Study of the ν_μ $1p0\pi$ Exclusive Channel at SBND

New Perspectives 2022
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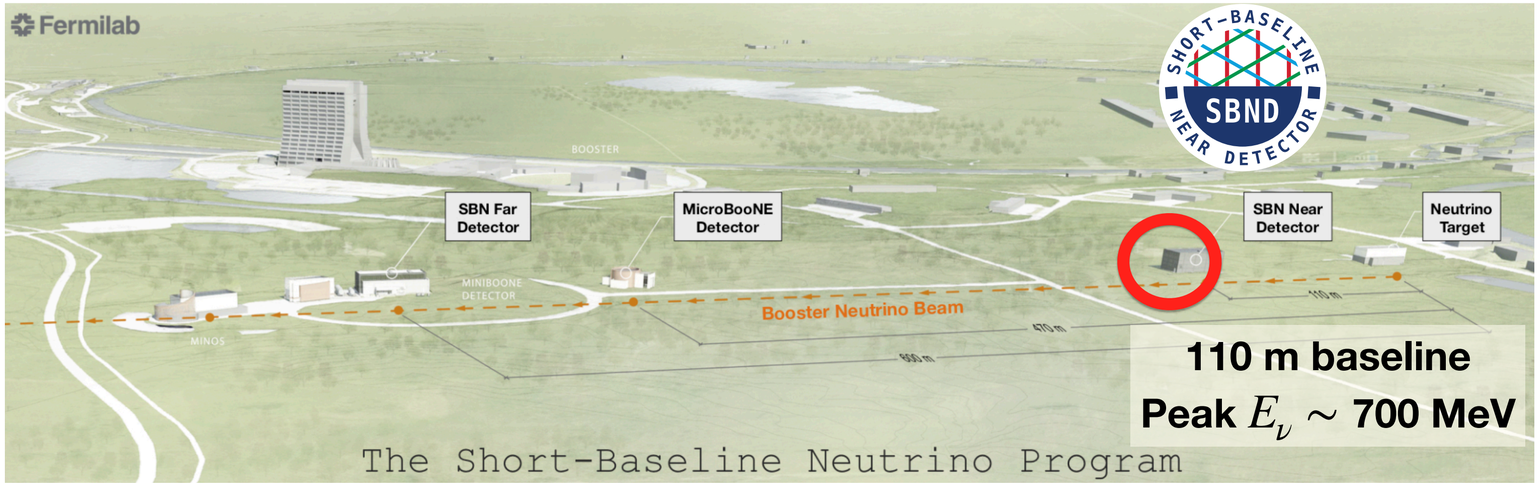
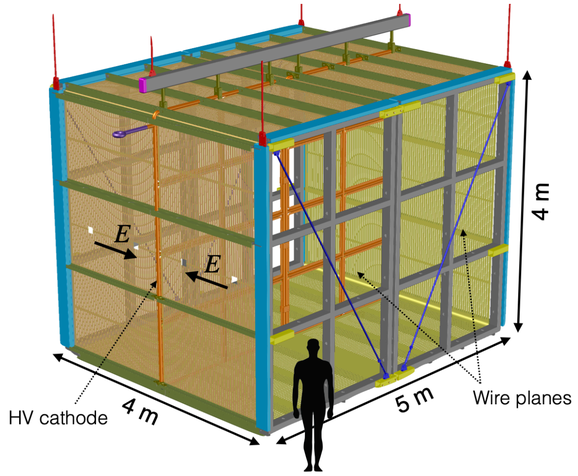
Mun Jung Jung, University of Chicago

Overview

- I will present a preliminary study with Monte Carlo simulated sample on the $1\mu 1p 0\pi$ **"QE-like" exclusive channel** at SBND
- The capabilities of the conventional and **new tools of reconstruction and selection** are shown
- The **energy reconstruction** for selected high purity sample is studied

The Short-Baseline Near Detector





- LArTPC near detector for SBN, search for sterile neutrinos
- Measure ν-nucleus cross section with many different channels
  - over 1 million neutrino events per year
  - reconstructs both leptons and hadrons
- Other BSM physics

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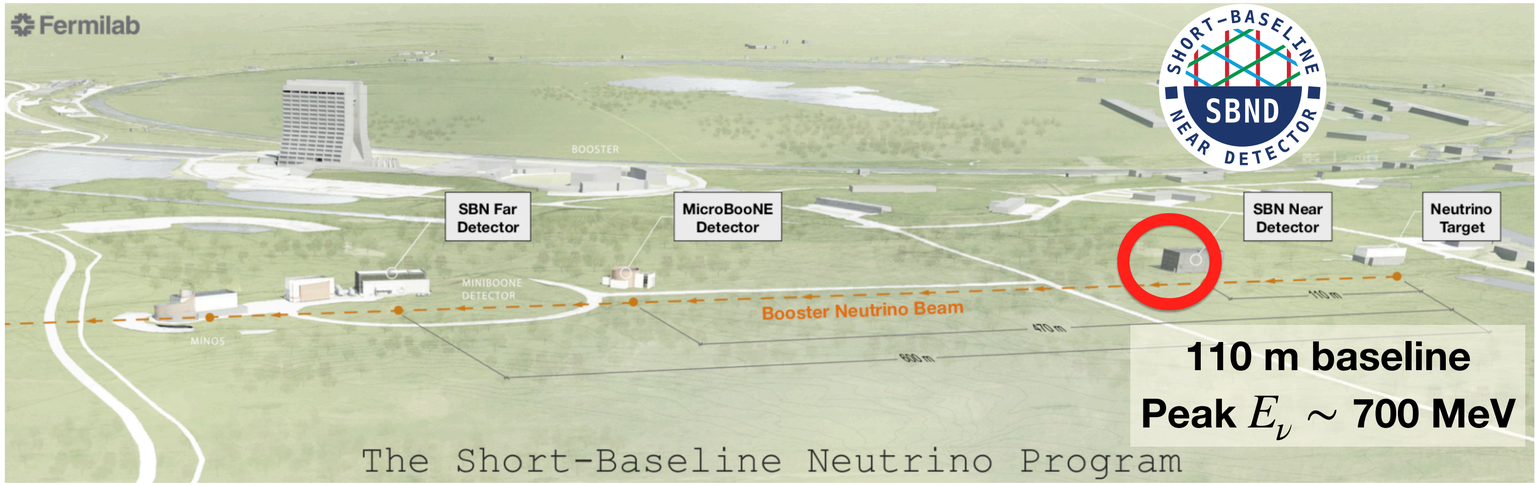

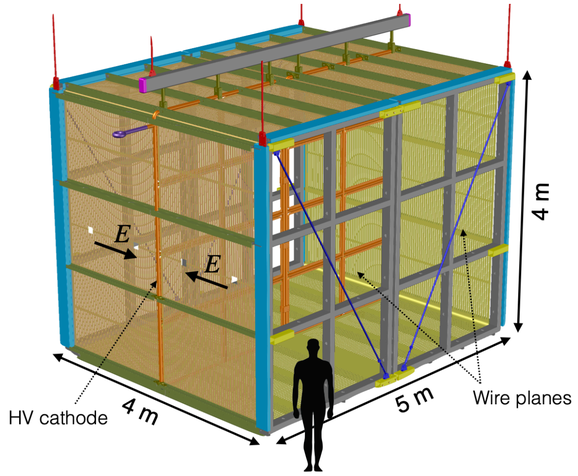

- LArTPC near detector for SBN, search for sterile neutrinos
- Measure ν-nucleus cross section with many different channels
  - over 1 million neutrino events per year
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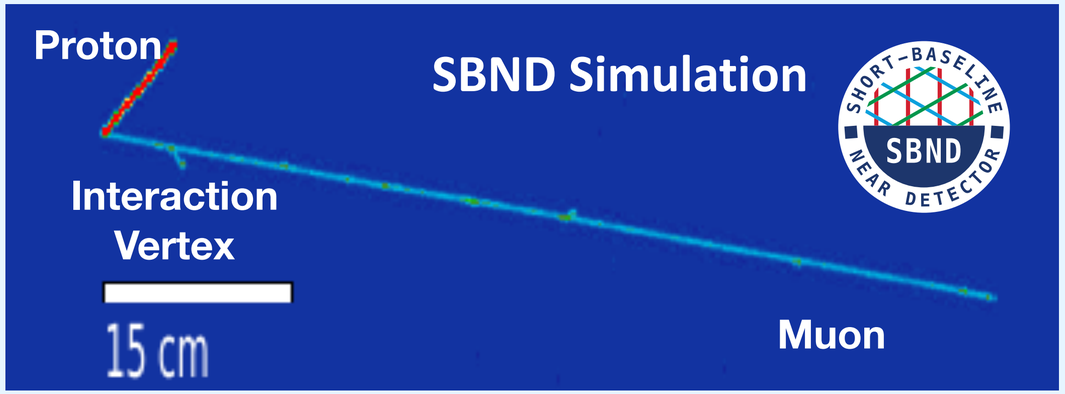
  → *Which channels are interesting?*
- Other BSM physics

$1p0\pi$ "Quasielastic-like" ("QE-like") Channel

$1p0\pi$ Event Display in SBND

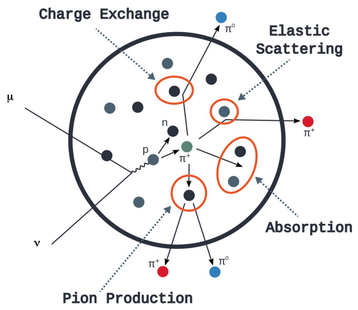


- **Interaction vertex** within the fiducial volume
- **1 muon track** with momentum > 100 MeV/c
- **1 contained proton track** with momentum > 100 MeV/c
- **0 charged pion tracks** with momentum > 70 MeV/c
- No other meson tracks, Any number of neutrons or gammas or electrons

Reconstruction

$\sim$

Nuclear effects



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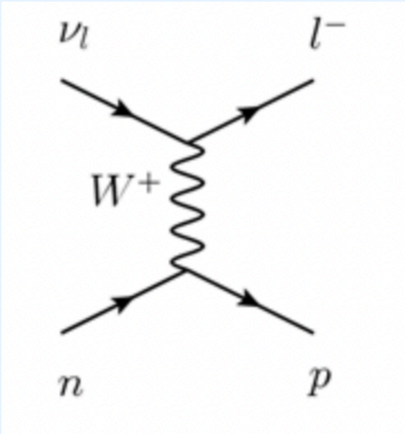
CCQE interaction



- Well understood interaction, interesting for ν-nucleus interaction studies
- Good energy resolution, desirable for oscillation searches

High purity → **High purity**

Event Selection for a High Purity QE-like sample

conventional

SBND MC → **Precut**
Select neutrino-like events from scores

Pandora ν score > 0.4
$\wedge$
Flash match score > 7

→ **Track PID**
Identify each tracks as a particle, choose $1p0\pi$

1 μ track
$\wedge$
1 p track
$\wedge$
0 π tracks

→ **Proton stub rejection**
Discard events with proton stubs

No proton stubs

→ **Momentum imbalance cut**
Require small momentum imbalance

$\delta p < 250\,MeV$

→ **SBND QE-like**

$1p0\pi$ purity	21%
$1p0\pi$ efficiency	97%
QE purity	34%

$1p0\pi$ purity	69%
$1p0\pi$ efficiency	35%
QE purity	69%

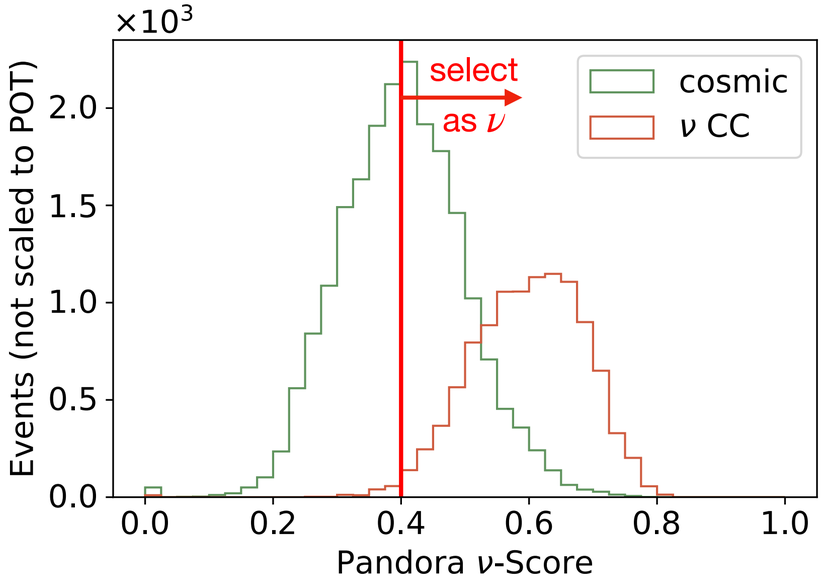
$1p0\pi$ purity	79%
$1p0\pi$ efficiency	27%
QE purity	75%

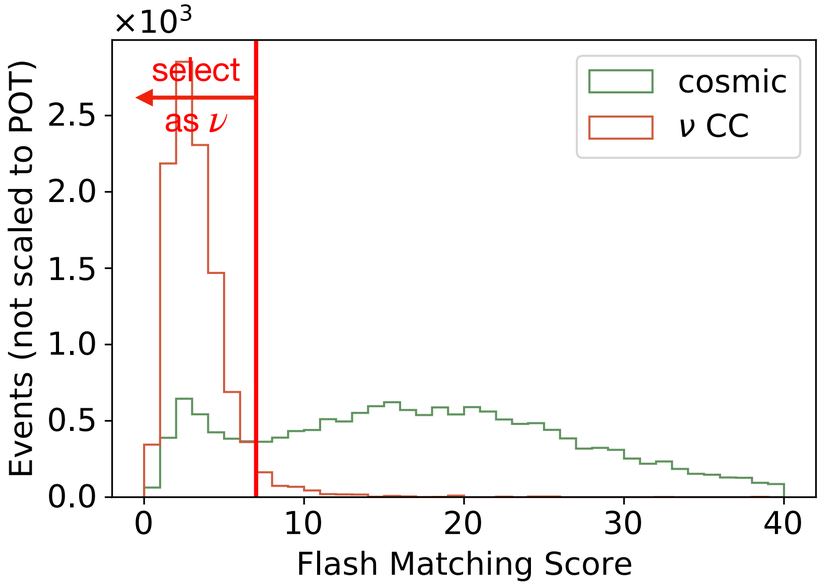
$1p0\pi$ purity	91%
$1p0\pi$ efficiency	16%
QE purity	91%

$$\text{QE purity} = \frac{N_{selected,\ QE}}{N_{selected}} \qquad 1\mu 1p \text{ purity} = \frac{N_{selected,\ 1p0pi}}{N_{selected}} \qquad 1\mu 1p \text{ efficiency} = \frac{N_{selected,\ 1p0pi}}{N_{1p0pi}}$$

Precut

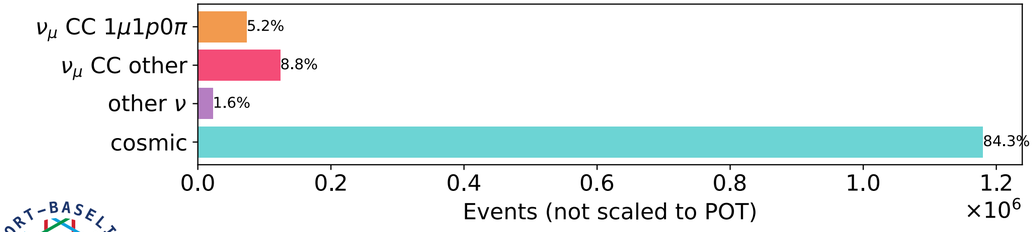
- Reject cosmic background and **select neutrino-like events** with score cuts





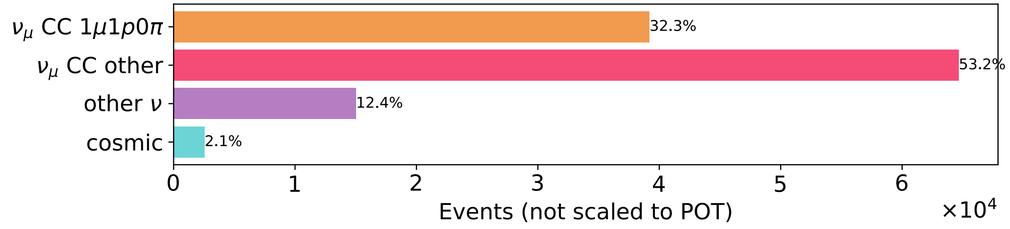
1. **Pandora ν score > 0.4**
   - Remove unambiguous cosmics
   - Neutrino candidate score
2. **Flash matching score < 7.0**
   - Match TPC to PDS

Before precut



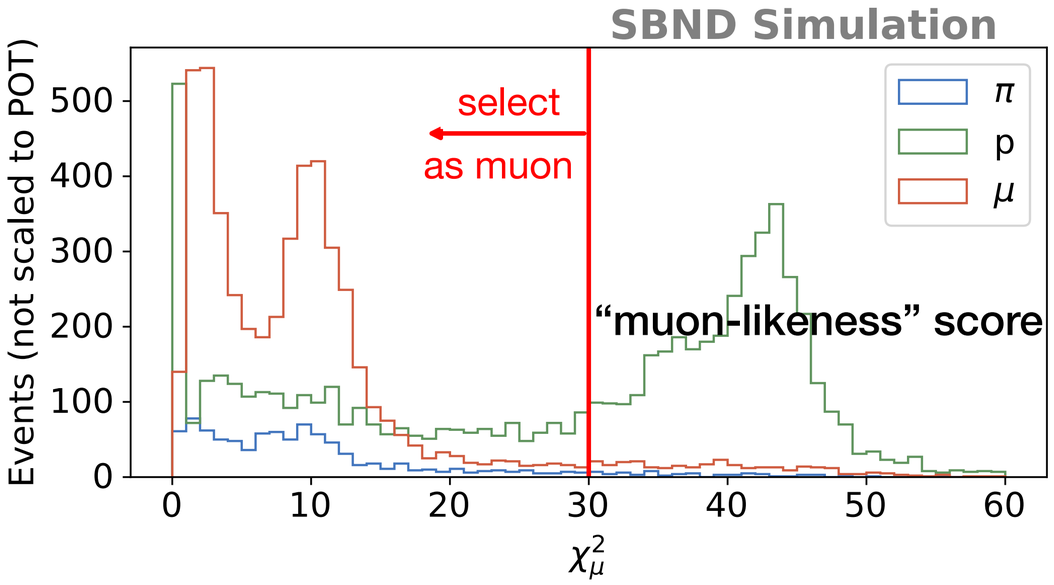
Rejects > 99% of cosmic events

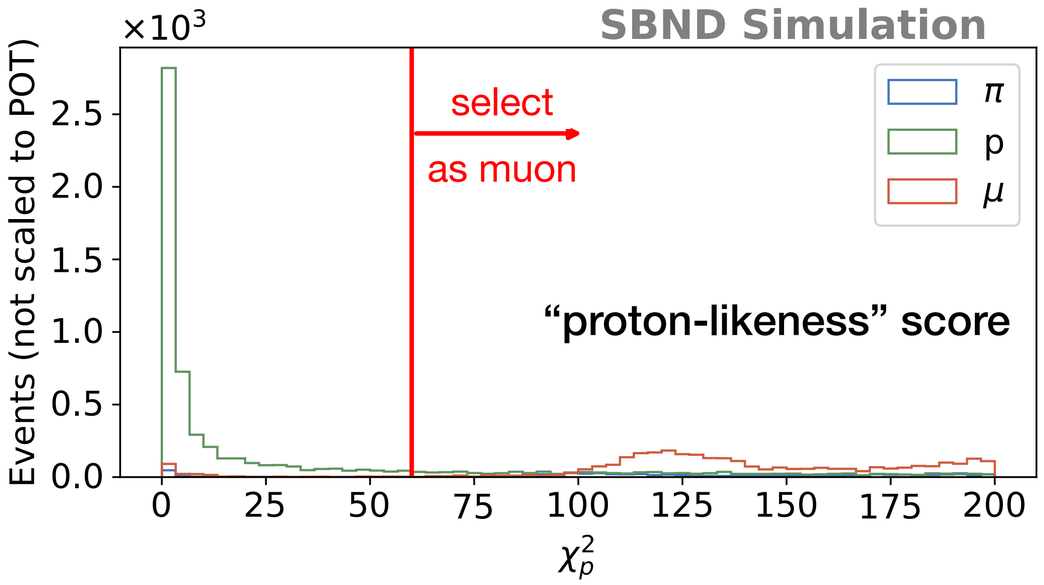
After precut



Track Particle Identification

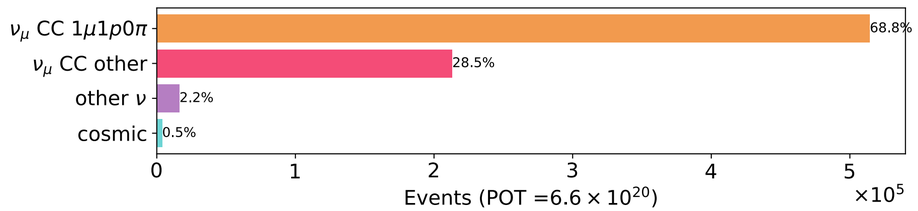
PID	Selection Criteria
μ	$(L_{track} > 50\,cm)$ & $(\chi^2_\mu < 30)$ & $(\chi^2_p > 60)$
p	$(\chi^2_p < 90)$

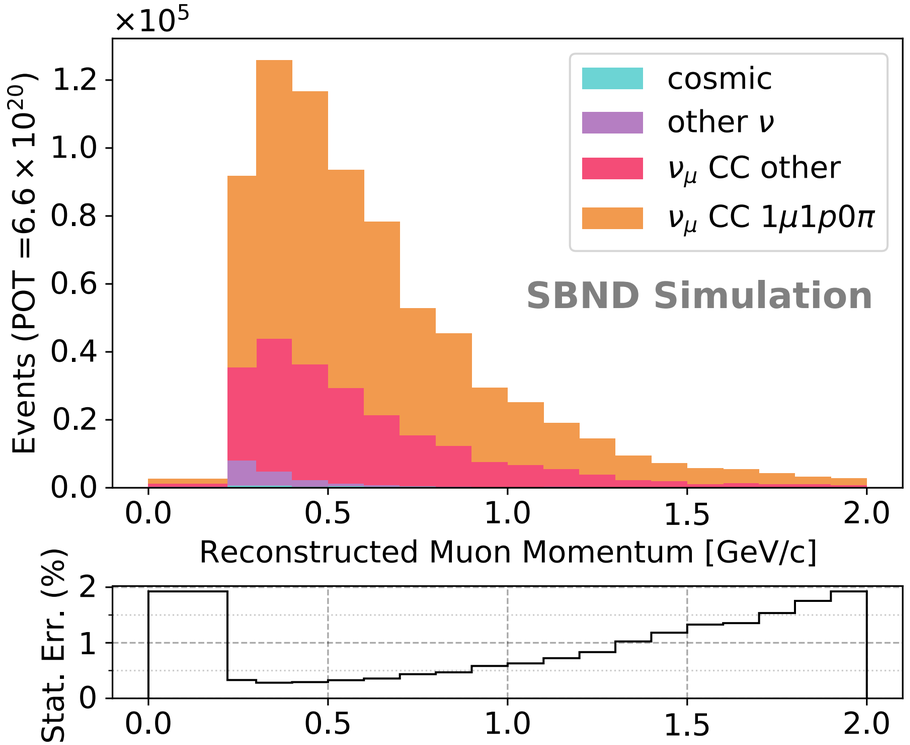


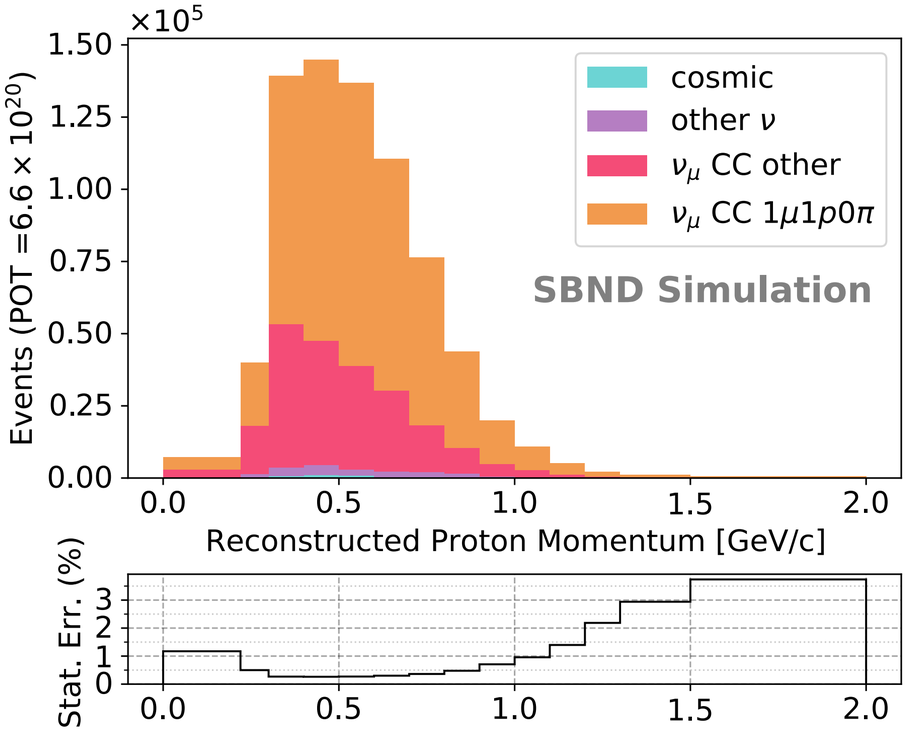


- Compare charge distribution to Bethe-Bloche formula to assign particle hypothesis scores to each reconstructed track, and identify particle types
- Choose events with 1 muon track, 1 proton track, and no other tracks

Selected $1p0\pi$ Channel

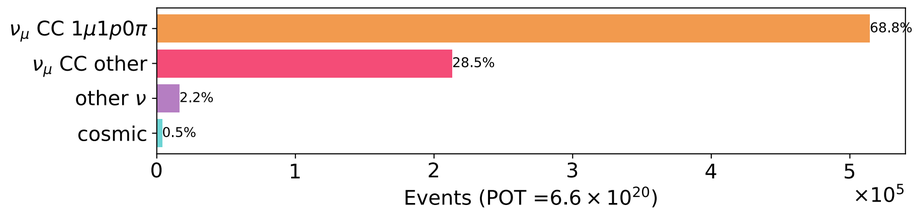


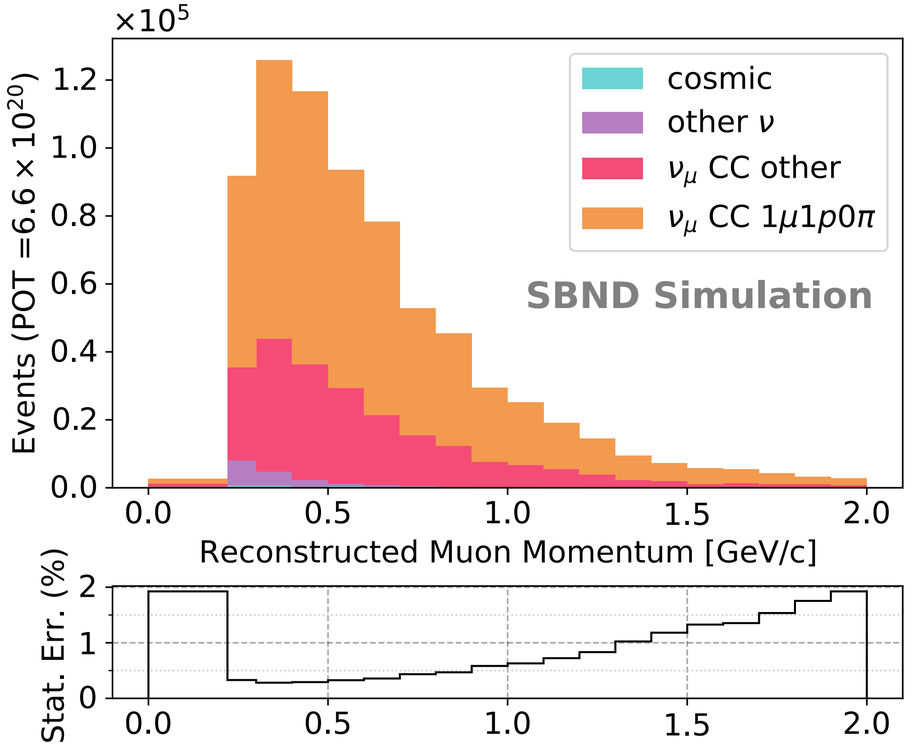


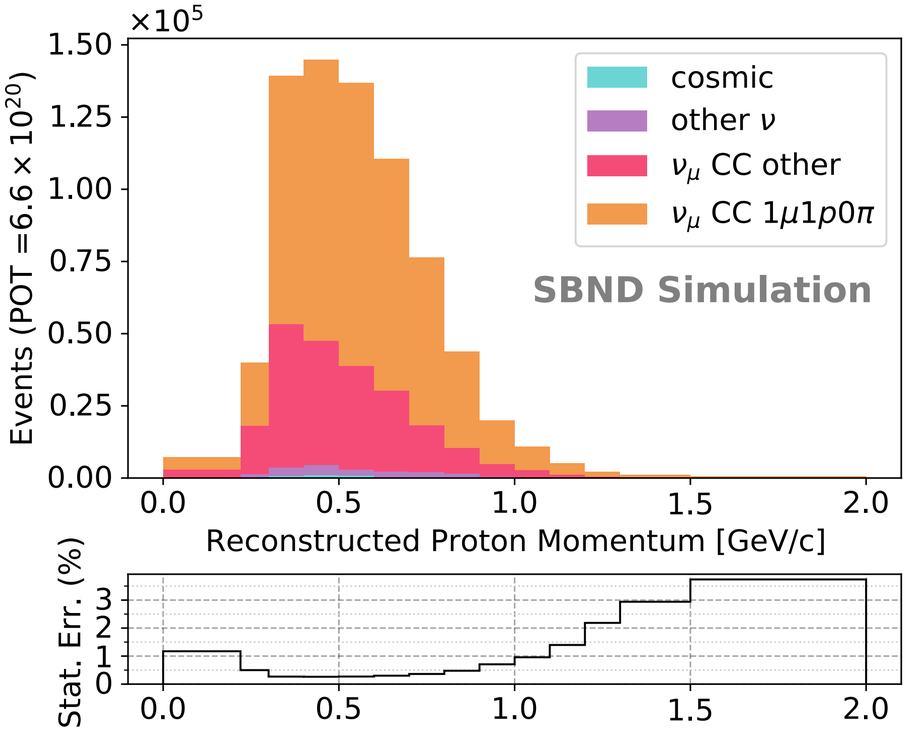


- Covers a wide range of kinematic phase space with high statistics
- Short proton tracks are missed by reconstruction, resulting in a large Np background and low $1p0\pi$ purity of 69%

Selected $1p0\pi$ Channel







- Covers a wide range of kinematic phase space with high statistics
- Short proton tracks are missed by reconstruction, resulting in a large Np background and low $1p0\pi$ purity of 69% → ***How to improve?***

Proton stubs

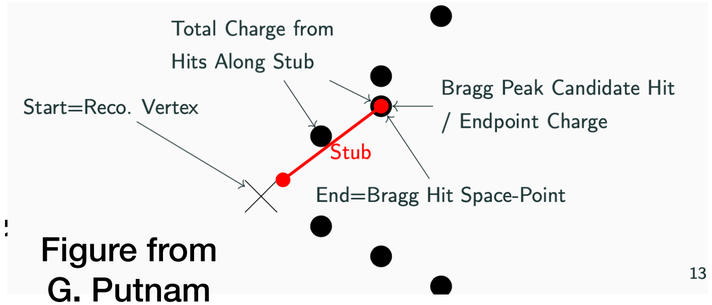
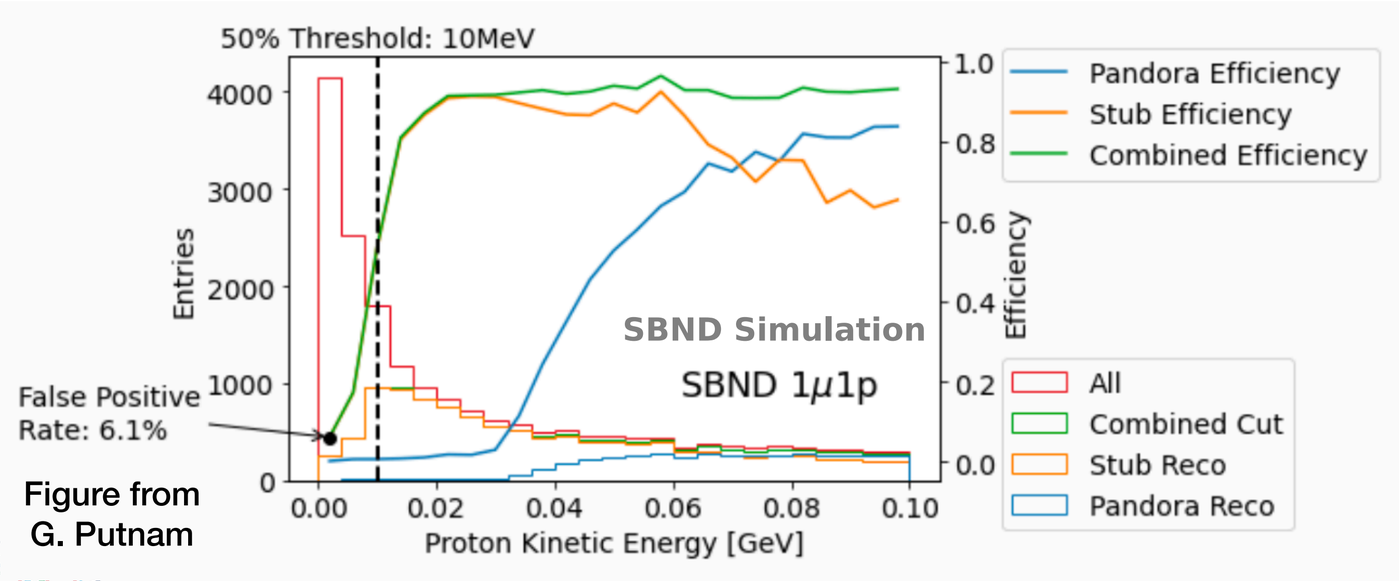


Figure from G. Putnam

- Finds **large charge depositions near vertex**, the "stubs"
- **Identify short proton tracks** missed by Pandora, pushes down proton threshold to ~10 MeV
  - Can be used to *reject* multiple-proton events (as done here)
  - Or *better reconstruct the proton multiplicity*



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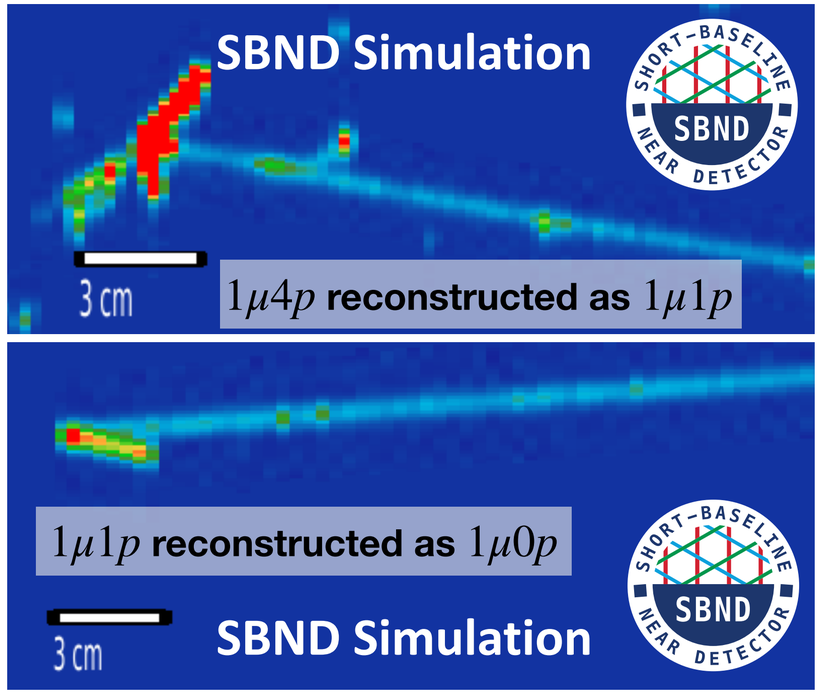

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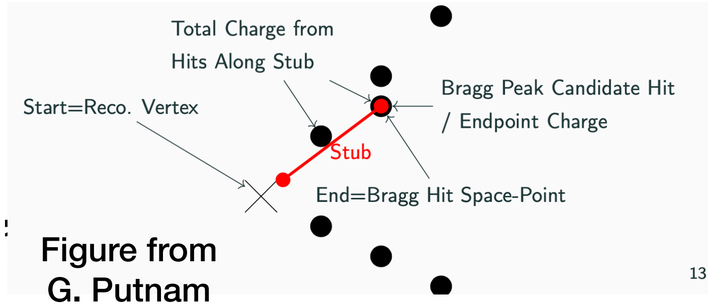

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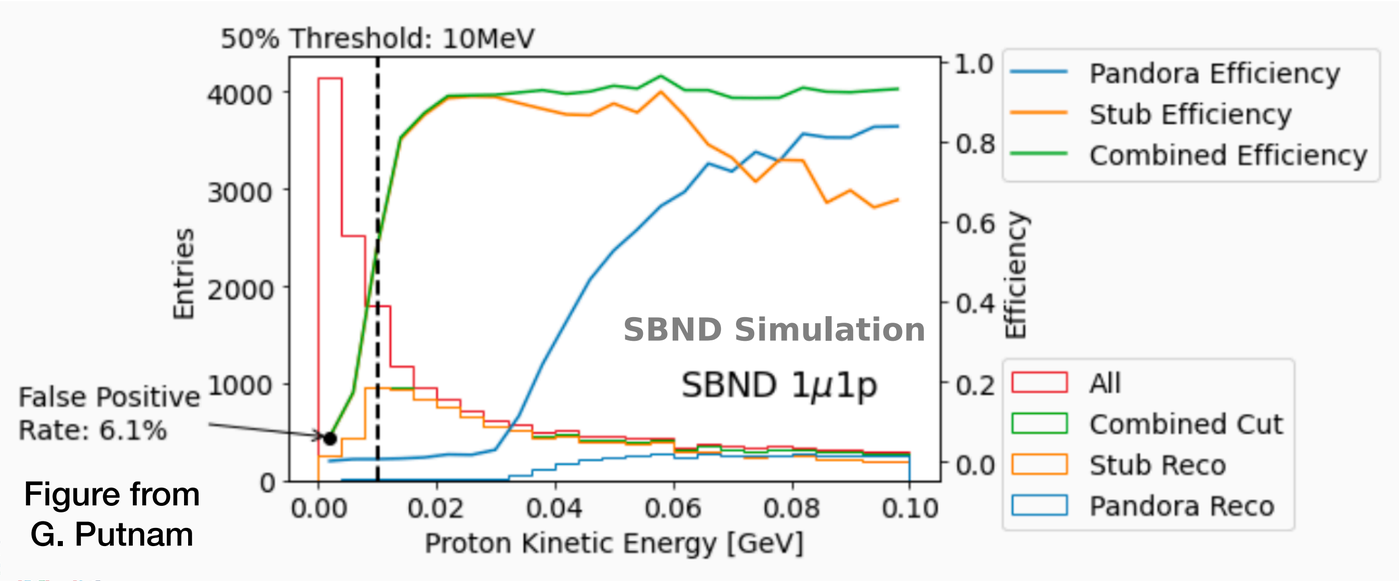
- Finds **large charge depositions near vertex**, the "stubs"
- **Identify short proton tracks** missed by Pandora, pushes down proton threshold to ~10 MeV
  - Can be used to *reject* multiple-proton events (as done here) → Reject events with any number of stubs!
  - Or *better reconstruct the proton multiplicity*



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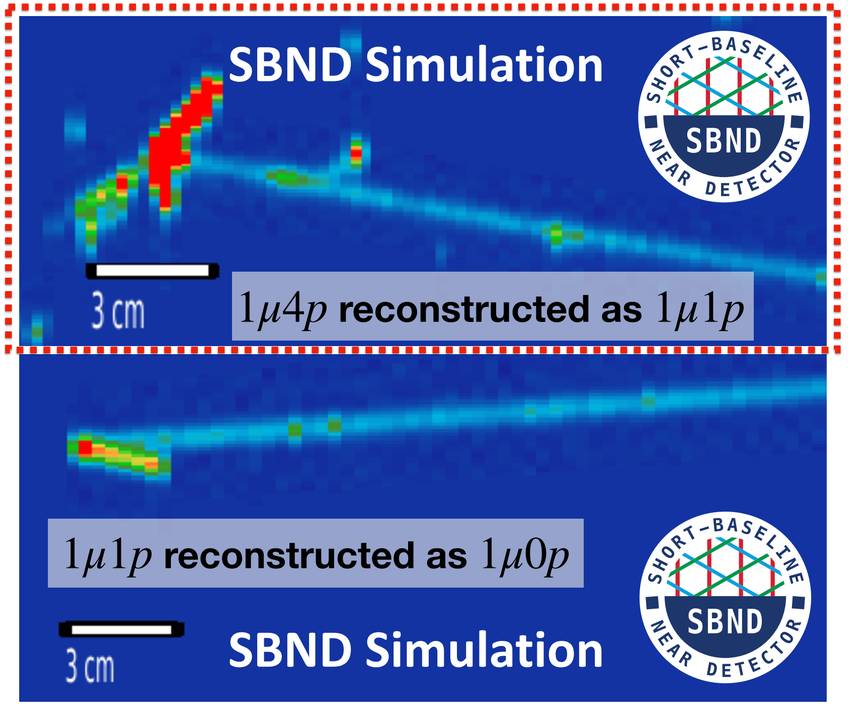
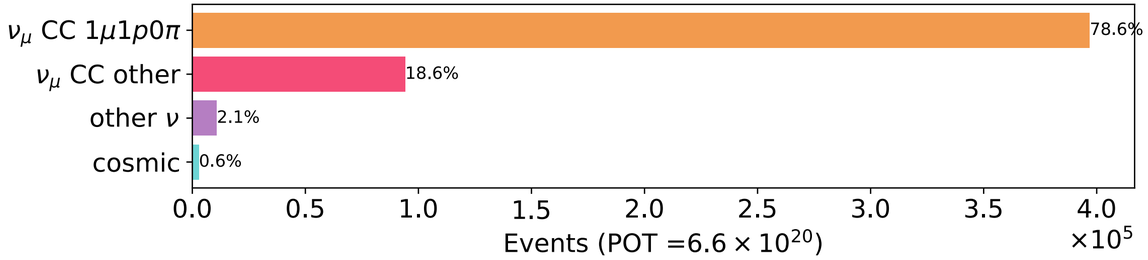
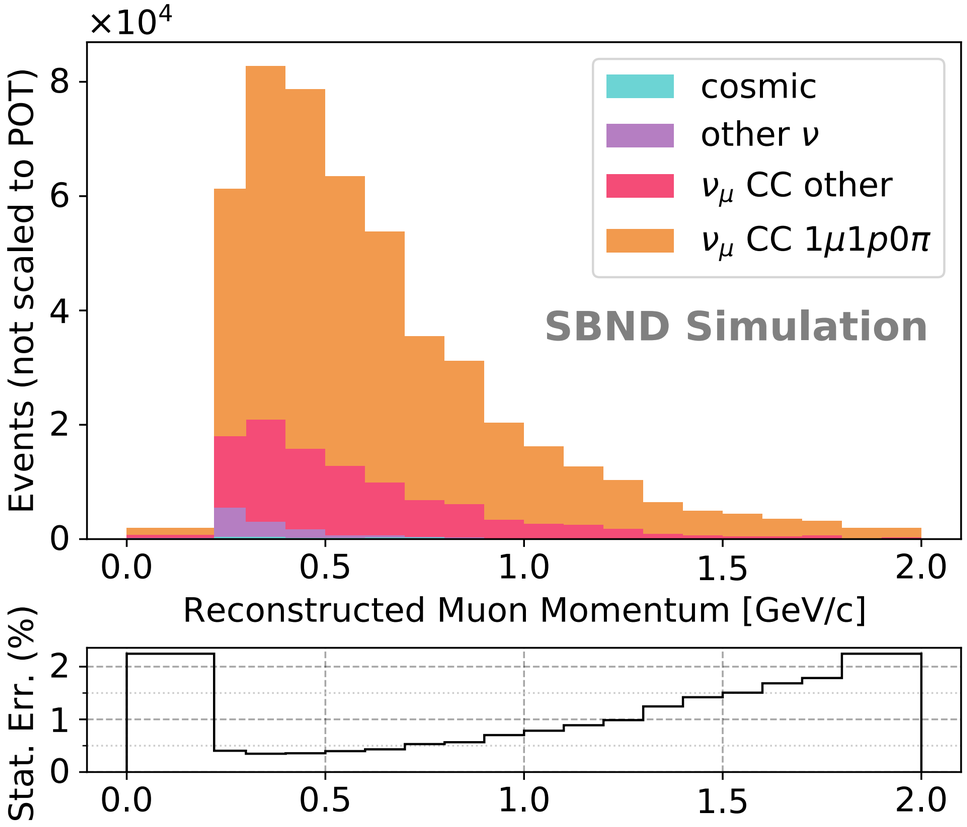
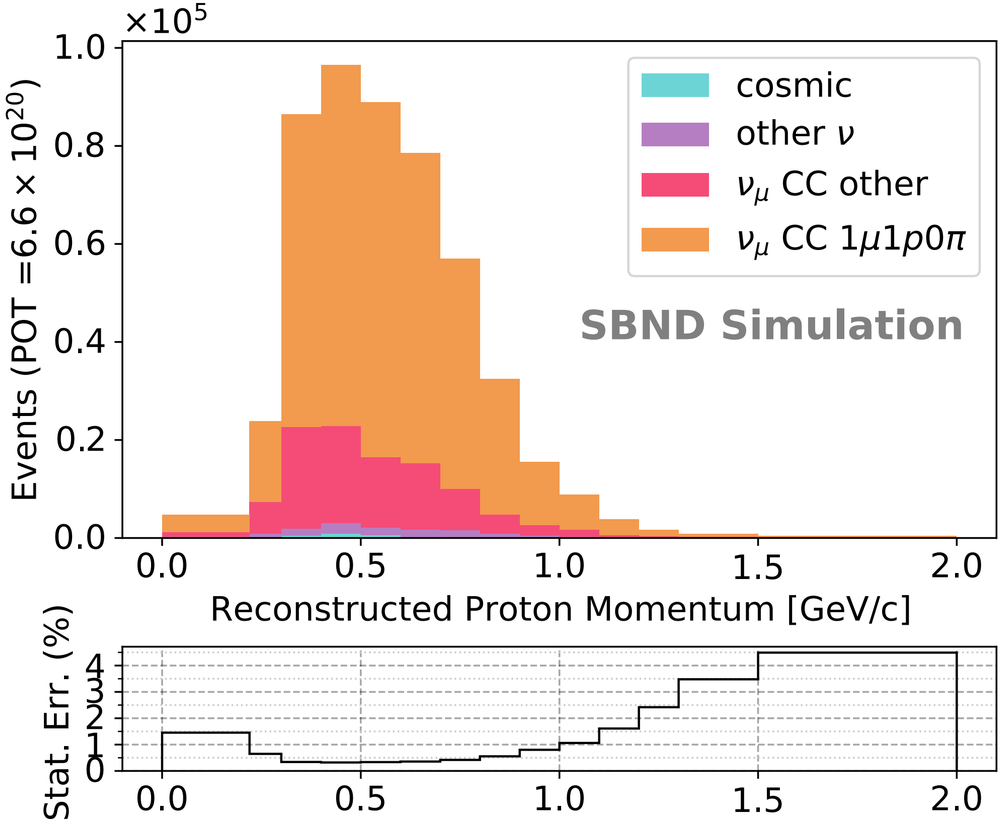


Get rid of these

Proton stubs cut



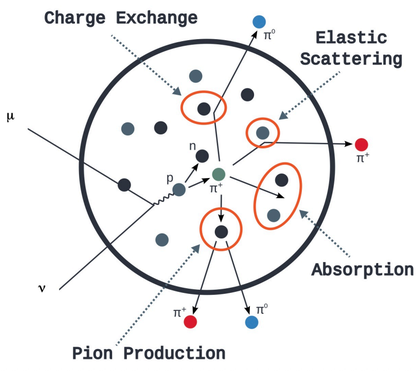




- Proton stub cut reduces Np background, increases $1p0\pi$ purity to 79%

Momentum Imbalance

- Kinematics on the plane transverse to neutrino direction are independent of the neutrino energy
  - Instead sensitive to nuclear effects such as Fermi motion, FSI, BE
  - Studied to understand cross section systematics
- With QE, IA, can calculate the longitudinal momentum imbalance



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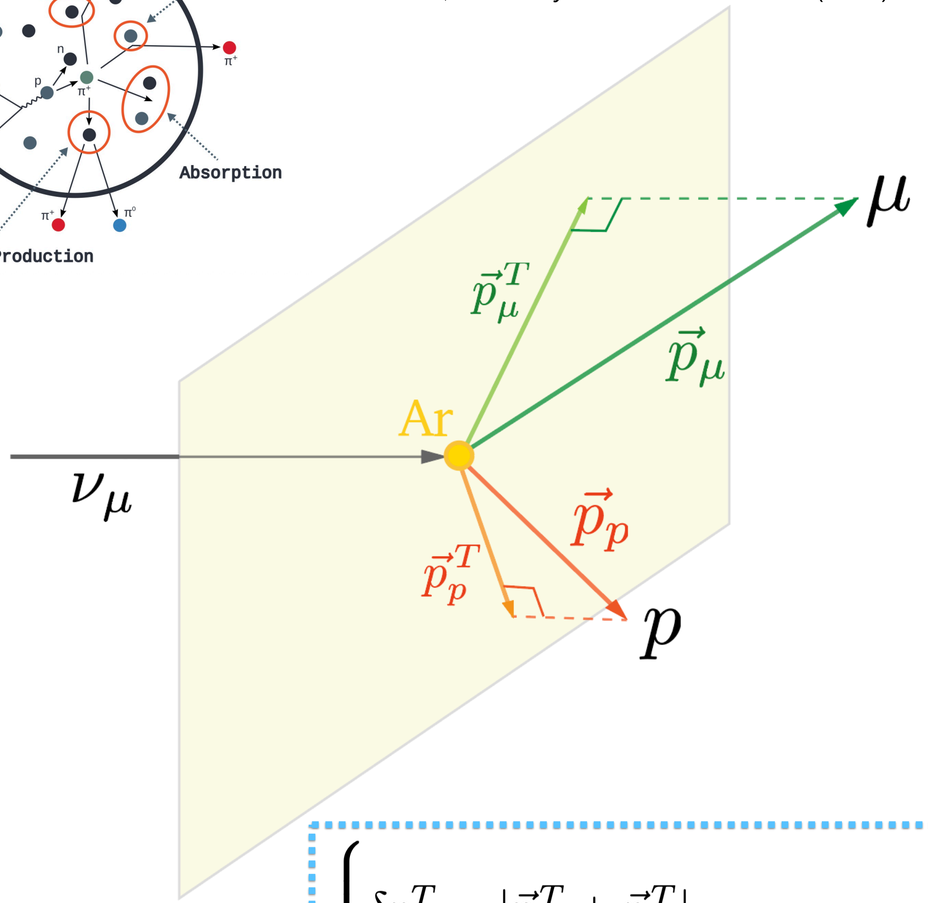


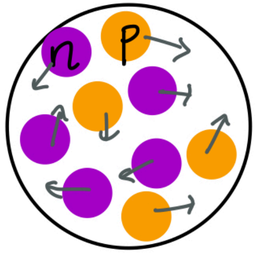
$$E_\nu + M_A = E_\mu + E_p + E_{A-1}$$
$$p_\nu = p_\mu^L + p_p^L - p^L$$
$$0 = \vec{p}_\mu^{\,T} + \vec{p}_p^{\,T} - \vec{p}^{\,T}$$

$$\begin{cases} \delta p^T = |\vec{p}_\mu^T + \vec{p}_p^T| \\ \delta p^L = \frac{1}{2}R - \frac{m_{A'}^2 + (\delta p^T)^2}{2R} \end{cases}$$
$$R = m_A + p_L^\mu + p_L^p - E^\mu - E^p$$

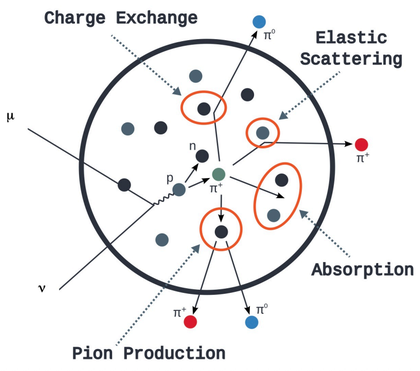
Momentum Imbalance

- Kinematics on the plane transverse to neutrino direction are independent of the neutrino energy
  - Instead sensitive to nuclear effects such as Fermi motion, ~~FSI, BE~~
  - Studied to understand cross section systematics
- With QE, IA, can calculate the longitudinal momentum imbalance

$$\delta p = \sqrt{(\delta p^T)^2 + (\delta p^L)^2} = p_n$$



Total momentum imbalance can be thought of as the initial nucleon momentum



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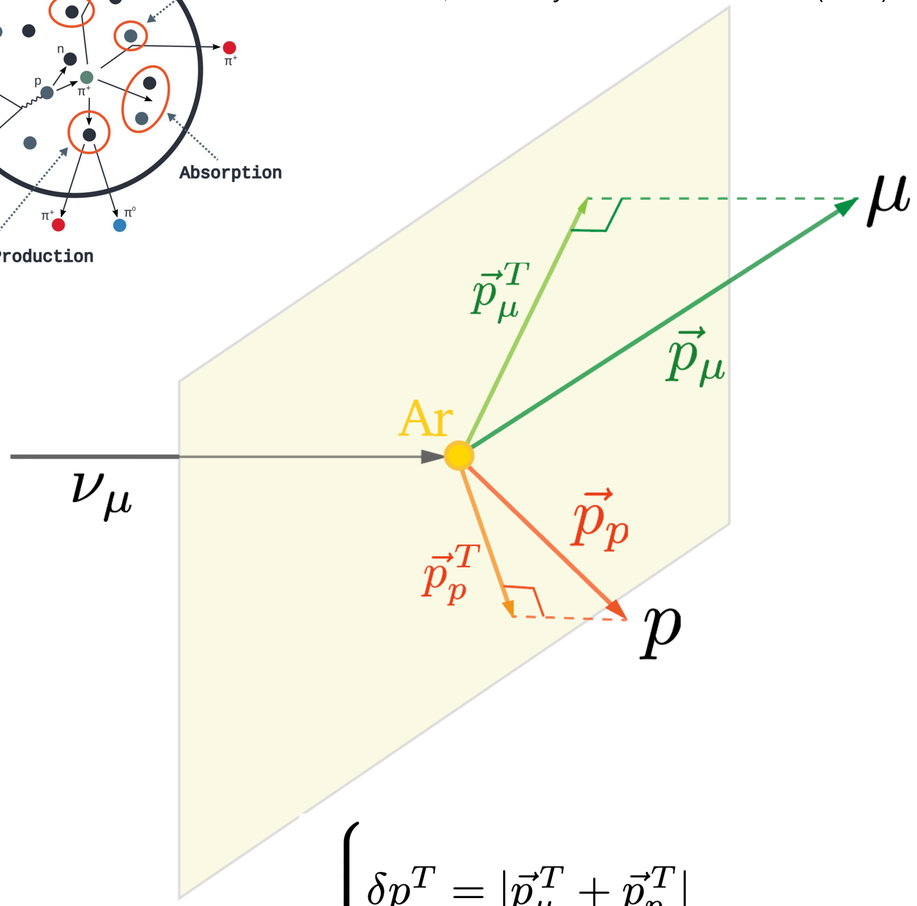

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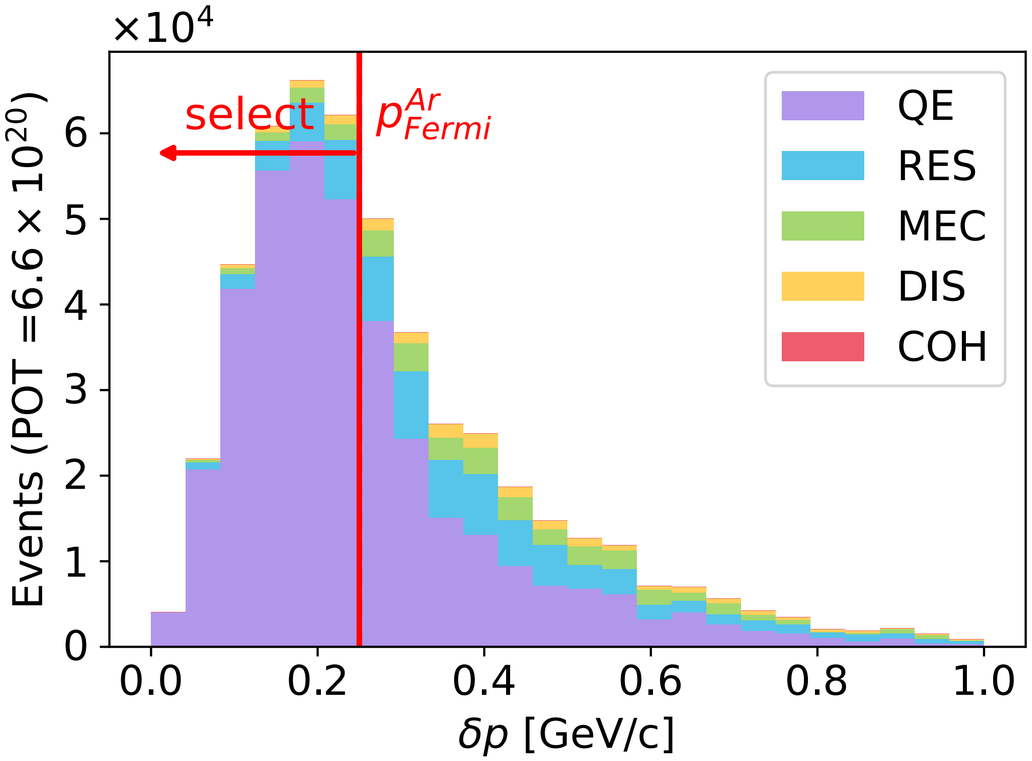
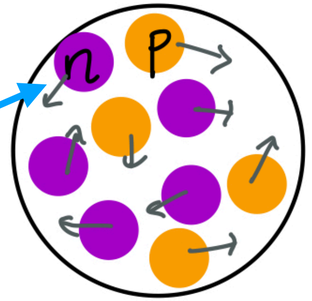
$$R = m_A + p_L^\mu + p_L^p - E^\mu - E^p$$

Momentum Imbalance Cut

- Argon Fermi momentum ~ 250 MeV
- **Momentum imbalance larger than this implies missing energy** due to background interactions or nuclear effects
- Rejecting these events to increase the QE purity



These fermi momentum of the struck nucleon should be the only source of momentum imbalance in a simplified picture



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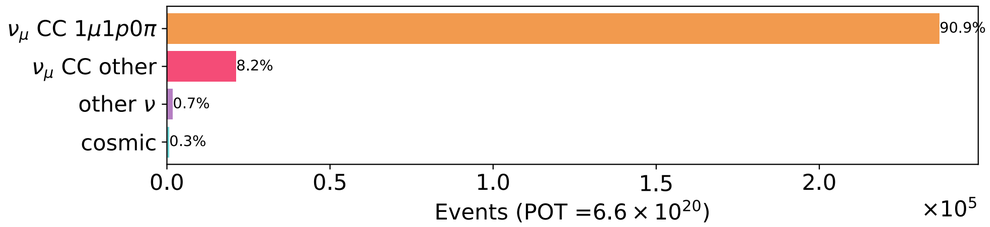
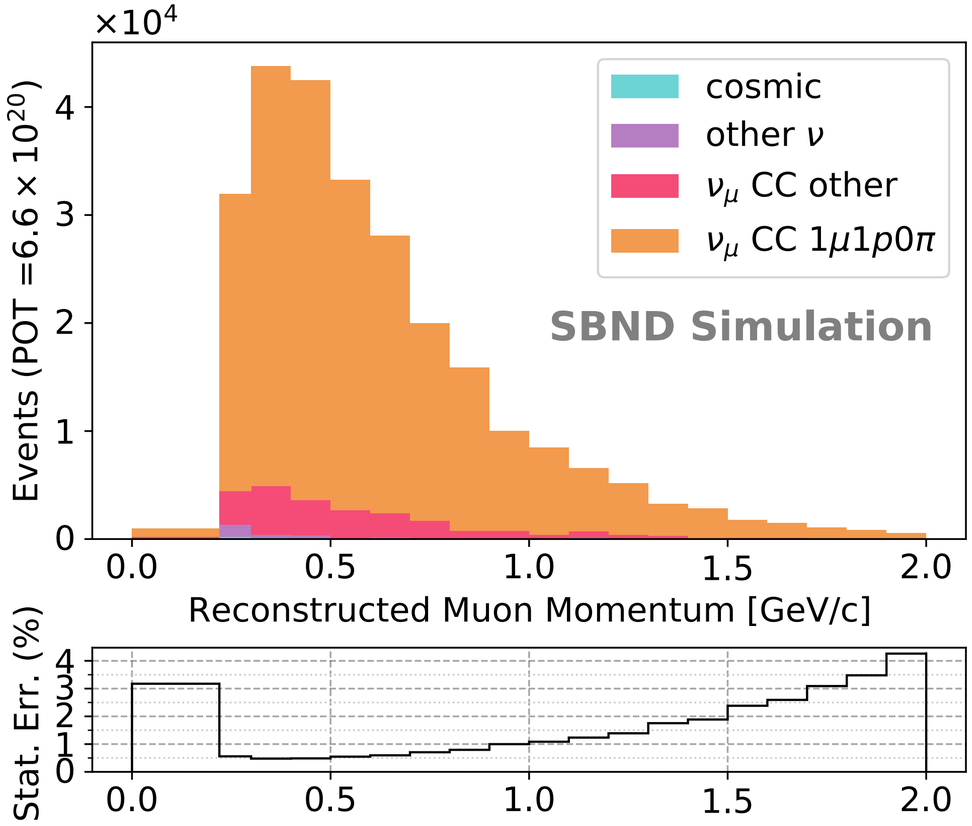
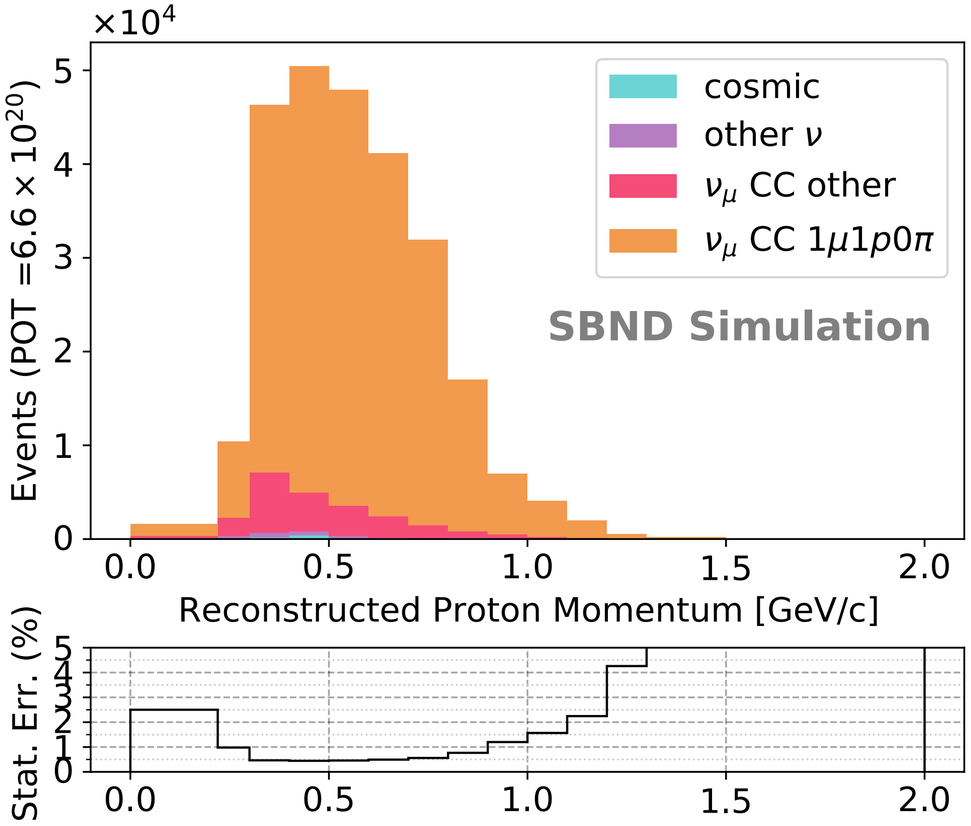
Momentum Imbalance Cut

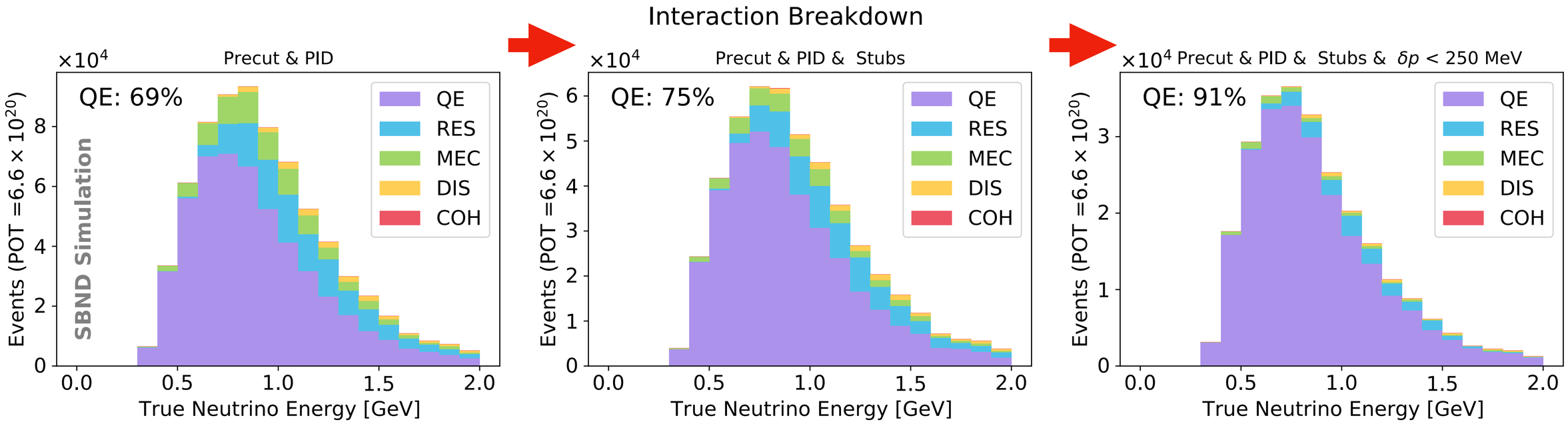






- Decreases neutral current background significantly
- **Final $1p0\pi$ purity 91%, efficiency 16%, mostly good statistics**

QE purity



- Final selected sample has high QE purity of 91%, **"QE-like"**
- This is at the cost of efficiency, but **SBND statistics can afford this**
- Remaining backgrounds are mainly due to low energy/neutral particles escaping detection

Energy reconstruction

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Calorimetric Reco

- Add all visible energy (of μ and p here)
- Model independent, but sensitive to missing energy

$$E_\nu = E_\mu + T_p + E_B + E_T$$

E_μ : reconstructed muon energy
T_p : proton kinetic energy
E_B: separation energy
E_T: transverse recoil energy

Kinematic Reco

- Assume: QE, IA, nucleon at rest
- Model dependent, use only μ

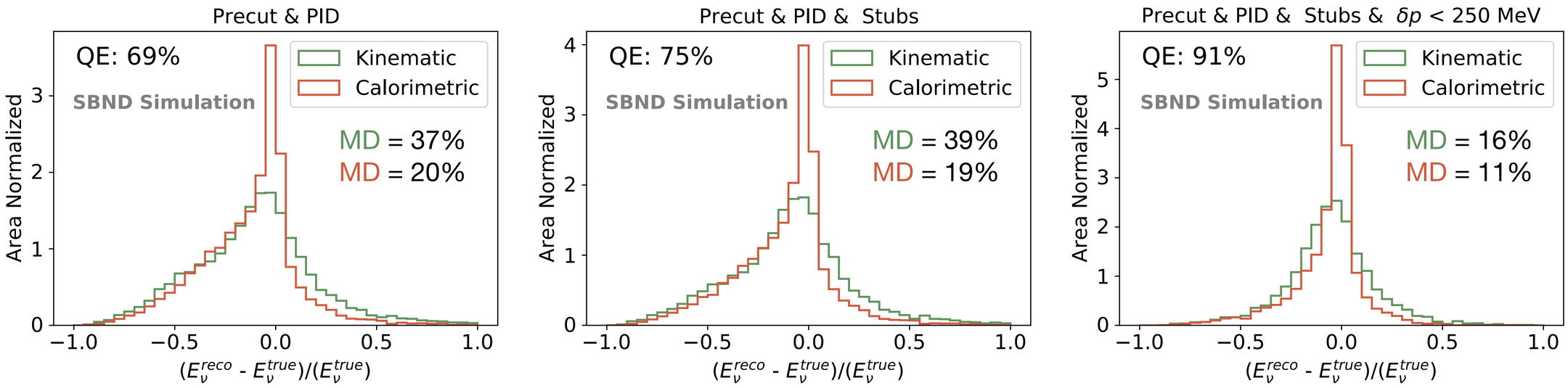
$$E_\nu = \frac{2(M_n - E_B)E_\mu - [(M_n - E_B)^2 + m_\mu^2 - M_p^2]}{2[M_n - E_B - E_\mu + p_\mu cos(\theta_\mu)]}$$

M_n: neutron mass
M_p: proton mass
E_B: separation energy
m_μ: muon mass
E_μ: muon energy
θ_μ: muon angle

Energy reconstruction

$$\text{Mean Deviation} = \frac{\sum_{i=1}^{N_{bins}} |(E_{\nu,i}^{reco} - E_{\nu,i}^{true})/(E_{\nu,i}^{true})|}{N_{bins}}$$

All Muons



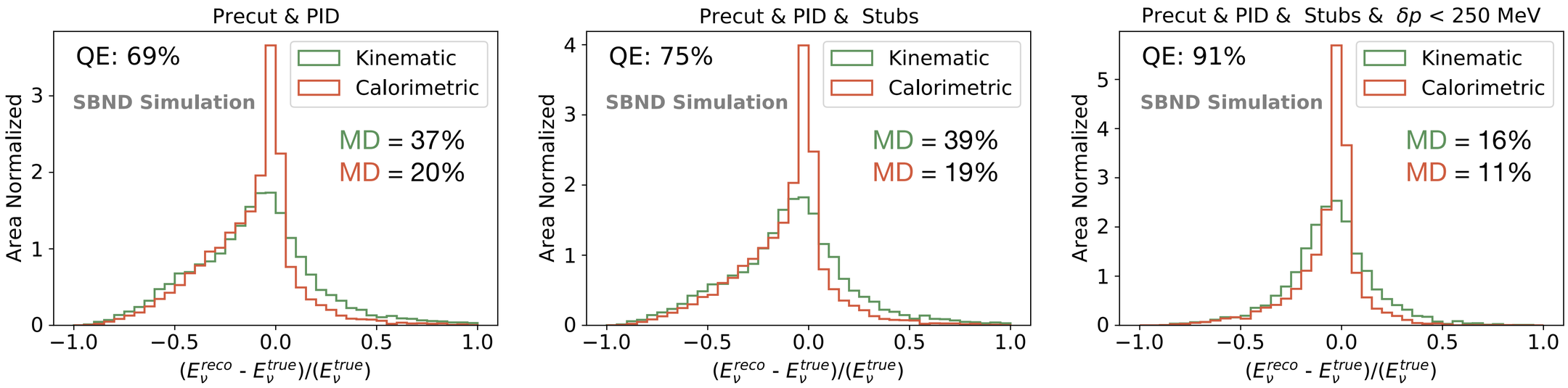
Better energy reconstruction

- Energy reconstruction improves with the increase of QE purity
- Calorimetric method has better neutrino energy resolution here
- Track momentum resolution directly effects neutrino energy resolution
  - Contained tracks have better momentum resolution (range calculation)

Energy reconstruction

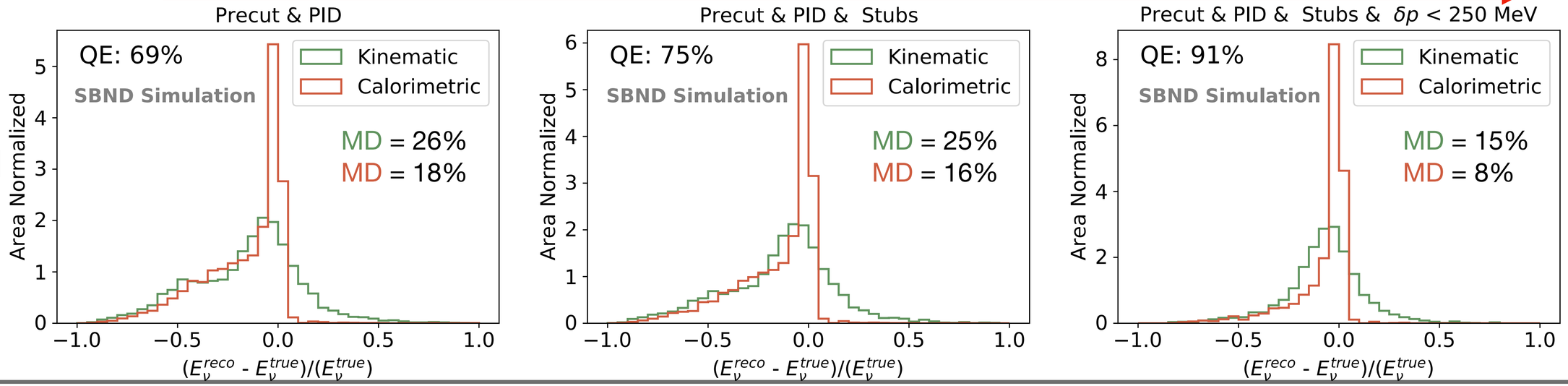
$$\text{Mean Deviation} = \frac{\sum_{i=1}^{N_{bins}} |(E_{\nu,i}^{reco} - E_{\nu,i}^{true})/(E_{\nu,i}^{true})|}{N_{bins}}$$

All Muons



Better energy reconstruction

Contained Muons



Outlook

- SBND will allow us to study **exclusive channels with high statistics**
- The $1\mu 1p 0\pi$ **channel** is an interesting one to study
  - We can get **high QE interaction purity** sample and **good neutrino energy estimation**
  - Good channel for oscillation studies and cross section studies
- Room for optimization of selection for better purity or efficiency
- **Many interesting directions to go from here!**