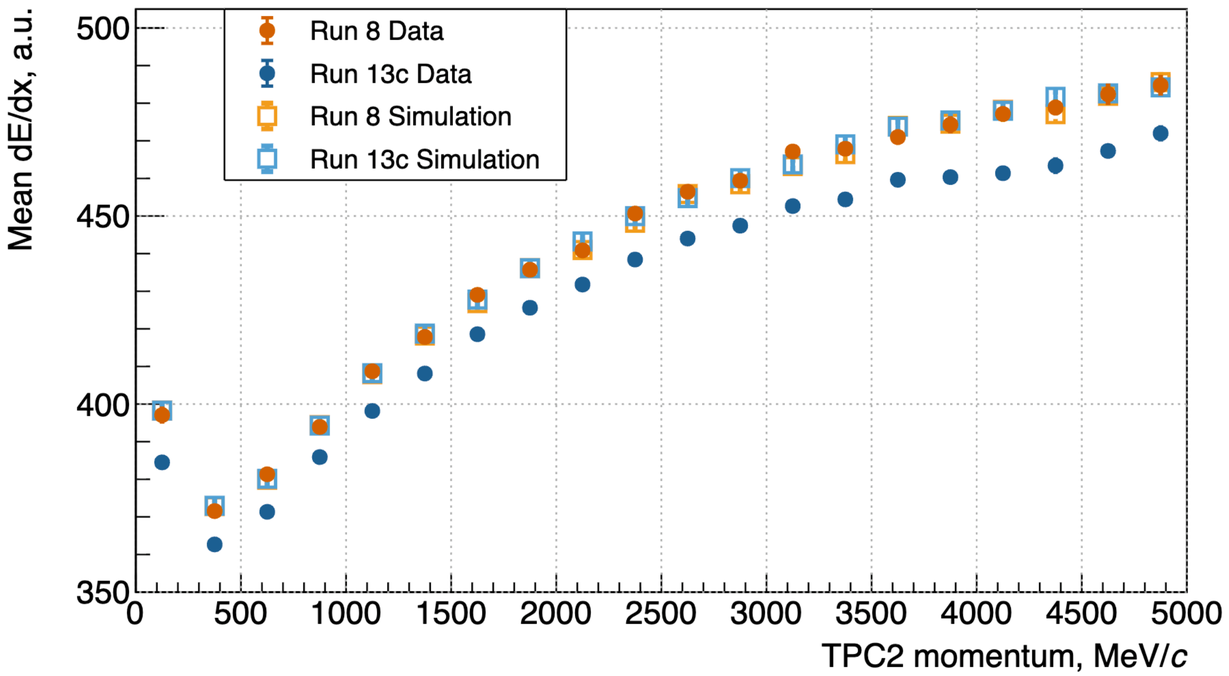
i – Run index, j – TPC index



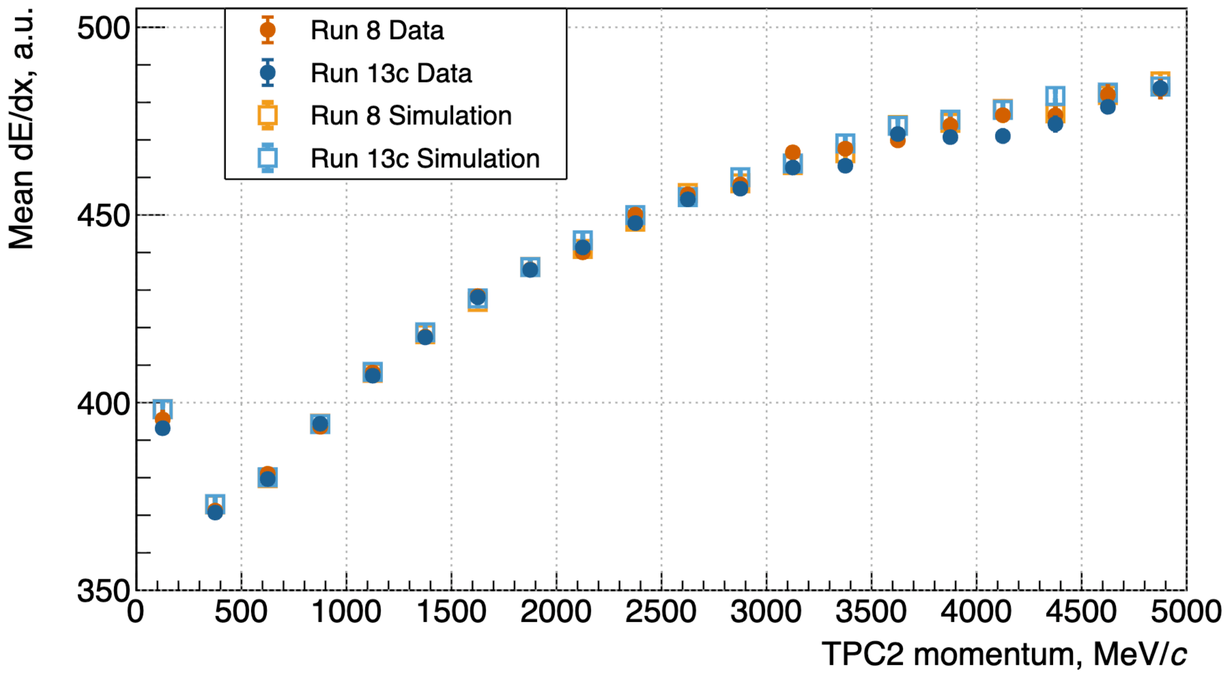
Parameter	Run	TPC1	TPC2	TPC3
Corr factor	8	1,0109 ± 0,0028	1,0012 ± 0,0026	1,0079 ± 0,0027
	13c	0,9941 ± 0,0015	0,9781 ± 0,0015	0,9941 ± 0,0016

Effect of dE/dx correction — **TPC2**

Before Data correction



After Data correction



Correction results in the 700–1000 MeV/c momentum range:

Run 13c · TPC2

Before correction		**After** correction	**TPC2 ref.**
383.01	→	**391.52**	**391.57**
Mean dE/dx, a.u.			

Run 8 · TPC2

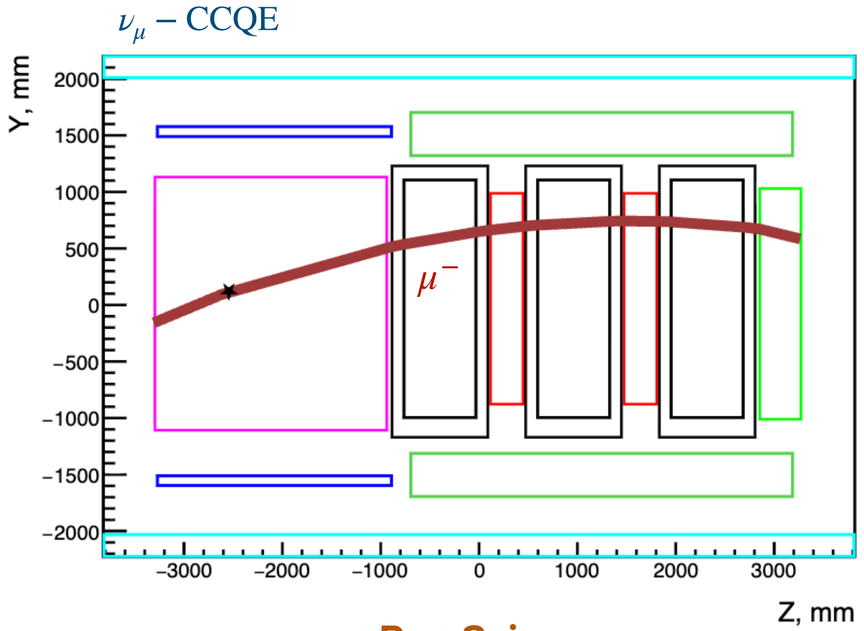
Before correction		**After** correction	**TPC2 ref.**
392.35	→	**391.94**	**391.89**
Mean dE/dx, a.u.			

TPC PID Control-Sample Selection

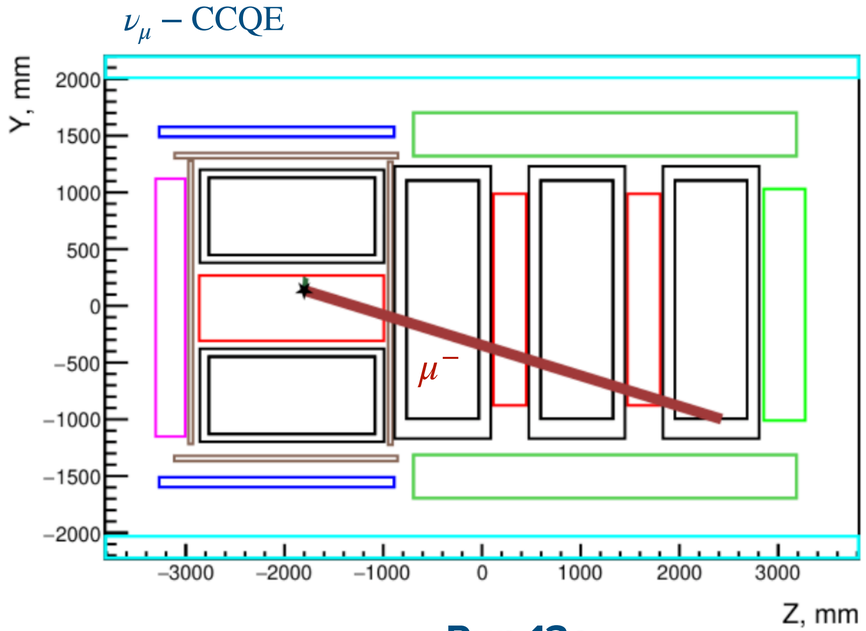
Muon candidates

Event quality → Reconstructed TPC tracks → Track quality

1. Track reconstructed in all three TPCs
2. Track quality: > 35 nodes in each TPC segment
3. One track per bunch
4. Track momentum > 100 MeV/c



Run 8air



Run 13c

TPC PID Control-Sample Selection

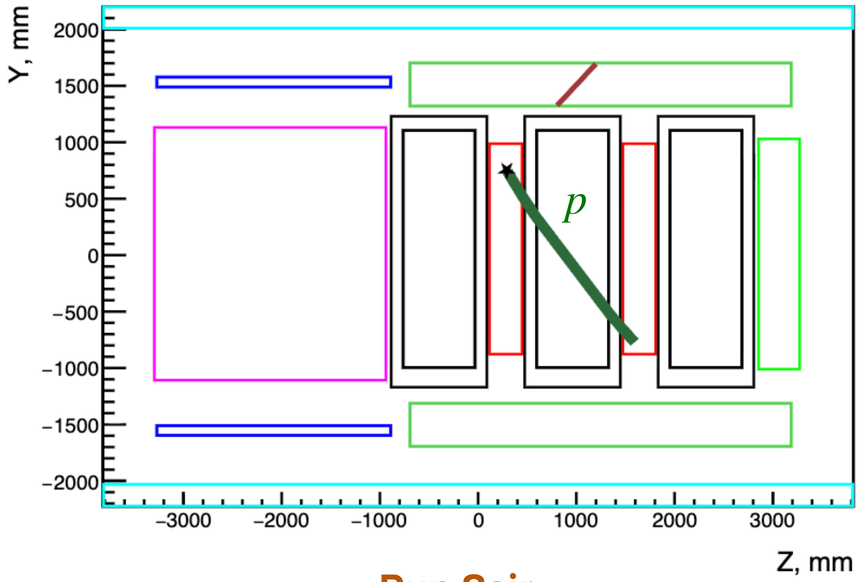
Proton candidates

Event quality → Reconstructed TPC tracks → Track quality

Start in FGD1/FGD2/TECAL/PECAL and in P0D (Run 8)/ SFGD or HAT (Run 13c)

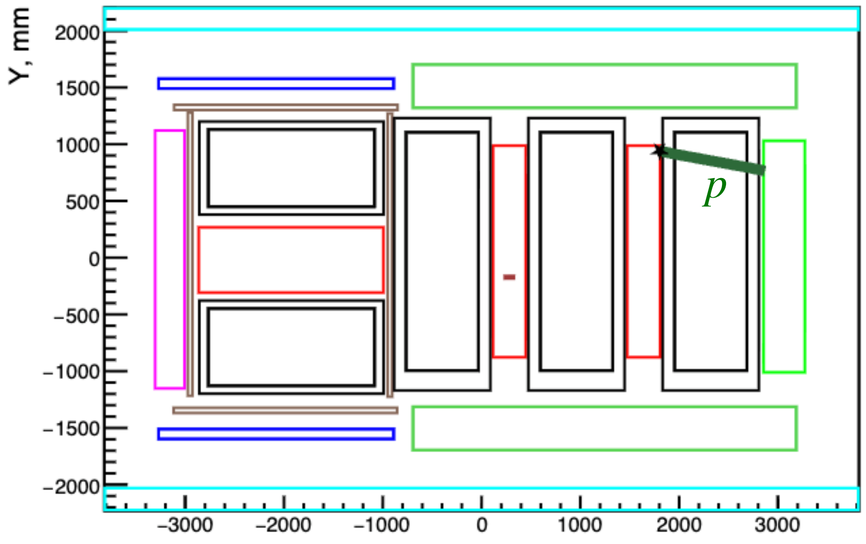
1. Positive-charge candidate
2. Use the closest TPC segment
3. Track momentum > 200 MeV
4. Measured dE/dx > 700 a.u.

ν_μ – CCQE



Run 8air

ν_μ CC 2p2h



Run 13c

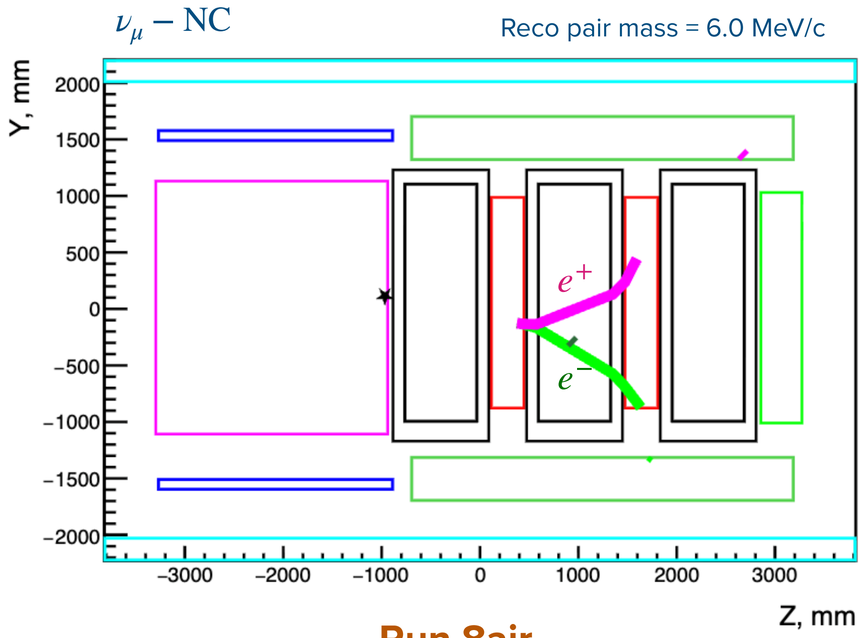
TPC PID Control-Sample Selection

Electron candidates

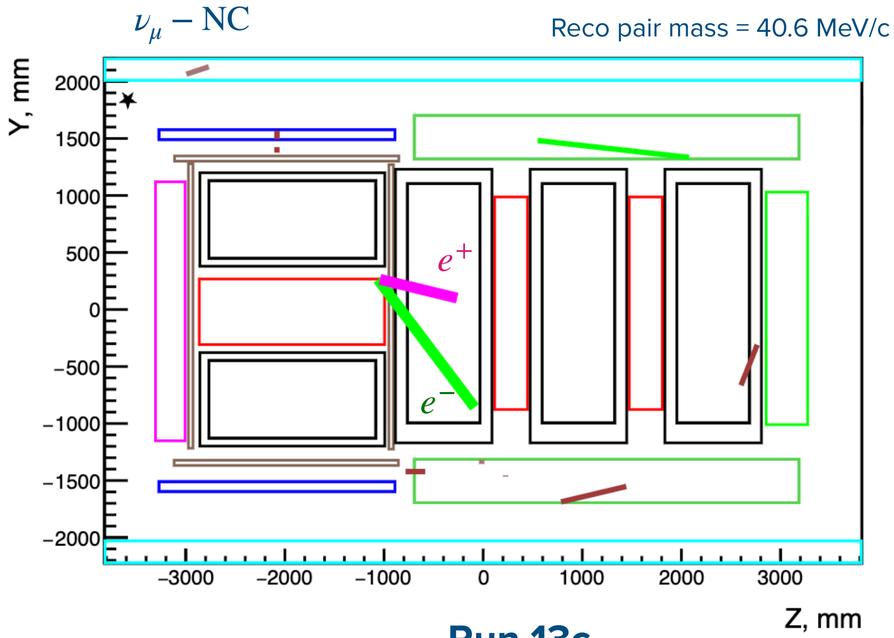
Event quality → Reconstructed TPC tracks → Track quality

Start in FGD1/FGD2/TECAL/PECAL and in P0D (Run 8)/ SFGD or HAT (Run 13c)

1. Pairs of e^+e^- from γ - conversion
2. Distance between the starting points of the tracks < 100 mm
3. Reconstructed invariant mass < 50 MeV/c^2



Run 8air



Run 13c

Selection results

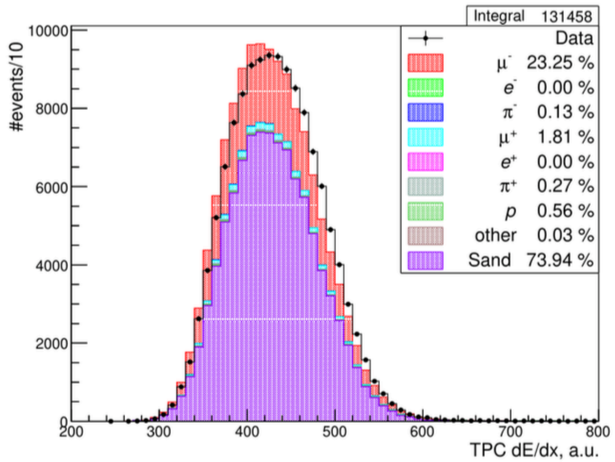
TPC1 + TPC2 + TPC3
area-normalised dE/dx distributions

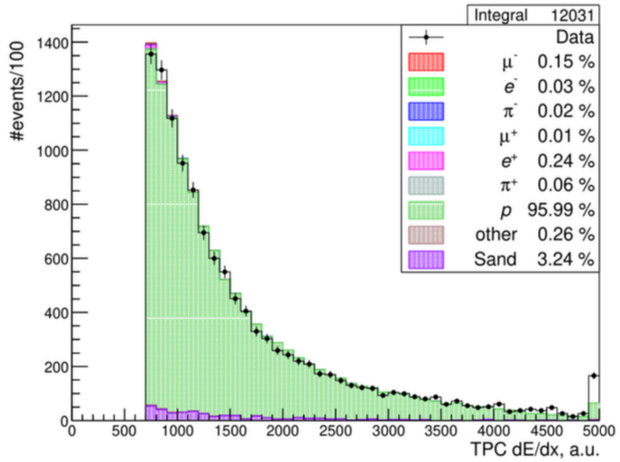
Muon candidates

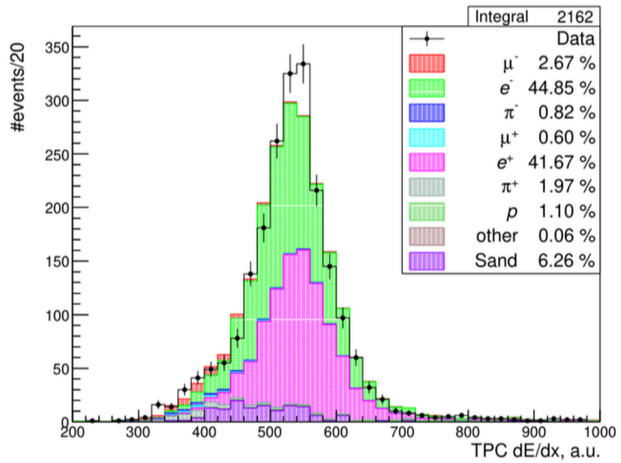
Proton candidates

Electron candidates

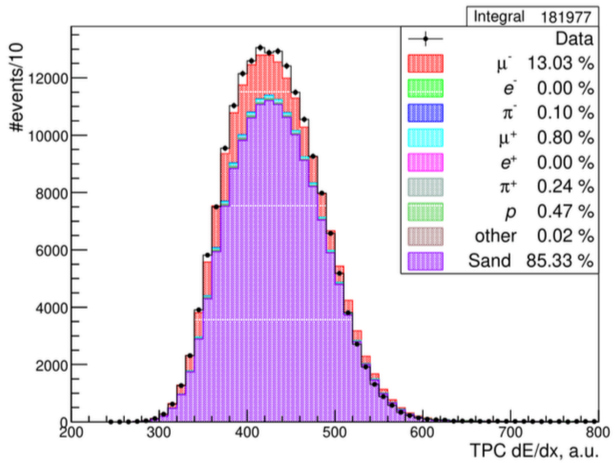
Run 8air

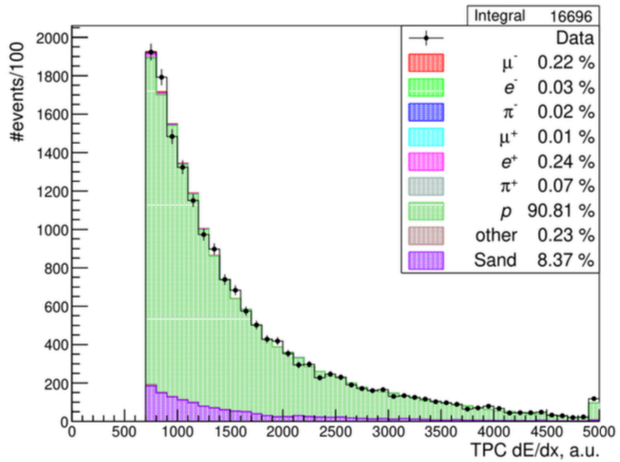


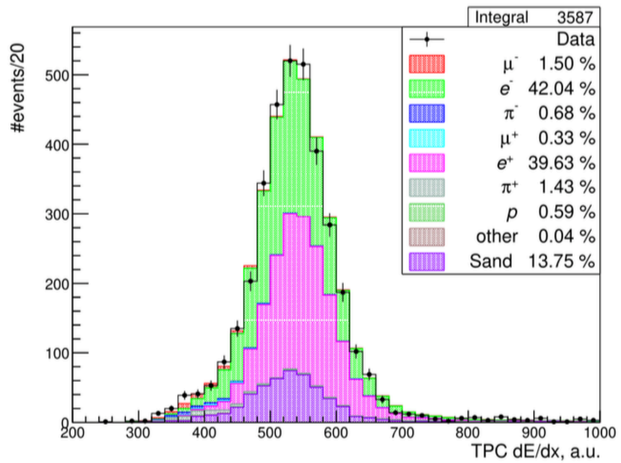




Run 13c



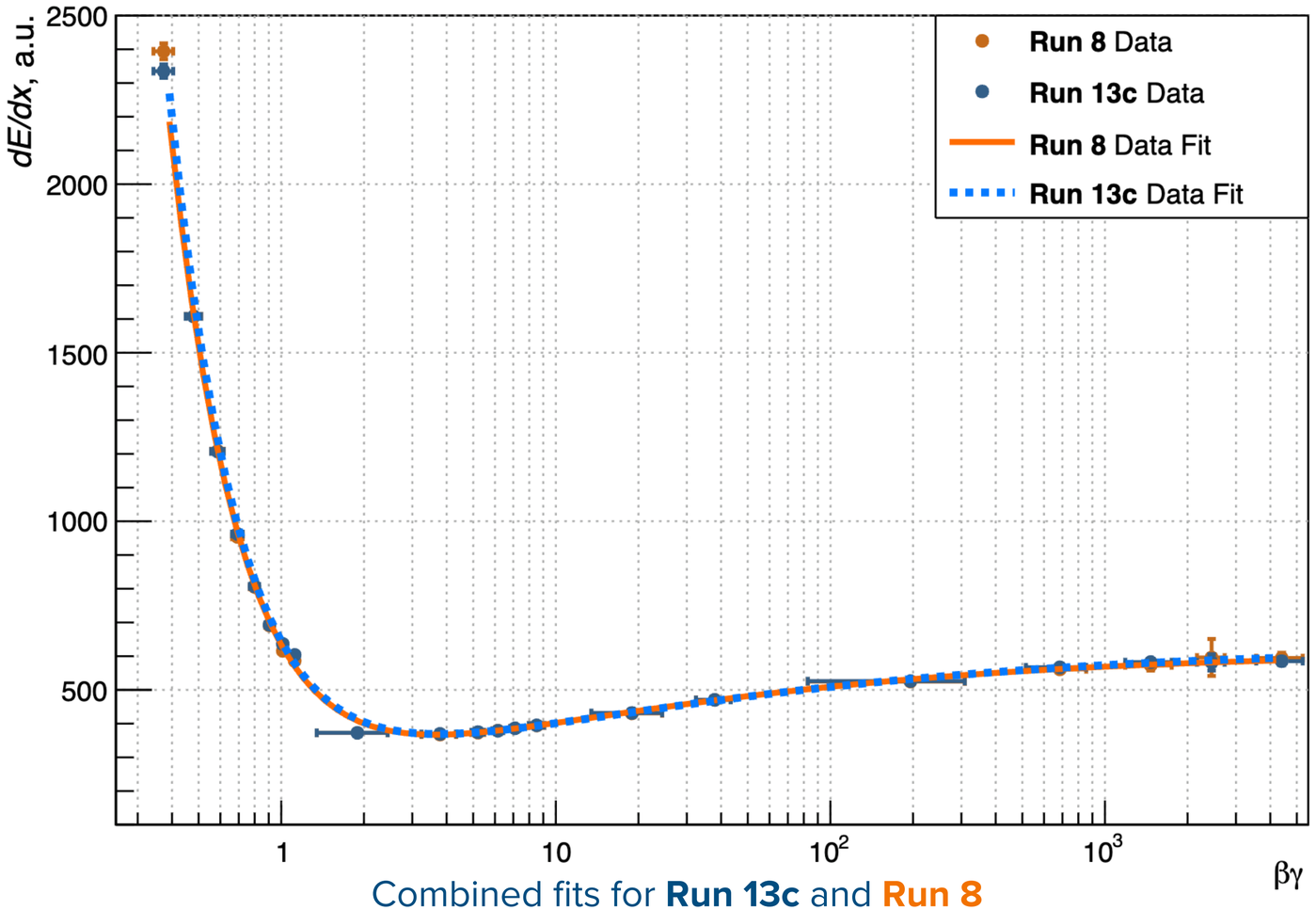




Purity	Muon	Proton	Electron
Run 8: Beam MC + Sand	98.79%	99.17%	91.37%
Run 13c: Beam MC + Sand	98.51%	99.03%	94.77%

Expected dE/dx Parametrization

$$dE/dx^{\exp} = \frac{p_0}{\beta^{p_3}}\left[p_1 - \beta^{p_3} - \log\left(p_2 + \frac{1}{(\beta\gamma)^{p_4}}\right)\right]$$



Combined fits for **Run 13c** and **Run 8**
to muon, proton, and electron control samples

Run-dependent dE/dx corrections applied to data

Run 8

p_0 = 211.95 ± 33.2

p_1 = 2.2725 ± 0.146

p_2 = 0.20145 ± 0.0598

p_3 = 1.8658 ± 0.0926

p_4 = 0.45724 ± 0.044

χ^2/NDF = 3.13/16

Run 13c

p_0 = 194.227 ± 20.502

p_1 = 2.386 ± 0.115

p_2 = 0.1625 ± 0.0360

p_3 = 1.8980 ± 0.0749

p_4 = 0.44456 ± 0.0353

χ^2/NDF = 7.43/16

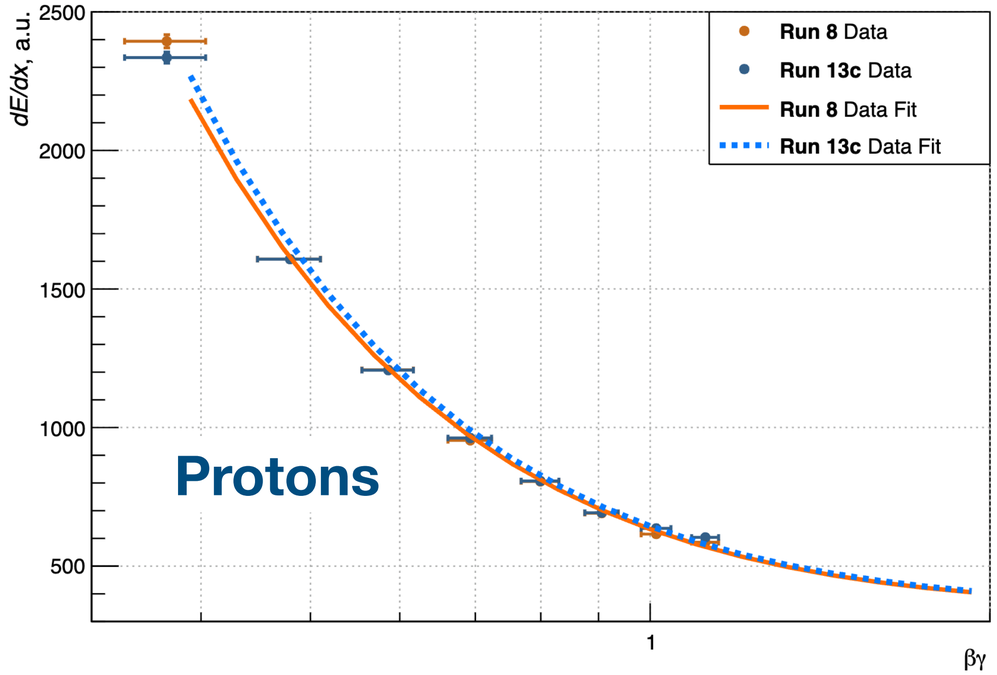
Expected dE/dx Parametrization

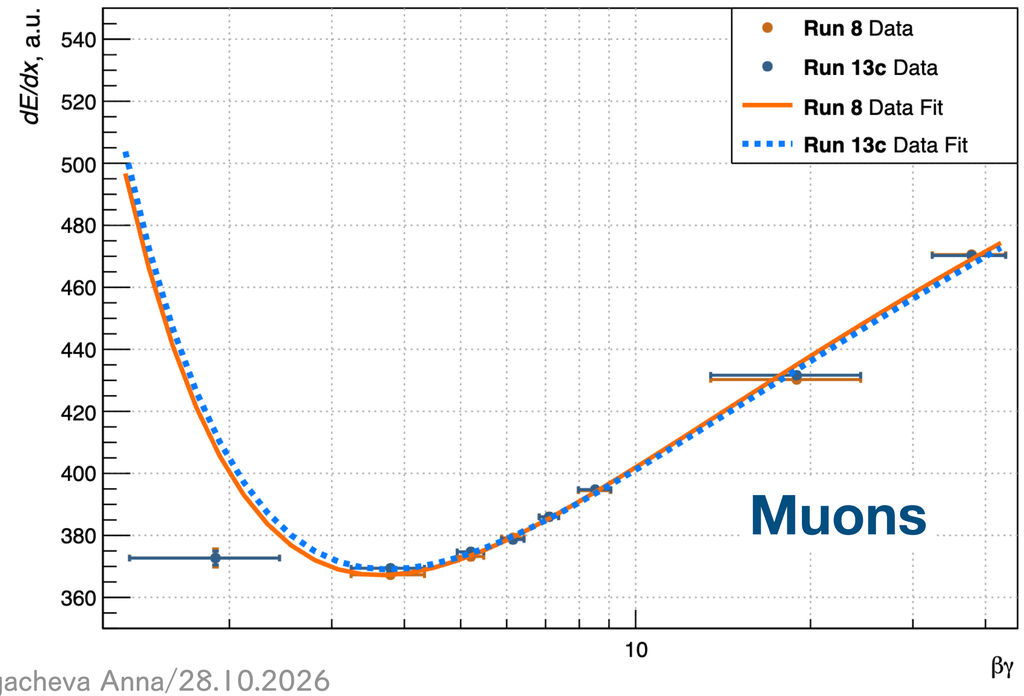
$$dE/dx^{\exp} = \frac{p_0}{\beta^{p_3}}\left[p_1 - \beta^{p_3} - \log\left(p_2 + \frac{1}{(\beta\gamma)^{p_4}}\right)\right]$$

Error Bars:

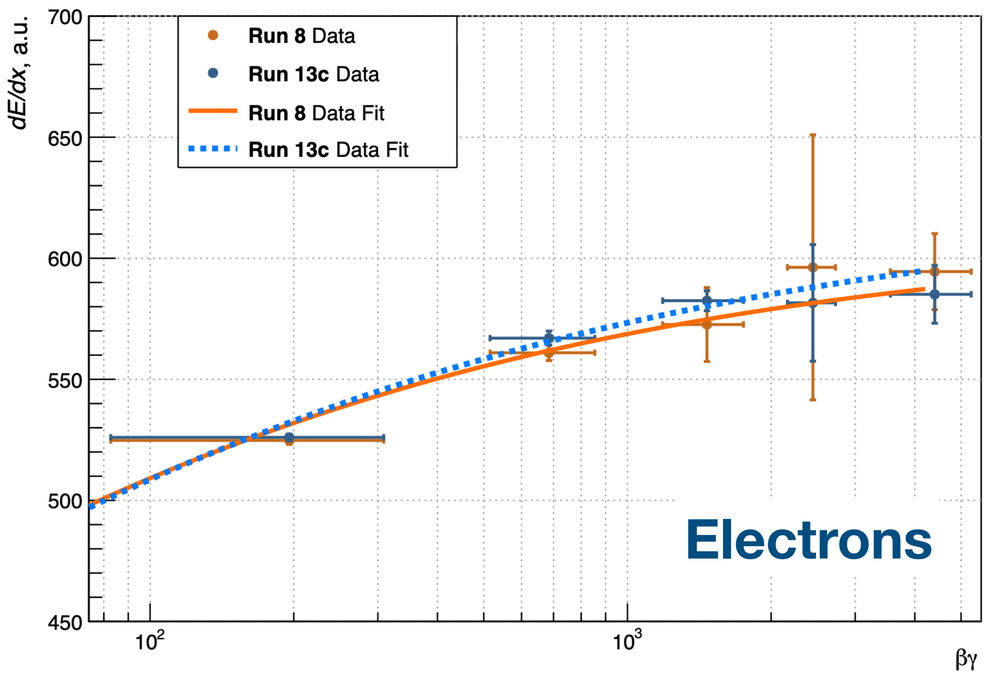
$$\sigma_{\beta\gamma}^{(i)} = \frac{\Delta p}{m_i\sqrt{12}}, \qquad i = e, \mu, p$$

$$\sigma_{dE/dx}^{(i)} = \Delta\mu_{\text{fit}}^{(i)}$$



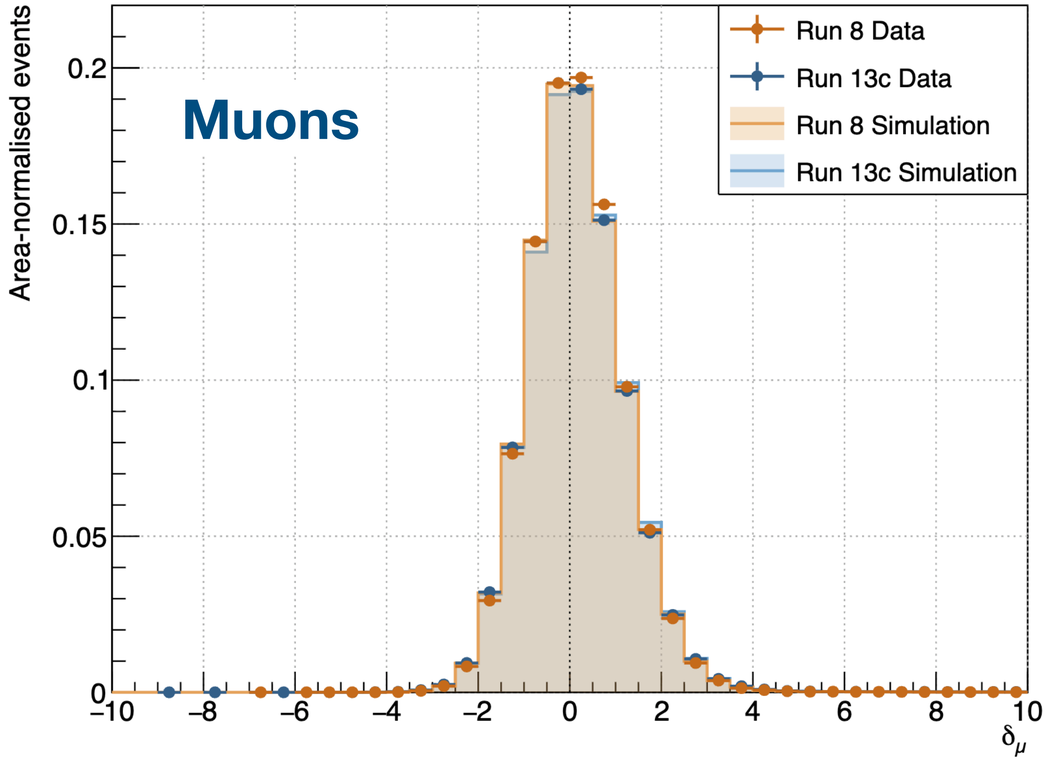


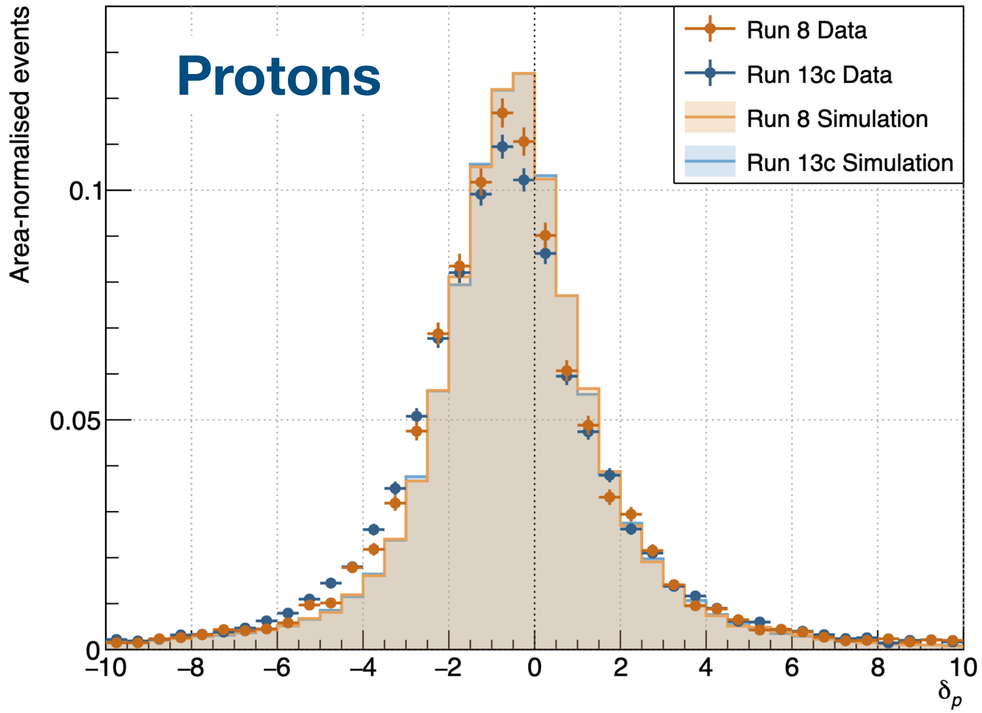
electron

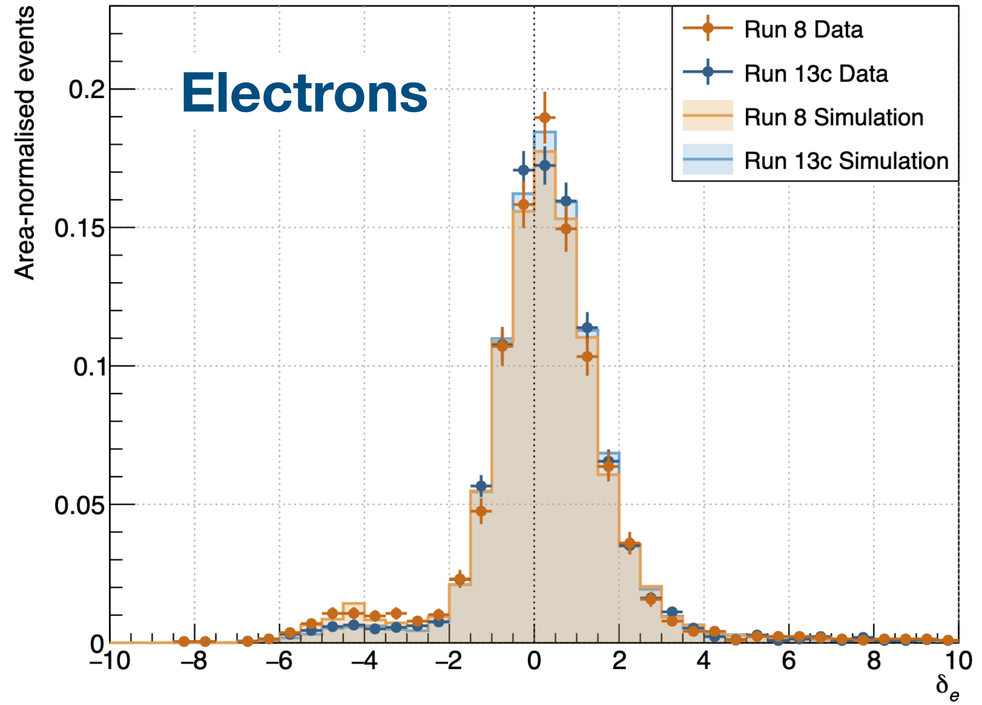


Pull. TPC1 + TPC2 + TPC3

$$\delta_i = \frac{dE/dx^{\text{meas}} - dE/dx_i^{\text{exp}}}{\sigma_i^{\text{exp}}}$$







Pull. TPC1 + TPC2 + TPC3

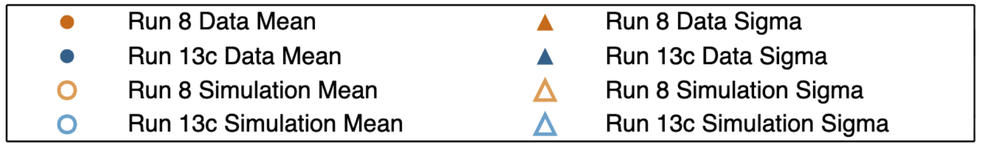
Pull mean **difference**

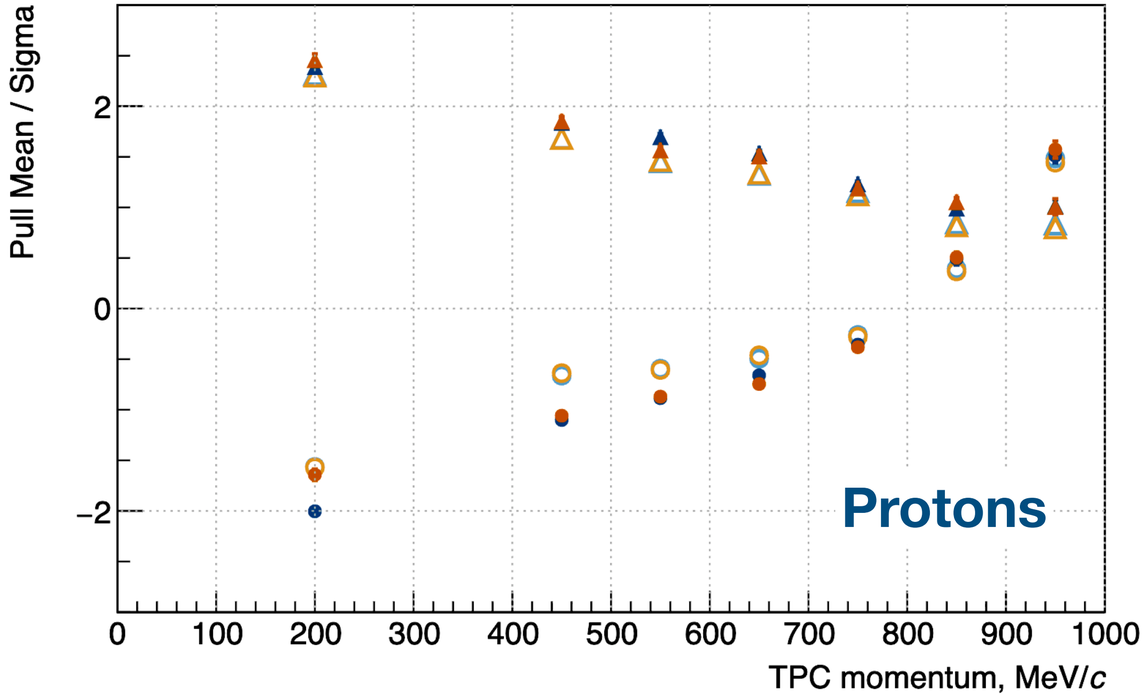
$$\Delta_\delta = \delta^{\text{Data}} - \delta^{\text{NEUT}}$$

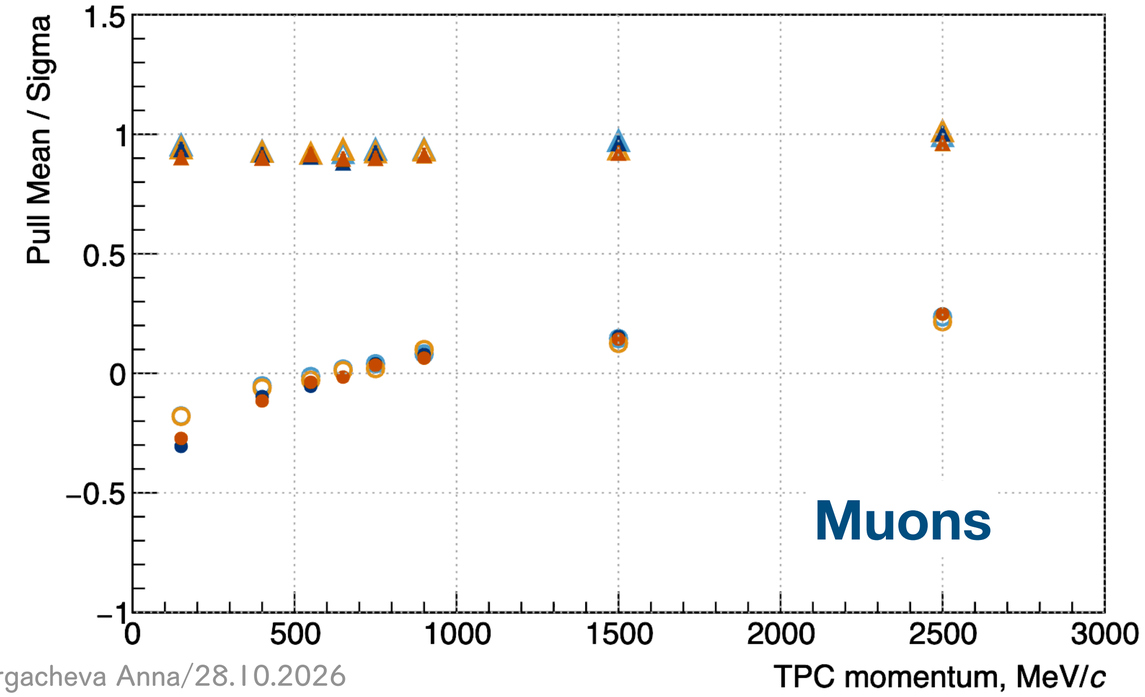
Pull sigma **ratio**

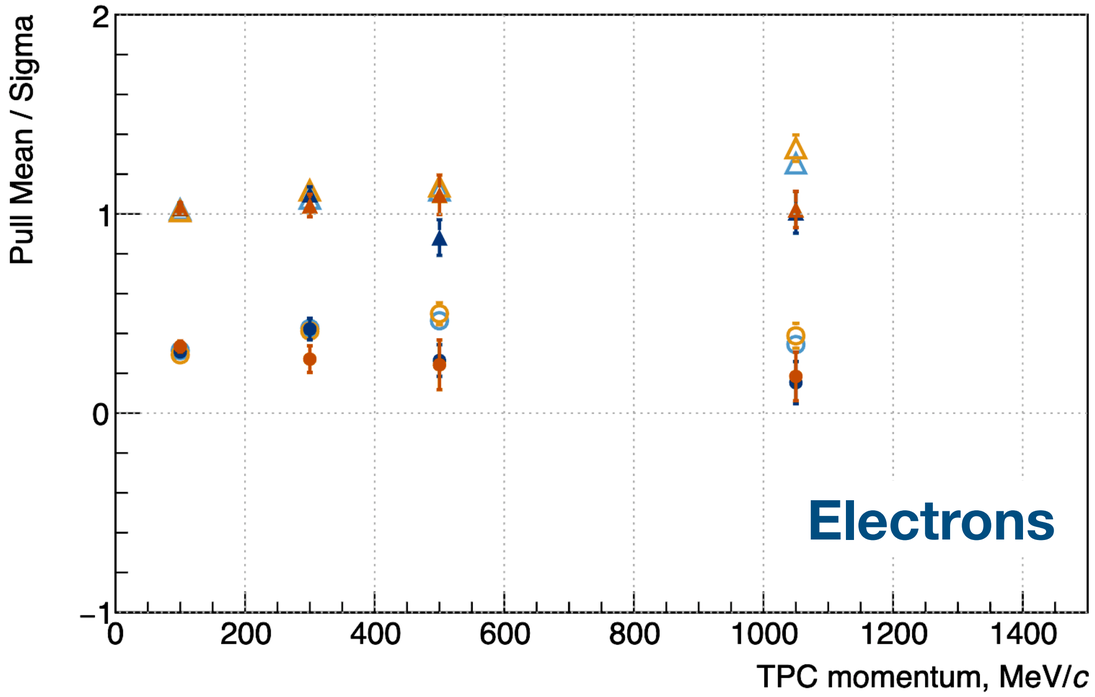
$$R_\sigma = \sigma_\delta^{\text{Data}} / \sigma_\delta^{\text{NEUT}}$$

MC PID correction: $\delta^{\text{corr}} = R_\sigma \cdot \delta^{\text{NEUT}} + \Delta_\delta$

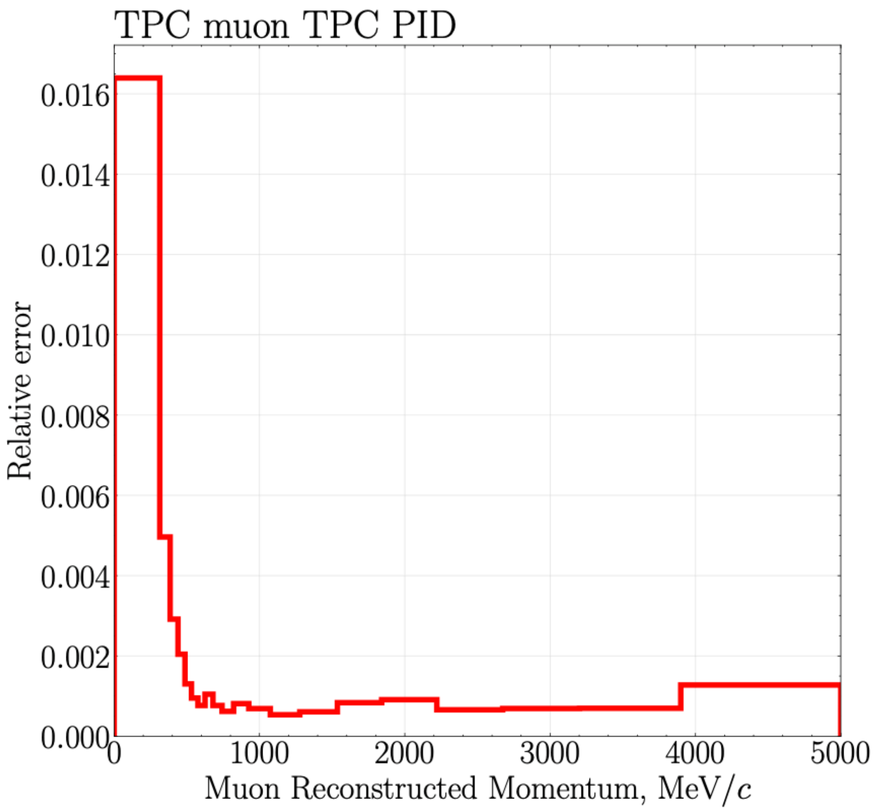


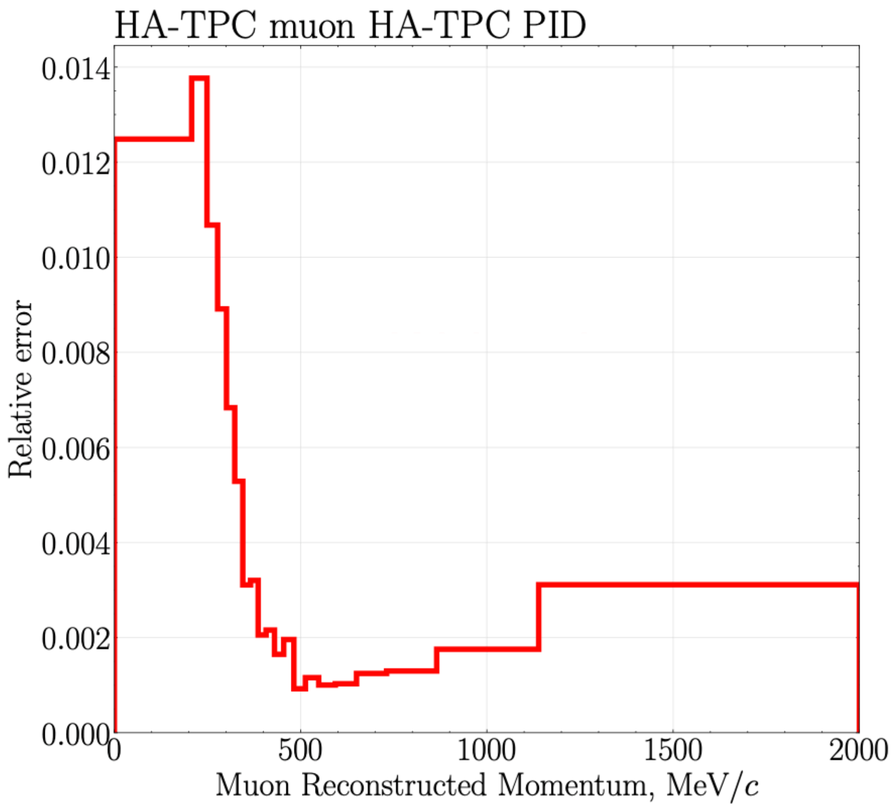






Impact of TPC and HA-TPC PID systematics





Relative error evaluated after the propagation of the uncertainty on the **TPC PID/ HA-TPC PID** as function of the reconstructed muon momentum

TN525, t2k.org

Conclusion

- **TPC PID response** was studied using muon, proton, and electron control samples for Run 8 (before the upgrade) and Run 13c (after the upgrade).

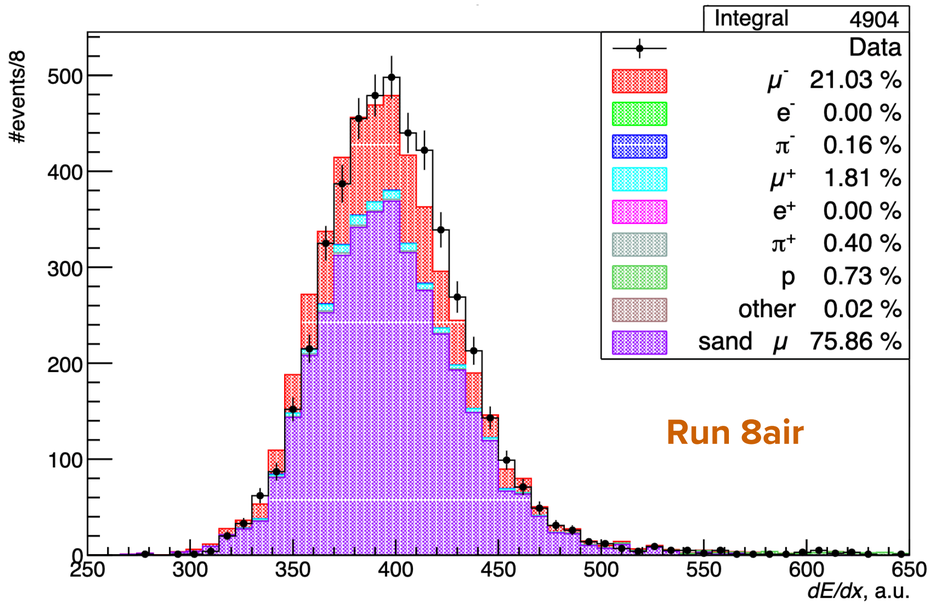
- **Run- and TPC-dependent dE/dx** calibration substantially improve Data–Simulation agreement, with the largest correction observed for TPC2 in Run 13c.

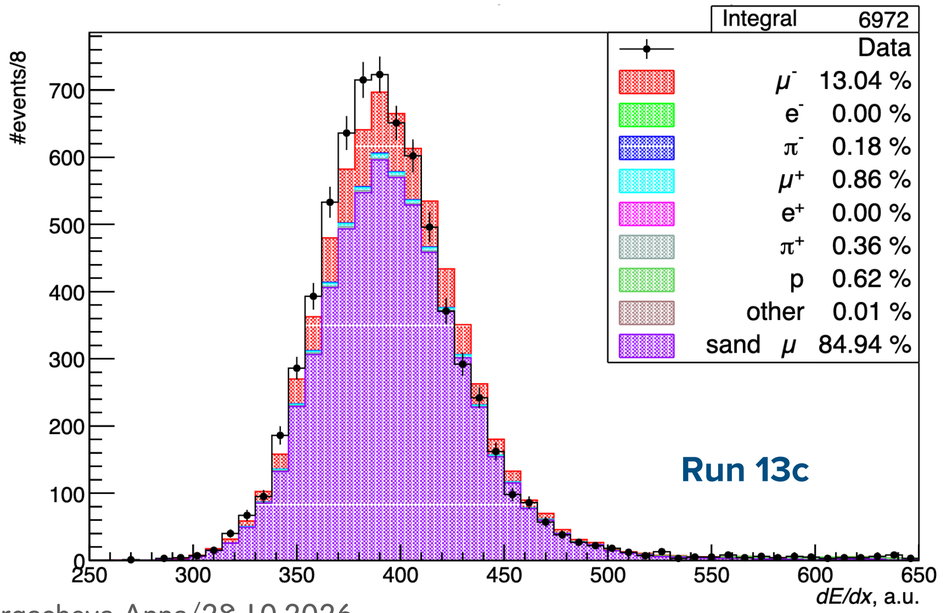
- **PID corrections and systematic uncertainties** were evaluated using differences in the mean and width of the pull distributions between data and MC. The corrections are applied to MC, while their uncertainties are propagated as variation-like systematics.

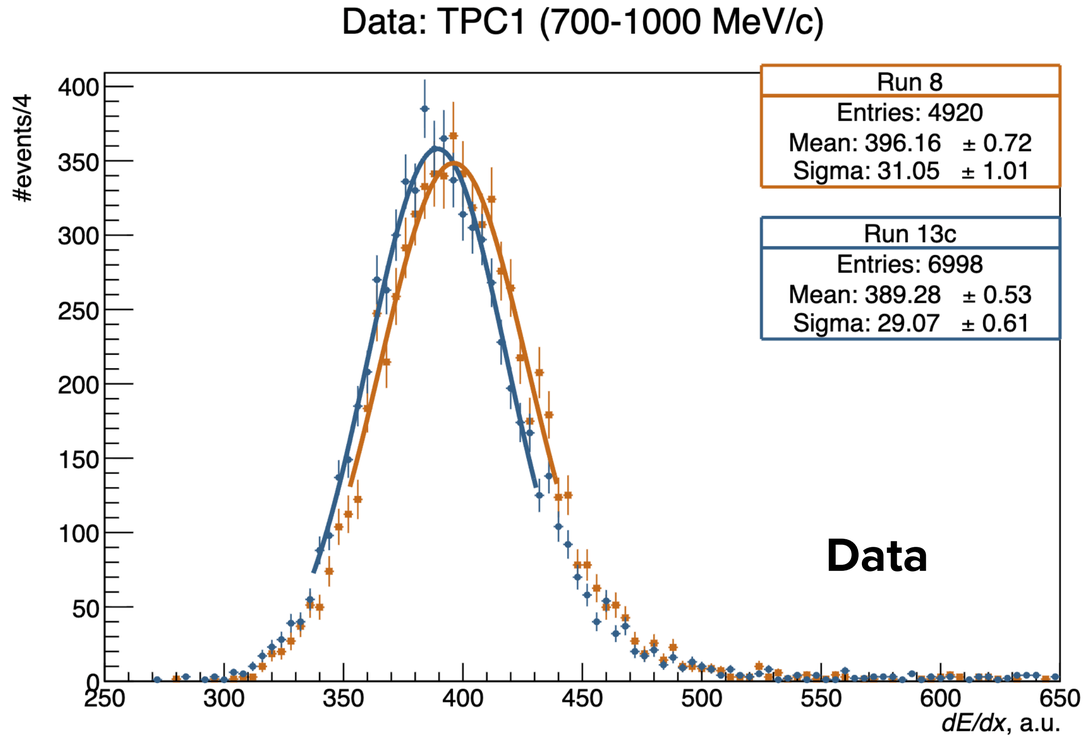
- **TPC and HA-TPC PID systematics** have the largest impact at low muon momenta, reaching approximately 1.6% for TPC PID and 1.4% for HA-TPC PID in their respective muon samples. The impact decreases at higher momenta.

Back up

Measured dE/dx calibration — **TPC1**

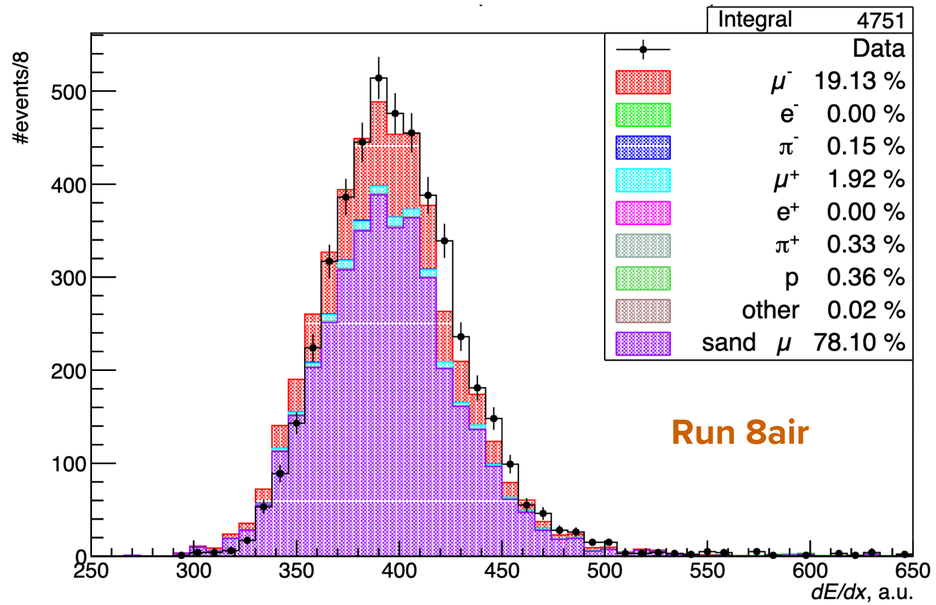


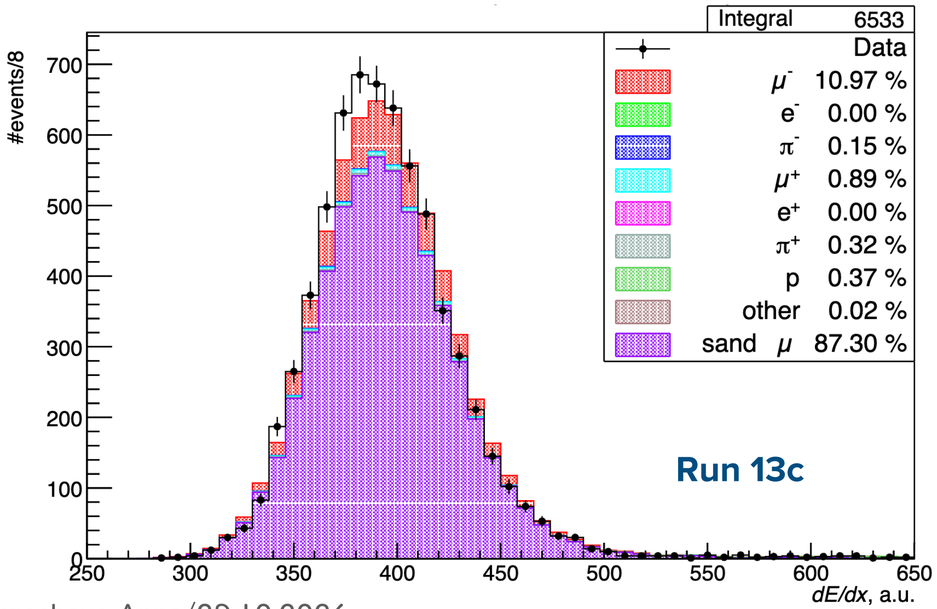


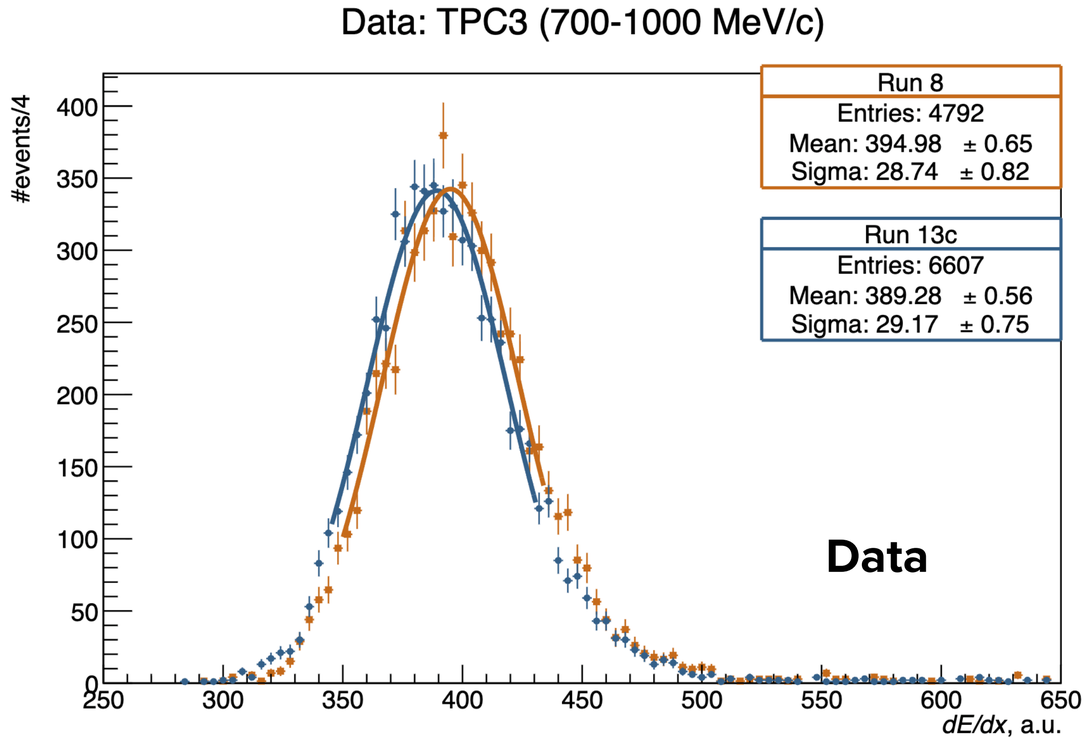


Mean dE/dx (a.u.)	Run 8	Run 13c
Data: before Correction	396,16 ± 0,72	389,28 ± 0,53
Data: after Correction	391,87 ± 0,71	391,60 ± 0,51
Simulation	392,37 ± 0,63	392,80 ± 0,23

Measured dE/dx calibration — **TPC3**







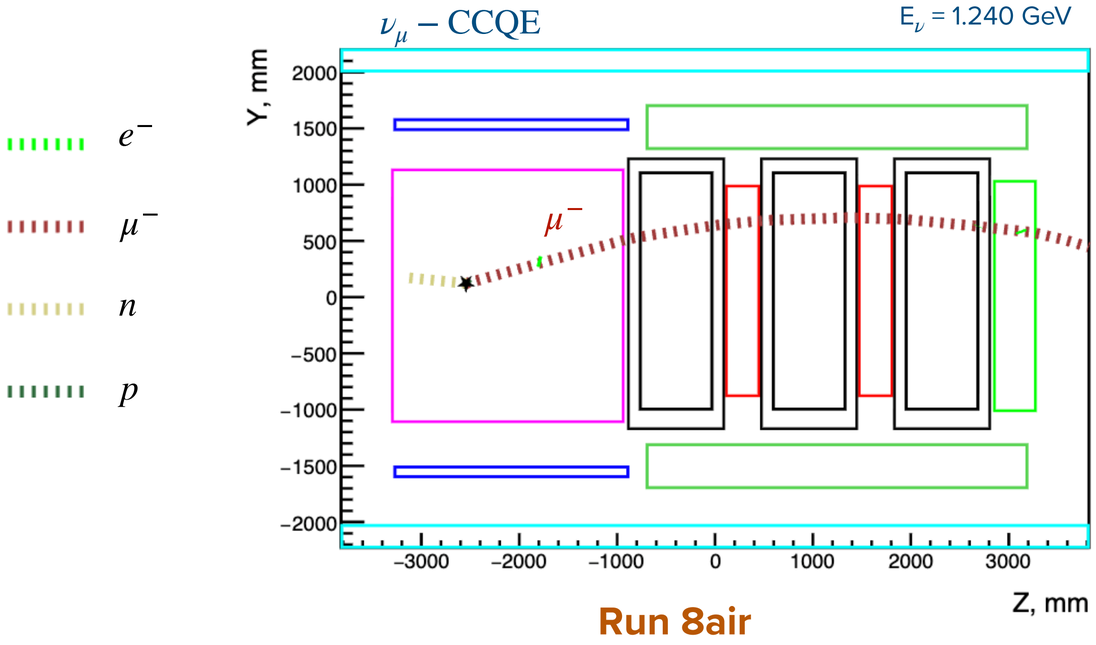
Mean dE/dx (a.u.)	Run 8	Run 13c
Data: before Correction	394,98 ± 0,65	389,28 ± 0,56
Data: after Correction	391,96 ± 0,67	391,35 ± 0,56
Simulation	391,18 ± 0,60	391,66 ± 0,24

TPC PID Control-Sample Selection

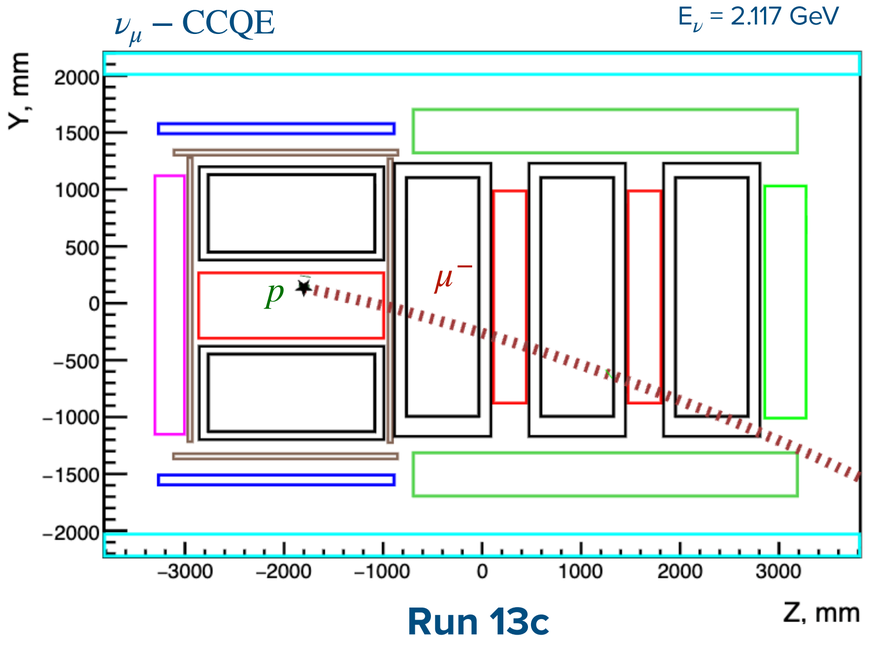
Muon candidates

Event quality → Reconstructed TPC tracks → Track quality

1. Track reconstructed in all three TPCs
2. Track quality: > 35 nodes in each TPC segment
3. One track per bunch
4. Track momentum > 100 MeV/c



Run 8air



Run 13c

TPC PID Control-Sample Selection

Proton candidates

Event quality → Reconstructed TPC tracks → Track quality

Start in FGD1/FGD2/TECAL/PECAL and in P0D (Run 8)/ SFGD or HAT (Run 13c)

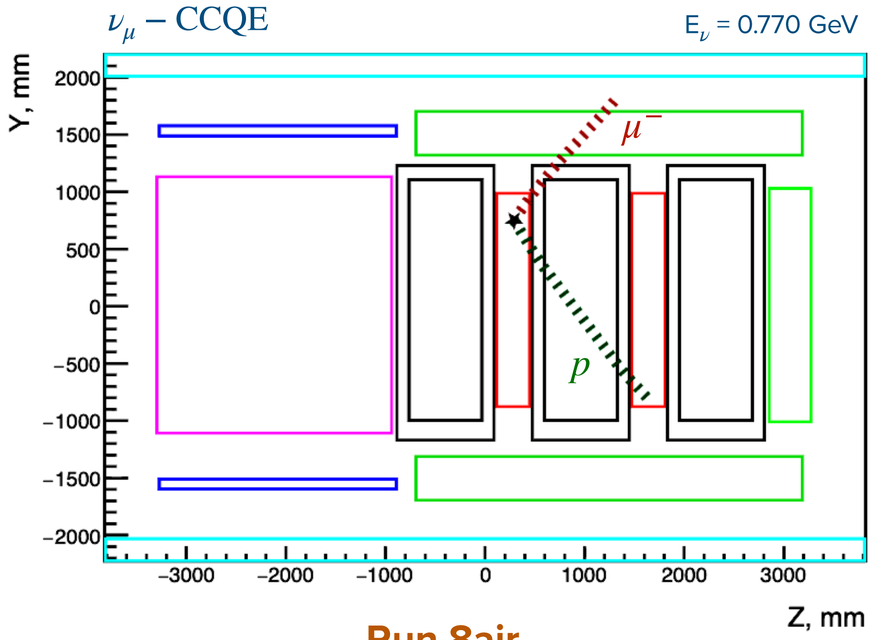
1. Positive-charge candidate
2. Use the closest TPC segment
3. Track momentum > 200 MeV
4. Measured dE/dx > 700 a.u.

e^-

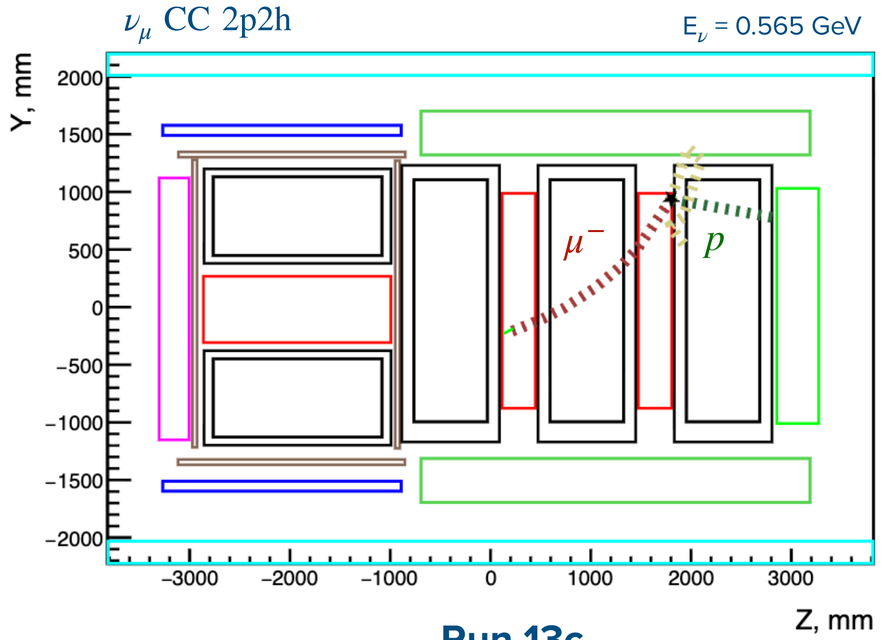
μ^-

n

p



Run 8air



Run 13c

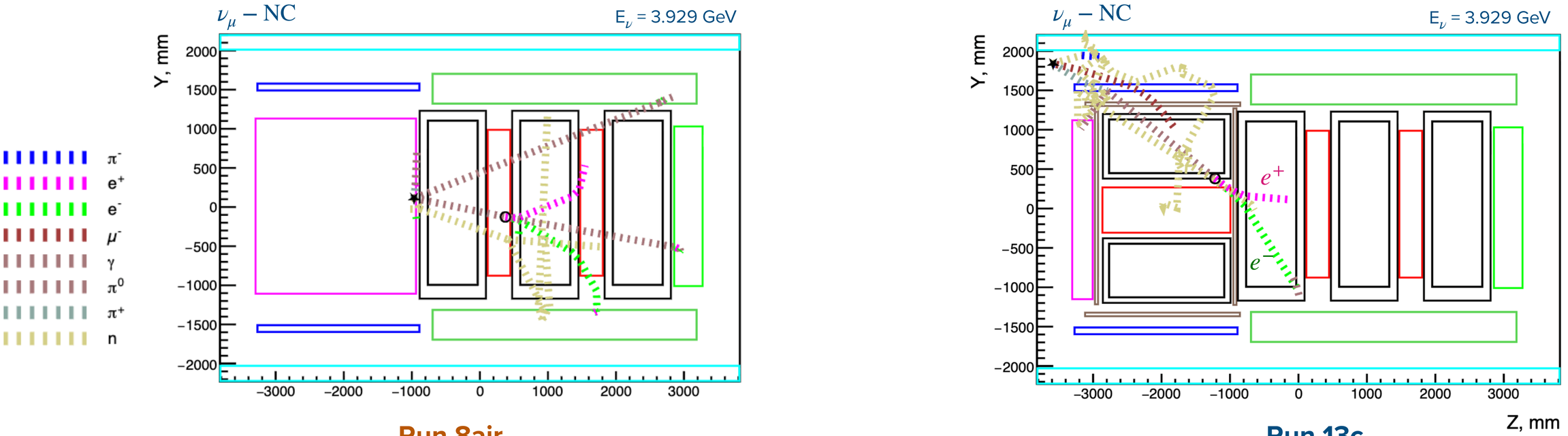
TPC PID Control-Sample Selection

Electron candidates

Event quality → Reconstructed TPC tracks → Track quality

Start in FGD1/FGD2/TECAL/PECAL and in P0D (Run 8)/ SFGD or HAT (Run 13c)

1. Pairs of e^+e^- from γ - conversion
2. Distance between the starting points of the tracks < 100 mm
3. Reconstructed invariant mass < 50 MeV/c^2



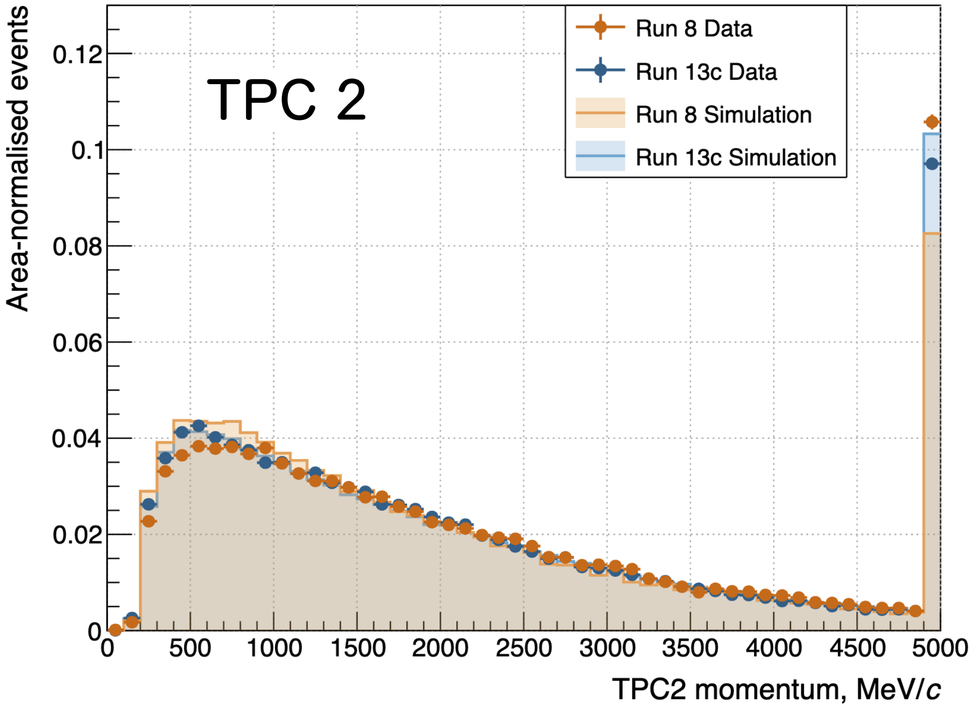
Run 8air

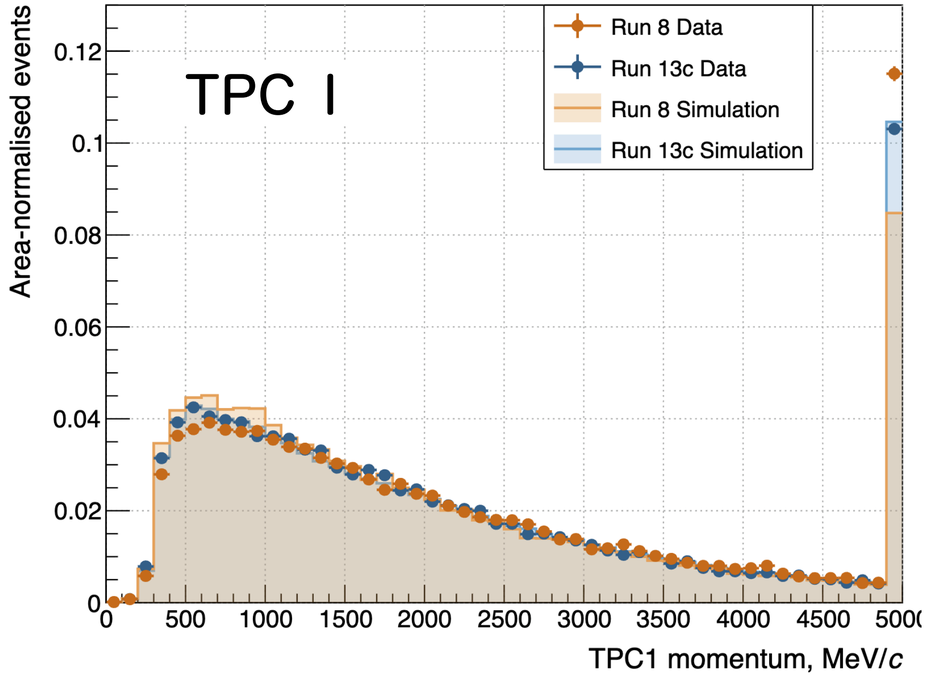
Run 13c

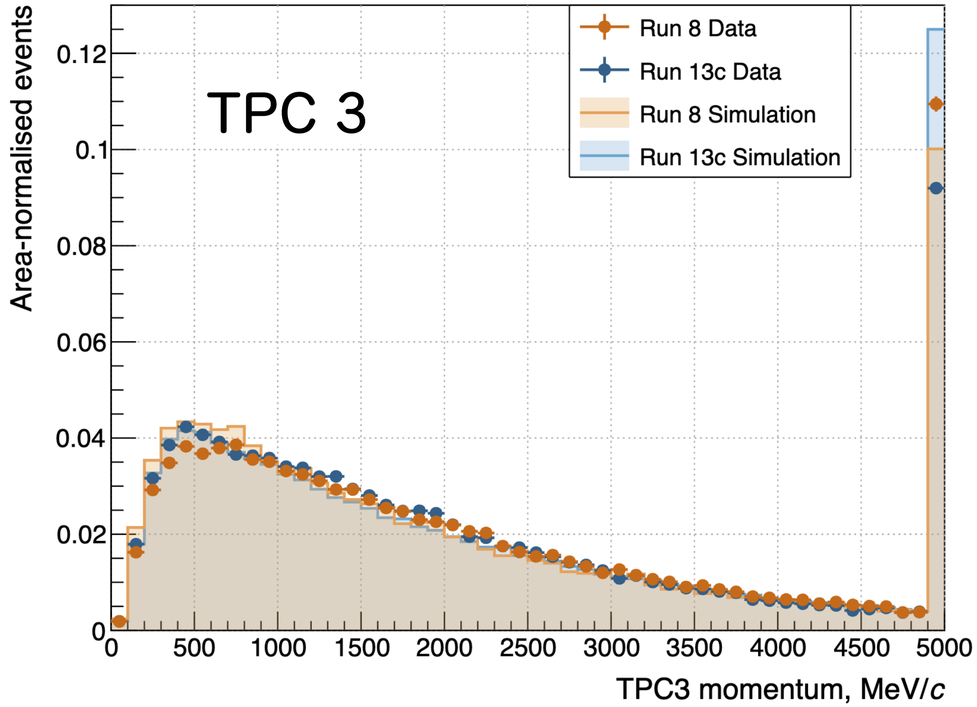
Muon candidates — **Momentum**

1. Track reconstructed in all three TPCs
2. Track quality: > 35 nodes in each TPC segment
3. One track per bunch
4. Track momentum > 100 MeV/c

Number of Data events	
Run 8	**Run 13c**
43, 870	**60, 749**



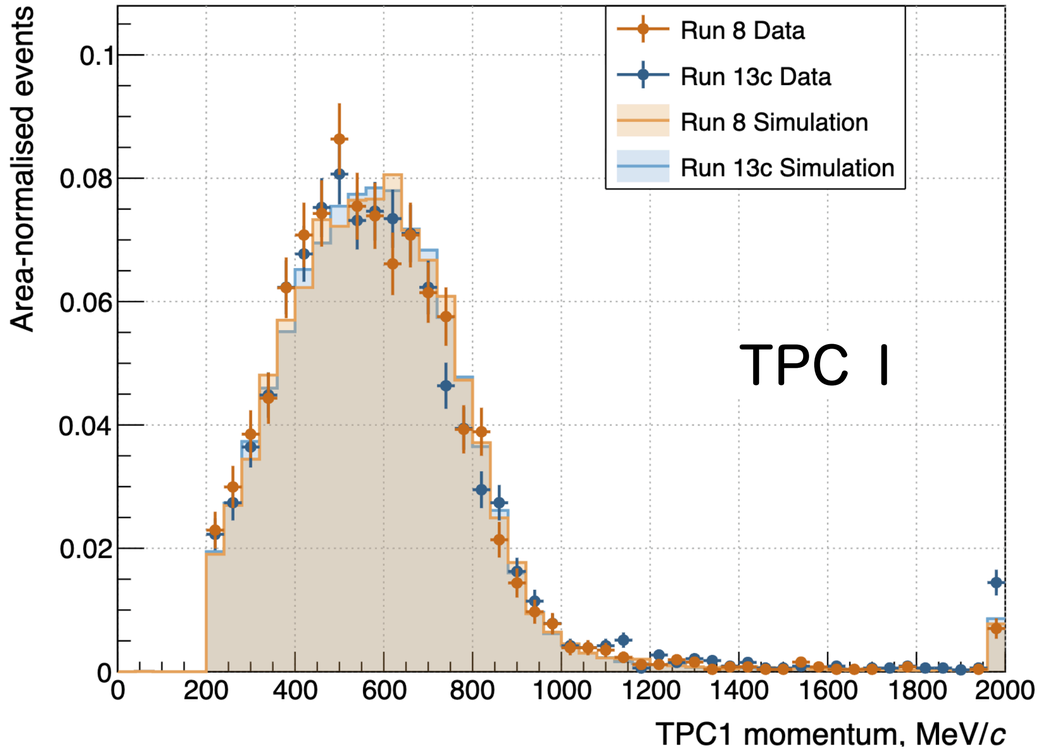


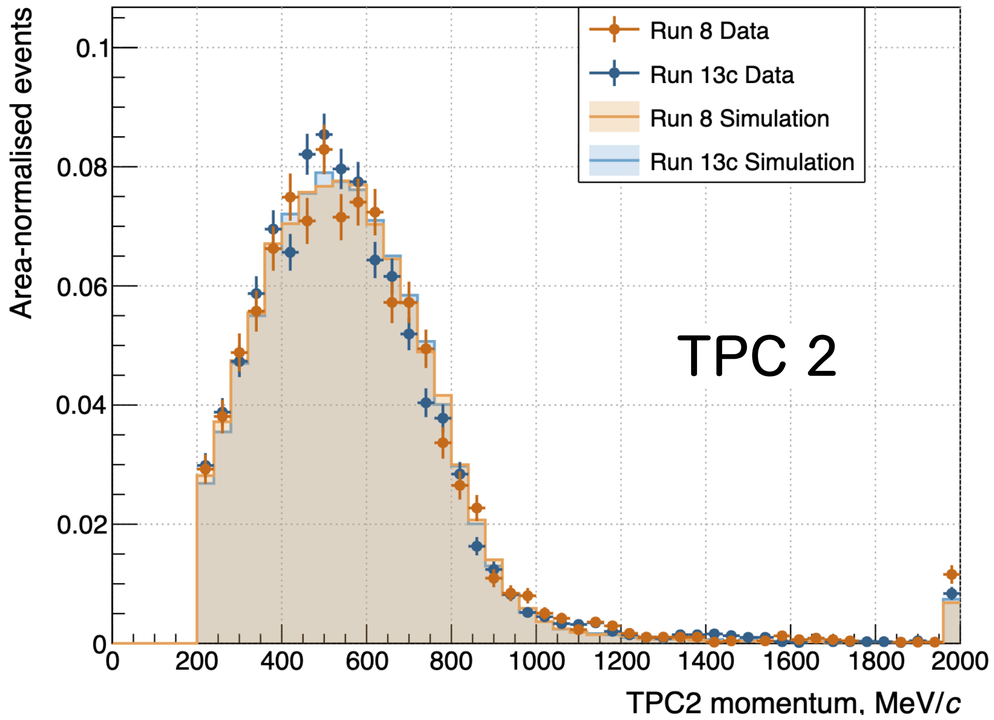


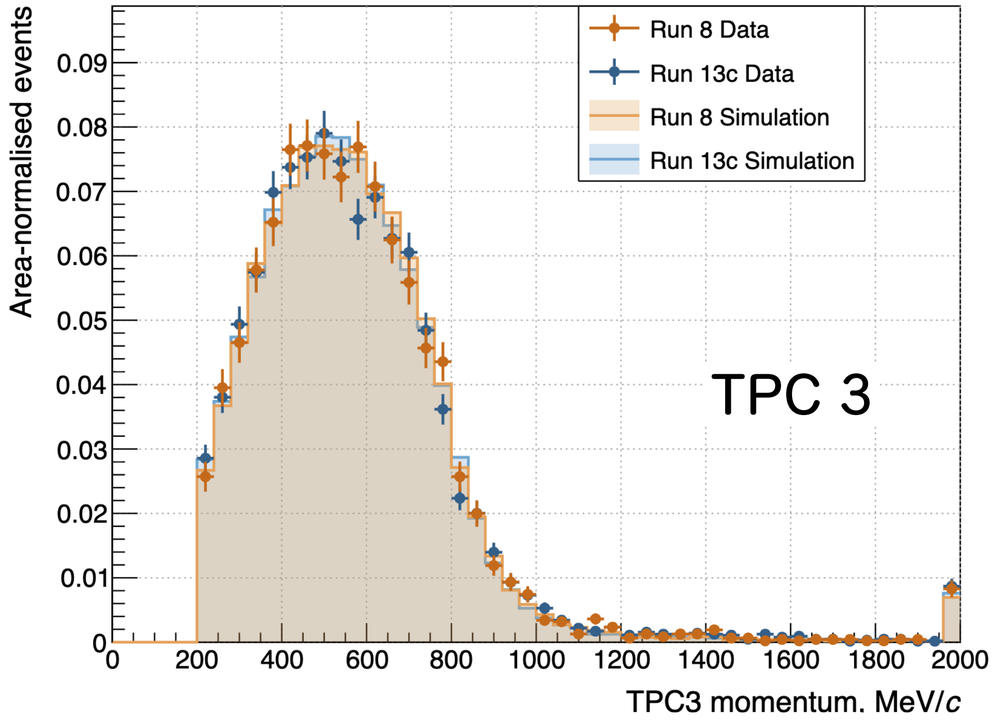
Proton candidates — **Momentum**

Start in FGD1/FGD2/TECAL/PECAL
and in P0D (Run 8)/ SFGD or HAT (Run 13c)

1. Track momentum > 200 MeV
2. Measured dE/dx > 700 MeV



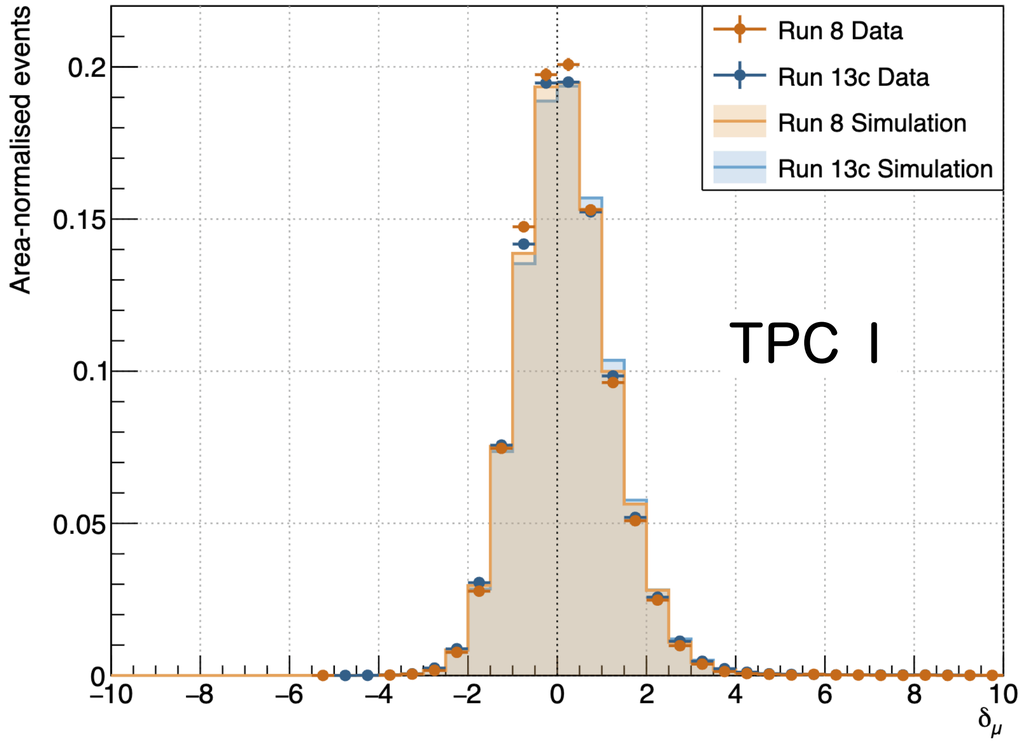


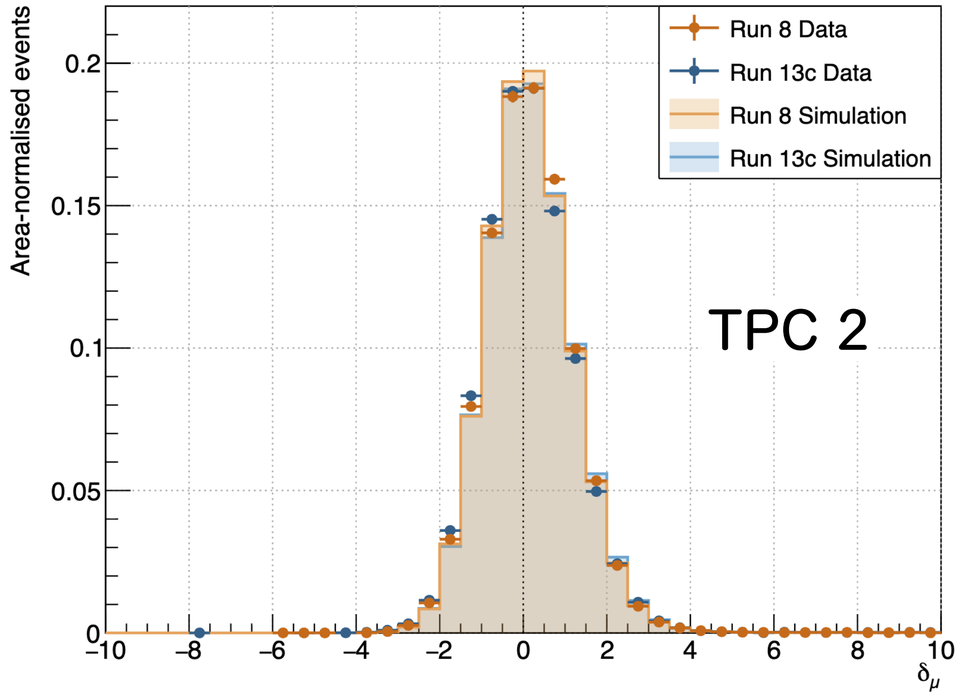


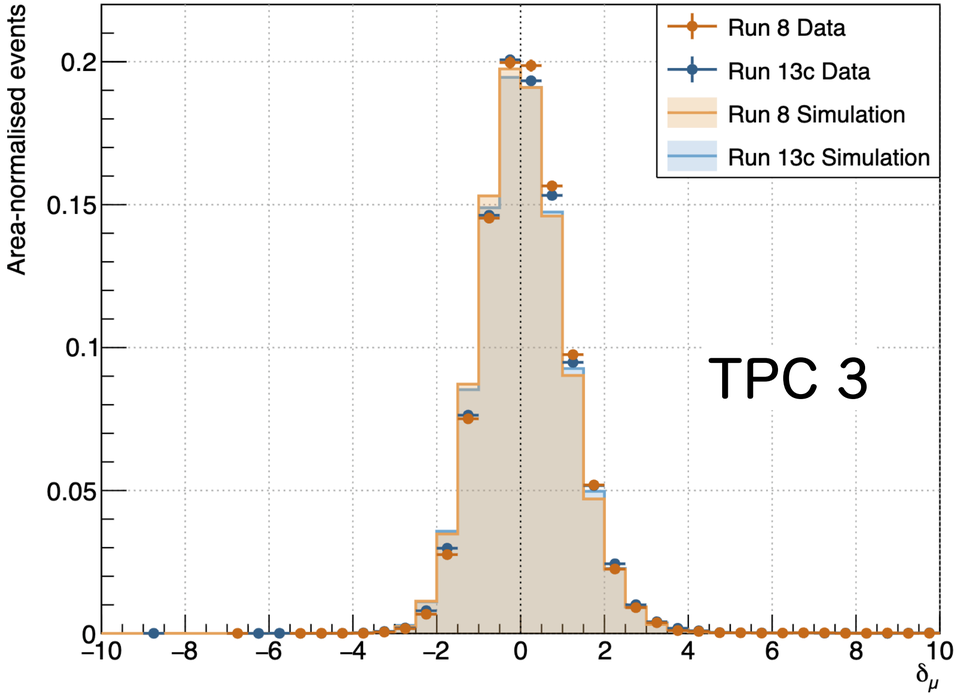
28

Muon candidates — **Pull**

1. Track reconstructed in all three TPCs
2. Track quality: > 35 nodes in each TPC segment
3. One track per bunch
4. Track momentum > 100 MeV/c



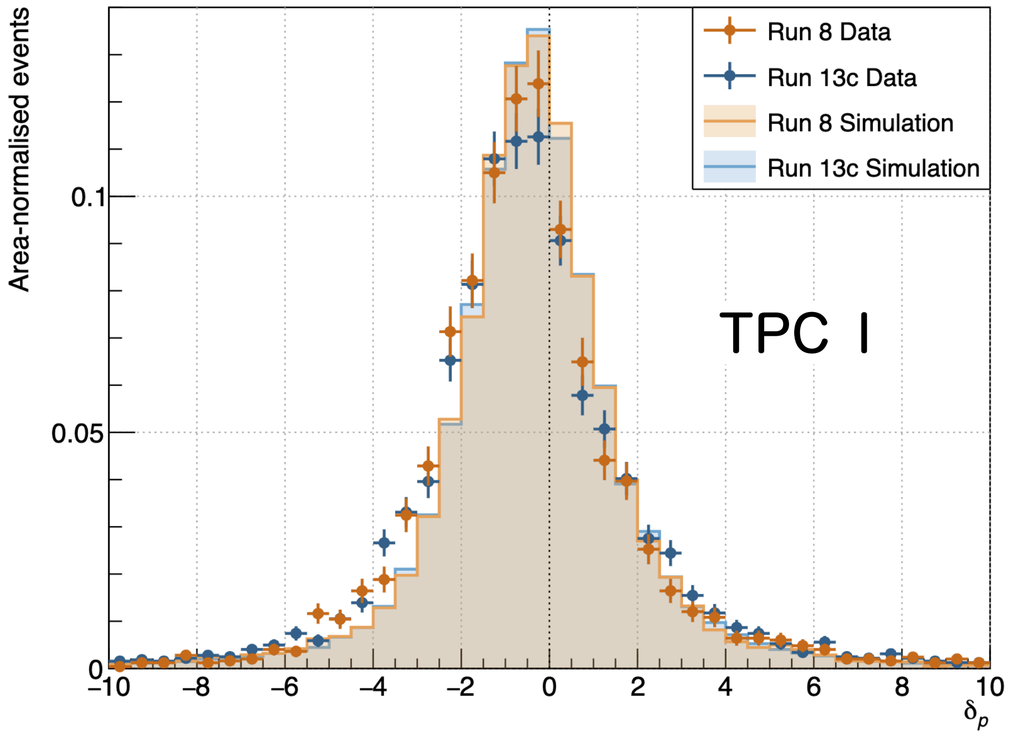


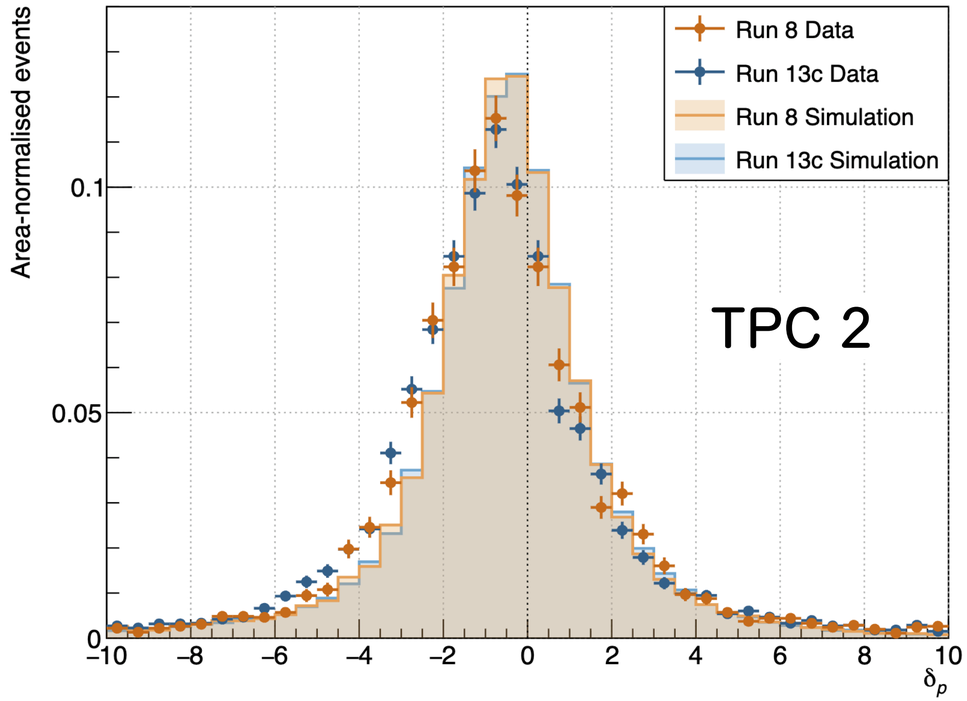


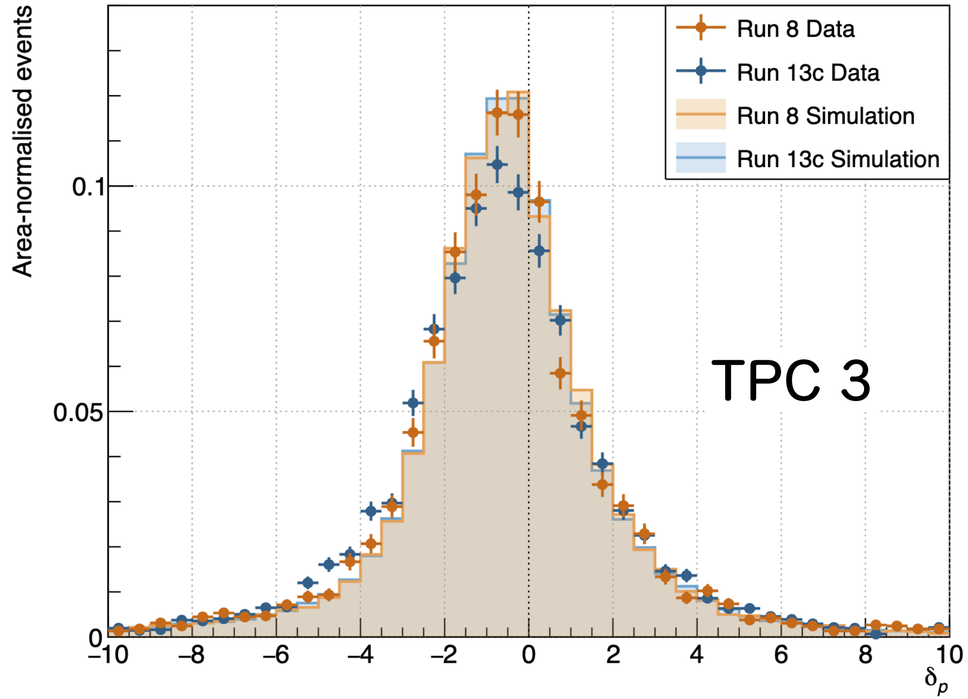
Proton candidates — **Pull**

Start in FGD1/FGD2/TECAL/PECAL
and in P0D (Run 8)/ SFGD or HAT (Run 13c)

1. Positive-charge candidate
2. Use the closest TPC segment
3. Track momentum > 200 MeV
4. Measured dE/dx > 700 a.u.



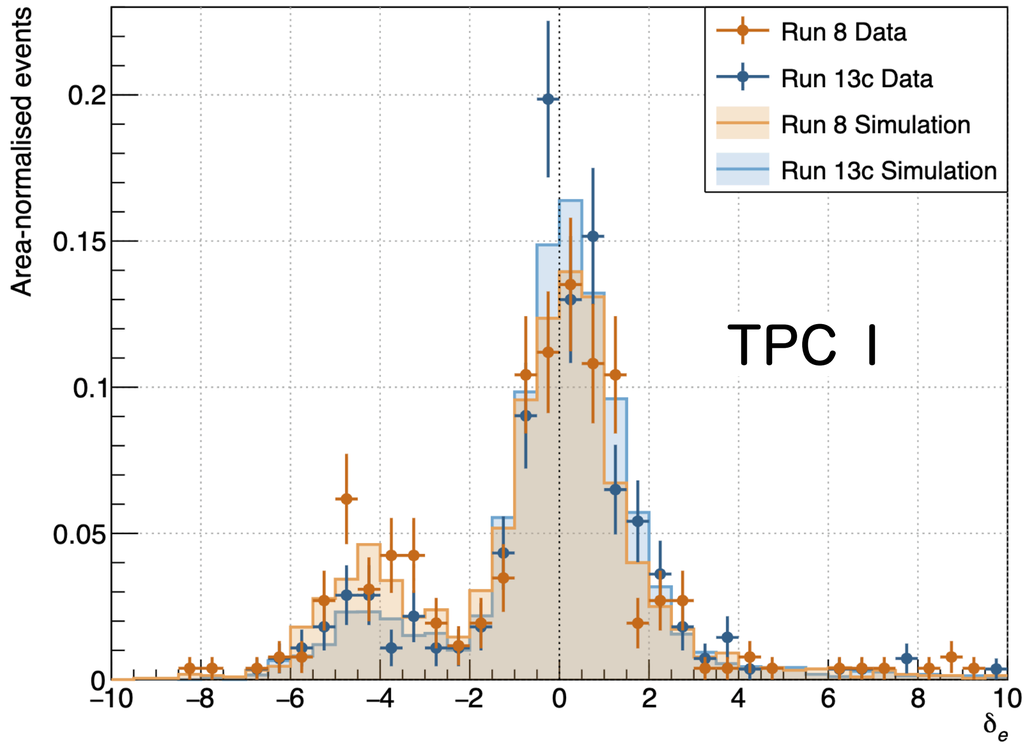


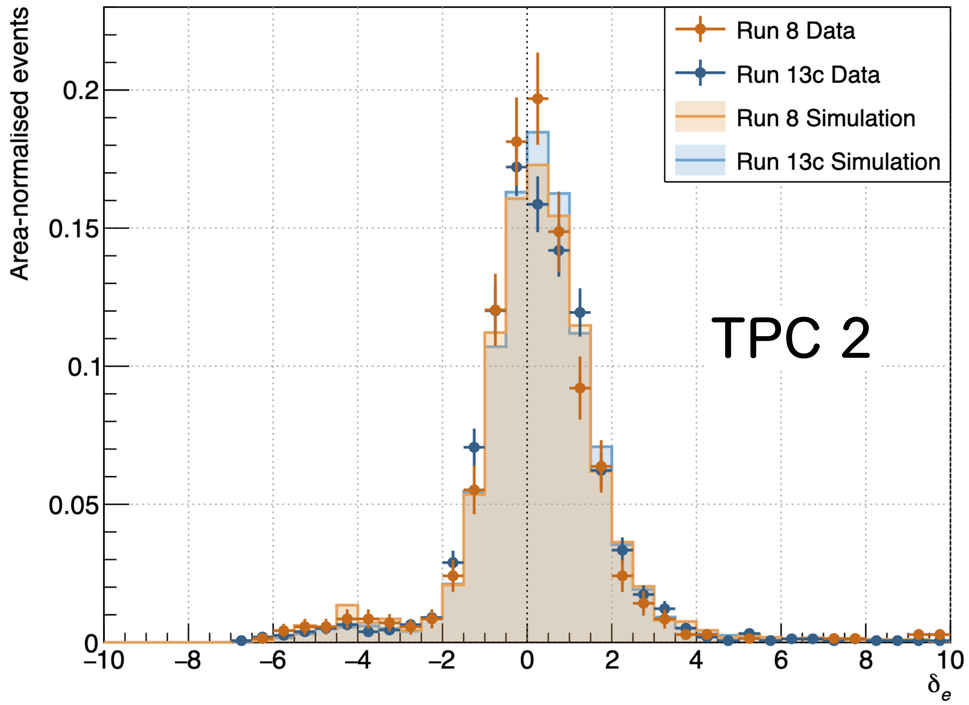


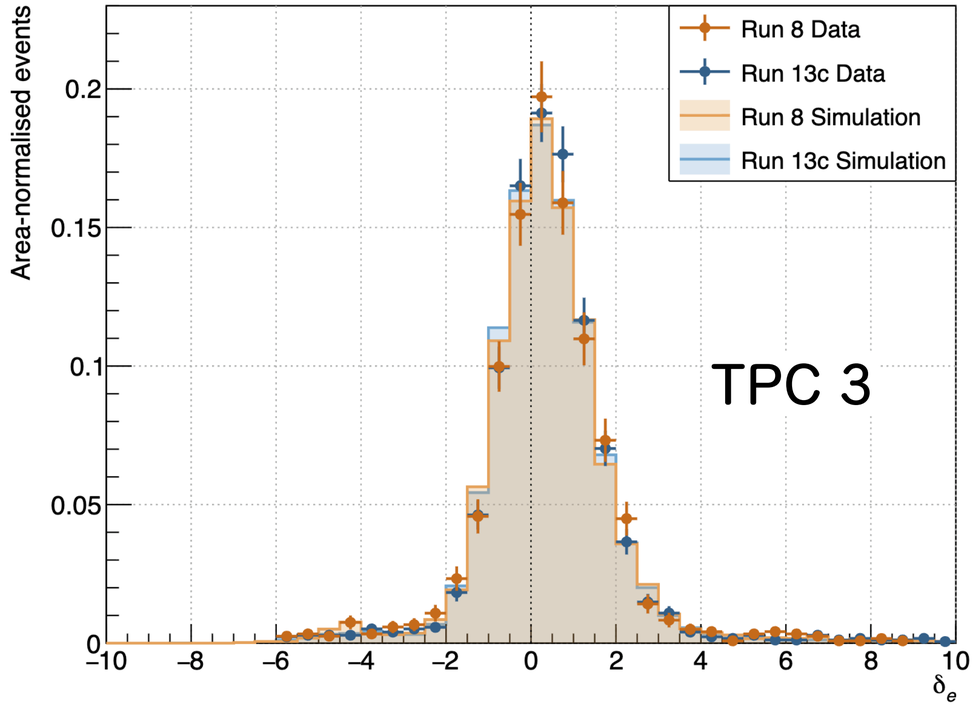
Electron candidates — **Pull**

Start in FGD1/FGD2/TECAL/PECAL
and in P0D (Run 8)/ SFGD or HAT (Run 13c)

1. Pairs of e^+e^- from γ - conversion
2. Distance between the starting points of the tracks < 100 mm
3. Reconstructed invariant mass < 50 MeV/c^2

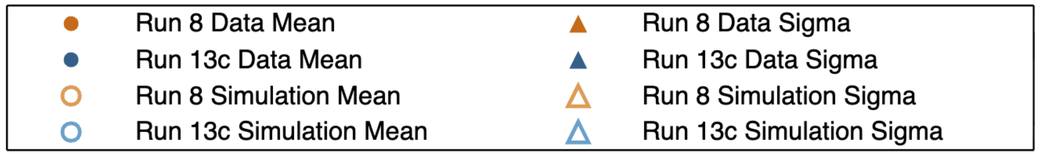


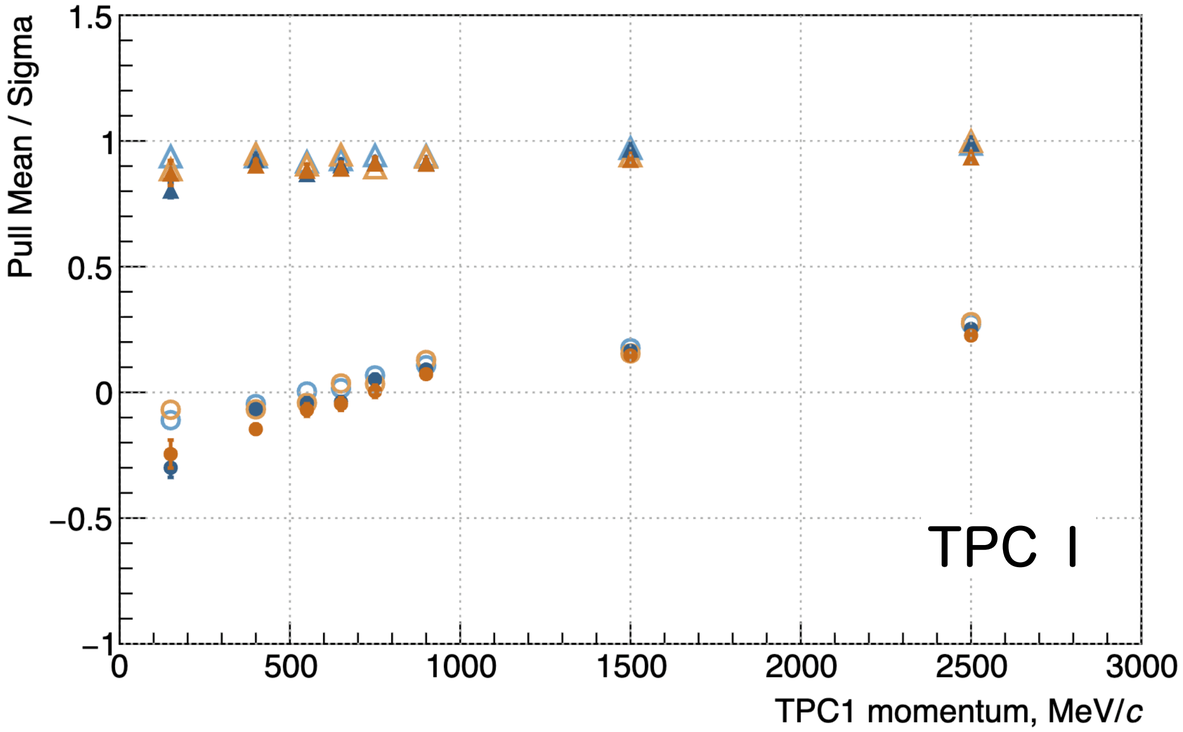


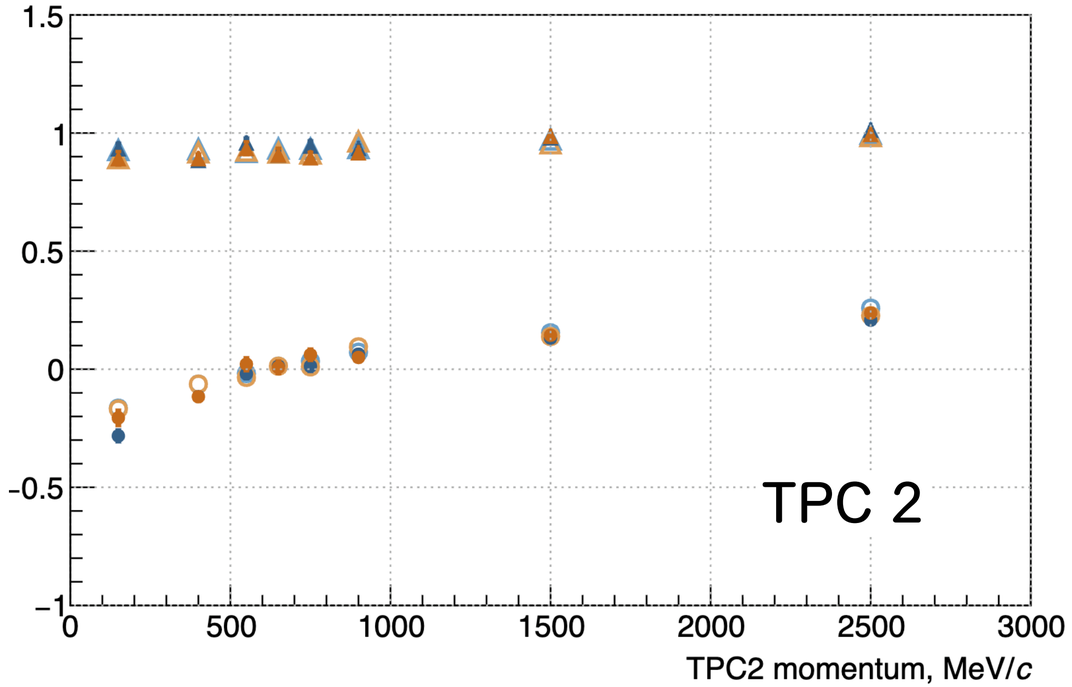


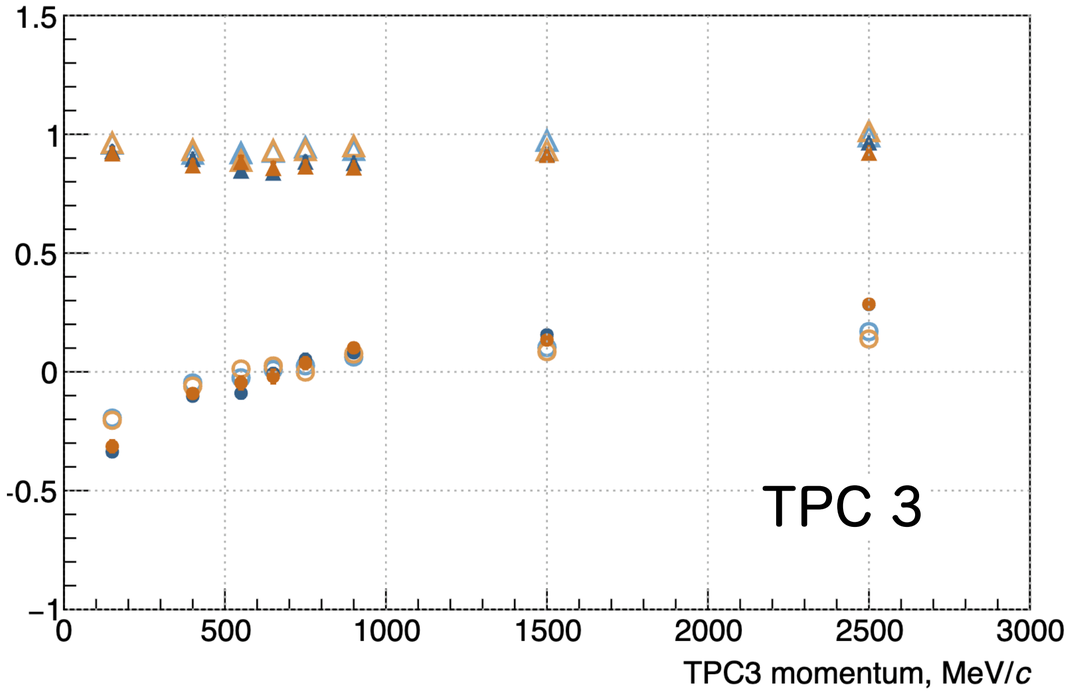
Muon candidates — **Pull**

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2. Track quality: > 35 nodes in each TPC segment
3. One track per bunch
4. Track momentum > 100 MeV/c









Proton candidates — **Pull**

Start in FGD1/FGD2/TECAL/PECAL
and in P0D (Run 8)/ SFGD or HAT (Run 13c)

1. Track momentum > 200 MeV
2. Measured dE/dx > 700 MeV

