π-Ar Quasi-elastic Scattering and Transverse Kinematic Imbalance Study

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ProtoDUNE π-Ar QE and TKI Meeting

16 August 2022

Generator Level Studies

GEANT4 and FLUKA

- 1 GeV/c π^+ beam on thin (1 cm) LAr target

Event topology - Xianguo's idea

- Single nucleon knocking-out
  - Quasi-elastic : $\pi^+ + {}^{40}Ar \rightarrow \pi^+ + p + {}^{39}Cl$
  - Charge exchange : $\pi^+ + {}^{40}Ar \rightarrow \pi^0 + p + {}^{39}Ar$
  - To study π^+-Ar quasi-elastic scattering cross section, TKI, and Fermi motion
- Double nucleon knocking-out
  - $\pi^+ + {}^{40}Ar \rightarrow \pi^+ + p + p + {}^{38}S$
  - $\pi^+ + {}^{40}Ar \rightarrow \pi^- + p + p + {}^{38}Cl$
  - A unique chance to study meson exchange with known incoming beam energy
- I reproduced Xianguo's work and studied background compositions

Single Nucleon Knocking-out : Neutral Current

Signal process : $\pi^+ + {}^{40}Ar \rightarrow \pi^+ + p + {}^{39}Cl$

Particle selection

- Signal particles
  - Proton : |P| > 300 MeV
  - π^+ : |P| > 100 MeV
  - π^0 : full acceptance
- Background particles
  - π^-, Kaon, and muon : |P| > 100 MeV

Event selection

- Exact number of signal particles : N(p) = 1, N(π^+) = 1, and N(π^0) = 0
- Allow any number of photons
- No background particles

Single Nucleon Knocking-out : Neutral Current

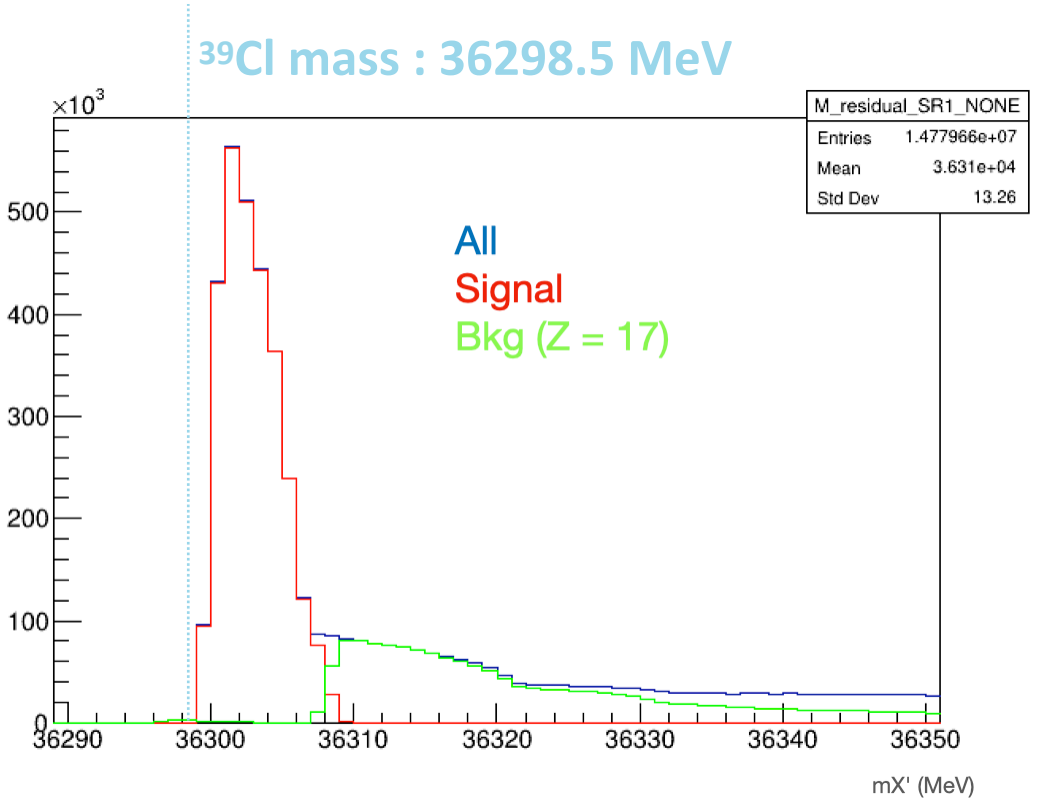
Residual nuclear (X) mass

- Using four-vectors of beam, ^{40}Ar (at rest), out-going π+ and proton
  - Four-vector of X : beam - ^{40}Ar - π^+ - p

Signal : X is ^{39}Cl

Background : other nuclei at final state

- Bkg(Z = 17)
  - Cl with different atomic mass
  - Multiple neutrons at final state



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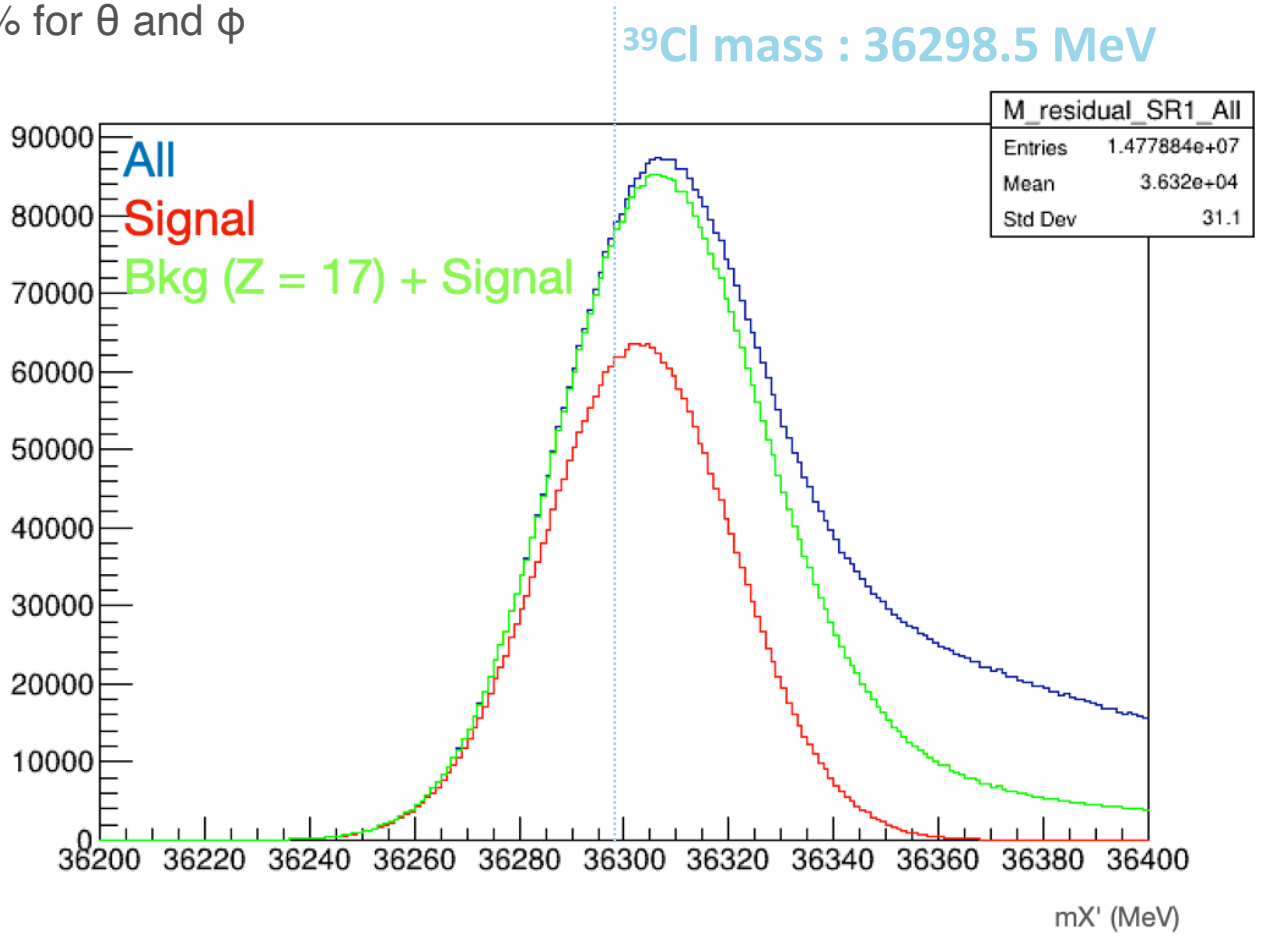
Single Nucleon Knocking-out : Neutral Current

Smearing on final state particles

- Momentum : π^+ (2%), π^0 (5%), and proton (2%)
- Angle : 5% for θ and ϕ



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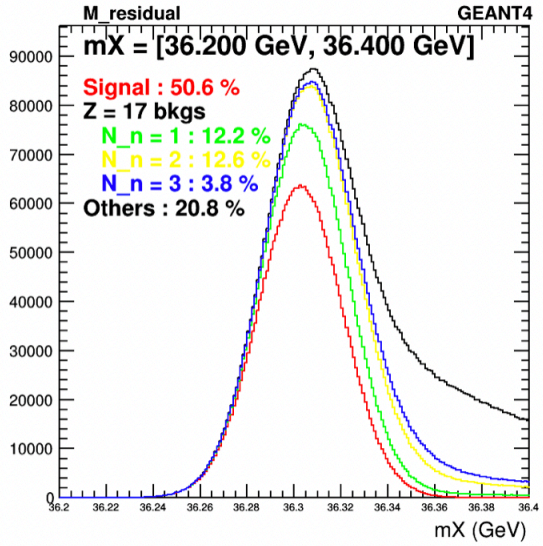
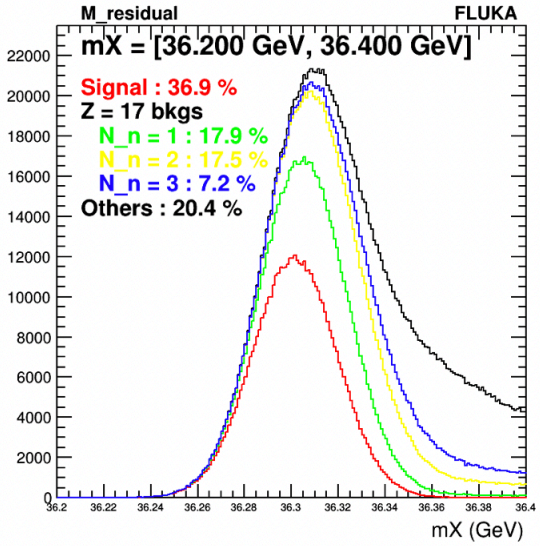
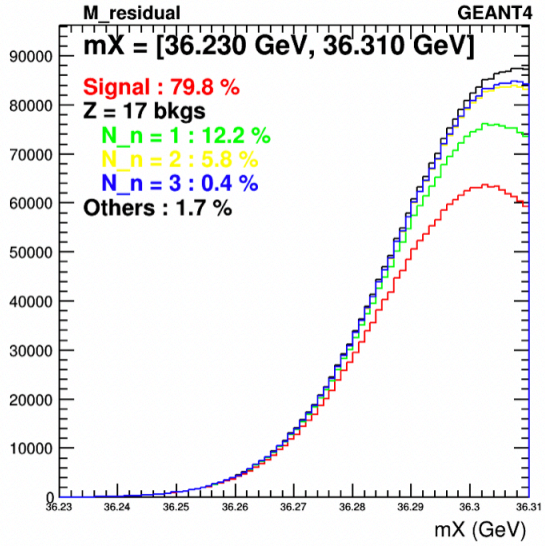
Single Nucleon Knocking-out : Neutral Current

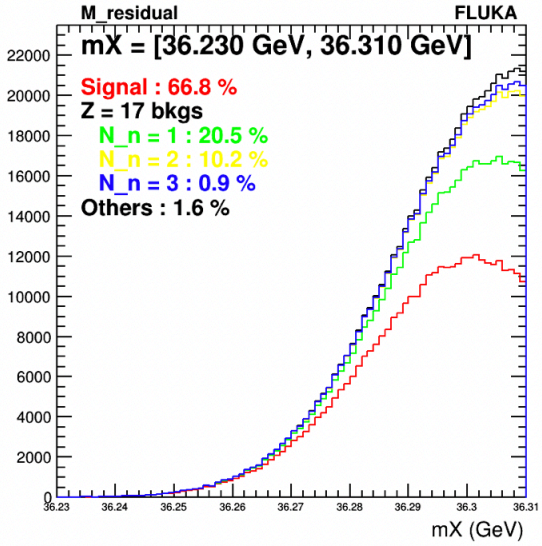
Background composition

- GEANT4 vs FLUKA
- 70 - 80% signal fraction with mX < 36.310 GeV cut









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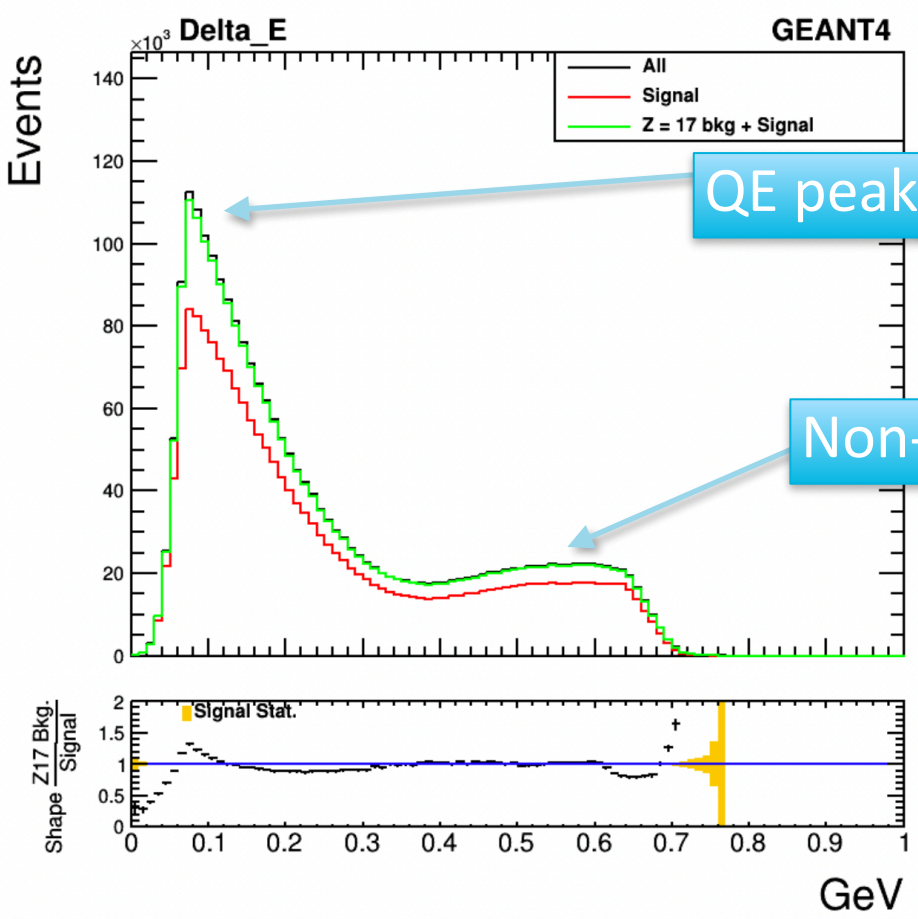
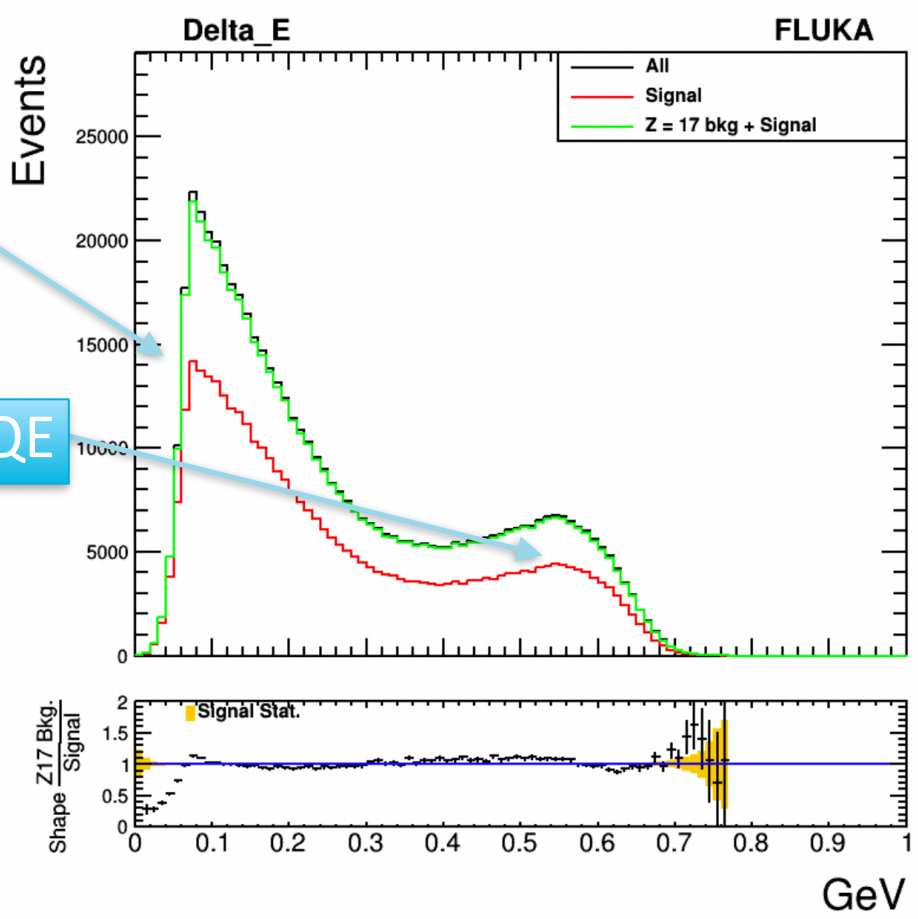
Single Nucleon Knocking-out : Neutral Current

Energy loss of π+ : $E_{incoming}$ - $E_{outgoing}$

- GEANT4 vs FLUKA





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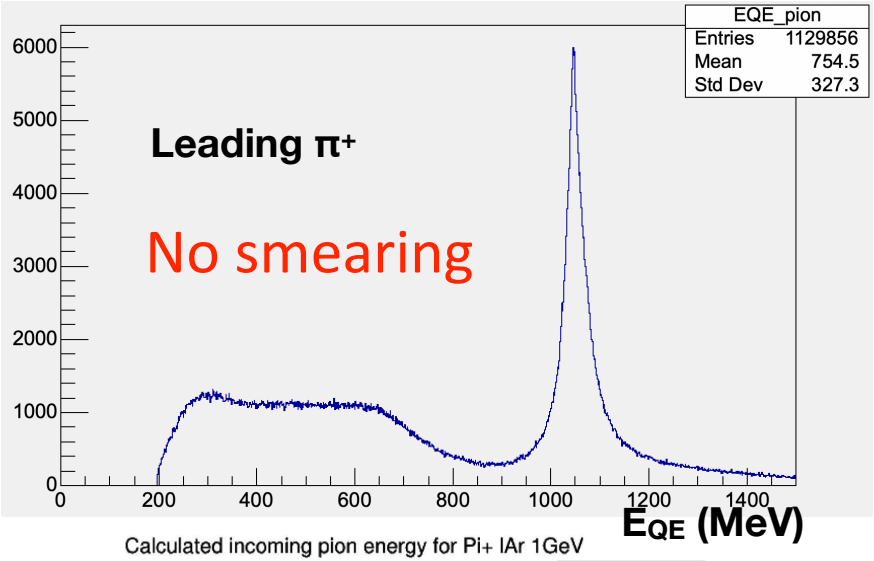
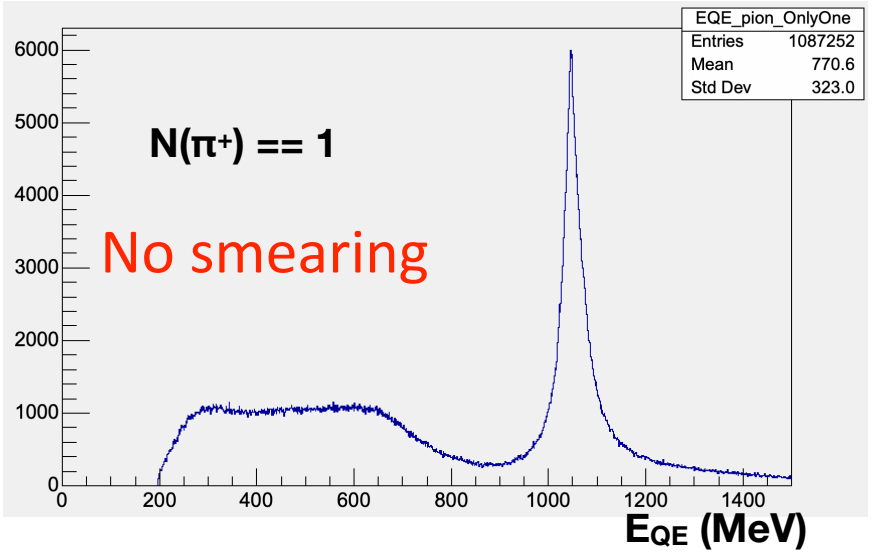
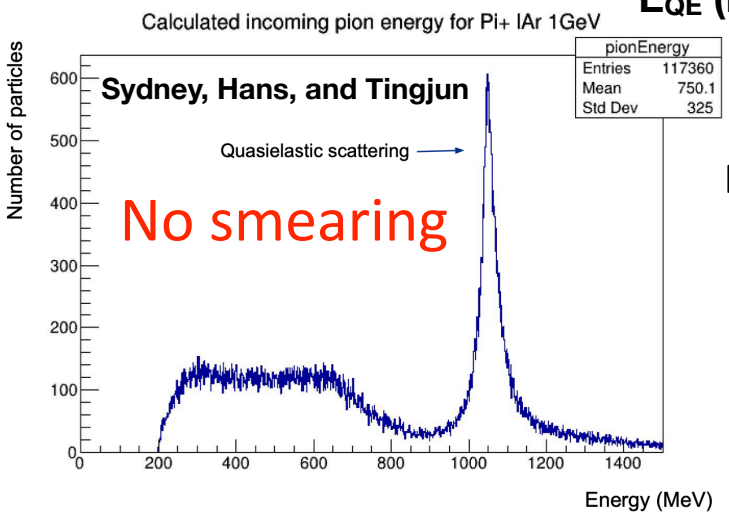
Study for Quasi-elastic Scattering of Charged Pions

Can we select QE events using only out-going pion and not other final state particles? [link]







For ν_μ CCQE, m(μ) → m(π+)

$$E_\pi^{QE} = \frac{m_p^2-(m_n-E_b)^2-m_\pi^2+2(m_n-E_b)E_\pi}{2(m_n-E_b-E_\pi+|\vec{p_\pi}|cos\theta)}$$

m_p: proton mass (938.272 MeV/c^2)

m_n: neutron mass (939.565 MeV/c^2)

m_π: pion mass (139.57 MeV/c^2)

E_b: binding energy of a single nucleon in the nucleus (40 MeV)

E_π: outgoing pion energy (MeV)

E_π^{QE}: calculated incoming pion energy (MeV)

p_π: outgoing pion momentum (MeV/c)

θ: angle between the z axis and the outgoing pion momentum vector

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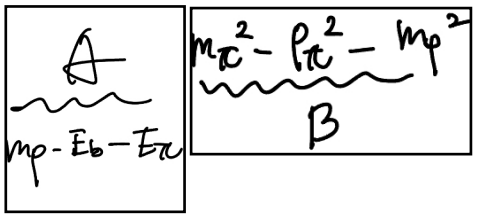
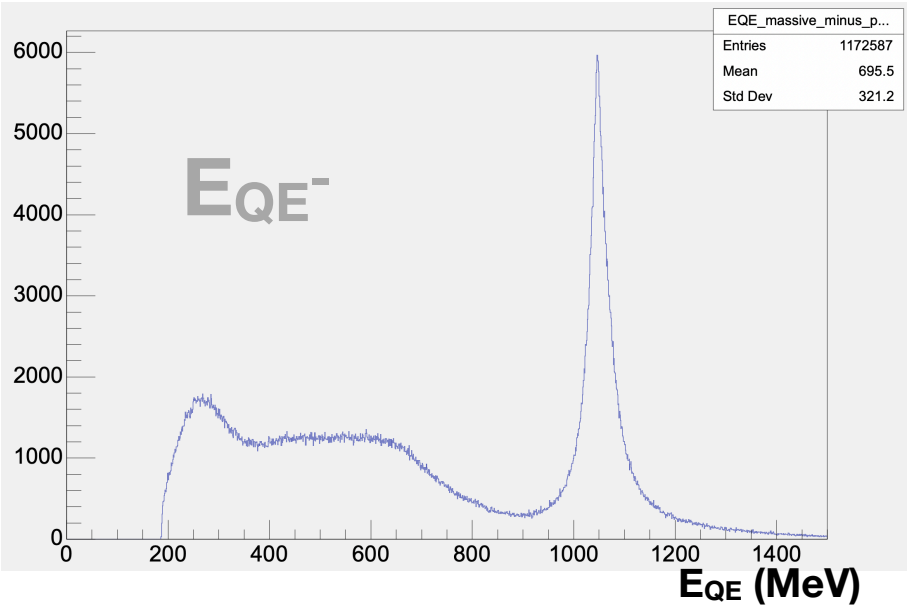
Study for Quasi-elastic Scattering of Charged Pions

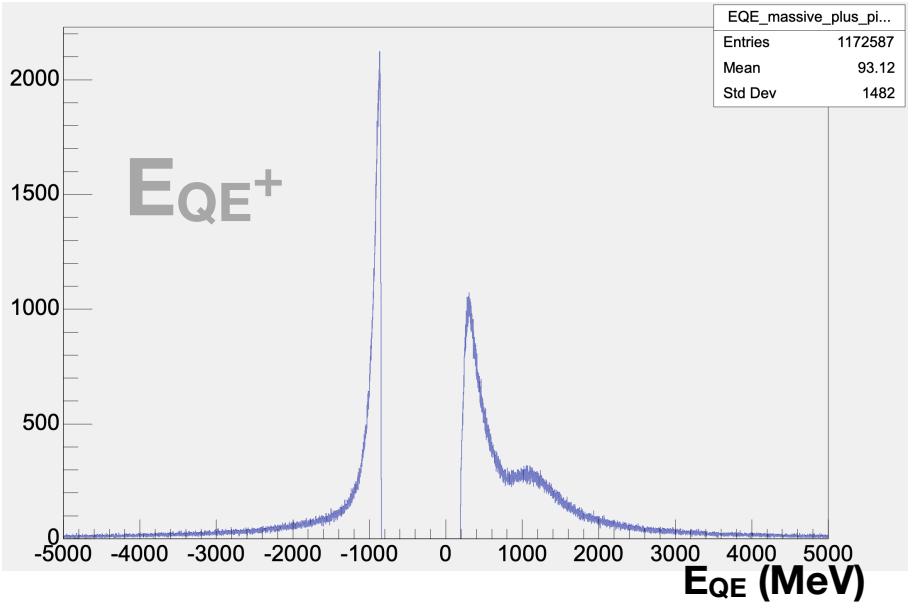
E_{QE} using massive incoming pion

$$4E_0^2\left(A^2 - P_\pi^2\cos^2\theta\right) + 4AE_0(A+B) + (A+B)^2 + 4m_p^2 P_\pi^2\cos^2\theta = 0$$



Two solutions for E_0, E_{QE}^+ and E_{QE}^-

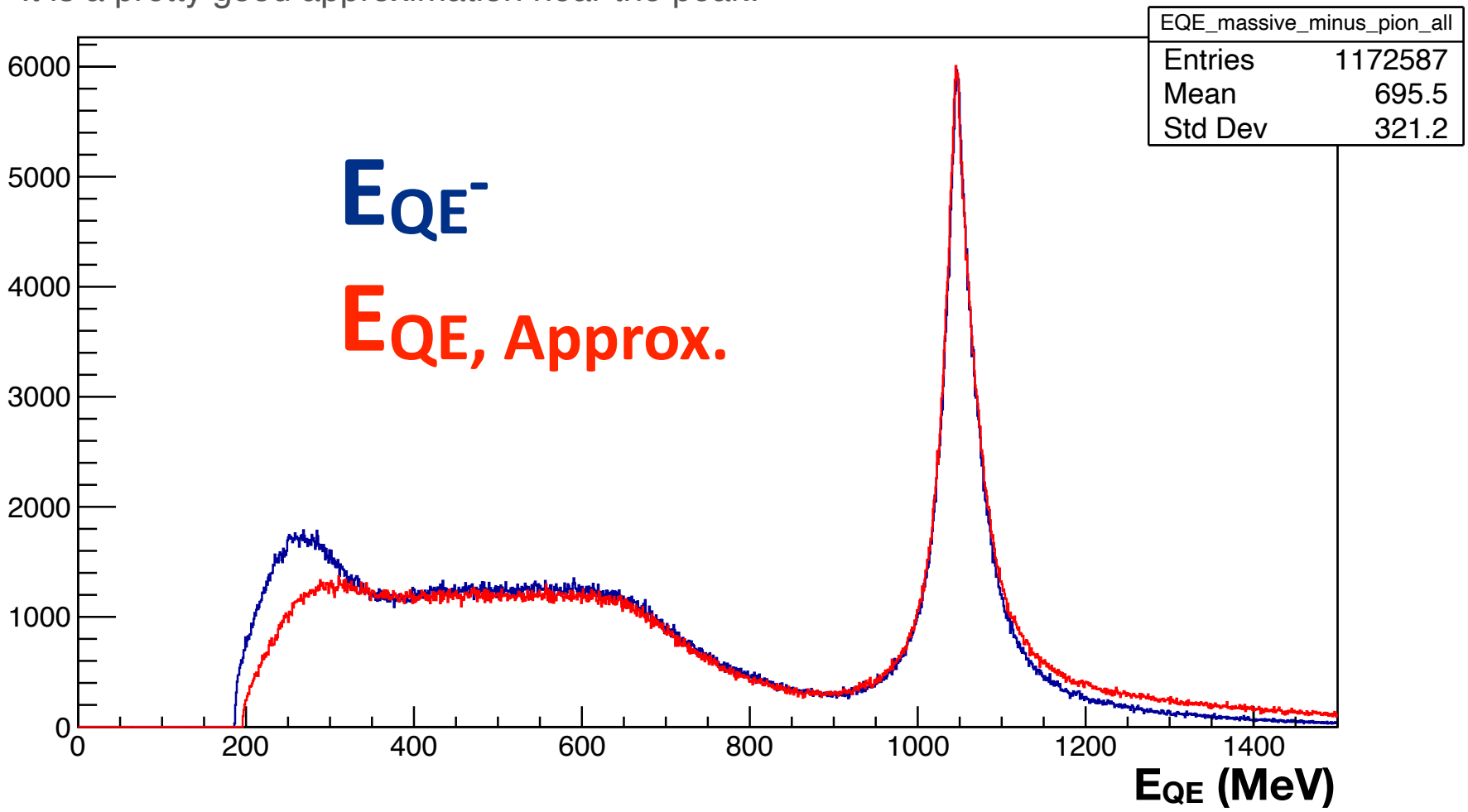




Study for Quasi-elastic Scattering of Charged Pions

Comparison between E_{QE}- and the approximated formula

- It is a pretty good approximation near the peak!



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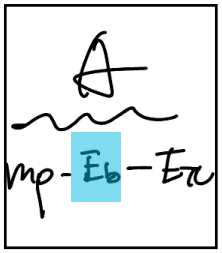
Study for Quasi-elastic Scattering of Charged Pions

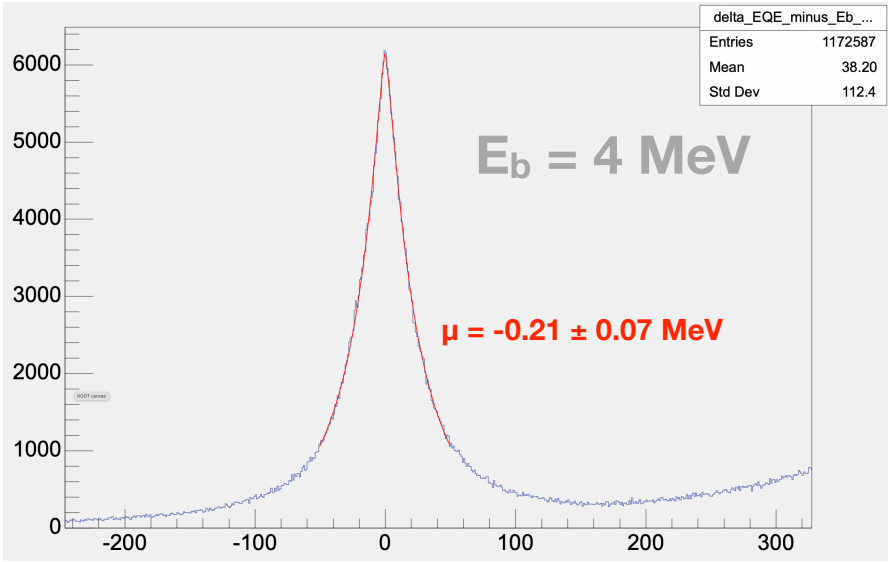
What is binding energy values used by the GEANT4?

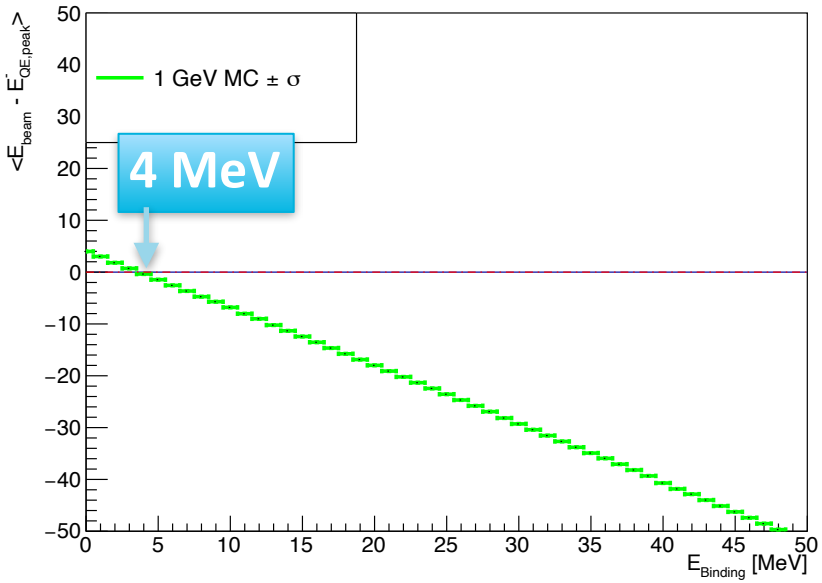
- Scanned $E_{binding}$ in 0 - 50 MeV region to see which value gives E_{QE}^{-} - E_{Beam} = 0 at the peak



- Fitting function

$$f(x) = \frac{a}{1 + (|x-\mu|/\sigma)^{\beta}} + bx + c$$





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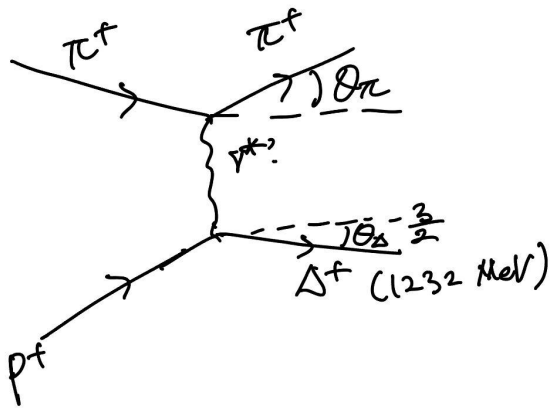
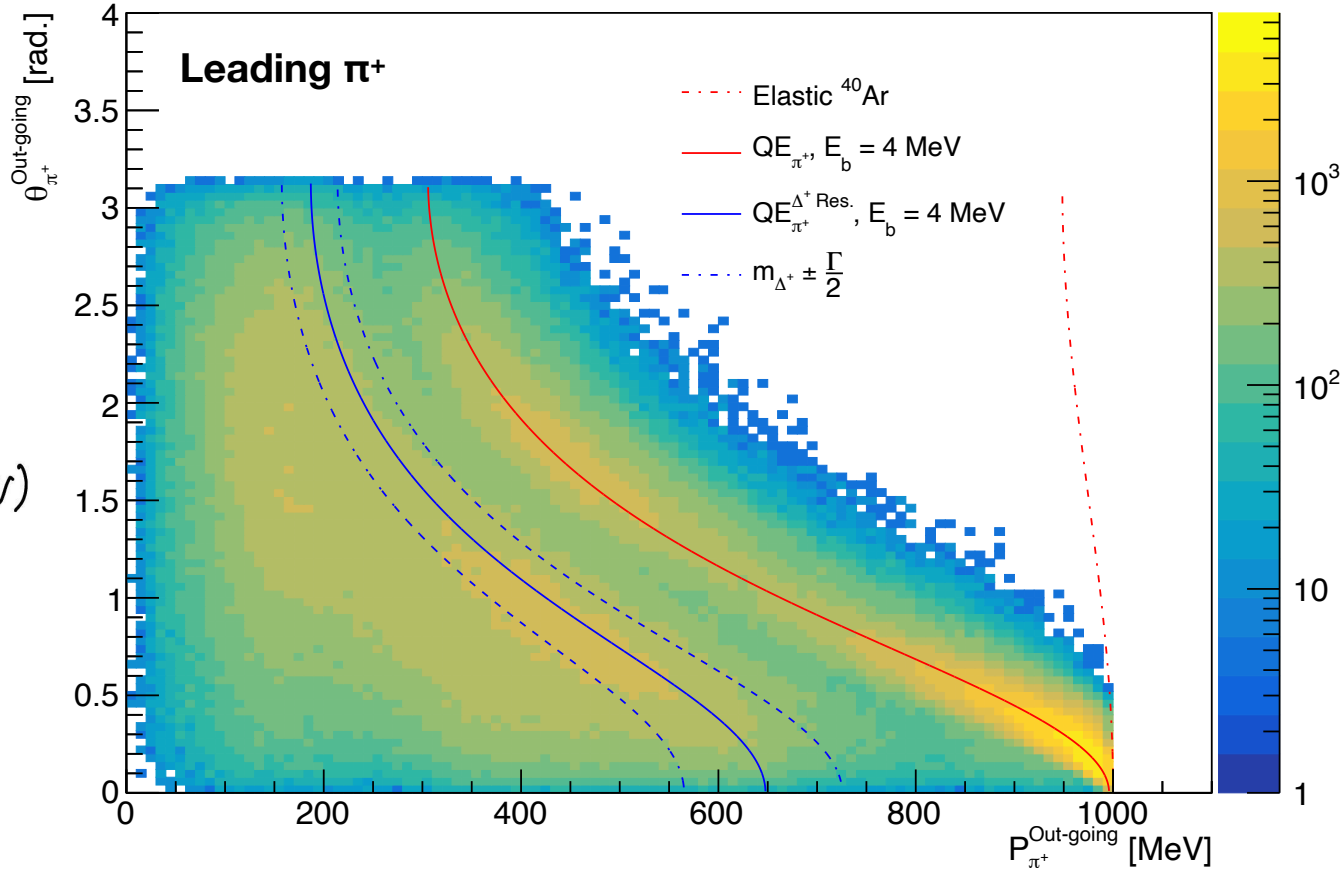
Study for Quasi-elastic Scattering of Charged Pions

2D figure : outgoing π^+ momentum vs outgoing π^+ angle

- It seems that Δ^+ resonance QE is also simulated
- There are many interesting structures that can be studied





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Used Samples for ProtoDUNE-SP Study

MC

- PDSPProd4a_MC_**1GeV**_reco1_sce_datadriven_v1_ntuple_v09_41_00_03.root

Data

- PDSPProd4_data_**1GeV**_reco2_ntuple_v09_41_00_04.root

Input beam root file

- G4beamlineVersion3.06

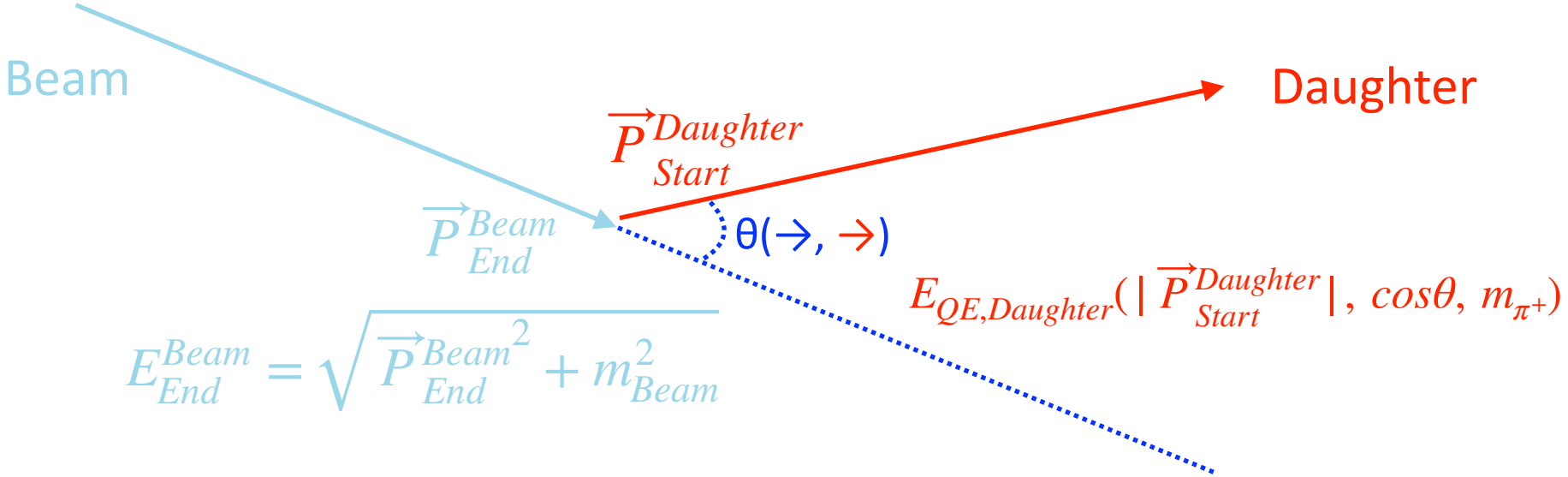
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Using ProtoDUNE MC samples

- Truth level information of 1 GeV/c beam MC sample

Event Selection

- Daughters not coming from broken beam track
  - True beam ID ≠ True daughter



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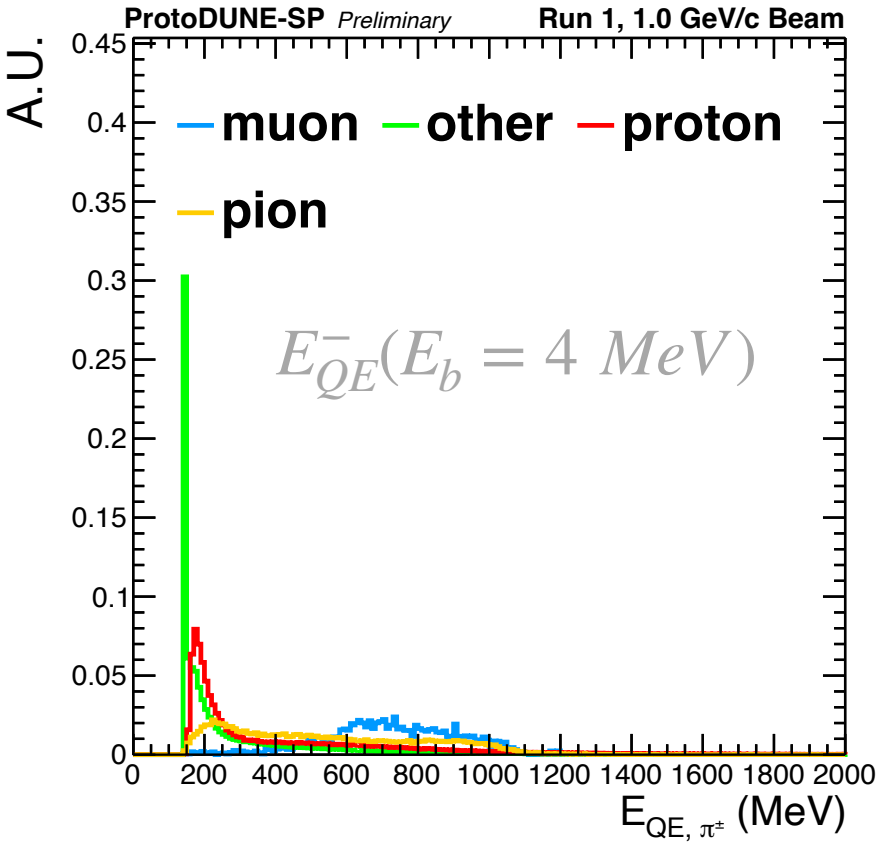
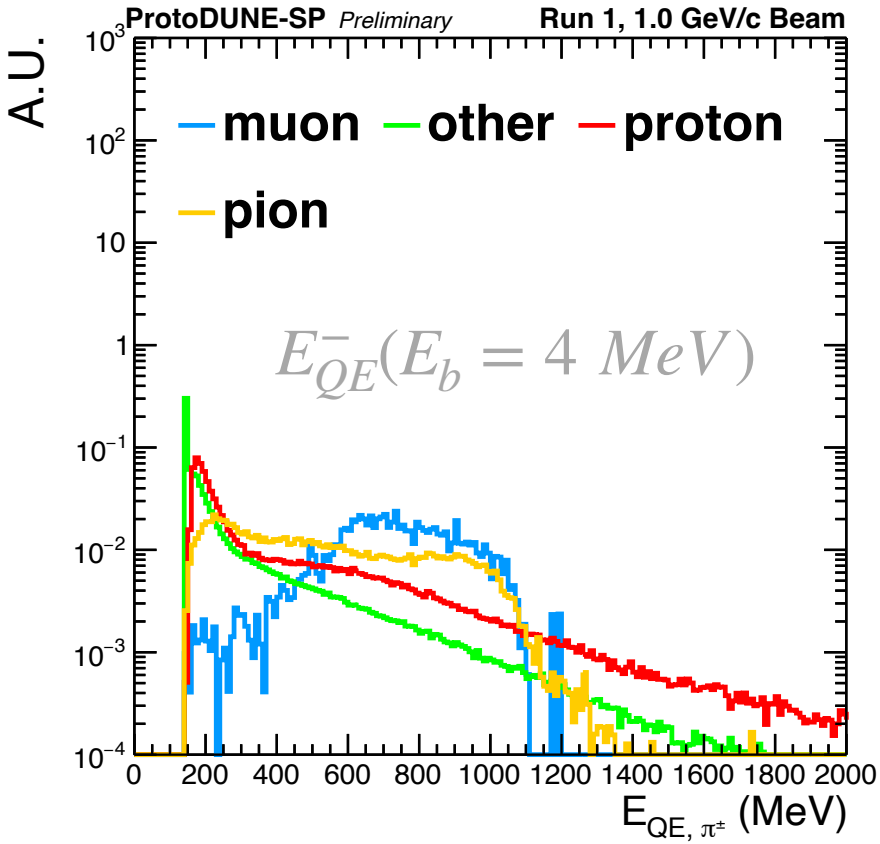
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Using ProtoDUNE MC samples at generator level

- Used the exact formula : massive pion with neutral current QE proton knocking out (E_{QE}^{-})
- $E_{binding}$ = 4 MeV

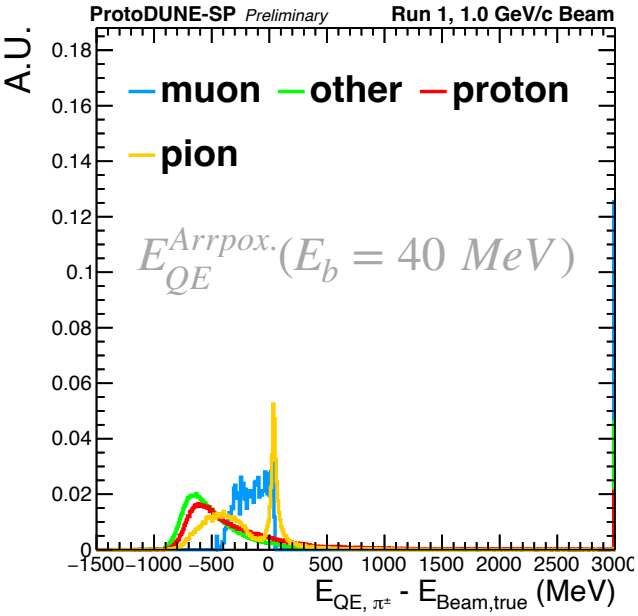


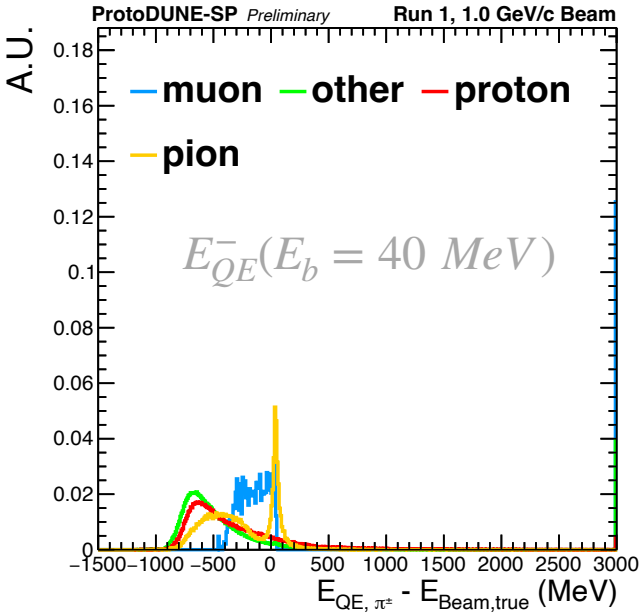


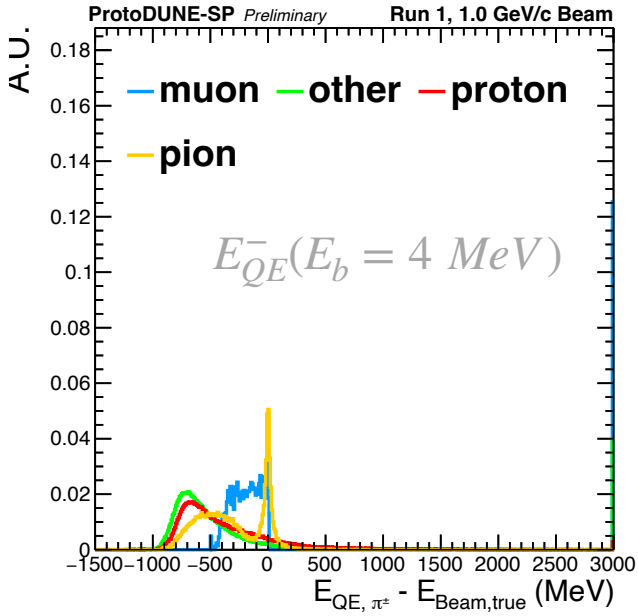
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Using ProtoDUNE MC samples at generator level

- Difference between truth level beam particle energy at interaction point and E_{QE}
- The QE peak is observed







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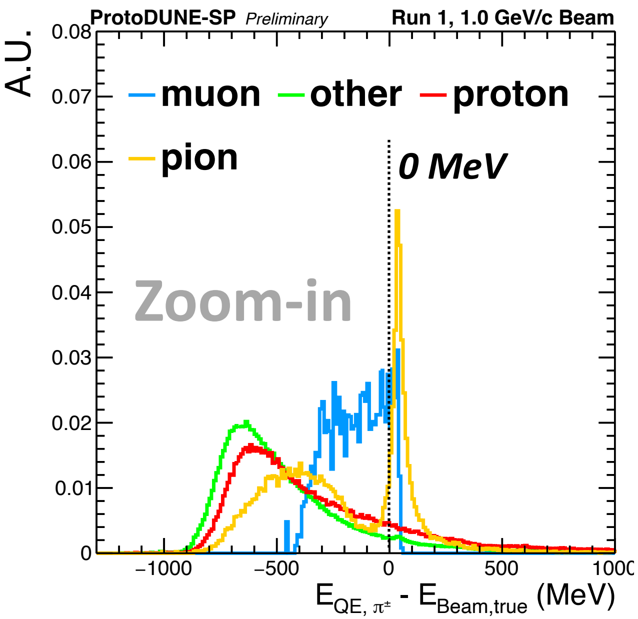
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

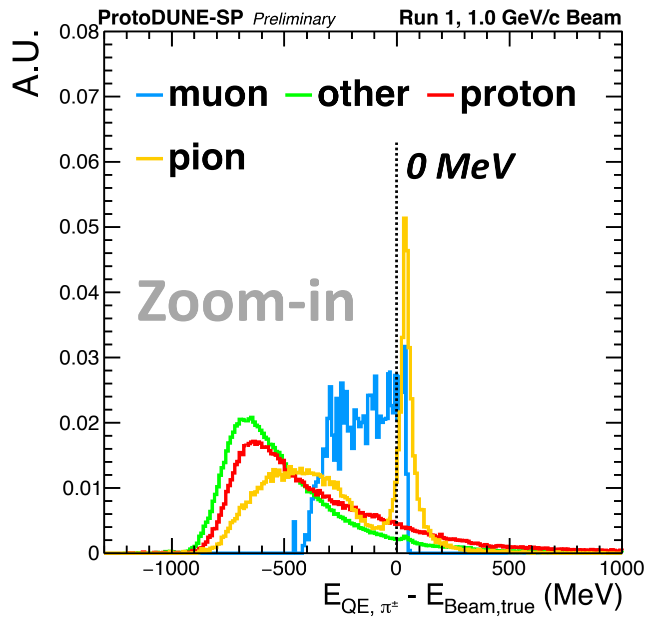
Using ProtoDUNE MC samples at generator level

- Difference between truth level beam particle energy at interaction point and E_{QE}
- The QE peak is observed
- E_b = 4 MeV gives the peak near 0 MeV

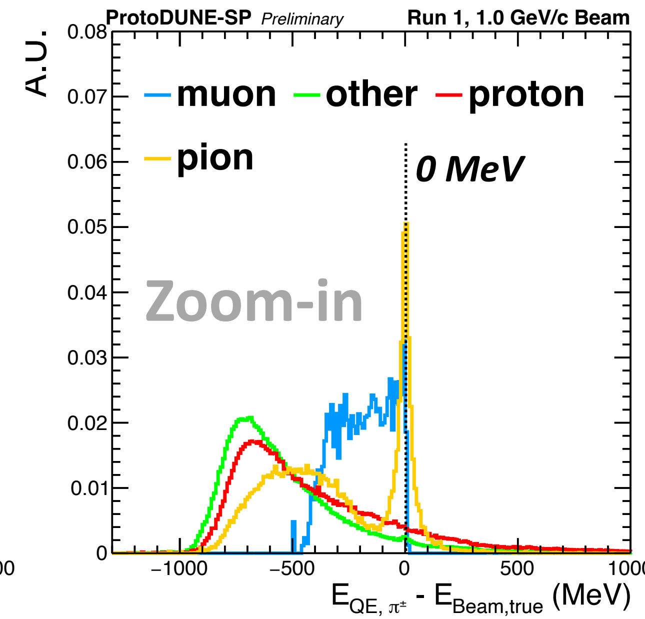
$E_{QE}^{Arrpox.}(E_b = 40\ MeV)$



$E_{QE}^{-}(E_b = 40\ MeV)$



$E_{QE}^{-}(E_b = 4\ MeV)$



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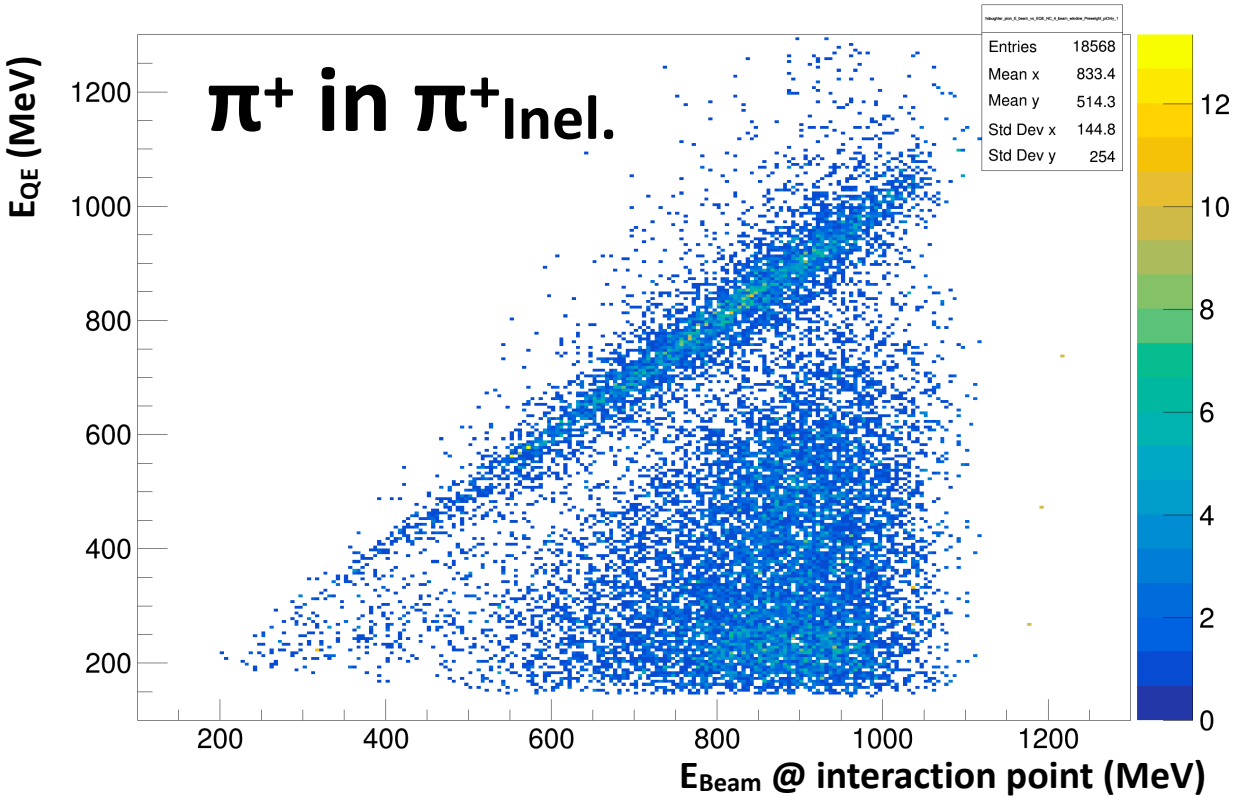
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Using ProtoDUNE MC samples at generator level

- Difference between truth level beam particle energy at interaction point and E_{QE}
- A clear QE band is observed
- E_b = 4 MeV



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Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

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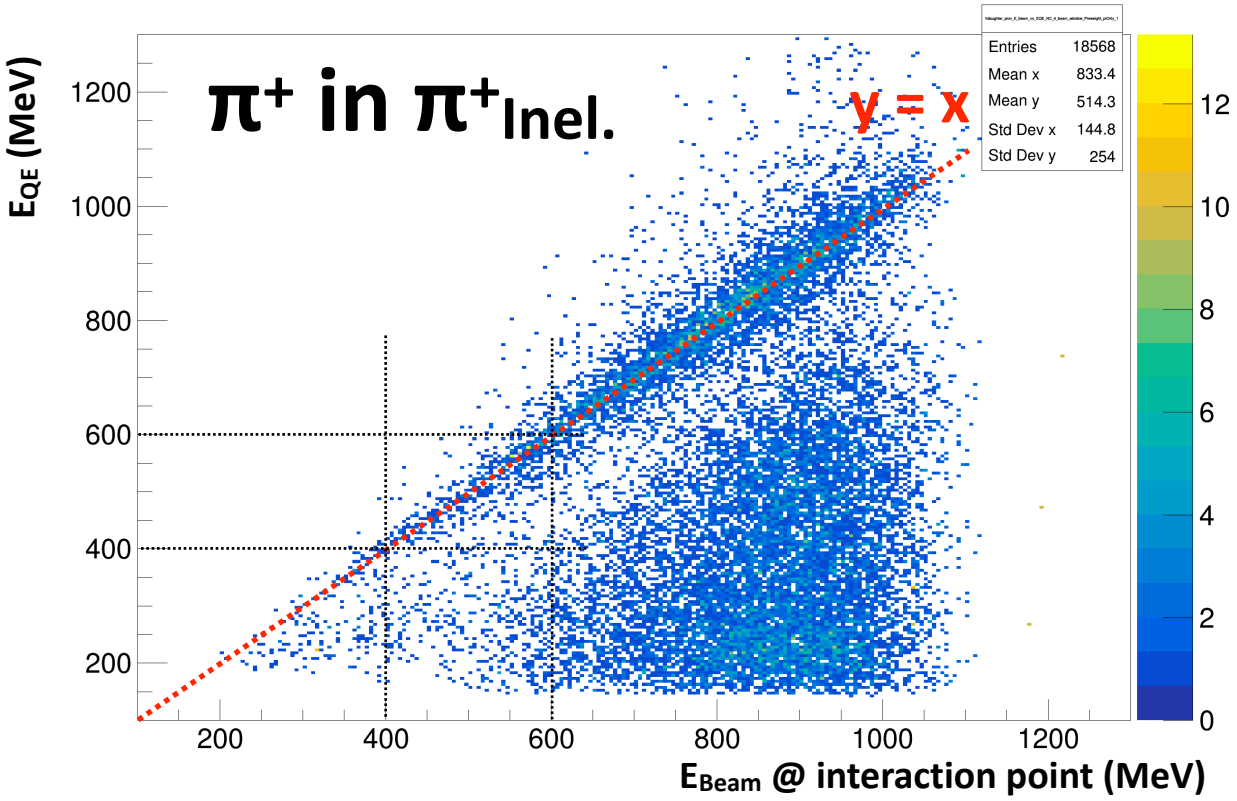

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Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Using ProtoDUNE MC samples

- Using reconstructed information

Beam

- Using momentum measured by spectrometer
  - 10 MeV flat energy loss is assumed
- Kinetic energy of the beam at interaction point
  - CSDA using pion^{+} mass

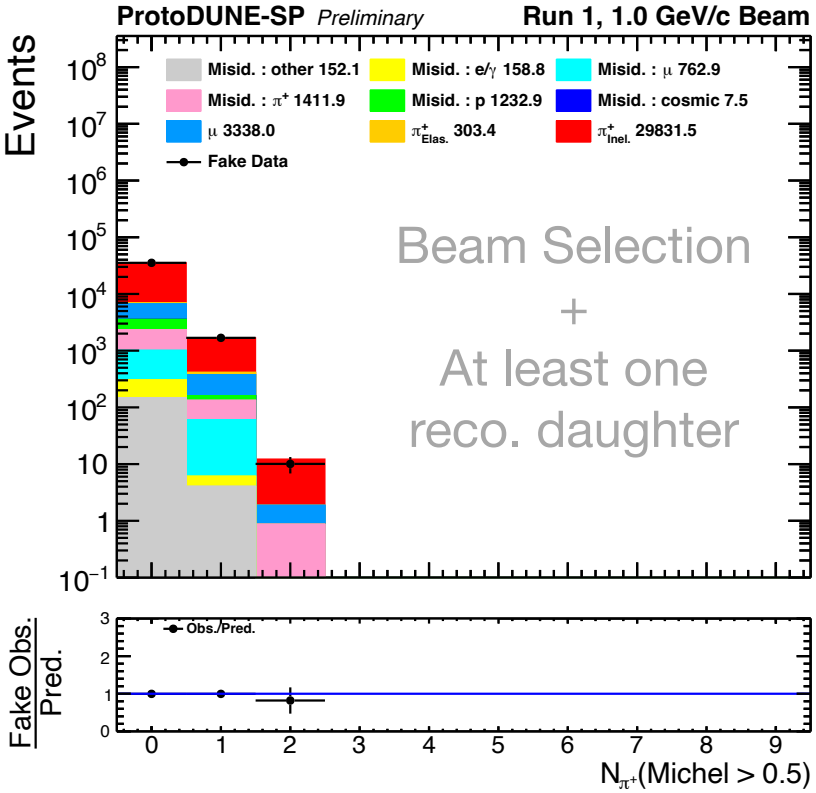
Pion selection

- Basic selection
  - $N_{Hits} > 20$, track score > 0.5, and $\chi^2_{proton} > 60$, $\cos\theta_{Beam,Daughter} < 0.95$, $distance_{Beam,\ Daughter} < 10$ cm
- Michel score > 0.5
- Energy of pion : CSDA using reconstructed track length

Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Using ProtoDUNE MC samples at detector level

- For events passed the π^+ beam selection (in back-up)
- Number of reconstructed pions



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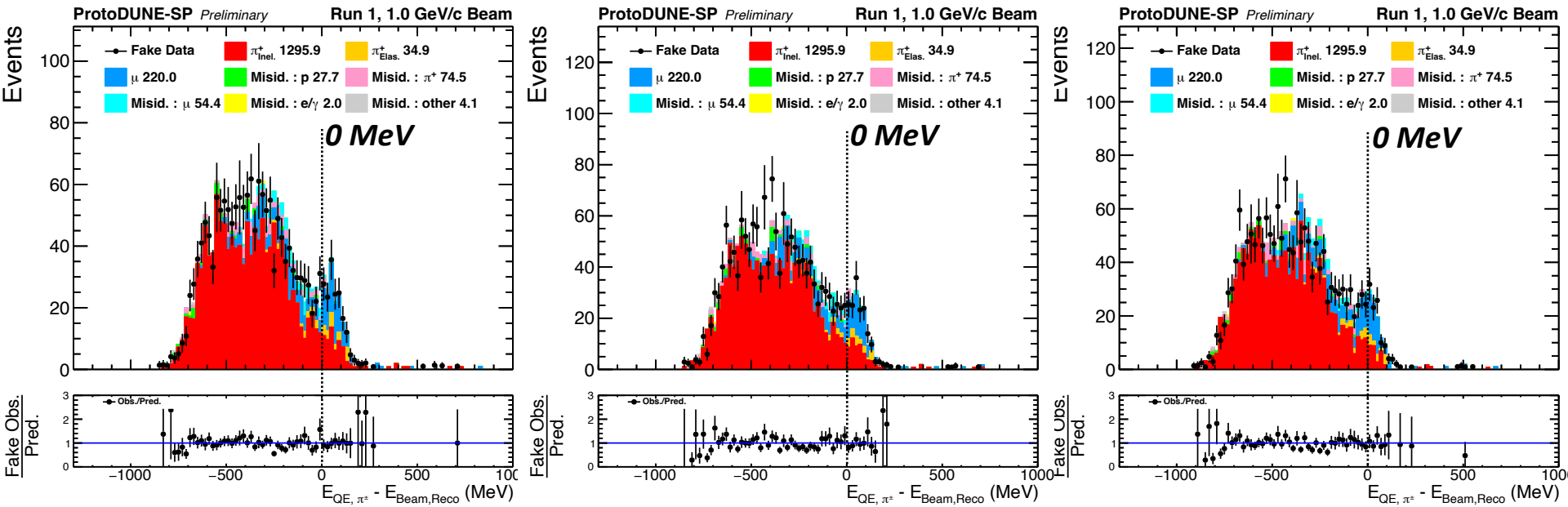
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Using ProtoDUNE MC samples at detector level

- At least one reconstructed π^+ passing Michel score > 0.5 cut
- Small QE peaks are observed
- But, many muon beam events at the QE peak position

$E_{QE}^{Arrpox.}(E_b = 40\ MeV)$ $E_{QE}^{-}(E_b = 40\ MeV)$ $E_{QE}^{-}(E_b = 4\ MeV)$



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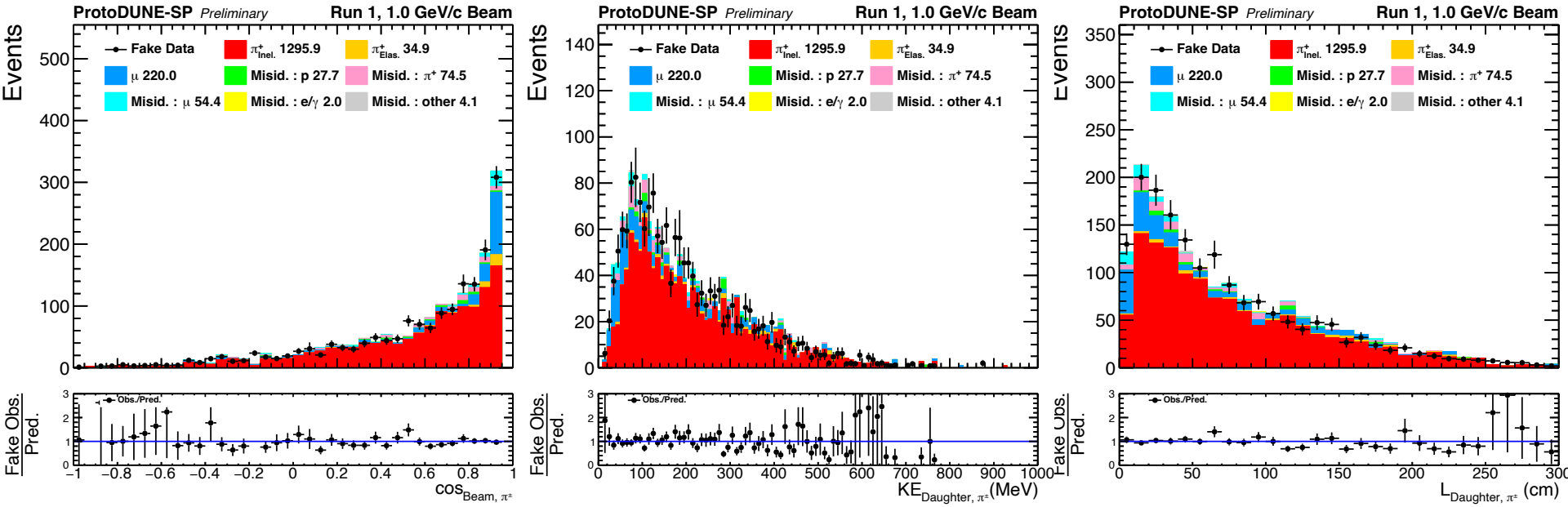
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Using ProtoDUNE MC samples at detector level

- I want to reduce muon beam background
- It is difficult to apply tighter cosθ cut : most of remaining QE events are there
- Pions coming from muon beam events are usually soft
  - How about to apply cut on length (KE) of reconstructed π^+?



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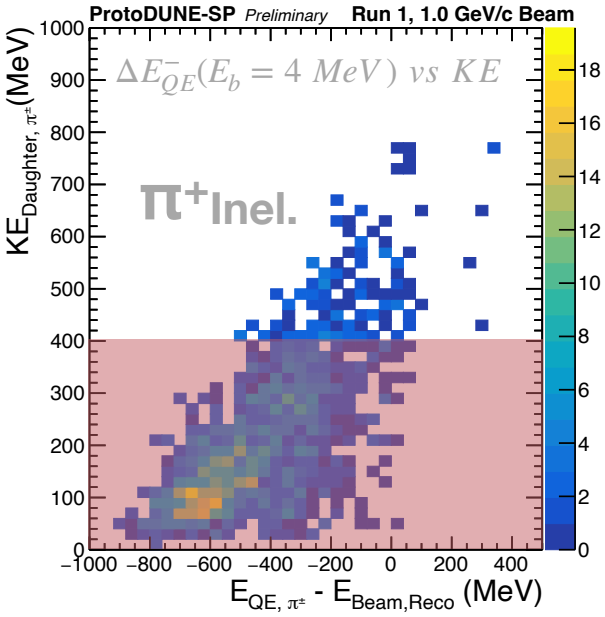
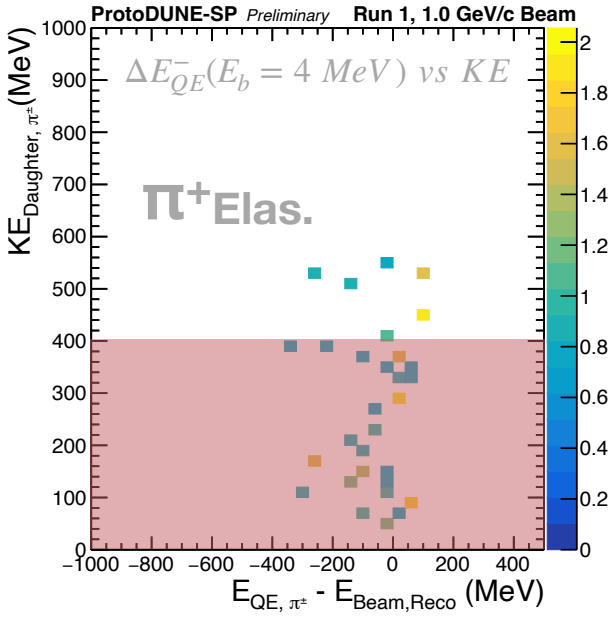
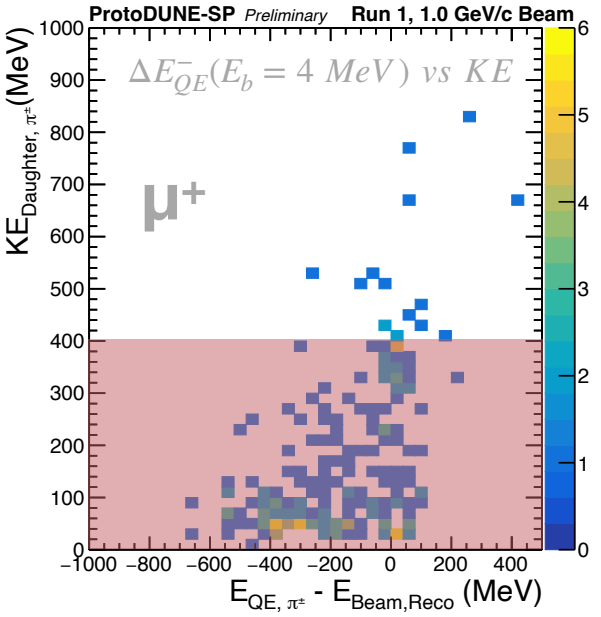




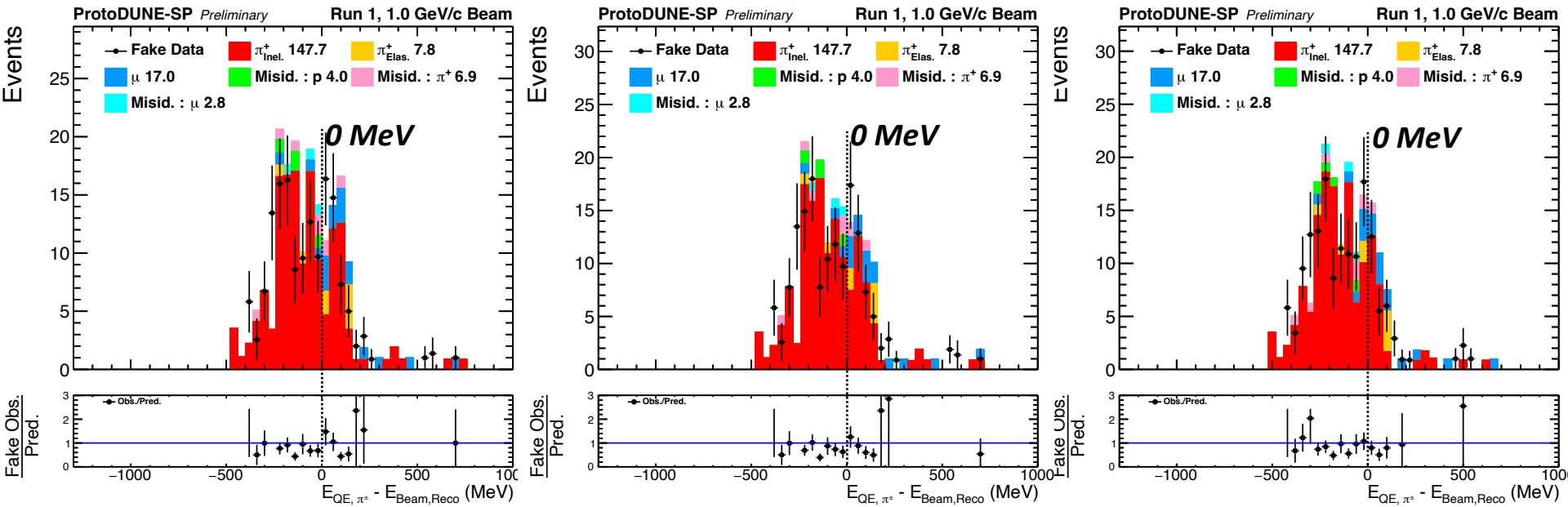


Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Using ProtoDUNE MC samples at detector level

- Muon beam contribution is reduced much
- Still, we need to enhance signal efficiency…
  - Interacted pions using hypothetical track length fitting method?

$E_{QE}^{Arrpox.}(E_b = 40\ MeV)$ $E_{QE}^{-}(E_b = 40\ MeV)$ $E_{QE}^{-}(E_b = 4\ MeV)$



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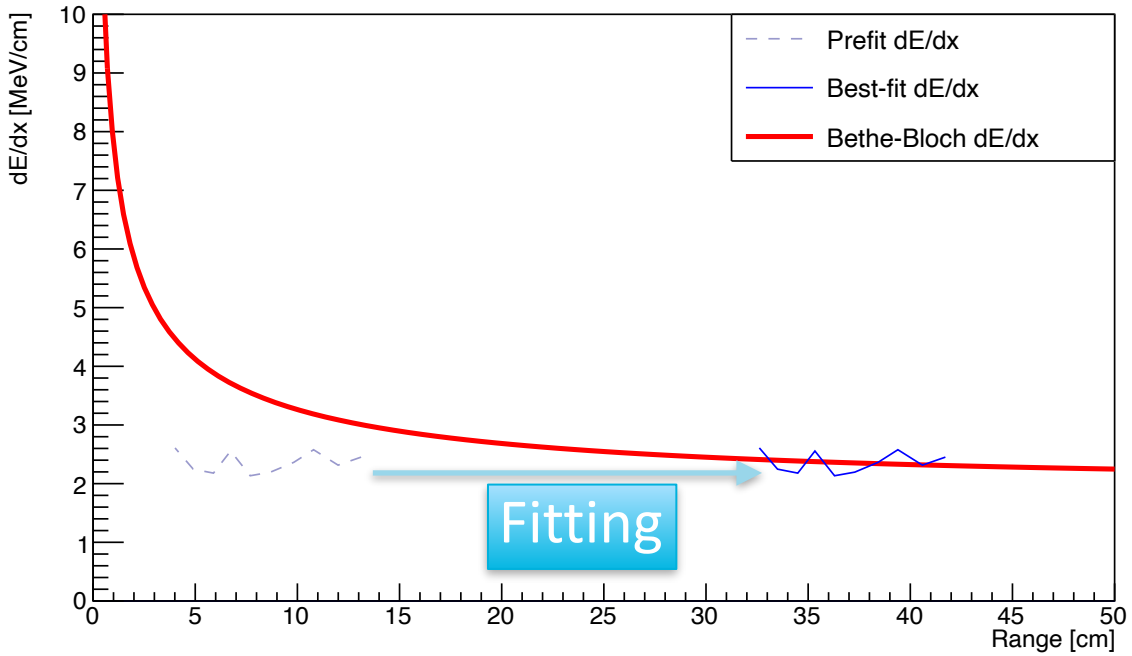
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

For pions not passing the Michel score cut

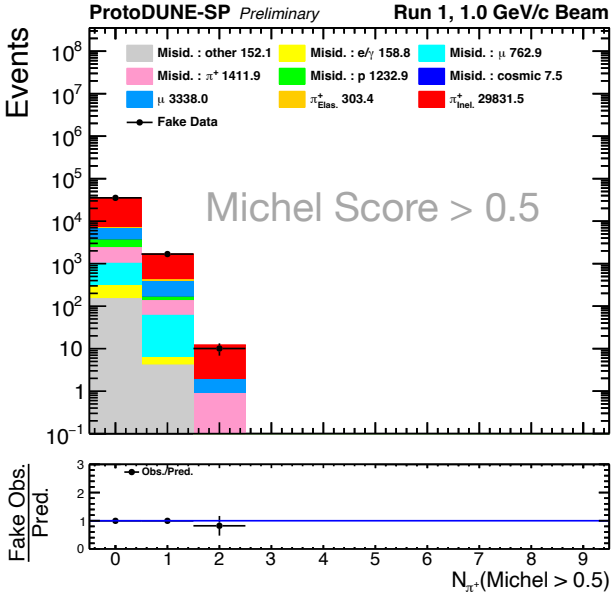
- Perform the hypothetical track length fitting
- Measure energy of interacted charged pion using dE/dx and residual range vectors
- Minimum χ^2 using Gaussian approximation
- Maximum likelihood using Vavilov PDF for dE/dx

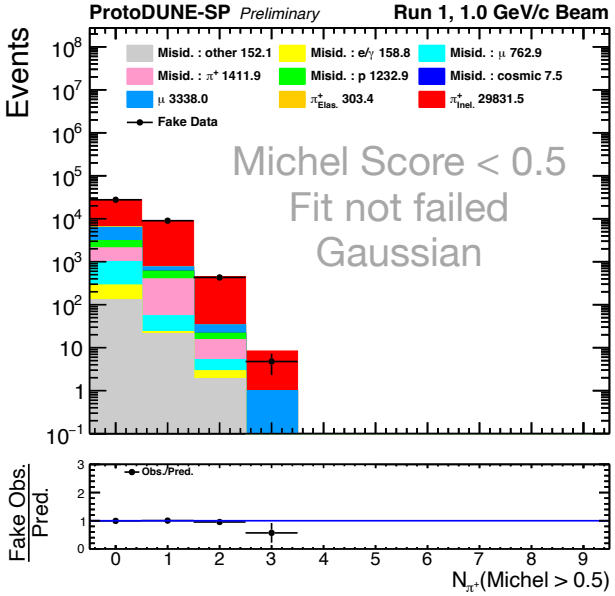


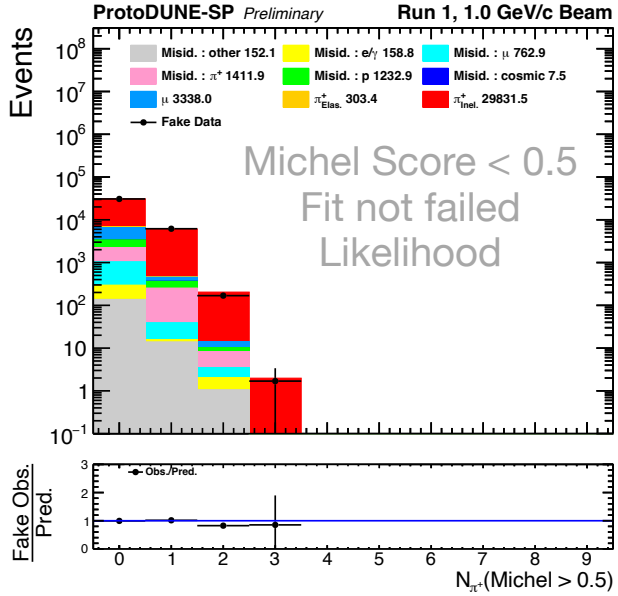
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

For pions not passing the Michel score cut

- Perform the hypothetical track length fitting
- Measure energy of interacted charged pion using dE/dx and residual range vectors
- More statistics with lower muon background contribution
- Poorer energy resolution compared to pions passed the Michel score cut







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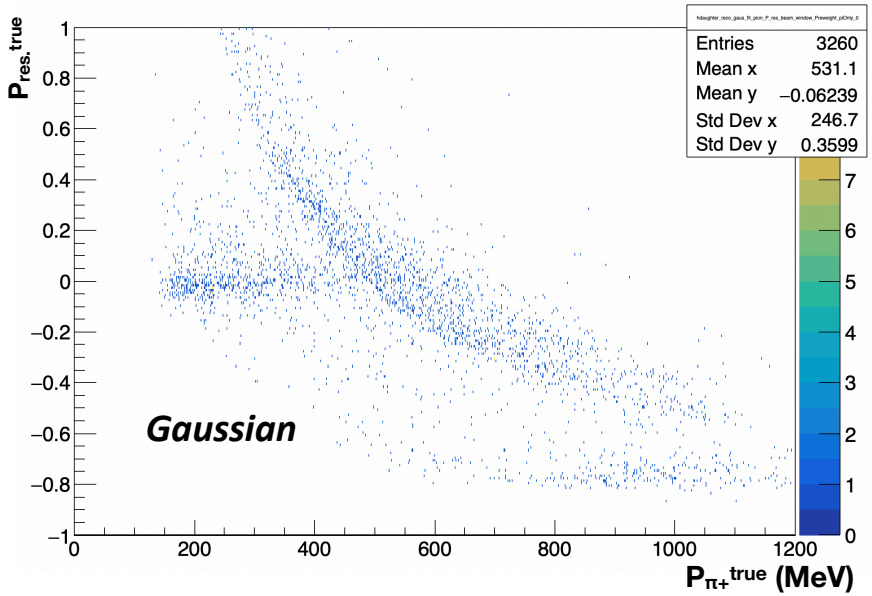
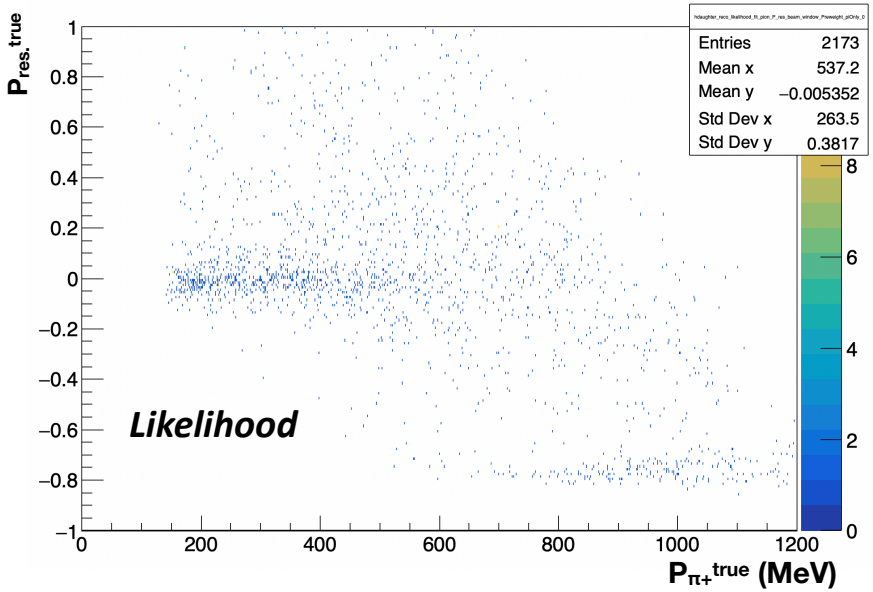
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

- Measure energy using the hypothetical track length fitting method
  - Gaussian approximated least χ2 fitting
  - Best likelihood method using
    - Landau, Vavilov and Gaussian dE/dx PDF depending on κ value
- Performance comparison : 1 cm step in [0, 450] cm additional track length range





Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

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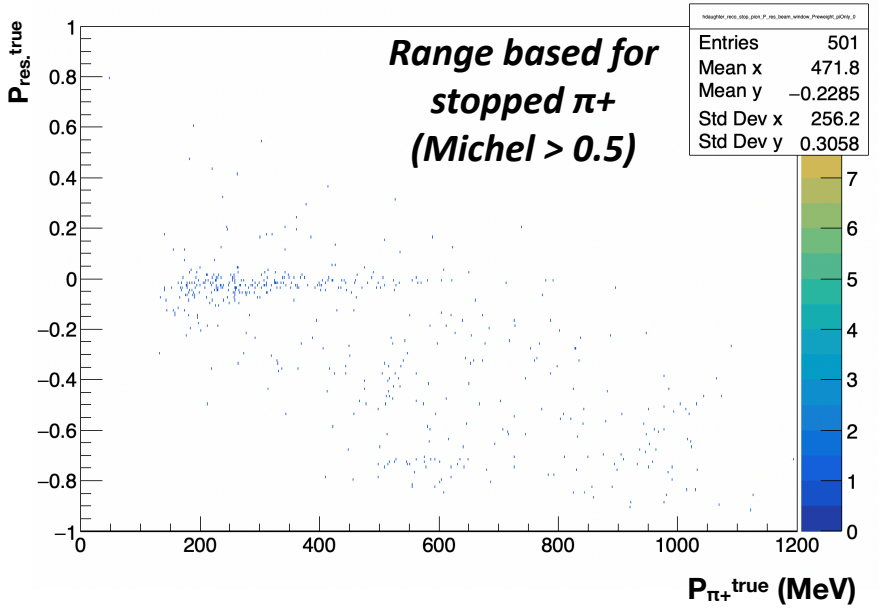
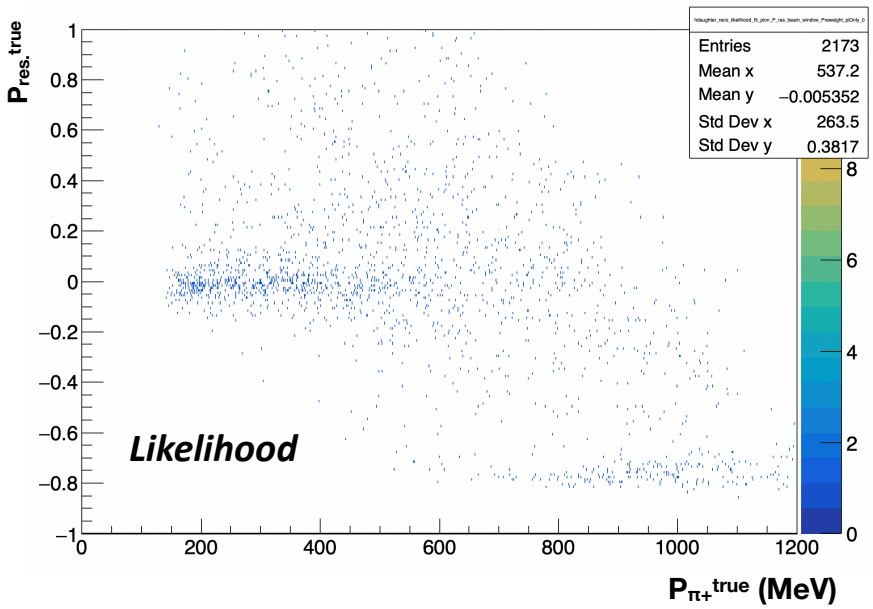
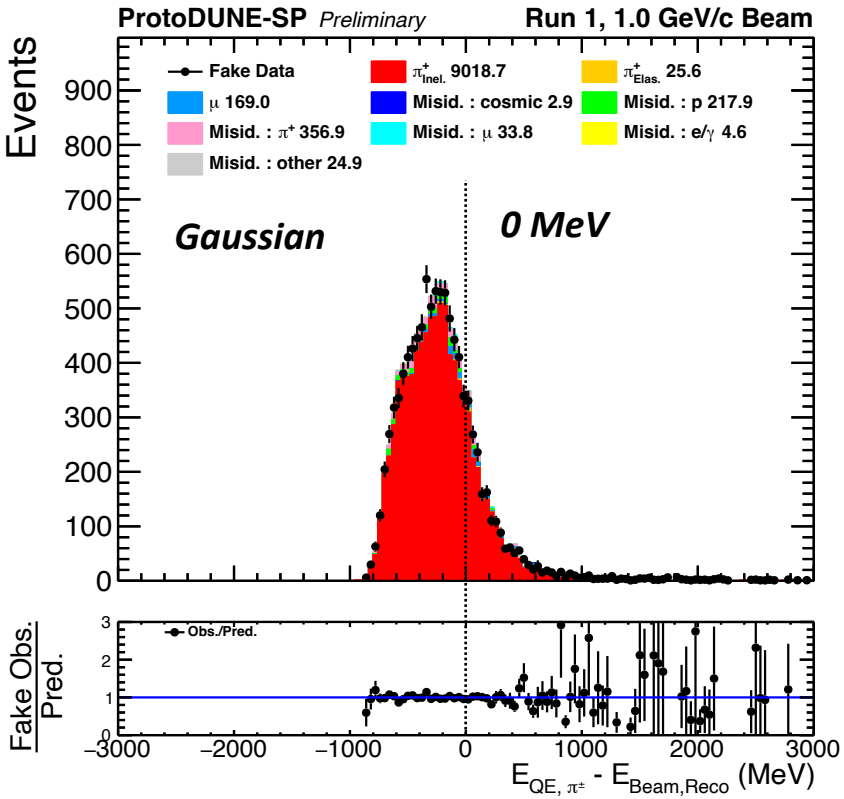
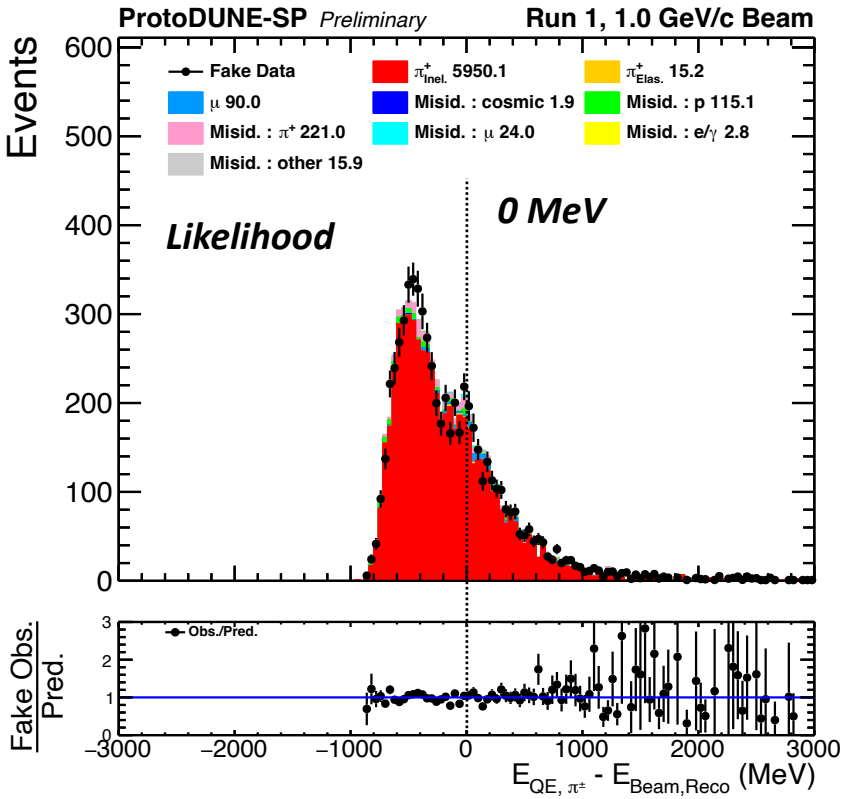




Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

- ΔQE distributions
  - As expected, the likelihood method shows better performance for reconstruction of ΔQE
  - A peak at zero is observed



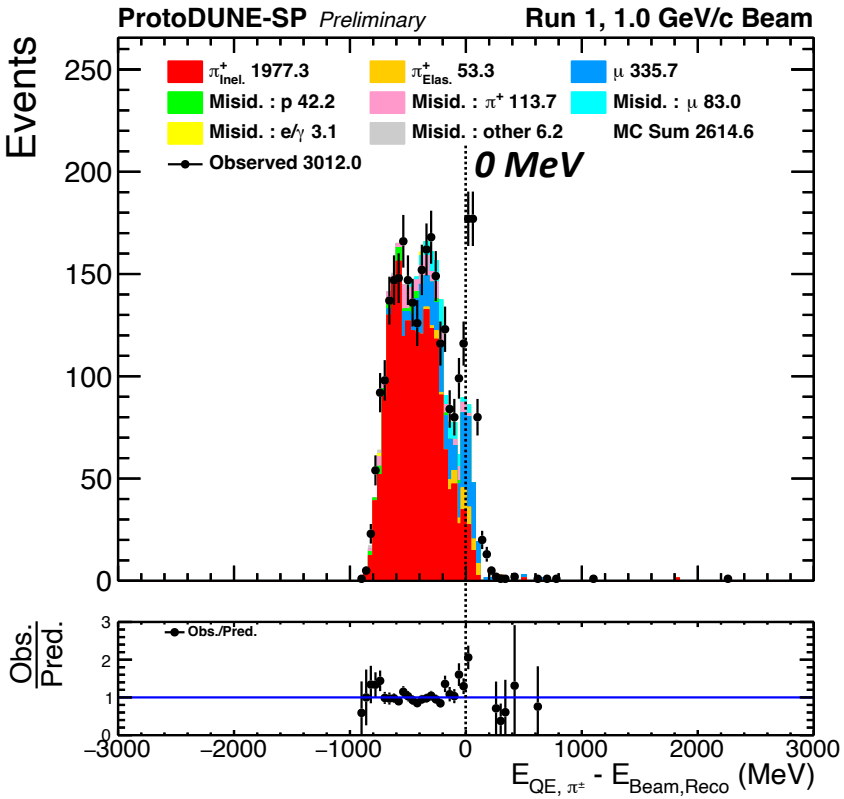


Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Data vs MC distributions

- Charged pions with Michel score > 0.5, energy using the CSDA
- A clear peak at zero from data : it could be muon's peak, need more study on it

$E^{-}_{QE}(E_b = 4\ MeV)$



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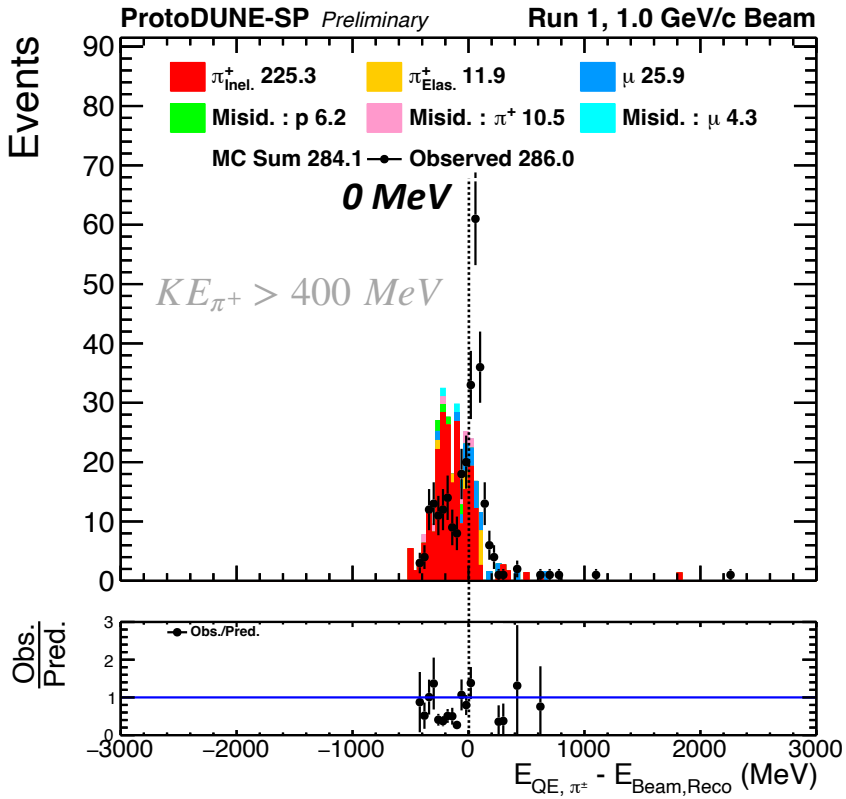

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Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Data vs MC distributions

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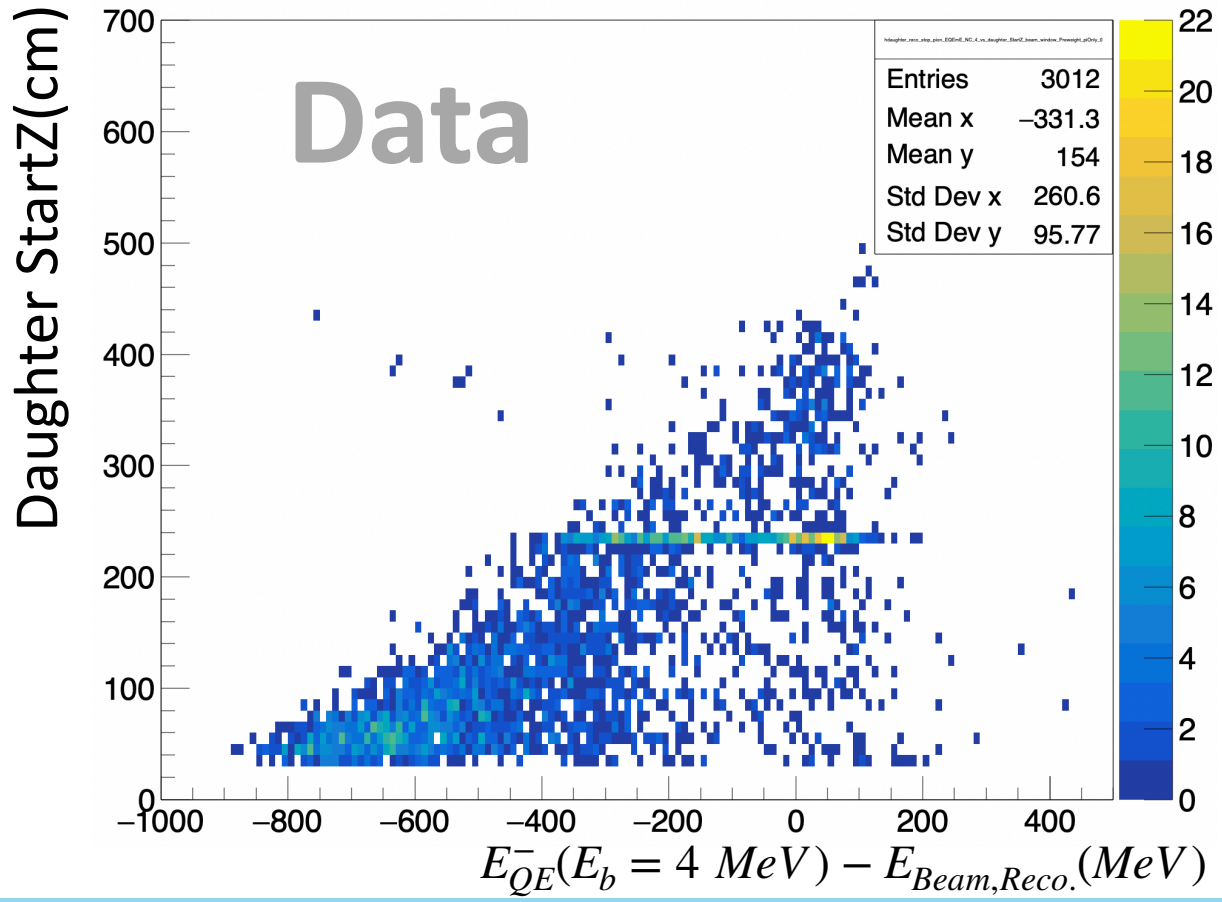

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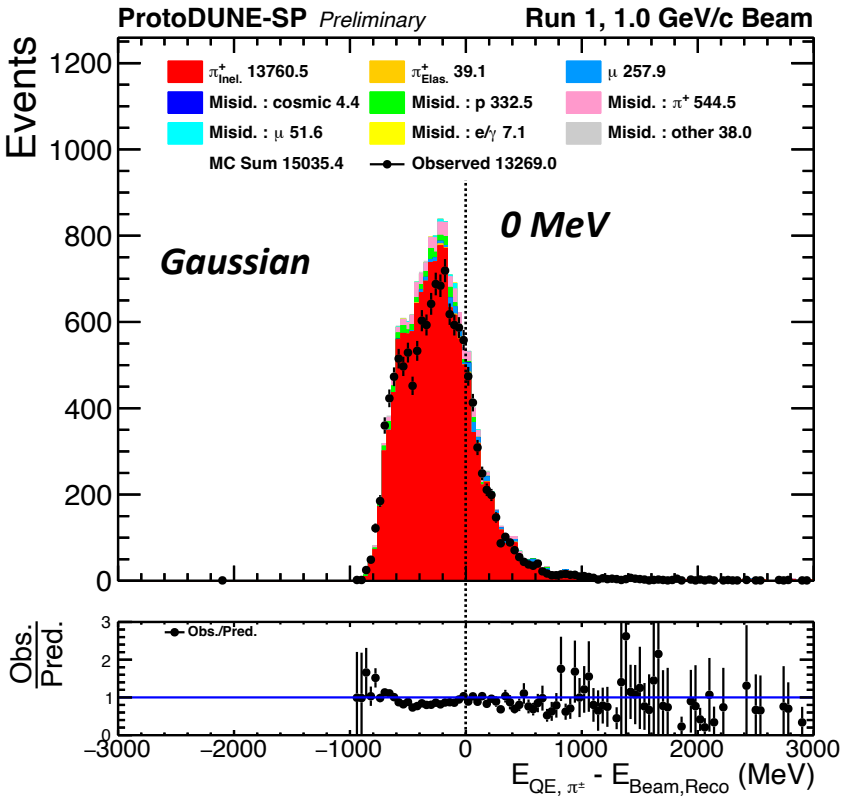
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

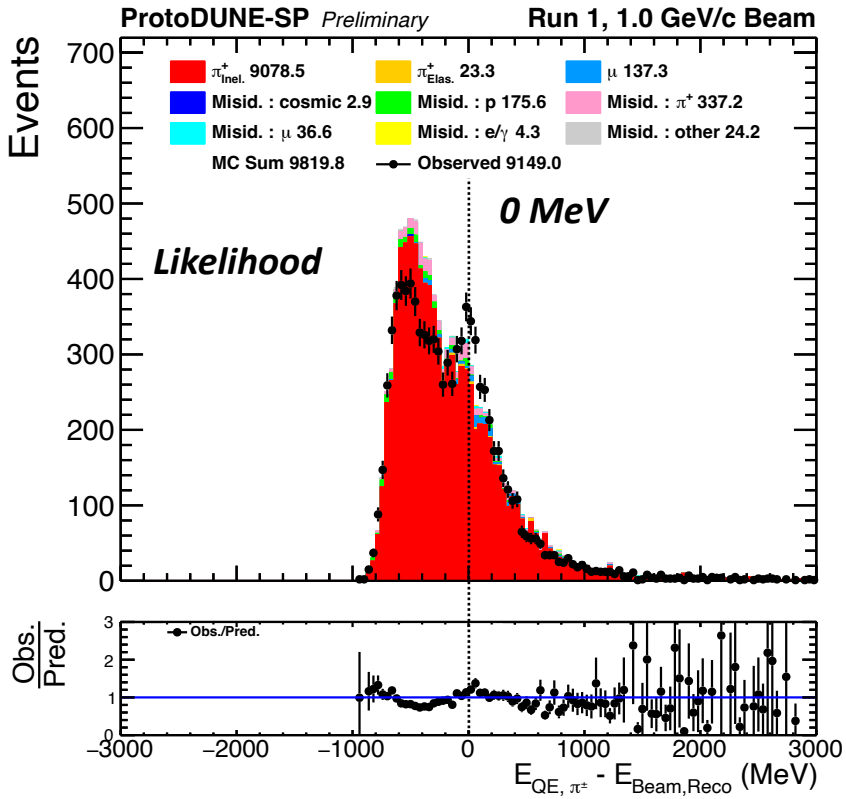
Data vs MC distributions

- Charged pions with Michel score < 0.5, energy using hypothetical track length
- A clear peak at zero from the maximum likelihood method

$E_{QE}^{-}(E_b = 4\ MeV)$



$E_{QE}^{-}(E_b = 4\ MeV)$



Summary

Study for π^+-Ar quasi-elastic scattering using the GEANT4 sample

- It is possible to select quasi-elastic event using only charged pion at the final state
- There is more complicated structure that can be studied

Study using ProtoDUNE-SP MC samples and data

- The QE peak is observed
  - We can select QE events only using final state charged pion and beam information
- Energy of out-going charged pion is required
  - Michel score > 0.5 cut and use range to measure energy
    - Best energy resolution, significant muon background, and low stat.
  - Utilized the hypothetical track length fitting method
    - Maximum likelihood method shows a good energy resolution
    - Clear QE peak with small muon background and more stat.
- Plan : test performance of $E_{visible}$ (out-going charged pion and its daughters)
  - As an additional information for interacted charged pion energy measurement

Back Up

ProtoDUNE-SP : Pion Beam Study

Basic beam selection

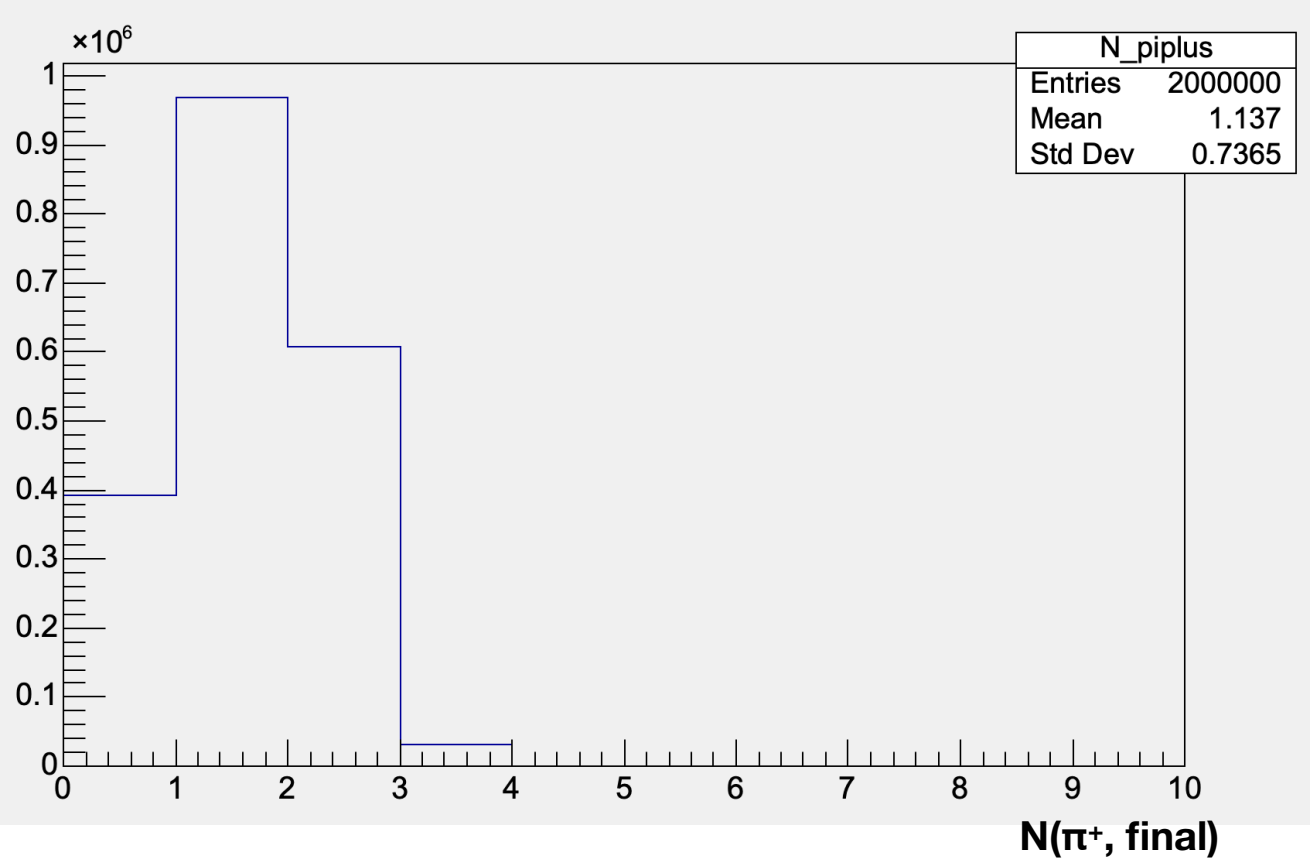
- MC : true beam PDG = 211 or ±13
- Data
  - No cosmic trigger
  - N(reco beam particle) = 1
  - At least one of “beam_inst_PDG_candidates” should be 211 or ±13

Additional beam selection

- Pandora slice cut : beam is reconstructed as track by the Pandora
- Calo size cut : at least one reconstructed hit in the collection plane
- Beam quality cut : cut on beam angle and entrance positions
  - $-3 < dz/\sigma_z < 3$, $-1 < dxy/\sigma_{xy} < 3$, $\cos\theta > 0.95$
- Daughter Michel score < 0.55
  - Hit charge weighted average of CNN Michel scores near vertex
- Pass proton veto cut
  - $\chi^2_{proton} > 80$

Study for Quasi-elastic Scattering of Charged Pions - Thin LAr Target

Number of π+ at final state



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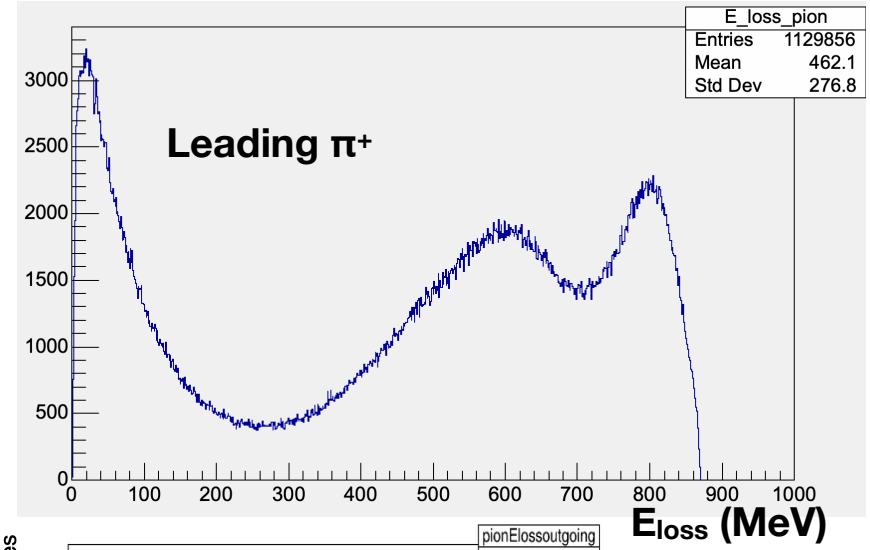
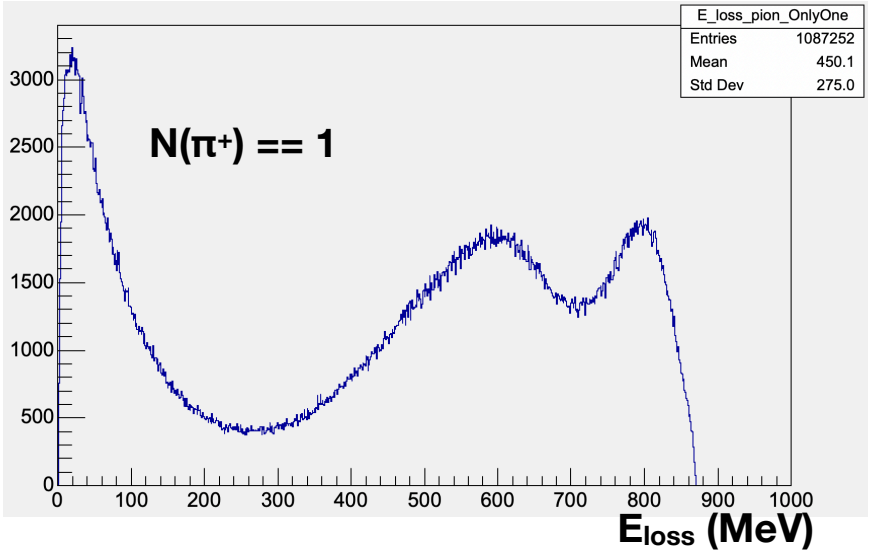
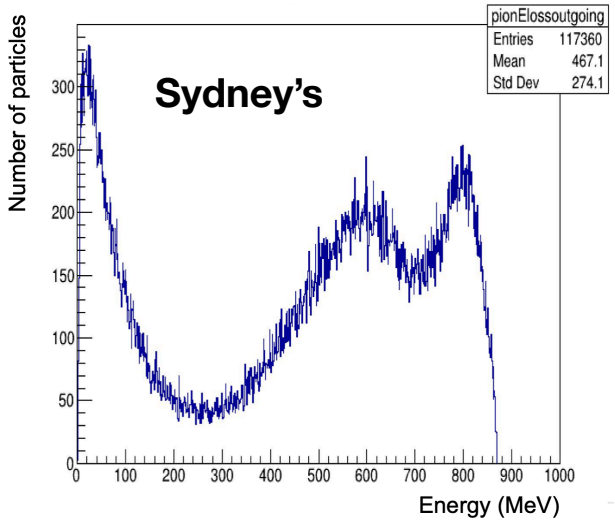
Study for Quasi-elastic Scattering of Charged Pions - Thin LAr Target

Energy loss of π+ : $E_{incoming}$ - $E_{outgoing}$







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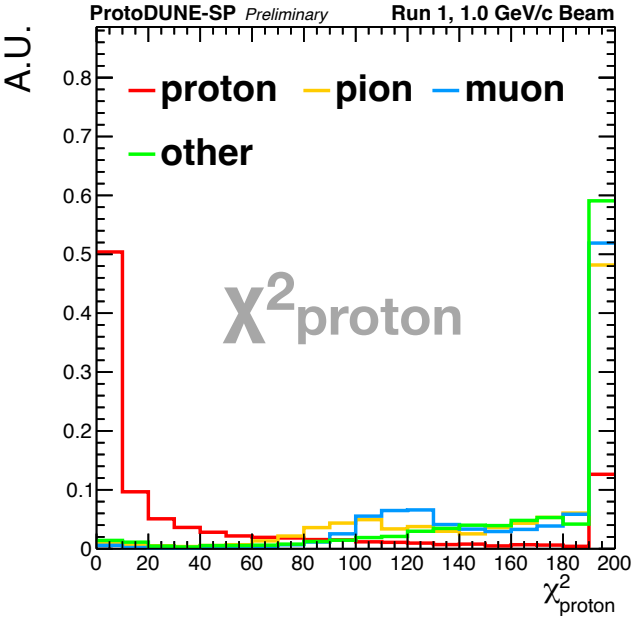
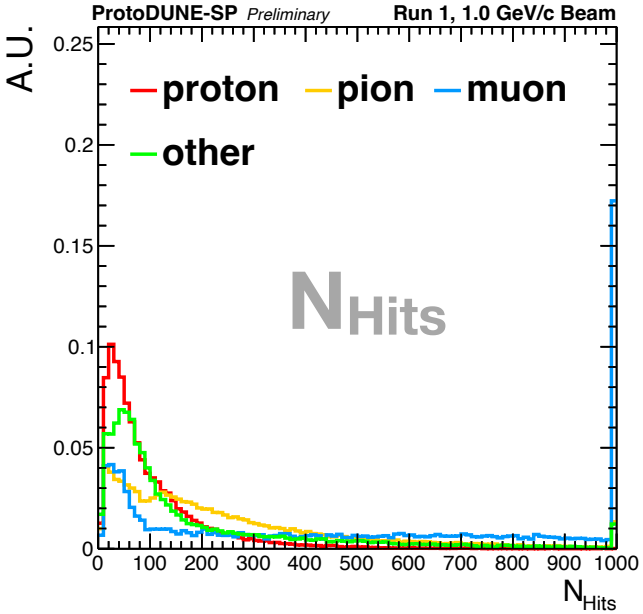
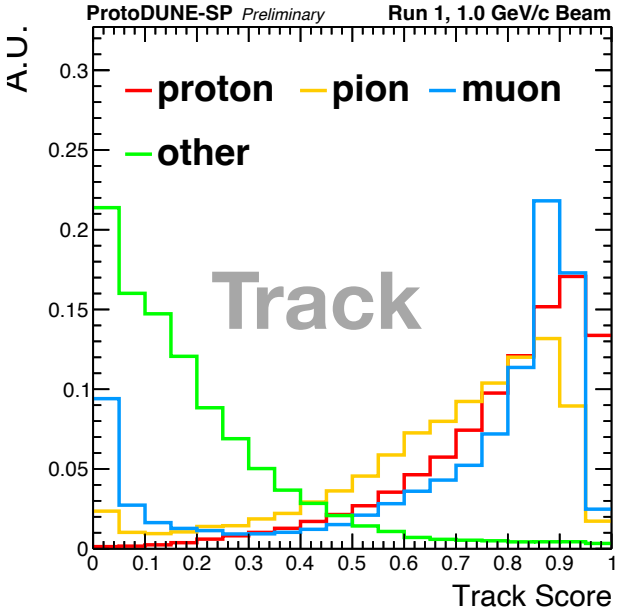
Daughter Particle Identification : Variables

MC 1 GeV/c sample with pion beam selection







Proton selection

- $\chi^2_{proton} < 50$, $N_{Hits} > 20$, Track score > 0.5

π^+ selection

- $\chi^2_{proton} > 60$, $N_{Hits} > 20$, Track score > 0.5

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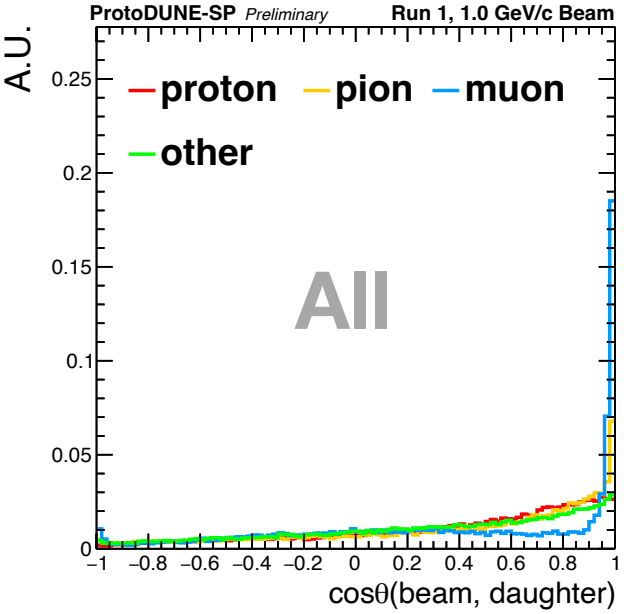
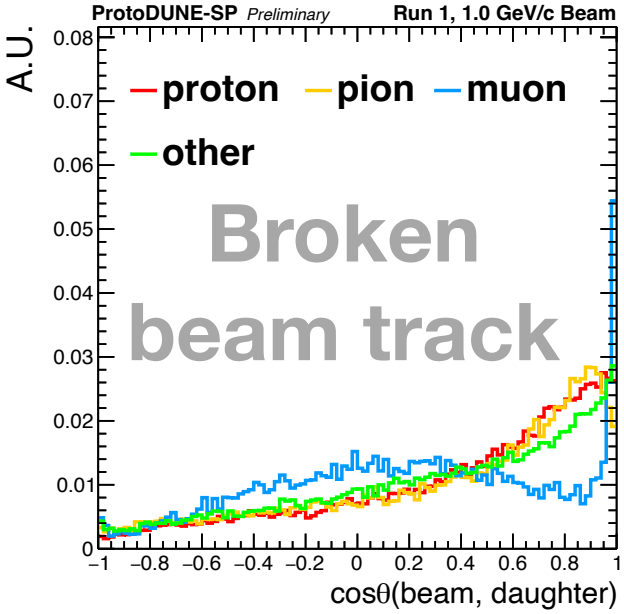
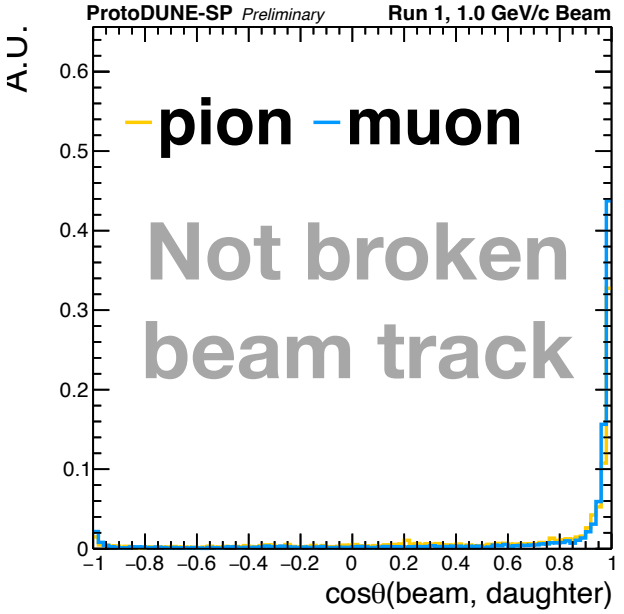
Daughter Particle Identification : Variables

MC 1 GeV/c sample with pion beam selection







Proton selection

- $\cos\theta < 0.95$

π^+ selection

- $\cos\theta < 0.95$

Daughter direction : $\overrightarrow{X}_{\text{Reco, End}} - \overrightarrow{X}_{\text{Reco, Start}}$

Beam direction : reco track direction

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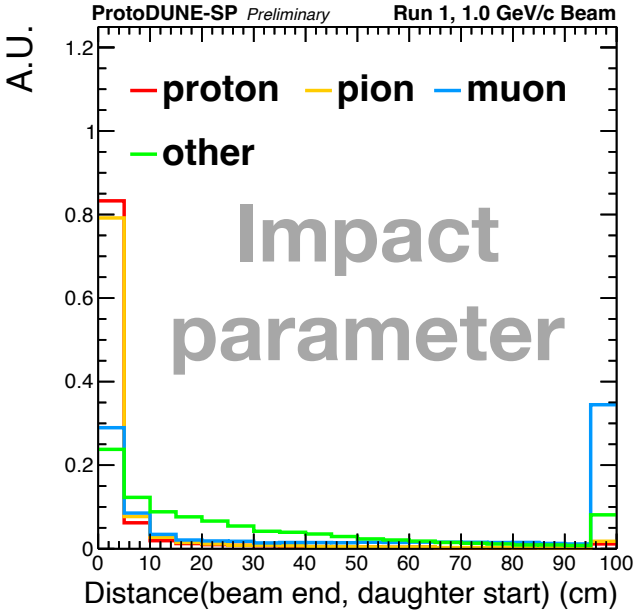
Daughter Particle Identification : Variables

MC 1 GeV/c sample with pion beam selection



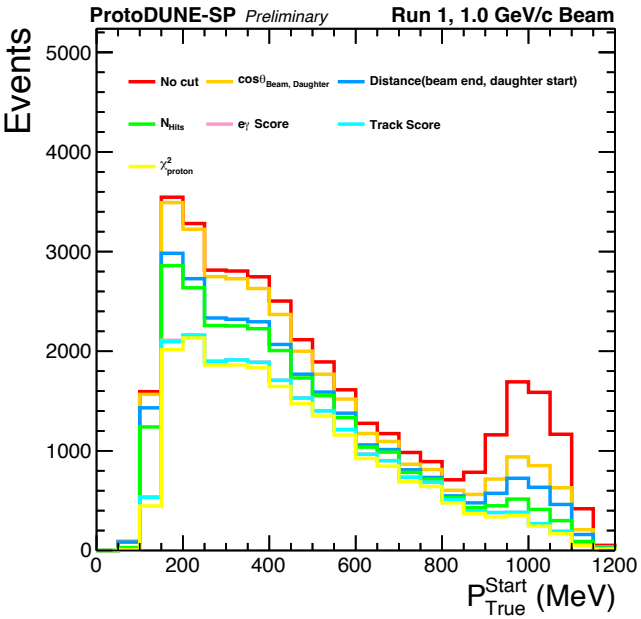
Proton selection

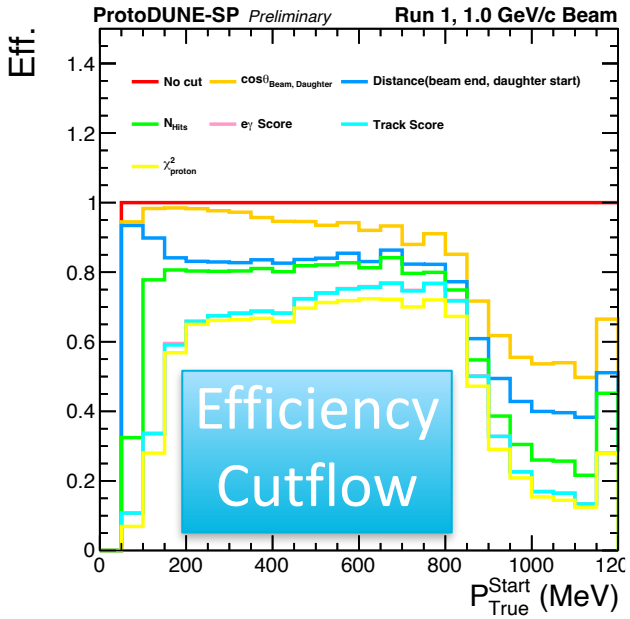
- Distance < 10 cm

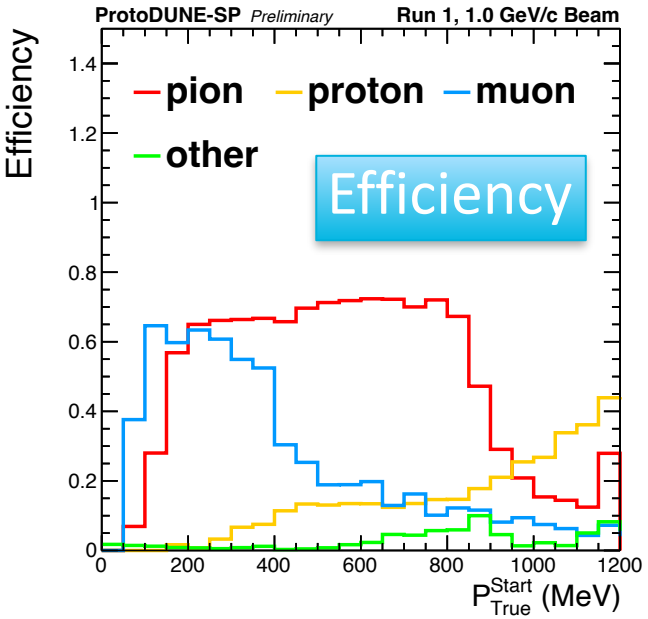
π^+ selection

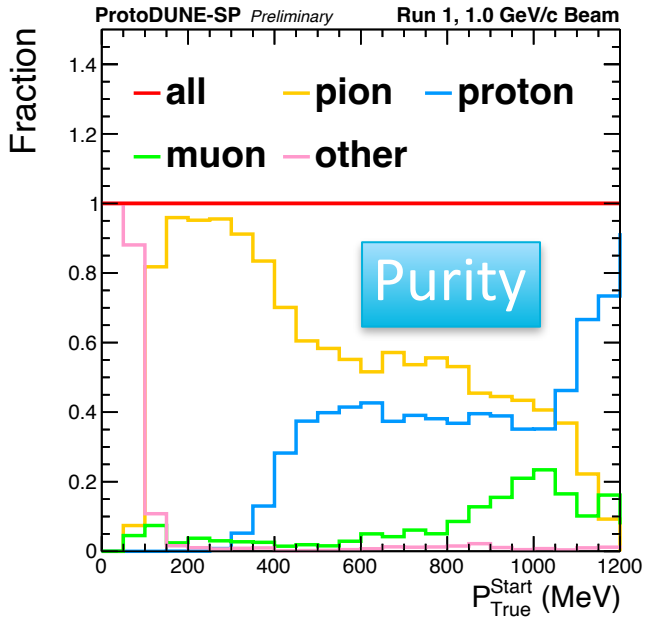
- Distance < 10 cm

Daughter Particle Identification - Pion Selection



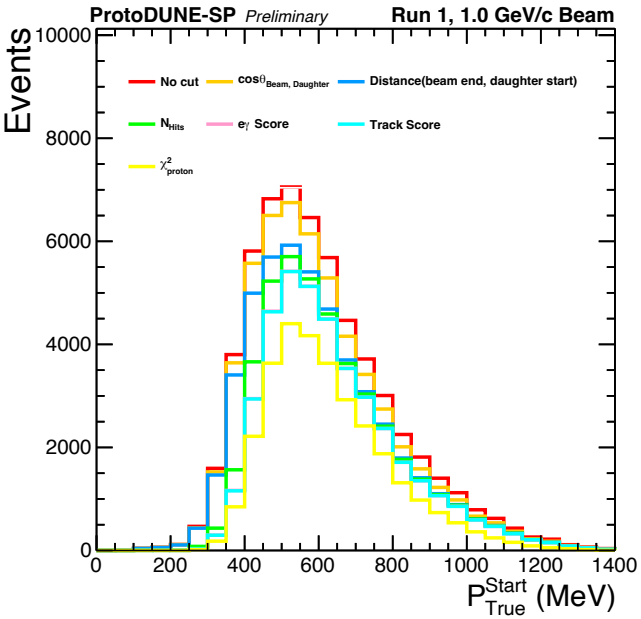


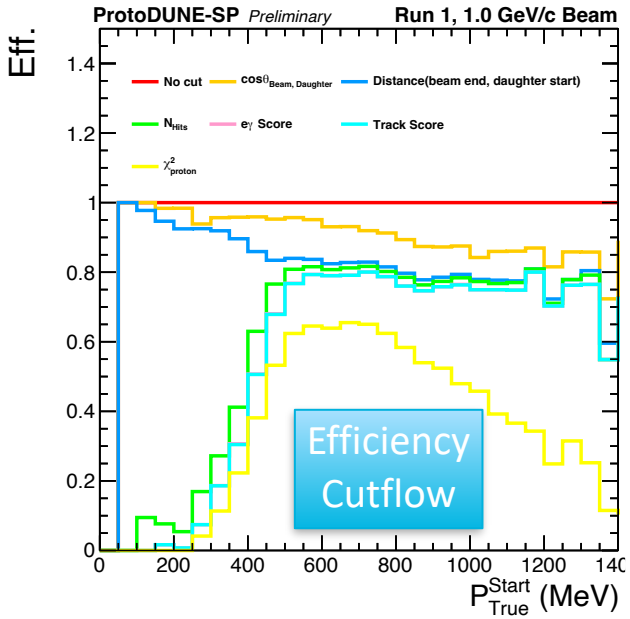


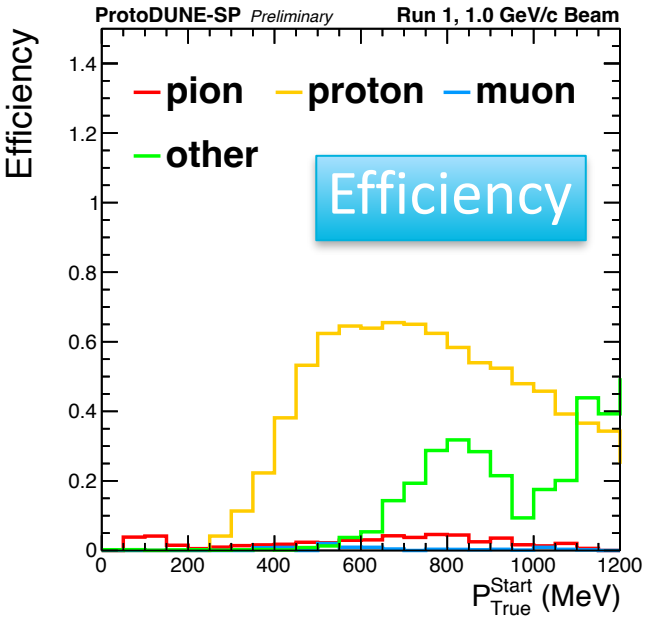


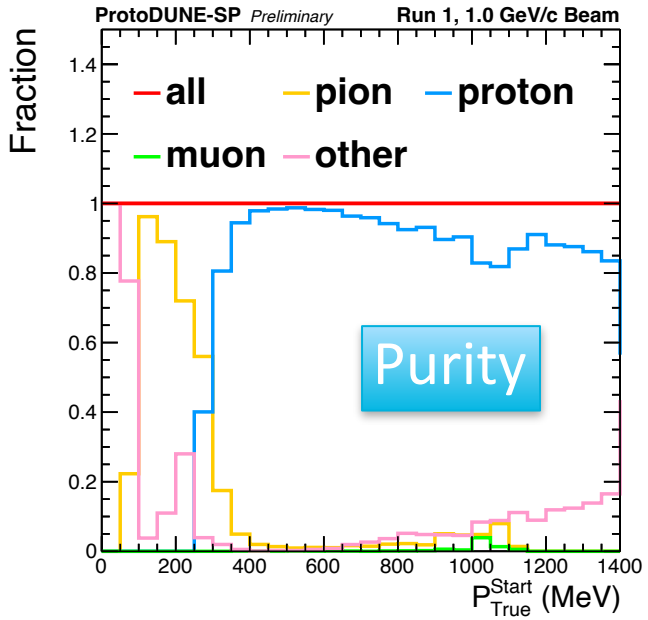
- $N_{hits} > 20$, e/γ score < 0.5, track score > 0.5, and $\chi^2_{proton} > 60$, $\cos\theta_{Beam,Daughter} < 0.95$, $distance_{Beam,\ Daughter} < 10$ cm
- Track score is the strongest cut for pions
- Large contribution from protons depending on P_{True}
  - Improvement using the hypothetical residual length fit?

Daughter Particle Identification - Proton Selection







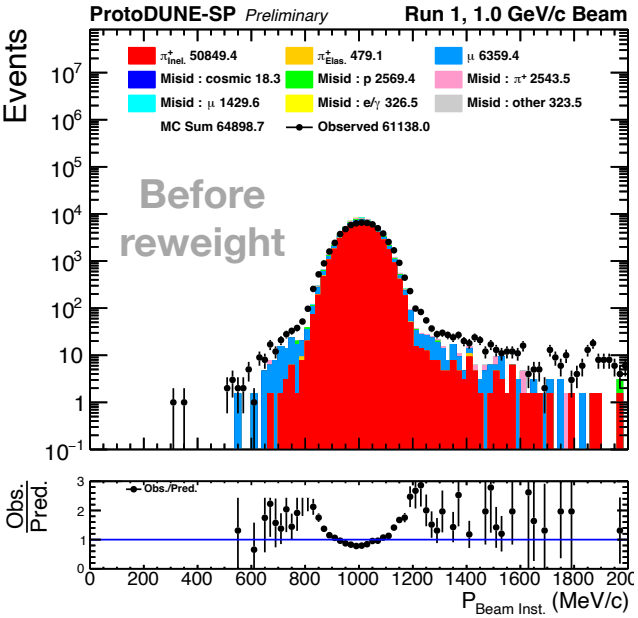


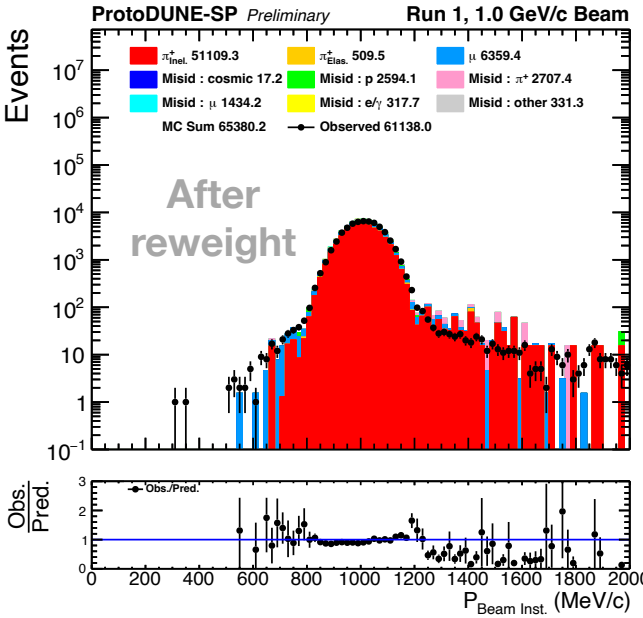
- $N_{hits} > 20$, e/γ score < 0.5, track score > 0.5, and $\chi^2_{proton} < 50$, $\cos\theta_{Beam,Daughter} < 0.95$, $distance_{Beam,\ Daughter} < 10$ cm
- The χ^2_{proton} score is the strongest cut for protons
- Large contribution from protons and muons depending on P_{True}
  - Improvement using the hypothetical residual length fit?

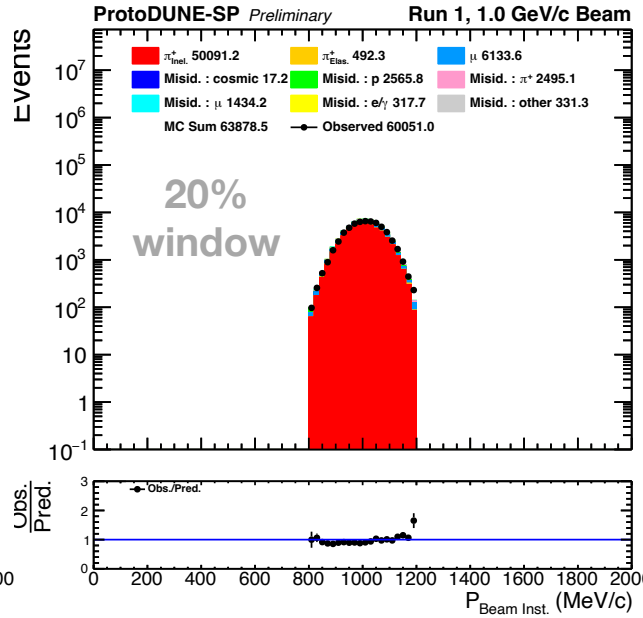
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

For data vs MC comparison

- Truth level beam momentum reweighting is applied
- Additional cut on $P_{\text{Beam Inst.}}$: 20 % window
- Pion beam : 78%
- Muon beam : 10%
- Beam track reconstructed by daughters (Misid.) : 12%







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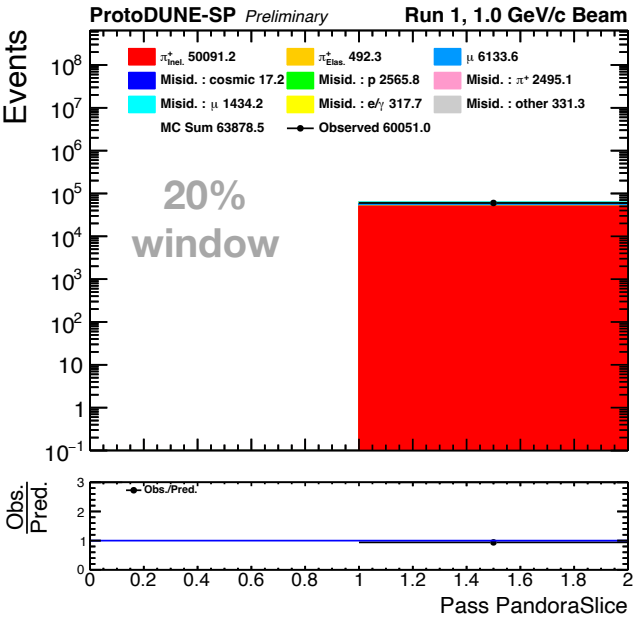
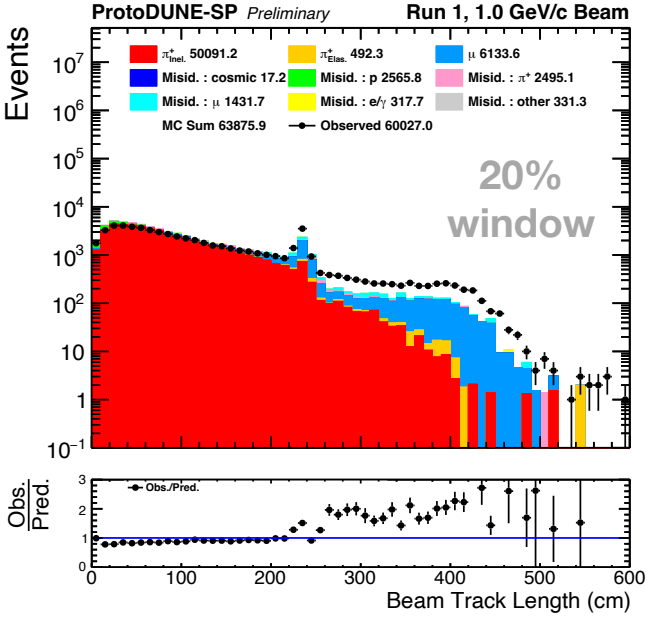
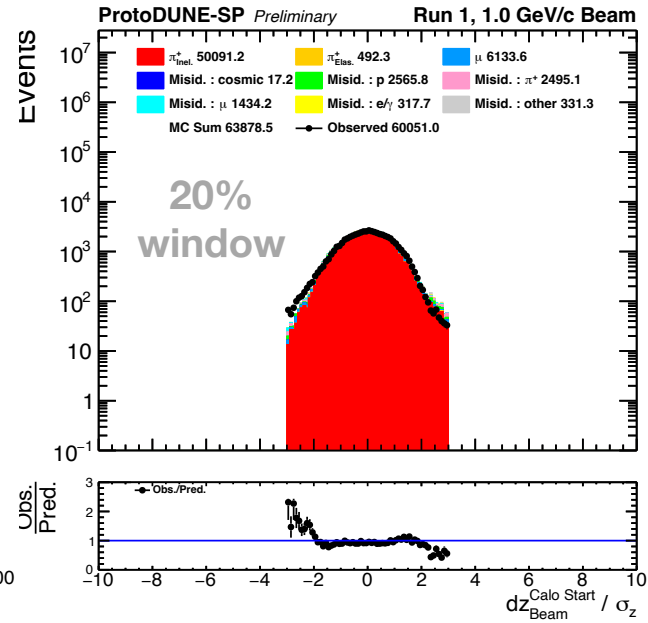
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

For data vs MC comparison

- Truth level beam momentum reweighting is applied
- Additional cut on $P_{\text{Beam Inst.}}$: 20 % window
- Additional variables
- Beam track length distribution
  - Data has less pions and more muons : problem related with decay-in-flight simulation?







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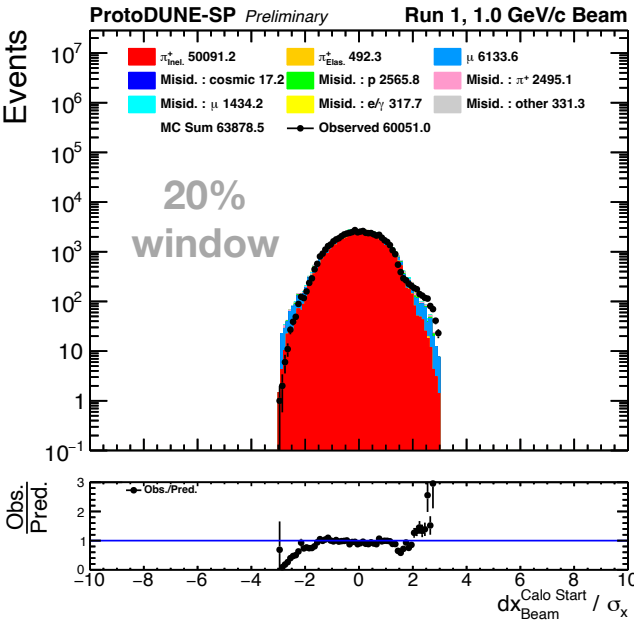
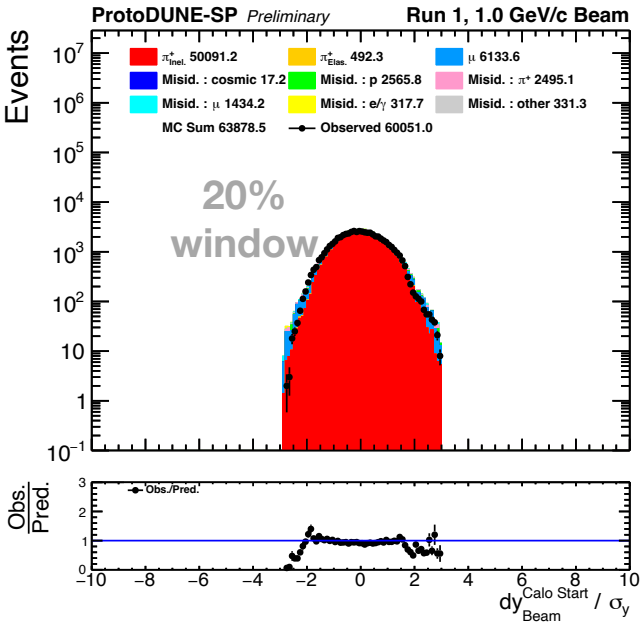
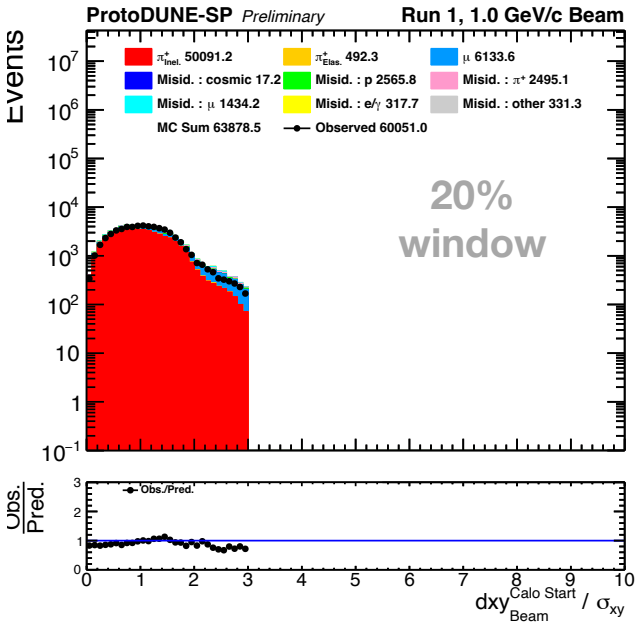
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

For data vs MC comparison

- Truth level beam momentum reweighting is applied
- Additional cut on $P_{\text{Beam Inst.}}$: 20 % window
- Additional variables



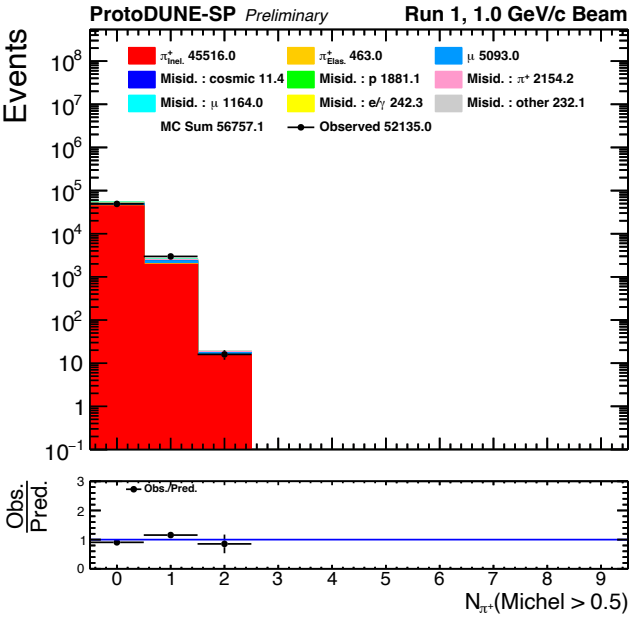


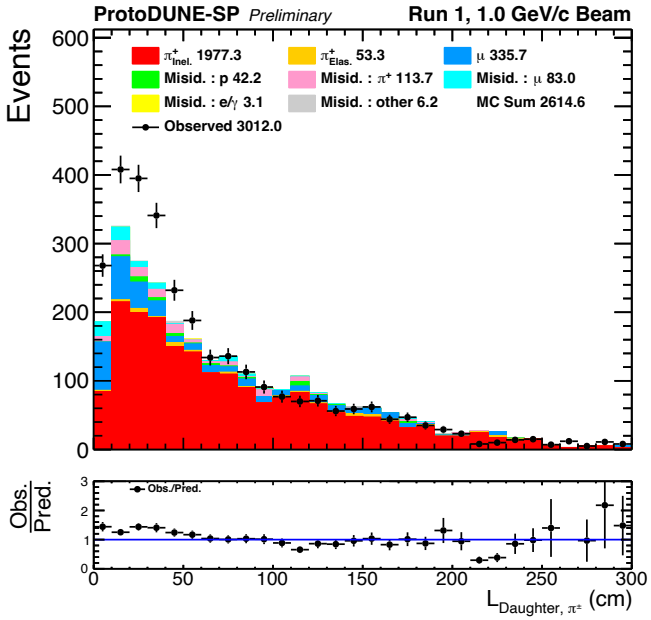


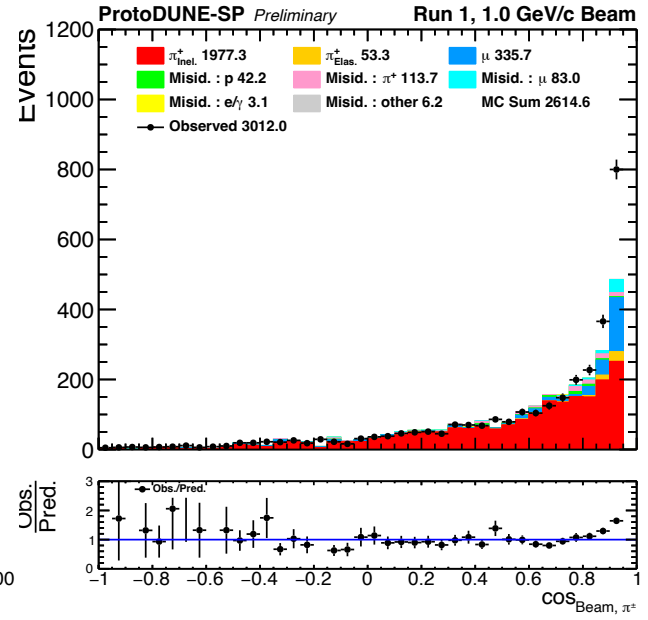
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Daughter variables

- At least one reconstructed daughter
- Mismodeling on muon beam contribution is suspected
  - I need to go back to beam momentum reweighting
- γcτ of 1 GeV/c π^+ is $\gamma \times 7.8$ m = 7.23×7.8 m = 56.4 m
- H4-VLE beam's secondary target to ProtoDUNE distance is about 40 m : exp[-40/56.4] ~ 0.5







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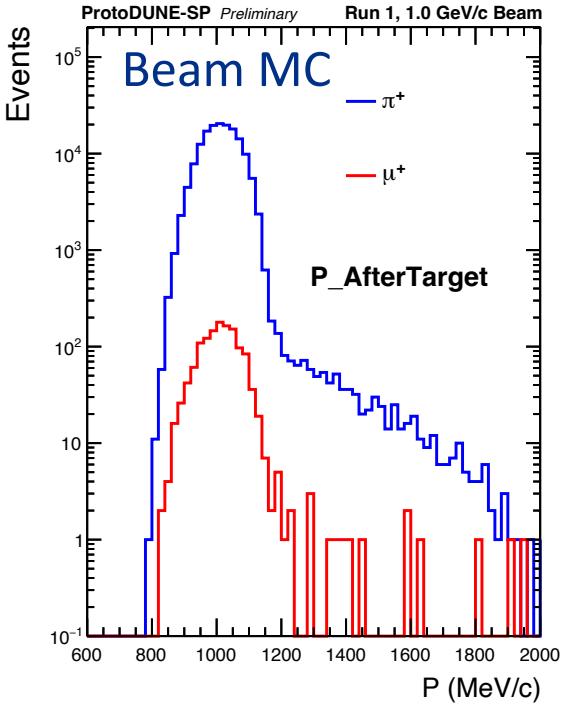
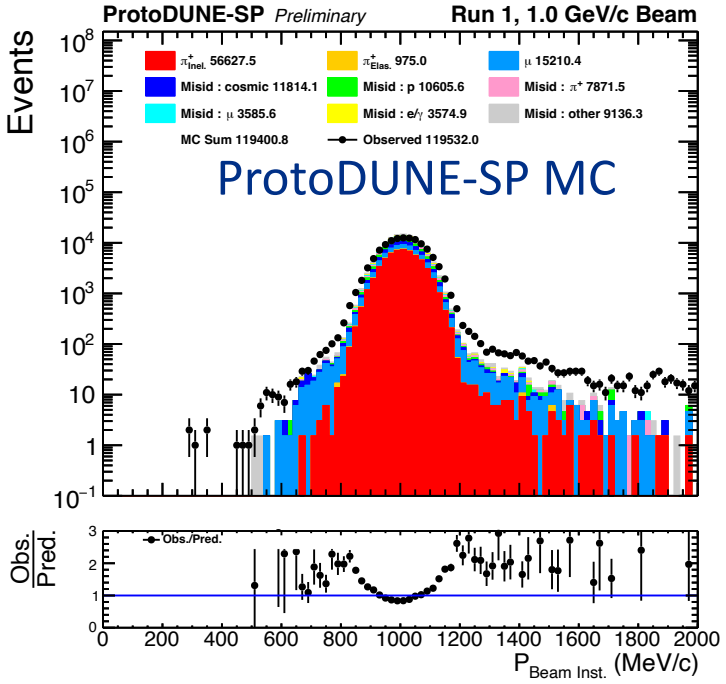
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Beam simulation sample vs ProtoDUNE-SP MC

- Beam simulation
  - After the secondary target of the H4-VLE beam : $N(\mu^+)/N(\pi^+) = 0.83\%$
- ProtoDUNE-SP MC
  - $N(\mu^+)/N(\pi^+) = 26\%$ (smaller than 50%, need more study)





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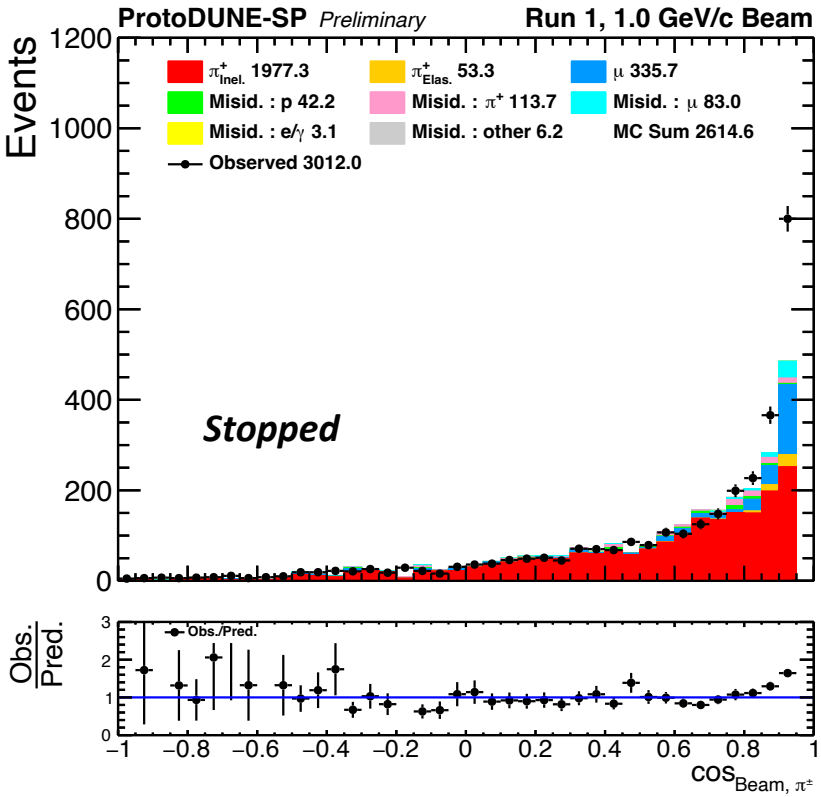
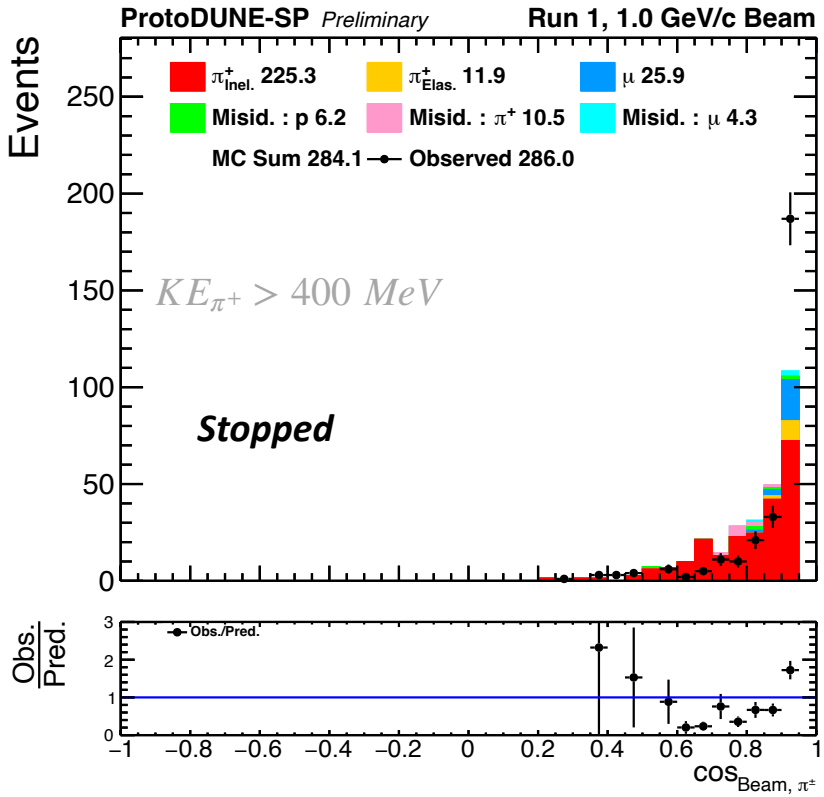
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Data vs MC distributions

- Charged pions with Michel score > 0.5

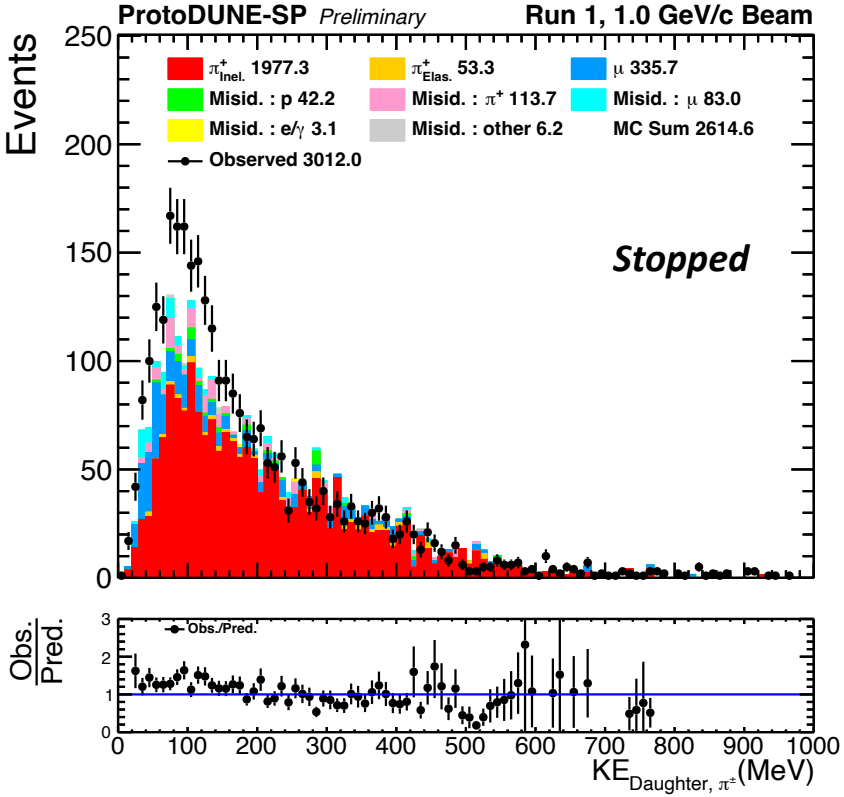


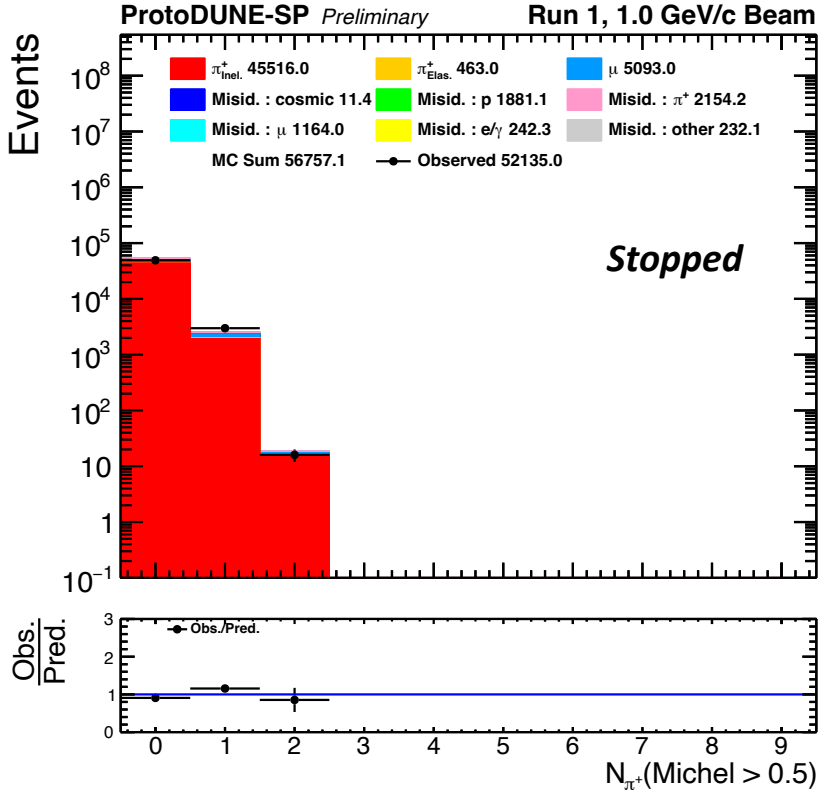


Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Data vs MC distributions

- Charged pions with Michel score > 0.5





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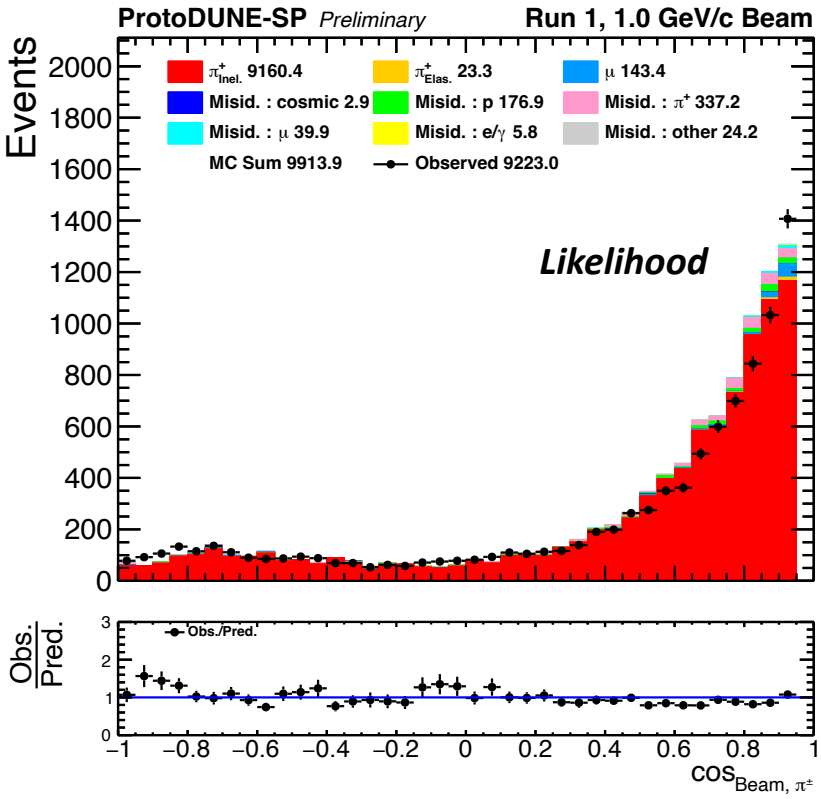
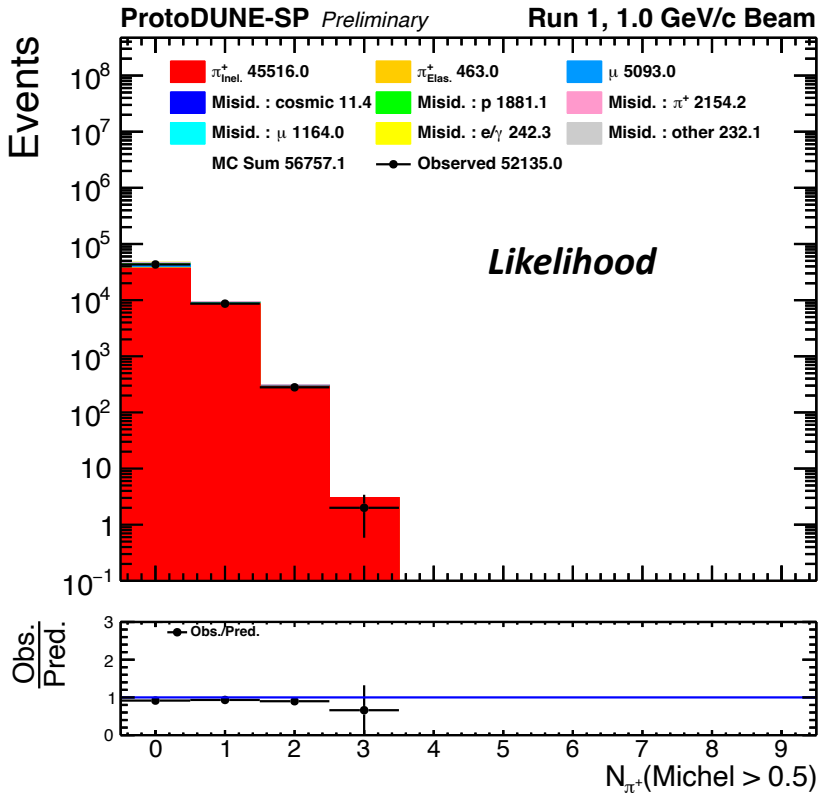
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Data vs MC distributions

- Charged pions with Michel score < 0.5
- Fit not failed : maximum likelihood using the Vavilov PDF for dE/dx





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Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Data vs MC distributions

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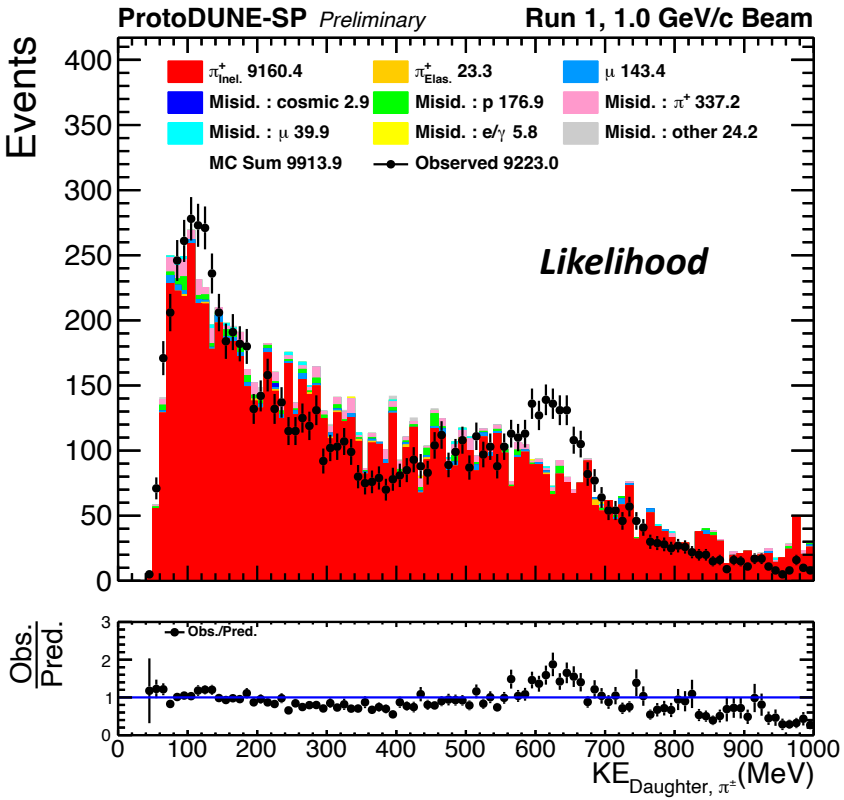

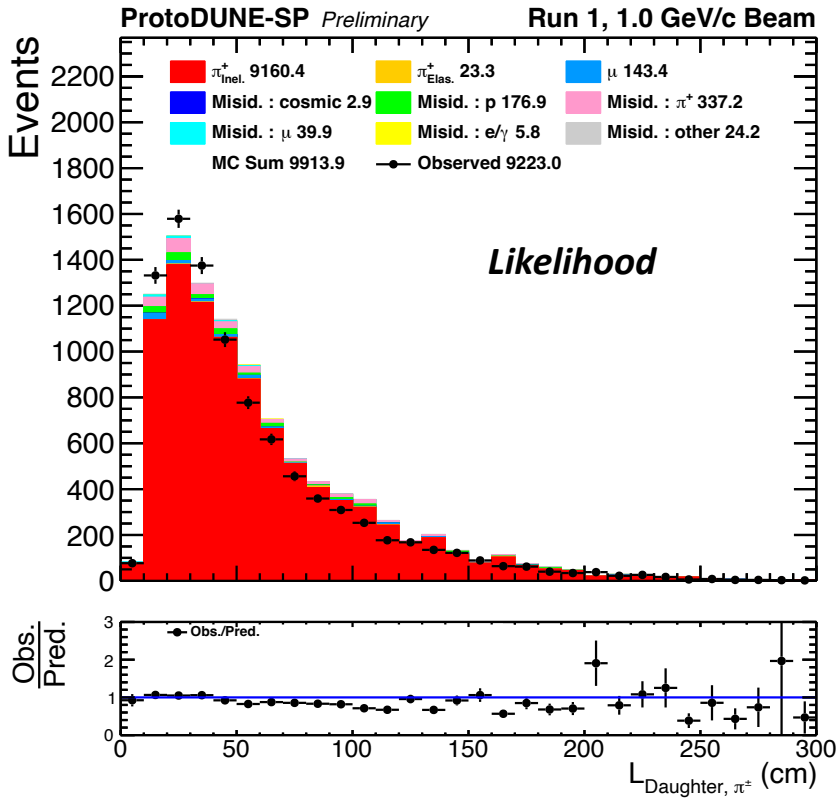

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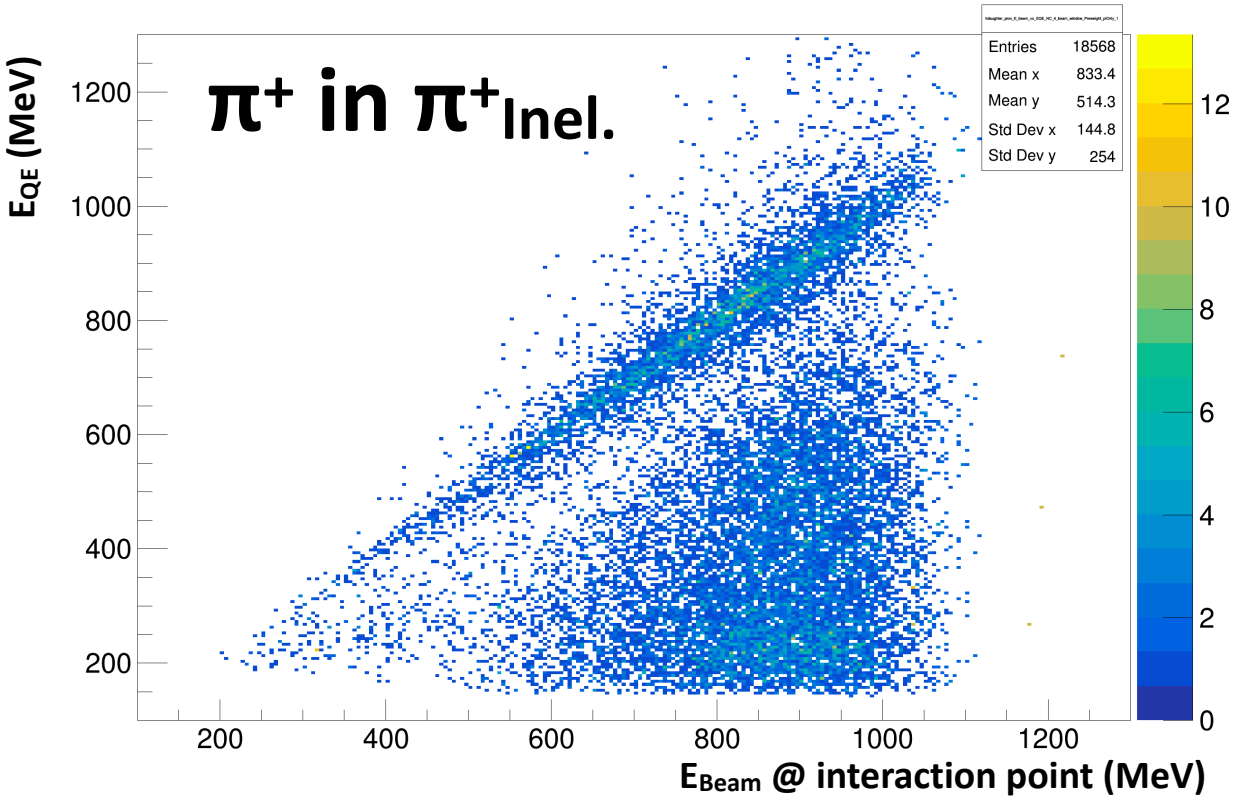
Study for Quasi-elastic Scattering of Charged Pions - ProtoDUNE-SP

Using ProtoDUNE MC samples at generator level

- Difference between truth level beam particle energy at interaction point and E_{QE}
- A clear QE band is observed
- E_b = 4 MeV



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