Neutrino physics in forward experiments

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GNU-IBS Workshop on Particle Physics and Cosmology
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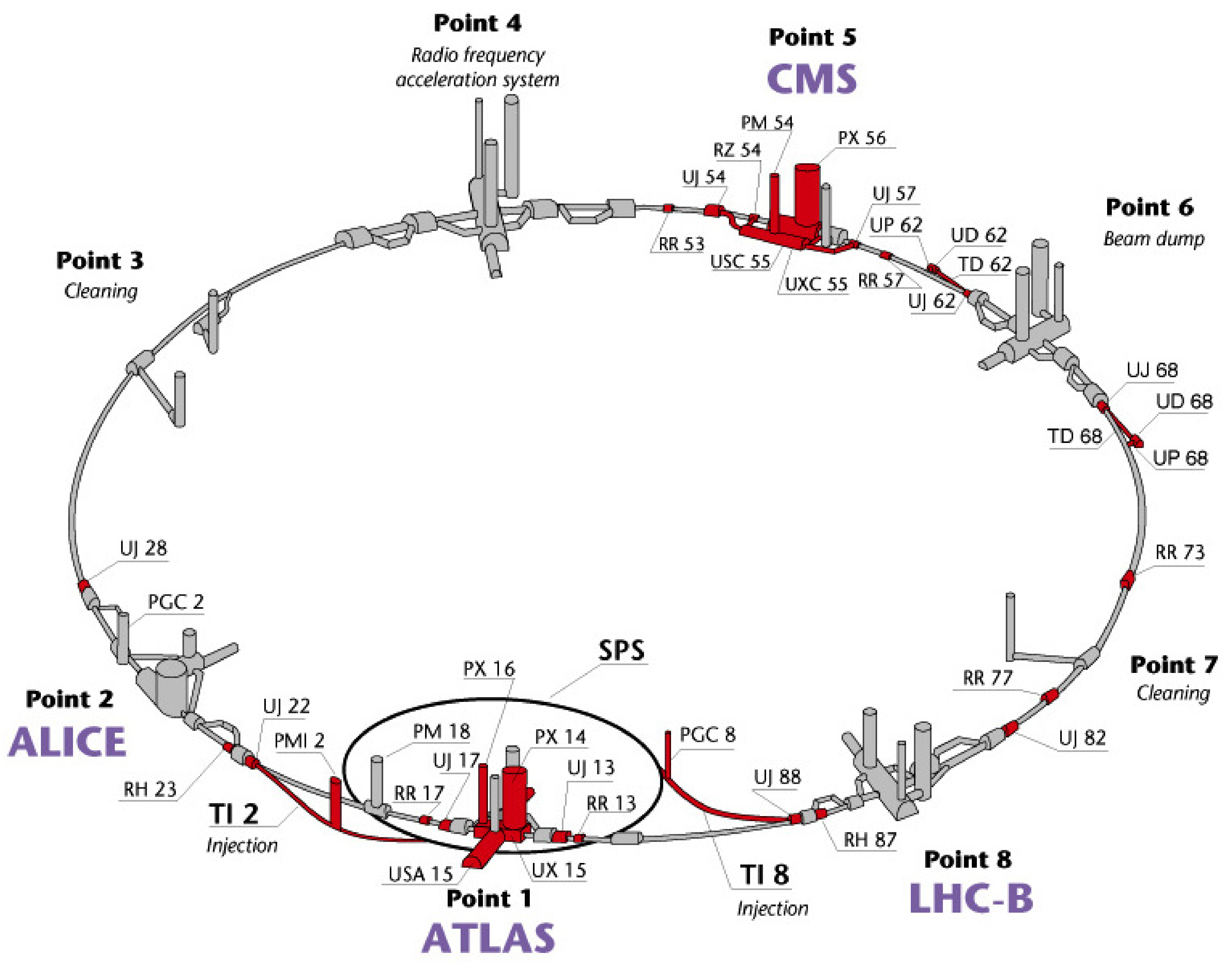
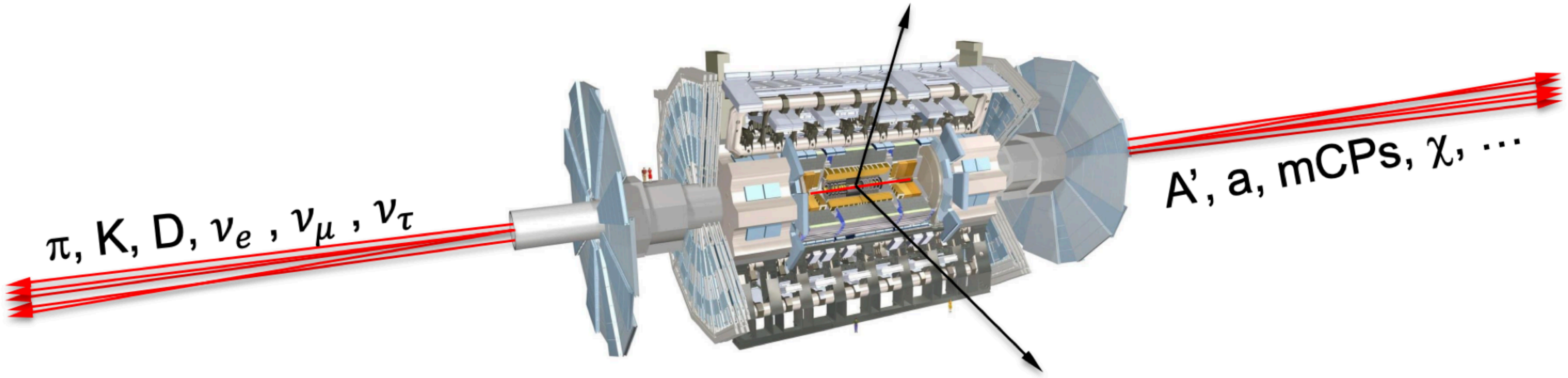
Motivation of forward experiments?

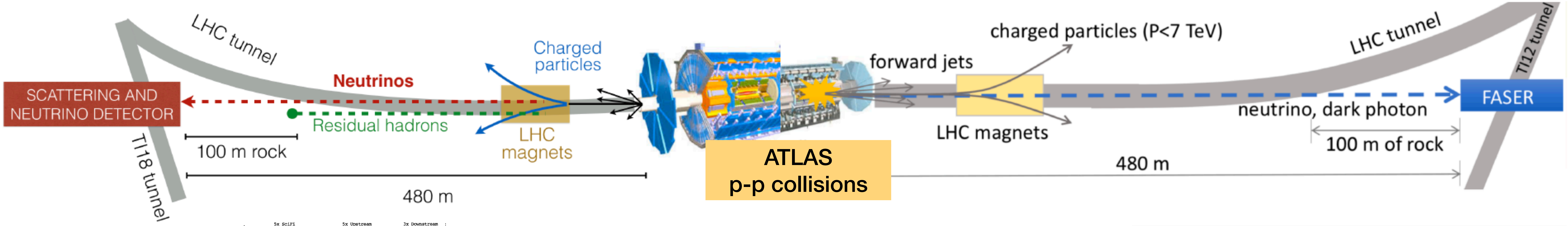


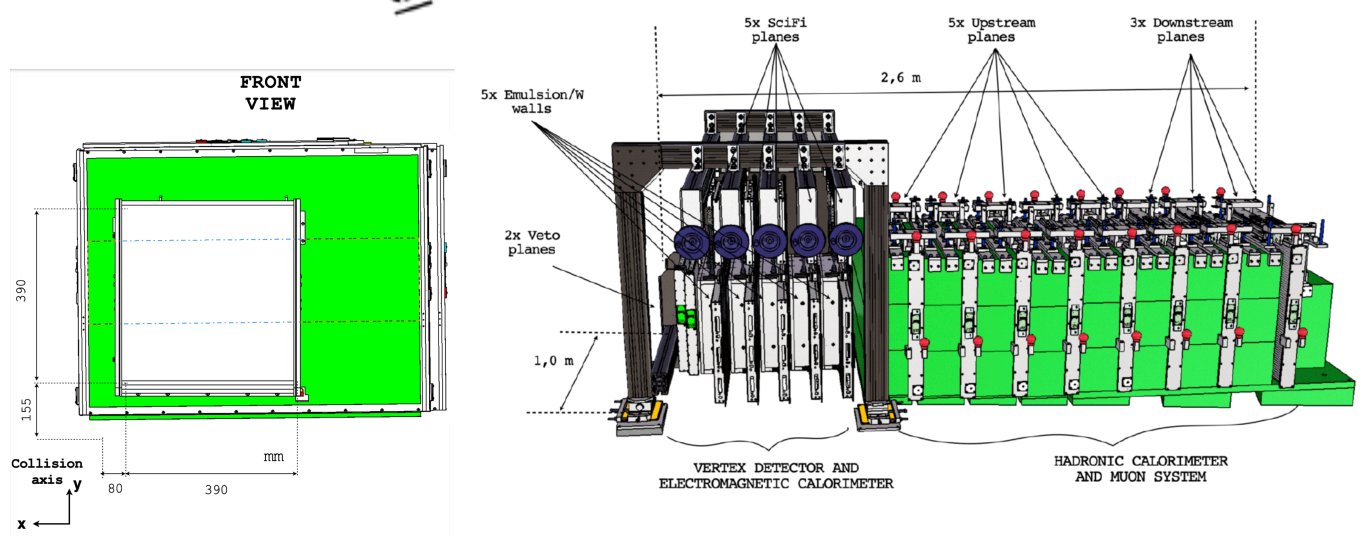
- The major experiments of the LHC have explored the central regions focusing on heavy particles produced with high p_T .
- Most light and weakly interacting particles are emitted into the very forward direction along the beam line.
- Evidence for TeV-scale new physics hasn't been discovered.
- It is worth exploring different kinematic regions.

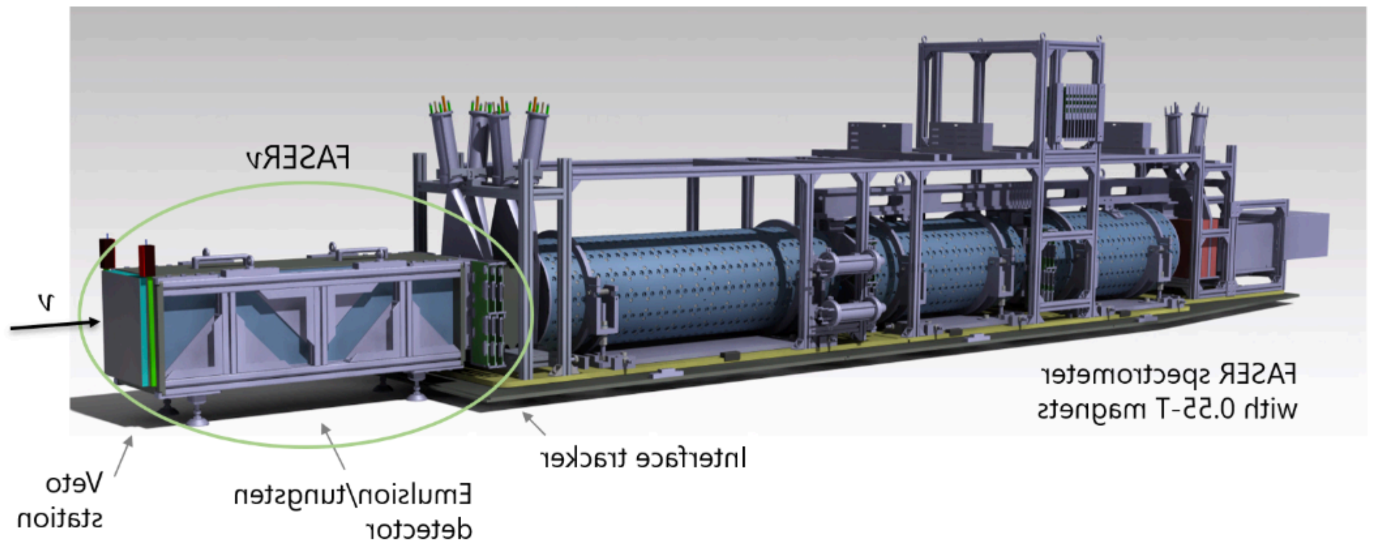
- Earlier discussions about forward neutrinos: deRujula & Ruckl (1984), Winter (1990)



Forward experiments during the Run 3





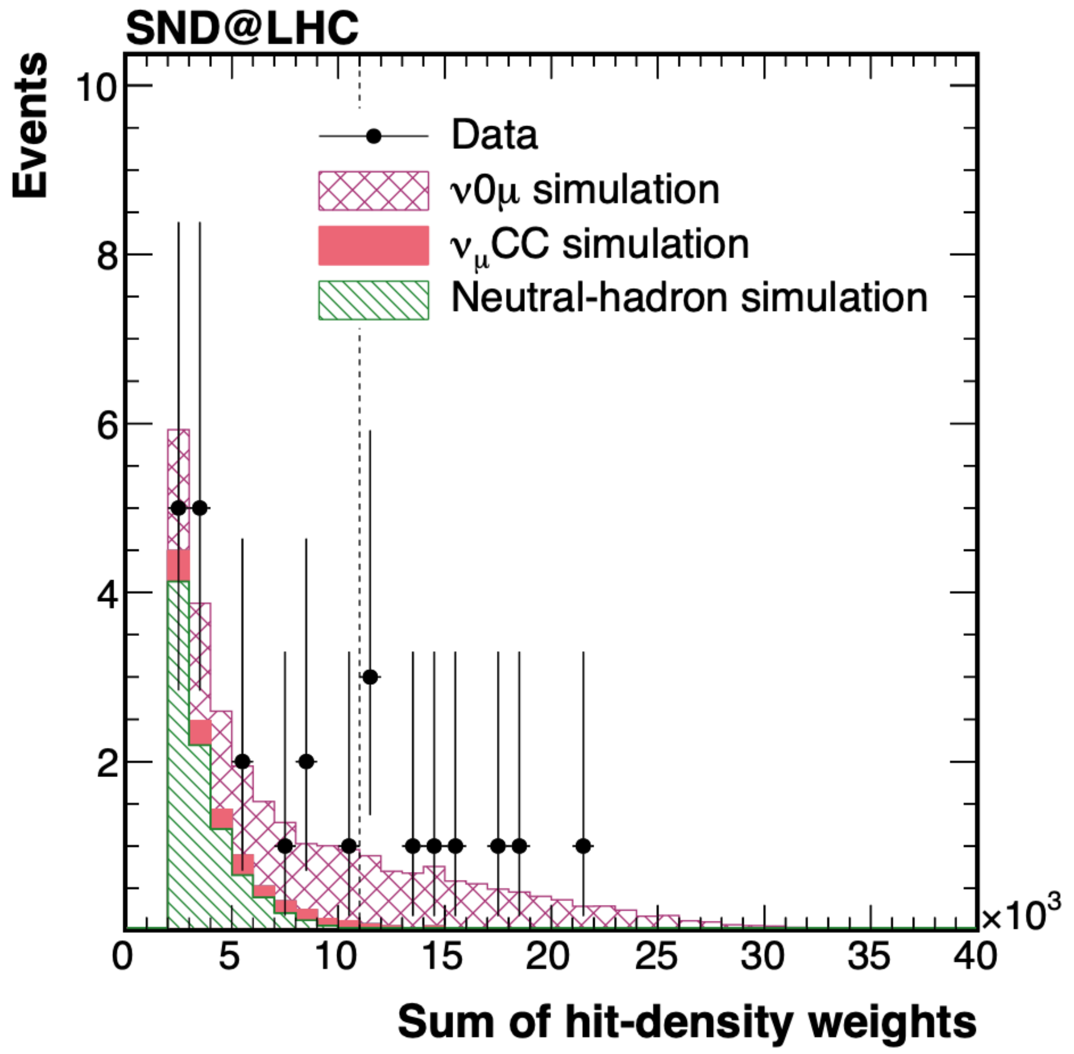


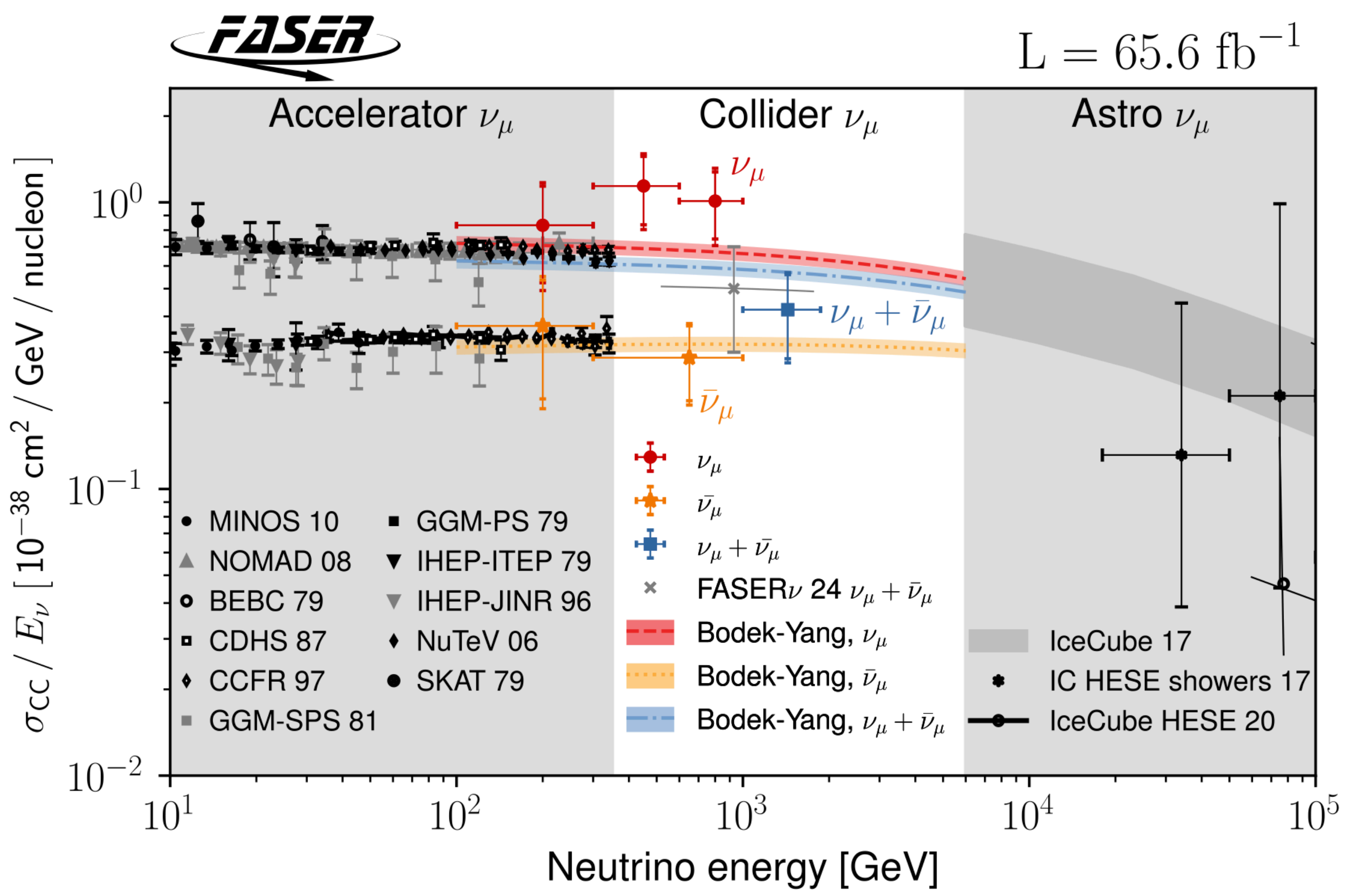
	SND@LHC	FASERν
Rapidity	$7.2 < \eta < 8.4$ (off-axis)	$\eta \gtrsim 8.5$ (on-axis)
Target material	Tungsten (w/ emulsion film)	Tungsten (w/ emulsion film)
Target mass	830 kg	1.1 tons
Surface	39 x 39 cm^2	25 x 30 cm^2 (1.1 m long)

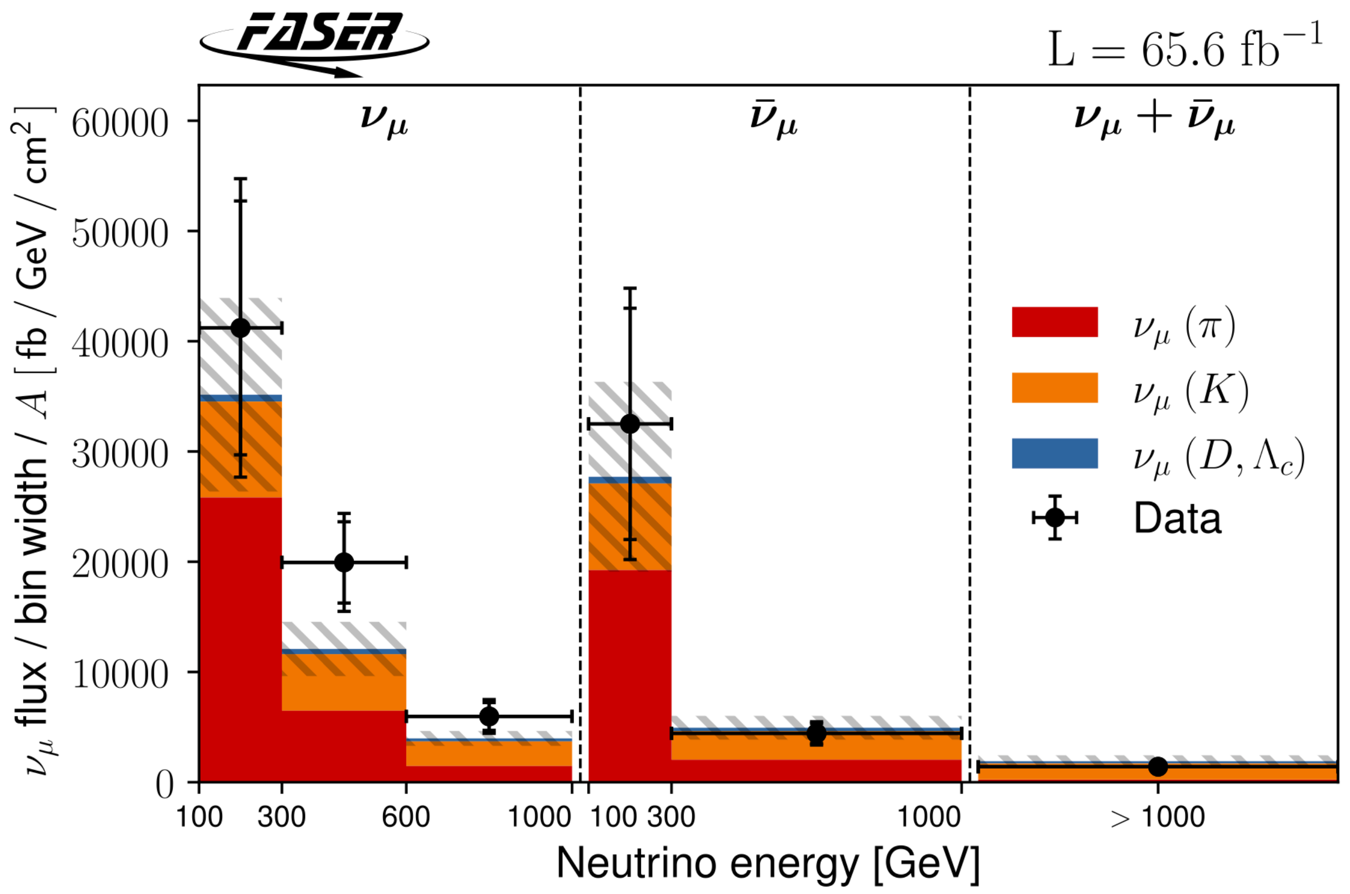
Neutrino results from the Run-3 experiments

- Observation of Collider Neutrinos
  - PRL 131, 031801 (2303.14185; FASER) - 153^{+12}_{-13} muon neutrinos
  - PRL 131, 031802 (2305.09383, SND@LHC) - 8 muon neutrinos
  - PRL 134, 231802 (2411.18787, SND@LHC) - 9 neutrino events without final-state muons

- Measurement of the neutrino interaction cross sections and flux
  - PRL 133, 021802 (2403.12520, FASER) - ν_e and ν_μ cross sections at TeV energies
  - PRL 134, 211801 (2412.03186, FASER) - cross section and flux of ν_μ as function of Energy





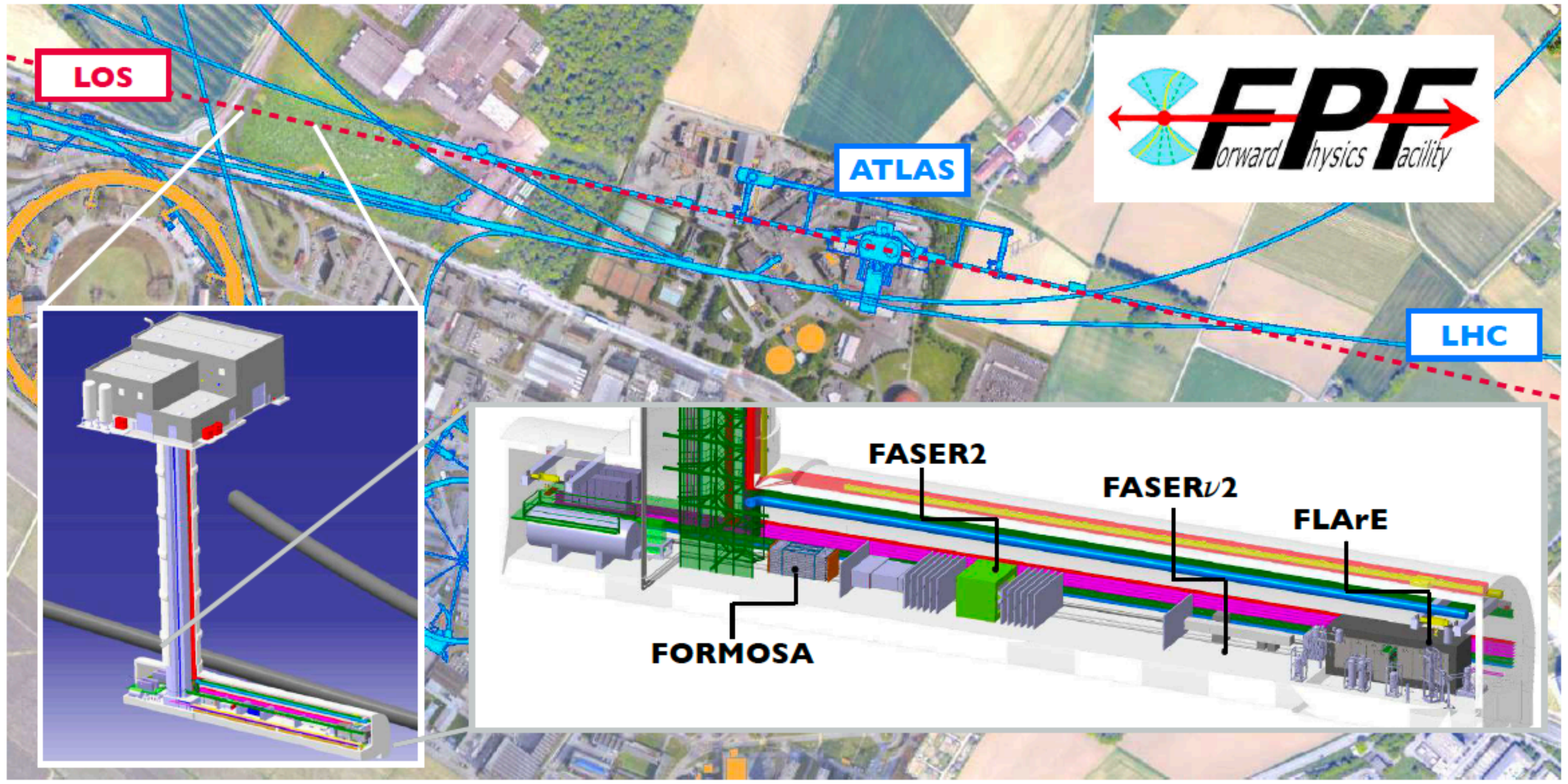


Forward neutrino program at the HL-LHC

- Approved experiments during HL-LHC era
  - Advanced SND (AdvSND, upgraded SND)
  - FASER/FASERν

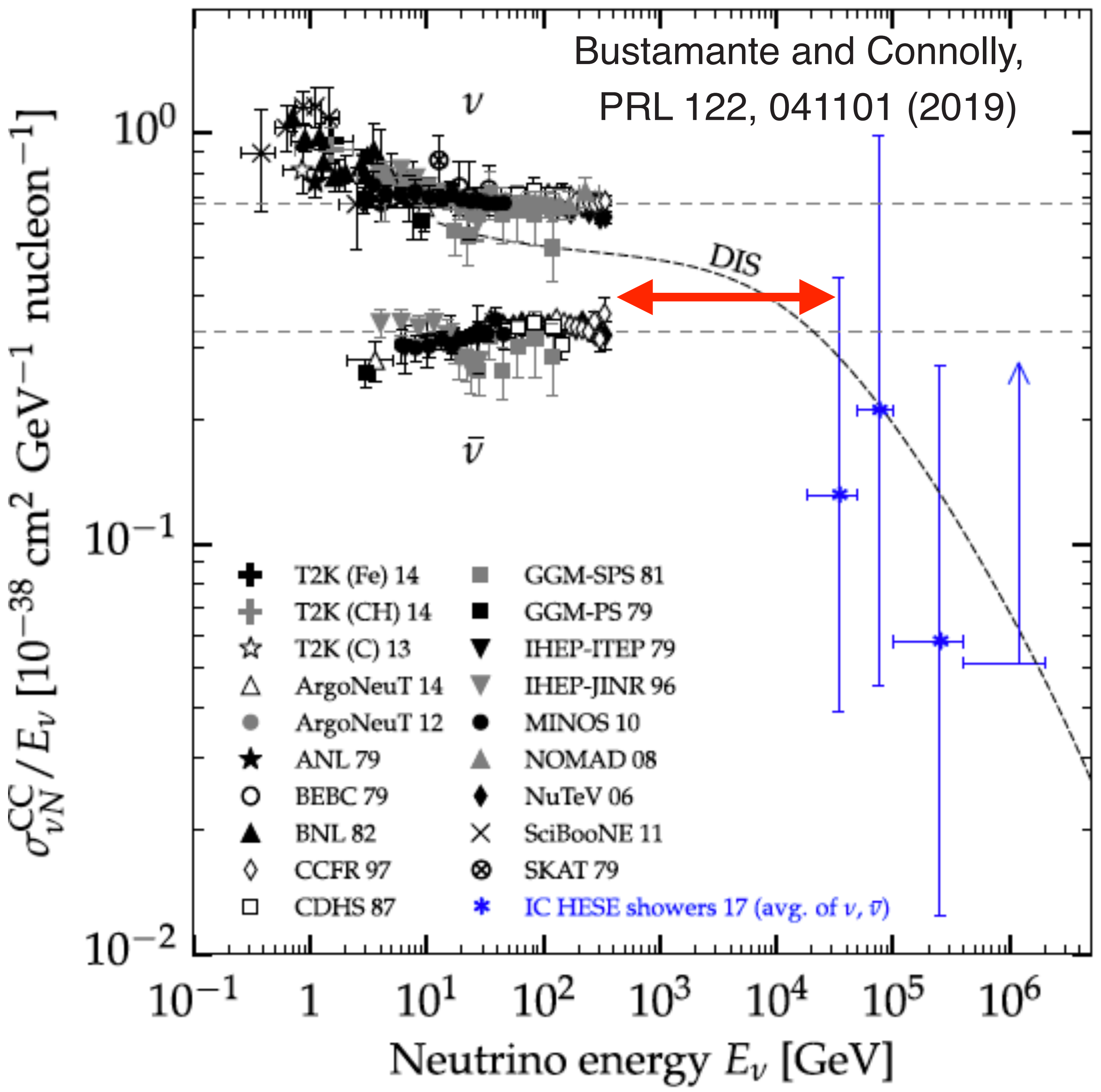
✓ Nearly same location
✓ Similar scale detectors
✓ About 10 times higher statistics

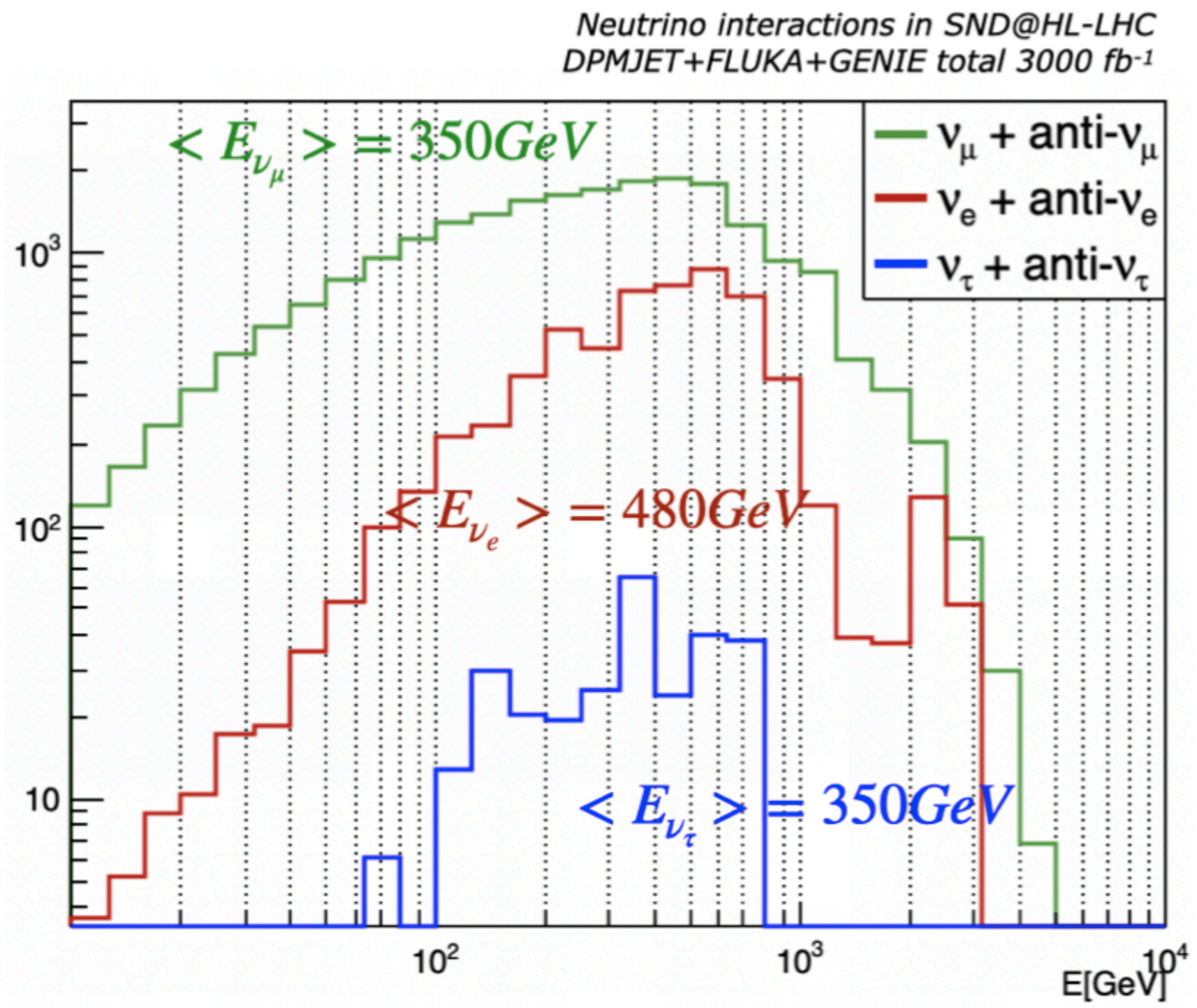
- Forward Physics Facility (FPF - proposal)
  - FASER2 / FASERν2 (upgraded detectors)
  - FLArE (LArTPC, neutrino and dark matter)
  - FORMOSA (millicharged particle search)



Primary goals: Neutrino Cross Sections at TeV Energies

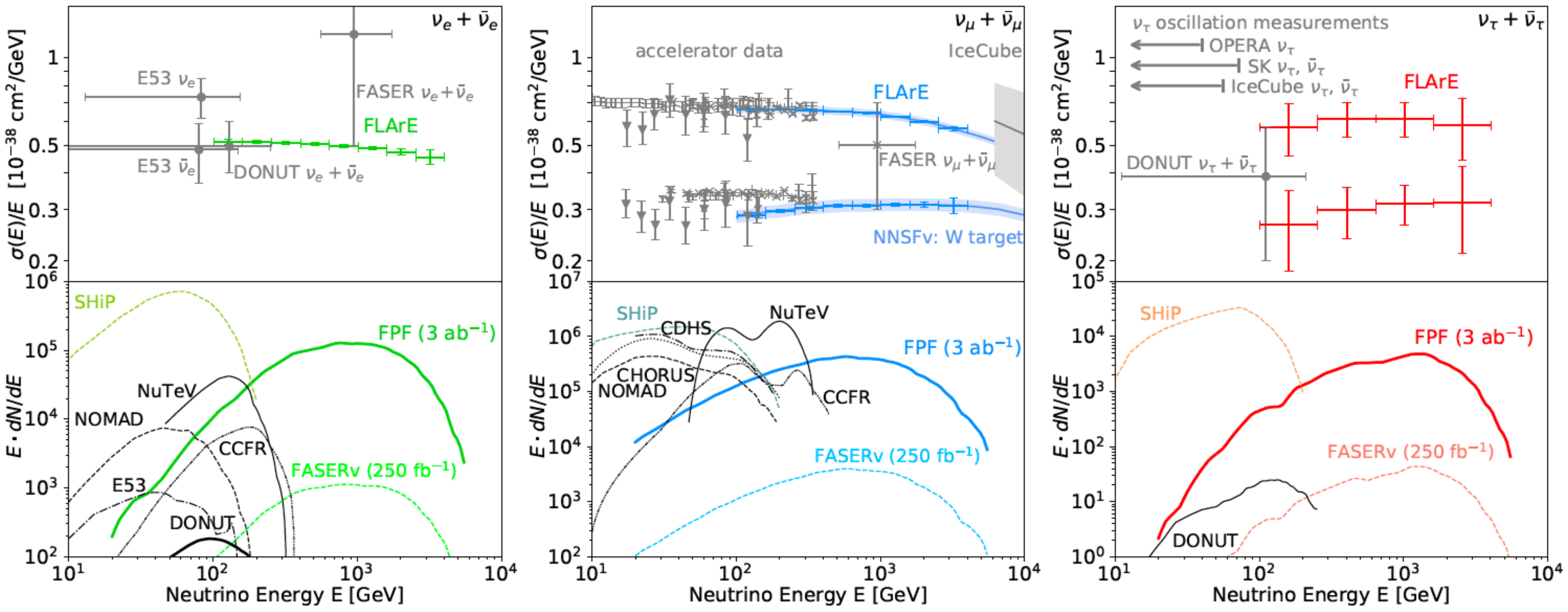
- Measurement of neutrino cross section in the TeV energy range
  - Neutrino cross sections have been measured below 400 GeV by fixed target accelerator experiments and above 10 TeV by IceCube.
  - LHC neutrinos are distributed from about 10 GeV - a few TeV with majority of neutrinos over 100 GeV region.
- LHC neutrinos could fill the gap between the existing measurements.





Primary goals: Precision of cross sections & ν_τ studies

- Cross section measurement with high precision
  - Large numbers of neutrino events are expected at the HL-LHC stage
  - Significant improvement for all three flavors
- Tau neutrino interaction with unprecedented high statistics
  - Provide the potential to test lepton flavor universality (in the neutrino sector)

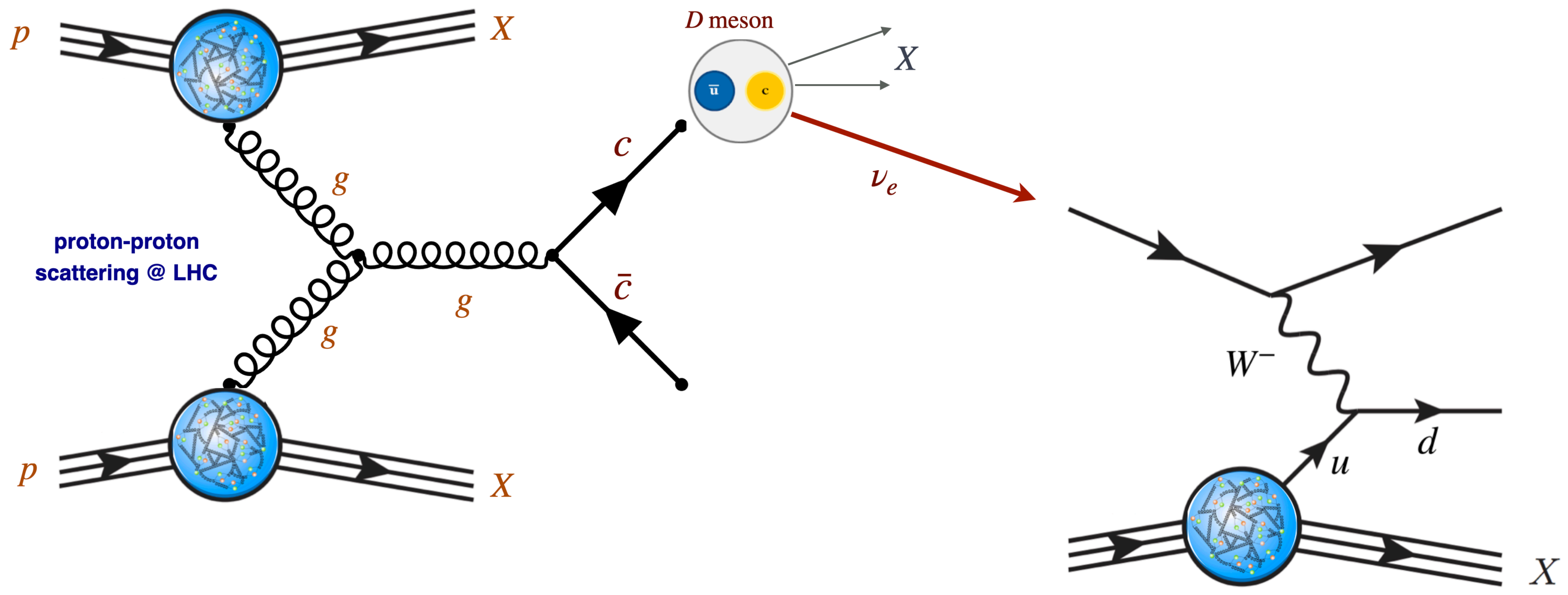


(e.g.) expected events at the FPF:

$\sim 10^5\ \nu_e$, $\sim 10^6\ \nu_\mu$, $\sim 10^3\ \nu_\tau$

Further physics potential (SM)

- QCD
  - Forward particle production, (small-x physics)
  - Charm production models
  - Proton and nuclear structure



- Implication for astroparticle physics
  - Muon puzzle
  - Atmospheric neutrino fluxes

- Neutrino interactions
  - Heavy flavor-involved neutrino interactions
  - Deep-/shallow-inelastic scattering

Figures from Juan Rojo's slide (FPF meetings)

Forward charm production

charm production as the source of TeV-scale neutrinos

Neutrino production at the LHC

- In proton collisions at the high energy of the LHC, various hadrons are produced, some of which subsequently decay and produce a number of neutrinos.

- Conventional neutrinos: neutrinos from the decay of light flavor hadrons
  - Charged pions ($\pi^{\pm}$), kaons ($K^{\pm}$, K_L) ...
  - $c\tau_{\pi^{\pm}} \simeq 7.8\, m, \quad c\tau_{K^{\pm}} \simeq 3.7\, m, \quad c\tau_{K_L} \simeq 15.3\, m$

- Prompt neutrinos: the heavy flavor hadron decays
  - Charm mesons (D^0, $D^{\pm}$, $D_s^{\pm}$), B-mesons (B^0, $B^{\pm}$) ...
  - $c\tau_{D^{\pm}} \simeq 312\, \mu m, \quad c\tau_{D^0} \simeq 123\, \mu m, \quad c\tau_{D_s^{\pm}} \simeq 151\, \mu m$

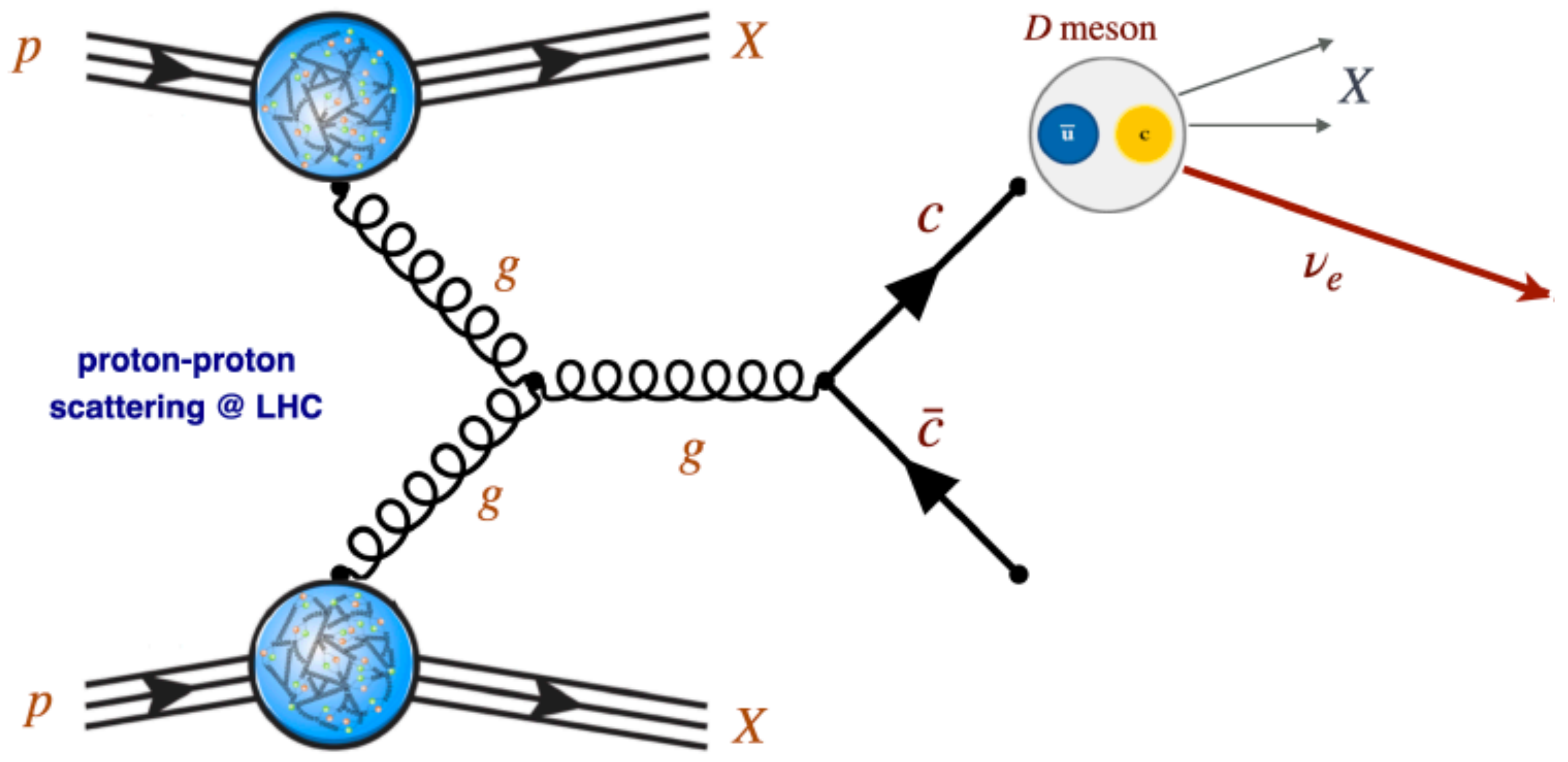
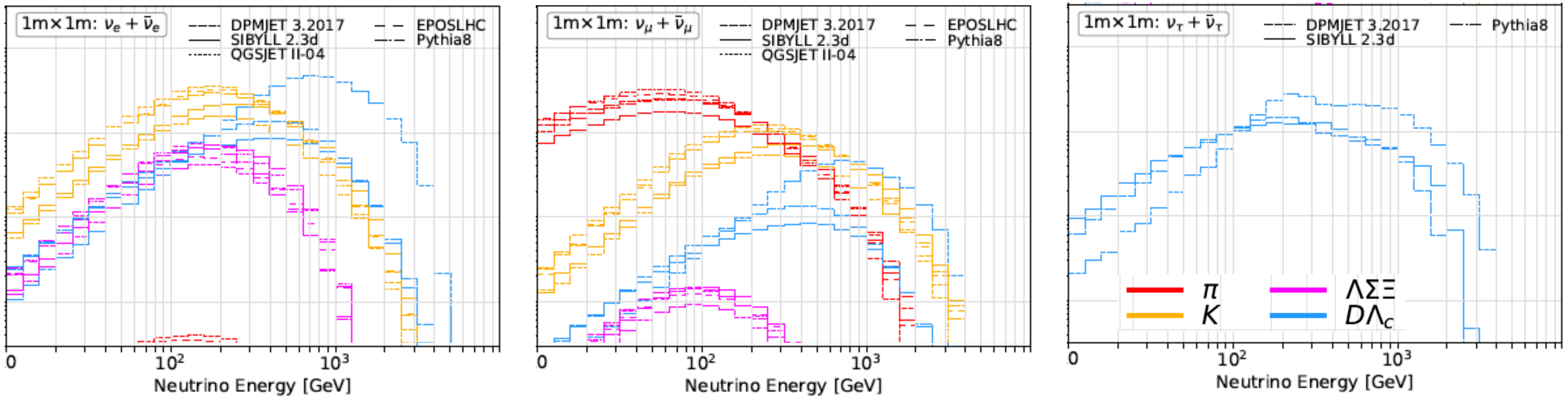


Figure from J. Rojo's slides, FPF7

Predictions of neutrino fluxes at the FPF

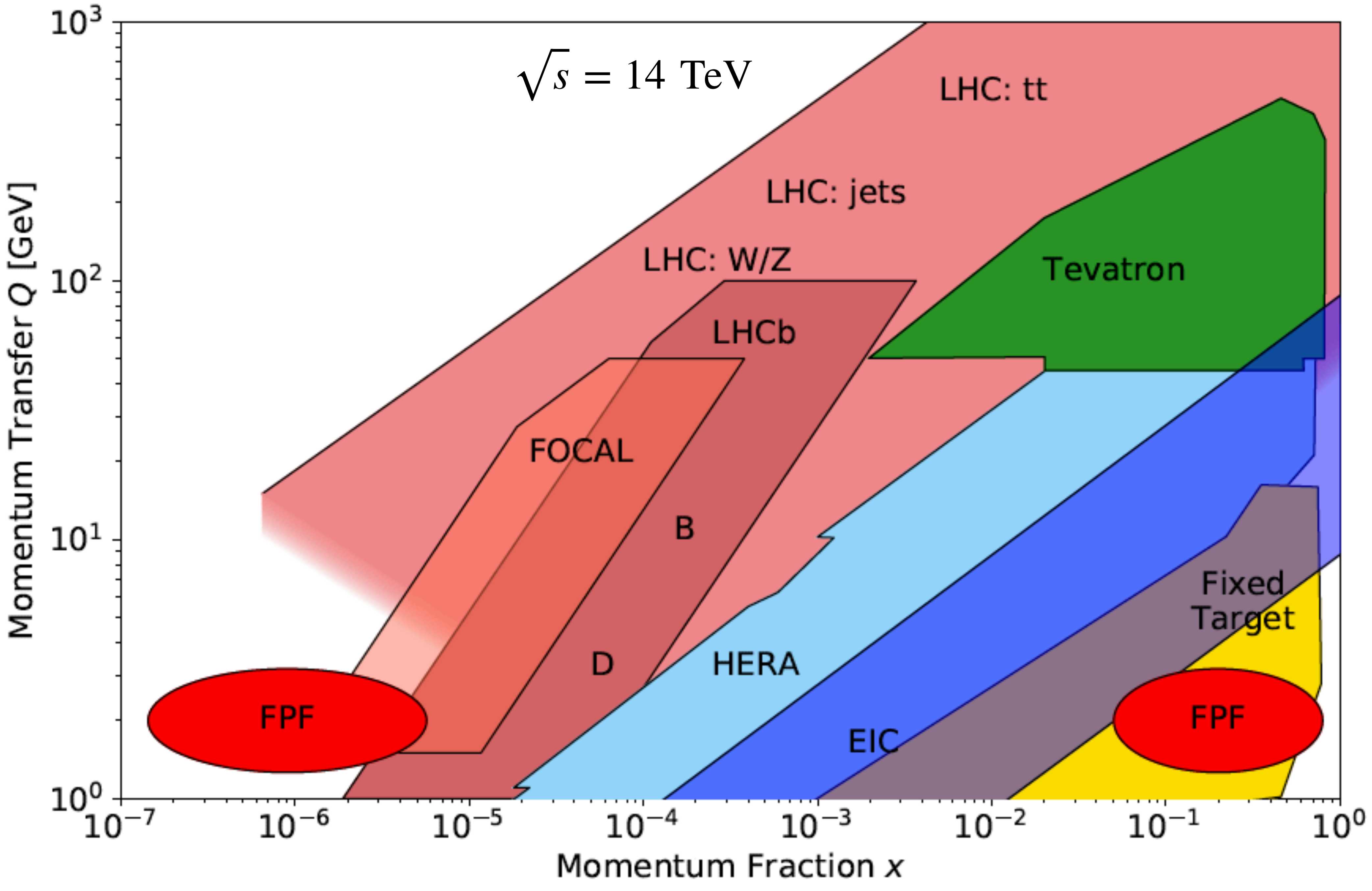
J. Feng et. al., *J.Phys.G* 50 (2023) 3, 030501



- Neutrinos from charm become important at high energies while neutrinos from π and K dominate at relatively lower energy region.
- There is no contribution from π and K for tau neutrinos fluxes.
- The fluxes of neutrinos from charm have large difference at high energies.

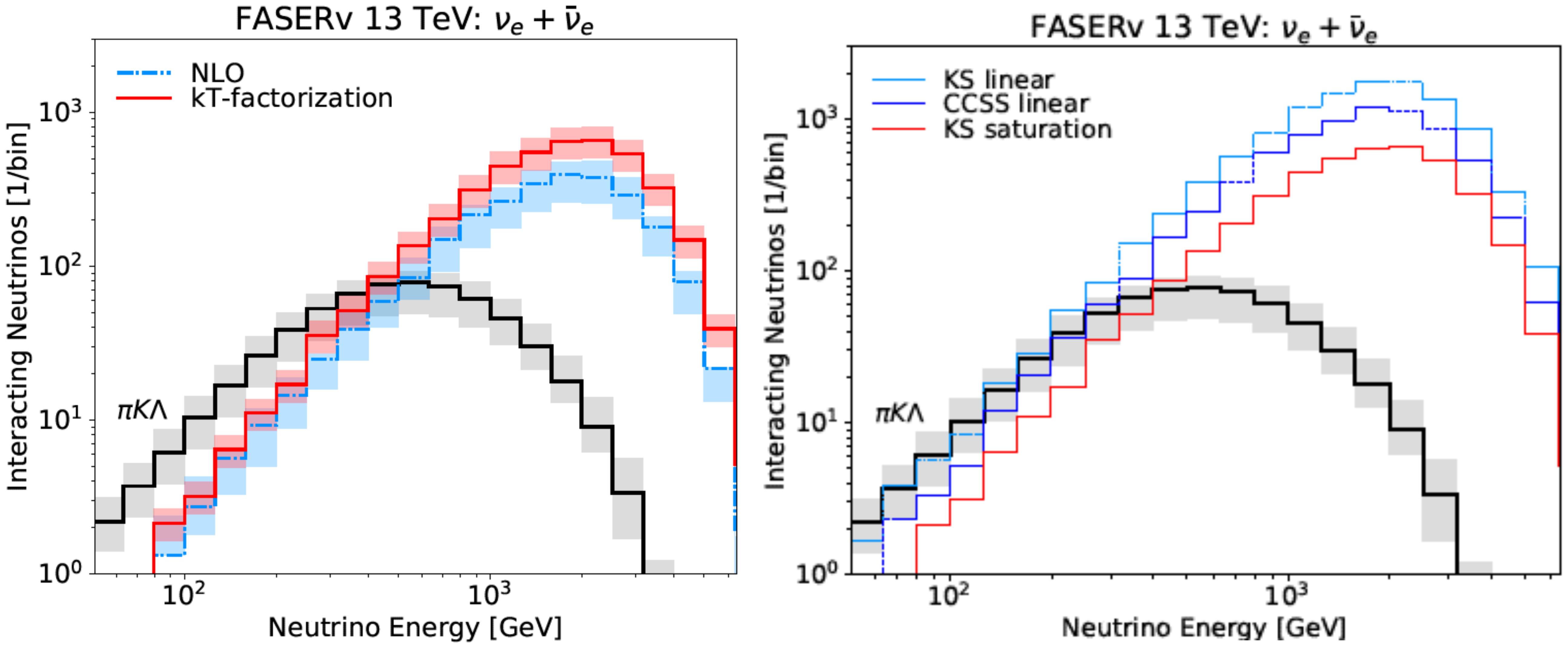
Charm production & small-x physics

✱ Kinematic region for D meson production



J. Feng et. al., *J.Phys.G* 50 (2023) 3, 030501

- Small-x physics:
  - PDF constraints, esp. gluon distributions
  - Gluon saturation
  - Collinear/kT factorization, color dipole model
  - Large log(1/x) resummation

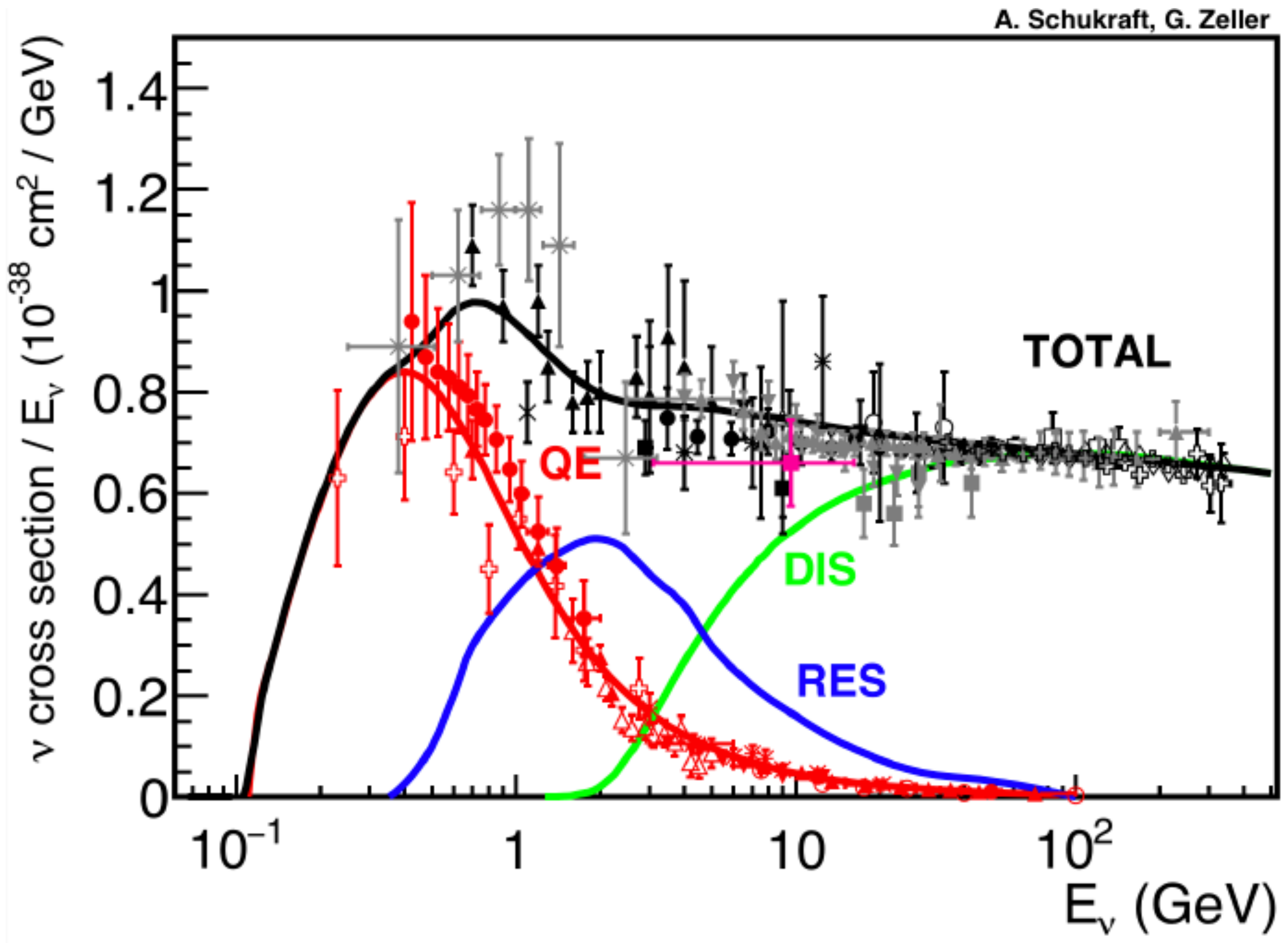


Bhattacharya, Kling, Sarcevic, Statsto,
Phys.Rev.D 109 (2024) 1, 014040

Neutrino Interactions

Deep inelastic scattering

- Most of LHC neutrinos have energies above 100 GeV, where neutrinos interact through deep inelastic scattering (DIS).
- In DIS, neutrinos interact with quark inside proton. Therefore DIS interaction is a strong probe for nucleon/nuclear structure by constraining the parton distribution functions.



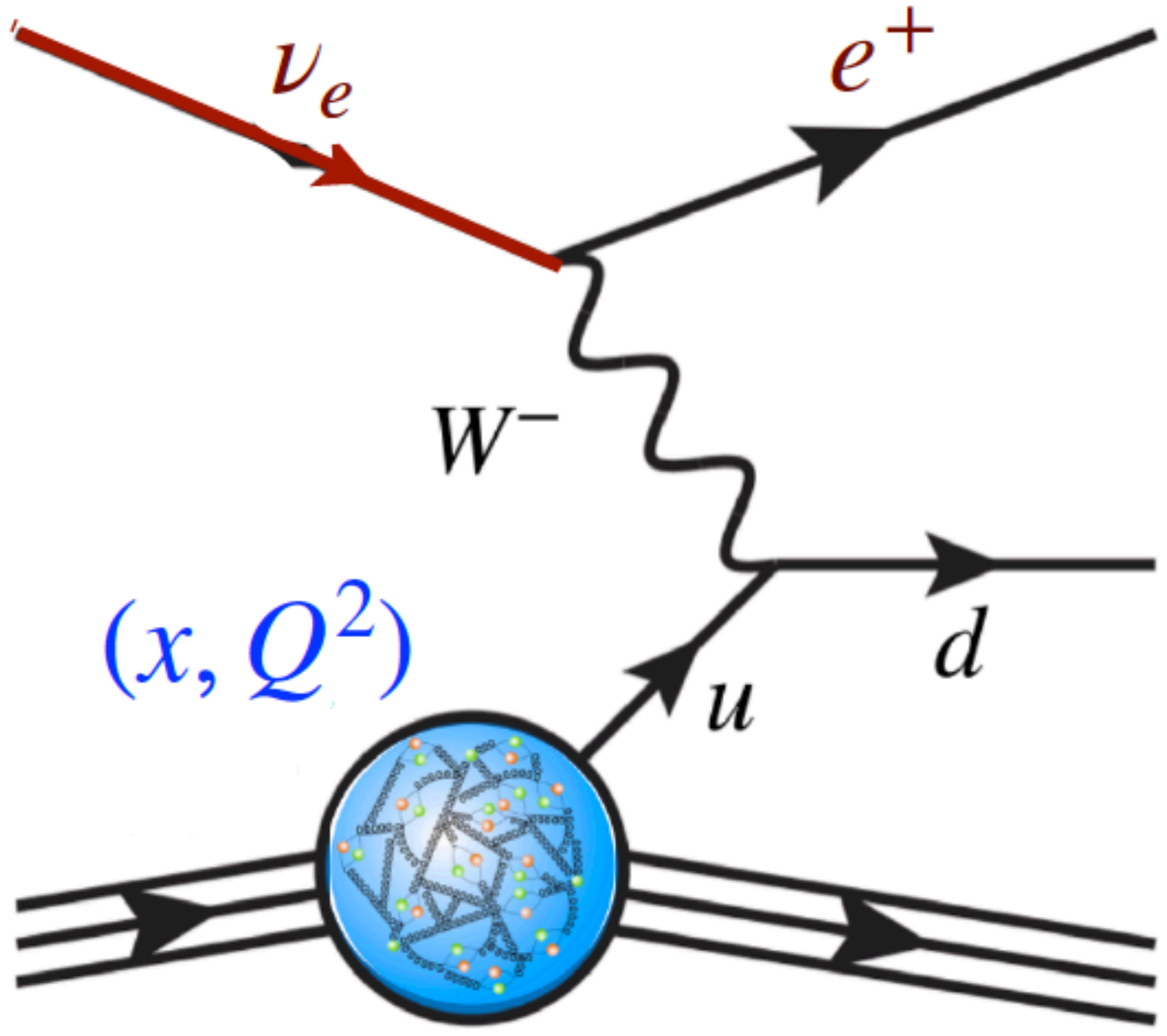
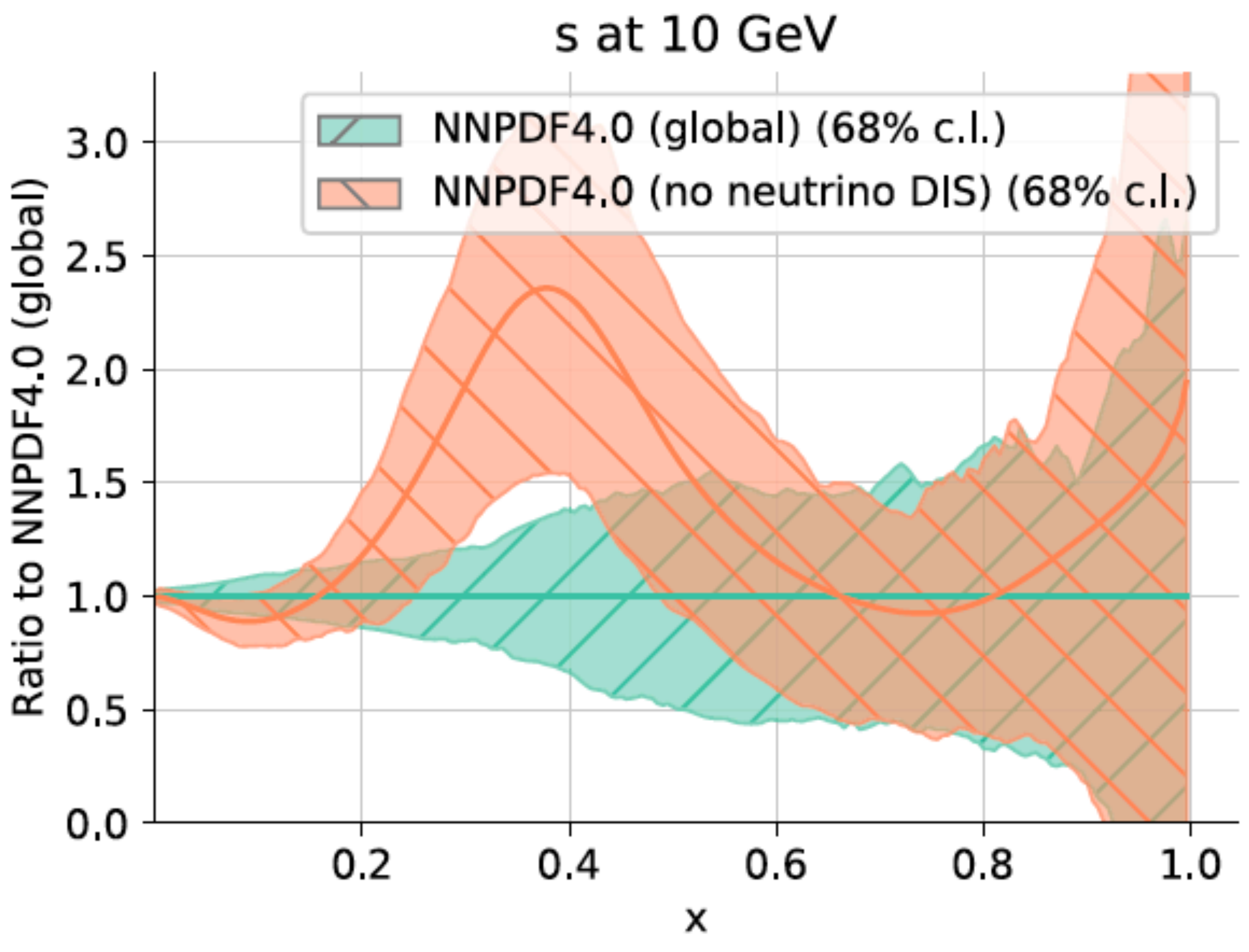
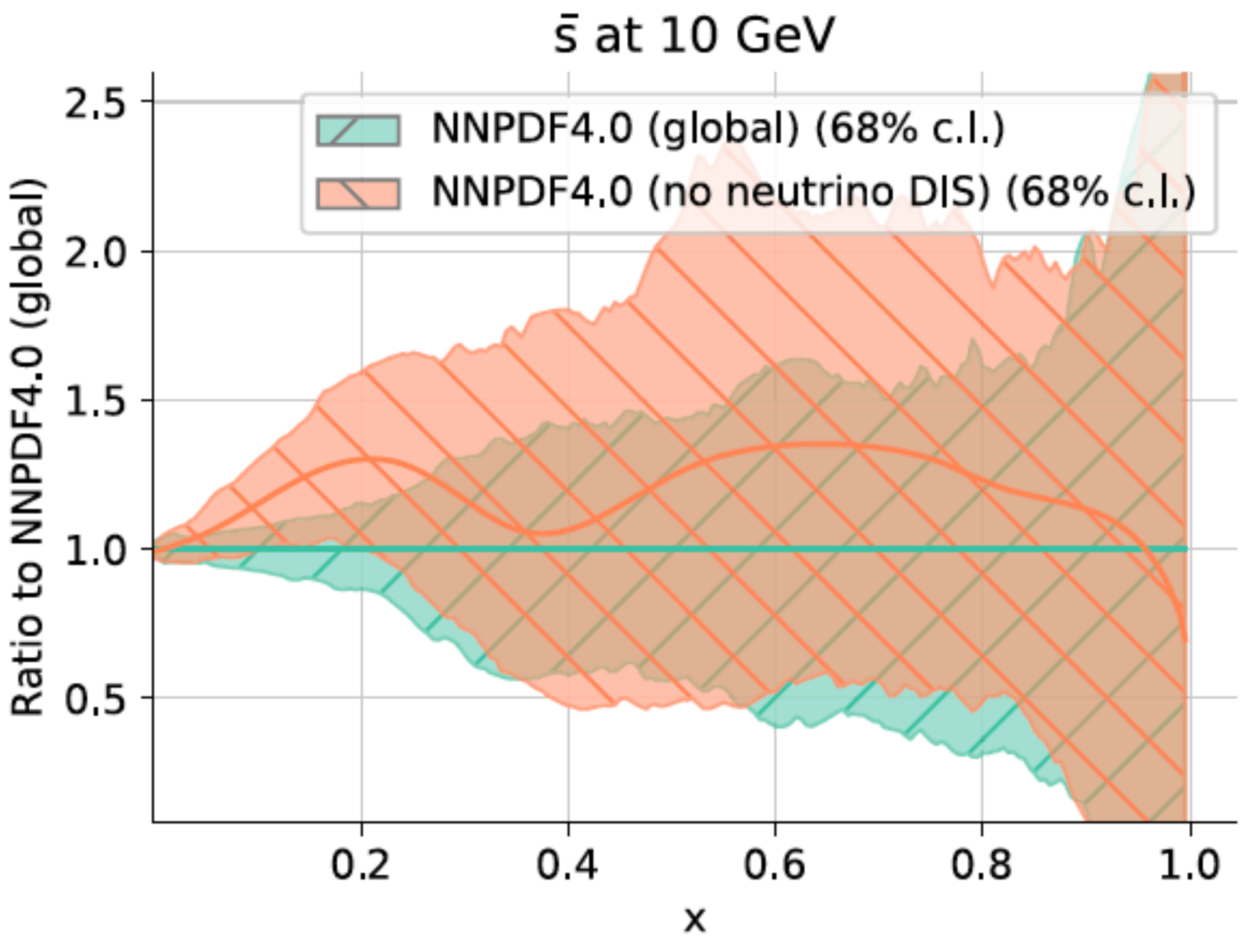


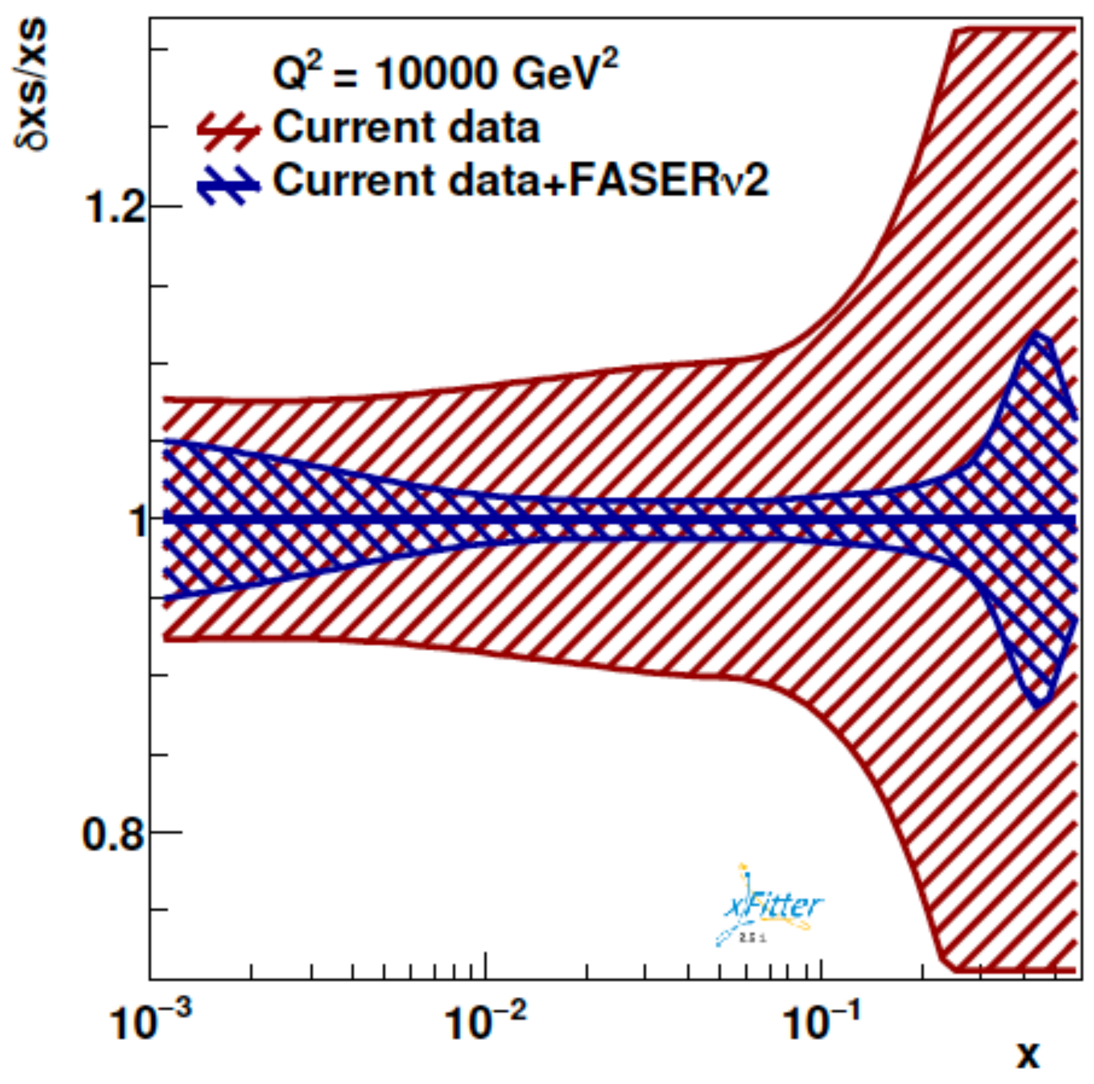
Figure from J. Rojo's slides, FPF7

Constraints on PDFs & strangeness puzzle

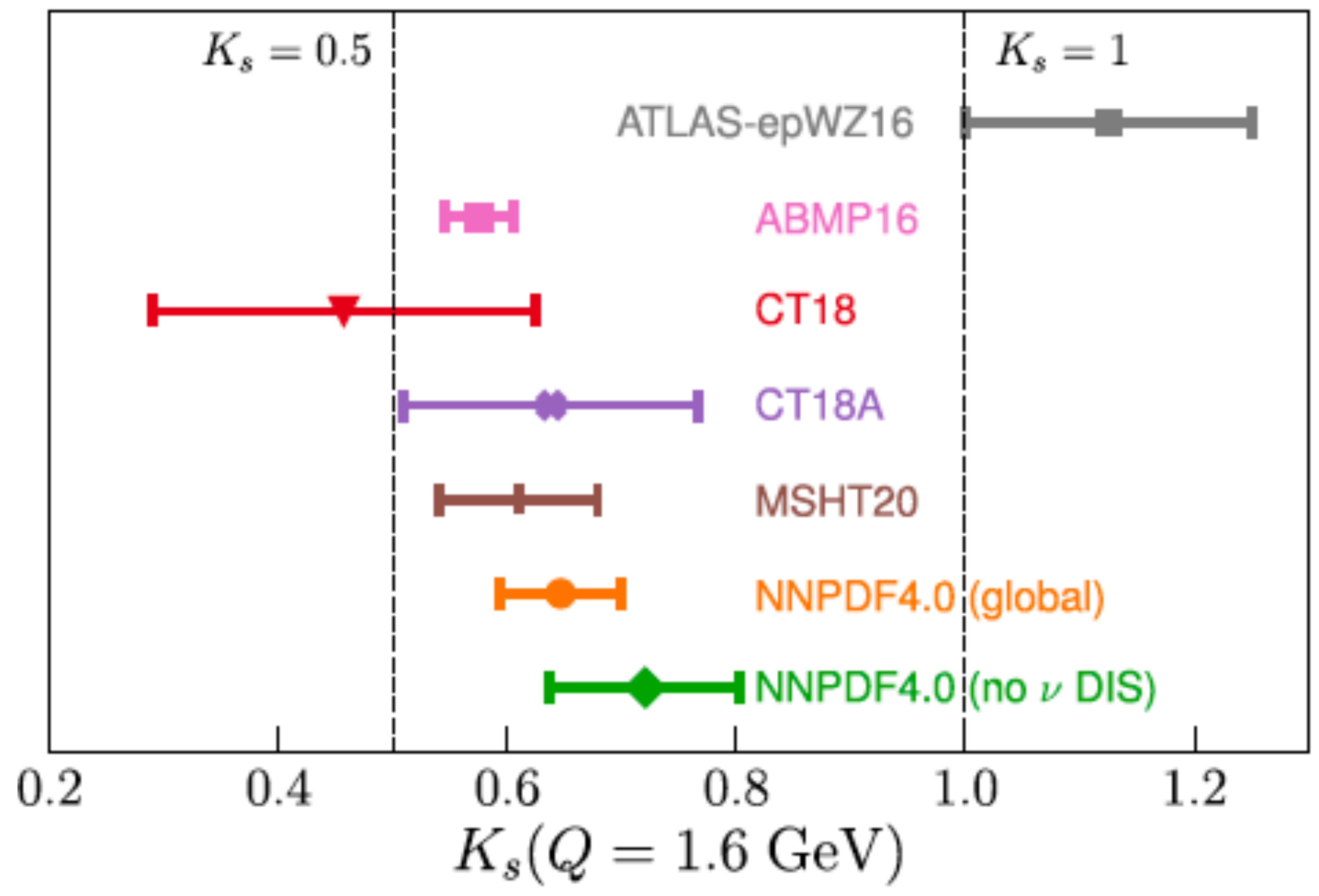




$$K_s \equiv \frac{\int_0^1 \mathrm{d}x\, x[s(x,Q) + \bar{s}(x,Q)]}{\int_0^1 \mathrm{d}x\, x[\bar{u}(x,Q) + \bar{d}(x,Q)]}$$

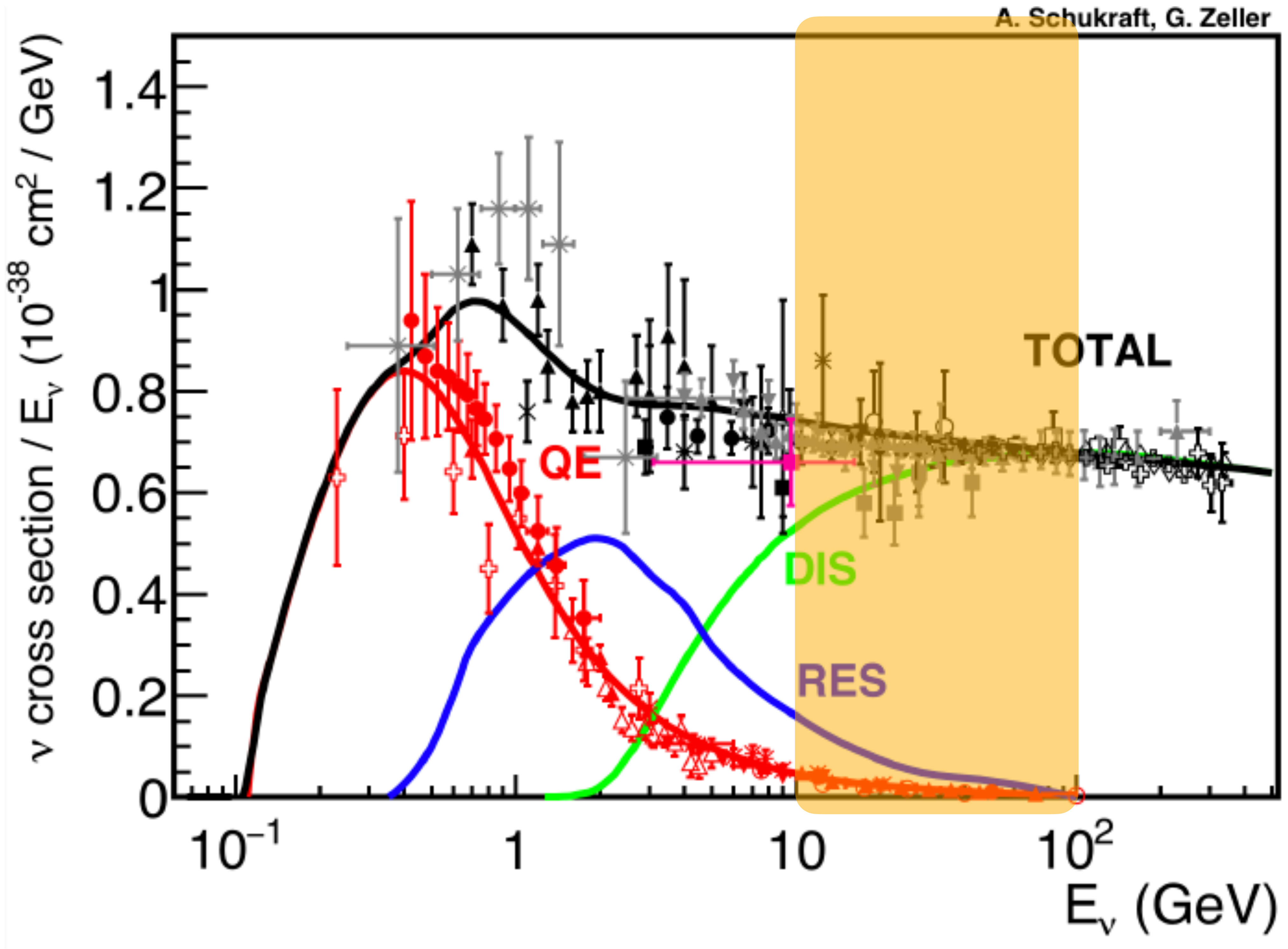


- Neutrino DIS data can improve in constraining the PDFs.
- Investigation on the strange PDF at forward experiments can shed light on the strangeness puzzle.



J. Feng et. al., *J.Phys.G* 50 (2023) 3, 030501

Non-DIS interactions of LHC neutrinos

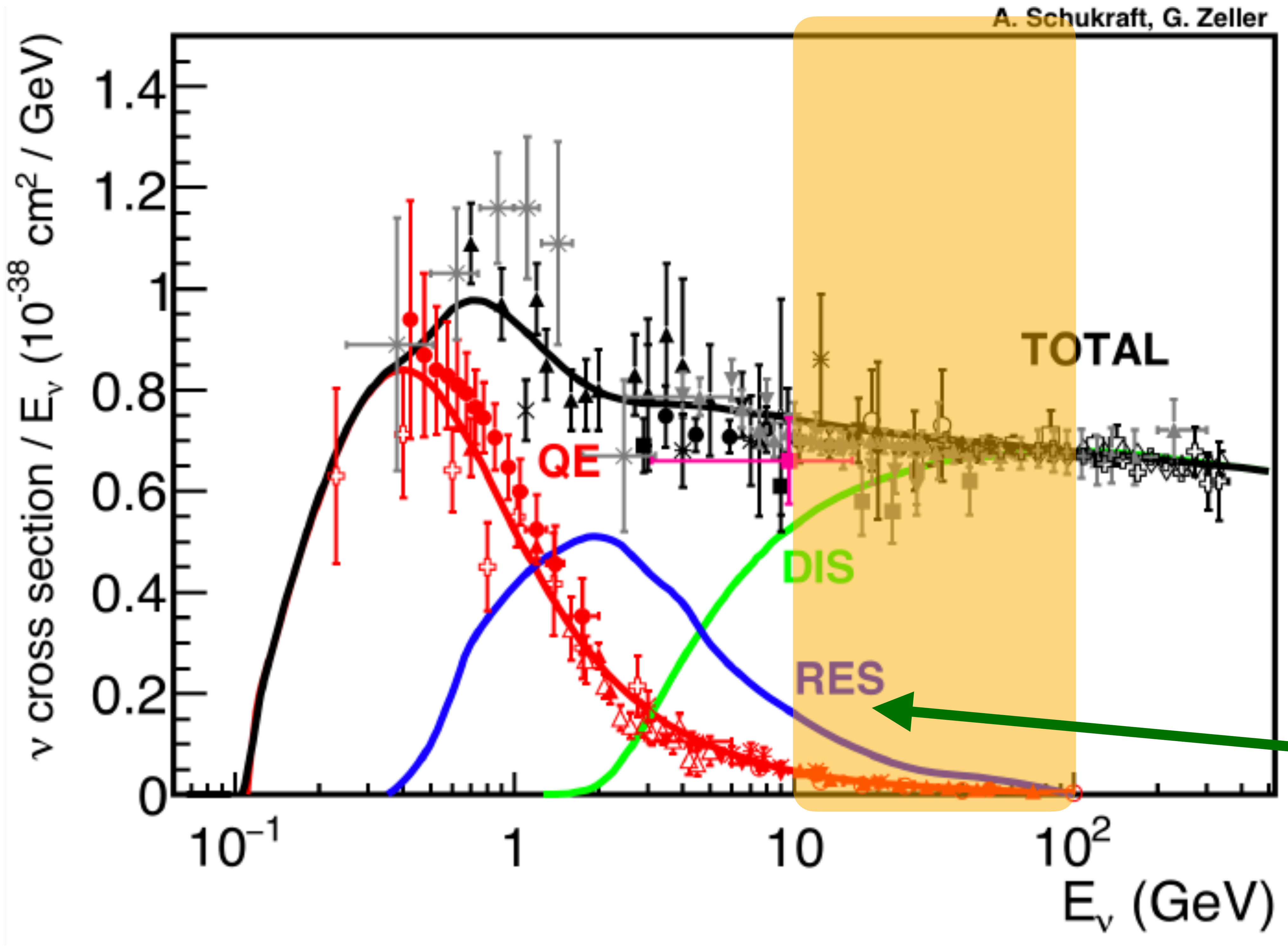


- In the 10s GeV energies, there exist different types of interactions
- Forward experiments at the HL-LHC could obtain sufficient neutrino events from non-DIS interactions in the 10s GeV energy range.

	CCQE					CCRES					NCEL	NCRES
Detector	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	all	all
FASERν2	60	50	570	350	3.5	170	180	1.6k	1.1k	10	170	1.3k
FLArE	40	40	420	260	3.5	120	140	1.2k	860	10	130	940

Table from FPF White paper: *J.Phys.G 50 (2023) 3, 030501*

Transition region: SIS-DIS



- It is important to understand the cross sections in the transition regions to avoid double counting.

Single pion production

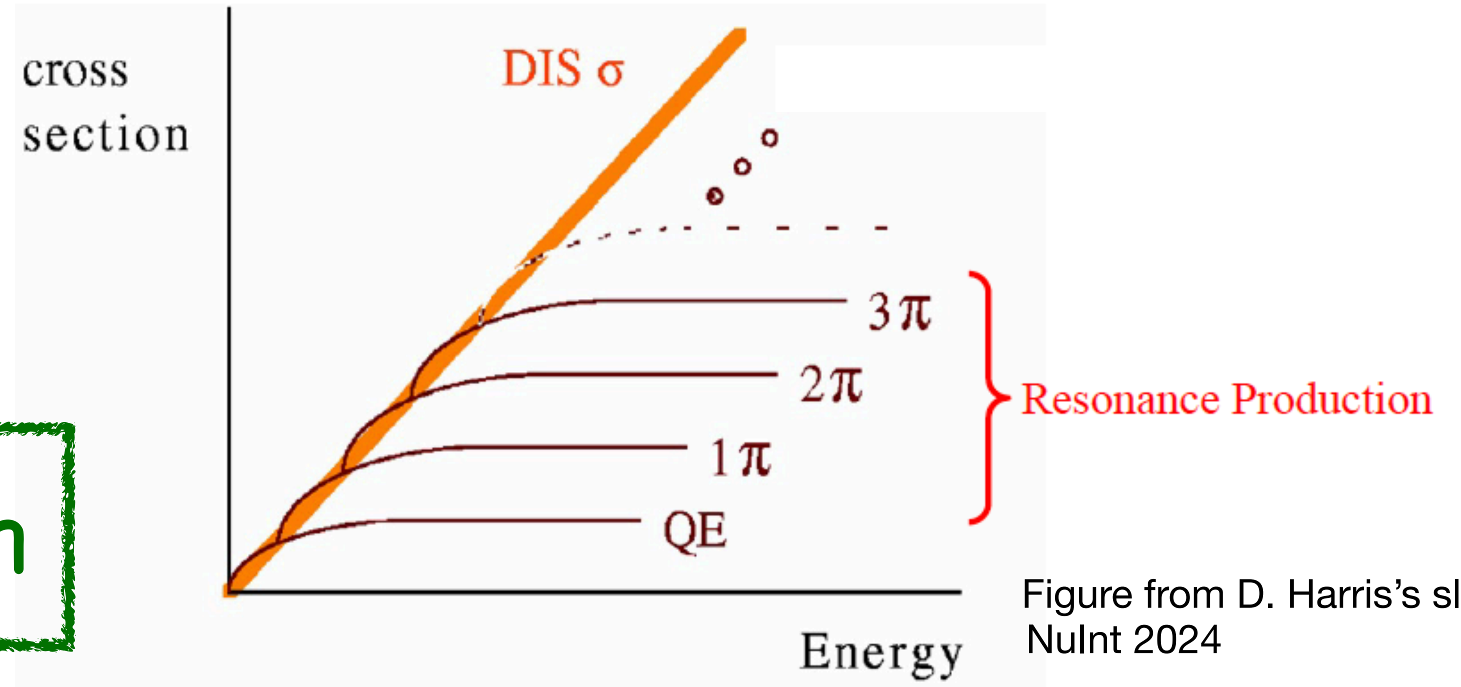


Figure from D. Harris's slides, NuInt 2024

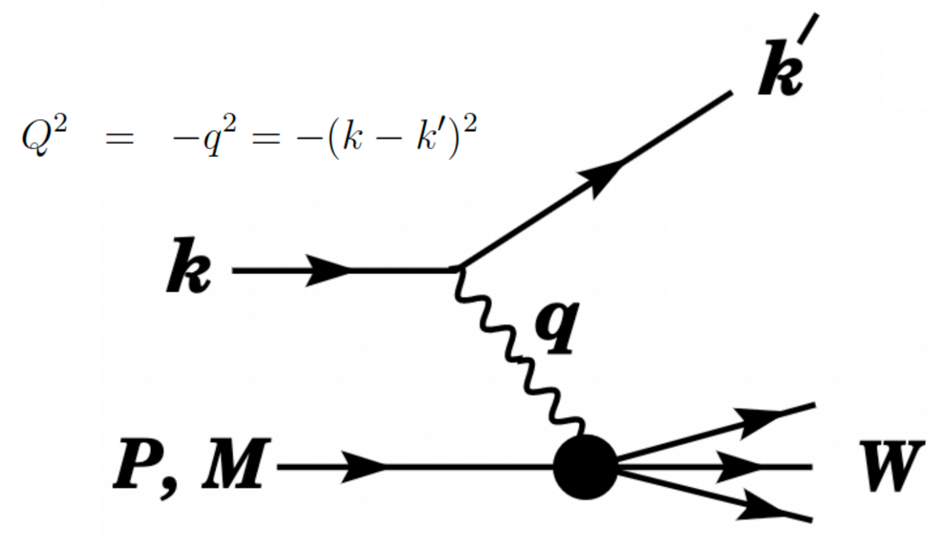
	CCQE					CCRES					NCEL	NCRES
Detector	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	all	all
FASERν2	60	50	570	350	3.5	170	180	1.6k	1.1k	10	170	1.3k
FLArE	40	40	420	260	3.5	120	140	1.2k	860	10	130	940

Table from FPF White paper: *J.Phys.G 50 (2023) 3, 030501*

Impact of Low-Q structure functions on DIS cross sections

- Neutrino-nucleon charged-current (CC) cross section for deep inelastic scattering :

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx\,dy} \simeq \frac{G_F^2 m_N E_\nu}{\pi(1+Q^2/M_W^2)^2}\left[y^2 x\, F_{1,\mathrm{CC}}(x,Q^2) + \left((1-y) - \frac{m_N x}{2E_\nu} y\right) F_{2,\mathrm{CC}}(x,Q^2) \pm xy\left(1-\frac{y}{2}\right) F_{3,\mathrm{CC}}(x,Q^2)\right]$$

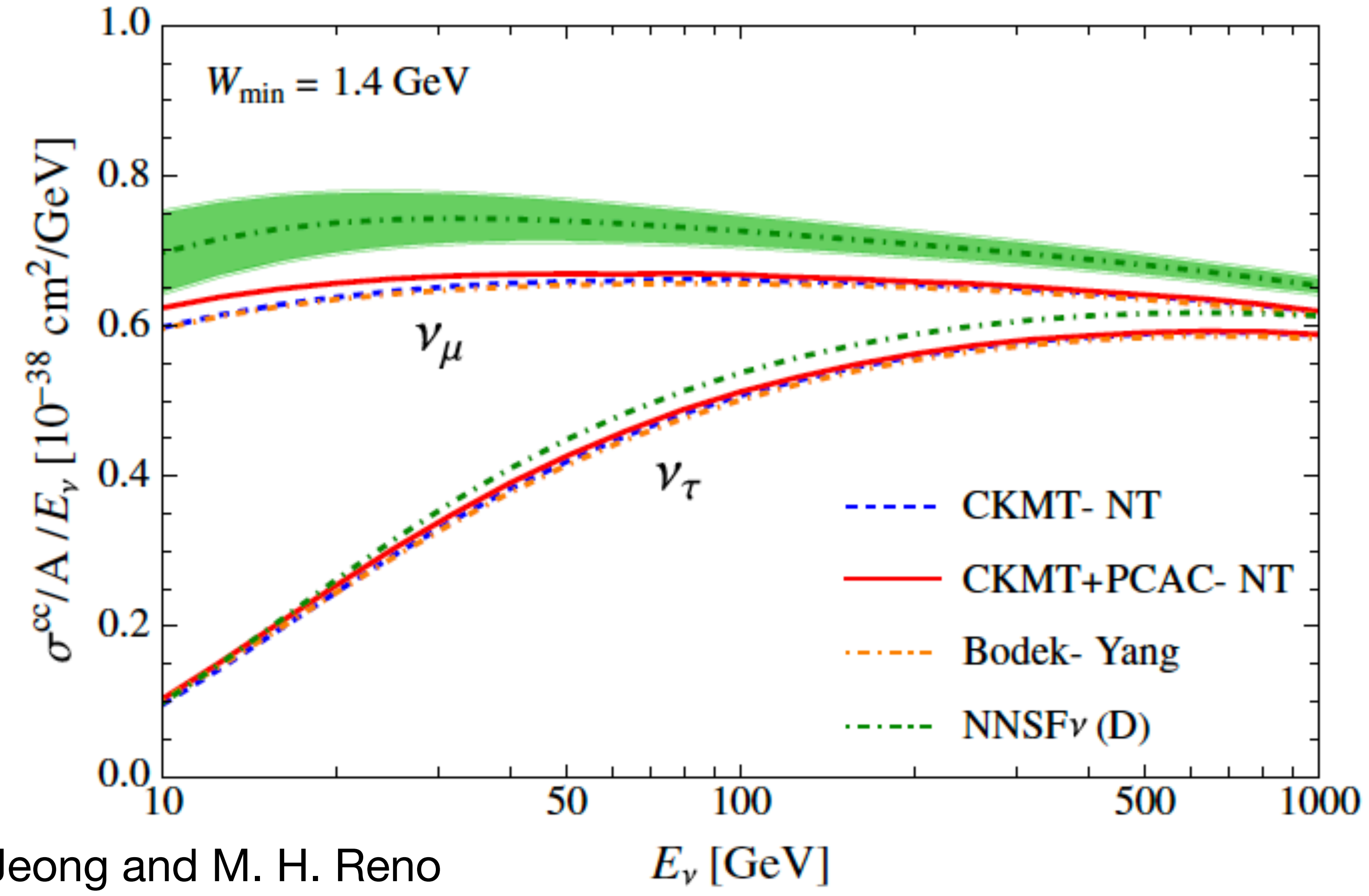


Kinematic region for DIS:

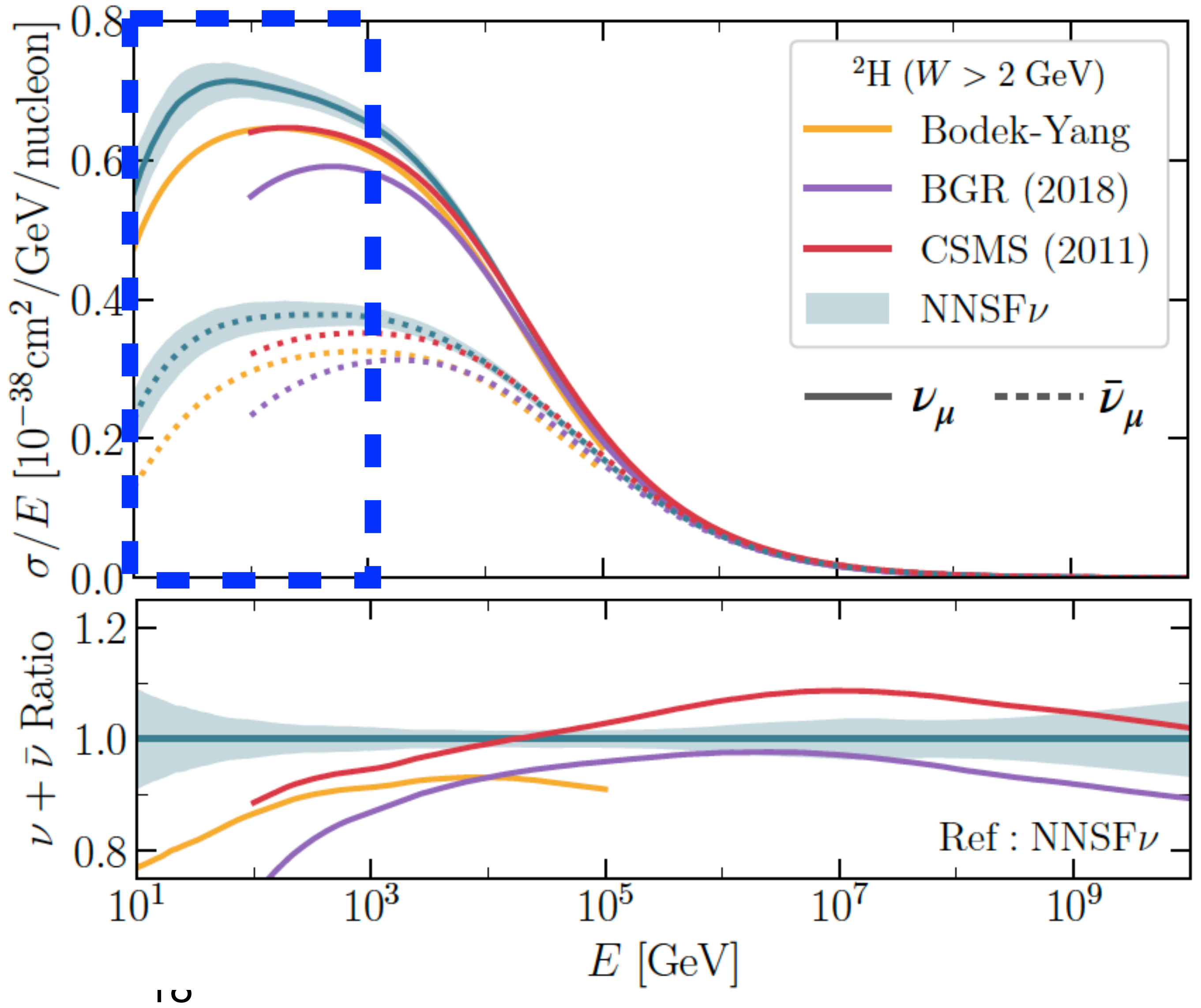
$W > 2$ GeV & $Q^2 > 1$ GeV^2

- The PDF-based structure functions are not reliable for $Q^2 < 1\ \mathrm{GeV}^2$.

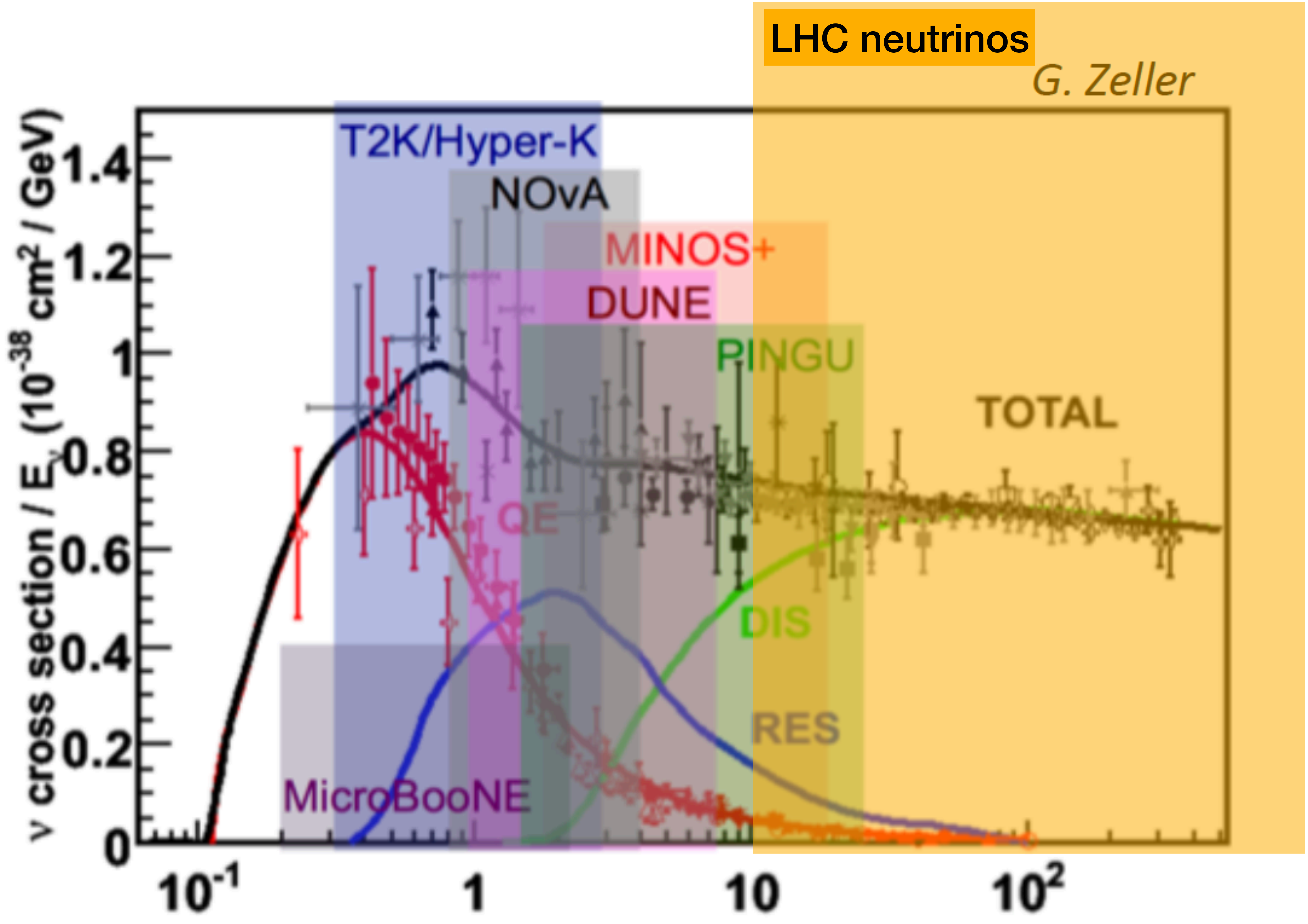
  -> phenomenologically constructed by fitting to the experimental data.



Y. S. Jeong and M. H. Reno
Phys. Rev. D 108, 113010 (2023)

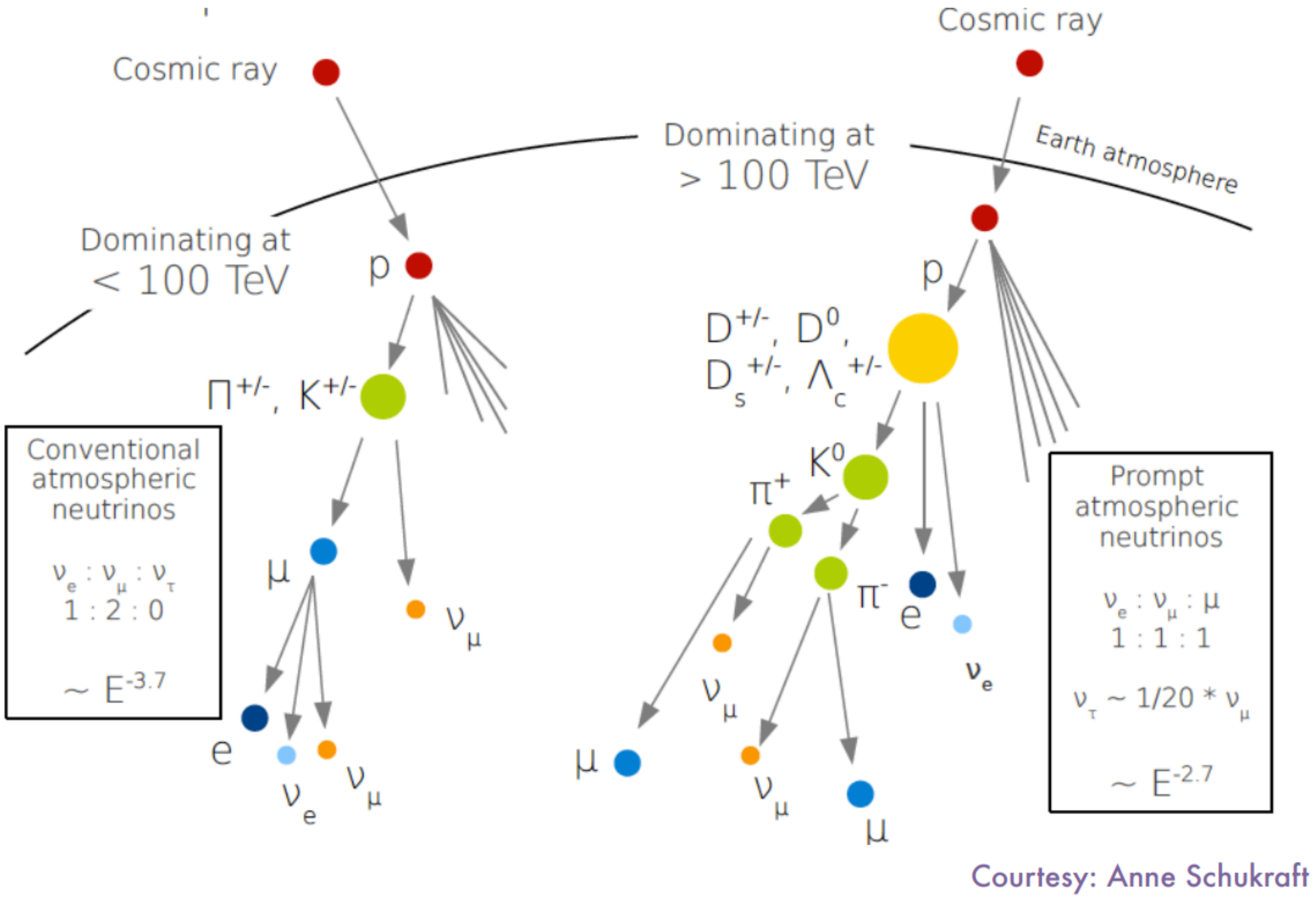


Energy region for oscillation experiments



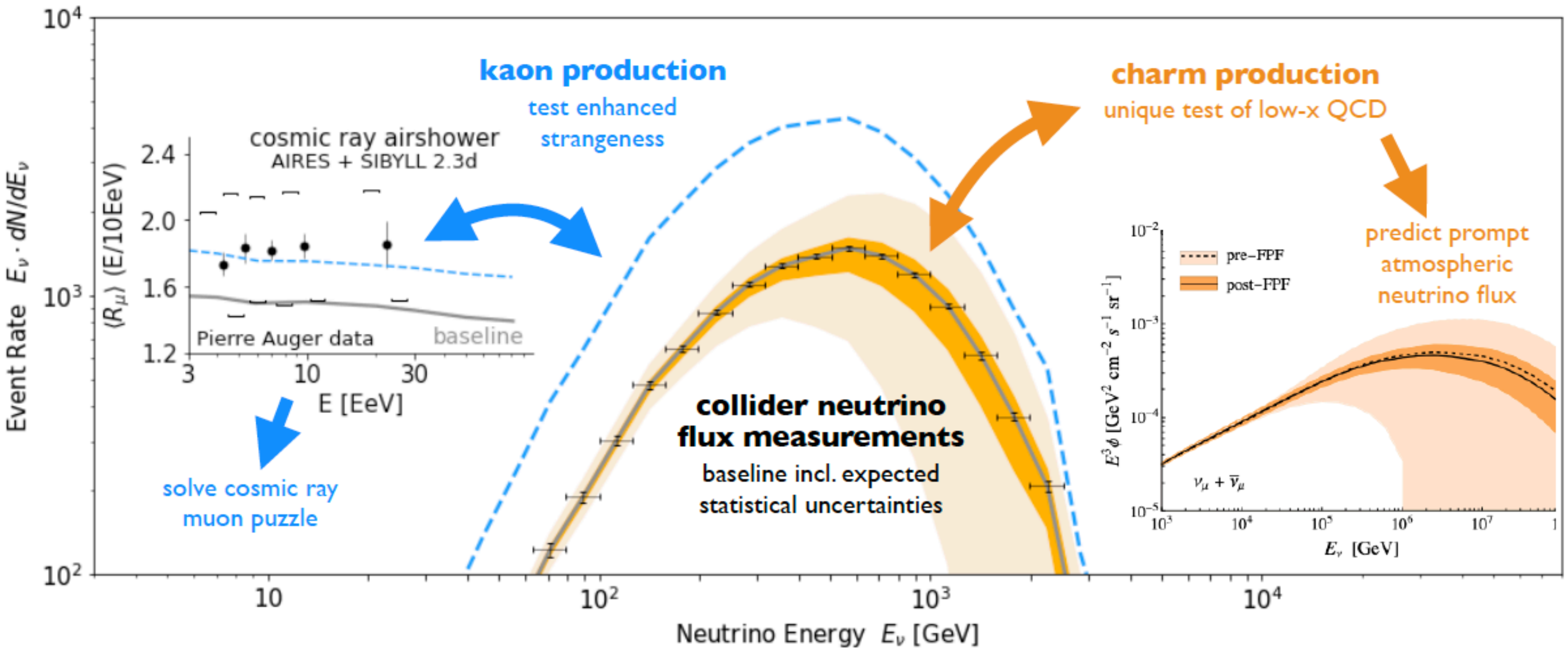
Connection to astroparticle physics

Cosmic ray - air interactions



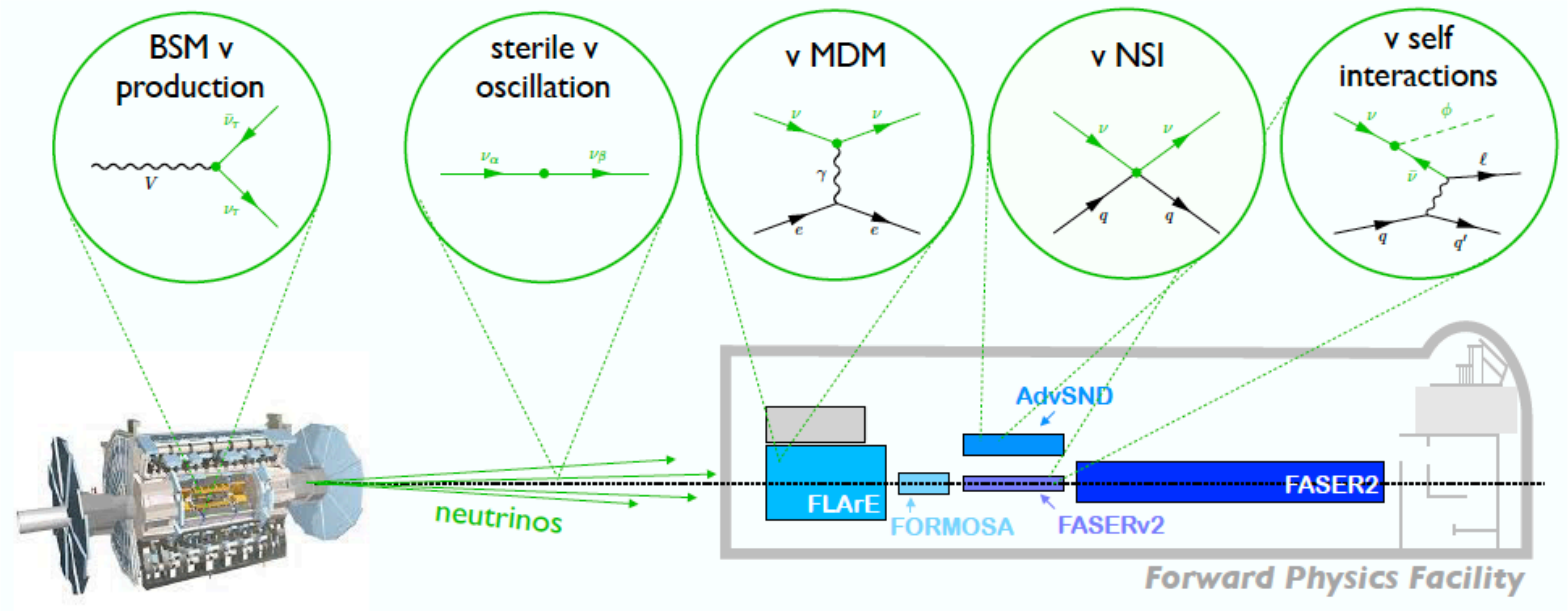
- Collision energy $\sqrt{s} = 14$ TeV corresponds to $E_p \sim 100$ PeV in the lab frame energy.
- Forward particle production at the LHC can mimic air shower from cosmic ray interactions in the atmosphere.

Impact on Astroparticle physics



✓ Muon Puzzle: the excess of muons observed in air showers compared to predictions

Opportunities for BSM Physics with LHC neutrinos



- For more informations and physics potentials:
  - Phys. Rept. 968, 1 (2022), arXiv: 2109.10905.
  - J. Phys. G 50 (2023), arXiv: 2203.05090.
  - + 7 FPF Meetings

J. Feng et. al., *J.Phys.G* 50 (2023) 3, 030501

Neutrino BSM (1): oscillation with sterile neutrinos

- With the baseline of 500-700m and neutrino energies from ∼10 GeV to a few TeV, forward experiments are not sensitive to the standard oscillations among the three active neutrinos.

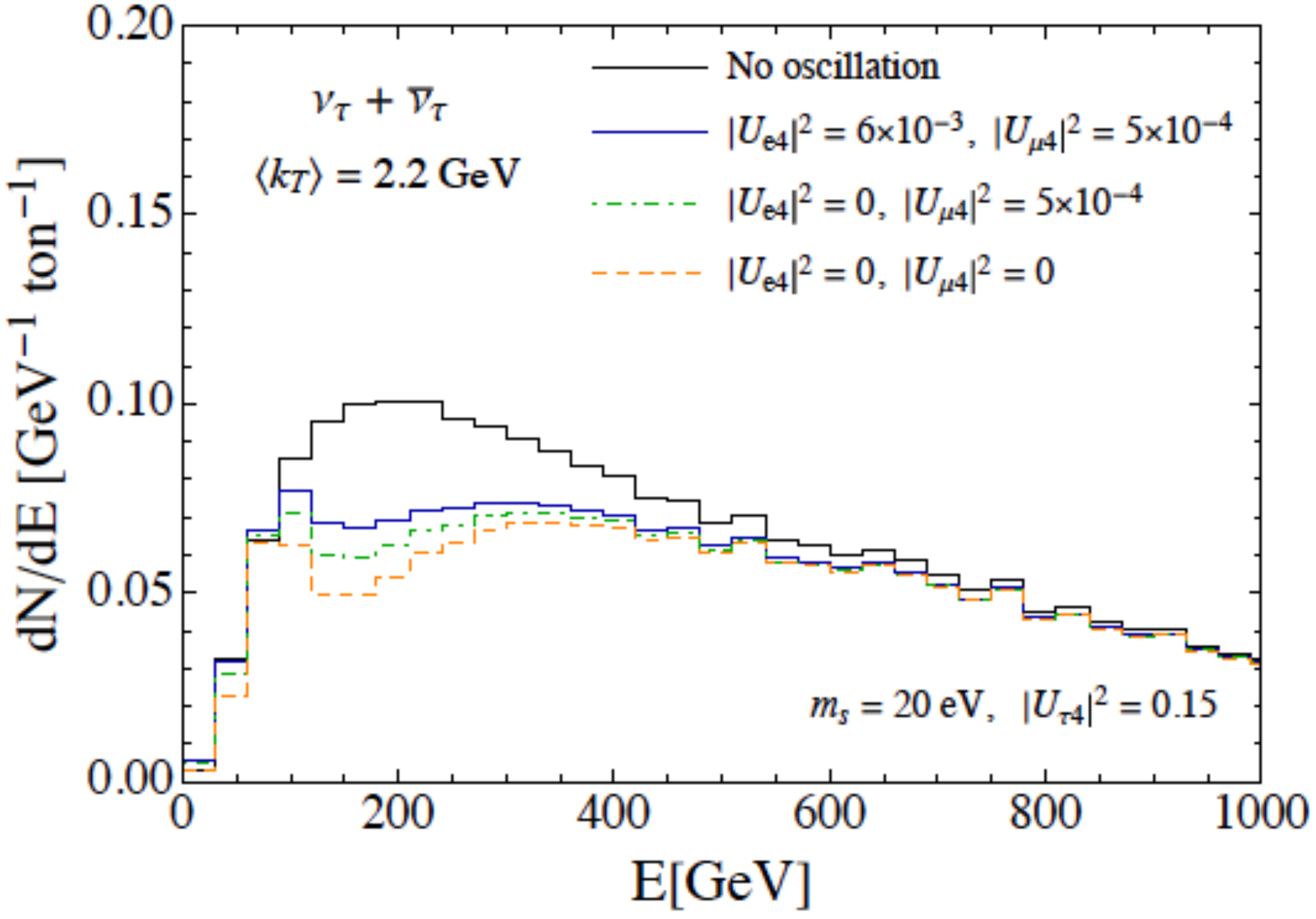
- Any distortion in the event spectrum could be interpreted as a signal for oscillations associated with sterile neutrinos.

- Forward experiments at the LHC are sensitive to the sterile neutrinos with $\Delta m^2_{41} \sim 10^3\ \mathrm{eV}^2$, which corresponds to $m_s \sim \mathcal{O}(10)\,\mathrm{eV}$.

  - Oscillation probability in the 3+1 scenario:

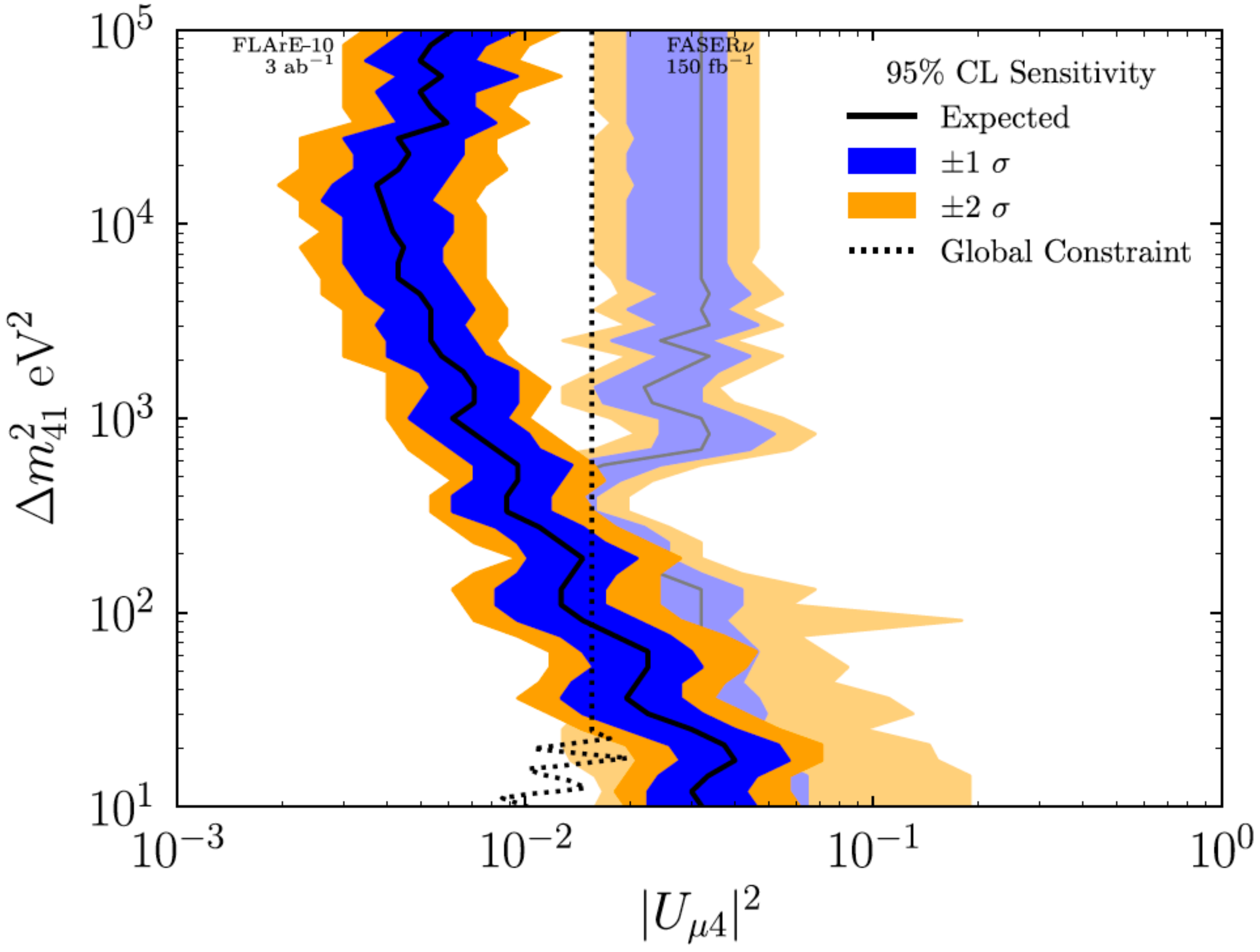
$$P(\nu_\alpha \to \nu_\beta) \simeq \delta_{\alpha\beta} - 4\left(\delta_{\alpha\beta} - |U_{\beta 4}|^2\right)|U_{\alpha 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

Neutrino BSM (1): oscillation with sterile neutrinos



$$\Delta m^2 = 400\,\mathrm{eV}^2 \ (m_4 = 20 \text{ eV}),$$
$$|U_{e4}|^2 = 6 \cdot 10^{-3},\ |U_{\mu4}|^2 = 5 \cdot 10^{-4},\ |U_{\tau4}|^2 = 0.15$$

W. Bai, M. Diwan, M. V. Garzelli, YSJ, M. H. Reno,
JHEP 06 (2020) 032



Expected sensitivity from the ν_μ disappearance channel for FASERν (Run-3) and FLArE-10 (HL-LHC).

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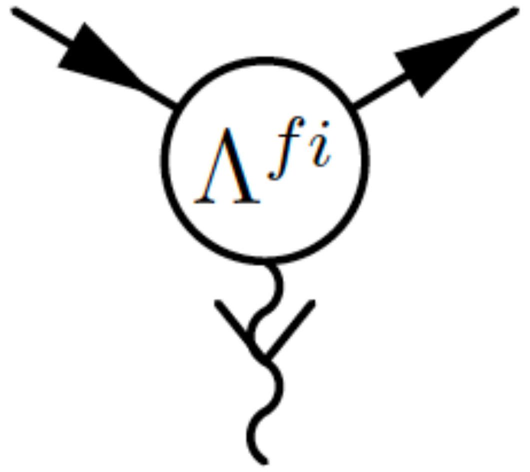
Neutrino BSM (2): neutrino magnetic moment



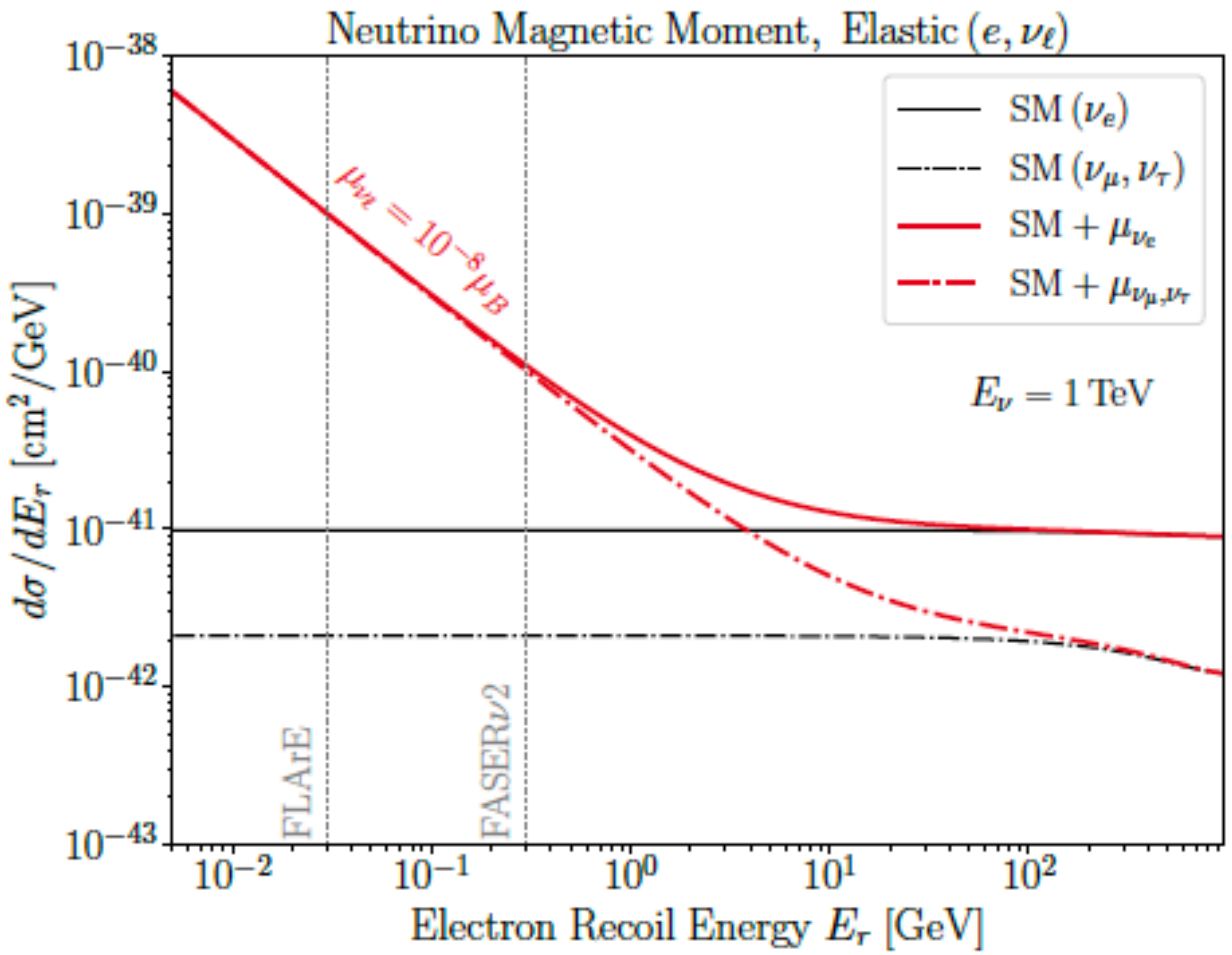
$$\langle \nu_f(p_f)|j^{\mu}_{\nu,\mathrm{EM}}|\nu_i(p_i)\rangle = \overline{u}_f(p_f)\Lambda^{\mu}_{fi}(q)u_i(p_i)$$

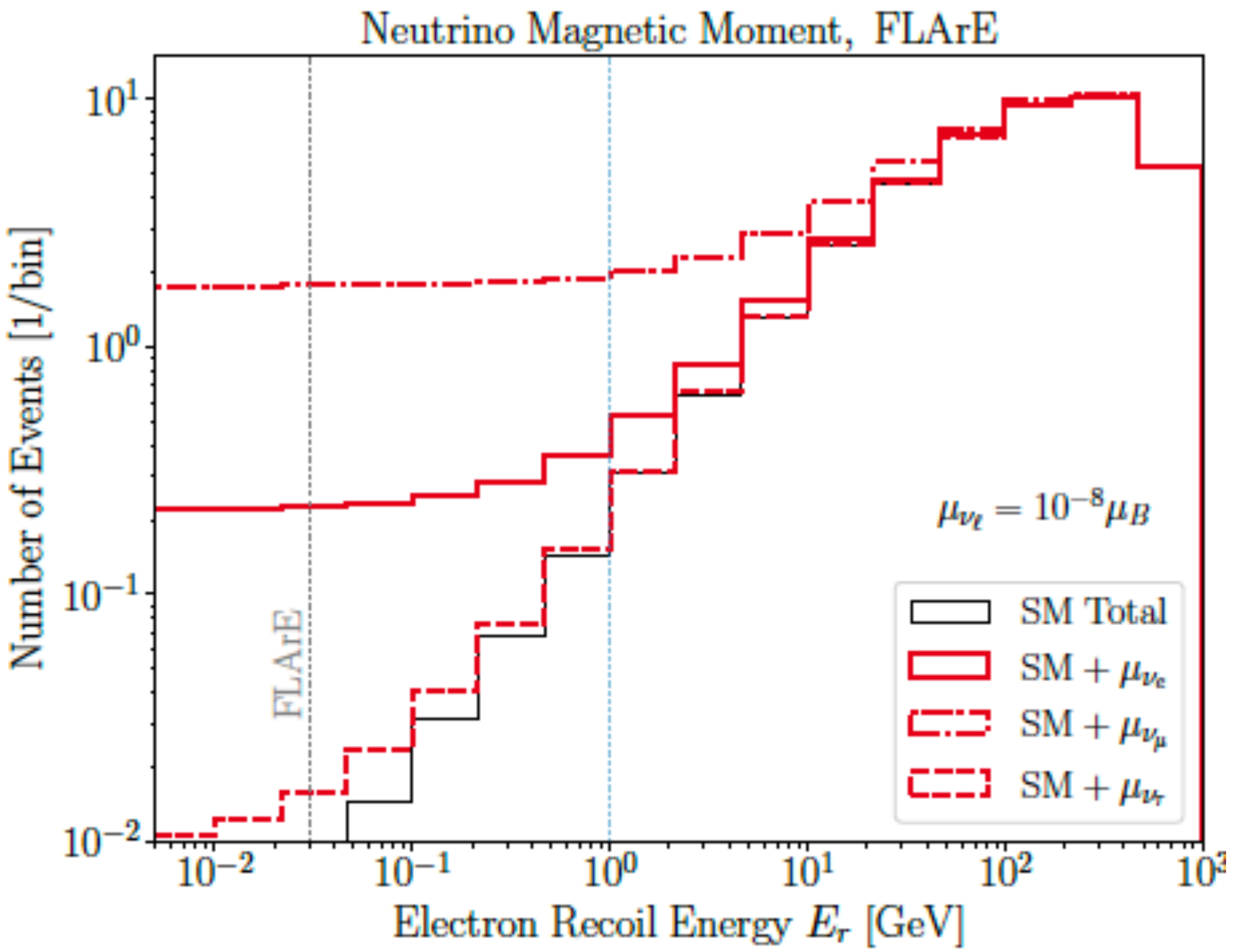
$$\Lambda^{fi}_{\mu}(q) \supset -i\sigma^{\mu\nu}q_{\nu}\mu_{fi}$$

μ_{fi} : Neutrino magnetic moment

- Non-zero neutrino mass implies the existence of neutrino magnetic moment (NMM).
  - $\mu_\nu \approx \frac{3eG_F}{8\sqrt{2}\pi^2}m_\nu \approx 3 \cdot 10^{-19}\mu_B \left(\frac{m_\nu}{1\ \mathrm{eV}}\right)$
- Additional BSM contribution can increase the value of NMM.

Neutrino BSM (2): neutrino magnetic moment





$$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm NMM} = \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm SM} + \frac{\pi^2}{m_e^2}\left(\frac{1}{E_r} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_\ell}}{\mu_{\rm B}}\right)^2$$

R. M. Abraham, S. Foroughi-Abari, F. Kling, and Yu-Dai Tsai (arXiv:2301.10254)

Summary and Outlook

- SND@LHC and FASER have successfully observed collider neutrinos for the first time. These measurements
  - extend the accessible neutrino energy up to TeV scale.
  - bridge the gap between accelerator- and cosmic ray- originated neutrinos.

- Forward neutrino measurements could complement and advance research in neutrino physics and related fields.
  - QCD: forward heavy flavor production, nucleon/nuclear structure (via PDFs, non perturbative structure functions)
  - Astroparticle physics: cosmic ray air shower modeling, prompt atmospheric neutrino flux
  - BSM searches: Opportunities to test and explore various new physics scenarios.

- Forward experiments in the HL-LHC era will dramatically improve statistics.
  - ➡ Together with Run-3 data, they will enable precision studies and significantly improve research in neutrino physics, QCD, astroparticle physics and BSM physics searches.

Thank you for your attention