Deep inelastic scattering with collider neutrinos at the LHC and beyond

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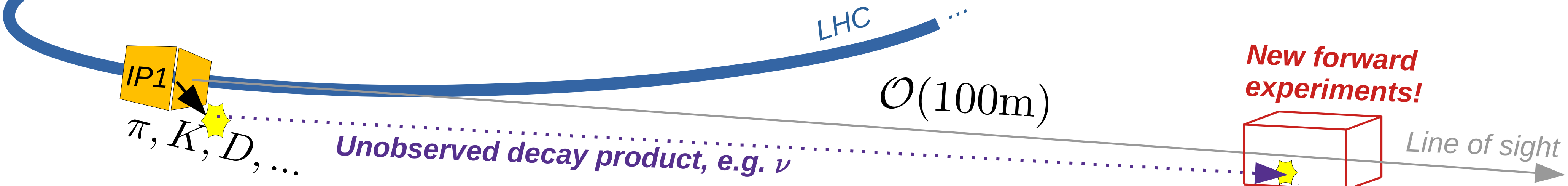
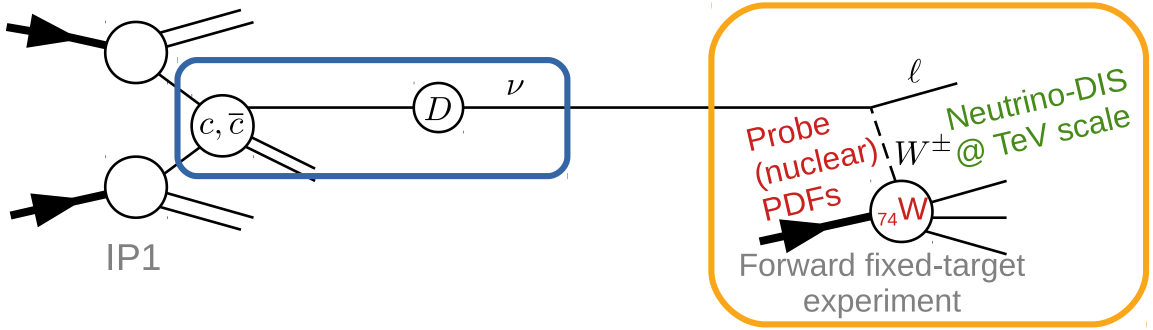
Introduction
Neutrinos at the LHC

- The hadron collisions at the LHC produce a myriad of hadrons, which can produce neutrinos via weak decays
  - Neutrinos & possible LLPs never observed at the IP



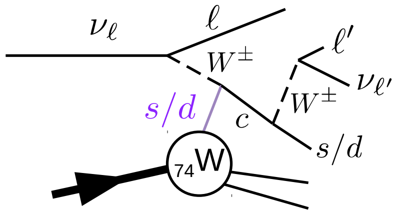
Inclusive DIS

Physics at **production** and **detection** sites can affect spectra of observed neutrino interactions



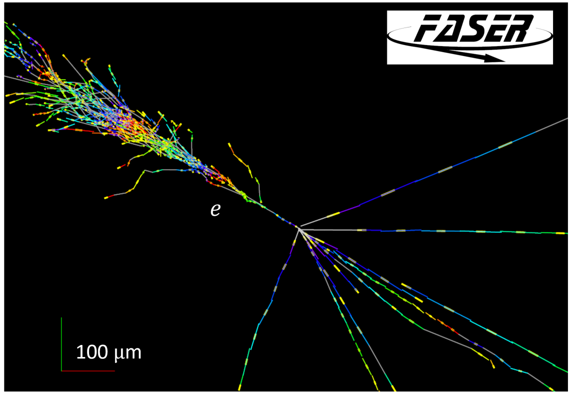
Charm-tagged DIS

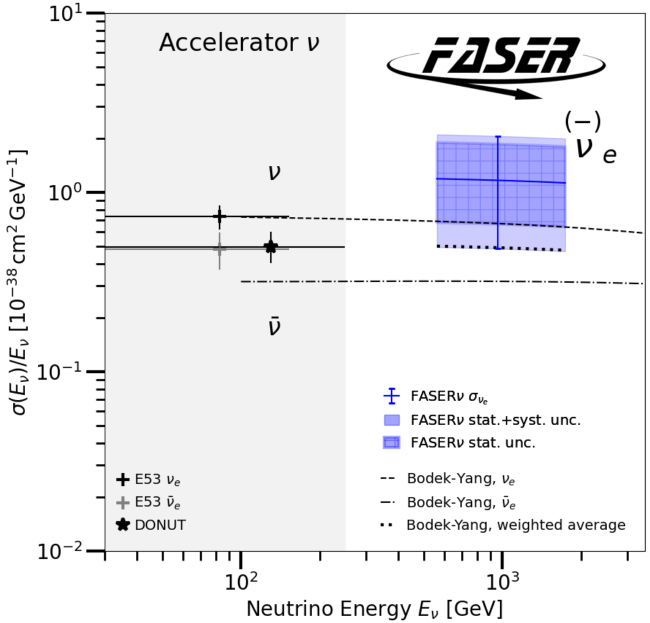
Handle to s-quark PDF

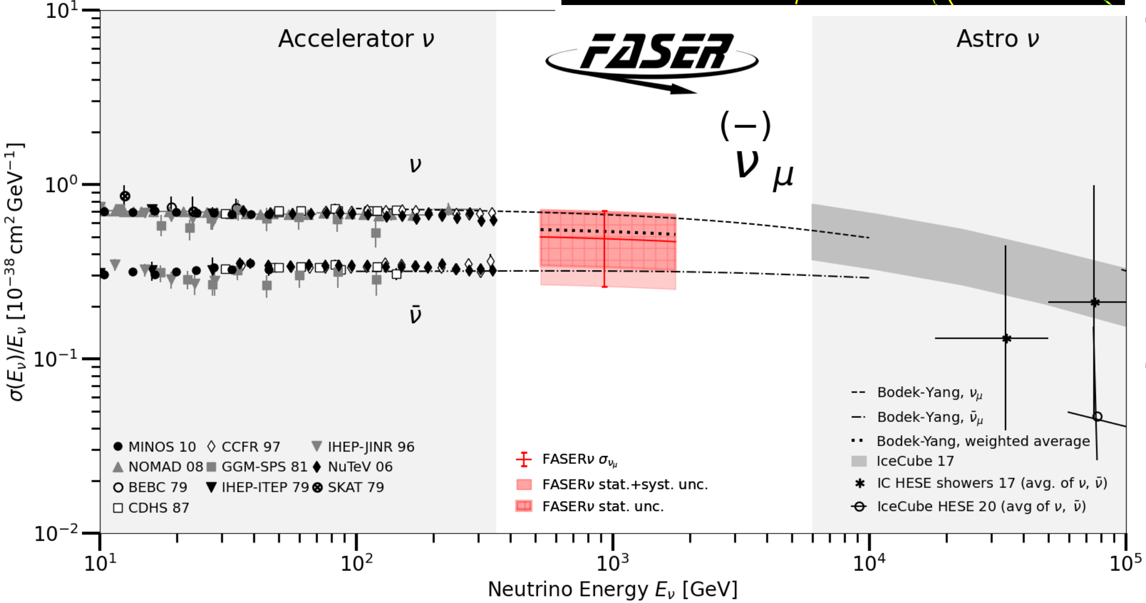


Observation and cross section measurement

- First LHC neutrinos observations!
  - **FASER** DOI:10.1103/PhysRevLett.131.031801
  - **SND@LHC** DOI:10.1103/PhysRevLett.131.031802
- **FASER**: first measurement of ν_e and ν_μ int.ac. cross section DOI:10.1103/PhysRevLett.133.021802



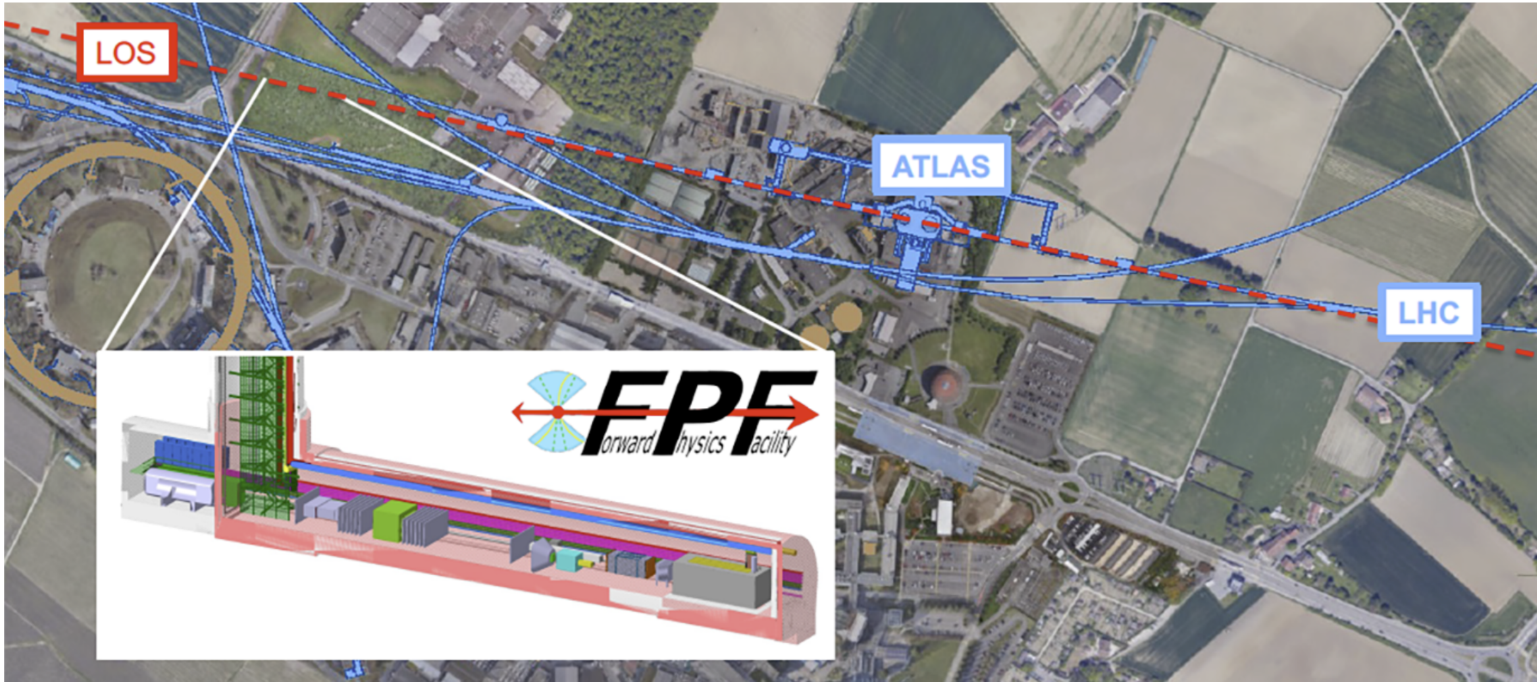




Images from DOI:10.1103/PhysRevLett.133.021802 https://fpf.web.cern.ch/

The Forward Physics Facility

- Run III experiments demonstrate great potential, but statistics will be limited
- FPF: a proposed dedicated multi-experiment facility at 620 m from IP1 (ATLAS)
  - *FLArE, FORMOSA, FASER2 & FASERν2*
- Would ensure a rich neutrino program at hi-lumi LHC
- Here we assess the potential of forward experiments to constrain the neutrino flux and several (B)SM processes



DOI:10.1140/epjc/s10052-024-12665-1

The LHC as a neutrino-ion collider

Run III

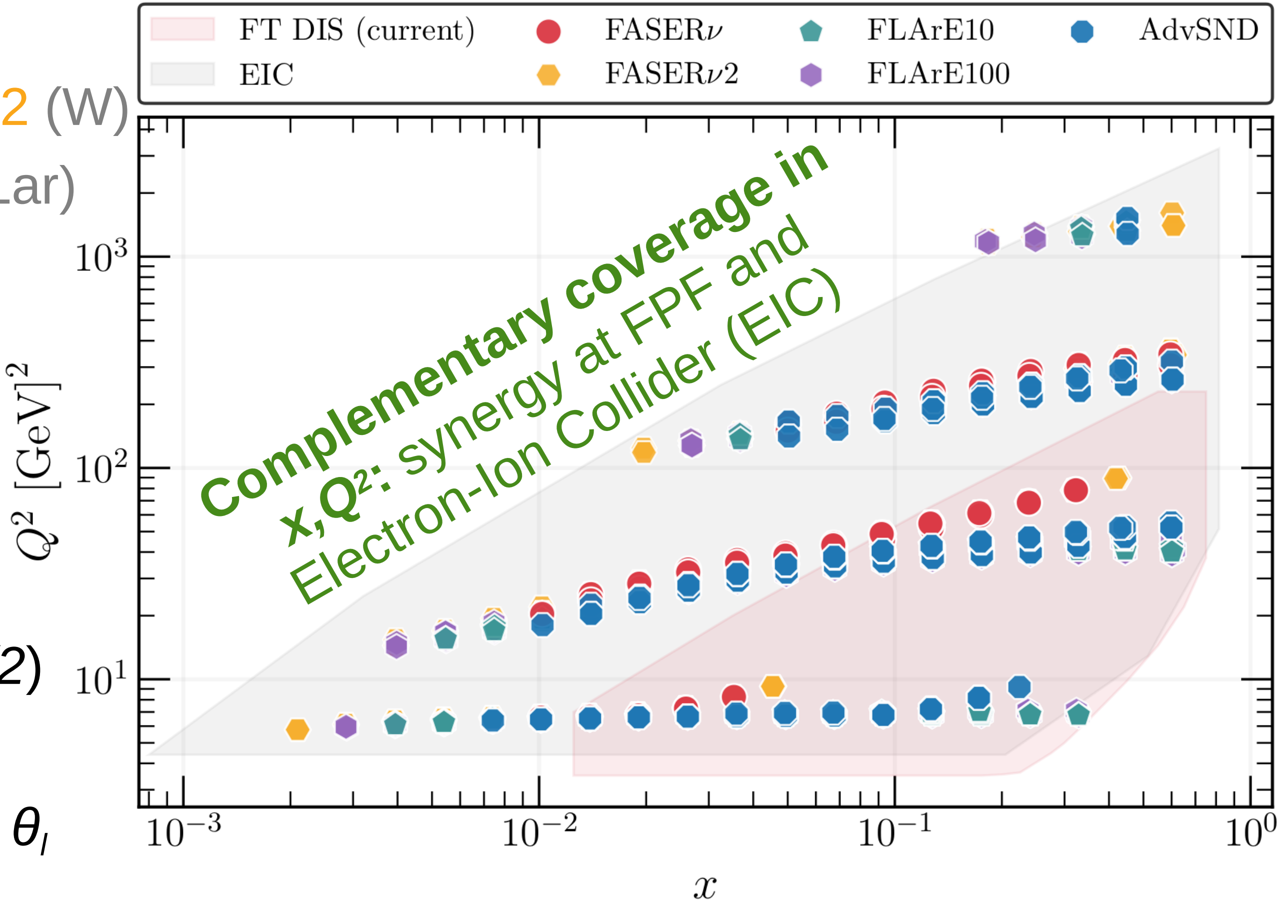
- FASERν (W)
- SND@LHC (W)

FPF

- FASERν2 (W)
- FLArE (Lar)

Estimate impact to the global PDF4LHC21, EPPS21 (W) sets via profiling with xFitter

- Experimental variables
  - $E_\nu = E_h + E_l$
  - $Q^2 = 4(E_h + E_l)\, E_l \sin^2(\theta_l/2)$
  - $x = Q^2 / (2\, m_N E_h)$
    - Equivalent to E_l, E_h, θ_l



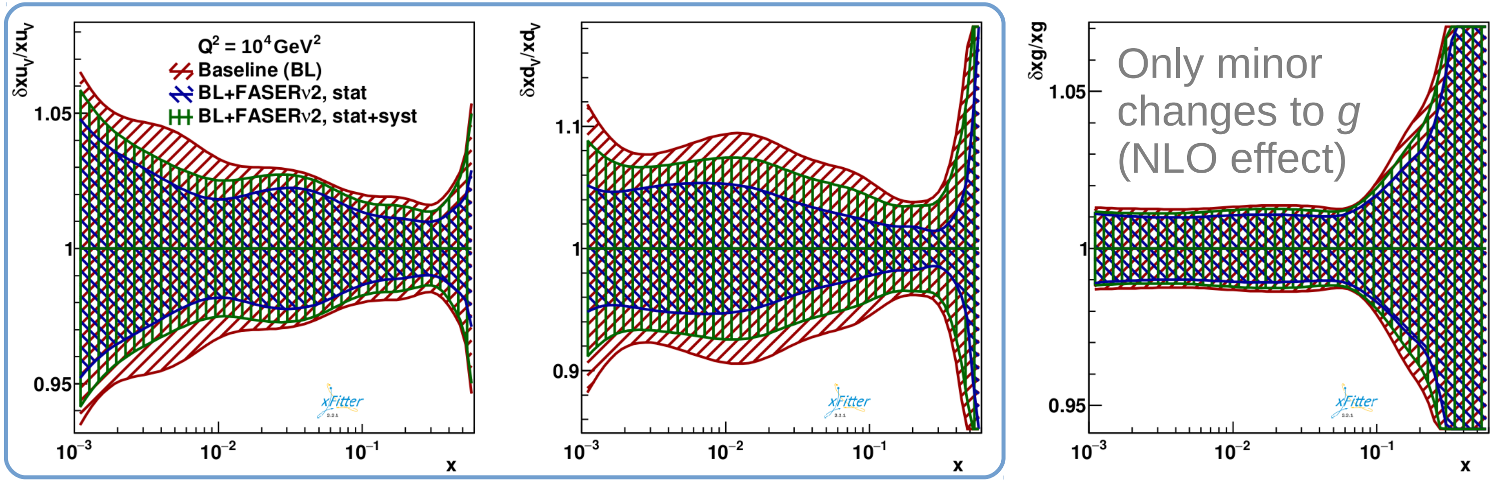
FASERν2

PDF4LHC21

Protons: assume isoscalar free-nucleon target

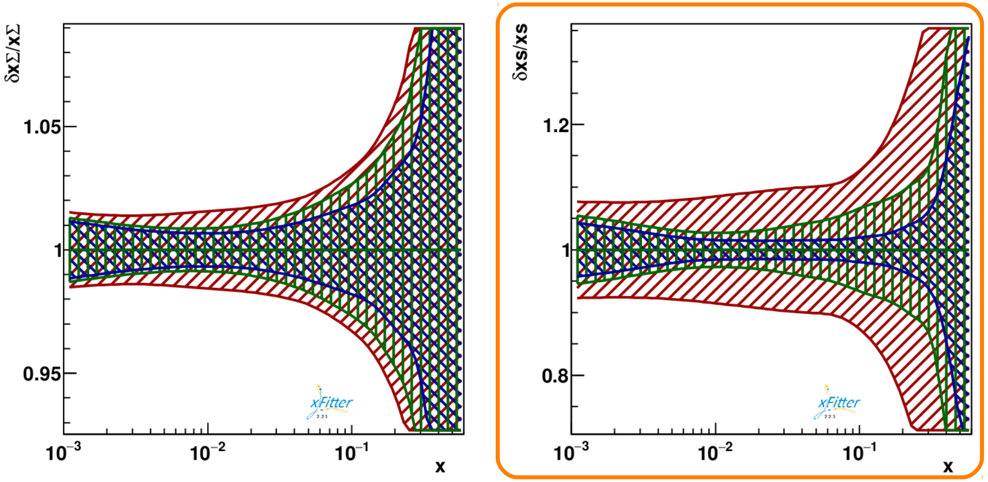
Most improvement observed for u_v, d_v, s

- s benefits from charm tagging
- u_v,d_v from charge ID



PDF4LHC21 includes νDIS, FPF constrains further!

Run III stats too small to constrain PDFs, further motivates FPF & EIC

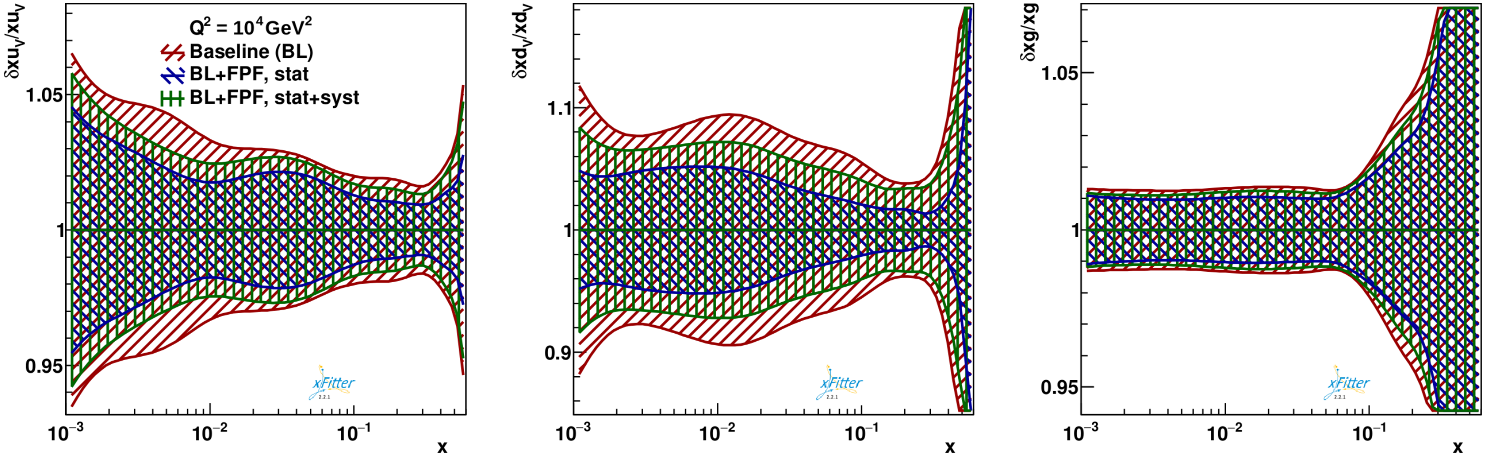


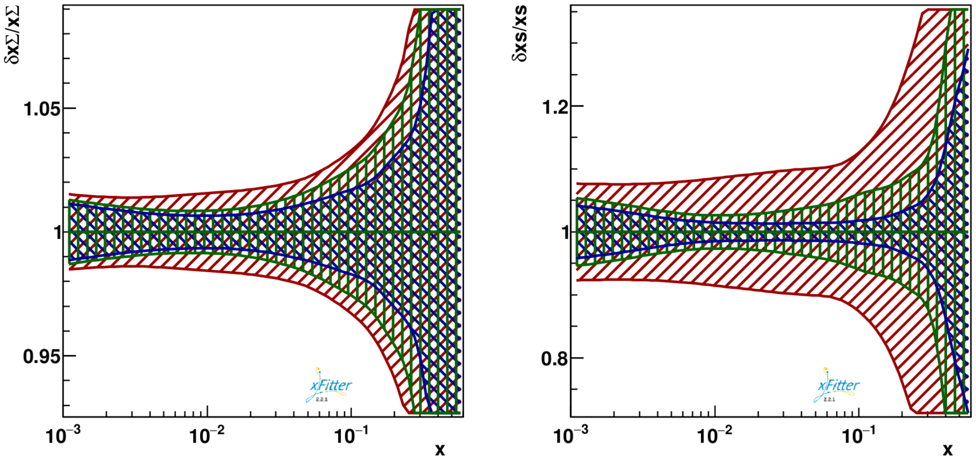
FPF combination
PDF4LHC21

Protons: assume isoscalar free-nucleon target

Most improvement observed for u_v, d_v, s

- s benefits from charm tagging
- u_v,d_v from charge I

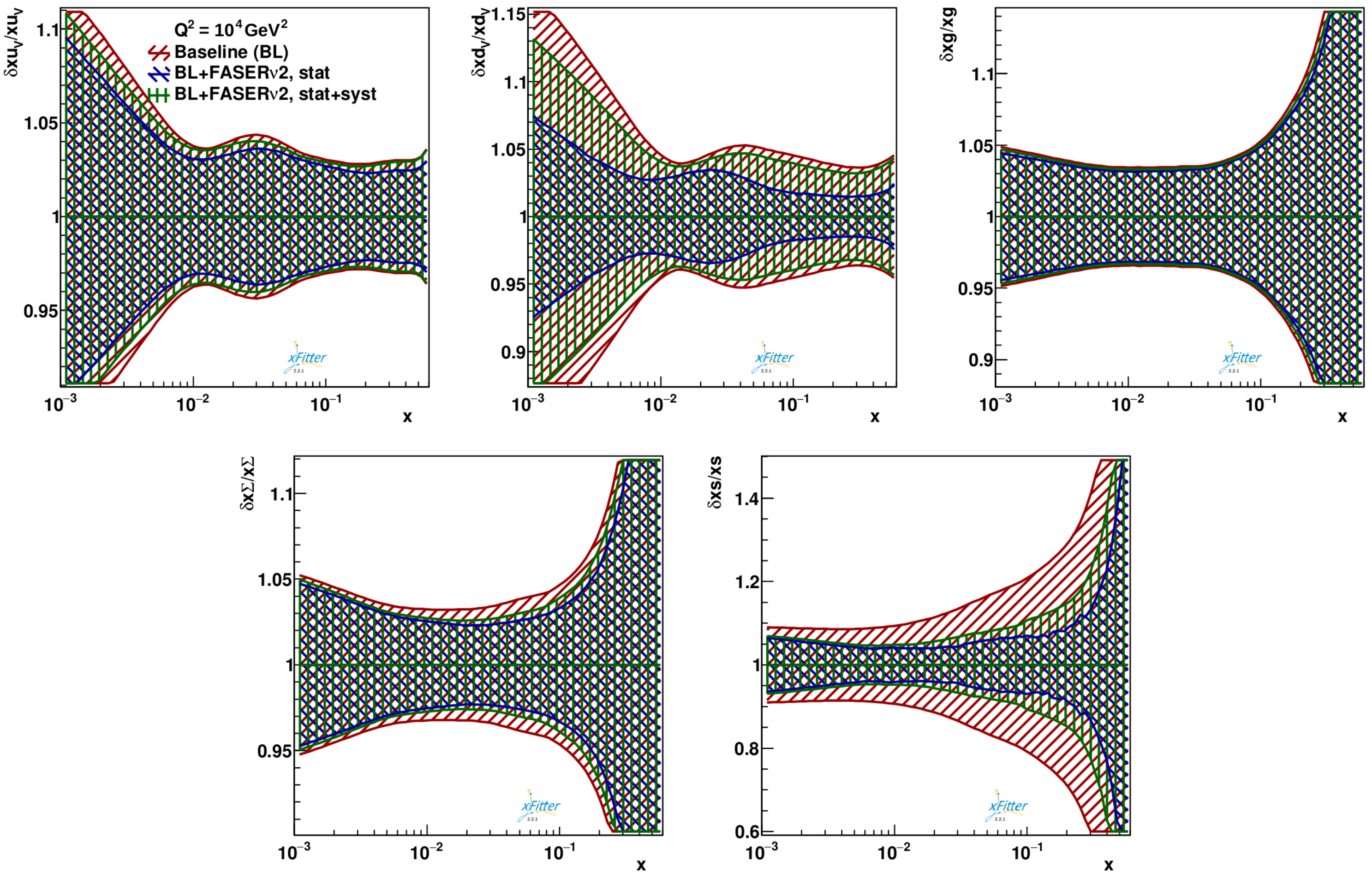




For the proton PDF study, combine information from FASERv2 and FLArE

FASERν2 impact on nuclear PDFs
EPPS21 (W)

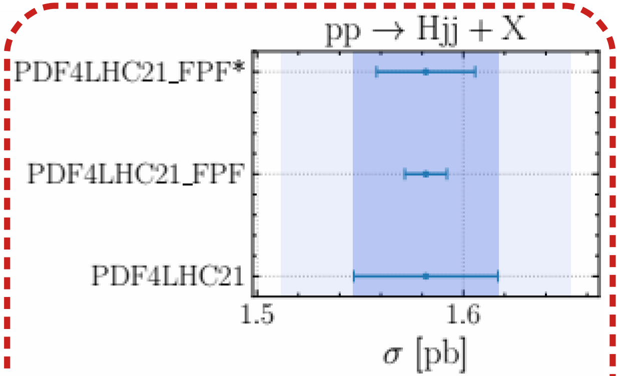
- Observed improvement also after accounting for nuclear corrections
- Most notable effects for u_v, d_v and *s*, as expected

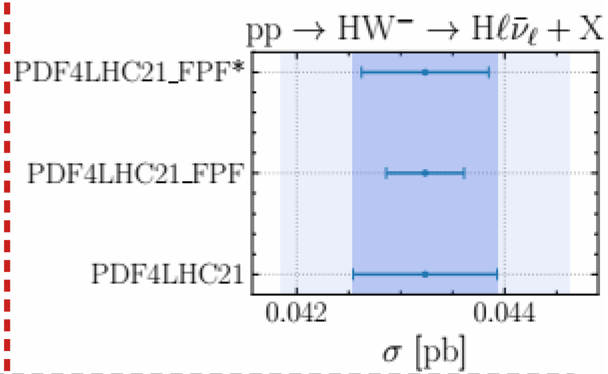


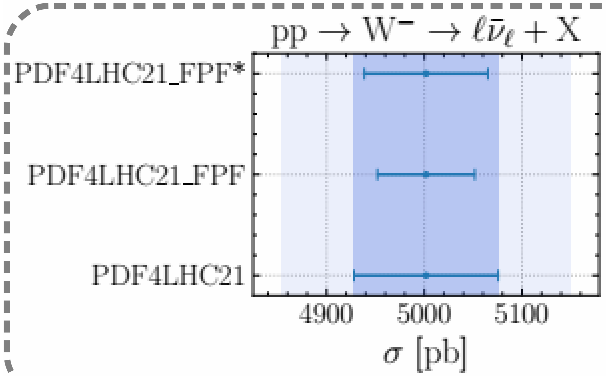
Implications to phenomenology

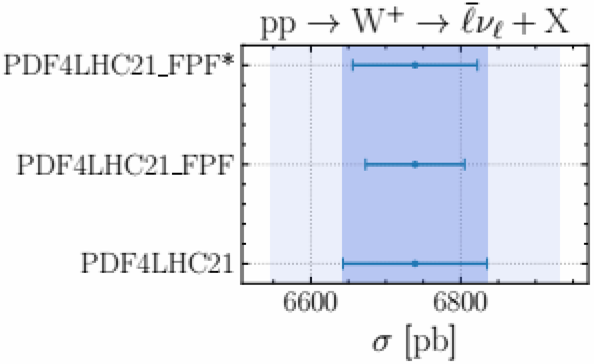
Processes at central experiments

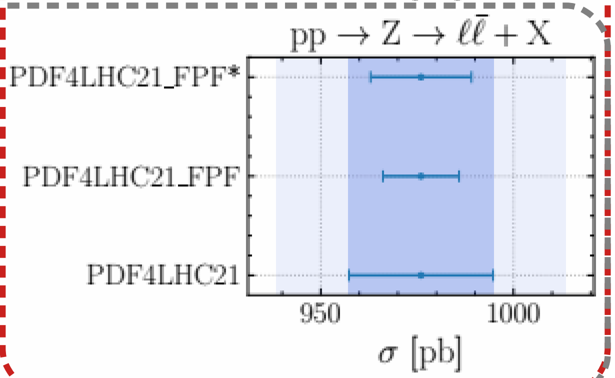
- Test the impact of the obtained PDF sets to the precision of SM cross sections
- *Baseline* (PDF4LHC21) vs *stat+syst* (*) vs *stat-only*
- Here e.g. processes relevant to **inclusive Drell-Yan** and **measurements of m_W & $\sin^2\theta_W$**









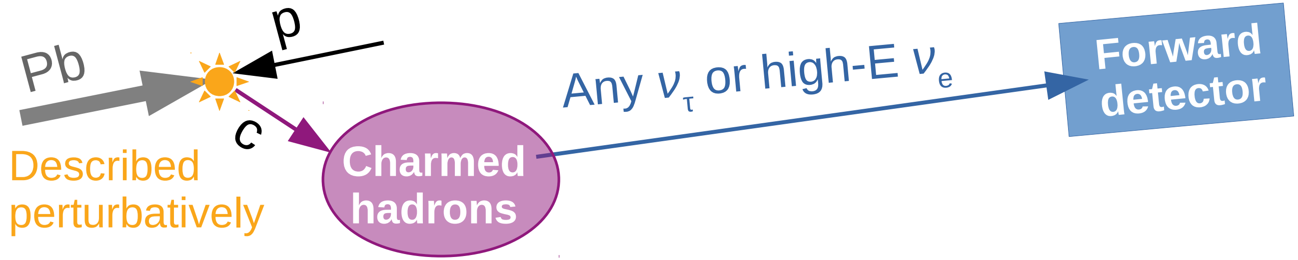


FPF@FCC

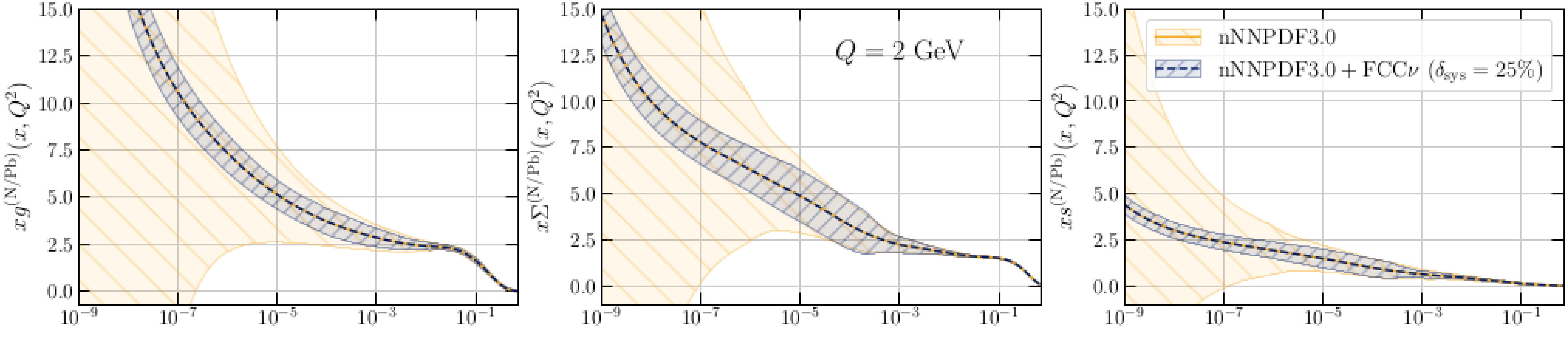
Cold nuclear matter at x~10^{-9}

Fresh results from colleagues, out last week!
arXiv:2409.021631 [hep-ph]

- Pb PDF in p-Pb collisions: forward ν detection can probe nPDF at IP!



- Also other great opportunities at FCC, e.g.polarized PDFs



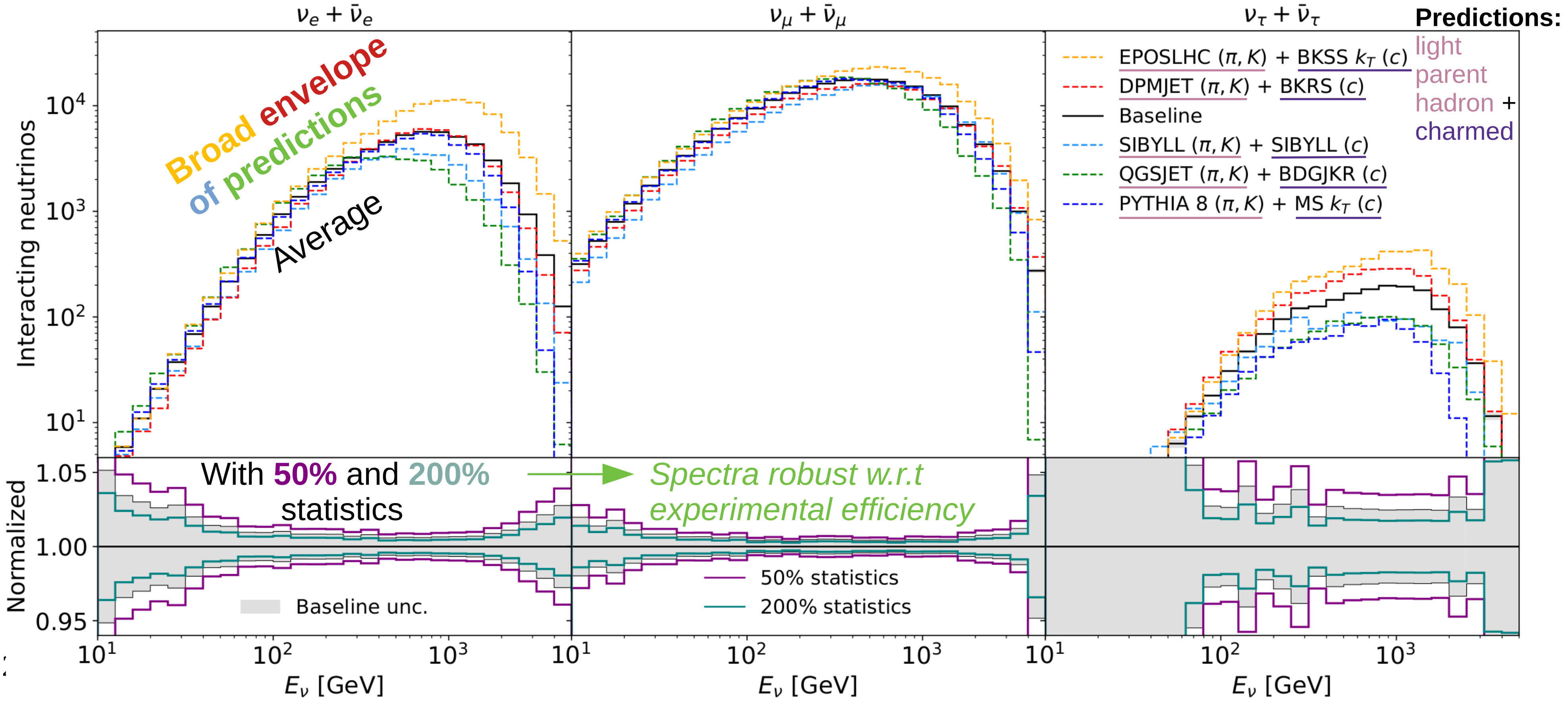
DOI:10.1103/PhysRevD.108.095020

What about neutrino flux uncertainties?

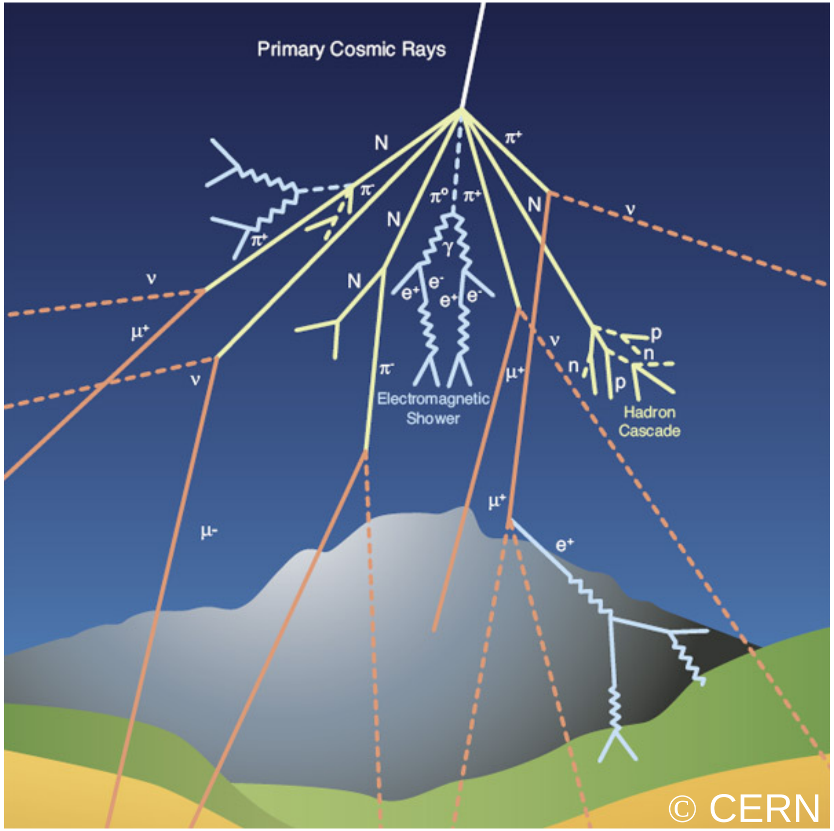
- Predictions for the incoming flux obtained using various generators, different models for ν production
  - Model assumptions affect ν spectra shape & magnitude, predictions differ greatly
  - Previously unexplored kinematic region, MC generators will need new tunes
- Important step in understanding 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!**
- Using Fisher information, estimate the ultimate uncertainty for the flux by parametrizing correlations between a broad set of different predictions
  - Examine spectra in terms of energy and radial bins, ν flavor, ν parent hadrons
  - Profiling: exclusion bounds for various processes at existing & proposed detectors

The neutrino spectra

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



Physics applications – enhanced strangeness and the cosmic ray muon puzzle



- **Muon puzzle**: 8σ deficit of high-E muons in air shower simulations (QCD) vs measurements
- Is the distribution of produced secondary particles predicted correctly by current models?
  - Enhancement of s production would increase number of muons
  - Should lead to less pions and more kaons at LHC (Enhanced strangeness hypothesis)
- Reweigh the counts of neutrinos associated with pions by $(1 - f_s)$, and those from kaons by $(1 + F f_s)$

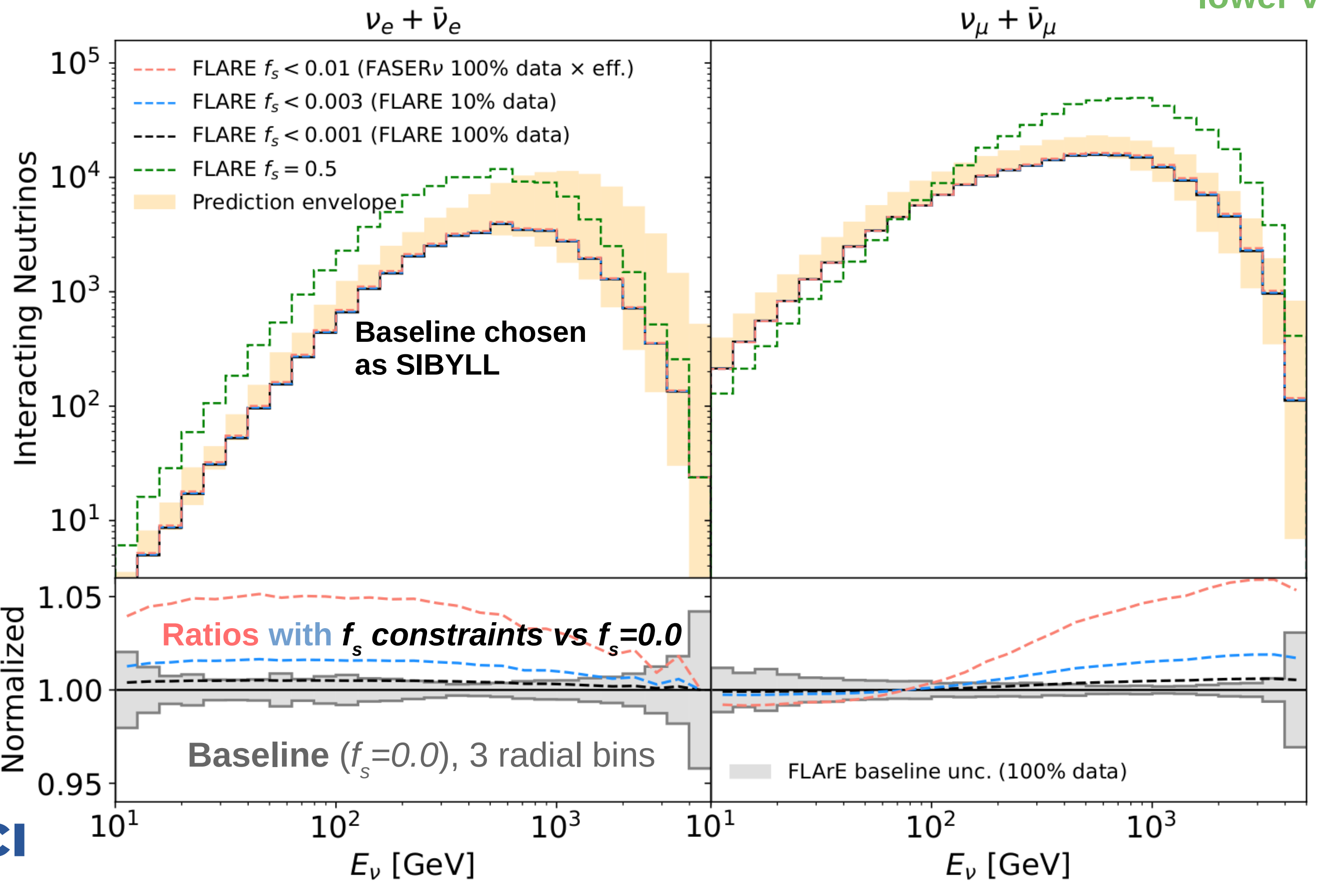
  F: **Phenomenological factor, account for difference in π / *K* production rates**
- *arXiv: 2202.03095 [hep-ph]:*
  f_s=0.5 could explain the cosmic ray muon excess

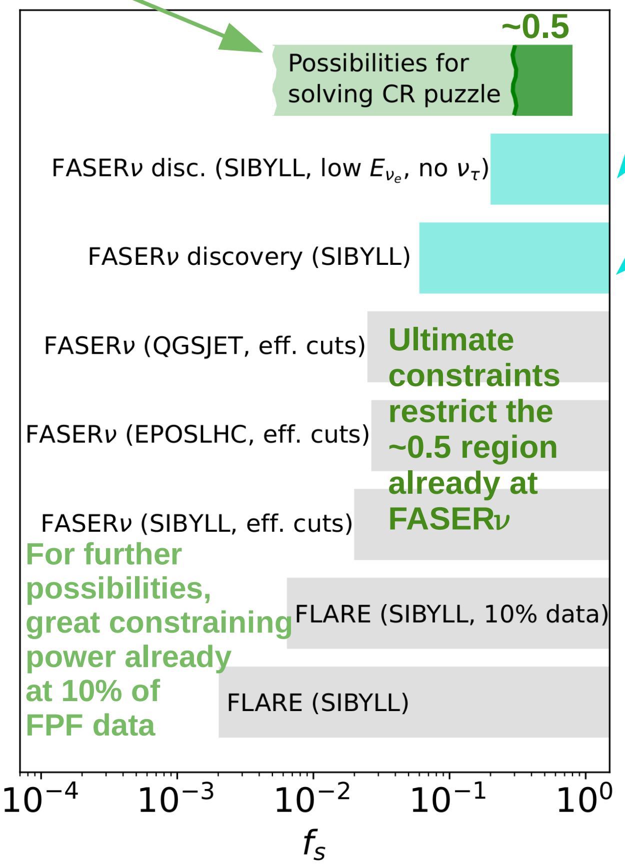
See e.g. arXiv:2105.06148 [hep-ph] for a review

Enhanced strangeness

At LHC energies, f_s might also have lower values

Discovery potential: examine cases with non-zero baseline f_s





UCI

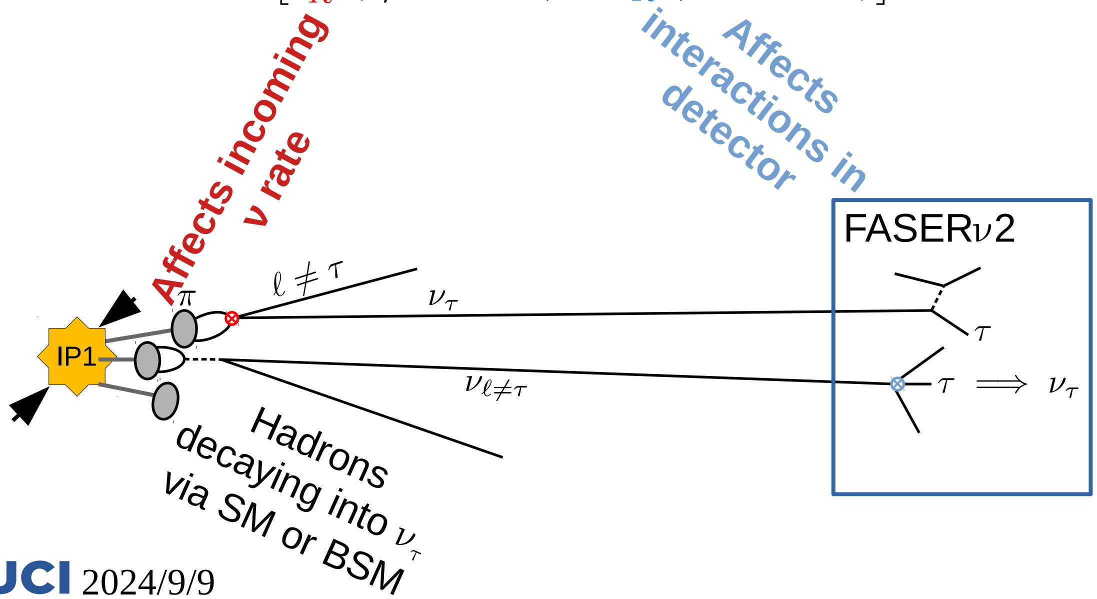
Non-standard interactions (NSI)

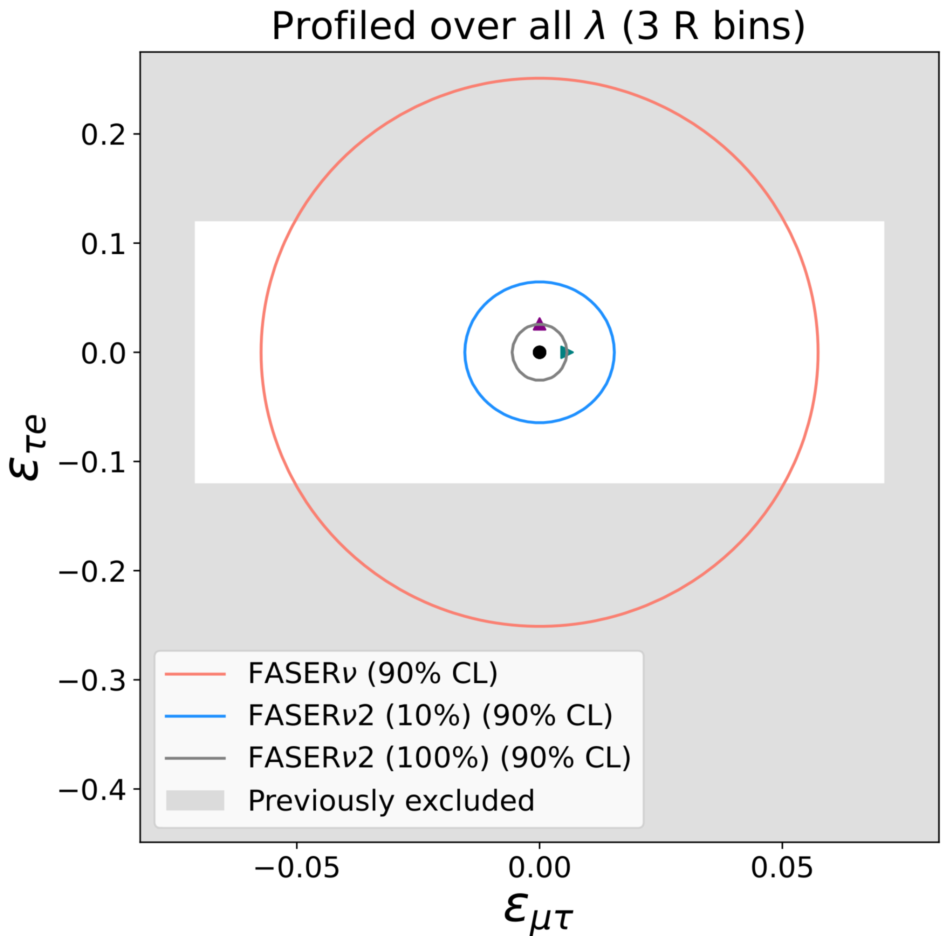
(See doi:10.1007/JHEP10(2021)086)

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

- Extend the SM Lagrangian by dimension-6 EFT terms

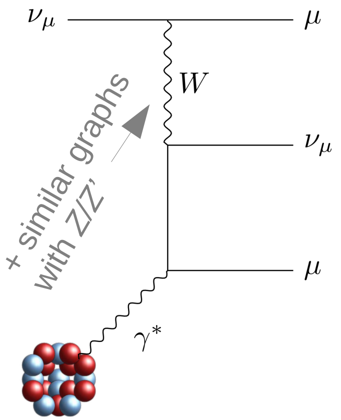
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{2V_{ud}}{v^2} \times (\bar{u}\gamma^\kappa P_R d) \times \left[\epsilon_R^{\mu\tau}(\bar{\ell}_\mu \gamma_\kappa P_L \nu_\tau) + \epsilon_R^{\tau e}(\bar{\ell}_\tau \gamma_\kappa P_L \nu_e)\right]$$



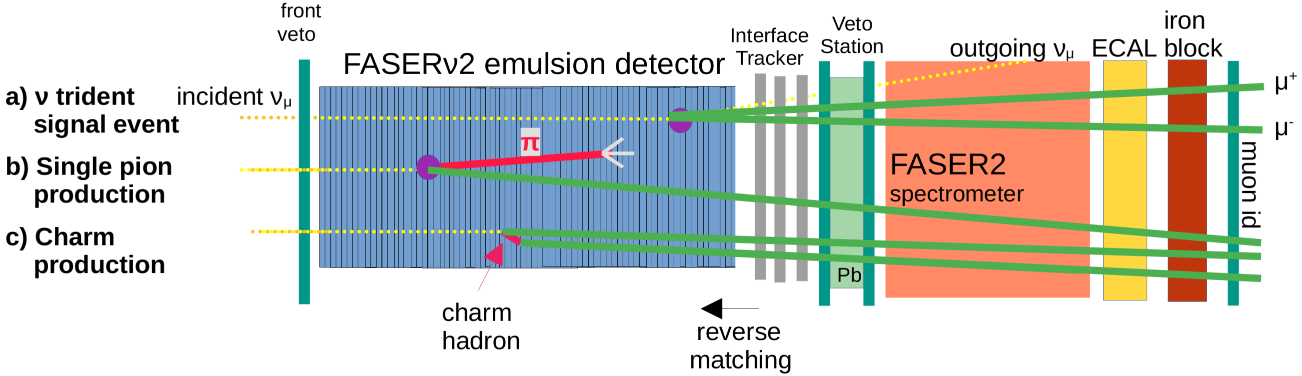


Neutrino tridents @ FASERν2

- Neutrino-induced charged lepton production in Coulomb fields of heavy nuclei



- Signal: two μ from one vertex
- LHC: E_ν up to ~5 TeV, below W production

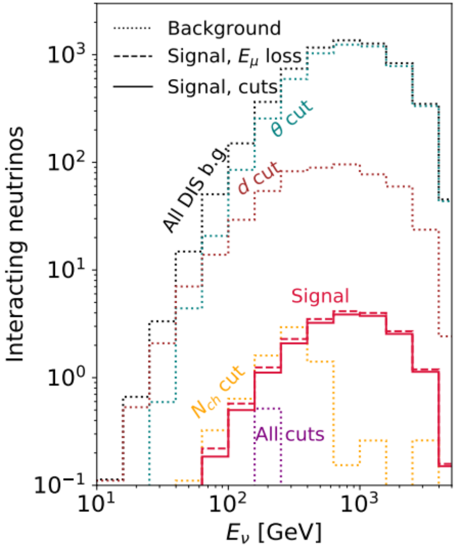


Observations claimed at

- CHARM II, 3σ, E_ν~20 GeV
- CCFR, 3σ
- NuTeV

} E_ν~160 GeV

Identified diffractive charm b.g. neglected elsewhere!



- Possible to resolve signal with cuts that diminish all b.g.

Great potential for conclusive observation at FASERν2!

Summary and outlook

- We have entered the era of using LHC neutrinos directly for physics
- Proposed forward experiments at the LHC (& beyond) have potential e.g. for
  - Solving the cosmic muon ray excess
  - Probing proton and nuclear PDFs, notable improvement in s PDF
  - Great constraining potential for neutrino NSI & 4-Fermi interactions
  - Conclusive observation of neutrino trident interactions
    - Probe physics at the EW scale and below
    - Also non-$\mu^+\mu^-$ final states may be possible (no prior observations!)

Thanks for your attention!

Back up

Workflow

Software package available at github

Predictions for hadron production at IP1

- Light mesons

$\pi^{\pm},\ K^{\pm},\ K^0_L,\ K^0_S$

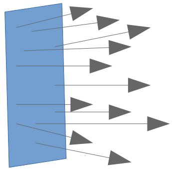
- Charm hadrons

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

$D^{\pm}_s,\ \Lambda^{\pm}_c$

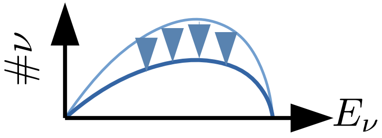
Decays into neutrinos

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



Propagate to forward experiments

- Some models affect the spectra of *incoming neutrinos*

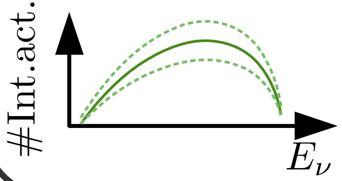


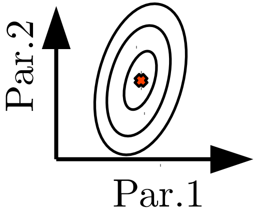
Interactions within detector

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

↓

Observed ν spectra, with uncertainties





N(π,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*

Synergy in DIS @ FPF & EIC

- Double-differential cross section
  - PDF information in structure functions *F*

$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{(1+Q^2/m_W^2)^2}\left[Y_+F_2^{\nu A}(x,Q^2) - y^2F_L^{\nu A}(x,Q^2) + Y_- xF_3^{\nu A}(x,Q^2)\right]$$

$$\frac{d^2\sigma^{\bar\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{(1+Q^2/m_W^2)^2}\left[Y_+F_2^{\bar\nu A}(x,Q^2) - y^2F_L^{\bar\nu A}(x,Q^2) - Y_- xF_3^{\bar\nu A}(x,Q^2)\right]$$

- E.g. with 4 active flavors, diagonal CKM, and no heavy quark effects:

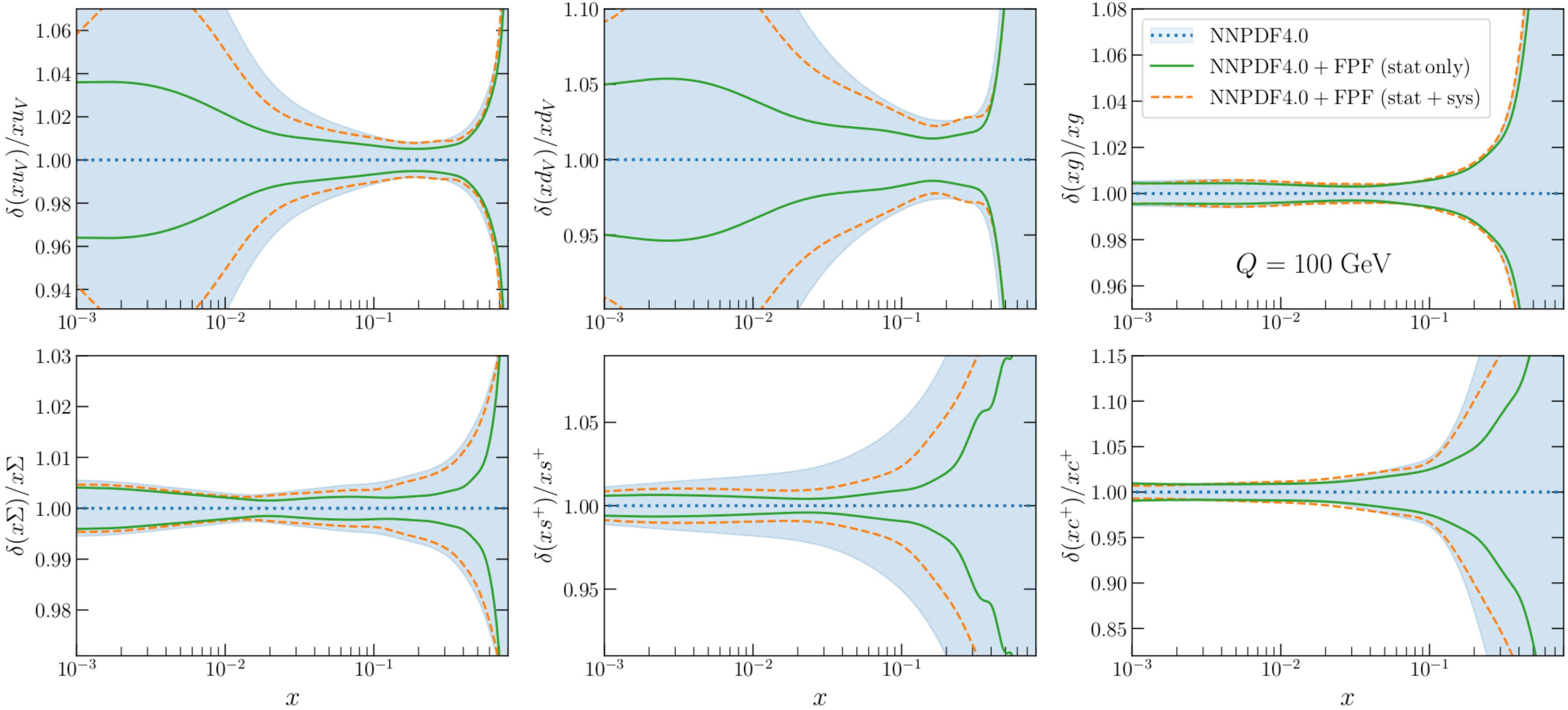
$$F_2^{\nu p}(x,Q^2) = 2x(f_{\bar u} + f_d + f_s + f_{\bar c})(x,Q^2)$$

$$F_2^{\ell p}(x,Q^2) = x\left(\frac{4}{9}[f_{u^+} + f_{c^+}] + \frac{1}{9}[f_{d^+} + f_{s^+}]\right)(x,Q^2), \quad f_{q^\pm} = f_q \pm f_{\bar q}$$

- **Synergy: CC** from FPF, **NC** from EIC - *best quark flavor separation sensitivity*

FPF pseudodata in the NNPDF fit

- Independent cross check: include the FPF pseudodata in the NNPDF fit
- Indicating similar impact as the xFitter profiling studies with PDF4LHC21



Polarized PDF (pPDF) with FPF@FCC

Fresh results from colleagues, out last week!
arXiv:2409.021631 [hep-ph]

- How do parton spins & angular momenta lead to a proton spin ½?
- Polarized DIS is a good probe, pPDF part of e.g. the future EIC program
- Neutrinos approx. massless, beam is polarized: polarize target to probe pPDF
- High event rates at FCC, overcoming smallness of neutrino interaction cross sections