Proton-pion Transverse Kinematic Imbalance analysis

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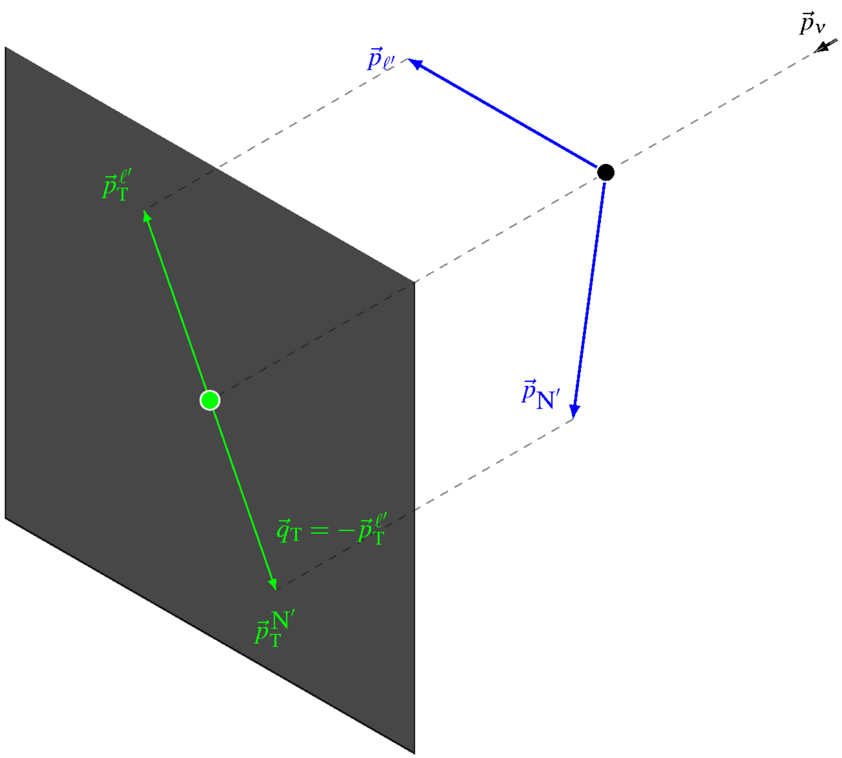
2020 May 21
ProtoDUNE Analysis Meeting

Transverse Kinematic Imbalance (TKI)

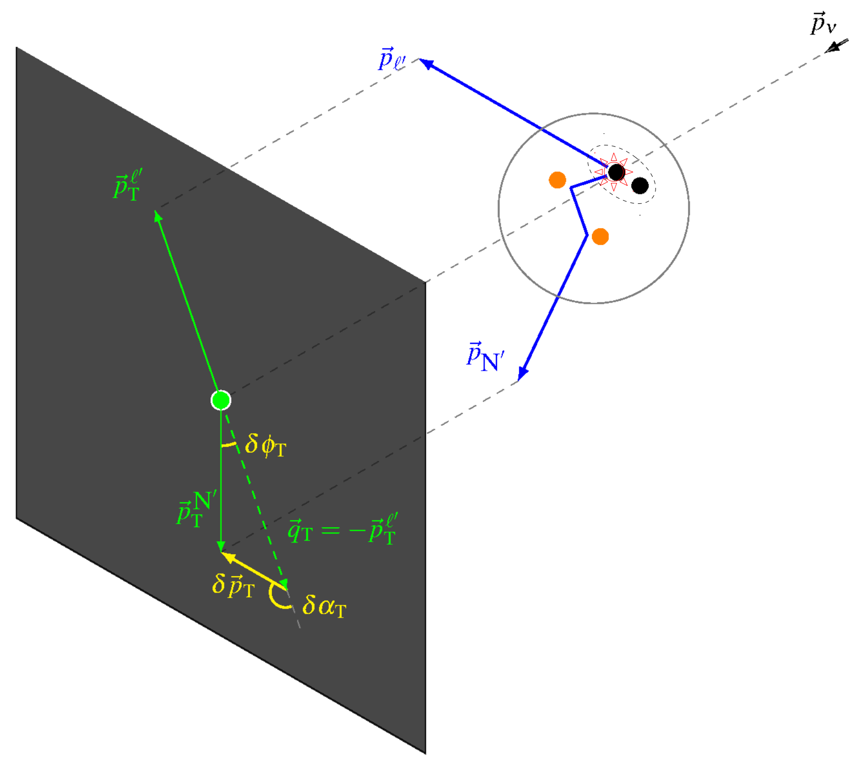
to precisely identify intranuclear dynamics and the absence thereof

XL *et al*. Phys. Rev. D92, 051302 (2015), arXiv:1507.00967 [hep-ex]

XL *et al*. Phys. Rev. C94, 015503 (2016), arXiv:1512.05748 [nucl-th]

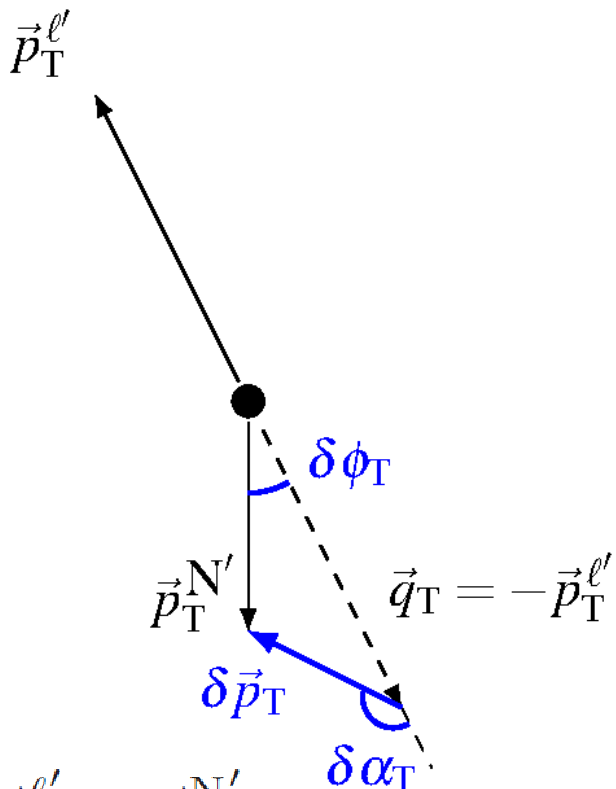


Stationary nucleon target

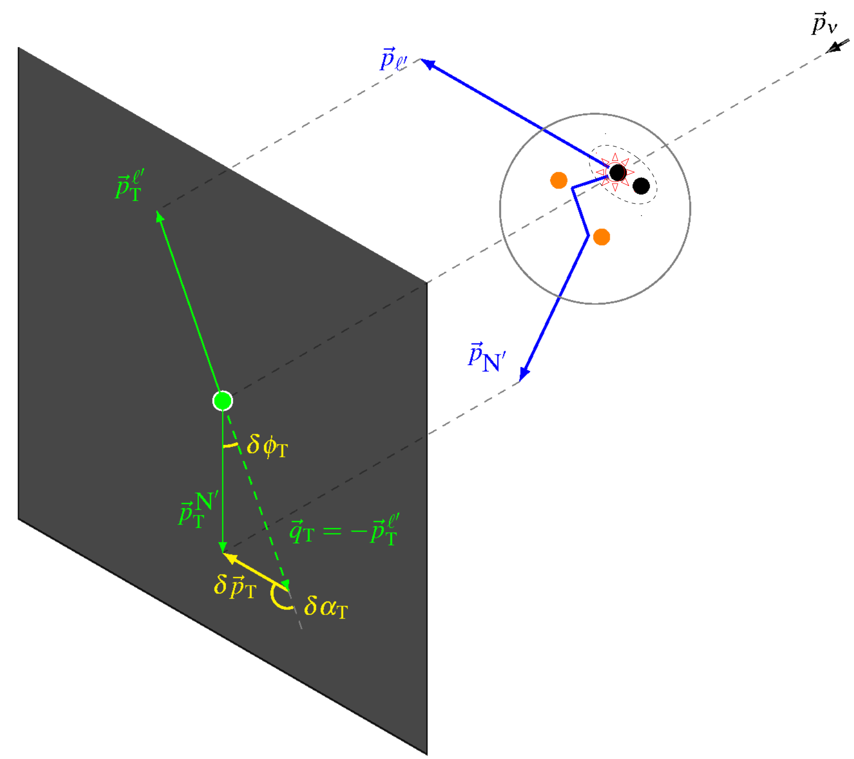


Nuclear target (A>1)

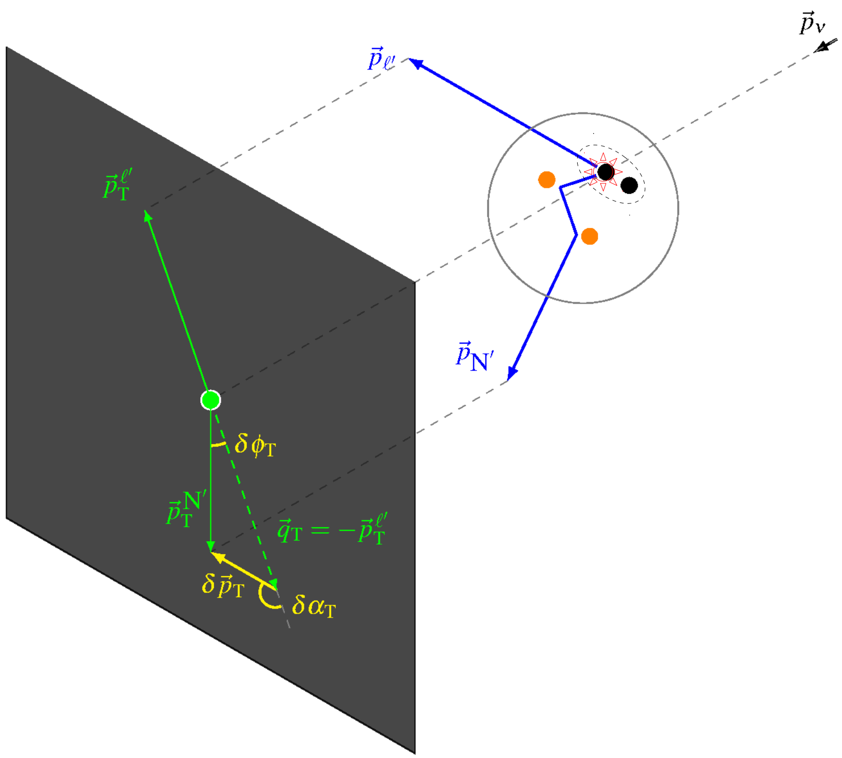
Fermi motion
Final-state interactions
Pion absorption
2p2h
...



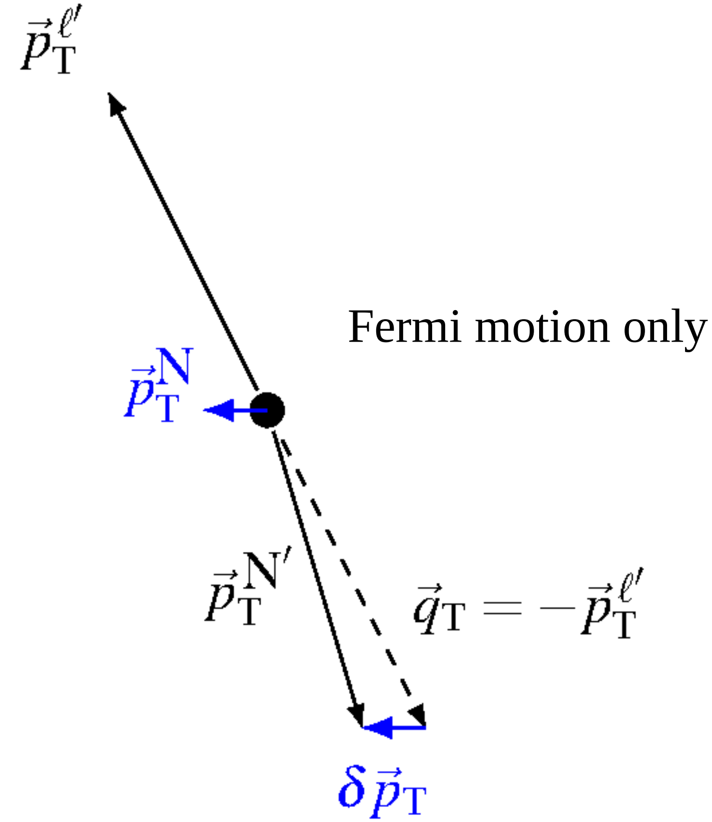
$$\delta\vec{p}_{\mathrm{T}} \equiv \vec{p}_{\mathrm{T}}^{\ell'} + \vec{p}_{\mathrm{T}}^{\mathrm{N}'}$$



Nuclear target

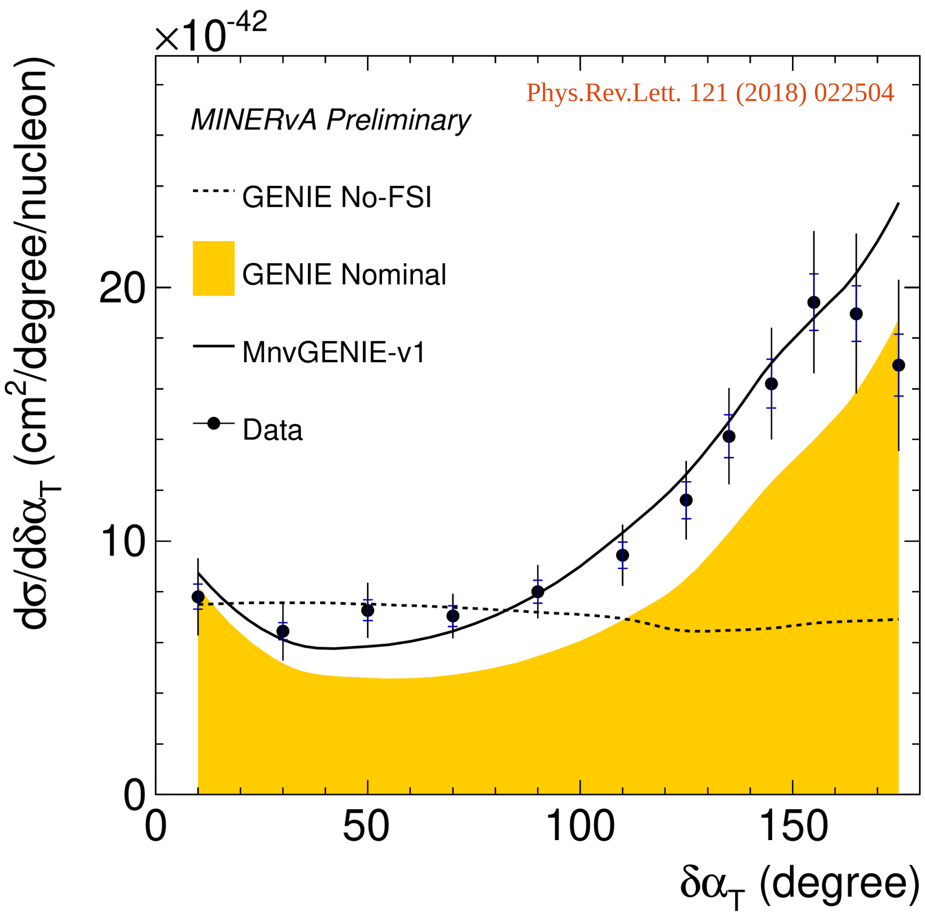


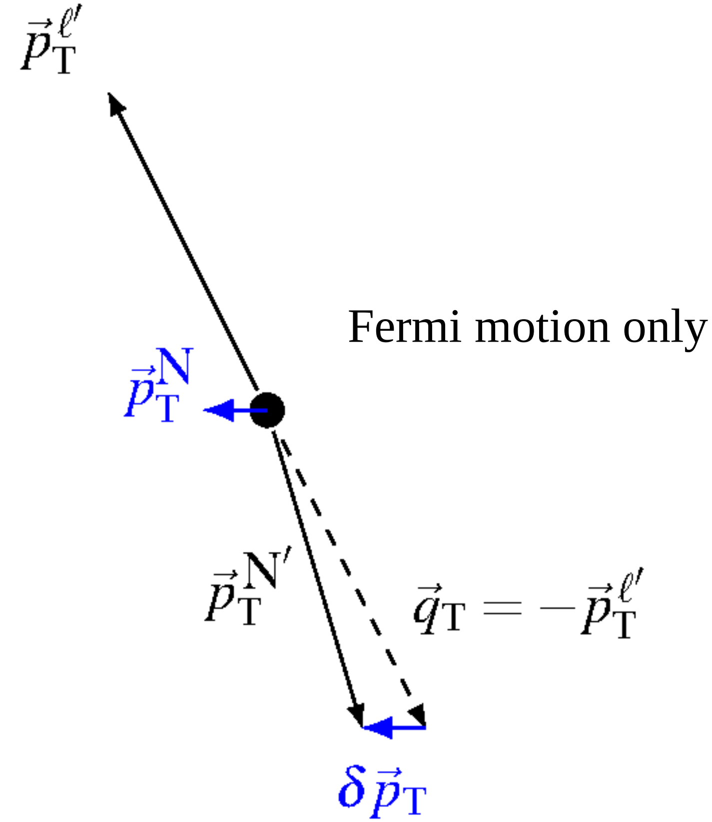
Nuclear target



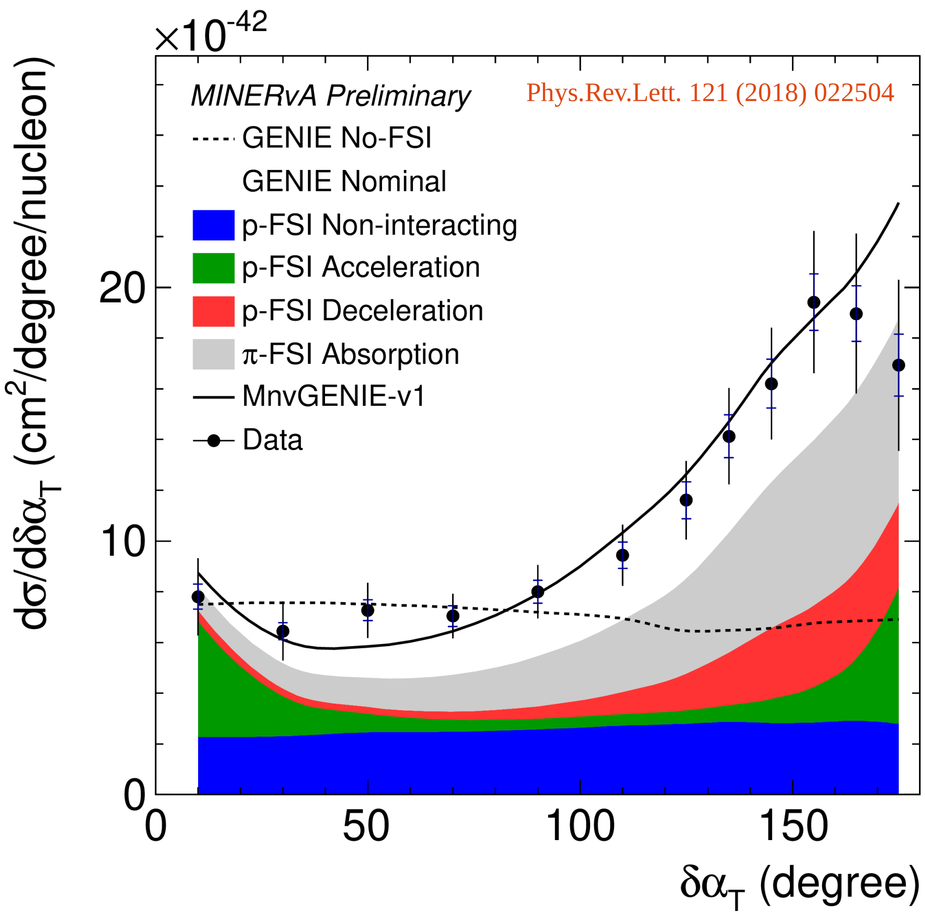
$$\delta\vec{p}_{\mathrm{T}} = \vec{p}_{\mathrm{T}}^{\mathrm{N}}$$

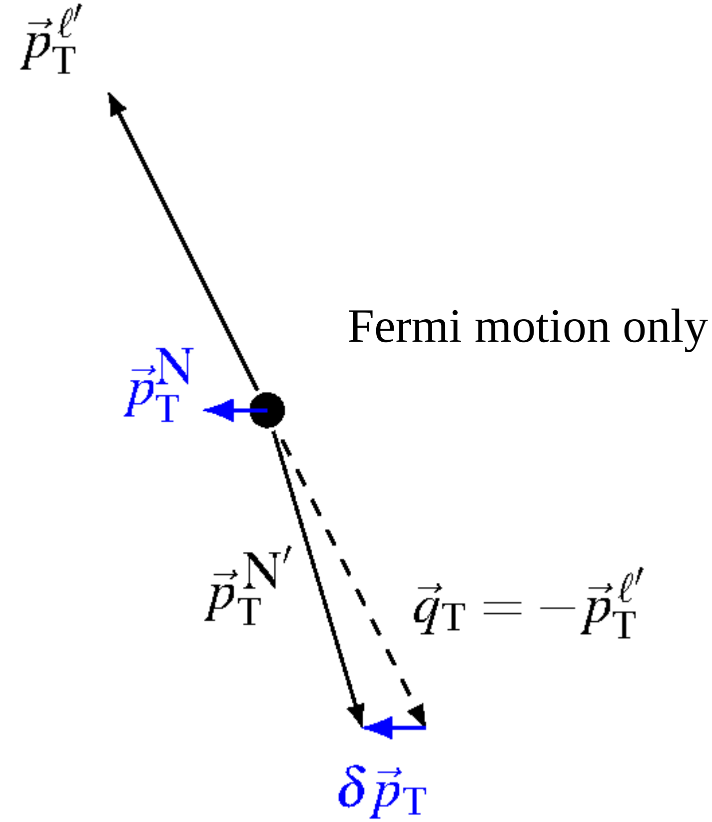
$\delta\alpha_{\mathrm{T}}$ is Fermi motion direction → isotropic





$\delta\alpha_T$ is Fermi motion direction → isotropic – GENIE No-FSI

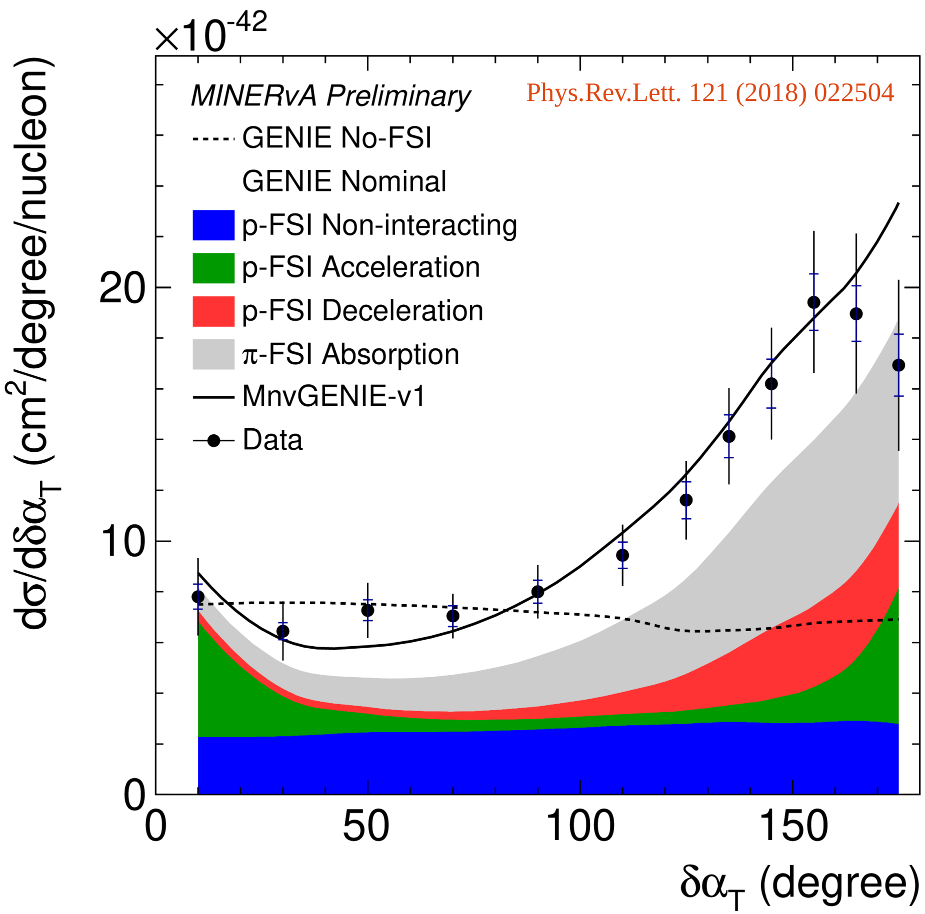


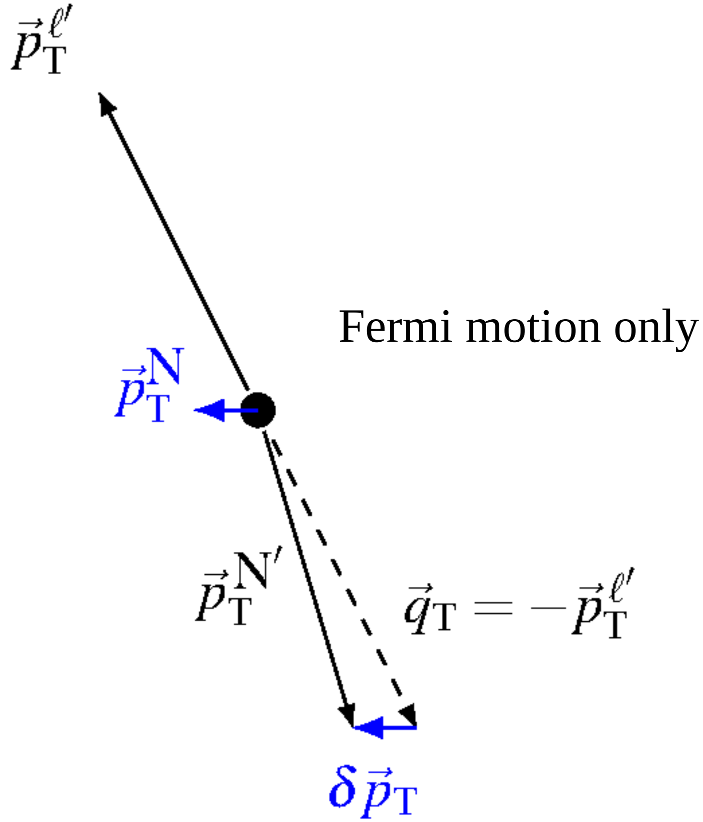


$\delta\alpha_T$ is Fermi motion direction → isotropic

– GENIE No-FSI

– p-FSI Non-interacting

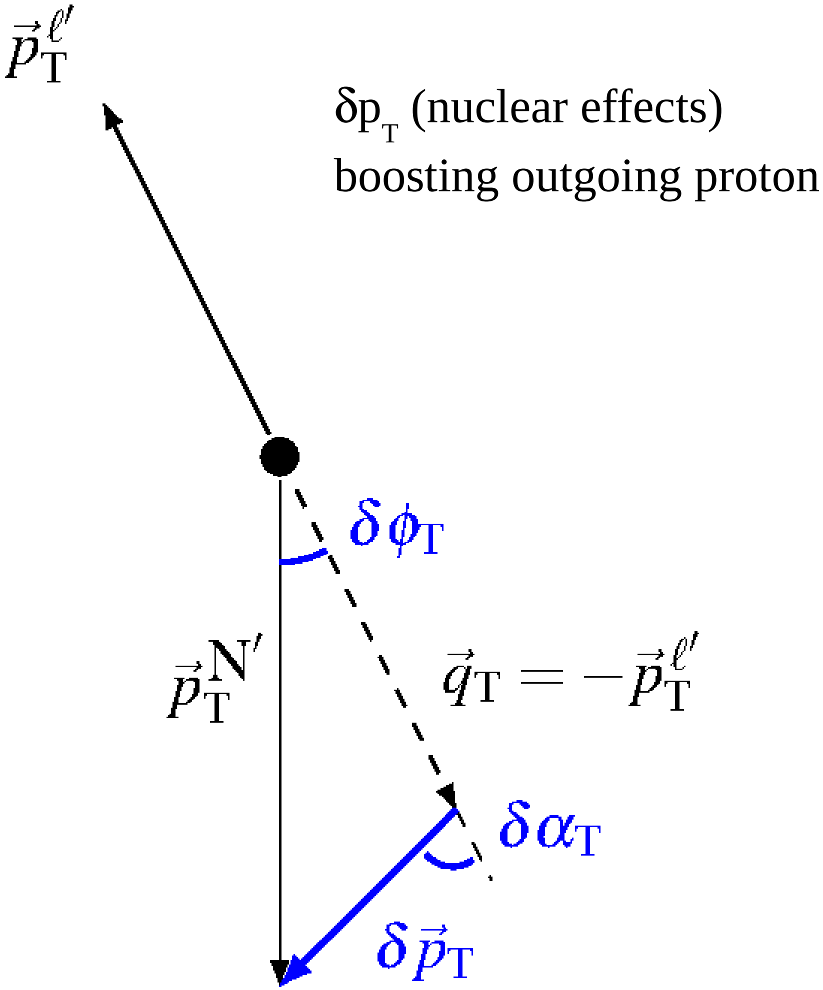


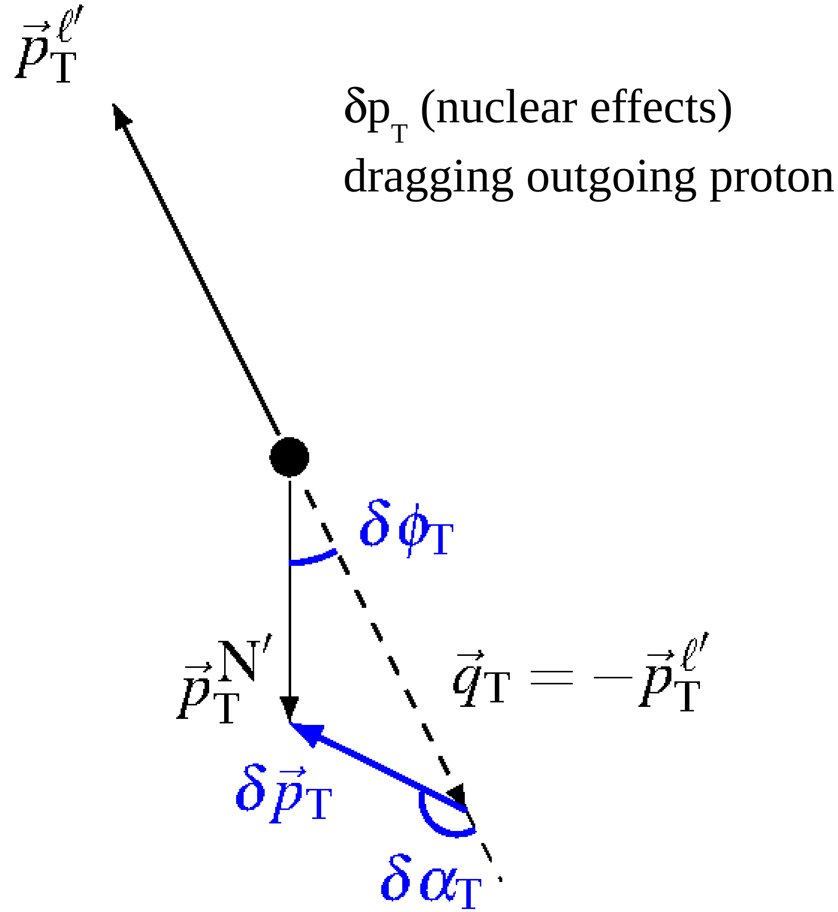


$\delta\alpha_T$ is Fermi motion direction → isotropic
– GENIE No-FSI
– p-FSI Non-interacting

- Impact from interaction on nucleon canceled by lepton-hadron correlation;
- Impact from Fermi motion also canceled due to isotropy.

Transverse Boosting Angle

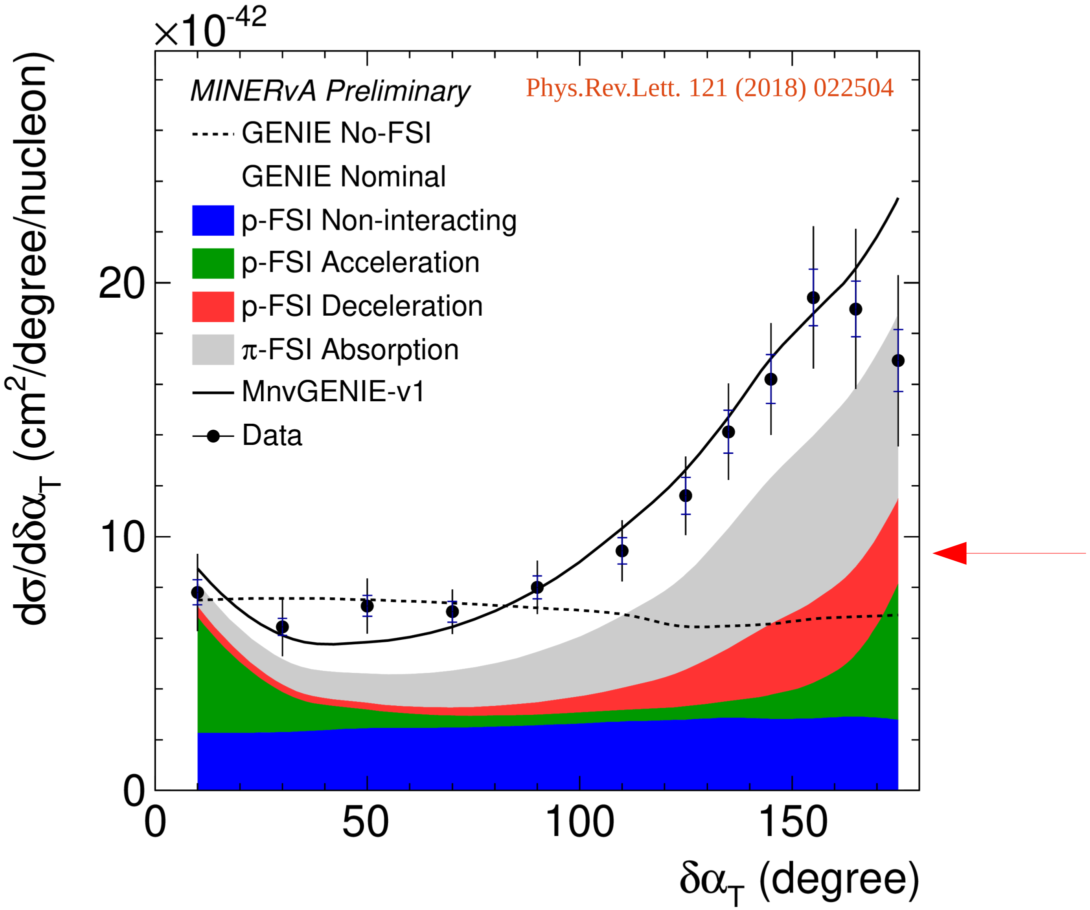


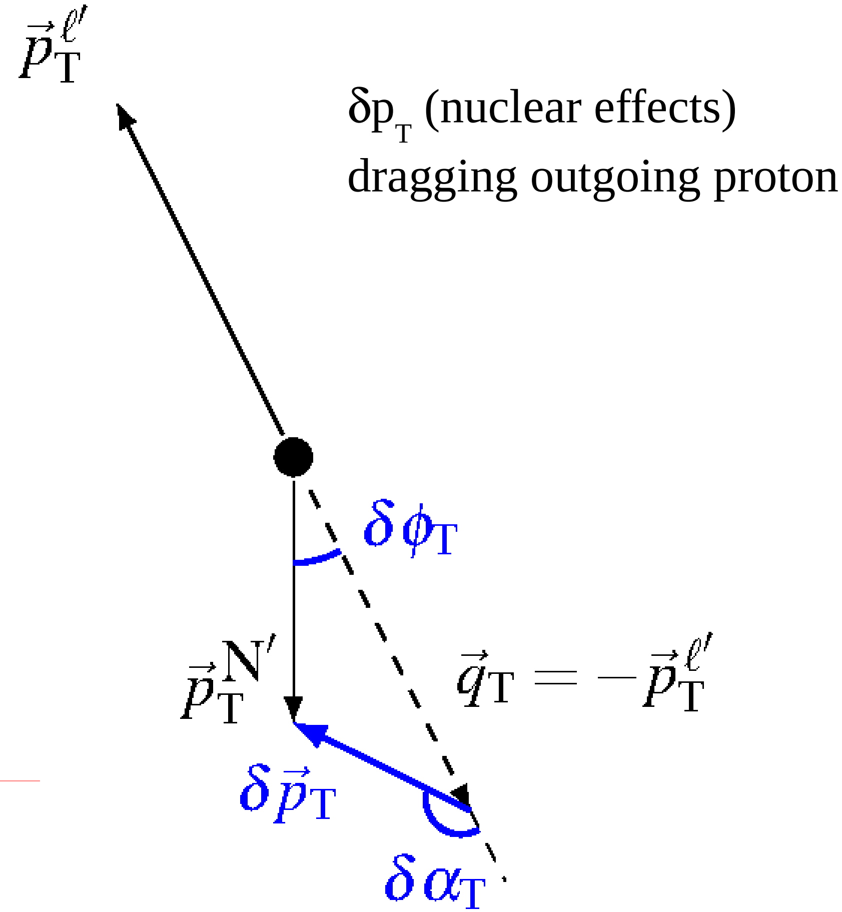


With full nuclear effects

$$\delta\vec{p}_T = \vec{p}_T^N - \Delta\vec{p}_T$$ non-Fermi motion effects

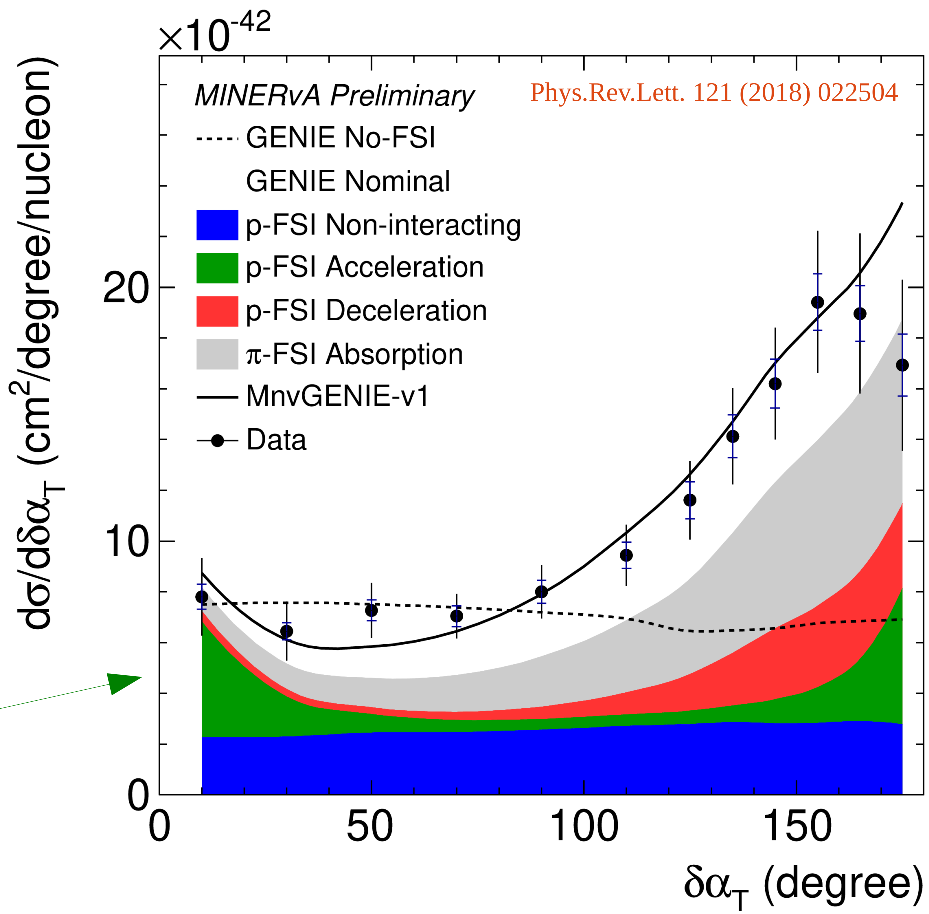
Transverse Boosting Angle

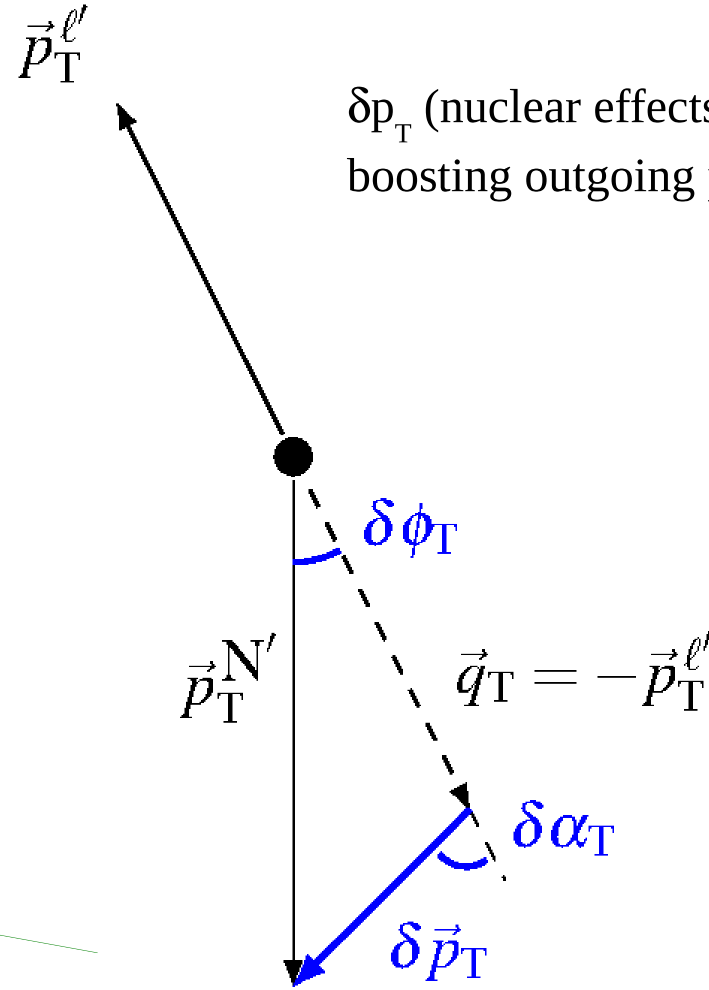




Deceleration at large $\delta\alpha_T$

Transverse Boosting Angle



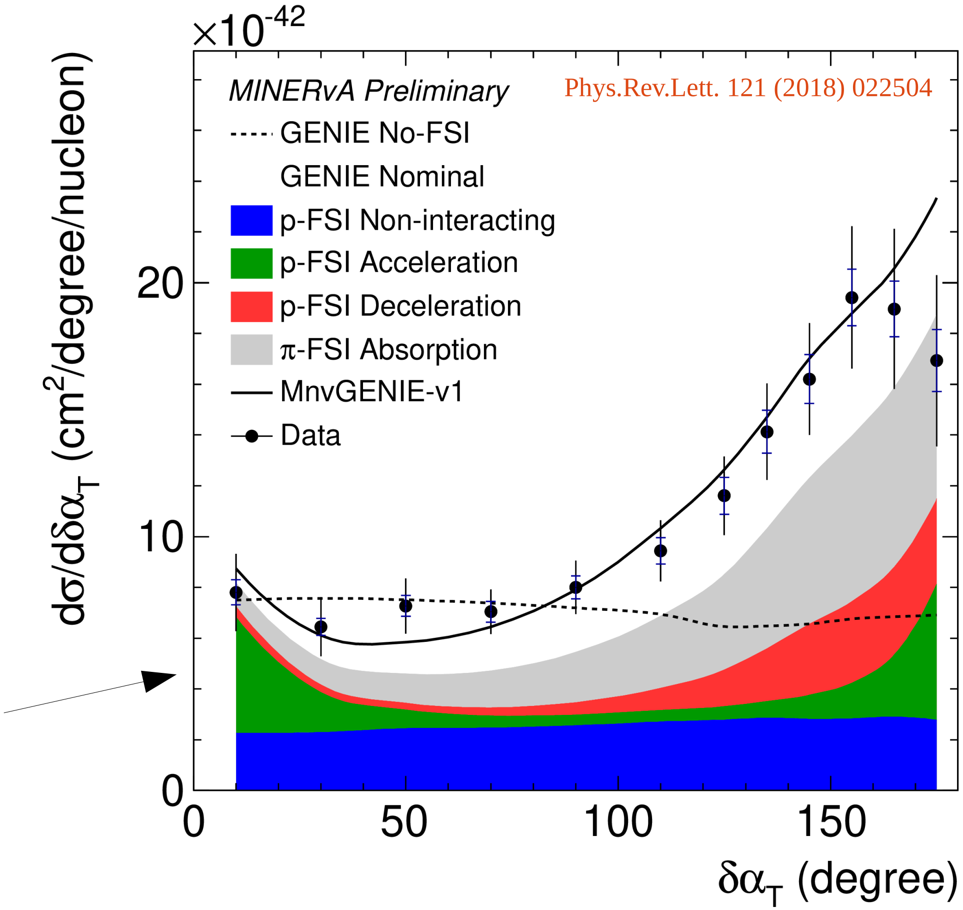


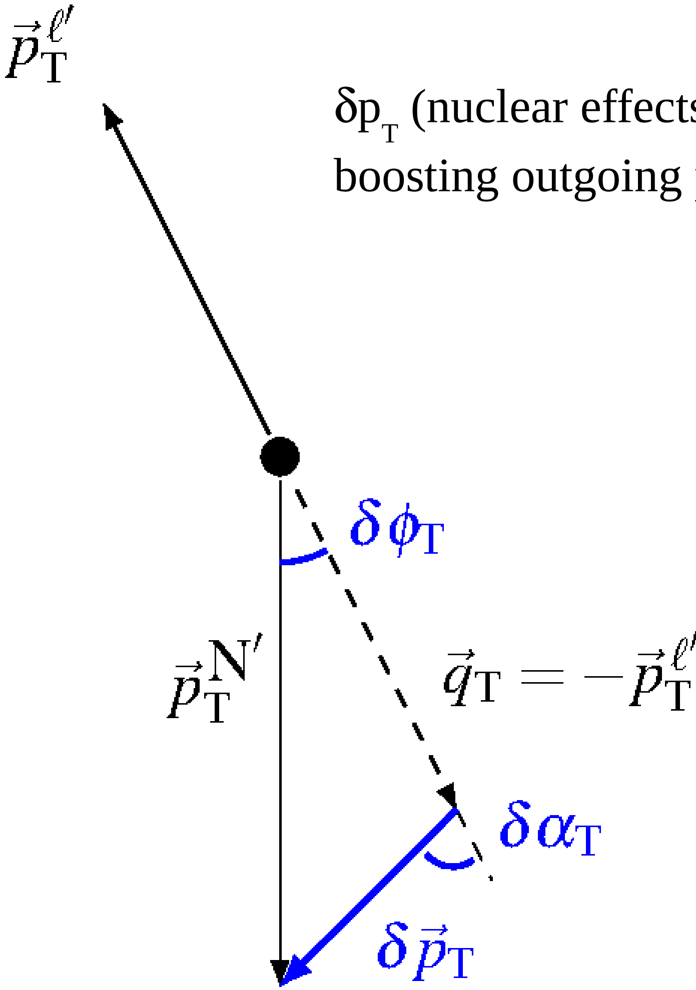
δp_T (nuclear effects) boosting outgoing proton

Deceleration at large $\delta\alpha_T$

Acceleration at both small and (due to transverse projection) large $\delta\alpha_T$

Transverse Boosting Angle



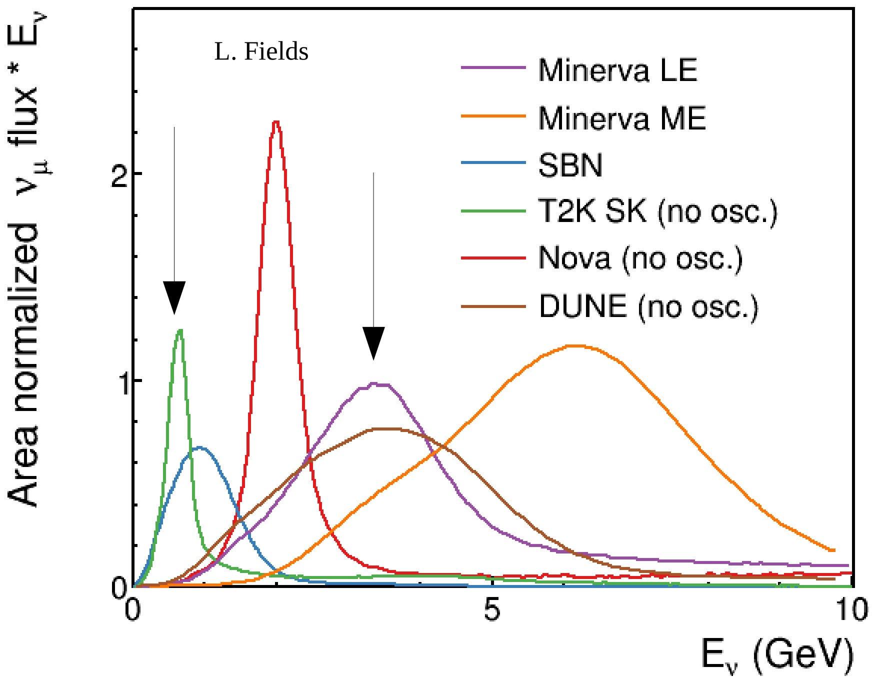


- Accelerating FSI is singled out
- Discovered from model for the first time

Deceleration at large $\delta\alpha_T$

Acceleration at both small and (due to transverse projection) large $\delta\alpha_T$

Transverse Boosting Angle

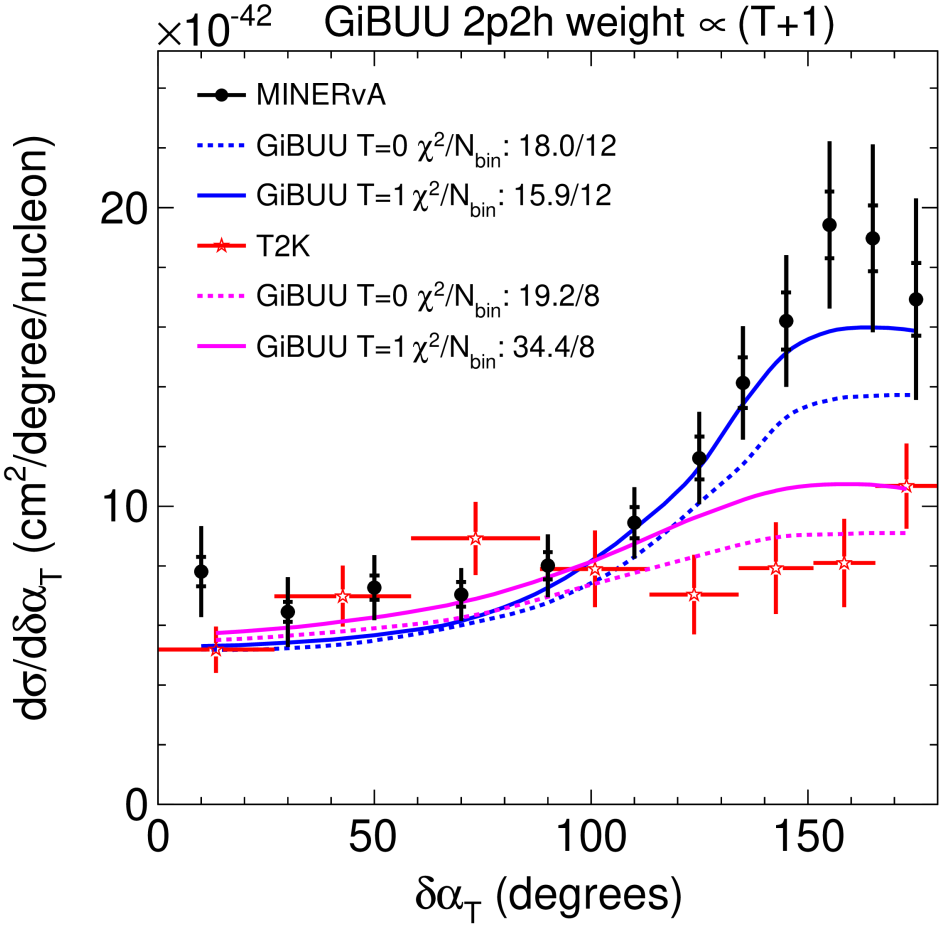


T2K neutrino beam peak at 0.6 GeV

[T2K, Phys. Rev. D 98, 032003 (2018)]

MINERvA at 3 GeV

[MINERvA, Phys. Rev. Lett. 121, 022504 (2018)]



- Gross feature of energy dependence confirmed by data

Emulated Nucleon Momentum

A more general analysis of kinematic imbalance

Transverse: $0 = \vec{p}_{\mathrm{T}}^{\,\ell'} + \vec{p}_{\mathrm{T}}^{\,\mathrm{N}'} - \delta\vec{p}_{\mathrm{T}}$

Longitudinal: $E_\nu = p_{\mathrm{L}}^{\ell'} + p_{\mathrm{L}}^{\mathrm{N}'} - \delta p_{\mathrm{L}}$

New variable: $p_{\mathrm{n}} \equiv \sqrt{\delta p_{\mathrm{T}}^2 + \delta p_{\mathrm{L}}^2}$

[Furmanski, Sobczyk, Phys.Rev. C95 (2017) 065501]

Neutrino energy is unknown (in the first place), equations are not closed.

Assuming exclusive μ-p-A' final states
Use energy conservation to close the equations

$$E_\nu + m_{\mathrm{A}} = E_{\ell'} + E_{\mathrm{N}'} + E_{\mathrm{A}'}$$

$$E_{\mathrm{A}'} = \sqrt{m_{\mathrm{A}'}^2 + p_{\mathrm{n}}^2}$$

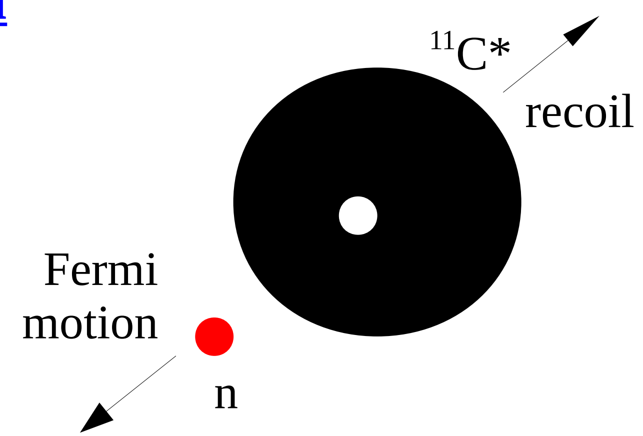
p_{n}: recoil momentum of the nuclear remnant

final-state

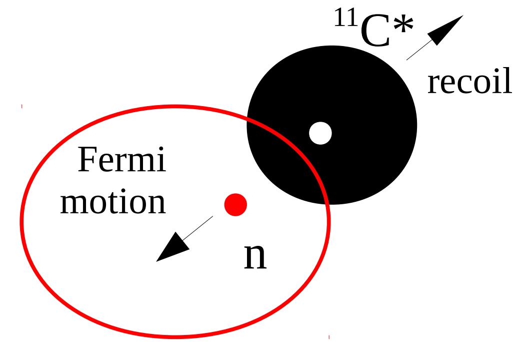
Dual Interpretation

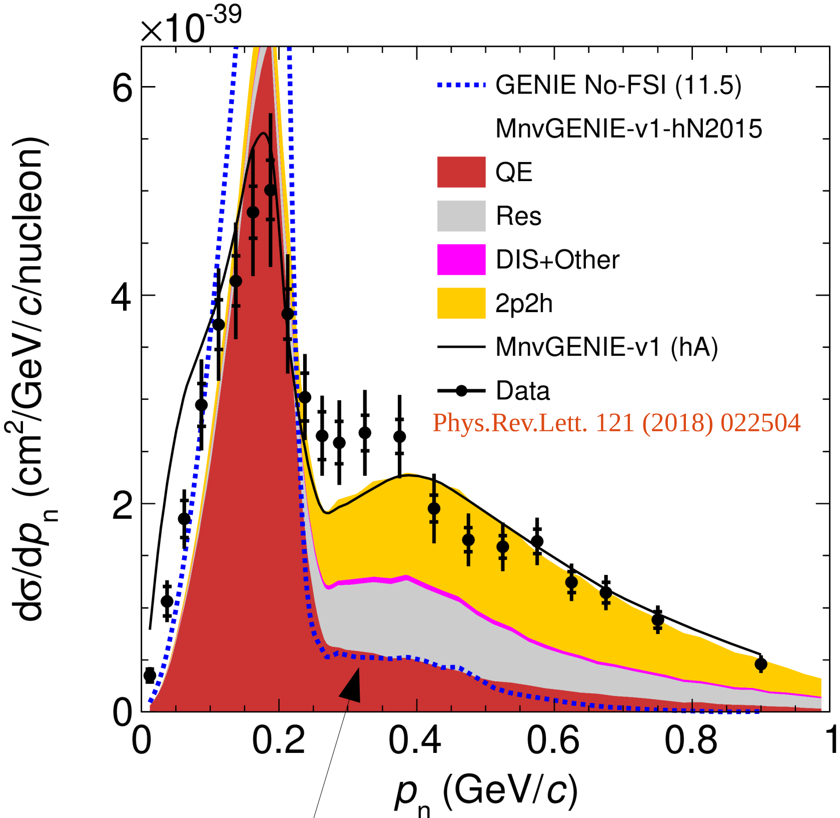
For CCQE, A' = ^{11}C*
No more unknowns
p_{n}: neutron Fermi motion

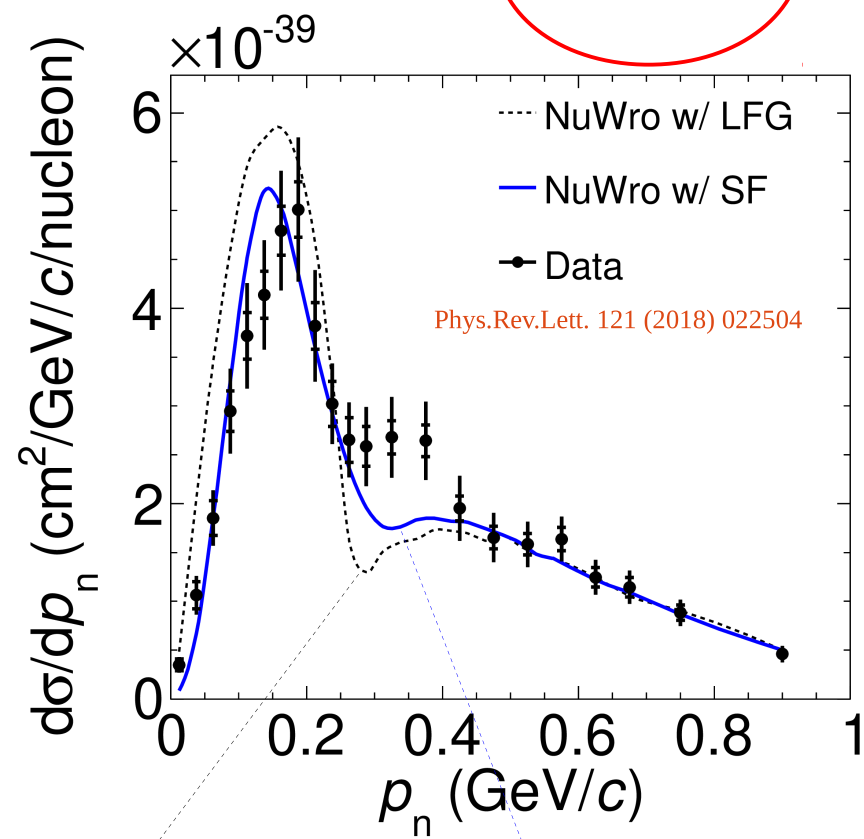
initial-state



Emulated Nucleon Momentum







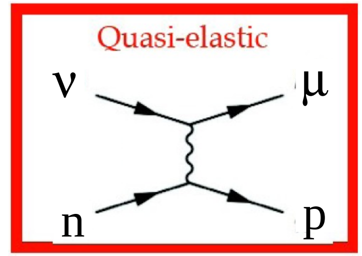
Global Fermi Gas with Bodek-Ritchie tail

Local Fermi Gas

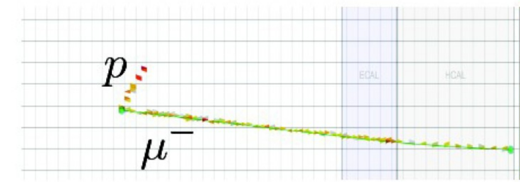
Spectral Function

$$p_{\rm n} \equiv \sqrt{\delta p_{\rm T}^2 + \delta p_{\rm L}^2}$$

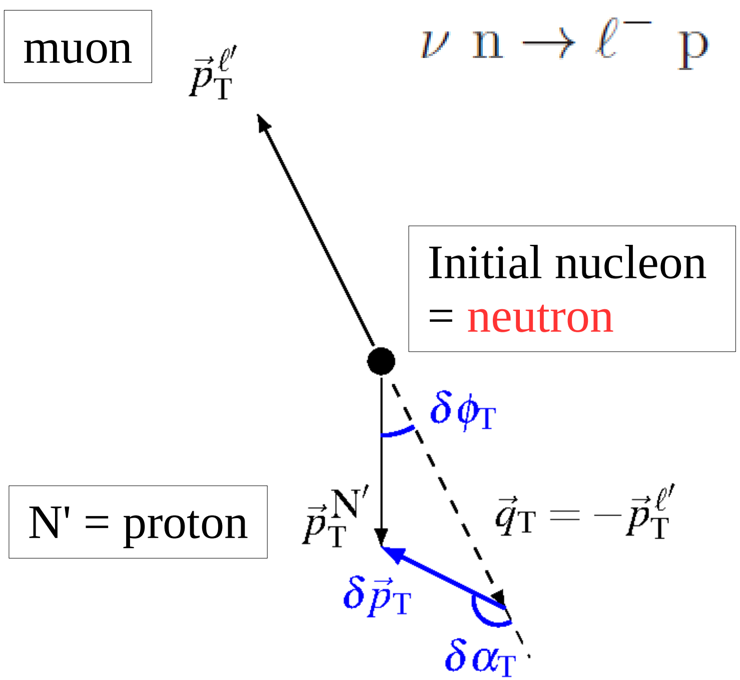
TKI
– Neutron initial-state kinematics

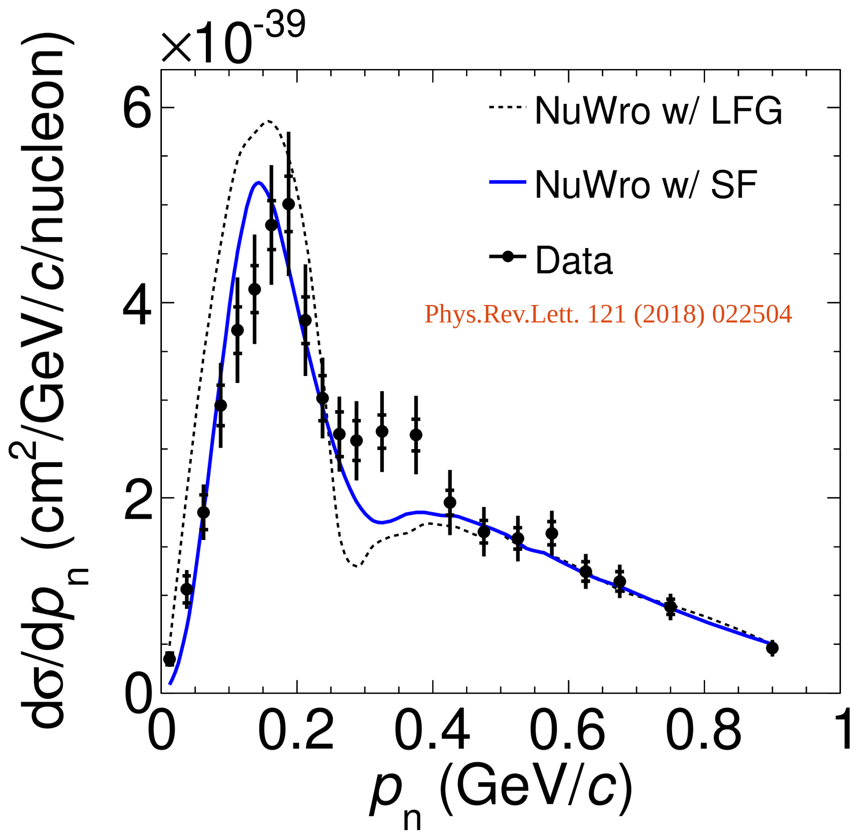


QE



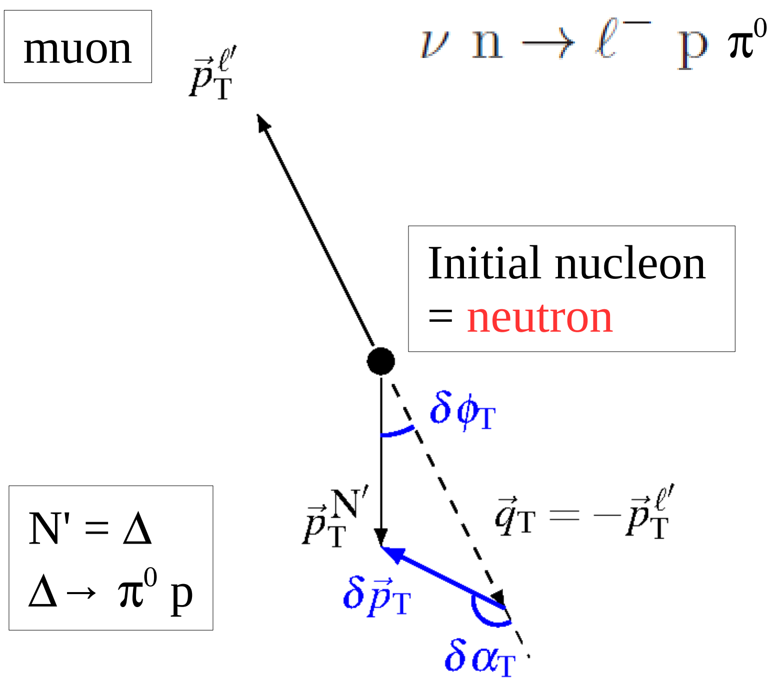
$\nu\ \mathrm{n} \to \ell^-\ \mathrm{p}$

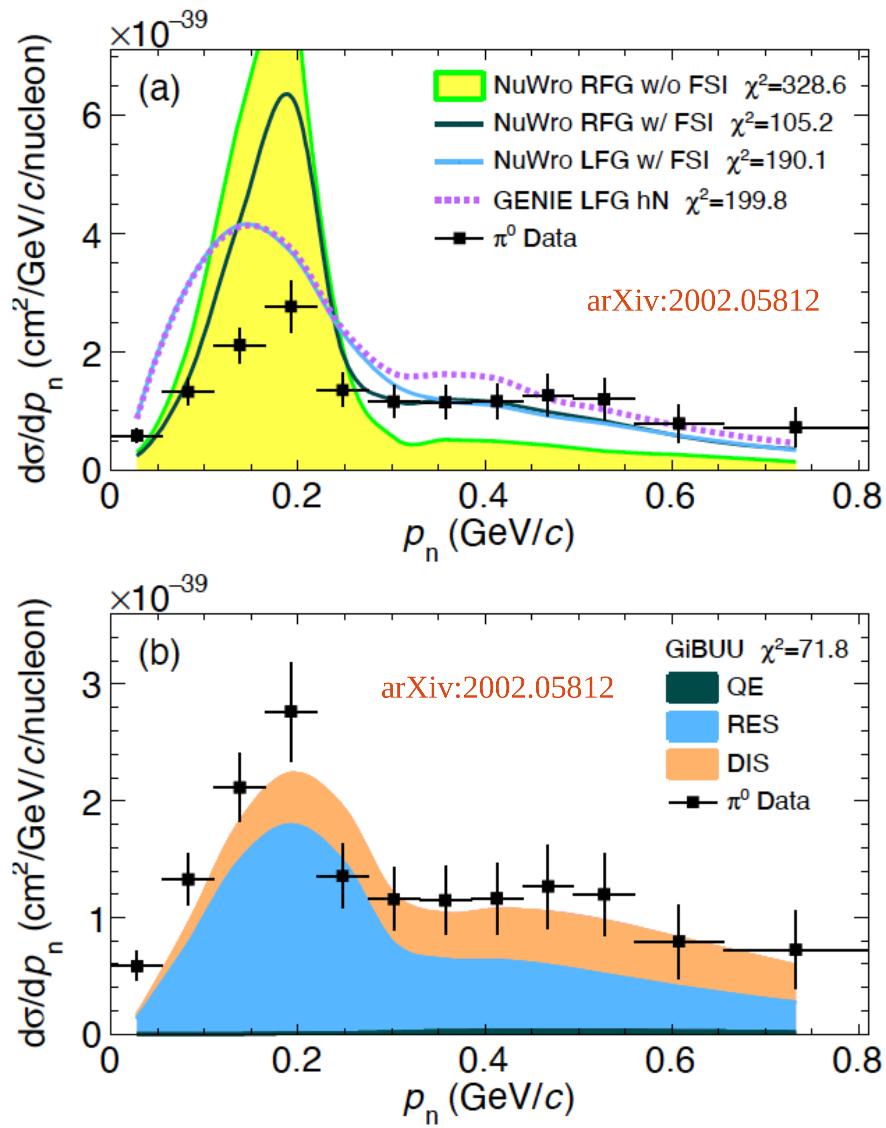




TKI

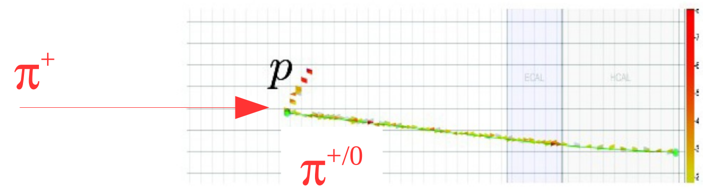
– *Neutron initial-state kinematics*

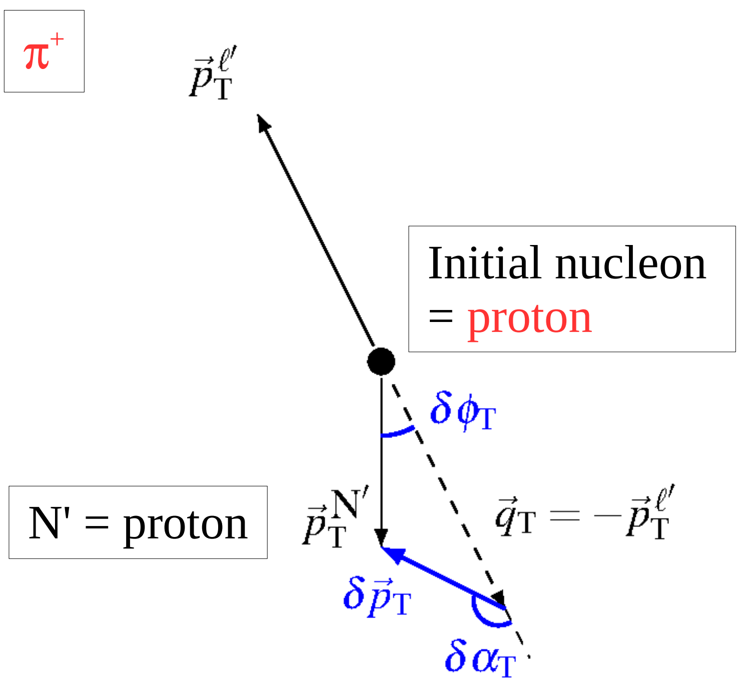


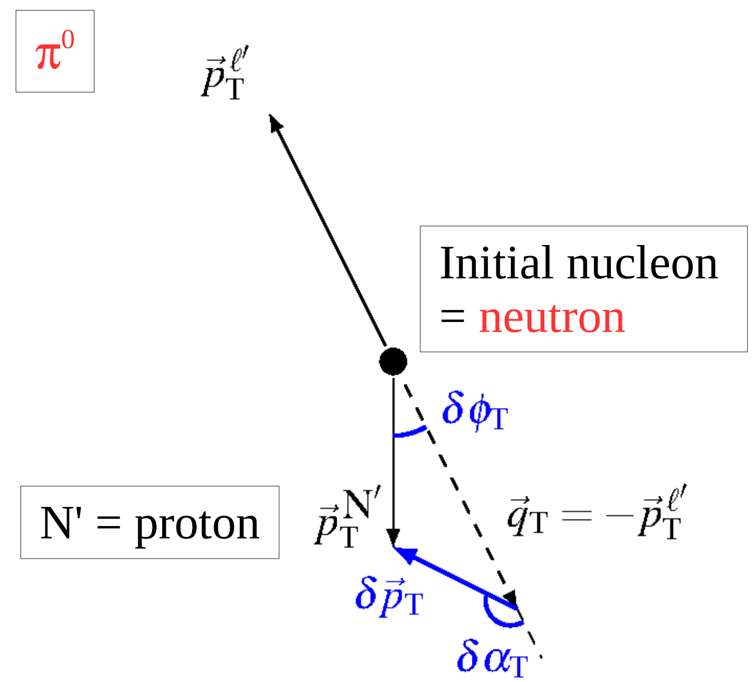


TKI + protoDUNE

– Proton/Neutron initial-state kinematics







Data set:

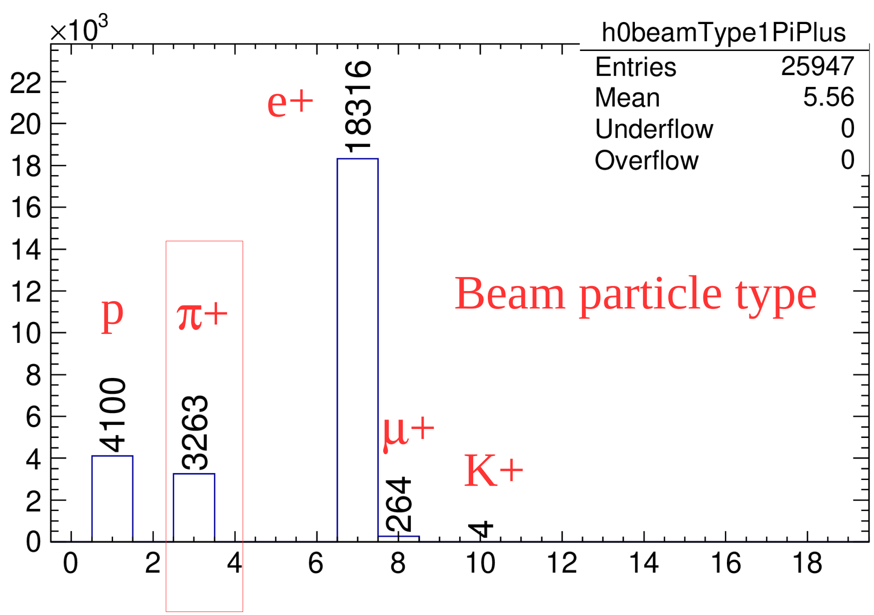
calcuttj_PDSPProd2_MC_1GeV_reco_sce_datadriven_forced_reco

3447 out of all 3486 files finished without error

statistics: the total merged file size is 381M. The merged tree has 25947 entries.

The following **true-level** variables are used:

```
vector<int> *true_beam_daughter_PDG=0x0;
vector<double> *true_beam_daughter_startPx=0x0;
vector<double> *true_beam_daughter_startPy=0x0;
vector<double> *true_beam_daughter_startPz=0x0;
double true_beam_endPx = -999;
double true_beam_endPy = -999;
double true_beam_endPz = -999;
int true_beam_PDG   = -999;
```

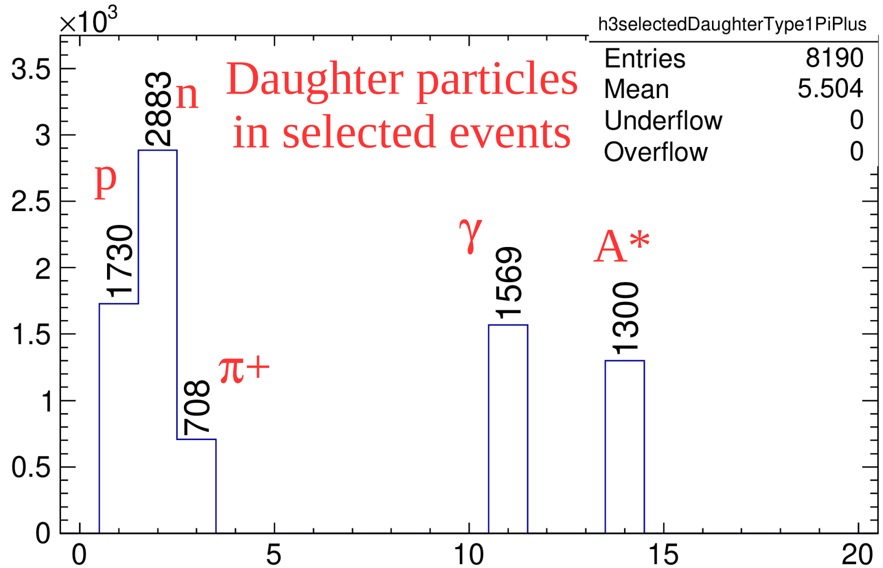


Purpose of this feasibility study:

- Figure out signal definition
- Estimation statistics

3263 pi+ beam events
(3263/25947 = 12.6%)

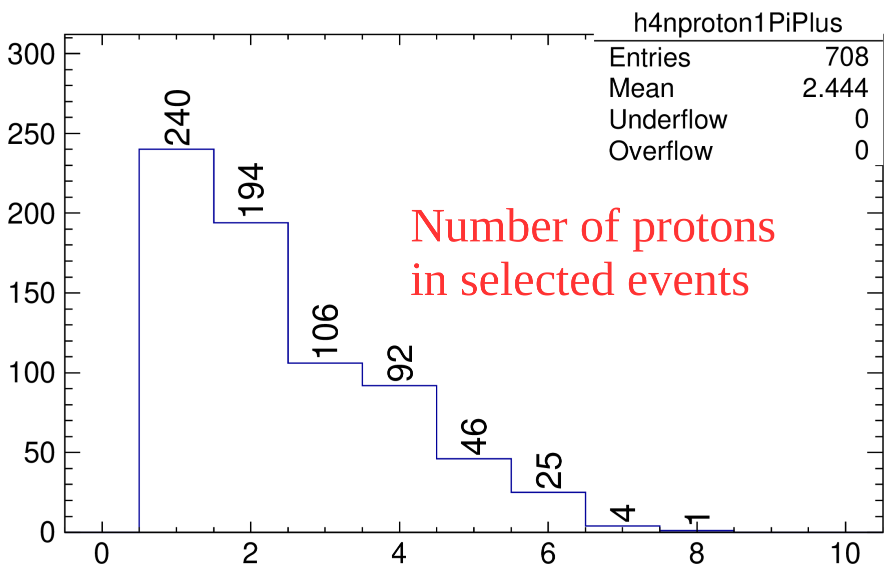
Q: are these true events AFTER reconstruction?
(That is, already suppressed by 1-efficeincy?)

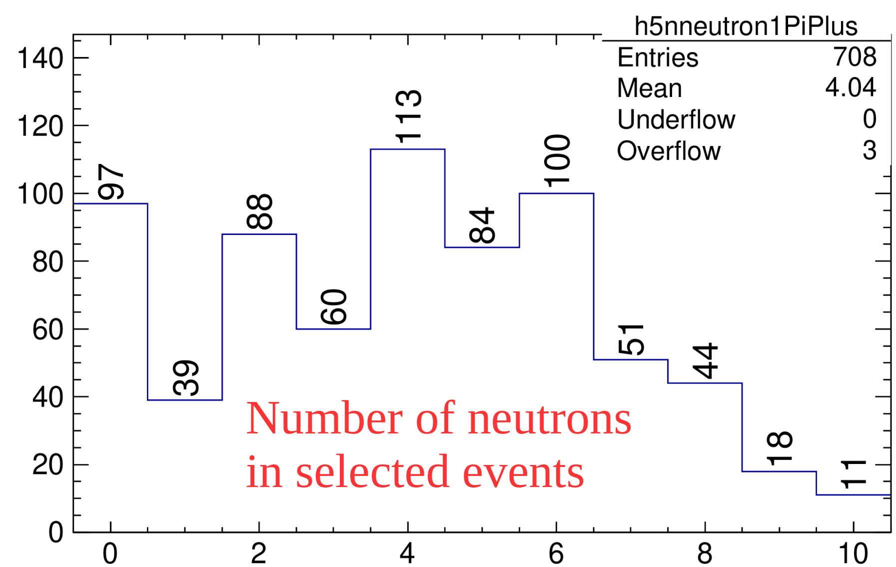


Exclusive pπ+ event selection:

- At least 1 proton (leading proton kinematics used in calculation)
- Exactly 1 π+, no other pions
- Don't care about neutron, gamma, nucleus
- Phase space cut (to be added after a few slides)

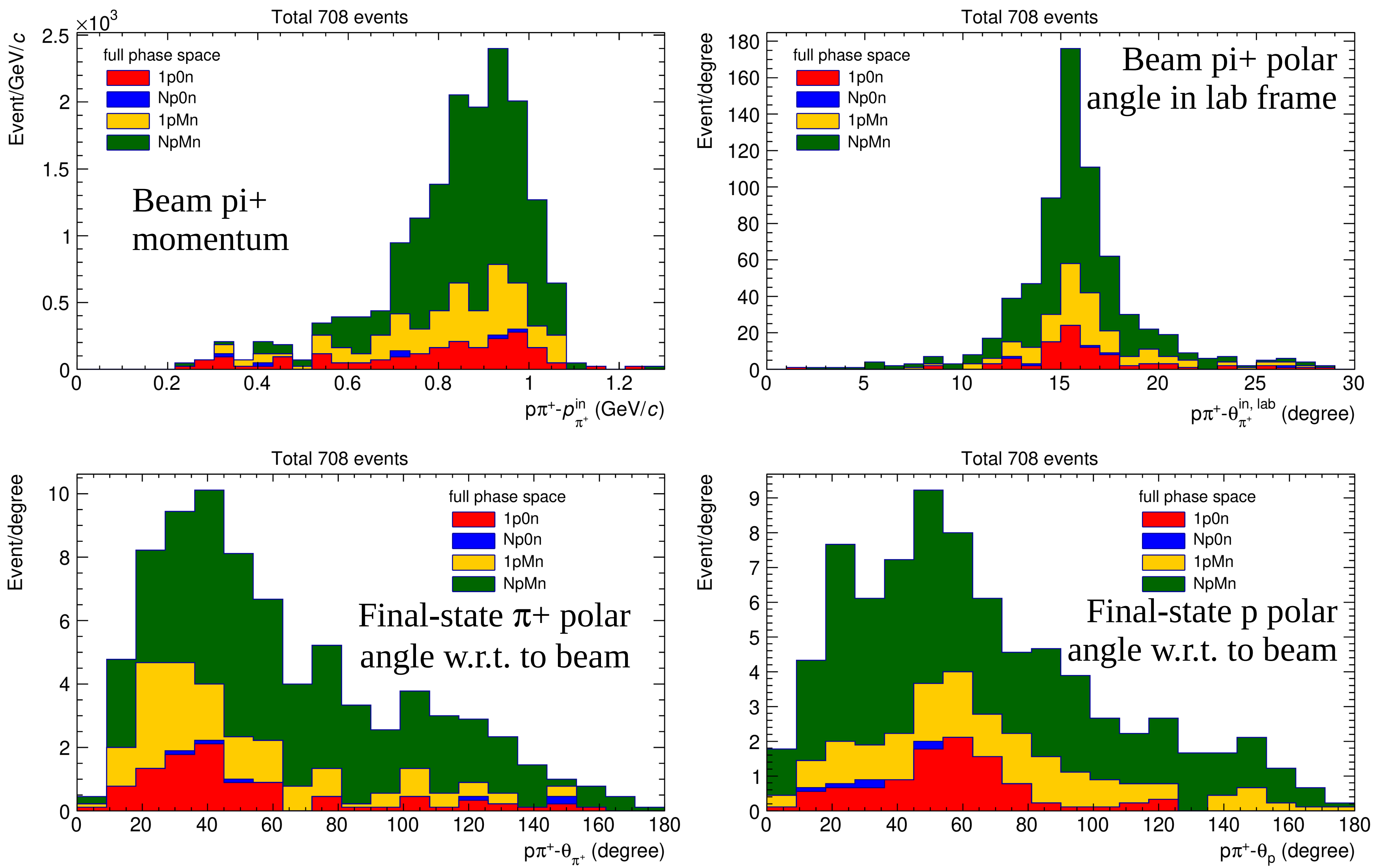
→ 708 pπ+ events selected
(708/3263= 22%)





Selected pπ+ events

Decomposed into proton-neutron topology
1p0n expected to be sensitive to initial state

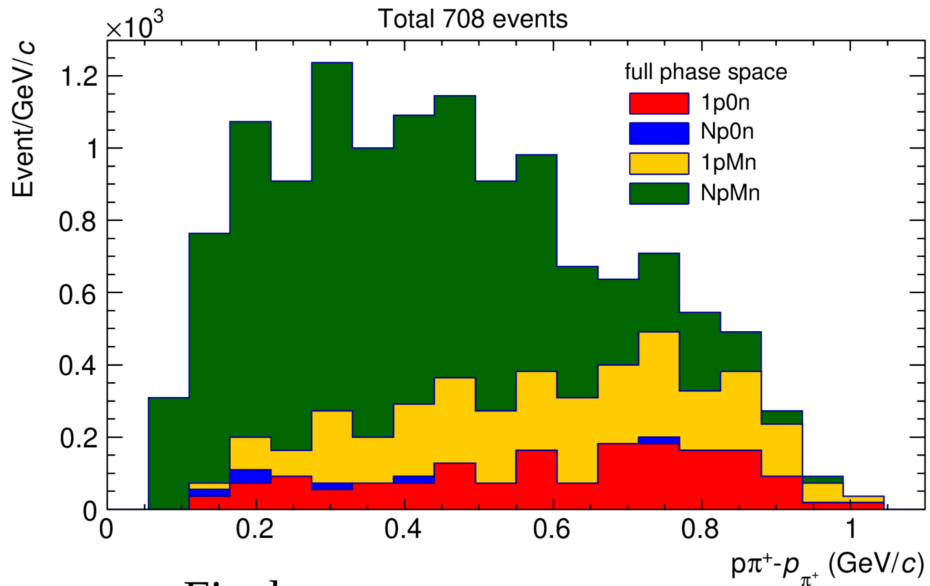


→ 1p0n proton angle resembles neutrino QE proton angle distribution

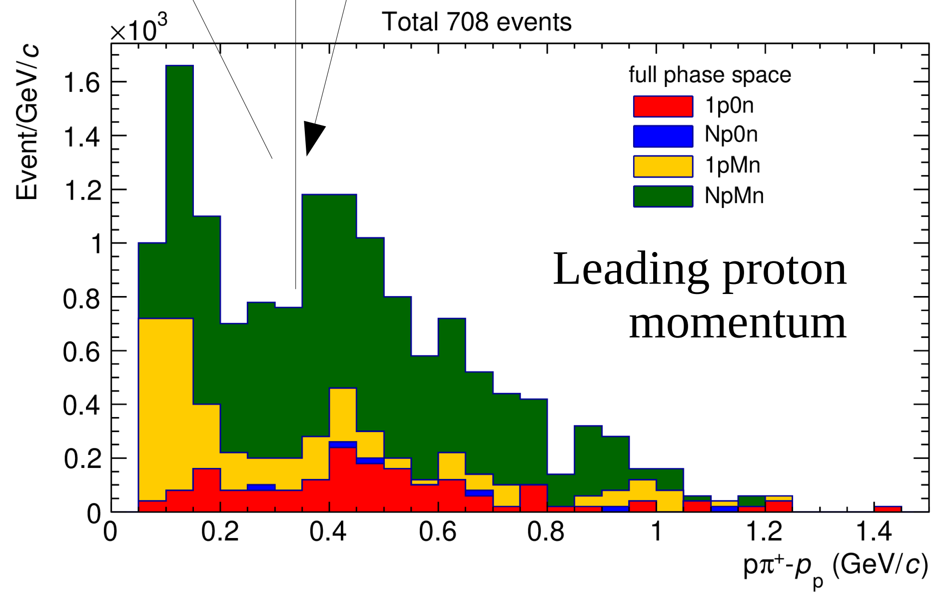
Selected pπ+ events

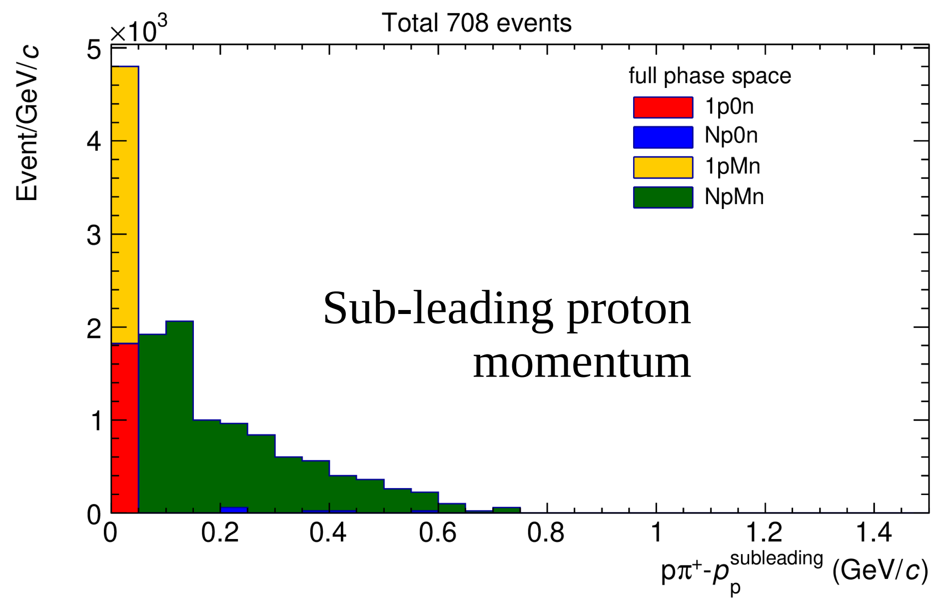
Mis-reconstructed as pi+?

proton reconstruction efficiency onset?



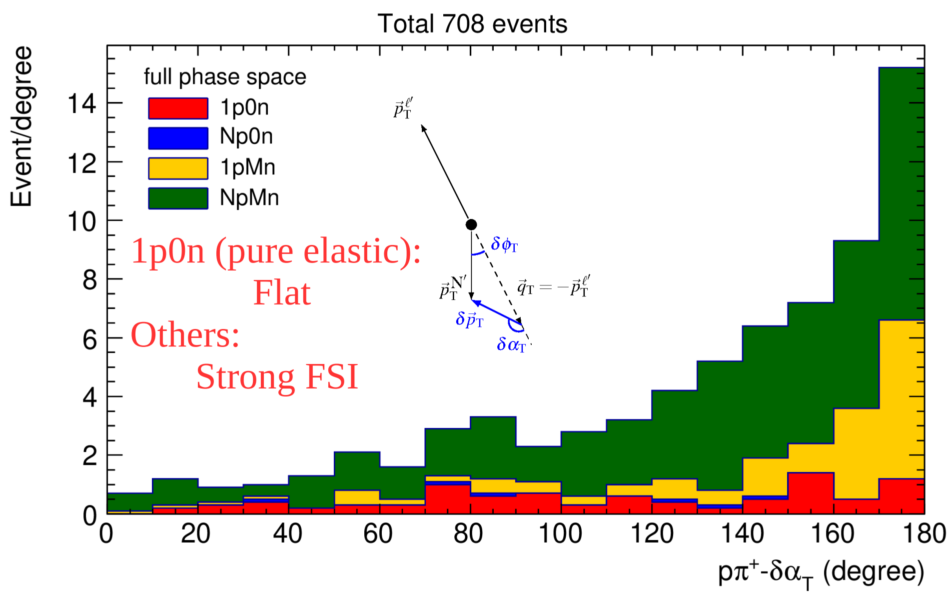
Final-state π+ momentum

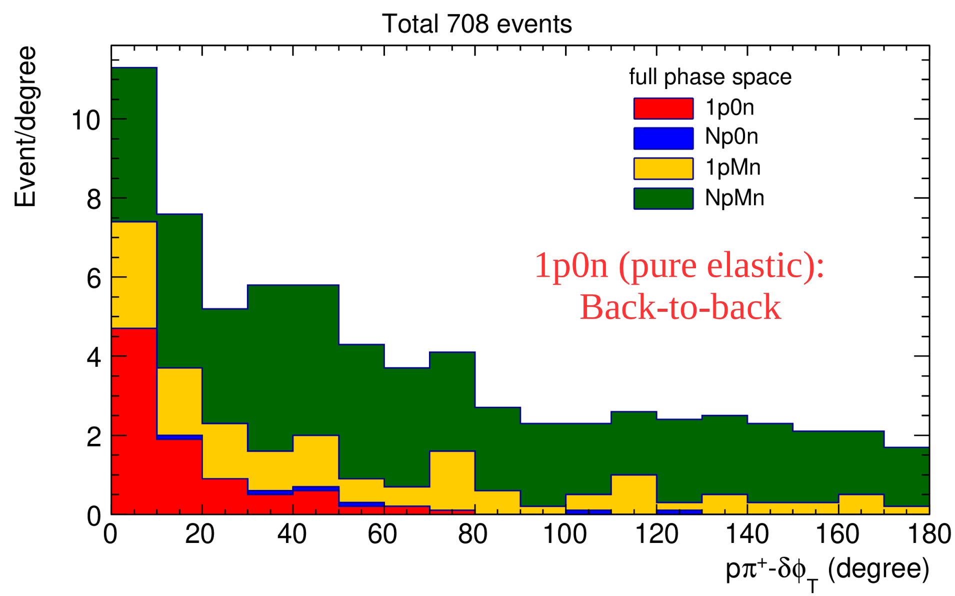


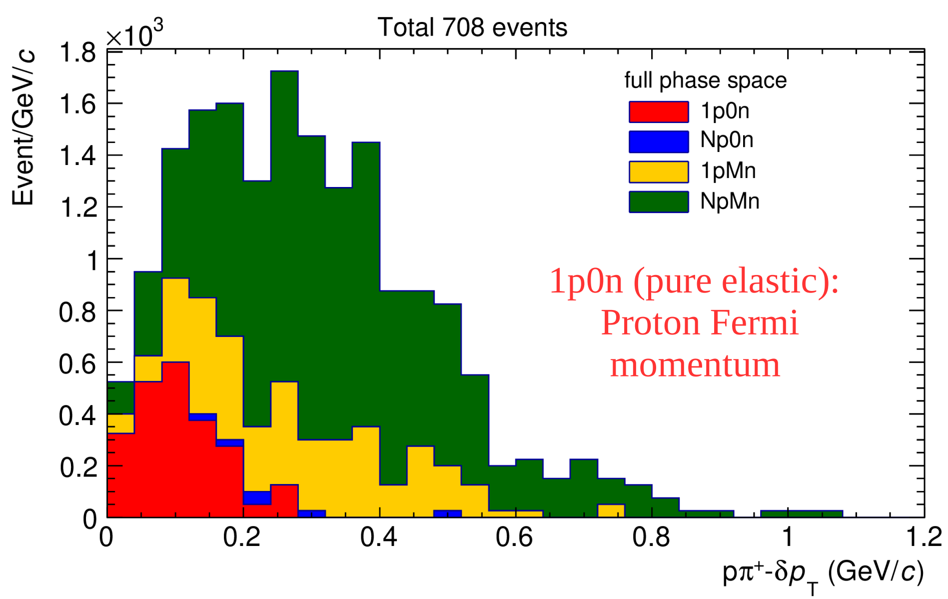


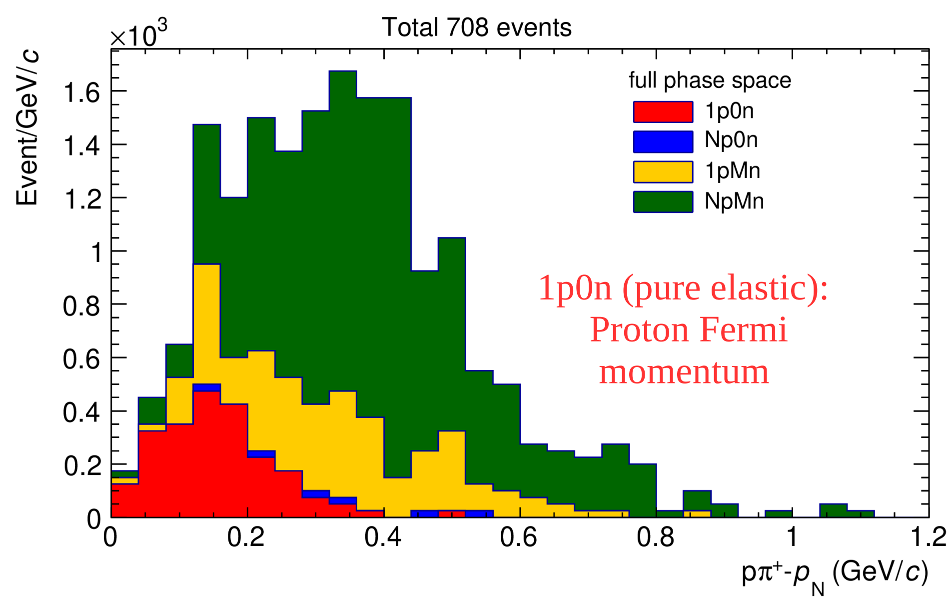
(Recap: all true-level quantities)

Selected pπ+ events







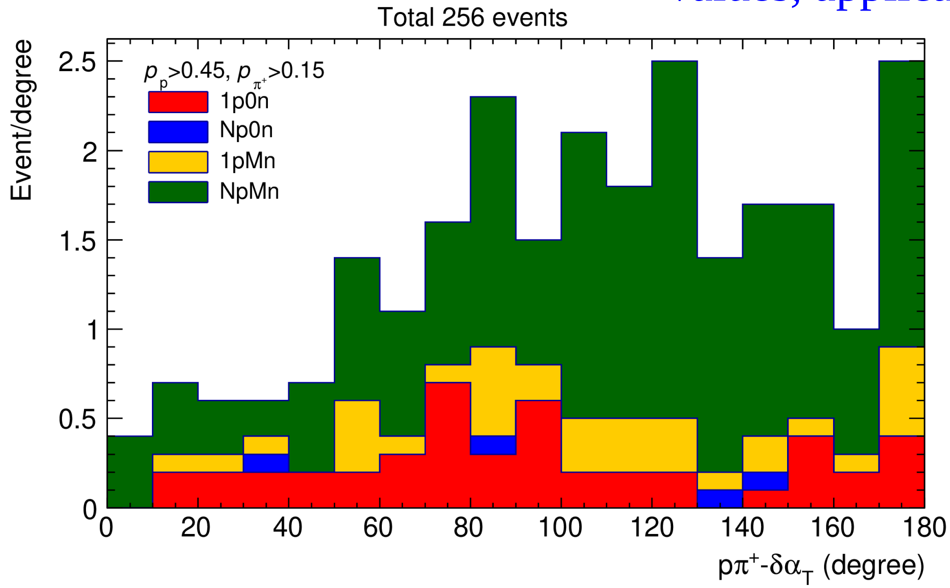


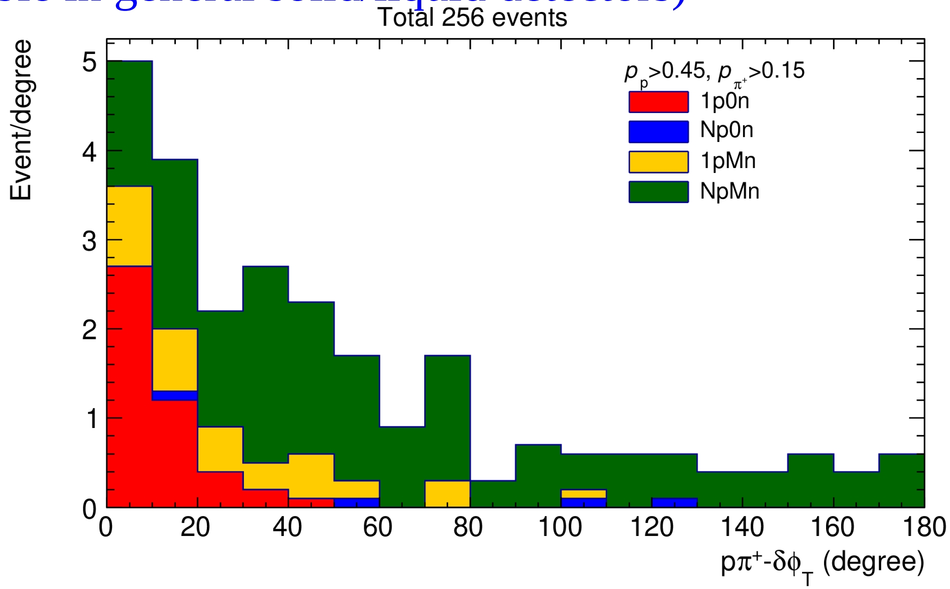
→ Proton Fermi momentum is indeed observed

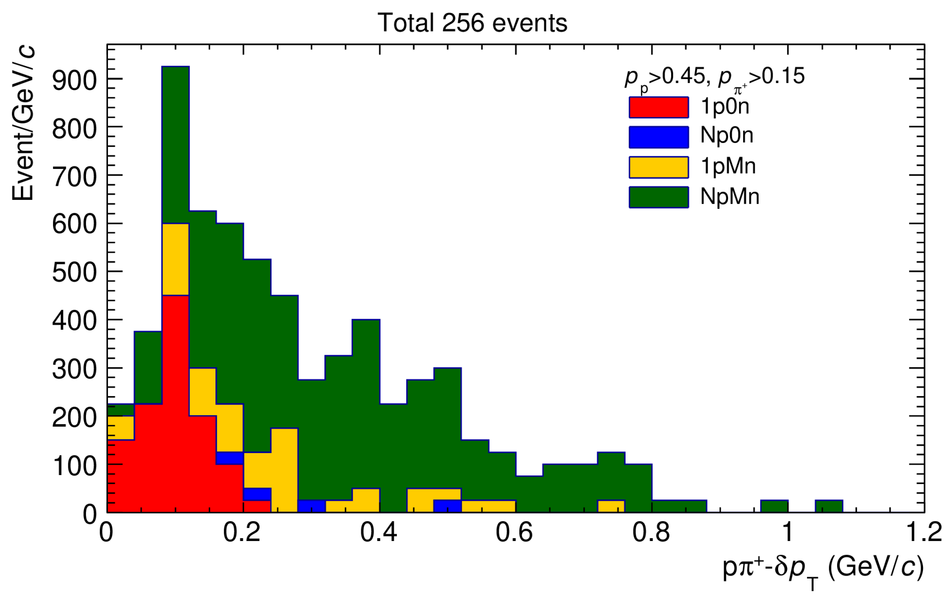
→ need to reduce Np contributions (strong FSI)

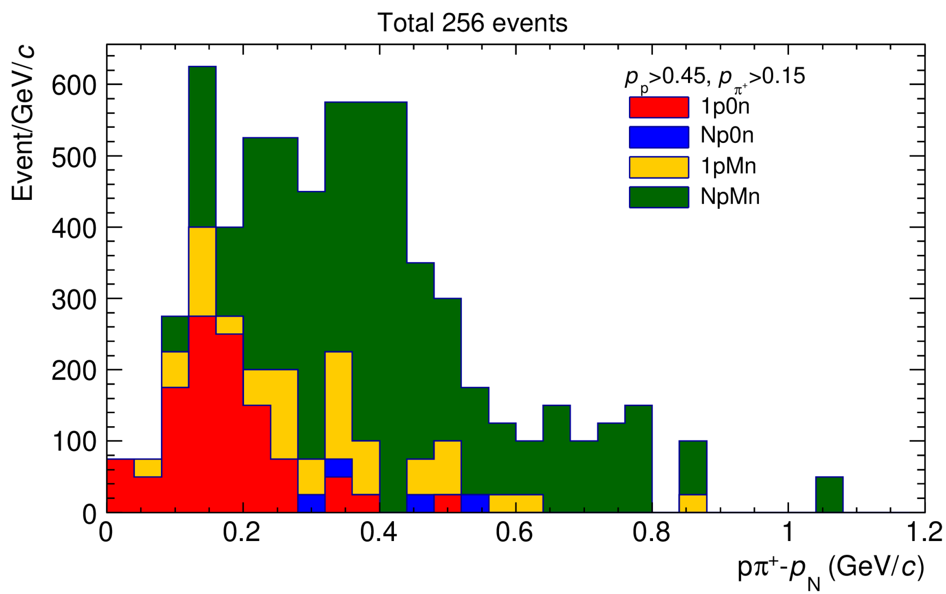
Selected pπ+ events

Impose kinetic energy threshold for p π+
T_p > ~100 MeV (~9 cm range) and $T_{\pi+}$ > ~70 MeV (MINERvA values, applicable in general solid/liquid detectors)





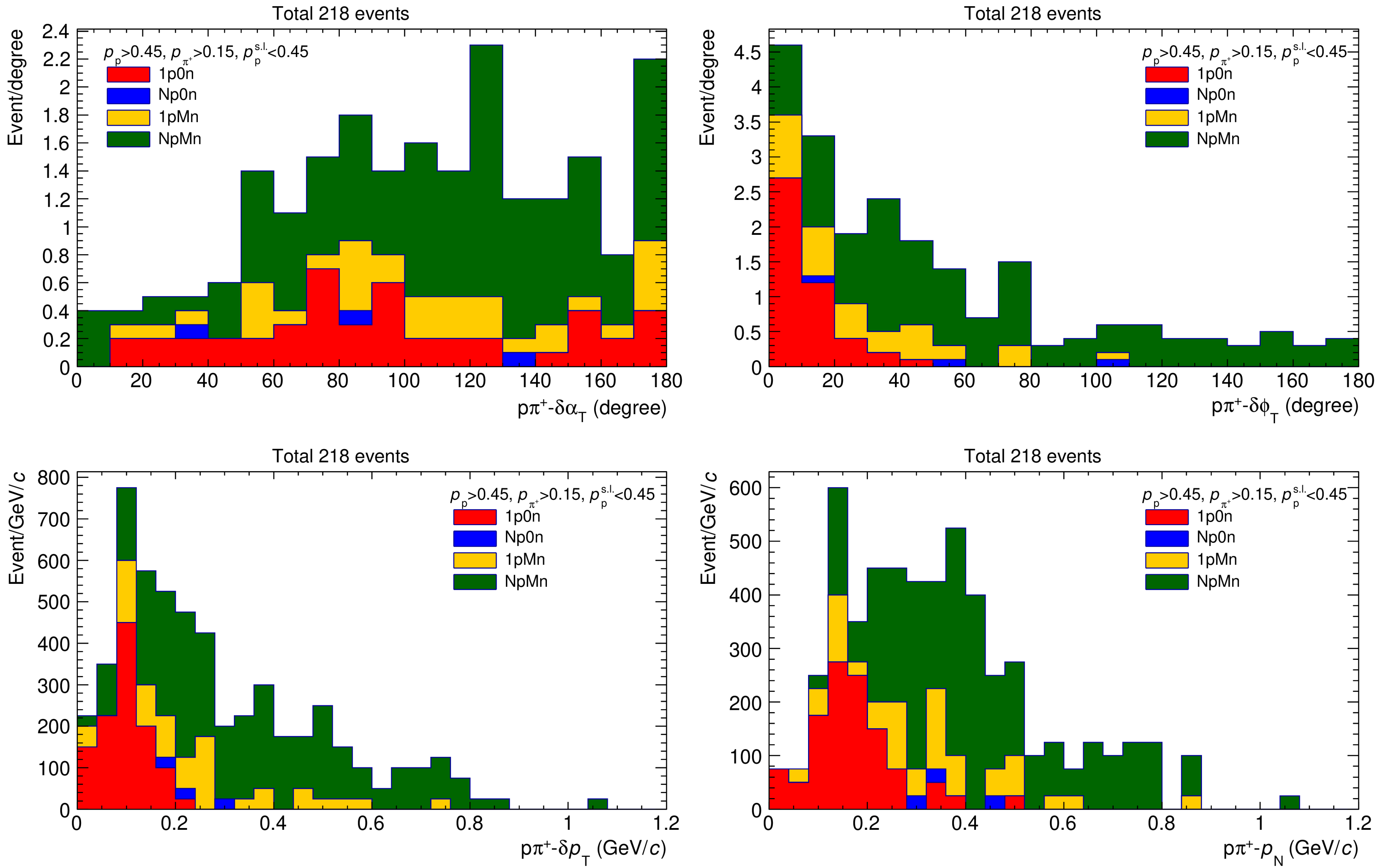




→ Strong FSI part reduced (below threshold events are most likely mis-reconstruction any way)

Selected pπ+ events

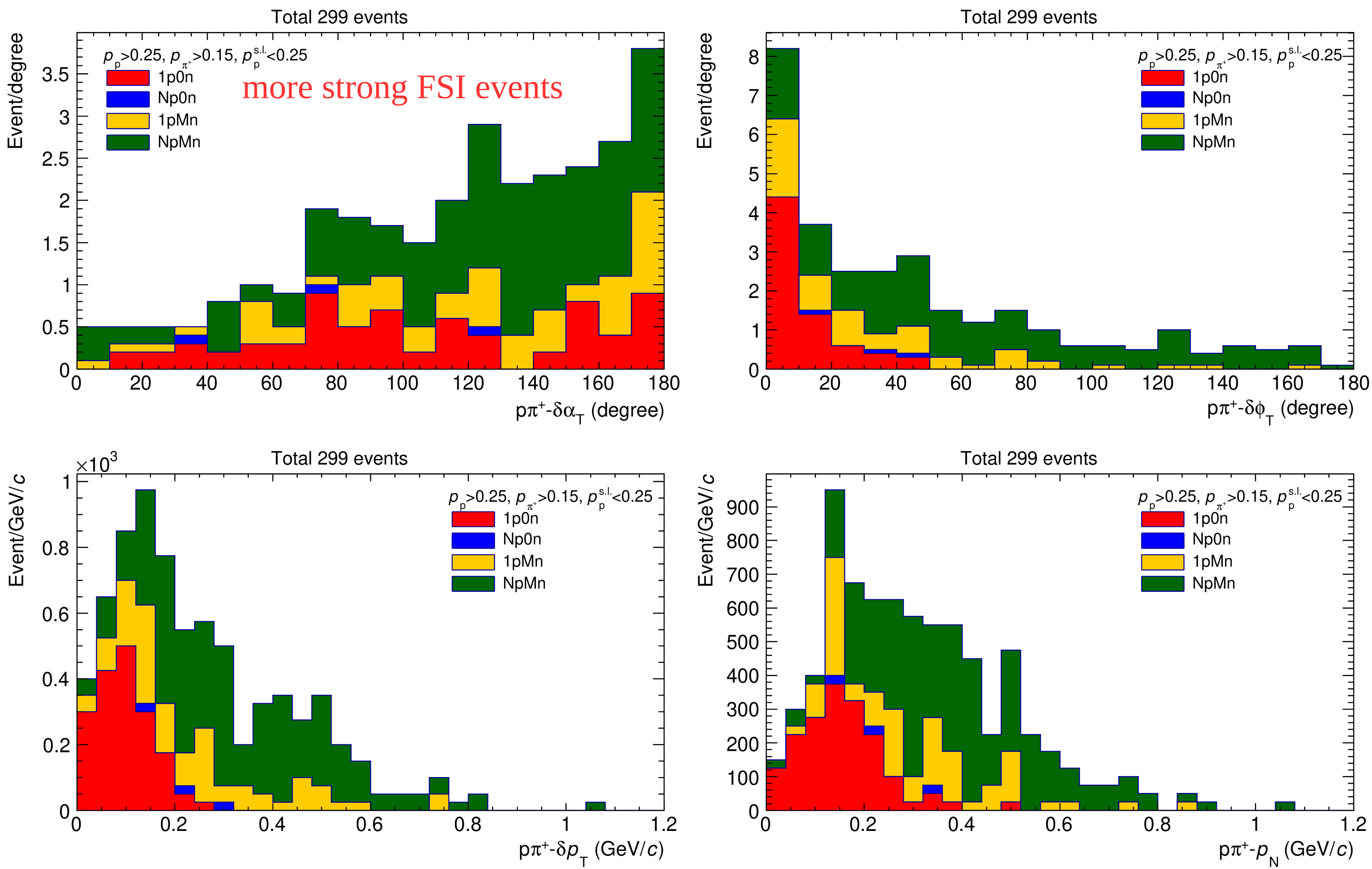
- Impose kinetic energy threshold for p π+
- require exactly 1 proton above threshold (=remove events with subleading proton above threshold)



→ Further clean-up. Total 218 events.
(218 phase-space cut exclusive events / 3263 pi+ beam events = 6.7%)

Selected pπ+ events

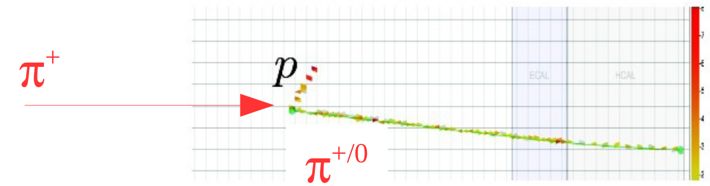
Alternative **hypothetical** proton threshold
T>33 MeV (1cm proton range)

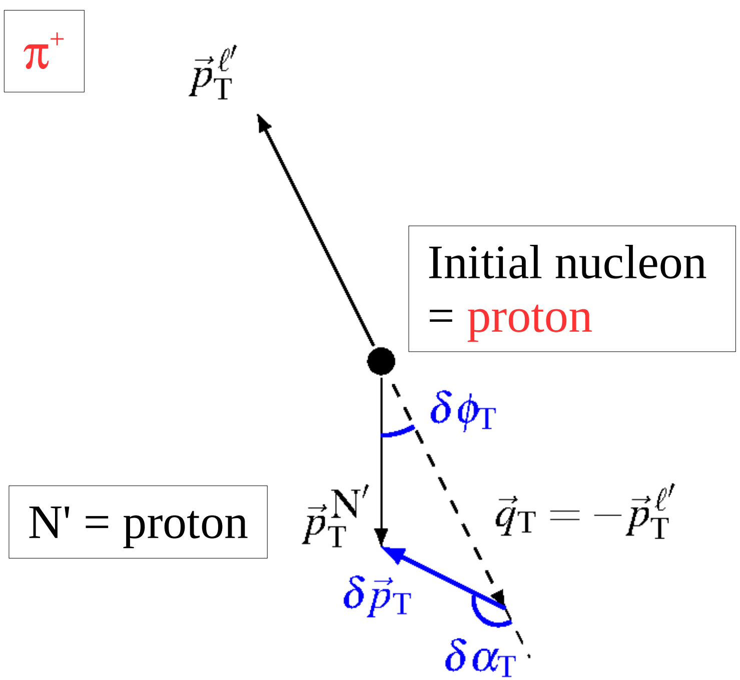


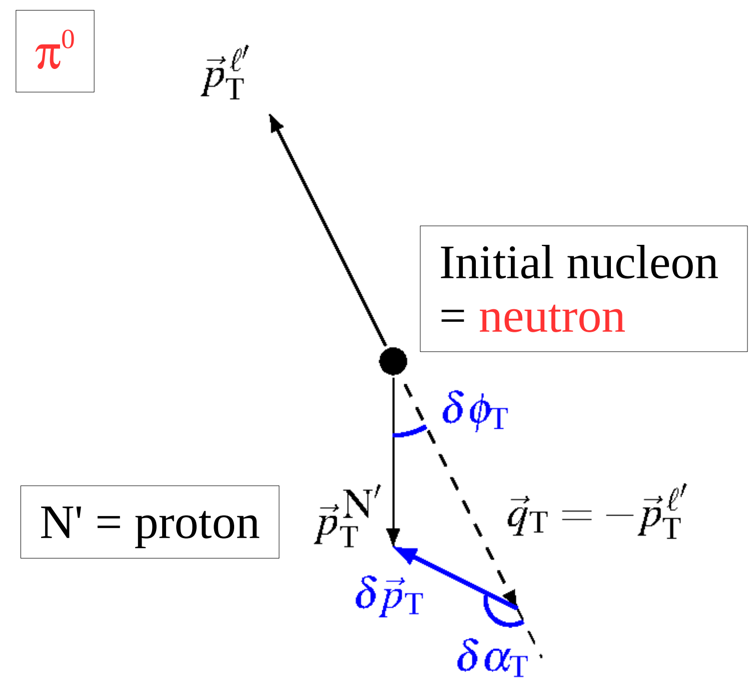
→ Lower threshold accepts more strong FSI events.
(299 hypothetical phase-space cut exclusive events / 3263 pi+ beam events = 9.1%)

TKI + protoDUNE

– *Proton/Neutron initial-state kinematics*

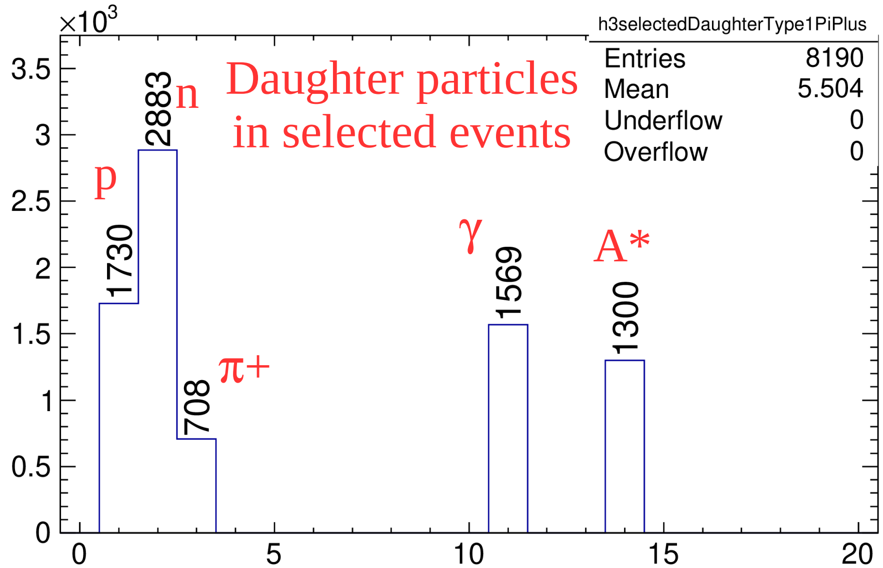






- Proton Fermi motion observed
- 218 phase-space cut exclusive events / 3263 pi+ beam events = 6.7%

Recap



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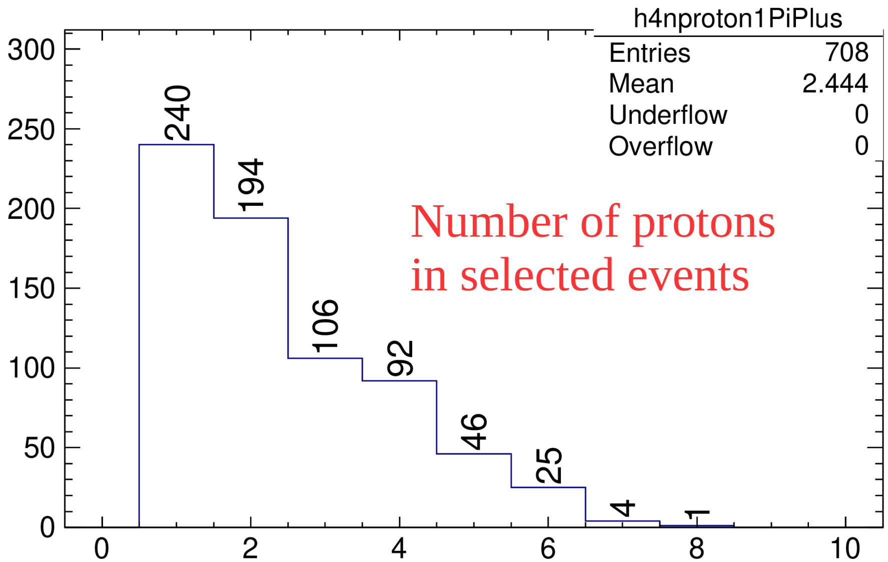
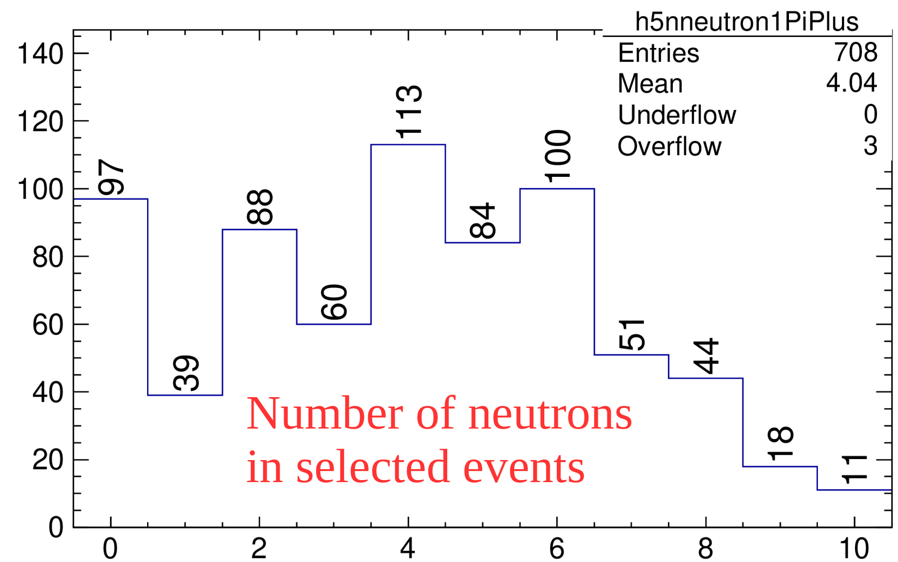
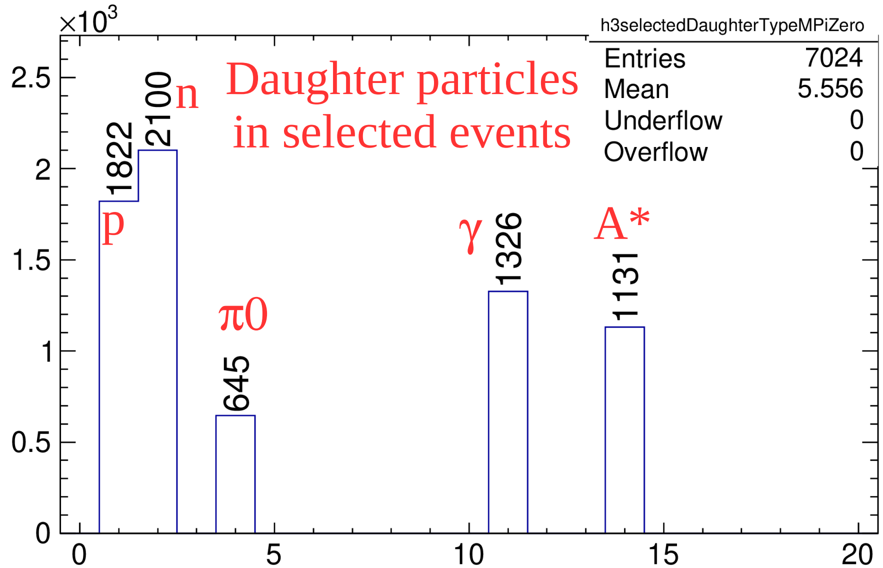


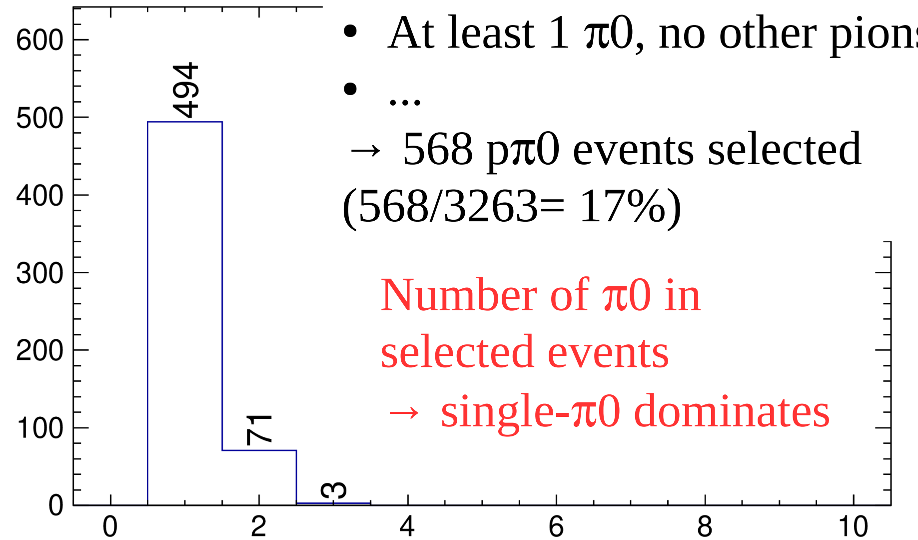


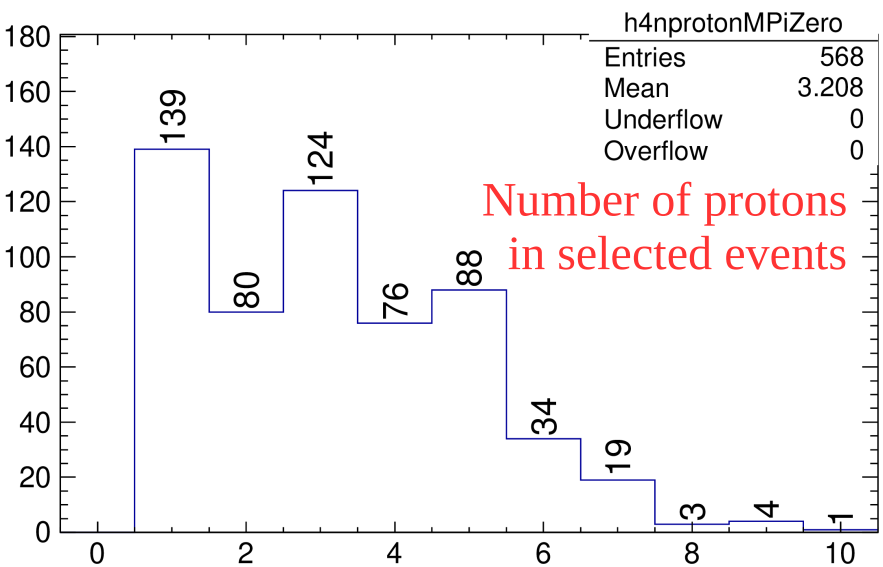
Exclusive pπ0 event selection:

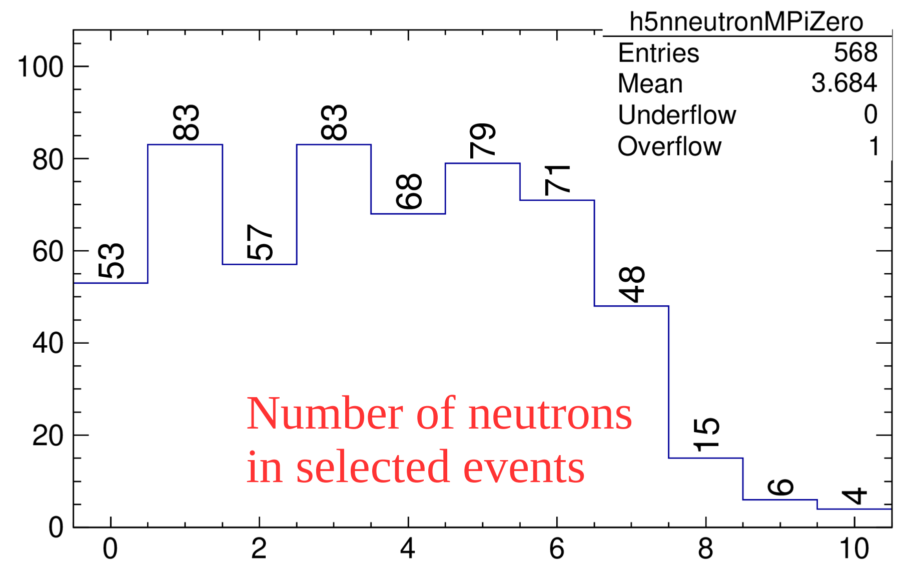
- …
- At least 1 π0, no other pions
- …

→ 568 pπ0 events selected (568/3263= 17%)





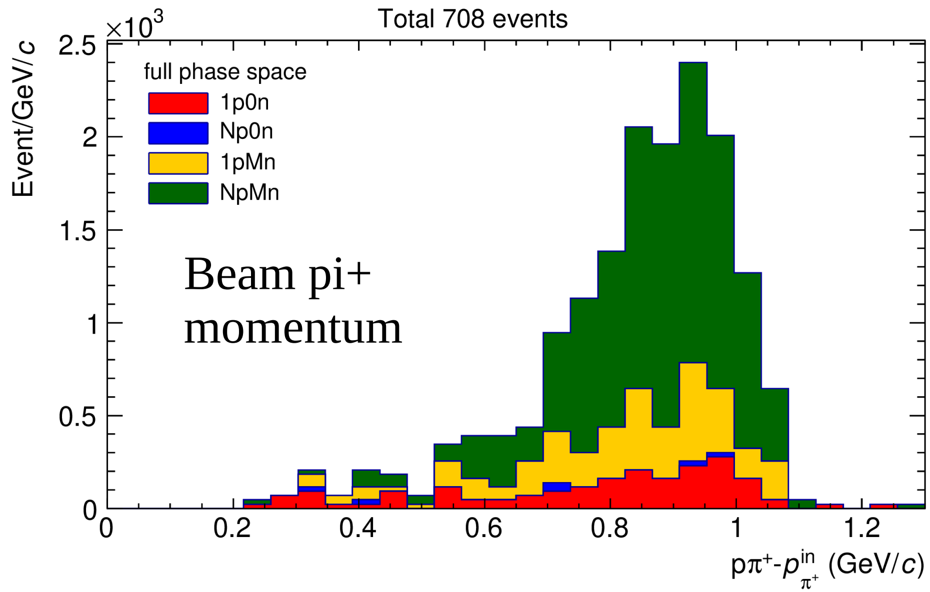


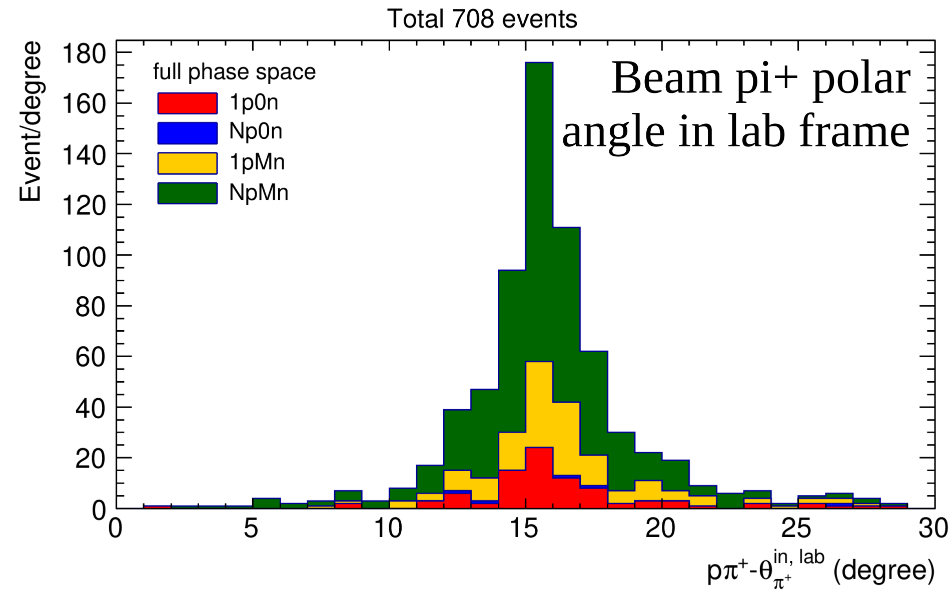


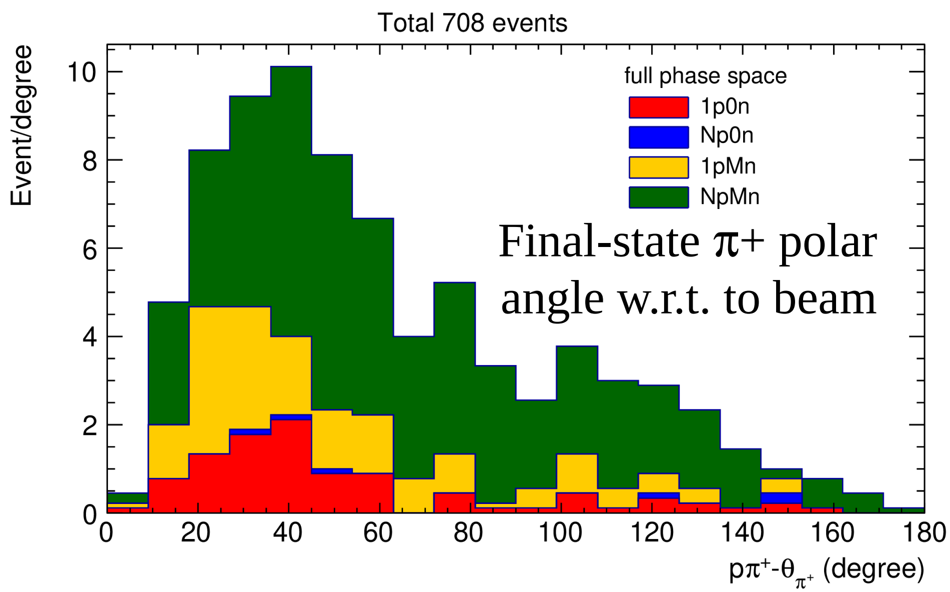
Selected pπ+ events

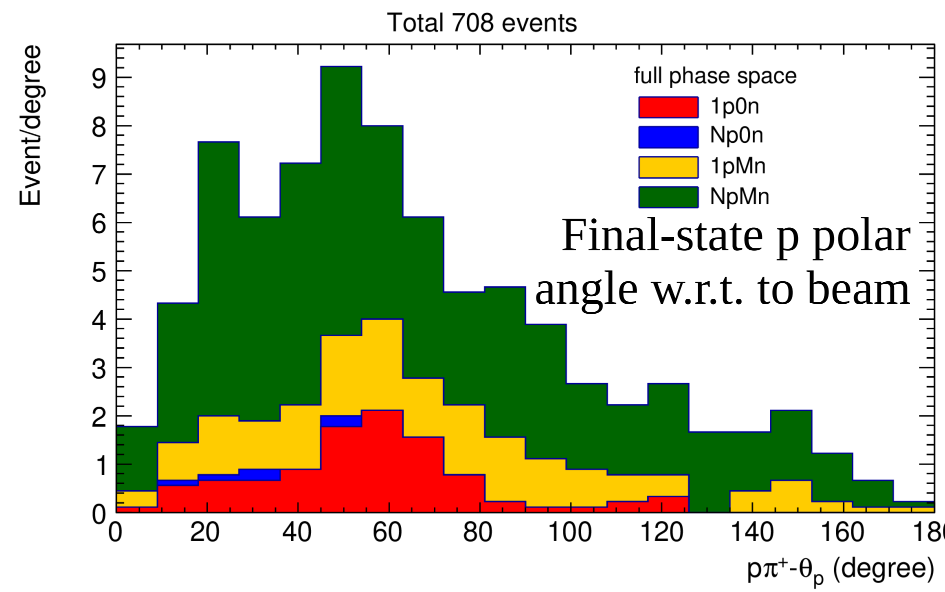
Decomposed into proton-neutron topology
1p0n expected to be sensitive to initial state

Recap





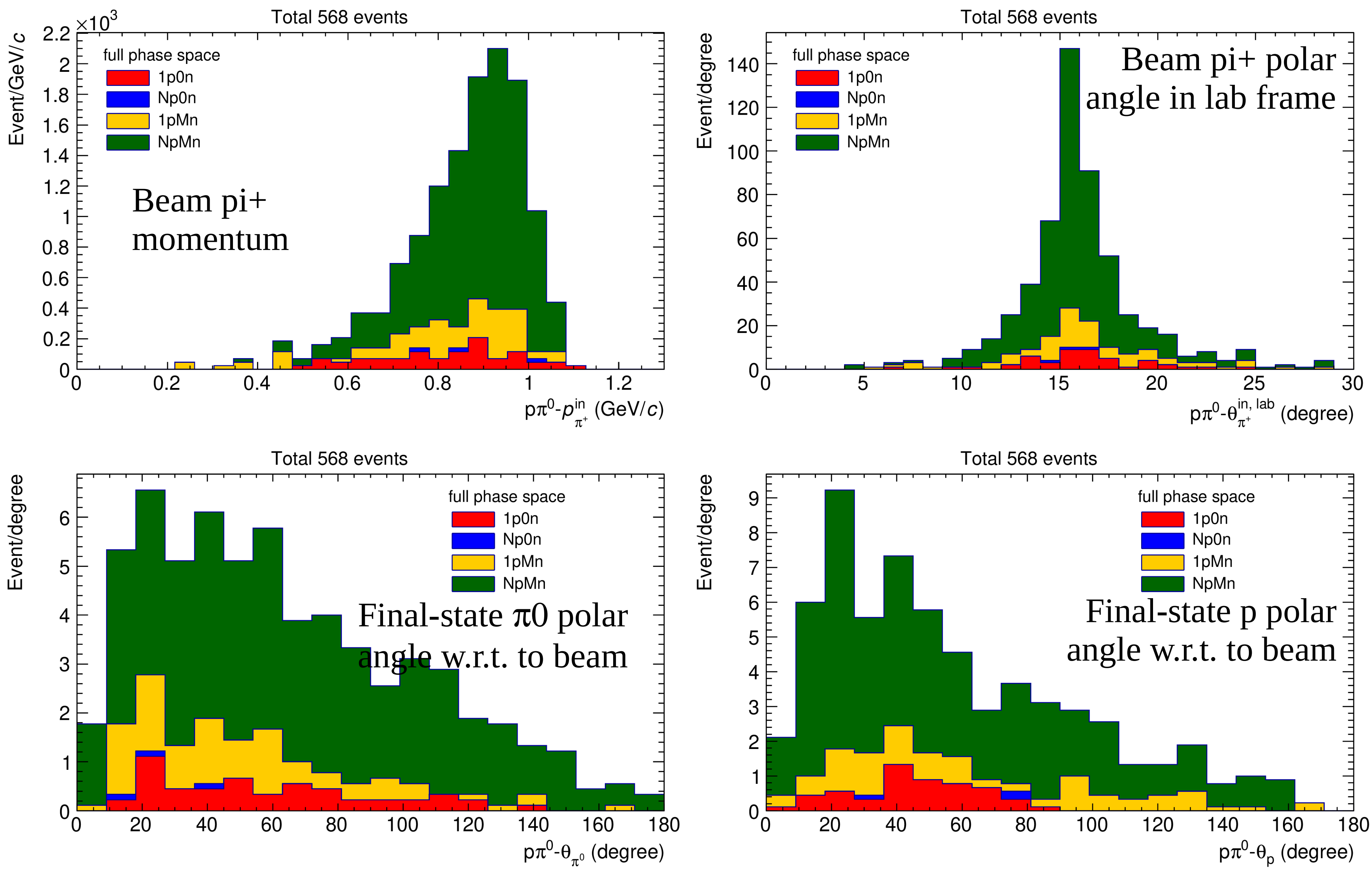




→ 1p0n proton angle resembles neutrino QE proton angle distribution

Selected pπ0 events

Decomposed into proton-neutron topology
1p0n expected to be sensitive to initial state

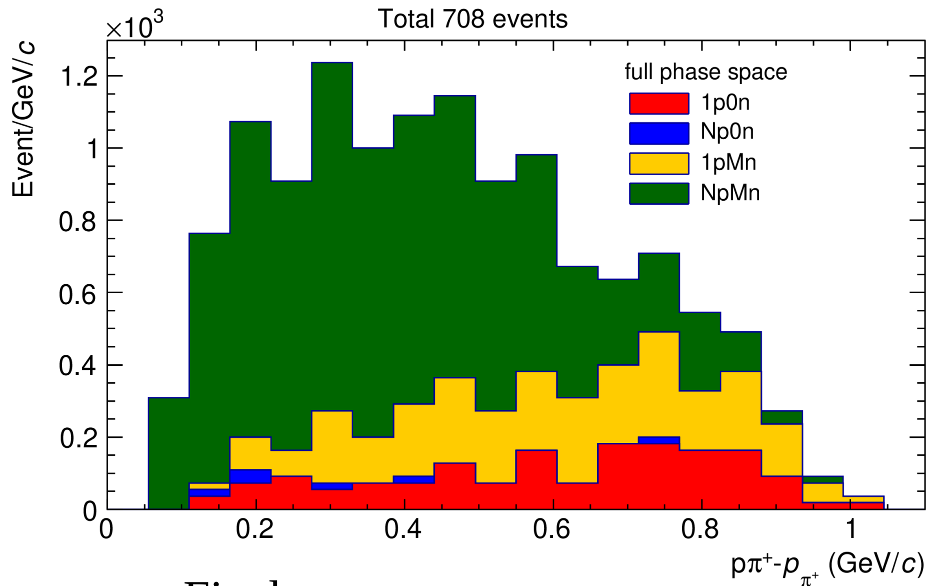


→ Wider final-state pion angle distribution

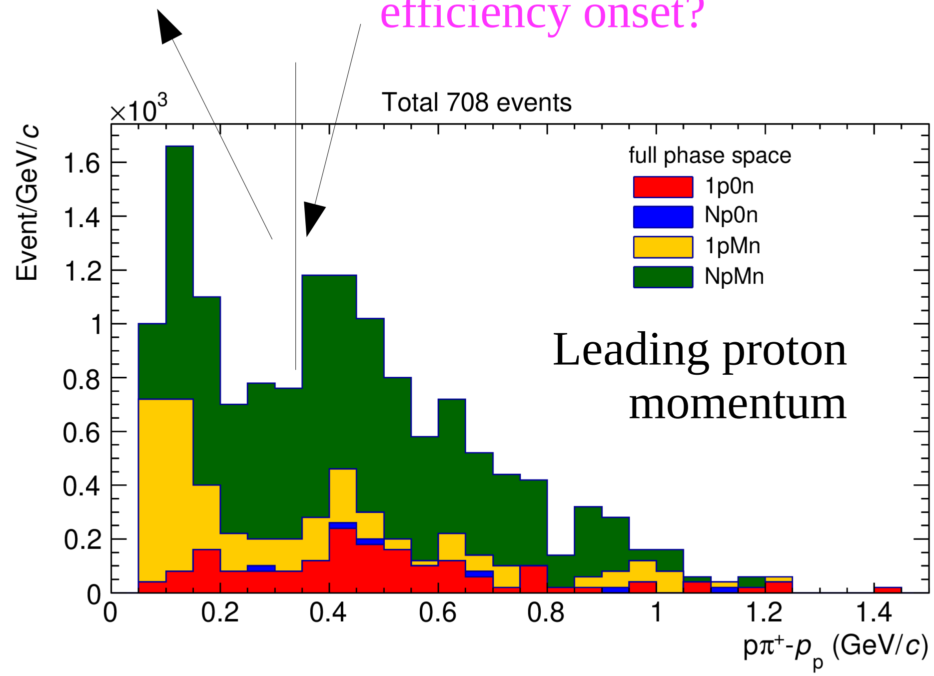
Selected pπ+ events

Mis-reconstructed as pi+?

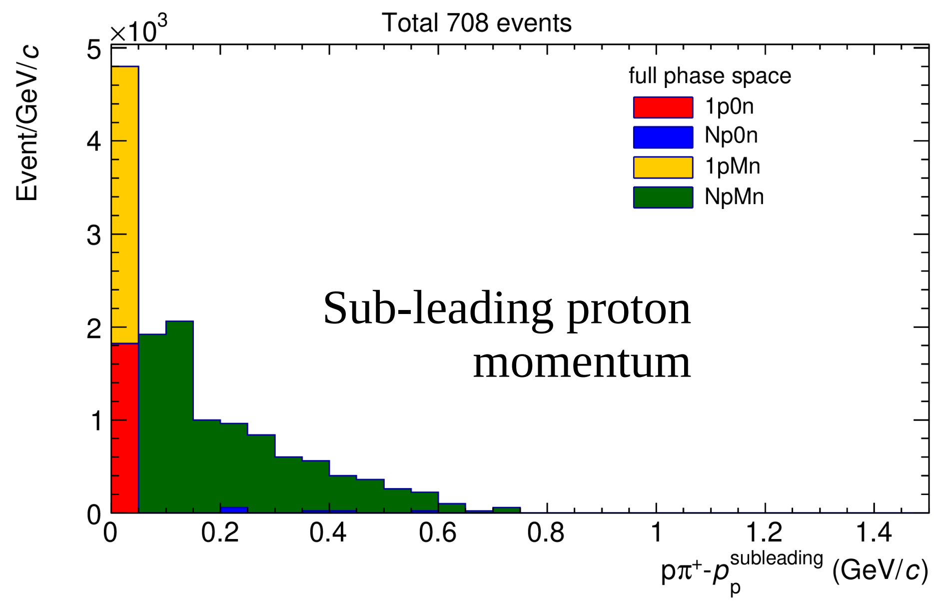
proton reconstruction efficiency onset?



Final-state π+ momentum



(Recap: all true-level quantities)

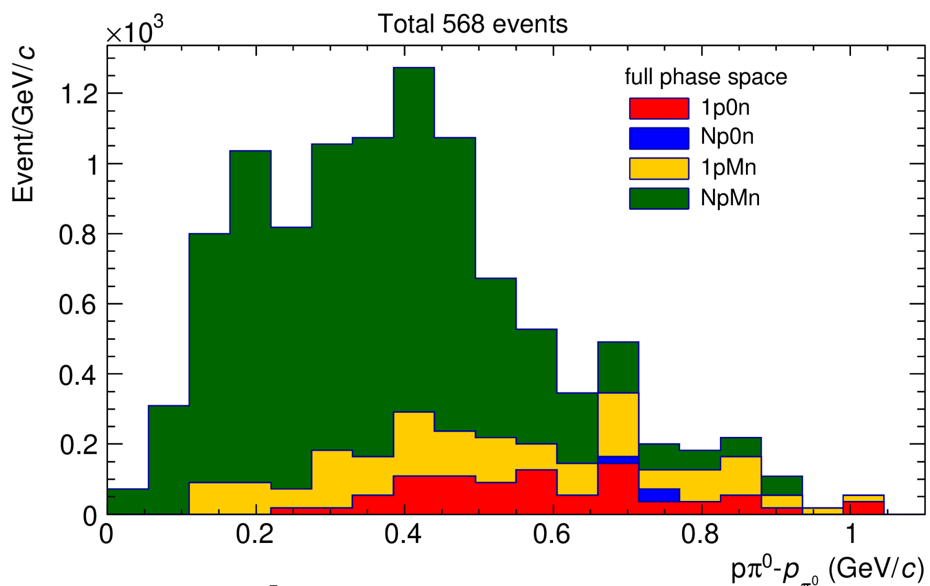


Recap

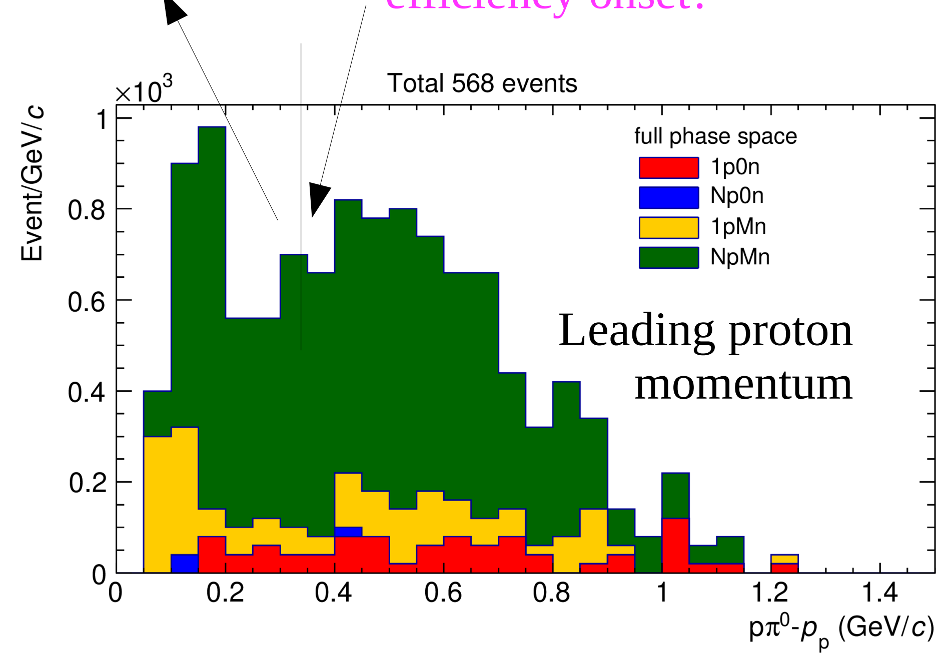
Selected pπ0 events

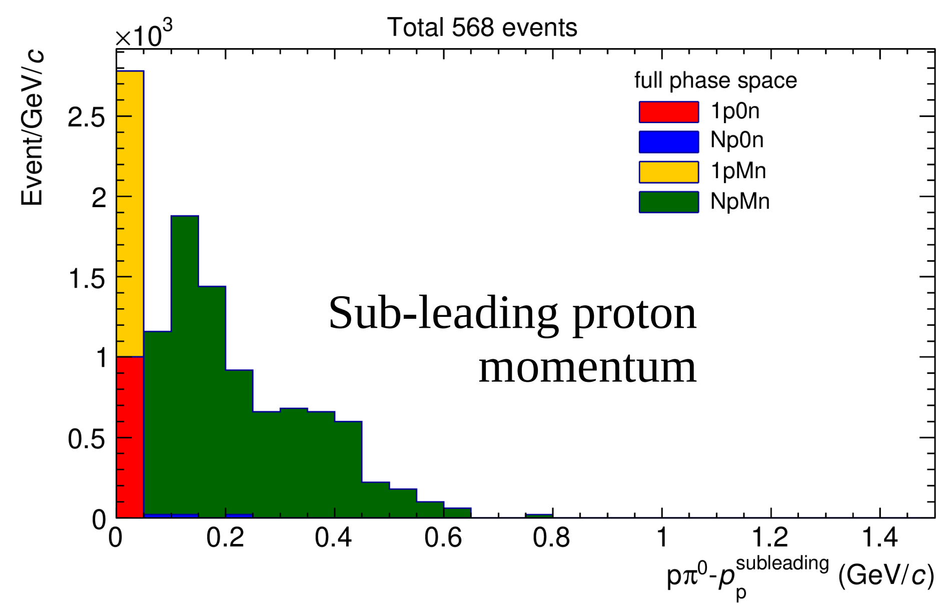
Mis-reconstructed as pi+?
(no true pi+, but still reco pi+?)

proton reconstruction
efficiency onset?



Final-state π+ momentum

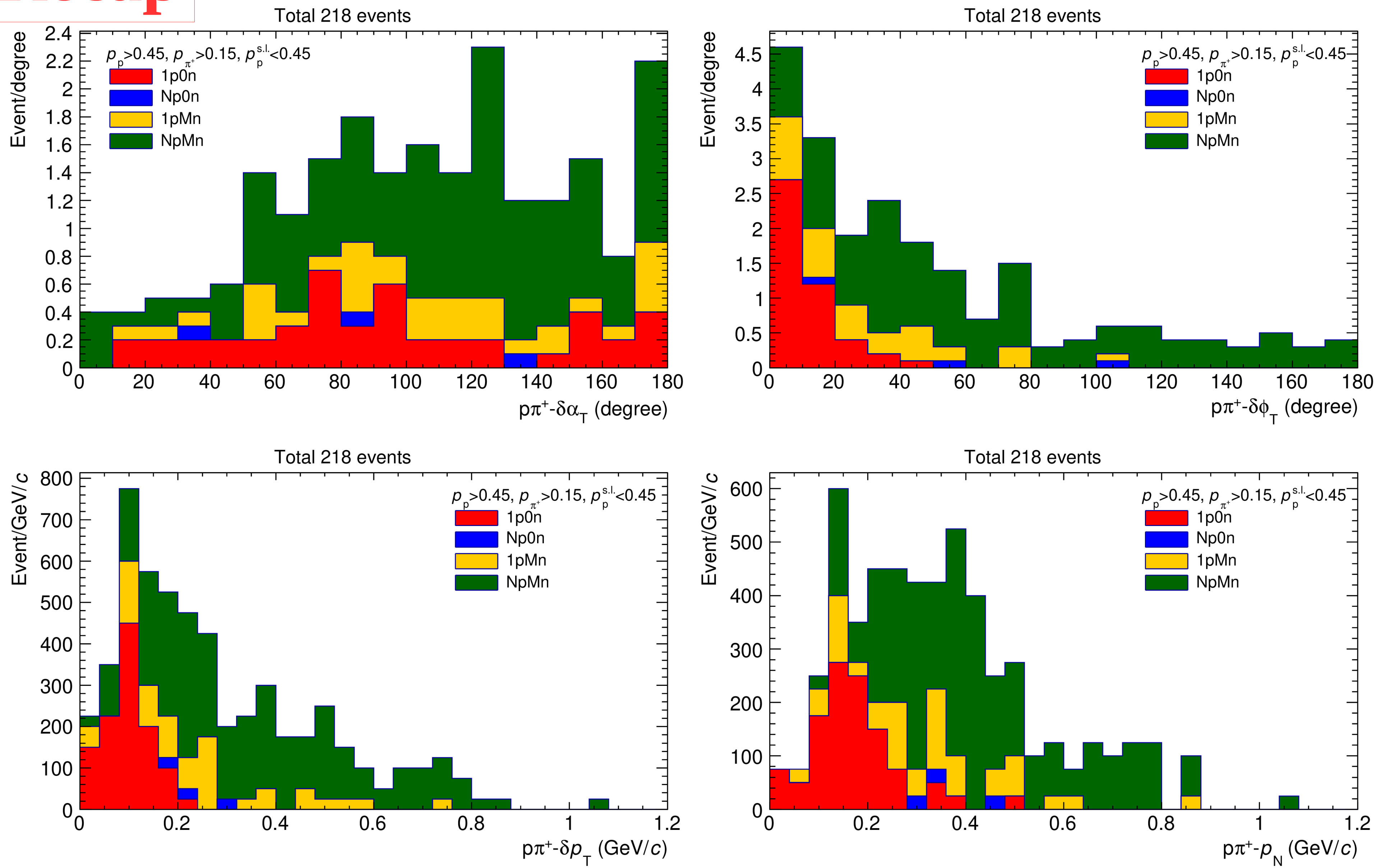




Selected pπ+ events

Recap

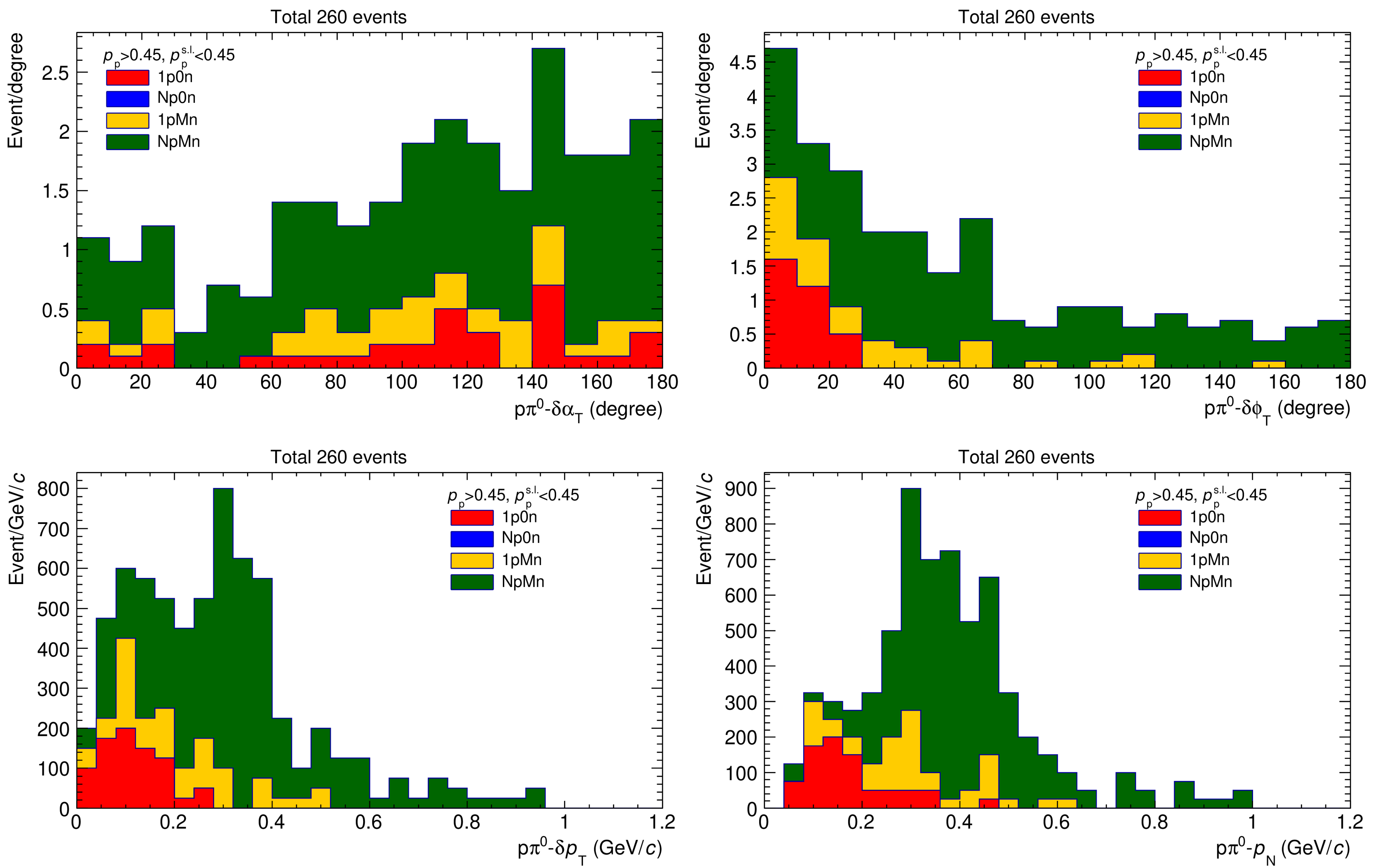
- Impose kinetic energy threshold for p π+
- require exactly 1 proton above threshold (=remove events with subleading proton above threshold)



→ Further clean-up. Total 218 events.
(218 phase-space cut exclusive events / 3263 pi+ beam events = 6.7%)

Selected pπ0 events

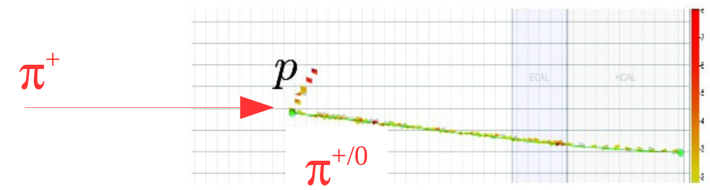
- Impose kinetic energy threshold for p ONLY (100MeV K.E.)
- require exactly 1 proton above threshold (=remove events with subleading proton above threshold)

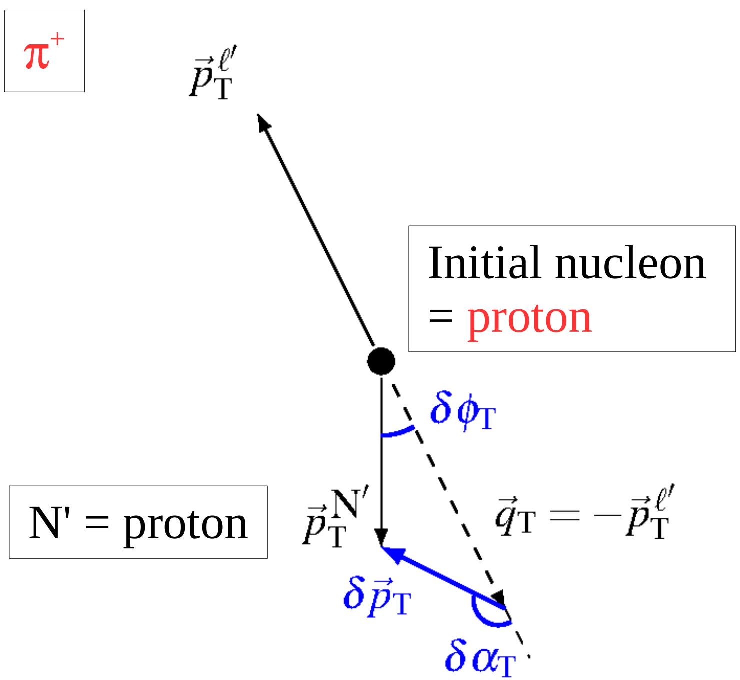


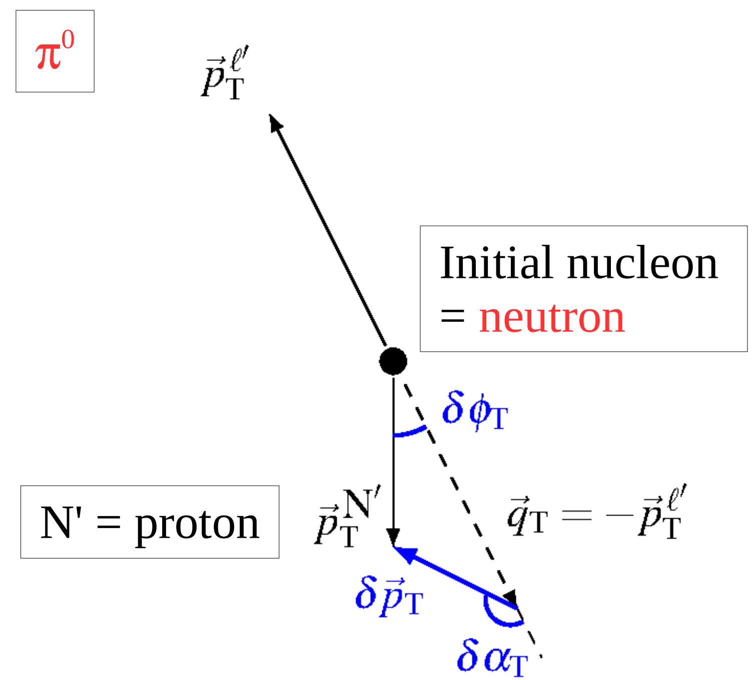
→ Neutron Fermi momentum is indeed observed
(260 phase-space cut exclusive events / 3263 pi+ beam events = 8.0%)

TKI + protoDUNE

– *Proton/Neutro initial-state kinematics*







- Proton Fermi motion observed
- 218 phase-space cut exclusive events / 3263 pi+ beam events = 6.7%

- Neutron Fermi motion observed
- 260 phase-space cut exclusive events / 3263 pi+ beam events = 8.0%

Summary and discussions

1. TKI + protoDUNE → argon intranuclear dynamics: Fermi motion + FSI
   - No need to know the beam particle momentum, just need direction
     - Because the beam momentum (right before interaction) can be measured, we can trade one final-state momentum magnitude as follows:
       - Compare the momentum resolution of the incoming and outgoing particles
       - For the one with the worst resolution, don't require its momentum magnitude, just measuring the direction is enough
     - This opens up other possibilities: neutron final-state, need direction only
   - Argon 18 protons, 22 neutrons: Fermi motion might be different
   - pπ0 channel is in fact charge exchange channel we've been talking about

2. Even though true variables used, doesn't seem to be true/theoretical shape due to reconstruction efficiency (cf. Final-state proton momentum spectra).
3. How many events do we expect in full data set?
4. How is proton and π0 reconstruction? Can be used?
5. Currently using tracking threshold to reject N-proton events. Need to optimize because non-trackable activities with much lower energy can also be rejected.

6. Would be very interesting to parallelize both measurements

   elastic pπ+ to probe proton in argon

   charge-exchange pπ0 to probe neutron in argon
7. More interesting to compare to (near-future) neutrino results on argon from, e.g. MicroBooNE.

BACKUP

END