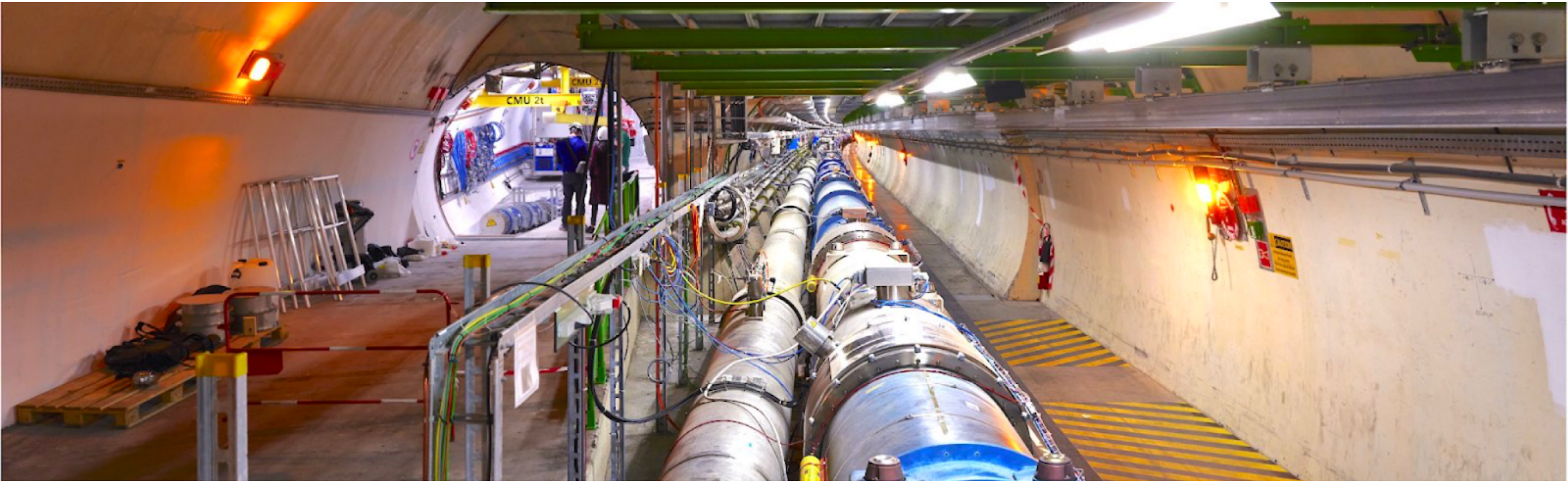
Academic Training Lecture Programme:

Forward detectors at the LHC for searches and high energy neutrinos measurements



Lecture 3: Neutrino Measurements

October 21th 2022
Felix Kling

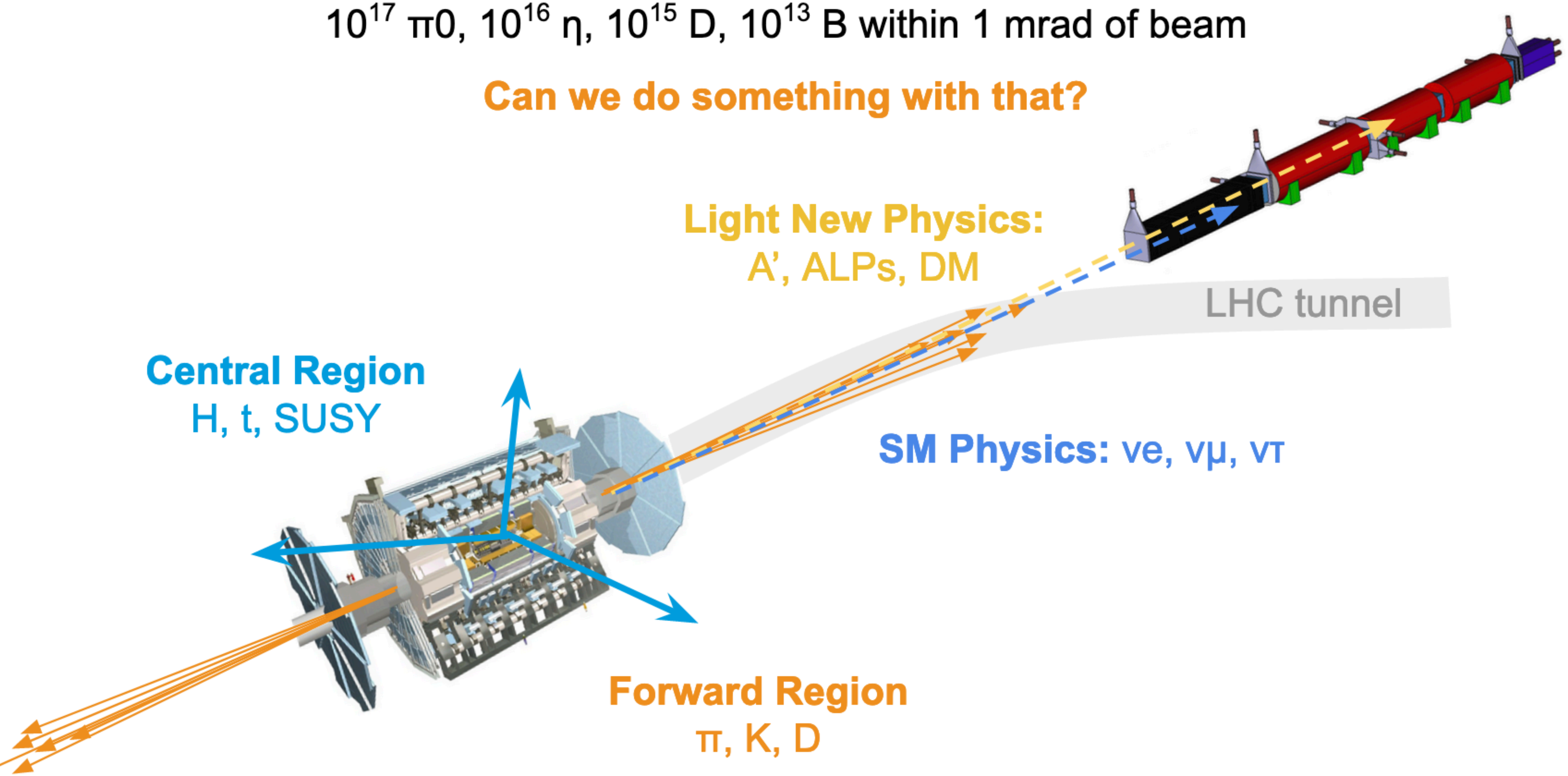
DESY.

Review:

The LHC produces an intense and strongly collimated beam of highly energetic particles in the forward direction.

10^{17} π0, 10^{16} η, 10^{15} D, 10^{13} B within 1 mrad of beam

Can we do something with that?

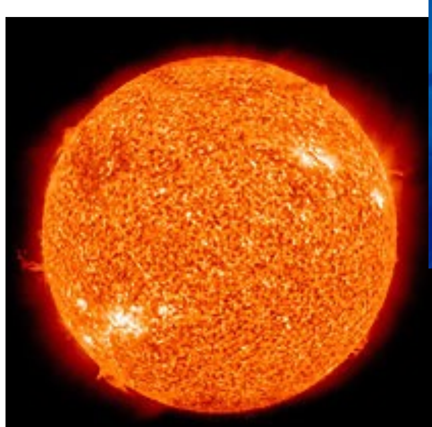


Motivation

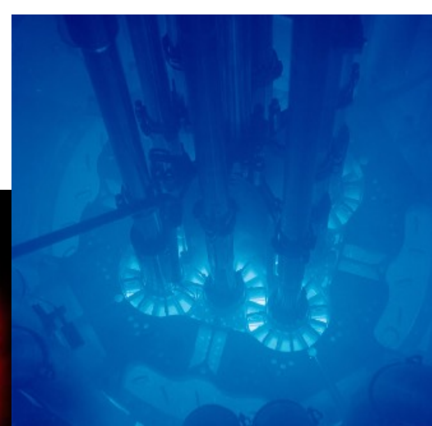
Collider Neutrinos

- neutrinos detected from many sources, but not from colliders

Solar

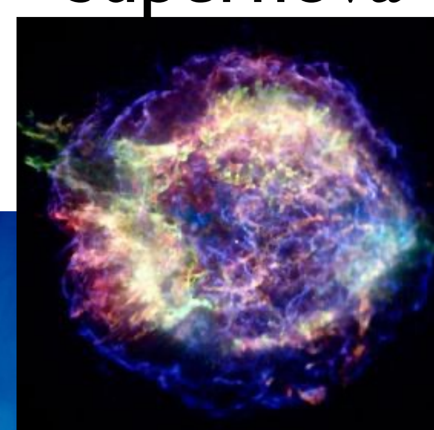


Reactor



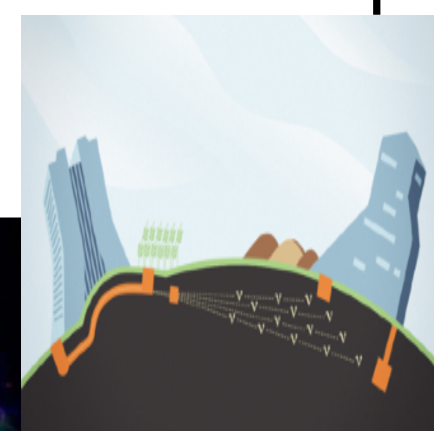
~MeV

Supernova



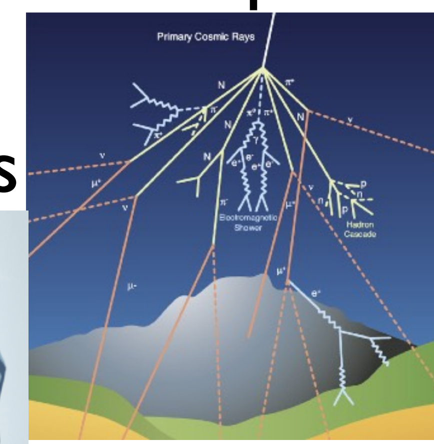
~MeV

Beam Dumps



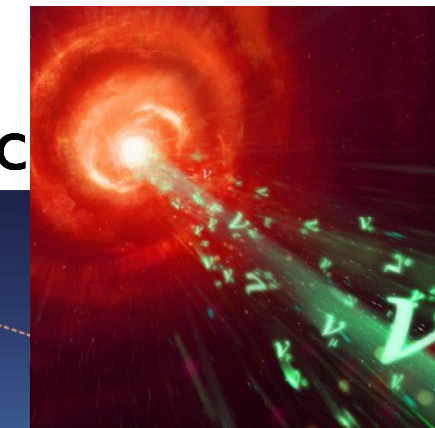
GeV-subTeV

Atmospheric



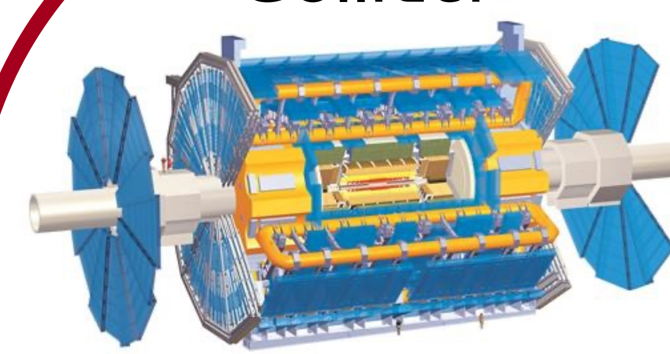
subGeV-PeV

Cosmic



TeV-EeV

Collider

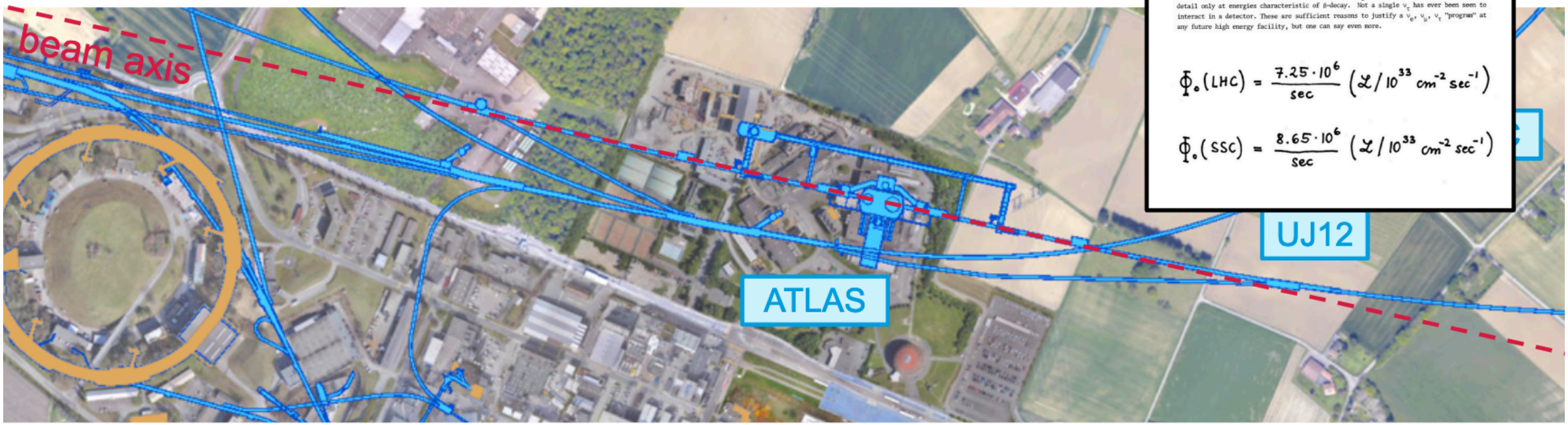


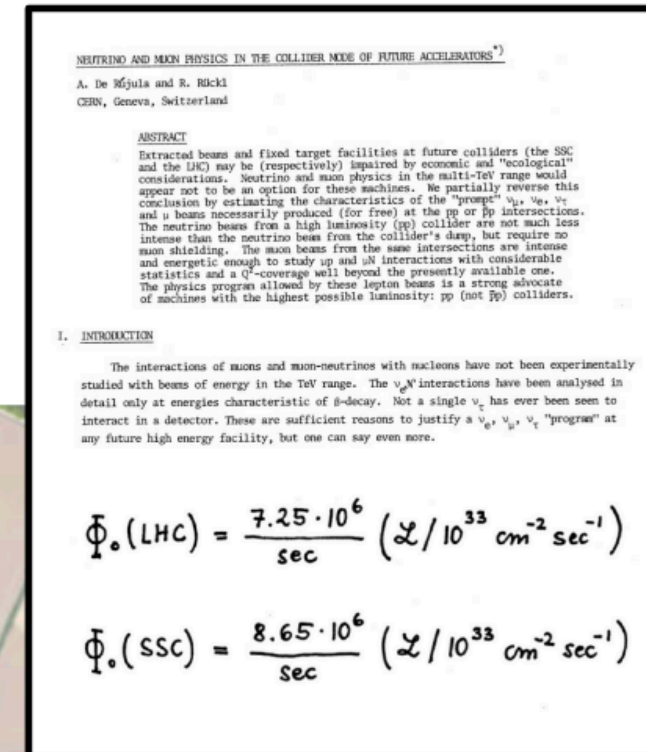
100GeV-multiTeV

First Collider Neutrinos

There is a huge flux of neutrinos in the forward direction, mainly from π, K and D meson decays.

[De Rujula et al. (1984)]





NEUTRINO AND MUON PHYSICS IN THE COLLIDER MODE OF FUTURE ACCELERATORS*)

A. De Rújula and R. Rückl

CERN, Geneva, Switzerland

ABSTRACT

Extracted beams and fixed target facilities at future colliders (the SSC and the LHC) may be (respectively) impaired by economic and "ecological" considerations. Neutrino and muon physics in the multi-TeV range would appear not to be an option for these machines. We partially reverse this conclusion by estimating the characteristics of the "prompt" ν_μ, ν_e, ν_τ and μ beams necessarily produced (for free) at the pp or $\bar{p}p$ intersections. The neutrino beams from a high luminosity (pp) collider are not much less intense than the neutrino beam from the collider's dump, but require no muon shielding. The muon beams from the same intersections are intense and energetic enough to study μp and μN interactions with considerable statistics and a Q^2-coverage well beyond the presently available one. The physics program allowed by these lepton beams is a strong advocate of machines with the highest possible luminosity: pp (not $\bar{p}p$) colliders.

I. INTRODUCTION

The interactions of muons and muon-neutrinos with nucleons have not been experimentally studied with beams of energy in the TeV range. The $\nu_e N$ interactions have been analysed in detail only at energies characteristic of β-decay. Not a single ν_τ has ever been seen to interact in a detector. These are sufficient reasons to justify a ν_e, ν_μ, ν_τ "program" at any future high energy facility, but one can say even more.

$$\Phi_0(LHC) = \frac{7.25 \cdot 10^6}{sec} \left(\mathcal{L}/10^{33}\ cm^{-2}\, sec^{-1}\right)$$

$$\Phi_0(SSC) = \frac{8.65 \cdot 10^6}{sec} \left(\mathcal{L}/10^{33}\ cm^{-2}\, sec^{-1}\right)$$

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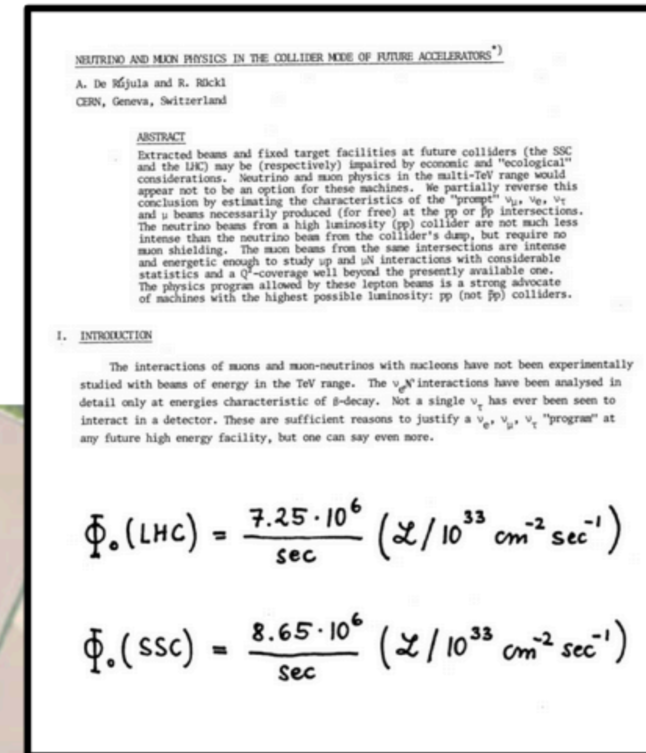

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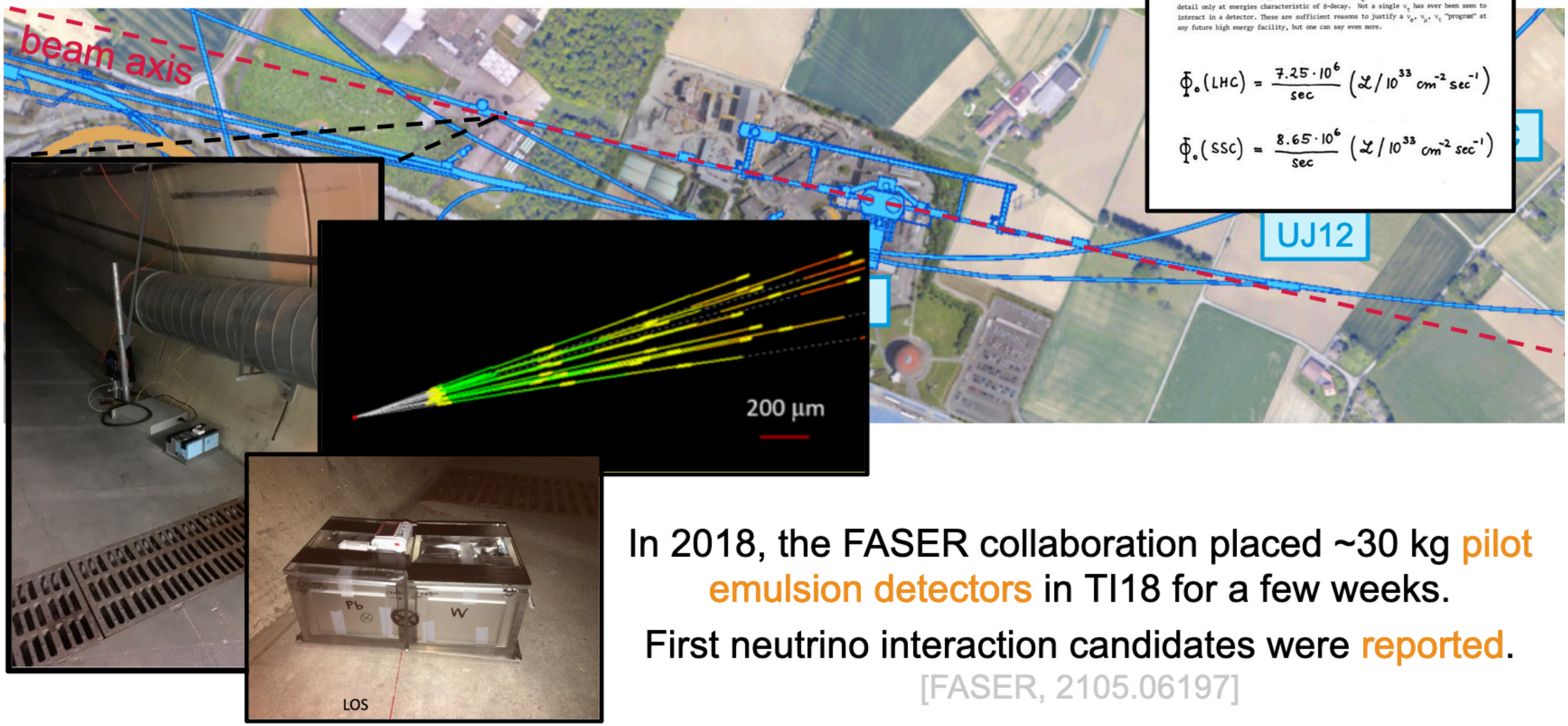
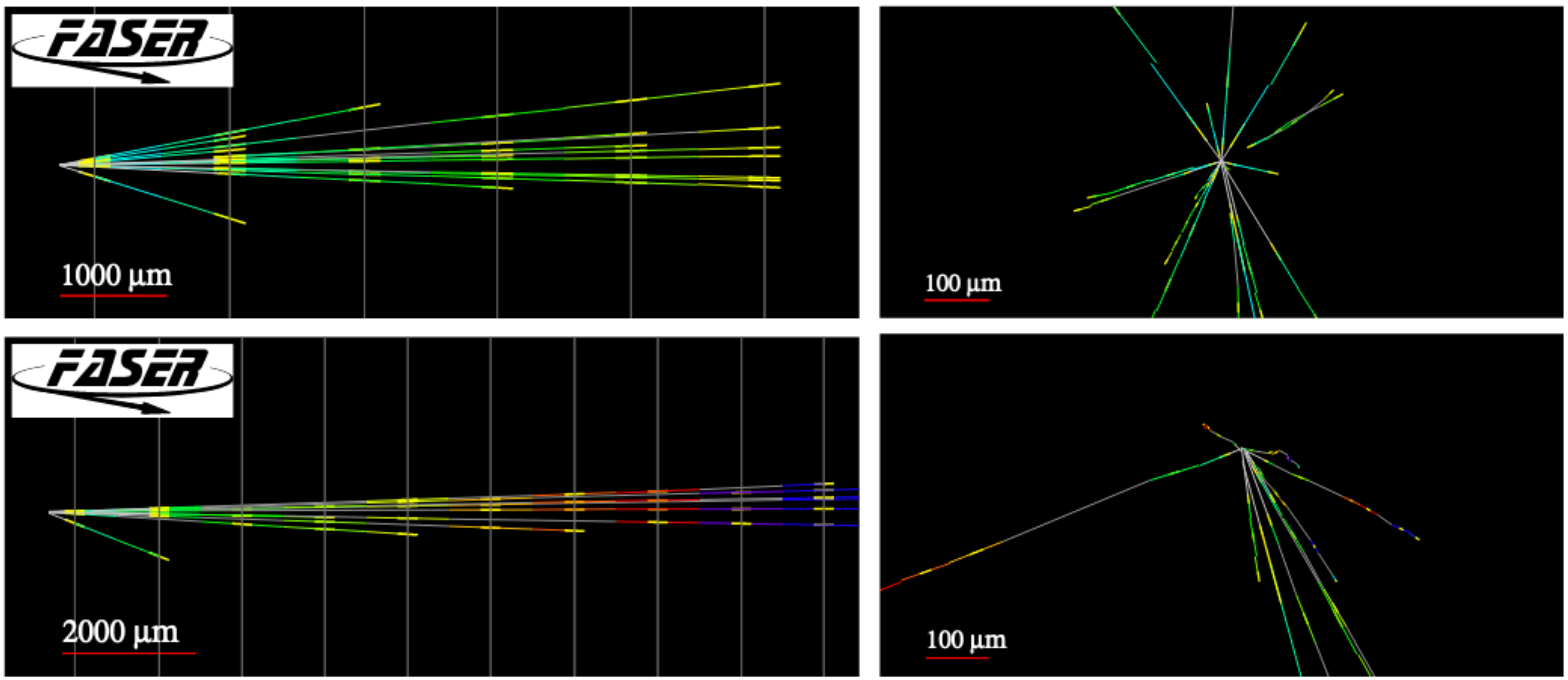


In 2018, the FASER collaboration placed ~30 kg pilot emulsion detectors in TI18 for a few weeks.

First neutrino interaction candidates were reported.
[FASER, 2105.06197]

First Collider Neutrinos



First Collider Neutrinos

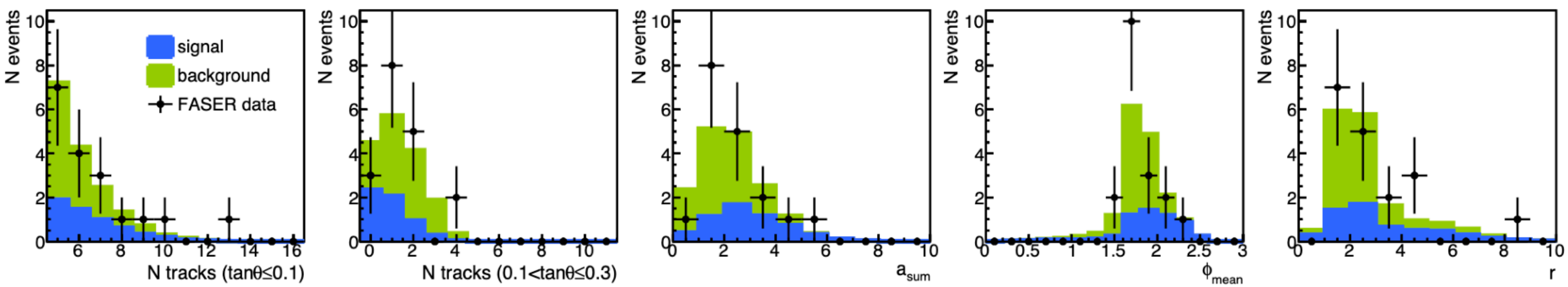


FIG. 4. Monte Carlo simulation distributions of the BDT input variables for the neutrino signal and neutral hadron background. The observed neutral vertices in the data sample are shown in black. The Monte Carlo simulation distributions are normalized to 12.2 fb^{-1}.

First Collider Neutrinos

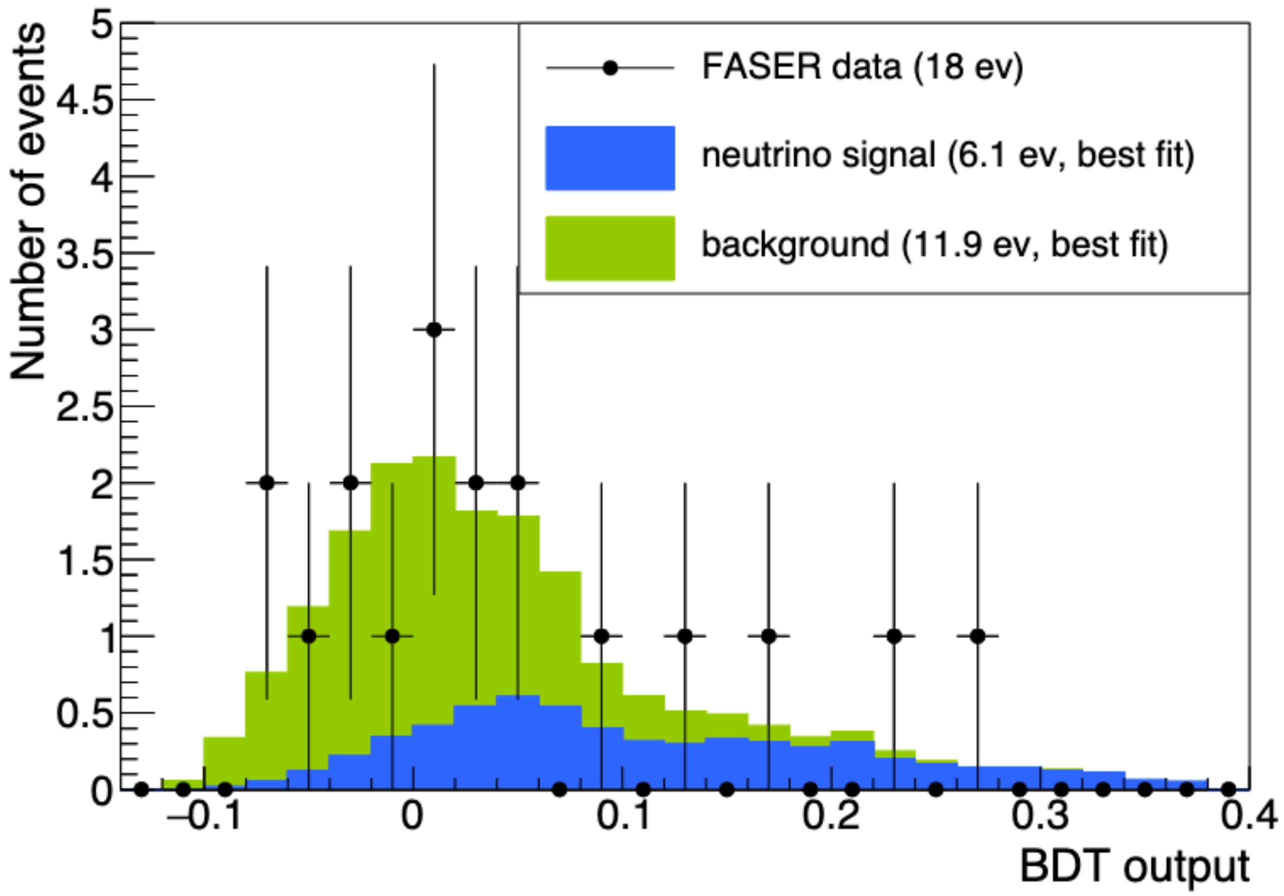


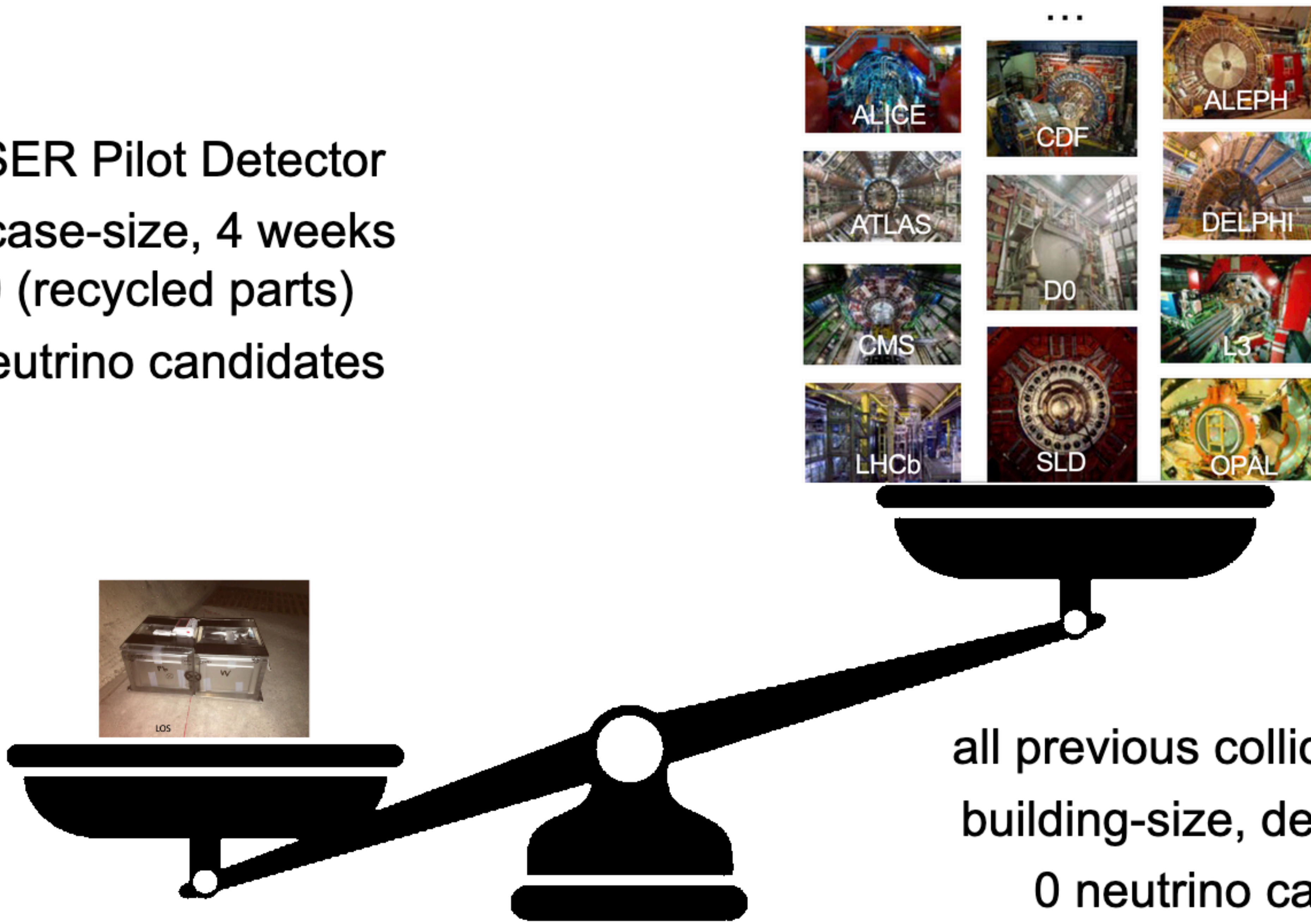
FIG. 6. The BDT outputs of the observed neutral vertices, and the expected signal and background distributions (stacked) fitted to data. Higher BDT output values are associated with neutrino-like vertex features.

First Collider Neutrinos

FASER Pilot Detector

suitcase-size, 4 weeks
$0 (recycled parts)

6 neutrino candidates



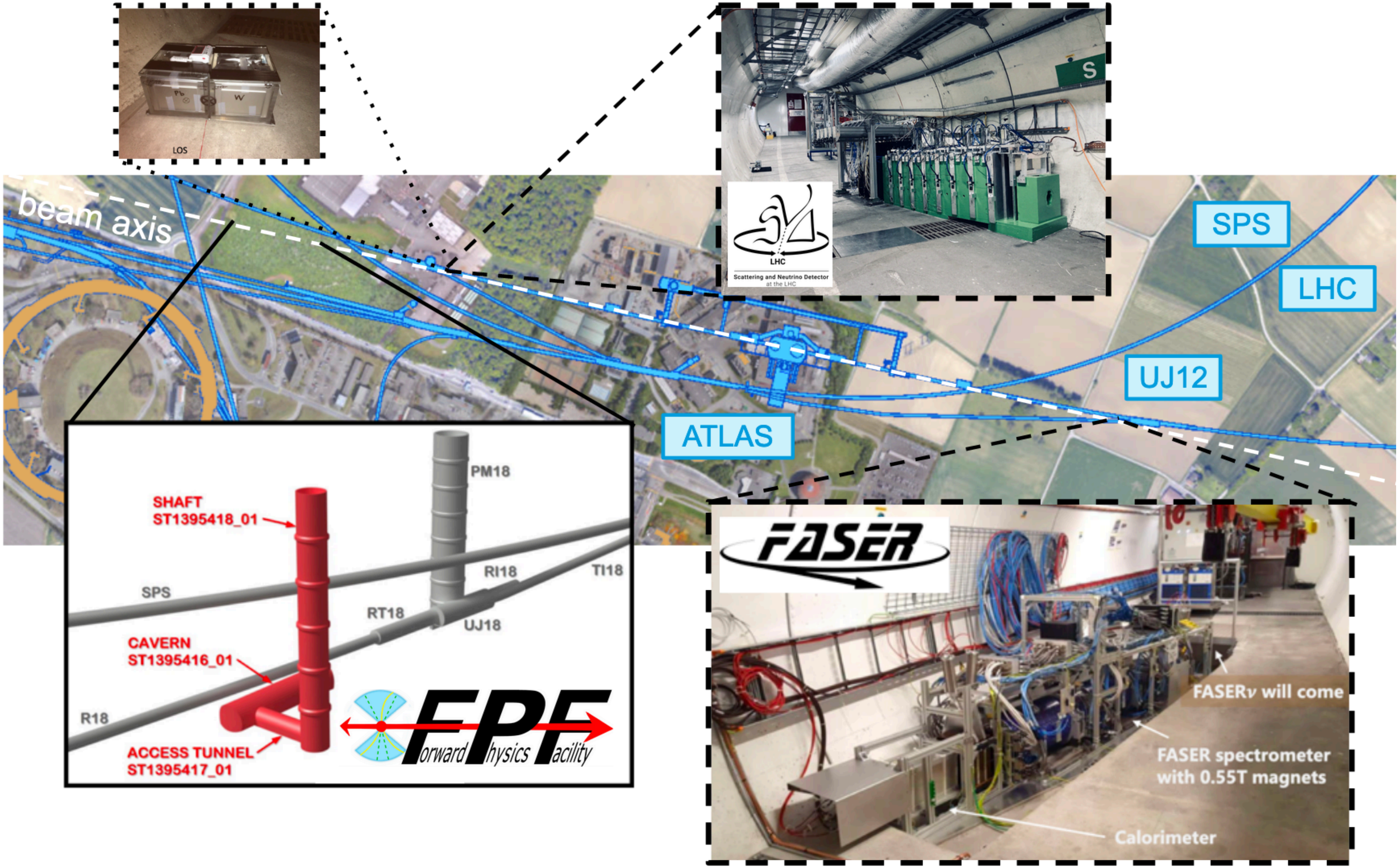
all previous collider detectors

building-size, decades ~$1B

0 neutrino candidates

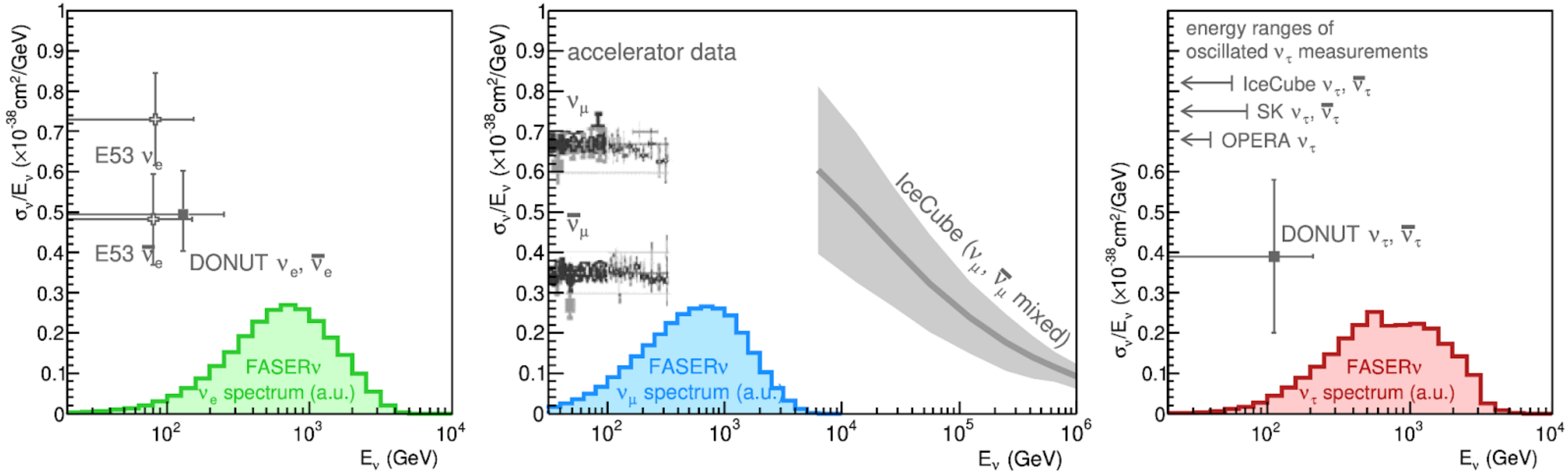
slide by Jonathan Feng

Collider Neutrinos



Collider Neutrinos

LHC provides a strongly collimated beam of TeV energy neutrinos of all three flavours in the far forward direction.



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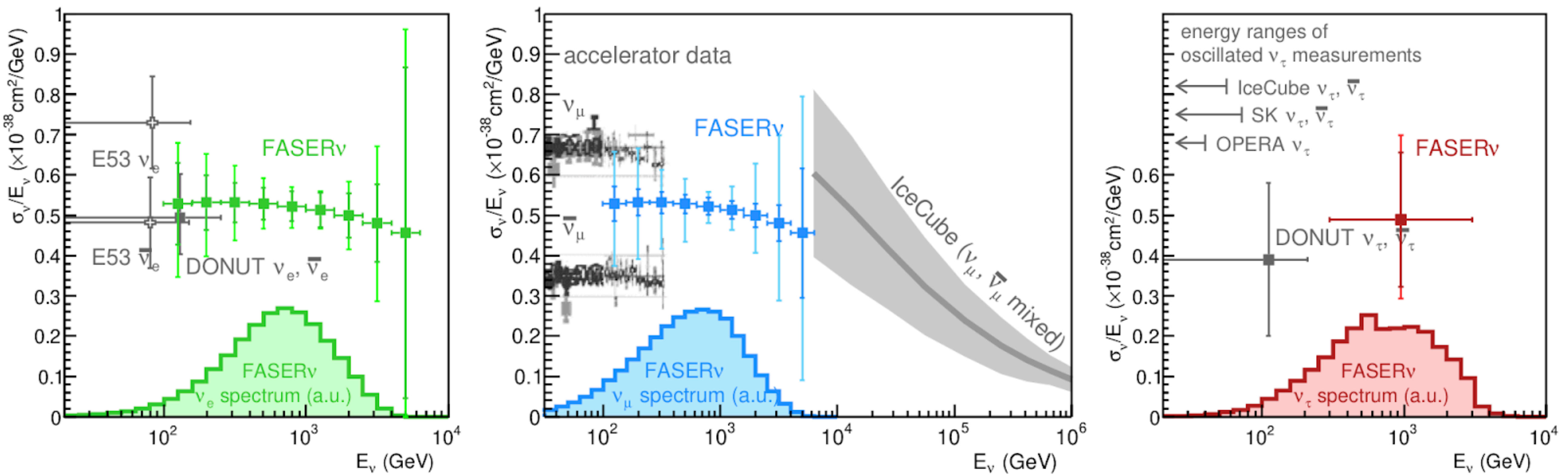

FASERν and SND@LHC will detect O(10k) neutrinos.

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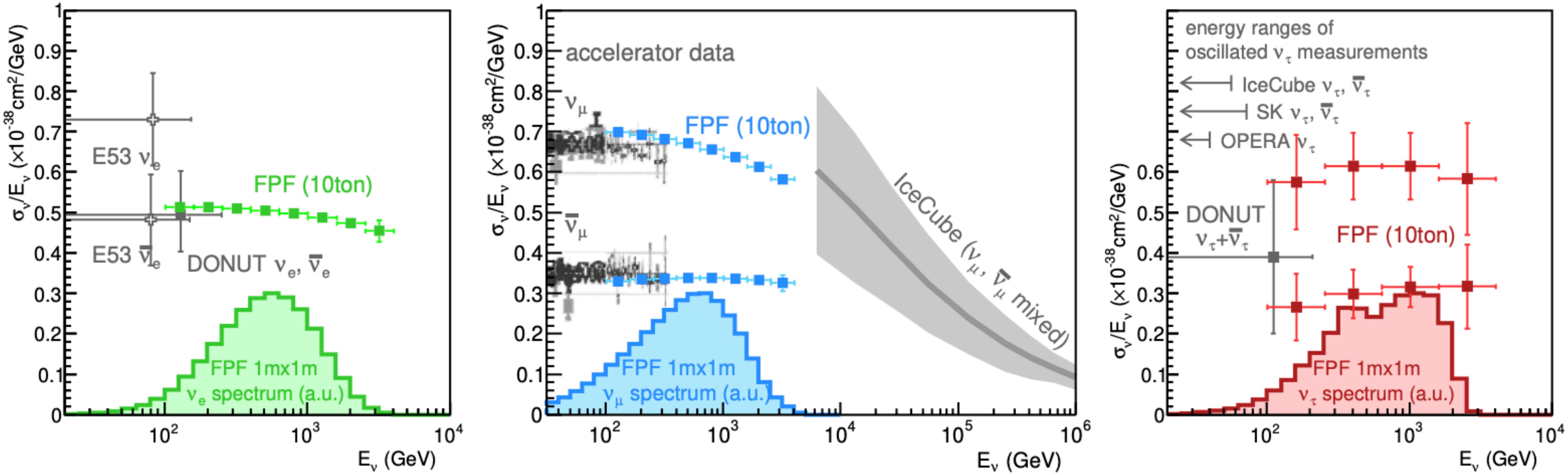


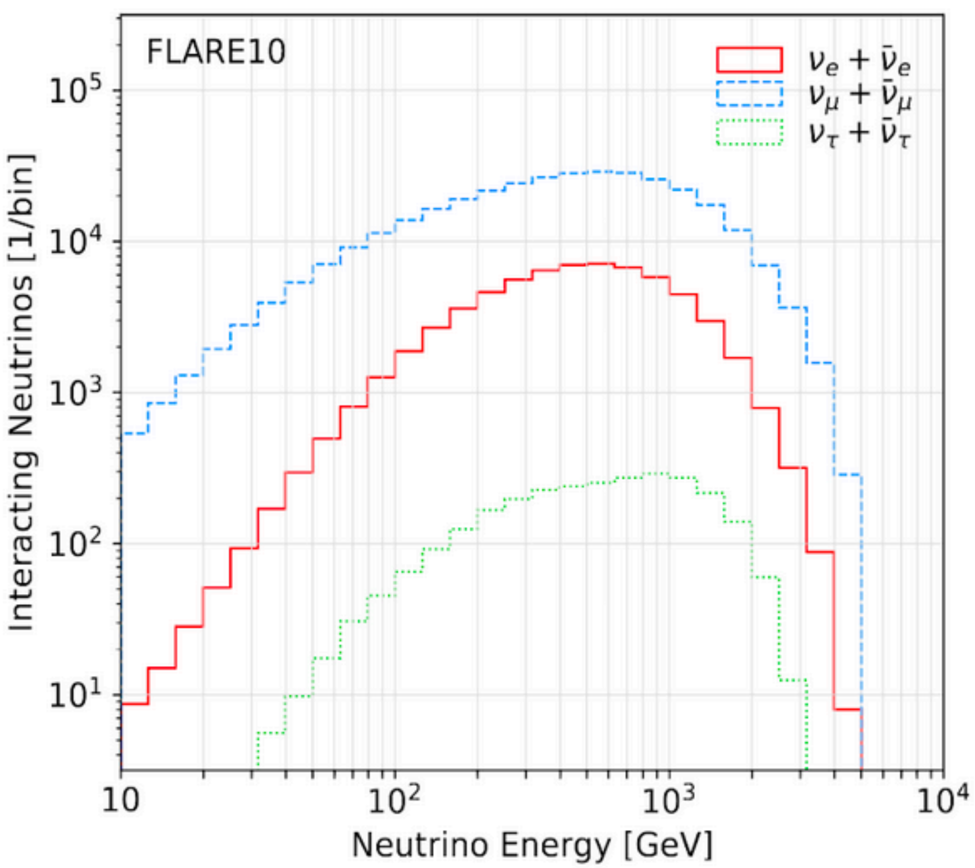
FASERv and SND@LHC will detect O(10k) neutrinos.

Proposed FPF experiment have potential to detect O(1M) neutrinos.

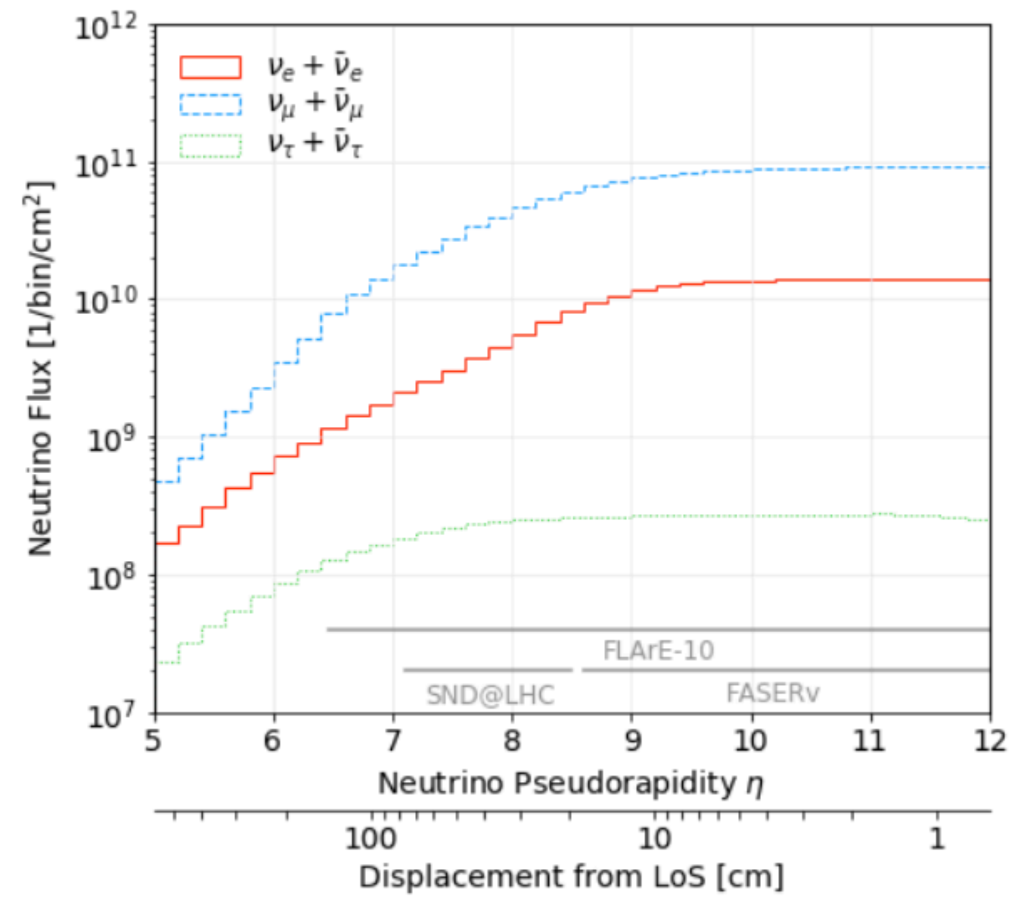
Neutrino Fluxes and Interaction

Collider Neutrinos

energy spectrum of interacting neutrinos



neutrino flux as function of displacement from LoS



100 GeV - few TeV energies

flux peaked around LoS, start to drop around 1m away from LoS

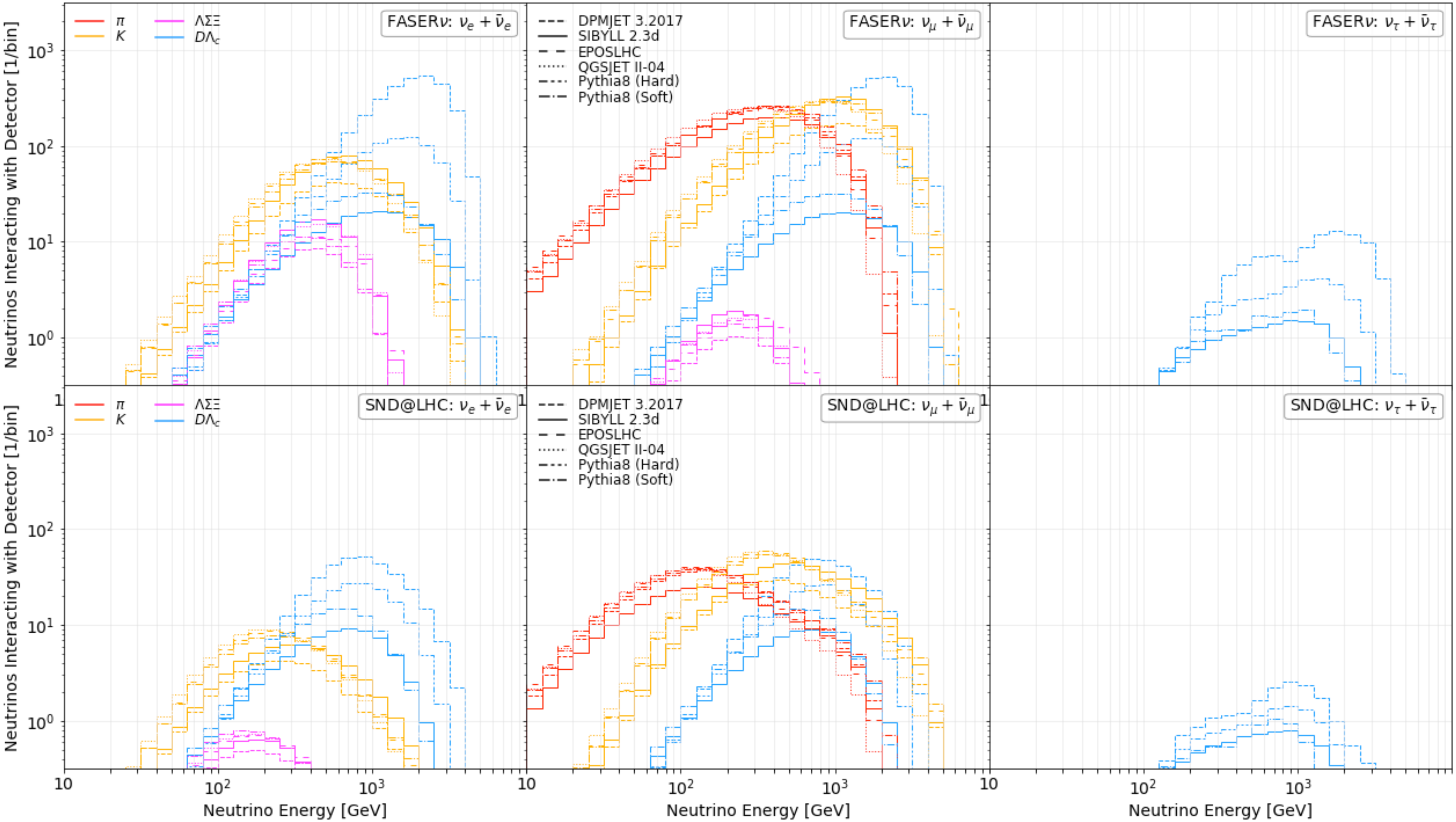
complementary coverage of FASERν and SND@LHC

Event Rates

Generators		FASERν			SND@LHC		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1501	7971	24.5	223	1316	12.6
DPMJET	DPMJET	5761	11813	161	658	1723	31
EPOSLHC	Pythia8 (Hard)	2521	9841	57	445	1871	19.2
QGSJET	Pythia8 (Soft)	1616	8918	26.8	308	1691	12
Combination (all)		2850^{+2910}_{-1348}	9636^{+2176}_{-1663}	67.5^{+94}_{-43}	408^{+248}_{-185}	1651^{+220}_{-333}	$18.8^{+12}_{-6.6}$
Combination (w/o DPMJET)		1880^{+641}_{-378}	8910^{+930}_{-938}	$36^{+20.8}_{-11.5}$	325^{+118}_{-101}	1626^{+243}_{-308}	$14.6^{+4.5}_{-2.5}$

TABLE II. Expected number of charged current neutrino interaction events occurring in FASERν and SND@LHC during LHC Run 3 with 250 fb^{-1} integrated luminosity. Here we assume a target mass of 1.2 tons for FASERν and 800 kg for SND@LHC; further details on the experimental setup are provided in ??. We provide predictions for `SIBYLL 2.3d`, `DPMJET III.2017.1`, `EPOSLHC`/`Pythia 8.2` with `HardQCD`, and `QGSJET II-04`/`Pythia 8.2` with `SoftQCD`. The two bottom rows provide a combined average, both including and excluding the `DPMJET` prediction, where the uncertainties correspond to the range of predictions obtained from different MC generators.

Where do neutrinos come from?



Neutrinos from Light Hadron Decays

Two issues to consider

Event Generation

Light hadron production cannot be described by perturbative QCD.
Instead, one has to use hadronic interaction models / MC generators.

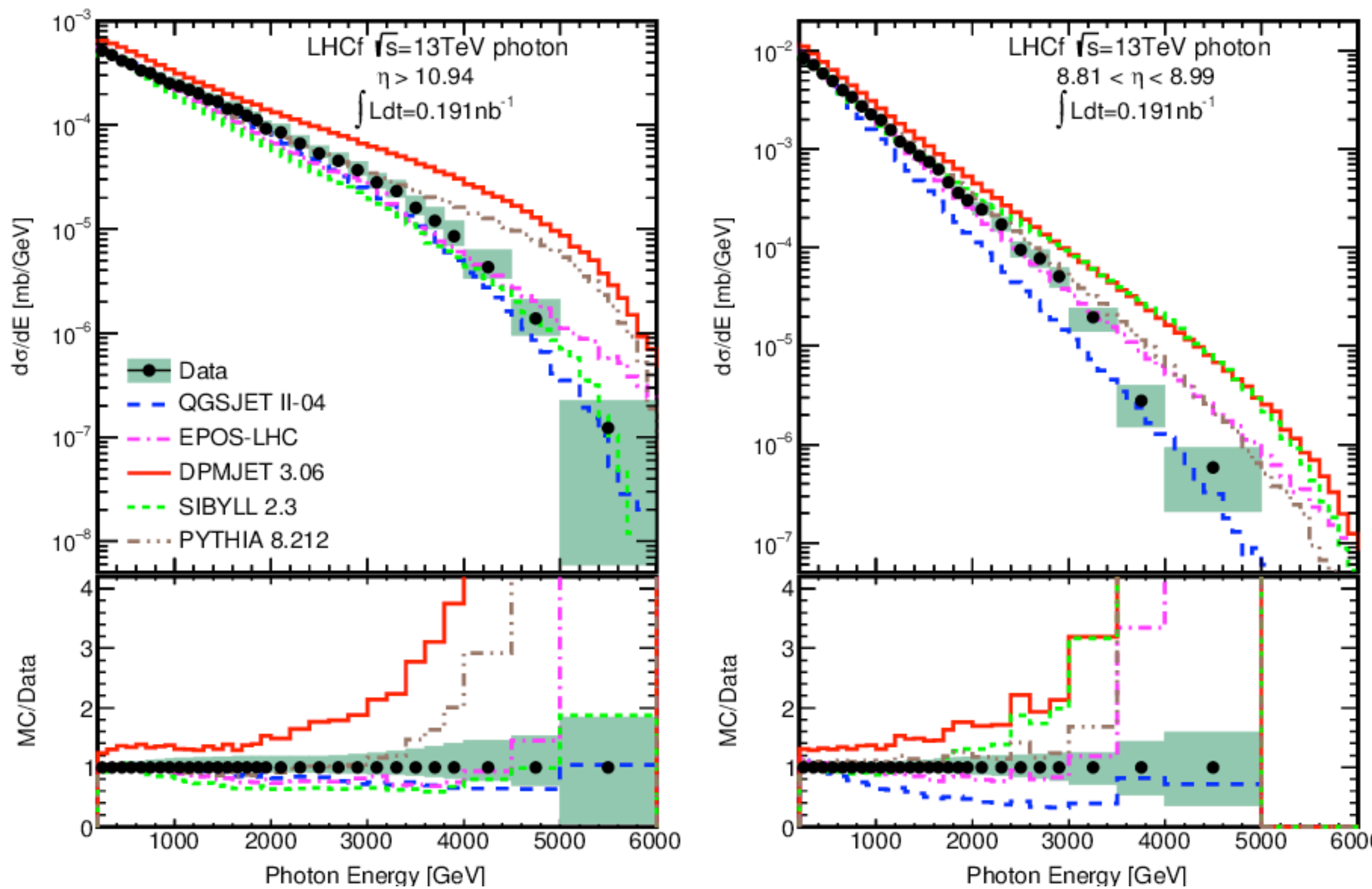
Particle Propagation

Light hadron (pions, kaons, hyperons) are long-lived.
So one need to model their propagation, absorption and decays in the LHC infrastructure.

Neutrinos from Light Hadron Decays

Typical generators from cosmic ray physics: EPOS, QGSJET, SIBYLL, DMPJET, (Pythia)

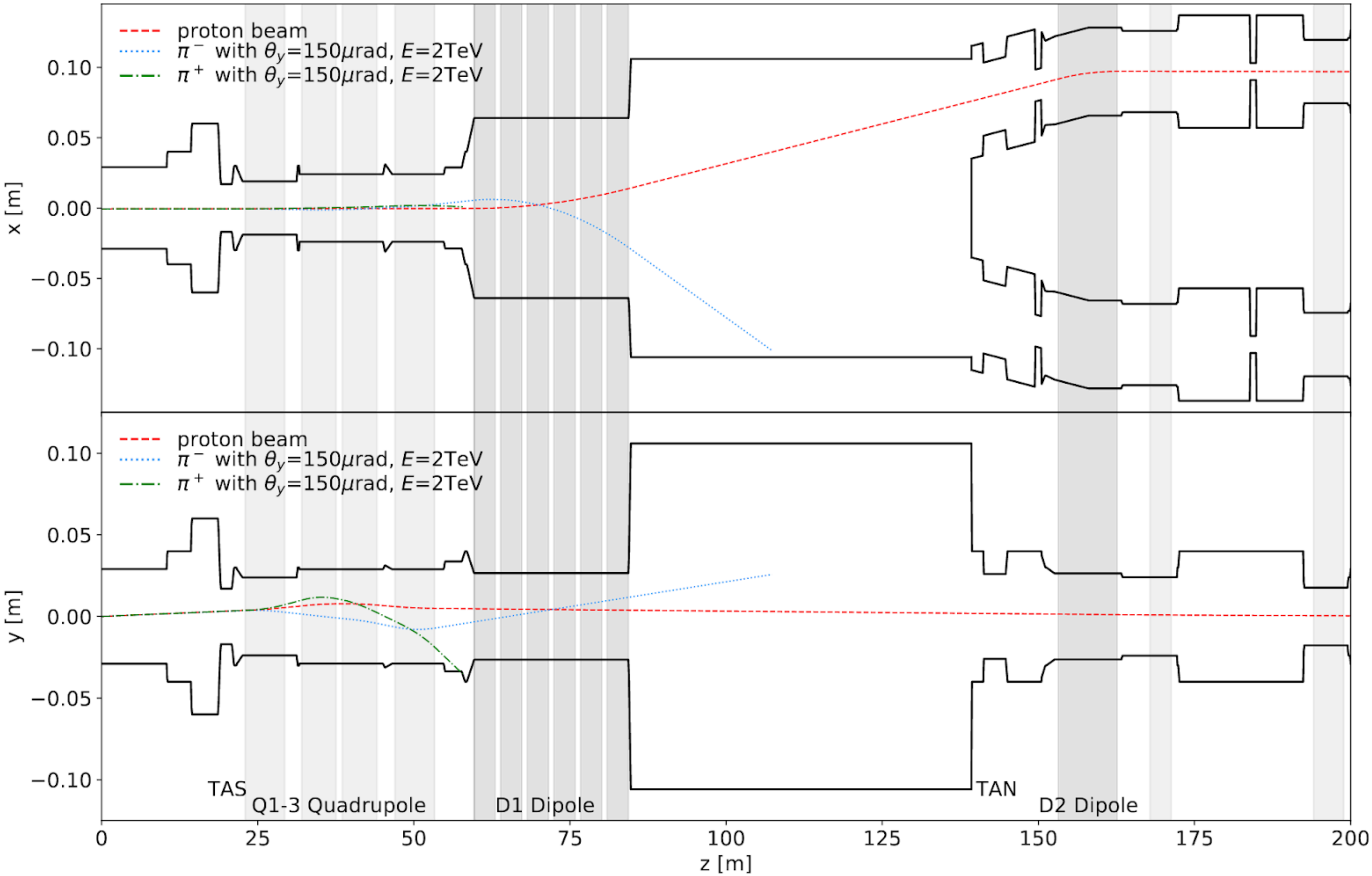
Some guidance by data: forward photon at LHCf [1703.07678]



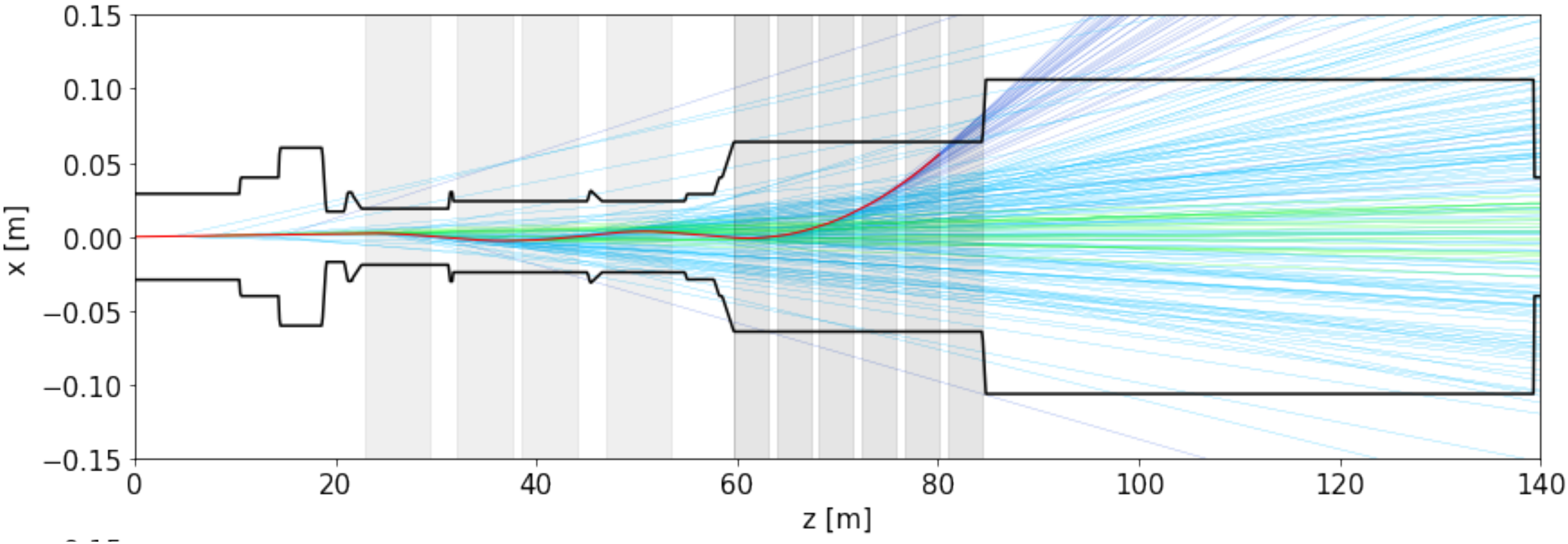
Neutrinos from Light Hadron Decays

This has been realized as fast neutrino flux simulation implemented as RIVET module.

[Kling, 2105.08270]



Neutrinos from Light Hadron Decays

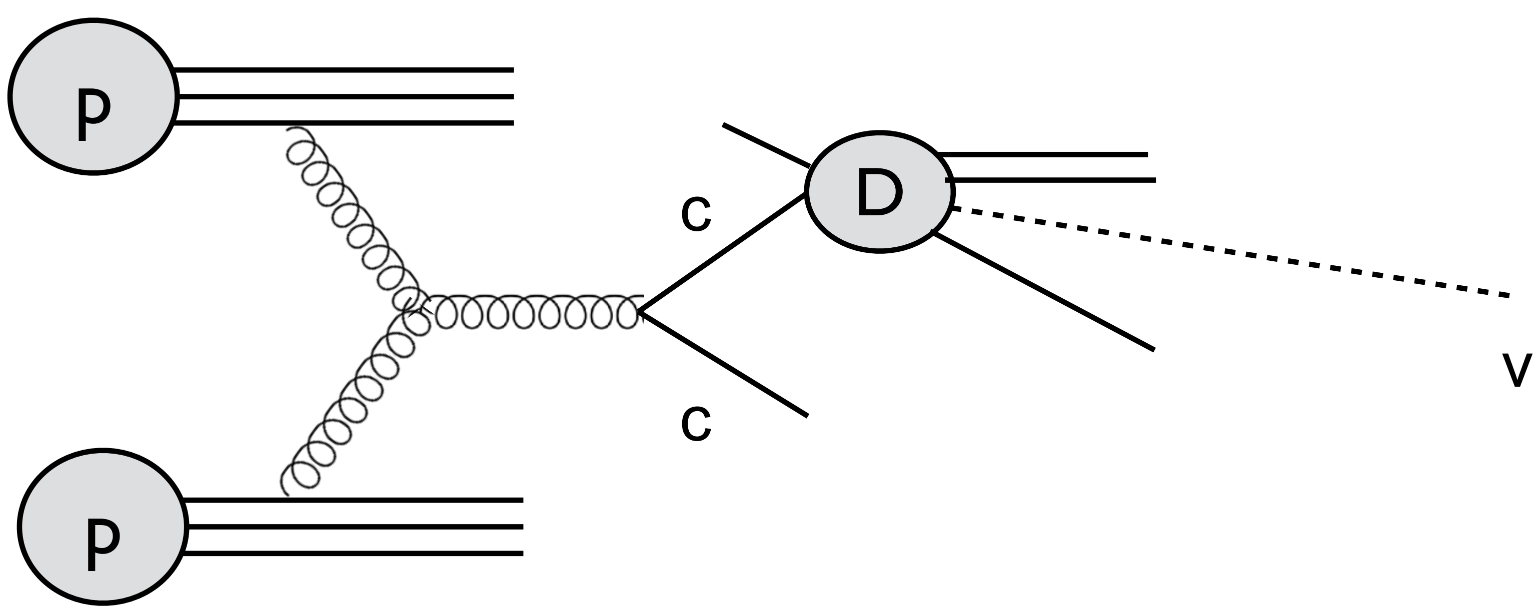


Neutrinos from Charm Decay

Charm production can (in principle) be described by perturbative QCD: g g → c c

$$d\sigma(pp\to D + X) \quad = \quad f_g(x_1)f_g(x_2) \quad \otimes \quad d\sigma(gg\to c + X) \quad \otimes \quad F(c\to D)$$

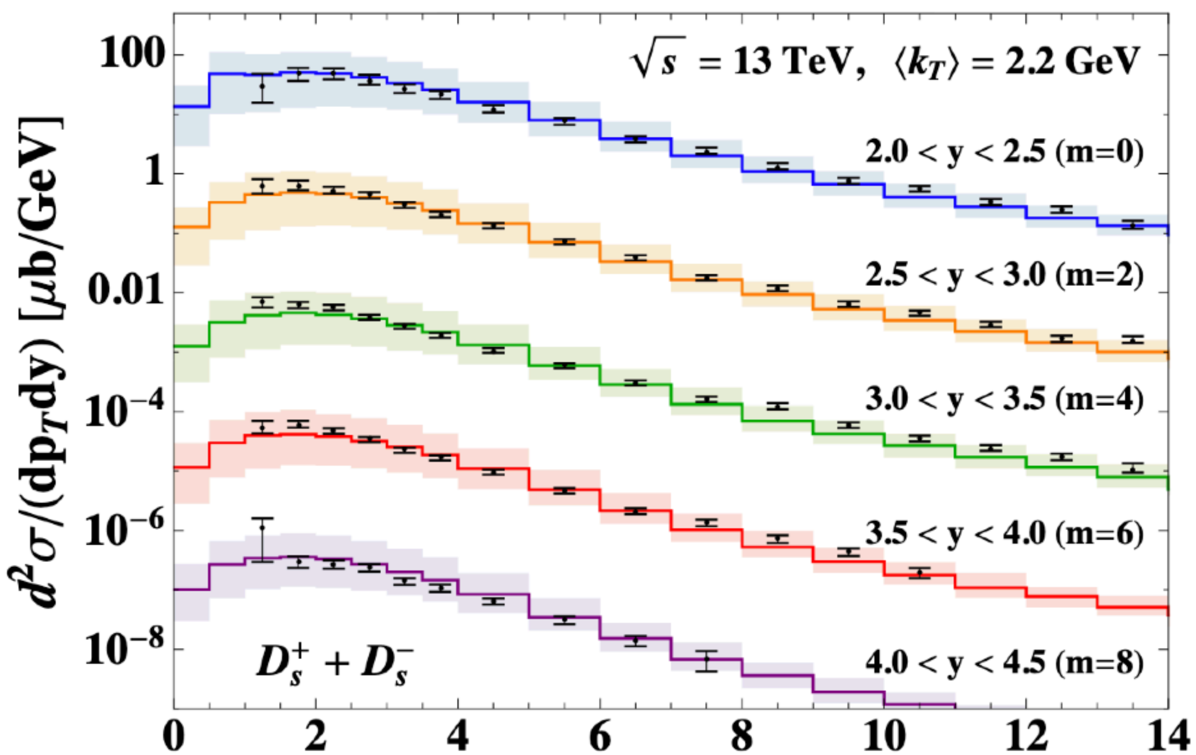
hadronic cross section — PDF — partonic cross section — hadronization

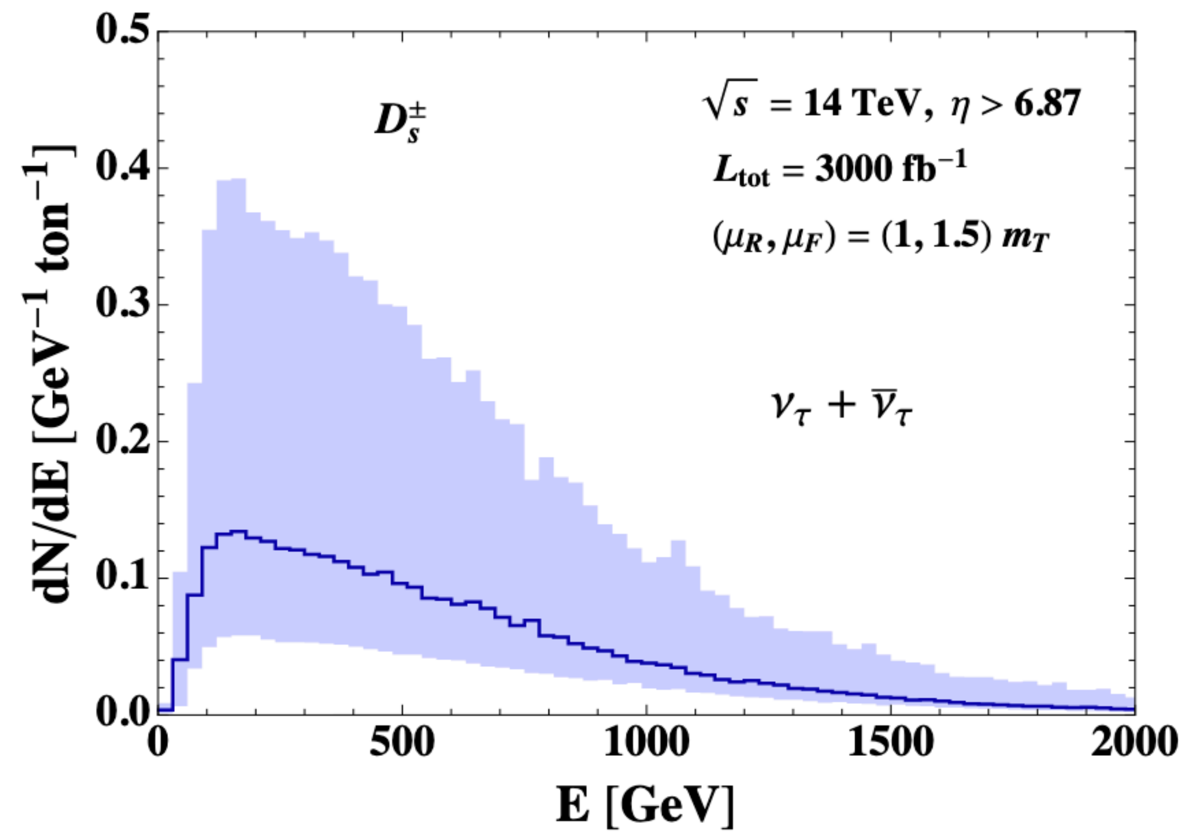


Some guidance by data: D-meson spectra by LHCb [1510.01707]

Neutrinos from Charm Decay

First estimate at NLO by Bai et al: 2002.03012

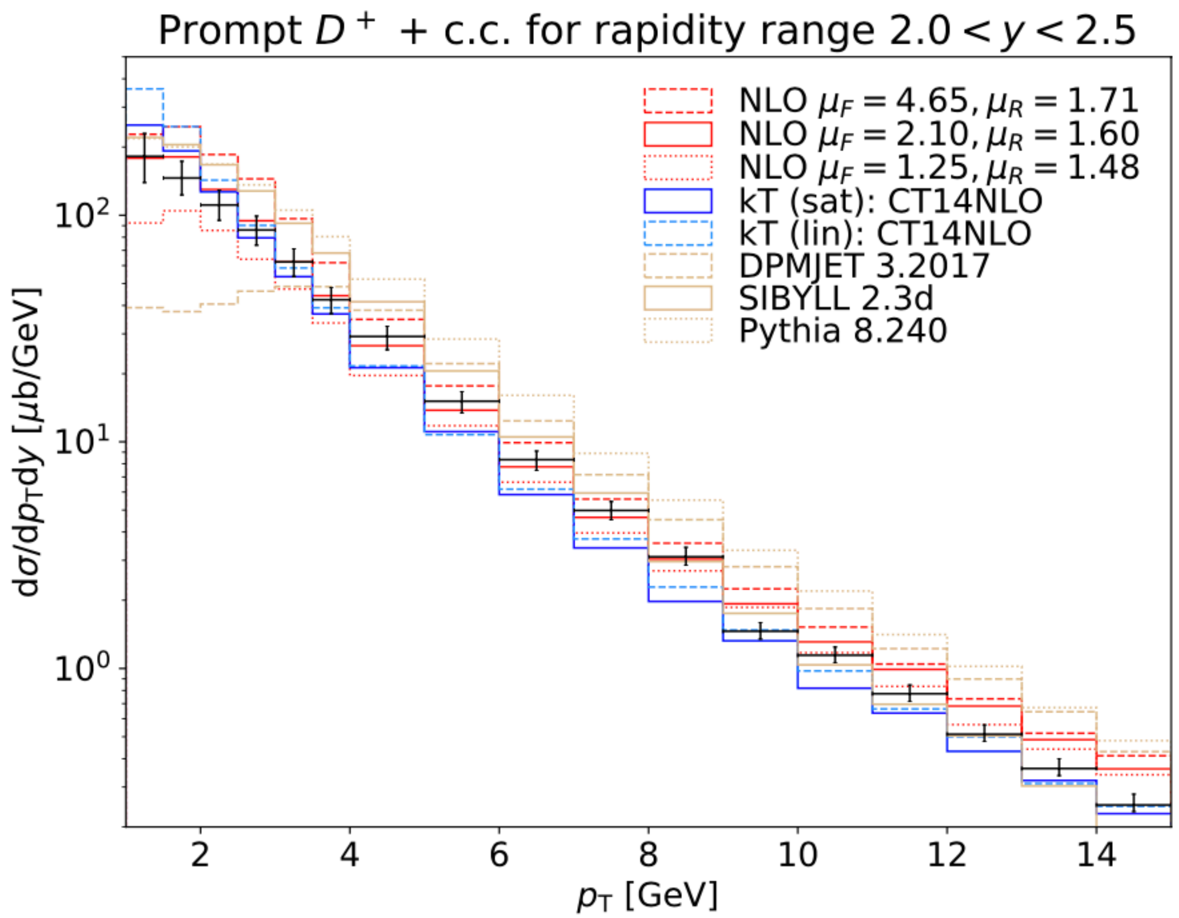


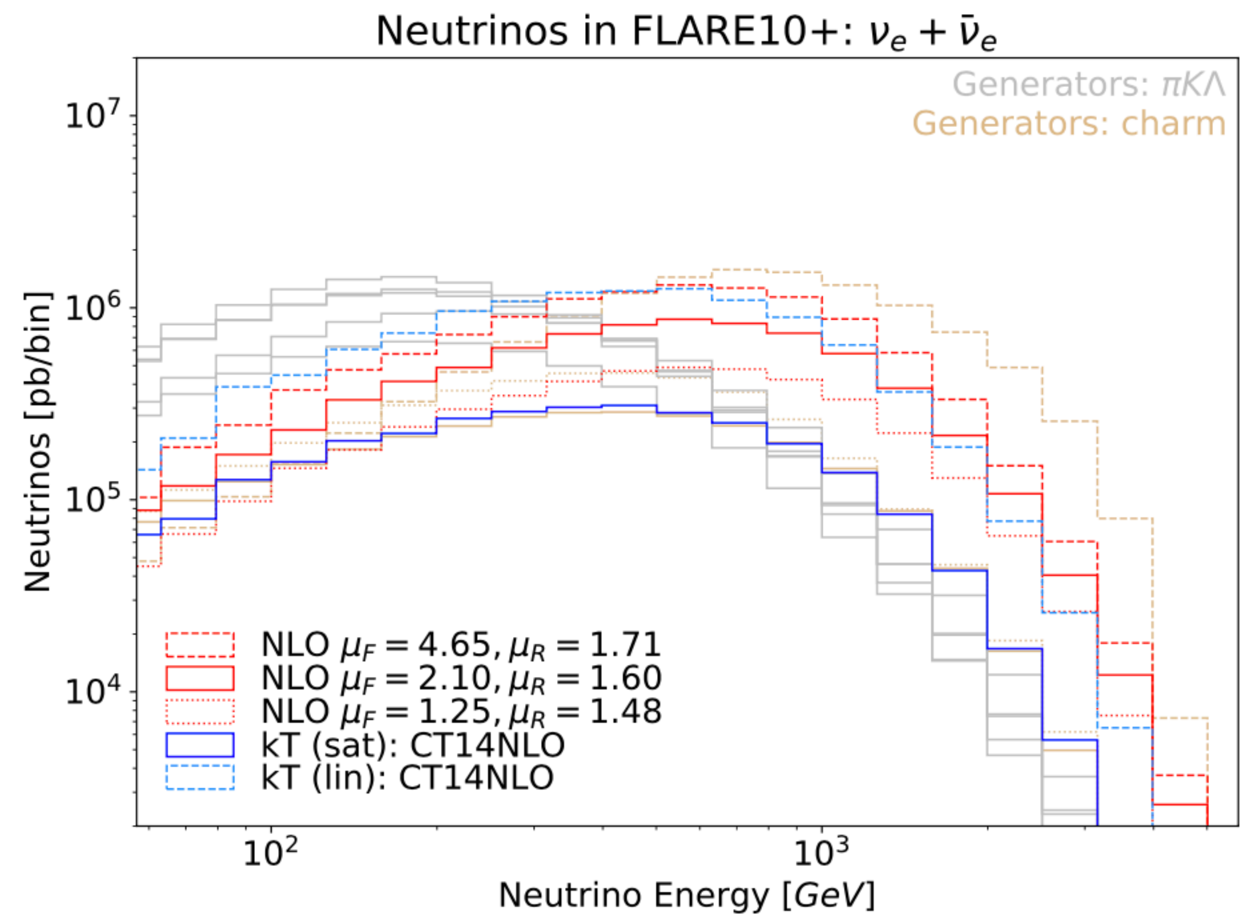


uncertainty band: vary scales by factor two

Neutrinos from Charm Decay

Estimate based on a different approaches (NLO collinear and kT factorization)
by Bhattacharya, Kling, Sarcevic and Stasto: 2203.05090





Neutrinos from Charm Decay

Event rates at LHC neutrino experiments
estimated with two LO MC generators: SIBYLL / DPMJET

	Detector			Number of CC Interactions		
	Name	Mass	Coverage	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
LHC Run3	FASERν	1 ton	$\eta \gtrsim 8.5$	1.3k / 4.6k	6.1k / 9.1k	21 / 131
	SND@LHC	800kg	$7 < \eta < 8.5$	180 / 500	1k / 1.3k	10 / 22
HL-LHC	FASERν2	20 tons	$\eta \gtrsim 8$	178k / 668k	943k / 1.4M	2.3k / 20k
	FLArE	10 tons	$\eta \gtrsim 7.5$	36k / 113k	203k / 268k	1.5k / 4k
	AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	6.5k / 20k	41k / 53k	190 / 754

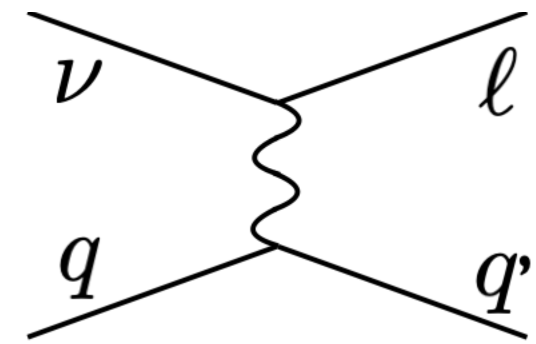
Large spread in generator predictions:

Challenge: For neutrino physics measurement we need to quantify and reduce neutrino flux uncertainties

Opportunity: Forward neutrino flux measurement can help to improve our understanding of underlying physics.

Neutrino Interactions

for E_ν>100GeV: deep inelastic scattering (DIS) $q\nu \rightarrow q'\ell$



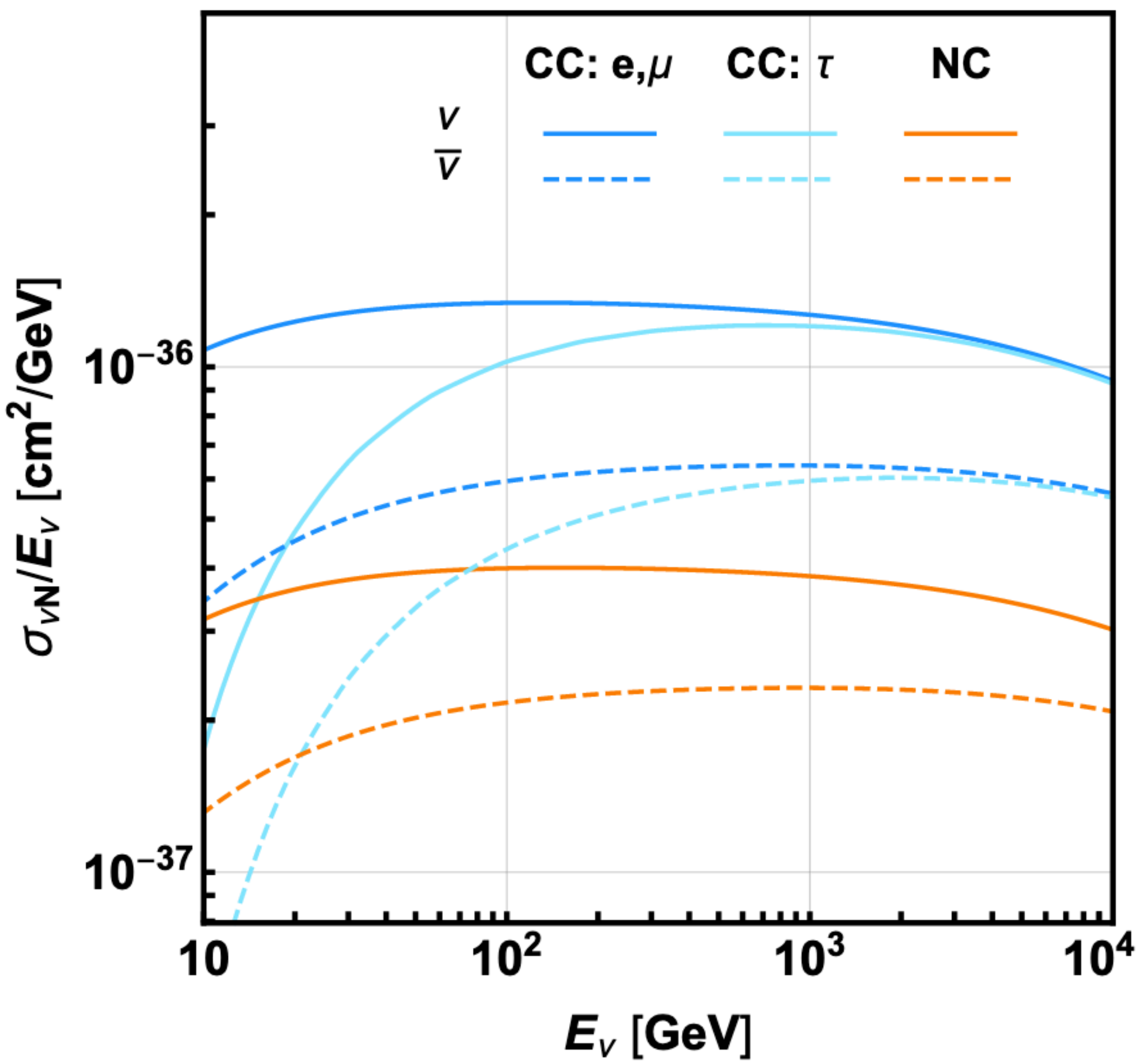
$$\frac{d\sigma_{\nu p}}{dx\, dy} = \frac{G_F^2 m_p E_\nu}{\pi} \frac{m_{W,Z}^4}{(Q^2 + m_{W,Z}^2)^2} \times \left[x f_q(x, Q^2) + x f_{\bar{q}}(x, Q^2)(1-y)^2 \right]$$

* cross section grows linear with energy: σ~E

* proton momentum carried by the quark q: x~0.1

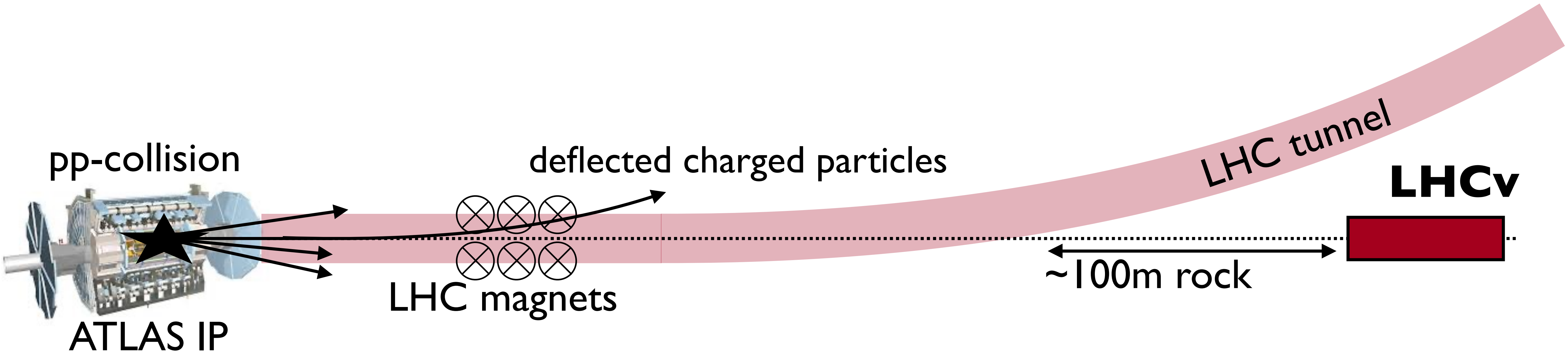
* fraction of the neutrino energy transferred: y~0.5

* transferred four-momentum: $Q^2 \sim (10\ \mathrm{GeV})^2$



Physics Potential

Overview



neutrino production

neutrino propagation

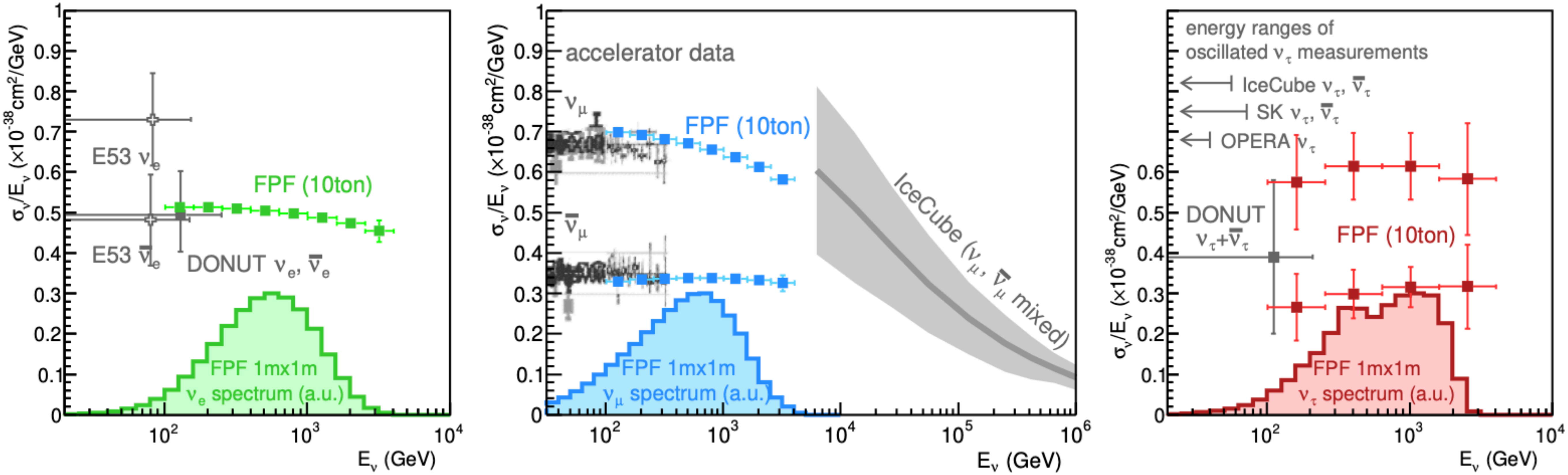
neutrino interactions

Forward Particle Production

LHC as Short Baseline Neutrino Experiment

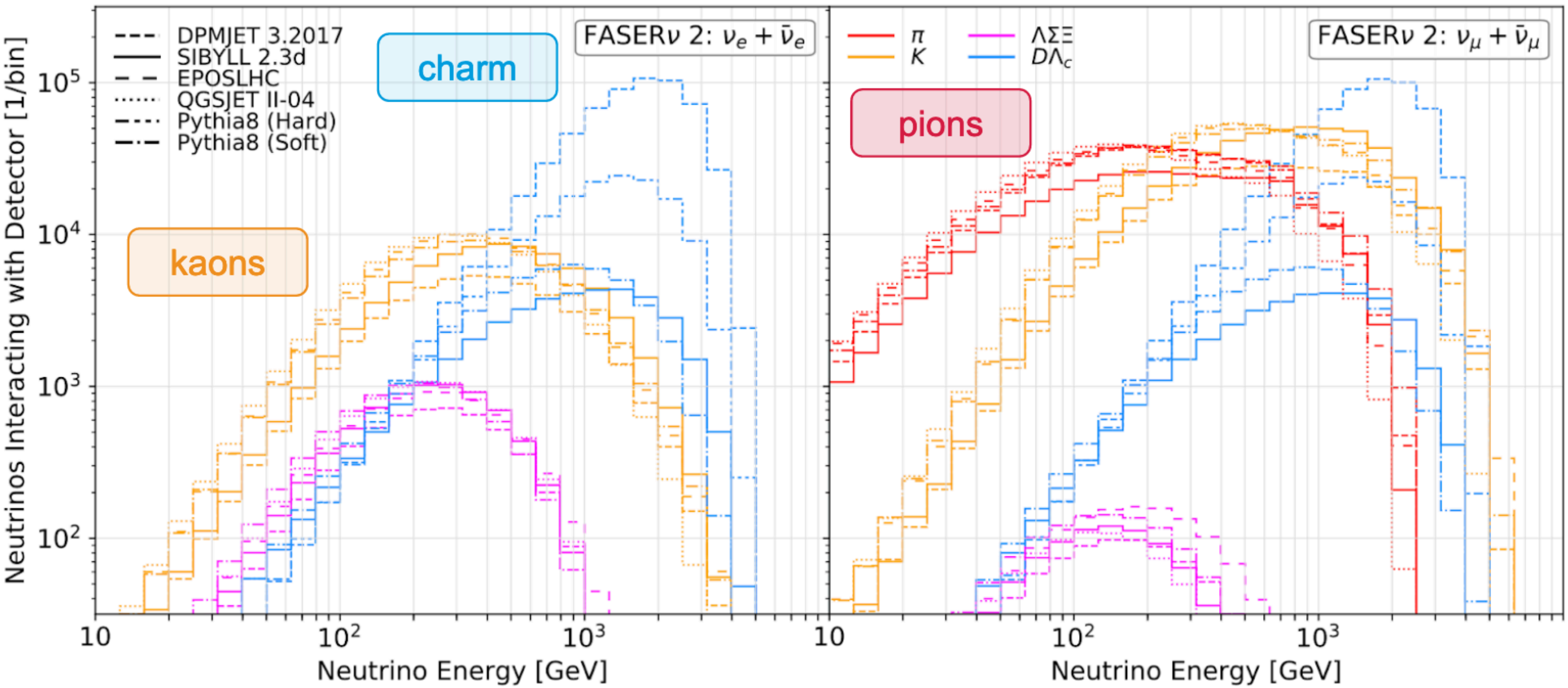
TeV-energy Neutrino Interaction

Neutrino Cross Sections



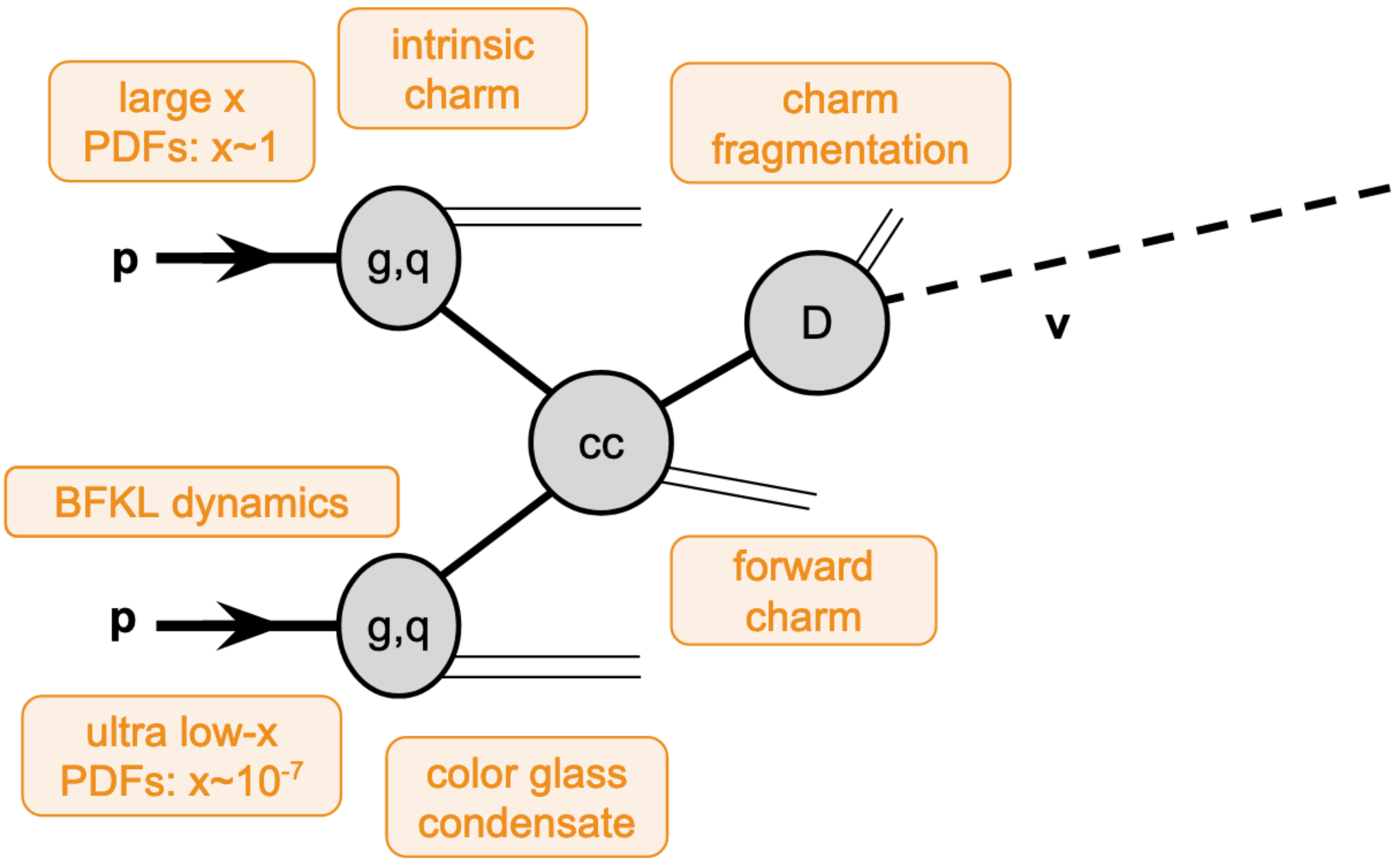
Forward Particle Production

Where do the LHC neutrinos come from?



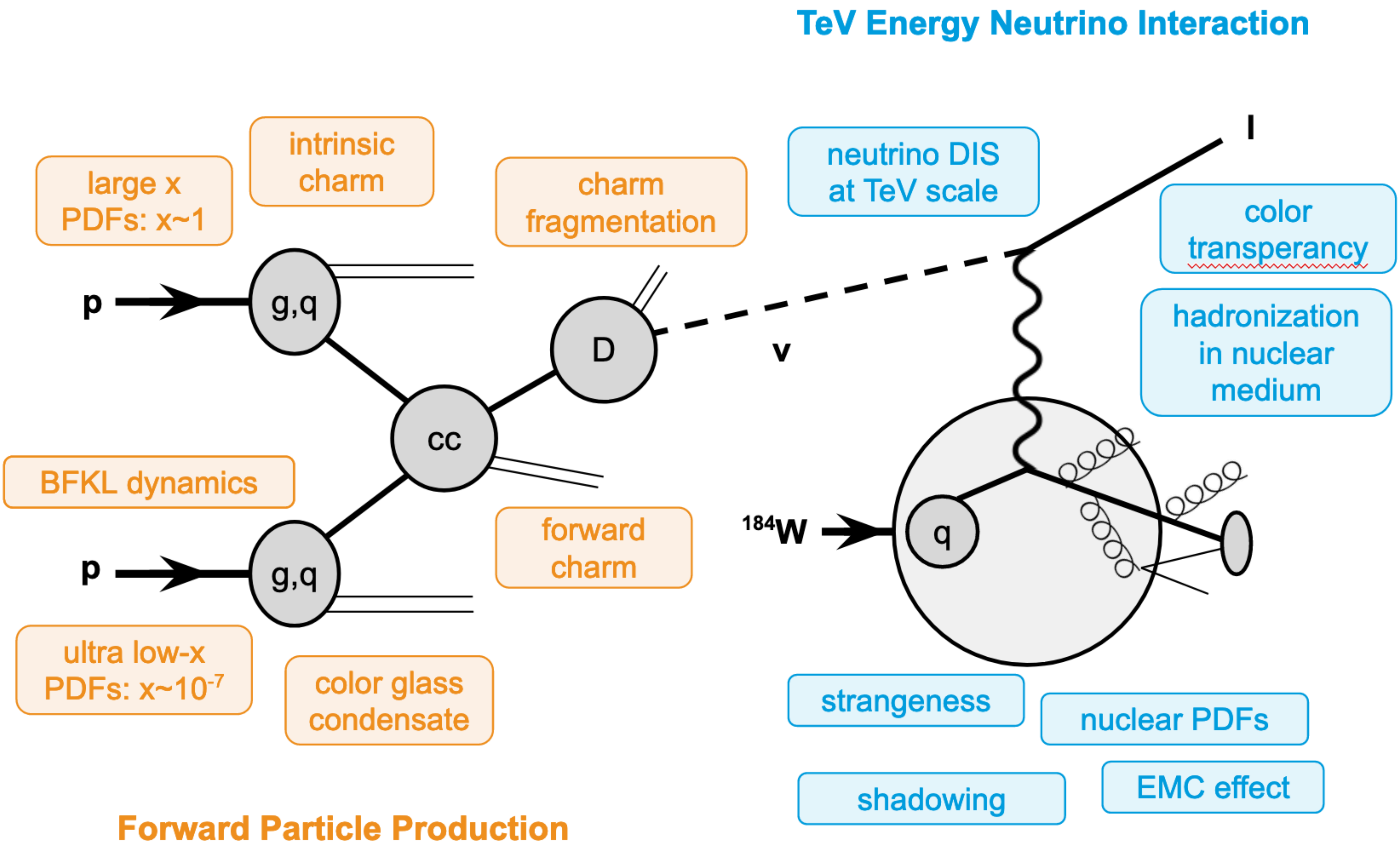
LHC neutrinos = probe of forward particle production

QCD - Overview



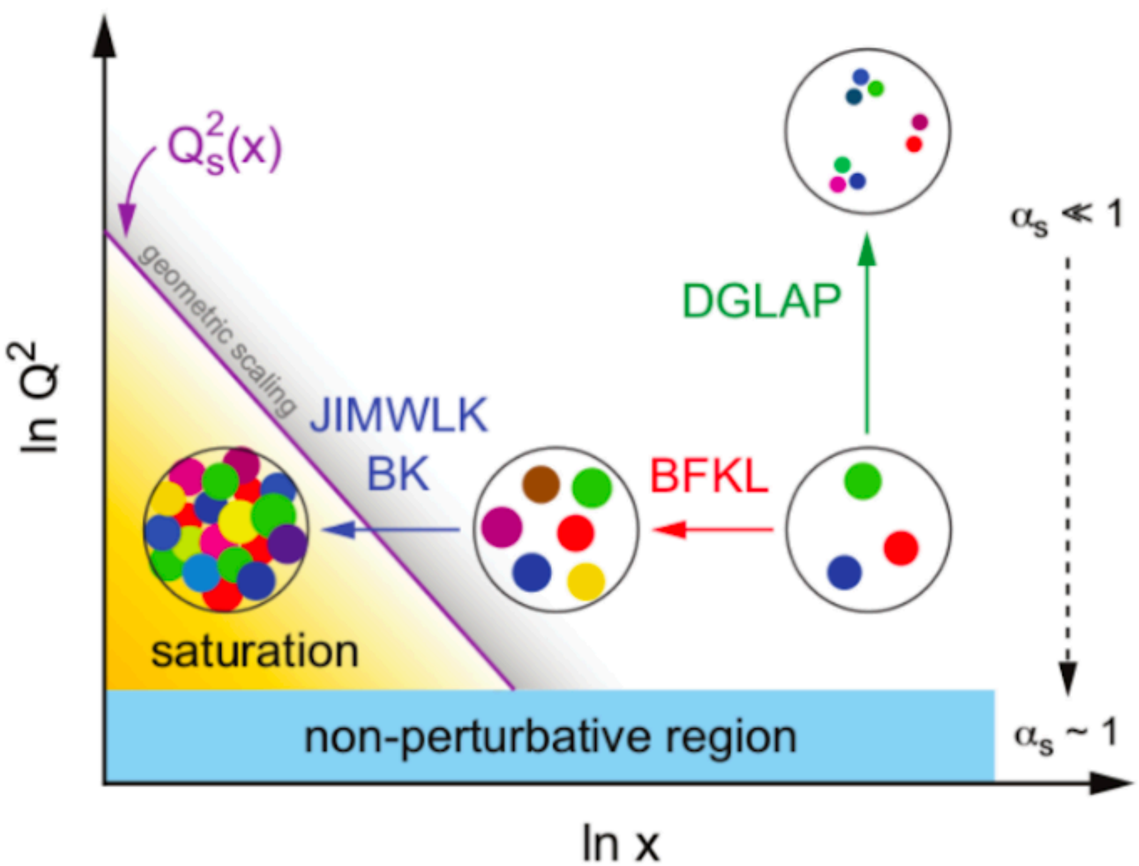
Forward Particle Production

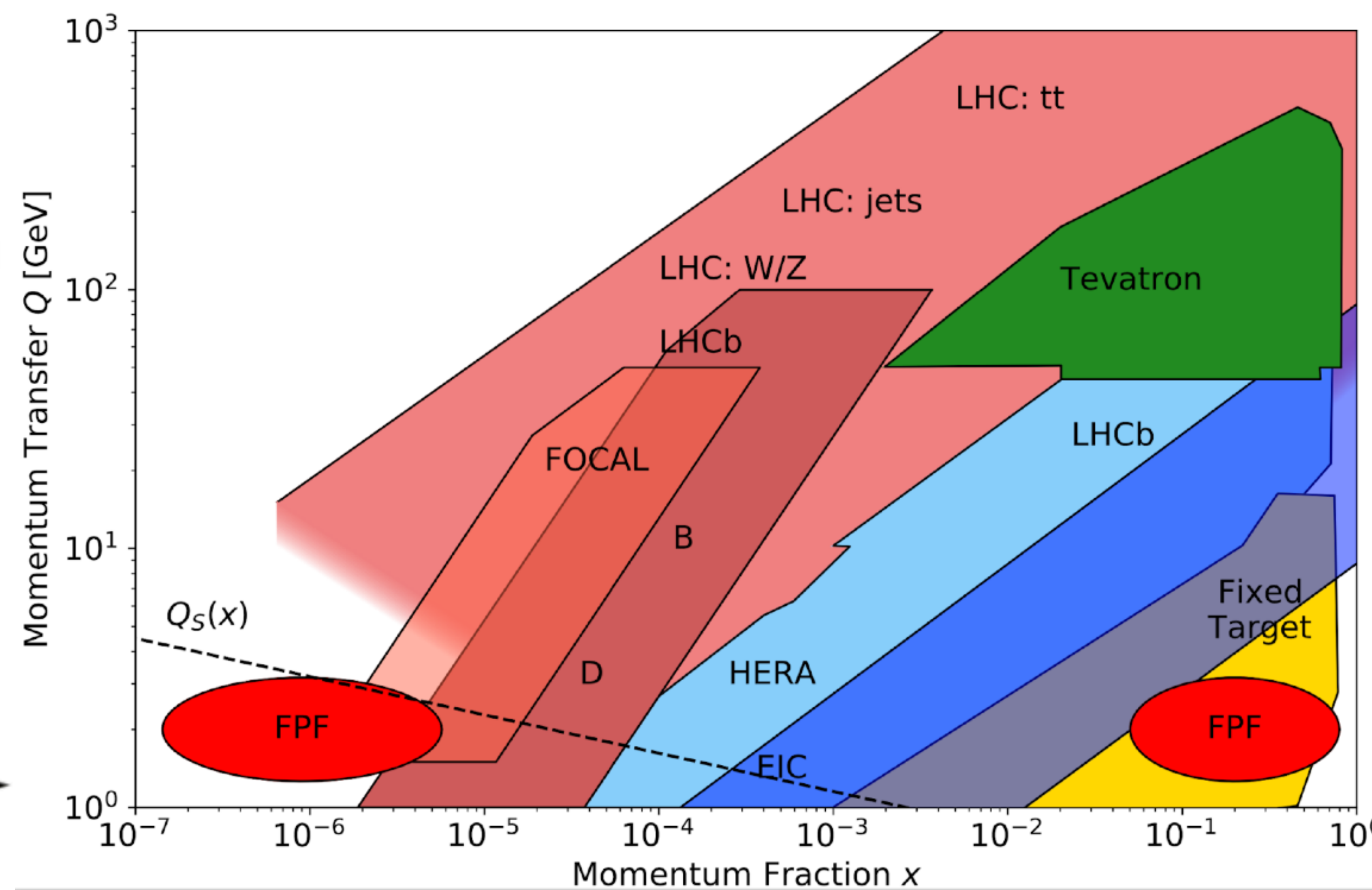
QCD - Overview



QCD with charm production

Neutrinos from charm decay could allow to test transition to small-x factorization and constrain low-x gluon PDF

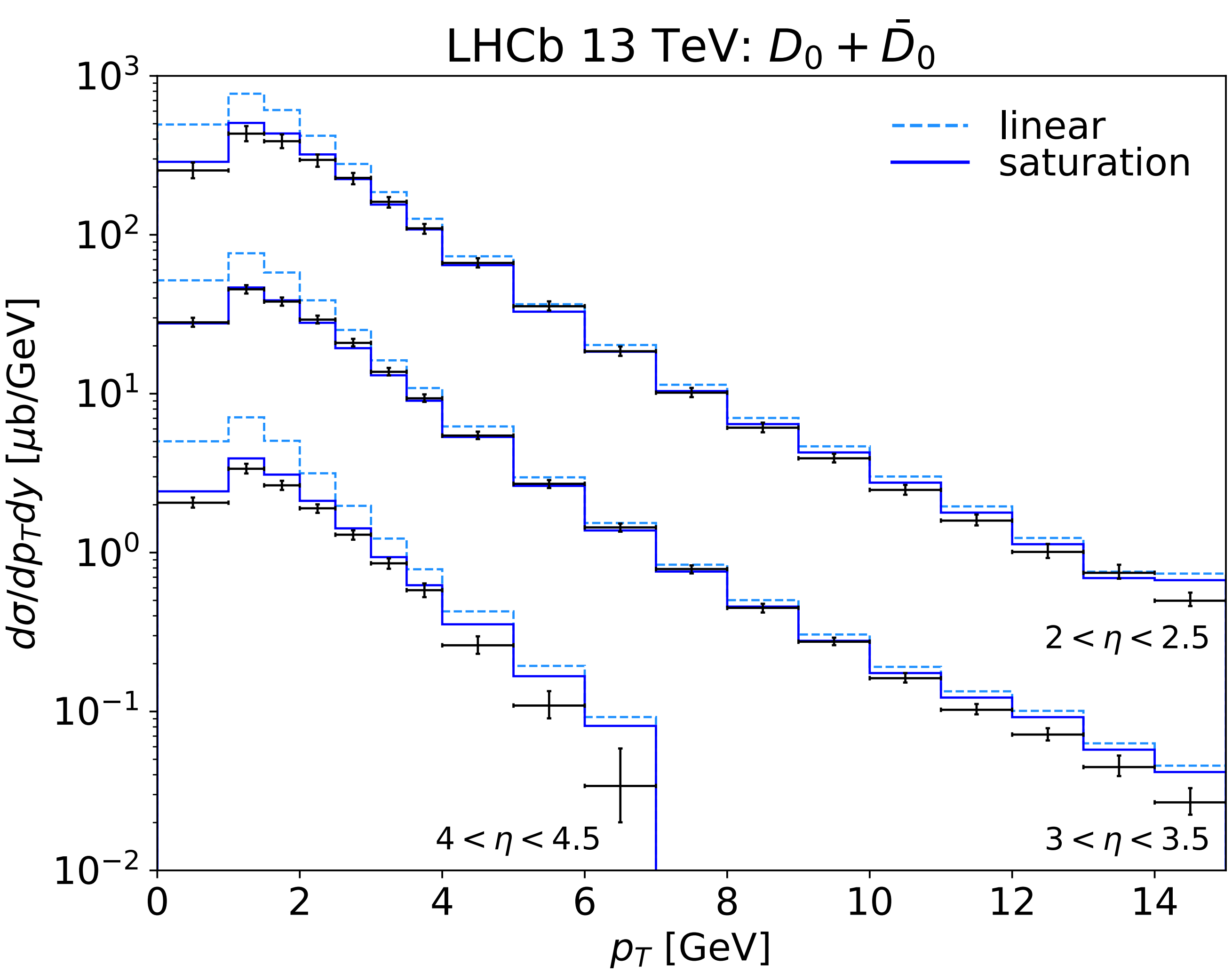


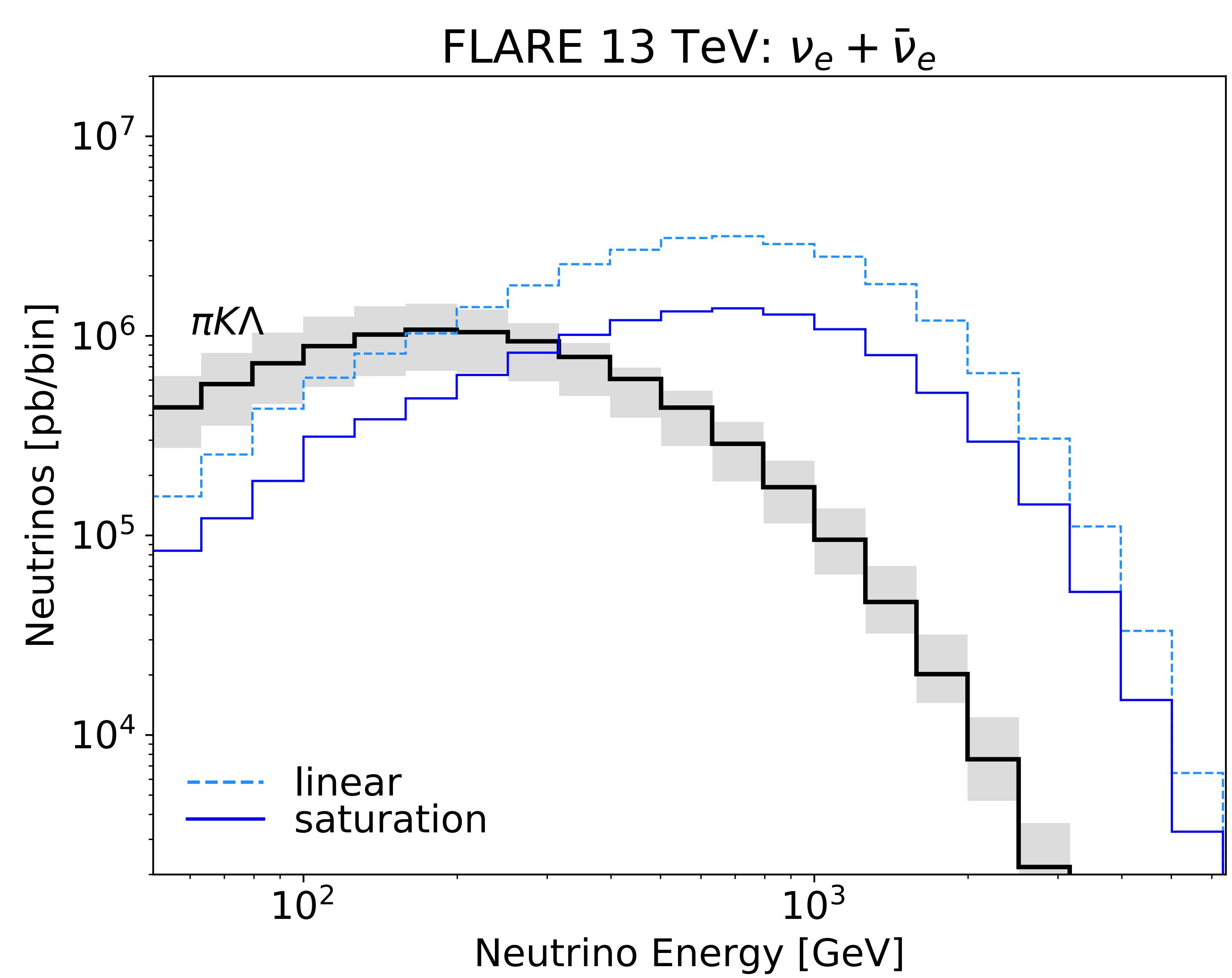


QCD with charm production

Gluon saturation

Bhattacharya, Kling, Sarcevic and Stasto: (unpublished)

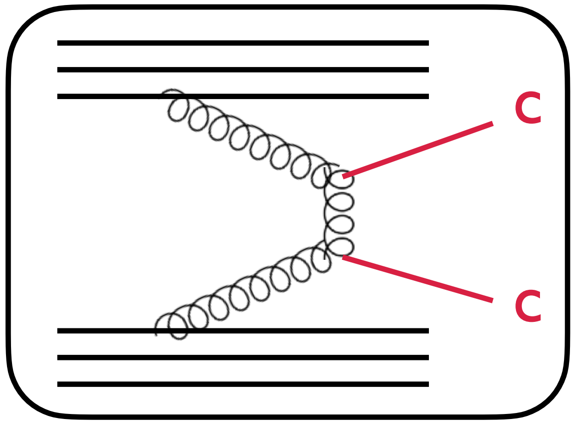


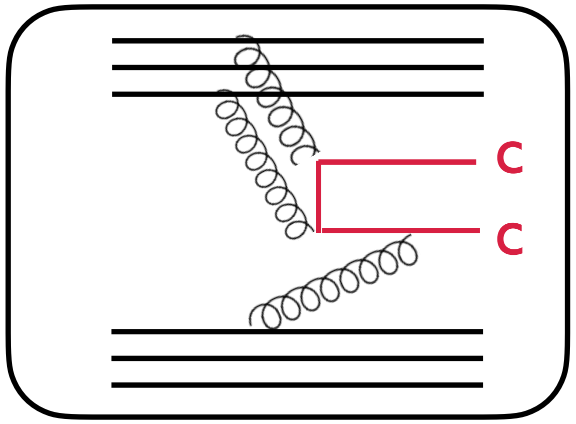


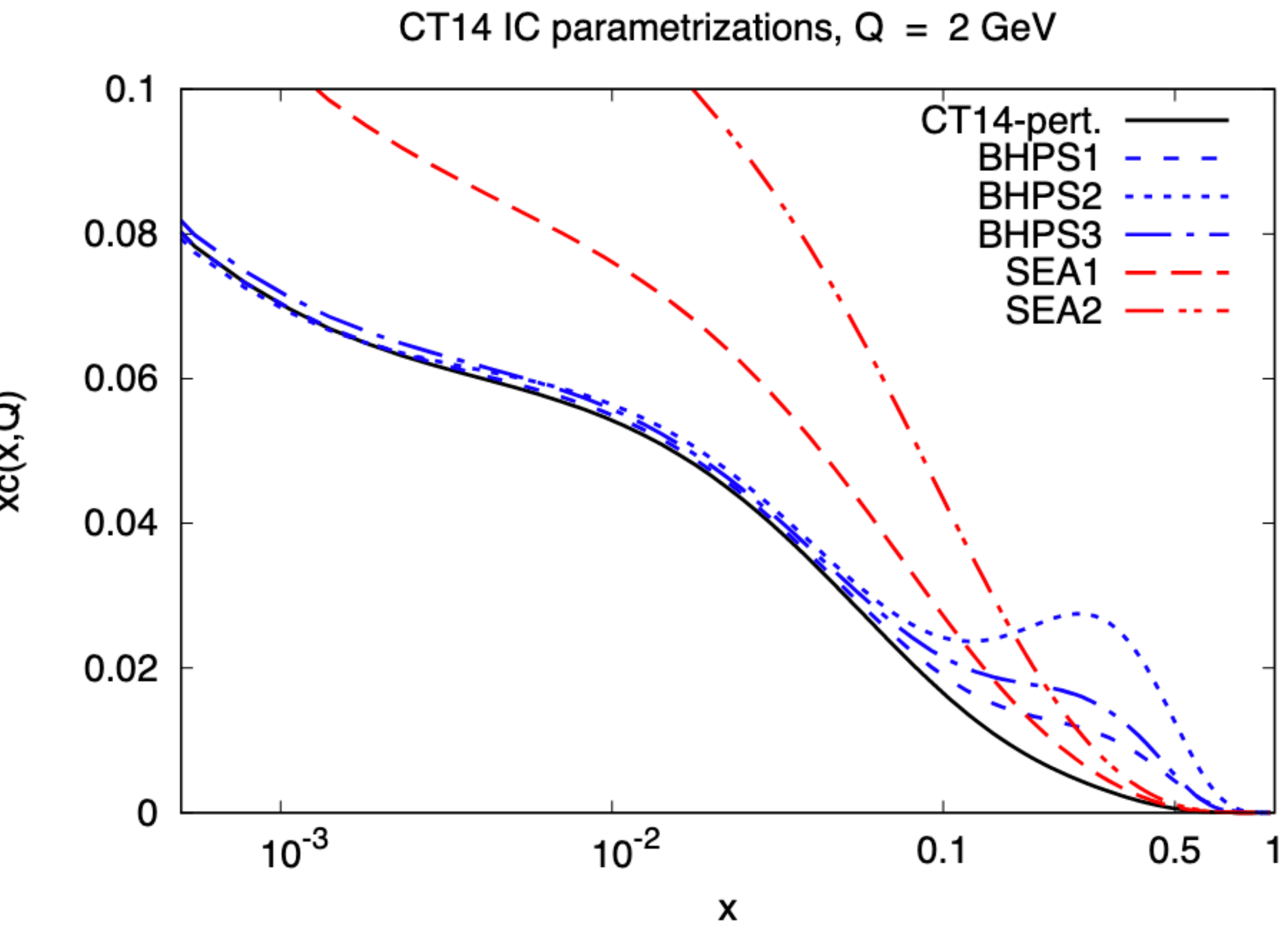
QCD with charm production

Intrinsic Charm (IC)

- charm in pQCD mainly via gluon scattering
- possible non–perturbative component to charm PDF: IC
- leads to forward, high-xF charm production
- not observed experimentally, existence is controversial



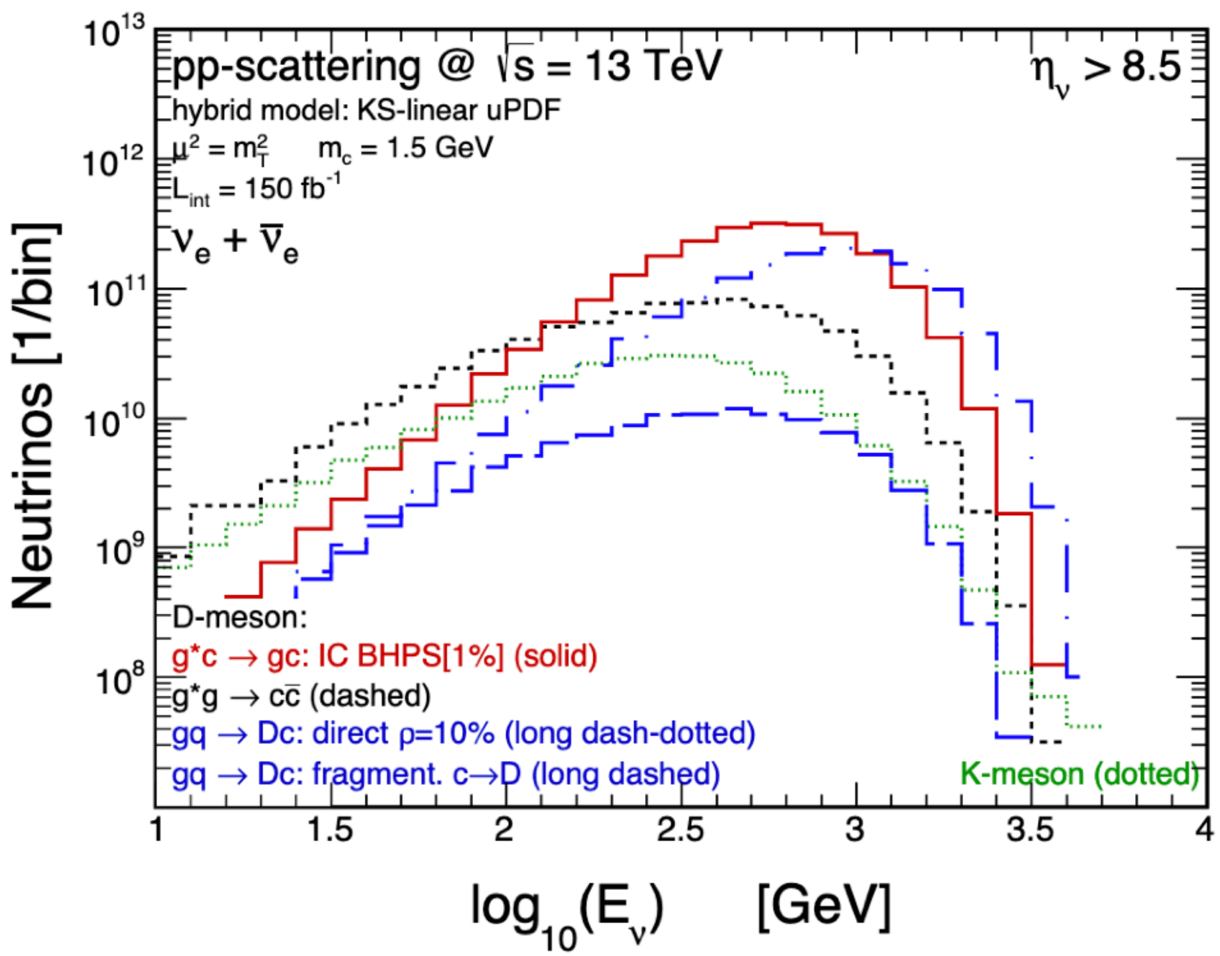


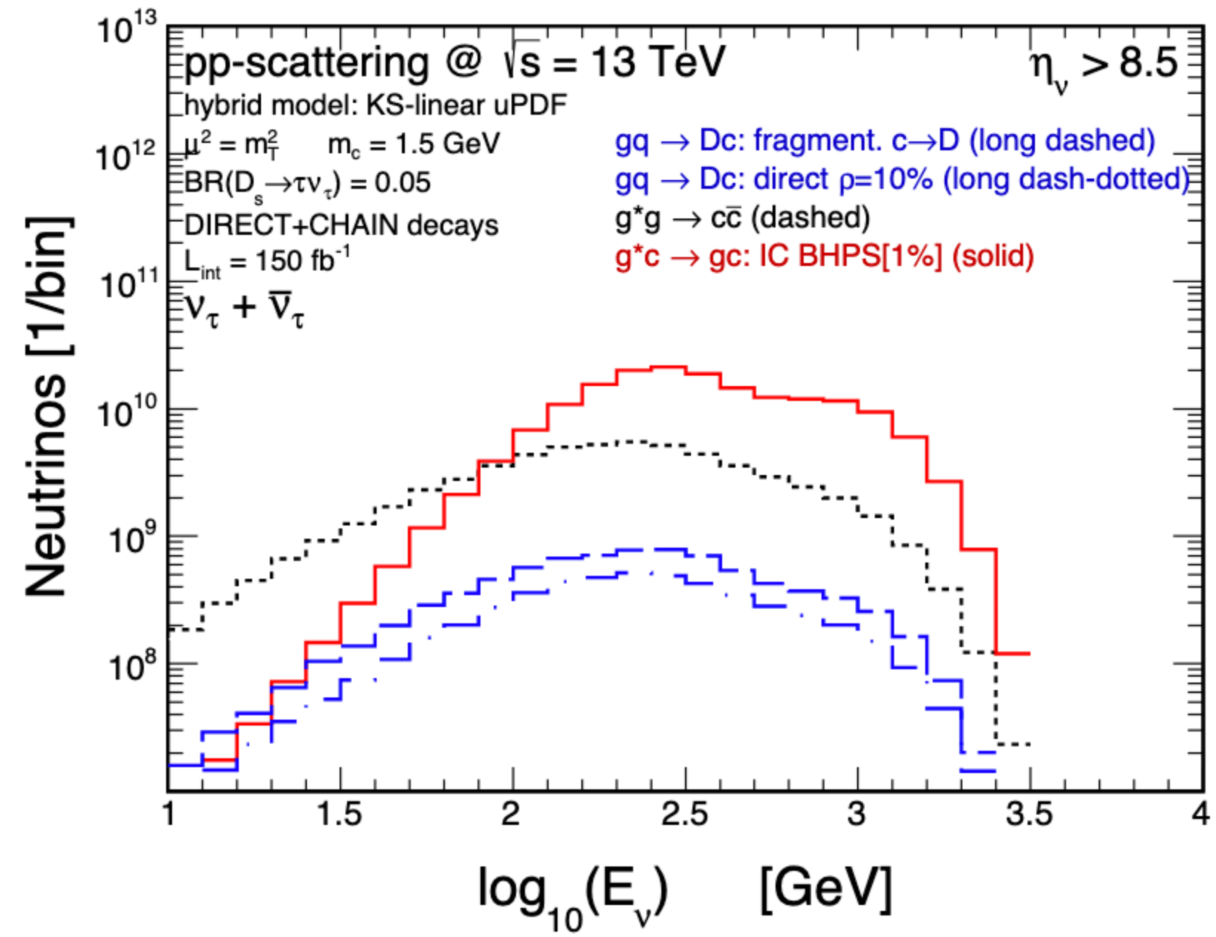


QCD with charm production

Intrinsic Charm

Goncalves, Maciula, Szczurek: 2210.08890





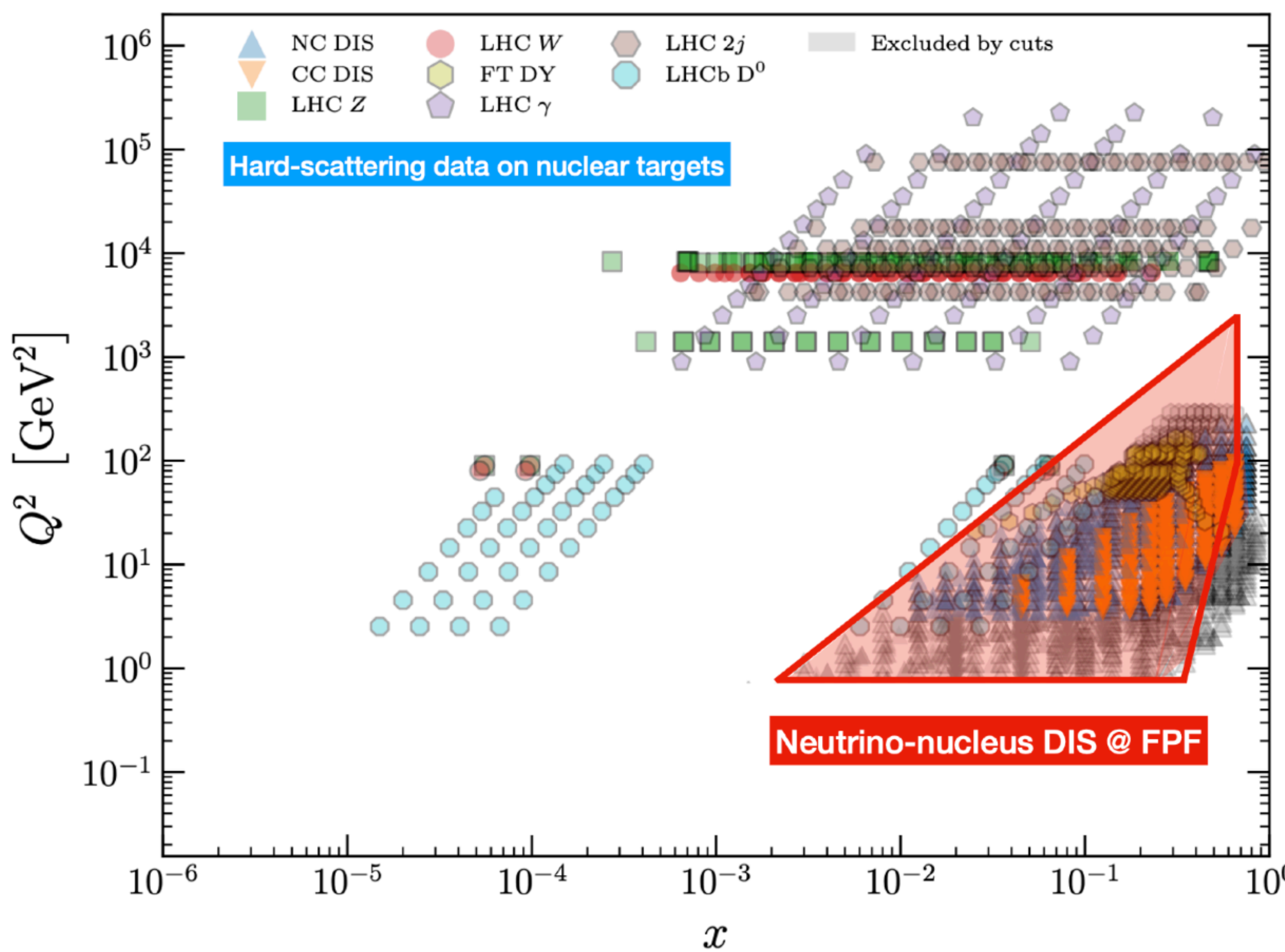
QCD - Neutrino Scattering

DIS neutrino interactions $\nu_\mu\, q \to \mu\, q'$ can be used to probe PDFs.

$$\frac{d\sigma_{\nu p}}{dx\; dy} = \frac{G_F^2 m_p E_\nu}{\pi} \frac{m_{W,Z}^4}{(Q^2 + m_{W,Z}^2)^2} \times \left[x f_q(x, Q^2) + x f_{\bar{q}}(x, Q^2)(1-y)^2 \right]$$

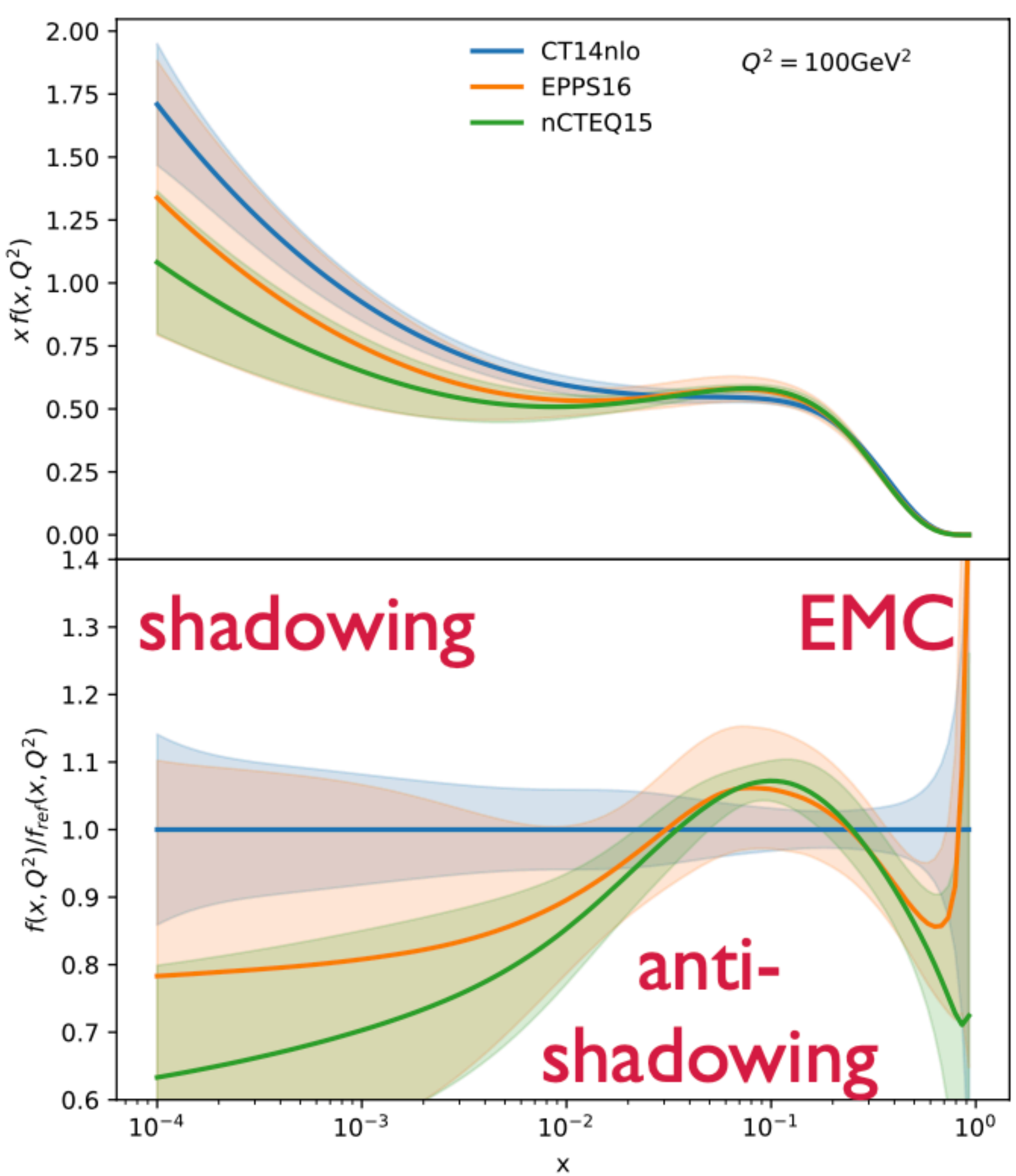
LHC Neutrino experiments can measure
- the muon charge q_μ
- the muon energy E_μ,
- the neutrino energy E_ν
- the muon angle θ_μ

This allows to reconstruct the DIS variables
- $Q = E_\mu * \theta_\mu$,
- $y = 1 - E_\mu / E_\nu$,
- $x = Q^2 / (2\, E_\nu\, M\, y)$

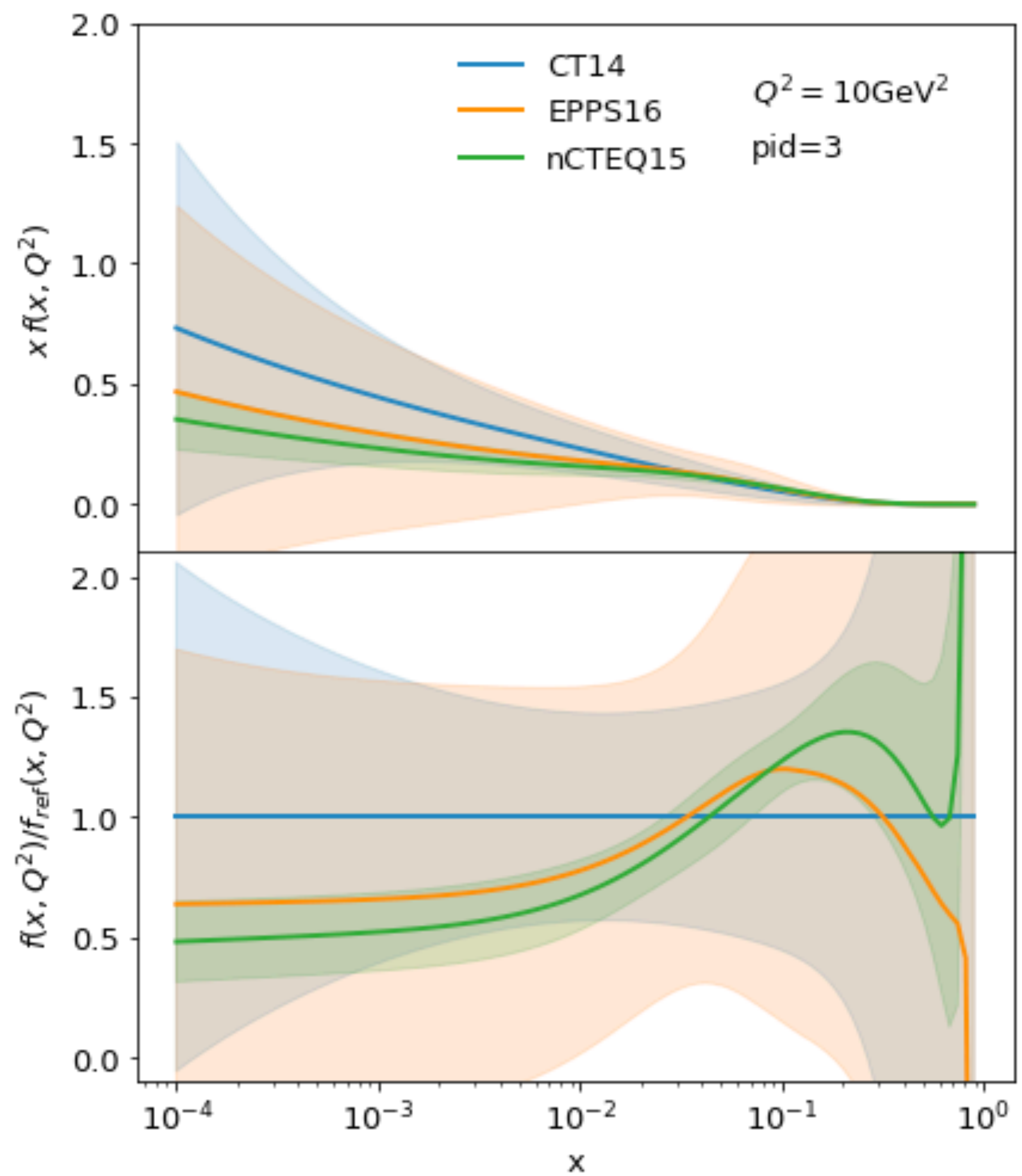


QCD - Neutrino Scattering

Nuclear effects

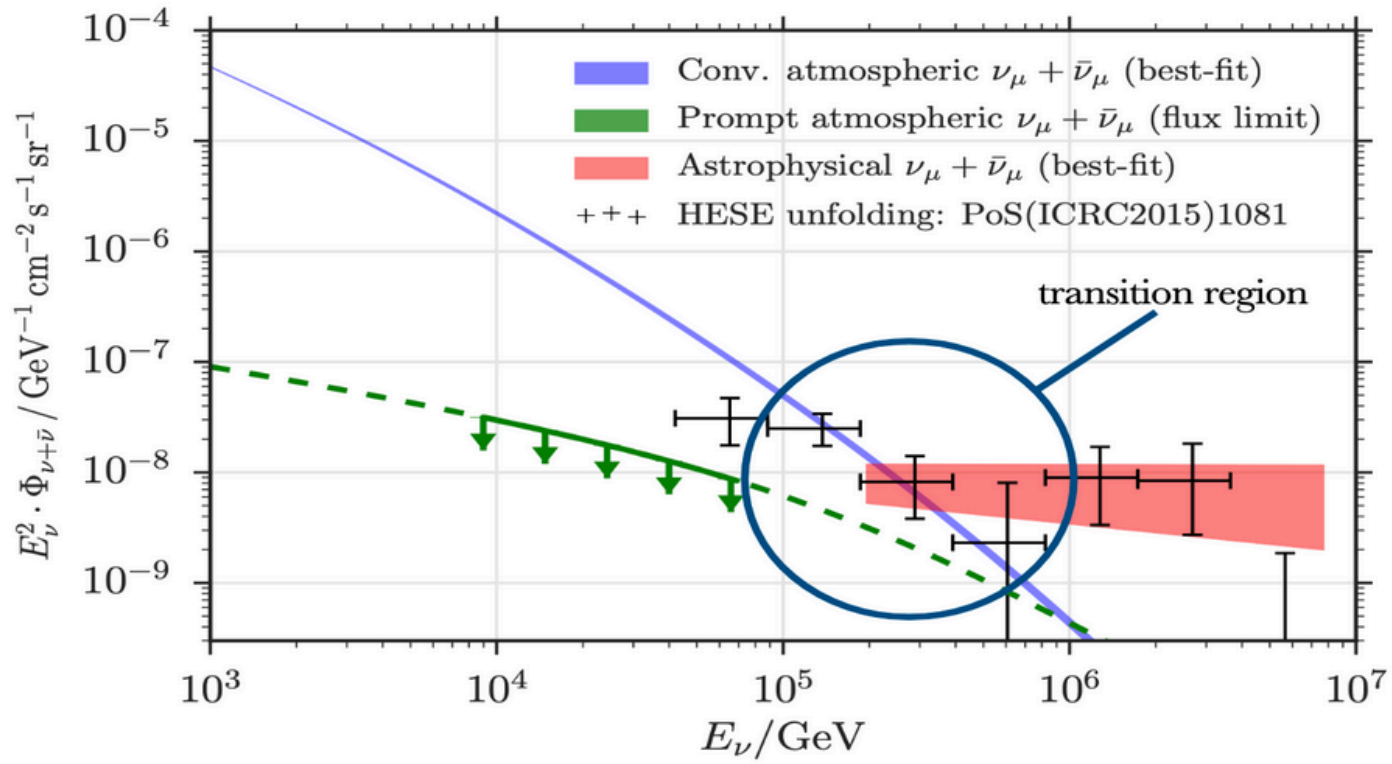


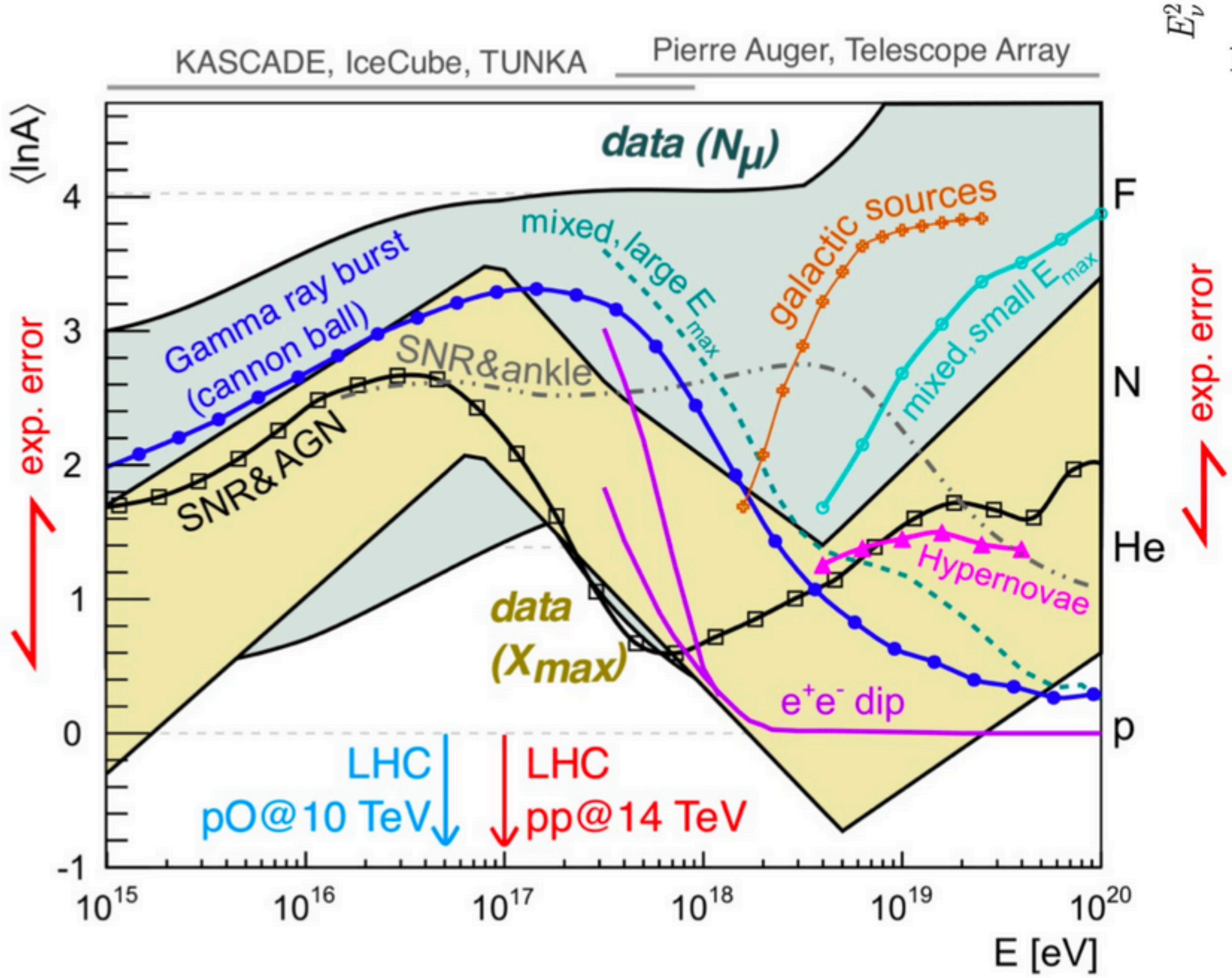
(anti-)strange quark PDF
using ν s → ℓ c



Astroparticle Physics

forward charm production at the LHC
↓
constraints on prompt atmospheric neutrino flux at IceCube



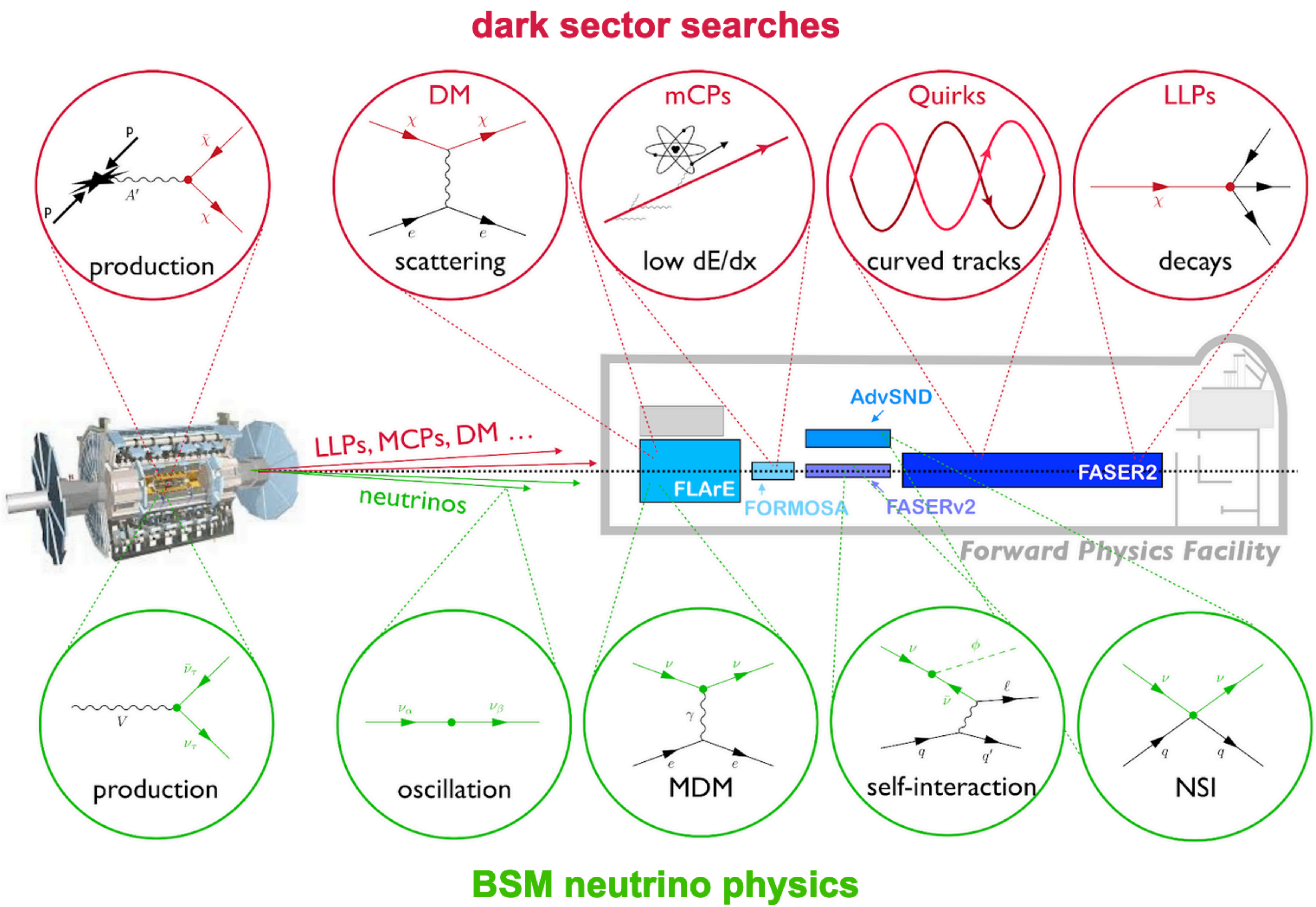


Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

cosmic ray muon puzzle:
observed excess of muons compared to hadronic interaction models

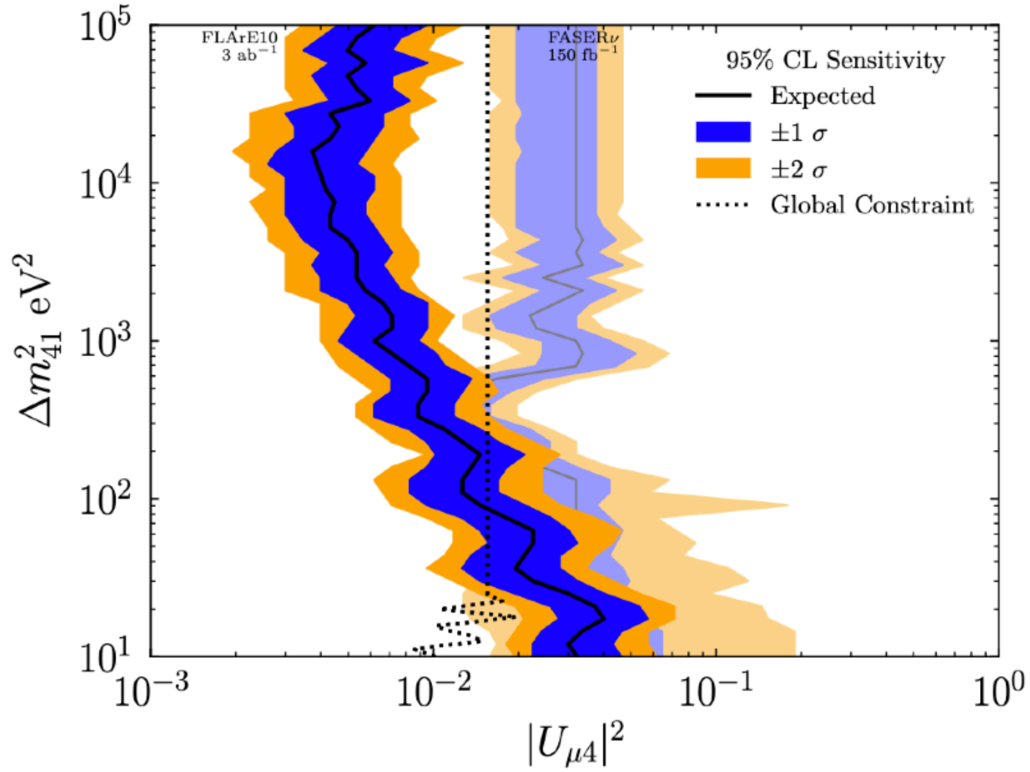
forward pion/kaons fluxes will provide crucial input

BSM Physics Searches

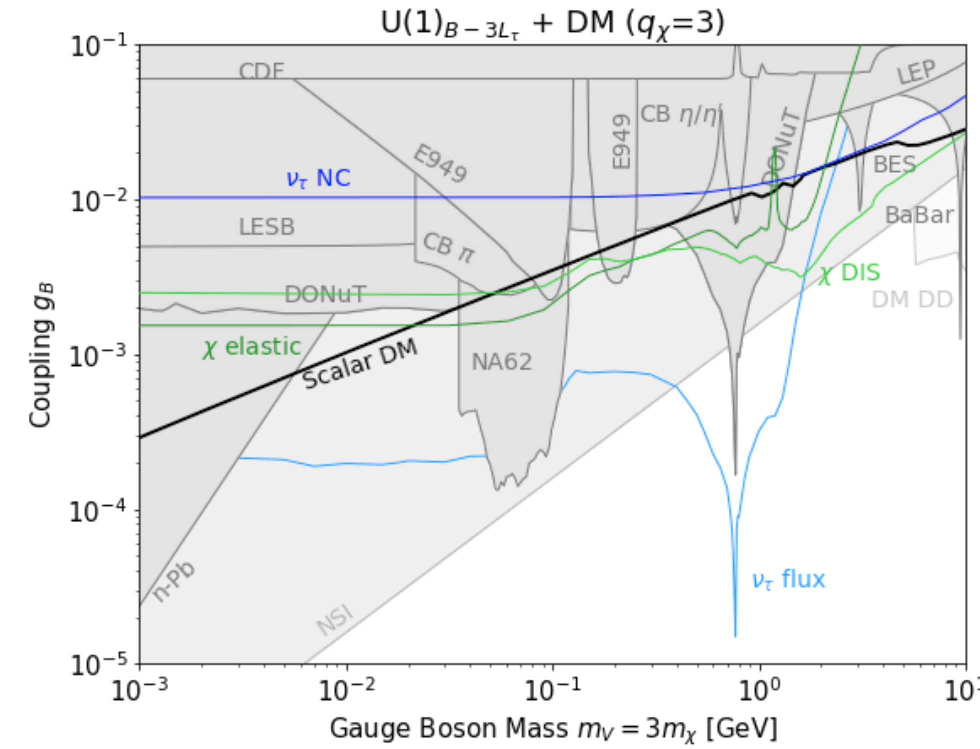


BSM Physics Searches

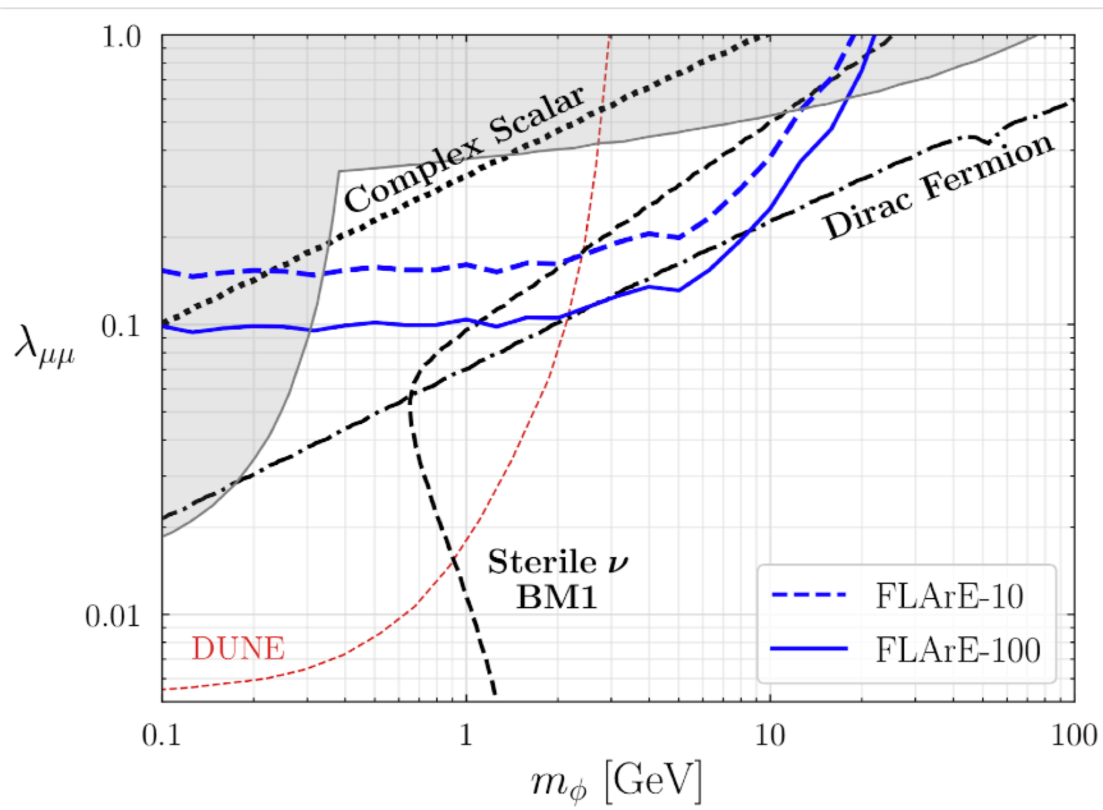
Sterile Neutrino Oscillations: 2109.10905



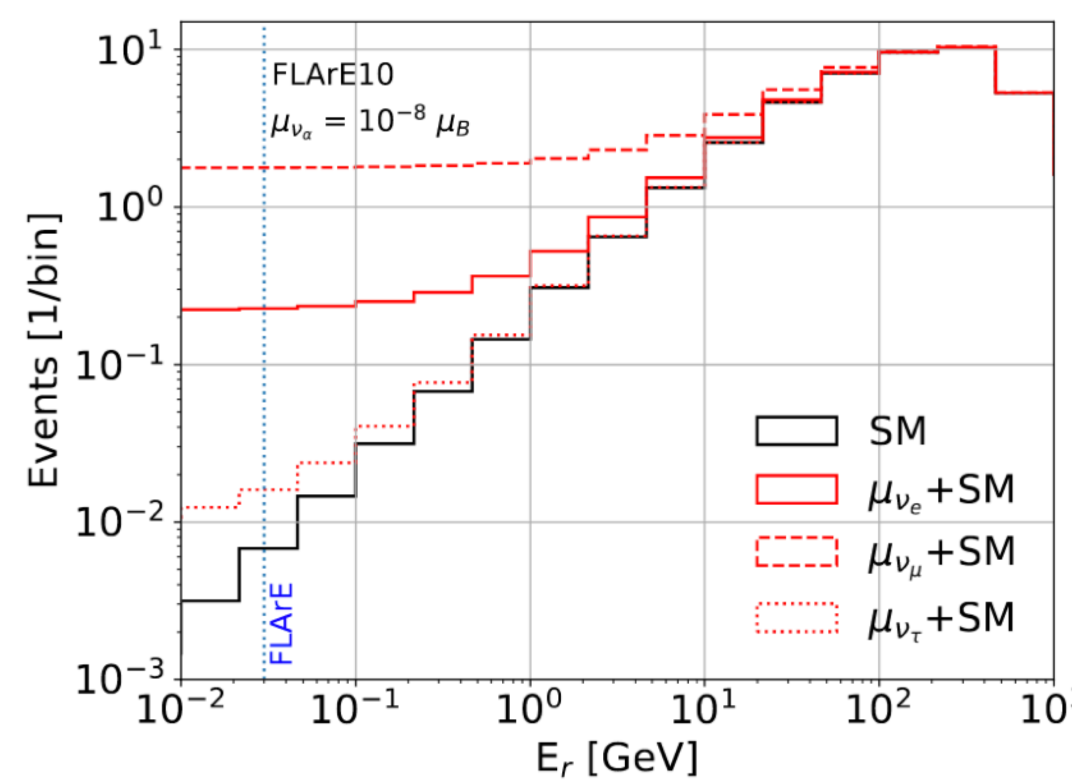
dark sectors: 2111.10343



Neutrinophilic mediators: 2111.05868

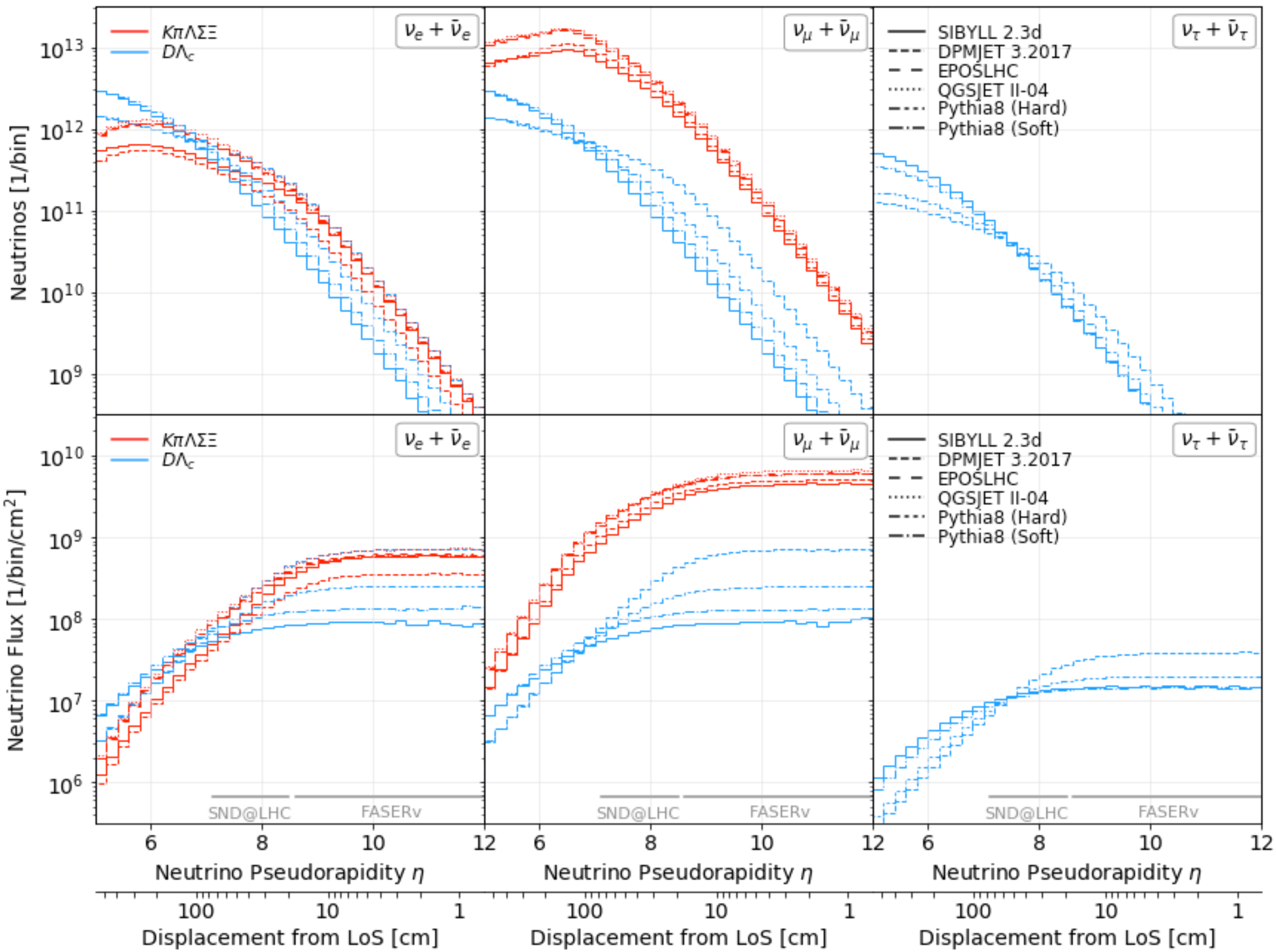


Neutrino electromagnetic properties



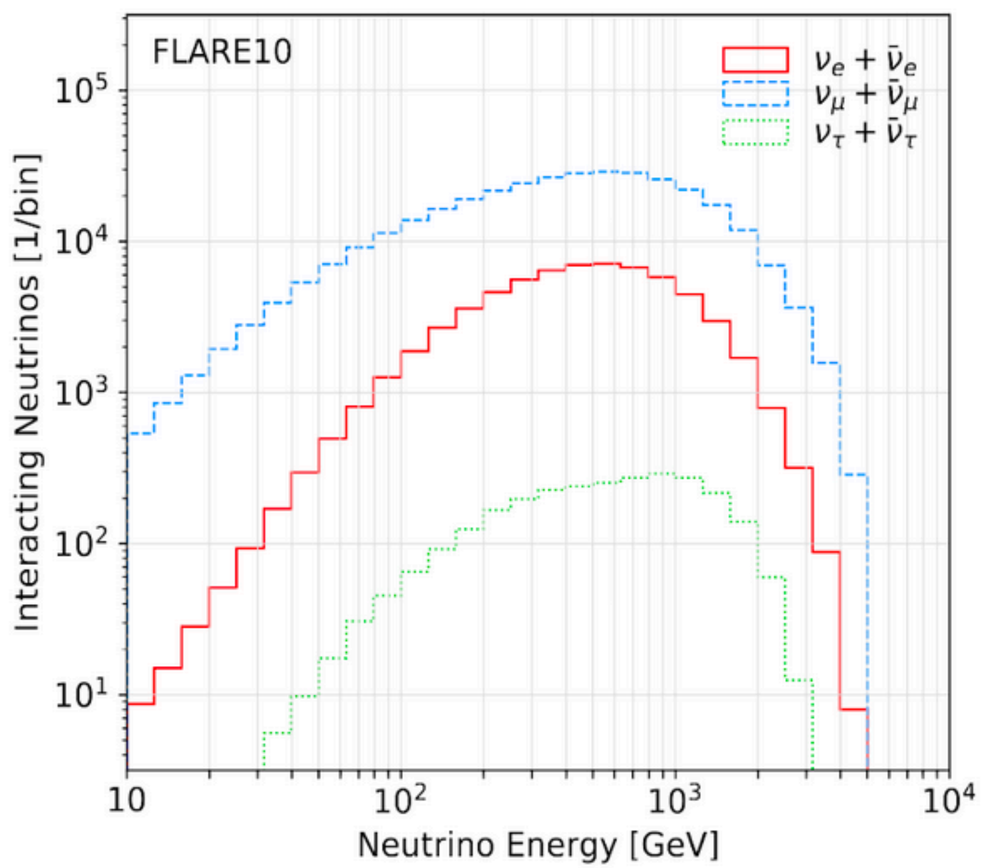
Backup

Angular / Rapidity Distribution

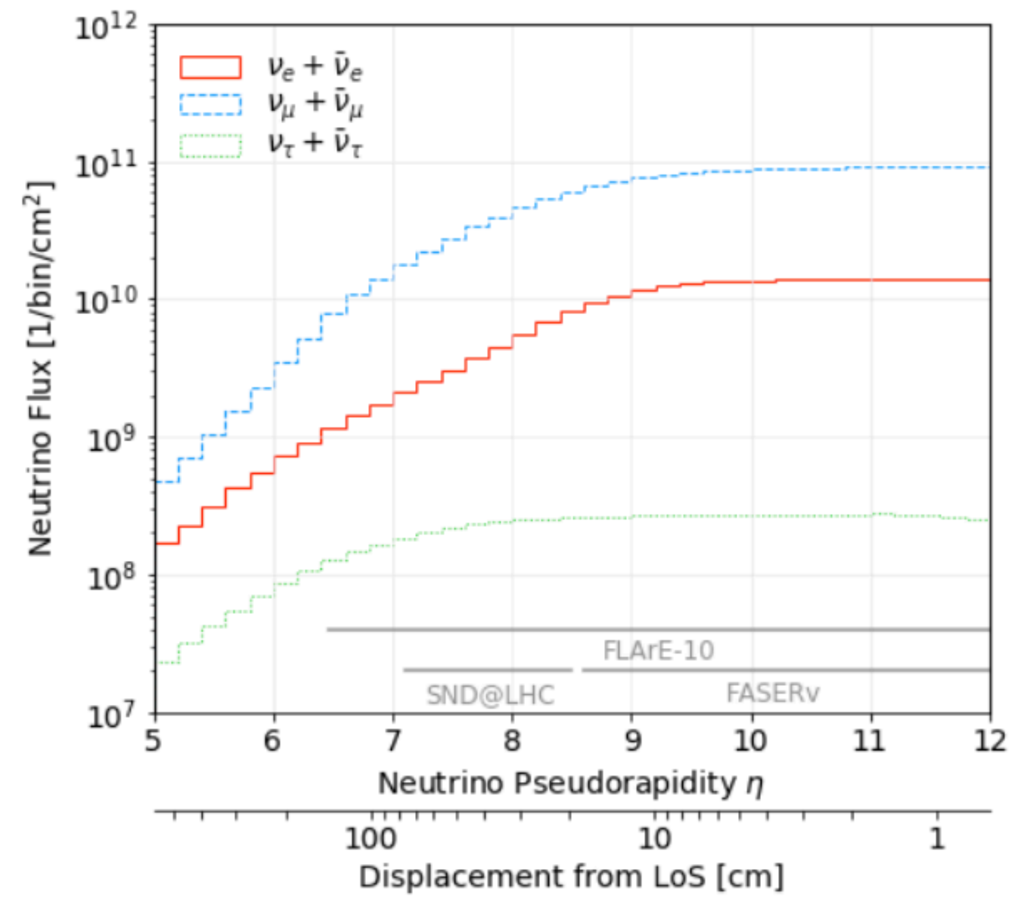


Collider Neutrinos

energy spectrum of interacting neutrinos



neutrino flux as function of displacement from LoS



100 GeV - few TeV energies

flux peaked around LoS, start to drop around 1m away from LoS

complementary coverage of FASERν and SND@LHC