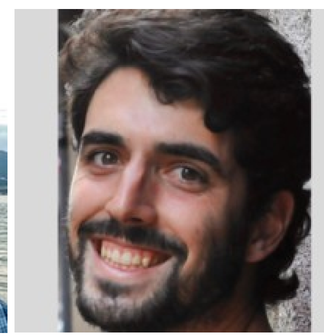
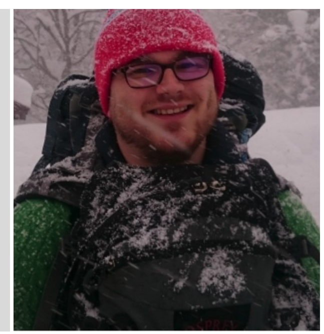
Low-ν: a tale of two energies

It was the best of methods, it was the worst of methods, ...

ICHEP 2024, 18th July 2024

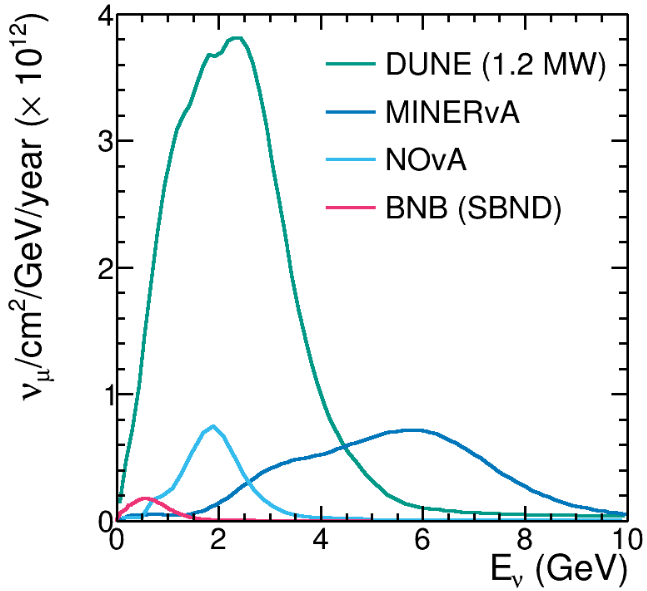
C. Wilkinson, S. Dolan, A. Garcia Soto, L. Pickering, C. Wret

BERKELEY LAB

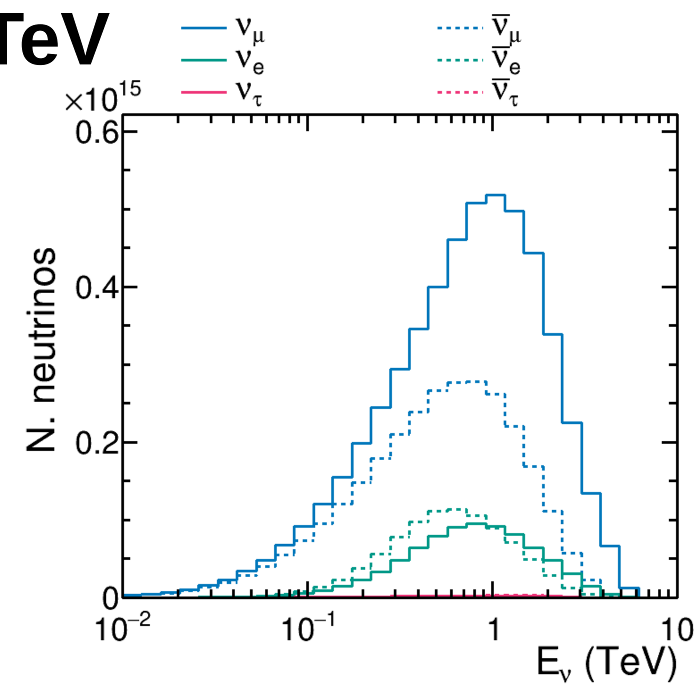
Two energy regimes

Few-GeV



- Flux from $\pi^\pm$ and $K^\pm$ decay
- Constrained at 5-10% by dedicated experiments
- Primary interest in oscillation + secondary XSEC, BSM goals

TeV



- Flux from $K^\pm$ and charmed meson decay
- Unmeasured, the production mechanism is of interest
- XSEC and BSM searches are also primary goals

We don’t understand the flux or the cross section that well at either few-GeV or TeV energies…

…so, how can the degeneracy be broken?

Standard candles?

Specific processes with a known cross section to break the degeneracy with the flux

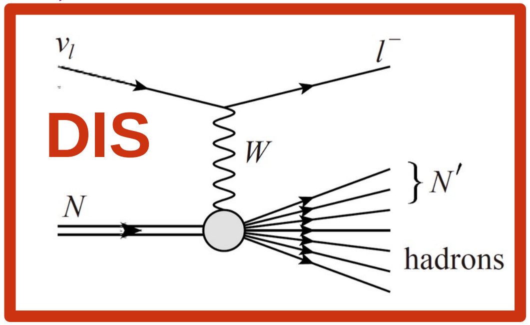
Powerful beams at current and future experiments make small signals accessible

- $\nu_l + e^- \rightarrow \nu_l + e^-$ elastic scattering
- Inverse muon decay: $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$
- **The low-ν method**
- …?

"ν" refers to energy transfer. Here I'll use q_0 to denote energy transfer, and low-ν for the method

The low-ν method [1,2]

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



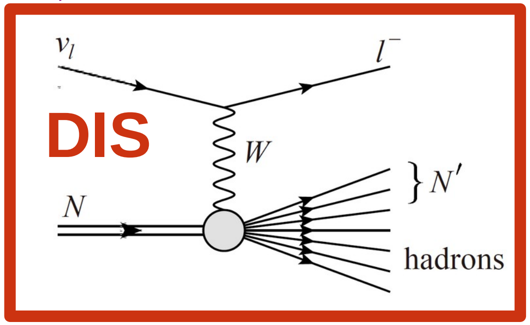
- Comes from the observation that if **$q_0/E_\nu \ll 1$**, the cross section is approximately constant with **E_ν**
- The rate as a function of E_ν gives access to the flux *shape*
- Very closely linked to the "low-y" ($y = q_0/E_\nu$) method [2]

[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

Low-ν method requirements

$$\frac{d\sigma}{dq_0} = \frac{G_F^2 M}{\pi} \int_0^1 \left(F_2 - \frac{q_0}{E_\nu} [F_2 \mp x F_3] + \frac{q_0}{2E_\nu^2} \left[\frac{Mx(1-R_L)}{1+R_L} F_2 \right] + \frac{q_0^2}{2E_\nu^2} \left[\frac{F_2}{1+R_L} \mp x F_3 \right] \right) dx$$



The method works if:

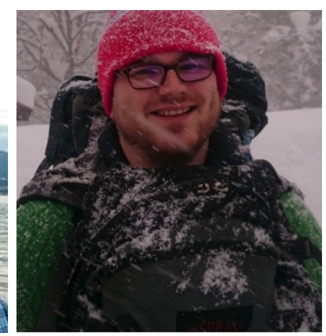
1) There is a low-q_0 region with a constant cross section in E_ν

2) It can be selected without significant model dependence

3) It provides a useful number of events

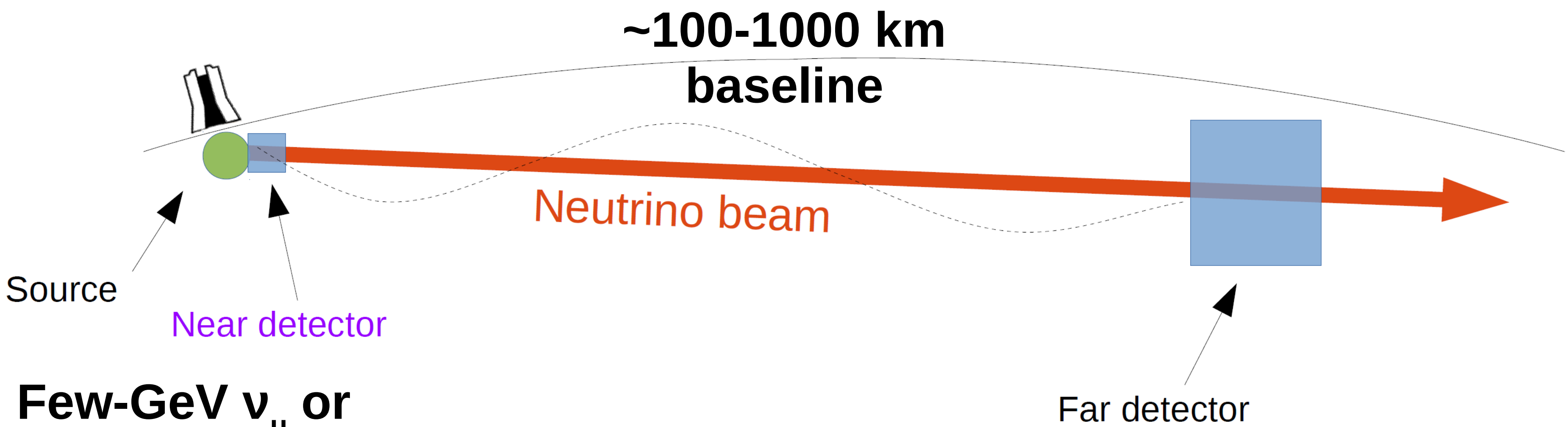
Part I: few-GeV energies

(the worst of methods)

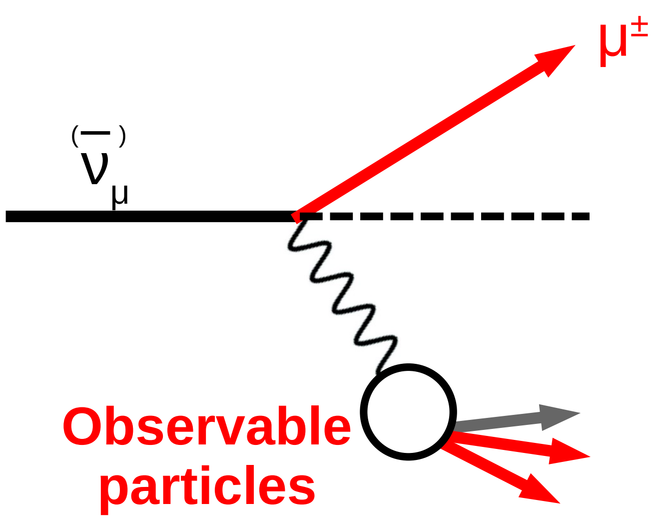
   

EPJC **82**, 808 (2022)
arXiv:2203.11821 [hep-ph]

Accelerator neutrino experiments



Few-GeV ν_μ or $\bar{\nu}_\mu$ beam

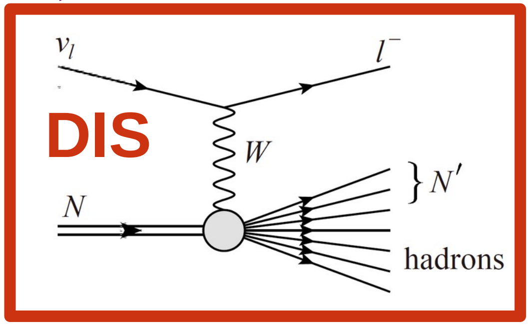


$$R(\vec{\mathbf{x}}) = \underbrace{\overbrace{\int dE \;\; \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(E_\nu; \nu_A \to \nu_B)}_{\text{Far}}$$

Event rate
Neutrino flux
Cross section
Detector smearing
Oscillation probability

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:

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

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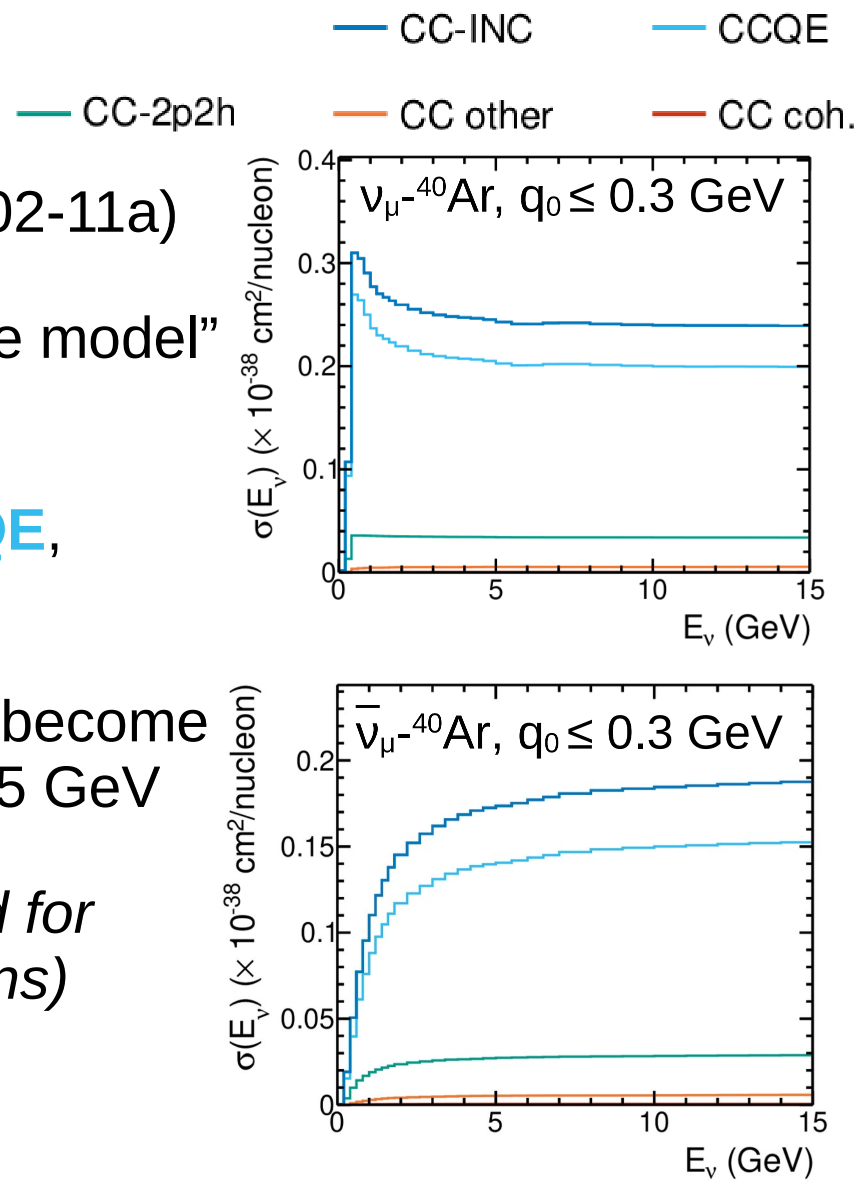
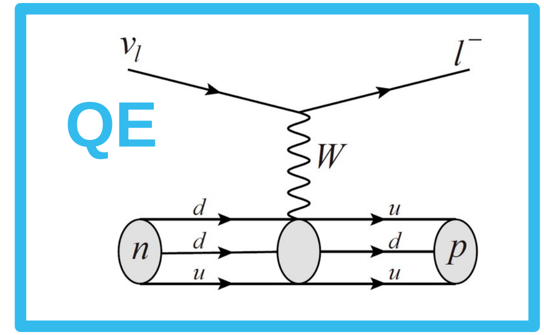
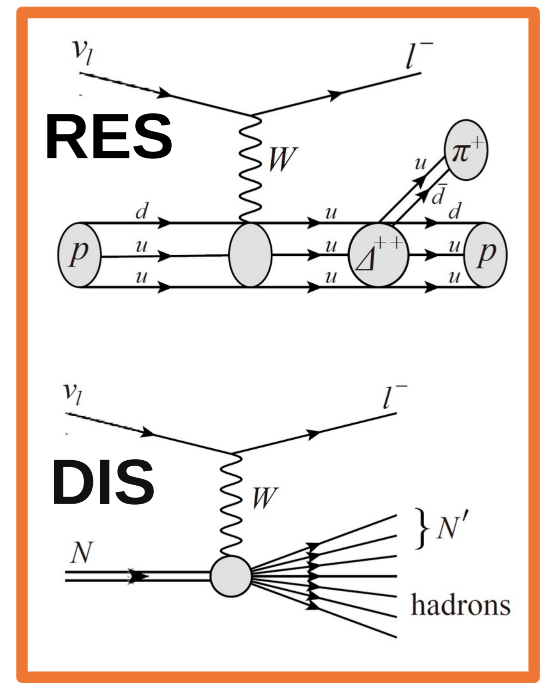
Is the low-q_0 cross section flat in E_ν?

- GENIEv3 (10a-02-11a)
- A common “base model” for experiments
- Dominated by **QE**, **2p2h**, and **RES**
- XSEC does not become constant until ≥ 5 GeV

(Also studied for hydrocarbons)







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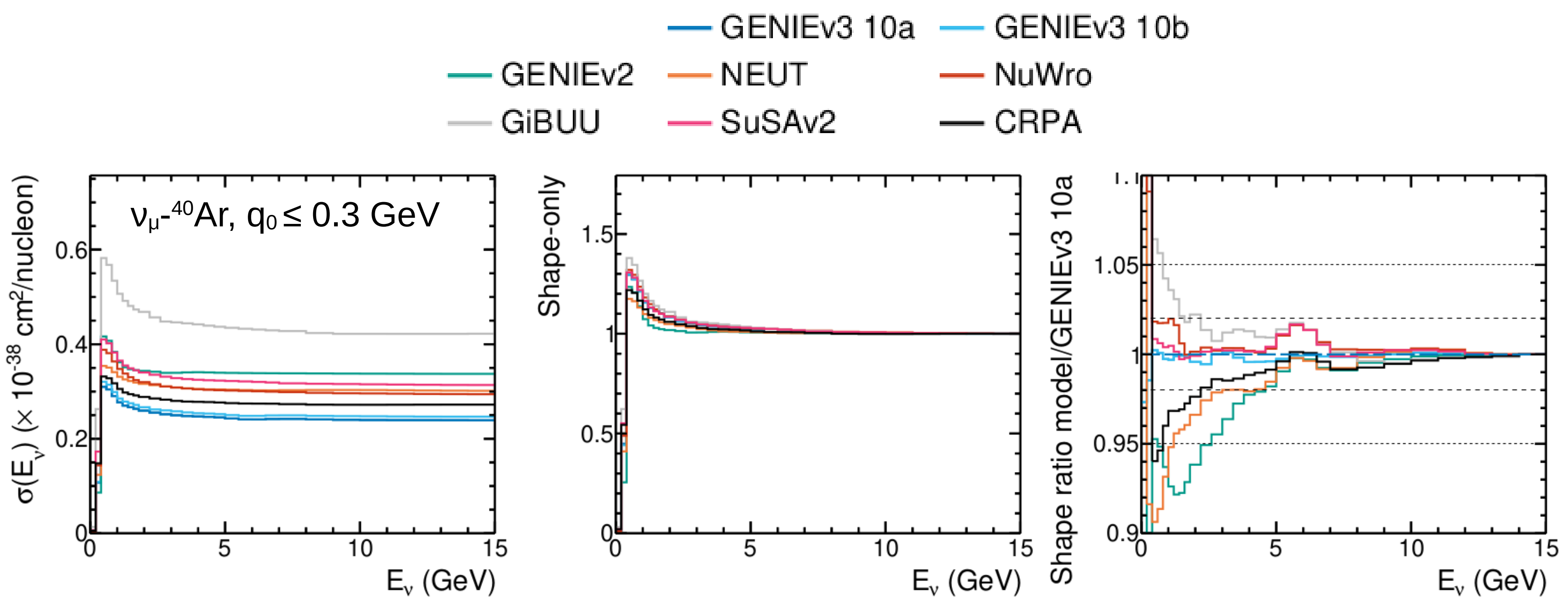


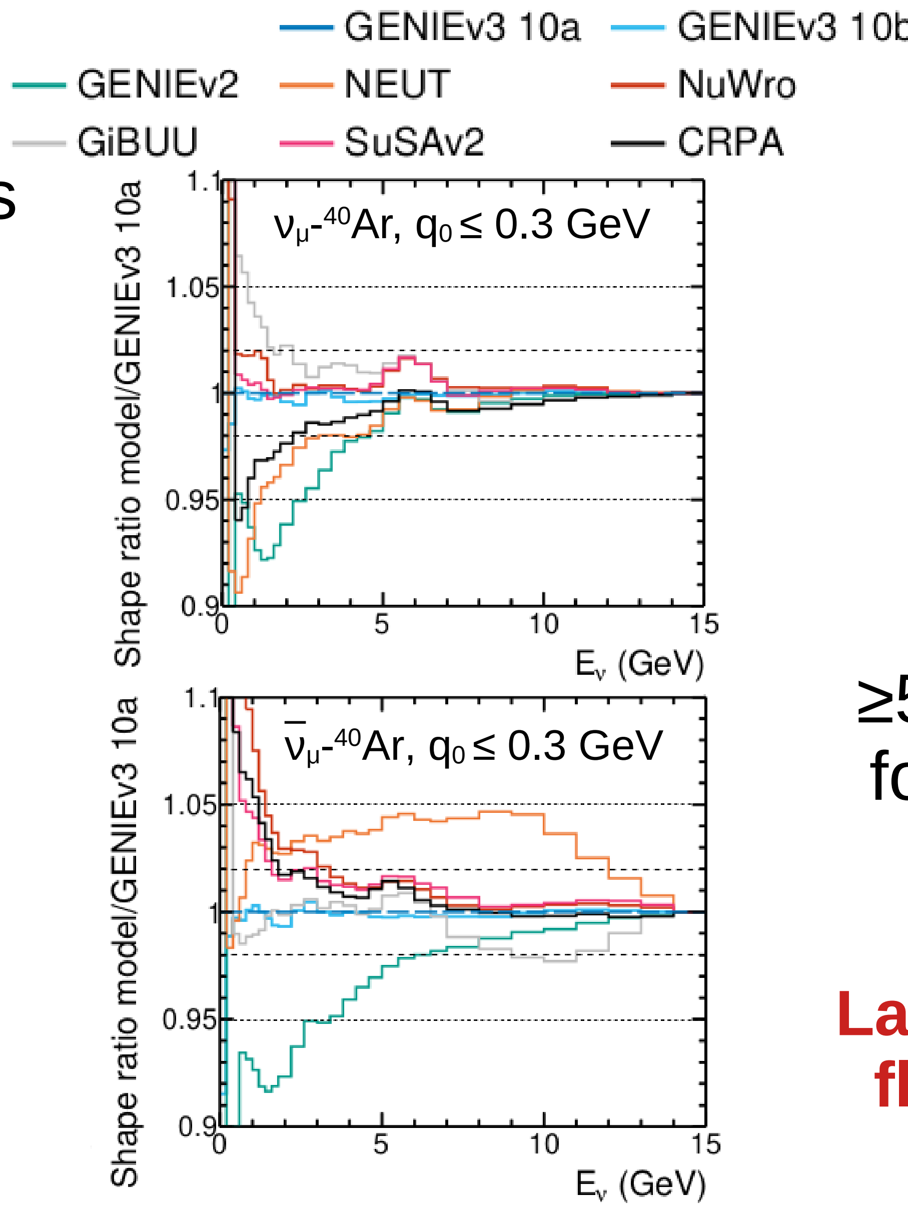
Compare a variety of new/commonly used generator models

Normalize to a fixed point at high energy – where q_0/E_ν corrections are smallest

Take a ratio w.r.t a reference model

Is the low-q_0 cross section flat in E_ν?

≥2% differences for $E_\nu \leq$ 5 GeV

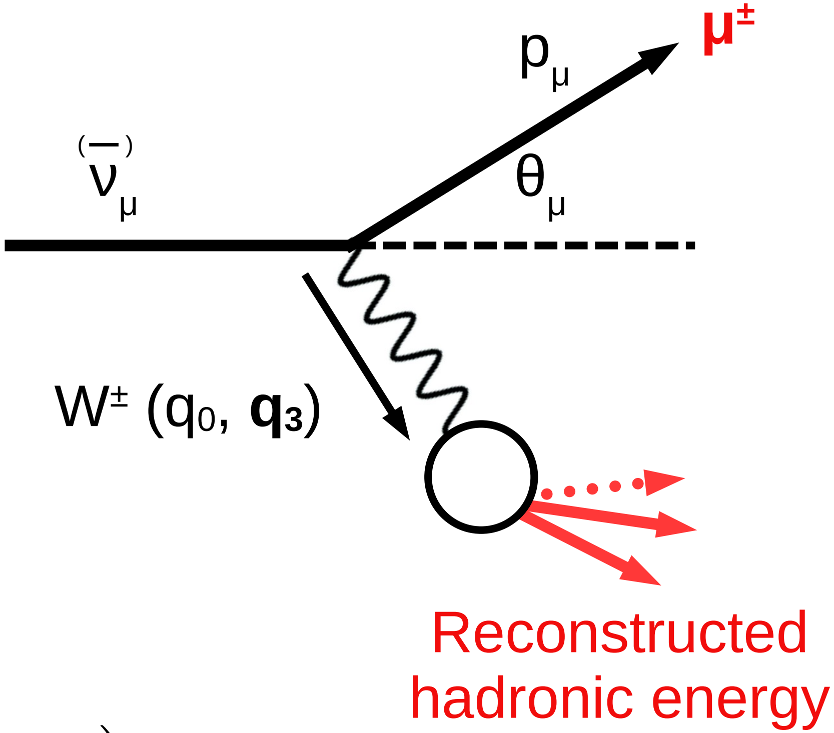


≥5% differences for $E_{\bar{\nu}} \leq$ 12 GeV

Large w.r.t a priori flux predictions

Can a low-q_0 sample be experimentally selected?

- E_ν is not known
- Not all hadrons are visible (detector dependent)
- Relevant, complex, nuclear dynamics
- I'll show two variables here:



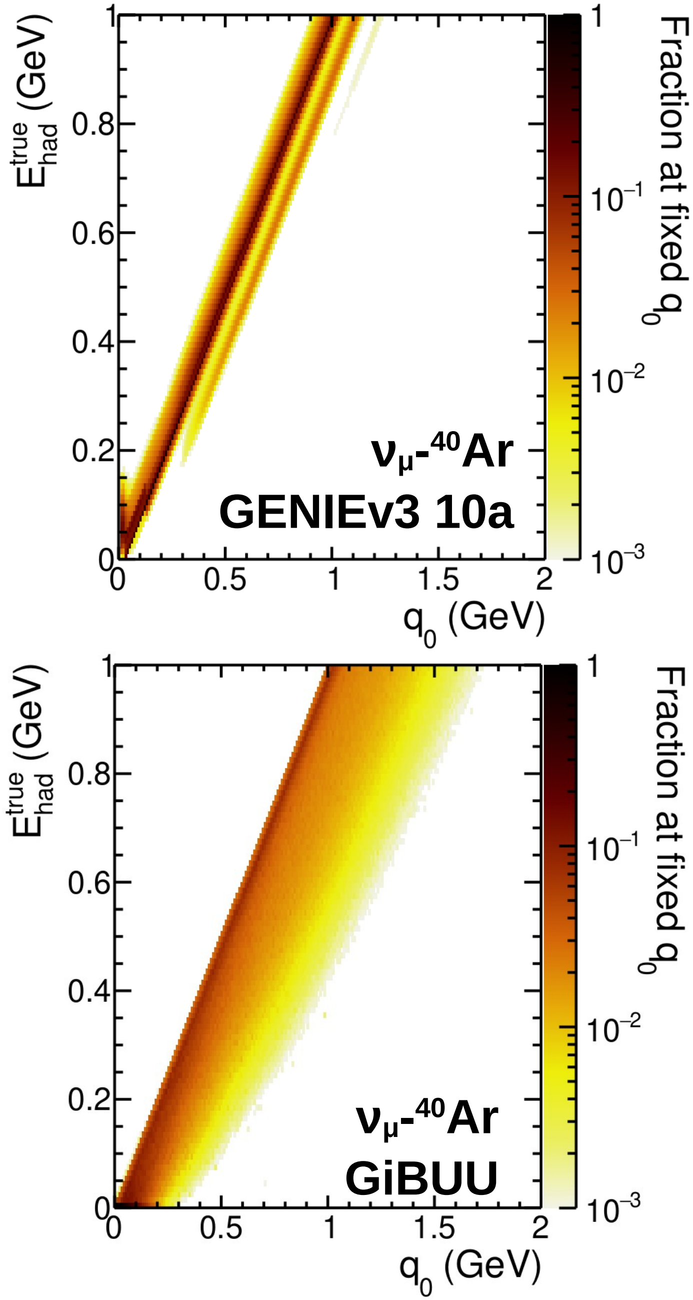
1) $E_{\mathrm{had}}^{\mathrm{true}} = \left(\sum_{i=n,p} E_{\mathrm{kin}}^{i}\right) + \left(\sum_{i=\pi^\pm,\pi^0,\gamma} E_{\mathrm{total}}^{i}\right)$ **Perfect!**

2) $E_{\mathrm{had}}^{\mathrm{reco}} = \left(\sum_{i=p} E_{\mathrm{kin}}^{i}\right) + \left(\sum_{i=\pi^\pm,\pi^0,\gamma} E_{\mathrm{total}}^{i}\right)$ **Miss neutrons**

Can a low-q_0 sample be experimentally selected?

- Even with perfect reco, complex $q_0 \leftrightarrow E_{had}$ relationship
- **Cannot infer q_0 without assuming a model!**

$$E_{\rm had}^{\rm true} = \left(\sum_{i=n,p} E_{\rm kin}^{i} \right) + \left(\sum_{i=\pi^{\pm},\pi^{0},\gamma} E_{\rm total}^{i} \right)$$

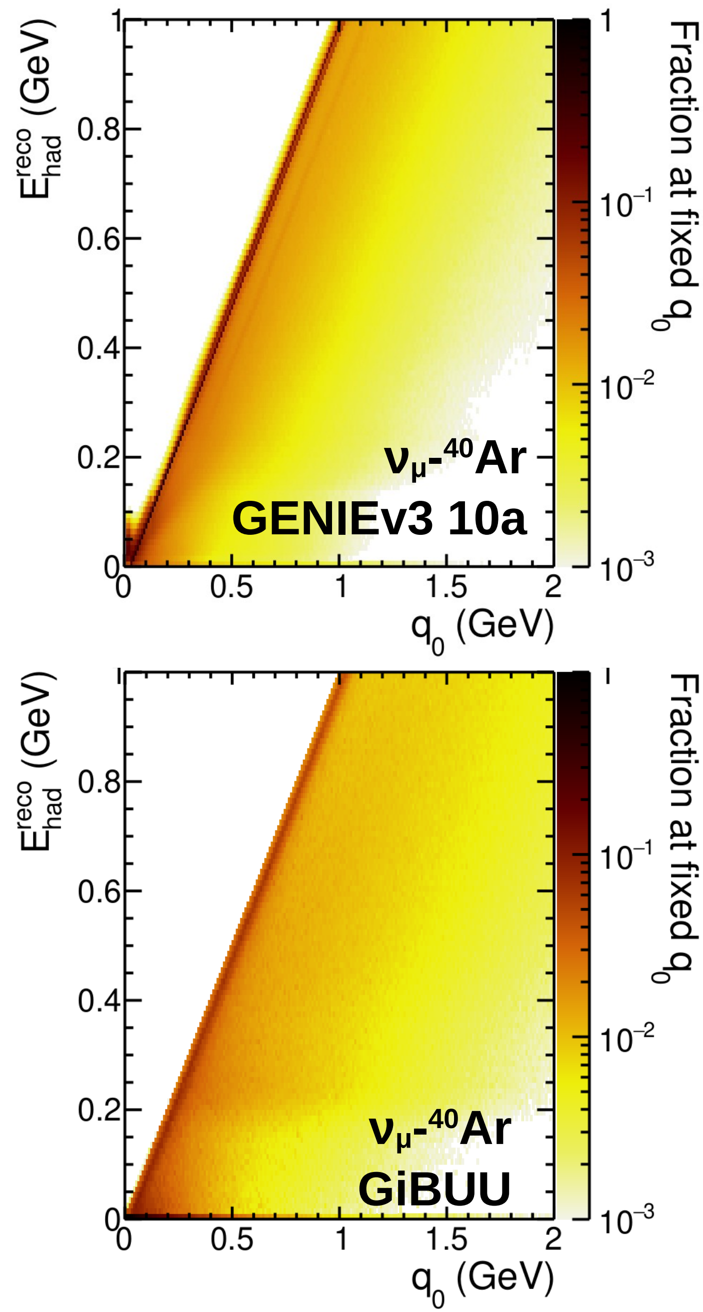


Can a low-q_0 sample be experimentally selected?

- Most detectors cannot recover energy lost to neutrons
- Significantly increases the smearing between $q_0 \leftrightarrow E_{\mathrm{had}}$

$$E_{\mathrm{had}}^{\mathrm{reco}} = \left(\sum_{i=p} E_{\mathrm{kin}}^{i} \right) + \left(\sum_{i=\pi^{\pm},\pi^{0},\gamma} E_{\mathrm{total}}^{i} \right)$$

Situation worsens considerably if pion misreconstruction is included: EPJC 82 (2022) 9, 808



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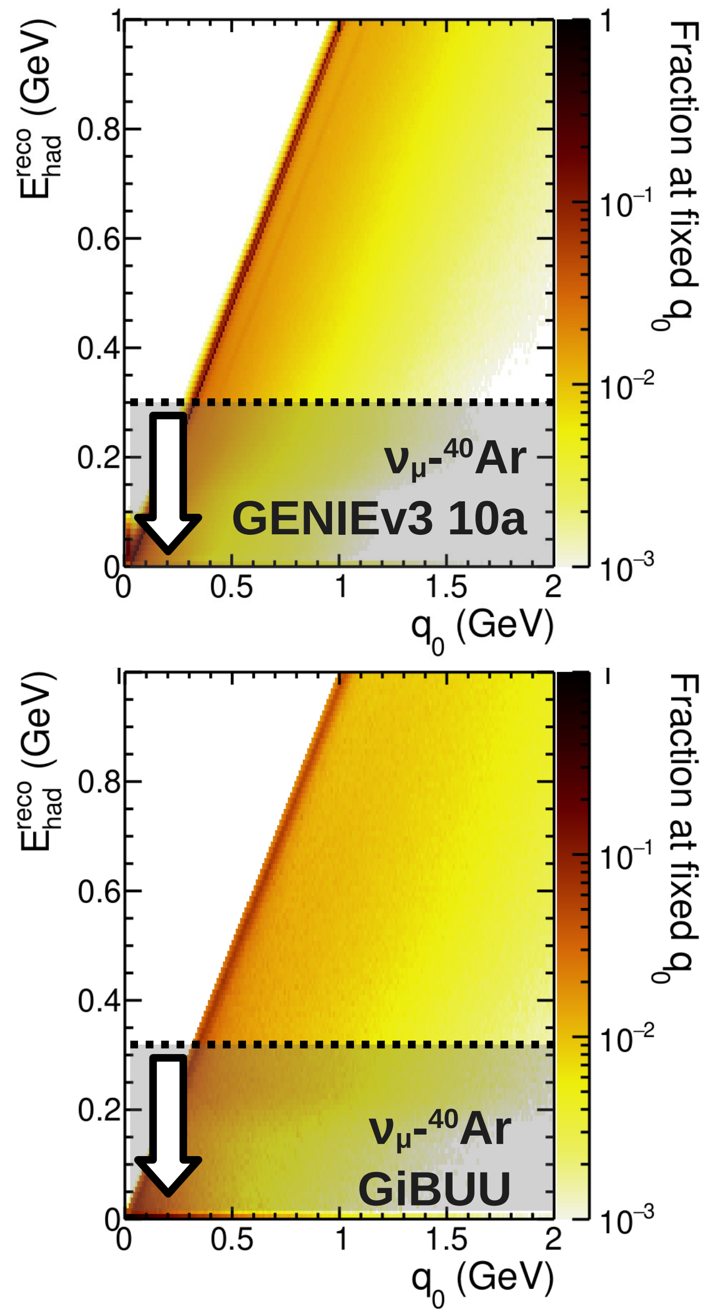
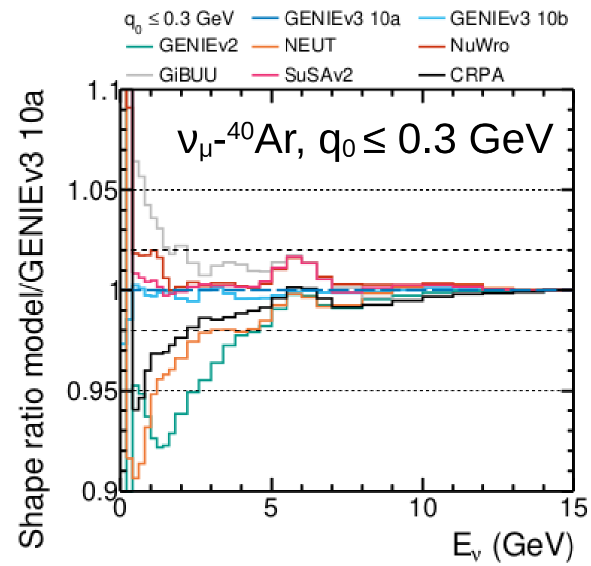
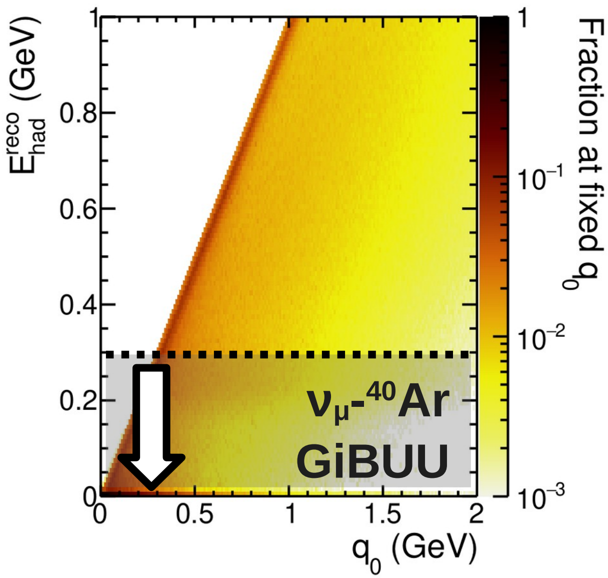


Few-GeV accelerator neutrino conclusions



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~~

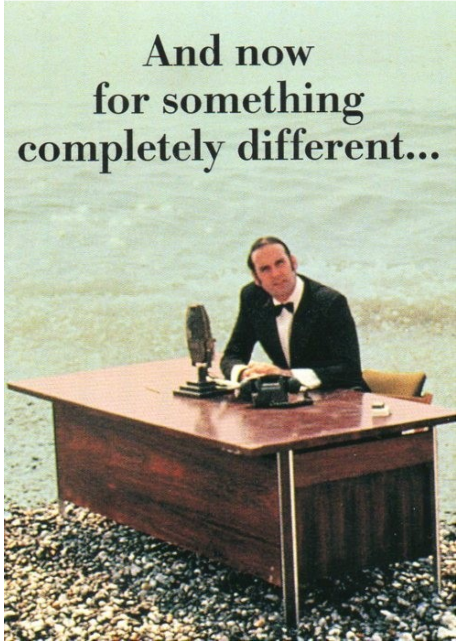
3) It provides a useful number of events

Part II: TeV energies

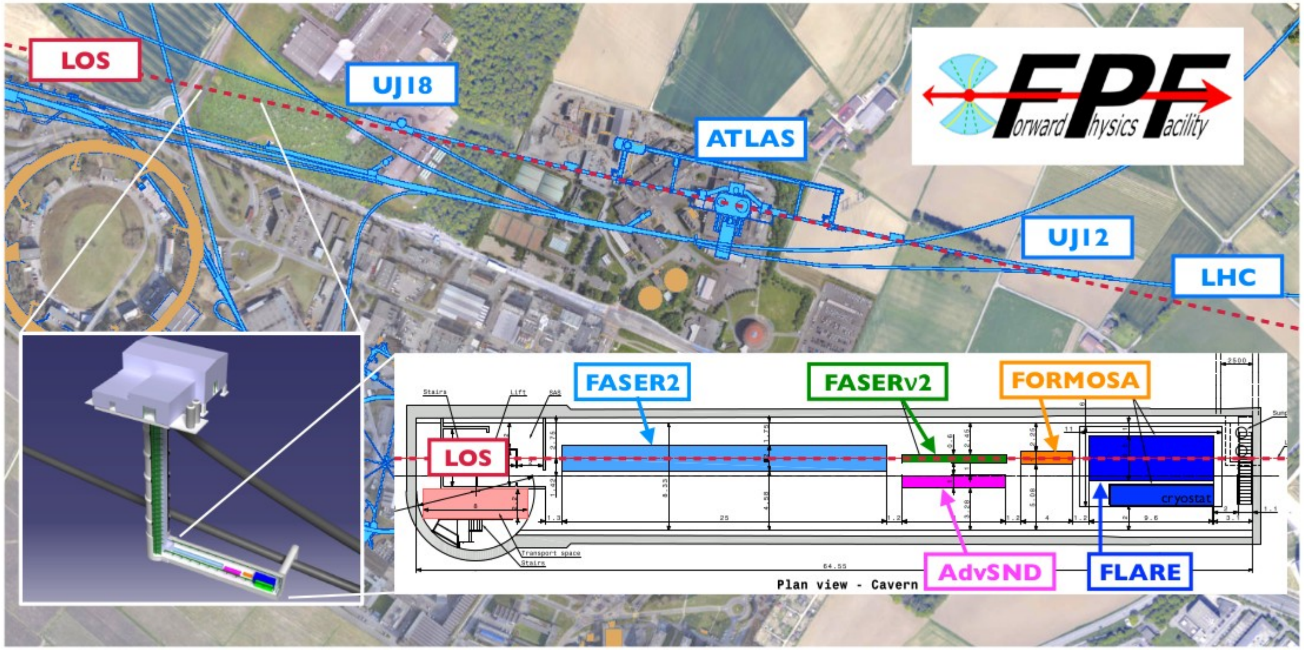
(the best of methods)

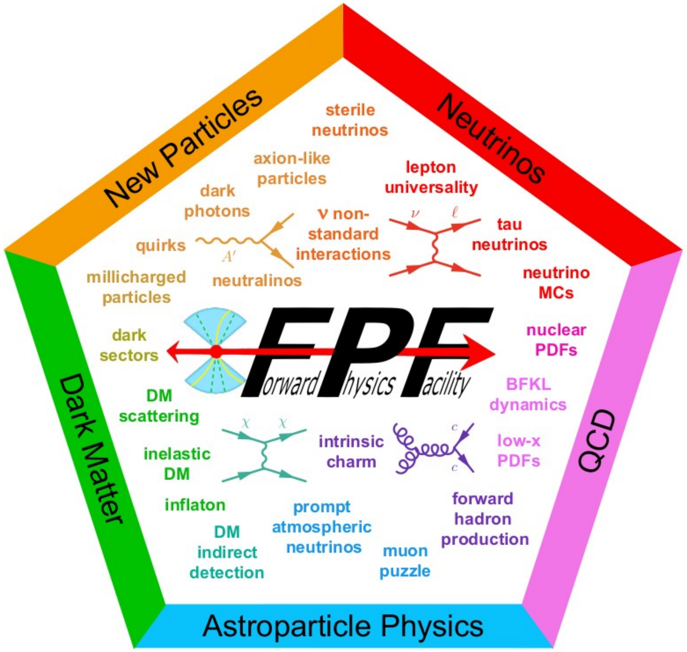
PRD 109 (2024) 3, 033010

arXiv:2310.06520 [hep-ph]



The Forward Physics Facility (FPF)



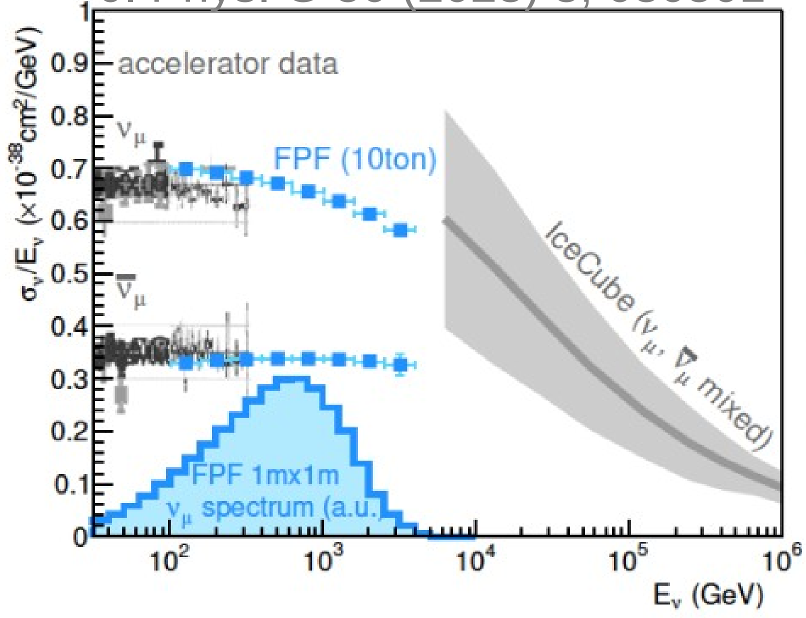


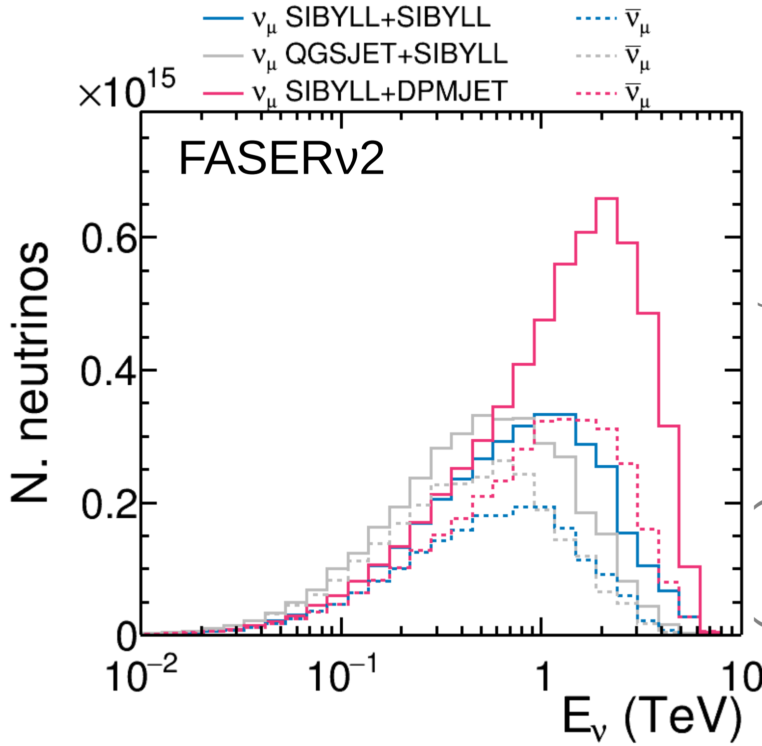
J. Phys. G 50 (2023) 3, 030501

- Planned far-forward search experiment to be located 617 m from the ATLAS collision point in HL-LHC era
- Rich physics program exploiting a previously unsampled (very low-x interactions) regime $x = \frac{Q^2}{2Mq_0}$

FPF neutrino physics

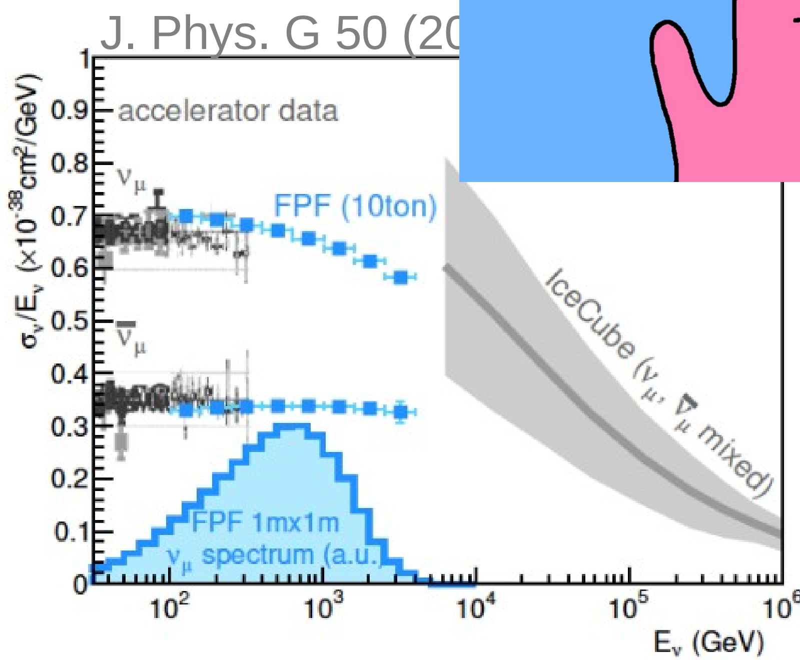
J. Phys. G 50 (2023) 3, 030501

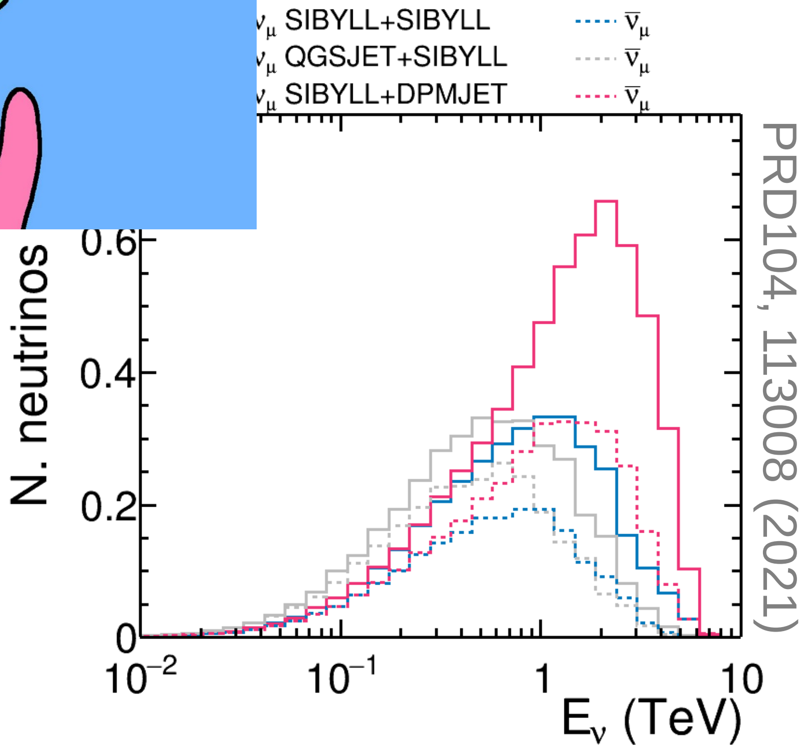




PRD104, 113008 (2021)

- First neutrino cross sections in $0.3 \leq E_\nu \leq 10$ TeV, *for all flavors*
- A probe of far-forward hadron production, related to various QCD questions, and a host of BSM scenarios
- *No other data available for hadron production in this regime*



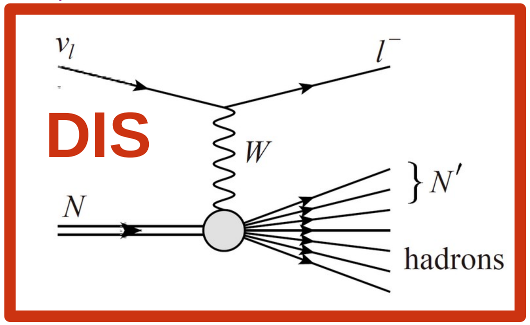


Event rate
Neutrino flux
Cross section
Detector smearing
Generic propagation effect

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

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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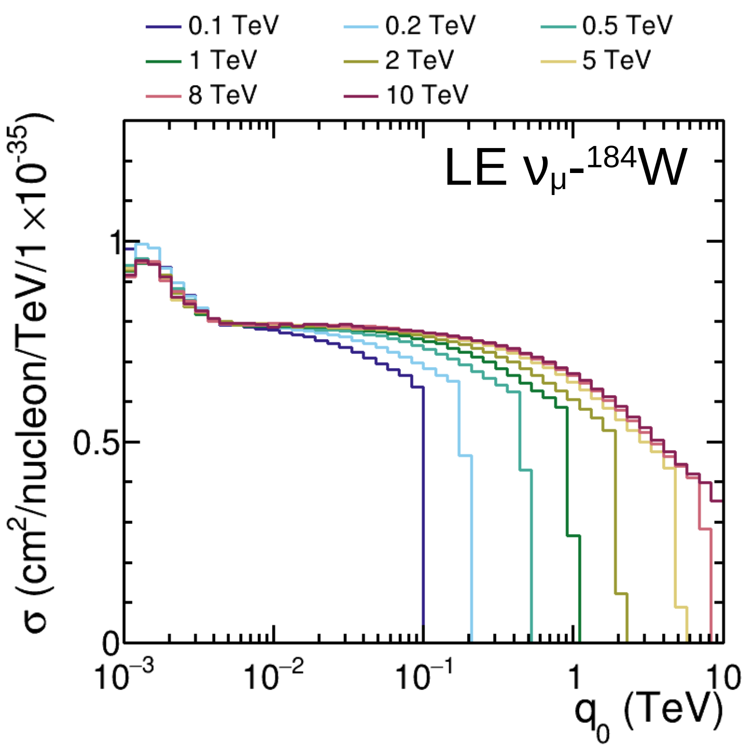
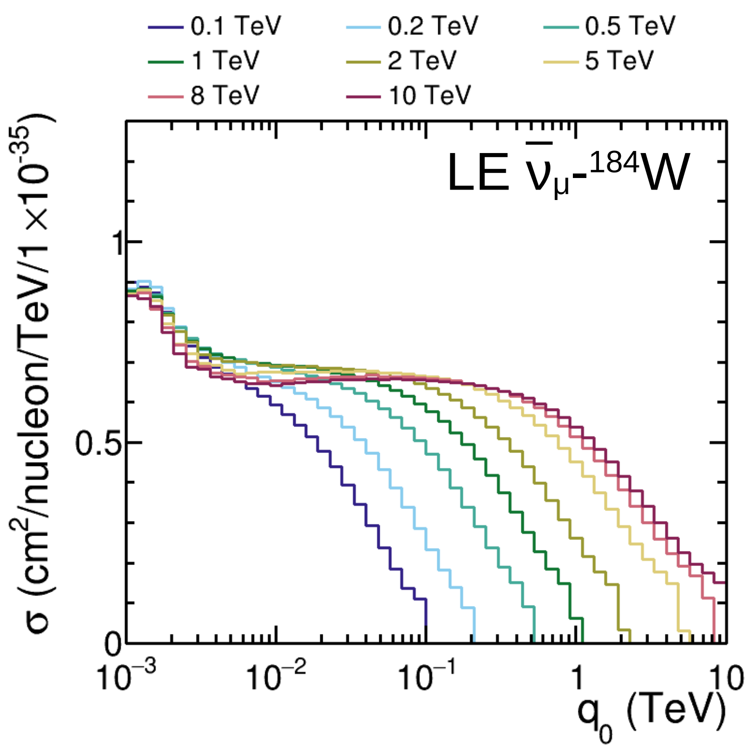
Is the low-q_0 cross section flat in E_ν?

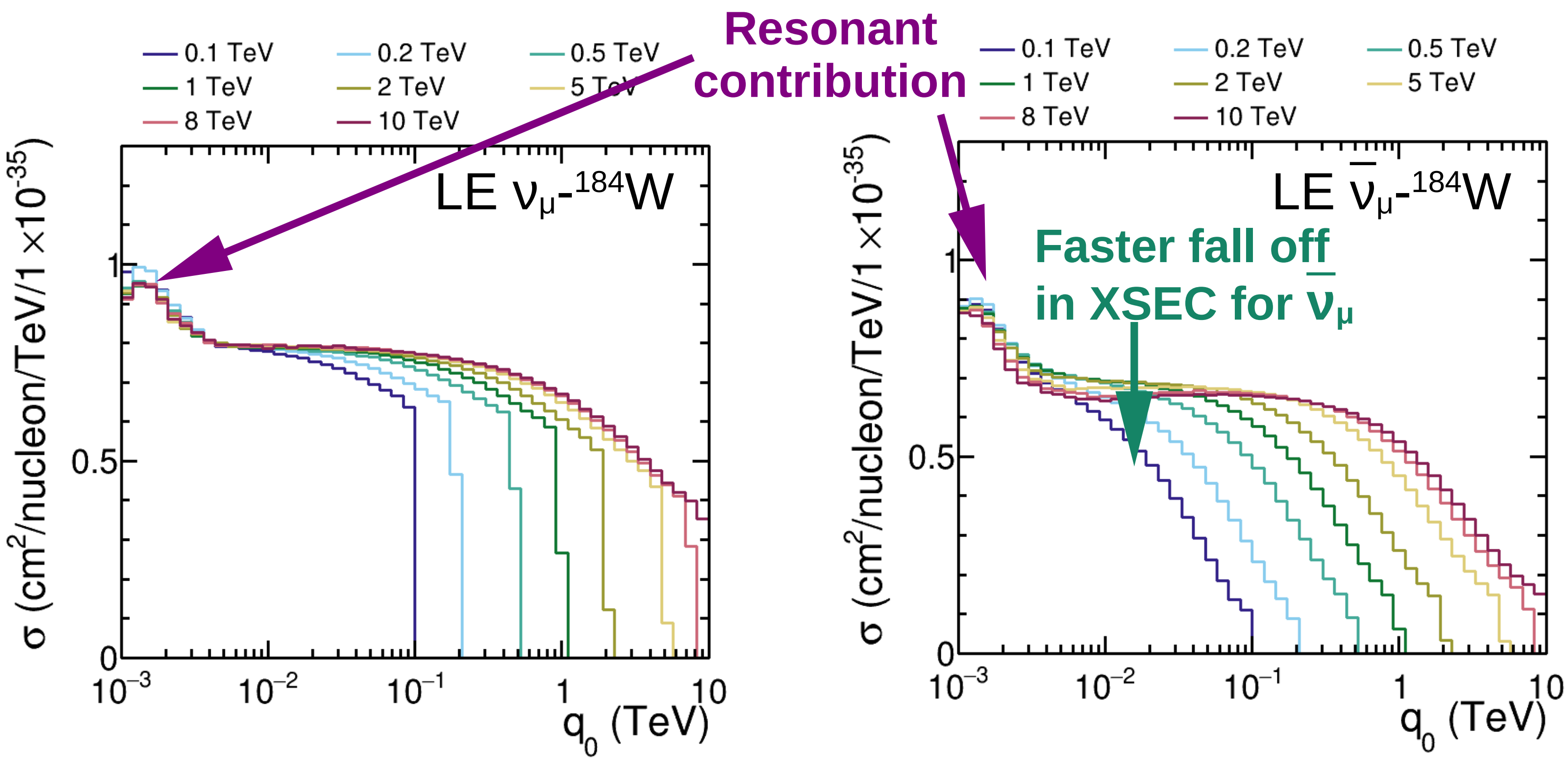




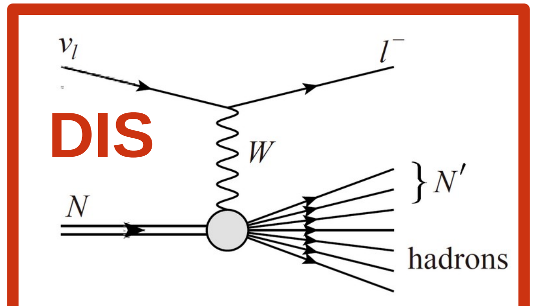
$\boldsymbol{\nu_\mu}$: relatively constant with E_ν for $q_0 \leq 20$ GeV

$\boldsymbol{\bar{\nu}_\mu}$: within a few-% $q_0 \leq 10$ GeV

Is the low-q_0 cross section flat in E_ν?



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



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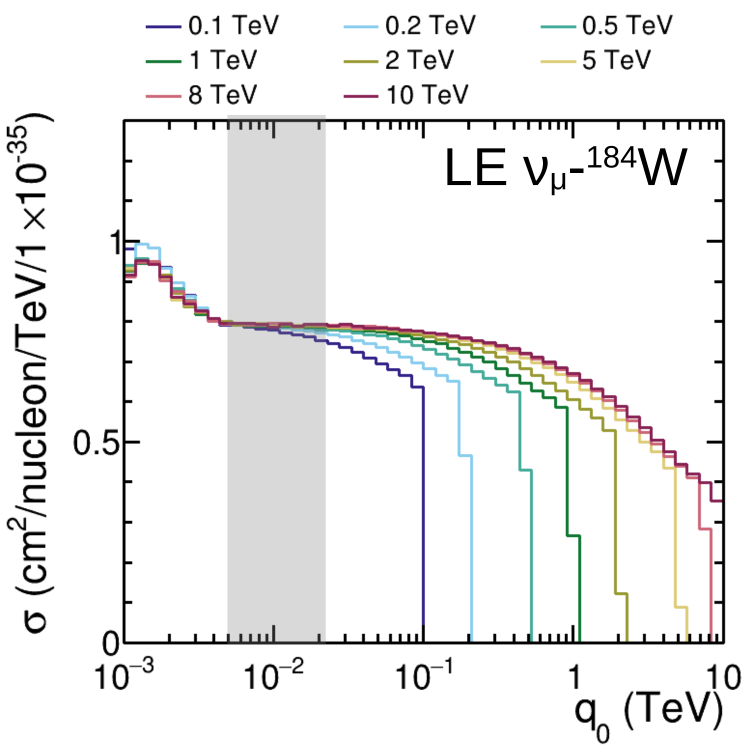
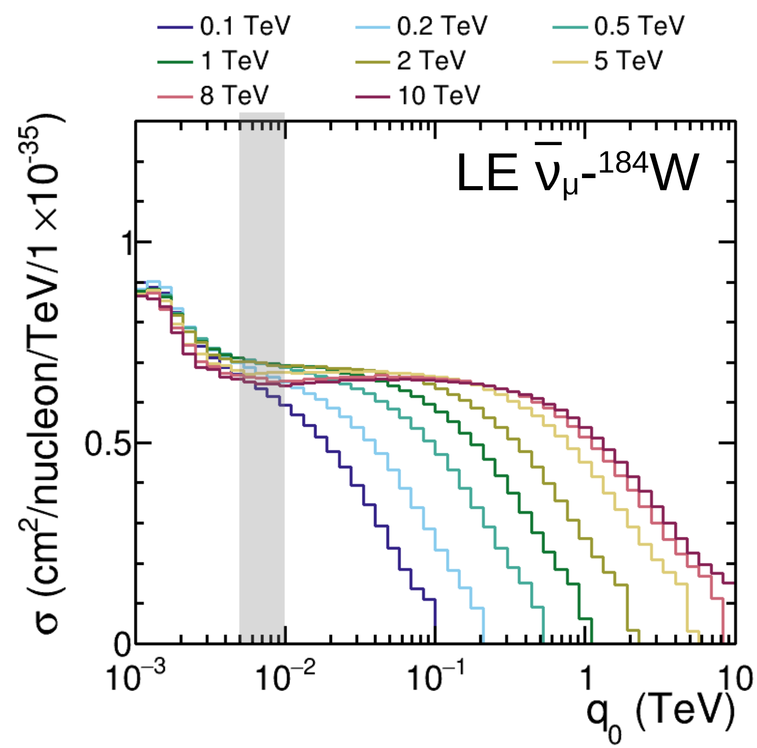
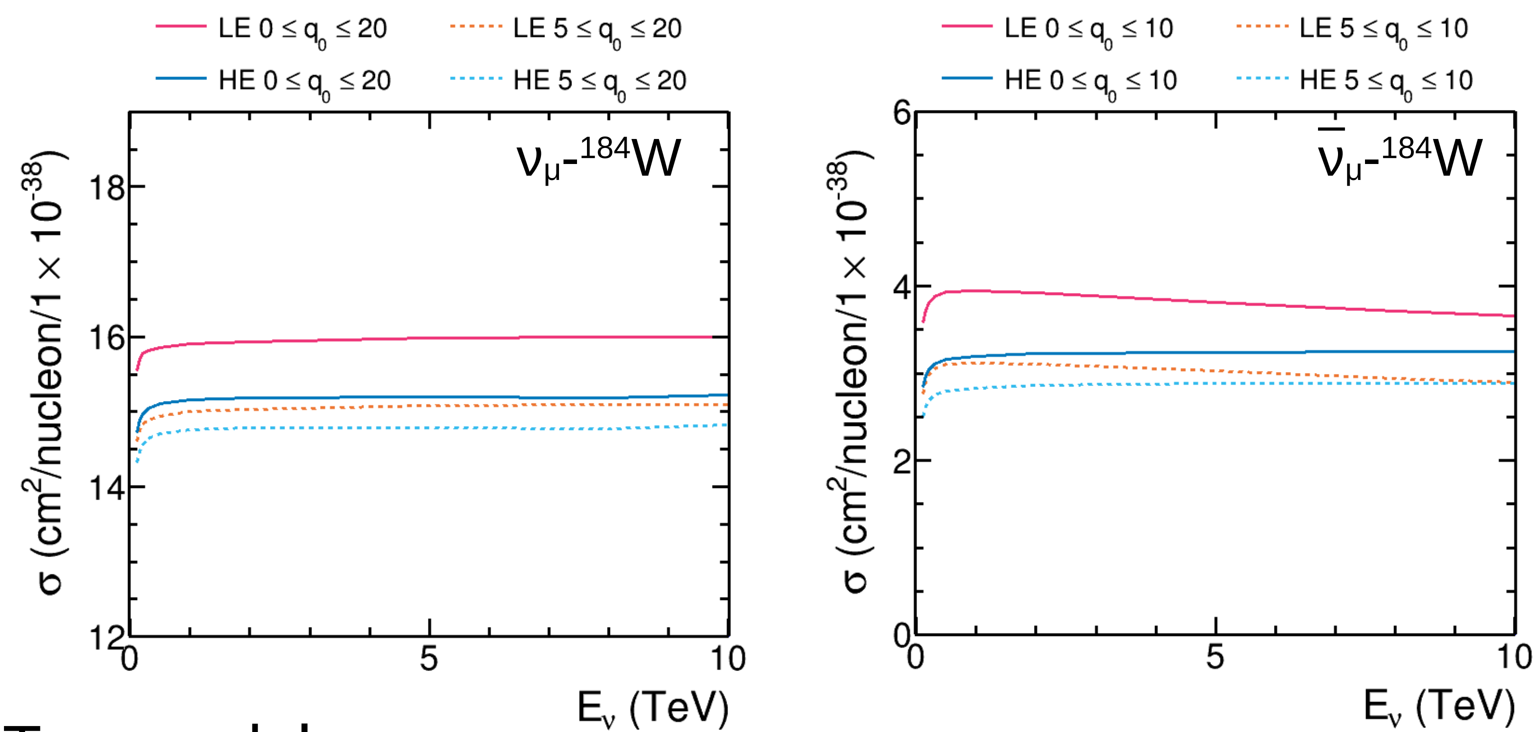




Define low-ν region as:

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

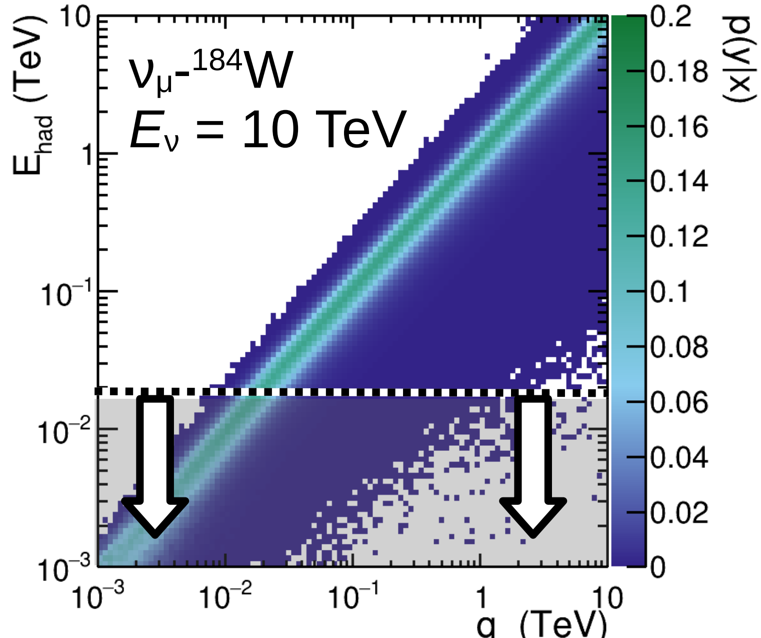
Is the low-q_0 cross section flat in E_ν?

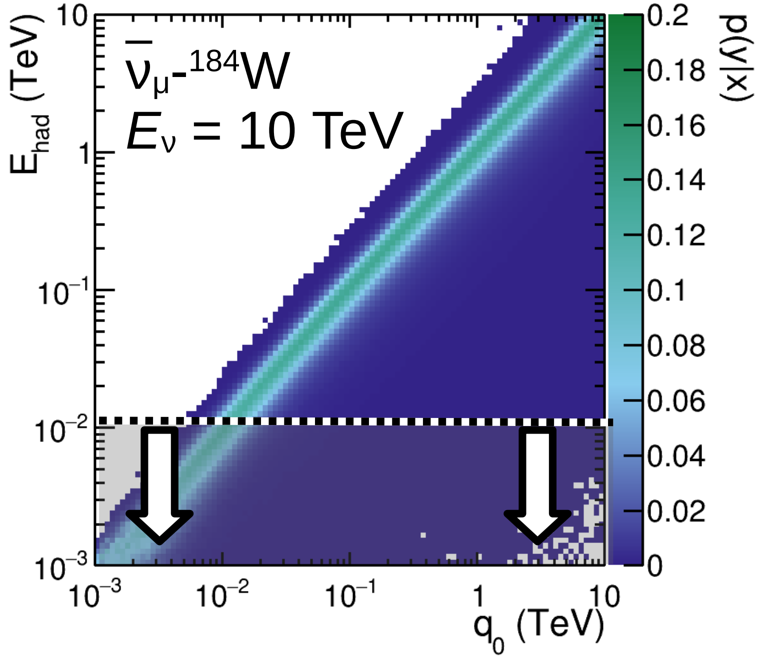


- Two models:
  - **LE:** low energy tuned model (accelerator community)
  - **HE:** high energy tuned model (telescope community)
- Few-% non-linearity for ν_μ, **LE**/**HE** similar
- ~10% non-linearity for $\bar{\nu}_\mu$, larger **LE**/**HE** differences

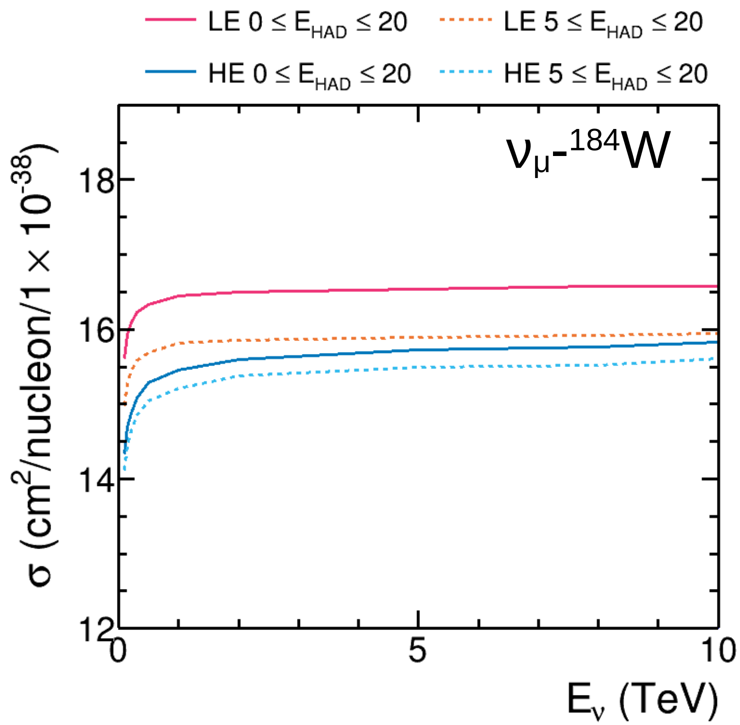
Can a low-q_0 sample be experimentally selected?

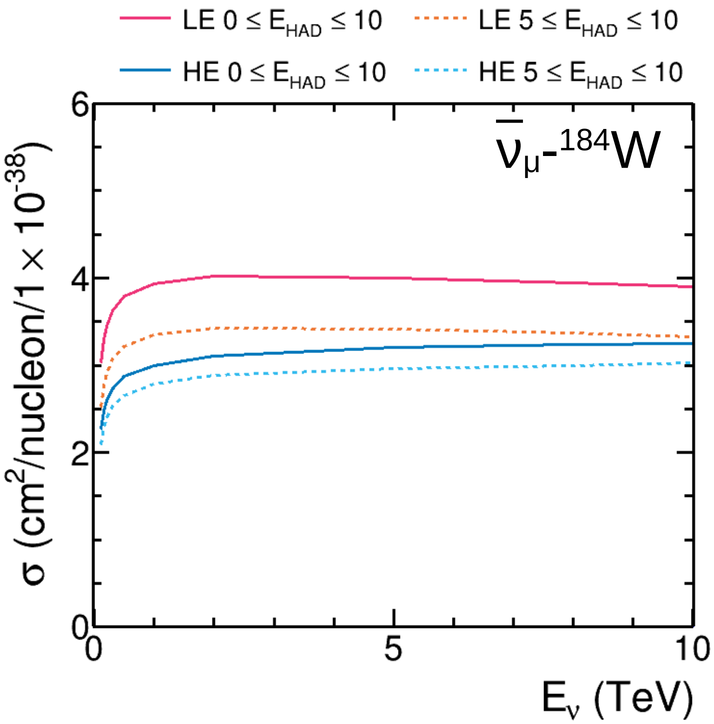
- Smearing assumptions idealized, but follow FPF design docs
- E_{had} cuts introduce a high-q_0 tail
- E_ν dependent to *some* extent
- More pronounced for $\bar{\nu}_\mu$ (≈10%) than ν_μ (≈1%)





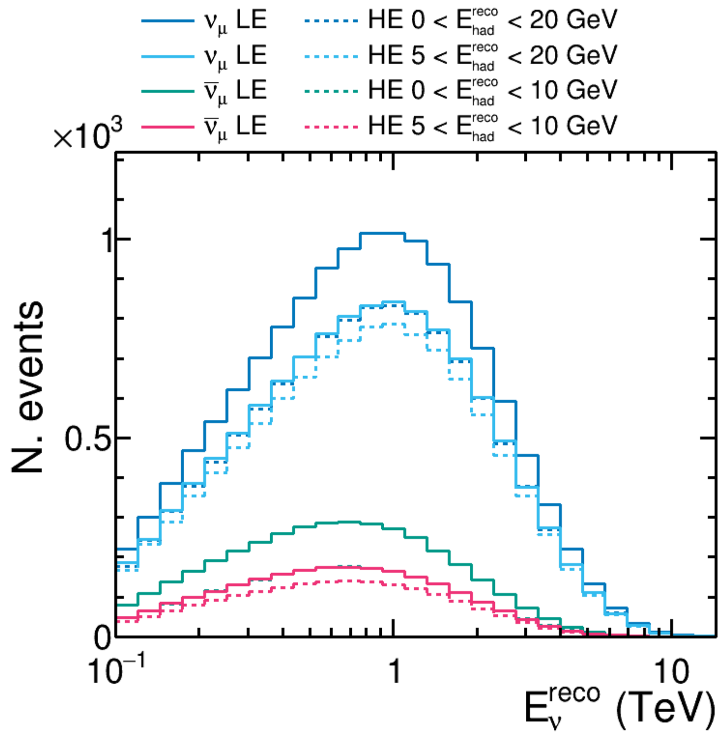
Can a low-q_0 sample be experimentally selected?

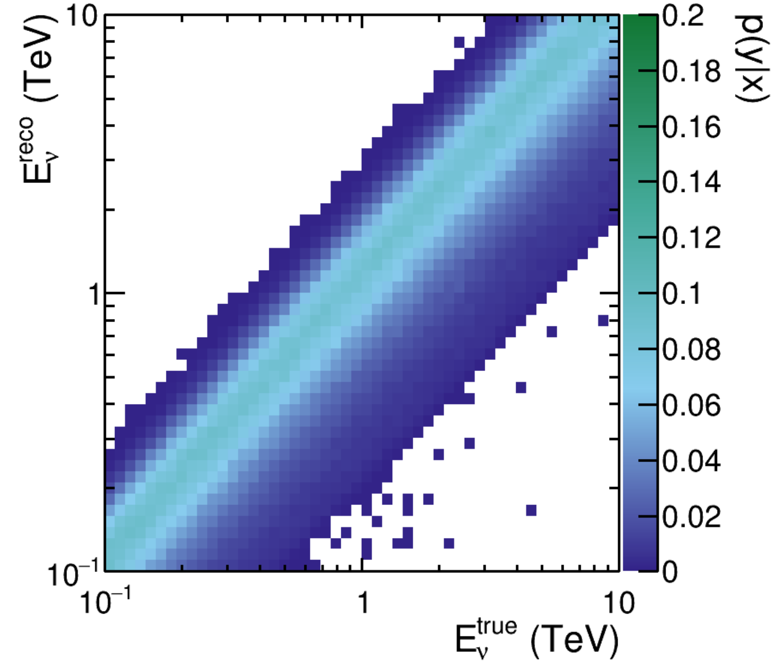




- Low-E_{had} sample cross sections ≈linear with E_ν
- Slightly less flat for both ν_μ and $\bar{\nu}_\mu$ than low-q_0 case
- Larger **LE**/**HE** differences: few-% for ν_μ, ≈10% for $\bar{\nu}_\mu$

Low-ν sample event rate



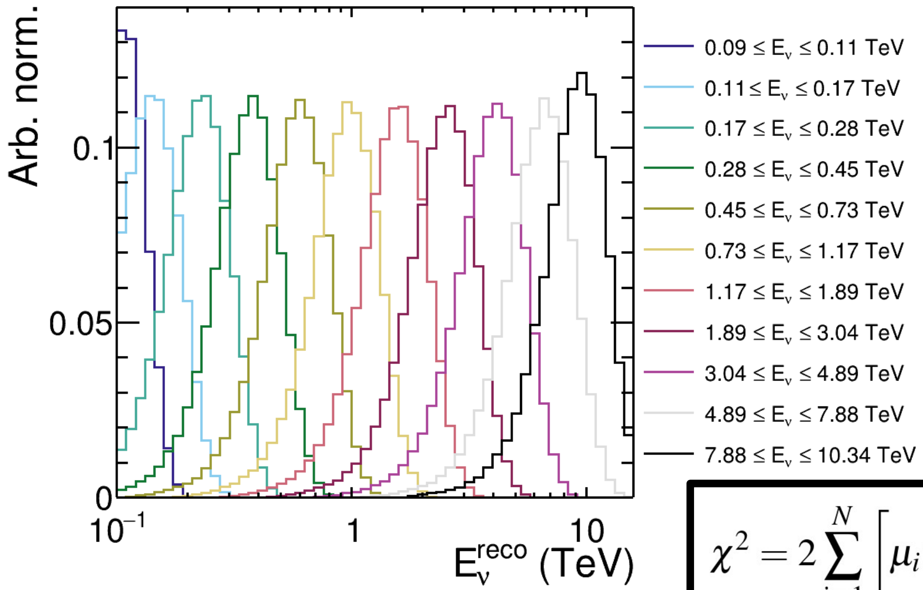


- For 3000 fb^{-1} FPF exposure, FASERν2 low-ν gives O(10,000) ν_μ and O(1,000) $\bar{\nu}_\mu$ events

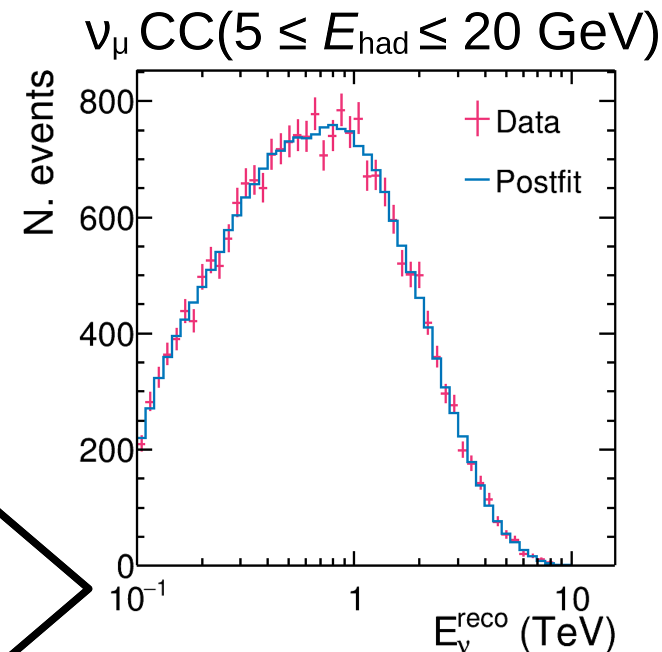
- Relationship between reco. and true E_ν is fairly diagonal (dominated by E_μ)

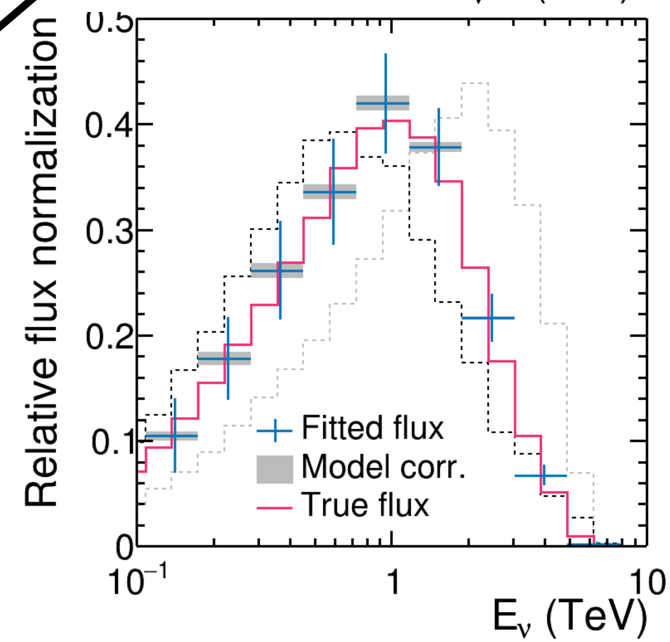
$$E_\nu^{\text{reco}} = E_\mu + E_{\text{had}}^{\text{reco}}$$

FASERν2 ν_μ flux constraint



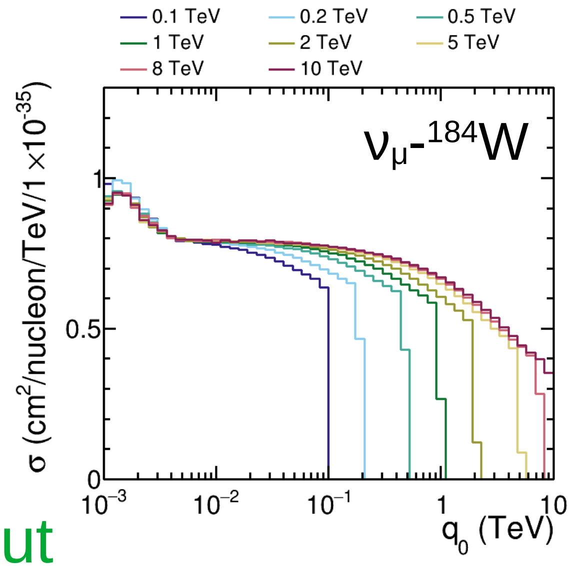
$$\chi^2 = 2\sum_{i=1}^{N}\left[\mu_i(\vec{\mathbf{x}}) - n_i + n_i \ln \frac{n_i}{\mu_i(\vec{\mathbf{x}})}\right]$$





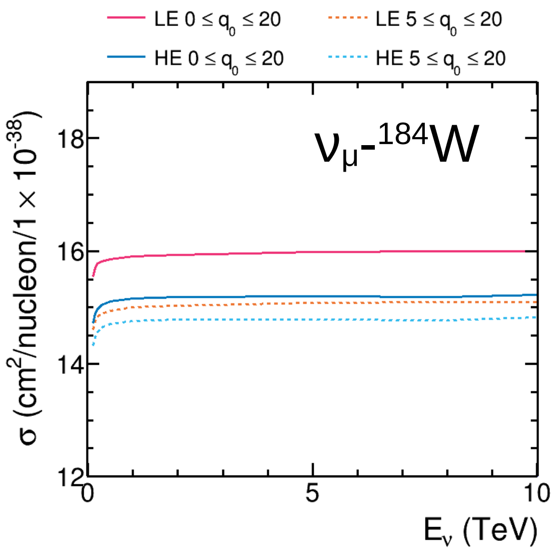
- Fit templates with a fixed true E_ν, binned in reco E_ν
- Postfit normalizations and uncertainties give the flux constraint in true E_ν bins
- Uncertainty due to model correction, but sufficient to resolve flux models

TeV neutrino conclusions



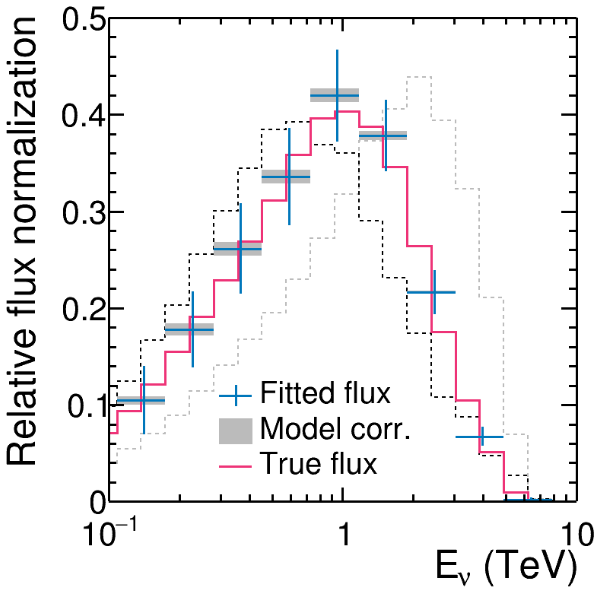
The method works if:

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



Backup

History of the low-ν method

- Widely known/used in accelerator neutrino community:
  - **CCFR**, $30 \le E_\nu \le 360$ GeV, 1985–1988*
  - **NuTeV**, $30 \le E_\nu \le 360$ GeV, 1996–1997*
  - **NOMAD**, $3 \le E_\nu \le 100$ GeV, 1995–1998*
  - **MINOS(+)**, $2 \le E_\nu \le 10$ GeV, 2005–2016*
  - **MINERvA**, $2 \le E_\nu \le 10$ GeV, 2009–2019*

*all dates indicate data-taking periods

- Discussed for use in current/future precision experiments:
  - **MicroBooNE**, $0.3 \le E_\nu \le 2$ GeV, 2015–2021*
  - **DUNE**, $1 \le E_\nu \le 5$ GeV, 2030's
  - ...

History of the low-ν method

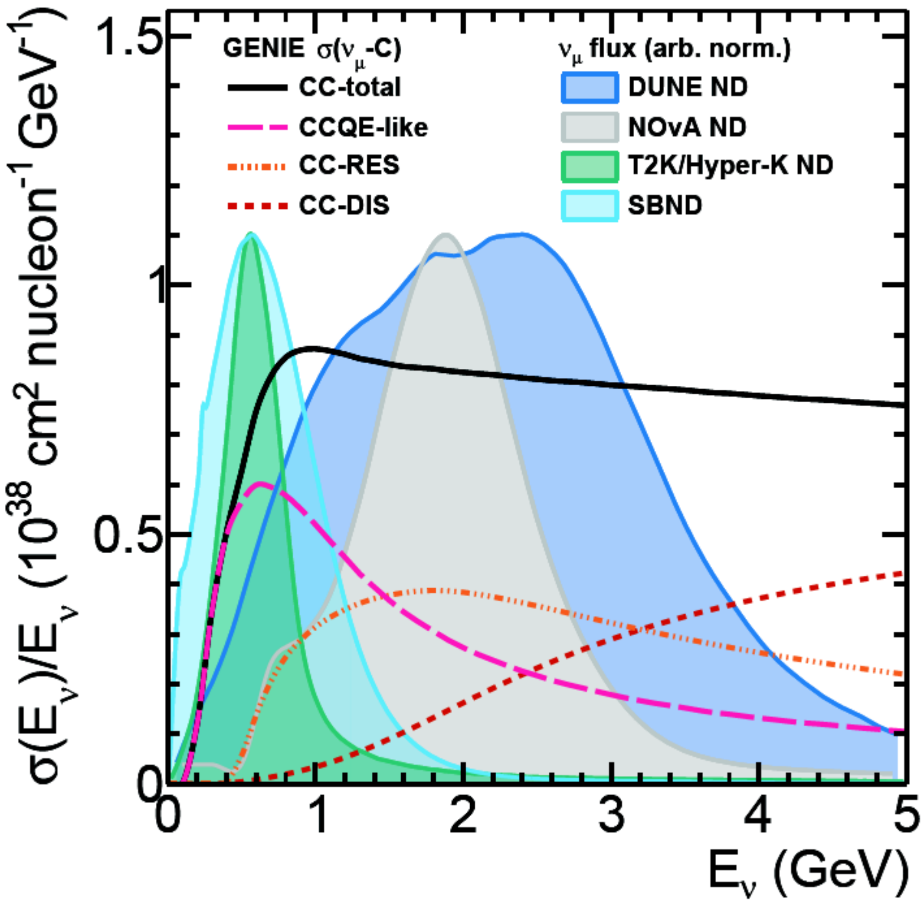
Average neutrino energy

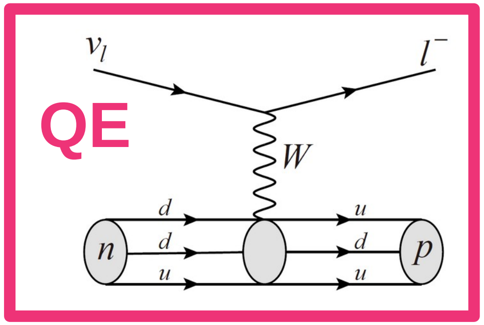
- Widely known/used in accelerator neutrino community:
  - **CCFR**, $30 \le E_\nu \le 360$ GeV, 1985–1988*
  - **NuTeV**, $30 \le E_\nu \le 360$ GeV, 1996–1997*
  - **NOMAD**, $3 \le E_\nu \le 100$ GeV, 1995–1998*
  - **MINOS(+)**, $2 \le E_\nu \le 10$ GeV, 2005–2016*
  - **MINERvA**, $2 \le E_\nu \le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

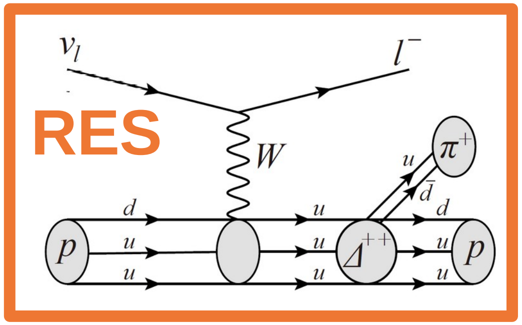
*all dates indicate data-taking periods

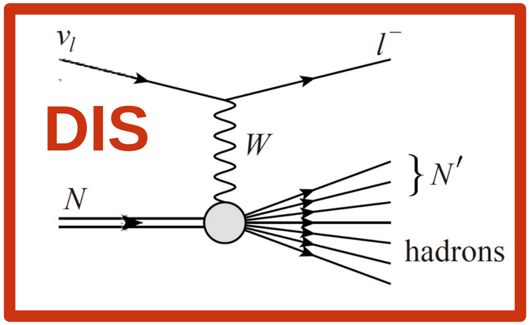
Few-GeV cross sections are not well understood

- Large a priori uncertainties
- Broad E_ν range in beam
- Multiple interaction processes
  → **not just DIS!**
- Measureable states convolved by nuclear effects







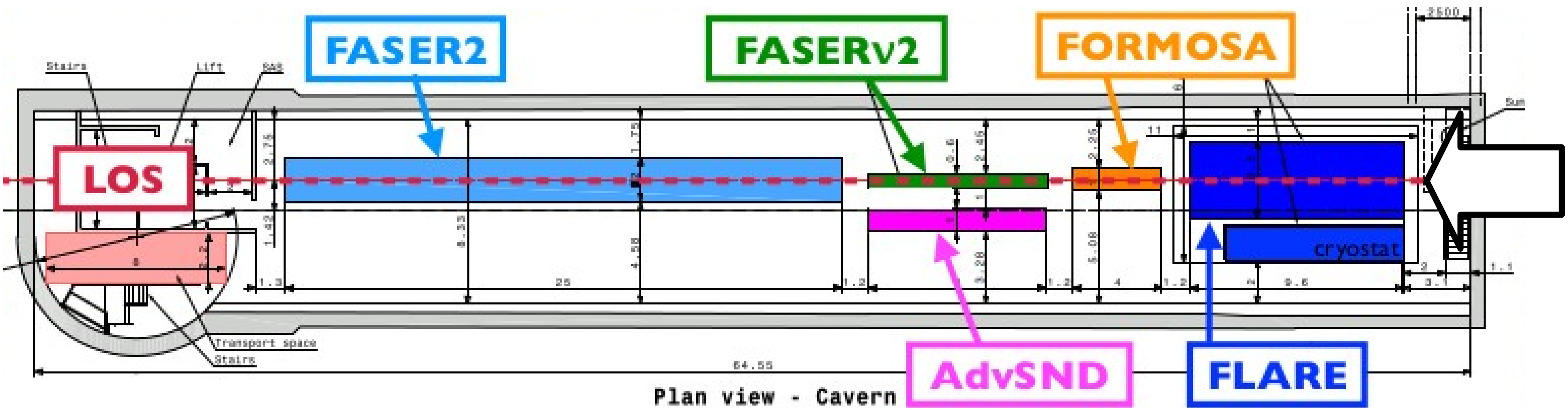


Few-GeV cross-section models

A variety of model predictions are on the market – use a variety to investigate potential for bias:

- **GENIEv2** – used in many published results
- **GENIEv3 10a** and **GENIEv3 10b** – currently used by many active experiments (10a vs 10b have different FSI models)
- **SUSAv2** and **CRPA**: state-of-the-art nuclear response modeling for pionless events (implemented in GENIE ~v3.2.0)
- **NEUT**: used by T2K
- **NuWro**: performs well w.r.t. world cross-section data
- **GiBUU**: sophisticated hadron-transport, different neutrino–nucleon model, also performs well in world data comparisons

FPF detectors

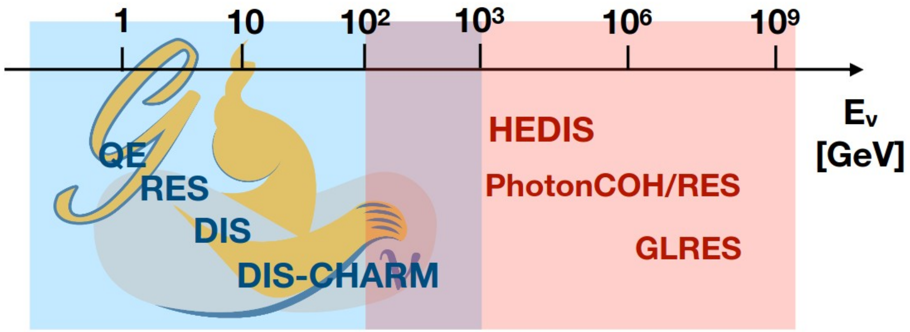


- **FASER2:** low-density magnetized tracker
- **FASERν2:** 20 t tungsten and nuclear emulsion
- **FLArE:** 10/100 t liquid argon TPC

High-energy cross-section modeling

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

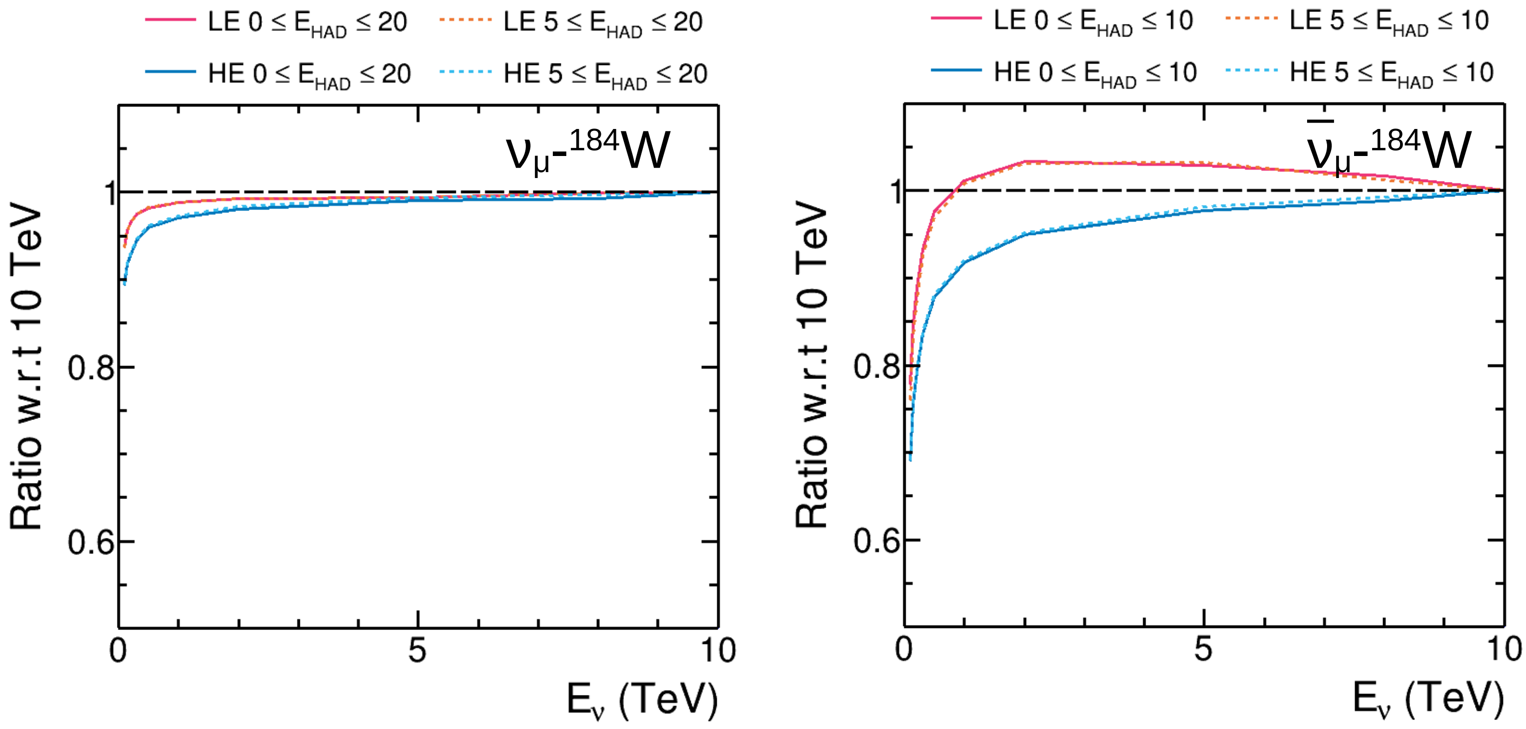
- Developed for few-GeV accelerator neutrino community
- DIS from Bodek-Yang model → tuned for low-Q^2
- LO structure functions, use GRV98LO PDFs
- Contributions from heavy quarks not included



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

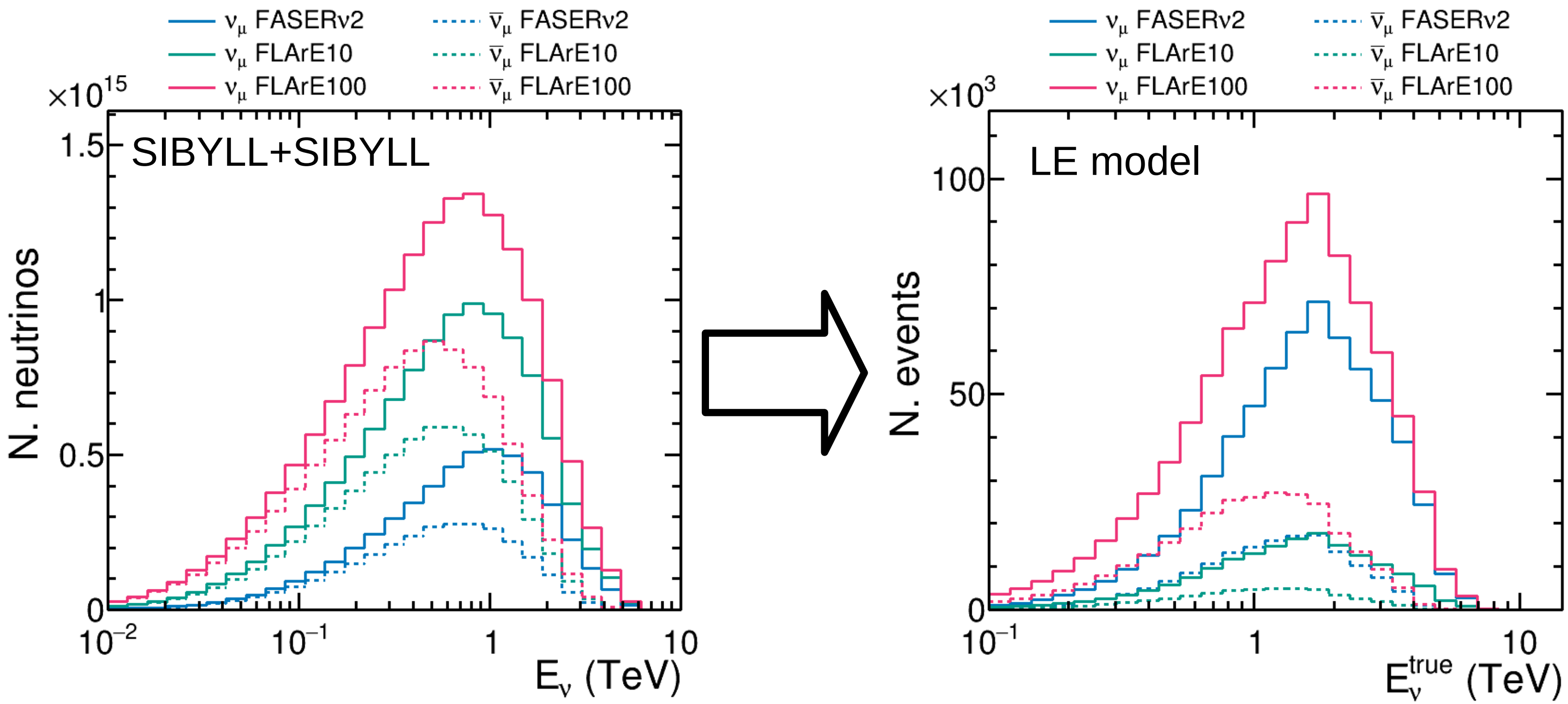
- Developed for UHE, high-Q^2 regime (neutrino telescopes)
- Use new NLO PDFs → NLO structure functions
- Include heavy quark contributions
- Non-DIS interactions are neglected

Can a low-q_0 sample be experimentally selected?



- 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 $\bar{\nu}_\mu$

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 planned 3000 fb^{-1} HL-LHC run
- Cross section ≈linear with E_ν

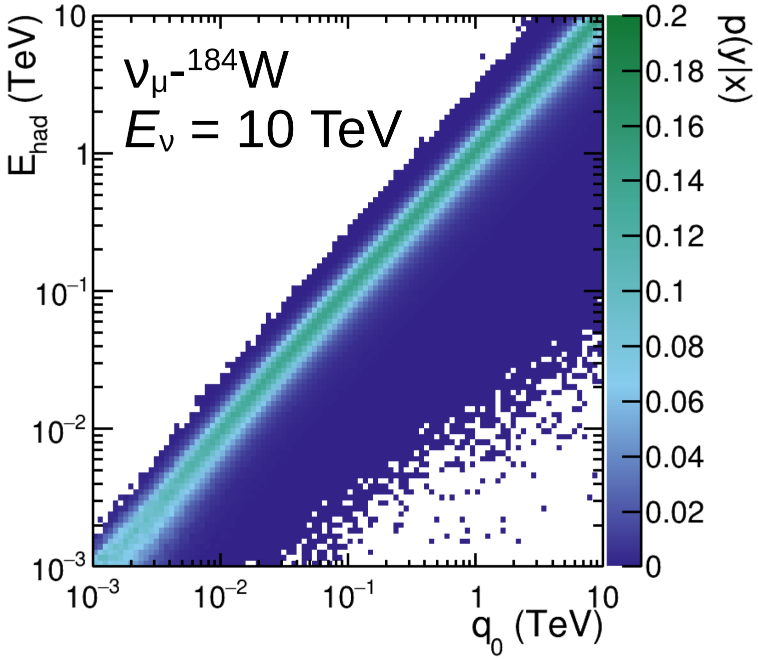
*PRD104, 113008 (2021)

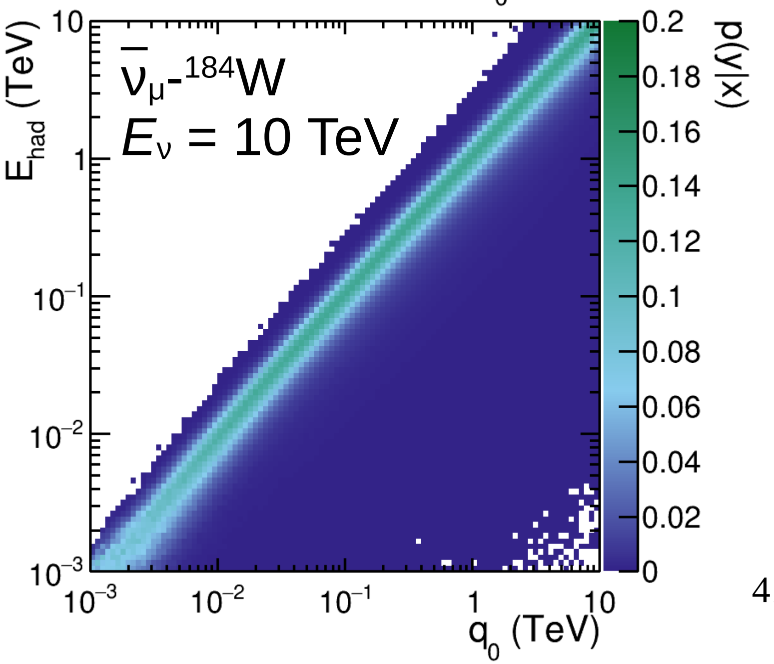
Detector smearing

	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

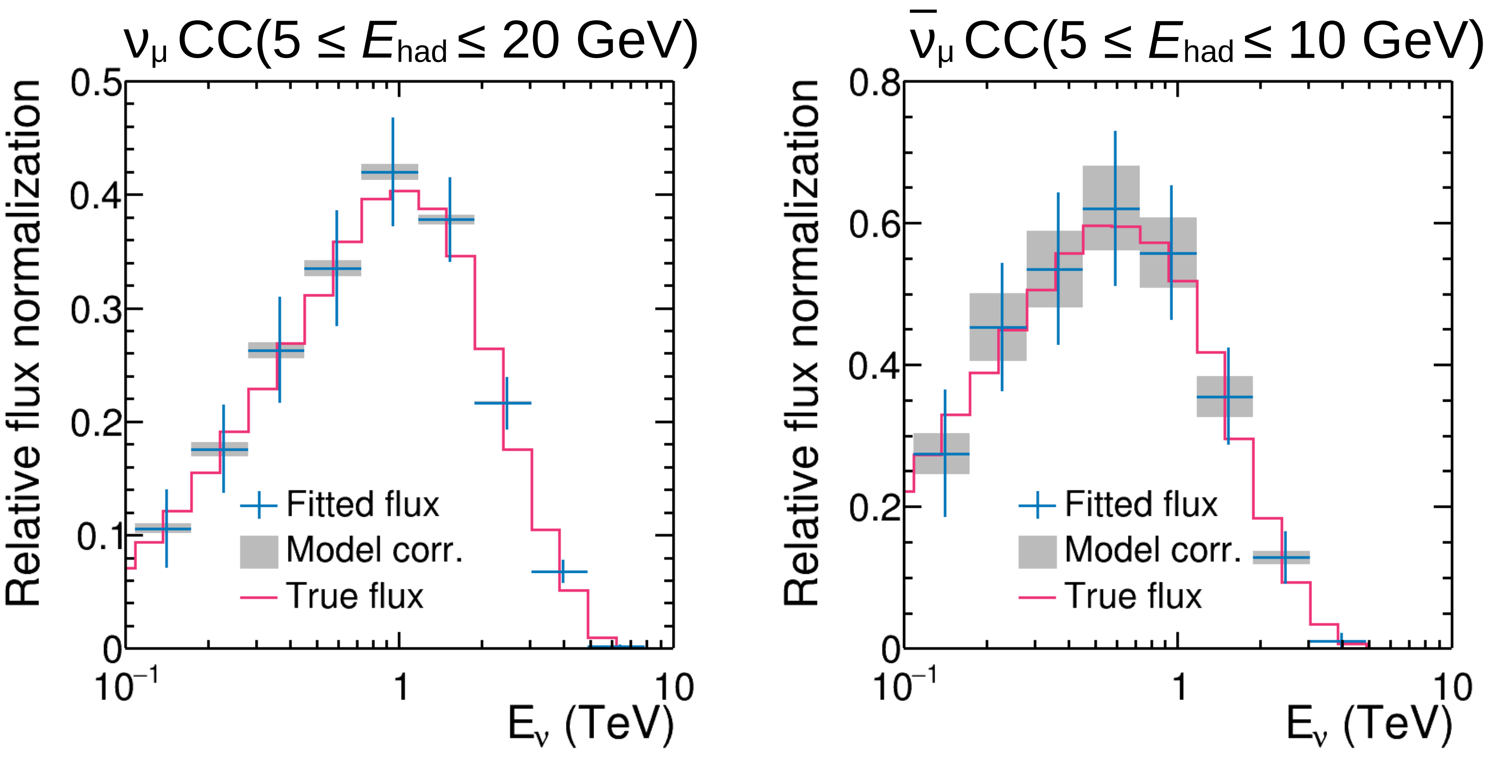
$$E_{\text{had}}^{\text{reco}} = \left(\sum_{i=p,\bar{p}} E_{\text{kin}}^{i} \right) + \left(\sum_{i=\pi^{\pm},K^{\pm},\gamma,l^{\pm},K_S^0} E_{\text{total}}^{i} \right)$$

- Assumptions follow FPF design docs
- $E_{\text{had}} \approx q_0$ for central population
- Low E_{had} tail from unobserved particles



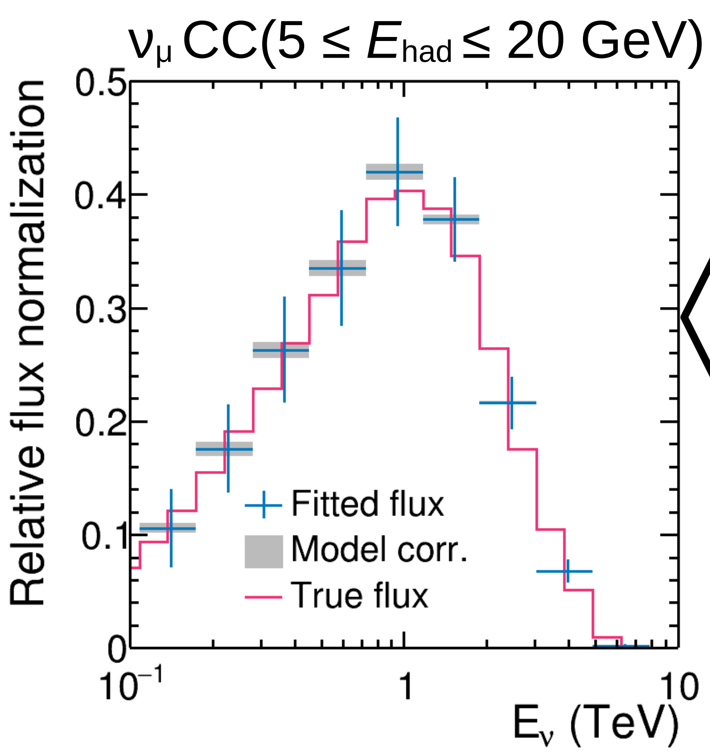


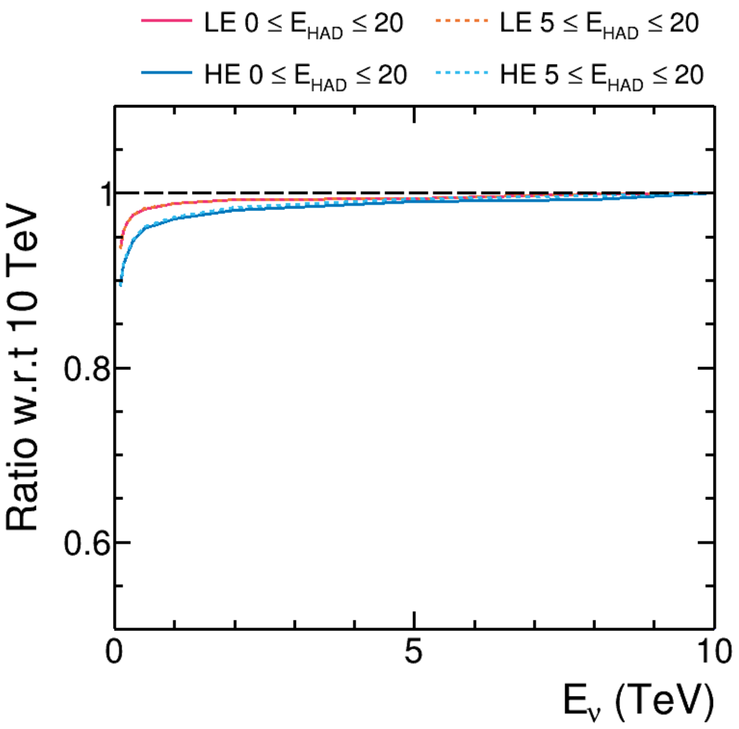
What about $\bar{\nu}_\mu$?



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

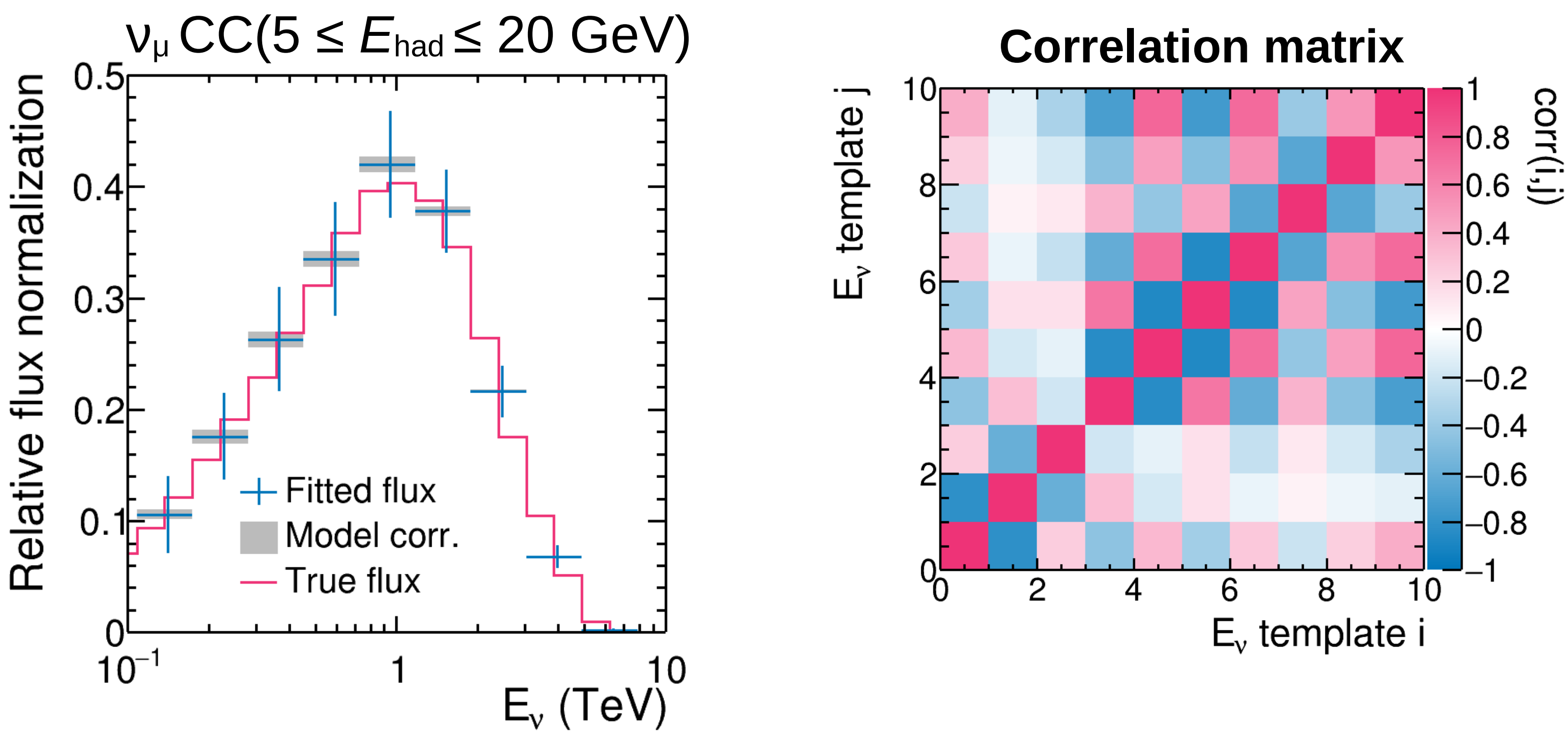
FPF ν_μ flux constraint





- 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

FPF 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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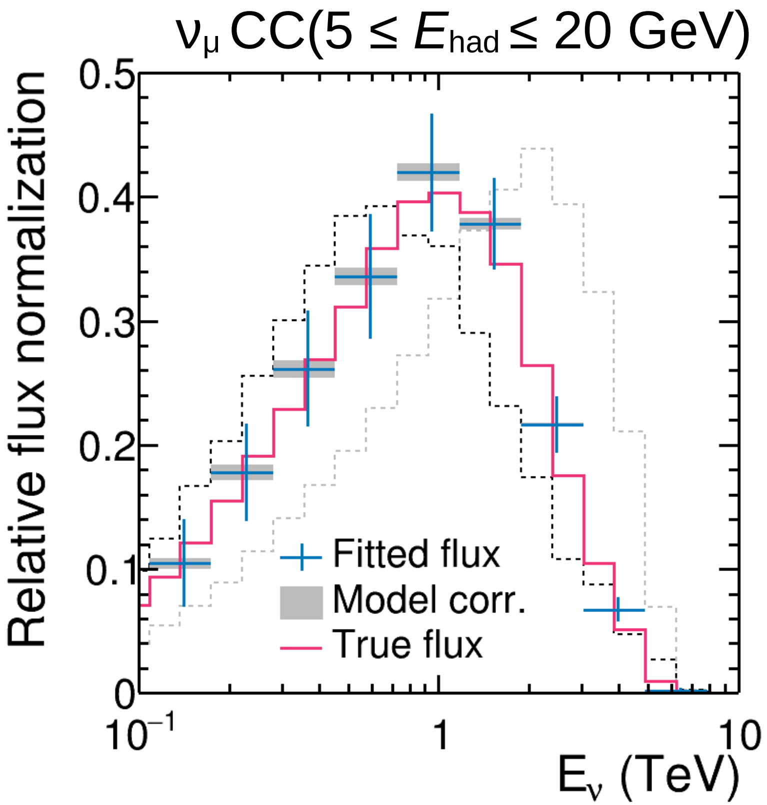
Hadron production model selection



- 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)

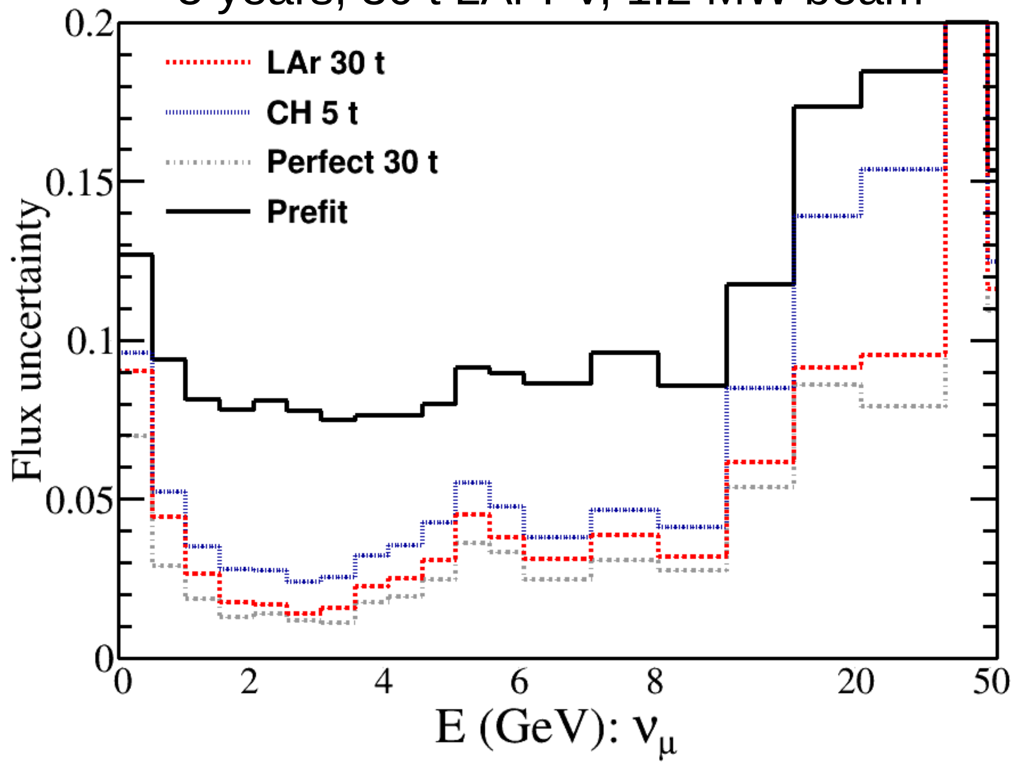
EPOSLHC: PRC92, 034906 (2015)

DPMJET-III: arXiv:hep-ph/0012252

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



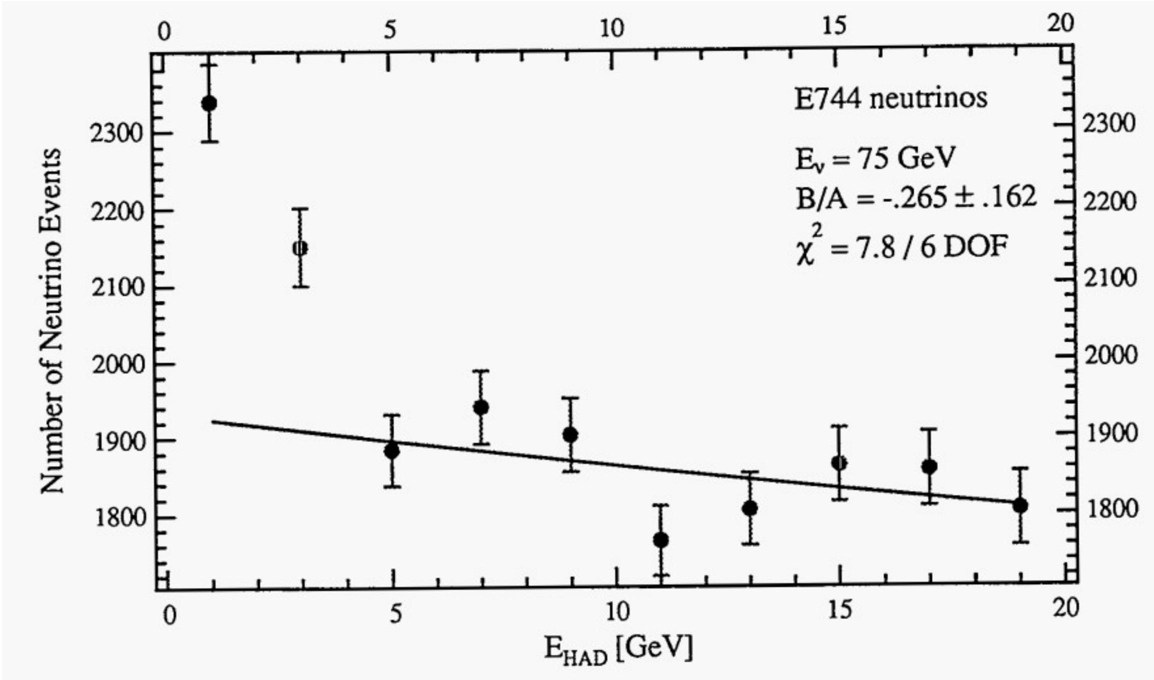
PRD 101, 032002 (2020)

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

- Strong normalization contraint due to known XSEC
- Weak shape constraint due to detector smearing and beam divergence

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