Physics with neutrinos at a Large Hadron Collider Forward Physics Facility

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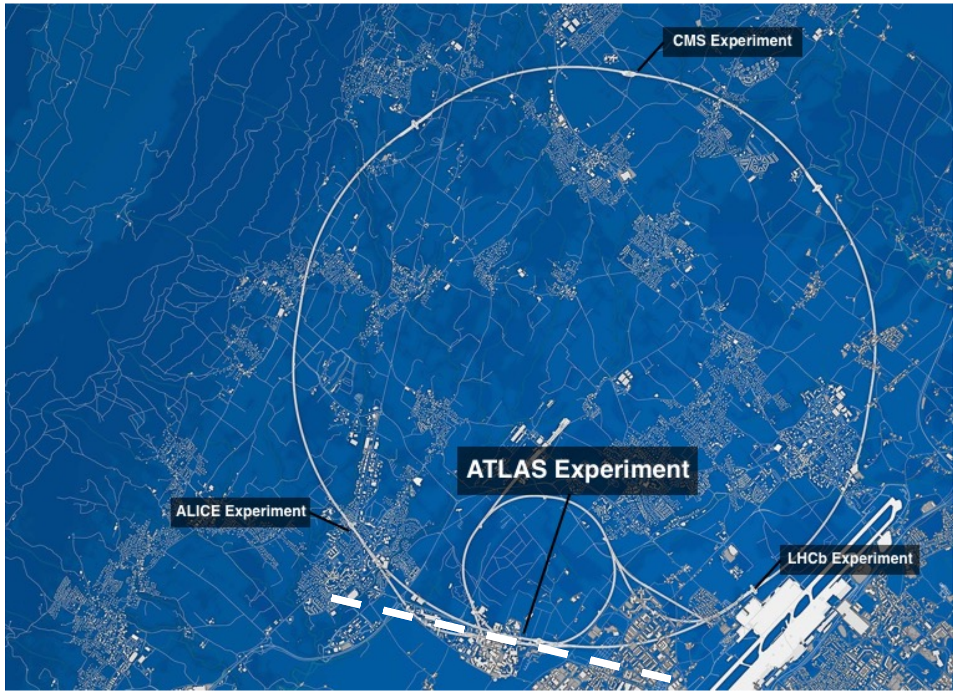
University of Iowa

Brookhaven Forum, October 6, 2023

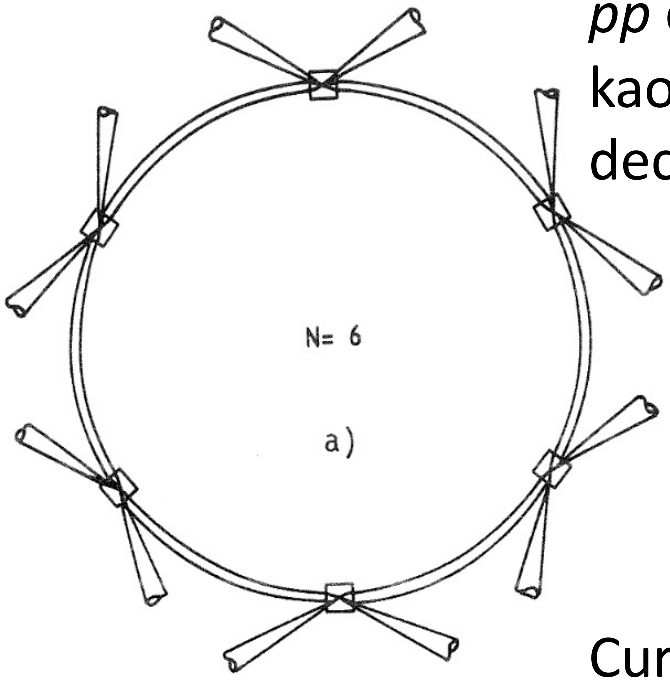
Work supported in part by the US Department of Energy

Collider neutrinos – more than missing energy!



atlas.cern/about

Neutrinos produced that go down the beam pipe.



deRujula and Ruckl, 1984

CERN TH 3892

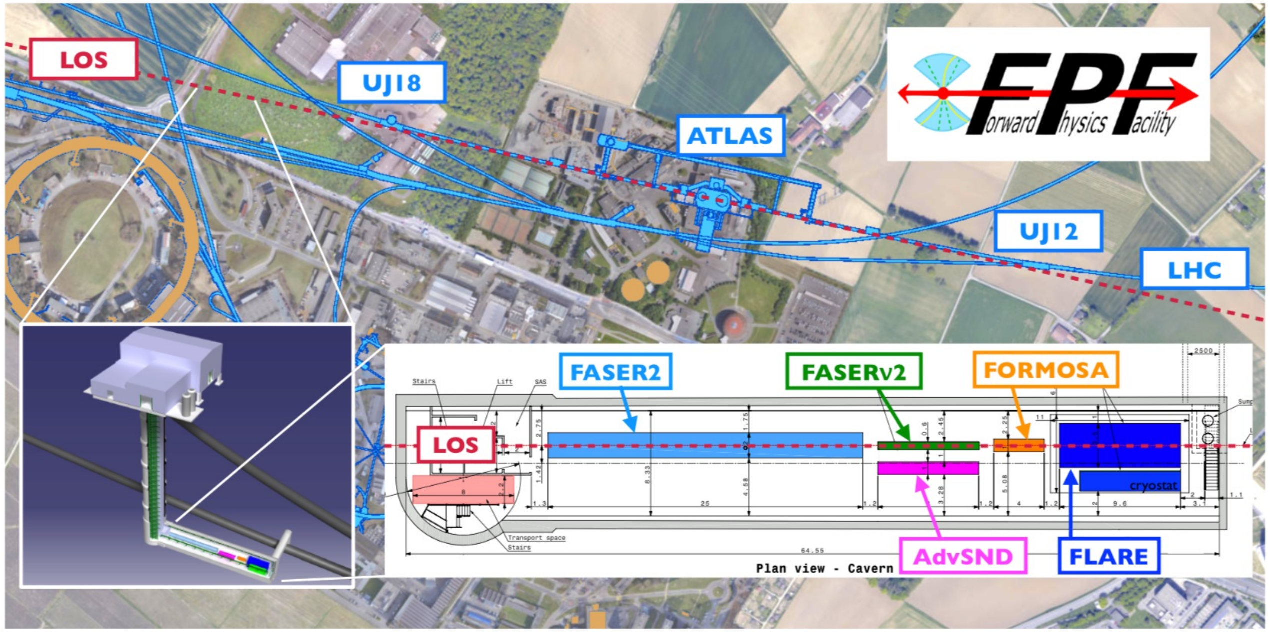
SSC and LHC,
pp collisions to make pions, kaons, charm hadrons, etc, that decay into neutrinos + X.

Early discussions including:
deRujula & Ruckl (1984)
Winter (1990), deRujula, Fernandez & Gomez (1993), Vannucci (1993)

Currently: FASERν and SND@LHC installed in existing tunnels.
Proposed: Forward Physics Facility.

Purpose-built Forward Physics Facility

Underground facility ~620 m far forward from the ATLAS IP, shielded by concrete and rock. FPF experiments to detect $\sim 10^6$ neutrino interactions in high-luminosity run, energies up to a few TeV.



White paper: Feng et al., *Phys.G* 50 (2023) 030501

Detectors designed for Standard Model and BSM Physics.

Neutrino detection at FASERv2, AdvSND and FLArE.

Report on core samples taken to evaluate site/cost complete.

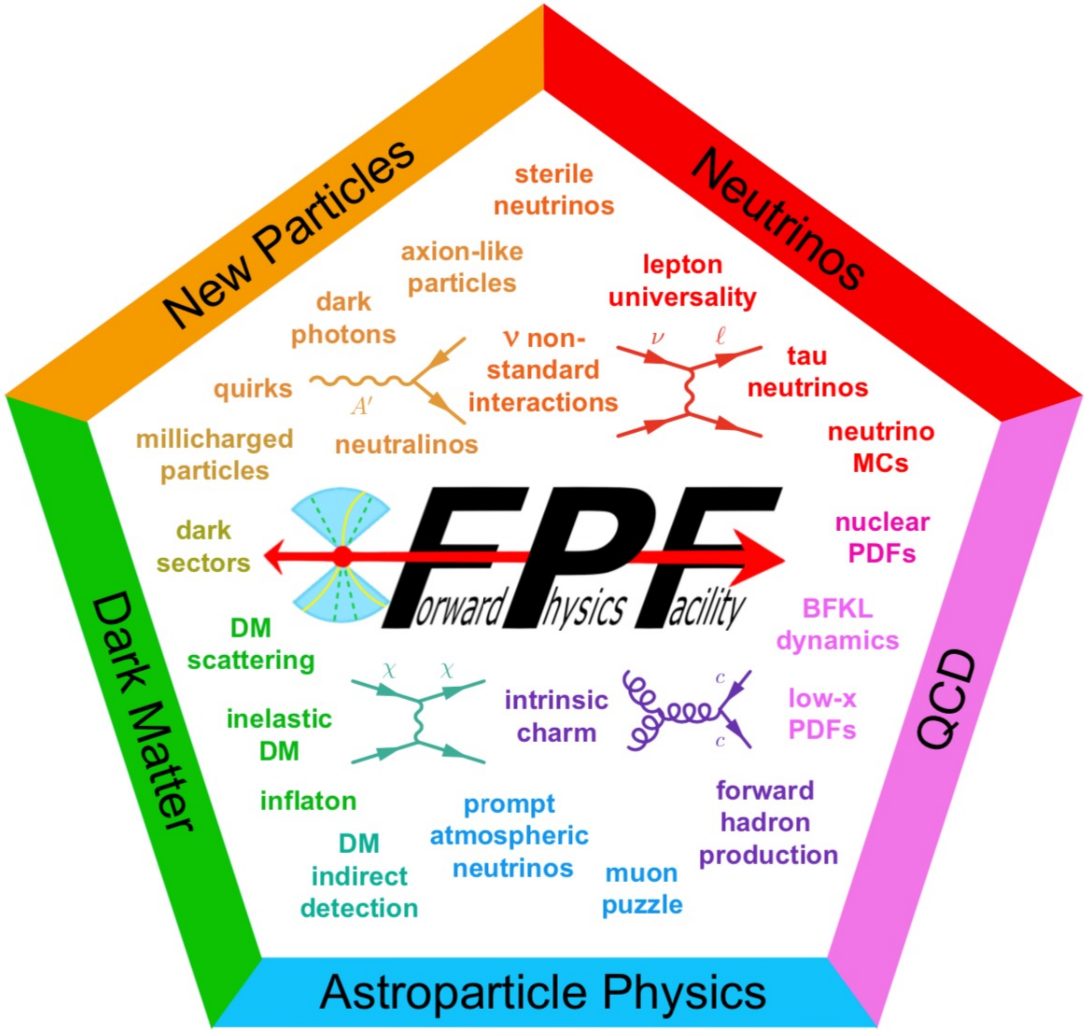
FPF white papers

<u>short</u>:

Anchordoqui et al, 2109.10905

<u>long</u>: Feng et al, 2203.05090

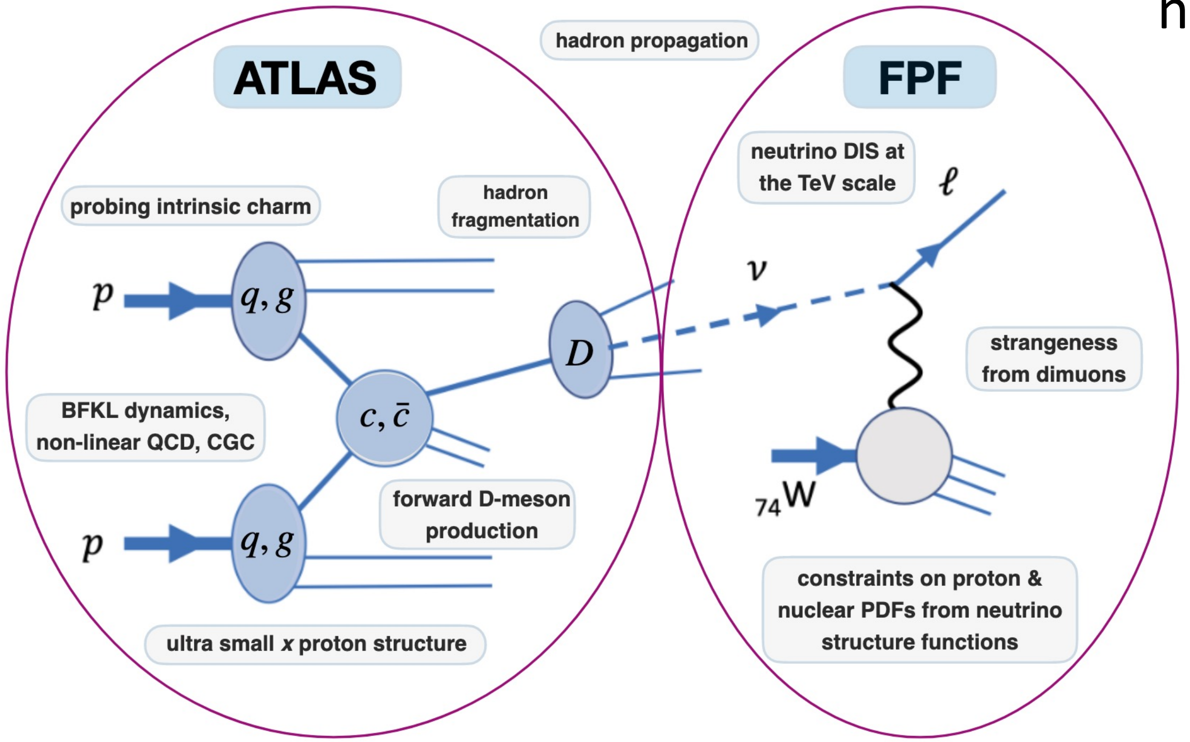
and see references therein!



https://indico.cern.ch/event/1296658/ Recent Forward Physics Theory Workshop Sept 18-19 @ CERN, Forward Physics Facility Slack channel, FPF Workshops

Collider neutrinos: pp and νA collisions

hadron production that ultimately yields neutrinos of all 3 flavors



neutrino interactions (all 3 flavors, from different hadron sources) on nuclear targets

Neutrino flavor, neutrino interactions (SM and BSM)

Neutrinos as proxies for hadrons

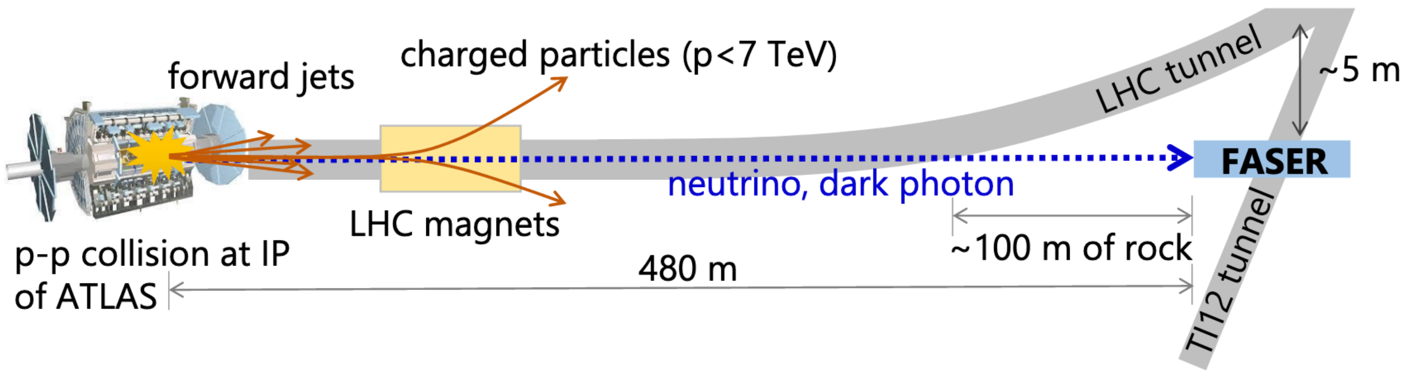
LHC Run 3

Both experiments installed, in T12 and T18 existing injector tunnels on either side of the ATLAS IP.

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

θ	η
0°	∞
0.1°	7.04
0.5°	5.43
1°	4.74

FASERν



Figures “not to scale.”

FASERν 1.2 ton, 25 cm x 25cm

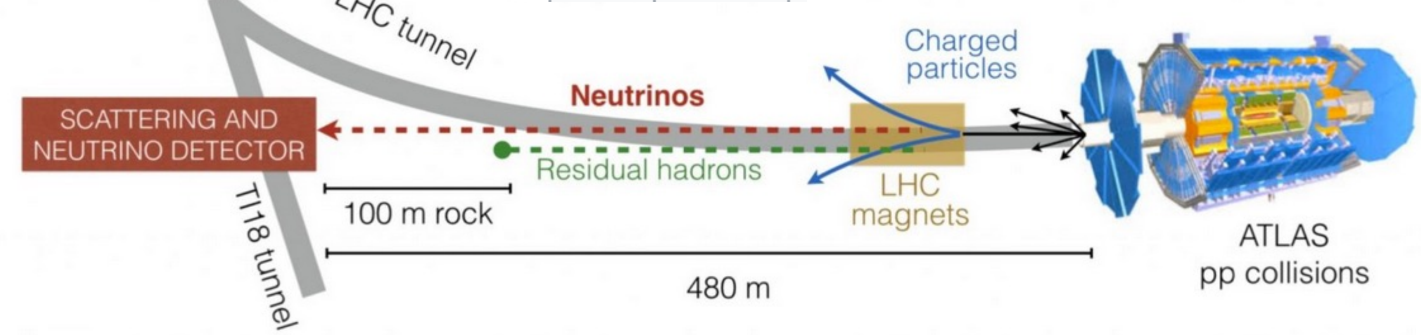
on axis, $\eta > 8.5$

SND@LHC 800 kg, 39 cm x 39 cm

off axis, $8.5 > \eta > 7$

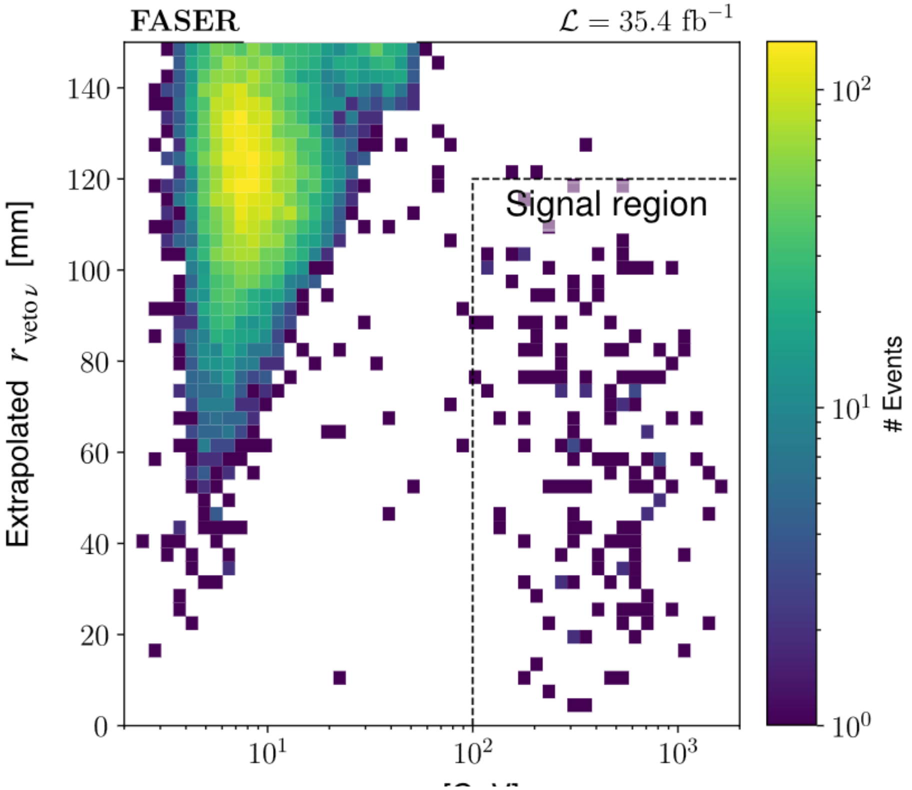
150 fb^{-1}

SND@LHC

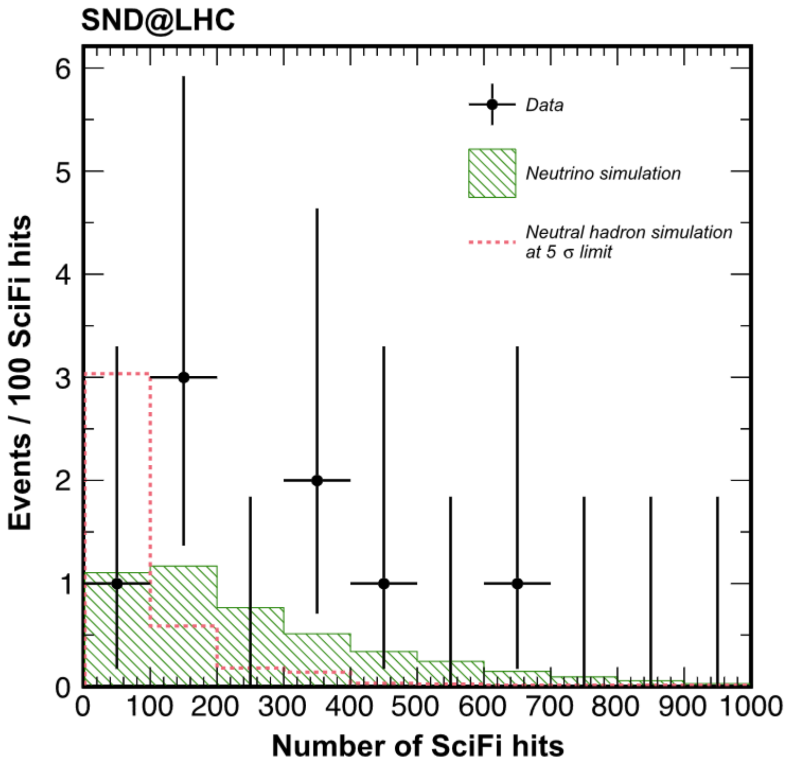


https://www.epfl.ch/labs/lphe/en/4266-2/

First neutrino events at LHC Run 3: $\nu_\mu CC$ (muons)



$$n_\nu = 153^{+12}_{-13}(\text{stat})\,^{+2}_{-2}(\text{bkg}) = 153^{+12}_{-13}(\text{tot})$$



FASER Collab, PRL 131 (2023) 031801

SND@LHC Collab, PRL 131 (2023) 031802

Run 3 & FPF Detectors

Emulsion detectors w/ tungsten plates and auxiliary detectors:

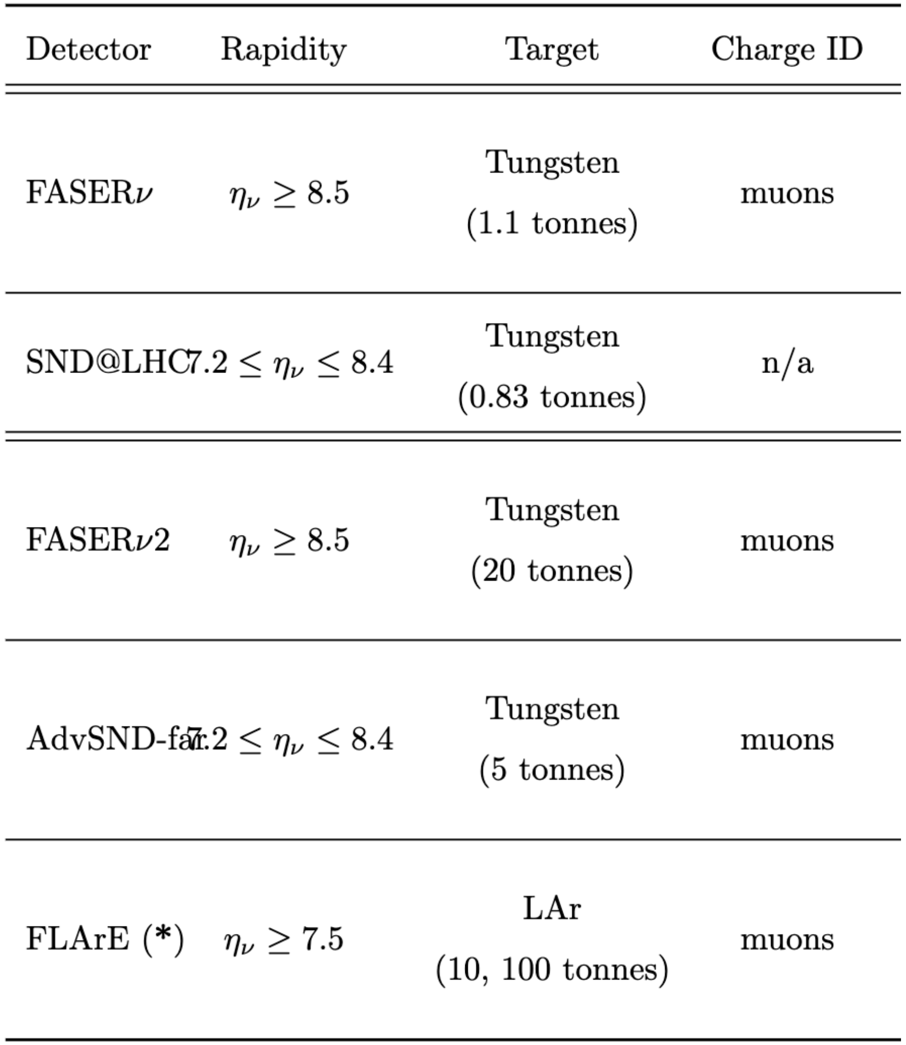
- FASERν, FASERν2
- SND@LHC, AdvSND

LAr TPC:

- FLArE

Magnetic field:

- FASER, FASER2
- AdvSND

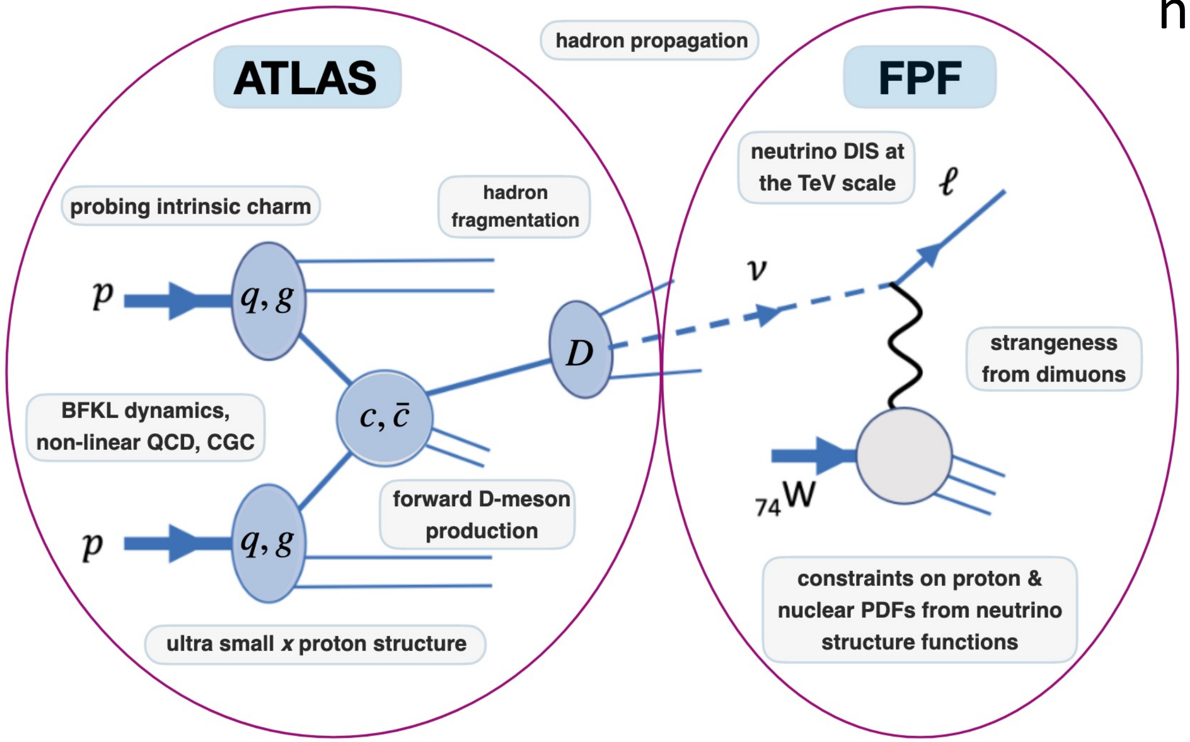


Detector	Rapidity	Target	Charge ID
FASERν	$\eta_\nu \geq 8.5$	Tungsten (1.1 tonnes)	muons
SND@LHC	$7.2 \leq \eta_\nu \leq 8.4$	Tungsten (0.83 tonnes)	n/a
FASERν2	$\eta_\nu \geq 8.5$	Tungsten (20 tonnes)	muons
AdvSND-far	$7.2 \leq \eta_\nu \leq 8.4$	Tungsten (5 tonnes)	muons
FLArE (*)	$\eta_\nu \geq 7.5$	LAr (10, 100 tonnes)	muons

Cruz-Martinez et al, 2309.09581

Collider neutrinos: pp and νA collisions

hadron production that ultimately yields neutrinos of all 3 flavors



neutrino interactions (all 3 flavors, from different hadron sources) on nuclear targets

Neutrino flavor, neutrino interactions (SM and BSM)

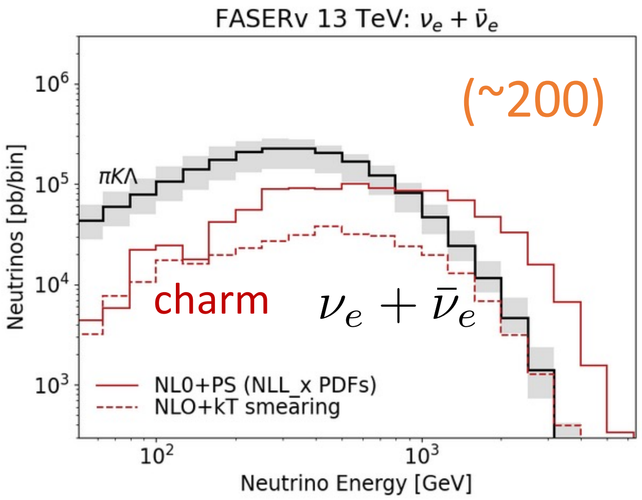
Neutrinos as proxies for hadrons

Neutrinos as proxies for hadrons at the LHC

Example: Interactions at FASERv with 35 fb^{-1} (will extend to 150 fb^{-1} in Run 3)

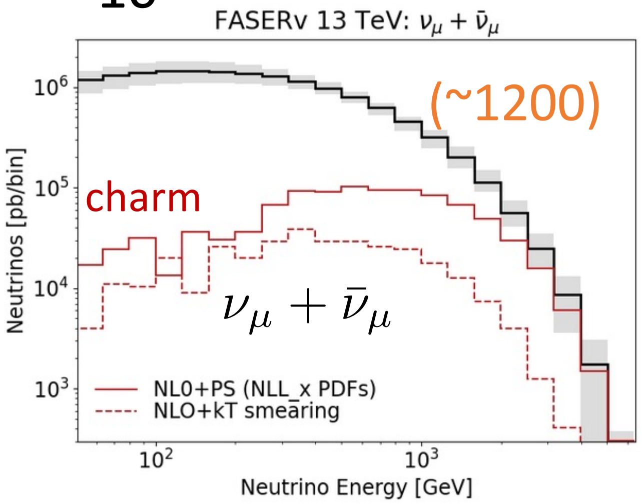
and event numbers of interacting ν_i at 10-ton detector at FPF (3000 fb^{-1})

~10^5



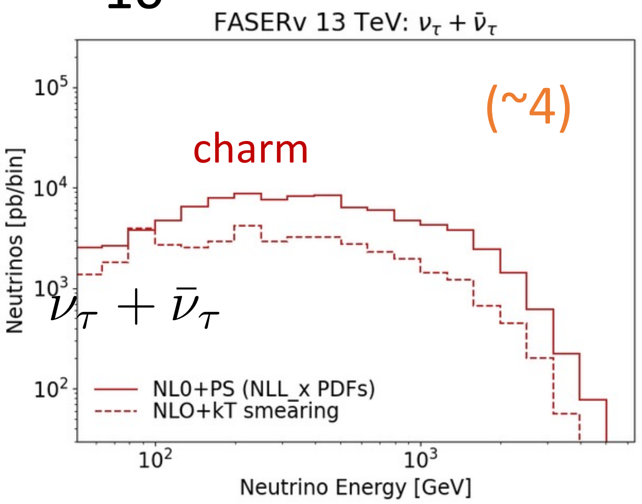
HE charm, plus kaons.

~10^6



HE charm, lots of pions.

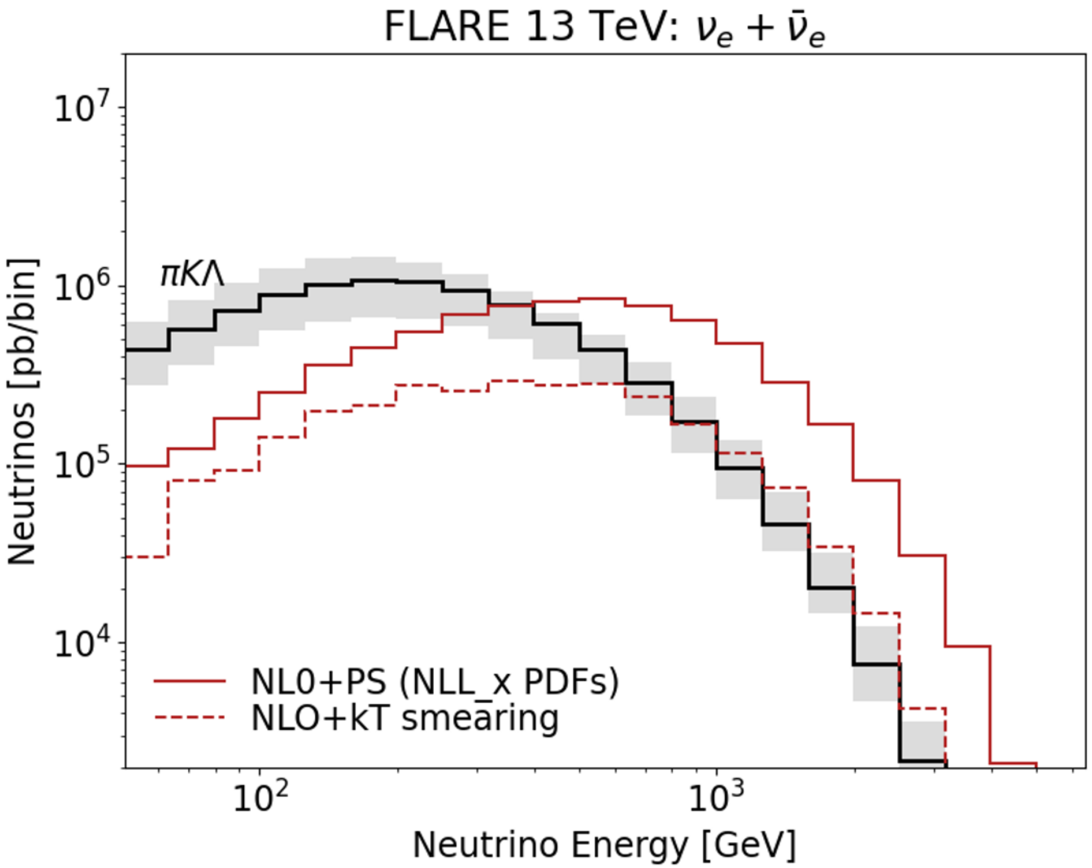
~10^3



All from charm.

Charm contributions: Jeong, Bai, MHR (similar to Bai, Diwan, Garzelli et al, 2112.11605,2203.07212) NLO+kT smearing; L. Buonocore and L. Rottoli, in preparation (2023) NLO+PS (NLL_x PDFs);
Light meson contributions: see e.g., Kling & Nevay, Phys.Rev.D 104 (2021) 113008

Neutrino flux example



light mesons and baryons, uncertainties from different Monte Carlo evaluations

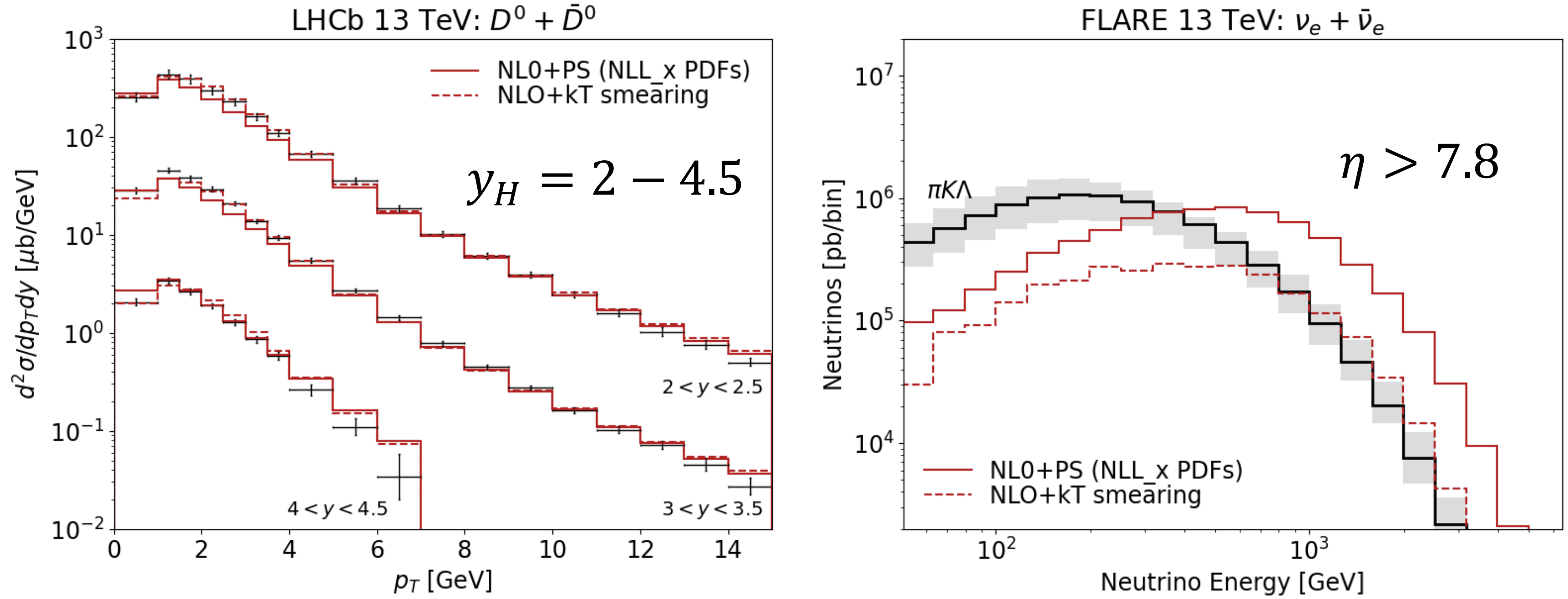
charm contributions (shown here are 2 calculations, both NLO)

Charm uncertainties from:

- small-x PDF extrapolations
- m_c close to 1 GeV (QCD)
- non-perturbative effects
- new kinematic region
- very forward – factorization & fragmentation

Strategy: LHCb extrapolated to FPF

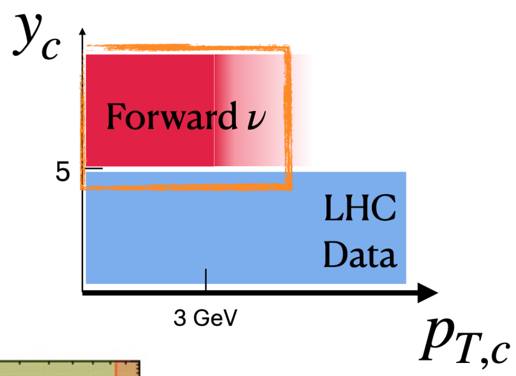
<u>Differences</u>: primarily in PDFs, one has NLL_x PDFs sum ln(1/x_2).

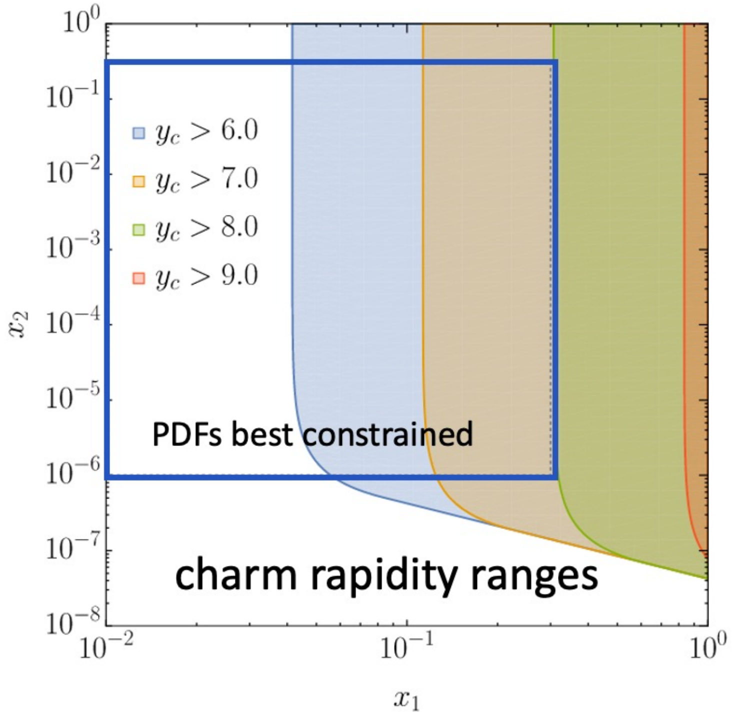


Histograms almost the same for most of LHCb range, much different at FLArE.

Jeong, Bai, Reno (similar to Bai, Diwan, Garzelli et al, JHEP 06 (2022) 148, JHEAp 34 (2022) 212)
NLO+kT smearing; L. Buonocore and L. Rottoli, in preparation (2023) NLO+PS (NLL_x PDFs)

What kinematic regions for charm at FPF ?

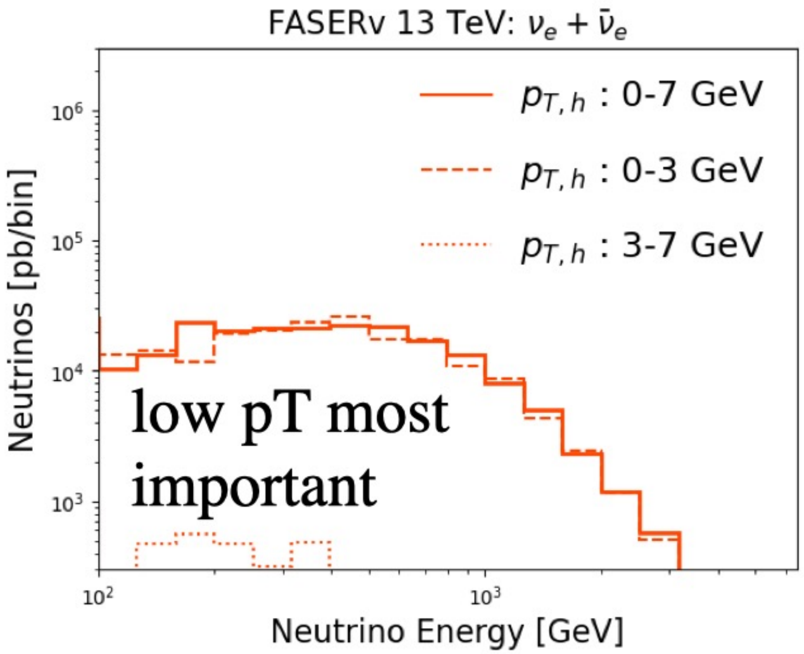




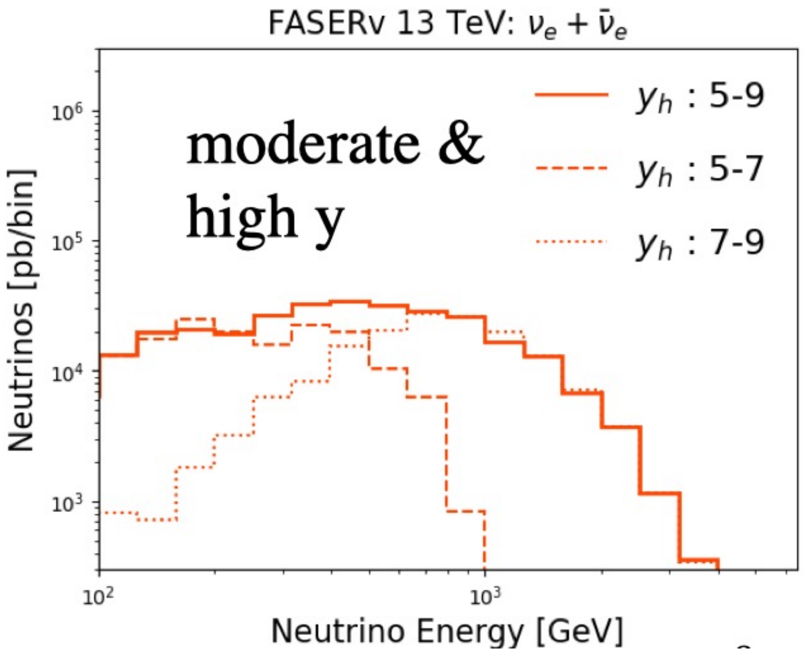
PDFs best constrained

charm rapidity ranges

Fig: W. Bai, M. V. Diwan, M. V. Garzelli, K. Kumar, Y. S. Jeong & MHR. (2212.07865).



low pT most important

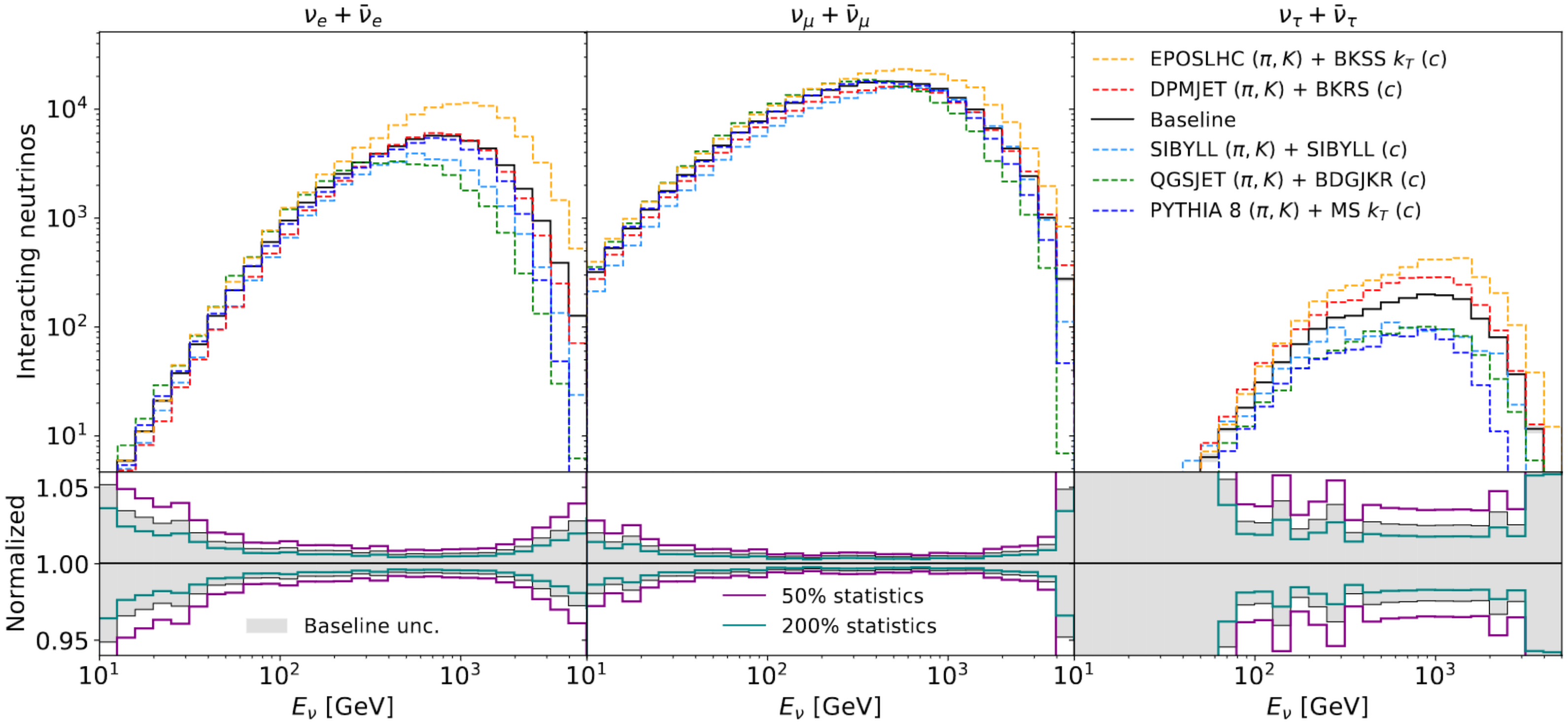


moderate & high y

Figs. courtesy of B. Chauhan

Neutrino fluxes – correlations

Correlations between spectra of different neutrino flavors, projected statistical uncertainties allows differentiation between flux results.



Kling, Makela, Trojanowski, 2309.10417

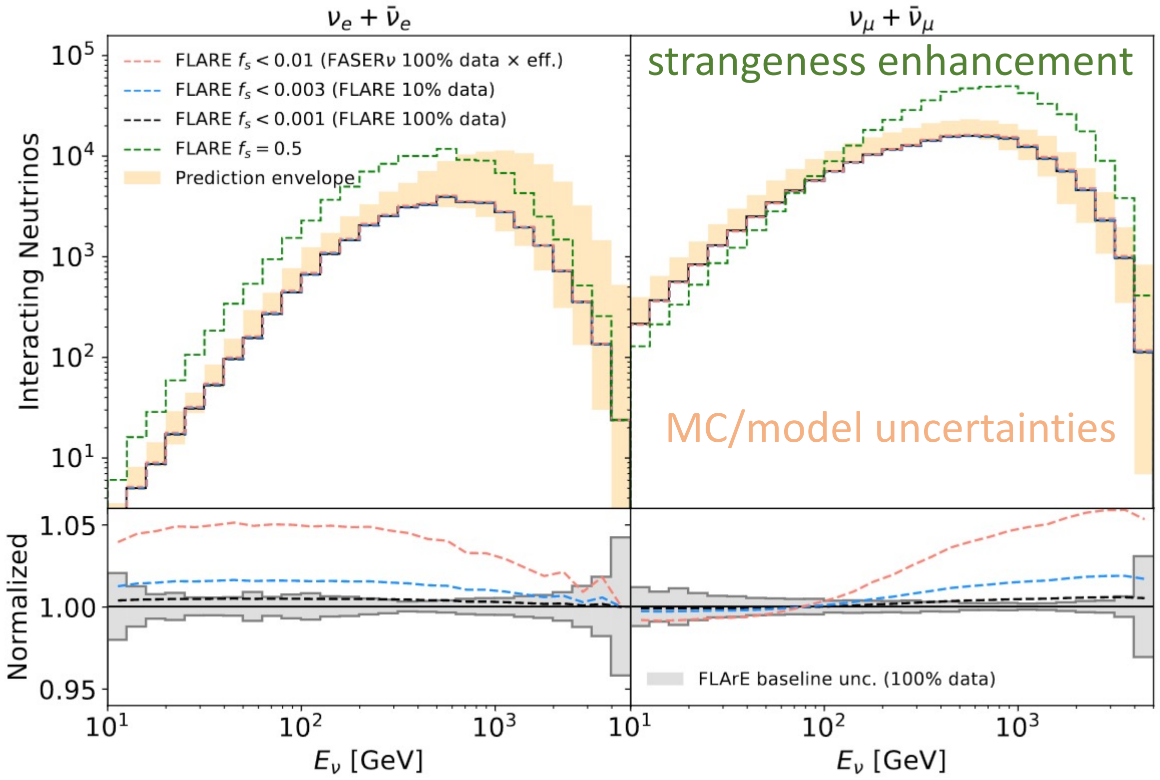
Can also look at radial dependence in detector – details in *Kling, Makela, Trojanowski, 2309.10*

Figures show interacting neutrinos

Astroparticle physics implications

Muon puzzle in cosmic ray air showers: discrepancy between observed and predicted muon rates in high energy cosmic ray induced air showers. Is the π/K ratio wrong in Monte Carlos?

Test with LHC neutrino flux: Enhanced strangeness model of Anchordoqui et al. JHEAp 34 (2022) 19, applied by Kling et al., distinguishable in FPF experiments.

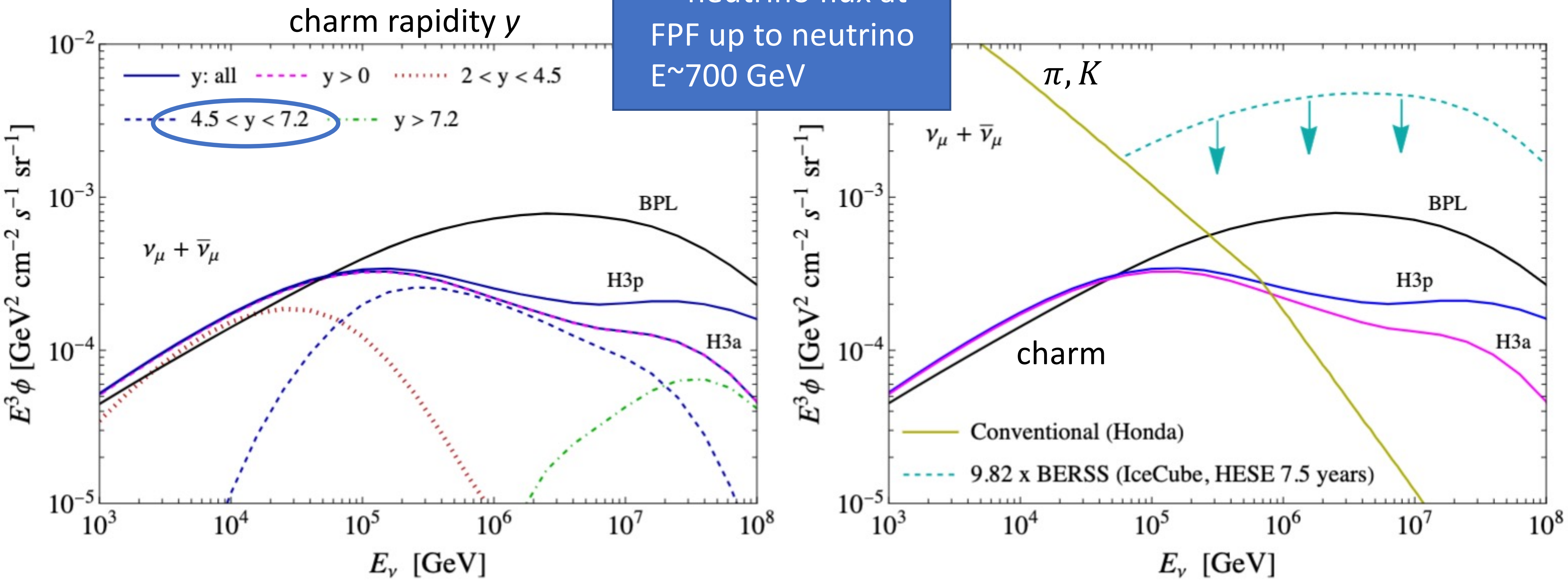


Kling, Makela, Trojanowski, 2309.10417

Astroparticle physics implications

Prompt atmospheric neutrino flux from cosmic ray interactions with air, background to diffuse astrophysical flux.

dominates charm → neutrino flux at FPF up to neutrino E~700 GeV



charm rapidity y

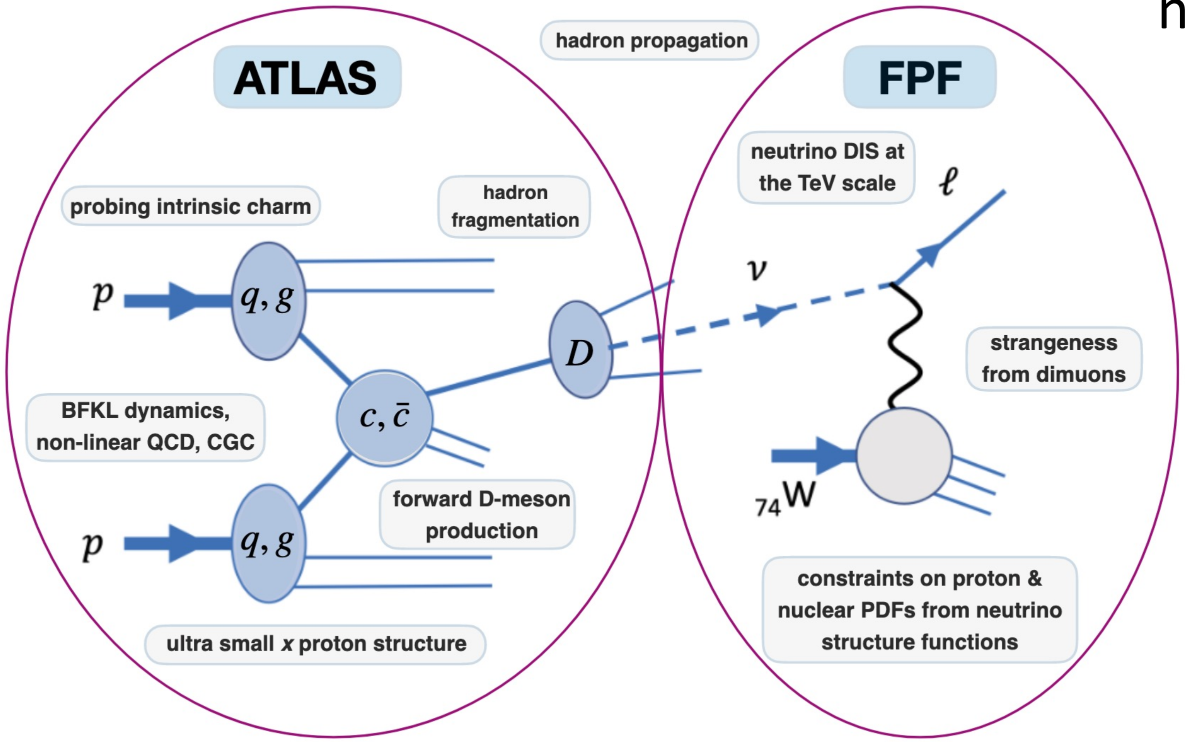
π, K

charm

Bai, Diwan, Garzelli et al, 2212.07865

Collider neutrinos: pp and νA collisions

hadron production that ultimately yields neutrinos of all 3 flavors



neutrino interactions (all 3 flavors, from different hadron sources) on nuclear targets

Neutrino flavor, neutrino interactions (SM and BSM)

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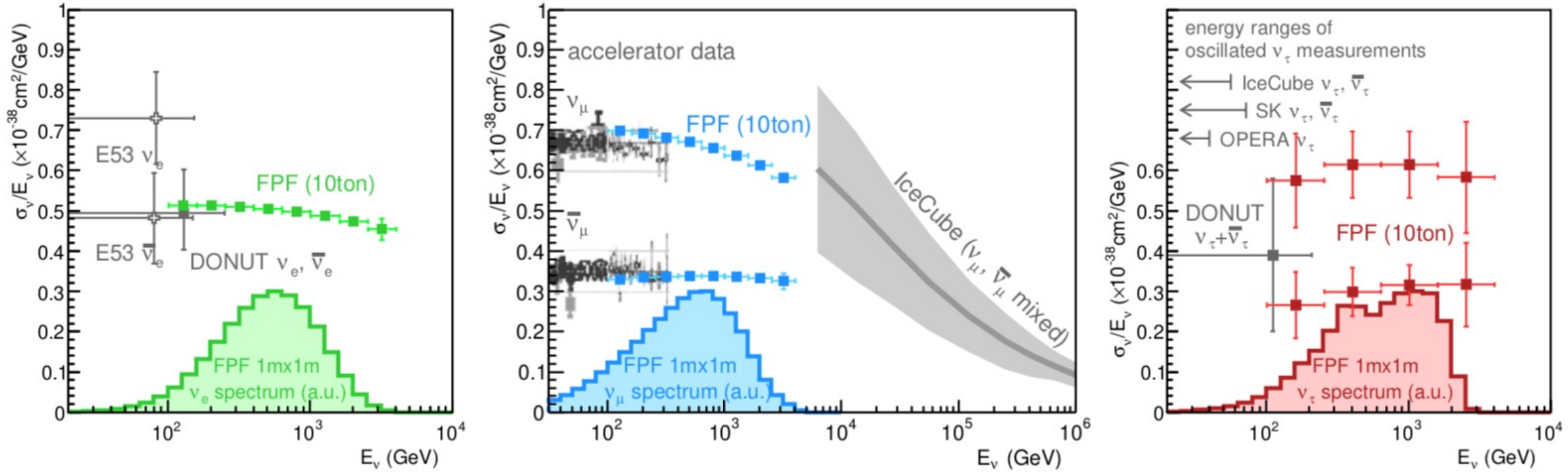
Neutrino interactions – SM physics with neutrinos

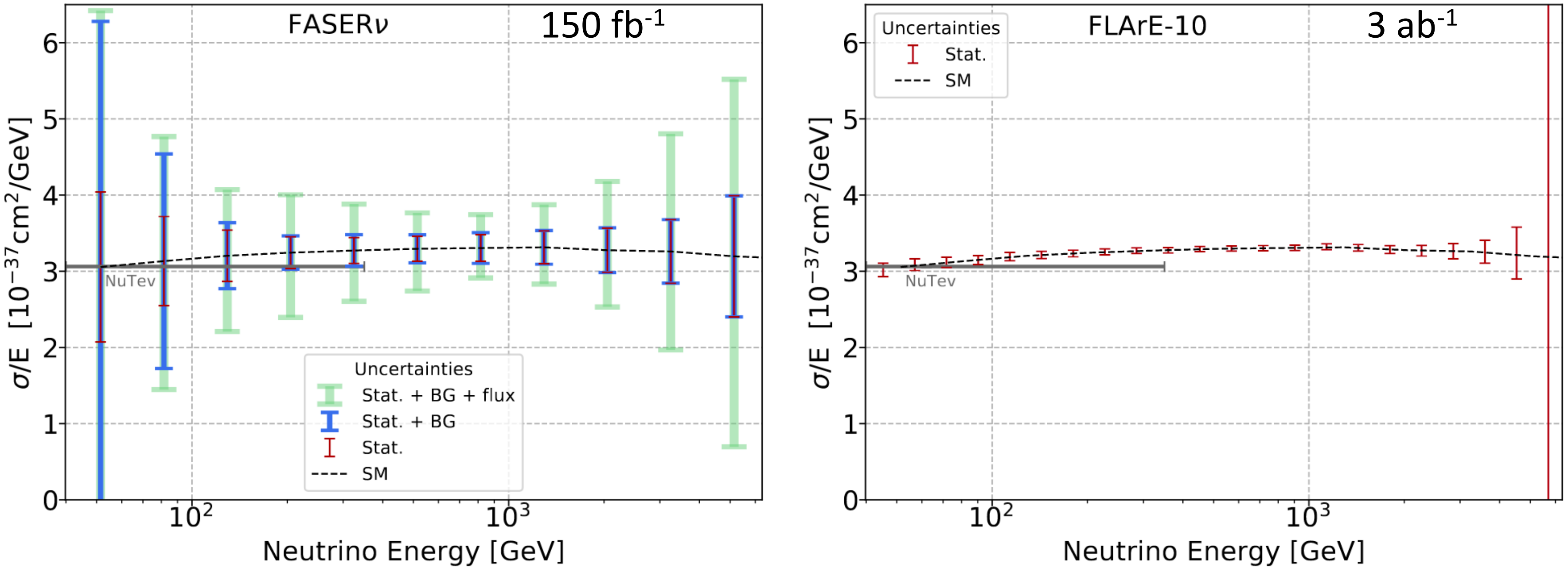
CC DIS cross sections



Statistical uncertainty only in figures

Feng et al. 2203.05090

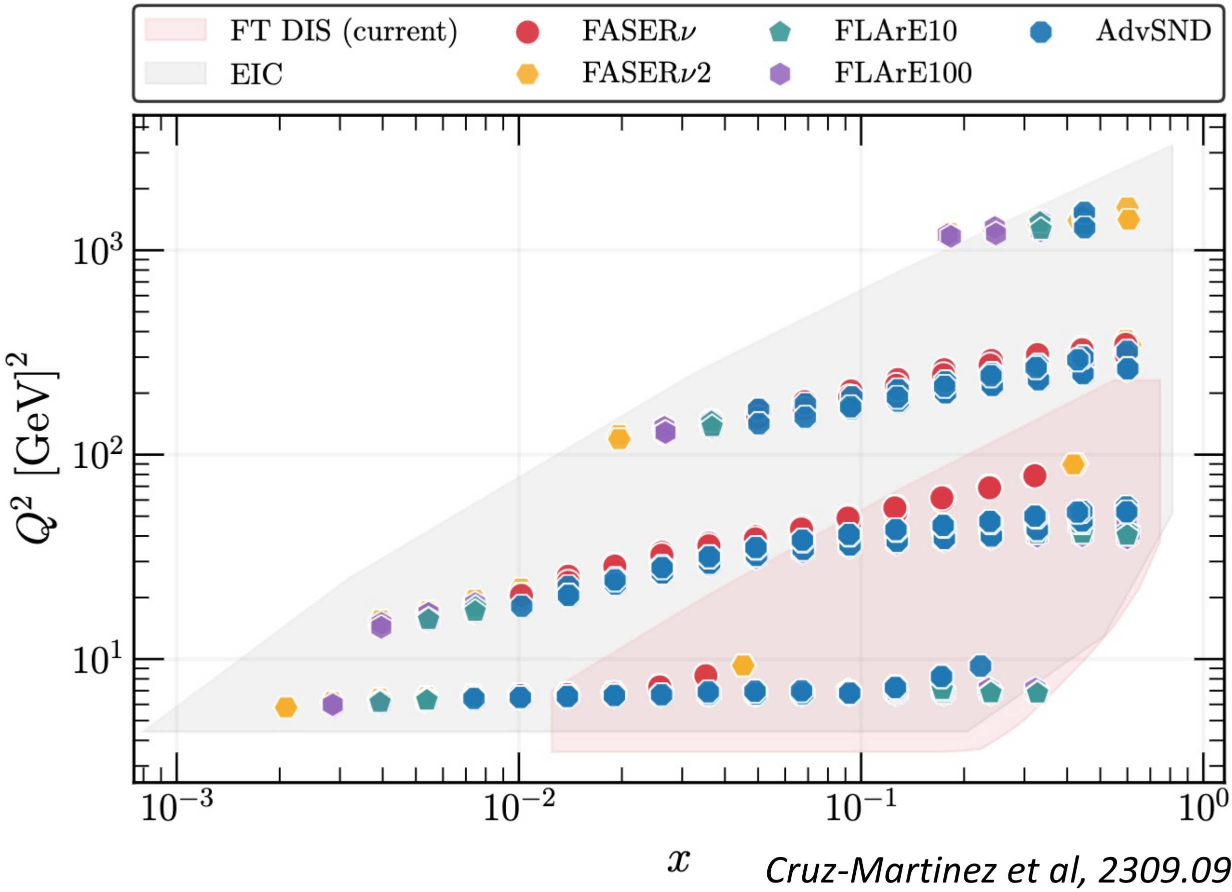
Neutrino NC DIS cross sections



Estimated sensitivities, averaged neutrino plus antineutrino.

Figs. from *Feng et al. 2203.05090.* See also *Ismail, Mammen Abraham & Kling, PRD 103 (2021) 056014*.

PDF determinations from DIS



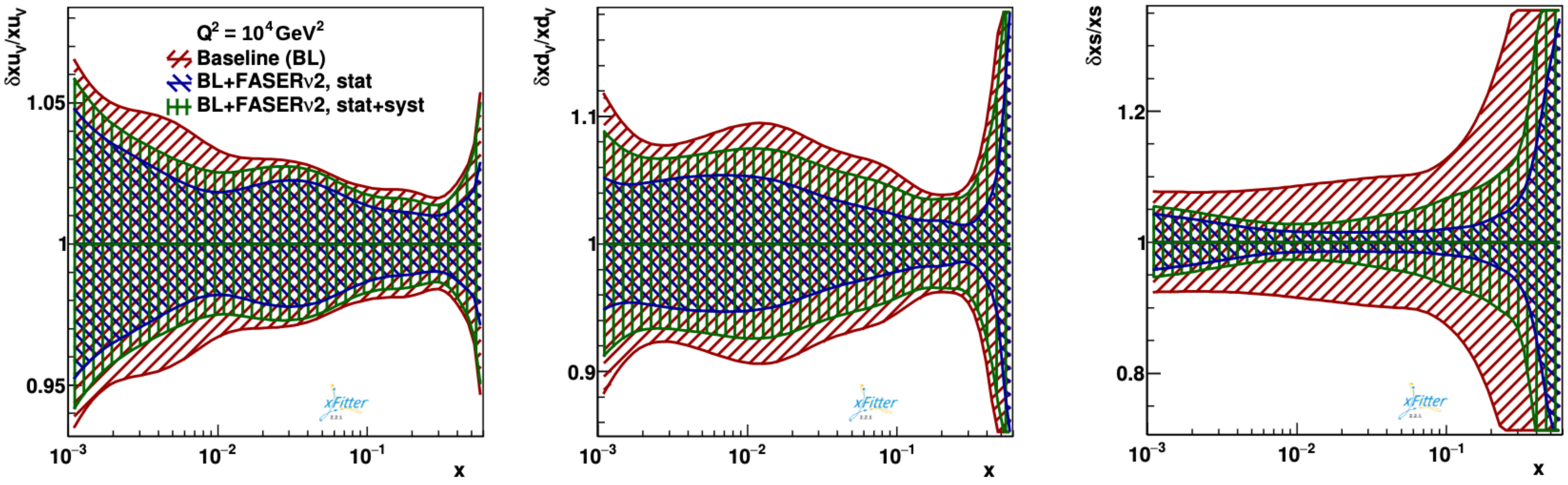
Cruz-Martinez et al, 2309.09581

In perturbative regime:

- Nuclear targets (tungsten & argon)
- Complementary to EIC
- Extends fixed target program (FT)

Better PDFs, better precision measurements at LHC

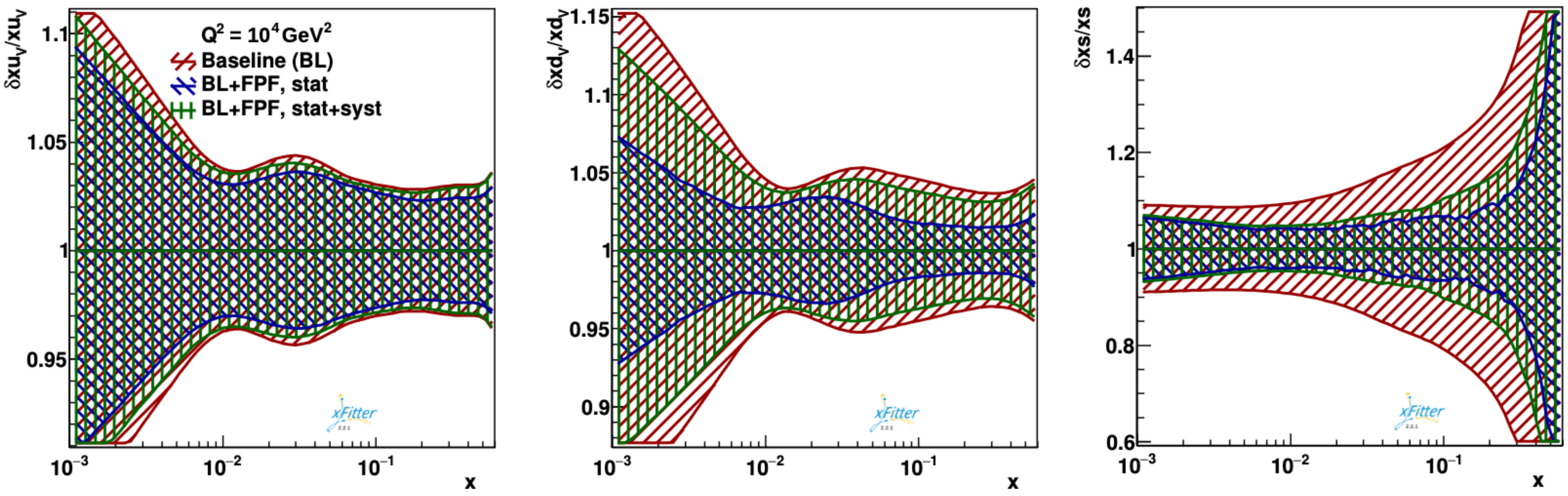
Improved *p/N* PDF determinations from DIS



Cruz-Martinez et al, 2309.09581

PDF4LHC21 baseline proton PDF uncertainties and projected improvements for one experiment. Improvements in valence and strange quark PDFs.

Improved *p/W* PDF determinations from DIS

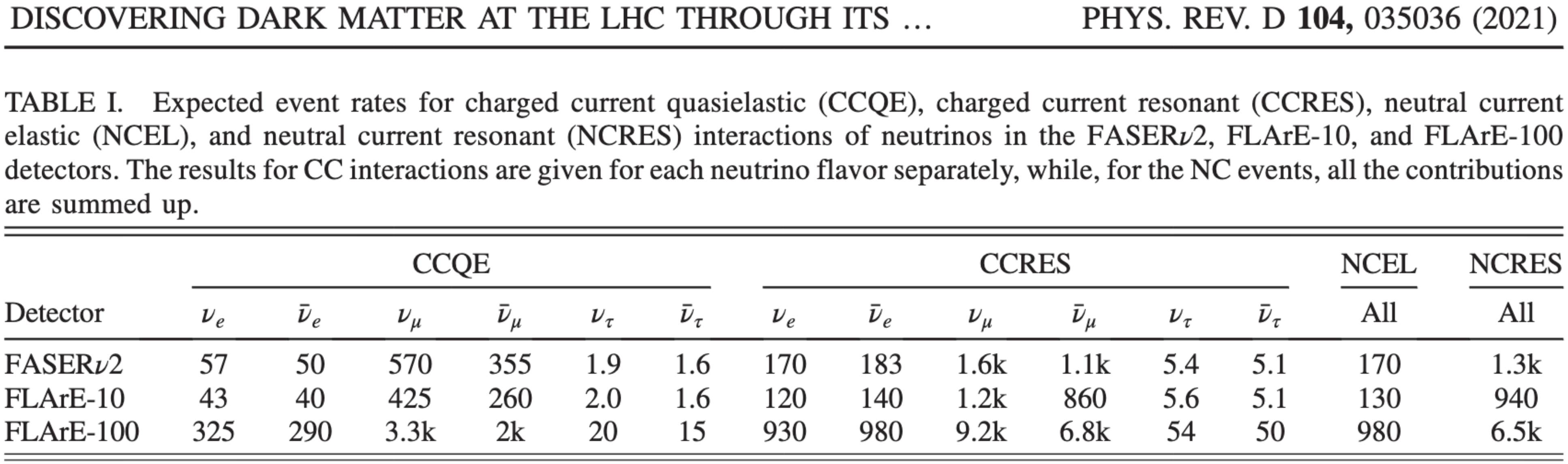


Cruz-Martinez et al, 2309.09581

EPPS21 baseline proton PDF in tungsten, two FPF experiments combined, for uncertainties and projected improvements. Improvements in valence and strange quark PDFs.

Quasi-elastic, resonant, shallow interactions

Batell et al.



DISCOVERING DARK MATTER AT THE LHC THROUGH ITS … PHYS. REV. D **104,** 035036 (2021)

TABLE I. Expected event rates for charged current quasielastic (CCQE), charged current resonant (CCRES), neutral current elastic (NCEL), and neutral current resonant (NCRES) interactions of neutrinos in the FASERν2, FLArE-10, and FLArE-100 detectors. The results for CC interactions are given for each neutrino flavor separately, while, for the NC events, all the contributions are summed up.

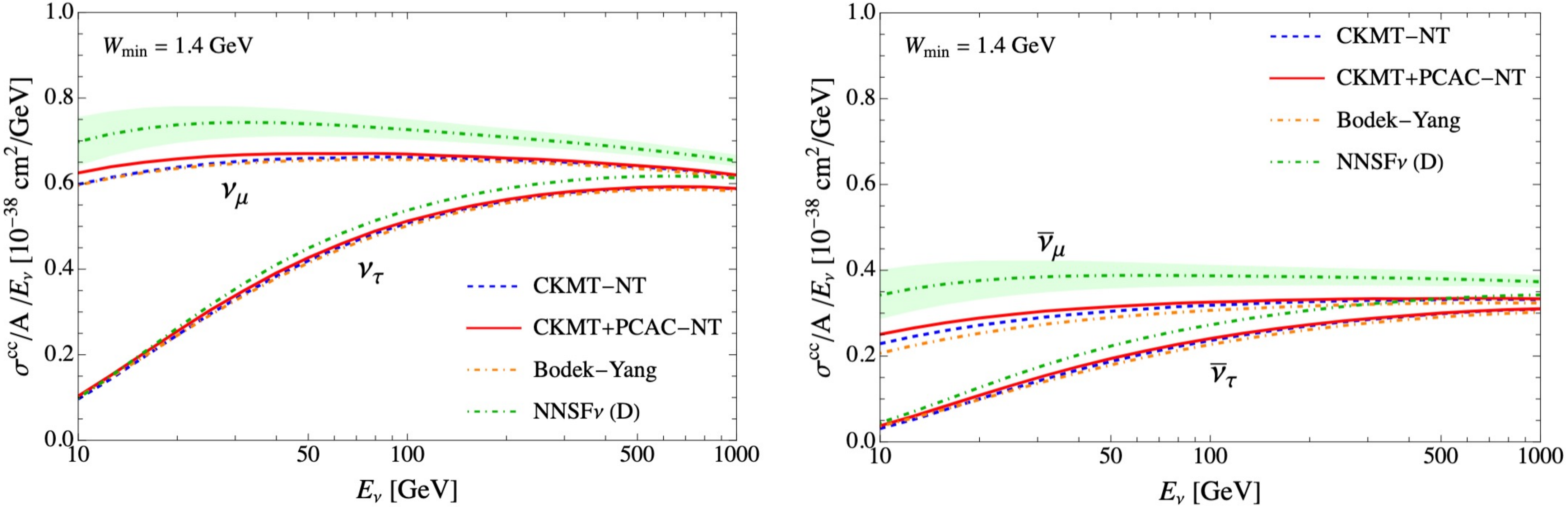
	CCQE						CCRES						NCEL	NCRES
Detector	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	ν_τ	$\bar{\nu}_\tau$	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	ν_τ	$\bar{\nu}_\tau$	All	All
FASERν2	57	50	570	355	1.9	1.6	170	183	1.6k	1.1k	5.4	5.1	170	1.3k
FLArE-10	43	40	425	260	2.0	1.6	120	140	1.2k	860	5.6	5.1	130	940
FLArE-100	325	290	3.3k	2k	20	15	930	980	9.2k	6.8k	54	50	980	6.5k

FASERv2 and FLArE-10 with 10 tons, FLArE-100 100-ton LArTPC. Numbers for LHC-HL 3 ab^{-1} with Sibyll 2.3c in CRMC.

- About 10% of $\sigma_{CC}(\nu N)$ is from Q<1.3 GeV for $E_\nu = 100$ GeV in "DIS" evaluation.
- Resonant production below a TeV for $\bar{\nu}_e\ e$ scattering. *Brdar et al. PRD 105 (2022) 093004*

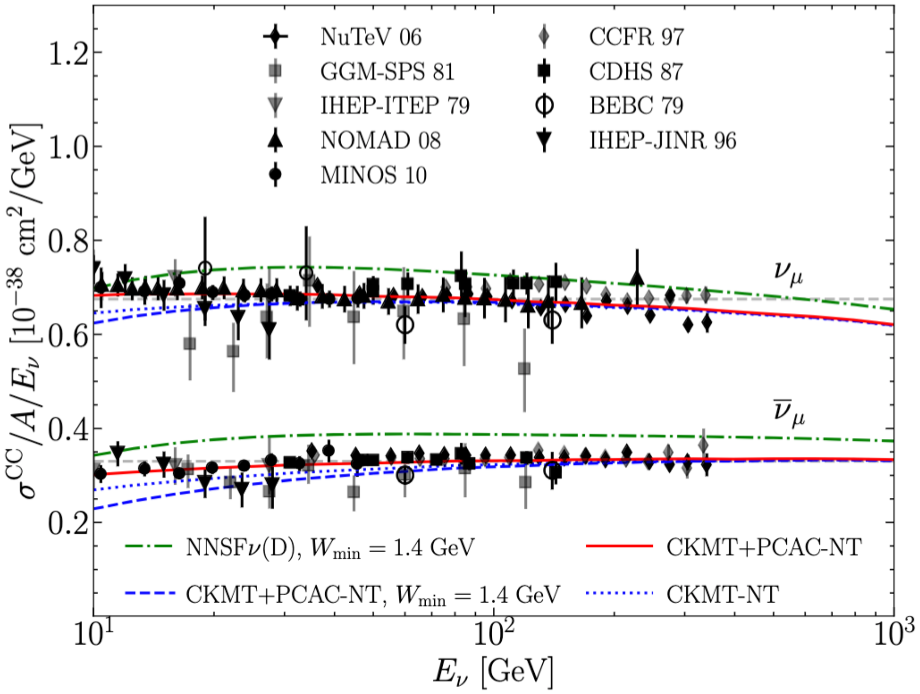
DIS CC with low Q structure functions

- Recent work on low *Q*:
  CKMT+PCAC-NT extrapolation of EM fit plus PCAC corrections Jeong & Reno 2307.09241
- NNSFν using NNPDF fitting methodology for low *Q* SF Candido et al *JHEP* 05 (2023) 149

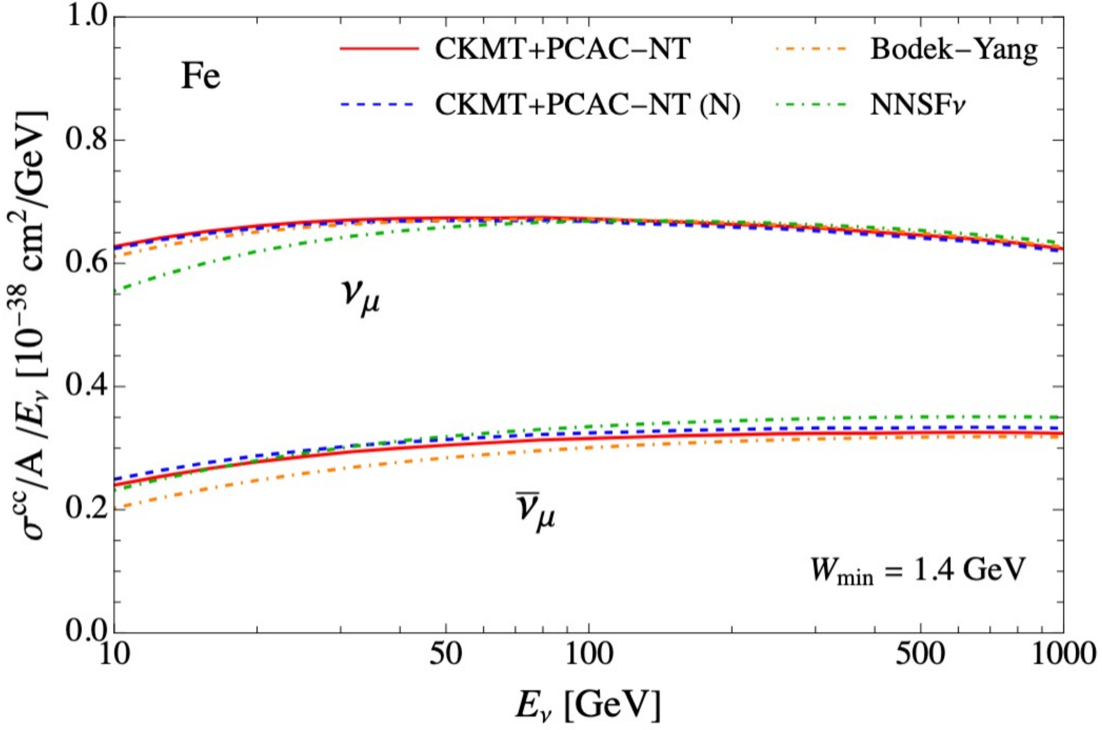


DIS CC, low Q and nuclear dependence

note: many nuclear targets



better agreement with Fe



Jeong & Reno 2307.09241

BSM physics with neutrinos

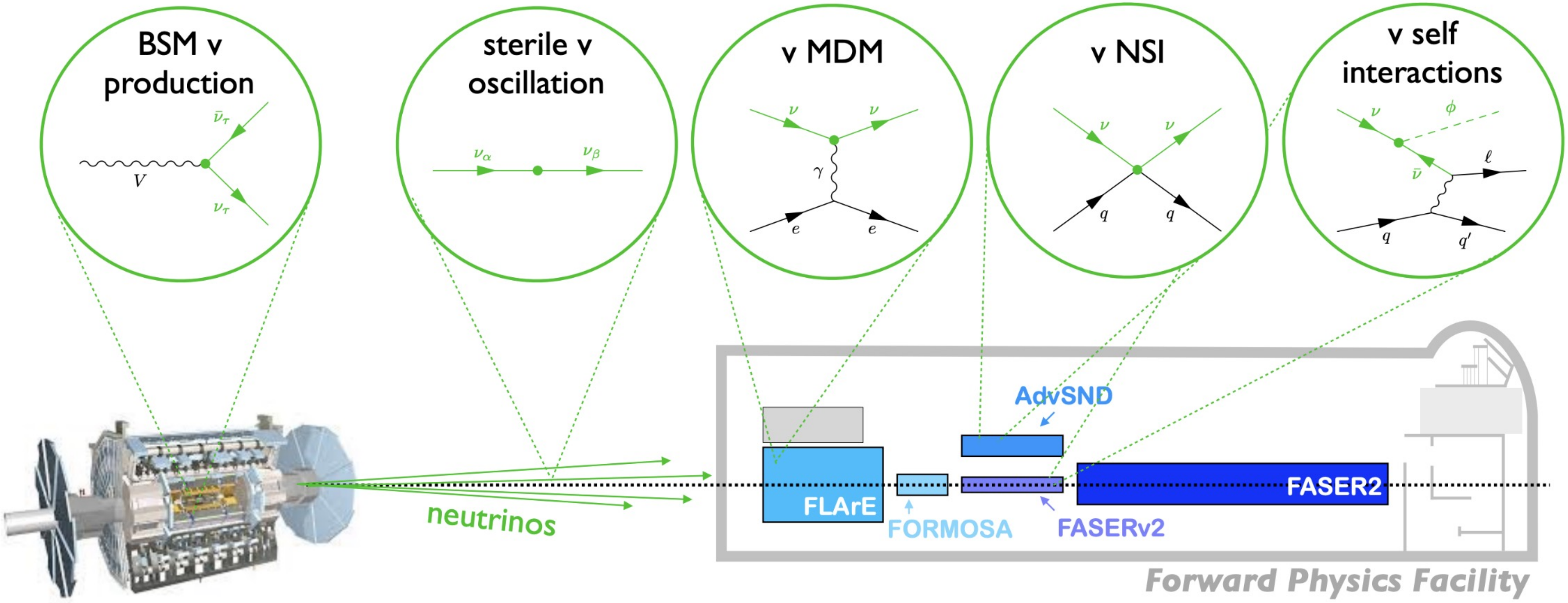
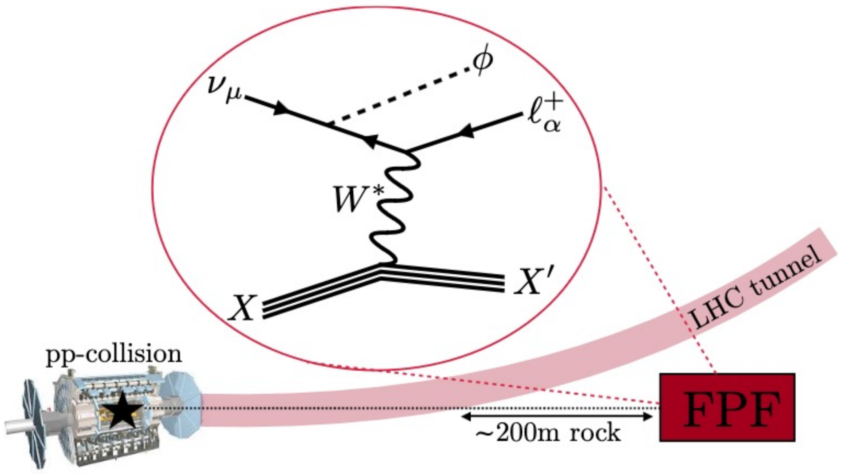


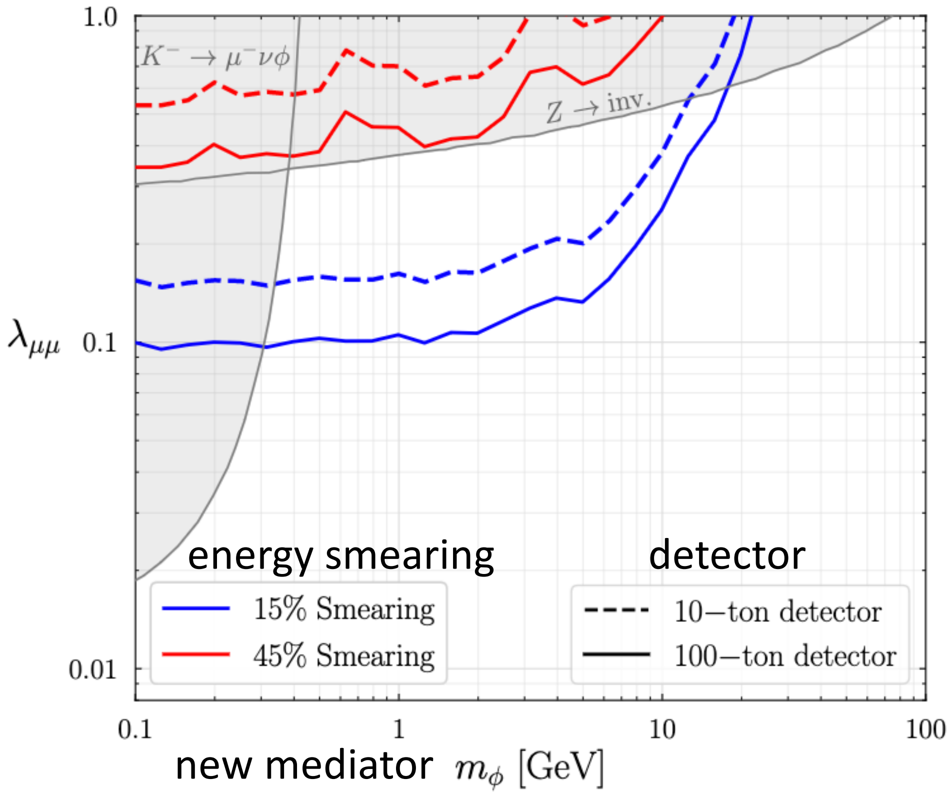
Fig. from Feng et al. 2203.05090

Example: new interactions



- Search for neutrino CC interactions and missing transverse momentum in FPF detectors.
- Motivated by dark matter considerations.

FLArE-like detector



Kelly et al, 2111.05868.

Example:
BSM EFT constraints

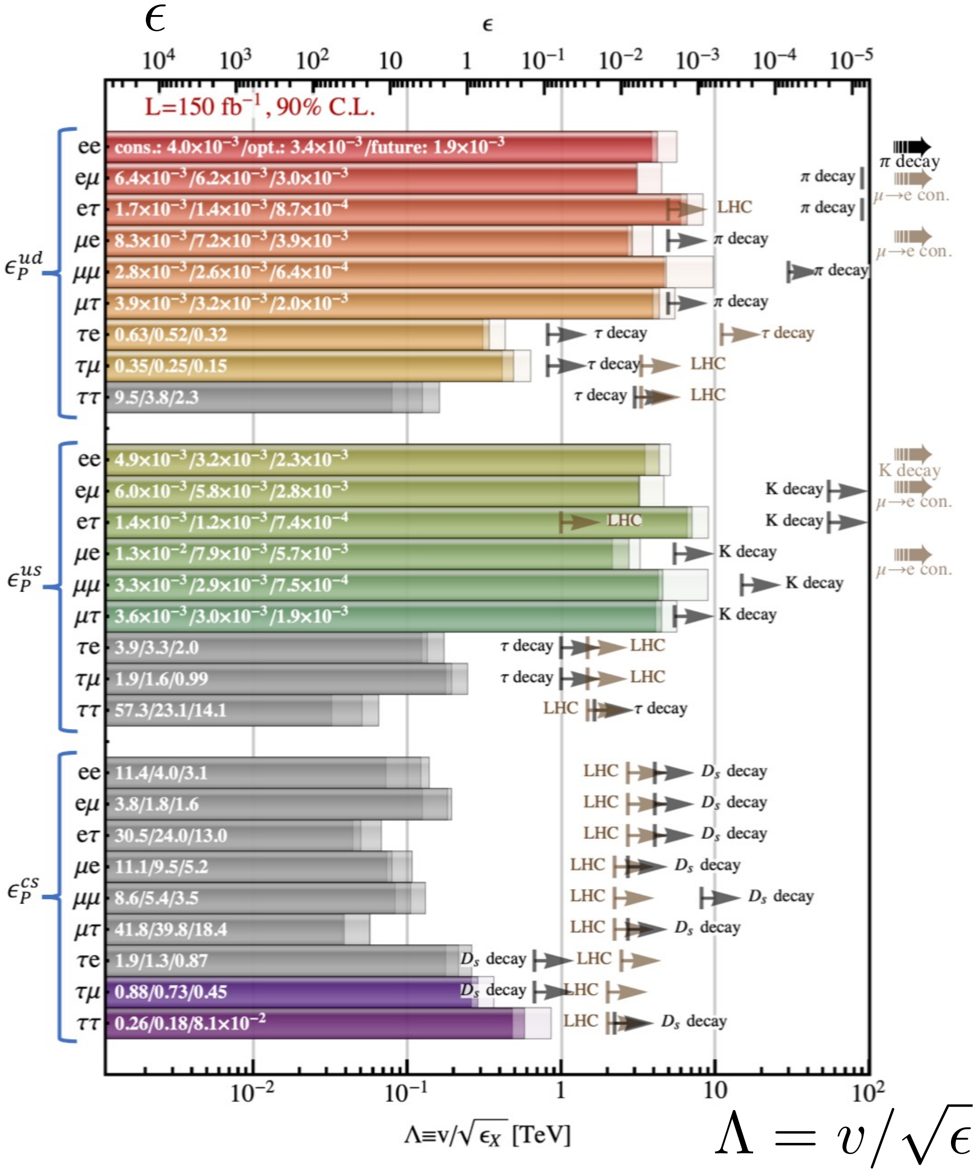
Example: pseudoscalar, dimensionless ϵ_P

$$\mathcal{L}_{\mathrm{WEFT}} \sim \frac{V_{jk}}{v^2}[\epsilon_P^{jk}]_{\alpha\beta}(\bar{u}^j\gamma_5 d^k)(\bar{\ell}_\alpha P_L \nu_\beta)$$

- Constraints from production, e.g., lots of pions produced, decays to off-diagonal neutrino flavors like ν_τ.
- Constraints from detection, e.g., where electron neutrino produces a tau.
- Projected with conservative (optimistic) systematics for FASERν, and for 20x statistics.

This example from *Falkowski et al, JHEP 10 (2021) 086*.

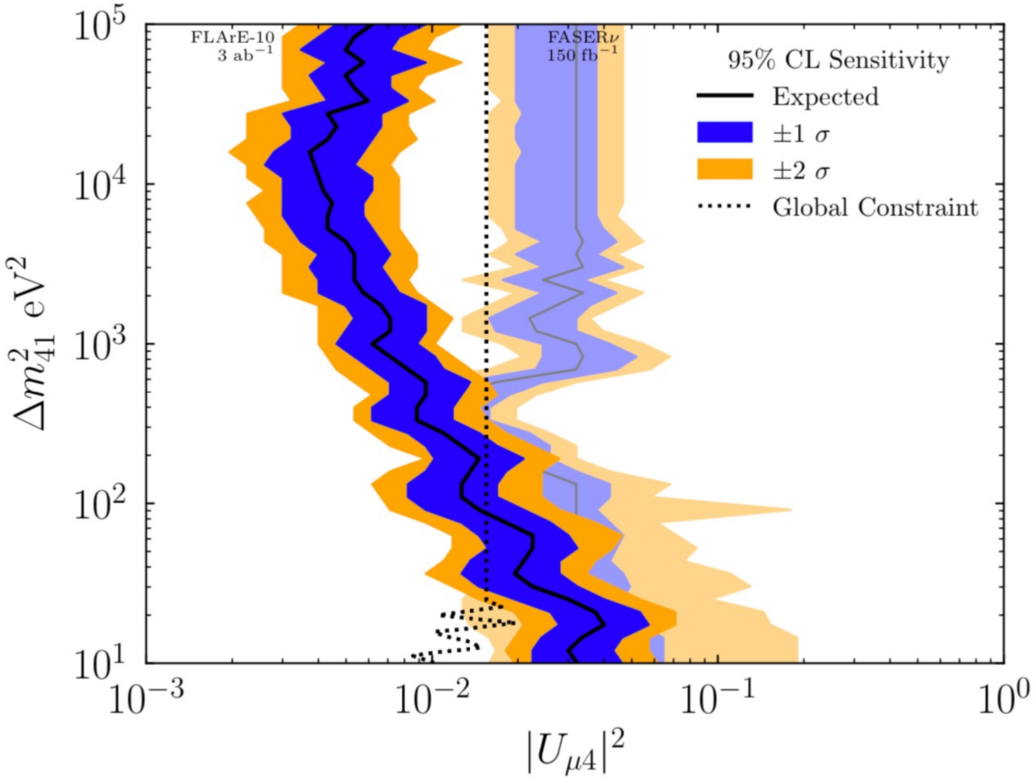
$$V_{jk} = \text{Cabibbo ME} \qquad v \simeq 246\ \text{GeV}$$



$$\Lambda = v/\sqrt{\epsilon}$$

Fig. from 2203.05090, see also expanded discussion from other contributors.

Oscillation to sterile neutrinos, 3+1



arXiv:2109.10905

Baseline of ~620 m and energy range of 100 GeV - 1 TeV, probes mass-difference squared higher than DUNE, etc.:

$$\Delta m^2_{41} \sim 1000\ \mathrm{eV}^2$$

Sensitivity from muon neutrino disappearance for FASERv in Run 3 (light colors) and FLArE-10 at HL-LHC run (dark colors).
(Note scale on y-axis.)

Final remarks

- Neutrino fluxes:
  - High energy neutrinos and all tau neutrinos come from heavy flavor decays. FPF probes large-x and small-x regimes of PDFs. Heavy flavor production and decays to neutrinos tied to astroparticle physics.
  - Predictions of neutrinos from light meson decays related to simulations of cosmic ray air showers. FPF measurements -> air shower Monte Carlo improvements.
- Neutrino interactions:
  - Standard model interactions probe PDFs, structure functions for nuclear targets.
  - Complementary to EIC, and ties into DUNE cross sections.
- BSM physics can distort SM flux and neutrino interactions. We expect rich data sets.