Tau Polarization and Correlated Decays in Neutrino Experiments

Joshua Isaacson

In collaboration with: Stefan Höche, Frank Siegert, and Sherry Wang

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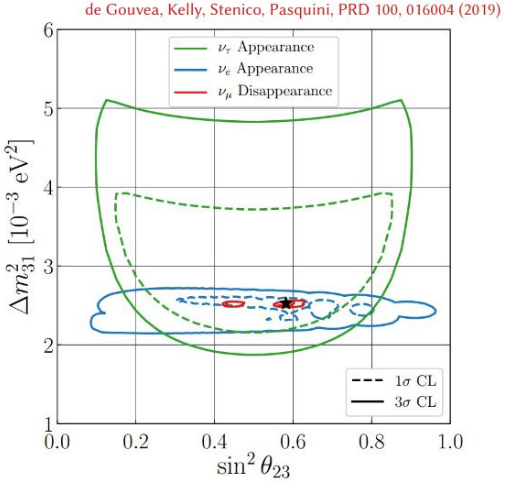
7 December 2023

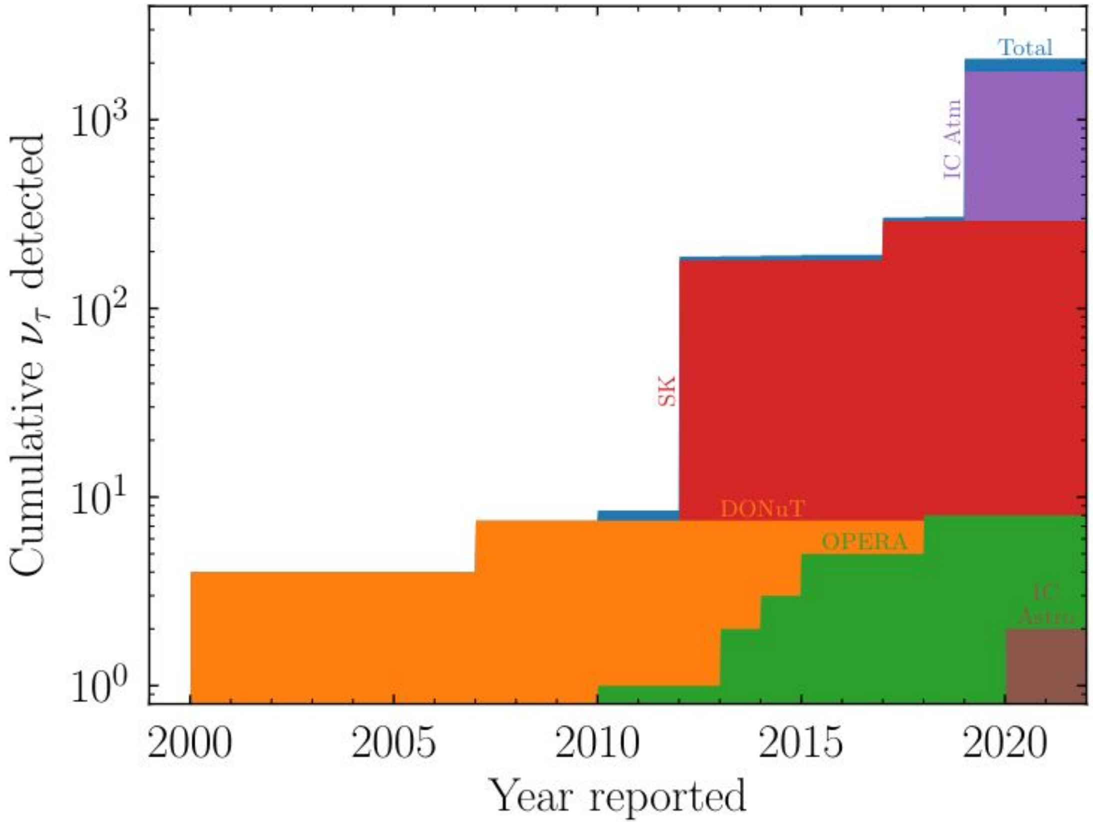
Motivation



Beam sample - expected counts/year:

~**130** ν_τ in low-energy neutrino mode
~**30** $\bar{\nu}_\tau$ in low-energy antineutrino mode
~**800** ν_τ in high-energy neutrino mode

From Adam Aurisano's Talk



[NuTau2021 Report: arXiv:2203.05591]

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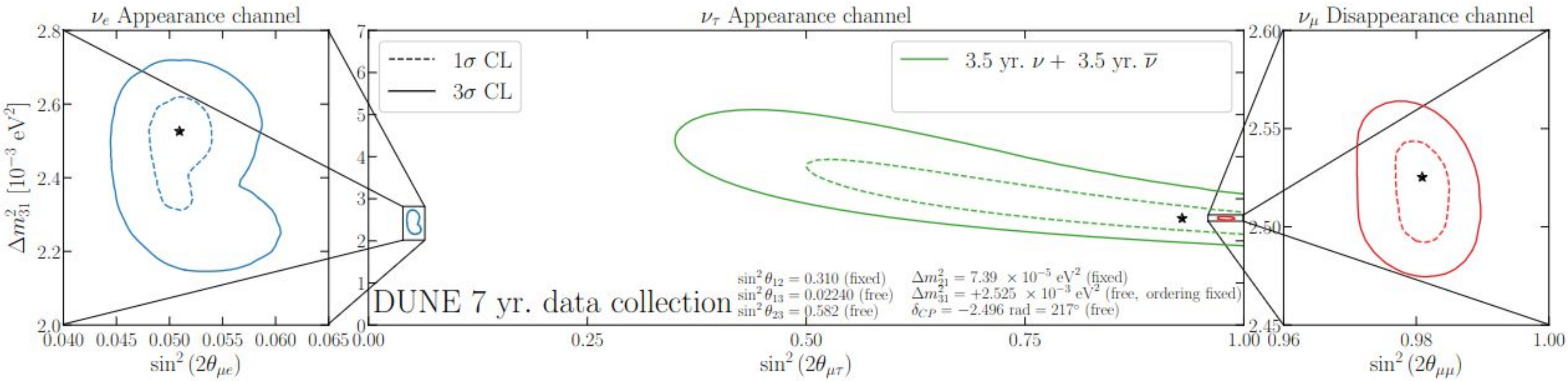

From Kevin Kelly's Talk

de Gouvêa, Kelly, Pasquini, Stenico [1904.07265]

How to do you extract these parameters from data?

Motivation

$$\frac{N_{FD}}{N_{ND}} \propto \frac{\int \mathrm{d}E_\nu \frac{\mathrm{d}\phi_\alpha^{FD}}{\mathrm{d}E_\nu} P(\nu_\alpha \to \nu_\beta; E_\nu) \sigma_\beta(E_\nu) \mathcal{M}_\alpha^{FD}(E_\nu, E_{reco})}{\int \mathrm{d}E_\nu \frac{\mathrm{d}\phi_\alpha^{ND}}{\mathrm{d}E_\nu} \sigma_\alpha(E_\nu) \mathcal{M}_\alpha^{ND}(E_\nu, E_{reco})}$$

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- Number of events in near / far detector

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- Migration matrix (Depends on topology of events)

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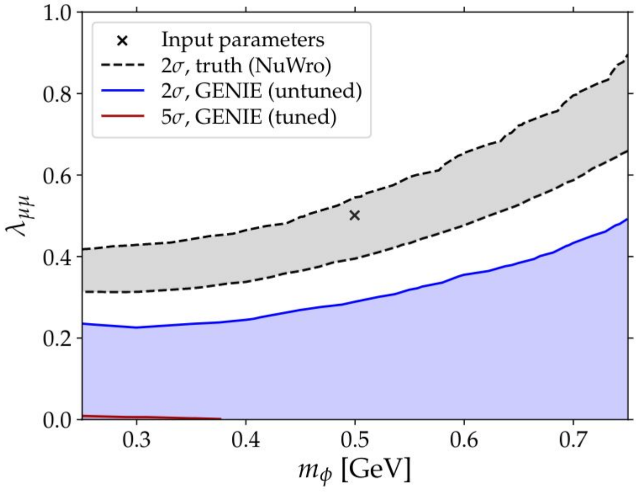
- Number of events in near / far detector
- Oscillation probability
- Neutrino-nucleus cross section
- Migration matrix (Depends on topology of events)
- **Conclusion:** Need theory driven neutrino event generators

What about tuning?



[N. Coyle, S. Li, and P. Machado: arXiv:2210.03753]

- Tuning can hide new physics if not handled correctly
- Even with tuning, theory uncertainty is dominant systematic

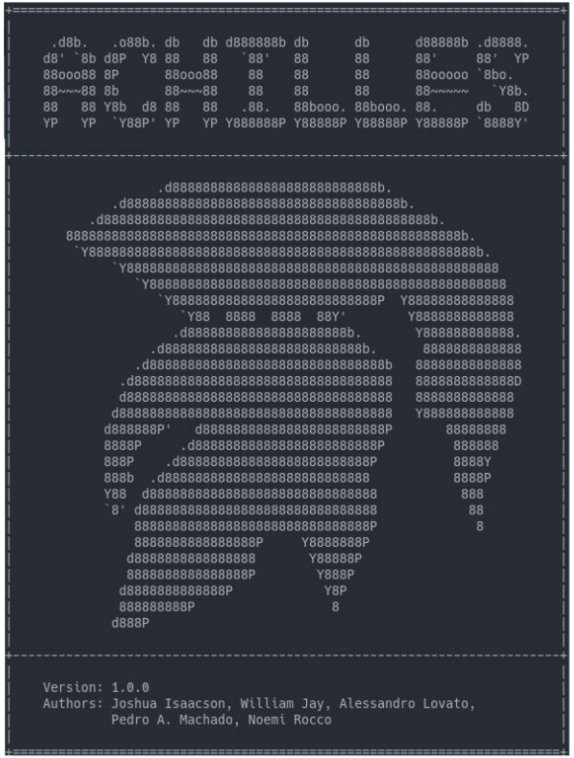
Source of Uncertainty	ν_e signal (%)	Total beam background (%)
Cross-section and FSI	7.7	8.6
Normalization	3.5	3.4
Calibration	3.2	4.3
Detector response	0.67	2.8
Neutrino flux	0.63	0.43
ν_e extrapolation	0.36	1.2
Total systematic uncertainty	9.2	11
Statistical uncertainty	15	22
Total uncertainty	18	25

[M. A. Acero, et al. NOvA collaboration, Phys. Rev. D 98, 032012]

Achilles: A CHIcagoLand Lepton Event Simulator

Project Goals:

- Theory driven
- Leverage experiences from LHC event generators
- Develop modular neutrino event generator
- Provide automated BSM calculations for neutrino experiments
- Evaluate theory uncertainties
- Appropriately handle correlations within events



Spin Correlations

	Achilles	Every other neutrino generator
2 to n-body scattering		
Spin-density Matrices		

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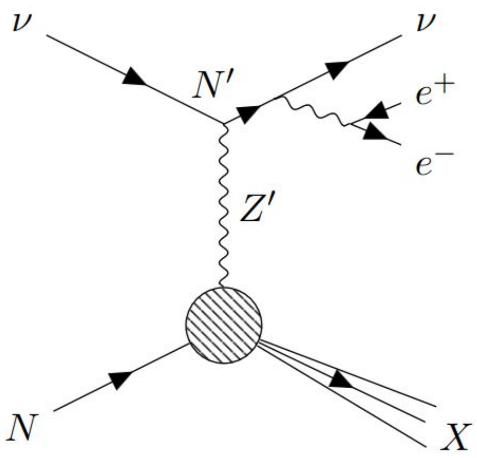

[JI et al. arXiv:2110.15319]

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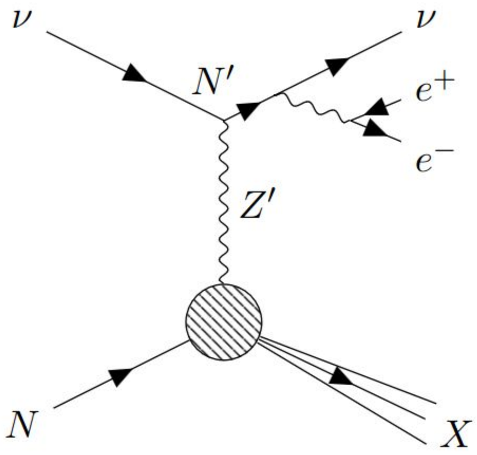

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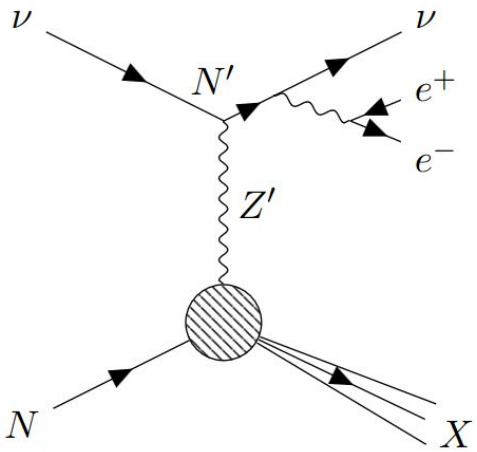

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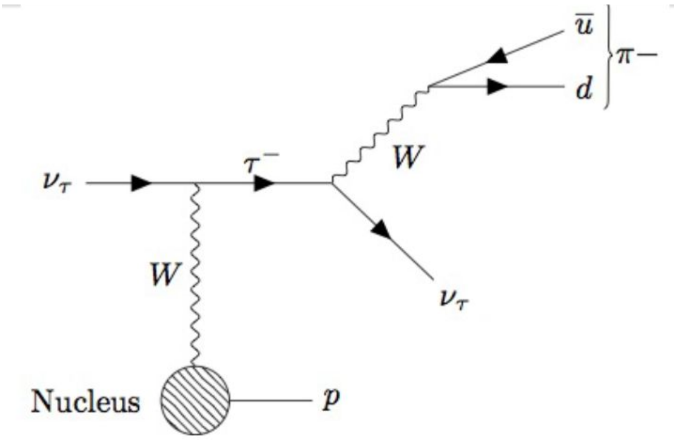

[JI et al. arXiv:2303.08104]

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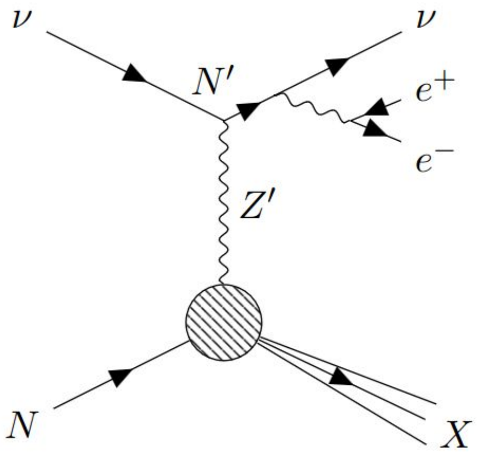

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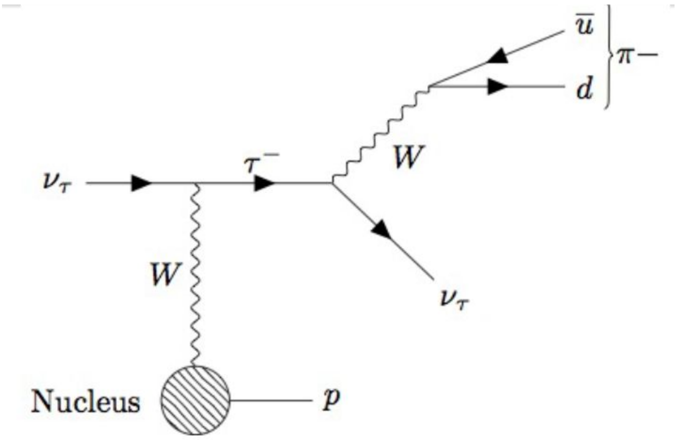


[JI et al. arXiv:2303.08104]

Spin Correlations: 2 to n-body scattering

- Full phase space → separation of Dirac and Majorana
- GENIE includes this model, but handles it with repeated decays → only can simulate Majorana case (by accident)

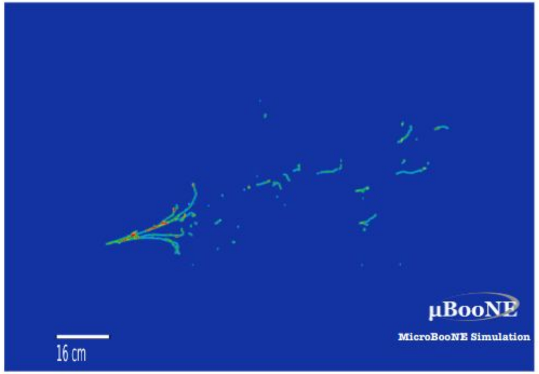
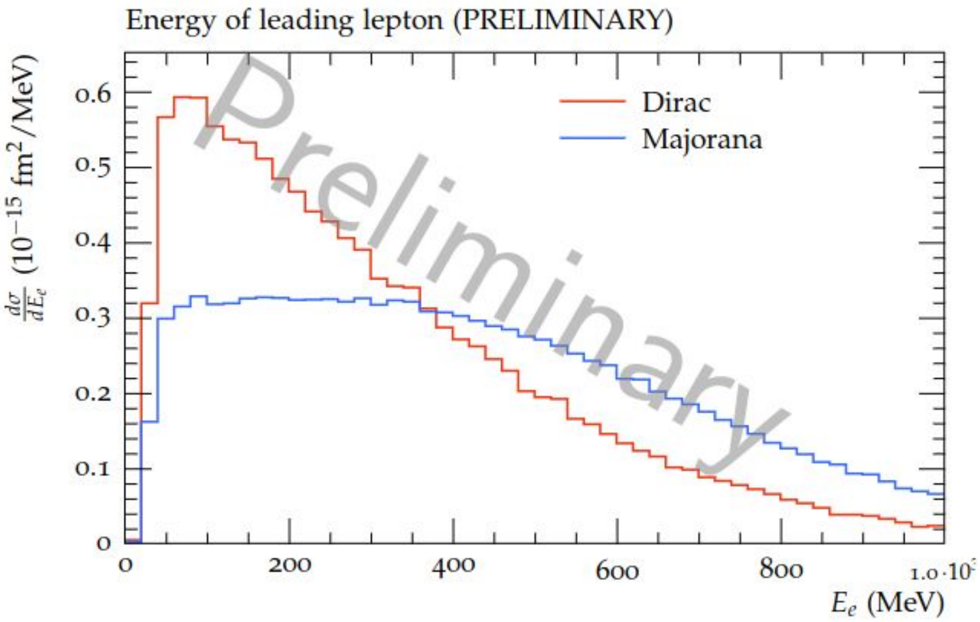


Image generated by the MicroBooNE collaboration using Achilles

Example: Dark Neutrino explanation of MiniBooNE

[E. Bertuzzo, et. al. arXiv:1807.09877]



Spin Correlations: Spin-Density Matrix

[P. Richardson arxiv:hep-ph/0110108]

Step 1:

- Calculate the matrix elements tracking spin
- ρ is the spin density matrix for incoming particles
- D is the spin dependent decay matrix
- Initialize D to be diagonal

$$\rho^1_{\kappa_1\kappa_1'}\rho^2_{\kappa_2\kappa_2'}\mathcal{M}_{\kappa_1\kappa_2;\lambda_1\ldots\lambda_n}\mathcal{M}^*_{\kappa_1'\kappa_2';\lambda_1'\ldots\lambda_n'}\prod_{i=1,n}D^i_{\lambda_i\lambda_i'}$$

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Step 3:

- Select decay channel based on branching ratio
- Generate momentum according to →
- Continue down decay chain until only stable particles remain

$$\rho_{\lambda_0\lambda'_0}\mathcal{M}_{\lambda_0;\lambda_1\ldots\lambda_k}\mathcal{M}^*_{\lambda'_0;\lambda'_1\ldots\lambda'_k}\prod_{i=1,k}D^i_{\lambda_i\lambda'_i}$$

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- Continue down decay chain until only stable particles remain

$$D_{\lambda_0\lambda'_0} = \frac{1}{N_D}\mathcal{M}_{\lambda_0;\lambda_1\ldots\lambda_k}\mathcal{M}^*_{\lambda'_0;\lambda'_1\ldots\lambda'_k}\prod_{i=1,n}D^i_{\lambda_i\lambda'_i}$$

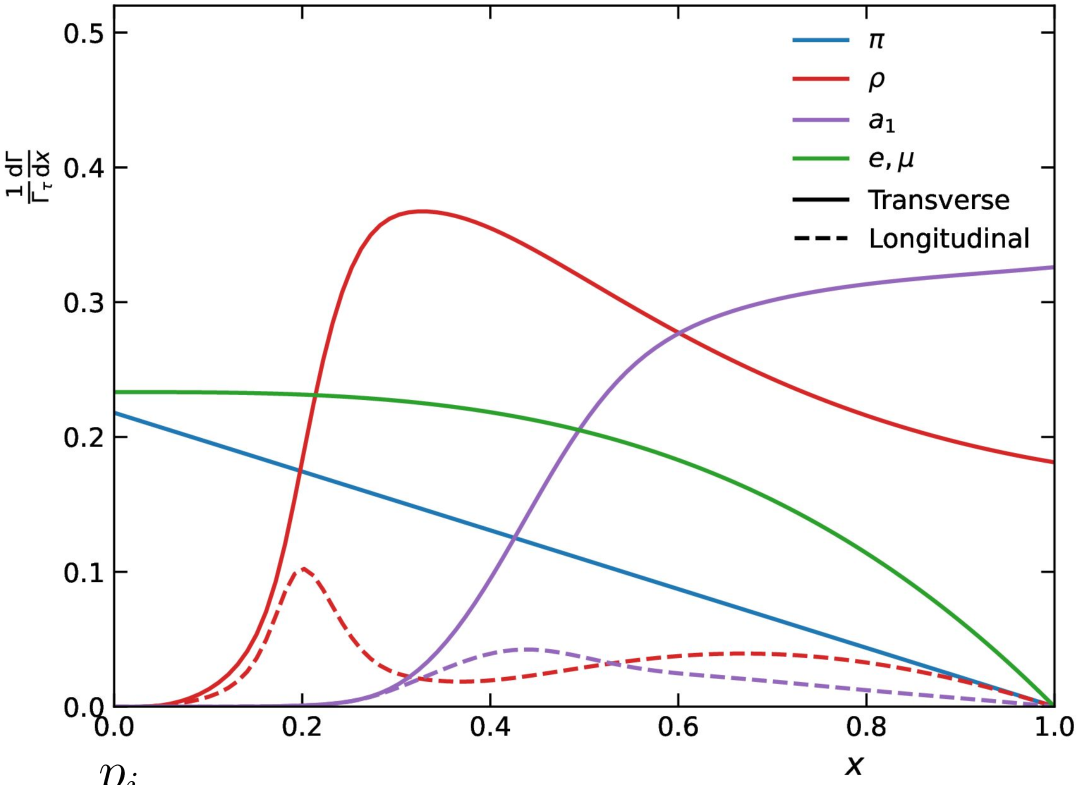
Step 4:

- Final decay matrix is obtained
- Repeat above steps until all particles are stable

Collinear Limit

- Possible to calculate decays in collinear limit ($p_\tau \to \infty$)
- Useful to validate predictions in the same limit

Decay mode	Branching ratio (%)
Leptonic decays	35.21
$e^-\nu_\tau\bar{\nu}_e$	17.85
$\mu^-\nu_\tau\bar{\nu}_\mu$	17.36
Hadronic decays	64.79
$\pi^-\pi^0\nu_\tau$	25.50
$\pi^-\nu_\tau$	10.90
$\pi^+\pi^-\pi^-\nu_\tau$	9.32
$\pi^-\pi^0\pi^0\nu_\tau$	9.17
$\pi^+\pi^-\pi^-\pi^0\nu_\tau$	4.50
$\pi^-\pi^0\pi^0\pi^0\nu_\tau$	1.04
$K^-\nu_\tau$	0.70
$\pi^+\pi^-\pi^-\pi^0\pi^0$	0.55
other	3.11

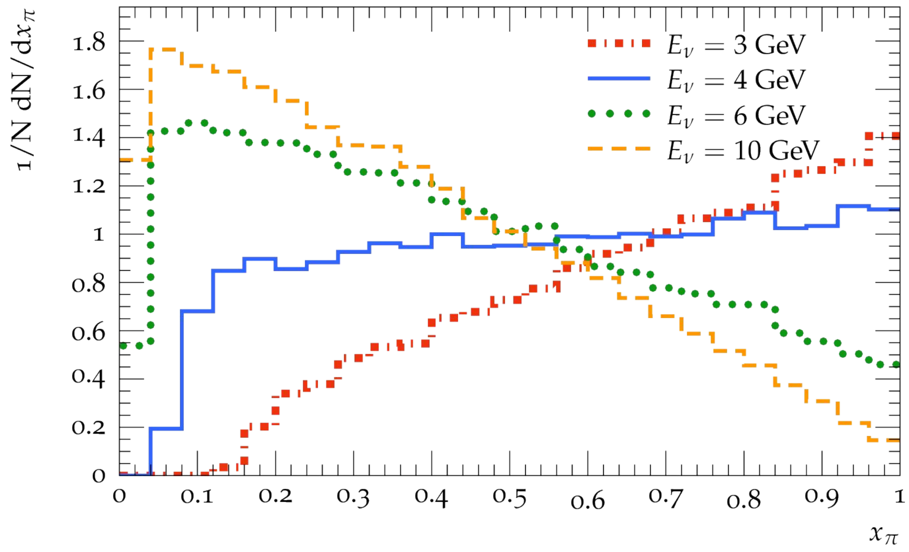


$$x_i = \frac{p_i}{p_\tau}$$

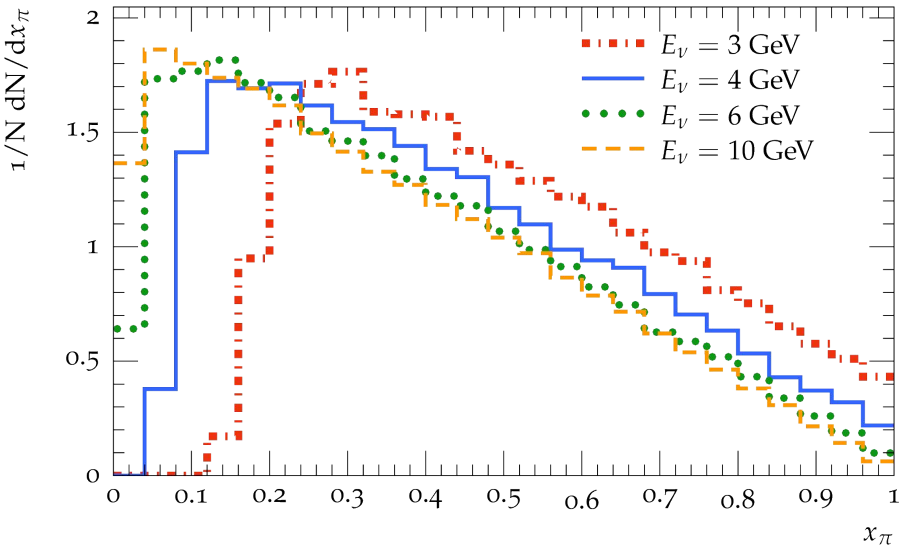
B. K. Bullock, K. Hagiwara, and A. D. Martin, Nucl. Phys. B 395, 499 (1993).

Monoenergetic Validation

$$\nu_\tau A \rightarrow \tau^-(A-1)p, \quad \tau^- \rightarrow \nu_\tau \pi^-$$



Correct handling of polarization



Left-handed only assumption

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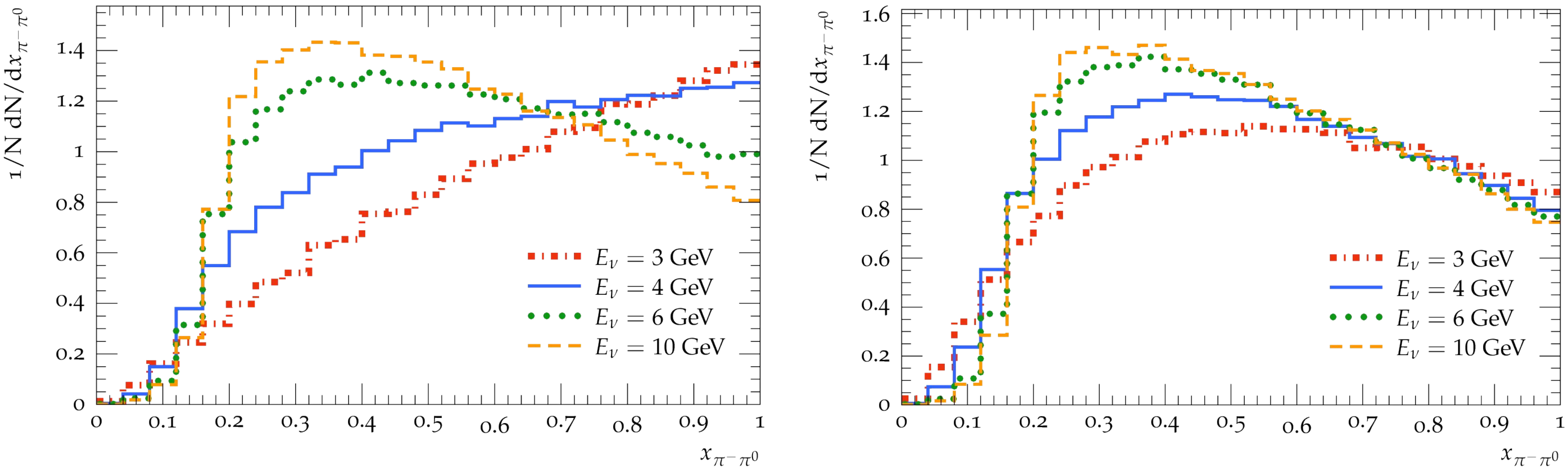

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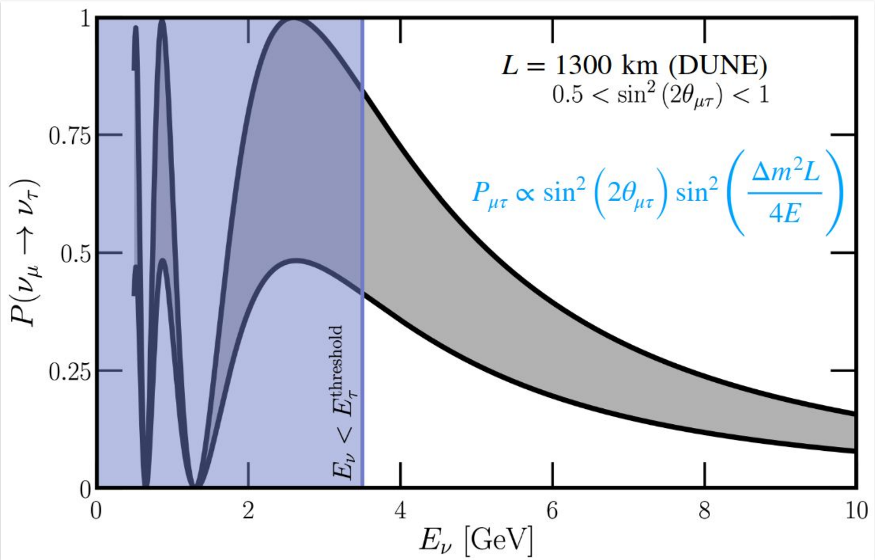
DUNE Tau Optimized Flux



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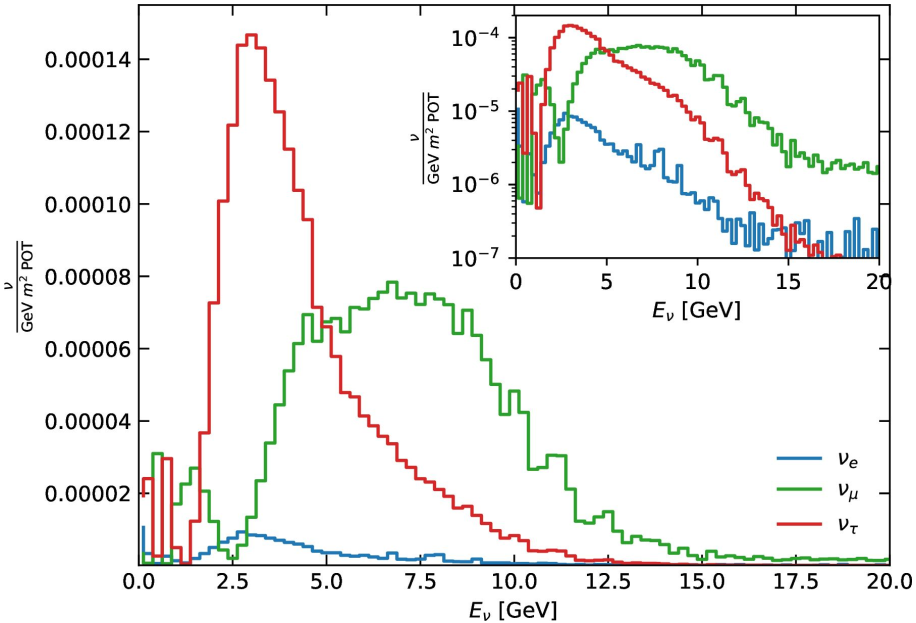

L. Fields, "DUNE Fluxes," https://glaucus.crc.nd.edu/DUNEFluxes/

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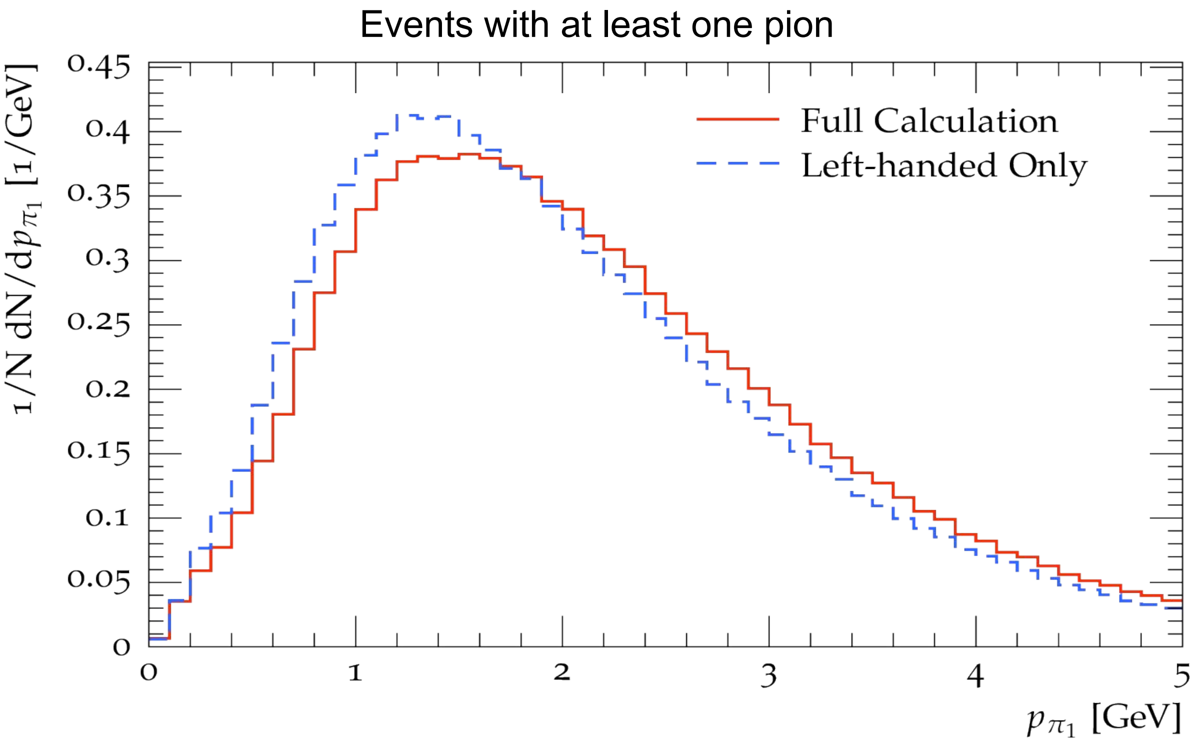

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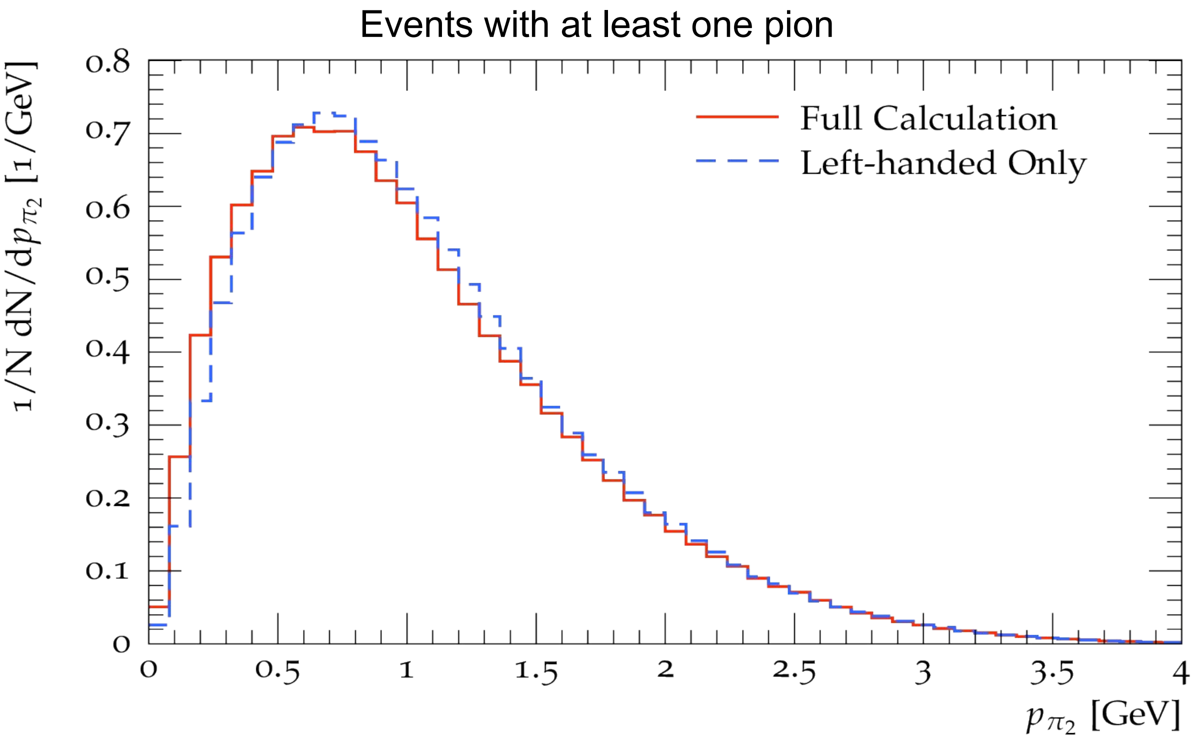

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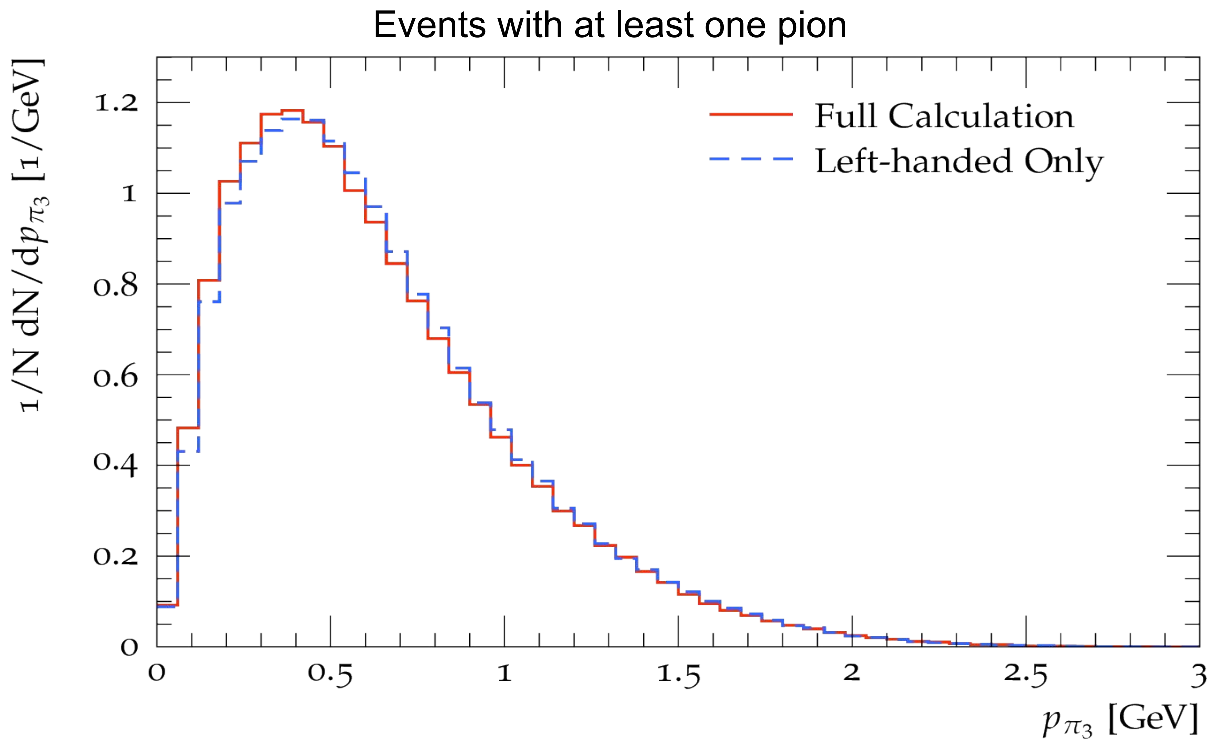
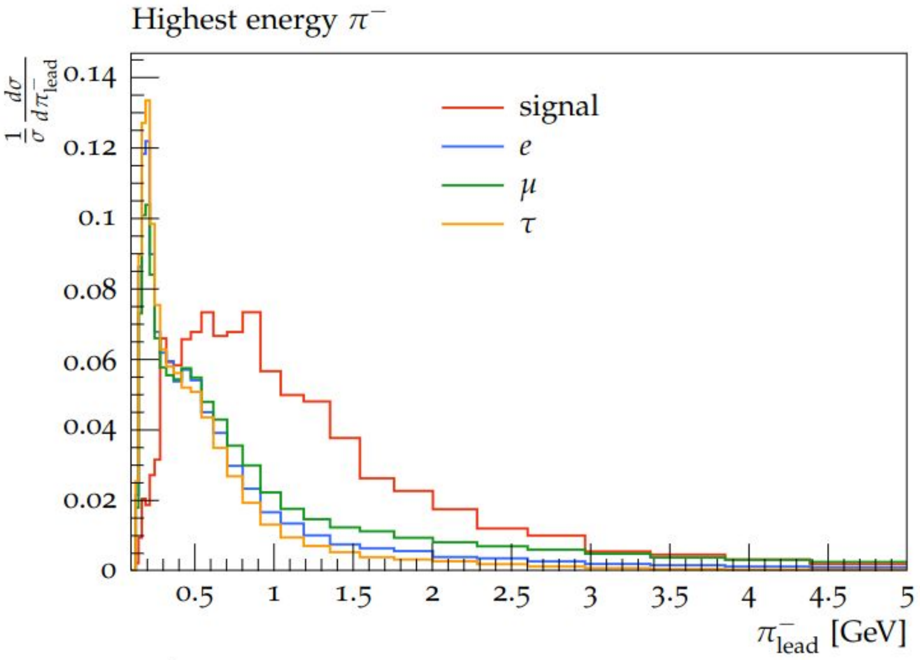
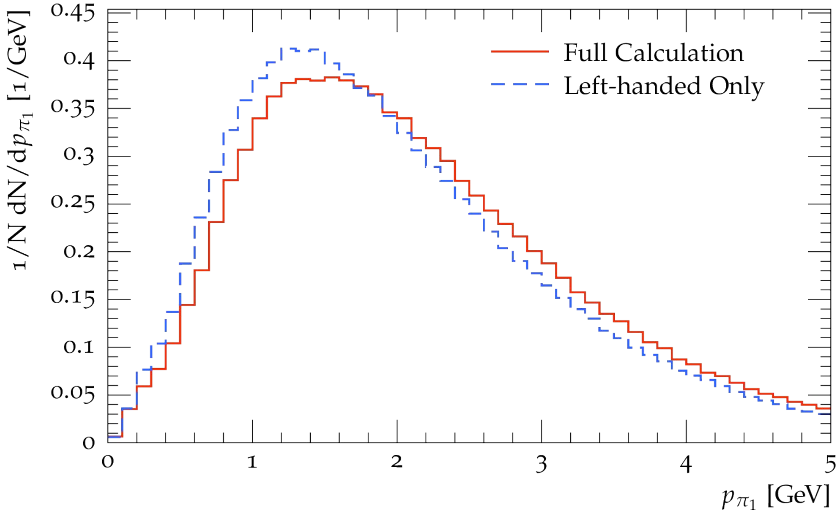


DUNE Tau Optimized Flux

Comparison to backgrounds





[P. Machado et. al. arXiv:2007.00015]

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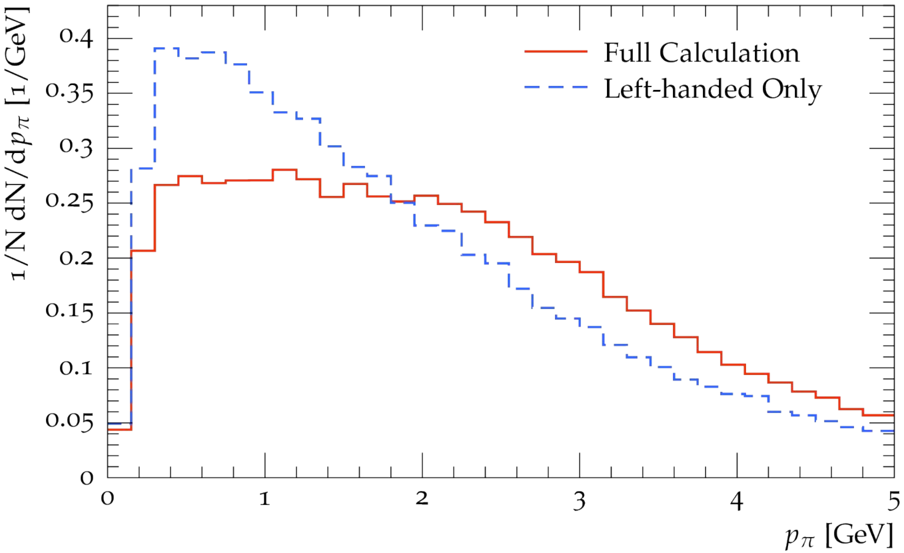

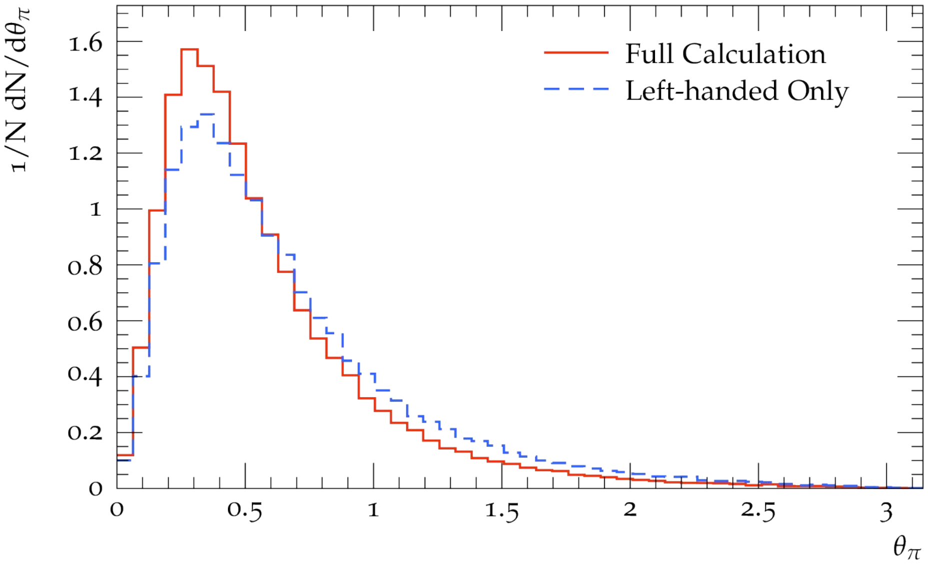

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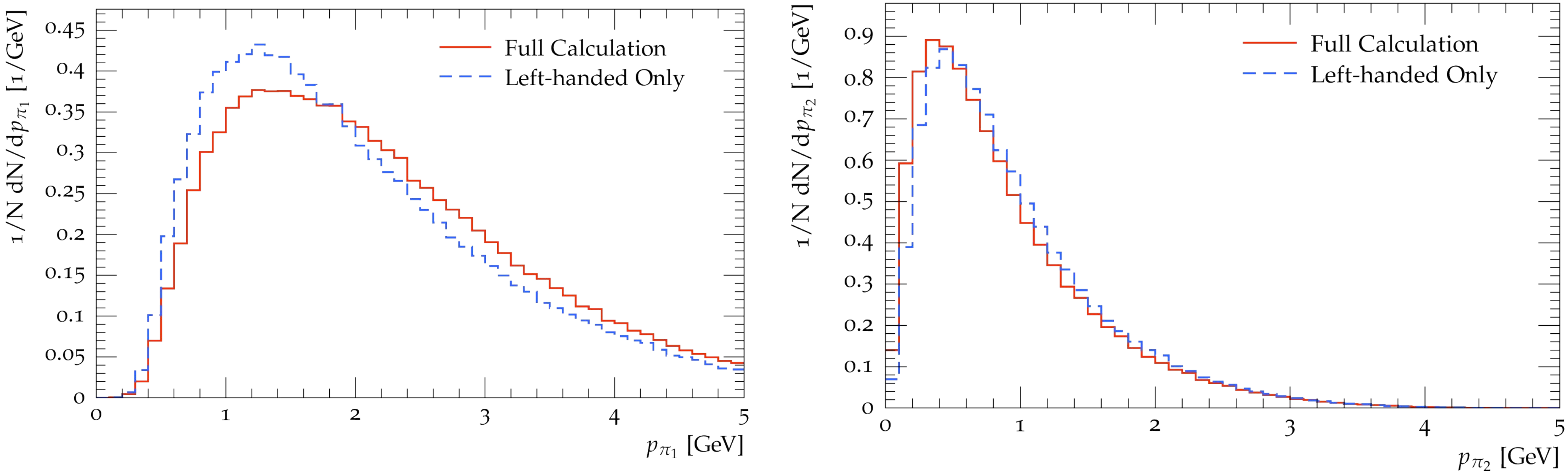


Conclusions

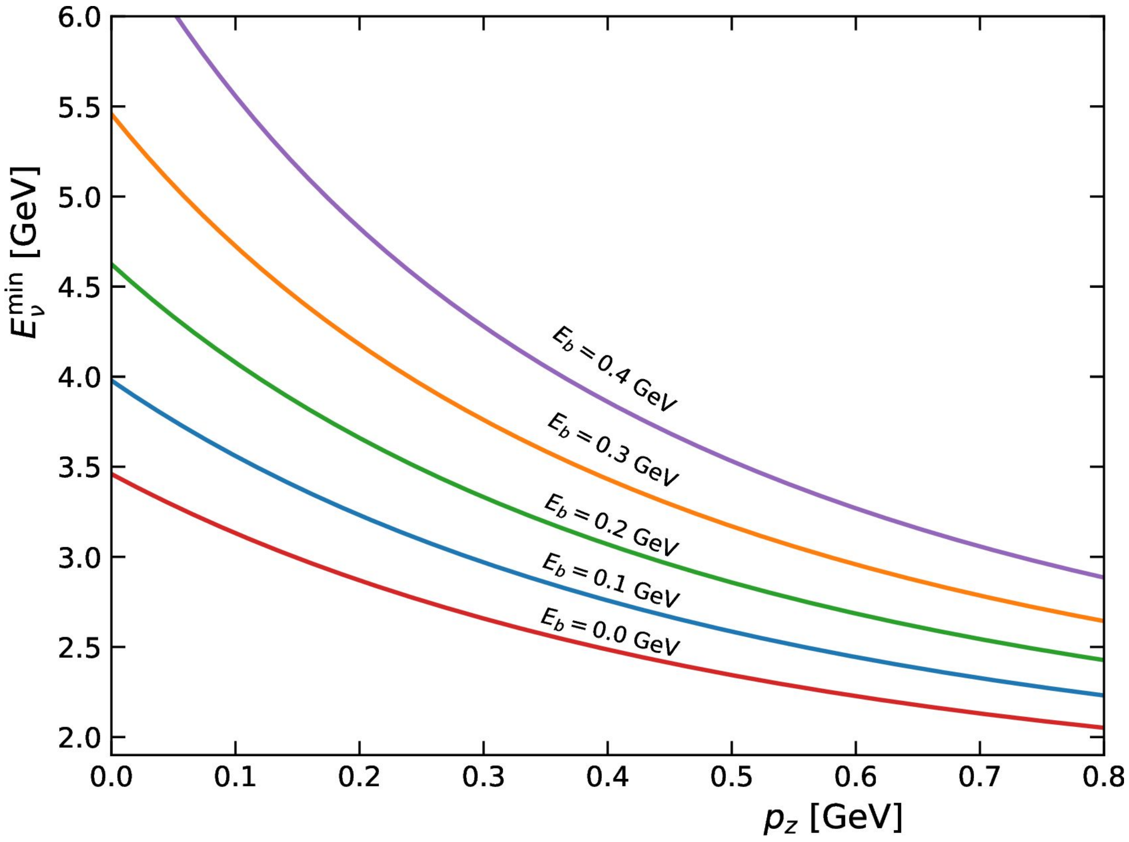
- Extracting underlying physics parameters requires accurate modeling of the underlying theory
- Largest systematic uncertainty arises from event generator modeling of cross-sections
- Handling spin correlations will be vital for any process beyond 2→2 scattering
- Achilles only tool on the market that can handle this
- These effects are important for tau neutrino charged current interactions
- Future steps:
  - Investigate improvements on tau separation from background
  - Leverage spin-correlations for more accurate BSM studies

Codes can be found at:
- Achilles: https://github.com/AchillesGen/Achilles/releases/tag/v0.2.0
- Sherpa: https://gitlab.com/sherpa-team/sherpa/-/tree/achilles

Backup

Tau Threshold

- Minimum neutrino energy depends on the nuclear structure.
- Nucleon momentum along z-axis
- Binding energy (E_b) impacts threshold



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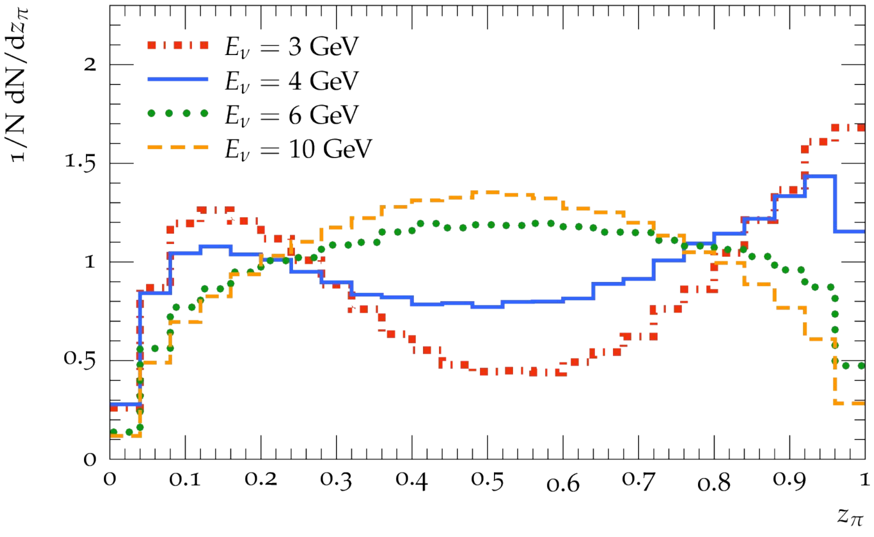

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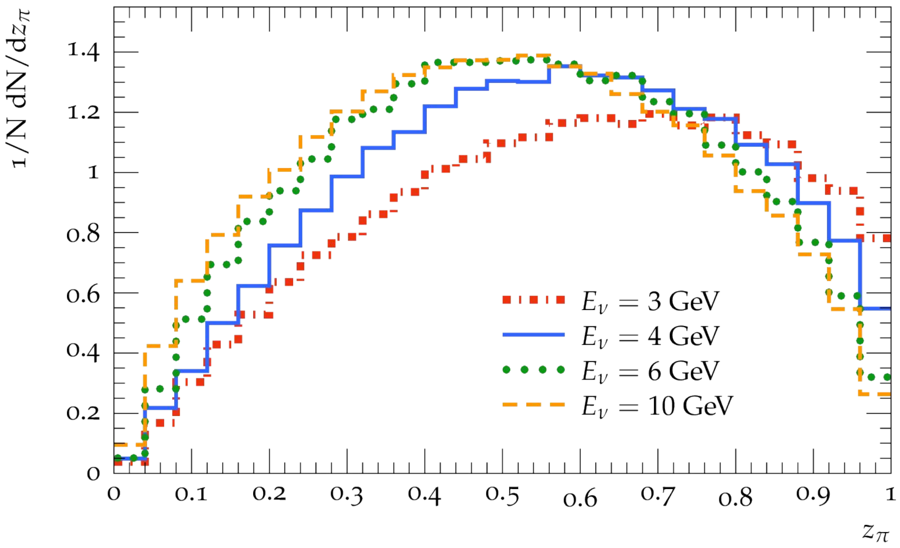

Left-handed only assumption

$$z_\pi = \frac{p_\pi^-}{p_{\pi^-\pi^0}}$$