Collider Neutrino Physics

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Fermilab Neutrino Seminar

Work supported in part by the US Department of Energy.

Neutrinos at colliders, historically

- Missing energy, e.g., in W-boson decays

$$M_T^2 = 2E_T^e E_T^\nu (1 - \cos\phi_{e\nu})$$

- Understanding SM background to BSM missing energy events.

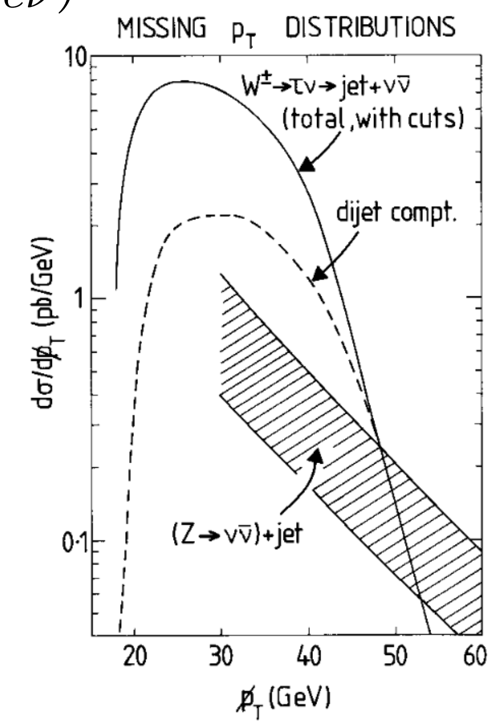
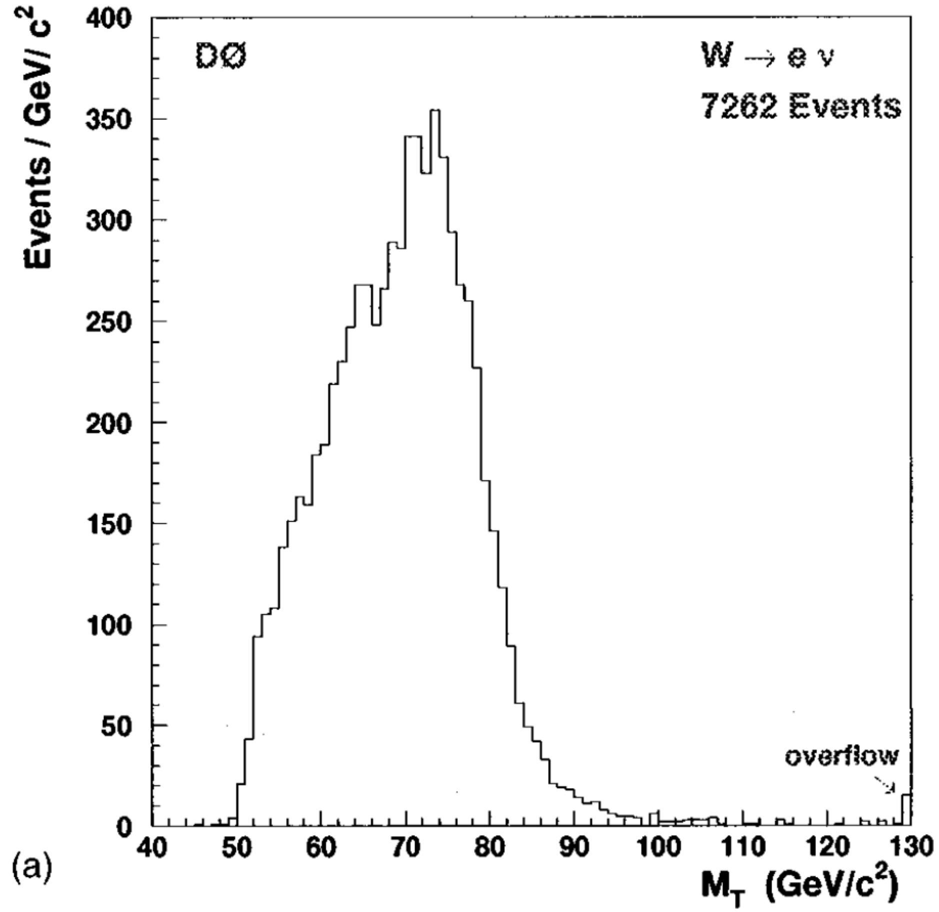
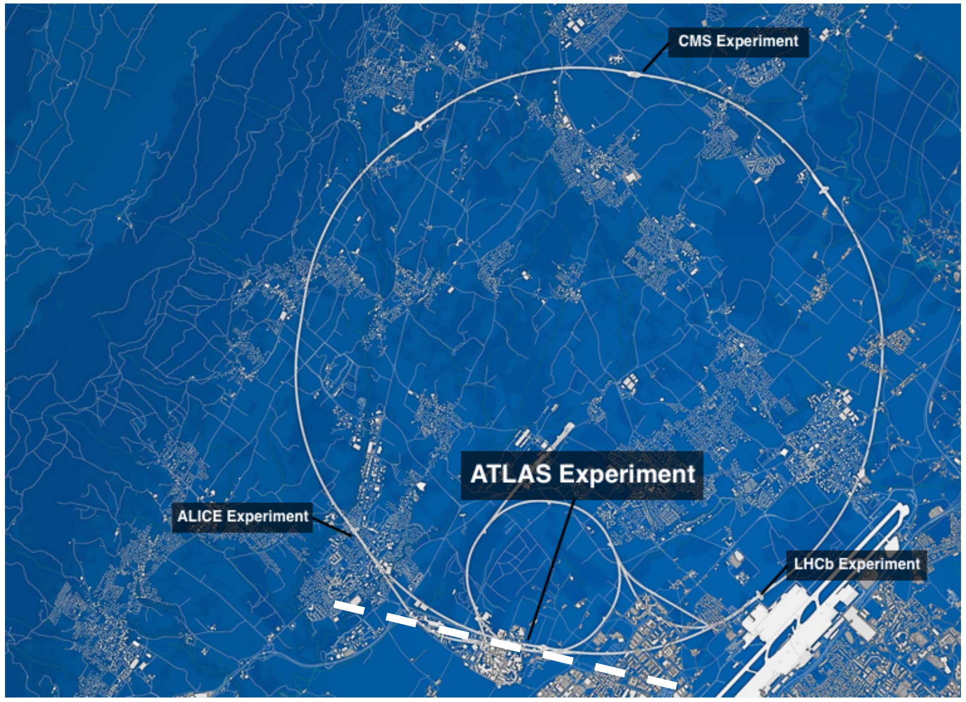


Fig. Glover & Martin, ZPC 29 (1985) 399

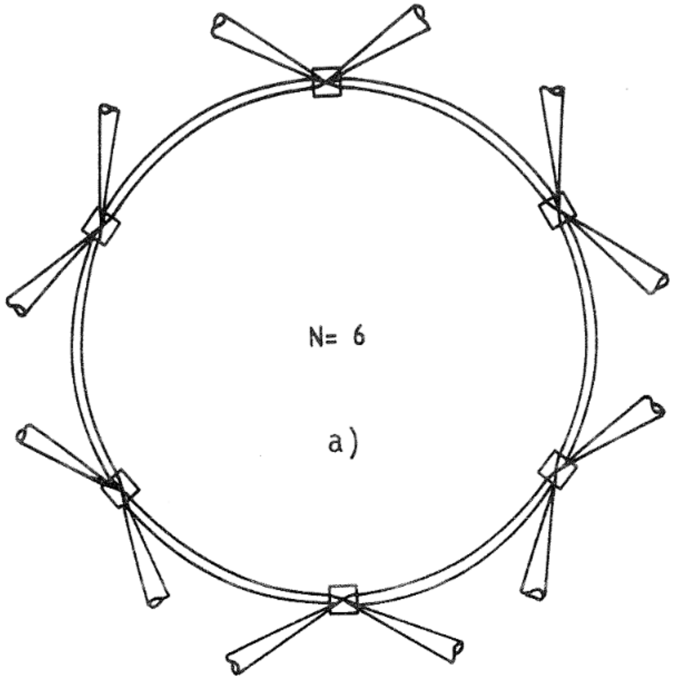
D0 Collaboration, PRD 58 (1998) 012002



Collider neutrinos



atlas.cern/about



deRujula and Ruckl, 1984

CERN TH 3892

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

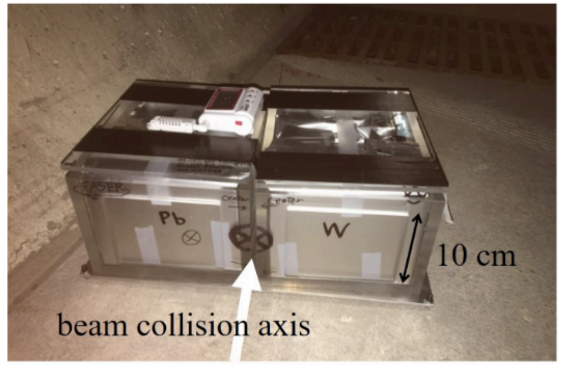
Early discussions including:

deRujula & Ruckl (1984)
Winter (1990)
deRujula, Fernandez & Gomez (1993)
Vannucci (1993)

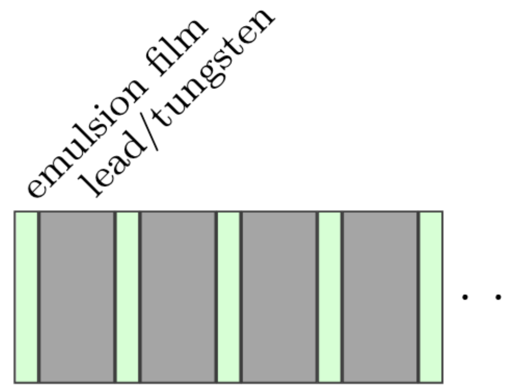
Currently, FASERν and SND@LHC installed. Proposed Forward Physics Facility.

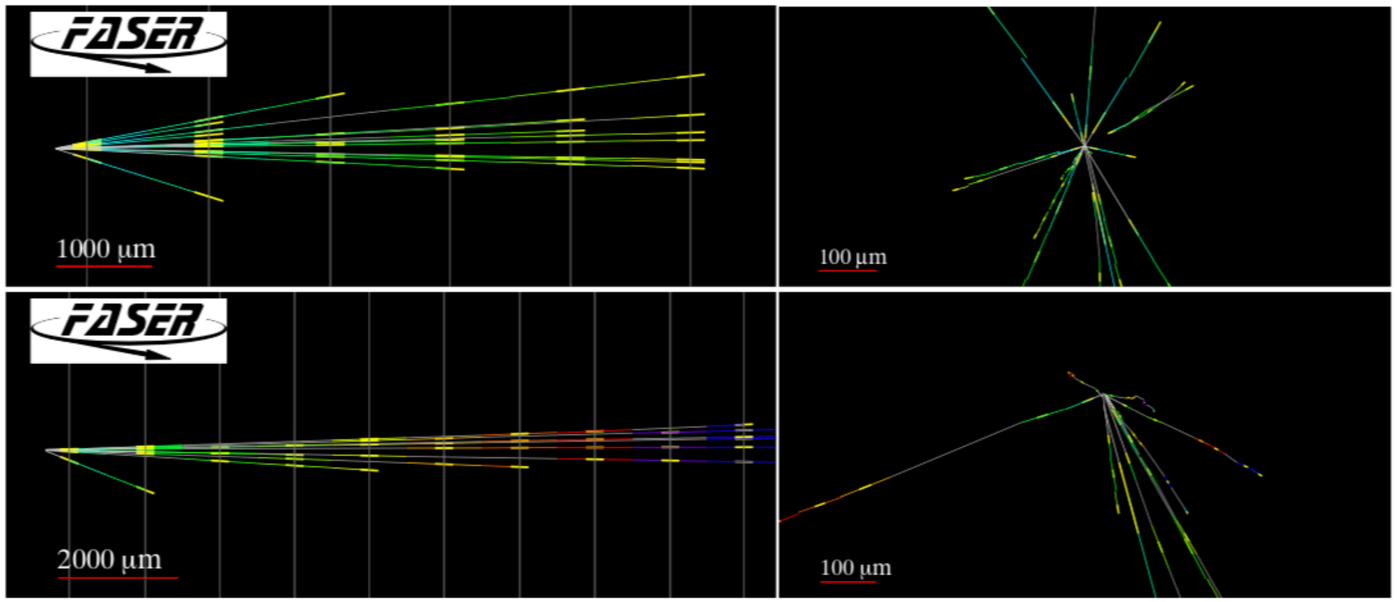
FASERν pilot @ LHC

Neutrino candidates, proof of principle.
FASER, Phys. Rev. D 104 (2021) L091101



emulsion detector





Data from pilot run in 2018.

29 kg "suitcase size" prototype detector, 480 m from interaction point, for 12.2 fb $^{-1}$ in *pp* collisions at 13 TeV.

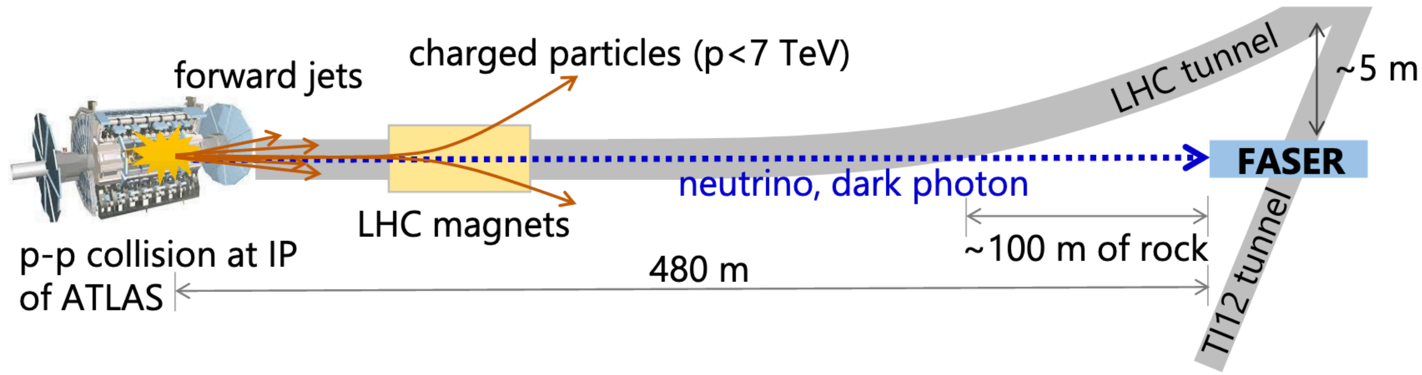
FASERν and SND@LHC in Run 3

pp at 14 (13.6) TeV with 150 fb $^{-1}$
480 m from ATLAS IP

LHC Run 3

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

FASERν

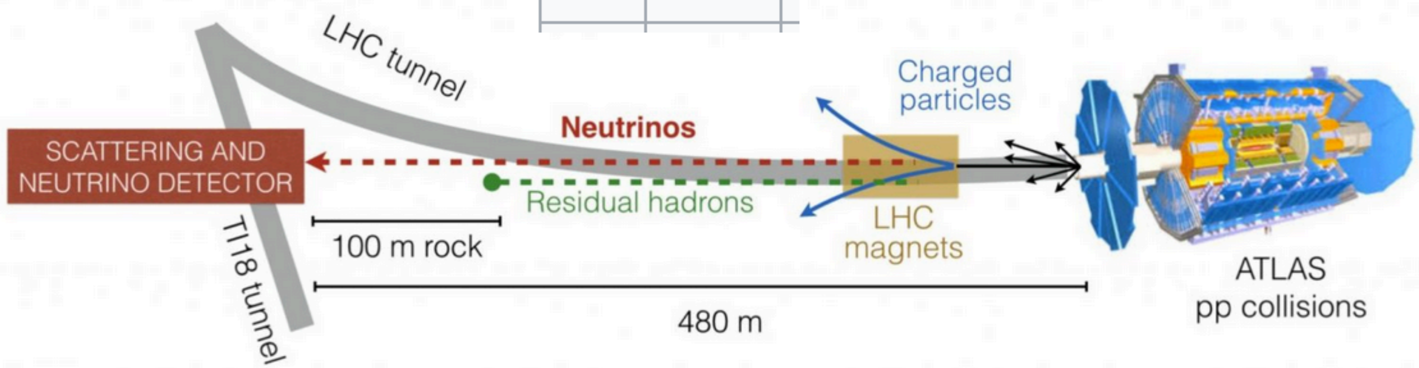


Figures "not to scale."

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

θ	η
0°	∞
0.1°	7.04
0.5°	5.43
1°	4.74

SND@LHC



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

FASERν 1.2 ton, 25 cm x 25cm

on axis, $\eta > 8.5$

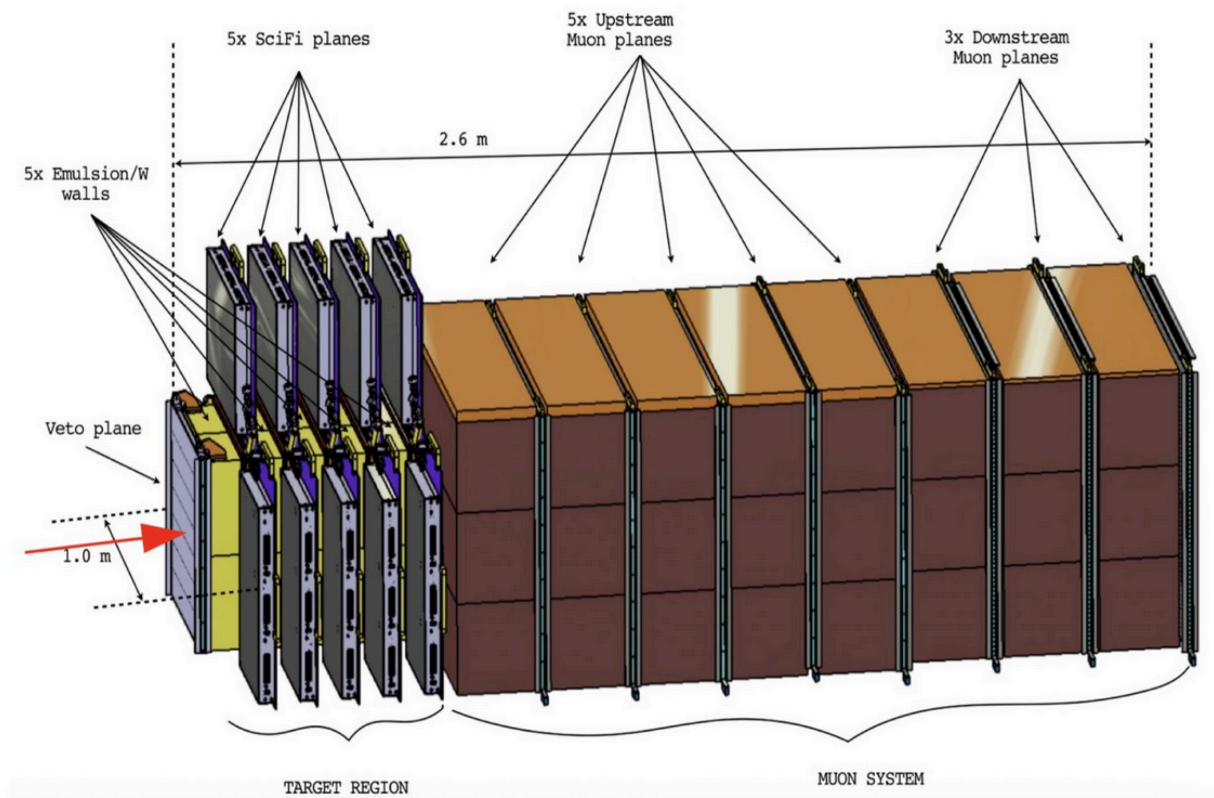
SND@LHC 800 kg, 39 cm x 39 cm

off axis, $8.5 > \eta > 7$

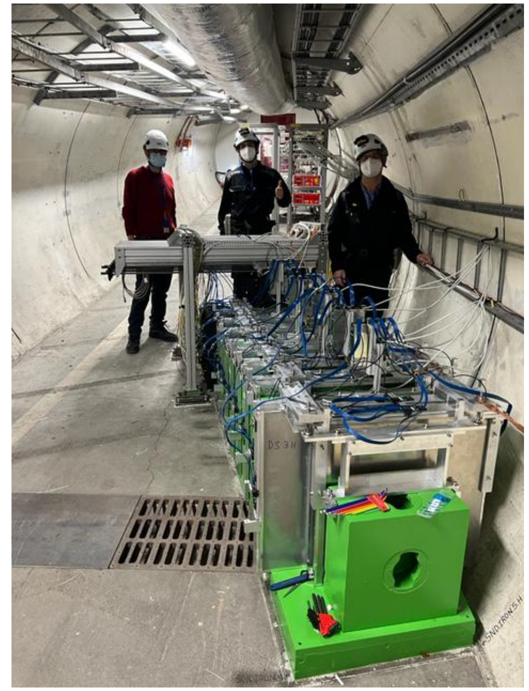
150 fb $^{-1}$

https://www.physik.hu-berlin.de/de/eephys/sndlhc

SND@LHC

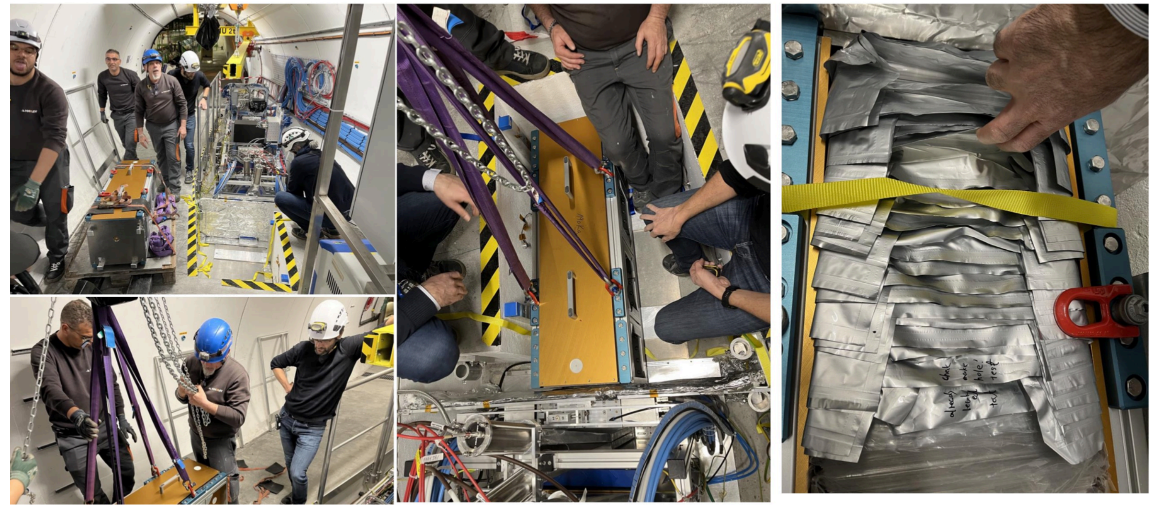


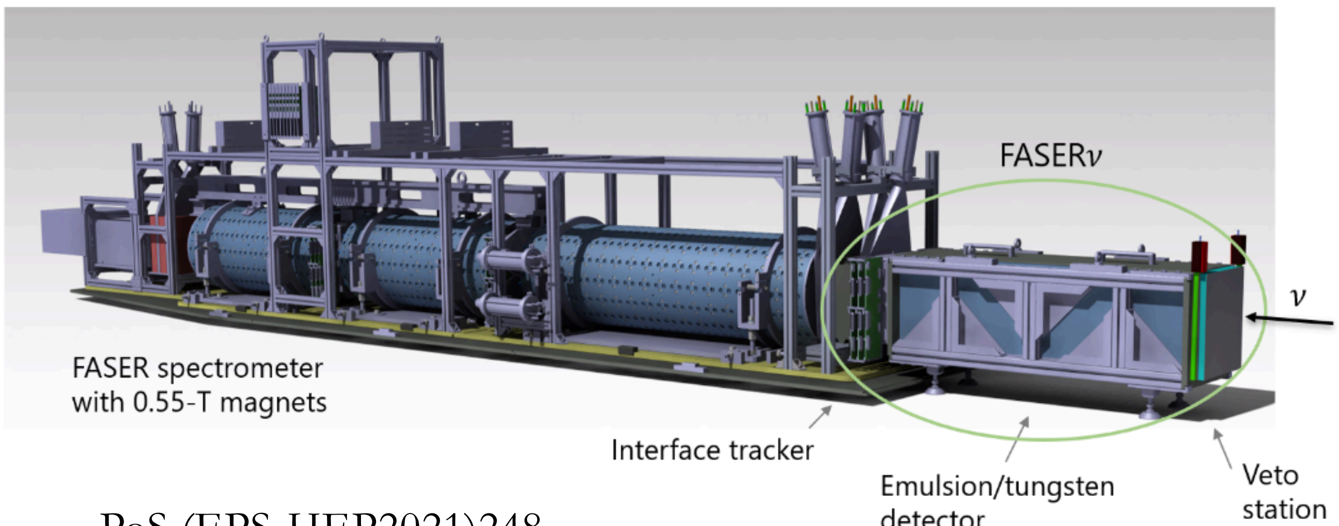
https://www.epfl.ch/labs/lphe/en/4266-2/



- Veto plane.
- Tungsten plates, emulsion film and SciFi tracker.
- Iron and scintillating bars muon detector.

FASERν



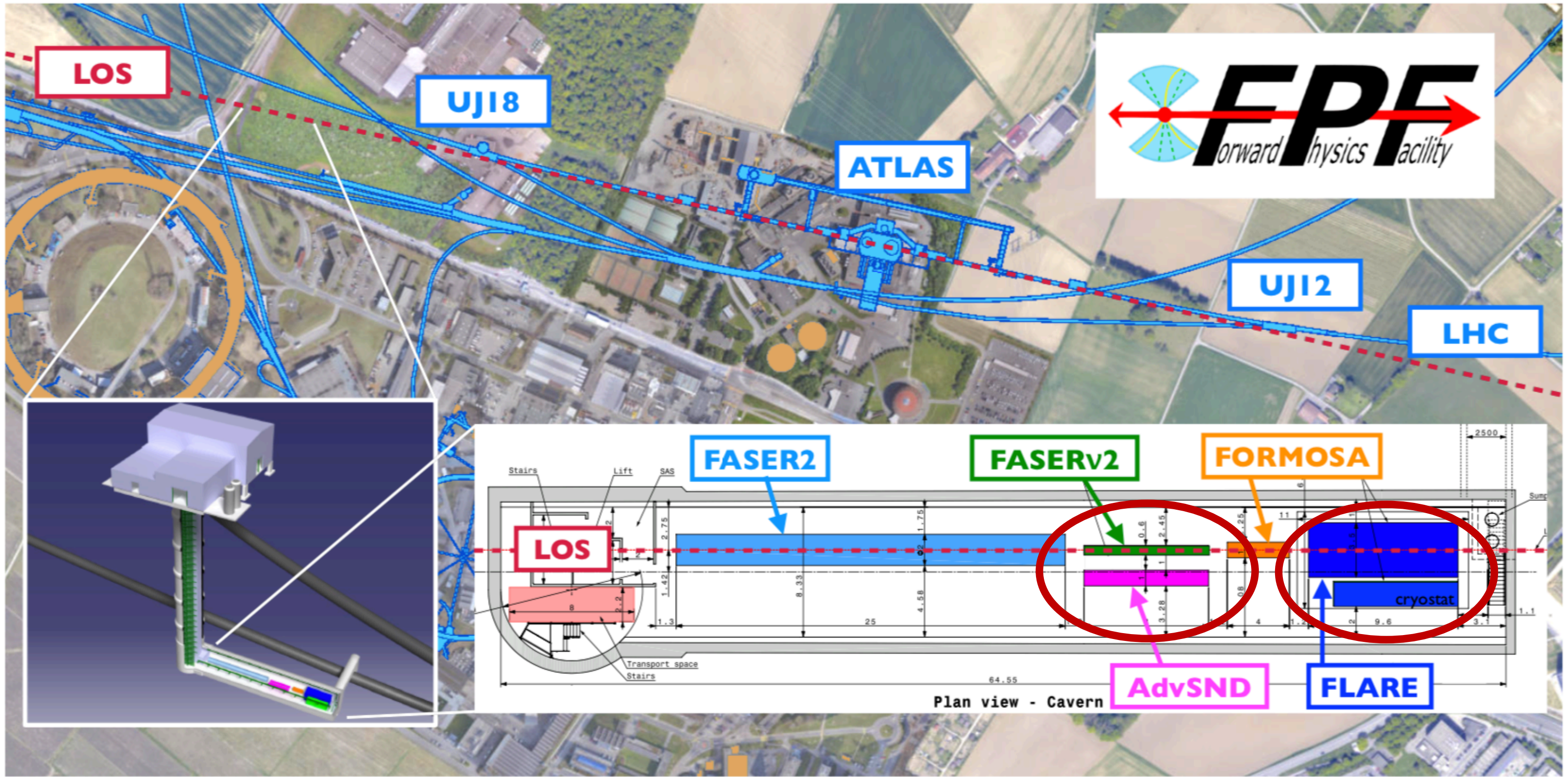


PoS (EPS-HEP2021)248

- 1.1 tonnes tungsten target
- Emulsion based detector, with emulsion replaced every ~3 months during technical stops of the LHC.
- Veto detector and interface trackers.
- Emulsion detector readout for track densities up to ~10^6 tracks/cm^2.

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, energies up to a few TeV.



- Detectors designed for Standard Model and BSM Physics.
- Neutrino detection at FASERv2, AdvSND and FLArE.
- Snowmass White Paper: 2203.05090

See also, Anchordoqui et al., 2109.10905 (now Phys. Rept.).

Run 3 and HL Summary (with approx. η range)

Run 3: 150 fb^{-1} at 480 m from ATLAS IP
Faserν with front surface 25cm x 25cm, $\eta > 8.5$
SND@LHC off axis, front surface 39cm x 39cm, $8.5 > \eta > 7$

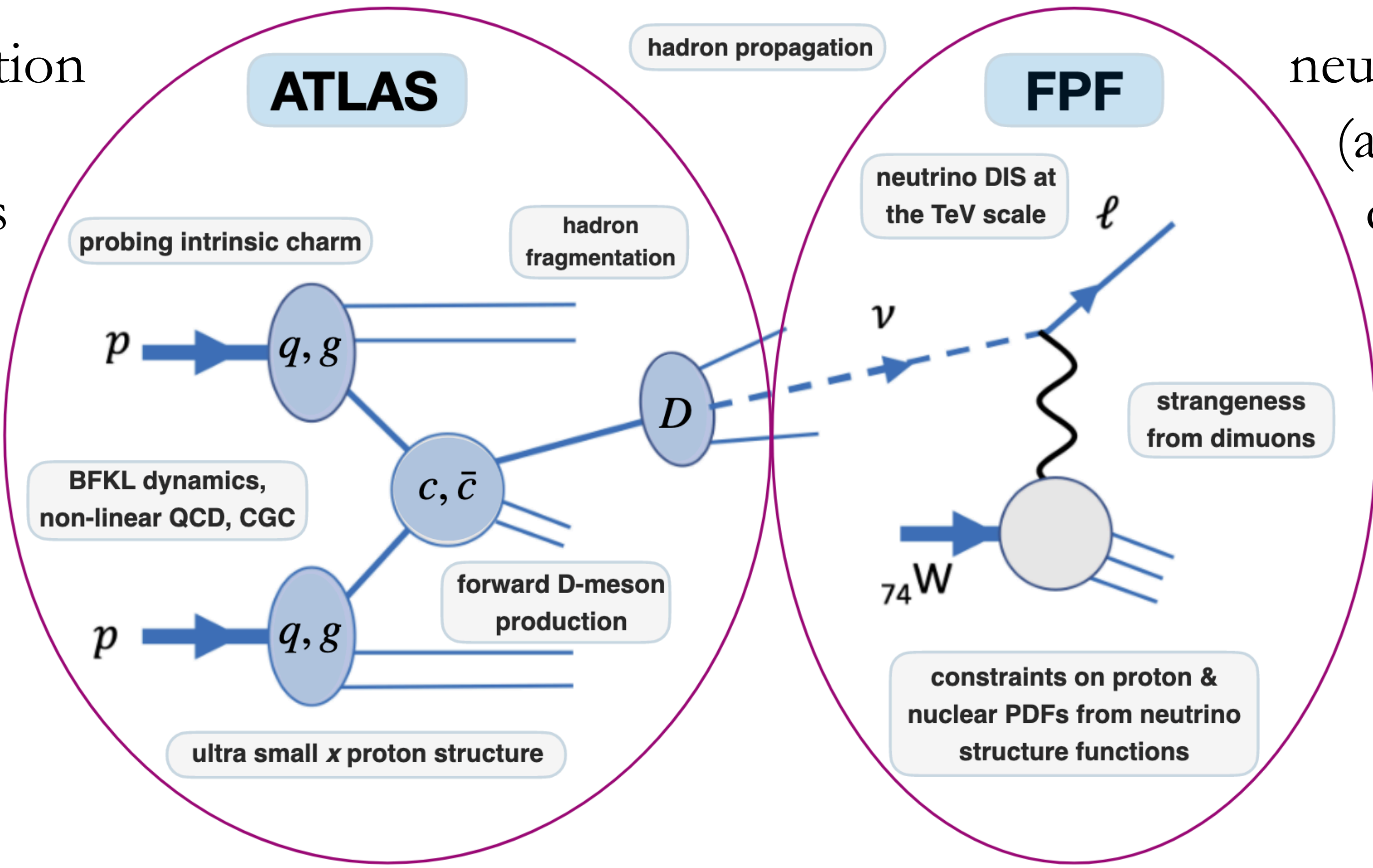
High Luminosity: 3000 fb^{-1} with FPF at 620 m from ATLAS IP
FASERν2, $\eta > 8.7$
AdvSND (in FPF), $8.4 > \eta > 7.2$
FLArE, $\eta > 7.8$

in development for future facility

AdvSND ("near") in range $4 < \eta < 5$

Collider neutrinos: *pp* and νA collisions

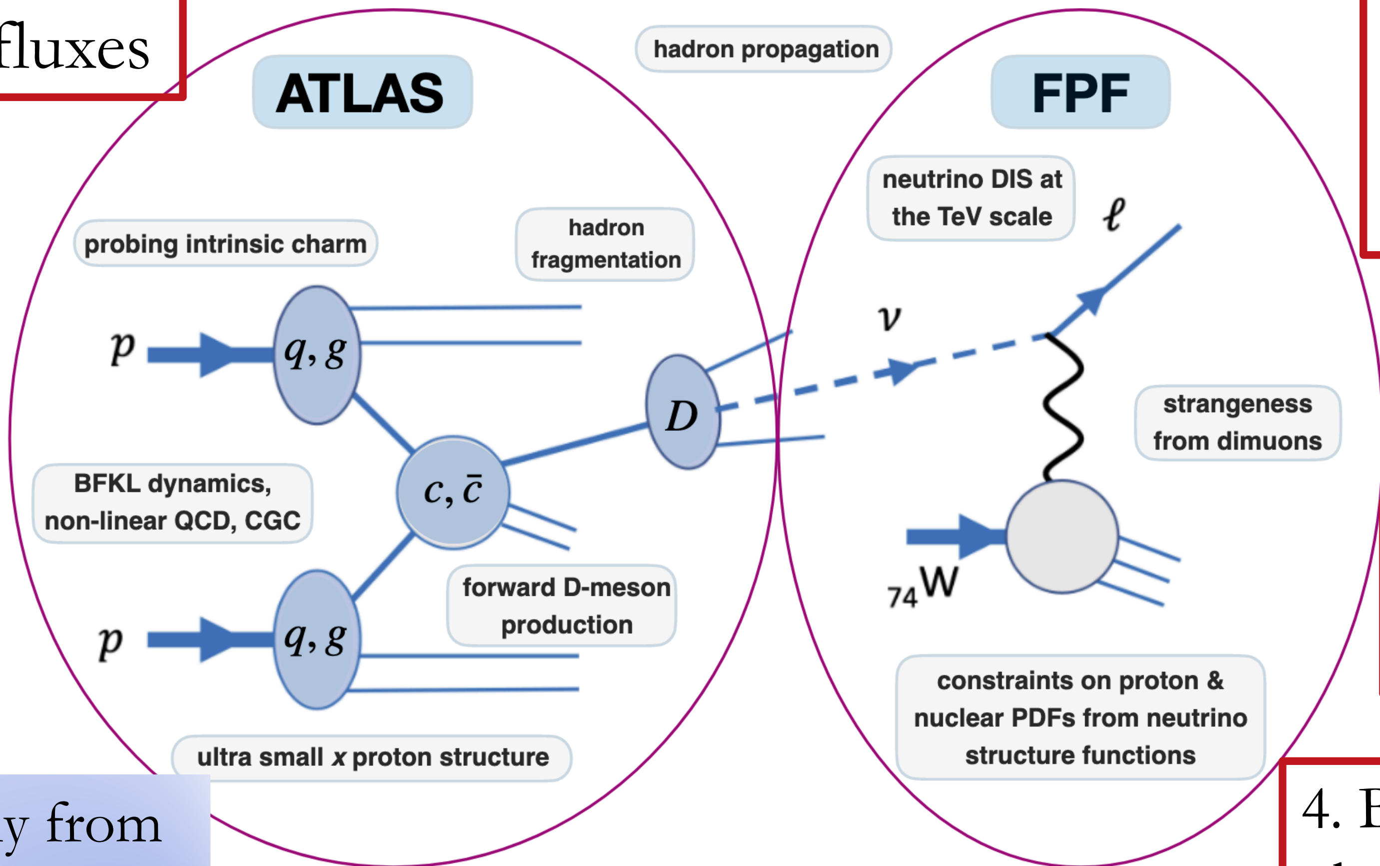
hadron production that ultimately yields neutrinos of all 3 flavors



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

Collider neutrinos: pp and νA collisions

1. Neutrino fluxes



2. Standard model neutrino interactions on nuclear targets

3. BSM with neutrinos (selected)

4. Brief astroparticle physics connection.

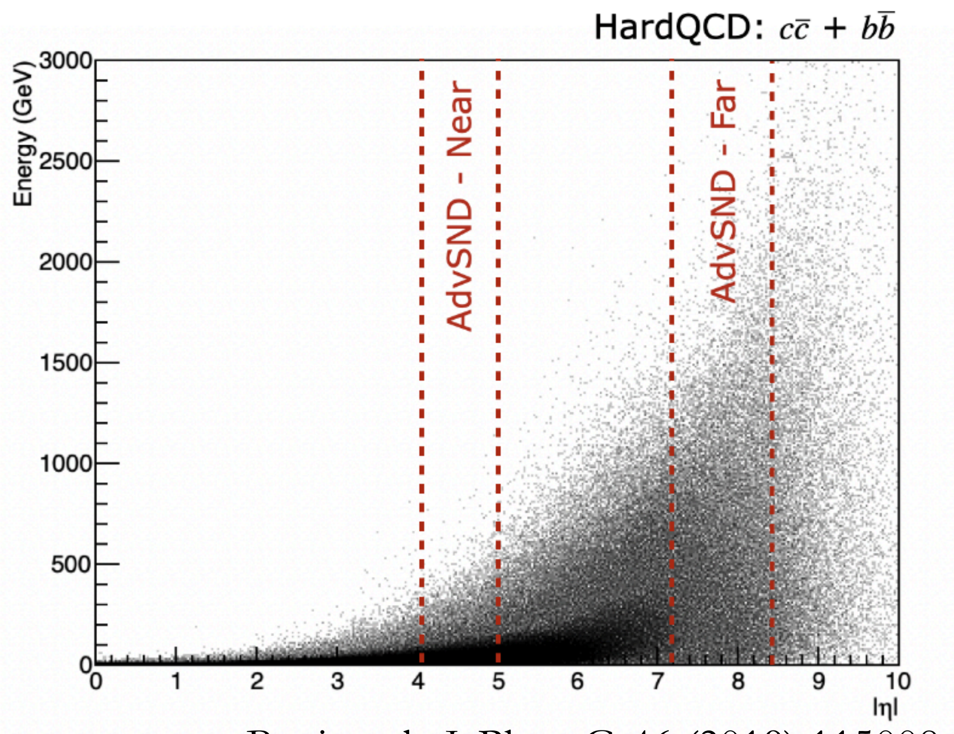
Will draw heavily from FPF Snowmass white paper, 2203.05090.

Neutrino fluxes

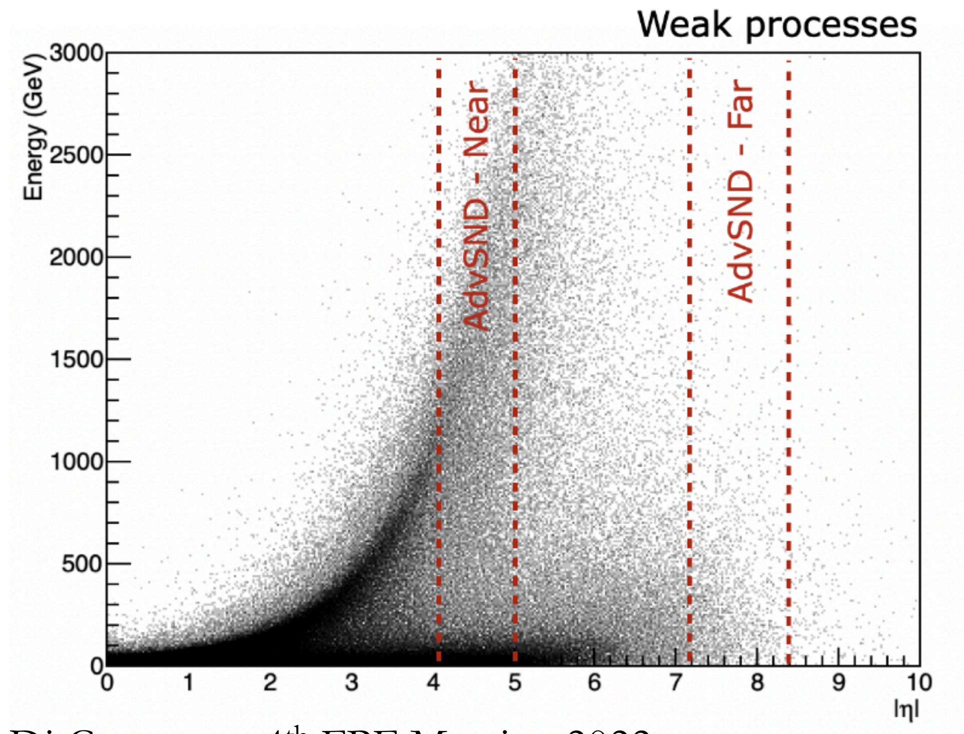
Fluxes and pseudorapidity η

look at the distribution in rapidity

b and c production and decay to neutrinos



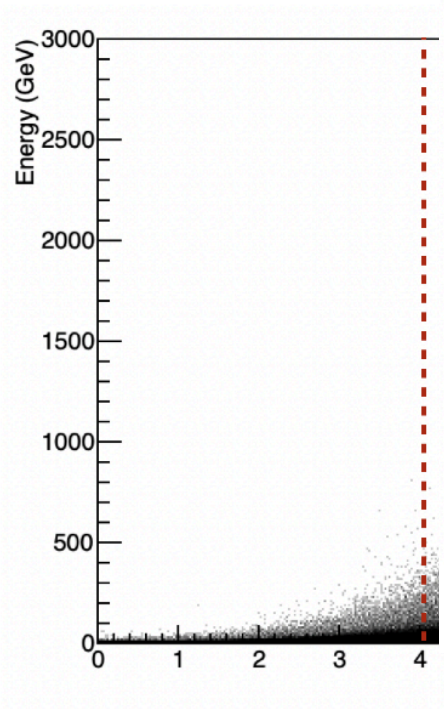
Weak production and decay to neutrinos

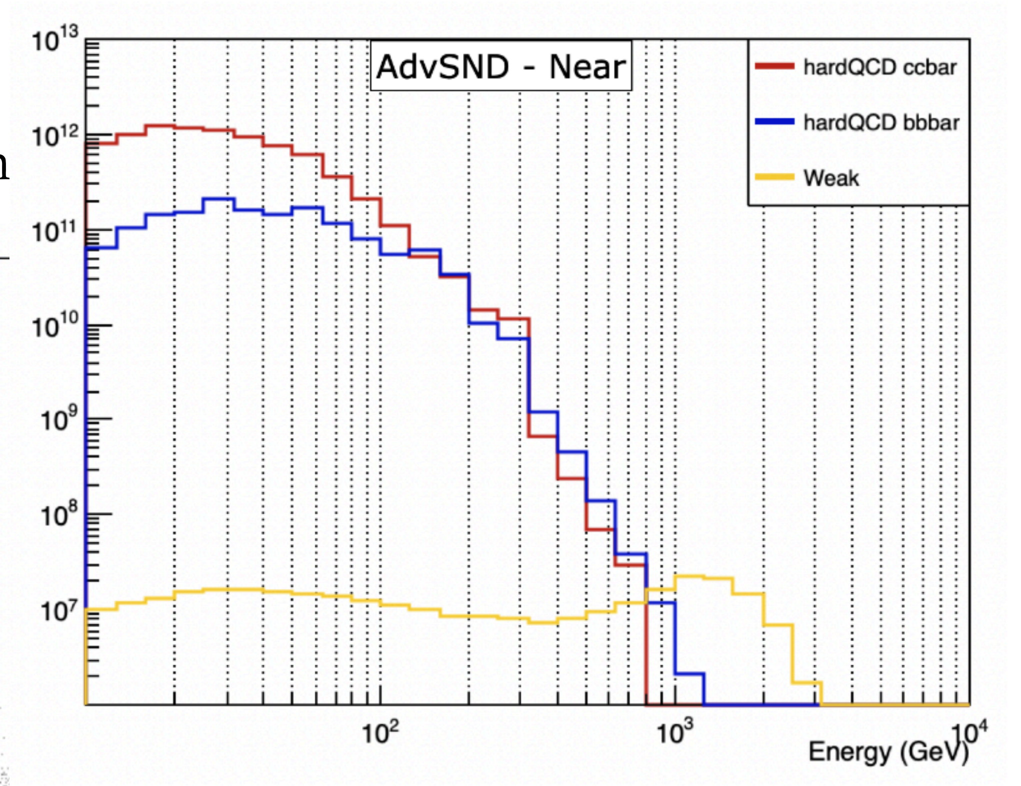


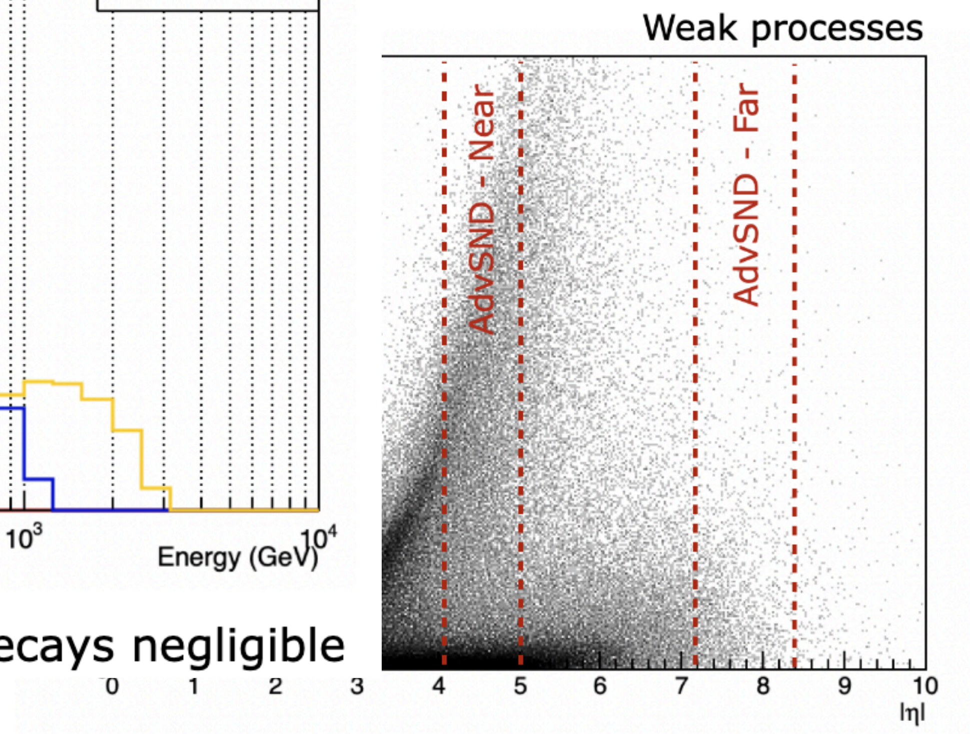
Beni et al., J. Phys. G 46 (2019) 115008 and A. Di Crescenzo 4th FPF Meeting 2022

Fluxes and pseudorapidity η

b and c production an … ı and decay to neutrinos



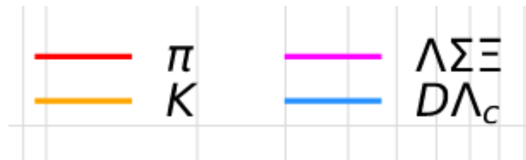


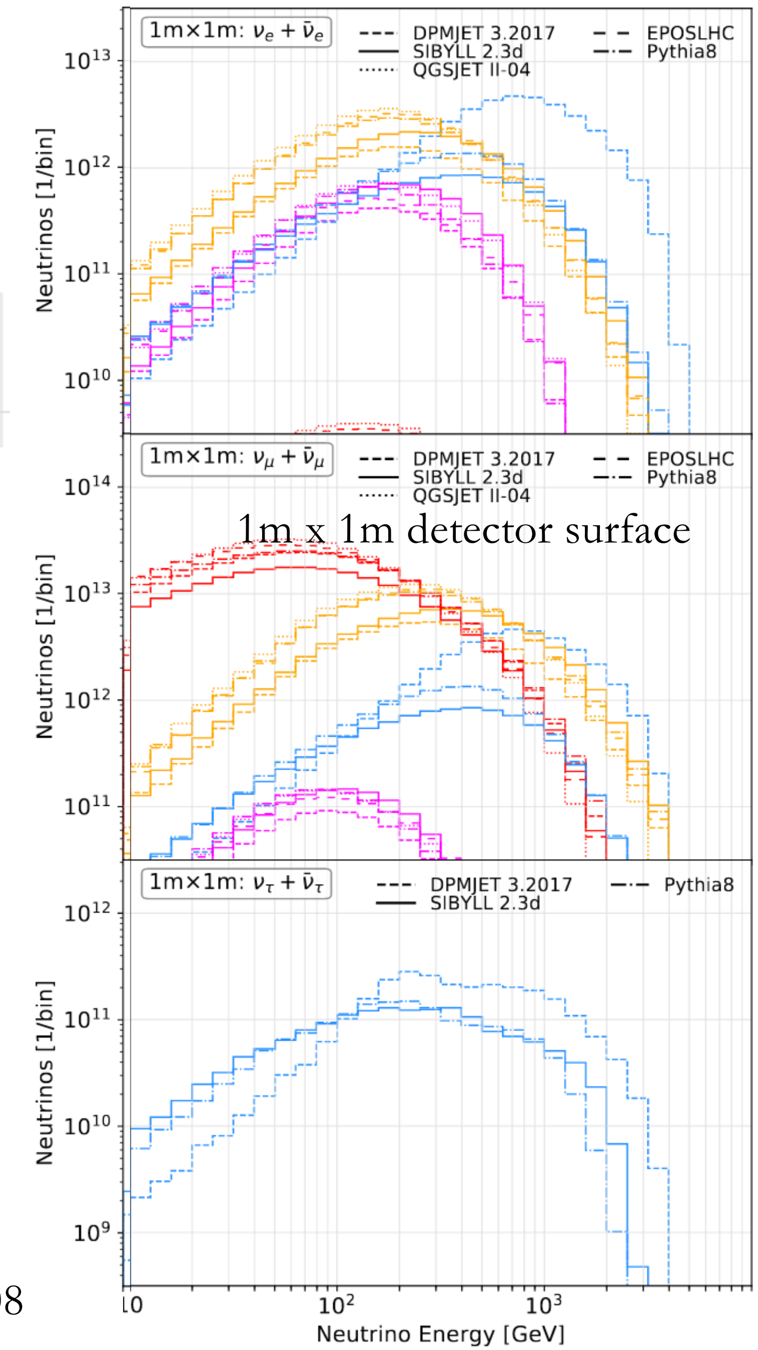


- Contribution from W/Z decays negligible

A. Di Crescenzo 4th FPF Meeting 2022

$\nu_i + \bar{\nu}_i$ fluxes at detector





- Fluxes in forward region evaluated with several MC generators of hadronic interactions for cosmic ray and forward physics + Pythia 8.2 Monash.
- Kaons dominate lower energy $\nu_e + \bar{\nu}_e$.
- Pions dominate lower energy $\nu_\mu + \bar{\nu}_\mu$.
- High energy neutrino fluxes from charm – QCD!
- In fact, $\nu_\tau + \bar{\nu}_\tau$ is all from charm.

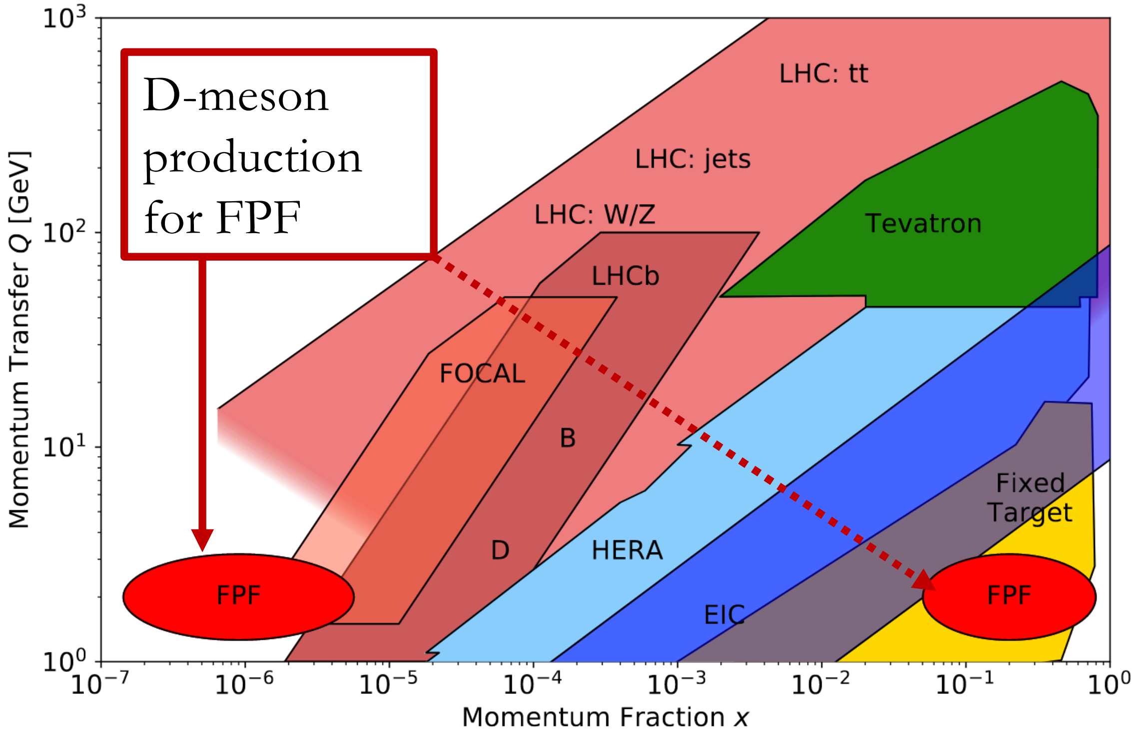
arXiv:2203.05090

see also Kling & Nevay, PRD104(2021)113008

Charm production for neutrinos

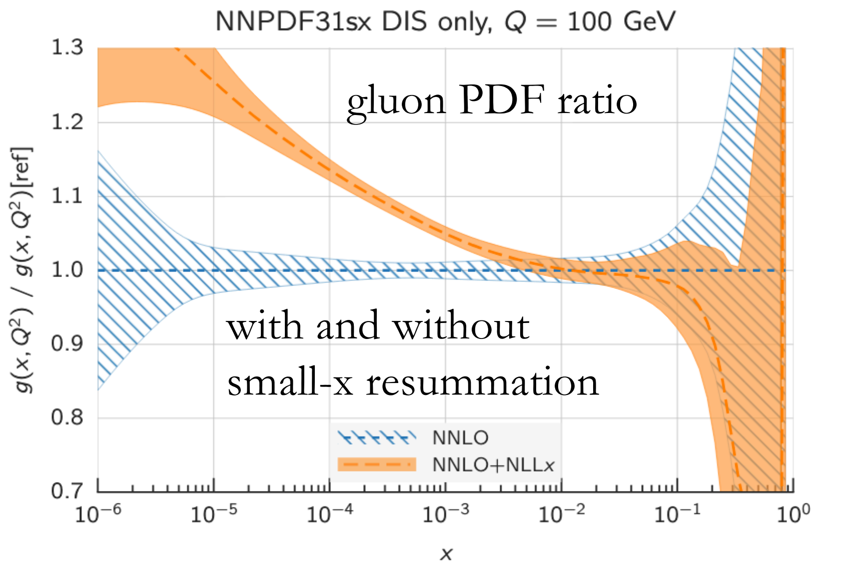
New kinematic regimes.

forward charm: high rapidity, $x_1 \gg x_2$ in gluon PDF



Small-x region for PDFs:

- PDF fits and uncertainties
- large ln(1/x) and resummation
- collinear and kT factorization approaches
- small-x gluon saturation



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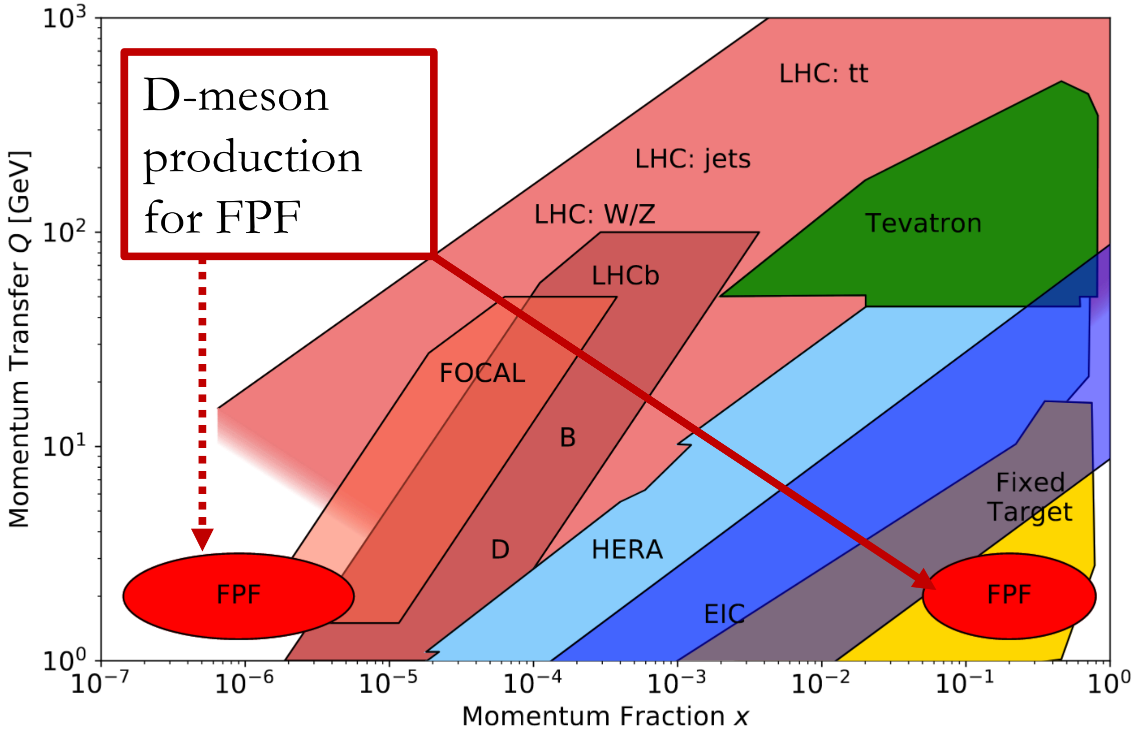
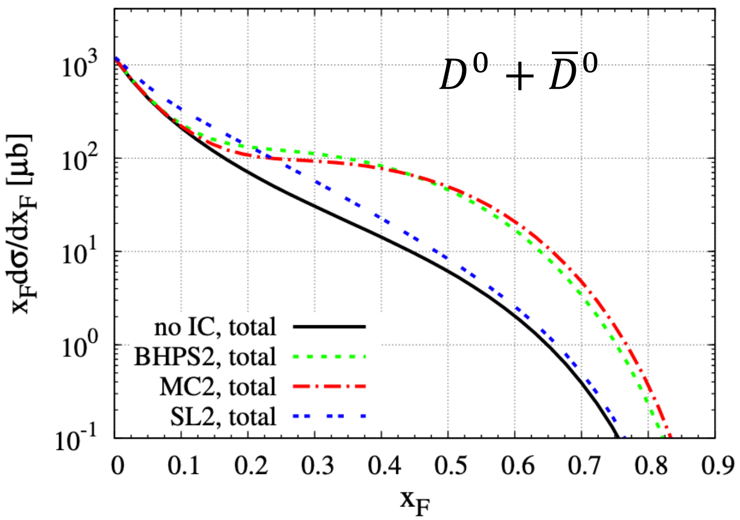
Charm production for neutrinos

forward charm: high rapidity, $x_1 \gg x_2$ in gluon PDF



Large-x region emphasized:

- large PDF uncertainties
- charm sea and potentially intrinsic charm, e.g.:
  - fitted charm (a la CT)
  - meson cloud model
  - BHPS model with Fock states w $\bar{c}c$

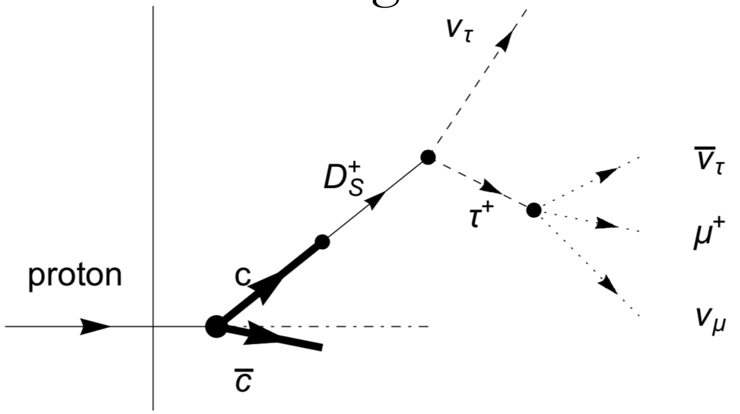


$$x_F = \frac{p_z}{p_z^{max}}$$

arXiv:2203.05090

Tau neutrino production at the LHC

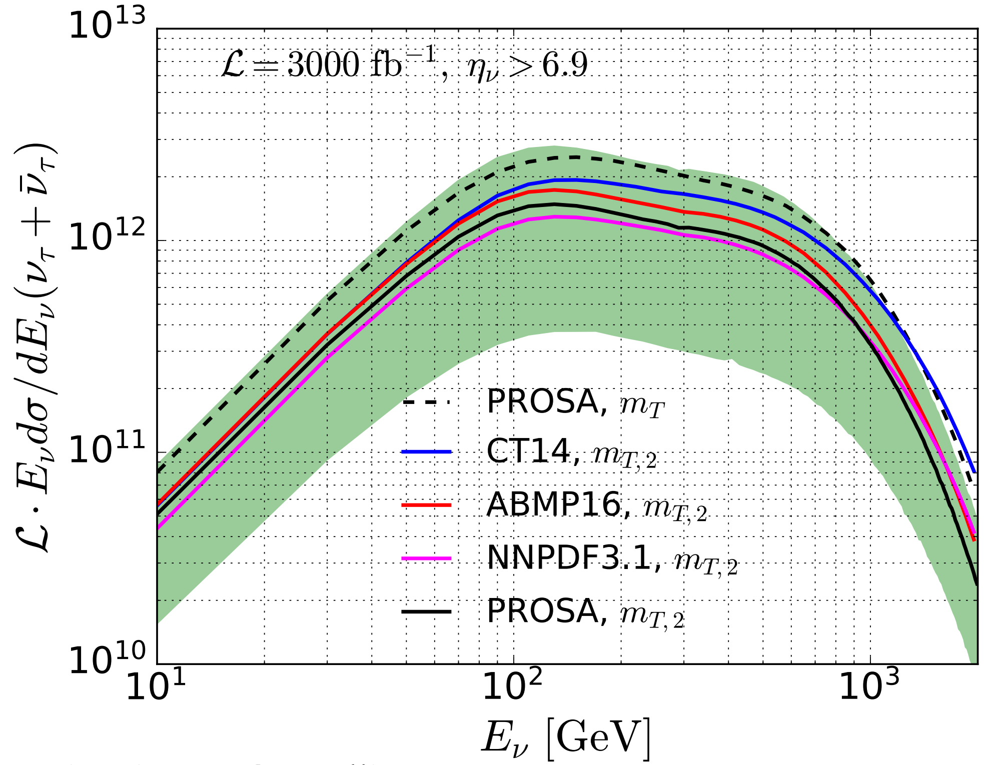
Primarily from Ds leptonic decays, a factor of more than 10 larger than from b-quarks.



Including and beyond charm production, on-going assessments in:

- Monte Carlo modeling for the forward region
- Hadronization/fragmentation
- Intrinsic pT
- Beam remnants
- Particle-antiparticle asymmetries

NLO perturbative QCD evaluation
PDF and large scale variation uncertainties (green).
Tied to LHCb data on charm production.



Bai, Diwan, Garzelli, Jeong, Kumar, MHR, 2112.11605 and 2203.05090, central set PROSA19, Zenaiev, Garzelli et al., JHEP 04 (2020) 118.

Neutrino interactions

2203.05090

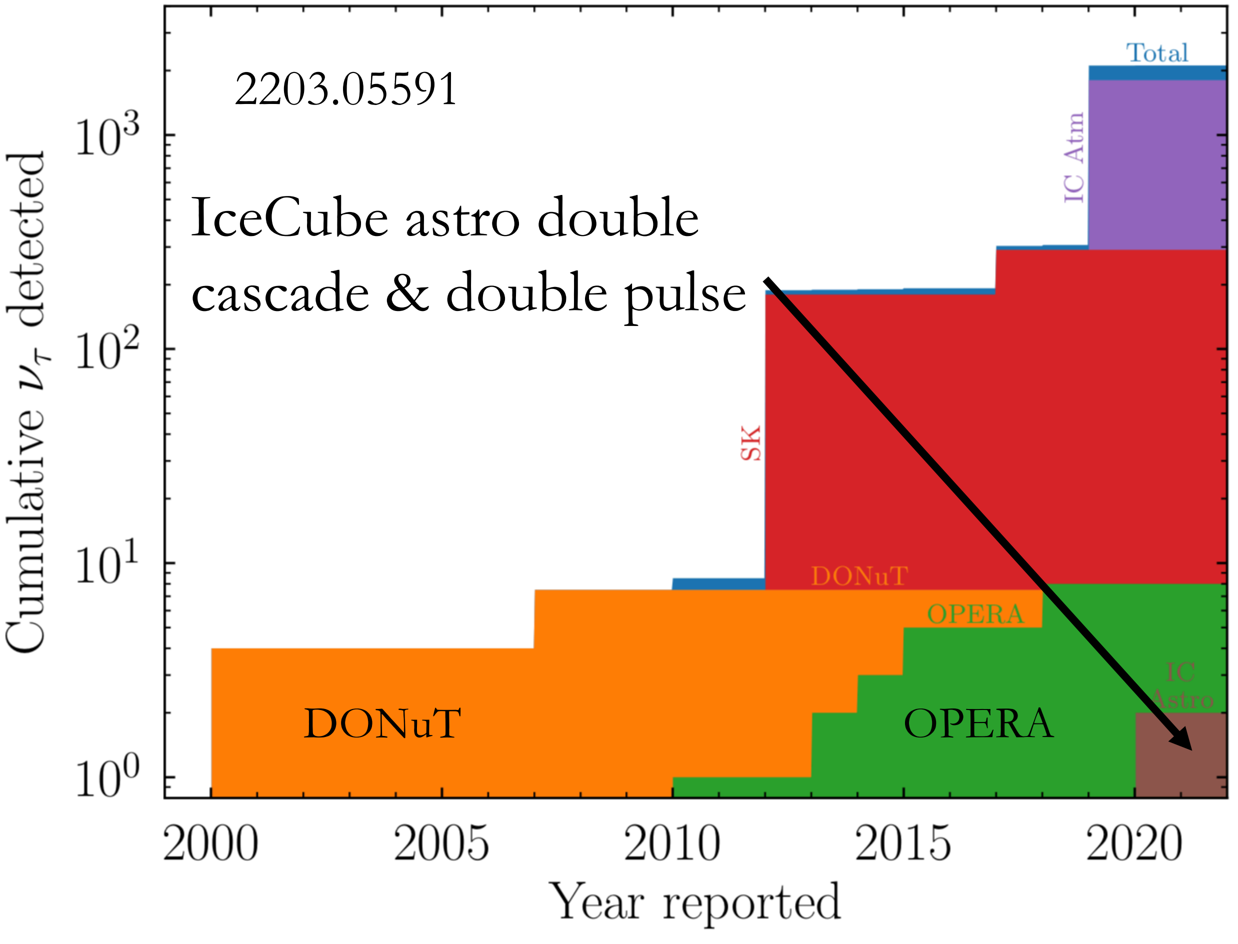
Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

Estimated number of CC interactions for Run 3 and HL LHC. Sibyll 2.3d/DPMJet 3.2017

Snowmass white paper: Tau neutrinos in the next decade: from GeV to EeV 2203.05591

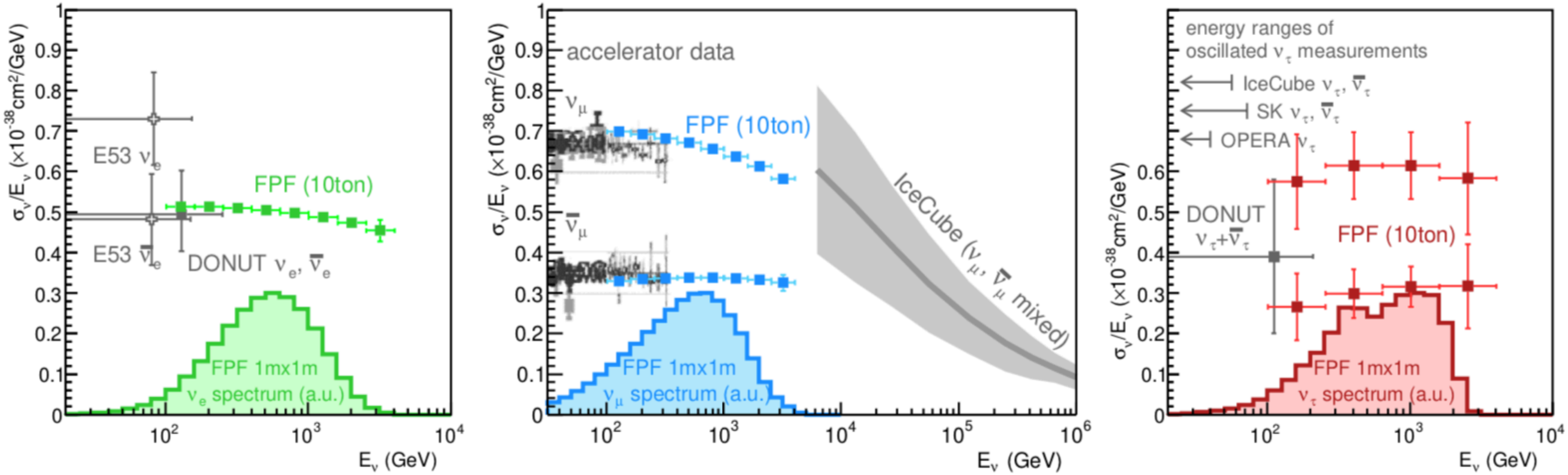
Few direct identifications of tau neutrinos: DONUT, OPERA, IceCube.

Key feature of FPF experiments: neutrino flavor ID.



Standard Model neutrino interactions

Neutrino CC DIS cross sections

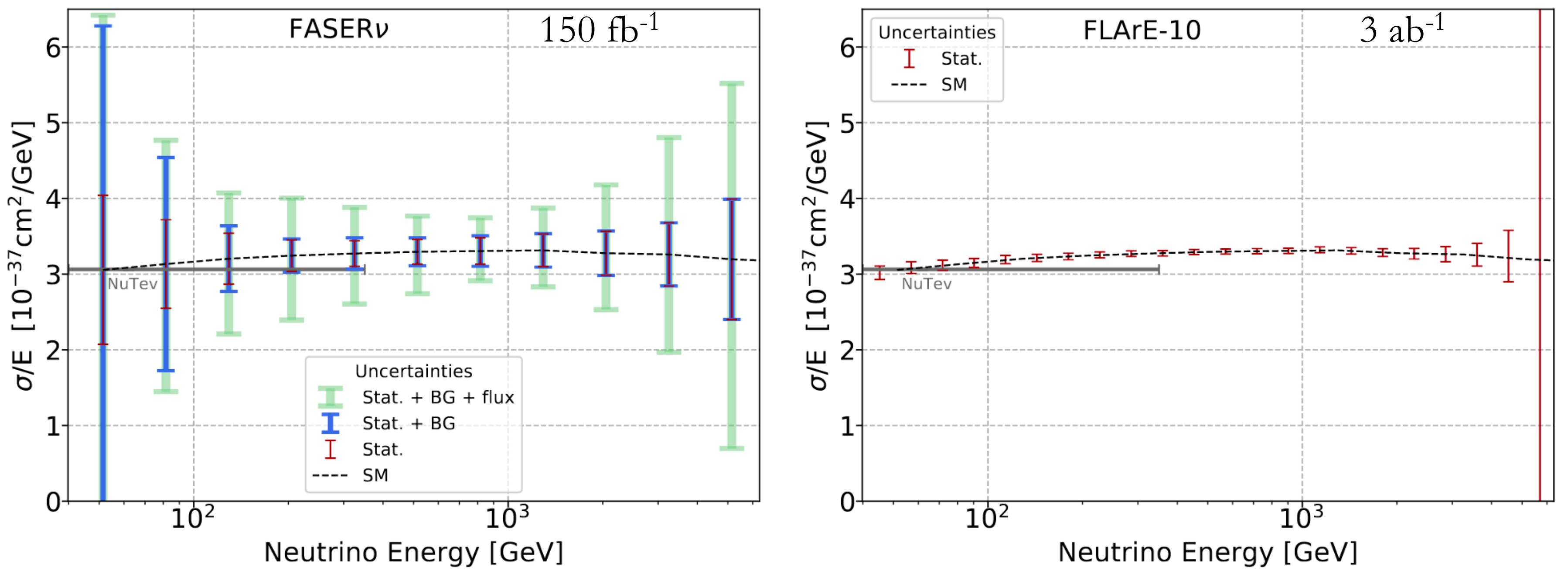


Statistical uncertainty only in figures (from 2203.05090).

• Neutrinos and antineutrinos. • Many more tau neutrinos!

Important to understand QCD and MC generation of light hadrons in predictions of the flux of neutrinos from the ATLAS interaction point.

Neutrino NC DIS cross sections



Estimated sensitivities, averaged neutrino plus antineutrino, from 2203.05090.

See also Ismail, Mammen Abraham & Kling, PRD 103 (2021) 056014.

Quasi-elastic, resonant, shallow interactions

Batell et al.

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

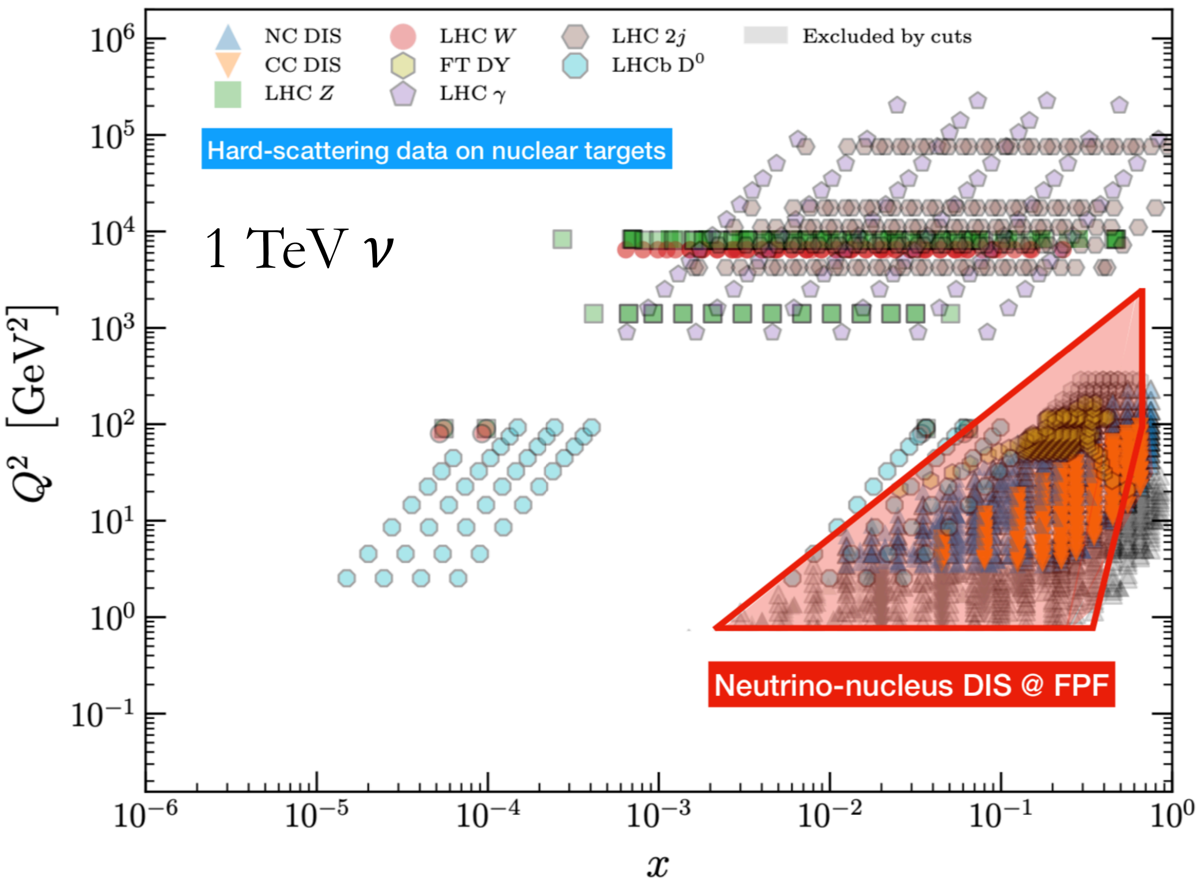
TABLE I. Expected event rates for charged current quasielastic (CCQE), charged current resonant (CCRES), neutral current elastic (NCEL), and neutral current resonant (NCRES) interactions of neutrinos in the FASERν2, FLArE-10, and FLArE-100 detectors. The results for CC interactions are given for each 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

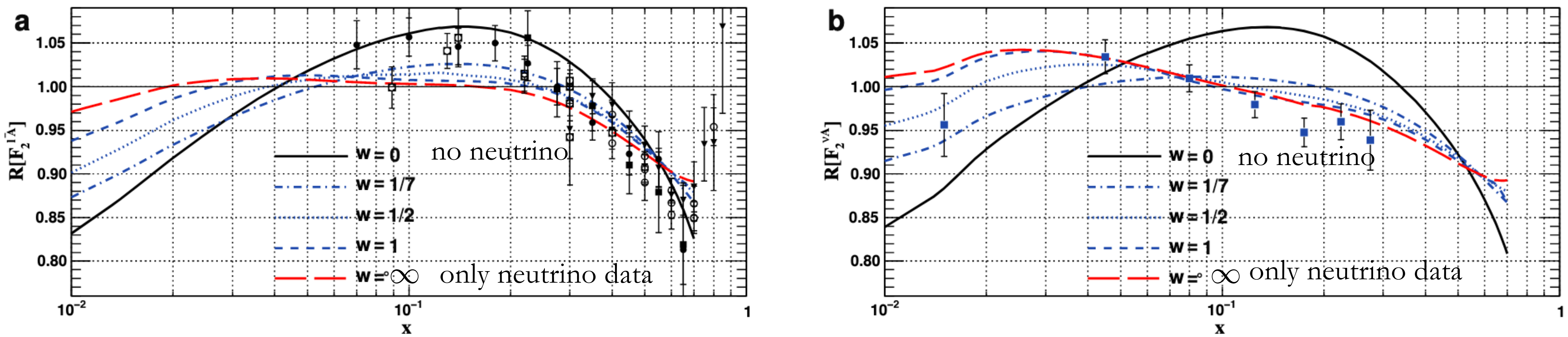
νA collisions



2203.05090

- Extends (x,Q) coverage for nuclear targets.
- Shown here, for 1 TeV neutrino energy, along with hard scattering data on nuclear targets.
- Tungsten, argon targets.

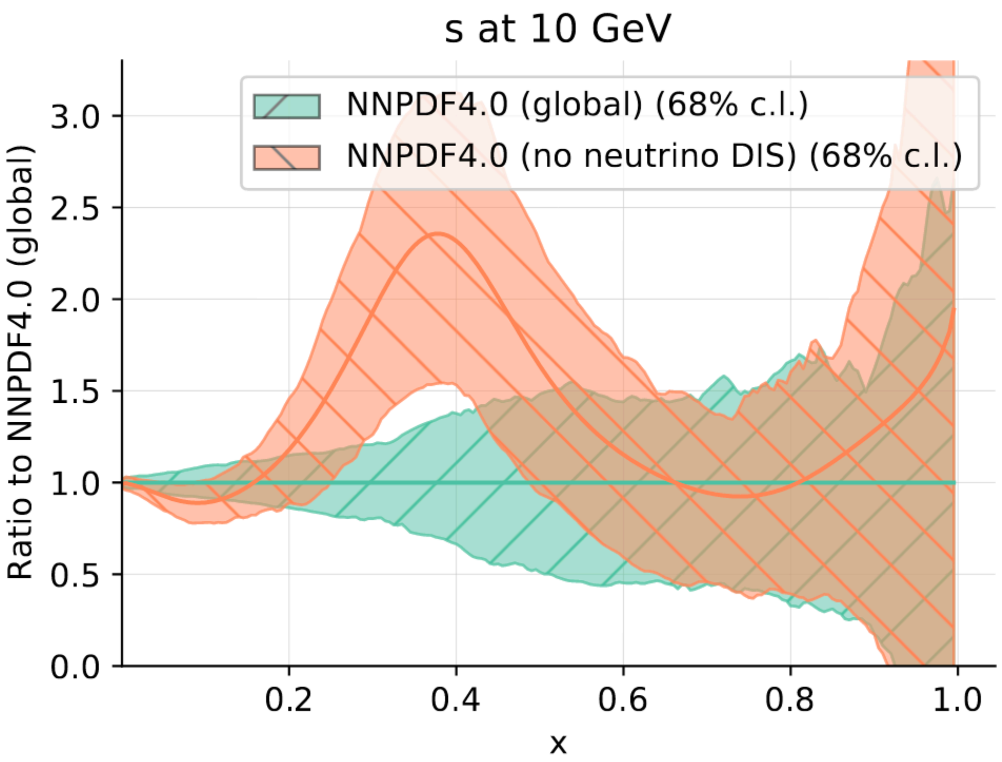
Nuclear effects in neutrino scattering



Fits from Kovarik et al, PRL 106 (2011) 122301, as shown in 2203.05090 for Q^2 = 5 GeV^2.

- Ratios of F_2 for iron and free nucleon for a) charged leptons (BCDMS & SLAC experiments) and b) neutrino scattering (NuTeV).
- Difficult to satisfy lepton NC and neutrino CC scattering with nuclei.

Strange PDF

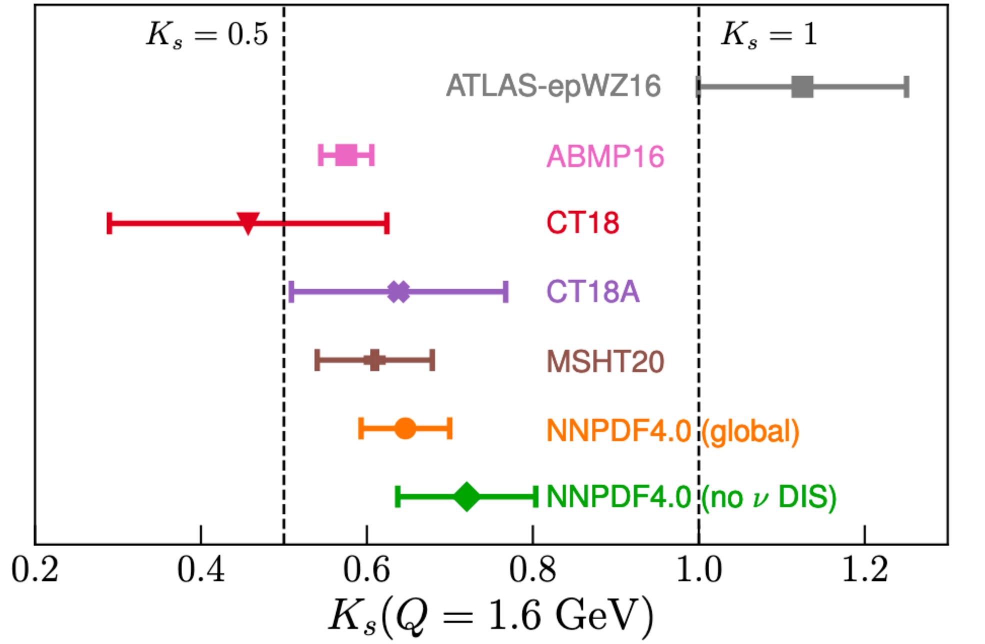


NNPDF4.0 normalized to central value of default PDF set.

Figs. from 2203.05090.

- inclusive DIS
- dimuon production (neutrino production of charm)

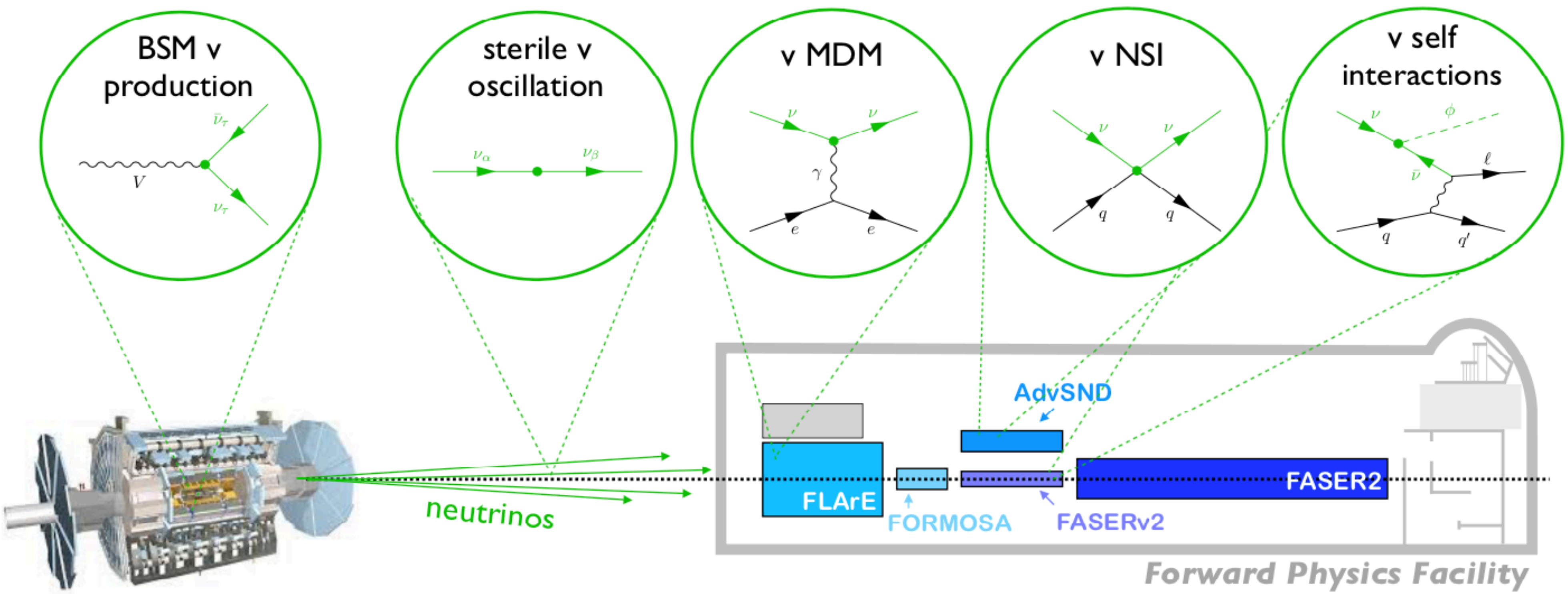
$$K_s \equiv \frac{\int_0^1 dx x[s(x,Q)+\bar{s}(x,Q)]}{\int_0^1 dx x[\bar{u}(x,Q)+\bar{d}(x,Q)]}$$



Beyond the Standard Model neutrino physics

Some examples

BSM physics at production and detection point



2203.05090

BSM EFT constraints

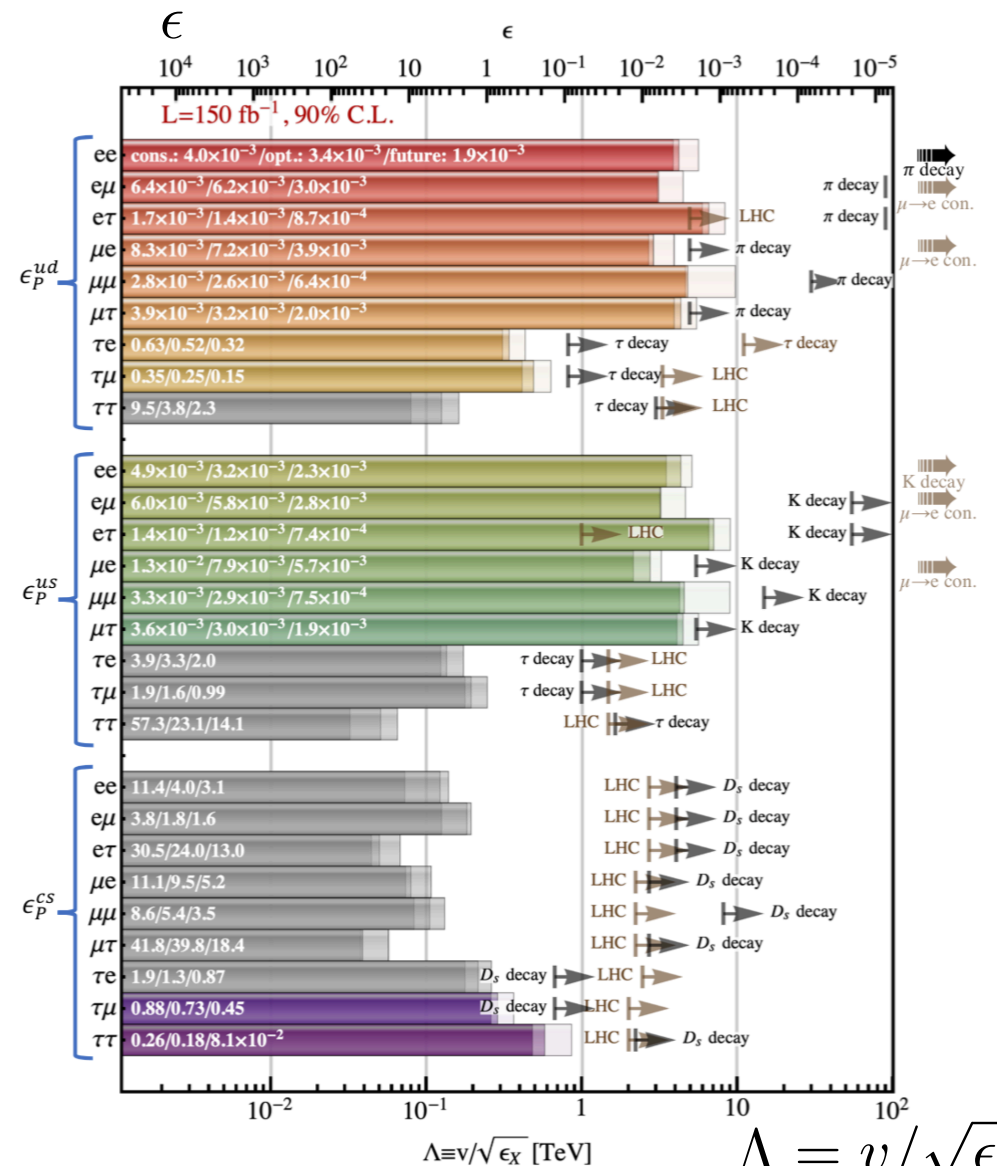
Example: pseudoscalar dimensionless ϵ_P

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

- 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.

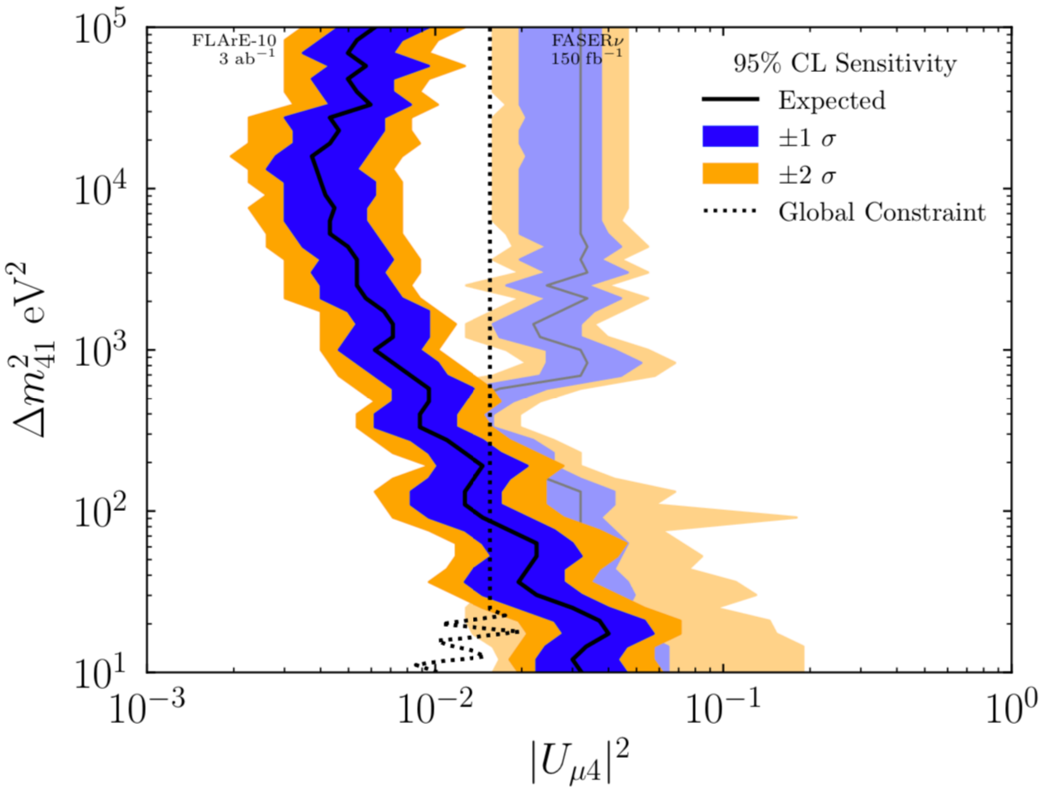
$V_{jk} = $ Cabibbo ME $\quad v \simeq 246$ GeV



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

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

Oscillation to sterile neutrinos, 3+1



arXiv:2109.10905

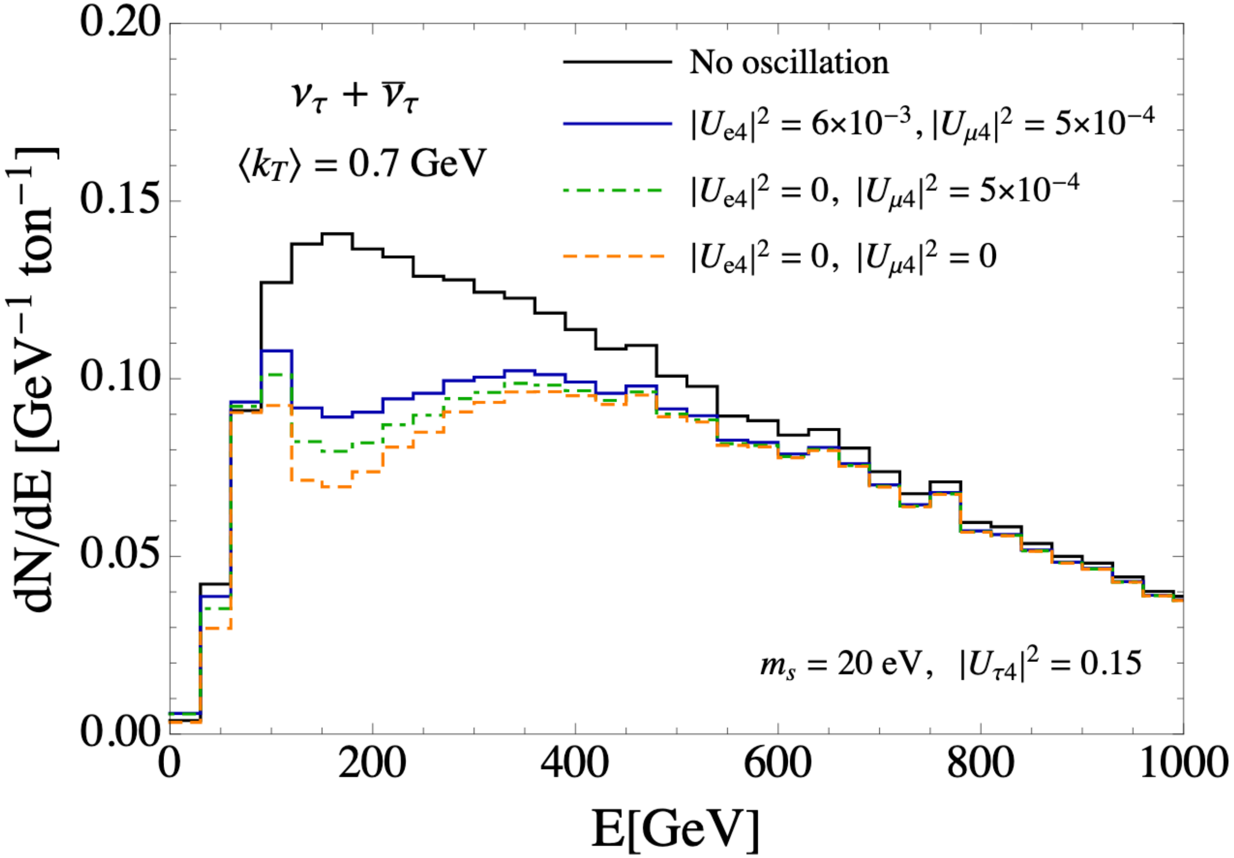
Baseline of ~620 m and energy range of 100 GeV - 1 TeV, probes mass-difference squared higher than DUNE, etc.:

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

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.)

Oscillations to sterile neutrinos, 3+1

CC events, $\eta > 6.87$, 3 ab^{-1}



Mixing of tau neutrinos with sterile neutrinos are not well constrained:

$$|U_{\tau 4}|^2 < 0.18 \text{ (90\% CL)},$$
$$\Delta m^2 > 0.1 \text{ eV}^2$$

SuperK, PRD 91 (2015) 052019

Spectral distortions from tau neutrino oscillations to sterile neutrinos over 480 m baseline, neutrino energies between 100 GeV- 1 TeV. Example: m_s=20 eV.

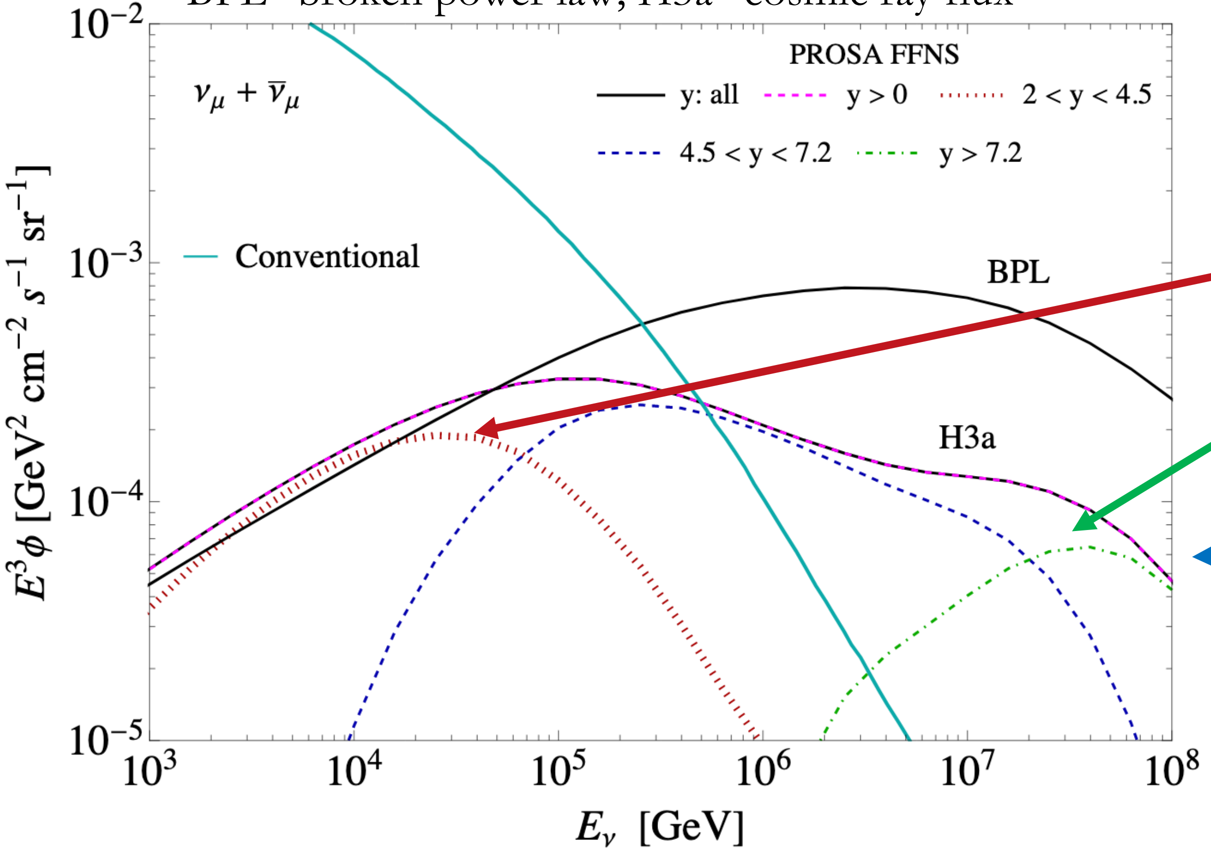
Essential is understanding of the flux of tau neutrinos.

Bai, Diwan, Garzelli, Jeong, Kumar, MHR, JHEP 06 (2020) 032.

Astroparticle physics connections (briefly)

Astroparticle physics connections – prompt atmospheric neutrinos

BPL=broken power law; H3a=cosmic ray flux



2203.05090, see also Jeong, Bai, Diwan, Garzelli, Kumar, MHR, 2107.01178

Prompt neutrinos are a background to the diffuse astrophysical flux for underground neutrino detectors.

LHCb

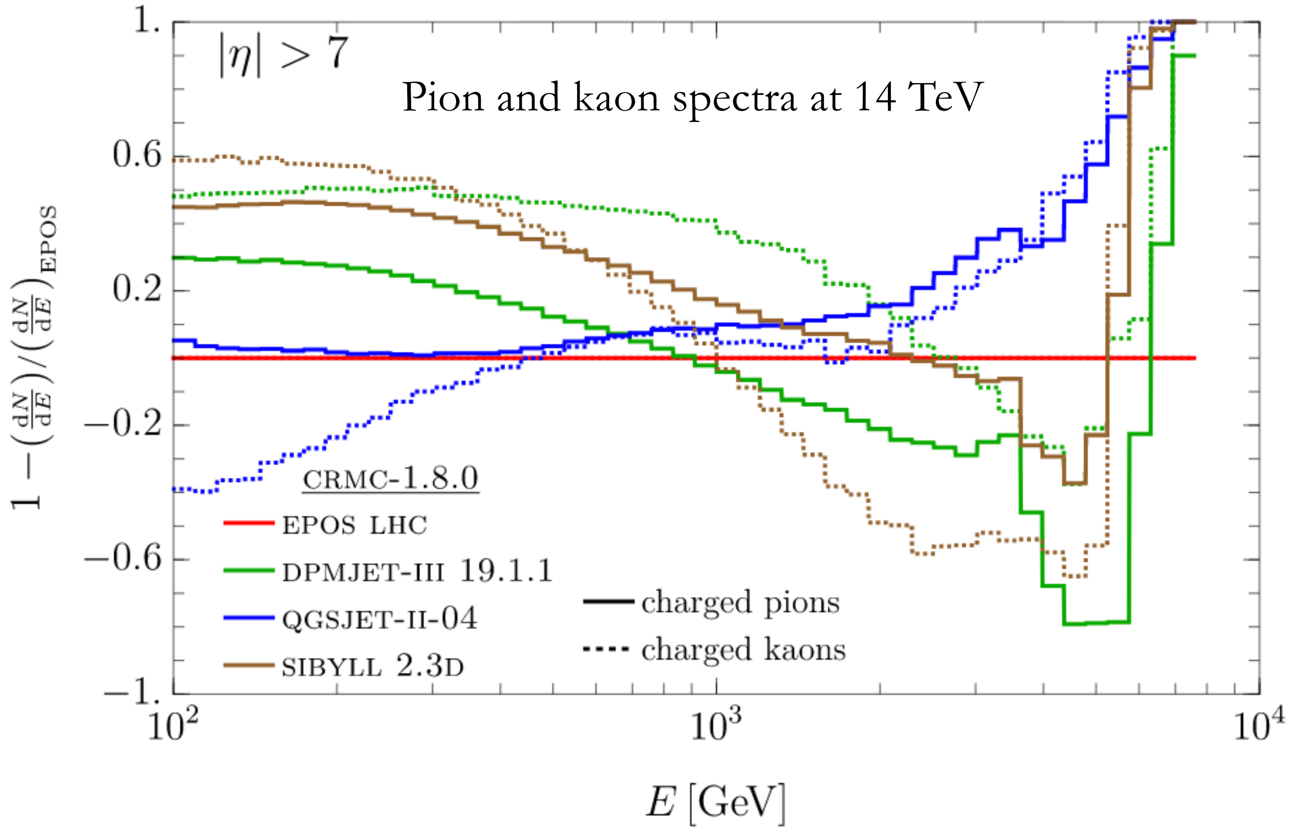
FPF

charm production and decay "prompt atmospheric neutrinos"

y is charm rapidity in collider frame

Interplay between FPF and cosmic ray measurements and modeling

Cosmic ray air shower Monte Carlos
Energy distributions of pions and kaons relative to EPOS.



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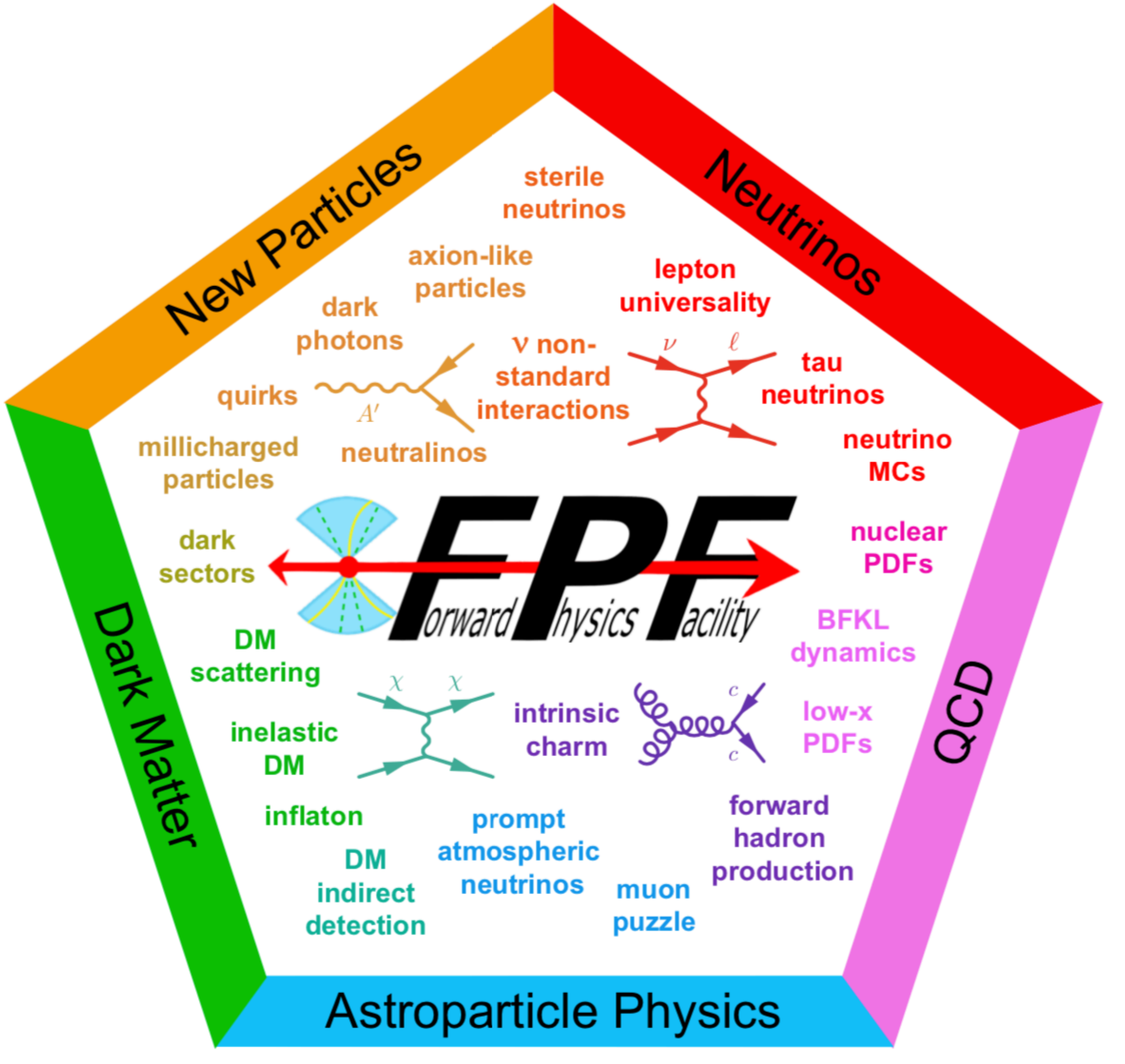
- Neutrinos as proxies for charged mesons: e.g., energy distribution of ν_e/ν_μ
- Modeling of cosmic ray air showers.
- Hadron multiplicities.
- Forward strangeness and atmospheric muons: the muon problem (too many muons in HE cosmic ray air showers).

See, e.g., Anchordoqui et al., JHEAp 34 (2022) 19.


New Particles
Neutrinos
QCD
Astroparticle Physics
Dark Matter
sterile neutrinos
axion-like particles
dark photons
quirks
millicharged particles
neutralinos
ν non-standard interactions
lepton universality
tau neutrinos
neutrino MCs
nuclear PDFs
BFKL dynamics
low-x PDFs
forward hadron production
intrinsic charm
muon puzzle
prompt atmospheric neutrinos
DM indirect detection
inflaton
inelastic DM
DM scattering
dark sectors
FPF
Forward Physics Facility

Summary and final remarks

- Neutrino fluxes:
  - High energy neutrinos and all of tau neutrinos and antineutrinos come from heavy flavor decays. Very forward means large-x and small-x regimes for PDFs. Can tie heavy flavor predictions to LHCb and DsTau (NA65) with 400 GeV proton beam, also to the prompt atmospheric neutrino flux.
  - Prediction of neutrinos from light meson decays related to simulations of cosmic ray air showers: Monte Carlo developments.

Summary and final remarks

- Neutrino fluxes:
- Neutrino interactions:
  - Cross sections - dominated by DIS but also contributions of QE and RES, new information for neutrino Monte Carlos.
  - Nuclear effects
  - PDFs in new kinematic ranges.

Summary and final remarks

- Neutrino fluxes:
- Neutrino interactions:
- BSM physics:
  - Through flux and through interactions of neutrinos.
  - See the White Paper for more BSM physics that does not necessarily require neutrinos (429 pages and references therein!)

Summary and final remarks

- Neutrino fluxes
- Neutrino interactions
- BSM physics

- Still work to be done to realize a forward physics facility.

Thank you!