# Determination of the Forward Neutrino Fluxes at FASER

## NN$\nu$flux: An NNPDF-based Approach

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Collaborators: Jukka John, Felix Kling, Peter Krack, Juan Rojo

March 5, 2026

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NN$\nu$flux


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**First** ever detection in 2023

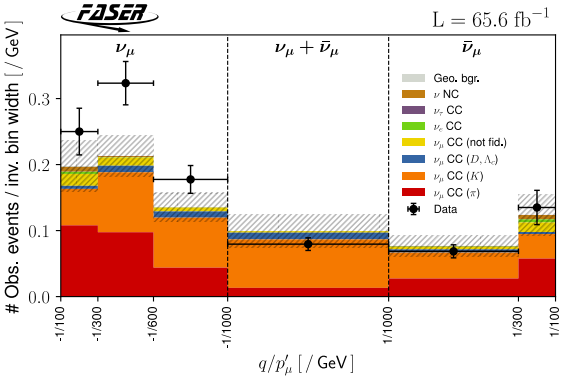
- FASER($\nu$)
- SND@LHC

**New** FASER measurement in 2024 $\longrightarrow$

- 338 interacting neutrinos
- Binned in $E_\nu$, $\eta_\nu$

**Upcoming** FASER$\nu$ Run3

- Approved for High-Lumi!



# Motivation

## Collider Neutrinos

**New** Access to forward hadron production

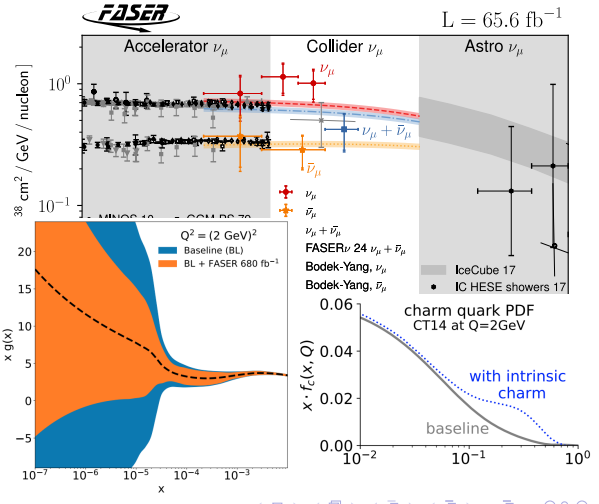
- Light (K,$\pi$) $\rightarrow \nu_\mu$
- Heavy charmed ($D_c$, $\Lambda_c^+$) $\rightarrow \nu_e, \nu_\tau$

**New** TeV Neutrino DIS

- Measure CC cross-sec $\longrightarrow$
- Investigate DIS kinematics
- Probe specific channel e.g. $\nu_\mu s \rightarrow \mu c$

**Sensitive** to

- High/low $x$ gluon PDFs through charm production ($g(x \sim 1) + g(x \sim 10^{-7})$)
- Intrinsic charm
- Strangeness enhancement



# Motivation

## Fitting the fluxes

Roadmap:

- **Constrain** the neutrino fluxes from data
- Do so in a **theory-agnostic** manner $\rightarrow$ NN!
- **Investigate** FASER($\nu$)'s potential for coming LHC runs
- **Apply** to nice physics
  - MC generators
  - Optimal Observable

Need to be computationally **efficient**

# Neutrino "PDF"

## Neutrino fluxes as a quasi-PDF: factorizing flux and cross-section

Now, number of neutrinos **interacting** at FASER:

$$N_{\rm int}^{(\nu_i)} \equiv \int_{Q^2_{\rm min}}^{Q^2_{\rm max}} dQ^2 \int_{x_{\rm min}}^{x_{\rm max}} dx \int_{E_\nu^{\rm (min)}}^{E_\nu^{\rm (max)}} dE_\nu \times \widetilde{N}_{\rm int}^{(\nu_i)}(x, Q^2, E_\nu)$$

$$\widetilde{N}_{\rm int}^{(\nu_i)}(x, Q^2, E_\nu) \equiv n_T L_T \times \frac{dN_{\nu_i}(E_\nu)}{dE_\nu} \times \frac{d^2\sigma^{\nu_i A}(x, Q^2, E_\nu)}{dx dQ^2} \times \mathcal{A}(E_\ell, \theta_\ell, E_h)$$

**Like SF**

obs $= \int$ "PDF" $\otimes$ function

This factorization motivates a treatment of the **neutrino flux as a PDF:**

$$f_{\nu_i}(x_\nu) \equiv \frac{\sqrt{s_{\rm pp}}}{2} \frac{dN_{\nu_i}(E_\nu)}{dE_\nu}, \quad x_\nu \equiv \frac{2E_\nu}{\sqrt{s_{\rm pp}}} \sim \frac{E_\nu}{7\ \text{TeV}}, \quad 0 \leq x_\nu \leq 1$$

with $x_\nu$ the neutrino momentum fraction.

# Neutrino PDF

## Continuing

Full expression for neutrinos at FASER:

$$N_{\text{int}}^{(\nu_i)} = n_T L_T \int_{Q^2_{\text{min}}}^{Q^2_{\text{max}}} dQ^2 \int_{x_{\text{min}}}^{x_{\text{max}}} dx \int_0^1 dx_\nu \left[ f_{\nu_i}(x_\nu) \right] \left[ \frac{d^2\sigma^{\nu_i A}(x, Q^2, E_\nu)}{dx dQ^2} \right] \mathcal{A}(E_\ell, \theta_\ell, E_h)$$

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**Our goal:** extract $f_{\nu_i}(x_\nu)$ from $N_{\text{int}}^{(\nu_i)}$
**Missing:** computation of the full DIS cross-section at NLO+PS
$\rightarrow$ `POWHEG-Pythia8`

# Neutrino PDF

## Continuing

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**Problem**

Calculation takes$\mathcal{O}(1\ \text{hr})$ on 8 cores $\rightarrow$ *highly* infeasible for $\sim$ 10000 epochs $\times$ 1000 replicas $\times$ (4 generators + 3 BSM + 1 IC) $\times$ 4 observables $\times$ 4 flavors $\times$ 4 detectors $= 5 \cdot 10^9$ full computations

To extract $f_{\nu_i}(x_\nu)$ without recomputing all DIS kinematics every single time, we exploit the resemblence of the problem at hand to PDF fitting

**Strategy**:

- Precompute all DIS+PS on an interpolation grid
- Use an deep NN to parametrize $f_{\nu_i}(x_\nu)$
- Perform NNPDF-like closure tests to propagate uncertainties and check whether input == output
- Plots!

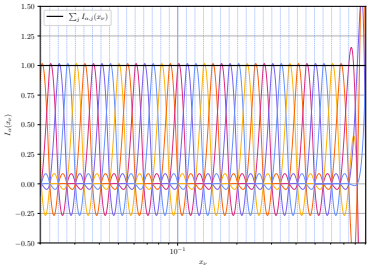
# Fast-Interpolation à la NNPDF

## FK-tables

Introduce a set of interpolation basis functions $\{I_\alpha(x)\}$

$$f_{\nu_i}(x_\nu) \simeq \sum_{\alpha=1}^{n_x} f_{\nu_i}(x_{\nu,\alpha}) I_\alpha(x_\nu)$$

... so that we can get $f_{\nu_i}(x_{\nu,\alpha})$ in front of the integral




$$N_{\rm int}^{(\nu_i)}(E_\nu) = \sum_{\alpha=1}^{n_x} f_{\nu_i}(x_{\nu,\alpha}) \frac{2 n_T L_T}{\sqrt{s_{\rm pp}}} \int_{E_\nu^{(\rm min)}}^{E_\nu^{(\rm max)}} dE_\nu \int_{Q_0^2}^{Q^2_{\rm max}} dQ^2 \int_{x_{\rm min}}^{1} dx \left[ I_\alpha(x_\nu) \frac{d^2\sigma^{\nu_i A}_{\rm NLO+PS}(x, Q^2, E_\nu)}{dx dQ^2} \right|_{\rm fid}$$

$$N_{\rm int}^{(\nu_i)}(E_\nu) = \sum_{\alpha=1}^{n_x} f_{\nu_i}(x_{\nu,\alpha}) \mathrm{FK}_\alpha \rightarrow \text{Precompute once by feeding } I_\alpha(x_\nu) \text{ to POWHEG}$$

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**Problem solved**

Replaced a $\mathcal{O}(1\ \mathrm{hr})$ call to POWHEG+Pythia8 with a 20 $\mu s$ call to np.matmul

$$N_{\mathrm{int}}^{(\nu_i)}(E_\nu) = \sum_{\alpha=1}^{n_x} f_{\nu_i}(x_{\nu,\alpha}) \frac{2 n_T L_T}{\sqrt{s_{\mathrm{pp}}}} \int_{E_\nu^{(\mathrm{min})}}^{E_\nu^{(\mathrm{max})}} dE_\nu \int_{Q_0^2}^{Q^2_{\mathrm{max}}} dQ^2 \int_{x_{\mathrm{min}}}^{1} dx \left[ I_\alpha(x_\nu) \frac{d^2\sigma_{\mathrm{NLO+PS}}^{\nu_i A}(x, Q^2, E_\nu)}{dx dQ^2} \right|_{\mathrm{fid}}$$

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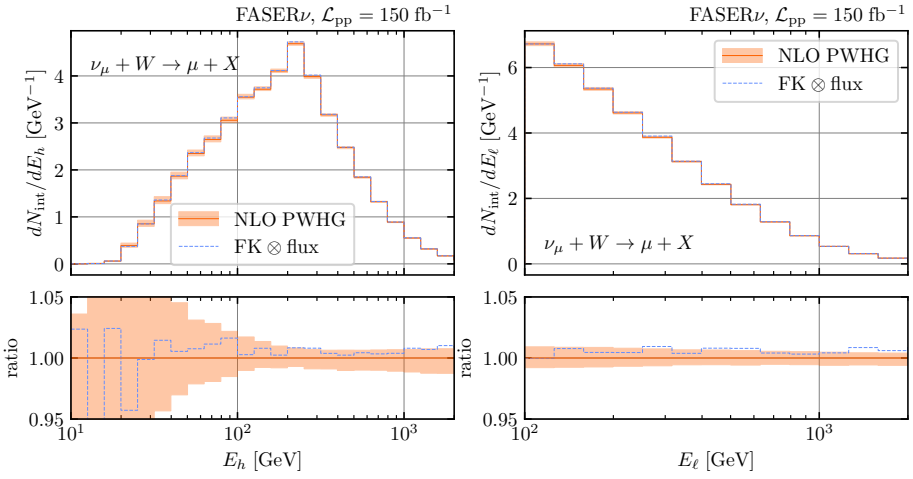
# Let's check:

## FK-tables



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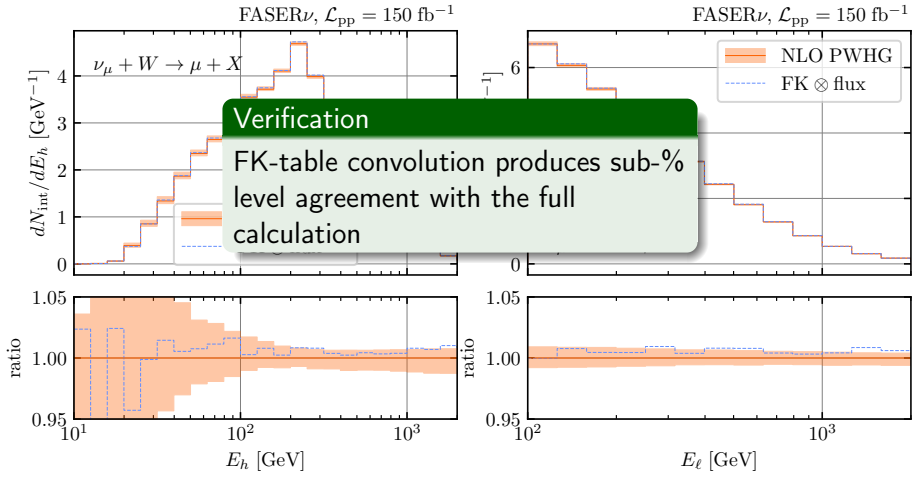



**Verification**

FK-table convolution produces sub-% level agreement with the full calculation

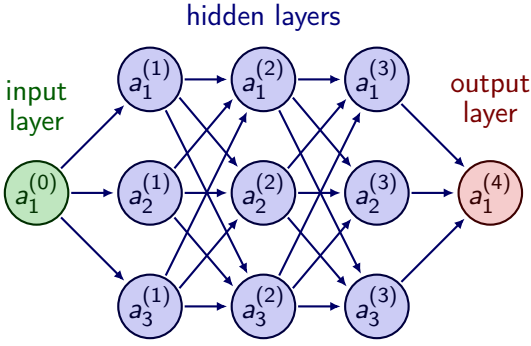
As in NNPDF to fit DIS structure functions, we parametrise

$$f_{\nu_i}(x_\nu) = x_\nu^{a_i}(1-x_\nu)^{b_i}\mathrm{NN}_{\nu_i}(x_\nu), \quad b_i \geq 0$$

Using a feed-forward neural net, composed of nodes $a_i^{(l)} = \mathrm{act}(W_i^{(l)} a_i^{(l-1)} + b_i^{(l)})$

**Why?**

- → Fully unbiased, model agnostic
- → Adapt to local variations
- → Computationally efficient
- → Can be scaled to include $\eta_\nu$ easily



# Let's fit!

## But first a few checks

What do we see?

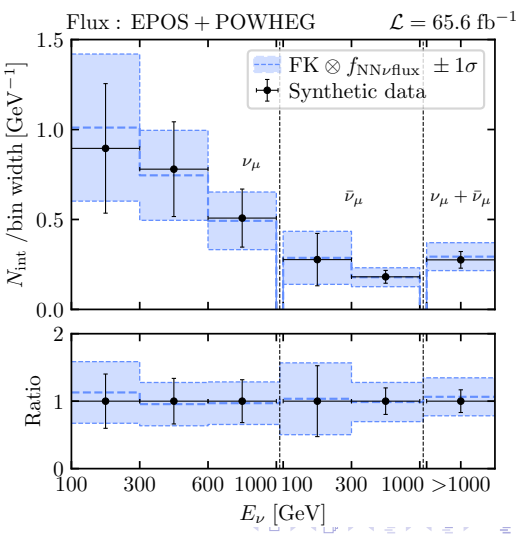
- Fake flux from MC generator
- Fit to the event rates with loss

$$E^{(k)} = \frac{1}{n_{\text{dat}}} \sum_{i,j=1}^{n_{\text{dat}}} (D^{(k)} - T^{(k)})_i (\text{cov}^{-1})_{ij} (D^{(k)} - T^{(k)})_j$$

- $D^{(k)} = N_{\text{int}}$ pseudodata binned like 2024 data
- $T^{(k)} = \sum_{\alpha=1}^{n_x} f_{\text{NN}}(x_{\nu,\alpha}) \text{FK}_\alpha$

Uncertainties: NNPDF closure test

- Level 0: $D_j^{(0)} = N_{\text{th}}(E_\nu, j)$
- Level 1: $D_j^{(1)} = D_j^{(0)} + r_i^{(m)} \sigma_i^{(\text{stat,sys})}$
- Level 2: $D_j^{(2,k)} = D_j^{(1)} + r_i^{(k)} \sigma_i^{(\text{stat,sys})}$



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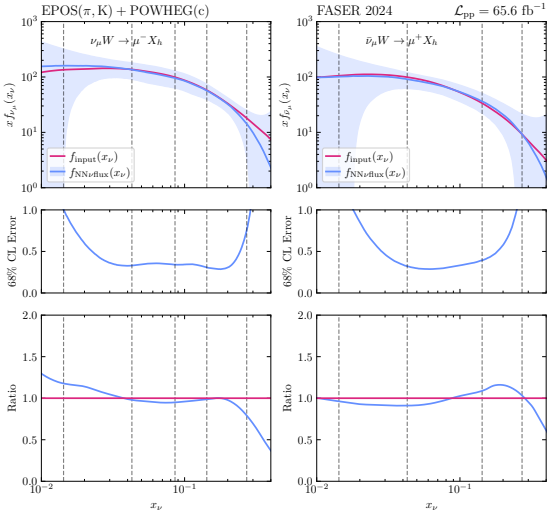


# Let's fit!

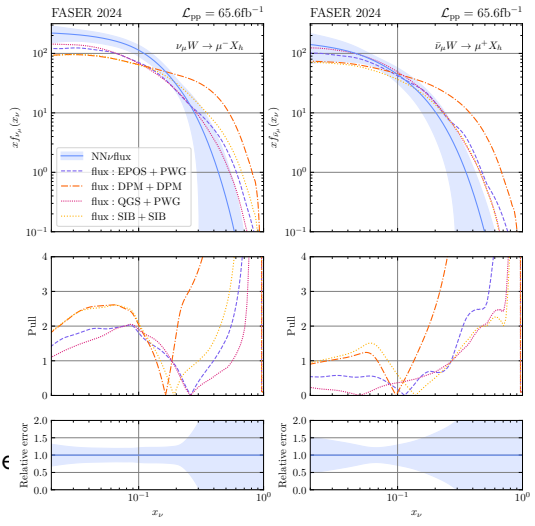
## Extraction of the LHC forward muon neutrino flux

The (anti) forward muon neutrino flux

- NN fit to real data
- Comparison to FASER MC
- Shared preprocessing weights

Comparison to MC generators

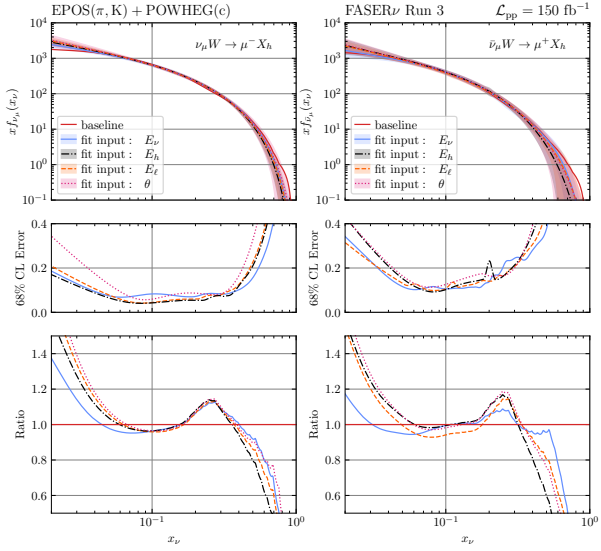
- Pull $= \frac{|\langle f_{\nu_\mu}^{\text{NNfit}}(x_\nu)\rangle - f_{\nu_\mu}^{(gen)}(x_\nu)|}{\sigma_{\nu_\mu}^{\text{NNfit}}}$
- Gen($\pi, K$) + Gen(charmed hadrons)
- DPMJET thinks $m_c = 0 \rightarrow$ overproduction high energy region
- General trend: more low energy neutrinos, le high



# Let's fit!

Comparison of **detector observables**

- Synthetic data FASER$\nu$ Run 3
- $E_\nu,\ E_h,\ E_\ell,\ \theta$
- Methdology works for all observables
- $E_\nu$ slightly closer to input
- Uncertainties behave as expected



# Let's fit!

Comparison of **detectors**

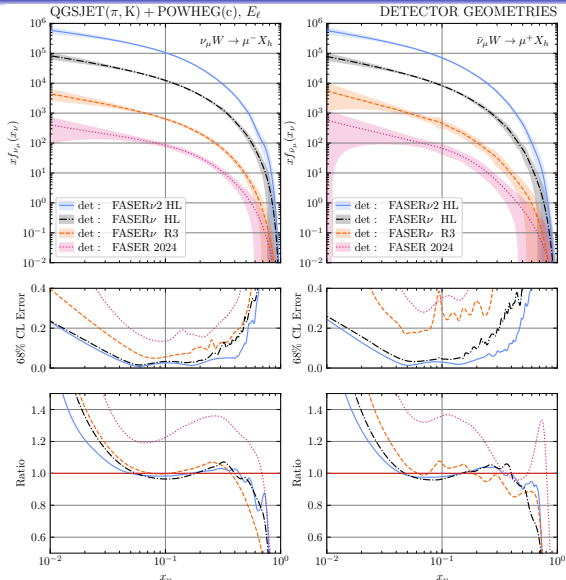
- Lepton energy $E_\ell$ used in fit
- More neutrinos = better fit

Predicted **event rates**:

- FASER 2024: 338.1 (measured)
- FASER$\nu$ Run 3: 2100
- FASER$\nu$ Run 4+5: 42000
- FASER$\nu$2 Run 4+5: 340000

**Effect:**

- Better test event generators
- Constrain BSM decays
- Constrain IC channels



# Conclusion & Outlook

What we have done

- Studied far-forward neutrinos at FASER
- First ever extraction of LHC forward neutrino flux using NNPDF-like fitting framework
- Efficient using FK-tables
- Made predictions for future detectors, benchmarked event generators, applied to an IC scenario
- Far-forward neutrinos are interesting!

What we can do

- Extend to fit $f_\nu(x_\nu, y_\nu)$ recent measurement of $y_\nu$
- Connect experiment directly to theory
- Bypass first-principles calculations in favor of data-driven extractions
- Translate our prompt neutrinos to prompt KM3NeT neutrinos
- Reconstruct physics at the pp level from the flux