Investigating the reach of LHC neutrino experiments

Toni Mäkelä, *Felix Kling, Sebastian Trojanowski*

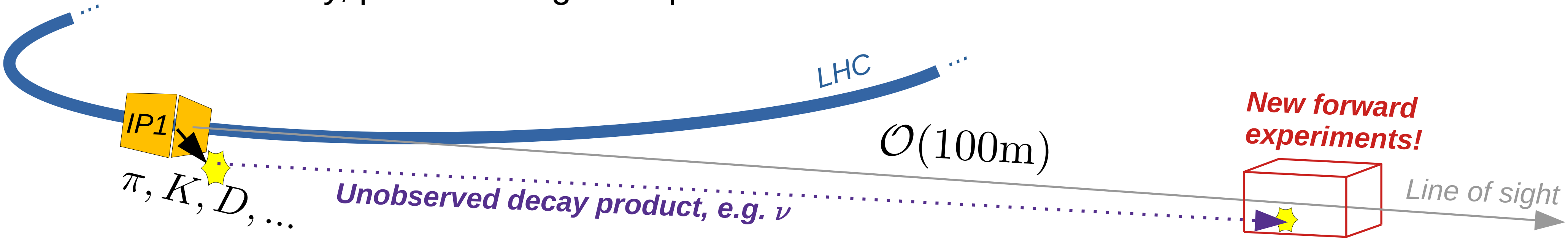
Phys. Rev. D 108, 095020

Polish Particle and Nuclear Theory Summit
IFJ PAN, Kraków
November 24, 2023

NCBJ NATIONAL SCIENCE CENTRE POLAND

Introduction
Neutrinos at the LHC

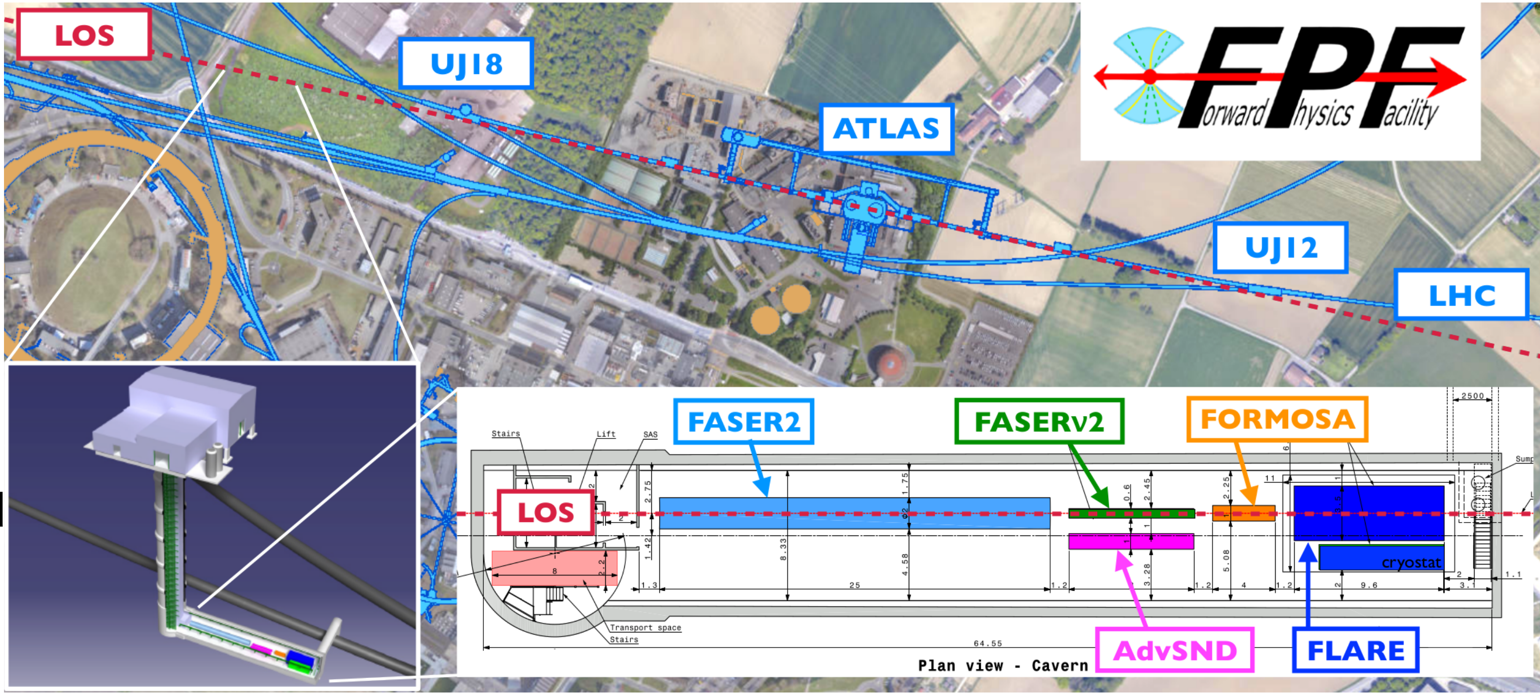
- Hadron collisions at the LHC produce a myriad of hadrons, which can produce neutrinos via weak decays
  - Neutrinos never observed by central experiments e.g. ATLAS, CMS
  - Similarly, possible long-lived particles not observed at the IP



- LHC neutrinos observed by FASER and SND@LHC!
  - However, only little statistics expected
  - What if we had a purpose-built facility to study this hitherto unavailable ν beam?

The Forward Physics Facility

- Proposed location at 620 m from IP1 (ATLAS)
- To host several experiments: here, focus on *FASERν2* (W) and *FLArE* (Ar)
- With this, we could expect a rich neutrino program during the hi-lumi LHC run
- Here we assess the potential of such a facility to constrain the neutrino flux and several (B)SM processes



What about neutrino flux uncertainties?

- Predictions for the incoming neutrino flux can be obtained using e.g. various generators, based on different models for neutrino production. However, kinematic region previously unexplored
  - MC generators need new tunes to describe this as well as possible
  - Different models will produce greatly different spectra shapes & magnitudes
  - Using a Fisher information approach, we can estimate the ultimate uncertainty for the flux based on parametrizing the correlations between a broad set of different predictions
- 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!**

Workflow

Predictions for hadron production at IP1

- Light mesons

  $\pi^{\pm},\ K^{\pm},\ K_L^0,\ K_S^0$

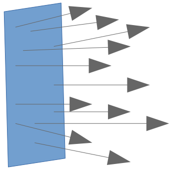
- Charm hadrons

  $D^{\pm},\ D^0,\ \overline{D}^0,$

  $D_s^{\pm},\ \Lambda_c^{\pm}$

Decays into neutrinos

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



$N(\pi,K,c)x(N_{predictions}\text{-}1)$ = 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 FPF WG2 for their efforts!

Workflow

Predictions for hadron production at IP1

- Light mesons

$\pi^{\pm},\ K^{\pm},\ K_L^0,\ K_S^0$

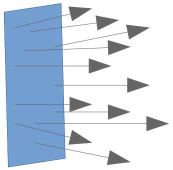
- Charm hadrons

$D^{\pm},\ D^0,\ \overline{D}^0,$

$D_s^{\pm},\ \Lambda_c^{\pm}$

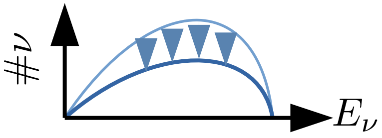
Decays into neutrinos

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



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

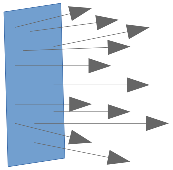
Software package available at github

Predictions for hadron production at IP1

- Light mesons
  $\pi^{\pm},\ K^{\pm},\ K^0_L,\ K^0_S$
- Charm hadrons
  $D^{\pm},\ D^0,\ \overline{D}^0,$
  $D^{\pm}_s,\ \Lambda^{\pm}_c$

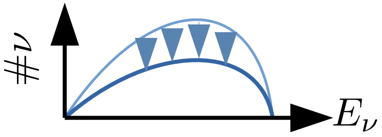
Decays into neutrinos

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



Propagate to forward experiments

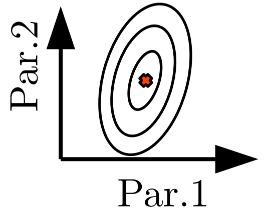
- Some models affect the spectra of *incoming neutrinos*



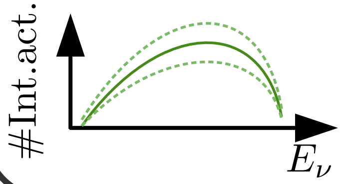
Interactions within detector

Combine predictions to estimate unc. via Fisher information

Maximal constraints



Observed ν spectra, with uncertainties



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

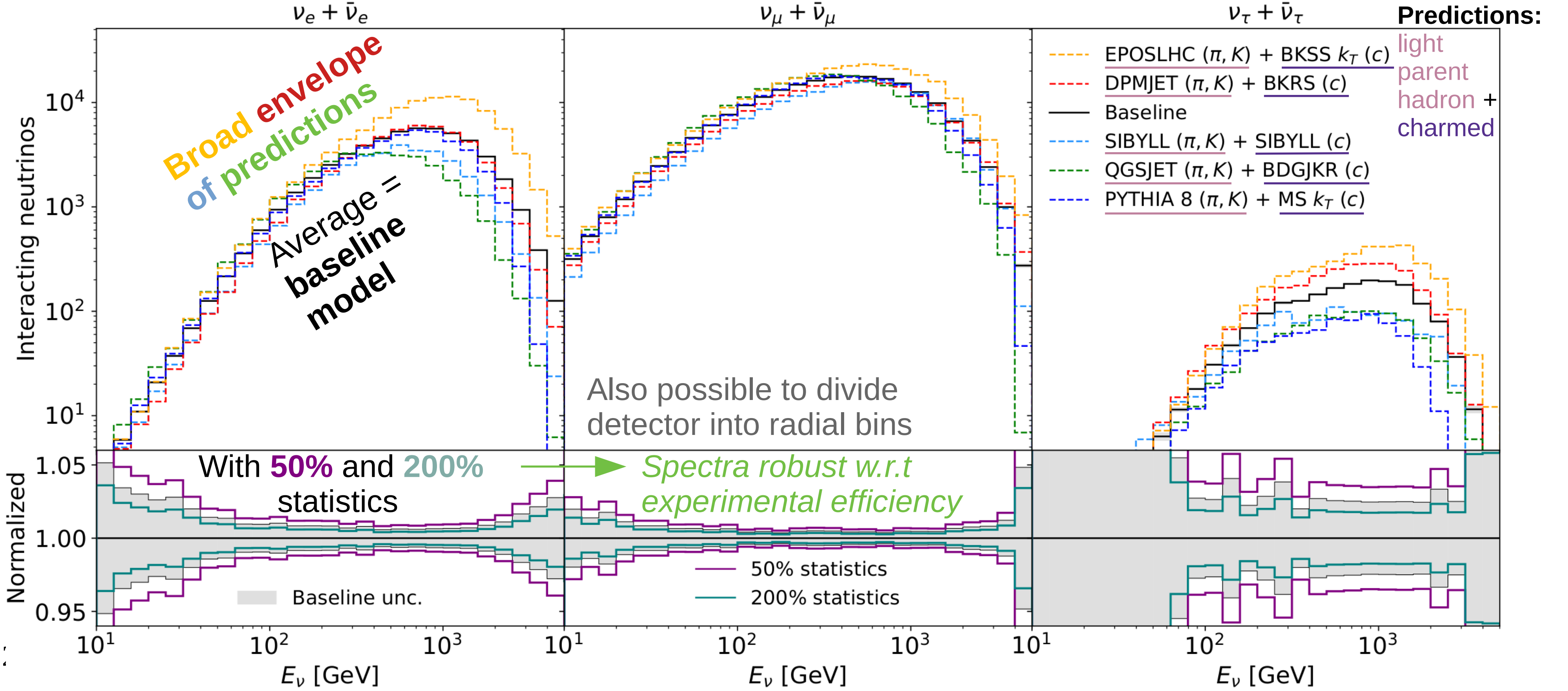
Parameters *p* changing produced ν distr.

Param. *p'* changing observed ν distr.

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

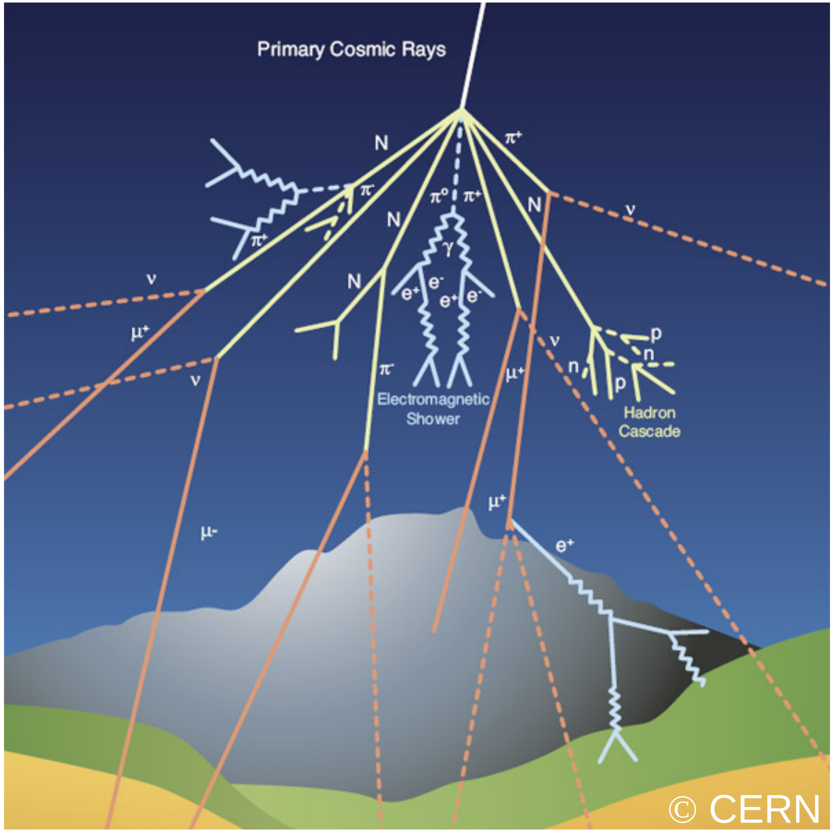
The neutrino spectra

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



NCBJ

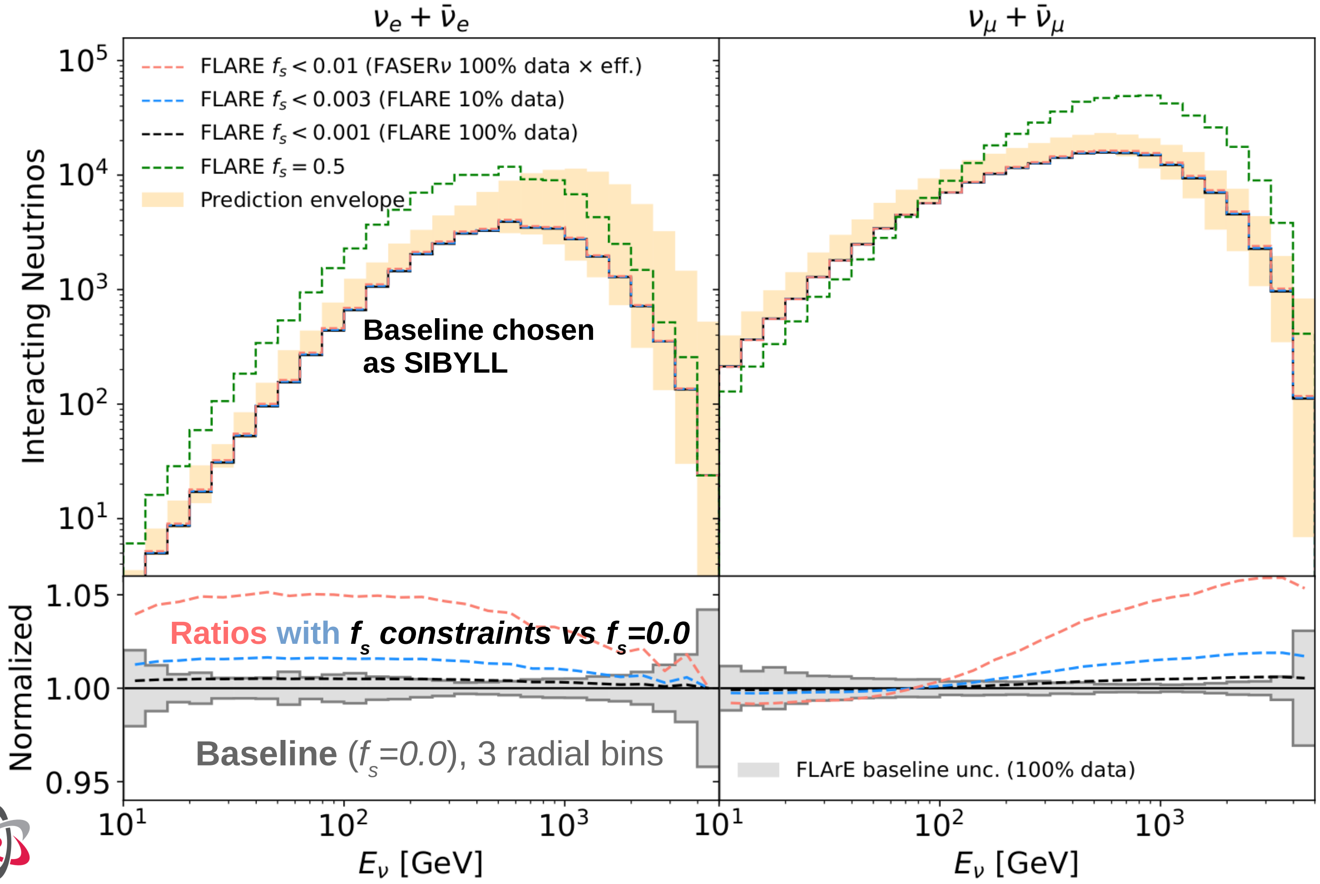
Enhanced strangeness
and the cosmic ray muon puzzle



- The hadronic cascades of air showers give rise to a muon component through hadron decays
- The number of muons is used for determining the cosmic ray mass composition
- **The muon puzzle**: a significant deficit (~8σ) of high-E muons in air shower simulations using contemporary QCD models vs measurements
- Possible solution: perhaps the distribution of secondary particles produced in high-energy hadronic interactions is not predicted correctly by current models?
  - Suggests an enhancement of strangeness production

See e.g. arXiv:2105.06148 [hep-ph] for a review

Enhanced strangeness



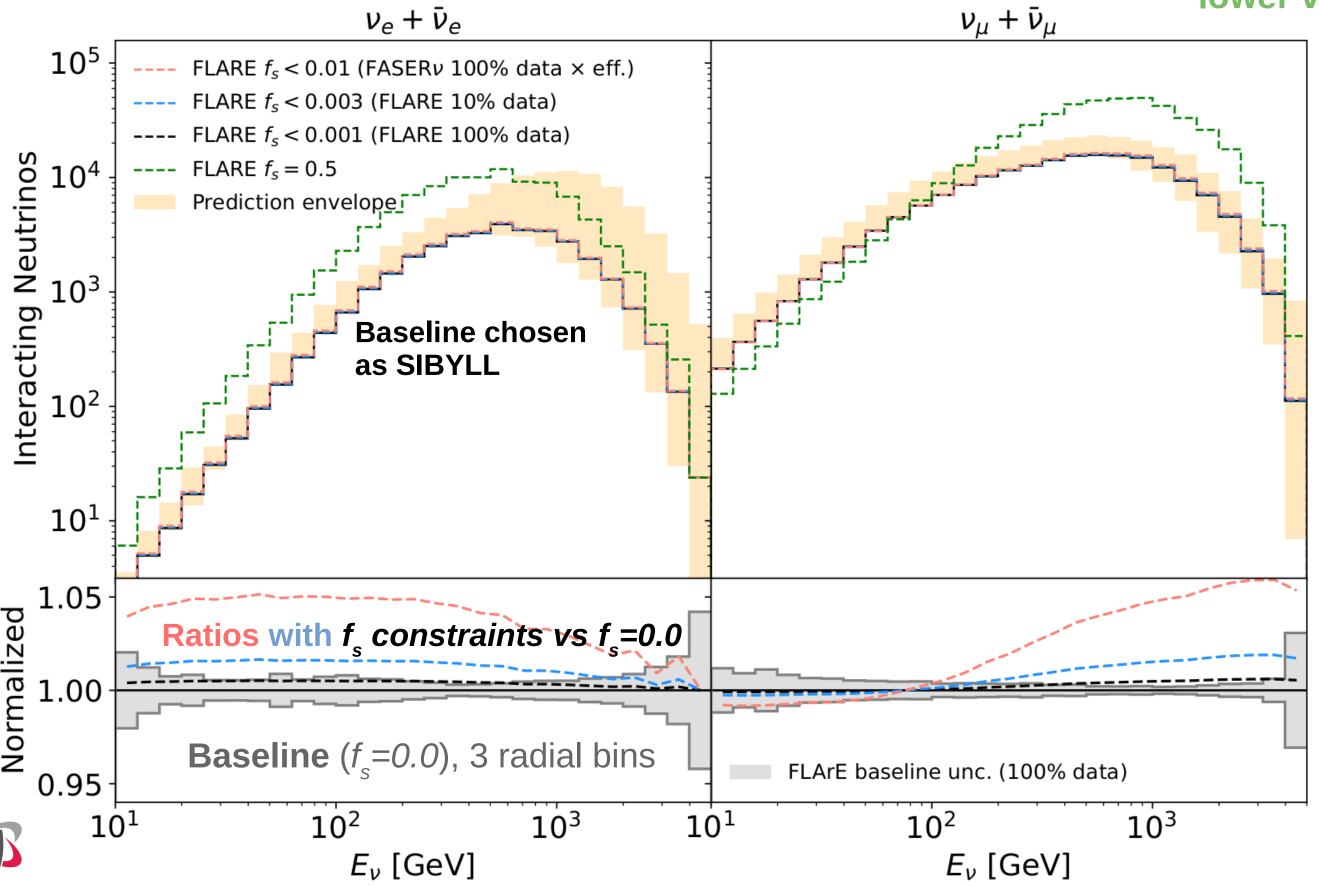
- What if there should be less pions, and kaons produced instead of them? (Enhanced strangeness hypothesis)
- Reweigh the counts of neutrinos associated with pions by $(1 - f_s)$, and those from kaons by $(1 + F f_s)$

  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

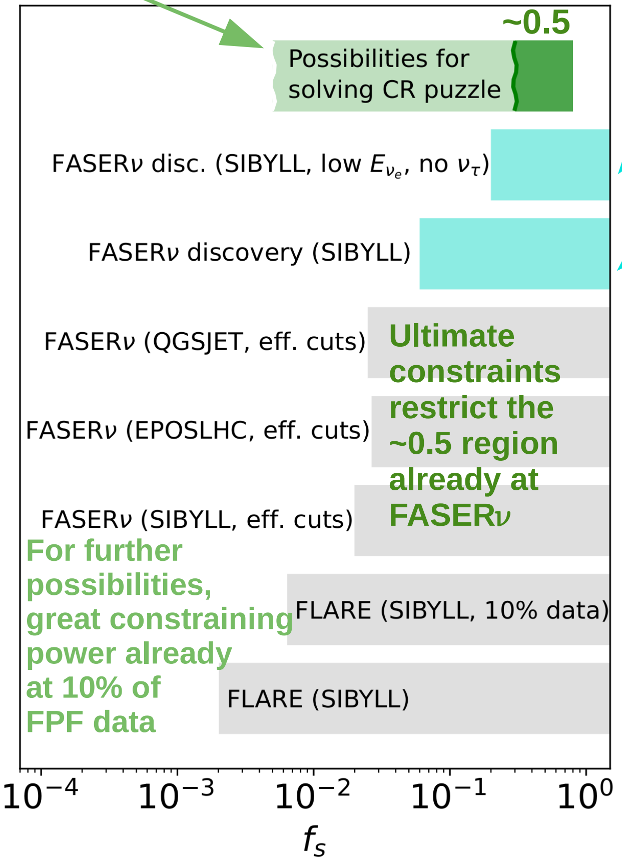
NCBJ

Enhanced strangeness



At LHC energies, f_s might also have lower values

Discovery potential: examine cases with non-zero baseline f_s



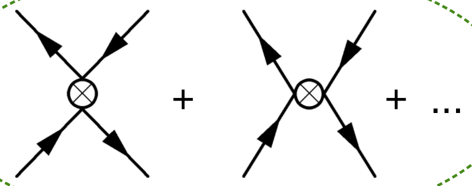
Ultimate constraints restrict the ~0.5 region already at FASERν

For further possibilities, great constraining power already at 10% of FPF data

NCBJ

(See doi:10.1007/JHEP10(2021)086)

Non-standard interactions (NSI)



- General standard model effective field theory (SMEFT)

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{2\pi}{\Lambda^2}\sum_n c_n O_n$$

  - Extend SM by non-renormalizable operators
  - High-energy effects integrated out
    - Operators may correspond to ~any BSM effect / exchange

- Weak effective field theory (WEFT): *E* below EW scale; *t*, *h*, *Z*, *W* integrated out

- SM CC ν scatterings off nuclei driven by W exchange

  - BSM modifications to interaction rates: new physics scales typically above characteristic momentum transfer in neutrino interactions at the LHC: $Q \sim \mathcal{O}(10\mathrm{GeV})$

Λ ≫ Q conveniently described by EFT

(See doi:10.1007/JHEP10(2021)086)

Non-standard interactions (NSI)

- The presence of neutrino NSI would affect both production and interaction rates of neutrinos
- Extend the SM Lagrangian by dimension-6 EFT terms

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

Consider changes to tau neutrino spectrum:

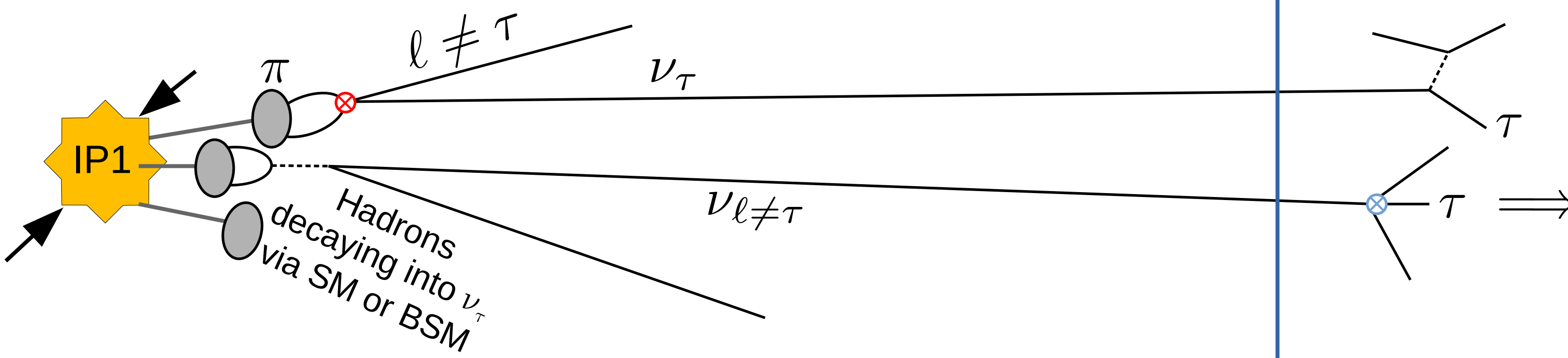
- Effects on **production** side

- Effects on **detection** side

FASERν2

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

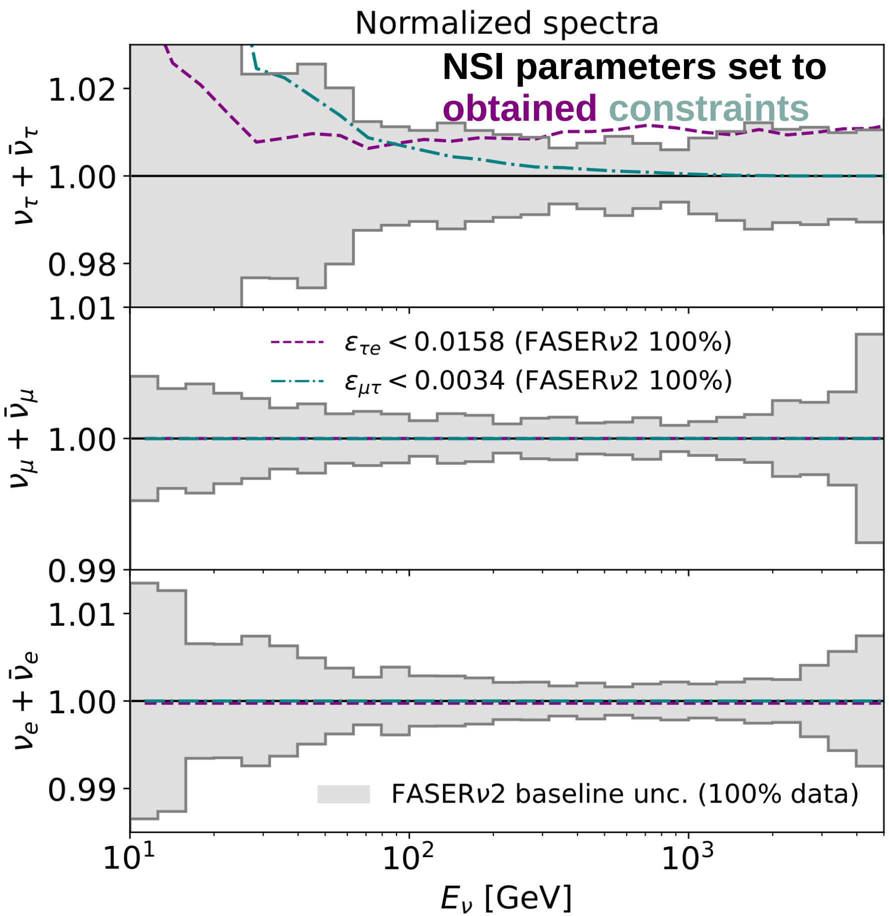
Effect approximated energy independent

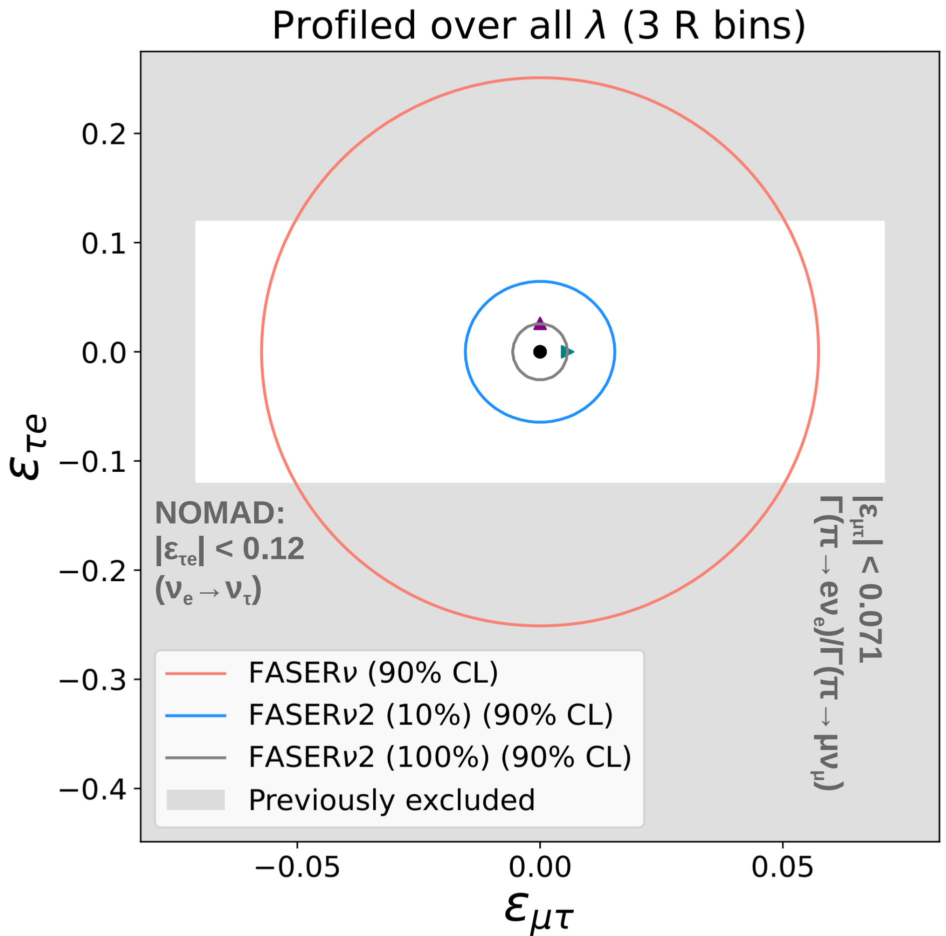


The presence of additional operators increases incoming tau neutrino spectrum

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

Collinear and k_T factorization

Predictions for hadron production at IP1

- Light mesons

$\pi^\pm,\ K^\pm,\ K_L^0,\ K_S^0$

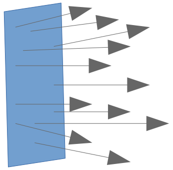
- Charm hadrons

$D^\pm,\ D^0,\ \overline{D}^0,$

$D_s^\pm,\ \Lambda_c^\pm$

Decays into neutrinos

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



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

- Light meson production for $m \lesssim 1\mathrm{GeV}$ described non-perturbatively
  - various models mostly developed for cosmic ray and forward LHC physics
- In contrast, charm calculated perturbatively
  - **Collinear factorization**

Partonic momentum fraction

$$\sigma = \sum_{i,j}^{\mathrm{partons}} \int dx_1 dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}$$

  - **k_T factorization**

Off-shell gluon transverse momenta

$$\sigma = \sum_{i,j}^{\mathrm{partons}} \int \frac{d^2\mathbf{k}_{T1}}{\pi} \frac{d^2\mathbf{k}_{T2}}{\pi} \mathcal{F}_i(\mathbf{k}_{T1}) \mathcal{F}_j(\mathbf{k}_{T2}) \hat{\sigma}$$

  - Unintegrated gluon distribution functions contain more information about parton dynamics

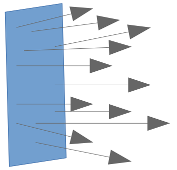
Collinear and k_T factorization

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

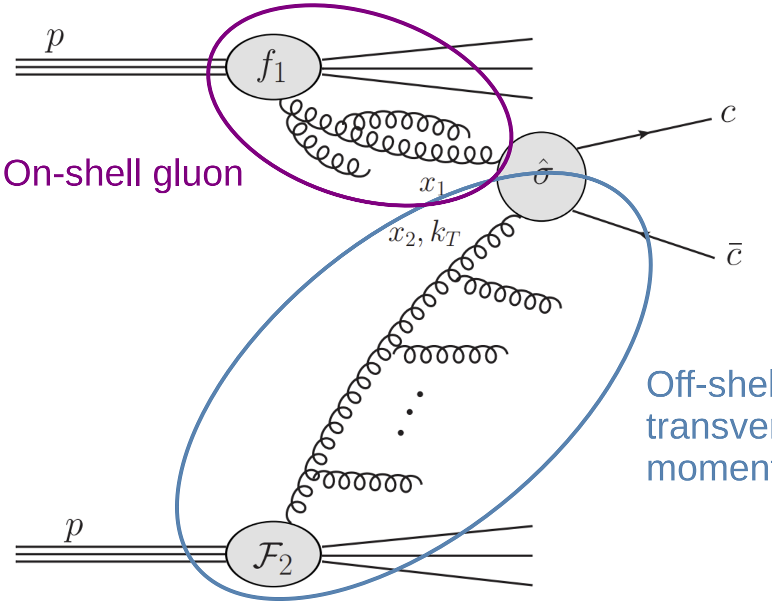
MC samples of neutrinos (flavor, position, energy, momentum)



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

- Light meson production for $m \lesssim 1\mathrm{GeV}$ described non-perturbatively
  - various models mostly developed for cosmic ray and forward LHC physics
- In contrast, charm calculated perturbatively

On-shell gluon



Off-shell gluon, transverse momentum k_T

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 via 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!*

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

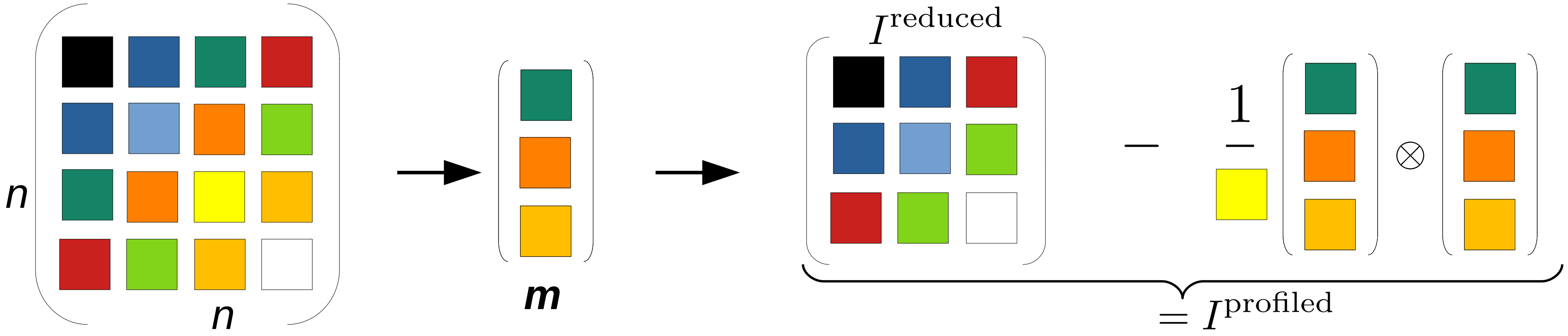
Poisson distributions; examine differences between any set of λs and the baseline

Profiling

A parallel projection of a generalized ellipsoid in parameter space

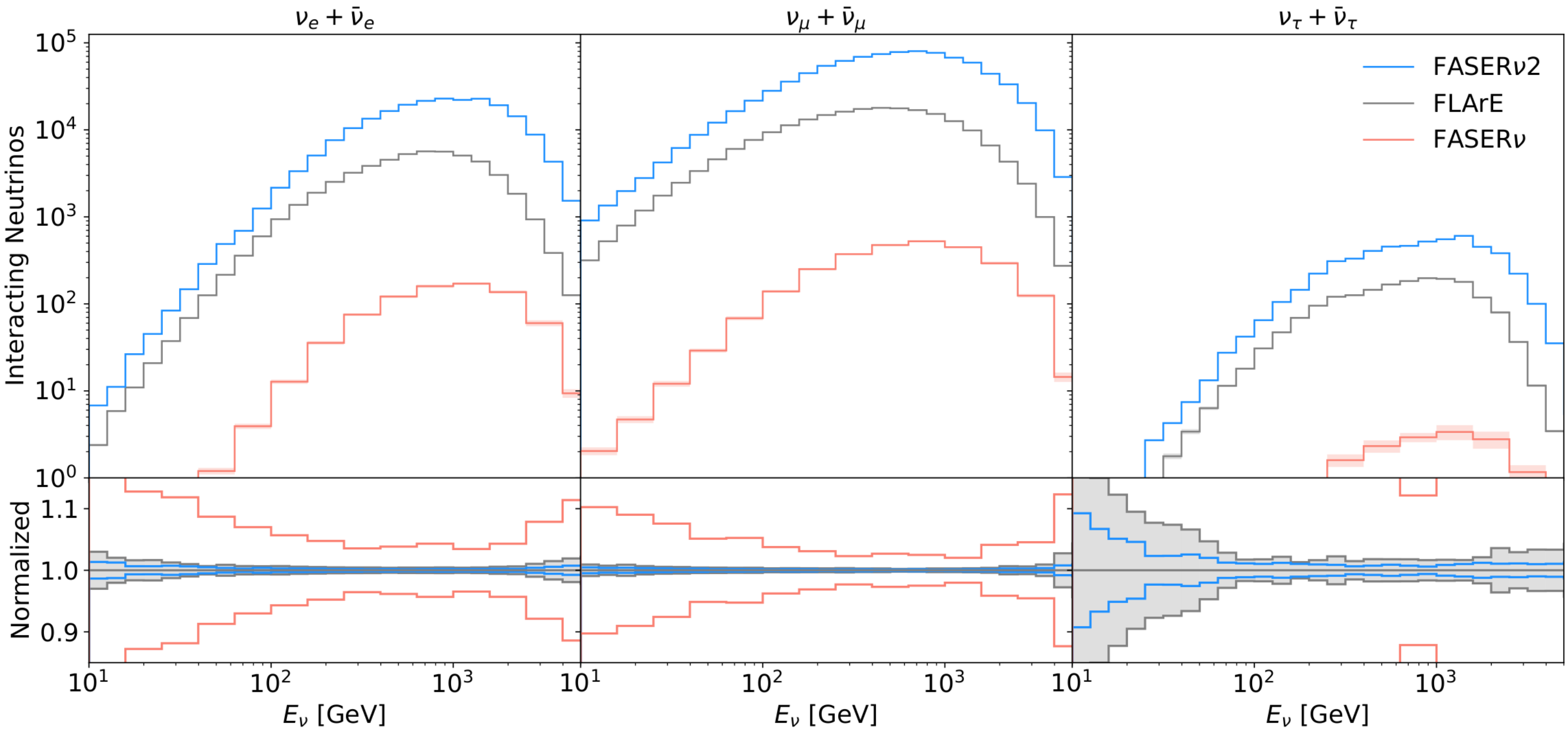
- Estimate ultimate constraints for a parameter in the model computation by profiling over the *n*-th parameter in the information matrix *I*: the *n*-th column (or row) of *I*, with the *n*-th entry removed, is taken as the vector **m** describing the mixing between the profiled parameter and the remainder

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



- Profiling multiple parameters: iterate procedure starting with previous I^{profiled}
- Profiling over all but one parameter reduces I^{profiled} into a single entry *a:* ultimate constraint for the corresponding parameter is $a^{-1/2}$

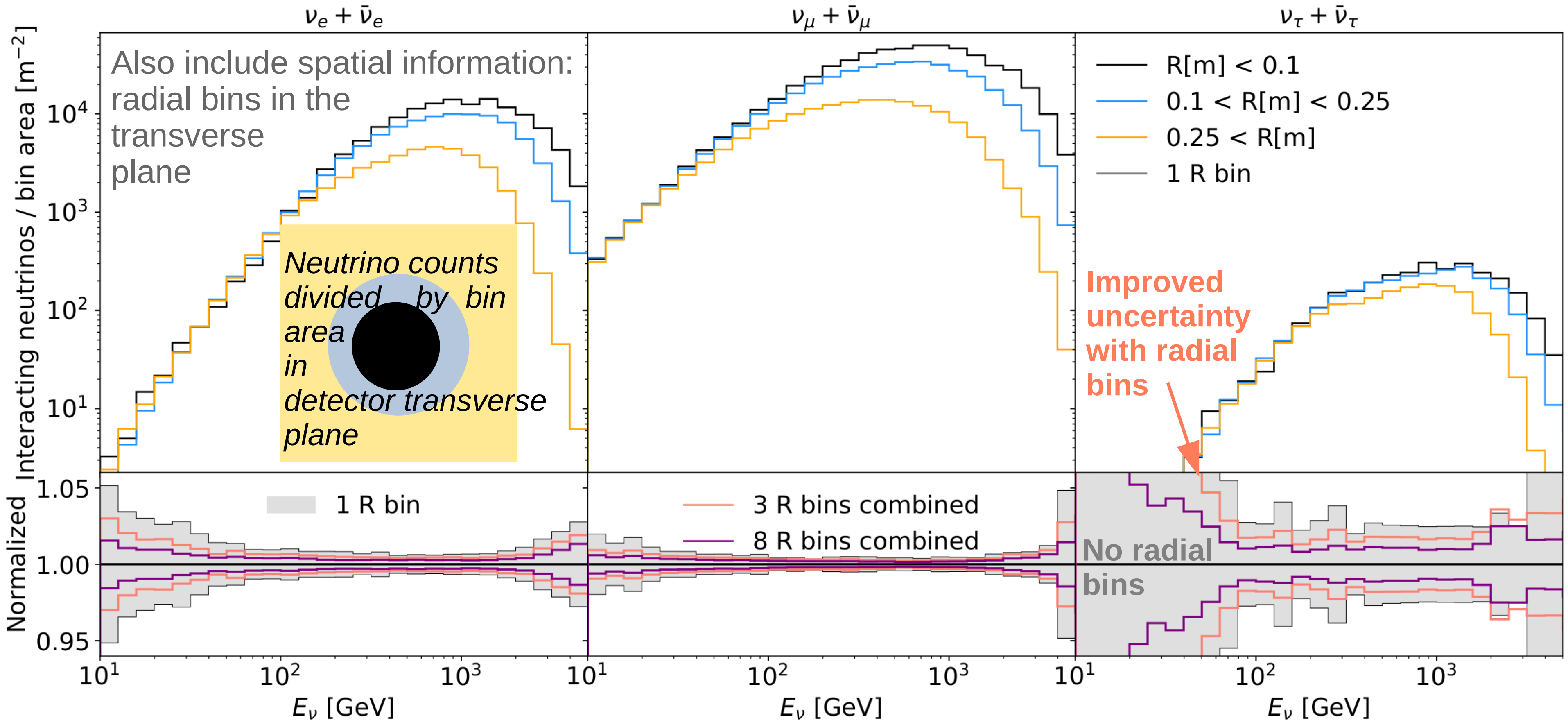
Experiment comparison



NCBJ

The neutrino spectra

1 vs 3 radial bins



Enhanced strangeness
and the cosmic ray muon puzzle

- Dominant explanation likely due to reduced transfer of energy from hadronic to electromagnetic components of the shower, suppressing neutral pion production / decay in air showers. Possible mechanisms e.g.
  - Core-corona effect
    - Consider a mixture of underlying particle production mechanisms
      - collective statistical hadronization (core)
      - string fragmentation (corona)
    - The mechanisms have different electromagnetic energy fractions
      - possible connection between statistical hadronization in hadron collisions and muon production in air showers.
  - Strange fireballs (consisting of *d, u, g*)
    - CR collisions produce deconfined thermal fireballs undergoing sudden hadronization.
    - $u\bar{u}$ and $d\bar{d}$ production suppressed by high baryochemical potential, gluons mostly split to $s\bar{s}$

Non-standard interactions (NSI)

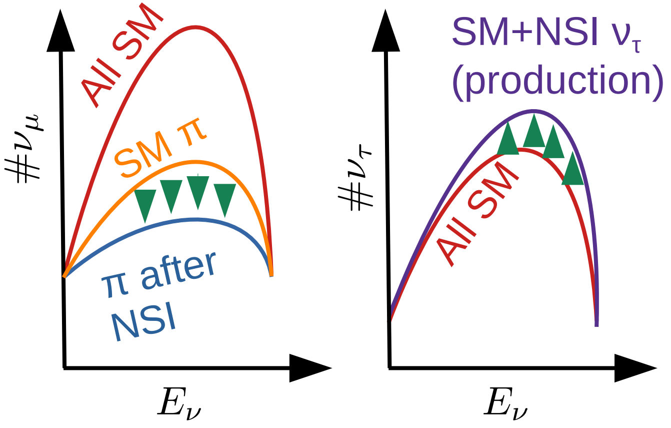
- Extend the SM Lagrangian by dimension-6 EFT terms (See doi:10.1007/JHEP10(2021)086)

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

Consider changes to tau neutrino spectrum:

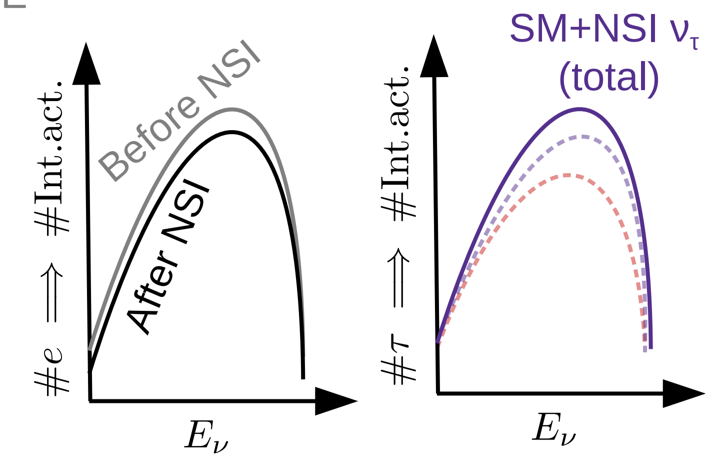
Relevant production/detection coefficients approx. constant in E

- Effects on **production** side



Production side: shape of pion contribution to muon neutrino spectrum affects addition to tau neutrinos

- Effects on **detection** side



Detection side: #electrons decrease uniformly, observed #tau spectrum increases by corresponding shape