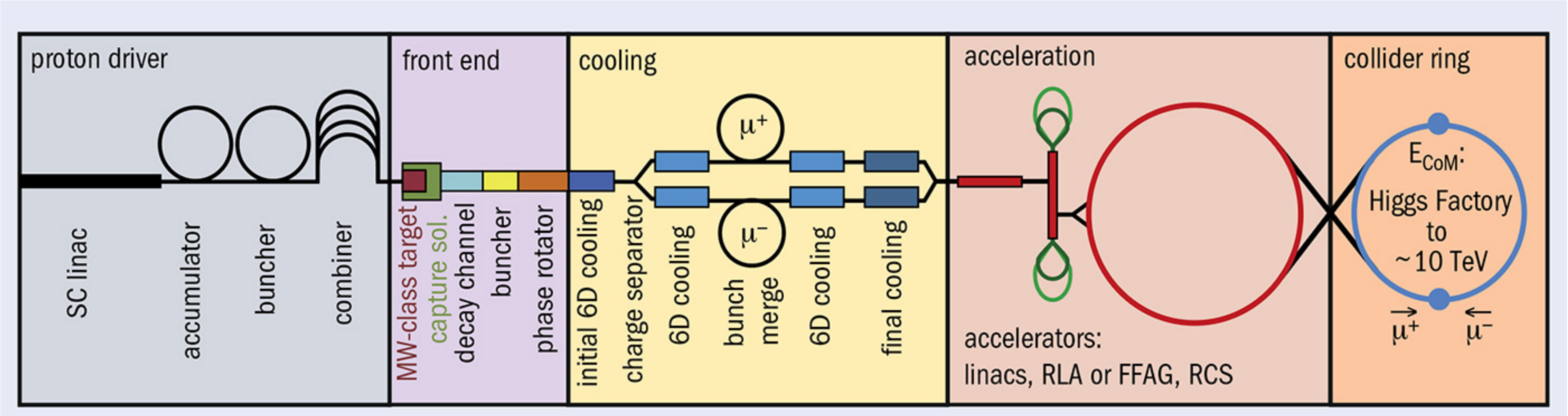
Neutrino Physics at a Muon Collider

Juan Rojo, VU Amsterdam & Nikhef



IMCC and MuCol Annual Meeting 2024

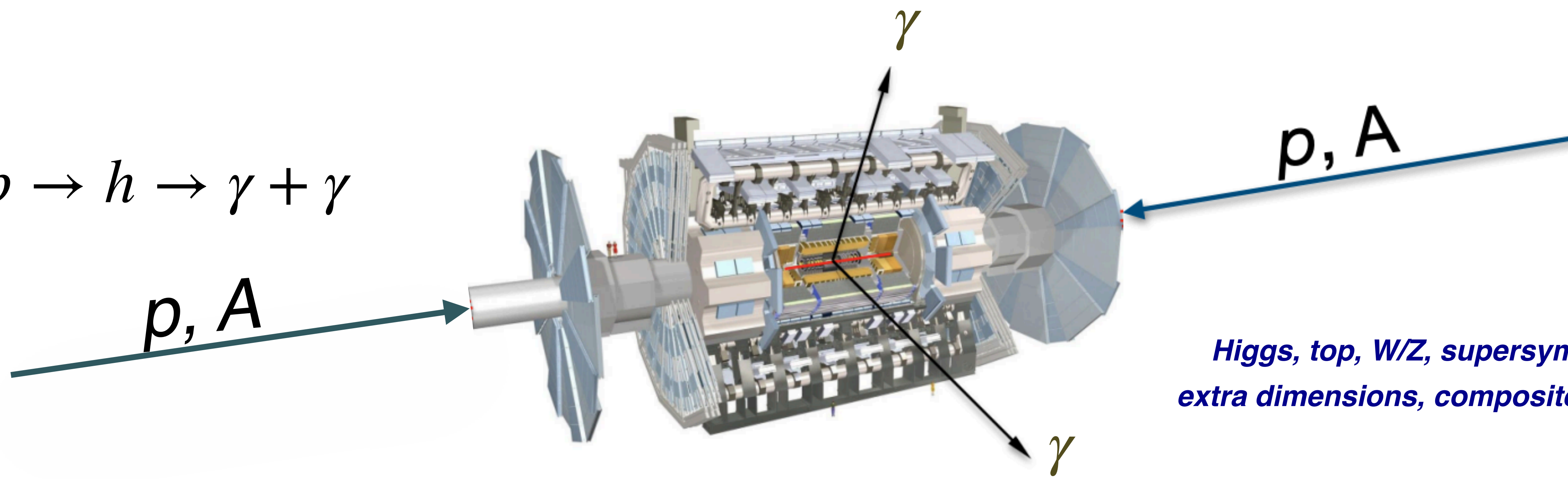
CERN, 12 March 2024

Neutrino Physics at the LHC

Neutrinos at the LHC

- The ATLAS and CMS detectors were designed with a focus on identifying particles **with masses at the electroweak and TeV scale**
- Due to kinematics**,** their decay products lie in the **central rapidity** acceptance region

$$p + p \rightarrow h \rightarrow \gamma + \gamma$$



Higgs, top, W/Z, supersymmetry, extra dimensions, composite Higgs…

neglecting mass effects

$$y \simeq \eta = \log \tan(\theta/2)$$

scattering angle

$$\cosh(\eta_{\rm max}) = \frac{\sqrt{s}}{m_h}$$

for ATLAS & CMS

$$|\,\eta_{\rm max}\,| \leq 2.5 \ (3.5)$$

central region covered

- Light particles (pions, kaons, protons, heavy flavour mesons) produced predominantly in the **forward rapidity region**, justifying e.g. the design of **LHCb**

for LHCb

$$2.0 \leq \eta \leq 4.5$$

Neutrinos at the LHC

- However, New Physics, if **light and feebly-interacting,** could already be copiously produced at the LHC, but missed due to the **blind spots** of existing detectors in the **far-forward region**

- In addition, there are **guaranteed physics targets** to be reached should we instrument the forward region of the LHC, based on exploiting **the most energetic, high-intensity neutrino beam ever produced in a laboratory**

Neutrino and muon physics in the collider mode of future accelerators

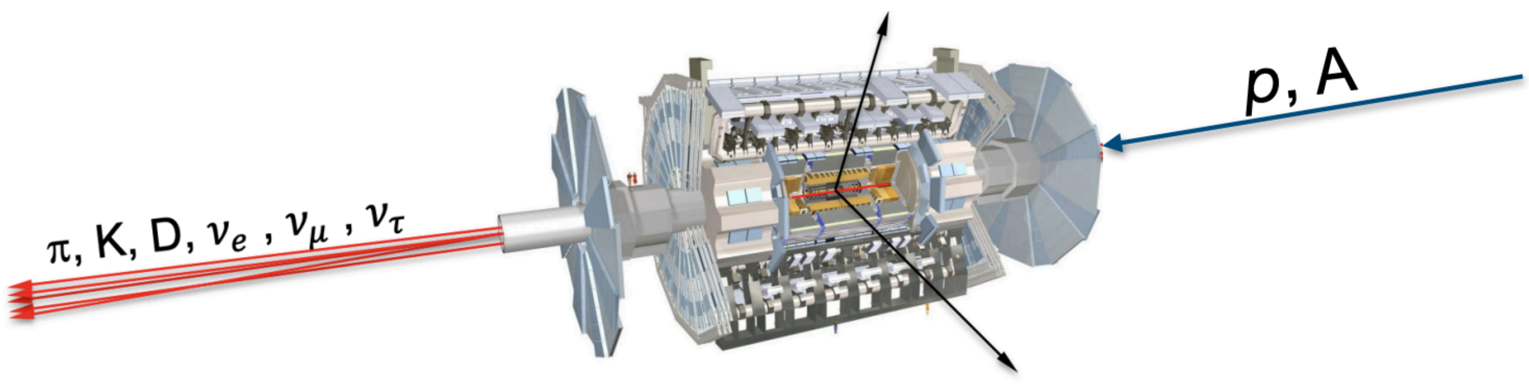
A. De Rujula (CERN), R. Ruckl (CERN)
May, 1984

24 pages
Part of Proceedings, ECFA-CERN Workshop on large hadron collider in the LEP tunnel : Lausanne and Geneva, Switzerland, March 21-27 March, 1984, 571-596
Contribution to: CERN - ECFA Workshop on Feasibility of Hadron Colliders in the LEP Tunnel (2nd part of Lausanne mtg. of 3/21), 571-596, SSC Workshop: Superconducting Super Collider Fixed Target Physics
DOI: 10.5170/CERN-1984-010-V-2.571
Report number: CERN-TH-3892/84
View in: CERN Document Server, KEK scanned document

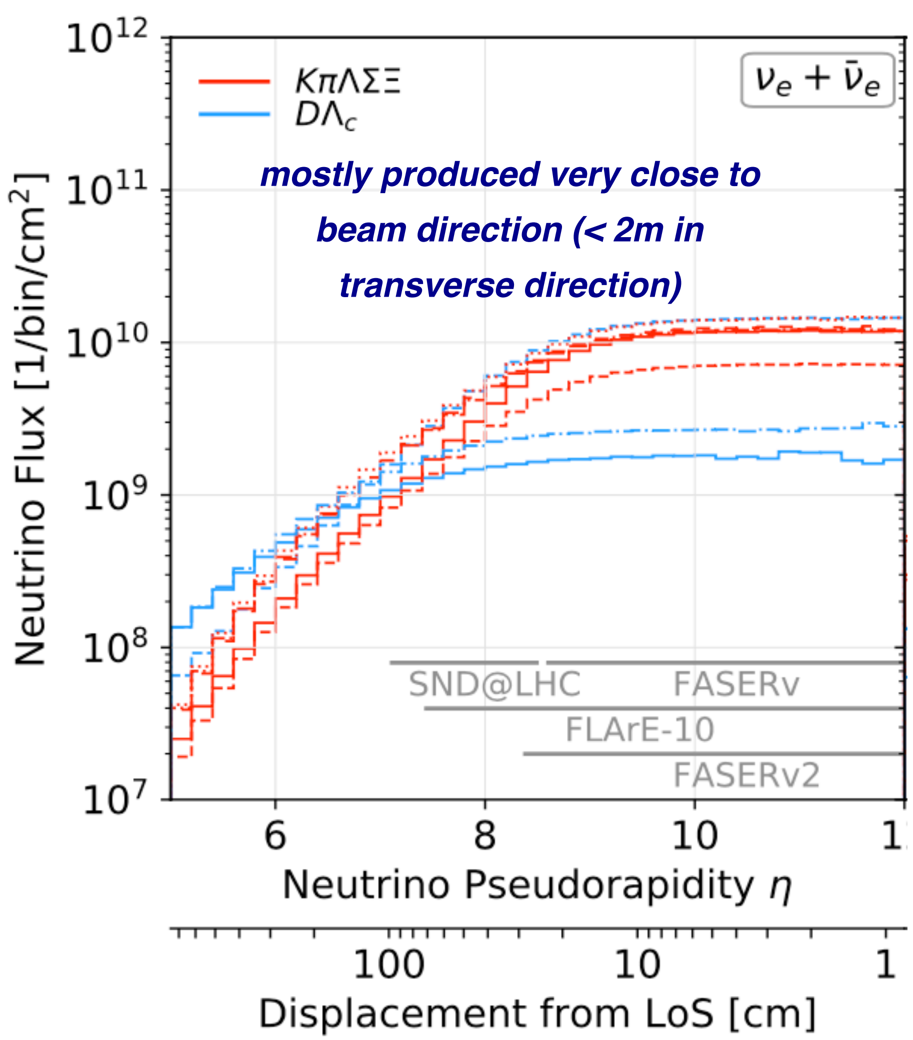
pdf cite claim reference search 14 citations

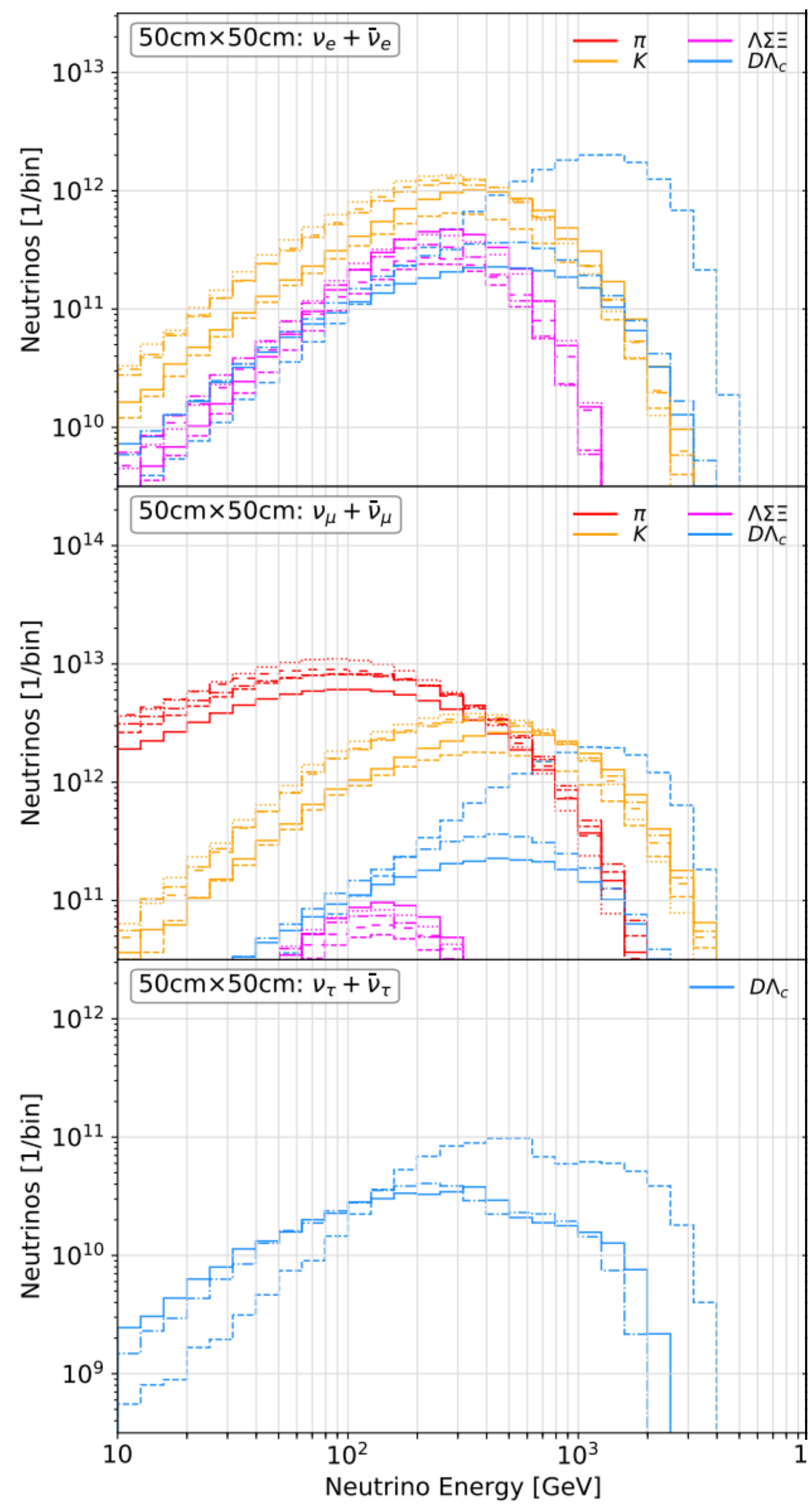
First proposal in 1984

Neutrinos at the LHC

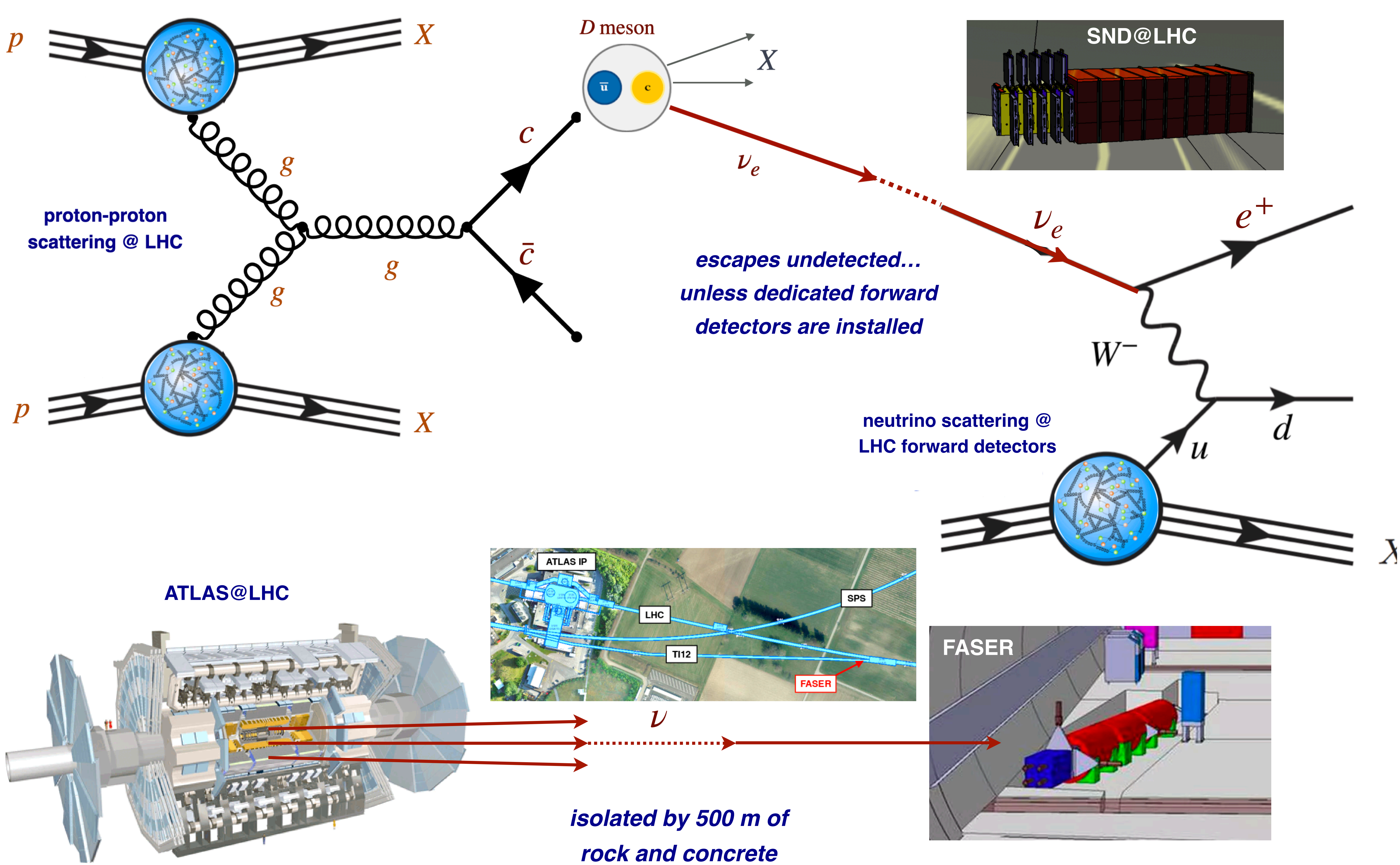


- **electron neutrinos** mostly from *D*-meson decays above 500 GeV
- **muon neutrino** flux dominated by pion & kaon decays
- **tau neutrinos** entirely from D-meson decays
- Reaching **multi-TeV region** in all cases





Neutrinos at the LHC



The dawn of the LHC neutrino era

- Two far-forward experiments, **FASER** and **SND@LHC**, have been instrumenting the LHC far-forward region since the begin of Run III and reported **evidence for LHC neutrinos** (March 2023)

PHYSICAL REVIEW LETTERS **131,** 031801 (2023)

Editors' Suggestion | Featured in Physics

First Direct Observation of Collider Neutrinos with FASER at the LHC

We report the first direct observation of neutrino interactions at a particle collider experiment. Neutrino candidate events are identified in a 13.6 TeV center-of-mass energy pp collision dataset of 35.4 fb^{-1} using the active electronic components of the FASER detector at the Large Hadron Collider. The candidates are required to have a track propagating through the entire length of the FASER detector and be consistent with a muon neutrino charged-current interaction. We infer 153^{+12}_{-13} neutrino interactions with a significance of 16 standard deviations above the background-only hypothesis. These events are consistent with the characteristics expected from neutrino interactions in terms of secondary particle production and spatial distribution, and they imply the observation of both neutrinos and anti-neutrinos with an incident neutrino energy of significantly above 200 GeV.

DOI: 10.1103/PhysRevLett.131.031801

PHYSICAL REVIEW LETTERS **131,** 031802 (2023)

Editors' Suggestion

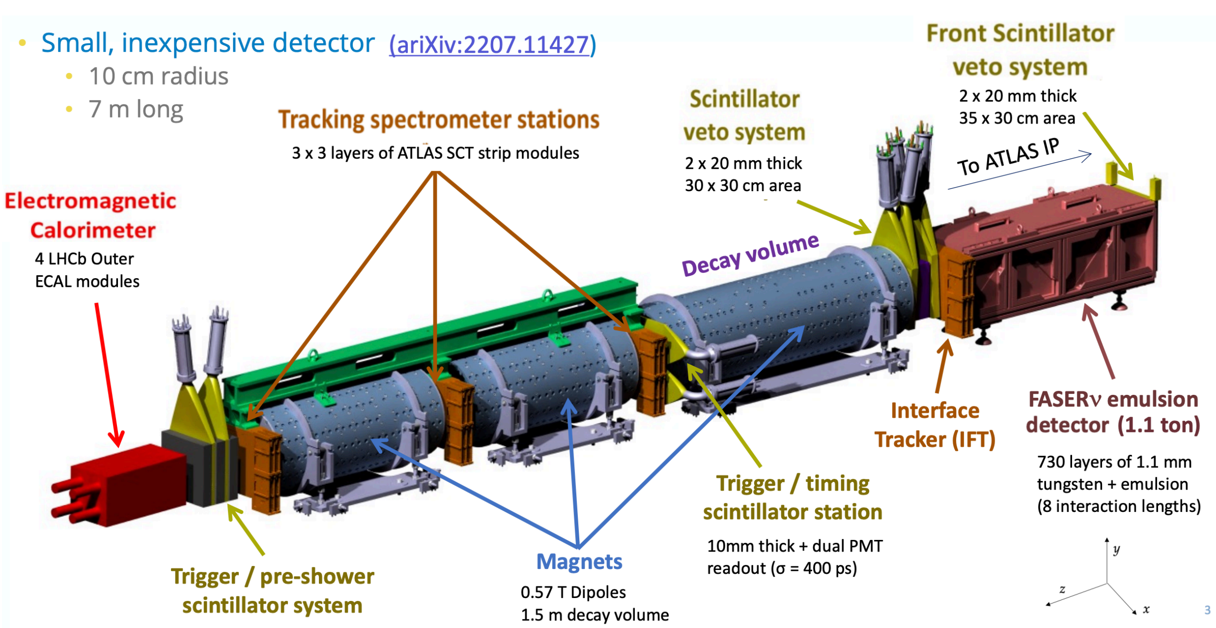
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

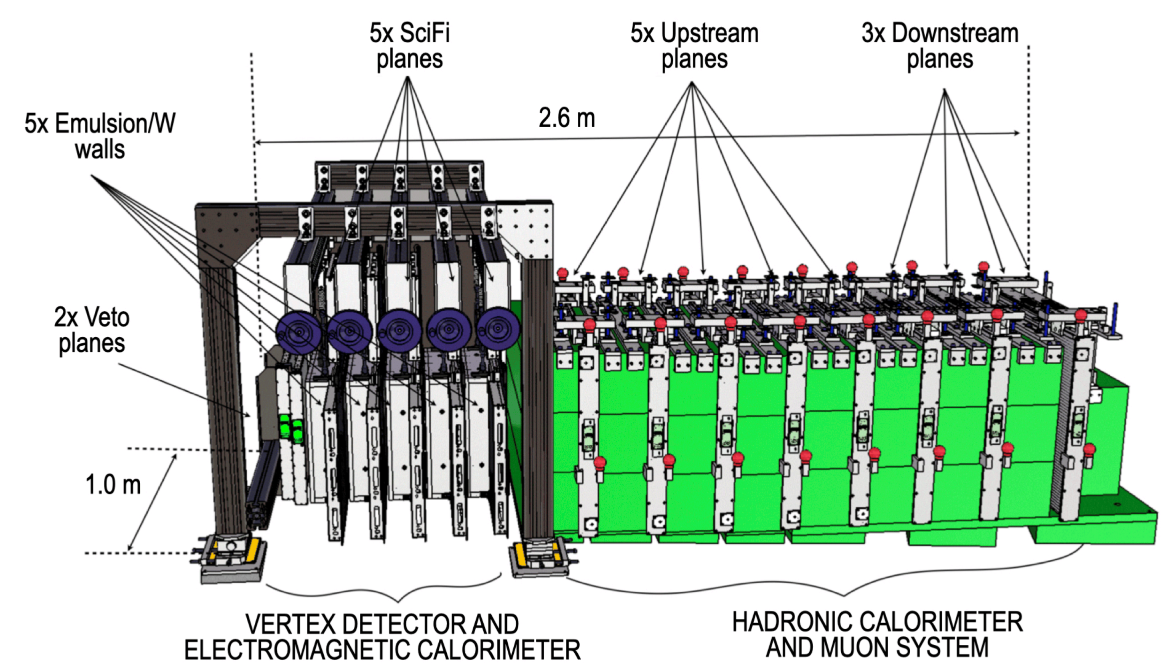
We report the direct observation of muon neutrino interactions with the SND@LHC detector at the Large Hadron Collider. A dataset of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected by SND@LHC in 2022 is used, corresponding to an integrated luminosity of 36.8 fb^{-1}. The search is based on information from the active electronic components of the SND@LHC detector, which covers the pseudorapidity region of $7.2 < \eta < 8.4$, inaccessible to the other experiments at the collider. Muon neutrino candidates are identified through their charged-current interaction topology, with a track propagating through the entire length of the muon detector. After selection cuts, 8 ν_μ interaction candidate events remain with an estimated background of 0.086 events, yielding a significance of about 7 standard deviations for the observed ν_μ signal.

DOI: 10.1103/PhysRevLett.131.031802

153 neutrinos detected, 151± 41 expected

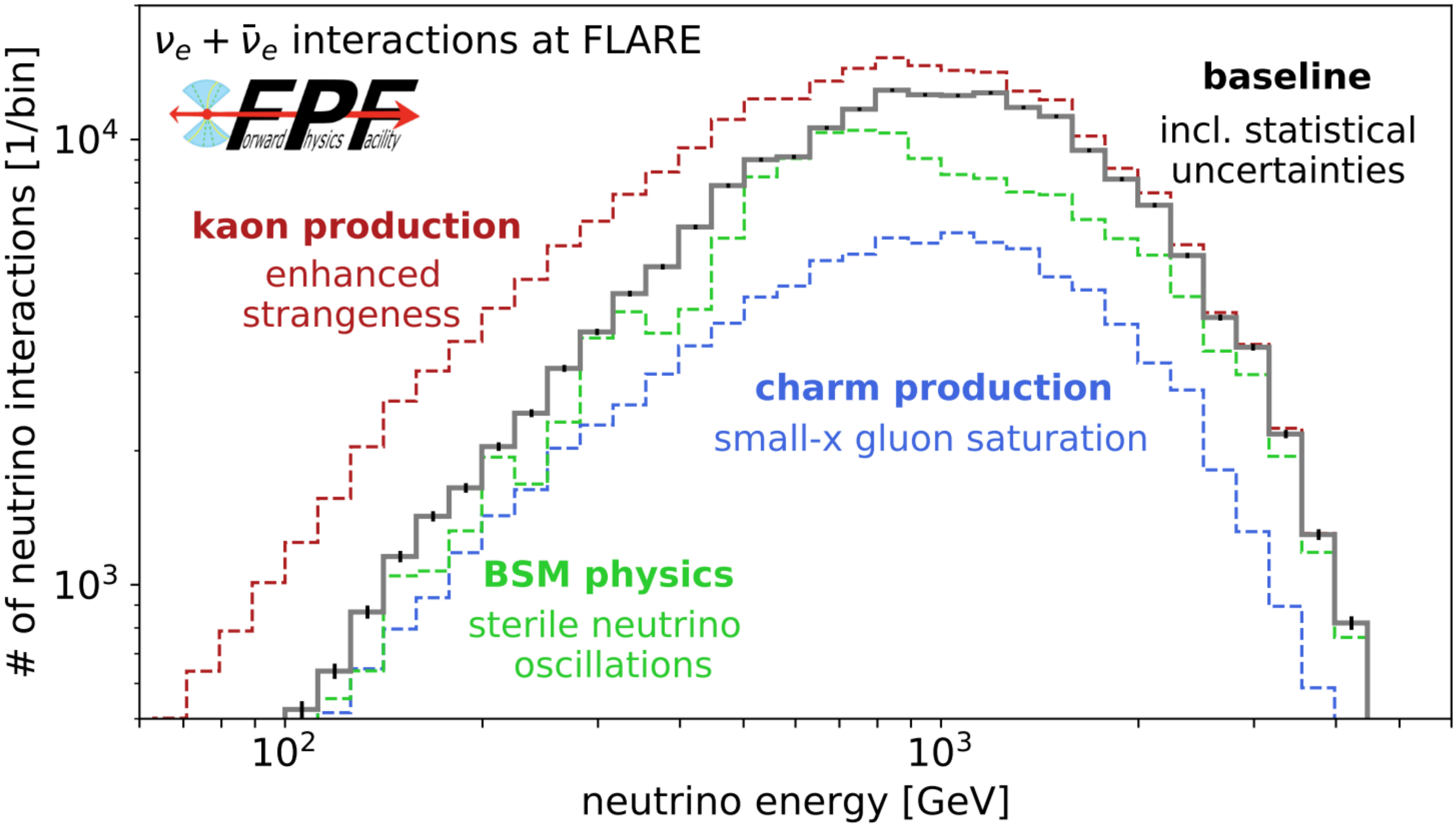
8 neutrinos detected, 4 expected





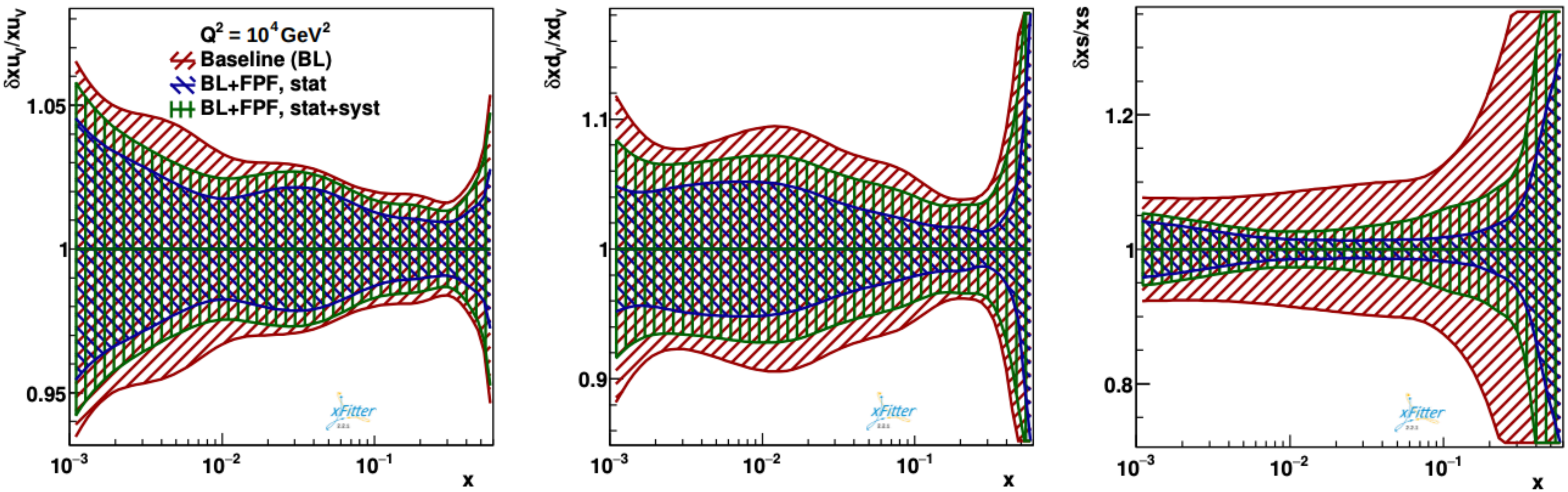
Now is the time to start exploiting their physics potential

Physics with LHC neutrinos

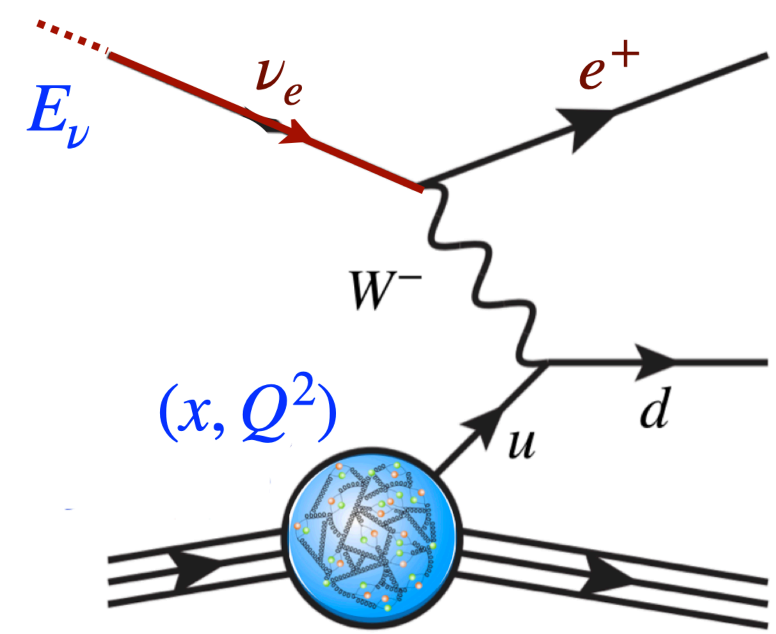


- Probe **small-*x* QCD** (e.g. non-linear dynamics) in uncharged regions
- Provide a laboratory validation of **muon puzzle** predating **cosmic ray physics**
- New channels for **BSM searches** e.g. via sterile neutrino oscillations

Proton Structure from LHC neutrinos



- Significant impact on **proton PDFs** of neutrino DIS structure function measurements at the LHC
- Most impact on **up and down valence, strangeness** & **charm**



Far-forward neutrino detectors effectively extend the LHC with a **Neutrino-Ion Collider** by ``recycling'' an otherwise discarded beam

$$\sigma_{\nu p \to e^+ X}(E_\nu) = \widetilde{\sigma}_{\nu u \to d} \otimes u(x, Q^2)$$

neutrino-proton scattering rate

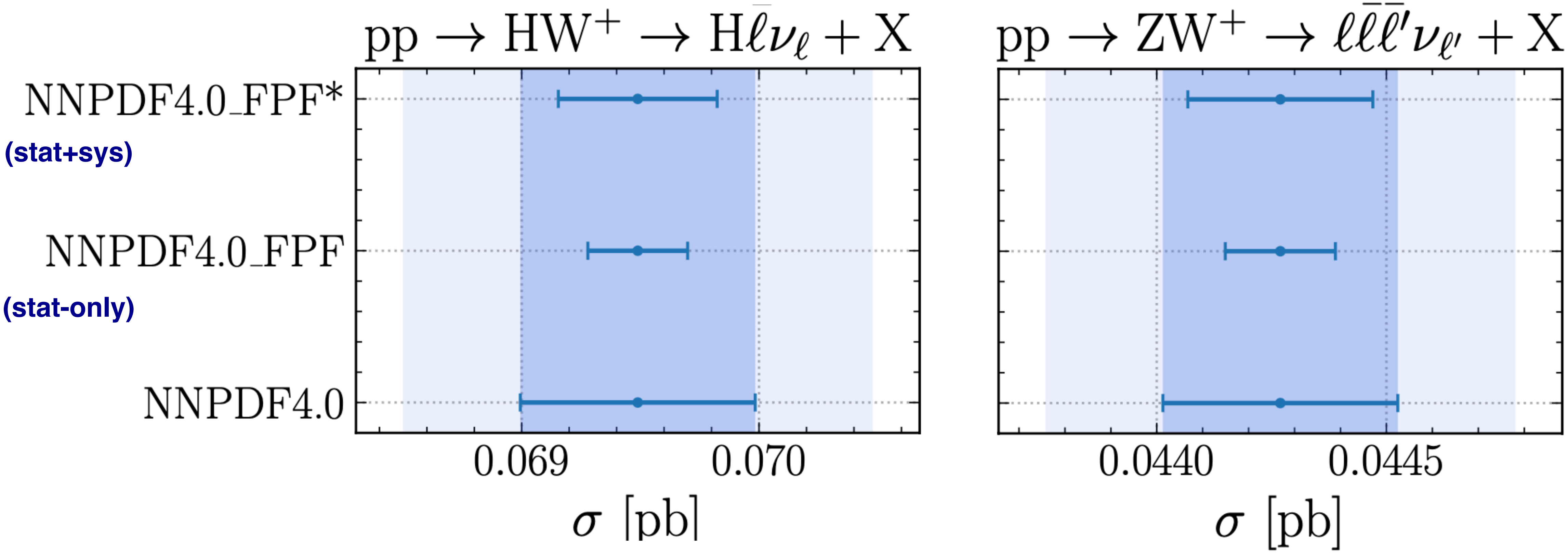
partonic cross-section

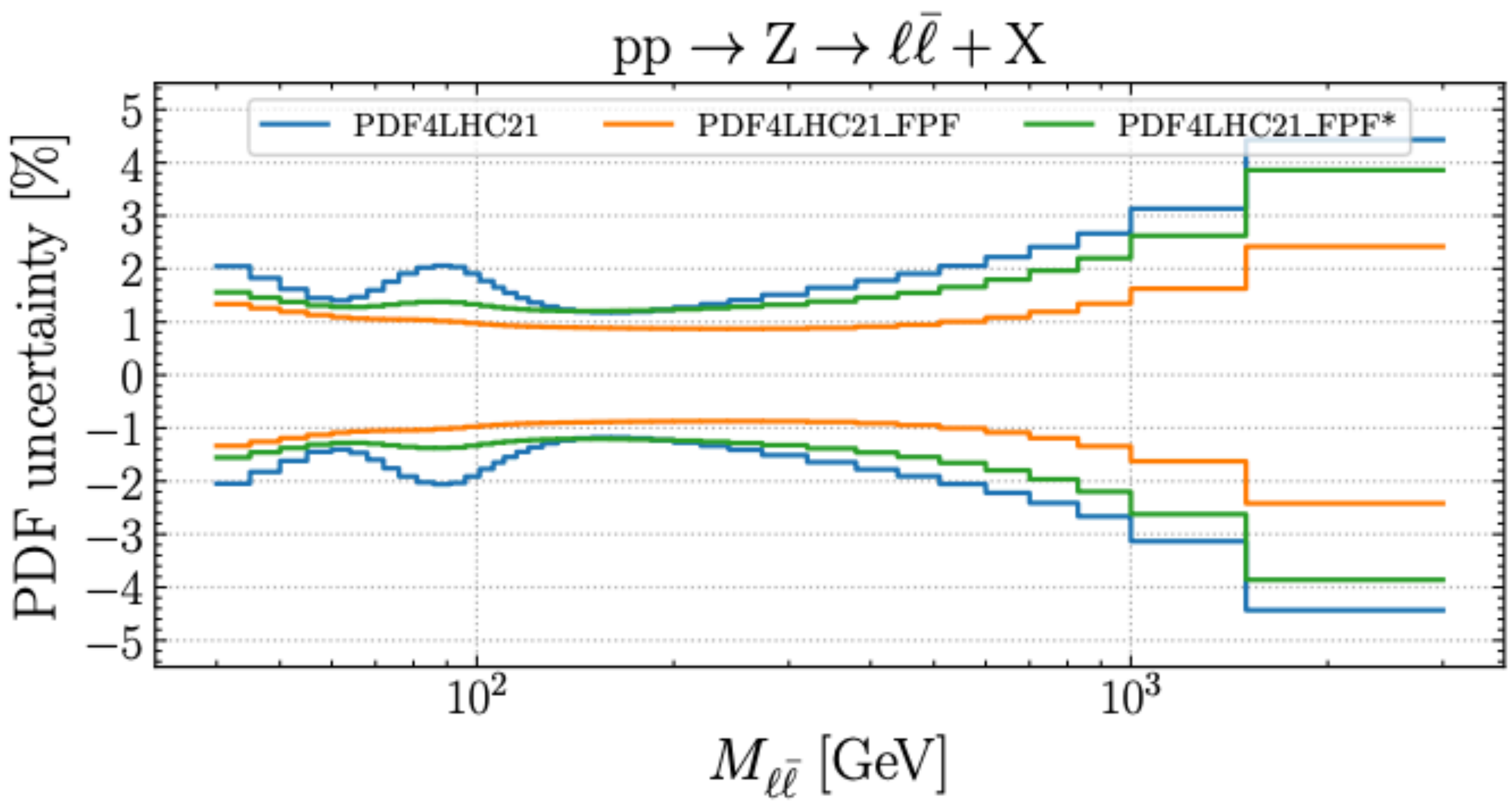
up-quark content int the proton

Charged-current DIS counterpart of the **Electron-Ion Collider**

J. M. Cruz-Martinez, M. Fieg, T. Giani, P. Krack, T. Makela, T. Rabemananjara, and J. Rojo, ***arXiv:2309.09581 (JHEP)***

Impact at the HL-LHC





- Impact on **core HL-LHC processes** i.e. single and double weak boson production and Higgs production (VH, VBF)

- Also relevant for **BSM searches at large-mass** (via large-*x* PDFs)

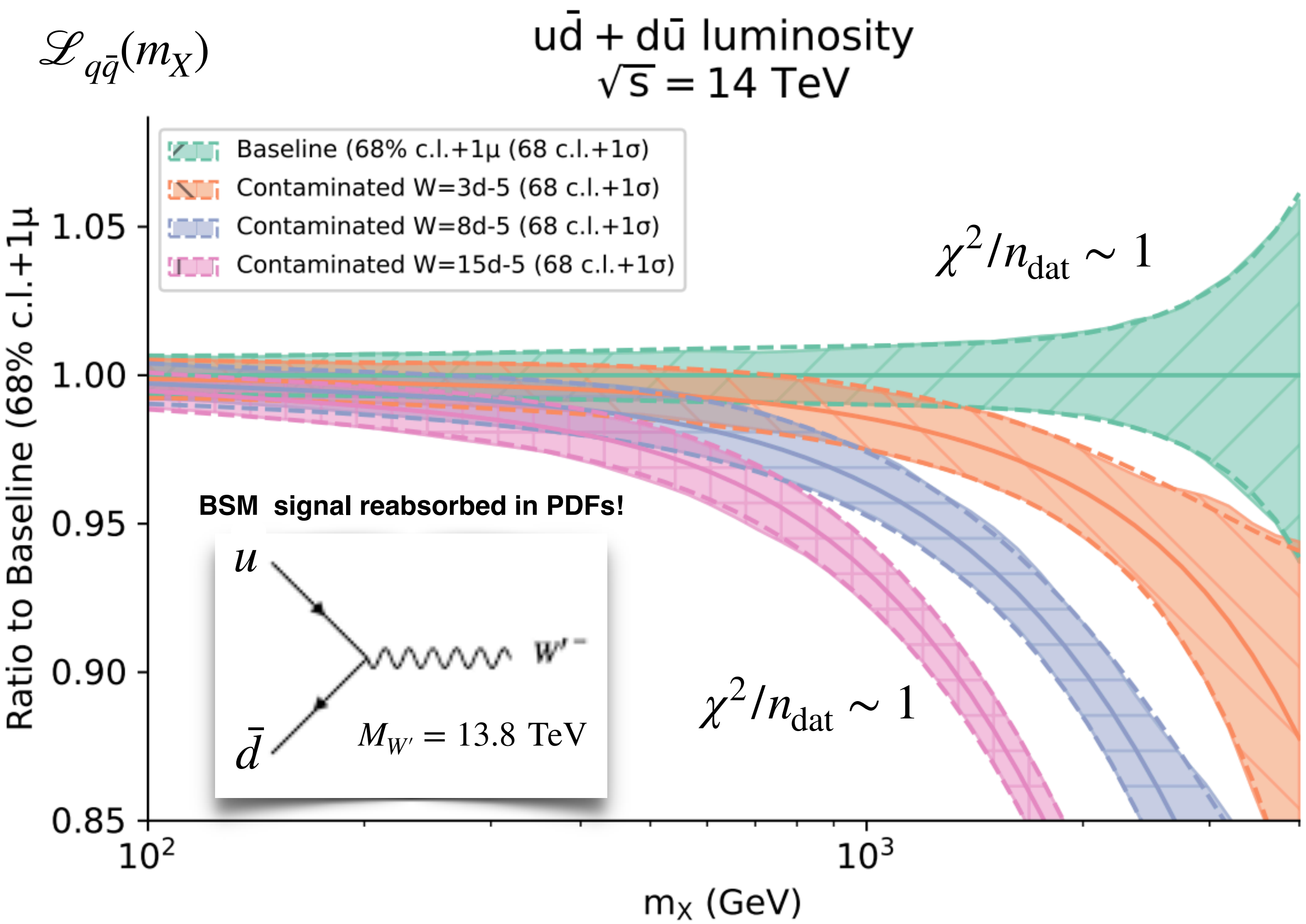
e.g. high-mass dilepton resonances

Fully independent constraints on proton structure, crucial to disentangle possible BSM signatures in high p_T data

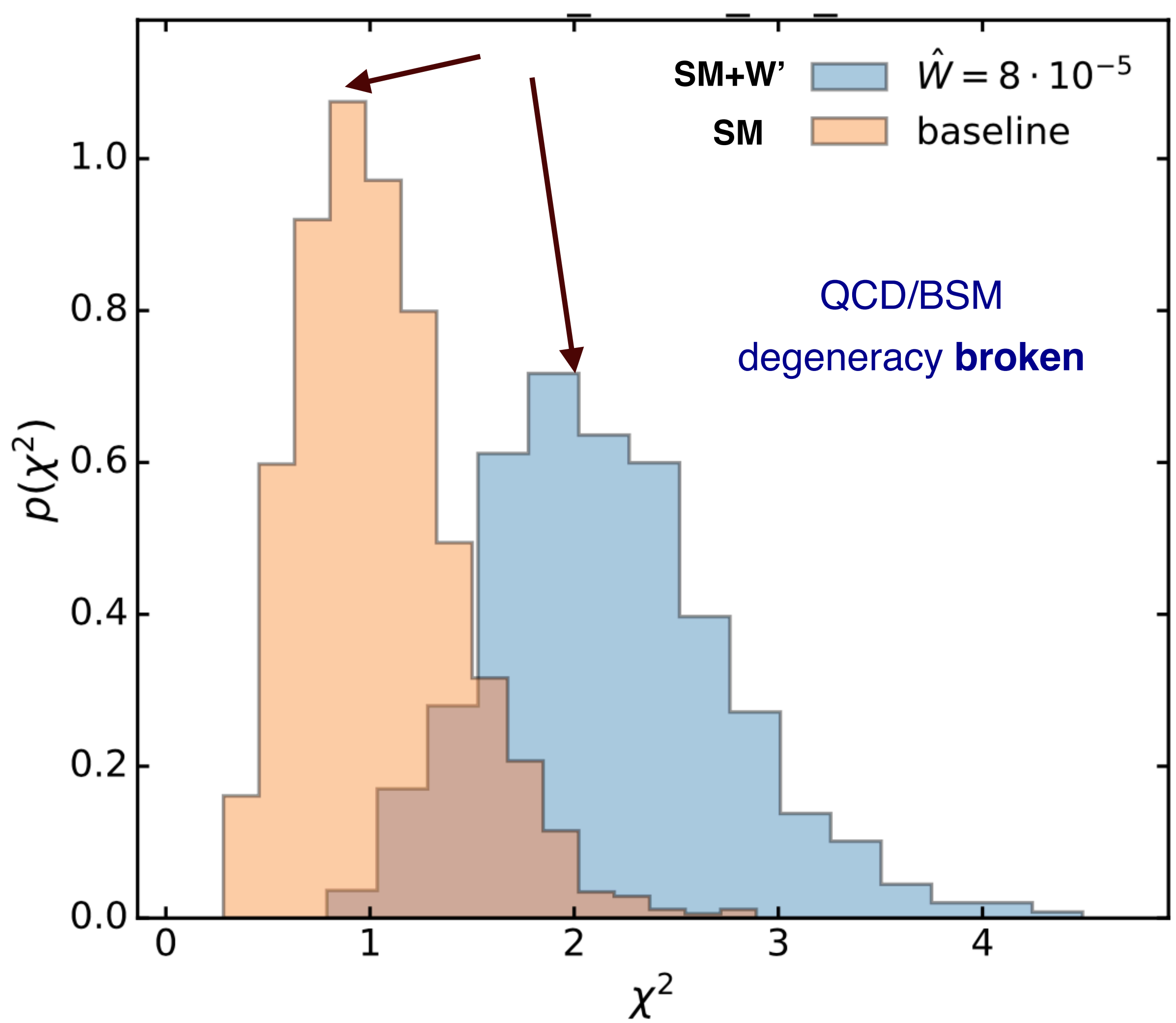
Impact at the HL-LHC

- Assume a BSM scenario with an extra W' gauge boson with **$M_{W'}$ = 13.8 TeV**
- Generate **HL-LHC pseudo-data** (NC & CC Drell-Yan) for this model and include in global PDF fit
- **Data-theory agreement unchanged,** but the $q\bar{q}$ luminosity **shifts far beyond PDF uncertainties**.
- Including **LHC neutrino DIS measurements** would break this QCD/BSM degeneracy: Essential input to realise the **full BSM search potential of the HL-LHC**

Global PDF fit + HL-LHC pseudo-data



Global PDF fit + HL-LHC & FPF pseudo-data



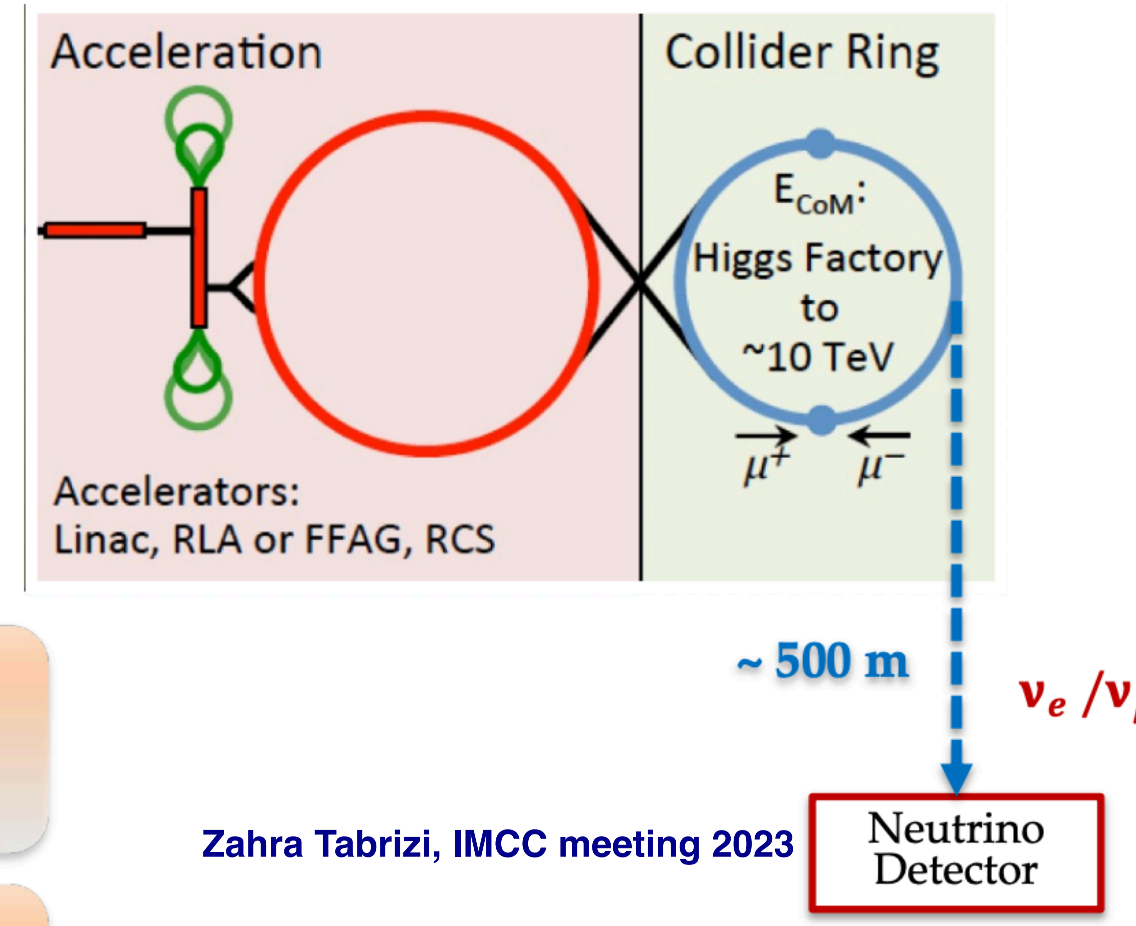
Hammou, Madigan, Ubiali, **WIP**

Neutrino Physics at a Muon Collider

Physics with Neutrino Beams at MuCol

Why would a Muon Collider Help?

No oscillation, but:



Zahra Tabrizi, IMCC meeting 2023

Very high beam luminosity	Precisely known energy spectra
Equal numbers of e/μ (anti)neutrinos	Very well determined beam intensity

FASER-like experiment(s) at a **MuCol** have pros and cons as compared to **HL-LHC** or future pp colliders

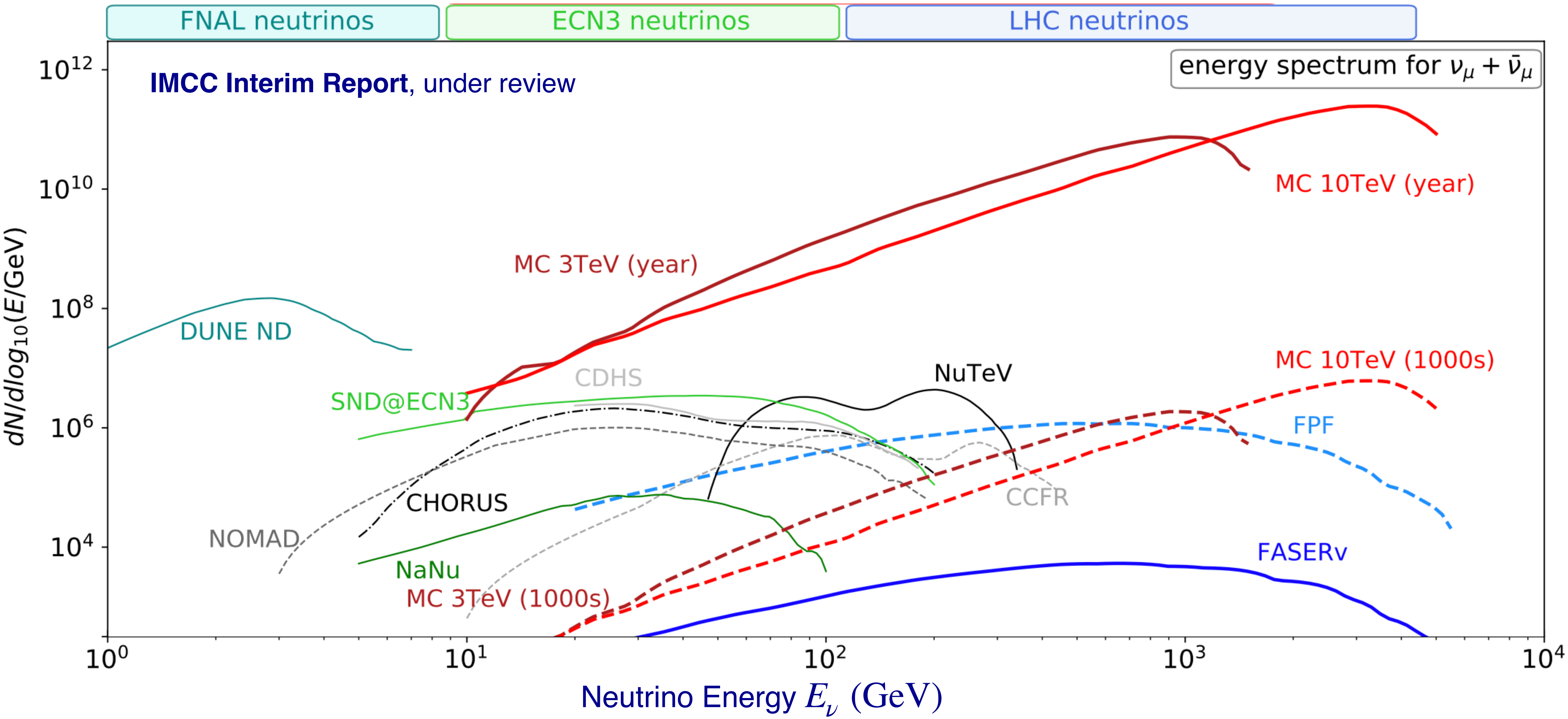
Pros

- Much higher **event rates**
- No neutrino **flux uncertainties**
- Balanced ν_e and ν_μ fluxes

Cons

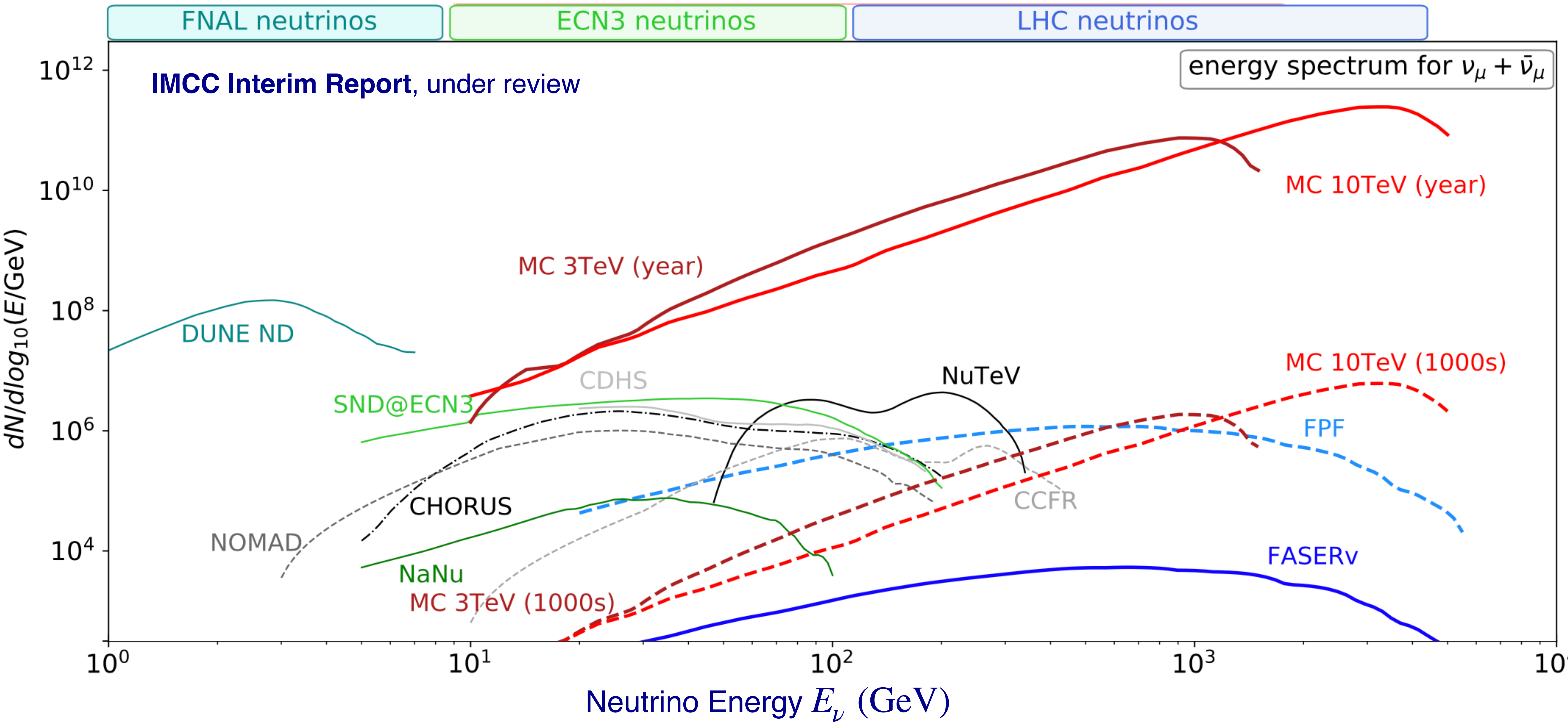
- No access to **tau neutrinos**
- No sensitivity to **small-x QCD & PDFs**
- Missing connection with **astroparticles**

Event rates



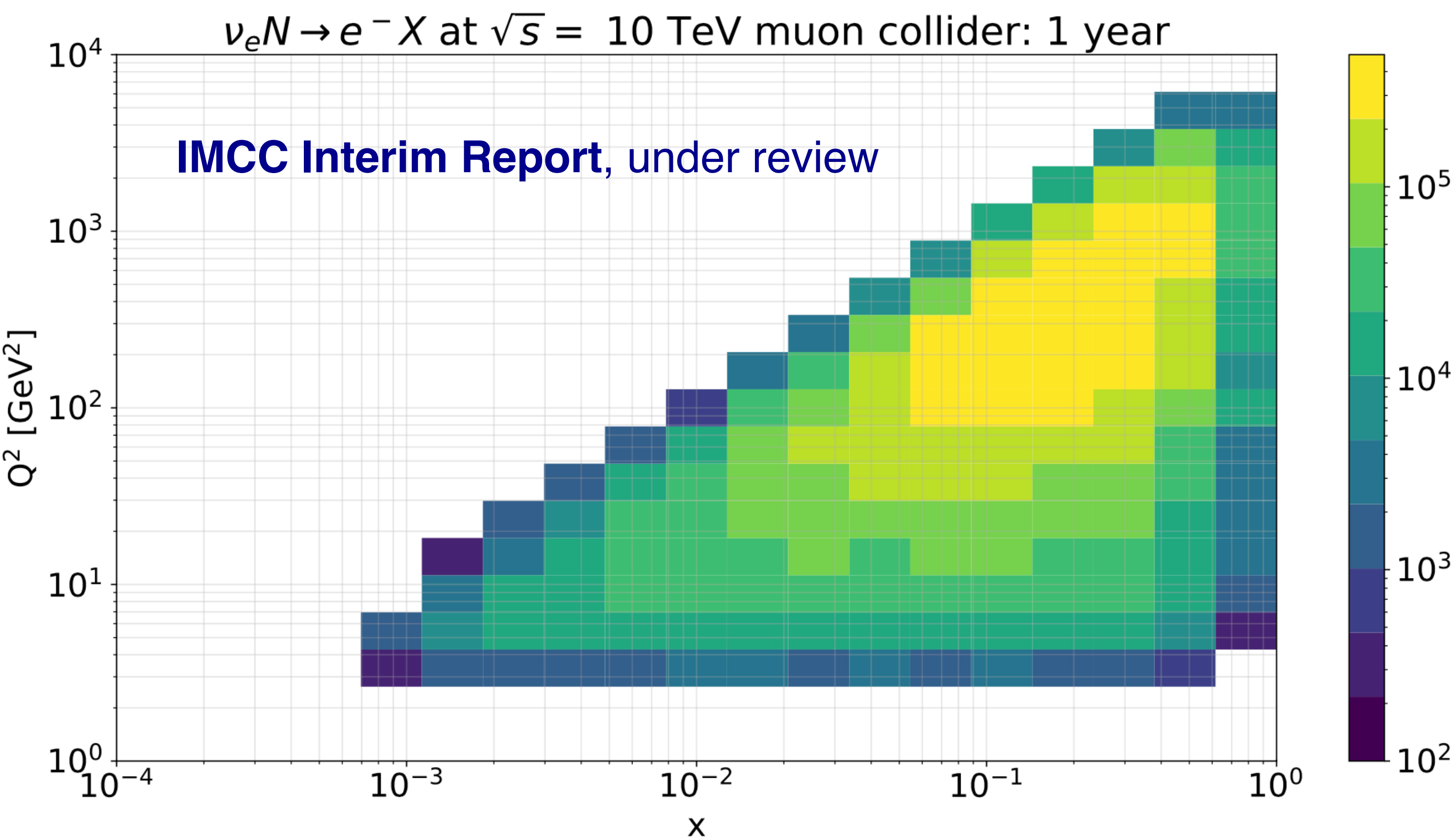
- Consider bunches composed by $N_{\pm} = 1.8 \times 10^{12}$ muons injected every $1/f_r = 0.2\ s$
- At MuCol (10 TeV), this results into $N_\nu \sim 10^{17}$ **neutrinos per year** from muon decays in straight sections
- Assume a detector with 10 cm radius & 1 m length and with mass per unit area of 50 $g \cdot \mathrm{cm}^2$
- This (very conservative!) detector leads to $N_{\mathrm{int}} \sim 3 \times 10^7$ **neutrino interactions per year**
- **Detector geometry and technology** need to be optimised to target the intended physics goals

Event rates

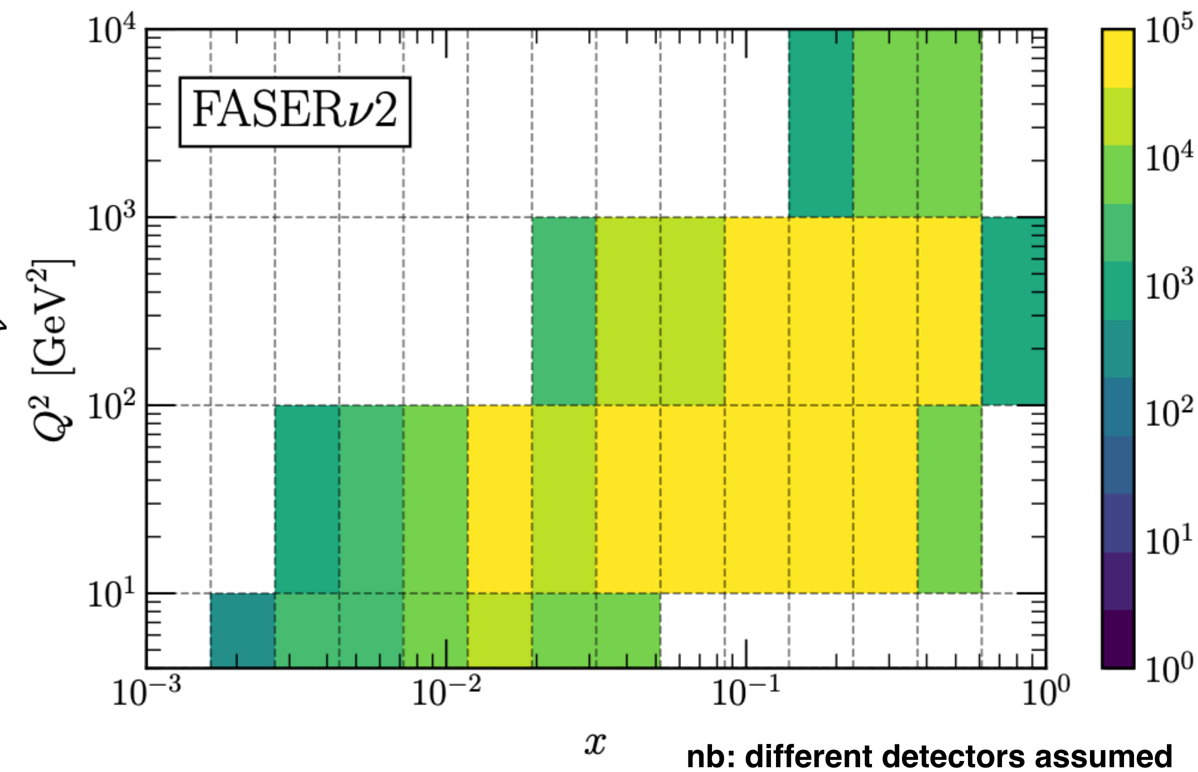


- For MuCol with $\sqrt{s} = 3\ \mathrm{TeV}\ (10\ \mathrm{TeV})$, neutrino energy spectrum peaks at **1 TeV (4 TeV)**
- **Unprecedented event rates:** one-year at MuCol (3 TeV or 10 TeV) increases the FASERν event yields (Run III, for same detector geometry) by a factor $\sim 10^7$
- In the region $E_\nu \geq 10\ \mathrm{GeV}$, MuCol would accumulate the **largest sample of neutrinos ever collected**

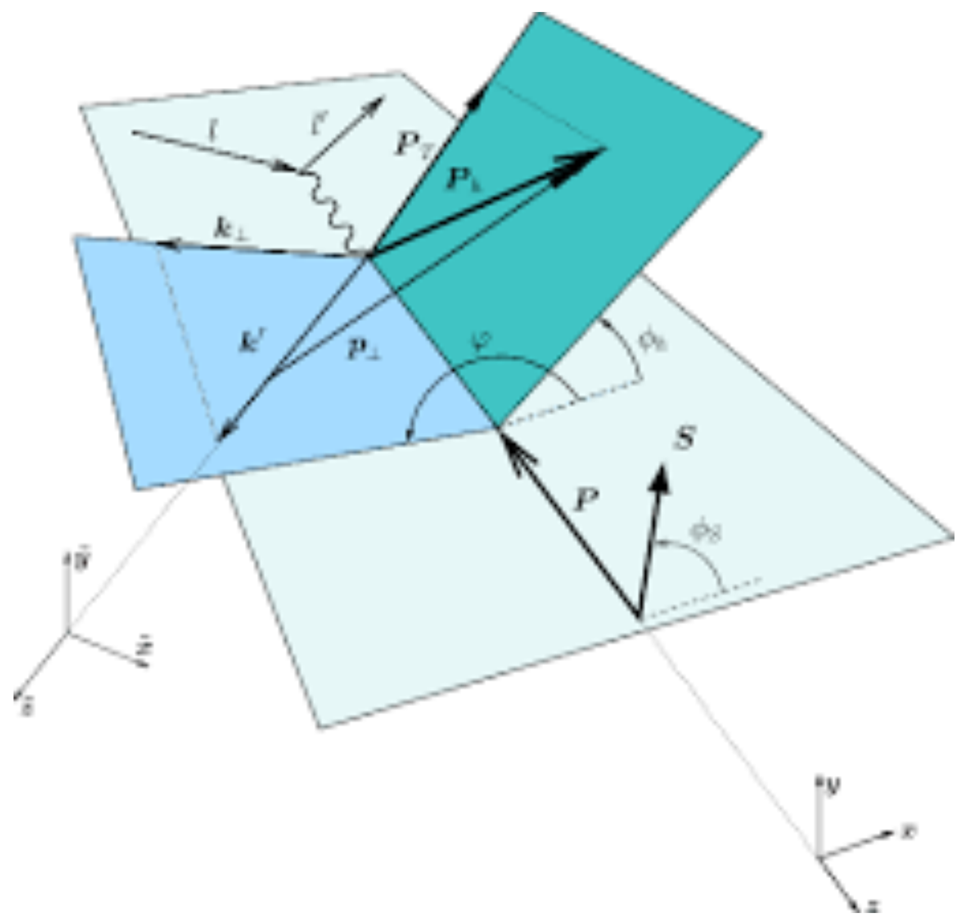
Kinematic distribution



FASERν2 @ HL-LHC



nb: different detectors assumed



- In terms of kinematical coverage, similar reach to the proposed FASERν2 at the HL-LHC
- Much higher event rates: **multi-differential neutrino DIS measurements,** enabling studies of nucleon 3D structure, TMD, GPDs…
- Rich program of **hadronic physics with neutrino beams,** complementary to the charged-lepton measurements from the EIC

dedicated impact studies for MuCol required

Neutrino DIS on polarised targets

Polarised DIS with neutrinos: **spin mapping**

arXiv:hep-ph/0101192v2 14 Mar 2001

RM3-TH/00-20

Polarized Parton Distributions
from Charged–Current Deep-Inelastic Scattering
and Future Neutrino Factories

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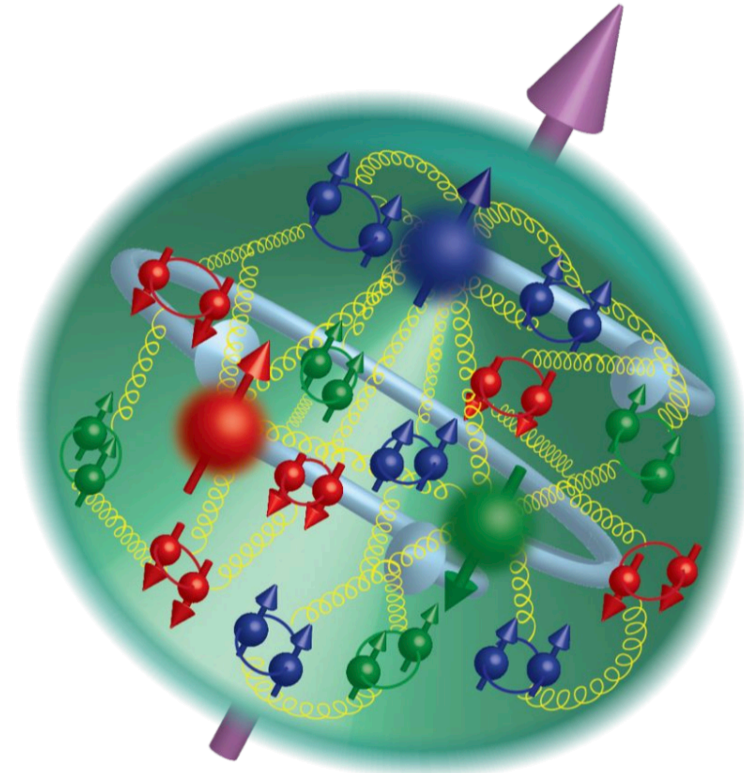
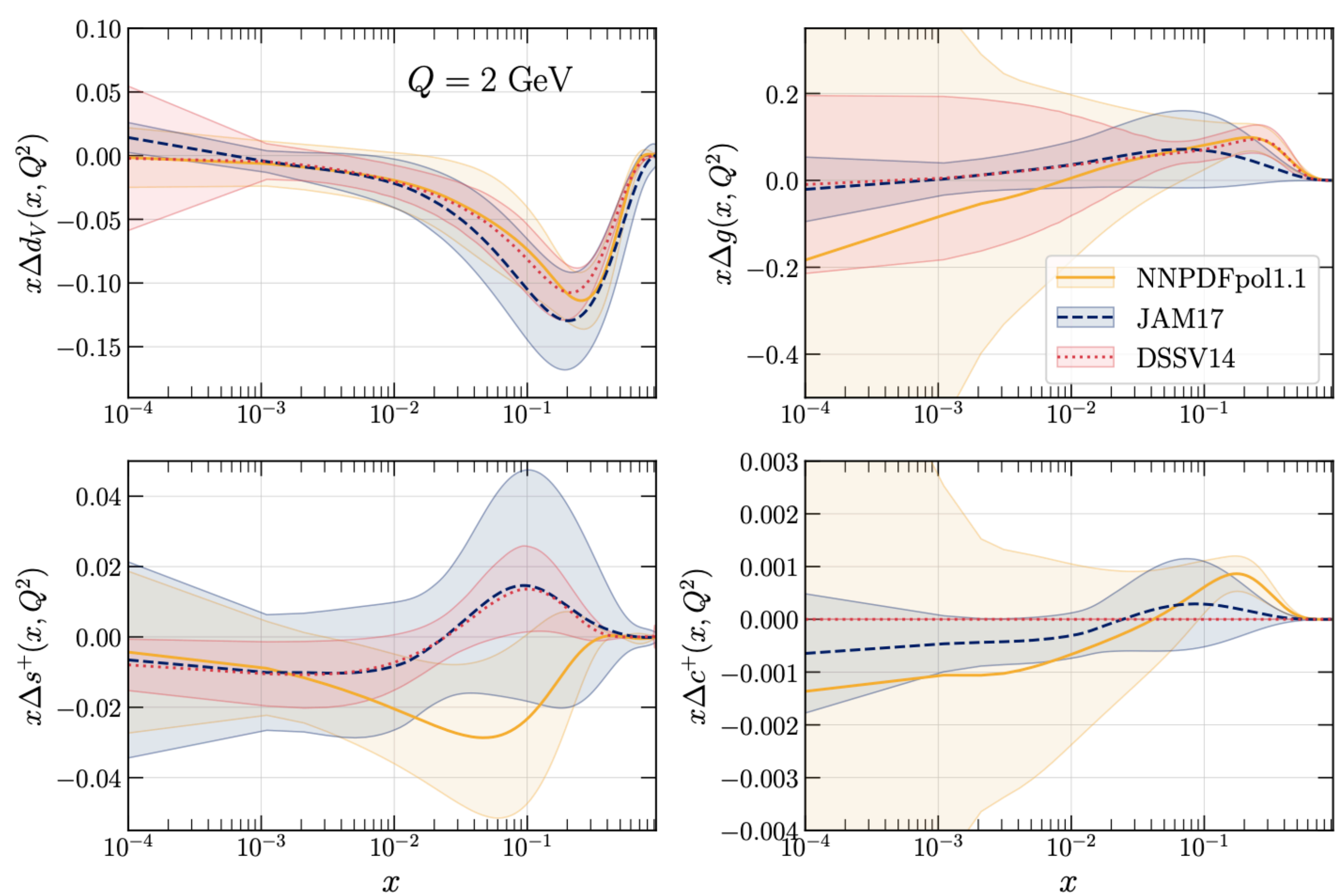
Abstract

We discuss the determination of polarized parton distributions from charged–current deep–inelastic scattering experiments. We summarize the next-to-leading order treatment of charged–current polarized structure functions, their relation to polarized parton distributions and scale dependence, and discuss their description by means of a next-to-leading order evolution code. We discuss current theoretical expectations and positivity constraints on the unmeasured C–odd combinations $\Delta q - \Delta\bar{q}$ of polarized quark distributions, and their determination in charged–current deep–inelastic scattering experiments. We give estimates of the expected errors on charged–current structure functions at a future neutrino factory, and perform a study of the accuracy in the determination of polarized parton distributions that would be possible at such a facility. We show that these measurements have the potential to distinguish between different theoretical scenarios for the proton spin structure.



Polarised proton PDFs affected by large uncertainties

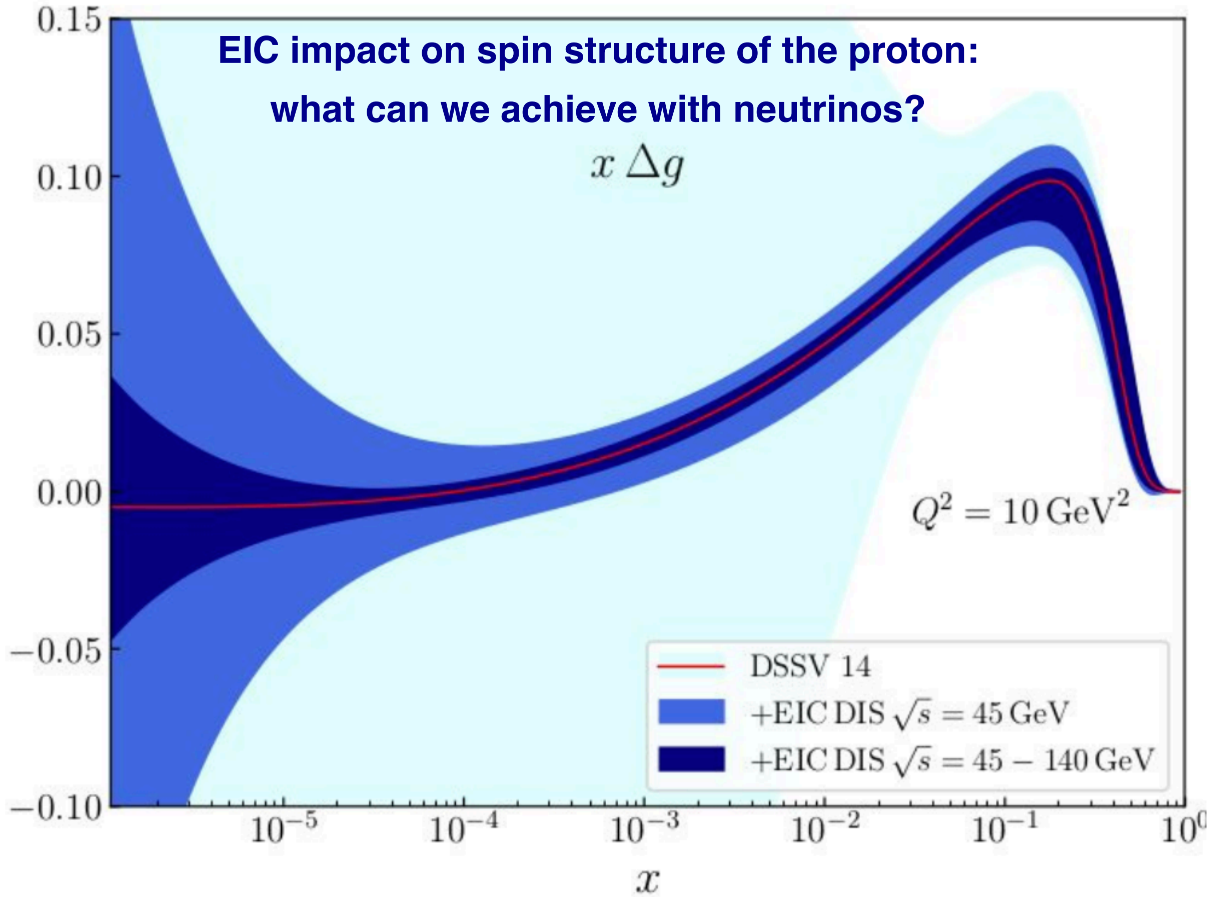


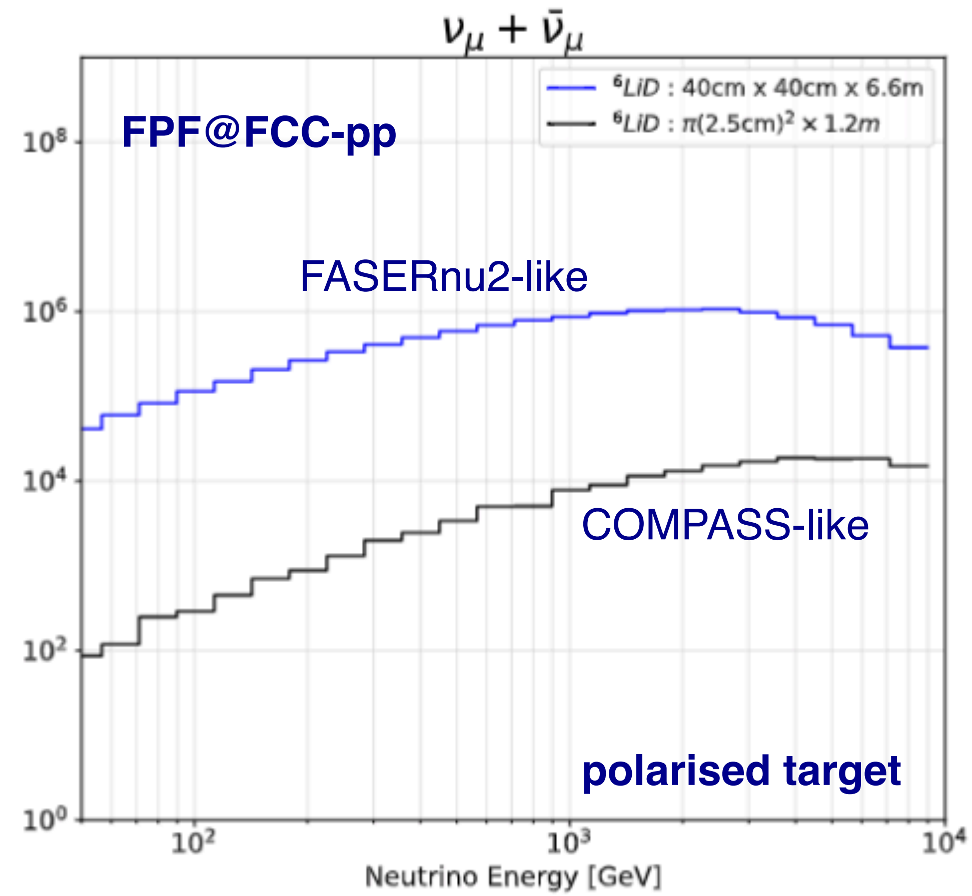
- A sufficiently intense neutrino beam could deliver enough intensity on a **polarised neutrino target**
- Studies in the context of a Neutrino Factory demonstrated their impact on **polarised PDFs**
- Should be revisited now for the MuCol: Realise the first neutrino DIS experiment on polarised target, a **CC analog of polarized EIC collisions**

Neutrino DIS on polarised targets

Polarised DIS with neutrinos: **spin mapping**

Novel probe to scrutinize **proton spin and 3D structure!**





Abraham, Adhikary, Feng, Fieg, Kling, JR, Trojanowski**, WIP**

- Study polarised neutrino scattering in the context of a **100 TeV proton-proton collider**
- Assuming a COMPASS-like **^{6}LiD polarised target**, FPF@HL-LHC would record O(10 events)
- FPF@FPF: **O(100K) muon neutrino events** with COMPASS-like target, increases to **O(10^7) events** if FASERv2-like geometry can be polarised

dedicated impact studies for MuCol required

Summary and outlook

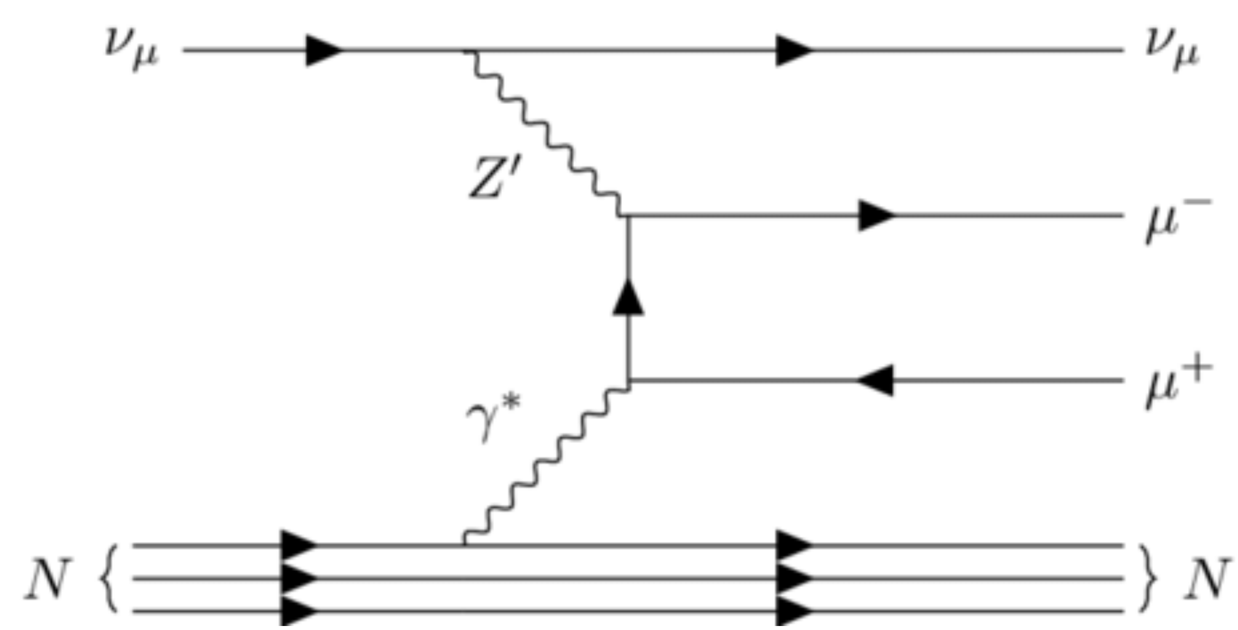
- The high-intensity, high-energy, collimated neutrino beam delivered by MuCol offers **novel physics opportunities** which only now we are starting to explore

- Focusing on QCD applications, this neutrino beam would enable a **rich program of unpolarised and polarised hadron structure**, including 3D and transverse structure & cold nuclear matter studies, which in turn benefit **other (astro-)particle physics experiments**

- Other possible applications of this program include the precision determination of **CKM matrix elements and of the weak mixing angle**, studies of light and heavy **hadron fragmentation**, as well as new avenues for BSM searches via rare processes e.g. **trident production**

- Ideas and suggestions more than welcome!

New applications of the largest sample of electron and muon neutrinos with $10\ \mathrm{GeV} \leq E_\nu \leq 5\ \mathrm{TeV}$ ever assembled?



neutrino tridents in DIS