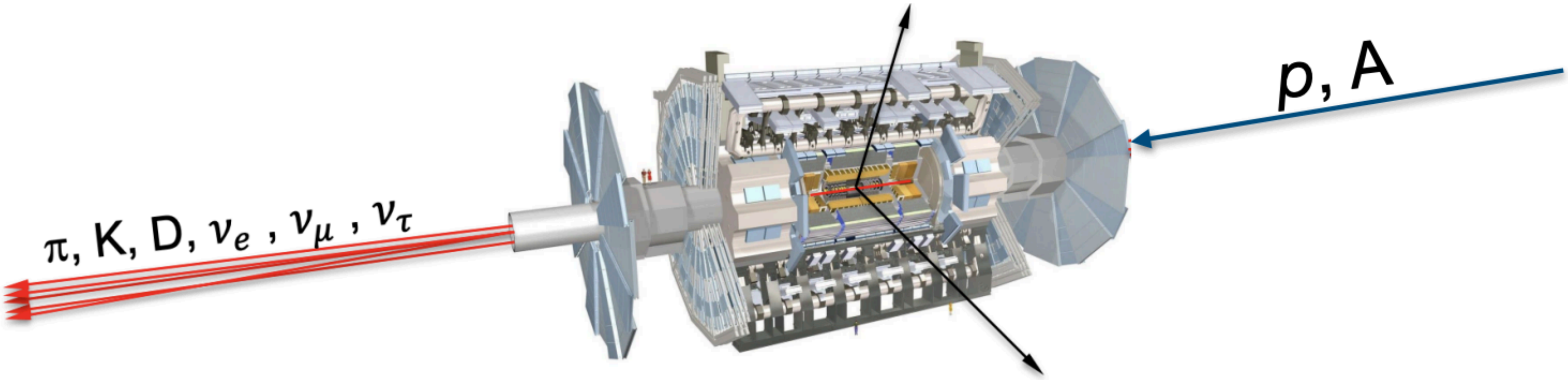
Physics with TeV Neutrinos from the LHC

Juan Rojo, VU Amsterdam & Nikhef



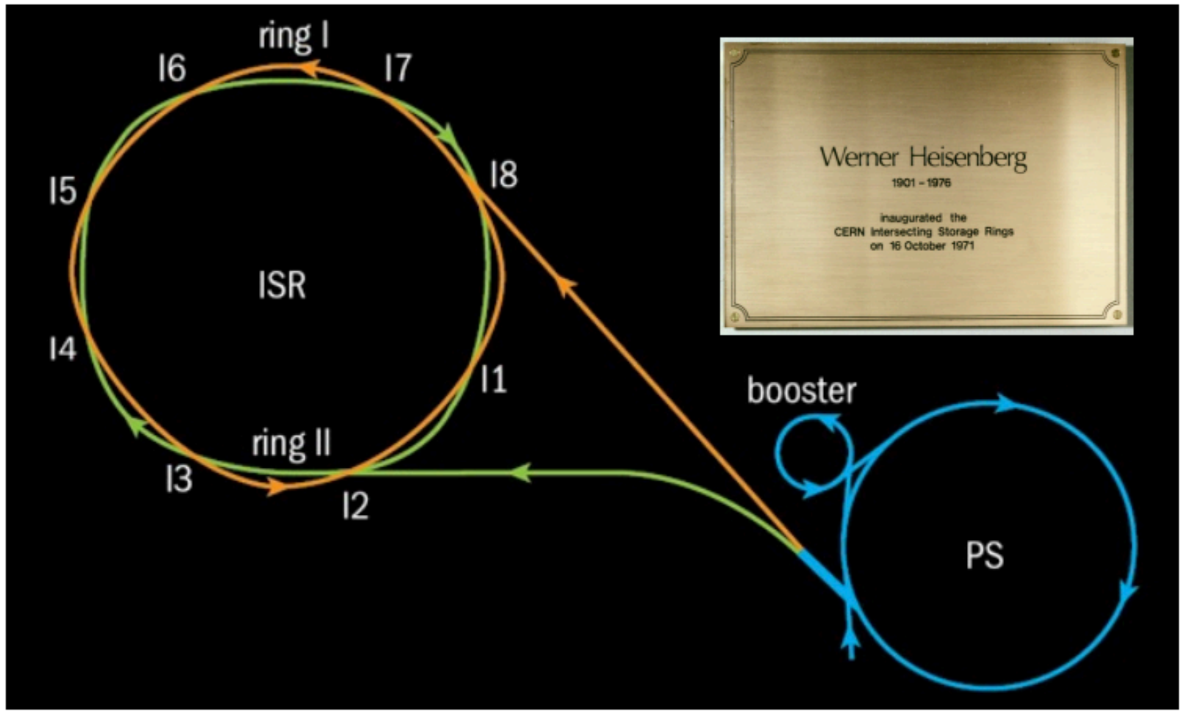
Nikhef Theory Day

Nikhef, 8th December 2023

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.

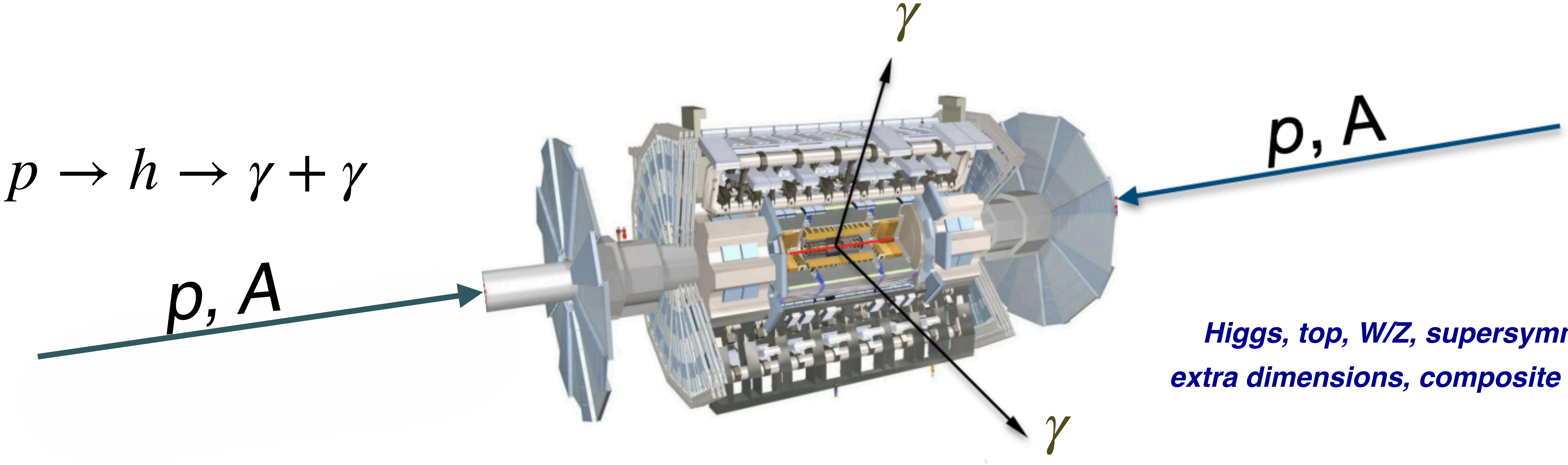
J. Feng, CERN Colloquium, June 2023

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**

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



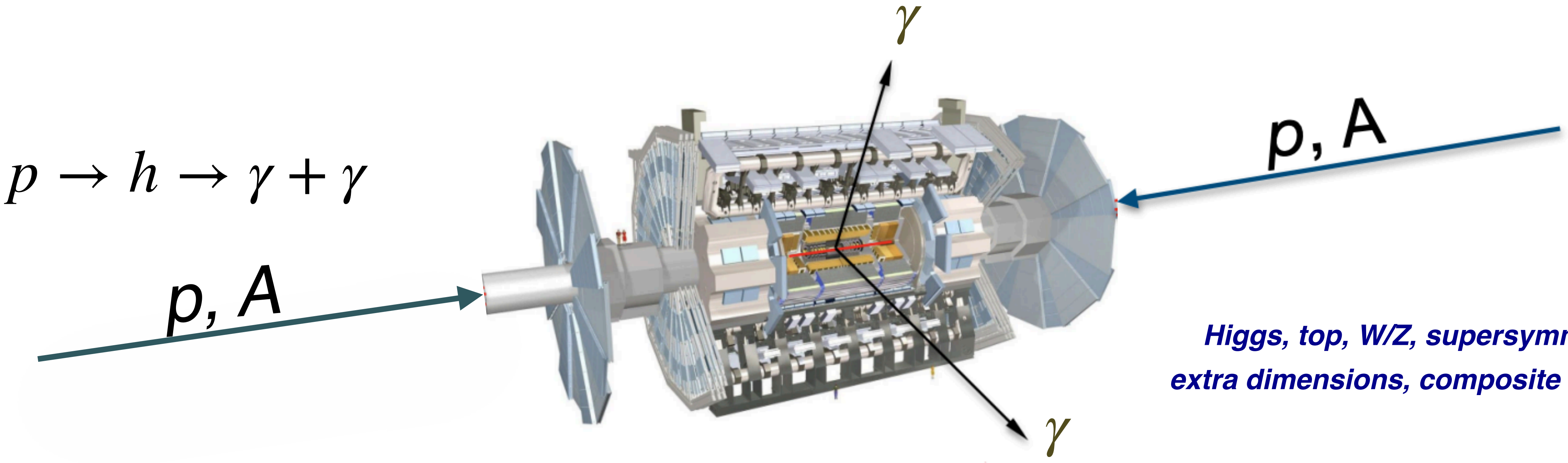
Higgs, top, W/Z, supersymmetry, extra dimensions, composite Higgs…

Central region of the detector fully instrumented
Forward region (proton beam direction) ignored

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

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

for ATLAS & CMS

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

central region covered

Neutrinos at the LHC

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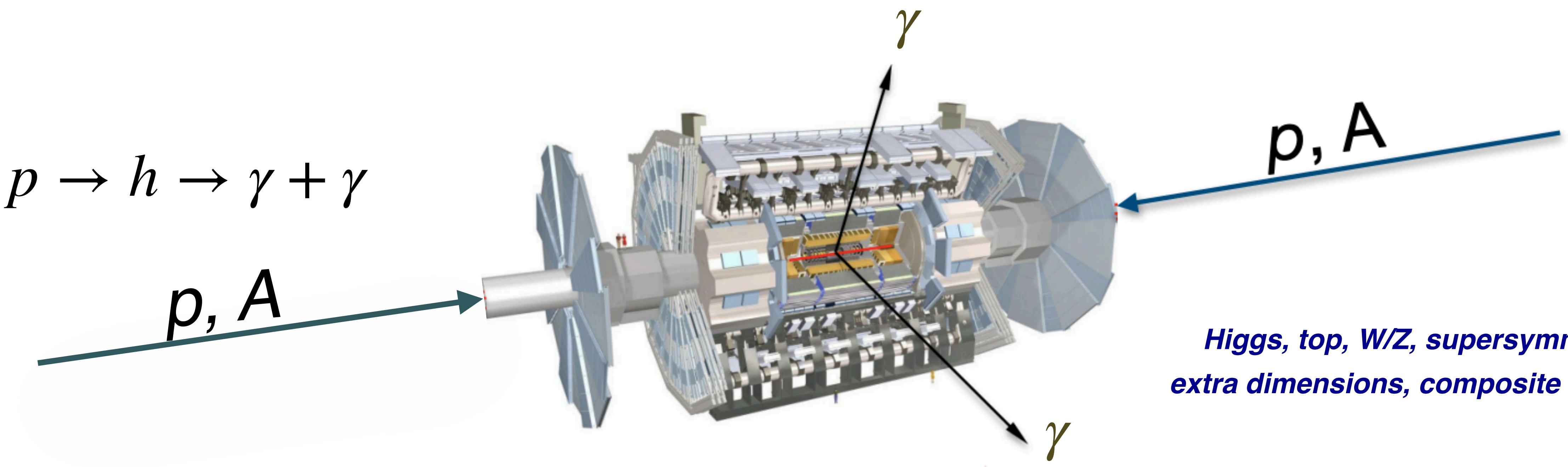

Higgs, top, W/Z, supersymmetry, extra dimensions, composite Higgs…

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scattering angle

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

for ATLAS & CMS

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

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**

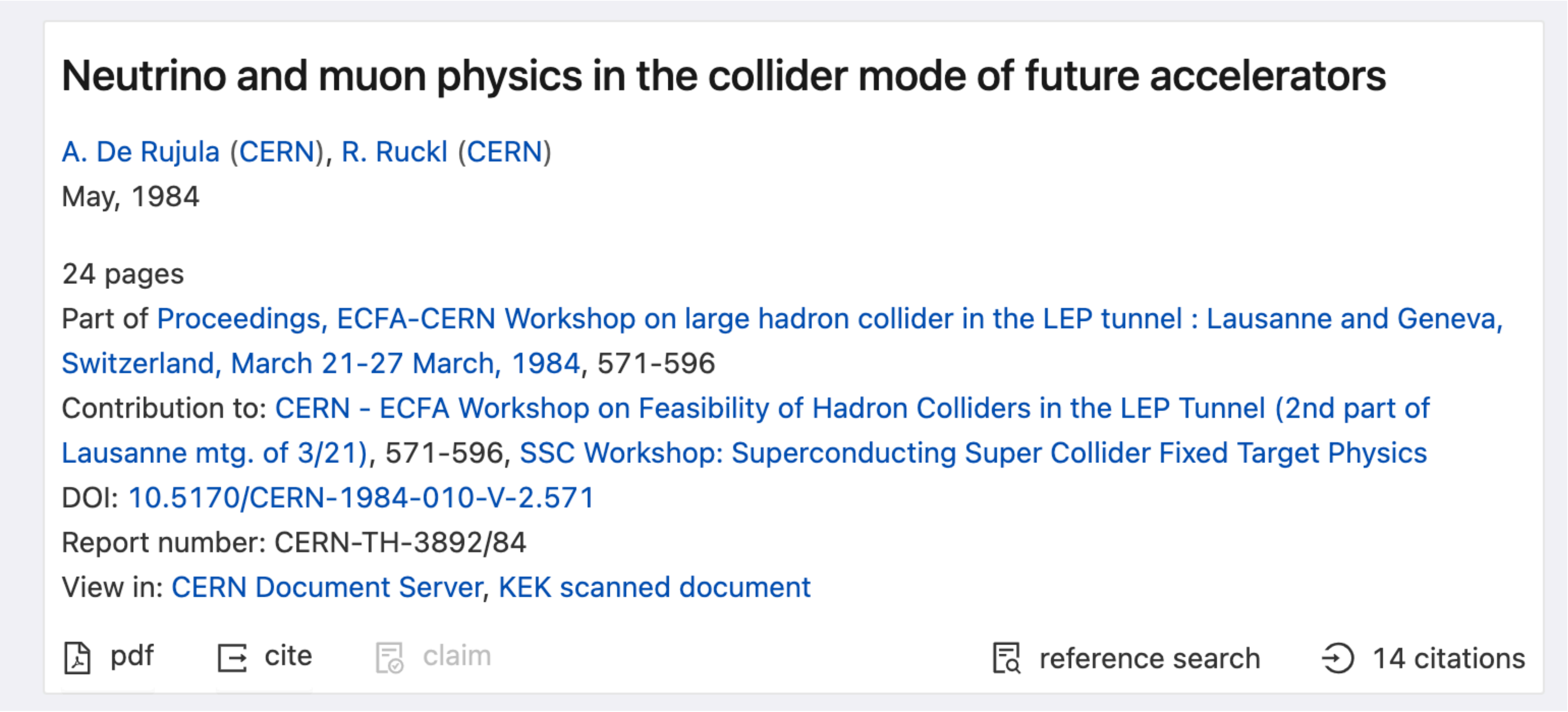
for LHCb

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

Neutrinos at the LHC

- New physics, if **light and feebly-interacting,** could already be copiously produced at the LHC, but fail to be detected due to the **blind spots** of existing LHC 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

First proposal in 1984

Neutrinos at the LHC

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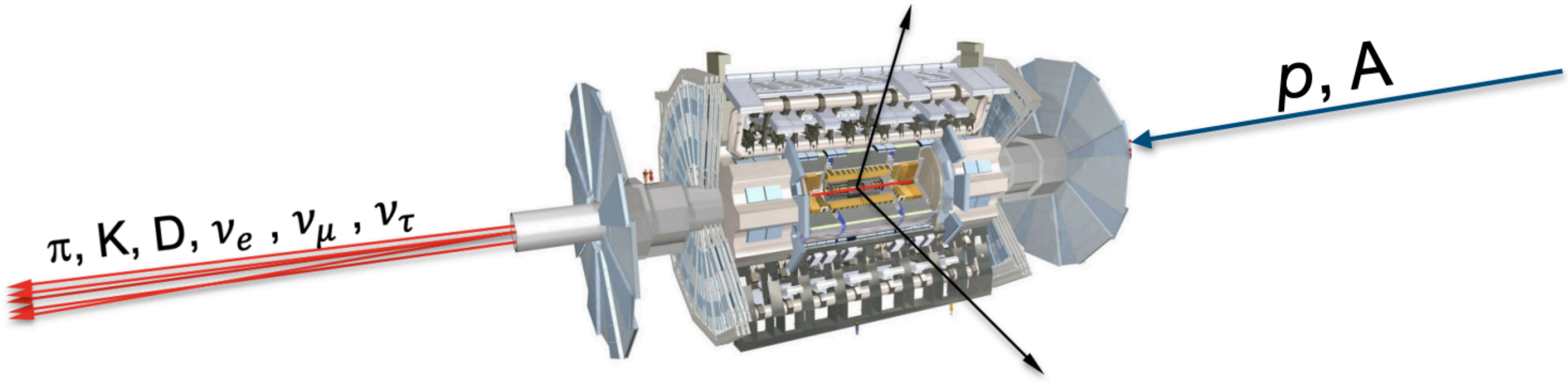
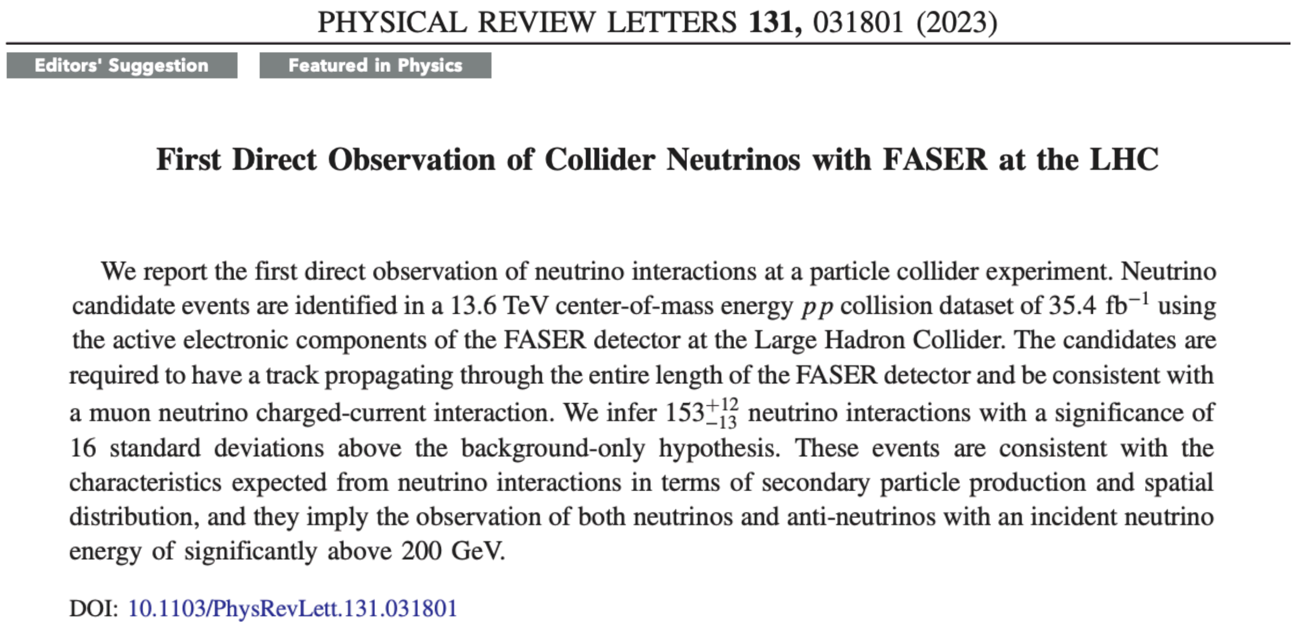


electron (tau) neutrinos mostly (entirely) from D-meson decays,
muon neutrinos from pion/kaon decays

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)



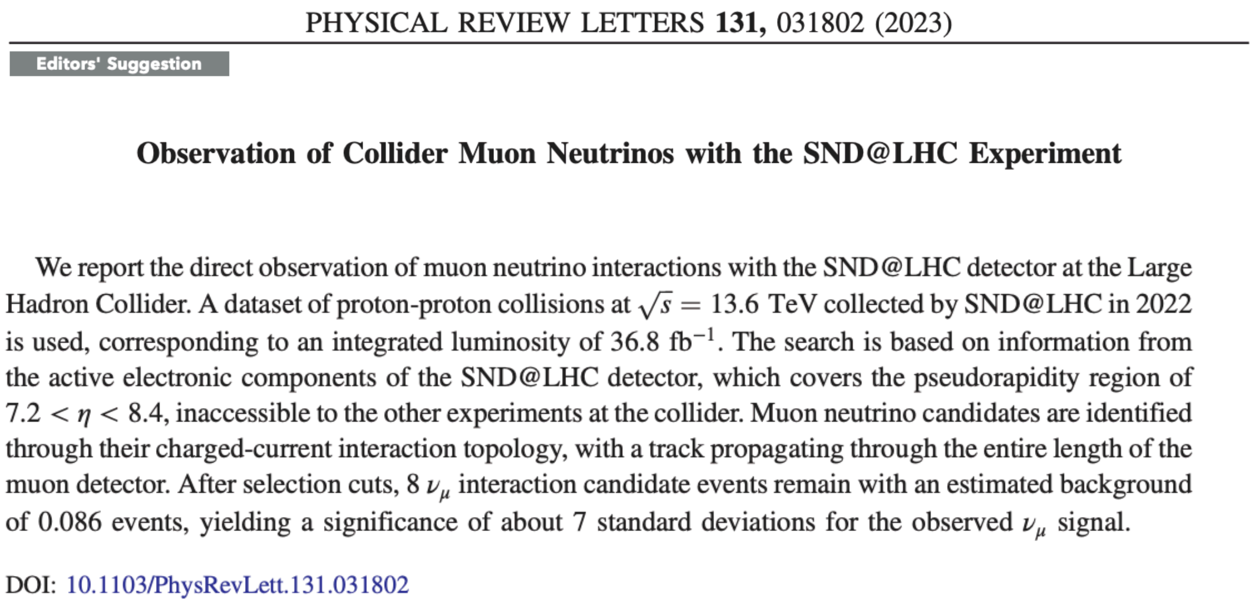
PHYSICAL REVIEW LETTERS **131,** 031801 (2023)

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

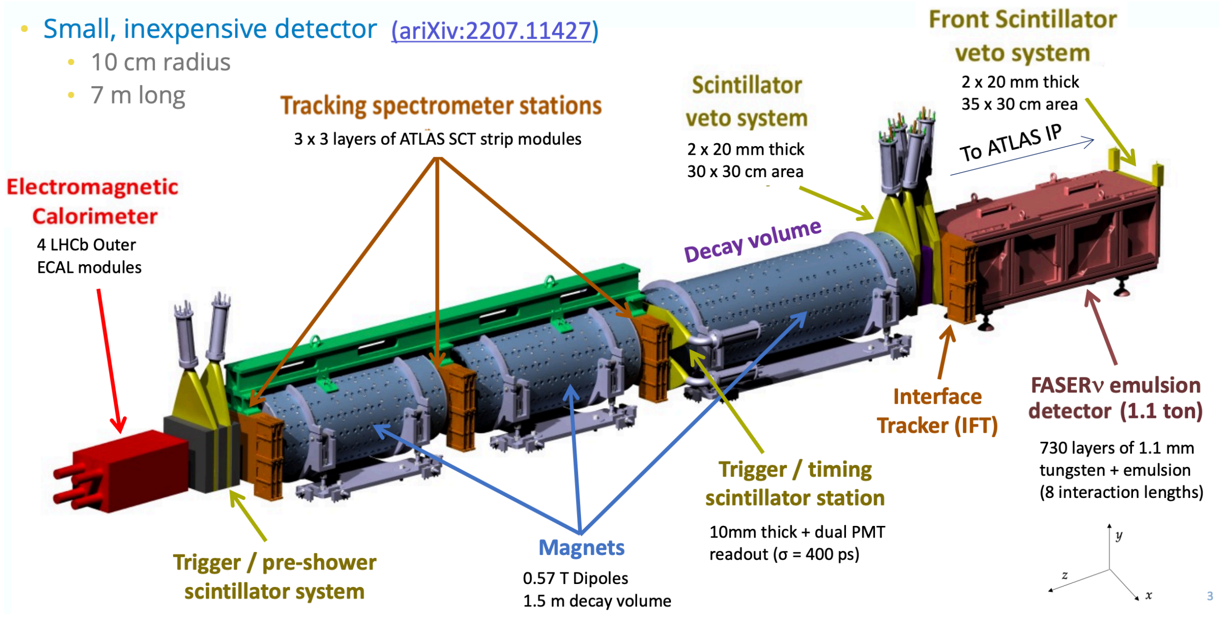
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

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.

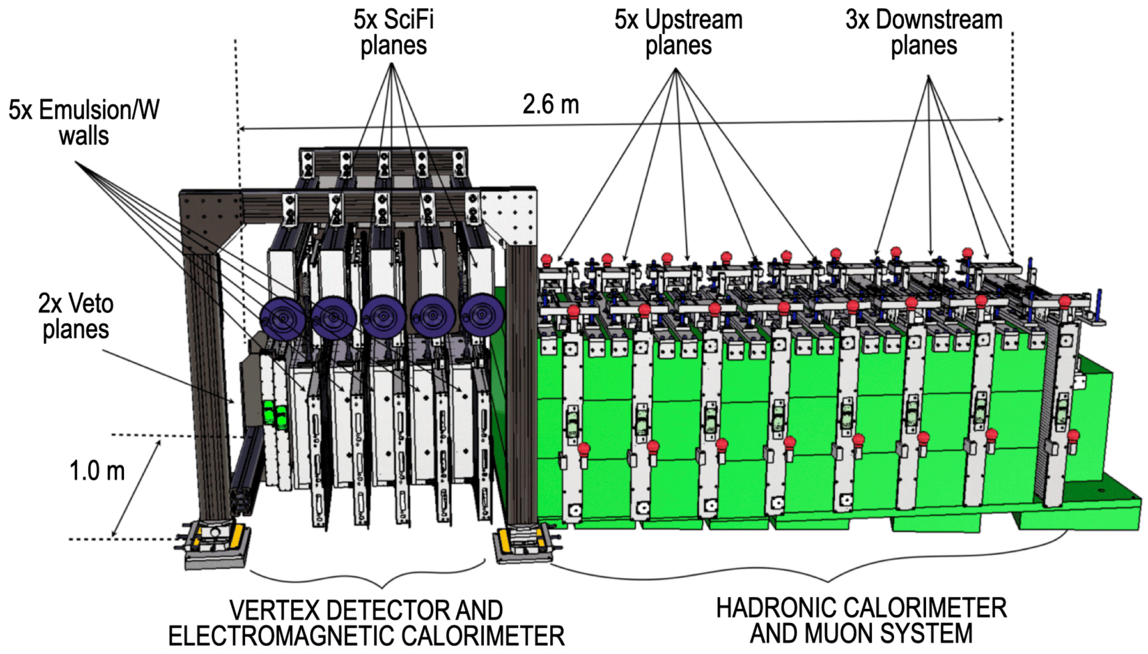
DOI: 10.1103/PhysRevLett.131.031802

153 neutrinos detected, 151± 41 expected

8 neutrinos detected, 4 expected

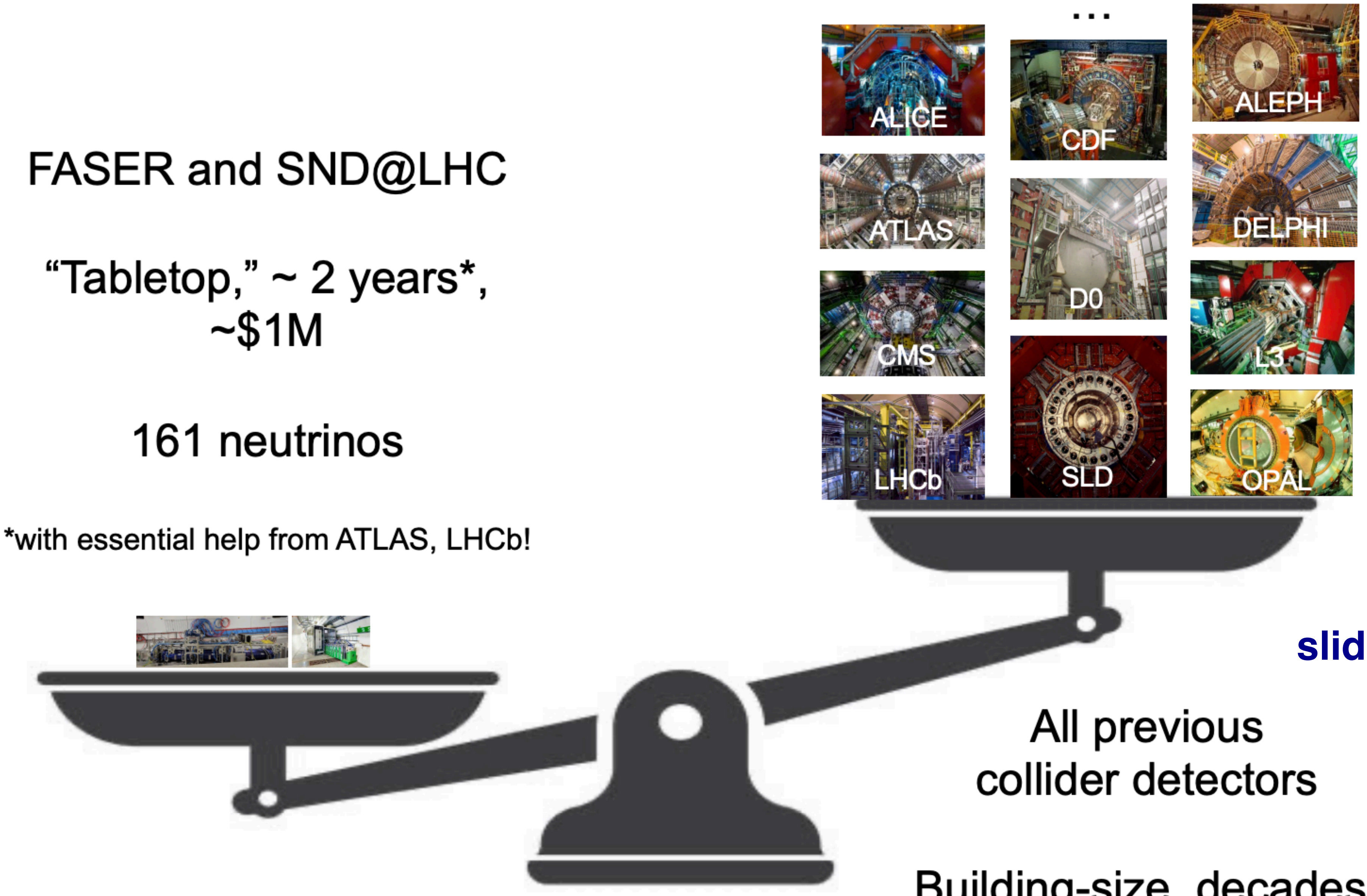


- Small, inexpensive detector (ariXiv:2207.11427)
  - 10 cm radius
  - 7 m long



Now is the time to start exploiting their physics potential

The dawn of the LHC neutrino era



FASER and SND@LHC

“Tabletop,” ~ 2 years*,
~$1M

161 neutrinos

*with essential help from ATLAS, LHCb!

Unambiguous discovery,
opening up the new field of
neutrino physics at colliders

slide by J. Feng

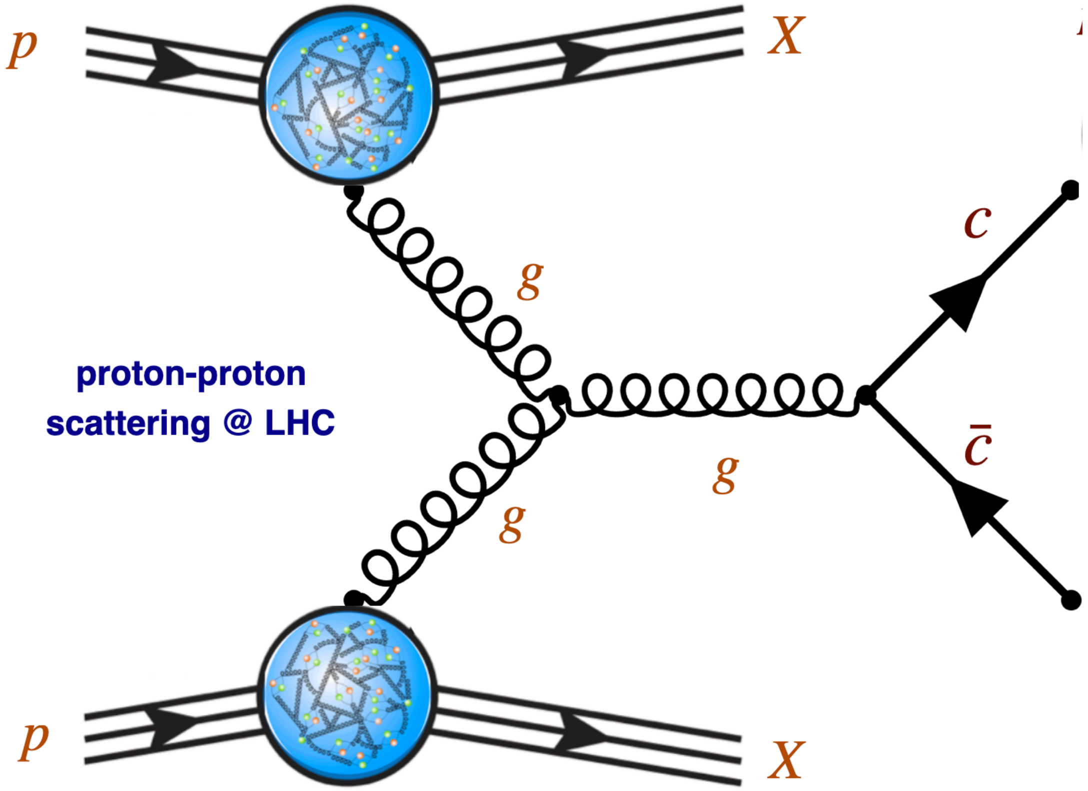
All previous
collider detectors

Building-size, decades,
~$1B

0 neutrinos

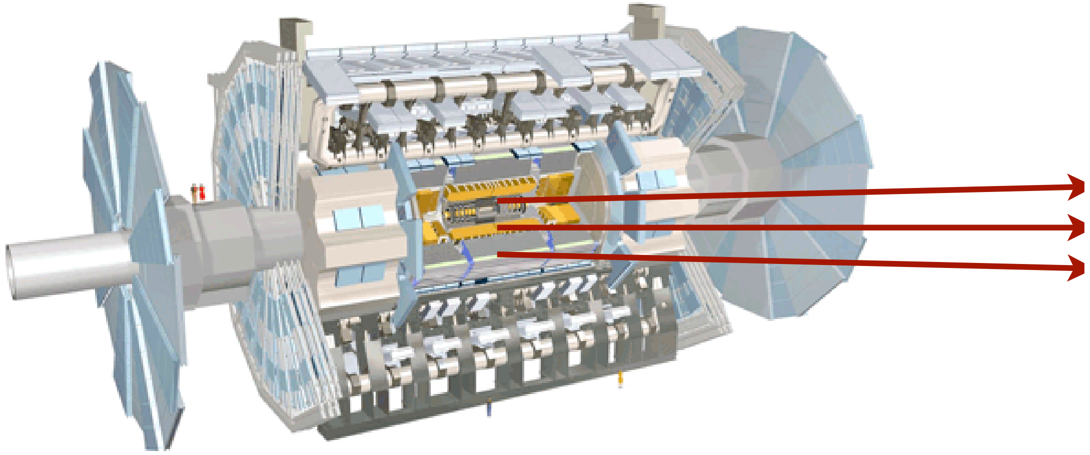
LHC neutrino & far-forward detectors are **compact and cost-effective**, yet realise an immense physics potential that has been laid dormant for 15 years

Neutrinos at the LHC

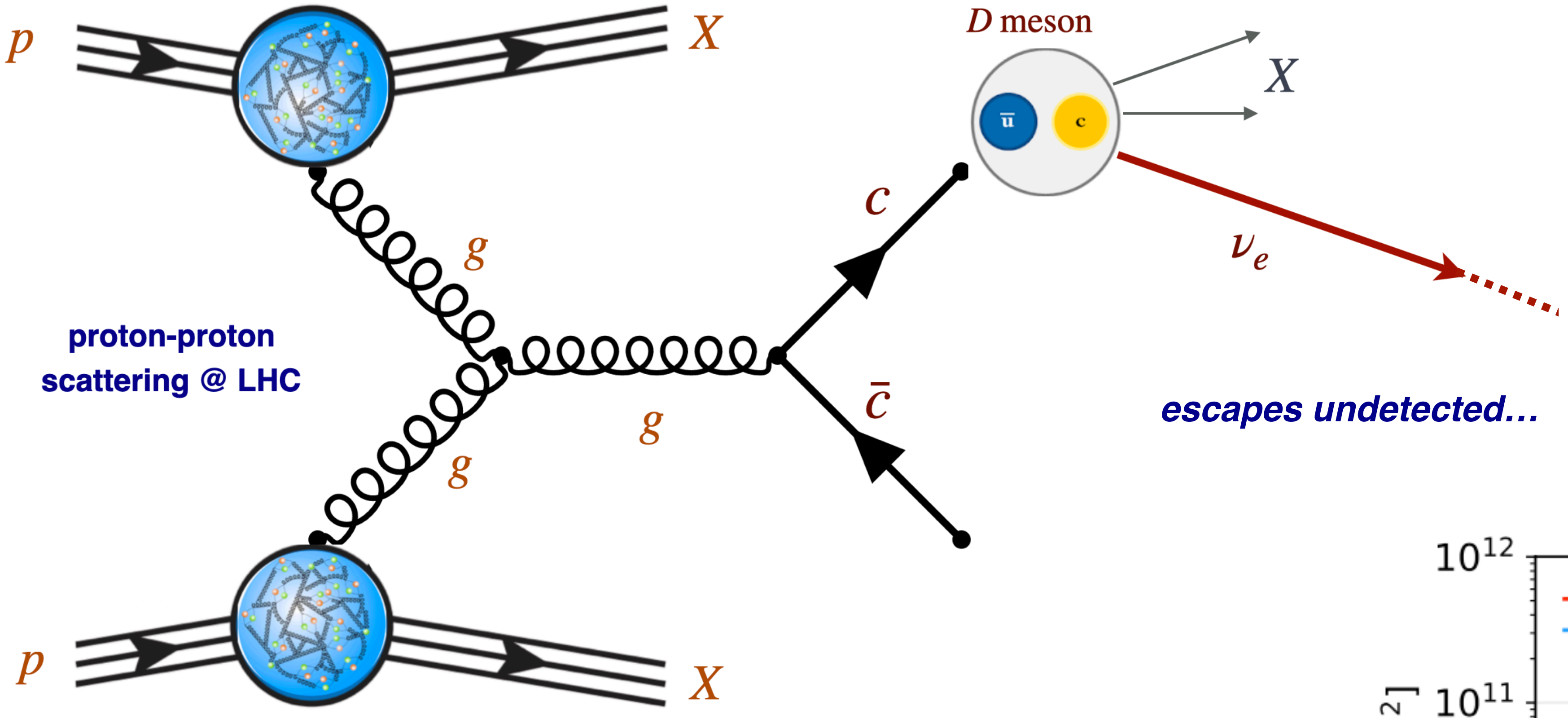


proton-proton scattering @ LHC

ATLAS@LHC



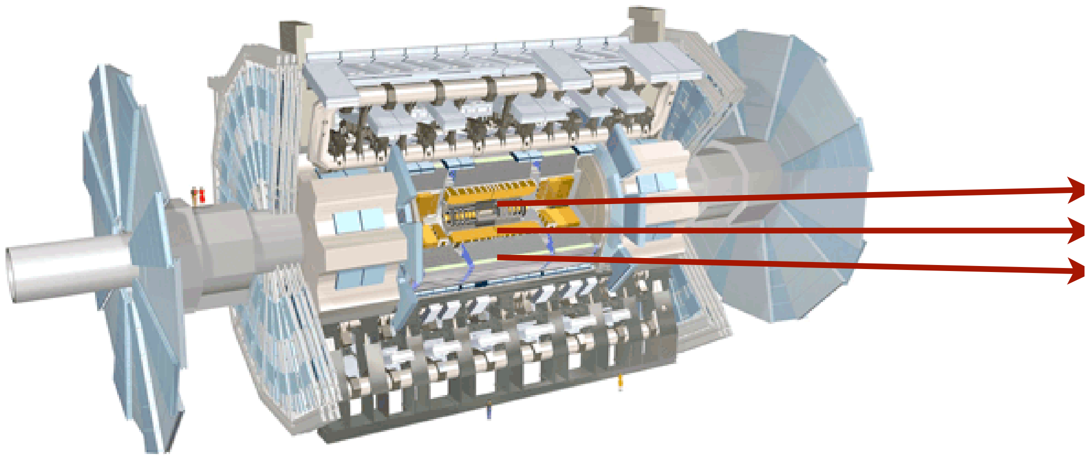
Neutrinos at the LHC

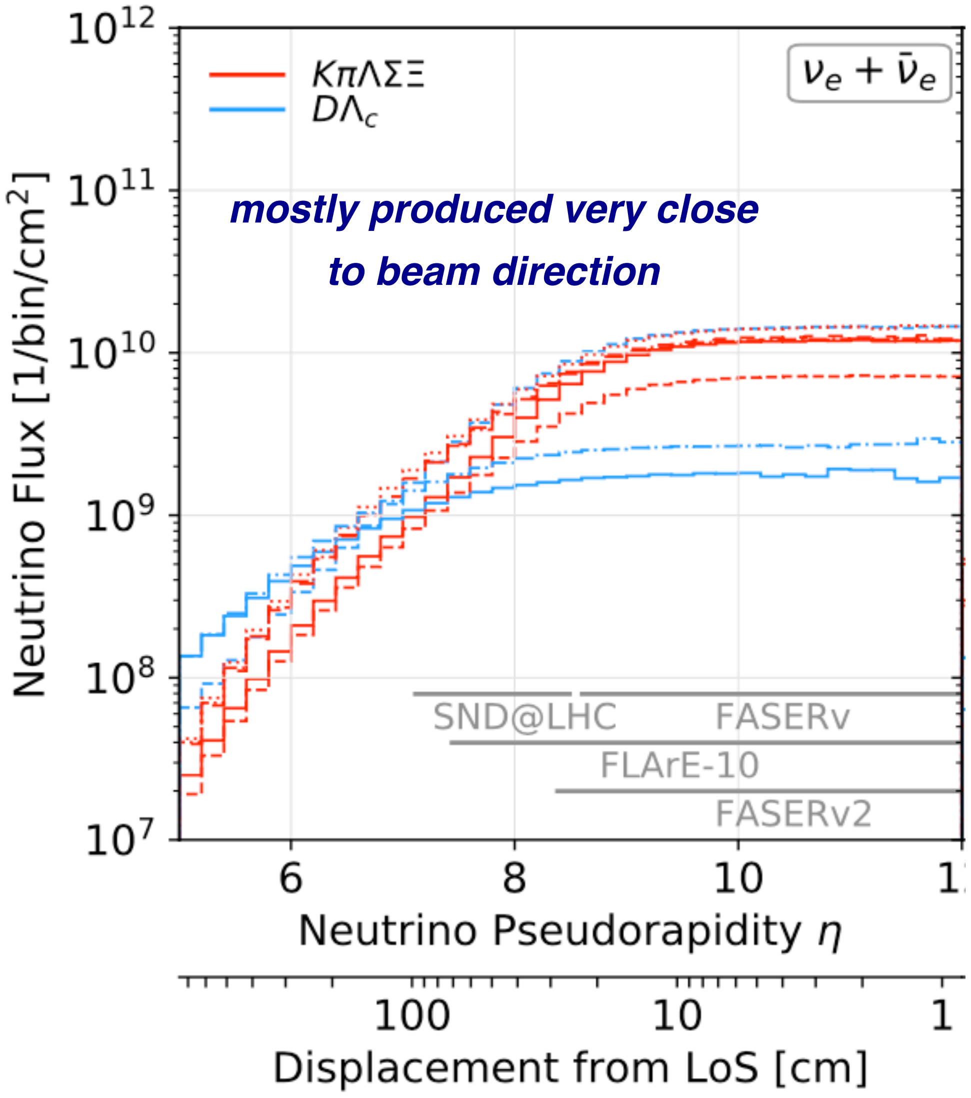


proton-proton scattering @ LHC

escapes undetected…

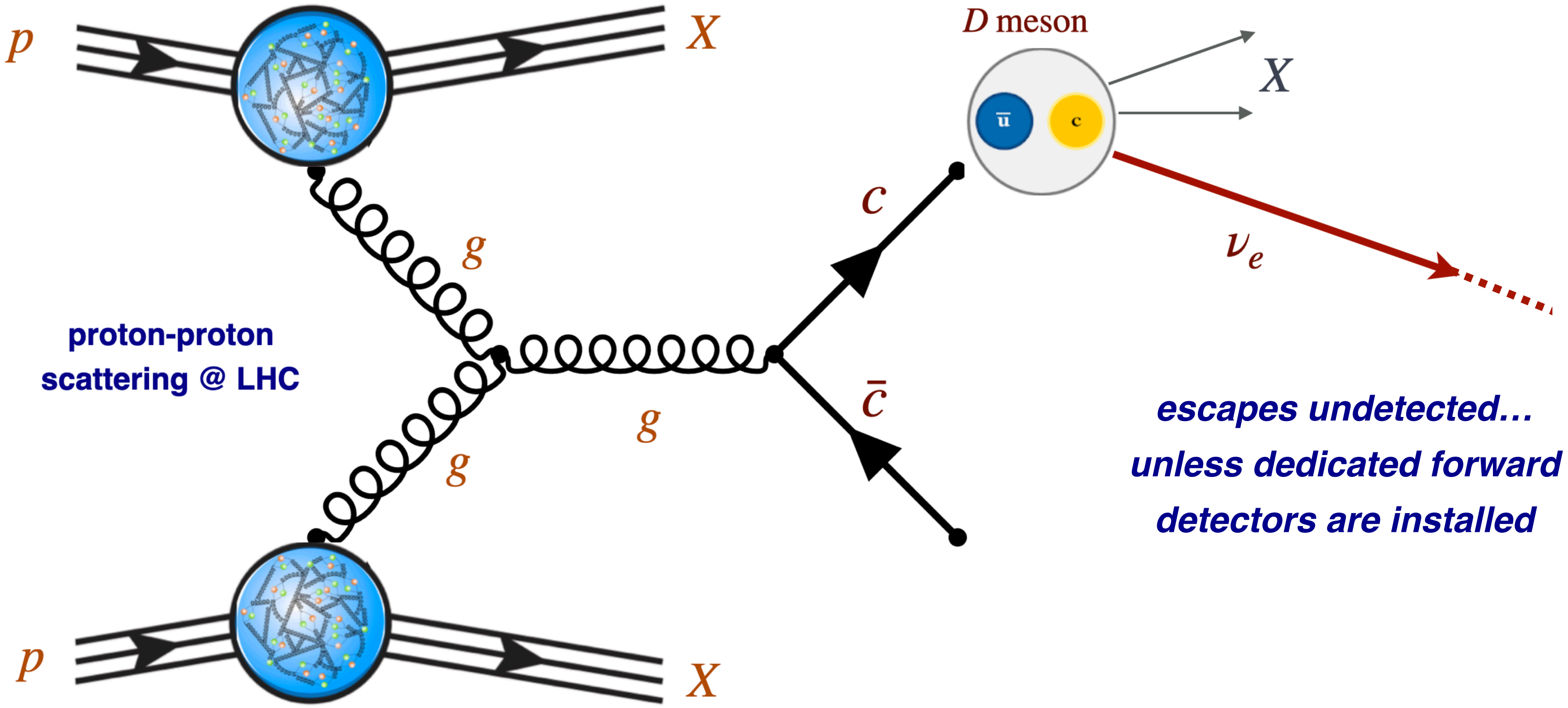
ATLAS@LHC





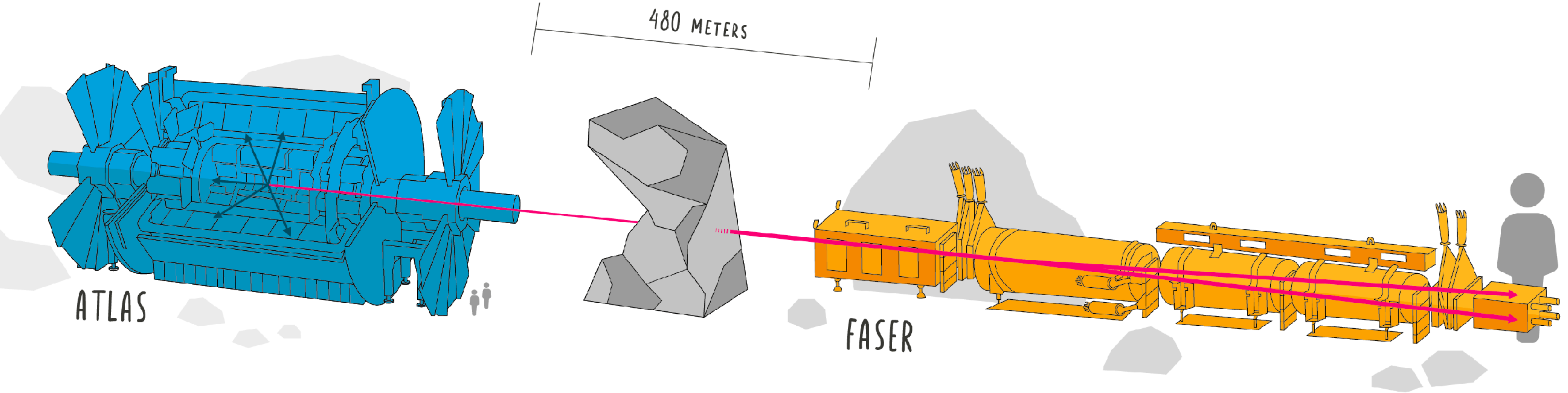
mostly produced very close to beam direction

Neutrinos at the LHC

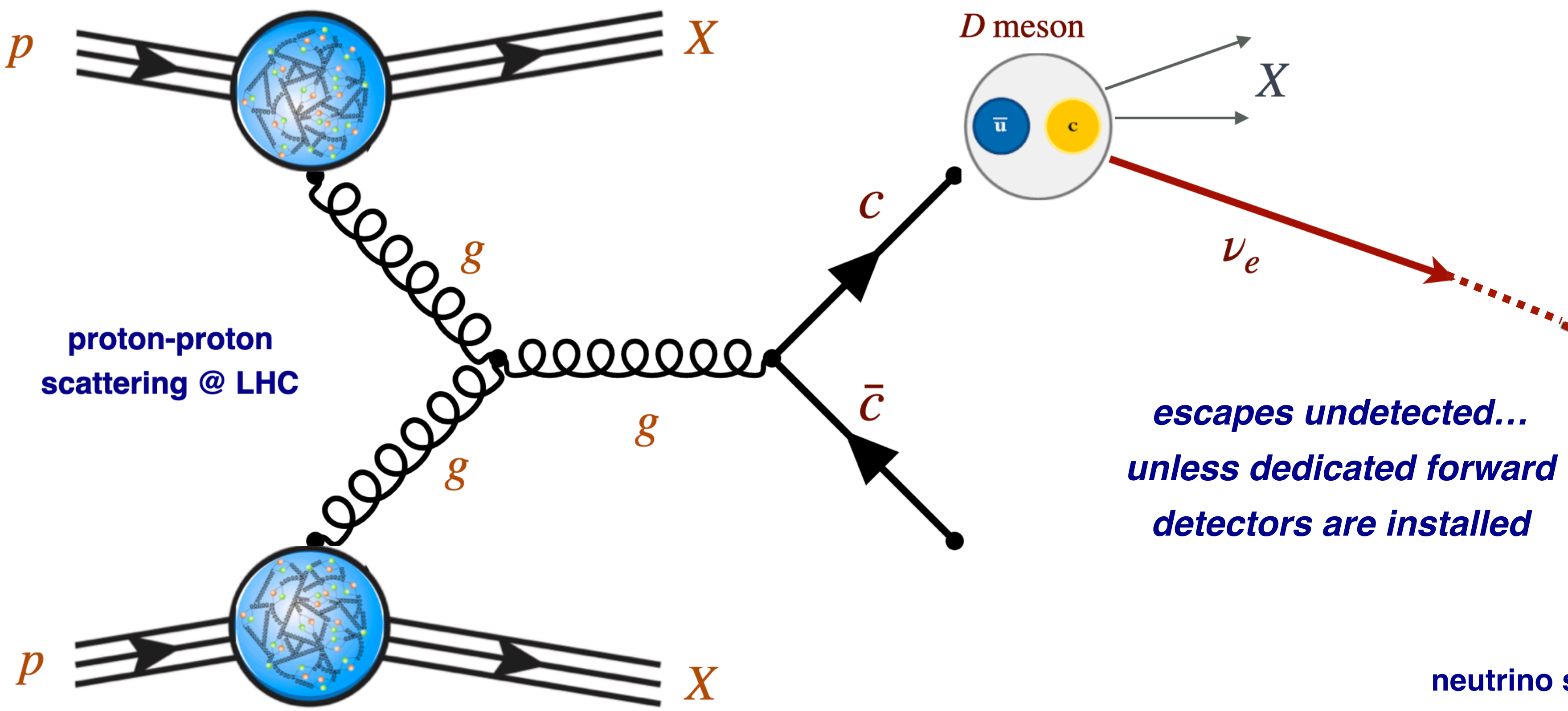


proton-proton scattering @ LHC

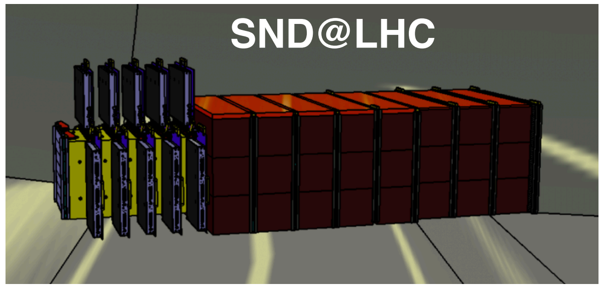
escapes undetected… unless dedicated forward detectors are installed



Neutrinos at the LHC



proton-proton scattering @ LHC



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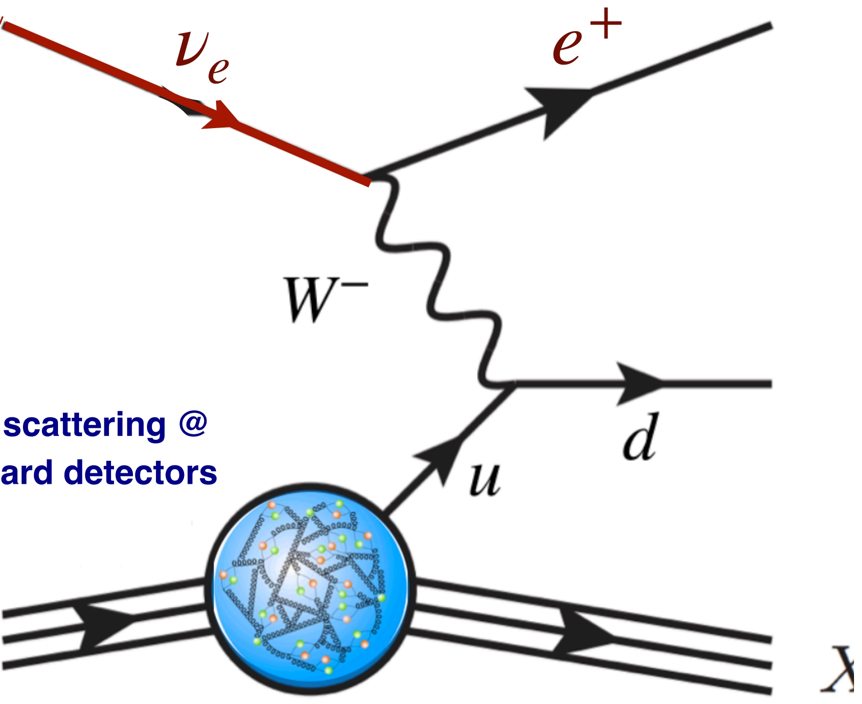
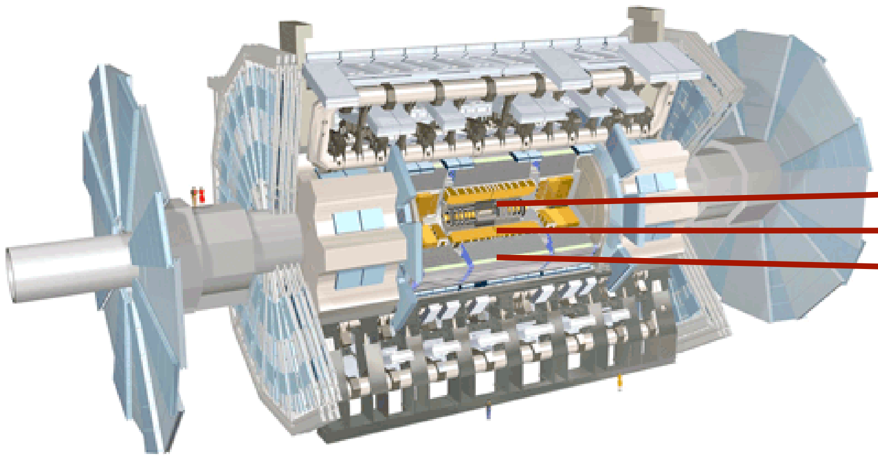
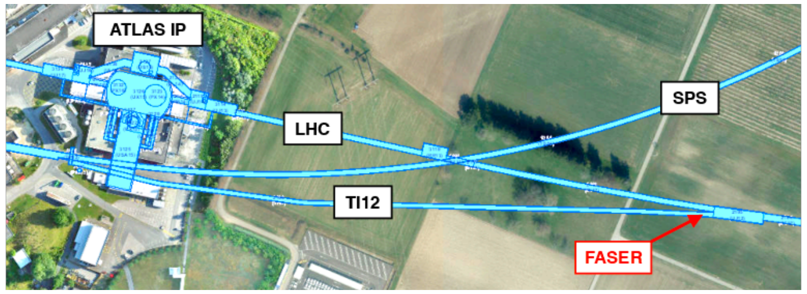


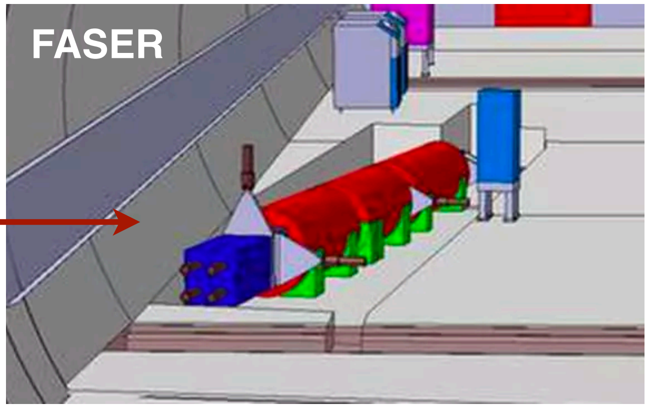
neutrino scattering @ LHC forward detectors

ATLAS@LHC





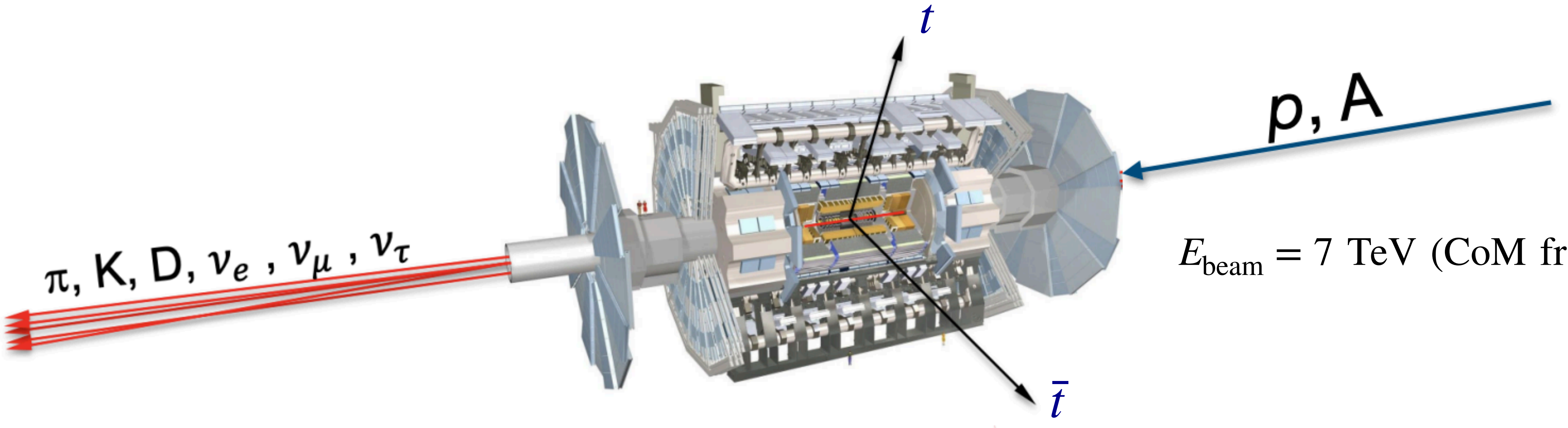
ν



isolated by 500 m of rock and concrete

Neutrinos at 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**

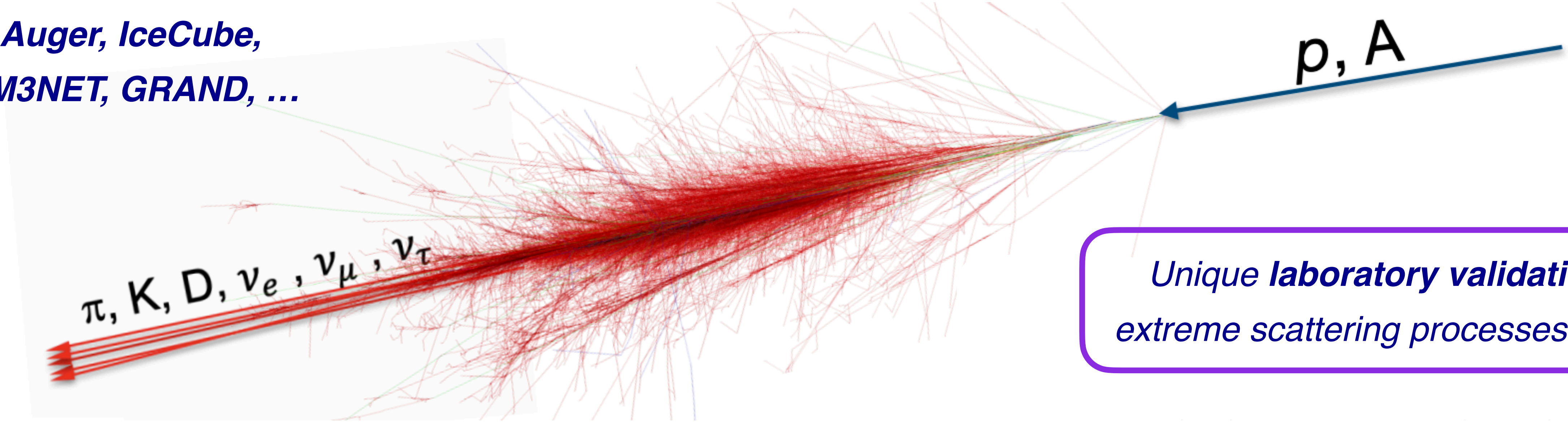


$E_{\text{beam}} = 7\ \text{TeV (CoM frame)}$

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

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

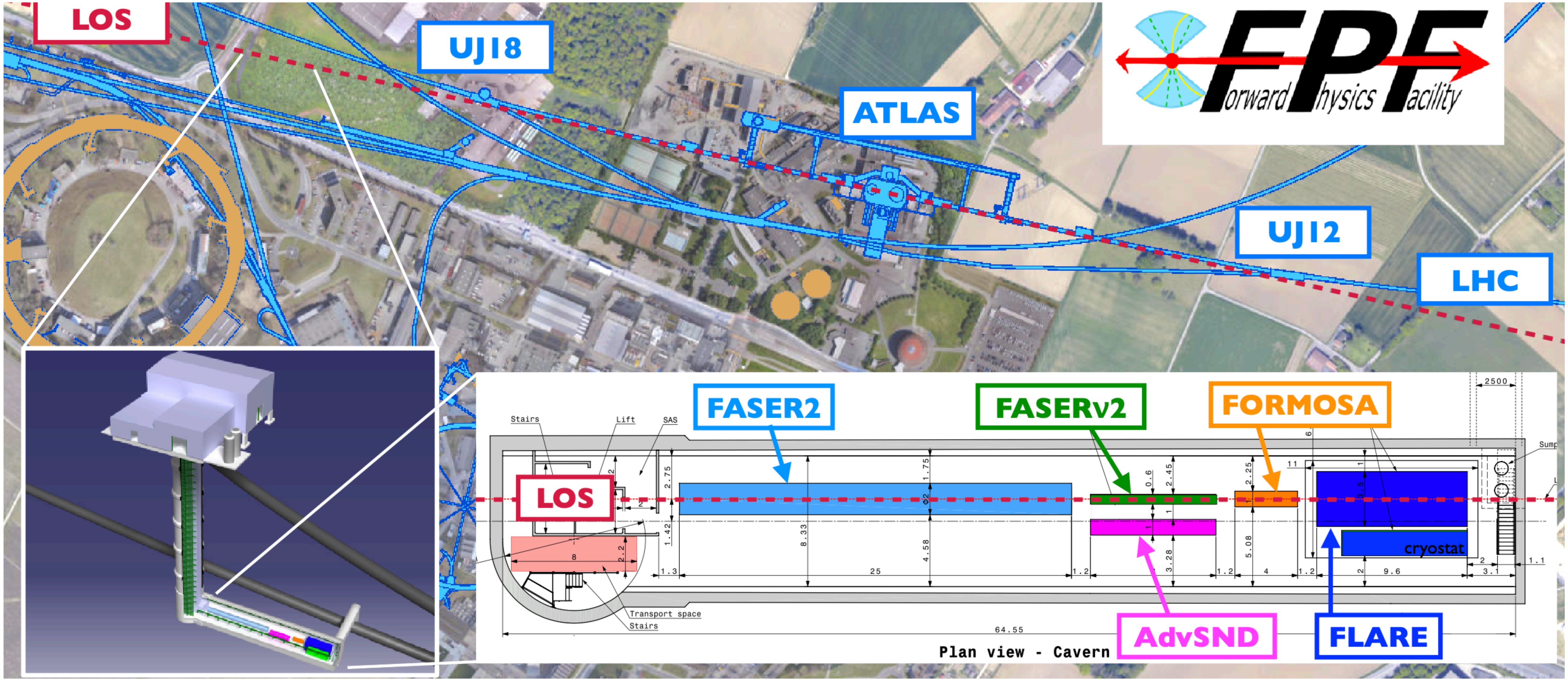
Auger, IceCube,
KM3NET, GRAND, …



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

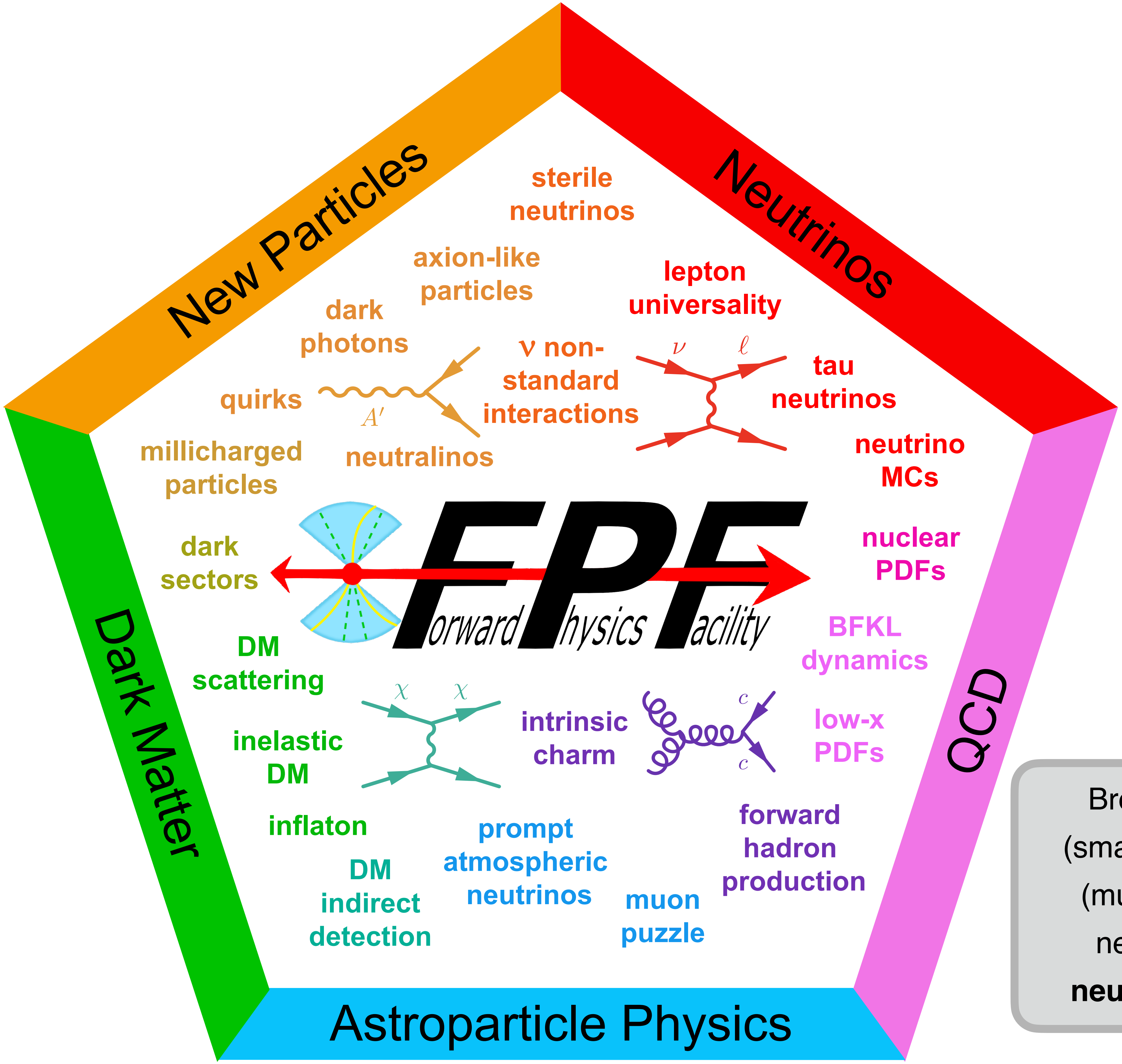
The Forward Physics Facility

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)

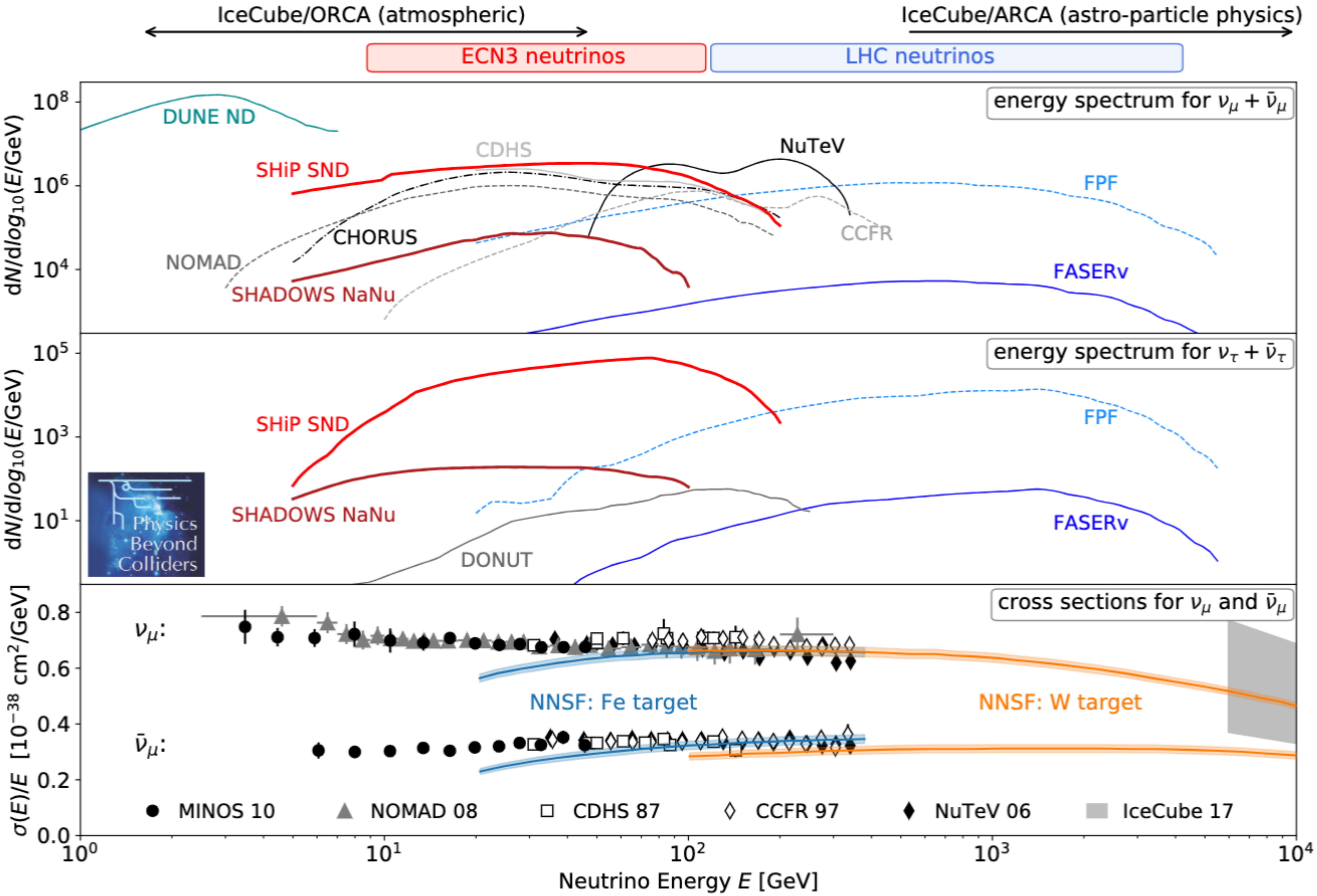
Physics with LHC neutrinos



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** …

here focus on QCD aspects

Physics with LHC neutrinos

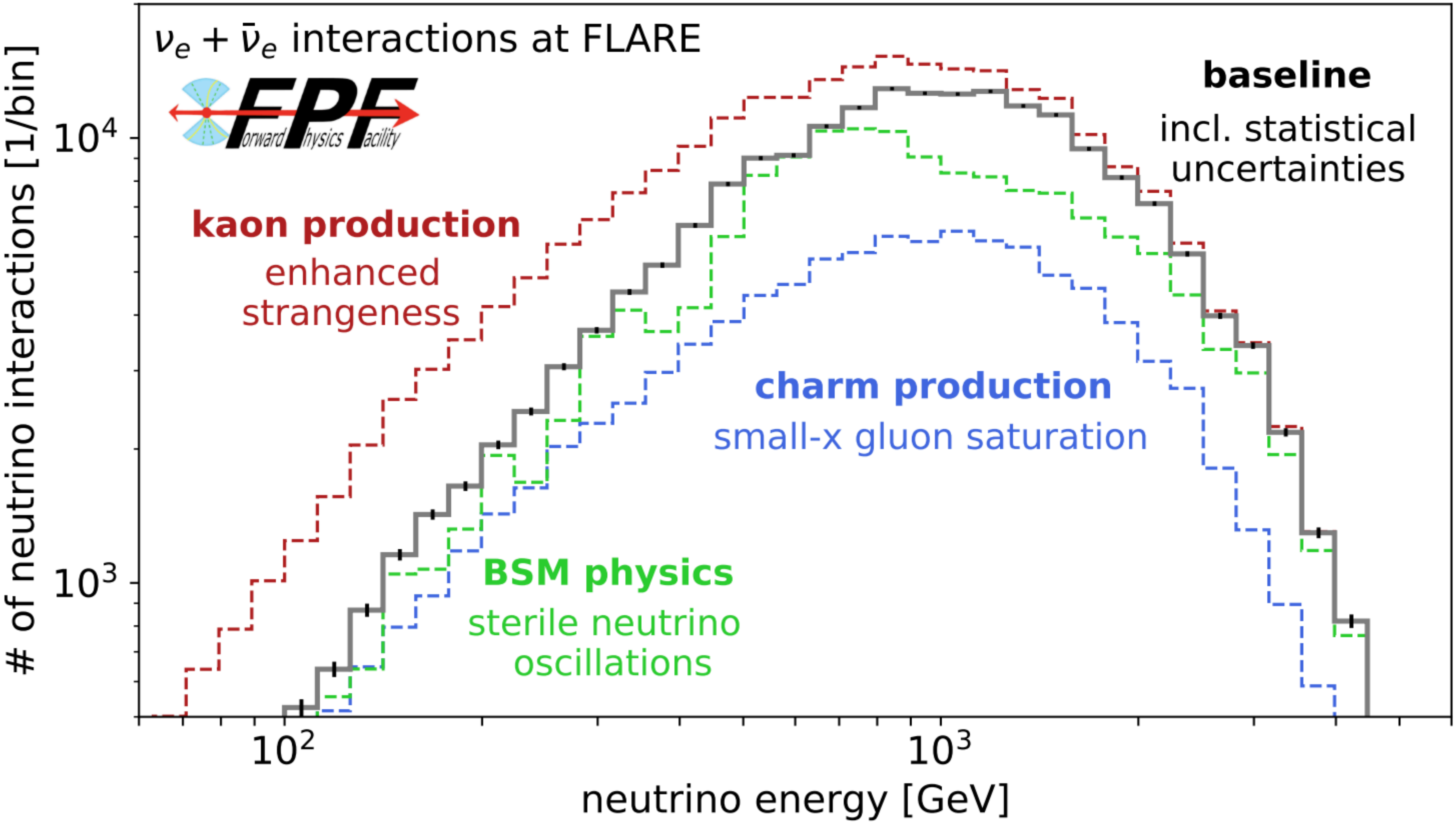


plot by F. Kling

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

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

Physics with LHC neutrinos



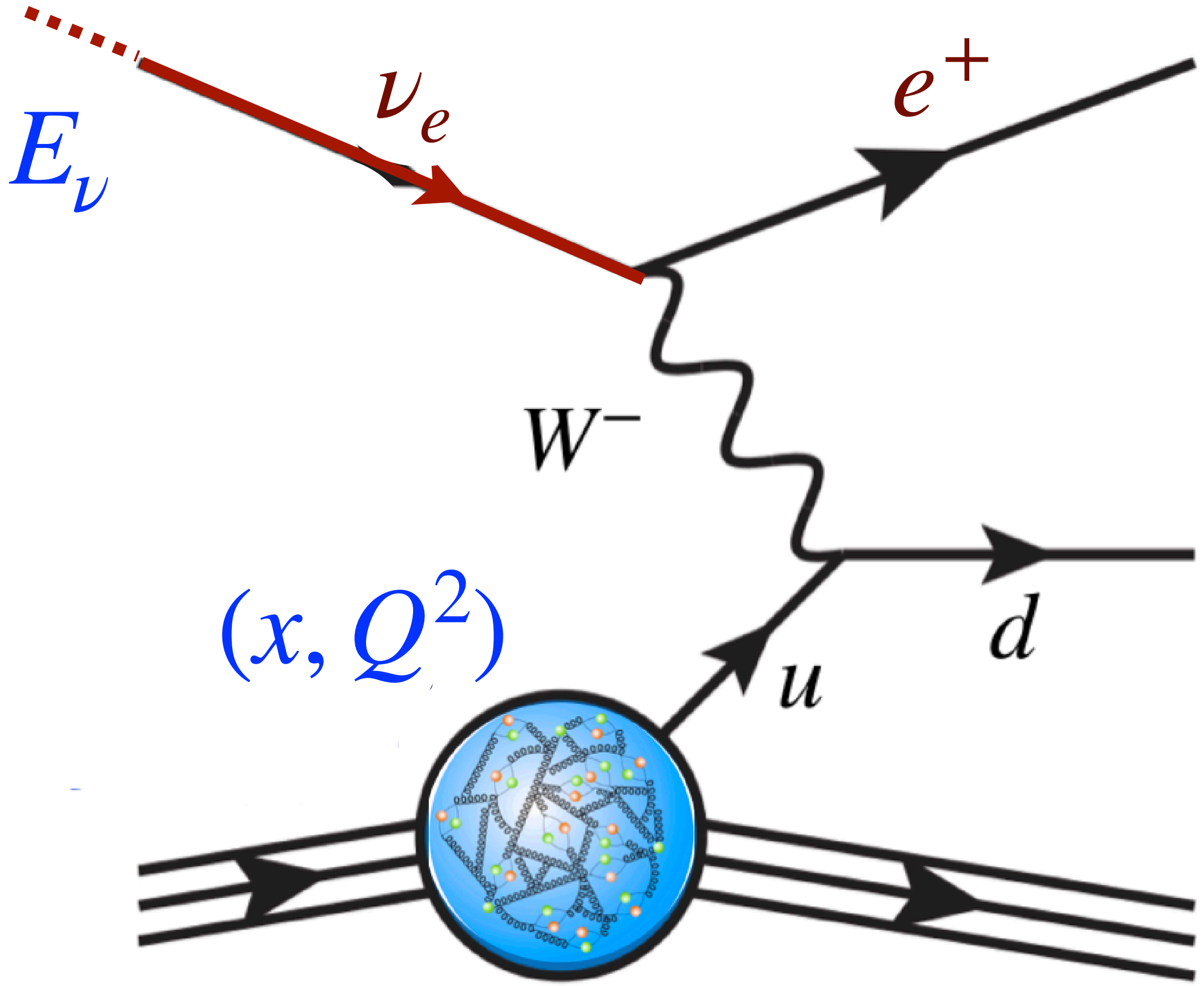
- Probe **small-*x* QCD** (e.g. non-linear dynamics) in uncharged regions
- Provide a laboratory validation of **muon puzzle** predating **cosmic ray physics**
- New channels for **BSM searches** e.g. via sterile neutrino oscillations

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



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

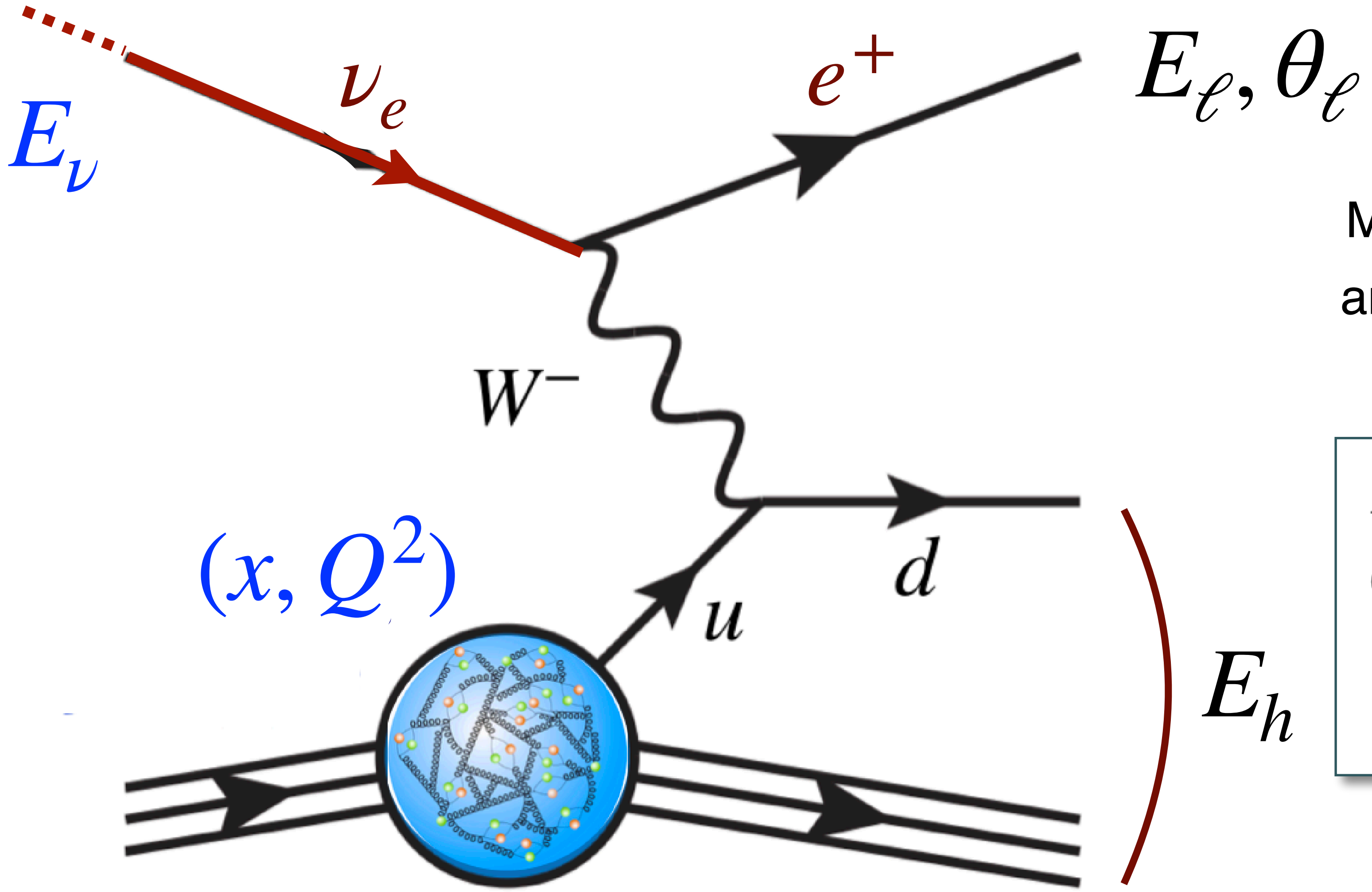
neutrino-proton scattering rate

partonic cross-section

up-quark content int the proton

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

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

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

neutrino-proton scattering rate

partonic cross-section

up-quark content int the proton

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

key for core LHC theory predictions

Parton Distributions

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

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

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

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

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

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

$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2}\left[Y_+F_2^{\nu A}(x,Q^2) - y^2F_L^{\nu A}(x,Q^2) + Y_- xF_3^{\nu A}(x,Q^2)\right]$$

$$y = Q^2/(2xm_nE_\nu)$$

Cross-section expressed in terms of LO structure functions:

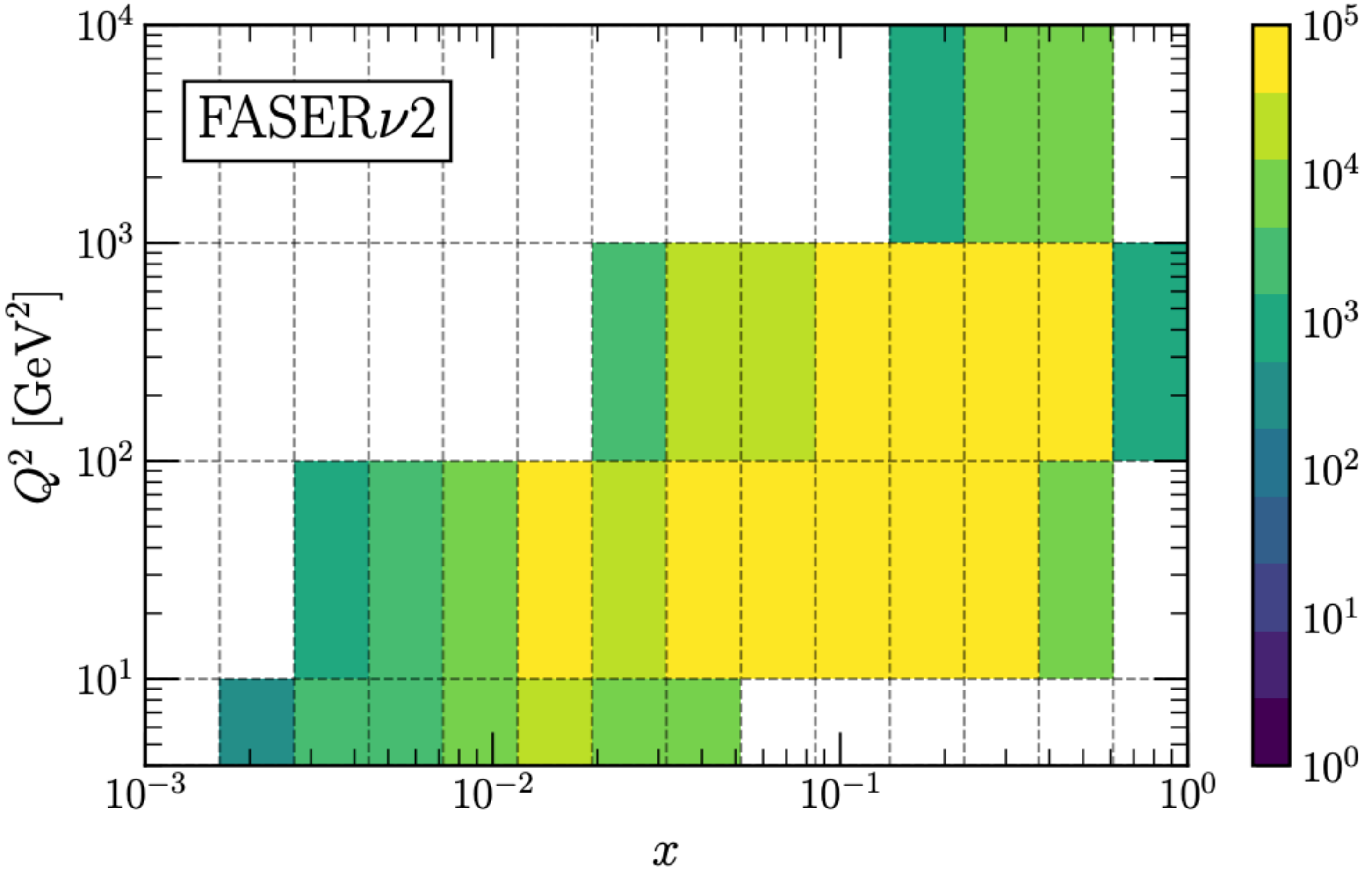
$$\begin{aligned}
F_2^{\nu p}(x,Q^2) &= 2x\left(f_{\bar{u}} + f_d + f_s + f_{\bar{c}}\right)(x,Q^2)\,,\\
F_2^{\bar{\nu} p}(x,Q^2) &= 2x\left(f_u + f_{\bar{d}} + f_{\bar{s}} + f_c\right)(x,Q^2)\,,\\
xF_3^{\nu p}(x,Q^2) &= 2x\left(-f_{\bar{u}} + f_d + f_s - f_{\bar{c}}\right)(x,Q^2)\,,\\
xF_3^{\bar{\nu}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

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

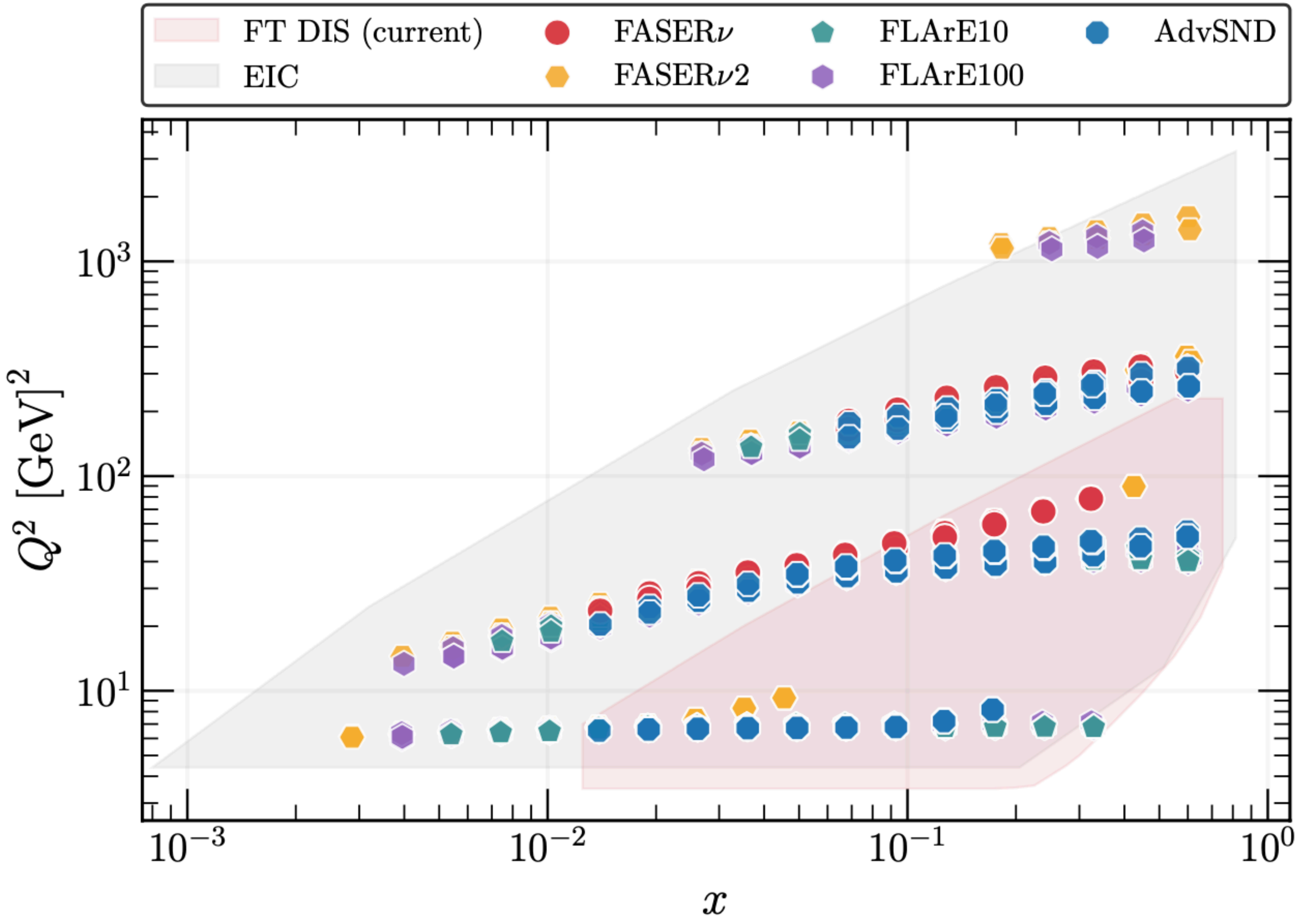
neutrino fluxes (include rapidity acceptance)

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

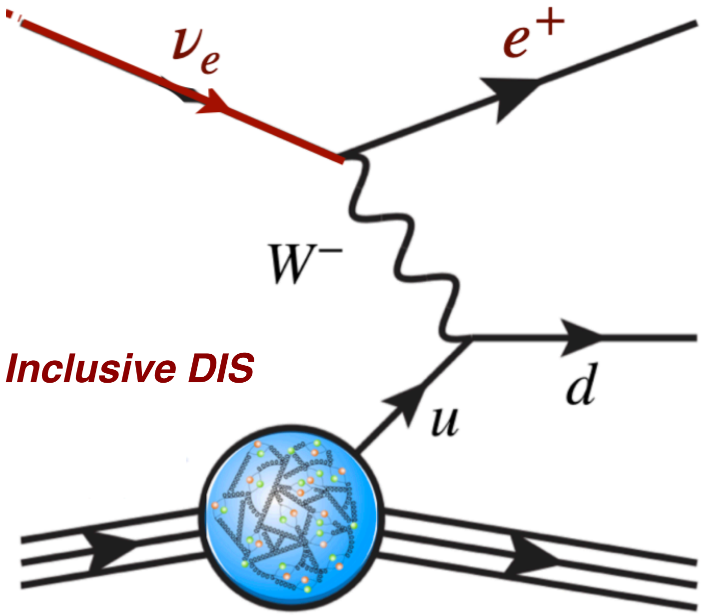
- Continue highly succesful program of neutrino **DIS experiments @ CERN**
- **Expand kinematic coverage** of available experiments by an order of magnitude in *x* and *Q²*
- Charged-current counterpart of the **Electron-Ion Collider** covering same region of phase space

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

Neutrino DIS at the LHC

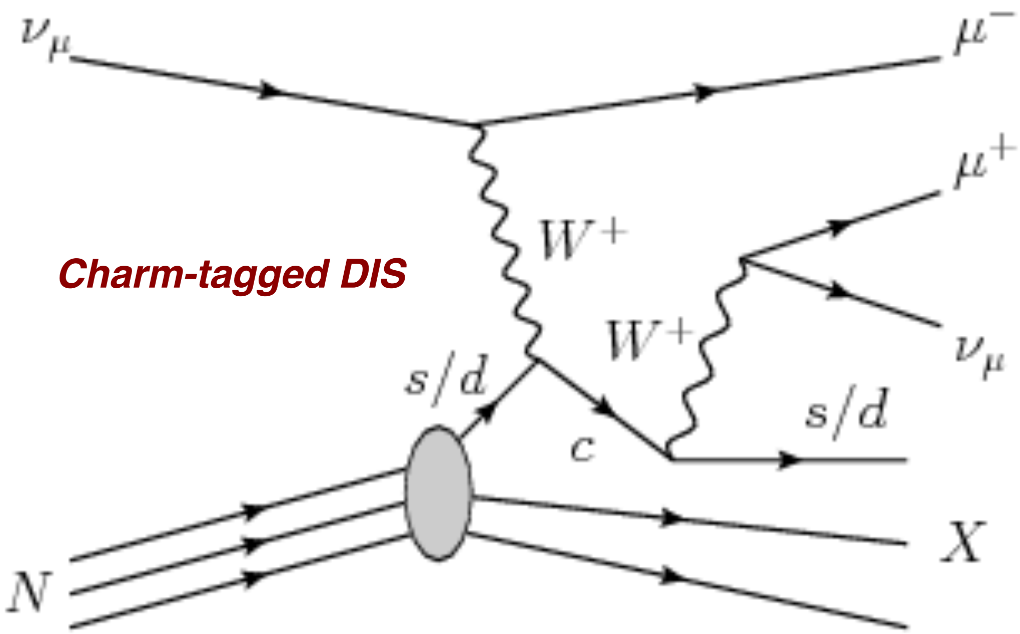
Integrated event rates for DIS kinematics for **inclusive (charm-tagged)** production

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)



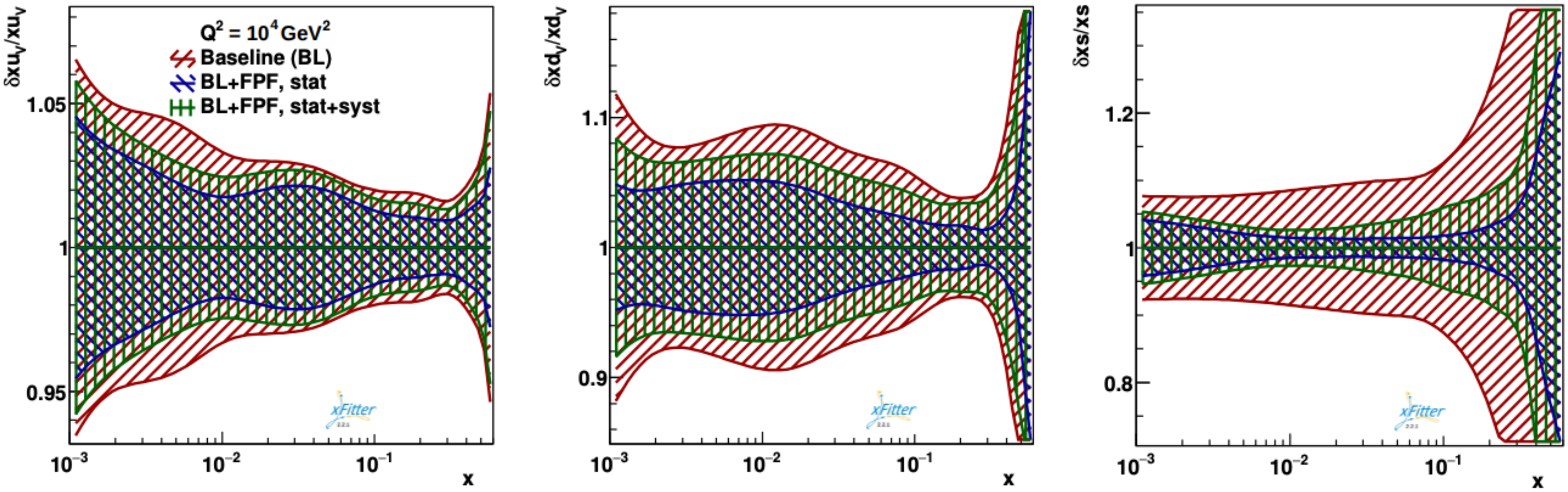
Inclusive DIS

- 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

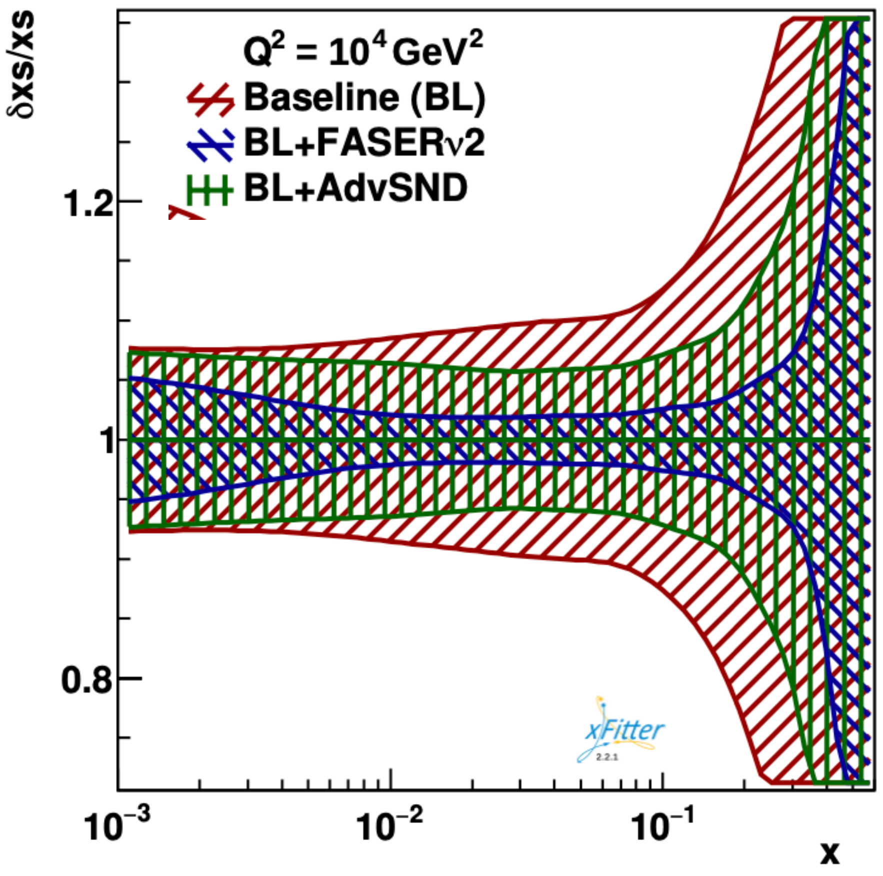
PDF constraints from LHC neutrinos



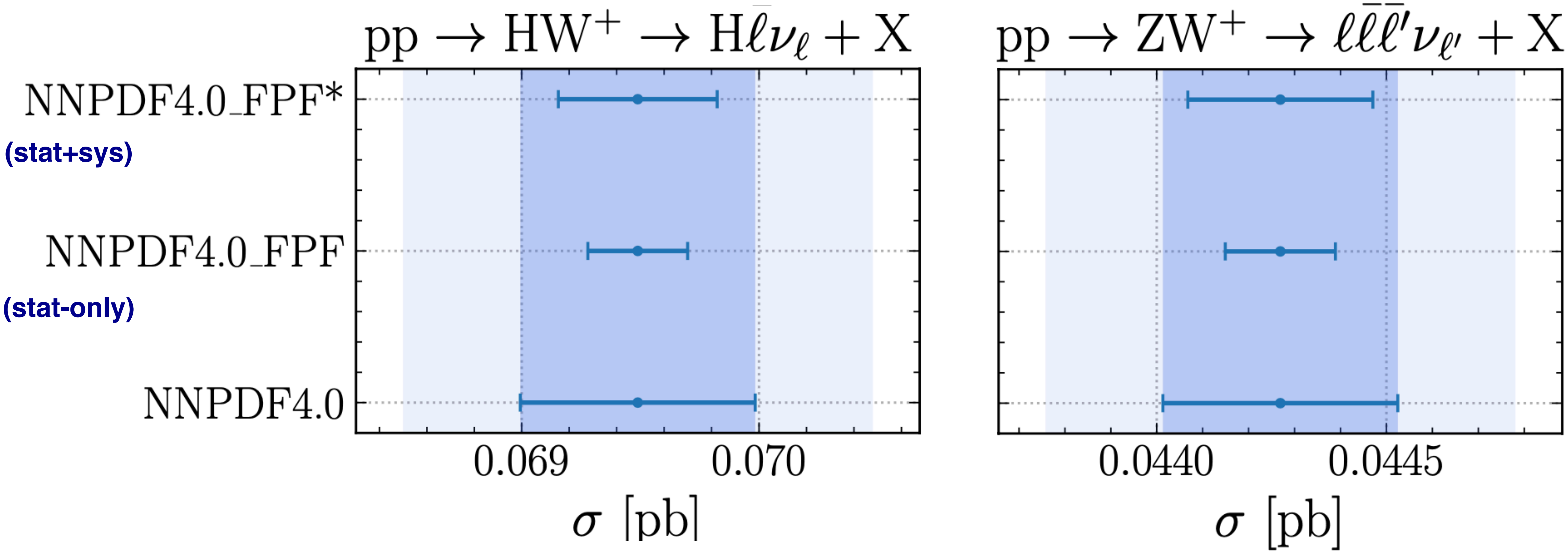
- Impact on proton PDFs quantified by the **Hessian profiling of PDF4LHC21** (xFitter) and by direct inclusion in the global **NNPDF4.0 fit**

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

- Quantitative analysis **guiding detector design** for the FPF, highlighting complementarity between experiments

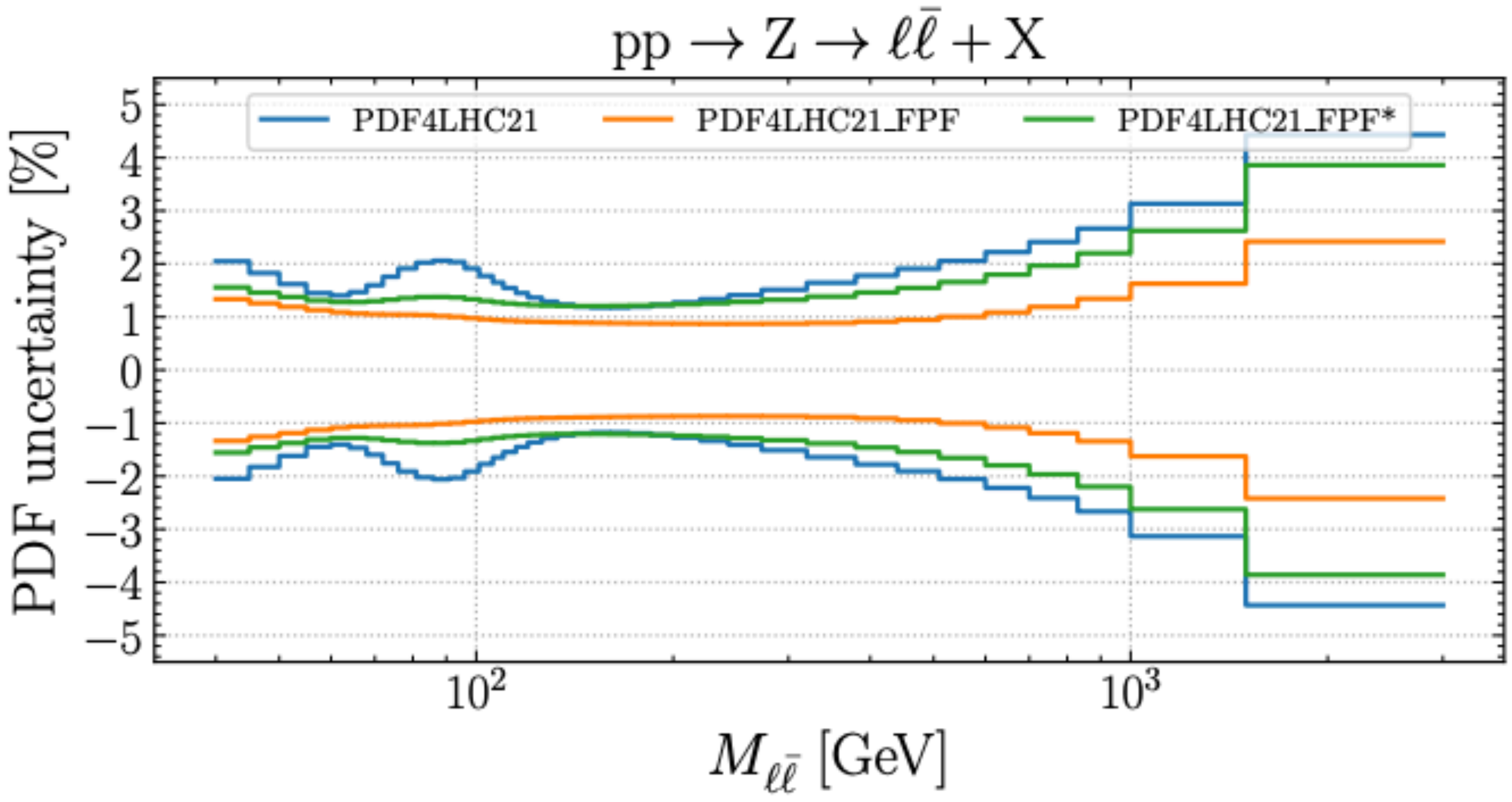


Impact at the HL-LHC



(stat+sys)

(stat-only)



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

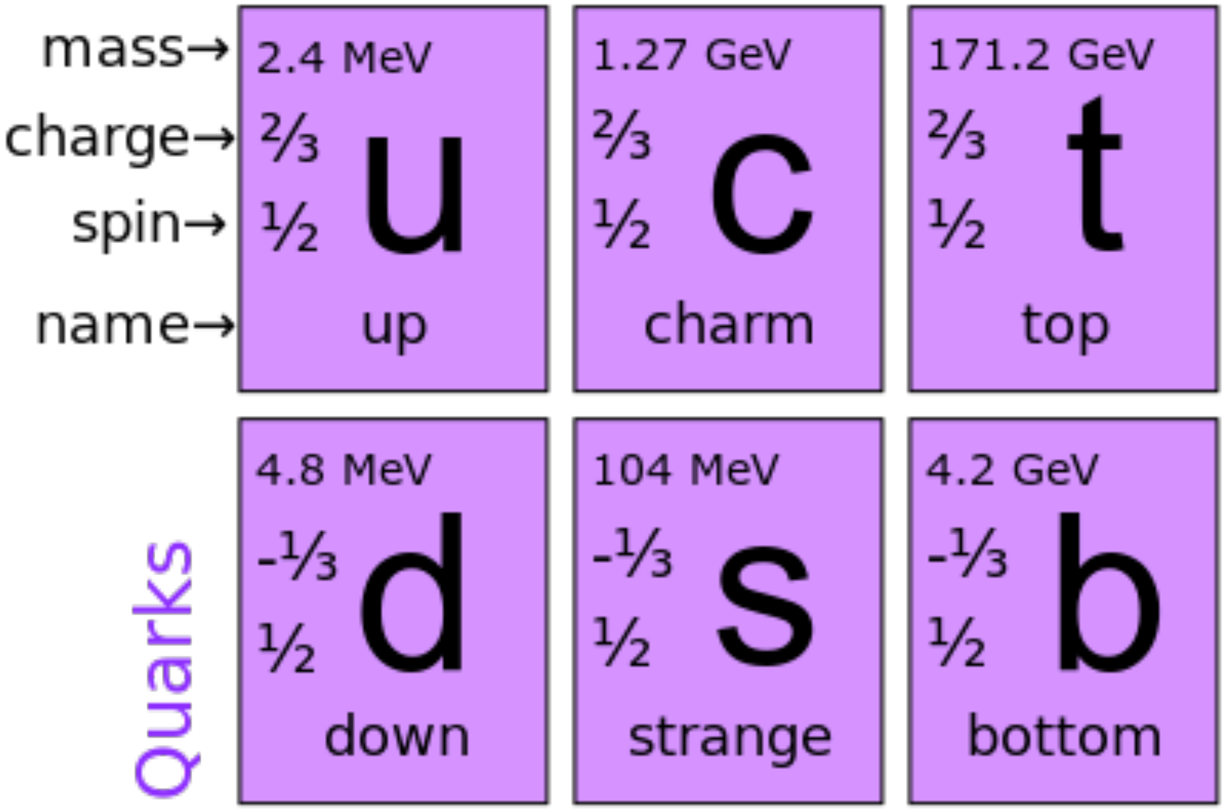
- Also relevant for **BSM searches at large-mass** (via large-*x* PDFs)

e.g. high-mass dilepton resonances

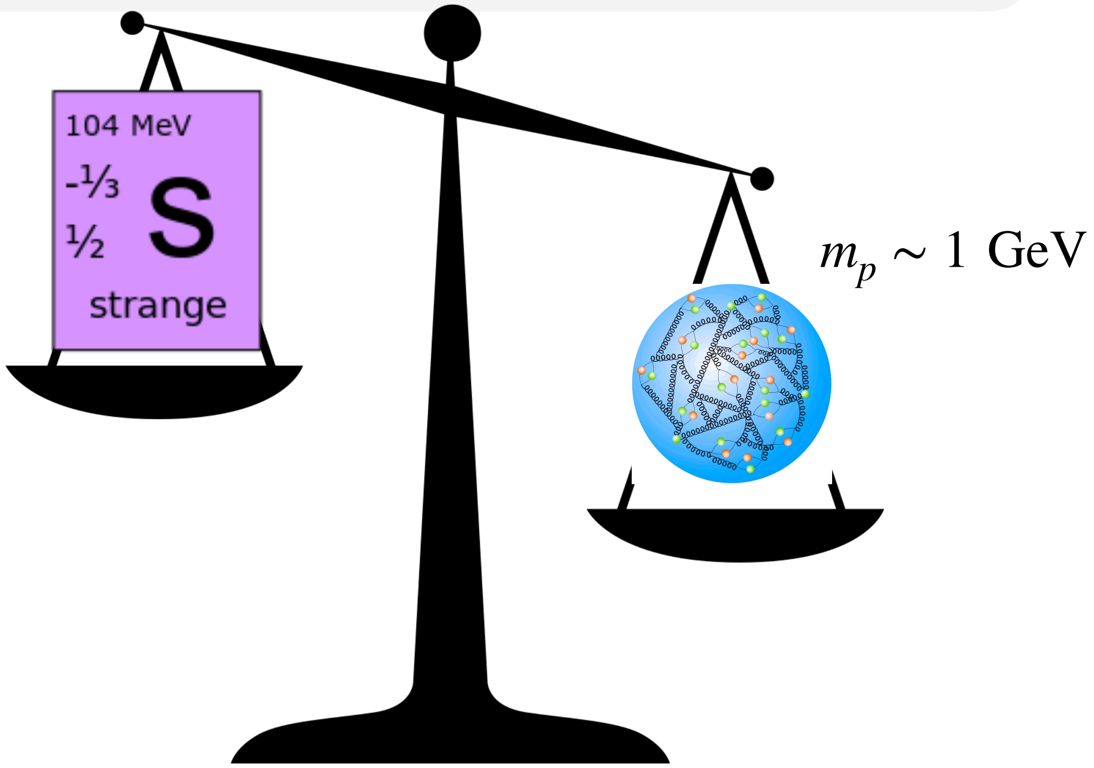
Fully independent constraints on proton structure, crucial to disentangle possible BSM signatures in high p_T data

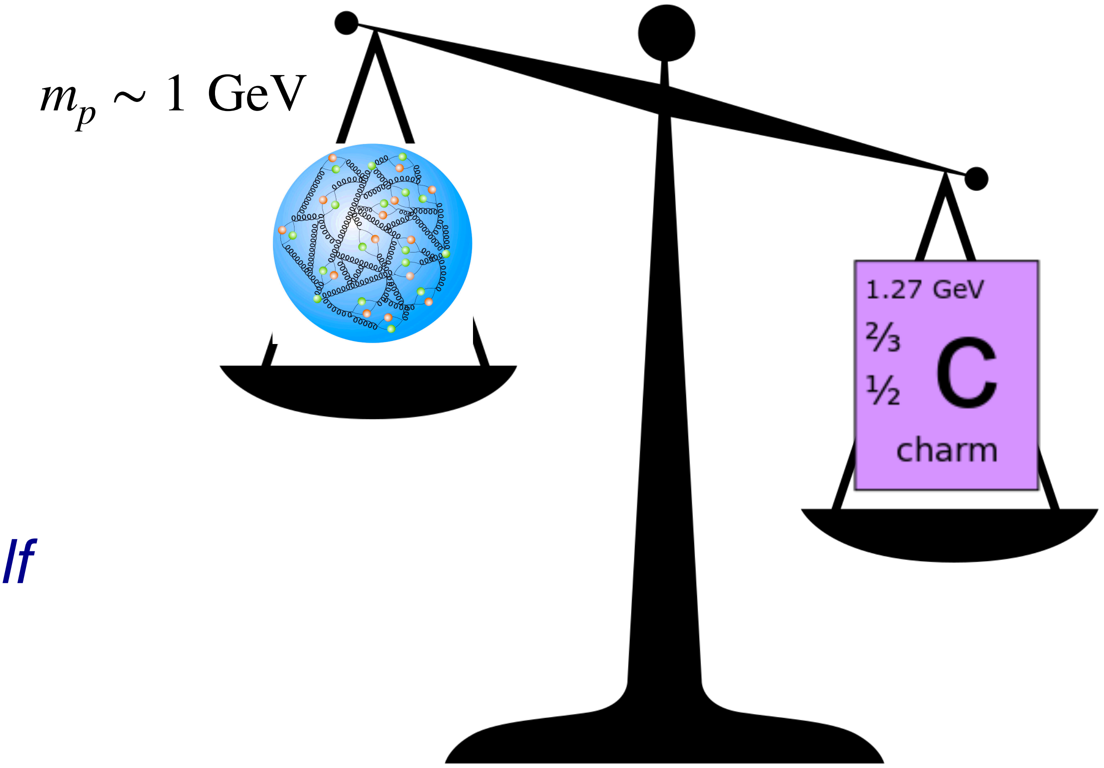
Impact on Intrinsic Charm

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**



mass→	2.4 MeV	1.27 GeV	171.2 GeV
charge→	⅔	⅔	⅔
spin→	½	½	½
	u	c	t
name→	up	charm	top
Quarks	4.8 MeV	104 MeV	4.2 GeV
	-⅓	-⅓	-⅓
	½	½	½
	d	s	b
	down	strange	bottom



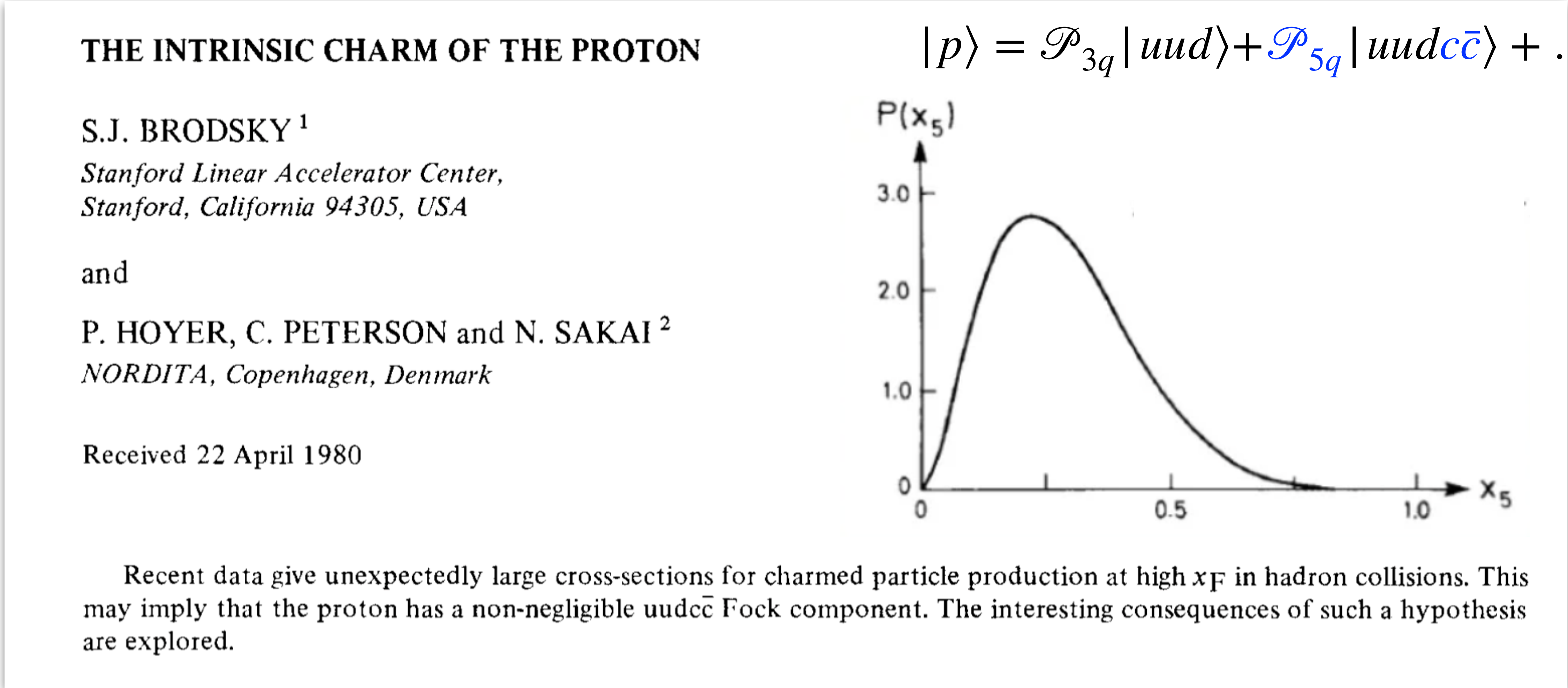


charm quarks heavier than the proton itself

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



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

THE INTRINSIC CHARM OF THE PROTON

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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:

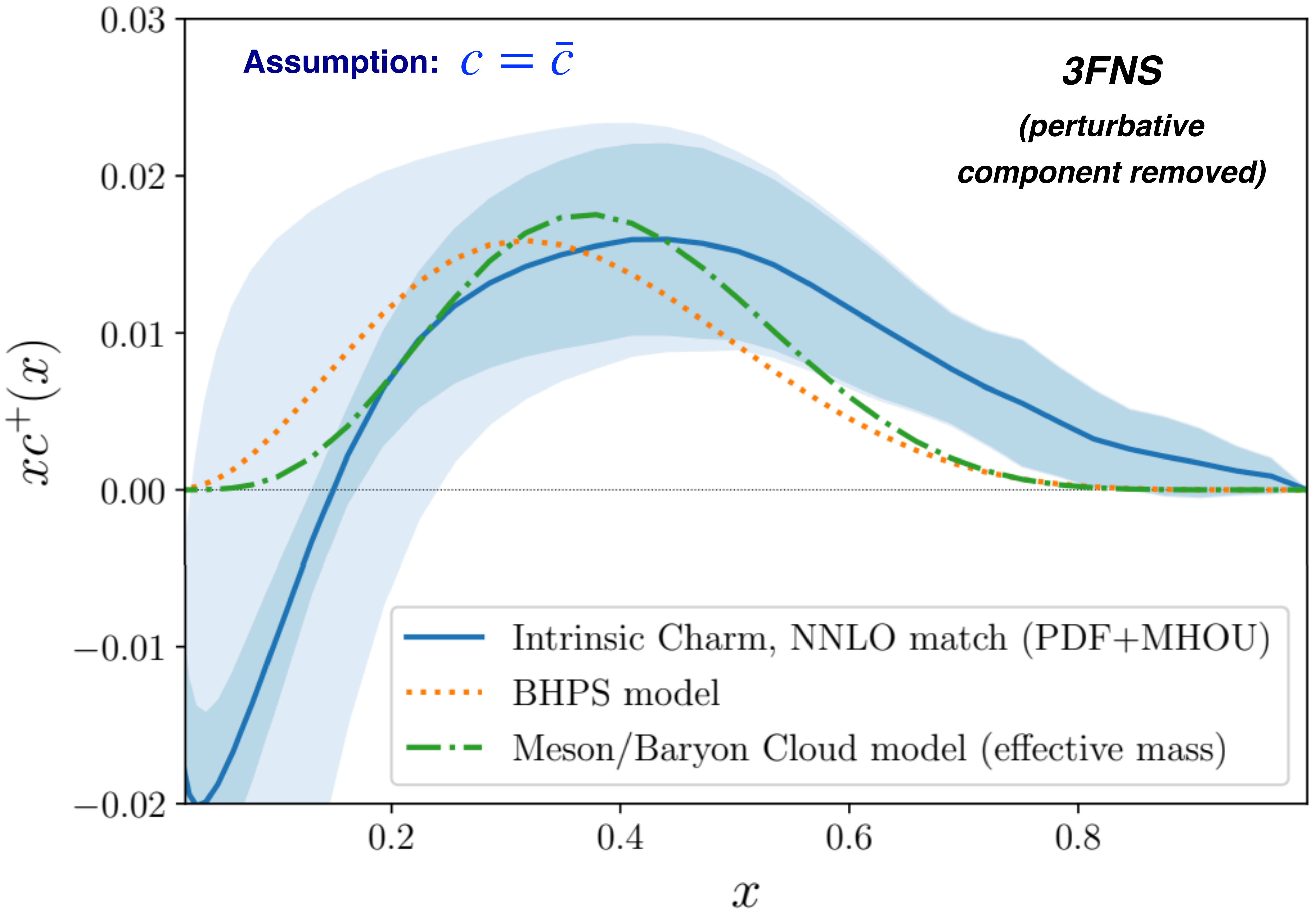
$$c^{(n_f=4)}(x,Q) \simeq c^{(n_f=4)}_{(\mathrm{pert})}(x,Q) + c^{(n_f=4)}_{(\mathrm{intr})}(x,Q)$$

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**

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

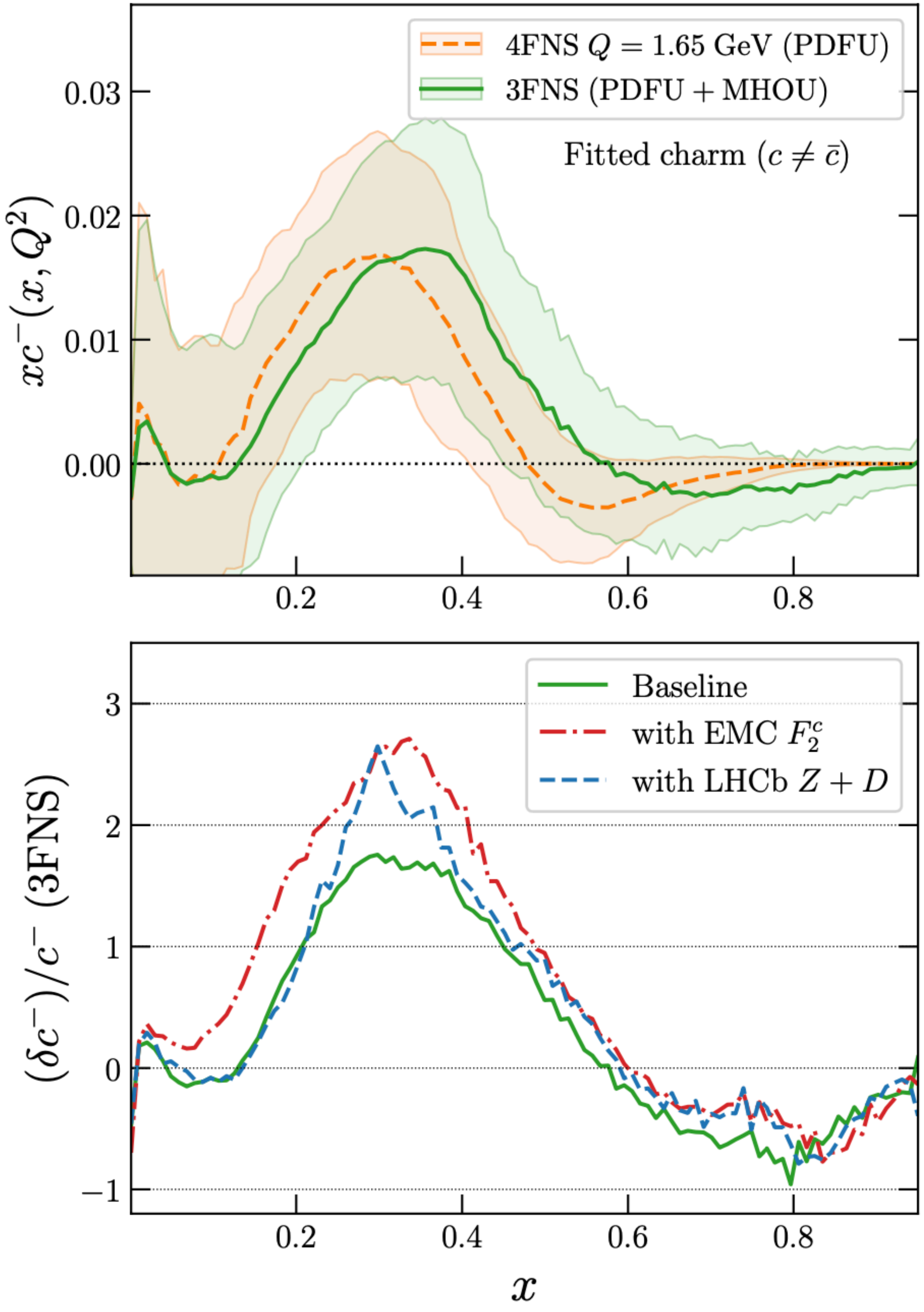
- Extend the NNPDF4.0 analysis with an **separate determination of charm and anti-charm PDFs**

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

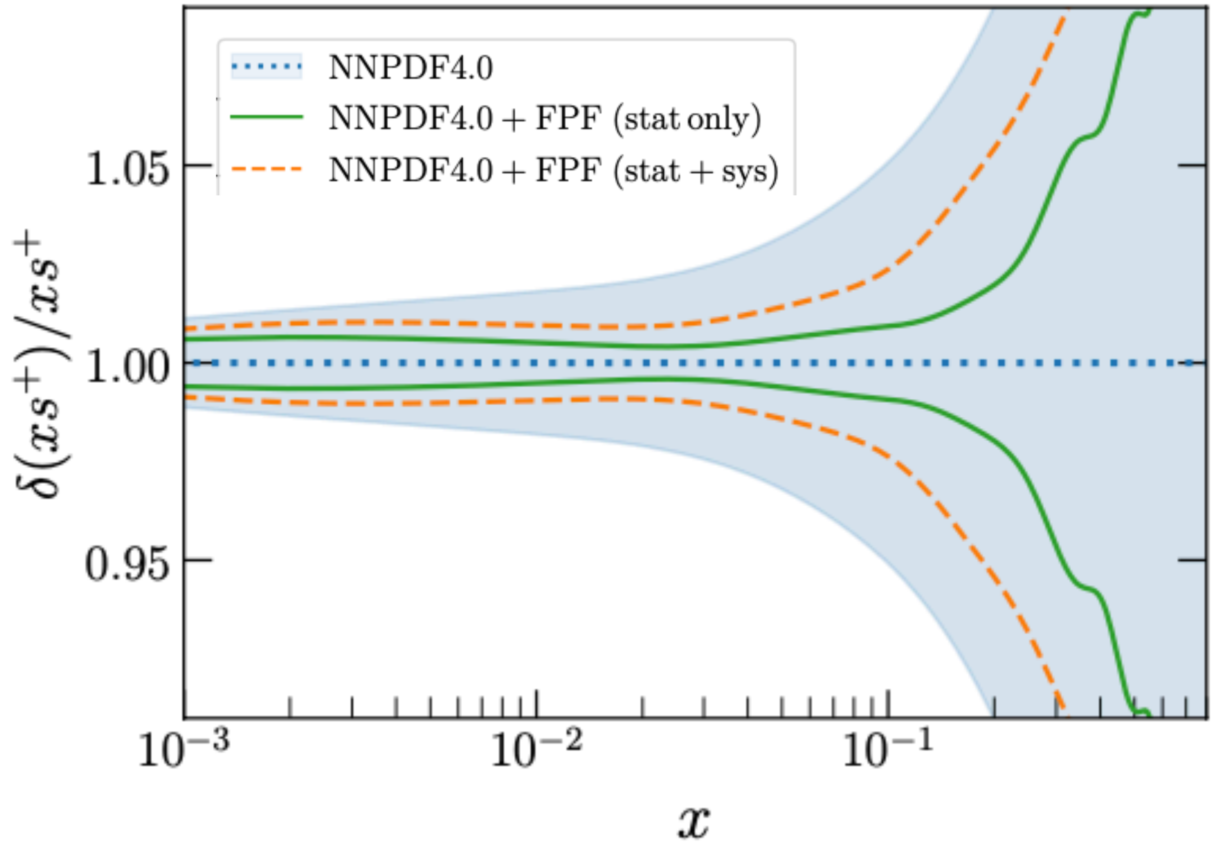
A non-zero valence charm PDF is the ultimate smoking gun for IC, since no perturbative mechanism can generate it

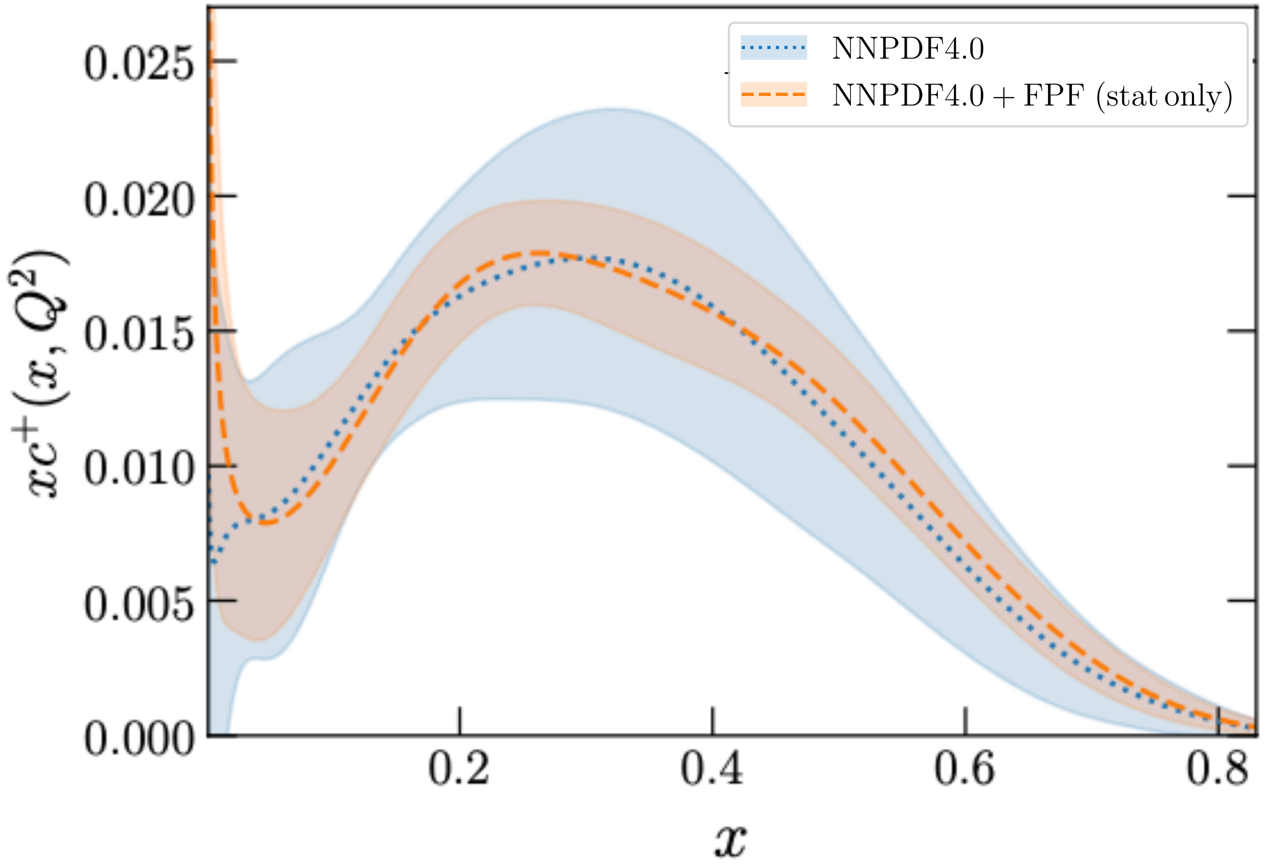
R. D. Ball, A. Candido, J. Cruz-Martinez, S. Forte, T. Giani, F. Hekhorn, K. Kudashkin, G. Magni & J. Rojo, ***Nature* 608 (2022) 7923, 483-487**

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***

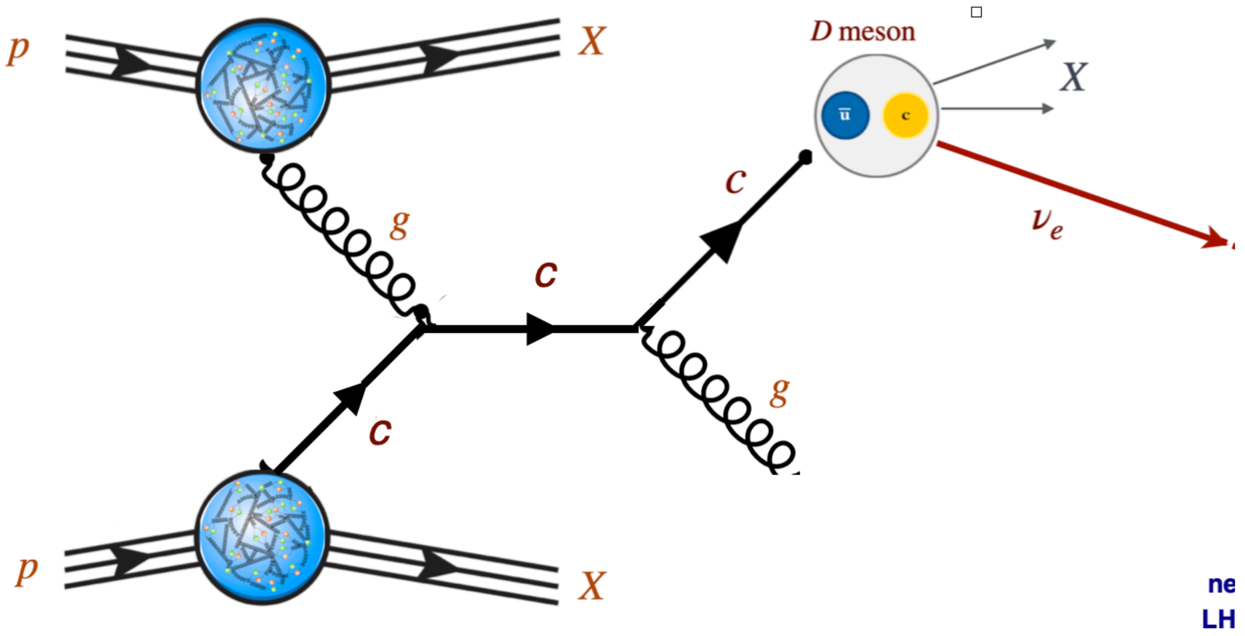


Impact on Intrinsic Charm

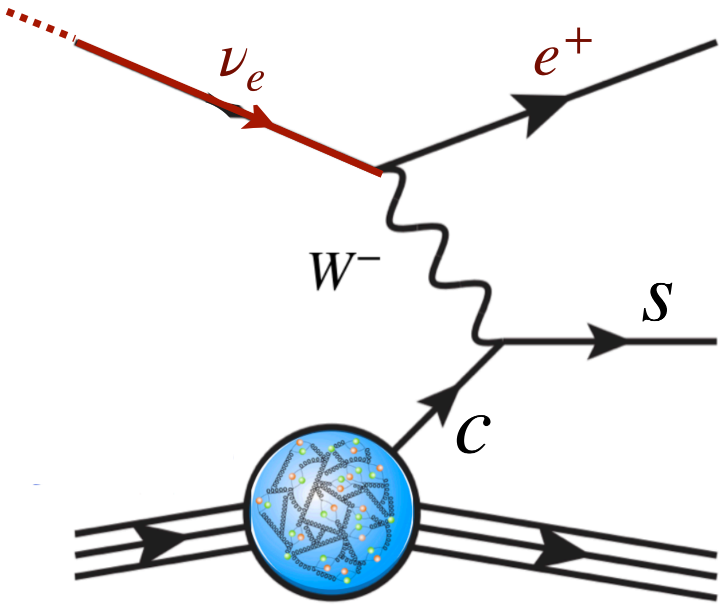




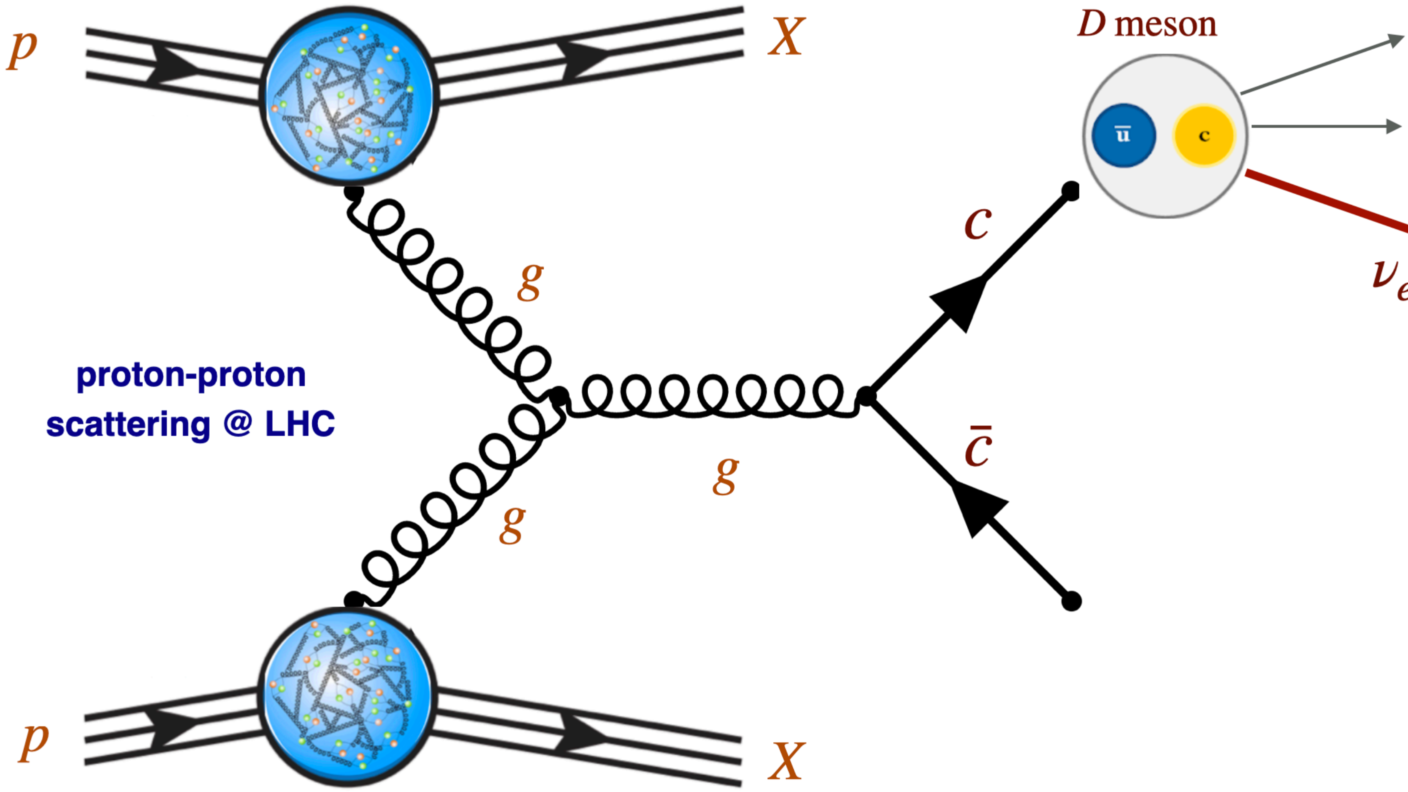
- Sensitivity to the charm PDF via the **gluon-charm initial state ….**

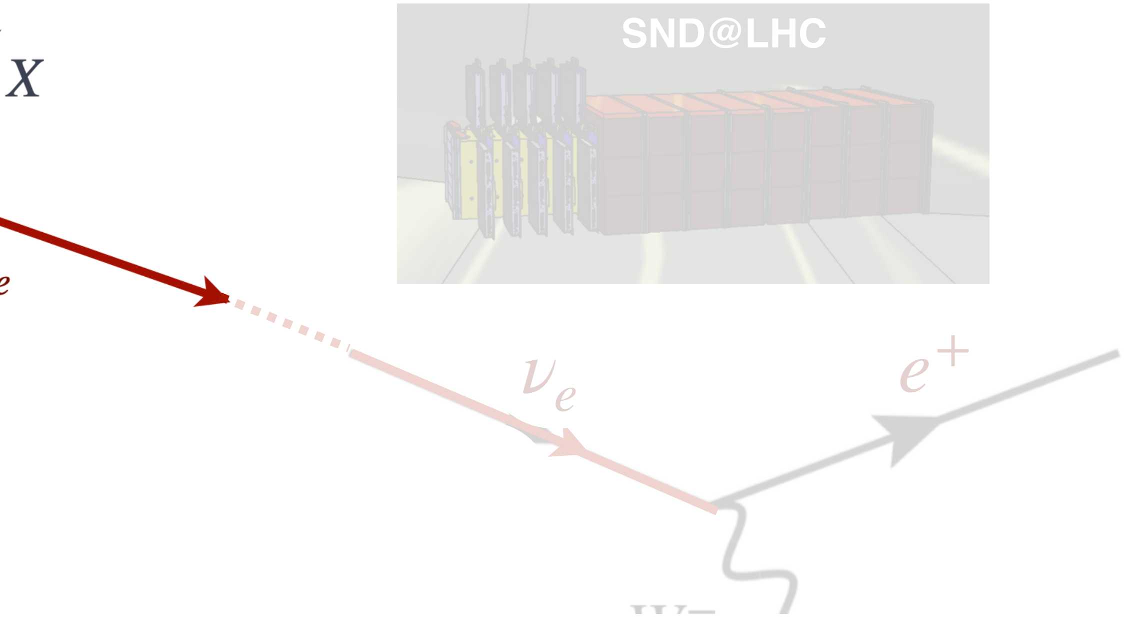


- …as well as via **neutrino scattering off charm quarks** in the target



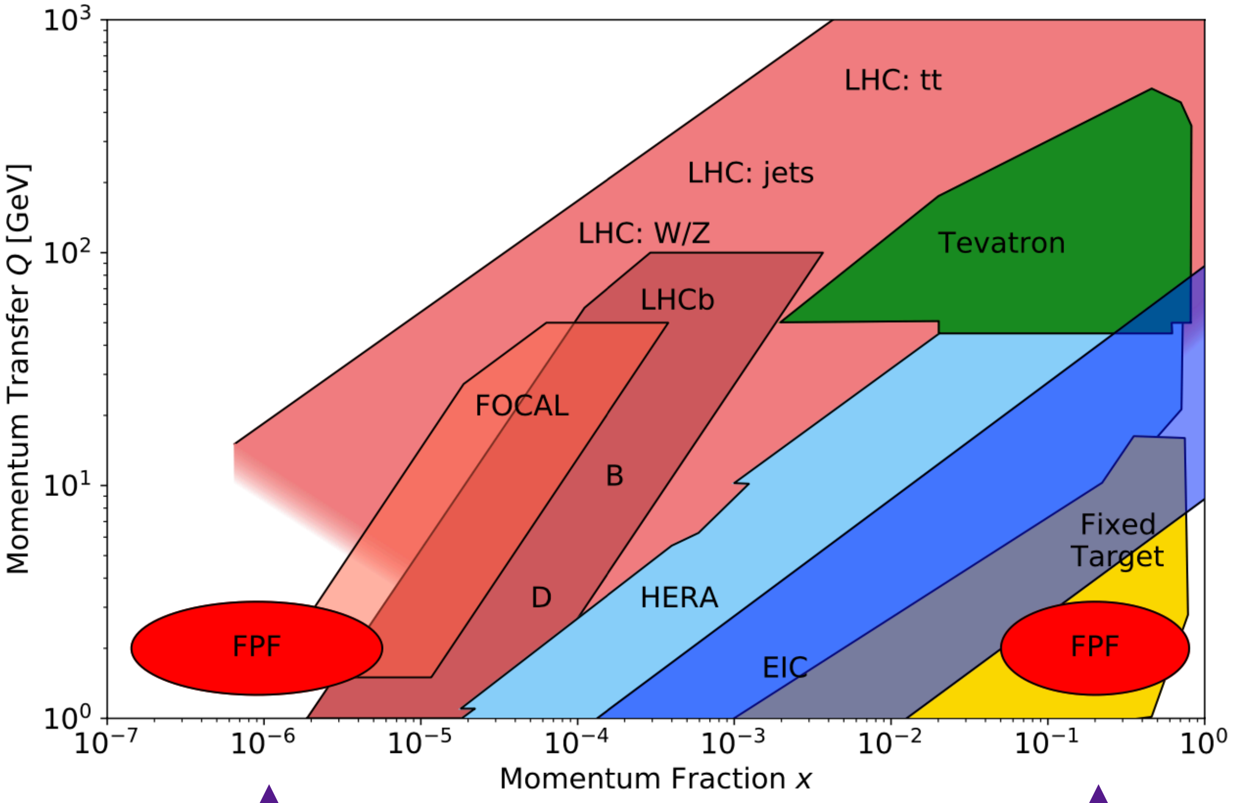
LHC neutrinos and small-x QCD





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



small-x gluon

large-x

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

LHC neutrinos and small-x QCD

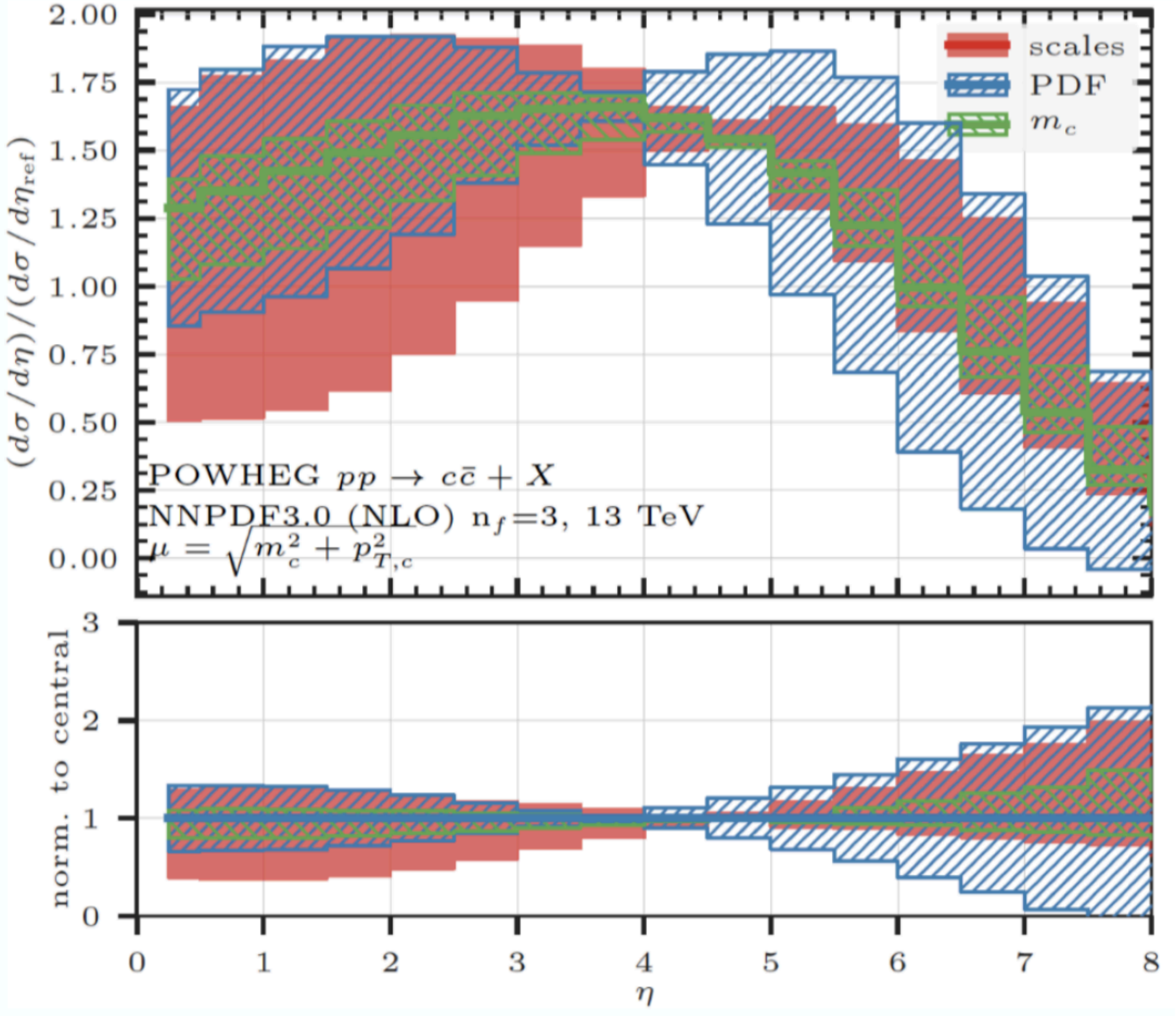
$$\frac{d^2\sigma(\mathrm{pp}\to D(\to\nu)+X)}{p_T^\nu y_\nu} \propto f_g(x_1,Q^2)\otimes f_g(x_2,Q^2)\otimes \frac{d^2\hat{\sigma}(gg\to c\bar{c})}{p_T^c y_c}\otimes D_{c\to D}(z,Q^2)\otimes \mathrm{BR}(D\to\nu+X)$$

Extract from measured neutrino fluxes

Constrain from LHC neutrino data

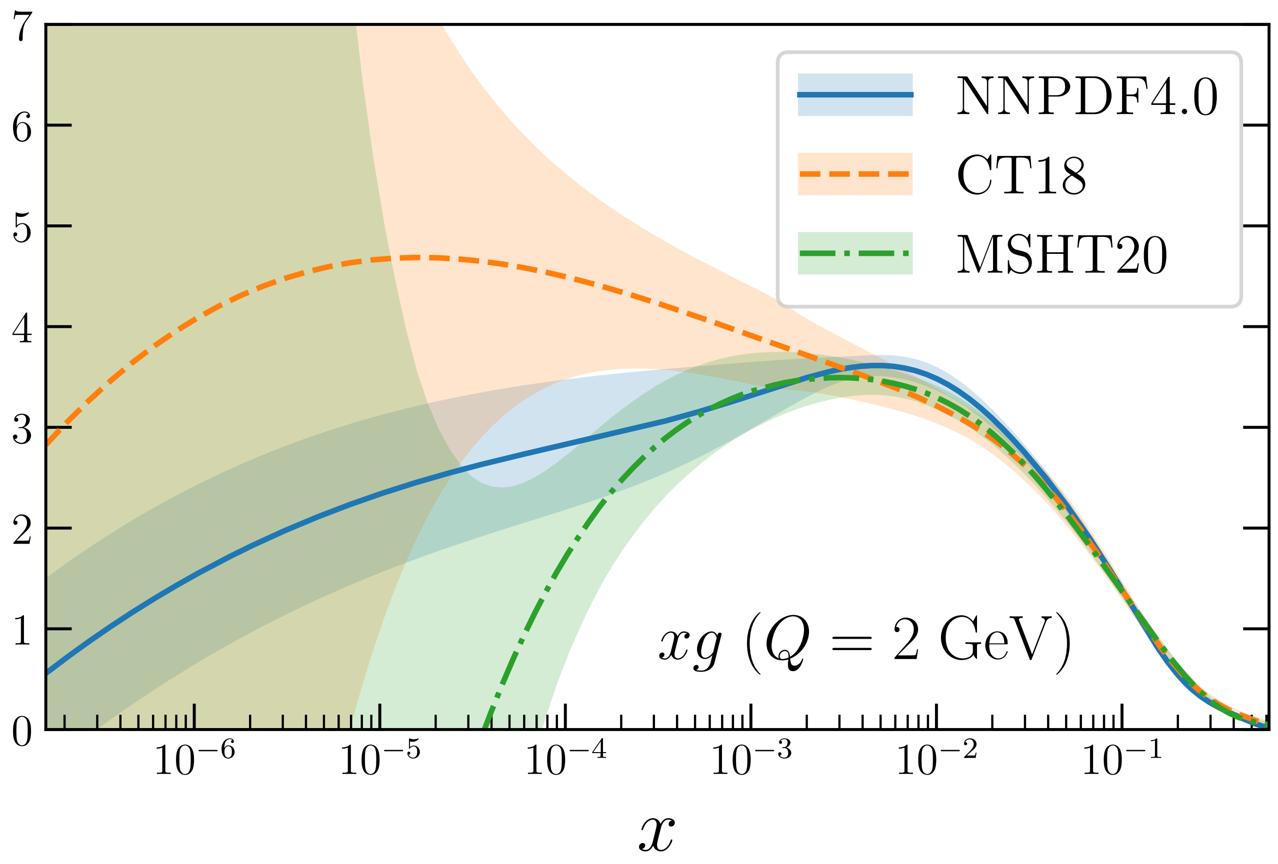
QCD prediction: NLO + PS large theory uncertainties

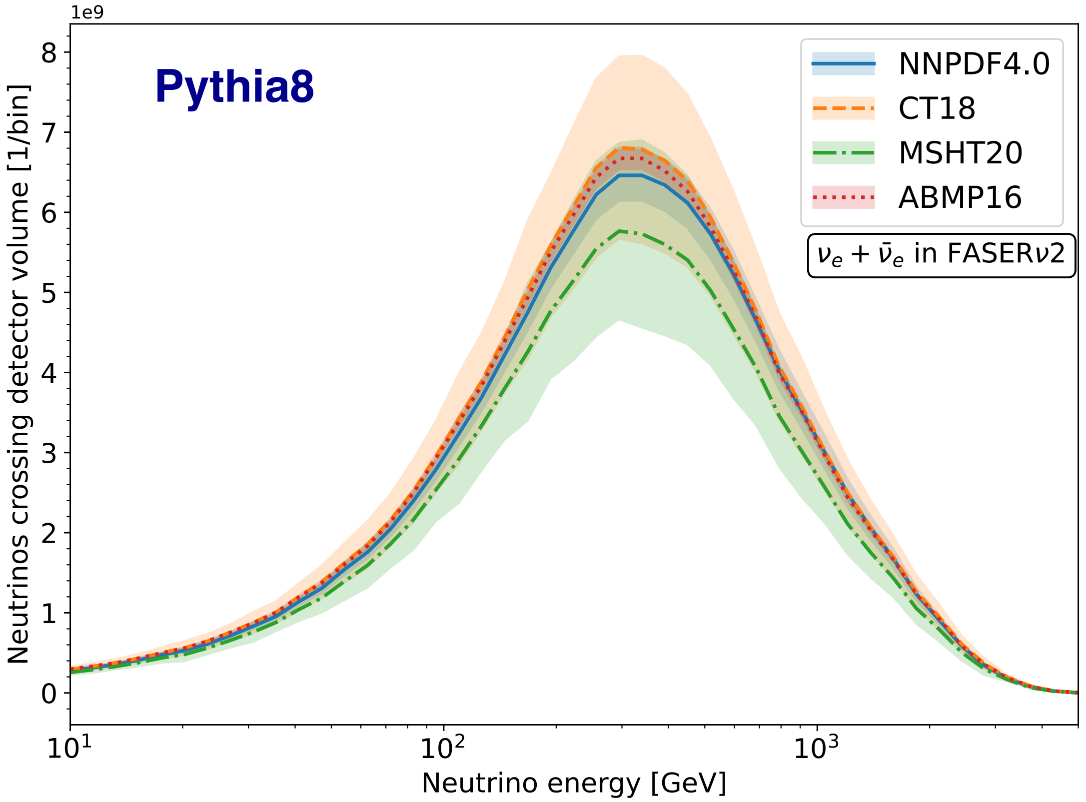
QCD prediction/models + non-perturbative physics



- **Only laboratory experiment** which can inform both UHE neutrino interactions, cosmic ray collisions, and FCC-pp cross-sections
- Challenges in **modelling forward charm production**: QCD corrections, fragmentation, interaction with beam remnants ….
- Requires designing observables where **theory systematics cancel out**
  - ☑ Ratios to reference rapidity bin
  - ☑ Ratios between CoM energy
  - ☑ Ratios between correlated observables

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

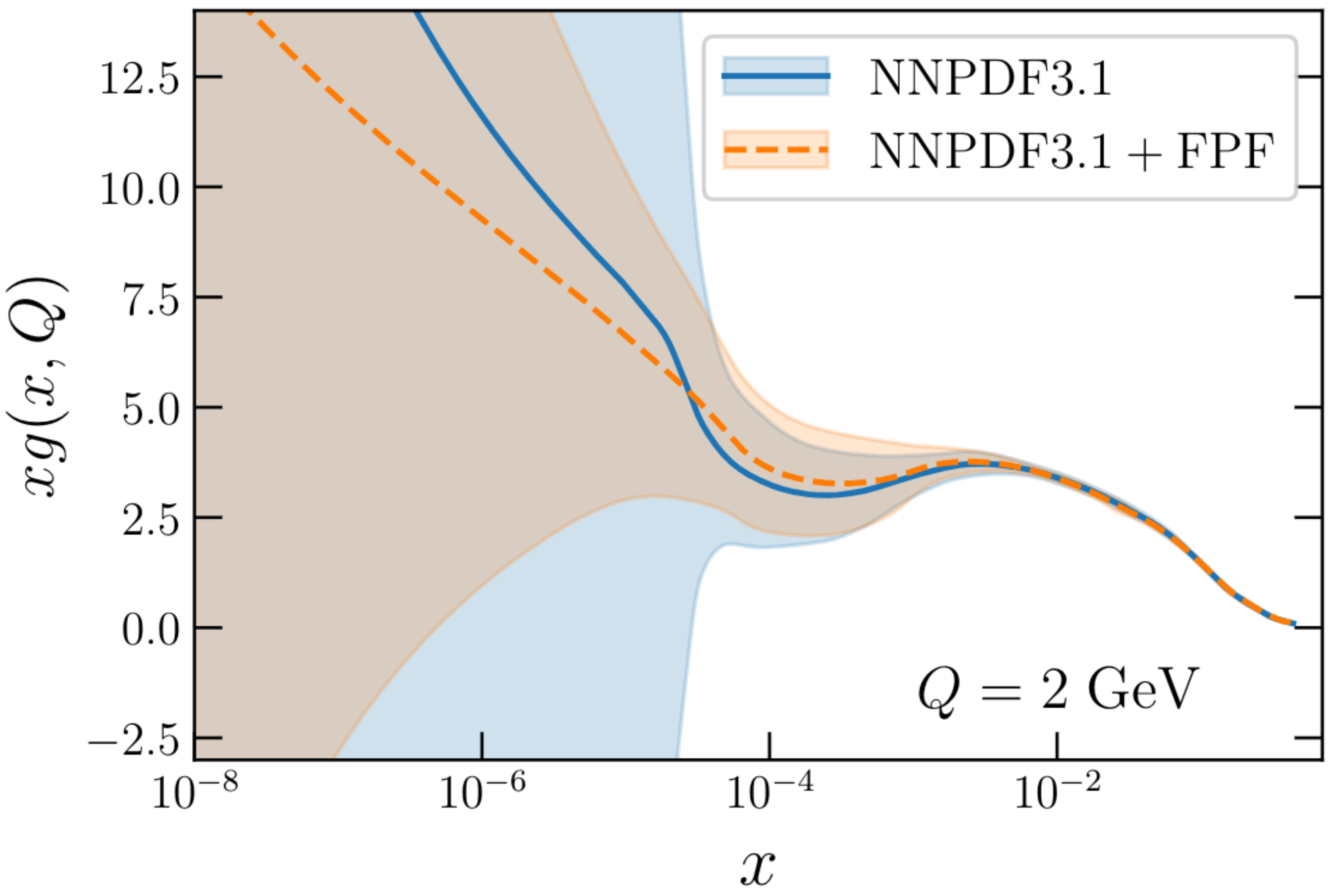
$$R_{\tau/e}(E_\nu) \equiv \frac{N(\nu_\tau + \bar{\nu}_\tau; E_\nu)}{N(\nu_e + \bar{\nu}_e; E_\nu)}\,, \qquad R^{\nu_e}_{\rm exp}(E_\nu) = \frac{N_{\rm FASER\nu}(\nu_e + \bar{\nu}_e E_\nu)}{N_{\rm SND@LHC}(\nu_e + \bar{\nu}_e; E_\nu)}$$

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

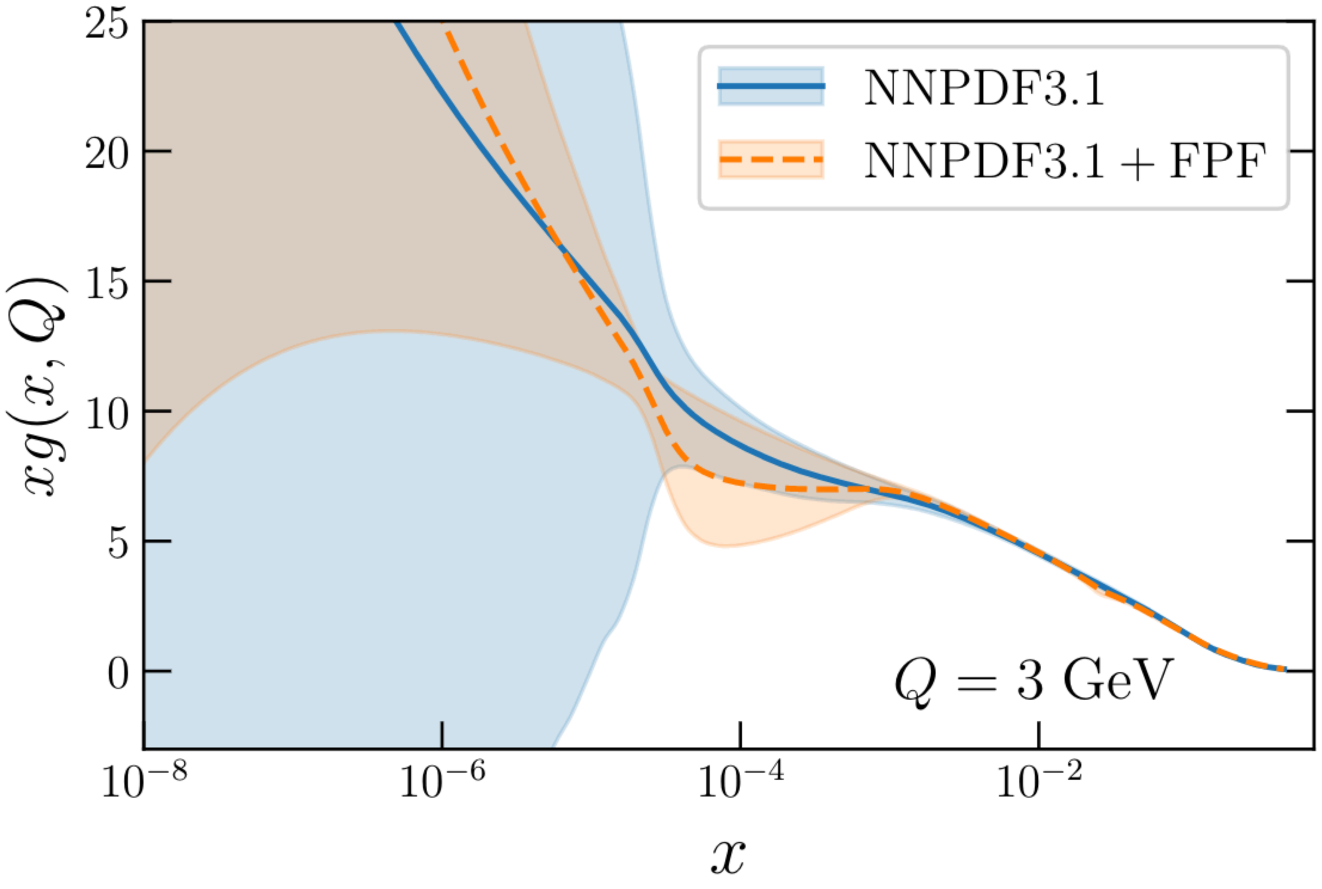
Proxy for 2D xsec differential in (energy, rapidity)

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

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**

- They provide a unique perspective on **quark flavour separation,** enhance theory predictions for HL-LHC observables, and scrutinise the **charm content of the proton**

- 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: a key ongoing development for LHC neutrino experiments