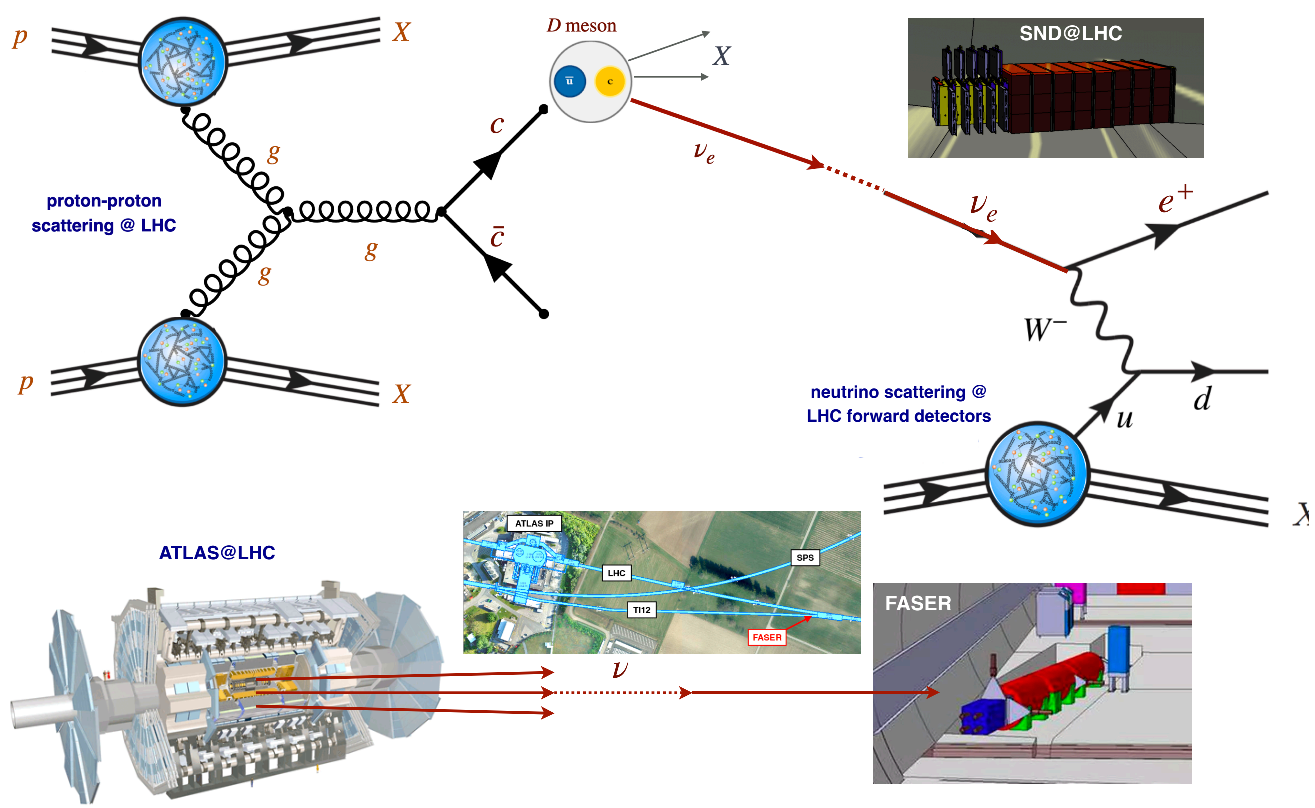
Physics with TeV Neutrinos at the LHC

Juan Rojo, VU Amsterdam & Nikhef



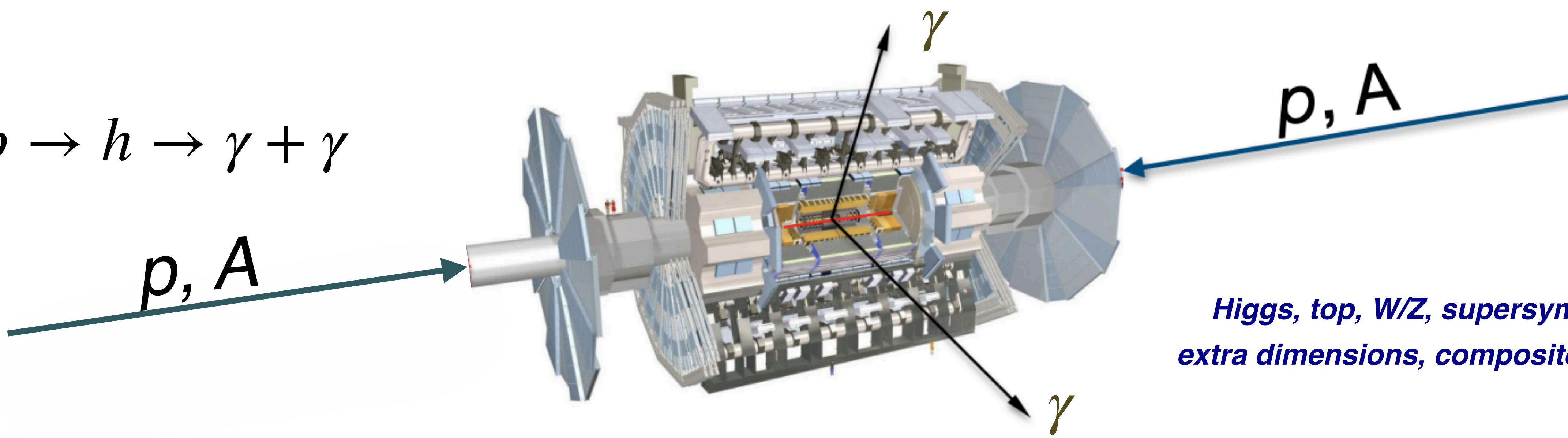
Particle Physics seminar, UC Irvine, 23.08.2023

The Far-Forwards Frontier of LHC Physics

Neutrinos at the LHC

- The ATLAS and CMS detectors were designed with a focus on **identifying weak-scale and heavier particles**, whose 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

Neutrinos at the LHC

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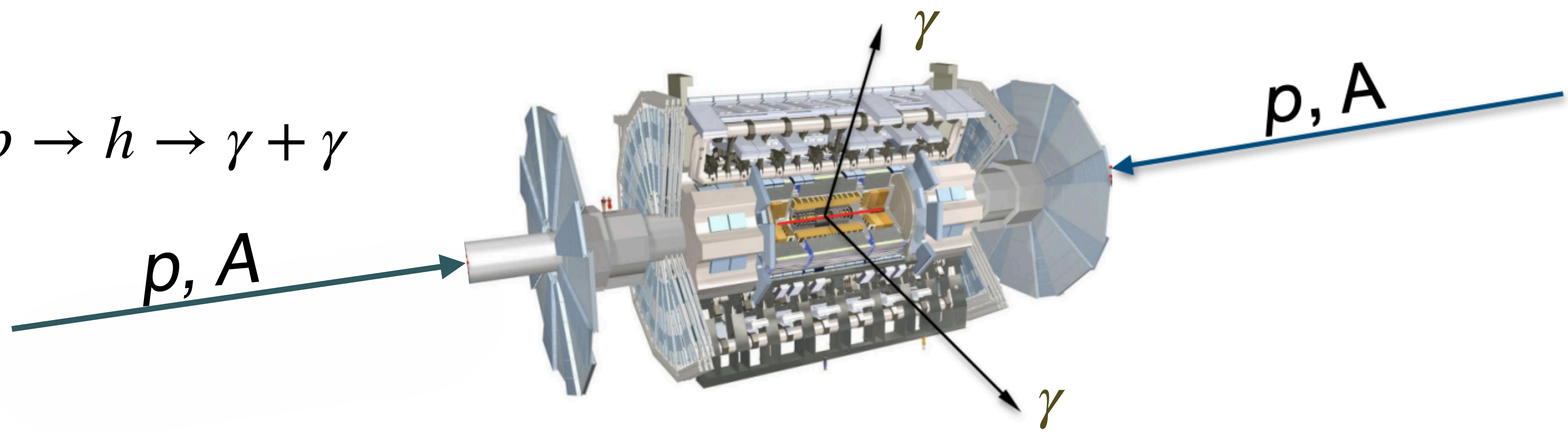
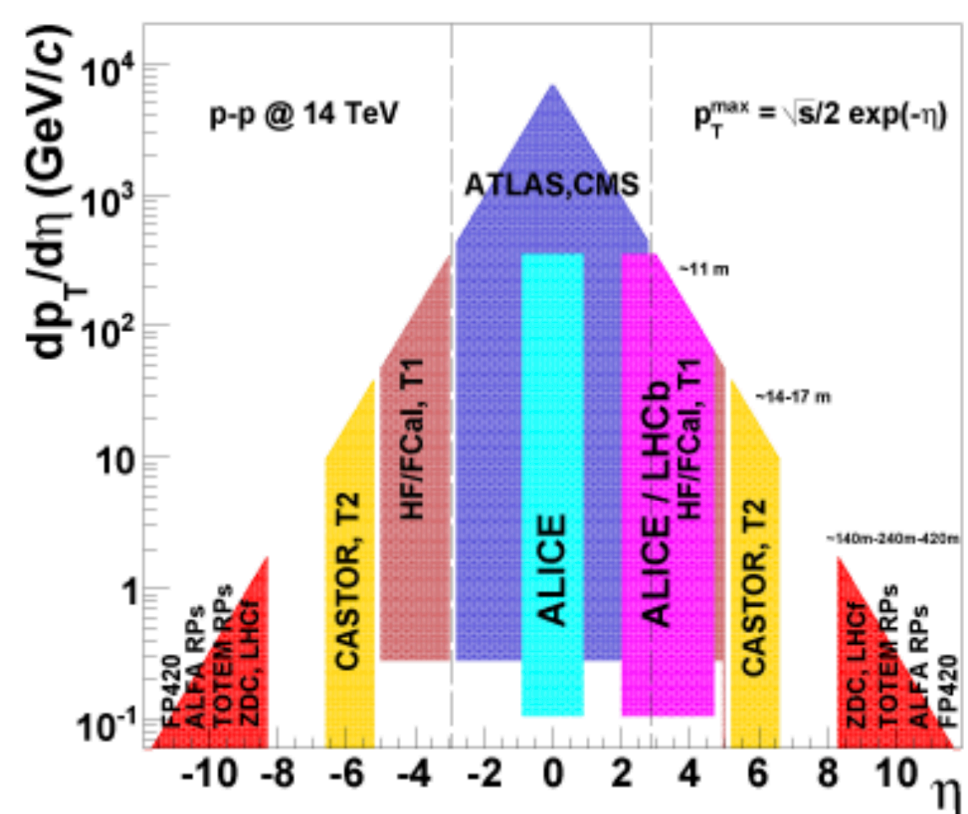
$$p + p \to h \to \gamma + \gamma$$



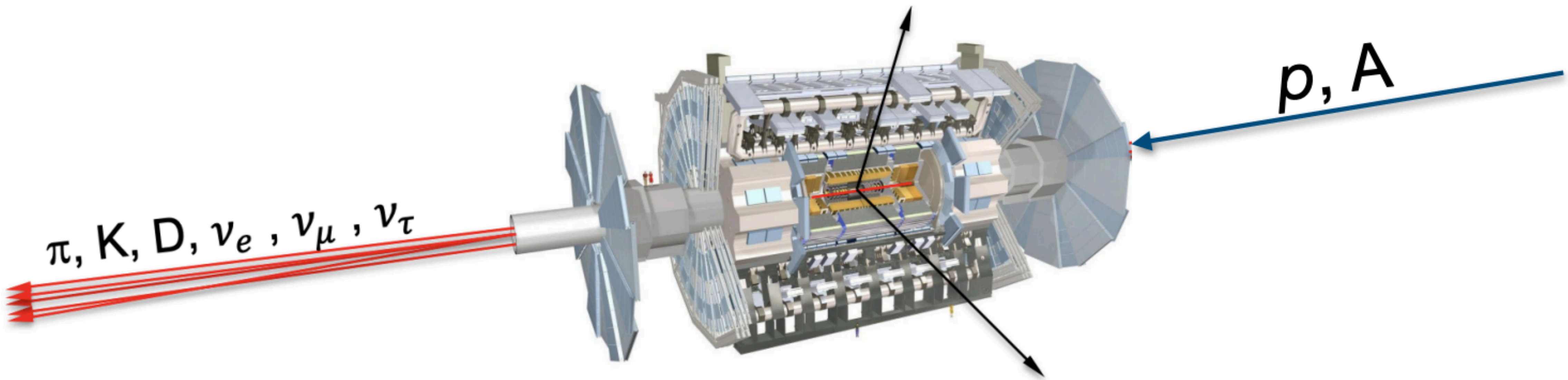
- Forward region for hard-scattering physics restricted to **LHCb** (η < 4.5) and (in the future) **ALICE-FoCal** (η < 5.0)

- **Far-forward region** mostly not instrumented, except for *e.g.* total cross-section analyses



Neutrinos at the LHC

- LHC collisions result into a **large flux of energetic neutrinos** which escape the detectors unobserved: **major blind spot of the LHC**



- Being able to detect and utilise the **most energetic human-made neutrinos ever produced** would open many exciting avenues in QCD, neutrino, and astroparticle physics

Neutrino Physics

Precision study of **tau-neutrino interactions**

Neutrino **coupling universality** at TeV energies

BSM/DM in neutrino sector e.g. **sterile neutrino**

QCD & Hadron Structure

Proton and nuclear **antimatter & charm**

Gluon PDF at ultra-small-*x*; saturation/QGP

Cross-sections for **UHE astroparticle physics**

Neutrinos at the LHC

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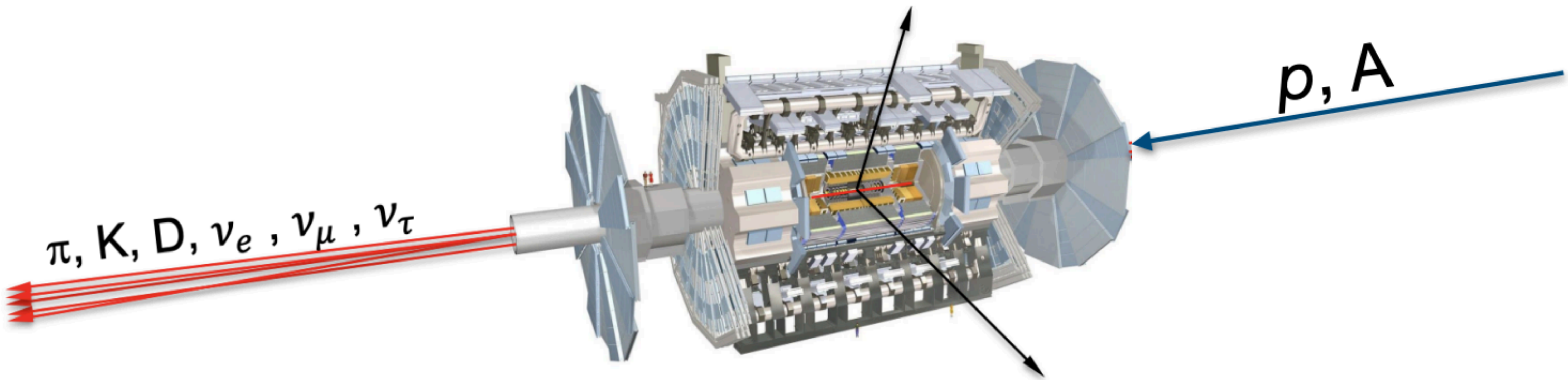

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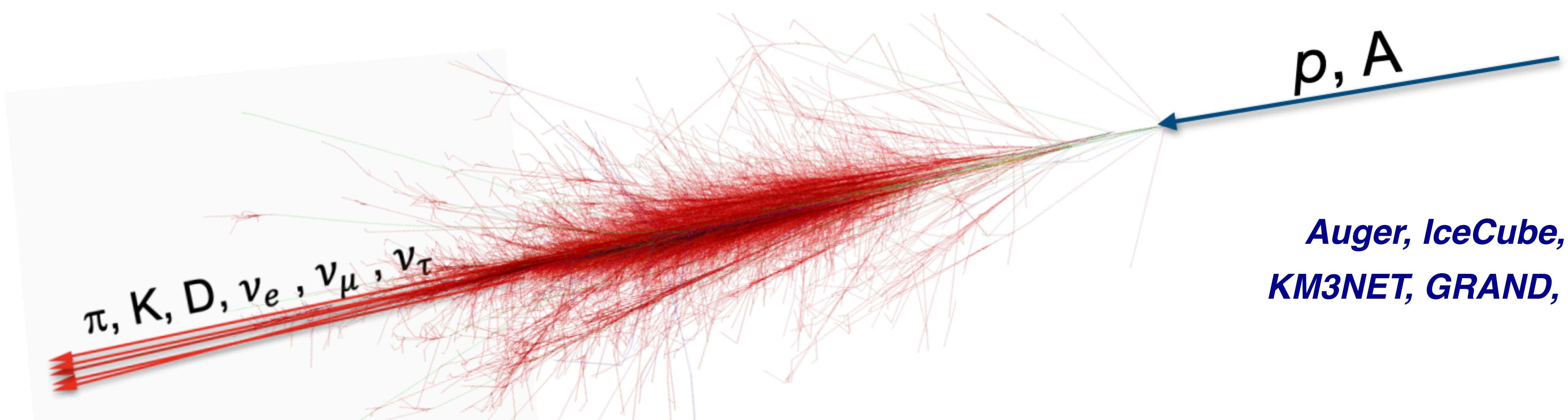
Collider counterpart of high-energy cosmic rays interactions, including prompt neutrino flux



Auger, IceCube, KM3NET, GRAND, …

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

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

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8 neutrinos detected, 4 expected

- Impressively fast progress **from inception to installation** and to the discovery of LHC neutrinos

PHYSICAL REVIEW D **97,** 035001 (2018)

ForwArd Search ExpeRiment at the LHC

Jonathan L. Feng,[1,*] Iftah Galon,[1,†] Felix Kling,[1,‡] and Sebastian Trojanowski[1,2,§]

[1] *Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA*

[2] *National Centre for Nuclear Research, Hoża 69, 00-681 Warsaw, Poland*

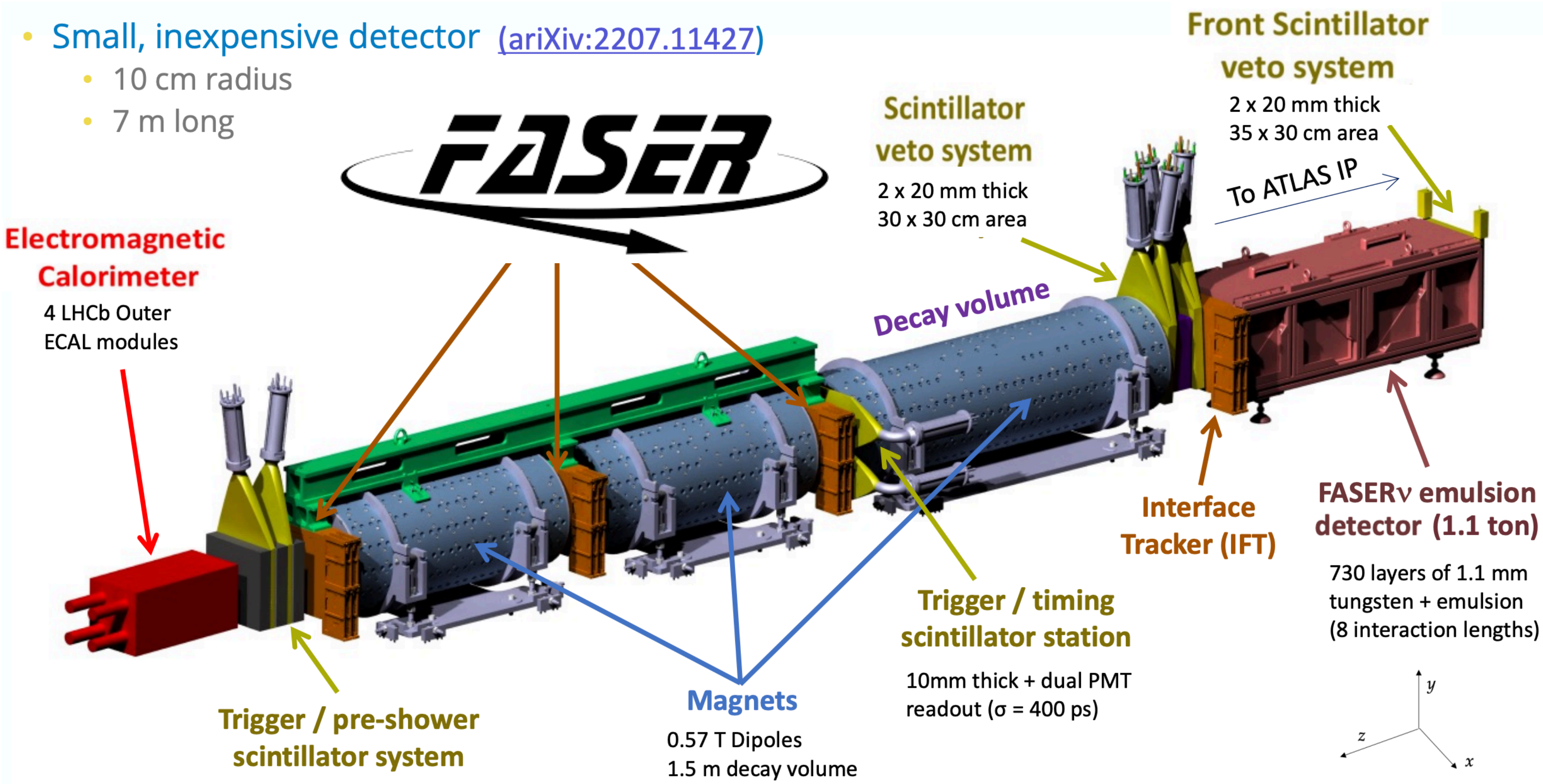
(Received 13 October 2017; published 5 February 2018)

New physics has traditionally been expected in the high-p_T region at high-energy collider experiments. If new particles are light and weakly coupled, however, this focus may be completely misguided: light particles are typically highly concentrated within a few mrad of the beam line, allowing sensitive searches with small detectors, and even extremely weakly coupled particles may be produced in large numbers there. We propose a new experiment, forward search experiment, or FASER, which would be placed downstream of the ATLAS or CMS interaction point (IP) in the very forward region and operated concurrently there.

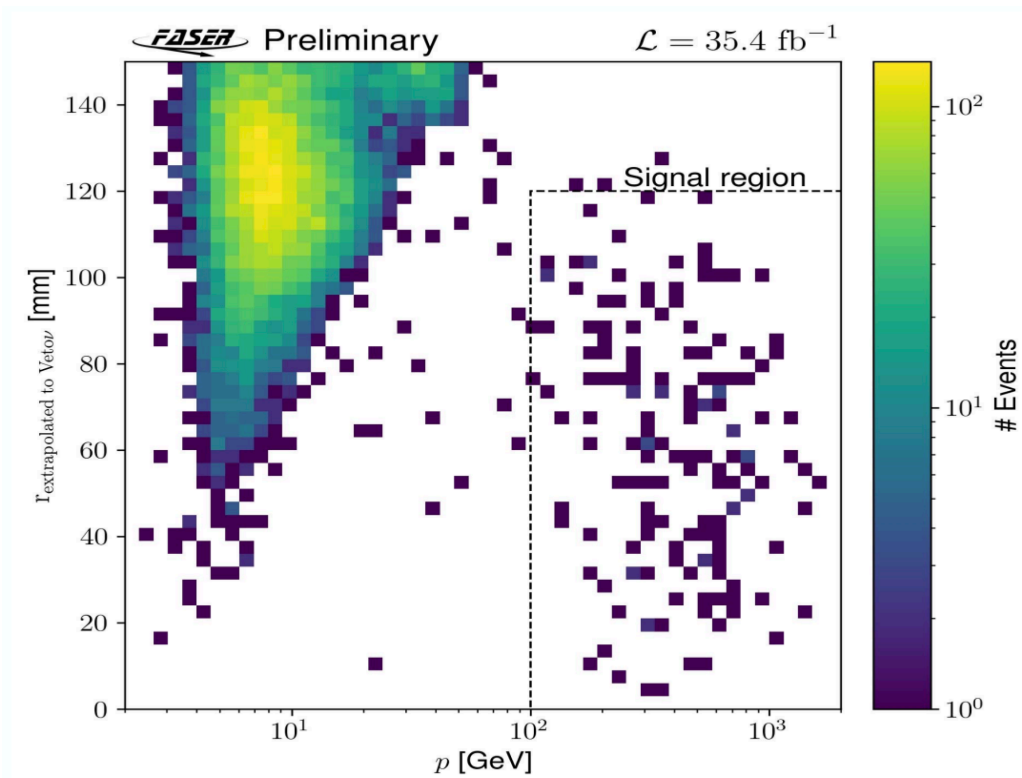
neutrinos were initially considered as a background …

The dawn of the LHC neutrino era

- Small, inexpensive detector (ariXiv:2207.11427)
  - 10 cm radius
  - 7 m long



- 150 (muon) neutrino candidates over **basically no background**
- Large uncertainties in theory predictions from LHC **forward particle production**
- Expected **O(thousands) neutrinos** by end Run III



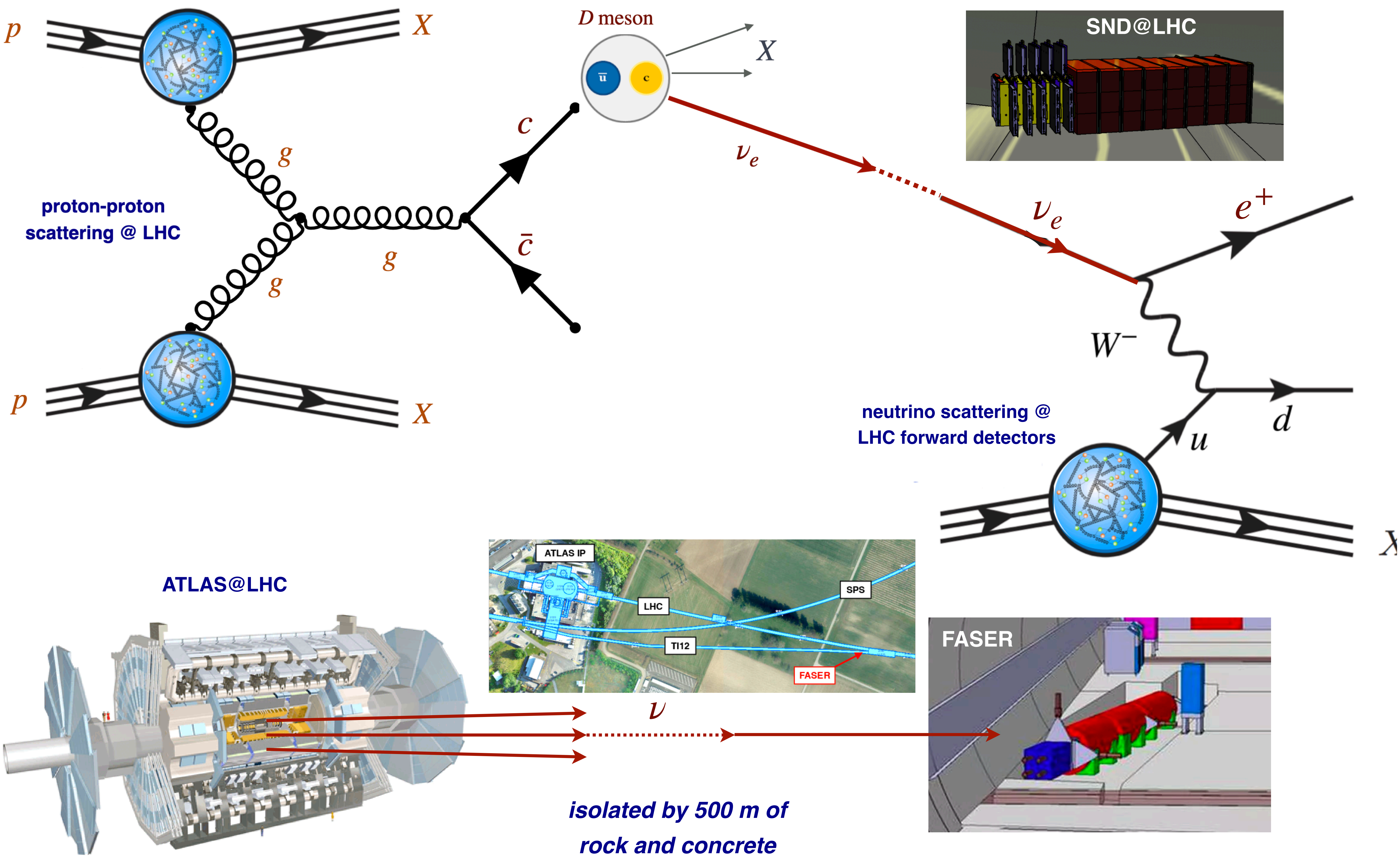
Candidate	Events
n_0	153 (151 ± 41)
n_{10}	4
n_{01}	6
n_2	64014695

Outline

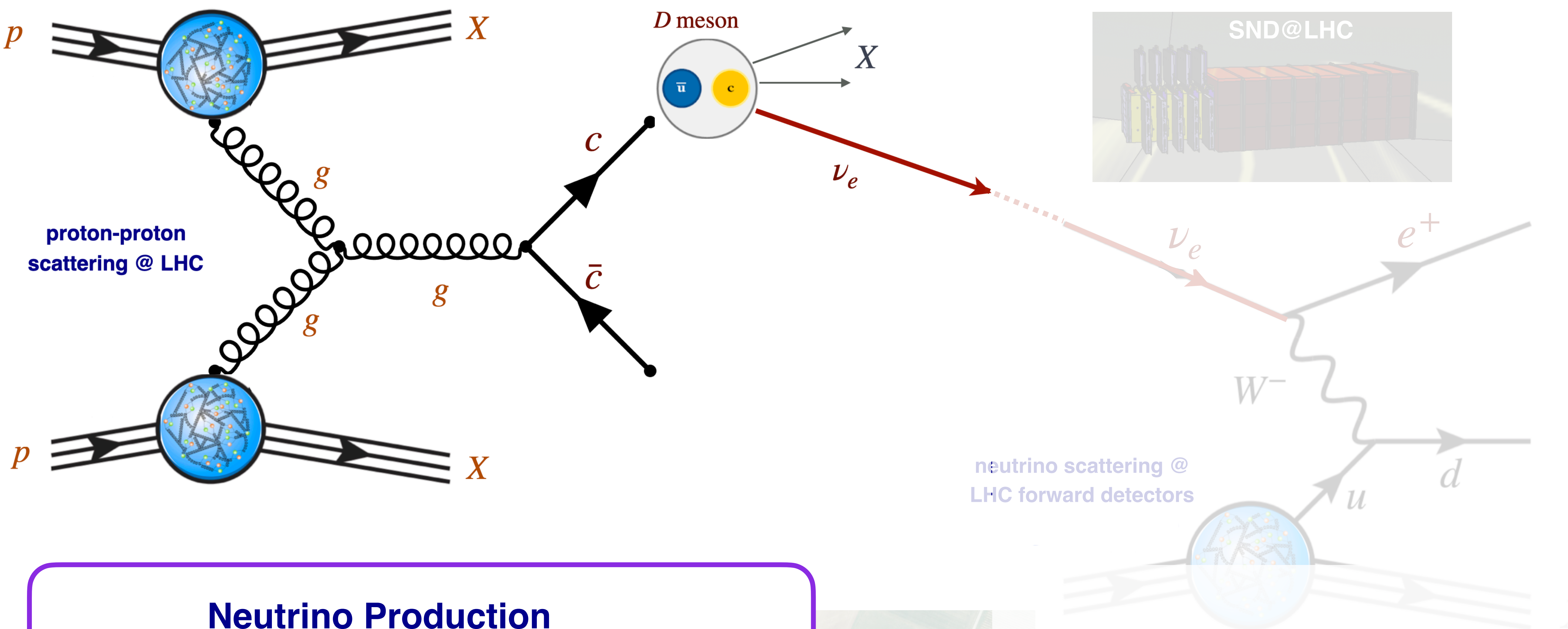
- QCD and neutrino physics with TeV neutrinos at the LHC
- Hadron structure with neutrino deep-inelastic scattering at the LHC
- Probing gluons at ultra-small-x at FASER and the FPF
- Neutrino inelastic cross-sections from low- to high-Q

The LHC as a Neutrino-Ion Collider

Physics with LHC neutrinos



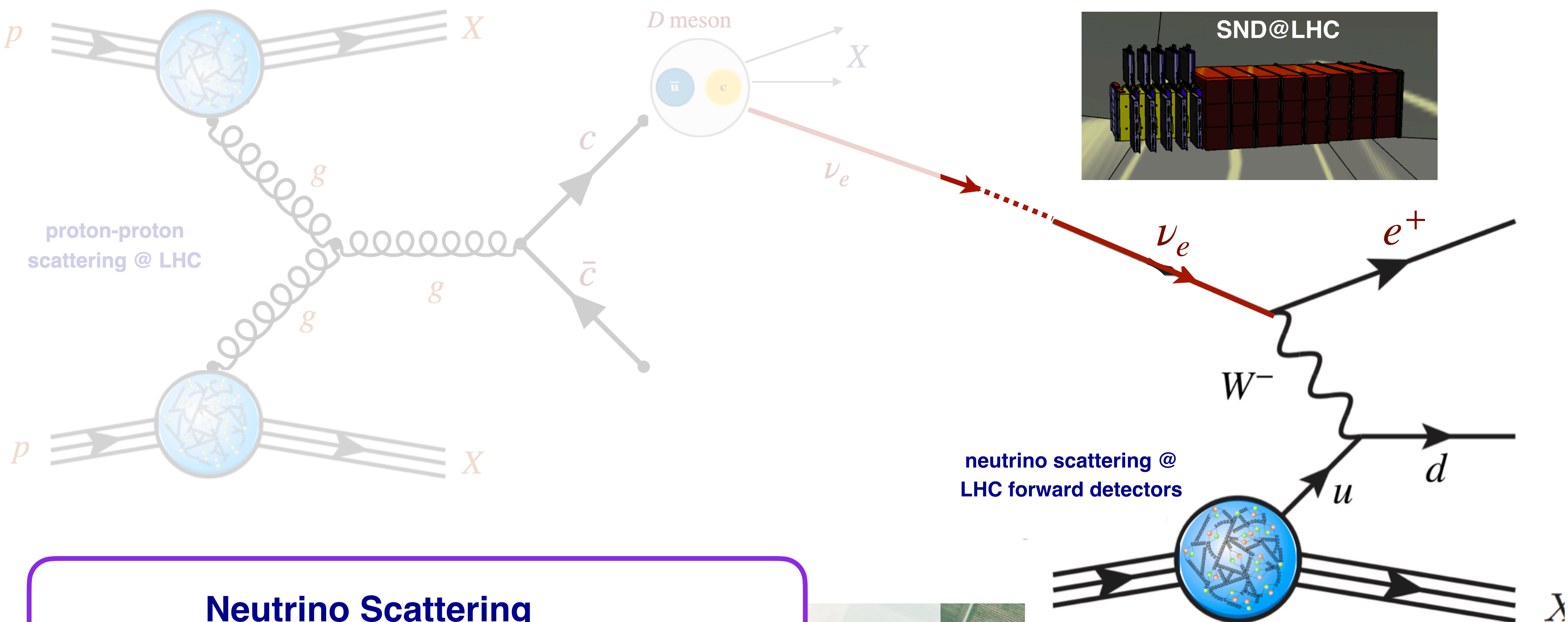
Physics with LHC neutrinos



Neutrino Production

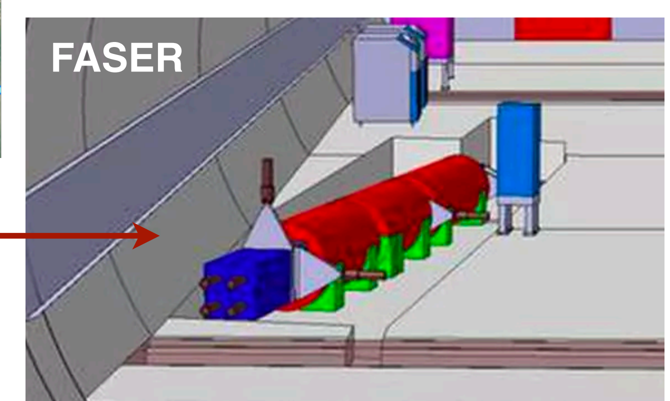
- Small-x gluon & large-x (intrinsic) charm
- *D*-meson fragmentation
- Cross-sections for UHE neutrinos (*e.g.* IceCube)
- Cosmic ray modelling, including muon puzzle

Physics with LHC neutrinos



Neutrino Scattering

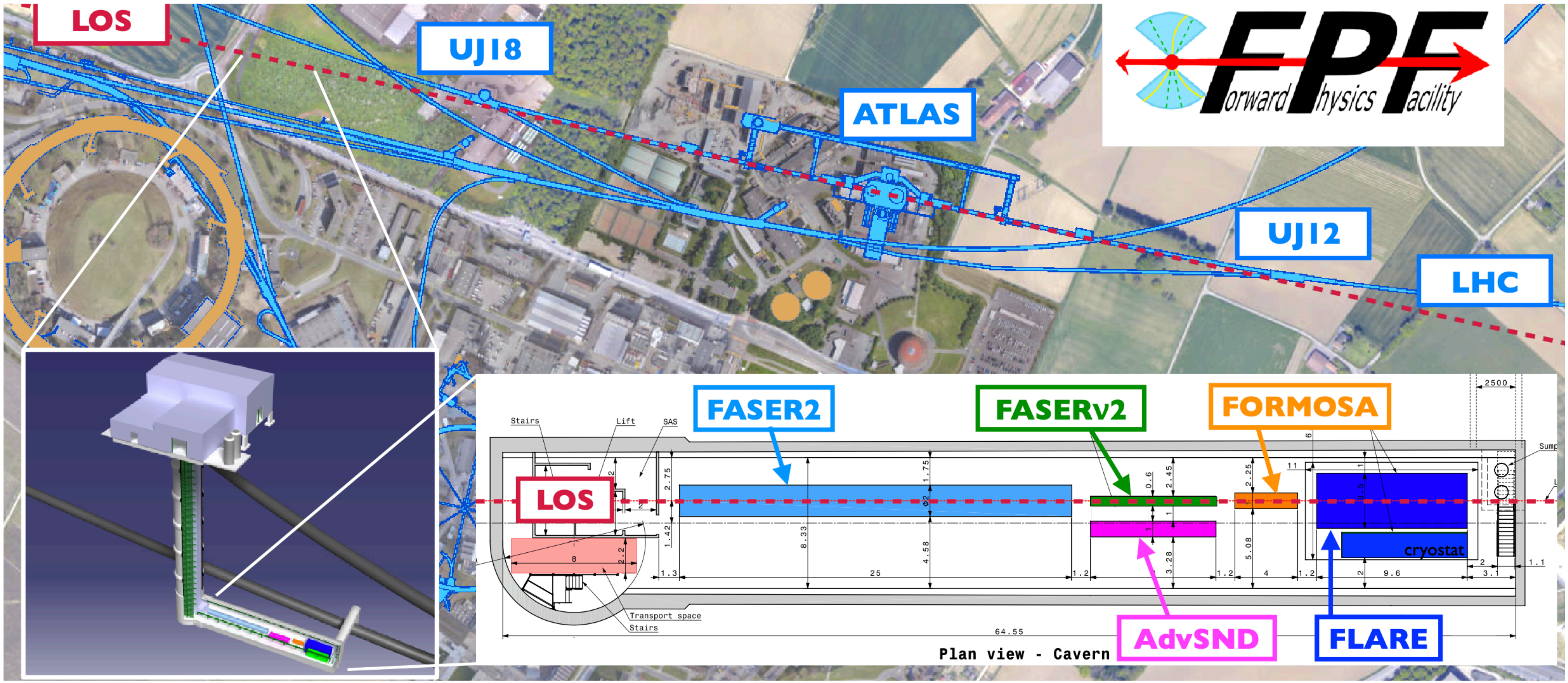
- DIS with TeV neutrinos: the Neutrino-Ion Collider
- Neutrino (effective) interactions at the TeV
- Tau-neutrino properties and flavour universality
- Nuclear PDFs, strangeness from charm prod
- BSM & Dark Matter in neutrino sector



FASER, SND@LHC will ``only" record a few thousand neutrinos: insufficient for most QCD/SM targets …

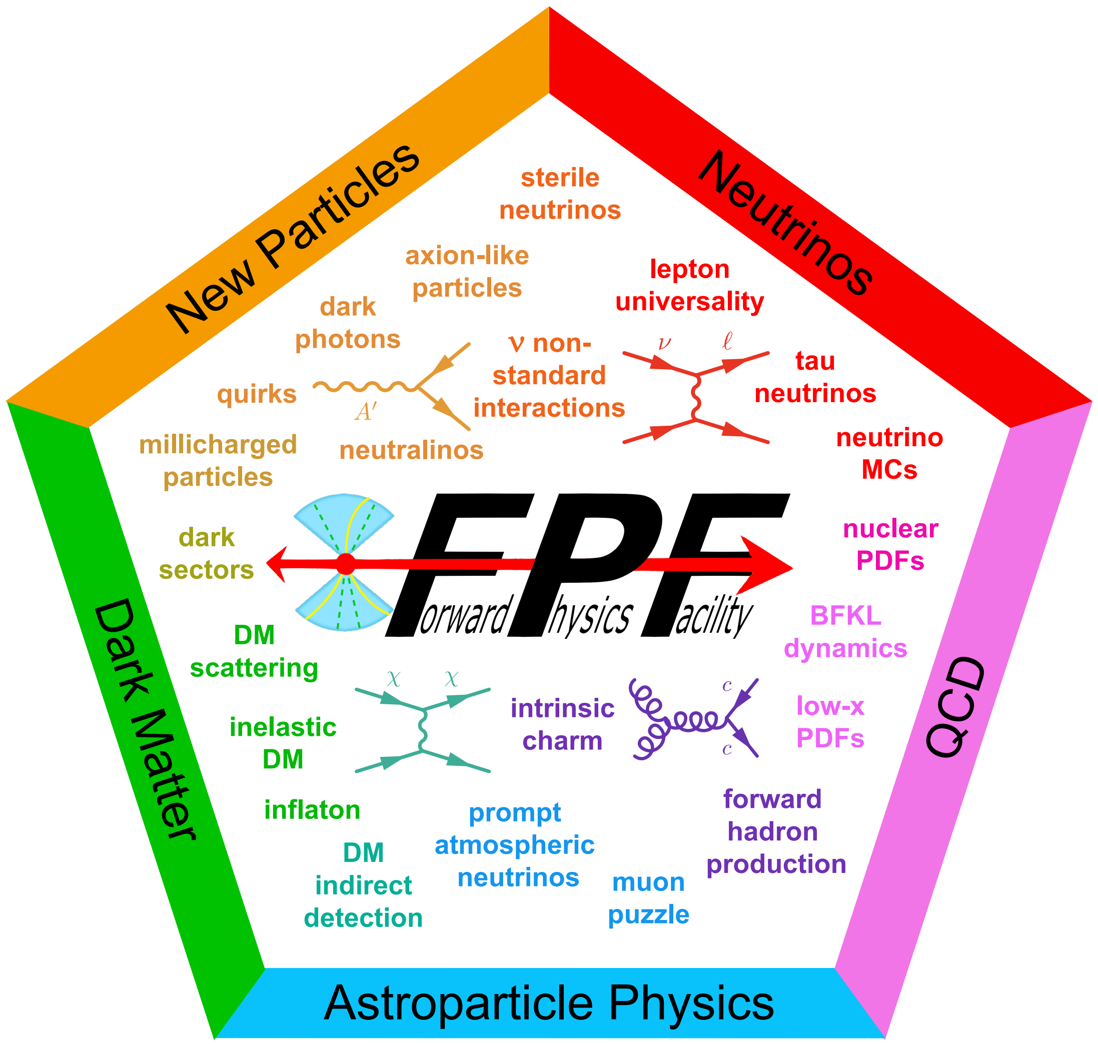
The Forward Physics Facility

The FPF: a 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 Forward Physics Facility



- **430 pages** describing scientific case, infrastructure, detectors, and simulations
- Stepping stone for the FPF **Conceptual Design Report**

arXiv:2203.05090v1 [hep-ex] 9 Mar 2022

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

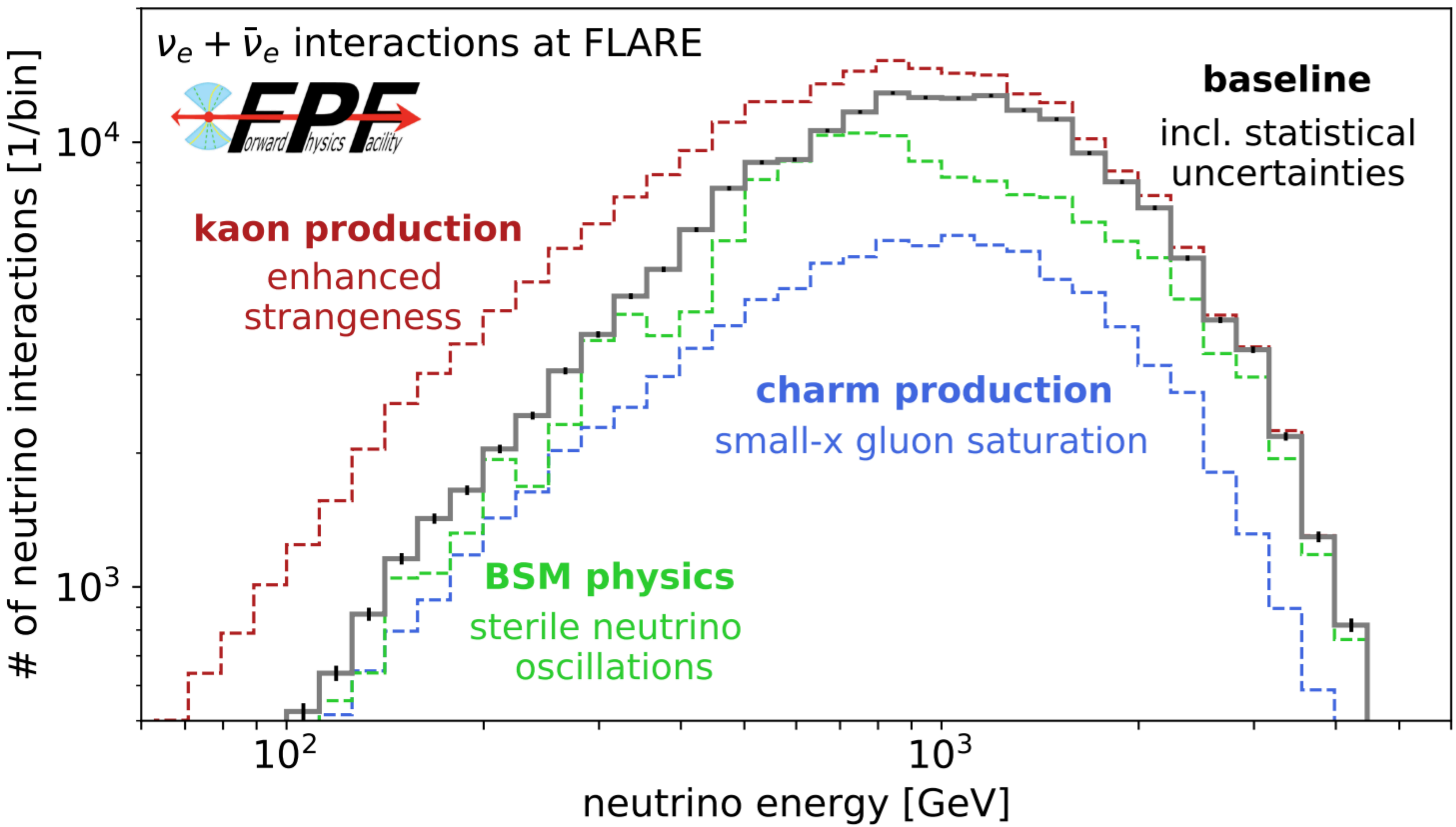
Lead Conveners

Jonathan L. Feng[1*], Felix Kling[2], Mary Hall Reno[3], Juan Rojo[4,5], Dennis Soldin[6]

Topical Conveners

Luis A. Anchordoqui[7], Jamie Boyd[8], Ahmed Ismail[9], Lucian Harland-Lang[10,11], Kevin J. Kelly[12], Vishvas Pandey[13], Sebastian Trojanowski[14,15], Yu-Dai Tsai[1],

The Forward Physics Facility



Broad, far-reaching program on **QCD** (small-x gluon, saturation), **cosmic rays** (muon puzzle), **neutrino BSM** (sterile neutrinos), hadronic structure, **UHE neutrinos**, **FCC-pp cross-sections** …

The Forward Physics Facility

- The unique SM and BSM physics potential of the FPF relies on the high CoM energy of the LHC: **unless it is realised at the HL-LHC it will disappear for decades** (or forever)!

- Strong alignment with **EPPSU** (2020) and **Snowmass** (2022) priorisation

2020 EPPSU 1st Recommendation

The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.

2022 Snowmass Energy Frontier Summary

Our highest immediate priority accelerator and project is the HL-LHC, the successful completion of the detector upgrades, operations of the detectors at the HL-LHC, data taking and analysis, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.

Resource needs and plan for the 5-year period starting 2025:

1. Prioritize HL-LHC physics program, including auxiliary experiments.

- Strong support from **CERN**, **LHCC**, and **Physics Beyond Collider** (PBC) group

C. Vallee, PBC workshop 11.2022

FORWARD PHYSICS FACILITY

Good progress in the conceptual design of the infrastructure and decoupling from LHC operation constraints

Strong support from Snowmass HE group to HL-LHC auxiliary detectors

LHCC statement in September recommending to further study the FPF in the global PBC context

Next steps:
- **CDR expected in 2023 with more details on detector technical aspects, physics complementarity and Collaboration structure**
- **Relevant information on physics reach (sensitivity curves, etc…) to be provided to FPC, BSM and QCD WGs to address comparison with other projects**

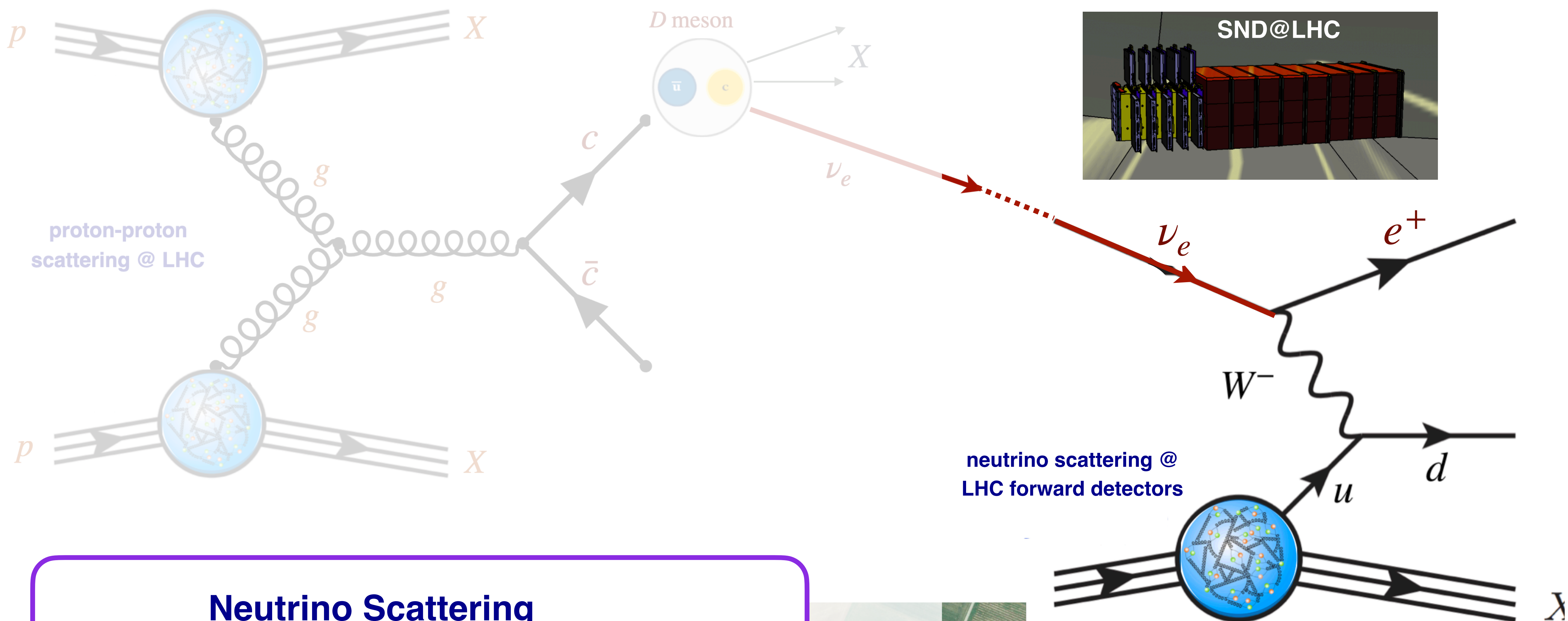
- Building a strong, focused, and diverse community of particle physicists interested in FPF

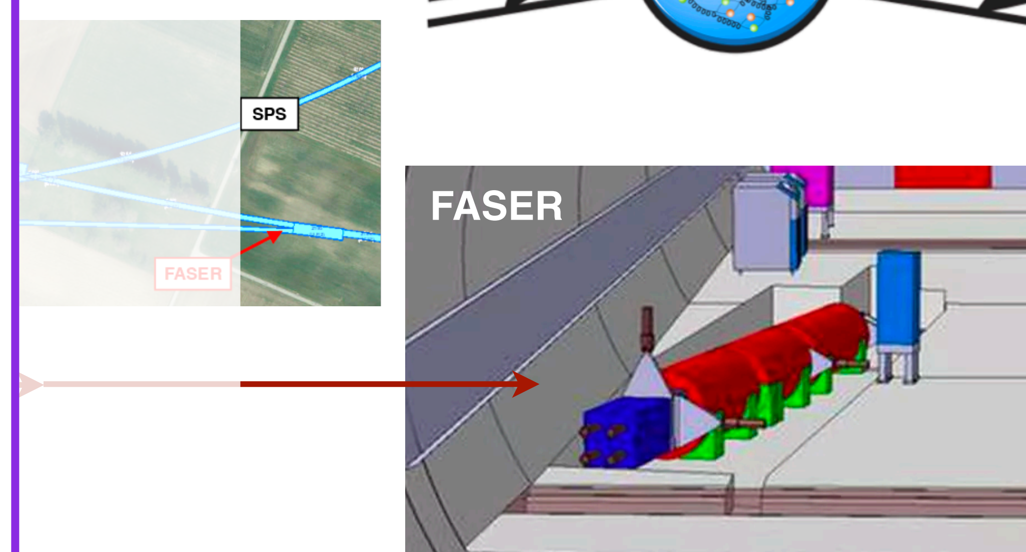
- Strong synergies with other next-generation facilities, such as the **Electron-Ion Collider**

Neutrino DIS at the LHC and hadron structure

Juan Cruz-Martinez, M. Fieg, T. Giani, P. Krack, G. Magni, T. Makela, T. Rabemananjara, JR, *in progress*

Physics with LHC neutrinos





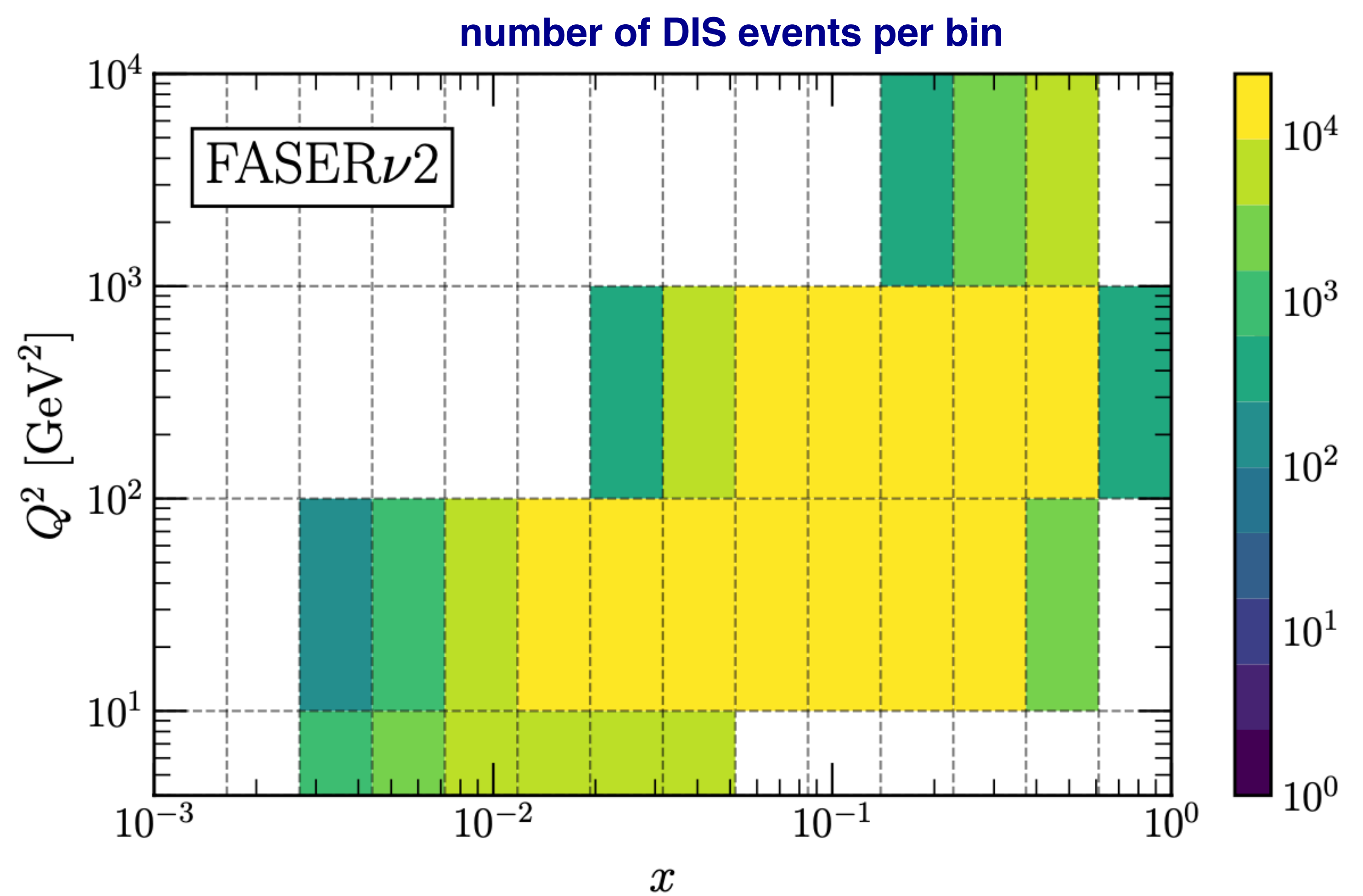
Neutrino Scattering

- **DIS with TeV neutrinos: Neutrino-Ion Collider**
- Neutrino (effective) interactions at the TeV
- Tau-neutrino properties and flavour universality
- **Nuclear PDFs, strangeness from charm prod**
- BSM & Dark Matter in neutrino sector

need quantitative impact projections!

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**



Events per bin

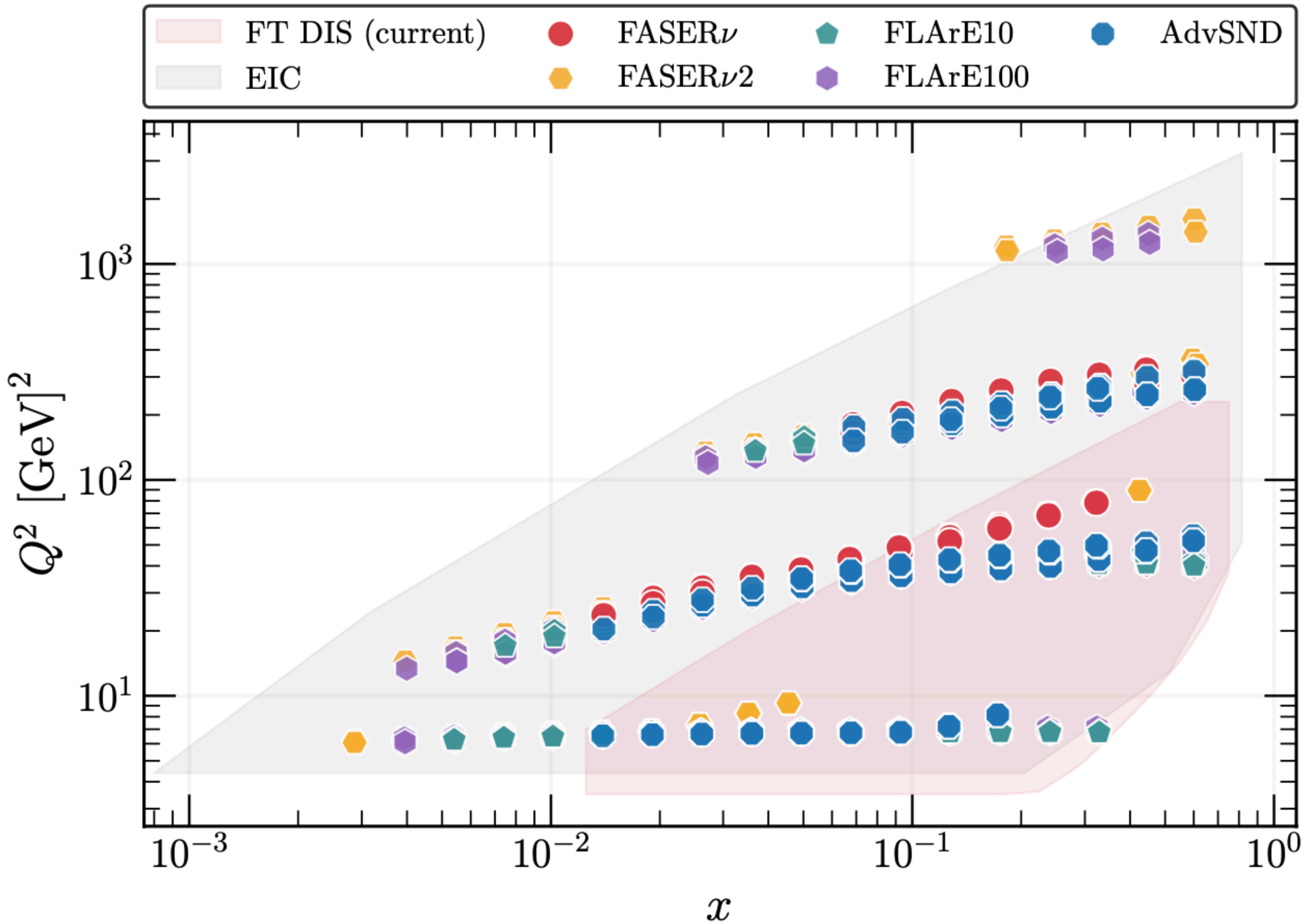
$$N_{\rm ev}^{(i)} = n_T L_T \int_{Q^{2(i)}_{\rm min}}^{Q^{2(i)}_{\rm max}} \int_{x^{(i)}_{\rm min}}^{x^{(i)}_{\rm max}} \int_{E^{(i)}_{\rm min}}^{E^{(i)}_{\rm max}} \frac{dN_\nu(E_\nu)}{dE_\nu} \left(\frac{d^2\sigma(x,Q^2,E_\nu)}{dx dQ^2} \right) \mathcal{A}(x,Q^2,E_\nu) dQ^2 dx dE_\nu$$

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

Close collaboration between **theorists and experiments** crucial!

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

Neutrino DIS at the LHC



x: momentum fraction of quarks/gluons in the proton

Q^2: 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 Q^2
- Charged-current counterpart of the **Electron-Ion Collider** in a comparable region of phase space

Pseudo-data generation

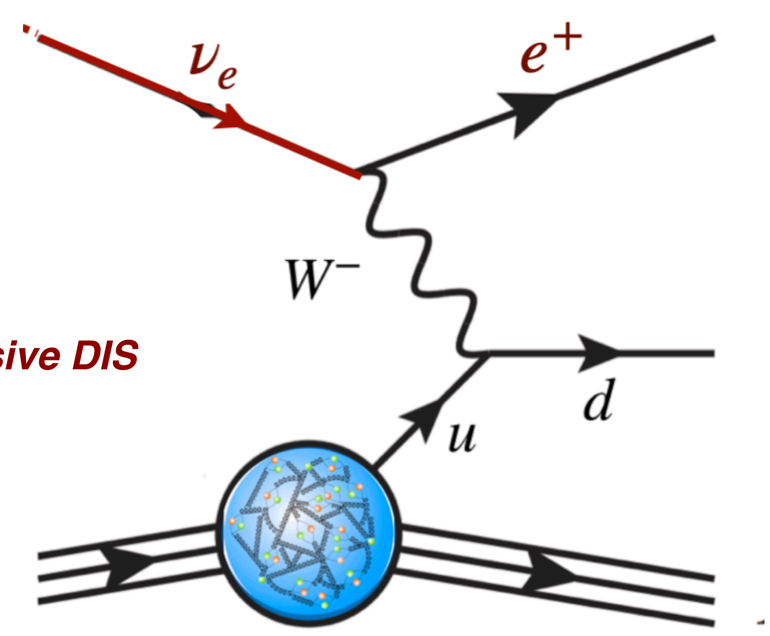
Detector	Rapidity	Target	Charge ID	Acceptance	Performance
FASERν	$\eta_\nu \geq 8.5$	Tungsten (1.1 ton)	muons	$E_\ell \gtrsim 100$ GeV $\tan\theta_\ell \lesssim 0.025$ reco E_h & charm ID	$\delta E_\ell \sim 30\%$ $\delta\theta_\ell \sim 0.06$ mrad $\delta E_h \sim 30\%$
SND@LHC	$7.2 \leq \eta_\nu \leq 8.4$	Tungsten (0.83 ton)	n/a	$E_\mu \gtrsim 20$ GeV $\theta_\mu \lesssim 0.15, \theta_e \lesssim 0.5$	n/a
FASERν2	$\eta_\nu \geq 8.5$	Tungsten (20 ton)	muons	$E_\ell \gtrsim 100$ GeV $\tan\theta_\ell \lesssim 0.05$ reco E_h & charm ID	$\delta E_\ell \sim 30\%$ $\delta\theta_\ell \sim 0.06$ mrad $\delta E_h \sim 30\%$
AdvSND-far	$7.2 \leq \eta_\nu \leq 8.4$	Tungsten (5 ton)	muons	$E_\mu \gtrsim 20$ GeV $\theta_\mu \lesssim 0.15, \theta_e \lesssim 0.5$ reco E_h	n/a
FLArE (*)	$\eta_\nu \geq 7.5$	LAr (10 ton) **(also 30 ton option)**	muons	$E_\mu \gtrsim 2$ GeV, $E_e \lesssim 2$ TeV $\theta_\mu \lesssim 0.025$, $\theta_e \lesssim 0.5$ reco E_h	$\delta E_e \sim 5\%$, $\delta E_\mu \sim 30\%$ $\delta\theta_e \sim 15$, $\delta\theta_\mu \sim 0.06$ mrad $\delta E_h \sim 30\%$

Current estimates for experimental acceptance and performance, likely to change in final realisation

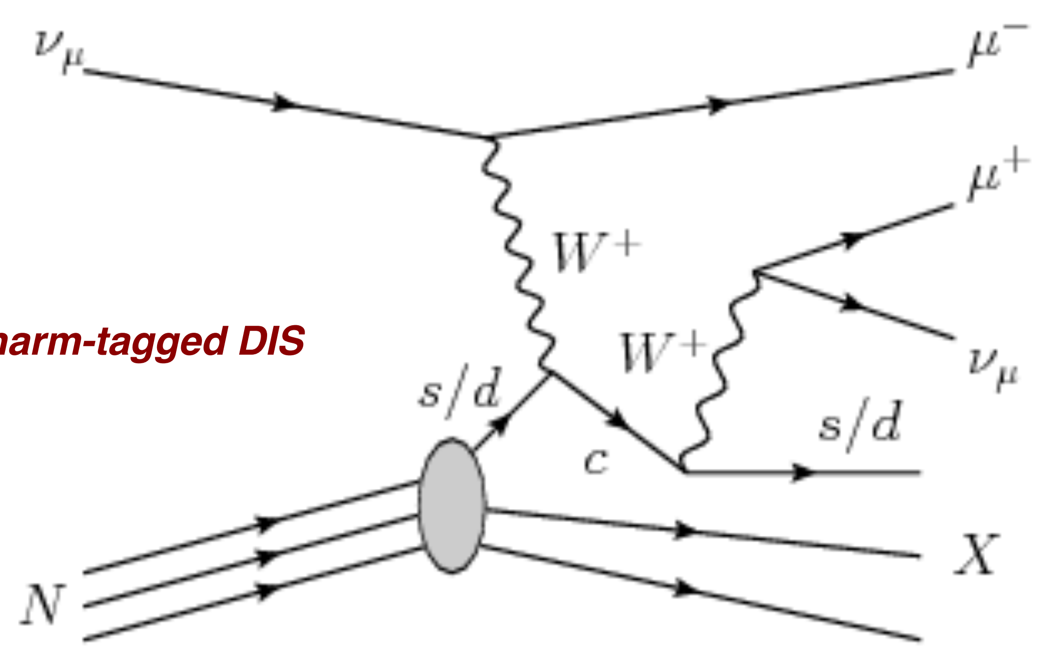
Pseudo-data generation

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	340 (56)	190 (36)	530 (92)	1100 (180)	440 (83)	1500 (260)
SND@LHC	140 (15)	60 (9)	200 (24)	390 (54)	150 (22)	550 (76)
FASERν2	84k (11k)	42k (6.6k)	130k (19k)	274k (40k)	100k (17k)	370k (57k)
AdvSND-far	8.6k (0)	3500 (0)	13k (0.5k)	30k (2.7k)	12k (0.8k)	43k (4.5k)
FLArE-10	33k (3.3k)	15k (1.4k)	50k (5.4k)	53k (6.5k)	28k (2.4k)	81k (11k)
FLArE-100	110k (13k)	58k (6.9k)	170k (21k)	302k (43k)	120k (15k)	420k (59k)



Inclusive DIS



Charm-tagged DIS

Pseudo-data generation

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}	$N_{\bar{\nu}_\mu}$	$N_{\nu_\mu} + N_{\bar{\nu}_\mu}$
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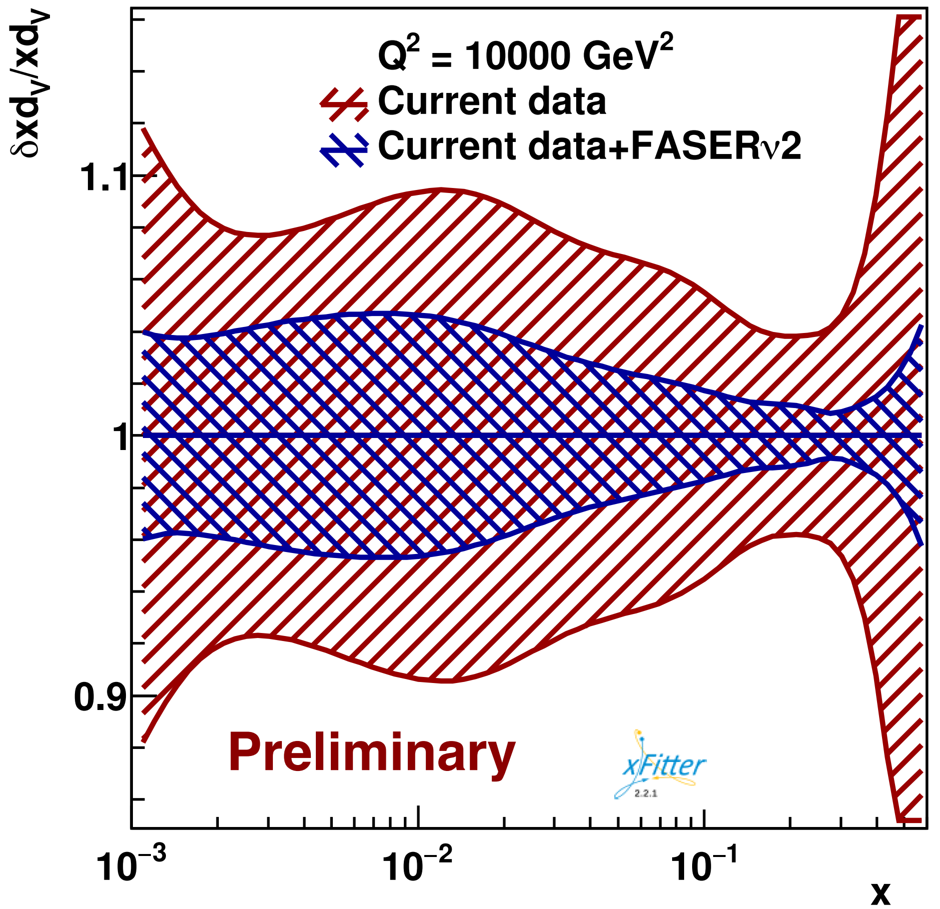
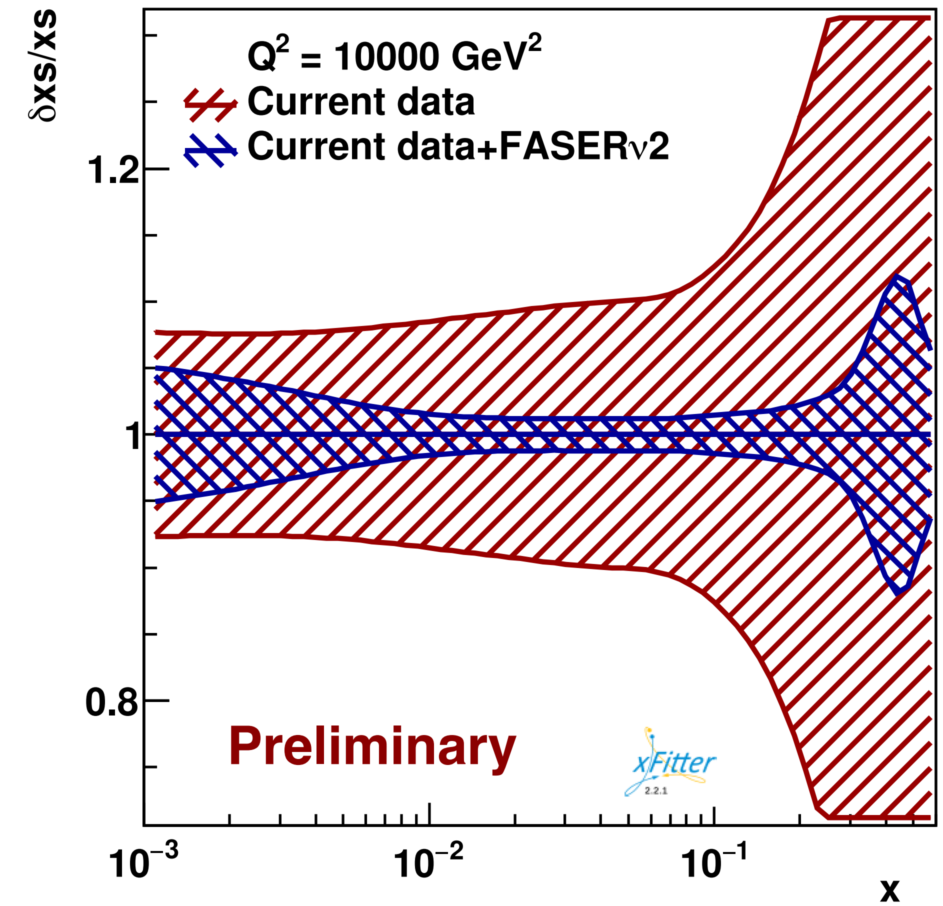
- Muon-neutrinos are best for DIS fits due to **larger event rates** and **smaller production uncertainties**
- *e.g.* FASERv2 would record around **500K (75K)** DIS inclusive (charm-tagged) muon-neutrino events
- Current experiments are limited by statistics, but FPF experiments will likely be **limited by systematics**
- Ultimate reach achieved by **combining data from all experiments** (systematics cross-calibration)

Impact on proton PDFs



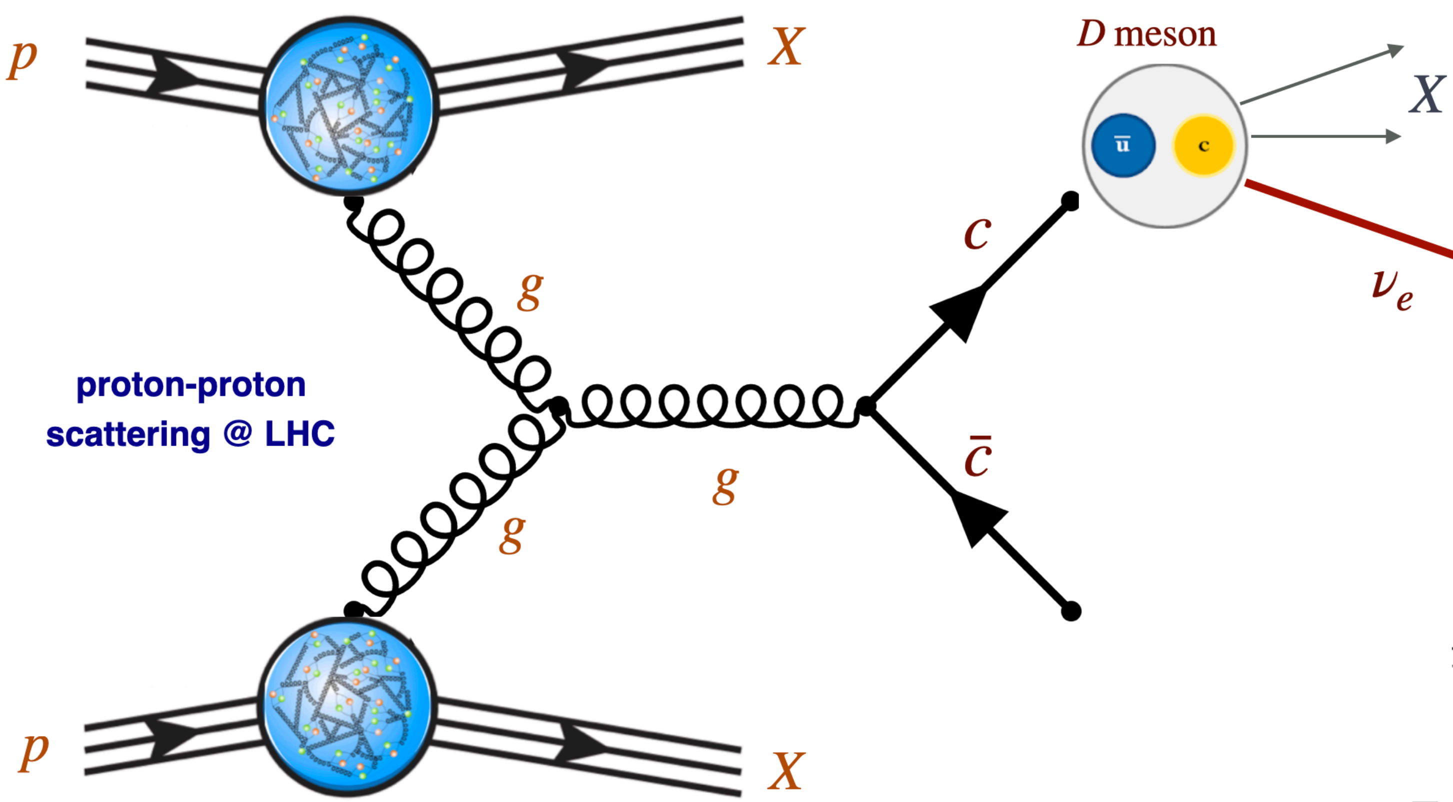


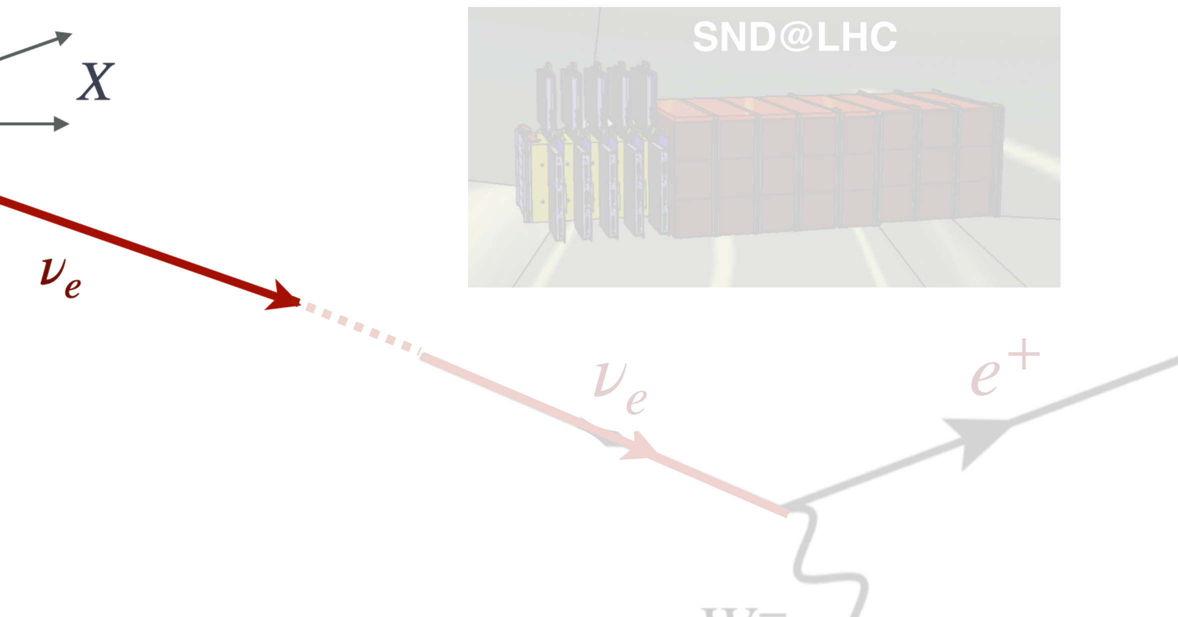
- Impact on proton PDFs quantified by the **Hessian profiling of PDF4LHC21** (xFitter) and by direct inclusion in the **global NNPDF4.0 fit**
- Most impact on **up and down valence quarks** as well as in **strangeness**
- Assume both conservative and optimistic models for systematic errors (limiting factor)
- PDFs improved with LHC neutrino data **enhance precision HL-LHC measurements like *W* mass**

Proton structure at small-x from forward LHC neutrinos

P. Krack, S. Niedenzu, J. Rojo,
J. Sola-Cava, *work in progress*

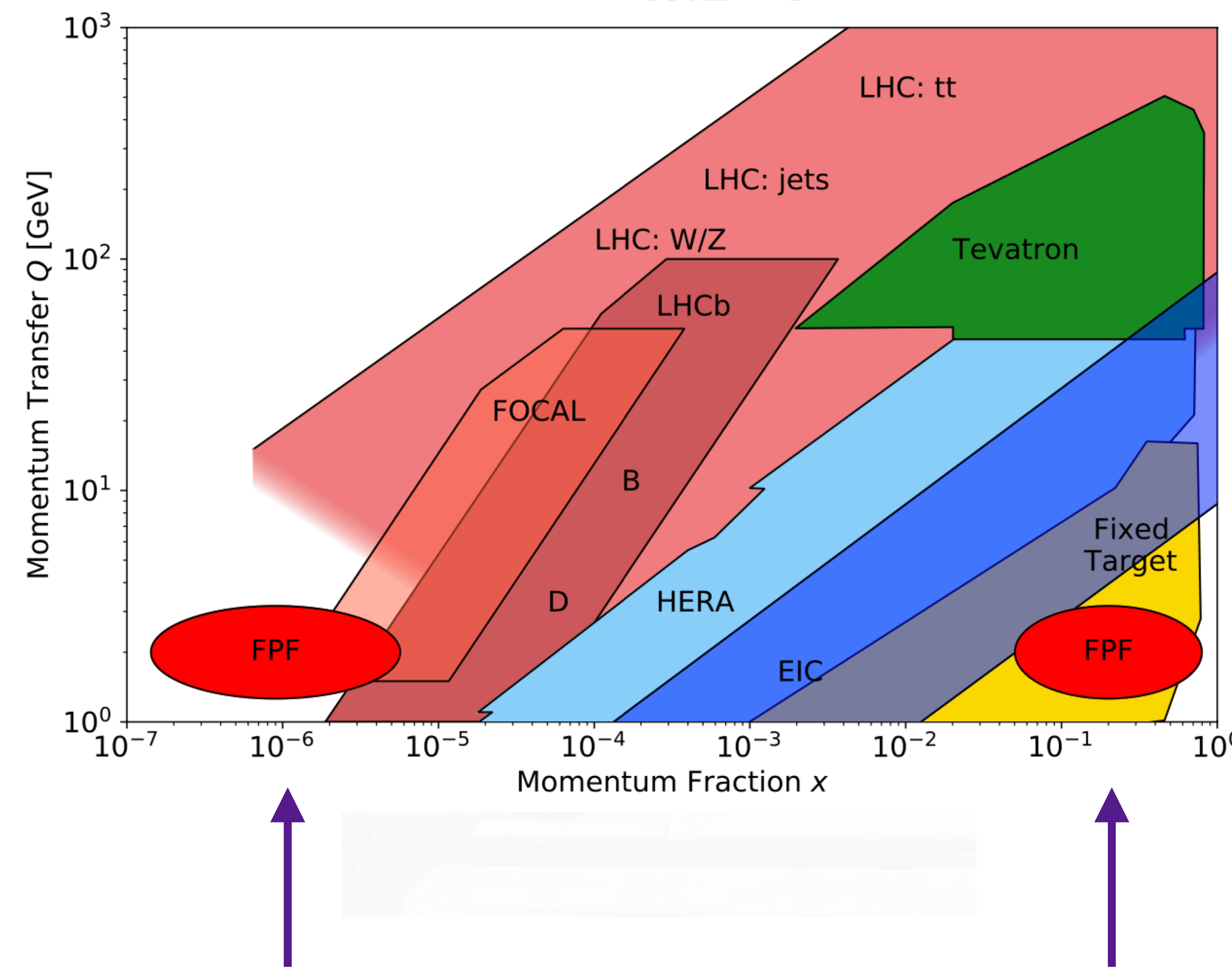
QCD and Neutrino Physics at FASER





Neutrino Production

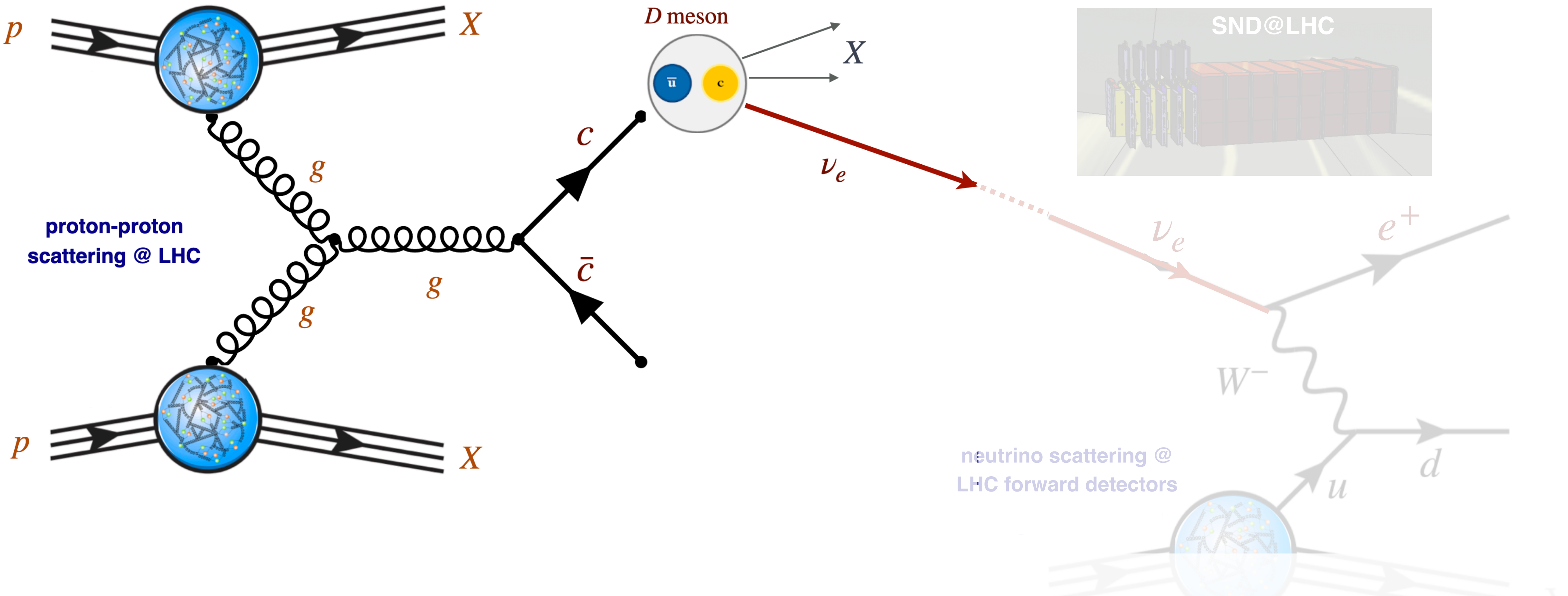
- **Small-x gluon & large-x (intrinsic) charm**
- *D*-meson fragmentation
- Cross-sections for UHE neutrinos (*e.g.* IceCube)
- Cosmic ray modelling, including muon puzzle



small-x gluon

large-x

QCD and Neutrino Physics at FASER



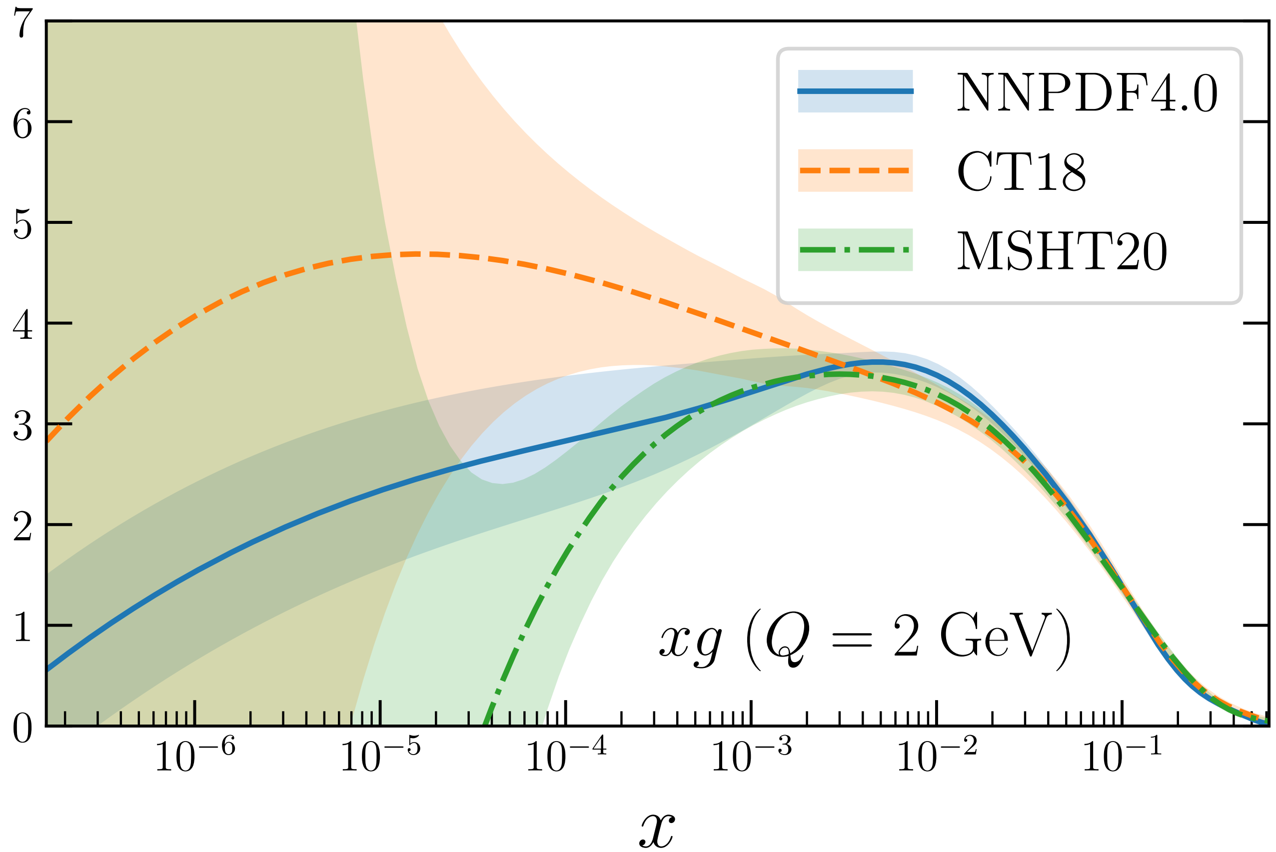
$$\frac{d^2\sigma(\mathrm{pp}\to D(\to\nu)+X)}{p_T^{\nu}y_{\nu}} \propto f_g(x_1,Q^2)\otimes f_g(x_2,Q^2)\otimes\frac{d^2\widehat{\sigma}(gg\to c\bar{c})}{p_T^{c}y_c}\otimes D_{c\to D}(z,Q^2)\otimes \mathrm{BR}(D\to\nu+X)$$

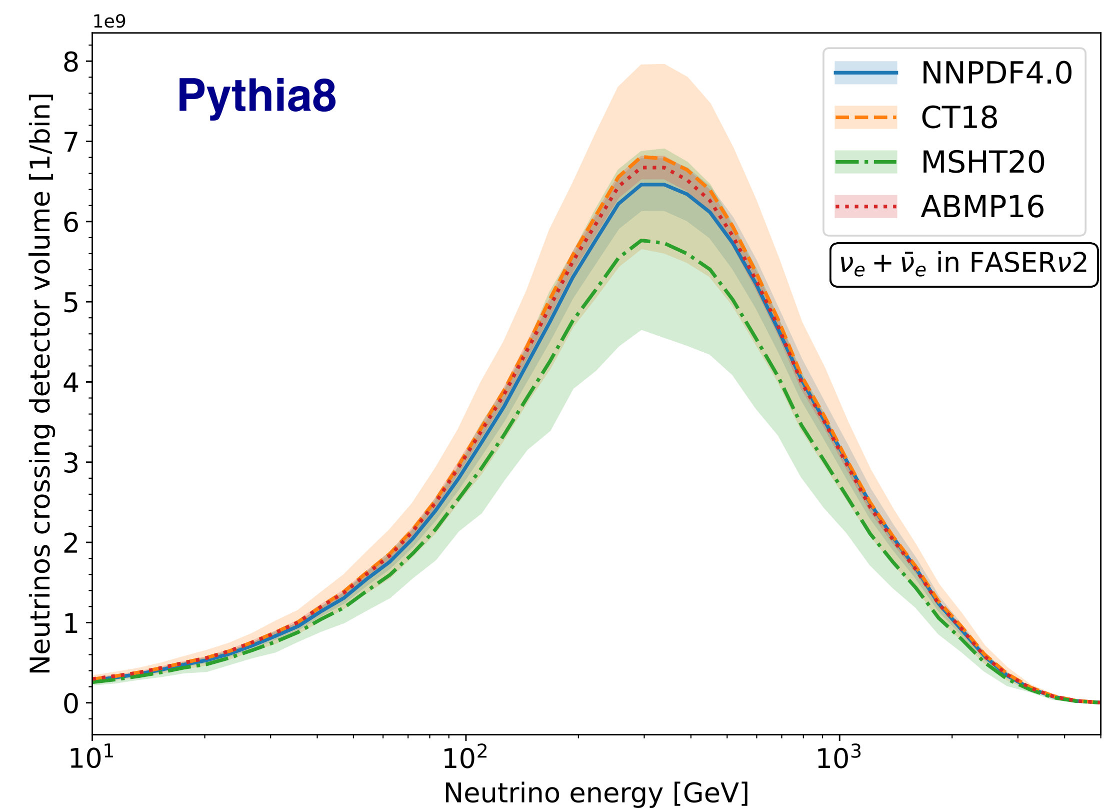
Extract from measured neutrino fluxes

Constrain from FASER/FPF data

QCD prediction: NLO + PS large theory uncertainties

Impact projections



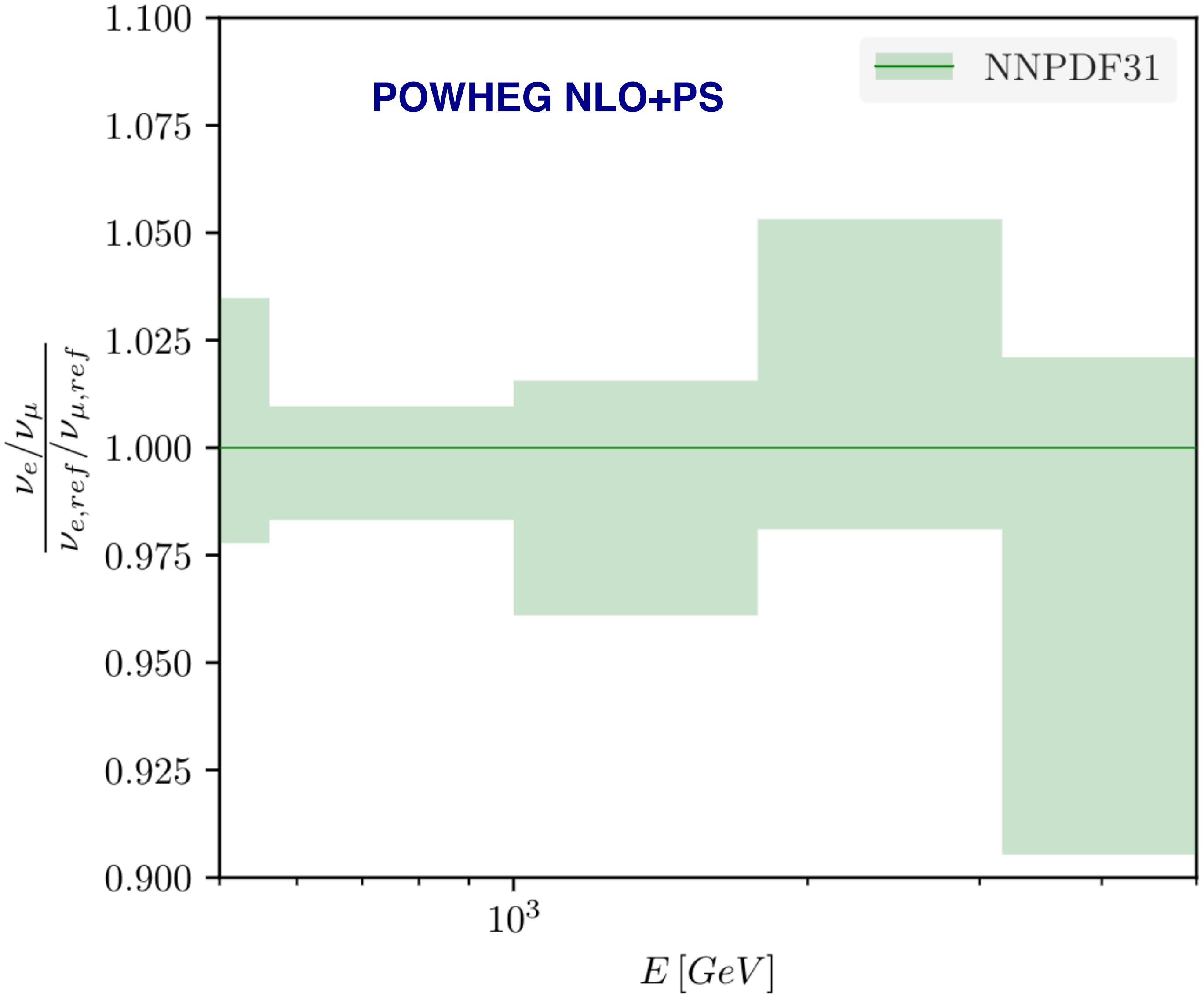


- Spread of PDF predictions (e.g. small-x gluon) modifies **predicted fluxes up to factor 2**
- Focus on electron and tau neutrinos, with the largest **contribution from charm production** where QCD factorisation can be applied
- Construct **tailored observables** where QCD uncertainties (partially)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

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

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

Impact projections



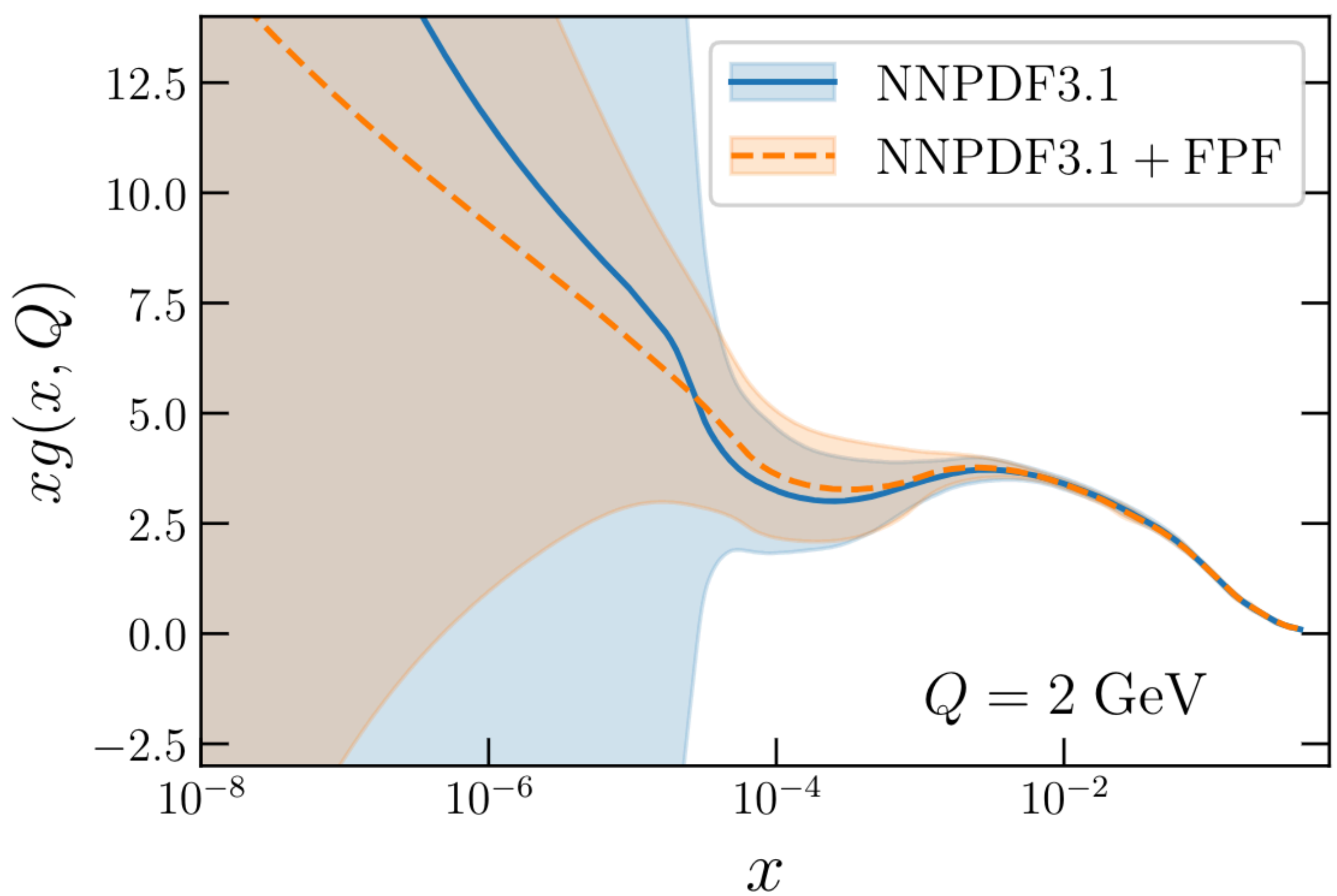
- When taking r**atios of event rates** (e.g. charm electron neutrinos vs charm muon neutrinos), QCD uncertainties reduced to O(few %)
- Strategy: assume a measurement of **inclusive event rates** as a function of neutrino energy with a given precision, quantify impact on PDFs via **Bayesian reweighting**

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

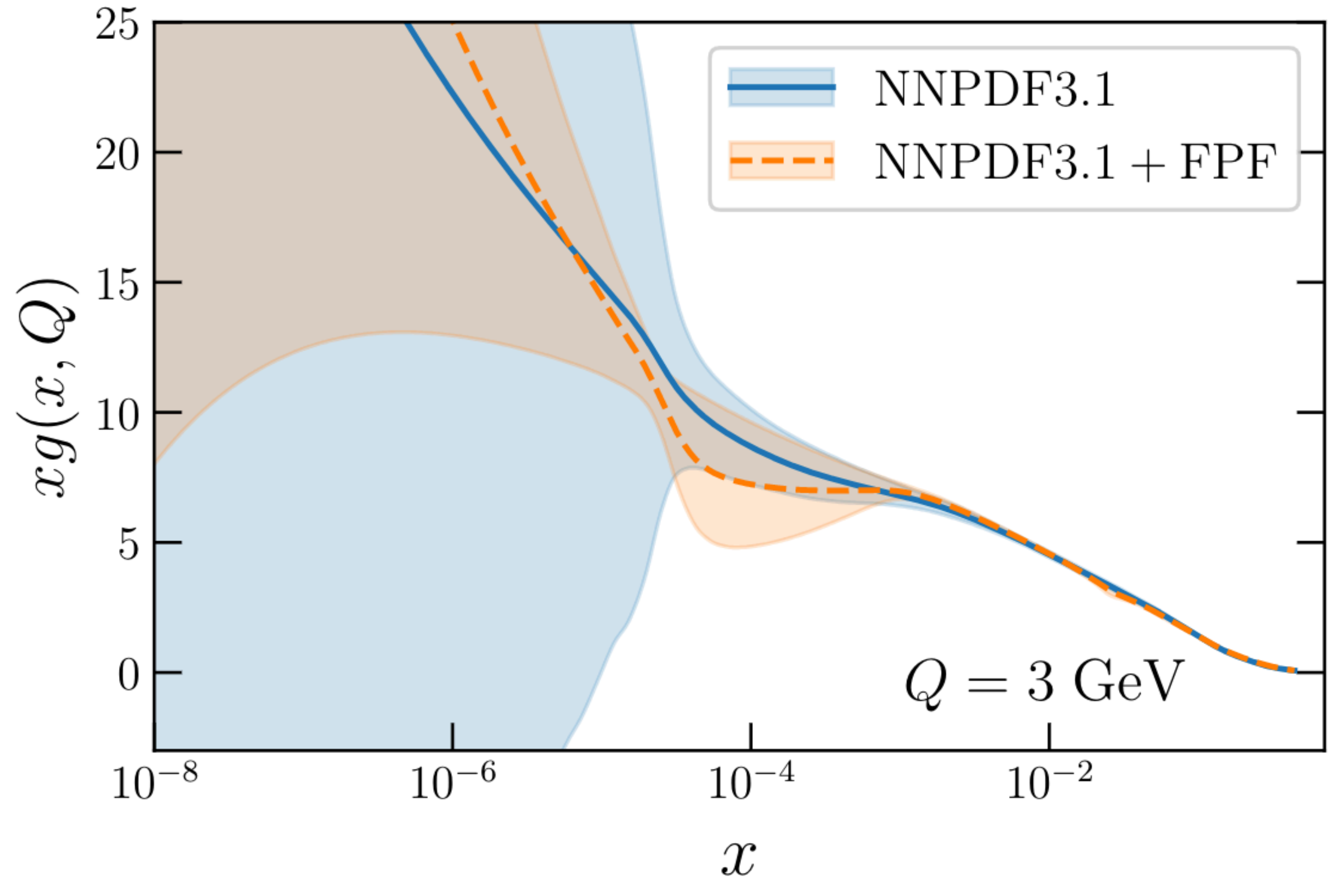
Retain PDF sensitivity while reducing the large QCD uncertainties in the theory prediction

Results

Electron neutrinos, 2% uncertainty in inclusive event rates



Tau neutrinos, 2% uncertainty in inclusive event rates



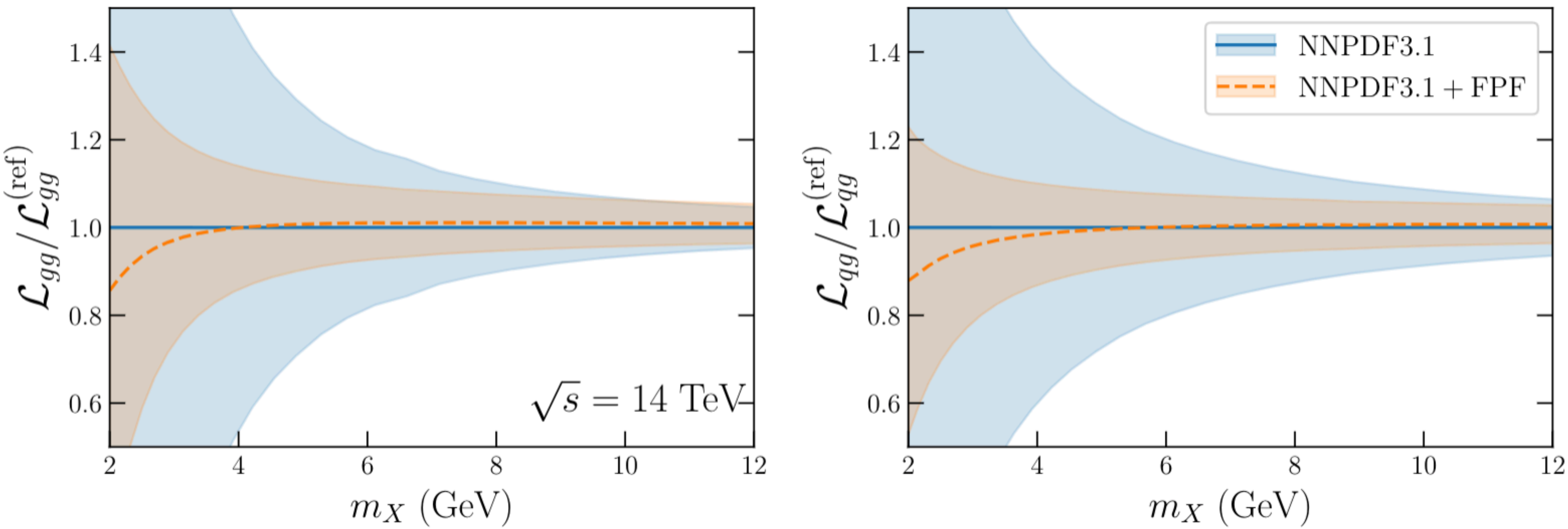
- Results based on pseudo-data for a **measurement of the rapidity ratio** (proxy for experiment ratio)

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

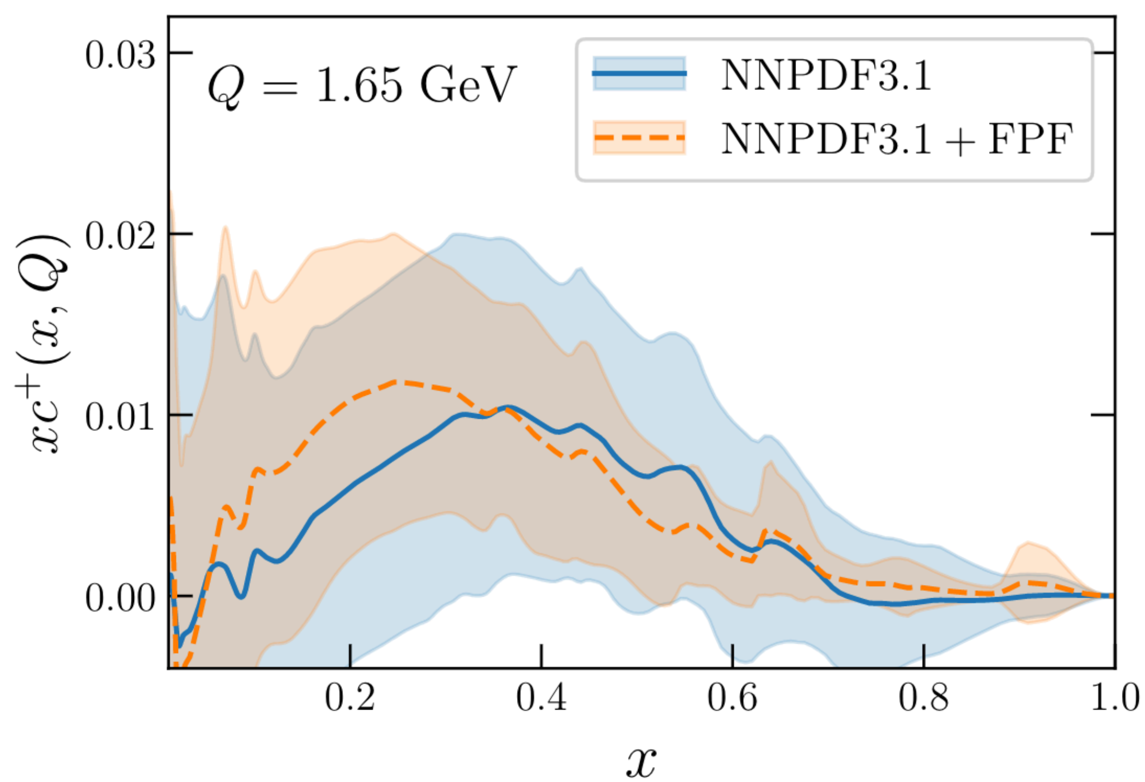
- Sensitivity to **small-x gluon** outside coverage of any other (laboratory) experiment
- Study impact of different observables, QCD errors, and the precision of measurement

Results

Electron neutrinos, 2% uncertainty in inclusive event rates



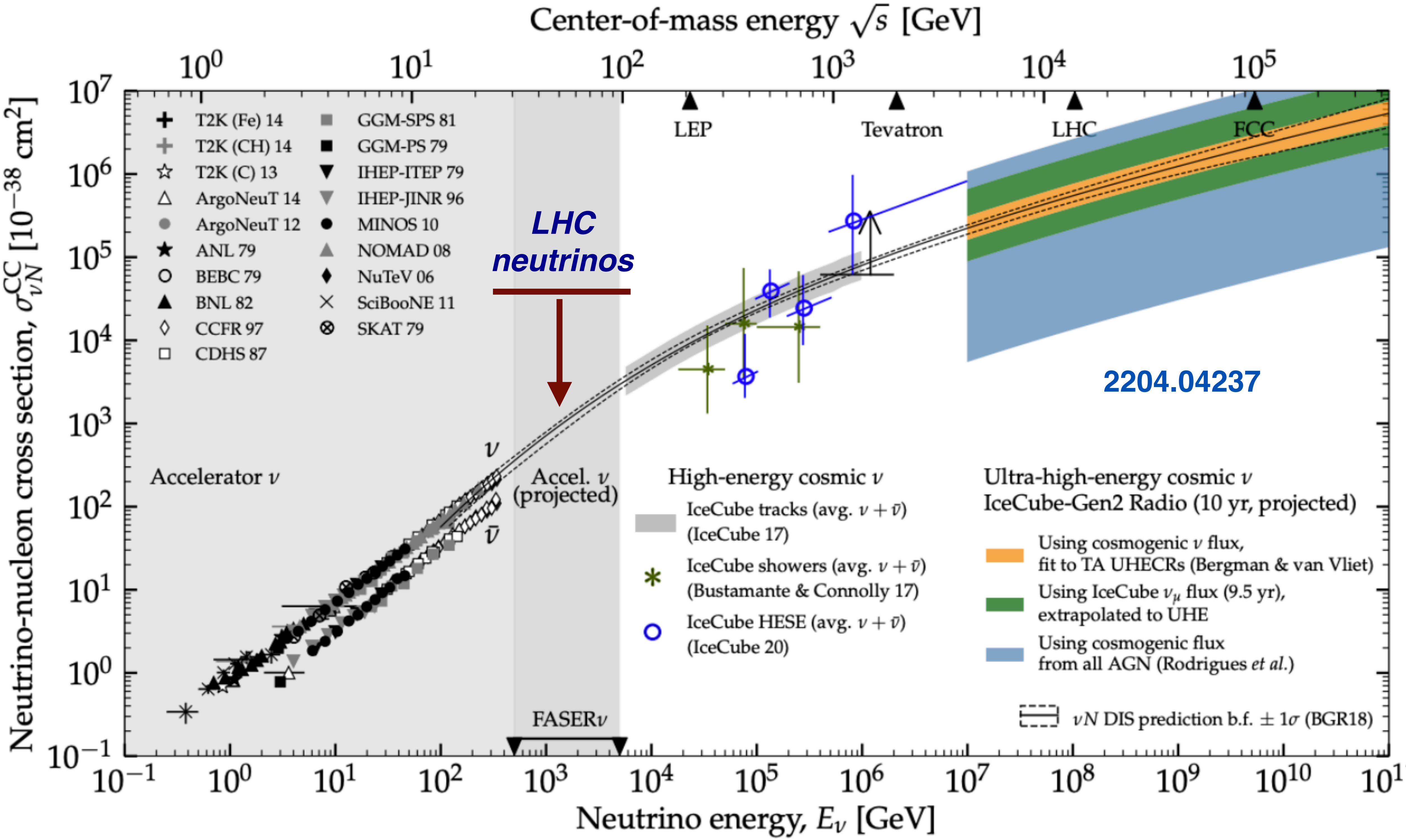
- General improvements of **low-mass gluon-initiated** processes at the LHC
- Constraints also on the **charm PDF** via the gluon-charm initial state
- Run III data should be able to provide a first measurement of the **gluon content of the proton at x=10^{-7}**



Neutrino Structure Functions from GeV to EeV Energies

A. Candido, A. Garcia, G. Magni, T. Rabemananjara, J. Rojo, R. Stegeman, JHEP 23

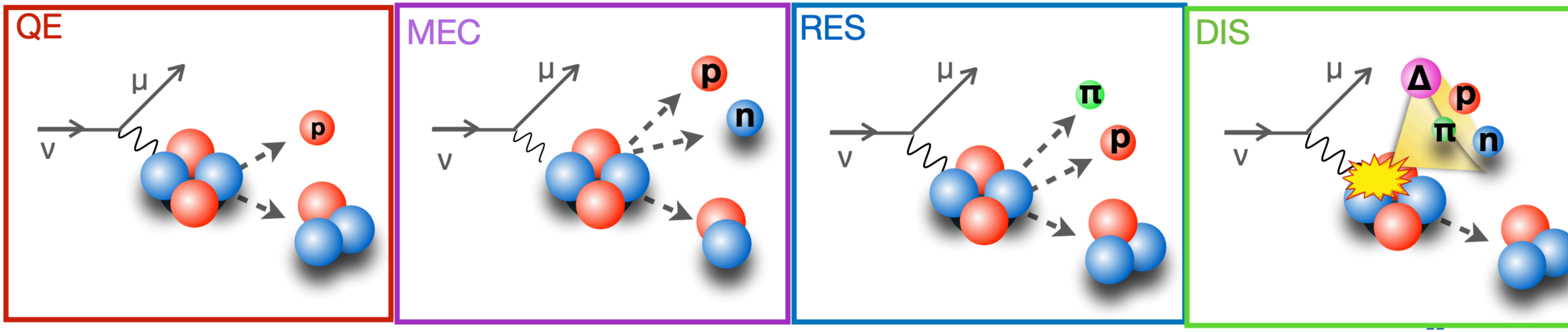
The neutrino cross-section landscape



Depending on the neutrino energy, **different interaction mechanisms** dominate the neutrino-nucleus cross-section

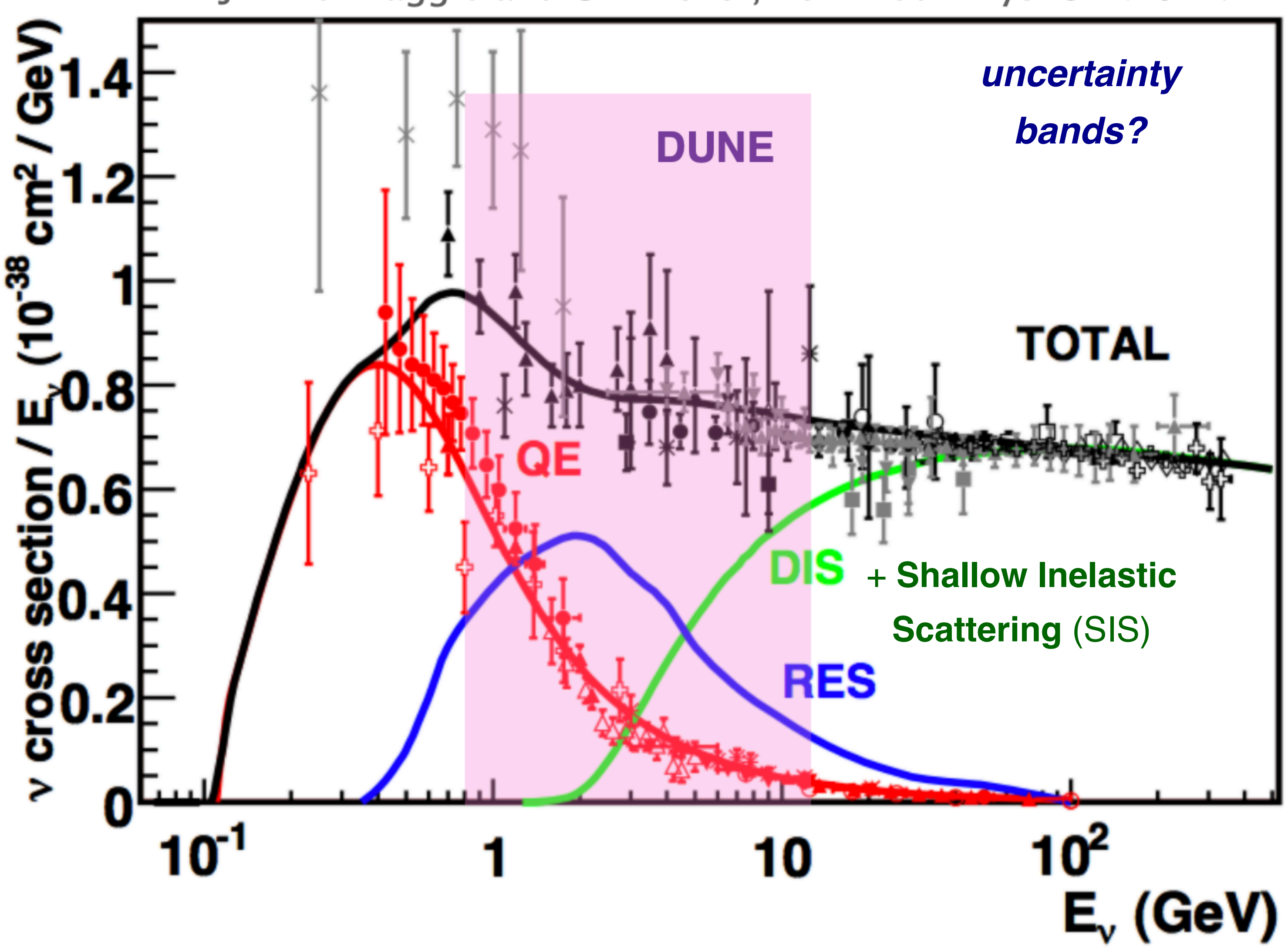
Collider neutrinos cover an uncharted range of neutrino cross-sections

The neutrino cross-section landscape

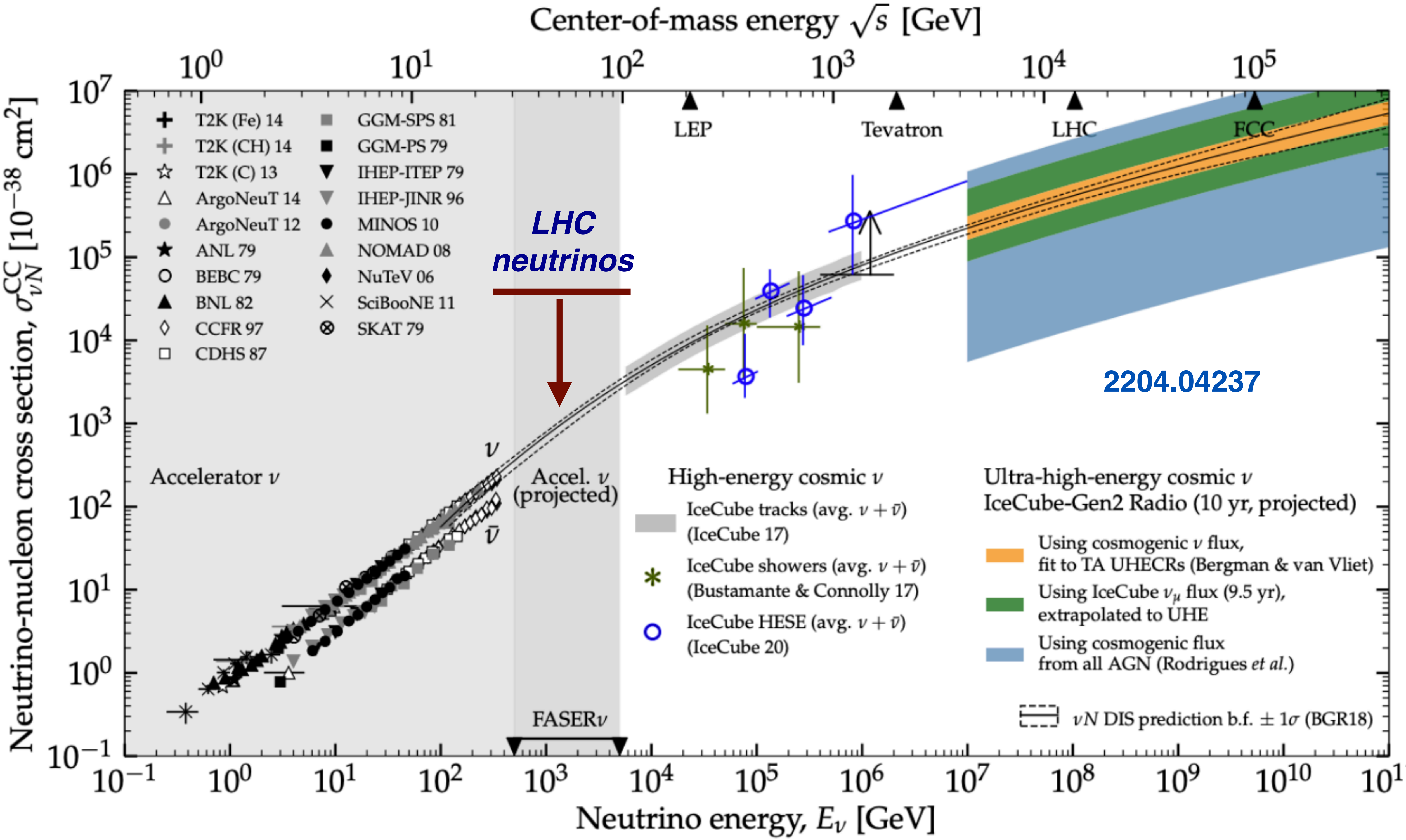


- For energies > 5 GeV, **inelastic scattering** dominates the inclusive cross-section
- Common misconception: inelastic scattering does **not** coincide with **deep-inelastic scattering** (DIS) where pQCD can be applied!
- How robust is our **theoretical understanding** of neutrino inelastic scattering interactions?

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)



The neutrino cross-section landscape



Inelastic scattering (SIS + DIS)

Deep-inelastic scattering (>95%)

sizable kinematic region where **Shallow Inelastic Scattering** (SIS) cannot be neglected

The role of the low-*Q* region

inclusive neutrino cross-sections receives **sizeable contributions from *Q* < 2 GeV region**, where structure functions cannot be evaluated in the pQCD framework

$$\sigma(E_\nu) = \int_{Q^2_{\rm min}}^{2m_N E_\nu} dQ^2 \left[\int_{Q^2/(2m_N y E_\nu)}^{1} dx \, \frac{d^2\sigma}{dx dQ^2}(x, Q^2, E_\nu) \right]$$

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

Deep-Inelastic Scattering

$$F_i^{\nu A}(x,Q^2) = \sum_{j=q,\bar{q},g} \int_x^1 \frac{dz}{z} C_{i,j}^{\nu N}(z, \alpha_s(Q^2)) f_j^{(A)}\left(\frac{x}{z}, Q^2\right)$$

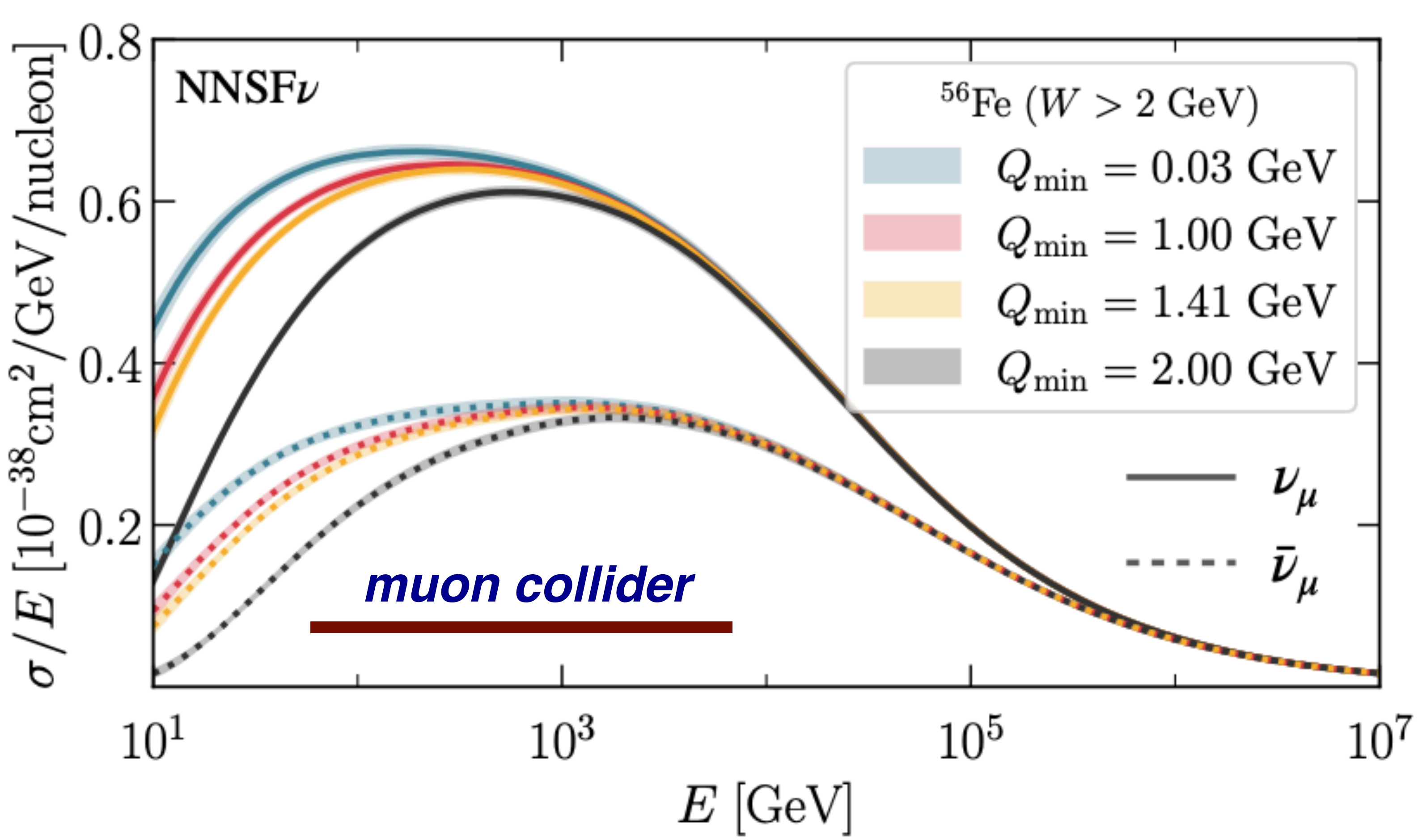
Shallow-Inelastic Scattering

$$F_i^{\nu A}(x,Q^2) = \quad ?$$

The role of the low-Q region

inclusive neutrino cross-sections receives **sizeable contributions from $Q < 2$ GeV region**, where structure functions cannot be evaluated in the pQCD framework

$$\sigma(E_\nu) = \int_{Q^2_{\min}}^{2m_N E_\nu} dQ^2 \left[\int_{Q^2/(2m_N y E_\nu)}^{1} dx \, \frac{d^2\sigma}{dx dQ^2}(x, Q^2, E_\nu) \right]$$



- Even for neutrino energies of hundreds of GeV, **sizeable contribution from low-Q region**
- Perturbative QCD not reliable, what to do?
- So far, most calculations used in phenomenology rely on **phenomenological models**

The Bodek-Yang model

The **Bodek-Yang model** is popular to describe **inelastic neutrino DIS** structure functions

based on **effective leading-order PDFs** (GRV98LO) supplemented to phenomenological scaling variables and *K*-factors to improve agreement with data

$$f_i^{\rm LO}(x, Q^2) \to f_i^{\rm LO,BY}(\xi, Q^2) \qquad \xi = \frac{2x(Q^2 + m_f^2 + B)}{Q^2\left[1 + \sqrt{1 + (2m_N x)^2/Q^2}\right] + 2Ax}$$

Limitations of the BY model of neutrino structure functions:

- Obsolete PDF parametrisation that **ignores constraints from the last 25 years**
- Neglects **higher-order QCD corrections** (can be up to 100%)
- Cannot be used above 100 TeV: **not an option for UHE neutrinos**
- Does not provide **uncertainty estimate**, difficult to assess its accuracy and precision
- Cannot be systematically improvable e.g. by new data

The Bodek-Yang model

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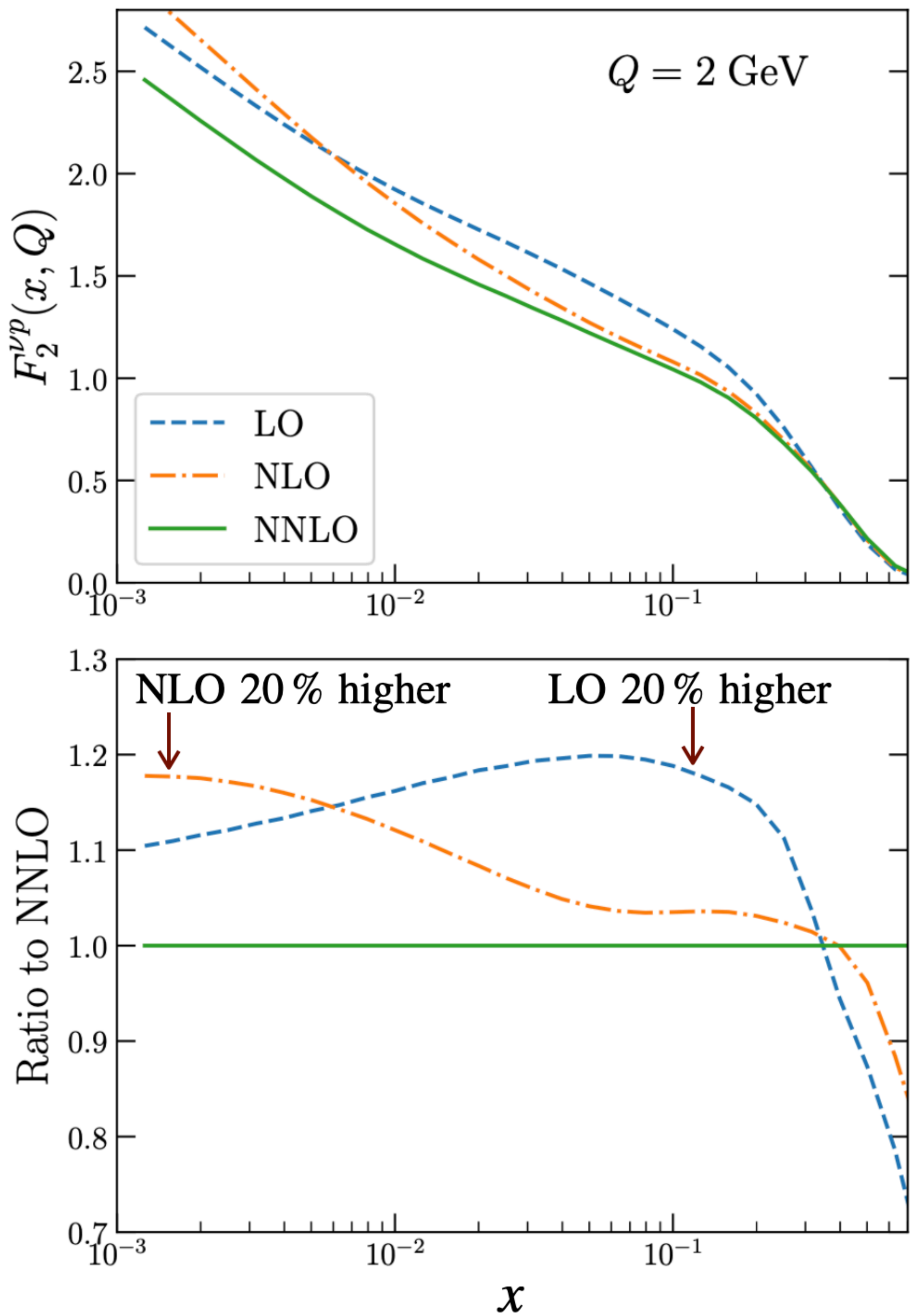
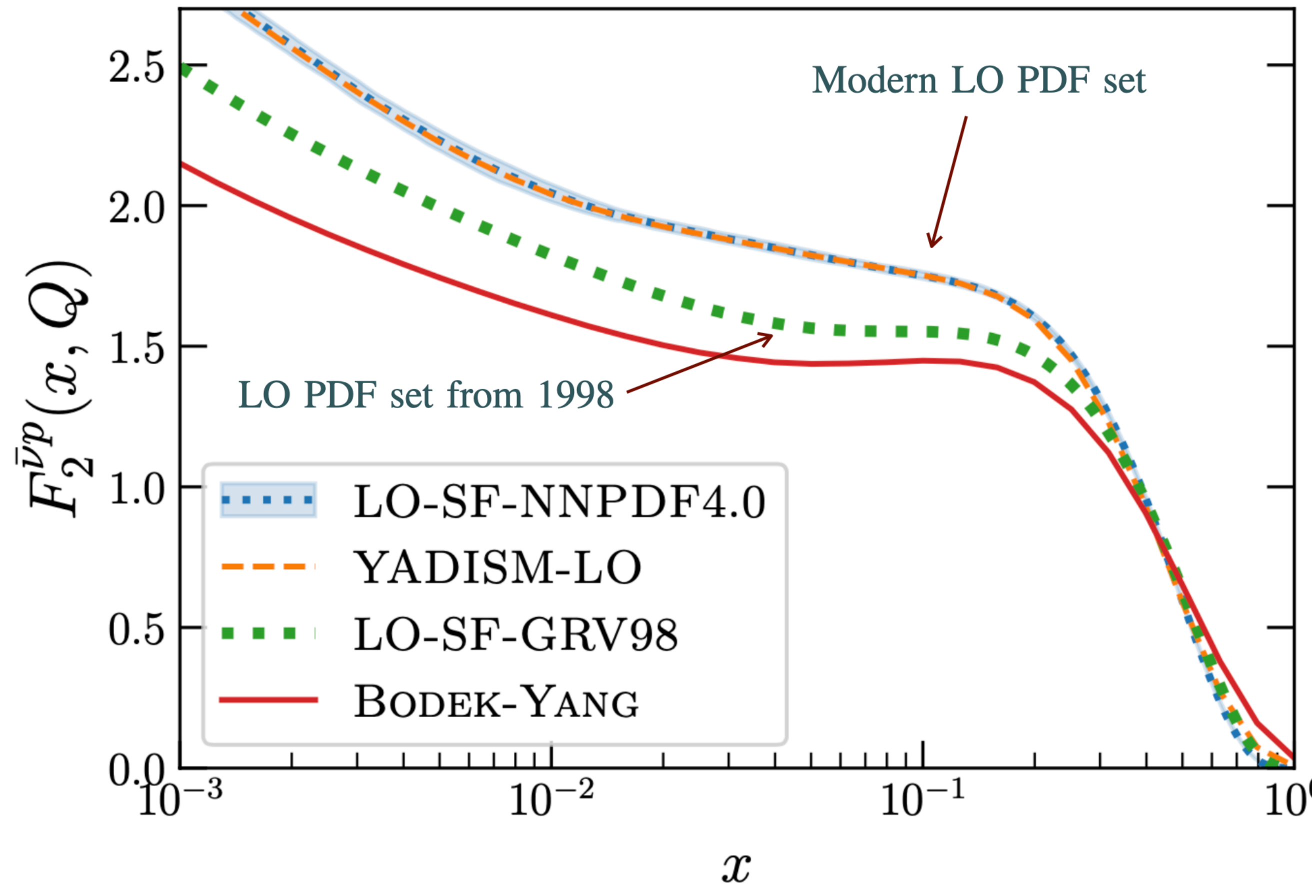
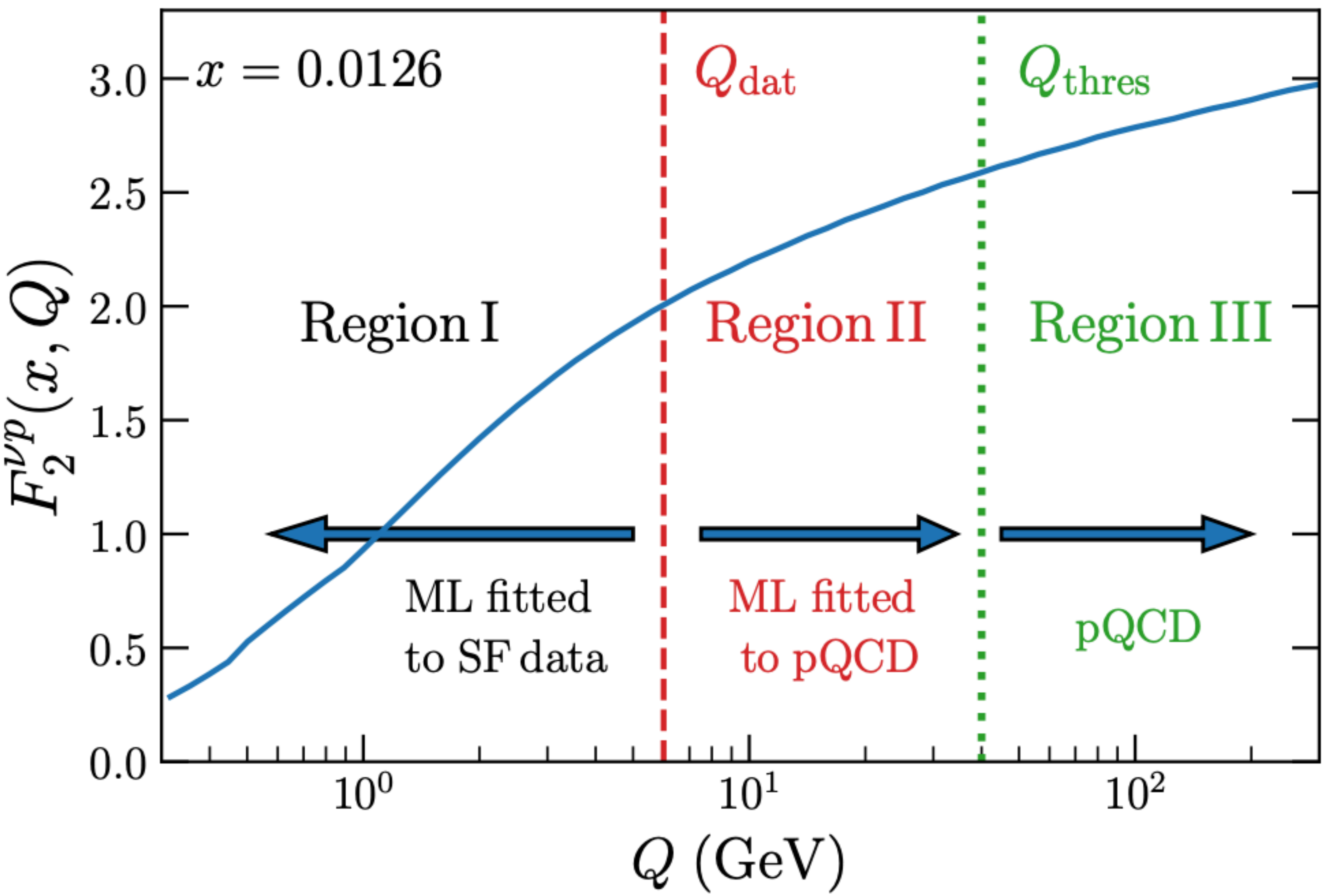




Improved models of neutrino-nucleon interactions essential for **LHC neutrino physics** as well as IceCube, KM3NET, …

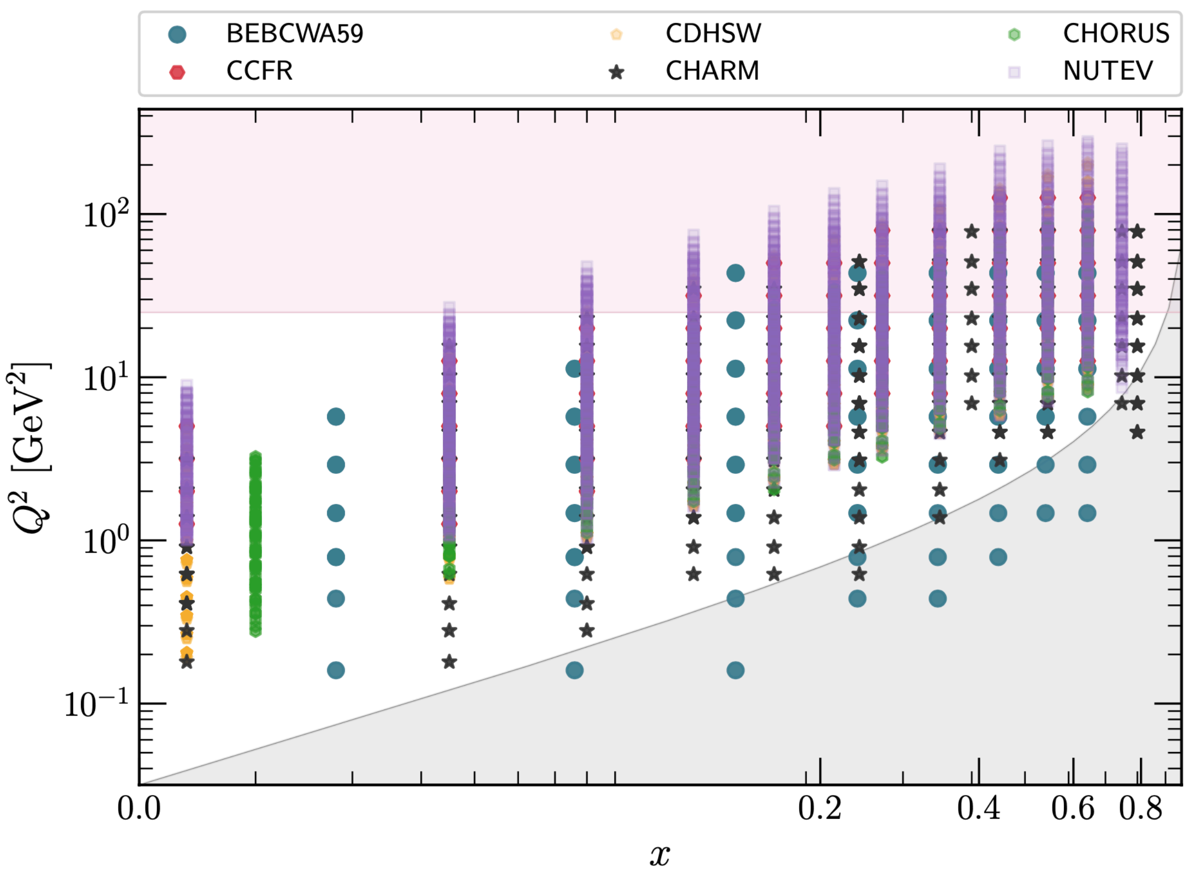
The NNSFν approach

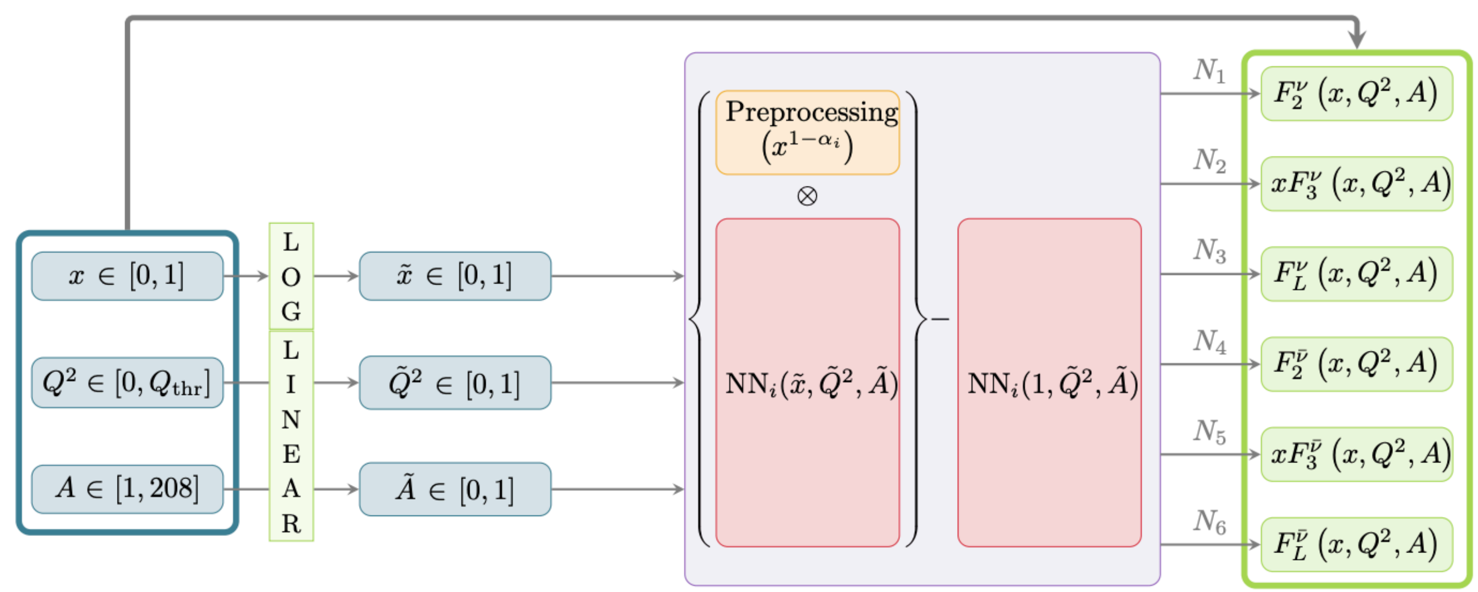
Motivation: realise the first determination of neutrino structure functions **valid from photoproduction $Q = 0$ all the way to $Q = 100$ TeV**, enabling calculation of inclusive inelastic cross-sections **for neutrinos from 5 GeV to 10^{12} GeV energies**



The NNSFν approach

- Use available data on neutrino-nucleus scattering to **parametrise and determine inelastic structure functions** by means of the NNPDF fitting methodology



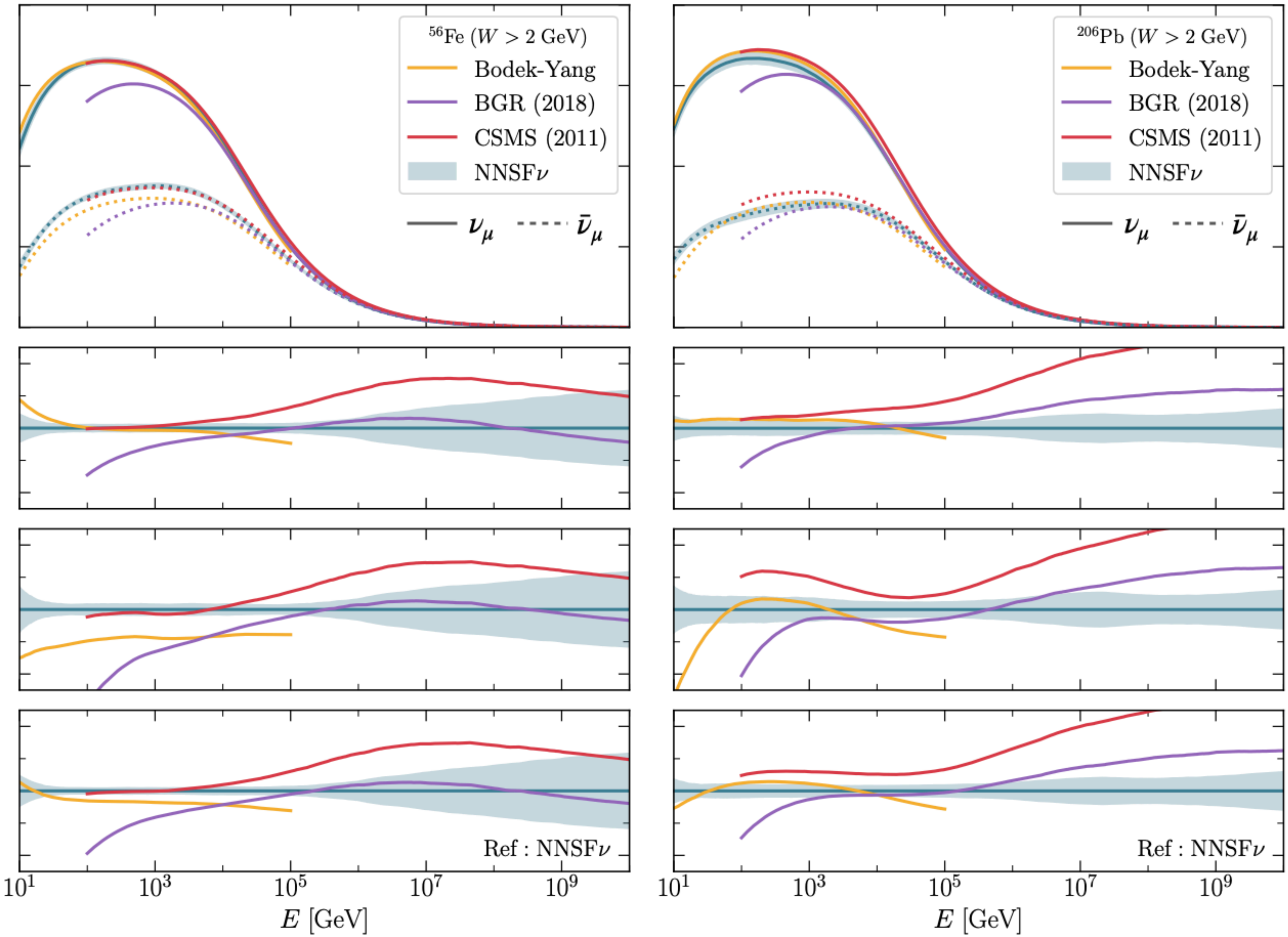


- This data-driven parametrisation is made to **converge to the pQCD calculation** for large enough Q^2 values as implemented with Lagrange multipliers

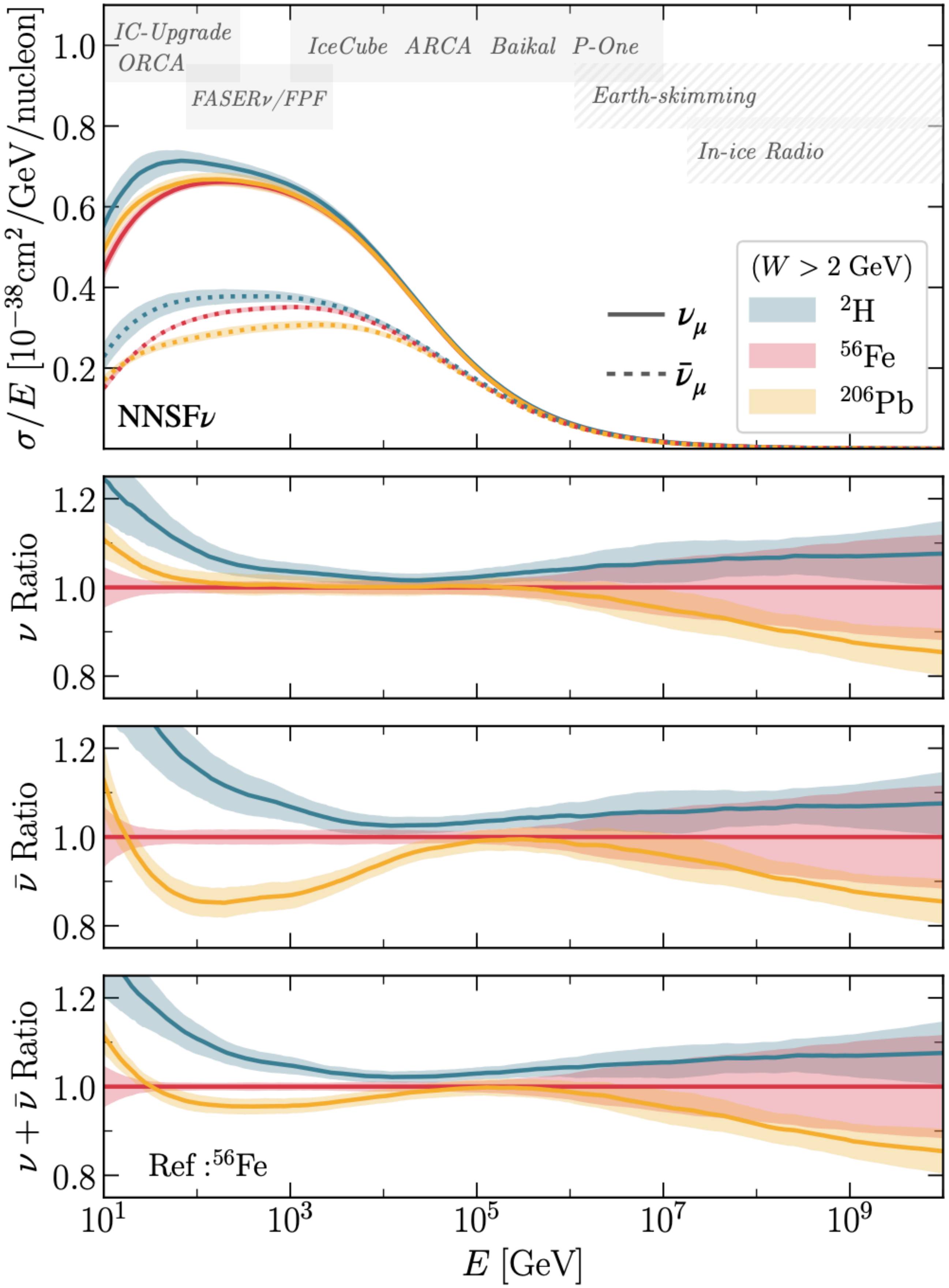
- In the neutrino energy region sensitive only to $Q >$ few GeV, **replace by pQCD calculation**

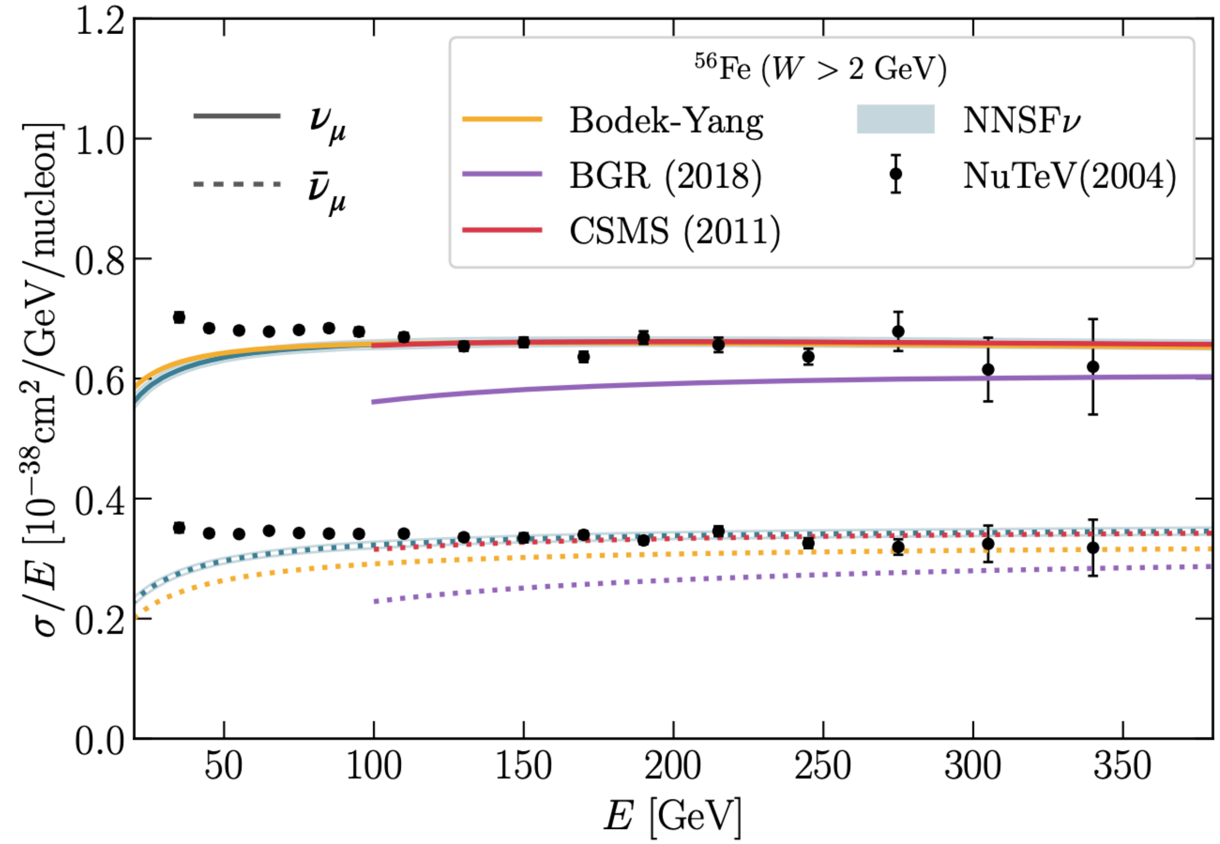
consistent determination of neutrino structure functions valid **for 12 orders of magnitude** from E_{nu} = few GeV up to $E_{nu}=10^{12}$ GeV

The NNSFν results



The NNSFν results





- Agreement with available neutrino structure function and **cross-section data**
- Estimate experimental & theory **uncertainties**
- Model-independent determination of **nuclear corrections**

Implemented in GENIE: ready to be used in your neutrino simulations!

Summary and outlook

- LHC neutrinos realise an exciting program in a broad range of topics from BSM 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

- 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

- Improved neutrino MC generators demand state-of-the-art QCD calculations suitable for a wide kinematic range: NNSFν provides DIS structure functions valid from **energies of a few GeV all the way up to multi-EeV energies**

Summary and outlook

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Thanks for your attention!