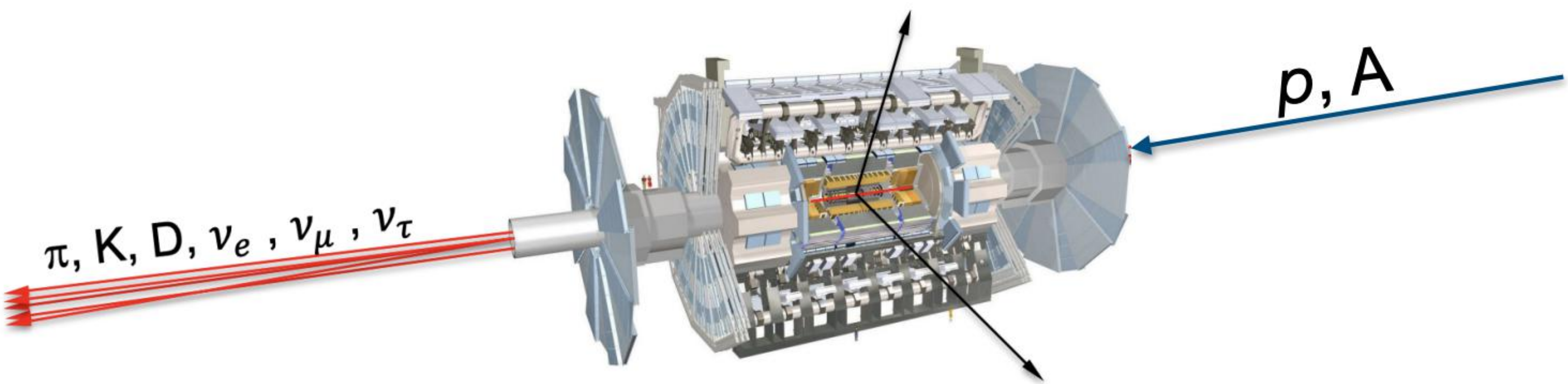
The LHC as a Neutrino Collider

Juan Rojo, VU Amsterdam & Nikhef



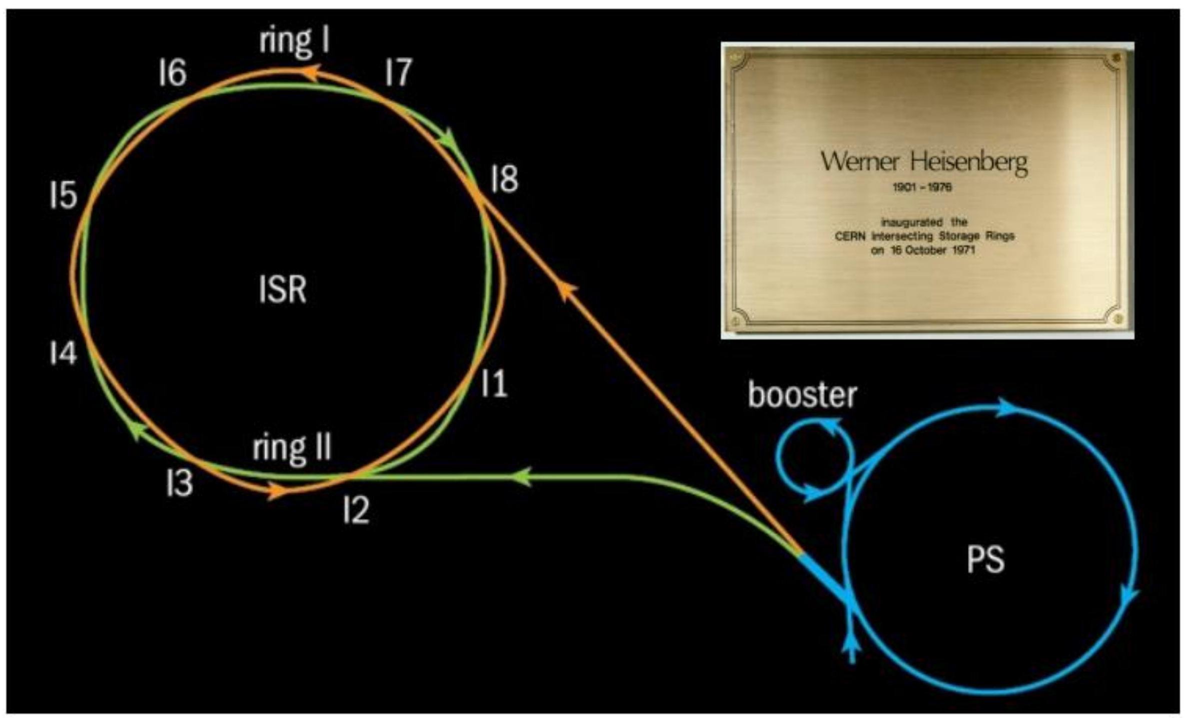
Department of Nuclear and Particle Physics

University of Geneva, 20th November 2024

The Dawn of the LHC Neutrino Era

Back to the Future

- In 1971, CERN's Intersecting Storage Rings (ISR), with a circumference of ~1 km, collided protons with protons at center-of-mass energy 30 GeV.



During ISR's 50th anniversary, there were many fascinating articles and talks by eminent physicists looking back on the ISR's legacy.

– "Enormous impact on accelerator physics, but sadly little effect on particle physics." – Steve Myers, talk at "The 50th Anniversary of Hadron Colliders at CERN," October 2021.

– "There was initially a broad belief that physics action would be in the forward directions at a hadron collider…. It is easy to say after the fact, still with regrets, that with an earlier availability of more complete… experiments at the ISR, CERN would not have been left as a spectator during the famous November revolution of 1974 with the J/ψ discoveries at Brookhaven and SLAC ." – Lyn Evans and Peter Jenni, "Discovery Machines," CERN Courier (2021).

Bottom line: The collider was creating new forms of matter (charm), but the detectors focused on the forward region (along the beamline) and so missed them.

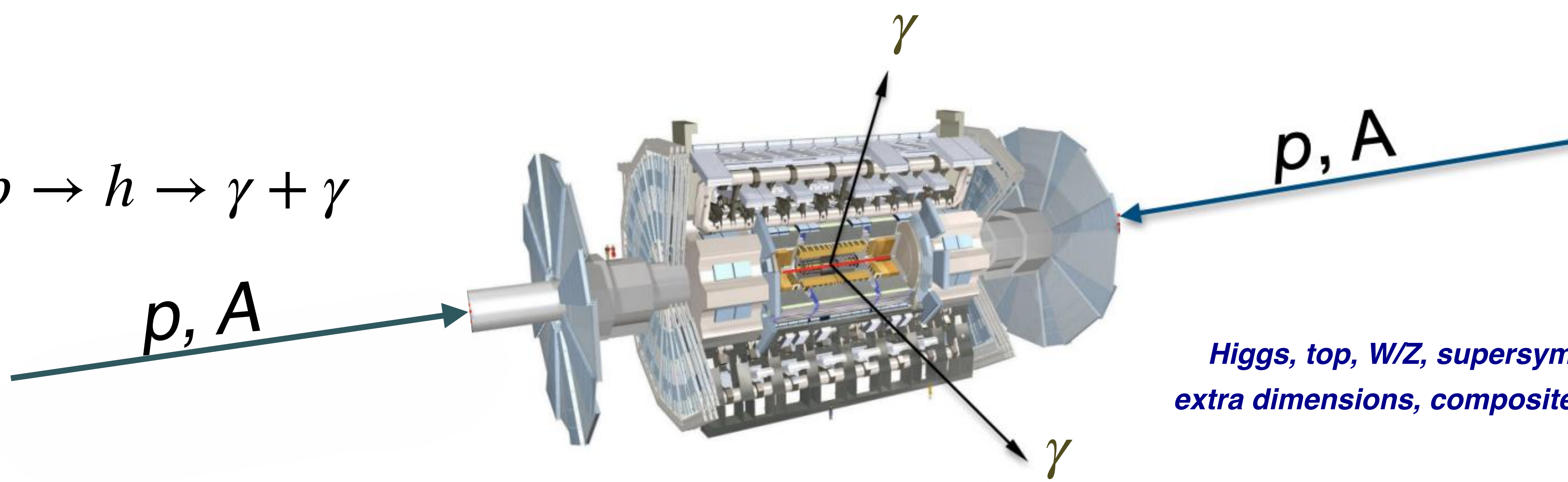
J. Feng, CERN Colloquium, June 2023

After the establishment of the SM and QCD in the early 70s, it became clear that the central/transverse (high-p_T) region is where new particles and phenomena were to be found

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

$$p + p \to h \to \gamma + \gamma$$



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

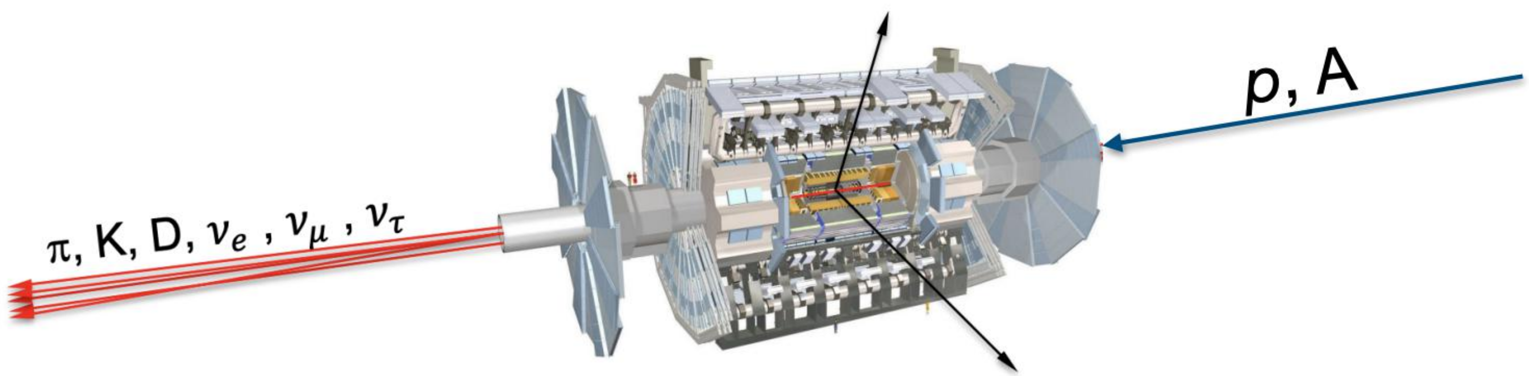
A. De Rujula (CERN), R. Ruckl (CERN)
May, 1984

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

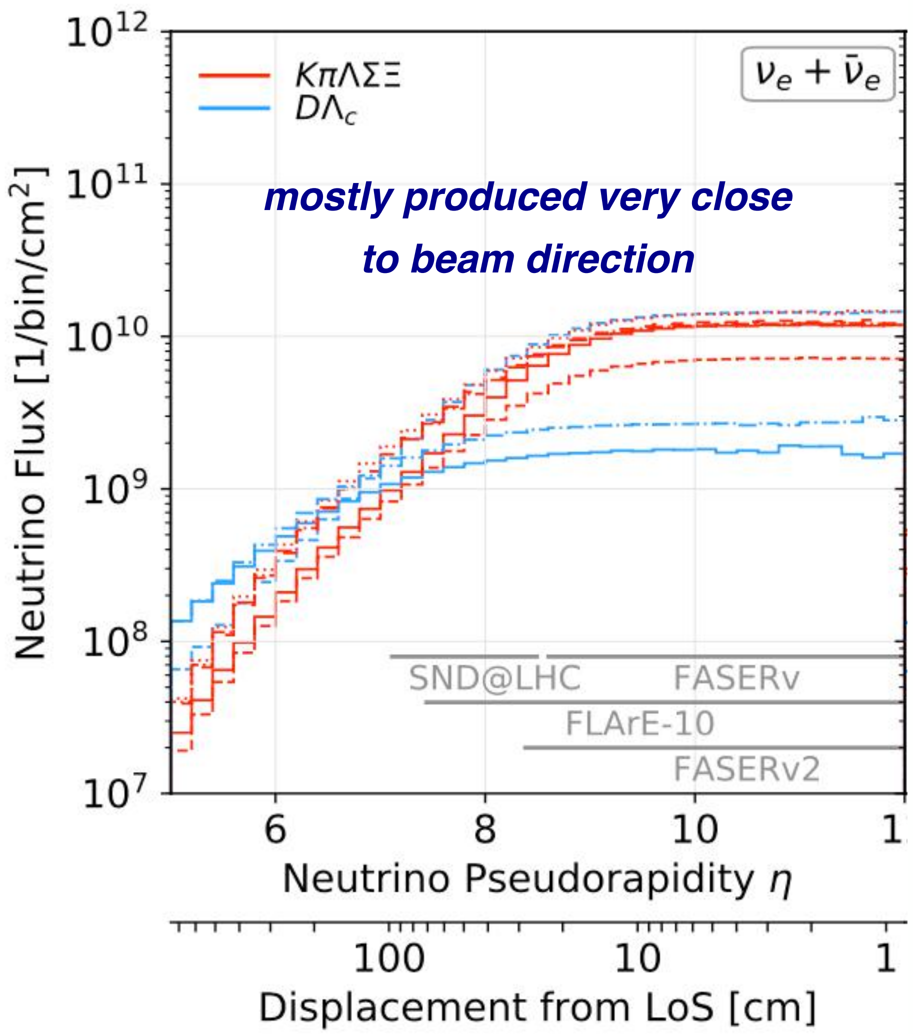
pdf cite claim reference search 14 citations

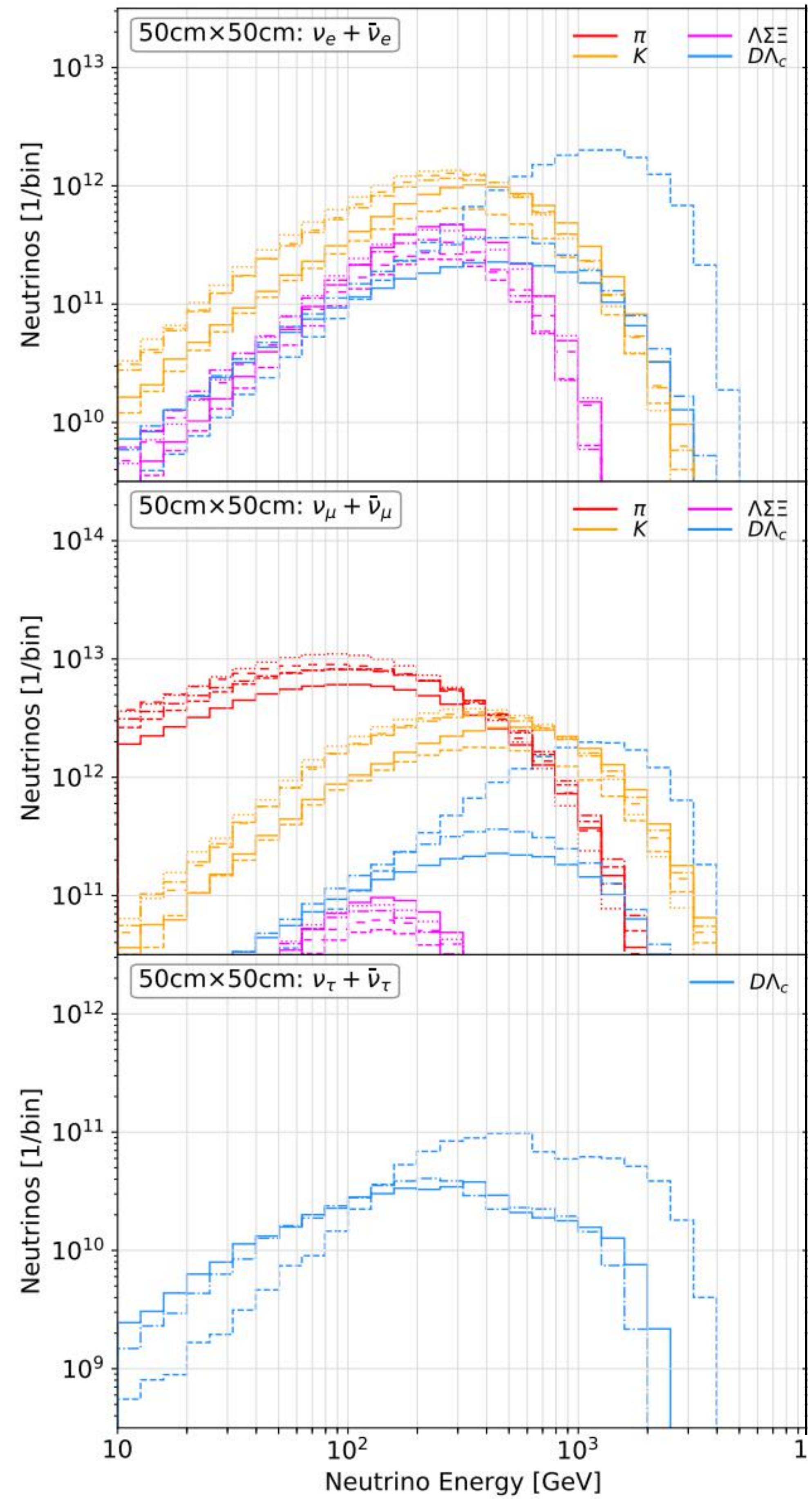
First proposal in 1984

Neutrinos at the LHC



- **electron neutrinos** mostly from *D*-meson decays above 500 GeV, below it mostly from kaon decays
- **muon neutrino** flux dominated by pion & kaon decays
- **tau neutrinos** entirely from D-meson decays





The dawn of the LHC neutrino era

- Two 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)

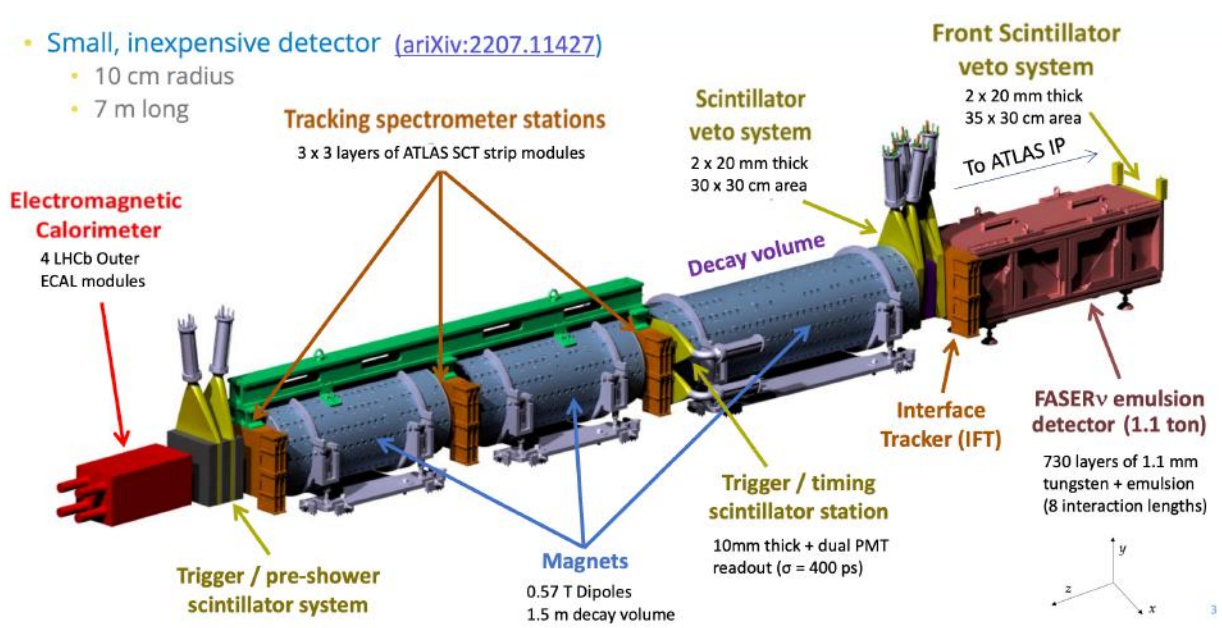
Editors' Suggestion | Featured in Physics

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

153 neutrinos detected, 151± 41 expected



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

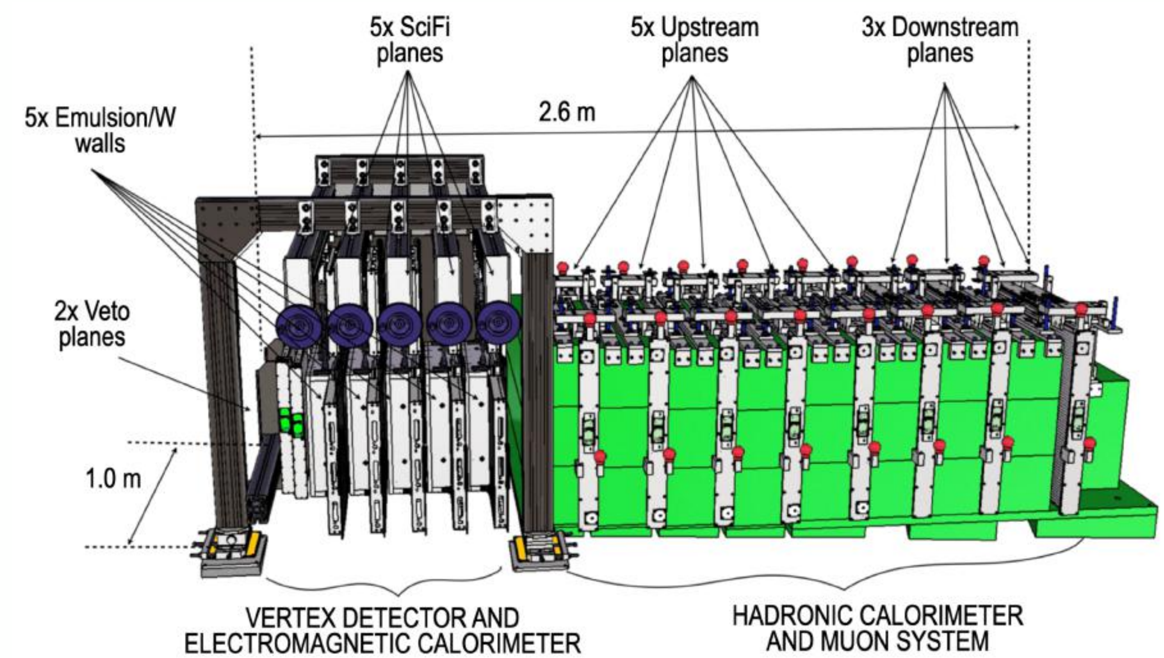
Editors' Suggestion

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

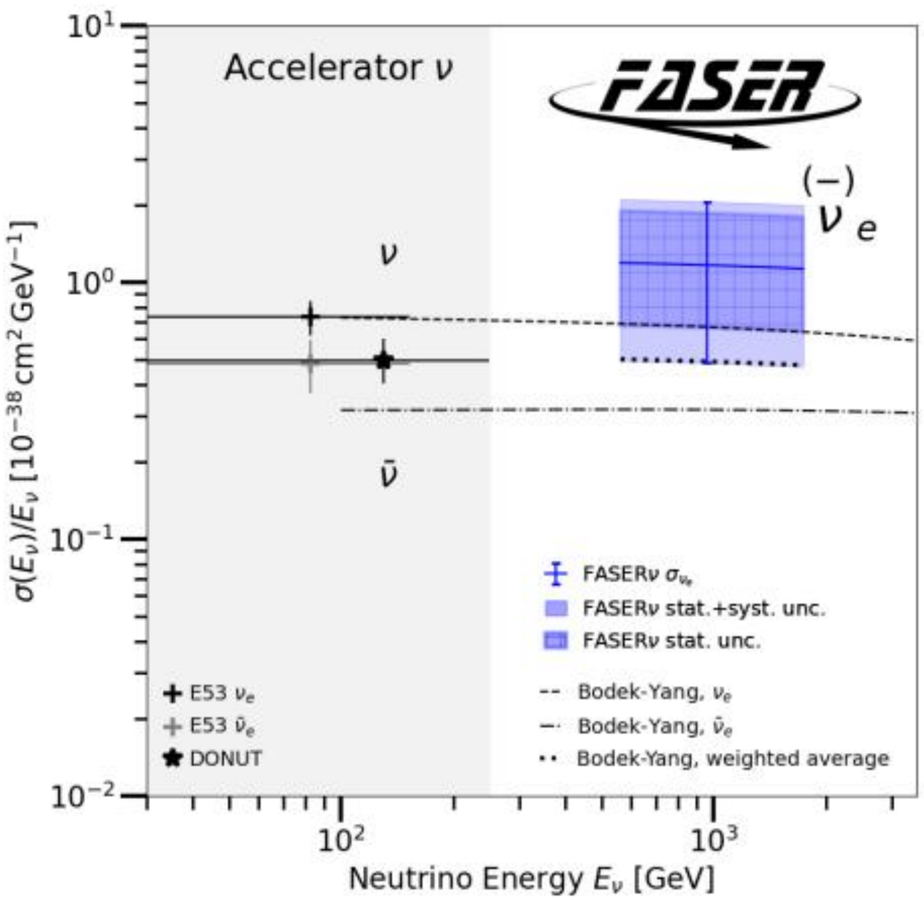
8 neutrinos detected, 4 expected

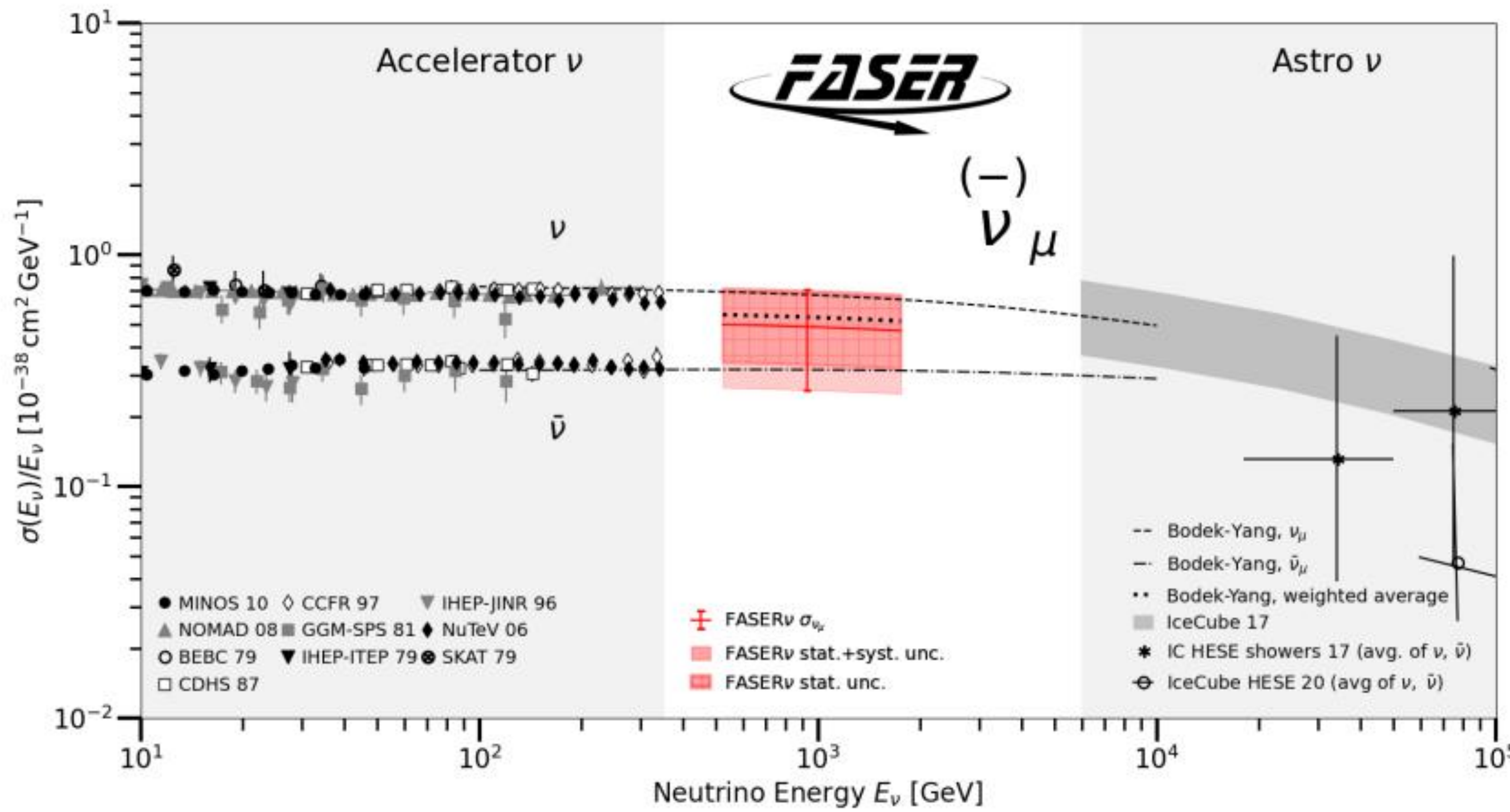


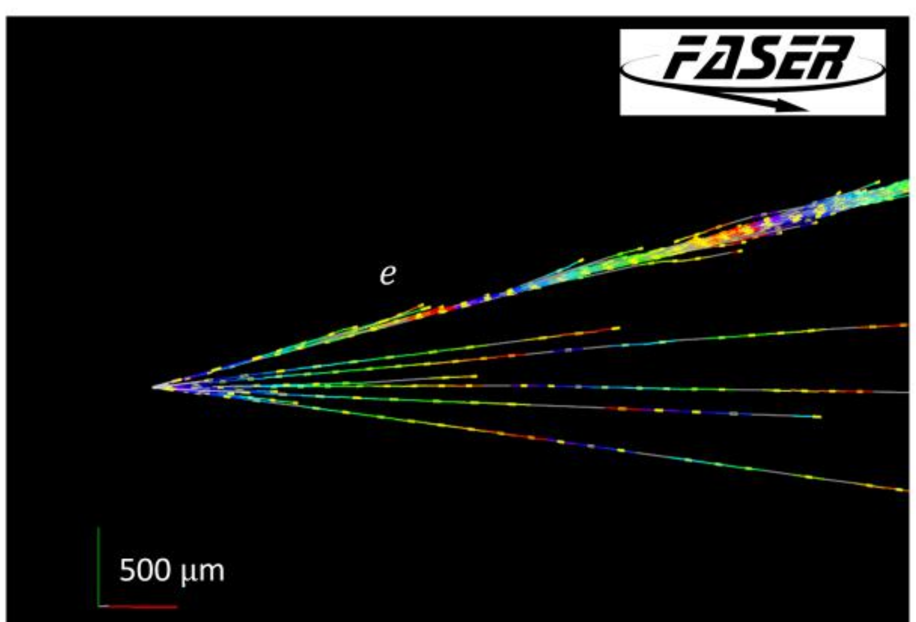
Now is the time to start exploiting their physics potential

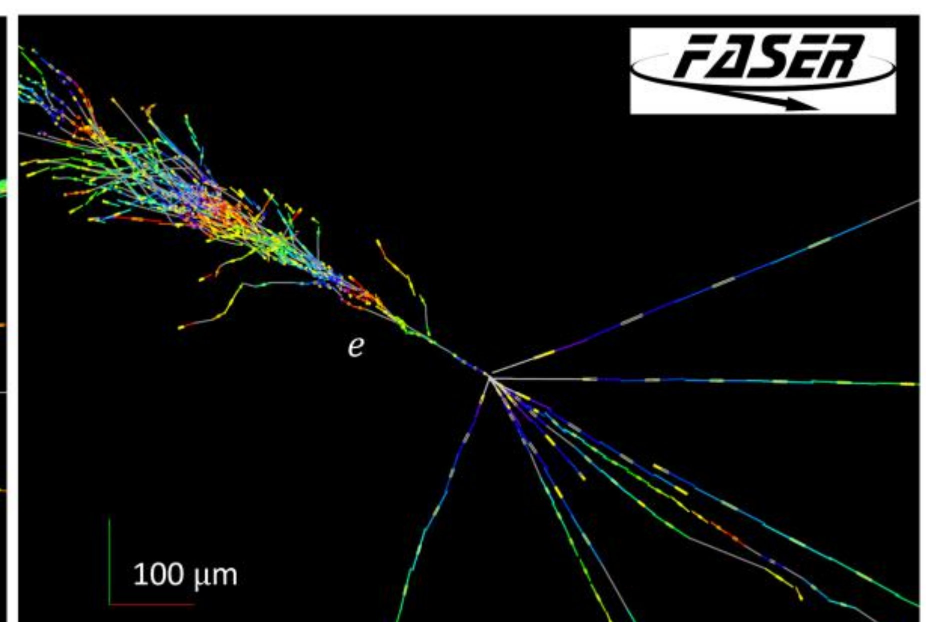
The dawn of the LHC neutrino era

- **…** as well as the first direct measurement of neutrino cross-section at TeV energies from FASER



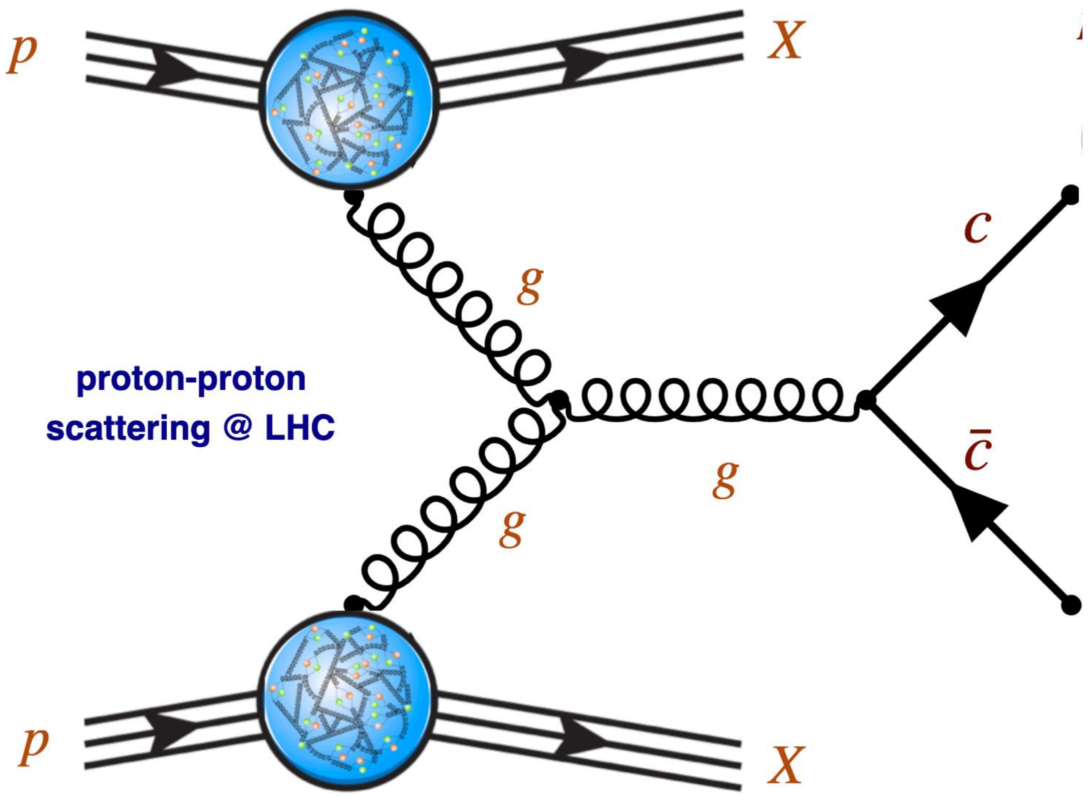


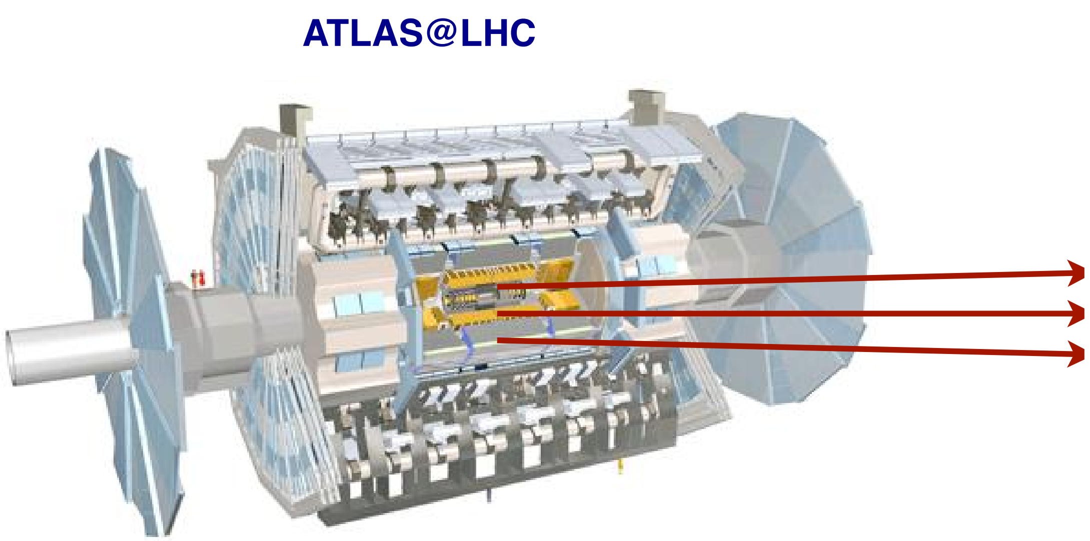




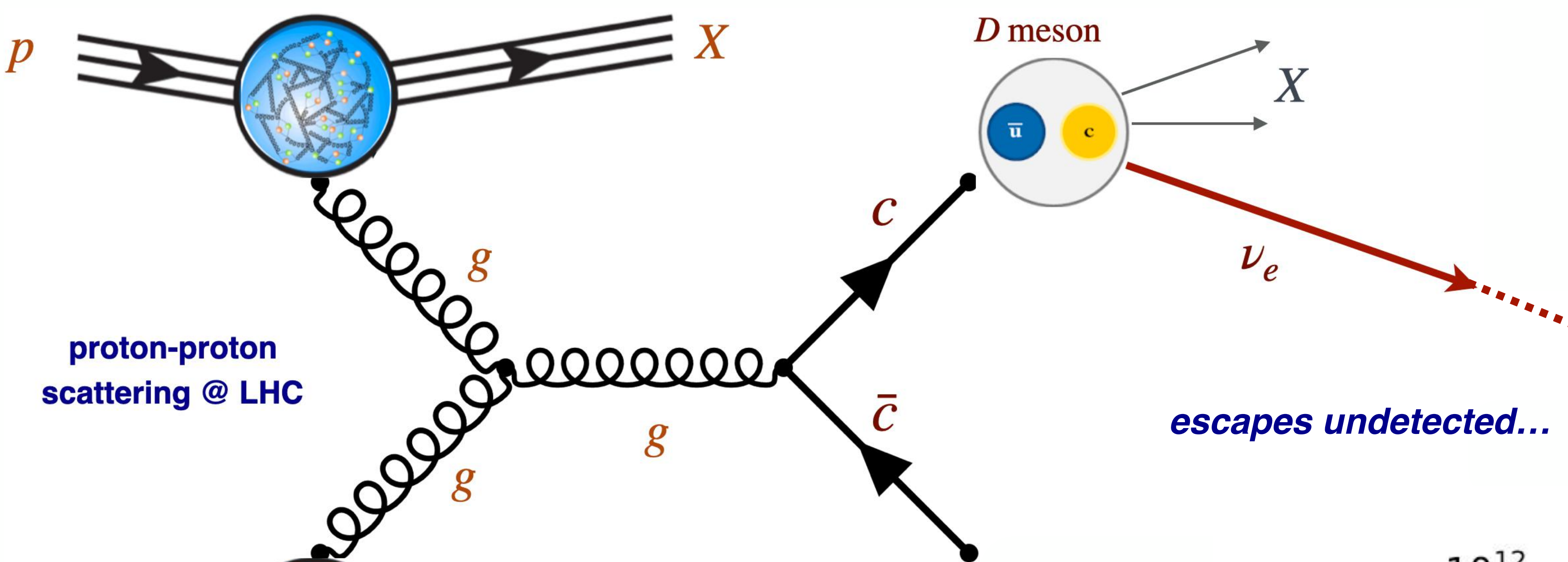
FASER's emulsion detector (FASERν) has excellent particle ID and spatial resolution

Neutrinos at the LHC

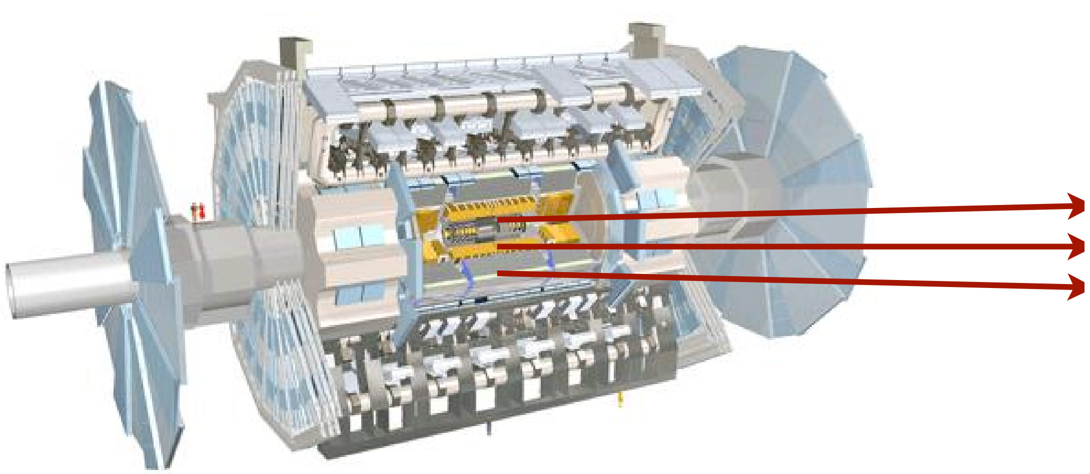


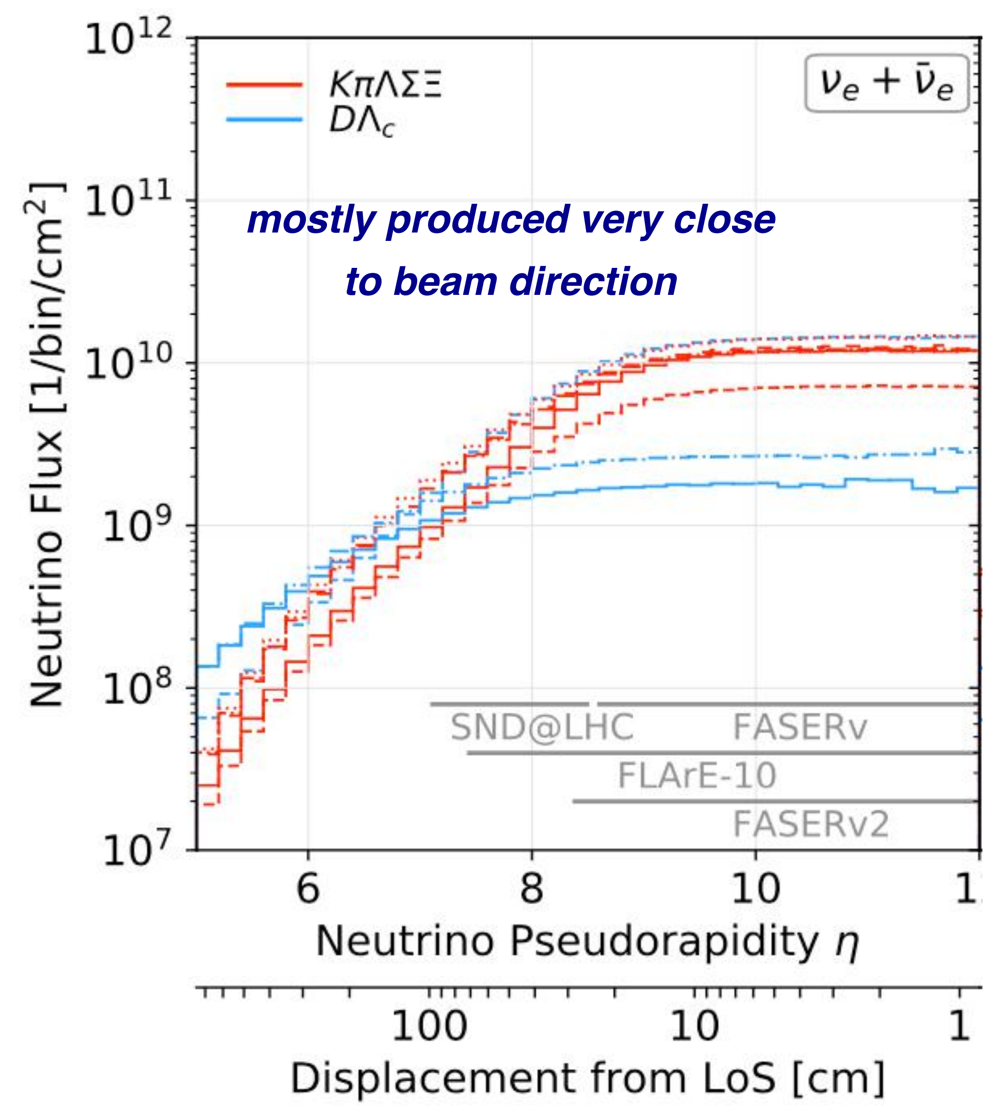


Neutrinos at the LHC

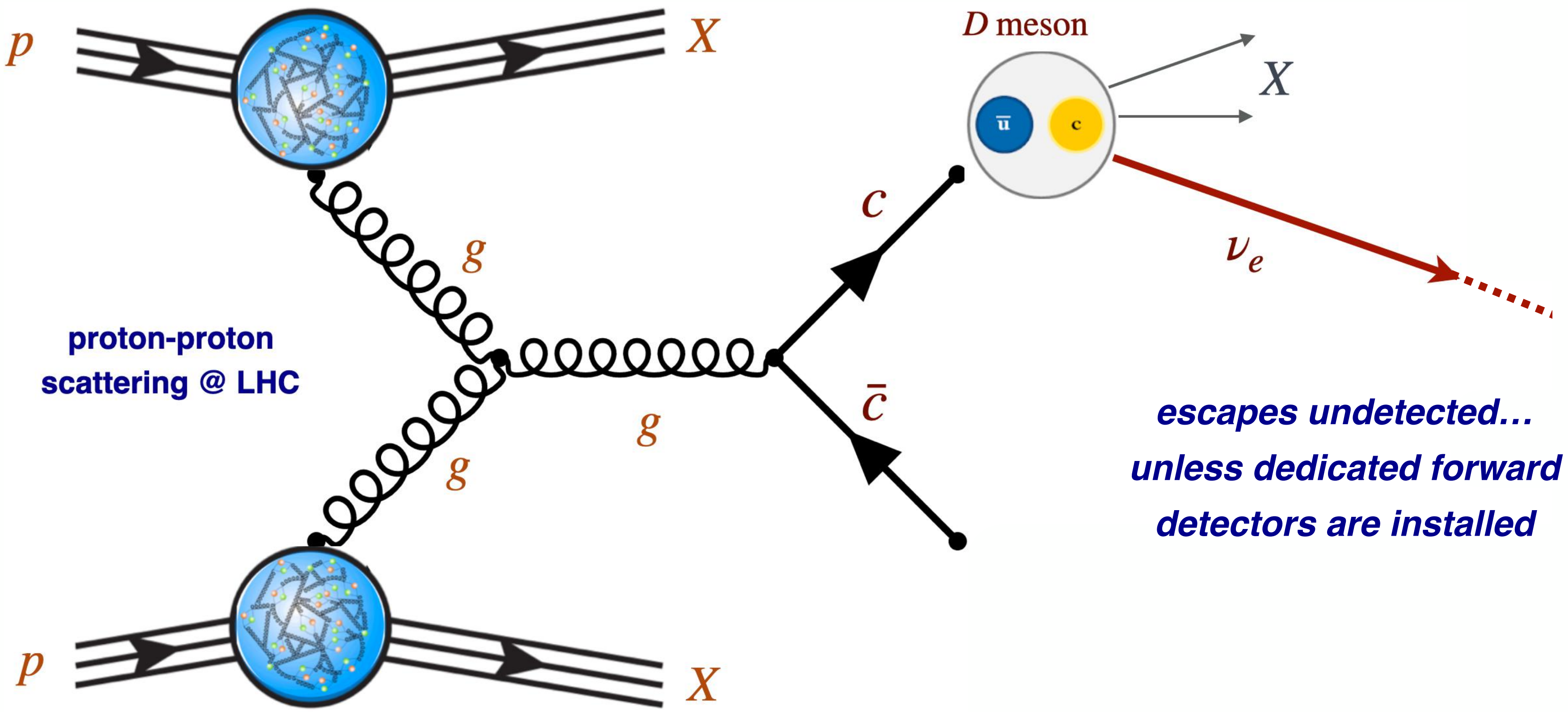


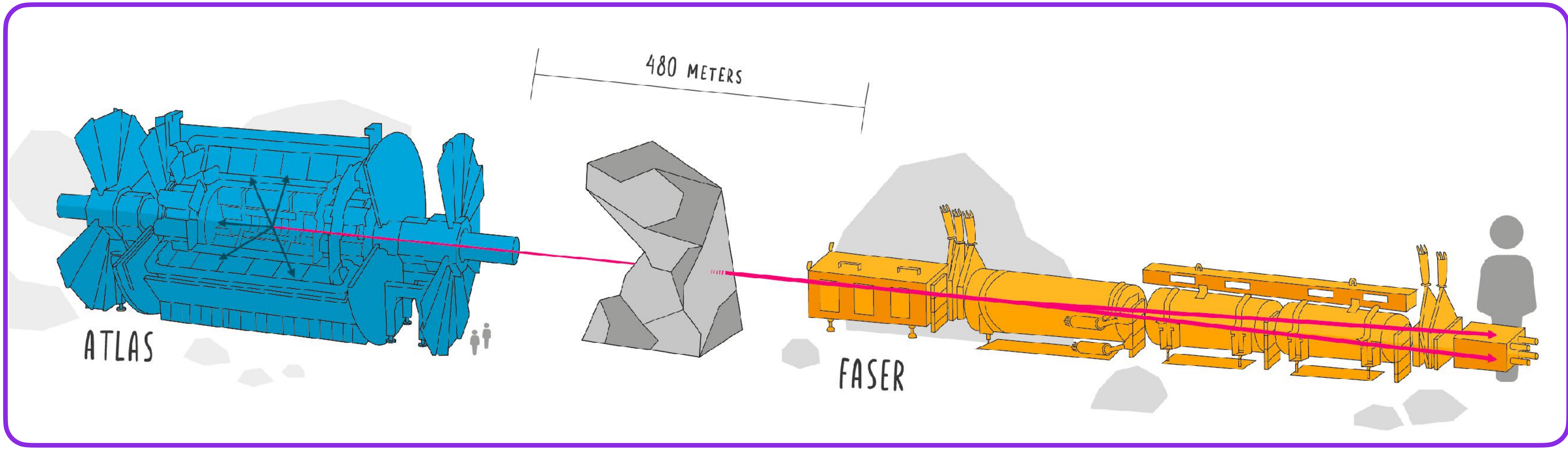
ATLAS@LHC



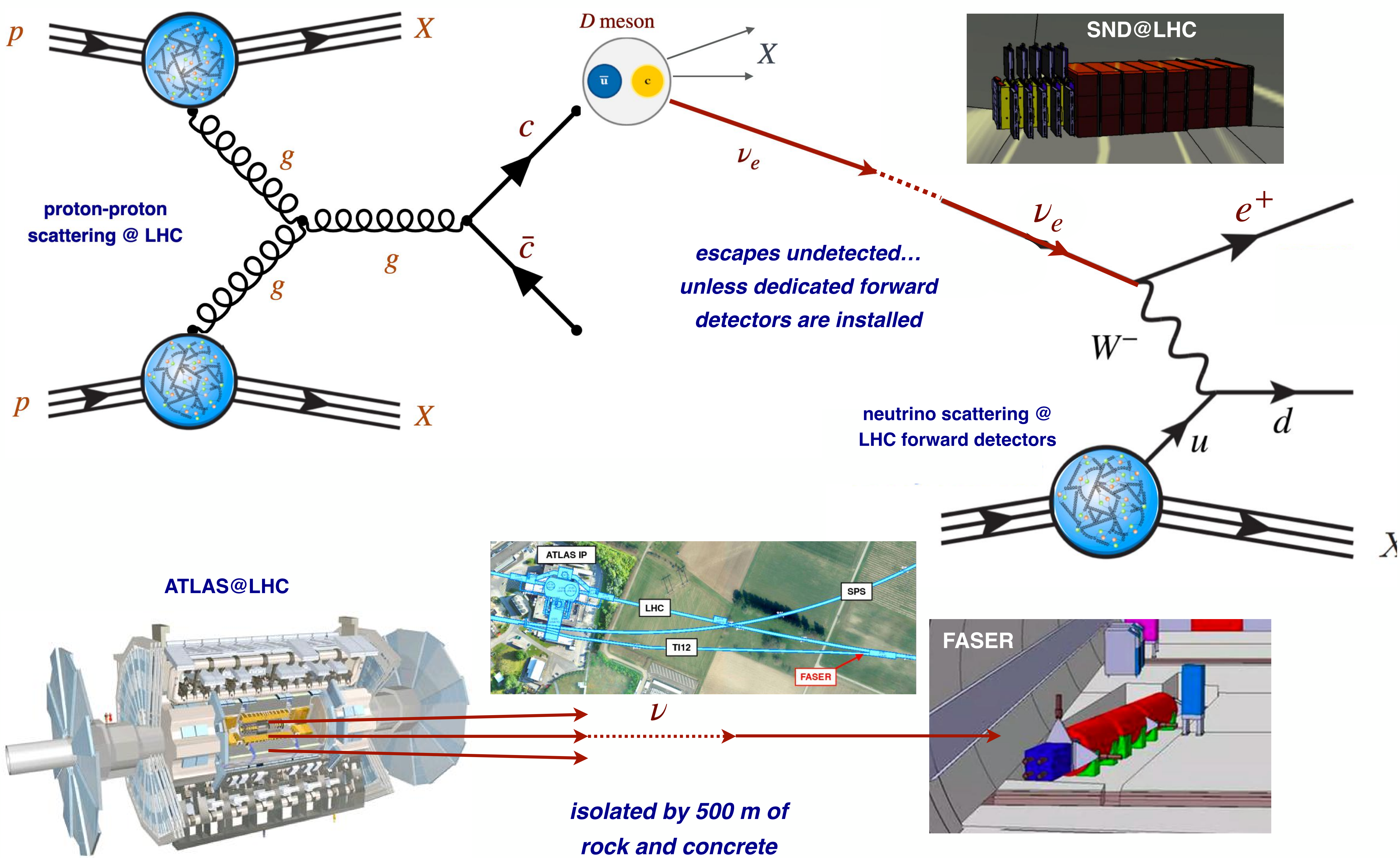


Neutrinos at the LHC



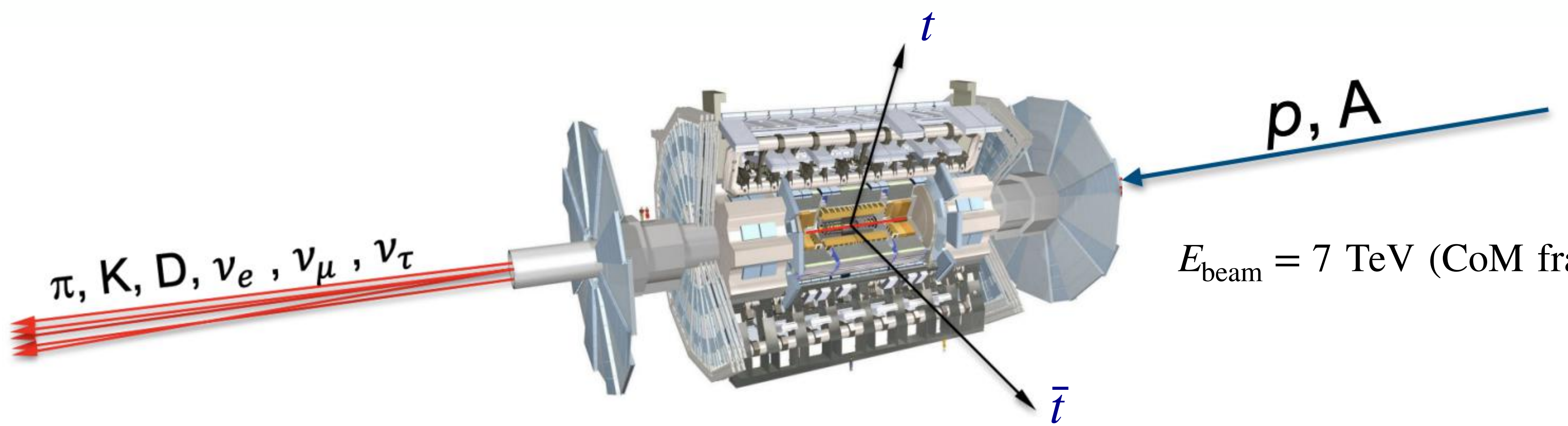


Neutrinos at the LHC



Neutrinos at the LHC

- Being able to detect and utilise the most energetic human-made neutrinos ever produced also opens exciting avenues in **astroparticle physics**



Collider counterpart of high-energy cosmic rays interactions, including prompt neutrino flux

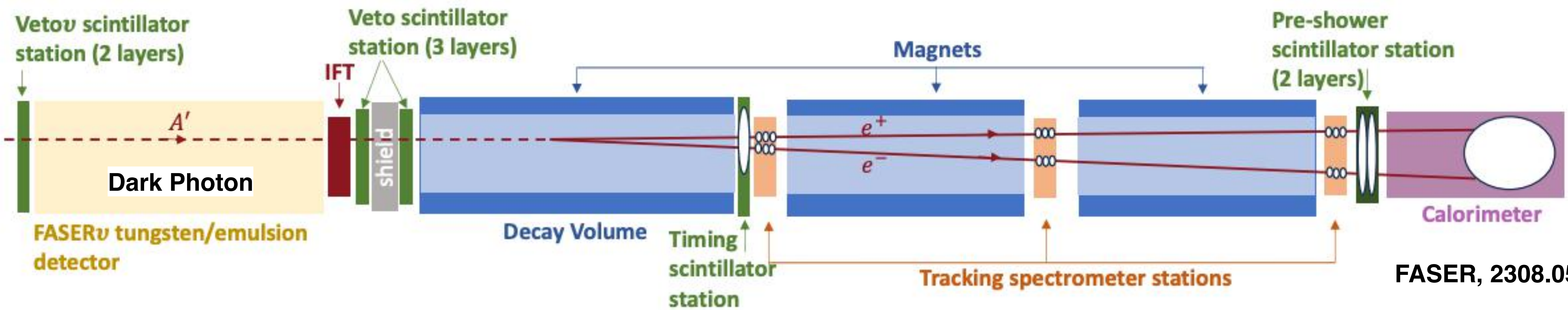
$E_{\rm beam} \sim 10^5$ TeV (fixed target frame)

Auger, IceCube, KM3NET, GRAND, …

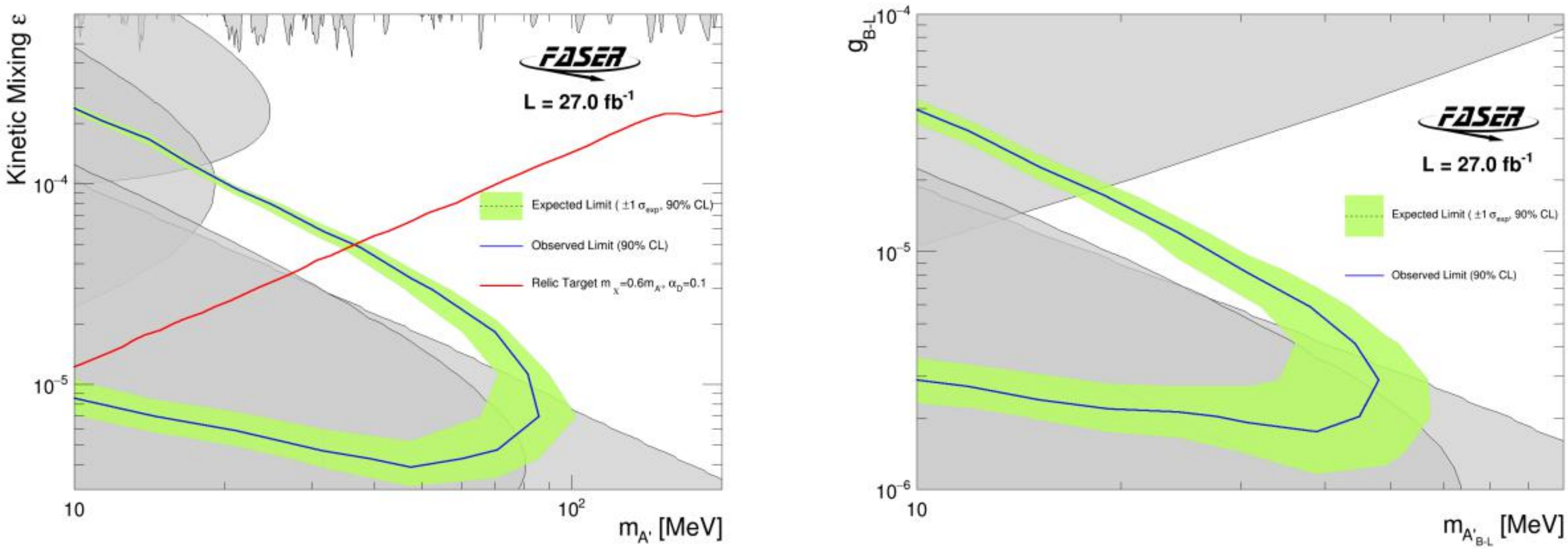
*Unique **laboratory validation** of extreme scattering processes in APP*

Searching for the invisible

- Far-forward LHC detectors also operate as background-free to search for dark sector particles, **feebly-interacting particles** (FIPs), long-lived particles (LLP), ….



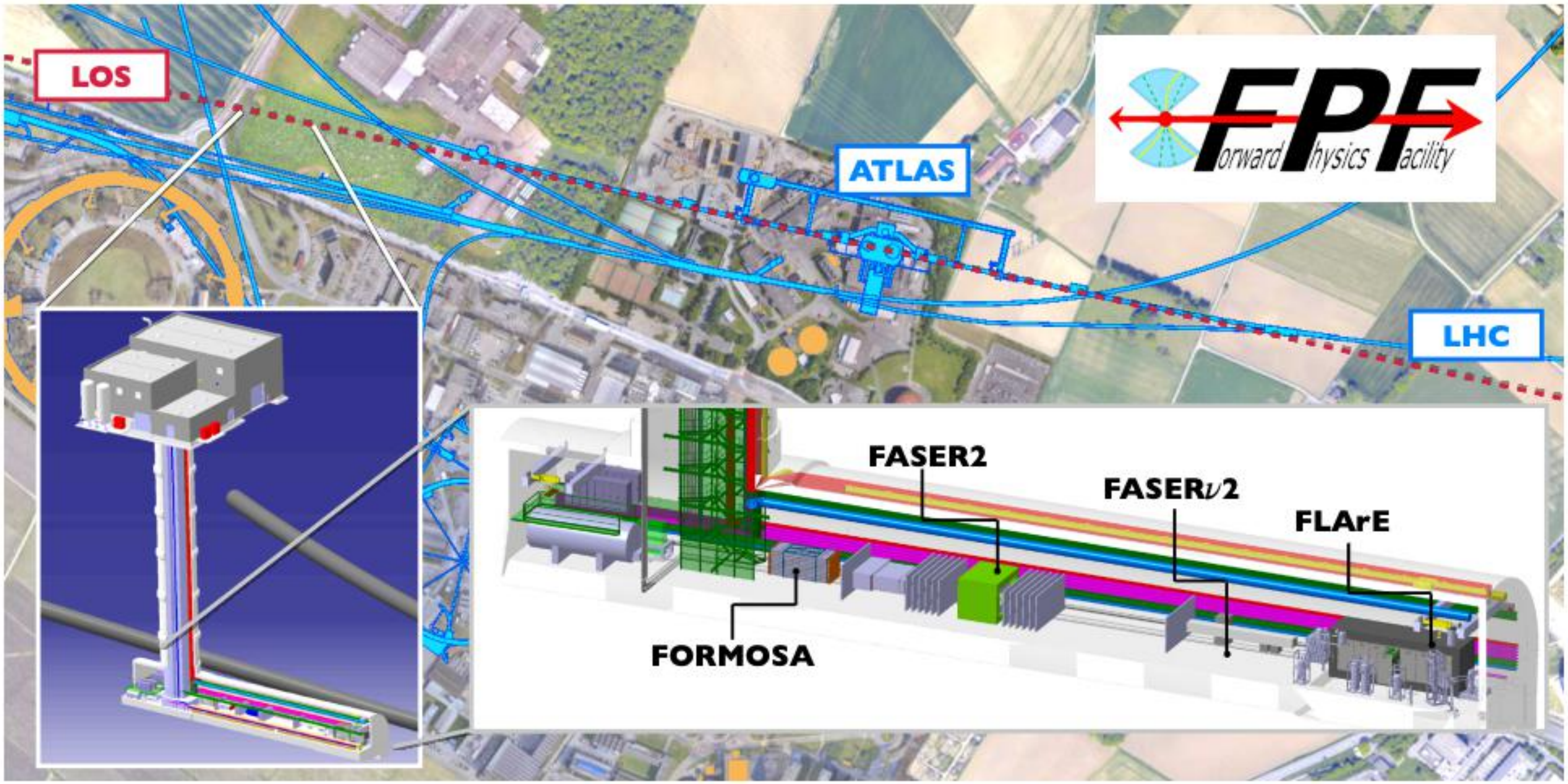
FASER, 2308.05587



Unique blend of guaranteed deliverables and exploration potential

The Forward Physics Facility

A proposed new CERN facility to achieve the full potential of **LHC far-forward physics**



- Complementary suite of **far-forward experiments,** operating **concurrently with the HL-LHC**
- Start **civil engineering during LS3** or shortly thereafter, to maximise overlap with HL-LHC
- Positive outcome of **ongoing site investigation** studies (geological drill down to the cavern depth)

The realisation of the FPF depends crucially on outcome of the European Strategy for Particle Physics Update

The Forward Physics Facility

A proposed new CERN facility to achieve the full potential of **LHC far-forward physics**

Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

The Forward Physics Facility at the High-Luminosity LHC

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from the ATLAS interaction point and shielded by concrete and rock, will host a suite of experiments to probe Standard Model (SM) processes and search for physics beyond the Standard Model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from SM expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will also provide valuable data for fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector, and simulation studies, and on future directions to realize the FPF's physics potential.

Snowmass Working Groups
EF4,EF5,EF6,EF9,EF10,NF3,NF6,NF8,NF9,NF10,RP6,CF7,TF07,TF09,TF11,AF2,AF5,IF8

SCIENCE AND PROJECT PLANNING FOR THE FORWARD PHYSICS FACILITY IN PREPARATION FOR THE 2024–2026 EUROPEAN PARTICLE PHYSICS STRATEGY UPDATE

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on behalf of the FPF Working Groups

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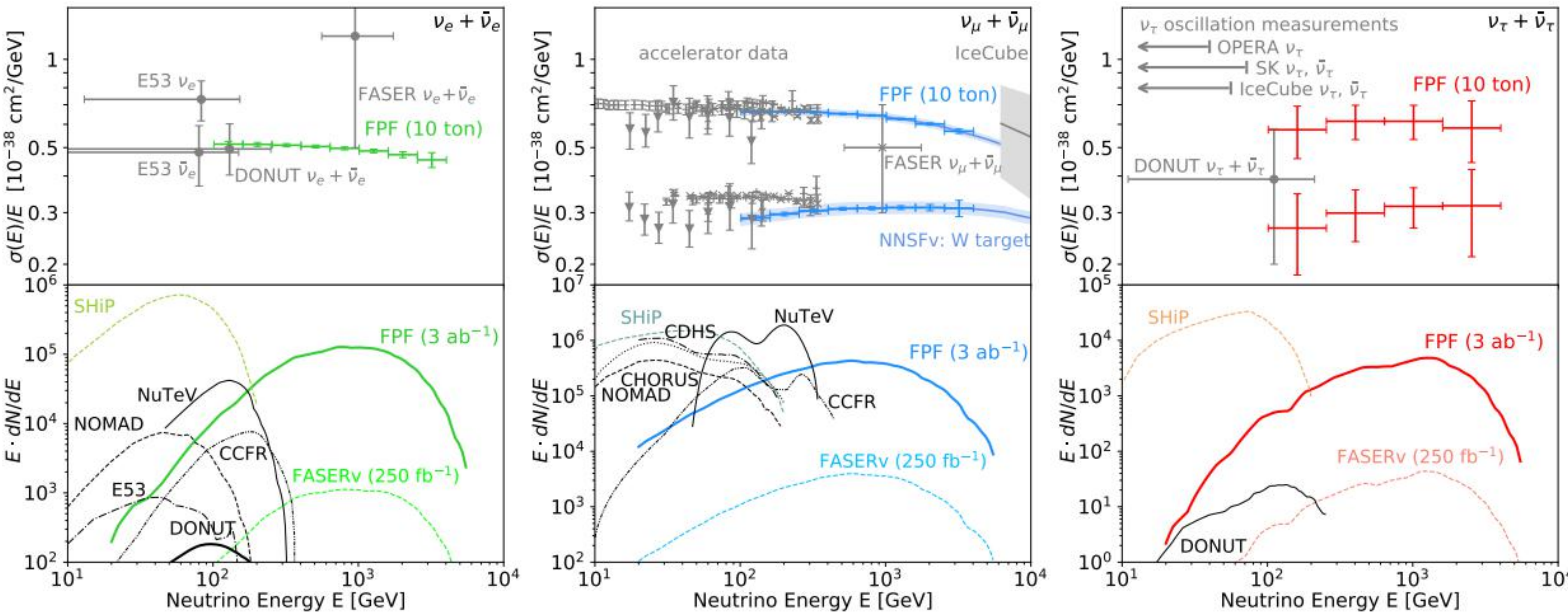
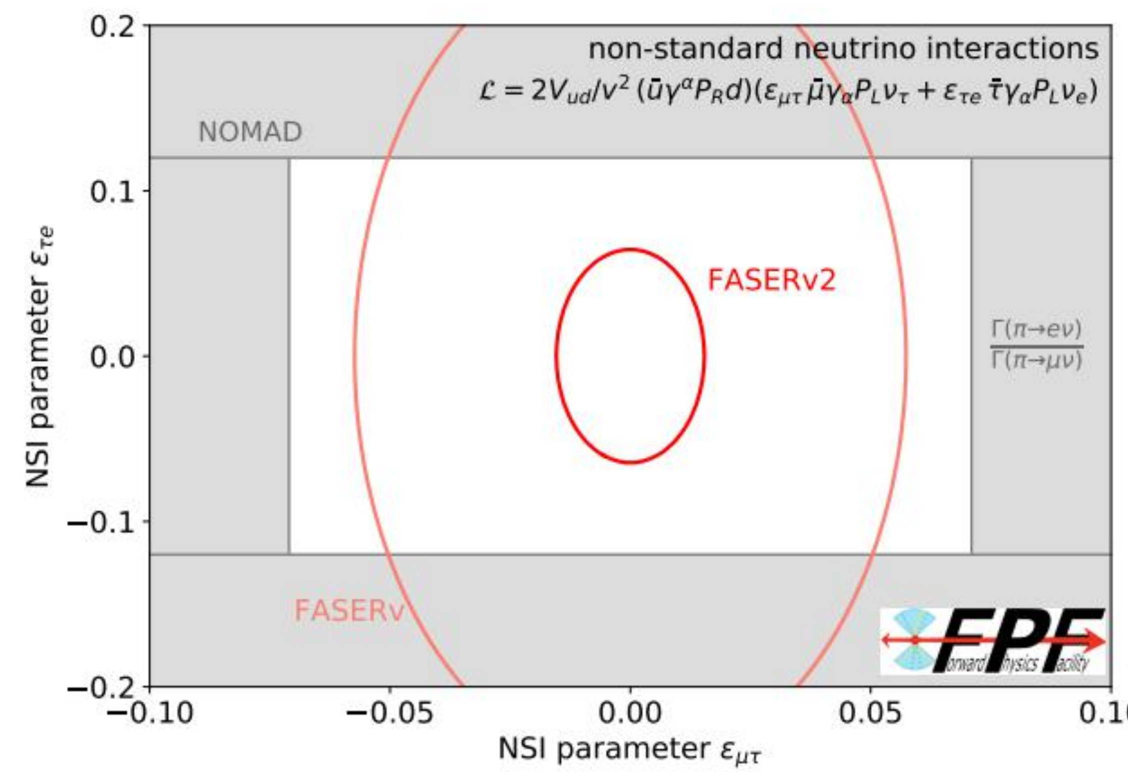
The recent direct detection of neutrinos at the LHC has opened a new window on high-energy particle physics and highlighted the potential of forward physics for groundbreaking discoveries. In the last year, the physics case for forward physics has continued to grow, and there has been extensive work on defining the Forward Physics Facility and its experiments to realize this physics potential in a timely and cost-effective manner. Following a 2-page Executive Summary, we present the status of the FPF, beginning with the FPF's unique potential to shed light on dark matter, new particles, neutrino physics, QCD, and astroparticle physics. We summarize the current designs for the Facility and its experiments, FASER2, FASERν2, FORMOSA, and FLArE, and conclude by discussing international partnerships and organization, and the FPF's schedule, budget, and technical coordination.

The Forward Physics Facility

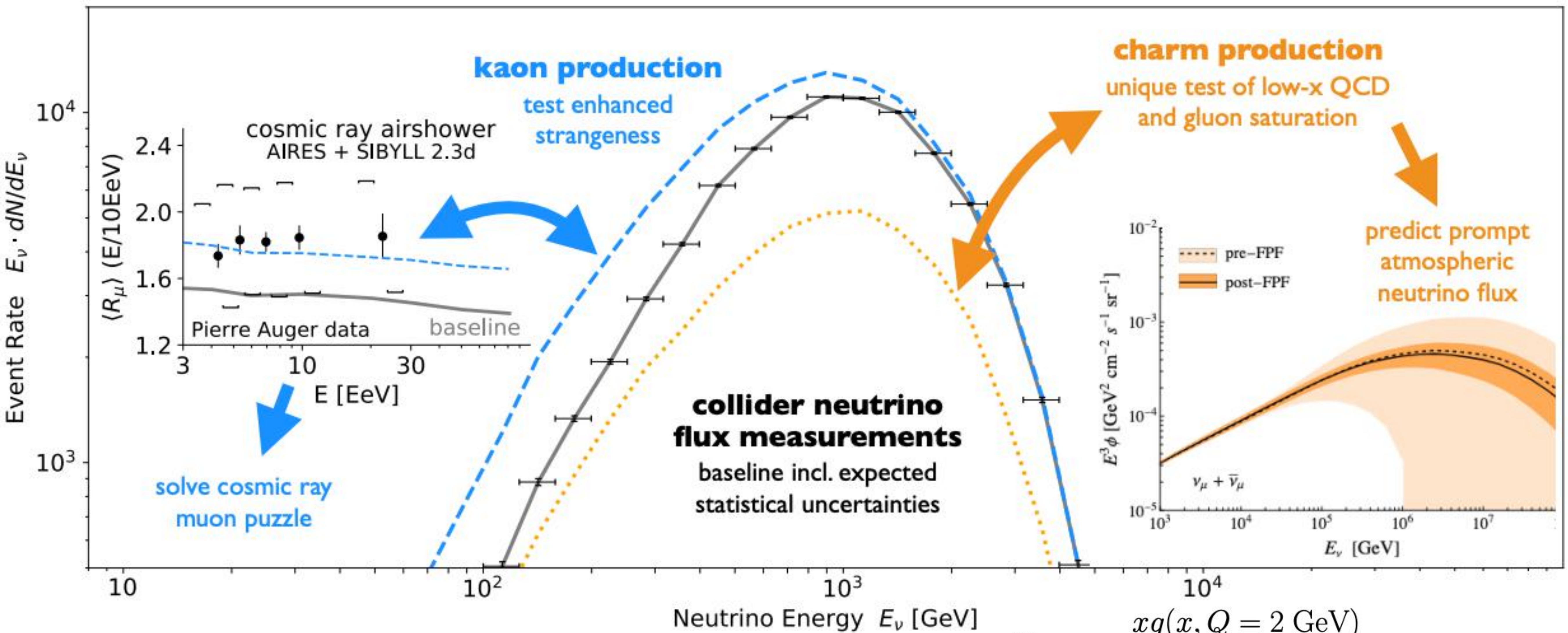


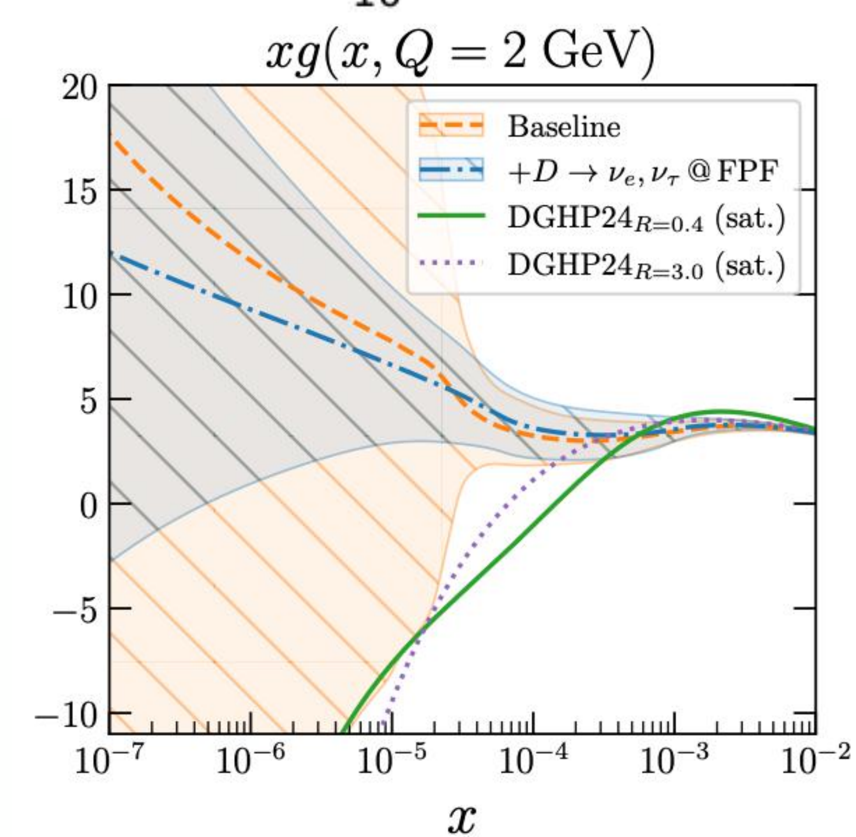
unique coverage of **TeV energy region**, high-statistics for **all three neutrino flavours**

anomalous neutrino couplings, **lepton-flavour universality** tests with neutrinos



The Forward Physics Facility





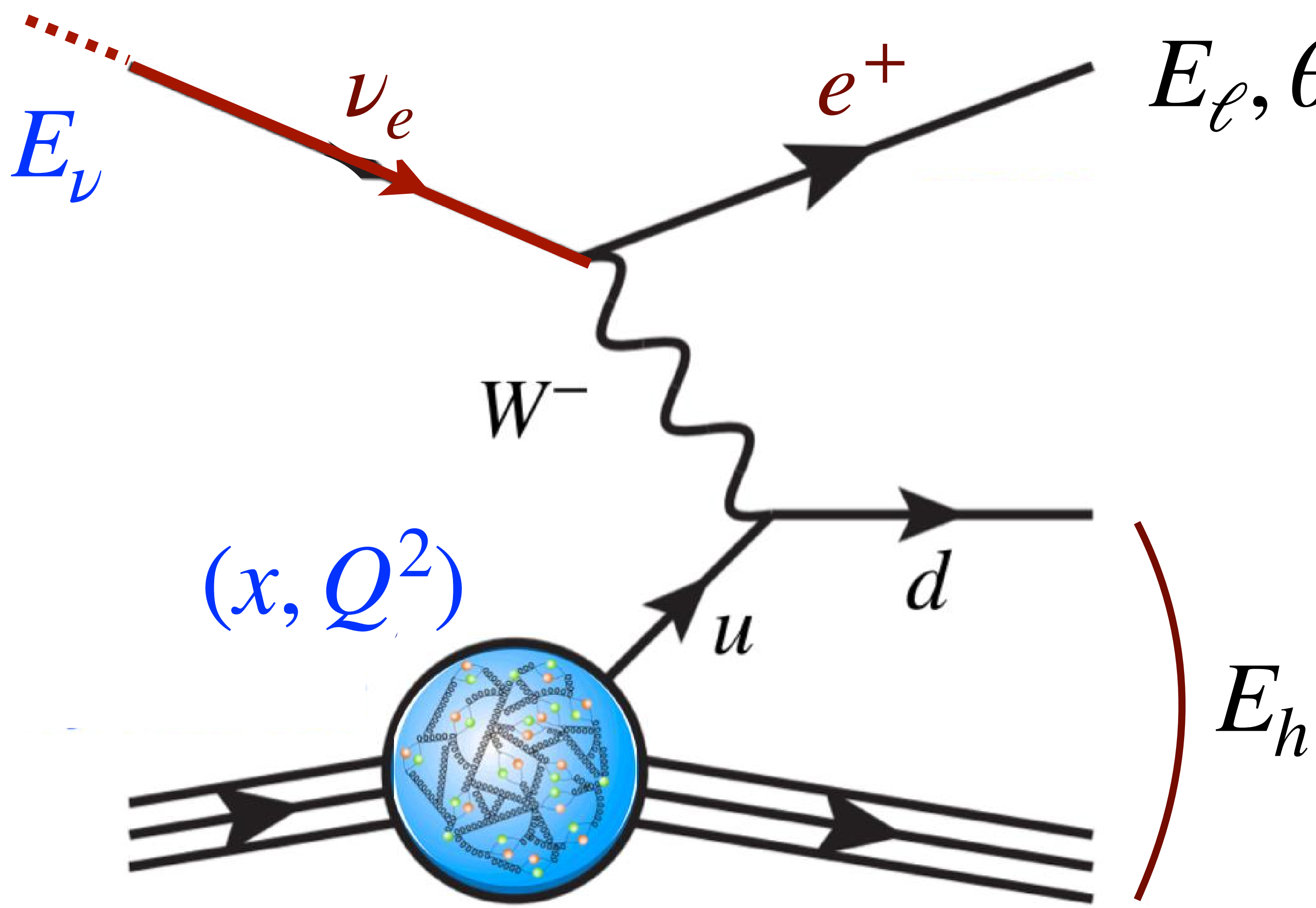
- Probe **small-*x* QCD** (e.g. non-linear dynamics) in uncharged regions
- Data-driven prediction of the prompt neutrino flux
- Laboratory validation of **muon puzzle** predating **cosmic ray physics**

The LHC as a Neutrino-Ion Collider

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

Neutrino DIS at the LHC

- Neutrino **deep-inelastic scattering** is a powerful probe of the quark/gluon structure of hadrons



Measuring outgoing **charged lepton** and **hadronic energy** specifies initial state of the collision

$$
\begin{aligned}
E_\nu &= E_h + E_\ell \,, \\
Q^2 &= 4(E_h + E_\ell)E_\ell \sin^2(\theta_\ell/2) \,, \\
x &= \frac{4(E_h + E_\ell)E_\ell \sin^2(\theta_\ell/2)}{2m_N E_h}
\end{aligned}
$$

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

- $\sigma_{\nu p \to e^+ X}(E_\nu)$ → **neutrino-proton scattering rate**
- $\tilde{\sigma}_{\nu u \to d}$ → **partonic cross-section**
- $u(x, Q^2)$ → **up-quark content int the proton**

Unique information on **quark & antiquark flavour separation**

key for core LHC theory predictions

Parton Distributions

$$u(x, Q^2)$$

Probability of **finding an up quark inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

x: fraction of proton momentum carried by gluon

Energy of hard-scattering reaction**:** inverse of resolution length

Dependence on *x* fixed by **non-perturbative QCD dynamics**: extract from experimental data

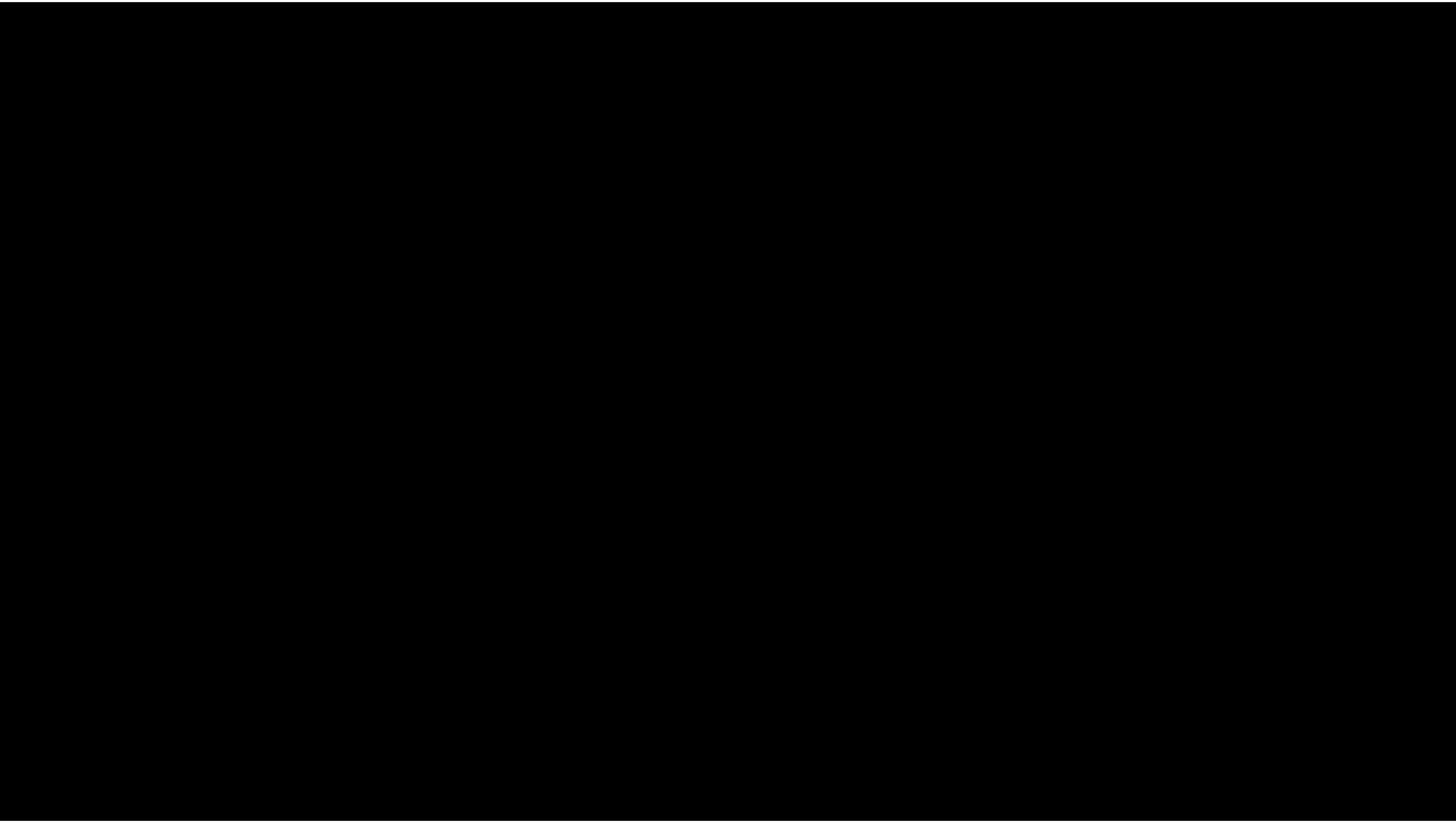
$$u(x, Q_0, \{a_g\}) = f_g(x, a_g^{(1)}, a_g^{(2)}, \ldots)$$

constrain from global fit to high-p_T data

Dependence on ***Q*** fixed by **perturbative QCD dynamics**: computed up to aN^{3}LO

$$\frac{\partial}{\partial \ln Q^2} q_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) q_j(z, Q^2)$$

Parton Distributions



credit: *visualising the proton*, Arts at MIT (https://arts.mit.edu/visualizing-the-proton/)

Bjorken-x: fraction of the proton energy carried by a quark or gluon

Neutrino DIS at the LHC

- Neutrino **deep-inelastic scattering** is a powerful probe of the quark/gluon structure of hadrons
- **Double-differential** measurements provide direct access to different flavour combinations

$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2}\left[Y_+ F_2^{\nu A}(x,Q^2) - y^2 F_L^{\nu A}(x,Q^2) + Y_- x F_3^{\nu A}(x,Q^2)\right]$$

$$y = Q^2/(2xm_n E_\nu)$$

Cross-section expressed in terms of LO structure functions:

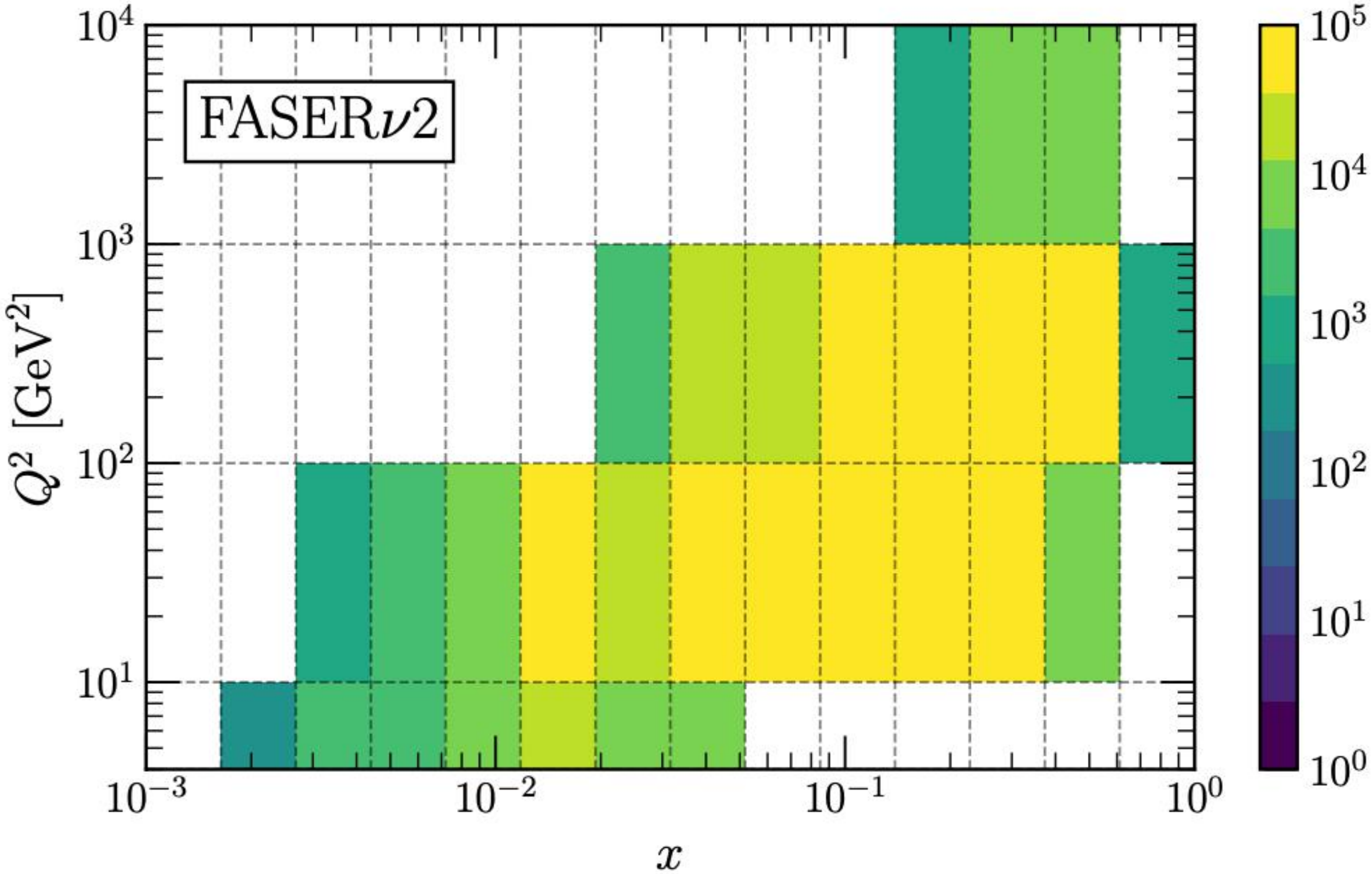
$$\begin{aligned}
F_2^{\nu p}(x,Q^2) &= 2x\left(f_{\bar{u}} + f_d + f_s + f_{\bar{c}}\right)(x,Q^2)\,,\\
F_2^{\bar{\nu} p}(x,Q^2) &= 2x\left(f_u + f_{\bar{d}} + f_{\bar{s}} + f_c\right)(x,Q^2)\,,\\
xF_3^{\nu p}(x,Q^2) &= 2x\left(-f_{\bar{u}} + f_d + f_s - f_{\bar{c}}\right)(x,Q^2)\,,\\
xF_3^{\bar{\nu} p}(x,Q^2) &= 2x\left(f_u - f_{\bar{d}} - f_{\bar{s}} + f_c\right)(x,Q^2)\,.
\end{aligned}$$

Goal: quantify the impact of **ongoing and future LHC neutrino experiments** on the proton PDFs, and assess their implications for the (**HL)-LHC precision physics program**

Neutrino DIS at the LHC

- Generate **DIS pseudo-data** at current and proposed LHC neutrino experiments
- Fully differential calculation based on **state-of-the-art QCD** calculations
- Model **systematic errors** based on the expected performance of the experiments
- Consider both inclusive and **charm-production DIS**

number of DIS events per bin



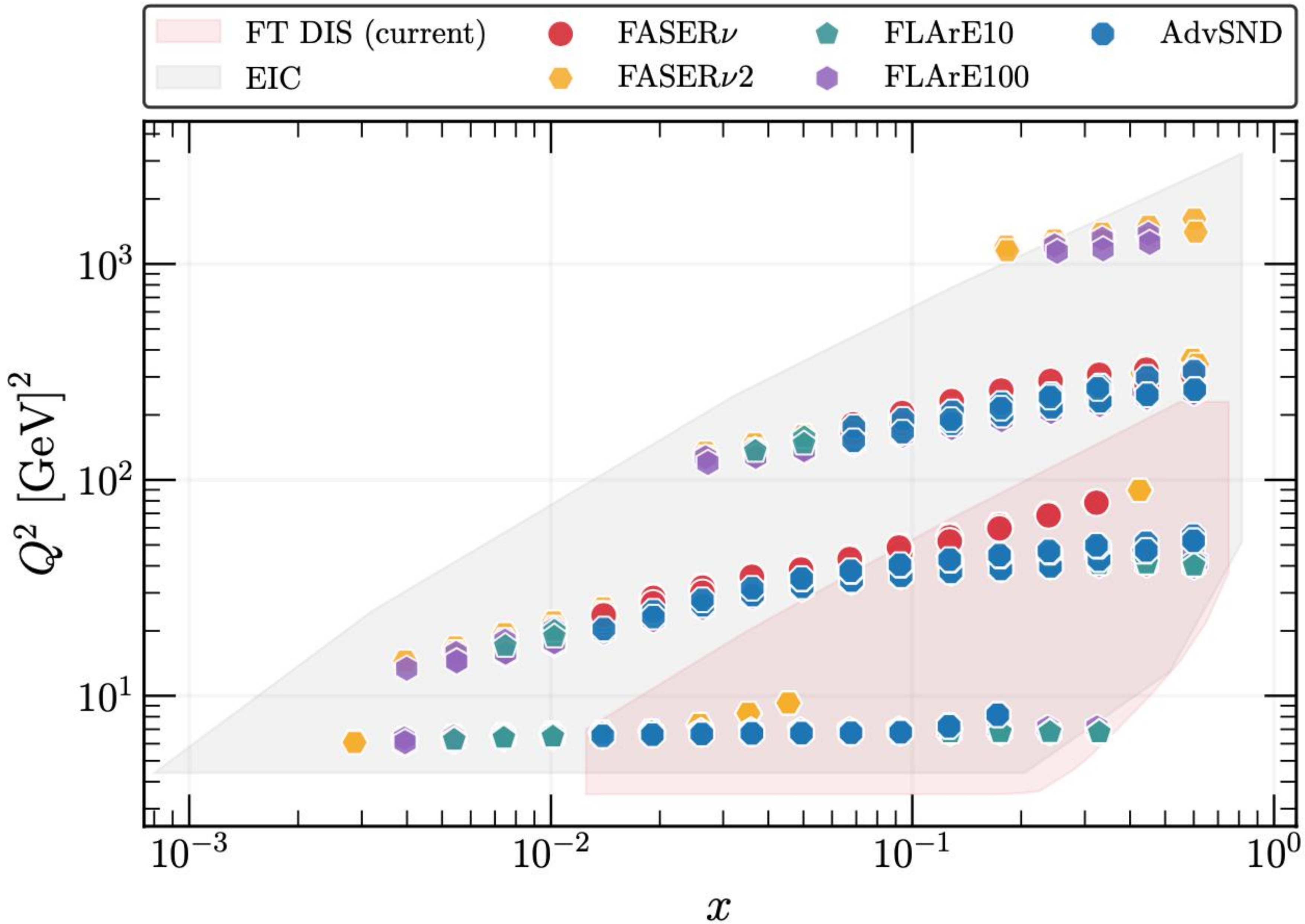
Events per bin

$$N_{\rm ev}^{(i)} = n_T L_T \int_{Q^{2(i)}_{\rm min}}^{Q^{2(i)}_{\rm max}} \int_{x^{(i)}_{\rm min}}^{x^{(i)}_{\rm max}} \int_{E^{(i)}_{\rm min}}^{E^{(i)}_{\rm max}} \frac{dN_\nu(E_\nu)}{dE_\nu} \left(\frac{d^2\sigma(x,Q^2,E_\nu)}{dx dQ^2} \right) \mathcal{A}(x,Q^2,E_\nu) dQ^2 dx dE_\nu$$

Geometry | *Binning* | *neutrino fluxes (include rapidity acceptance)* | *DIS differential cross-section* | *Acceptance*

Model **detector performance** based on most updated design

Neutrino DIS at the LHC



x: momentum fraction of quarks/gluons in the proton

Q²: momentum transfer from incoming lepton

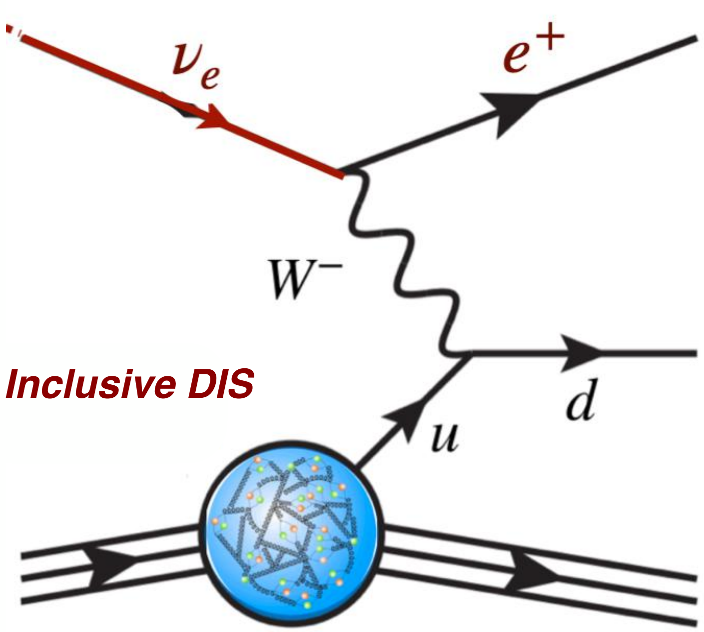
- Continue highly succesful program of neutrino **DIS experiments @ CERN**
- **Expand kinematic coverage** of available experiments by an order of magnitude in *x* and *Q²*
- Charged-current counterpart of the **Electron-Ion Collider** covering same region of phase space

Extend CERN infrastructure with an (effective) Neutrino-Ion Collider by ``recycling'' an otherwise discarded beam

Neutrino DIS at the LHC

Integrated event rates for DIS kinematics for **inclusive (charm-tagged)** production

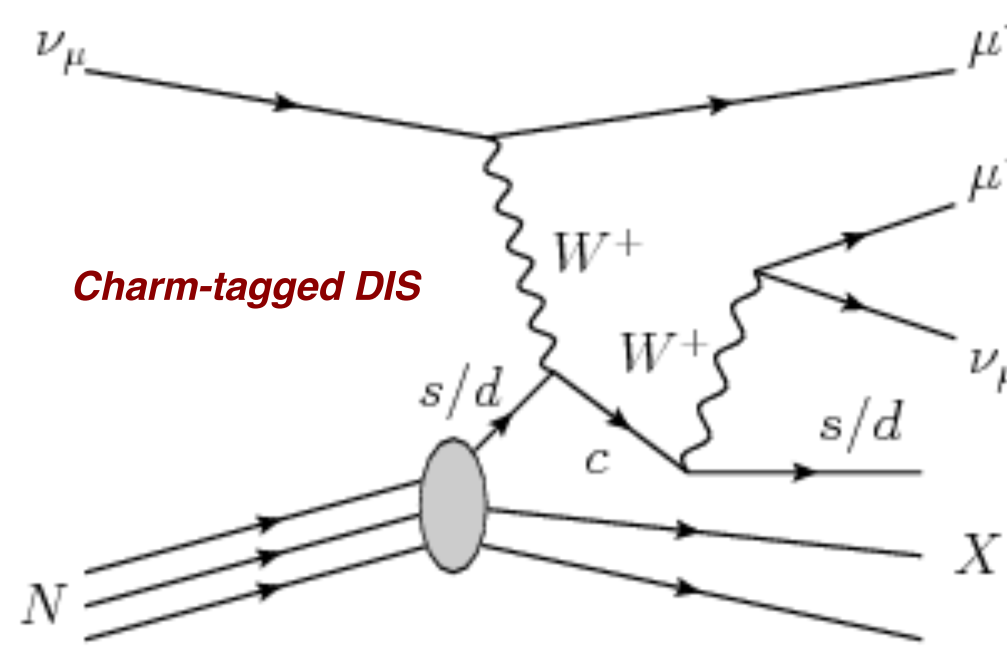
Detector	N_{ν_e}	$N_{\bar{\nu}_e}$	$N_{\nu_e} + N_{\bar{\nu}_e}$	N_{ν_μ}	$N_{\bar{\nu}_\mu}$	$N_{\nu_\mu} + N_{\bar{\nu}_\mu}$
FASERν	400 (62)	210 (38)	610 (100)	1.3k (200)	500 (90)	1.8k (290)
SND@LHC	180 (22)	76 (11)	260 (32)	510 (59)	190 (25)	700 (83)
FASERν2	116k (17k)	56k (9.9k)	170k (27k)	380k (53k)	133k (23k)	510k (76k)
AdvSND-far	12k (1.5k)	5.5k (0.82k)	18k (2.3k)	40k (4.8k)	16k (2.2k)	56k (7k)
FLArE10	44k (5.5k)	20k (3.0k)	64k (8.5k)	76k (10k)	38k (5.0k)	110k (15k)
FLArE100	290k (35k)	130k (19k)	420k (54k)	440k (60k)	232k (30k)	670k (90k)



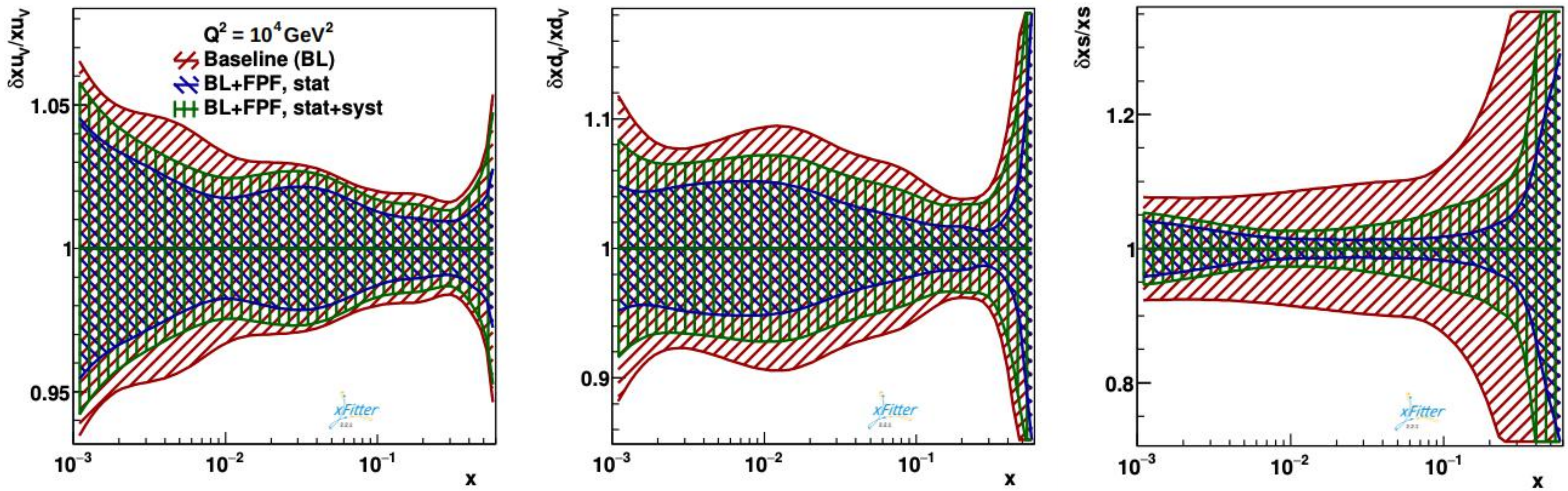
Inclusive DIS

- Muon-neutrinos: **larger event rates, smaller production uncertainties**
- Current experiments limited by statistics, FPF **by systematics**
- Ultimate reach achieved by **combining all experiments**

Charm-tagged DIS



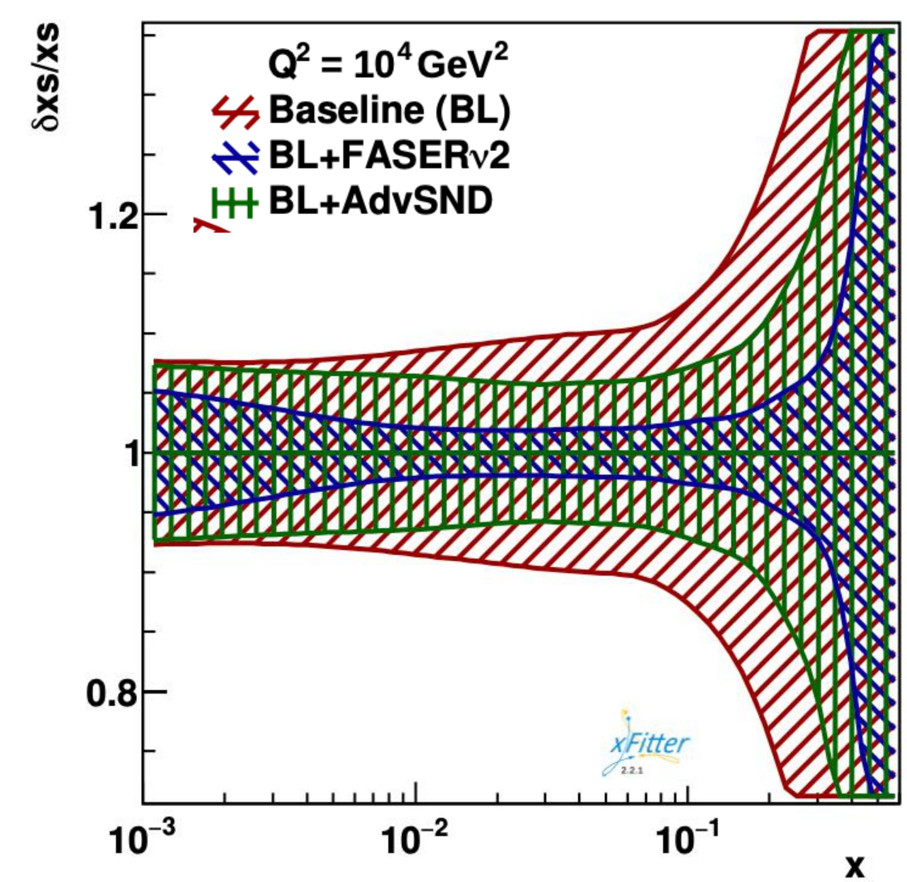
PDF constraints from LHC neutrinos



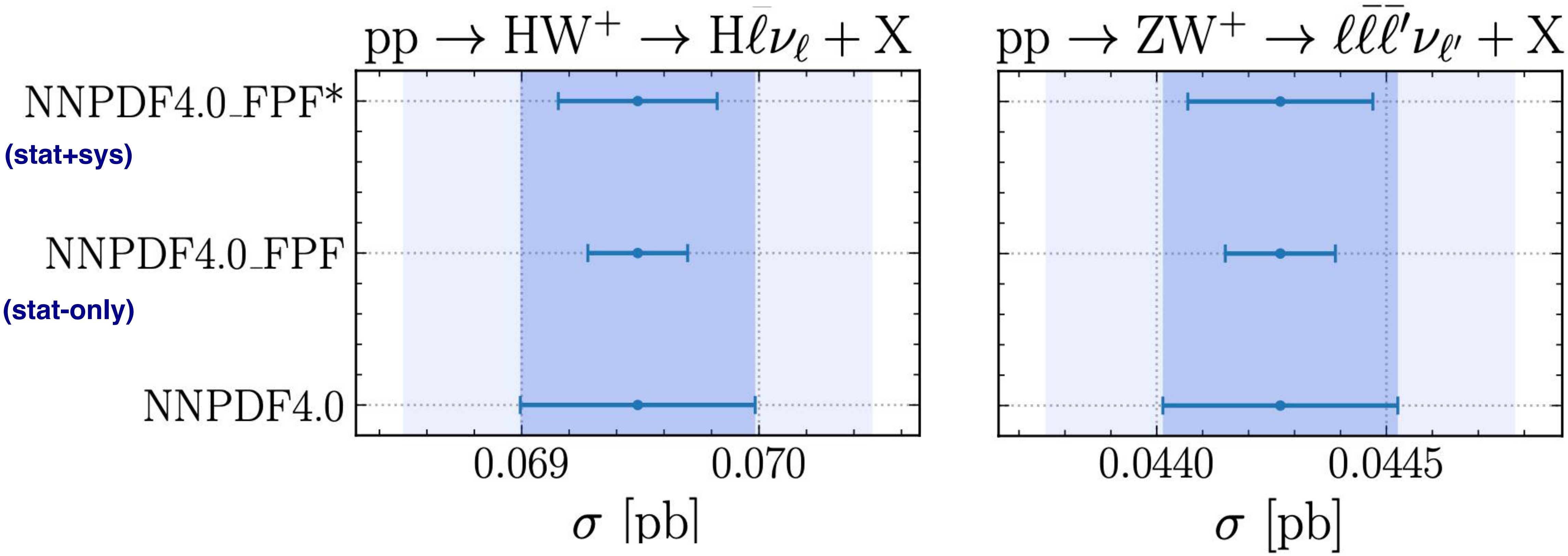
- Impact on proton PDFs quantified by the **Hessian profiling of PDF4LHC21** (xFitter) and by direct inclusion in the global **NNPDF4.0 fit**

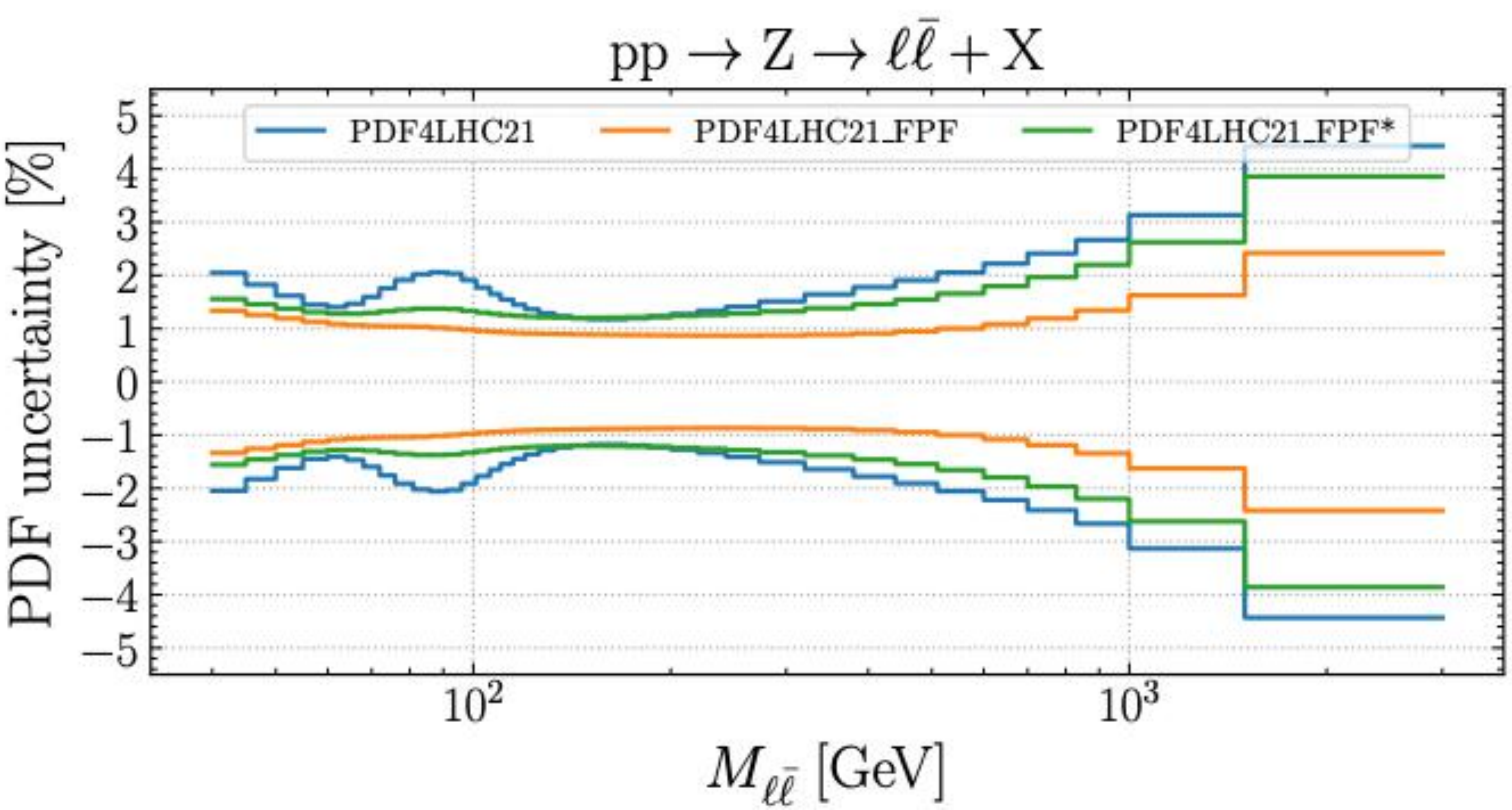
- Most impact on **up and down valence quarks** as well as in **strangeness,** ultimately limited by systematics

- Uncertainties in **incoming neutrino fluxes subdominant,** once constrained *in-situ* at FASER & FPF



Impact at the HL-LHC: Precision SM



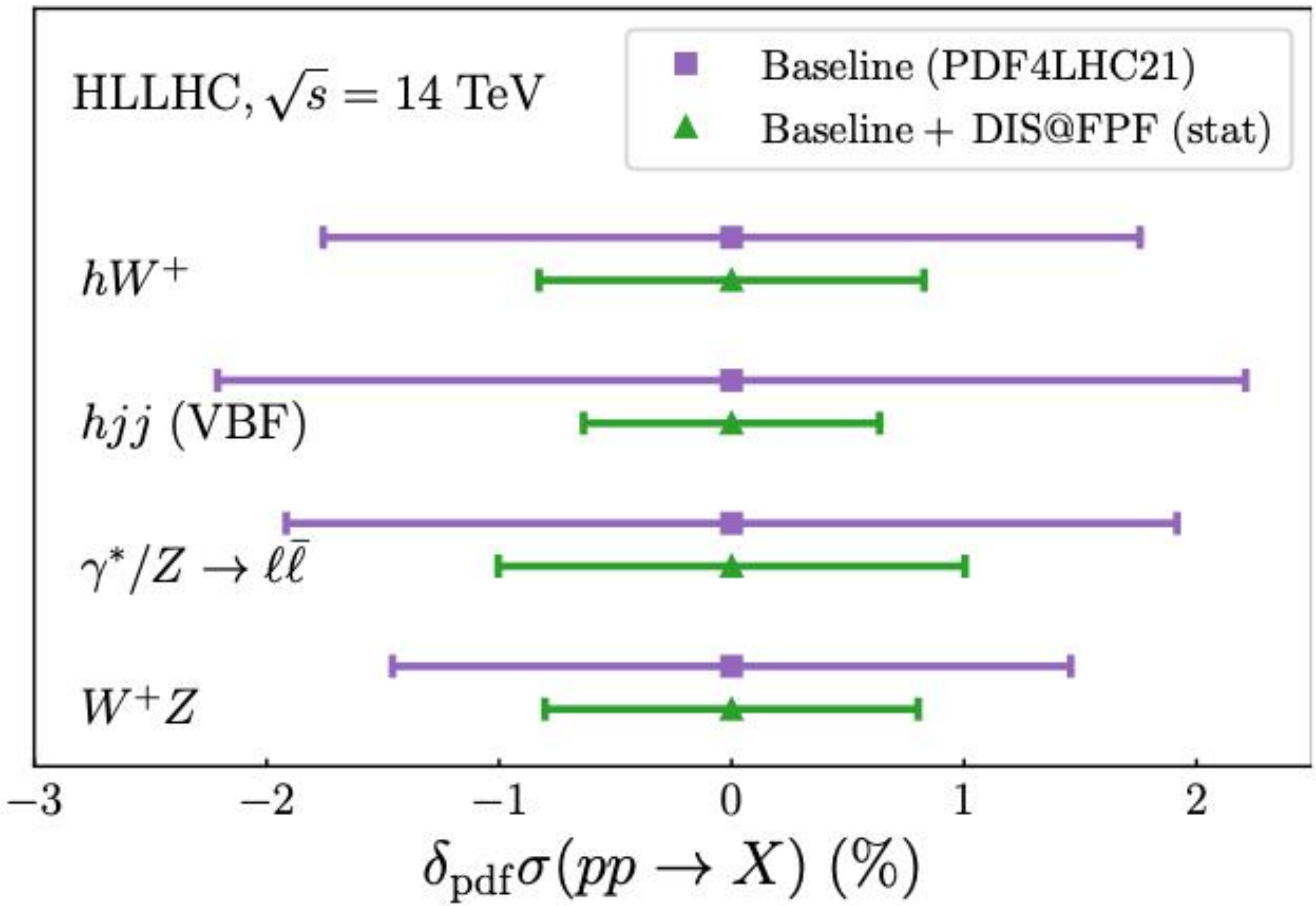


- Impact on **core HL-LHC processes** i.e. single and double weak boson production and Higgs production (VH, VBF)
- Also relevant for **BSM searches at large-mass** (via large-*x* PDFs)

e.g. high-mass dilepton resonances

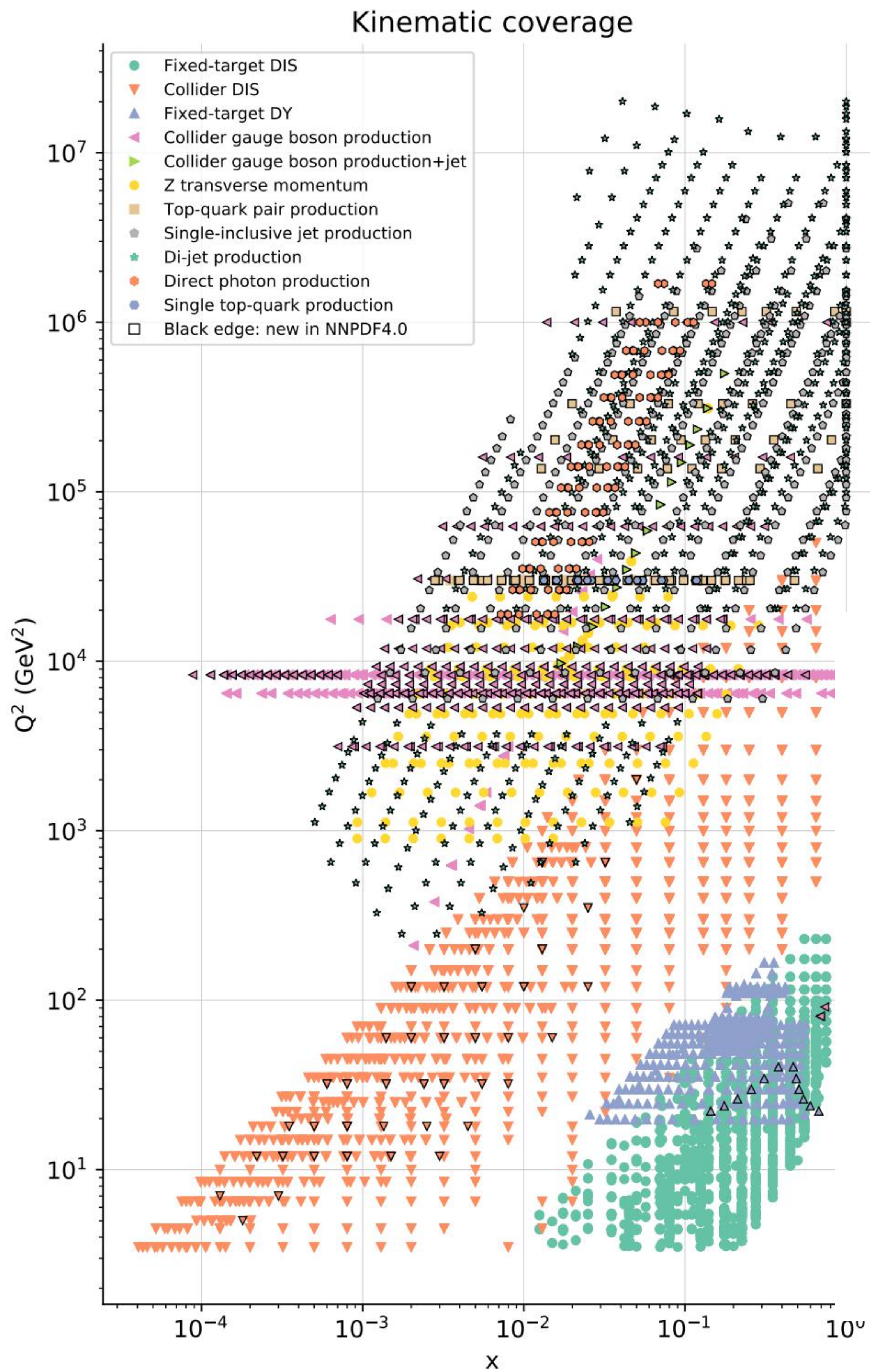
Fully independent constraints on proton structure, crucial to disentangle possible BSM signatures in high p_T data

Impact at the HL-LHC: Precision SM

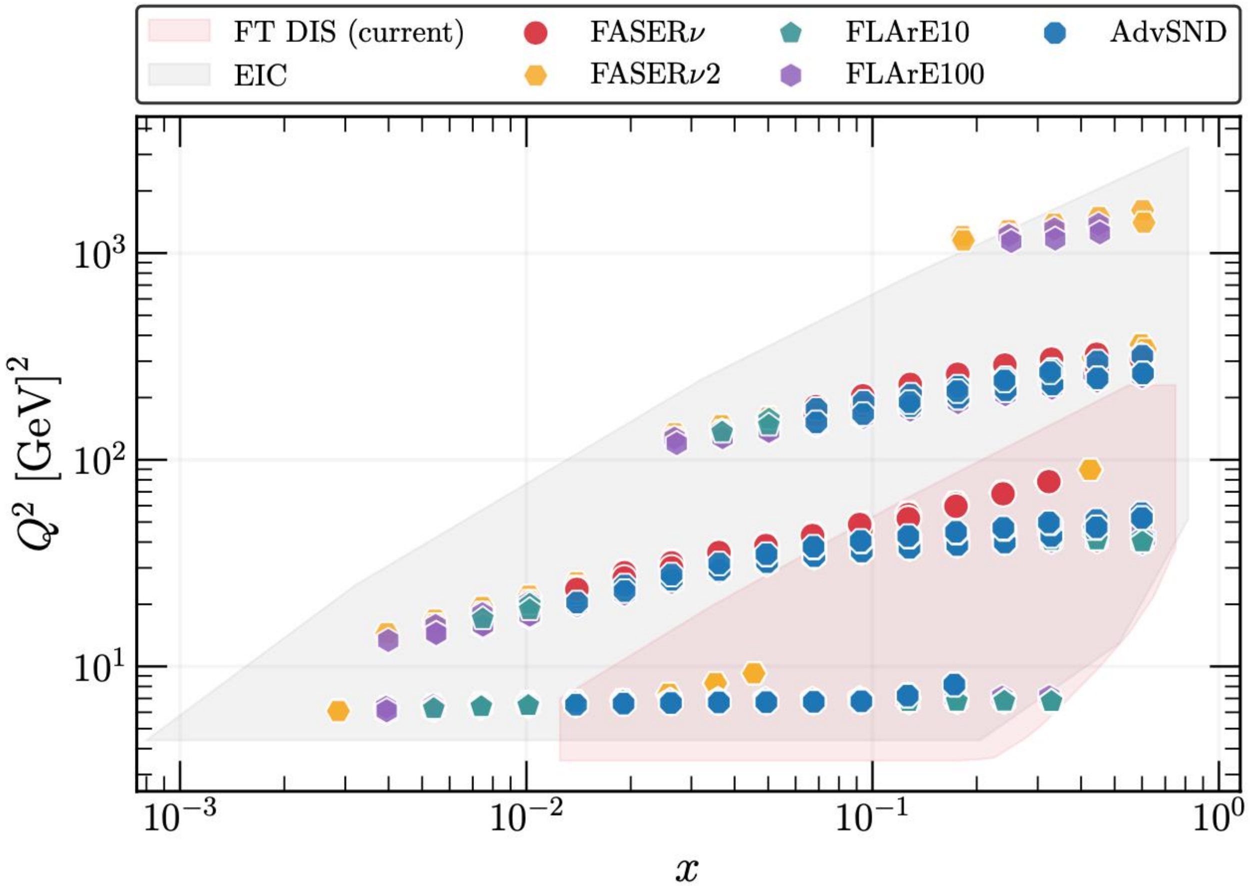


Realising the full potential of **TeV-energy neutrino DIS** at the LHC

Impact at the HL-LHC: BSM searches



- LHC data: sensitivity to large-x PDFs, but also to BSM signals (**high-Q^2 region**)
- How to separate QCD from BSM effects in high-mass LHC tails?
- FPF neutrino structure functions: sensitivity to large-x PDFs, but not BSM signals (**moderate-Q^2 region**)



Impact at the HL-LHC: BSM searches

In the presence of **BSM signals in high-p_T tails at the LHC**, the fitted PDFs may be distorted

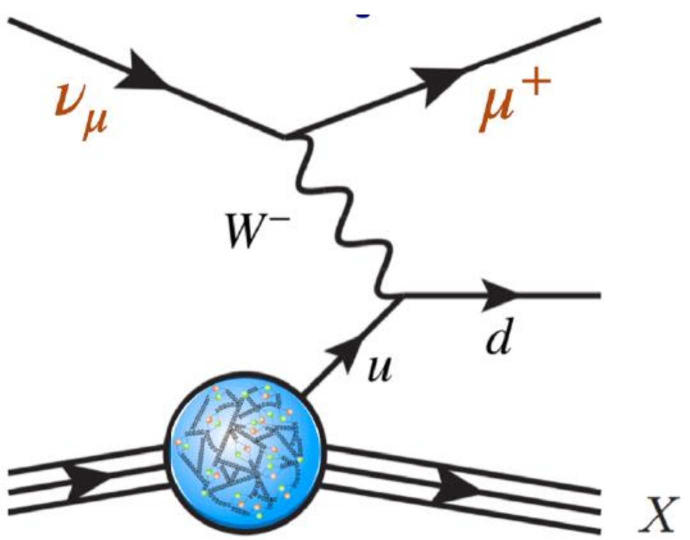
SM PDFs

$$\sigma_{\rm th}(\boldsymbol{\theta}, M_X) \propto \sum_{ij=u,d,g,\ldots} \int_{M_X^2}^{s} d\hat{s}\ \mathscr{L}_{ij}^{(\rm sm)}(M, \sqrt{s}, \boldsymbol{\theta})\ \widetilde{\sigma}_{ij}^{(\rm sm)}(\hat{s}, \alpha_s(M))$$

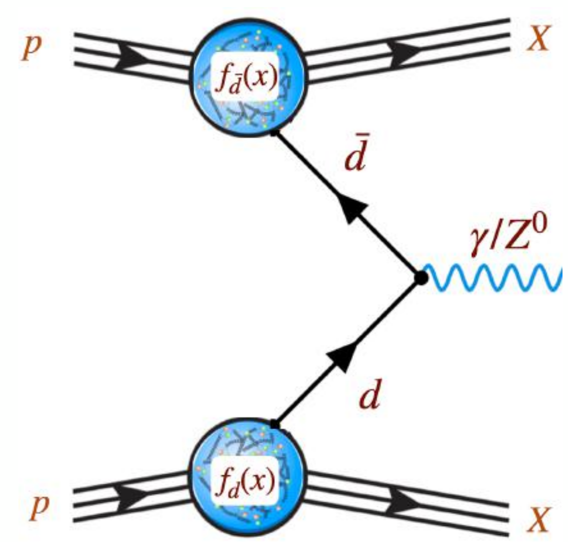
$$\sigma_{\rm th}(\boldsymbol{\theta}, M_X) \propto \sum_{ij=u,d,g,\ldots} \int_{M_X^2}^{s} d\hat{s}\ \mathscr{L}_{ij}^{(\rm smeft)}(M, \sqrt{s}, \boldsymbol{\theta}, \boldsymbol{c}/\Lambda^2)\ \widetilde{\sigma}_{ij}^{(\rm smeft)}(\hat{s}, \alpha_s(M), \boldsymbol{c}/\Lambda^2)$$

SMEFT PDFs

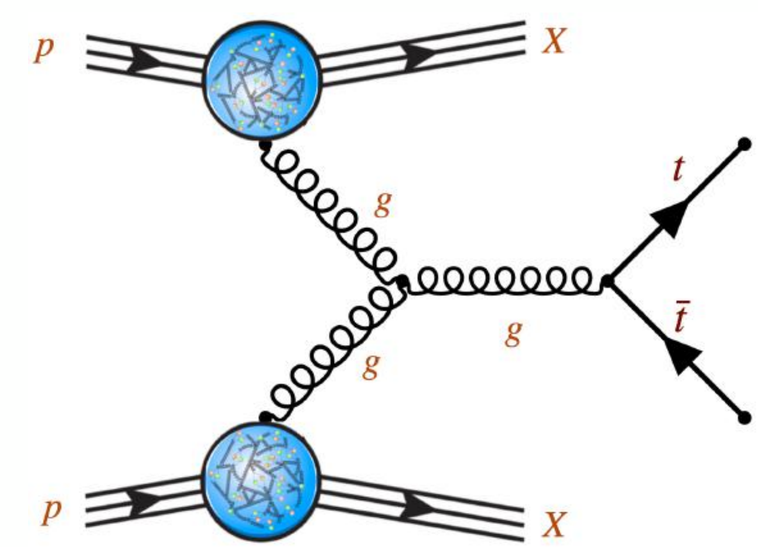
How to prevent ``**fitting away" BSM signals** into PDF fits of LHC data?



Deep-Inelastic Scattering*: S. Carrazza, C. Degrande, S. Iranipour, JR, M. Ubiali, PRL 2019*



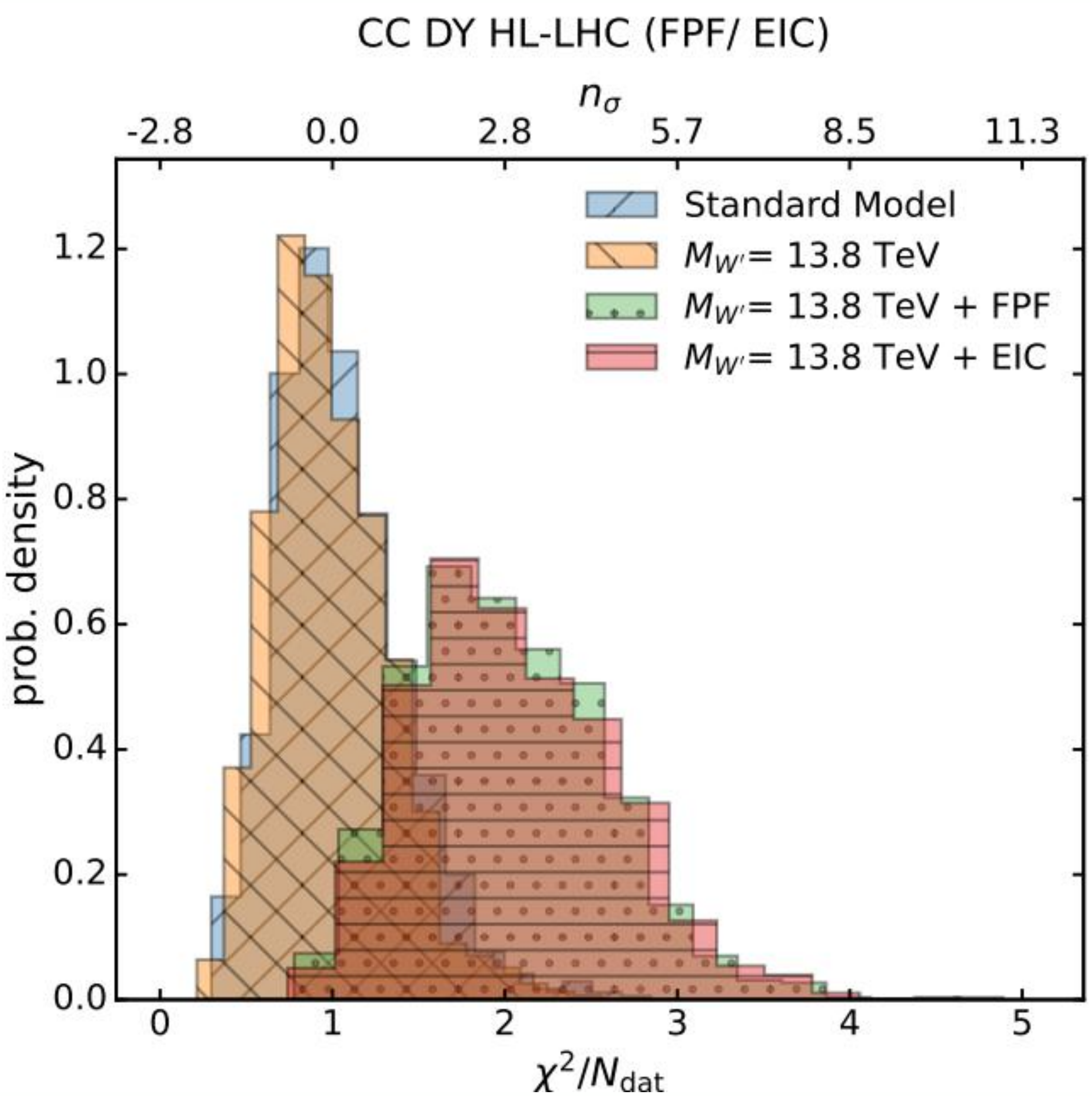
High-mass Drell-Yan: *A. Greljo, S. Iranipour, Z. Kassabov, M. Madigan, J. Moore, JR, M. Ubiali, C. Voisey, JHEP 2021*

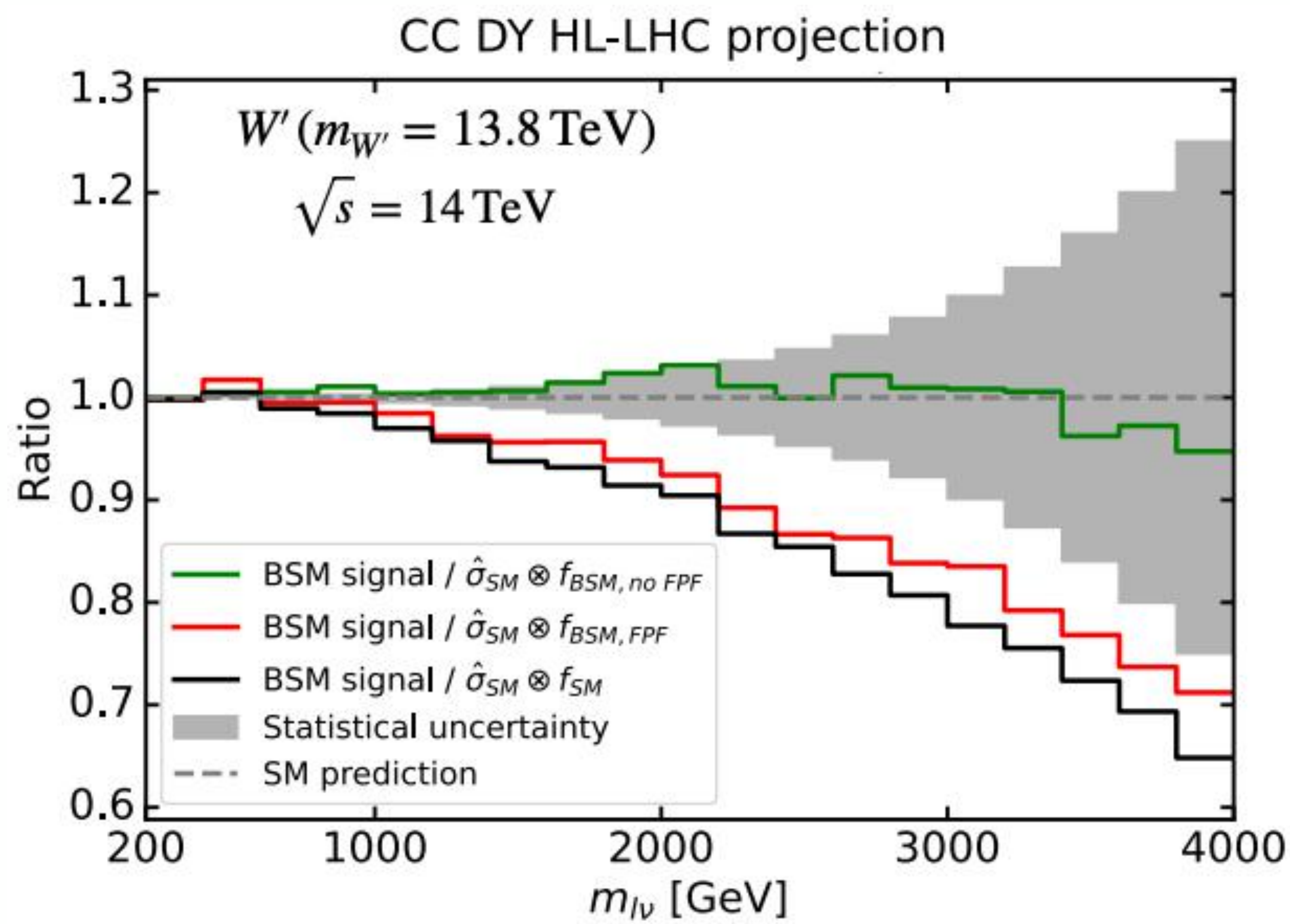


Top quark sector: *Z. Kassabov, M. Madigan, L. Mantani , J. Moore , M.Morales-Alvarado, JR , M. Ubiali, JHEP 2023*

Impact at the HL-LHC: BSM searches

- 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
- Without FPF, this BSM signal is completely reabsorbed by the PDF fit (softer large-*x* antiquarks)
- FPF constraints **disentangles BSM signals from QCD effects in LHC high-p_T tails**





Hammou & Ubiali, 2024

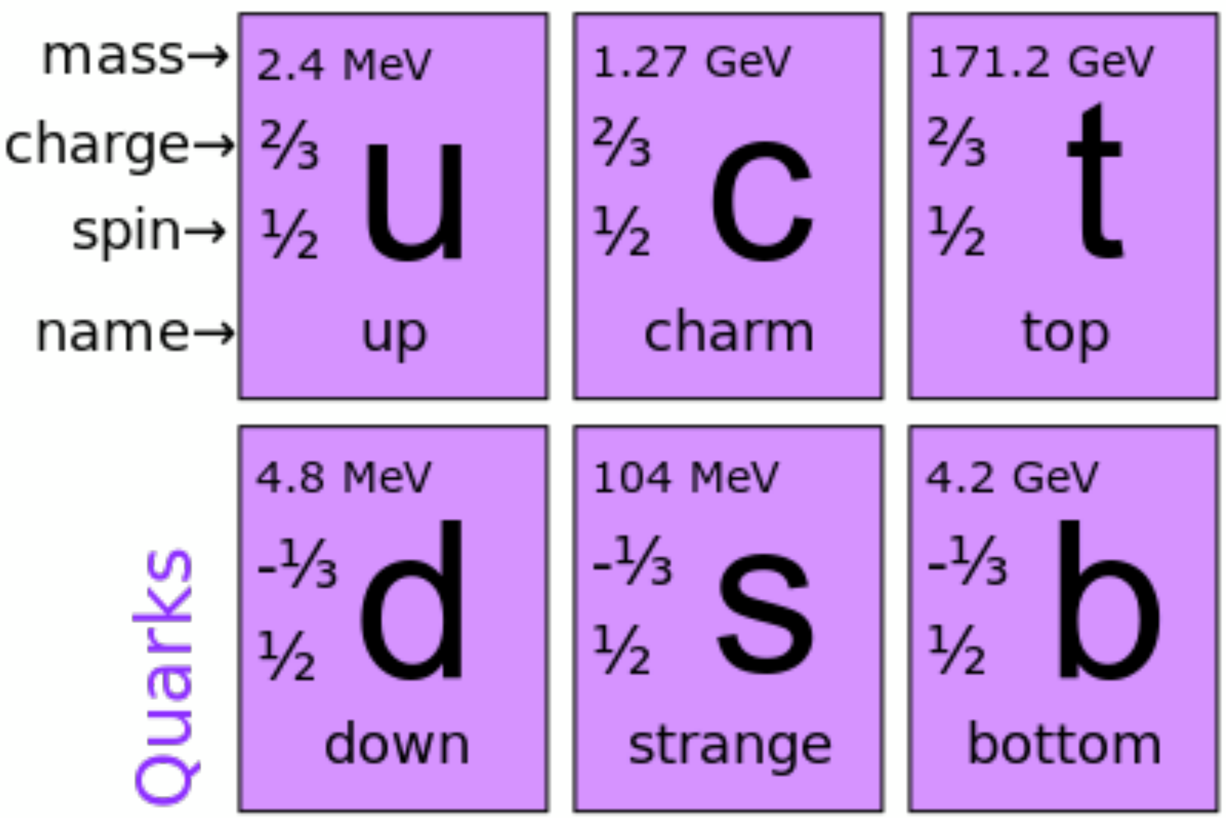
Evidence for Intrinsic Charm Quarks in the Proton

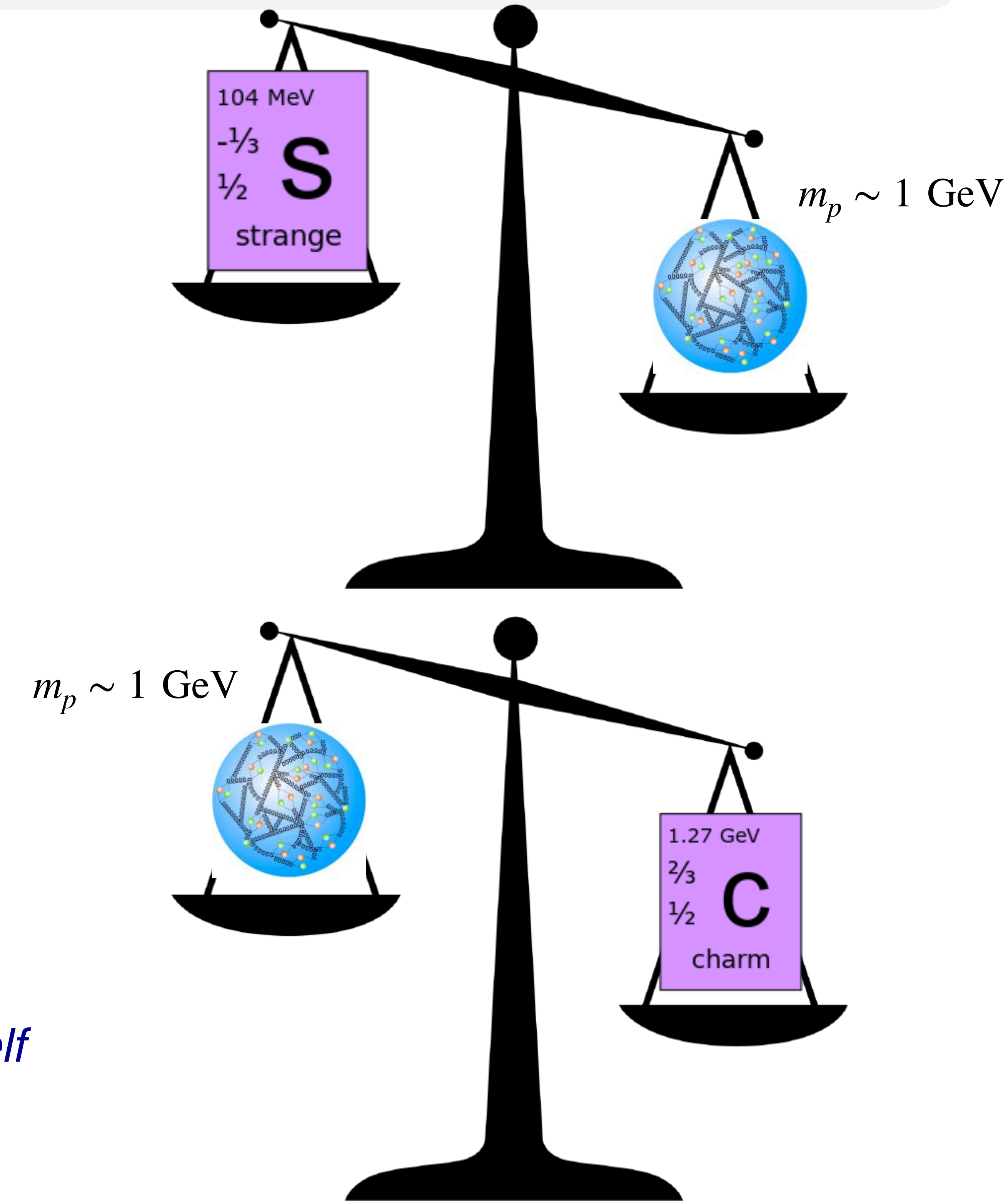
R. D. Ball, A. Candido, J. Cruz-Martinez, S. Forte, T. Giani, F. Hekhorn, K. Kudashkin, G. Magni & J. Rojo, ***Nature* 608 (2022) 7923, 483-487**

R. D. Ball, A. Candido, J. Cruz-Martinez, S. Forte, T. Giani, F. Hekhorn, E. R. Nocera, G. Magni, J. Rojo & R. Stegeman, ***arXiv:2311.00743***

Impact on Intrinsic Charm

common assumption: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**





charm quarks heavier than the proton itself

Impact on Intrinsic Charm

common assumption: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**

It does not need to be so! An **intrinsic charm component** predicted in many models

THE INTRINSIC CHARM OF THE PROTON

$$|p\rangle = \mathscr{P}_{3q}\,|uud\rangle + \mathscr{P}_{5q}\,|uudc\bar{c}\rangle + \ldots$$

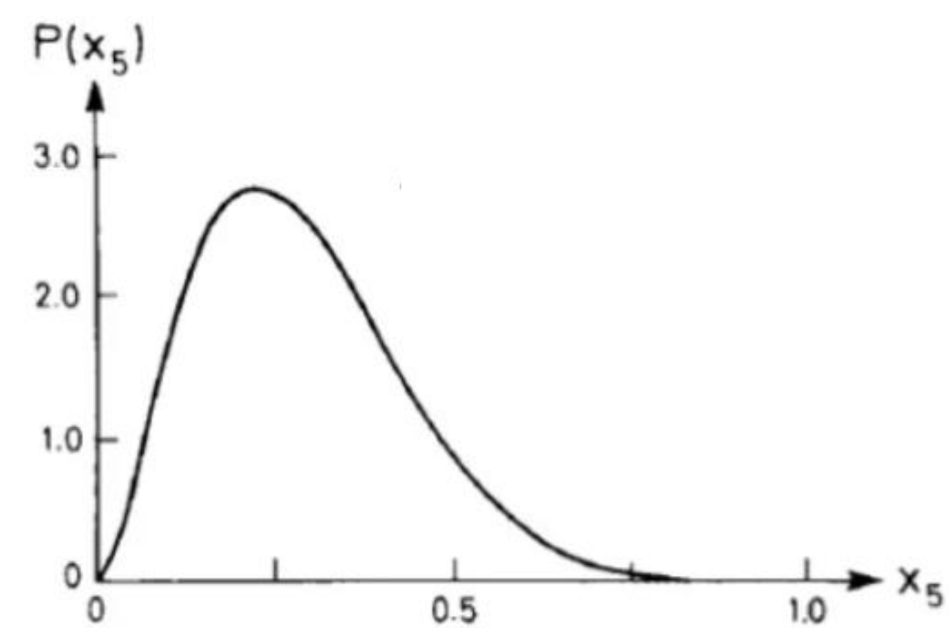
S.J. BRODSKY [1]

Stanford Linear Accelerator Center, Stanford, California 94305, USA

and

P. HOYER, C. PETERSON and N. SAKAI [2]

NORDITA, Copenhagen, Denmark



Received 22 April 1980

Recent data give unexpectedly large cross-sections for charmed particle production at high x_F in hadron collisions. This may imply that the proton has a non-negligible uudc$\bar{c}$ Fock component. The interesting consequences of such a hypothesis are explored.

within global PDF fit:

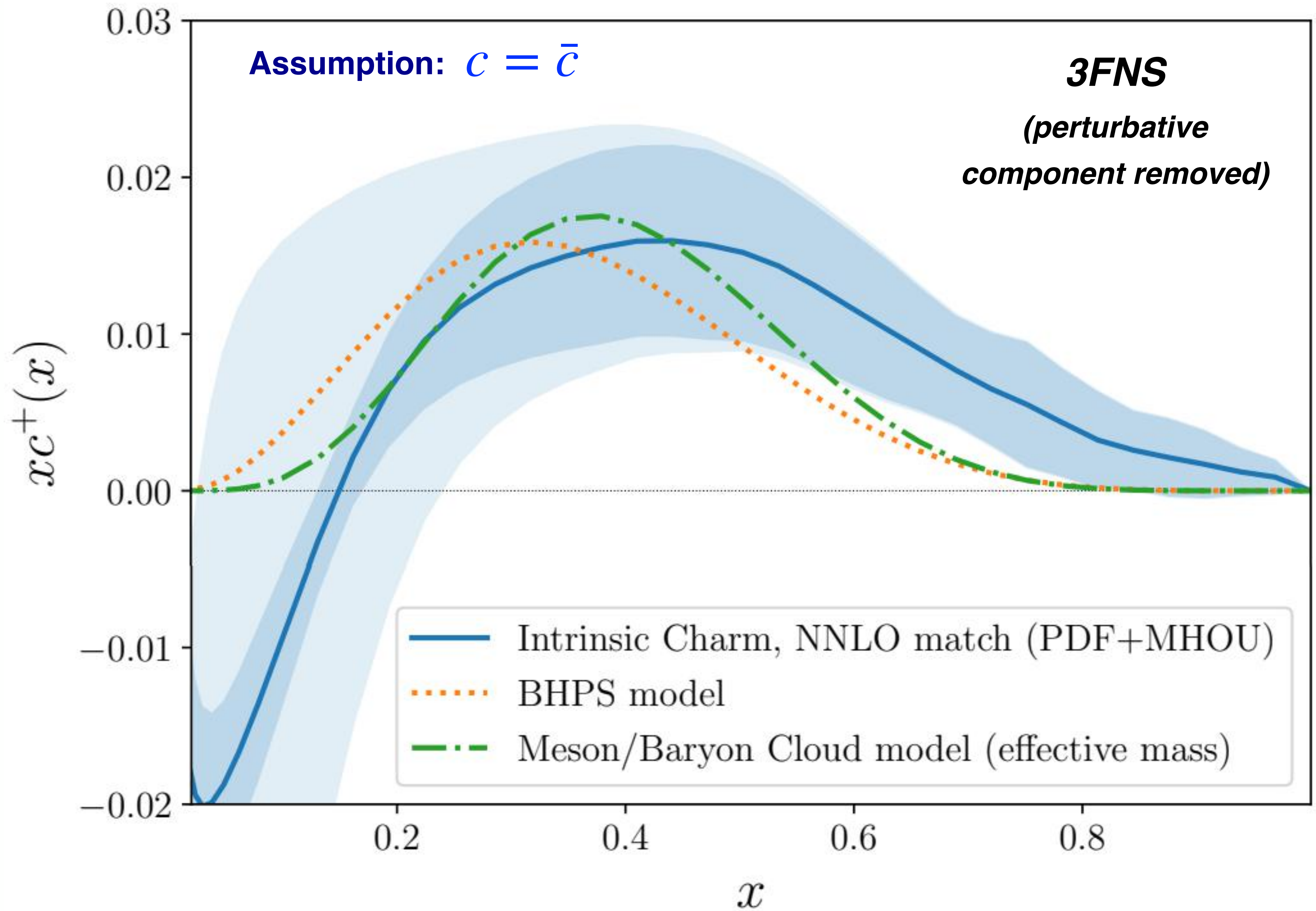
$$c^{(n_f=4)}(x,Q) \simeq c^{(n_f=4)}_{(\mathrm{pert})}(x,Q) + c^{(n_f=4)}_{(\mathrm{intr})}(x,Q)$$

Extracted from data

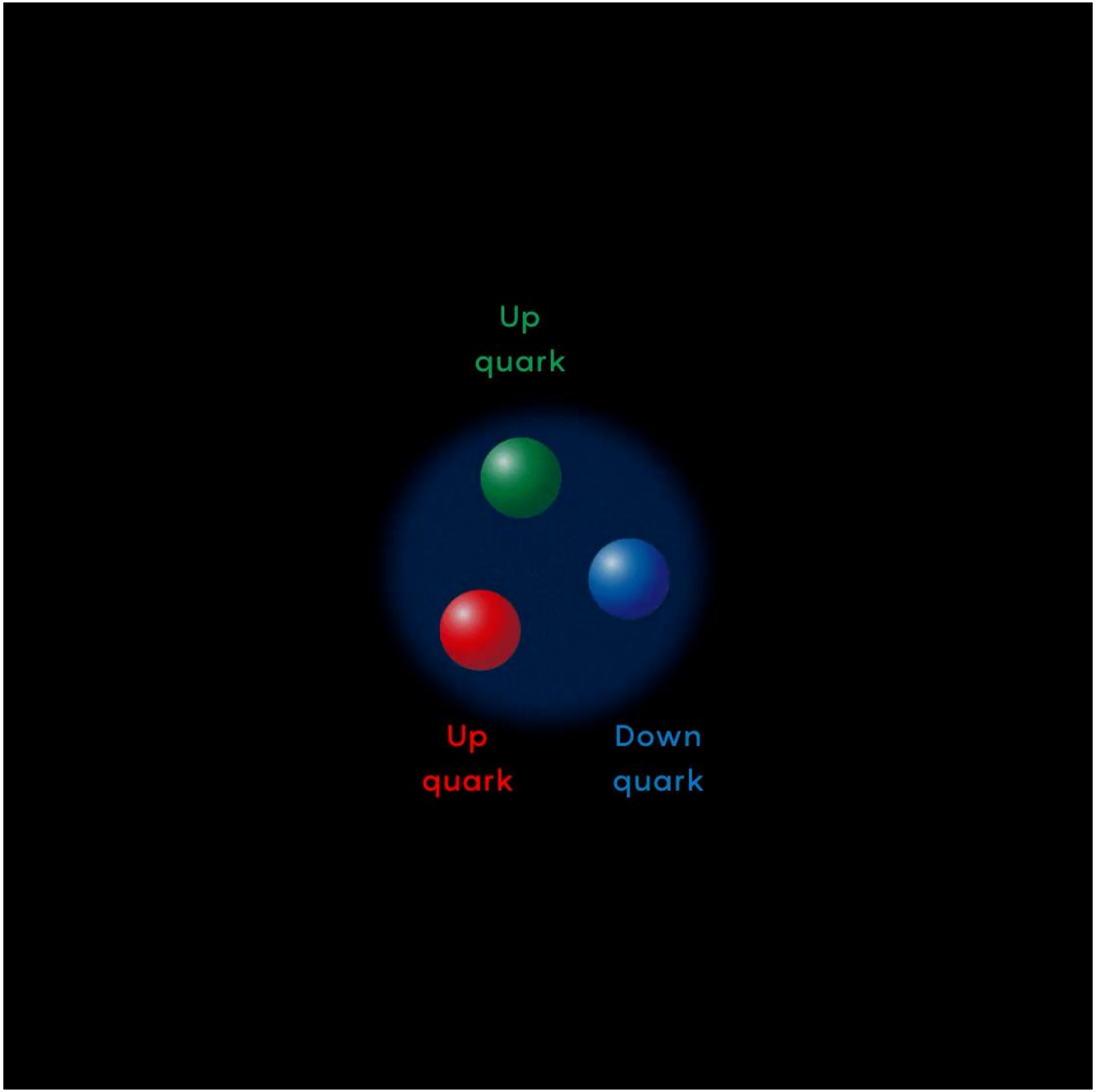
from QCD radiation and matching

from intrinsic component

Impact on Intrinsic Charm



The 3FNS charm PDF displays **non-zero component** peaked at large-*x* which can be identified with **intrinsic charm**



credits: https://www.quantamagazine.org/inside-the-proton-the-most-complicated-thing-imaginable-20221019/

Impact on Intrinsic Charm

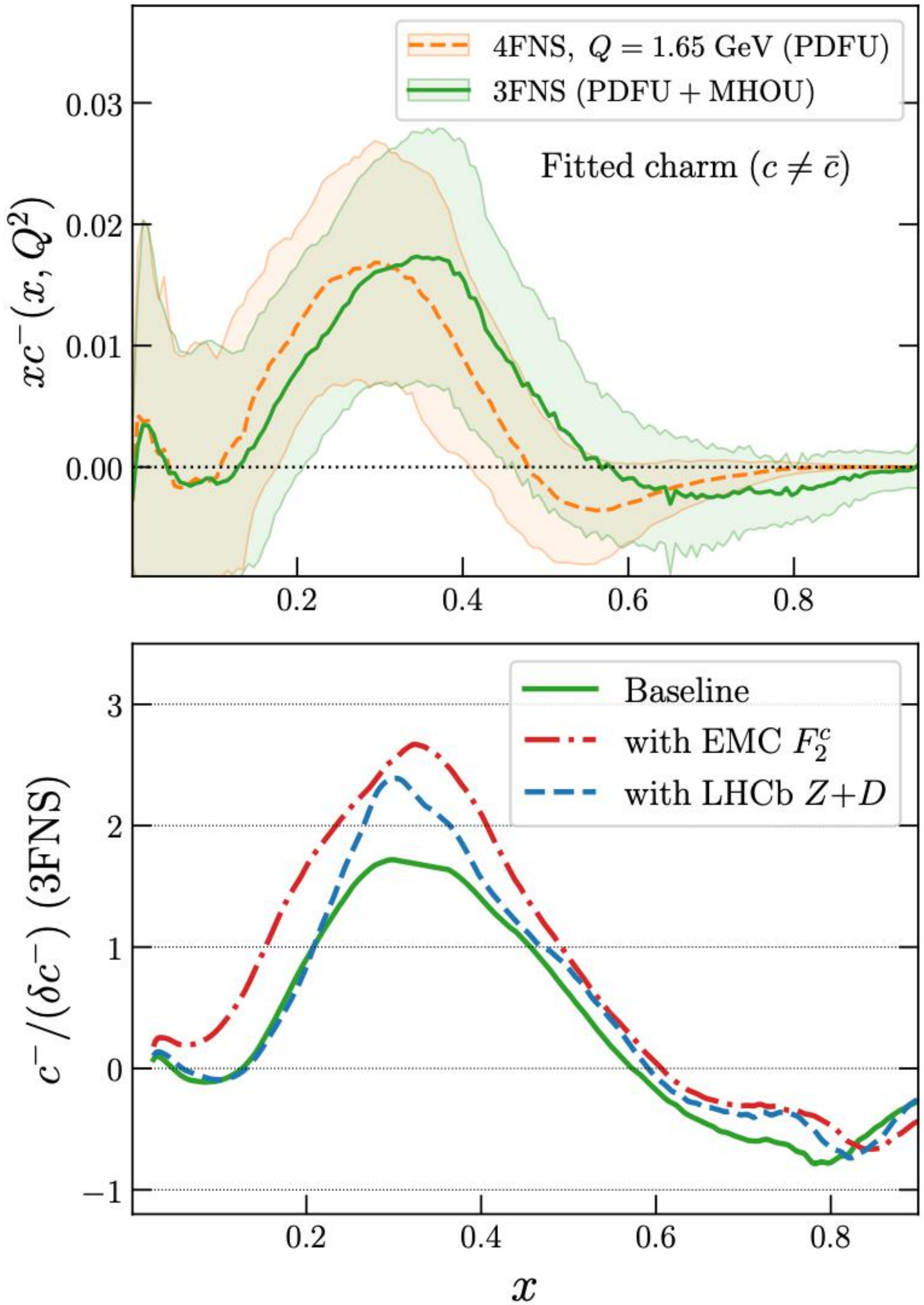
- No reason why intrinsic charm should be **symmetric** (it is not in most models)

  i.e. up, down, and strange quark PDFs are asymmetric

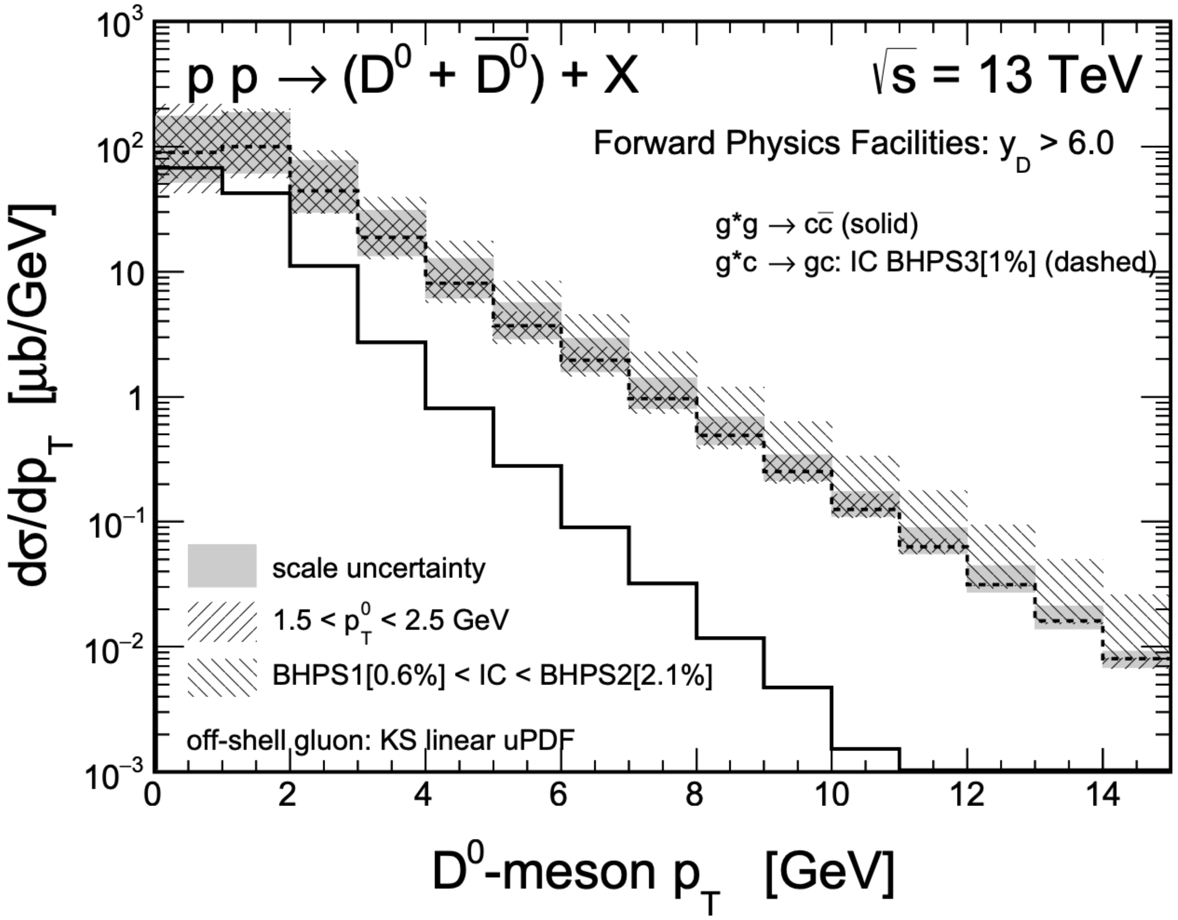
- Extend the NNPDF4.0 analysis with an **separate determination of charm and anti-charm PDFs**

- PDF uncertainties are large, but preference for a **non-zero, positive IC asymmetry** around *x*=0.3

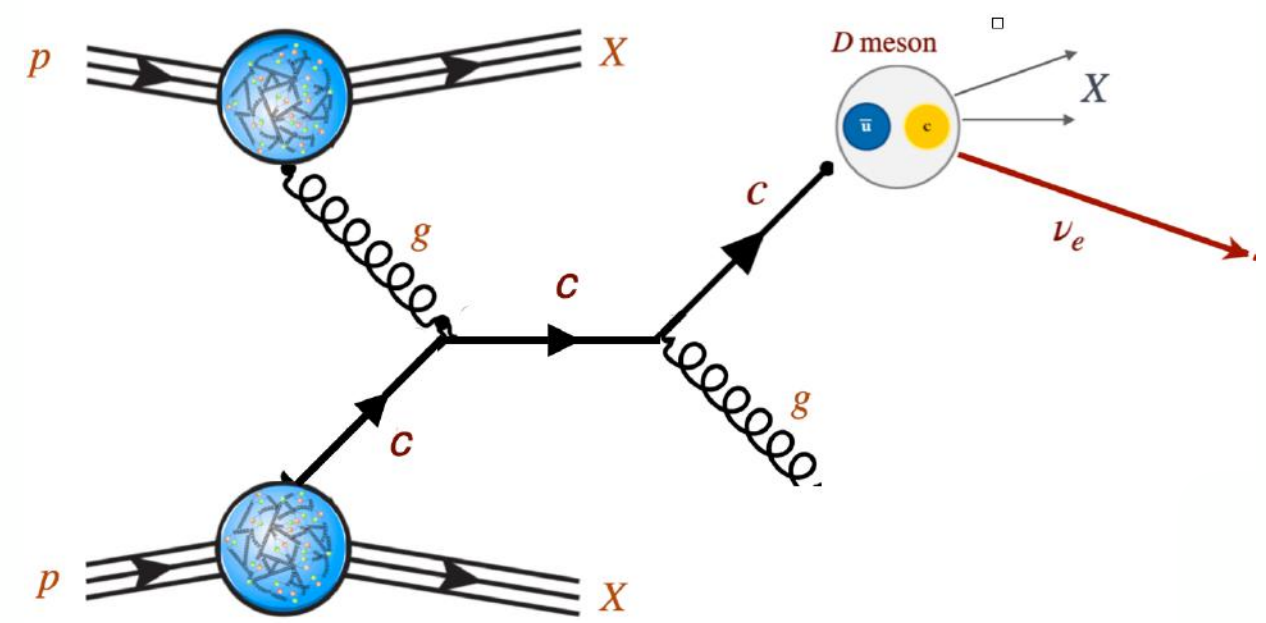
A non-zero valence charm PDF is the ultimate smoking gun for IC, since no perturbative mechanism can generate it

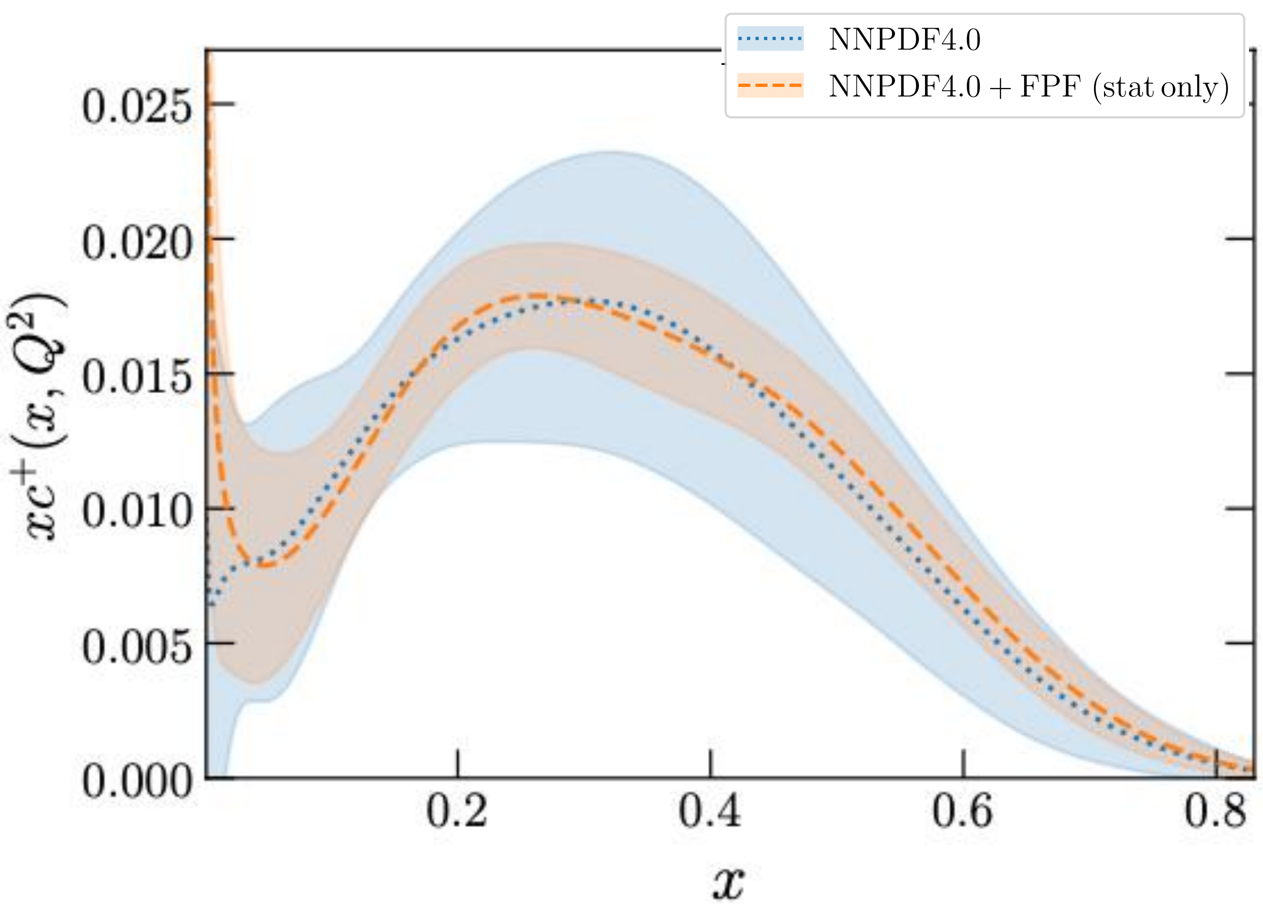


FPF & Intrinsic Charm

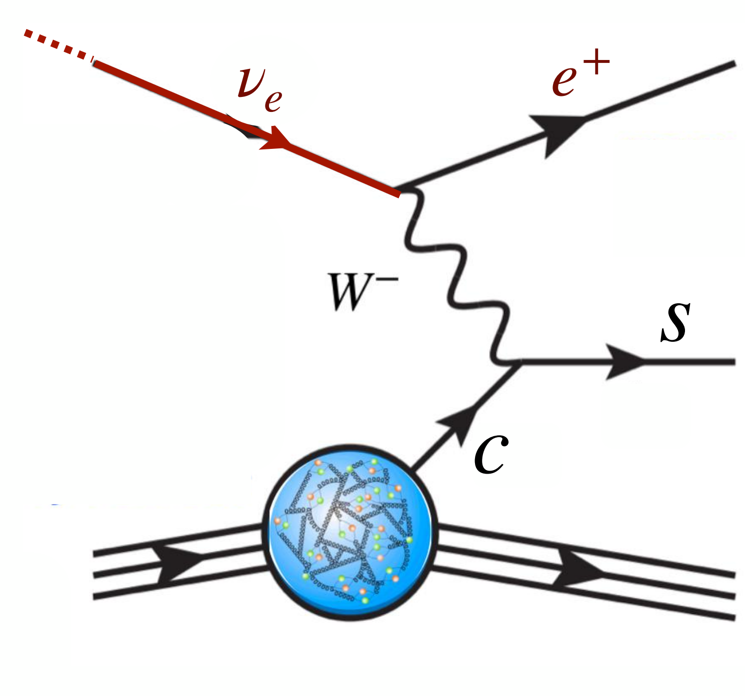


- Sensitivity to the charm PDF via the **gluon-charm initial state ....**



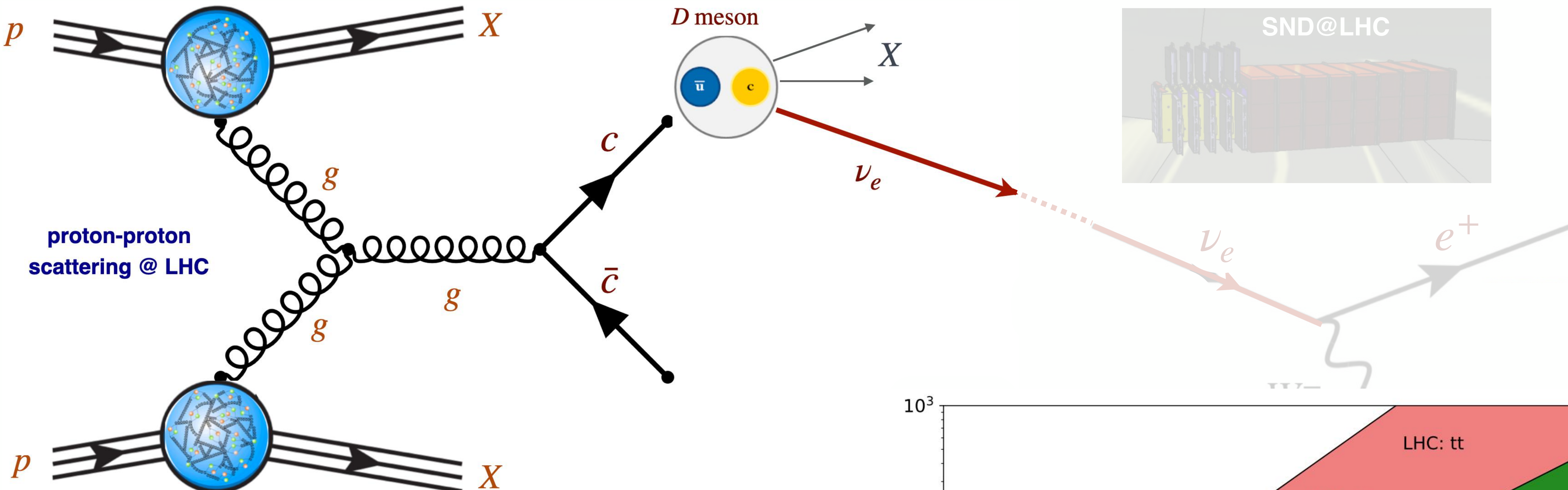


- …as well as via **neutrino scattering off charm quarks** in the target



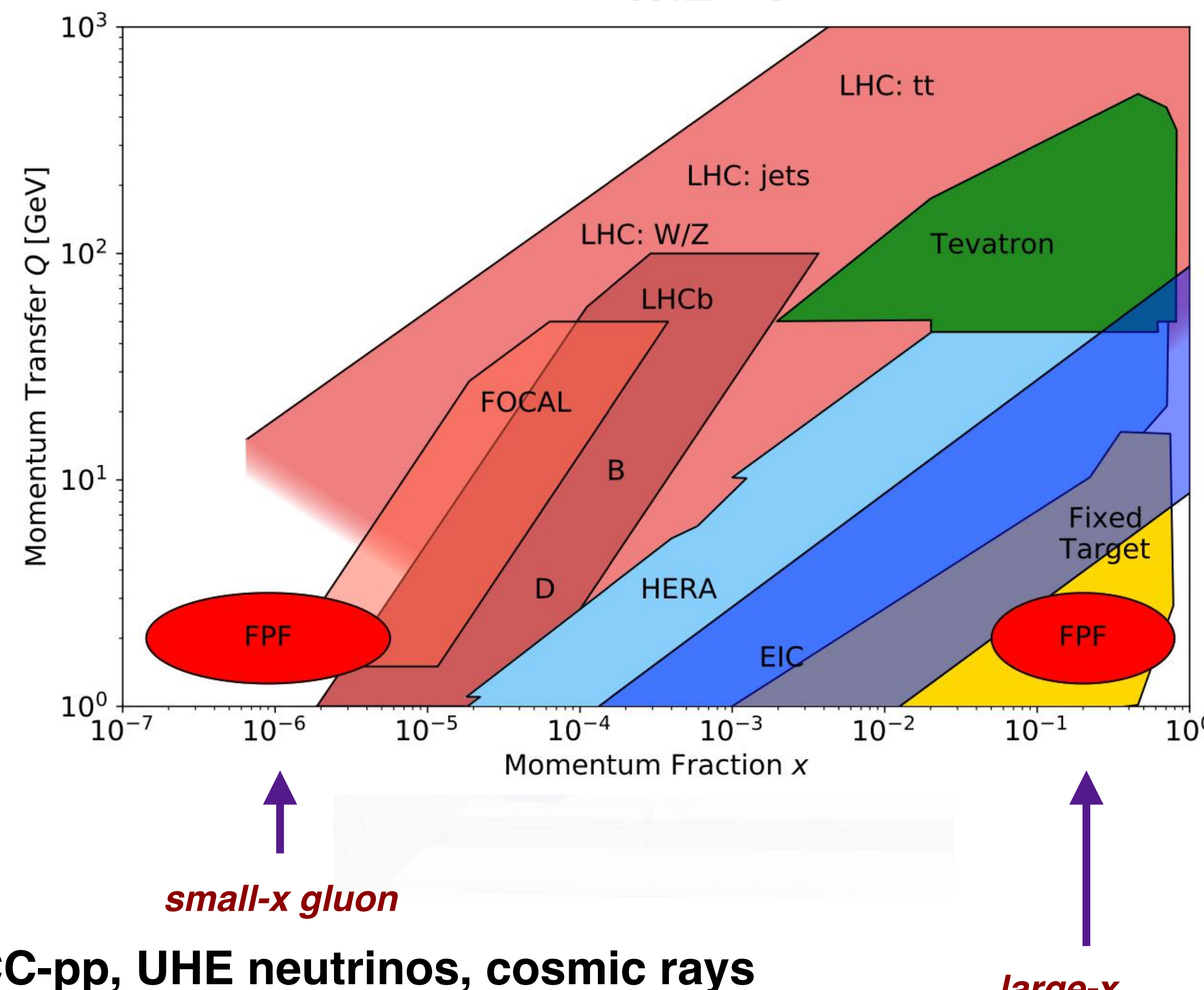
Probing Ultra-Small-x QCD

LHC neutrinos and small-x QCD



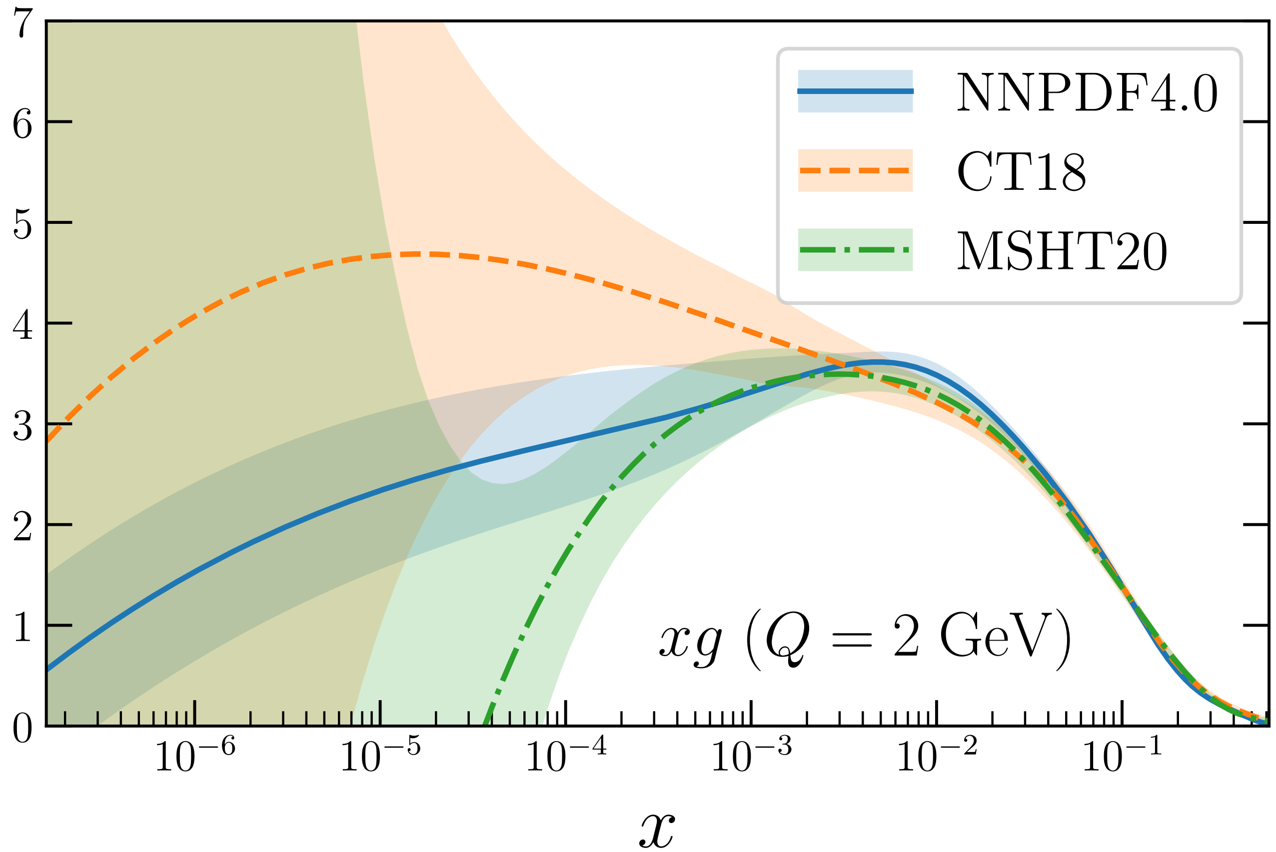
QCD in Neutrino Production

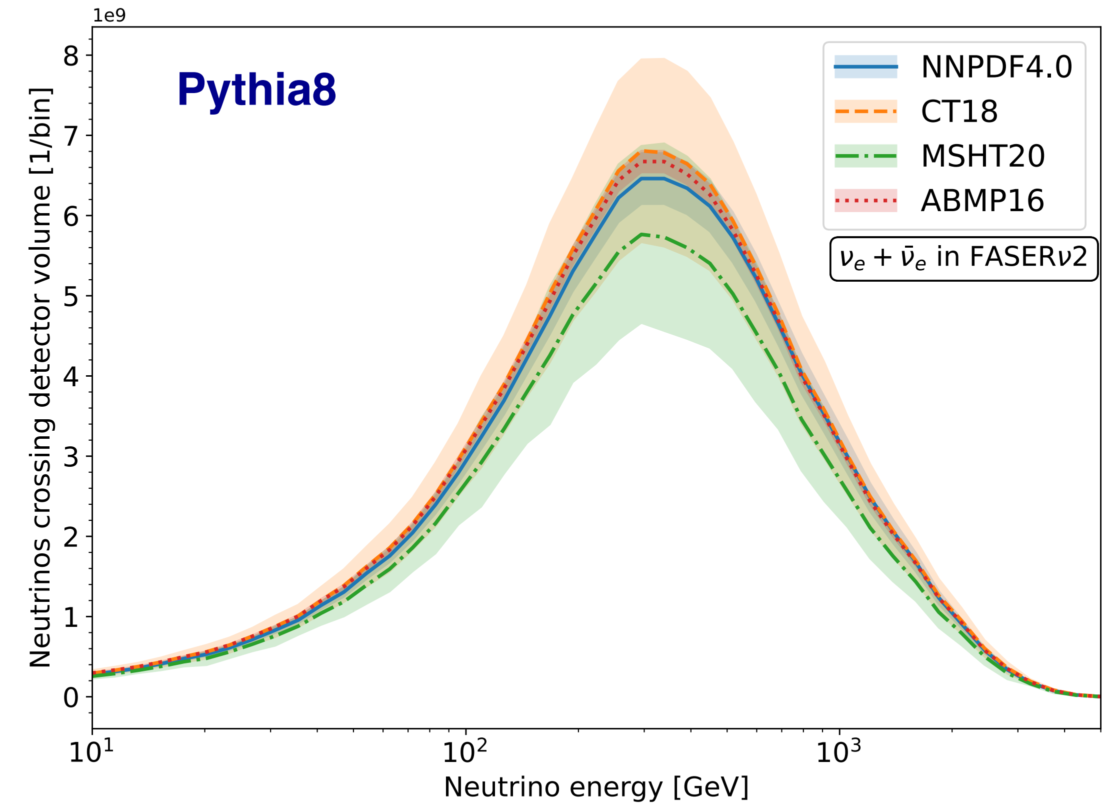
- Small-x gluon & large-x charm PDFs
- BFKL, non-linear QCD, cross-sections for UHE neutrinos
- *D*-meson fragmentation
- Forward light hadron production & cosmic ray modelling



Relevant for **FCC-pp, UHE neutrinos, cosmic rays**

LHC neutrinos and small-x QCD





- Spread of PDF predictions (e.g. small-x gluon) modifies **predicted fluxes up to factor 2**
- Focus on electron and tau neutrinos, with the largest **contribution from charm production** where QCD factorisation can be applied
- Construct **tailored observables** where QCD uncertainties (partially) cancel out

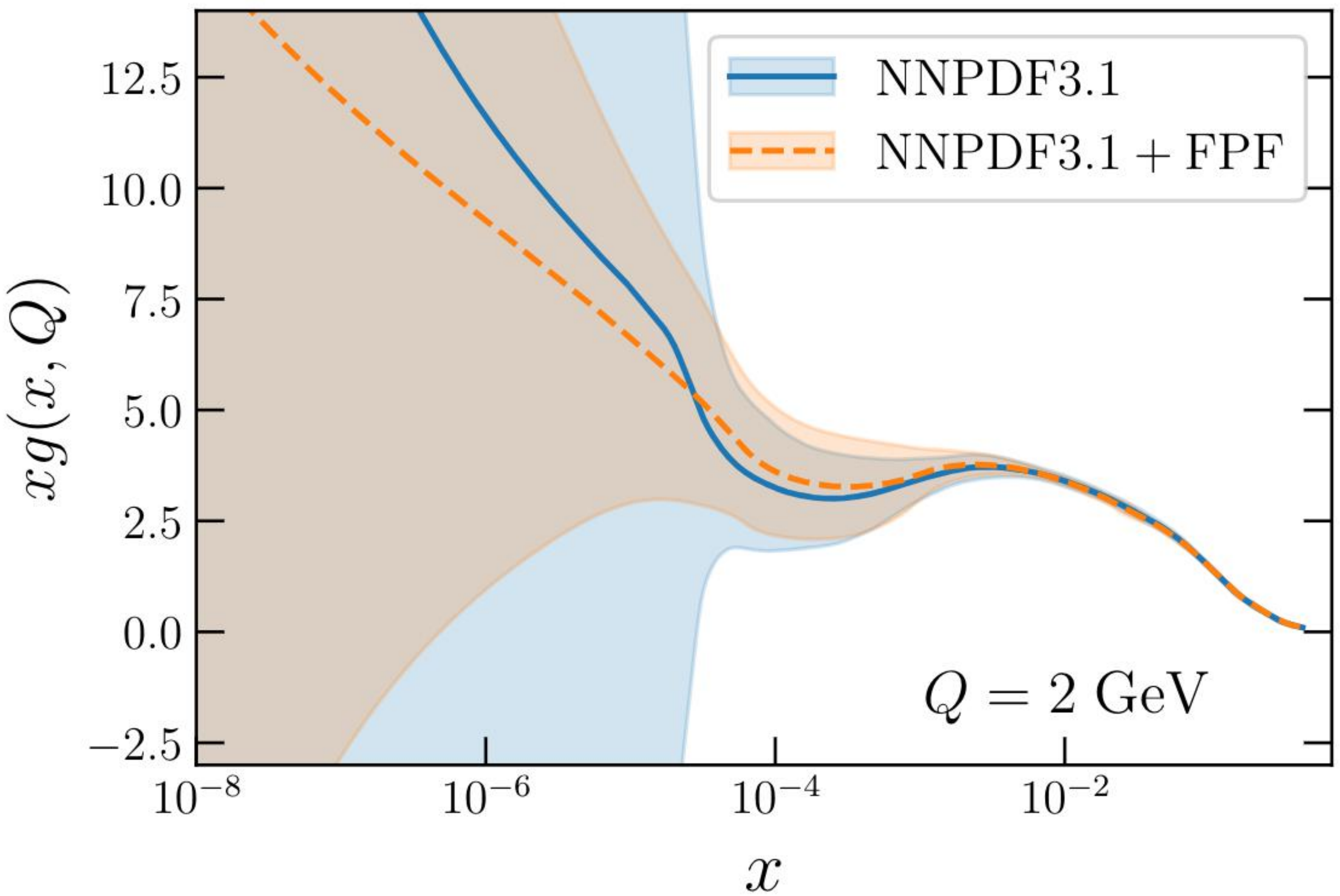
$$R_{\tau/e}(E_\nu) \equiv \frac{N(\nu_\tau + \bar{\nu}_\tau; E_\nu)}{N(\nu_e + \bar{\nu}_e; E_\nu)}, \qquad R^{\nu_e}_{\rm exp}(E_\nu) = \frac{N_{\rm FASER\nu}(\nu_e + \bar{\nu}_e E_\nu)}{N_{\rm SND@LHC}(\nu_e + \bar{\nu}_e; E_\nu)}$$

Retain PDF sensitivity while reducing the large QCD uncertainties in the theory prediction

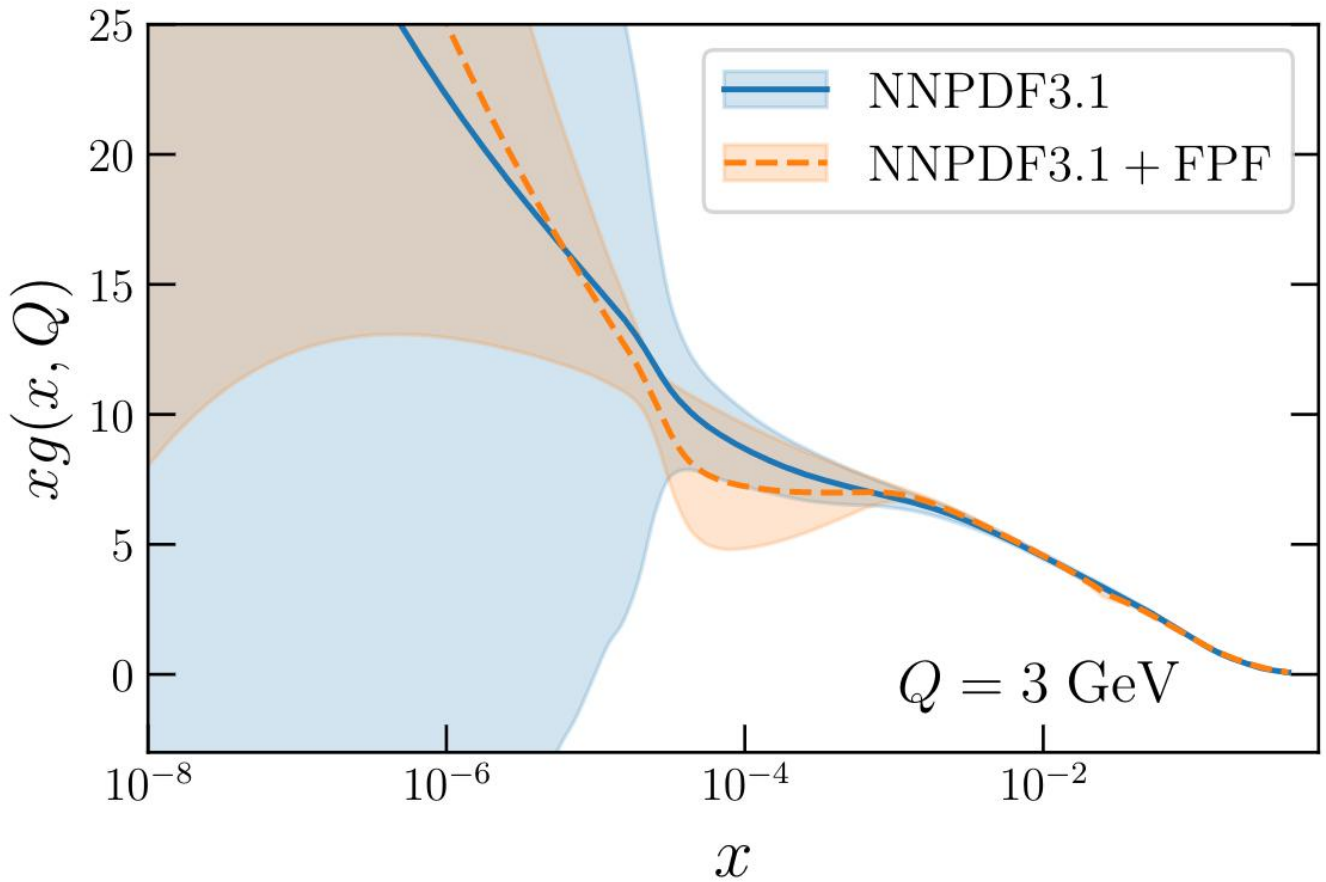
Proxy for 2D xsec differential in (energy, rapidity)

LHC neutrinos and small-x QCD

Electron neutrinos, 2% uncertainty in inclusive event rates



Tau neutrinos, 2% uncertainty in inclusive event rates

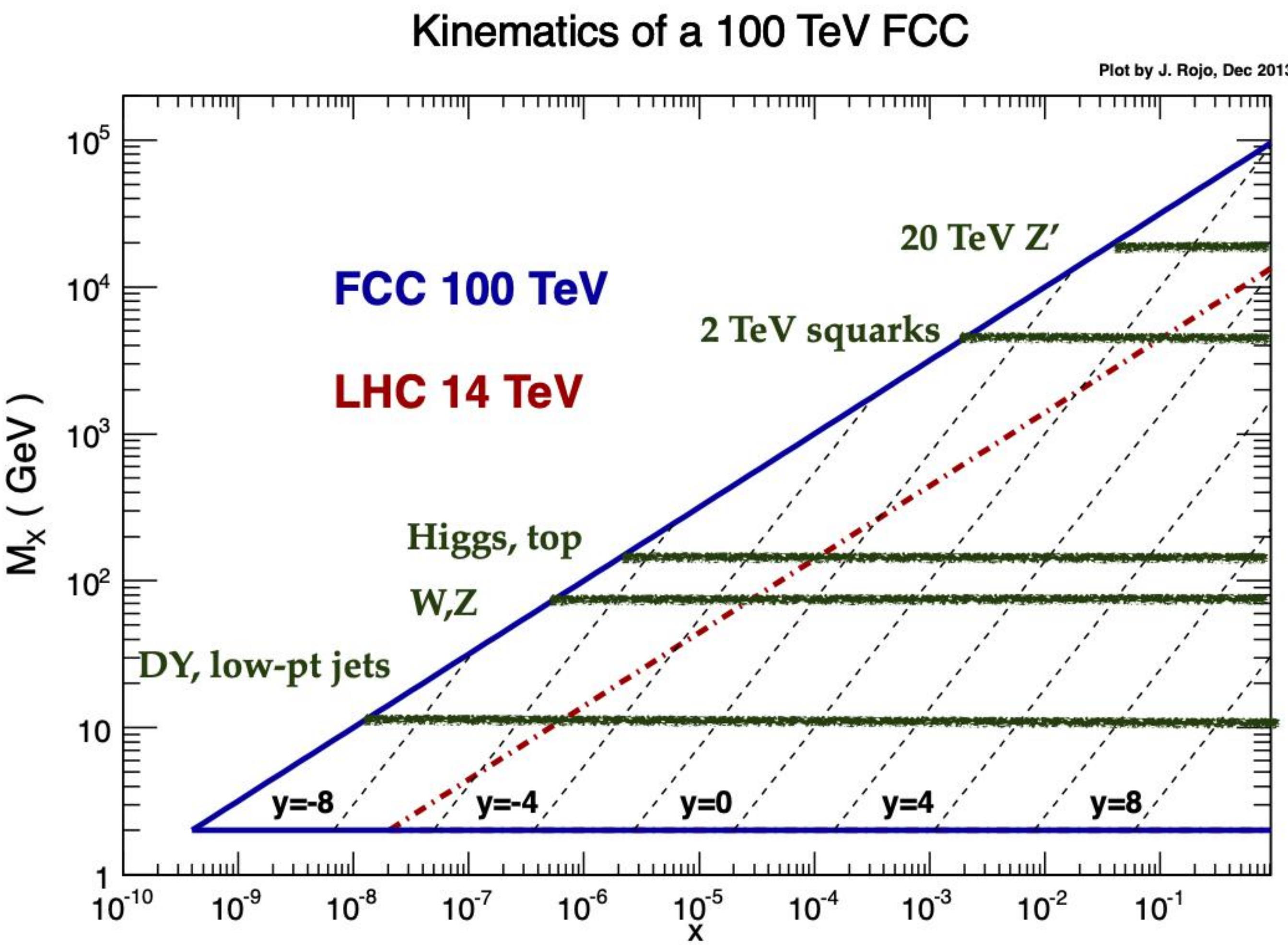


$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$

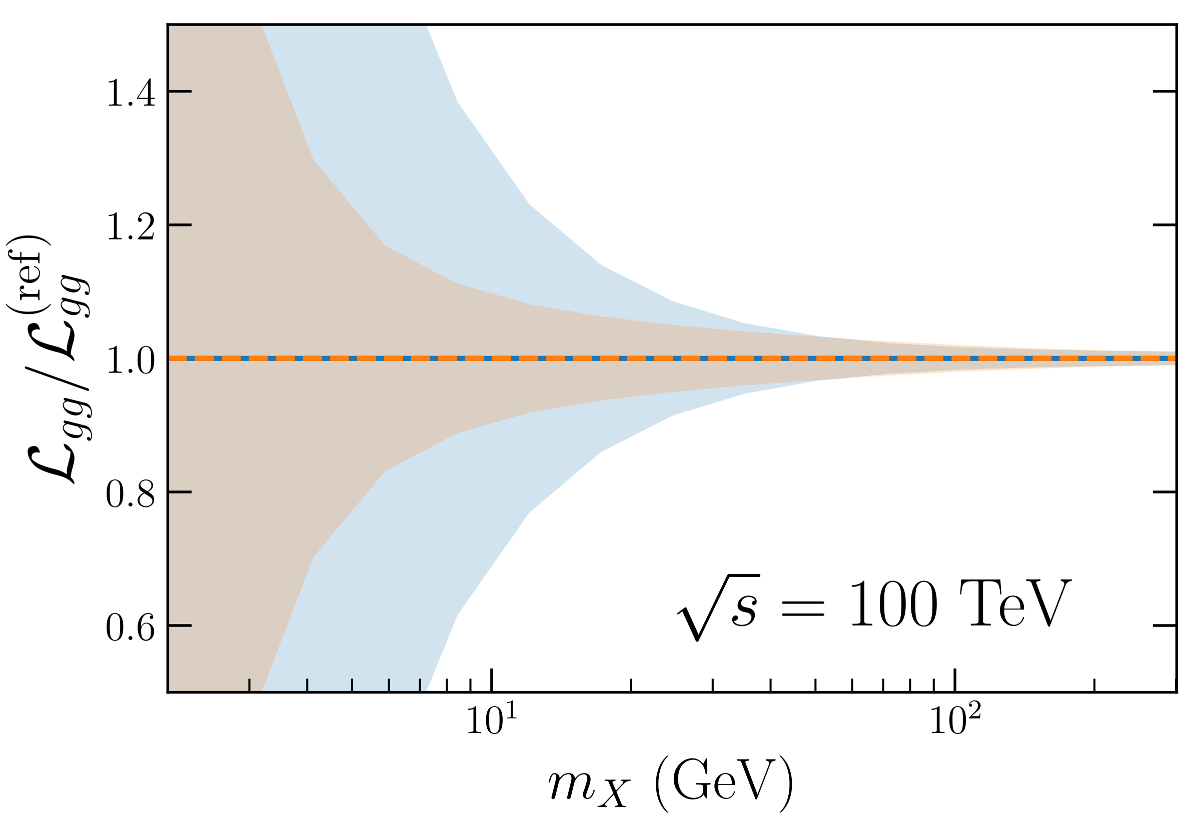
$$R_y^{(\tau)} \equiv \frac{N_{\nu_\tau}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_\tau}(E_\nu, 8.5 < y_\nu < 9.0)}$$

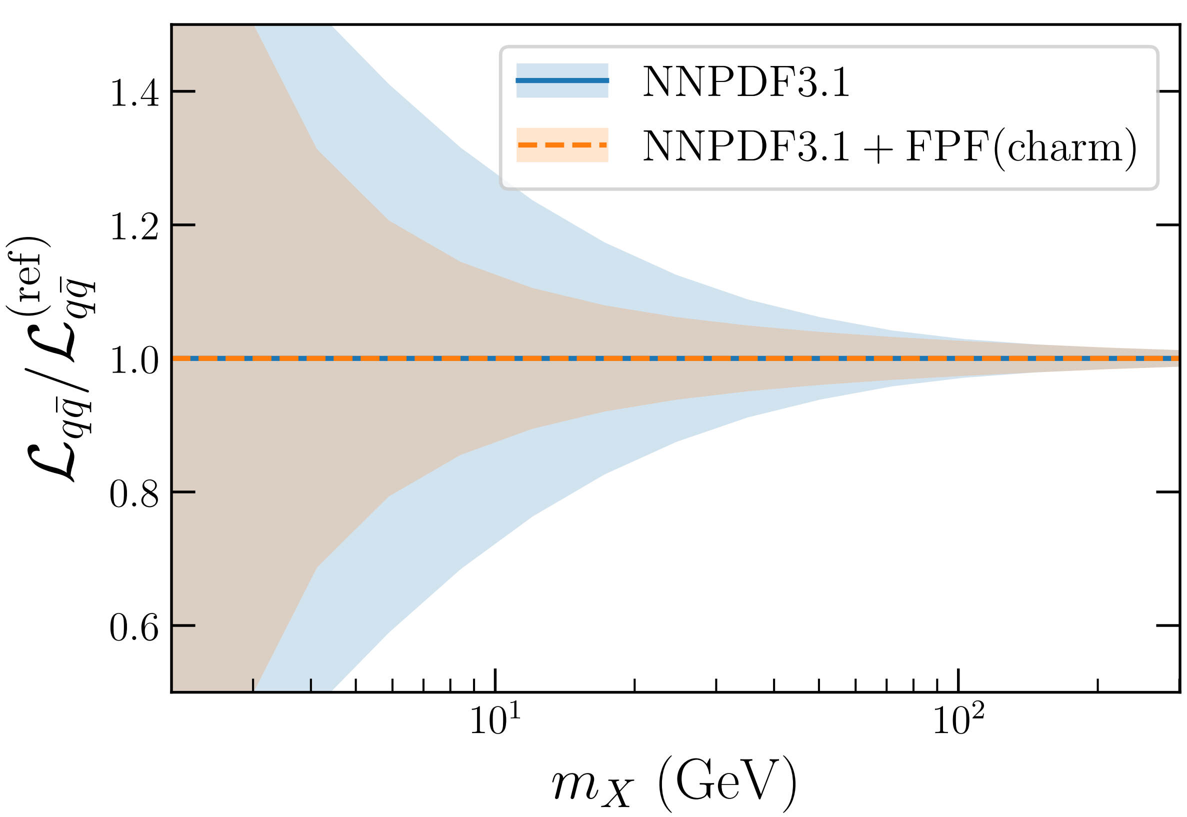
- Sensitivity to **small-x gluon** outside coverage of any other (laboratory) experiment
- These initial projections are now being extended to full-fledged simulations with state-of-the-art QCD
- Quantify impact for **UHE neutrinos** and for cross-sections at a 100 TeV proton collider

Implications for FCC-pp



- FCC-pp would be a **small-*x* machine,** even Higgs and EWK sensitive to small-*x* QCD
- LHC neutrinos: laboratory to test **small-x QCD** for dedicated FCC-pp physics and simulations
- Current projections show a marked PDF error reduction on **FCC-pp cross-sections** thanks to constraints from LHC neutrinos

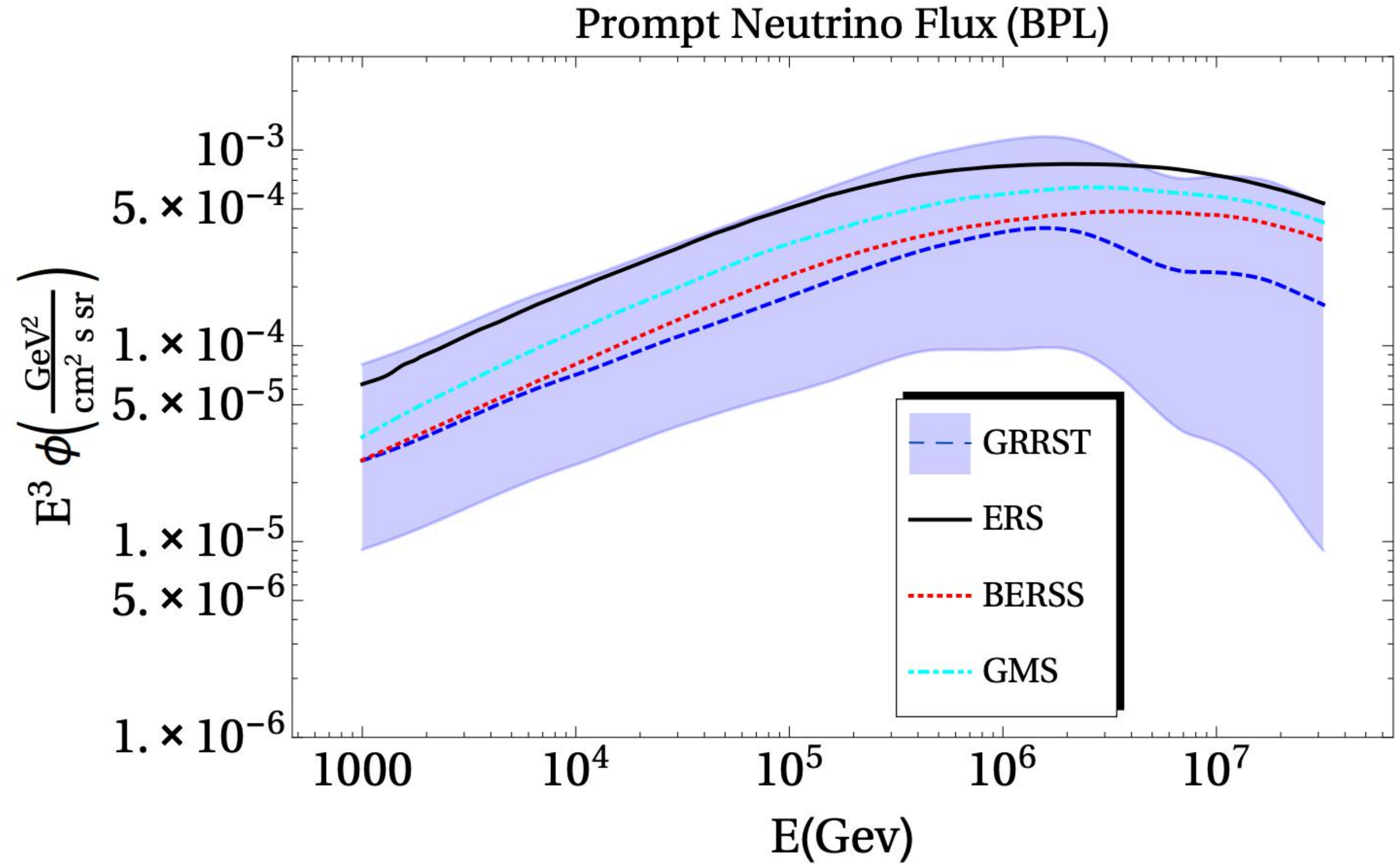


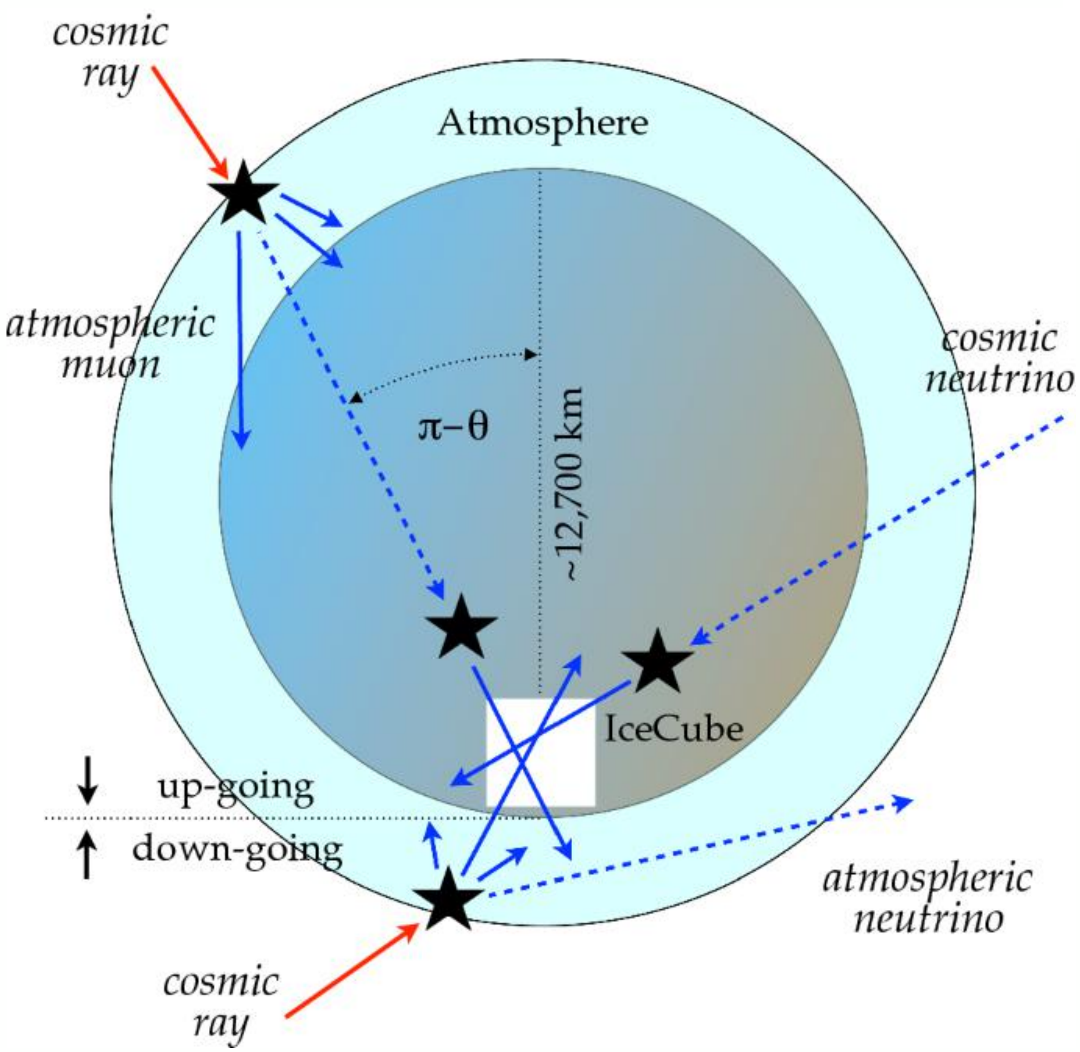


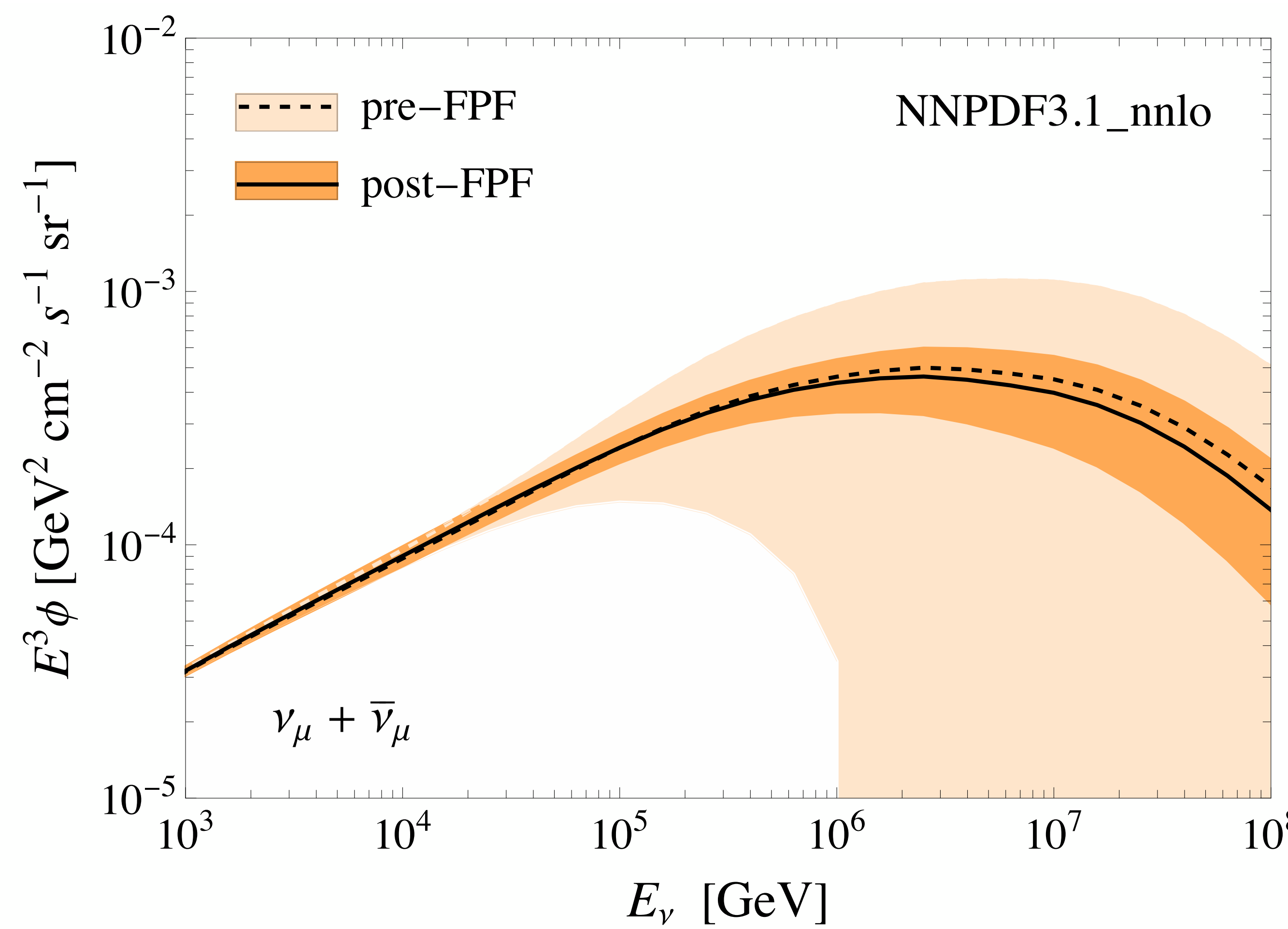
Implications for Neutrino Telescopes

- Prompt fluxes from charm are main backgrounds for UHE cosmic neutrinos

- FPF can provide a **precise lab-based calibration** of these prompt fluxes





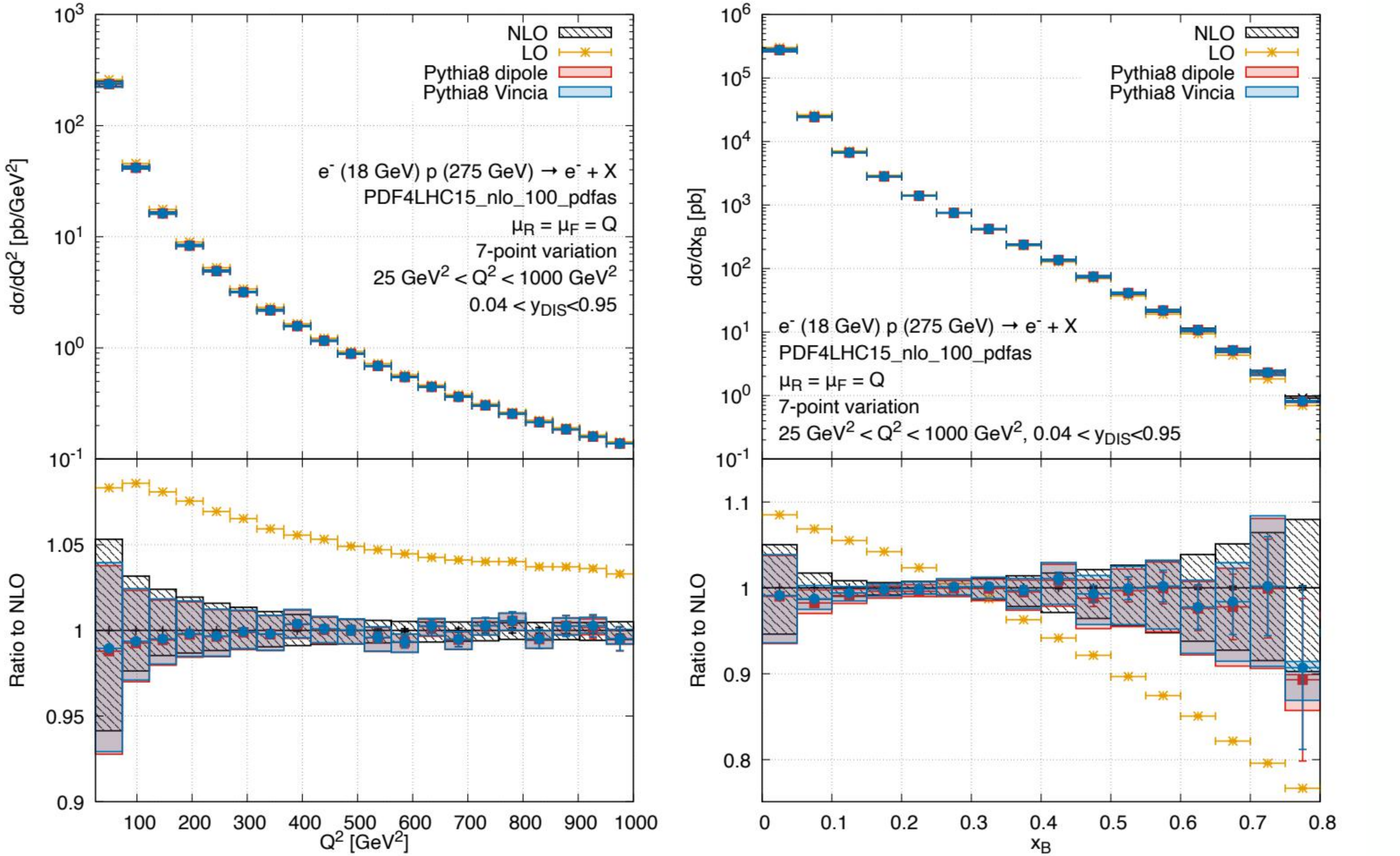


NLO QCD Predictions for Particle-Level Distributions in Neutrino-Ion Scattering

Van Beekveld, Ferrario Ravasio, Groenendijk, Krack**, JR,**
Shutze Sanchez, **arXiv:2409.02163 (EPJC)**

POWHEG for LHC neutrinos

A Monte Carlo generator with **NLO+PS accuracy** for lepton-proton scattering



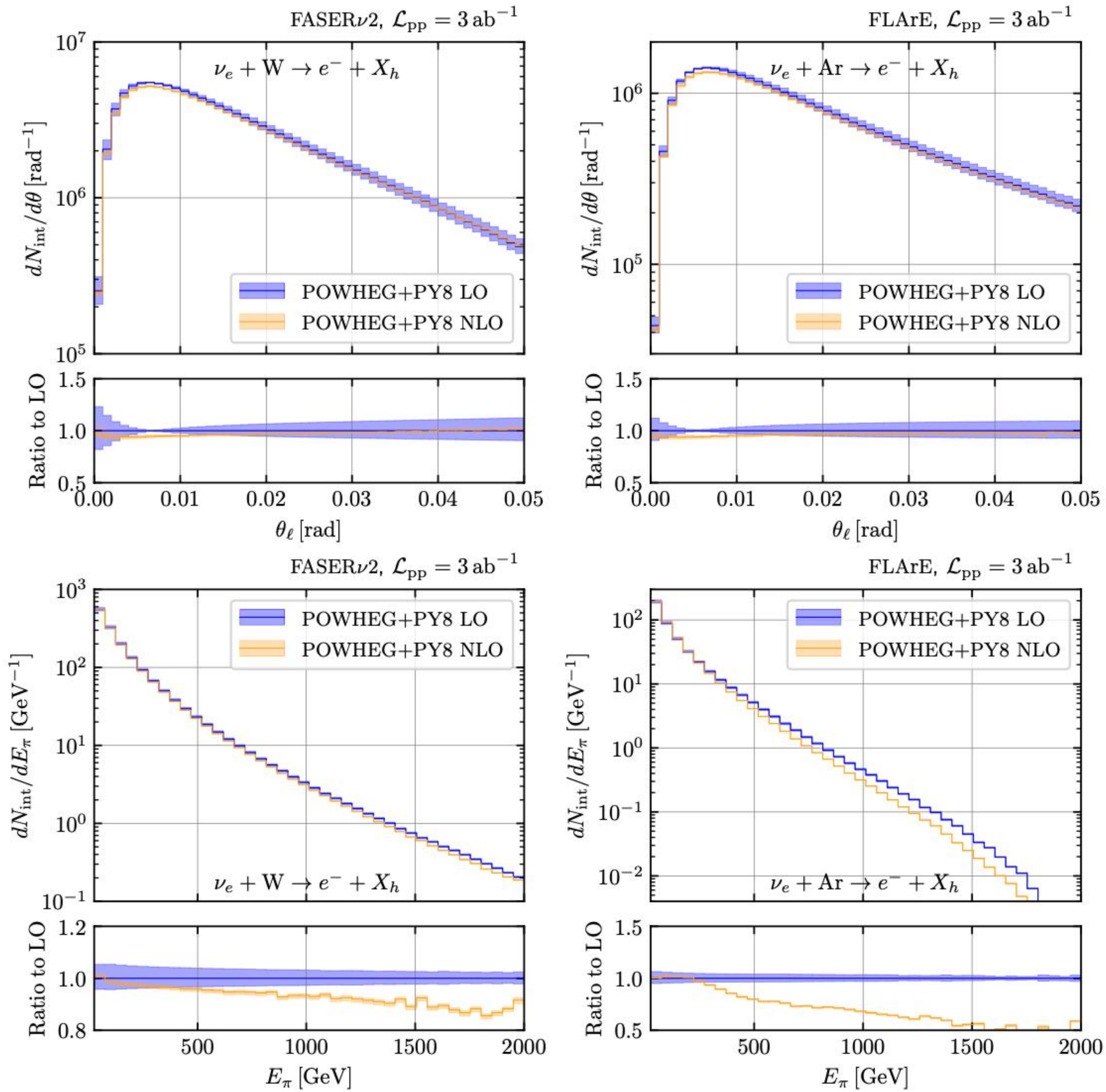
Banfi, Ferrario Ravasio, Jäger, Karlberg, Reichenbach, Zanderighi, arXiv:2309.02127 (charged lepton DIS)

Ferrario Ravasio, Gauld, Jager, Karlberg, Zanderighi, arXiv:2407.03894 (neutrino DIS, fixed energy)

See also alternative POWHEG implementation, including mass effects, from Buonocore, Limatola, Nason, Tramontano, arXiv:2406.05115

POWHEG for LHC neutrinos

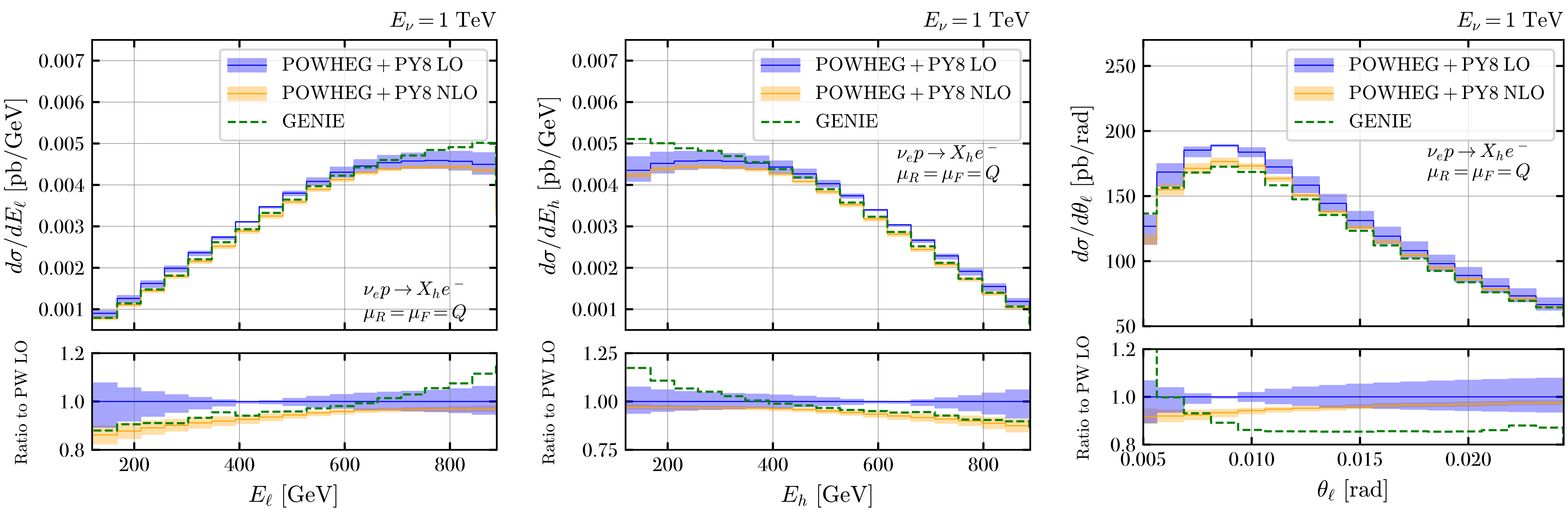
- Implement LHC neutrino fluxes via neutrino PDFs *a la* LHAPDF
- Ensure selection and acceptance cuts match those of the LHC far-forward experiments
- Gauge impact of **NLO QCD corrections, shower algorithm, hadronization, and QED effects** on final-state distributions



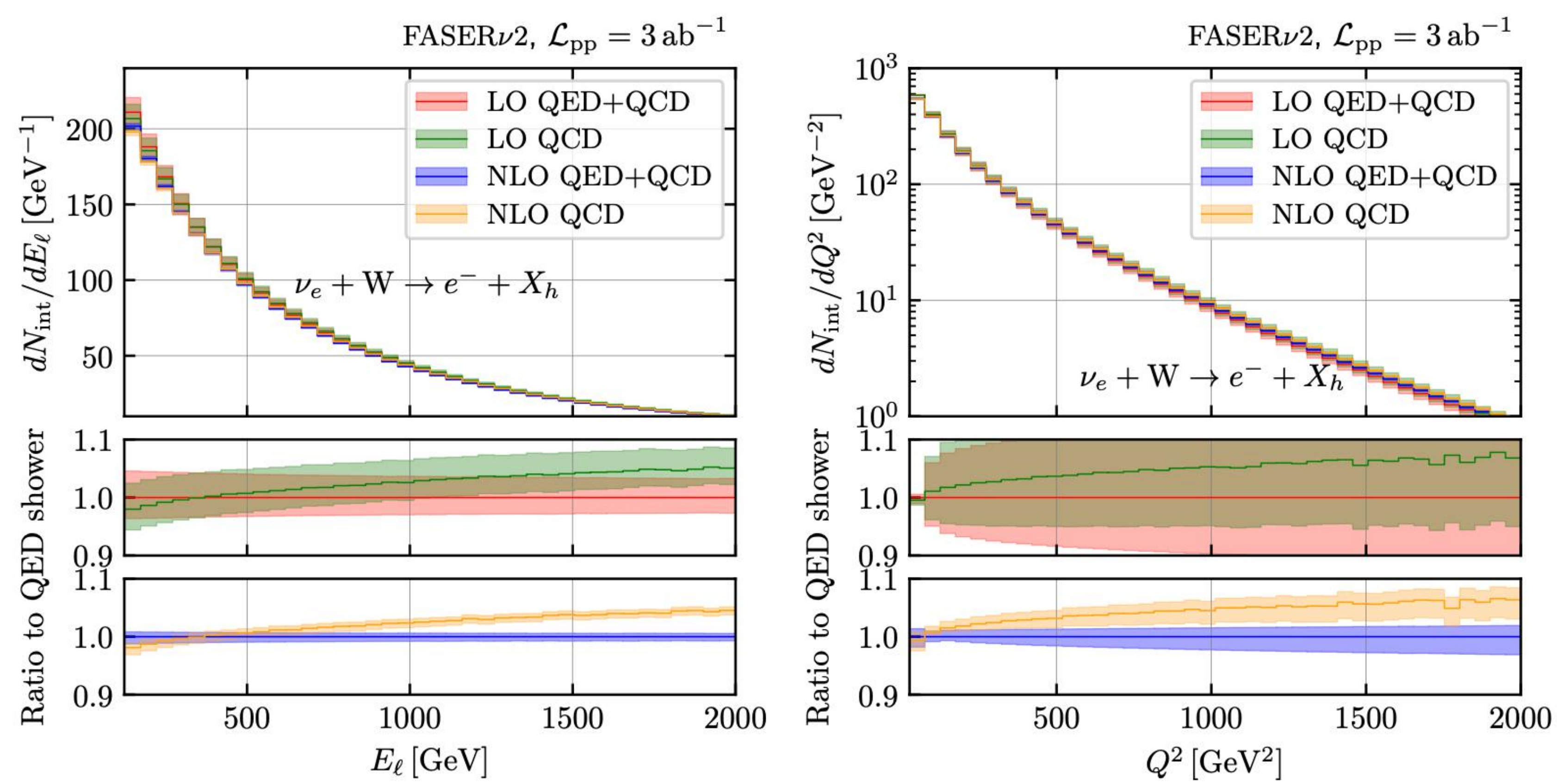
Van Beekveld, Ferrario Ravasio, Groenendijk, Krack**, JR,** Shutze Sanchez, **arXiv:2409.02163 (EPJC)**

POWHEG for LHC neutrinos

Comparison with the GENIE predictions



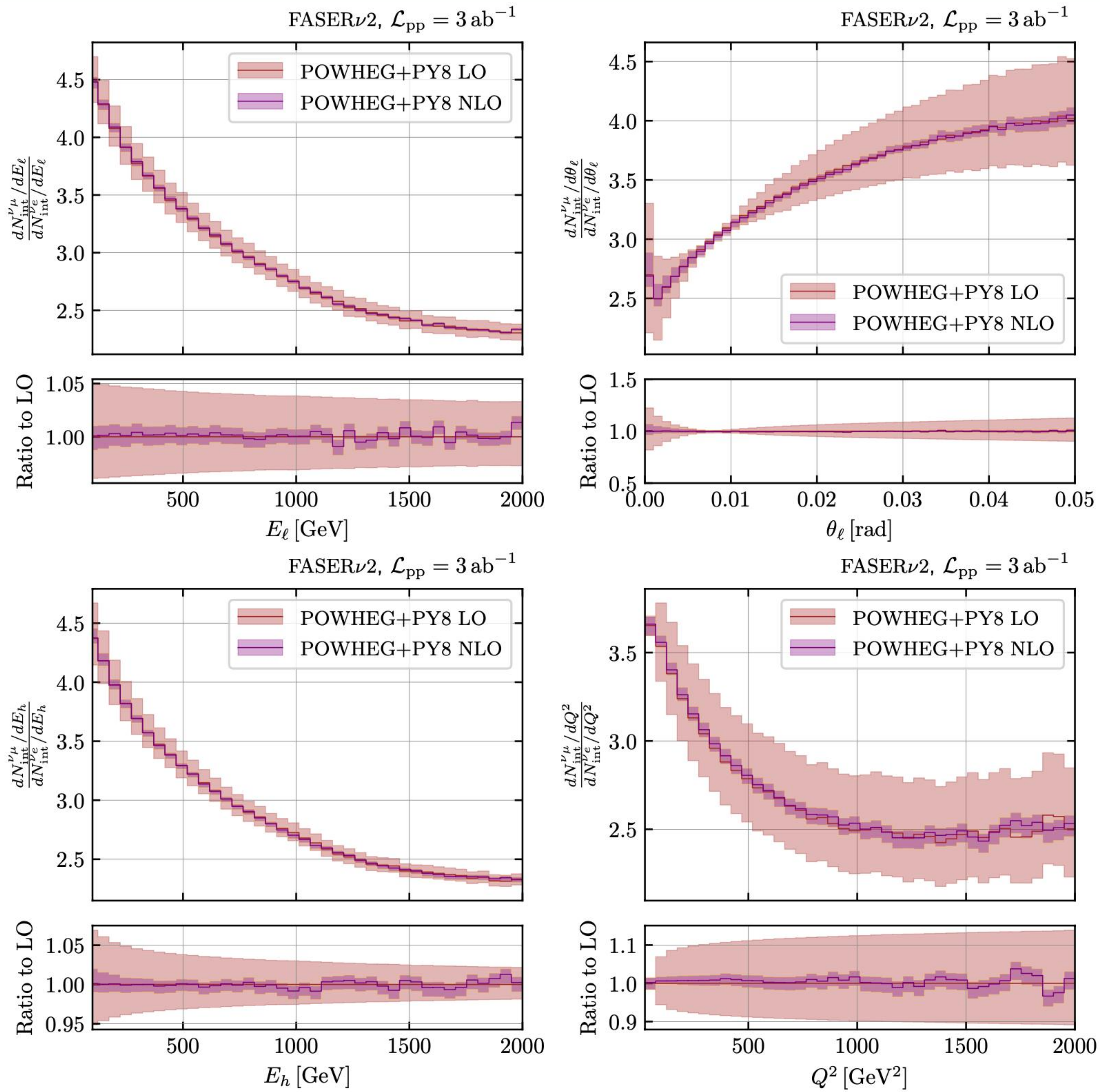
- Differences with GENIE due to matrix element, shower algorithm, hadronization, PDFs
- **QED shower effects** not negligible for electron neutrinos



POWHEG for LHC neutrinos

- Ratios between **muon and electron neutrinos** in differential distributions

- Can be **predicted very precisely** due to cancellation of theory errors, interesting for experimental analyses?

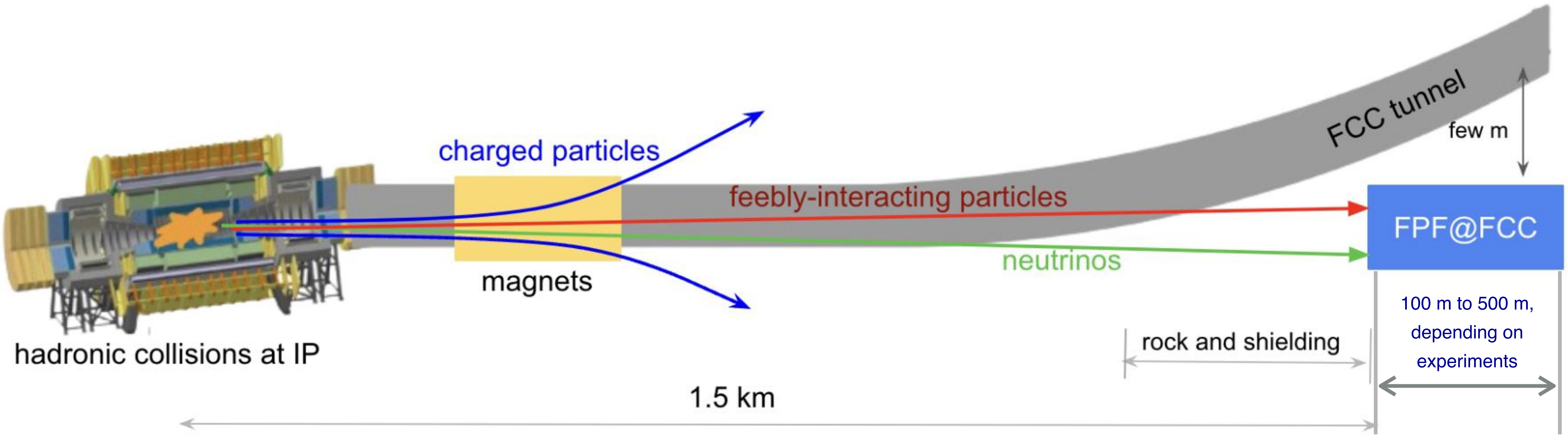


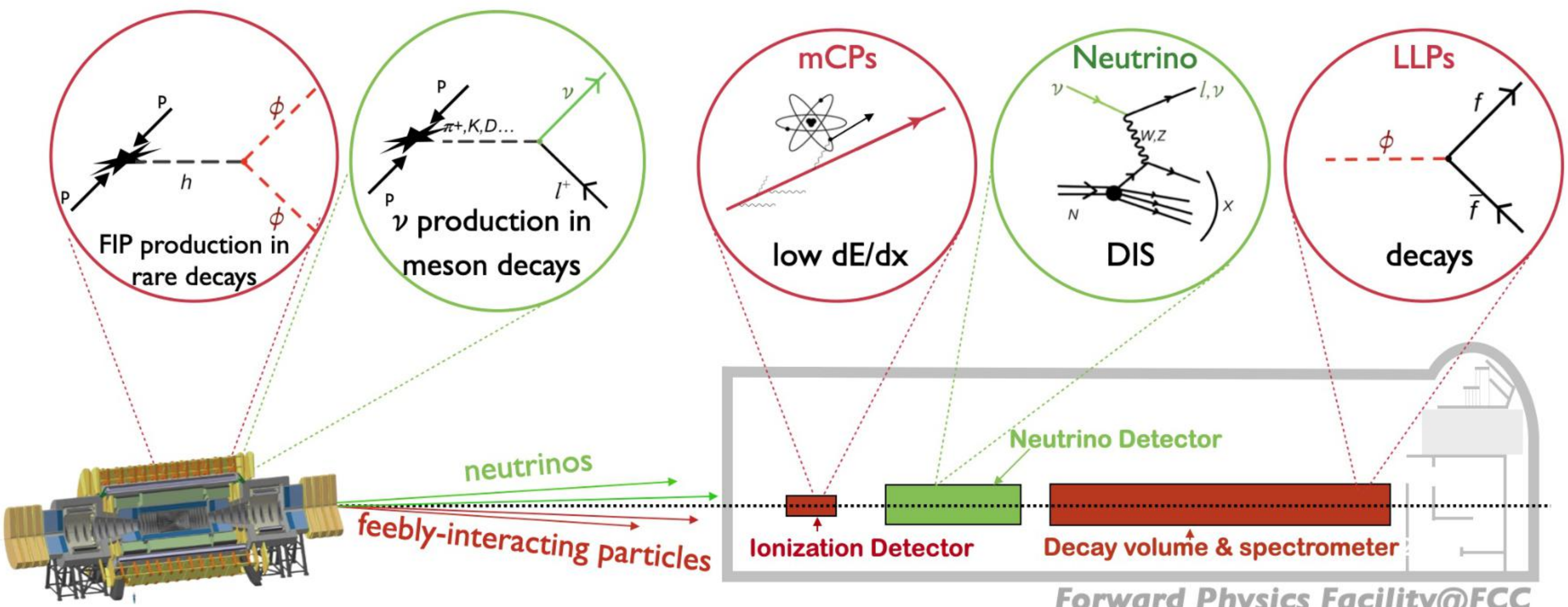
QCD, Neutrino, and BSM Physics Opportunities with Far-Forward Experiments at a 100 TeV Proton Collider

Roshan Abraham, Jyotismita Adhikary, Jonathan Feng, Max Fieg, Felix Kling, Jinmian Li, Junle Pei, Tanjona Rabemananjara, Juan Rojo, and Sebastian Trojanowski**, arXiv:2409.02163**

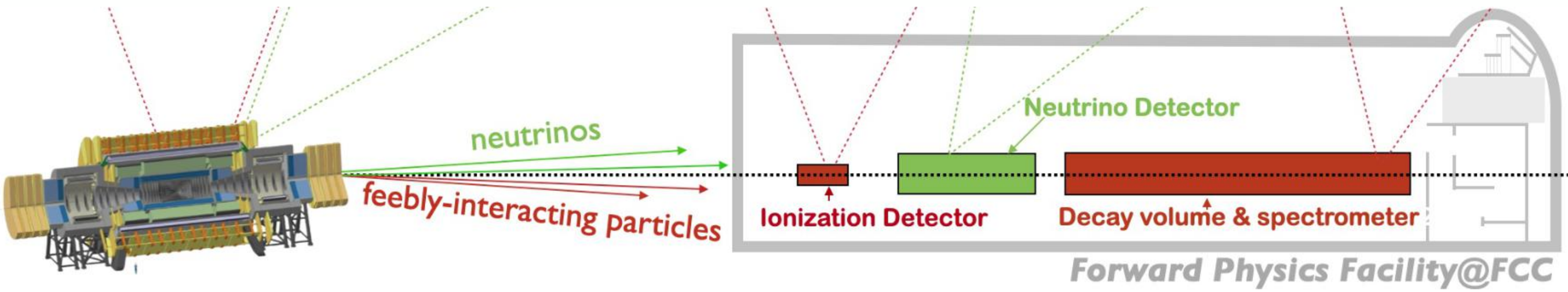
FPF@FCC

Facility to **detect neutrinos and BSM particles** produced at the FCC-hh in the **forward direction**





Detectors



Neutrino detectors

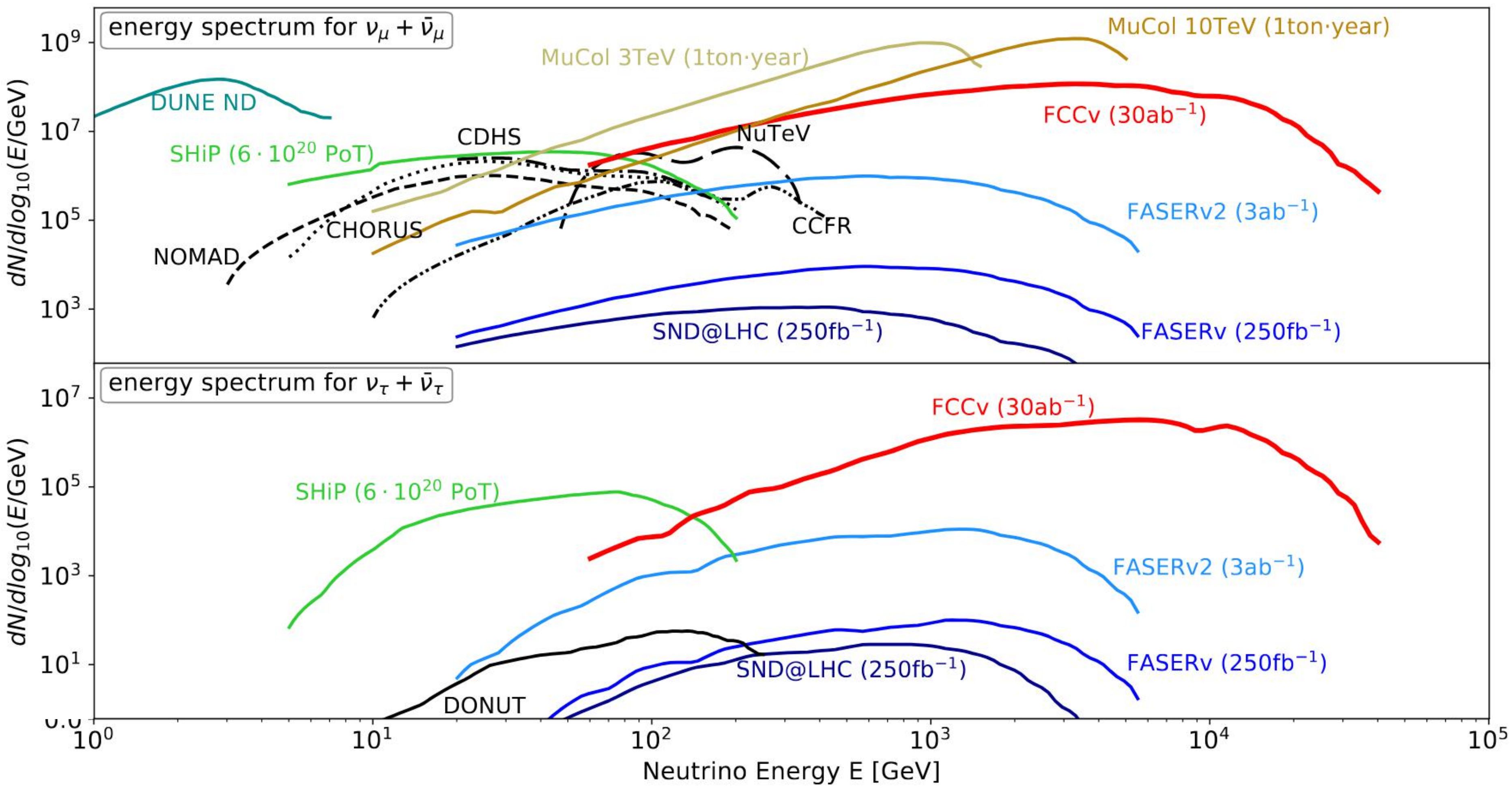
Detector	Geometry	Rapidity	$\mathcal{L}_{pp}$	$\sqrt{s}$	Acceptance
FASERν	20 cm × 25 cm × 80 cm	$\eta_\nu \geq 8.5$	250 fb^{-1}	13.6 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.025$
FASERν2	40 cm × 40 cm × 6.6 m	$\eta_\nu \geq 8.4$	3 ab^{-1}	14 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$
FCCν	40 cm × 40 cm × 6.6 m	$\eta_\nu \geq 9.2$	30 ab^{-1}	100 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$
FCCν(d)	40 cm × 40 cm × 66 m	$\eta_\nu \geq 9.2$	30 ab^{-1}	100 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$
FCCν(w)	1.25 m × 1.25 m × 6.6 m	$\eta_\nu \geq 8.1$	30 ab^{-1}	100 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$

Decay volume & spectrometer (targeting BSM)

Detector	Geometry	$\mathcal{L}_{pp}$	$\sqrt{s}$	Acceptance
FASER	$\pi(10\text{ cm})^2 \times 1.5$ m	150 fb^{-1}	14 TeV	$E_{\text{vis}} \gtrsim 100$ GeV
FASER2	$\pi(1\text{ m})^2 \times 5$ m	3 ab^{-1}	14 TeV	$E_{\text{vis}} \gtrsim 100$ GeV
FCC-LLP1	5 m × 5 m × 50 m	30 ab^{-1}	100 TeV	$E_{\text{vis}} \gtrsim 100$ GeV
FCC-LLP2	20 m × 20 m × 400 m	30 ab^{-1}	100 TeV	$E_{\text{vis}} \gtrsim 100$ GeV

- Ambitious detector concepts, **technology-agnostic**
- **FASERν2 as baseline**
- Consider also a **polarised detector** for neutrino DIS
- Costing of FPF@LHC is **O(CHF50M) for facility + O(CHF30M) for experiments**

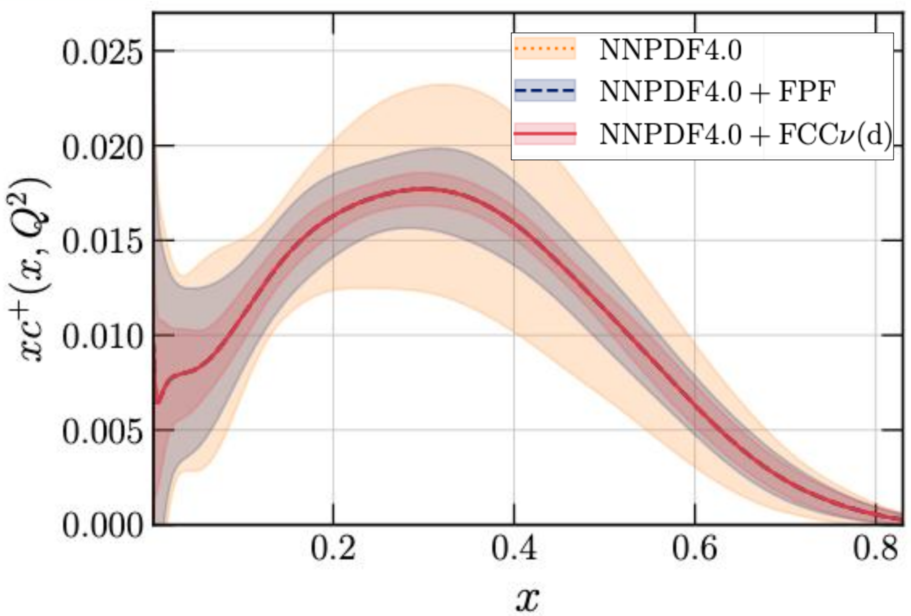
Neutrino Fluxes

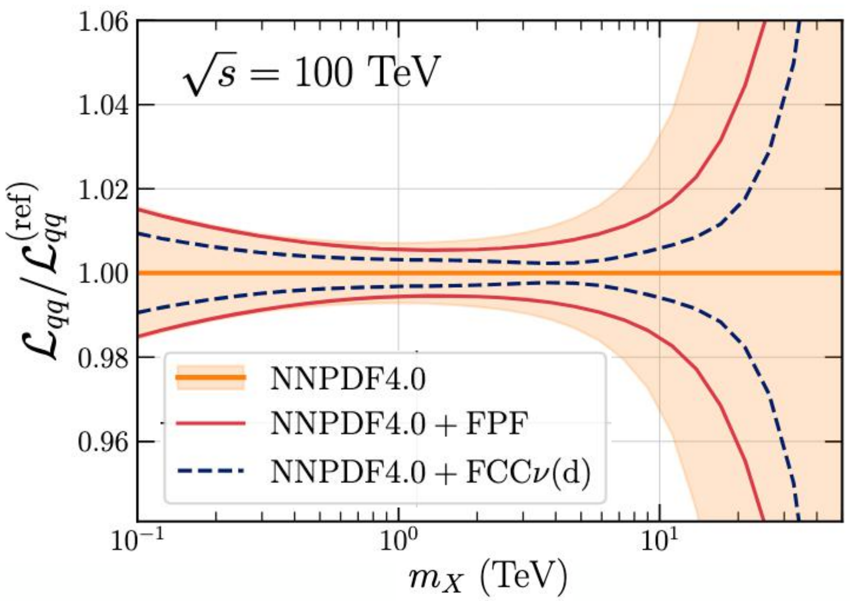


Detector	$N_{\nu_e} + N_{\bar{\nu}_e}$	$N_{\nu_\mu} + N_{\bar{\nu}_\mu}$	$N_{\nu_\tau} + N_{\bar{\nu}_\tau}$
FASERν	2.1k	11k	36
FASERν2	220k	1.1M	4.3k
FCCν	62M	130M	3.2M
FCCν(d)	620M	1.3B	32M
FCCν(w)	170M	370M	11M

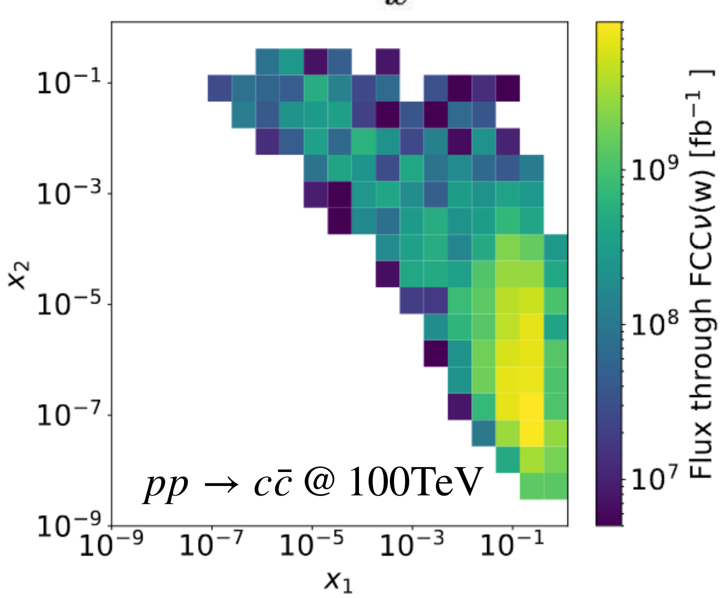
- Enormous neutrino fluxes with energies **reaching 40 TeV**
- Up to **10^9 electron & muon neutrinos**, **10^4 tau neutrinos**
- Sizeable event samples also for **neutrinos from p+Pb collisions**
- Extend FCC-hh physics program with a rich portfolio of **neutrino science**
- Most energetic neutrinos that would be ever produced in lab experiments, **overlap with cosmic neutrinos**

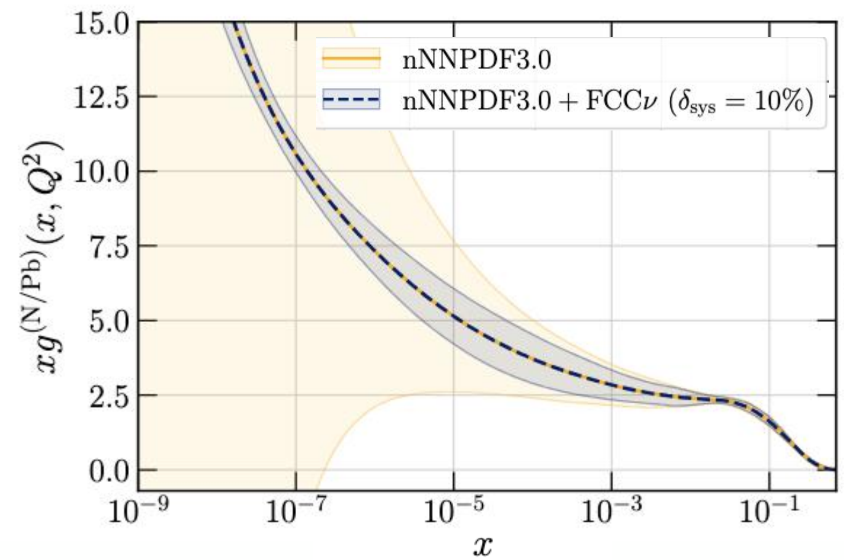
QCD studies



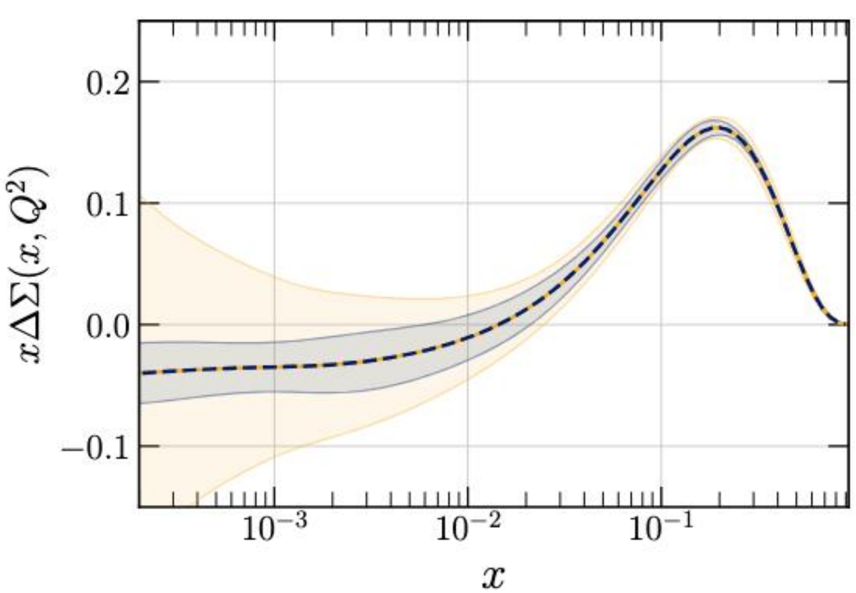


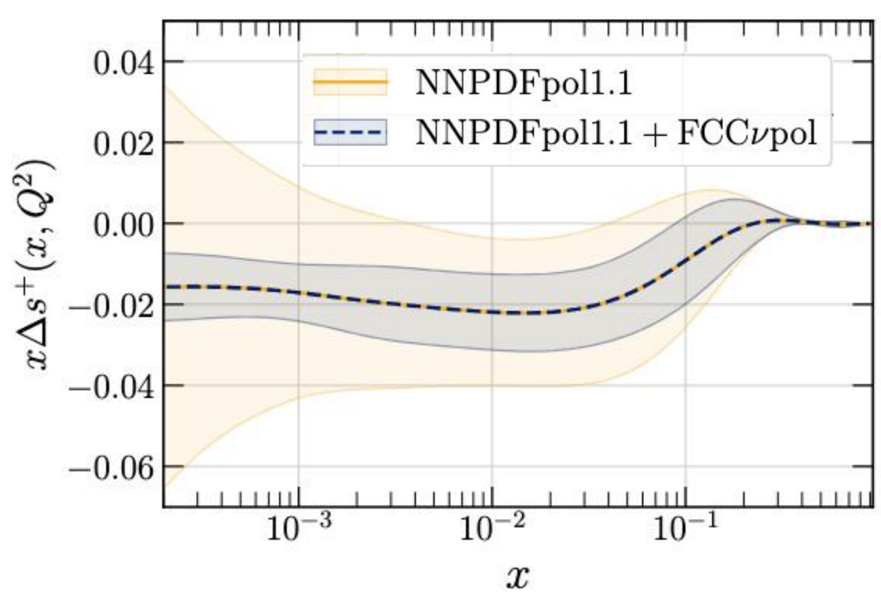
- Neutrino DIS with **< 0.1% statistical uncertainties**
- Stringent constraints in large-x PDFs, relevant for **searches in the $m_X > 10$ TeV region**





- Constrain **nuclear PDFs down to** $x \sim 10^{-9}$ via $\mathrm{p} + \mathrm{Pb} \to c + \bar{c} + X$
- Up to **10^5 events for charm production** (in hard scattering) in p+Pb at $\sqrt{s_{\mathrm{NN}}} = 63$ TeV

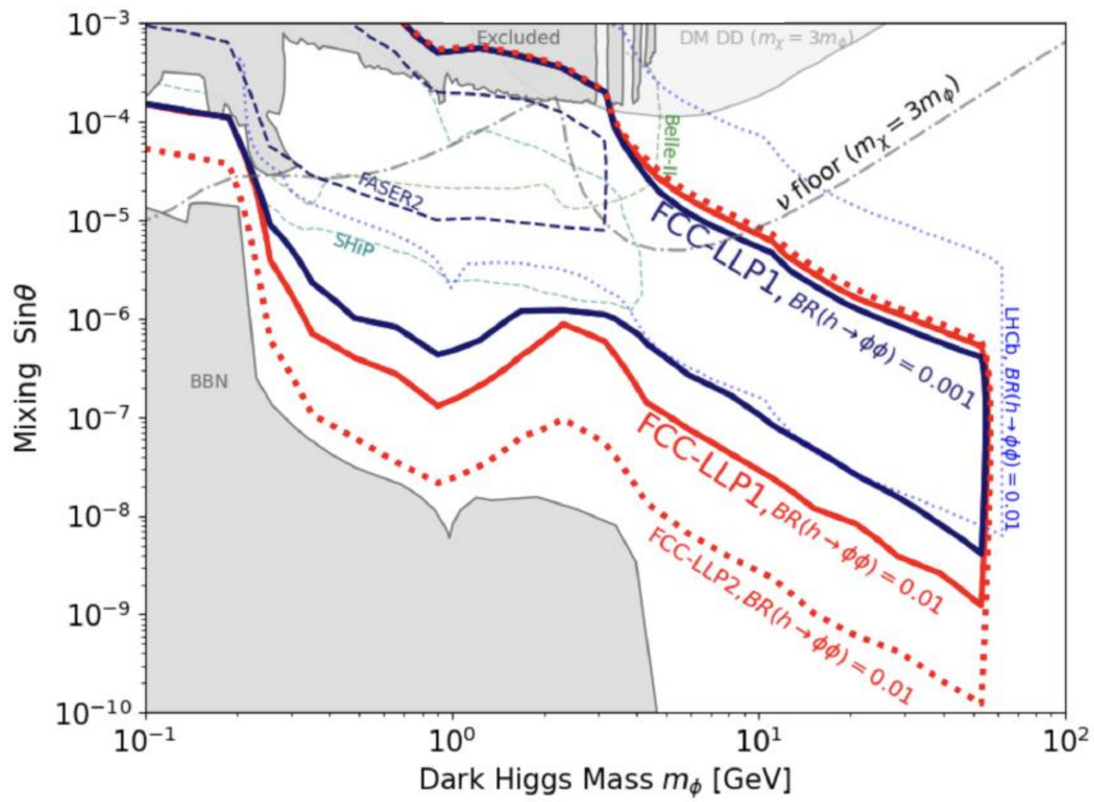




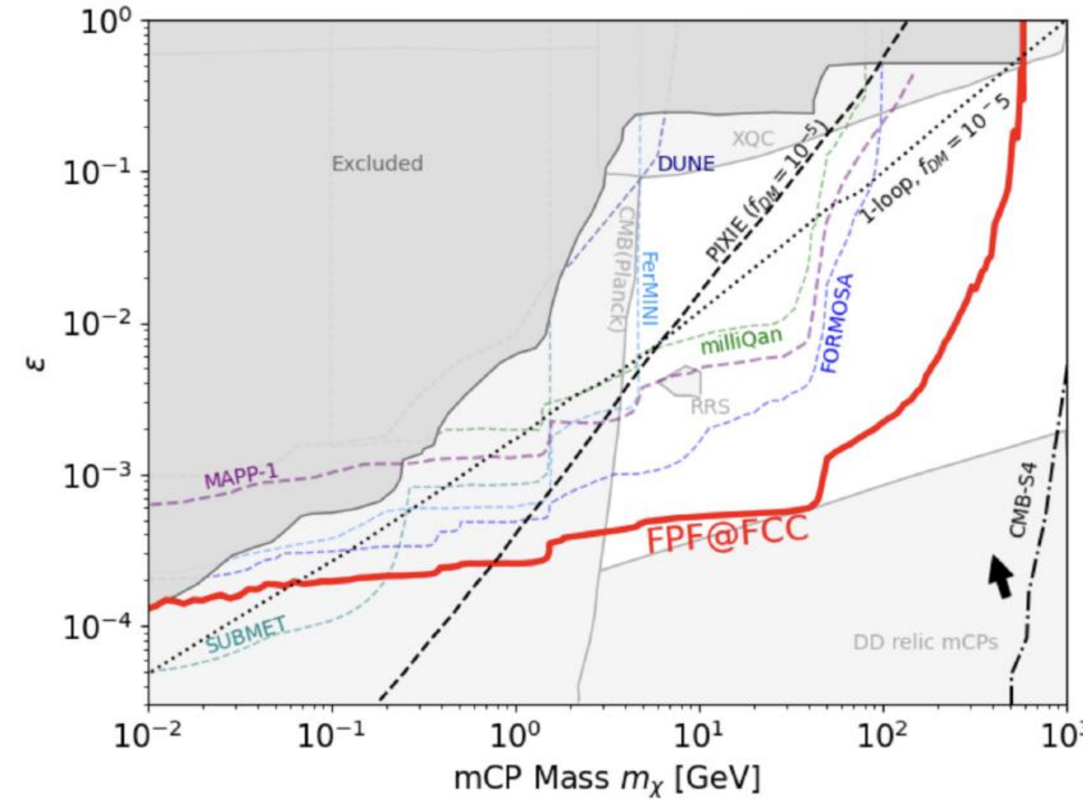
- First-ever neutrino DIS on polarised targets: pin down **proton spin decomposition**
- Up to **10^6 events** for COMPASS-like detector with FASERν2 geometry

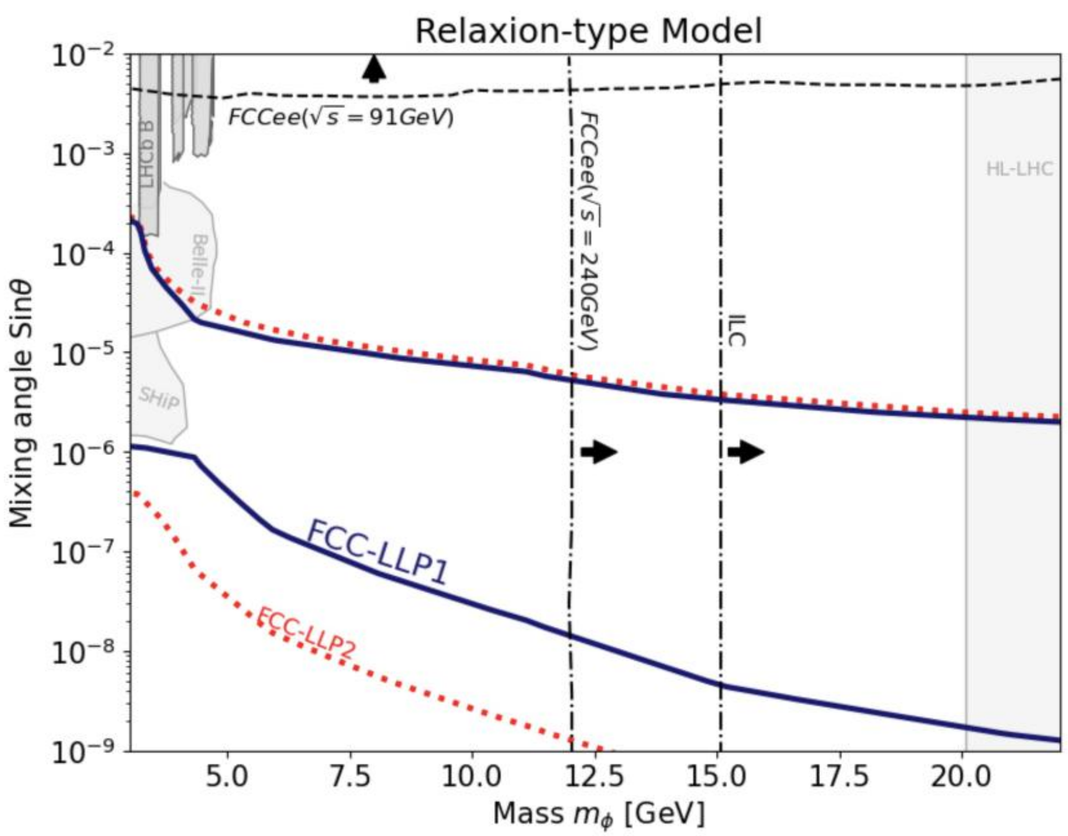
BSM physics sensitivity

Long-Lived Particles Searches



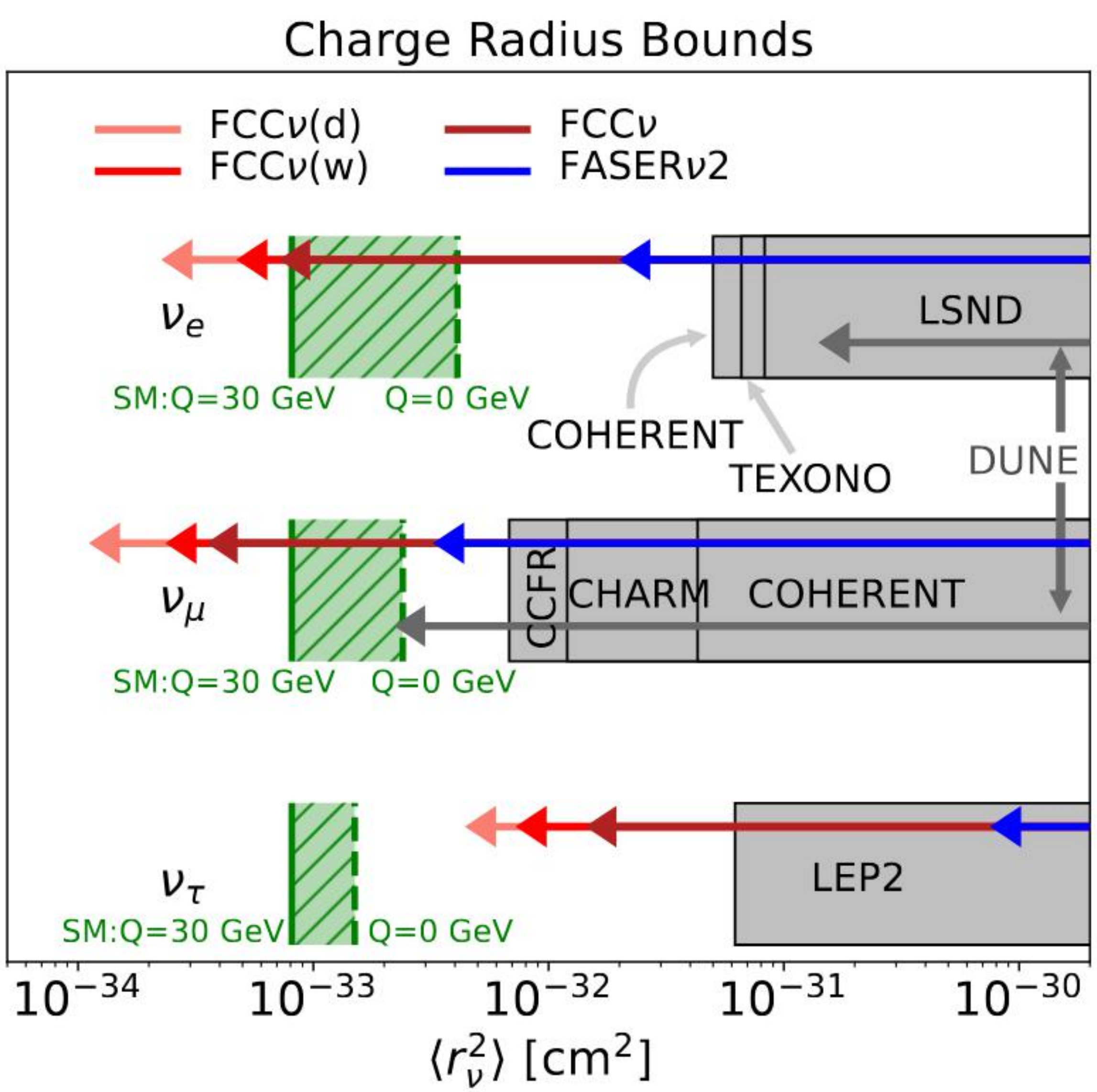
Millicharged Particles

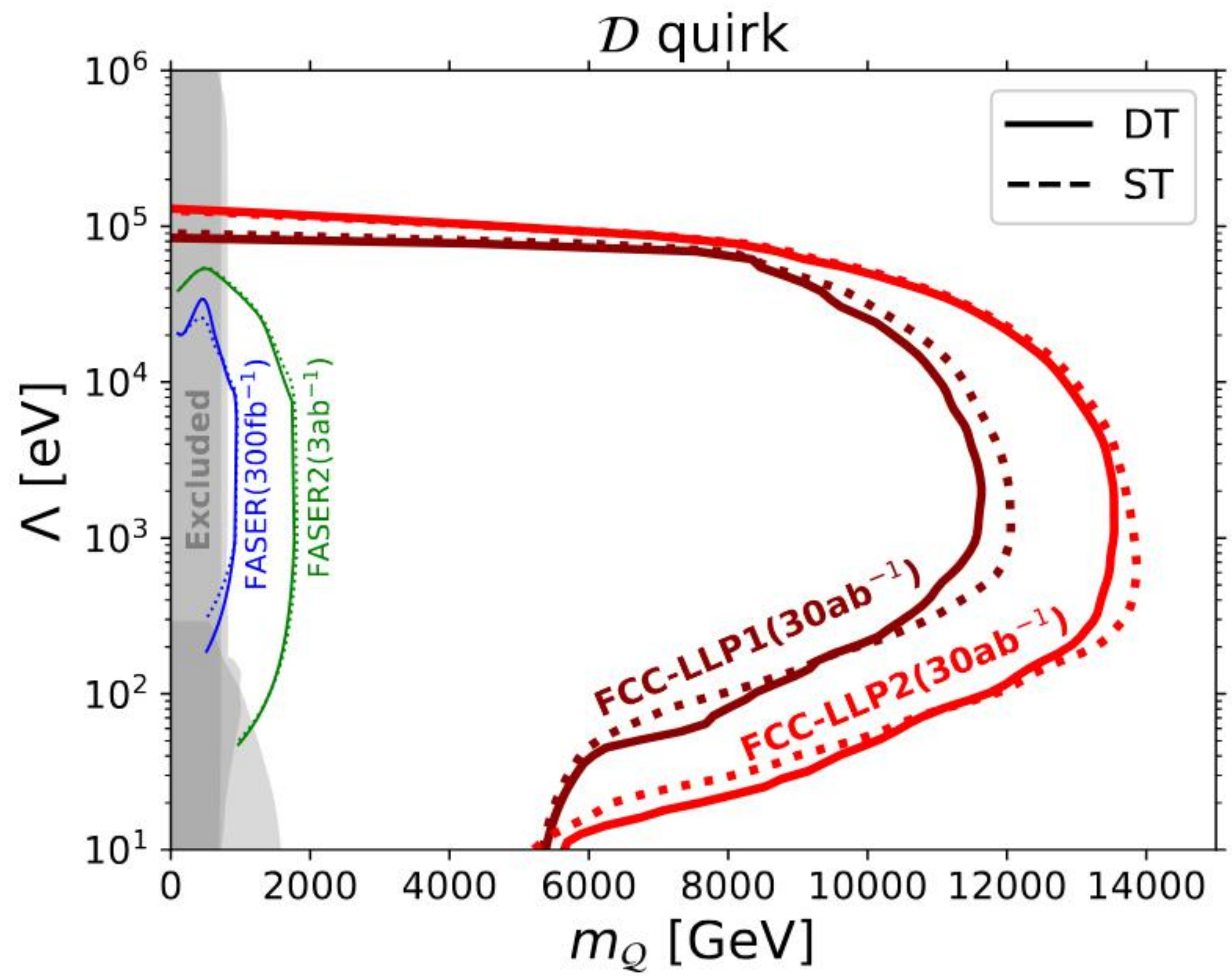




- **Dark Higgs bosons** produced from h→ϕϕ, thanks to enormous forward rate at 100 TeV
- Test **scalar portal to dark matter** far below the neutrino floor
- **Relaxion-type LLPs** sensitivity in low-mass region beyond reach of FCC-ee
- Close the gap **between accelerator and direct detection searches** for millicharged dark matter

BSM physics sensitivity





Measure for the first time **neutrino charge radius** and its flavour dependence

sterile neutrino oscillations, neutrino-philic new particles, neutrino **non-standard interactions**, …

Quirks: dark-sector particles charged under dark QCD, motivated by **neutral naturalness**

Discover Quirks **up to ~14 TeV** for a wide range of (dark) confinement scales Λ

Summary and outlook

- LHC neutrinos realise an exciting program in a broad range of topics from **BSM, dark matter, and long-lived particles** to **neutrinos, QCD and hadron structure**, **and astroparticle physics**

- Measurements of **neutrino DIS structure functions** at the LHC open a new probe to proton and nuclear structure with a **charged-current counterpart of the Electron Ion Collider**

- They provide a unique perspective on **quark flavour separation,** enhance theory predictions for HL-LHC observables, scrutinise the charm content of the proton**,** and can **disentangle QCD effects from BSM signals**

- Measurements of **electron and tau neutrino event rates** at the LHC constrain the **small-*x* gluon and large-*x* charm** in unexplored regions by using dedicated observables

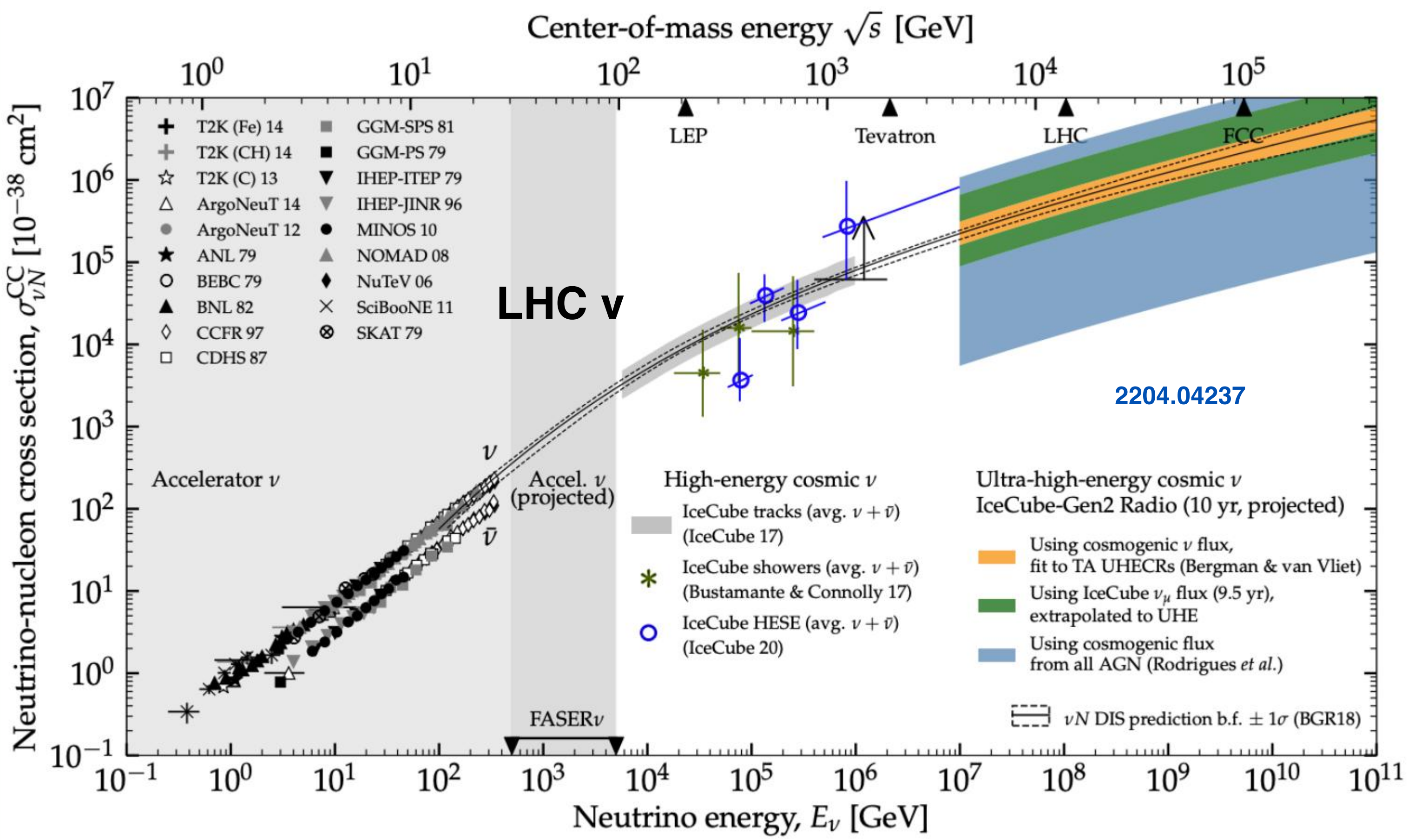
- **Higher-order Monte Carlo generators** are ready to be deployed for far-forward LHC experiments

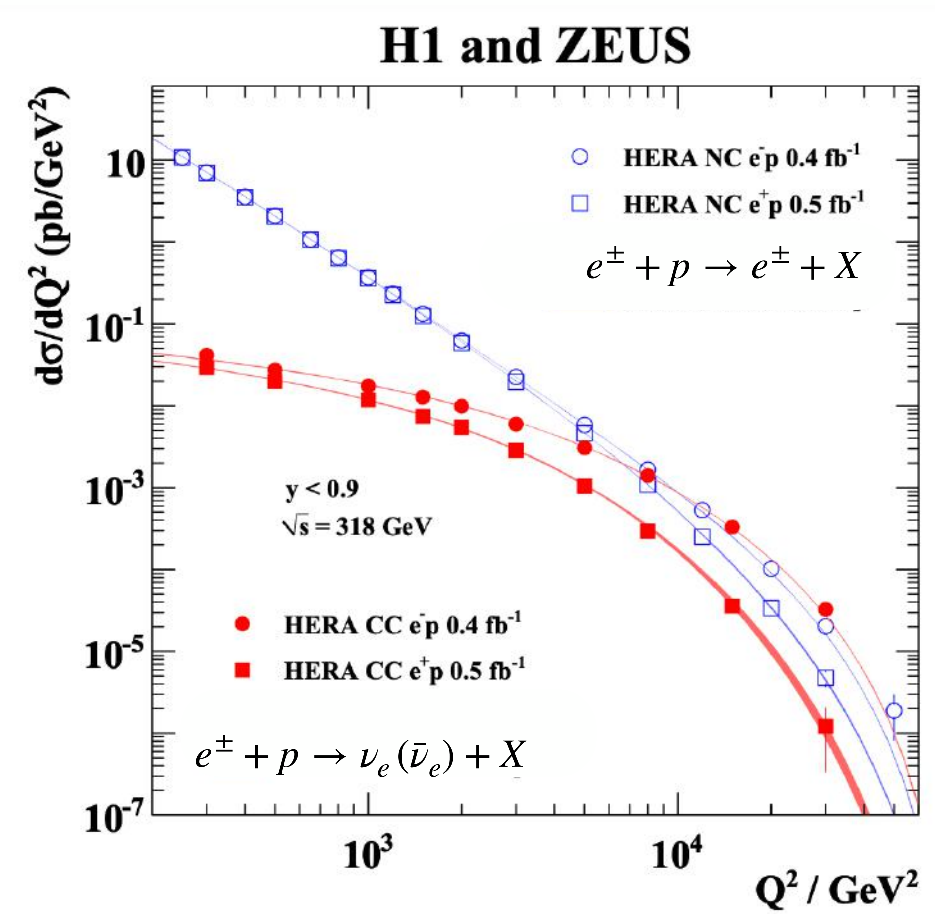
- Far-forward neutrino experiments **integrated in a O(100 TeV) pp collider** would collect a massive sample of O(1B) muon neutrinos and up to O(50M) tau neutrinos with multi-TeV energies

Extra Material

Neutrino Interactions at the TeV

- First measurement of **muon neutrino and tau neutrino cross-sections at the TeV**: test **lepton flavour universality,** search for anomalous interactions (*e.g.* in EFT framework)





LHC neutrinos cover unexplored gap in neutrino interactions

Indirect HERA constraints restricted to electron neutrinos, cross-sect measured at the 15% level at TeV energies

- **Largest sample of tau neutrinos**, explore with exquisite precision **worst known particle of the SM**

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

Thousands of tau neutrino events expected, current world sample being O(10)