Updates on TKI Analysis in Pion Charge Exchange Channel

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Hadron Analysis Meeting

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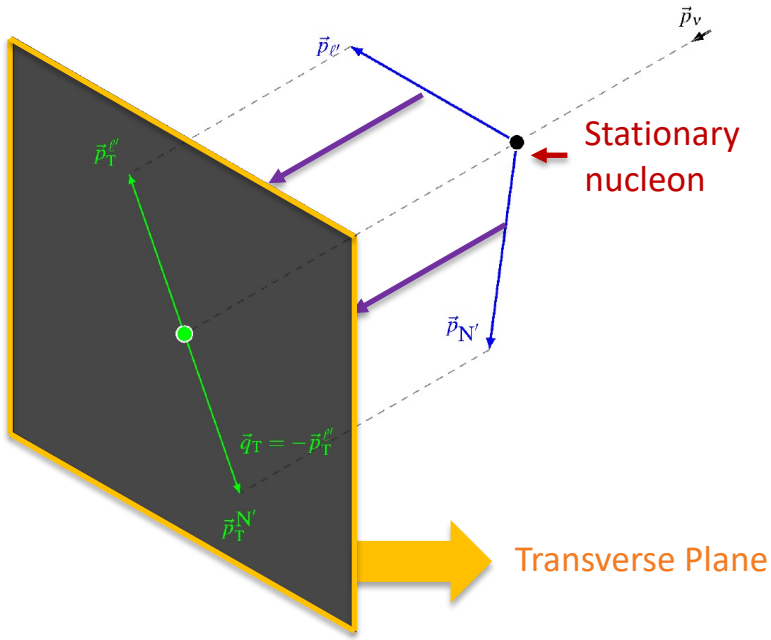
Contents

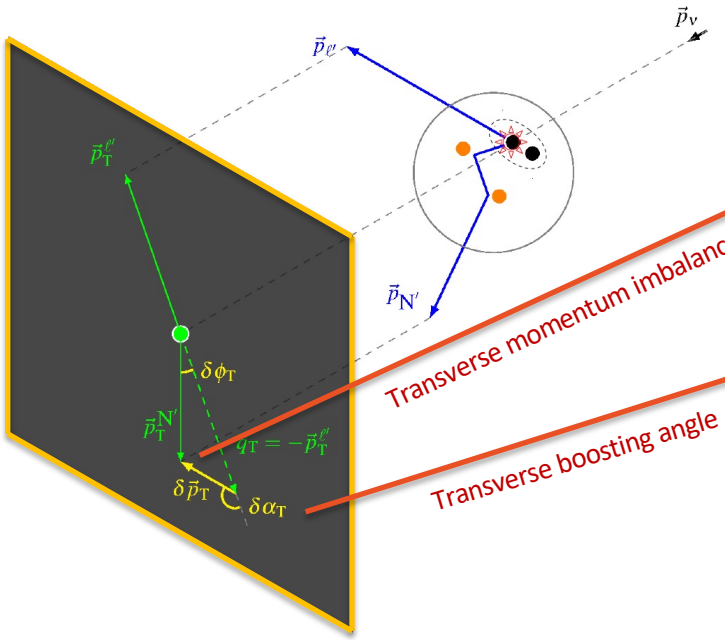
- TKI definition and analysis flowchart
- Beam & daughter particle reconstruction resolution
- Daughter proton, shower, π^0-particle selection purity and reconstruction efficiency
- Transverse boosting angle and struck neutron momentum

Transverse Kinematic Imbalance (TKI)

– Precisely identify intranuclear dynamics, or the absence thereof, in interactions between nuclei and GeV-neutrinos from accelerators



Stationary nuclear target



Nuclear target (A>1)

We can define several TKI variables:

- $\delta\vec{p}_{\mathrm{T}} \equiv \vec{p}_{\mathrm{T}}^{\,\ell'} + \vec{p}_{\mathrm{T}}^{\,\mathrm{N}'}$
- $\delta\alpha_{\mathrm{T}} \equiv \arccos \dfrac{-\vec{p}_{\mathrm{T}}^{\,\ell'} \cdot \delta\vec{p}_{\mathrm{T}}}{p_{\mathrm{T}}^{\ell'}\delta p_{\mathrm{T}}}$

Struck nucleon momentum p_N:

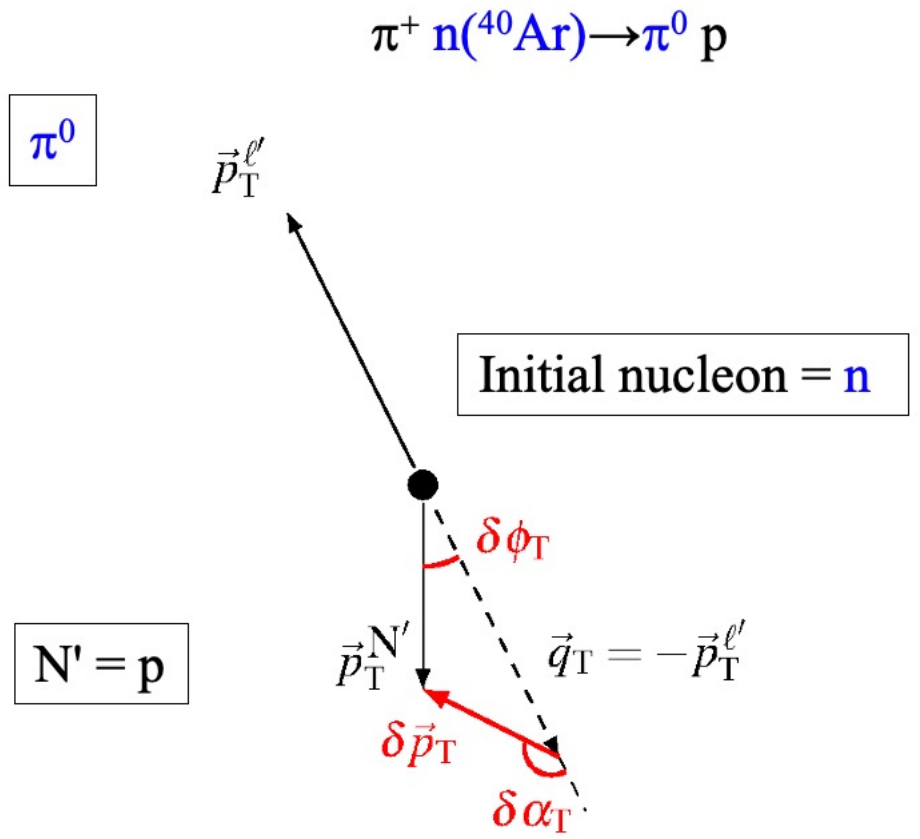
$$p_N = \left(\delta p_{\mathrm{T}}^2 + \delta p_{\mathrm{L}}^2\right)^{1/2}$$

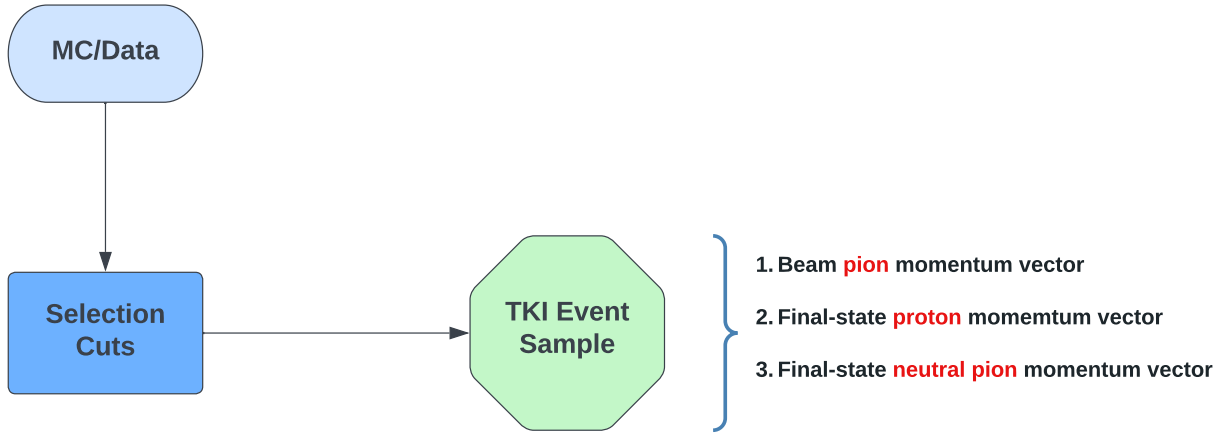
[Lu. *et al*. Phys. Rev. D92, 051302 (2015), Lu. *et al*. Phys. Rev. C94, 015503 (2016)]

[Furmanski & Sobczyk, Phys.Rev.C 95, 065501 (2017)]

TKI in protoDUNE

$\pi^+ n(^{40}Ar) \rightarrow \pi^0 p$ (Pion Charge Exchange)



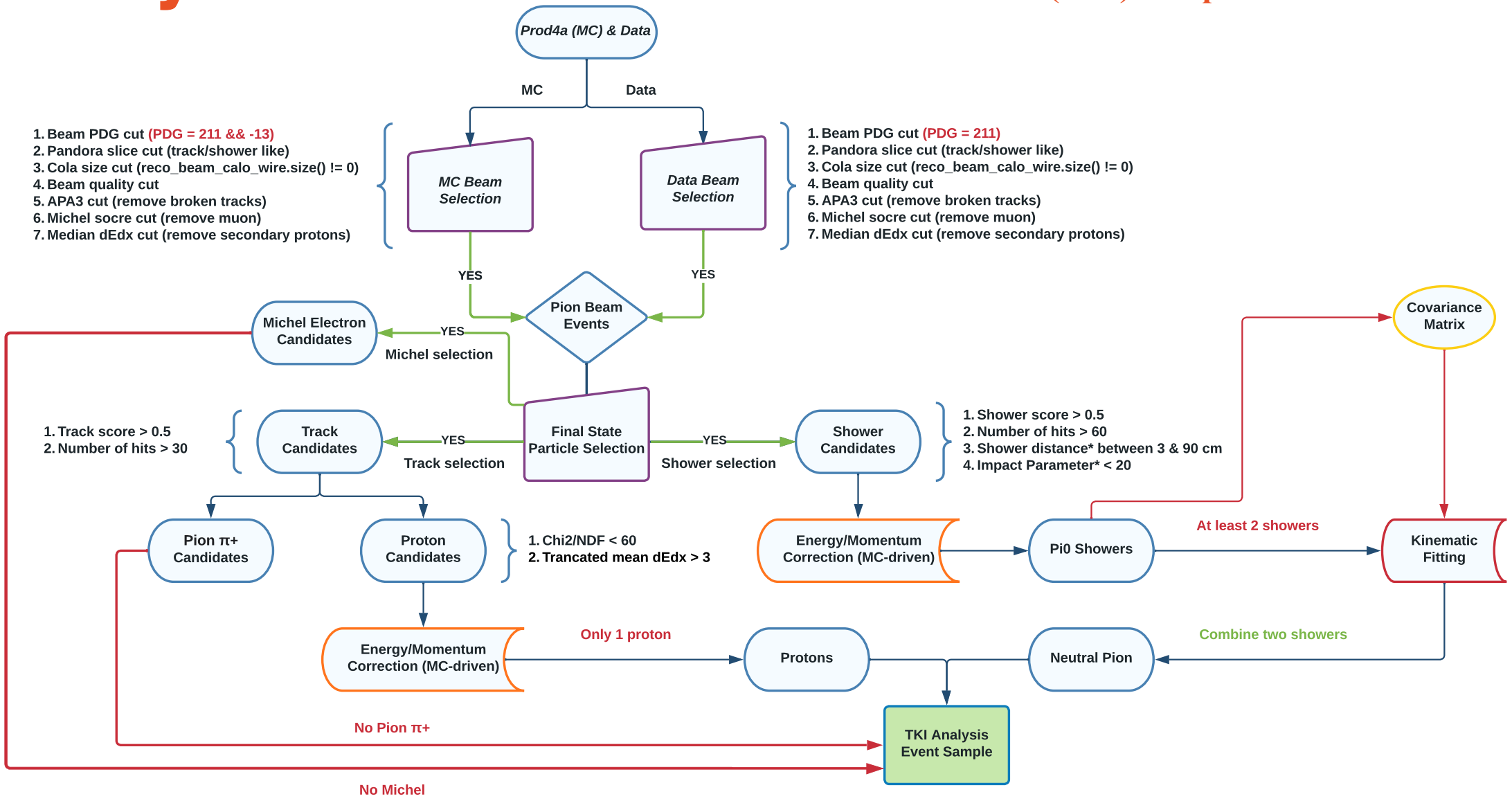


- p_{π^+} (beam pion) → transverse plane
- p_p (FS proton) → outgoing nucleon
- p_{π^0} (FS pion) → outgoing meson

- The incoming particle is pion in protoDUNE with precisely measured momentum on an event by event basis.
- Argon 18 protons, 22 neutrons, previous TKI measurements are on carbon and oxygen (iso-symmetric)

Analysis Flowchart

$\pi^+ n(^{40}Ar) \rightarrow \pi^0 p$



Beam & Daughter Particle Resolution

Particle Type	Energy/Mom. (frac. bias)	Theta (deg.) (abs. difference)	Phi (deg.) (abs. difference)	Performance
Beam	2.1%(0.04)	0.39 (1.65)	0.58 (5.54)	Good
Proton	-1.6% (0.02)*	2.47 (2.99)	0.16 (2.91)	Good
Shower	-15% (0.2)*	2.48 (6.16)	0.17 (8.54)	Need correction
Neutral Pion	-20% (0.2)*	2.92 (4.41)	0.16 (8.04)	Need correction

- Pion beam and final-state proton are reconstructed well by Pandora.
- The direction of each particle is good, ϕ angle abs. resolution has a mean value close to 0 but with a rather large spread.
- There is a ~ 3° bias in all final-state daughter particles.
- The energy resolution in shower is bad, which leads to a poor π^0 mom. res.

*** Do not have a proper fit curve (read values from distributions)**

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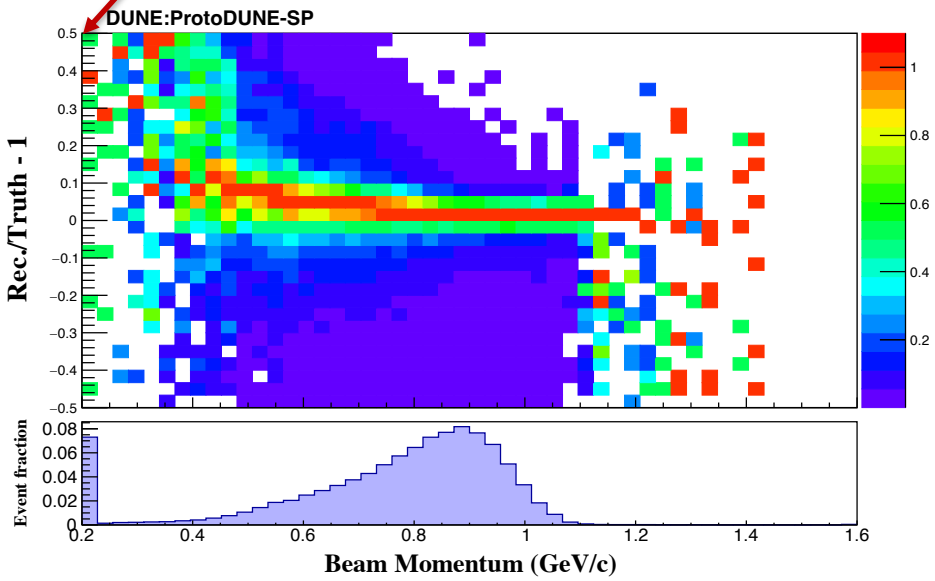
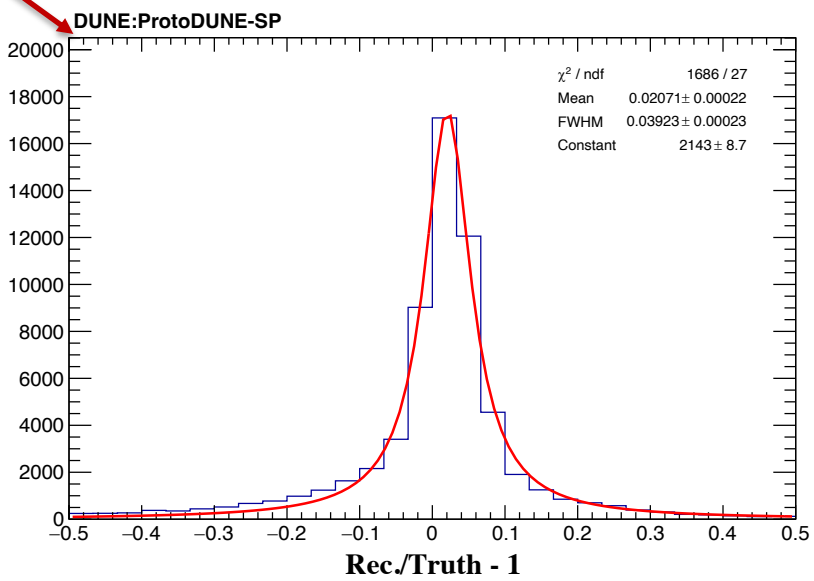




* Do not have a proper fit curve (read values from distributions)

All other resolution plots – see backups p23-34

Beam & Daughter Particle Resolution (After)

Particle Type	Energy/Mom. (frac. bias)	Theta (deg.) (abs. difference)	Phi (deg.) (abs. difference)	Performance
Beam	2.1%(0.04)	0.39 (1.65)	0.58 (5.54)	Good
Proton	0.06% (0.02)	-0.35 (2.70)	0.003 (2.83)	Good
Shower	3% (0.16)	-0.29 (5.95)	0.036 (8.34)	Good
Neutral Pion	-2.9% (0.09)	0.11 (4.87)	-0.047 (8.06)	Good

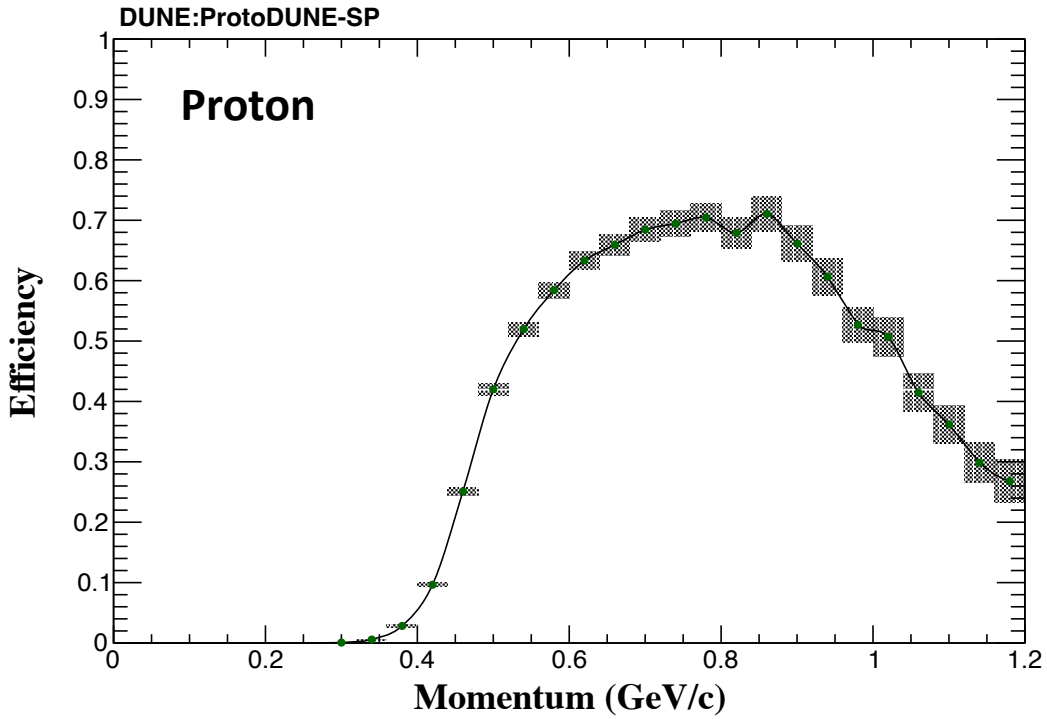
- The MC-driven correction method can be found in my previous talk.
- The π^0 energy is improved via the kinematic fitting after shower energy correction.
- After the correction, both beam and final-state particle have a good resolution.
- Both shower energy and π^0 momentum resolution are good enough for TKI calculation.

Purity and Efficiency Study (Daughter Proton)

Cut	Purity (Cumulative)	Efficiency (Cumulative)	Purity * Efficiency
Track Score > 0.5	**0.42**	**0.41**	**0.173**
# hits (total) > 30	**0.39**	**0.31**	**0.122**
Chi2NDF < 60 or lastTME > 3	**0.69**	**0.26**	**0.182**

- Purity: The fraction of the sample that consists of **true proton** daughters.
- Efficiency: The remaining fraction of the original **true photon** daughters

- Stat. error for each bin is shown in the colour bands.

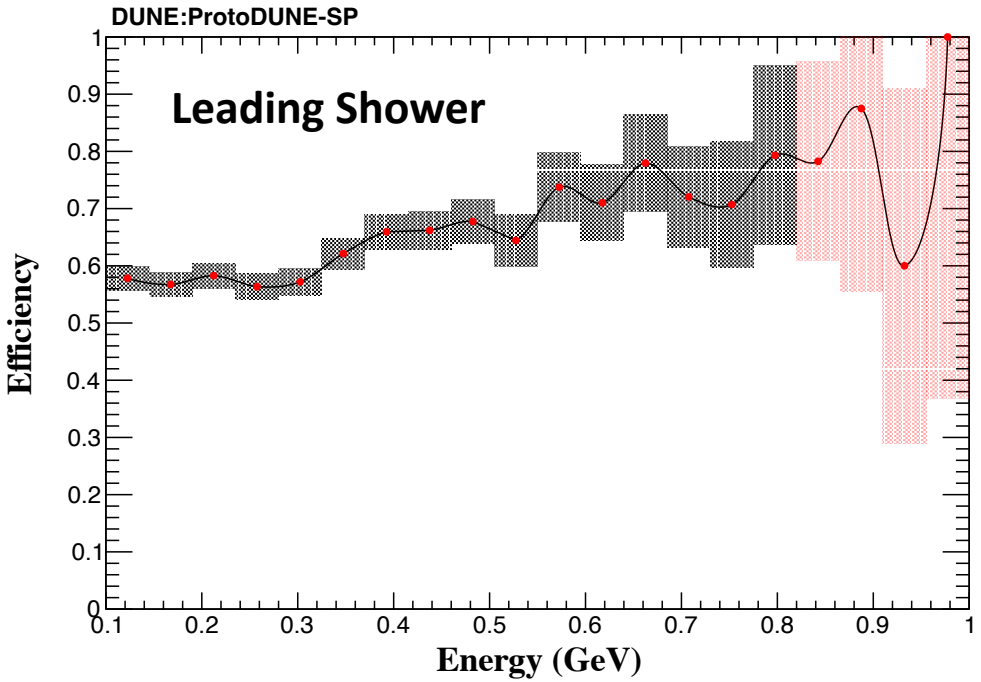


Purity and Efficiency Study (Daughter Shower)

Cut	Purity (Cumulative)	Efficiency (Cumulative)	Purity * Efficiency
EM score > 0.5	**0.45**	**0.71**	**0.321**
# hits (total) > 60	**0.63**	**0.53**	**0.332**
3 cm < dist. < 90 cm	**0.73**	**0.48**	**0.351**
IP < 20 cm	**0.77**	**0.42**	**0.325**

- Purity: The fraction of the sample that consists of **true leading photon** daughters.
- Efficiency: The remaining fraction of the original **true leading photon** daughters

- Stat. error for each bin is shown in the colour bands.

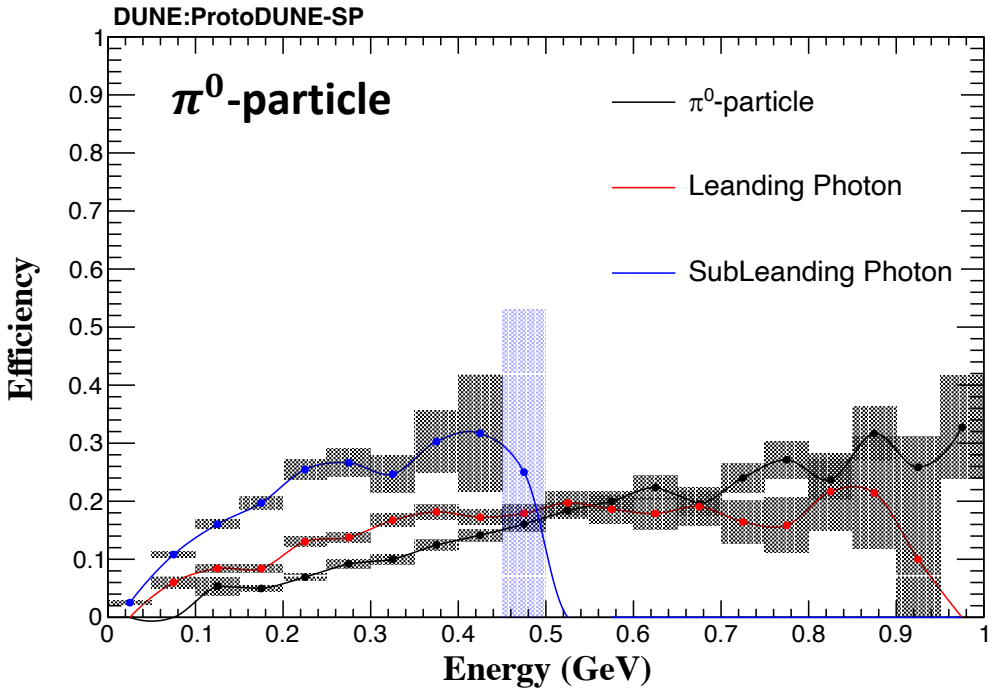


Purity and Efficiency Study (Daughter π^0-particle)

Cut	Purity (Cumulative)	Efficiency (Cumulative)	Purity * Efficiency
No cuts (use selected shower pairs)	**0.62**	**0.13**	**0.083**
50 < mass < 250 MeV	**0.71**	**0.11**	**0.077**
10 < OA < 80 deg.	**0.76**	**0.10**	**0.076**

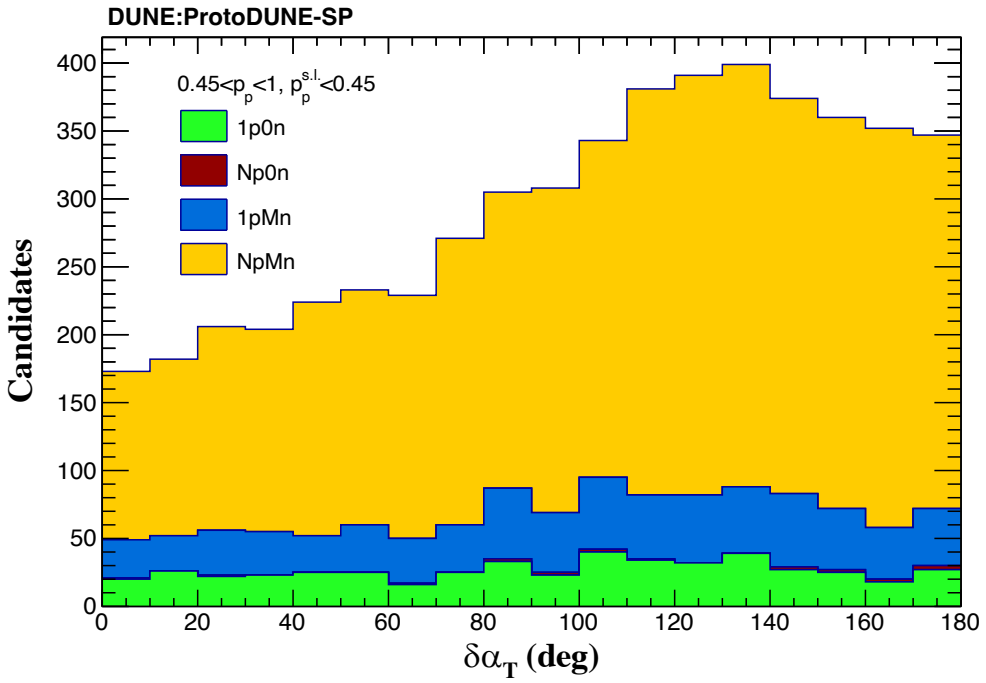
- Purity: The fraction of the sample that consists of **true π^0** daughters.
- Efficiency: The remaining fraction of the original **true π^0** daughters

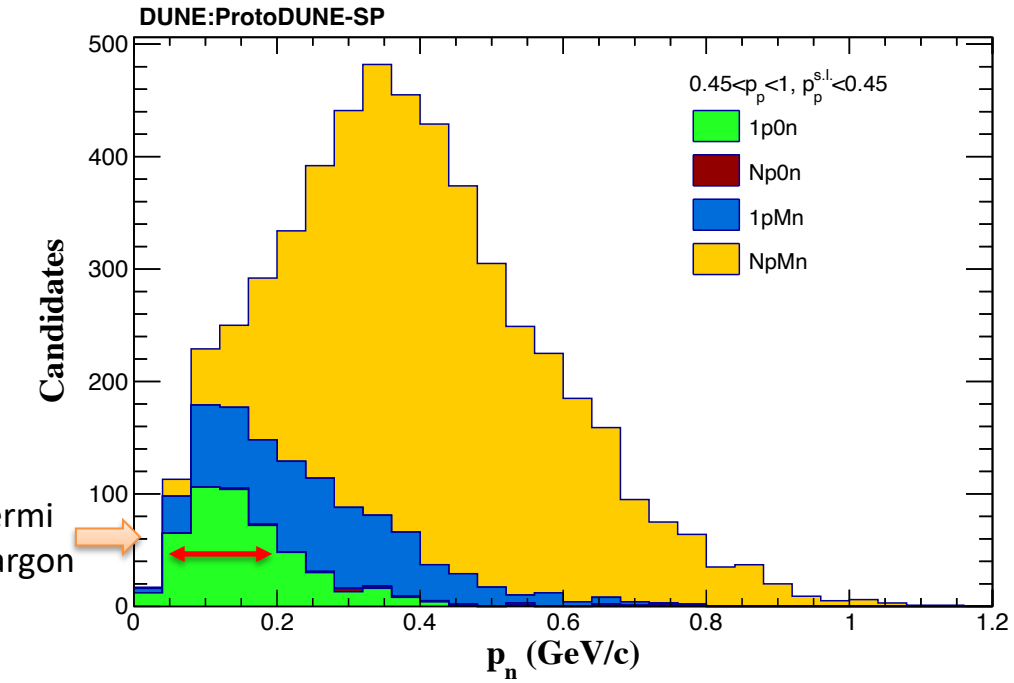
- Stat. error for each bin is shown in the colour bands.



Truth Signal at protoDUNE

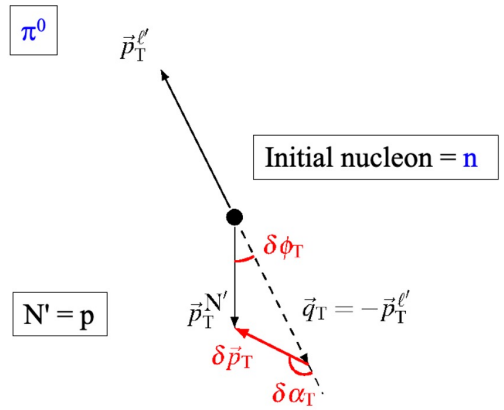
$\pi^+ n(^{40}Ar) \rightarrow \pi^0 p$





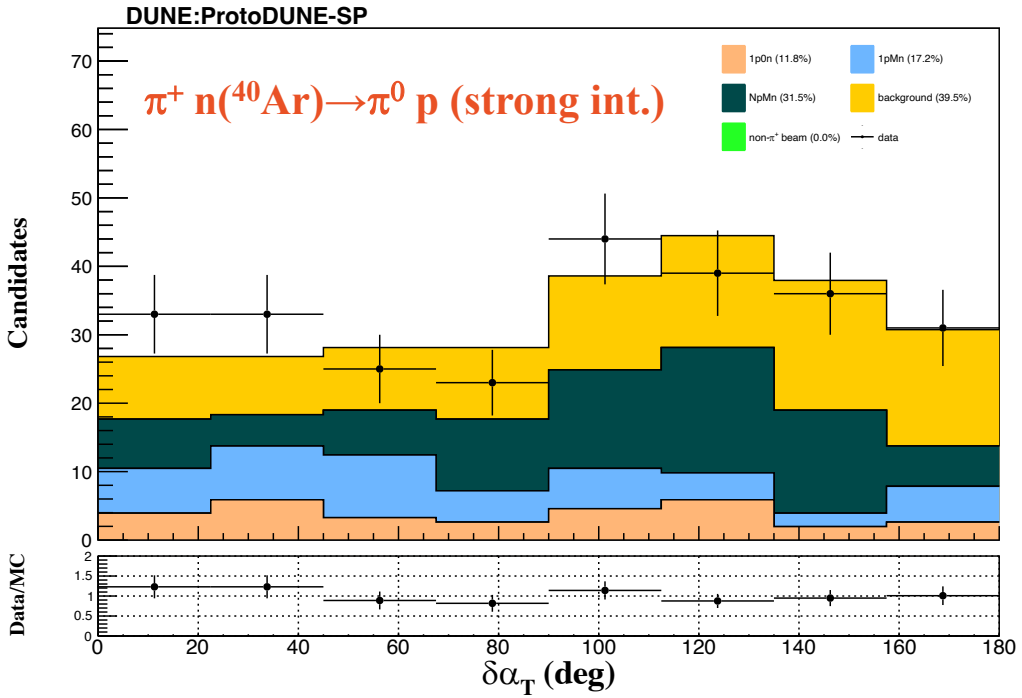
Neutron Fermi motion in argon

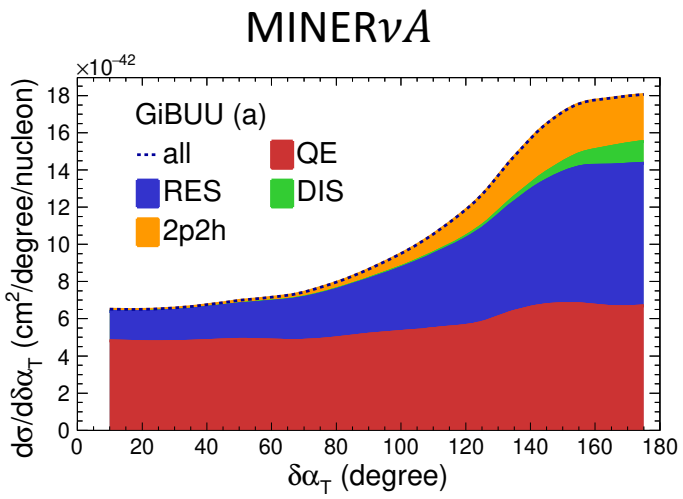
- Since the Fermi motion is isotropic, the distribution of α_T should be flat if we only consider Fermi motion of the initial nucleon.
- Large α_T indicates missing momentum from undetectable neutrons.
- A Fermi motion peak can be found around 0.2GeV/c.



Reconstructed TKI $\delta\alpha_T$

DUNE ND CDR – Sec. 6.6.2

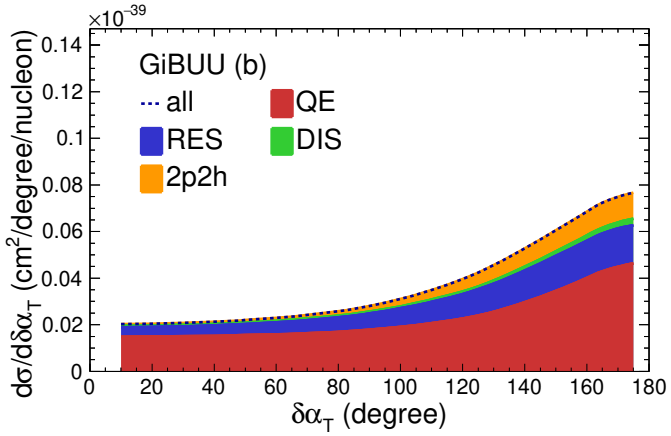




$$\begin{cases} p_\mu > 0.0254 \text{ GeV/c}, 4\pi \text{ full angle} \\ p_p > 0.0751 \text{ GeV/c}, , 4\pi \text{ full angle} \end{cases}$$

ν_μ n(^{12}C)→μ^-p (weak int.)

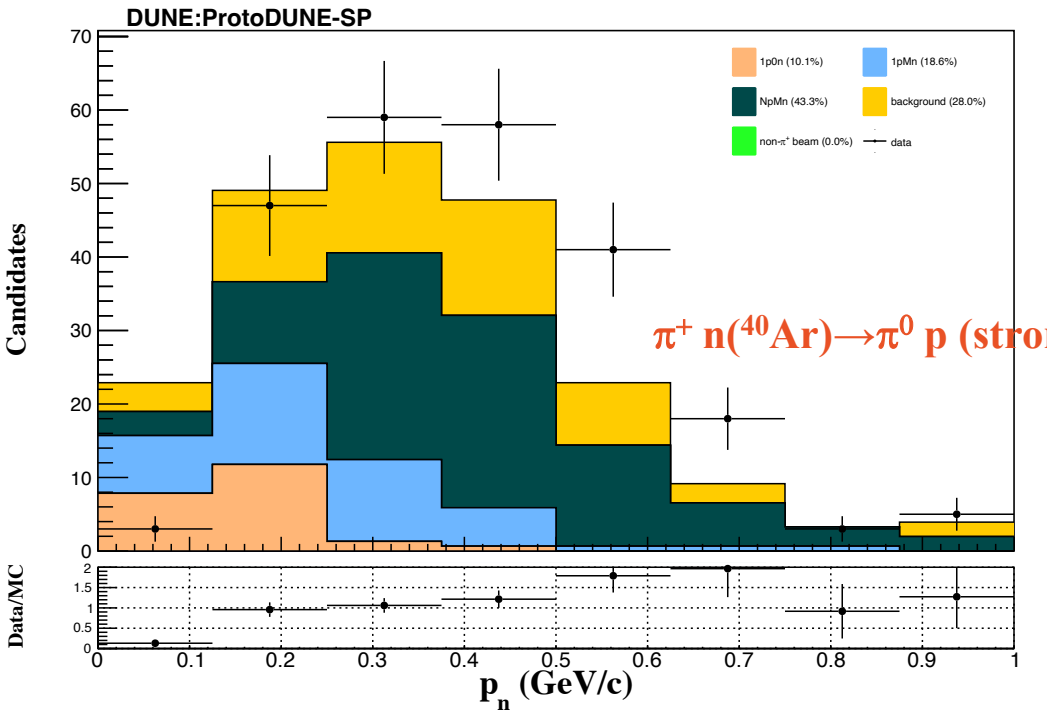
MINERνA, but HPgTPC detection threshold



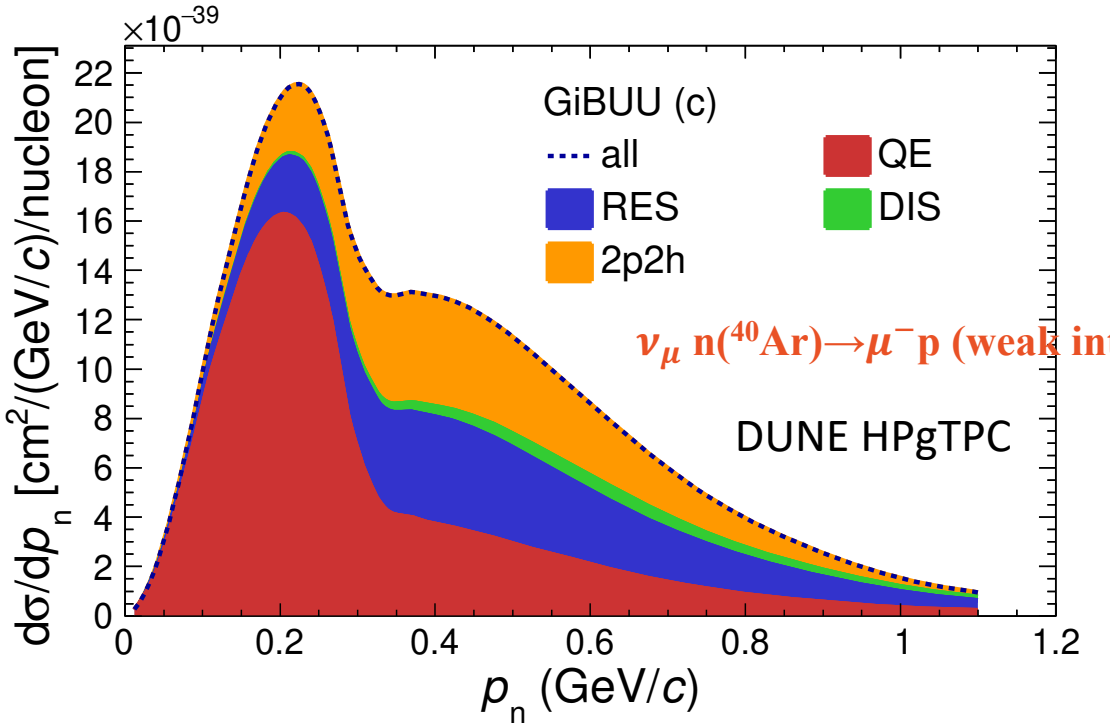
- For the 1p0n sample, a flat $\delta\alpha_T$ distribution is found, indicates no FSI. (due to the high proton momentum detection threshold $p_p > 0.45$ GeV/c, decelerated protons can't be detected.)
- The missing momentum from undetectable neutrons in NpMn sample causes a large $\delta\alpha_T$ distribution.

Reconstructed TKI p_n

DUNE ND CDR – Sec. 6.6.2



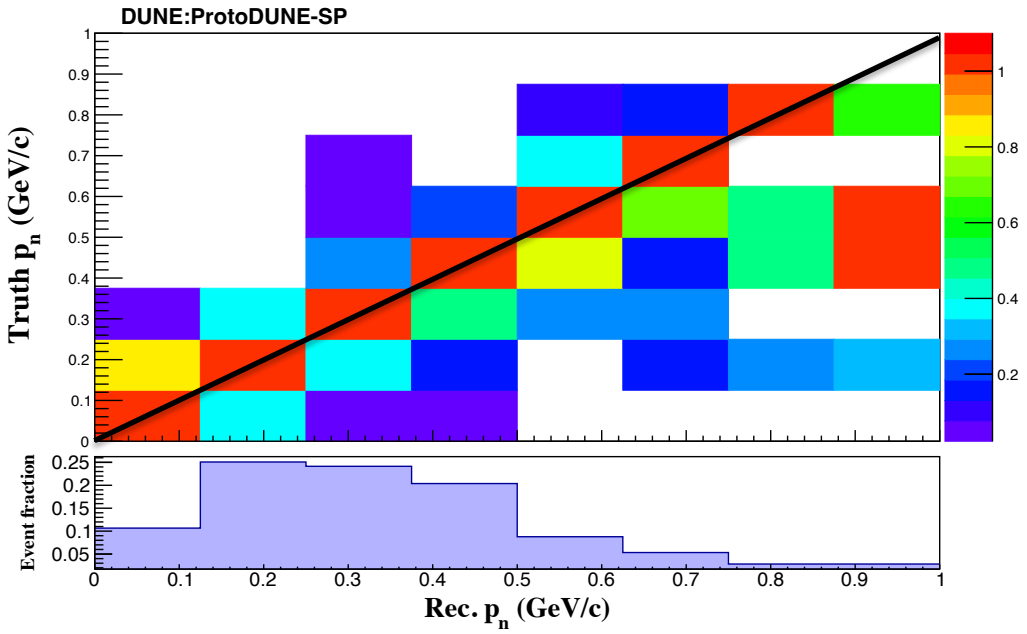
$\pi^+ n(^{40}Ar) \rightarrow \pi^0 p$ (strong int.)



$\nu_\mu n(^{40}Ar) \rightarrow \mu^- p$ (weak int.)

- For the 1p0n sample, a peak is found around 0.2 GeV indicates the initial Fermi motion of the struck neutron.
- Similar Fermi motion peak is also predicated by GiBUU in the DUNE HPgTPC detector with muon neutrino flux.

Smearing Matrix for p_n



Channel	Purity (Cumulative)	Efficiency (Cumulative)	Purity * Efficiency
Exclusive Charge-Exc. (1p0n + 1π^0)	**0.12**	**0.10**	**0.012**

- The smearing matrix of p_n looks great.
- Most of the events lie on the diagonal line, especially for the Fermi motion region (~ 0.2 GeV).
- The efficiency of pion charge exchange (exclusive) channel is about 10% and the purity is 12% due to the undetectable neutrons and high proton detection threshold.
- Veto neutrons could improve purity.

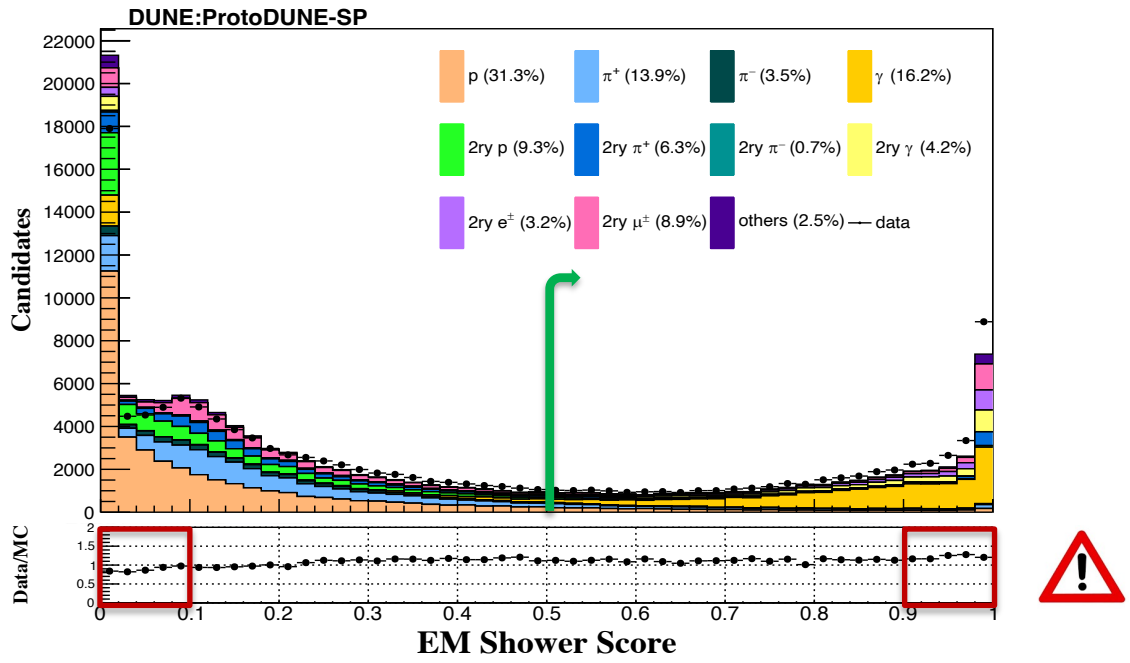
Summary

- A summary of 1GeV pion beam and daughter particles' reconstruction resolution is given. In general, beam pions and daughter protons are reconstructed well by Pandora.
- Both daughter shower objects and π^0-particles need to be corrected by an MC-driven method and kinematic fitting, respectively.
- An overview of the cuts and the cumulative purity and efficiency of each daughter particle is studied. After selection, around 70% of purity is achieved.
- The efficiency of reconstructing the exclusive charge exchange channel is only about 10%.
- Fermi motion peak of the struck neutron in Argon is observed for the first time.
- Veto neutrons in the final state could improve the purity of the TKI sample.

Back-ups

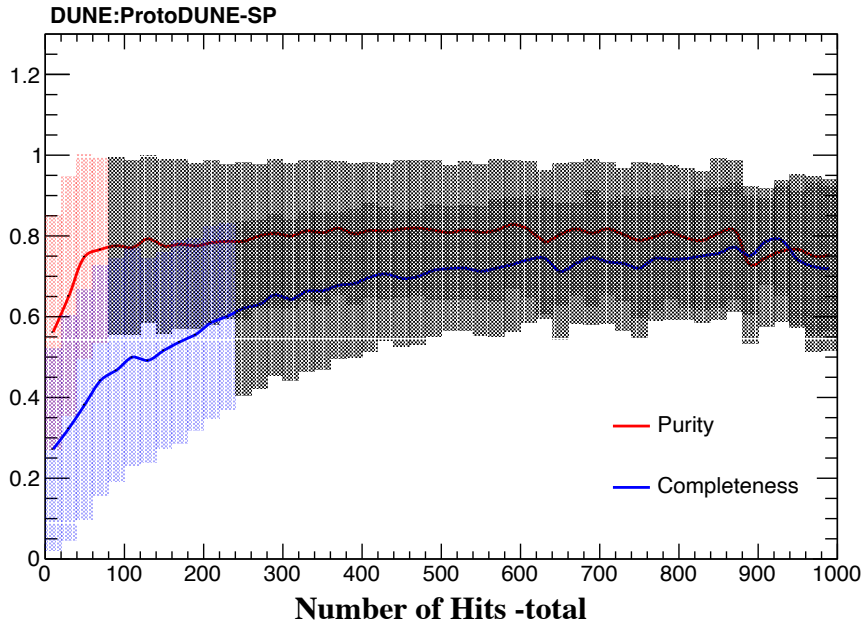
CNN EM Score of All Beam Daughters

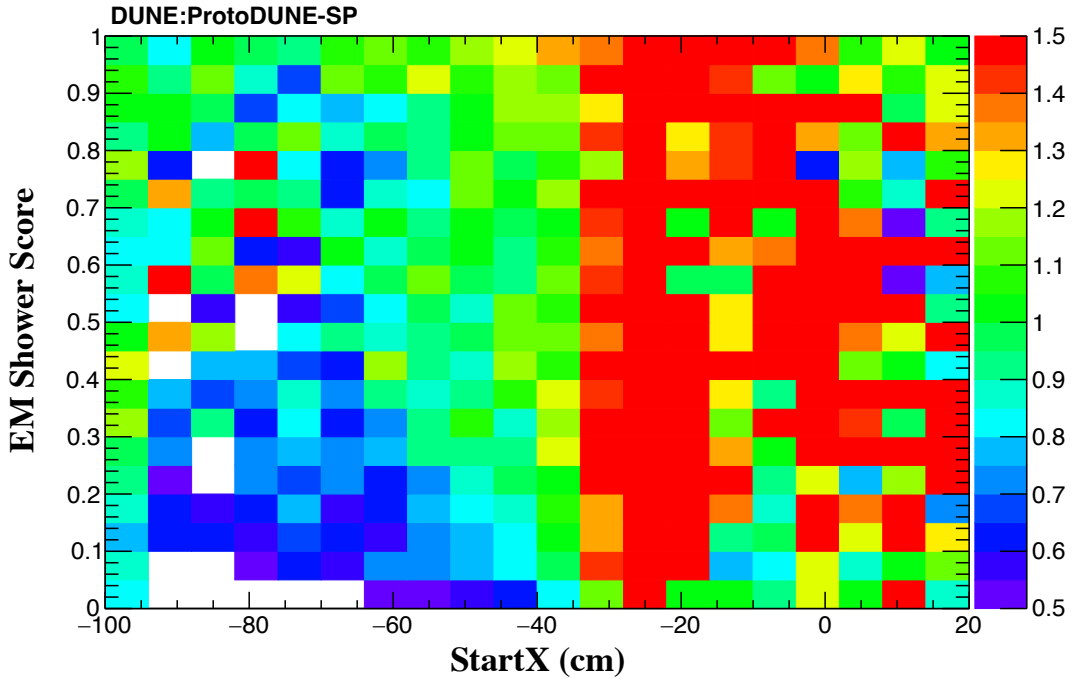
Recap

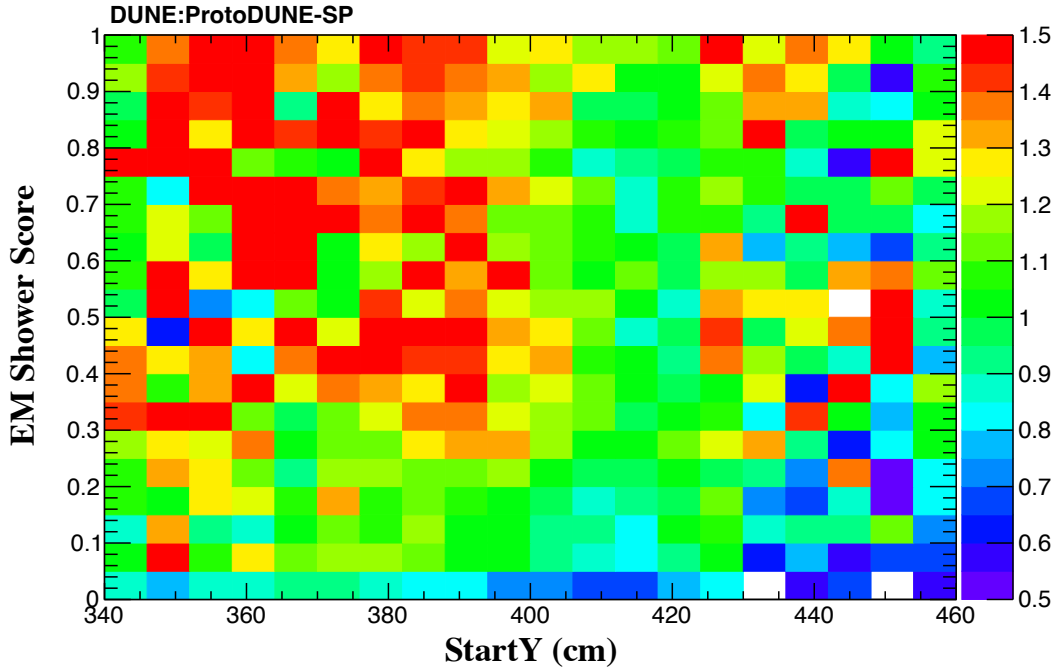


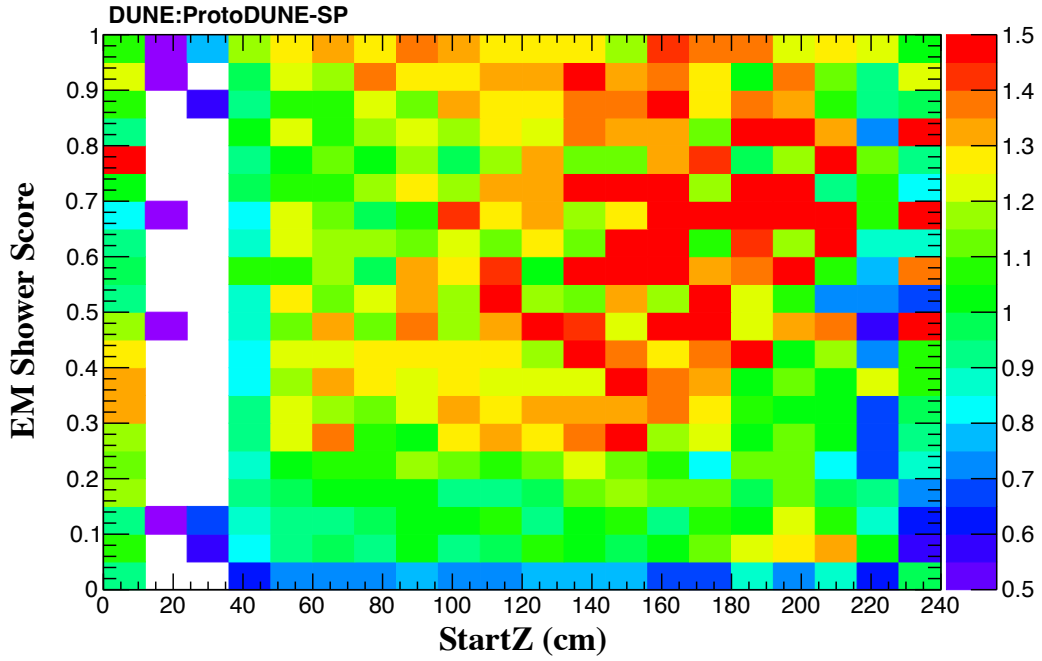
- Good data-MC agreement (except for score < 0.1 or > 0.9)
- Photons and electrons are in general very well classified using EM score.

- Select particle with **EM score > 0.5**.
- Average purity and completeness as a function of # total hits
- The colour bands indicate a 1σ spread of the mean values in each bin

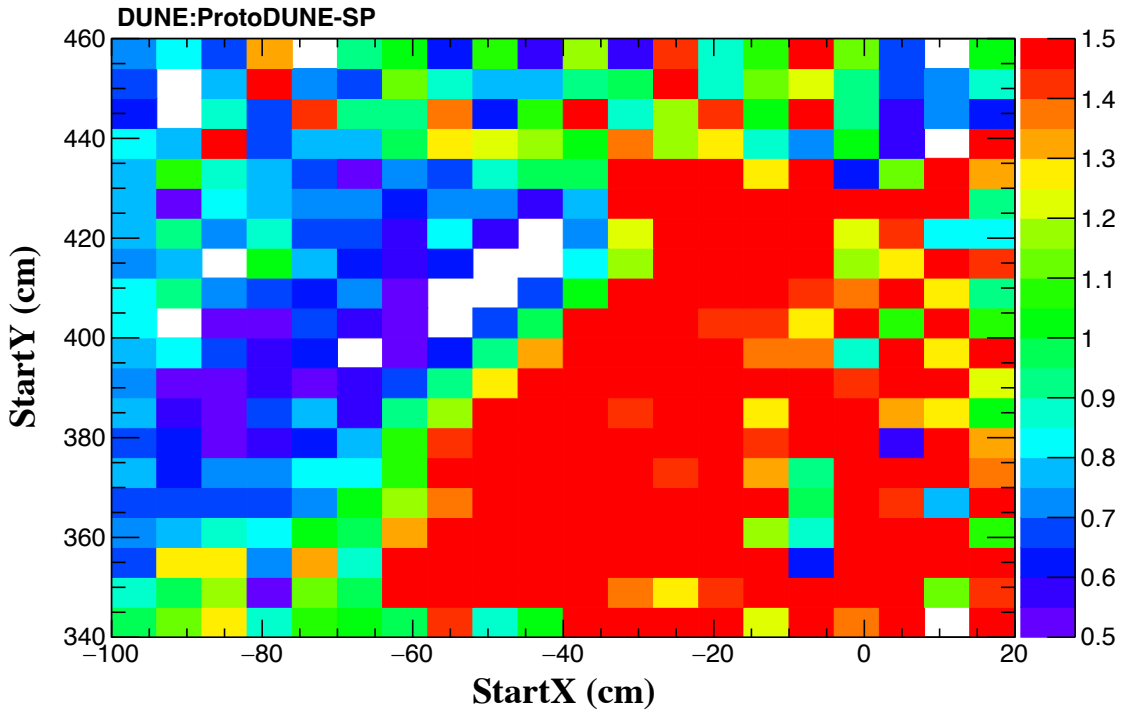


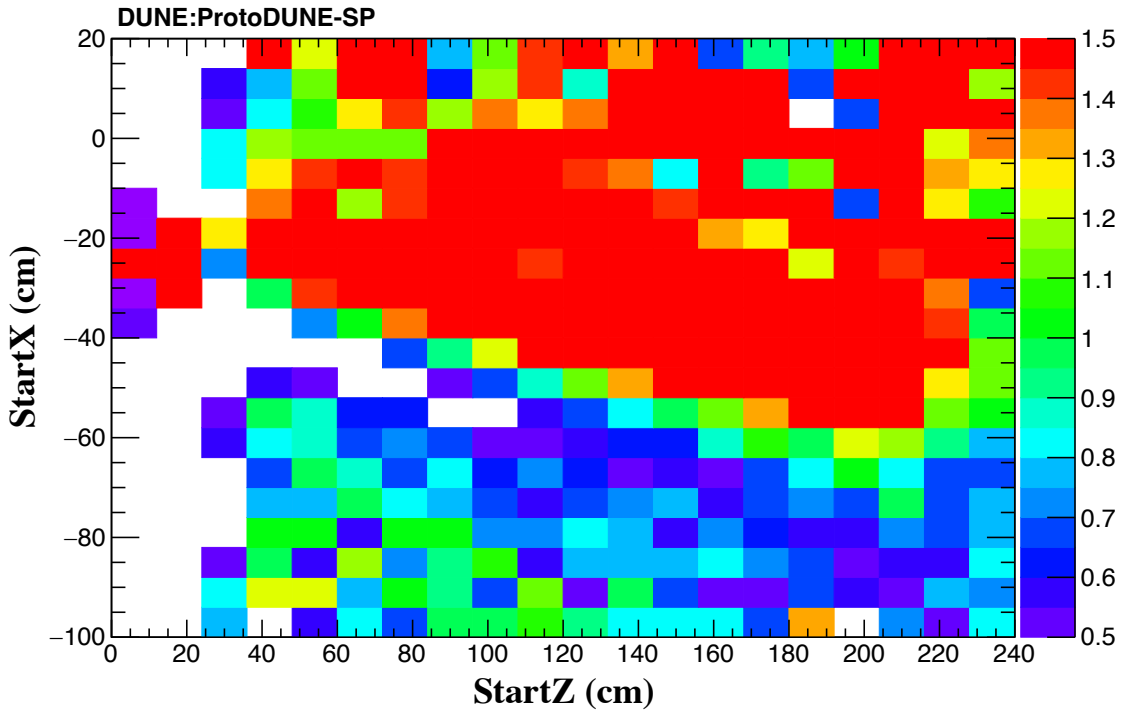






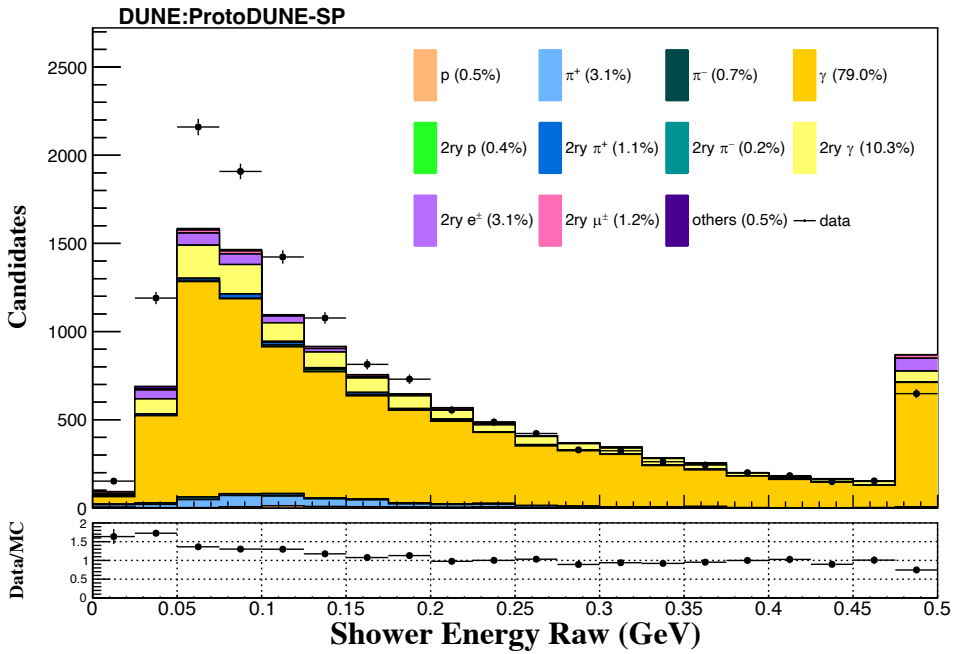
Color code in z-axis indicates the ratio of data/MC in that bin

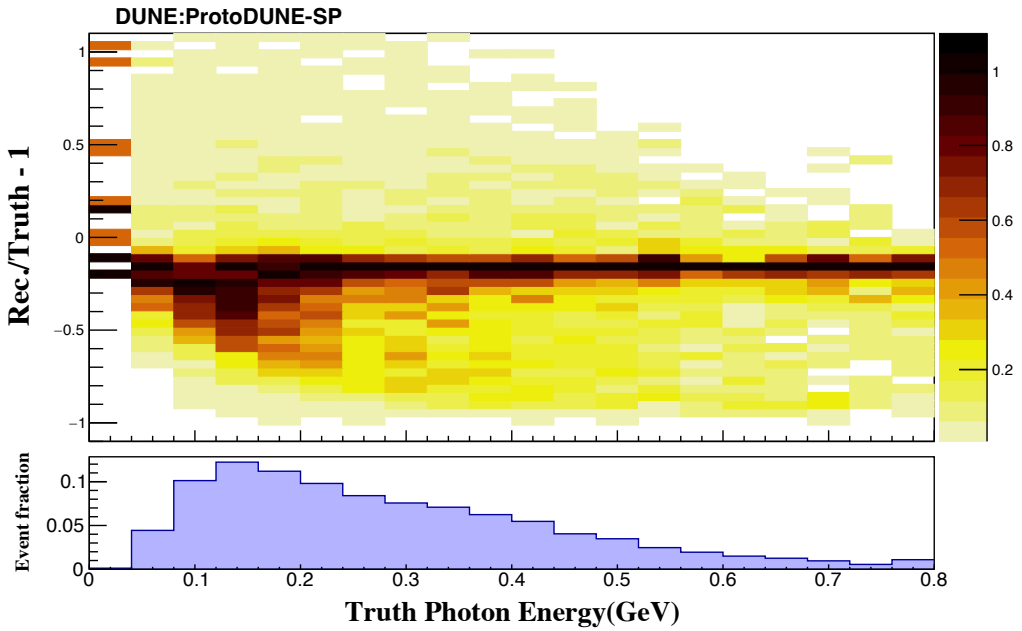




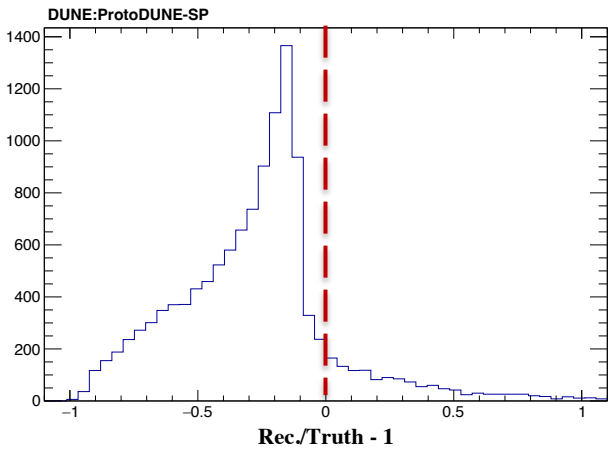
Color code in z-axis indicates the ratio of data/MC in that bin

Reconstructed Shower Energy

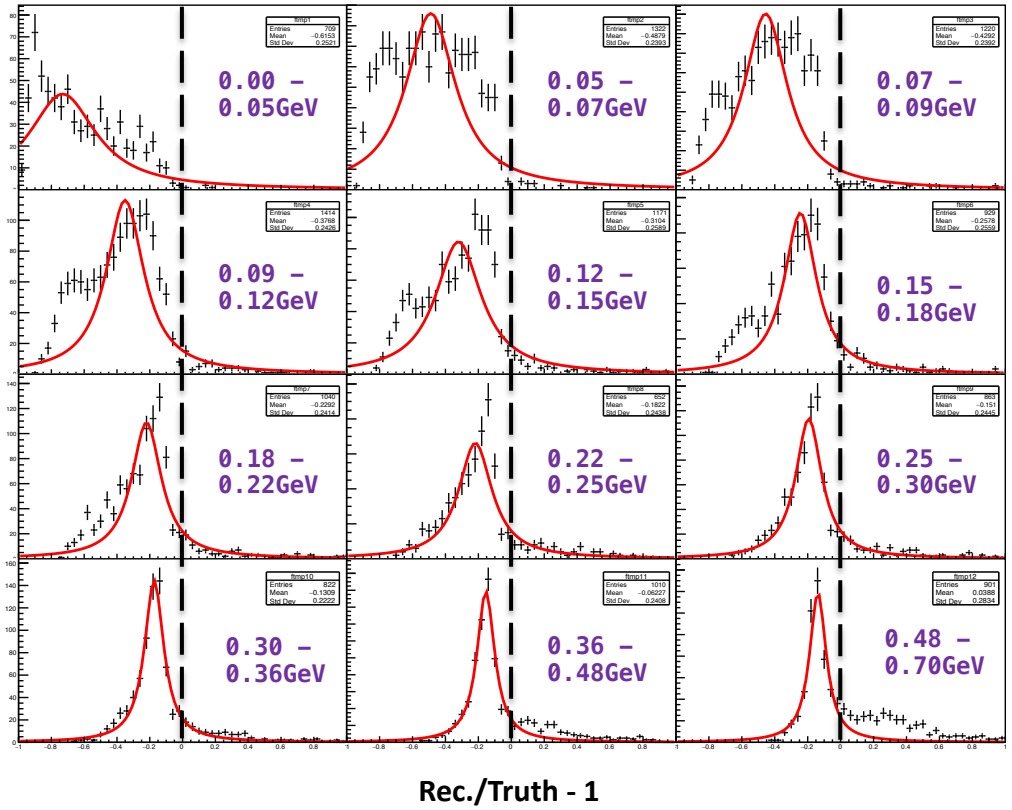




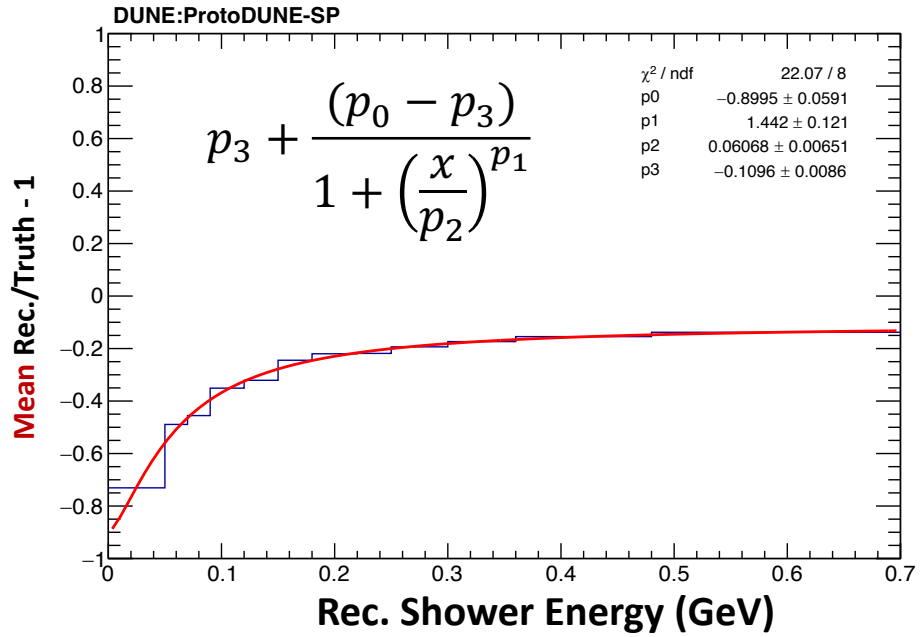
- A large data-MC discrepancy is found at the first few bins (might due to SCE).
- There is a significant negative bias (-15%) in the reconstructed shower energy (max. completeness is only 0.8)



Shower Energy Correction

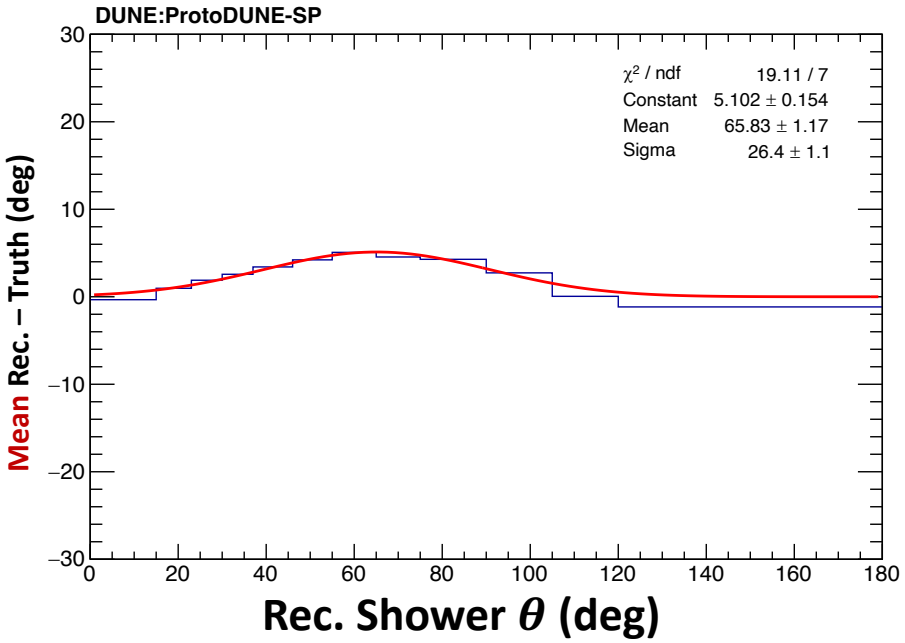


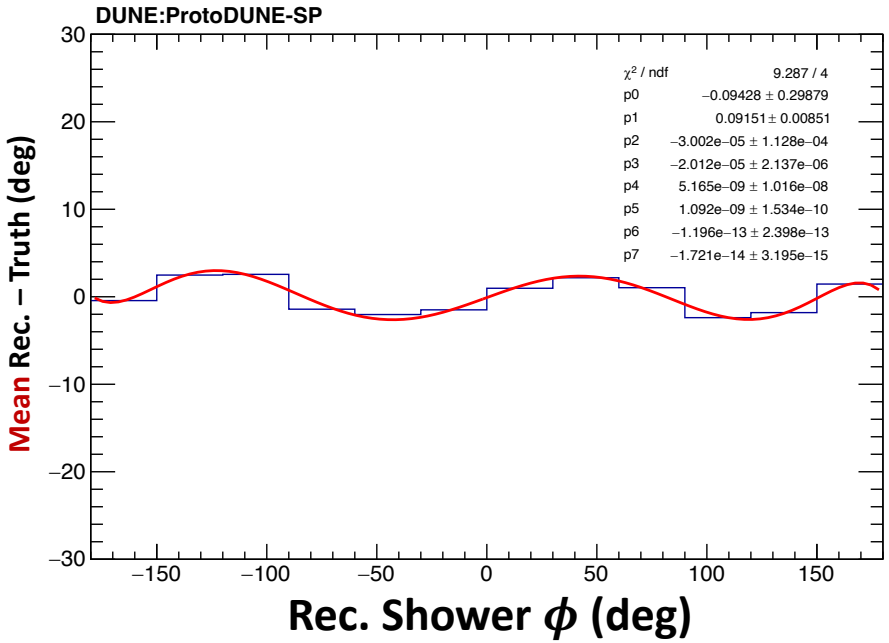
- Plot the fractional bias as a function of rec. shower energy (unequal binning).
- Fit the distribution by a **Cauchy–Lorentz** distribution.



- The MC-driven energy correction as a function of rec. shower energy.
- Input: raw shower energy
- Output: correction factor **(event by event)**

Shower Angle Correction

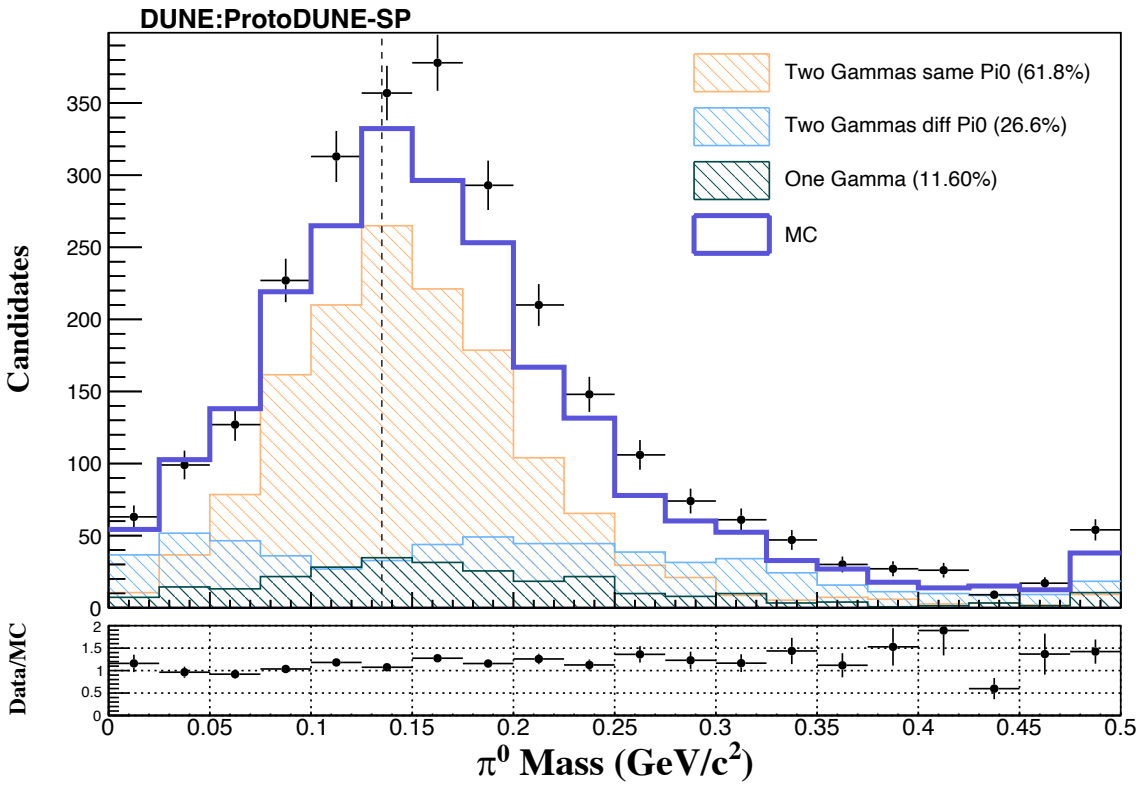




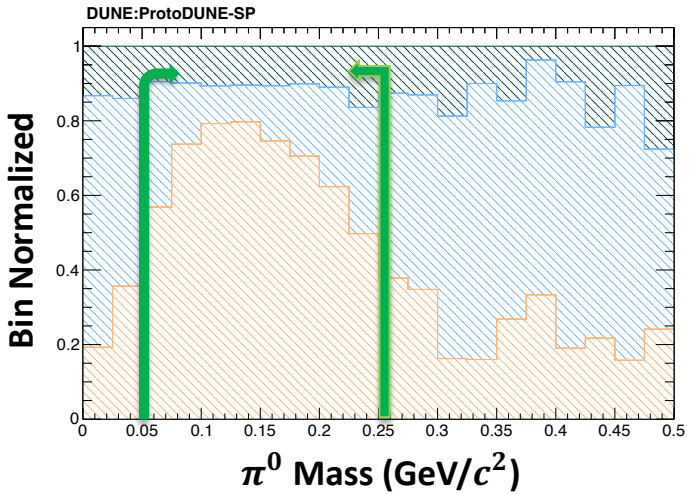
- Fit **θ** distribution by a **Gaussian** distribution (probably have better options).
- Fit **ϕ** distribution by a **Polynomial Order 7** distribution.
- An interesting feature is found in **the θ** angle (in detector coordinates).
- A similar feature is also found in proton angles.

Proton energy/angle correction – see backups p36

Reconstructed π^0 Mass

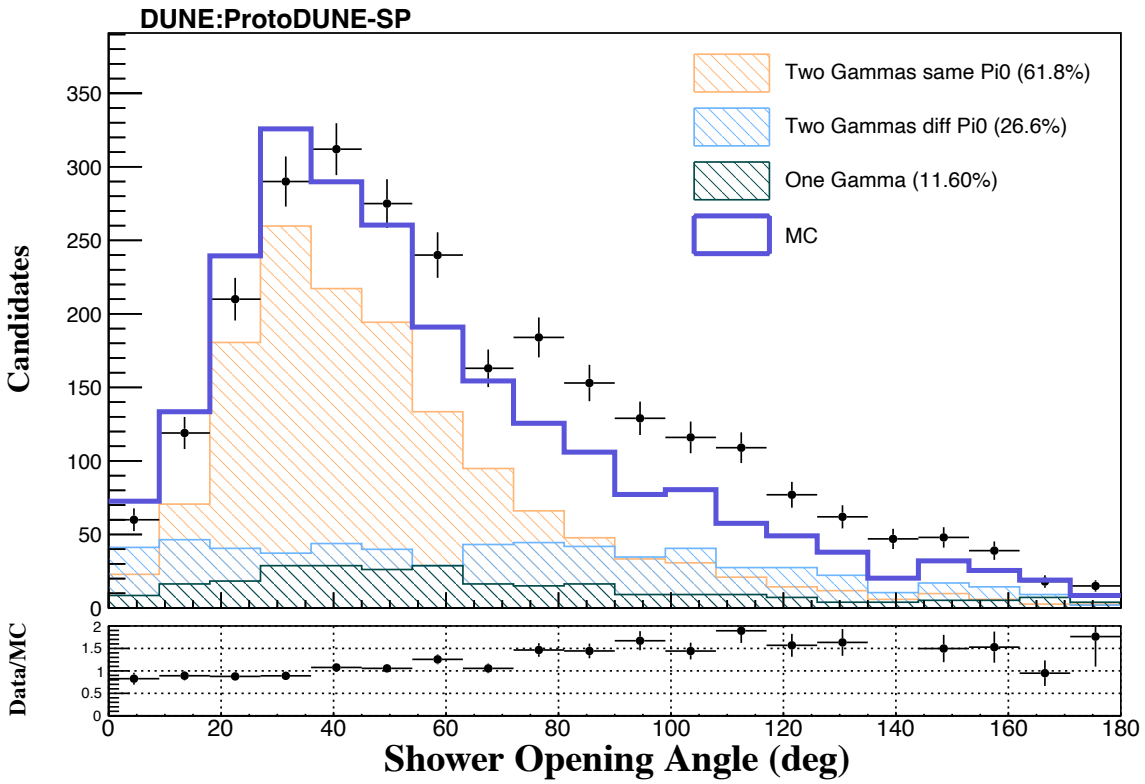


- Truth π^0 Mass is indicated by the dash line.
- The invariant mass peak from the signal (two gammas from same π^0) looks good!
- There is a continuous background from two gammas coming from different π^0 .
- One Gamma background also has a small mass peak around the true value.



- π^0 Mass distribution **after** shower energy and angle correction.

Shower Opening Angle



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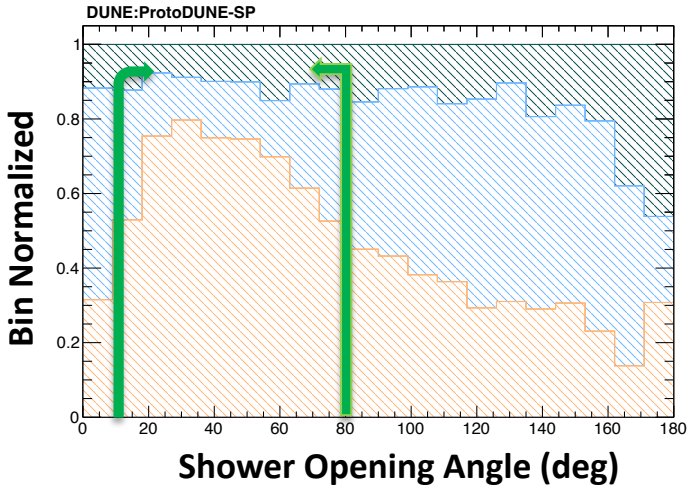
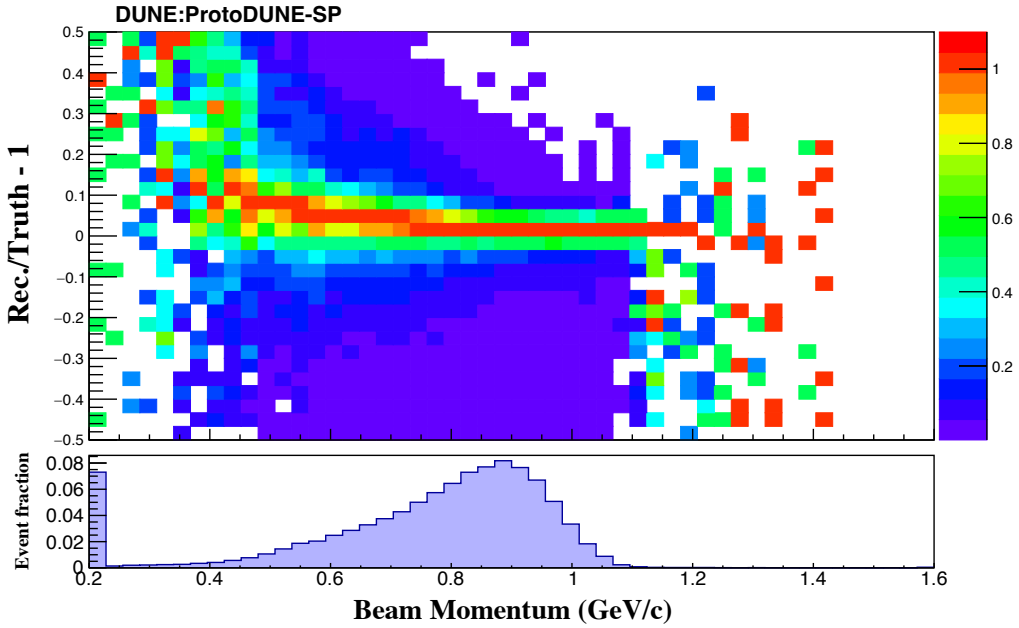
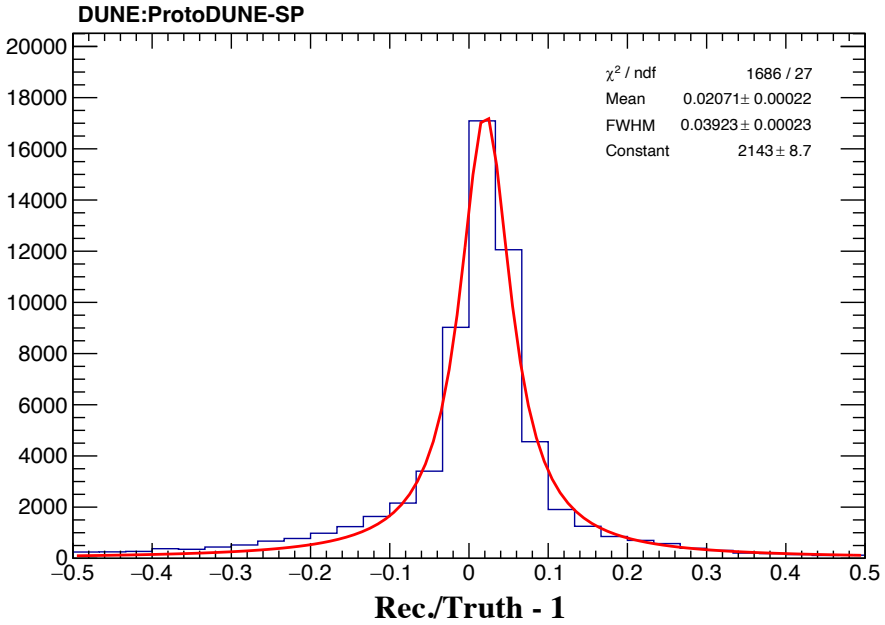


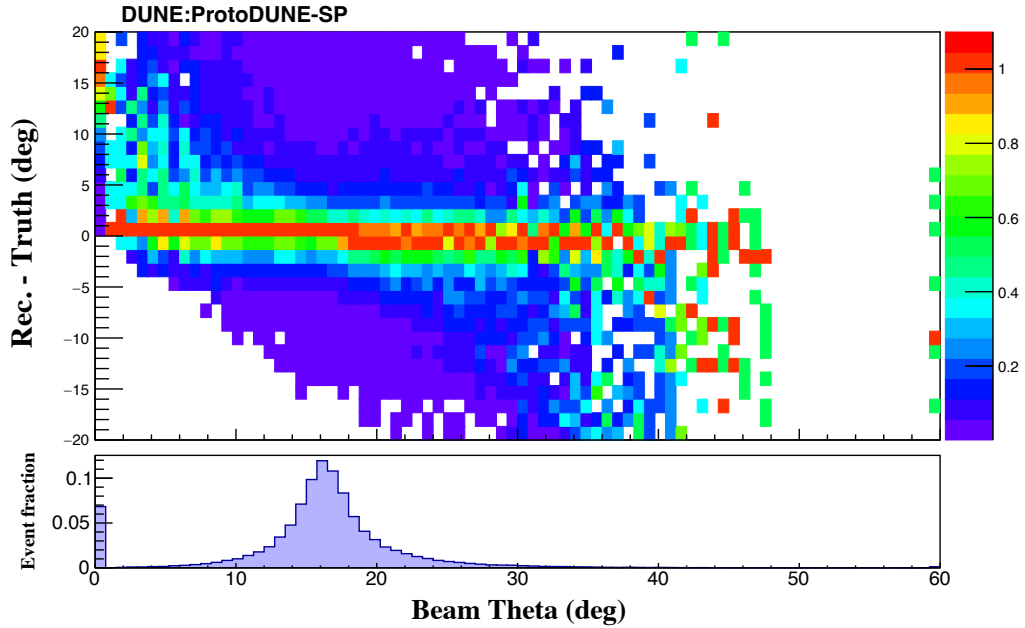
- Shower opening angle distribution **after** shower energy and angle correction.

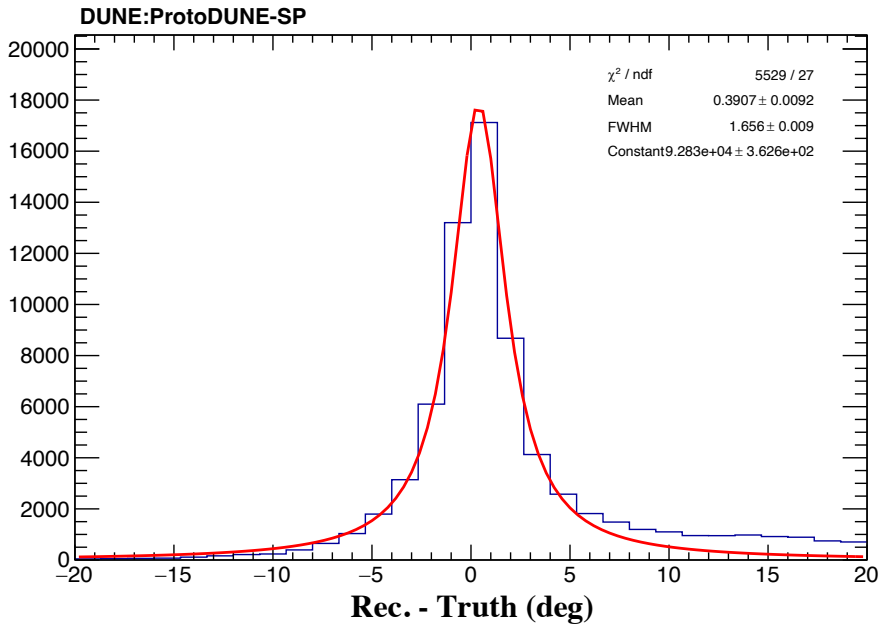
Beam Pion (Mom.)



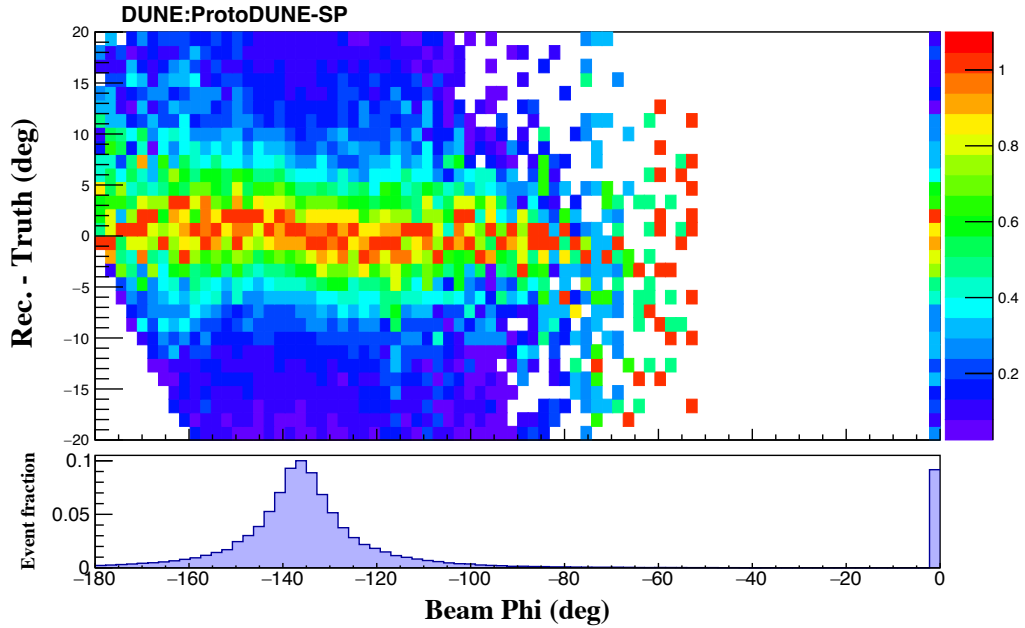


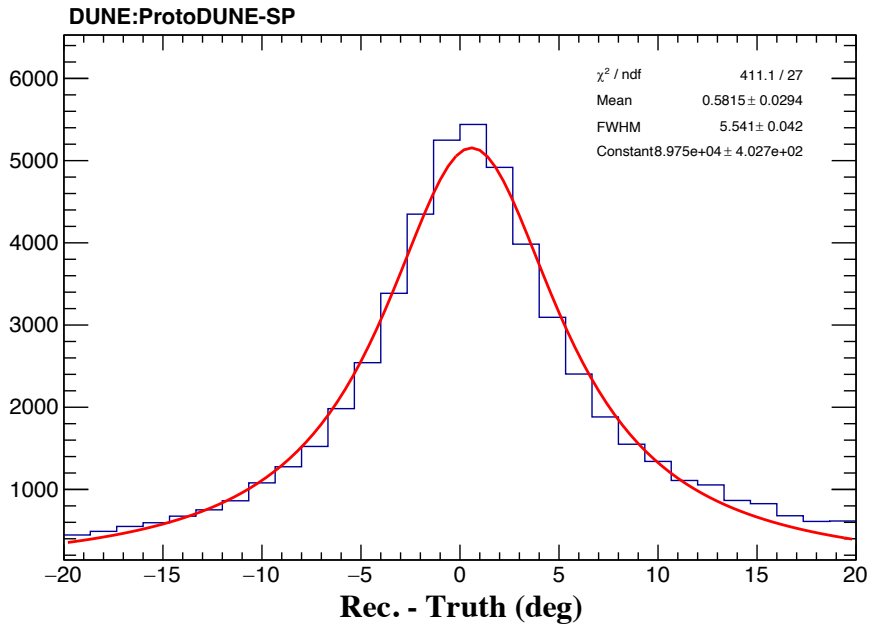
Beam Pion (Theta)



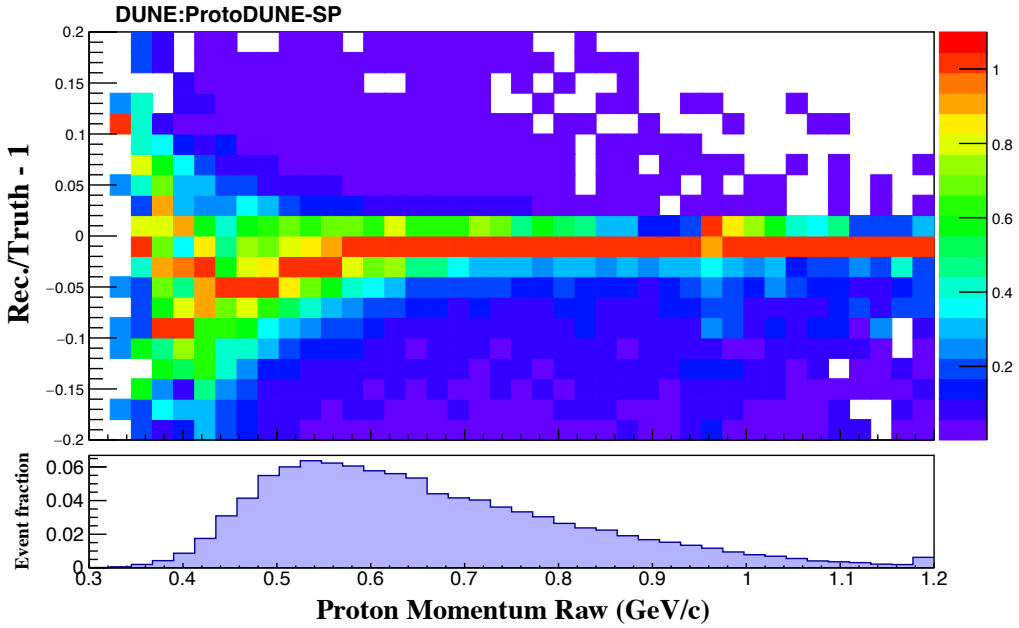


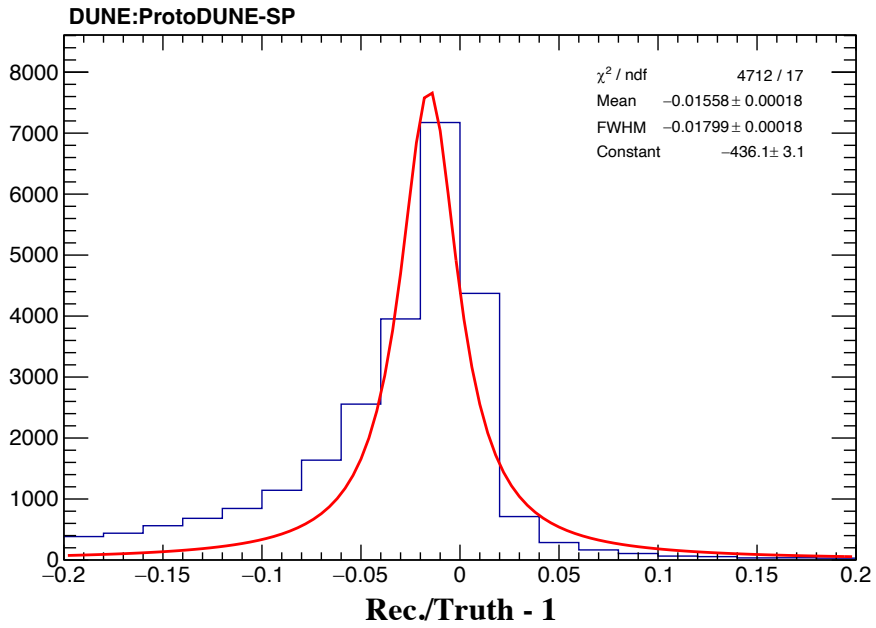
Beam Pion (Phi)



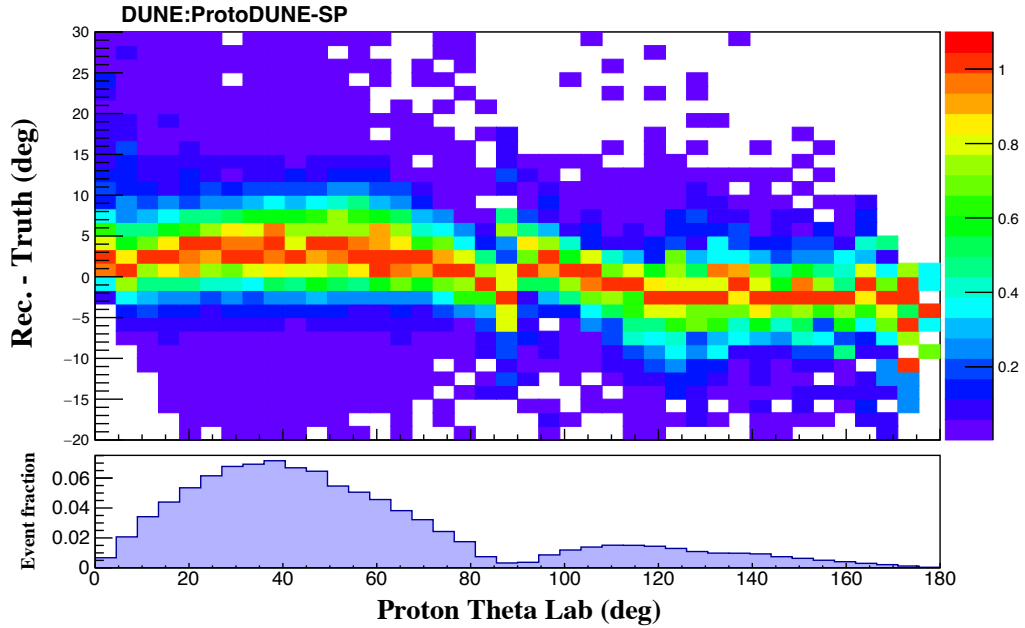


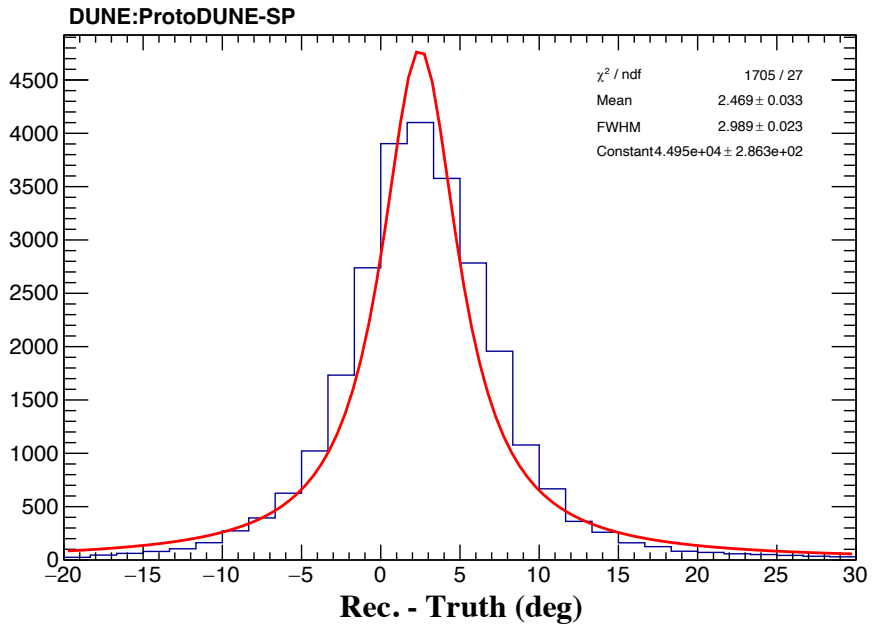
Daughter Proton (Mom.)



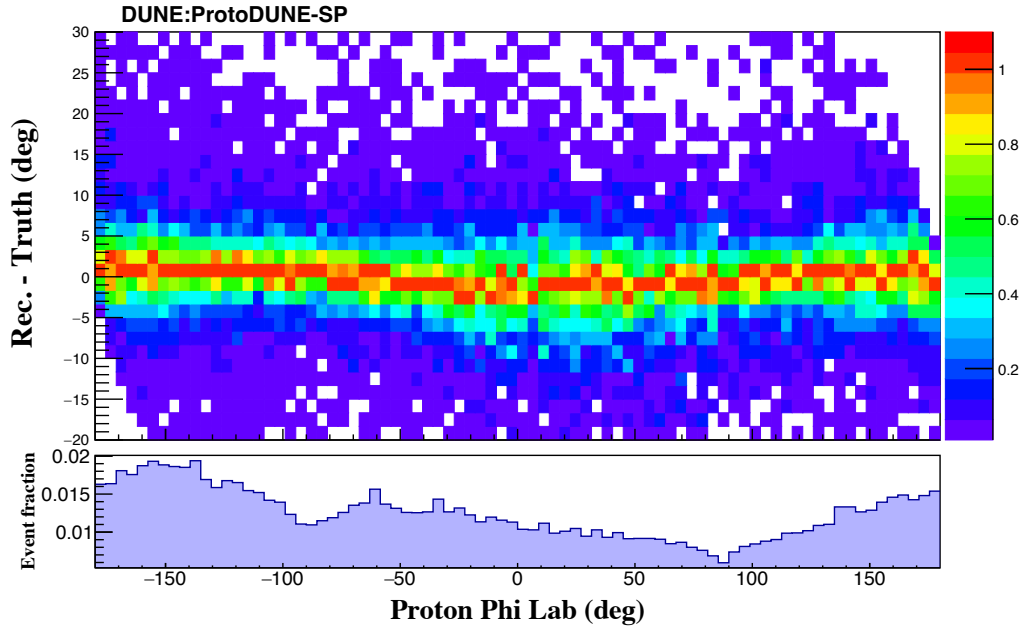


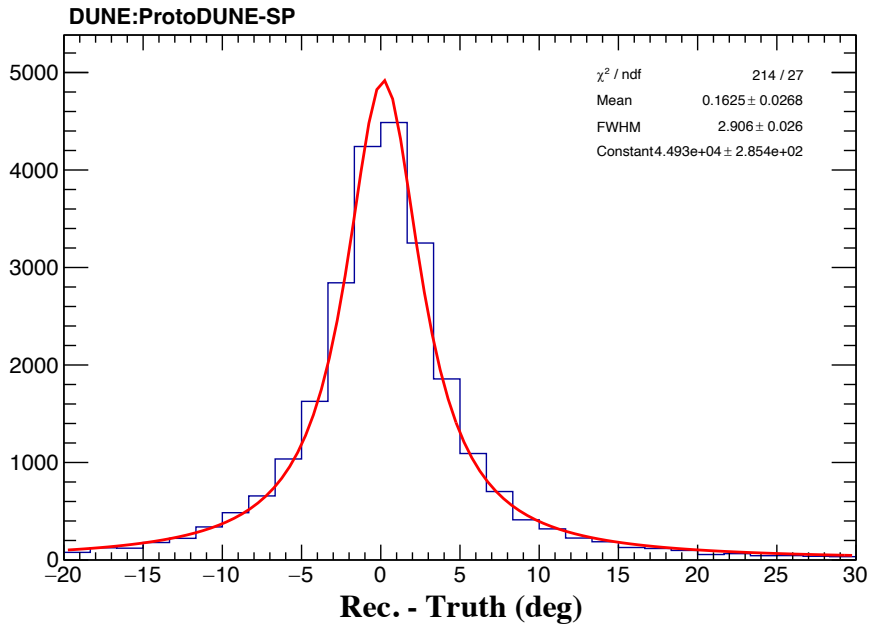
Daughter Proton (Theta)



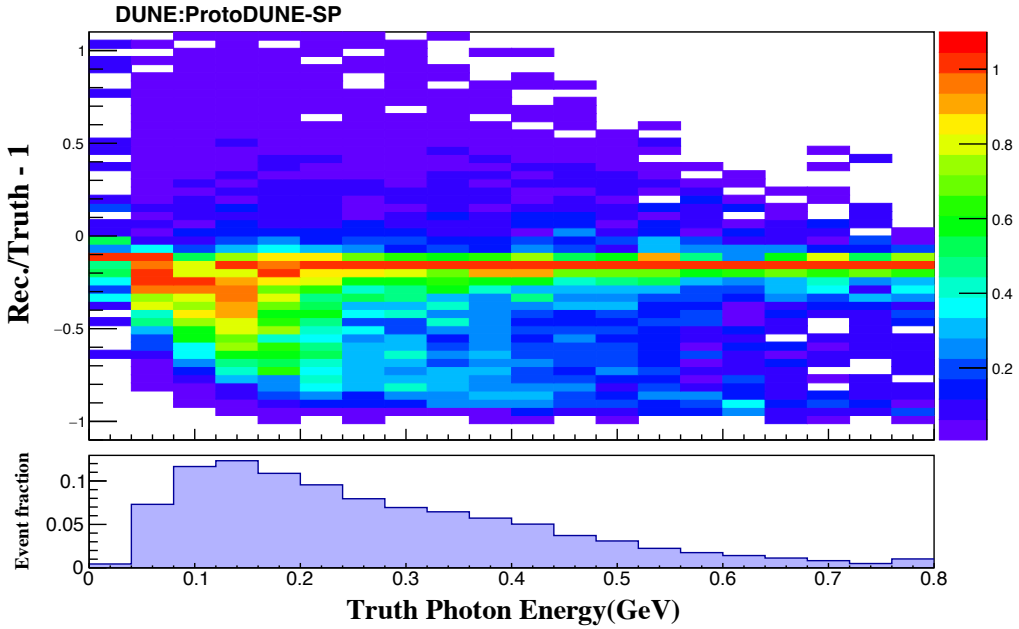


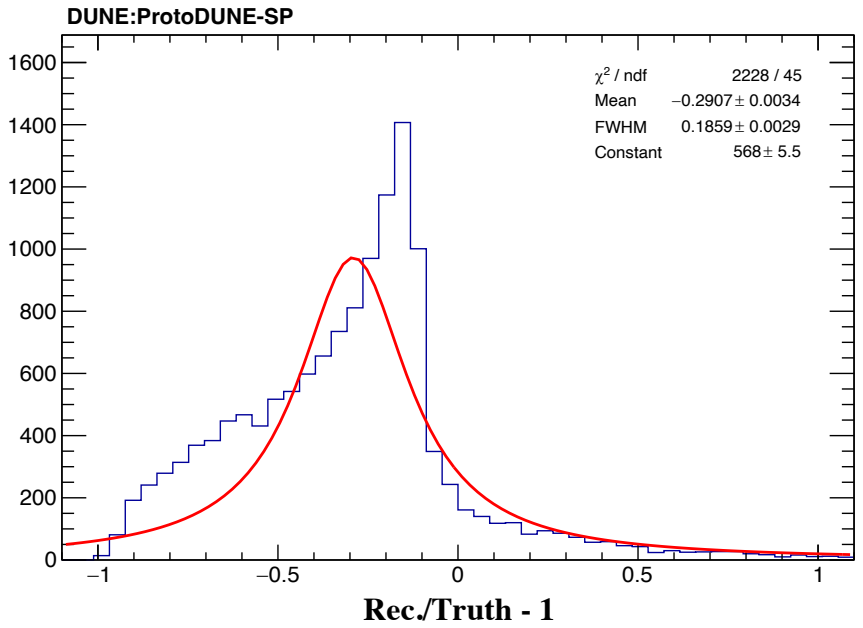
Daughter Proton (Phi)



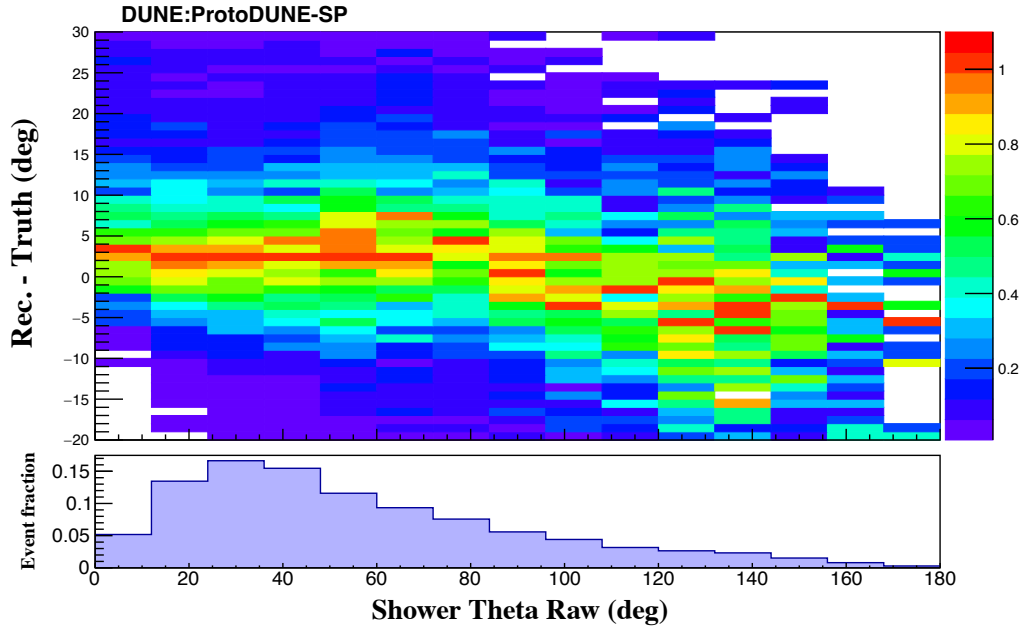


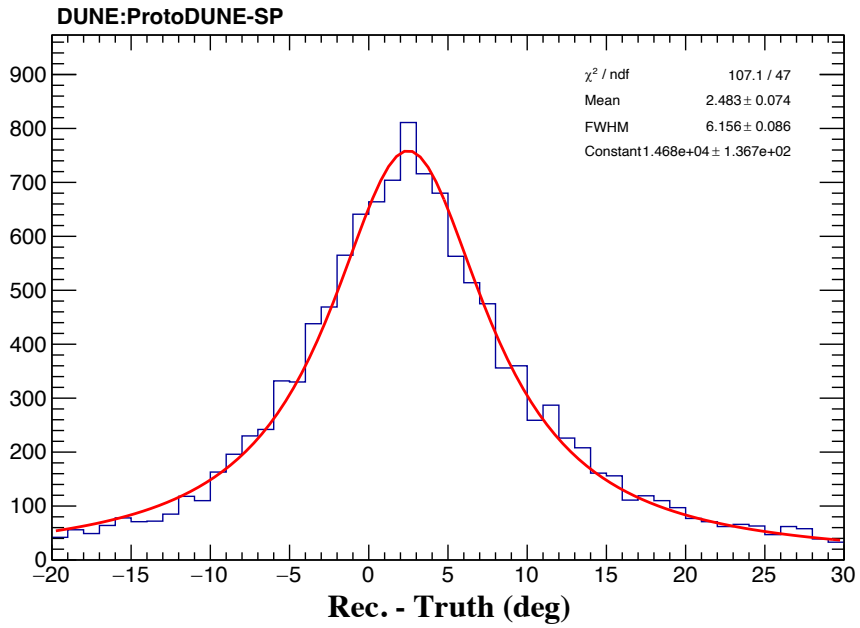
Daughter Shower (Energy)



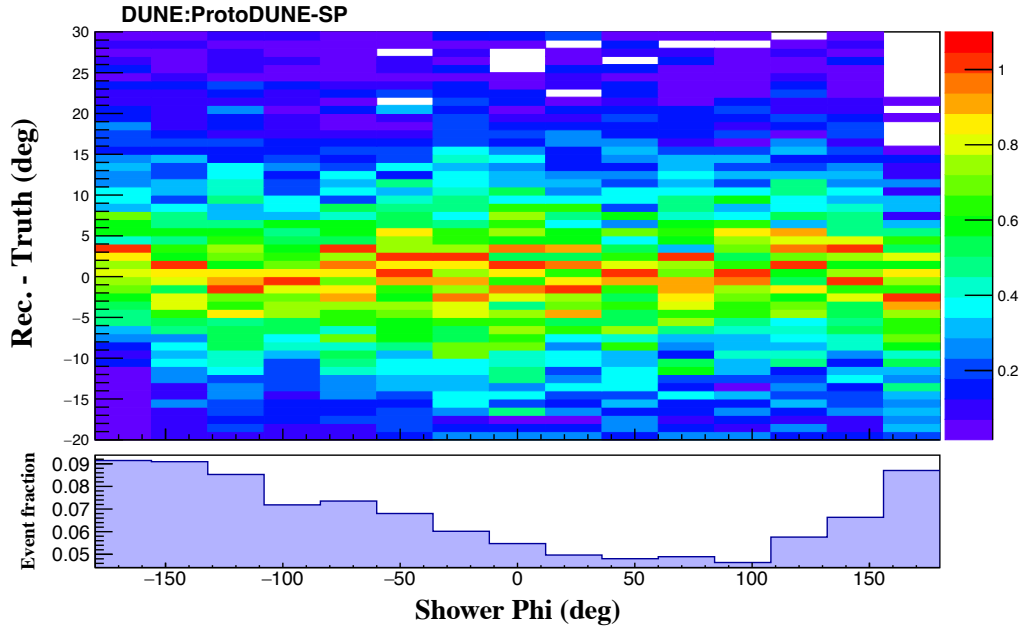


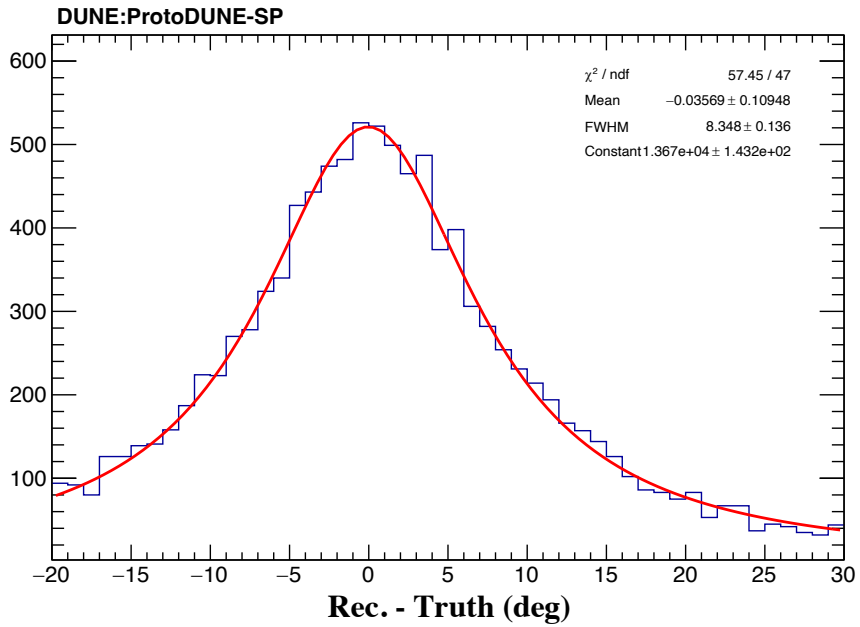
Daughter Shower (Theta)



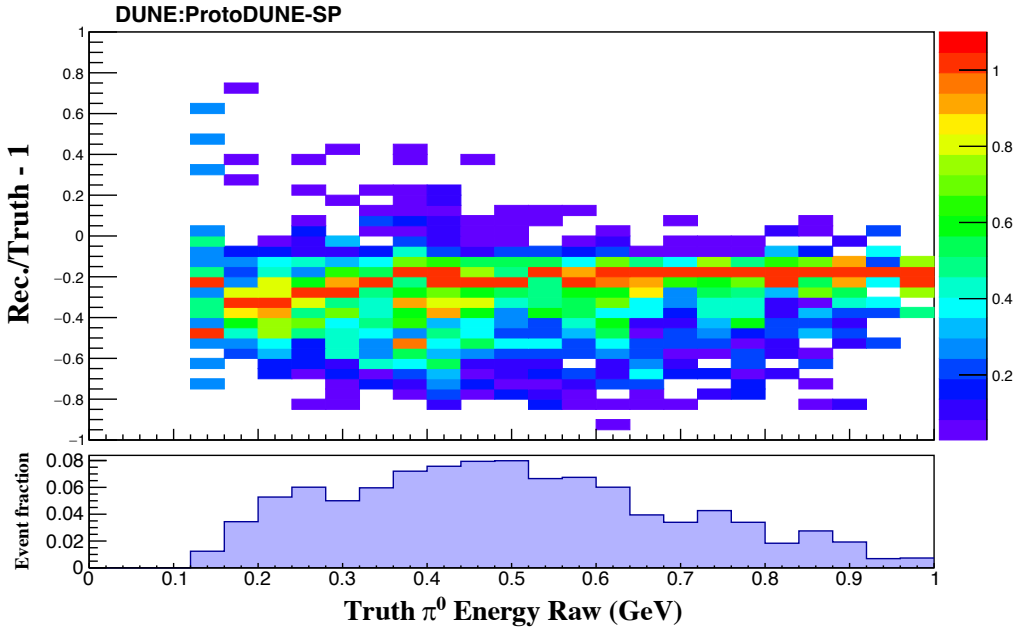


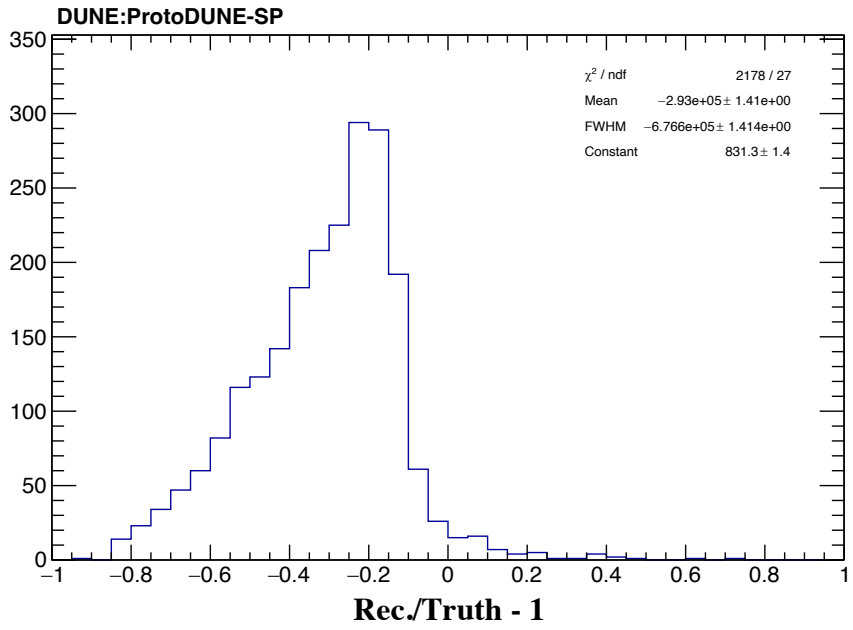
Daughter Shower (Phi)



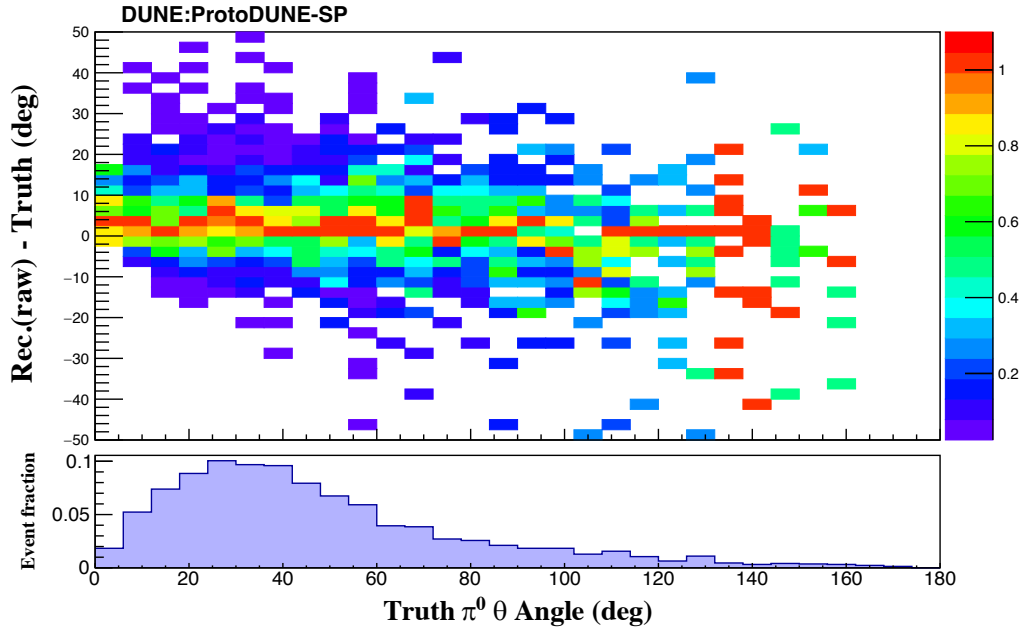


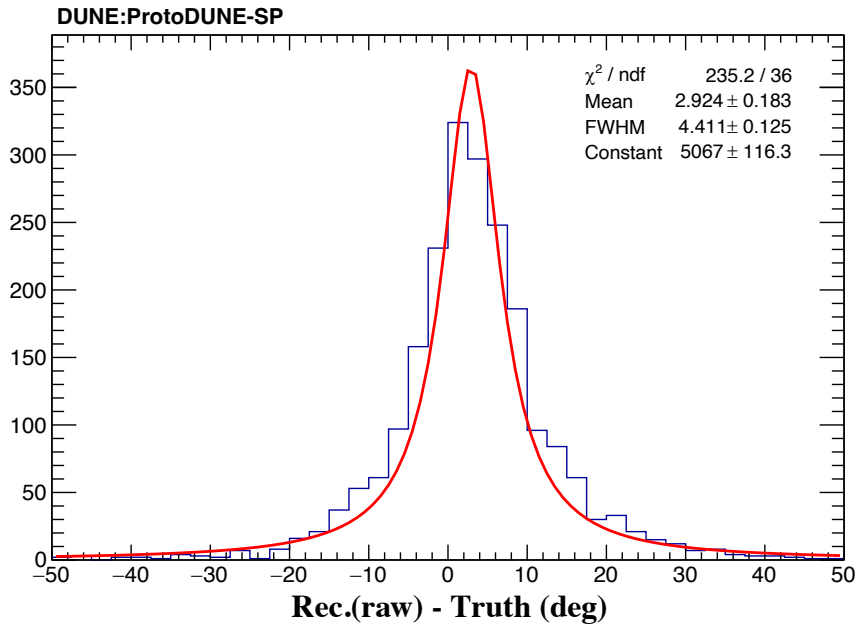
Daughter Pi0 (Mom.)





Daughter Pi0 (Theta)





Daughter Pi0 (Phi)