Neutrino flux constraints wth the low-ν method

7th FPF meeting, CERN, 29nd February 2024

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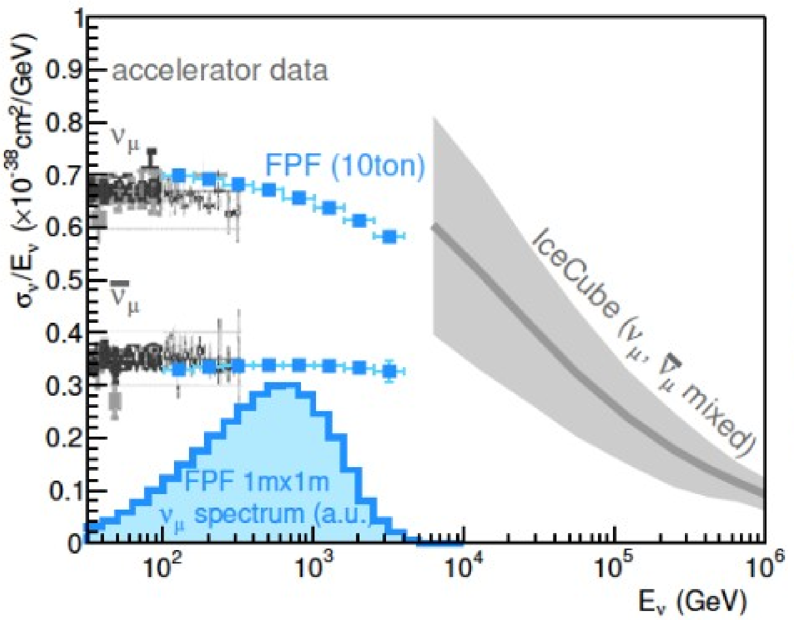
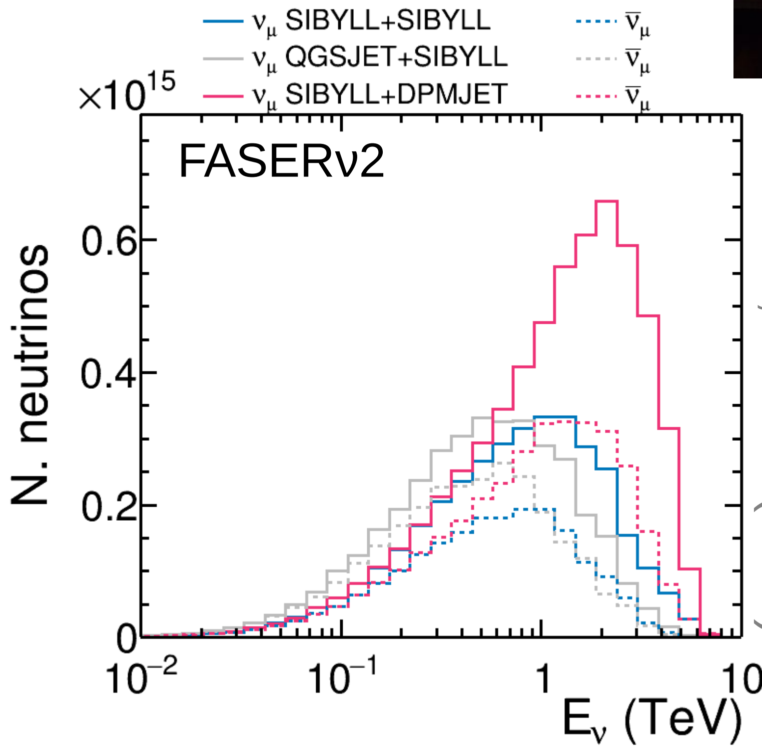
Motivation/background

- “Standard candles” isolate a region of phase-space with a known cross section as a way to help break flux/cross-section degeneracies
- The “low-ν” method is often discussed as a standard candle for few-GeV accelerator neutrino experiments
- Previous work showed it is not a good option for precision few-GeV experiments like DUNE: EPJC **82**, 808 (2022), arXiv:2203.11821
- But, followed this up by thinking about the potential use at higher energies → the FPF: PRD **109**, 033010 (2024), arXiv:2310.0652
- This is all very high-level, without proper reconstruction etc, and should be used to motivate a full study in future

Why do we need a standard candle?





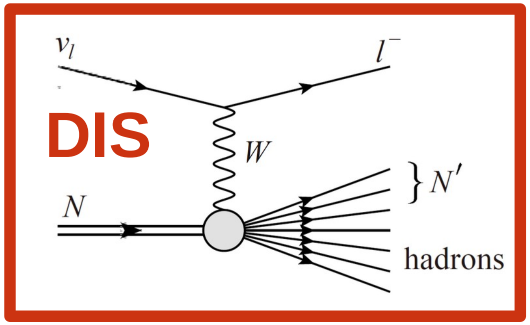
PRD104, 113008 (2021)

Event rate
Neutrino flux
Cross section
Detector smearing
Oscillation probability

$$R(\vec{\mathbf{x}}) = \int dE\ \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}}) \times P(E_\nu; \nu_A \to \nu_B)$$

The low-ν method [1,2]

$$\frac{d\sigma}{dq_0} = \frac{G_F^2 M}{\pi} \int_0^1 \left(F_2 - \frac{q_0}{E_\nu} [F_2 \mp xF_3] + \frac{q_0}{2E_\nu^2} \left[\frac{Mx(1-R_L)}{1+R_L} F_2 \right] + \frac{q_0^2}{2E_\nu^2} \left[\frac{F_2}{1+R_L} \mp xF_3 \right] \right) dx$$



- Comes from the observation that if q_0/E_ν << 1, the cross section is approximately constant with E_ν
- The rate as a function of E_ν gives access to the flux *shape*
- Very closely linked to the "low-y" ($y = q_0/E_\nu$) method [2]

[1] S. R. Mishra in Workshop on Hadron Structure Functions and Parton Distributions, 84 , p84. World Scientific, 1990

[2] R. Belusevic and D. Rein Phys. Rev. D 38 (1988) 2753–2757

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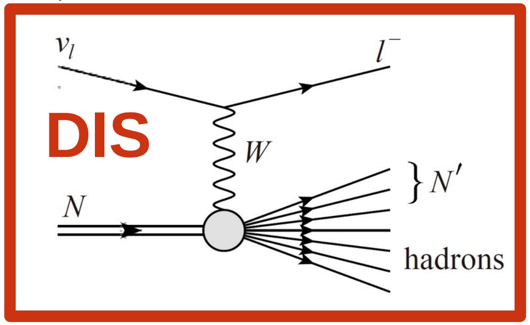

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Low-ν method requirements

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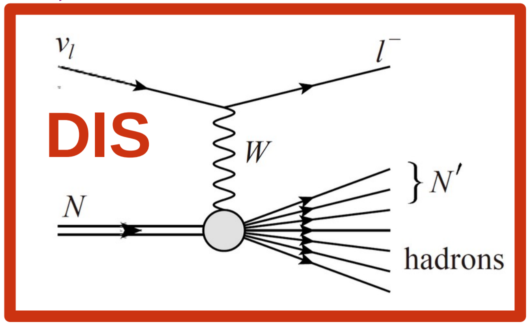


The method works if:

1) There is a low-q_0 region with a constant cross section in E_ν

2) It can be selected without significant model dependence

3) It provides a useful number of events

History of the low-ν method

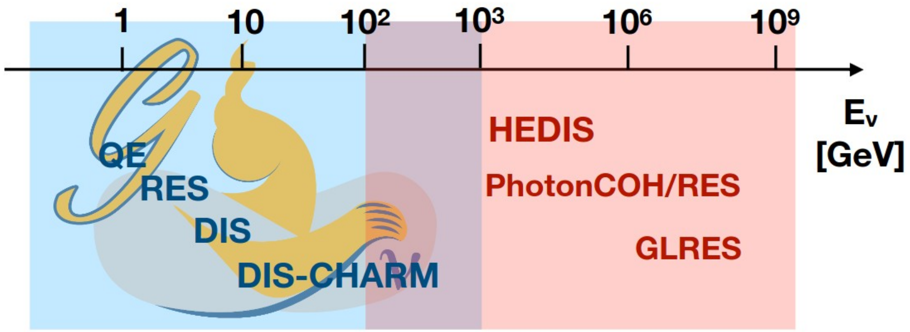
- Widely known/used in accelerator neutrino community:
  - **CCFR**, $30 \leq E_\nu \leq 360$ GeV, 1985–1988*
  - **NuTeV**, $30 \leq E_\nu \leq 360$ GeV, 1996–1997*
  - **NOMAD**, $3 \leq E_\nu \leq 100$ GeV, 1995–1998*
  - **MINOS(+)**, $2 \leq E_\nu \leq 10$ GeV, 2005–2016*
  - **MINERvA**, $2 \leq E_\nu \leq 10$ GeV, 2009–2019*
- Discussed for use in current/future precision experiments:
  - **MicroBooNE**, $0.3 \leq E_\nu \leq 2$ GeV, 2015–2021*
  - **DUNE**, $1 \leq E_\nu \leq 5$ GeV, 2030's
  - ...

*all dates indicate data-taking periods

Aside: cross-section models

Low energy (LE): EPJST 230 (2021) 24, arXiv:2106.09381

- Developed for few-GeV accelerator neutrino community
- DIS from Bodek-Yang model → tuned for low-Q^2
- LO structure functions, use GRV98LO PDFs
- Contributions from heavy quarks not included

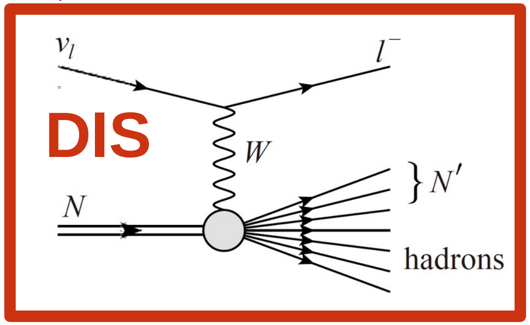


High energy (HE): JCAP **09** 025 (2020), arXiv:2004.04756

- Developed for UHE, high-Q^2 regime (neutrino telescopes)
- Use new NLO PDFs → NLO structure functions
- Include heavy quark contributions
- Non-DIS interactions are neglected

Low-ν method requirements

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_0} = \frac{G_{\mathrm{F}}^2 M}{\pi}\int_0^1 \left(F_2 - \frac{q_0}{E_\nu}\left[F_2 \mp xF_3\right] + \frac{q_0}{2E_\nu^2}\left[\frac{Mx(1-R_{\mathrm{L}})}{1+R_{\mathrm{L}}}F_2\right] + \frac{q_0^2}{2E_\nu^2}\left[\frac{F_2}{1+R_{\mathrm{L}}} \mp xF_3\right]\right)\mathrm{d}x$$



The method works if:

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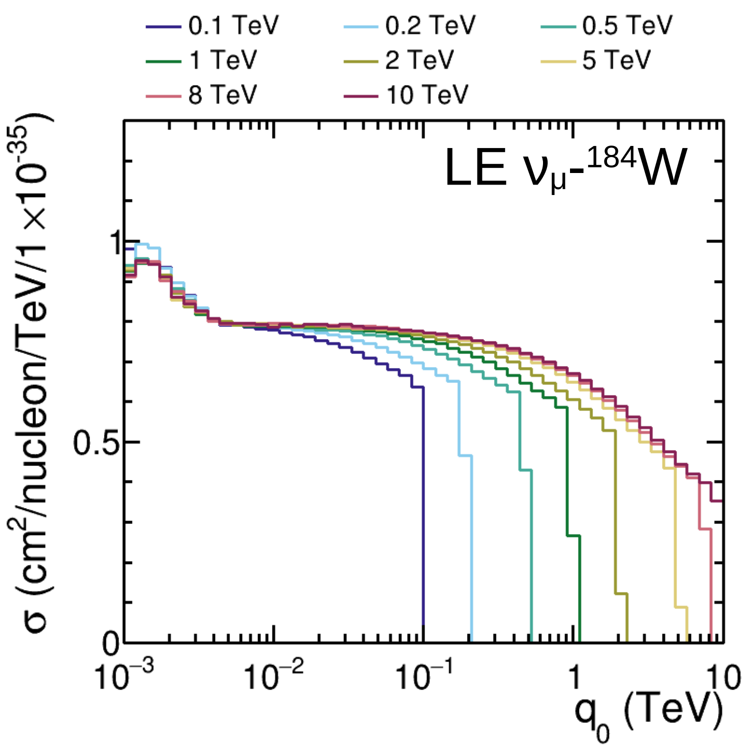
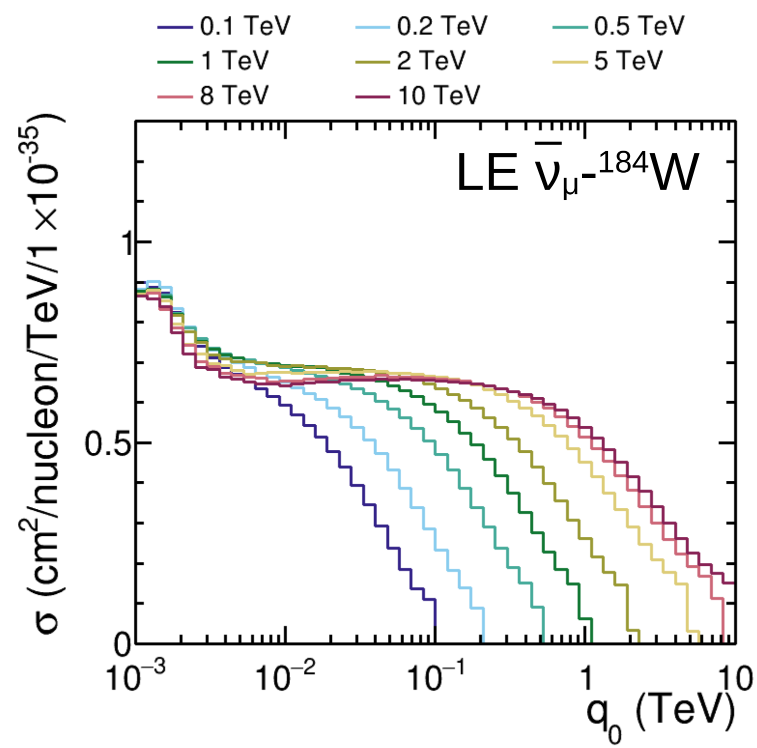
Is the low-q_0 cross section flat in E_ν?





- For ν_μ, $q_0 \leq 20$ GeV relatively constant with E_ν

  (CCFR* used $E_{had} \leq 20$ GeV to define low-ν at $30 \leq E_\nu \leq 360$ GeV)
- More restricted for $\bar{\nu}_\mu$, within a few-% up to $q_0 \leq 10$ GeV

*W. G. Seligman. PhD thesis, Nevis Labs, Columbia U., 1997

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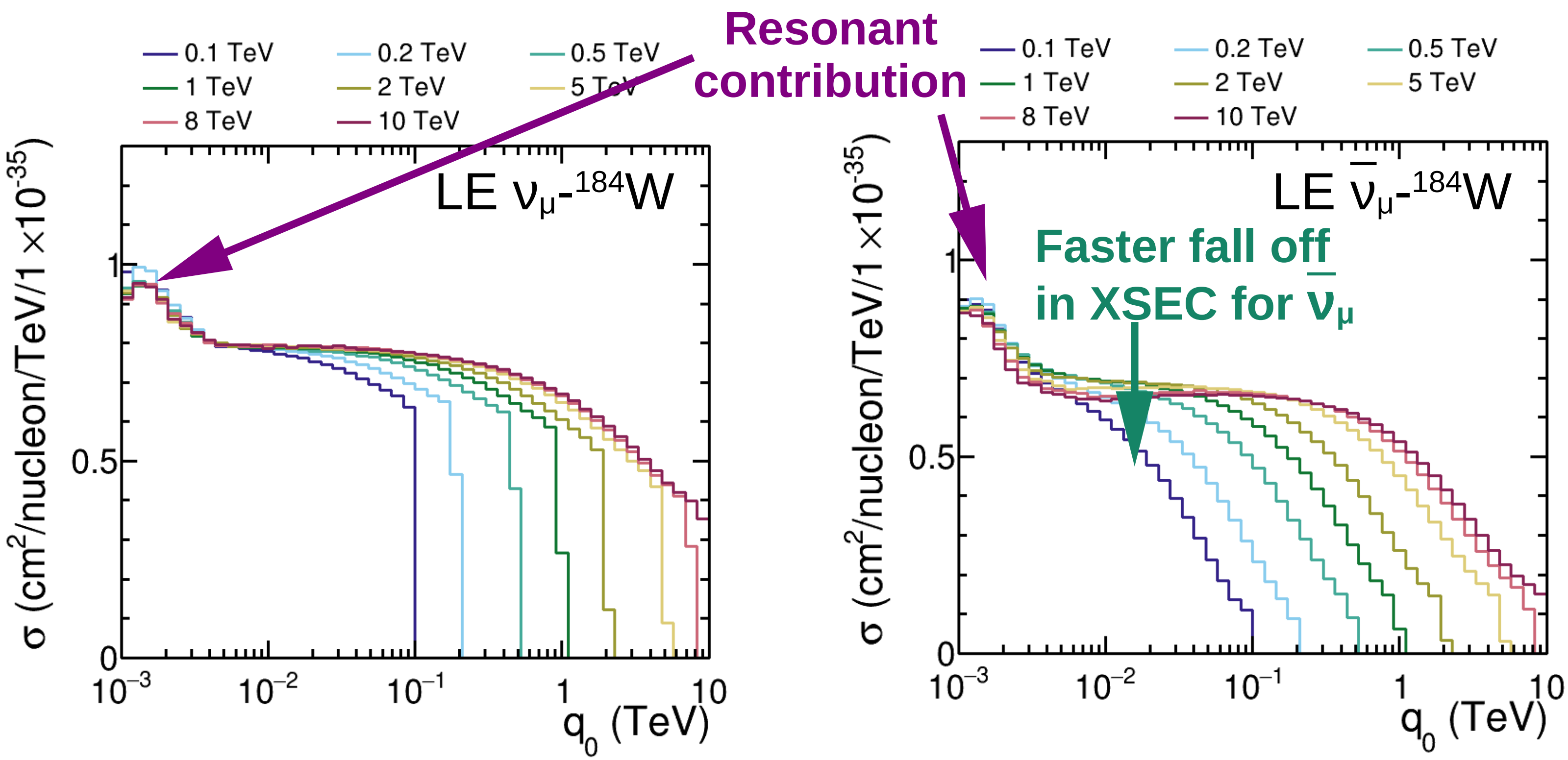

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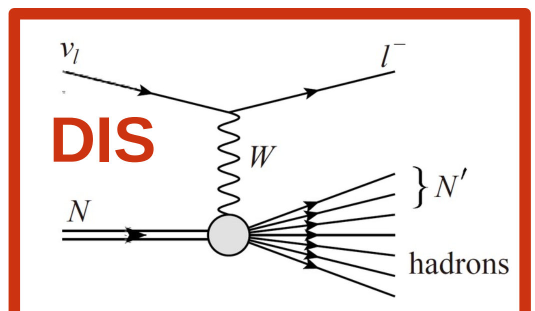

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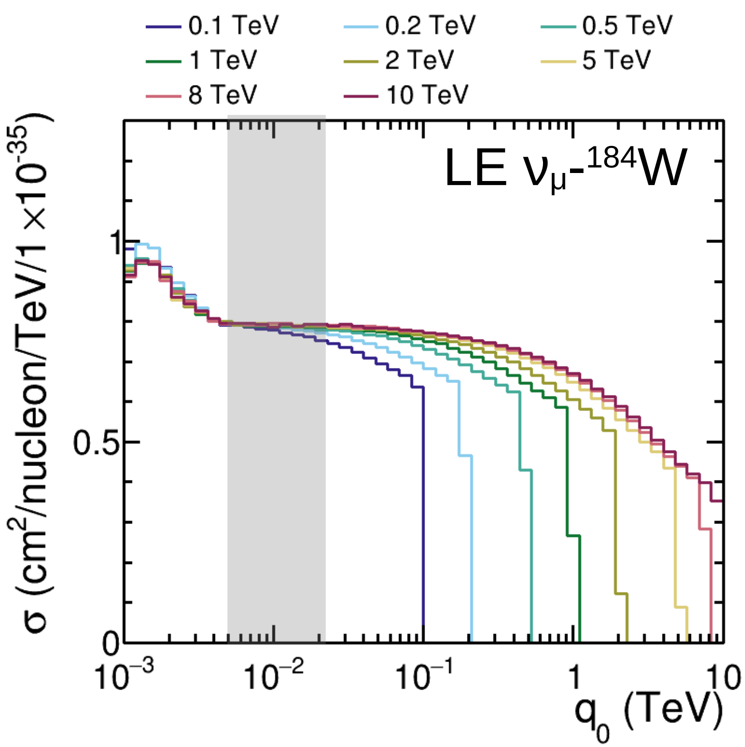

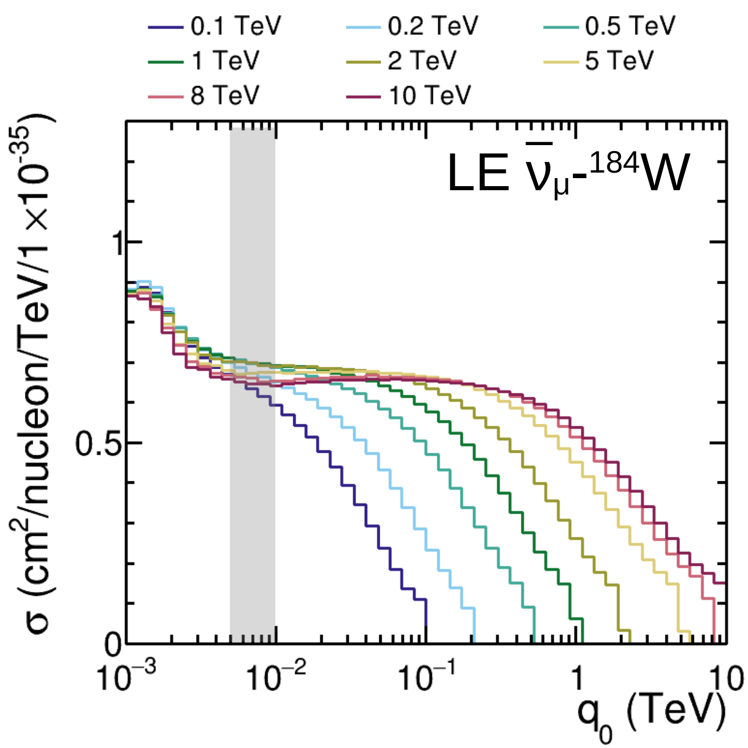

Define low-ν region as:

- ν_μ CC [5 ≤] $q_0 \leq 20$ GeV
- $\bar{\nu}_\mu$ CC [5 ≤] $q_0 \leq 10$ GeV

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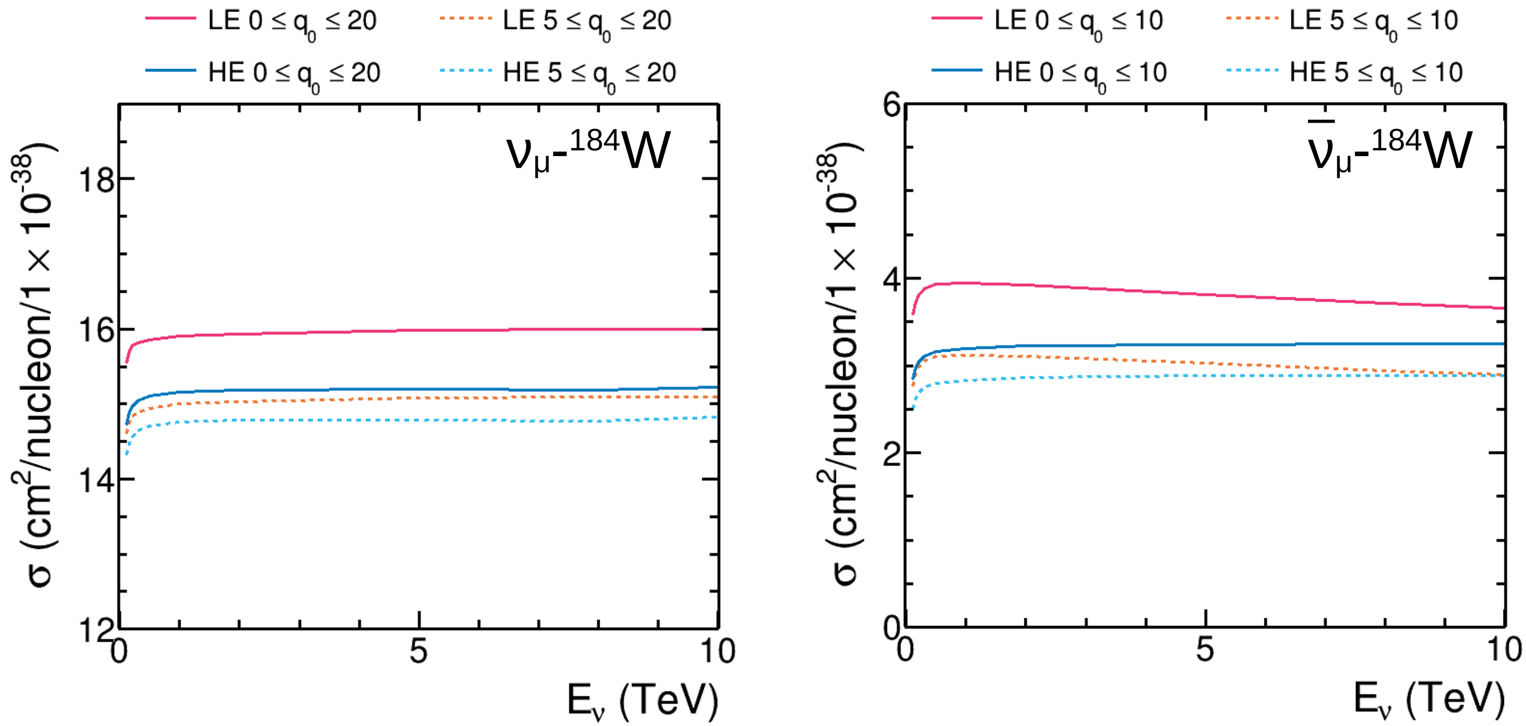
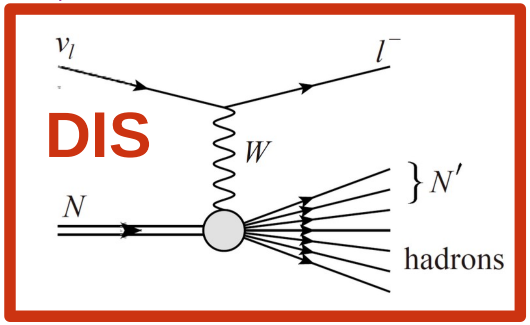


- Low-q_0 sample cross sections ≈linear with E_ν
- Few-% non-linearity at low-q_0 for ν_{μ}, similar for LE and HE
- Larger ≈10% non-linearity for $\bar{\nu}_\mu$, larger LE/HE differences
- Non-DIS contributes ≈10% (≈25%) of ν_μ ($\bar{\nu}_\mu$) low-q_0 region

Low-ν method requirements

$$\frac{d\sigma}{dq_0} = \frac{G_F^2 M}{\pi} \int_0^1 \left(F_2 - \frac{q_0}{E_\nu} [F_2 \mp xF_3] + \frac{q_0}{2E_\nu^2} \left[\frac{Mx(1-R_L)}{1+R_L} F_2 \right] + \frac{q_0^2}{2E_\nu^2} \left[\frac{F_2}{1+R_L} \mp xF_3 \right] \right) dx$$



The method works if:

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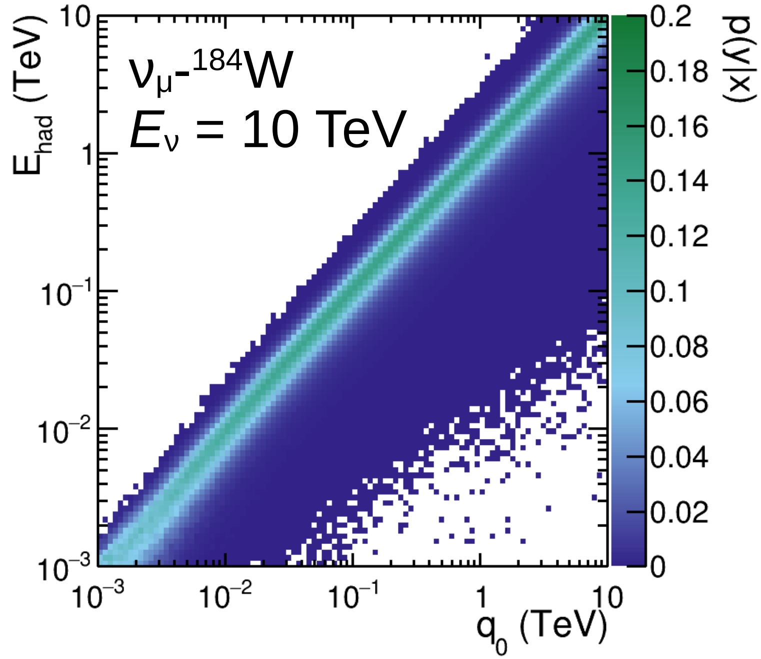
3) It provides a useful number of events

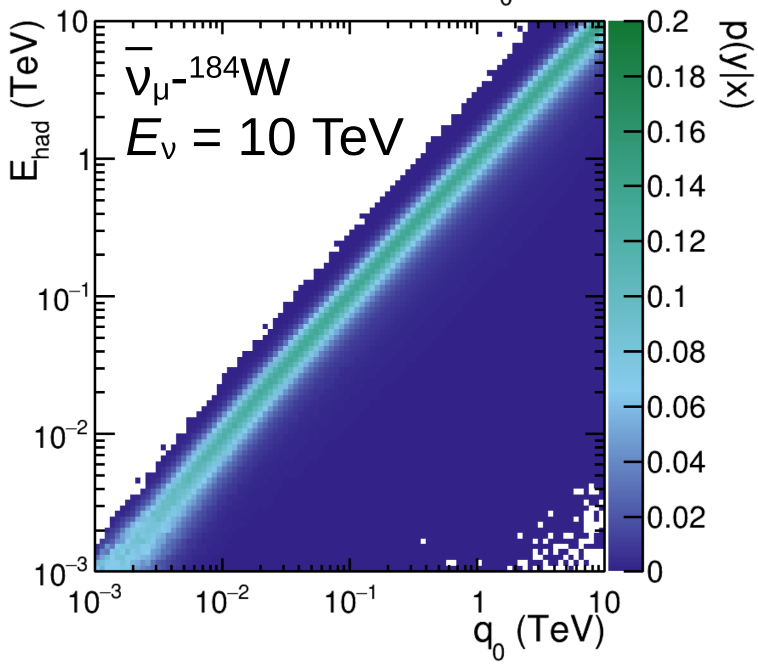
Detector smearing

	FASERν2
Fiducial mass	20 t
Det. cross-section	0.5×0.5 m
Target material	^{184}W
Muon resolution	5%
Charged had. res.	50%
Charged had. threshold	$p \geq 300$ MeV
EM shower res.	50%
Minimum track cut	5
Invisible particles	n, $\bar{n}$, K_L^0, ν_X

$$E_{\rm had}^{\rm reco} = \Big(\sum_{i=p,\bar{p}} E_{\rm kin}^i\Big) + \Big(\sum_{i=\pi^\pm,K^\pm,\gamma,l^\pm,K_S^0} E_{\rm total}^i\Big)$$

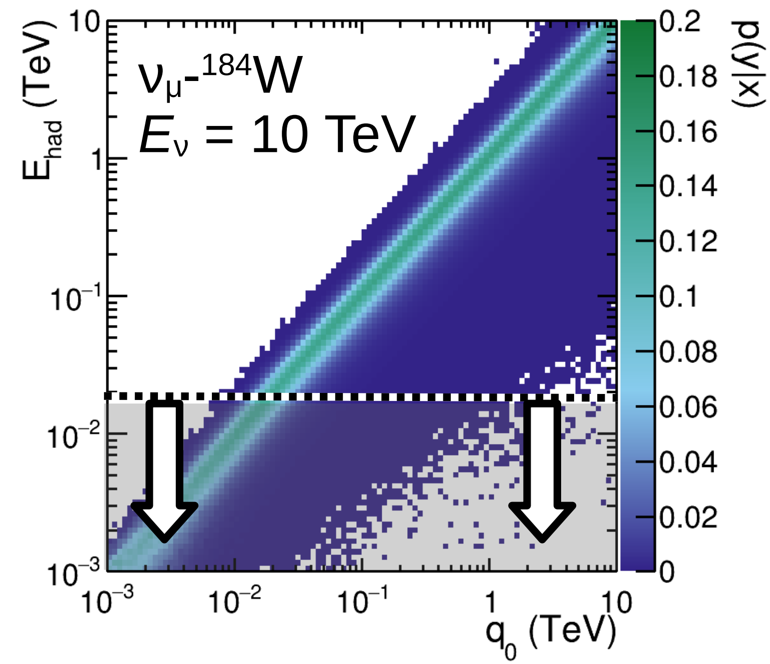
- Assumptions follow FPF design docs
  → *details in PRD **109**, 033010 (2024)*
- $E_{\rm had} \approx q_0$ for central population
- Low $E_{\rm had}$ tail from unobserved particles

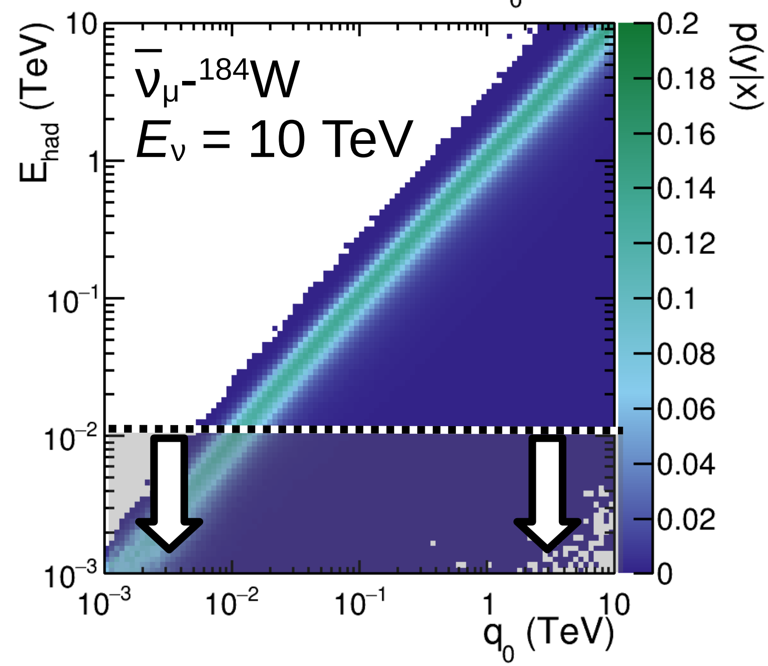




Can a low-q_0 sample be experimentally selected?

- Cutting on E_{had} introduces a high-q_0 tail to the sample
- Necessarily E_ν dependent to *some* extent
- Depends more on hadronization model (e.g., unobservable E_{loss})
- More pronounced for $\bar{\nu}_\mu$ (≈10%) than ν_μ (≈1%)





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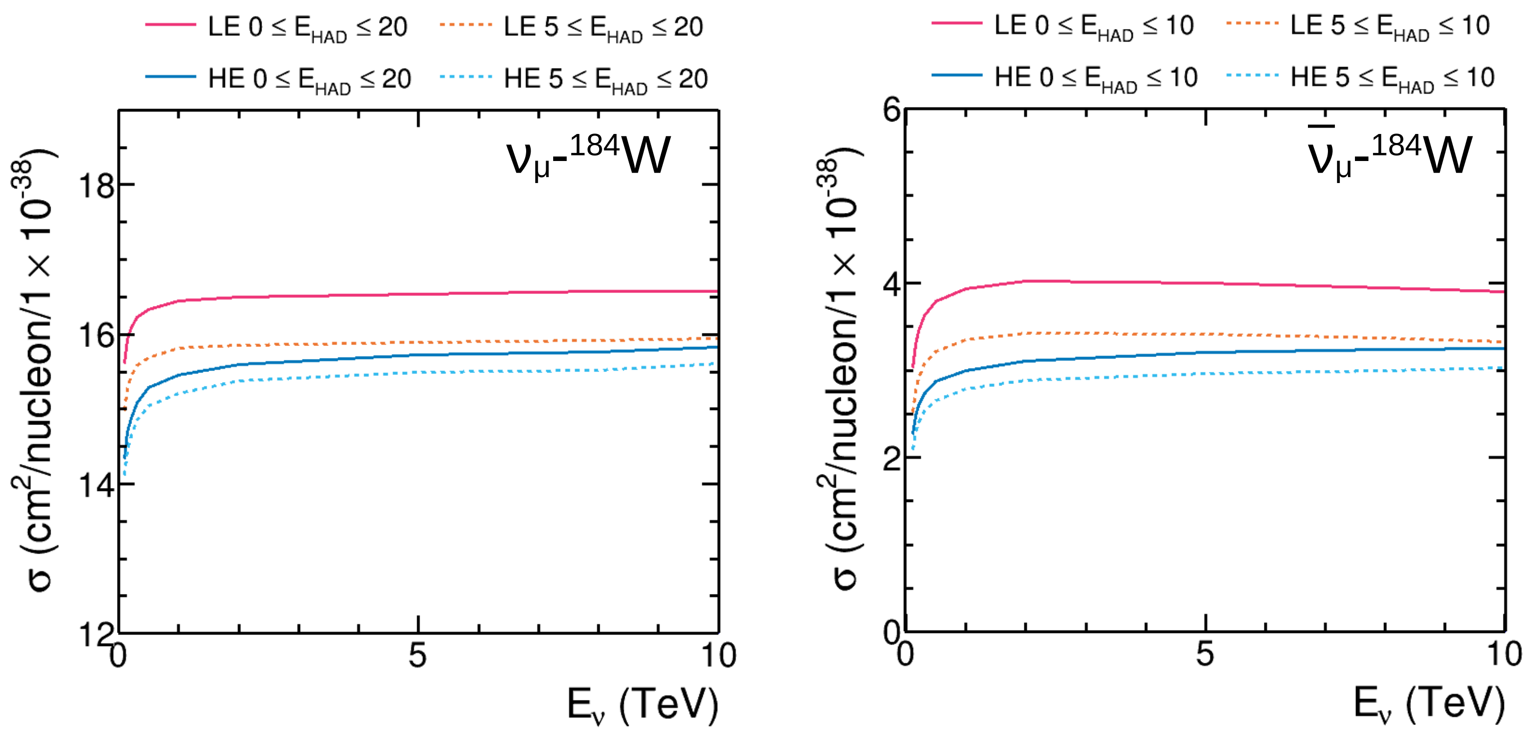

- Low-E_{had} sample cross sections ≈linear with E_ν
- Slightly less linear for both ν_μ and $\bar{\nu}_\mu$ than true-q_0 case
- Larger LE/HE differences: few-% for ν_μ, ≈10% for $\bar{\nu}_\mu$

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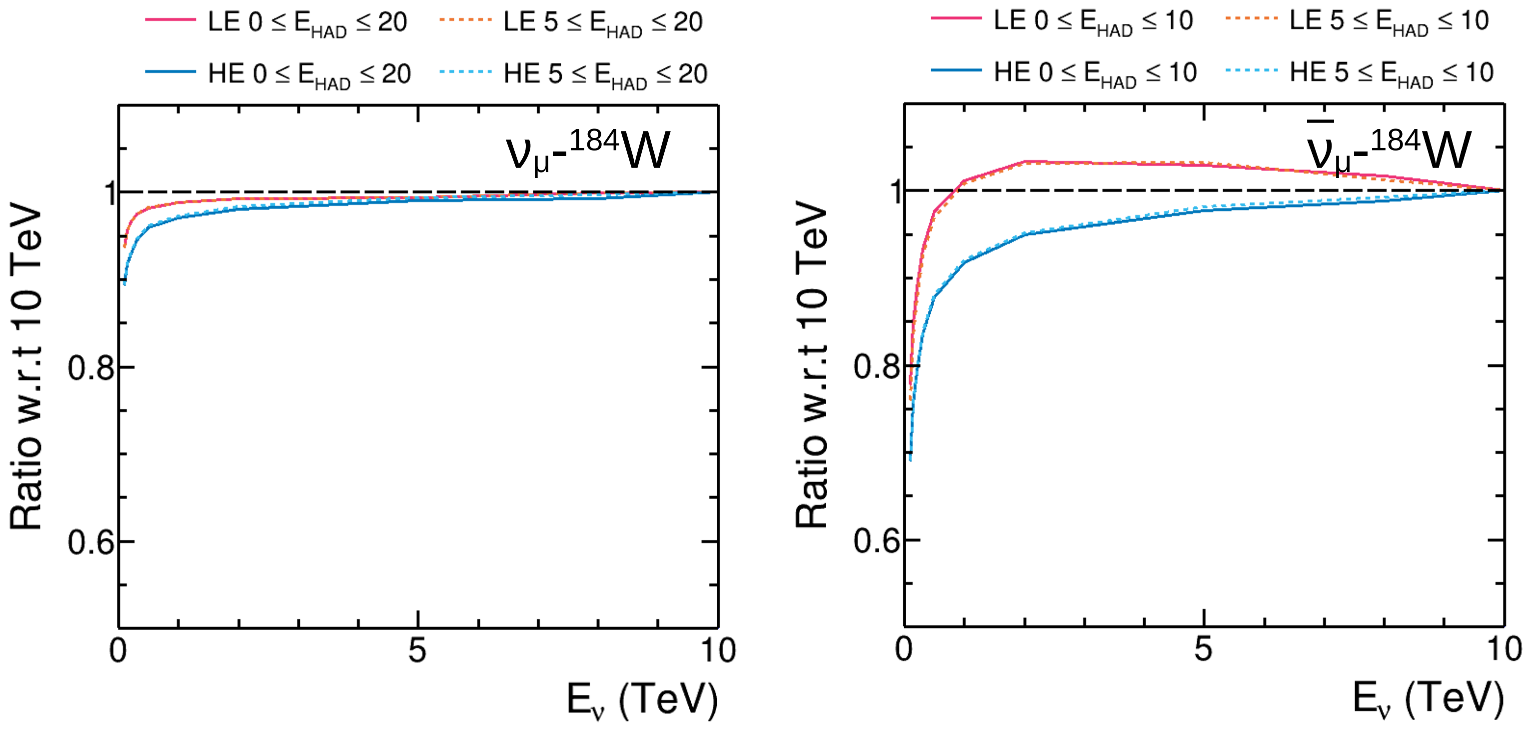

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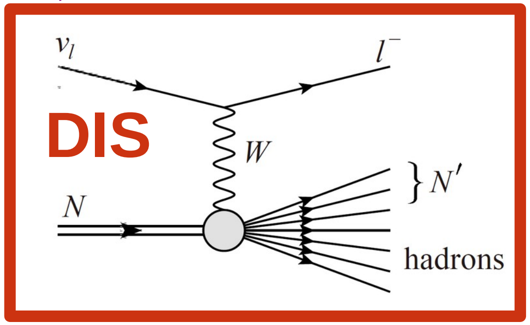

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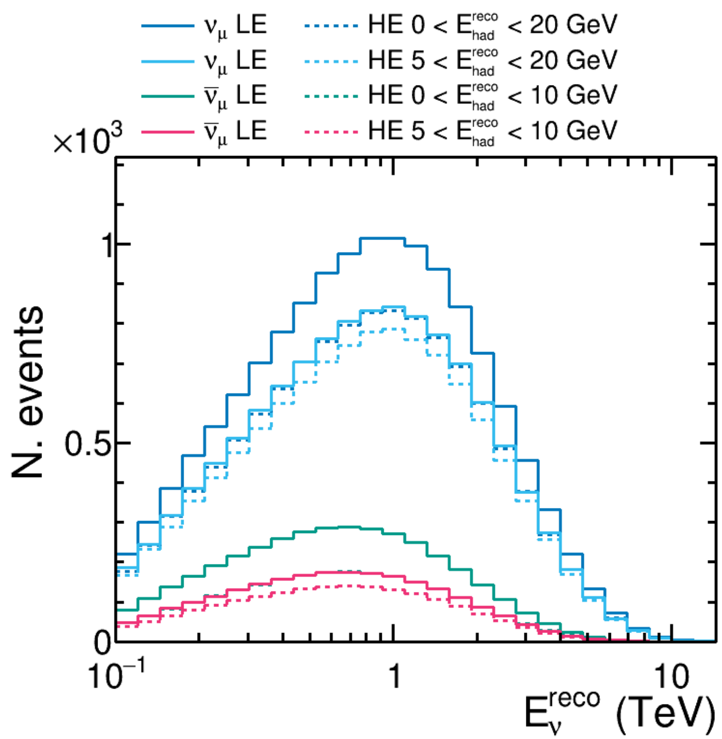
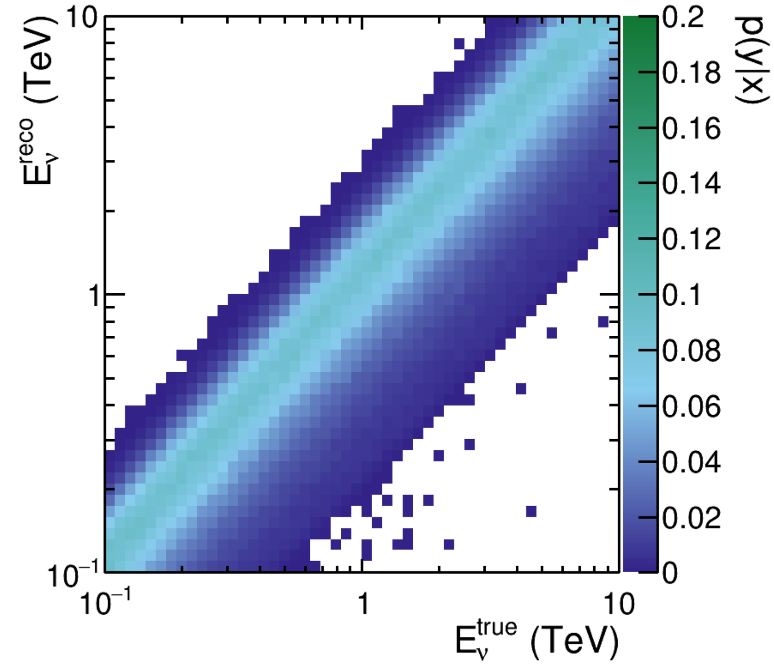
Low-ν sample event rate





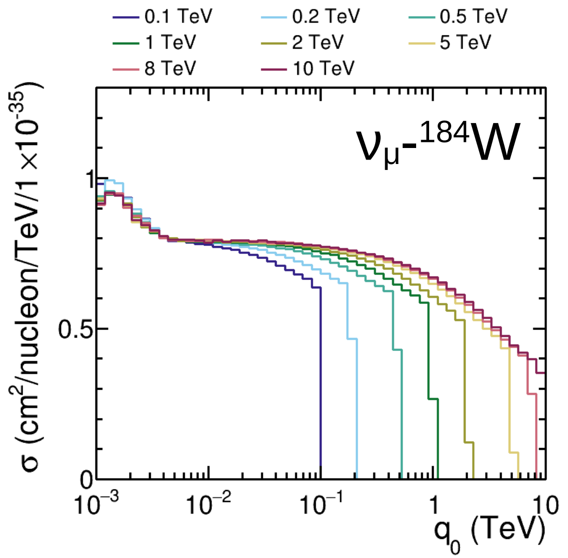
- For a 3000 fb^{-1} exposure, FASERν2 low-ν samples have O(10,000) ν_μ and O(1,000) $\bar{\nu}_\mu$ events
- Relationship between reco. and true E_ν is fairly diagonal (dominated by E_μ)

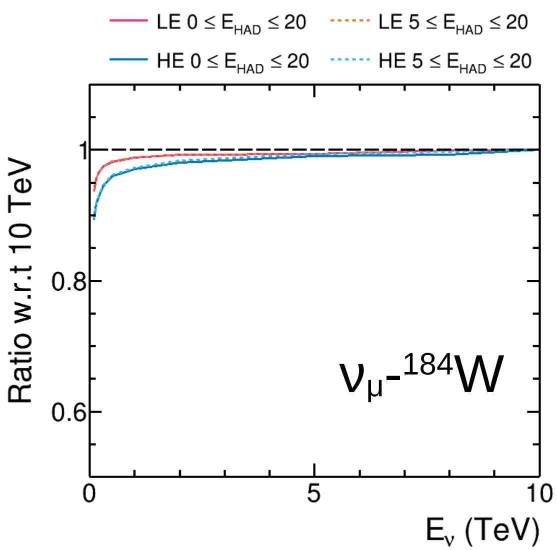
$$E_\nu^{\text{reco}} = E_\mu + E_{\text{had}}^{\text{reco}}$$

Low-ν method requirements

The method works if:

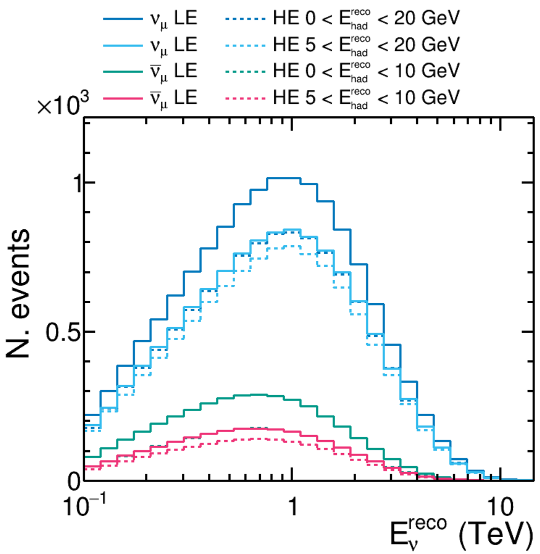
1) There is a low-q_0 region with a constant cross section in E_ν



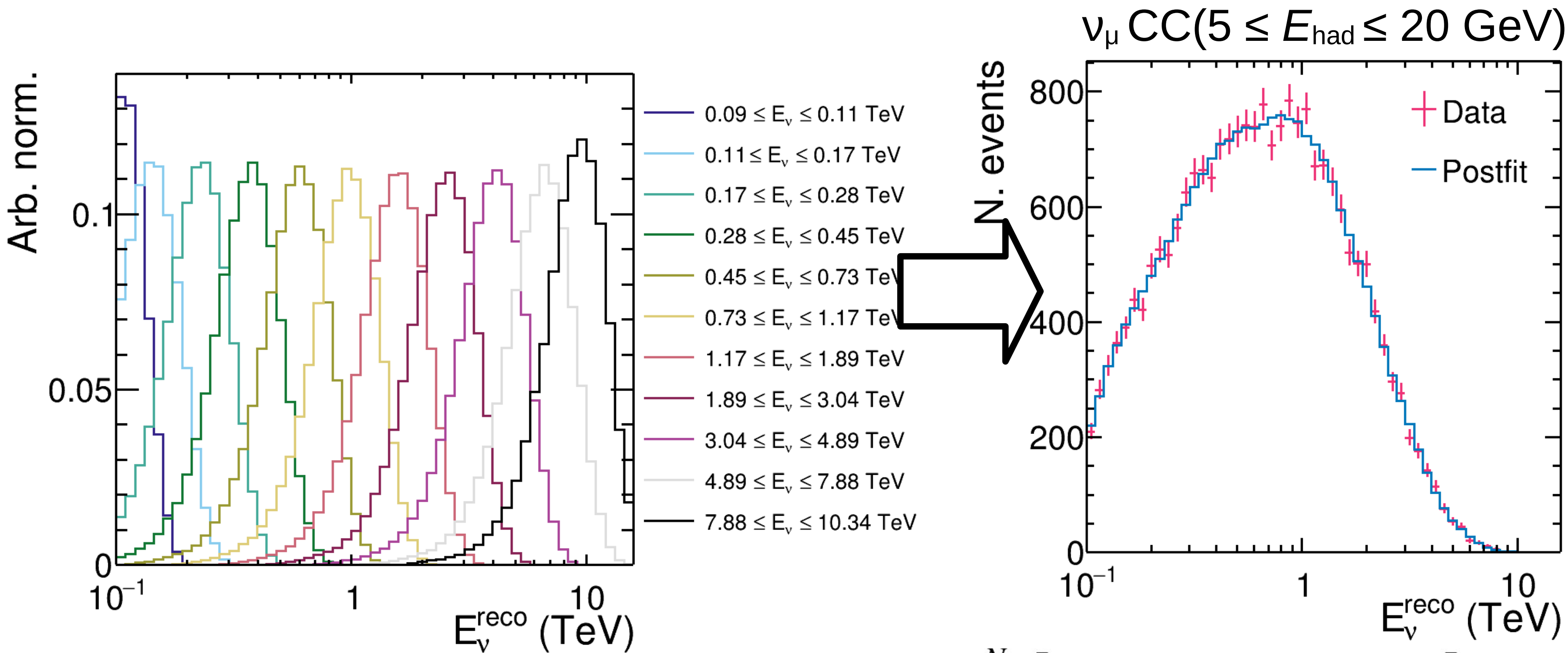


2) It can be selected without significant model dependence

3) It provides a useful number of events



FASERv2 ν_μ flux constraint

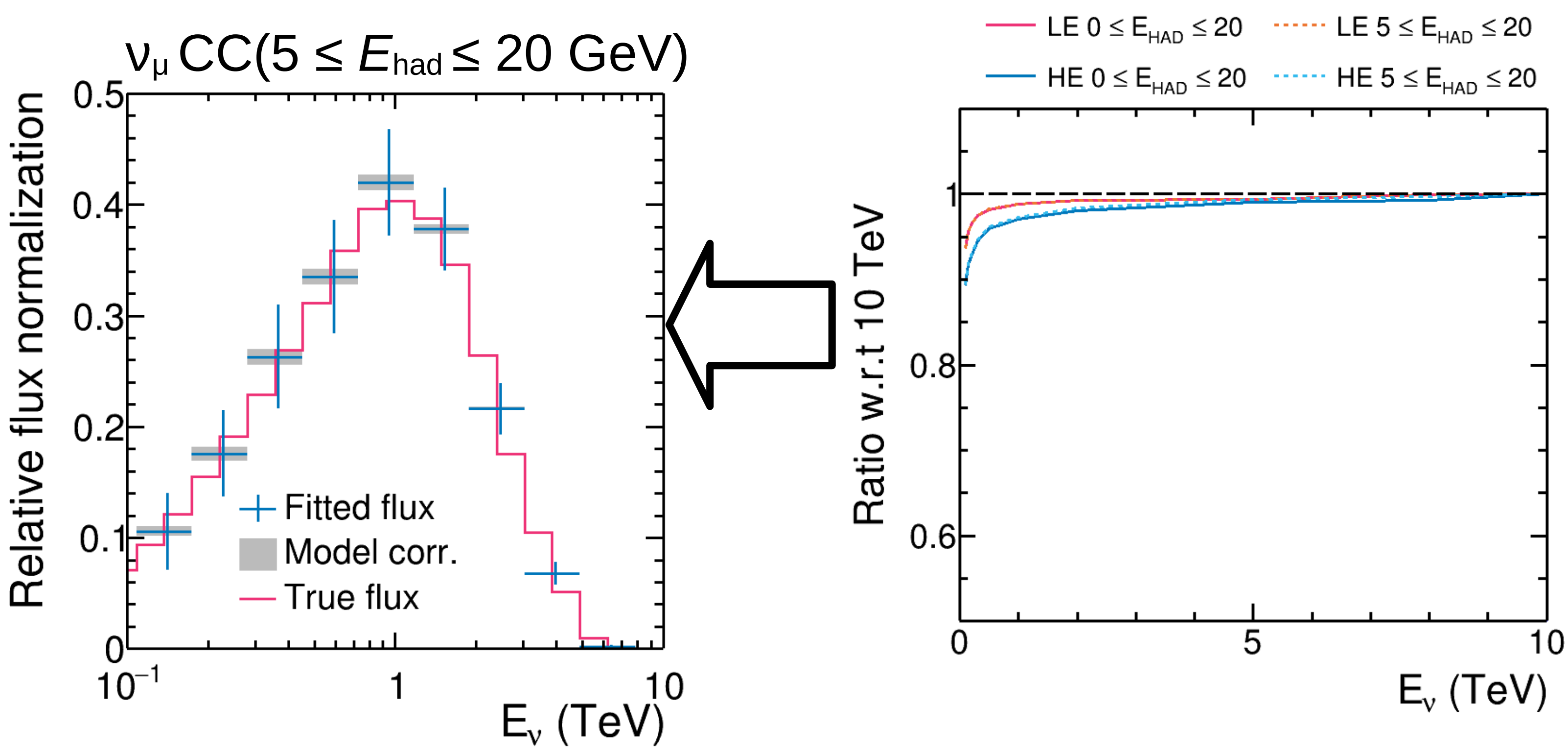


- Simple analysis to check utility

$$\chi^2 = 2\sum_{i=1}^{N}\left[\mu_i(\vec{\mathbf{x}}) - n_i + n_i \ln \frac{n_i}{\mu_i(\vec{\mathbf{x}})}\right]$$

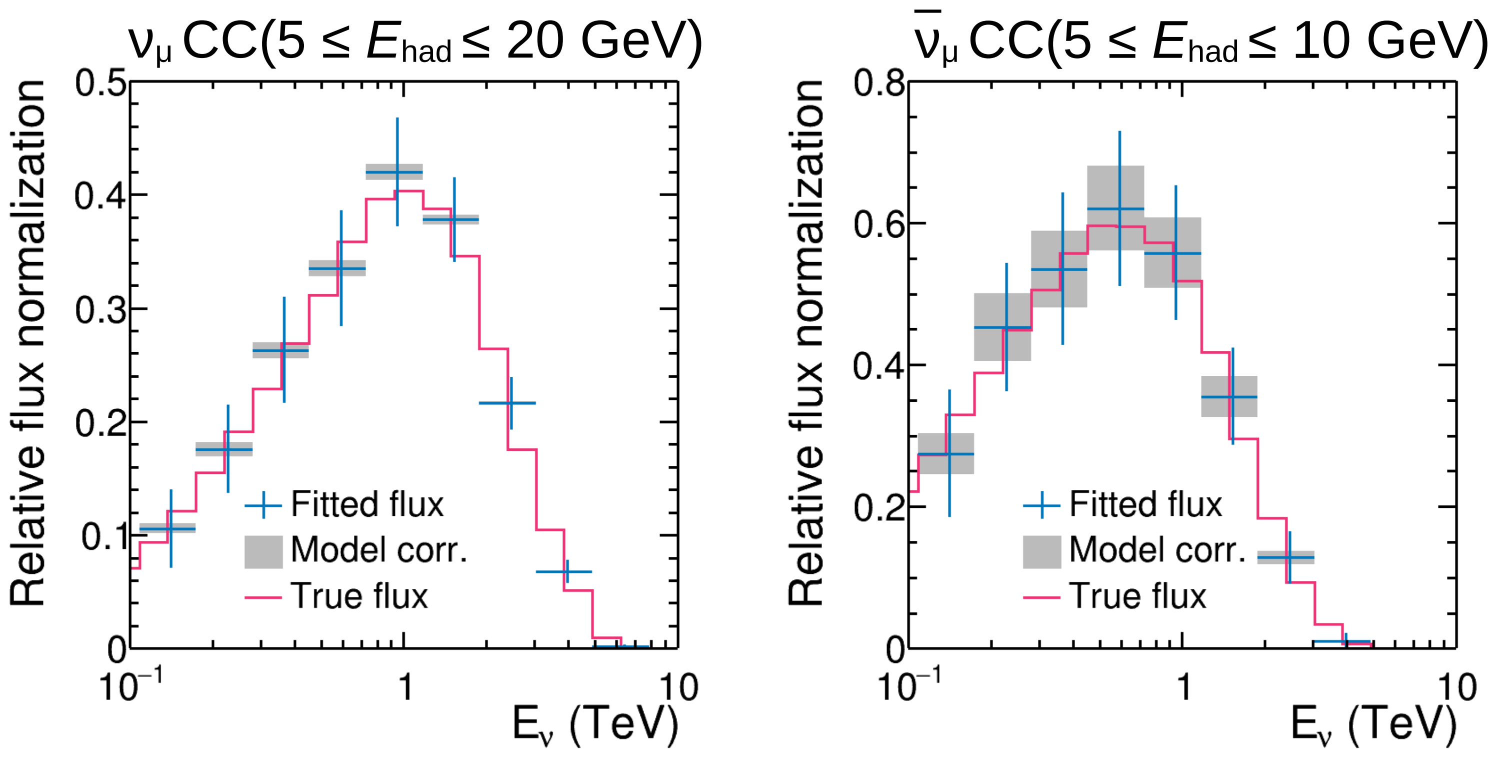
- Template LLH fit: vary normalizations of templates that correspond to a region of true E_ν, binned in reco E_ν
- Best fit template normalizations and uncertainties give the flux constraint in true E_ν bins

FASERv2 ν_μ flux constraint



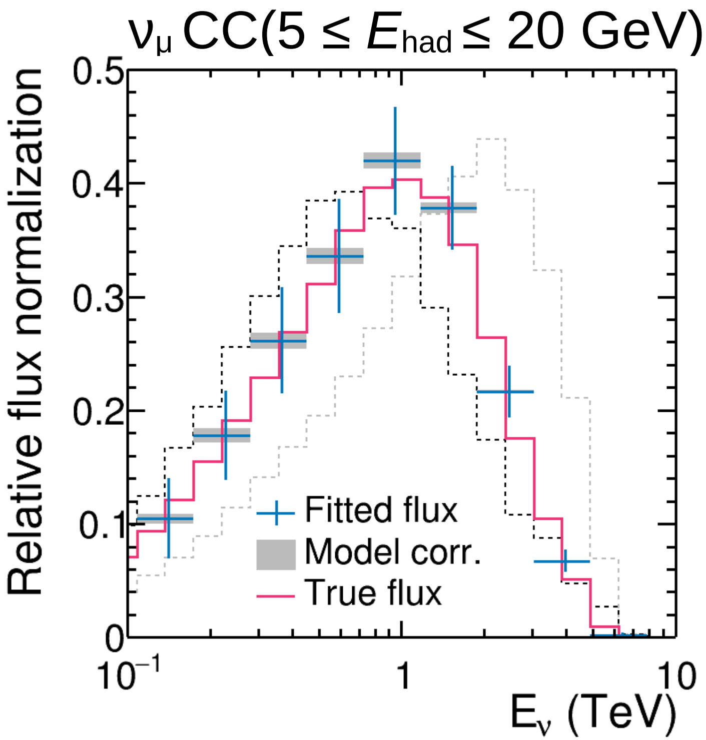
- The fitted flux shape has a 10-20% bin-to-bin uncertainties (although bins are correlated)
- The fitted flux is corrected for E_ν-dependence, the model correction uncertainty shows the full LE/HE difference

What about $\bar{\nu}_\mu$? (still FASERv2)



- Much larger model correction uncertainty ≈stat. uncertainty
- Potentially still useful as a cross-check given the huge differences between production models
- *Possible* for a more advanced analysis to attempt to constrain E_ν-dependence with data

FASERv2: hadron production model selection



- "True" flux uses SIBYLL v2.3d for both light and charmed hadron production
- Black (gray) lines use EPOSLHC (DPMJET-III) for light (charmed) hadron production

All fluxes from: PRD104, 113008 (2021)

SIBYLL v2.3d: PRD102, 063002 (2020)

EPOSLHC: PRC92, 034906 (2015)

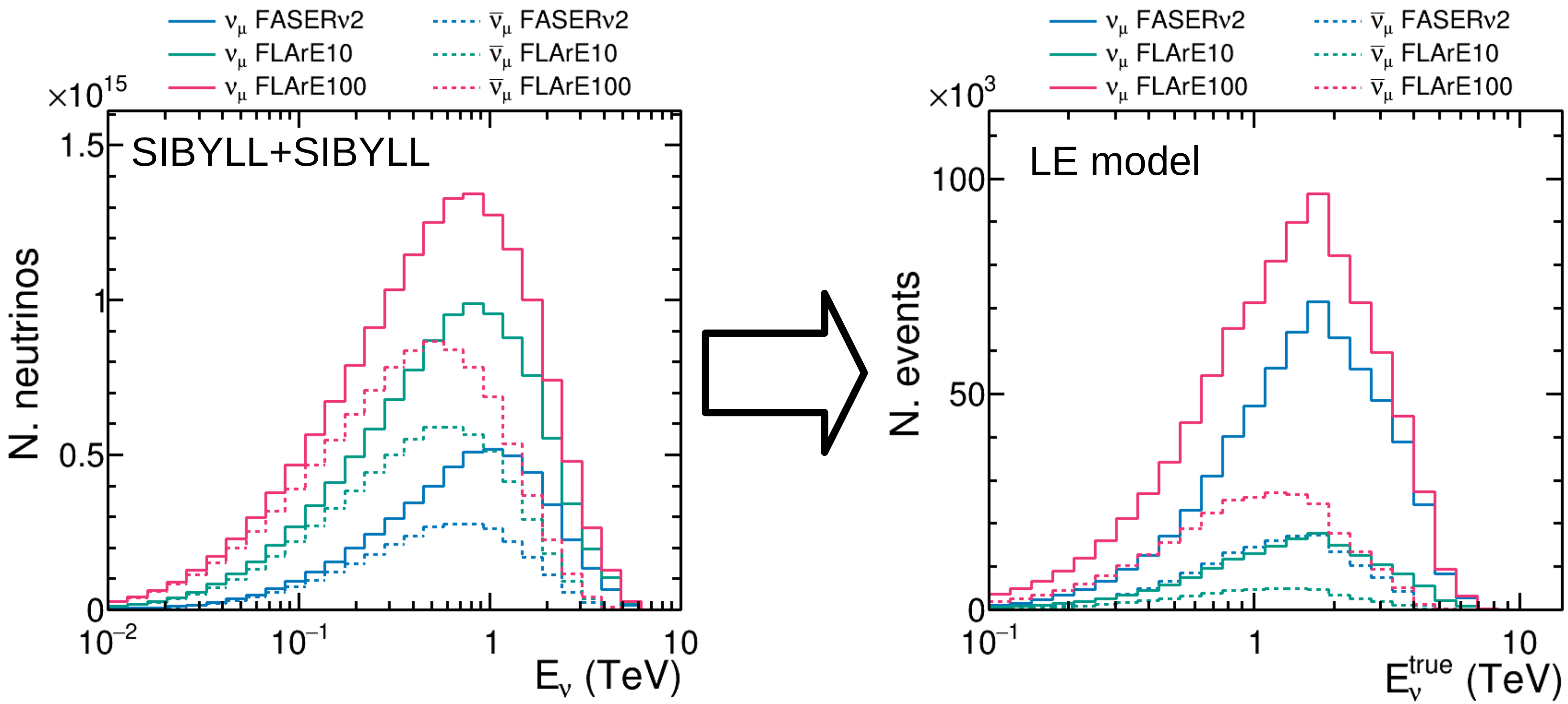
DPMJET-III: arXiv:hep-ph/0012252

Conclusions

- The low-ν method may be very useful for FPF physics by breaking production and interaction degeneracies
- For 3000 fb^{-1}, FASERv2 can make ν_μ flux shape measurements with 5–10% bin-to-bin uncertainties
- Situation is less clear for $\bar{\nu}_\mu$, other flavors not possible
- Similar conclusions for FLArE10 and FLArE100 in PRD **109**, 033010 (2024)
- This is all very high-level, without proper reconstruction etc, and should be used to motivate a full study in future

Backup

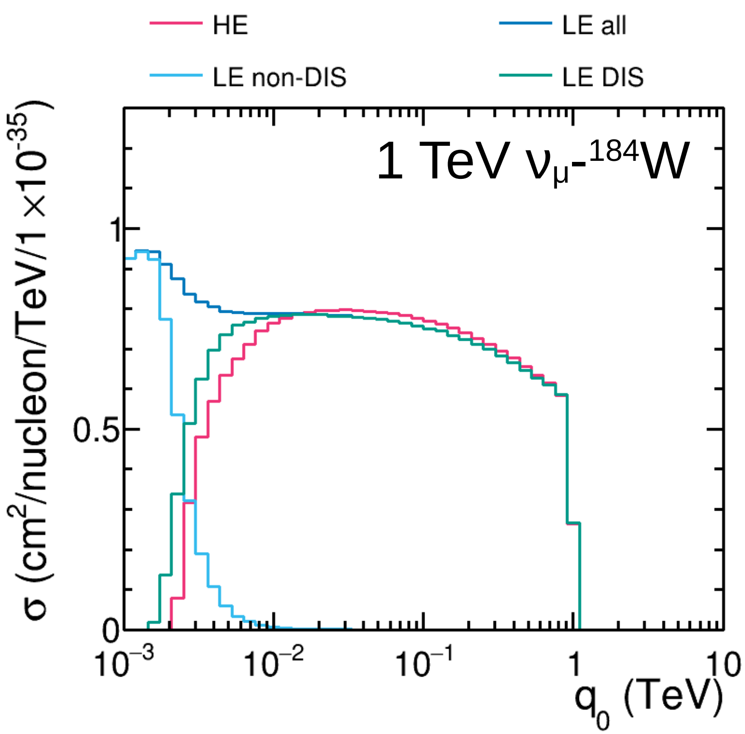
FPF event rate



- Neutrino flux predictions* for three FPF detector options
  Later I'll only show FASERν2 (but all are in the paper)
- Shown for 3000 fb^{-1} HL-LHC run
- Cross section ≈linear with E_ν

*PRD104, 113008 (2021)

LE/HE model differences

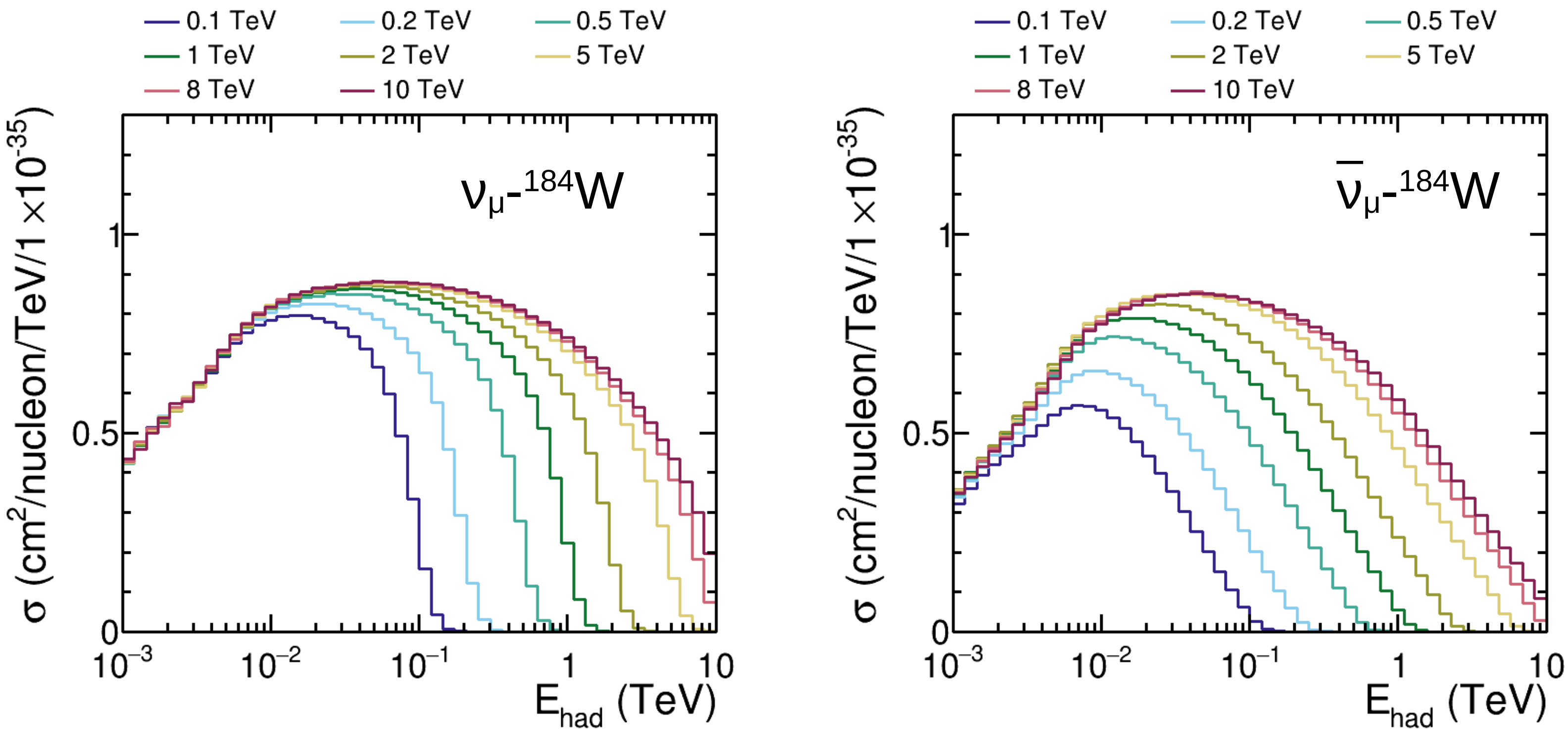


- LE non-DIS dominates $q_0 \leq 3$ GeV, large for $q_0 \leq 5$ GeV
- HE tune DIS qualitatively similar to LE, but turn-on differs
- General trends for both models similar for all energies, and for $\bar{\nu}_\mu$

Define low-ν region as:

- ν_μ CC [5 ≤] $q_0 \leq 20$ GeV
- $\bar{\nu}_\mu$ CC [5 ≤] $q_0 \leq 10$ GeV

Smeared cross section

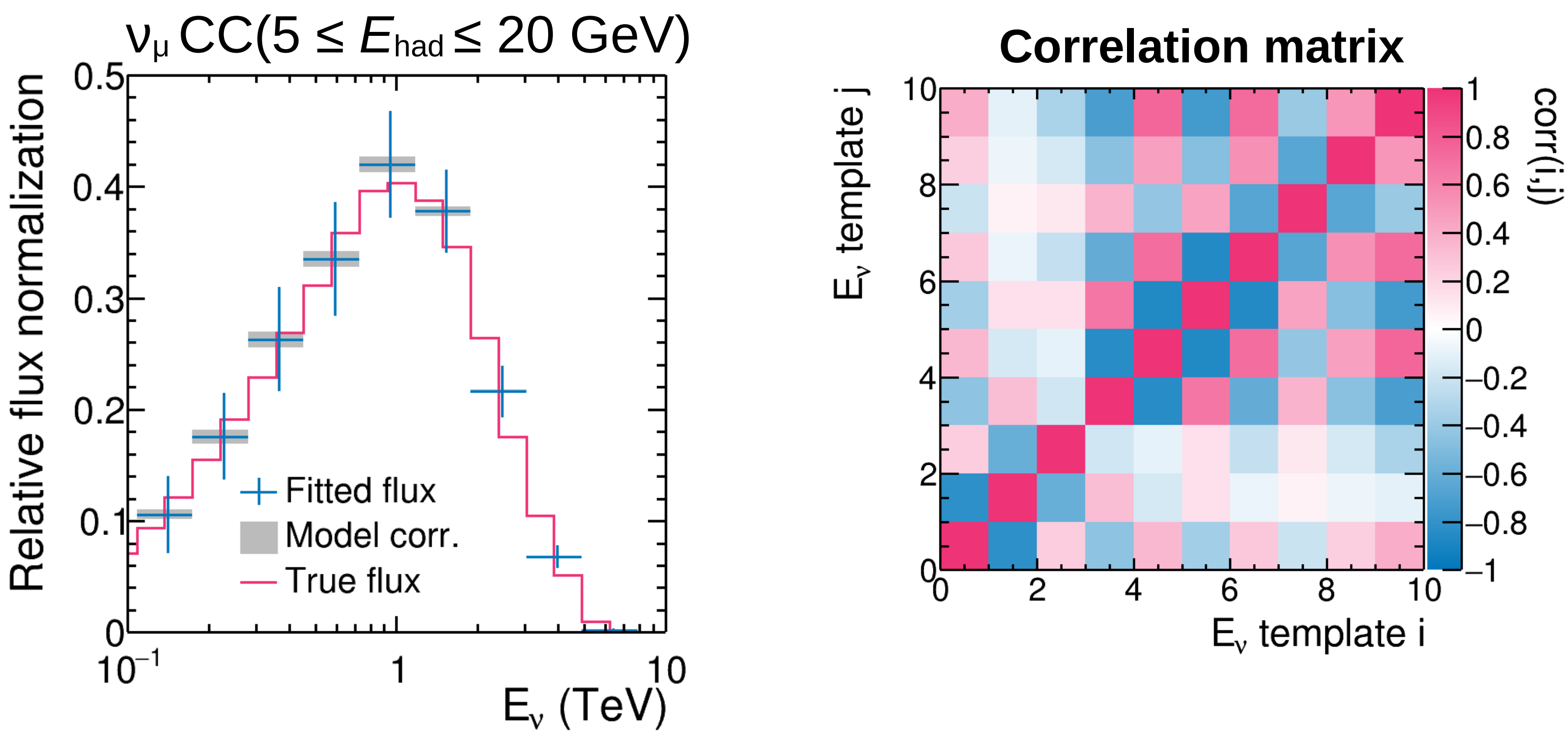


- Charged hadron track cut suppresses the resonance peak Low-E_{had} sample cross sections ~linear with E_ν

- Slightly less linear for both ν_μ and $\bar{\nu}_\mu$ than low-q_0 case

- Larger LE/HE differences: few-% for ν_μ, ~10% for $\bar{\nu}_\mu$

FASERv2 ν_μ flux constraint



- The fitted flux shape has a 10-20% bin-to-bin uncertainties (although bins are strongly correlated)
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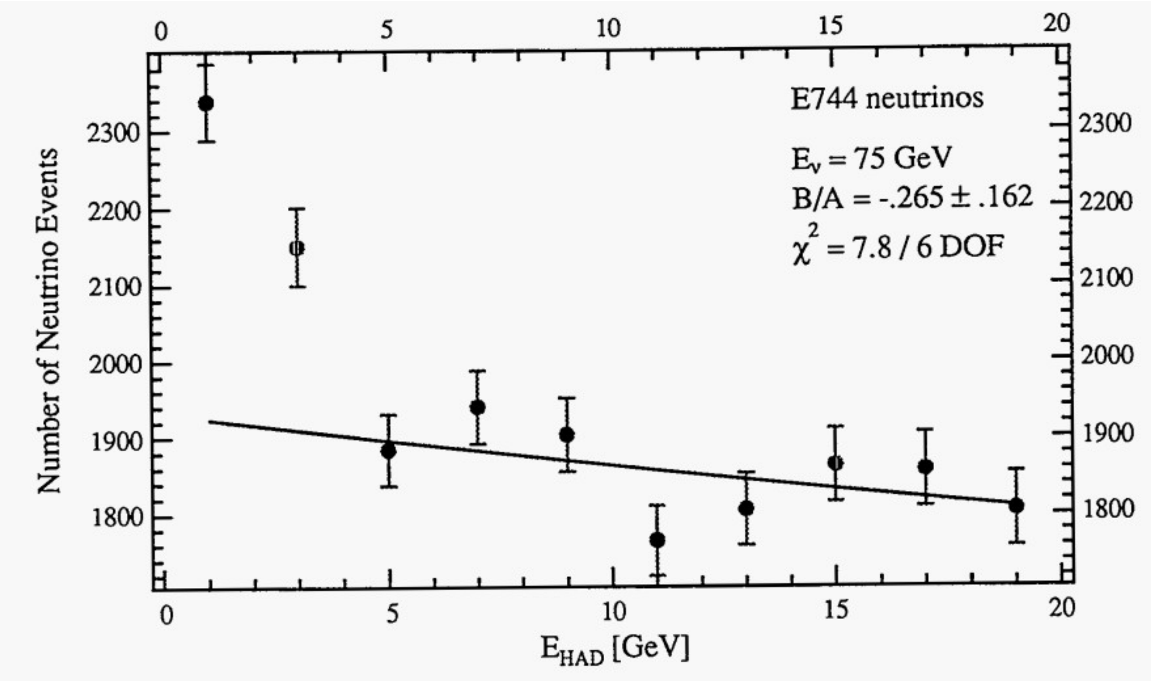
Example: CCFR analysis

W. G. Seligman. PhD thesis, Nevis Labs, Columbia U., 1997



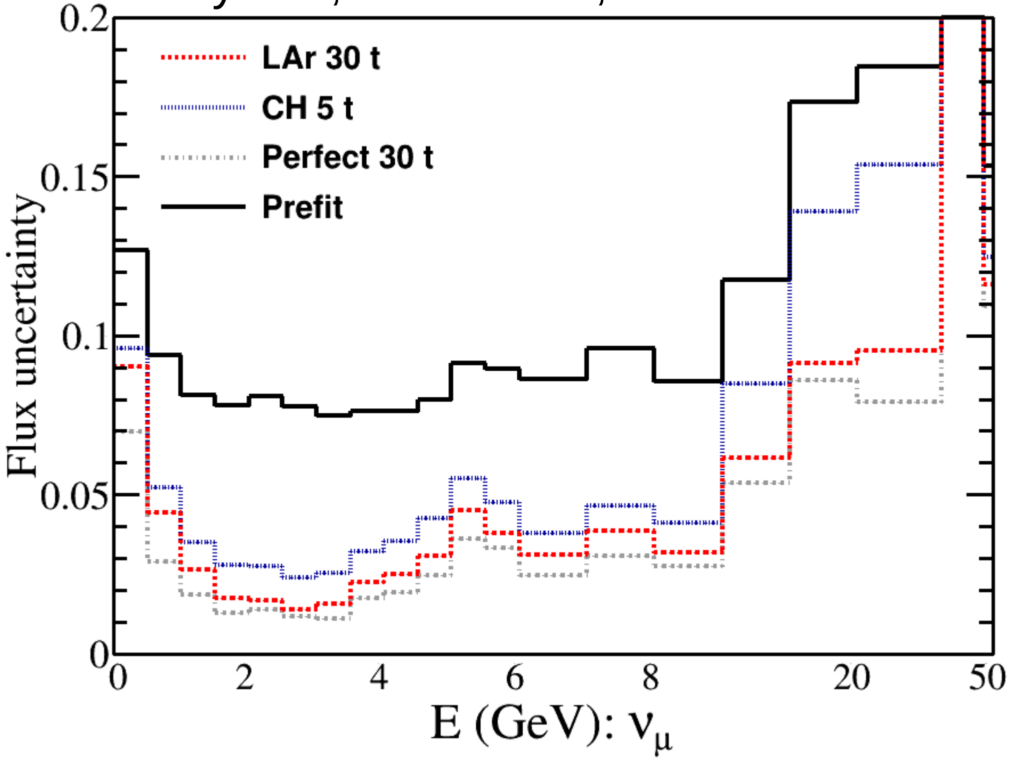
- CCFR use low-ν for $30 \leq E_\nu \leq 360$ GeV
- E_{HAD} is their q_0 proxy, and their low-ν sample is $E_{HAD} \leq 20$ GeV
- To estimate the q_0/E_ν correction, they exclude $E_{HAD} \leq 4$ GeV because resonant events don't have the correct scaling

Neutrino-electron elastic scattering

- The known, but small, cross section can be used to constrain the flux. ~5000 LAr ND events/year

- A powerful additional tool for achieving DUNE’s sensitivities, and resolving flux ↔ cross section ambiguities

5 years, 30 t LAr FV, 1.2 MW beam



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$$E_\nu = \frac{E_e}{1 - \frac{E_e(1-\cos\theta)}{m}}$$

- Strong normalization contraint due to known XSEC

- Weak shape constraint due to detector smearing and beam divergence