Tens of MeV ν_e-Ar CC Events and Energy Resolution in FD3 APEX

APEX Biweekly WGM
Jul 25, 2024

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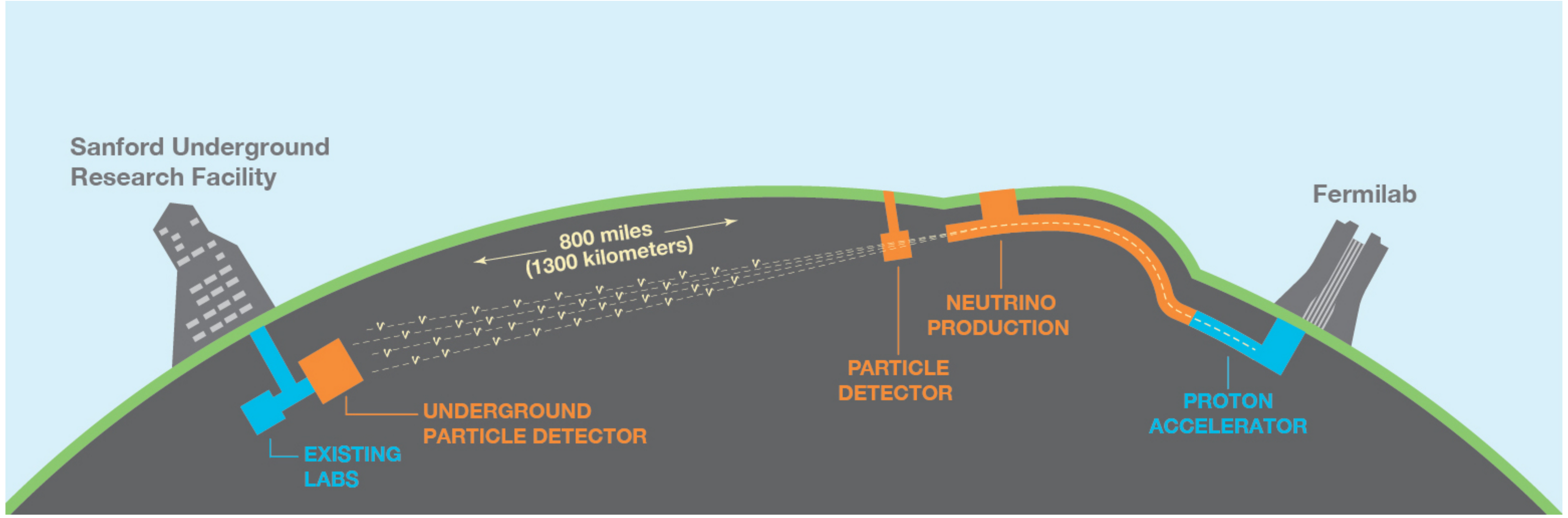
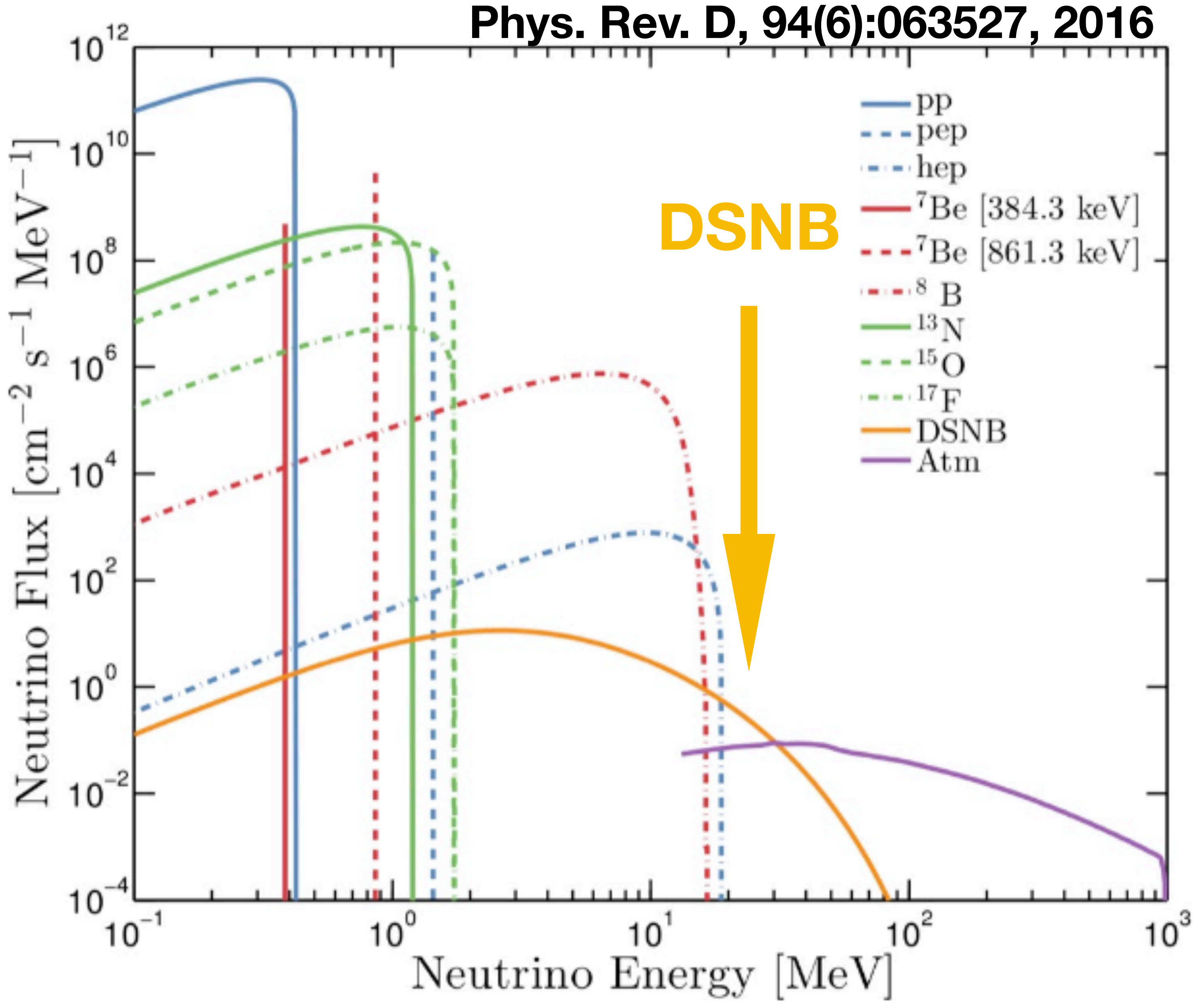


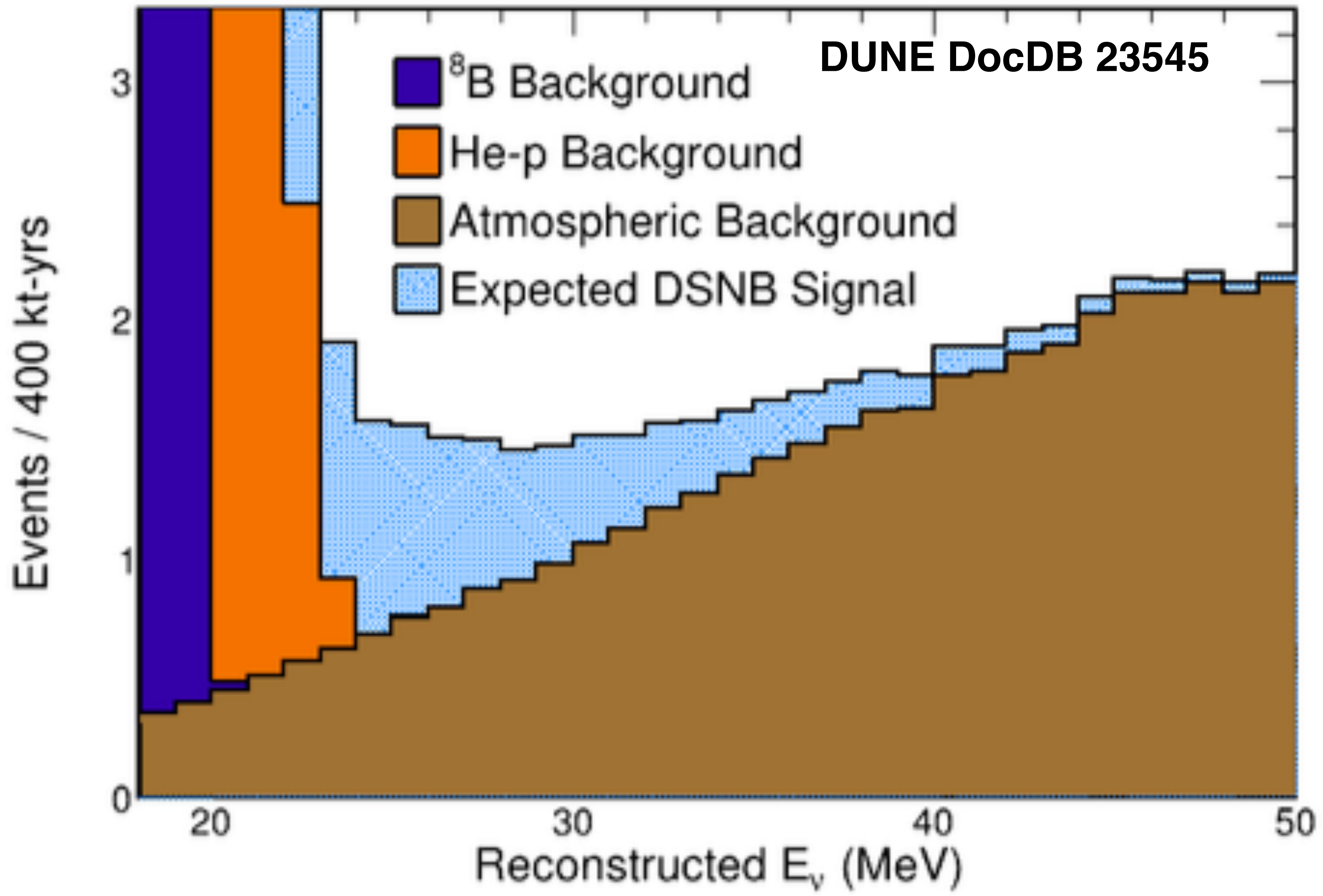
Motivation

- Diffused Supernova Neutrino Background (DSNB)
  - Neutrino fluxes from all core-collapse supernovae in the observable universe that arrive at Earth

- A potential major discovery channel for DUNE Phase II program
  - DUNE uniquely constrains ν_e via ν_e-Ar CC (<1 event/yr)
    - ν_e-e ES xsec 3 orders of magnitude smaller and energy resolution is poor due to unknown scattering angle
  - Challenging: ~2.2σ evidence of excess with an expectation of 6 DSNB events at 400 kt-yrs using Phase I FD and reconstruction (σ_E/E: ~8%)
    - If Phase 2 is same E res, we are talking year 2040!

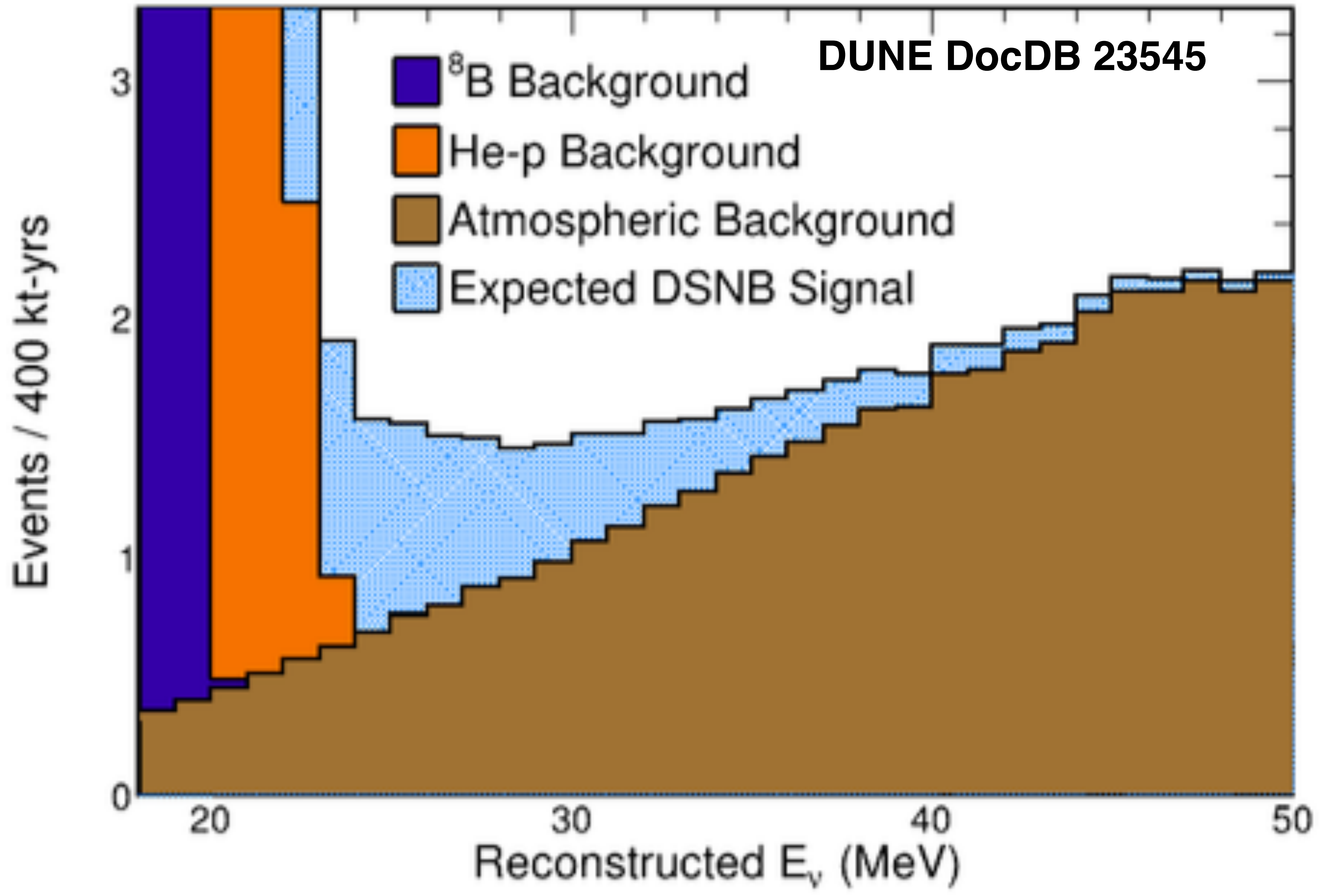
- JUNO and Hyper-K have better sensitivity to the $\bar{\nu}_e$ component via IBD
  - JUNO claims 3σ (>5σ) in 3 (10) years (JCAP 10 (2022) 033)



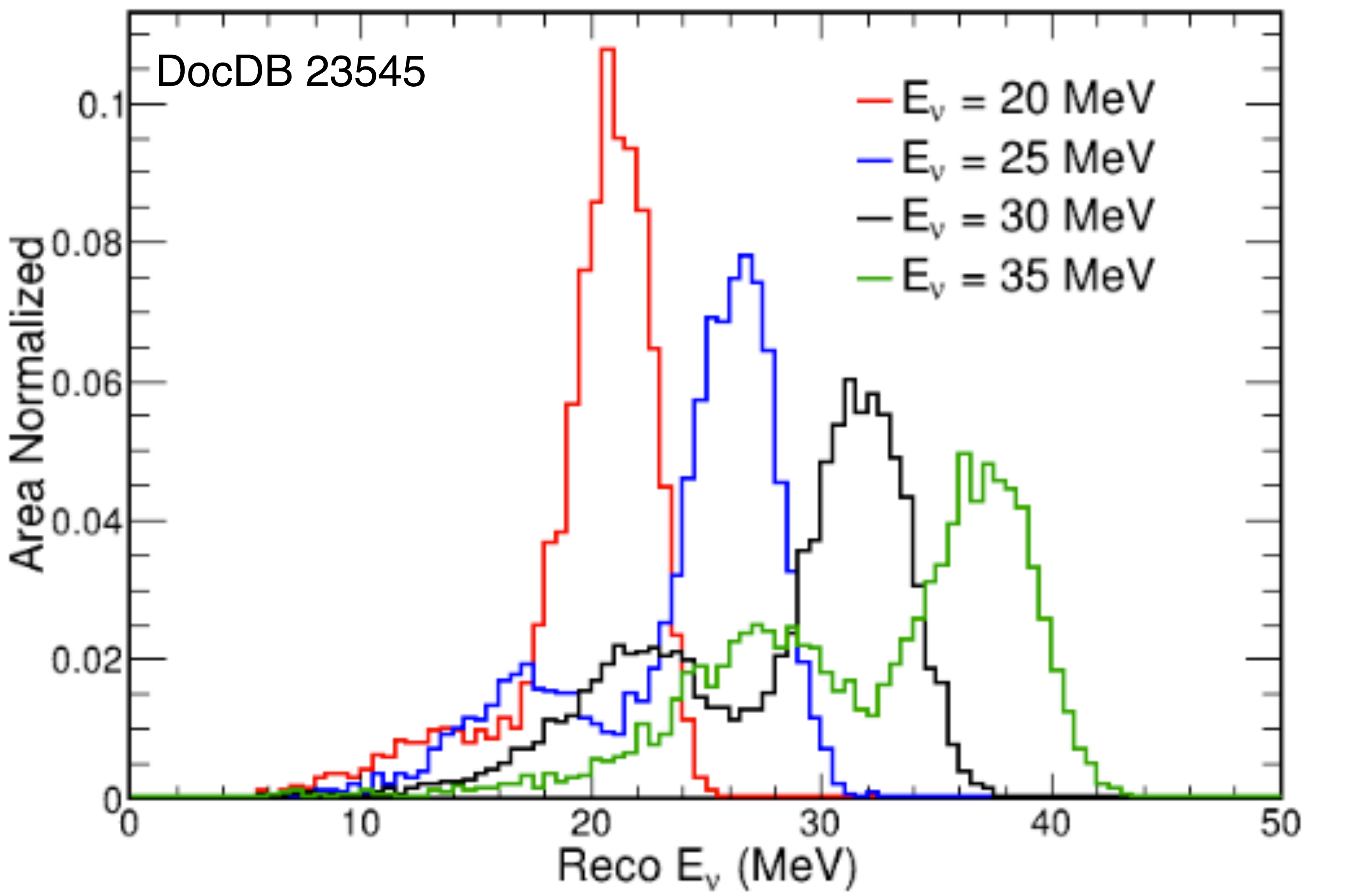


Motivation

- Previous studies by D. Pershey at reconstruction level (DocDB 23545)
  - Huge feed down in Phase I FD reconstruction
  - Many visible charge are lost, especially at higher energy
    - *A large lost fraction from clustering completeness in reconstruction*
    - *Invisible energy like neutron emission*
- Excellent energy resolution (<8%) at 10s of MeV will increase DSNB discovery potential
  - Resolve DSNB signal and three main backgrounds
  - Also helps other low energy physics programs (more at Dan's talk at May CM)



Full reconstruction at SinglePhase



Simulation $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

- Marley + edep-sim: mono-E from 5 MeV to 50 MeV, 1k events per 5 MeV

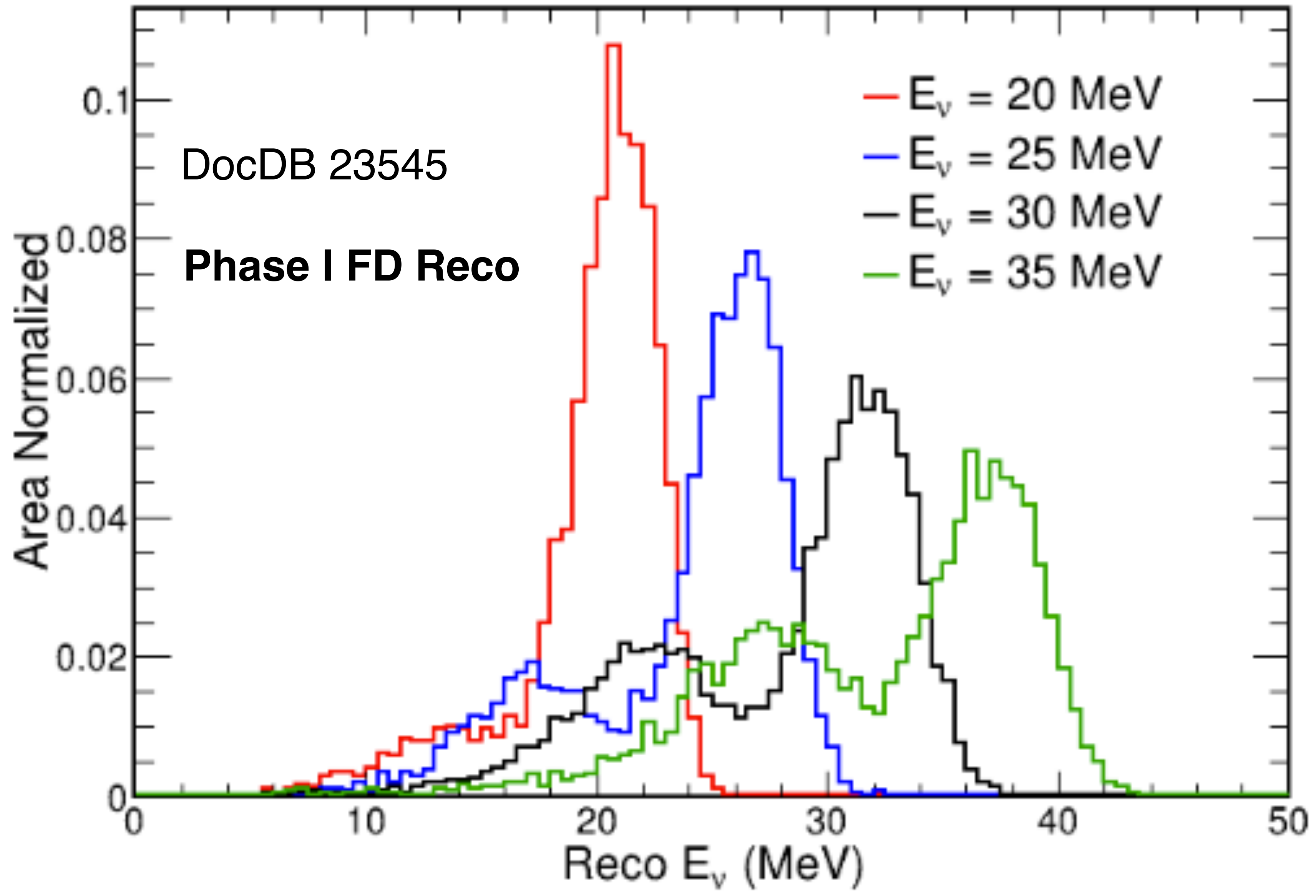
- Geometry: large LAr bath (200 meters long each dimension)

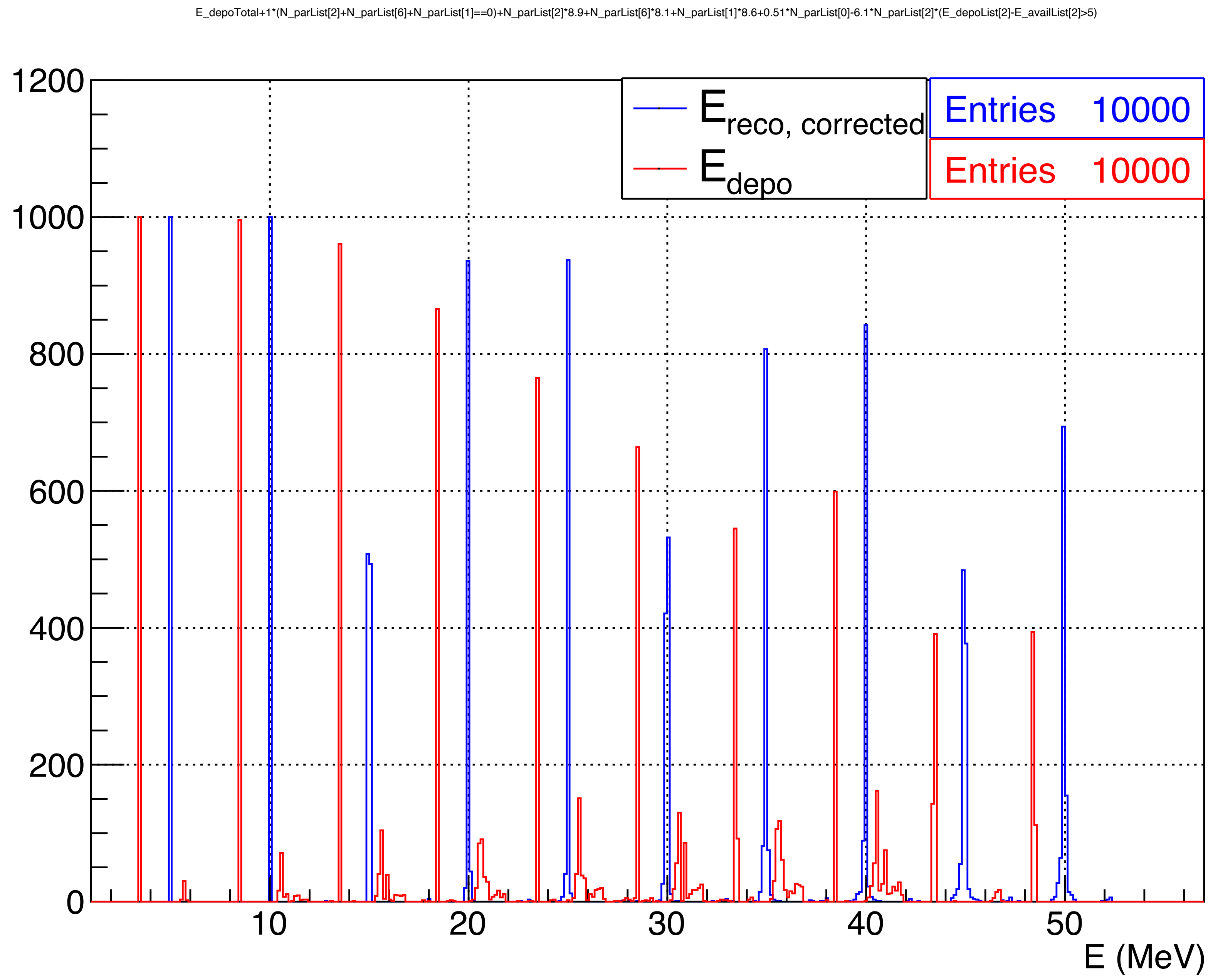
- Record Marley + G4 simulation info (dE/dx, timing)
  - Part I: only look at **GEN+SIM** without considering detector/light/reconstruction effects
    - See my January 11 talk at this call
    - Summary is provided next slide
  - Part II: consider dE/dx conversion to **charge, light, and detection thresholds, and reconstruction**
    - Presented at July 10 low energy physics WGM
    - This time with updated results with collected feedbacks

Summary - Part I

- **Generator level**:
  - **Correction rule 0:** add back the 1 MeV missing energy (change in nucleus binding)
  - **Correction rule 1:** add back the nucleon binding energy loss in 40K **(nucleon multiplicity, n/p/α)**
    - n: 7.9 MeV, α: 7.1 MeV, p: ~7.6 MeV
      - Challenge 1: n (13% captured, 87% not captured)
      - Challenge 2: α, p (high ionization)

- **LAr E deposition level:**
  - **Correction rule 2:** add 0.51 MeV back for created electron mass (energy bias, no smearing)
  - **Correction rule 3:** n capture events subtract over deposit 6.1 MeV





Almost perfect reconstruction!

Charge Detection Thresholds and Light Yields

- **Part II: consider charge, light detection, and reconstruction**
  - Applied detection thresholds: 75 keV, 500 keV (ColdBox, CRP) —> applied at each edep (not track level)
  - Applied realistic charge (dQ/dx) and light (dL/dx) yield from dE/dx
    - dQ: Birks model (N.B. **Modified Box model** produces similar results)
    - dL = dE - dQ
    - Use several APEX benchmark mean light yields 100-220 PE/MeV, and FD2 mean ~35 PE/MeV)

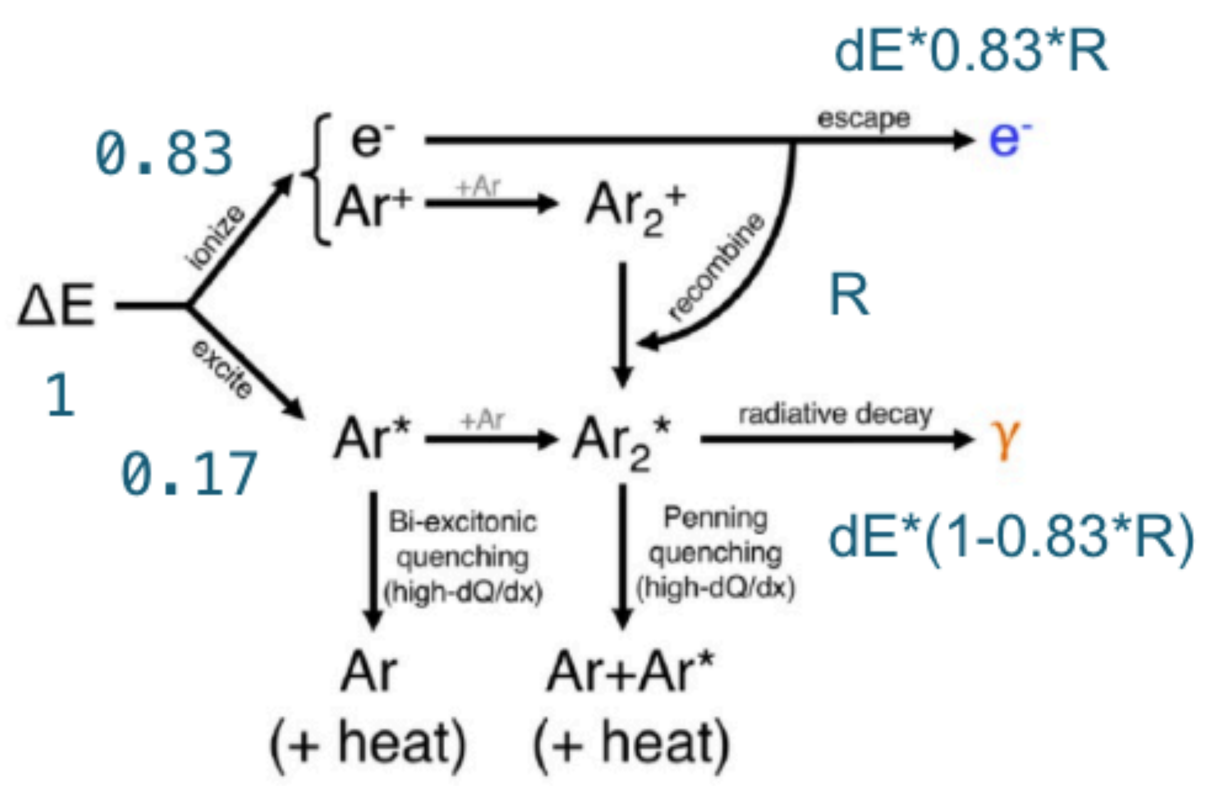


FIG. 1. Schematic diagram illustrating the production of free ionization electrons (e^-) and scintillation photons (γ) from energy deposited in liquid argon.

$\alpha = N_{ex}/N_i = 0.21$

$$dQ = 0.83 \times dE \times R_c$$

Birks model

$$R_c = \frac{dQ/dx}{dE/dx} = \frac{A_{3t}}{1 + k_{3t}/\varepsilon \times dE/dx}$$

$$A_{3t} = 0.8,\ k_{3t} = 0.0486 (g/MeV cm^2)(kV/cm)$$

❑ How we convert deposit energy to light:

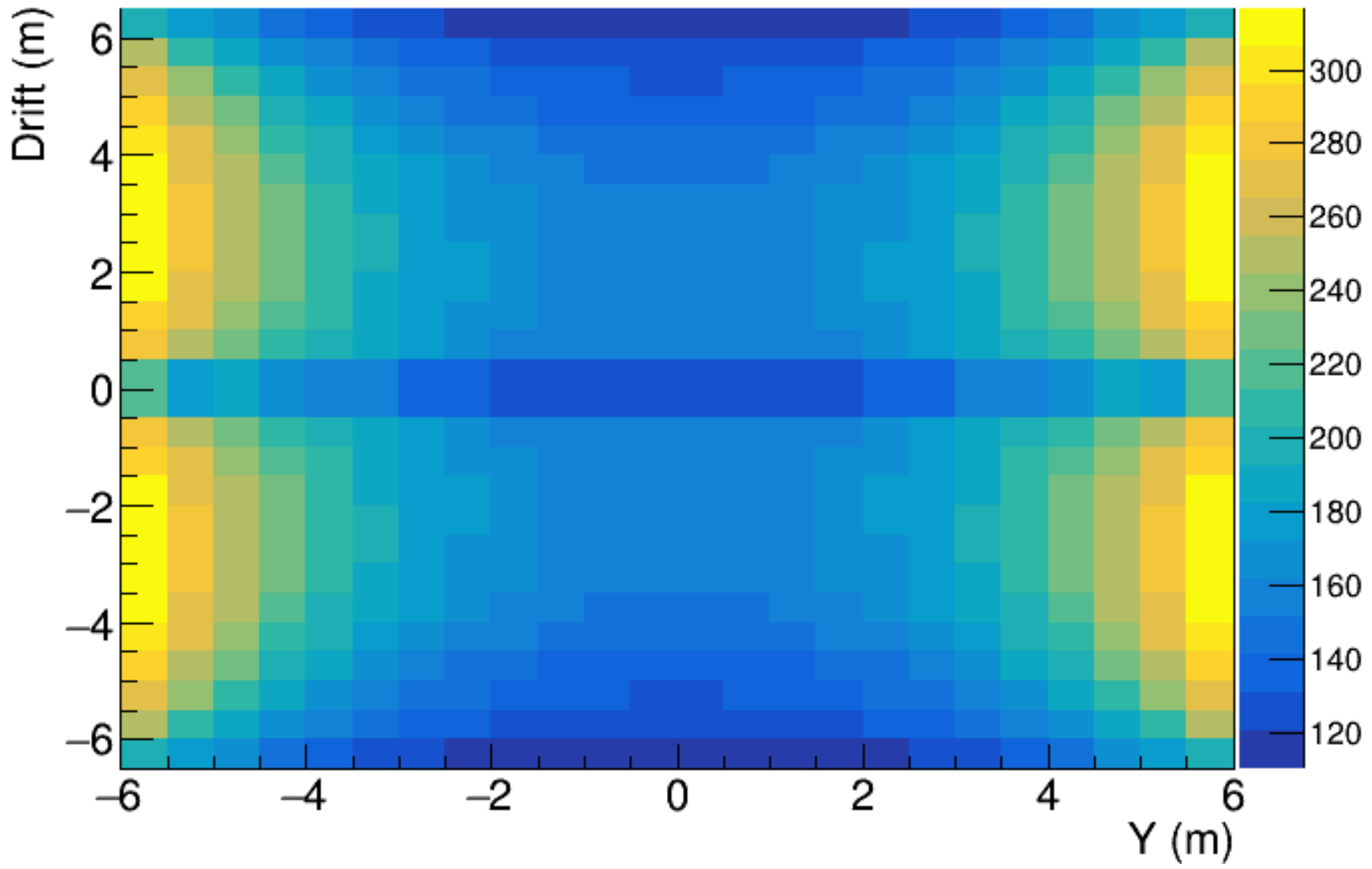
If we ignore heat loss, for deposit energy dE[MeV];

- Part of it goes to charge:
  dQ = dE*R*0.83;
- Rest of it will become light:
  dL = dE - dQ
- Apply the light yield: 180PE/MeV, the number of PE for an event would be:
  N_{PE} = L*180
- Apply the fluctuation, the detected photon number would be:
  N_{PE_rand} = Gaussian(N_{PE},$\sqrt{N_{PE}}$)
- The detected energy in light:
  $L_{detected}$ = N_{PE_rand} *180(PE/MeV)
- Combined with charge energy, the detected energy in total:
  E_{LQ} = $L_{detected}$ + Q

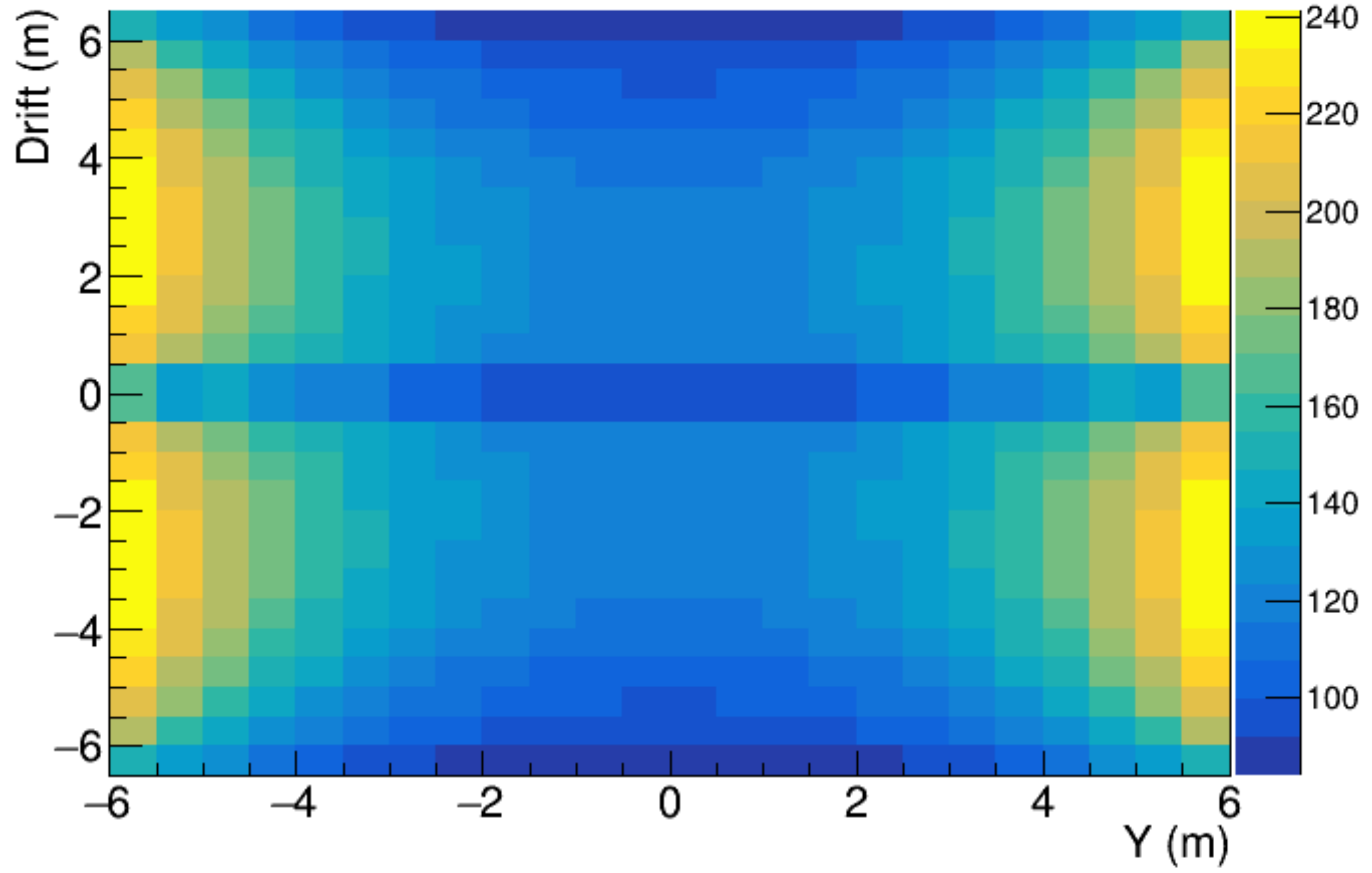
APEX Light Yields at Benchmark PDEs

F. Marinho

2.27%: double-side-sipm



1.73%: single-side-sipm-with-detached-WLS (Two layer)



1.23%: single-side-SiPM

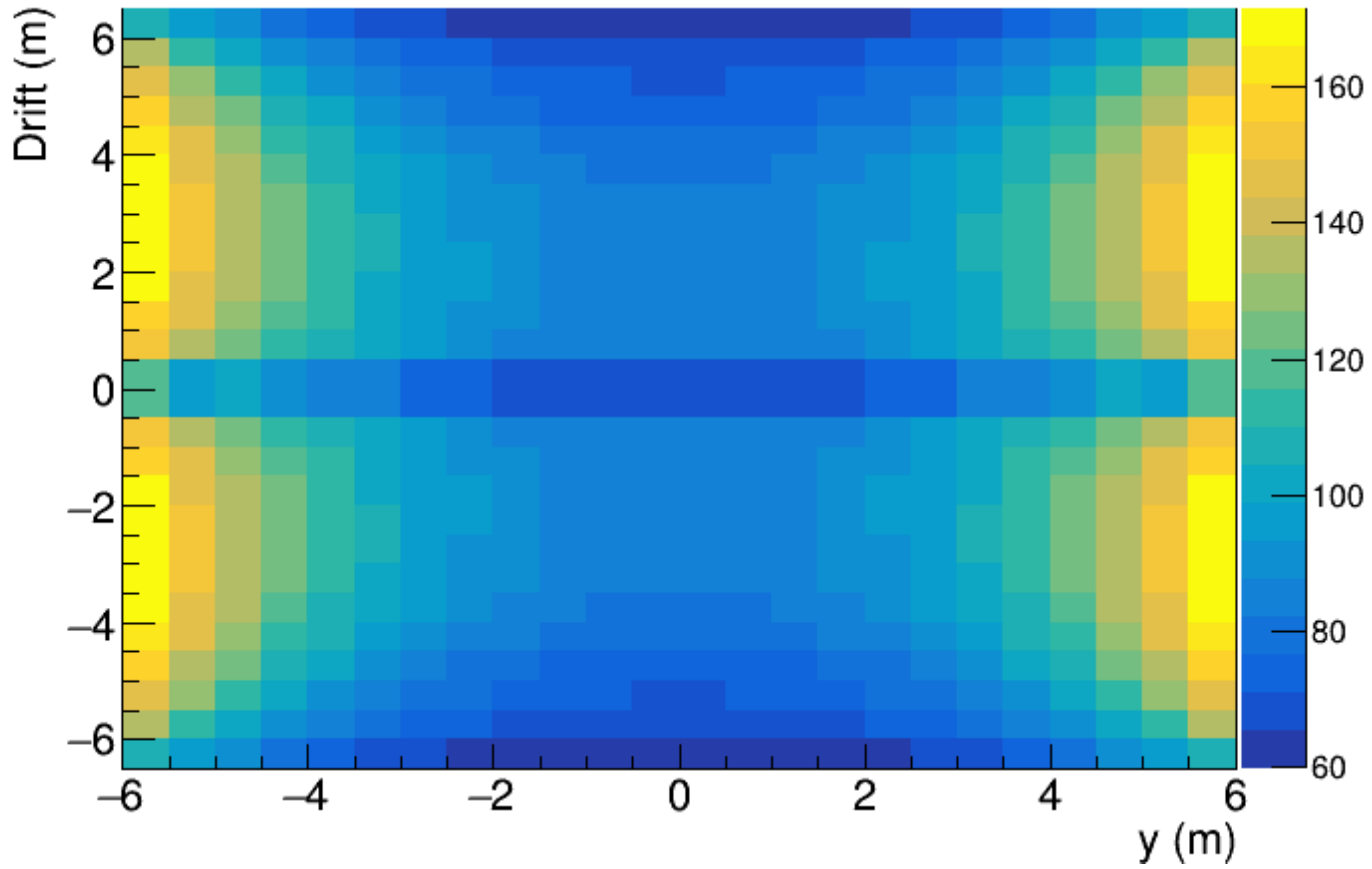


Table 1

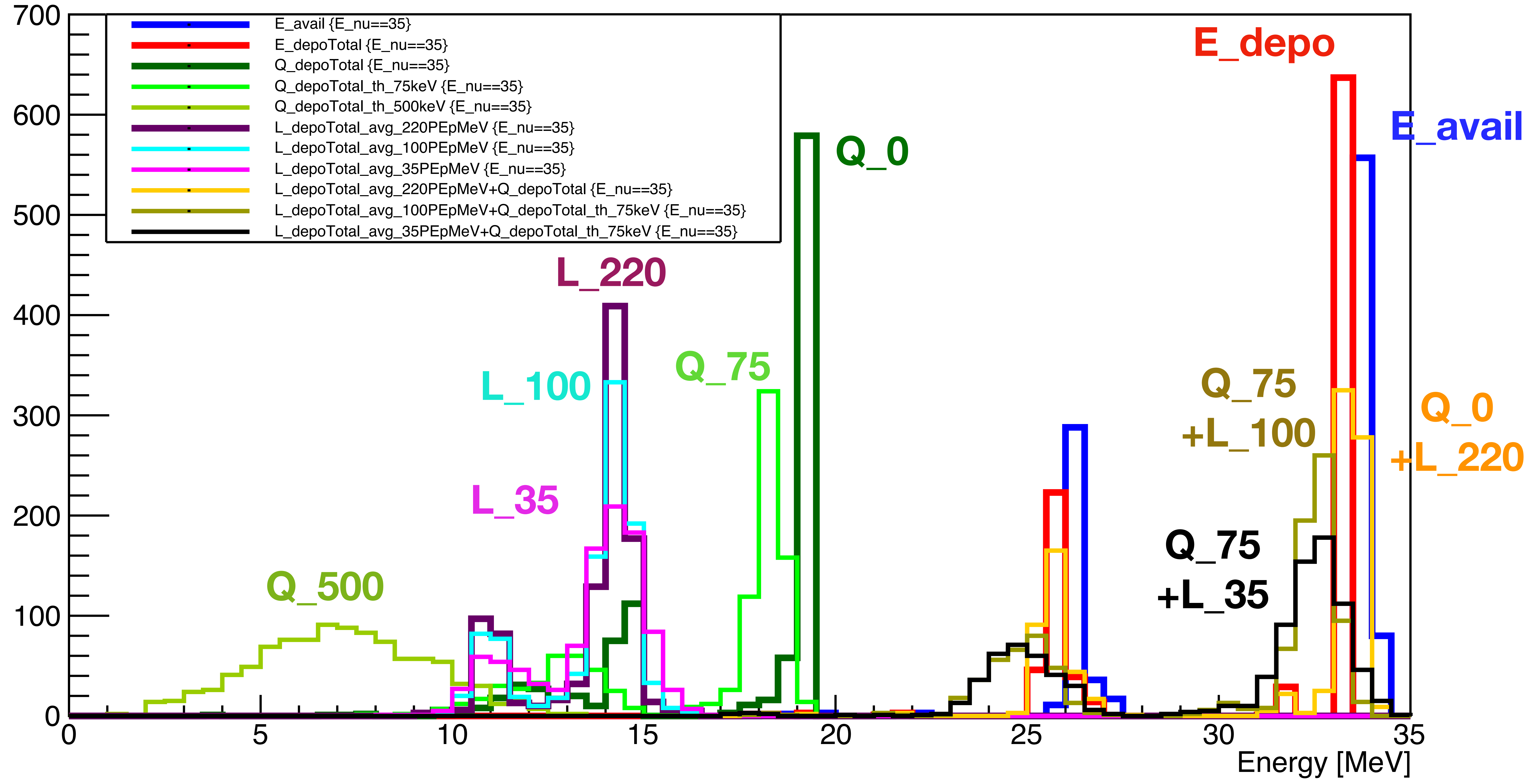
SiPM eff	LYmin (pe/MeV)	LYmax (pe/MeV)	LYave (pe/MeV)
1.23%	59.8	171.5	100.3
1.73%	84.1	241.2	141.1
2.27%	110.4	316.5	185.1


dQ>500keV
dE/dx [MeV/cm]
dQ>75keV
dE/dx [MeV/cm]
e-: 29.1 MeV
gamma: 2.1 MeV
gamma: 0.6 MeV
gamma: 1.6 MeV
gamma: 0.0 MeV
dQ>500keV
y [m]
z [m]
MeV/cm
e-: 29.1 MeV
gamma: 2.1 MeV
gamma: 0.6 MeV
gamma: 1.6 MeV
gamma: 0.0 MeV
dQ>75keV
y [m]
z [m]
MeV/cm
e-: 29.1 MeV
gamma: 2.1 MeV
gamma: 0.6 MeV
gamma: 1.6 MeV
gamma: 0.0 MeV
dQ>0
y [m]
z [m]
MeV/cm
dQ>0
dE/dx [MeV/cm]

Energy deposit dE —> dQ, dL, threshold

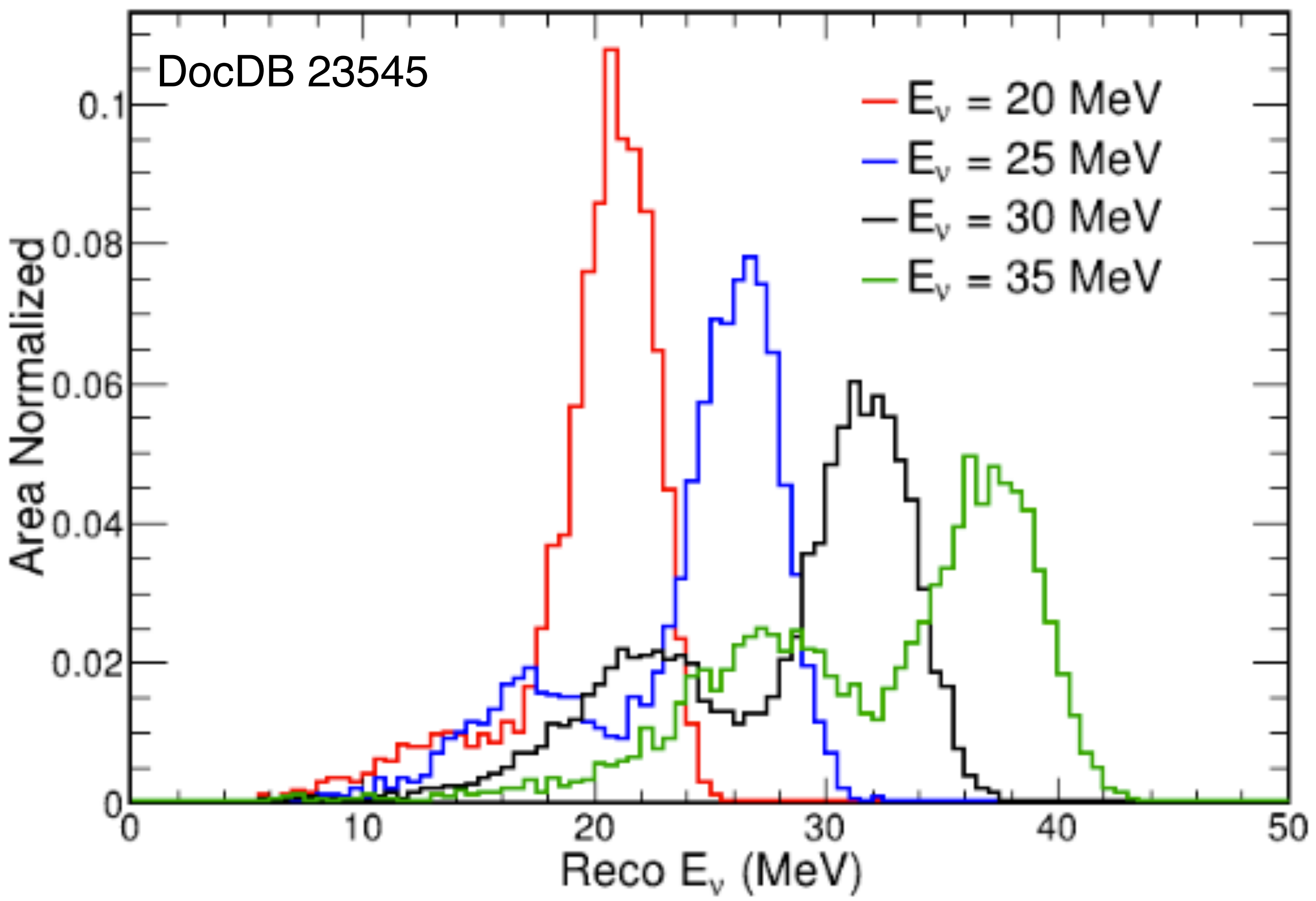
- dQ smearing is not small after adding threshold
  - 75keV is very ideal, current charge detection threshold is higher
  - If threshold is 500 keV, very poor
- Light deposit more symmetric
  - Less feed down than charge calorimetry
  - Smaller LY smears the peak
- Light calo. (220 PE/MeV LY) + charge calo. basically reproduces E_depo
  - dQ threshold drives the smearing

35MeV nue-Ar CC



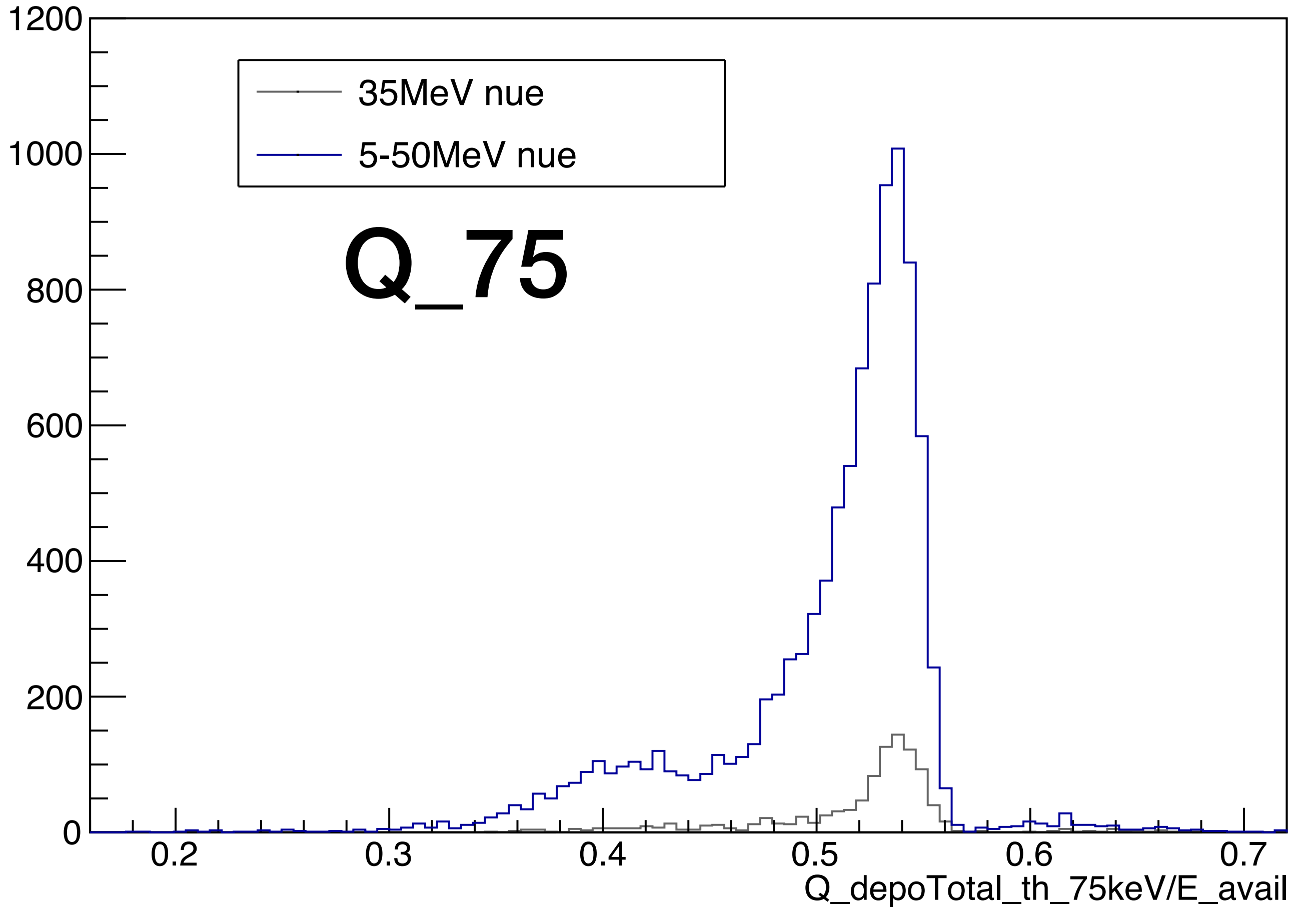
Reconstruction

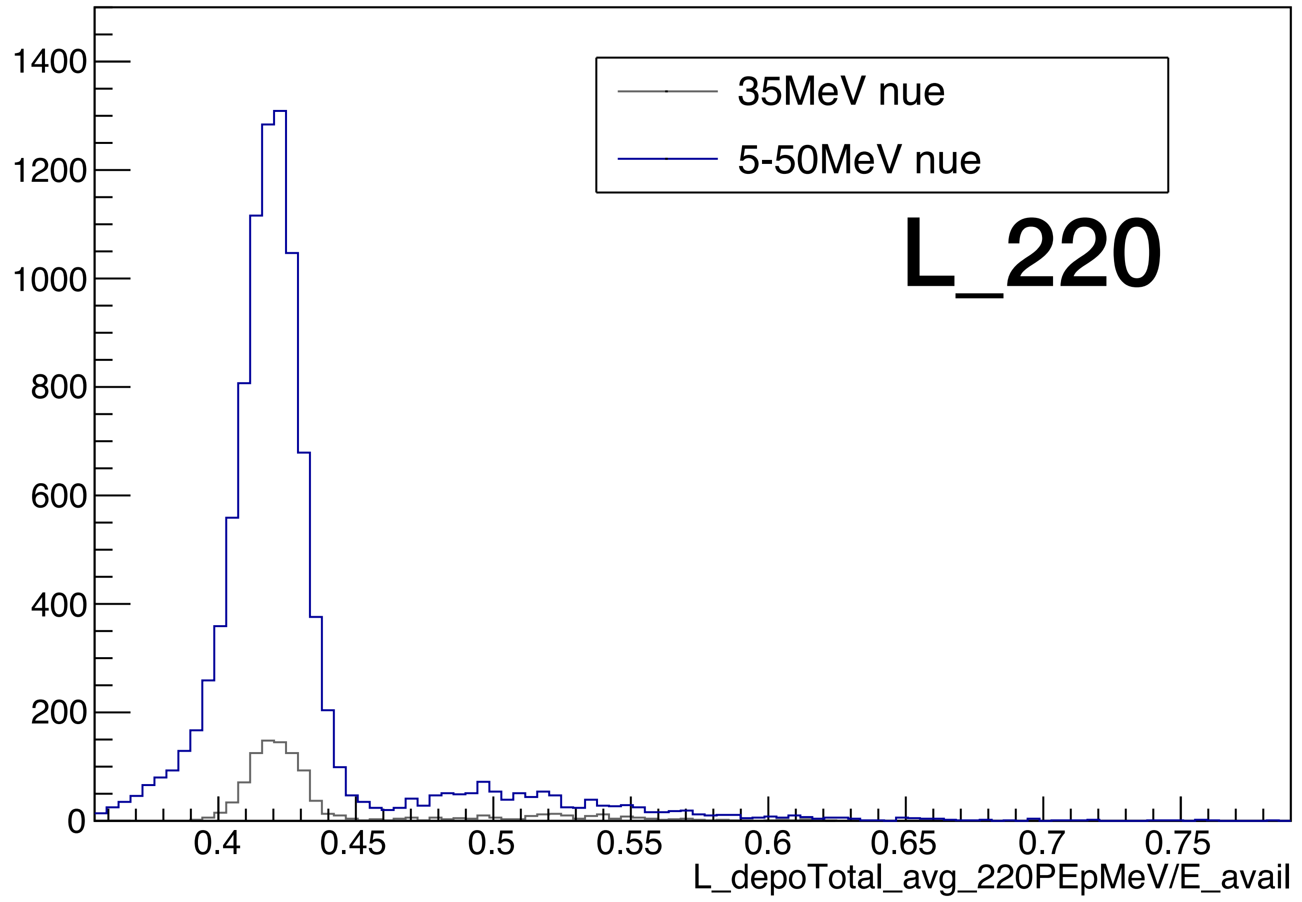
Full reconstruction at HD SinglePhase

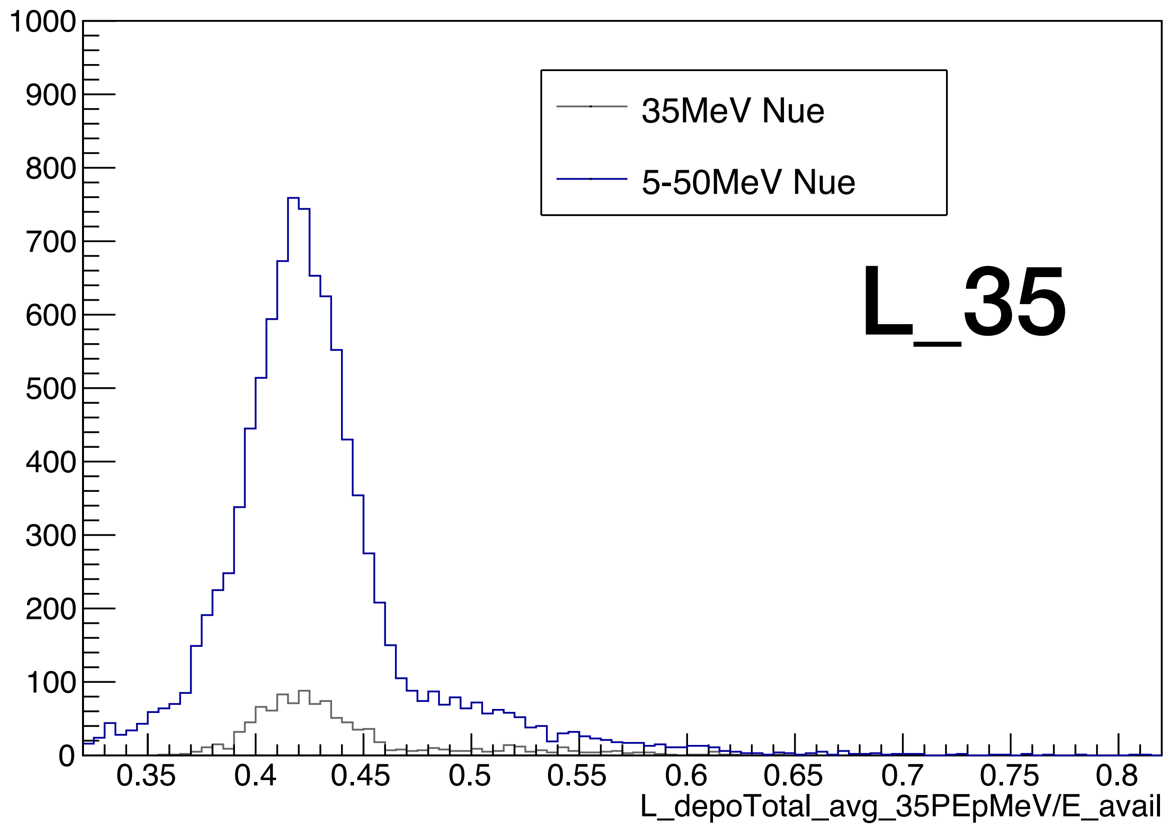


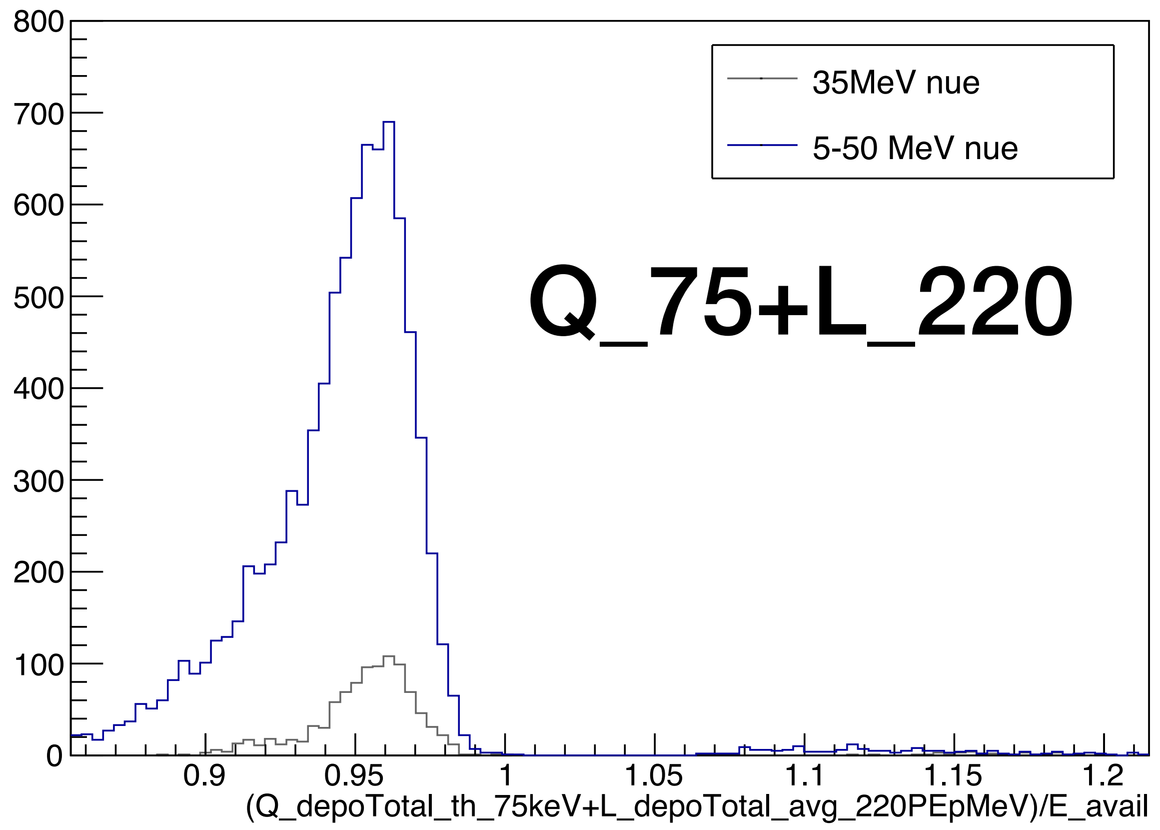
Reconstruction with Pure Calorimetry (Q, L, Q+L): correction factors

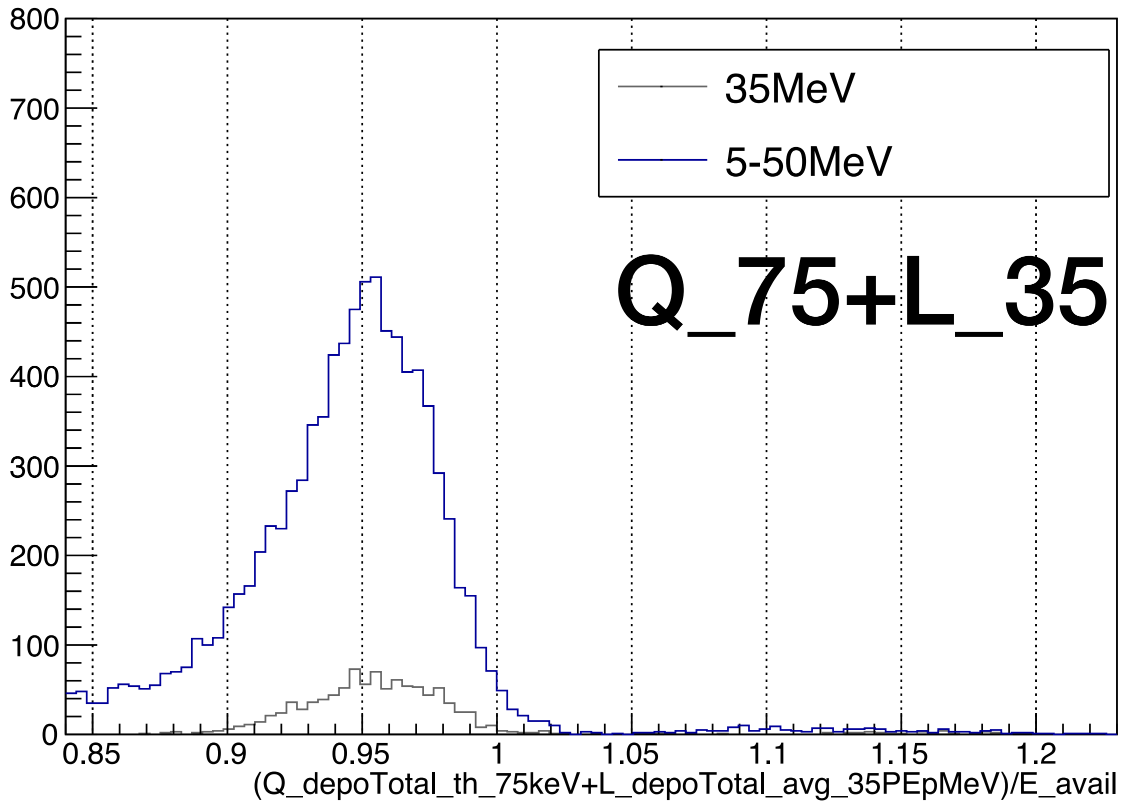
- **Reco 1:** pure charge calorimetry
  - Correction factor: Q_75/0.54
- **Reco 2:** pure light calorimetry (**FD3**)
  - Correction factor: L_220/0.42
- **Reco 2*:** pure light calorimetry (**FD2**)
  - Correction factor: L_35/0.42
- **Reco 3:** L + Q (**FD3**)
  - (Q_75+**L_220**)/0.96
- **Reco 3*:** L + Q (**FD2**)
  - (Q_75+**L_35**)/0.953





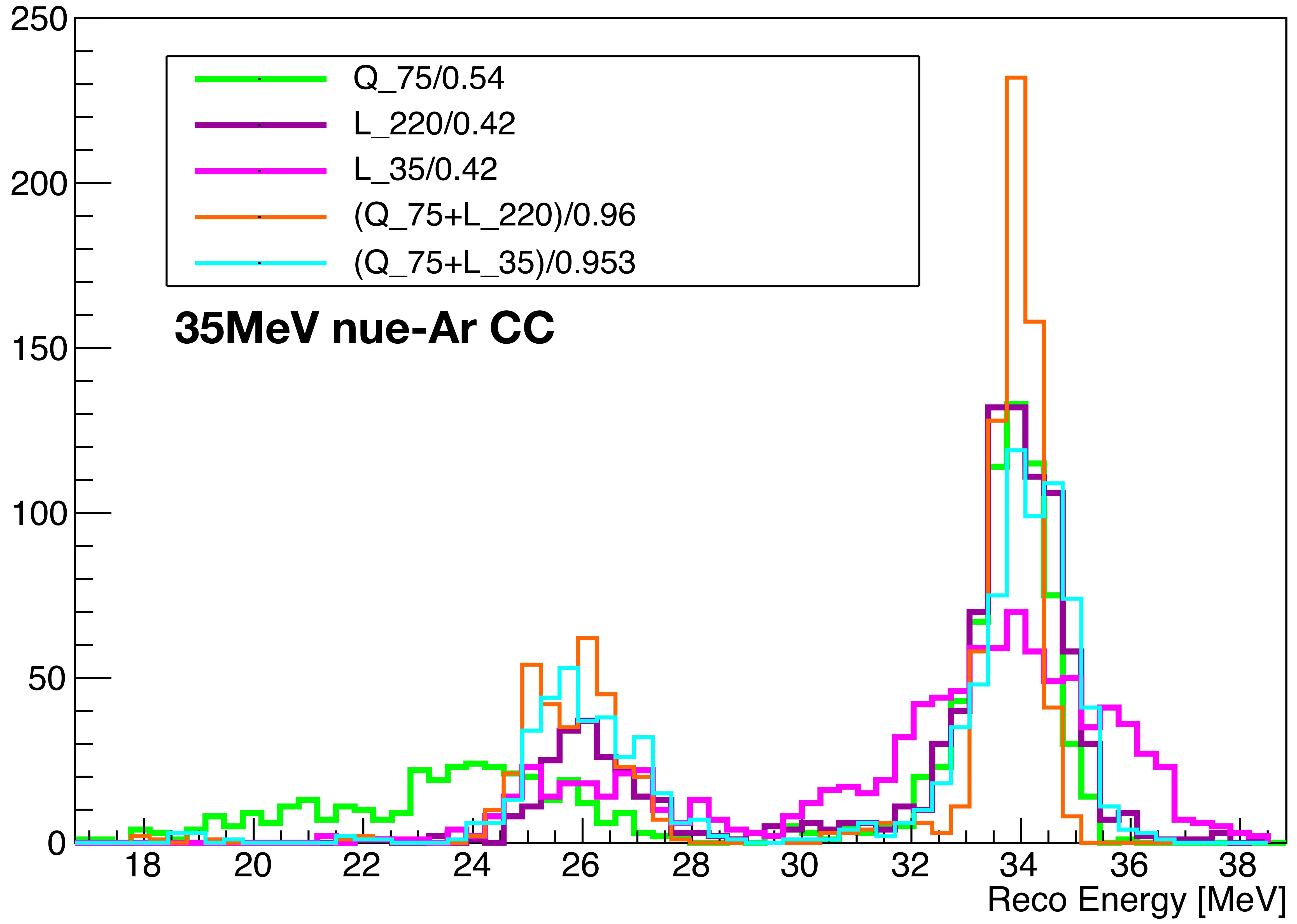






Reconstruction with Pure Calorimetry (Q, L, Q+L)

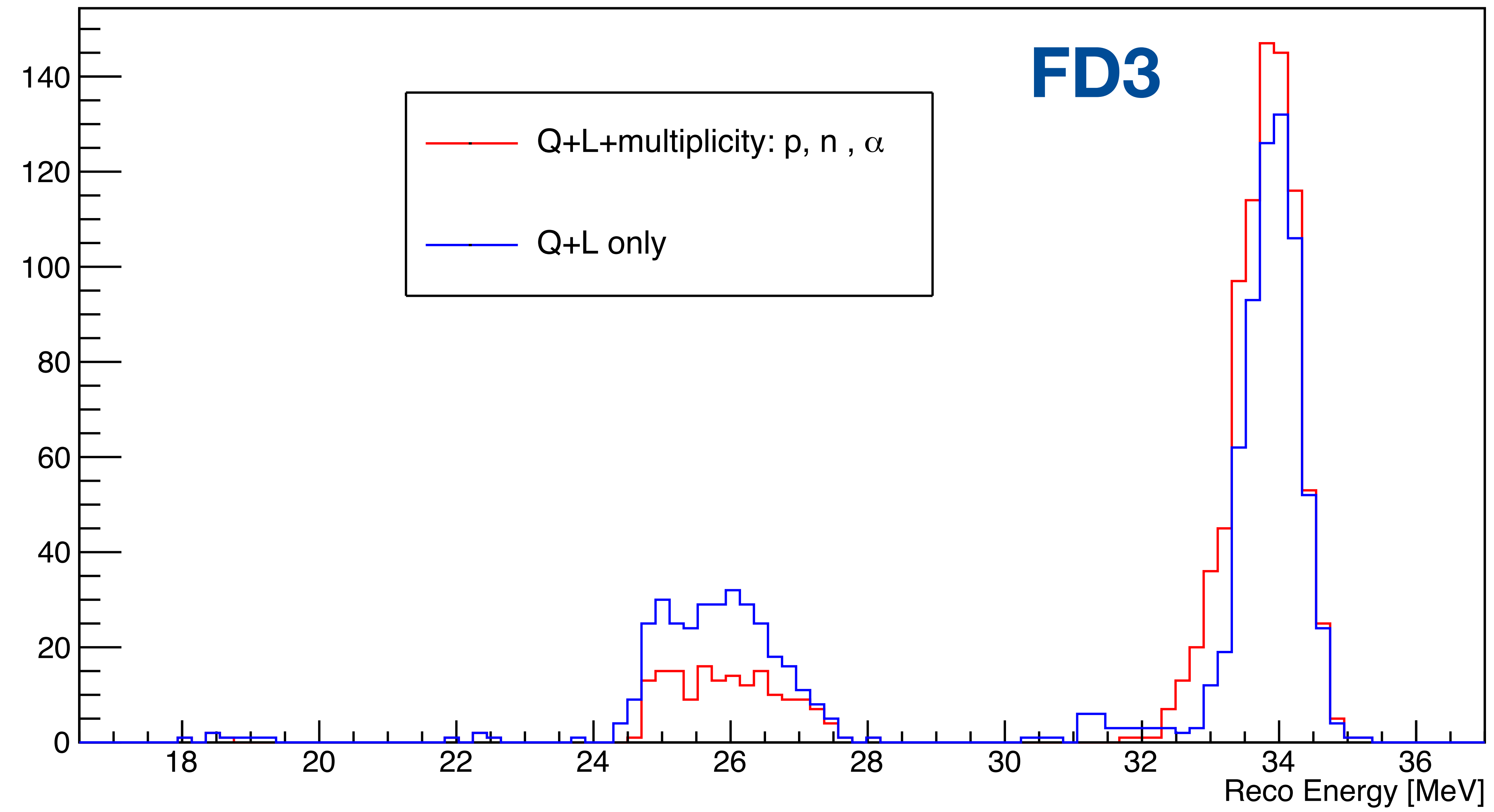
- **Reco 1:** pure charge calorimetry
  - Correction factor: Q_75/0.54
  - $\sigma/\bar{E}$ = 1.9% (11.3%/$\sqrt{\bar{E}}$) at the main peak
- **Reco 2:** pure light calorimetry (**FD3**)
  - Correction factor: L_220/0.42
  - $\sigma/\bar{E}$ = 2.2% (13.3%/$\sqrt{\bar{E}}$) at the main peak
  - **Pure charge and light resolution is comparable**
- **Reco 2*:** pure light calorimetry (**FD2**)
  - Correction factor: L_35/0.42
  - $\sigma/\bar{E}$ = 5.1% (29.4%/$\sqrt{\bar{E}}$) at the main peak
  - **FD3 light only E resolution can be ~2 times better than VD**
- **Reco 3:** L + Q (**FD3**)
  - (Q_75+**L_220**)/0.96
  - $\sigma/\bar{E}$ = 1.1% (6.5%/$\sqrt{\bar{E}}$) at the main peak
  - **Add L to Q in calorimetry improves the resolution at both peaks**
  - **Two times better resolution at the main peak**
- **Reco 3*:** L + Q (**FD2**)
  - (Q_75+**L_35**)/0.953
  - $\sigma/\bar{E}$ = 2.2% (13.1%/$\sqrt{\bar{E}}$) at the main peak
  - **FD3 Q+L resolution ~2 times better than FD2**

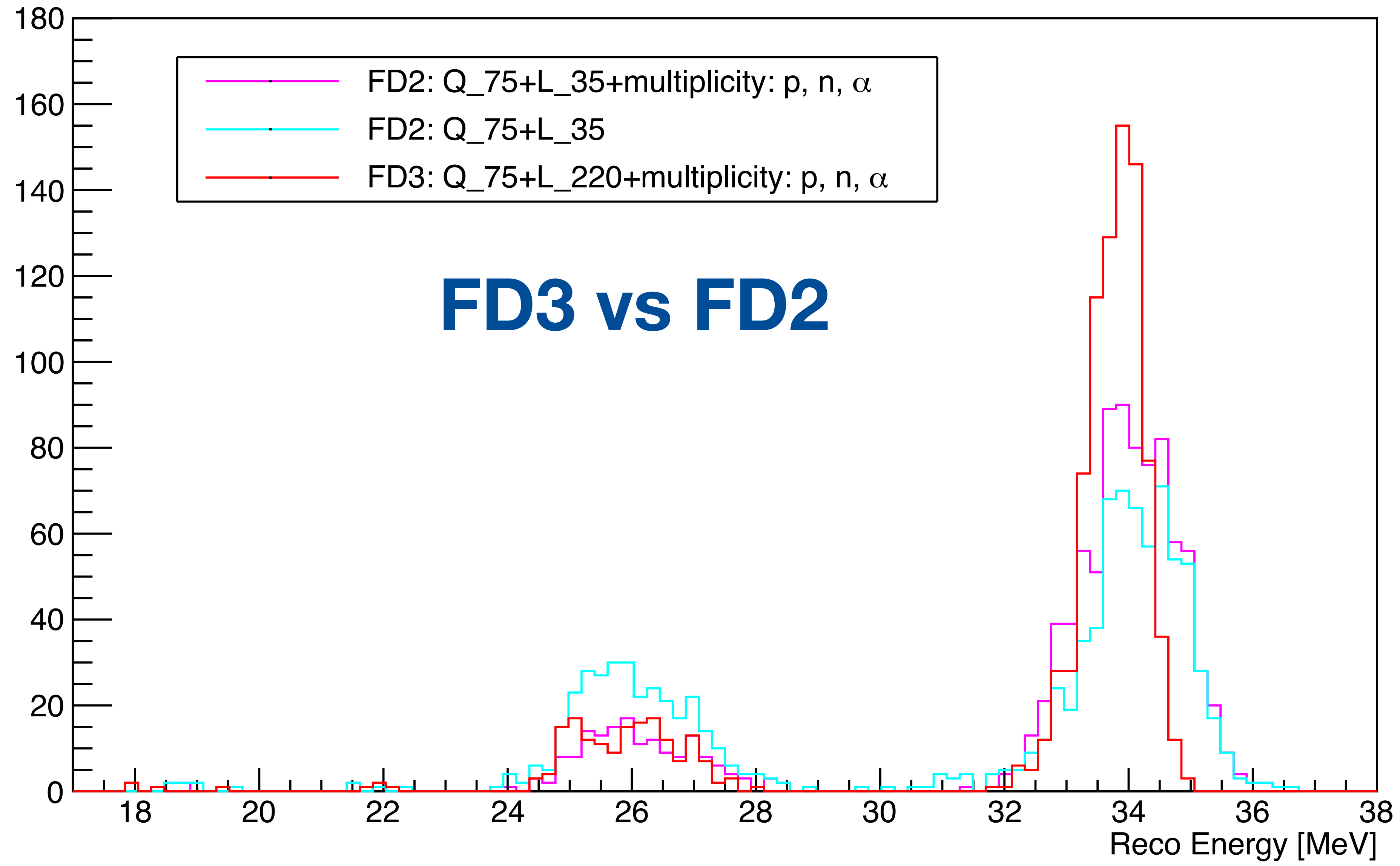


Reconstruction: Q + L + nucleons multiplicity (n/p/α)

- **Reco 8:** pure calorimetry Q+L and tag n/p/α nucleon multiplicity
  - **Assume can only tag nucleons passing Qdep threshold 75keV**
  - For p/α: add back binding E
  - For neutron: add back binding E + subtract over-deposit from capture
  - **FD3: $\sigma/\bar{E}$ = 1.3% (7.5%/$\sqrt{\bar{E}}$) @ main peak, secondary peak halved**
  - **FD2: $\sigma/\bar{E}$ = 2.2% (13.2%/$\sqrt{\bar{E}}$) @ main peak, secondary peak halved**

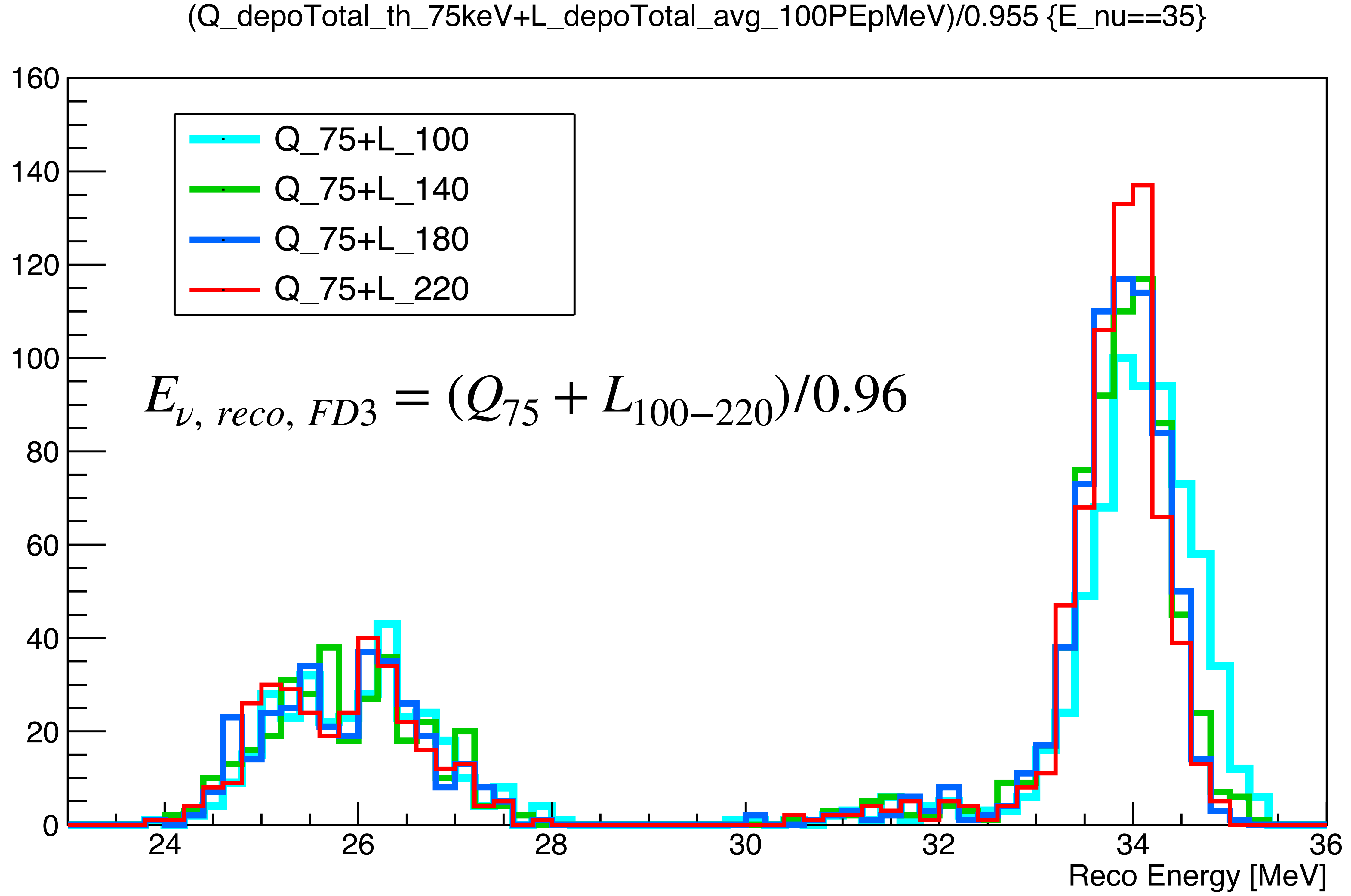
$$E_{\nu,\ reco,\ FD3} = (Q_{75} + L_{220})/0.96 + 7.35\ MeV * (N_{p,\ Q_{p,75keV}>0} + N_{\alpha,\ Q_{\alpha,75keV}>0}) + 7.9\ MeV * N_{n,\ Q_{p,75keV}>0} - 6.1\ MeV * N_{n,\ captured} + \bar{0}$$
$$E_{\nu,\ reco,\ VD} = (Q_{75} + L_{35})/0.953 + 7.35\ MeV * (N_{p,\ Q_{p,75keV}>0} + N_{\alpha,\ Q_{\alpha,75keV}>0}) + 7.9\ MeV * N_{n,\ Q_{p,75keV}>0} - 6.1\ MeV * N_{n,\ captured} + \bar{0}$$





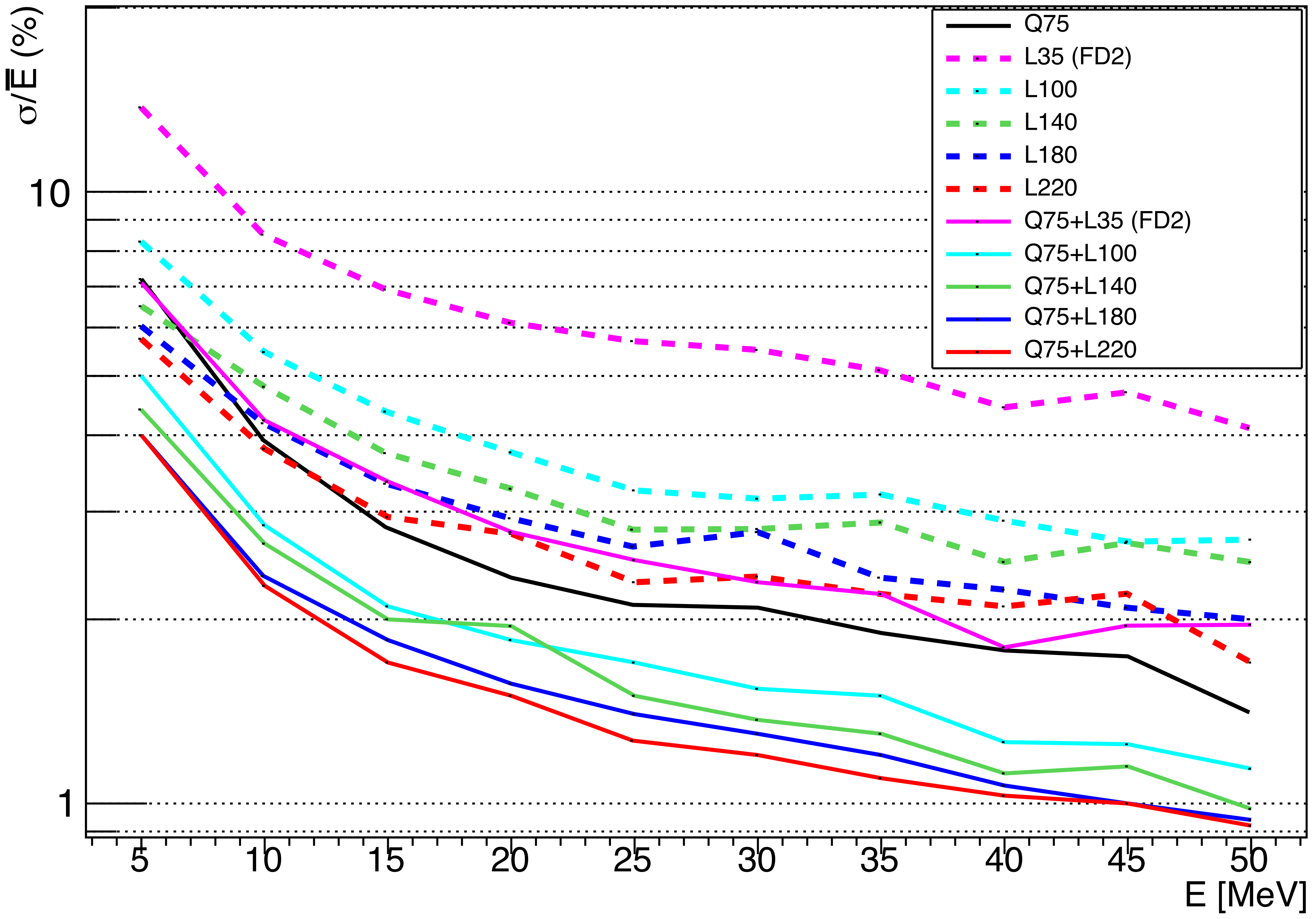
Reconstruction: Q + L
- different FD3 average LY

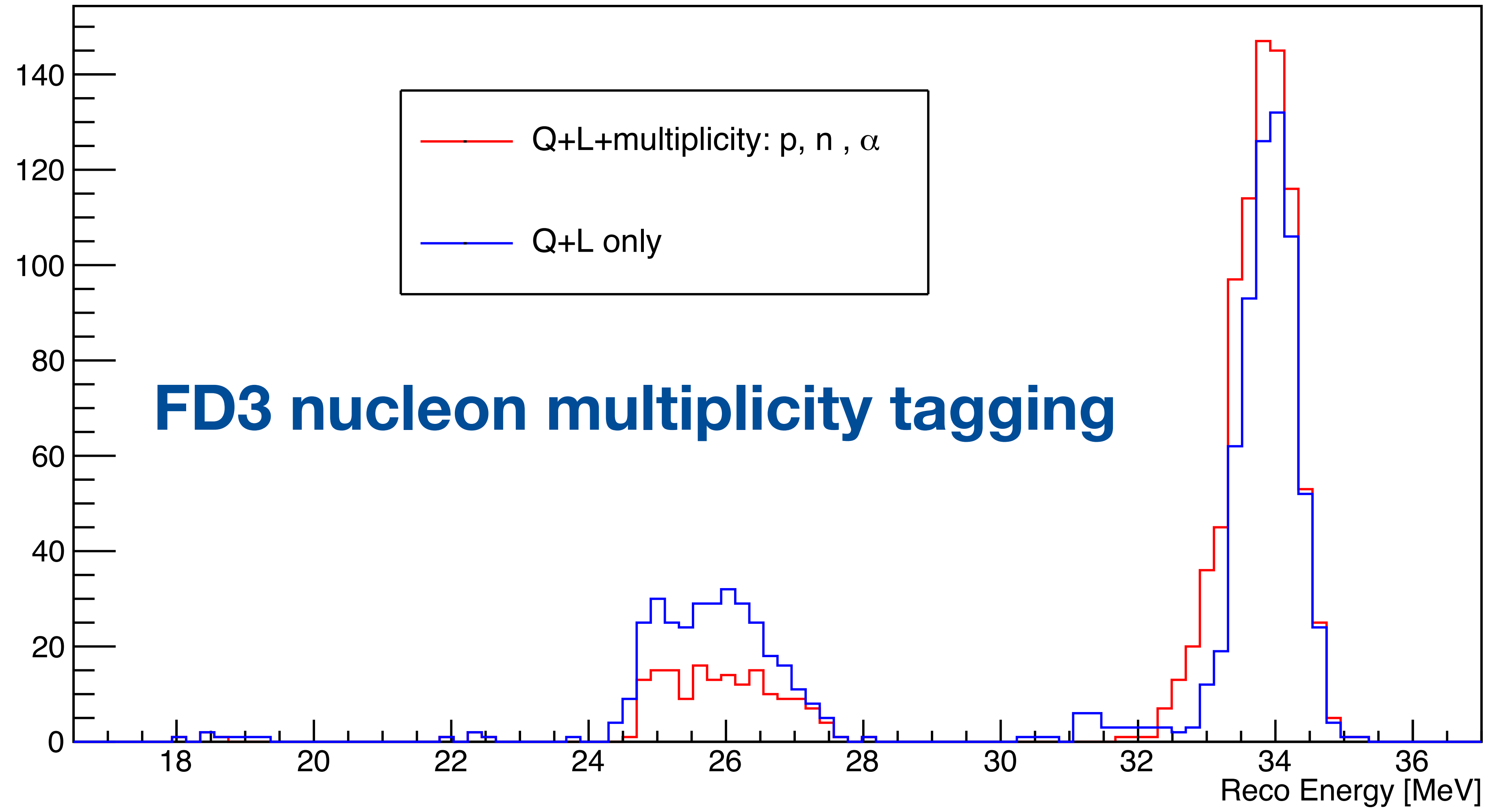
- **Reco 3**:** pure calorimetry Q+L
  - (Q_75+**L_100**)/0.955: main peak $\sigma/\bar{E}$ = 1.5% (8.8%/$\sqrt{\bar{E}}$)
  - (Q_75+**L_140**)/0.96: main peak $\sigma/\bar{E}$ = 1.3% (7.5%/$\sqrt{\bar{E}}$)
  - (Q_75+**L_180**)/0.96: main peak $\sigma/\bar{E}$ = 1.2% (7.1%/$\sqrt{\bar{E}}$)
  - (Q_75+**L_220**)/0.96: main peak $\sigma/\bar{E}$ = 1.3% (7.5%/$\sqrt{\bar{E}}$)
  - N.B. LY uniformity is not considered here



Summary - Part 2

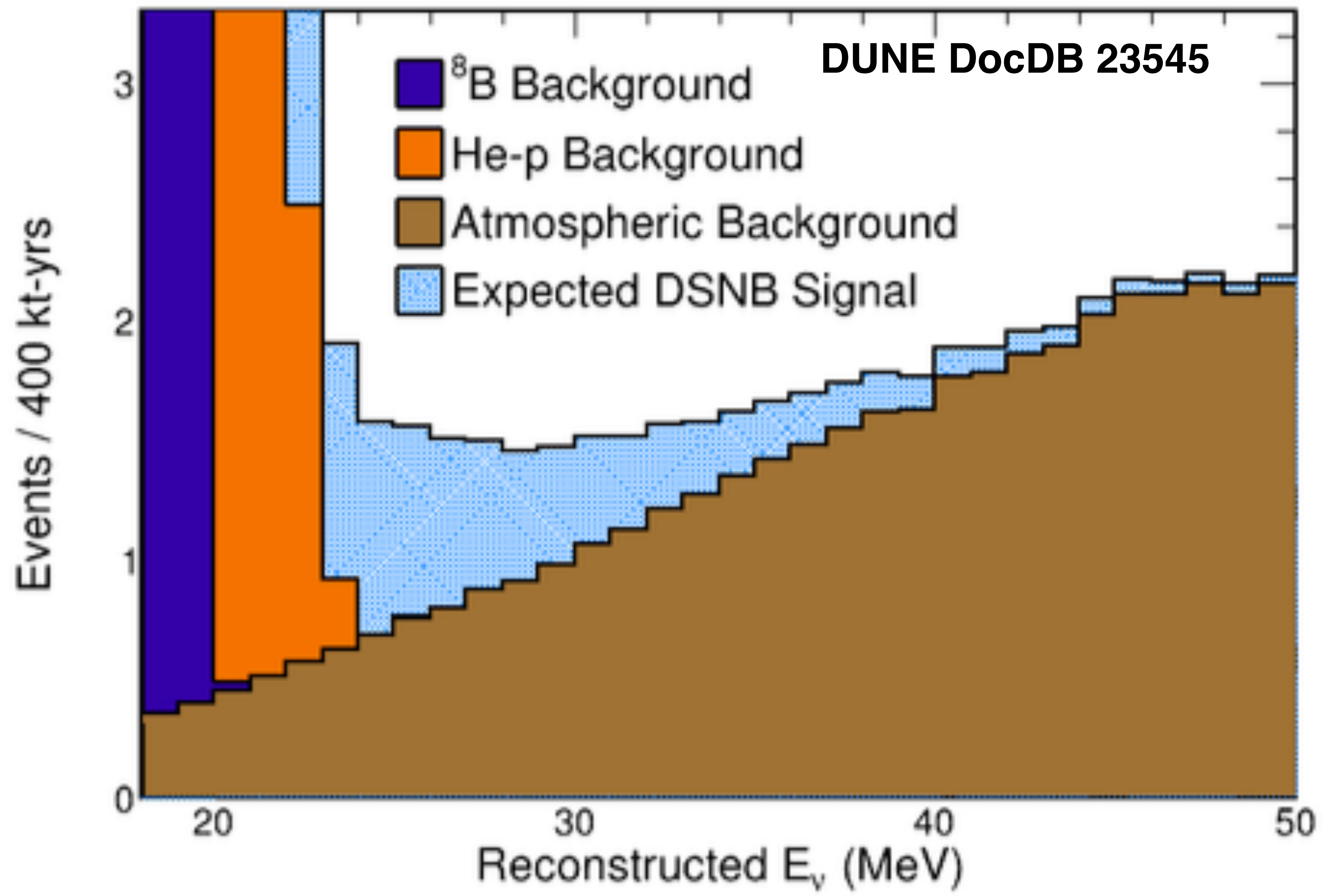
- **FD3 pure L** calorimetry can provide **comparable or better** resolution to pure Q calorimetry (**Q with very optimistic threshold 75keV**)
  - LY=220 PE/MeV: $\sigma/\bar{E}$ = 2.2% (13.3%/$\sqrt{\bar{E}}$) @35 MeV
  - Q (75keV): $\sigma/\bar{E}$ = 1.9% (11.3%/$\sqrt{\bar{E}}$) @35 MeV
- **Pure Q+L resolution ~2 times better than Q or L only**
  - $\sigma/\bar{E}$ = 1.1% (6.5%/$\sqrt{\bar{E}}$) @35MeV
- **FD3** E resolution can be ~2 times better than VD
  - 2.2% (FD3) vs 1.3% (VD) @35MeV
- **Nucleon** (**n**/alpha/p) multiplicity tagging (assume those failed 75 keV dQ threshold can't be tagged)
  - **Smearing to the secondary peak is reduced by 50%**





Conclusion & Discussion

- **Phase II** PDS can deliver **2 times better energy resolution (either L only or Q+L) compared to Phase I PDS** at the energy ROI of DSNB search
- **Binding energy loss** from **nucleon knockout** from primary ν_e-Ar CC interaction causes the secondary reconstructed peak seen in Phase I FD
- DSNB ROI window
  - Secondary peak from Hep/8B no impact on DSNB → **improve main peak E resolution, Q+L is our best shot (2 times better Eres than L or Q only)**
  - Secondary peak from atm bkg will affect DSNB → **tag and reject/include events with nucleons as many as we can**
- Nucleon tagging will be crucial for DSNB search to reject the secondary peak
  - **Neutrons** most important: can tag n-capture (ongoing program @VD CB/PD-VD), **more challenging if not captured**
  - Also important to tag **high dE/dx** nucleons: alphas/protons etc (can this be demonstrated in ProtoDUNE?)



Full reconstruction at HD SinglePhase