Сессия-конференция СЯФ ОФН РАН
«Физика фундаментальных взаимодействий»

Оценка неопределенностей, связанных с идентификацией частиц во время-проекционных камерах ближнего детектора ND280 эксперимента T2K

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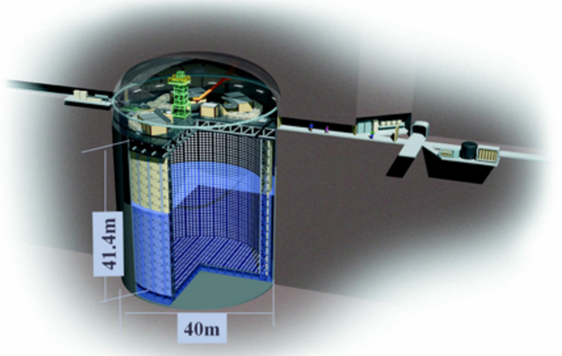
Эксперимент T2K (“Tokai to Kamioka”)

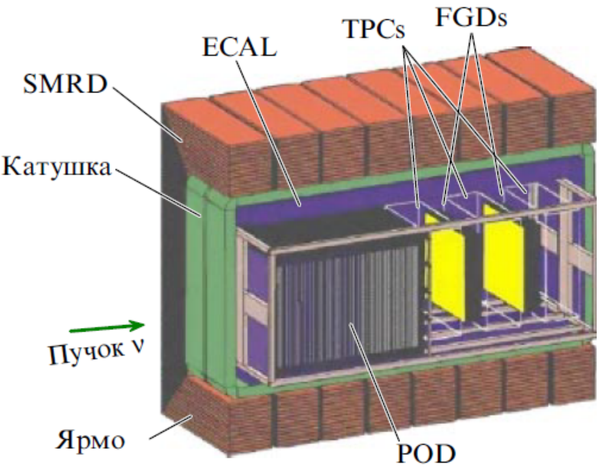
Цели эксперимента:

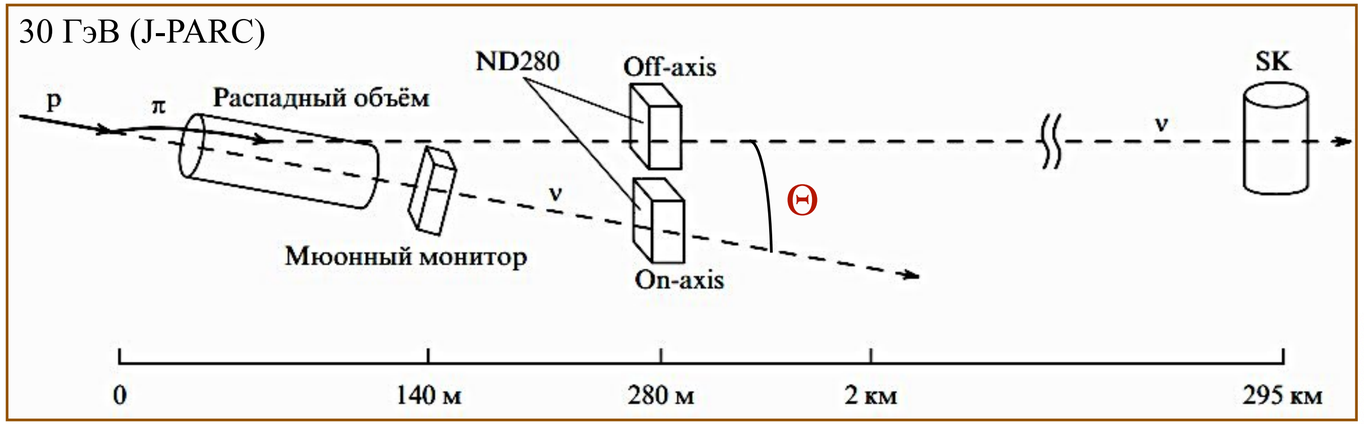
- измерение параметров осцилляций на пучке $\nu_\mu(\bar{\nu}_\mu)$;
- поиск CP-нарушения в нейтринном секторе, измерение δ_{CP}

Супер-Камиоканде

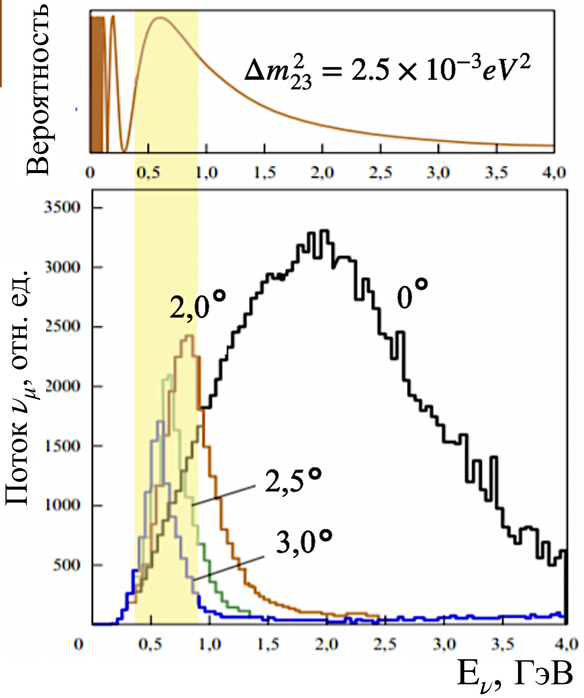


Ближний off-axis ν-детектор (ND280)



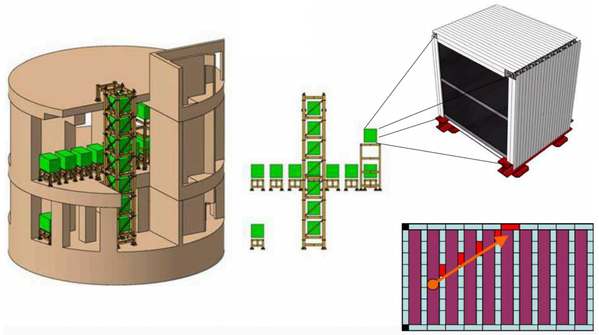


Off –axis ν-пучок



$$\Theta = 2.5^\circ \rightarrow E_\nu^{peak} = 0.6 \text{ ГэВ}$$

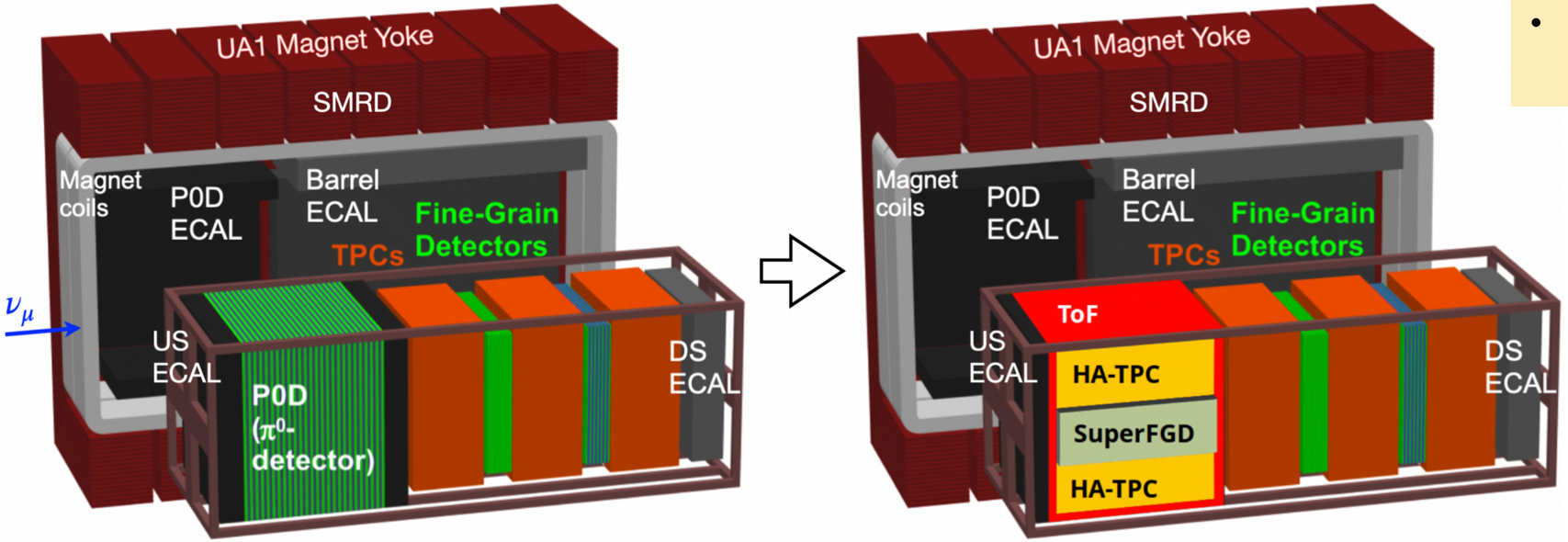
Монитор ν – пучка (INGRID)



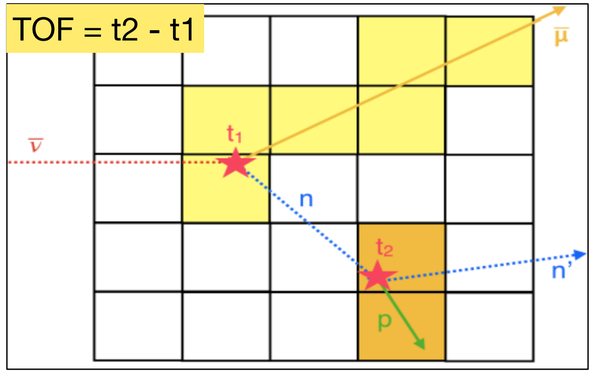
Задача: Снизить систематические погрешности осцилляционного анализа для повышения чувствительности к фазе CP-нарушения δ_{CP}

Детектор ND280.
Физическая мотивация модернизации

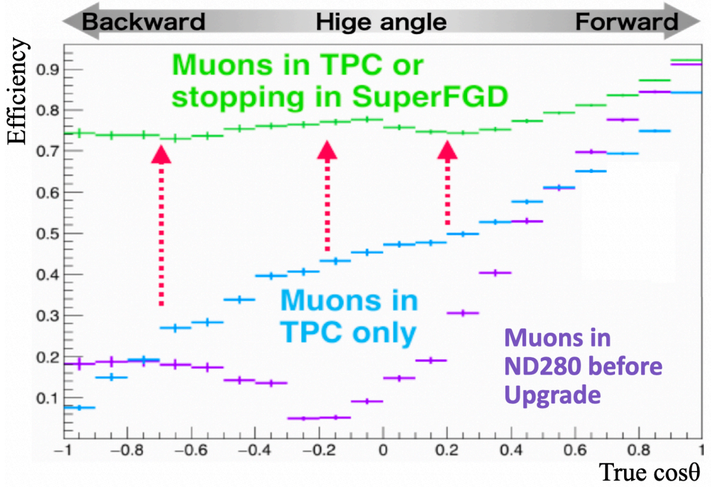
Новый трекер:
- 2 × High-Angle TPC (большой угол дет-я)
- 1 × SuperFGD (трековый детектор)
- 6 × Time-of-Flight (вето-система, триггер космических мюонов)



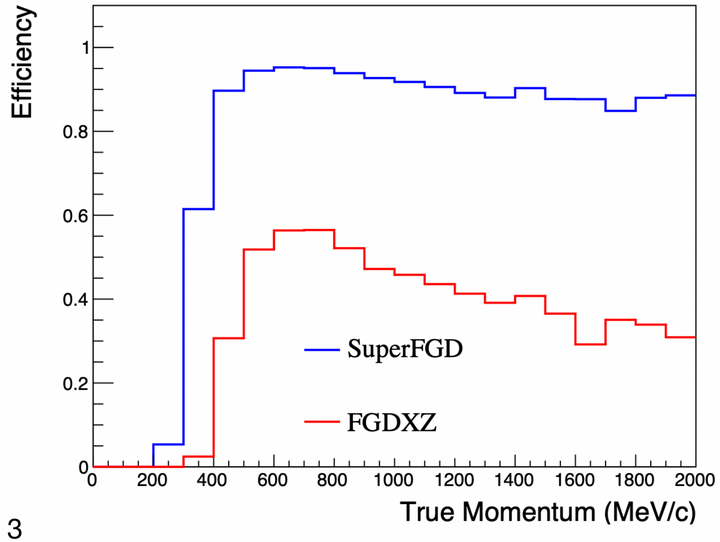
- Детектирование нейтронов:



- Детектирование заряженных частиц в 4π



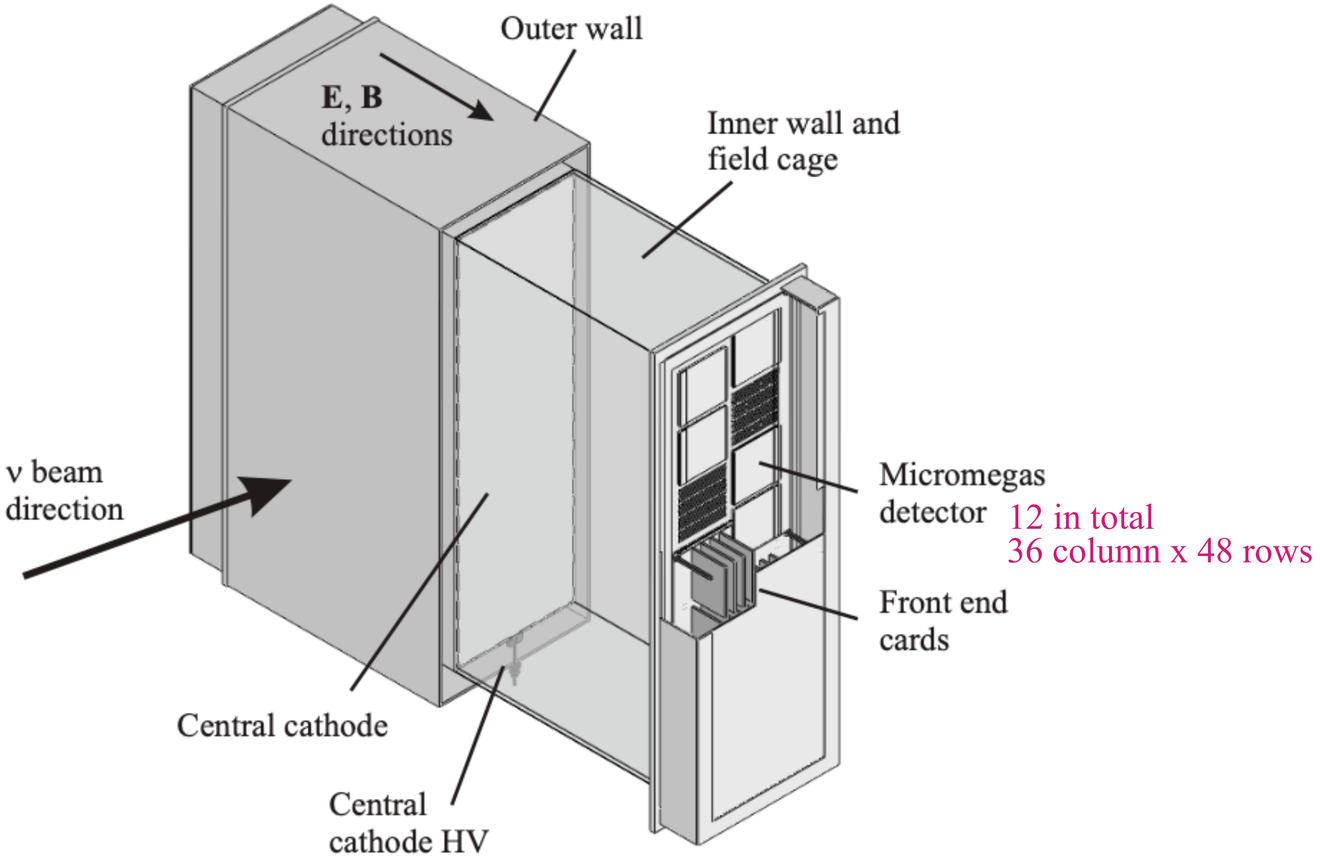
- Снижение порога регистрации протонов и пионов (~300 MeV/c)



- Разделение электронов и γ-квантов

Мотивация: снизить систематические неопределенности в T2K с 6-7% до 3-4%

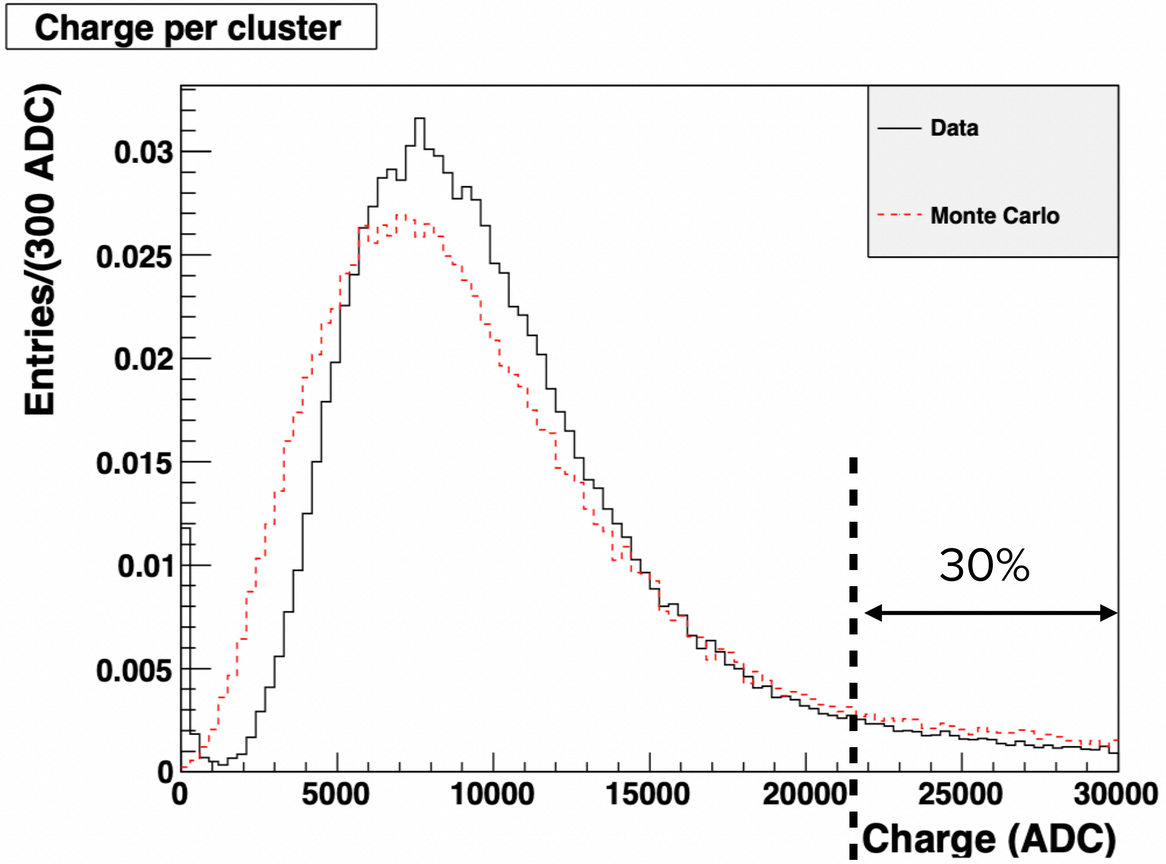
Идентификация частиц в TPC



Внешний объем: 2302 × 2400 × 974 мм
Внутренний объем: 1808 × 2230 × 854 мм

Пространственное разрешение ~0.7 мм
Энергетическое разрешение ~7-8%

Усеченное среднее dEdx для кластера:



Измерение pull для TPC

Pull:

$$\delta_i = \frac{dEdx^{meas} - dEdx_i^{exp}}{\sigma_i^{exp}}$$

i — мюон, протон, электрон

$dEdx^{meas}$ — измеренные потери энергии

$dEdx_i^{exp}$ — потери энергии, ожидаемые в предположении частицы определенного типа i (мюон, электрон или протон)

σ_i^{exp} — разрешение ожидаемых потерь энергии для частицы типа i

Калибровка $dEdx^{meas}$ (коррекция для данных)

- Калибровка выполняется для каждой TPC и для каждого Run
- Контрольные образцы — мюоны, проходящие через три TPC
- Эталонное значение — dEdx для TPC2 из Монте-Карло моделирования
- Диапазон импульсов мюонов: 700 MeV/c < p_μ < 1 GeV/c

$$corr(i,j) = \frac{dEdx^{DT}(\,i, TPC_j)}{dEdx^{MC}(TPC_2)}\ ,$$

i – Run 13c
j – TPC index

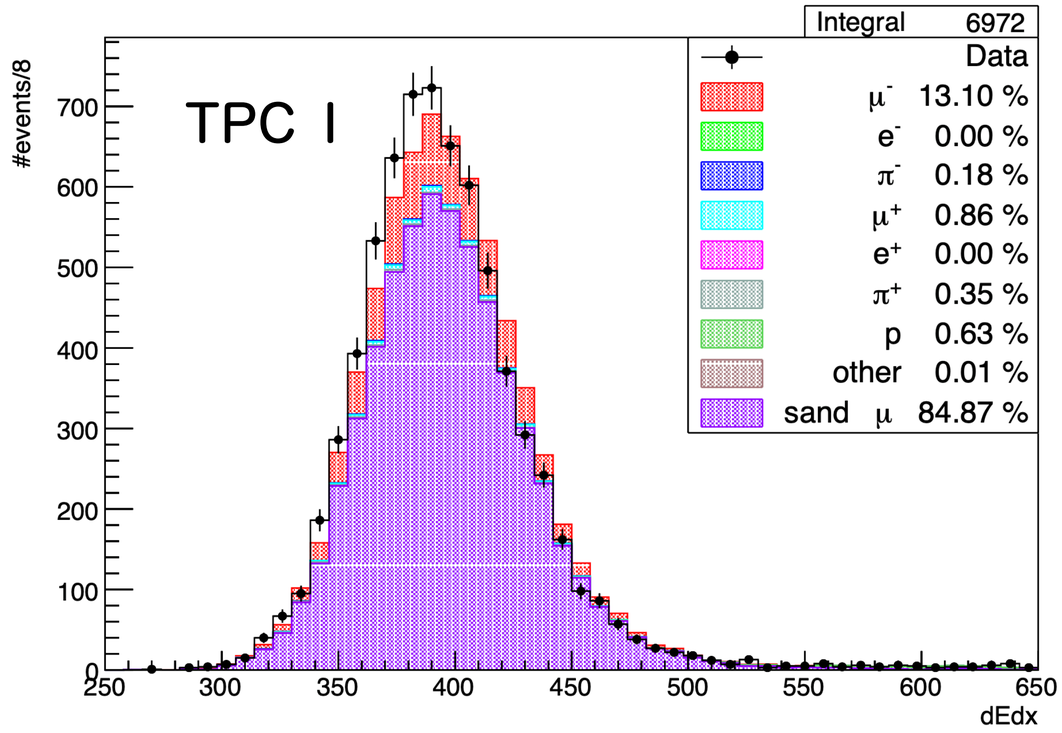
$$dEdx^{corr} = \frac{dEdx^{DT}(i, TPC_j)}{corr(i,j)}$$

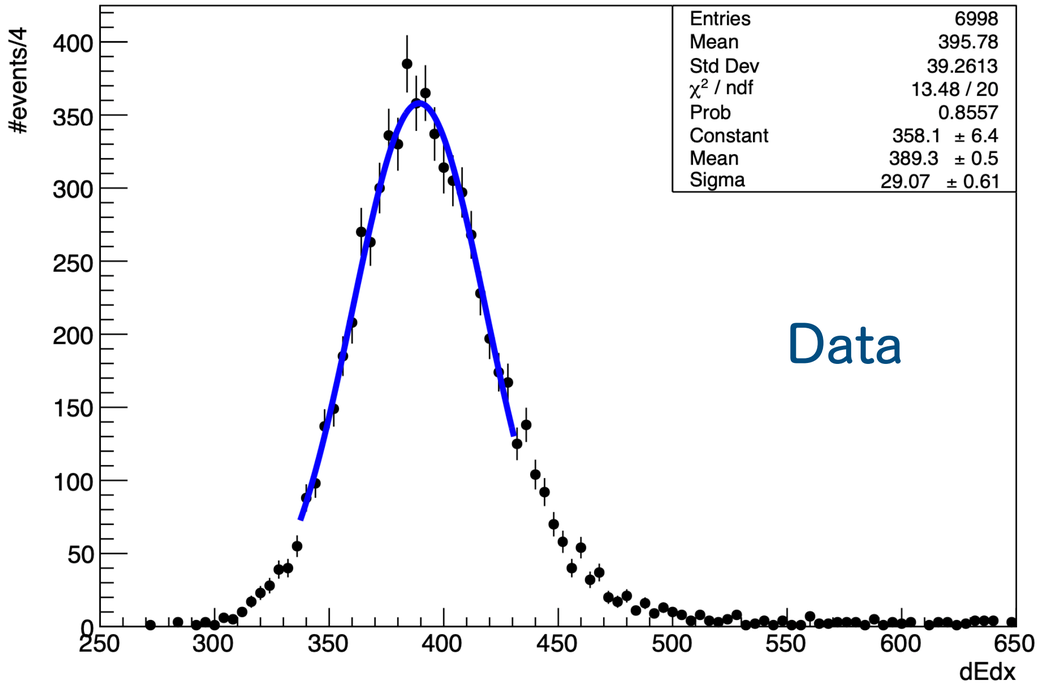
Package: tpcPIDSystematics
Highland2Master: 4.38.1
ND280: release_14.39
MC: FHC_P8_V17
Data: FHC_P8_V17

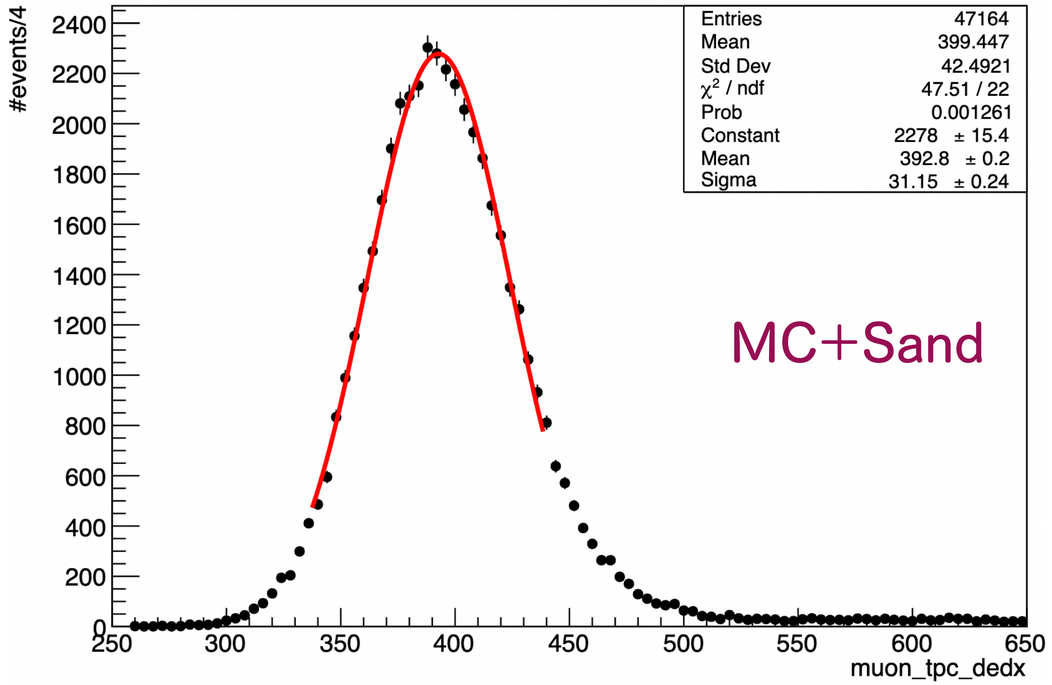
Мюоны. dEdx

MC vs Data

- 700 MeV/c < p_μ < 1 GeV/c





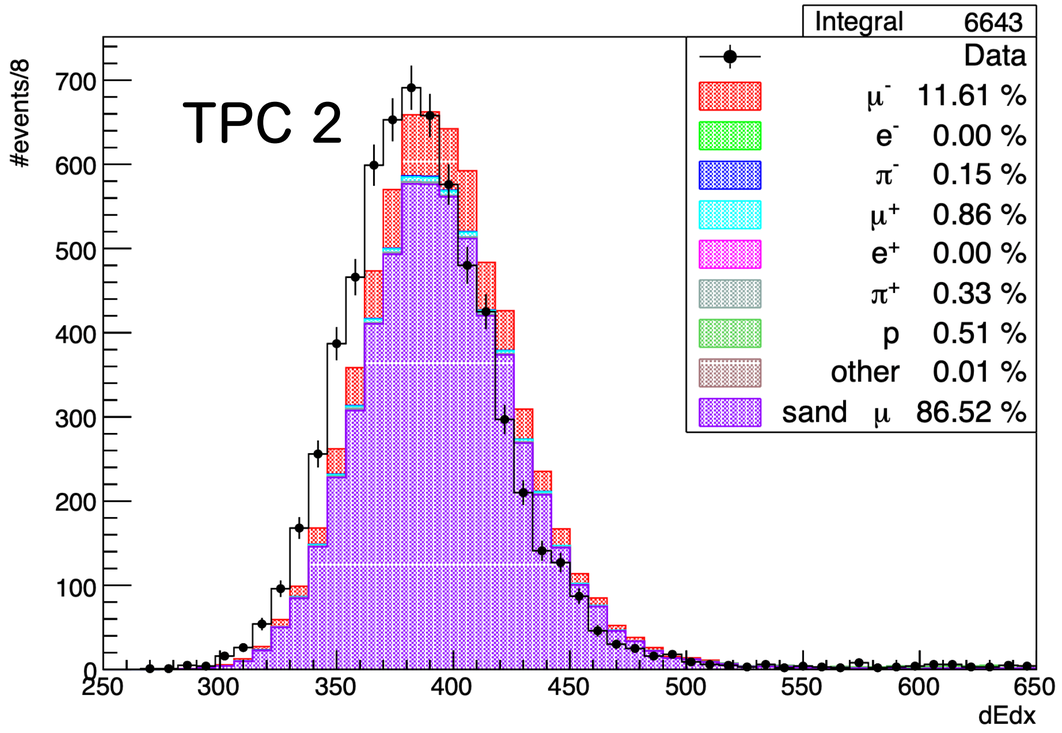


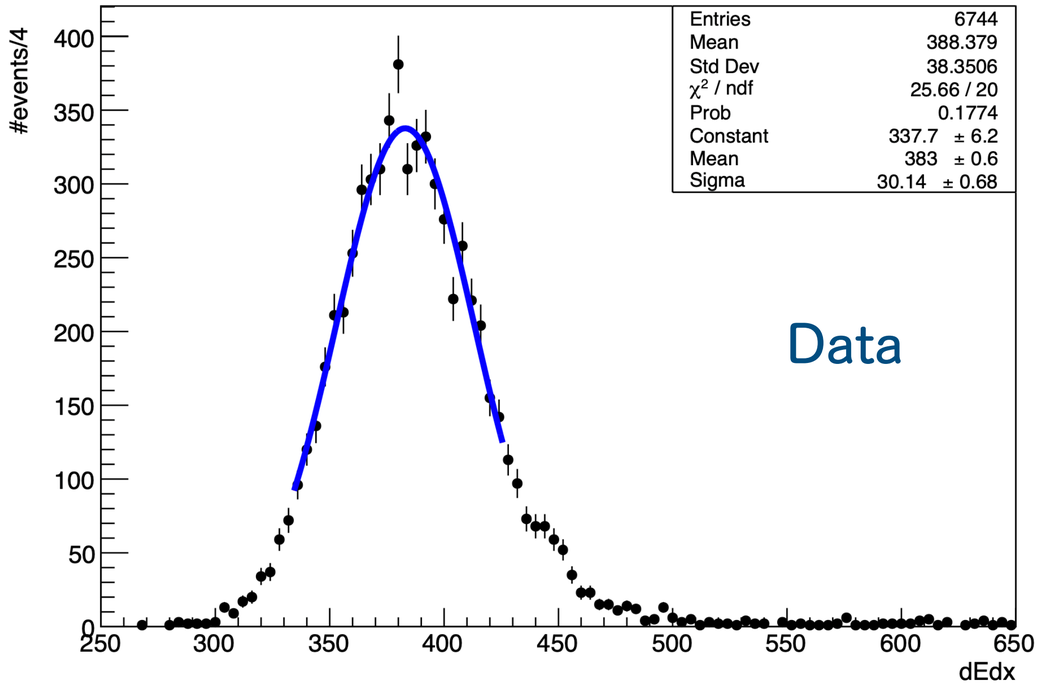
Package: tpcPIDSystematics
Highland2Master: 4.38.1
ND280: release_14.39
MC: FHC_P8_V17
Data: FHC_P8_V17

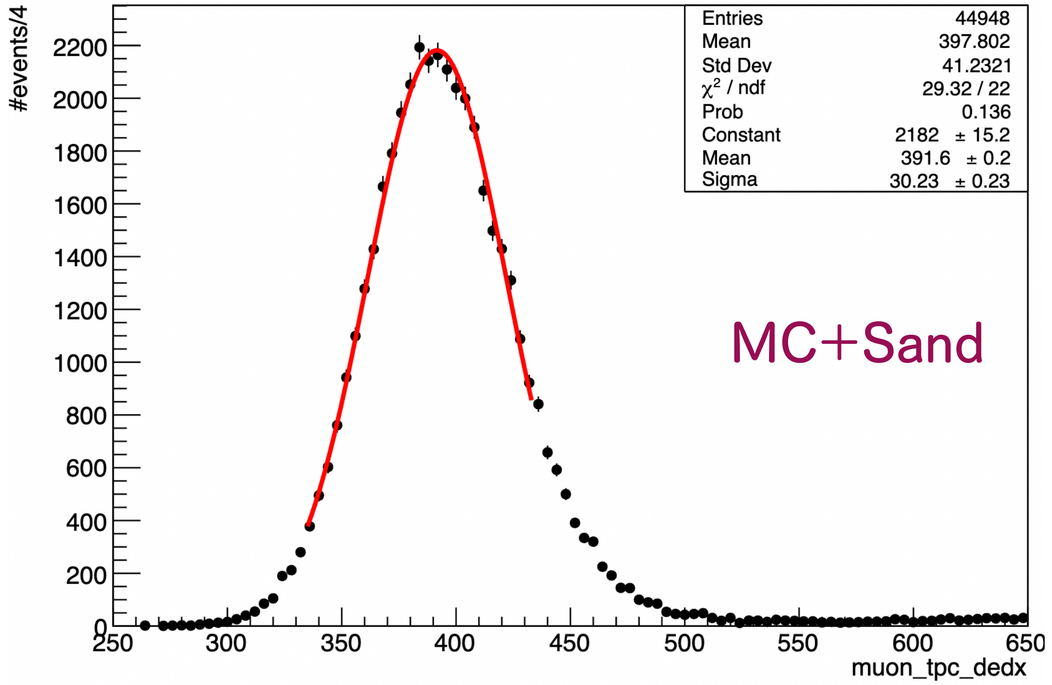
Мюоны. dEdx

MC vs Data

- 700 MeV/c < p_μ < 1 GeV/c





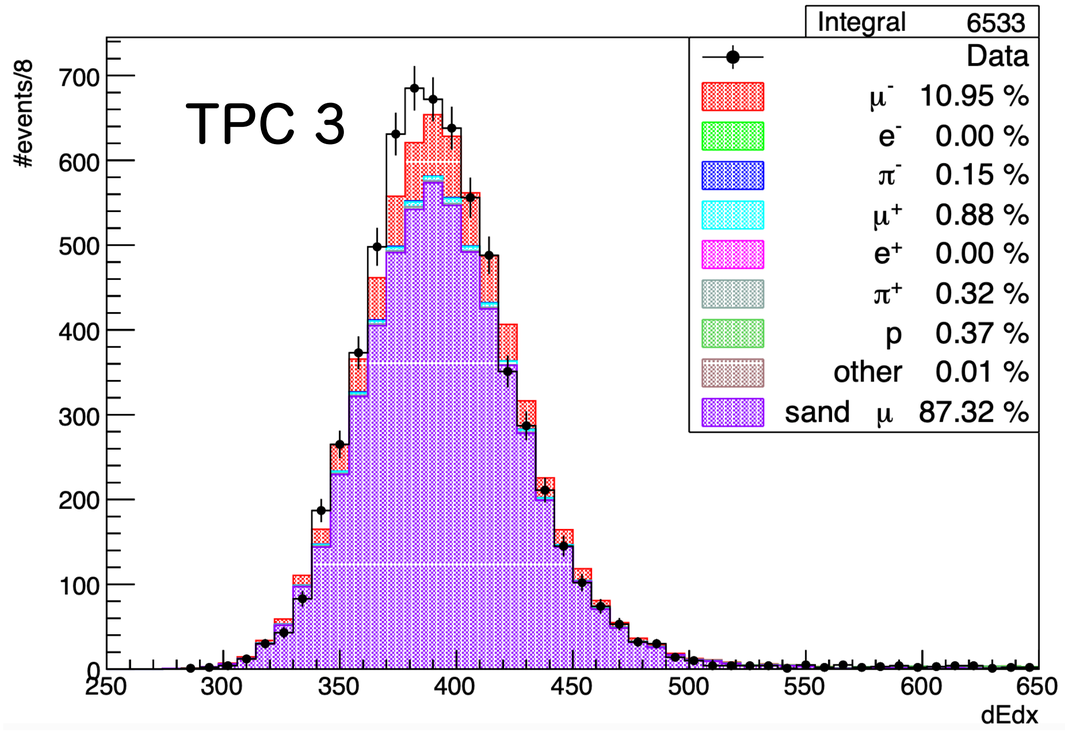


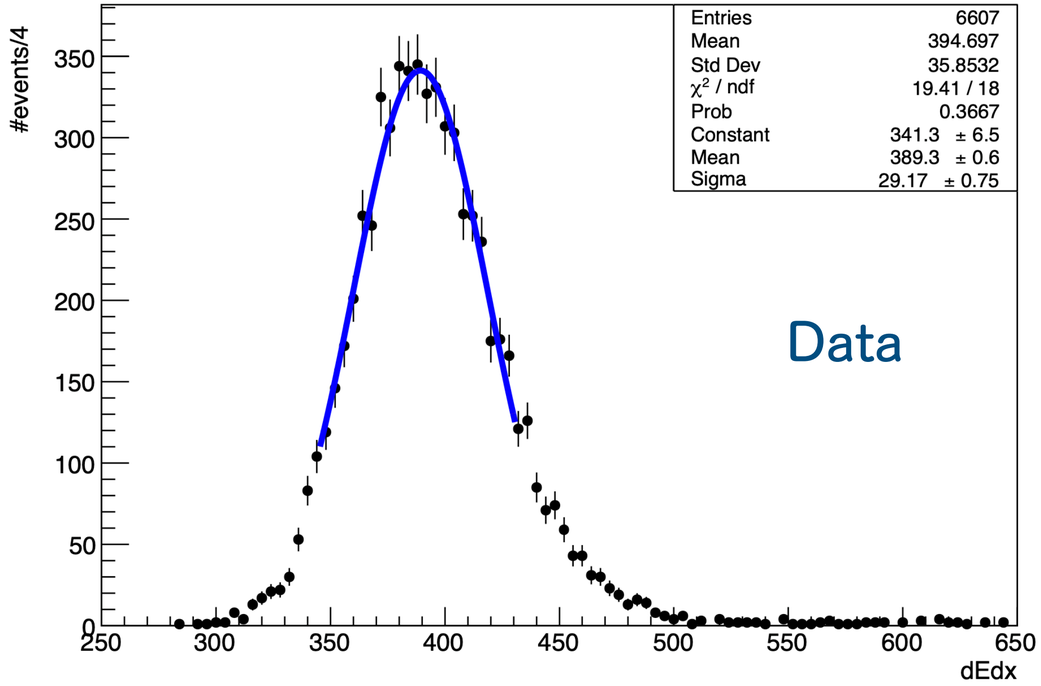
Package: tpcPIDSystematics
Highland2Master: 4.38.1
ND280: release_14.39
MC: FHC_P8_V17
Data: FHC_P8_V17

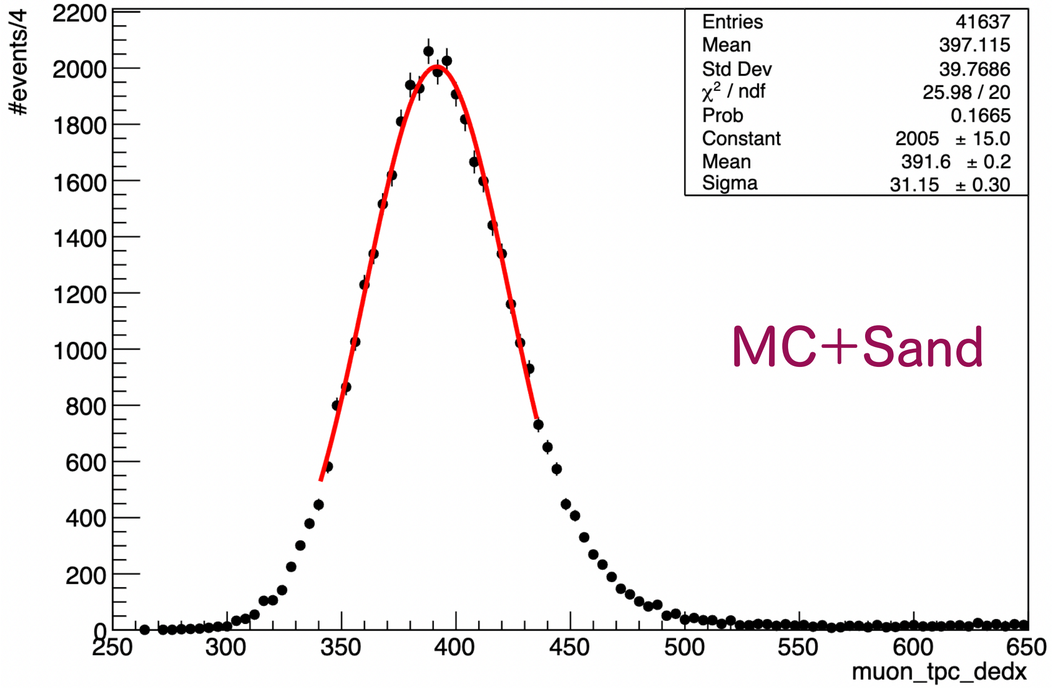
Мюоны. dEdx

MC vs Data

- 700 MeV/c < p_μ < 1 GeV/c



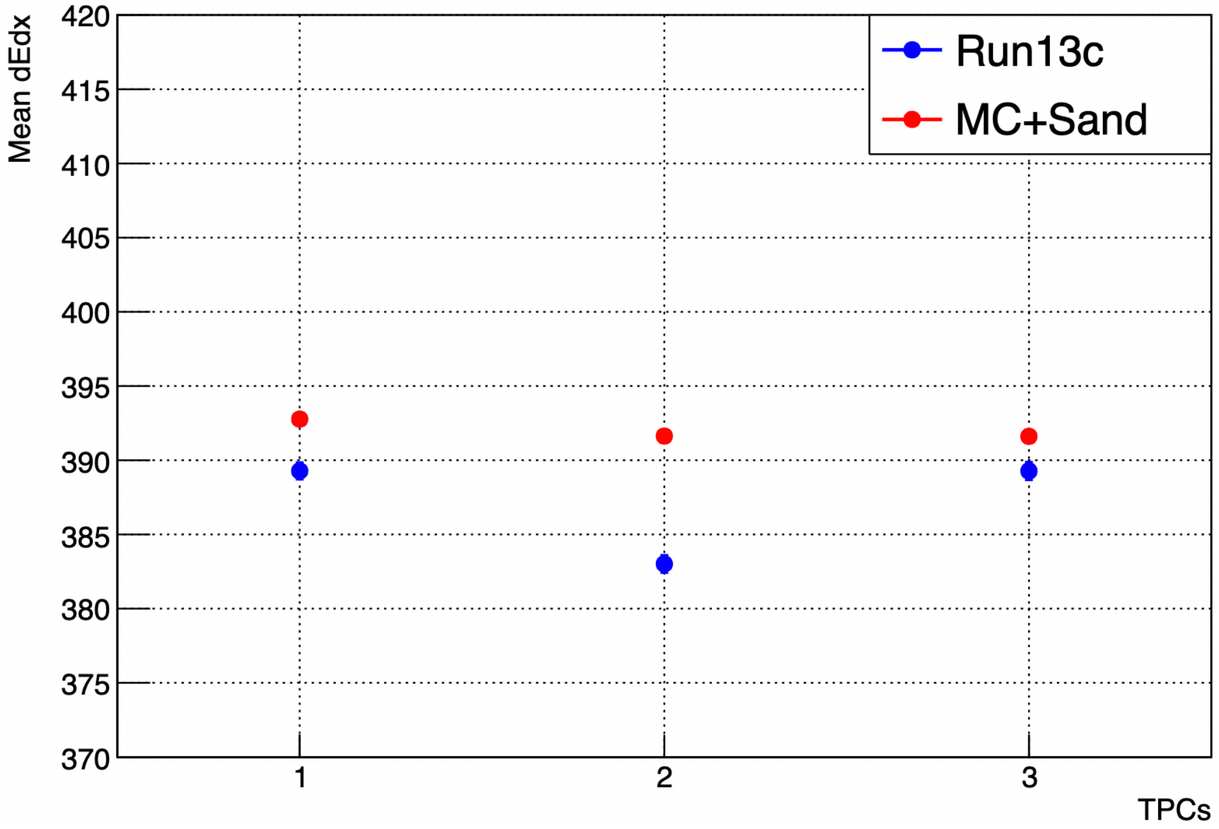


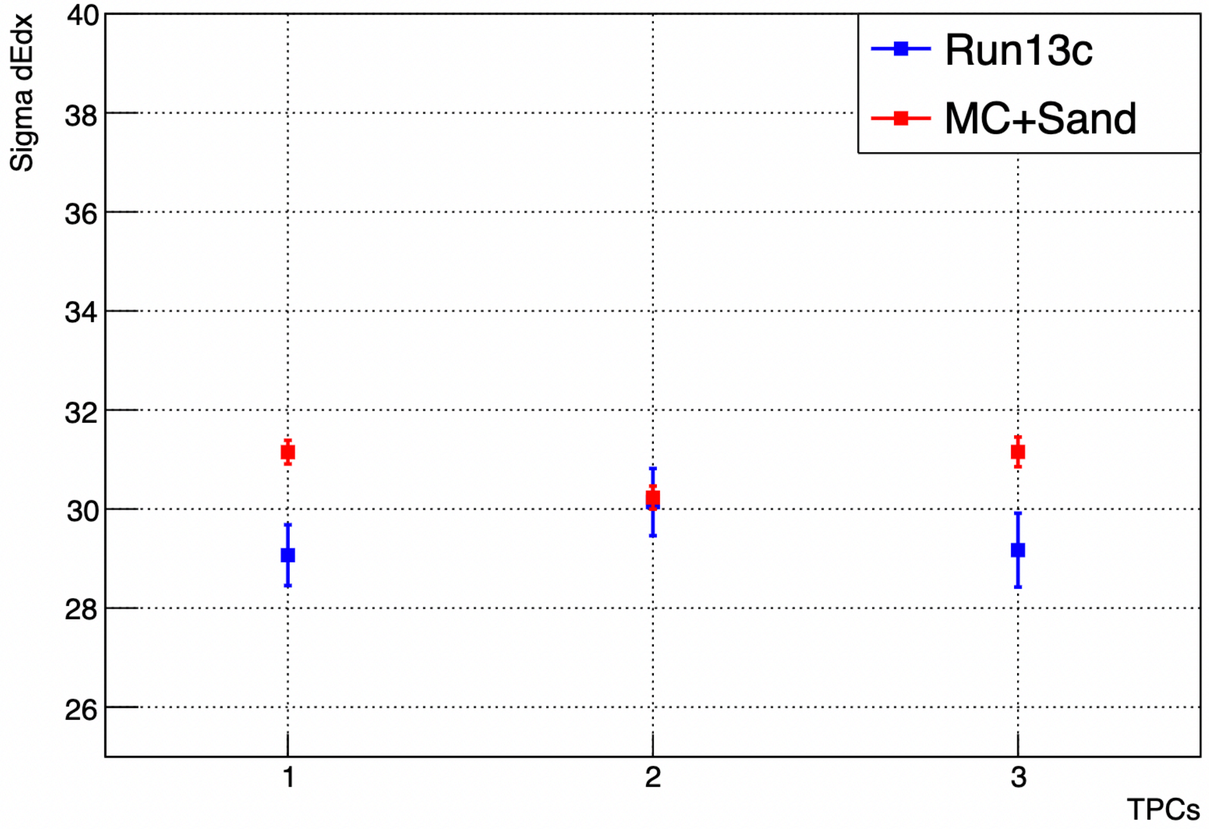


Package: tpcPIDSystematics
Highland2Master: 4.38.1
ND280: release_14.39
MC: FHC_P8_V17
Data: FHC_P8_V17

Калибровка $dEdx^{meas}$

MC vs Data





Package: tpcPIDSystematics
Highland2Master: 4.38.1
ND280: release_14.39
MC: FHC_P8_V17
Data: FHC_P8_V17

Калибровка $dEdx^{meas}$

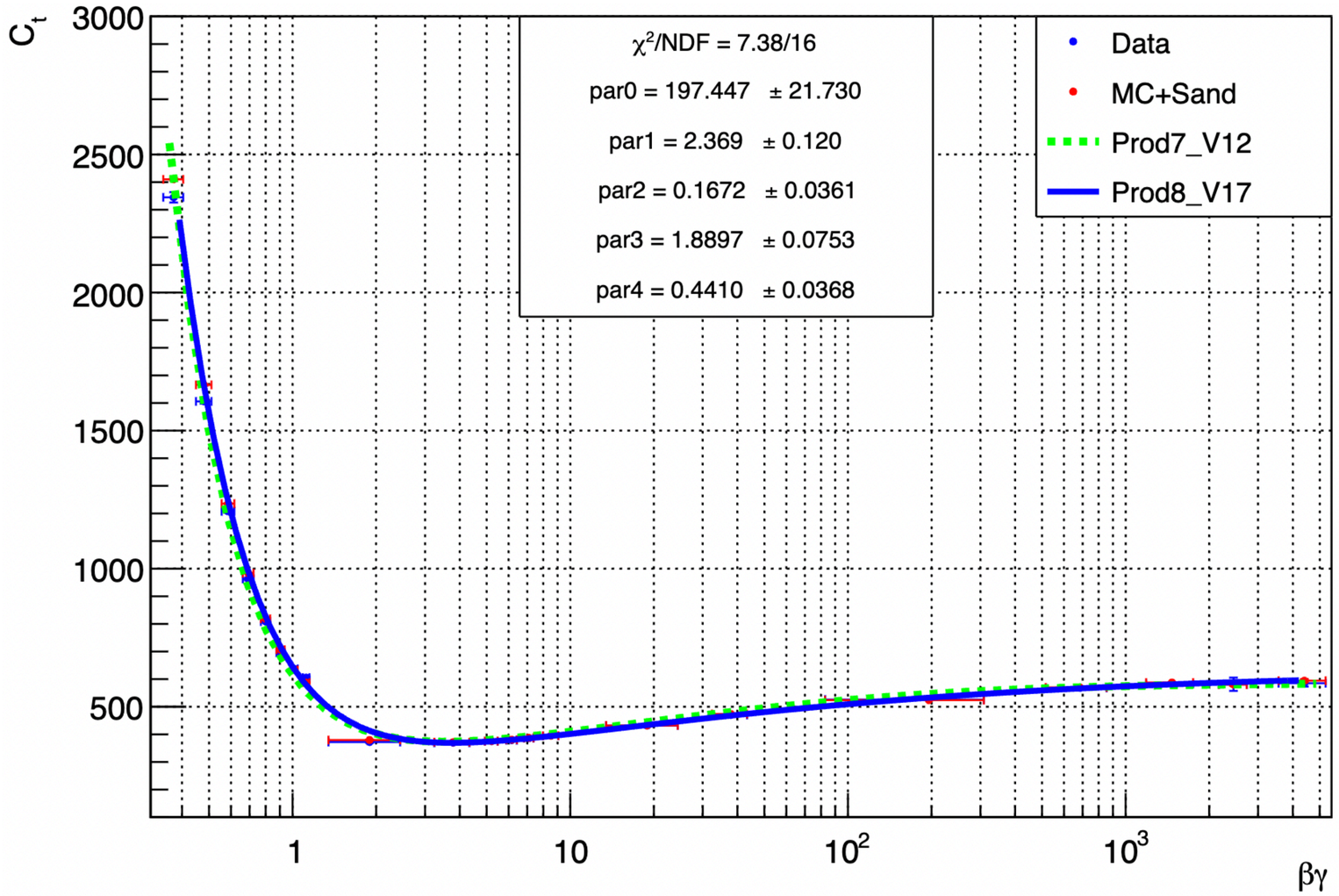
MC vs Data

$$dEdx^{corr} = \frac{dEdx^{DT}(i, TPC_j)}{corr(i,j)}$$

		TPC1	TPC2	TPC3
MC+Sand	Mean	392.77 ± 0.21	**391.63 ± 0.22**	391.61 ± 0.24
	Sigma	31.1 ± 0.2	30.2 ± 0.2	31.2 ± 0.3
Run 13c	Mean	389.28 ± 0.53	383.01 ± 0.55	389.28 ± 0.56
	Sigma	29.1 ± 0.6	30.1 ± 0.7	29.2 ± 0.7
	Corr factor	**0.9940 ± 0.0015**	**0.9780 ± 0.0015**	**0.9940 ± 0.0015**
	Mean with corr	**391.63 ± 0.78**	**391.63 ± 0.83**	**391.63 ± 0.83**

Параметризация $dEdx^{exp}$ с использованием функции Бете-Блоха

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



P8_V17

χ^2 / ndf	7.38/16
p0	194.447 ± 21.730
p1	2.369 ± 0.120
p2	0.1672 ± 0.0361
p3	1.8897 ± 0.0753
p4	0.4410 ± 0.0368

P7_V12

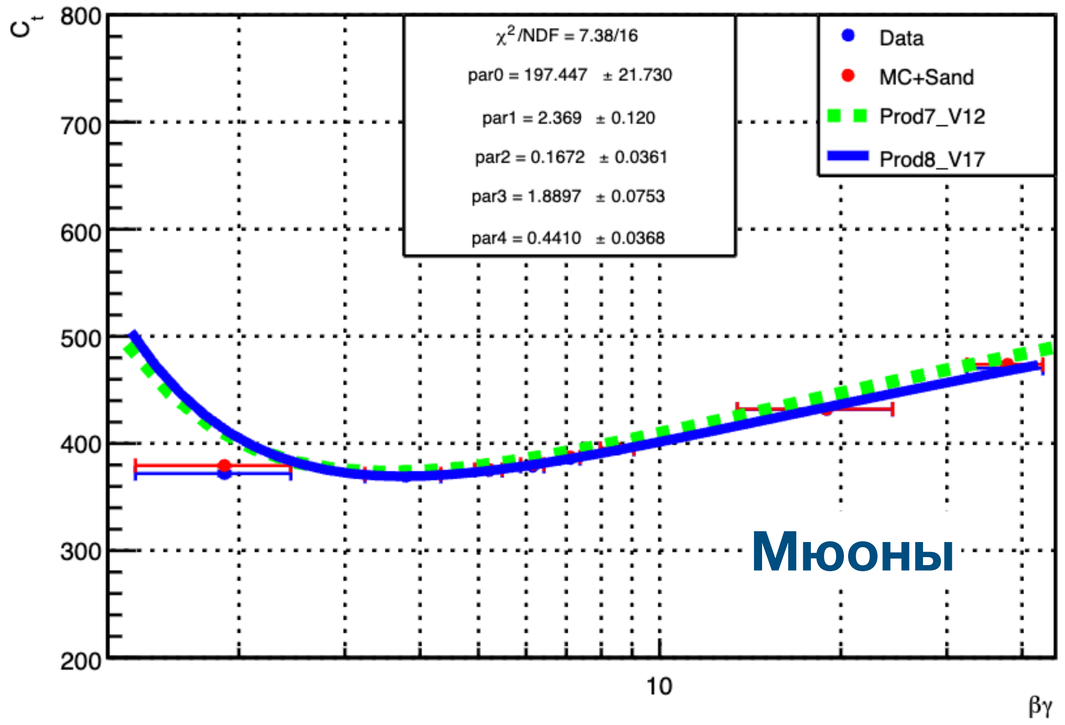
χ^2 / ndf	15.42 / 11
p0	77.47 ± 1.737
p1	4.286 ± 0.08613
p2	0.0138 ± 0.001297
p3	2.128 ± 0.08795
p4	0.8832 ± 0.02486

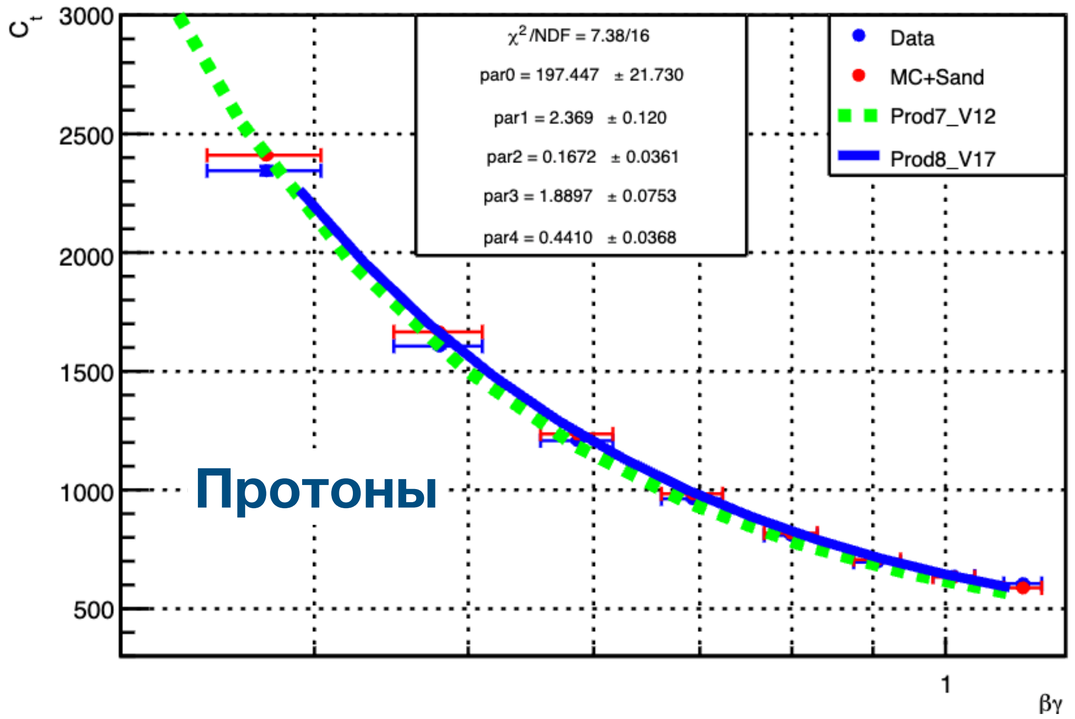
Параметризация dEdx^{Exp}

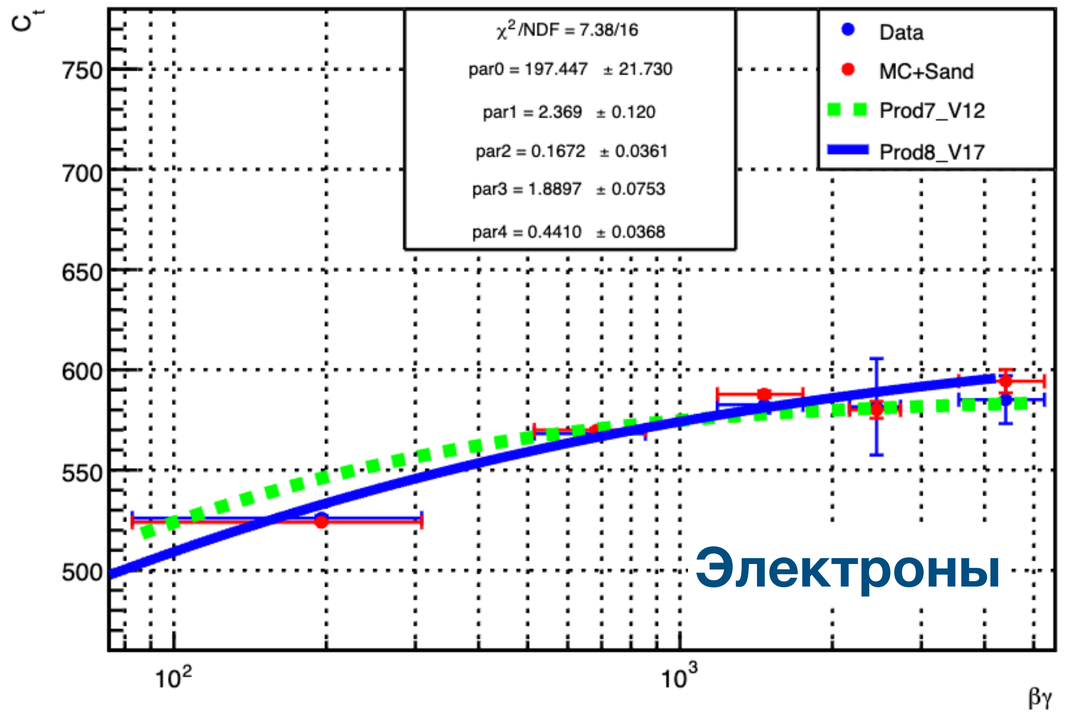
$$\mathrm{dEdx}^{\mathrm{exp}} = \frac{p_0}{\beta^{p_3}} \cdot \left\{ p_1 - \beta^{p_3} - \log\left[p_2 + \frac{1}{(\beta\gamma)^{p_4}} \right] \right\}$$

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

$$\sigma^{(i)}_{dEdx} = \Delta\mu^{(i)}_{fit},$$



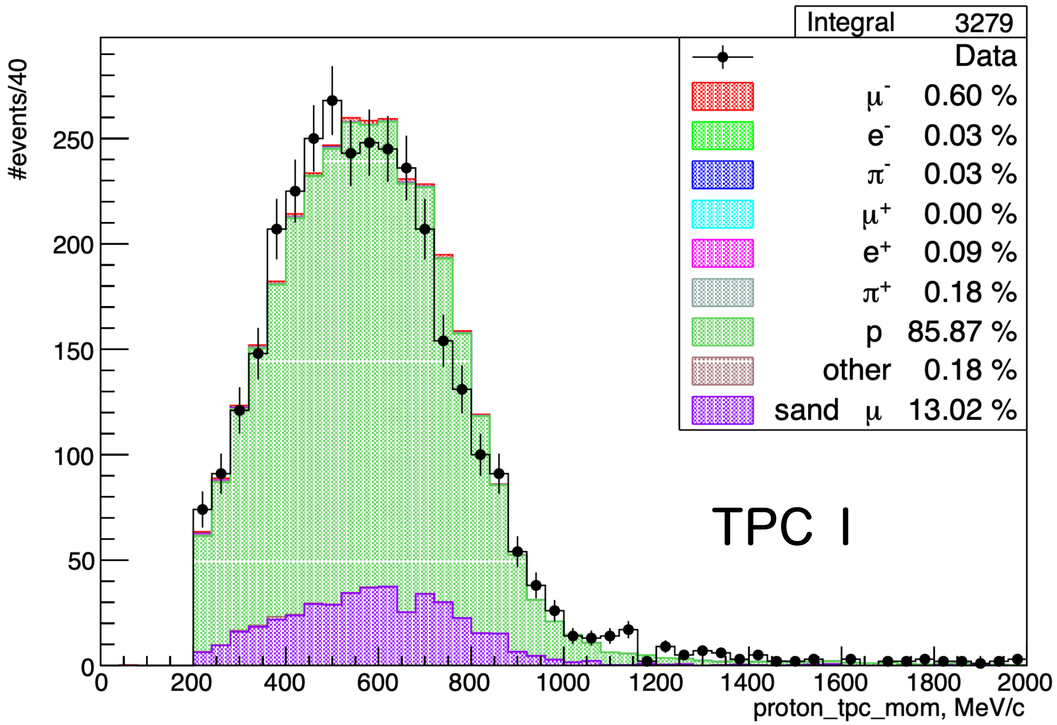


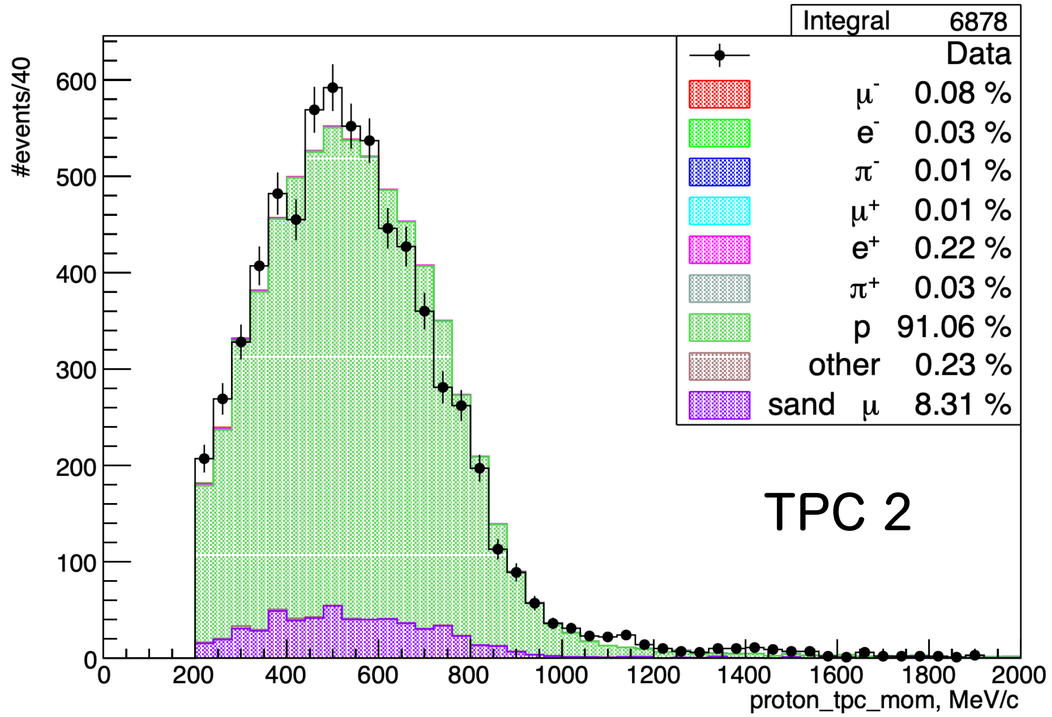


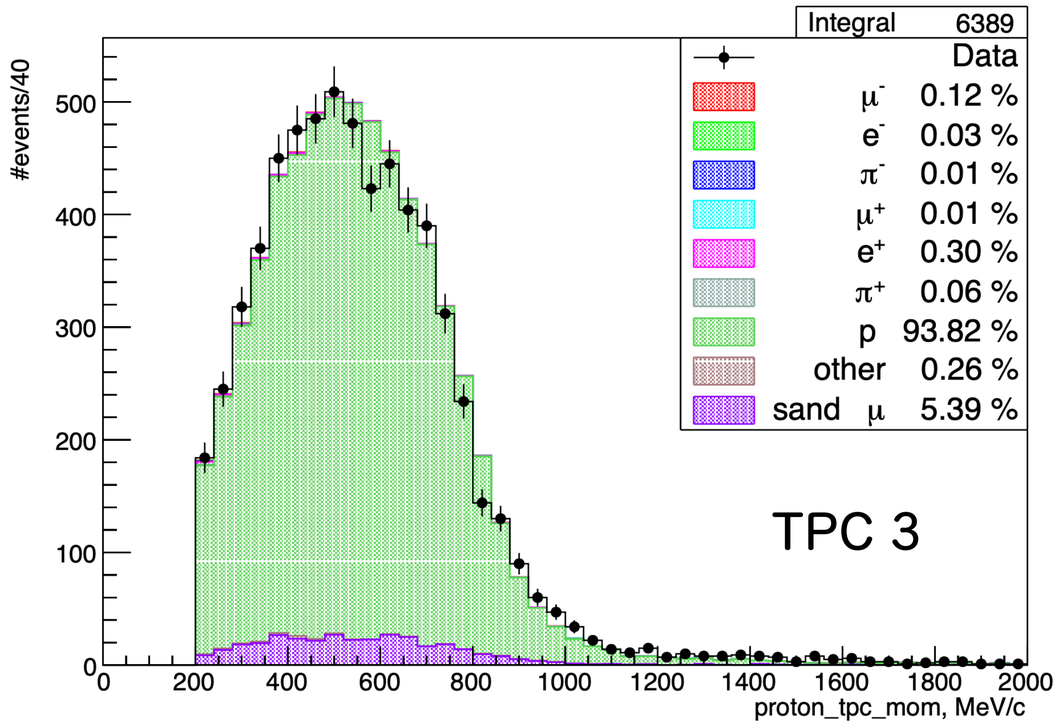
Протоны. Импульс в TPC

Начало трека в **FGD1/FGD2/SFG/TECAL/PECAL/HAT**

1. Track momentum > 200 MeV/c
2. dEdx > 700



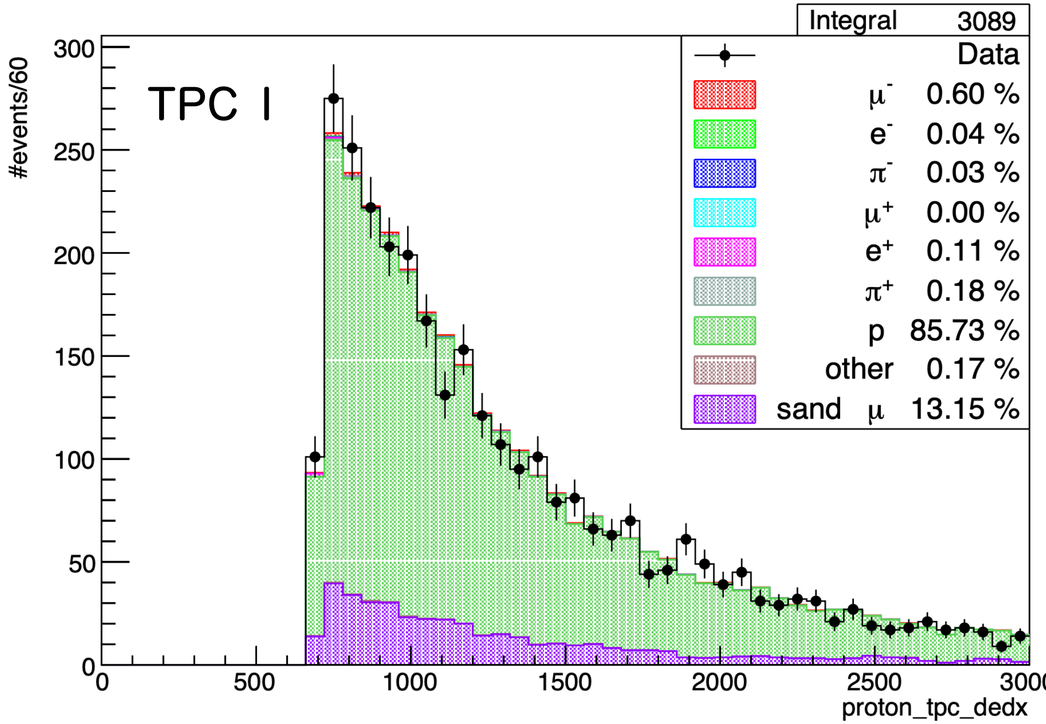


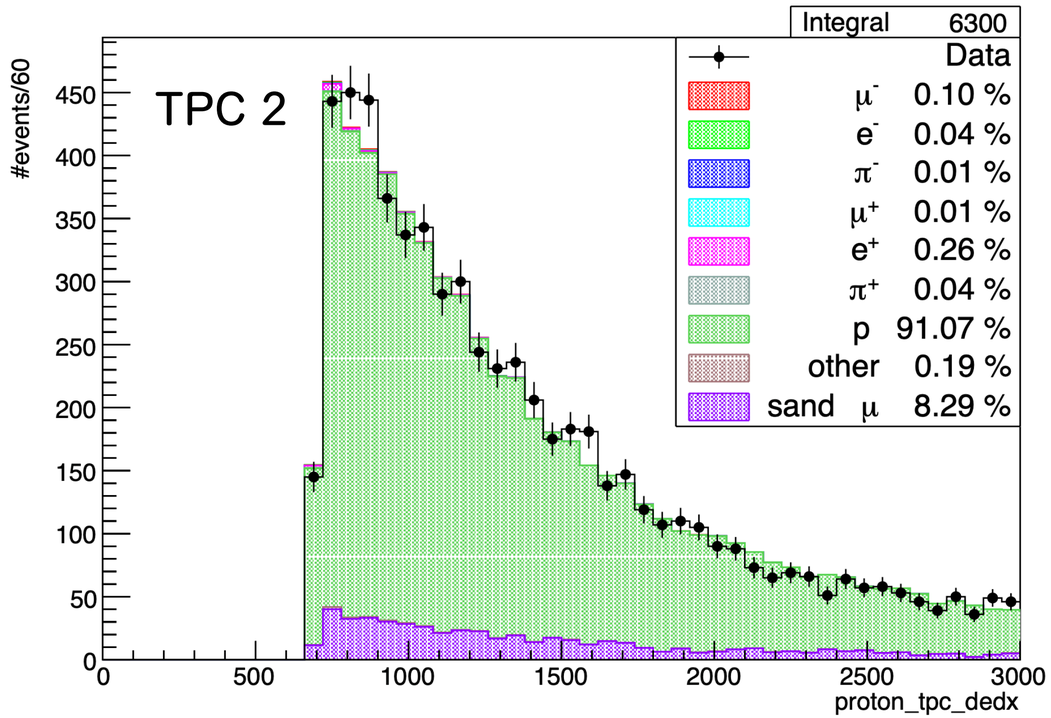


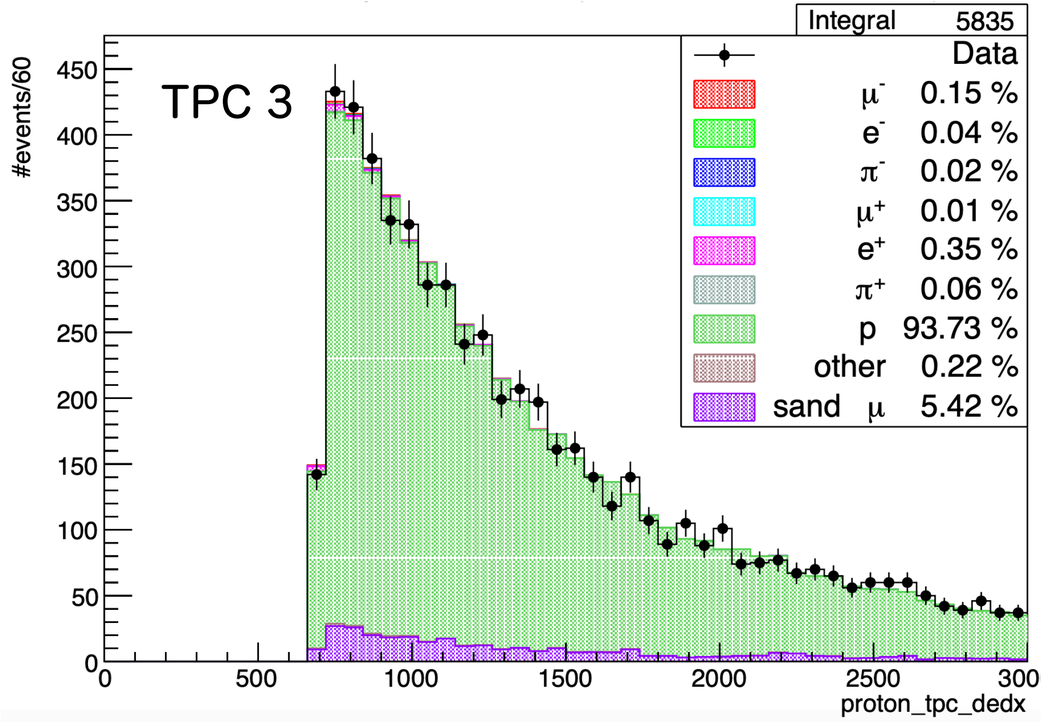
Протоны. dEdx в TPC

Начало трека в **FGD1/FGD2/SFG/TECAL/PECAL/HAT**

1. Track momentum > 200 MeV/c
2. dEdx > 700



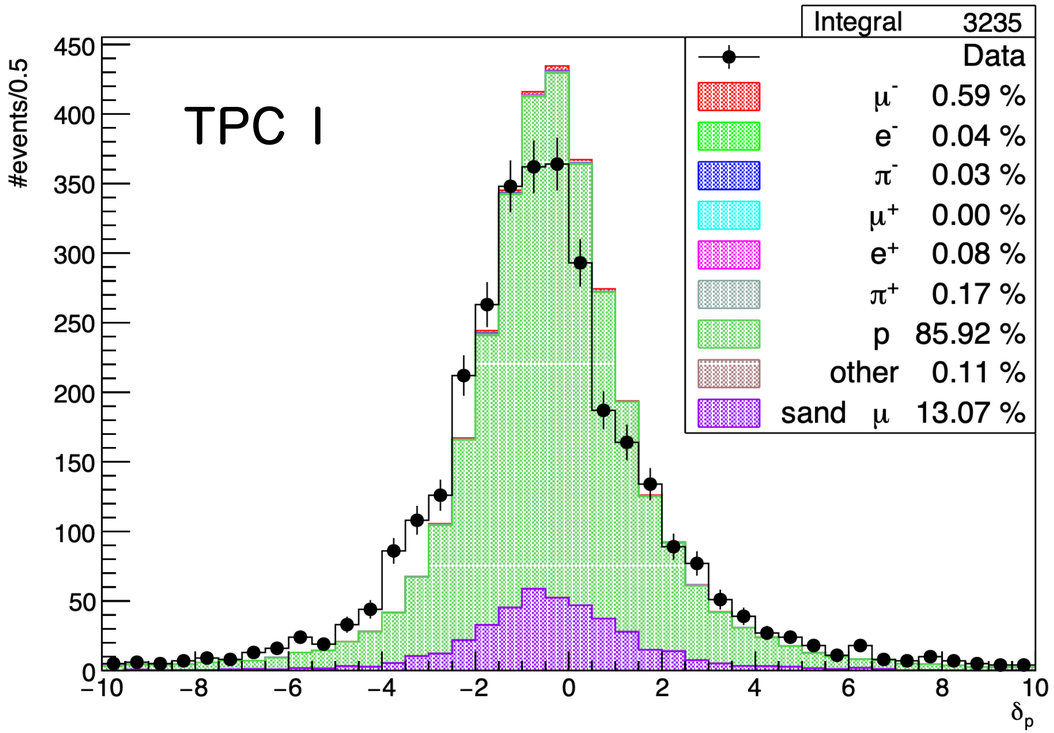


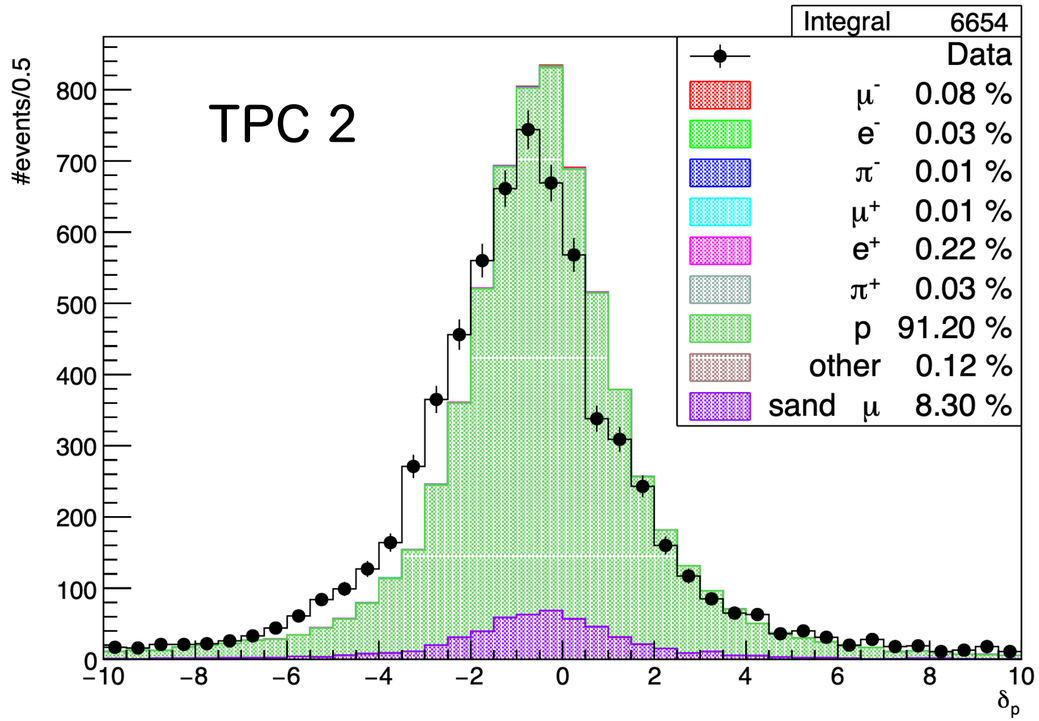


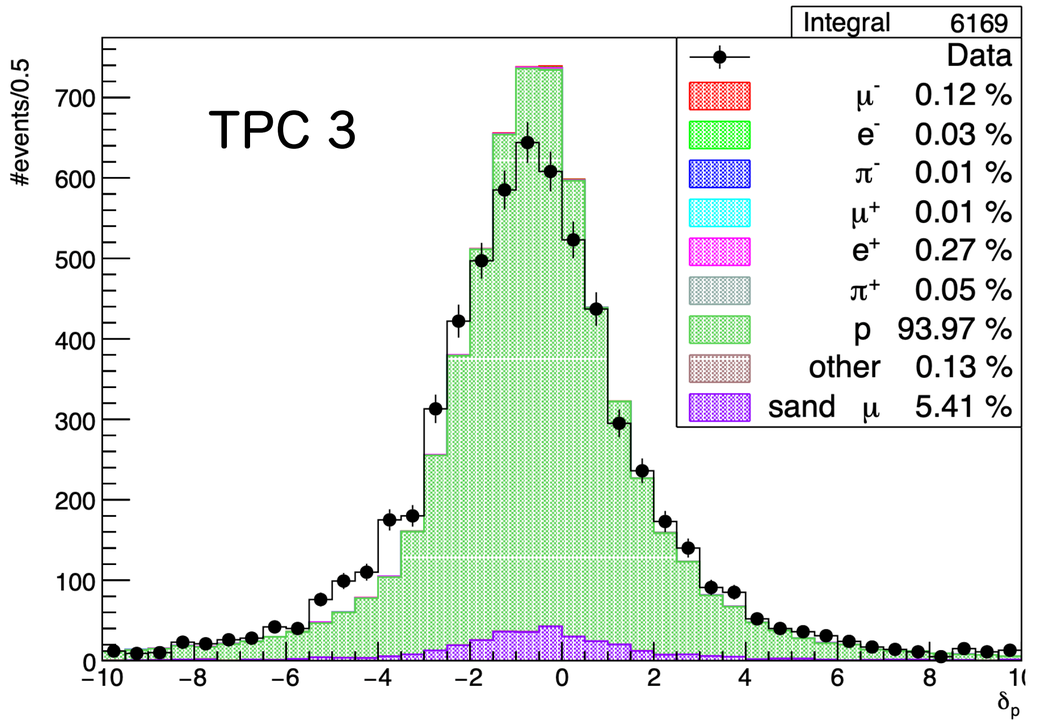
Протоны. Pull

Начало трека в **FGD1/FGD2/SFG/TECAL/PECAL/HAT**

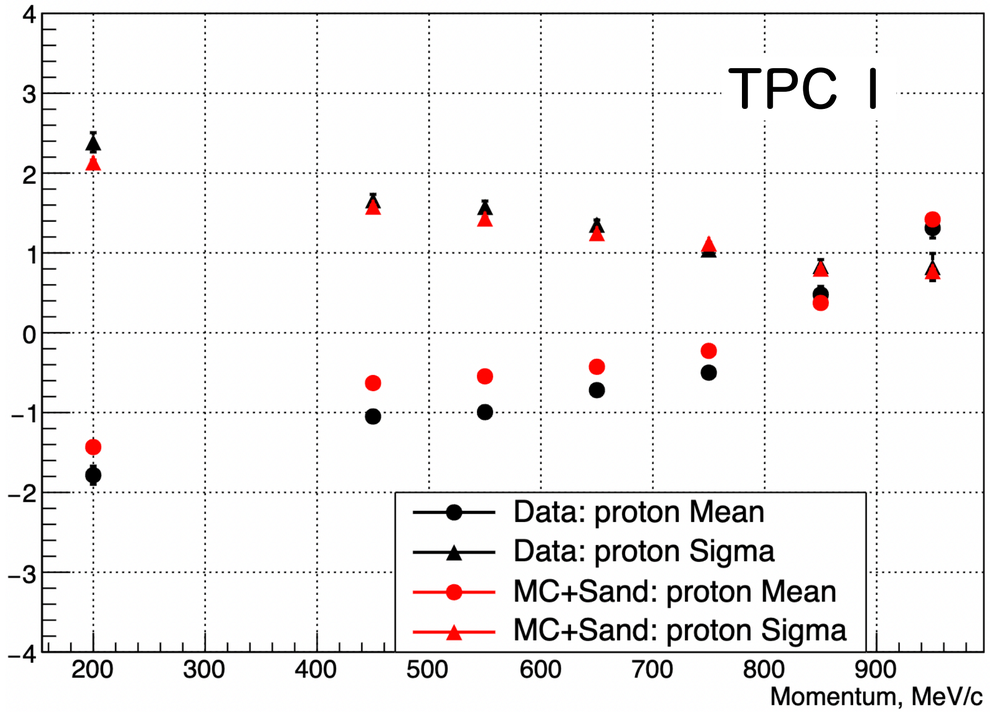
1. Track momentum > 200 MeV/c
2. dEdx > 700

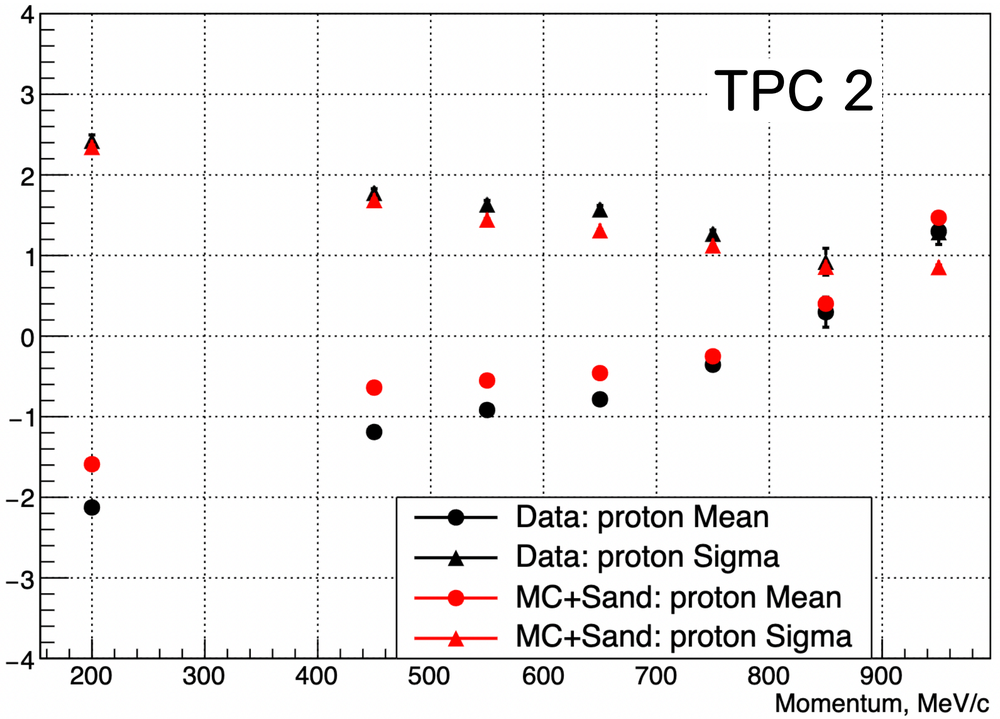


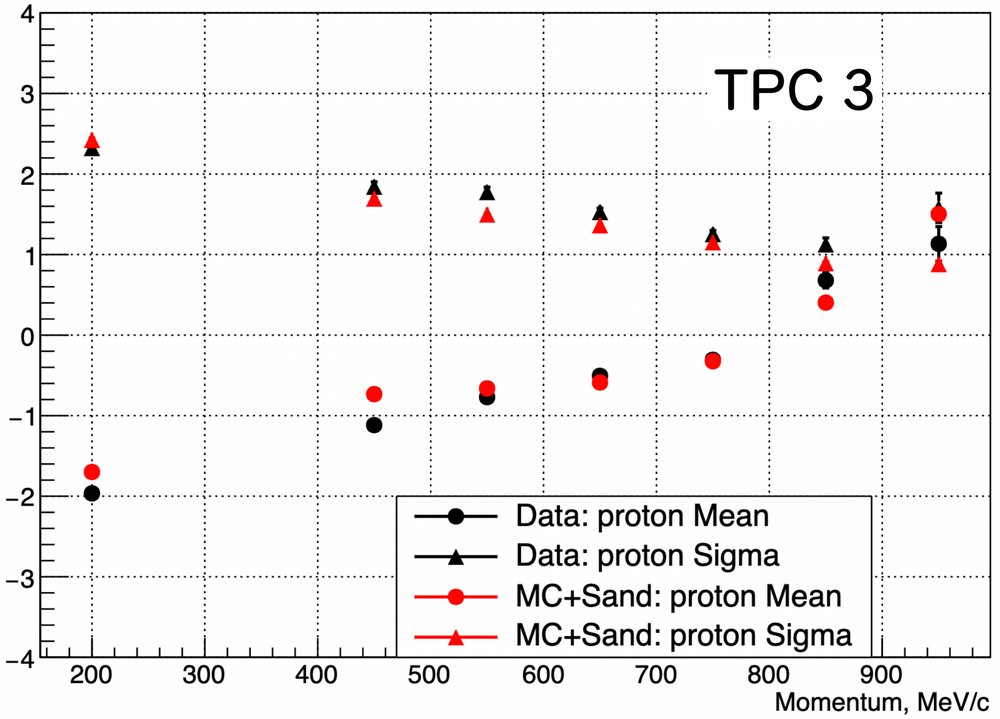




Протоны. Pull_mean и Pull_sigma.



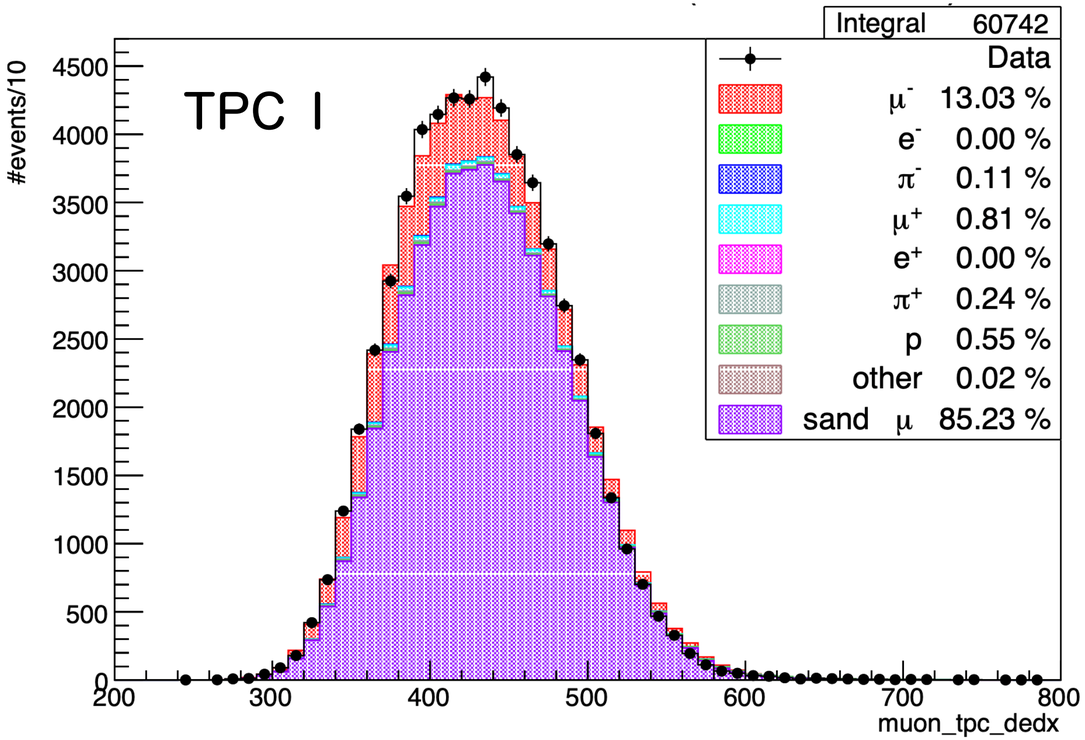


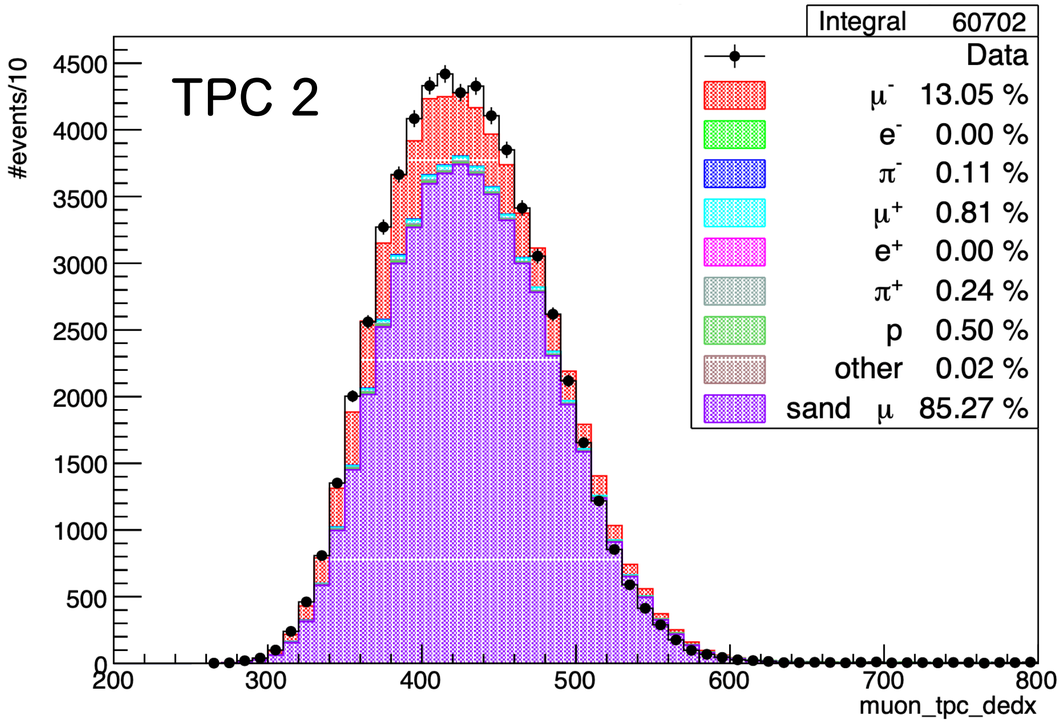


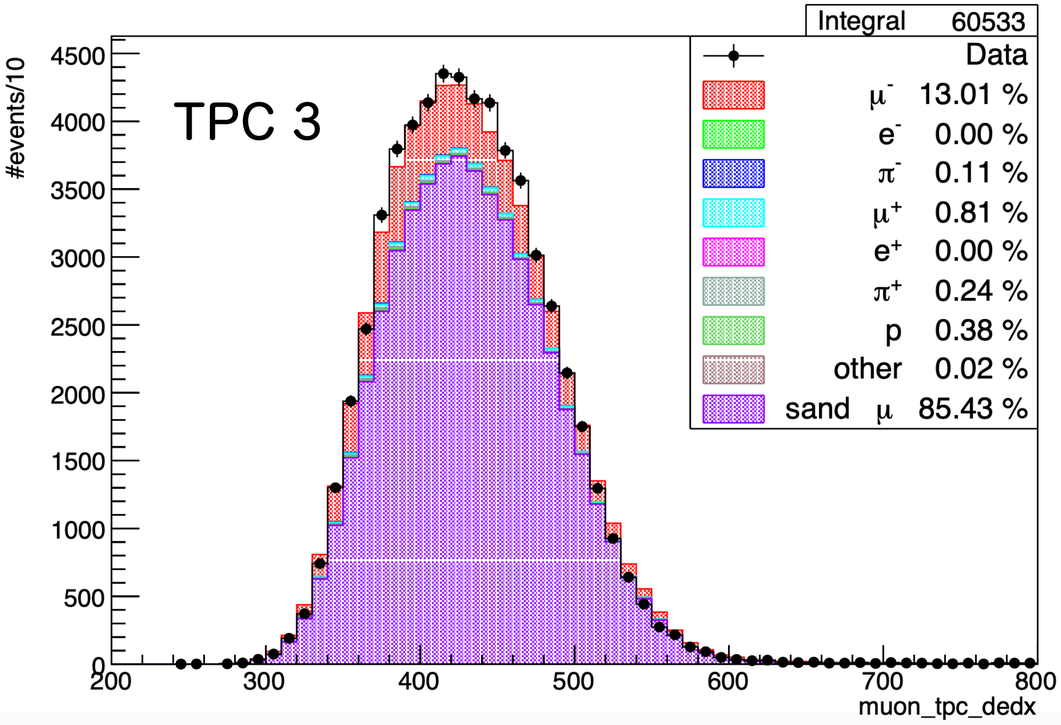
	Pull_mean difference		**Pull_sigma ratio**	
Binning, MeV	Data - MC	|Data - MC|	σ_Data / σ_MC	Ratio error
0 – 400	-0.352	0.352	1.118	0.118
400 — 500	-0.419	0.419	1.051	0.051
500 — 600	-0.448	0.448	1.100	0.100
600 — 700	-0.293	0.293	1.084	0.084
700 — 800	-0.273	0.273	0.935	0.065
800 — 900	+0.105	0.105	1.042	0.102
900 — 1000	-0.130	0.130	1.066	0.223
1000 — 1.0E+6	+0.370	0.370	1.421	0.452

Мюоны. dEdx в TPC

1. 3 TPCs in the event
2. 3 TPCs quality cut (each track segment with > 35 nodes)
3. One track per bunch
4. Track momentum > 100 MeV/c

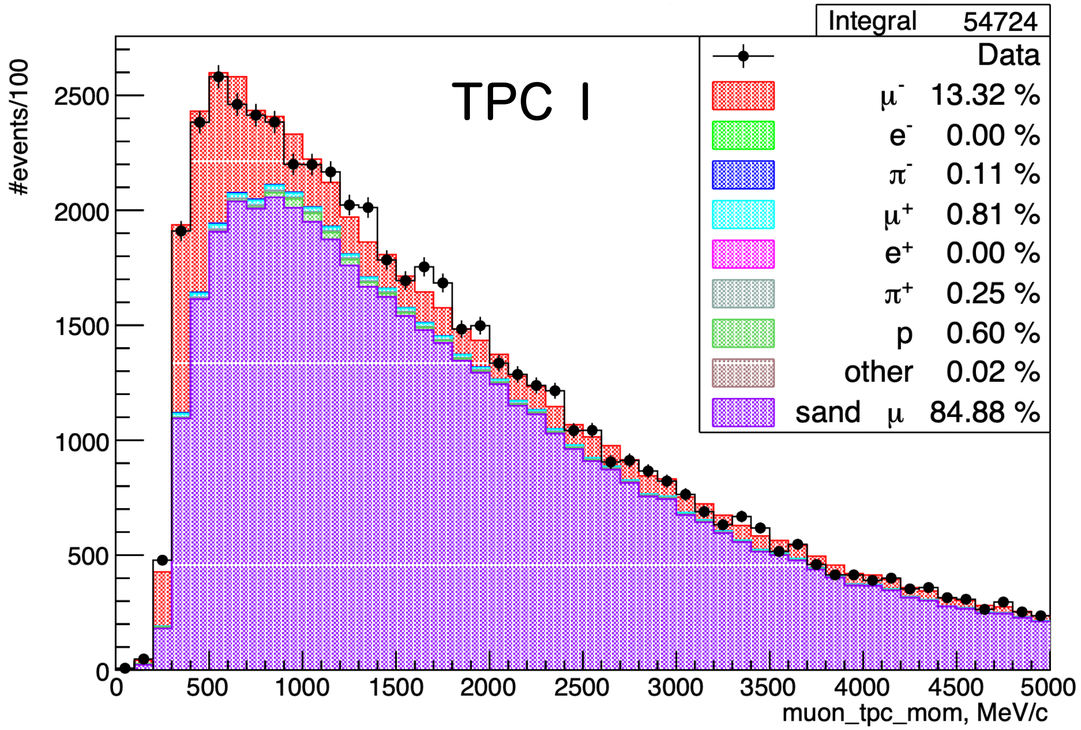


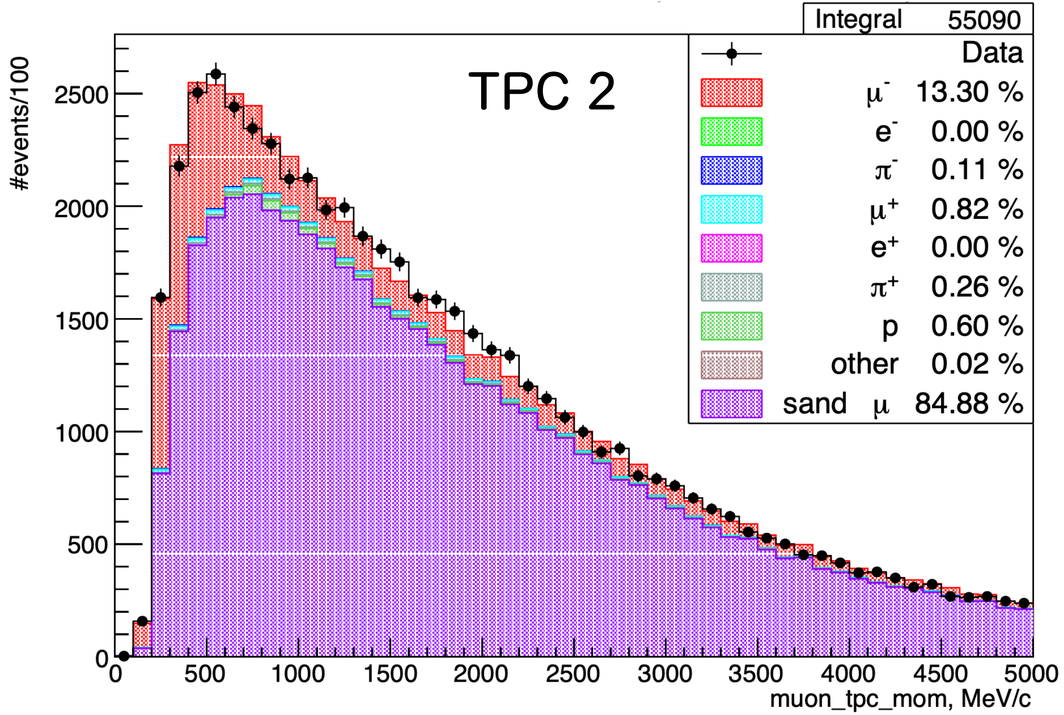


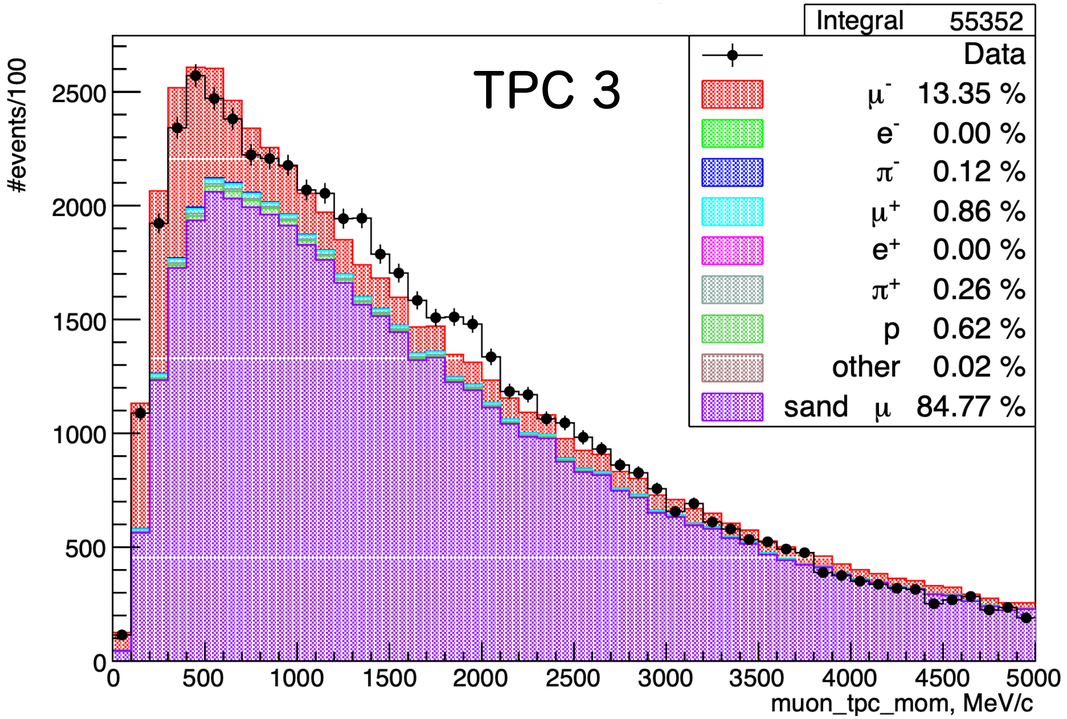


Мюоны. Импульс в TPC

1. 3 TPCs in the event
2. 3 TPCs quality cut (each track segment with > 35 nodes)
3. One track per bunch
4. Track momentum > 100 MeV/c

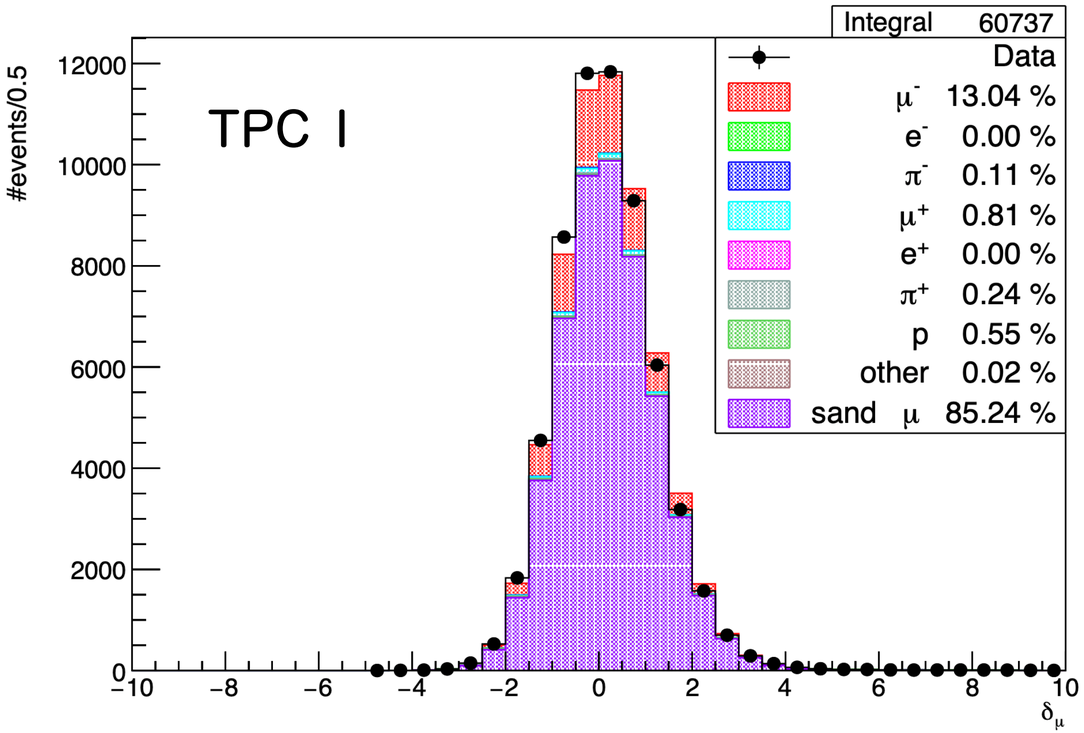


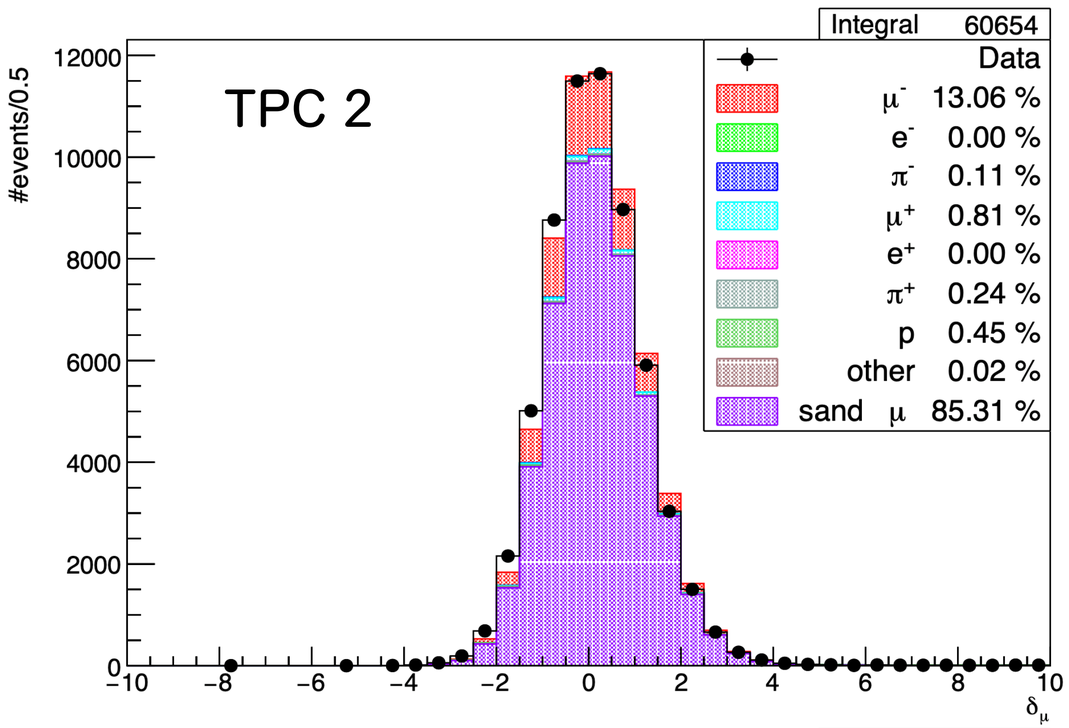


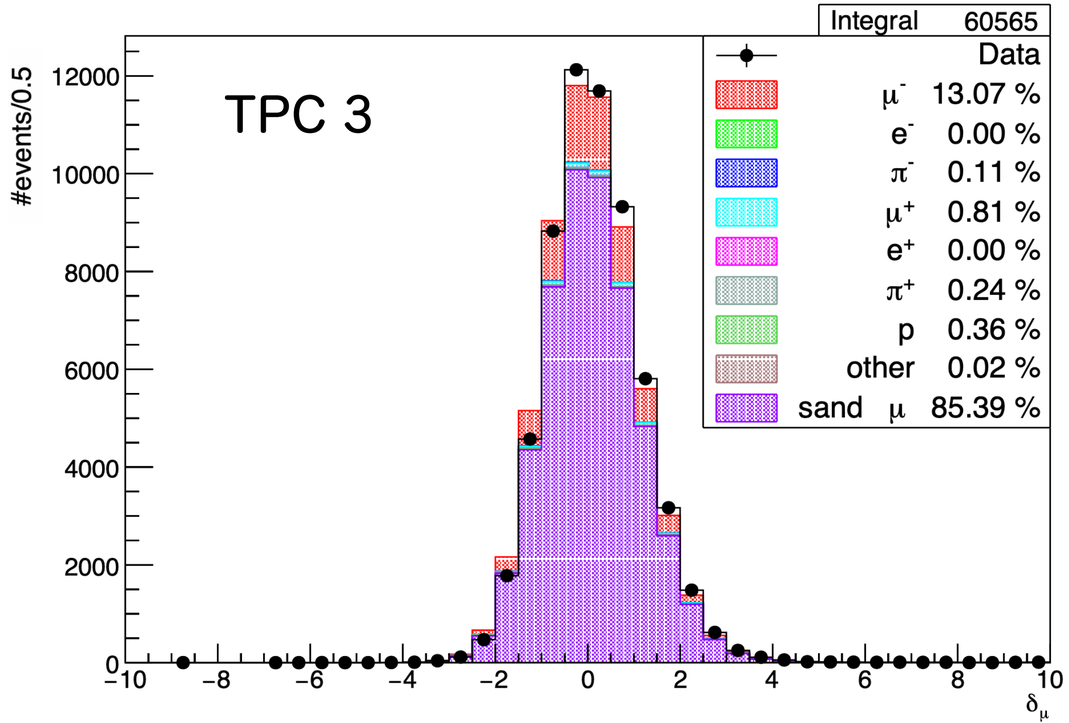


Мюоны. Pull

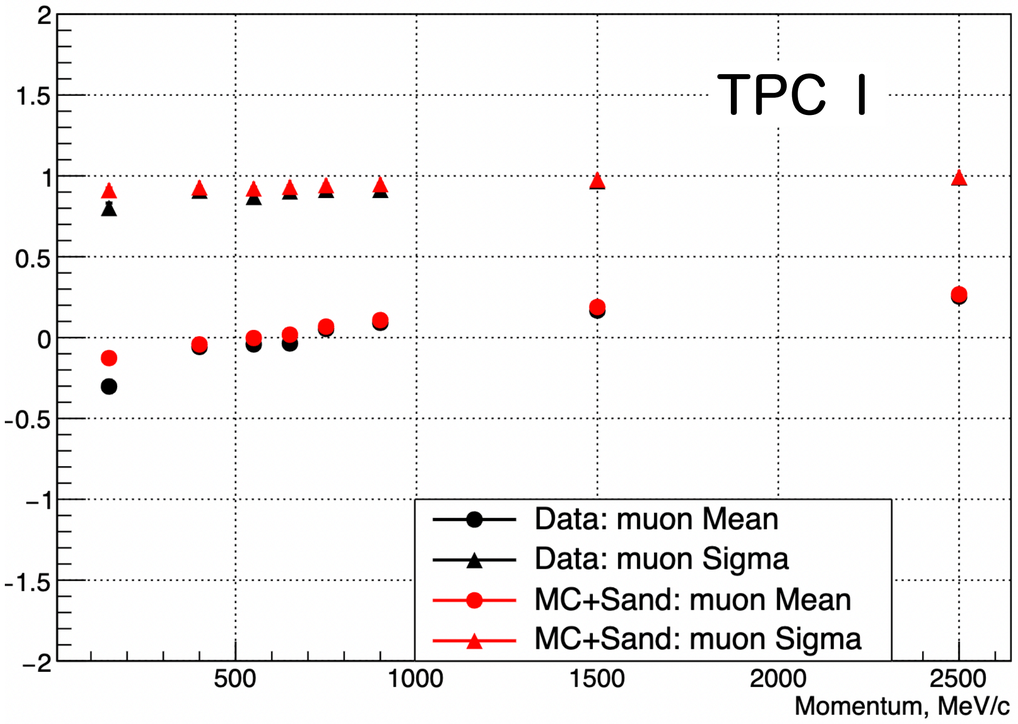
1. 3 TPCs in the event
2. 3 TPCs quality cut (each track segment with > 35 nodes)
3. One track per bunch
4. Track momentum > 100 MeV/c

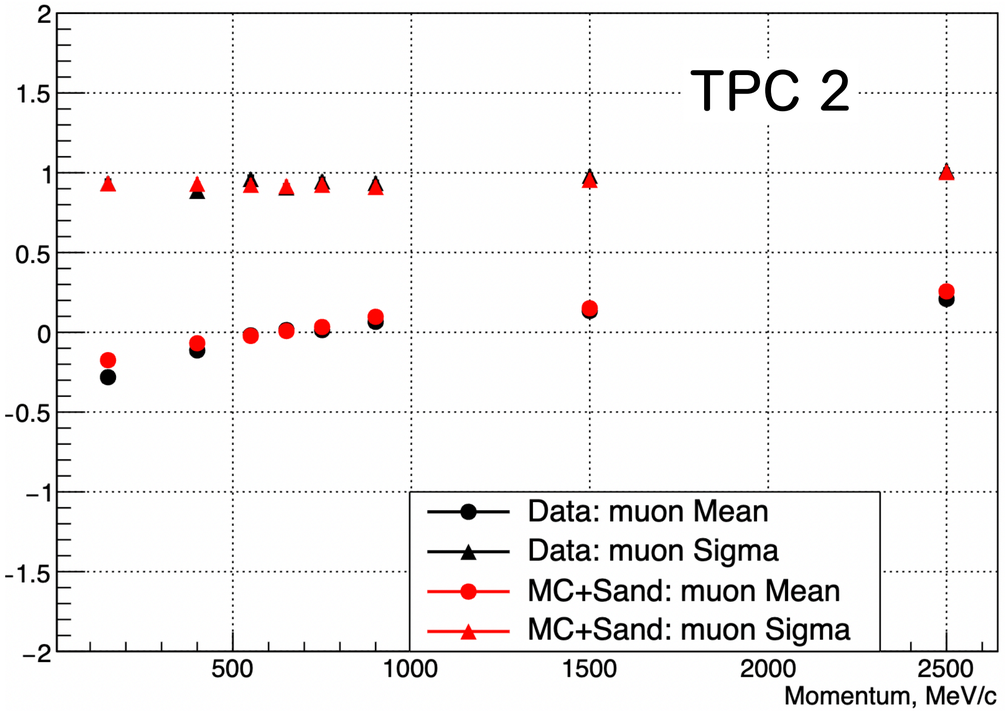


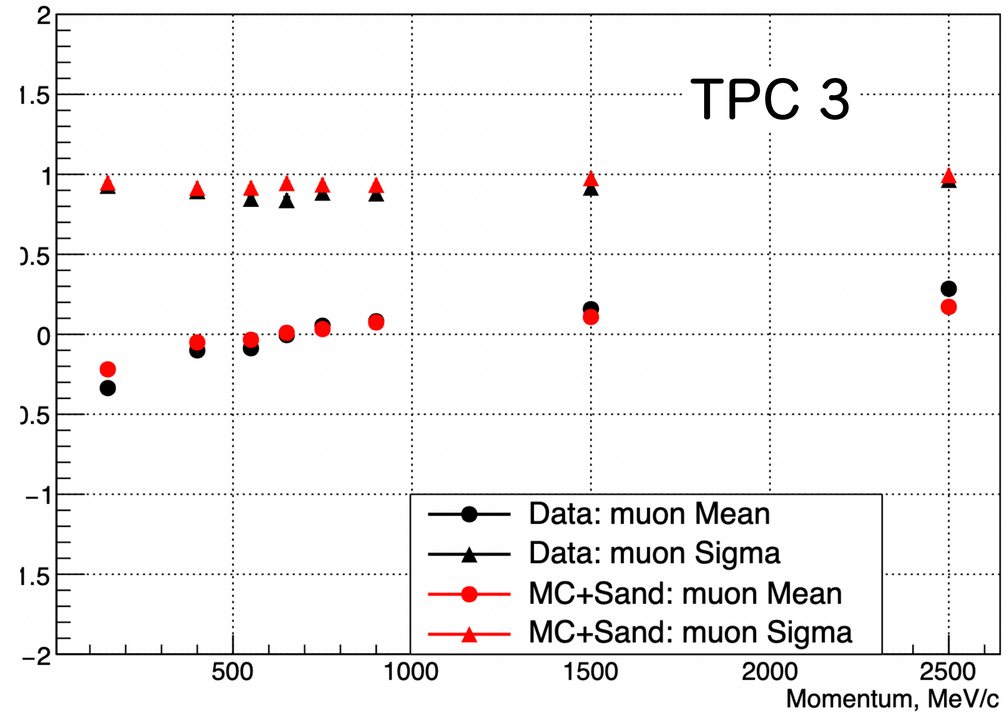




Мюоны. Pull_mean и Pull_sigma





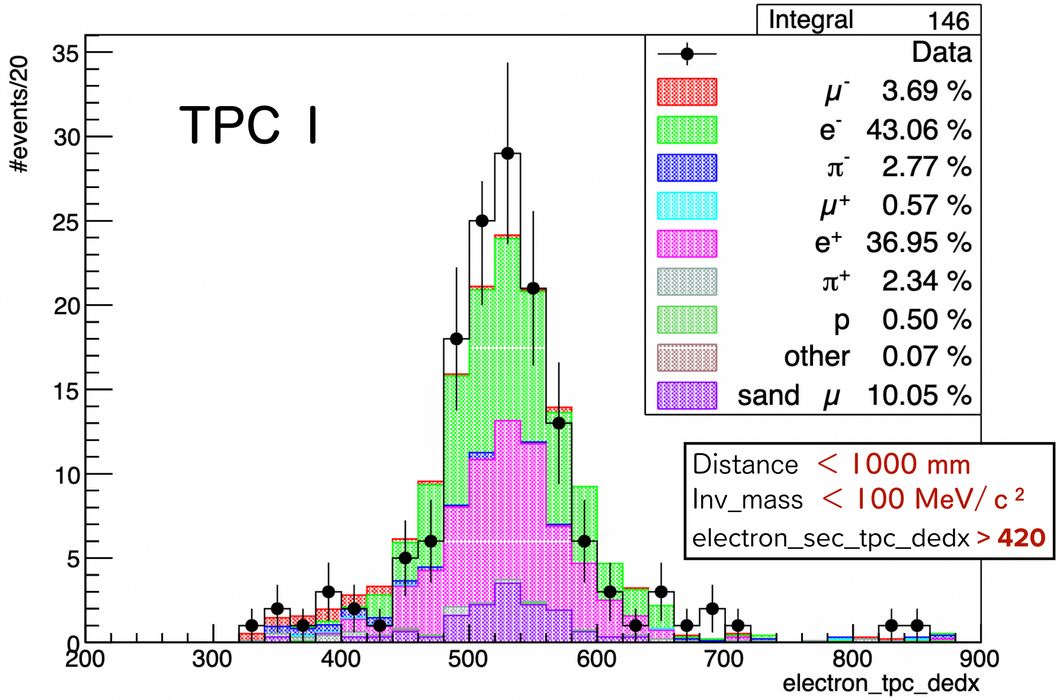


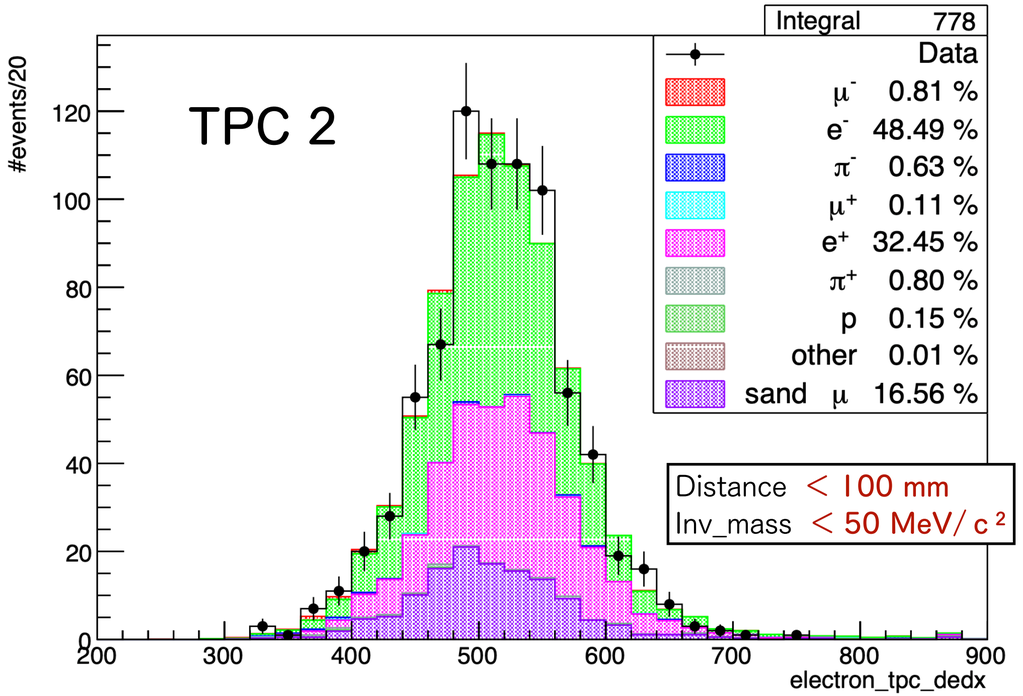
	Pull_mean difference		Pull_sigma ratio	
Binning, MeV	Data - MC	|Data - MC|	σ_Data / σ_MC	Ratio error
0 – 300	-0.176	0.176	0.879	0.121
300 — 500	-0.017	0.017	0.978	0.022
500 — 600	-0.039	0.039	0.943	0.057
600 — 700	-0.054	0.054	0.970	0.030
700 — 800	-0.022	0.022	0.969	0.031
800 — 1000	-0.016	0.016	0.963	0.037
1000 — 2000	-0.022	0.022	0.990	0.010
2000 — 3000	-0.014	0.014	0.997	0.011
3000 — 1.0E+6	-0.116	0.116	0.977	0.023

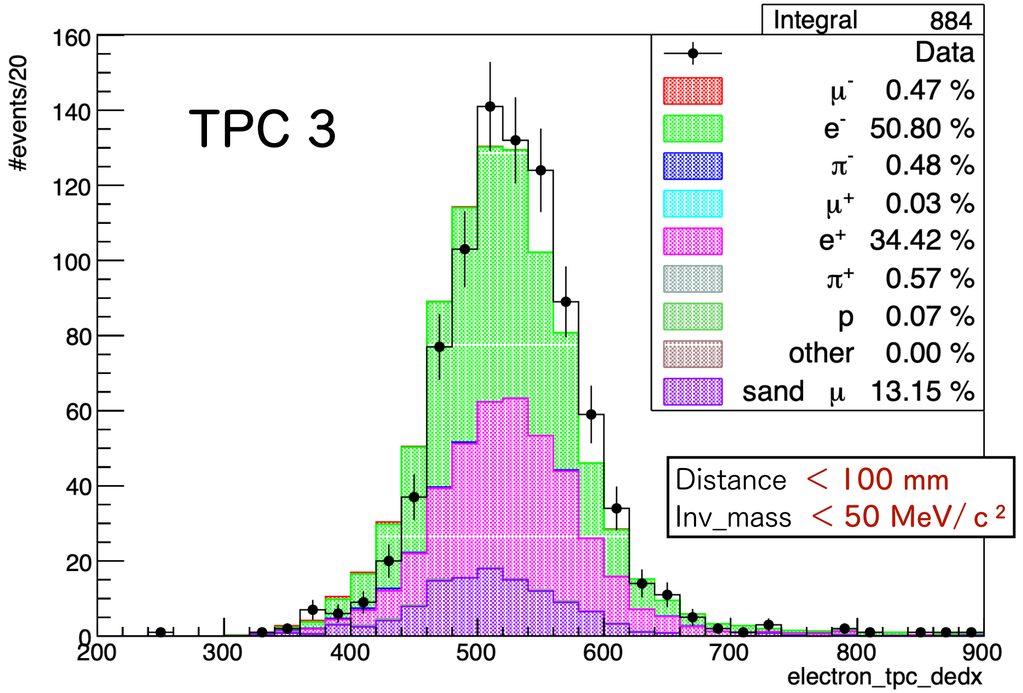
Первичные электроны. TPC_dedx

Начало трека в **FGD1/FGD2/SFG/TECAL/PECAL/HAT**

1. Electron candidat cut
2. Secondary electron find
   - 2.1 Quality cut
   - 2.2 FV cut
   - 2.3 Opposite charge
   - 2.4 Distance
   - 2.5 Invariant mass
   - 2.6 ClosestADistanceCut < 1000 mm
   - 2.7 ClosestAInvMassCut < 500 MeV/c²
3. Secondary electron cut



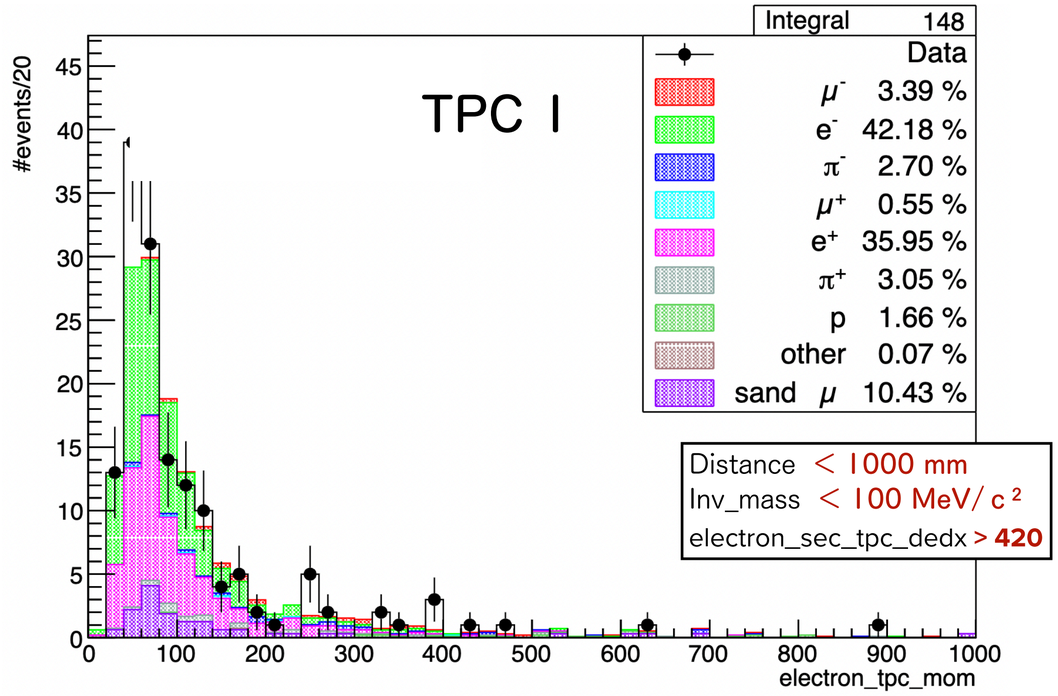


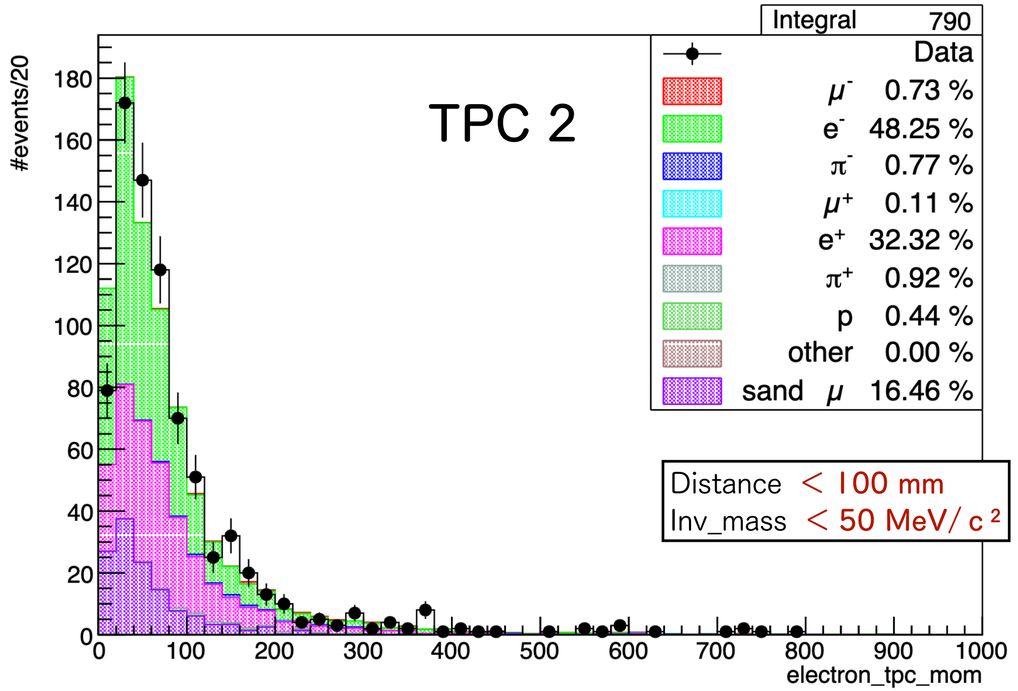


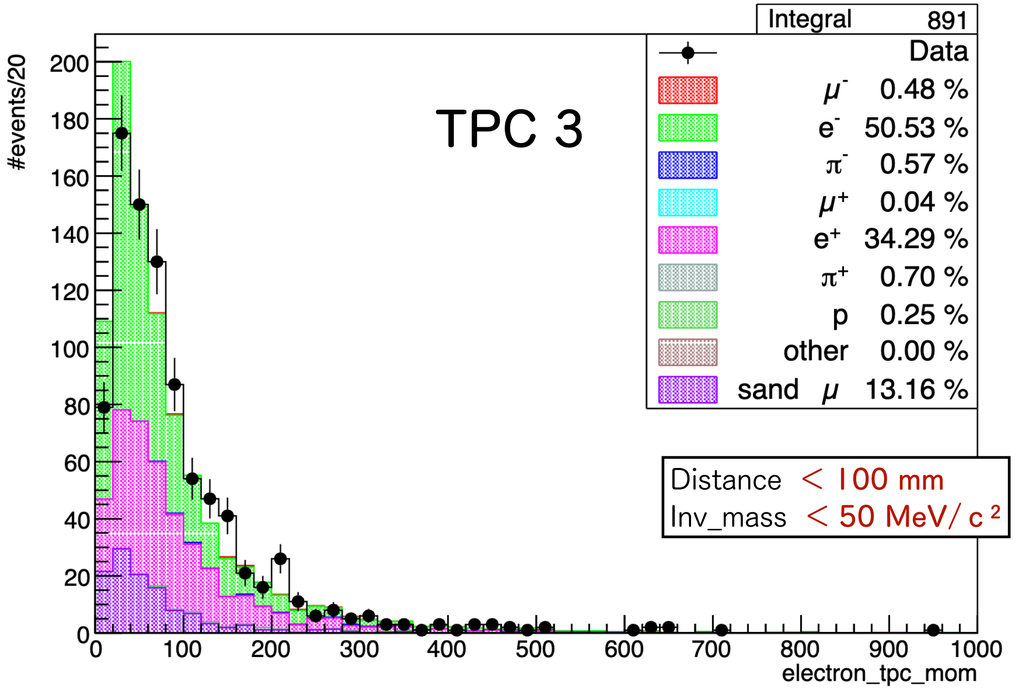
Первичные электроны. Импульс

Начало трека в **FGD1/FGD2/SFG/TECAL/PECAL/HAT**

1. Electron candidat cut
2. Secondary electron find
   - 2.1 Quality cut
   - 2.2 FV cut
   - 2.3 Opposite charge
   - 2.4 Distance
   - 2.5 Invariant mass
   - 2.6 ClosestADistanceCut < 1000 mm
   - 2.7 ClosestAInvMassCut < 500 MeV/c²
3. Secondary electron cut



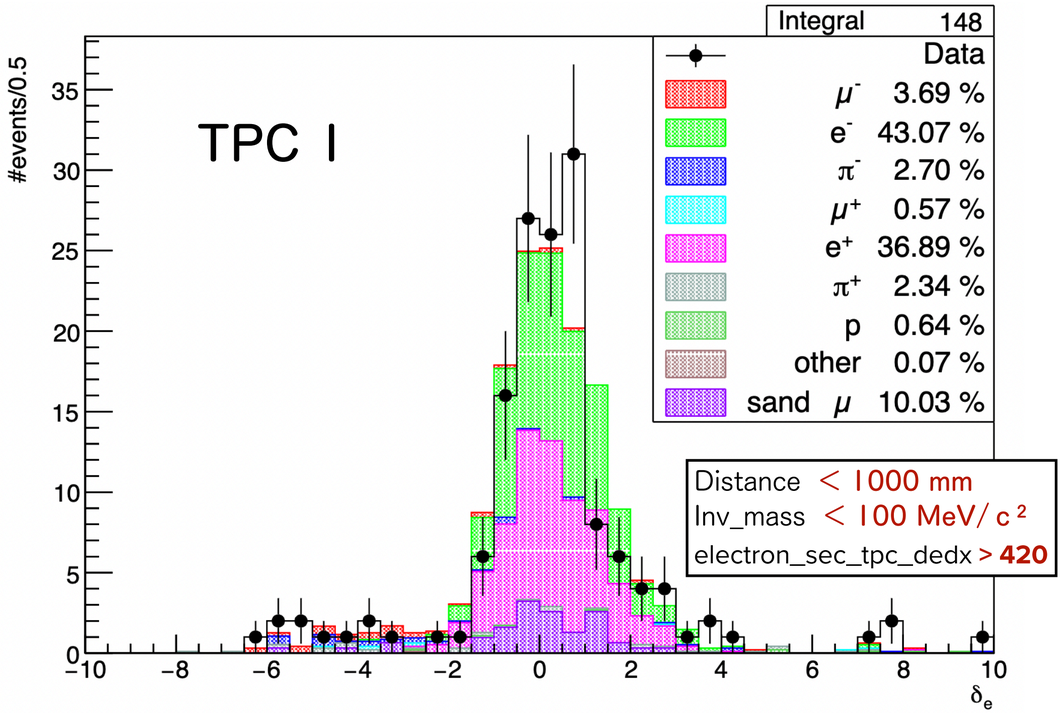


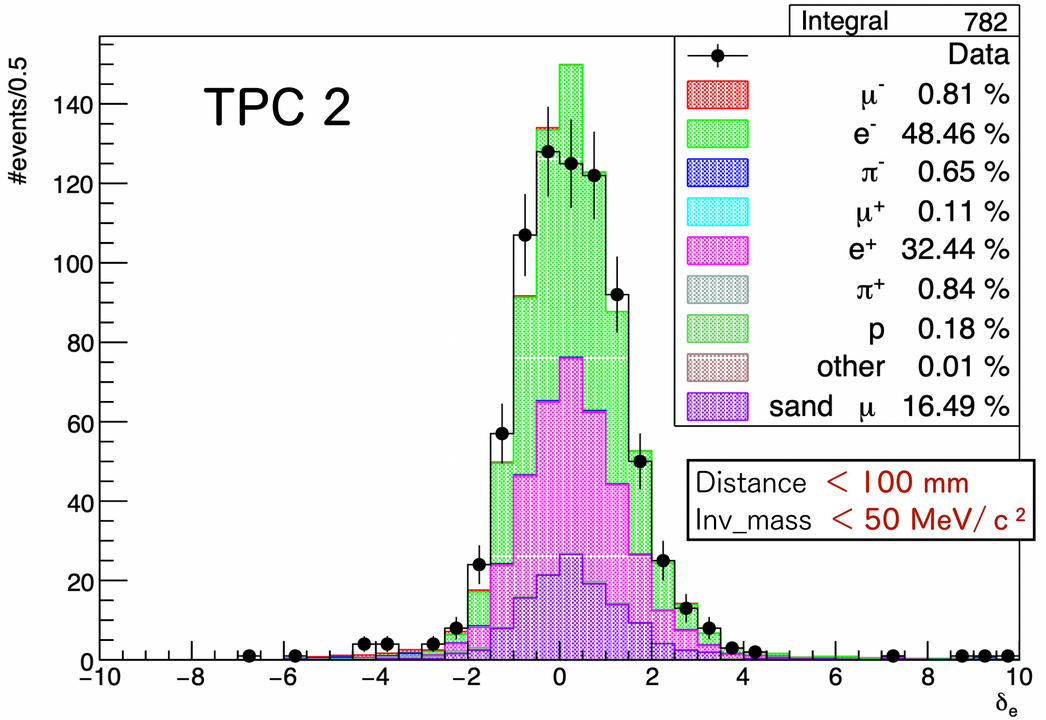


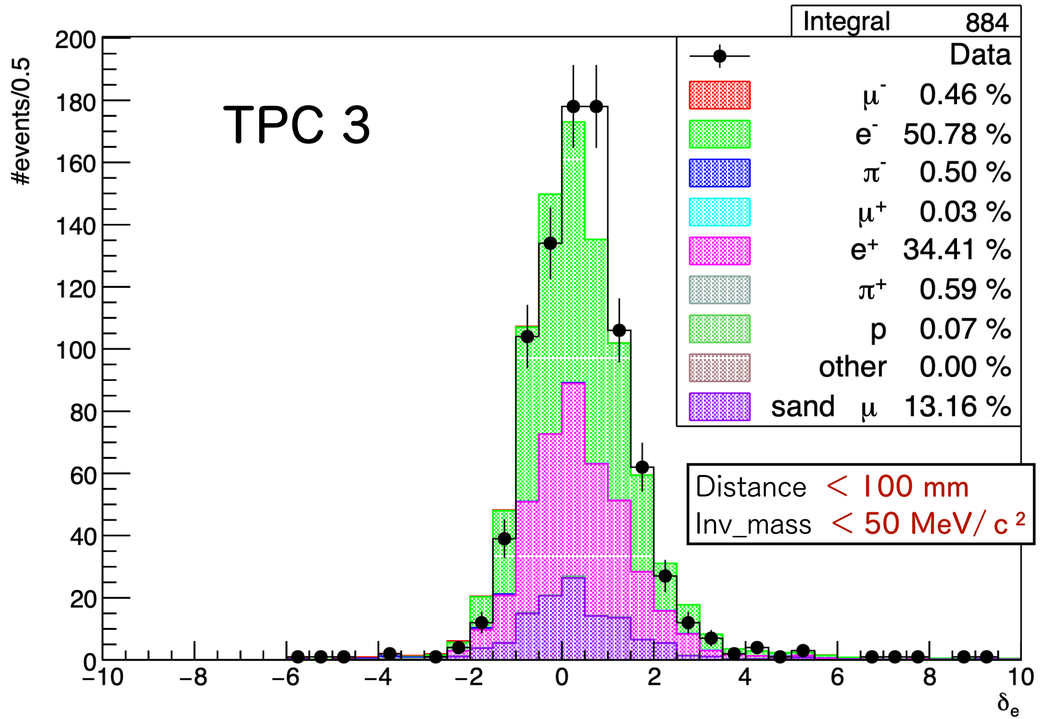
Первичные электроны. Pull

Начало трека в **FGD1/FGD2/SFG/TECAL/PECAL/HAT**

1. Electron candidat cut
2. Secondary electron find
   - 2.1 Quality cut
   - 2.2 FV cut
   - 2.3 Opposite charge
   - 2.4 Distance
   - 2.5 Invariant mass
   - 2.6 ClosestADistanceCut < 1000 mm
   - 2.7 ClosestAInvMassCut < 500 MeV/c²
3. Secondary electron cut



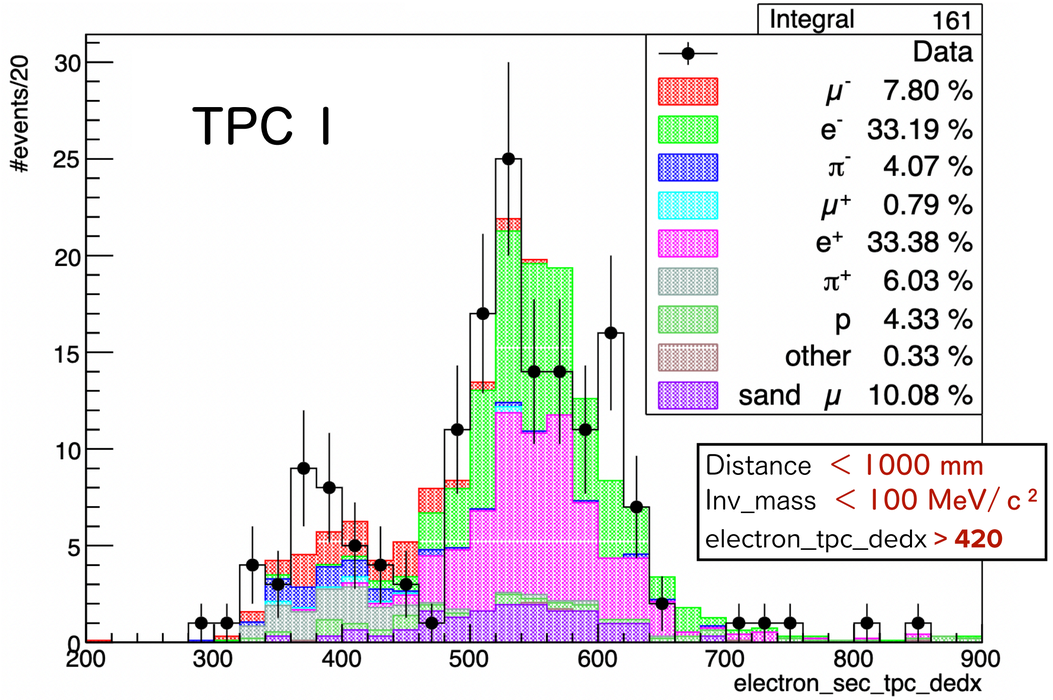


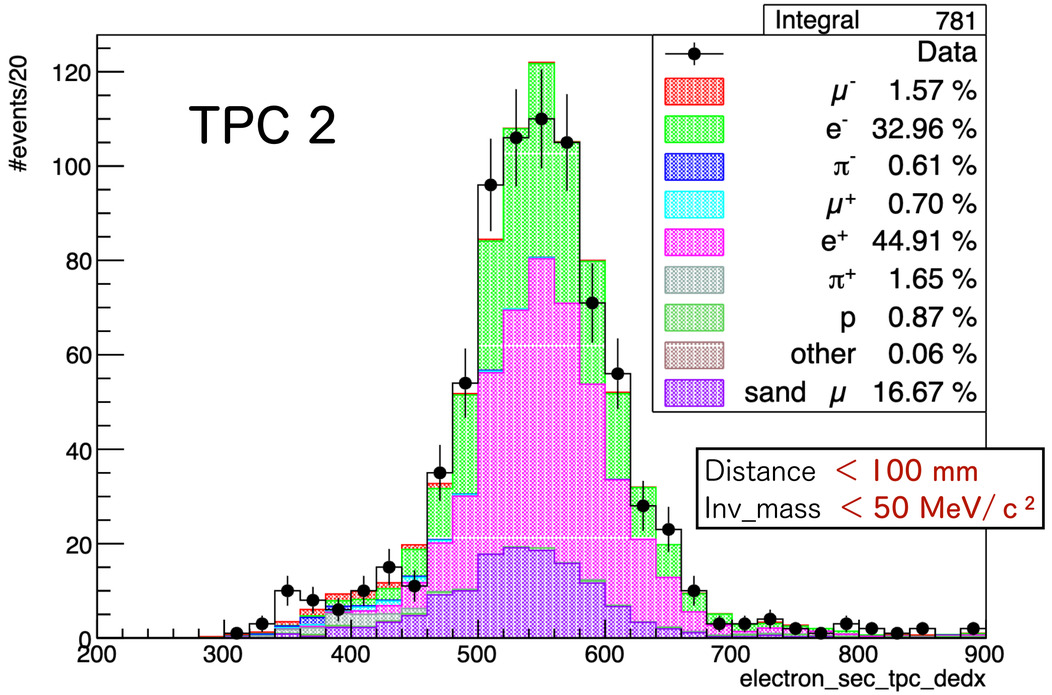


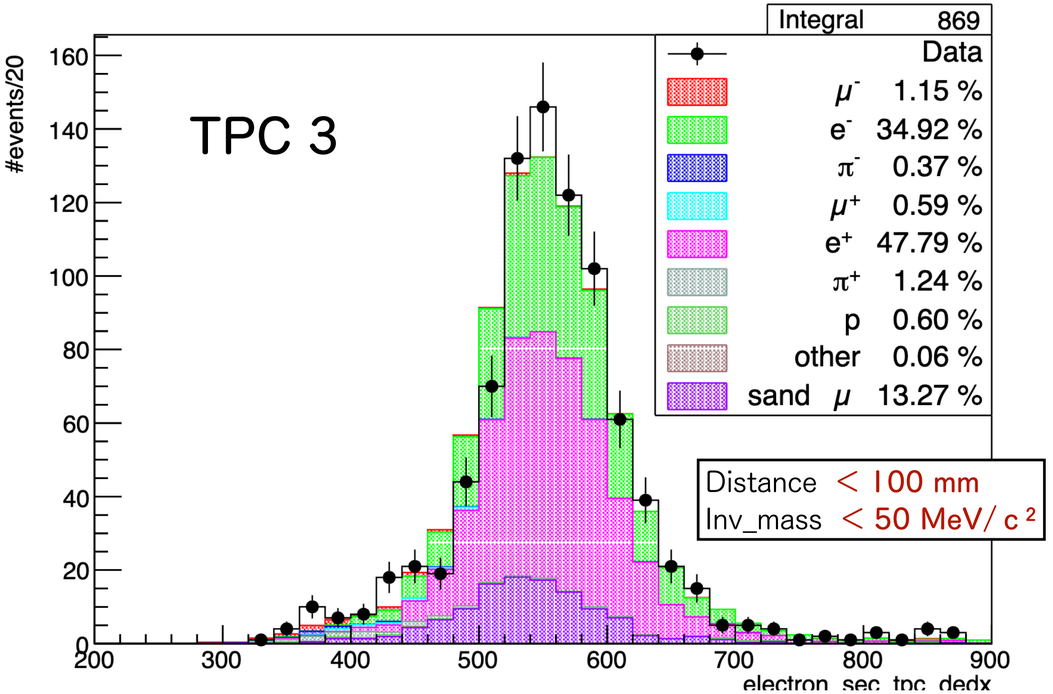
Вторичные электроны. TPC_dedx

Начало трека в **FGD1/FGD2/SFG/TECAL/PECAL/HAT**

1. Electron candidat cut
2. Secondary electron find
   - 2.1 Quality cut
   - 2.2 FV cut
   - 2.3 Opposite charge
   - 2.4 Distance
   - 2.5 Invariant mass
   - 2.6 ClosestADistanceCut < 1000 mm
   - 2.7 ClosestAInvMassCut < 500 MeV/c²
3. Secondary electron cut



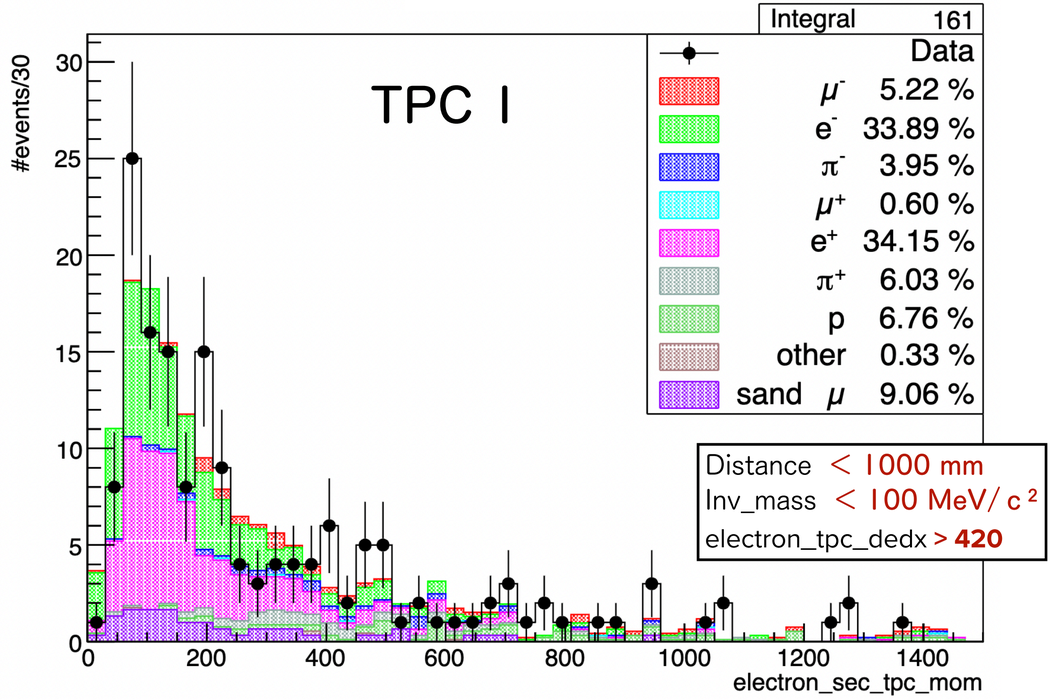


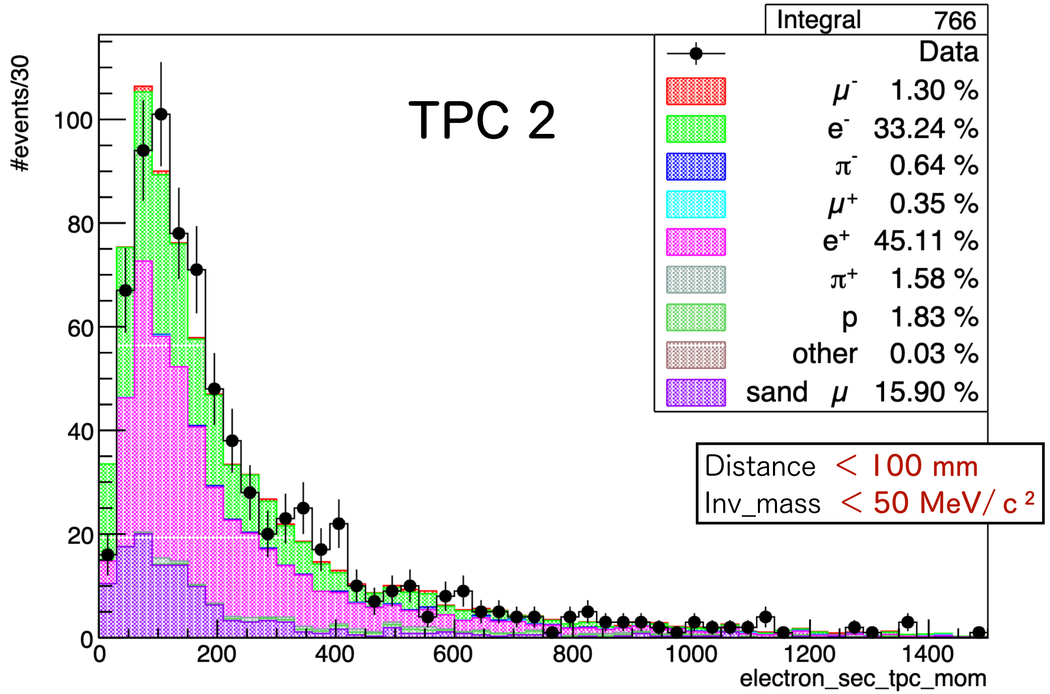


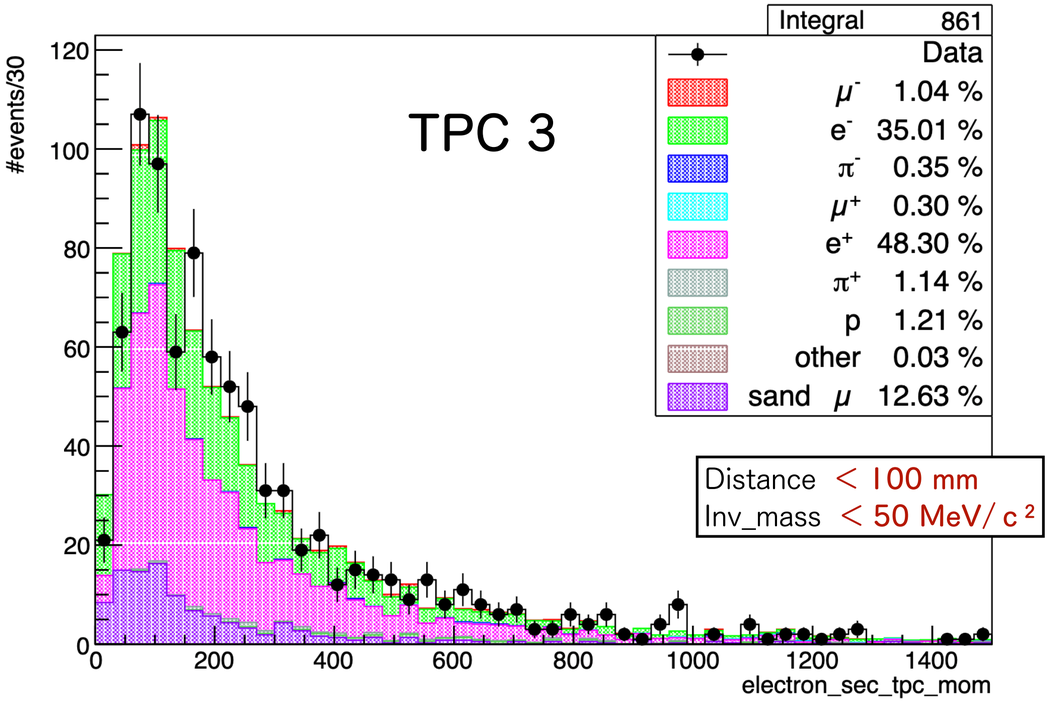
Вторичные электроны. Импульс

Начало трека в **FGD1/FGD2/SFG/TECAL/PECAL/HAT**

1. Electron candidat cut
2. Secondary electron find
   - 2.1 Quality cut
   - 2.2 FV cut
   - 2.3 Opposite charge
   - 2.4 Distance
   - 2.5 Invariant mass
   - 2.6 ClosestADistanceCut < 1000 mm
   - 2.7 ClosestAInvMassCut < 500 MeV/c²
3. Secondary electron cut



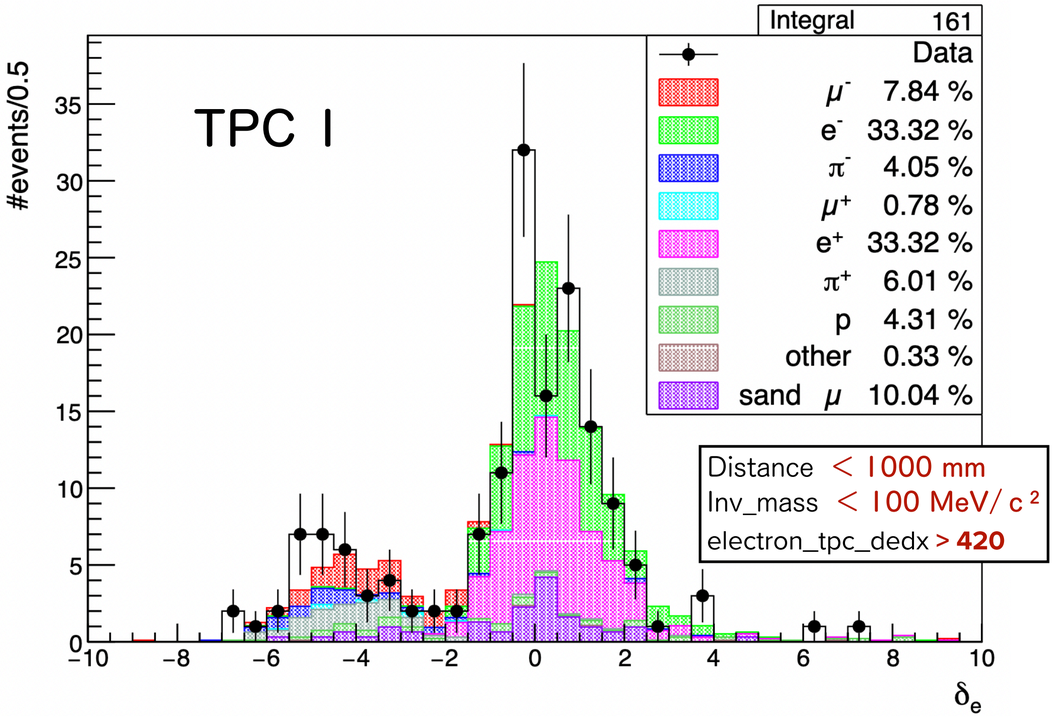


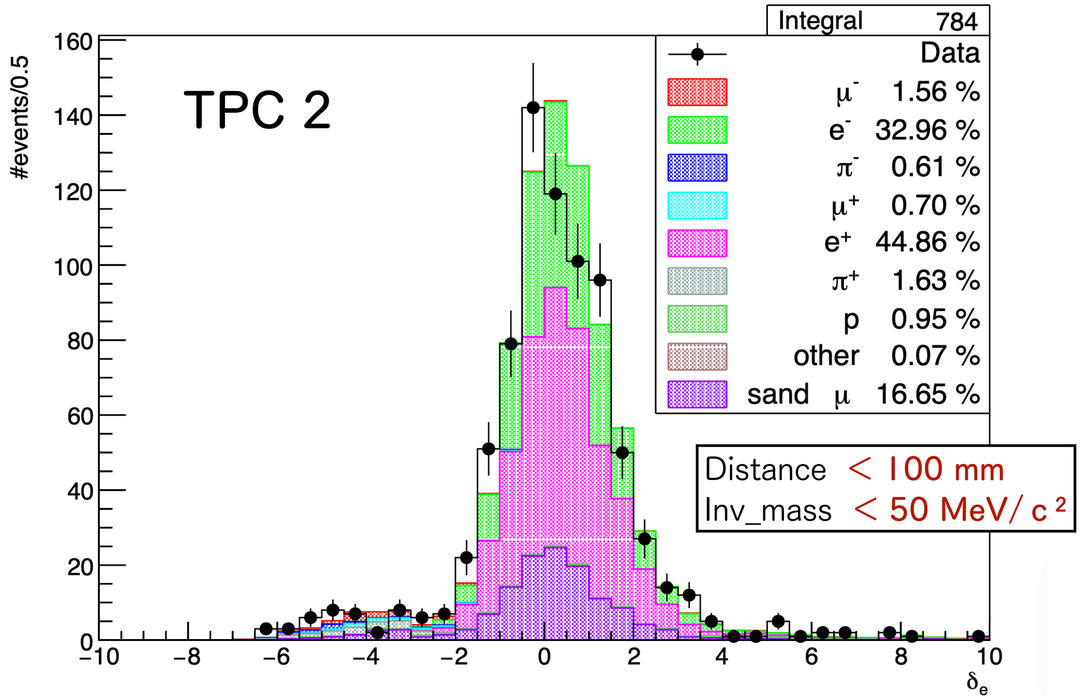


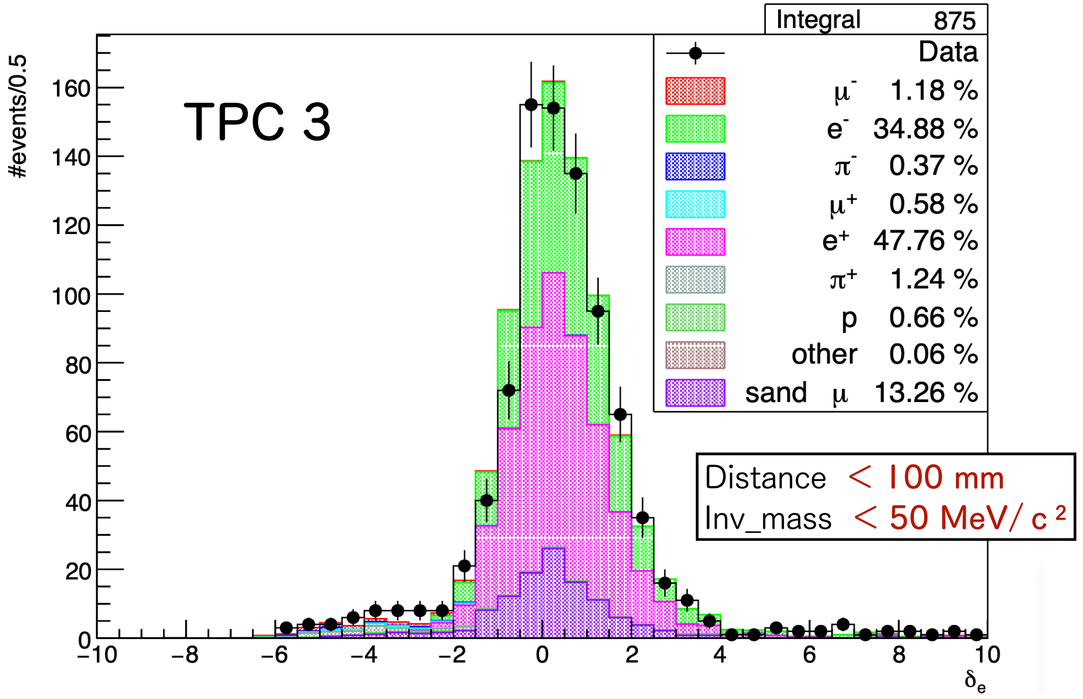
Вторичные электроны. Pull

Начало трека в **FGD1/FGD2/SFG/TECAL/PECAL/HAT**

1. Electron candidat cut
2. Secondary electron find
   - 2.1 Quality cut
   - 2.2 FV cut
   - 2.3 Opposite charge
   - 2.4 Distance
   - 2.5 Invariant mass
   - 2.6 ClosestADistanceCut < 1000 mm
   - 2.7 ClosestAInvMassCut < 500 MeV/c²
3. Secondary electron cut



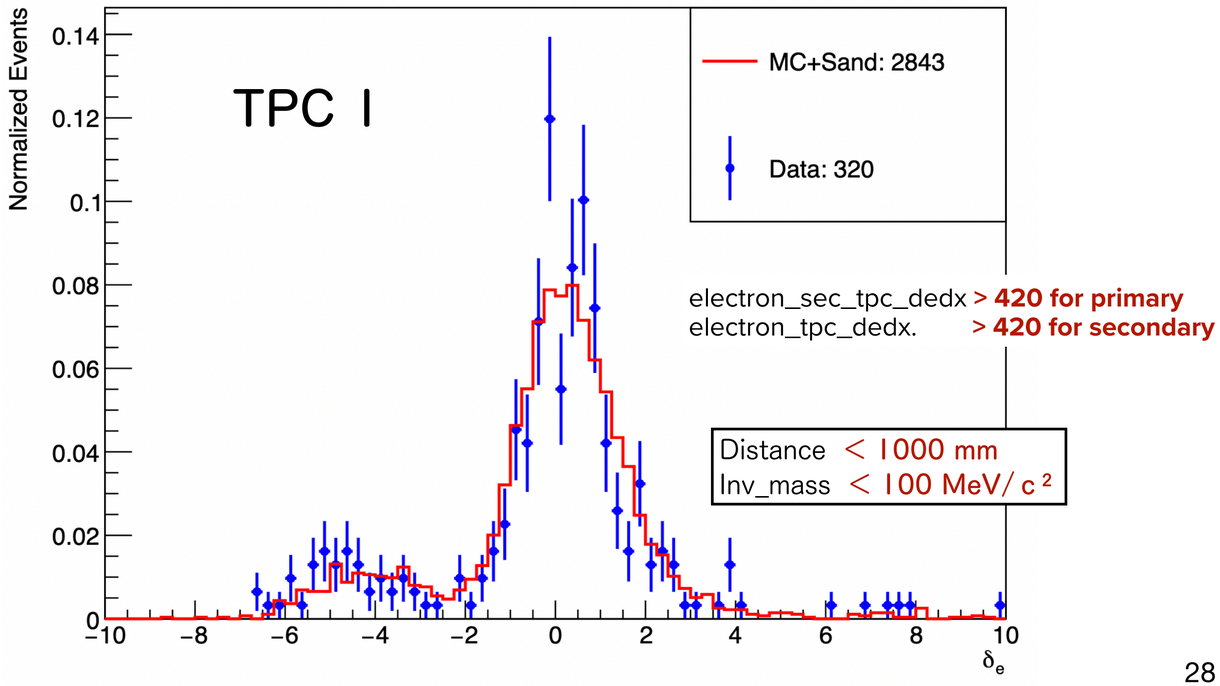


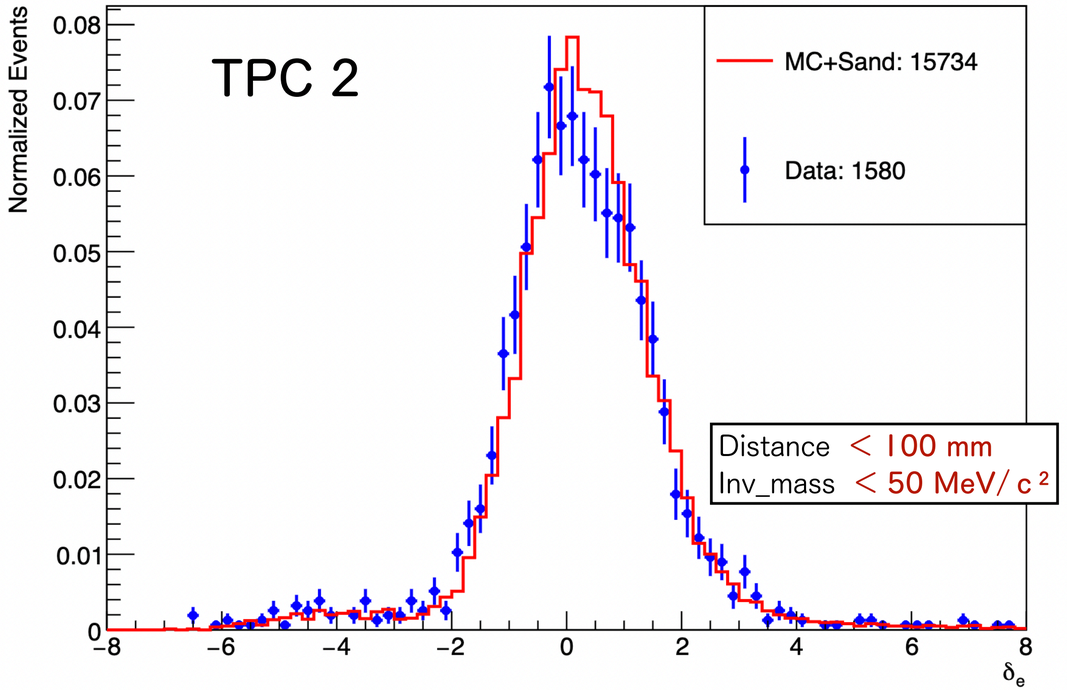


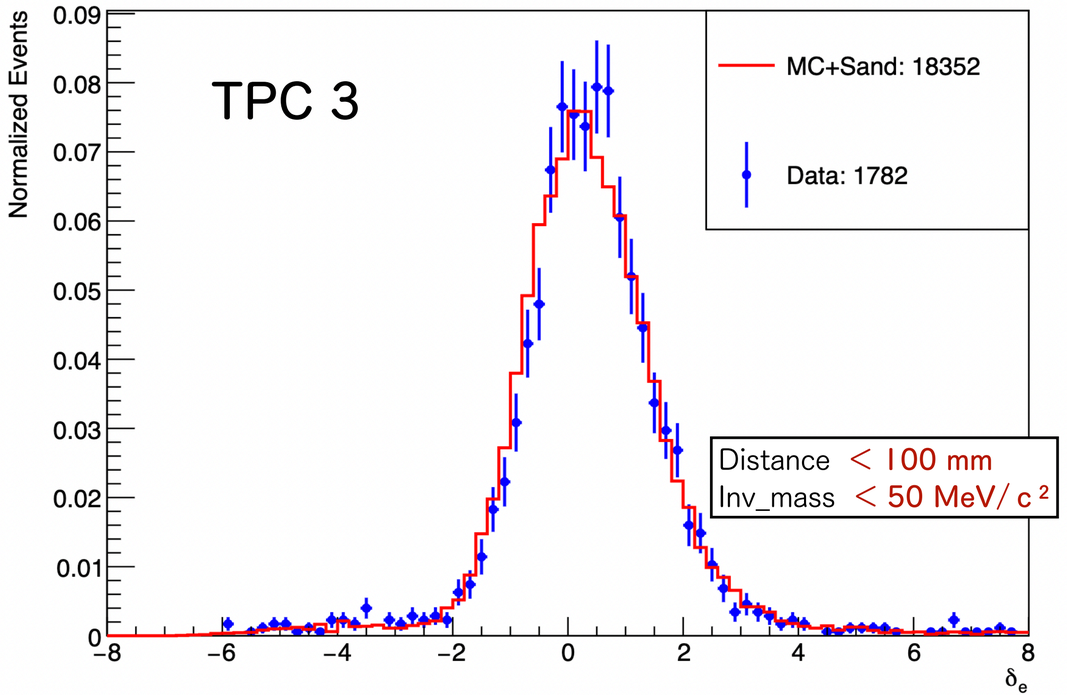
Электроны. Pull

Начало трека в **FGD1/FGD2/SFG/TECAL/PECAL/HAT**

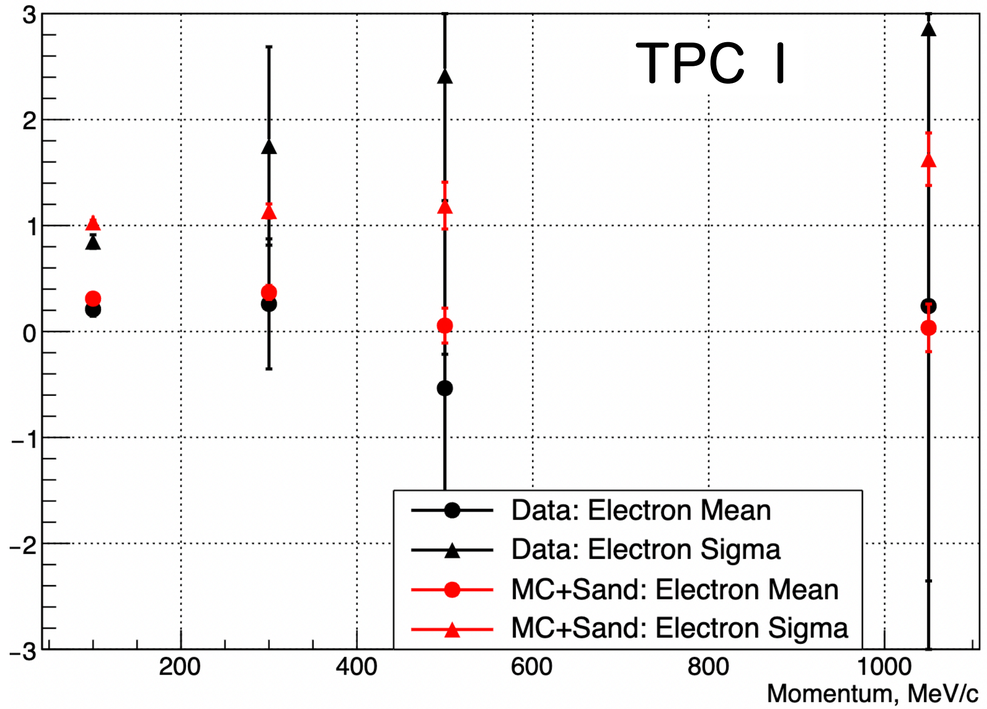
1. Electron candidat cut
2. Secondary electron find
   - 2.1 Quality cut
   - 2.2 FV cut
   - 2.3 Opposite charge
   - 2.4 Distance
   - 2.5 Invariant mass
   - 2.6 ClosestADistanceCut < 1000 mm
   - 2.7 ClosestAInvMassCut < 500 MeV/c²
3. Secondary electron cut

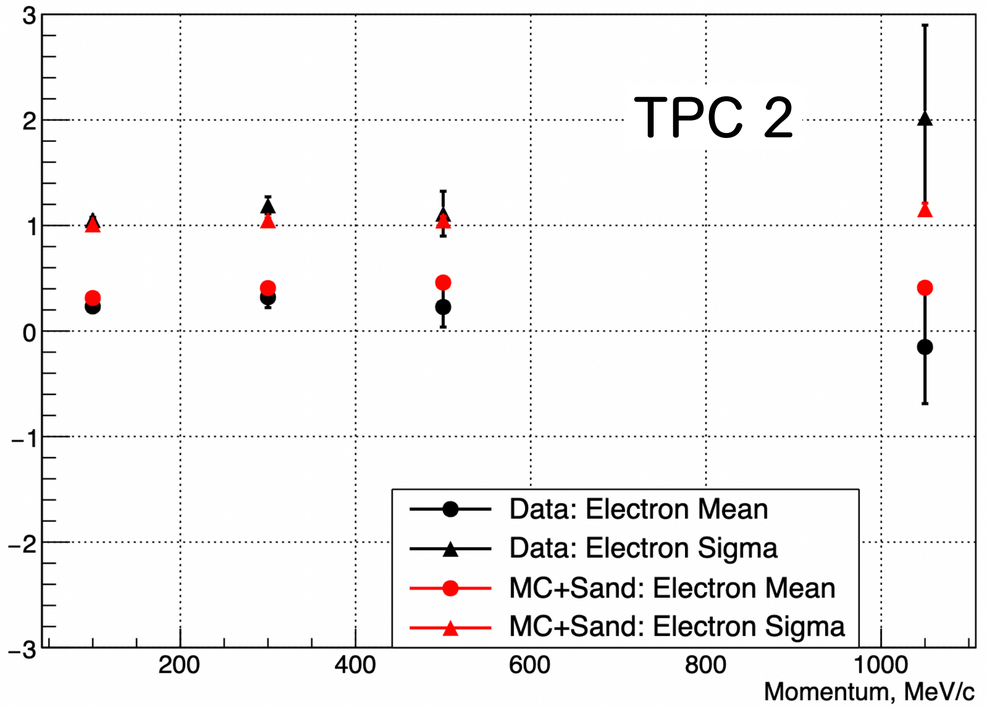


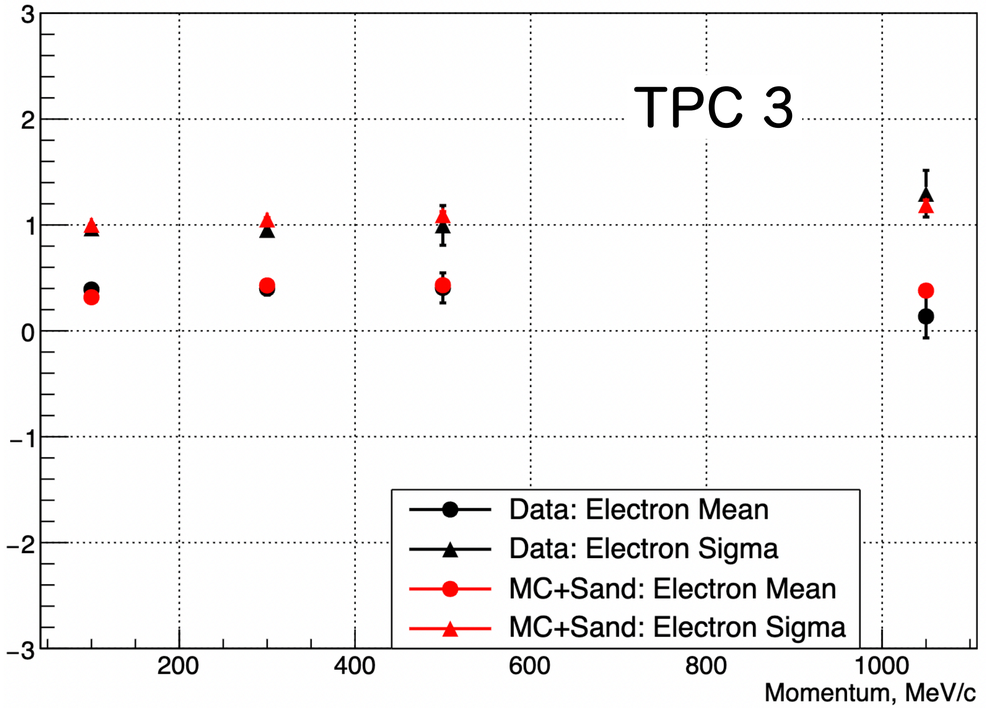




Электроны. Pull_mean и Pull_sigma





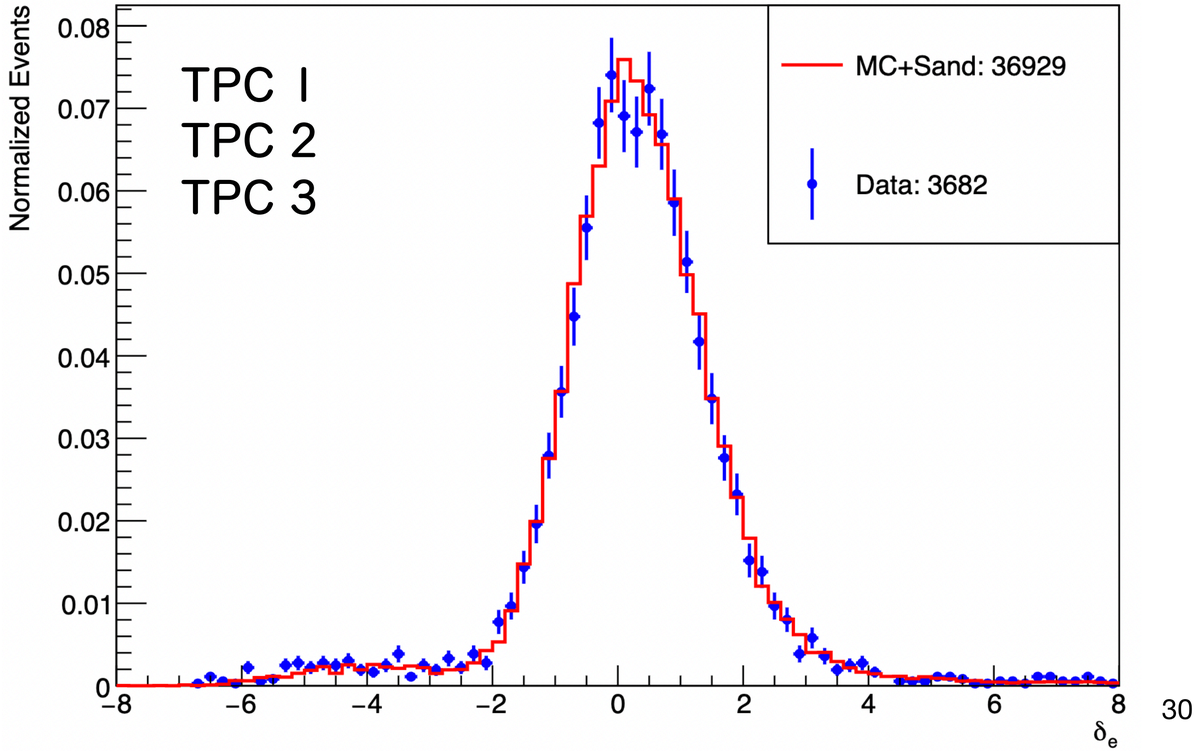


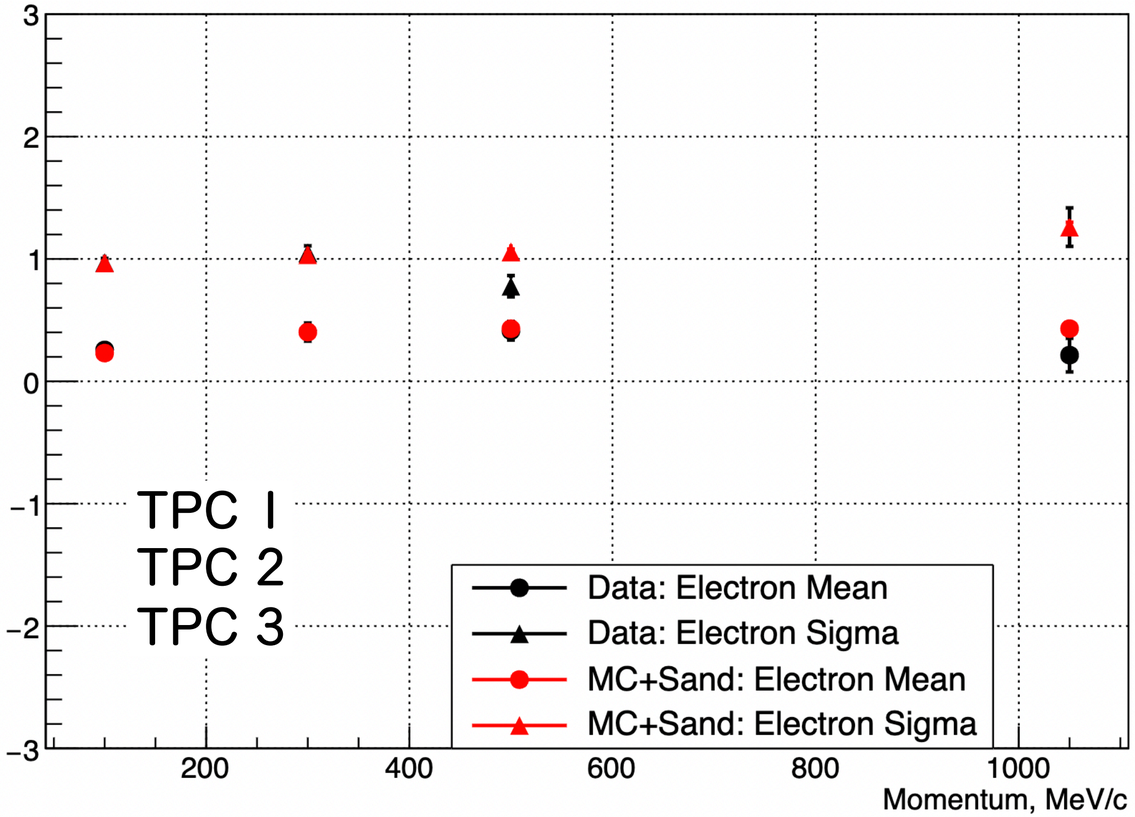
	Pull_mean difference		**Pull_sigma ratio**	
Binning, MeV	Data - MC	|Data - MC|	σ_Data / σ_MC	Ratio error
0 – 200	-0.101	0.101	0.824	0.176
200 — 400	-0.618	0.618	1.539	0.828
400 — 600	-1.778	1.778	2.033	2.246
600 — 1500	+2.604	2.604	1.760	4.808

Электроны. Pull

Начало трека в **FGD1/FGD2/SFG/TECAL/PECAL/HAT**

1. Electron candidat cut
2. Secondary electron find
   - 2.1 Quality cut
   - 2.2 FV cut
   - 2.3 Opposite charge
   - 2.4 Distance
   - 2.5 Invariant mass
   - 2.6 ClosestADistanceCut $<$ 1000 mm
   - 2.7 ClosestAInvMassCut $<$ 500 MeV/c²
3. Secondary electron cut





	Pull_mean difference		**Pull_sigma ratio**	
Binning, MeV	Data - MC	|Data - MC|	σ_Data / σ_MC	Ratio error
0 – 200	+0.036	0.036	1.003	0.039
200 — 400	+0.076	0.076	1.013	0.059
400 — 600	-0.083	0.083	0.735	0.265
600 — 1500	-0.216	0.216	1.000	0.129

Заключение

Выполнена оценка систематических неопределенностей связанных с идентификацией частиц во время-проекционных камерах ближнего детектора ND280 эксперимента T2K:

- Коррекция **dEdx**$^{\mathbf{meas}}$ для данных с использованием треков мюонов, проходящих через все три TPC;
- Параметризация **dEdx**$^{\mathbf{exp}}$ с использованием функции Бете-Блоха;
- Измерен **Pull** для мюонов, протонов, электронов и получены соответствующие значения Mean и Sigma.

Результаты используются для анализа данных ближнего детектора ND280 эксперимента T2K.

Работа выполнена при поддержке гранта РНФ №24-12-00271

MC vs Data

Highland: Production8 version 17

MC

- Run13c : FHC 23.1 × 10^{20} POT ➔ scaled to run13c(total) data POT
- Sand(13c): 3.4 × 10^{20} POT ➔ scaled to total data POT

Data

- Run13c : FHC 2.0 × 10^{20} POT

FHC - Forward Horn Current (neutrino beam mode)

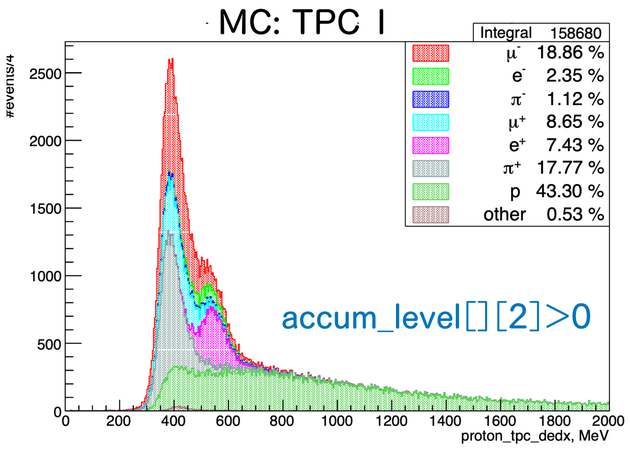
Proton_tpc_dedx

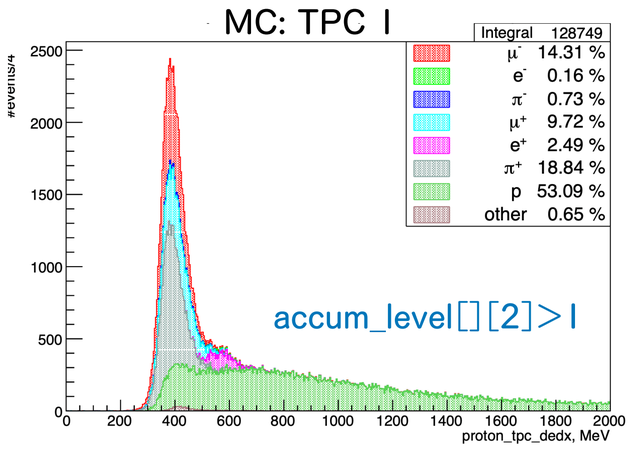
Start in **FGD1/FGD2/SFG/ TECAL/PECAL/HAT**

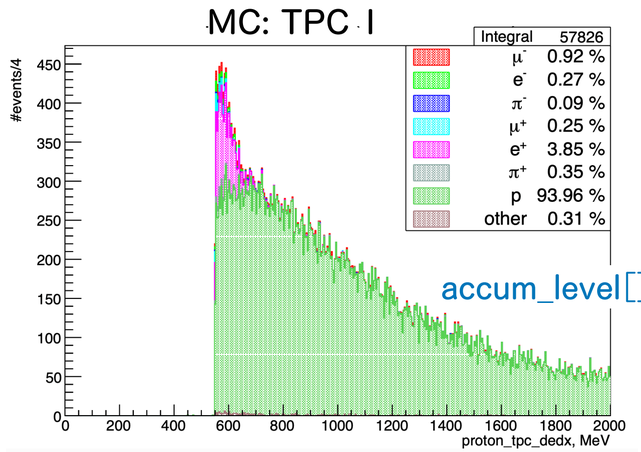
1. Track momentum > 200 MeV/c

1. Track momentum > 200 MeV/c
2. MinCtCut > 550 MeV

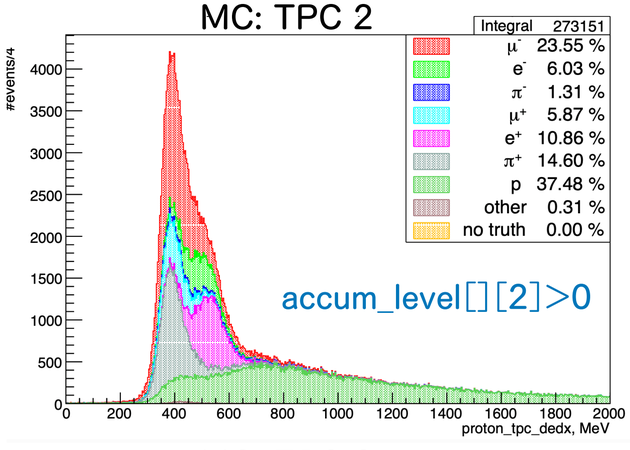
MC: TPC 1

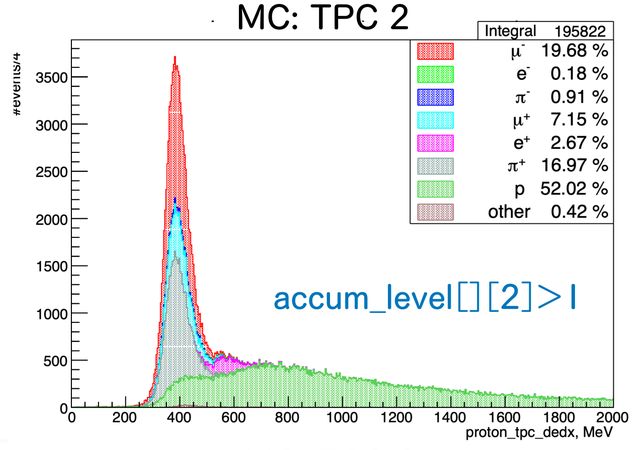


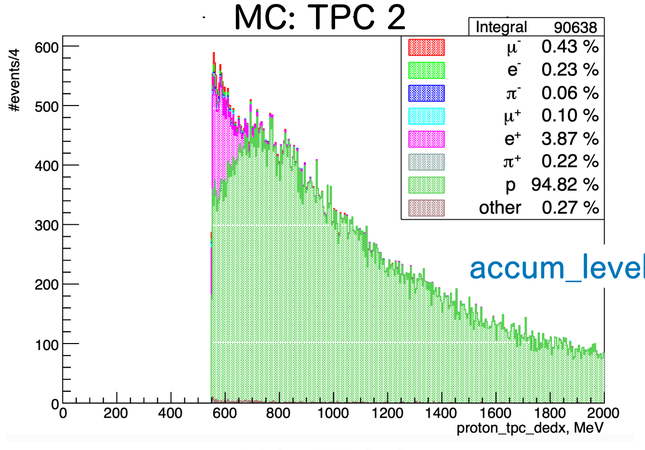




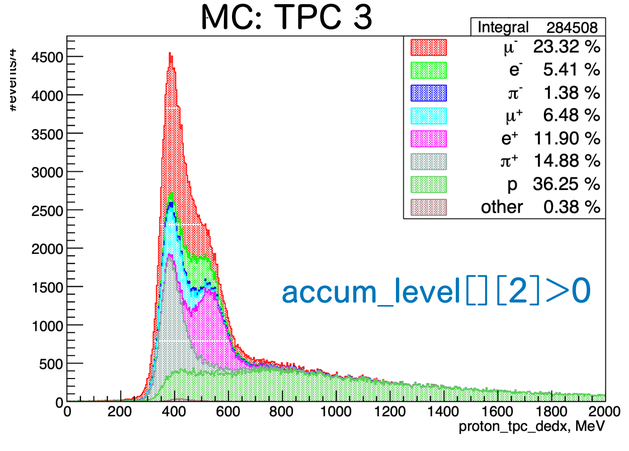
MC: TPC 2

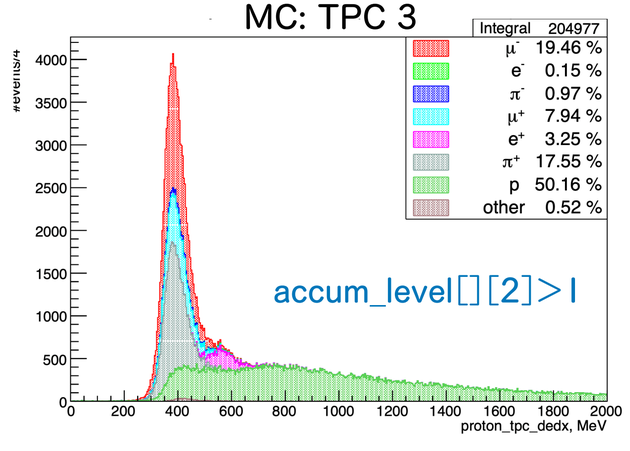


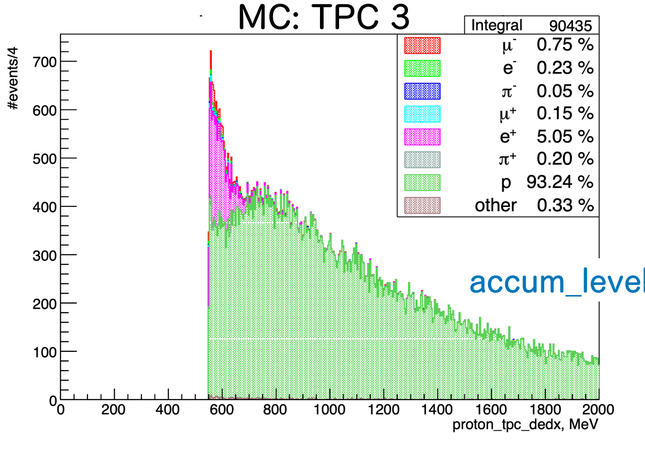




MC: TPC 3







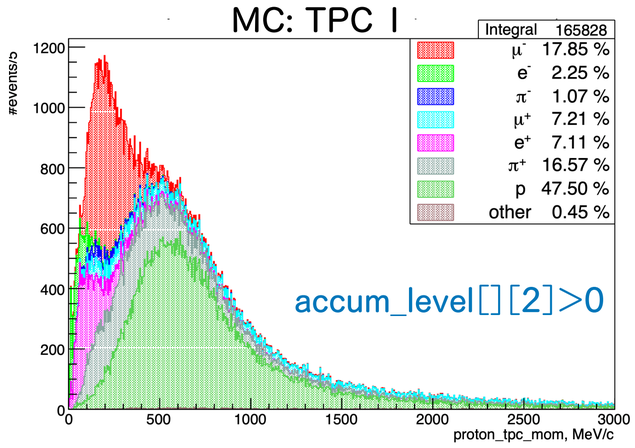
Proton_tpc_mom

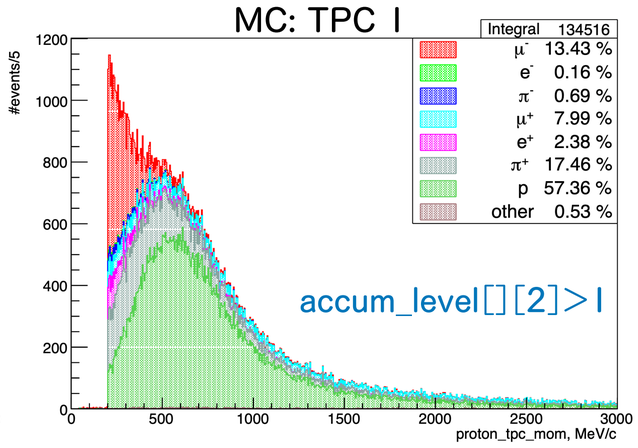
Start in **FGD1/FGD2/SFG/ TECAL/PECAL/HAT**

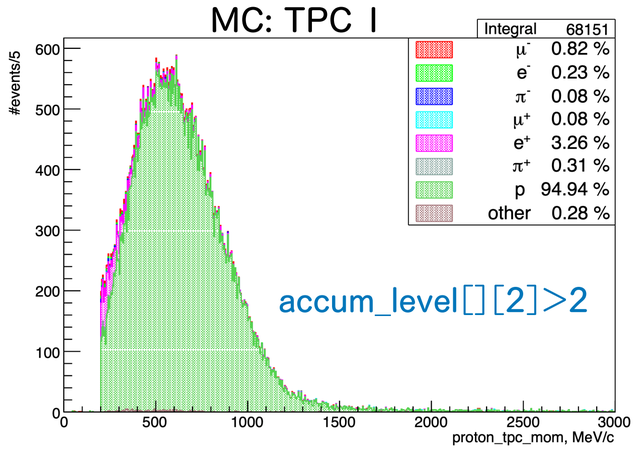
1. **Track momentum > 200 MeV/c**

1. **Track momentum > 200 MeV/c**
2. **2. MinCtCut > 550 MeV**

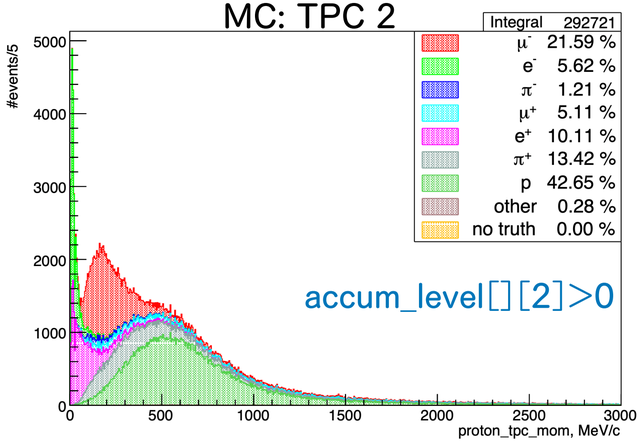
MC: TPC 1

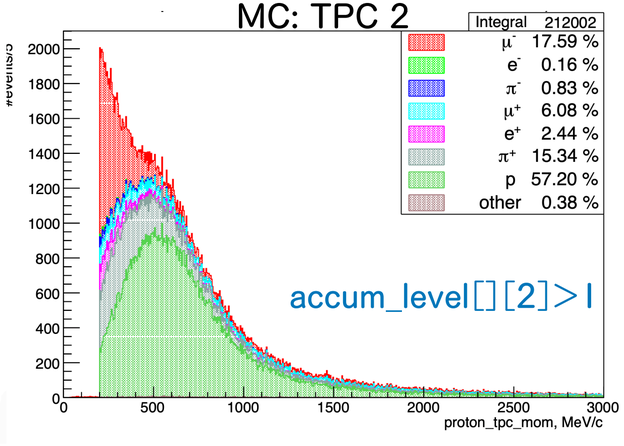


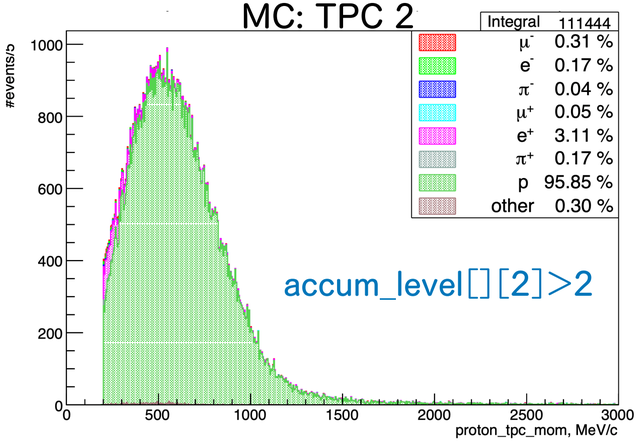




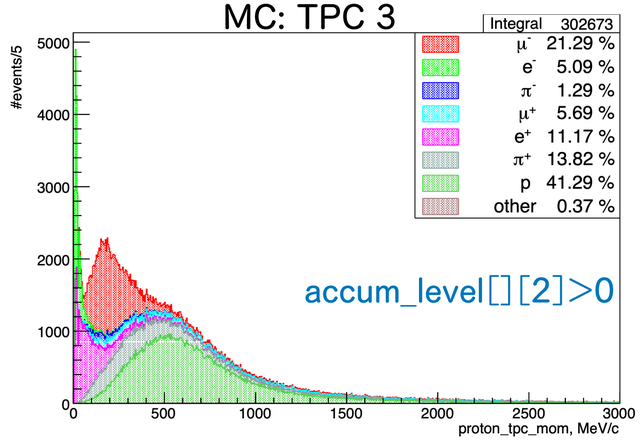
MC: TPC 2

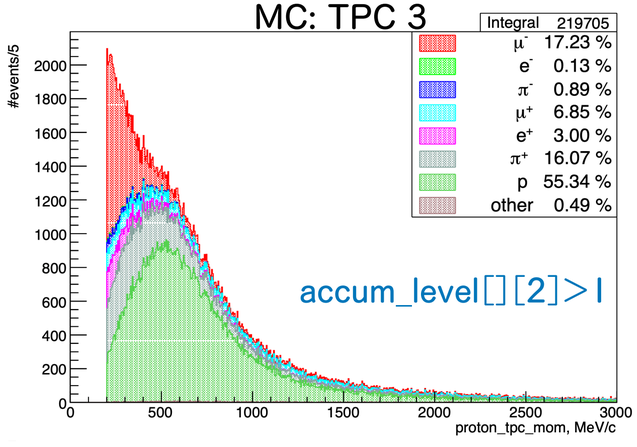


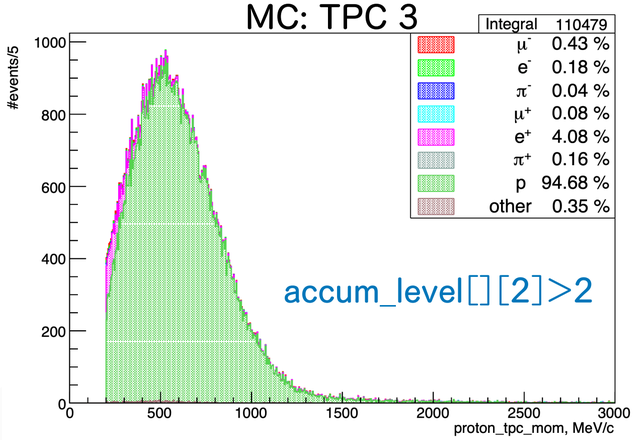




MC: TPC 3

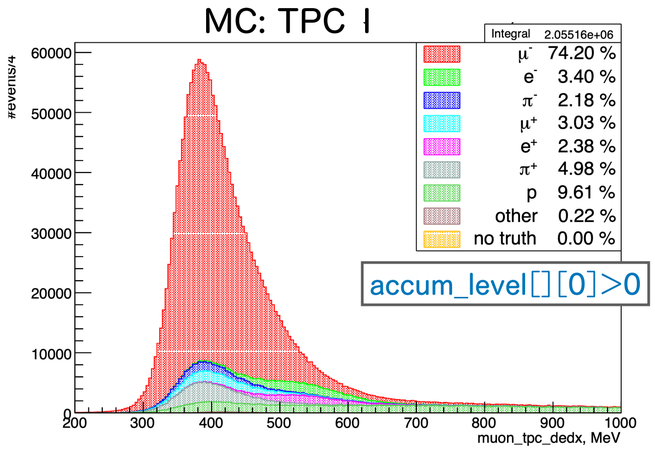


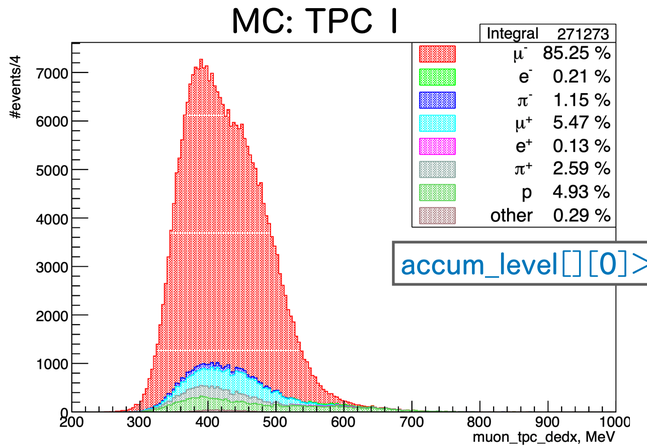


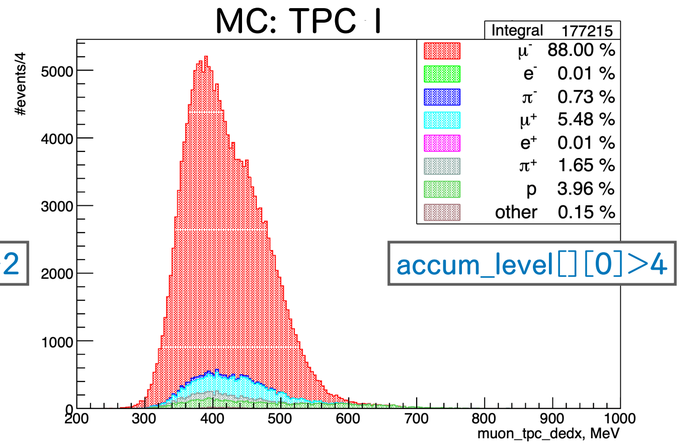


Muon_tpc_dedx

MC: TPC 1







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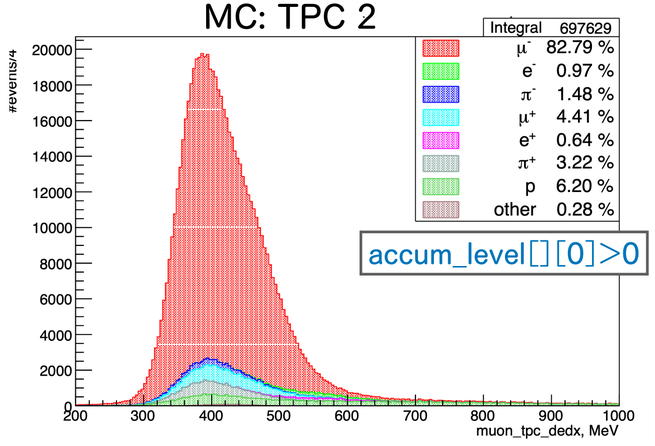
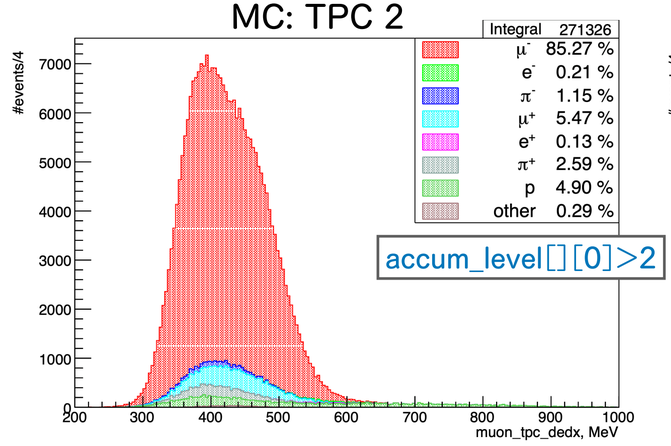
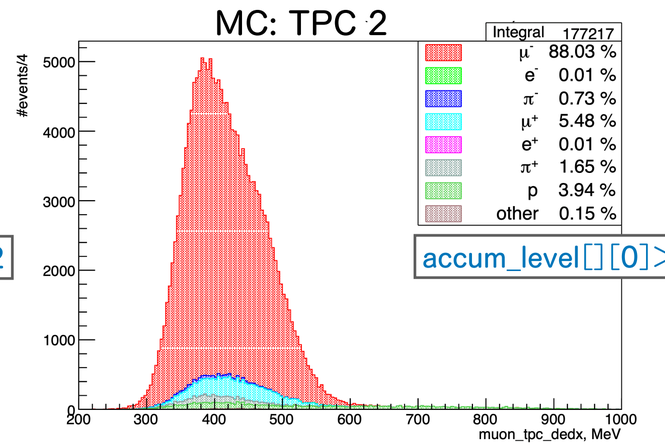
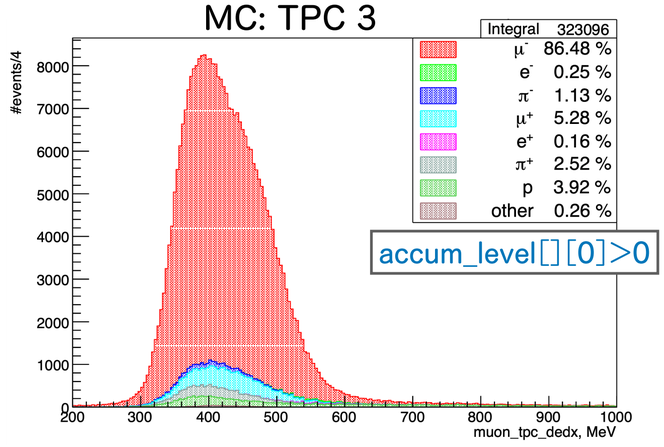
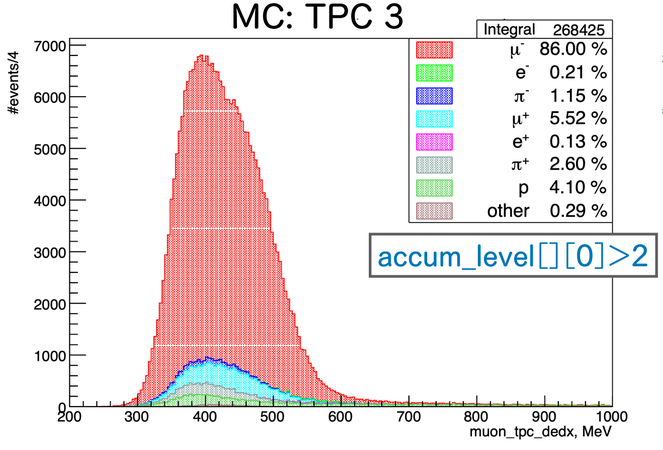


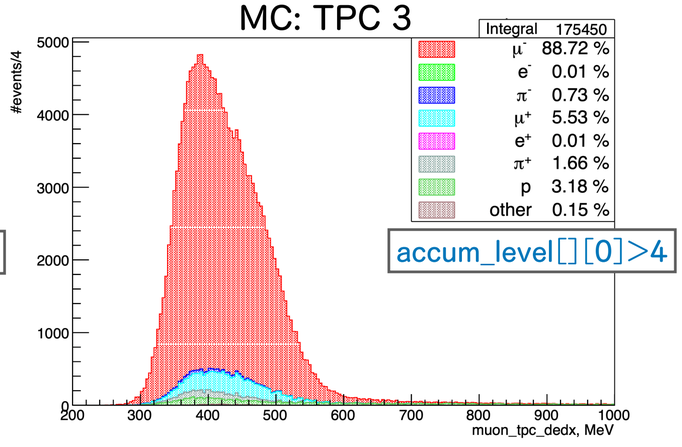




MC: TPC 3





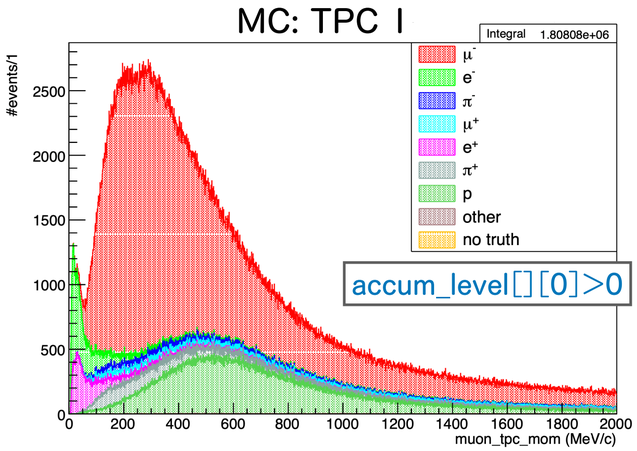


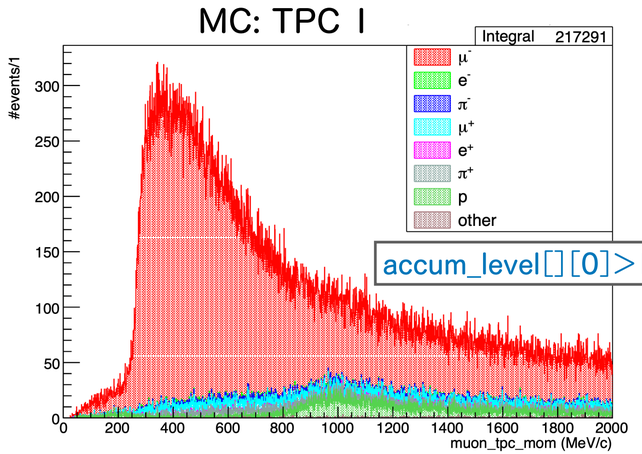
Muon_tpc_mom

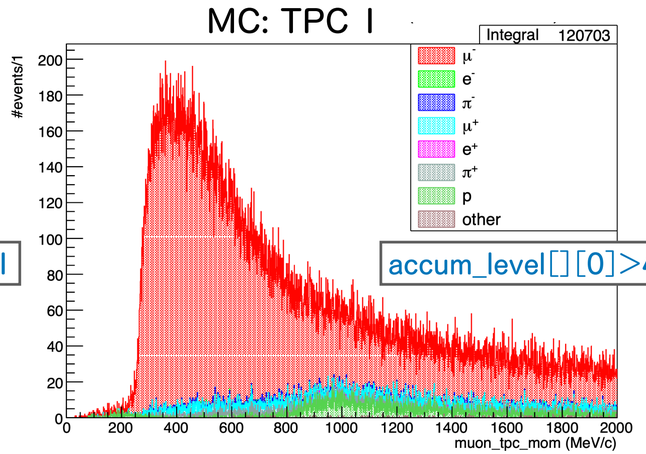
MC: TPC 1

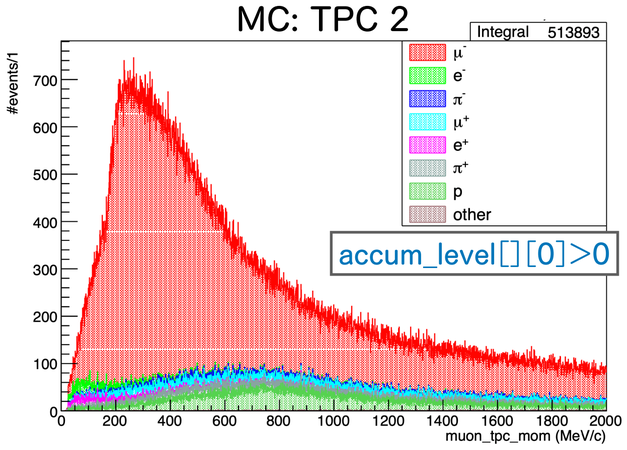
MC: TPC 2

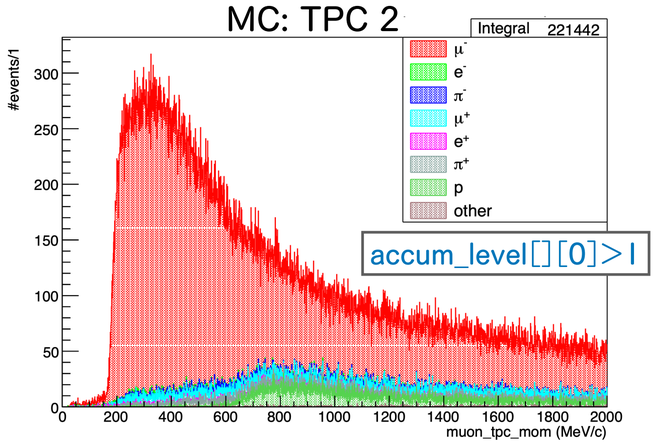
MC: TPC 3

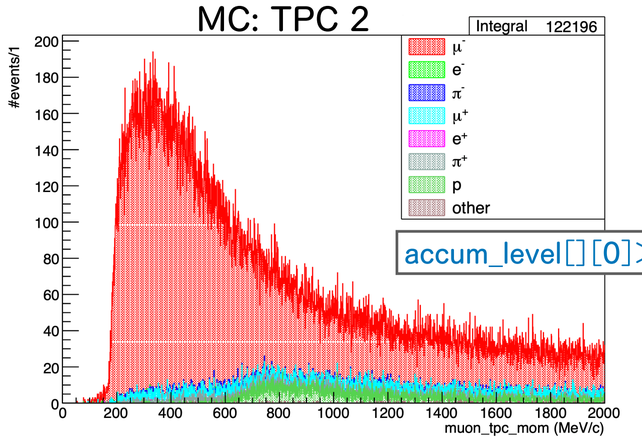


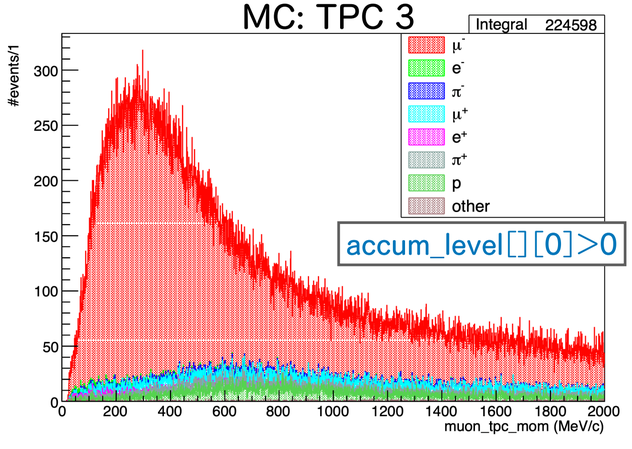


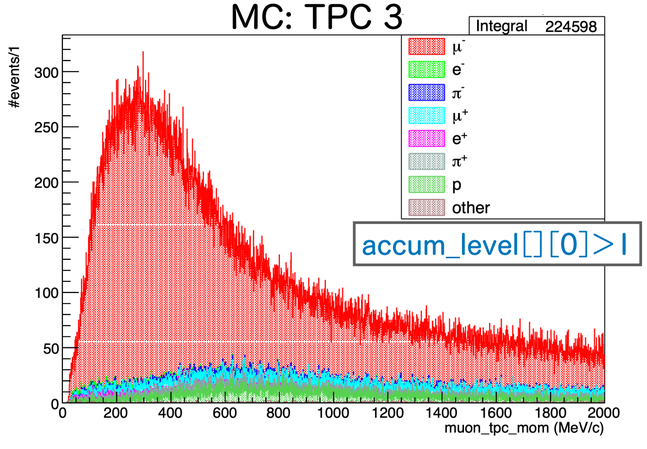


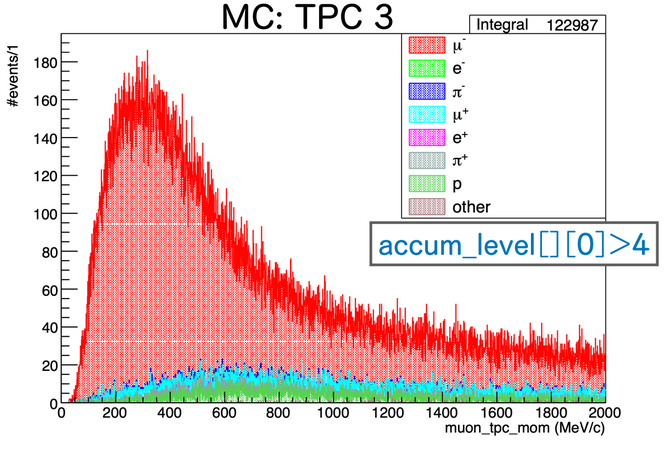






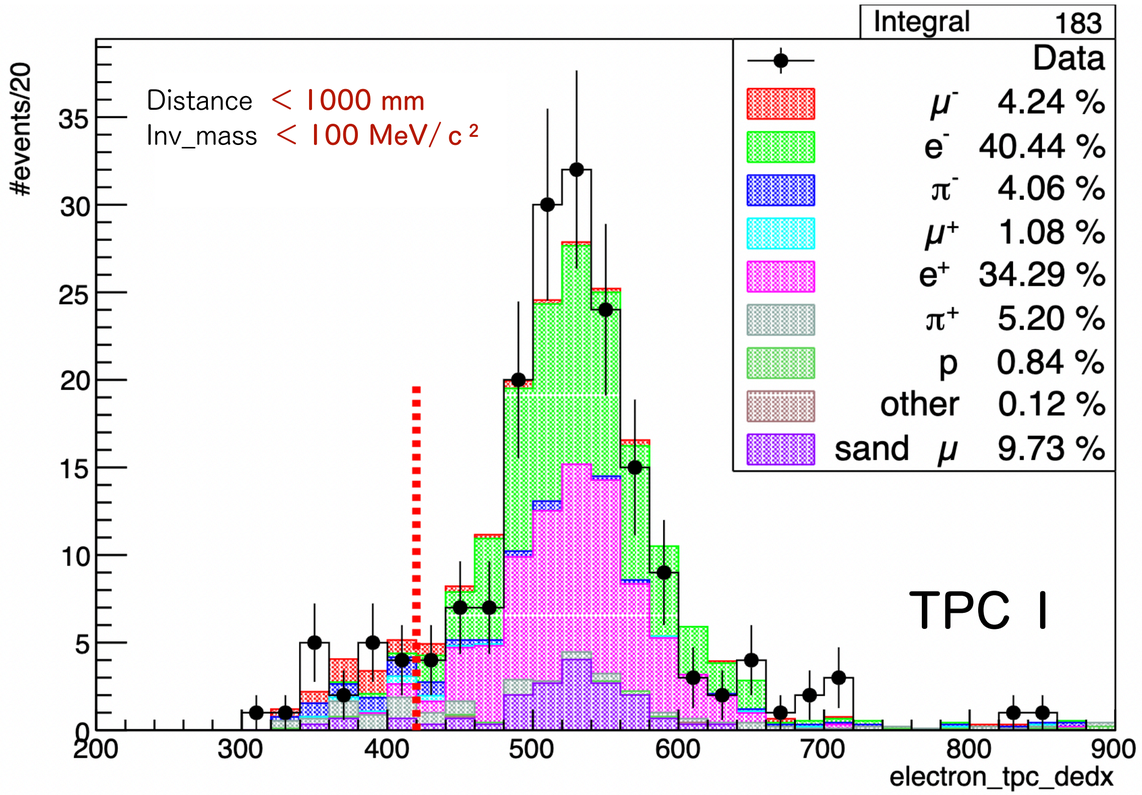




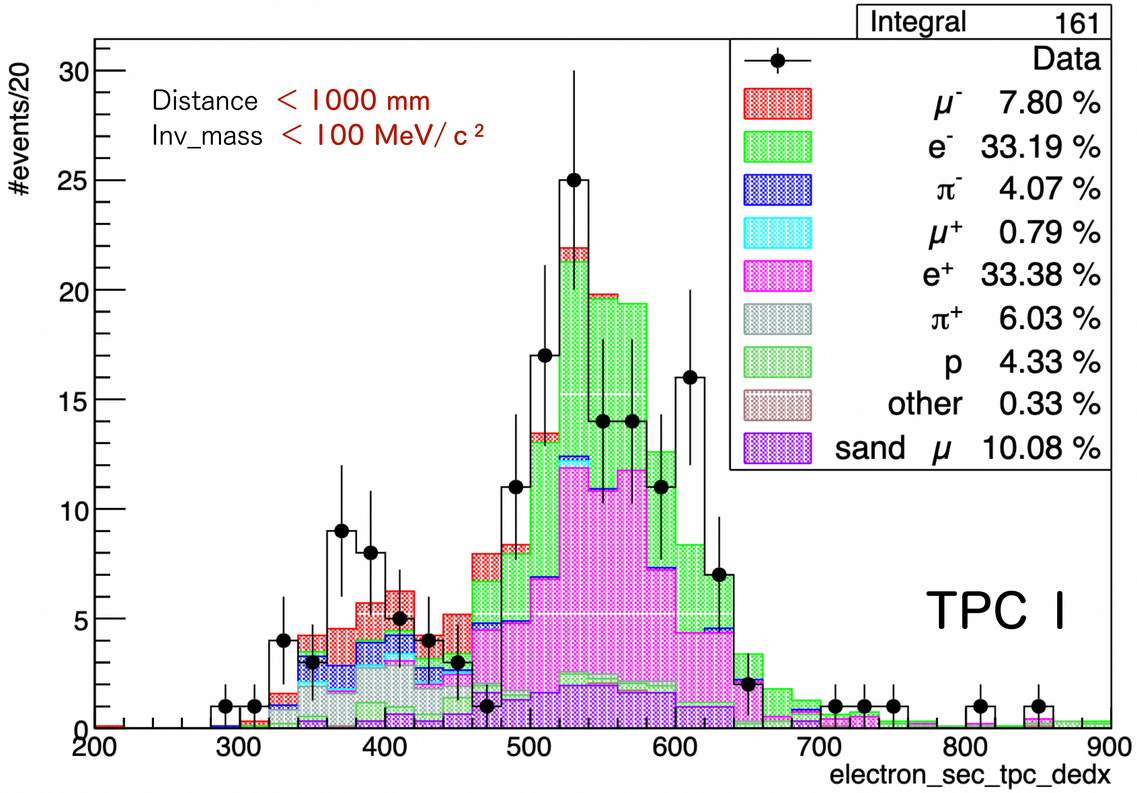


TPC_dedx. TPC1

Primary



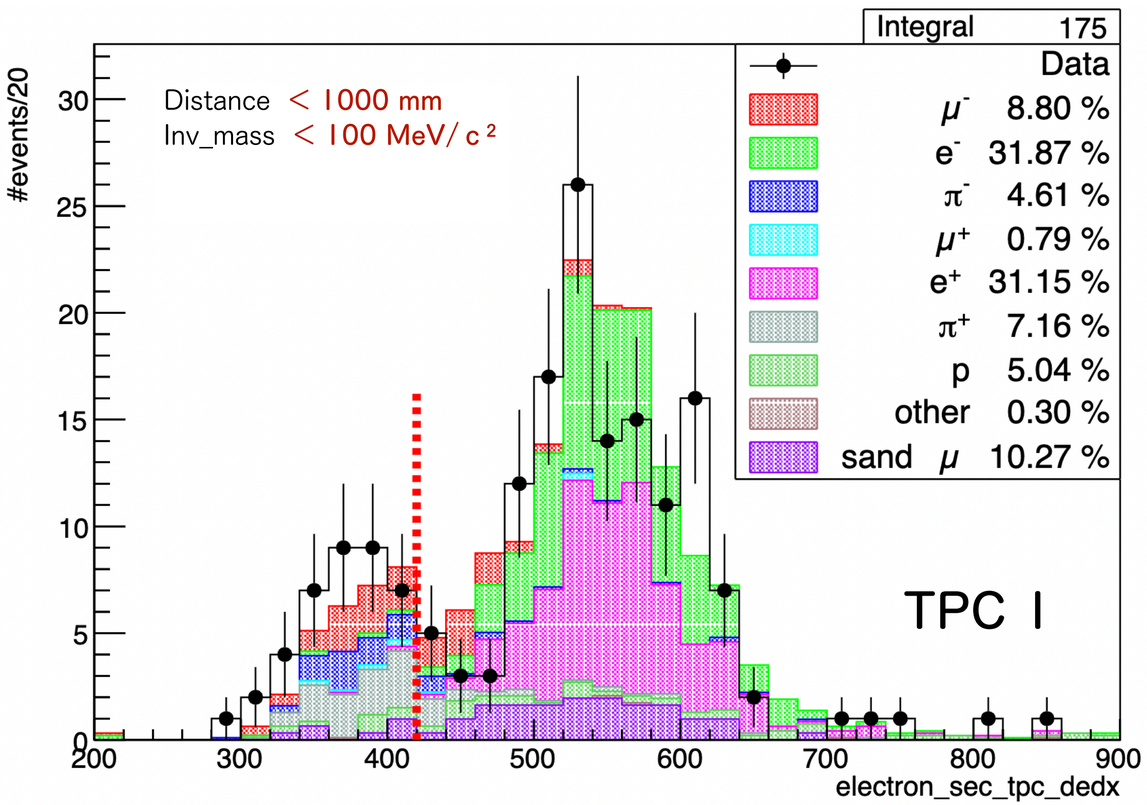
Secondary



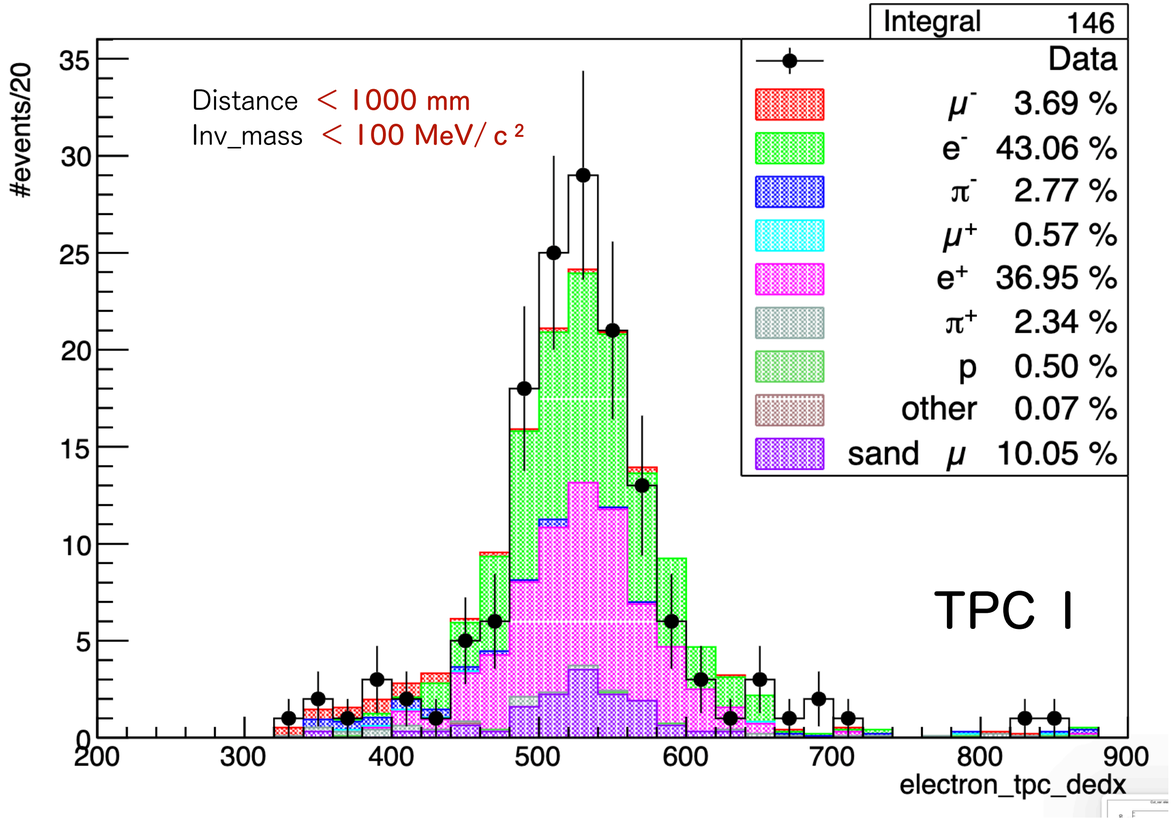
electron_tpc_dedx > 420

TPC_dedx. TPC1

Secondary



Primary



electron_sec_tpc_dedx > 420