Forward Physics Facility (FPF): Neutrinos

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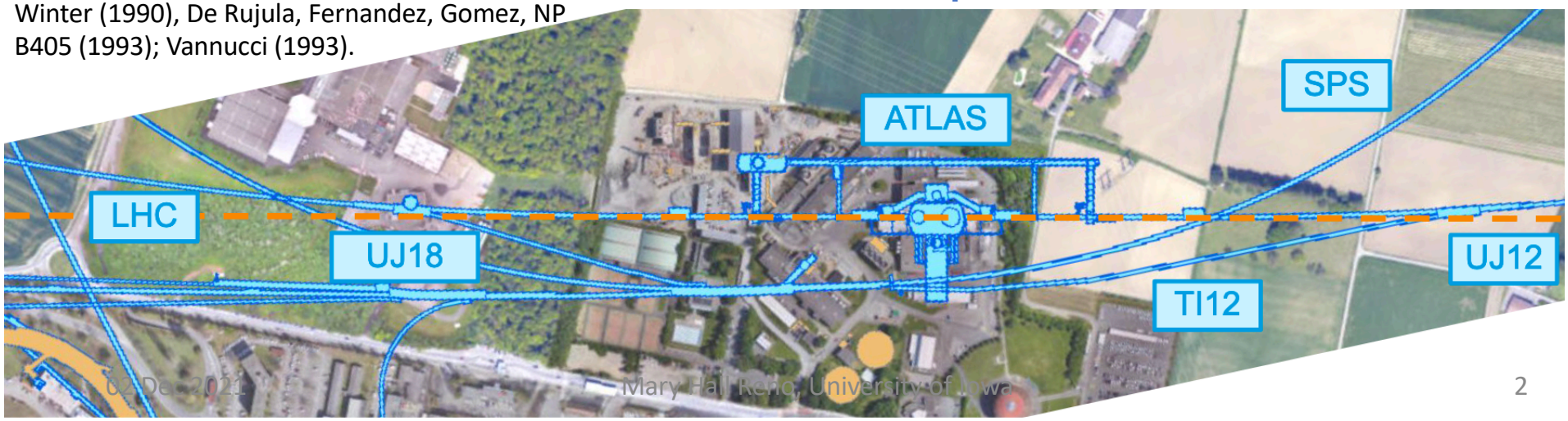
Physics beyond colliders: FPF

Proposal: Forward Physics Facility for the High Luminosity Era

<u>High energy collisions</u>:
- collect particles along the beamline
- shielded by at least 100 m concrete and rock

<u>Measurements and searches</u>:
- neutrinos – weakly-interacting
- BSM particles – light, extremely weakly-interacting

Early suggestion by De Rujula & Ruckl (1984); Winter (1990), De Rujula, Fernandez, Gomez, NP B405 (1993); Vannucci (1993).



Physics beyond colliders: FPF

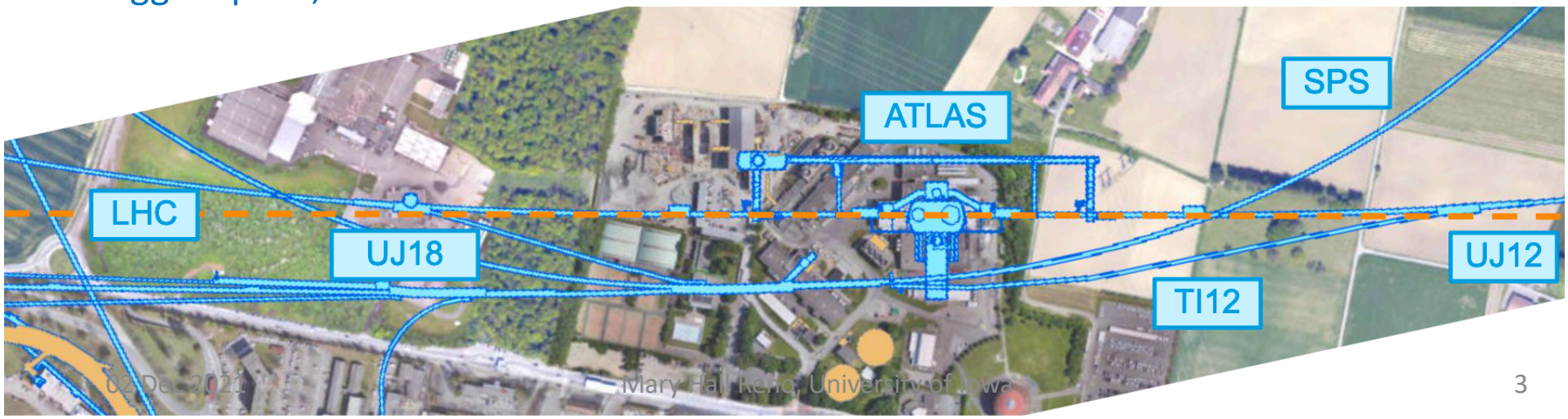
LHC Run 3: 480 m from ATLAS interaction point in existing tunnels TI12 and TI18

- FASERν approved in December 2019
- FASER approved March 2019
- SND@LHC approved March 2021

Measurements and searches:

- neutrinos – weakly-interacting
- BSM particles – light, extremely weakly-interacting

FPF: Bigger space, infrastructure

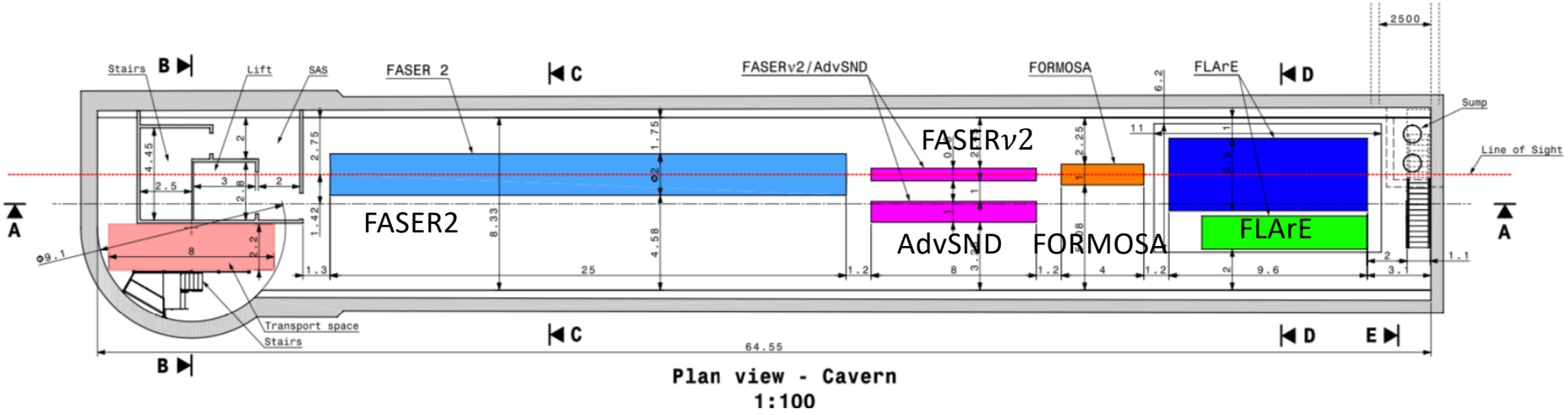


Proposed Experiments

Talk by Jamie Boyd later today.

- FLArE – *neutrinos*, LArTPC
- FORMOSA – Forward MicroCharge Search, BSM search, plastic scintillator
- FASER2 – BSM search, magnetized spectrometer
- FASERν2 – *neutrinos*, emulsion-based
- AdvSND (and AdvSND2) – *neutrinos*, calorimeters

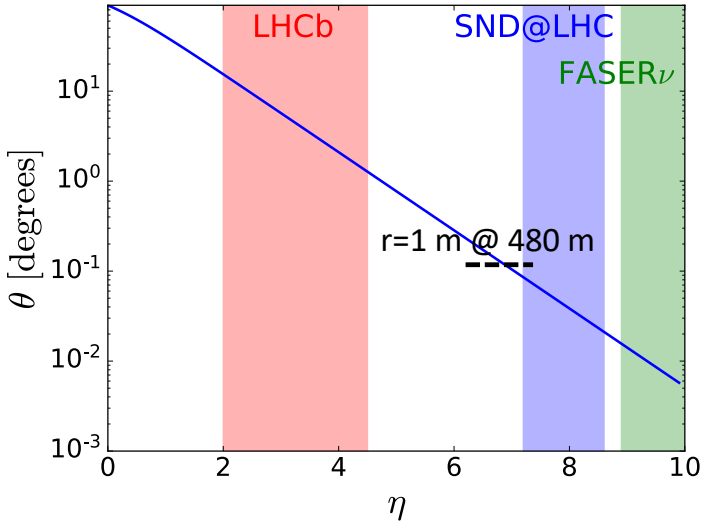
In a purpose-built facility, would like this:



Short white paper 2109.10905

Studies underway: Snowmass white papers

Short white paper - arXiv: 2109.10905, 80 authors, submitted to *Physics Reports*
Long white paper – in progress, J. Feng, F. Kling, J. Rojo, D. Soldin, MHR (editors)



How forward is FPF and Run 3 experiments?

A. Facility and Experiments
B. Tools: MC and other codes
C. BSM Physics
D. QCD
E. Neutrino physics
F. Astroparticle physics

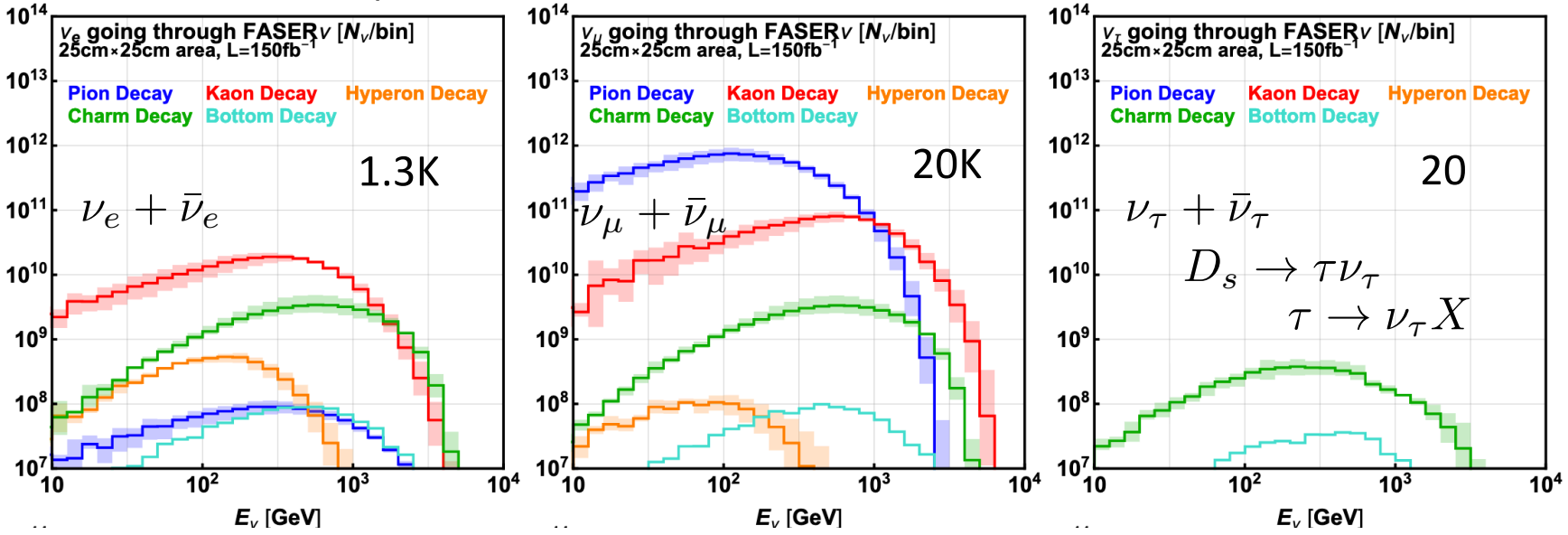
Snowmass Slack channel: #fpf-whitepaper
4th FPF Workshop: January 31-February 1, 2022

Neutrino production

- Charm production $\sigma_{c\bar{c}c}$ and fragmentation
- Charm hadron energy, decay distributions

Monte Carlo simulations of pion, kaon, charm production and decay – wider variation than shown here. Forward tuning … and NLO+ QCD for charm hadron production.

FASERν example:

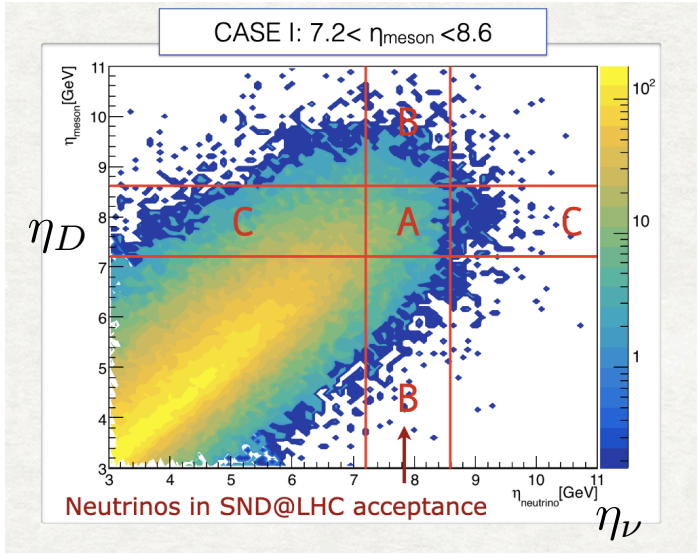


FASER Collab, Eur. J. Phys. C80 (2020) 81, 1908.02310. See also Kling, 2105.08270, Bai et al., JHEP 06 (2020) 032, 2002.03012

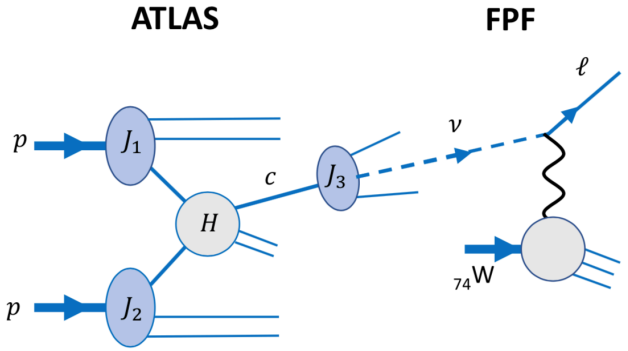
Charm production

Forward neutrino η_ν correlated with y_c.

meson=charm meson

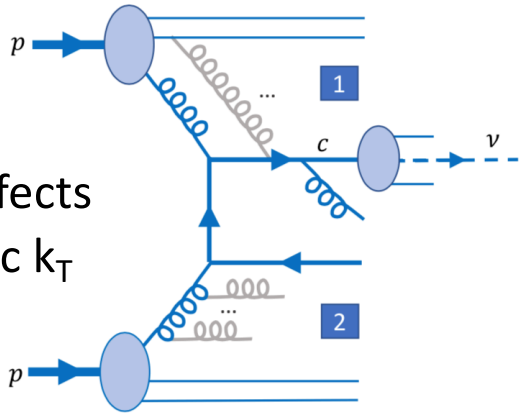


A. Di Crescenzo for SND@LHC, 3rd FPF Meeting



Many opportunities:

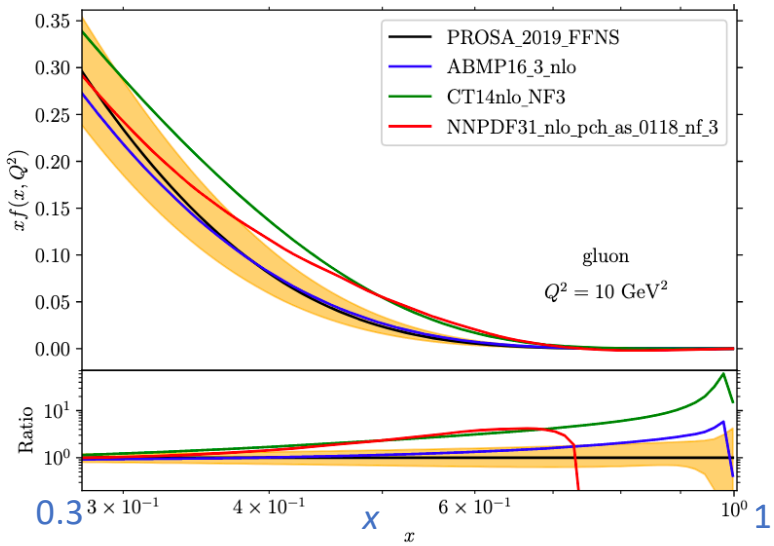
- PDFs, small *x* and large *x*
- PDFs, intrinsic charm
- Fragmentation, spectator effects
- Higher order effects, intrinsic k_T



Short white paper 2109.10905

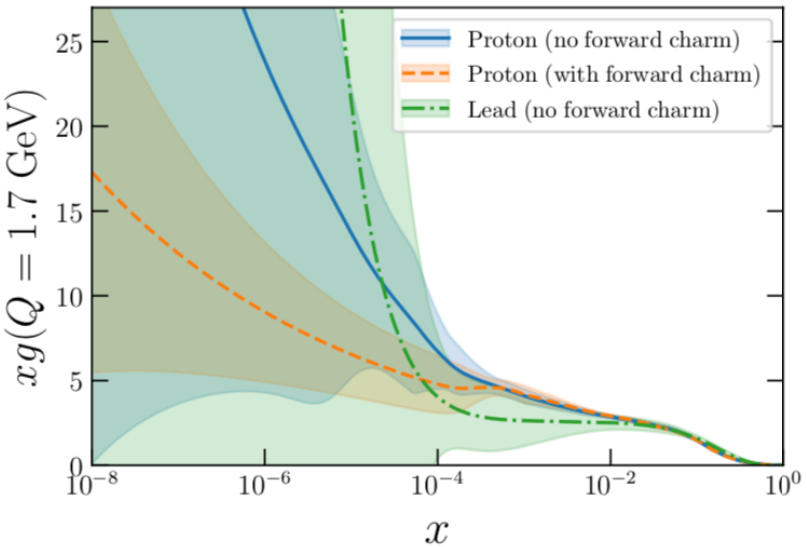
PDFs at large *x* and small *x*

Large *x* effects at high energy



Impacts HE neutrino flux, Bai et al., in preparation

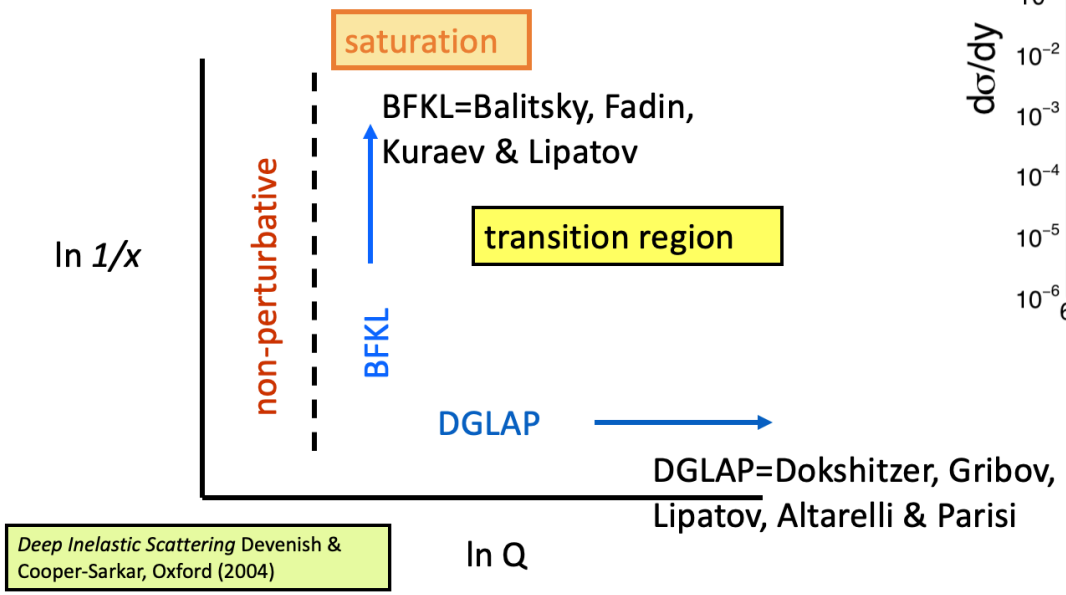
Low *x* uncertainty, NNPDF3.1 with/ without LHCb charm at 5, 7, 13 TeV. [See also Lead (green).]



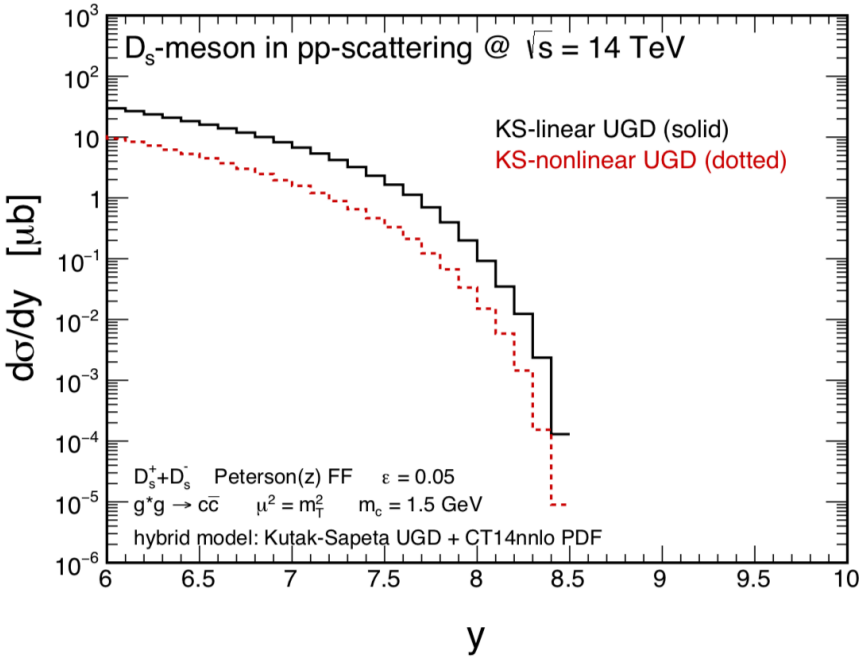
Short white paper 2109.10905, Gauld&Rojo, PRL 118 (2017) 072001, Zenaiev et al (PROSA), Eur. Phys. J C75 (2015) 396.

Gluon saturation

$gg \to g$



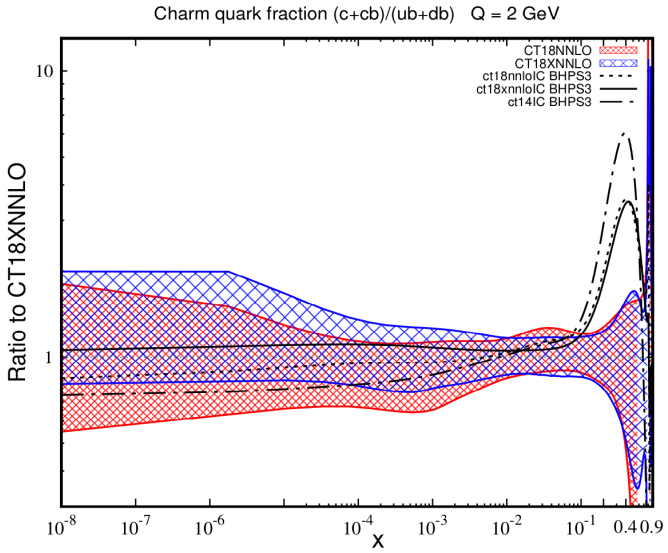
Short white paper 2109.10905, and e.g., Goncalves et al, 2103.05503



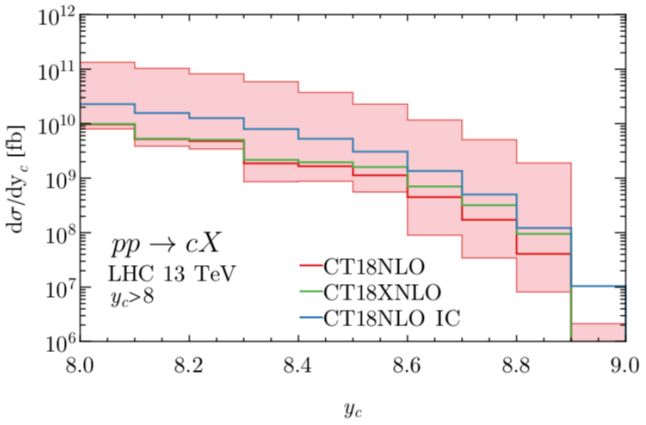
Example: BFKL resummation,, small x k_T dependent unintegrated DF, with/wo saturation, large x collinear PDF

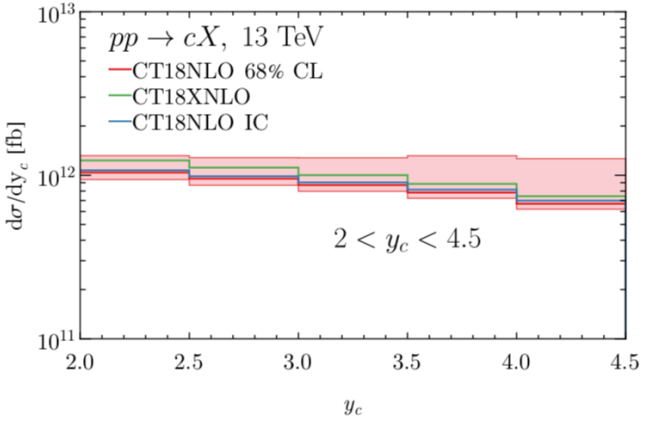
Intrinsic charm

charm quark fraction



Short white paper 2109.10905 and Hou et al, PRD 103 (2021) 014013

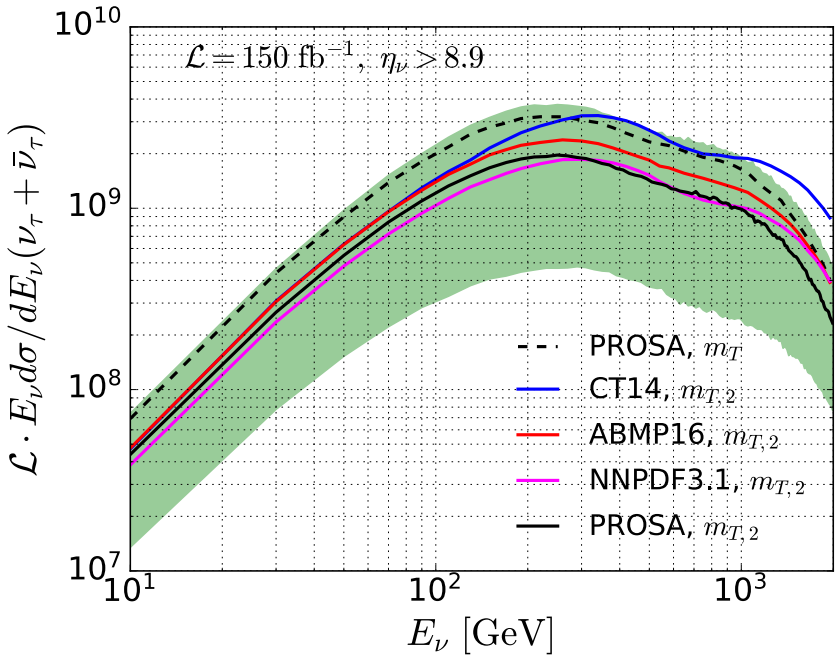




Relations between different rapidity regions.

- CT18NLO
- CT18XNLO (tuned $\mu_F(x, Q^2)$ in DIS)
- CT18NLO IC (intrinsic charm)

$\nu_\tau + \bar{\nu}_\tau$, collinear NLO QCD production of D_s



Bai et al., in preparation. See also,
Bai et al., JHEP 06 (2020) 032.

- Collinear parton model with Gaussian k_T smearing.
- Scale dependence: green band around central black curve.
- Based on PROSA PDFs and scale:

$$m_{T,2}^2 = p_T^2 + 4m_c^2 \qquad \langle k_T \rangle = 0.7\ \mathrm{GeV}$$

- Tie forward physics to LHCb charm measurements.

Numbers of neutrinos

Example: predictions from 2 leading-order generators. Still work to be done….

Detector			Interactions at FPF			
Name	Mass	Coverage	CC $\nu_e+\bar{\nu}_e$	CC $\nu_\mu+\bar{\nu}_\mu$	CC $\nu_\tau+\bar{\nu}_\tau$	NC
FASERν2	20 tonnes	$\eta \gtrsim 8.5$	178k / 668k	943k / 1.4M	2.3k / 20k	408k / 857k
FLArE	10 tonnes	$\eta \gtrsim 7.5$	36k / 113k	203k / 268k	1.5k / 4k	89k / 157k
AdvSND1	2 tonnes	$7.2 \lesssim \eta \lesssim 9.2$	6.5k / 20k	41k / 53k	190 / 754	17k / 29k
AdvSND2	2 tonnes	$\eta \sim 5$	29 / 14	48 / 29	2.6 / 0.9	32 / 17

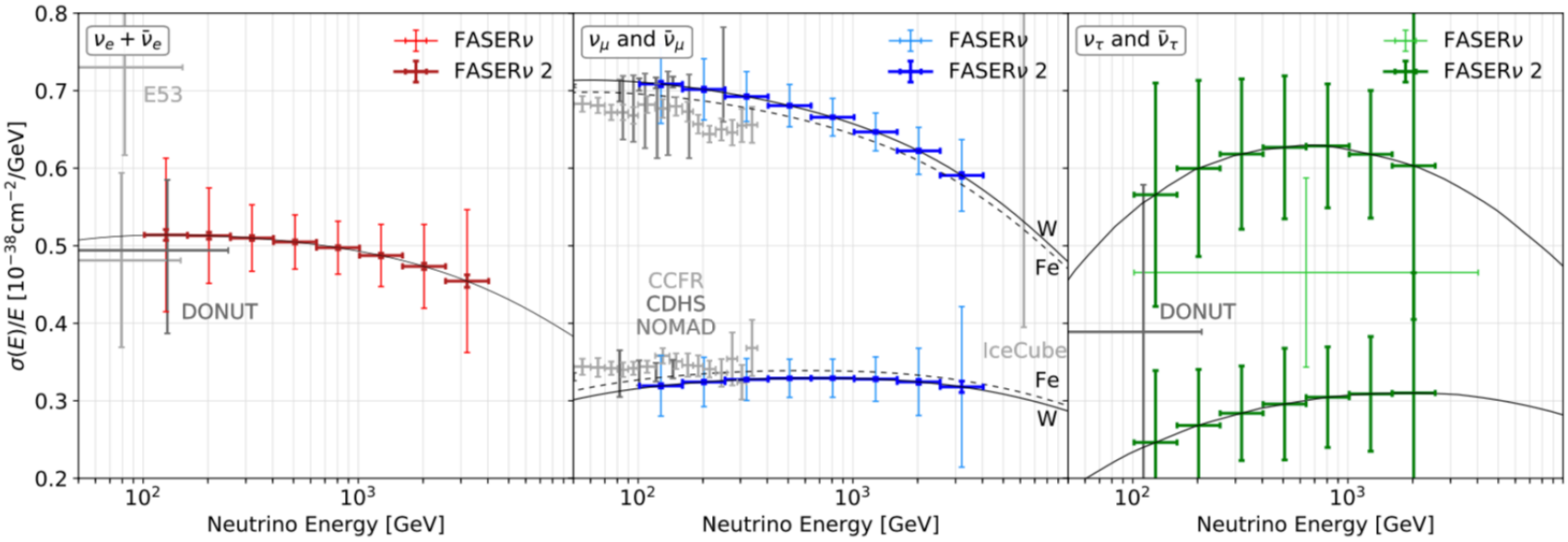
TABLE III. The estimated number of neutrino interactions as obtained using two different event generators, `Sibyll 2.3d` and `DPMJET 3.2017`, for FPF experiments located 620 m downstream of the ATLAS IP at the HL-LHC with 14 TeV pp collisions and an integrated luminosity of $\mathcal{L} = 3$ ab^{-1}.

Short white paper 2109.10905

DIS $\nu/\bar{\nu}$ cross sections

- New energy regimes
- Test lepton universality

Estimated statistical uncertainties for CC cross sections, 150/fb and 3/ab.
Systematic uncertainties under study.

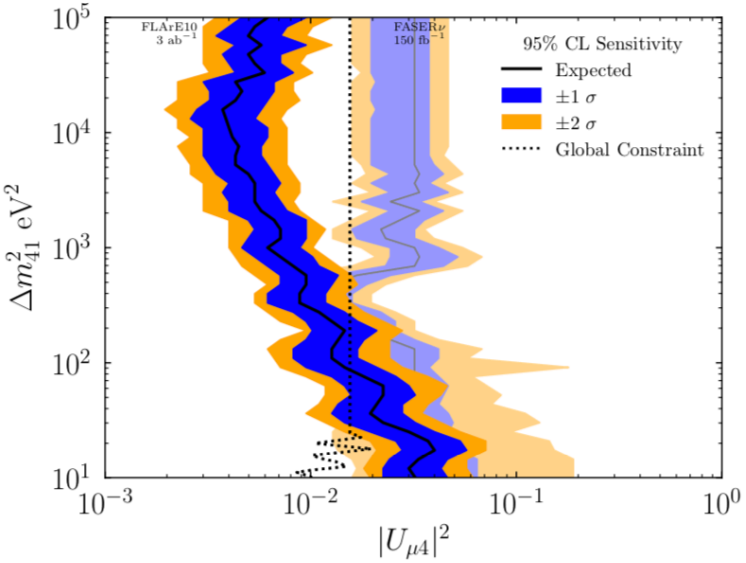


Short white paper 2109.10905

BSM physics – oscillation into sterile neutrinos

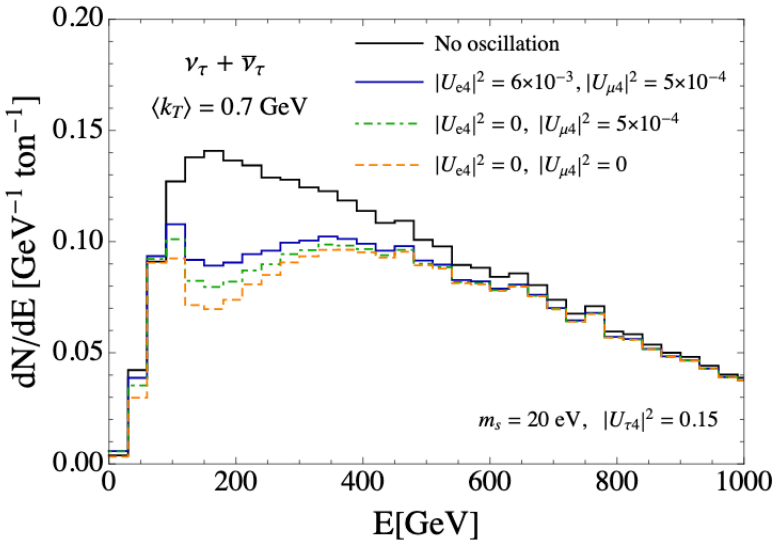
Disappearance, spectral distortions

FASERν Run 3 @150/fb, FLARE10 @3/ab



Short white paper 2109.10905

$\eta_\nu > 6.9,$ 3/ab

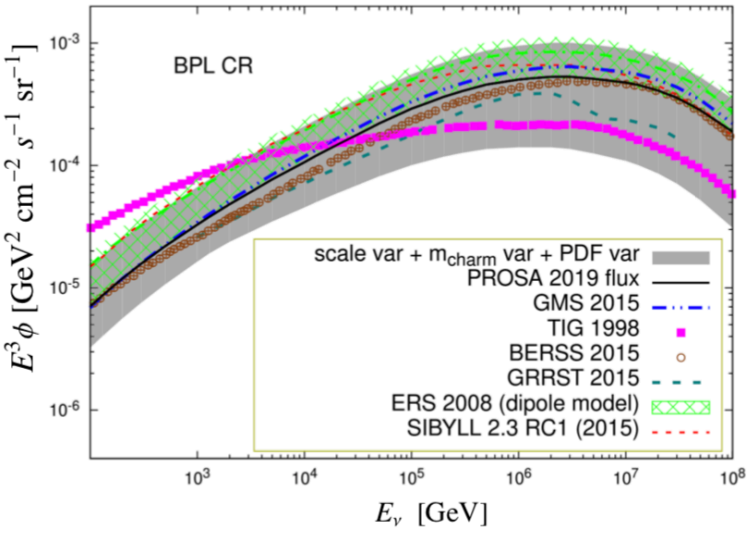


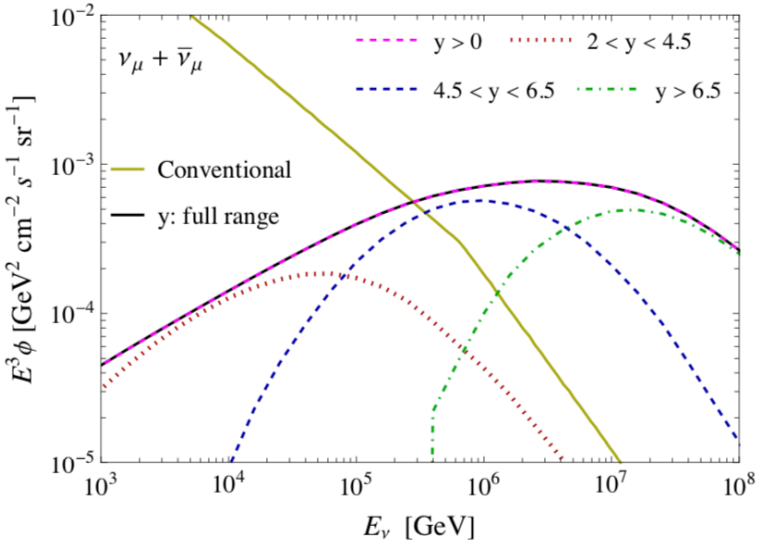
Bai et al., JHEP 06 (2020) 032

Astroparticle physics

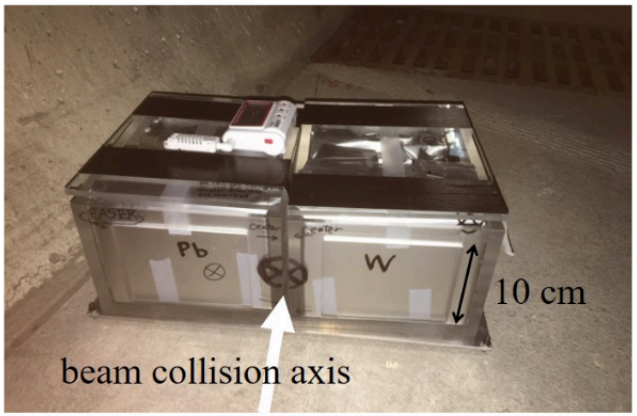
Natural connection to the prompt atmospheric neutrino flux (neutrinos from charm) and hadronic physics in cosmic ray air showers.

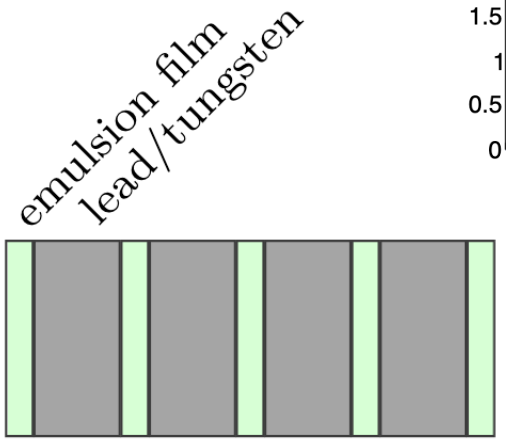
Neutrinos from charm:





So far – the FASER suitcase





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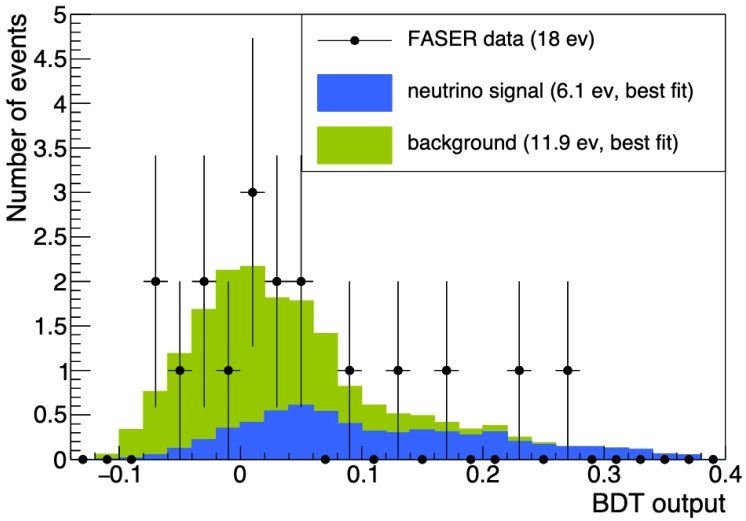

Beginning of the era of neutrino measurements in the LHC forward region.

Pilot emulsion detector (spare parts of NA65/DsTau)
29 kg with 2018 4-week run with 12.2/fb at 13 TeV.

FASER Collab, Abreu, Phys. Rev. D 104 (2021) 091101, 2105.06197

Summary

- FASER, SND@LHC start soon. Tens to a hundred $\nu_\tau + \bar{\nu}_\tau$ events depending on detector and production model. Hundreds to thousands for $\nu_e + \bar{\nu}_e$ and more for $\nu_\mu + \bar{\nu}_\mu$ events.
- Lots of work underway to better understand the forward physics environment.
- There a many opportunities that combine neutrino physics, QCD, BSM physics and astroparticle physics in Forward Physics Facility experiments.
  - PDFs in neutrino production and interactions, e.g.: ”extreme” x values, role of small x resummation, nuclear PDFs in neutrino scattering, strange distribution.
  - Tests of the SM & searches for BSM physics, e.g.: lepton flavor universality, oscillations to sterile neutrinos, NSI’s, neutrino magnetic moments.
  - Connections to astroparticle physics, e.g.: prompt lepton flux, hadronic interaction models, forward particle production at high energies.