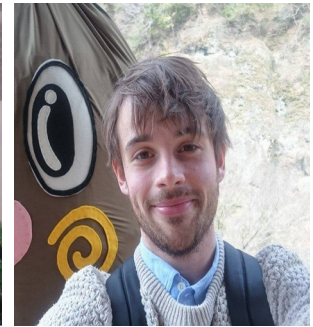


Low- v : a tale of two energies

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

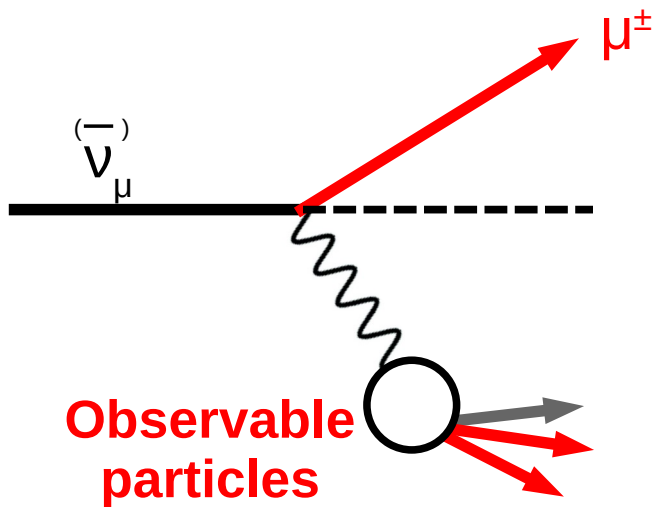
SLAC, 22nd September 2023

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



What do neutrino experiments measure?

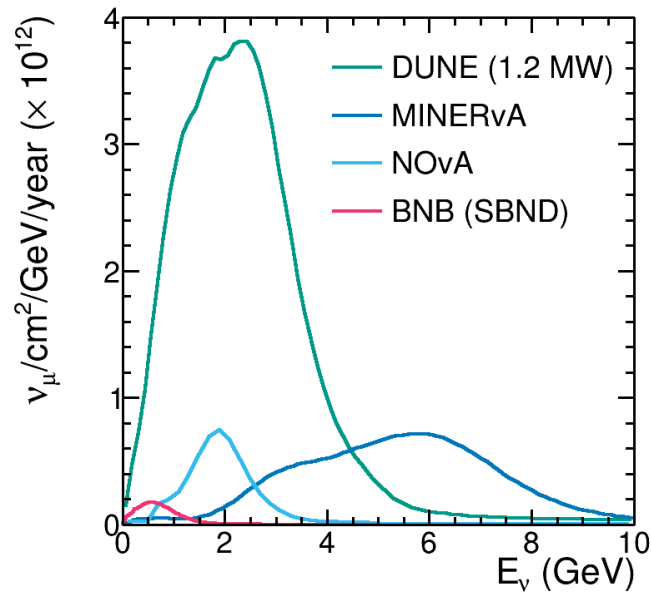
Event rate
Neutrino flux $R(\vec{x}) = \int dE \Phi(E_\nu) \times \sigma(E_\nu, \vec{x}) \times \epsilon(\vec{x}) \times P(E_\nu; \nu_A \rightarrow \nu_B)$
Cross section
Detector smearing
Oscillation probability



- If we want to measure the cross section, we need to understand the flux
- If we want to measure the flux, we need to understand the cross section
- If we want to measure the oscillation probability, we need to understand both

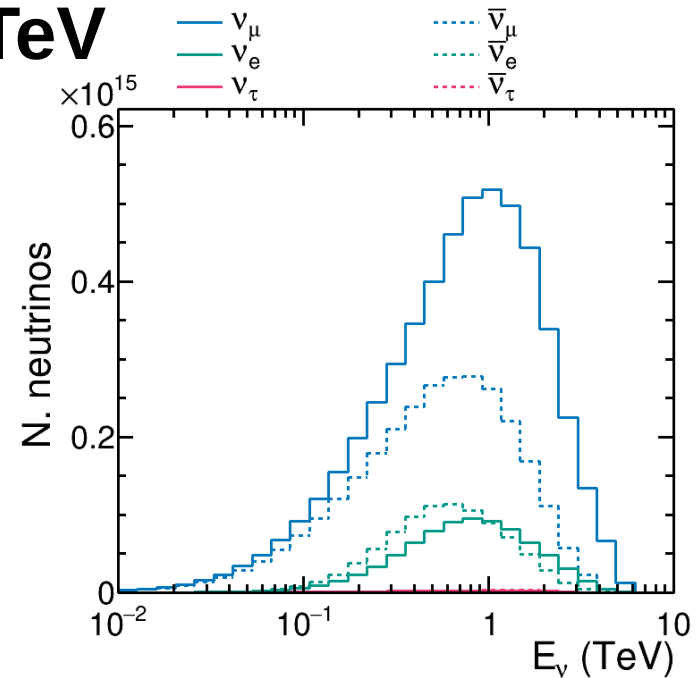
Two energy regimes

Few-GeV



- Flux from π^\pm and K^\pm decay
- Primarily interested in the oscillation probability
- Subdominant interest in cross section and BSM searches

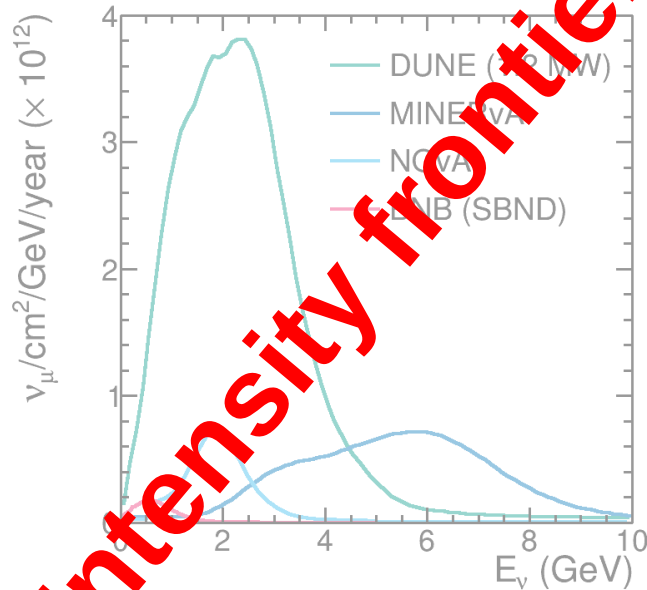
TeV



- Flux from K^\pm and charmed meson decay
- The hadron production mechanism is of interest
- Cross section and BSM searches are primary goals

Two energy regimes

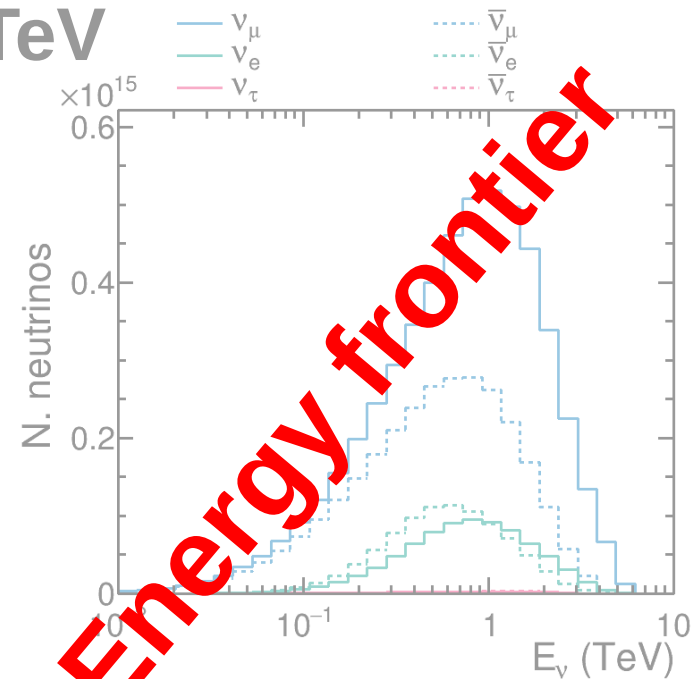
Few-GeV



Intensity frontier

- Flux from π^\pm and K^\pm decay
- Primarily interested in the oscillation probability
- Subdominant interest in cross section and BSM searches

TeV



Energy frontier

- Flux from K^\pm and charmed meson decay
- The hadron production mechanism is of interest
- Cross section and BSM searches are 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

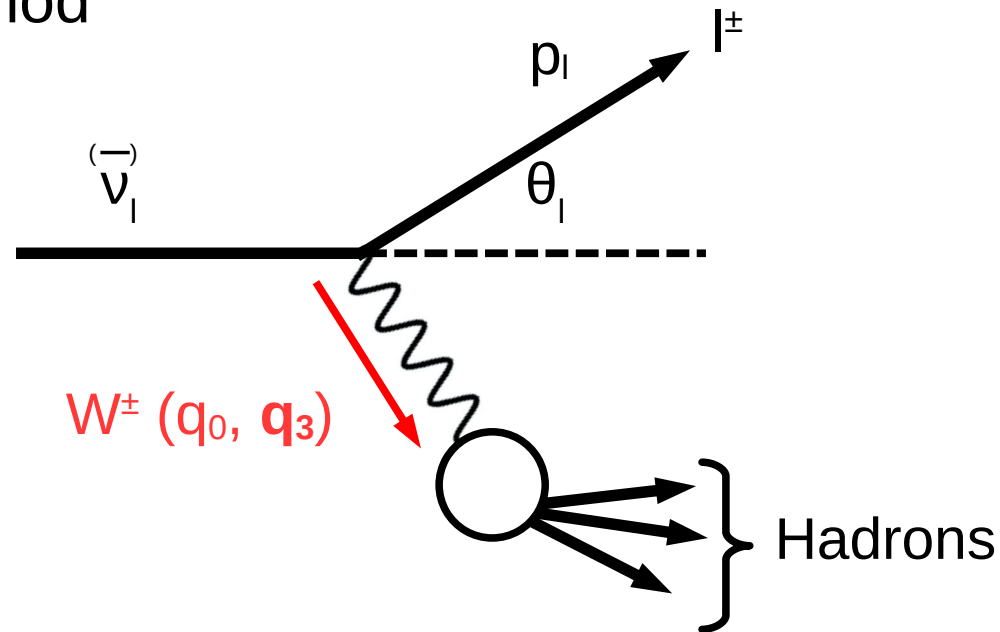
Powerful beams at current and future experiments make small signals accessible

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



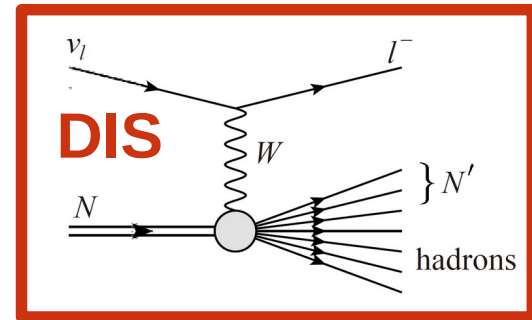
A note on terminology: what is ν ?

- An overloaded character in neutrino physics!
- Different communities denote energy transfer to the hadronic system with $\nu/\omega/q_0$
- Here I will use “ q_0 ” for the quantity and low- ν for the method



The low- ν method [1,2]

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



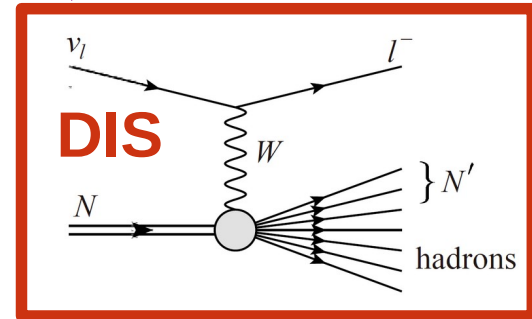
- Comes from the observation that if $q_0/E_\nu \ll 1$, the cross section is approximately constant with E_ν
- The rate as a function of E_ν gives access to the flux *shape*
- Very closely linked to the “low- y ” ($y = q_0/E_\nu$) method [2]

[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

The low- ν method [1,2]

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



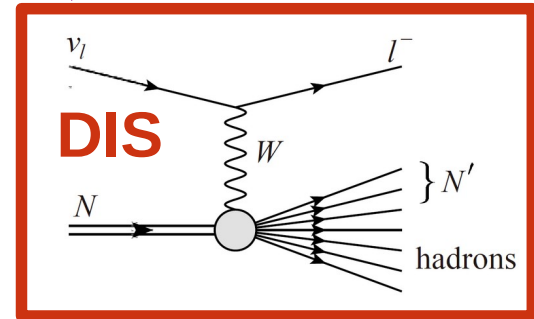
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Low- ν method requirements

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



The method works if:

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

History of the low- ν method



Average neutrino energy

- Widely known/used in accelerator neutrino community:
 - **CCFR**, $30 \leq E_\nu \leq 360$ GeV, 1985–1988*
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- Discussed for use in current/future precision experiments:
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 - **DUNE**, $1 \leq E_\nu \leq 5$ GeV, 2030's
 - ...

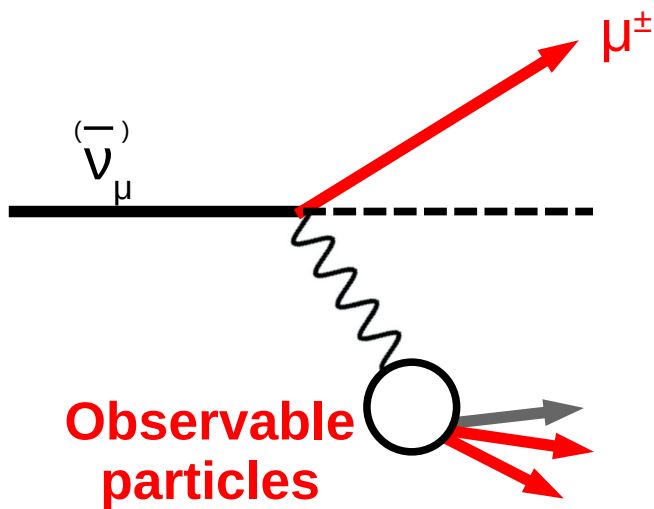
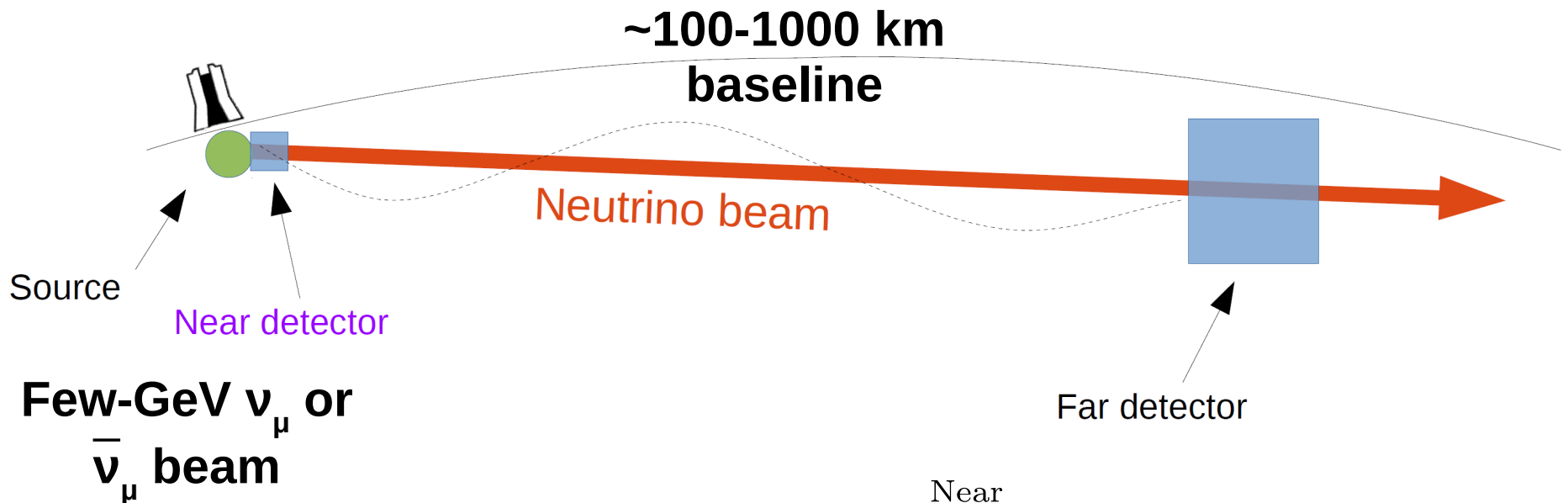
*all dates indicate data-taking periods

Part I: few-GeV energies *(the worst of methods)*



Eur. Phys. J. C **82**, 808 (2022), arXiv:2203.11821 [hep-ph]

Accelerator neutrino experiments



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

Event rate

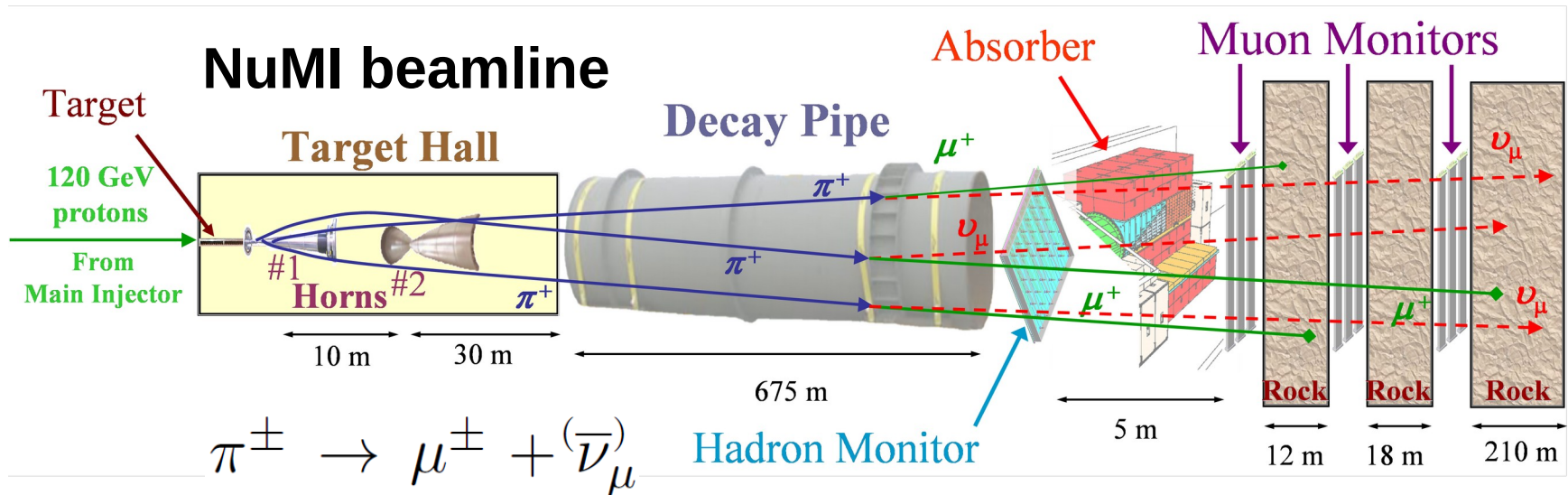
Neutrino flux

Cross section

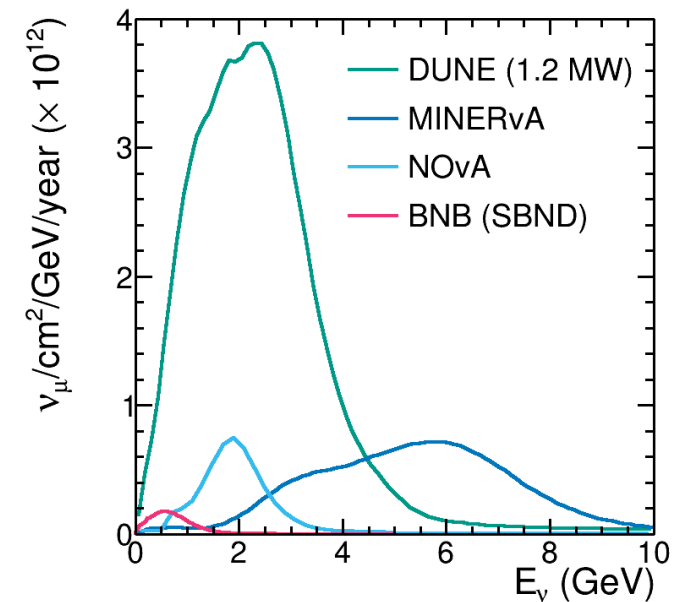
Detector smearing

Oscillation probability

Accelerator neutrino beams

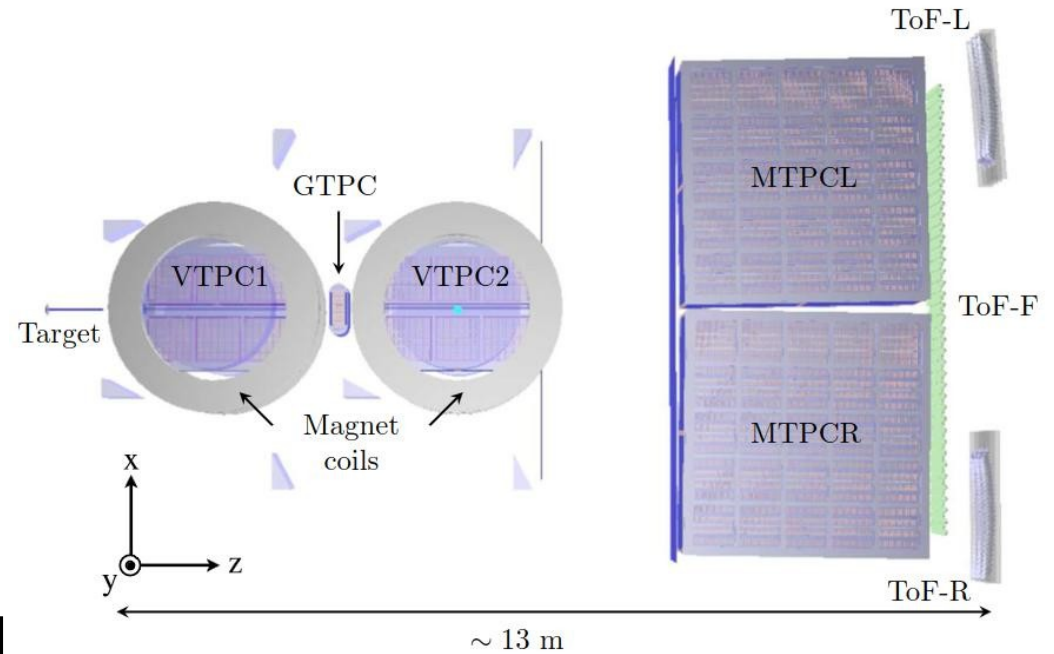


- O(10-100) GeV primary proton beams
- O(10 GeV) secondary pions and kaons
- Focused with electromagnetic horns
- *But still cover a broad E_ν range*



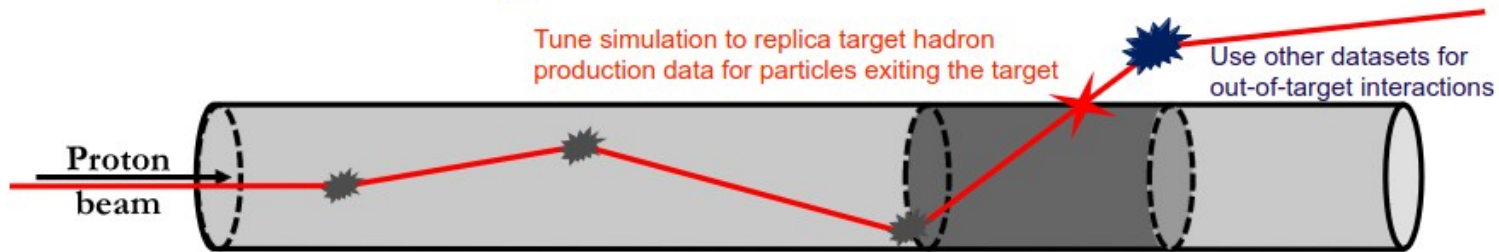
Accelerator neutrino flux uncertainty

- Dedicated hadron production measurements at fixed target beam facilities:
 - Thin target
 - Replica target
- Example: NA61/SHINE*, used for T2K → **5-10% uncertainties**

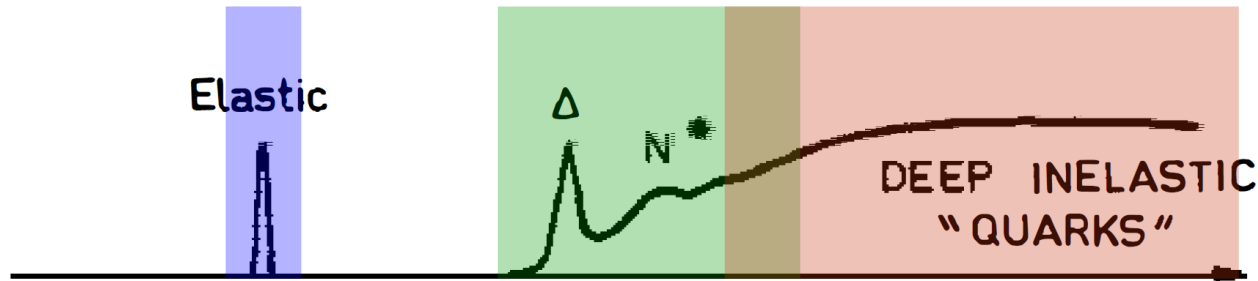


Eur. Phys. J. C76, 617 (2016)

Eur. Phys. J. C79, 100 (2019)

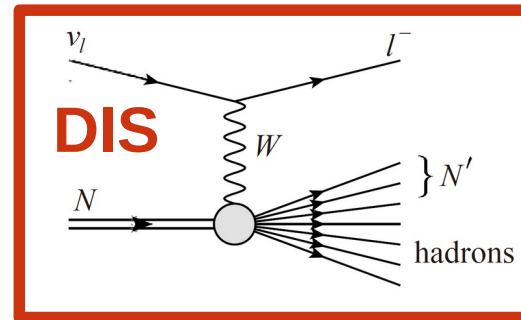
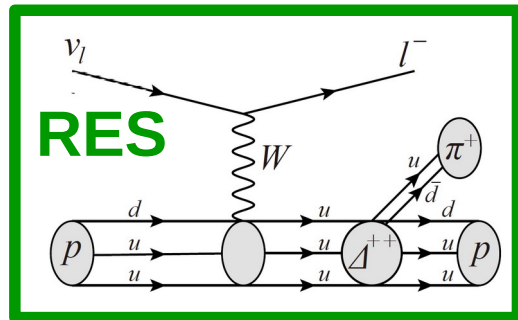
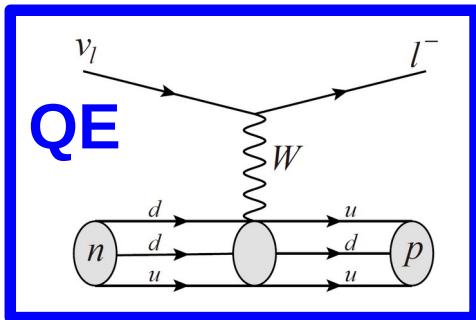


How do few-GeV neutrinos interact?

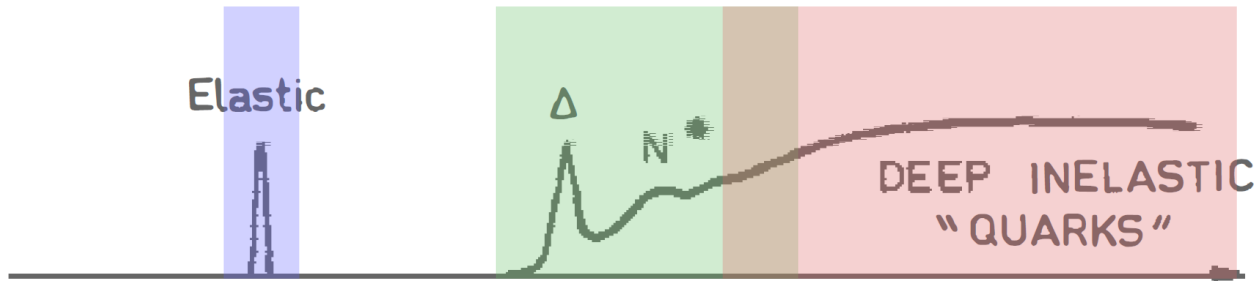


$$q_0 = E_\nu - E_l$$

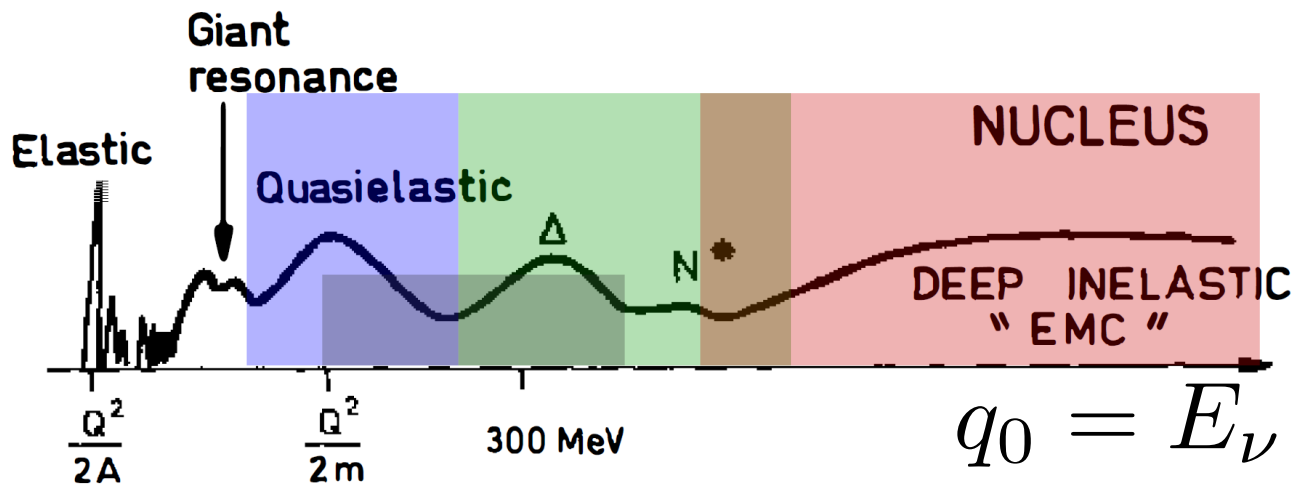
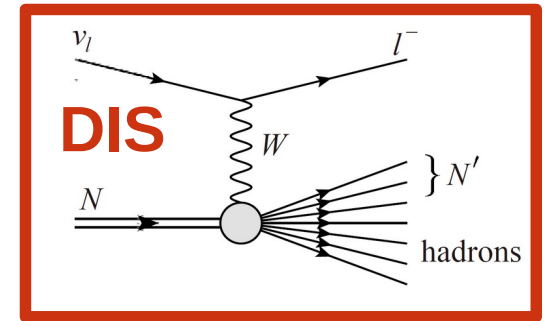
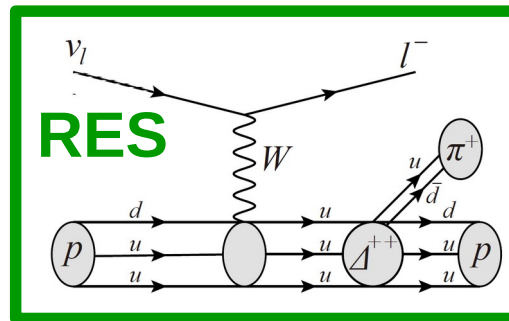
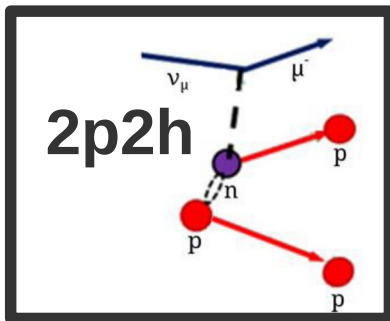
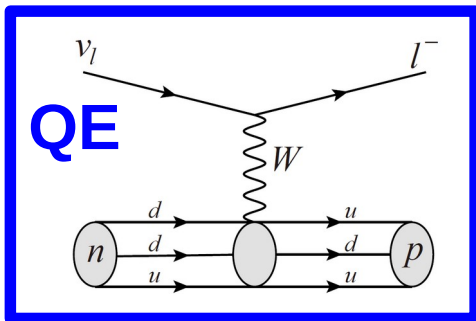
Energy transfer



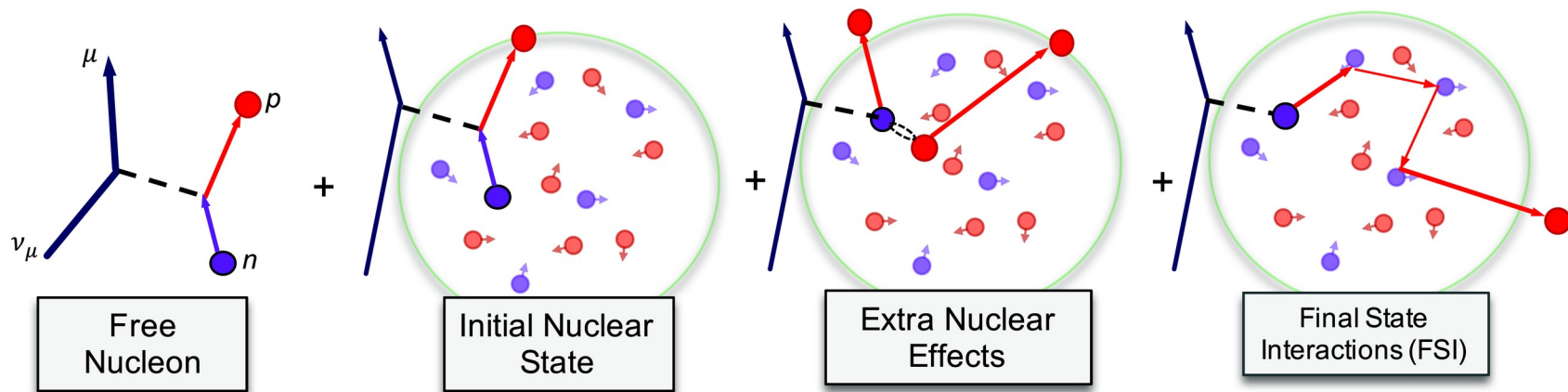
How do few-GeV neutrinos interact?



$$q_0 = E_\nu - E_l$$



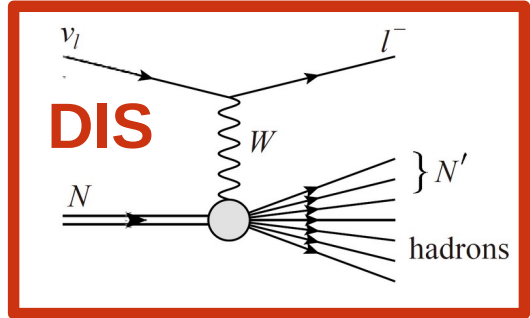
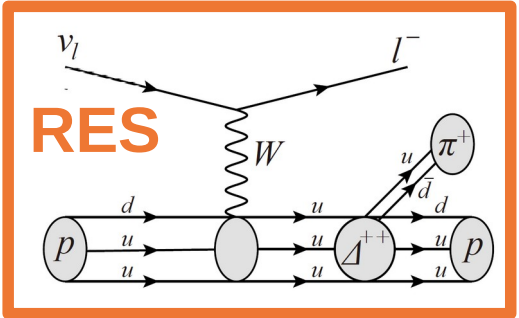
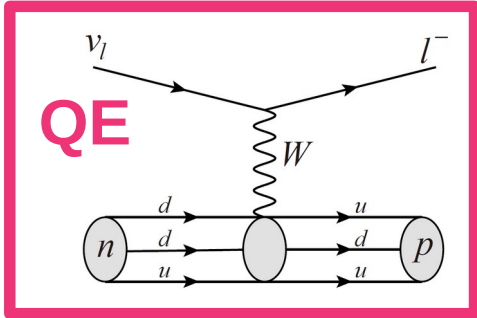
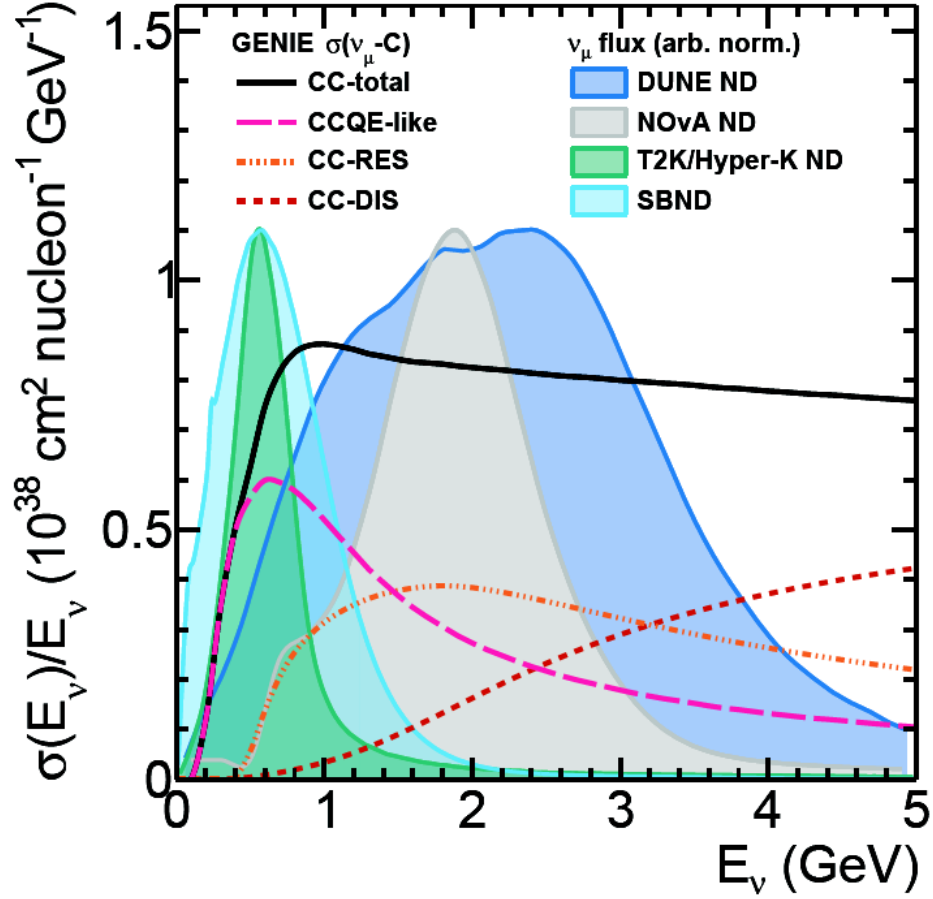
$$q_0 = E_\nu - E_l$$



Many nuclear effects impact what is visible
Final state particle content does not isolate
initial interaction type!

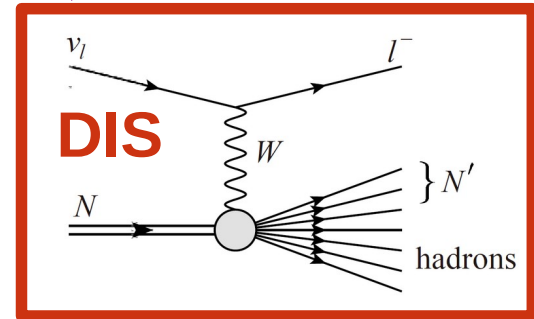
Few-GeV cross sections are not well understood

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



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:

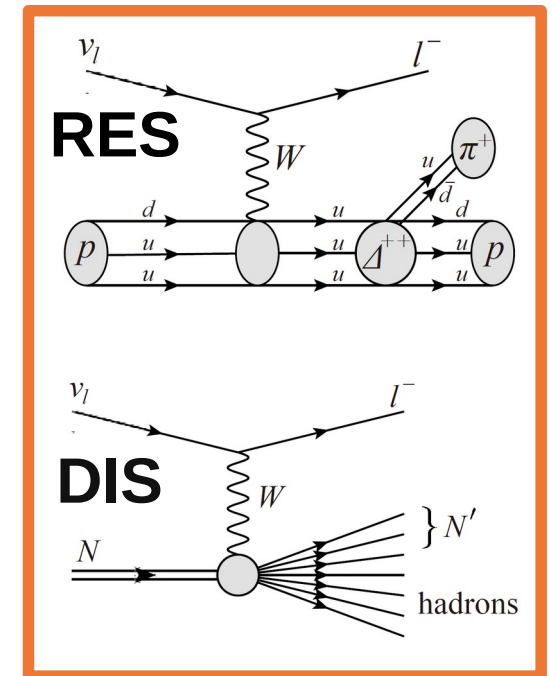
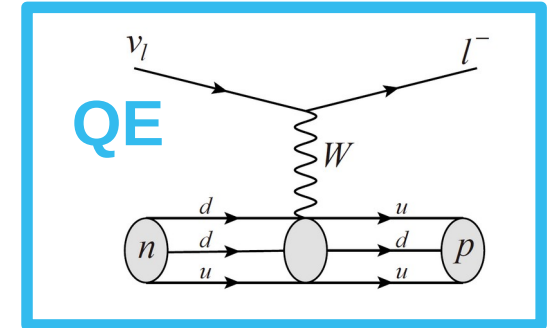
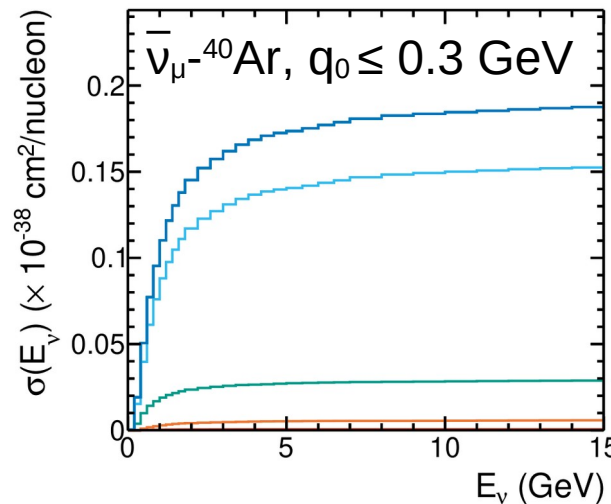
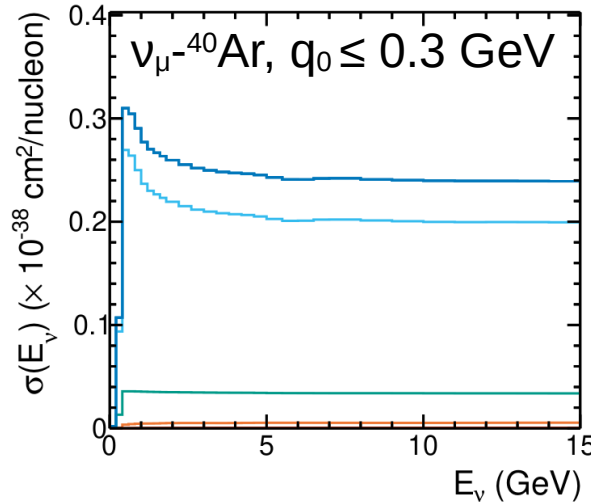
- 1) There is a low- q_0 region with a constant cross section in E_ν
- 2) It can be selected without significant model dependence
- 3) It provides a useful number of events

Is the low- q_0 cross section flat in E_ν ?

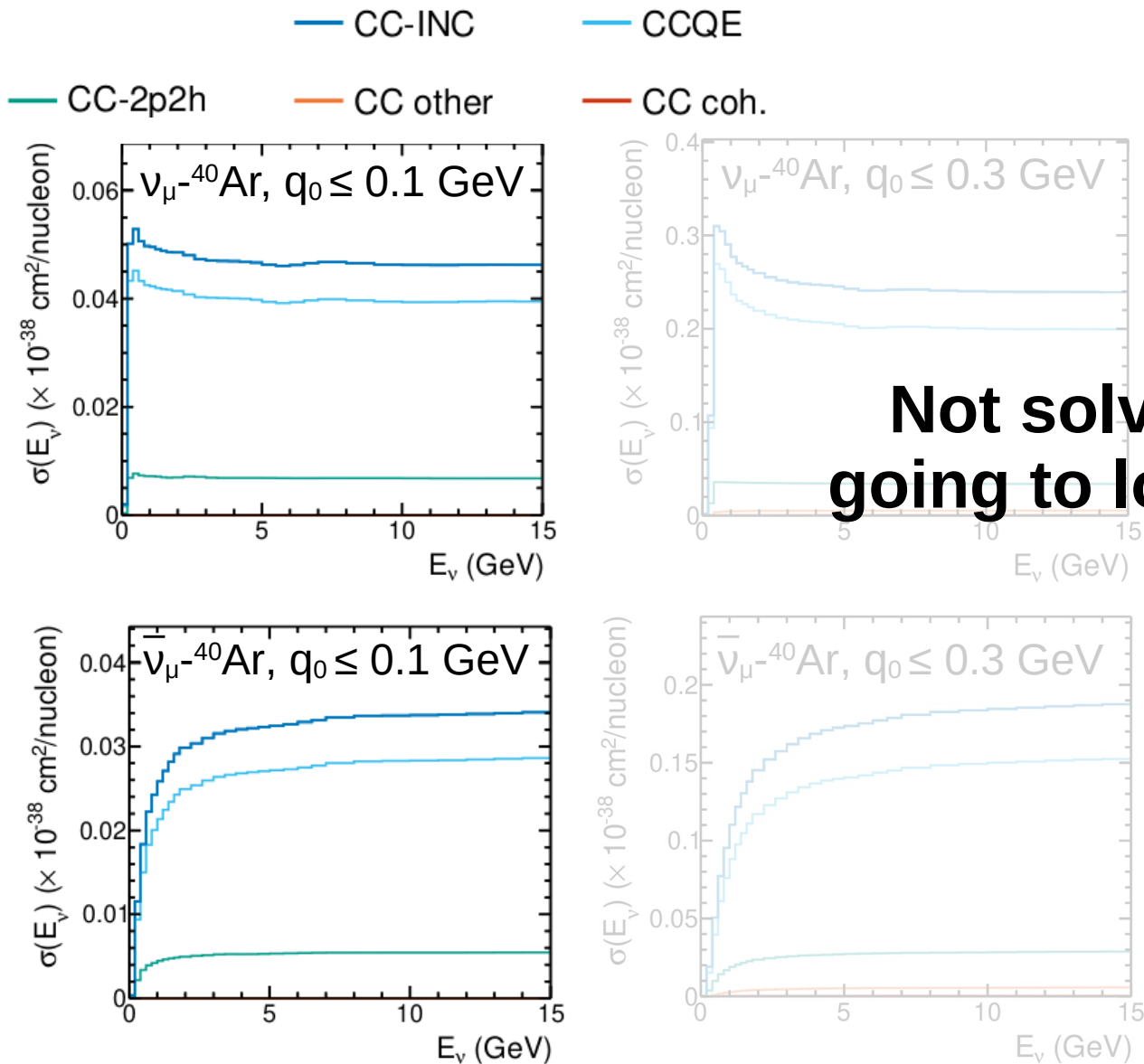
- GENIEv3 (10a-02-11a)
- A common “base model” for experiments
- Dominated by **QE**, **2p2h**, and **RES**
- XSEC does not become constant until ≥ 5 GeV

(Also studied for hydrocarbons)

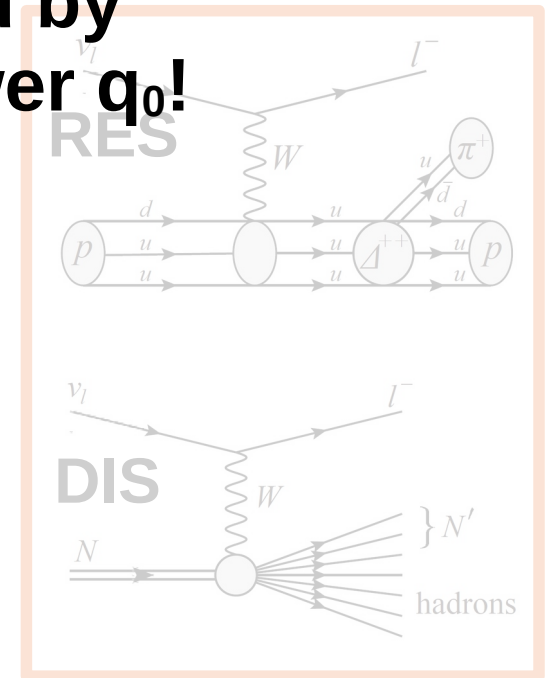
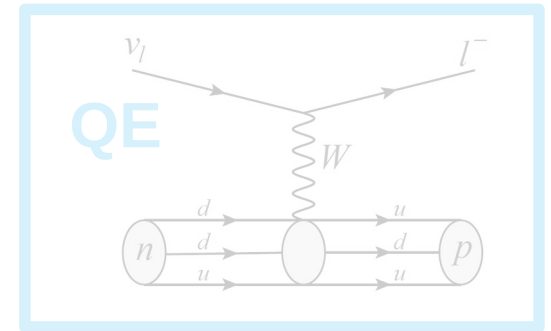
— CC-INC — CCQE
 — CC-2p2h — CC other — CC coh.



Is the low- q_0 cross section flat in E_ν ?



Not solved by going to lower q_0 !

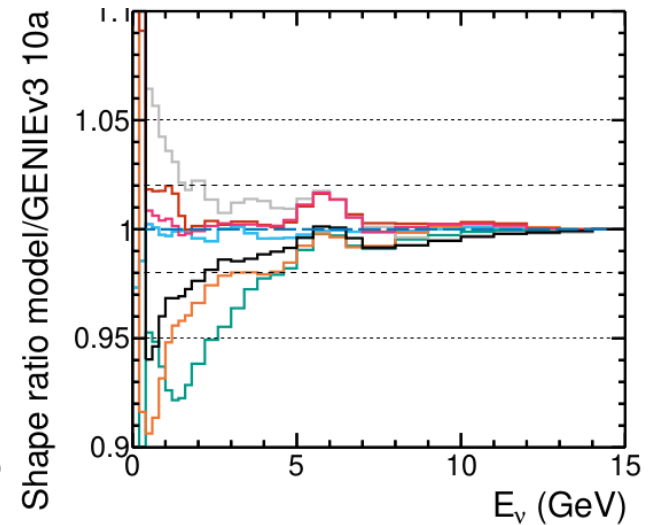
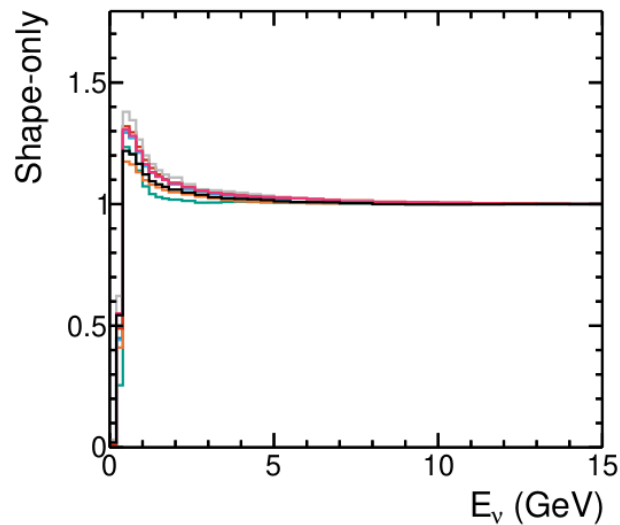
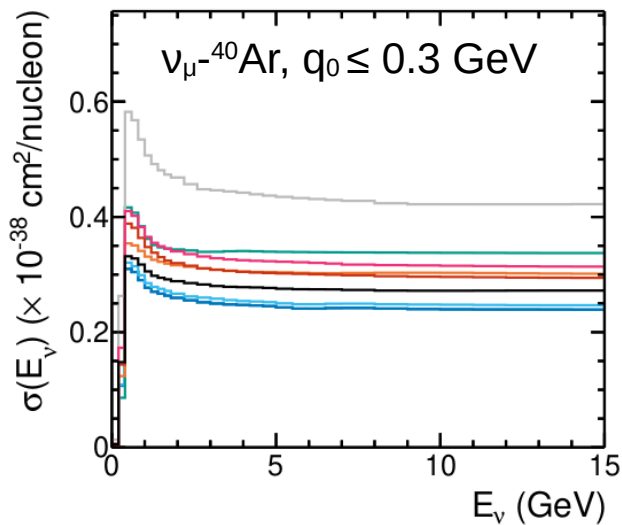
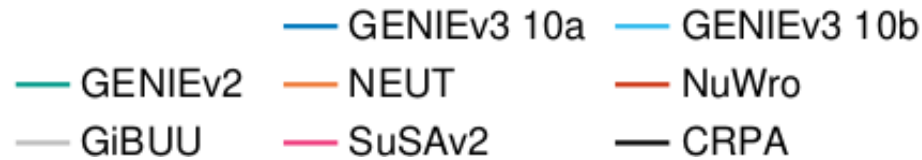


Few-GeV cross-section models

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

Is the low- q_0 cross section flat in E_ν ?



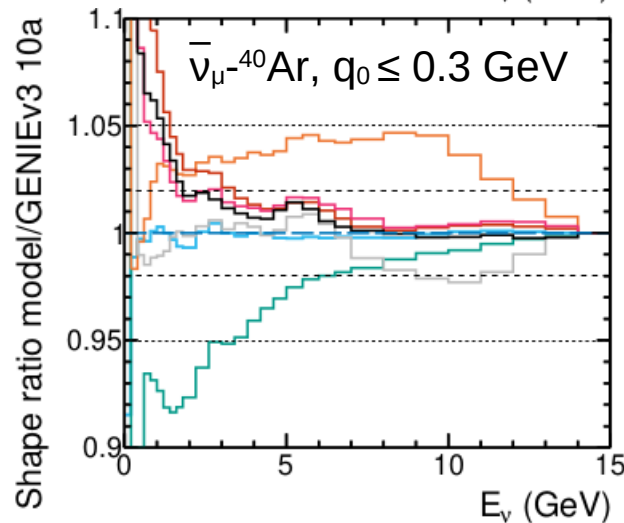
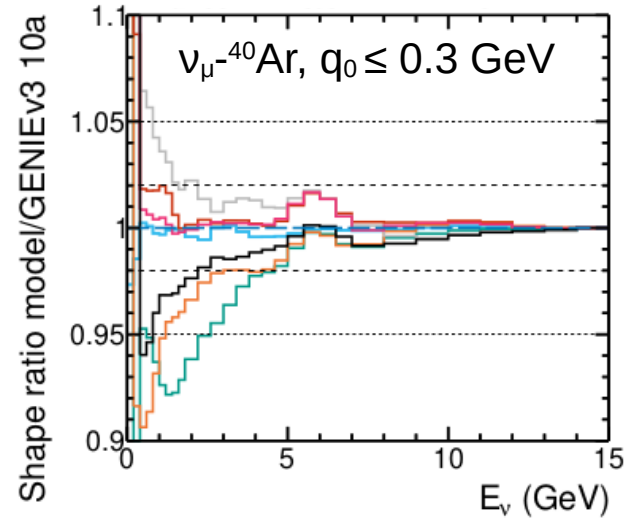
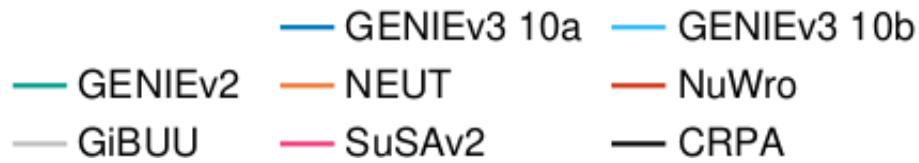
Compare a variety of new/commonly used generator models

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

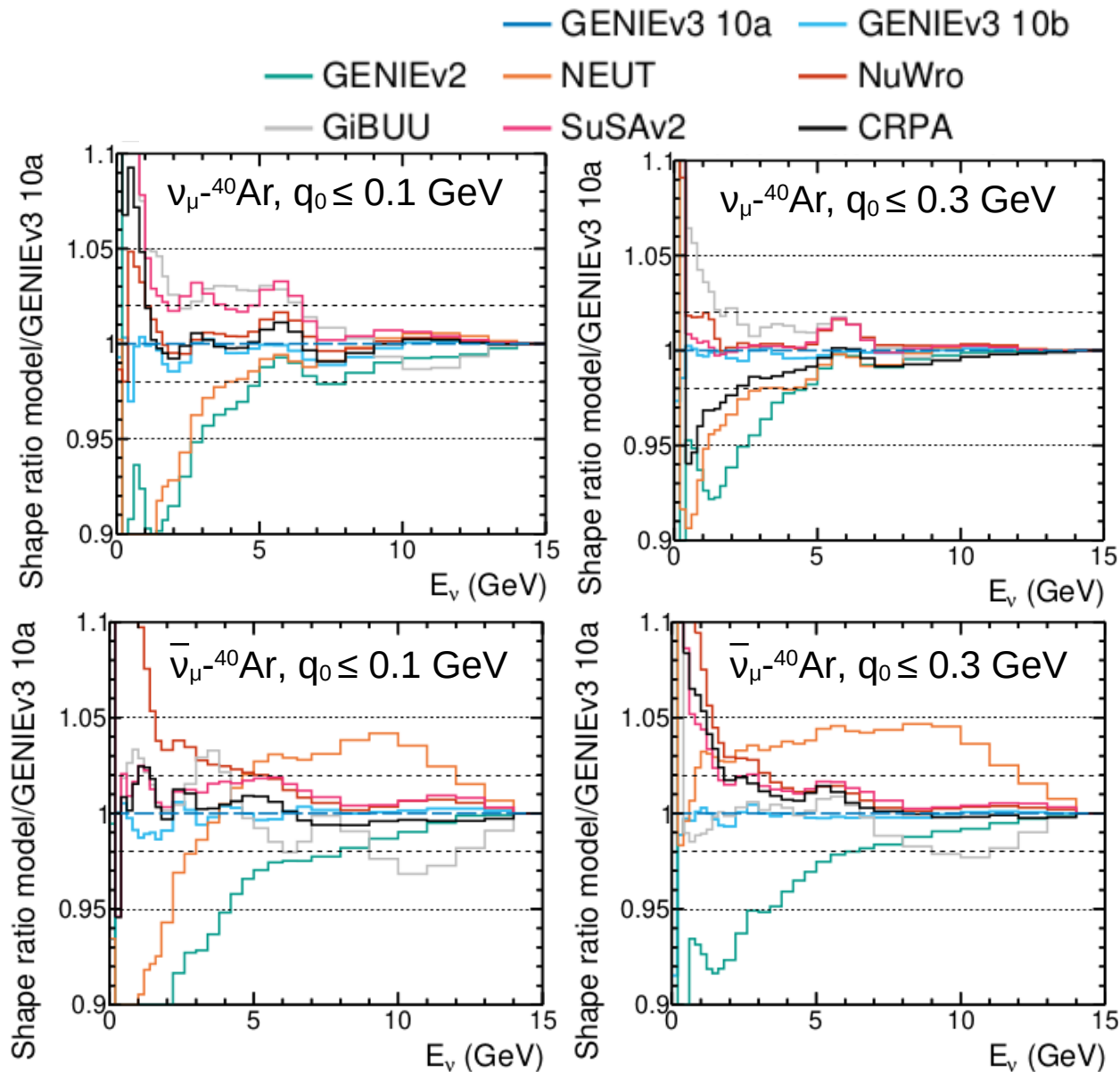
Is the low- q_0 cross section flat in E_ν ?

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



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

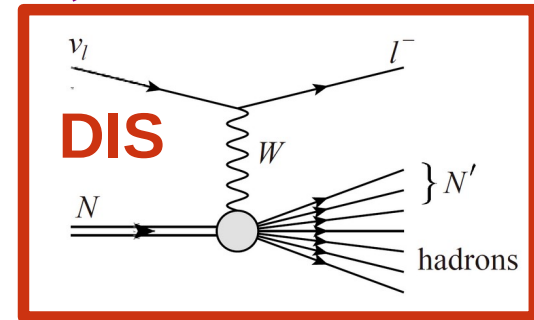
Is the low- q_0 cross section flat in E_ν ?



Situation not improved by going to a lower q_0 cut!

Low- ν method requirements

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

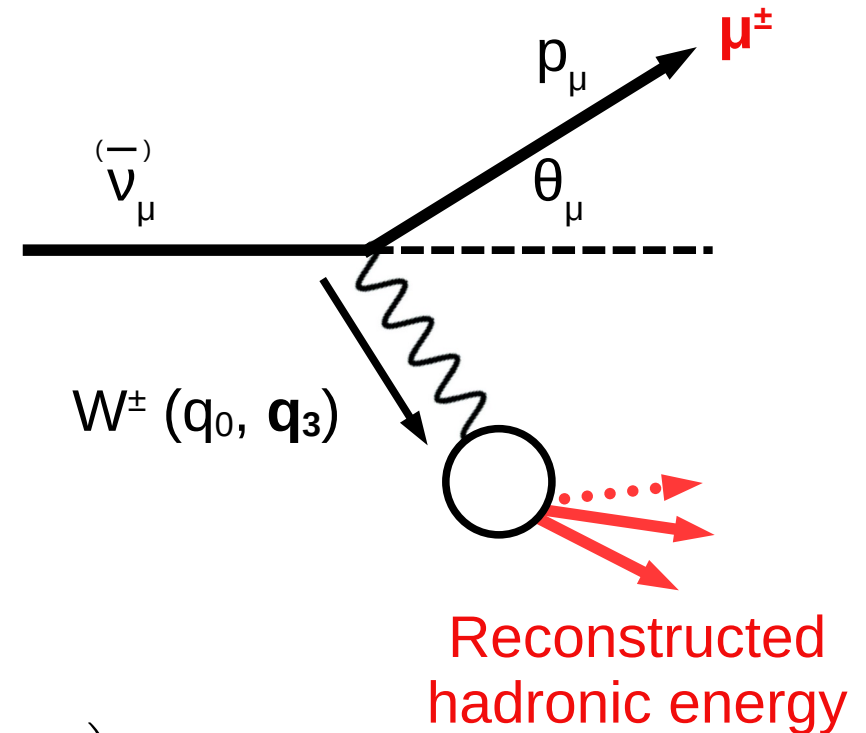


The method works if:

- 1) ~~There is a low- q_0 region with a constant cross section in E_ν~~
- 2) It can be selected without significant model dependence
- 3) It provides a useful number of events

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:



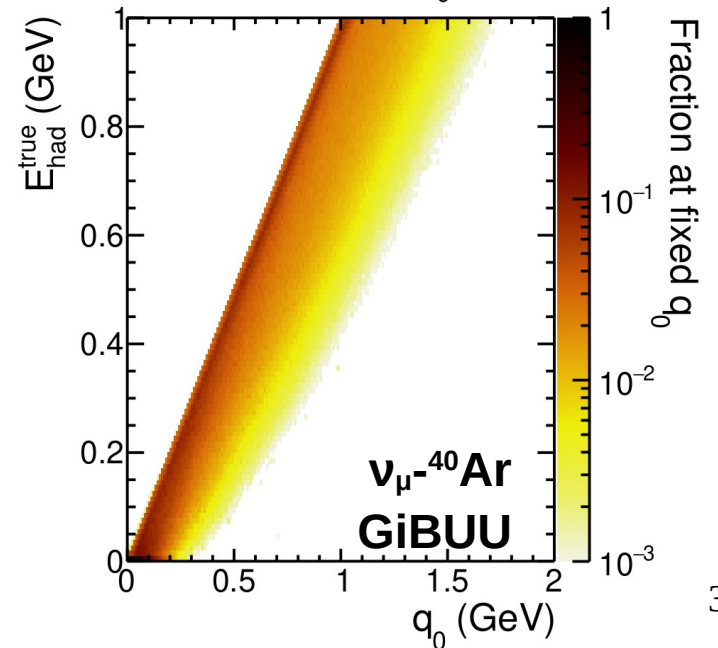
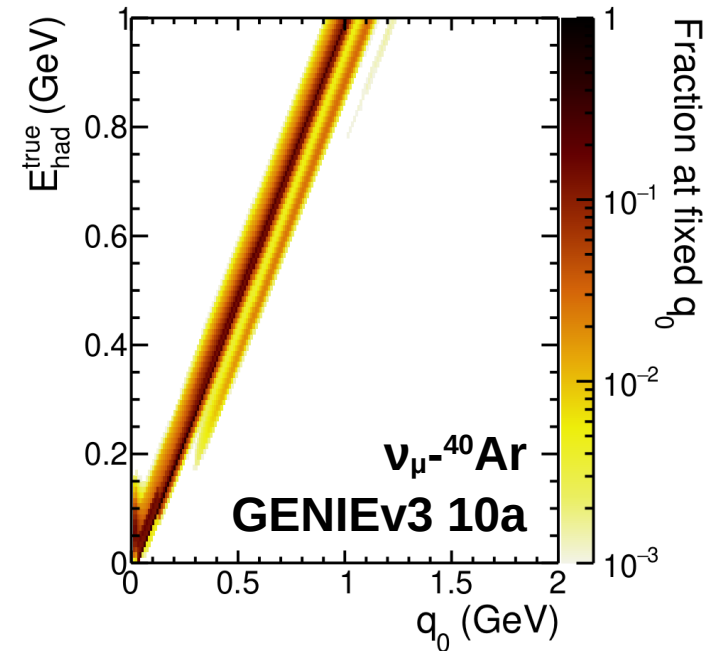
$$1) E_{\text{had}}^{\text{true}} = \left(\sum_{i=n,p} E_{\text{kin}}^i \right) + \left(\sum_{i=\pi^\pm, \pi^0, \gamma} E_{\text{total}}^i \right) \quad \text{Perfect!}$$

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

Can a low- q_0 sample be experimentally selected?

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

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

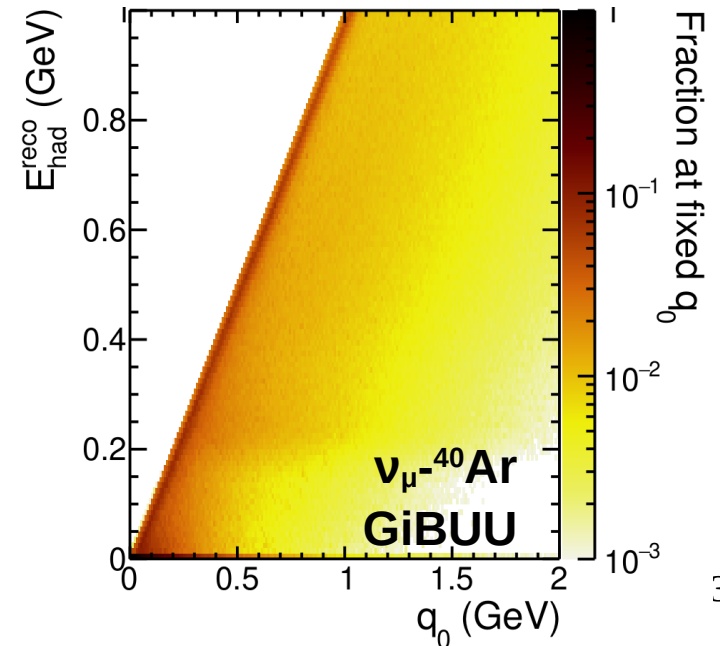
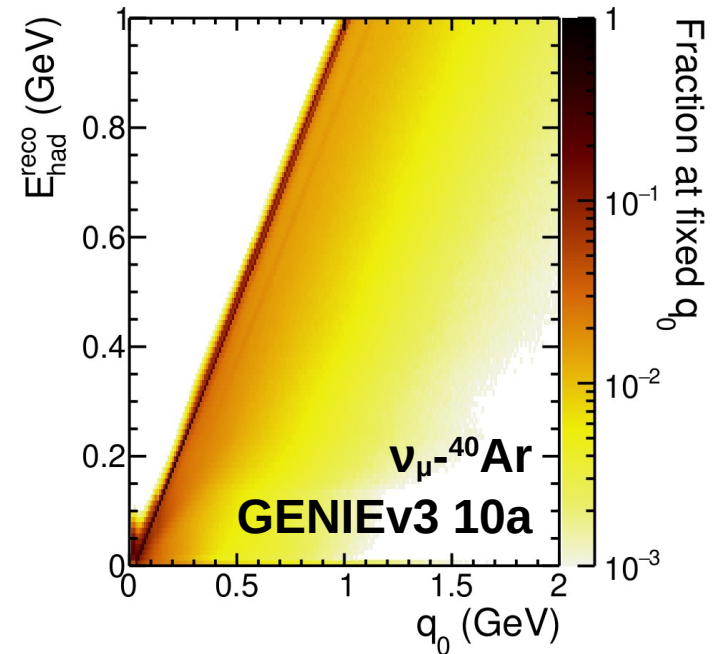


Can a low- q_0 sample be experimentally selected?

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

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

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

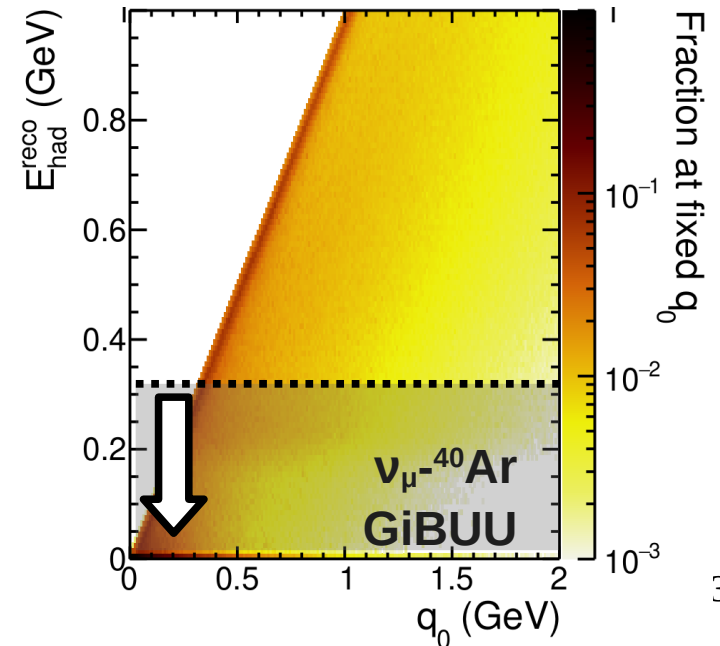
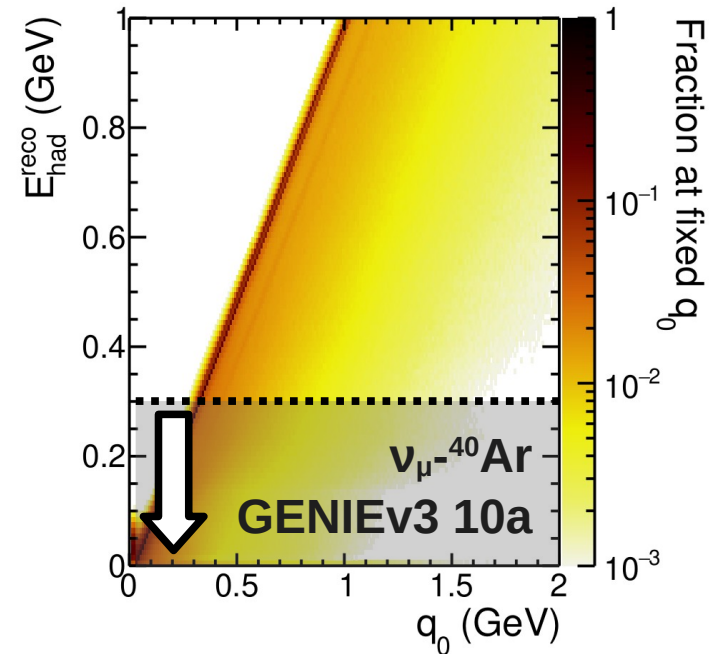


Can a low- q_0 sample be experimentally selected?

- Most detectors cannot recover energy lost to neutrons
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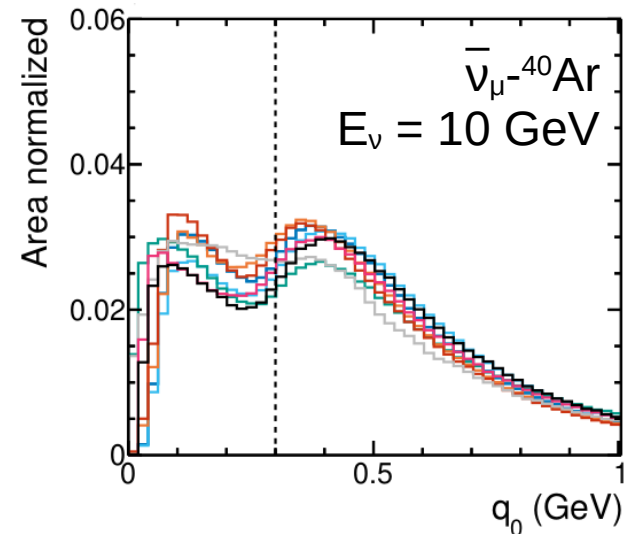
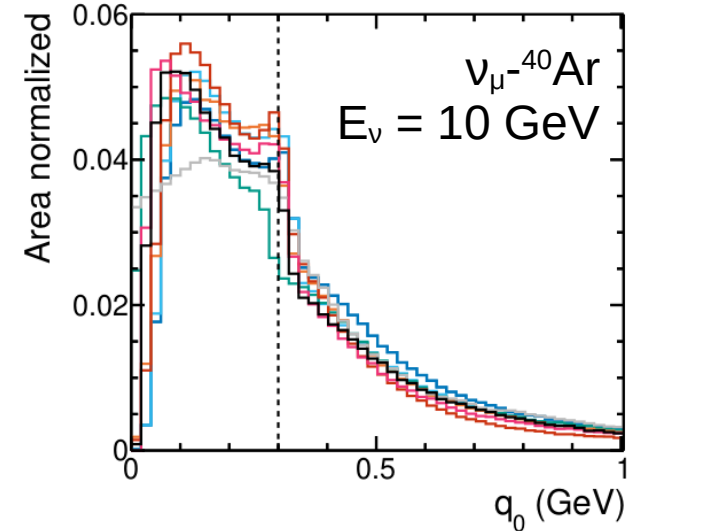
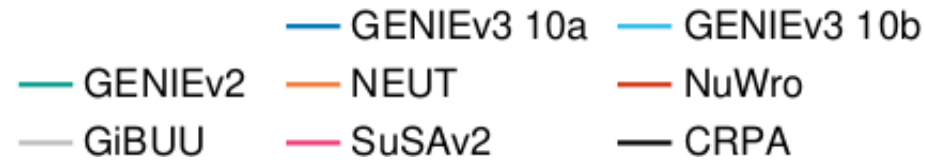
Situation worsens considerably if pion misreconstruction is included: EPJC 82 (2022) 9, 808



Can a low- q_0 sample be experimentally selected?

- Cutting on $E_{\text{had}} \leq 0.3$ GeV gives a different q_0 content between models
- More challenging for antineutrinos due to higher neutron content
- **Difficult to isolate a low- q_0 sample**

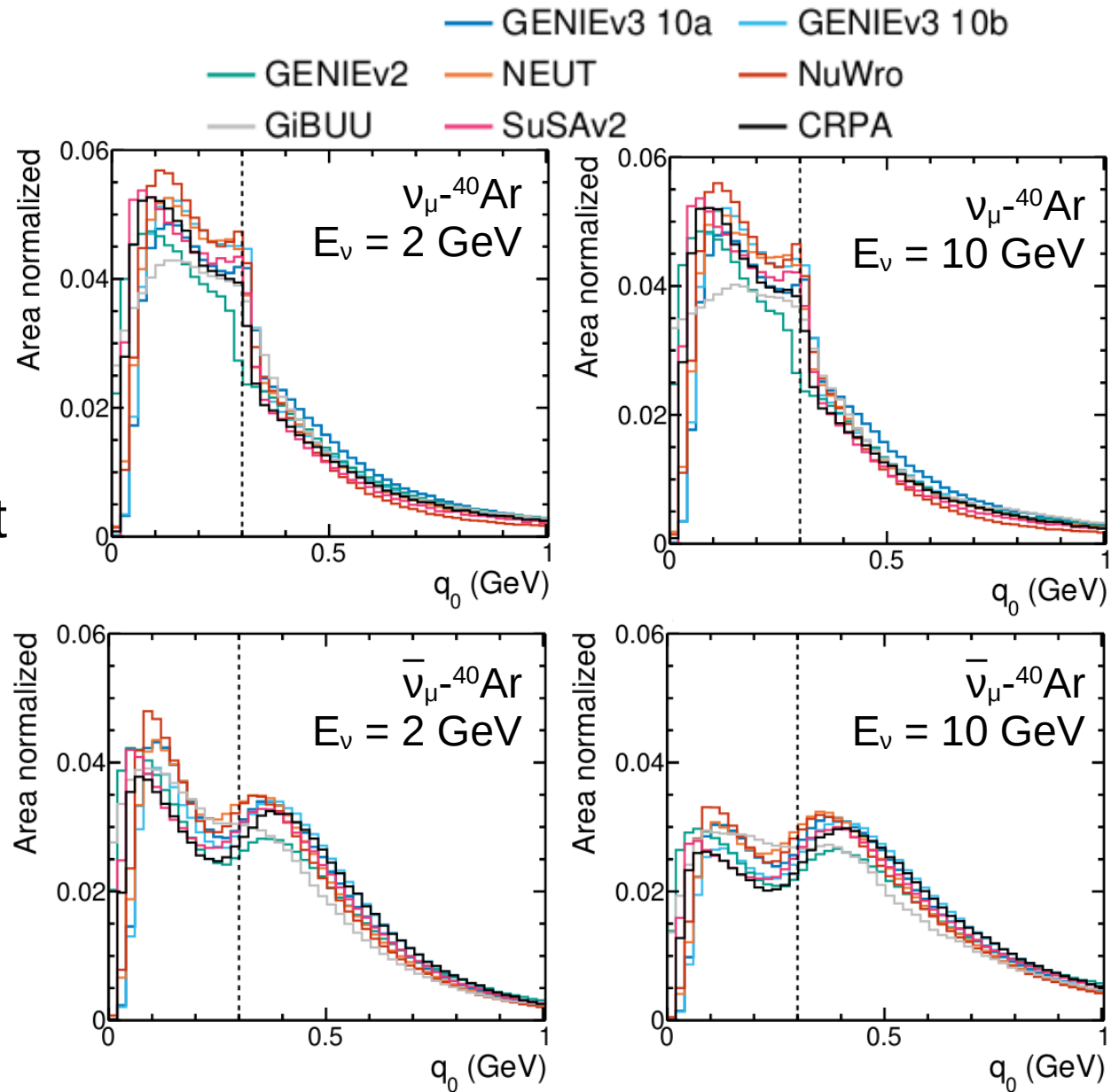
$$E_{\text{had}}^{\text{reco}} = \left(\sum_{i=p} E_{\text{kin}}^i \right) + \left(\sum_{i=\pi^\pm, \pi^0, \gamma} E_{\text{total}}^i \right)$$



Can a low- q_0 sample be experimentally selected?

Cut on $E_{\text{had}} \leq 0.3$ GeV

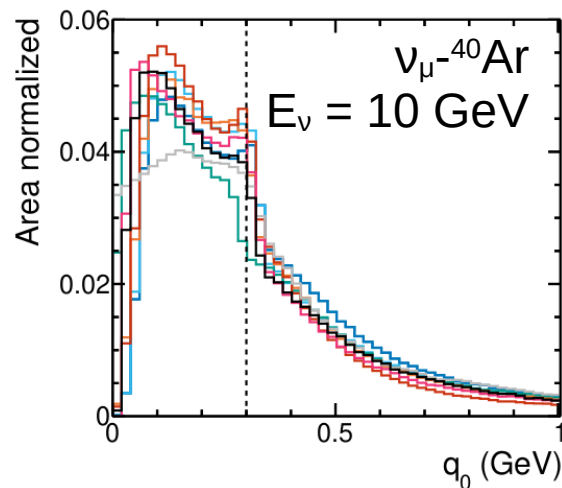
Smearing is not constant with E_ν , particularly for antineutrino!



Few-GeV accelerator neutrino conclusions

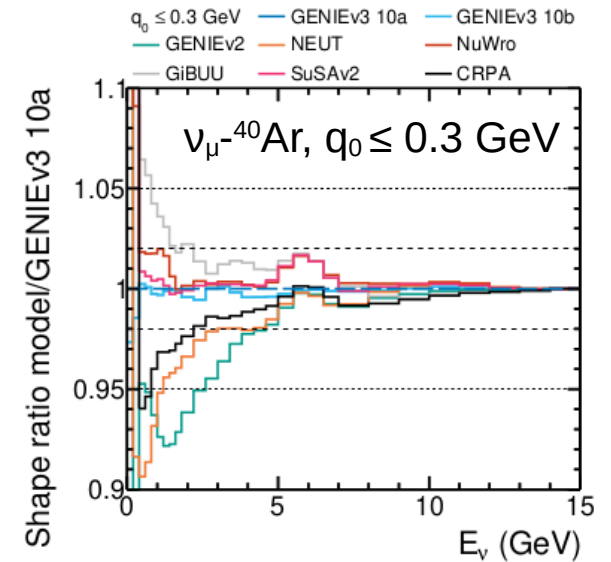
The method works if:

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



2) ~~It can be selected without significant model dependence~~

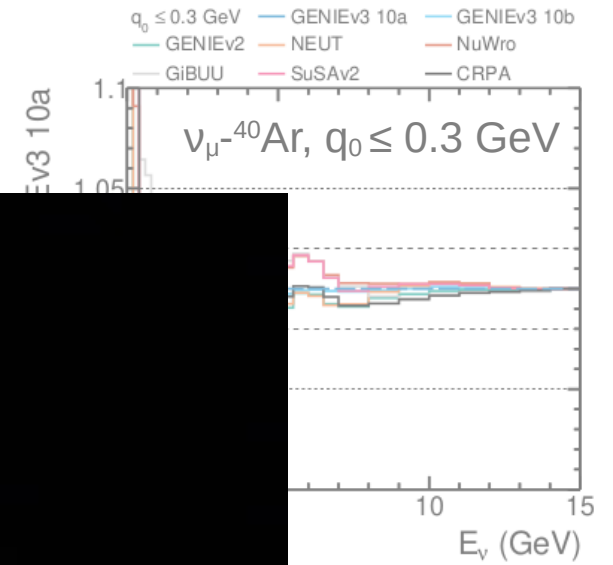
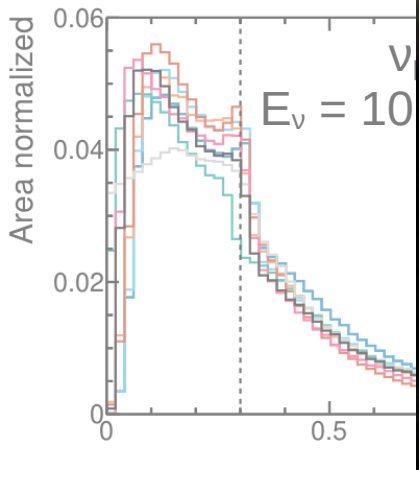
3) It provides a useful number of events



Few-GeV accelerator neutrino conclusions

The method works if:

1) τ
 ϵ



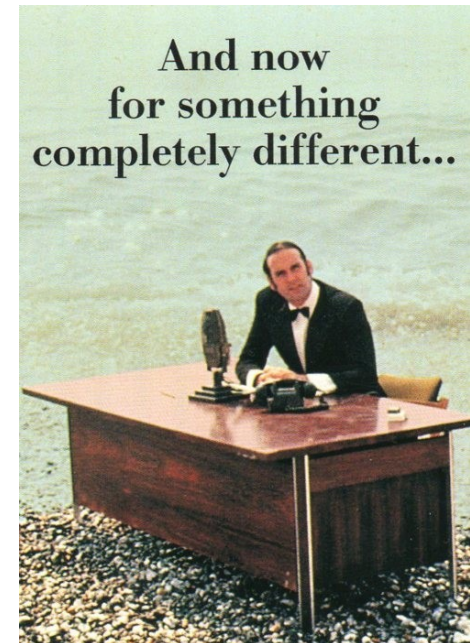
3) It provides a useful number of events

Part II: TeV energies

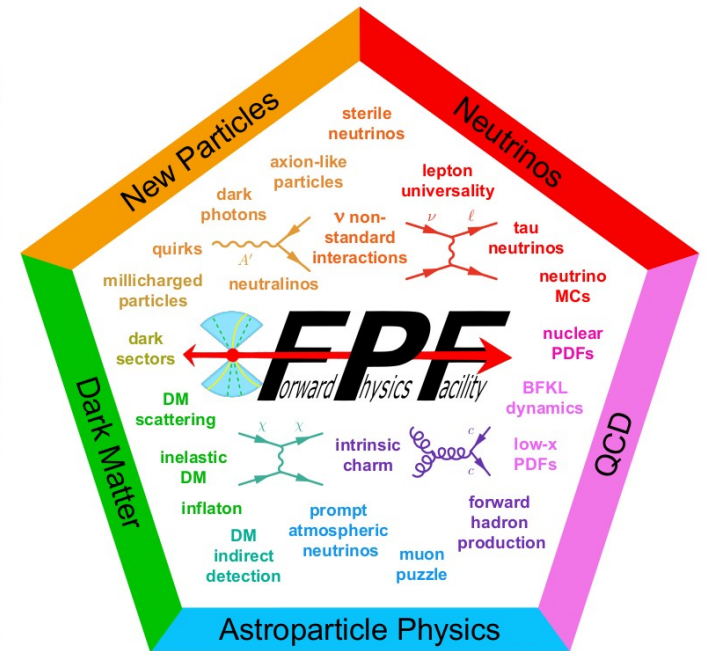
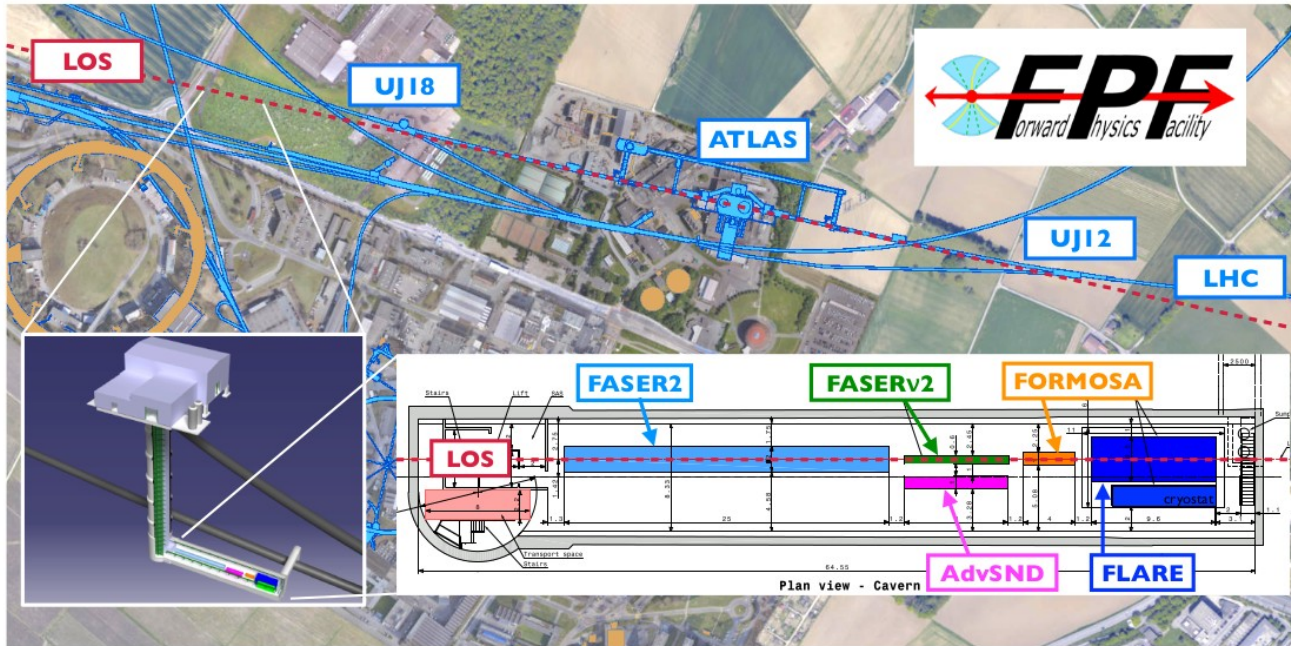
(the best of methods)



Paper in preparation...



The Forward Physics Facility (FPF)

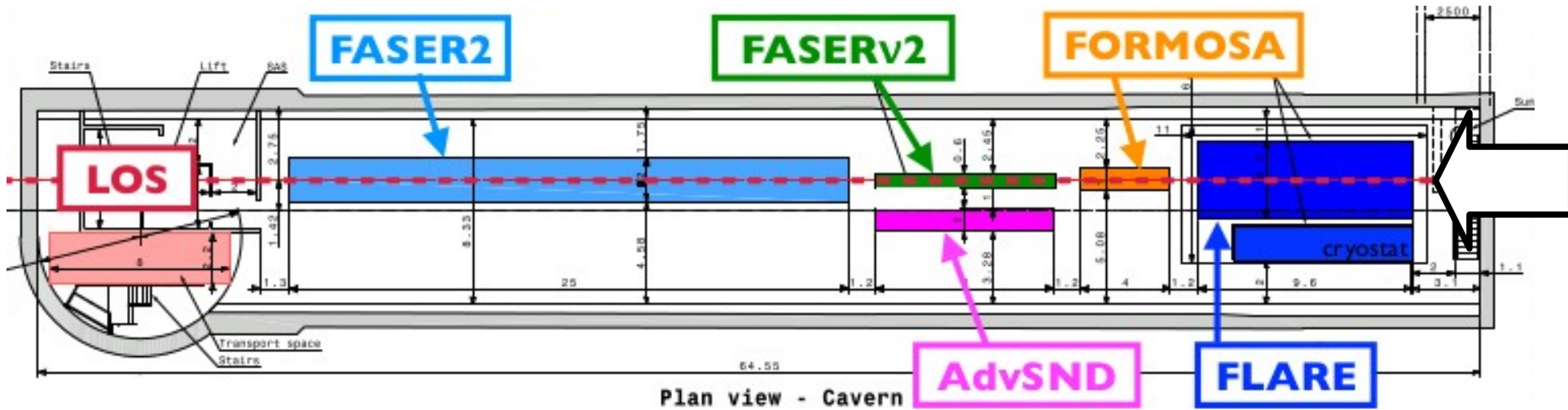


J. Phys. G 50 (2023) 3, 030501

- 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

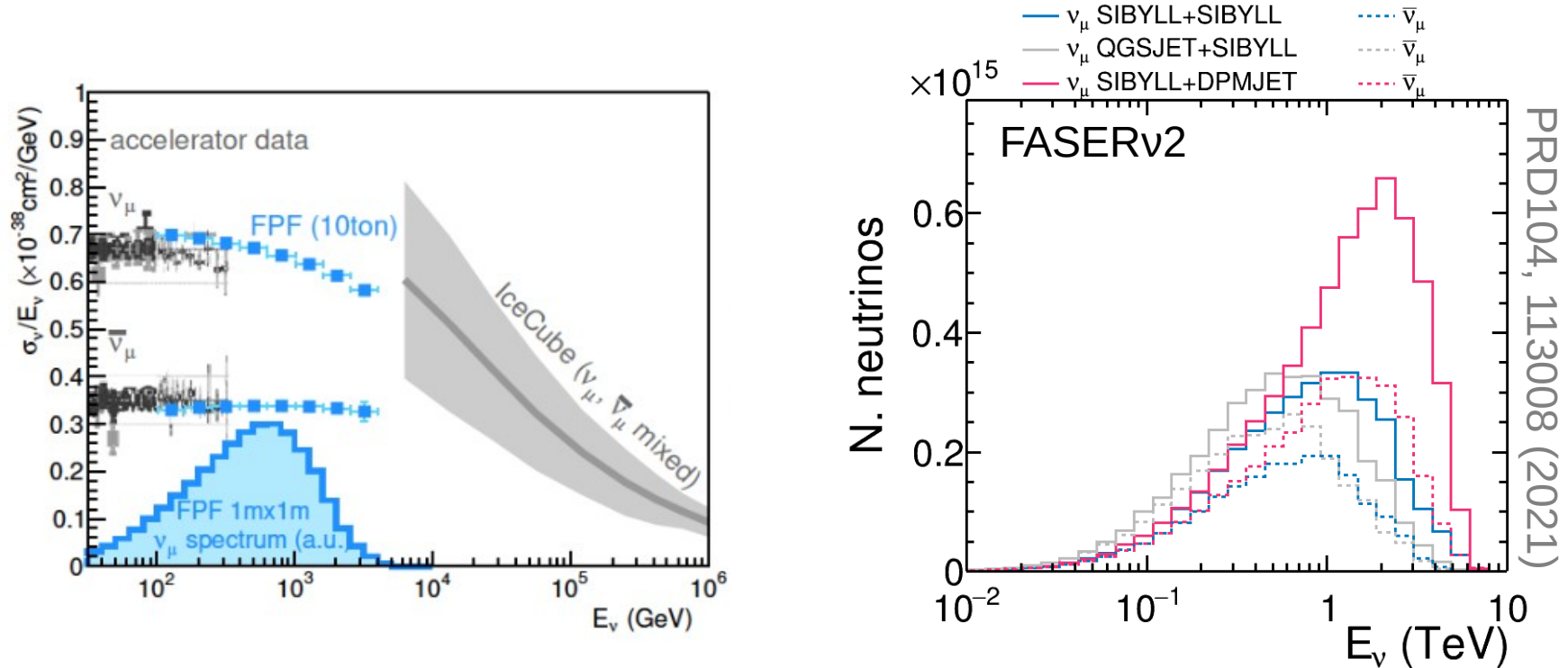
$$x = \frac{Q^2}{2Mq_0}$$

FPF detectors

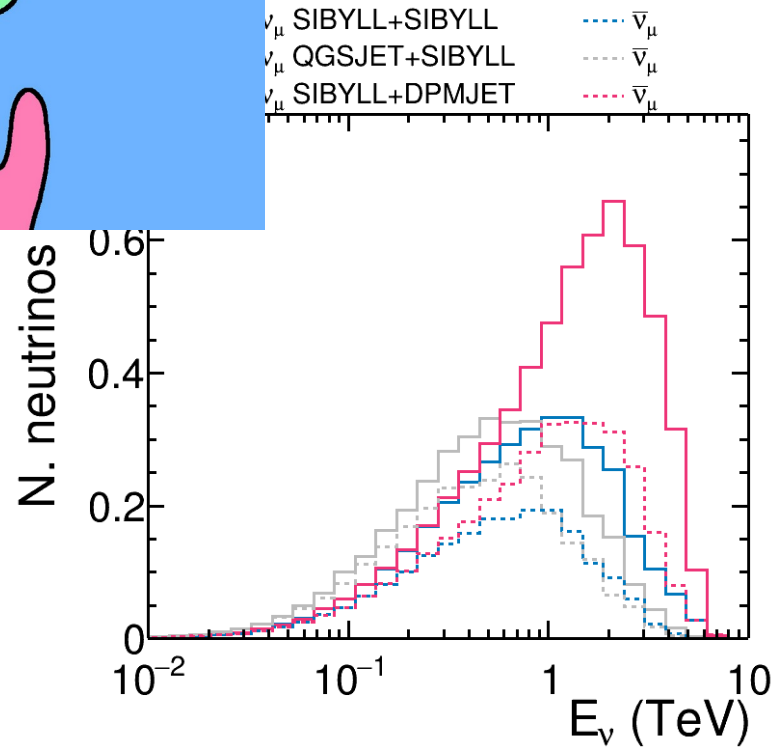
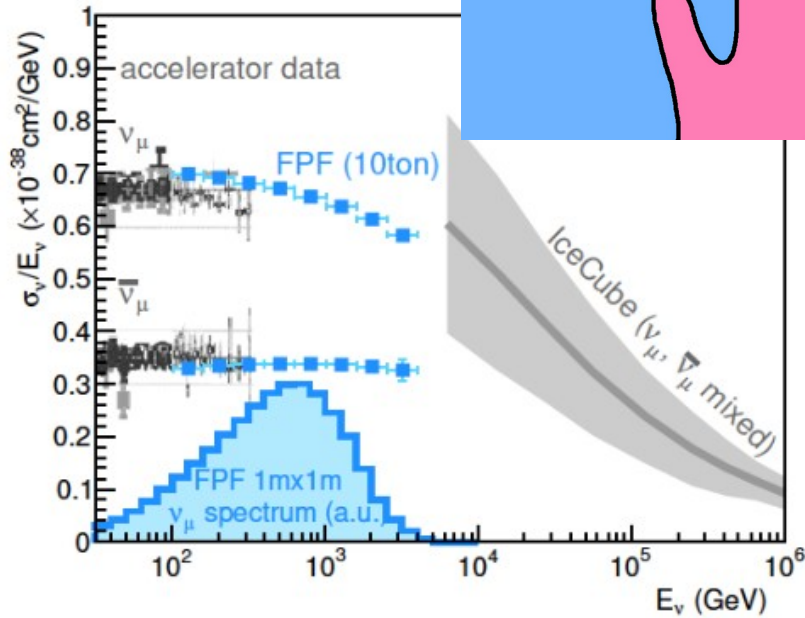


- **FASER2**: low-density magnetized tracker
- **FASERv2**: 20 t tungsten and nuclear emulsion
- **FLARE**: 10/100 t liquid argon TPC

FPF neutrino physics



- 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*

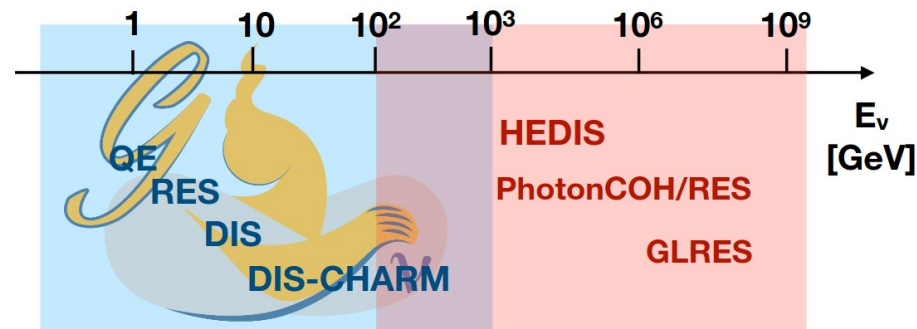


Event rate
Neutrino flux $R(\vec{x}) = \int dE \Phi(E_\nu) \times \sigma(E_\nu, \vec{x}) \times \epsilon(\vec{x}) \times P(E_\nu; \nu_A \rightarrow \nu_B)$
Cross section
Detector smearing
Oscillation probability

Cross-section modeling

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

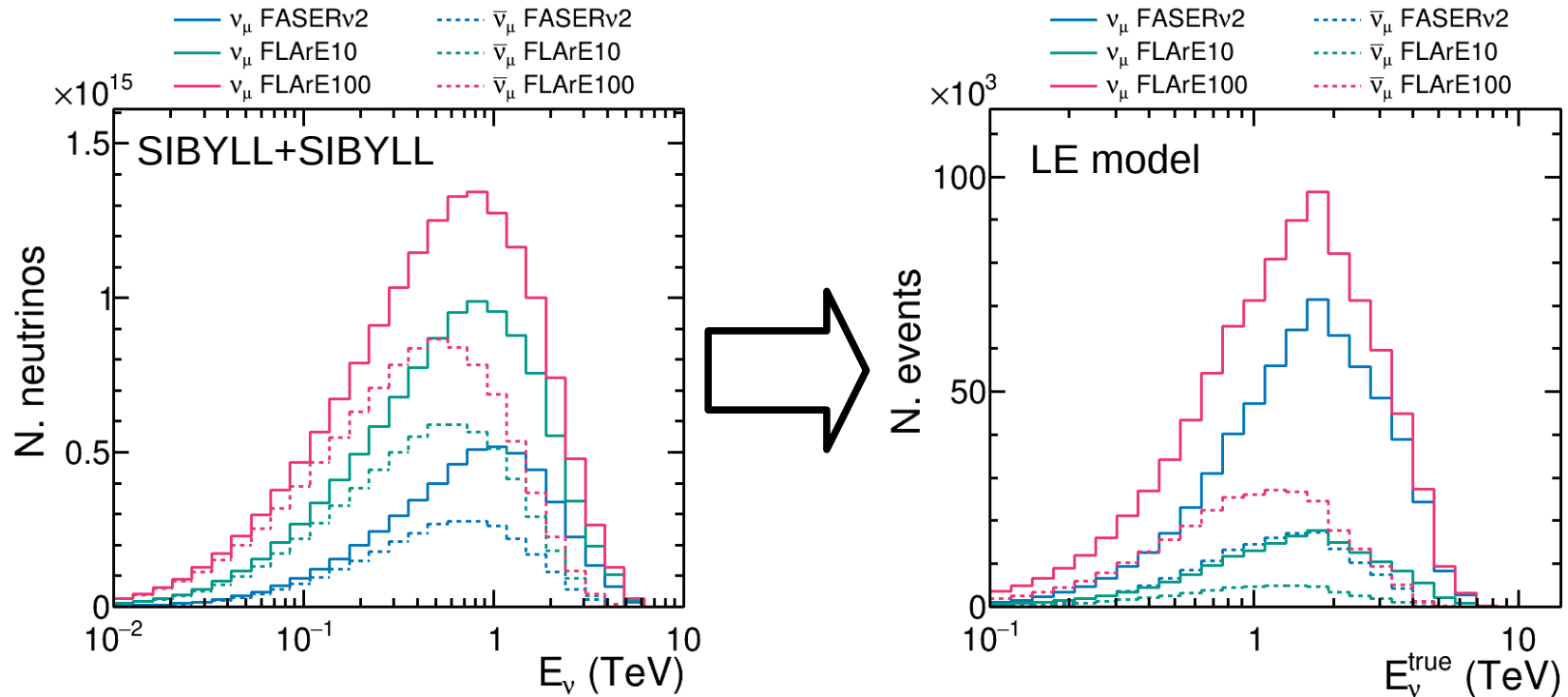
- Developed for few-GeV accelerator neutrino community
- DIS from Bodek-Yang model → tuned for low- Q^2
- LO structure functions, use GRV98LO PDFs
- Contributions from heavy quarks not included



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

FPF event rate

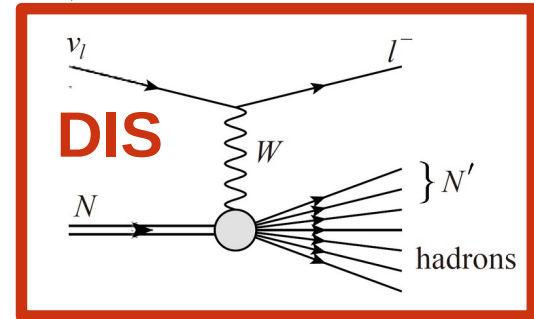


- Neutrino flux predictions* for three FPF detector options
Later I'll only show FASERv2 (but all are in the paper)
- Shown for planned 3000 fb^{-1} HL-LHC run
- Cross section \approx linear with E_ν

*PRD104, 113008 (2021)

Reminder: low- q_0 method requirements

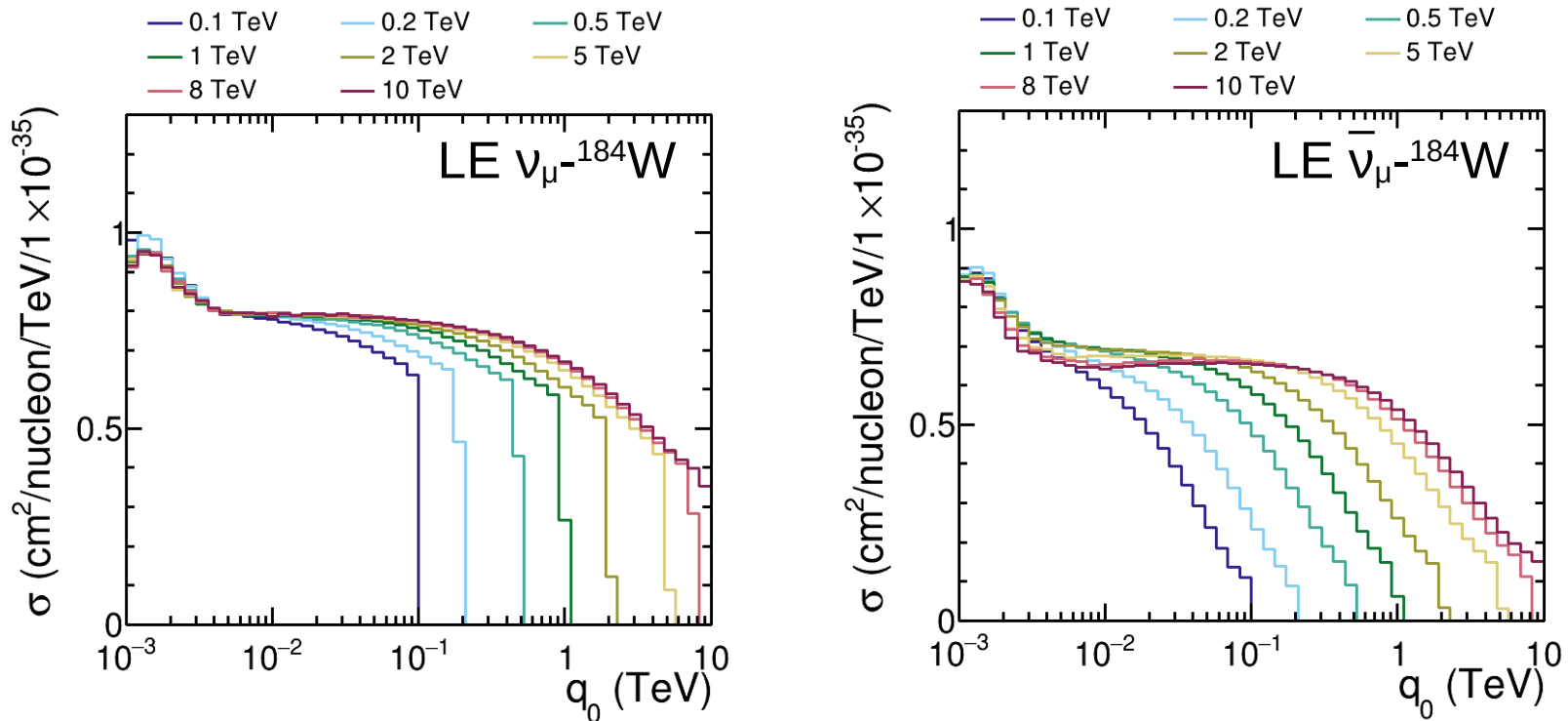
$$\frac{d\sigma}{dq_0} = \frac{G_F^2 M}{\pi} \int_0^1 \left(F_2 - \frac{q_0}{E_\nu} [F_2 \mp xF_3] + \frac{q_0}{2E_\nu^2} \left[\frac{Mx(1-R_L)}{1+R_L} F_2 \right] + \frac{q_0^2}{2E_\nu^2} \left[\frac{F_2}{1+R_L} \mp xF_3 \right] \right) dx$$



The method works if:

- 1) There is a low- q_0 region with a constant cross section in E_ν
- 2) It can be selected without significant model dependence
- 3) It provides a useful number of events

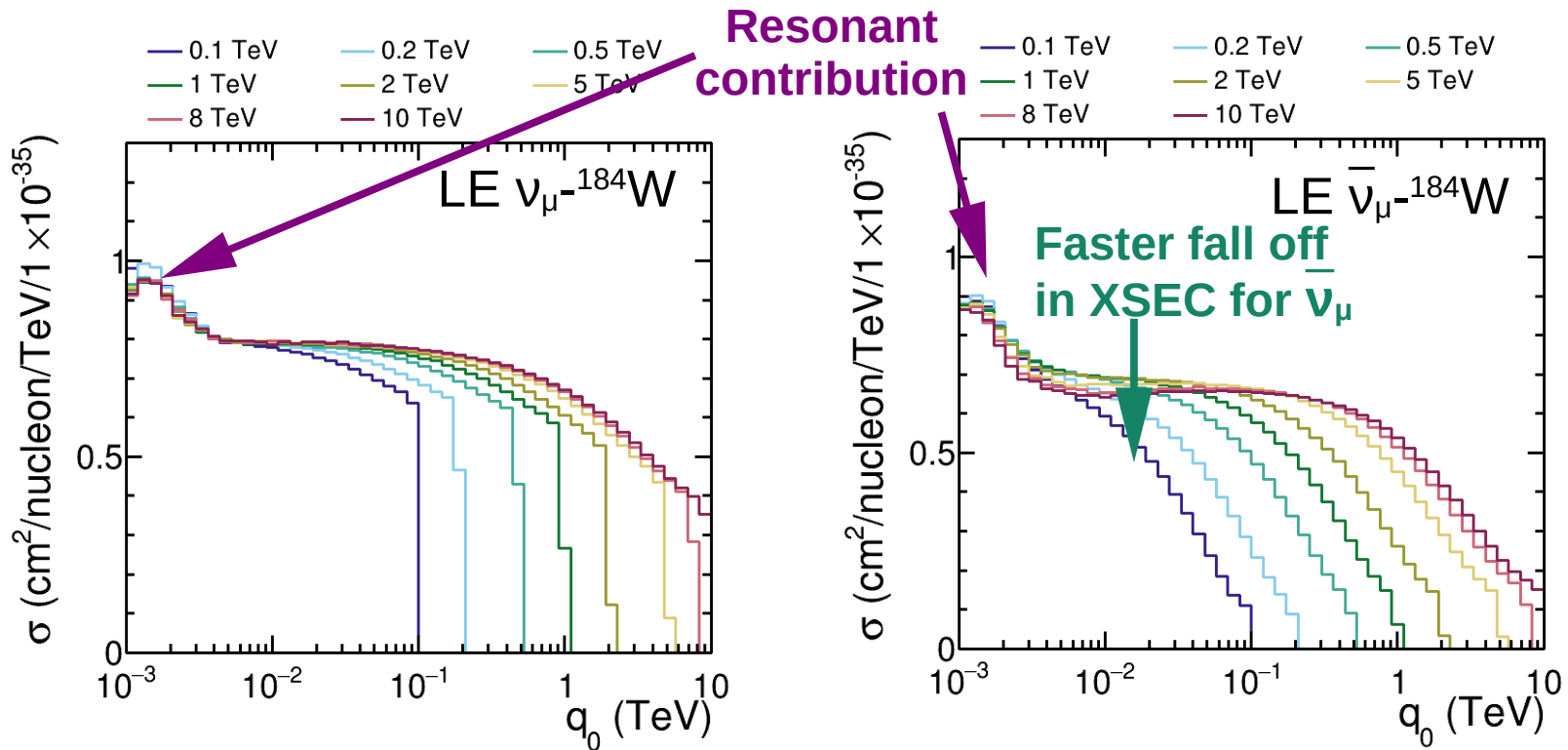
Is the low- q_0 cross section flat in E_ν ?



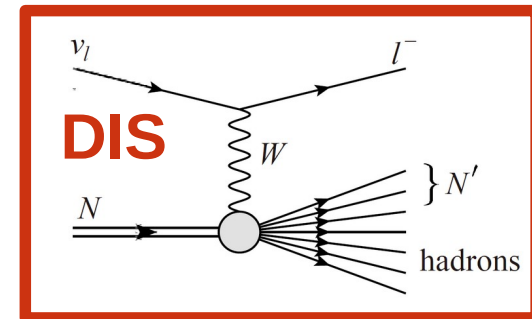
- For ν_μ , $q_0 \leq 20$ GeV seems to be relatively constant with E_ν
(CCFR* used $E_{\text{had}} \leq 20$ GeV to define low- ν at $30 \leq E_\nu \leq 360$ GeV)
- More restricted for $\bar{\nu}_\mu$, within a few-% up to $q_0 \leq 10$ GeV

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

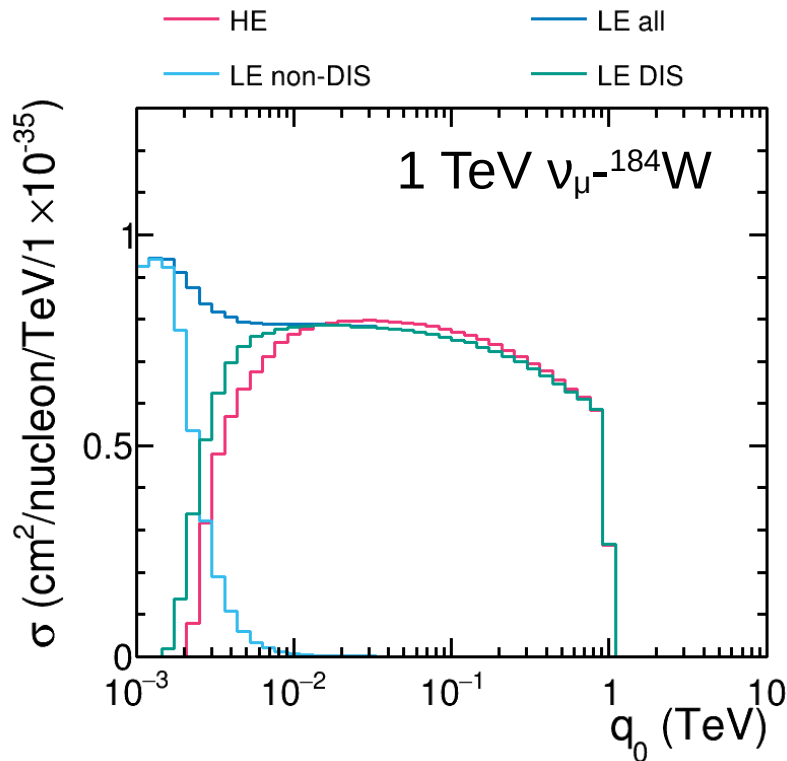
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LE/HE model differences

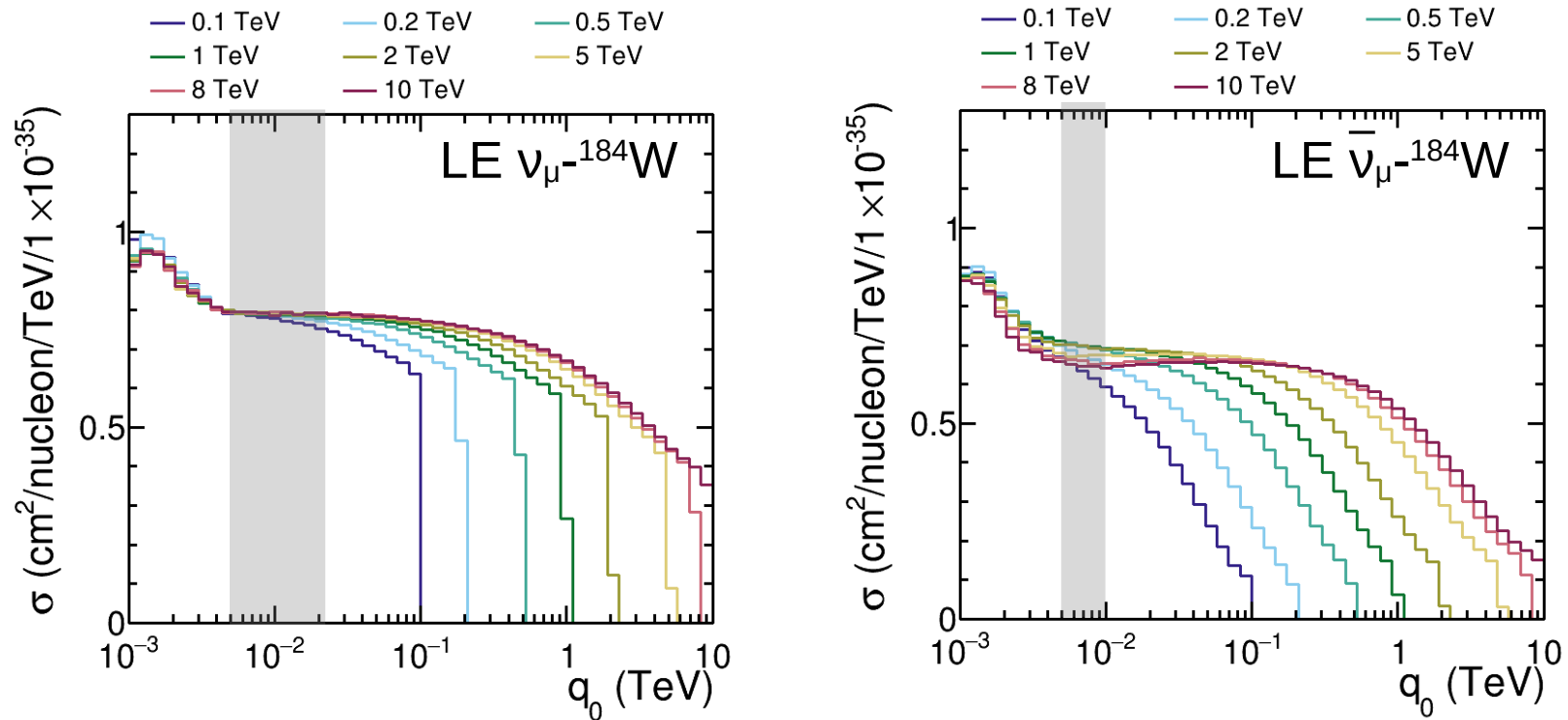


- LE non-DIS dominates $q_0 \leq 3$ GeV, large for $q_0 \leq 5$ GeV
- HE tune DIS qualitatively similar to LE, but turn-on differs
- General trends for both models similar for all energies, and for $\bar{\nu}_{\mu}$

Define low- ν region as:

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

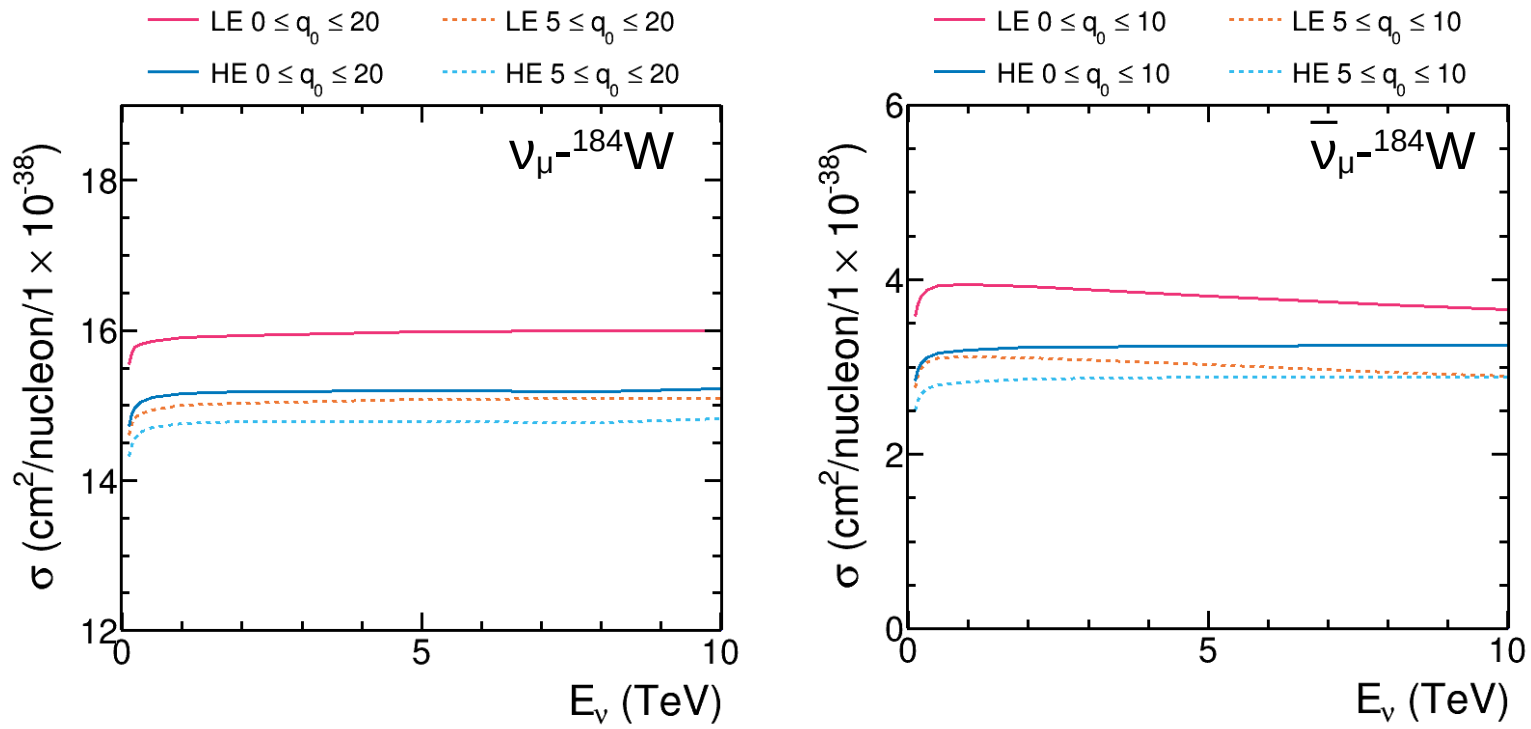
Is the low- q_0 cross section flat in E_ν ?



Define low- ν region as:

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

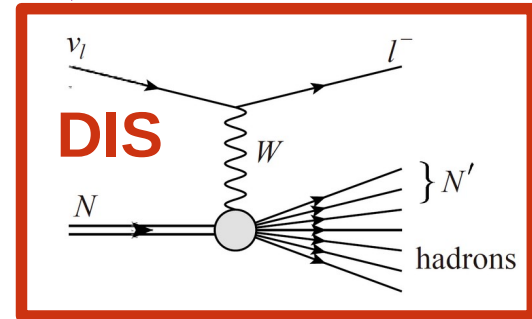
Is the low- q_0 cross section flat in E_ν ?



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

Low- q 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:

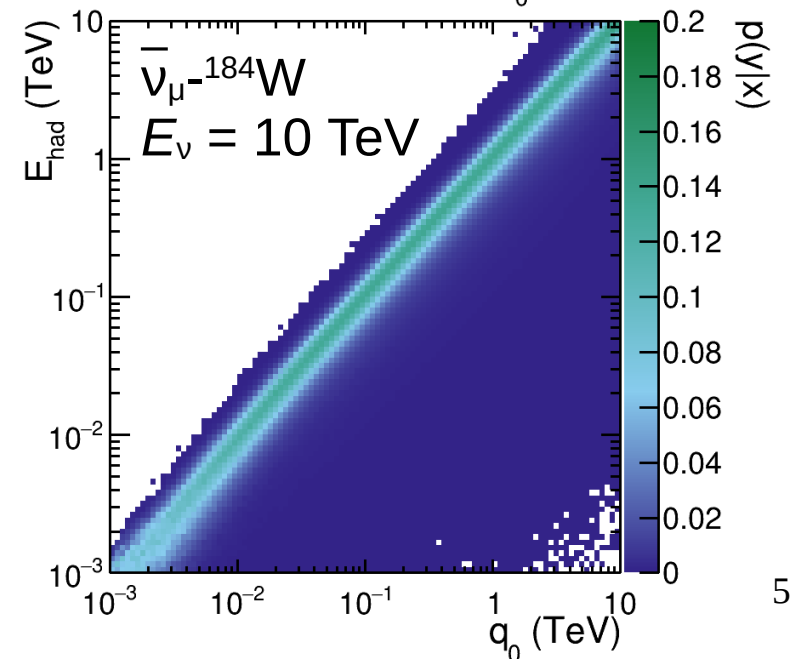
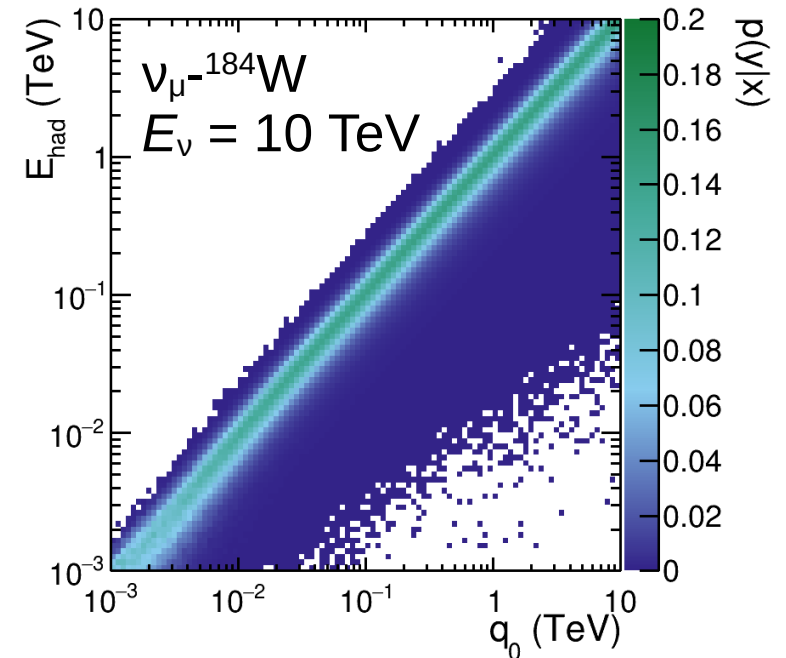
- 1) There is a low- q_0 region with a constant cross section in E_ν
- 2) It can be selected without significant model dependence
- 3) It provides a useful number of events

Detector smearing

	FASER ν 2
Fiducial mass	20 t
Det. cross-section	0.5 \times 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

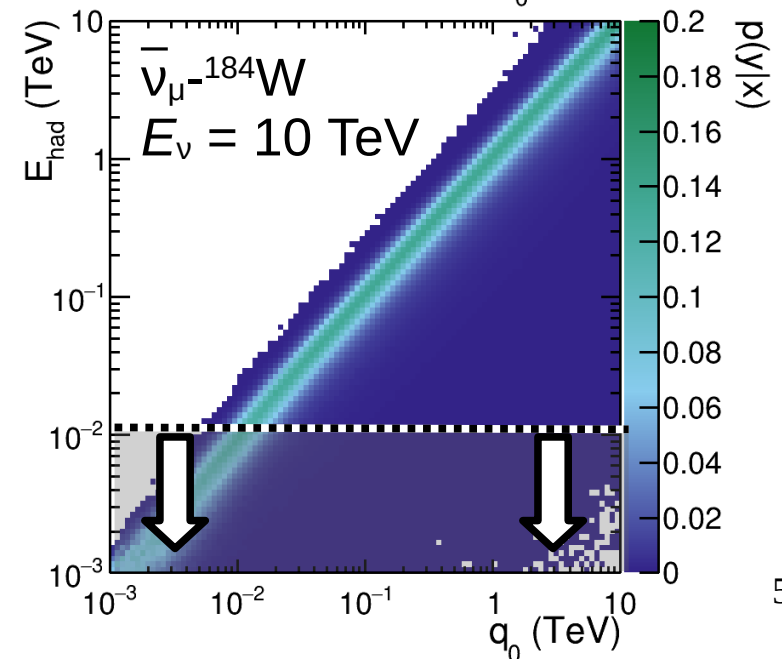
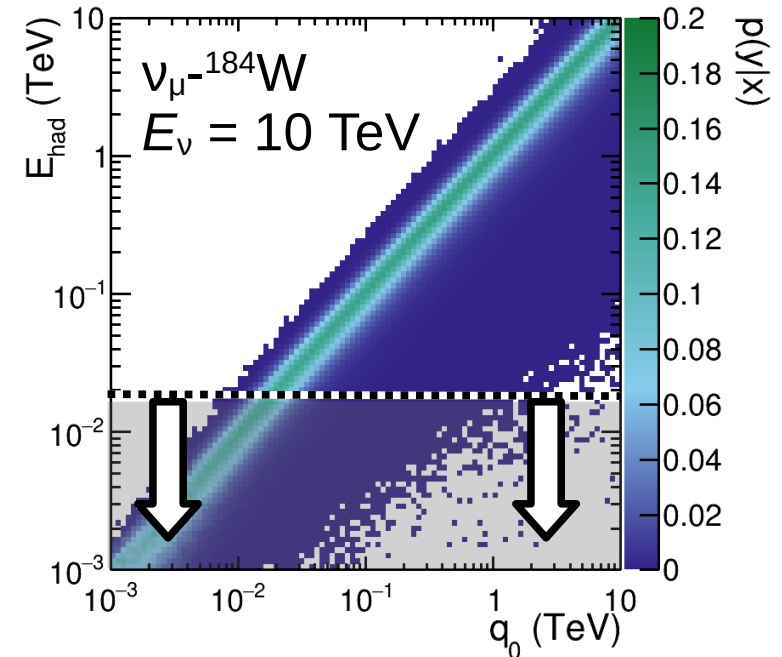
$$E_{\text{had}}^{\text{reco}} = \left(\sum_{i=p,\bar{p}} E_{\text{kin}}^i \right) + \left(\sum_{i=\pi^\pm, K^\pm, \gamma, l^\pm, K_S^0} E_{\text{total}}^i \right)$$

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

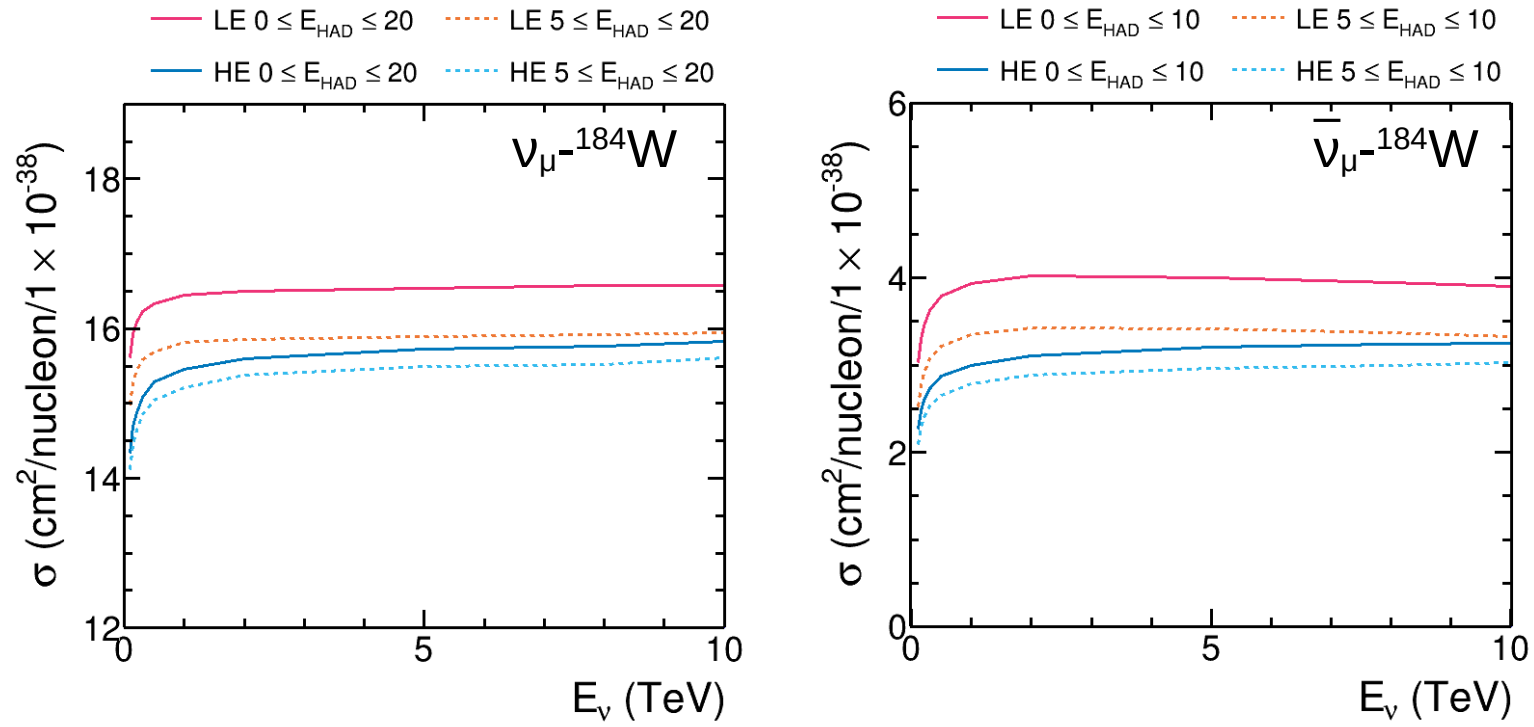


Can a low- q_0 sample be experimentally selected?

- 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 $\bar{\nu}_\mu$ ($\approx 10\%$) than ν_μ ($\approx 1\%$)

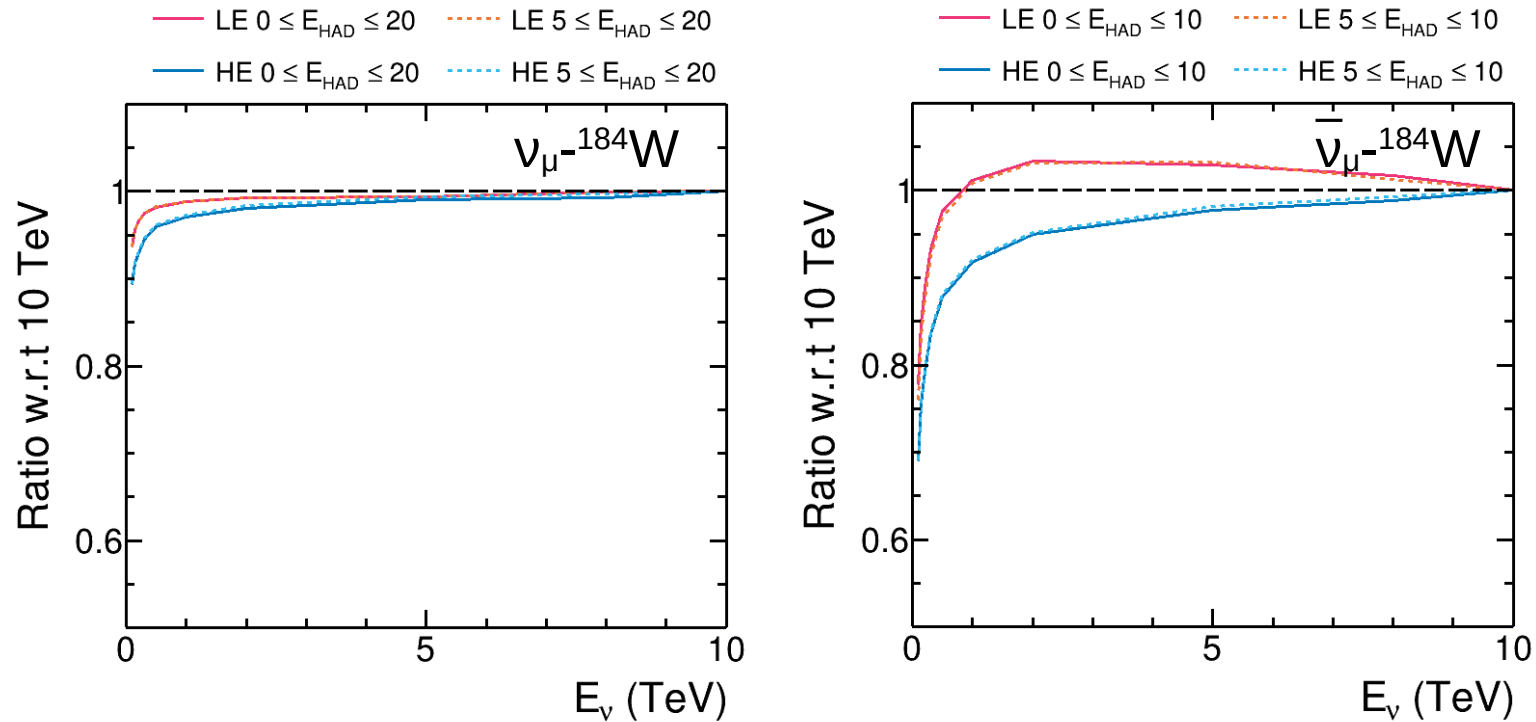


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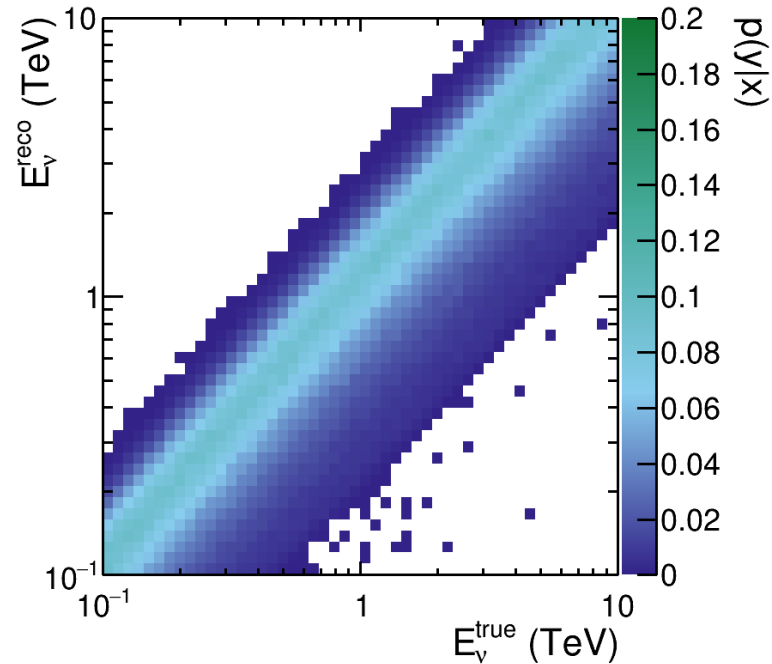
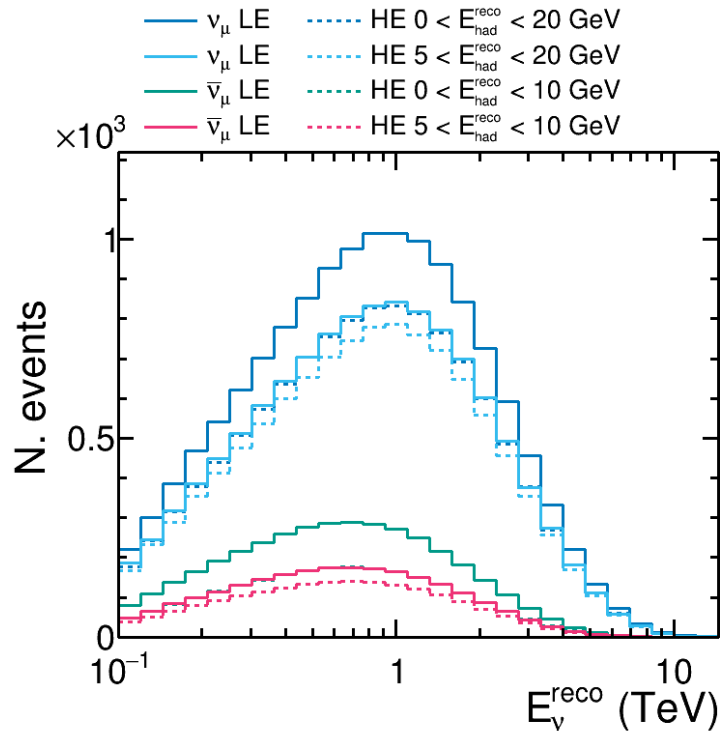
- Low- E_{had} sample cross sections \approx linear with E_{ν}
- Slightly less linear for both ν_{μ} and $\bar{\nu}_{\mu}$ than low- q_0 case
- Larger LE/HE differences: few-% for ν_{μ} , $\approx 10\%$ for $\bar{\nu}_{\mu}$

Can a low- q_0 sample be experimentally selected?



- Low- E_{had} sample cross sections \sim 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} , $\approx 10\%$ for $\bar{\nu}_{\mu}$

Low- ν sample event rate



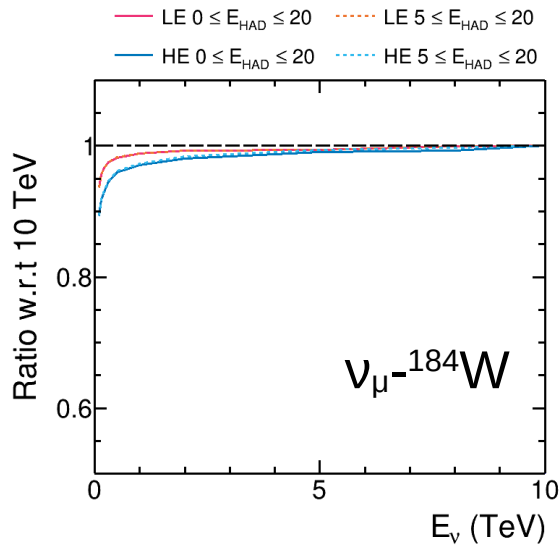
- For expected 3000 fb^{-1} FPF exposure, FASERv2 low- ν samples have $O(10,000)$ ν_μ and $O(1,000)$ $\bar{\nu}_\mu$ events
- Relationship between reco. and true E_ν is fairly diagonal (dominated by E_μ)

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

TeV neutrino conclusions

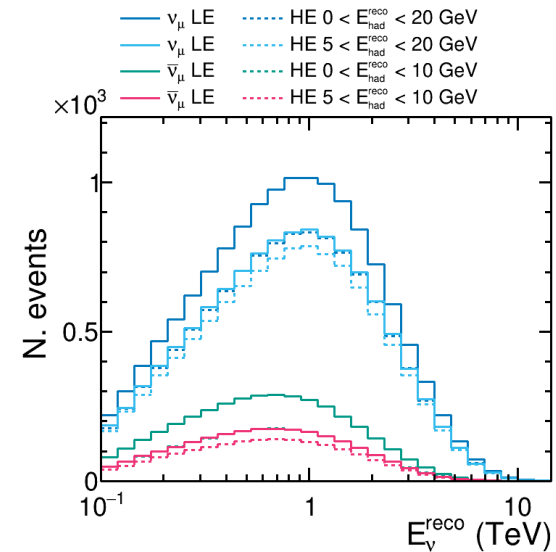
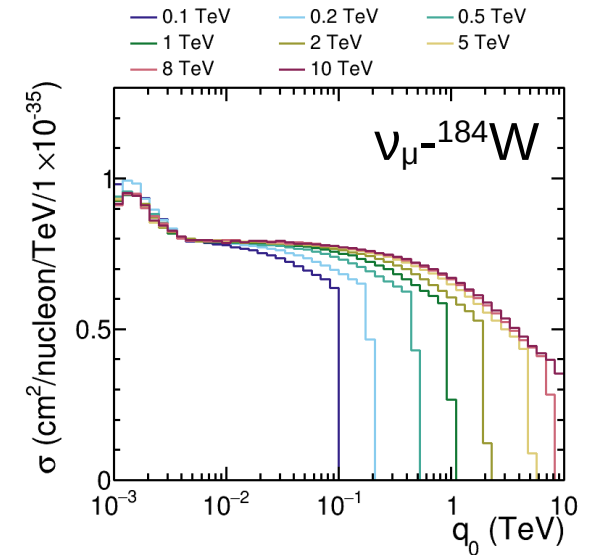
The method works if:

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

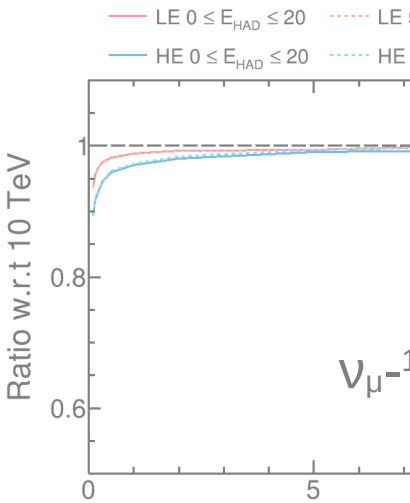
3) It provides a useful number of events



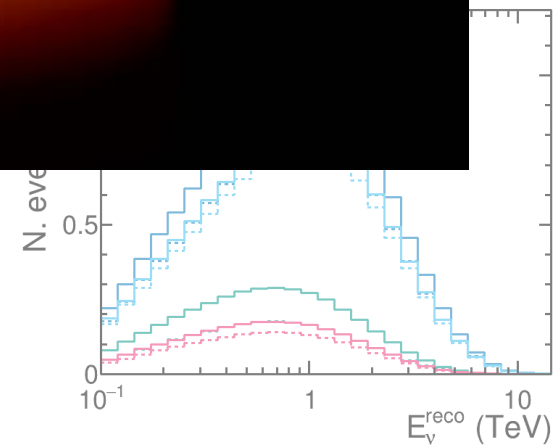
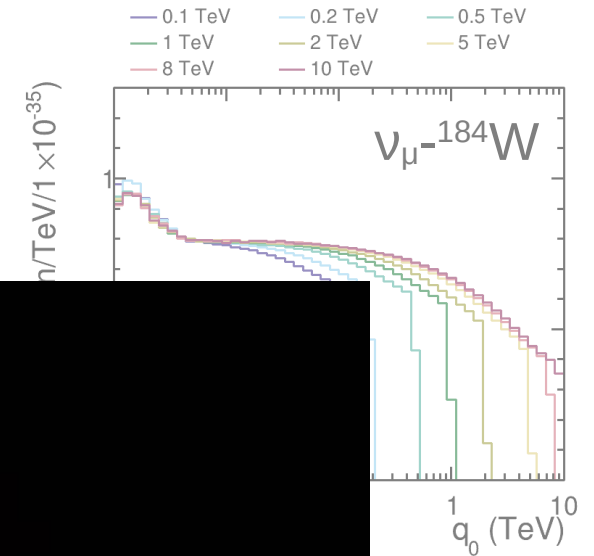
TeV neutrino conclusions

The method works if:

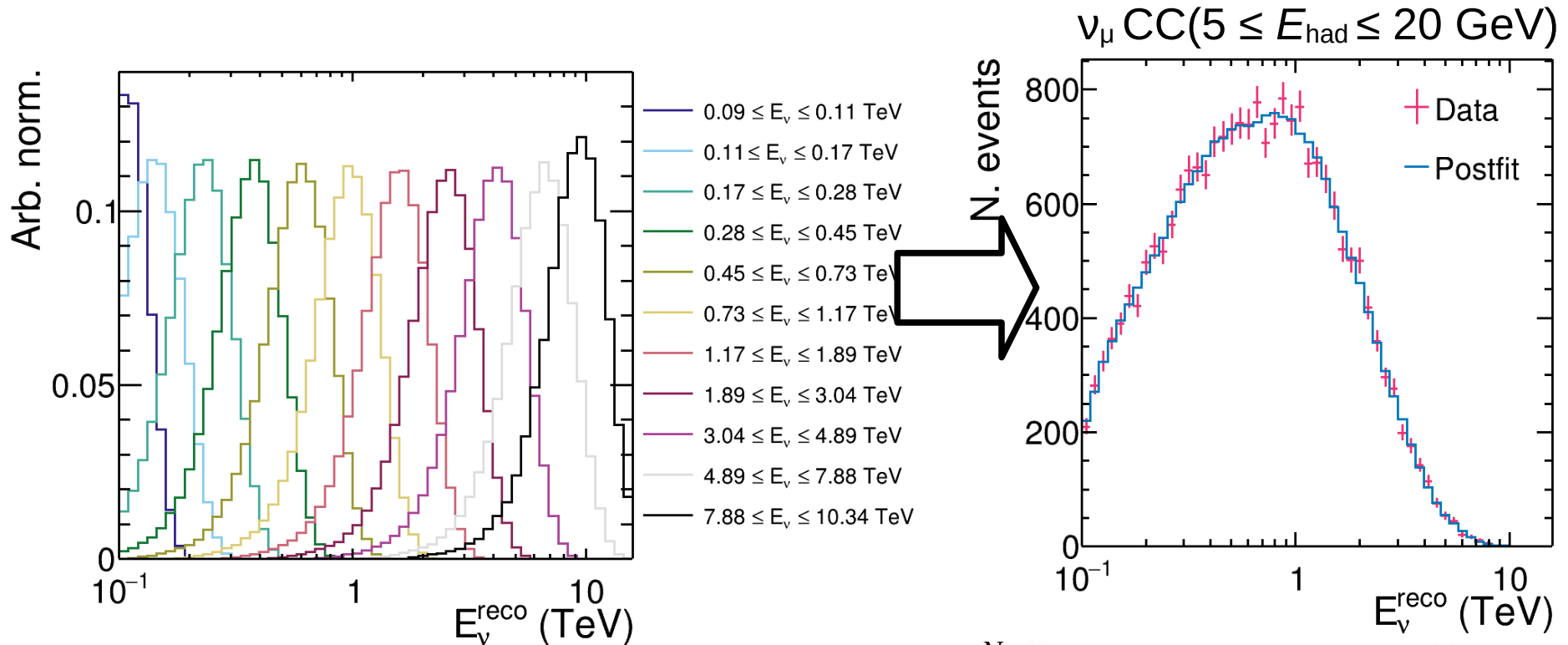
1) There is a low- q_0 region with a
 CO



3) It provides a useful number
 of events

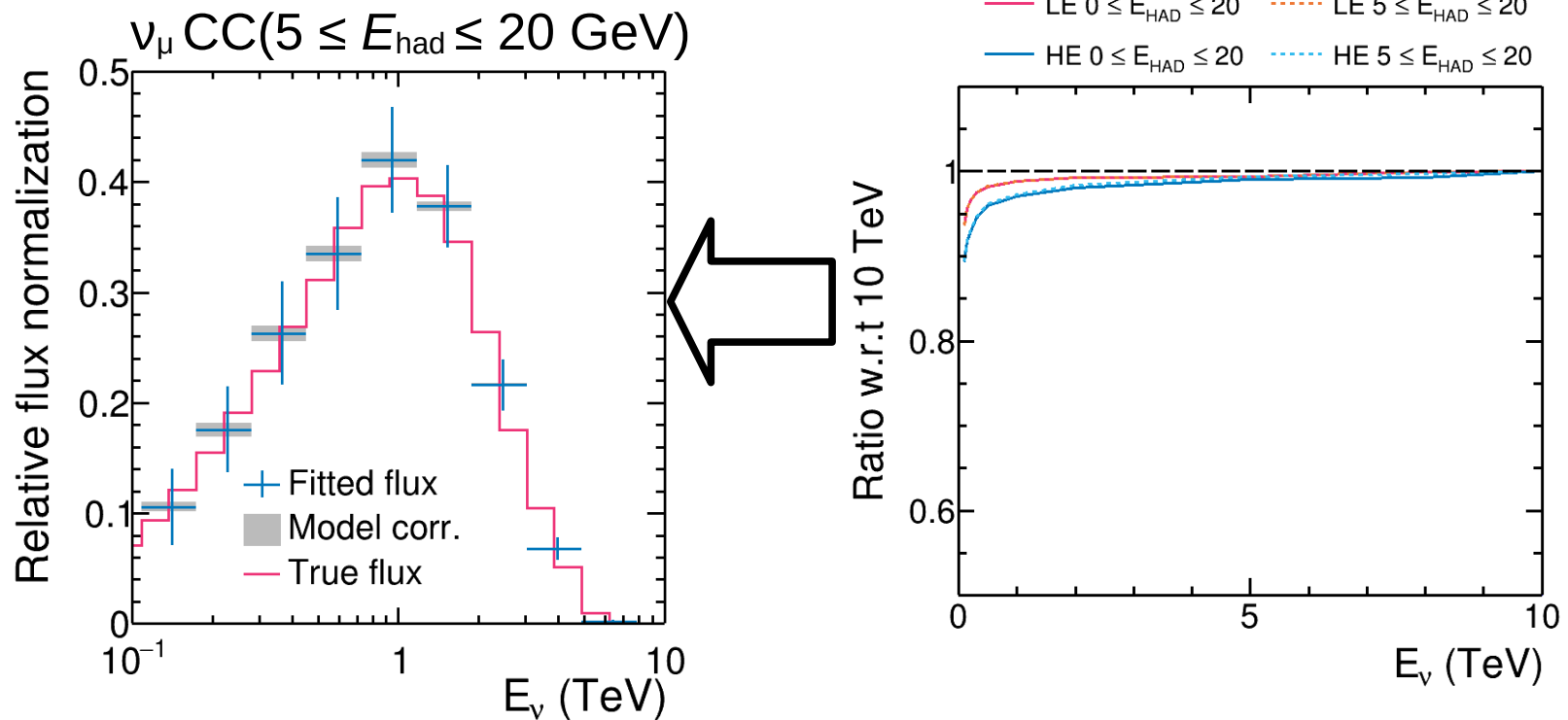


FPF ν_μ flux constraint



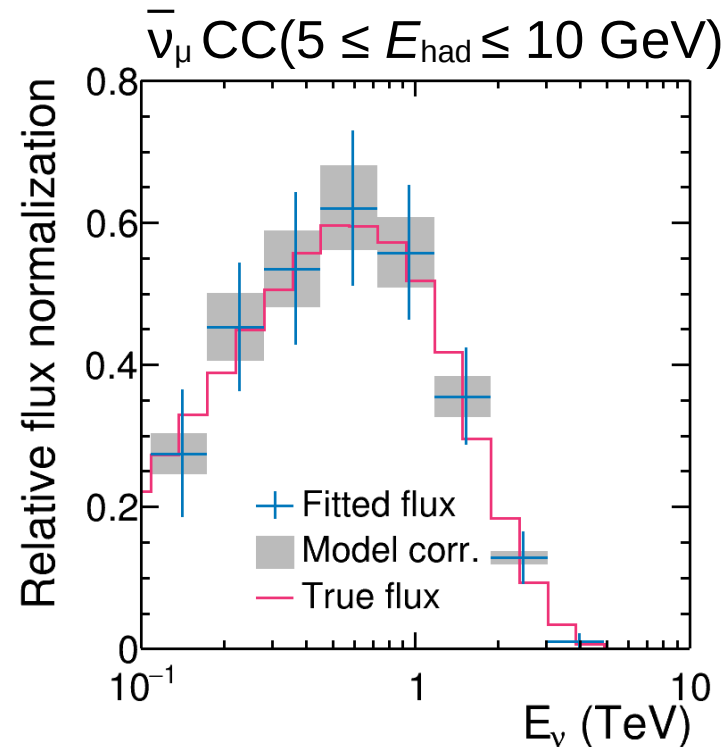
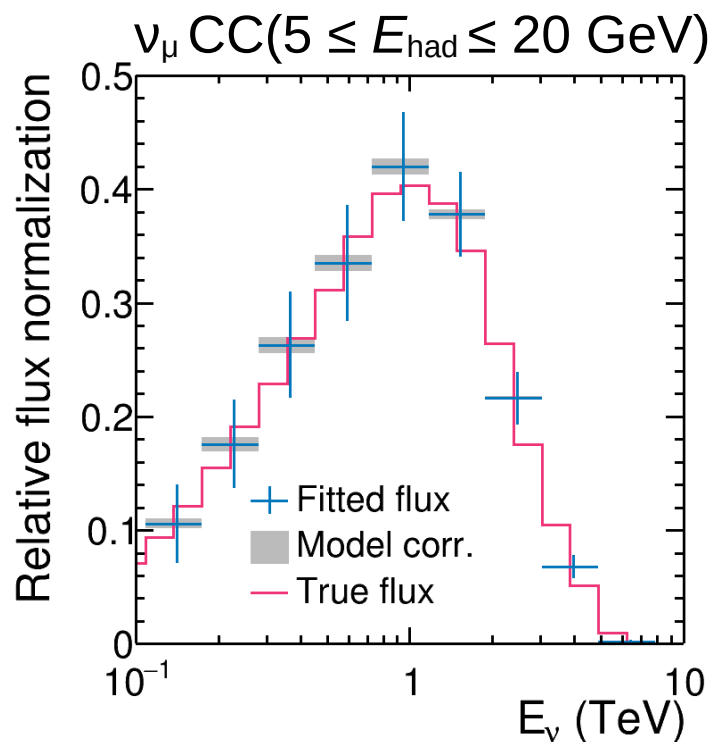
- Simple analysis to check utility $\chi^2 = 2 \sum_{i=1}^N \left[\mu_i(\vec{\mathbf{x}}) - n_i + n_i \ln \frac{n_i}{\mu_i(\vec{\mathbf{x}})} \right]$
- Template LLH fit: vary normalizations of templates that correspond to a region of true E_ν , binned in reco E_ν
- Best fit template normalizations and uncertainties give the flux constraint in true E_ν bins

FPF ν_μ flux constraint



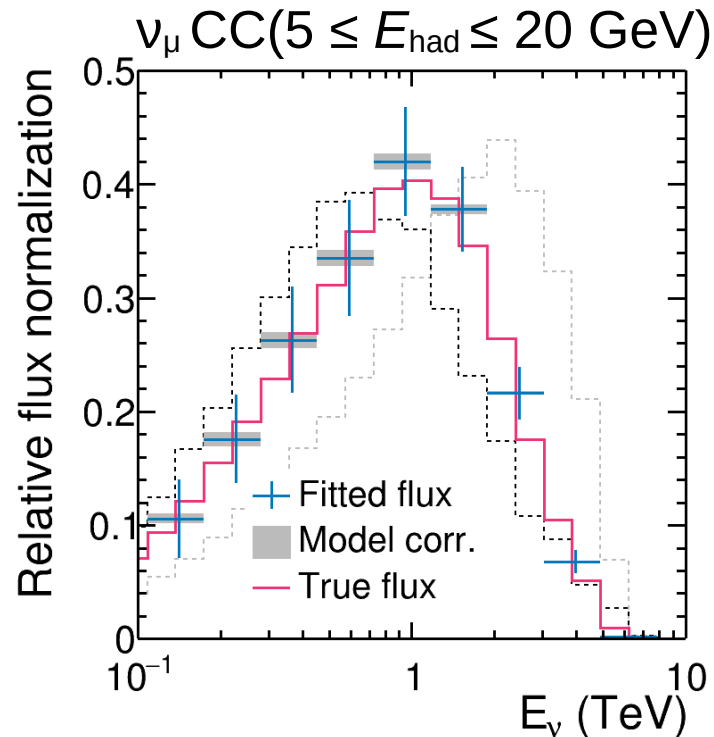
- The fitted flux shape has a 10-20% bin-to-bin uncertainties (although bins are correlated)
- The fitted flux is corrected for E_ν -dependence, the model correction uncertainty shows the full LE/HE difference

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



- Much larger model correction uncertainty \approx 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

Hadron production model selection



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

All fluxes from: PRD104, 113008 (2021)

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

EPOS LHC: PRC92, 034906 (2015)

DPMJET-III: arXiv:hep-ph/0012252

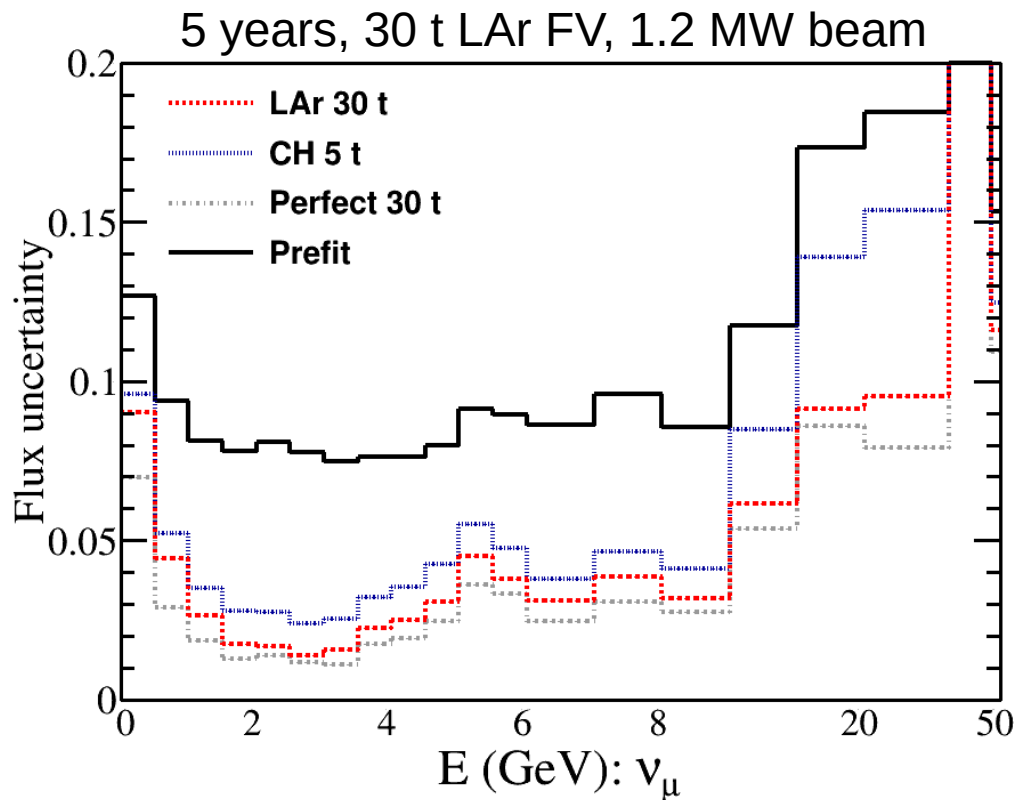
Closing remarks: few-GeV vs TeV

- The low- ν method is not reliable for percent-level flux constraints in few-GeV intensity frontier experiments:
 - Flux already constrained by dedicated hadron production experiments \rightarrow 5–10%
 - Not in DIS-regime, so basic premise is flawed
- But, it could be very useful at the FPF:
 - Flux is essentially unknown a priori
 - Physics of interest strongly affects the flux distribution
 - Strongly DIS-dominated

Backup

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 \leftrightarrow cross section ambiguities

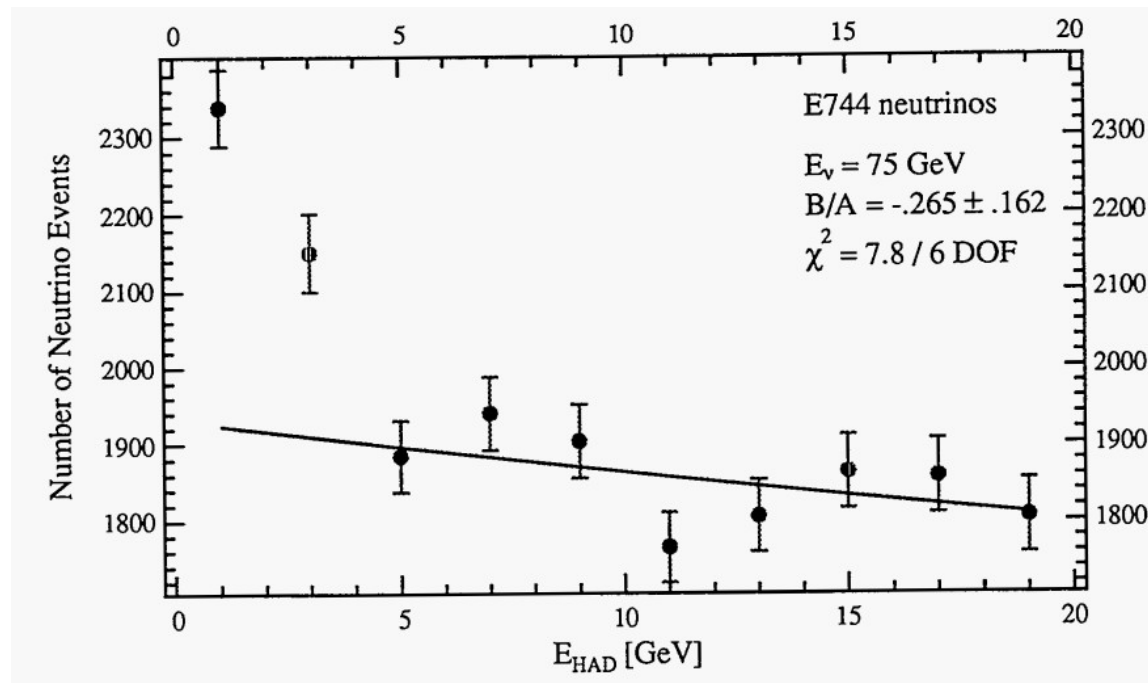


$$E_\nu = \frac{E_e}{1 - \frac{E_e(1 - \cos \theta)}{m}}$$

- Strong normalization constraint 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

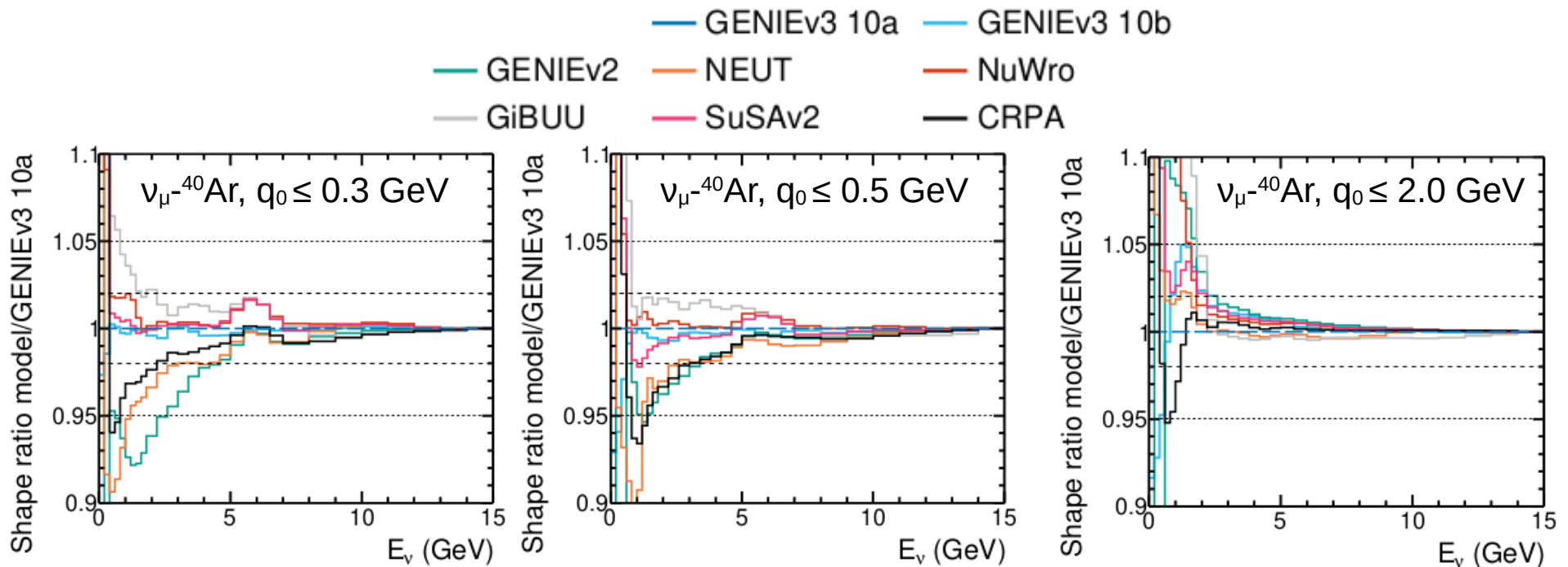


- CCFR use low- ν for $30 \leq E_\nu \leq 360 \text{ GeV}$
- E_{HAD} is their q_0 proxy, and their low- ν sample is $E_{\text{HAD}} \leq 20 \text{ GeV}$
- To estimate the q_0/E_ν correction, they exclude $E_{\text{HAD}} \leq 4 \text{ GeV}$ because resonant events don't have the correct scaling

Is the cross section well described?

Counterintuitive(?) improvement at higher q_0

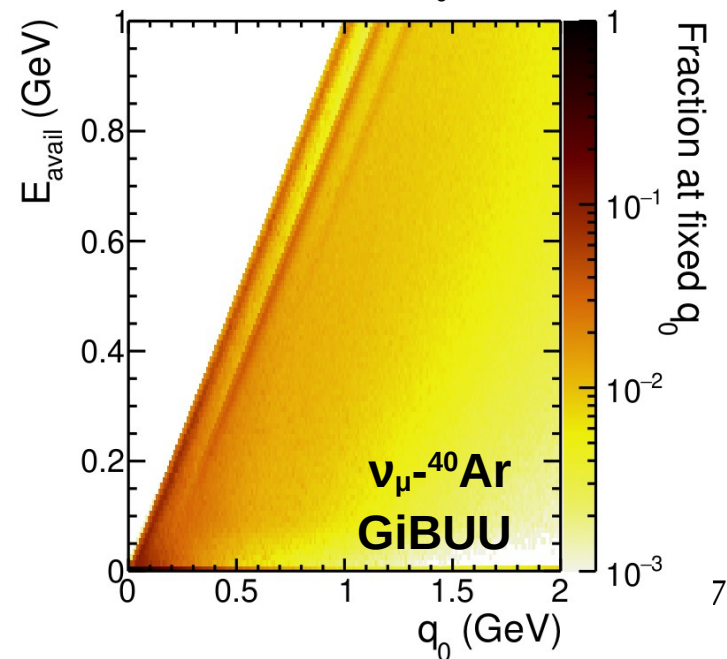
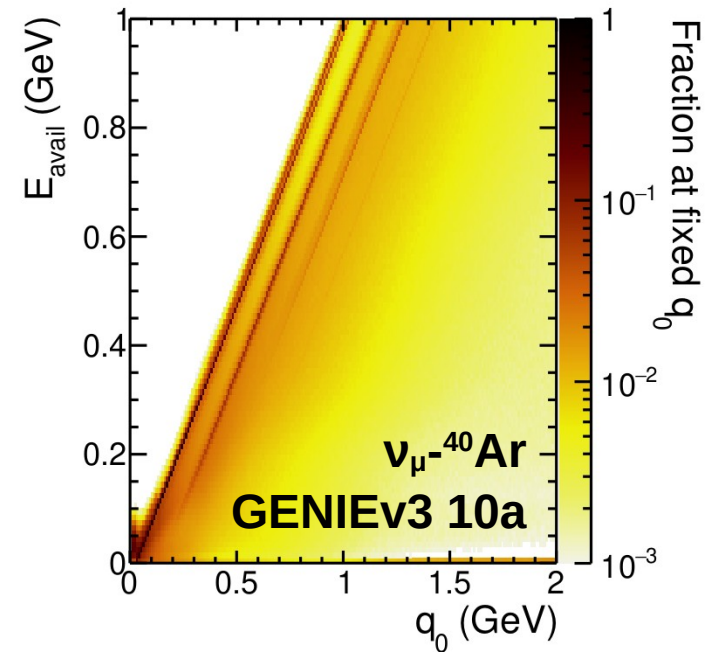
Larger model differences in the region low- v isolates!



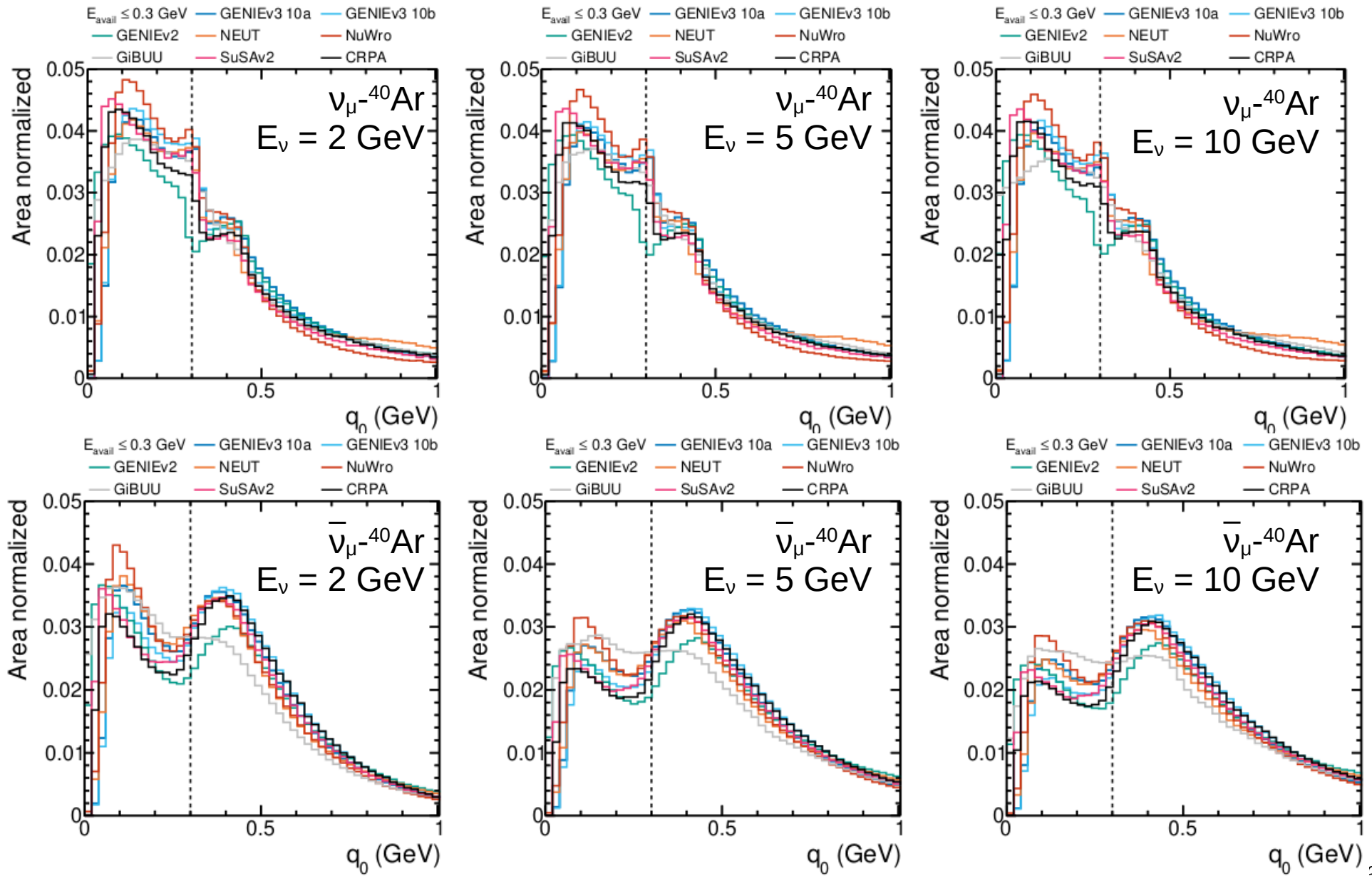
Can a low- q_0 sample be experimentally selected?

- Many detectors will mis-ID *some* pions as protons, missing the pion mass
- Here consider the case where all charged pions are mis-ID-ed

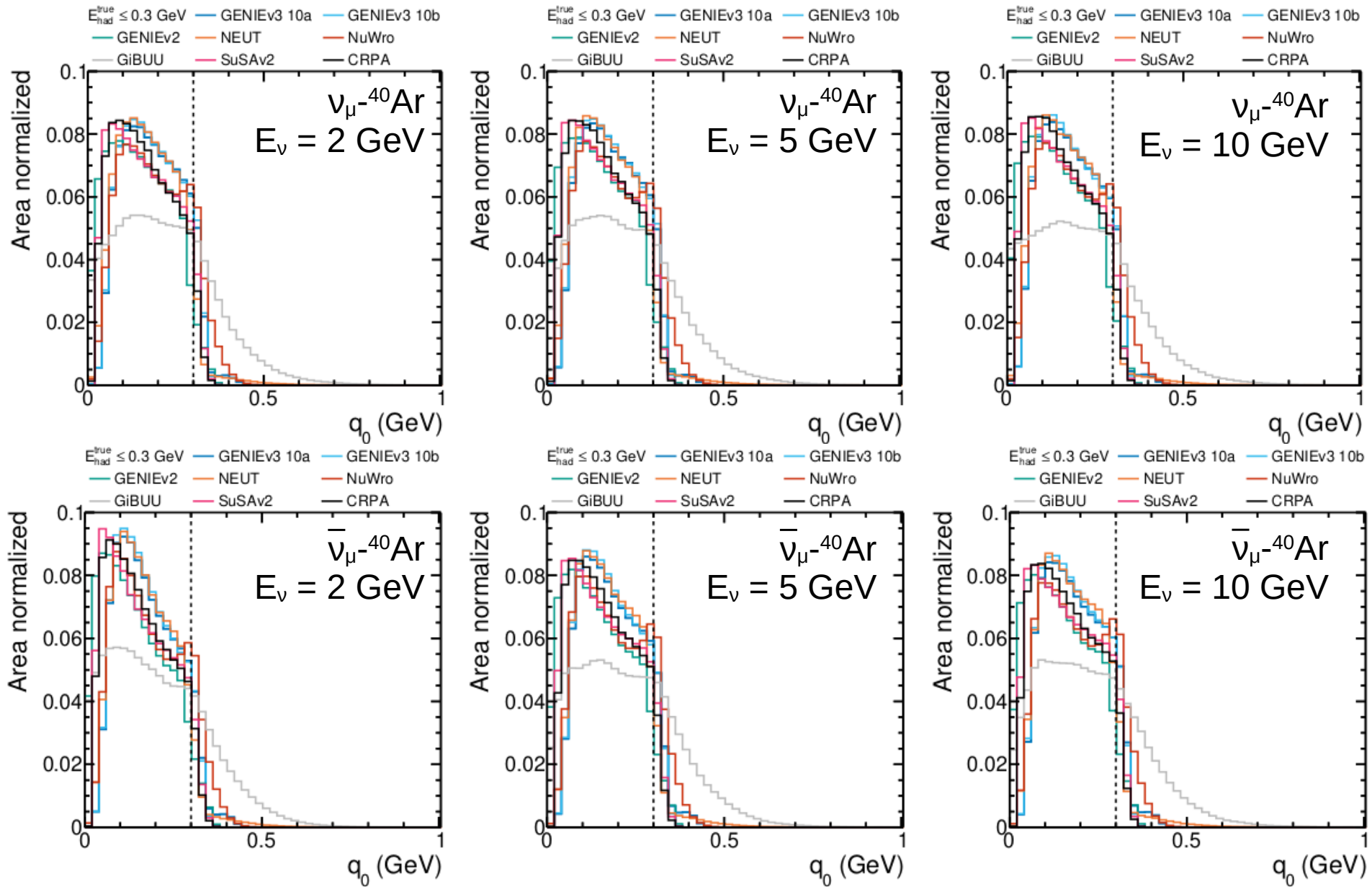
$$E_{\text{avail}} = \left(\sum_{i=\pi^\pm, p} E_{\text{kin}}^i \right) + \left(\sum_{i=\pi^0, \gamma} E_{\text{total}}^i \right)$$



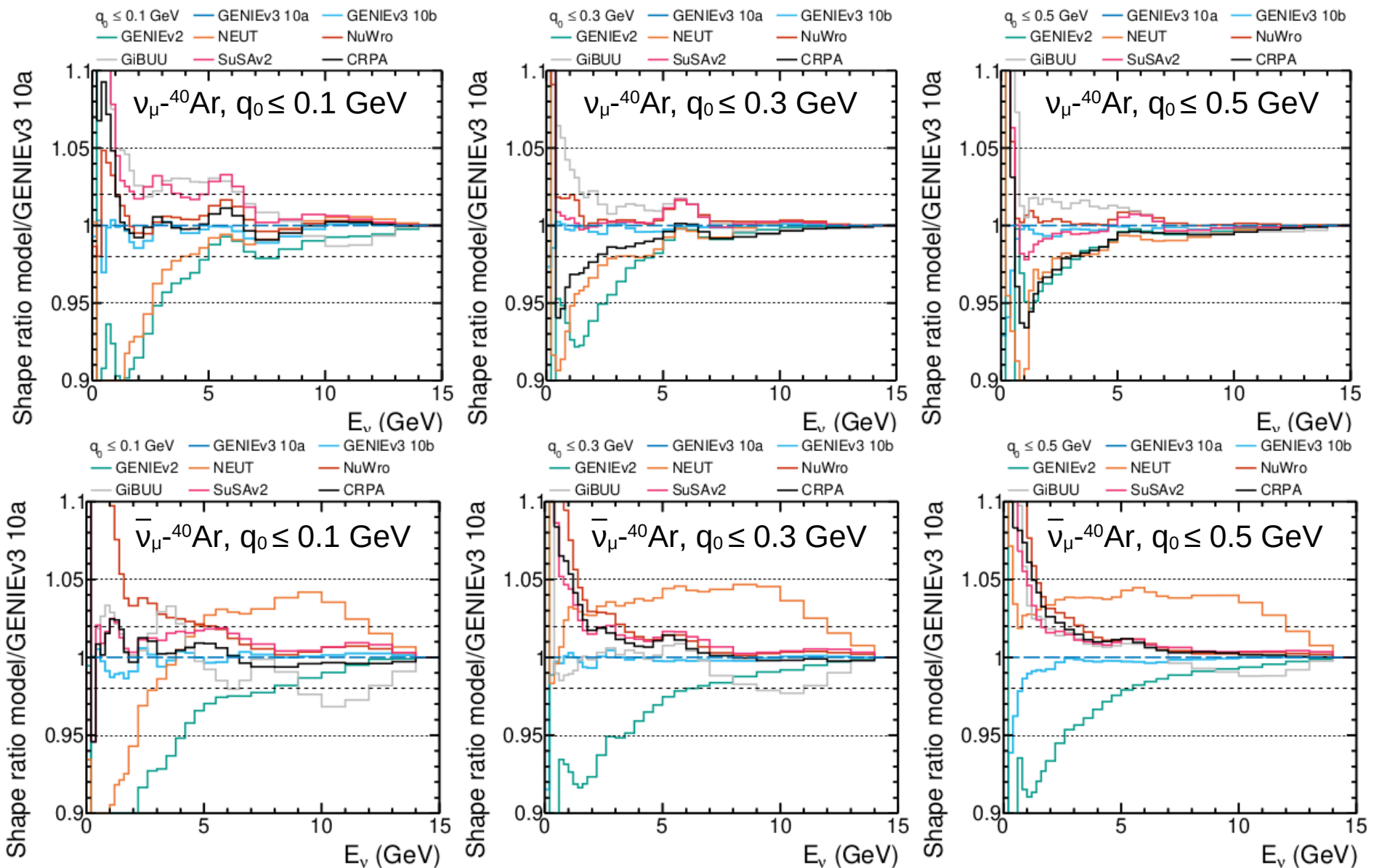
Can a low- q_0 sample be experimentally selected?



Can a low- q_0 sample be experimentally selected?



Is the cross section well described?



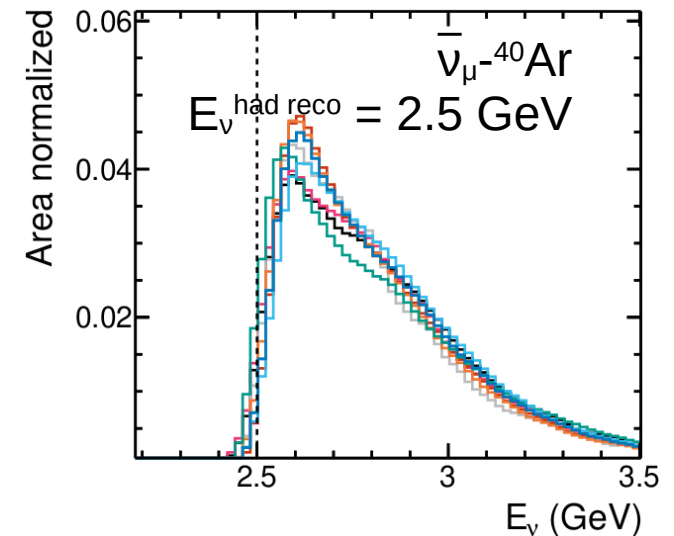
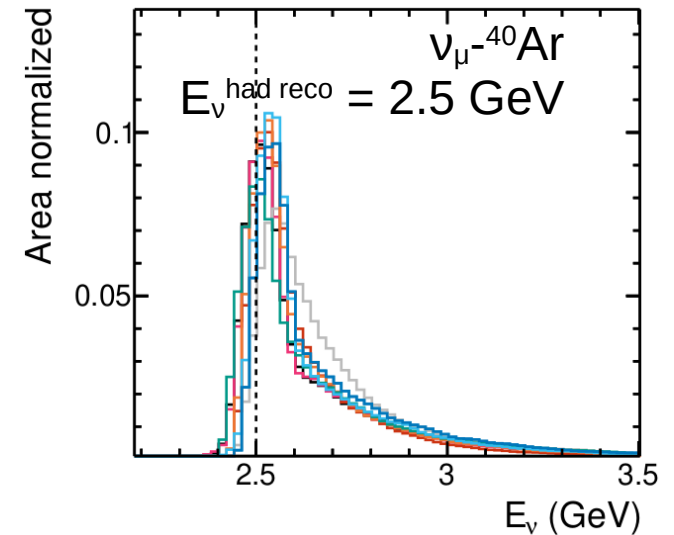
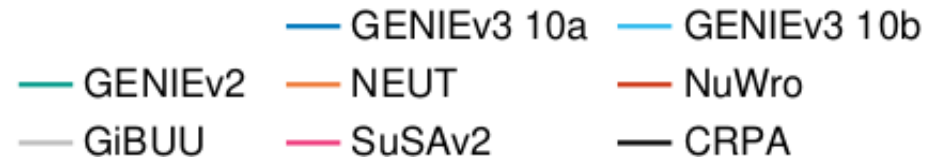
Can E_ν be reconstructed?

- Neutrino energy not known!
- Reconstructed from muon + the hadronic system
- The same caveats apply!

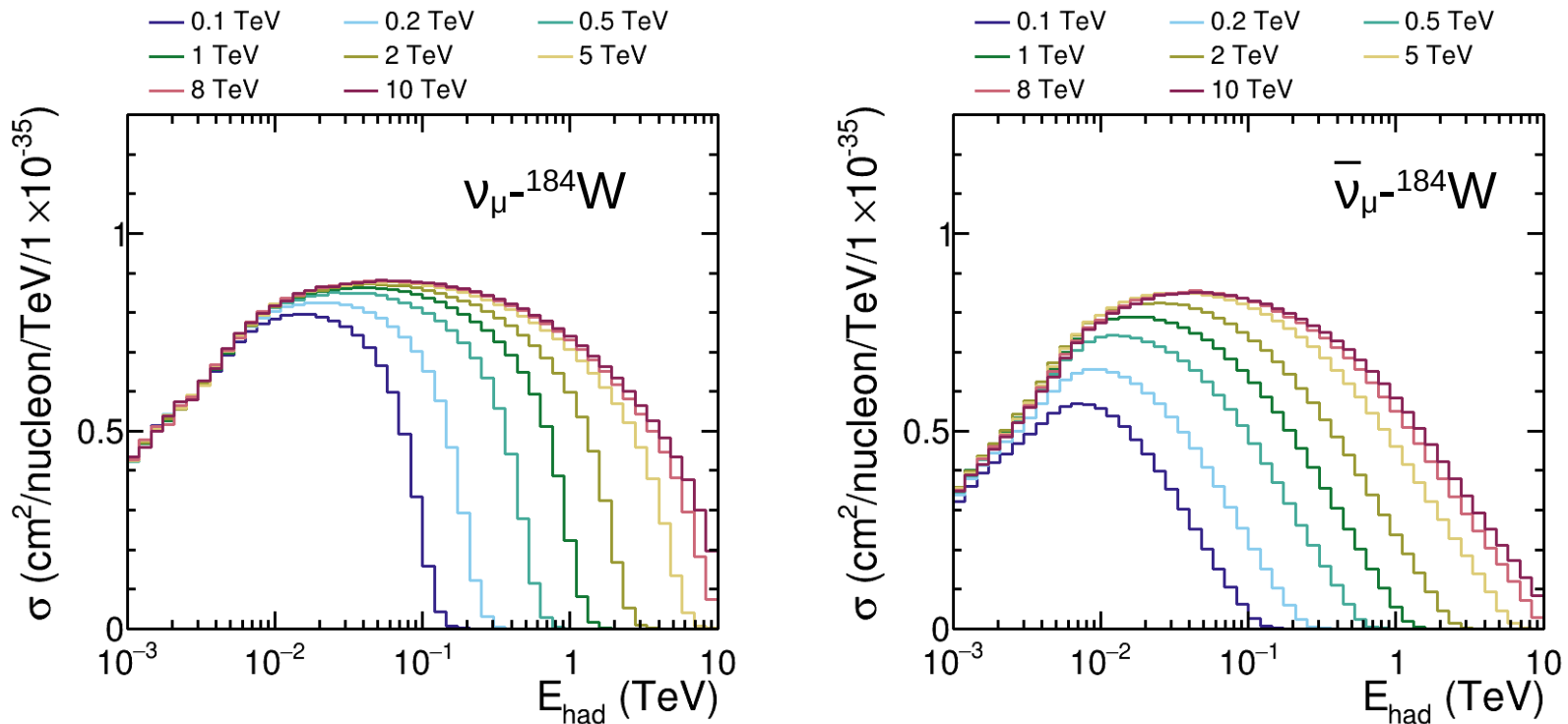
$$1) \quad E_\nu^{\text{had true}} = E_\mu + E_{\text{had}}^{\text{true}}$$

$$2) \quad E_\nu^{\text{had reco}} = E_\mu + E_{\text{had}}^{\text{reco}}$$

Additional challenge to extract the flux with the low- ν method \rightarrow model dependence

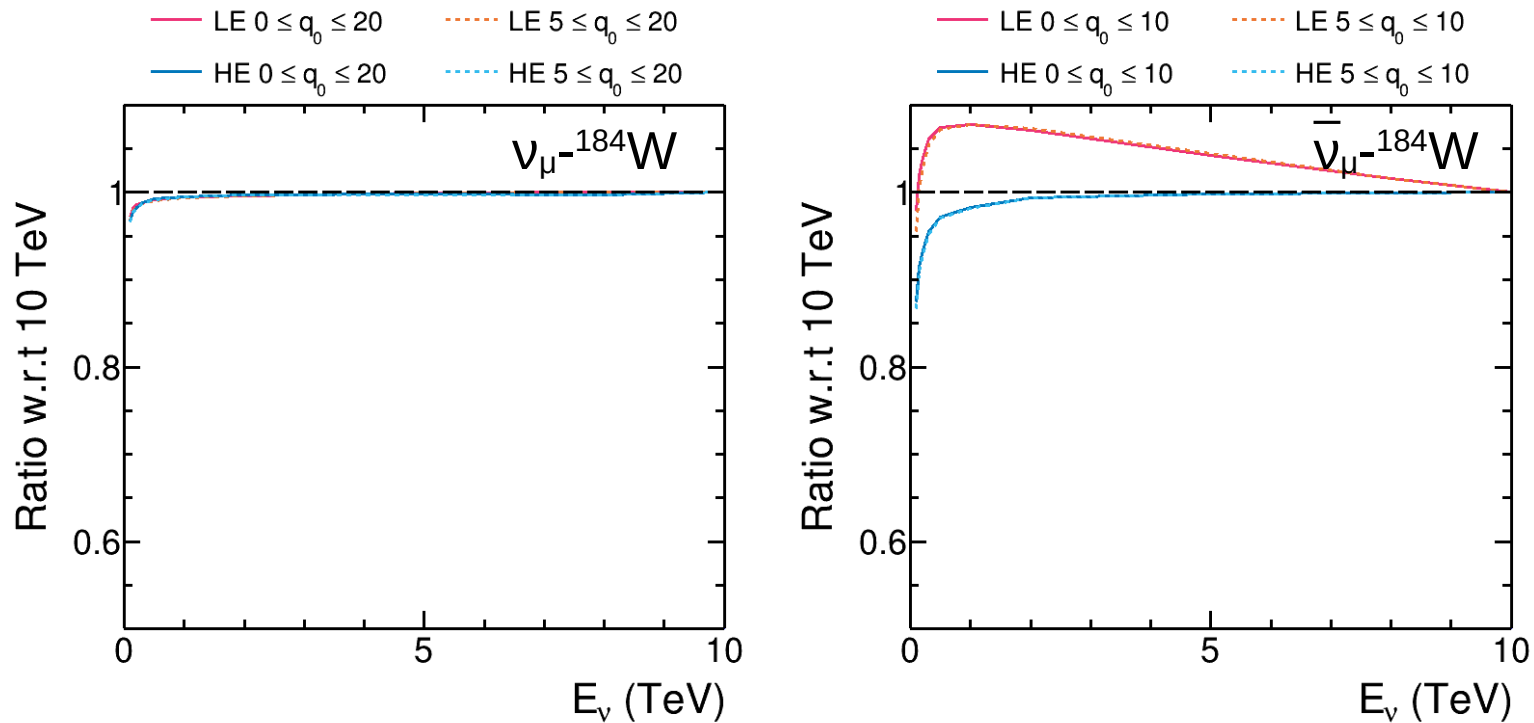


Smearred cross section



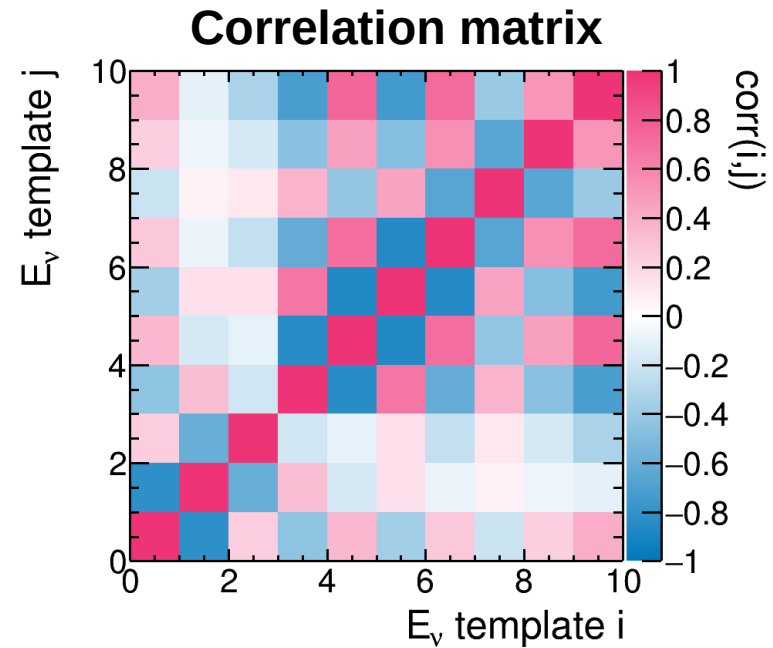
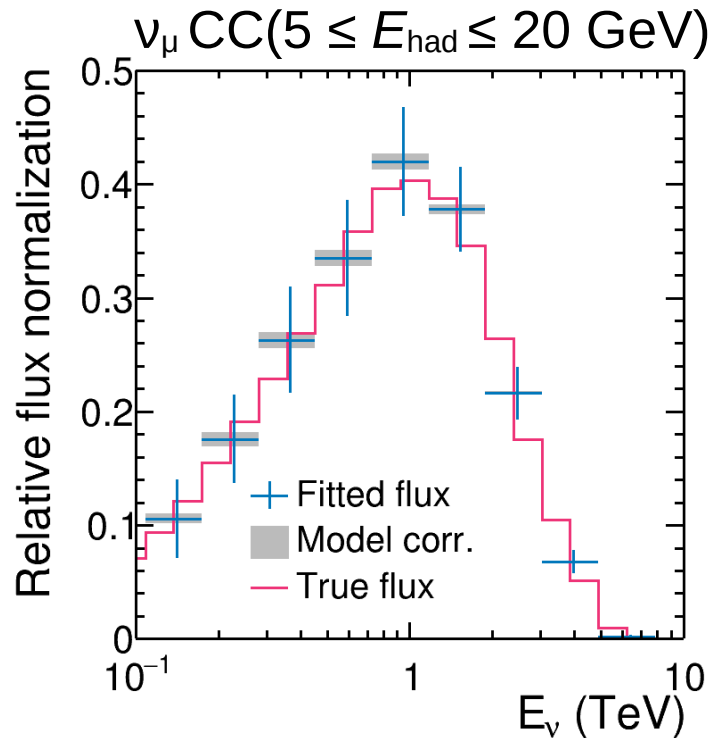
- Charged hadron track cut suppresses the resonance peak
- Low- E_{had} sample cross sections \sim linear with E_{ν}
- Slightly less linear for both ν_{μ} and $\bar{\nu}_{\mu}$ than low- q_0 case
- Larger LE/HE differences: few-% for ν_{μ} , $\sim 10\%$ for $\bar{\nu}_{\mu}$

Is the low- q_0 cross section flat in E_ν ?



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

FPF ν_μ flux constraint



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