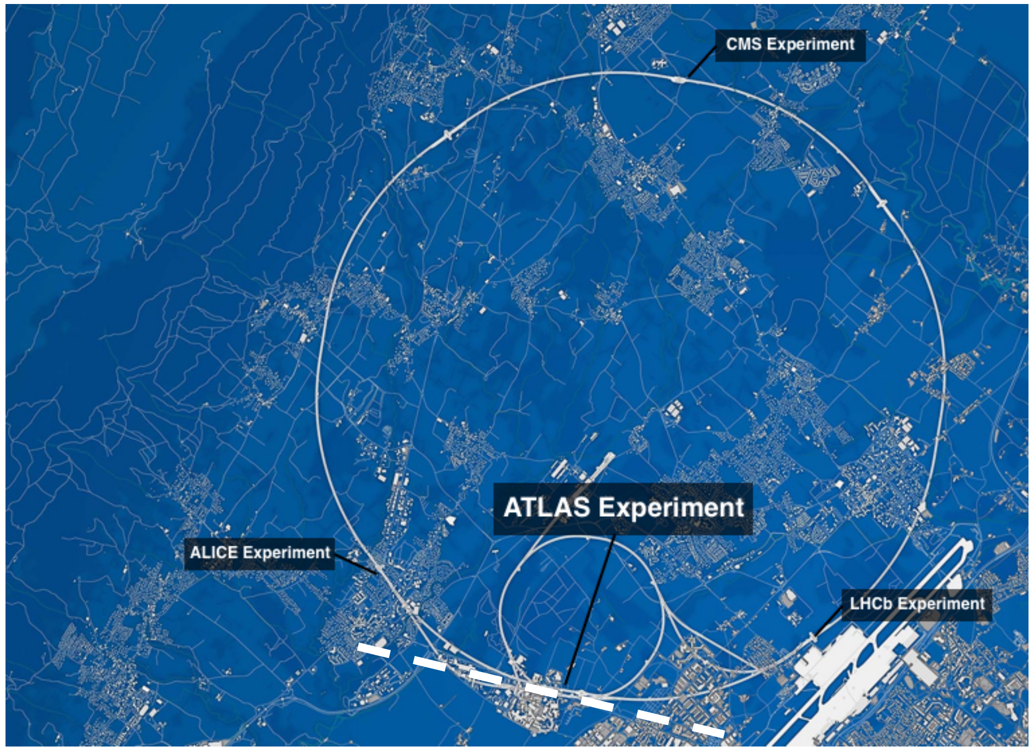
QCD with a Forward Physics Facility at the High-Luminosity LHC

M. H. Reno
University of Iowa
July 18, 2022

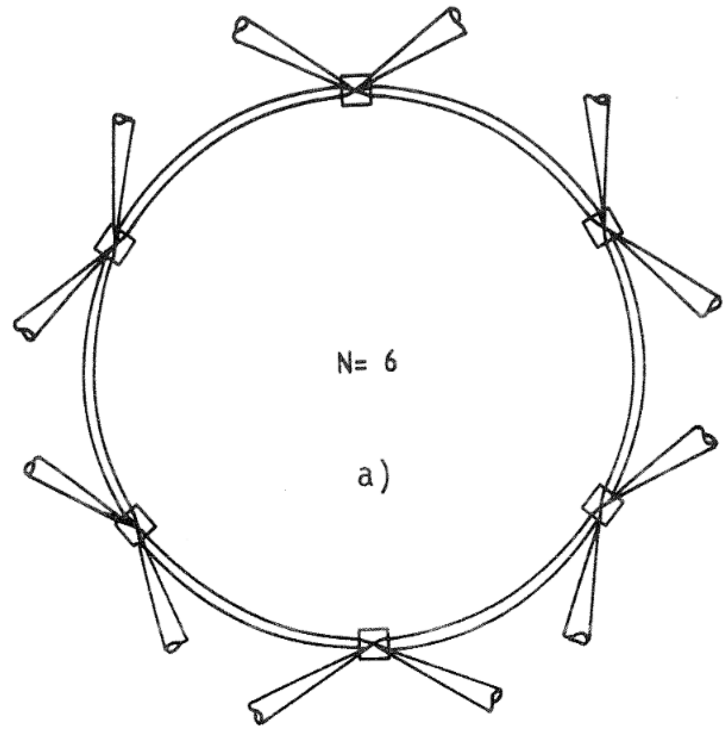
Snowmass Community Summer Study

MHR: work supported in part by the US Department of Energy.

Collider neutrinos as probes of QCD



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.

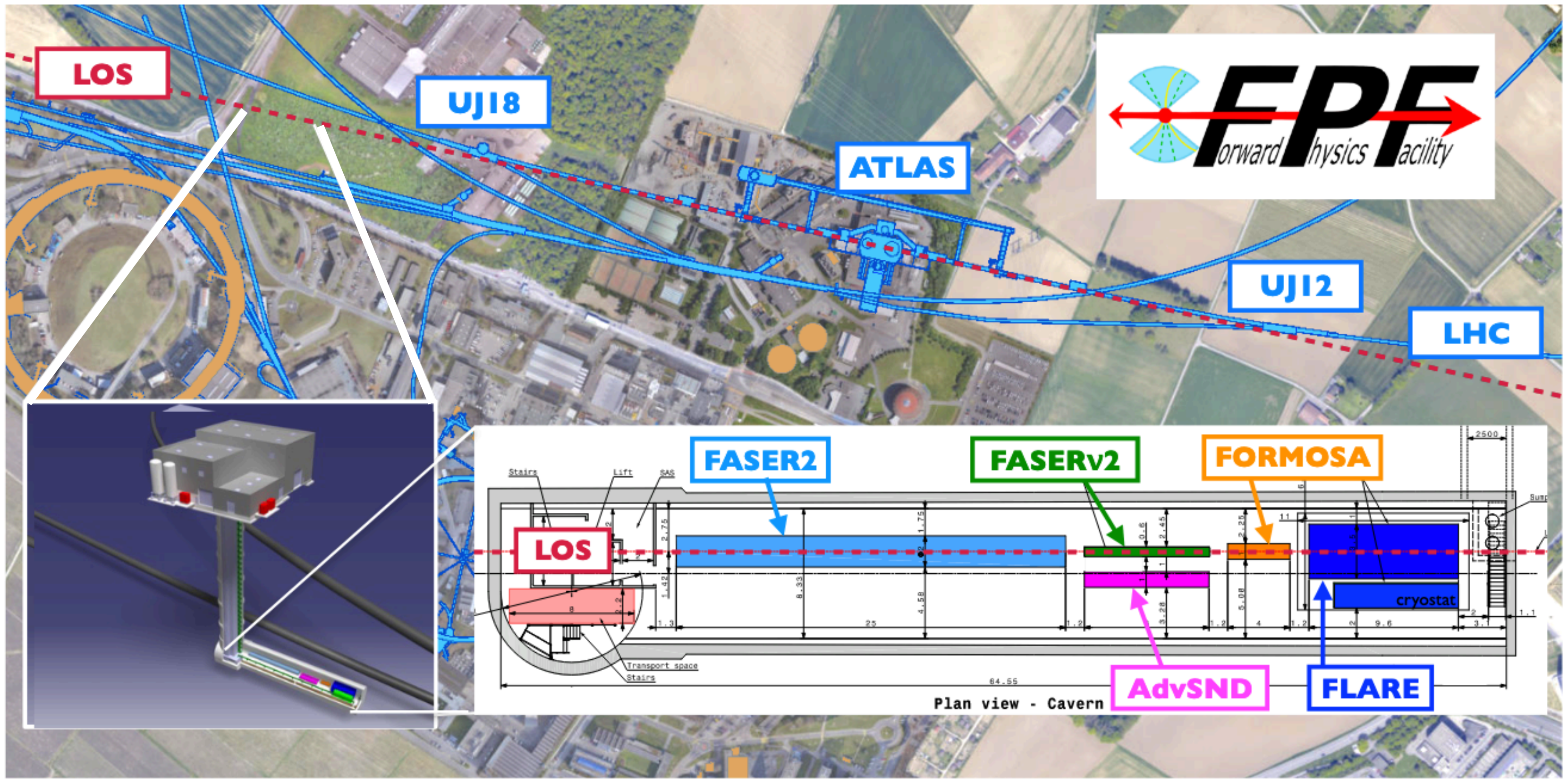
Early discussions including:

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

Currently, FASERν and SND@LHC installed for Run 3 based on this idea.

Purpose-built Forward Physics Facility initiative

Underground facility ~620 m far forward from the ATLAS IP, shielded by ~200 m concrete and rock. FPF experiments to detect $\sim 10^6$ neutrino interactions, energies up to a few TeV.



Relatively low cost – neutrinos are free!

Need the facility infrastructure and detectors designed for Standard Model and BSM Physics.

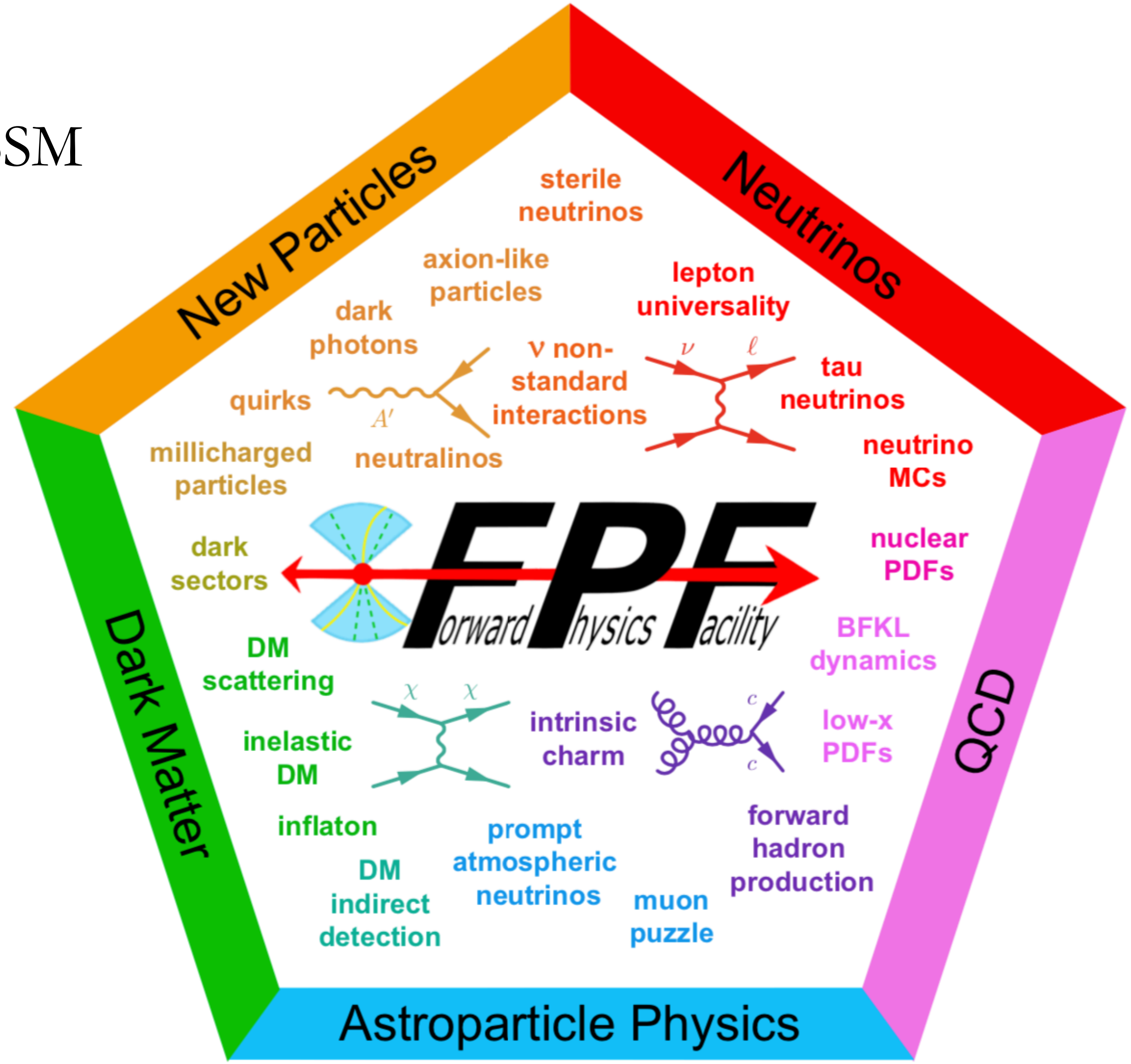
FPF White Papers: arXiv:2203.05090 ("long paper"), see also Anchordoqui et al. Phys. Rept. 968 (2022) 1 ("short paper")

- Purpose-built facility (FPF)
- Suite of experiments for standard model and BSM physics, a versatile program.
- Exploit HL-LHC with relatively low cost.

Beginning Fall 2020: CERN PBC civil engineering study started. Preferred location identified.

Possible timeline:

- Civil engineering, construction of experiments during long shut-down.
- Beginning of Run 4 – installation of services.
- Mid Run4 – installation of experiments. (Access FPF during LHC running.)



FPF White Papers: arXiv:2203.05090, edited by J. Feng, F. Kling, J. Rojo, D. Solding, MHR.

How forward is forward? New kinematic regimes

Run 3

Detector			
Name	Mass	Coverage	Luminosity
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}

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

FASERν 1.2 ton, 25 cm x 25cm

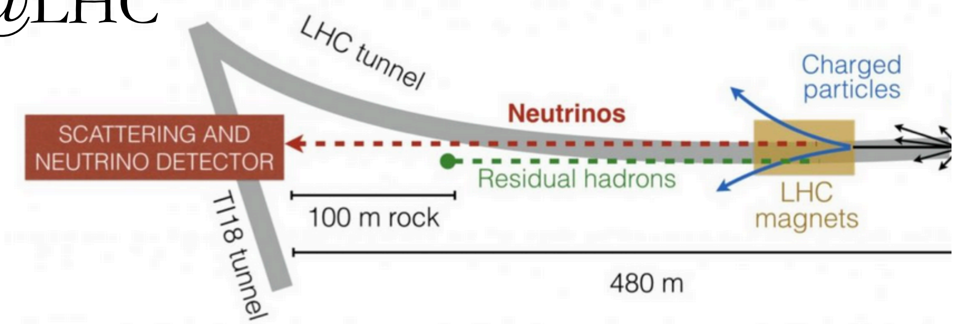
on axis, $\eta > 8.5$

SND@LHC 800 kg, 39 cm x 39 cm

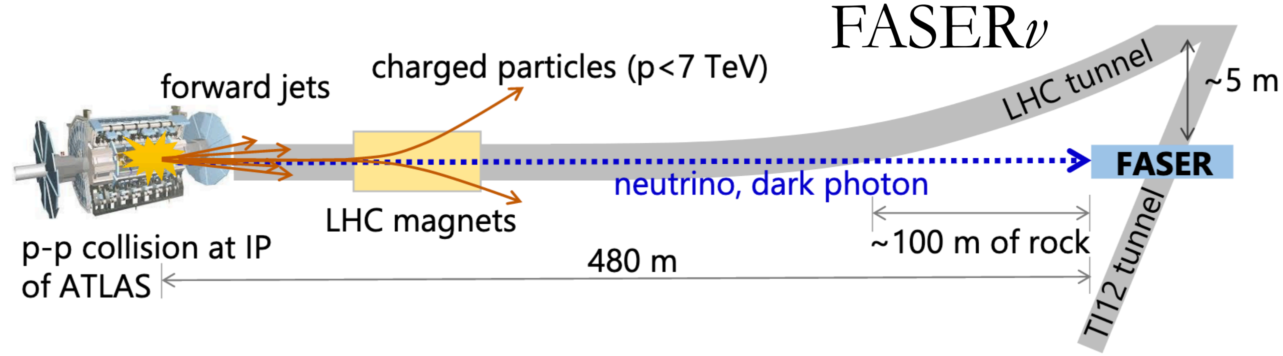
off axis, $8.5 > \eta > 7$

Run 3: Detectors are installed and taking data with ~30% emulsions.

SND@LHC



FASERν



How forward is forward?

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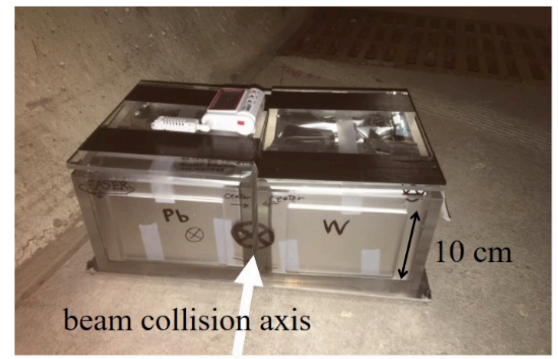
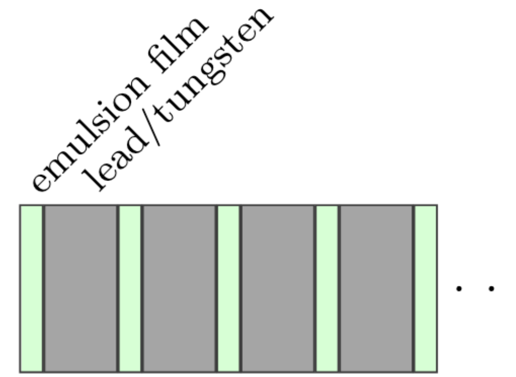
FASERν pilot: demonstration of potential and neutrino candidate events.

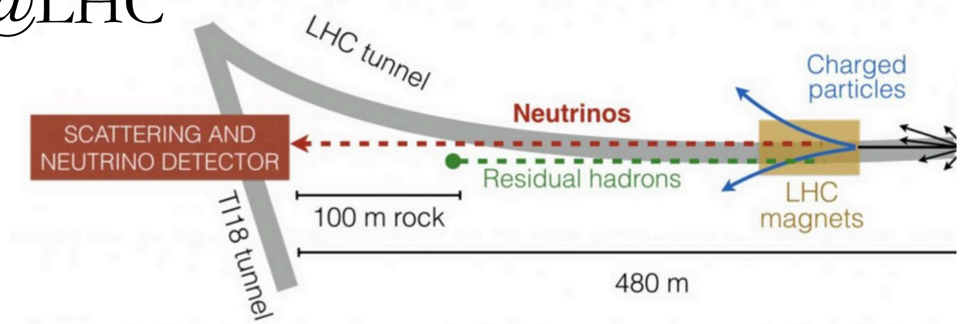
FASER, Phys. Rev. D 104 (2021) L091101



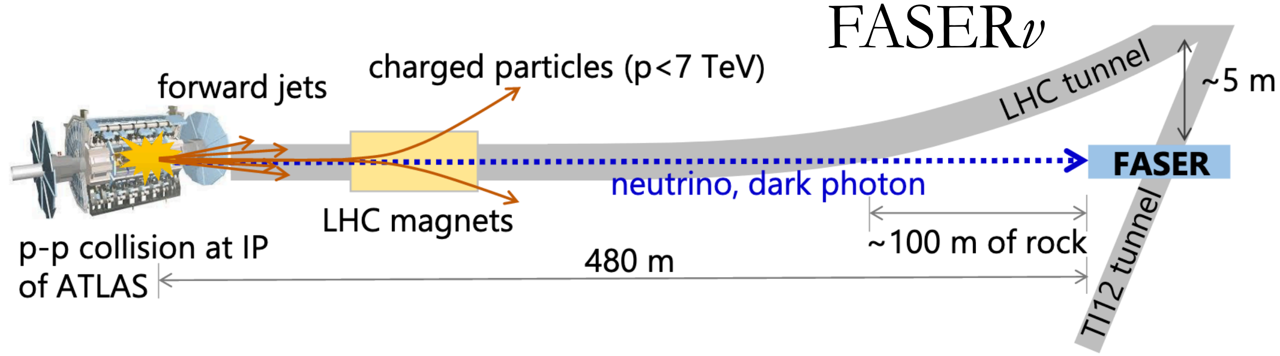


29 kg "suitcase size" prototype detector, 480 m from interaction point, for 12.2 fb^{-1} in *pp* collisions at 13 TeV.

SND@LHC



FASERν



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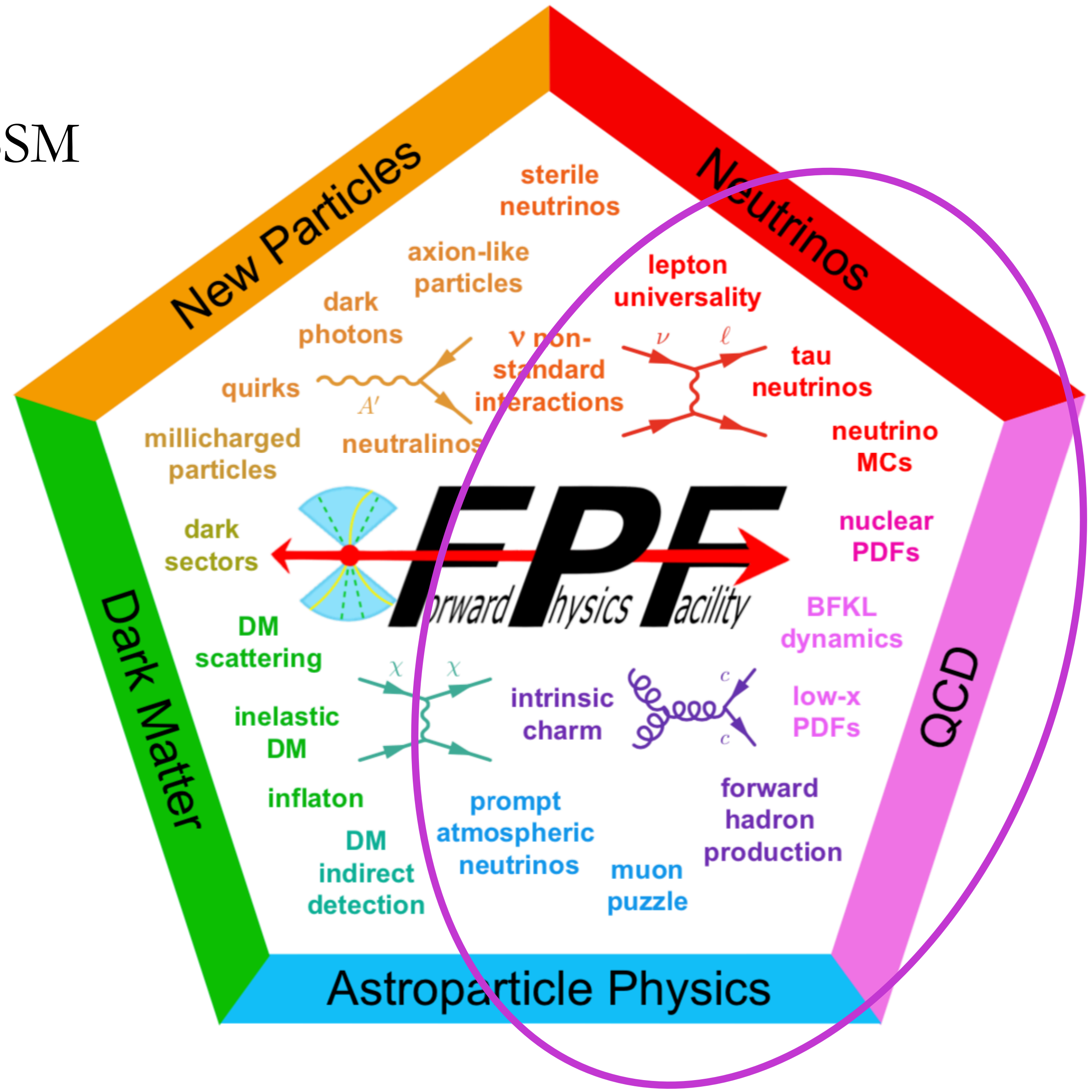
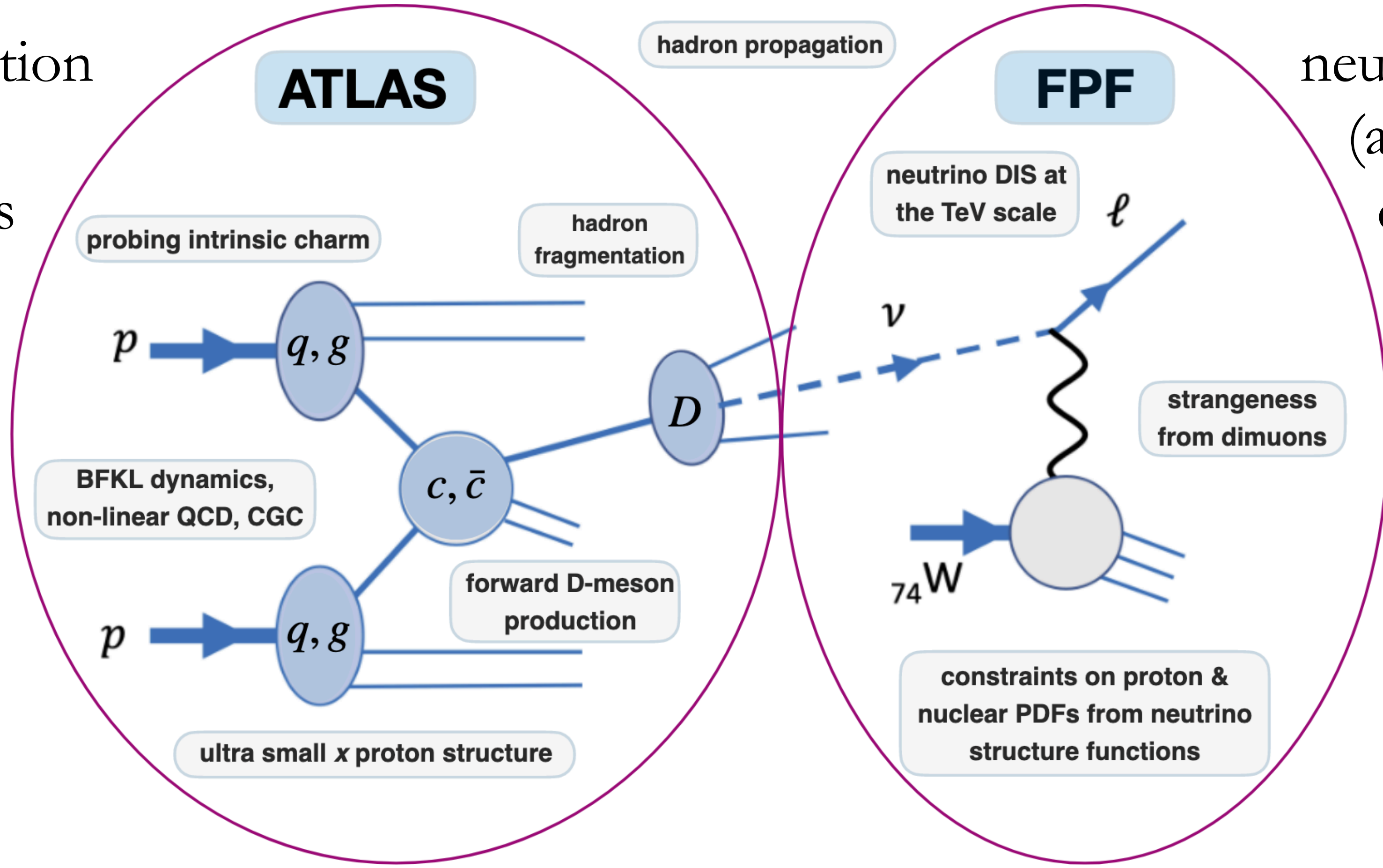


FPF White Papers: arXiv:2203.05090, edited by J. Feng, F. Kling, J. Rojo, D. Solding, MHR.

QCD in *pp* and *νA* collisions

hadron production that ultimately yields neutrinos of all 3 flavors



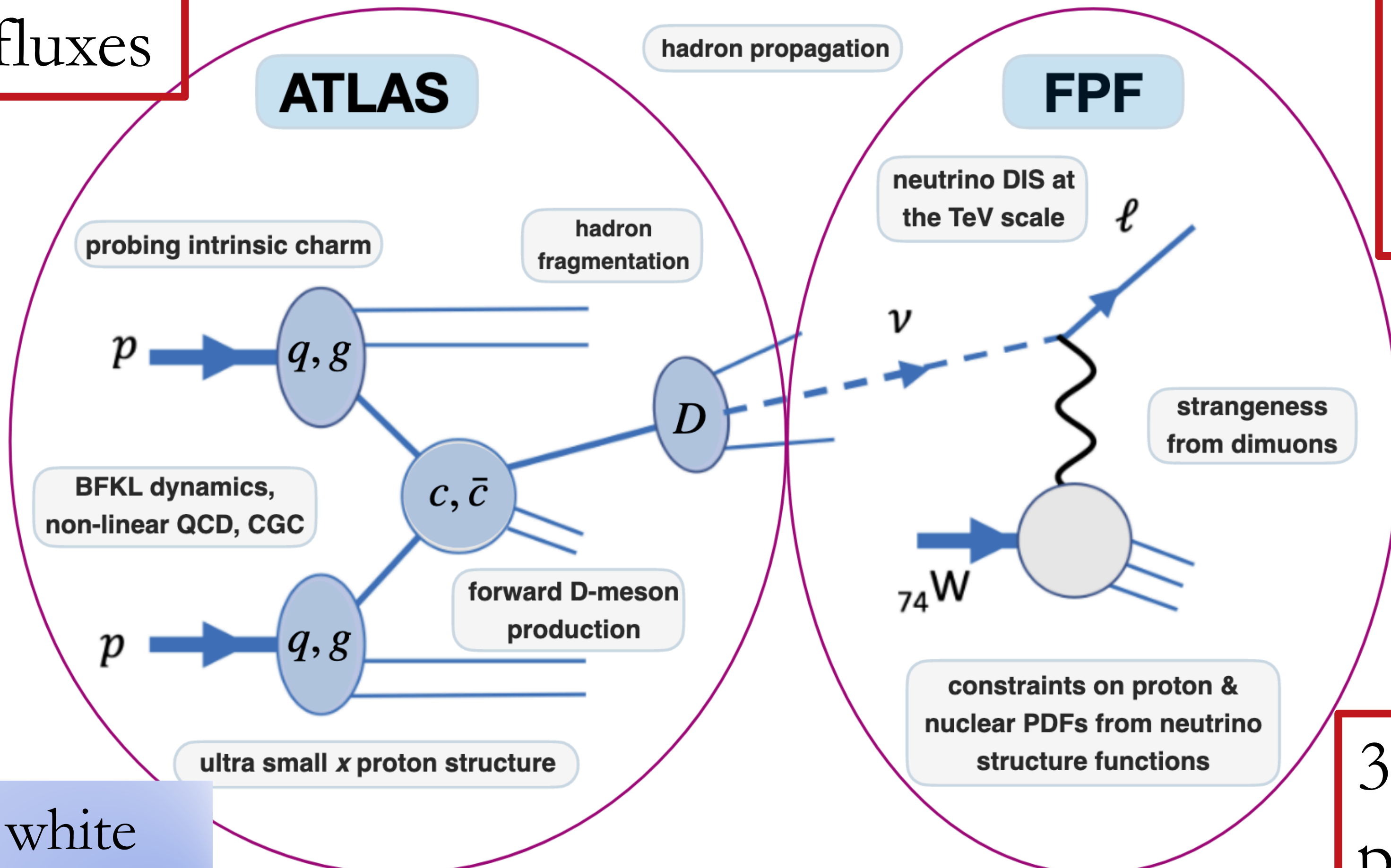
neutrino interactions (all 3 flavors, from different hadron sources) on nuclear targets

arXiv:2203.05090

QCD in pp and νA collisions

1. Neutrino fluxes

2. Standard model neutrino interactions on nuclear targets



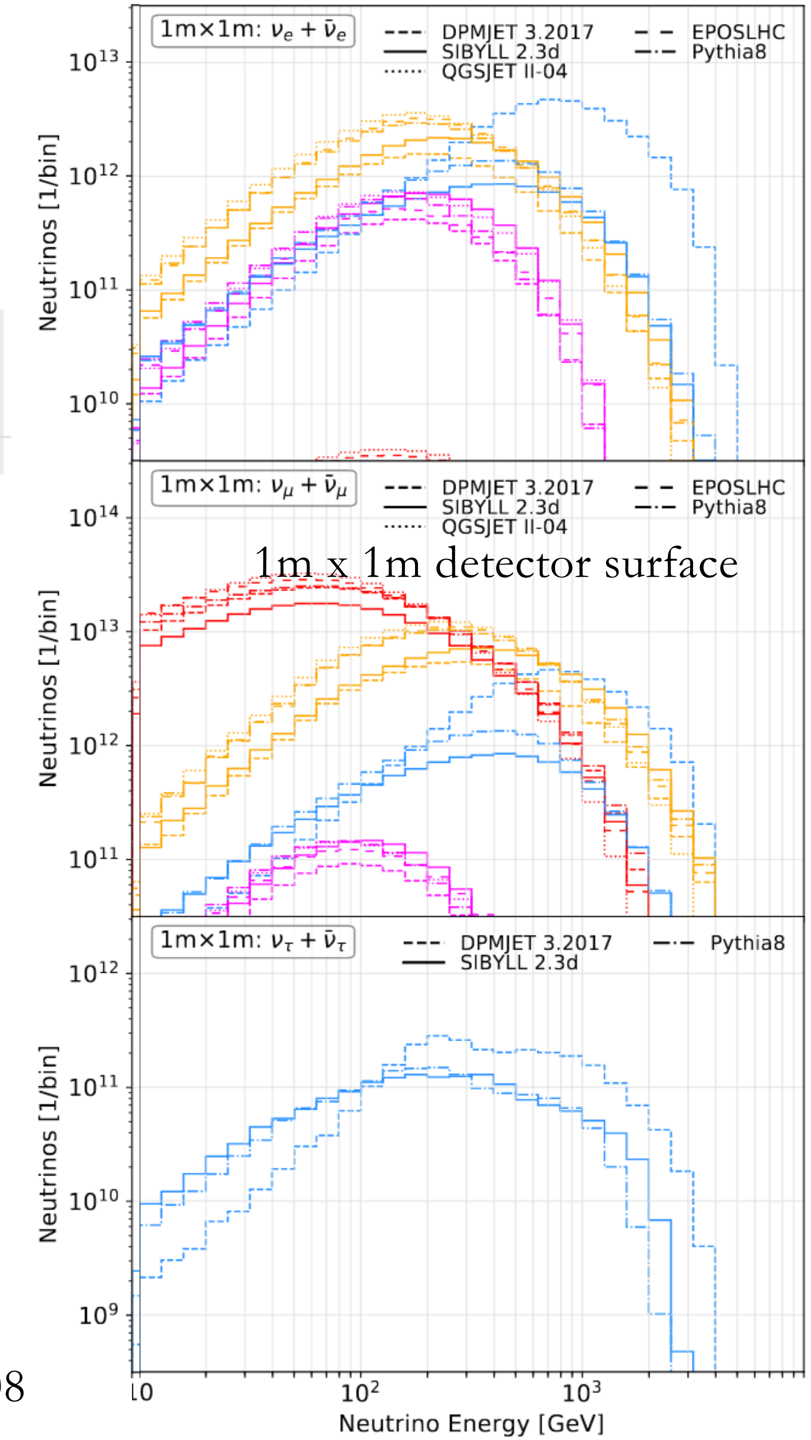
3. Brief astroparticle physics connection.

FPF Snowmass white paper, 2203.05090.

Neutrino fluxes

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

- Fluxes in forward region evaluated with several MC generators of hadronic interactions for cosmic rays 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 – perturbative QCD
- In fact, $\nu_\tau + \bar{\nu}_\tau$ all from charm.

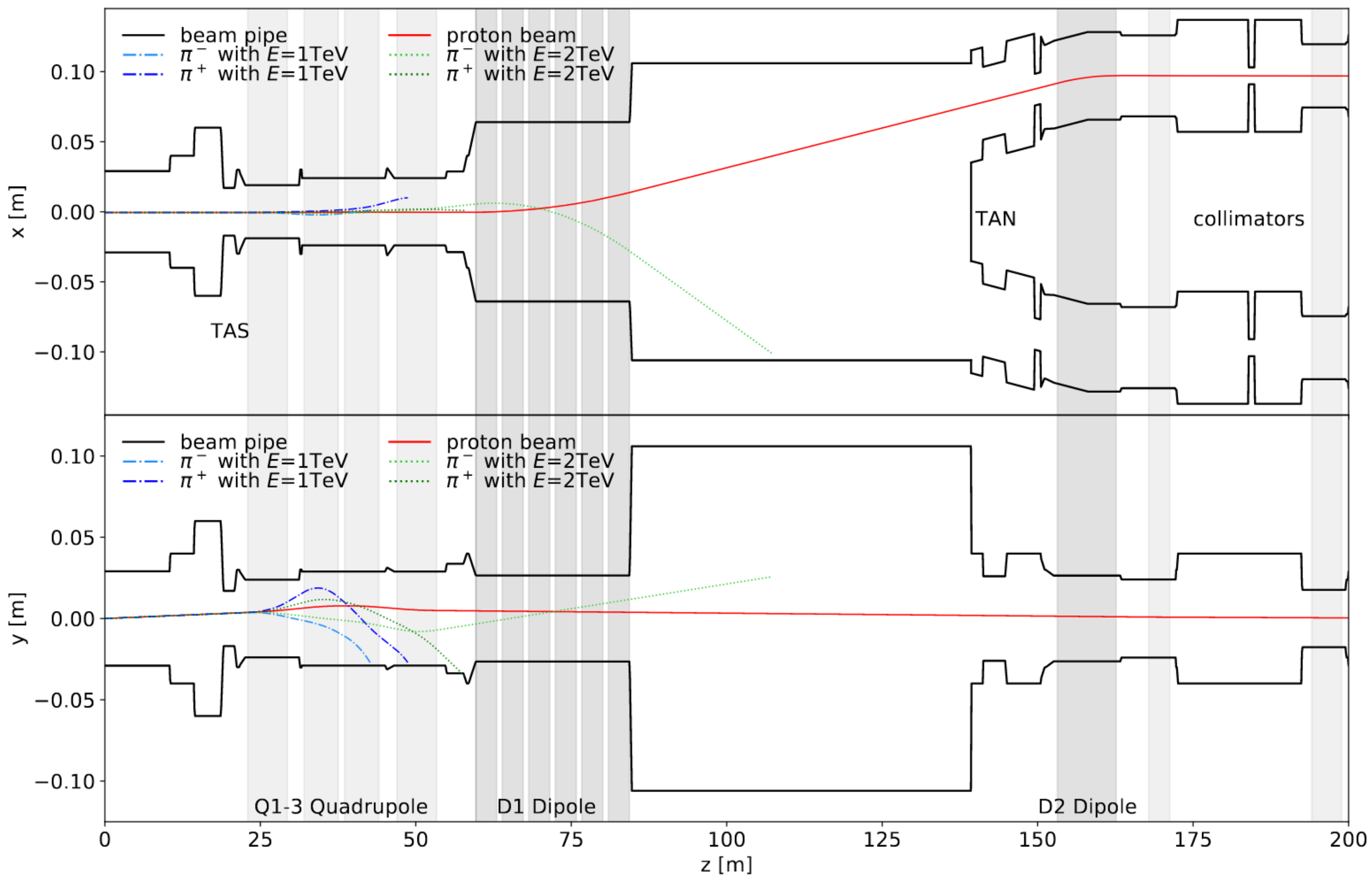


arXiv:2203.05090

see also Kling & Nevay, PRD104(2021)113008

Hadrons to neutrinos

Kling & Nevay, PRD 104 (2021) 113008



Neutrinos from hadron decays: Full simulation with BDSIM/Sibyll 2.3d to estimate neutrinos from downstream hadronic showers.

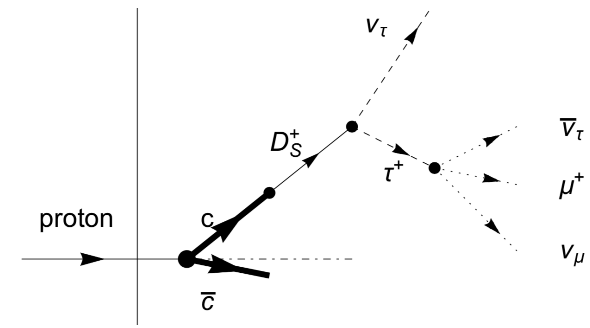
Sub-dominant, e.g., $\nu_\mu + \bar{\nu}_\mu$:

0.4% of total E_ν>1 TeV

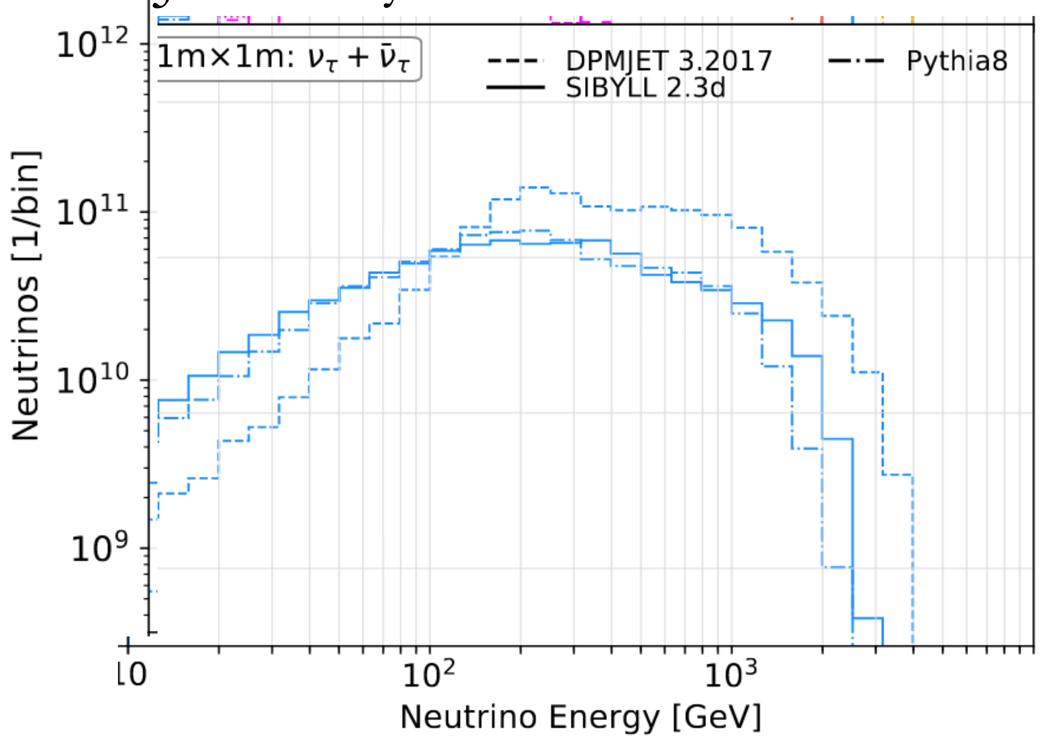
4% of total E_ν>30 GeV

Most neutrinos at FPF come from hadrons that decay in the beam pipe.

$\nu_\tau + \bar{\nu}_\tau$ fluxes at detector

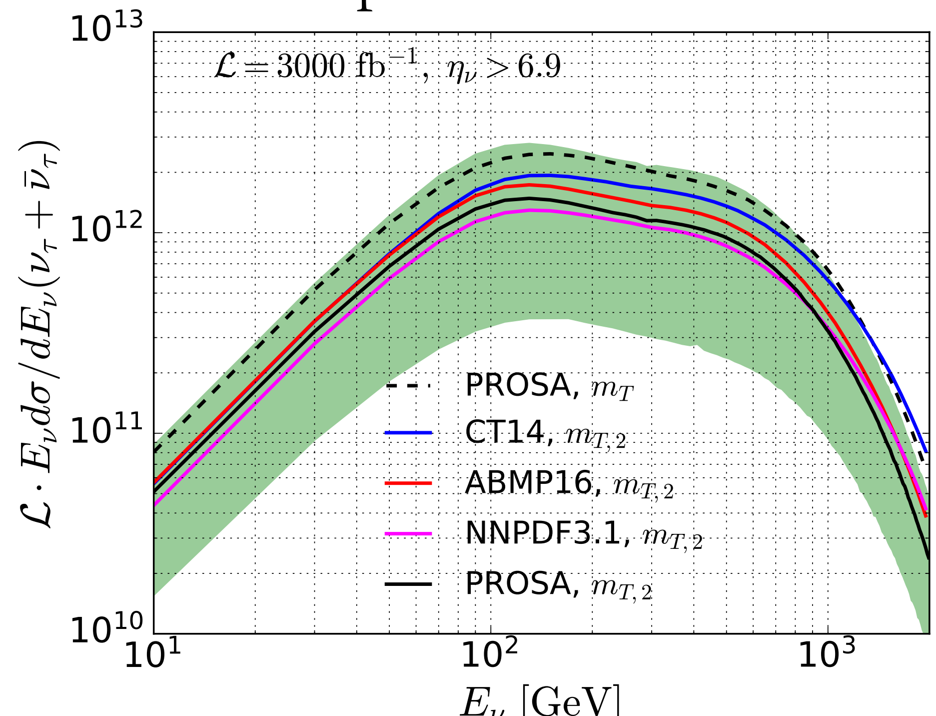


MC evaluations – all charm.
DPMJET & Pythia not tuned for charm.



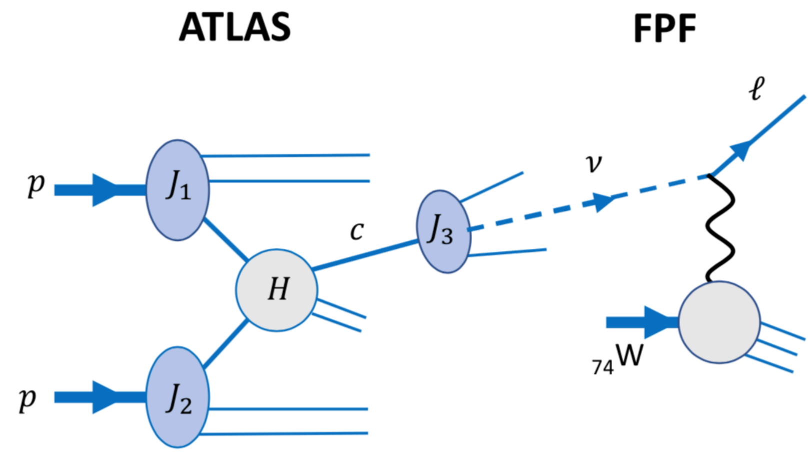
arXiv:2203.05090
see also Kling & Nevay, PRD104(2021)113008

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



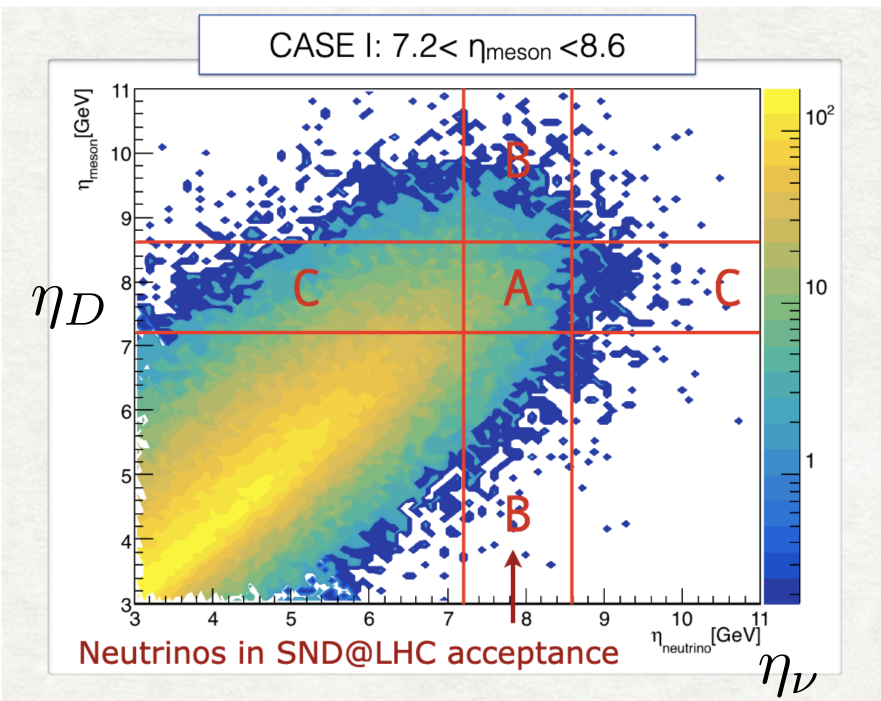
Bai, Diwan, Garzelli, Jeong, Kumar, MHR, 2112.11605 and 2203.05090, central set PROSA19, Zenaiev, Garzelli et al., JHEP 04 (2020) 118.

Charm production



Forward neutrino η_ν correlated with y_c.

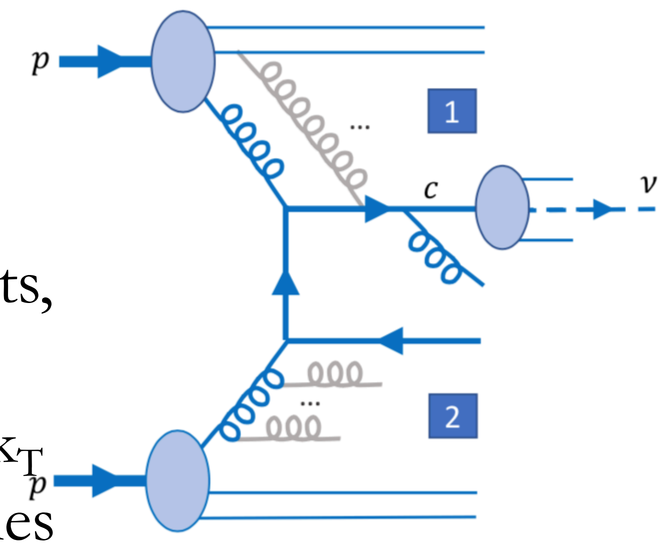
meson=charm meson



A. Di Crescenzo for SND@LHC, 3rd FPF Meeting

<u>Many opportunities</u>:

- PDFs, small x and large x
- PDFs, intrinsic charm
- Treatment of heavy flavor
- Fragmentation, spectator effects, forward baryon production
- Higher order effects, intrinsic k_T
- Particle/antiparticle asymmetries

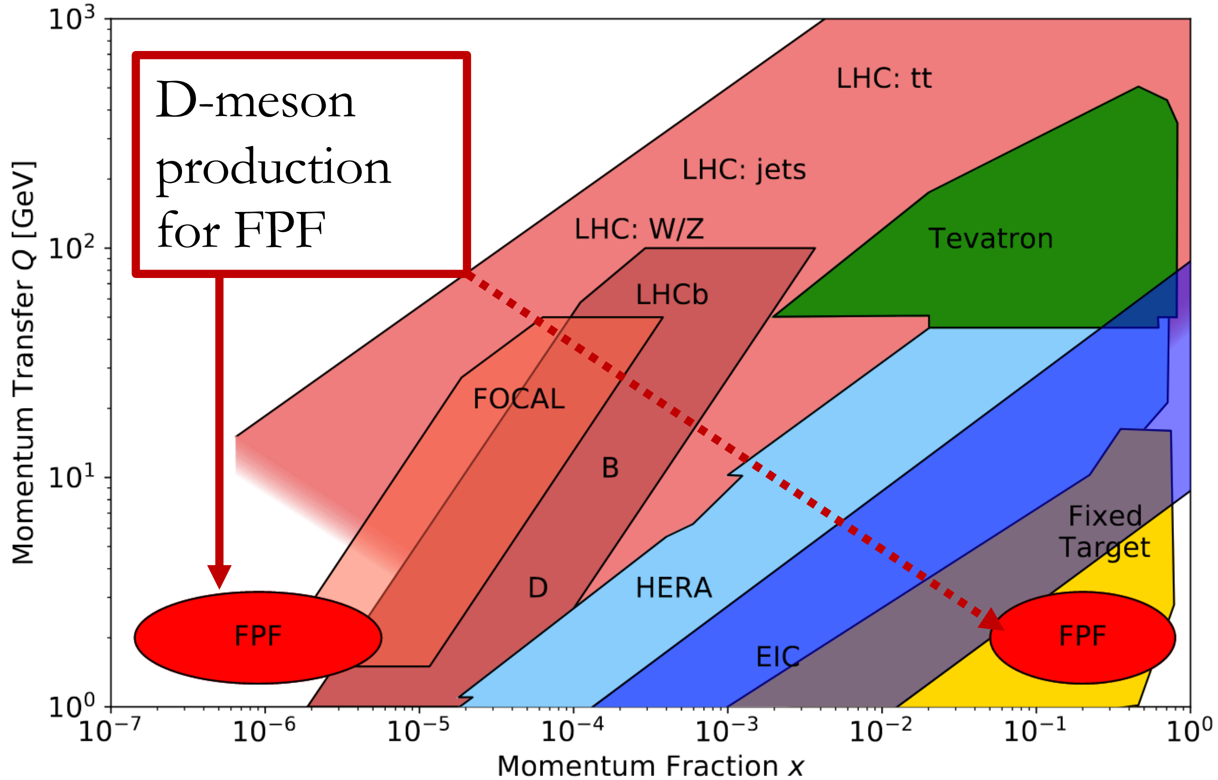


Short white paper 2109.10905

Charm production for neutrinos

New kinematic regimes.

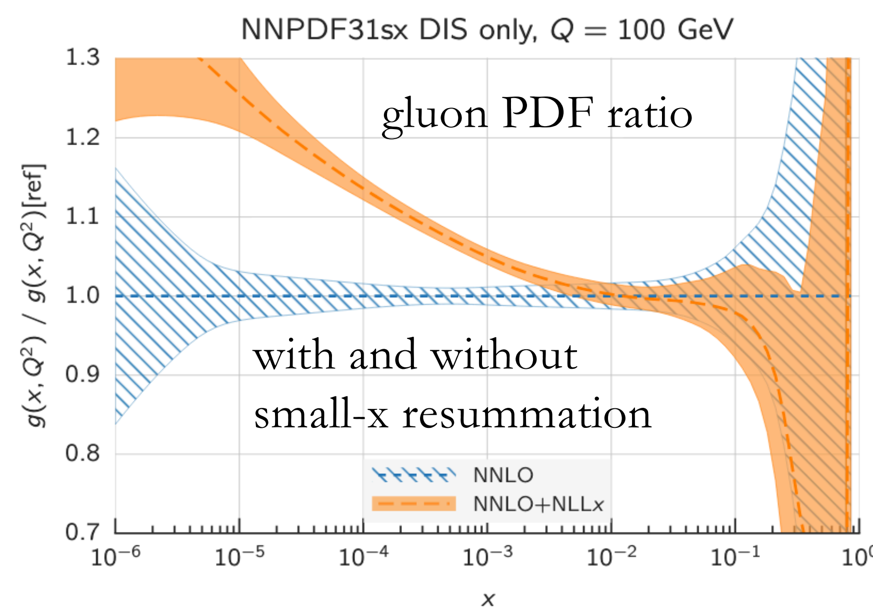
forward charm: high rapidity, $x_1 \gg x_2$ in gluon PDF



arXiv:2203.05090

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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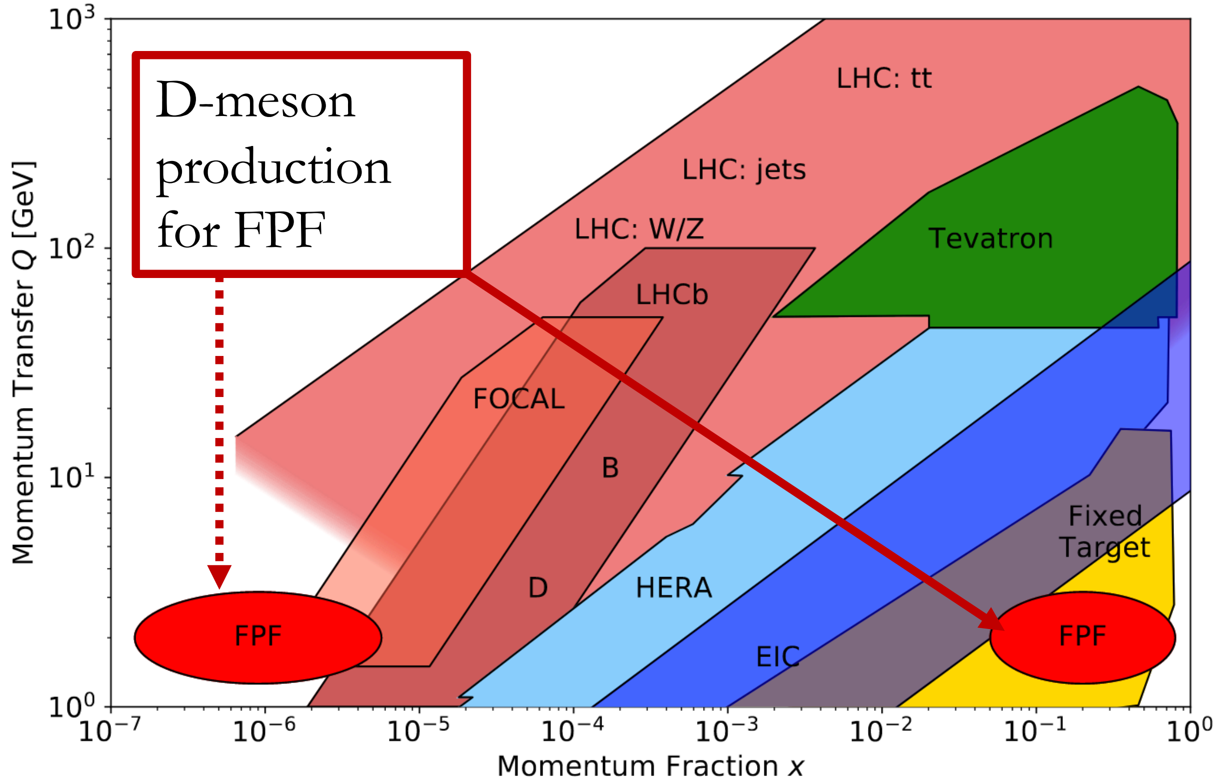
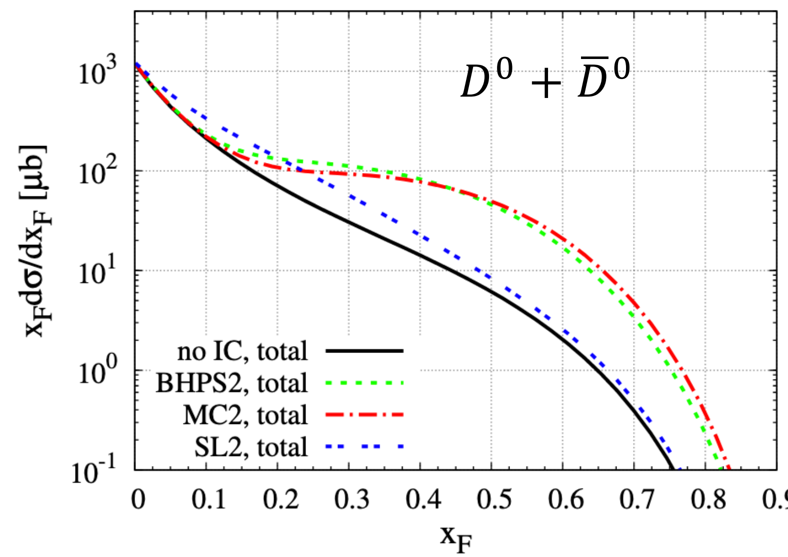


arXiv:2203.05090

Large-x region emphasized:

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

See also, e.g., Giannini et al, PRD 98 (2018) 014012



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

Standard Model neutrino interactions

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

	ν_τ	$\bar{\nu}_\tau$	$\nu_\tau+\bar{\nu}_\tau$	$\nu_\tau+\bar{\nu}_\tau$		
$(\mu_R,\ \mu_F),\ \langle k_T\rangle$	(1, 1) $m_{T,2}$, 0.7 GeV					
				scale(u/l)	PDF(u/l)	$\sigma_{\rm int}$
FASERν2 $\eta_\nu > 8.5$, 20 tons (W)	2296	1088	3384	+3144/-2519	+786/-1089	± 77
$\eta_\nu > 6.9$, 10 ton (Ar)	529	257	786	+692/-575	+152/-229	±11
$(\mu_R,\ \mu_F),\ \langle k_T\rangle$	(1, 2) m_T, 1.2 GeV			(1, 1) $m_{T,2}$, 0.7 GeV		
PDF	PROSA FFNS			NNPDF3.1	CT14	ABMP16
FASERν2 $\eta_\nu > 8.5$, 20 tons (W)	3808	1804	5612	3552	6492	4338
$\eta_\nu > 6.9$, 10 ton (Ar)	953	465	1418	748	1202	944

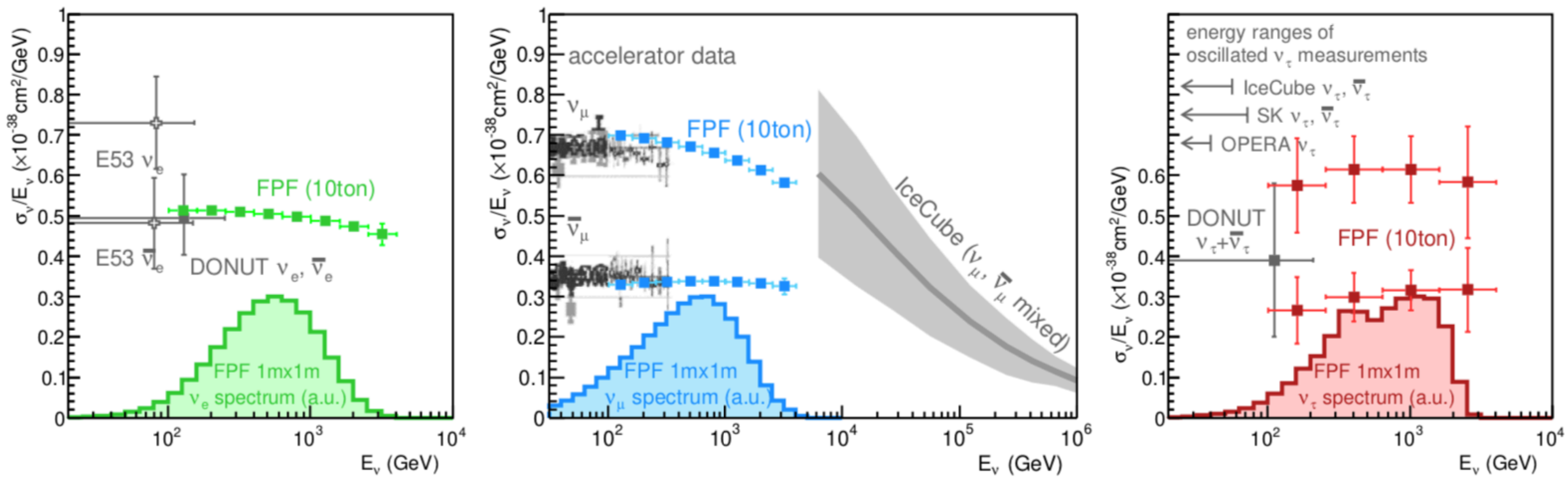
Estimated number of CC interactions for HL LHC, from NLO QCD w PROSA pdfs.

Ballpark for CC at HL-LHC:

- 200 K $\nu_e + \bar{\nu}_e$
- 1 M $\nu_\mu + \bar{\nu}_\mu$
- 5 K $\nu_\tau + \bar{\nu}_\tau$

Bai, Diwan, Garzelli, Jeong, Kumar, MHR, 2112.11605 & 2203.05090

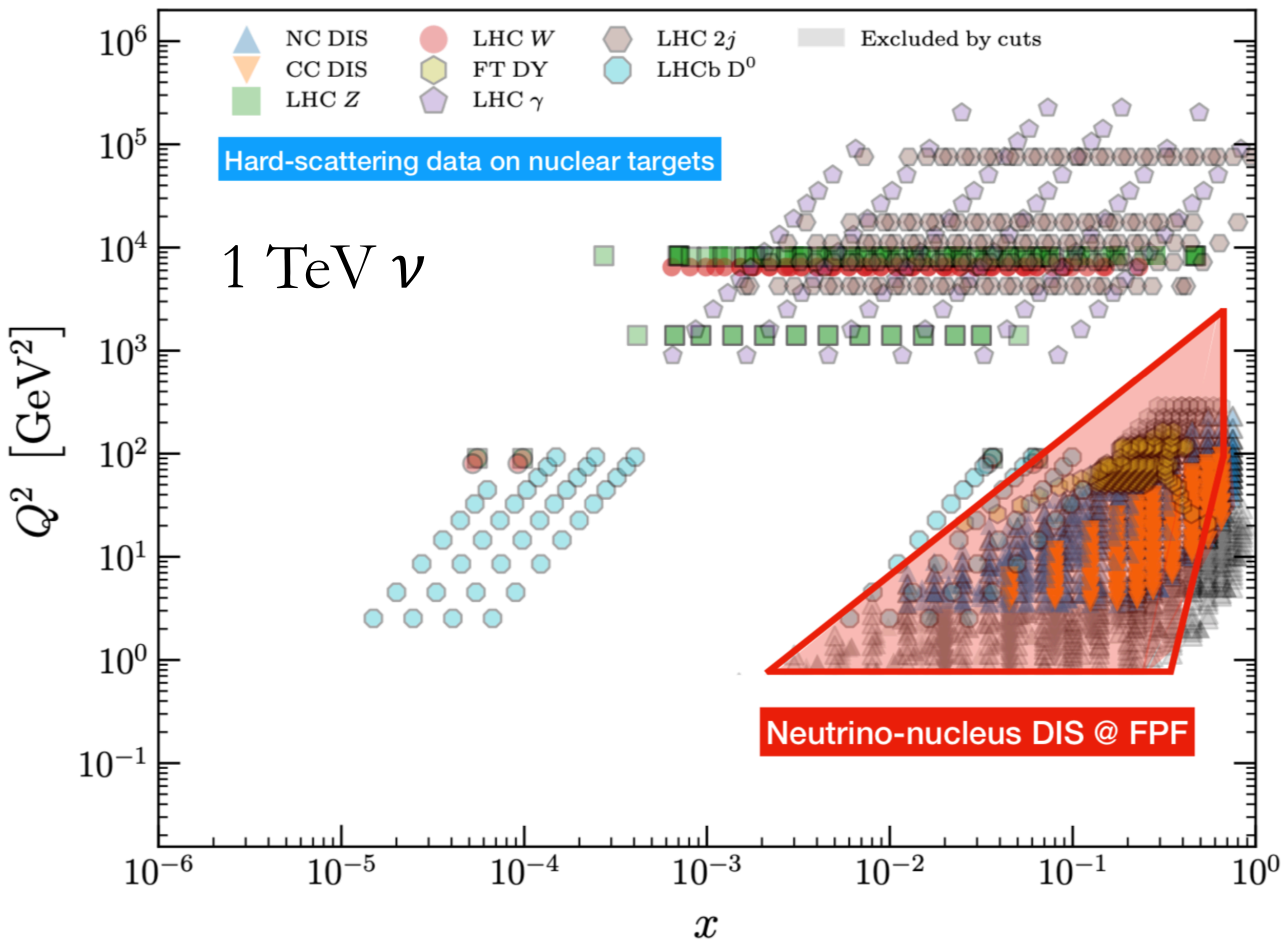
Neutrino CC DIS cross sections



Statistical uncertainty only in figures (from 2203.05090).

- Neutrinos and antineutrinos.
- Charge separation for muon neutrinos and tau neutrinos.
- Many more tau neutrinos!

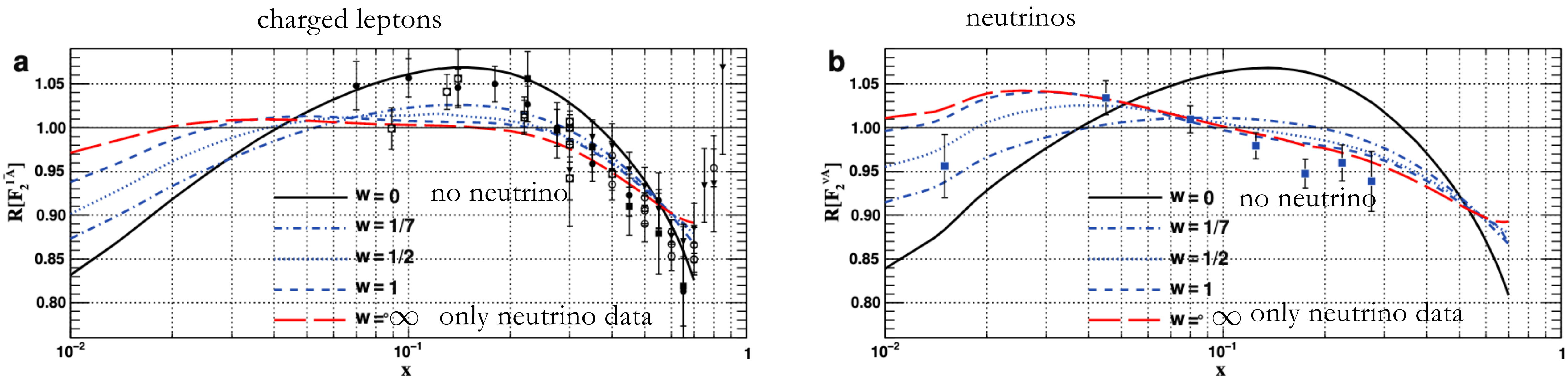
νA collisions



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.

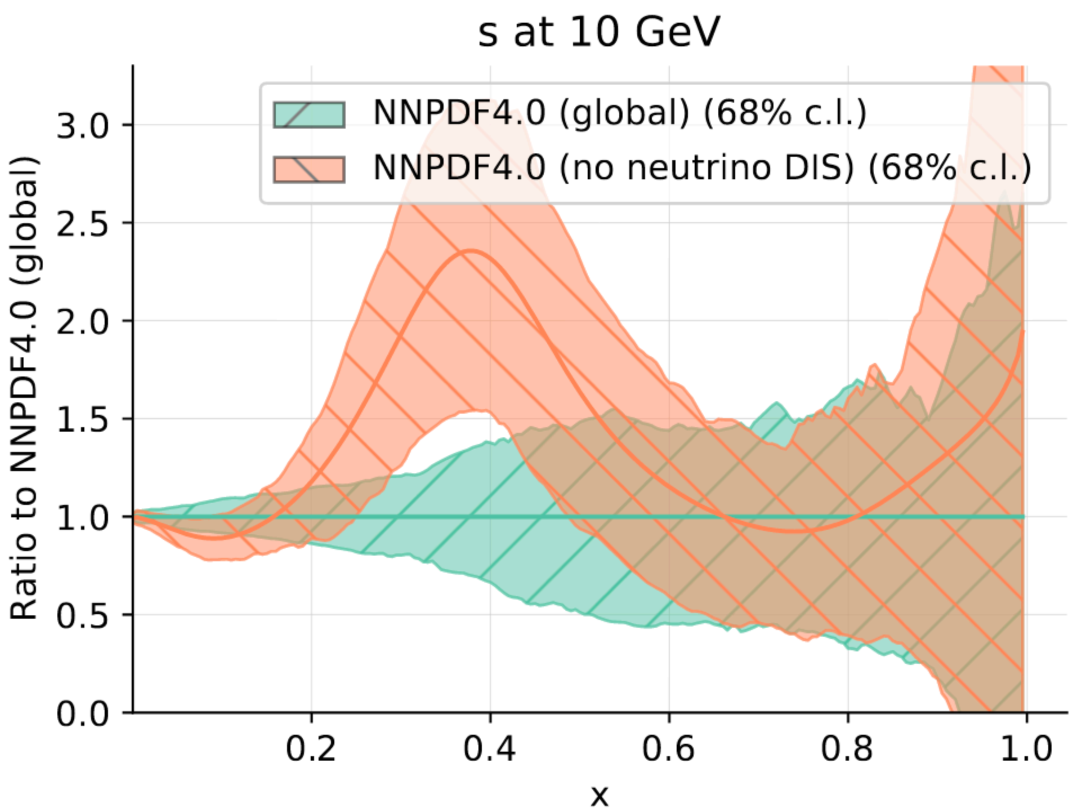
Nuclear effects in neutrino scattering



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 EM and neutrino CC scattering with nuclei.

Strange PDF

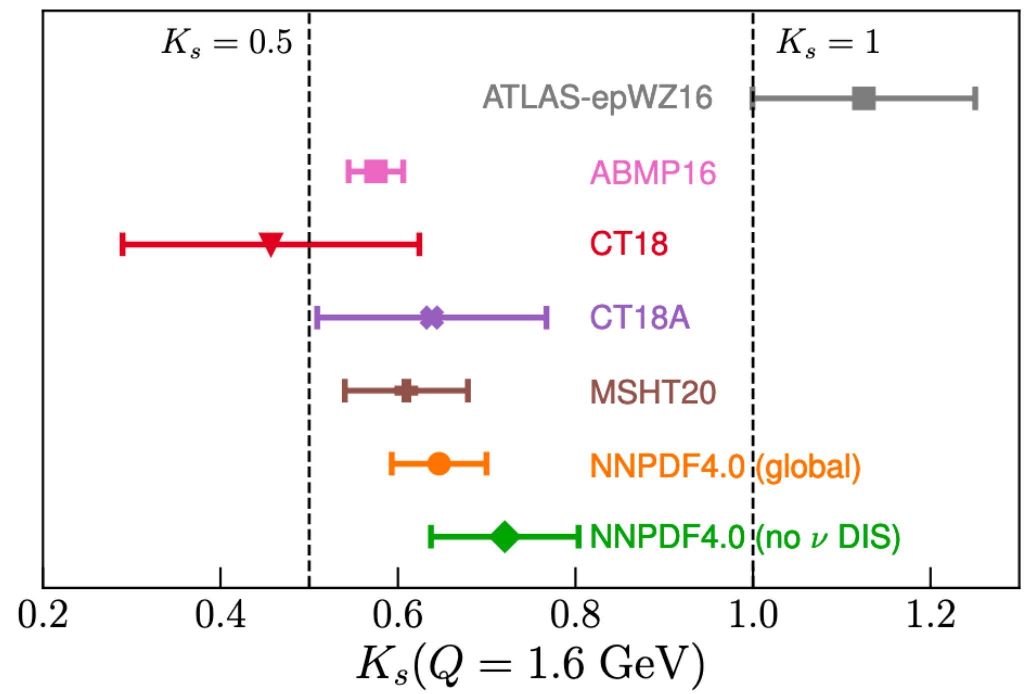


NNPDF4.0 normalized to central value of default PDF set.

Figs. from 2203.05090.

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

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



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

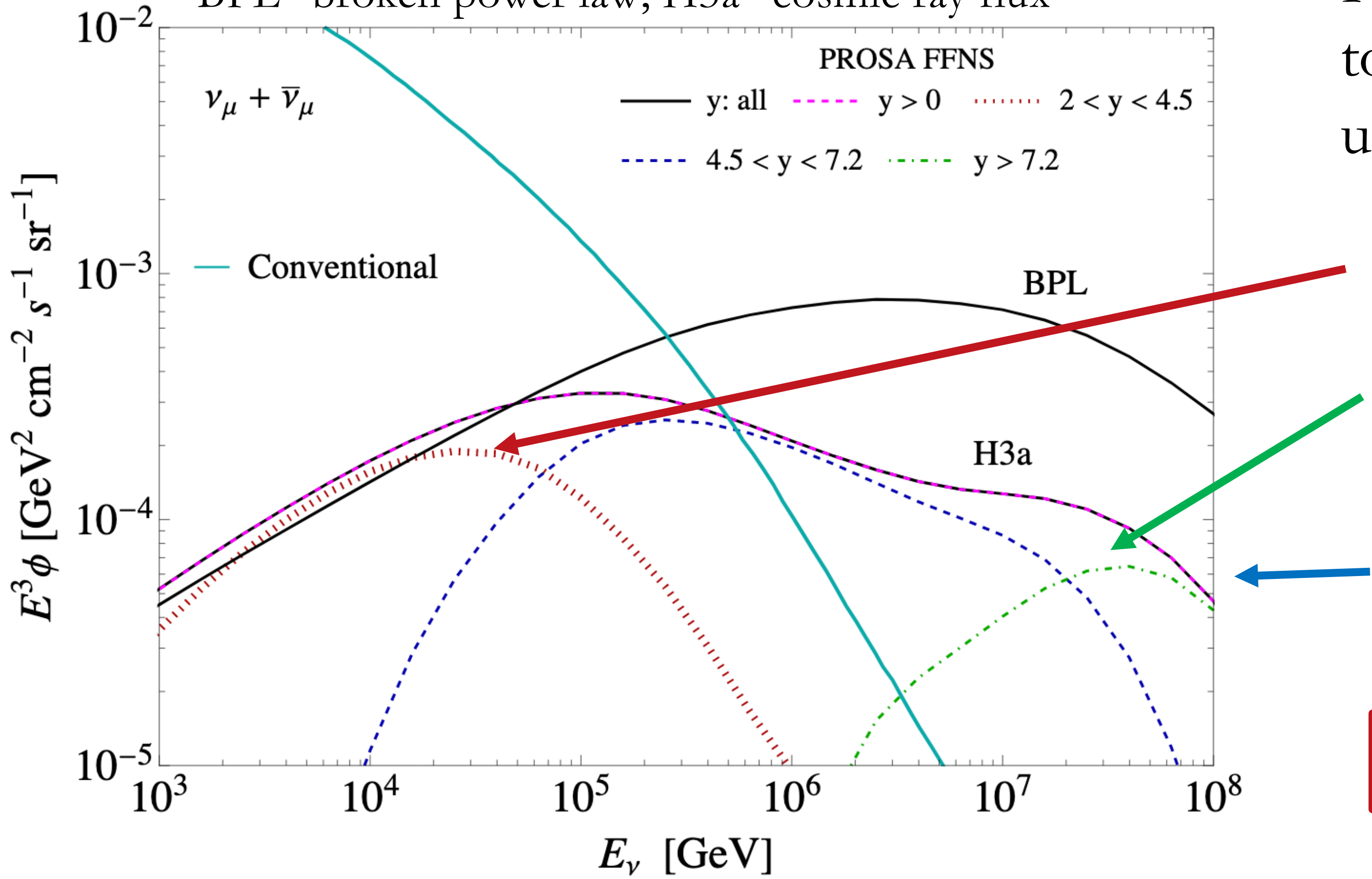
FASERν2 and FLArE-10 with 10 tons, FLArE-100 100-ton LArTPC. Numbers for LHC-HL 3 ab^{-1} with Sibyll 2.3c in CRMC.

- 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 (ρ^-) for $\bar{\nu}_e\ e$ scattering. Brdar et al. PRD 105 (2022) 093004

Astroparticle physics connections

Astroparticle physics connections – prompt atmospheric neutrinos

BPL=broken power law; H3a=cosmic ray flux



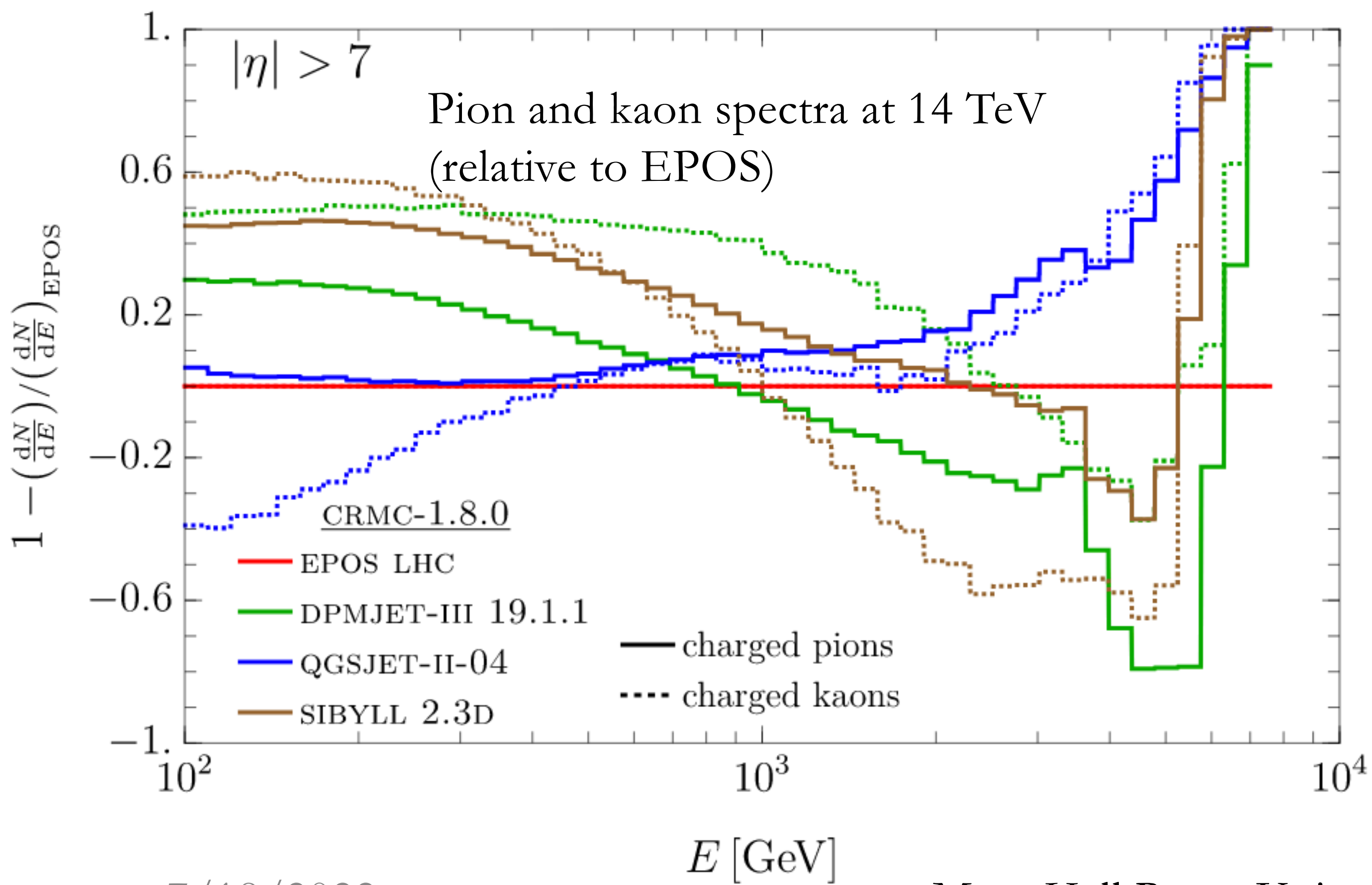
Prompt neutrinos are a background to the diffuse astrophysical flux for underground neutrino detectors.

y is charm rapidity in collider frame

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

Interplay between FPF and cosmic ray measurements and modeling

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



2203.05090

- 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.

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.
  - Ongoing assessments of Monte Carlo modeling, hadronization/fragmentation, intrinsic pT, beam remnants, particle-antiparticle asymmetries.

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.
- Forward Physics Facility – a relatively low cost facility and experiments can leverage the HL-LHC interactions to do interesting physics to better understand the fundamental physics of elementary particles, and perhaps, discover new particles and forces (lots more in the Snowmass White Paper).
- Our understanding of fundamental standard model physics (at the FPF and more broadly) is required to "explore the unknown."

Costs and timeline

Very preliminary:
- 25 MCHF for Civil Engineering
- 15 MCHF for Services
- say $10M/experiment

Possible timeline:
- Civil Engineering during long shutdown
- Installation of services at start of Run 4
- Install experiments to be ready during the last stages of Run4 and HL era