Investigating the reach of FPF via information geometry

using multidifferential neutrino spectra

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Introduction

- At FPF6, introduced a tool for estimating the uncertainty of neutrino flux predictions, and to study how various models can be constrained based on Fisher information
  - Important step in understanding SM and the stream towards refining BSM searches: large differences between flux predictions, uncertainties are potentially large. **Ensure physics effects are not covered by uncertainties!**
- Various effects could affect the shape / magnitude of the neutrino spectra. Here we present results for:
  - Non-standard neutrino interactions via effective field theory
  - Enhanced strangeness
    - Consider possibilities for solving the cosmic ray muon excess puzzle using proposed and existing LHC experiments

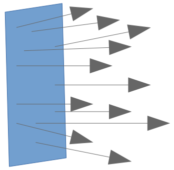
Workflow

Predictions for hadron production at IP1

- Light mesons
  $\pi^{\pm},\ K^{\pm},\ K_L^0,\ K_S^0$
- Charm hadrons
  $D^{\pm},\ D^0,\ \overline{D}^0,$
  $D_s^{\pm},\ \Lambda_c^{\pm}$

Decays into neutrinos

MC samples of neutrinos (flavor, position, energy, momentum)



$N(\pi,K,c) \times (N_{predictions}-1) = 12$ parameters λ

The results are based on using the predictions:

Light mesons (π, K) Name	Charm hadrons (D, Λ_c) Refs
SIBYLL 2.3d	SIBYLL 2.3d
EPOS-LHC	BKRS (NLO)
DPMJET 3.2019.1	BDGJKR (NLO)
QGSJET II-04	BKSS k_T
Pythia 8.2 (forward)	MS k_T

Many thanks to WG2 for their efforts!

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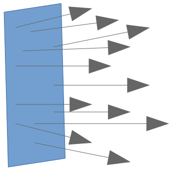
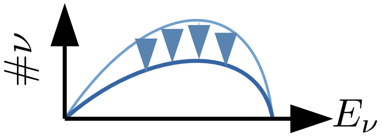


Propagate to forward experiments

- Some models affect the spectra of *incoming neutrinos*



N(π,K,c)x(N$_{predictions}$-1) = 12 parameters λ

Parameters *p* changing produced ν distr.

Workflow

Software package available at github

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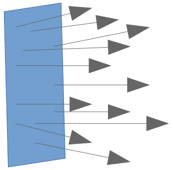

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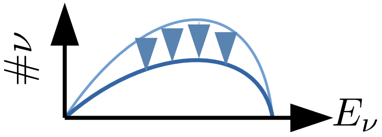
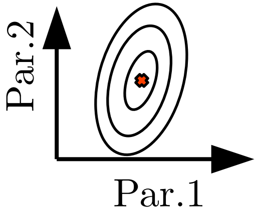


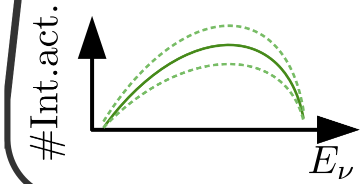
Interactions within detector

Combine predictions to estimate unc. via Fisher information

Maximal constraints



Observed ν spectra, with uncertainties



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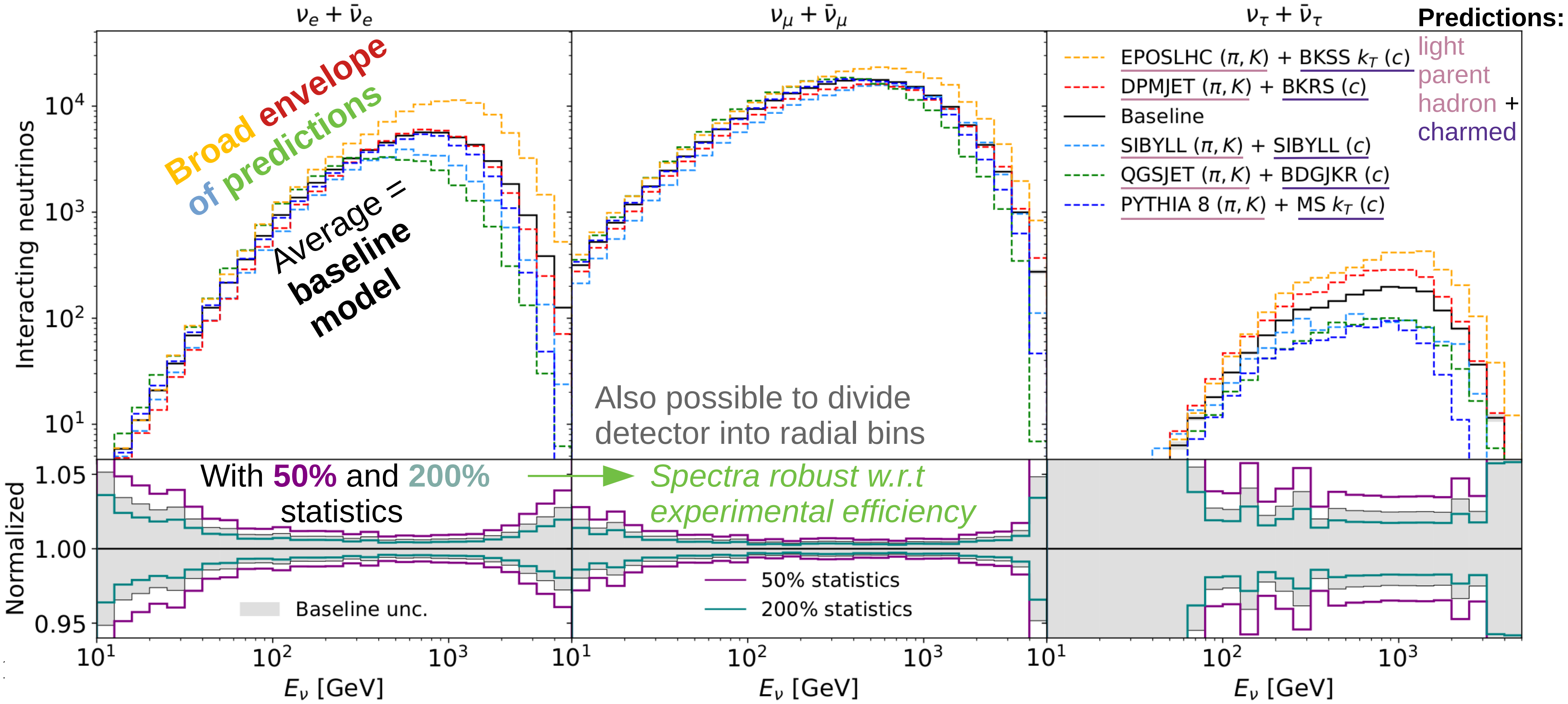
Parameters *p* changing produced ν distr.

Param. *p'* changing observed ν distr.

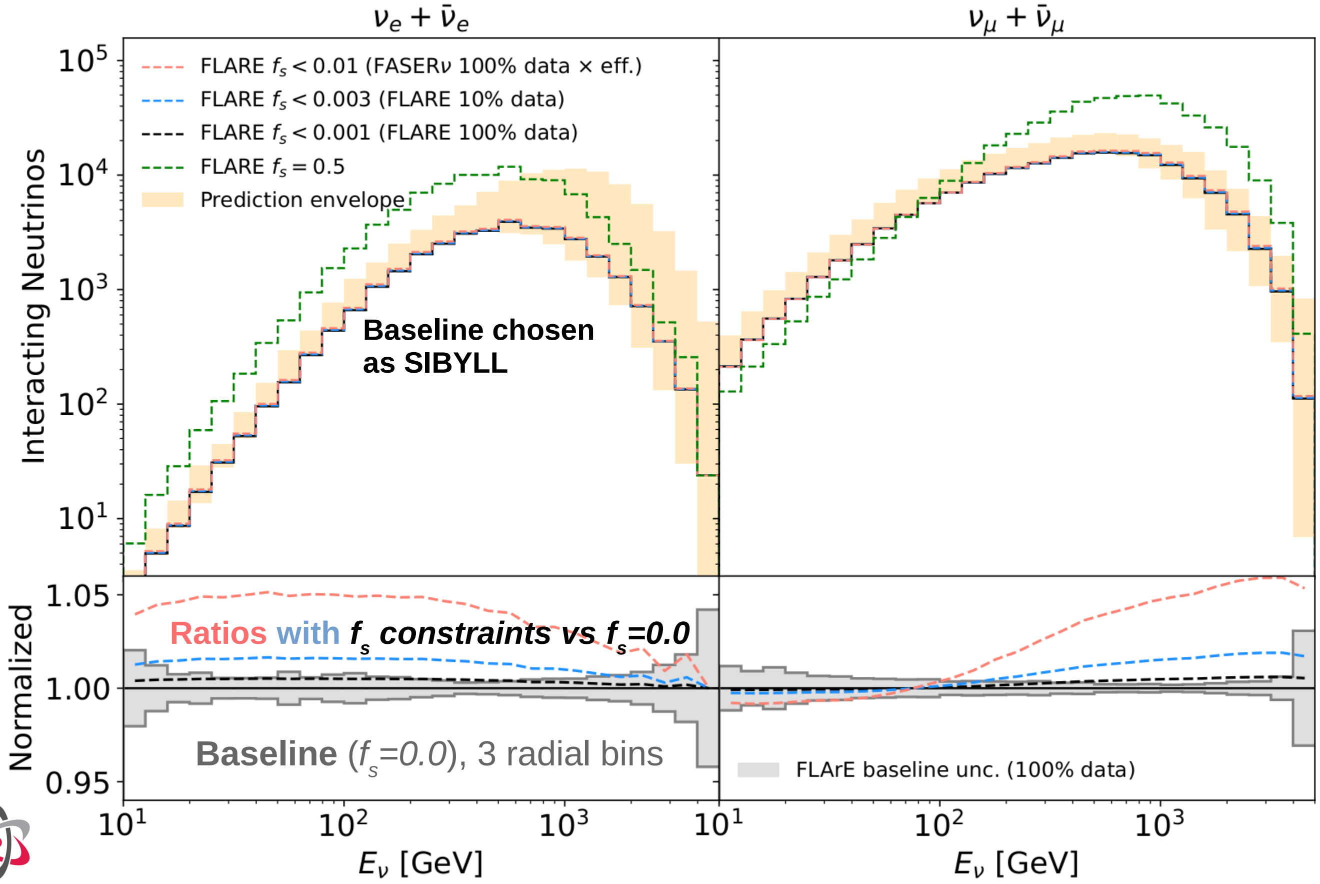
Find info matrix for observed spectrum *m(λ,p,p')* → *profiling* → *constraints*

The neutrino spectra

Separate spectra for neutrino flavors (no outgoing lepton charge discrimination here)



Enhanced strangeness

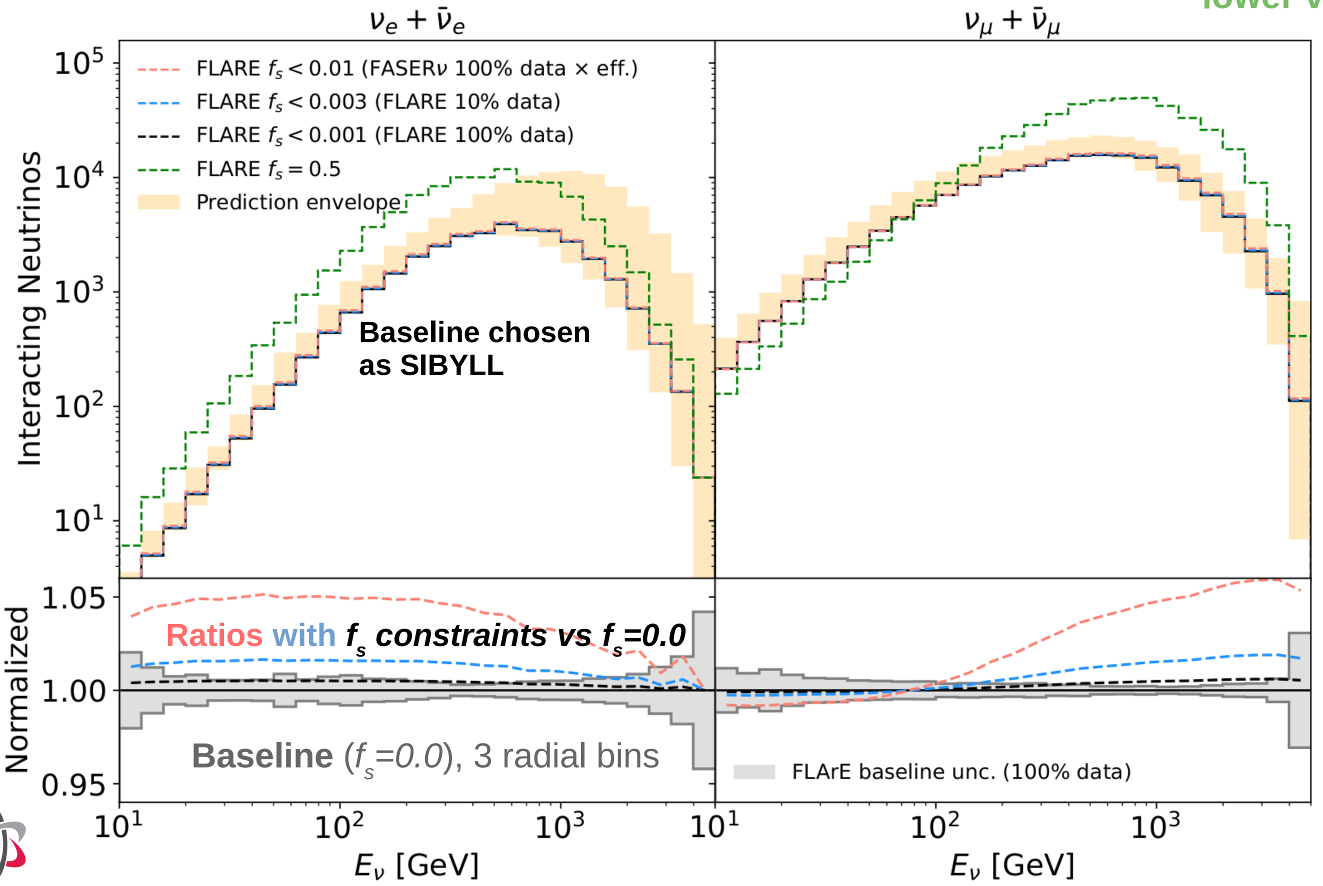


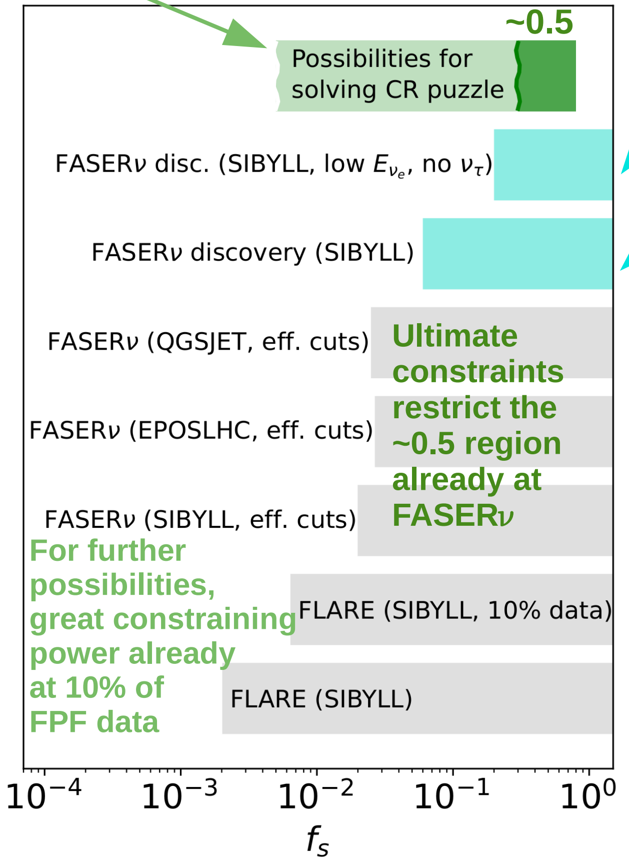
- What if there should be less pions, and kaons produced instead of them? (Enhanced strangeness hypothesis)
- Reweigh the counts of neutrinos associated with pions by $(1 - f_s)$, and those from kaons by $(1 + F f_s)$
  F: Phenomenological factor, account for difference in π / K production rates
- *arXiv: 2202.03095 [hep-ph]:* f_s=0.5 could explain the cosmic ray muon excess
  - Well distinguishable from the model *and* the broad prediction envelope

Enhanced strangeness

At LHC energies, f_s might also have lower values

Discovery potential: examine cases with non-zero baseline f_s





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Non-standard interactions (NSI)

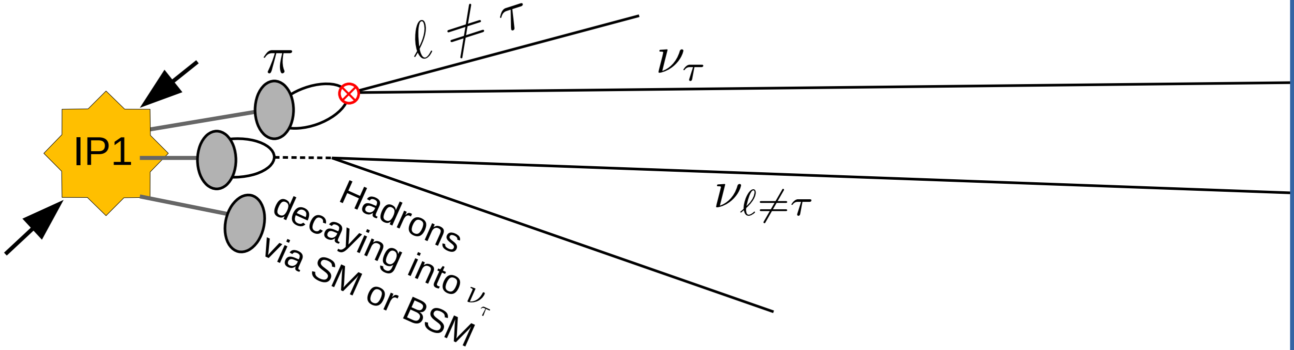
- Extend the SM Lagrangian by dimension-6 EFT terms (See doi:10.1007/JHEP10(2021)086)

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{2V_{ud}}{v^2} \times (\bar{u}\gamma^{\kappa} P_R d) \times \left[\epsilon_R^{\mu\tau}(\bar{\ell}_{\mu}\gamma_{\kappa} P_L \nu_{\tau}) + \epsilon_R^{\tau e}(\bar{\ell}_{\tau}\gamma_{\kappa} P_L \nu_e)\right]$$

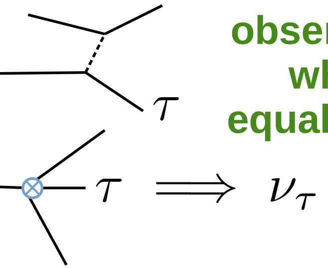
Consider changes to tau neutrino spectrum:

- Effects on **production** side

- Effects on **detection** side



FASERν2



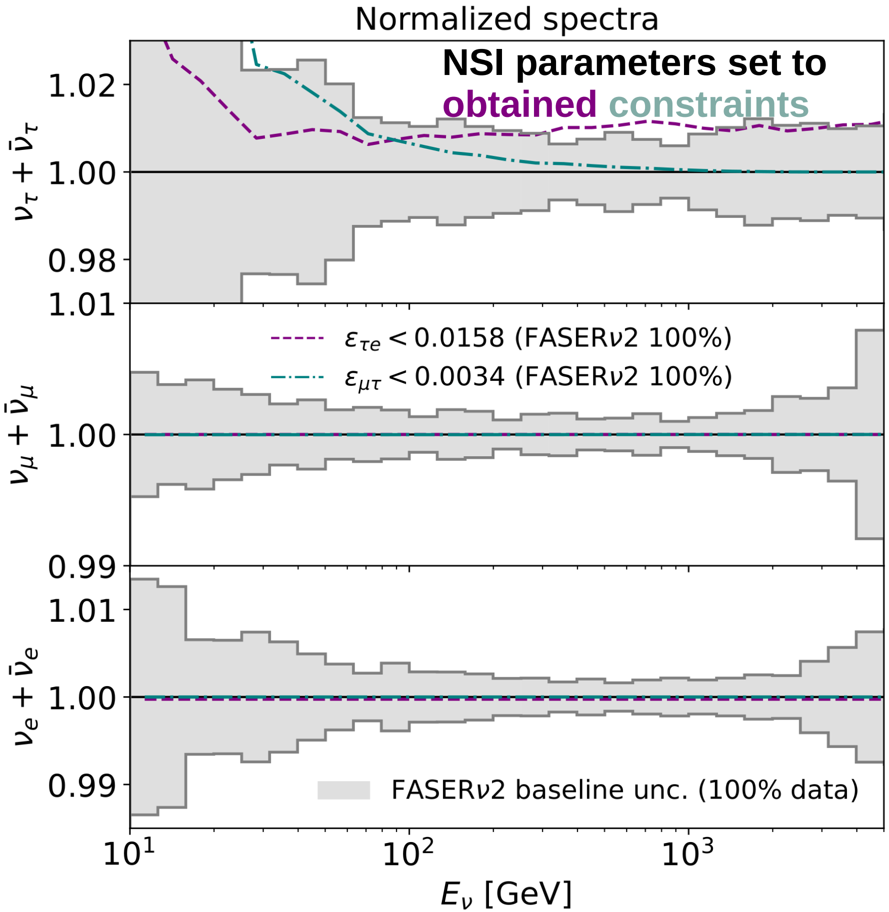
Additional interactions increase number of observed charged taus, which is assumed to equal the number of tau neutrinos

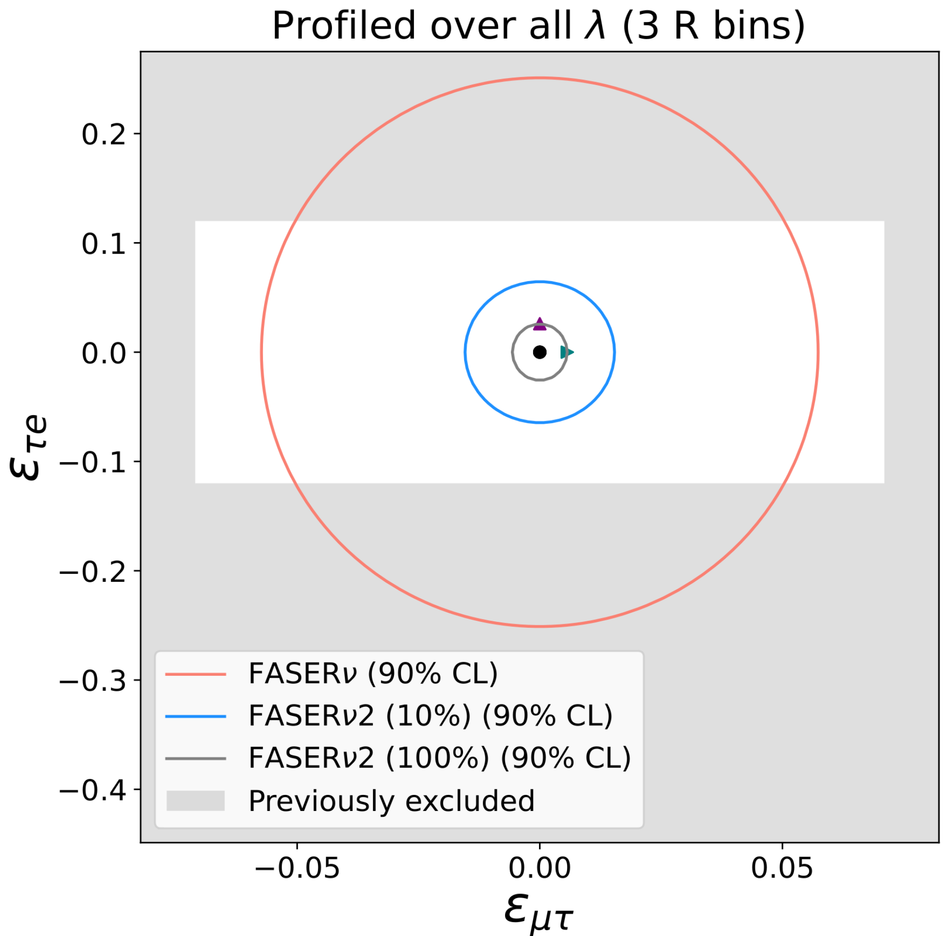
Effect approximated energy independent

The presence of additional operators increases incoming tau neutrino spectrum → Since we consider vertices connecting *u, d* quark legs, the production side change depends on pion energy spectrum shape

Non-standard interactions (NSI)

Projected FPF limits improve the constraints significantly already after 10% of data taking. Full result will improve select operators' limits by an order of magnitude





Summary and outlook

- Presented a model and **public software package** for evaluating the impact of various physics effects on neutrino spectra at FPF
  - Possible to estimate ultimate precision achievable at FPF
  - Easily extendible to further processes, both SM and BSM

- Demonstrated physics cases indicate
  - Potential to solve the cosmic muon ray excess using LHC neutrinos
  - FPF’s great constraining potential for non-standard interactions

Thanks for your attention!

Back-up

The model calculation

- Construct a model *m* giving amount of neutrinos as a weighted average of N_g predictions *G*

$$m(\{\lambda_i\}_{i=1}^{N_g-1}) = \frac{1}{N_g}\left[G_0\left(1 - \sum_{i=1}^{N_g-1}\lambda_i\right) + \sum_{i=1}^{N_g-1} G_i\left(1 + N_g\lambda_i - \sum_{j=1}^{N_g-1}\lambda_j\right)\right]$$

  - N_g-*1* parameters λ steer the result towards any prediction

Setting all λ=0 returns the mean, taken as the **baseline model** in most cases, but this choice is not imperative

- By The Cramér-Rao bound, the covariance matrix corresponding to the *highest obtainable precision* is obtained as the inverse of the *Fisher information I_{ij}*, approximated as the Hessian of the log likelihood ratio

$$-\frac{d^2 \log r}{d\lambda^i d\lambda^j}\Delta\lambda^i\Delta\lambda^j = I_{ij}\Delta\lambda^i\Delta\lambda^j$$

- **Obtain info matrix**
- **Perform eigenvector analysis**
  → ***Uncertainties!***

$$r(\lambda^\pi, \lambda^K, \lambda^c) = \frac{L(\text{expected data}|\lambda^\pi, \lambda^K, \lambda^c)}{L(\text{expected data}|\lambda^\pi = 0, \lambda^K = 0, \lambda^c = 0)}$$

Poisson distributions; examine differences between any set of λs and the baseline

Profiling

A parallel projection of a generalized ellipsoid in parameter space

- Estimate ultimate constraints for a parameter in the model computation by profiling over the *n*-th parameter in the information matrix *I*: the *n*-th column (or row) of *I*, with the *n*-th entry removed, is taken as the vector **m** describing the mixing between the profiled parameter and the remainder

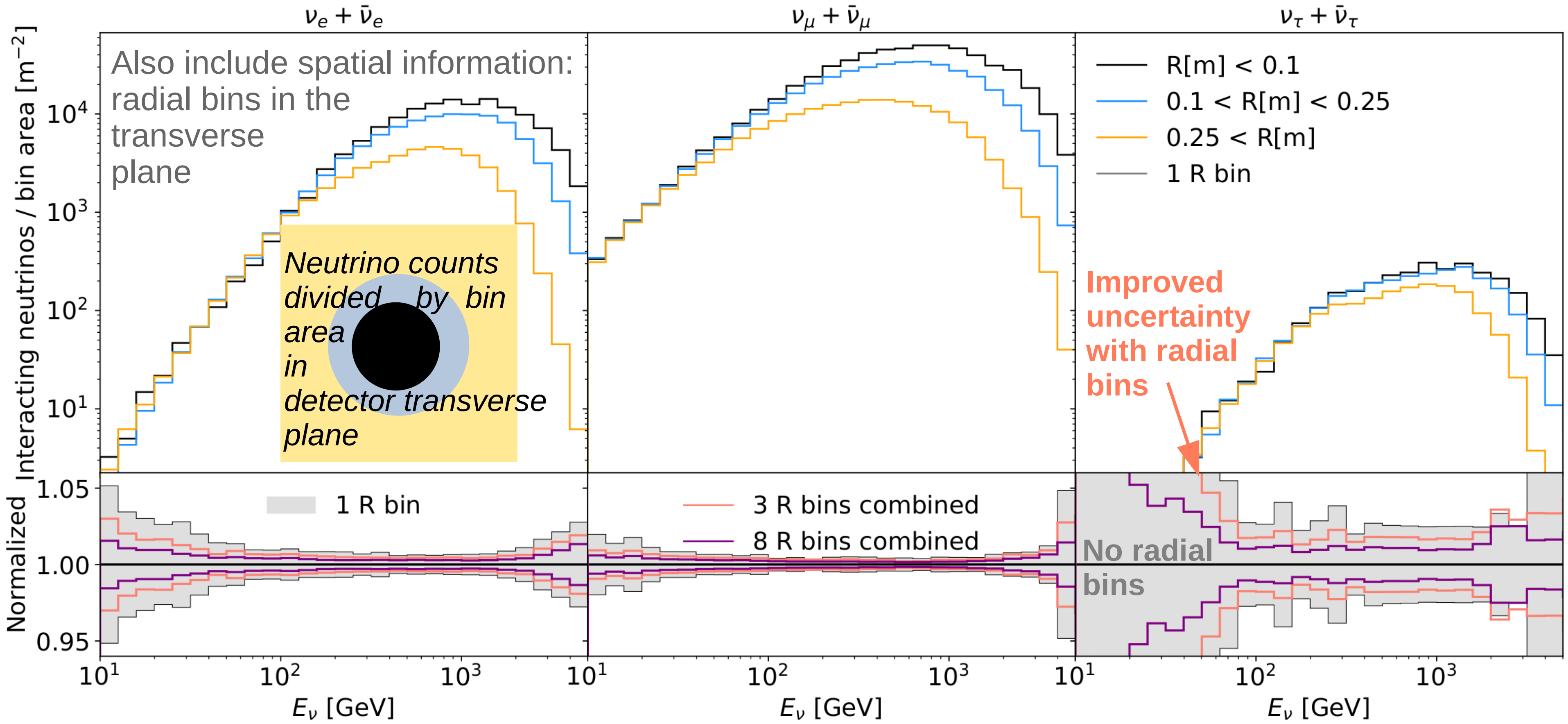
- A reduced information matrix I^{reduced} is attained by removing the *n*-th column and row from *I*. The profiled information matrix is $I^{\text{profiled}} = I^{\text{reduced}} - \mathbf{m} \otimes \mathbf{m} / I_{nn}$

- The procedure is repeated to profile over multiple parameters, starting with the information matrix resulting from the previous step

- By profiling over all but one parameter, the information matrix reduces into a single entry *a*. The ultimate constraint for the remaining parameter is then $a^{-1/2}$

The neutrino spectra

1 vs 3 radial bins



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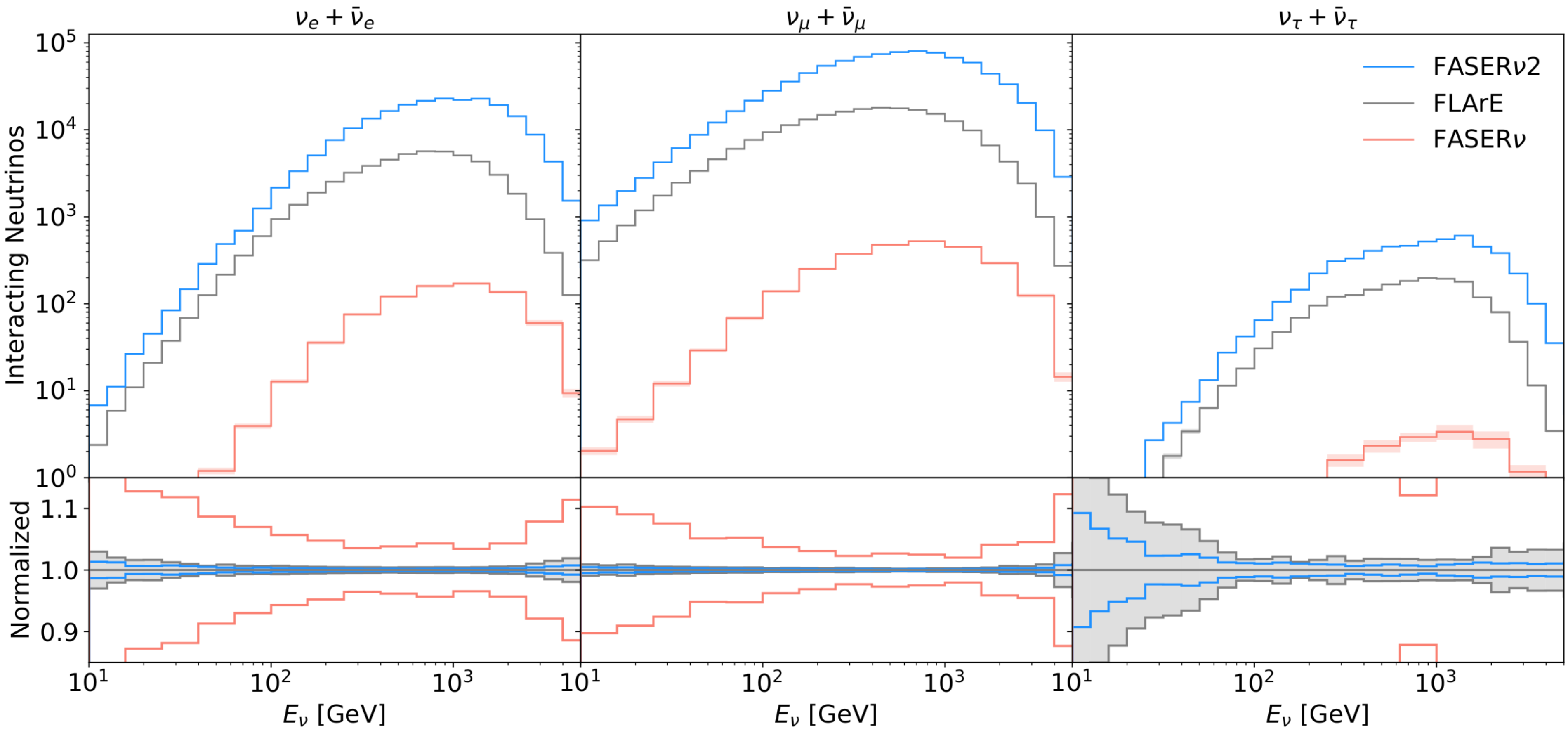
Experiment comparison



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