Investigating the reach of LHC neutrino experiments

Using a Fisher information approach with multidifferential neutrino spectra

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NCBJ

HECA seminar
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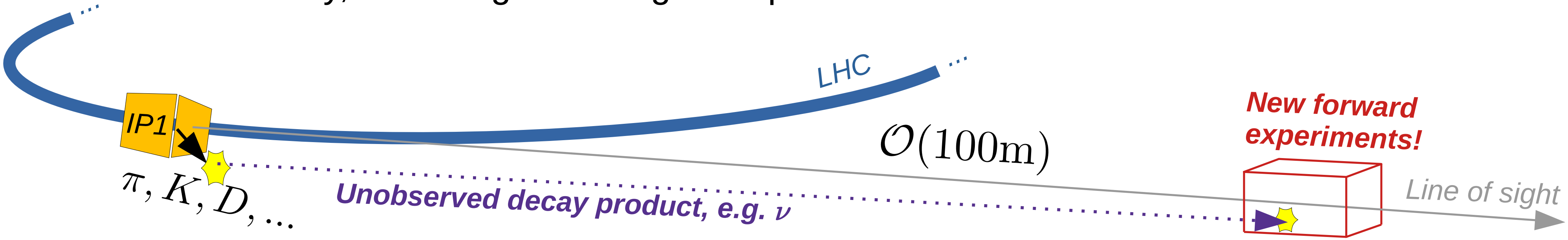
Introduction

Neutrinos at the LHC

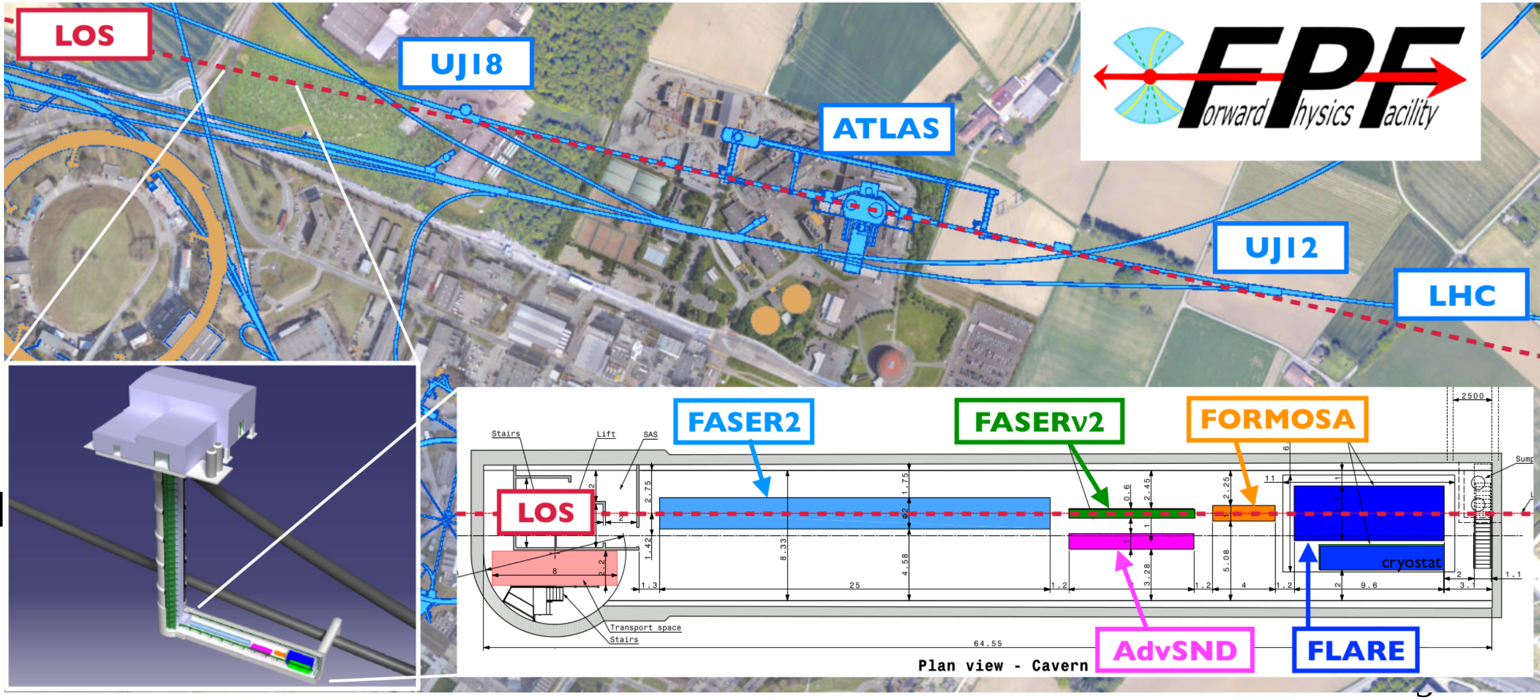
- The hadron collisions at the LHC produce a myriad of hadrons, which can produce neutrinos via weak decays
  - The neutrinos are never observed by central experiments e.g. ATLAS, CMS
  - Similarly, there might be long-lived particles that are not observed at the IP



- 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
  - Model assumptions affect shape & magnitude of resulting neutrino spectra
- However, we’re looking at a previously unexplored kinematic region
  - Various MC generators need new tunes to describe this as well as possible
  - Different models will produce greatly different spectra
  - 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

What about neutrino flux uncertainties?

- We have developed a public tool for estimating the uncertainties, available at

  https://github.com/makelat/forward-nu-flux-fit

- 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 BSM effects can affect the ν spectra. Here we demonstrate:
  - Non-standard neutrino interactions via effective field theory
  - Enhanced strangeness
    - Consider possibilities for solving the cosmic ray muon puzzle using proposed and existing LHC experiments

Workflow

Predictions for hadron production at IP1

- Light mesons

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

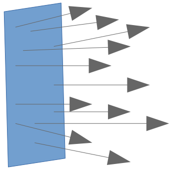
- Charm hadrons

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

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

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 FPF WG2 for their efforts!

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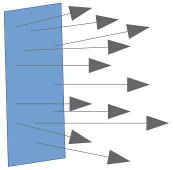

N(π,K,c)x(N$_{predictions}$-1) = 12 parameters λ

- 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

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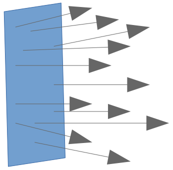

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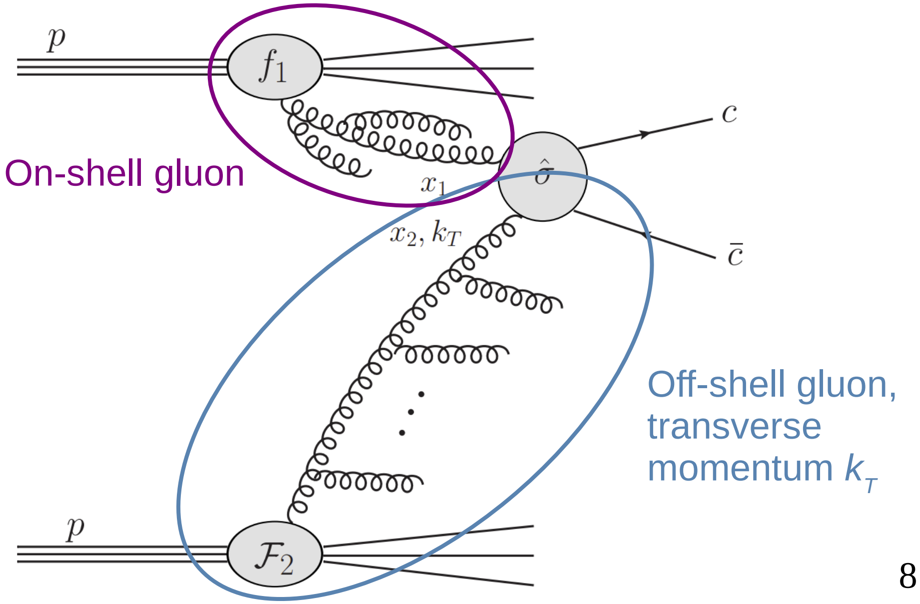

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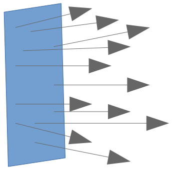
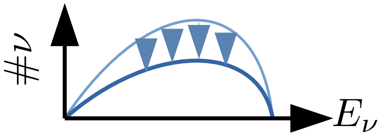


Propagate to forward experiments

- Some models affect the spectra of *incoming neutrinos*



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Parameters *p* changing produced ν distr.

Workflow

Software package available at github

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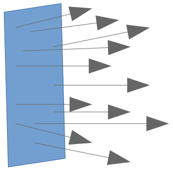

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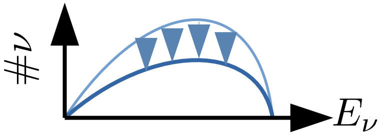
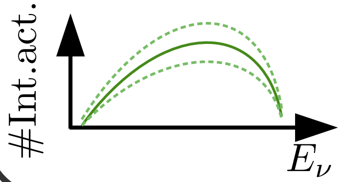


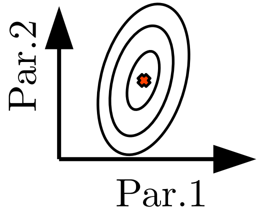
Interactions within detector

Combine predictions to estimate unc. via Fisher information → ***Maximal constraints***

↓

Observed ν spectra, with uncertainties





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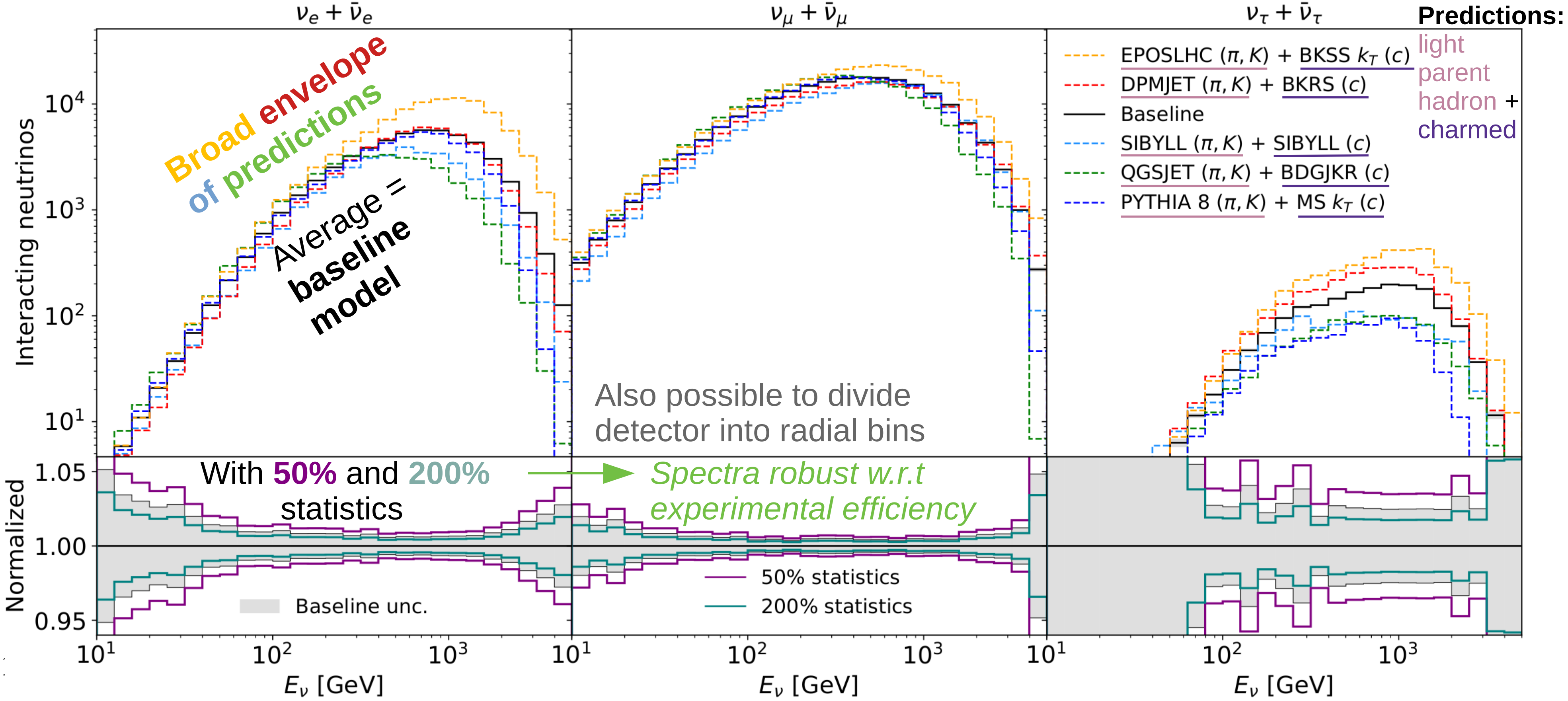
Parameters *p* changing produced ν distr.

Param. *p'* changing observed ν distr.

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

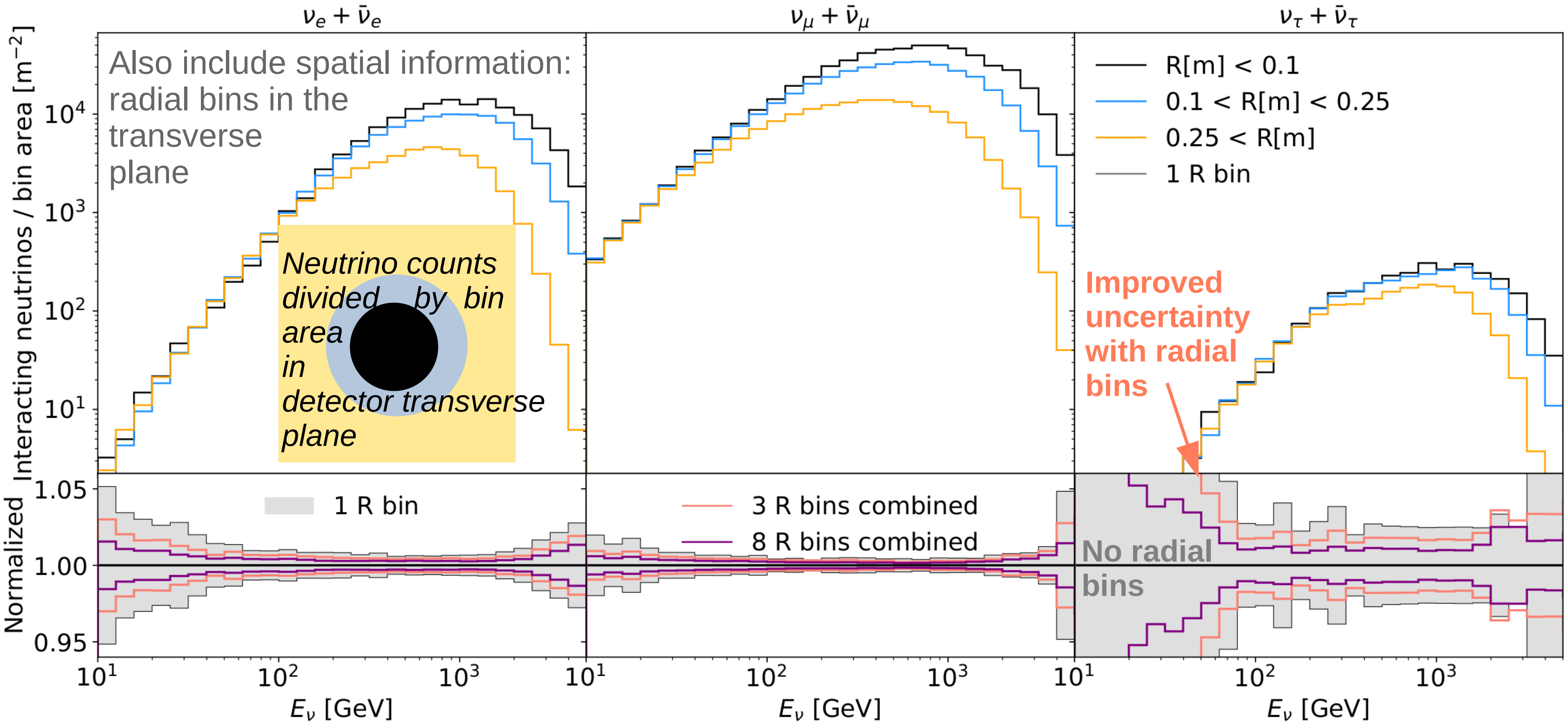
The neutrino spectra

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



The neutrino spectra

1 vs 3 radial bins



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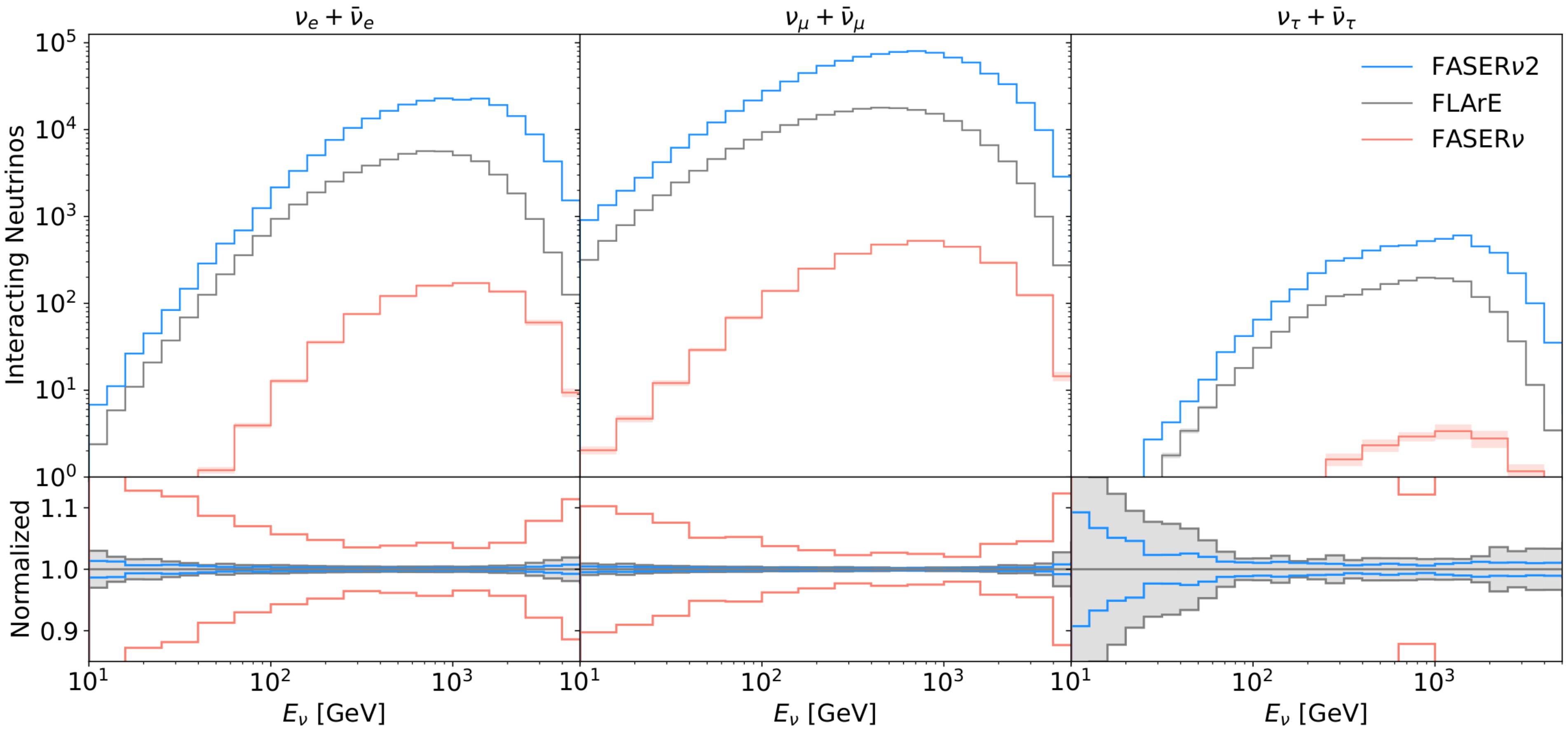
Experiment comparison



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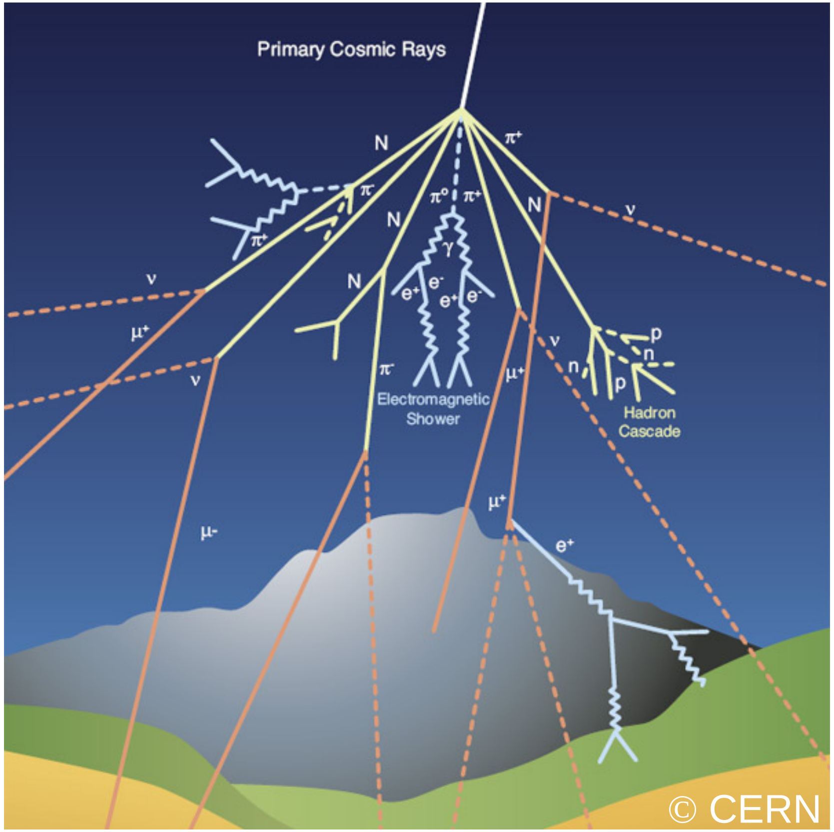
Physics applications – enhanced strangeness and the cosmic ray muon puzzle



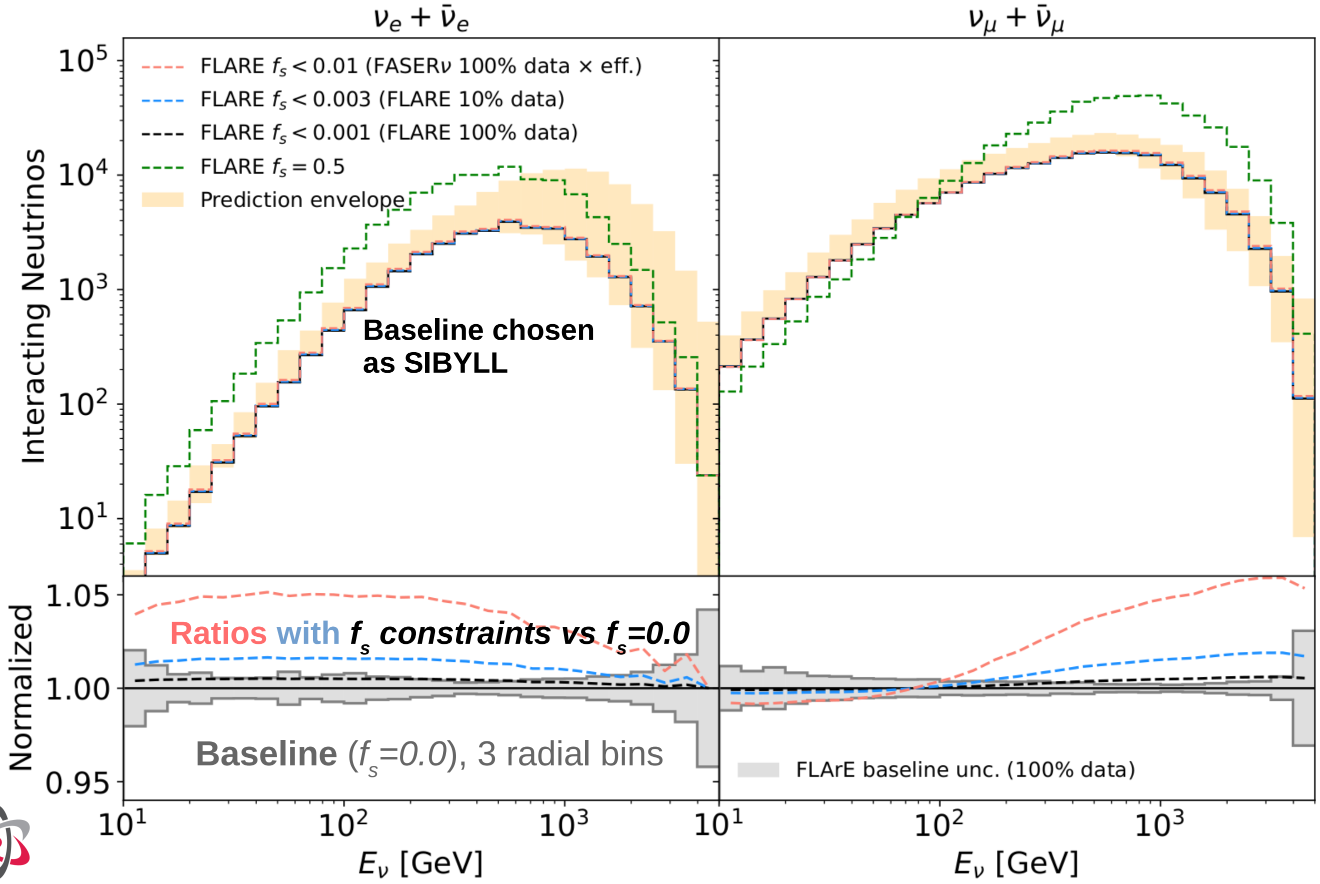
- The hadronic cascades of air showers give rise to a muon component through hadron decays
- The number of muons is used for determining the cosmic ray mass composition
- **The muon puzzle**: a significant deficit (~8σ) of high-E muons in air shower simulations using contemporary QCD models vs measurements
- 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

Physics applications – 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 $s\bar{s}$

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 $(1 + F f_s)$

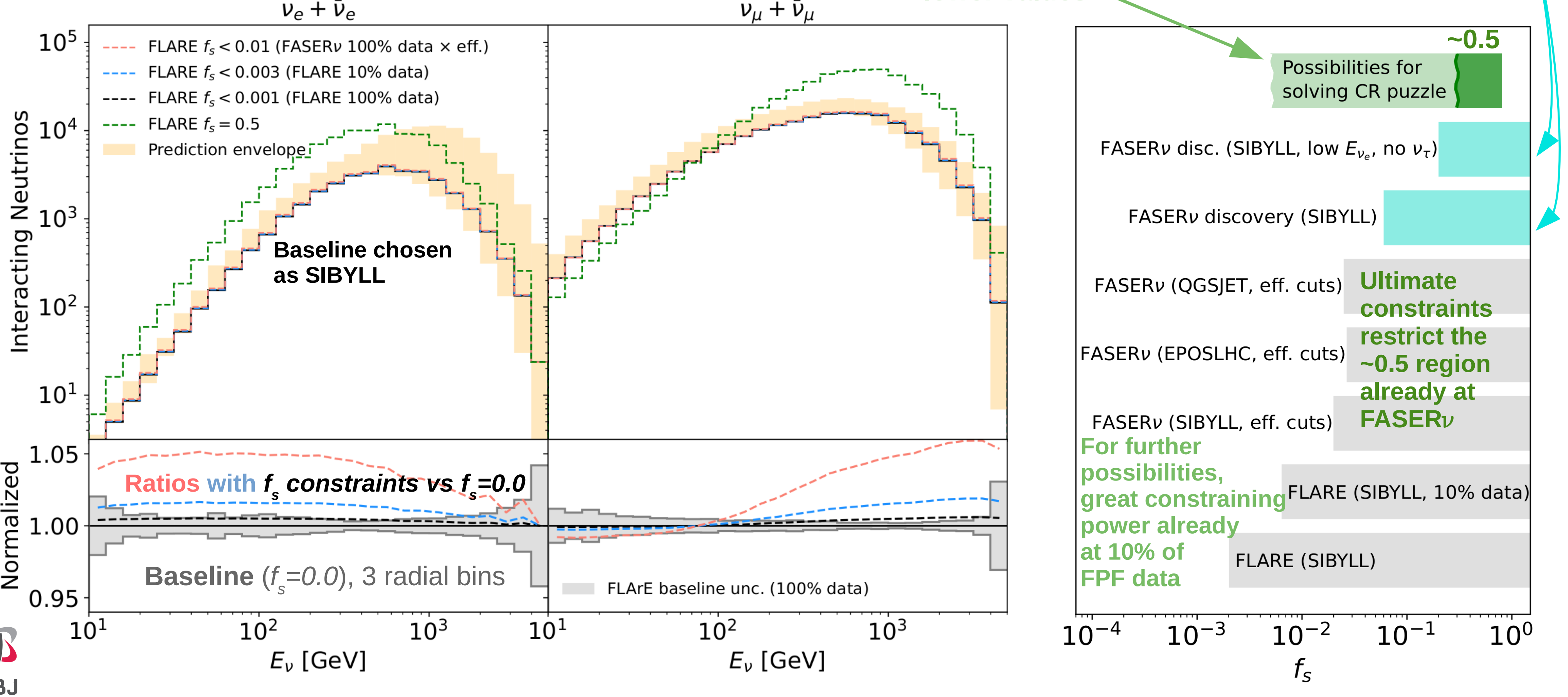
  Phenomenological factor, account for difference in π / K production rates (F)

- *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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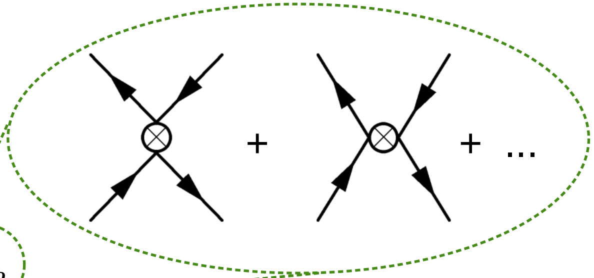
Physics applications – neutrino non-standard interactions (NSI)

- SM CC ν scatterings off nuclei driven by W exchange
- BSM modifications to interaction rates typically associated with new physics at scales above characteristic momentum transfer in neutrino interactions at the LHC: $Q \sim \mathcal{O}(10\mathrm{GeV})$
- Such BSM interactions conveniently described by effective field theory (EFT)
  - Require new physics scale $\Lambda \gg Q$ for the validity of the EFT
- The presence of neutrino NSI would affect both production and interaction rates of neutrinos

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

Physics applications – neutrino 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
  - Corresponding to integrated-out high-energy effects
    - Model independent, operators may correspond to ~any BSM effect / exchange

- Weak effective field theory (WEFT)
  - Idea of SMEFT, but at energies below electroweak scale
  - Top, Higgs and weak bosons integrated out

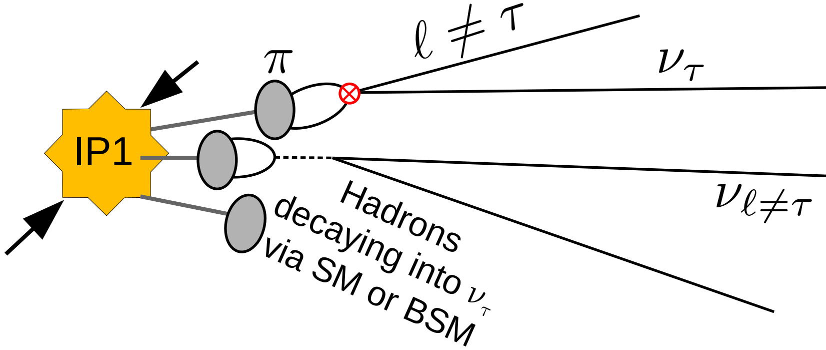
Non-standard interactions (NSI)

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

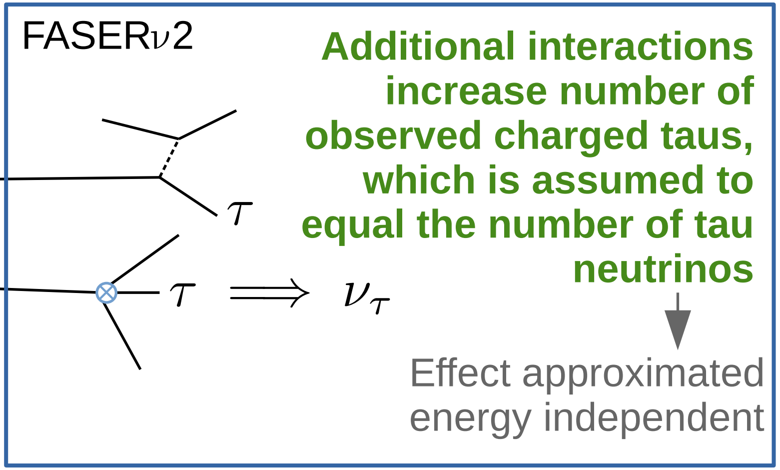
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{2V_{ud}}{v^2} \times (\bar{u}\gamma^{\kappa} P_R d) \times \left[\epsilon_R^{\mu\tau} (\bar{\ell}_{\mu}\gamma_{\kappa} P_L \nu_{\tau}) + \epsilon_R^{\tau e} (\bar{\ell}_{\tau}\gamma_{\kappa} P_L \nu_e)\right]$$

Consider changes to tau neutrino spectrum:

- Effects on **production** side



- Effects on **detection** side



The presence of additional operators increases incoming tau neutrino spectrum

Non-standard interactions (NSI)

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Consider changes to tau neutrino spectrum:

Relevant production/detection coefficients approx. constant in E

$$\Delta N_\tau = C_1[\epsilon_R^{\mu\tau}]^2 + C_2[\epsilon_R^{\tau e}]^2 > 0$$

$$\implies \Delta N_\mu < 0 \qquad \implies \Delta N_e < 0$$

N.B. we consider **vertices connecting *u, d* quark legs:** change on production side depends on the shape of π contributions to the energy spectrum

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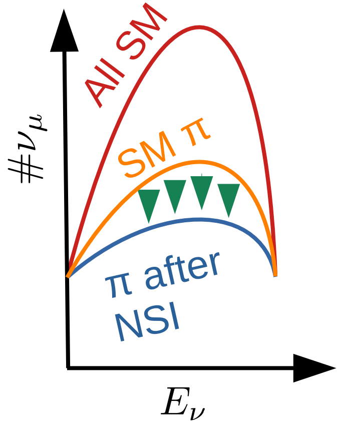

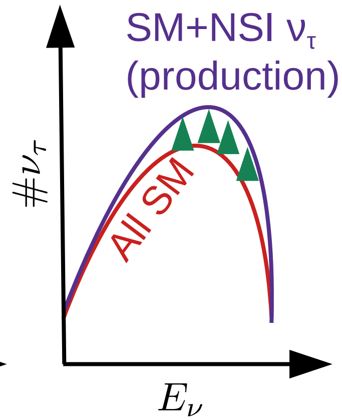

Production side: shape of pion contribution to muon neutrino spectrum affects addition to tau neutrinos

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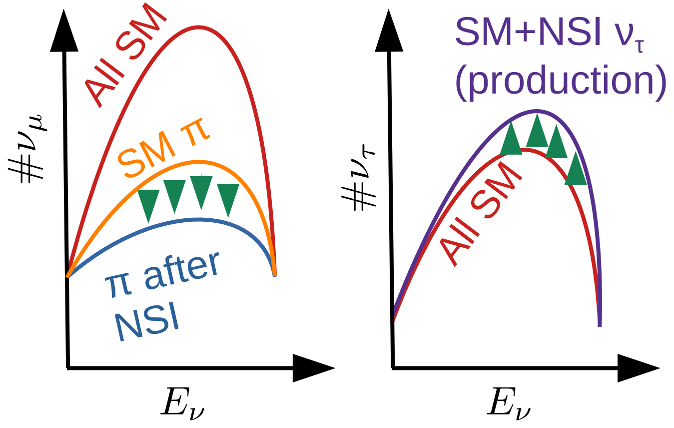

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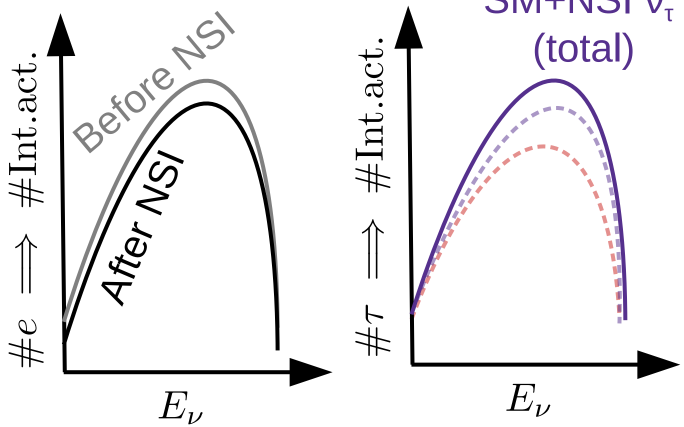
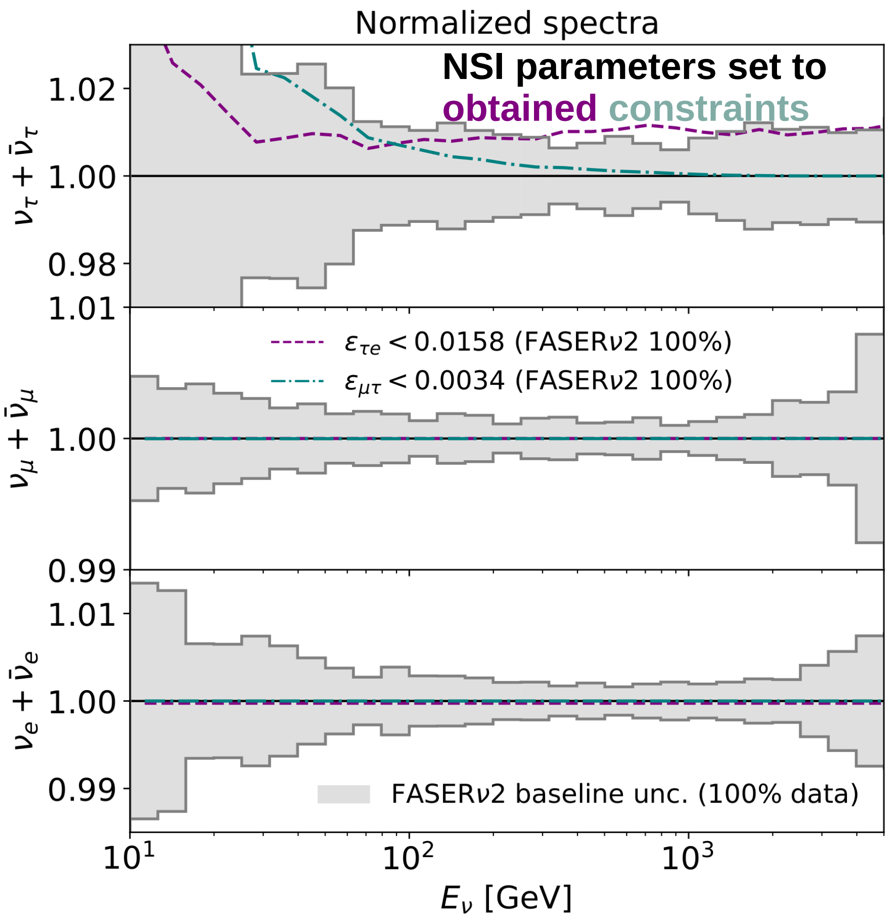
- Effects on **detection** side

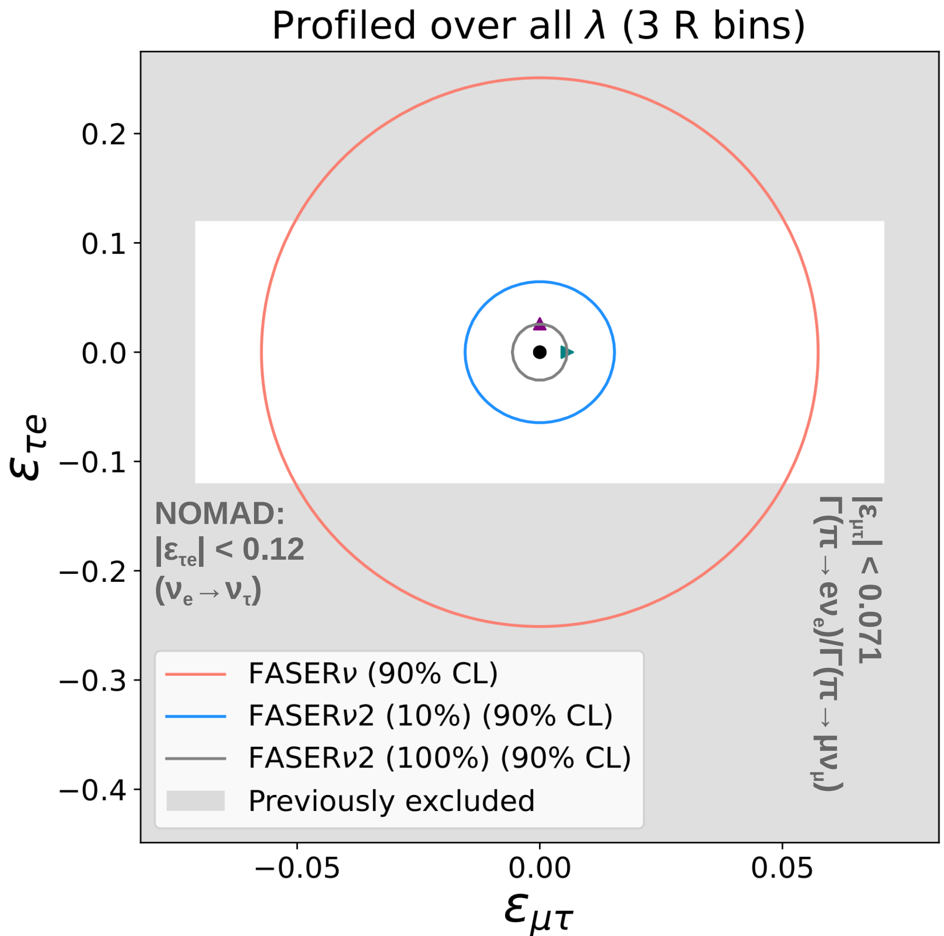


Detection side: #electrons decrease uniformly, observed #tau spectrum increases by corresponding shape

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 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!*

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

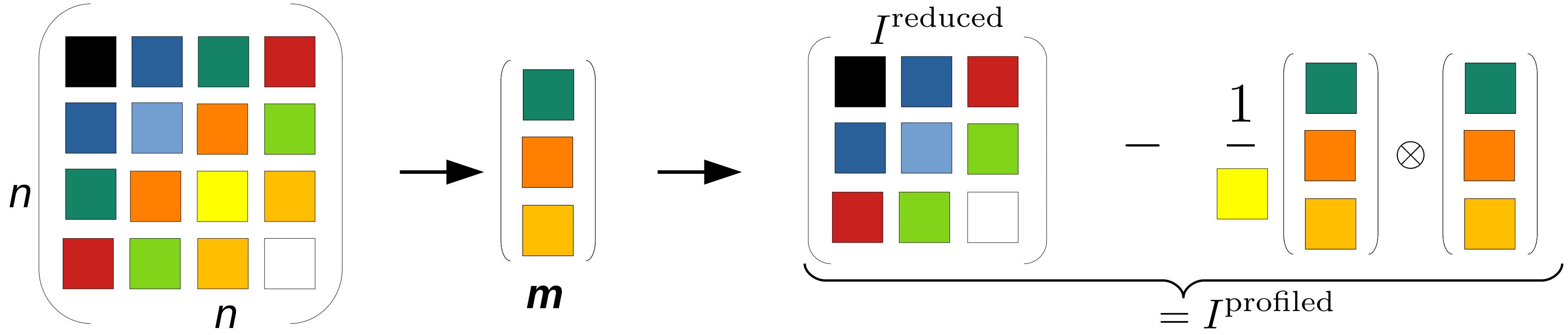
Poisson distributions; examine differences between any set of *λ*s and the baseline

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 $a^{-1/2}$