Neutrino physics (Theory)

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Outline

- Neutrino oscillation
- Neutrino physics at the LHC
  - Forward experiments
  - Potential for neutrino study

Discovery of neutrino oscillation

- Neutrino oscillation is one of great discoveries in the past three decades.
- Neutrino oscillation is the clear evidence for
  - Non-zero masses of neutrinos
  - Leptonic mixing

Neutrino oscillation in three flavor neutrinos

- In three flavor neutrino framework: $|\nu_\alpha\rangle = \sum_k U_{\mu k}|\nu_k\rangle \quad (\alpha = e,\, \mu,\, \tau)$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\nu_\alpha(t)\rangle = \sum_k U_{\alpha k} e^{-iE_k t}|\nu_k\rangle$$

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \sum_{k,j} U_{\alpha k} U^*_{\beta k} U^*_{\alpha j} U_{\beta j} \, \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$

Neutrino oscillation in three flavor neutrinos

- Oscillation parameters:
  - $\Delta m_{21}^2 = \Delta m_{sol}^2$, $\Delta m_{3l}^2 = \Delta m_{atm}^2$
  - $\theta_{12} = \theta_{sol}$, $\theta_{13} = \theta_{reactor}$, $\theta_{23} = \theta_{atm}$
  - CP phase: δ

- Solar, atmospheric, reactor, accelerator experiments have provided enormous data to determine the parameters.

JHEP02(2021)071

Parameter	Main contribution from	Other contributions from
Δm_{21}^2	KamLAND	SOL
$\lvert\Delta m_{31}^2\rvert$	LBL+ATM+REAC	–
θ_{12}	SOL	KamLAND
θ_{23}	LBL+ATM	–
θ_{13}	REAC	(LBL+ATM) and (SOL+KamLAND)
δ	LBL	ATM
MO	(LBL+REAC) and ATM	COSMO and $0\nu\beta\beta$

Current status of oscillation parameters

NuFIT 5.1 (2021)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

JHEP 09 (2020) 178 [arXiv:2007.14792],
NuFIT 5.1 (2021), www.nu-fit.org.

Current status of oscillation parameters (well measured)

NuFIT 5.1 (2021)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
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$\theta_{12} : 14\%$

$\theta_{13} : 9.0\%$

$\Delta m^2_{21} : 16\%$

$|\Delta m^2_{3\ell}| : 6.7\%\ [6.5\%]$

JHEP 09 (2020) 178 [arXiv:2007.14792], NuFIT 5.1 (2021), www.nu-fit.org.

What still need to be determined

NuFIT 5.1 (2021)

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- Mass ordering : the sign of Δm^2_{3l}
- Octant of θ_{23}
- $\delta_{CP} = ?$

JHEP 09 (2020) 178 [arXiv:2007.14792], NuFIT 5.1 (2021), www.nu-fit.org.

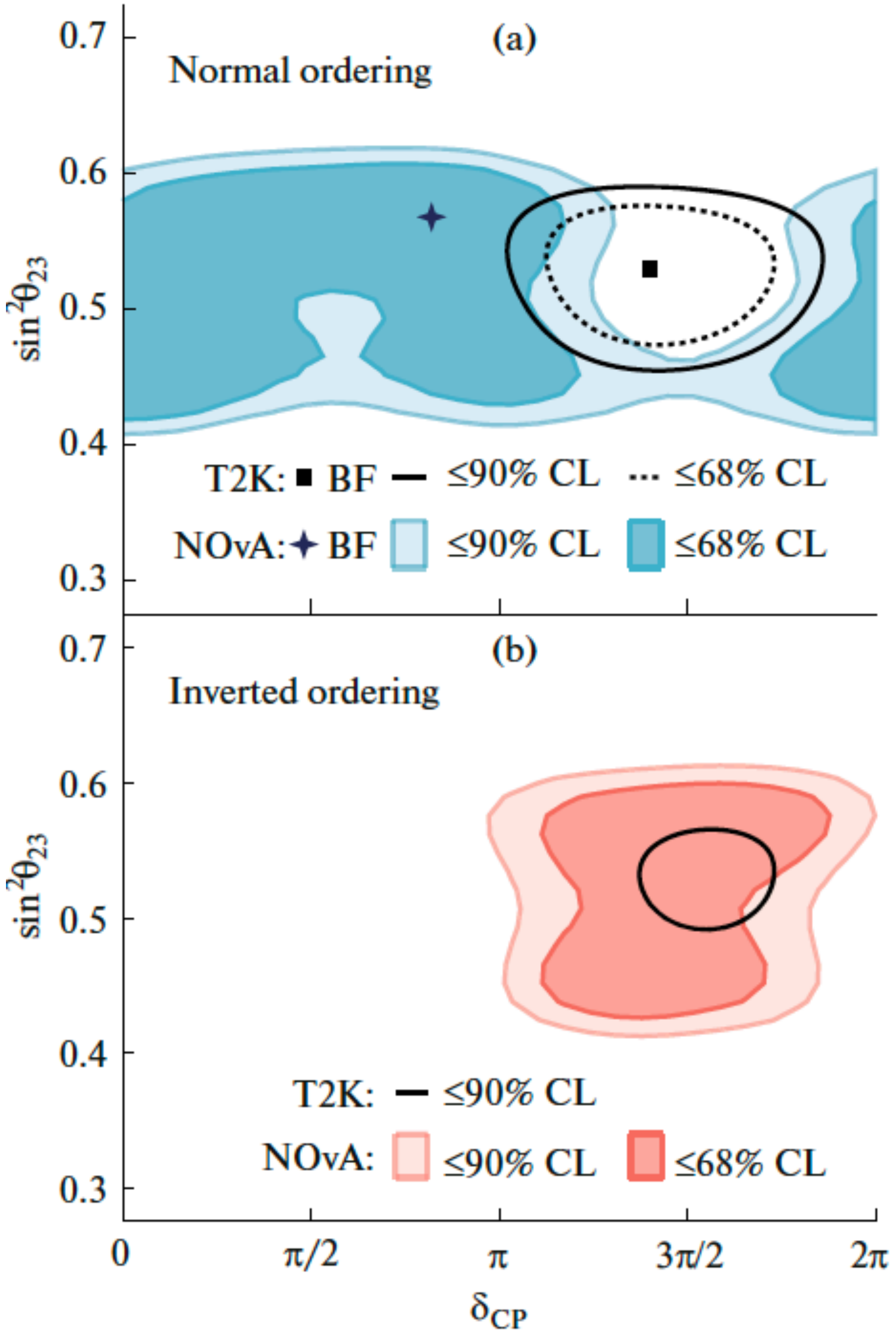
Current accelerator experiments for oscillation

Long baseline (LBL) accelerator experiments

- T2K (Tokai to Kamioka)
  - ν beam is from the 30 GeV proton beam at J-PARC.
  - Peak energy: 0.6 GeV
  - Baseline: 295km

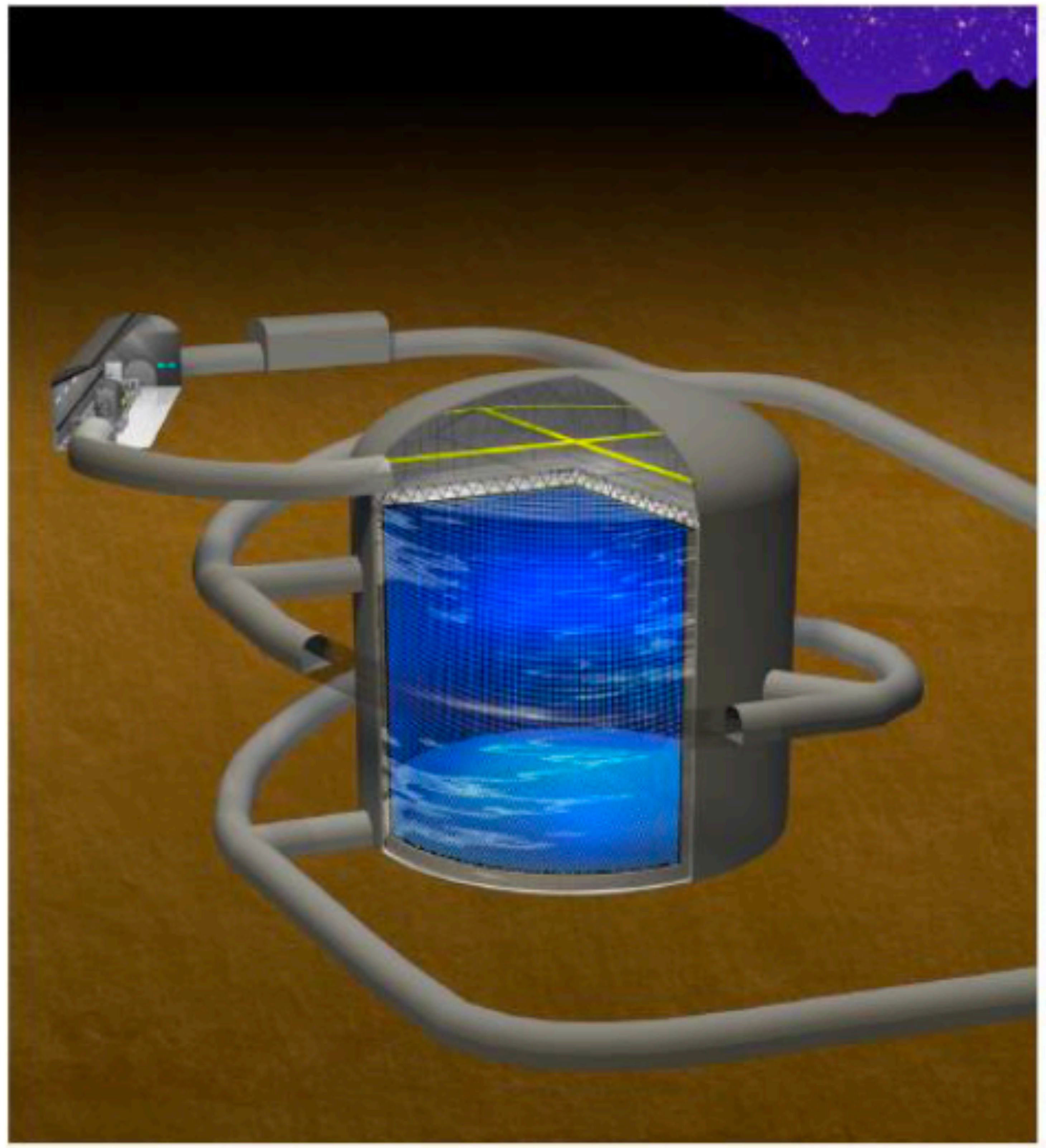
- NOvA
  - NuMI beam@Fermilab from Ep = 120 GeV.
  - Peak energy: 1.8 GeV
  - Baseline: 810km

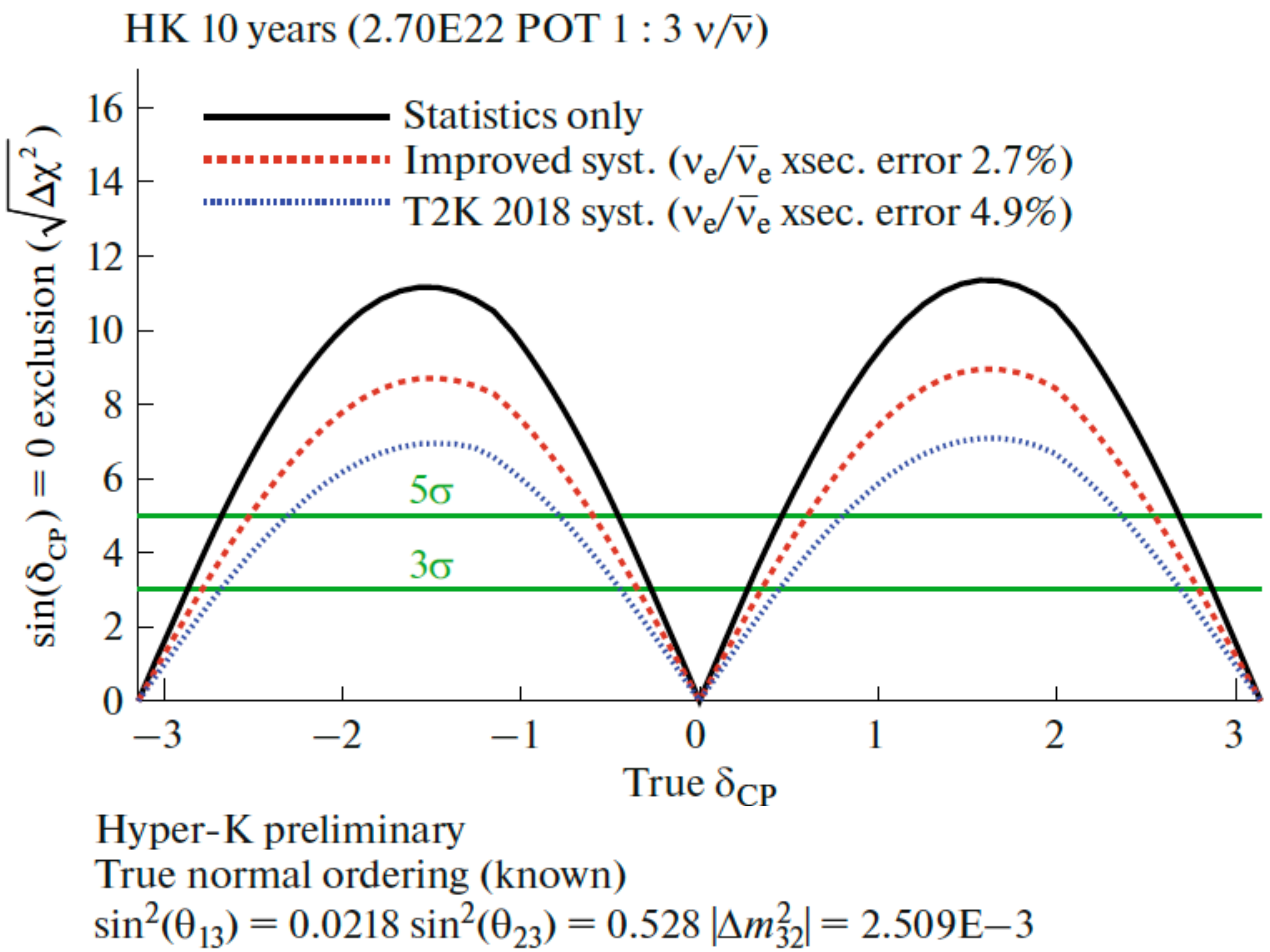
Tension between NOvA vs T2K



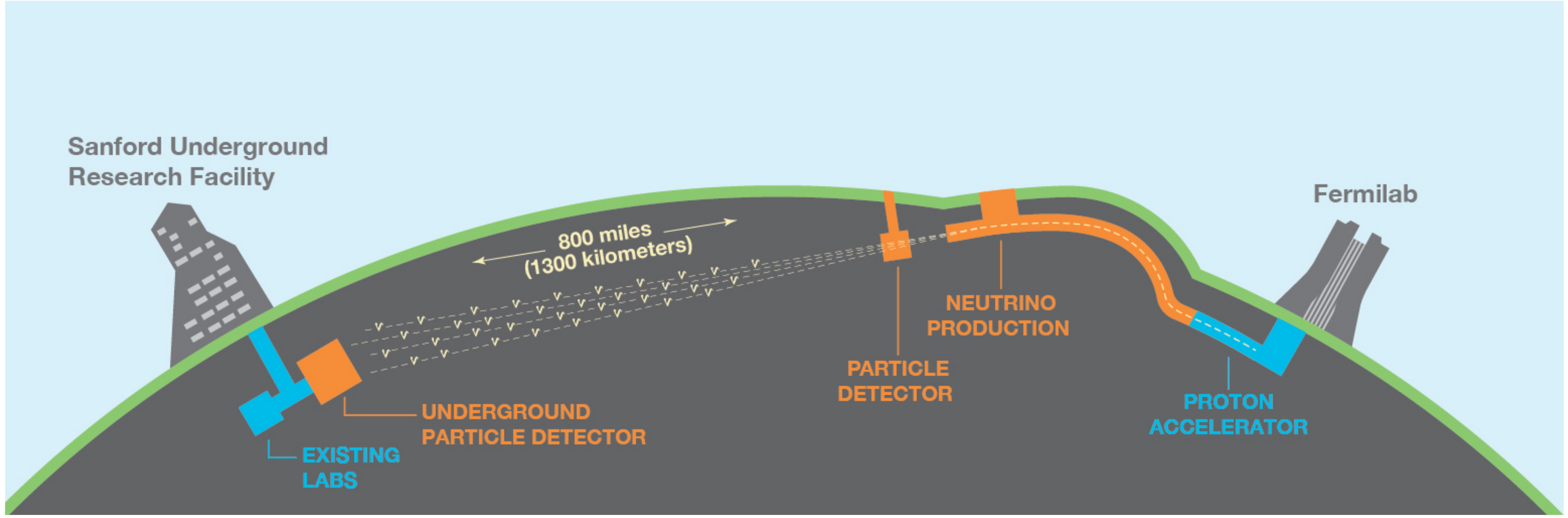
- For mass ordering, both NOvA and T2K prefers normal ordering.
- T2K and NOvA results coincide with the inverted ordering.

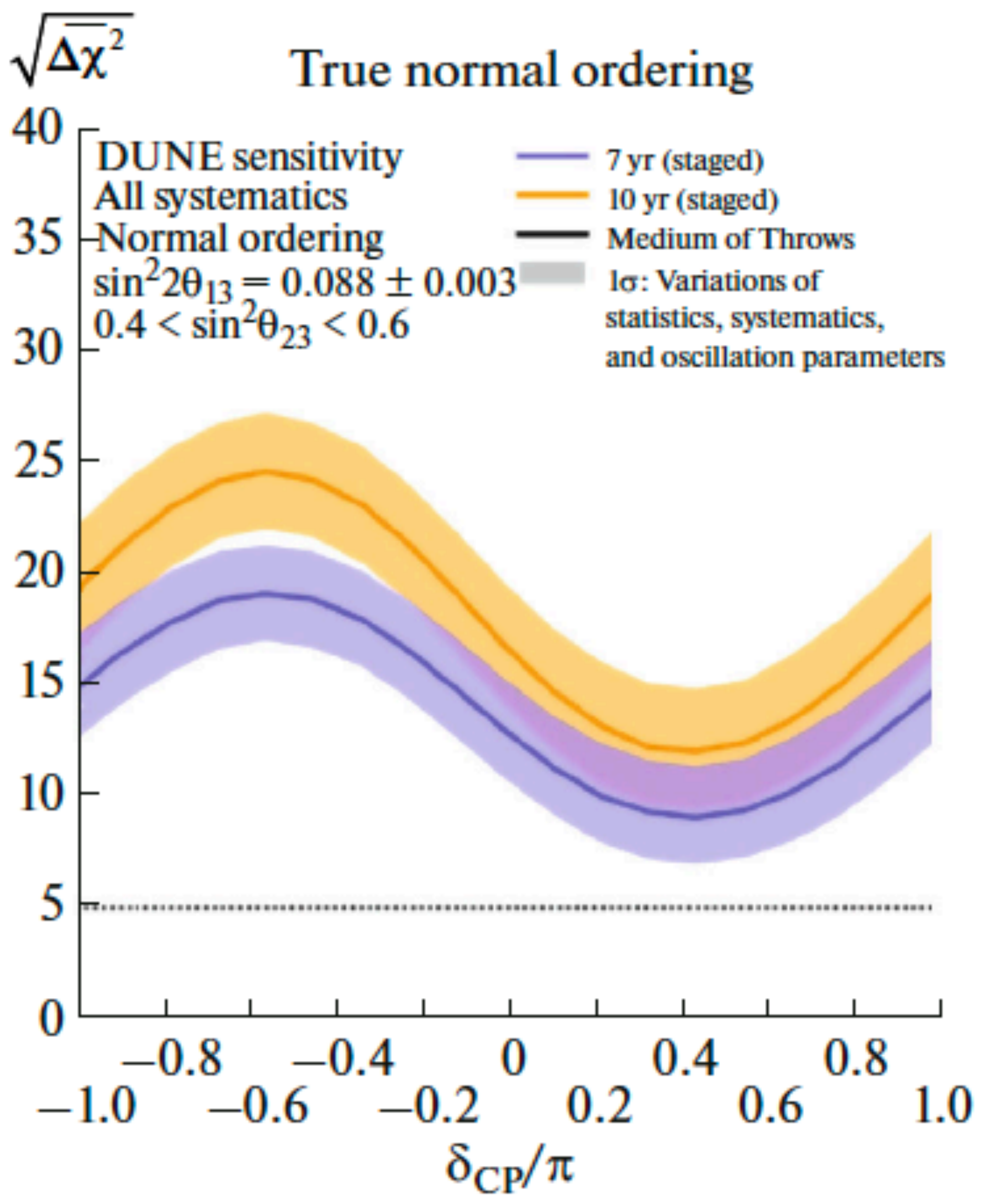
Future accelerator experiments for oscillation — HK

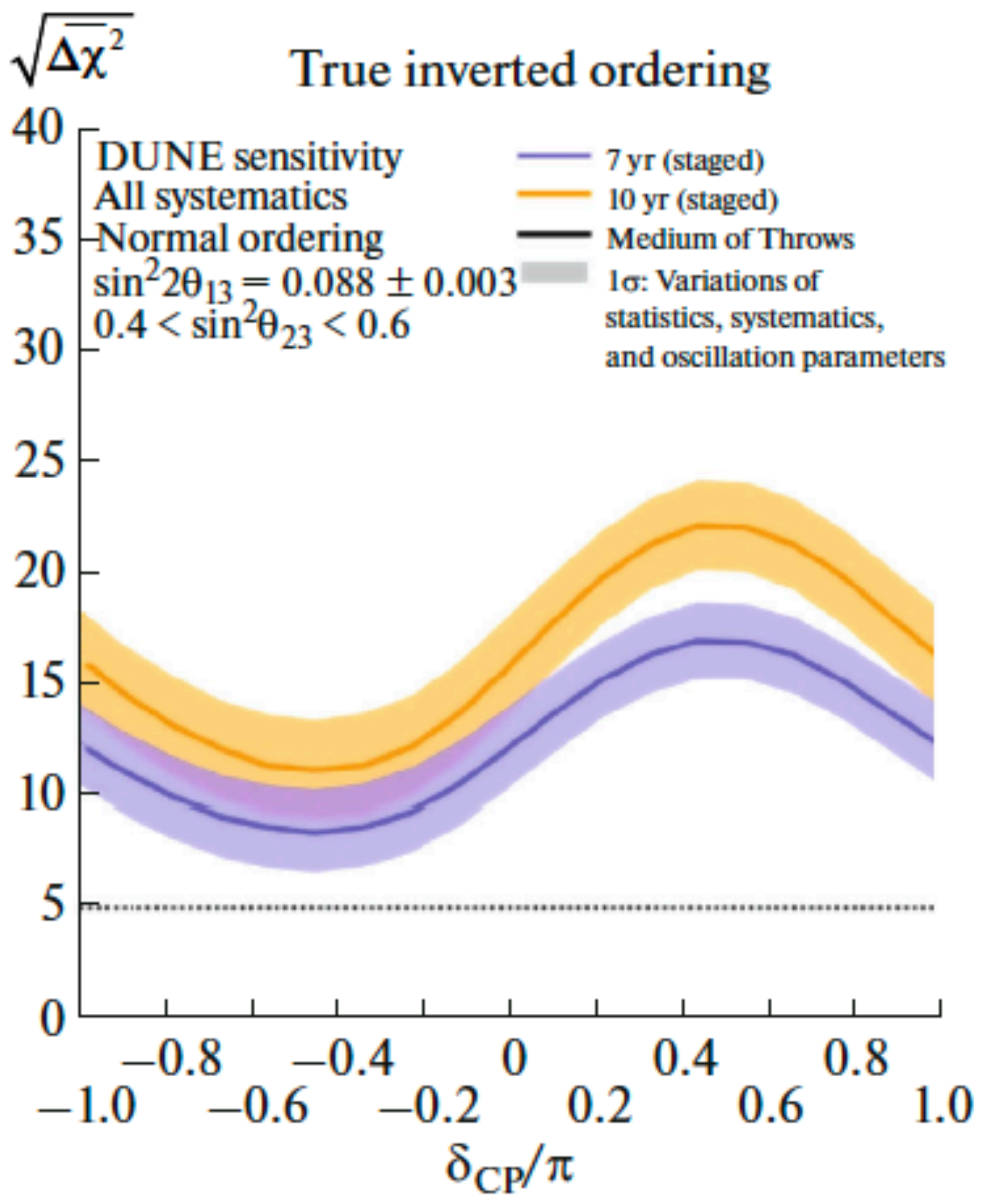




Future accelerator experiments for oscillation — DUNE







- Sensitivity on mass hierarchy

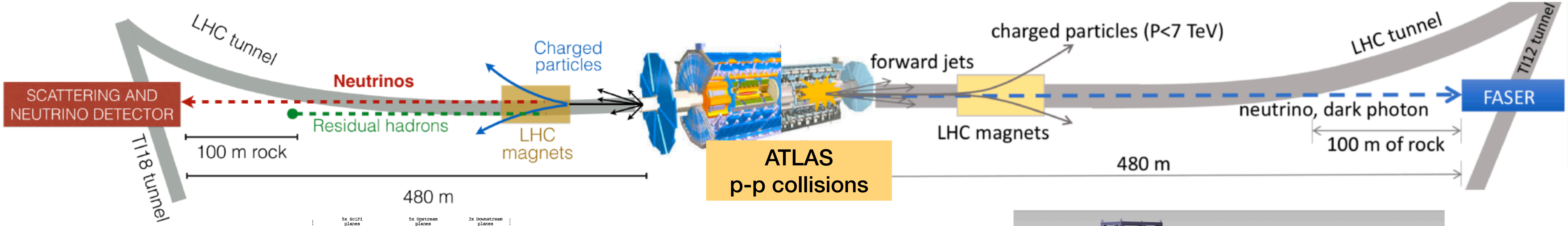
  After 7 years running, mass hierarchy can be determined for all δ_{CP} values.

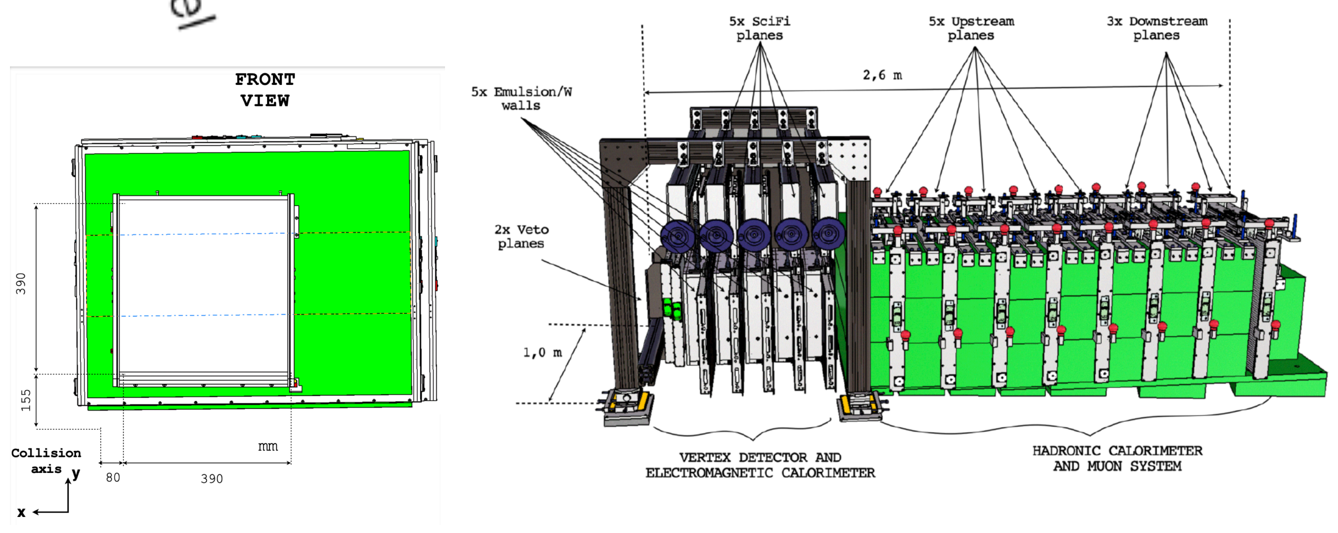
Summary I

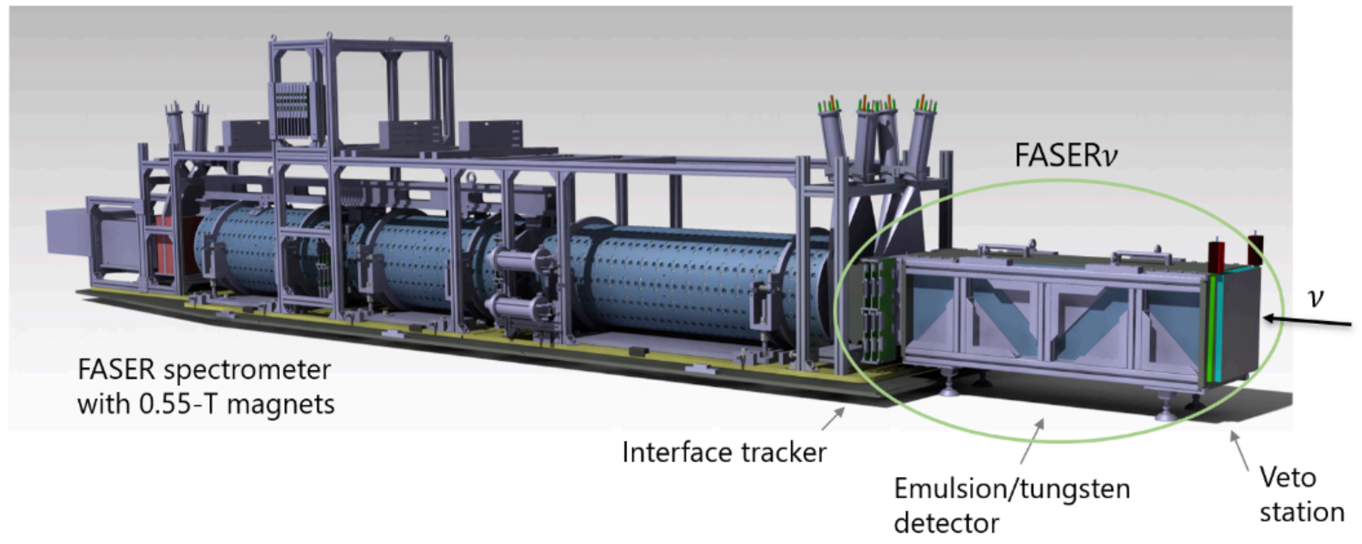
- The oscillation data are well described by the three flavor neutrino framework.
- There are still ambiguity in some parameters in mass hierarchy, θ_{23}, δ_{CP}.
- Current and future oscillation experiments will provide information for such parameters.

Neutrino physics at the LHC

Forward experiments during the Run 3 - SND@LHC



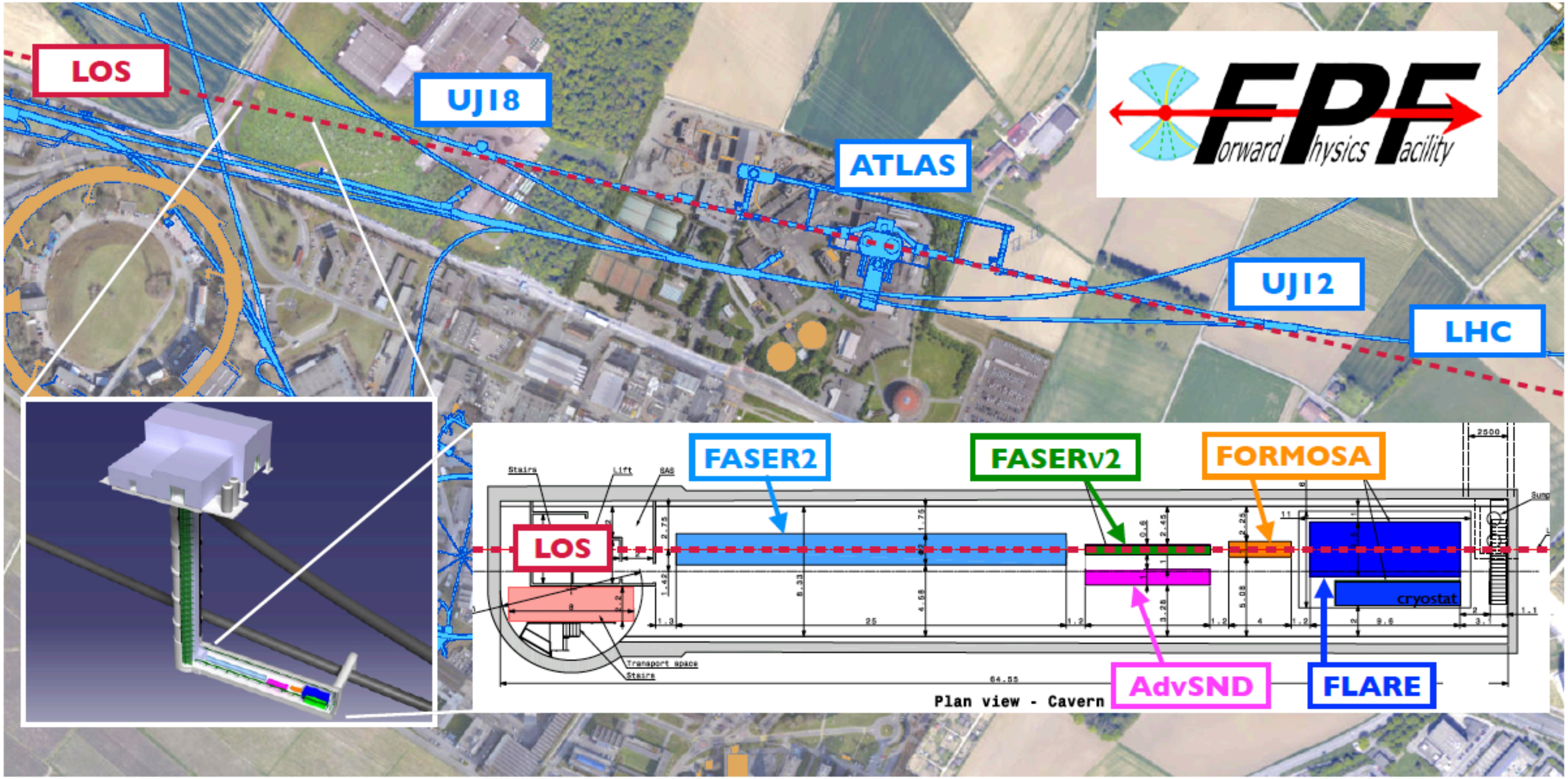




- Rapidity: $7.2 < \eta < 8.4$ (off-axis)
- Target material: Tungsten (w/ emulsion film)
- Target mass: 830 kg
- surface: 39 x 39 cm^2

- Rapidity: $\eta \gtrsim 8.5$ (on-axis)
- Target material: Tungsten (w/ emulsion film)
- Target mass: 1.1 tons
- surface: 25 x 30 cm^2 (1.1 m long)

Forward Physics Facility (FPF, High-Luminosity)



Ref: arXiv: 2203.05090

Forward Physics Facility

Ref: arXiv: 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	$\eta \gtrsim 8.5$	$150\ \text{fb}^{-1}$ $290\ \text{fb}^{-1}$	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	$150\ \text{fb}^{-1}$	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	$3\ \text{ab}^{-1}$	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	$3\ \text{ab}^{-1}$	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	$3\ \text{ab}^{-1}$	6.5k / 20k	41k / 53k	190 / 754

- The rapidity coverage of the detectors at the FPF is similar to the experiments for the Run 3.
- The increased detector/target mass and the luminosity can yield about two orders of magnitude larger number of events than the first phase experiments.
- The LHC produces large number of neutrinos in the far forward direction for all three different flavors.
  - Expected CC events: $10^5\ \nu_e$, $10^6\ \nu_\mu$, $10^3\ \nu_\tau$ in 10 ton scale detector

Neutrino production at the LHC

- In pp collisions, various hadrons are produced. Some of those hadrons subsequently decay and produce a number of neutrinos.

$$p + p \to \underline{h \text{ (hadrons)}} + X \quad \text{(interaction)}$$

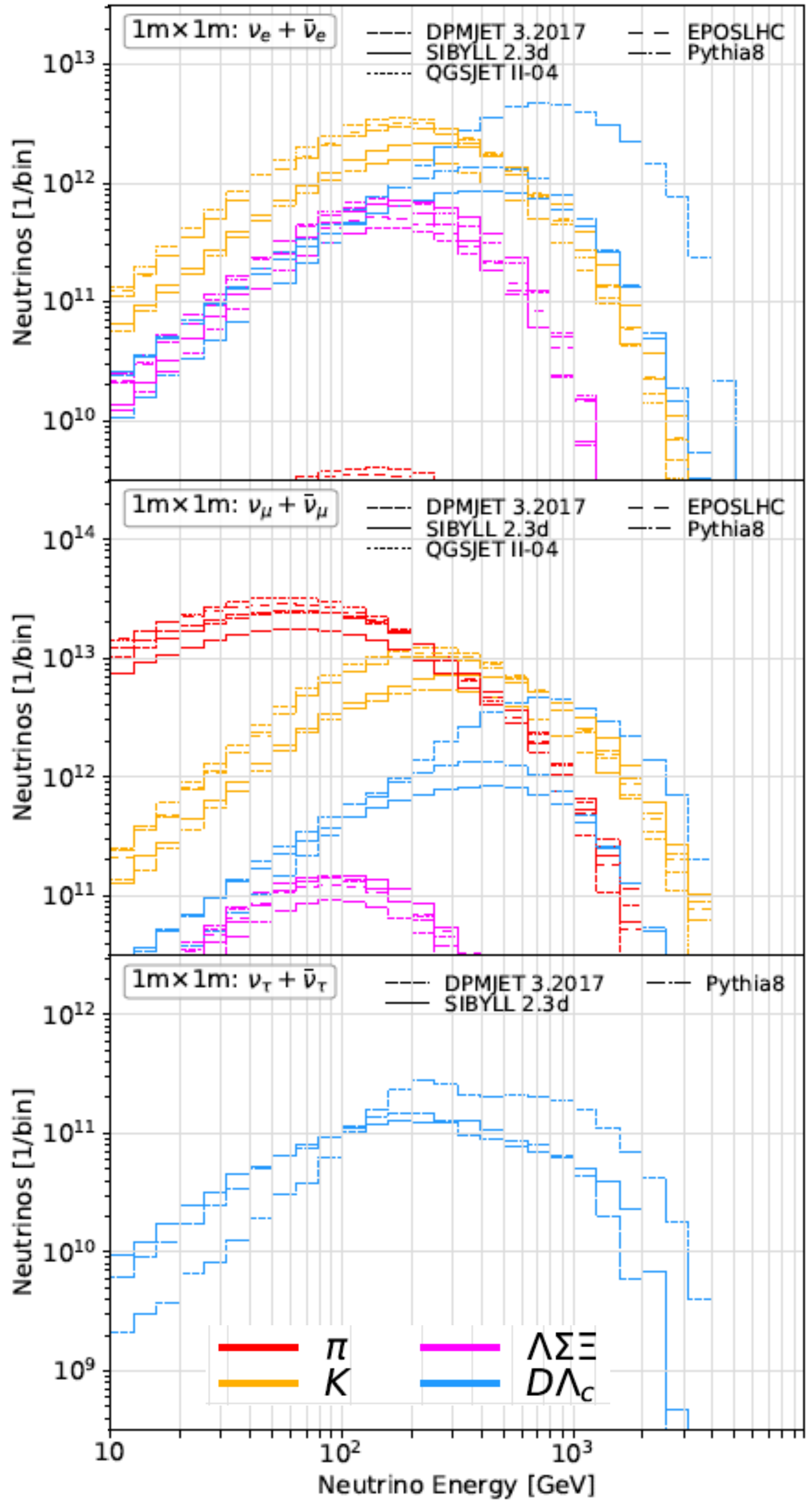
$$\hookrightarrow \nu_a + X' \quad (a = e, \mu, \tau) \quad \text{(decay)}$$

- Neutrinos from the light hadron decays: conventional neutrinos
  - $h = \pi^\pm,\ K^\pm,\ K_L$...

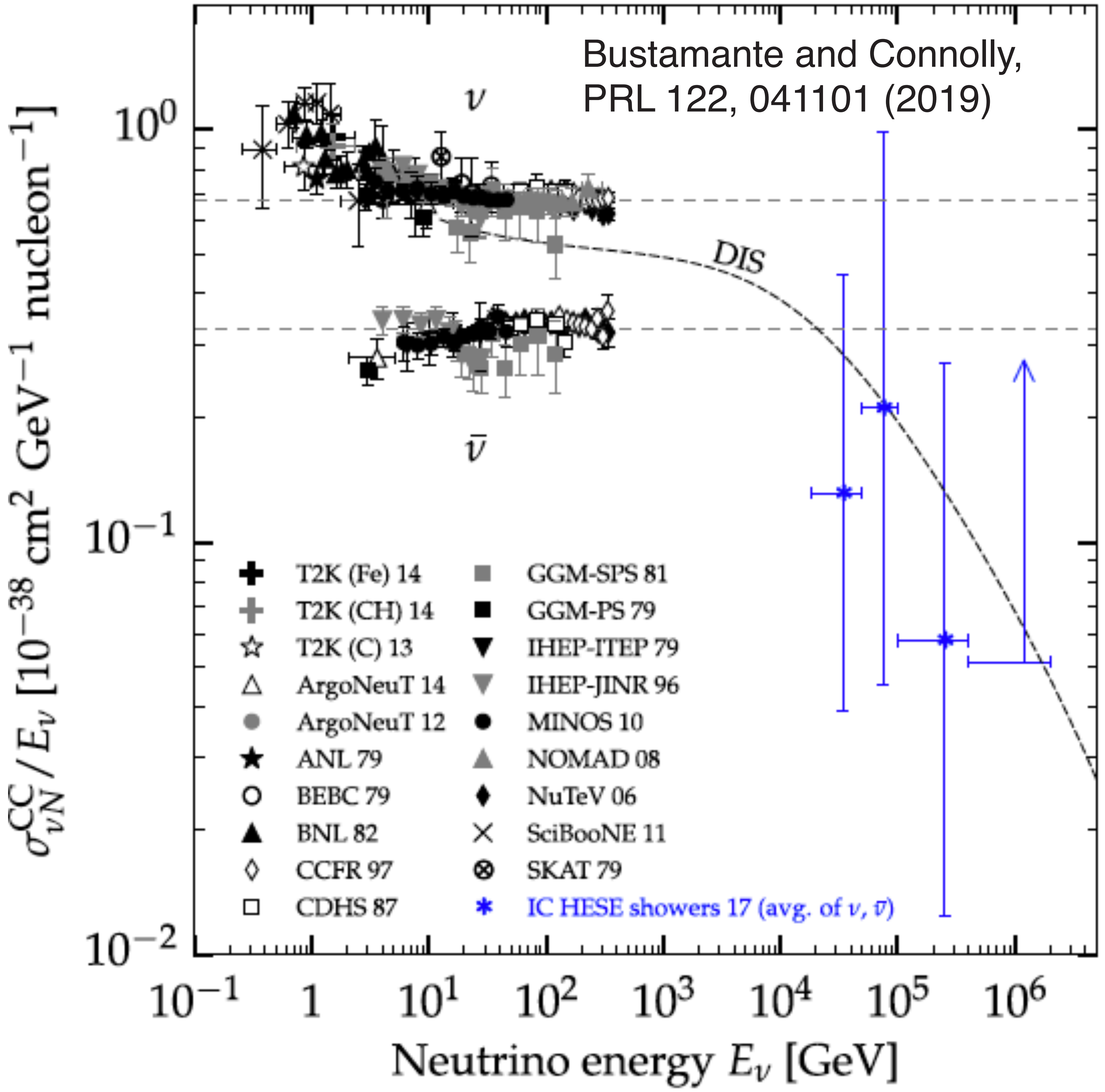
- Neutrinos from the heavy flavor hadron decays: prompt neutrinos
  - $h = D^0(\bar{D}^0),\ D^\pm,\ D_s^\pm, B^\pm$...

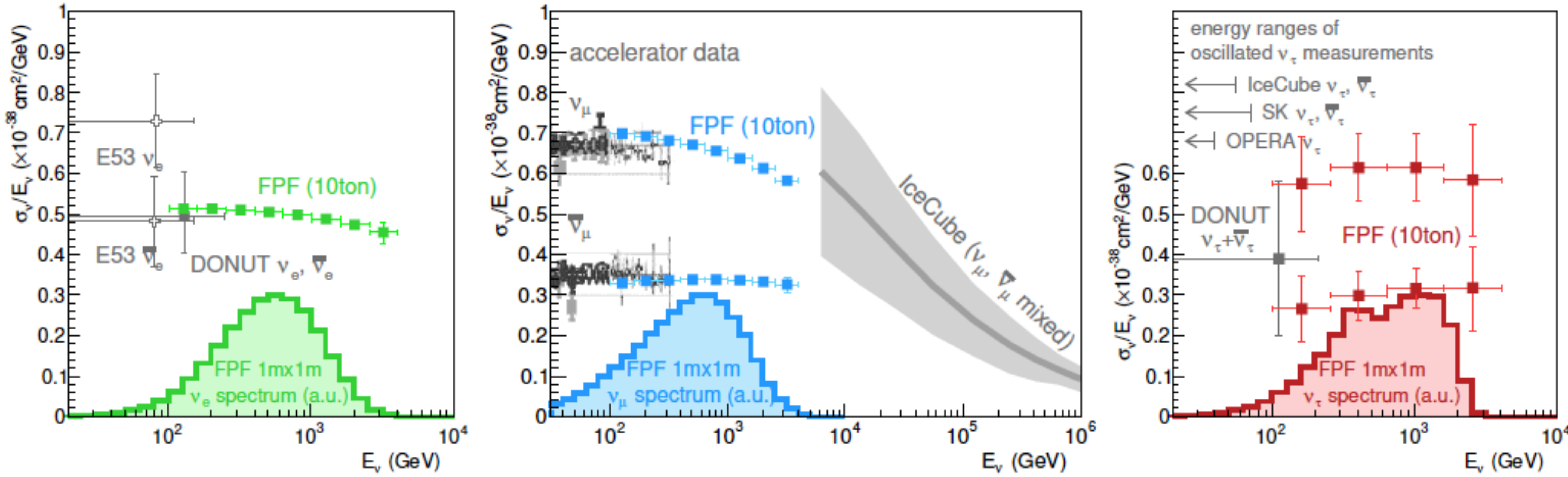
Predicted neutrino fluxes at the FPF

- Fluxes of $\nu_i + \bar{\nu}_i$ incident into the 1m x 1m cross sectional area at the FPF location of 620 m.
- Evaluated using several Monte Carlo generators.
- Neutrinos from light hadrons dominate at relatively lower energies.
- Neutrinos from charm are important at high energy range.
- Tau neutrinos are all from charm mesons.
- The prompt neutrino fluxes have large difference at high energies depending on the generator.



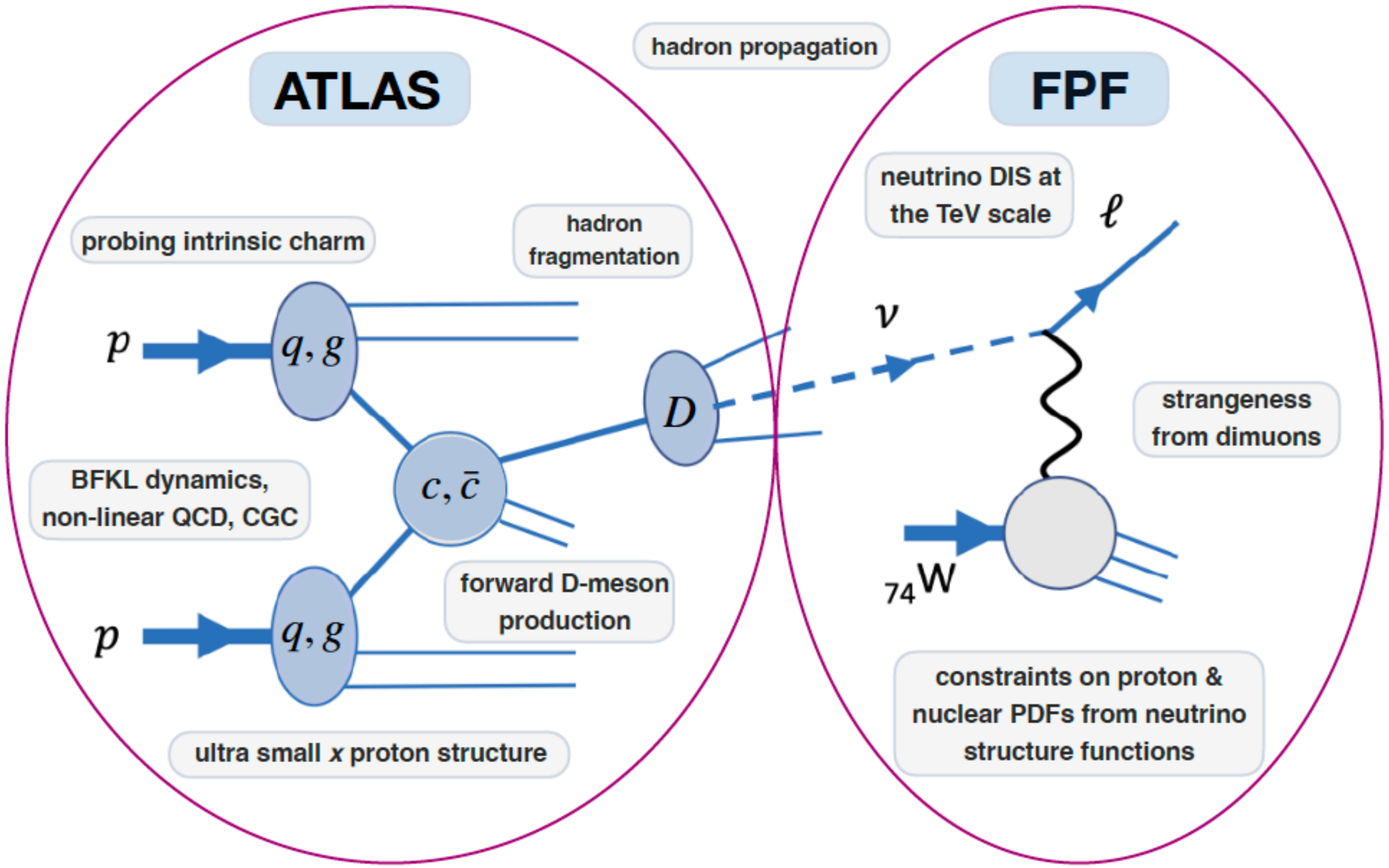
Primary goals for neutrino physics





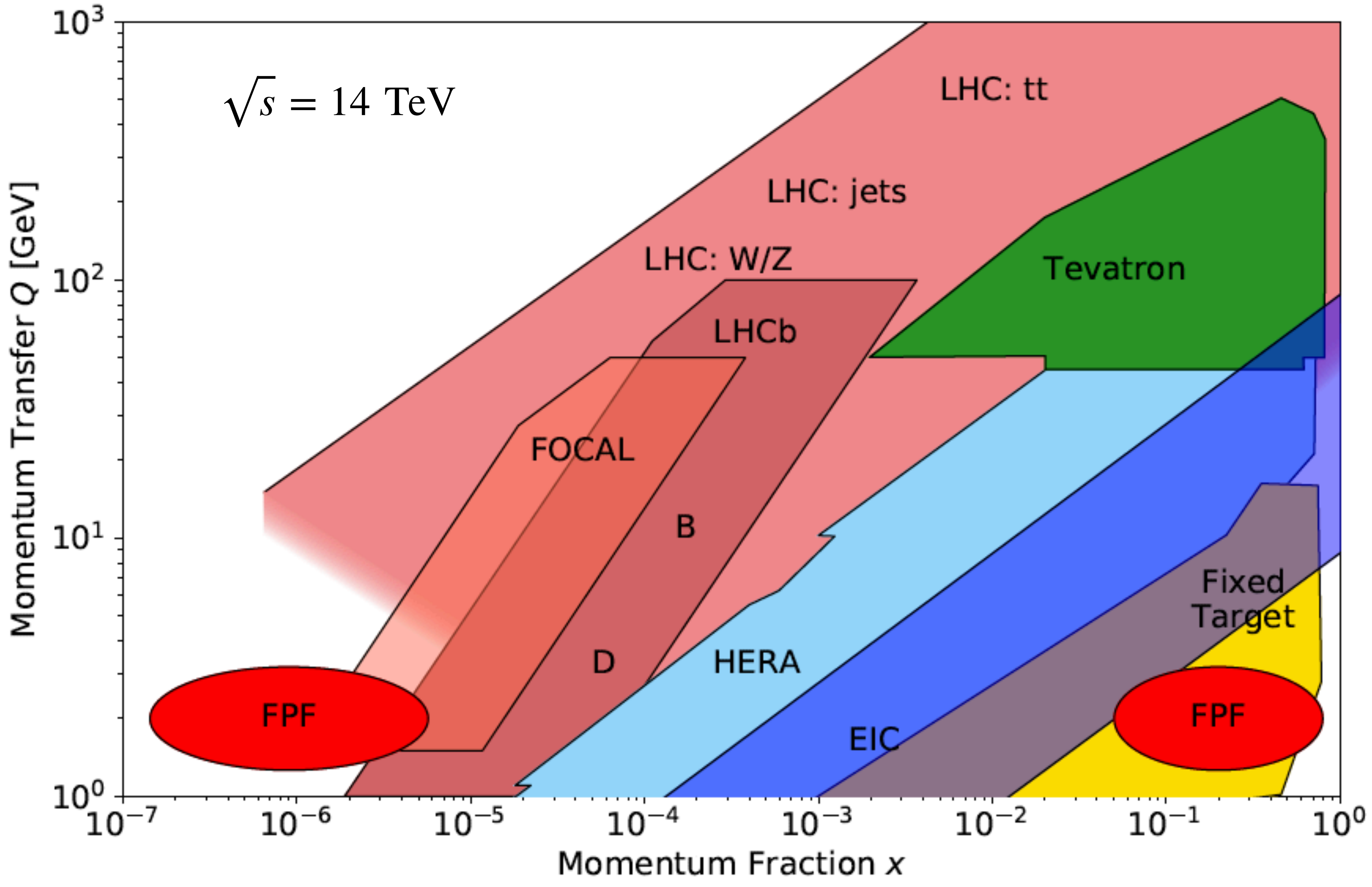
- Measurement of neutrino cross section in the (sub-)TeV energies.
- Measurement of the cross section for all three different flavors.

Prompt neutrino search at the FPF

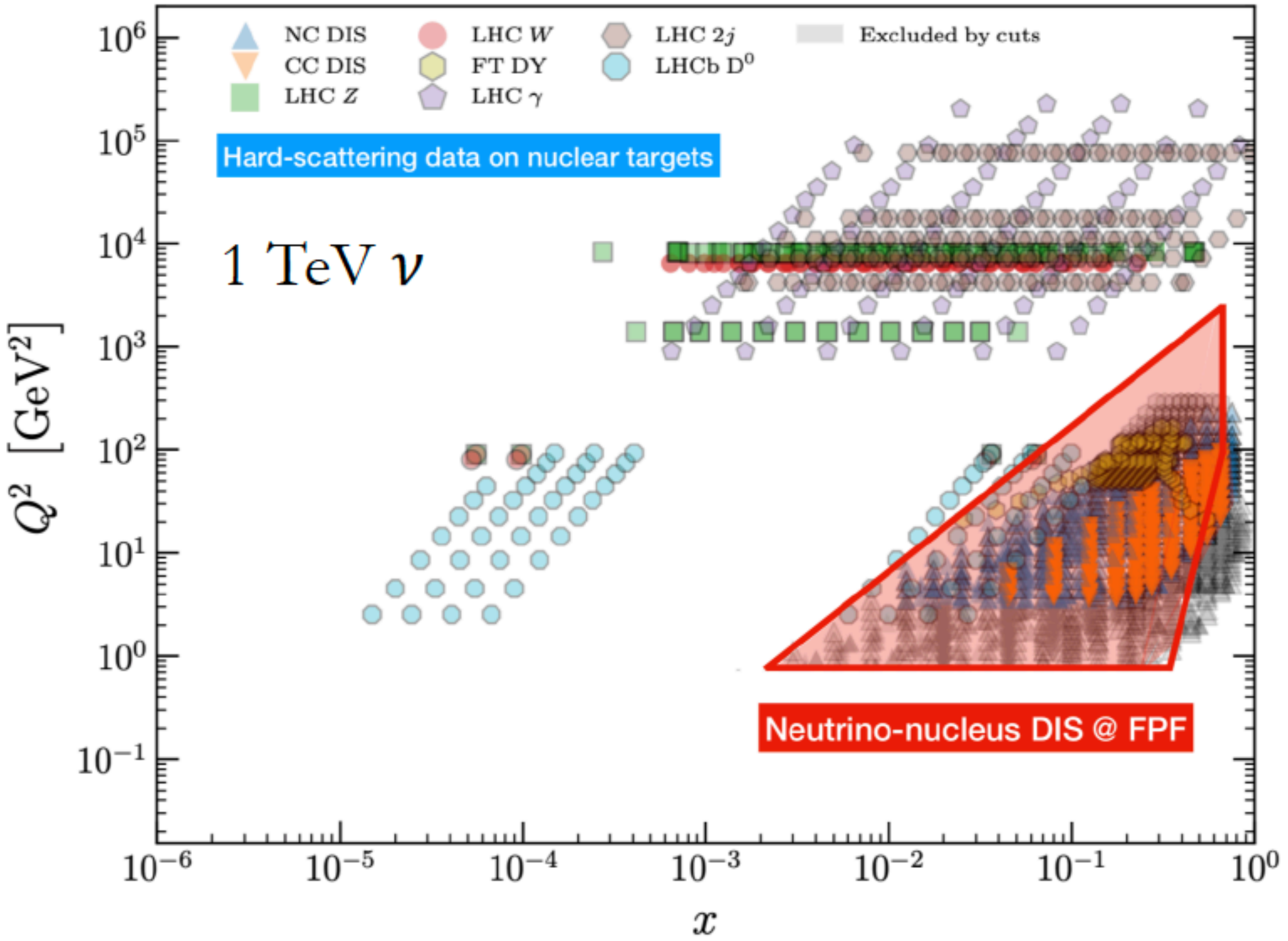


Kinematic region

Kinematic region for D meson production



Coverage for νA DIS structure function



- Small-x involved physics

  e.g.) PDF constraints, gluon saturation,

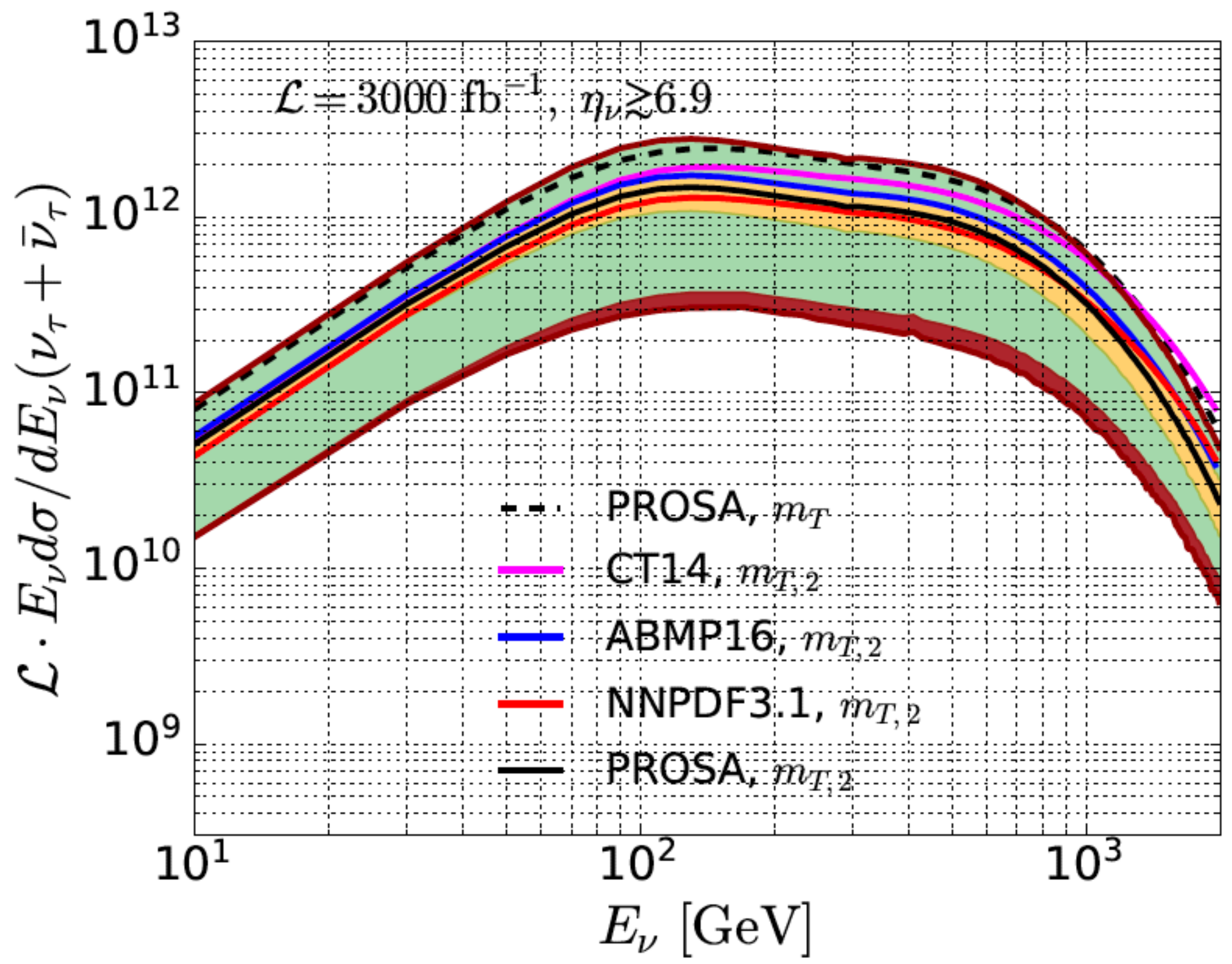
  HQ production approaches

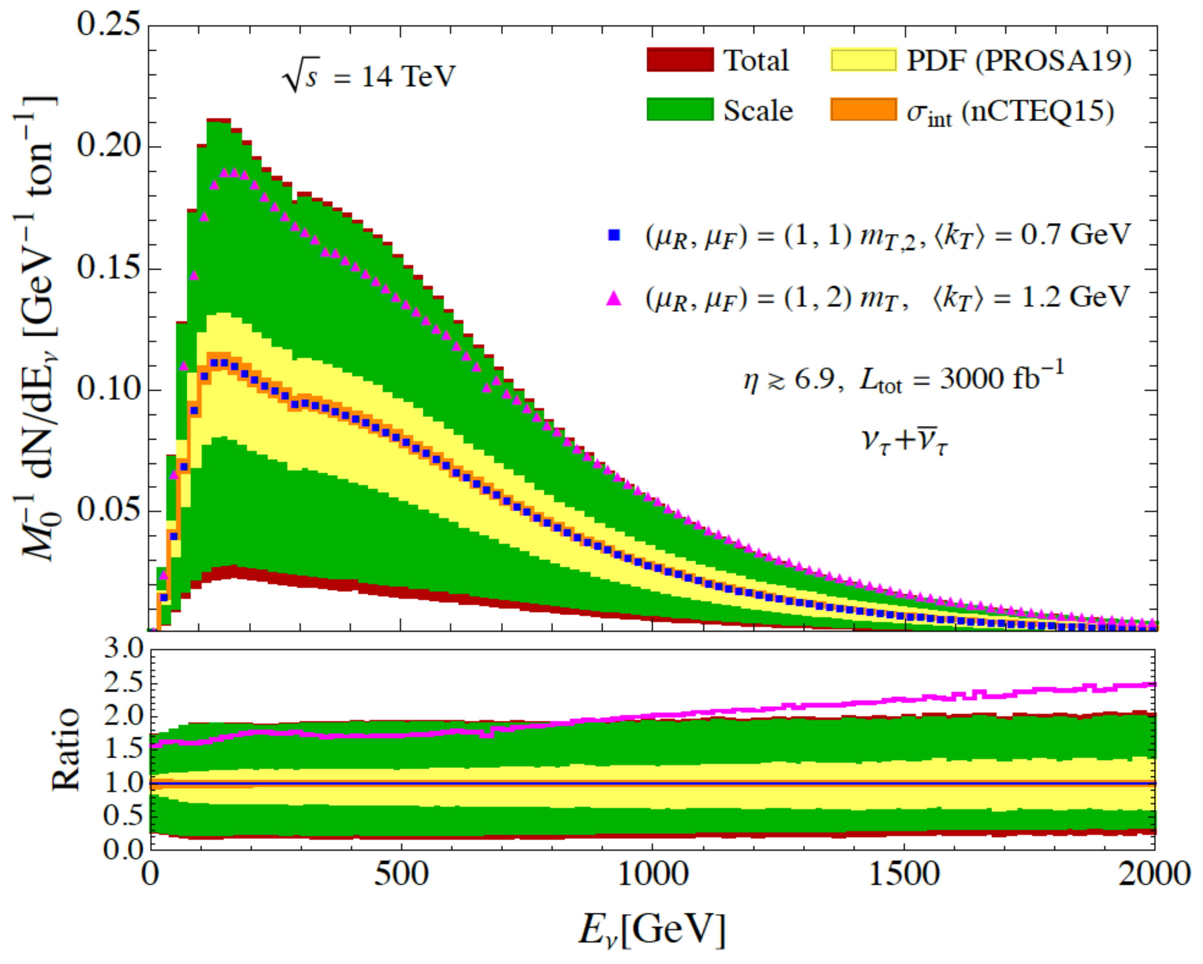
- To constrain proton and nuclear PDFs.

FPF white paper
(arXiv: 2203.05090)

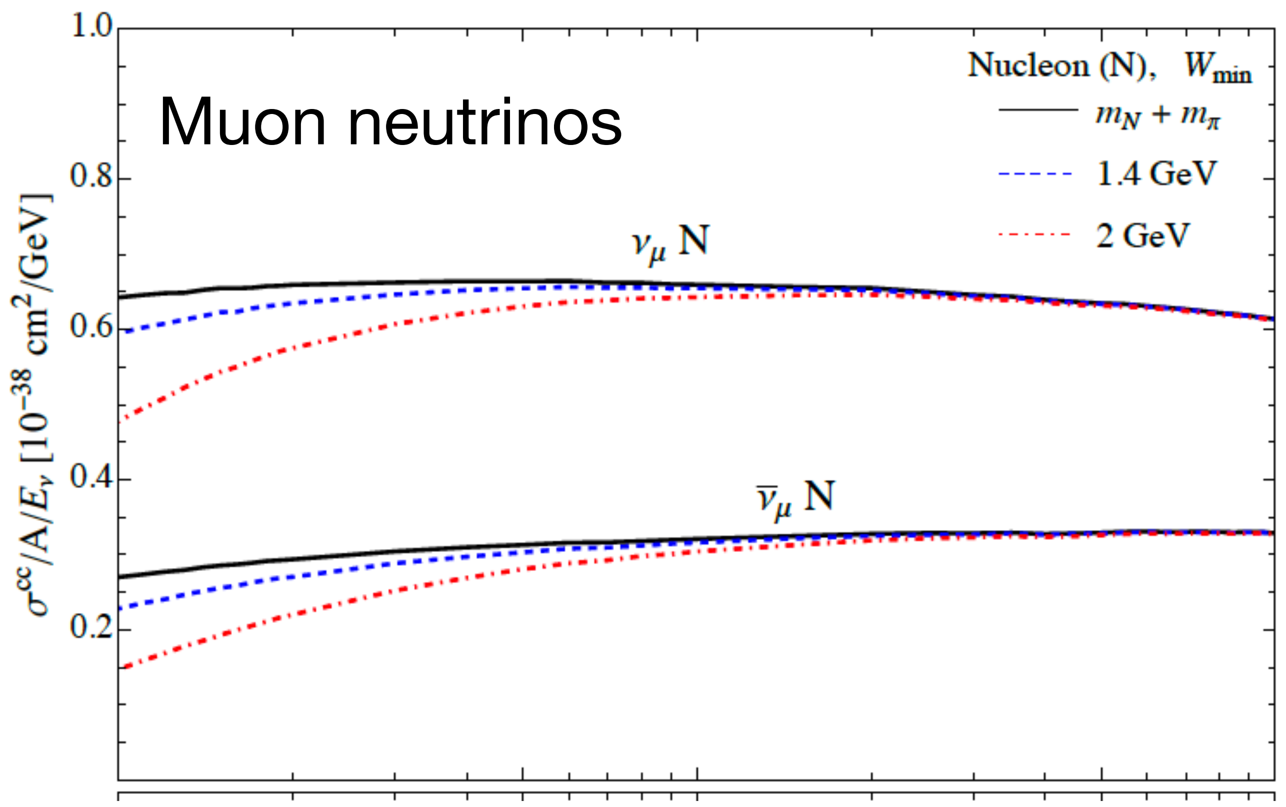
Neutrinos study for the FPF

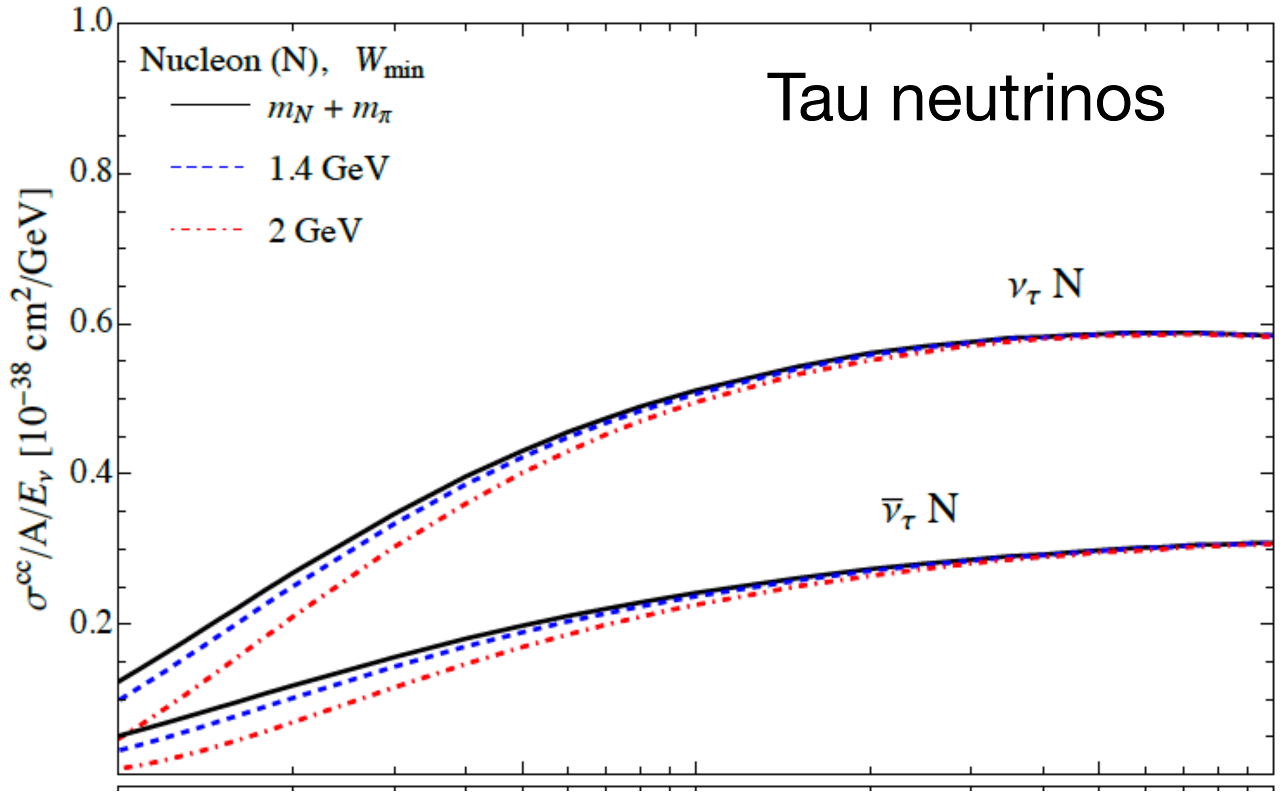
Tau neutrino prod. / events

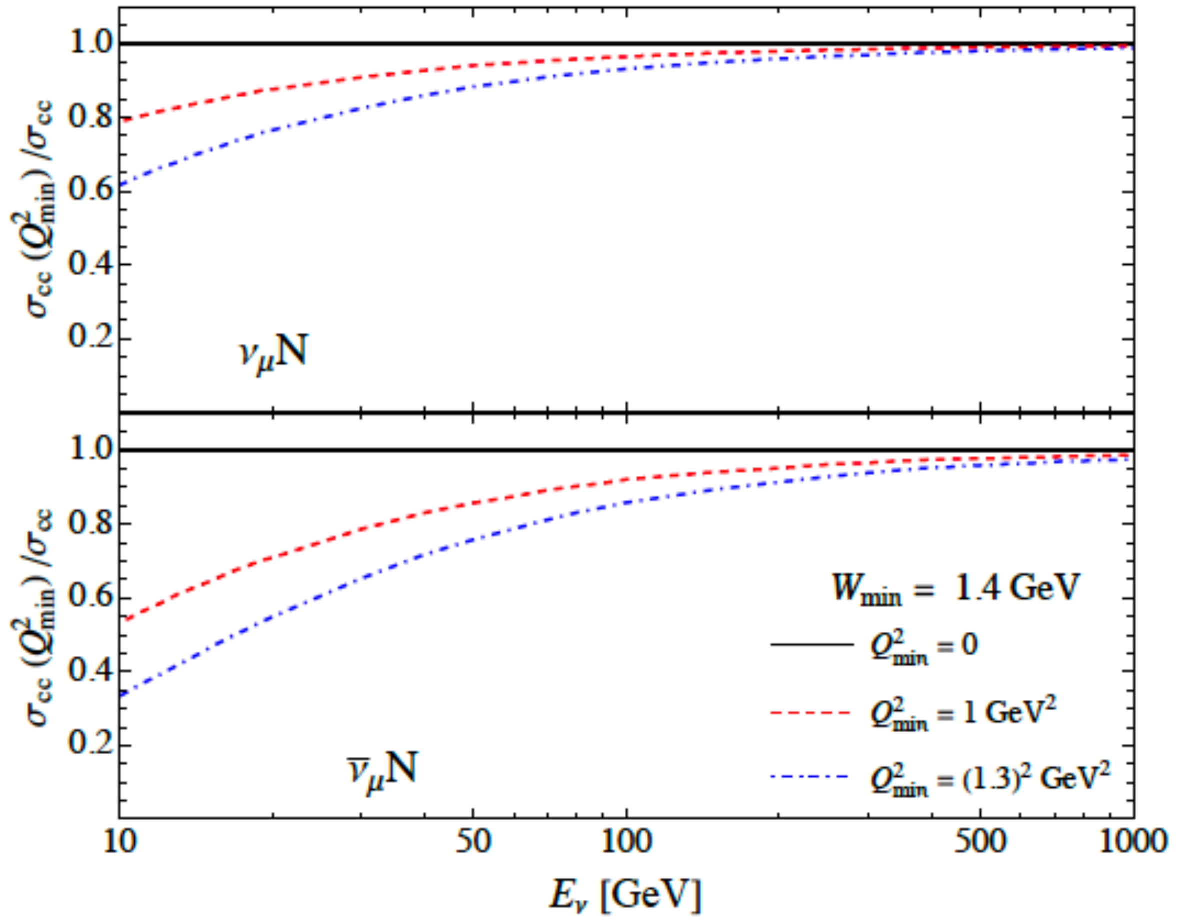


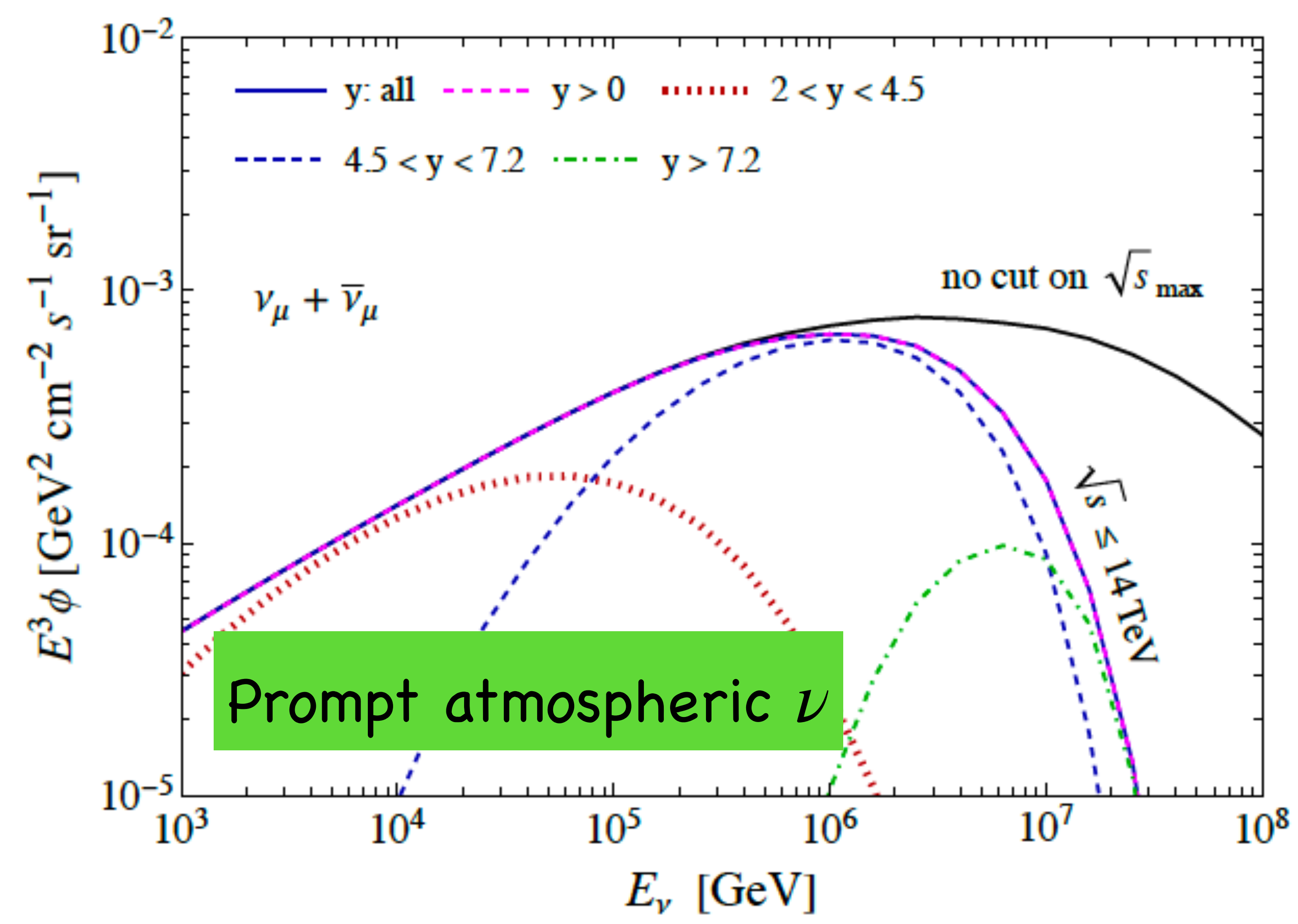


Neutrino cross sections with low Q structure functions









Prompt atmospheric ν

Summary II

- The LHC produce a large number of neutrinos in the far-forward region.

- The forward experiments at the LHC provide the unique opportunity to study neutrino interactions up to TeV energy range with high precision.
  - DIS is dominant interaction, which can be used to constrain the PDFs (nuclear PDFs, strange PDFs)

- Large fraction of high energy neutrinos and all tau neutrinos are produced from heavy flavor hadron decays (prompt). The measurement of these neutrinos will
  - provide neutrino data capable of probing proton structure and constraining the QCD evaluations for hadron production.
  - help to constrain/improve theoretical prediction on prompt atmospheric neutrinos

Thank you for your attention