Neutrino Rate Predictions For FASER (and the FPF)

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FPF7

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Neutrinos are one physicist's treasure, and another's garbage that must be taken out…

Neutrinos as a signal

- $\sigma_{\nu N}$ measurements
- forward hadron production
- DIS measurements to constrain PDF's
- BSM properties of neutrinos

Neutrinos as a background

- Dark photons
- ALPS
- Mili-charged particles

Bottom Line:

Neutrinos are involved in all forward physics analyses, so we study their **production, interaction,** and their **uncertainties** in detail for **Run 3 , Run 4/HL** measurements

One Slide Summary

1) Update the fast neutrino flux simulation for Run 3 and Run 4 configurations

$\sqrt{s}$, magnets+LHC , $\theta_{1/2}$

2) Produce different predictions for neutrino production from light and heavy hadron decays and their uncertainties

$$\text{Flux}_{\nu\alpha} \pm\delta_{\alpha}$$
$$(\pi^{\pm}, K, ..) + (D, \Lambda_{c}, ..)$$

3) Compare different predictions for the CC DIS cross section and their uncertainties

$$\sigma_{\nu_{\alpha}N}(CC) \pm \delta$$

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Neutrino CC rate predictions for upcoming FASER analyses.

Improves the simulation for future FPF measurements.

Also serves as a review of a lot of great work that’s recently been done.

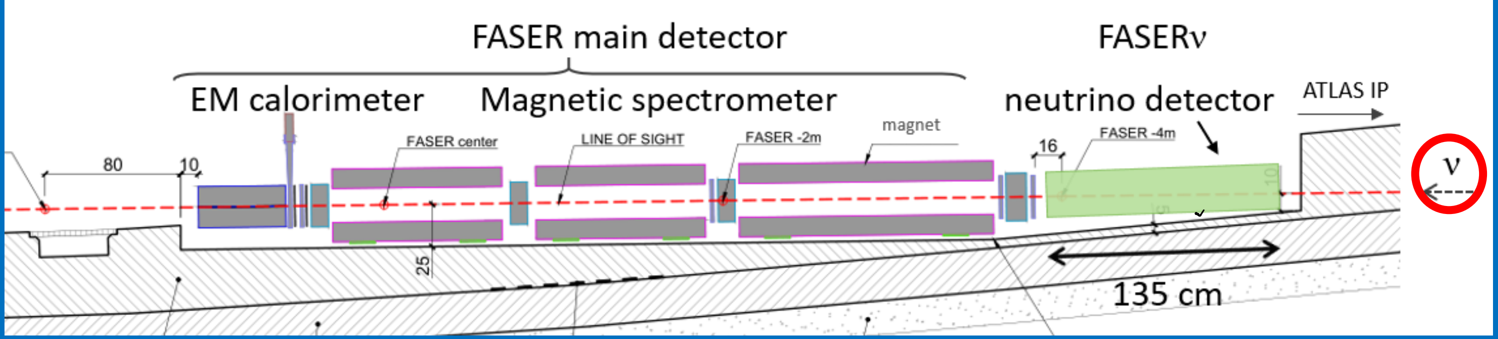
Quick Review

FASER is a decay volume experiment equipped with muon vetos, trackers and a calorimeter and is designed to search for the decays of BSM LLP’s

- Discovered the first collider neutrinos

FASERν is a high-density tungsten target, interleaved with emulsion for high spatial resolution tracking

Larger upgrades FASER2, FASERν2 proposed for the FPF



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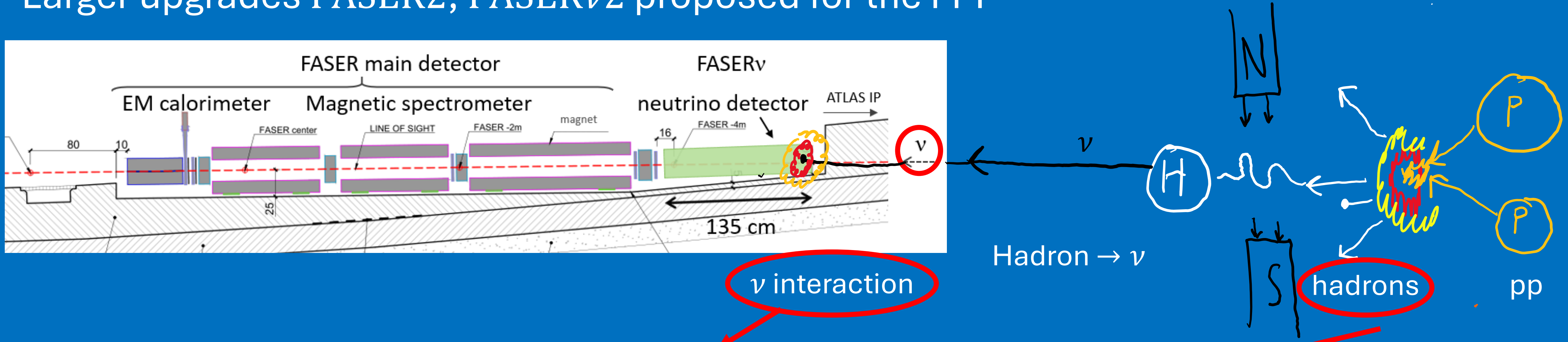
Propogate LLP through $\vec{B}$



Hadron → ν

ν interaction

hadrons

pp

Hadron production and ν interaction are both unknown

Neutrino Production Modelling

Neutrinos are dominantly produced from hadron decay with 2 components:

1. Light hadrons: $\pi^{\pm}, K, \ldots$
    - Modelled phenomenologically
    - Can be long-lived
    - ν_e, ν_μ

2. Heavy hadrons: $D, D_s, \Lambda_c, \ldots$
    - Can be treated with pQCD, with some caveats
    - Prompt decays
    - Only source of ν_τ

}

Light and heavy hadrons are treated differently and have different implications

I'll talk about each one in turn

Neutrino Production Modelling : Light Hadrons

Light hadron ($\pi^{\pm}, K, \Lambda, \Sigma , \Xi$), production is described with different models / generators

- **EPOS-LHC** , SIBYLL , QGSJET , PYTHIA(forward)

LHCf photon and neutron spectra as a proxy for hadrons of interest

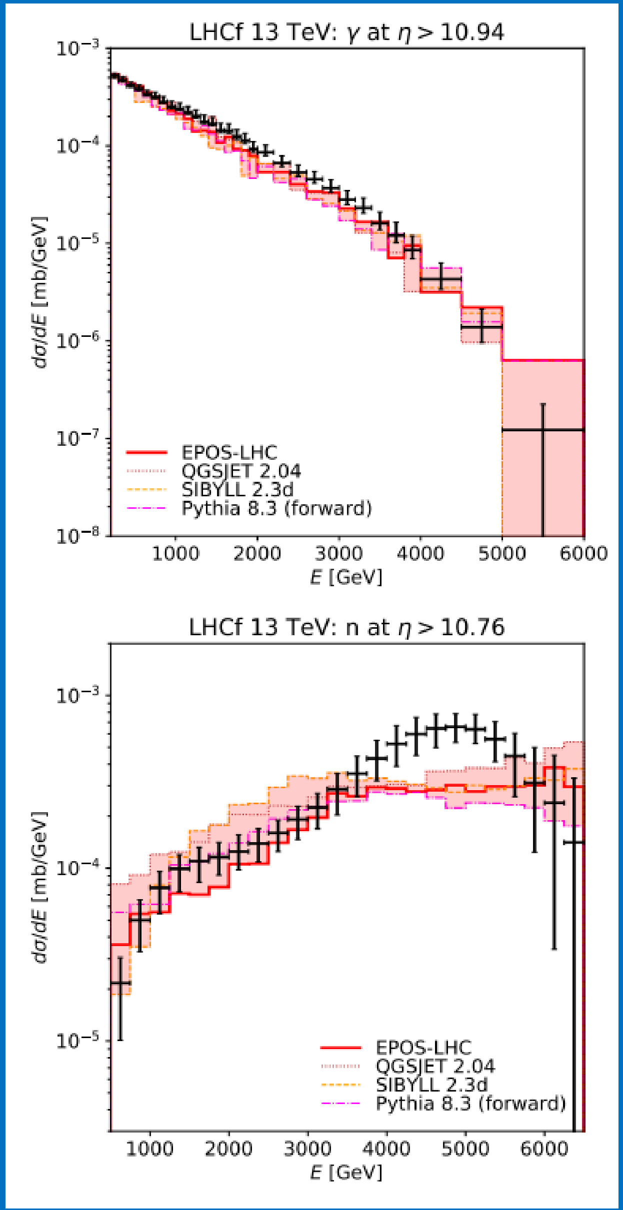
Generators have qualitative agreement with each other, but no generator fits all data very well

Uncertainty in the flux chosen to be their spread:

Advantage: Capture different physical effects present in the varied models

Disadvantage: Uncertainty driven by outlying generators

- Results in about 10% uncertainty on neutrinos from light hadrons
- Similar uncertainty to that obtained with the data-driven prescription obtained with PYTHIA(forward)



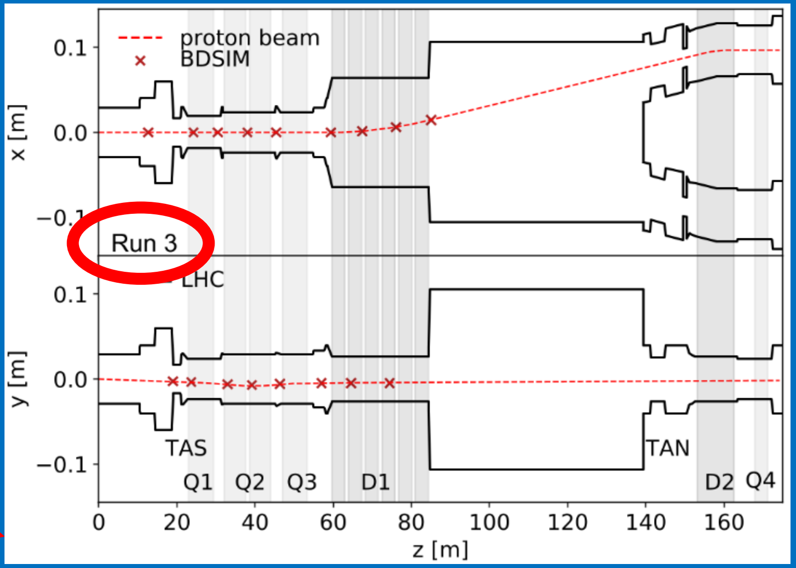
Neutrino Production Modelling : Light Hadrons

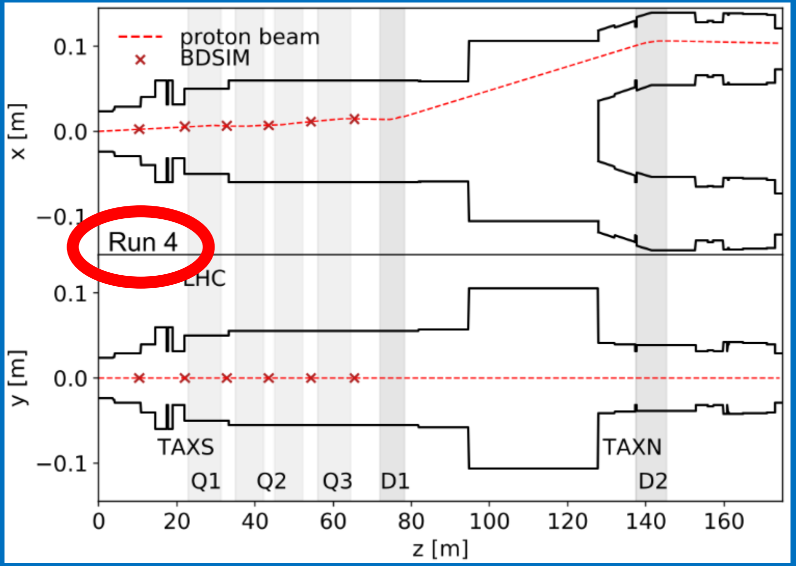
Light hadrons can be generally long-lived

To model their production (and decay) we must propagate these long-lived particles down the **beam pipe** and validate against BDSIM propagation

The fast neutrino flux was first developed for the Run 2 LHC configuration. We update from Run 2 → Run 3 , Run 4

- $\frac{\sqrt{s}}{\text{TeV}} = 13.0 \; \rightarrow 13.6\,, 14.0$
- $\theta_{1/2} = XXX \rightarrow 160\ \mu\text{rad} \downarrow, 250\ \mu\text{rad} \rightarrow$
- ✚ Updates to LHC infrastructure

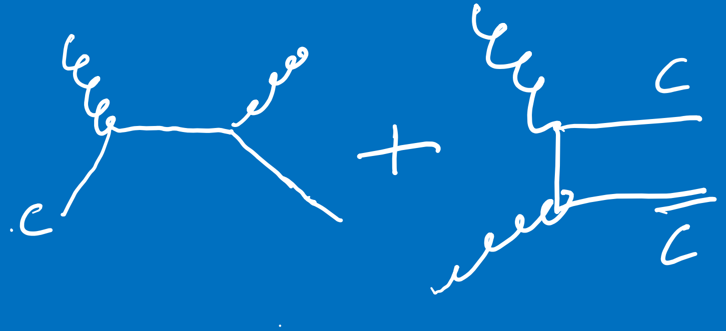




Neutrino Production Modelling : Heavy Hadrons

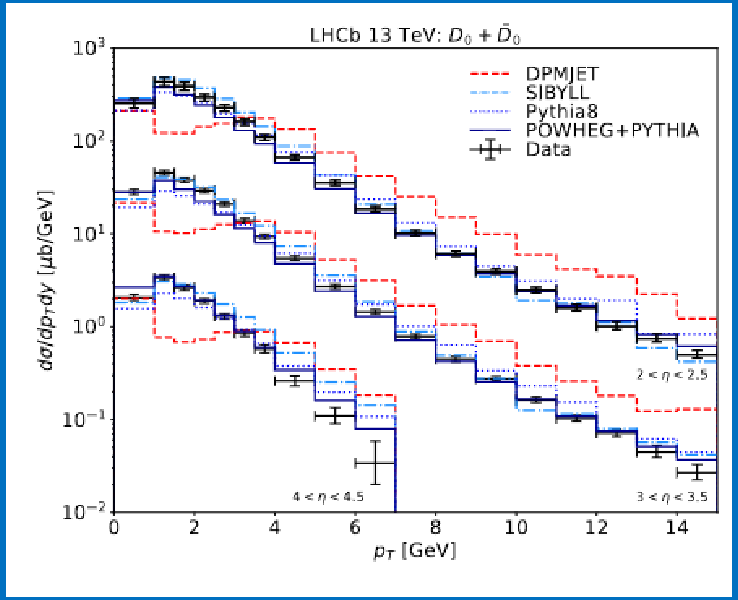
By measuring the neutrino flux, we can constrain forward charm production

- Implications for intrinsic charm + small-x gluon PDF



Only some generators include charm

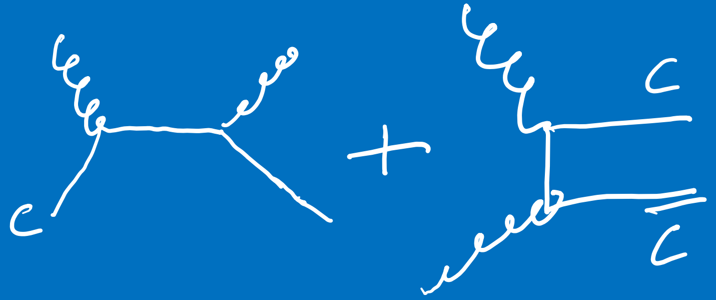
  - POWHEG, PYTHIA, SIBYLL, and DPMJET
  - With the exception of DPMJET*, agreement with LHCb D^0 spectra
  - In the far-forward direction, charm production rates vary widely between generators



We use state-of-the-art QCD predictions for heavy hadron production. We use POWHEG+PYTHIA

  - NLO in α_s with small-x resummation at NLL accuracy. PDF includes LHCb fit (NNPDF3.1sx+LHCb)

Neutrino Production Modelling : Heavy Hadrons



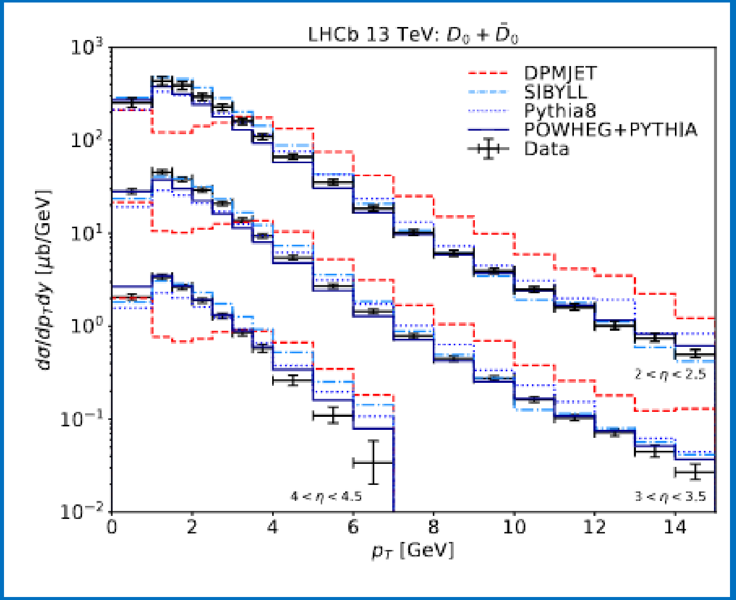
Charm hadron decays dominate the rate for

- ν_e for $\mathrm{E}_\nu \geq \mathrm{TeV}$. ≈30% of total rate
- ν_τ for all E_ν

(contribute $\approx$ 5% for ν_μ, LFU but $\pi^\pm$ dominates)

Uncertainty modelled with factorization and resummation scale variations (see 2309.12793)

- Produces an upper and lower error band that is roughly a factor of 2 up and down



Now we know the incident neutrino flux and we must choose a cross-section

Neutrino Interaction Modelling – Cross section

For the TeV energy range, the neutrino cross section has not been measured and there are different predictions

In the 100 GeV + energy range, most interactions can mostly be described as DIS which can be expressed in terms of structure functions $F_i(x, Q^2)$

$$\frac{d^2\sigma_{\nu N}}{dx\, dy} = \frac{G_F^2\, m_N\, E_\nu}{\pi\, (1 + m_W^2/Q^2)^2} \cdot \left[xy^2\, F_1 + (1-y)F_2 + xy\left(1 - \frac{y}{2}\right) F_3\right]$$

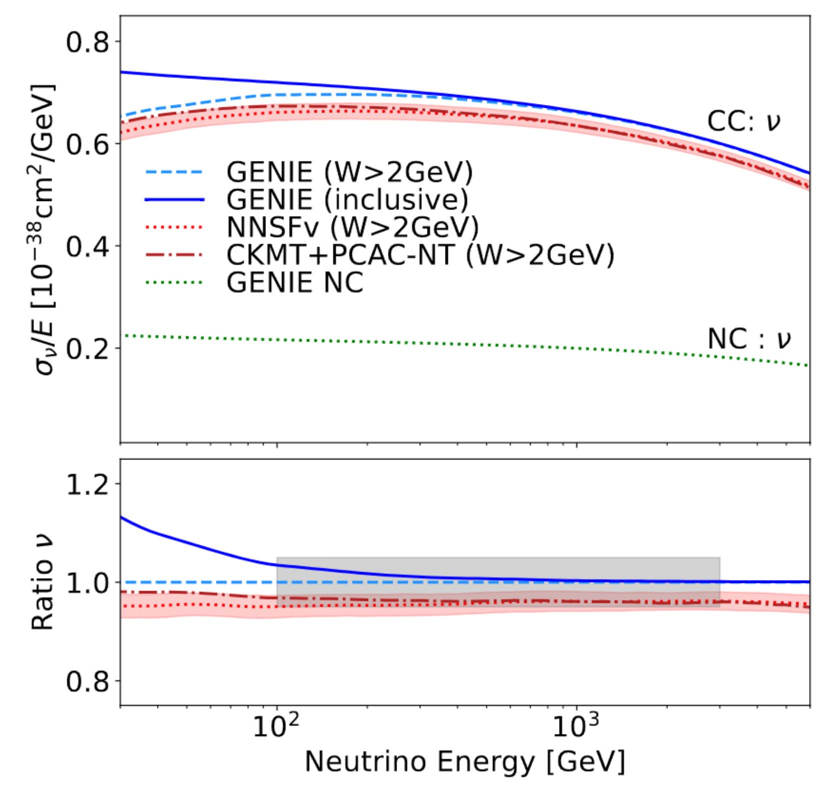
The Bodek-Yang description is used by GENIE and has been extensively tested for $E_\nu \leq 100\ \mathrm{GeV}$. GENIE also includes non-DIS contributions

- However, it is built on obsolete PDF's, so it must be compared against other predictions of the neutrino cross-section

New descriptions of DIS based on NLO structure functions have been introduced, namely $\mathrm{NNSF}\nu$ and CKMT+PCAC-NT, that build on modern PDF's .

- $\mathrm{NNSF}\nu$ also provides an uncertainty estimate

For $E_\nu > 100\ \mathrm{GeV}$ after DIS cuts, we find general agreement with these more recent descriptions, within $\approx 6\%$



Armed with a flux and cross-section, let's look at the event rate

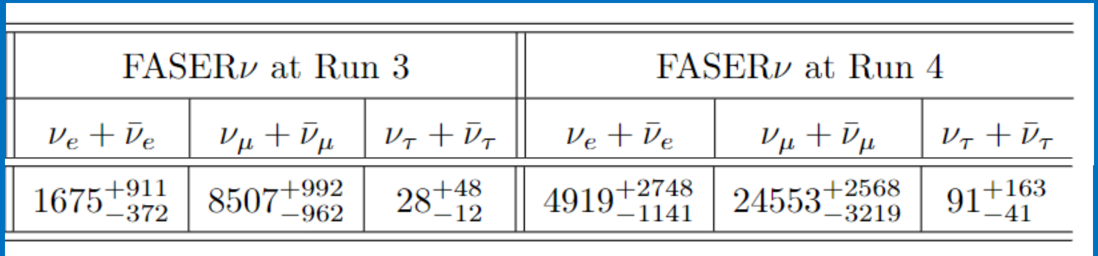
Neutrino Production Modelling: Result

Here the neutrinos from light and heavy hadrons, and their uncertainties are summed

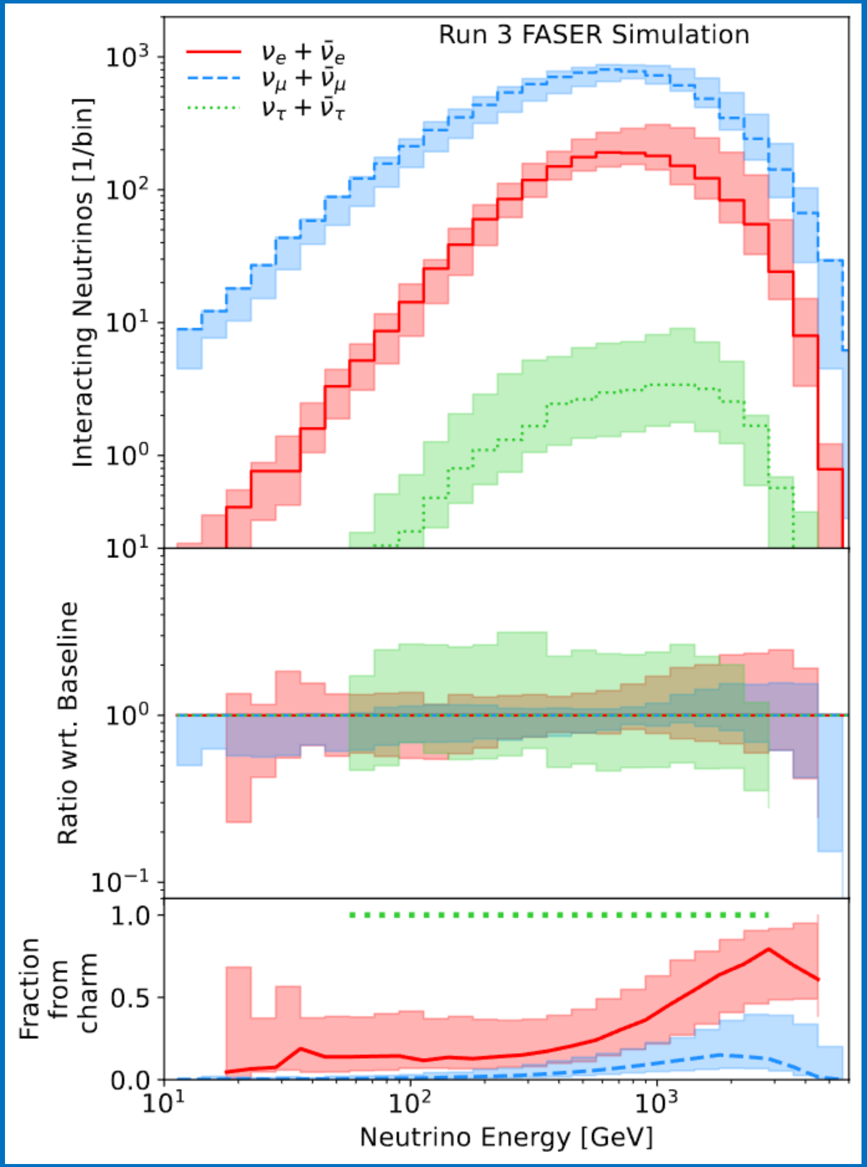
- Top: ν_e(red) , ν_μ(blue) , ν_τ (green) interacting spectra with errorbands at Run 3
- Middle: Uncertainty ratio w.r.t. baseline spectra
- Bottom: Fraction from charm for each flavor

Charm contribution dominates uncertainty

- $\approx 50\%$ for ν_e , 10% for ν_μ , 100% for ν_τ



FASERν at Run 3			FASERν at Run 4		
$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
1675^{+911}_{-372}	8507^{+992}_{-962}	28^{+48}_{-12}	4919^{+2748}_{-1141}	24553^{+2568}_{-3219}	91^{+163}_{-41}

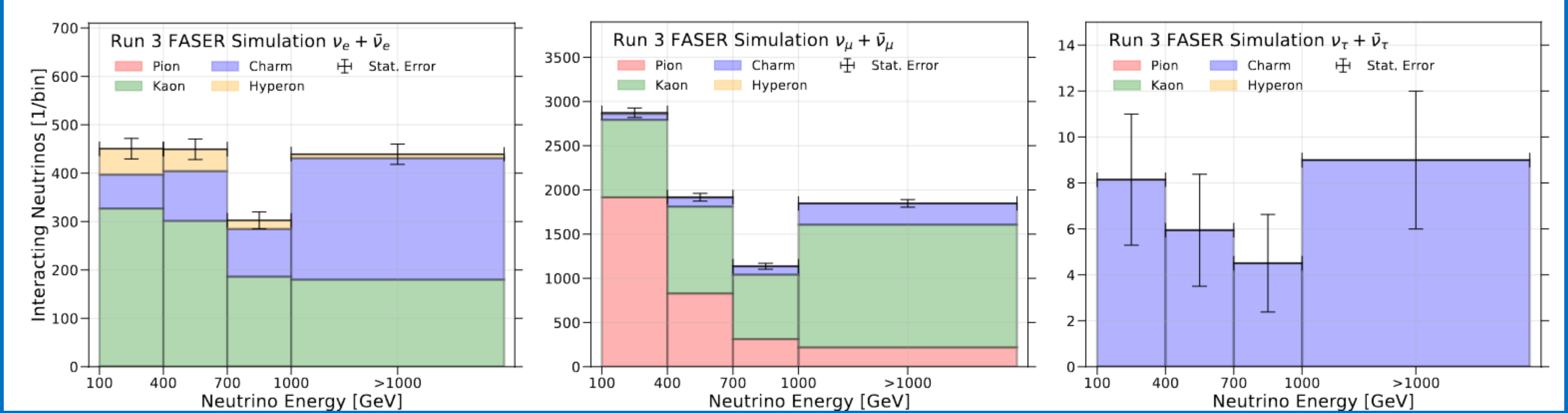


How does the spectra break down for different hadron species?

Neutrino Production Modelling: Hadron species

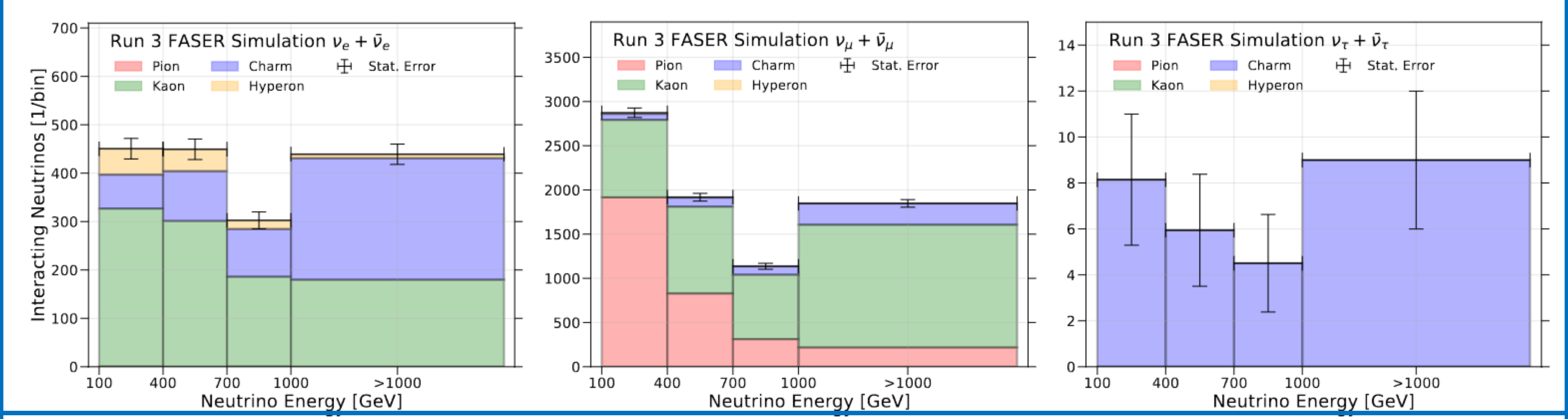
Binned interacting spectra in terms of parent hadron with statistical errorbars $\sqrt{N}$ for full **Run 3** at FASERν

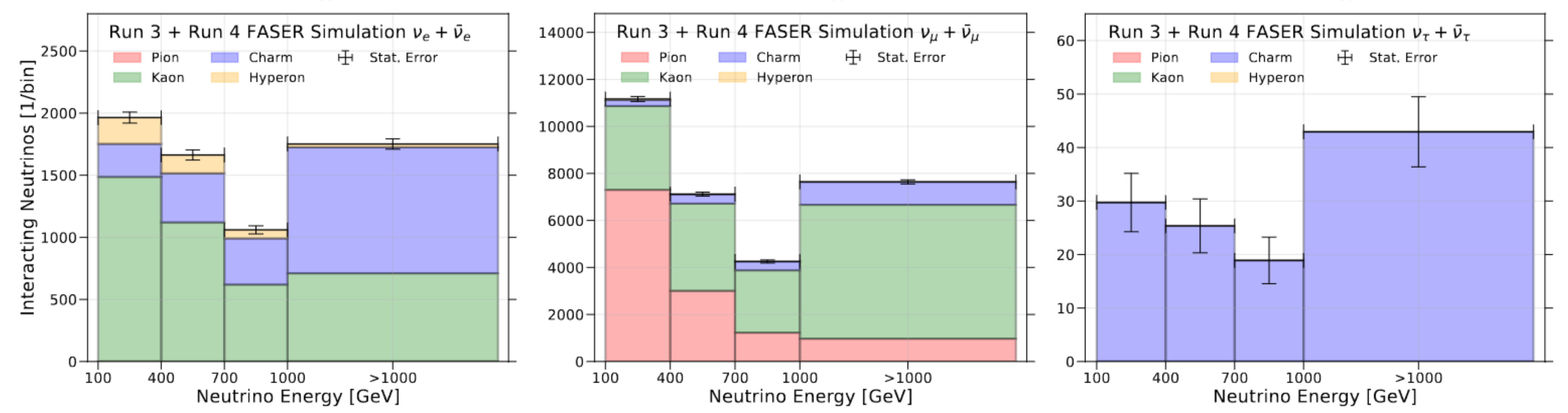
Enough statistics to probe forward hadron production



Neutrino Production Modelling: Hadron species

Similar result for **Run 4**, with slight differences due to location of detector w.r.t. line of sight





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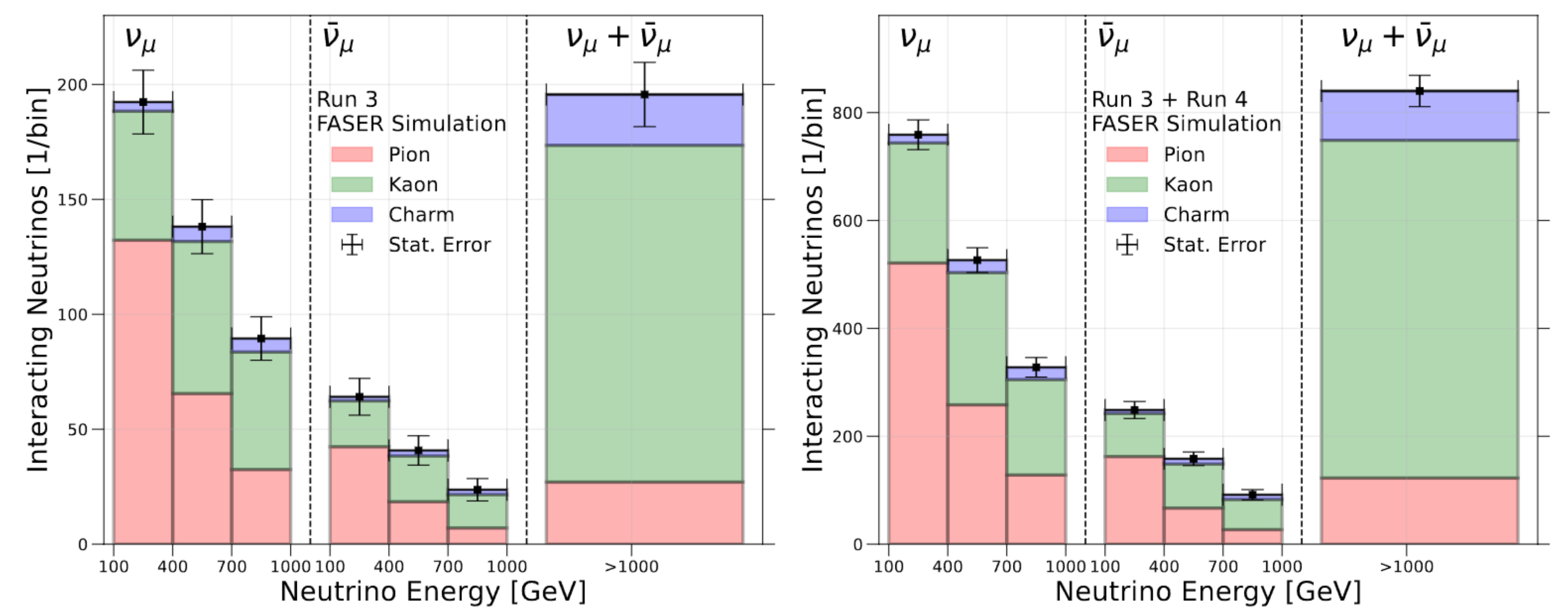
We can also use **FASER** to detect ν_μ which doesn't rely on the emulsion readout



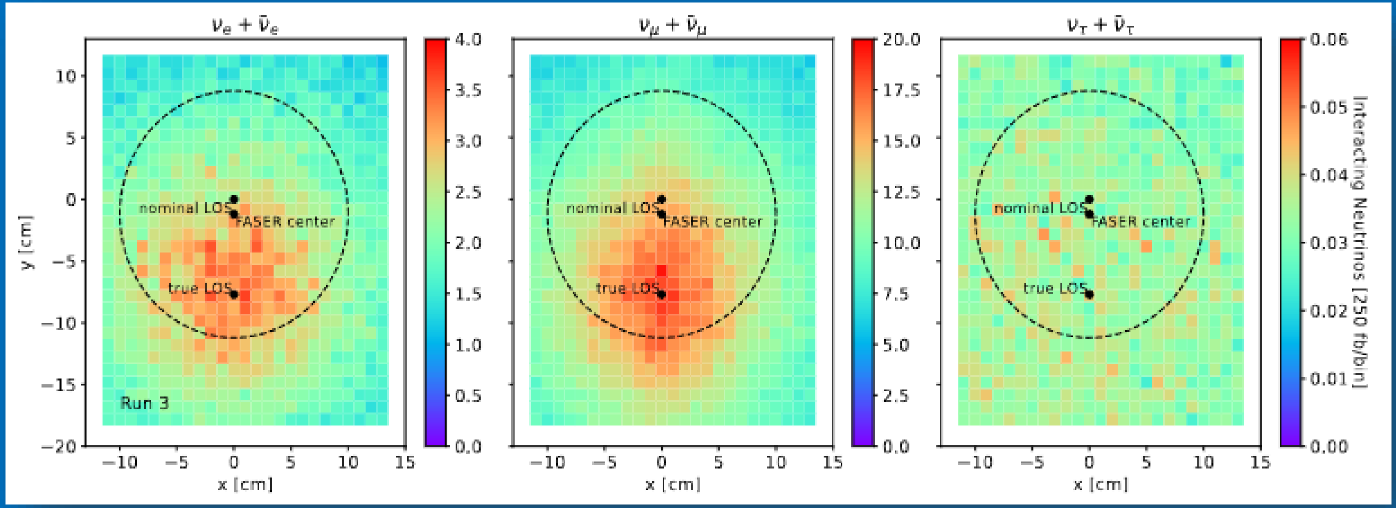
Neutrino Production Modelling: Spatial Distribution

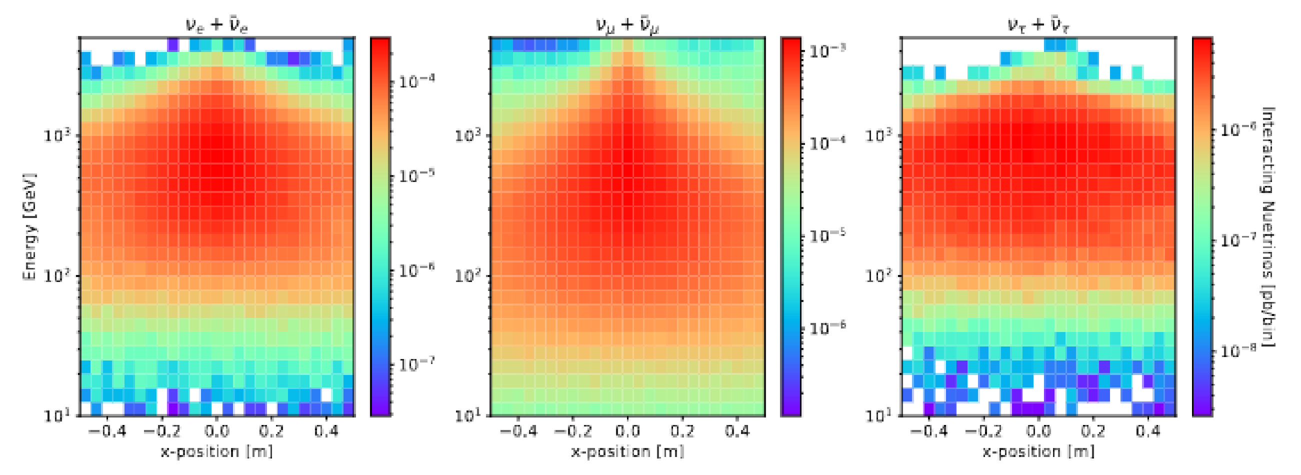
More information by studying the spatial distribution which gives information on parent hadron

- Top: (x , y)
- Bottom: (x , E_ν)

In general, ν_τ is the least collimated, ν_μ is the most.

- Radial bins give information on parent hadron
- For all flavors high energy neutrinos are collimated on LOS





Summary

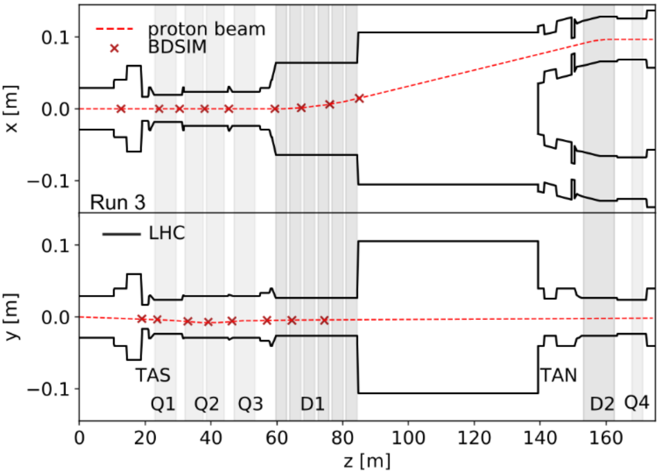
Neutrinos are present in all forward physics analyses, either as a signal or a background

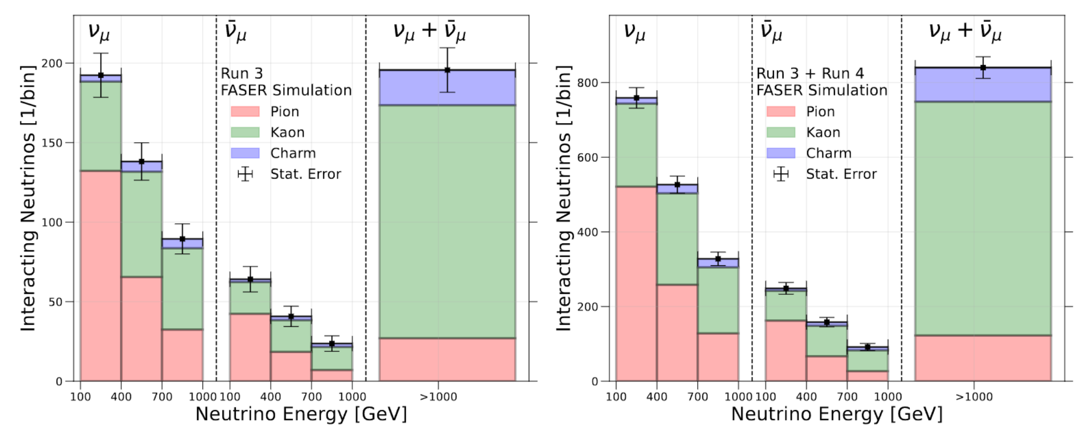
We update the fast neutrino flux simulation for the Run 3 and expected Run 4 conditions

We collect light+heavy hadron production treatments, cross-section and their uncertainties to produce interacting neutrino spectra

This work will serve as the basis for upcoming FASER analyses, and can be

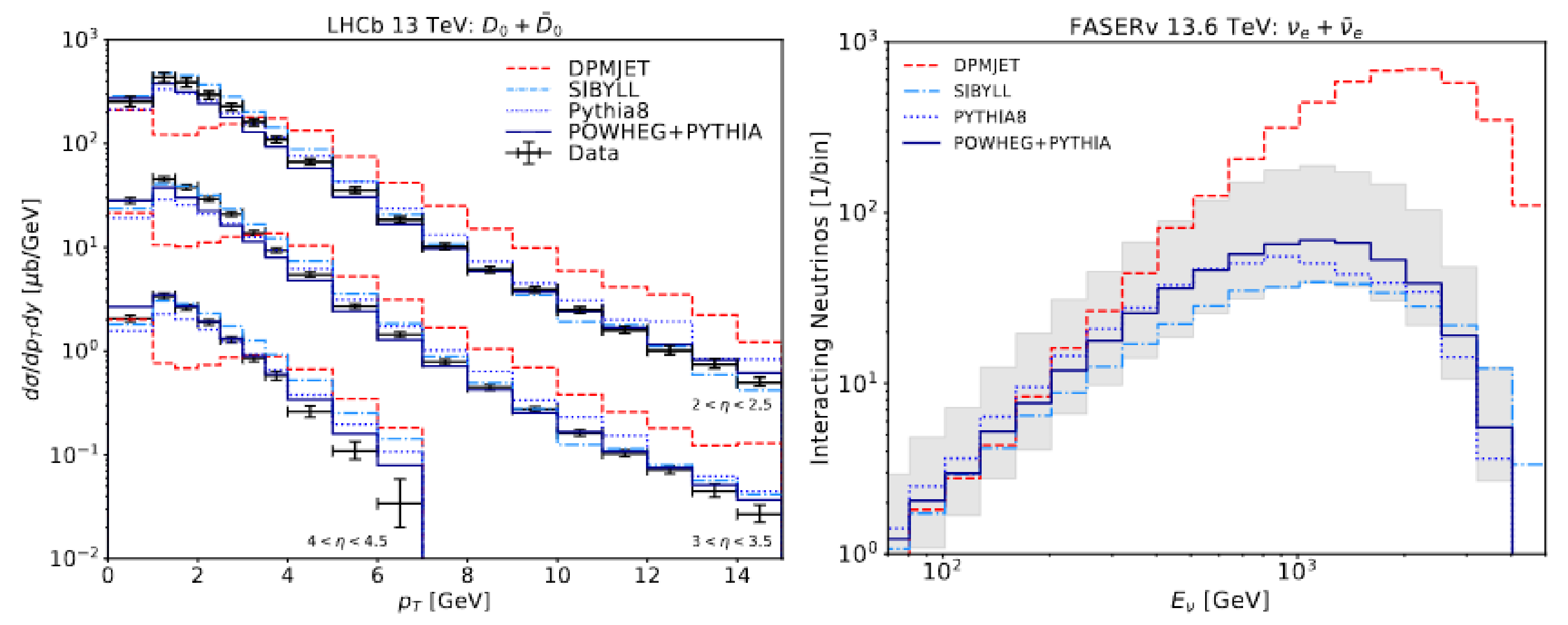
Thank you!





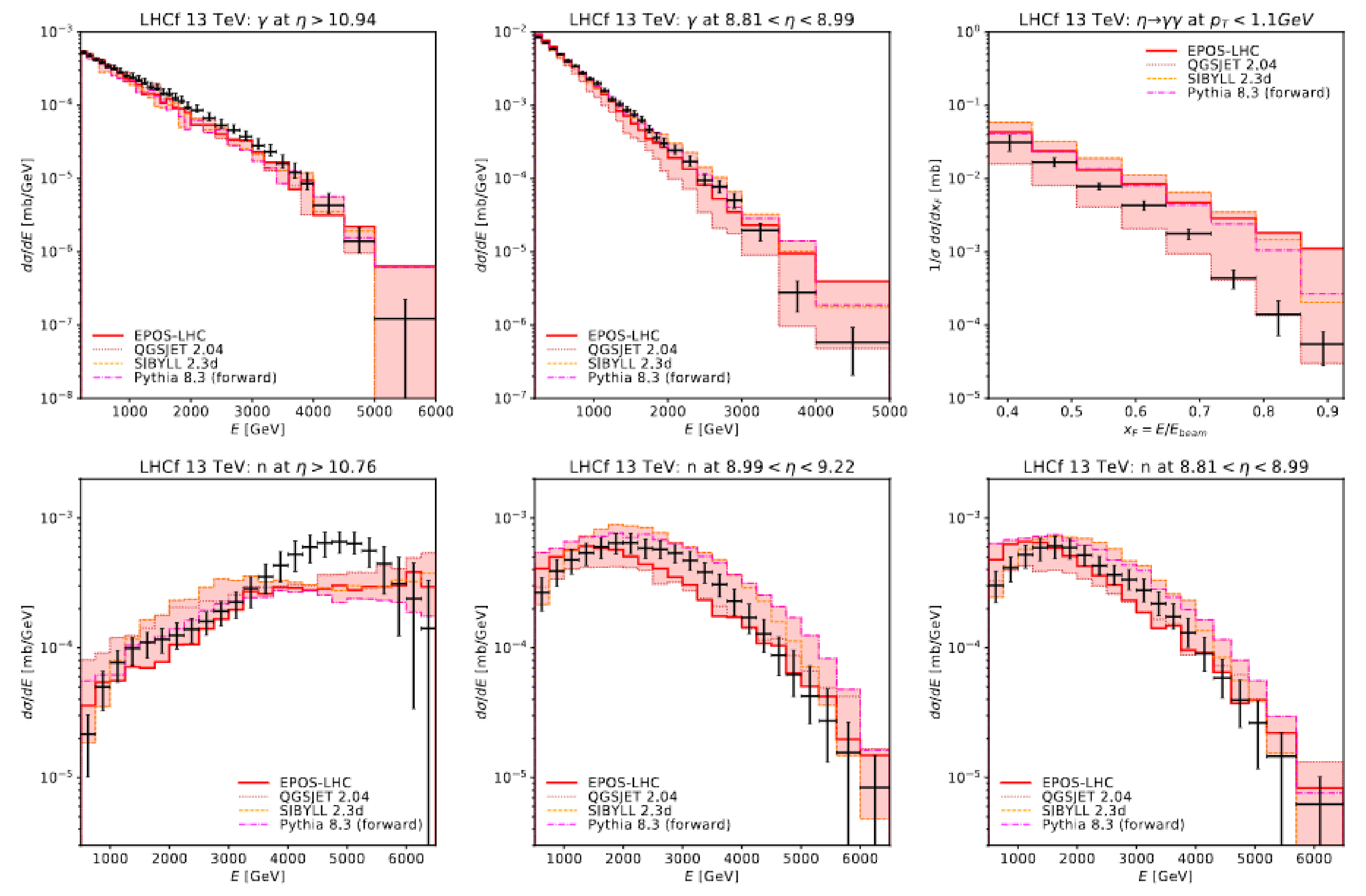
Backup

DPMJET

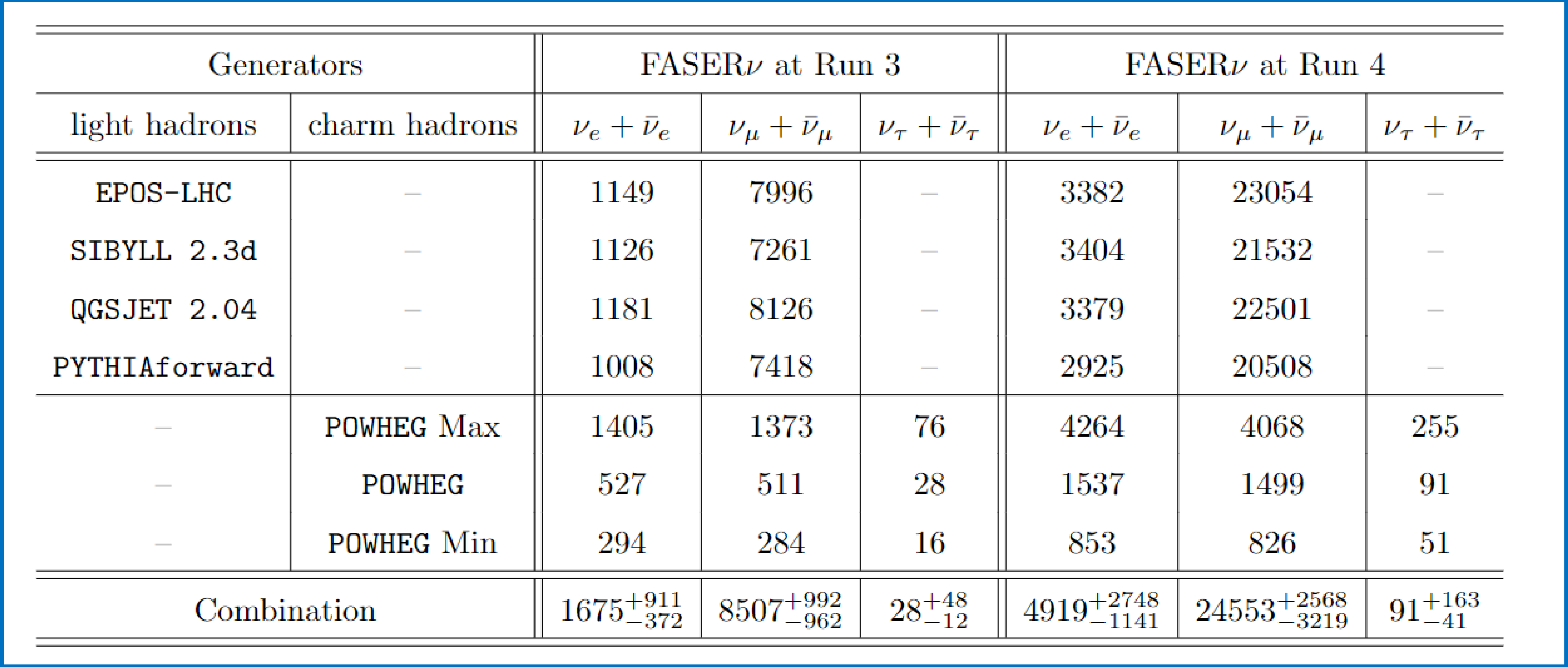


- DPMJET predicts an order of magnitude more neutrinos from charm
- DPMJET uses massless charm quarks and may also overestimate charm content of proton
- Never validated for charm production and should not be used

LHCf Spectra



Full table



Generators		FASERν at Run 3			FASERν at Run 4		
light hadrons	charm hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
`EPOS-LHC`	–	1149	7996	–	3382	23054	–
`SIBYLL 2.3d`	–	1126	7261	–	3404	21532	–
`QGSJET 2.04`	–	1181	8126	–	3379	22501	–
`PYTHIAforward`	–	1008	7418	–	2925	20508	–
–	`POWHEG` Max	1405	1373	76	4264	4068	255
–	`POWHEG`	527	511	28	1537	1499	91
–	`POWHEG` Min	294	284	16	853	826	51
Combination		1675^{+911}_{-372}	8507^{+992}_{-962}	28^{+48}_{-12}	4919^{+2748}_{-1141}	24553^{+2568}_{-3219}	91^{+163}_{-41}