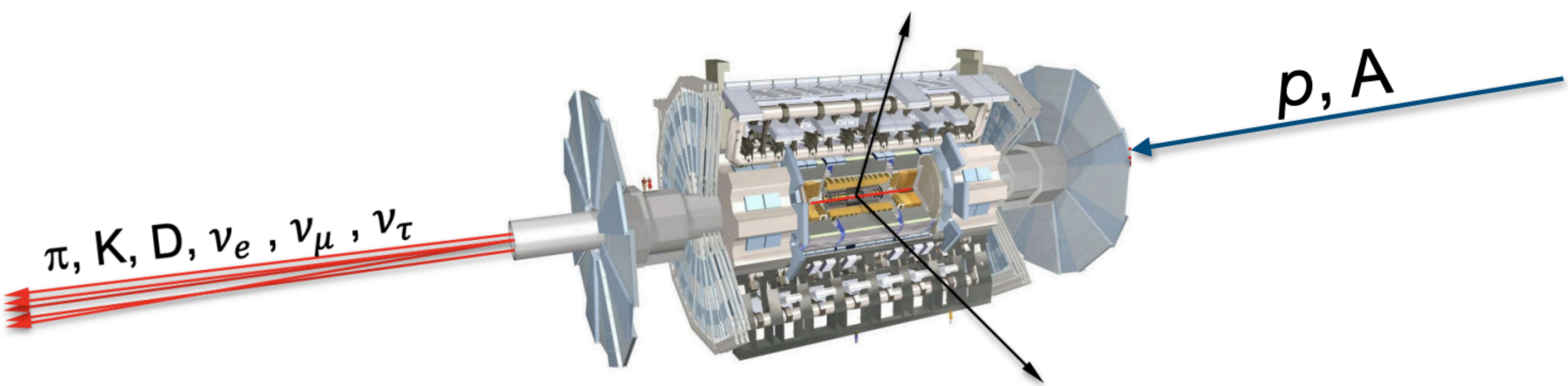
Forward Physics Facility @ LHC: SM Physics Case

Juan Rojo, VU Amsterdam & Nikhef



Physics Beyond Colliders (PBC) Annual Workhop

CERN, March 25th 2024

Forward Physics Facility @ LHC: SM Physics Case & high-p_T BSM searches at the HL-LHC

Physics Beyond Colliders (PBC) Annual Workhop

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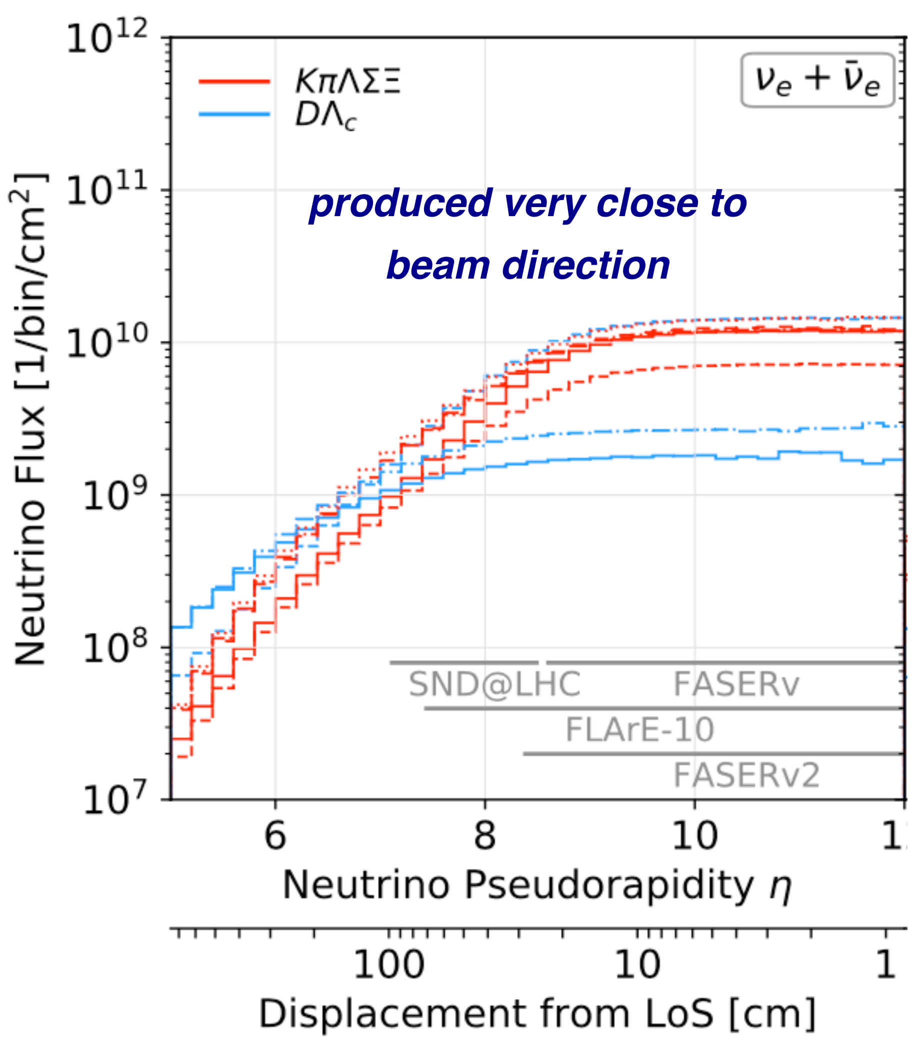
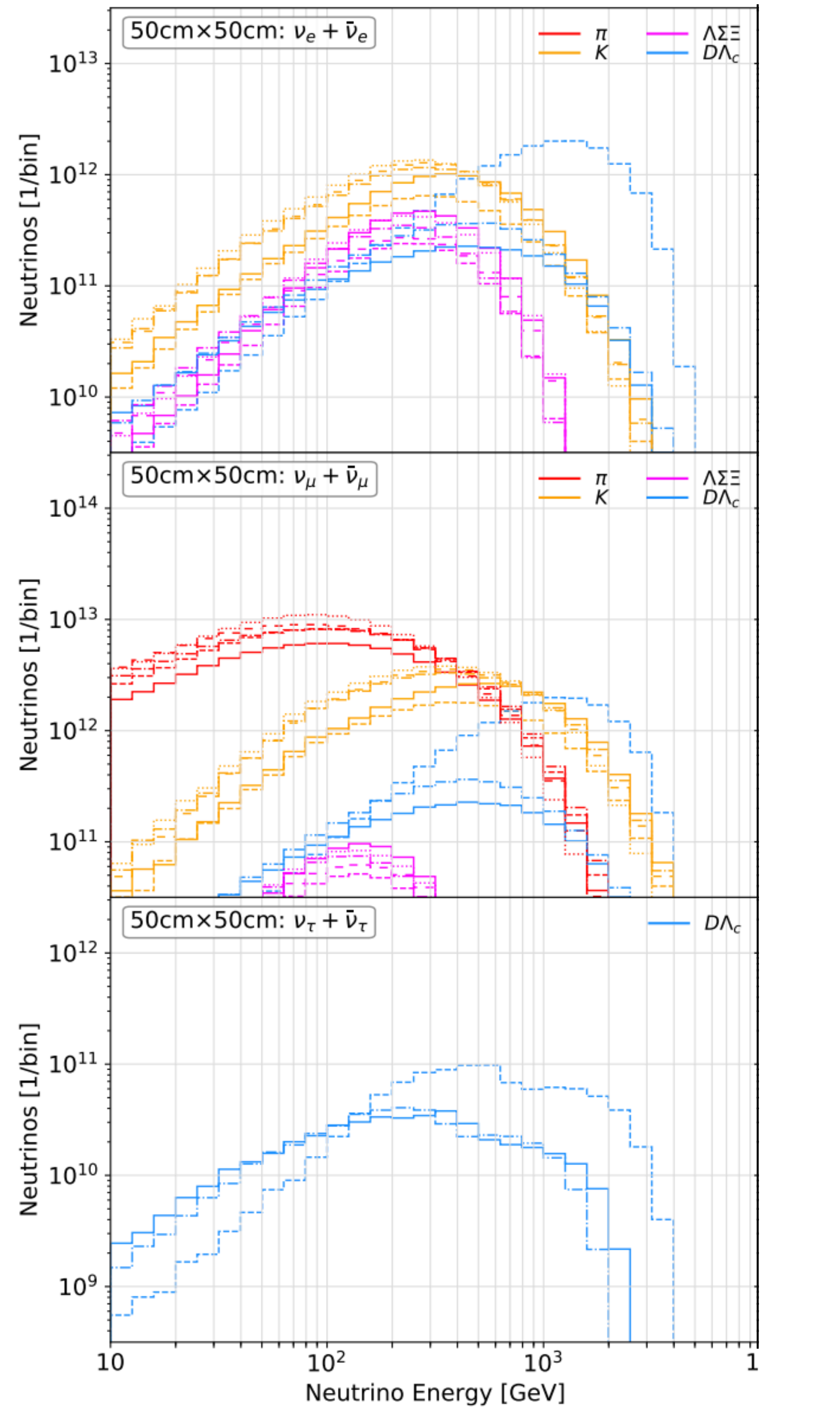
Neutrino Physics

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

Most energetic (TeV-scale) neutrinos ever produced in a laboratory!





The dawn of the LHC neutrino era

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

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

Editors' Suggestion | Featured in Physics

First Direct Observation of Collider Neutrinos with FASER at the LHC

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

DOI: 10.1103/PhysRevLett.131.031801

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

Editors' Suggestion

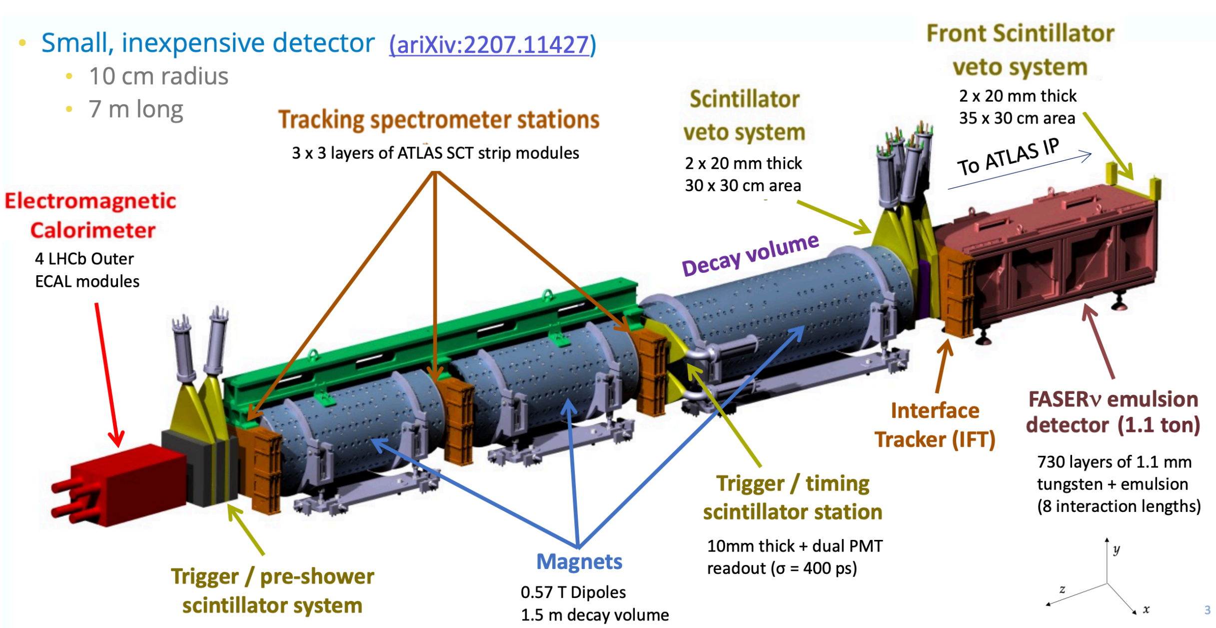
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

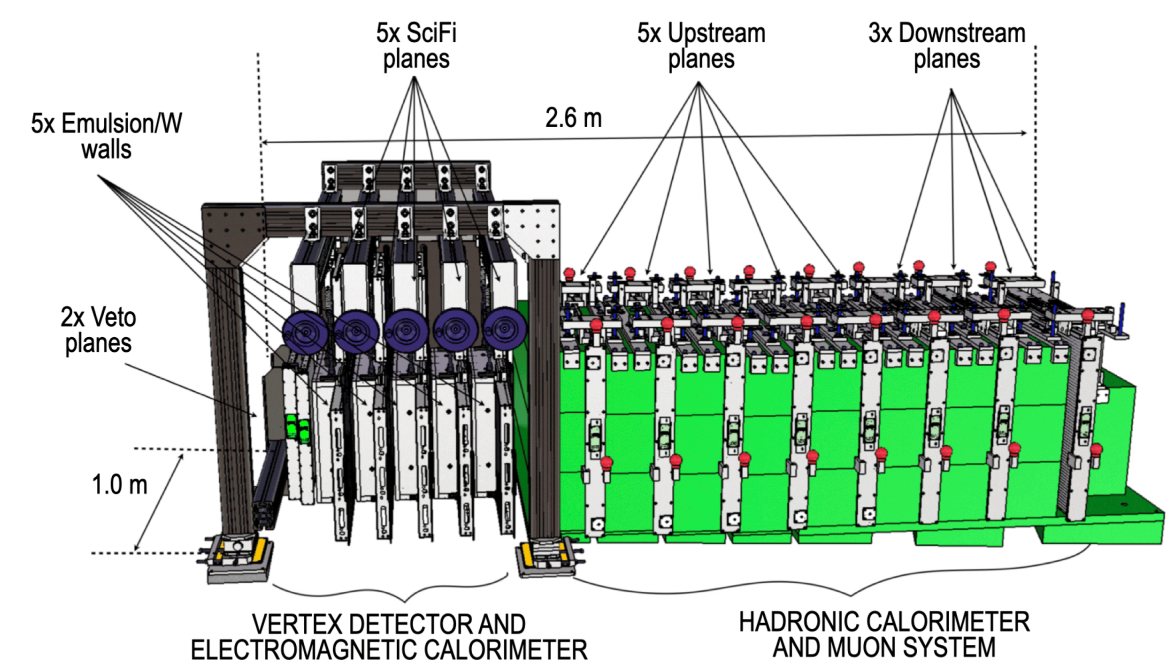
We report the direct observation of muon neutrino interactions with the SND@LHC detector at the Large Hadron Collider. A dataset of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected by SND@LHC in 2022 is used, corresponding to an integrated luminosity of 36.8 fb^{-1}. The search is based on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

DOI: 10.1103/PhysRevLett.131.031802

153 neutrinos detected, 151± 41 expected

8 neutrinos detected, 4 expected

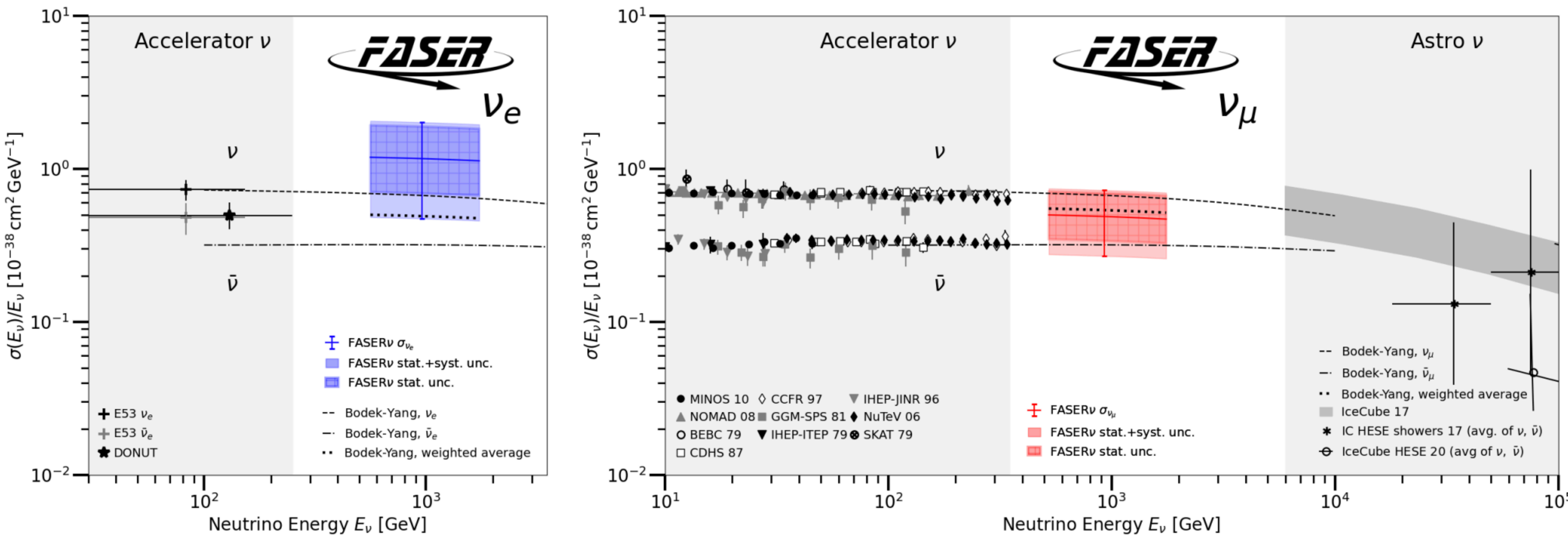




Now is the time to start exploiting their physics potential

The dawn of the LHC neutrino era

- **FASER** recently presented the first measurement of **cross-sections of** collider (TeV) neutrinos

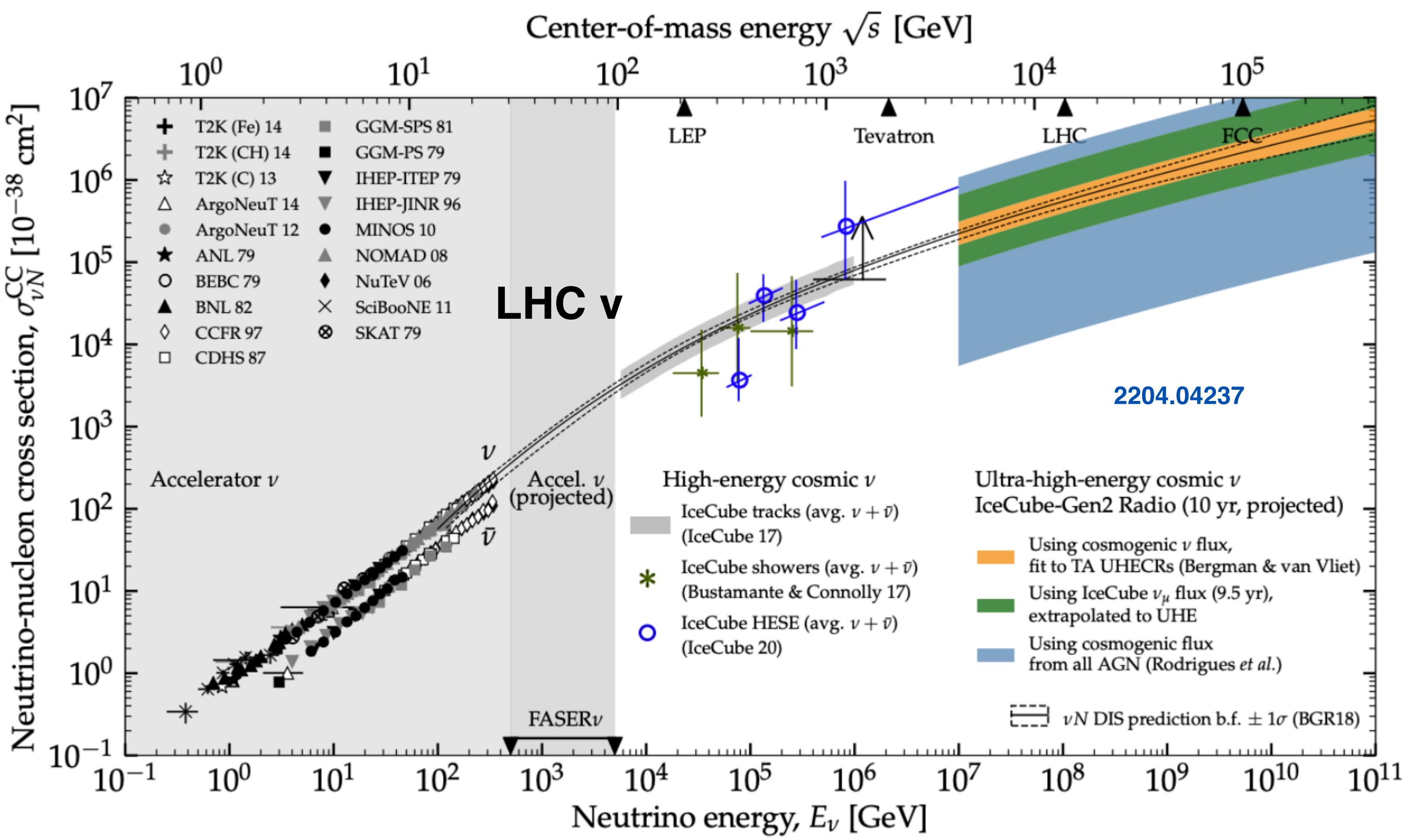


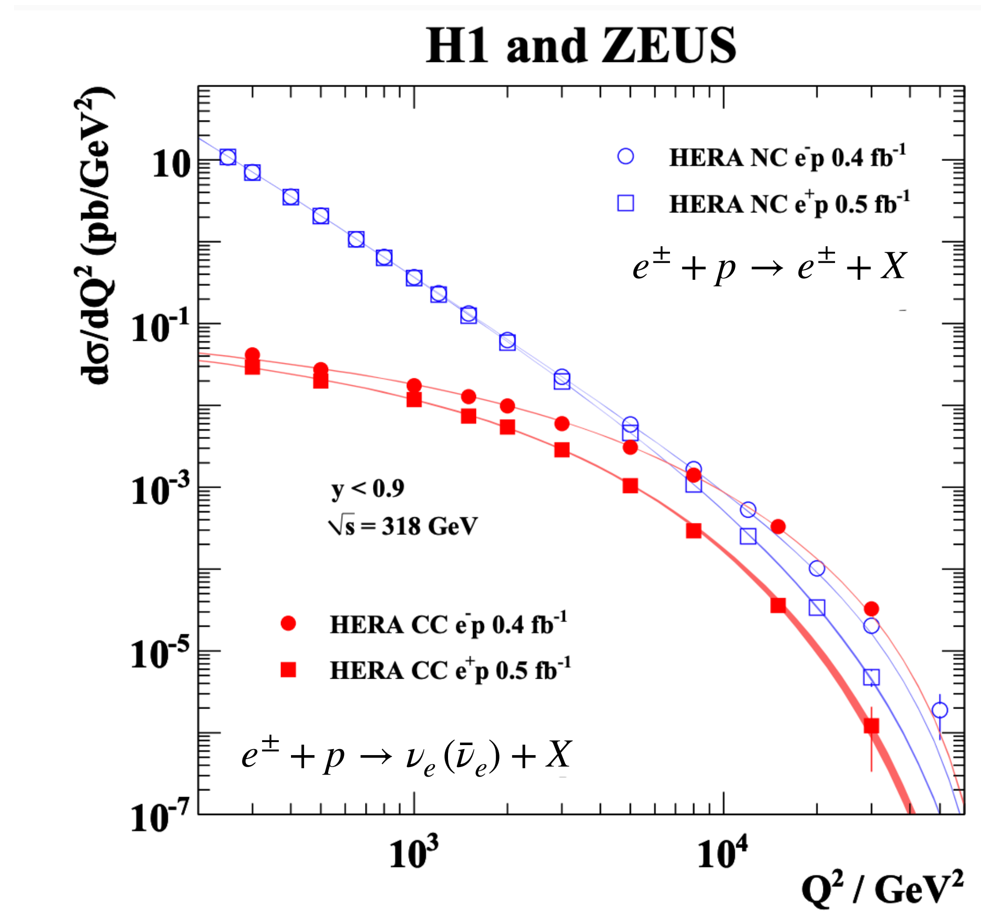
- Demonstrates the excellent performance of the experiment for neutrino interaction measurements
- Paves the way to more refined measurements, including **multi-differential** (structure functions)
- Ultimately FASER and SND@LHC neutrino measurements **will be limited by statistics …**

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

Neutrino Physics at the FPF

- Precise measurement of **electron, muon, 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		
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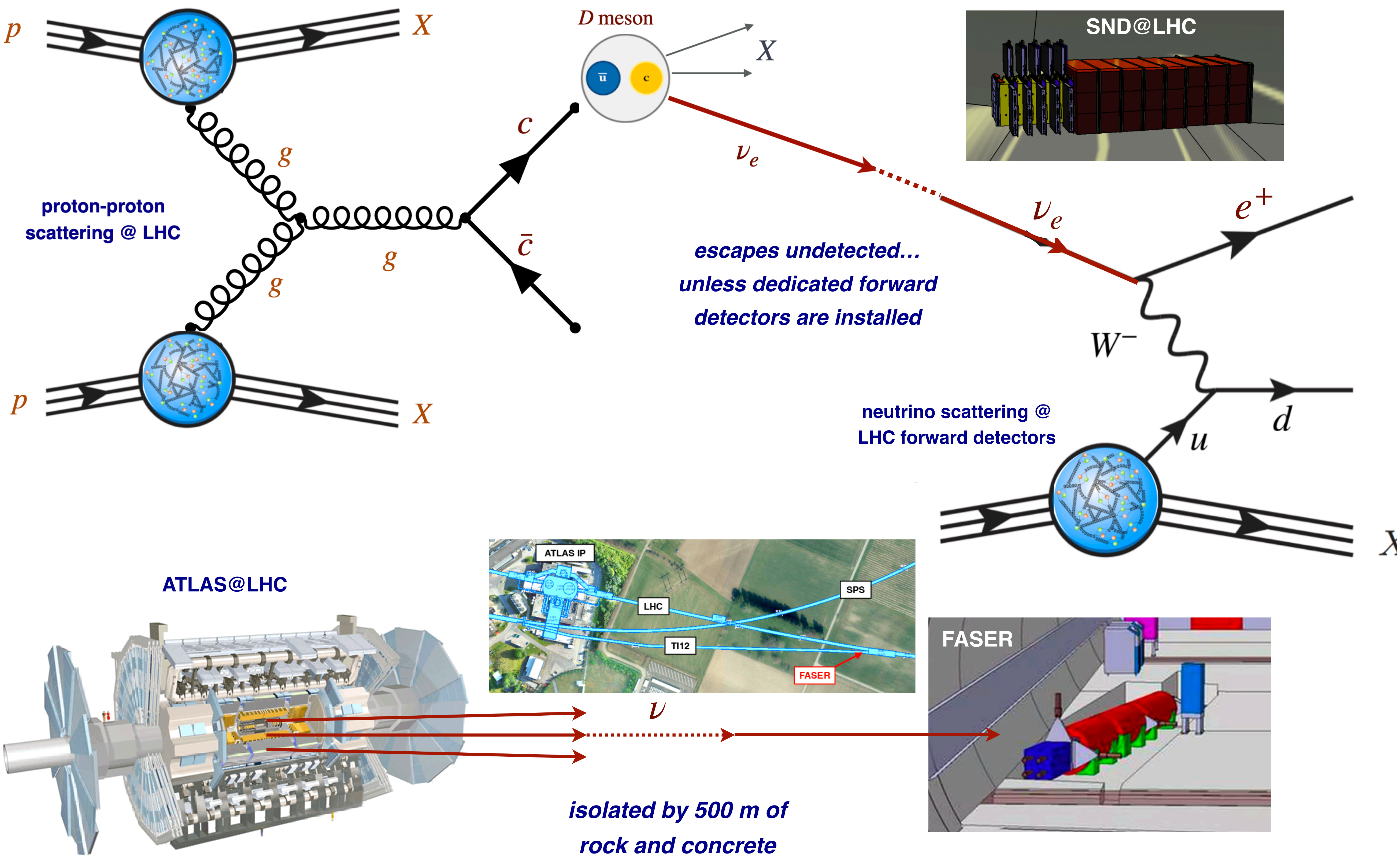
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

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

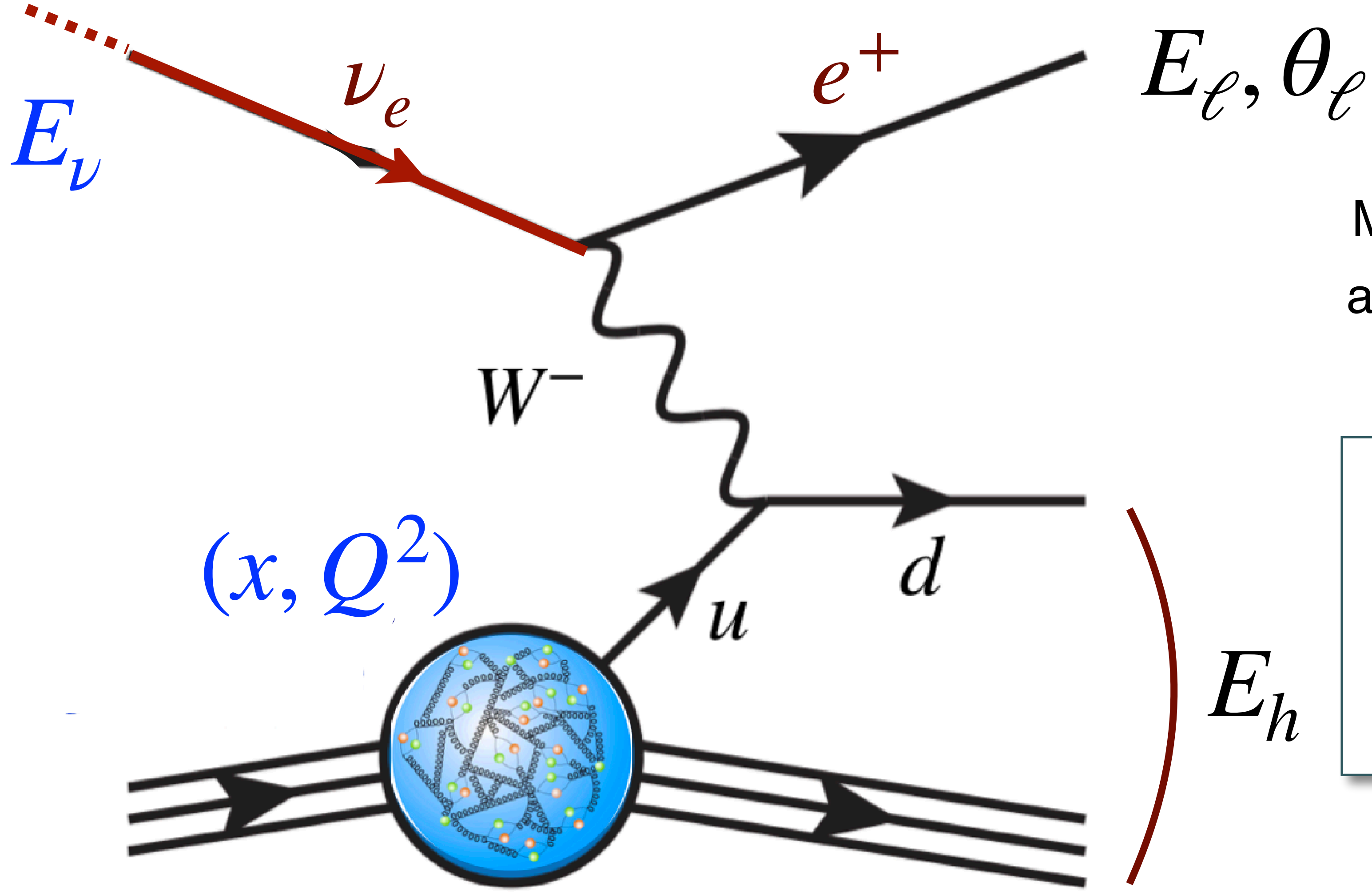
QCD & Astroparticle Physics

Neutrinos at the LHC



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

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

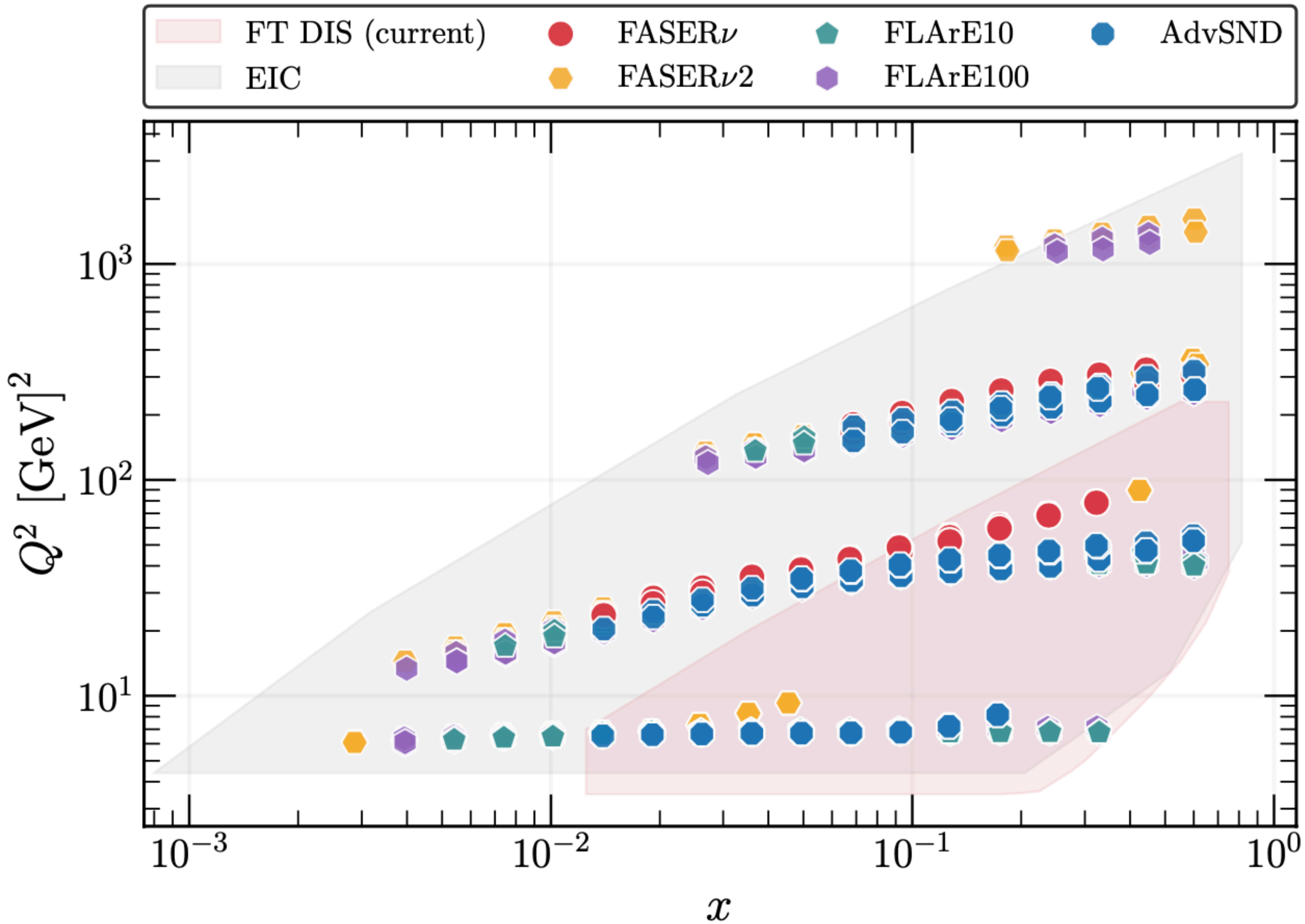
$$\sigma_{\nu p \to e^+ X}(E_\nu) = \tilde{\sigma}_{\nu u \to d} \otimes u(x, Q^2)$$

- $\sigma_{\nu p \to e^+ X}(E_\nu)$ → 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

Neutrino DIS at the LHC



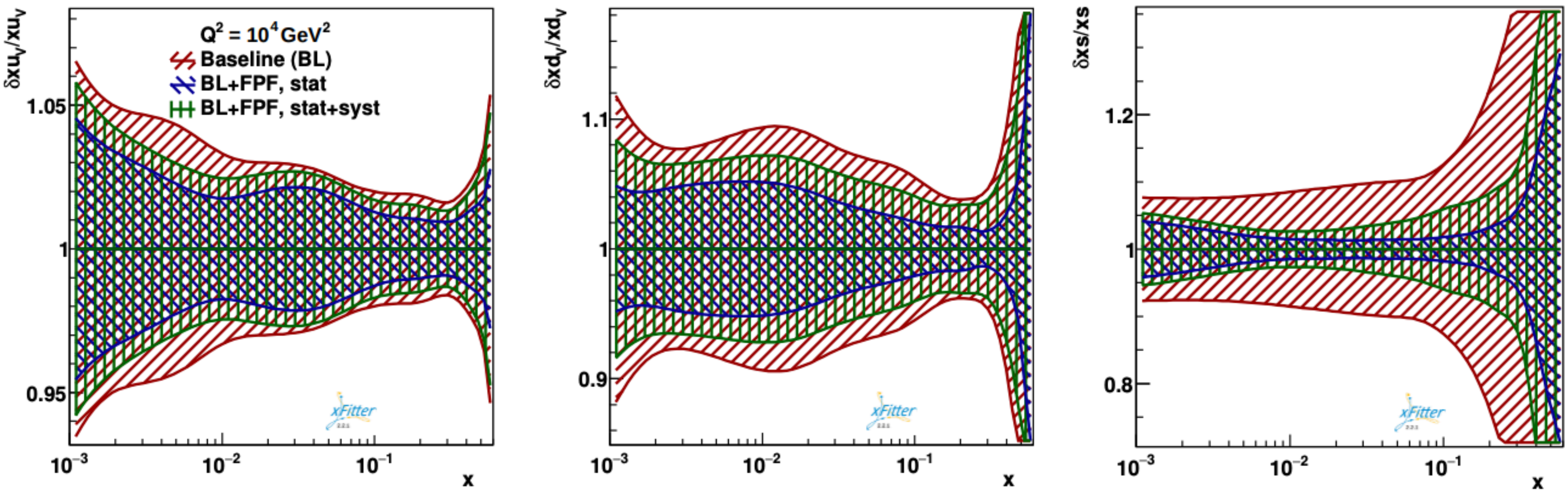
x: momentum fraction of quarks/gluons in the proton

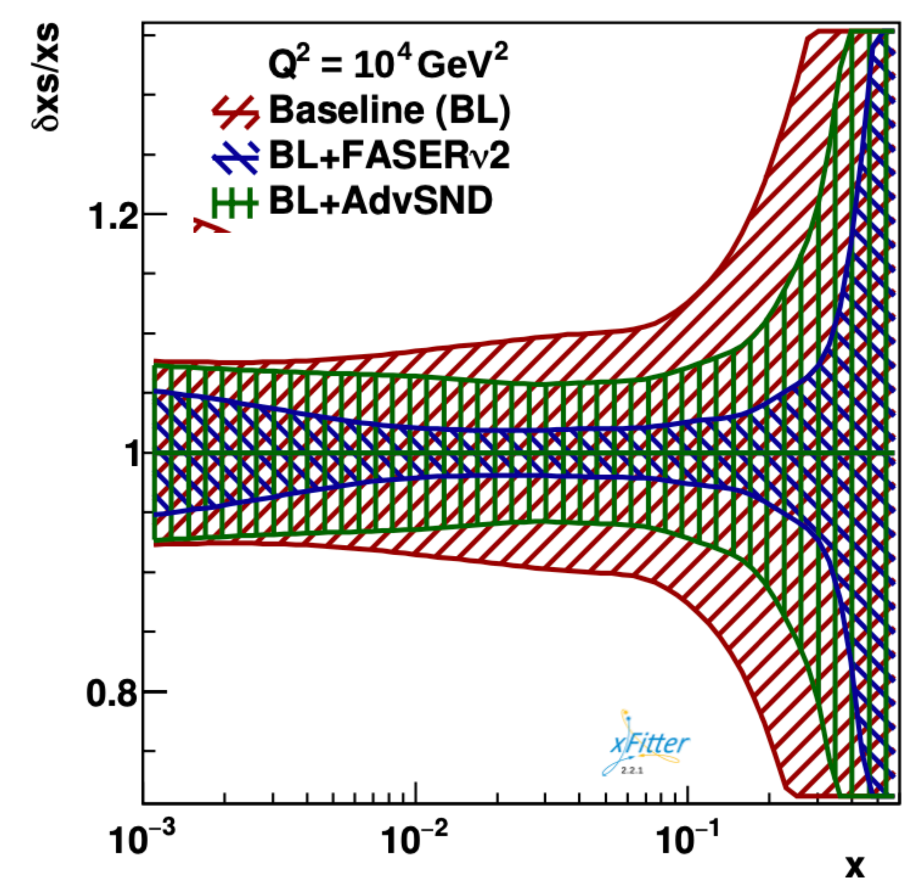
Q²: momentum transfer from incoming lepton

- Continue highly succesful program of neutrino **DIS experiments @ CERN**
- **Expand kinematic coverage** of available experiments by an order of magnitude in *x* and Q^2
- 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

PDF constraints from LHC neutrinos

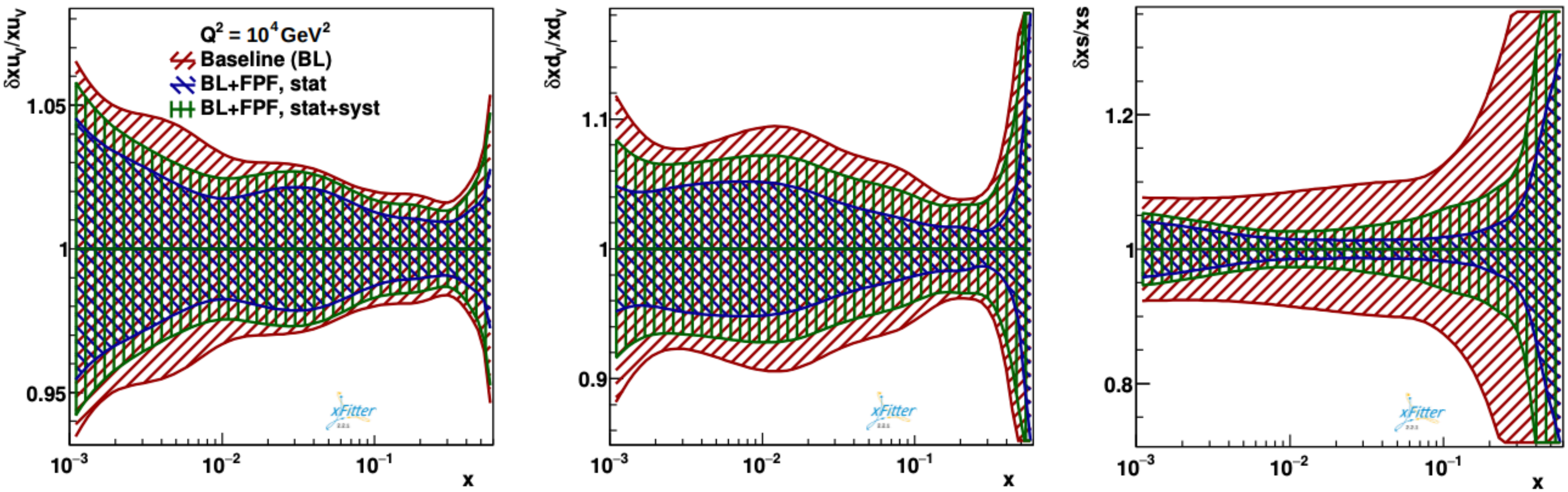




- Impact on proton PDFs quantified by the **Hessian profiling of PDF4LHC21** (xFitter) and by direct inclusion in the global **NNPDF4.0 fit**
- Most impact on **up and down valence quarks** as well as in **strangeness,** ultimately limited by systematics
- Uncertainties in **incoming neutrino fluxes subdominant,** once constrained *in-situ* at FASER & FPF

Cruz-Martinez et al 23

PDF constraints from LHC neutrinos



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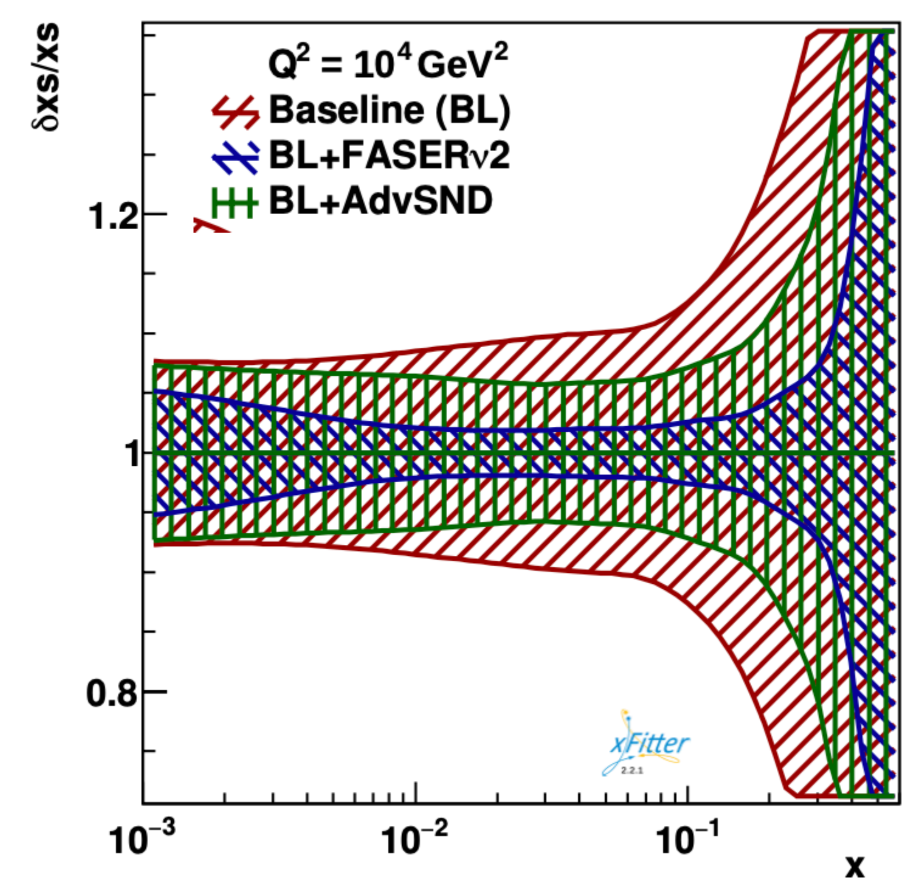

Cruz-Martinez et al 23

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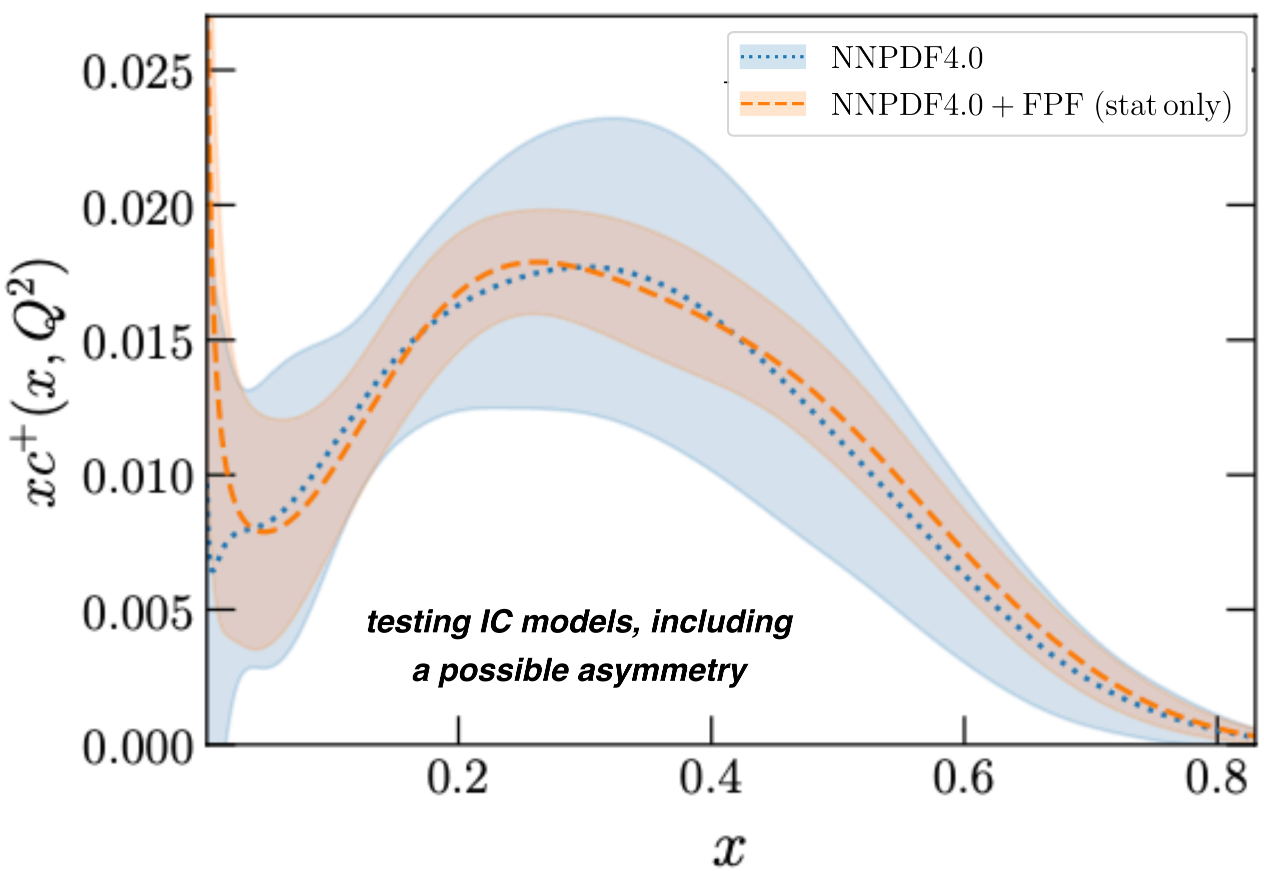

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Article | Open access | Published: 17 August 2022

Evidence for intrinsic charm quarks in the proton

The NNPDF Collaboration

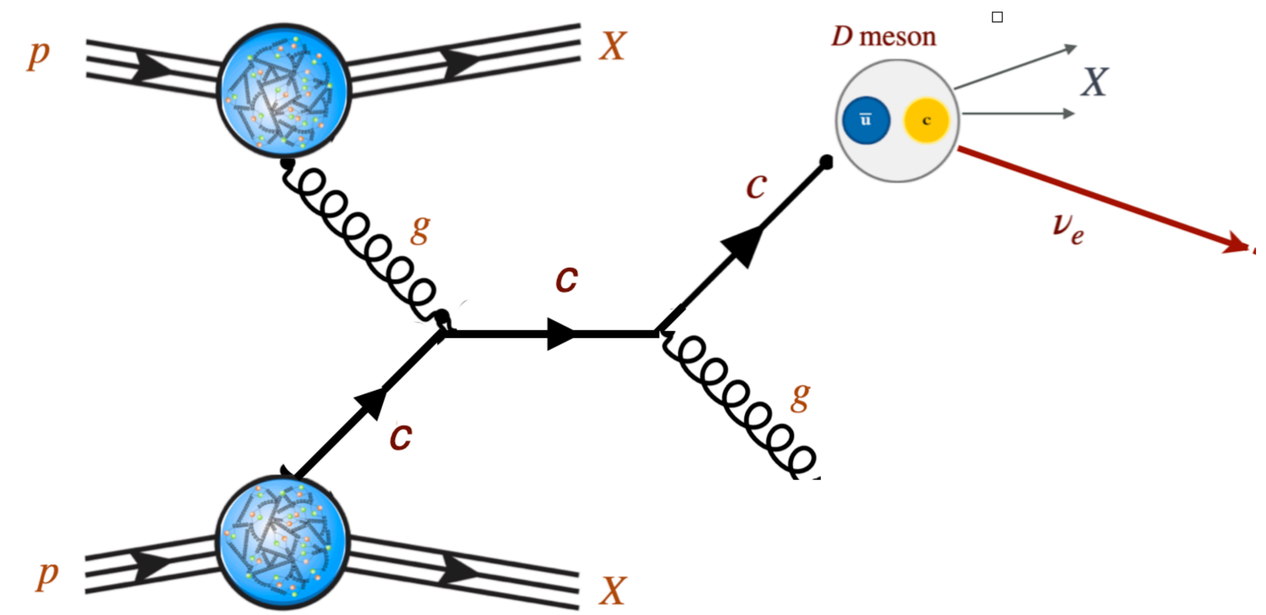
Nature **608**, 483–487 (2022) | Cite this article

53k Accesses | **27** Citations | **367** Altmetric | Metrics

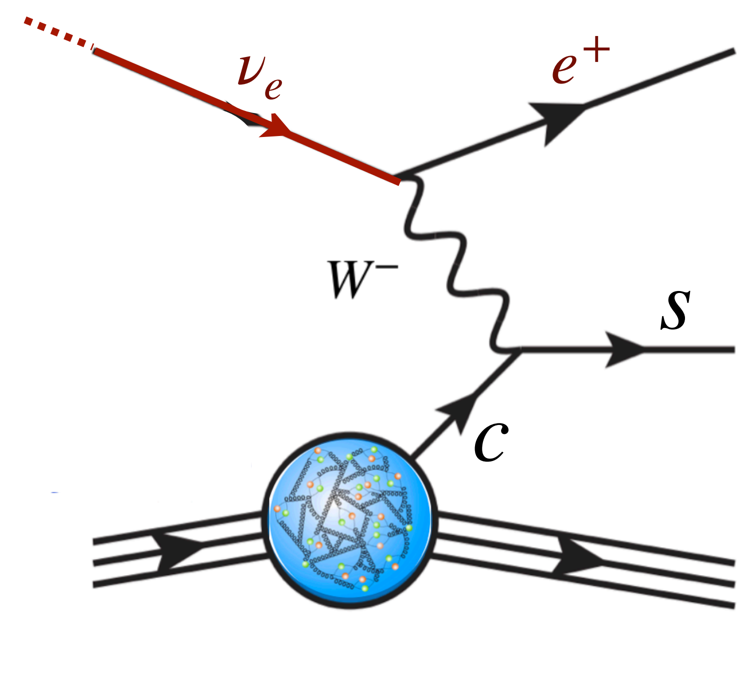
Abstract

The theory of the strong force, quantum chromodynamics, describes the proton in terms of quarks and gluons. The proton is a state of two up quarks and one down quark bound by gluons, but quantum theory predicts that in addition there is an infinite number of quark–

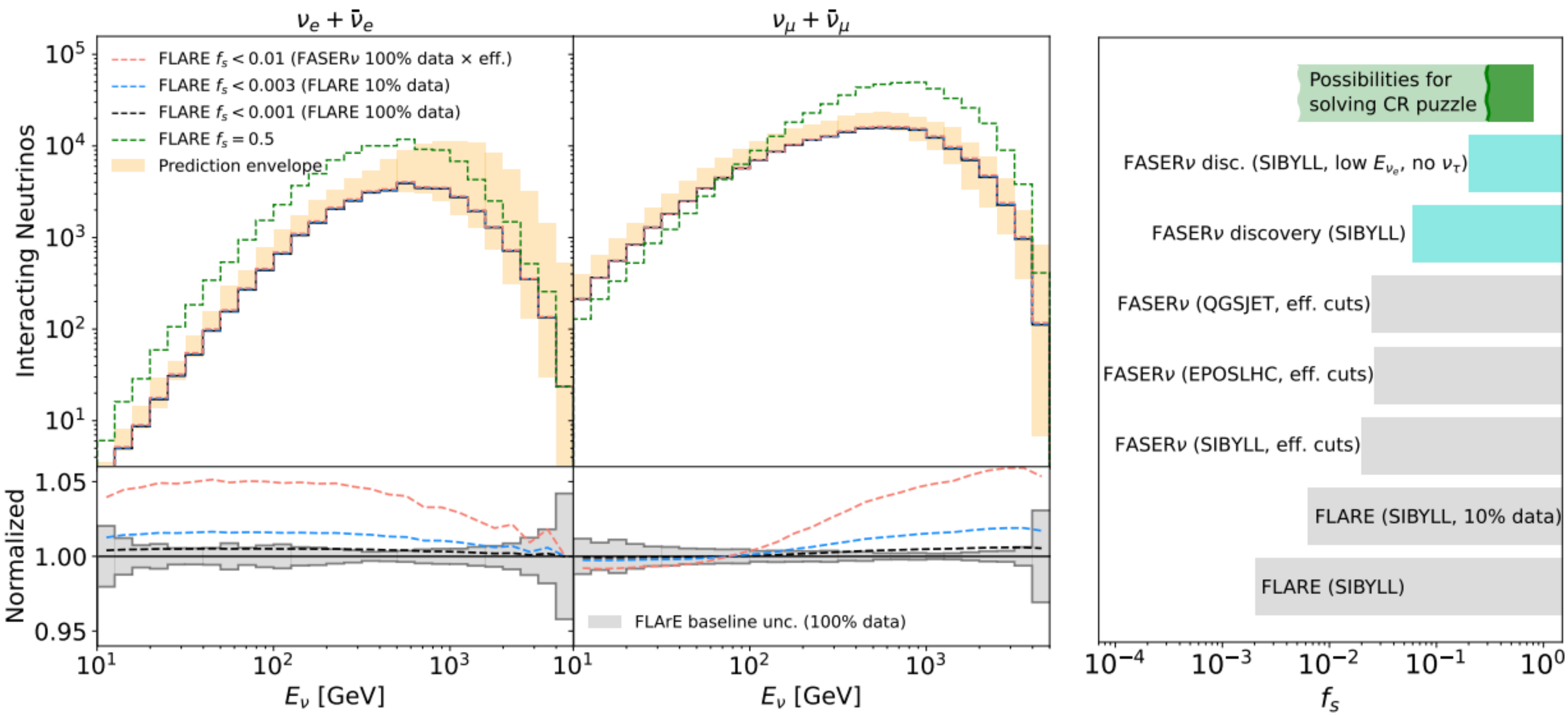
- Sensitivity to the charm PDF via the **gluon-charm initial state ....**



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



Muon Puzzle in Cosmic Ray Physics



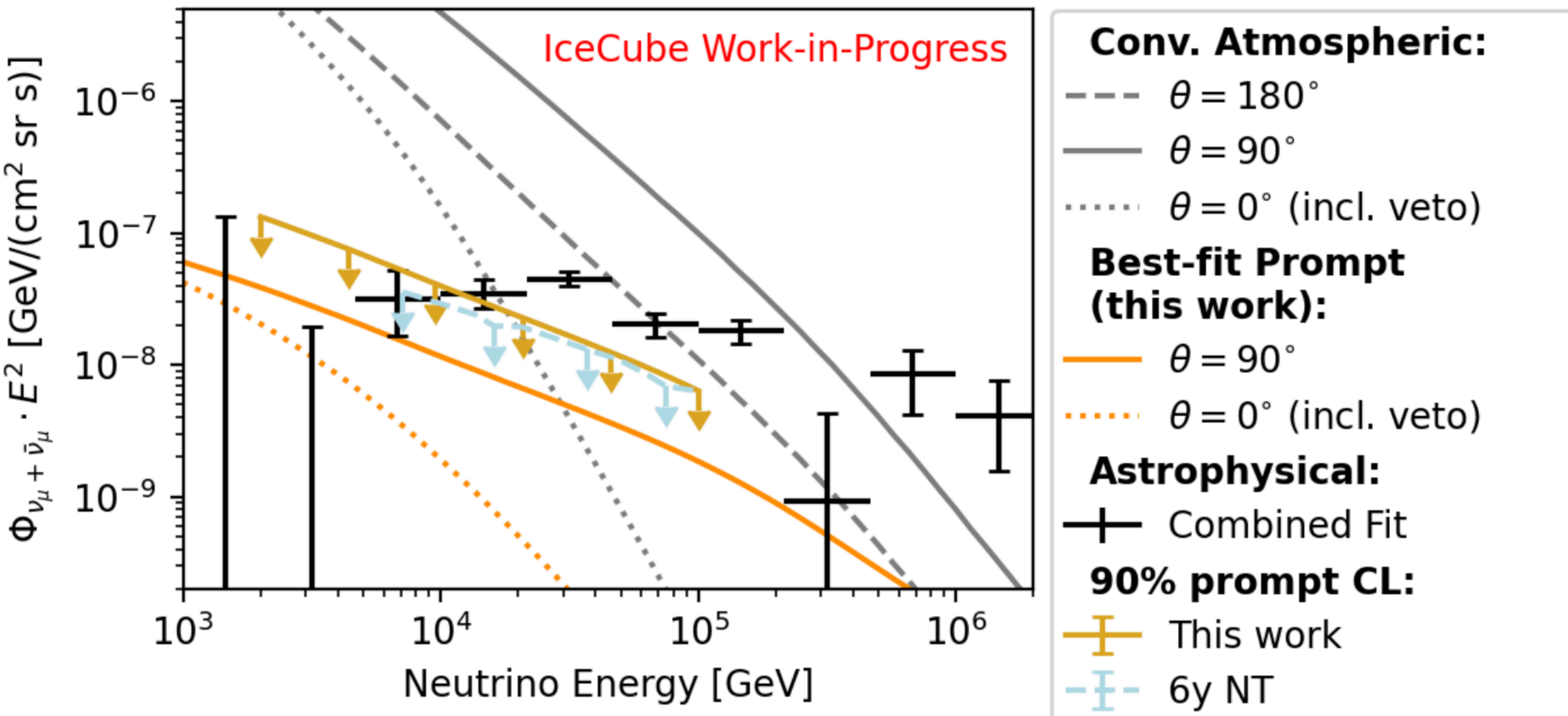
Kling et al. 23

$$N_{K\to\nu} \to (1 + 6.6\, f_s) N_{K\to\nu}. \qquad N_{\pi\to\nu} \to (1 - f_s)\, N_{\pi\to\nu}.$$

- Enhanced forward strangeness (kaon) production may explain the **muon puzzle in cosmic ray physics**
- The FPF would either **validate or exclude this scenario** via precise measurements of neutrino fluxes

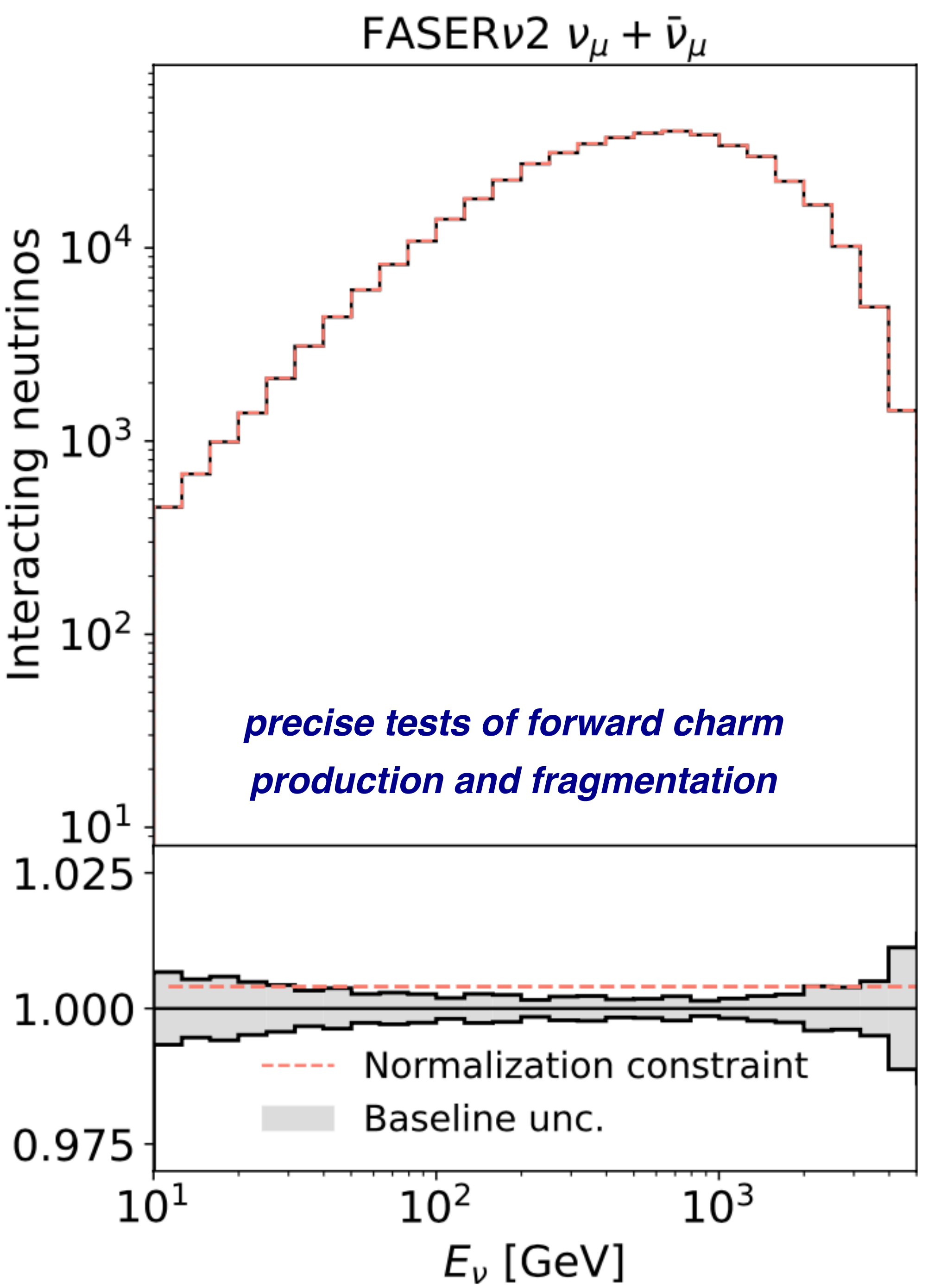
Neutrino Astronomy

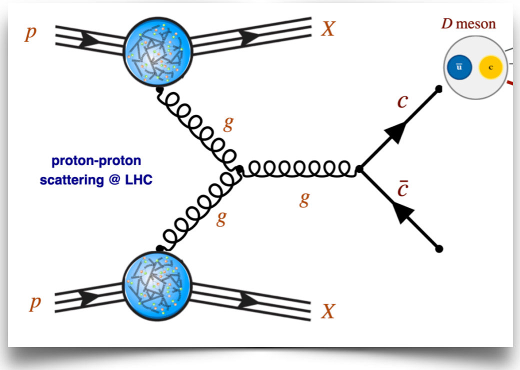
- **Prompt neutrino flux** dominates the systematic uncertainty for measurement of astrophysical parameters at IceCube: need independent constraints from **laboratory experiments**
- The FPF is uniquely suited to pin down **forward charm production** and related **small-x QCD phenomena**

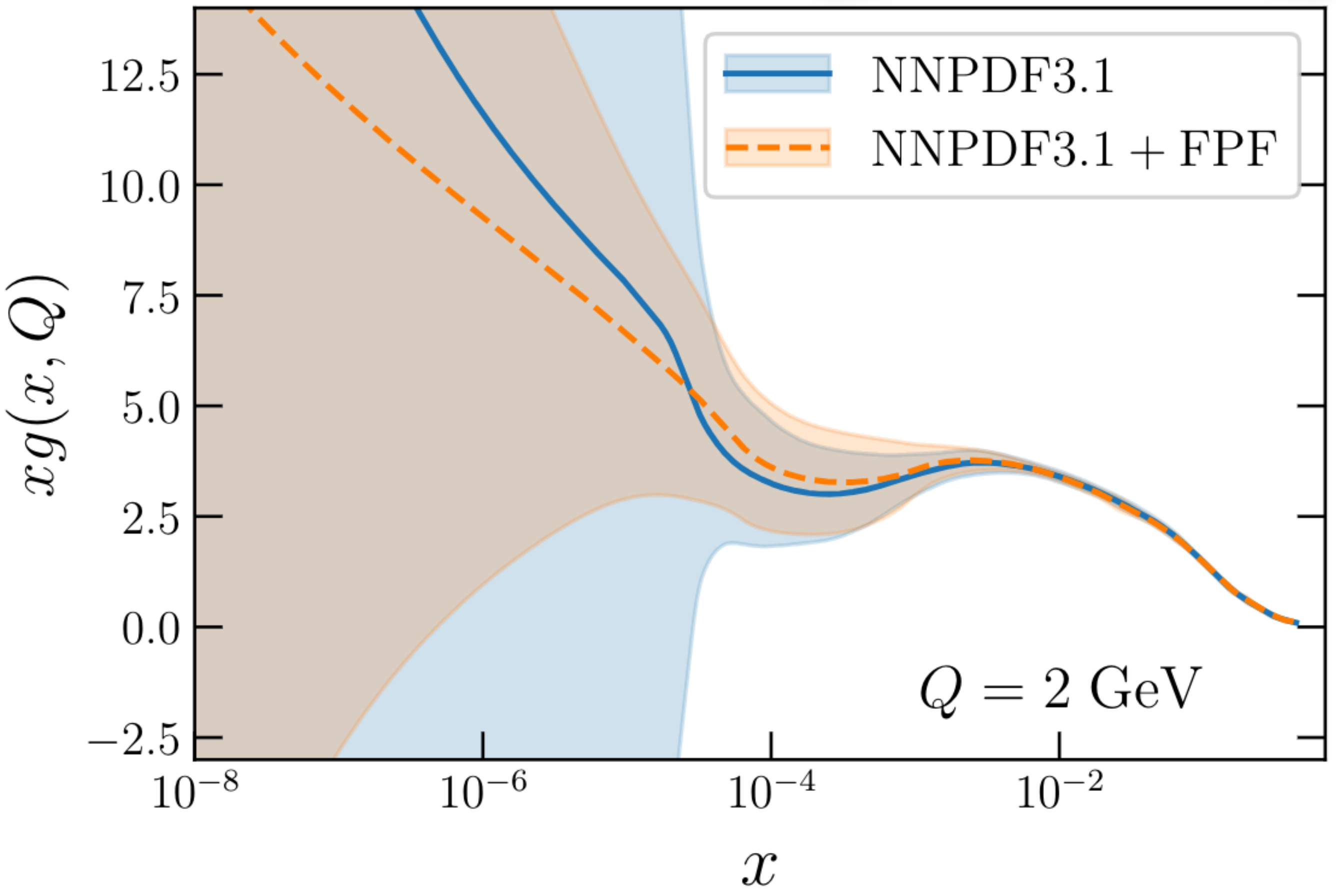


Lu Lu @ FPF7

FPF and small-x QCD



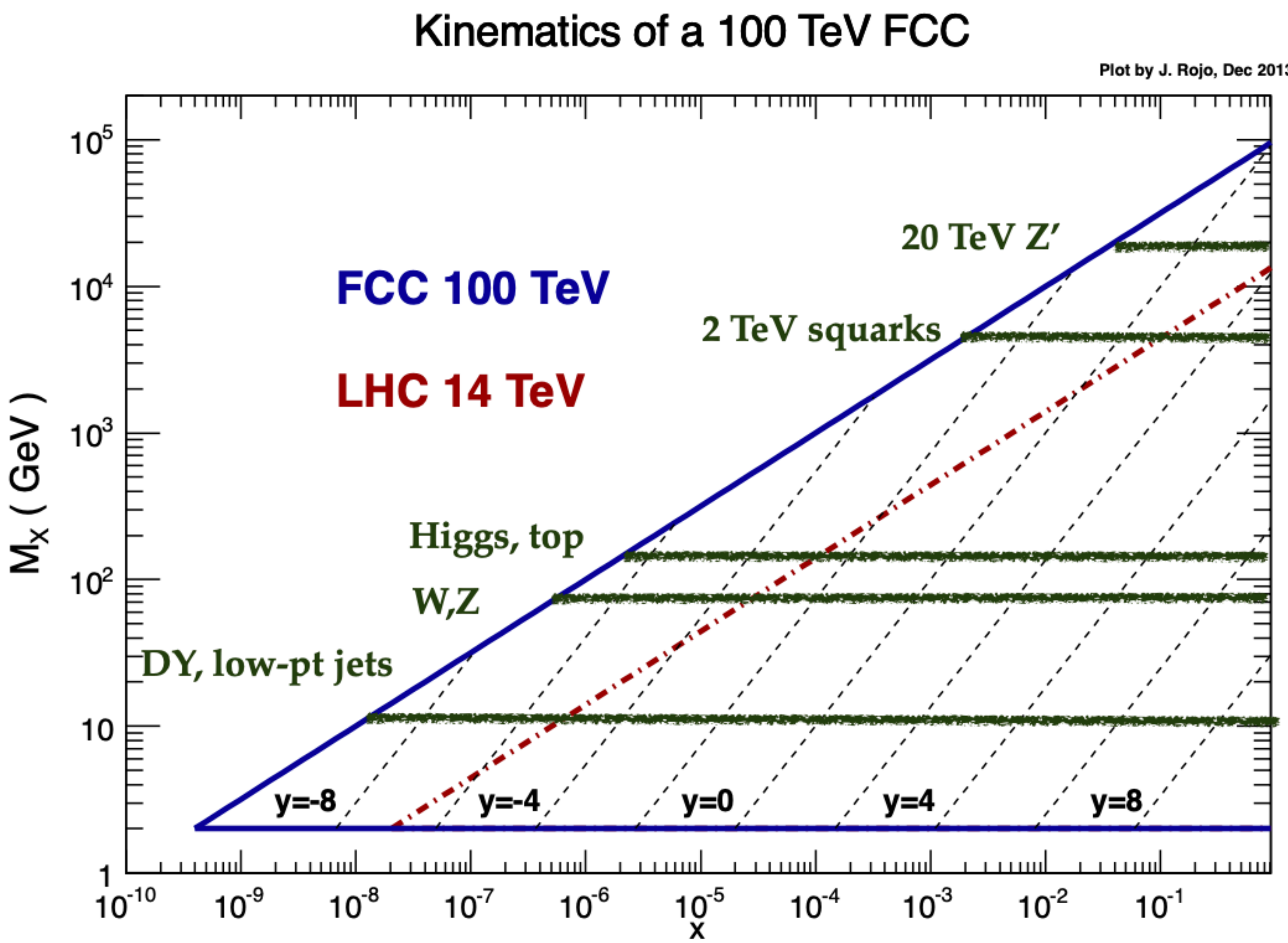




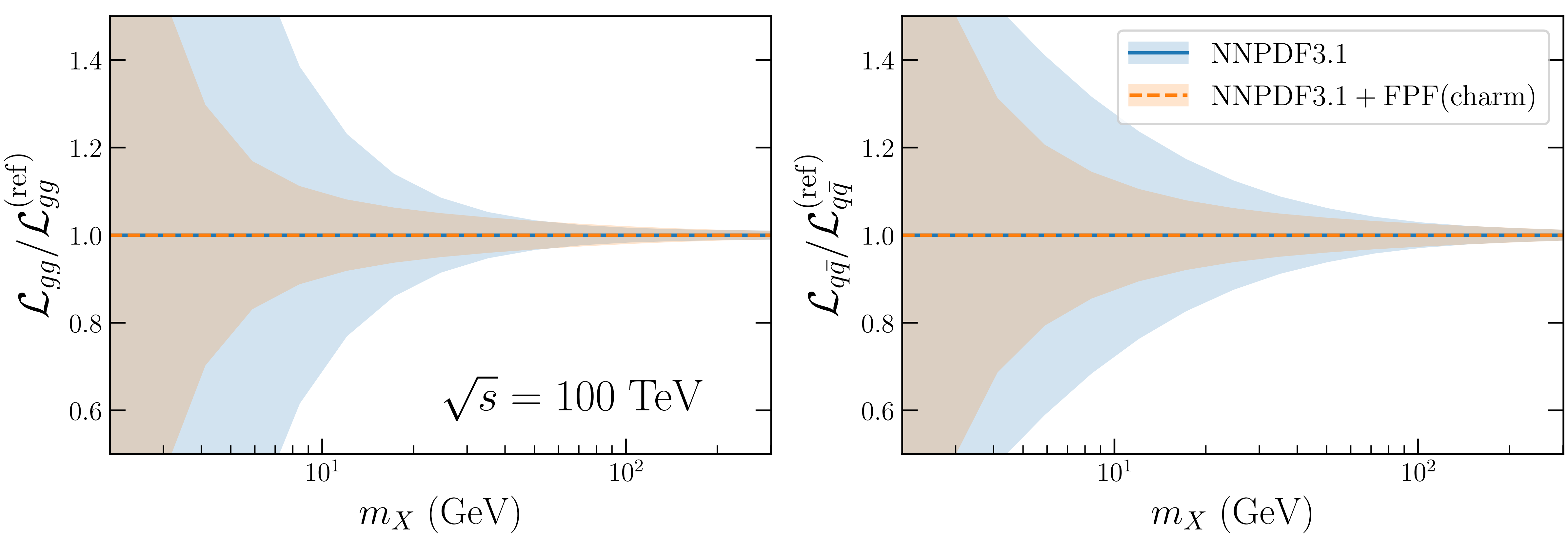
$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$

- Combined determination of the proton PDFs and the **normalisation** of muon neutrino flux
- FASER (Run-3) fixes flux normalisation to 6%, FASER2 pins it down at the **few-permille level**
- Pseudo-data for electron neutrino cross-sections at **different rapidities**
- Constraints small-x PDFs **down to 10^{-7}** , beyond the reach of any other (lab) experiment

Implications for the FCC-pp



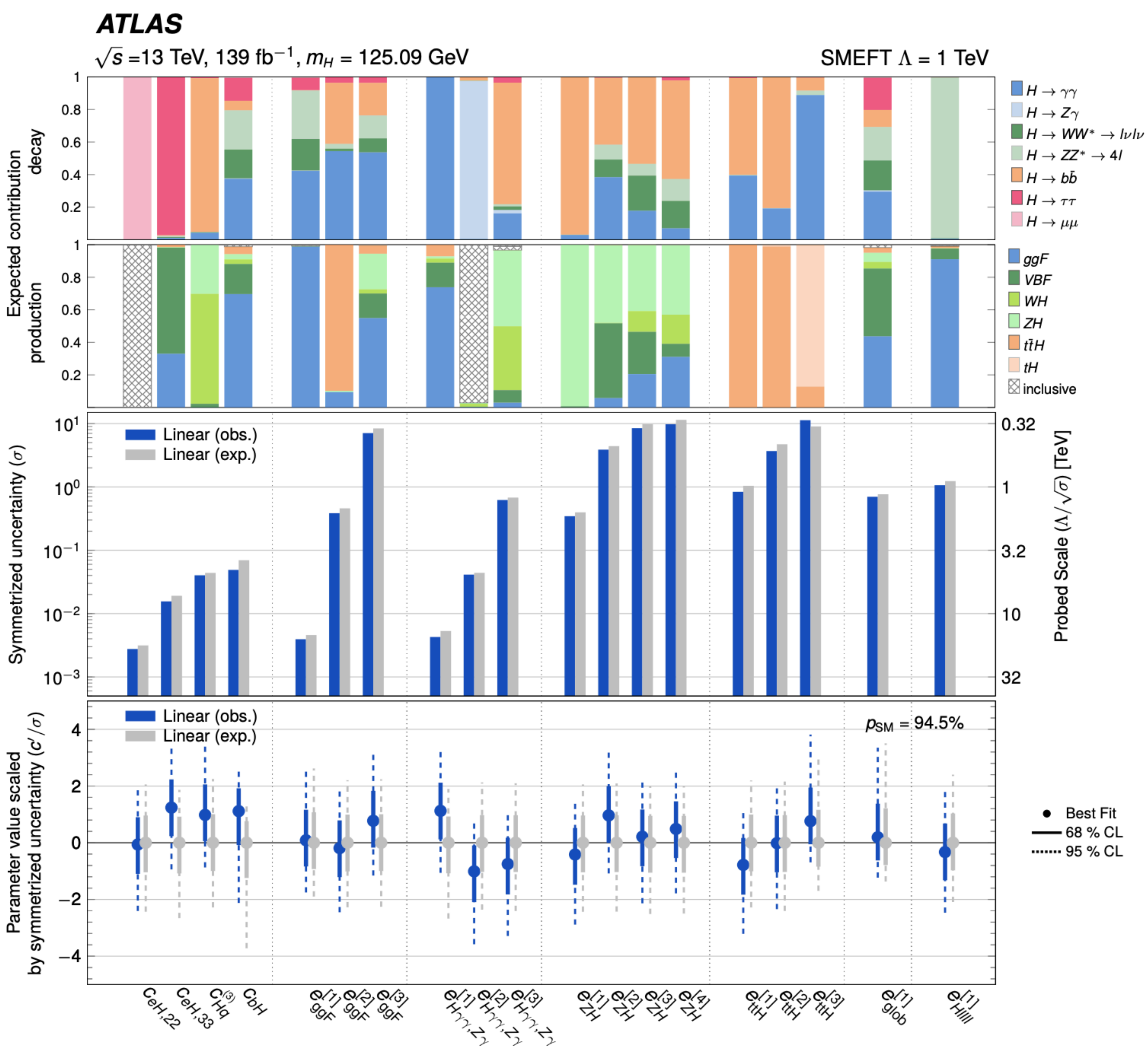
- FCC-pp would be a **small-*x* machine,** even Higgs and EWK sensitive to small-*x* QCD
- LHC neutrinos: laboratory to test **small-x QCD** for **dedicated FCC-pp physics** and simulations
- Current projections show a marked PDF error reduction on **FCC-pp cross-sections** thanks to constraints from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



The FPF and high-p_T BSM Searches at the HL-LHC

BSM @ HL-LHC (I)

- Common misconception: the BSM program of the FPF is limited to **FIPs/LLPs** and related light BSM scenarios
- Rich **direct high-p_t BSM program** via TeV neutrino cross-sections and interactions (e.g. via EFTs)
- Rich **indirect high-p_t BSM program** via PDF constraints essential for BSM searches at the HL-LHC



- Cornerstone of HL-LHC: search for BSM via **precision Higgs measurements** and their EFT global interpretation
- Full potential requires marked **reduction of current PDF uncertainties**

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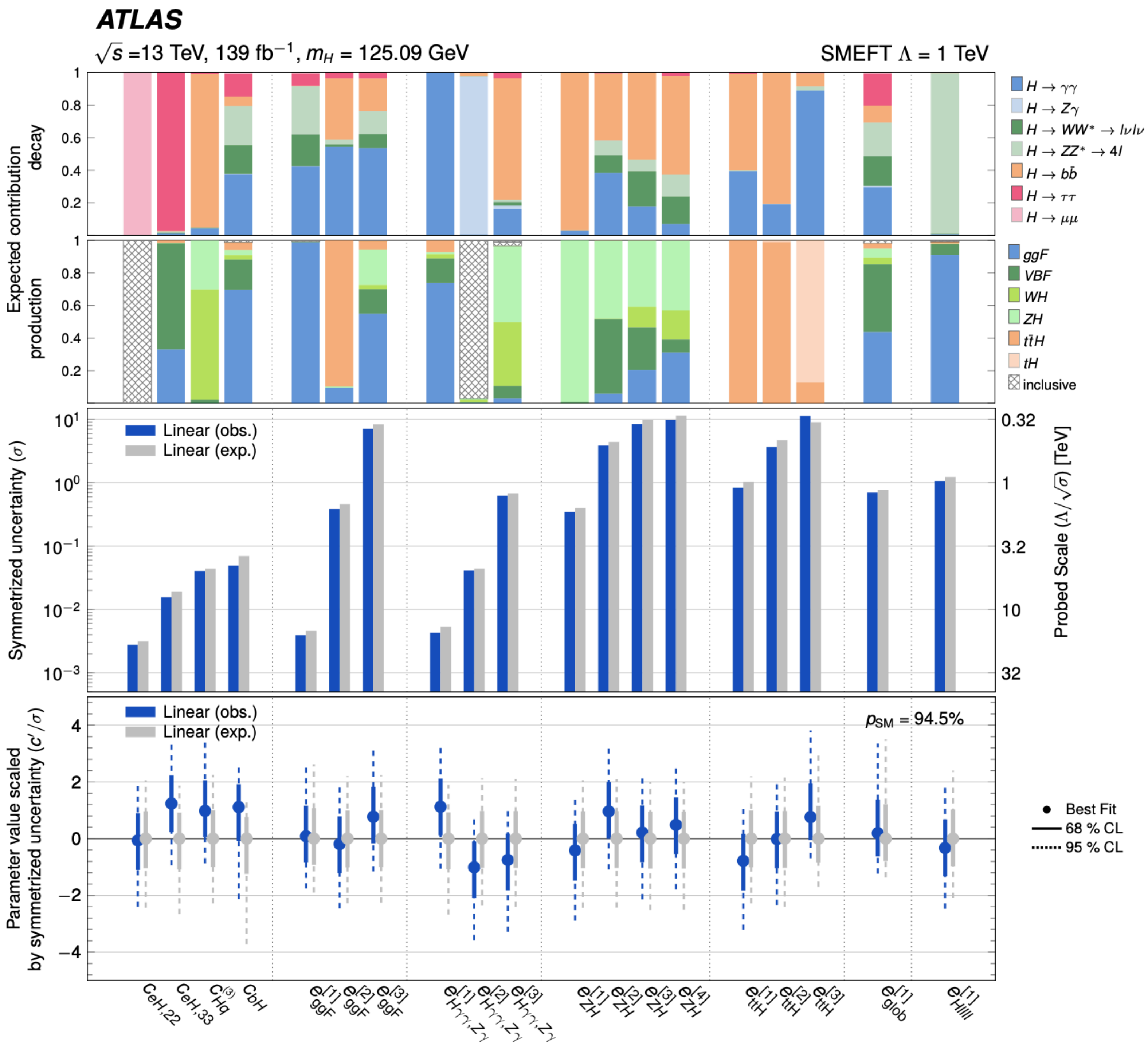

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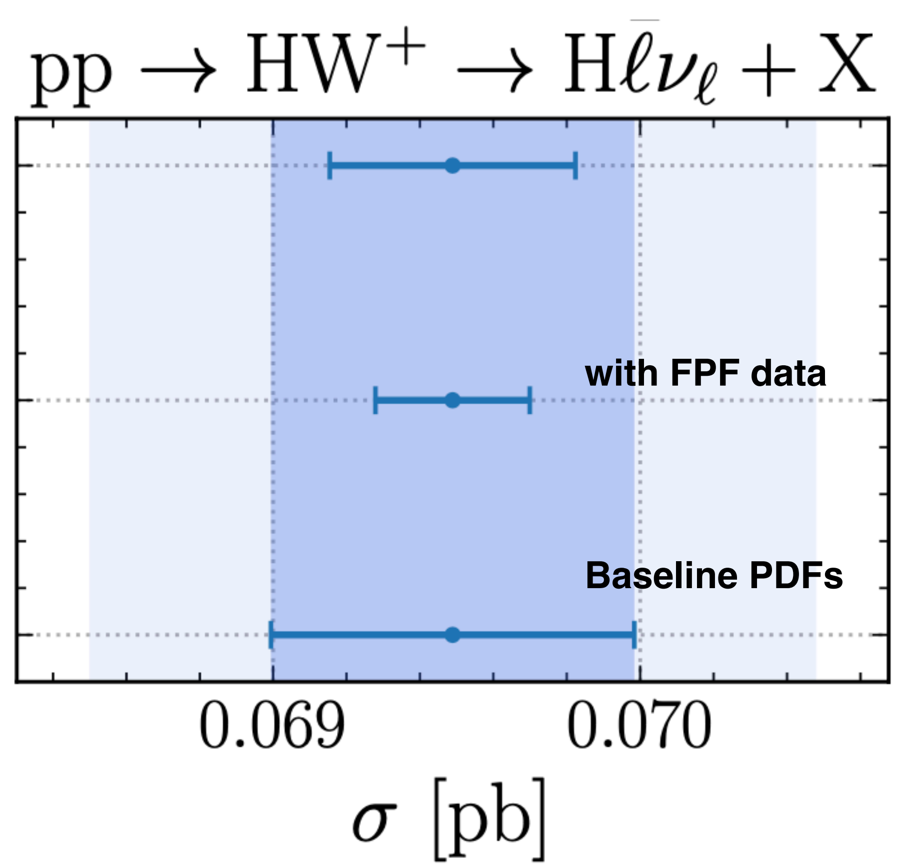
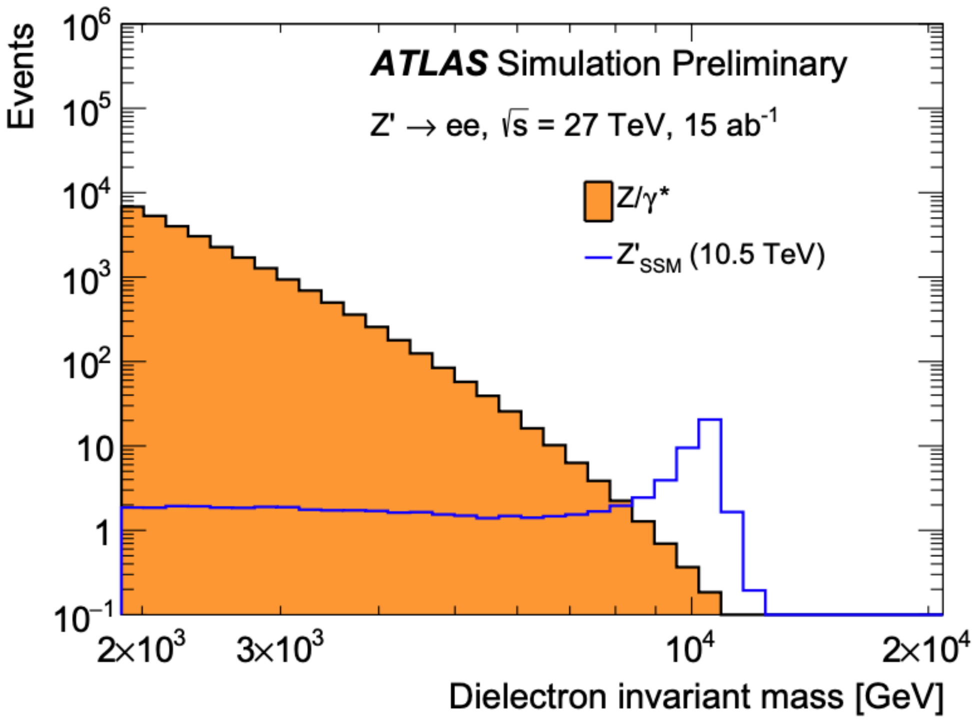
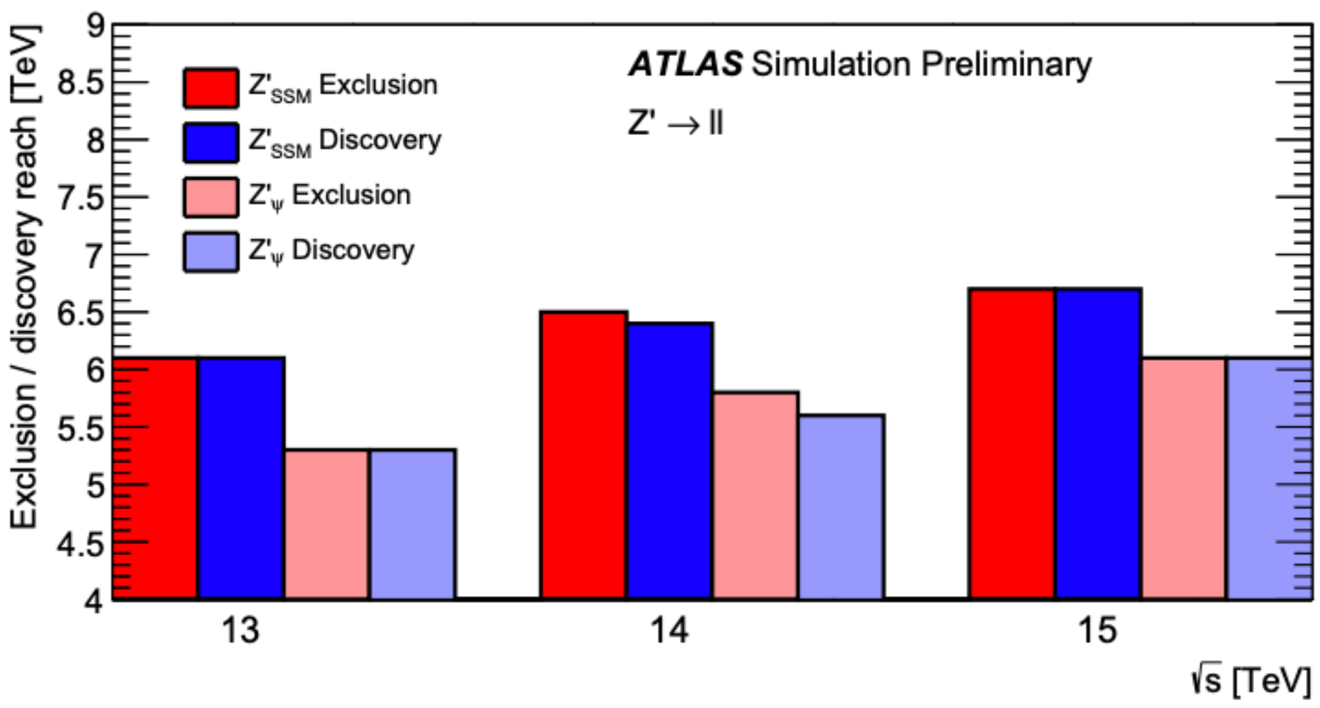
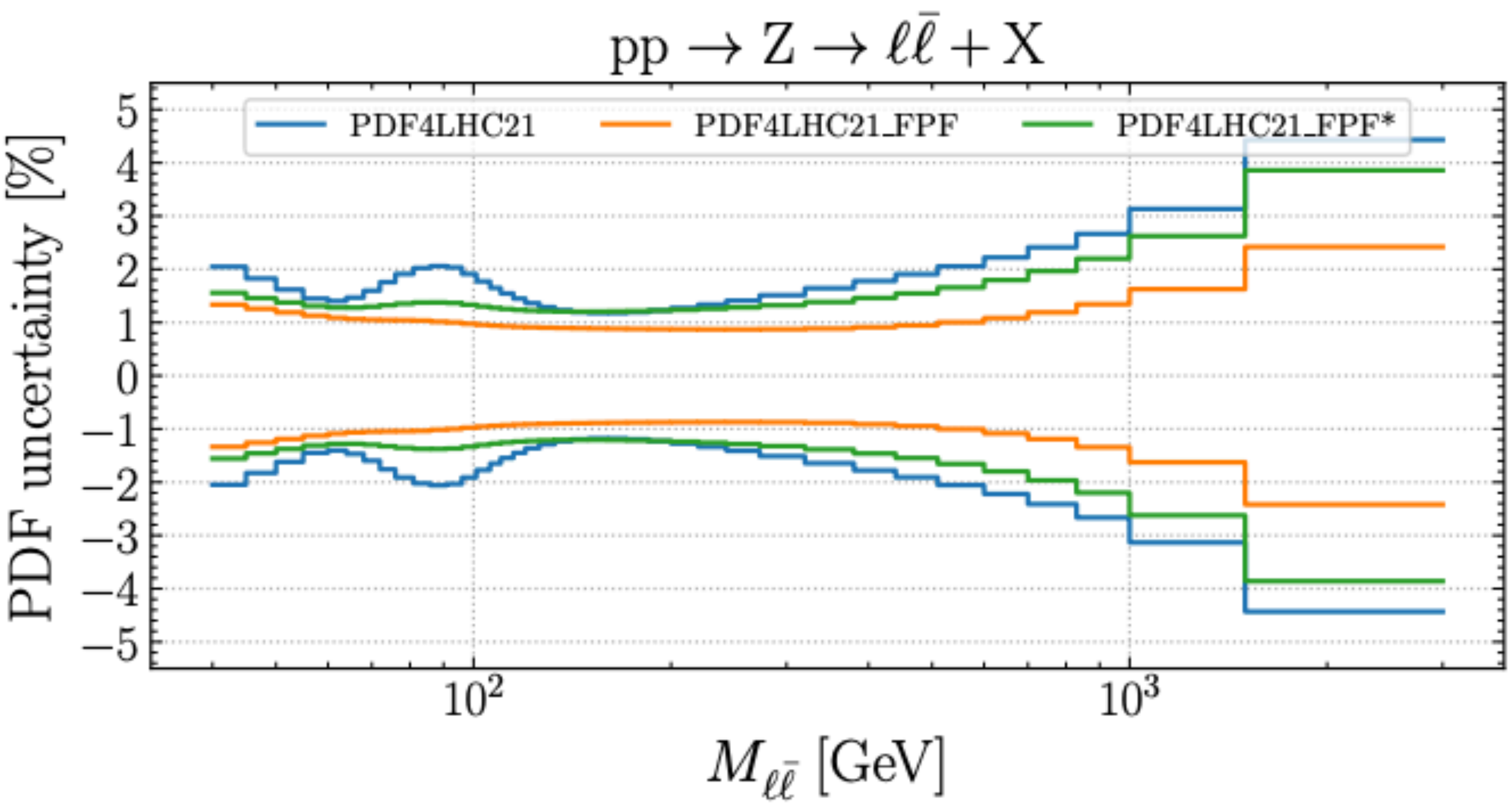


BSM @ HL-LHC (II)







- The HL-LHC will also extend the mass reach in **direct searches for new heavy particles** e.g. a Z'
- Large-*x* PDFs represent the dominant **theory uncertainty** limiting these analysis
- Again, PDF constraints at the FPF enable improved **background modelling for BSM searches** at HL-LHC

BSM @ HL-LHC (III)

Global PDF determinations are based on **Standard Model theoretical** calculations:

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

hadronic cross-section

Theory prediction to compare with experiment

SM PDF Luminosity

Constrain from data

PDF parameters

SM partonic cross-section

NNLO QCD & NLO EW

$$\mathscr{L}_{ij}^{(\rm sm)}(M, \sqrt{s}, \boldsymbol{\theta}) = \frac{1}{s} \int_{-\ln\sqrt{s}/M}^{\ln\sqrt{s}/M} {\rm d}y\, f_i^{(\rm sm)}\left(\frac{Me^{y}}{\sqrt{s}}, \boldsymbol{\theta}\right) f_j^{(\rm sm)}\left(\frac{Me^{-y}}{\sqrt{s}}, \boldsymbol{\theta}\right)$$

PDF parameters from likelihood maximisation: BSM effects potentially **``fitted away" into PDFs**

$$\chi^2\left(\boldsymbol{\theta}\right) = \frac{1}{n_{\rm dat}} \sum_{i,j=1}^{n_{\rm dat}} \left(\sigma_{\rm i,th}(\boldsymbol{\theta}) - \sigma_{\rm i,exp}\right) \left({\rm cov}^{-1}\right)_{ij} \left(\sigma_{\rm j,th}(\boldsymbol{\theta}) - \sigma_{\rm j,exp}\right)$$

BSM @ HL-LHC (III)

What is the underlying short-distance theory is **not the SM** but instead the **SMEFT**?

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

hadronic cross-section — ***SMEFT PDF luminosity*** — **PDF parameters** — ***SMEFT partonic cross-section*** — **EFT coefficients**

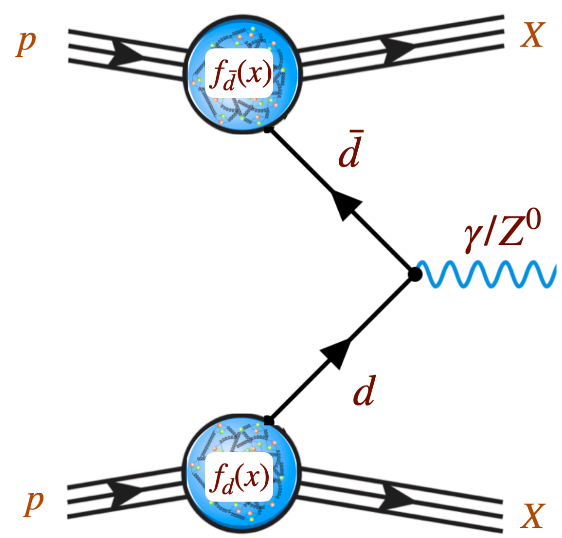
In the case of new physics described within the **dimension-6 SMEFT framework:**

$$\widetilde{\sigma}_{ij}^{(\rm smeft)}(\hat{s}, \alpha_s, \boldsymbol{c}/\Lambda^2) = \widetilde{\sigma}_{ij}^{(\rm sm)}(\hat{s}, \alpha_s)\left(1 + \sum_{m=1}^{N_6} c_m \frac{\kappa_m^{ij}}{\Lambda^2} + \sum_{m,n=1}^{N_6} c_m c_n \frac{\kappa_{mn}^{ij}}{\Lambda^4}\right)$$

SMEFT PDFs *defined as PDFs extracted from the data when SMEFT used to model* ***partonic hard-scattering***

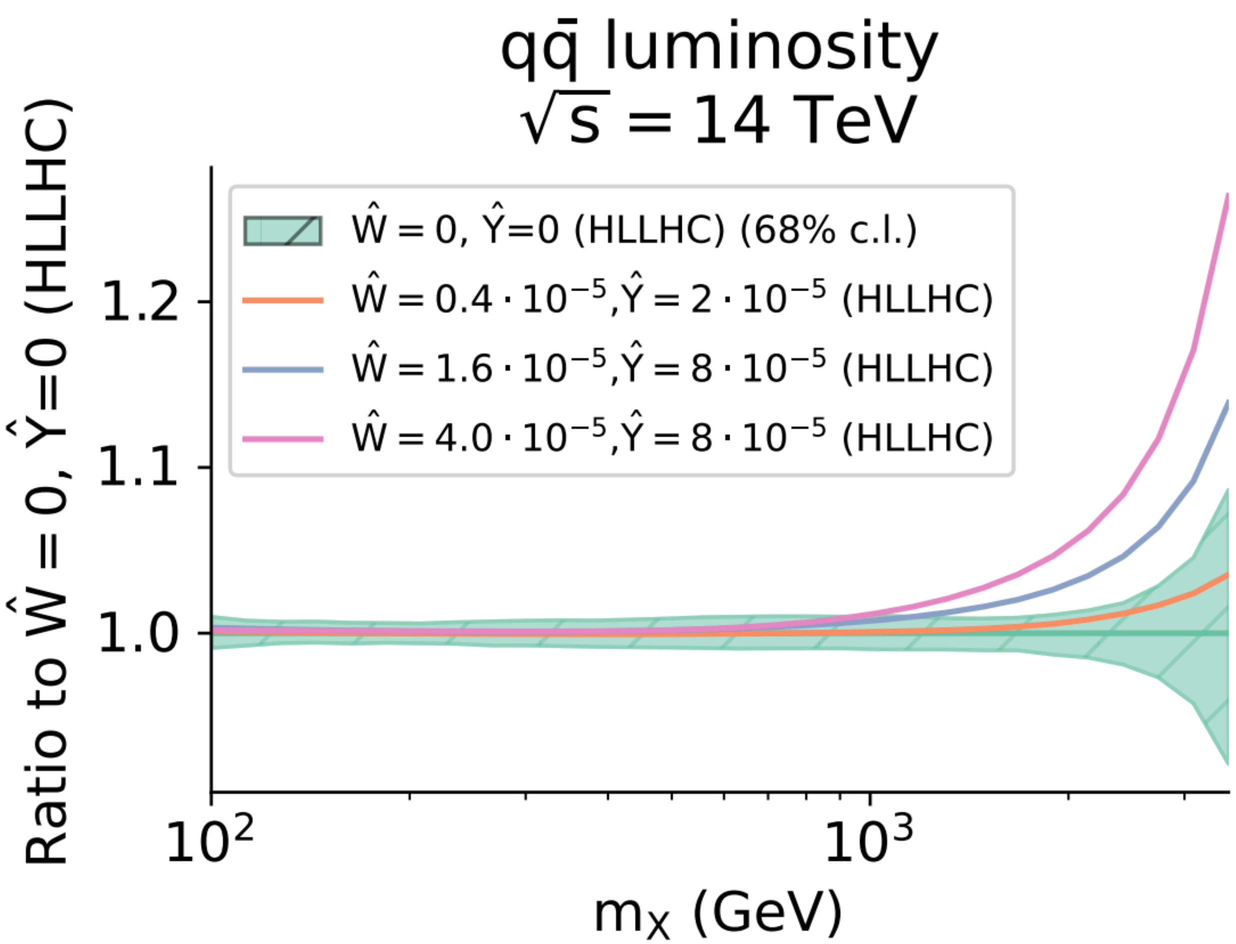
Given experimental constraints, how **different are SM and SMEFT PDFs**? Is there a risk to **fit away EFT effects into the PDFs?**

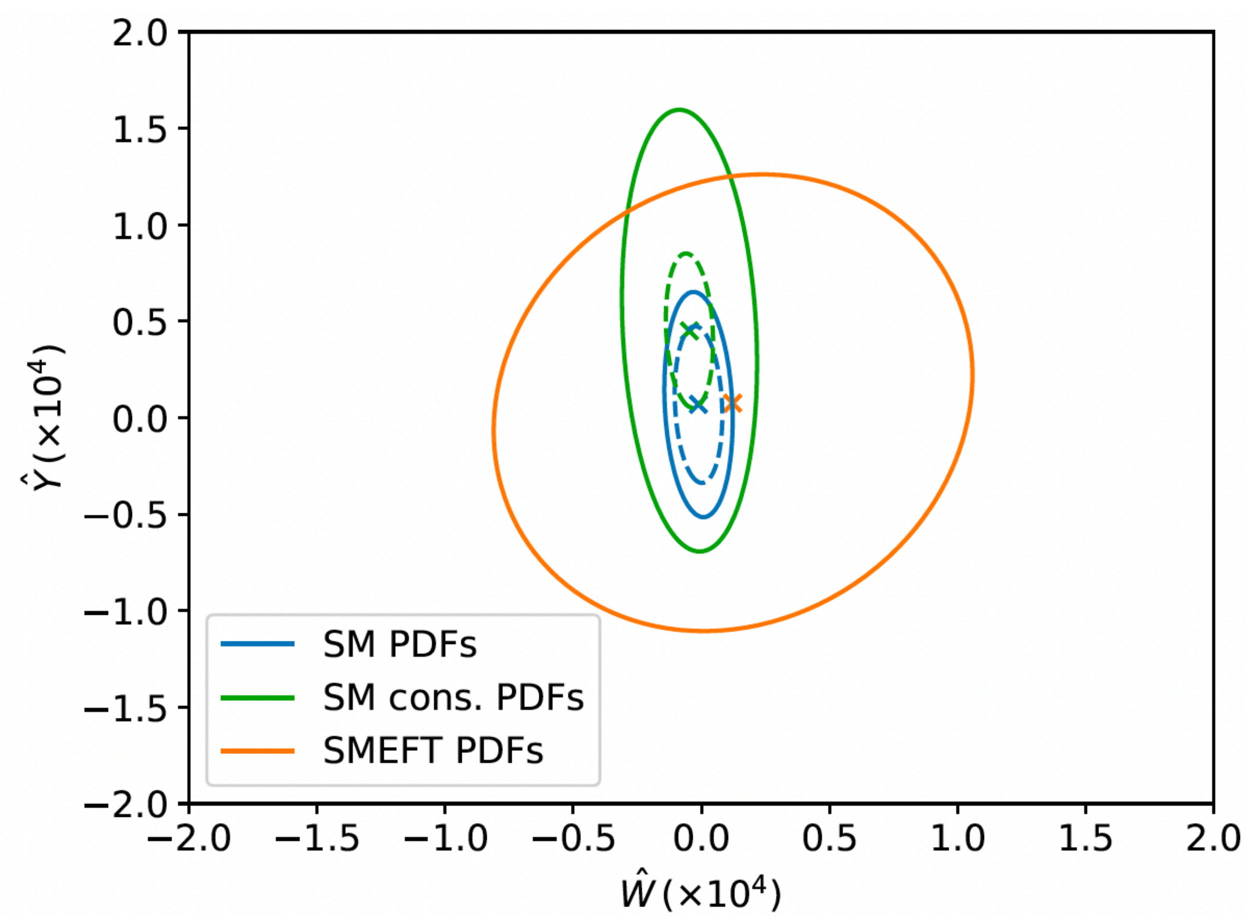
BSM @ HL-LHC (III)



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

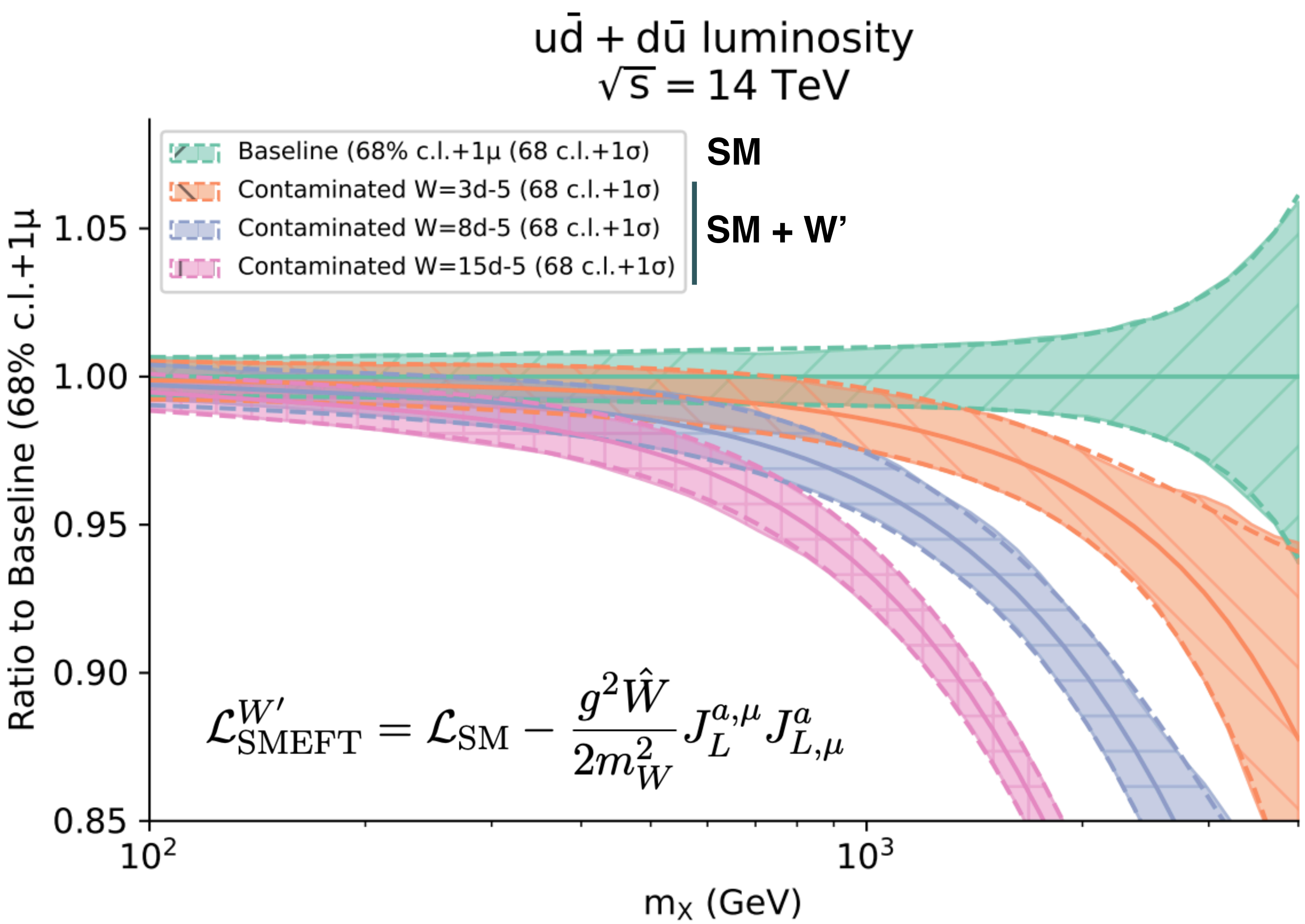
- HL-LHC projections: strong constraints on large-x antiquark PDFs, may be **reabsorbed into SMEFT PDFs**
- Bounds based on SM-PDFs **overly optimistic** as compared to those obtained from SMEFT-PDFs
- Emphasises importance of **SMEFT-PDF interplay** at the HL-LHC



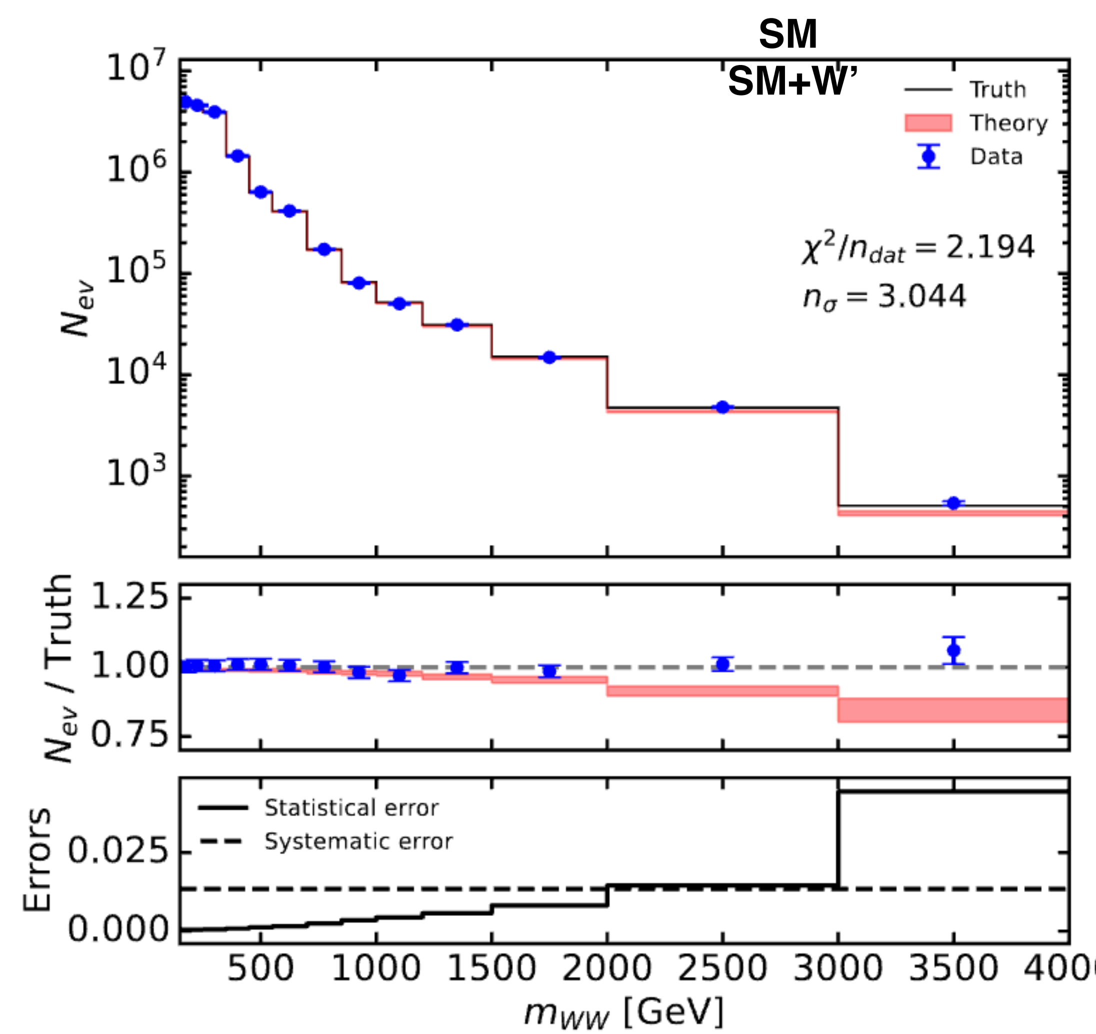


Lifting Degeneracies for BSM with FPF

- Assume a BSM scenario with an extra W' gauge boson with **$M_{W'}$ = 13.8 TeV**
- Generate **HL-LHC pseudo-data** (NC & CC Drell-Yan) for this model and include in global PDF fit
- **Data-theory agreement unchanged,** but the qqbar luminosity **shift far beyond PDF uncertainties**.
- Why? Because anti-quark PDFs at large-*x* poorly constrained, **"fitting away" BSM signals!**
- Result: miss BSM signals in SMEFT analysis & spurious effects in ``SM" processes (e.g. diboson)



$$\mathcal{L}_{\rm SMEFT}^{W'} = \mathcal{L}_{\rm SM} - \frac{g^2 \hat{W}}{2m_W^2} J_L^{a,\mu} J_{L,\mu}^a$$

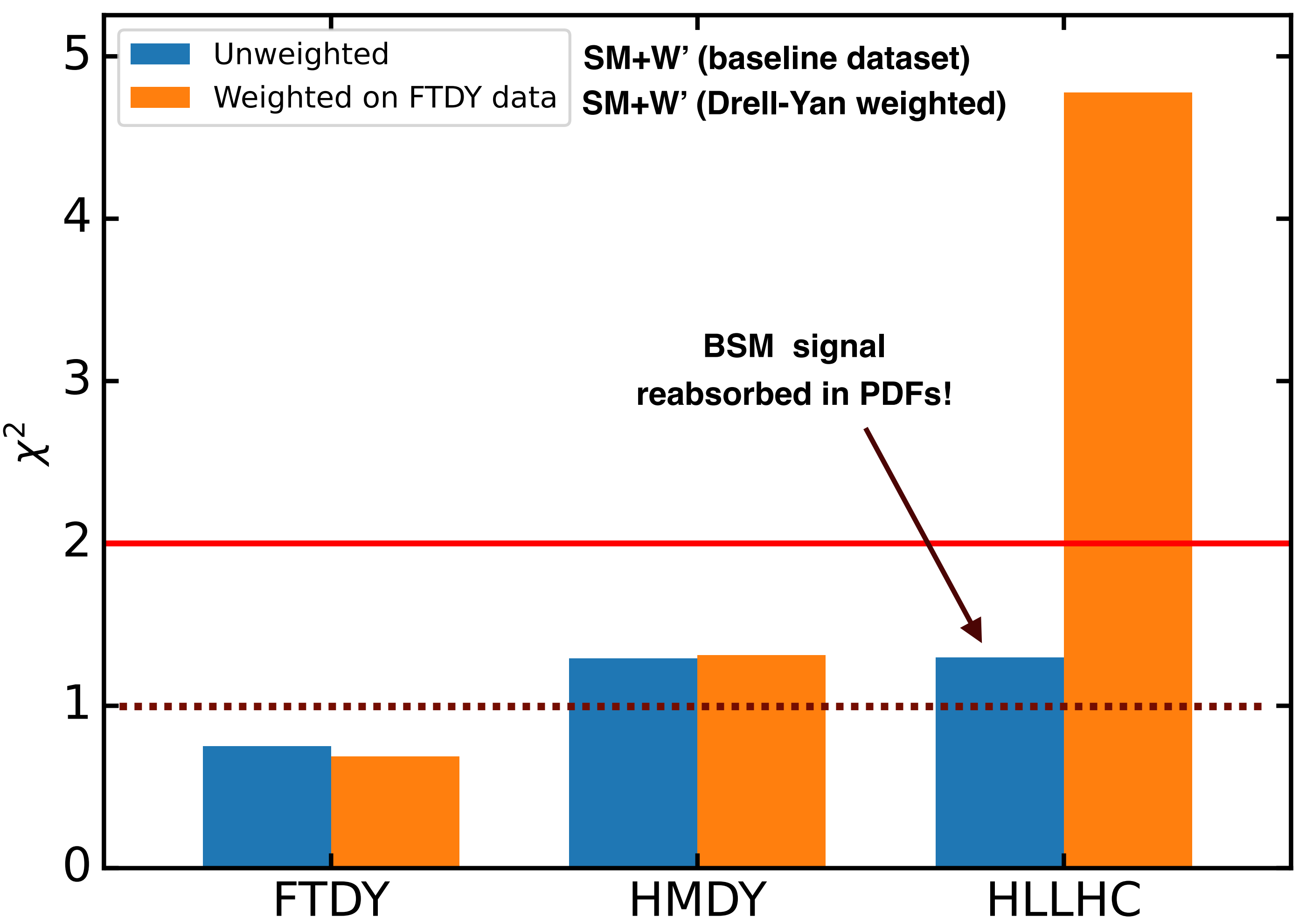


Hammou, Madigan, Mangano, Mantani, Morales, Ubiali, 2307.10370

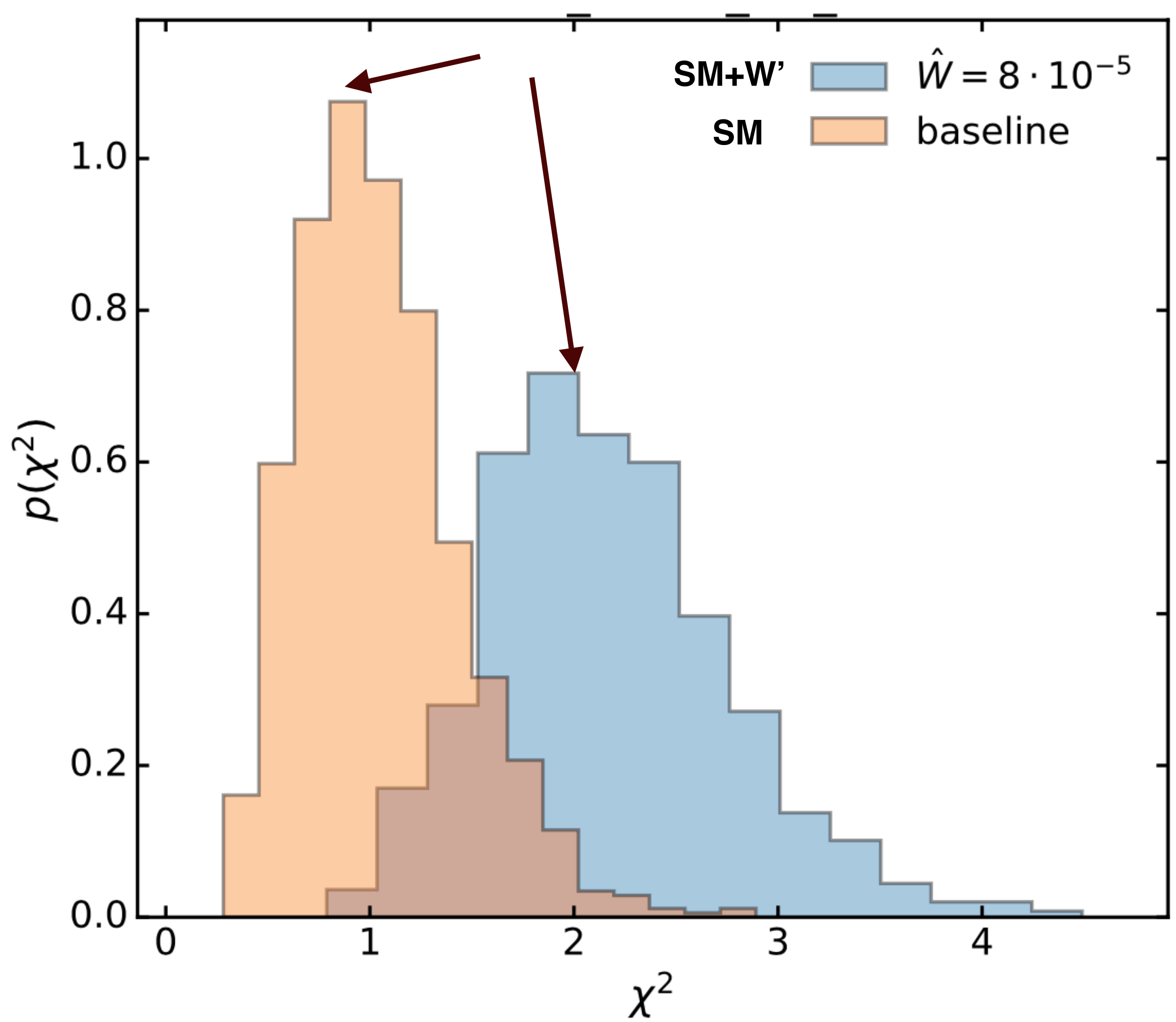
Lifting Degeneracies for BSM with FPF

- Need more accurate **low-energy measurements** constraining **large-*x* PDFs** to robustly disentangle QCD from BSM effects
- More precise **fixed-target Drell-Yan data** would help, but no experiments planned
- Including **FPF neutrino DIS measurements** would break this PDF/BSM degeneracy!
- Essential input to realise the **full BSM search potential of the HL-LHC**

Global PDF fit + HL-LHC pseudo-data



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



Hammou, Madigan, Ubiali, **WIP**

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**

- Measuring LHC neutrino fluxes enables **unprecedented probe of small-x QCD and forward hadron production**, instrumental for astroparticle physics but also **future colliders**

- In addition to FIP searches, the FPF provides unique constraints for **high-p_T searches at LHC**

QCD and neutrino measurements at the FPF enable the **ultimate ancillary experiment** to ensure that the full **BSM potential of the HL-LHC** can be realised