Forward Experiments
The search for Neutrinos and BSM

Saeed Ansarifard

SCHOOL OF PARTICLES AND ACCELERATORS
Nov 2022

پژوهشگاه دانش‌های بنیادی
IPM
INSTITUTE FOR RESEARCH IN FUNDAMENTAL SCIENCES

Introduction to Neutrino experiments

Characteristics of Forward Experiments

2HDM - Discovery of new physics

Future experiment - Forecast for the theories

Part One

Glorious History

Neutrino Physics in less than a century

From the core of our home, earth to the depth of our universe!

More than 10 Nobel prize since 1945

If, therefore, the neutrino has no interaction with other particles besides the processes of creation and annihilation mentioned—and it is not necessary to assume interaction in order to explain the function of the neutrino in nuclear transformations—one can conclude that there is no practically possible way of observing the neutrino.

H. BETHE.
R. PEIERLS.

Physical Laboratory,
University,
Manchester.
Feb. 20.

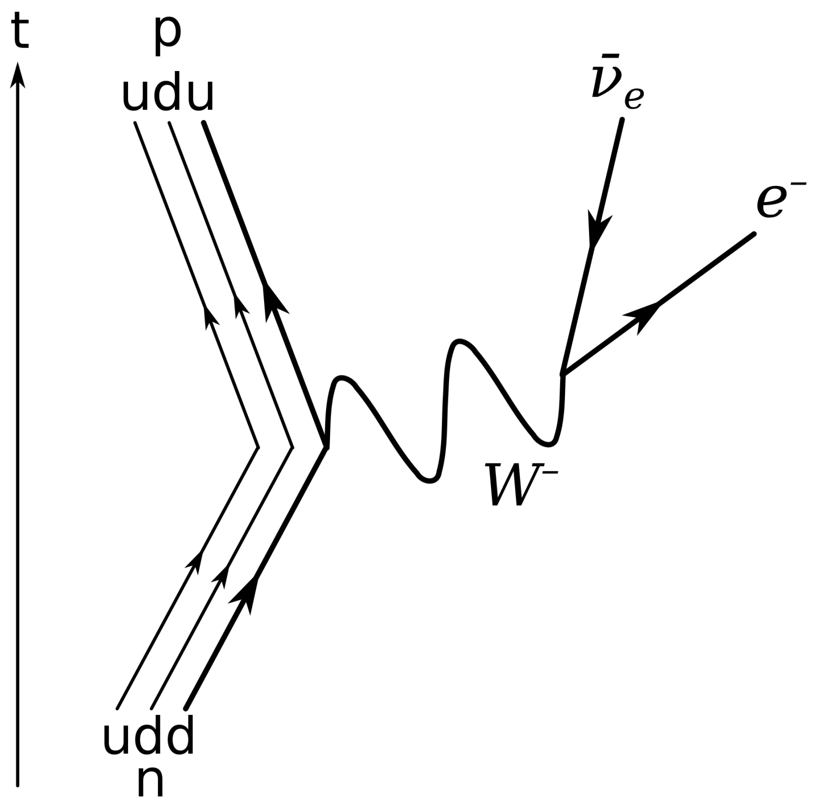
Nature volume133, page 532 (1934)

Earth as a main and available source of neutrino

Electron neutrino created in a nuclear reactor by beta decay

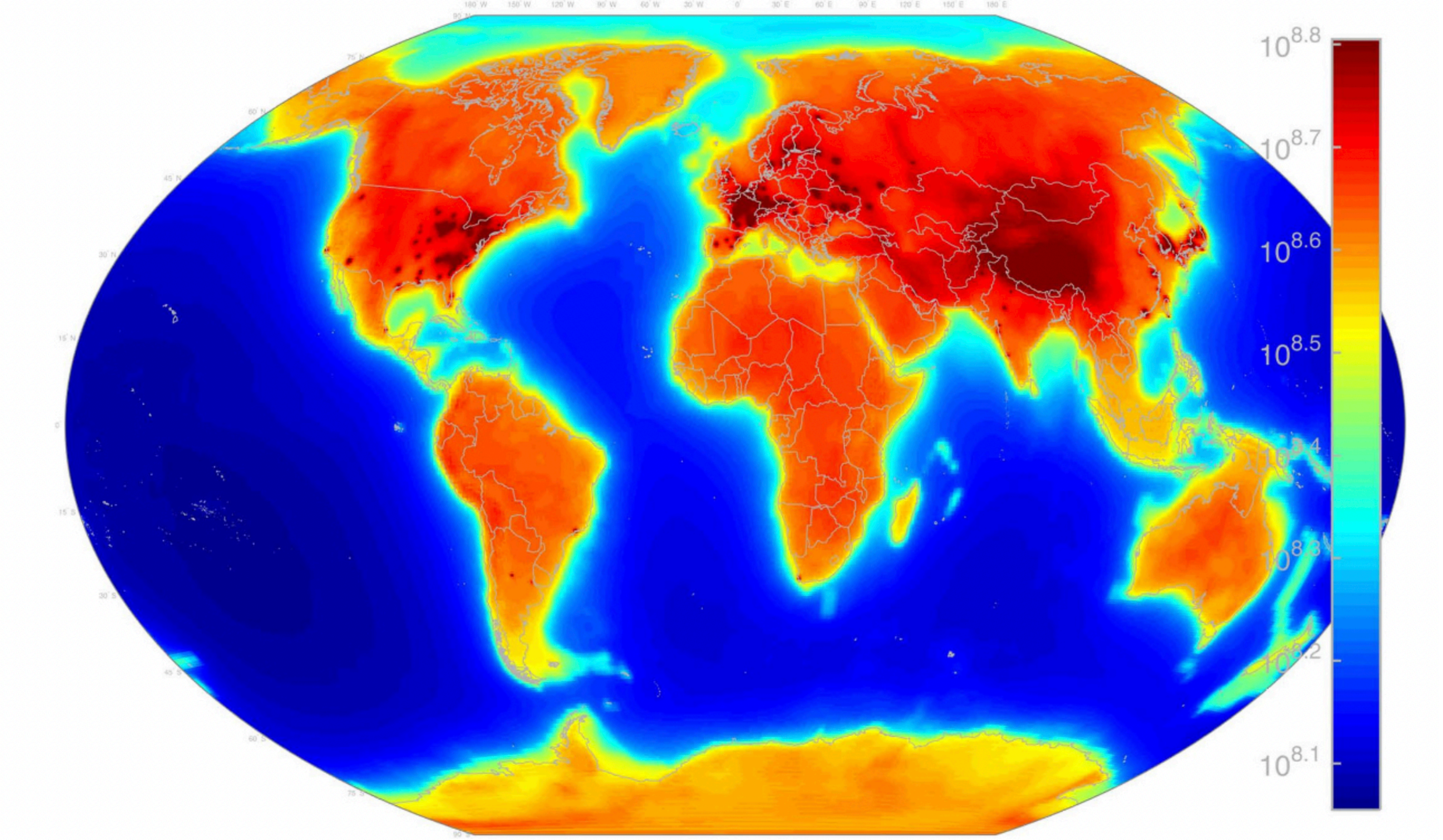
The signature was positron annihilation and neutron capture due to inverse beta decay

Matter composition and distribution deep whit in earth



$\sim 10^{20}$ per second

www.nature.com/scientificreports/
DOi: 10.1038/srep13945



~ 5 Mev

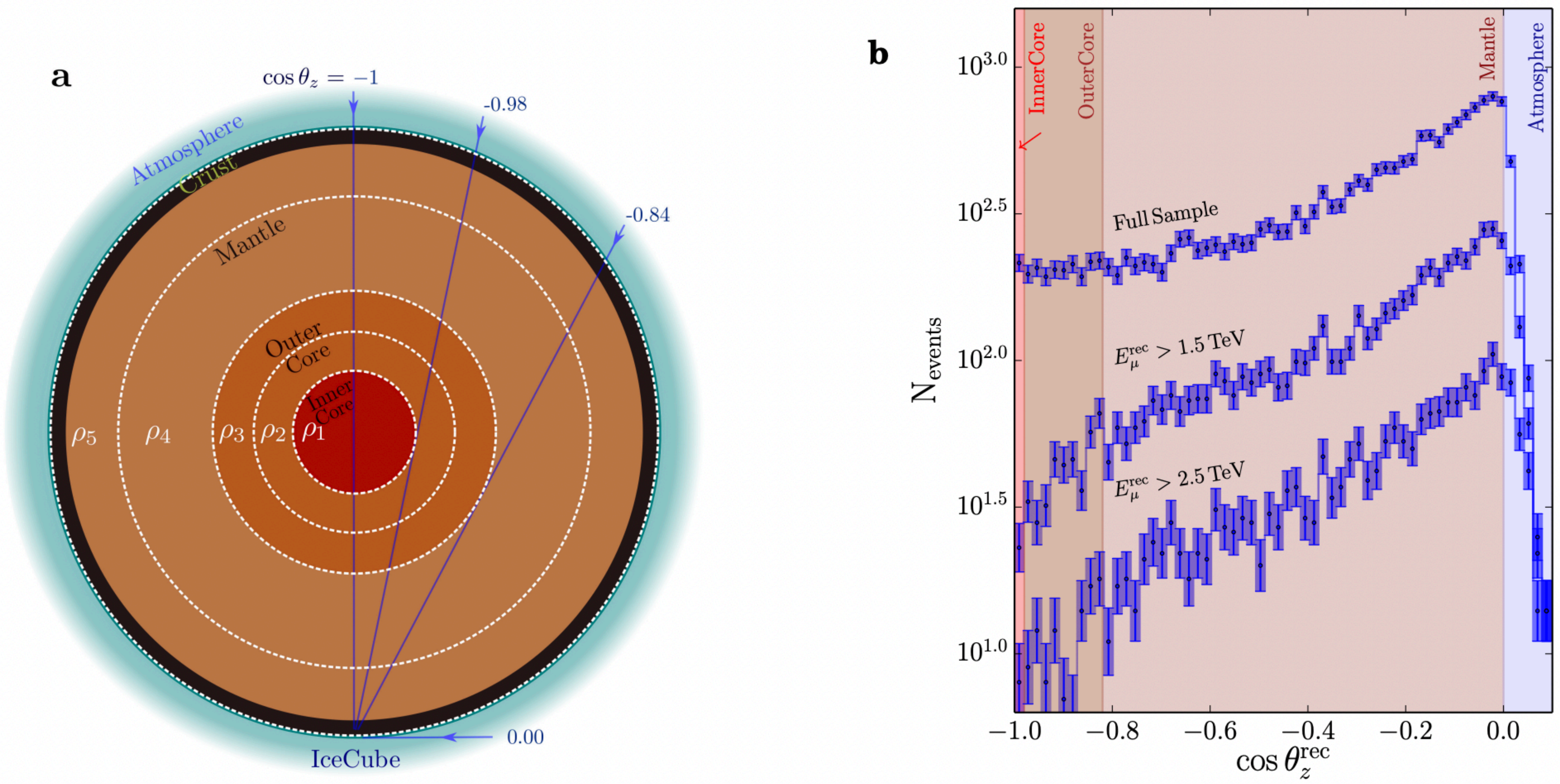
$\sim 10^{25}$ per second

${}^{238}_{92}\mathrm{U}$	$\longrightarrow$	${}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e$	$+\,51.698$ MeV
${}^{235}_{92}\mathrm{U}$	$\longrightarrow$	${}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e$	$+\,46.402$ MeV
${}^{232}_{90}\mathrm{Th}$	$\longrightarrow$	${}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e$	$+\,42.652$ MeV
${}^{40}_{19}\mathrm{K}$	$\xrightarrow{89.3\,\%}$	${}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e$	$+\,1.311$ MeV
${}^{40}_{19}\mathrm{K} + e^-$	$\xrightarrow{10.7\,\%}$	${}^{40}_{18}\mathrm{Ar} + \nu_e$	$+\,1.505$ MeV

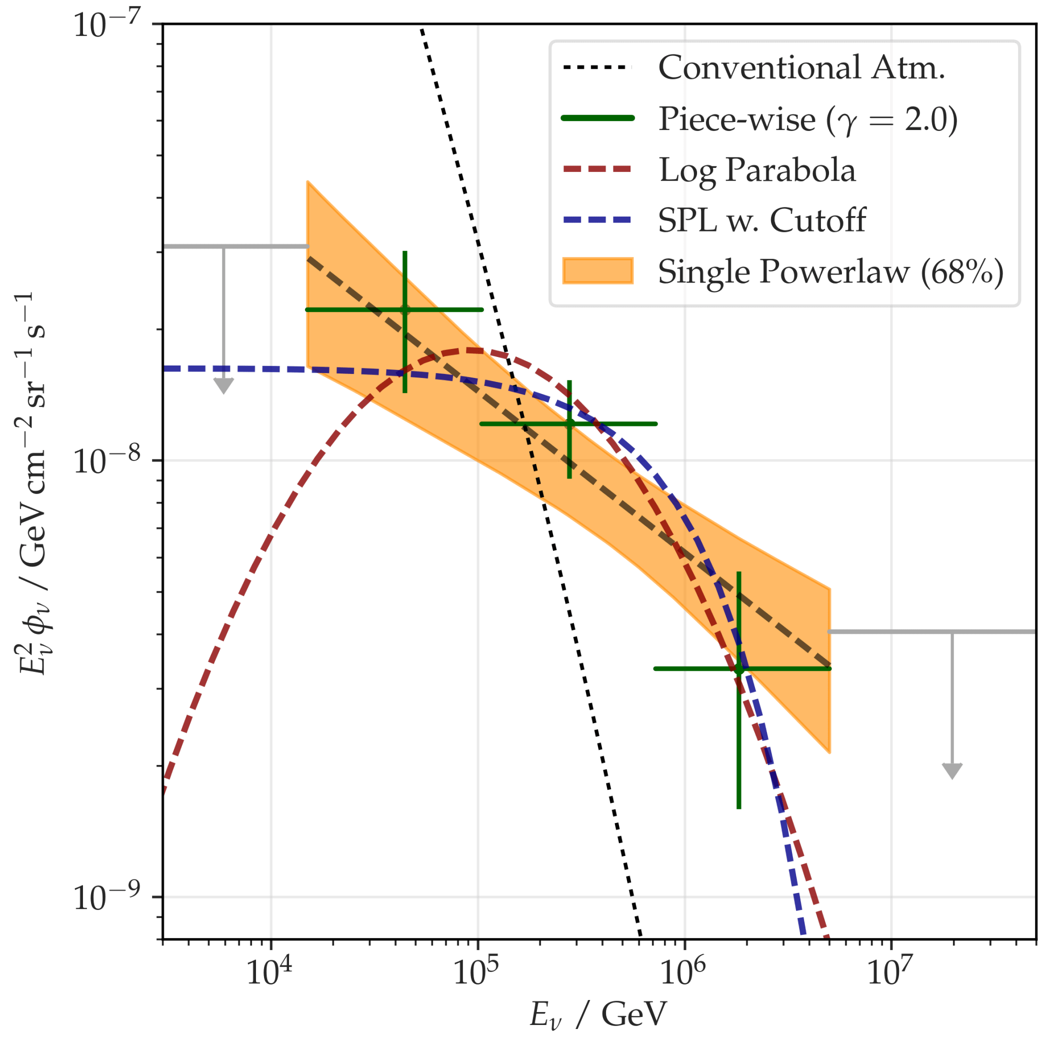
Neutrino astronomy

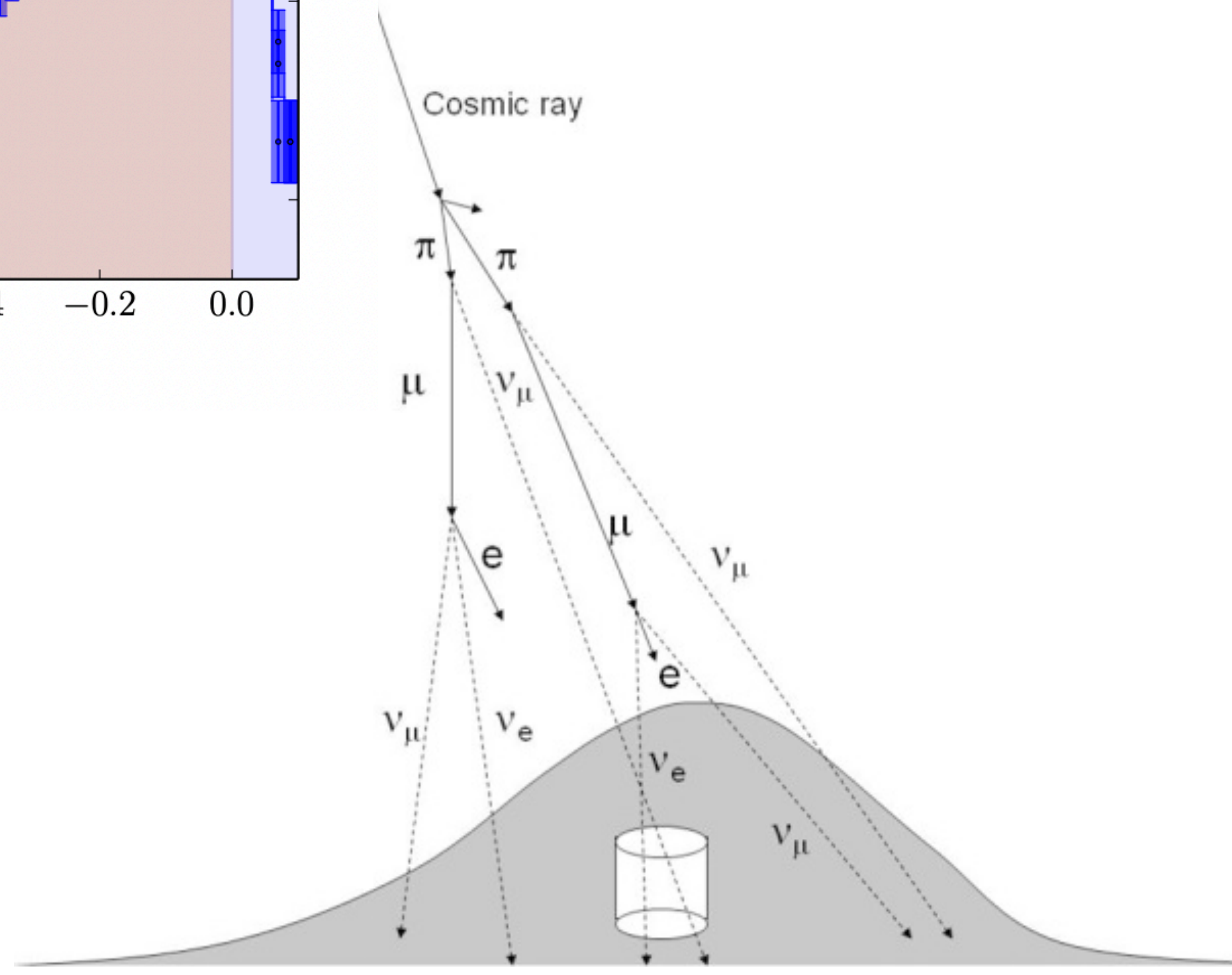
Cosmic ray interactions in atmosphere

Atmospheric neutrinos are typically produced around 15 kilometers above the ground.



Credit : 1803.05901



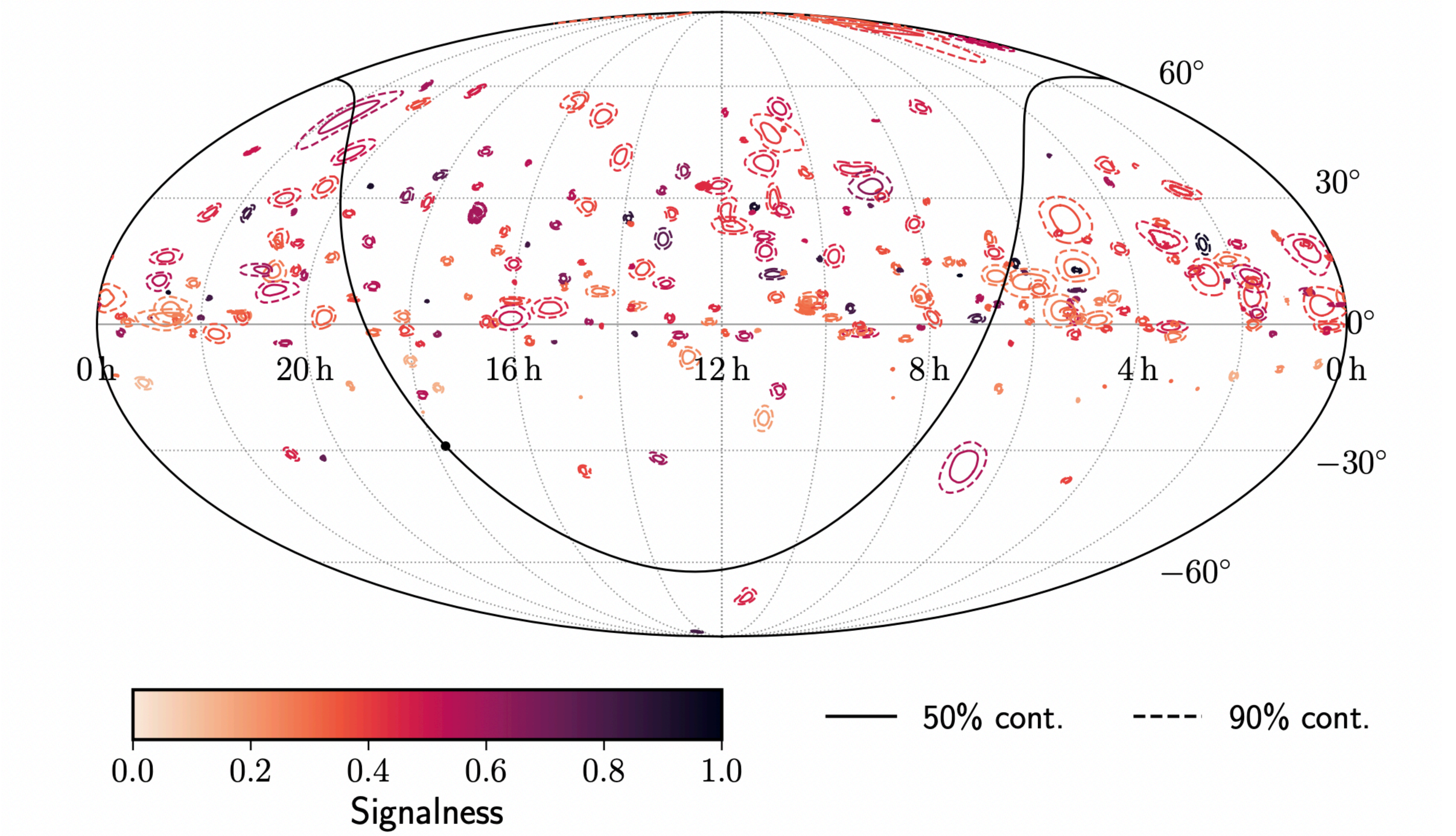


Credit: Takaaki Kajita in the Proceedings of the Japan Academy, Series B, Physical and Biological Sciences (10.2183/pjab.86.303)

Improved Characterization of the Astrophysical Muon-Neutrino Flux with 9.5 Years of IceCube Data, The IceCube Collaboration: R. Abbasi et al. The Astrophysical Journal 928.1 (2022): 50, arxiv.org/abs/2111.10299

SuperNova Early Warning System

Image obtained with the ESO Schmidt Telescope of the Tarantula Nebula in the Large Magellanic Cloud.



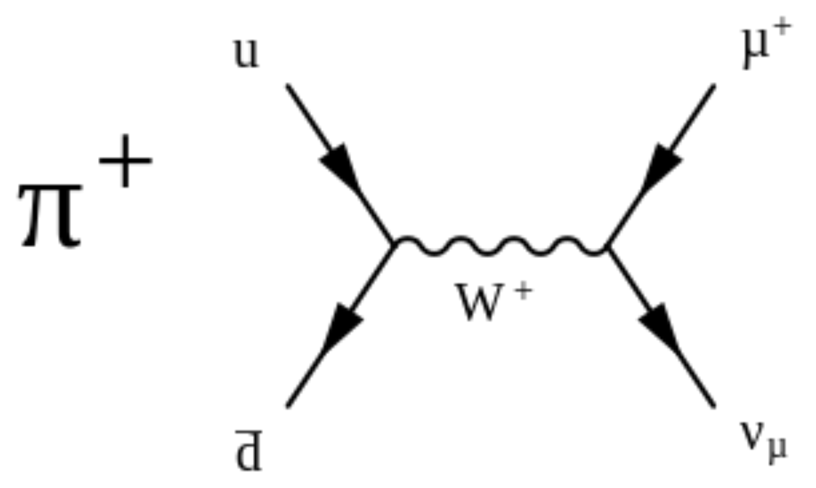
https://arxiv.org/pdf/2210.04930.pdf

Discovery of the doublet structure of the leptons

AGS produced proton in energy scale of GeV for the first time

5000 tons steel wall made of old battleship plates for beam dump

Impact of Neutrino on aluminum plates produced muon spark



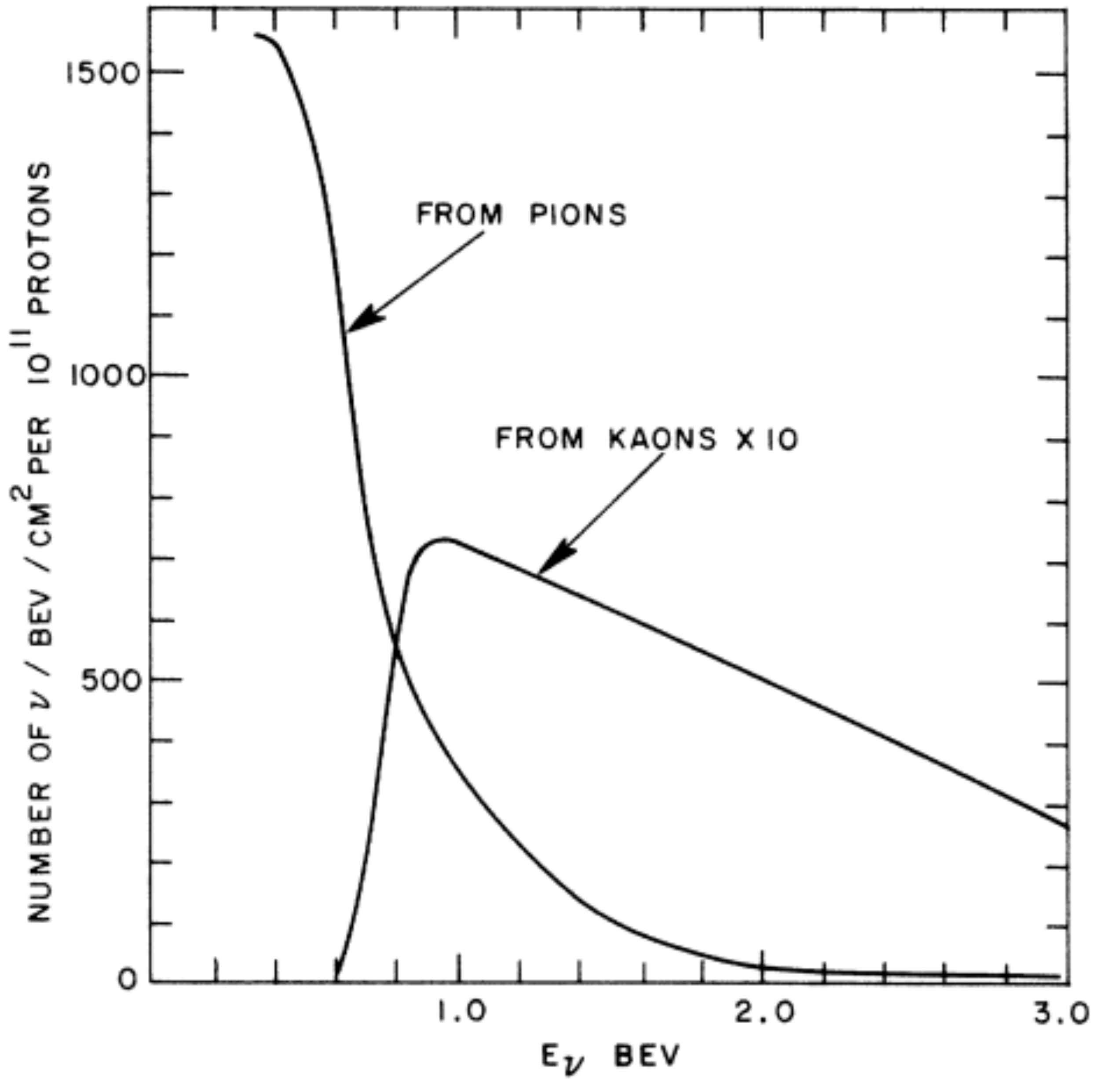
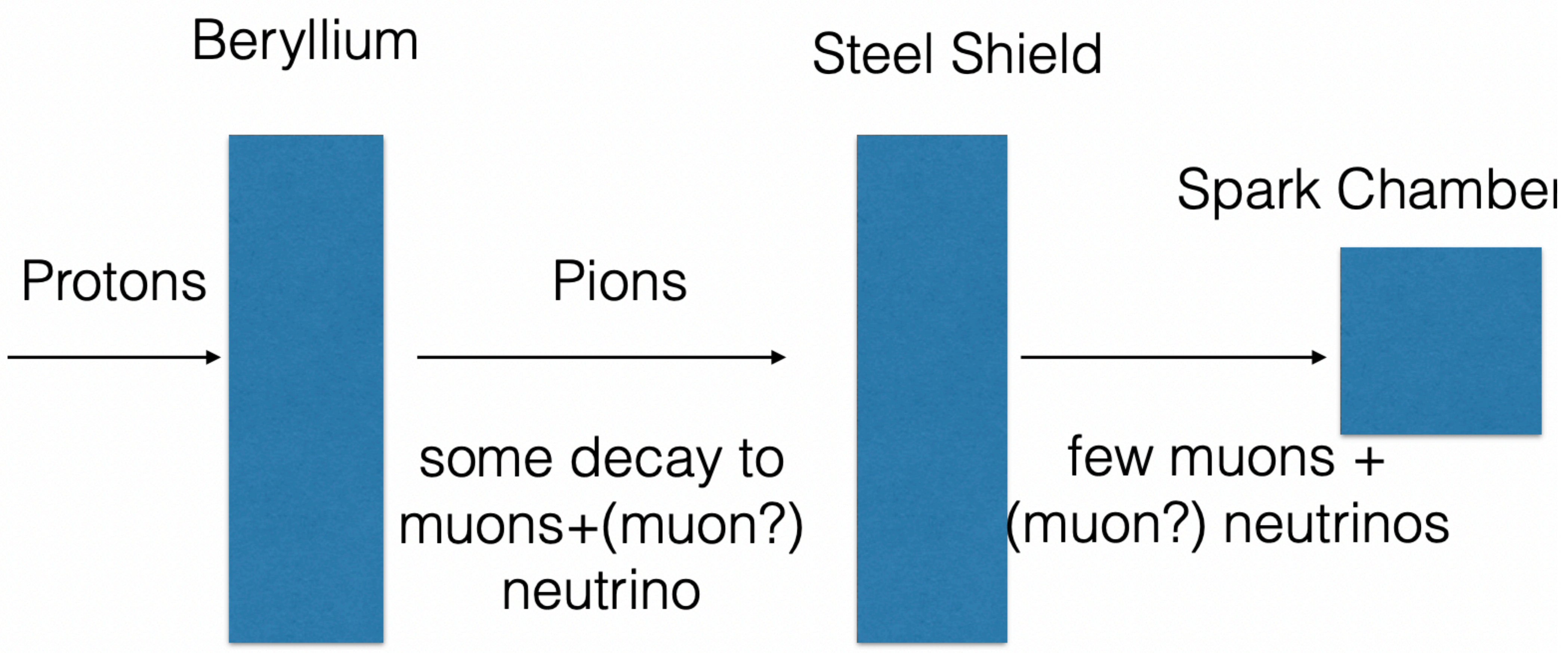
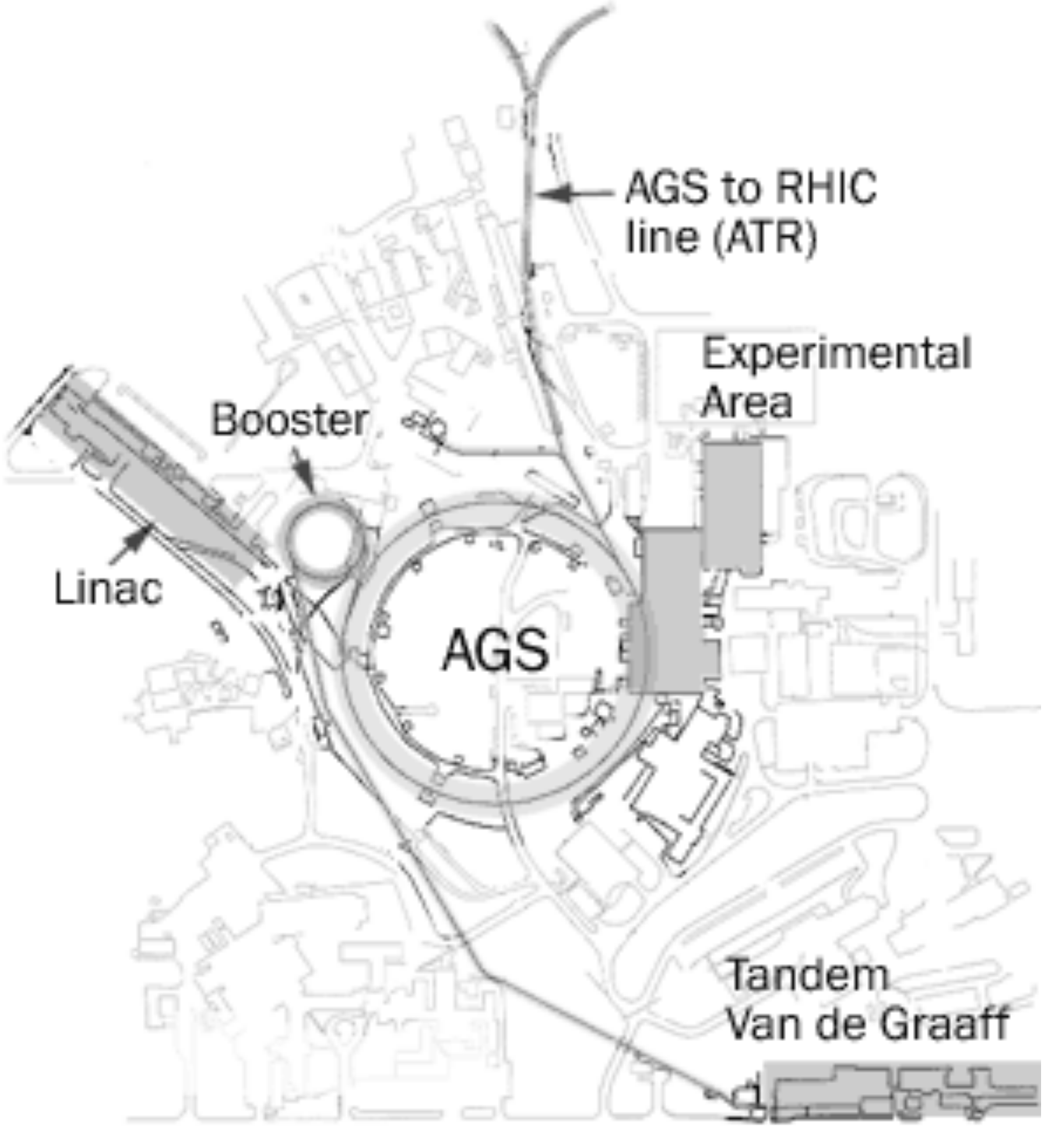


FIG. 2. Energy spectrum of neutrinos expected in the arrangement of Fig. 1 for 15-BeV protons on Be.





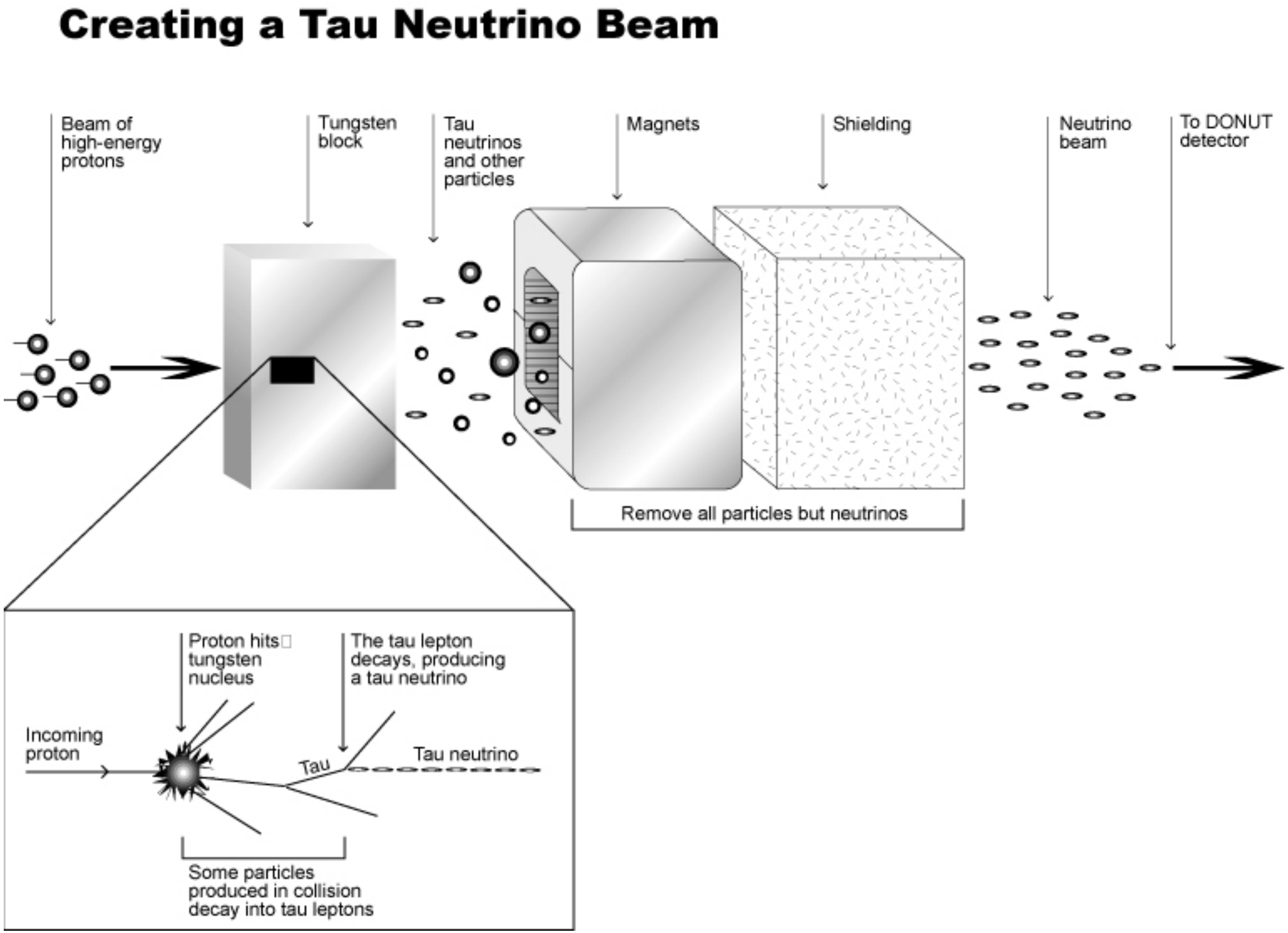
A schematic view of the Alternating Gradient Synchrotron

The DONuT detector (2000)

Tau neutrino had remained the only particle of SM that had not been directly observed except for the Higgs boson.

Tau lepton at low energies is short-lived

Conventional sources of Neutrinos produce only first and second generation



https://news.fnal.gov/2000/07/physicists-find-first-direct-evidence-tau-neutrino-fermilab/

Part Two

Forward Experiments

ForwArd Search ExpeRiment at LHC

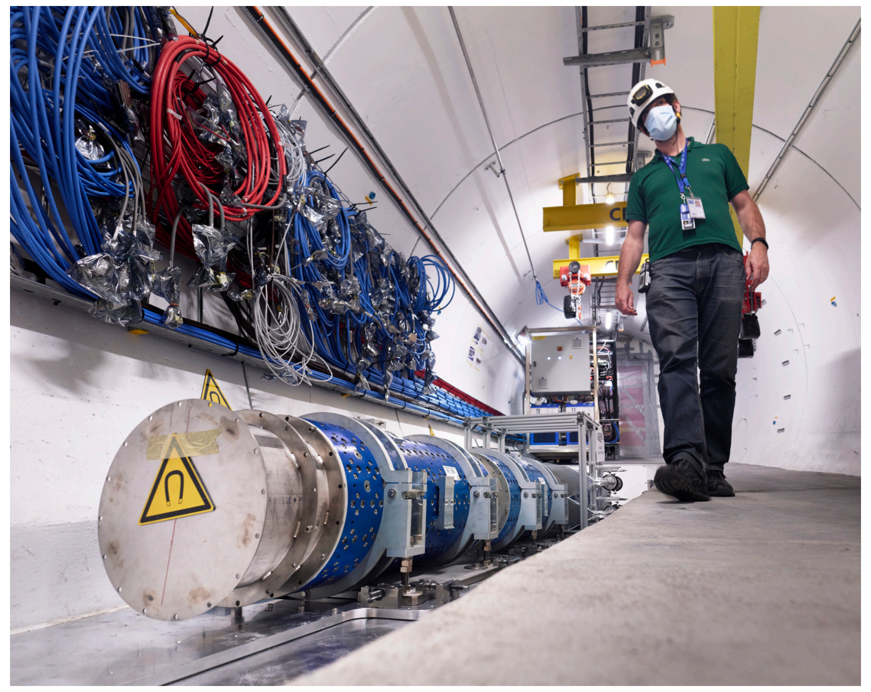
New light and weakly interacting particles

Detection along the beam collision axis of ATLAS IP

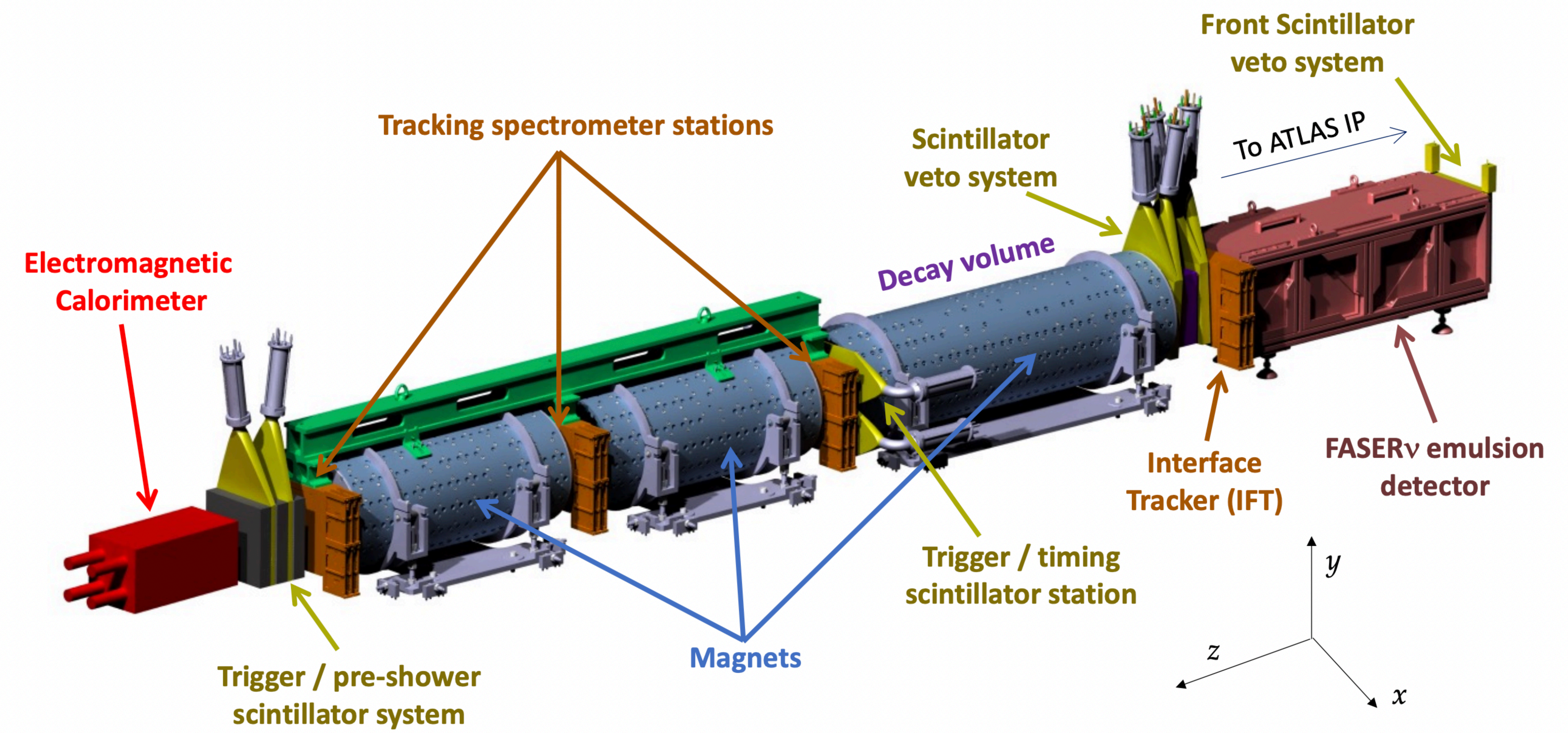
On-Axis with small angular acceptance

Studying the dark sector which go through chain decays

Saw first beam particles, May 2022



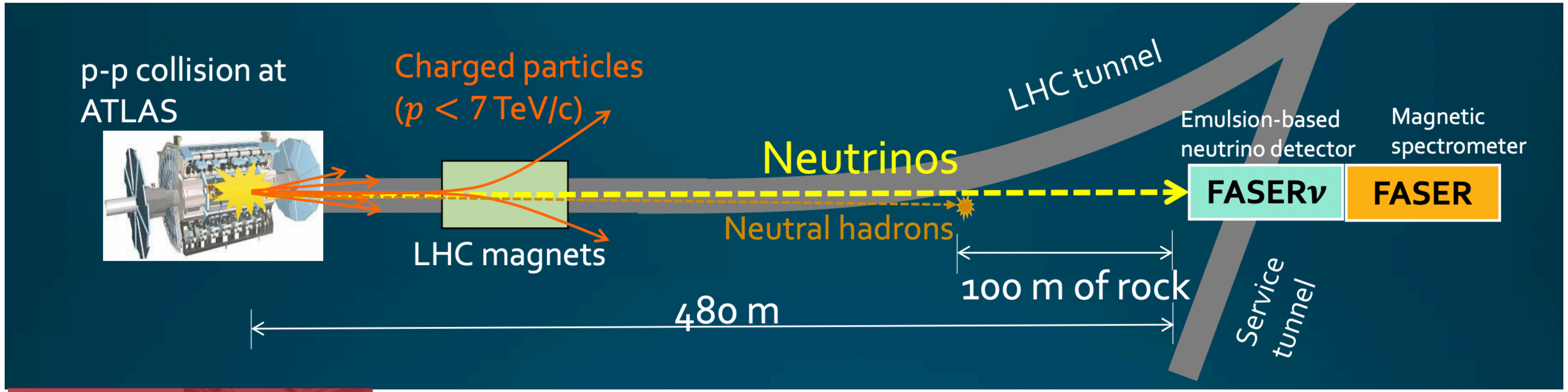
winter 2021



Arxiv : 2207.11427

$$\eta > 9$$

$$|\theta| < 0.4 \text{ mrad}$$



Search for Weakly Interacting Particles with the FASER Experiment

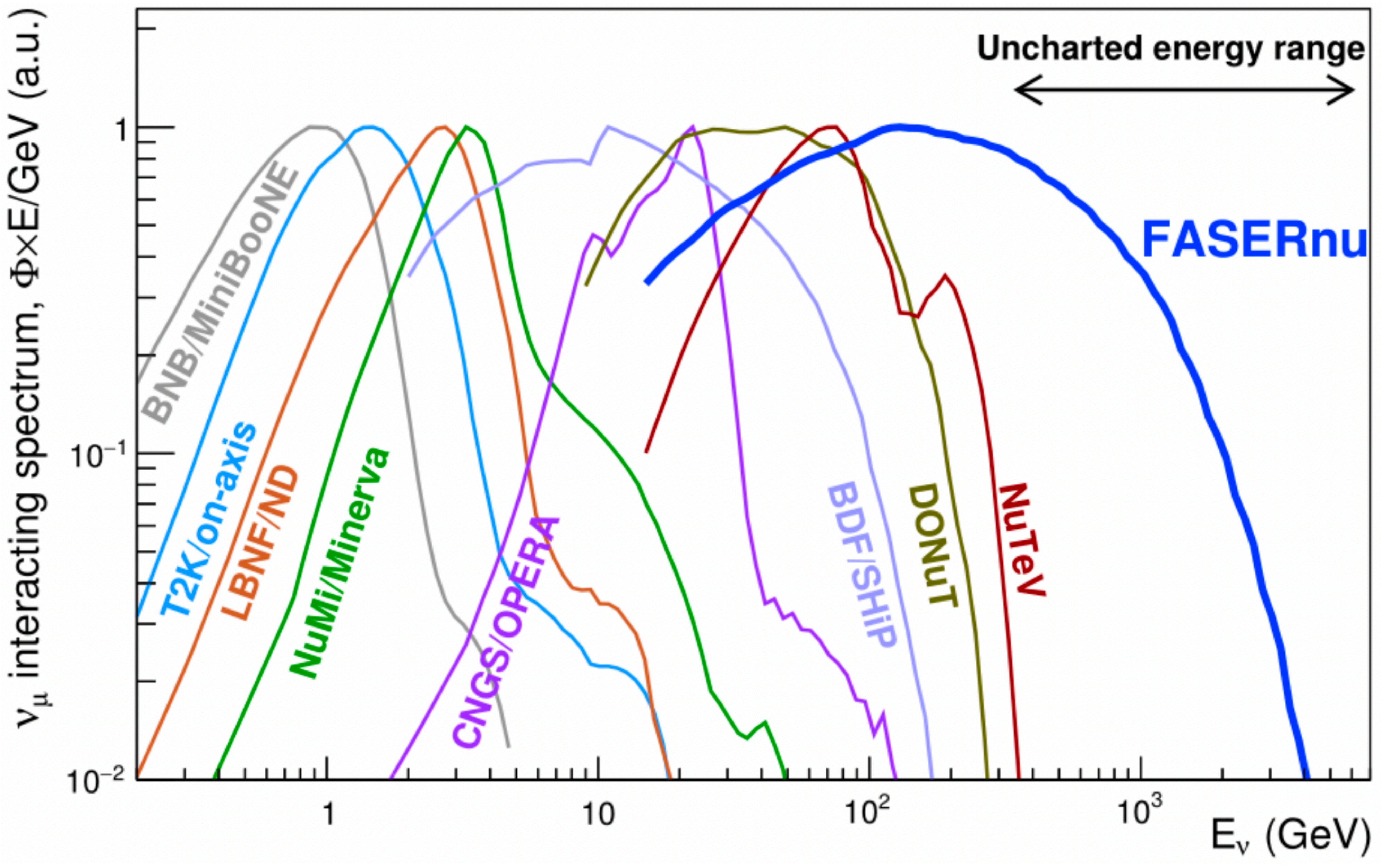
Matthias Schott on behalf of the FASER Collaboration

New range of Neutrino research

FASER ν and SND@LHC will take data during the run III of the LHC

Detector mass: 1200 and 850 kg,
Reach to 20 ton for proposed FASER ν 2

Integrated luminosity of 150 fb^{-1} up to 3000 for fb^{-1} FASER $\nu 2$



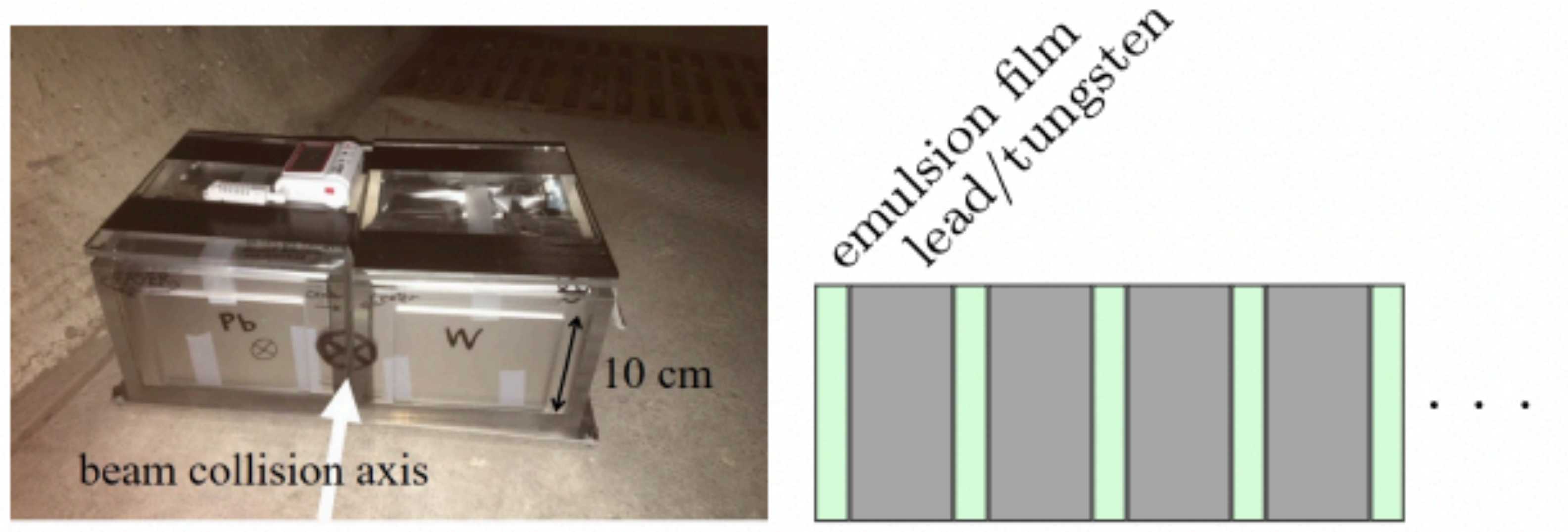
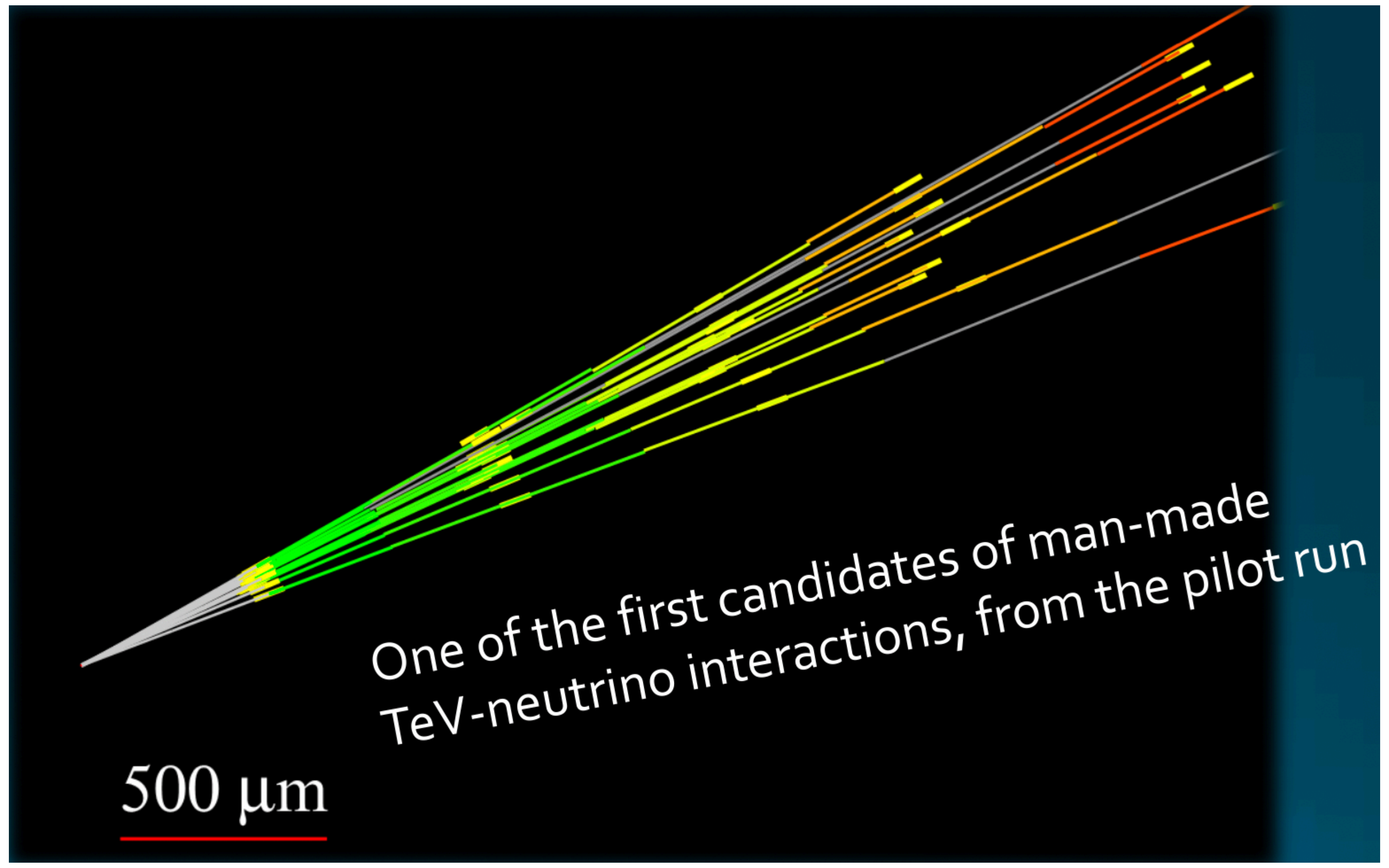


FIG. 1. Structure of the pilot emulsion detector. Metallic plates (1-mm-thick lead or 0.5-mm-thick tungsten) are interleaved with 0.3-mm-thick emulsion films. Only a schematic slice of the detector is depicted.



Abreu, Henso, et al. "First neutrino interaction candidates at the LHC." arXiv preprint arXiv:2105.06197 (2021)

Akitaka Ariga PD Dr., University of Bern
on behalf of the FASER collaboration

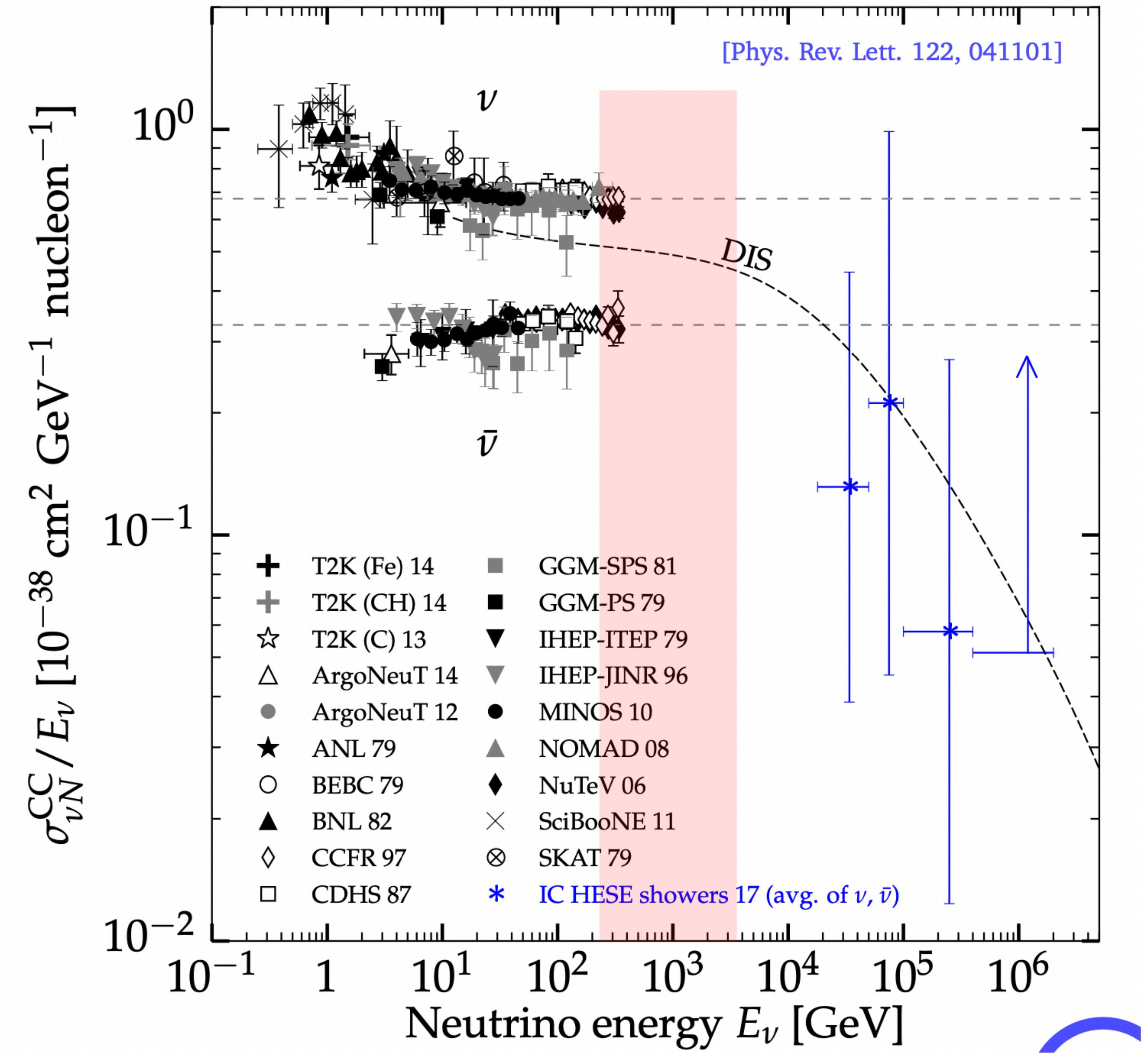
New range of Neutrino research

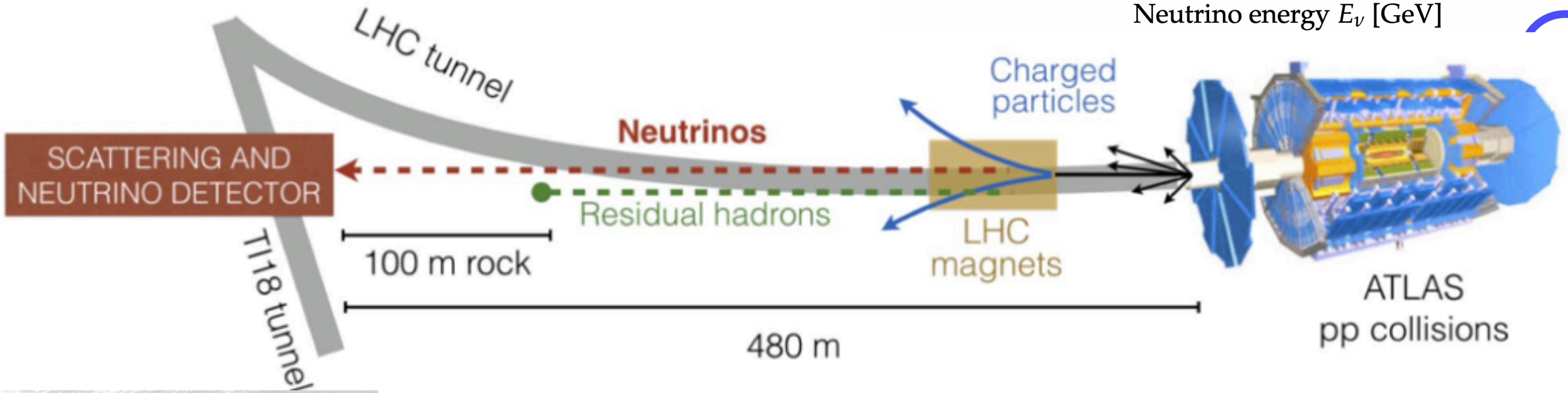
FASERν and SND@LHC will take data during the run III of the LHC

Detector mass: 1200 and 850 kg,
Reach to 20 ton for proposed FASERν2

Integrated luminosity of 150 fb^{-1} up to 3000 for fb^{-1} FASERν2

March 2022





$7.2 < \eta < 8.4$

Neutrino physics at the LHC

Elena Graverini for the SND@LHC collaboration

École Polytechnique Fédérale, Lausanne

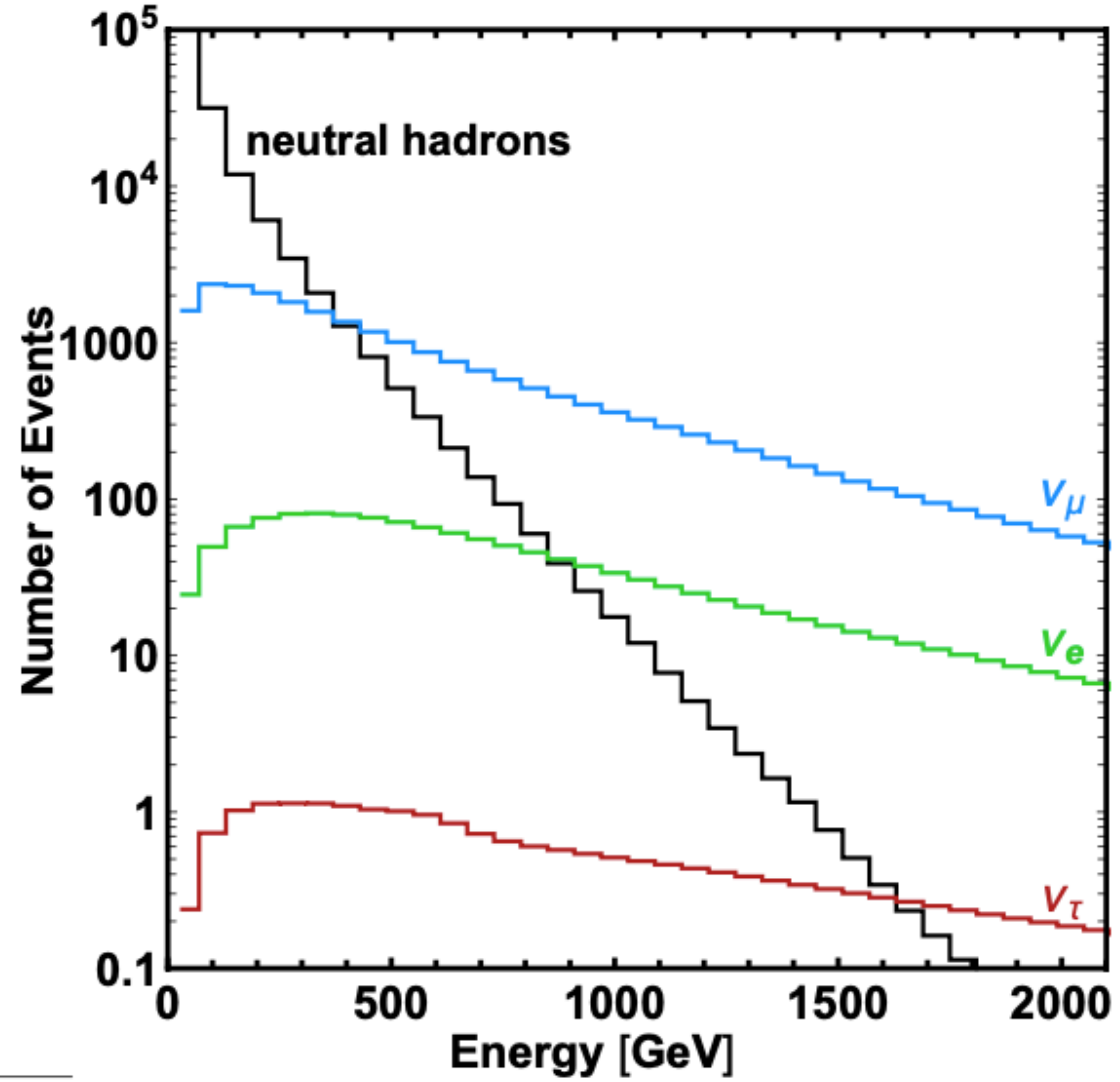
XIth International Conference on New Frontiers in Physics

Kolymbari, September 1, 2022

Signal and Background

Muons are the only SM particles that can efficiently transport energy through 100 m of concrete and rock.

Particle	Expected number of particles passing through FASERν			
	$E > 10$ GeV	$E > 100$ GeV	$E > 300$ GeV	$E > 1$ TeV
Neutrons n	27.8k / 138k	1.5k / 11.5k	150 / 1.1k	2.2 / 42
Anti-neutrons $\bar{n}$	15.5k / 98k	900 / 9k	110 / 1.5k	2.8 / 46
Λ	5.3k / 36k	390 / 4.1k	39 / 800	0.9 / 58
Anti-Λ	3.4k / 31k	290 / 3.5k	31 / 200	0.6 / 14
K_S^0	1.3k / 30k	240 / 6.8k	52 / 390	1.8 / 6.2
K_L^0	1.6k / 31k	270 / 5.7k	55 / 500	1.2 / 18
Ξ^0	240 / 1.3k	13 / 190	2.3 / 12	0.1 / –
Anti-Ξ^0	150 / 1k	10 / 200	1.4 / 19	–
Photons γ	2.2M / 62M	160k / 16.3M	38.2k / 6.3M	5.9k / 1.1M
$\nu_\mu + \bar{\nu}_\mu$ (signal int.)	23.1k	20.4k	13.3k	3.4k



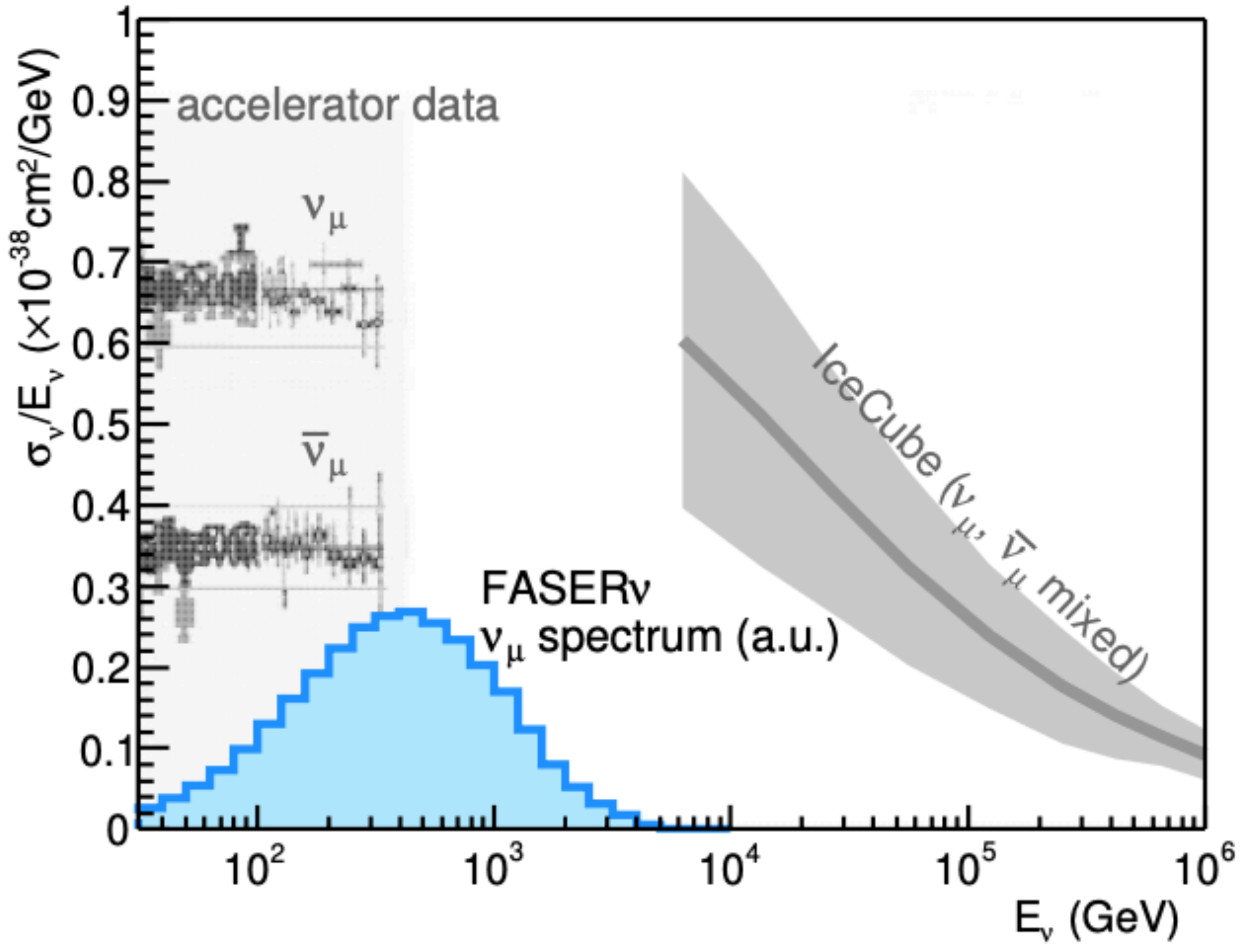
Type	Particles	Main Decays	E	Q	S	P
Pions	π^+	$\pi^+ \to \mu\nu$	√	√	√	—
Kaons	K^+, K_S, K_L	$K^+ \to \mu\nu,\ K \to \pi\ell\nu$	√	√	√	—
Hyperons	$\Lambda, \Sigma^+, \Sigma^-, \Xi^0, \Xi^-, \Omega^-$	$\Lambda \to p\ell\nu$	√	√	√	—
Charm	$D^+, D^0, D_s, \Lambda_c, \Xi_c^0, \Xi_c^+$	$D \to K\ell\nu,\ D_s \to \tau\nu,\ \Lambda_c \to \Lambda\ell\nu$	—	—	√	√
Bottom	$B^+, B^0, B_s, \Lambda_b, \ldots$	$B \to D\ell\nu,\ \Lambda_b \to \Lambda_c\ell\nu$	—	—	—	√

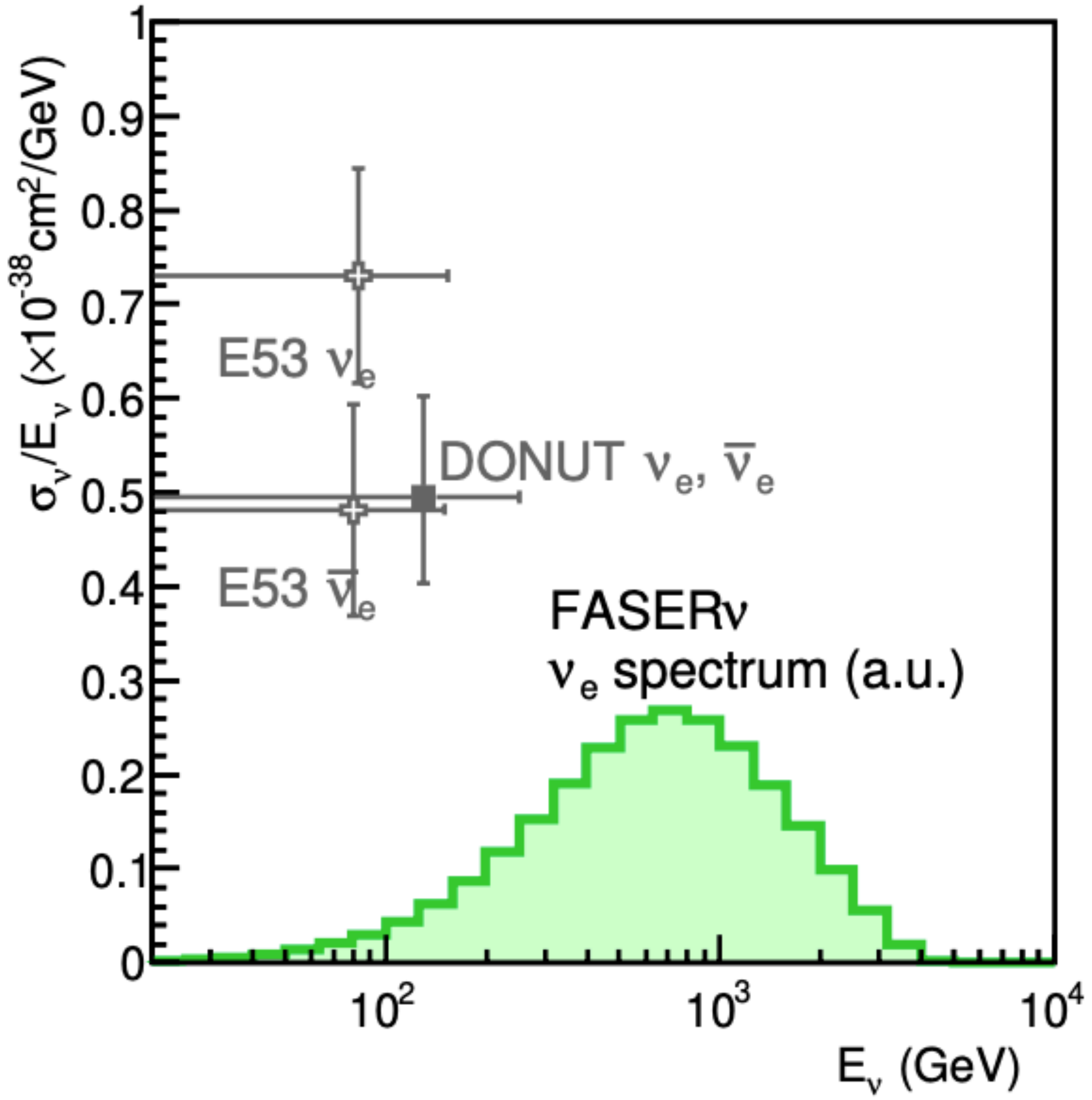
Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC, FASER Collaboration, Eur.Phys.J. C80 (2020) no.1, 61

ForwArd Search ExpeRiment at LHC

Search in the DIS region

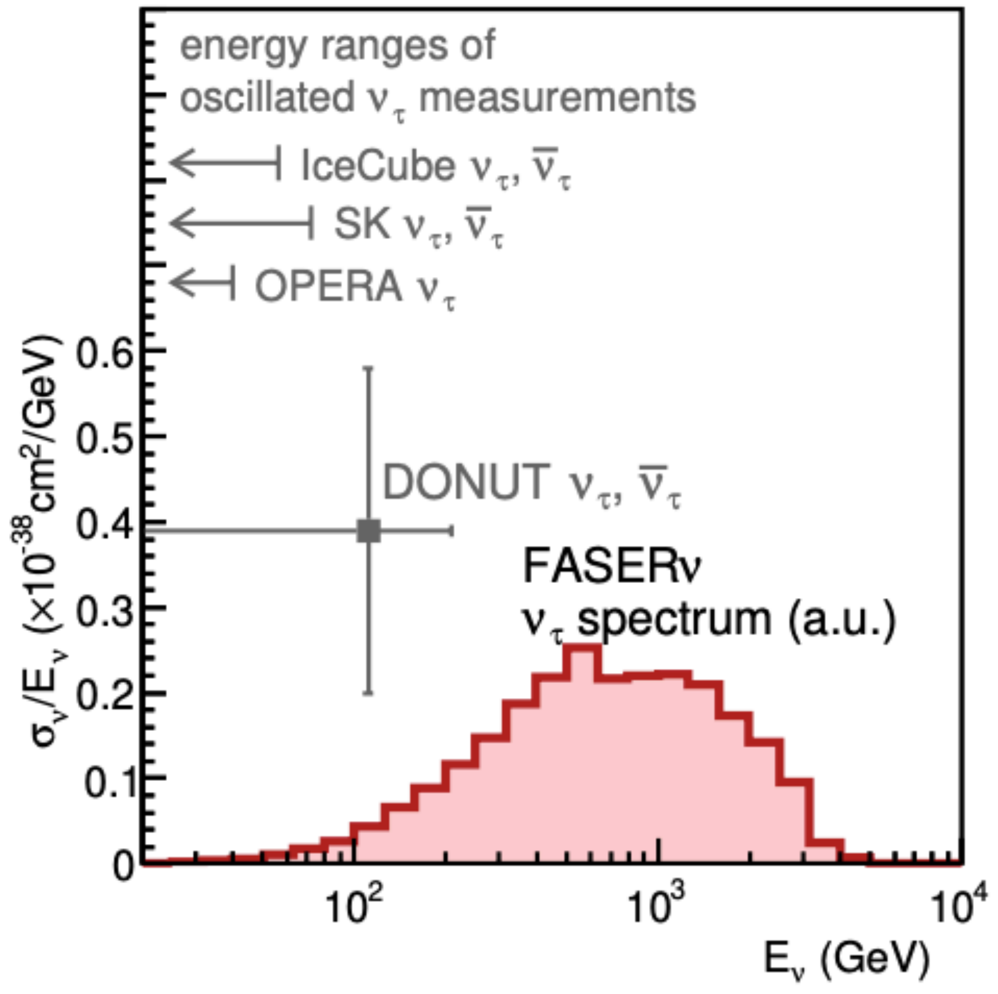
Test of lepton universality





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

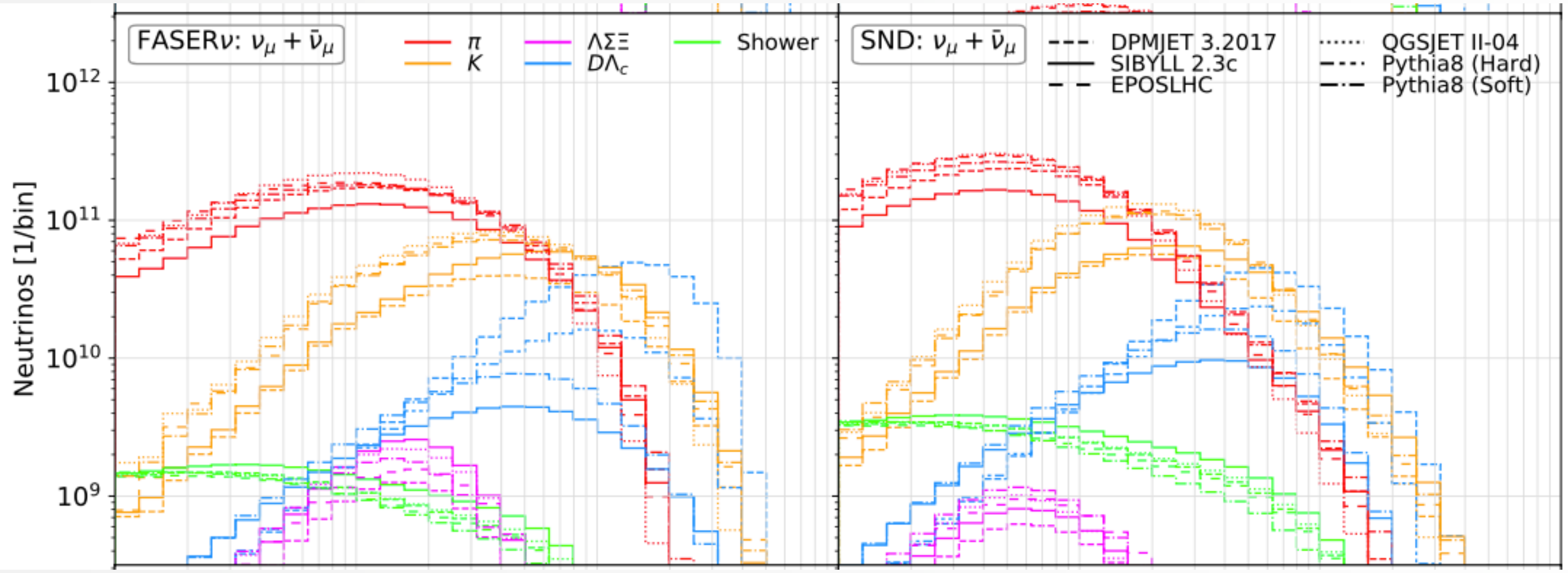
Generators		FASERν			SND@LHC		
light hadrons	heavy hadrons	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
SIBYLL	SIBYLL	1343	6072	21.2	184	965	10.1
DPMJET	DPMJET	4614	9198	131	547	1345	22.4
EPOSLHC	Pythia8 (Hard)	2109	7763	48.9	367	1459	16.1
QGSJET	Pythia8 (Soft)	1437	7162	24.5	259	1328	10.7

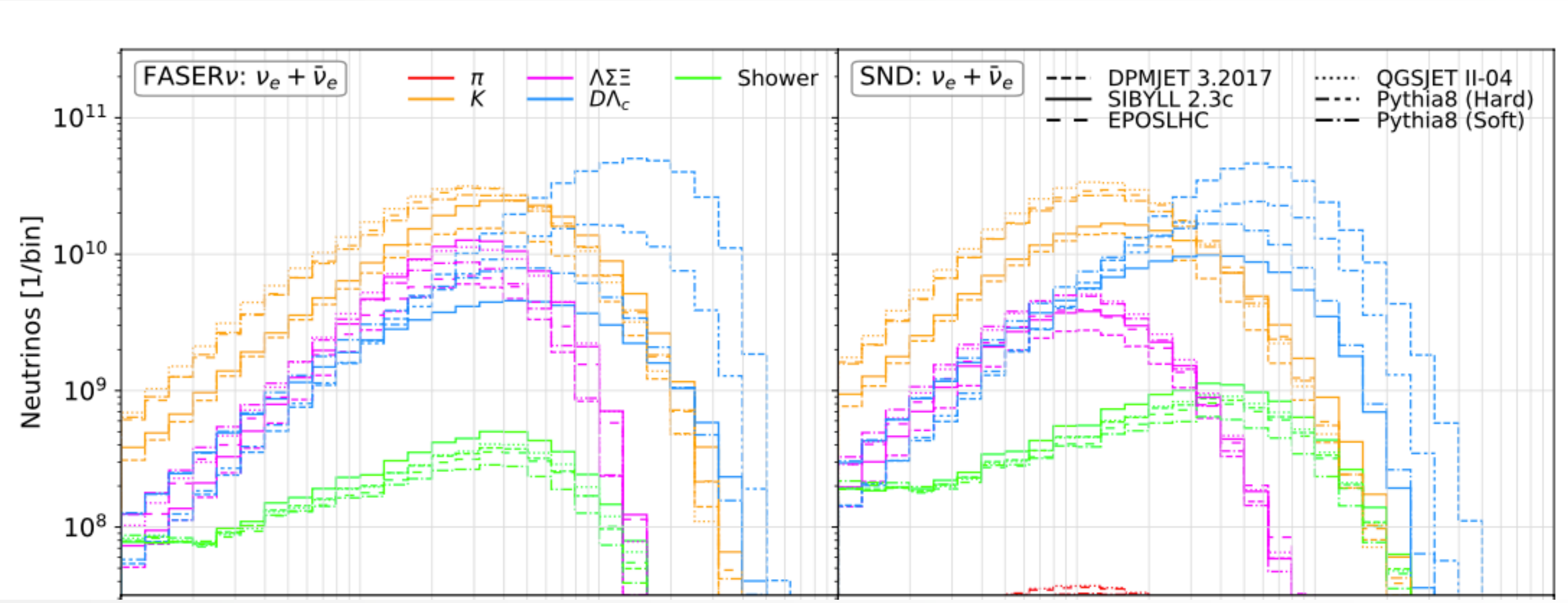


Forward Neutrino Fluxes at the LHC, Felix Kling, 2105.08270

Prediction of Neutrino fluxes

Different Sources of Neutrino





Forward Neutrino Fluxes at the LHC, Felix Kling, 2105.08270

Part Three

BSM models

2HDM One of the simplest extension of SM

The Lagrangian of the minimalistic version of the model

The present bounds from direct production of these particles at CMS and ATLAS must be avoided

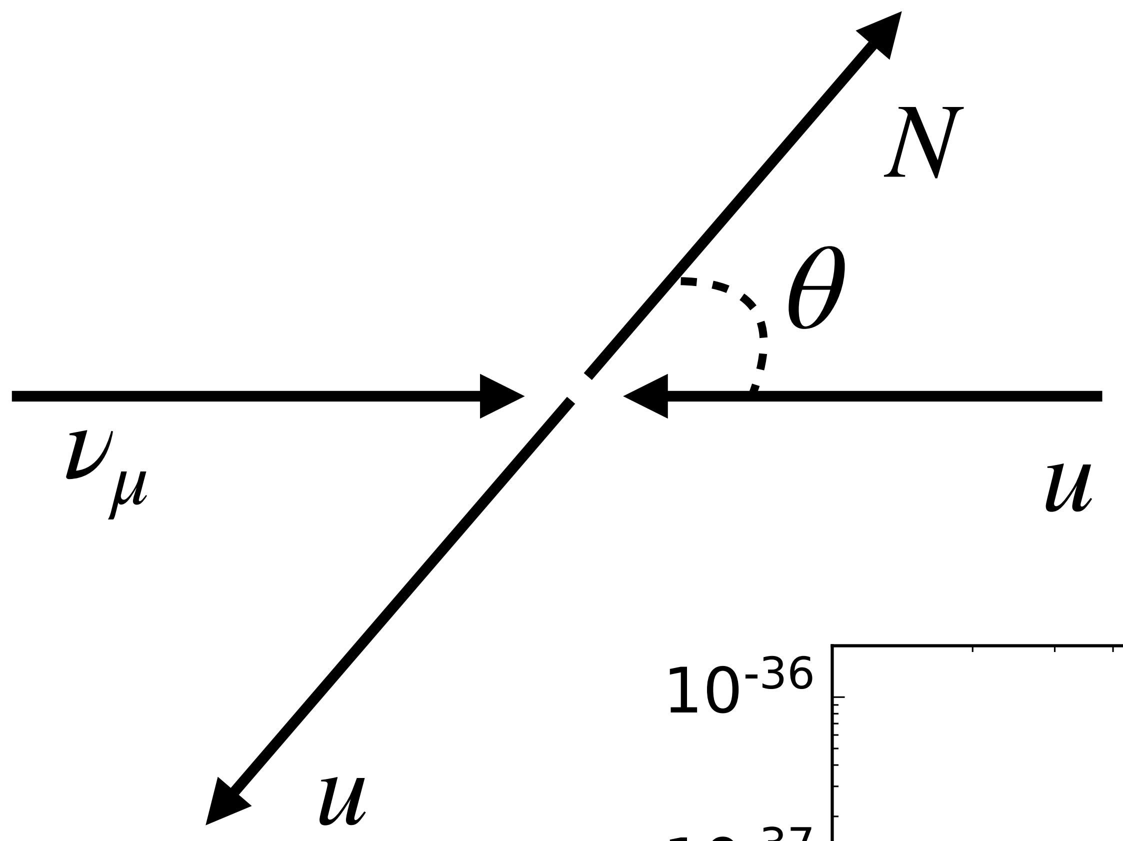
N is a right-handed singlet fermion

$Y_\mu \sim O(1)$ To have a high rate of N production.

$$\Phi = \begin{bmatrix} \Phi^+ \\ \Phi^0 \end{bmatrix}$$

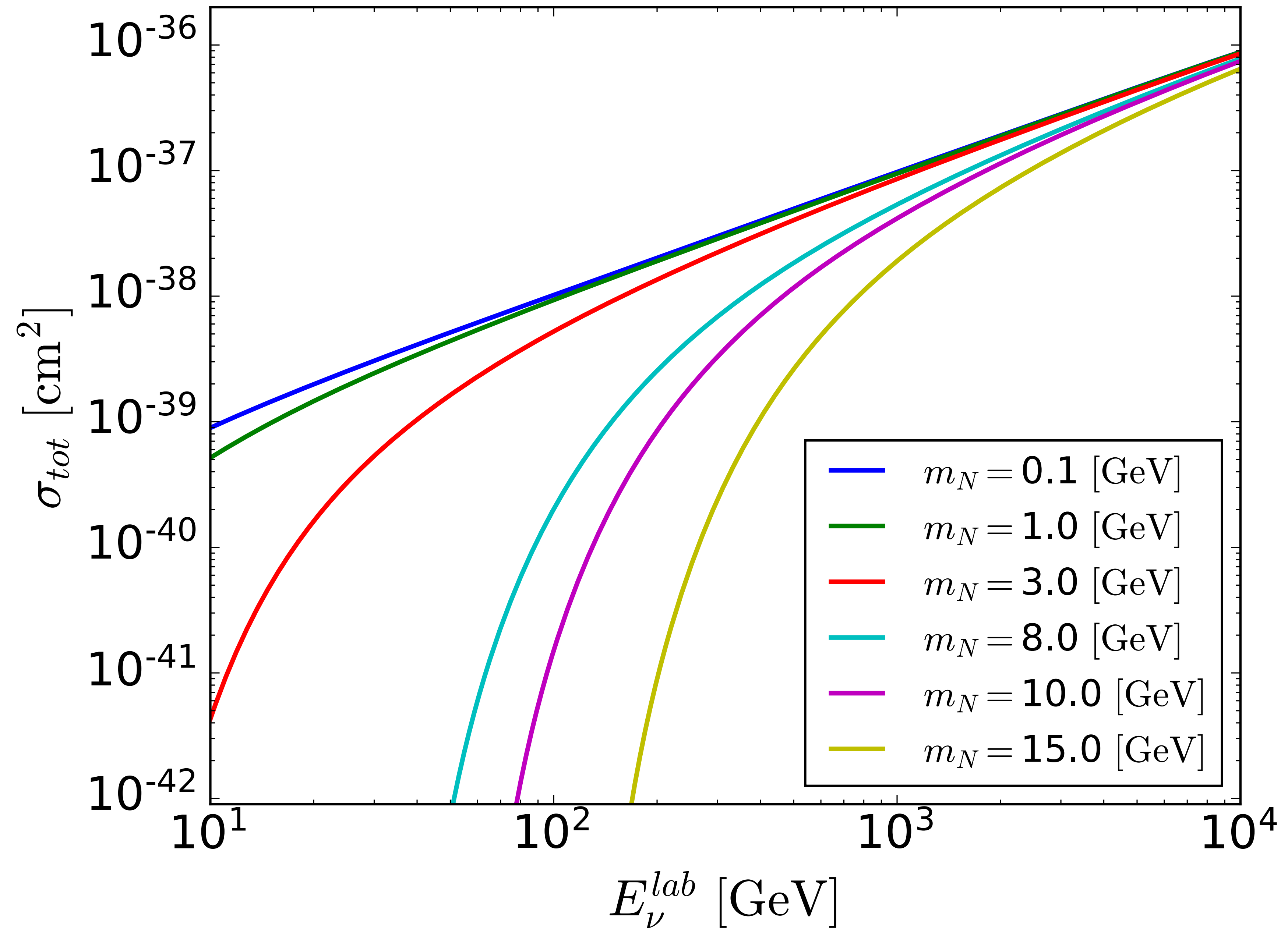
$$G_u \bar{N}_R \nu_\mu \bar{u}_L u_R + G_d \bar{N}_R \nu_\mu \bar{d}_R d_L$$

$$\Phi^0 \sim \Phi^+ \sim 300 \text{ GeV}$$

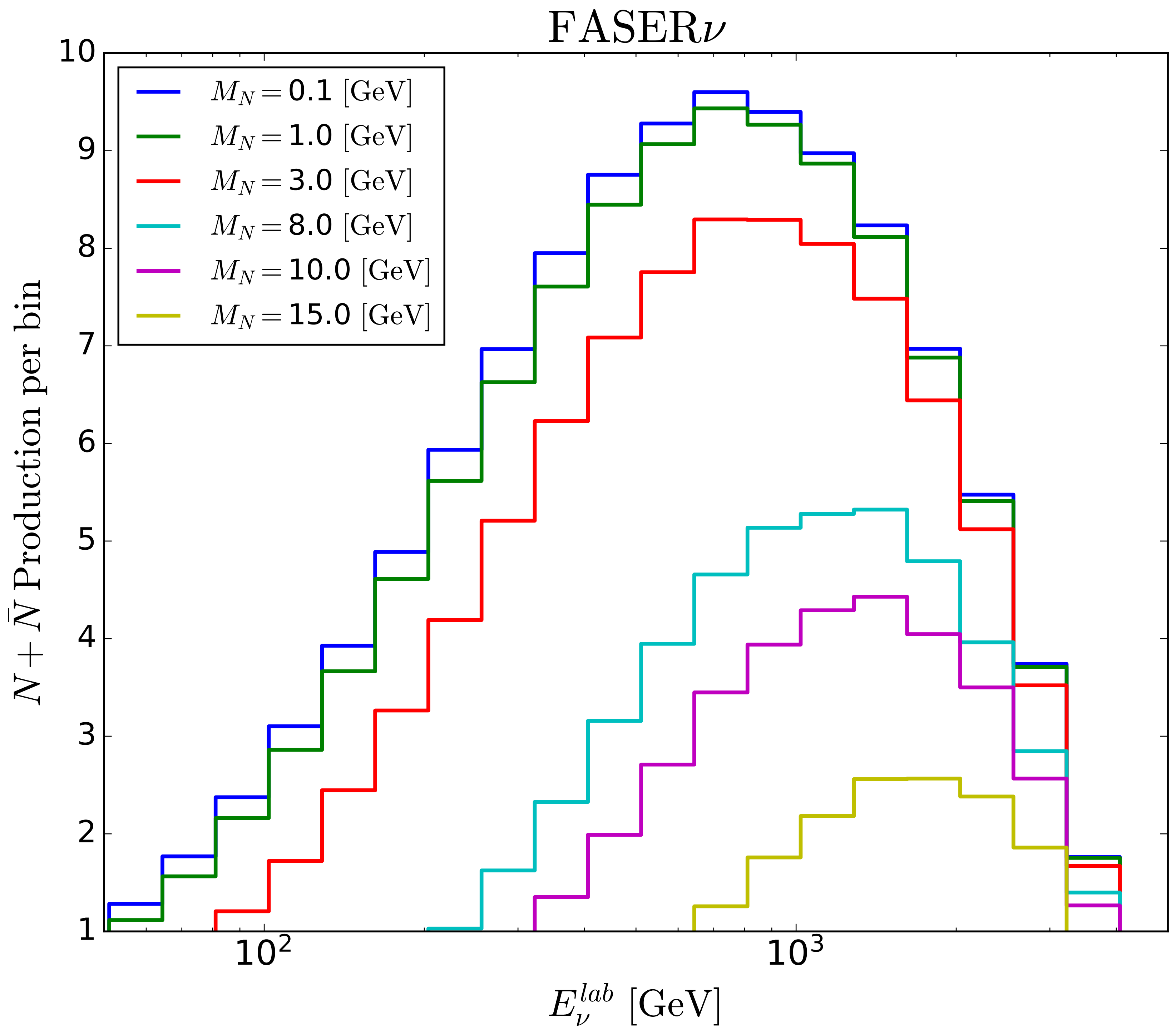


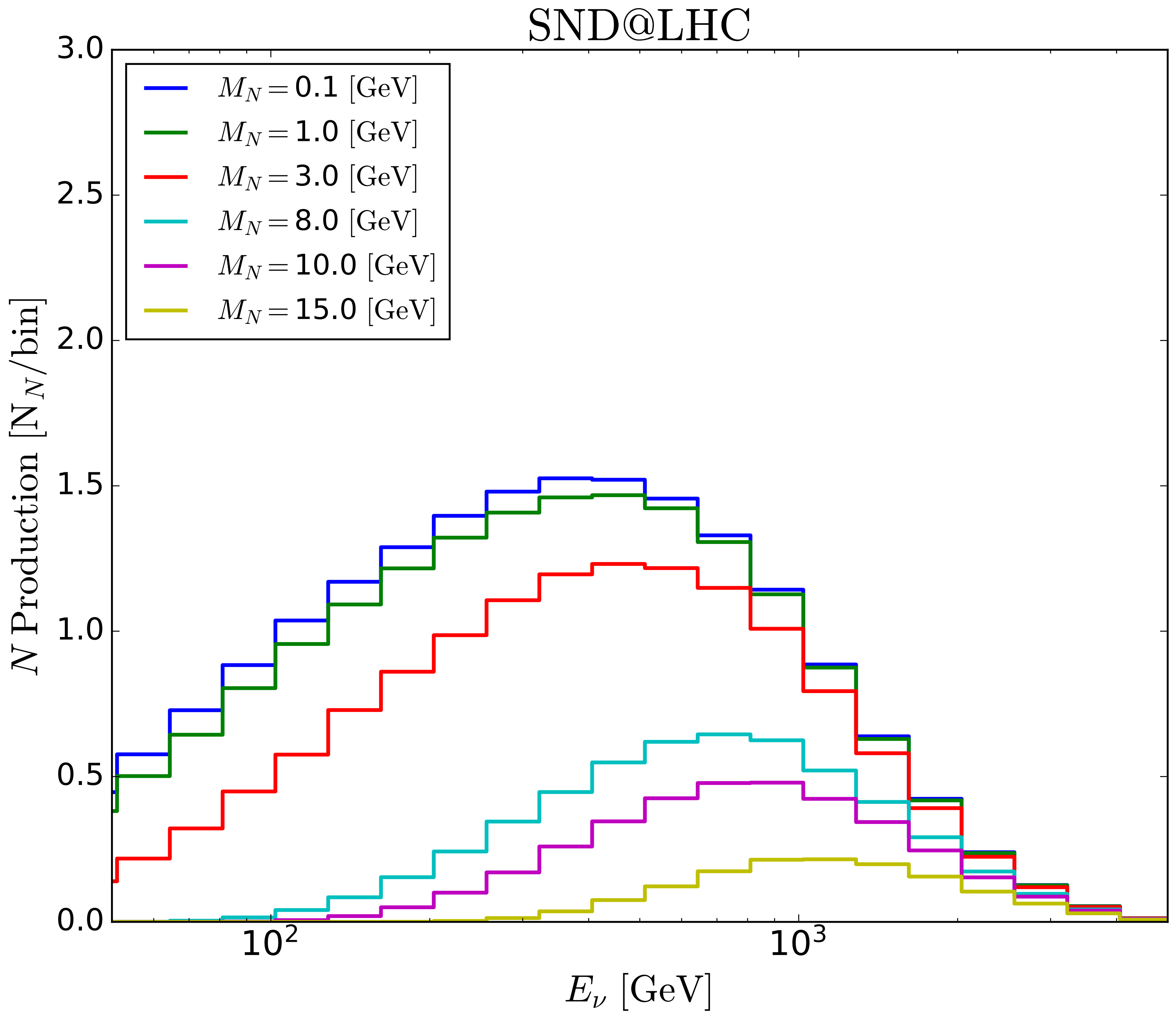
$$G_u = \frac{Y_\mu Y_u^*}{m_{\Phi^0}^2}, \; G_d = -\frac{Y_\mu Y_d}{m_{\Phi^0}^2},$$

$$Y_\mu \sim 3 \qquad Y_u \sim Y_d \sim 0.3$$



The total number of N and $\bar{N}$ production



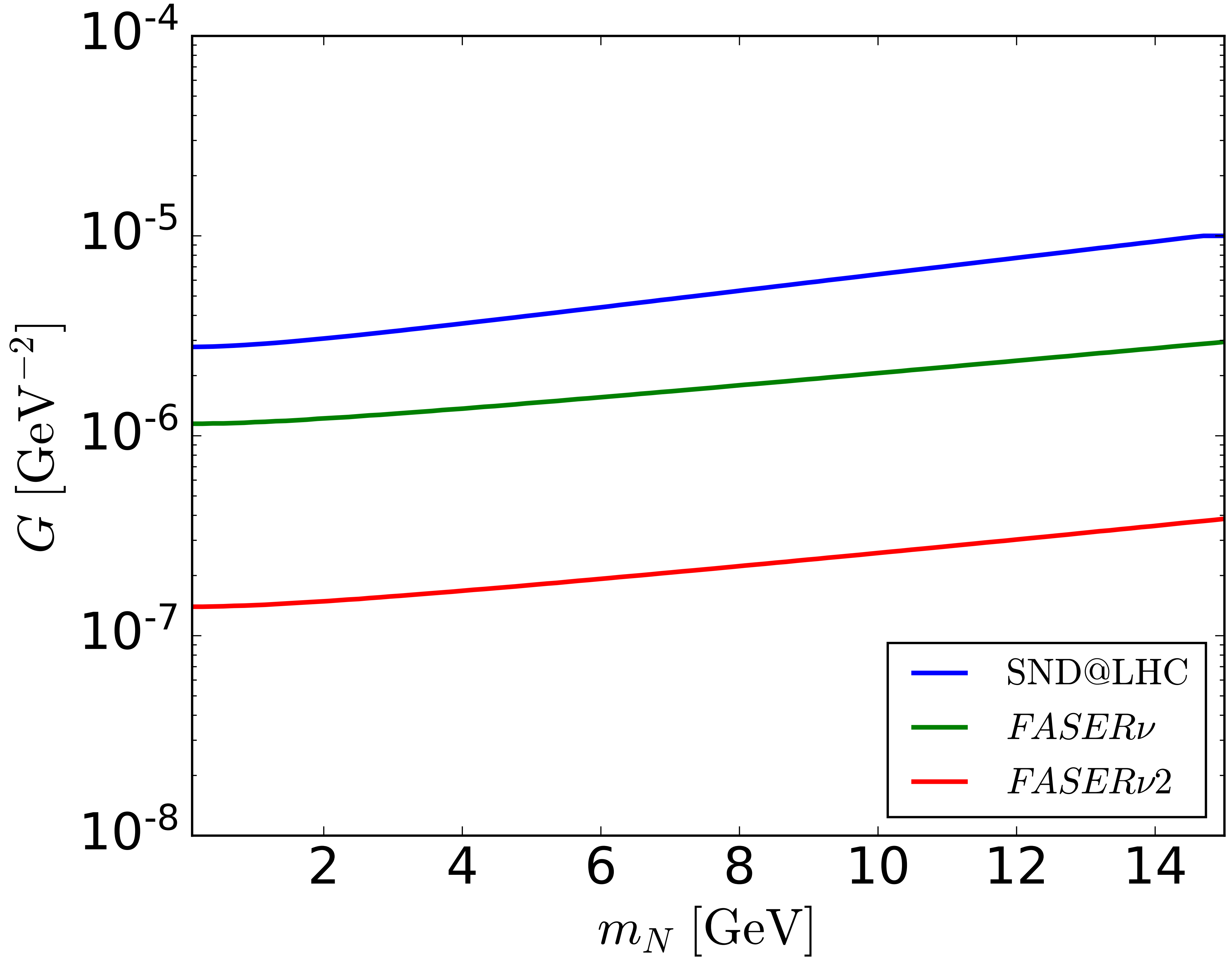


Number	$N+\bar{N}$					
m_N GeV	0.1	1	3	8	10	15
SND@LHC	19	18	13	5	3	1
FASERν	113	109	90	46	35	17
FASERν2	7685	7394	6045	3019	2229	1015

Neutral Exotica at FASERv and SND@LHC, Saeed Ansarifard and Yasaman Farzan, Journal of High Energy Physics 2022 (2), 1-20, 2109.13962

FASERν improves the theoretical limit on $G_u = G_d$ by a factor of 10

M_N > 3 GeV from NOMAD



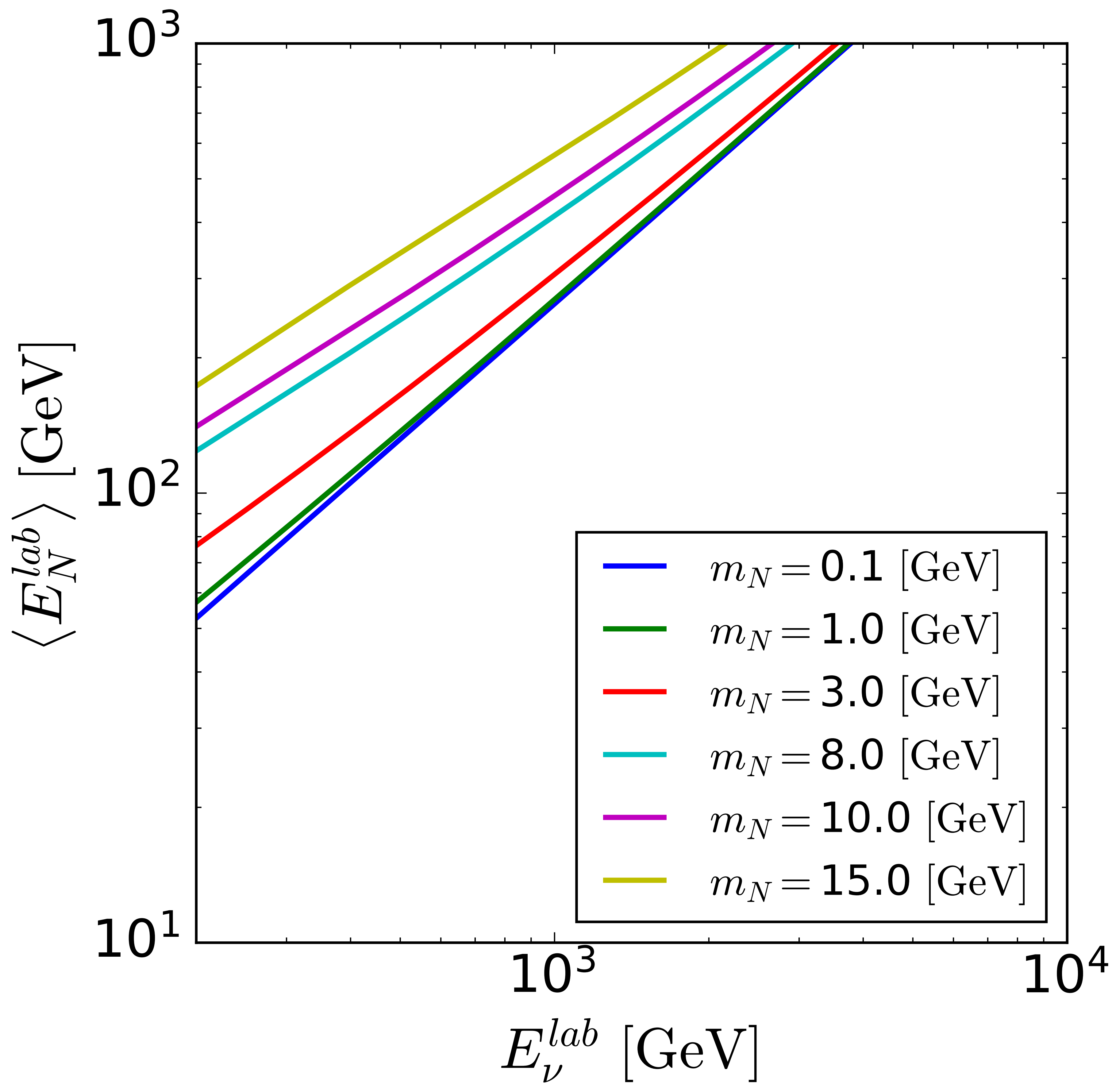
Neutral Exotica at FASERv and SND@LHC, Saeed Ansarifard and Yasaman Farzan, Journal of High Energy Physics 2022 (2), 1-20, 2109.13962

N carries a fraction of O(0.3) of the energy of the initial neutrino

Angle with the beam line

$\gamma_N^{-1} \sim 10^{-2}$

Dependence of the N decay on m_N is very strong



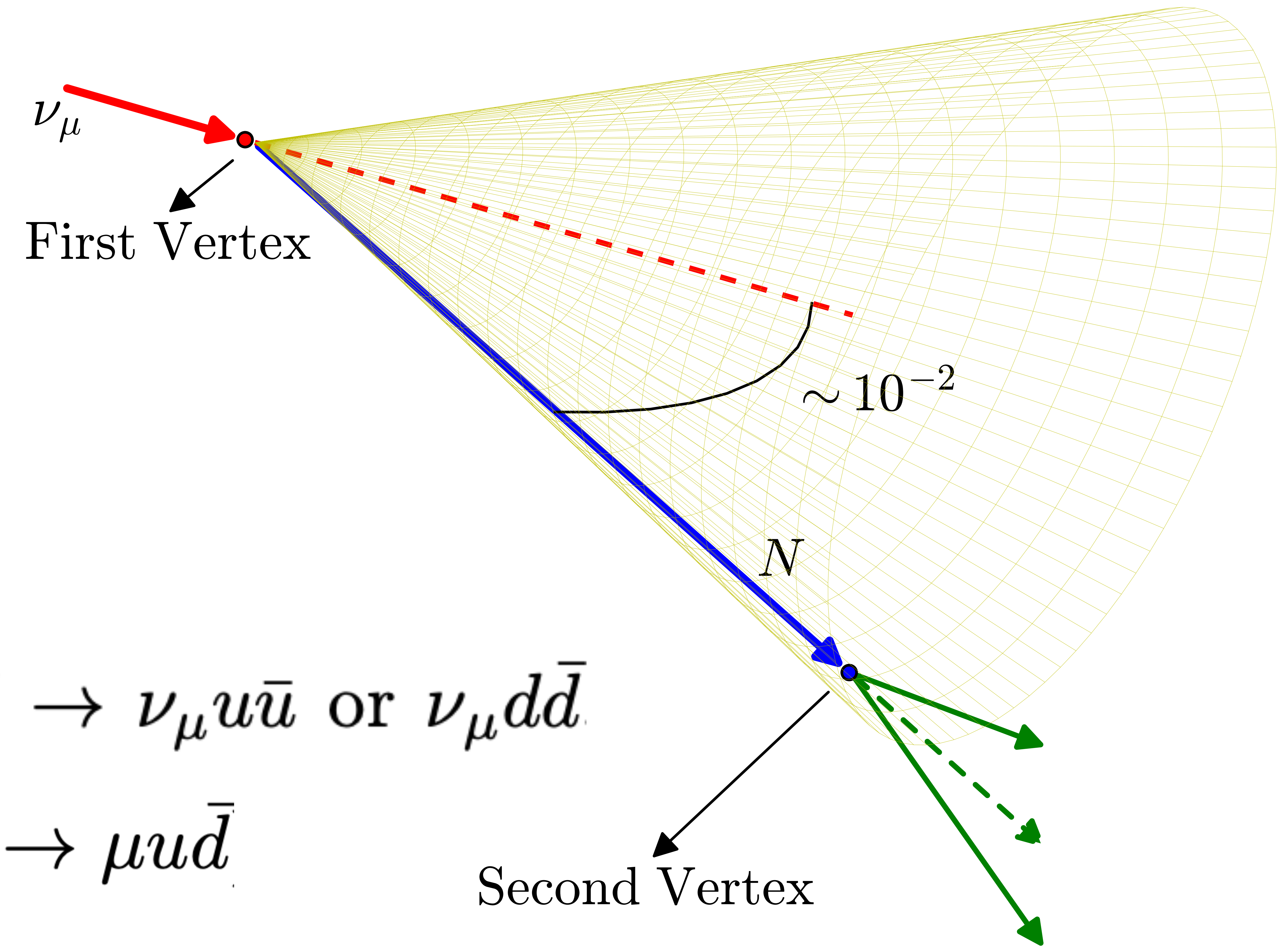
$$l = \Gamma_N^{-1}\gamma_N = 3\ \mu\text{m} \frac{(10^{-5}\ \text{GeV})^2}{|G_u|^2 + |G_d|^2 + |G_L|^2 + |G_R|^2} \left(\frac{10\ \text{GeV}}{m_N}\right)^6 \left(\frac{E_N^{lab}}{200\ \text{GeV}}\right) > 0.4\ \mu m \text{ and } < 10\ \text{cm}$$

Neutral Exotica at FASERv and SND@LHC, Saeed Ansarifard and Yasaman Farzan, Journal of High Energy Physics 2022 (2), 1-20, 2109.13962

The model predicts two signals

All vertex lies within a cone

The signals are background-free



$$N \to \nu_\mu u\bar{u} \text{ or } \nu_\mu d\bar{d}$$

$$N \to \mu u\bar{d}$$

$$\mathcal{N}_{NC} \times \mathcal{N}_\mu \times p \sim 0.12$$

$$\mathcal{N}_{NC}^2 \times p/2 \sim 0.02$$

Neutral Exotica at FASERν and SND@LHC, Saeed Ansarifard and Yasaman Farzan, Journal of High Energy Physics 2022 (2), 1-20, 2109.13962

The Y_μ coupling gives contribution to $(g-2)_\mu$

$$\Delta a_\mu = \delta \left(\frac{g-2}{2}\right) = 5 \times 10^{-10} \left(\frac{Y_\mu}{3}\right)^2 \left(\frac{300 \text{ GeV}}{m^2_{\Phi+}}\right)^2$$

$$G^{\mu}_{ij}(\bar{N}_i \mu)(\bar{\mu} N_j) + G^{\nu}_{ij}(\bar{N}_i \nu_\mu)(\bar{\nu}_\mu N_j)$$

The minimal model accounts for at most 25% of the anomaly

$$G^{\nu}_{ij} \sim G^{\mu}_{ij} \sim 10^{-4} \text{ GeV}^{-2}$$

$$N_i \to N_j \mu \bar{\mu} \quad \text{and} \quad N_i \to N_j \nu_\mu \bar{\nu}_\mu$$

Adding more generations the anomaly can be completely explained

$$\Delta a_\mu \sim \lambda^2_\mu m^2_\mu / (100 \pi^2 m^2_{\Phi_2})$$

$$\lambda_\mu \sim 3$$

Part Four

More for the future

The scenarios for overproduction of tau

Lepton number conserving versus lepton number violating

$$G_{\nu\mu}(\bar{\mu}\frac{1-\gamma_5}{2}\nu_\tau)(\bar{d}\frac{1\pm\gamma_5}{2}u)$$

$$\pi^+ \to \mu^+\nu_\tau$$

$$G_{\bar{\nu}\mu}(\bar{d}\frac{1-\gamma_5}{2}u)(\nu_\mu^T c\tau_L - \mu_L^T c\nu_\tau)$$

$$\pi^+ \to \mu^+\bar{\nu}_\tau$$

$$Br(\pi^+ \to \mu^+\nu_\tau) < 2.4\times 10^{-3} Br(\pi^+ \to \mu^+\nu_\mu) = 2.4\times 10^{-3}$$

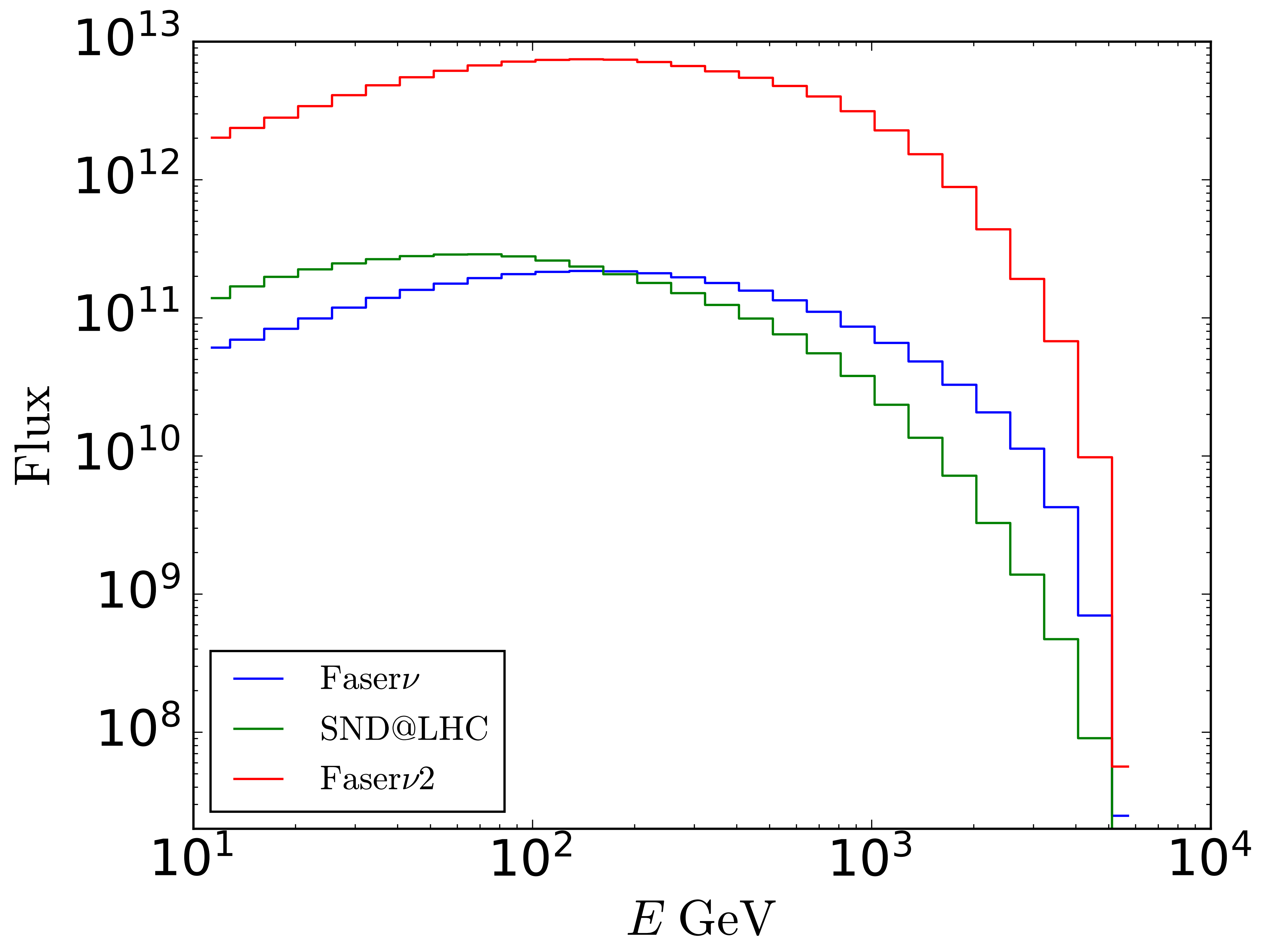
$$\nu_{e(\mu)} + \text{nucleus} \to \tau + X$$

$$G_e(\bar{\tau}_R\nu_e)(\bar{u}_L d_R) \quad \text{or} \quad G_\mu(\bar{\tau}_R\nu_\mu)(\bar{u}_L d_R)$$

$$5\times 10^{-8}\ \text{GeV}^{-2}$$

Tau neutrino number of events

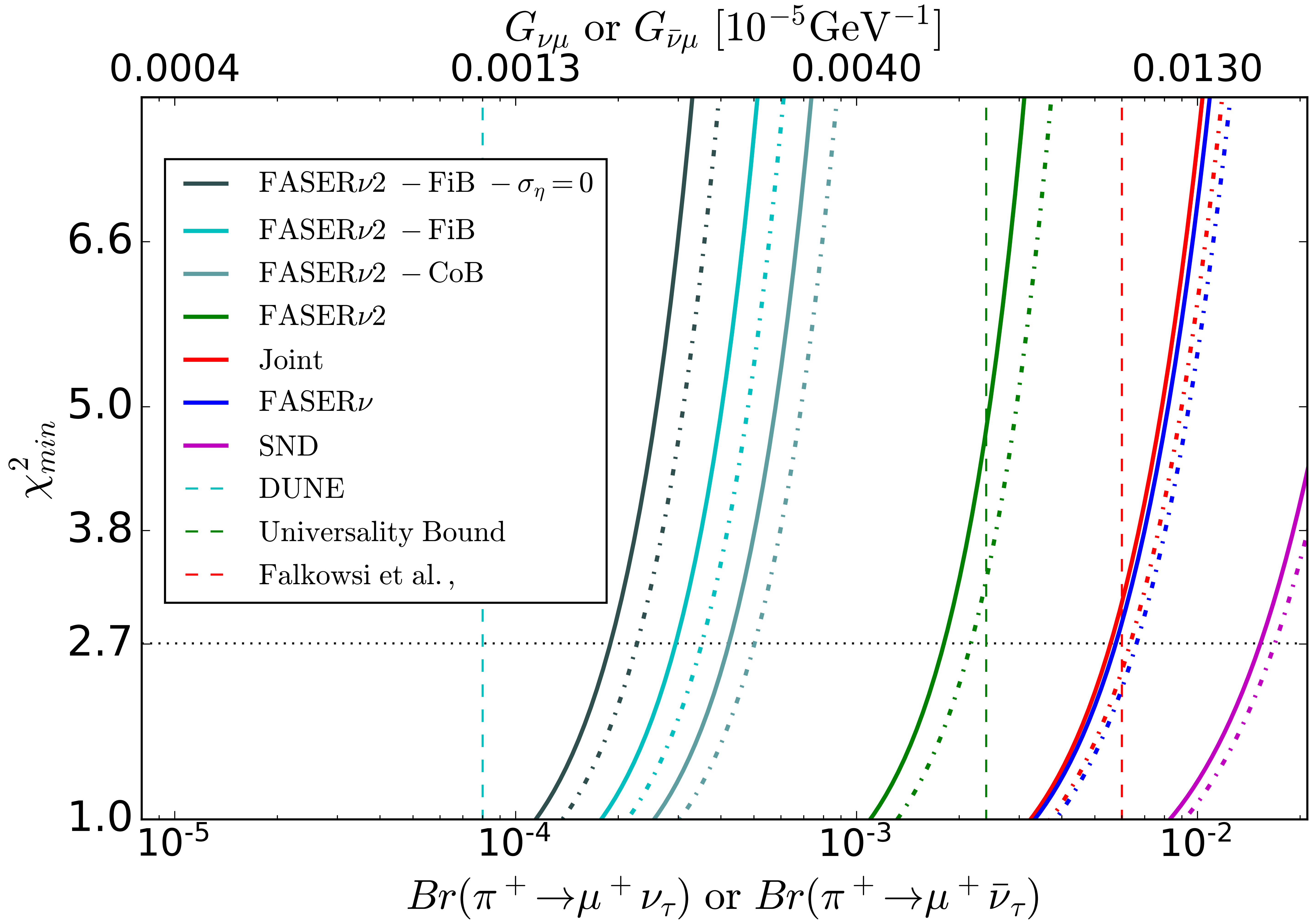
The number of event at SND@LHC and FASERnu can not reach a statistical limit for new physic



Detector	$Br(\pi^+ \to \nu_\tau \mu^+)$	$Br(\pi^+ \to \bar{\nu}_\tau \mu^+)$	G_e	SM
SND@LHC	1.0	0.9	0.003	6.6
FASERν	4.9	4.3	0.027	25.3
FASERν2	1125.9	938.0	9.6	3403.3

Excess of Tau events at SND@LHC, FASERν and FASERν2, Saeed Ansarifard and Yasaman Farzan, The European Physical Journal C 82 (6), 1-15, 2112.08799

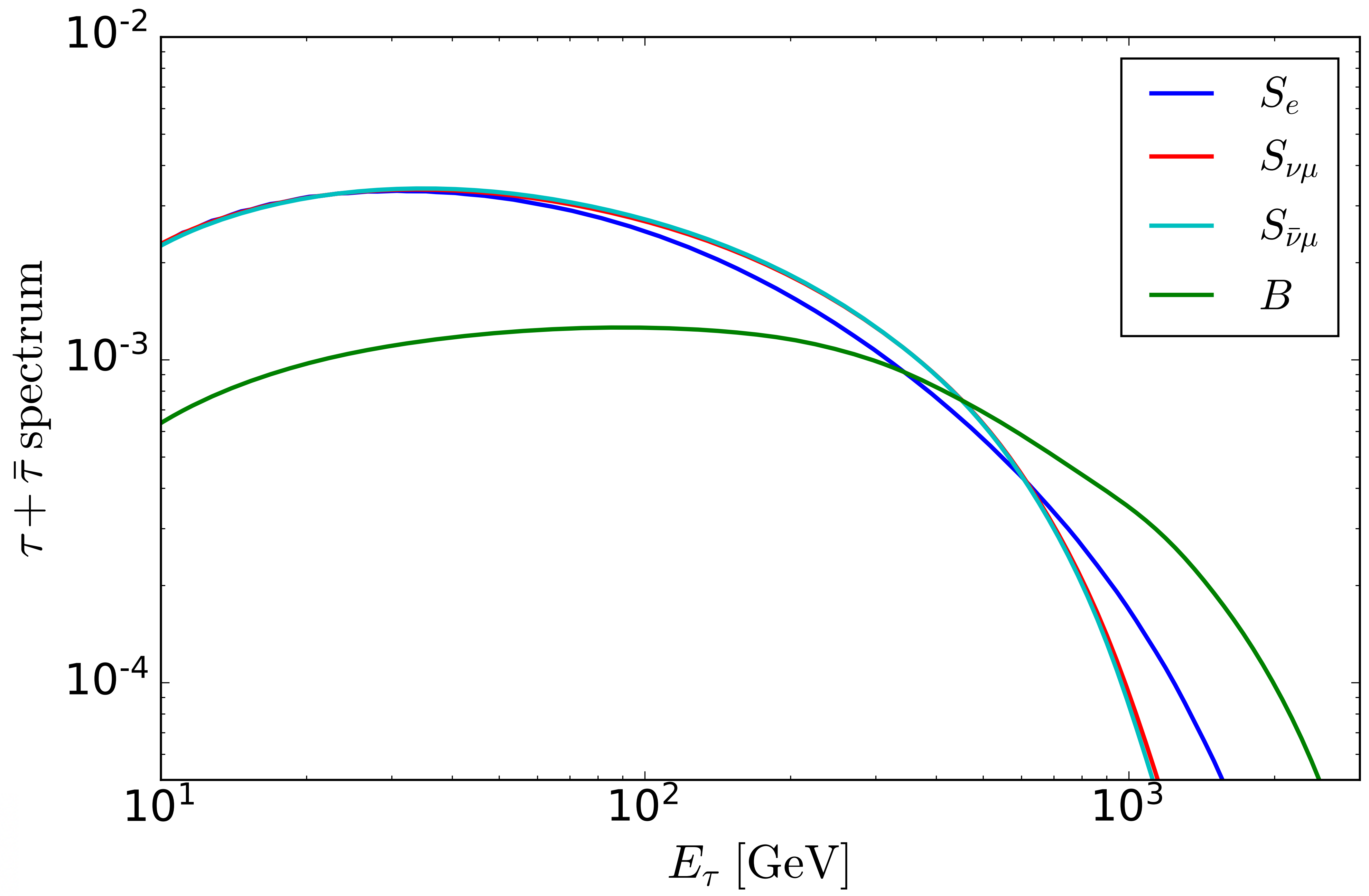
Using the spectral information dramatically increases the sensitivity to the new physics signal



Excess of Tau events at SND@LHC, FASERν and FASERν2, Saeed Ansarifard and Yasaman Farzan, The European Physical Journal C 82 (6), 1-15, 2112.08799

τ Spectrum

Spectrum from new physics versus the background



$$S_{\nu\mu}(E_\tau) \equiv \frac{\int_{E_\tau}[F^{\pi}_{\nu_\mu}(E_\nu)\frac{d\sigma^{SM}_{\nu}}{dE_\tau} + F^{\pi}_{\bar{\nu}_\mu}(E_\nu)\frac{d\sigma^{SM}_{\bar{\nu}}}{dE_\tau}]dE_\nu}{\int[F^{\pi}_{\nu_\mu}(E_\nu)\sigma^{SM}_{\nu} + F^{\pi}_{\bar{\nu}_\mu}(E_\nu)\sigma^{SM}_{\bar{\nu}}]dE_\nu},$$

$$S_{\bar{\nu}\mu}(E_\tau) \equiv \frac{\int_{E_\tau}[F^{\pi}_{\bar{\nu}_\mu}(E_\nu)\frac{d\sigma^{SM}_{\nu}}{dE_\tau} + F^{\pi}_{\nu_\mu}(E_\nu)\frac{d\sigma^{SM}_{\bar{\nu}}}{dE_\tau}]dE_\nu}{\int[F^{\pi}_{\bar{\nu}_\mu}(E_\nu)\sigma^{SM}_{\nu} + F^{\pi}_{\nu_\mu}(E_\nu)\sigma^{SM}_{\bar{\nu}}]dE_\nu}.$$

$$B = \frac{\int_{E_\tau}[F_{\nu_\tau}(E_\nu)\frac{d\sigma^{SM}_{\nu}}{dE_\tau} + F_{\bar{\nu}_\tau}(E_\nu)\frac{d\sigma^{SM}_{\bar{\nu}}}{dE_\tau}]dE_\nu}{\int[F_{\nu_\tau}(E_\nu)\sigma^{SM}_{\nu} + F_{\bar{\nu}_\tau}(E_\nu)\sigma^{SM}_{\bar{\nu}}]dE_\nu}.$$

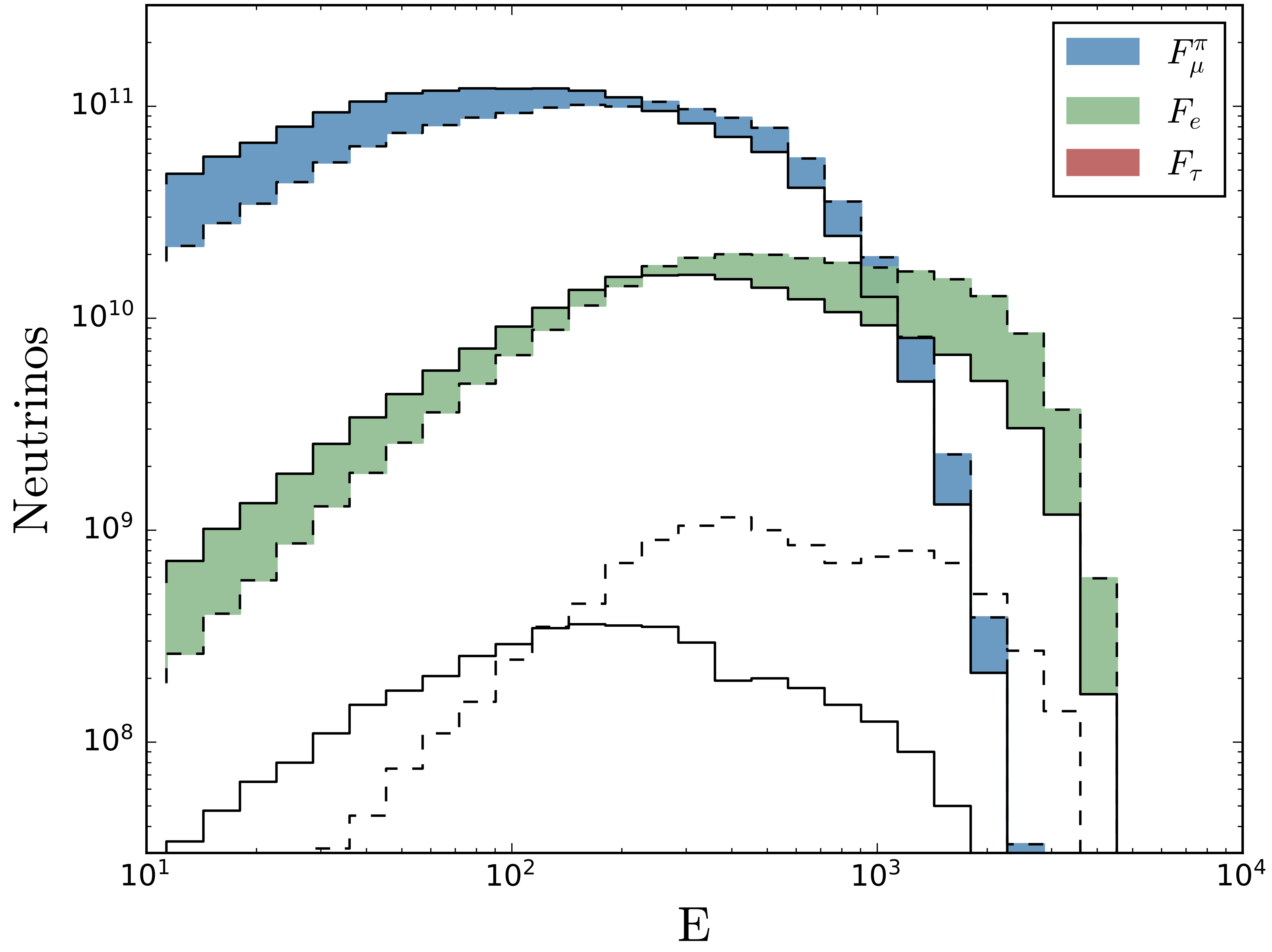
Excess of Tau events at SND@LHC, FASERν and FASERν2, Saeed Ansarifard and Yasaman Farzan, The European Physical Journal C 82 (6), 1-15, 2112.08799

Prediction of Neutrino fluxes

$$15\ \%\ \text{to}\ 50\ \%$$

$$1.8 \times 10^{-3}\ \text{to}\ 6 \times 10^{-3}$$

F_μ^π -> line : QGS and dash-line: DPM
F_e -> line : Pyth and dash-line: DPM
F_τ -> line : SIB and dash-line: DPM



Consideration of uncertainty in fluxes

$$\sigma_\eta = 0.25$$

$$4.6 \times 10^{-4} \qquad 2 \times 10^{-3}$$

Examining the shape and normalization of flux uncertainty

Simulator	bin limits in GeV					χ^2_{rel}
	< 50	$50 - 100$	$100 - 500$	$500 - 1000$	$1000 <$	
Pythia8 (Hard)	0.9	1.8	8.1	9.7	4.8	0.0
DPMJET 3.2017	1.5	3.1	16.2	23.3	14.5	43.7
SIBYLL 2.3c	0.7	1.1	3.7	3.1	0.7	9.6

Excess of Tau events at SND@LHC, FASERν and FASERν2, Saeed Ansarifard and Yasaman Farzan, The European Physical Journal C 82 (6), 1-15, 2112.08799

Summery

- We have proposed a model with new scaler doublet and right handed Neutrino.
- In the minimal version of the model, the signatures at forward experiments will be a multiple jet vertex due to N production
- The phi and N also could couple to the first and third lepton generations. However we focused on the second as it is less constrained than first and moreover, the possibility of an observable signal is higher
- In both version of minimal and model with multiple N, The predicted signals at FASERnu will be background free.
- Constructing the energy spectrum at FASERnu2 can significantly improve the sensitivity to the new physics.