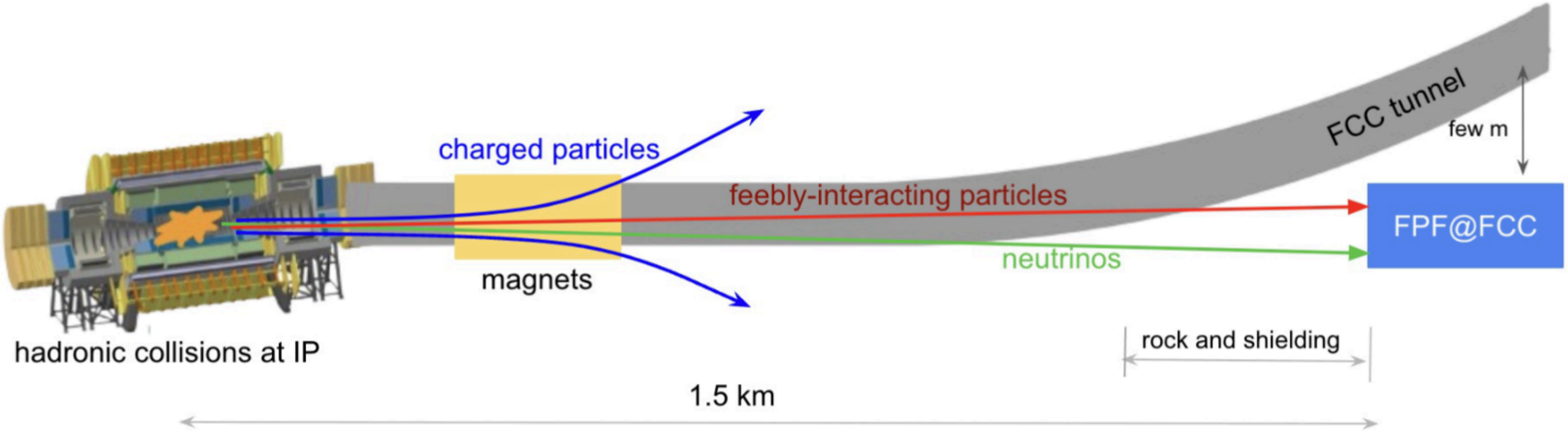
A Forward Physics Facility integrated in the FCC project

Juan Rojo, VU Amsterdam & Nikhef



based on Abraham, Adhikary, Feng, Fieg, Kling, JR, and Trojanowski**, WIP**

see also various talks in the parallel sessions!

7th Forward Physics Facility meeting (FPF7)

CERN, 1st March 2024

A Forward Physics Facility integrated in the FCC project

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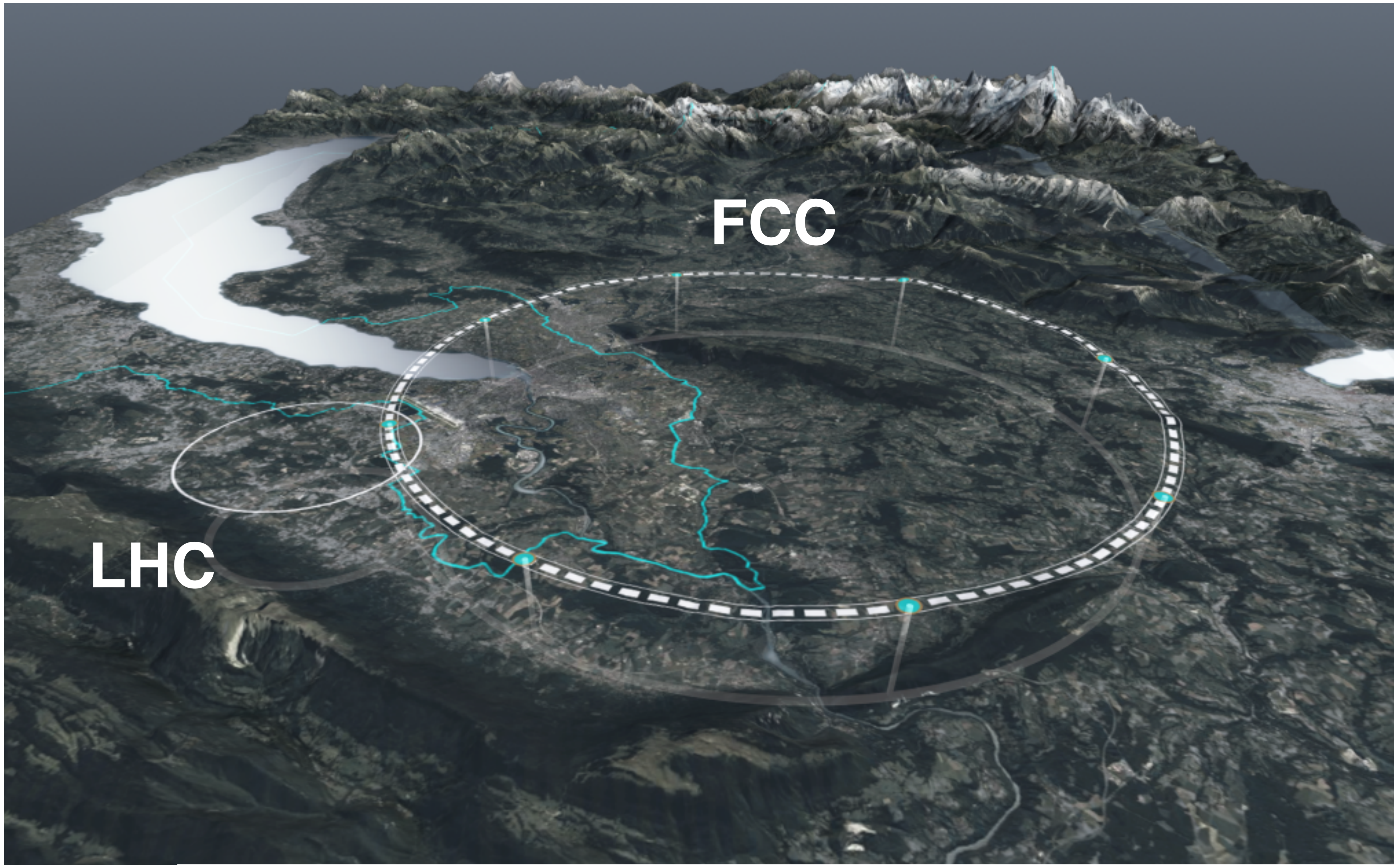
Bonus!

+ Lifting QCD vs BSM degeneracies in HL-LHC high-mass searches with the FPF

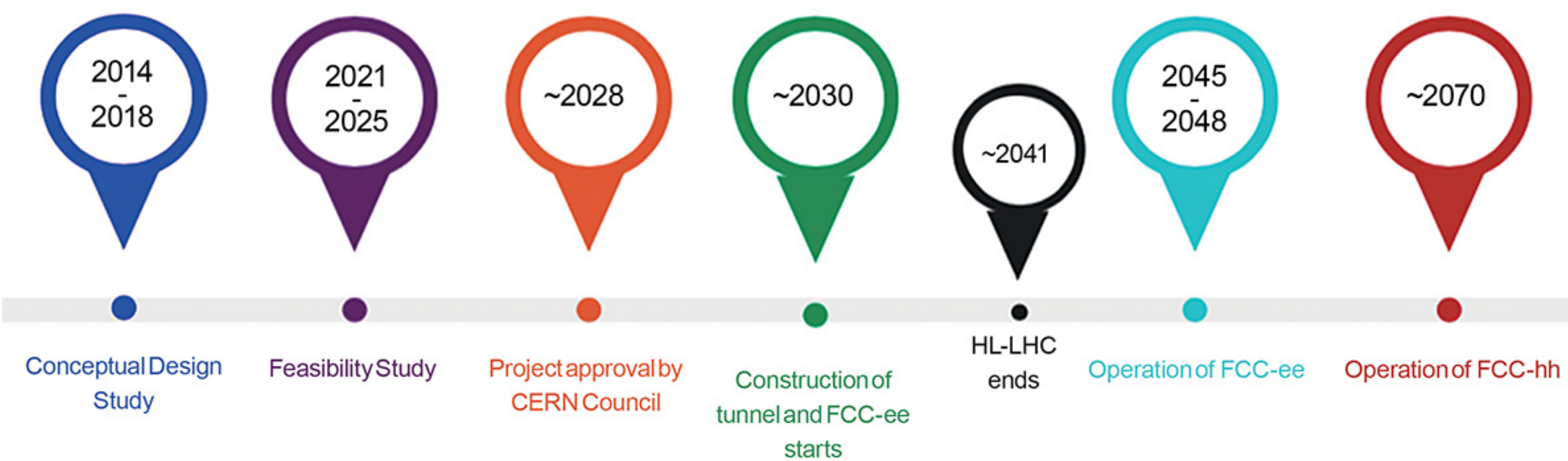
7th Forward Physics Facility meeting (FPF7)

CERN, 1st March 2024

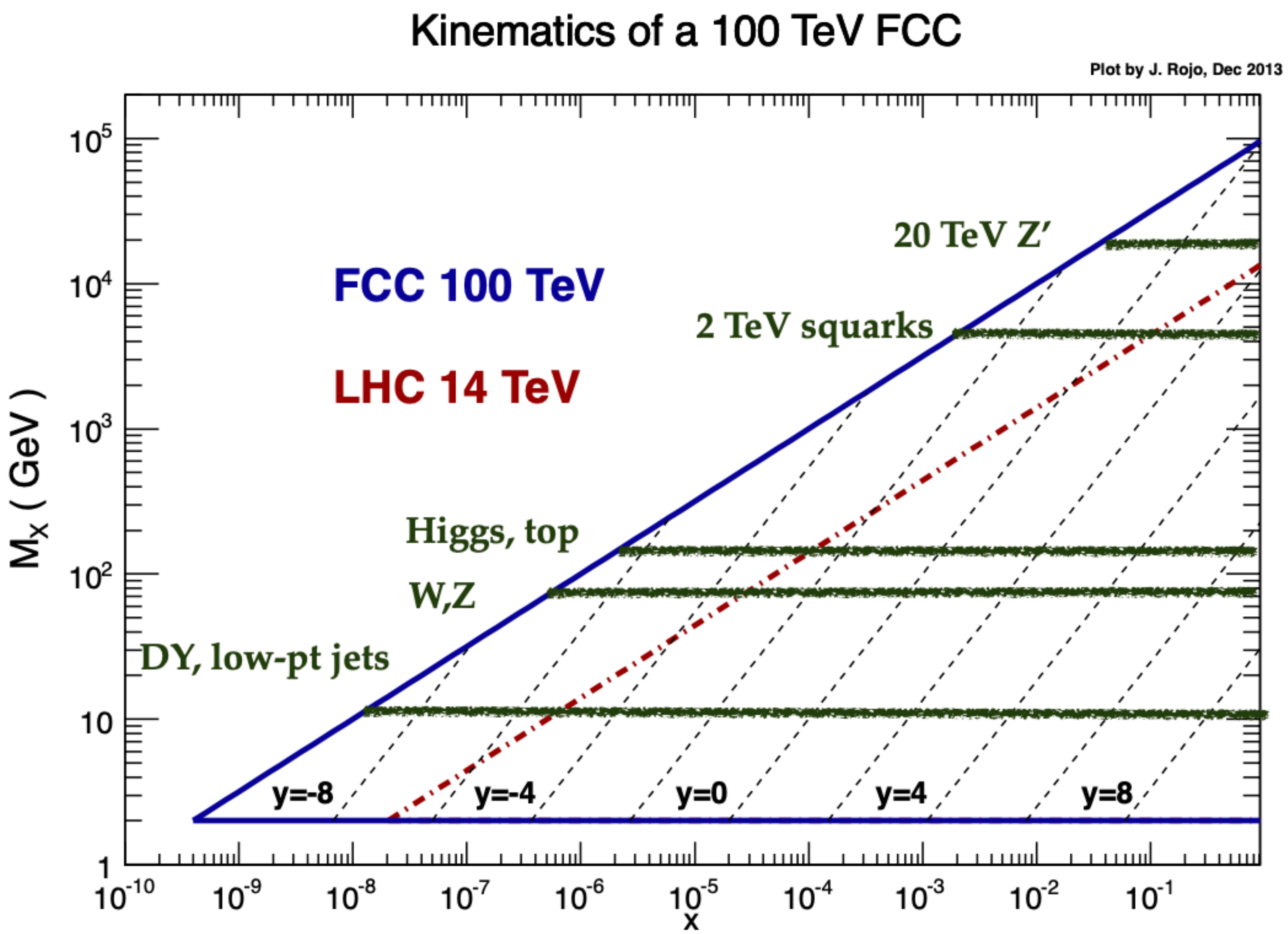
The Future Circular Collider



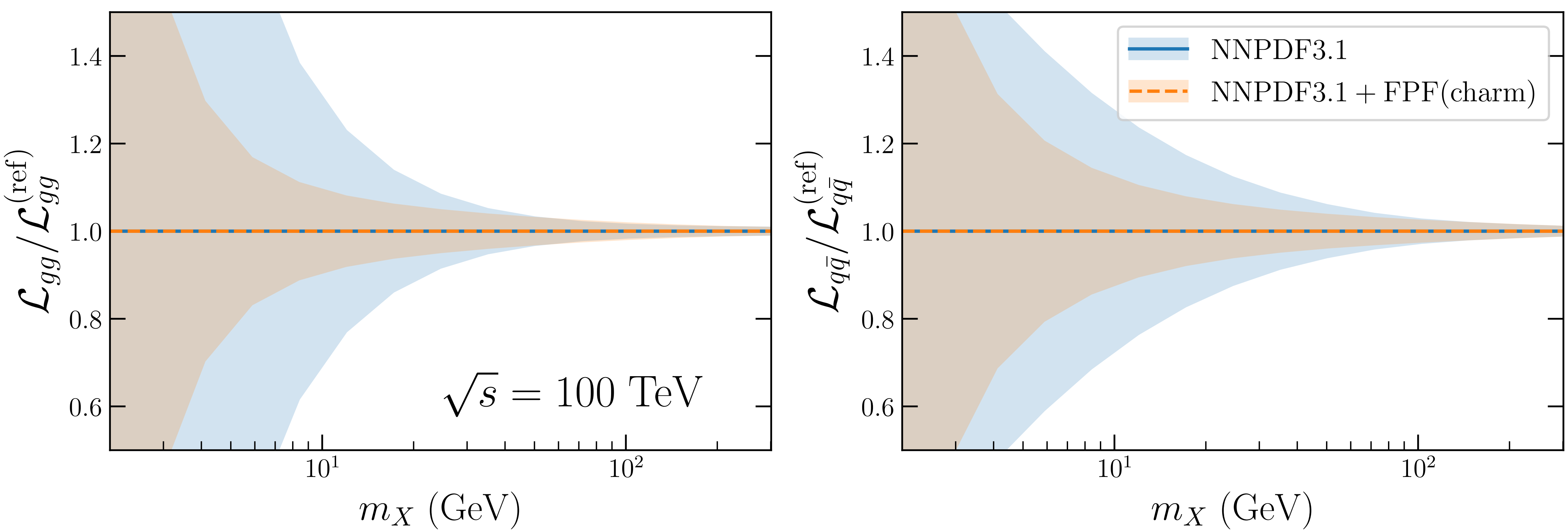
- A proposed new **91-km tunnel** in the CERN site
- First phase: **electron-positron collider** from the Z-pole to ttbar threshold
- Second phase: **proton-proton collider at 100 TeV** or beyond, with pA and AA options



LHC neutrinos and FCC-pp

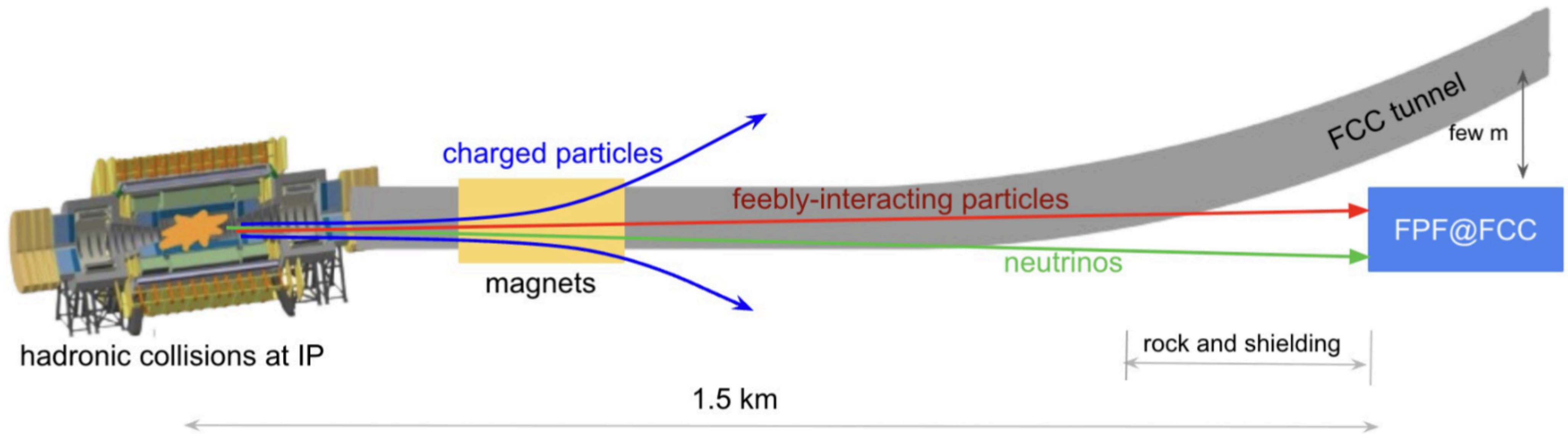


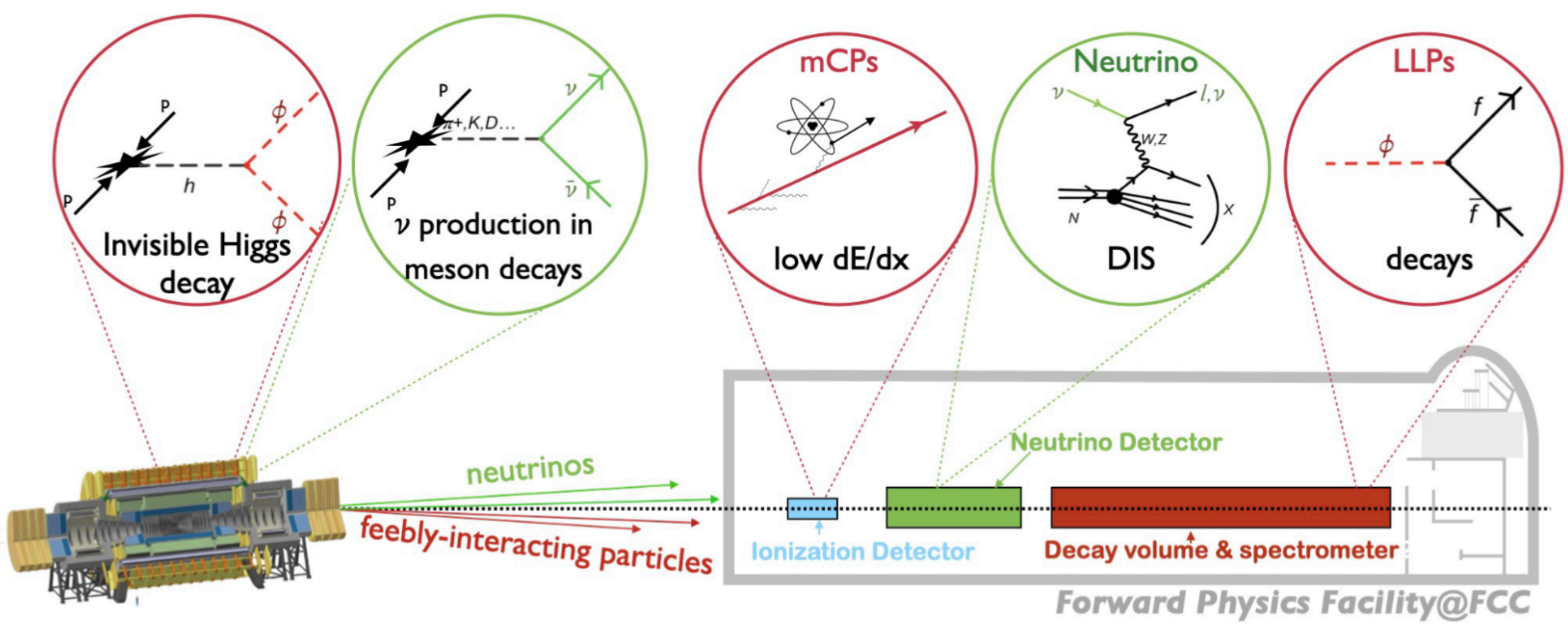
- FCC-pp would be a **small-*x* machine,** even Higgs and EWK sensitive to small-*x* QCD
- LHC neutrinos: laboratory to test **small-x QCD** for **dedicated FCC-pp physics** and simulations
- Current projections show a marked PDF error reduction on **FCC-pp cross-sections** thanks to constraints from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



FPF@FCC

- An FPF-like suite of far-forward experiments could be **integrated in FCC design** from day one
- Benefit from *i)* **higher CoM energy**, *ii)* **higher luminosity**, *iii)* larger/better **detectors**



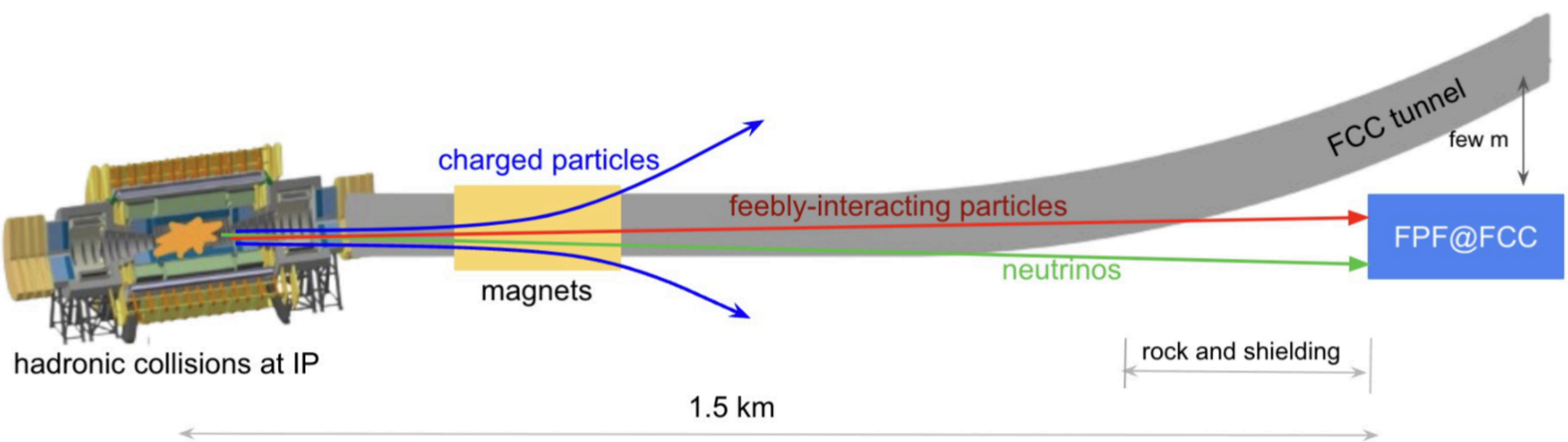


Why FPF@FCC?

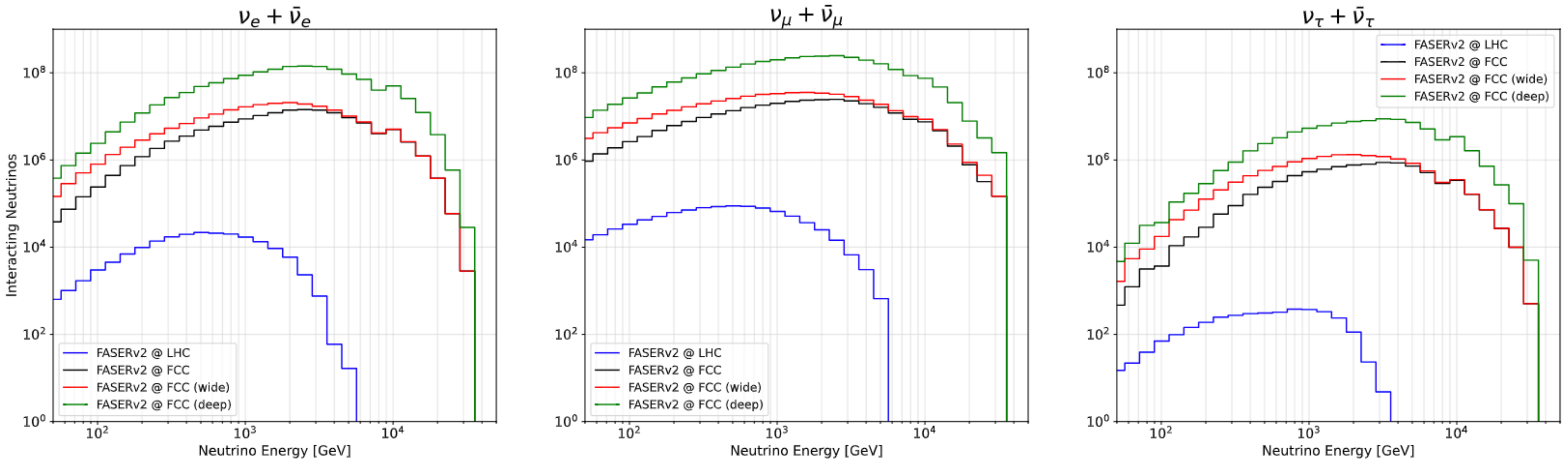
- FPF@HLLHC physics program on ``steroids'', thanks to **immense forward particle flux** and much **higher energies** available, enabling e.g. multi-differential neutrino DIS measurements

- Explore **completely new options** beyond the reach of FPF@HL-LHC, such as **neutrino DIS on polarised targets** and detecting neutrinos from proton lead collisions

- Enmesh the ``FPF physics'' program into **HEP mainstream**, demonstrating its flexibility and complementary to **future HEP projects,** and boosting the case for a first realisation at the HL-LHC



Event rates

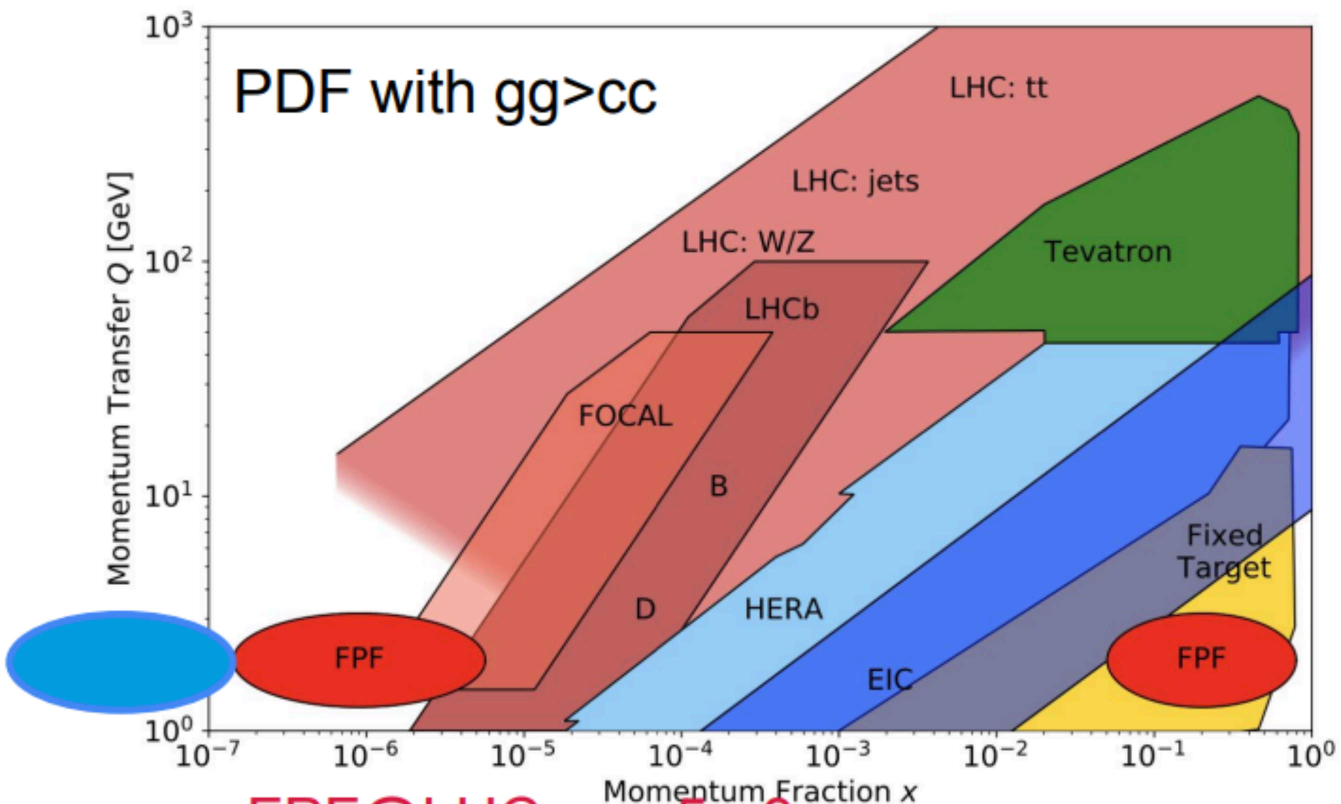


Detector	$\sqrt{s}$	$\mathcal{L}_{\rm int}$	$N_{\nu_e} + N_{\bar{\nu}_e}$	$N_{\nu_\mu} + N_{\bar{\nu}_\mu}$	$N_{\nu_\tau} + N_{\bar{\nu}_\tau}$
FASERν	13.6 TeV	150 fb^{-1}	610 (100)	1.8k (290)	
FASERν2	14 TeV	3 ab^{-1}	170k (27k)	510k (76k)	
FASERν2	100 TeV	30 ab^{-1}	145 M	308 M	8.7 M
FASERν2-deep	100 TeV	30 ab^{-1}	1.45 B	3.08 B	87 M
FASERν2-wide	100 TeV	30 ab^{-1}	216 M	488 M	14 M

- For the same FASERv2 detector: **factor O(10³) increase** due to **higher lumi** (x 10) and **higher CoM energy** (x 100)
- Neutrino energies reaching **40 TeV**
- Deeper (x 10) and wider (x 10) detectors can also be considered
- Up to **3B (!) muon neutrino** events, up to **O(100M) tau neutrino** events (!)

Access **neutrino cross-sections at multi-TeV energies**, test **Lepton Flavour Universality for the three neutrino generations,** and search for anomalous interactions with **permille precision**

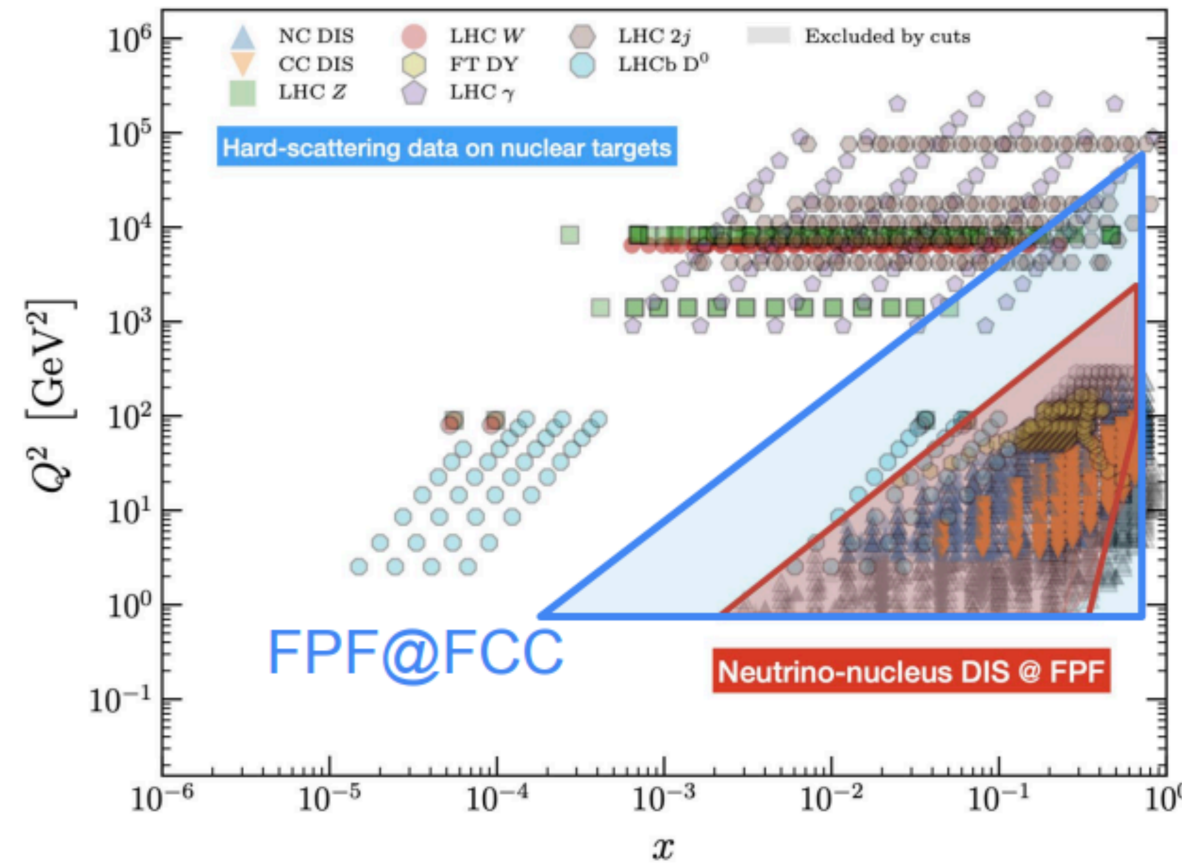
Proton Structure & Small-x QCD



FPF@LHC: x > 5e-8

FPF@FCC: x > 9e-10

PDF via ν-scattering: x ~ 1/Eν



- Access proton structure and **ultra-small-x QCD** in uncharted regimes

  input for UHE astroparticle physics

- Improved understanding of **small-x BFKL QCD** (& even **non-linear QCD**!) will be instrumental for core FCC-pp program

- Large statistics & extended kinematic coverage enable **multi-differential measurements** (e.g. proton 3D structure)

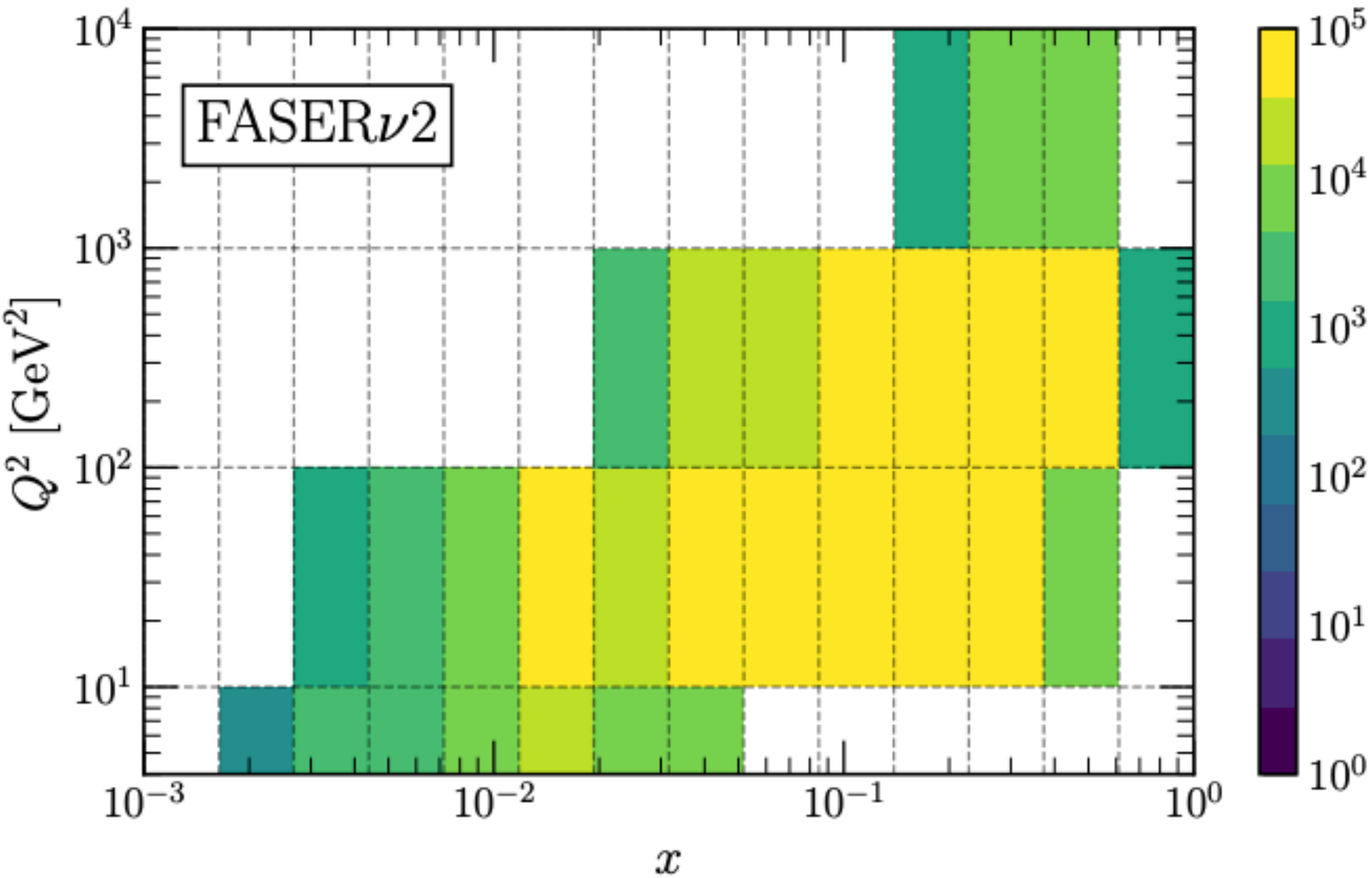
  Which novel features of proton 3D structure can be revealed by a neutrino probe?

- Would need dedicated ``**general-purpose**'' **detector** to extract all physics potential

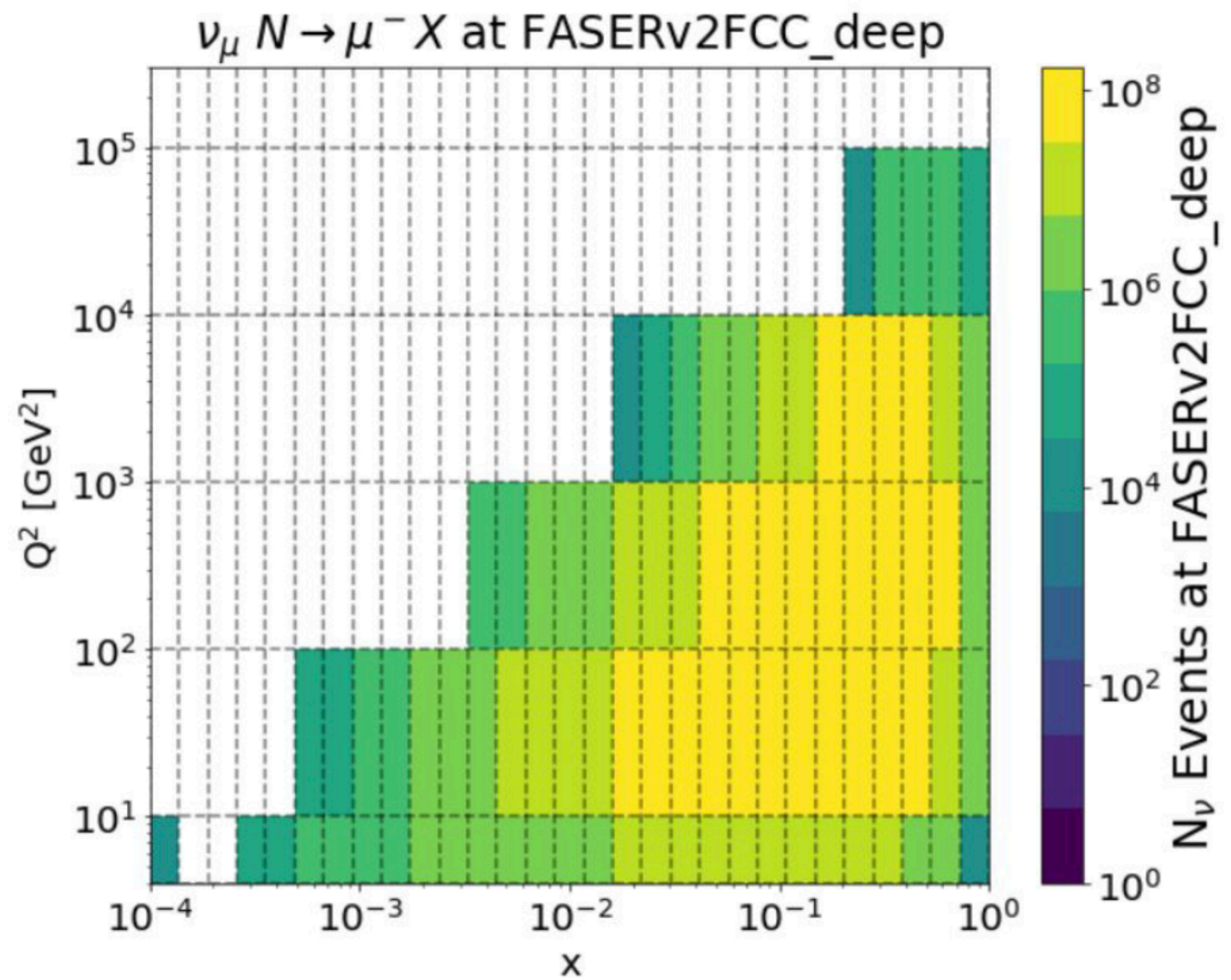
  hermeticity, particle ID, jet reconstruction ….

Kinematic coverage

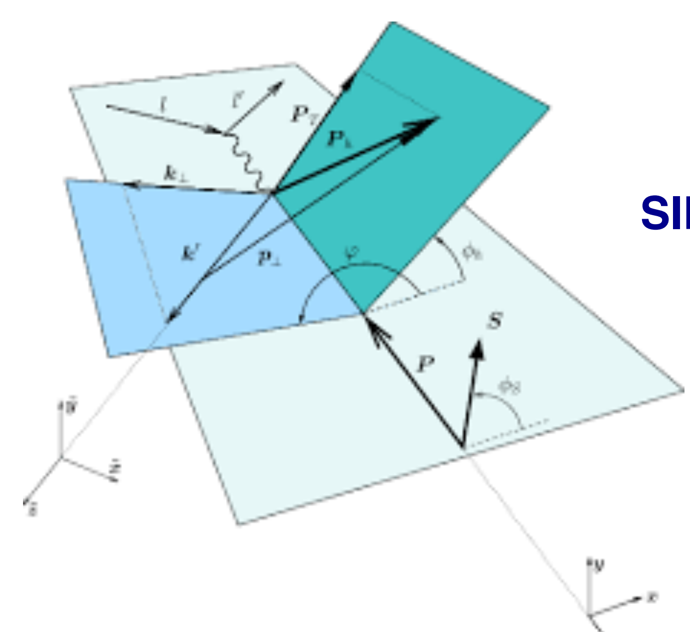
(x,Q²) coverage of muon-neutrino DIS @ FASERnu2



same for FASERnu2_deep@FCC



- Extend kinematic coverage at small-x and large-Q by an **order of magnitude**
- Unprecedented event rates: **multi-differential neutrino DIS measurements** (3D structure, TMD, GPDs…)
- Rich program of hadronic physics with neutrino beams (complementing charged-lepton measurements)



SIDIS@EIC

Neutrino polarised DIS

Polarised DIS with neutrinos: **spin mapping**

RM3-TH/00-20

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

Stefano Forte†

INFN, Sezione di Roma III
Via della Vasca Navale 84, I-00146 Rome, Italy

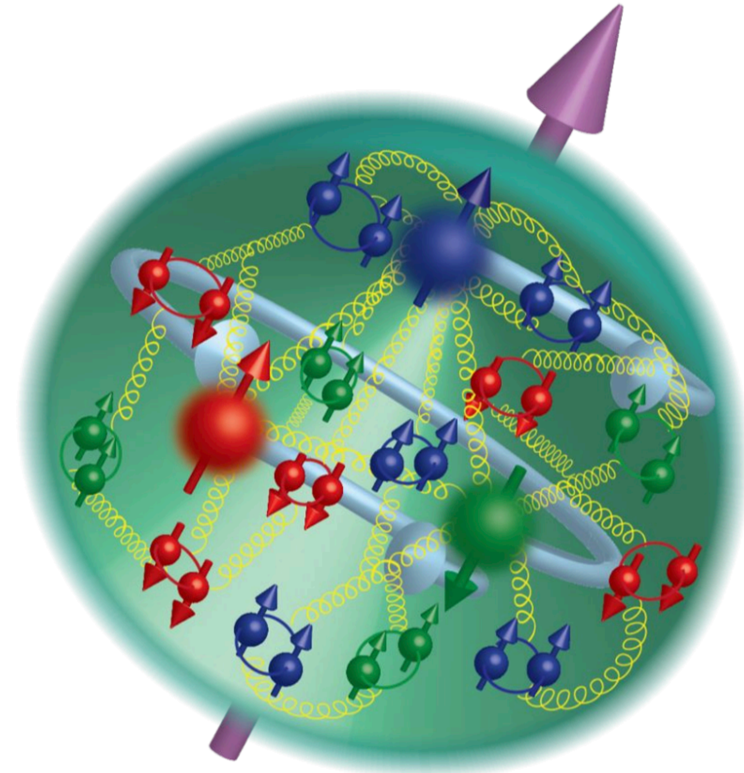
Michelangelo L. Mangano and Giovanni Ridolfi*

Theory Division, CERN
CH-1211 Geneva 23, Switzerland

Abstract

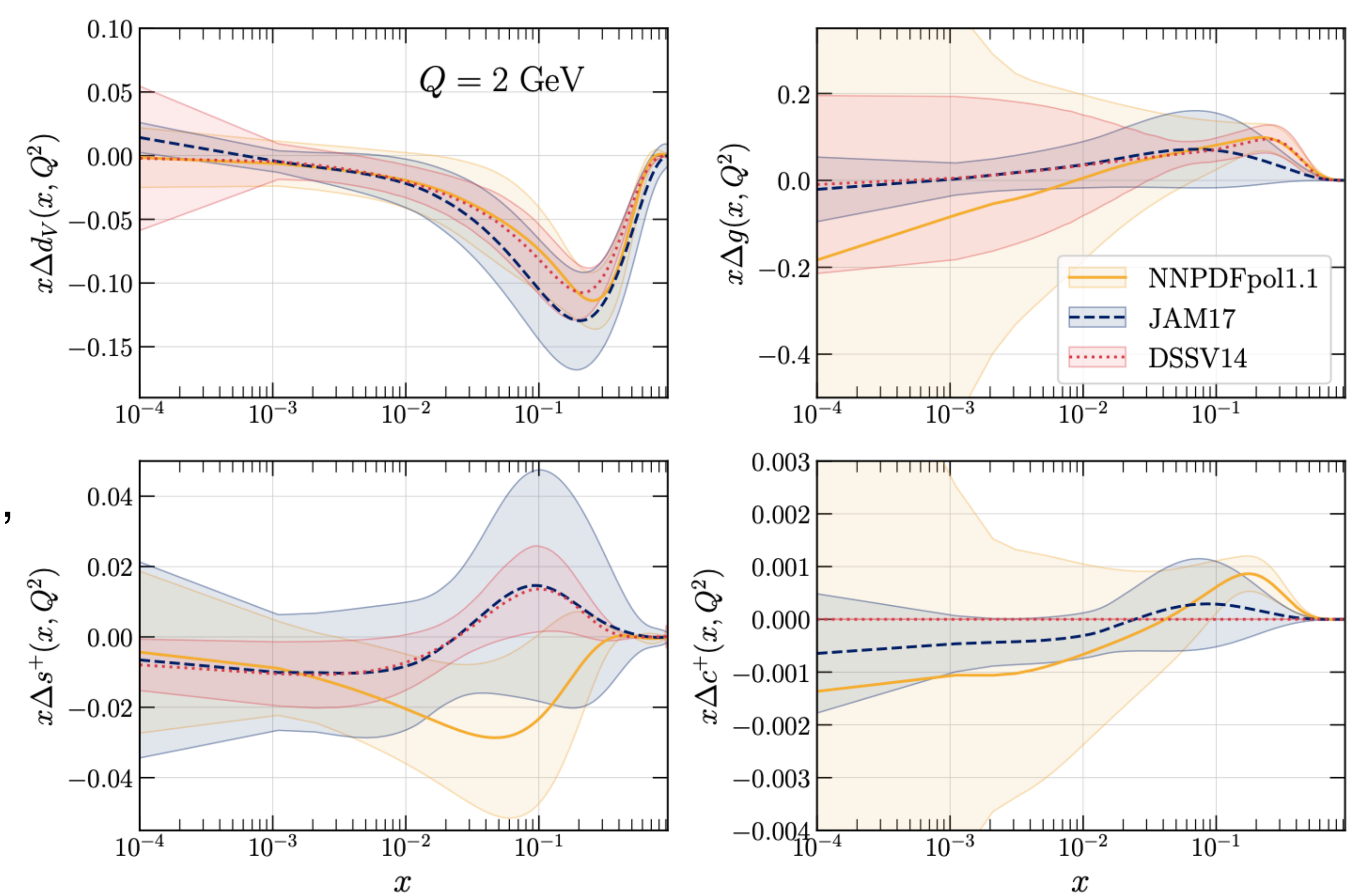
We discuss the determination of polarized parton distributions from charged–current deep–inelastic scattering experiments. We summarize the next-to-leading order treatment of charged–current polarized structure functions, their relation to polarized parton distributions and scale dependence, and discuss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

arXiv:hep-ph/0101192v2 14 Mar 2001



Polarised proton PDFs affected by large uncertainties

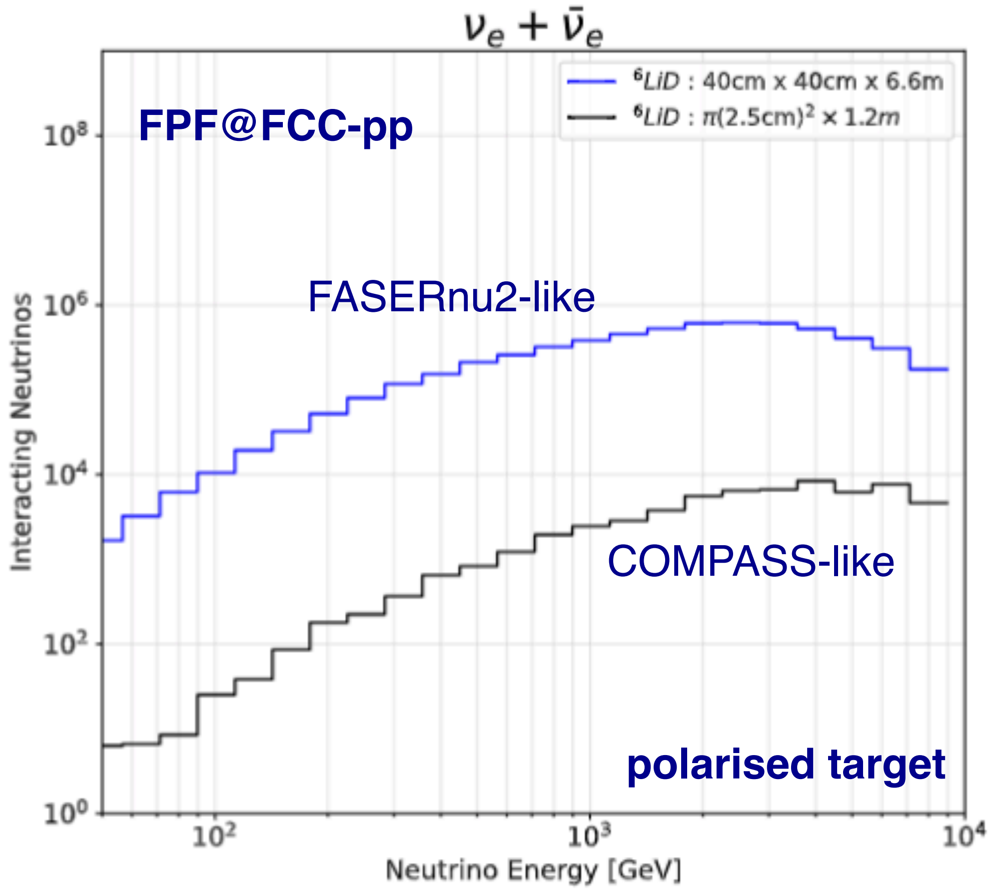
- Realise first neutrino DIS experiment on polarised target: **CC analog of polarized EIC collisions**
- Assuming a COMPASS-like **^{6}LiD polarised target**, FPF@HL-LHC would record O(10 events)

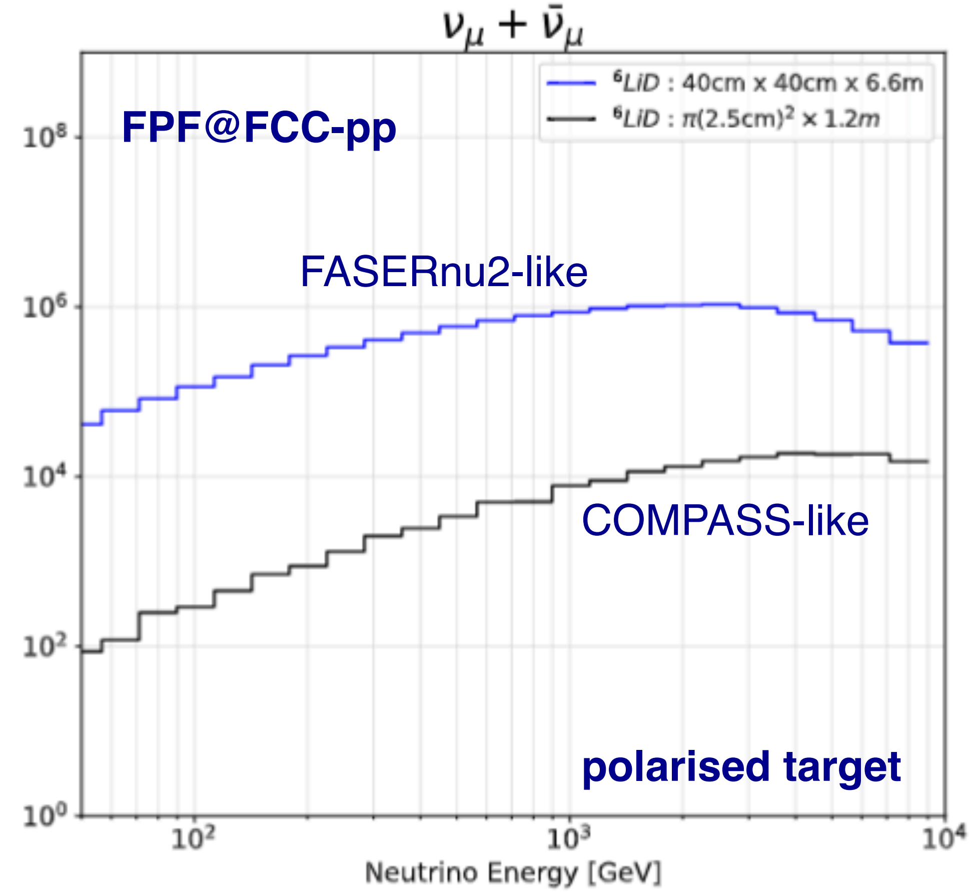


Neutrino polarised DIS

Polarised DIS with neutrinos: **spin mapping**

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





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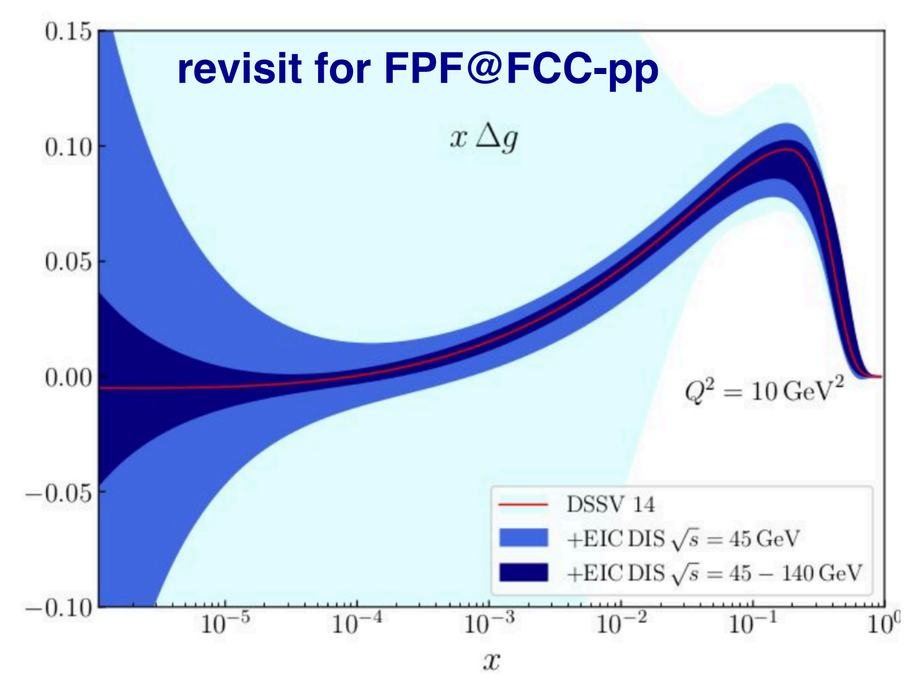
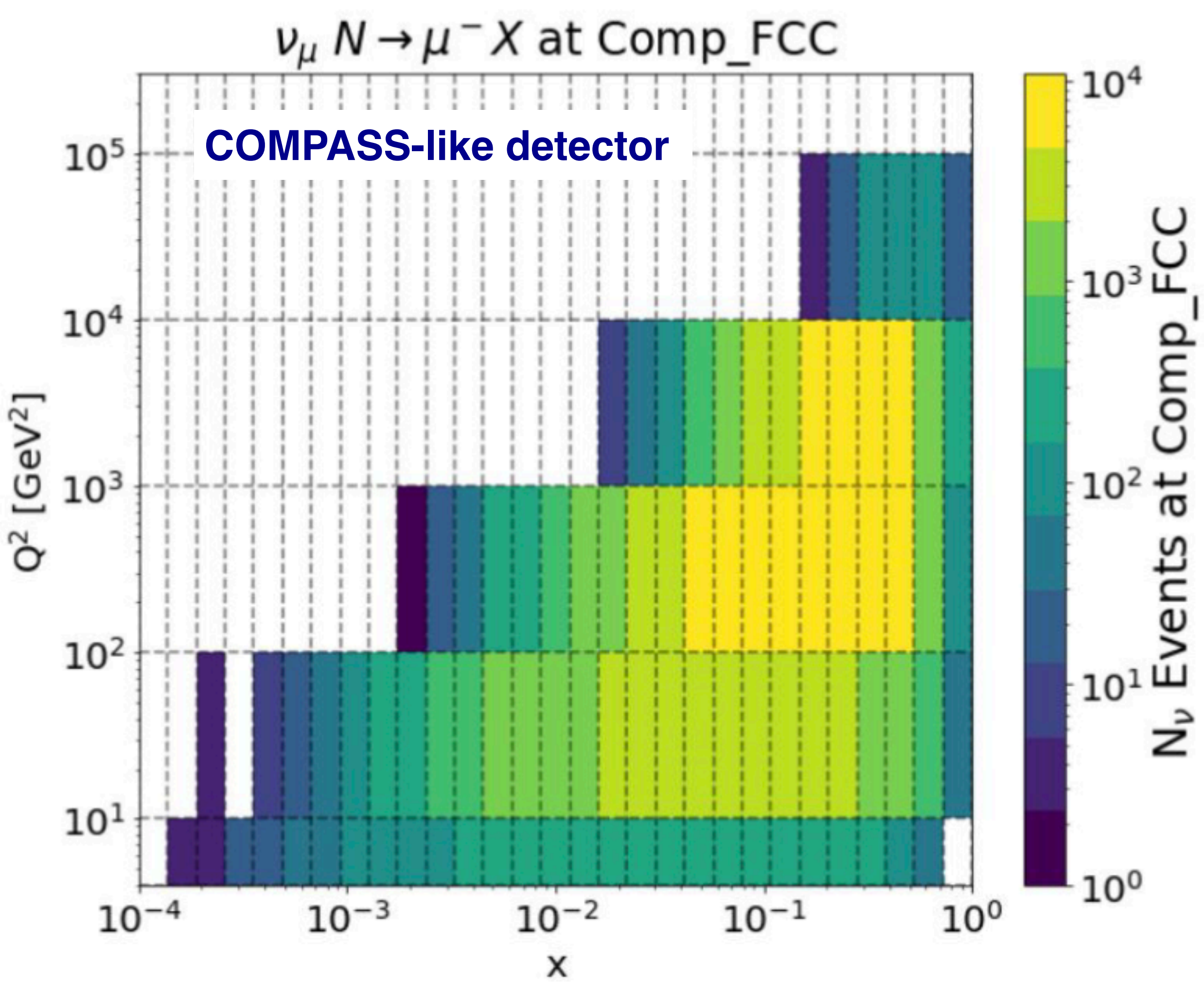
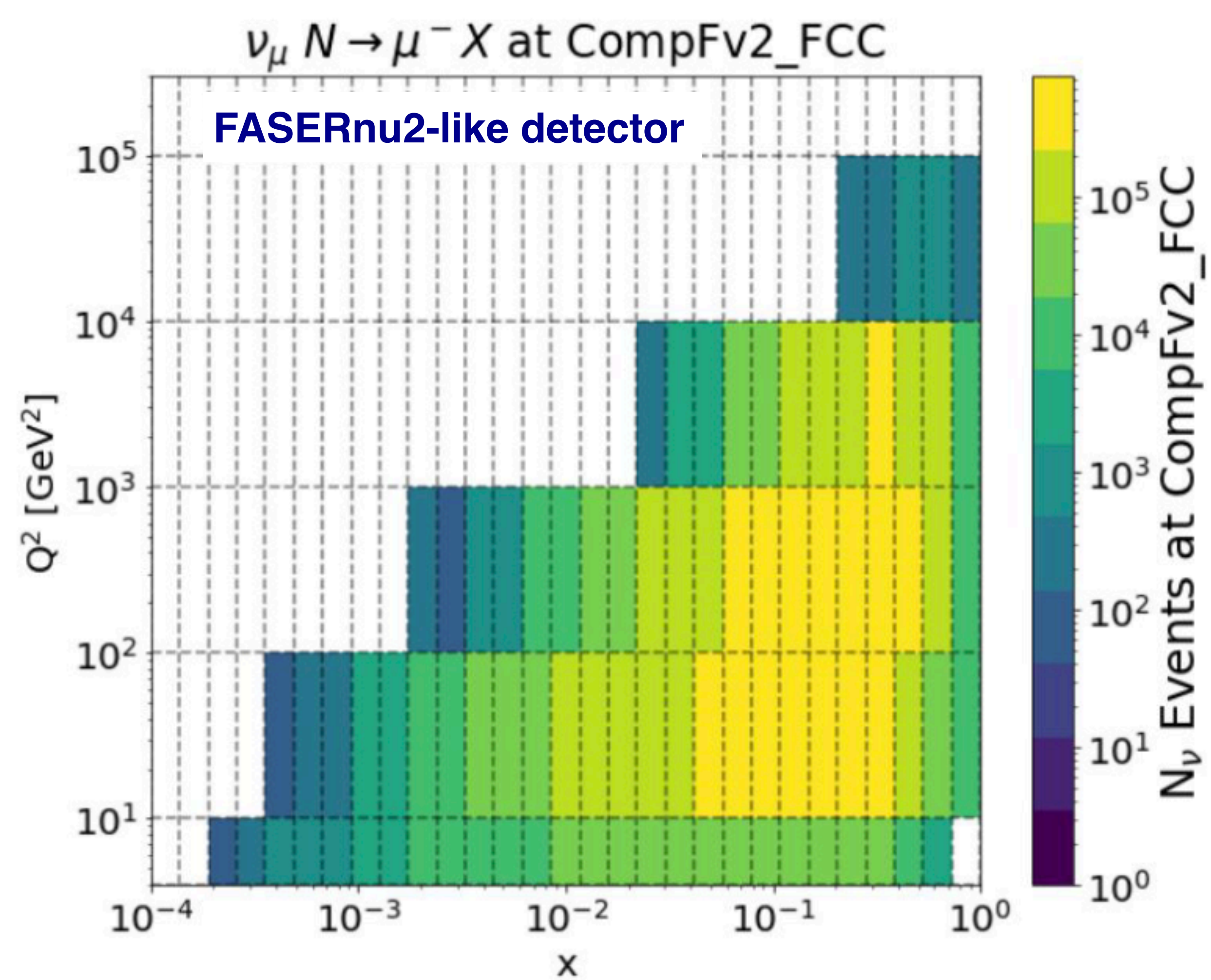


Neutrino polarised DIS





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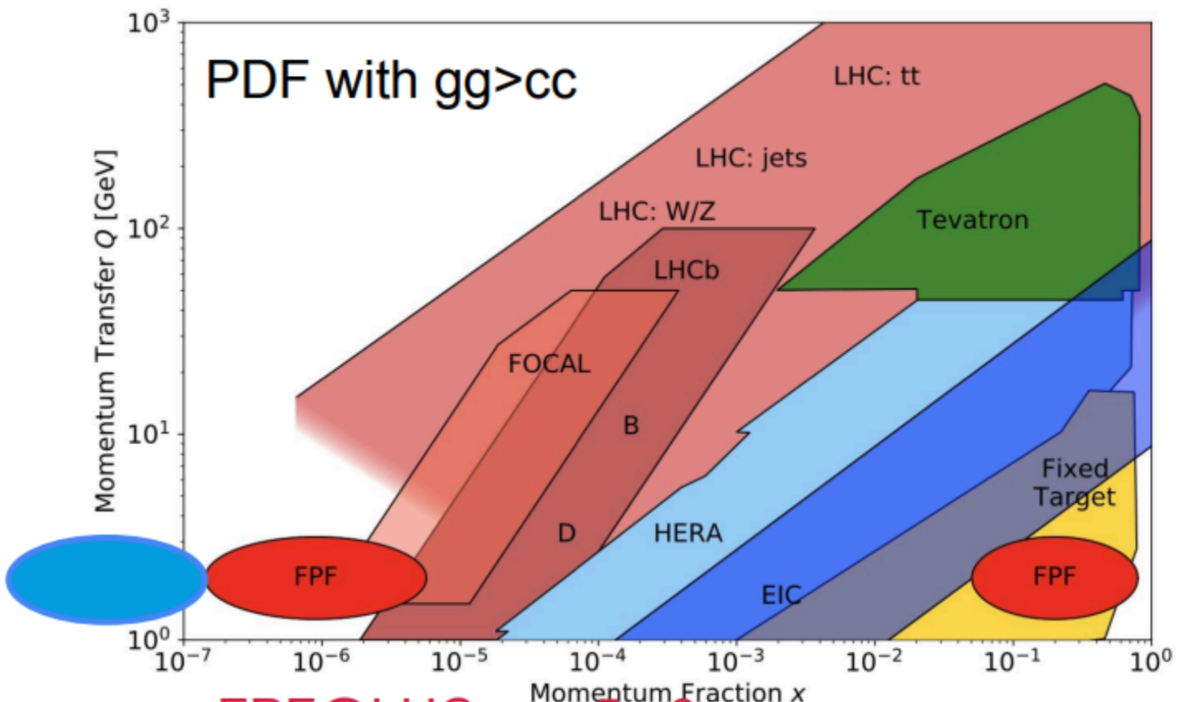
First ever neutrino DIS measurements on polarised targets, extending coverage of EIC charged-lepton measurements

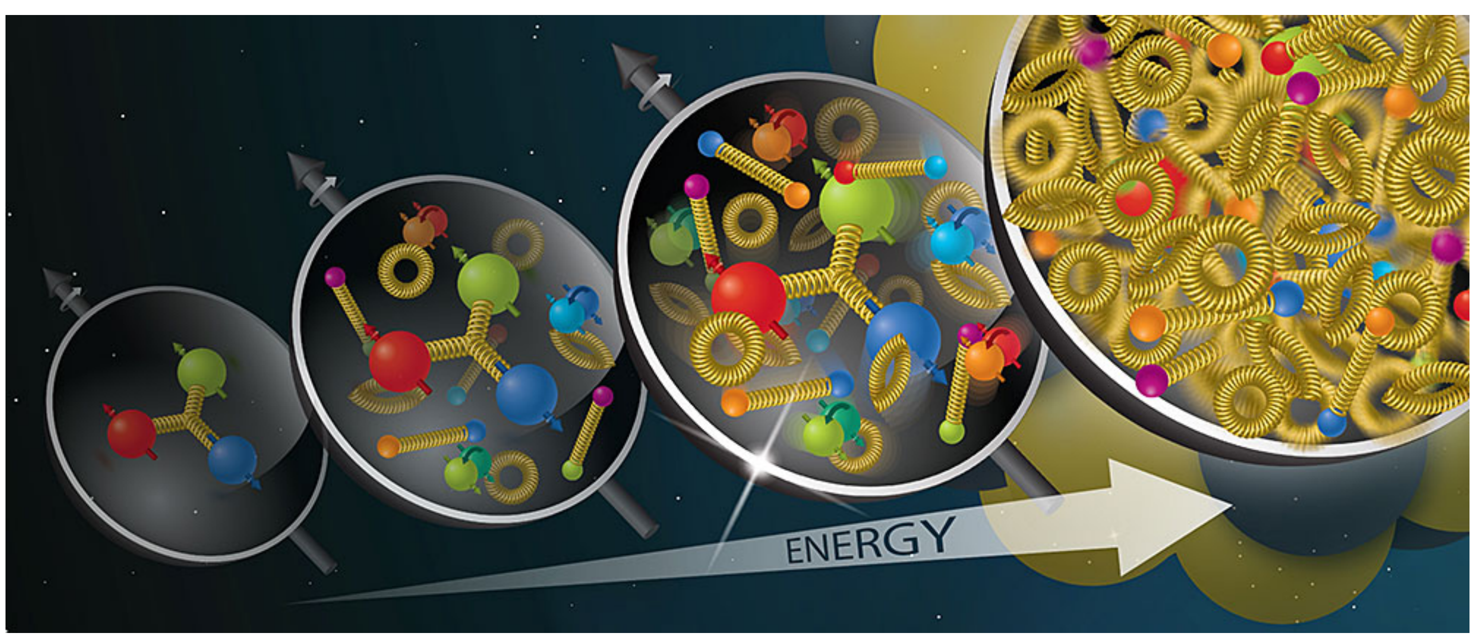
Neutrinos from p+A collisions



FPF@LHC: x > 5e-8

FPF@FCC: x > 9e-10

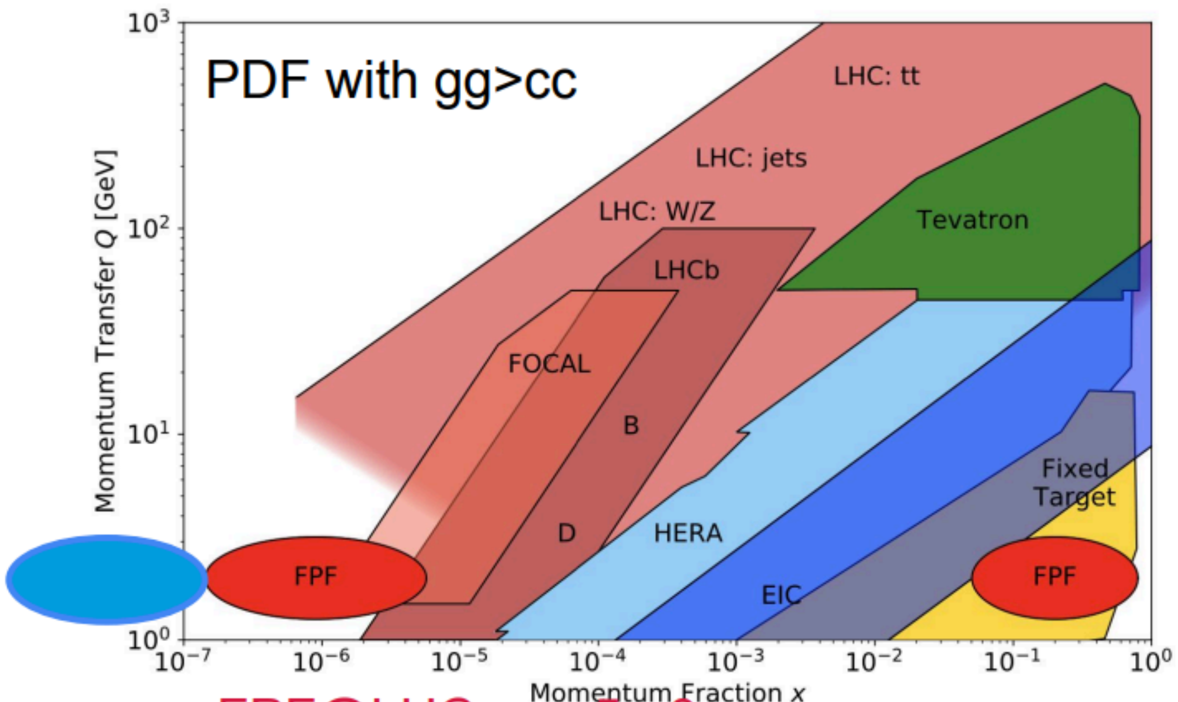
Neutrinos from **proton-ion collisions**



- Neutrinos from proton-lead collisions unique probe of nuclear modifications & possible **gluon saturation** at small-x
- Due to lower lumis of p+Pb collisions, at the HL-LHC event rates are **negligible**

Neutrinos from p+A collisions

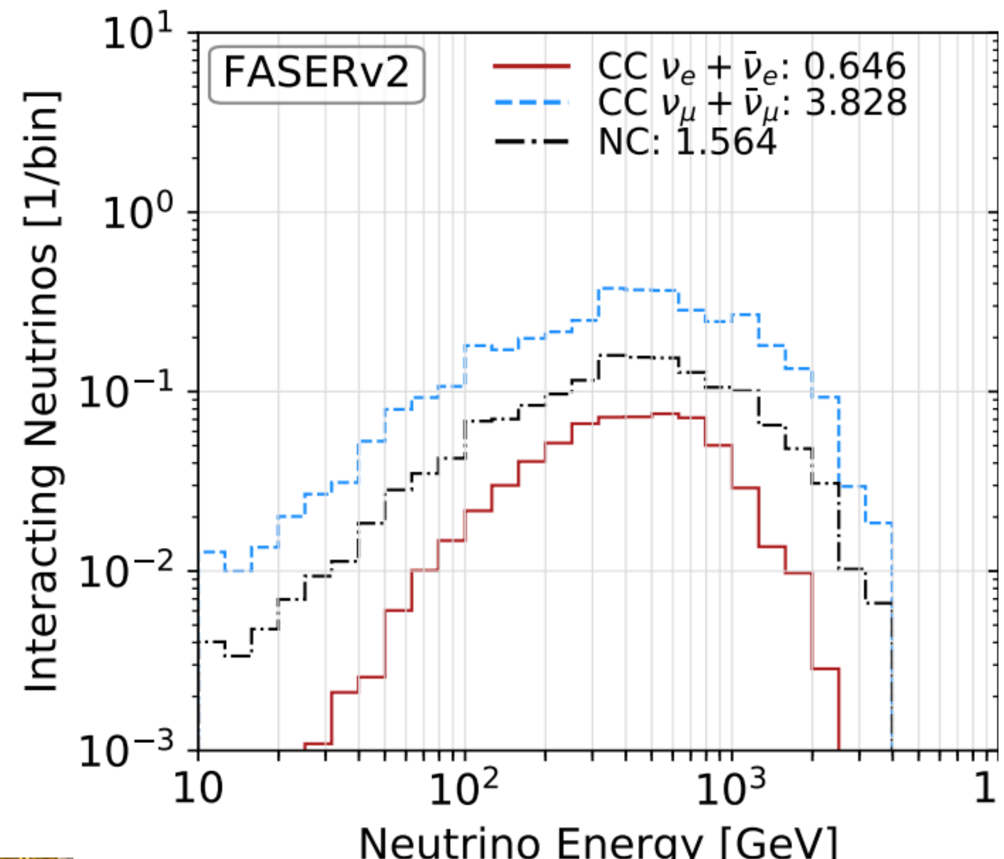
Neutrinos from **proton-ion collisions**

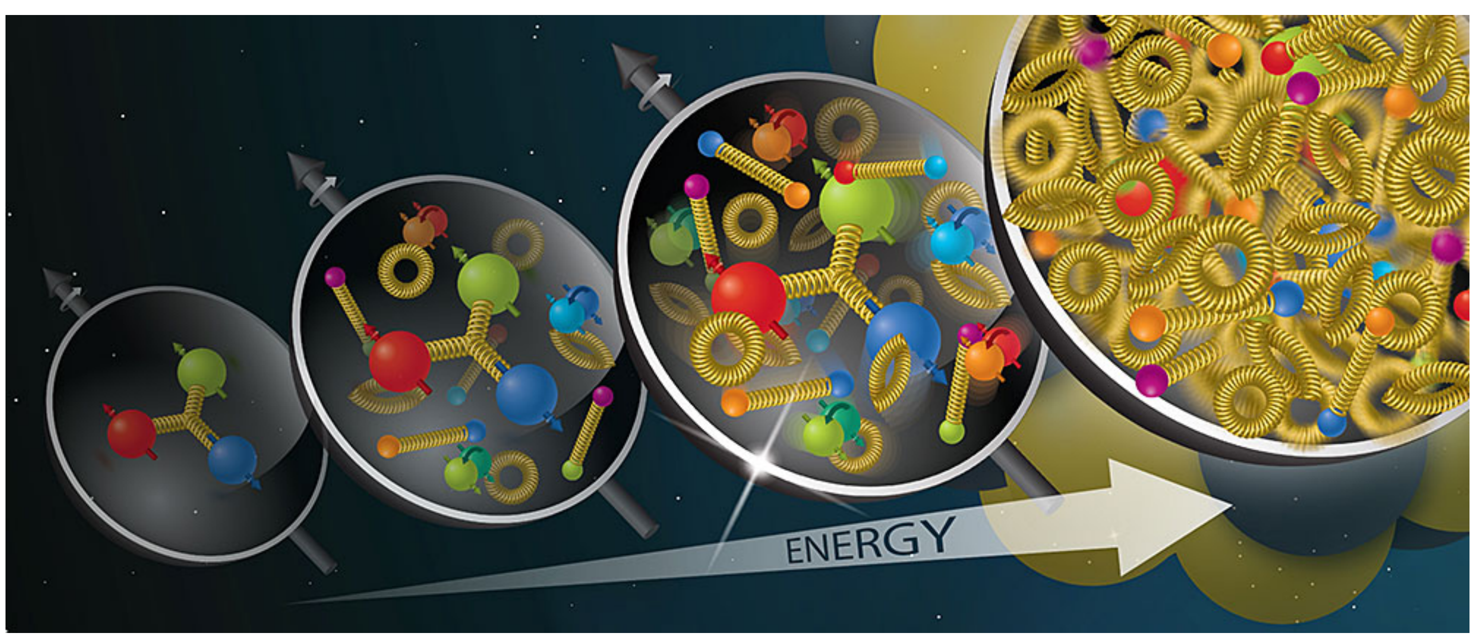


FPF@LHC: x > 5e-8

FPF@FCC: x > 9e-10

FPF@HL-LHC: $\sqrt{s_{NN}}$ = **8.16 TeV**, L_{pPb} = **1 pb^{-1}**





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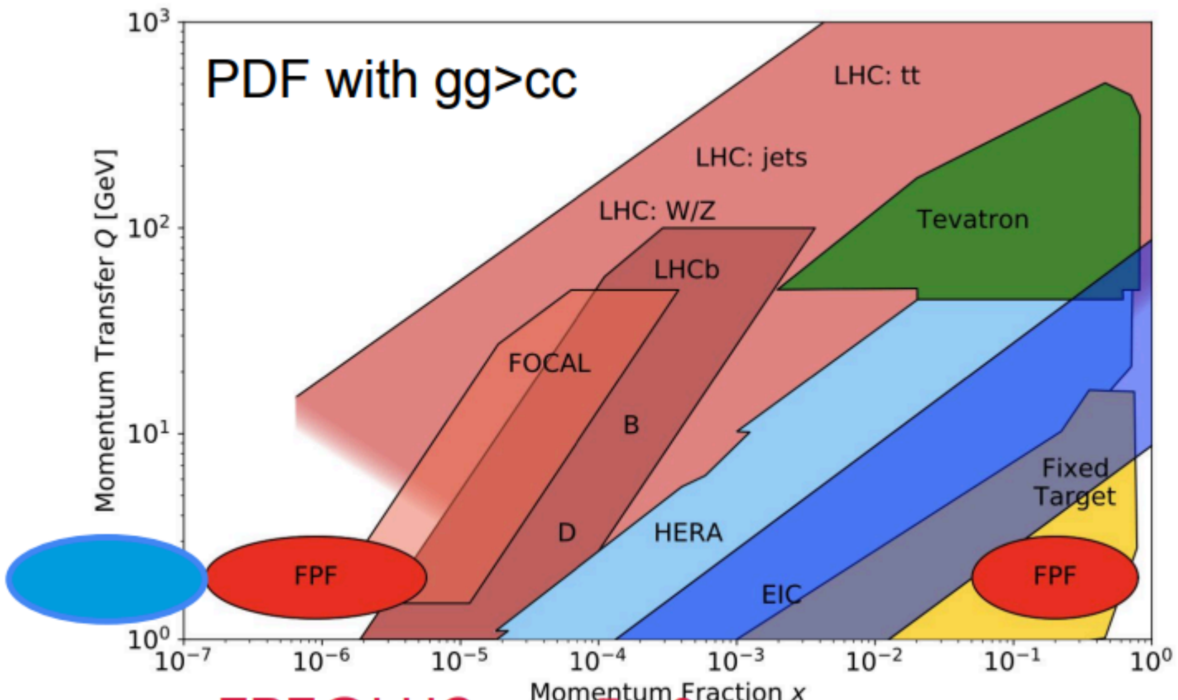

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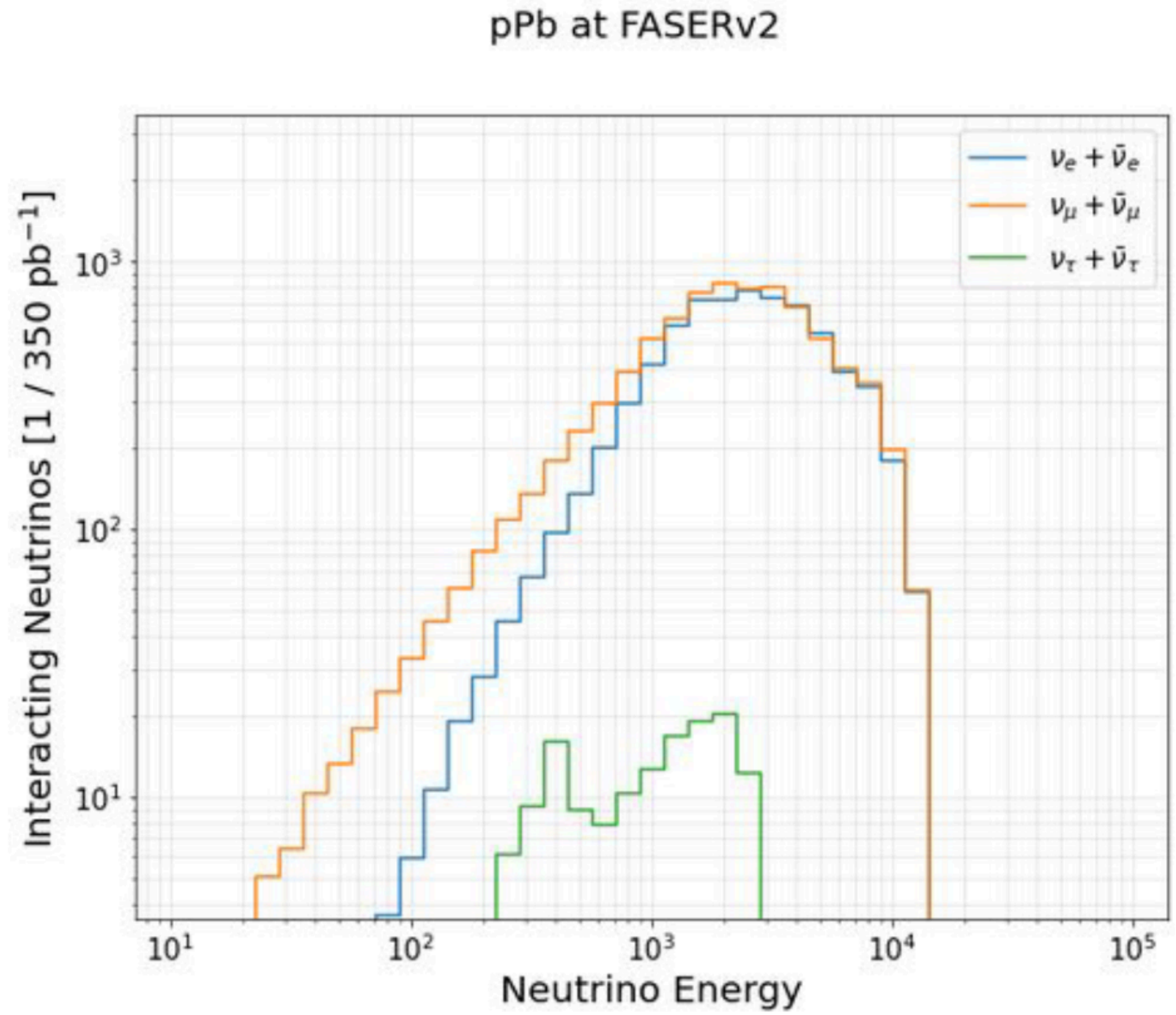
Neutrinos from **proton-ion collisions**

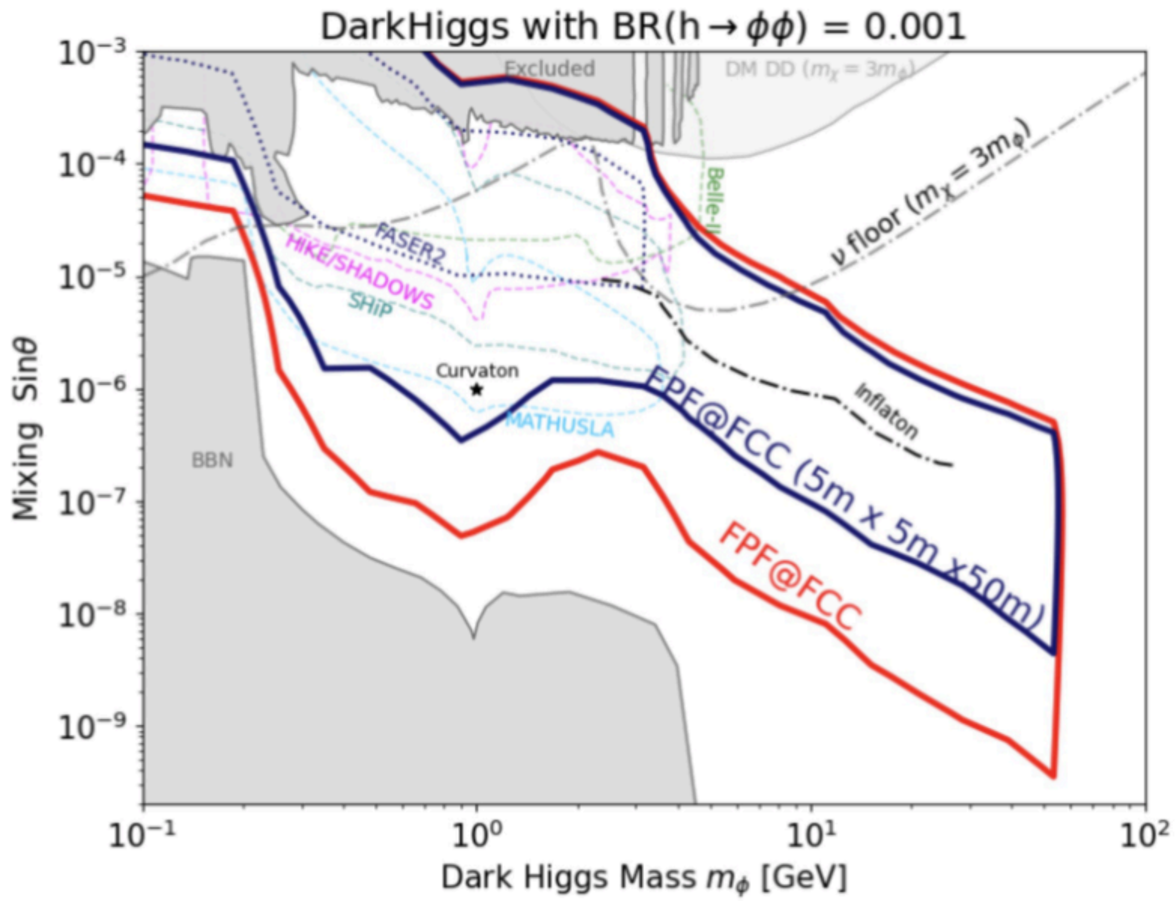


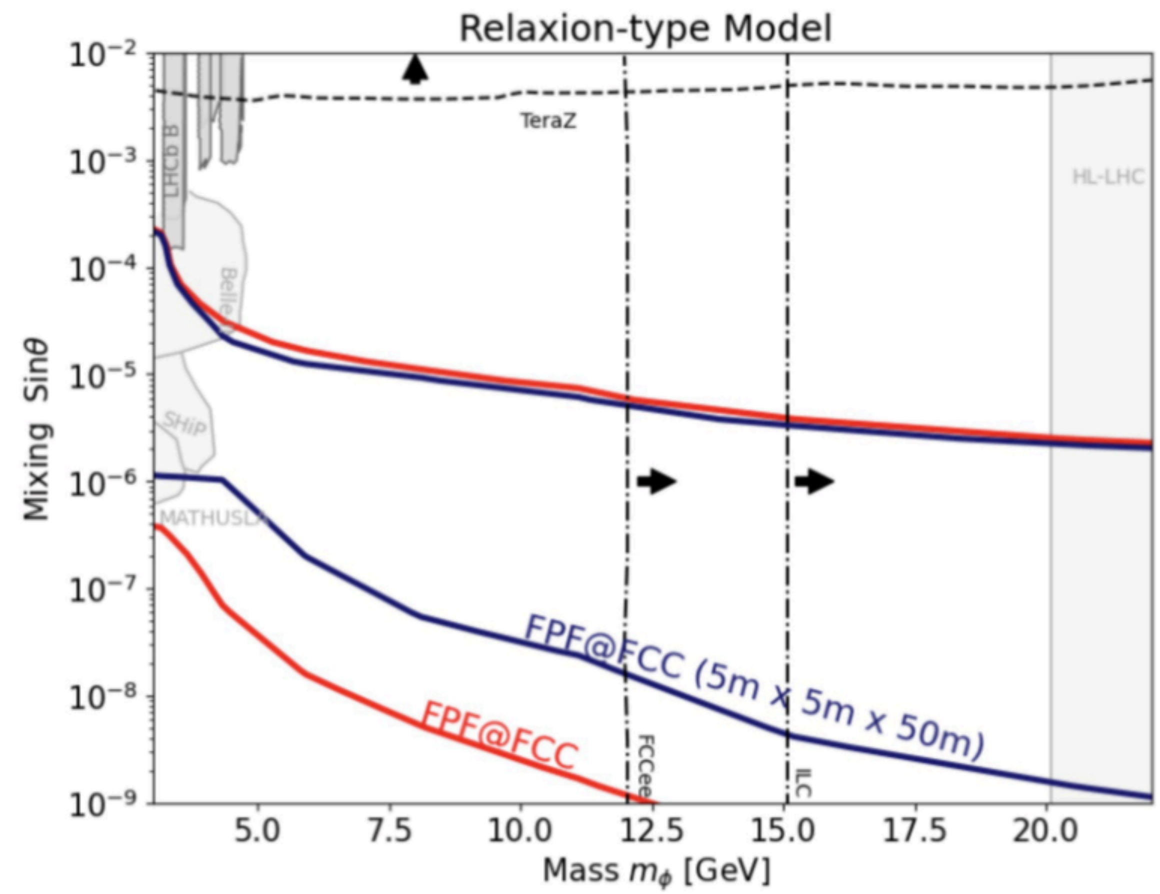
FPF@FCC $\sqrt{s_{NN}}$ = **63 TeV**, L_{pPb} = **29 pb^{-1}**/month

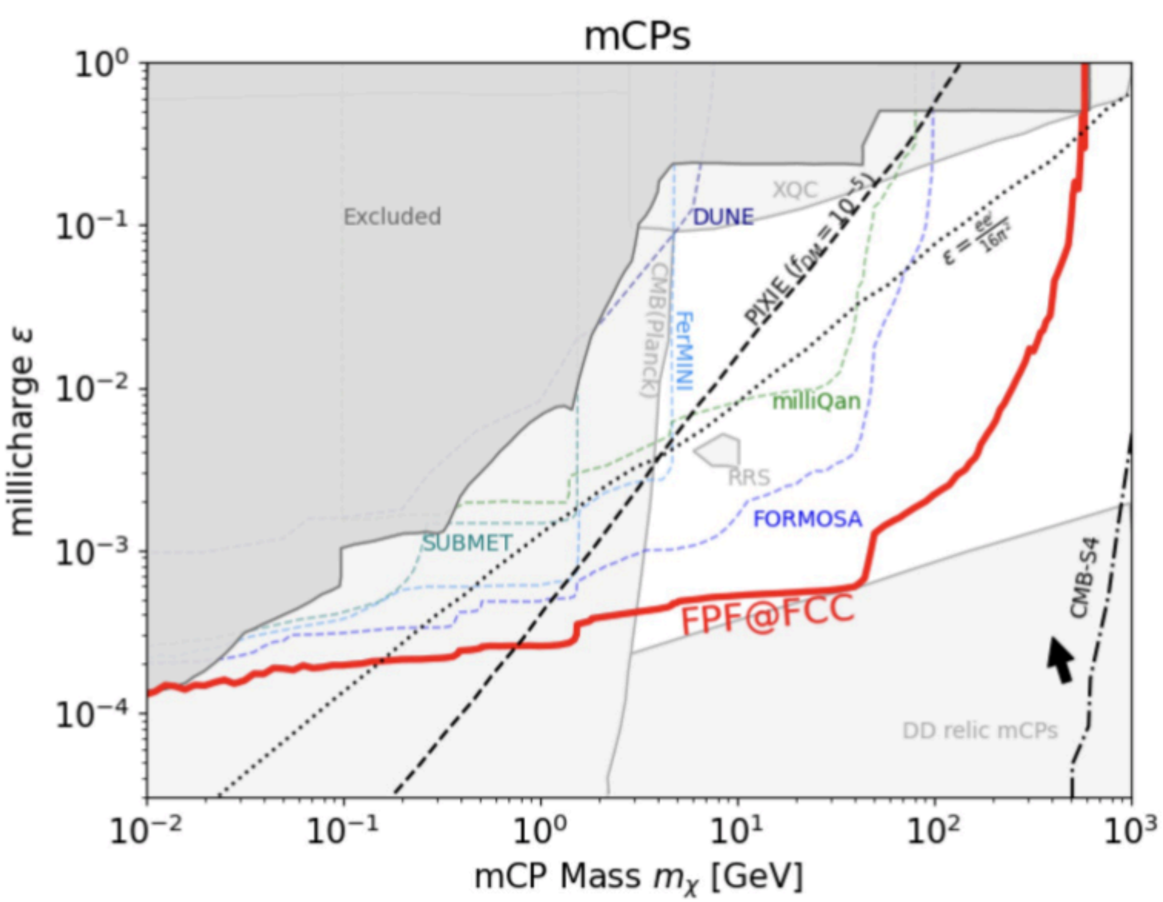
- x100 from **higher $\sqrt{s_{NN}}$** , x150 **higher L_{pPb}**
- **O(30K) muon neutrinos** from p-Pb scattering
- Unique probe of **ultra-dense gluonic matter**
- Different ions: map **nuclear dependence** of exotic QCD dynamics

An new microscope on extreme nuclear QCD matter!

BSM Opportunities



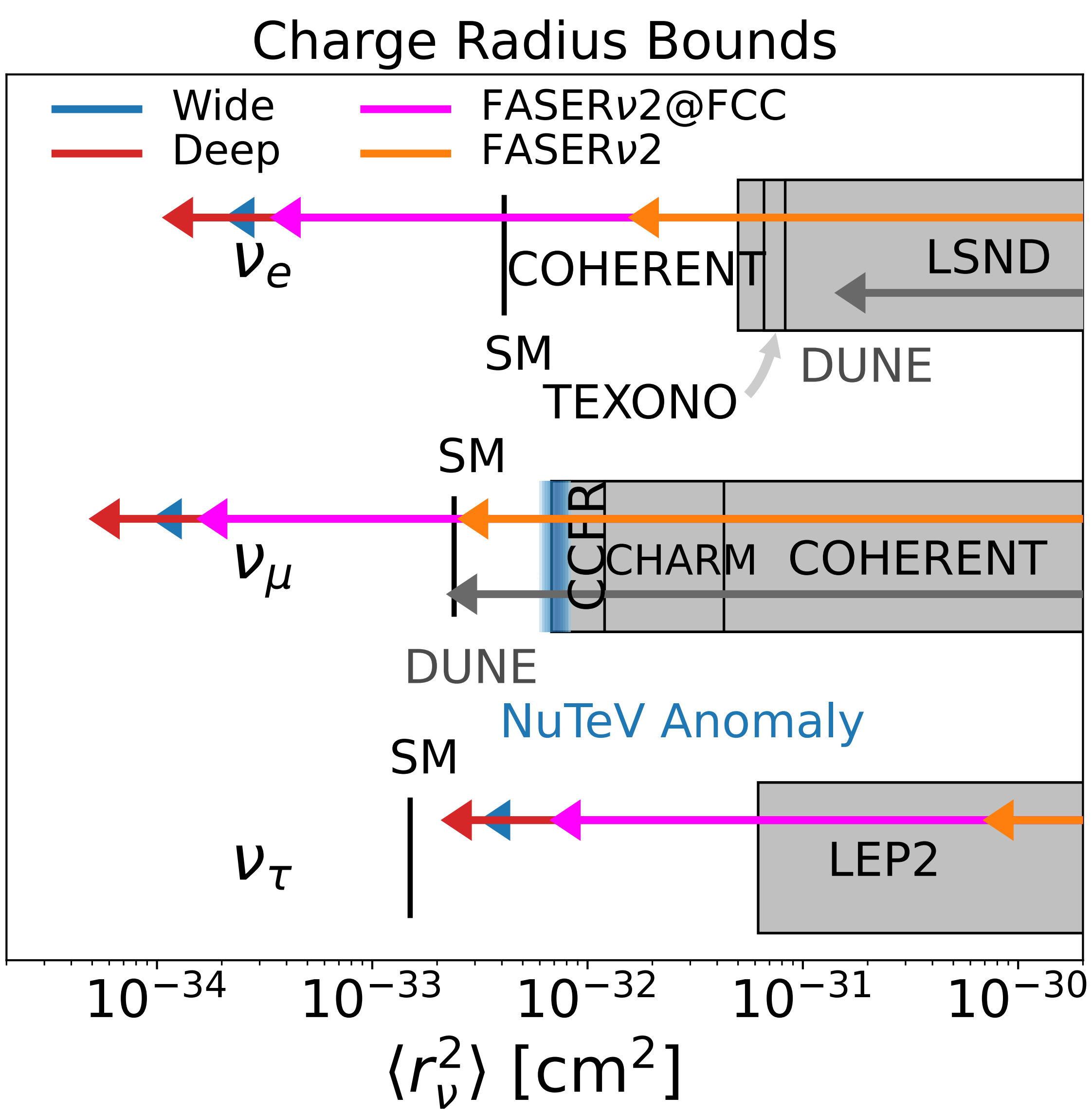


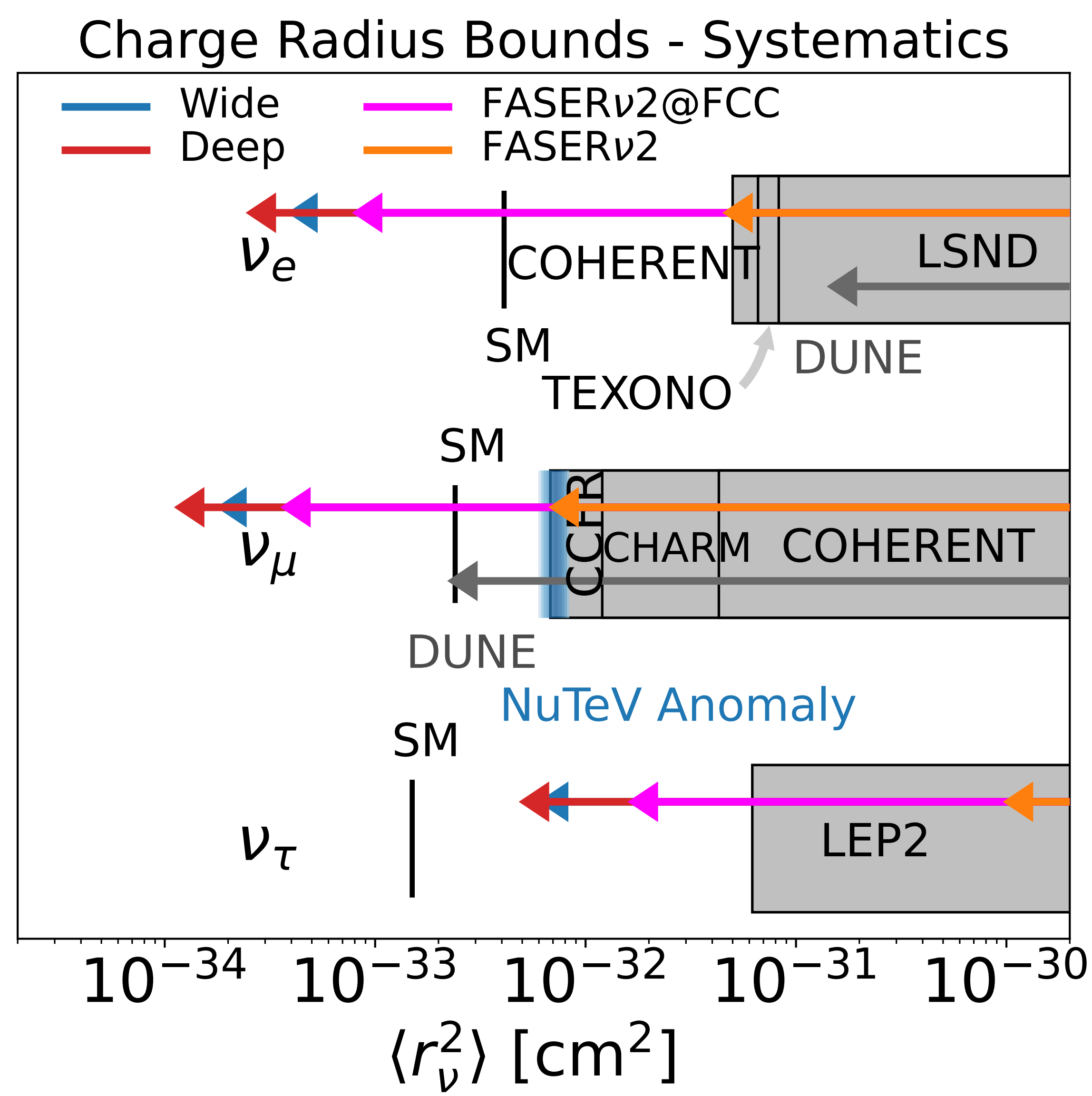


Huge increase in light forward particle production fluxes leads to many new avenues for BSM searches: e.g. **dark Higgs, relaxion-type, milli-charged particle scenarios**

see also talks at the parallel sessions

Neutrino Charge Radius





$$\langle r^2_{\nu_\ell} \rangle_{\rm SM} = \frac{G_f}{4\sqrt{2}\pi^2}\left[3 - 2\log\frac{m_\ell^2}{m_W^2}\right]$$

$$g_V^q \to g_V^q - \frac{2}{3} Q_q m_W^2 \langle r^2_{\nu_\ell} \rangle \sin^2\theta_w$$

modify neutrino DIS interaction vertex

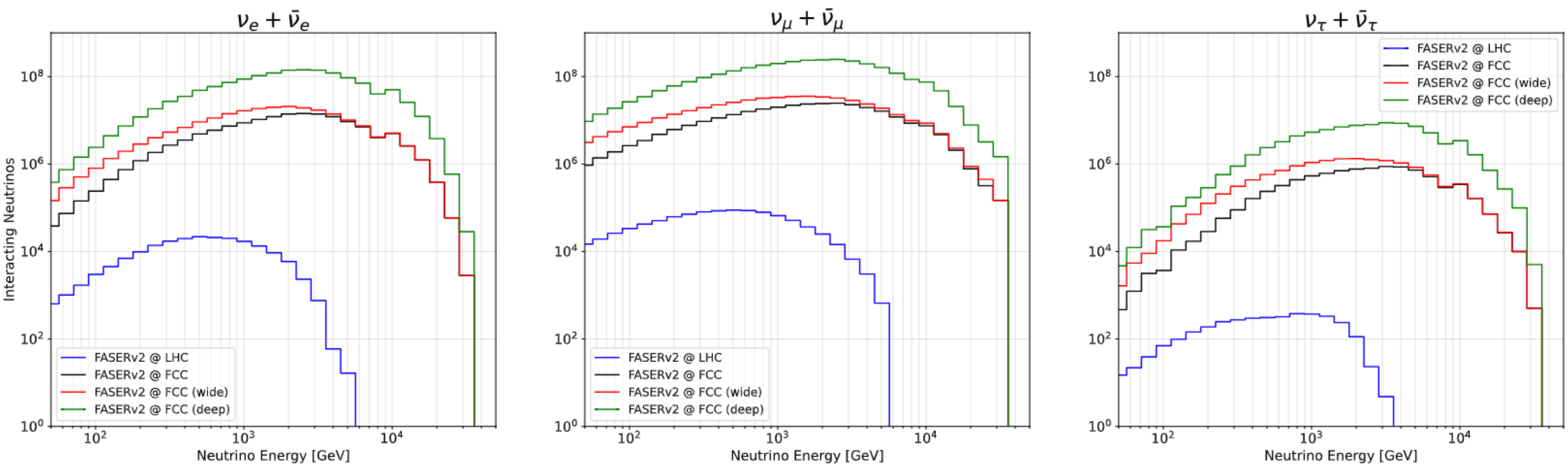
Reaching the **SM floor** for the neutrino charge radius measurements **for the three neutrino flavours**

Summary and outlook (part I)

- An FPF-like suite of experiments could be **integrated in FCC design from day one:** unique physics opportunities within the SM and beyond it, for a **moderate increase of the overall price tag**)

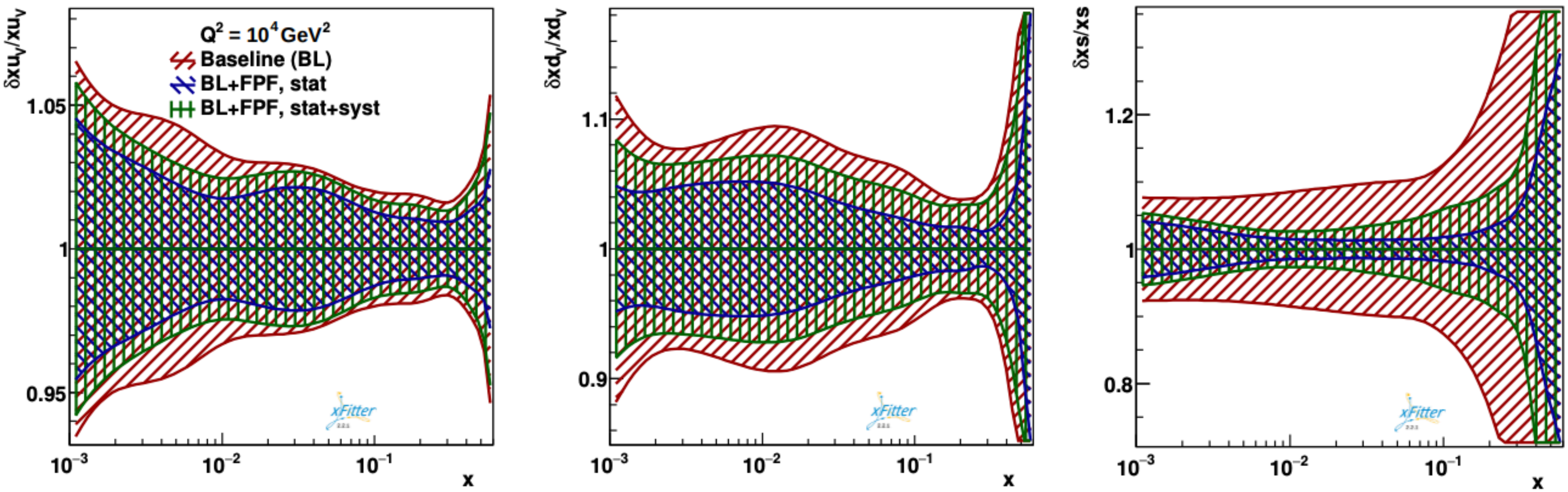
- **Integrating a FPF into the FCC project** pushes ``FPF physics" into mainstream HEP, enhancing the likelihood of its realisation at HL-LHC

- Ideas and suggestions more than welcome **- fun to play with**, e.g. what can one do with 3**B muon neutrinos** and **100M tau neutrinos** with 10 TeV energies?



Using FPF Data to Lift Degeneracies in BSM Searches at the HL-LHC

PDF constraints from LHC neutrinos



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

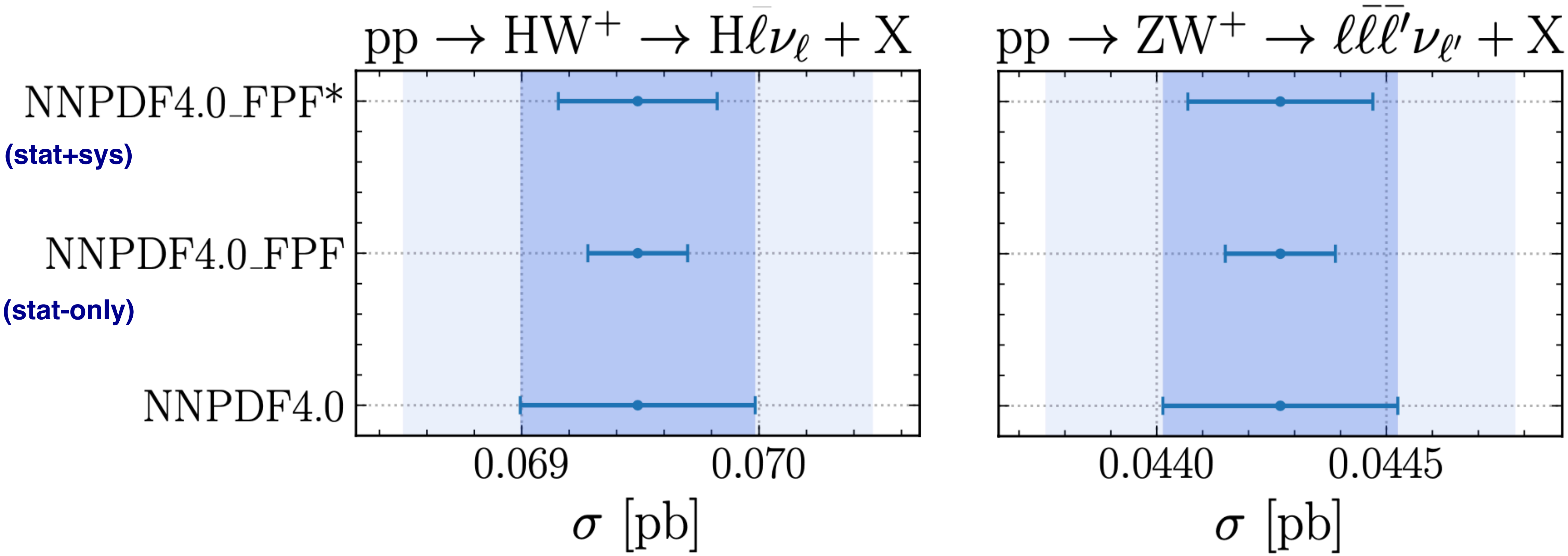
PineAPPL interface to xFitter
enables use of YADISM, MATRIX, aMC@NLO calculations

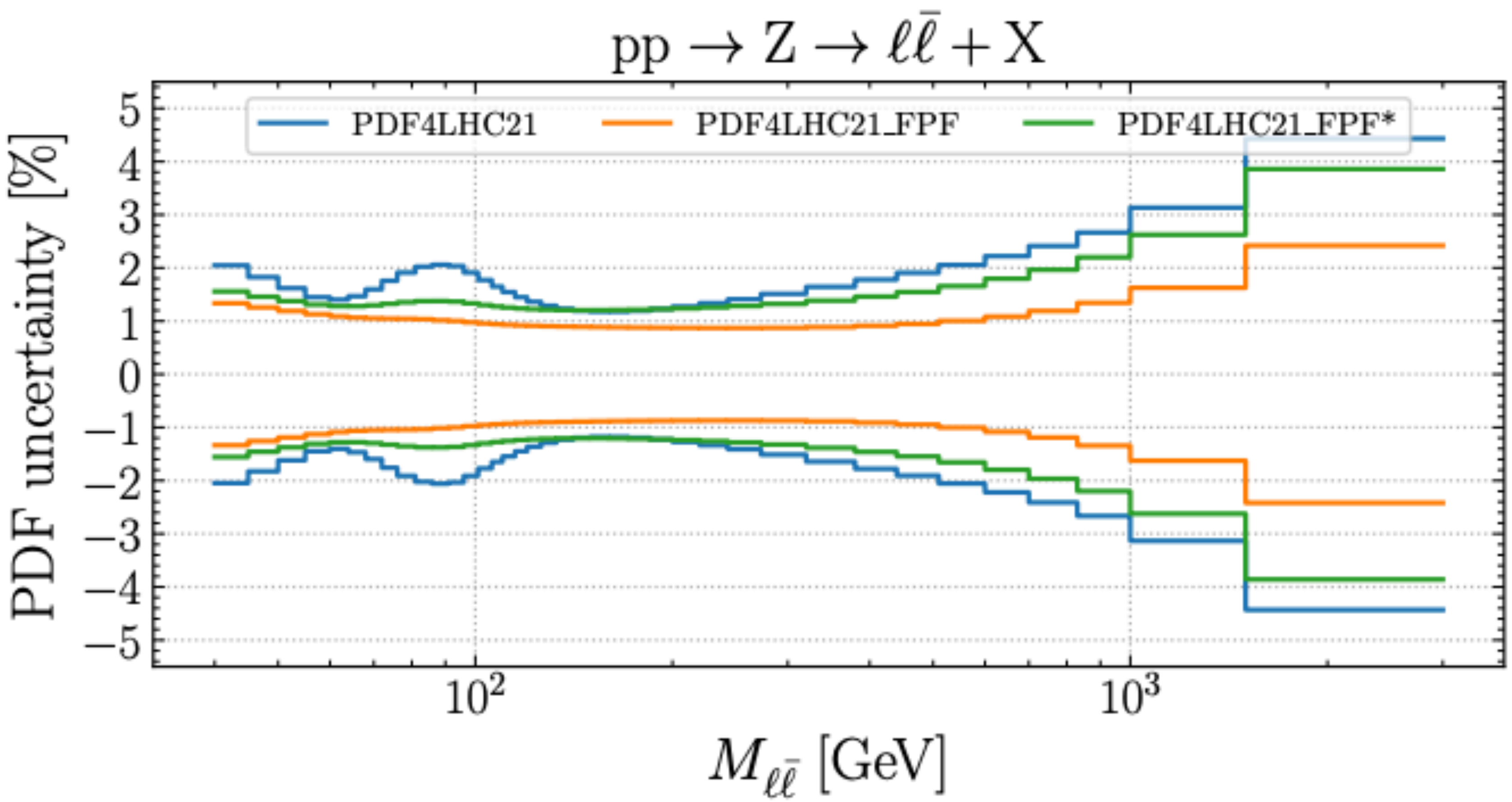
- Impact on **up/down valence quarks** as well as in **strangeness,** ultimately limited by systematics

Far-forward neutrino detectors effectively extend CERN with a **Neutrino-Ion Collider** by ``recycling'' an otherwise discarded beam (with the highest energies ever achieved in a lab)

Cruz-Martinez et al,. 2309.09581

Impact on HL-LHC predictions





- 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

Independent extraction of large-x PDFs
without risk of absorbing BSM

Standard Model PDFs

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**

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

SMEFT PDFs

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

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

- $\sigma_{\rm th}(\boldsymbol{\theta}, M_X)$: ***hadronic cross-section***
- $\mathscr{L}_{ij}^{(\rm smeft)}$: ***SMEFT PDF luminosity***
- $\boldsymbol{\theta}$: **PDF parameters**
- $\widetilde{\sigma}_{ij}^{(\rm smeft)}$: ***SMEFT partonic cross-section***
- $\boldsymbol{c}/\Lambda^2$: **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***

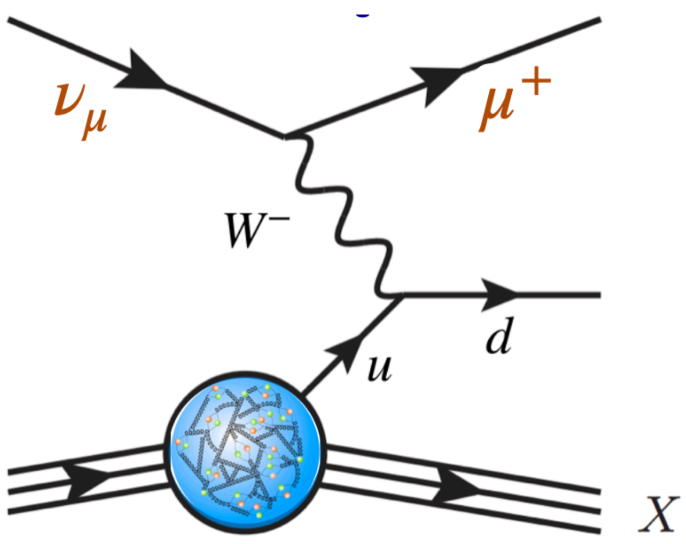
Given experimental constraints, how **different are SM and SMEFT PDFs**? Is there a risk to **fit away EFT effects into the PDFs?**

SMEFT PDFs

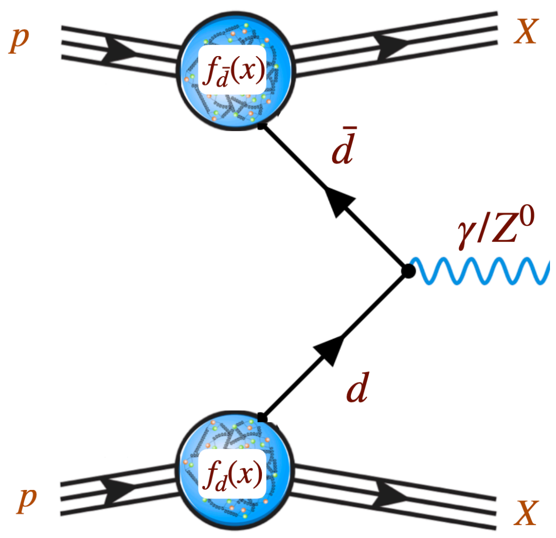
Differences between SM-PDFs and SMEFT-PDFs have two main consequences:

- Effects of higher-dimensional SMEFT operators **are partially reabsorbed into PDFs**, affecting indirectly prediction for other processes and **jeopardising validity of SM predictions**
- Bounds in **SMEFT operators will be modified** as compared to the assumption of SM-PDFs

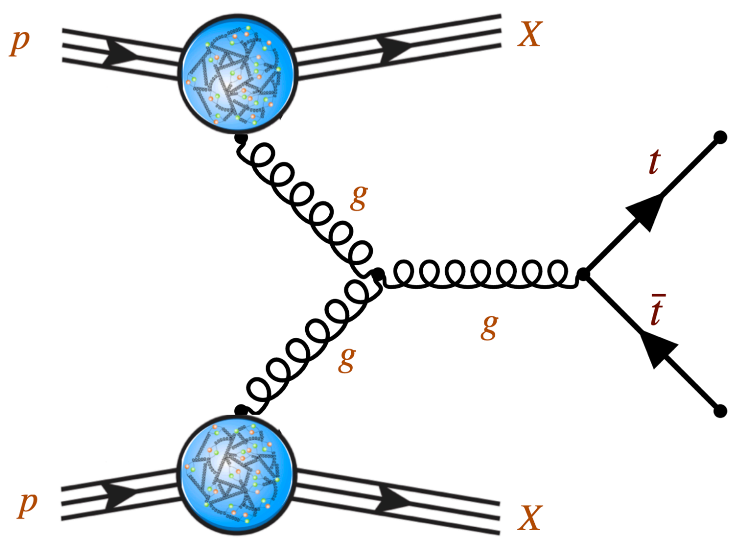
The answer depends on the **process** and on the **sensitivity** of available data. Needs to be studies on a case-by-case basis



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

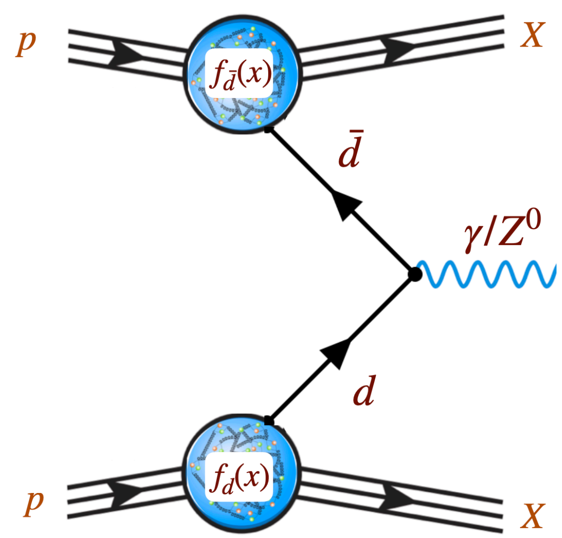


High-mass Drell-Yan: *A. Greljo, S. Iranipour, Z. Kassabov, M. Madigan, J. Moore, JR, M. Ubiali, C. Voisey, JHEP 2021*



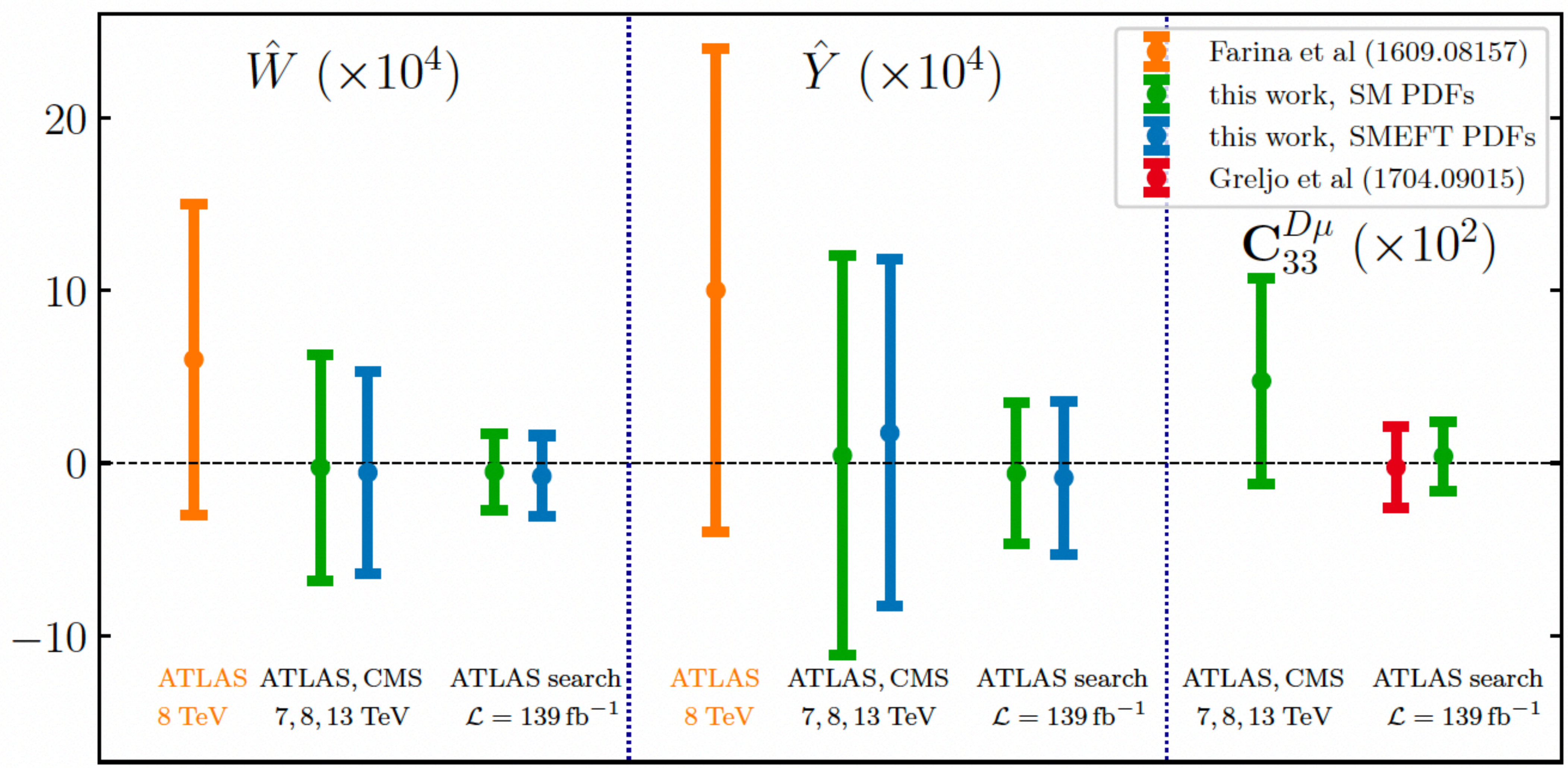
Top quark sector: *Z. Kassabov, M. Madigan, L. Mantani , J. Moore , M.Morales-Alvarado, JR , M. Ubiali, JHEP 2023*

SMEFT PDFs from high-mass Drell-Yan

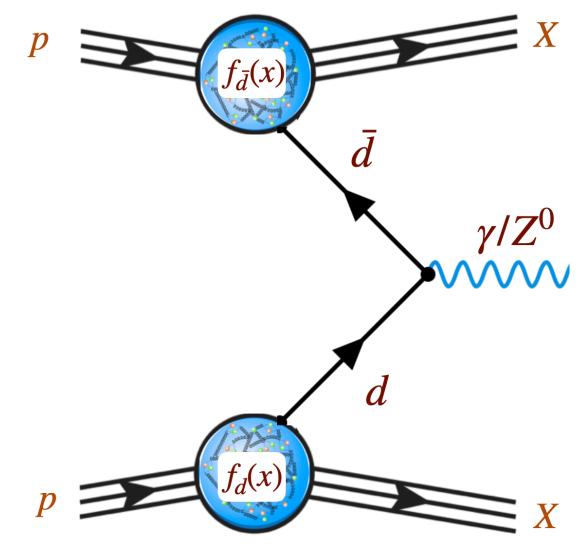


High-mass Drell-Yan: *A. Greljo, S. Iranipour, Z. Kassabov, M. Madigan, J. Moore, JR, M. Ubiali, C. Voisey, JHEP 2021*

- Available data: **limited interplay** between PDF and EFT fits
- Best constraints from **searches,** but corresponding unfolded measurements not yet available
- SMEFT-PDFs modify bounds from SM-PDFs by around **10%**

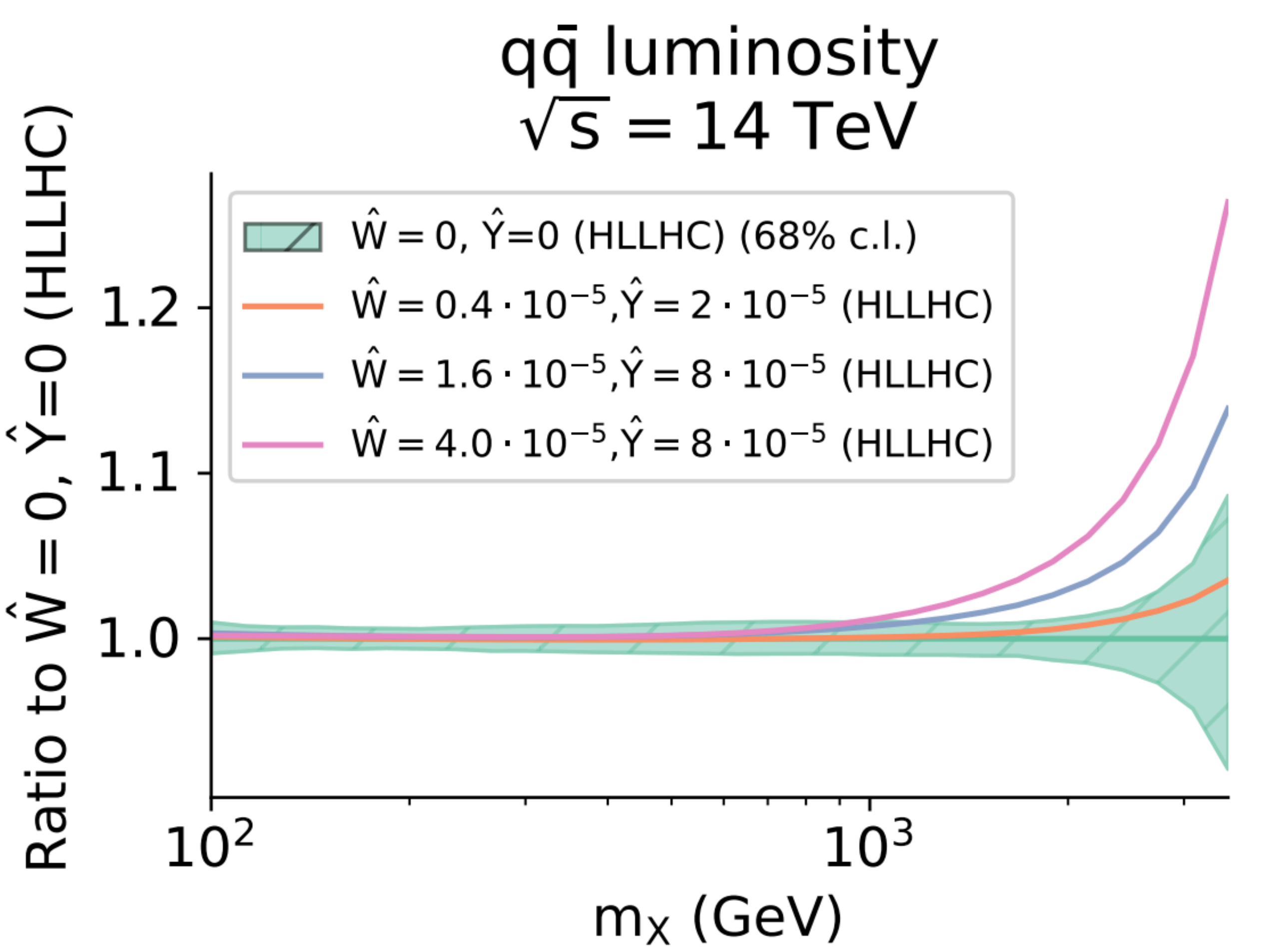


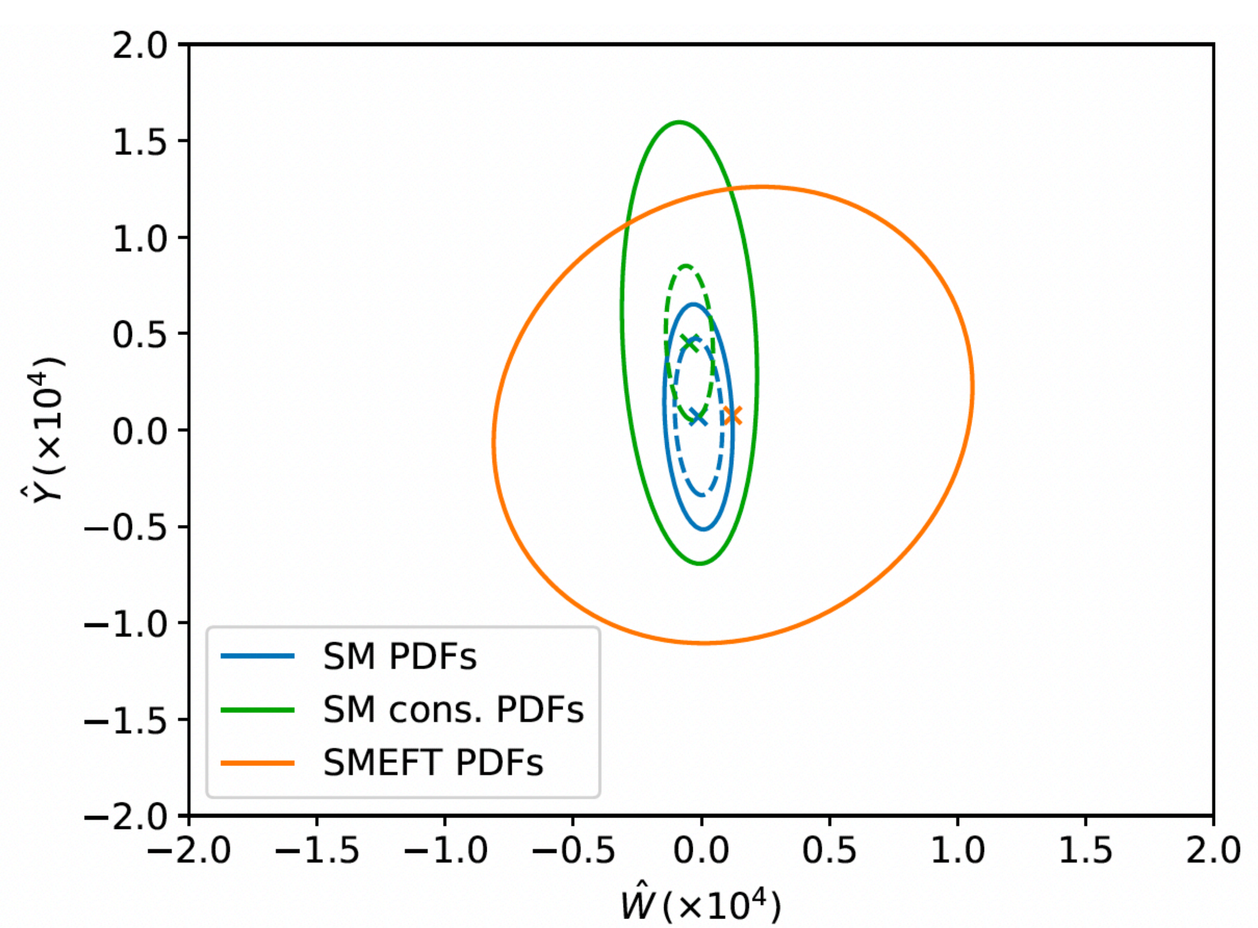
SMEFT PDFs from high-mass Drell-Yan



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

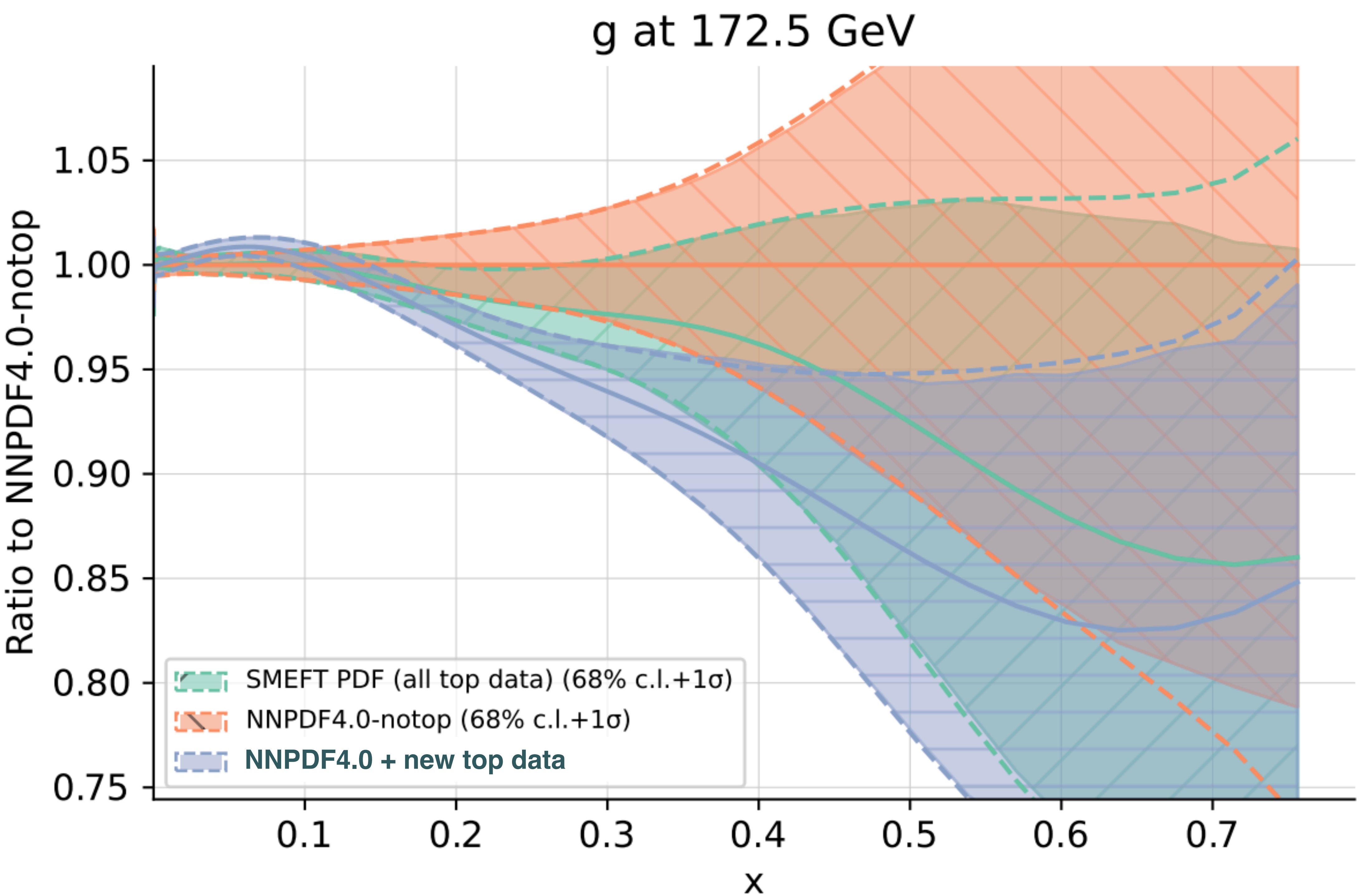




relevant also for legacy Run III measurements

SMEFT PDFs from top quark data

SMEFT-PDF results

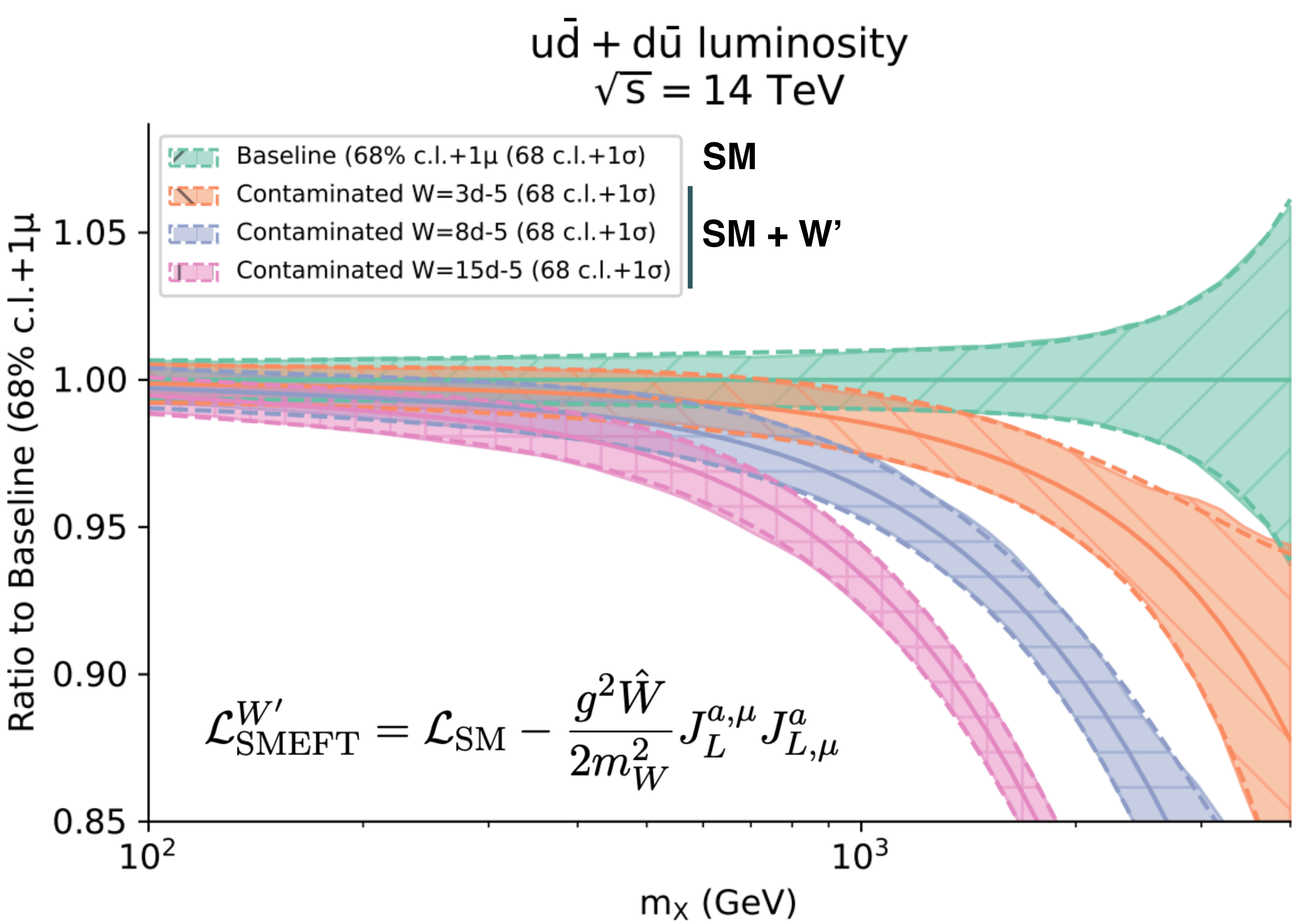


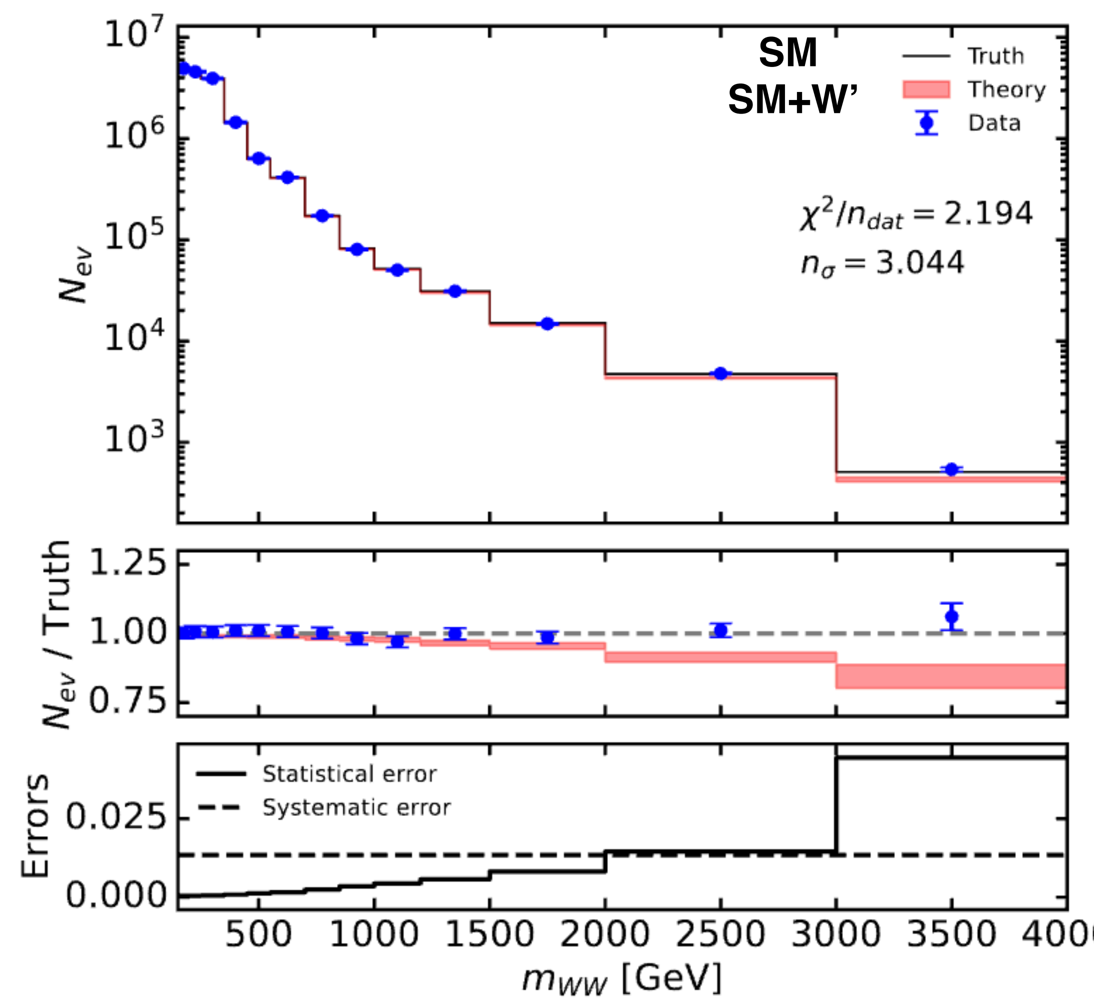
Large-*x* gluon **distorted by EFT effects**, which partially absorb the data pulls

As a result, net effect of top quark data on PDFs **reduced** as compared to SM-PDFs

Fitting Away New Physics at the HL-LHC

- Assume a BSM scenario with an extra W' gauge boson with **$M_{W'}$ = 13.8 TeV**
- Generate **HL-LHC pseudo-data** (NC & CC Drell-Yan) for this model and include in global PDF fit
- **Data-theory agreement unchanged,** but the 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)

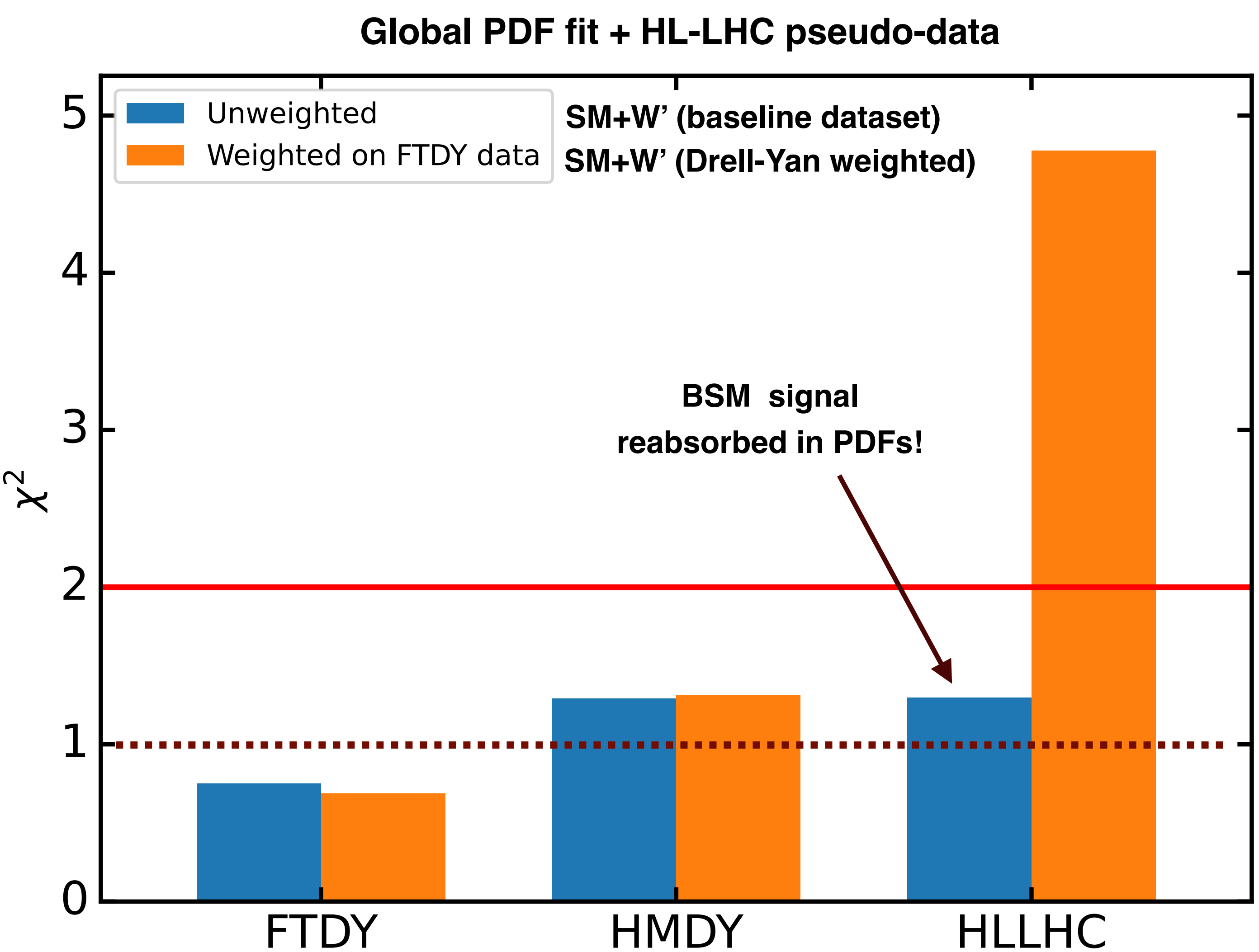


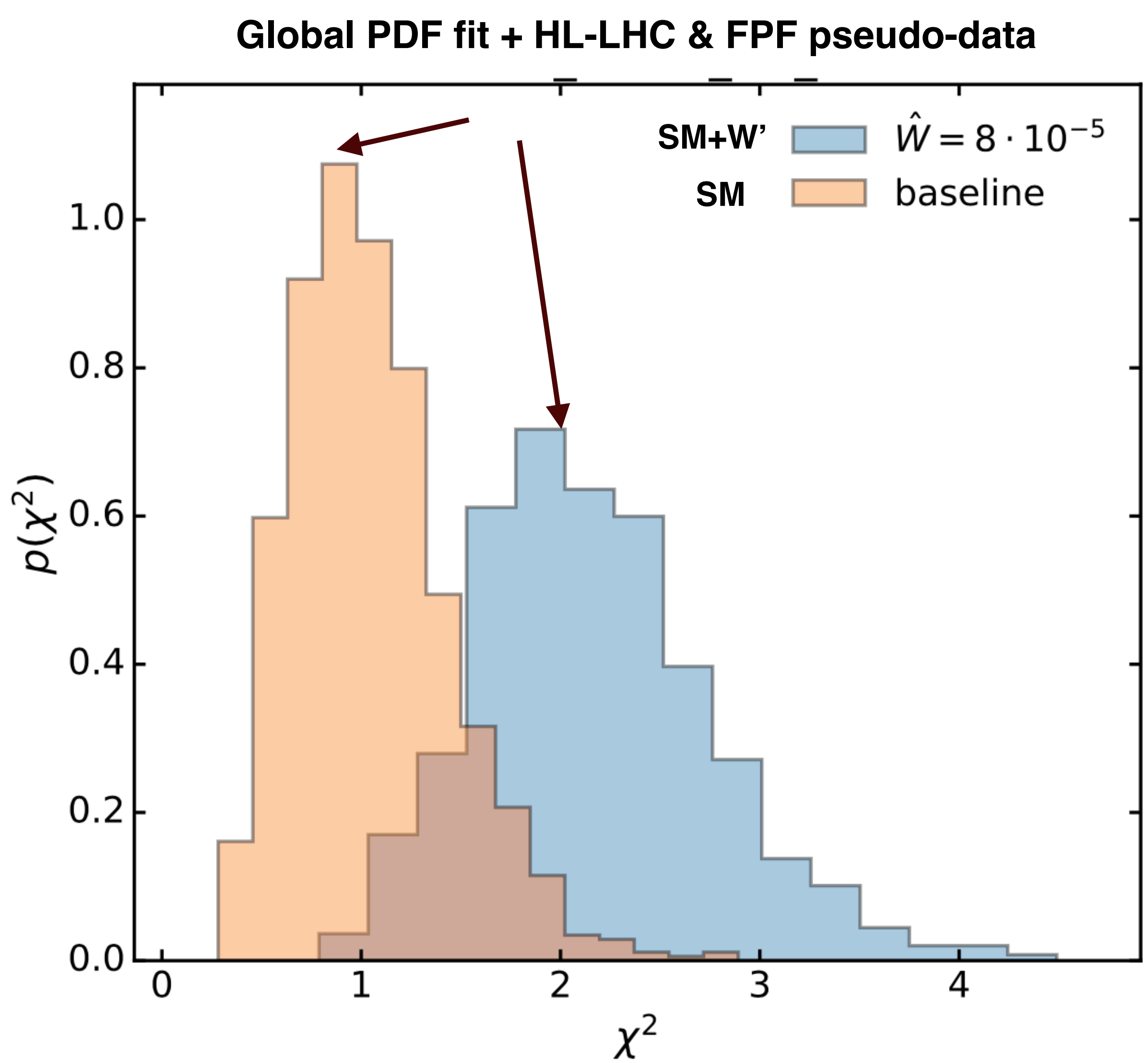


Hammou, Madigan, Mangano, Mantani, Morales, Ubiali, 2307.10370

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**





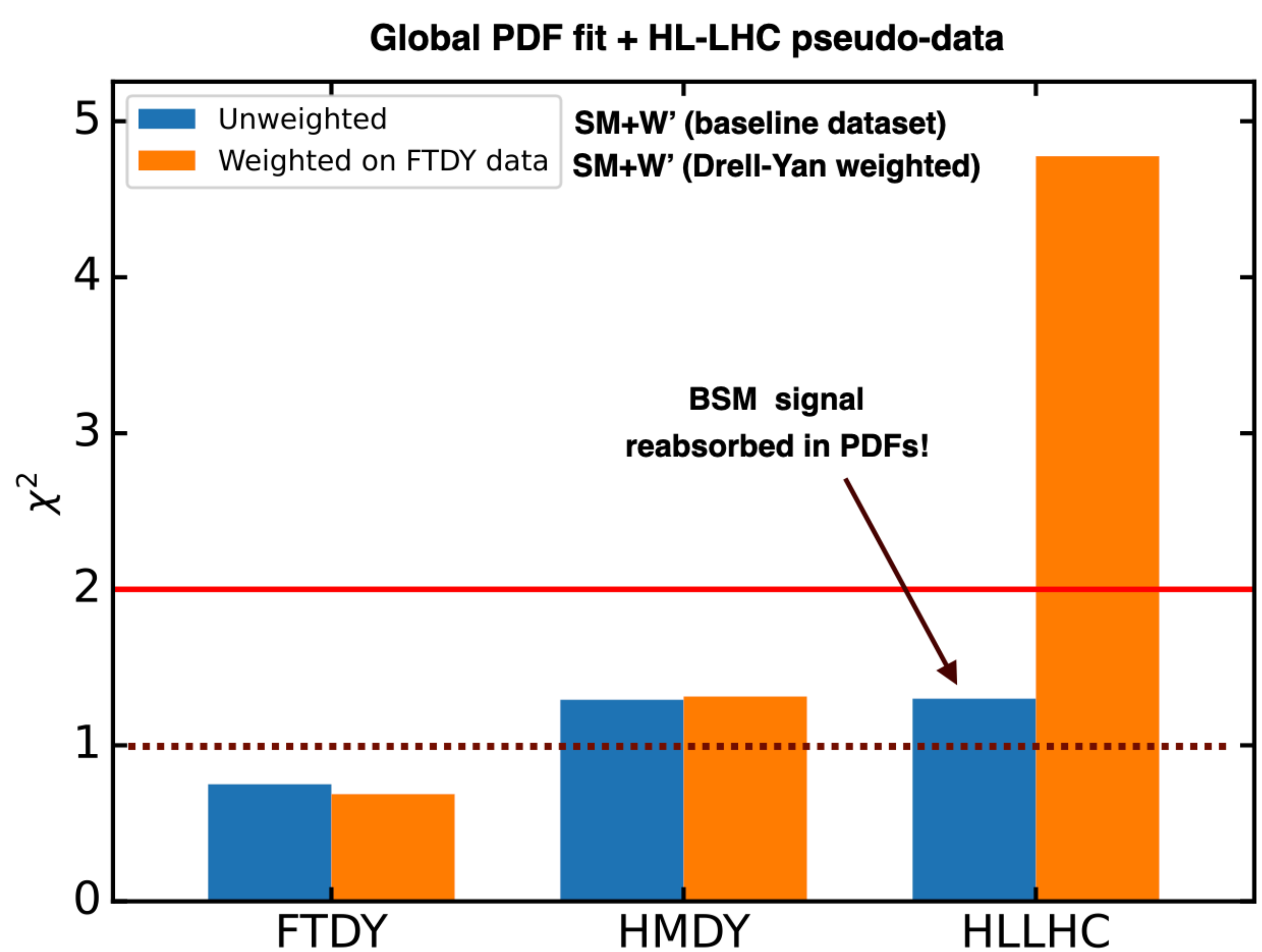
Hammou, Madigan, Ubiali, **WIP**

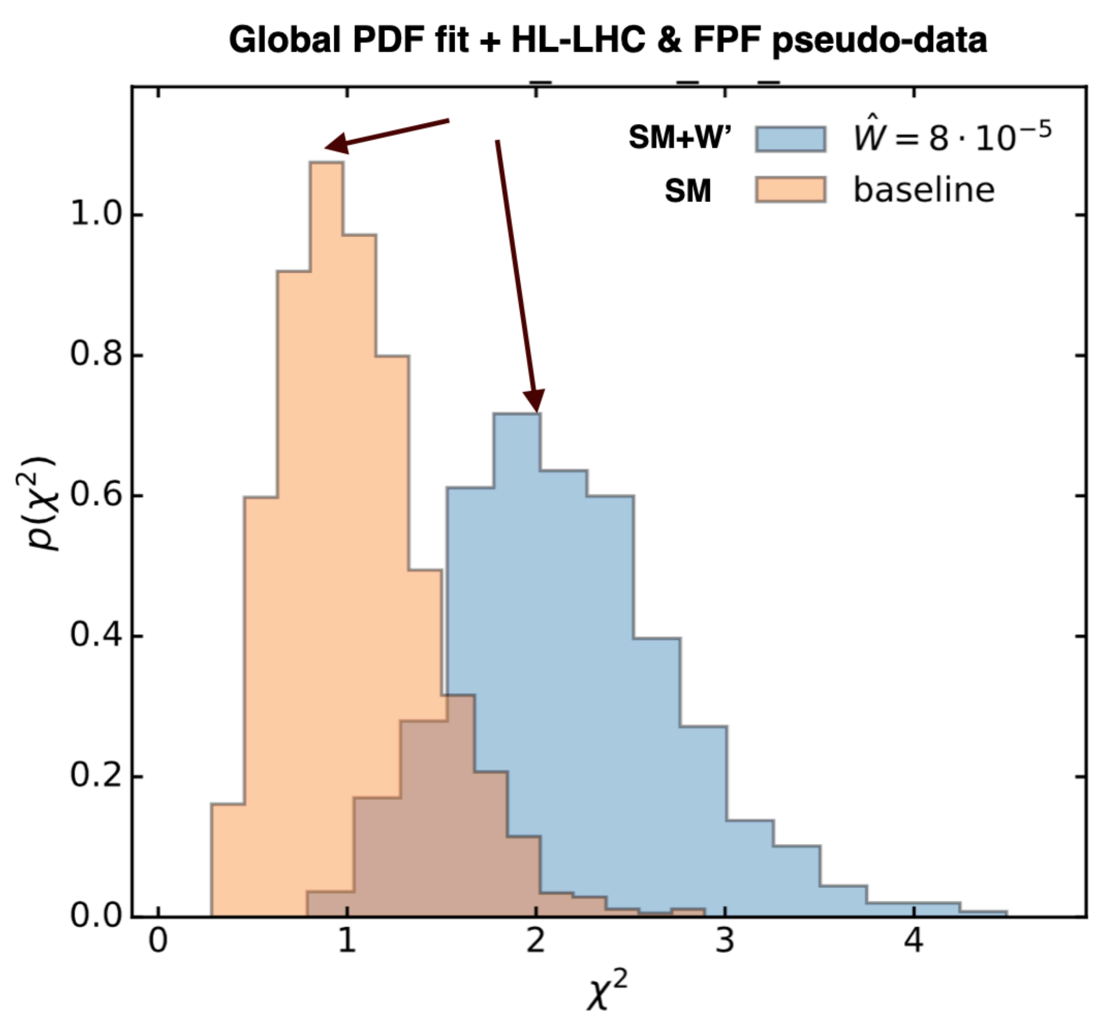
Summary and outlook (now for real!)

- Neutrino DIS at the FPF is not only interesting because it constrains the PDFs: it does so at **much lower energies** than (HL-)LHC constraints in large-x PDFs

- Availability of FPF data prevents the possible BSM contamination of PDF fits including HL-LHC data: cleanly **disentangle possible degeneracies** between QCD/PDF and BSM effects in LHC processes

- Further highlights unique potential of the FPF as a **cost-effective auxiliary experiment** to boost the physics reach of the HL-LHC program

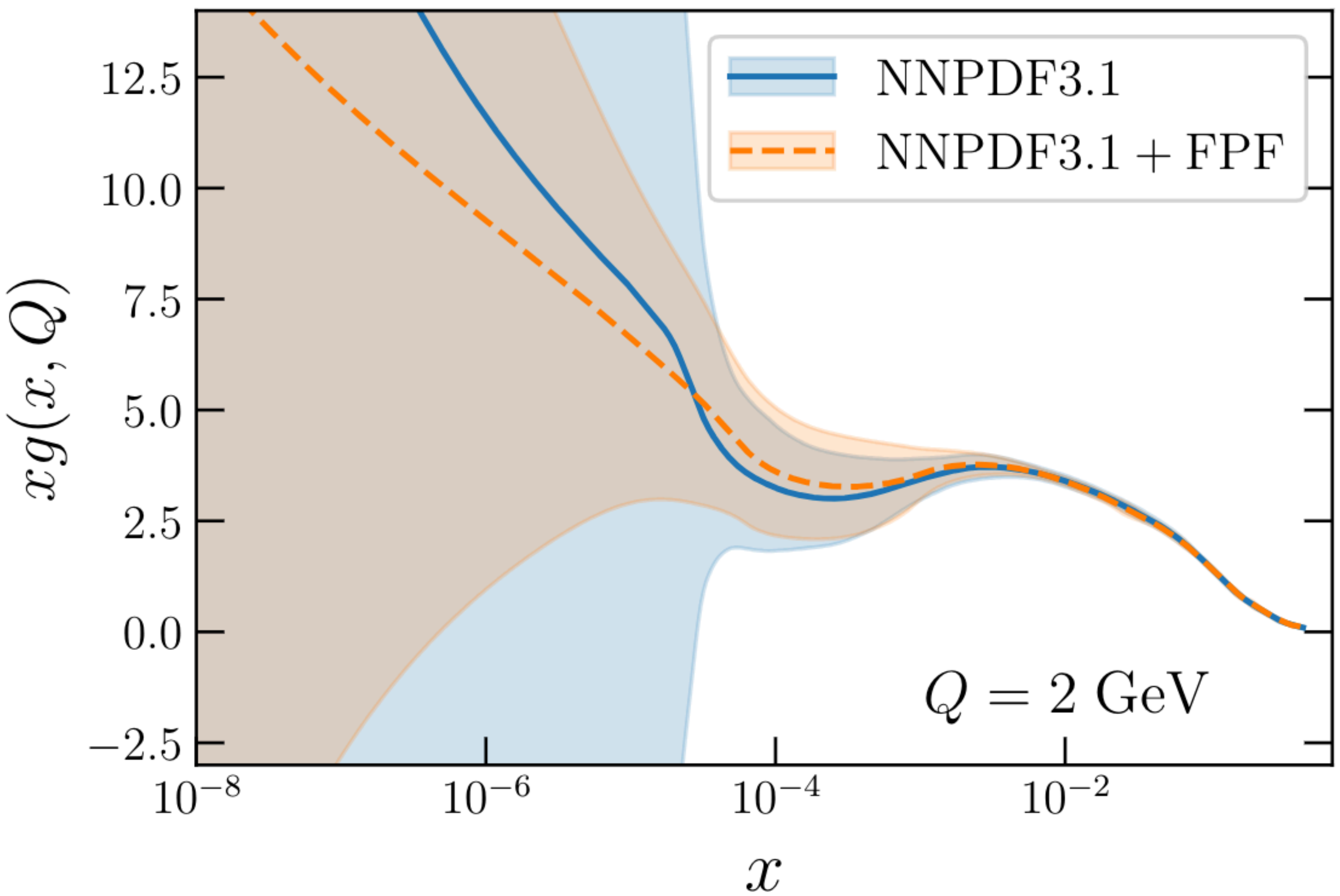




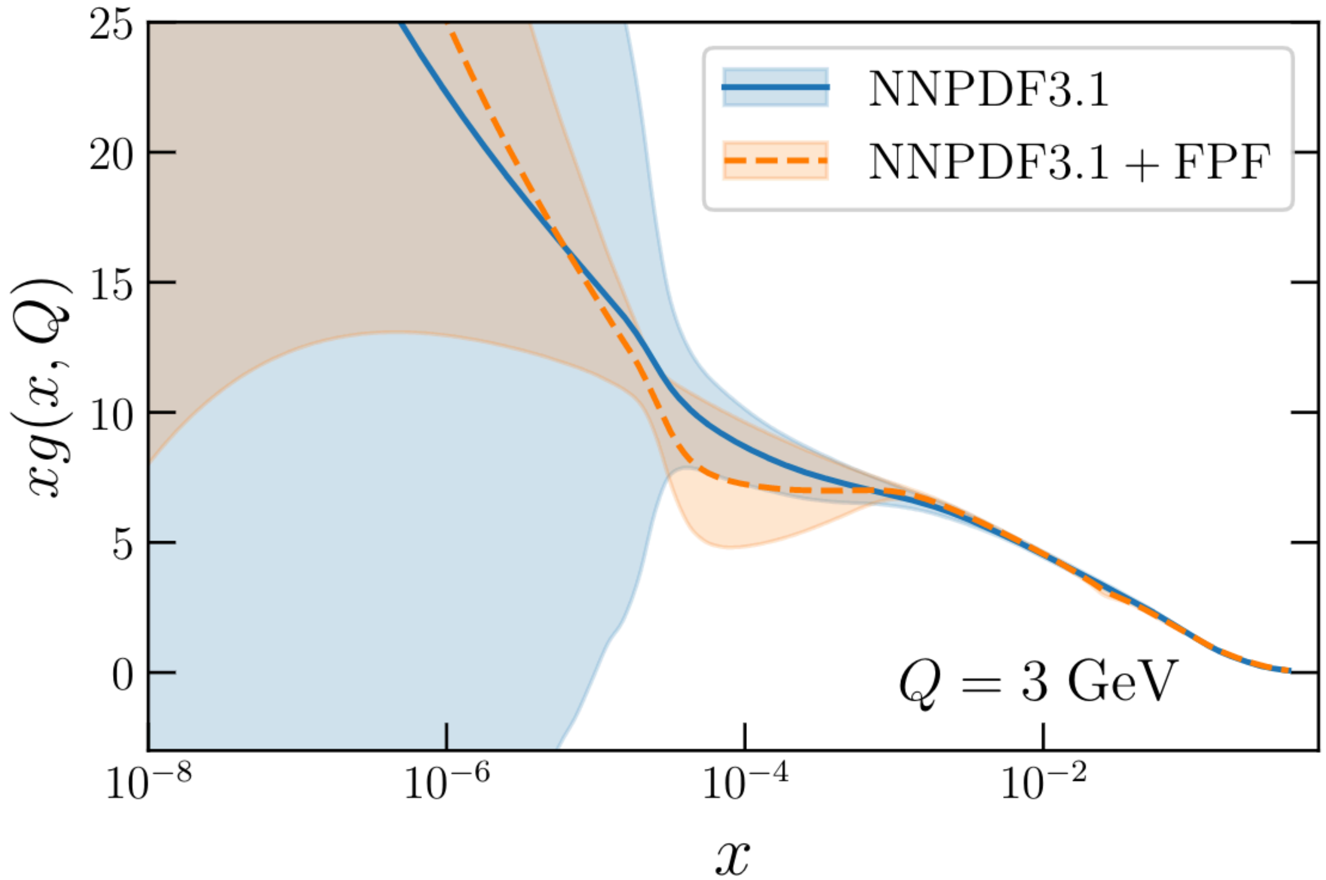
Extra Material

LHC neutrinos and FCC-pp

Electron neutrinos, 2% uncertainty in inclusive event rates



Tau neutrinos, 2% uncertainty in inclusive event rates

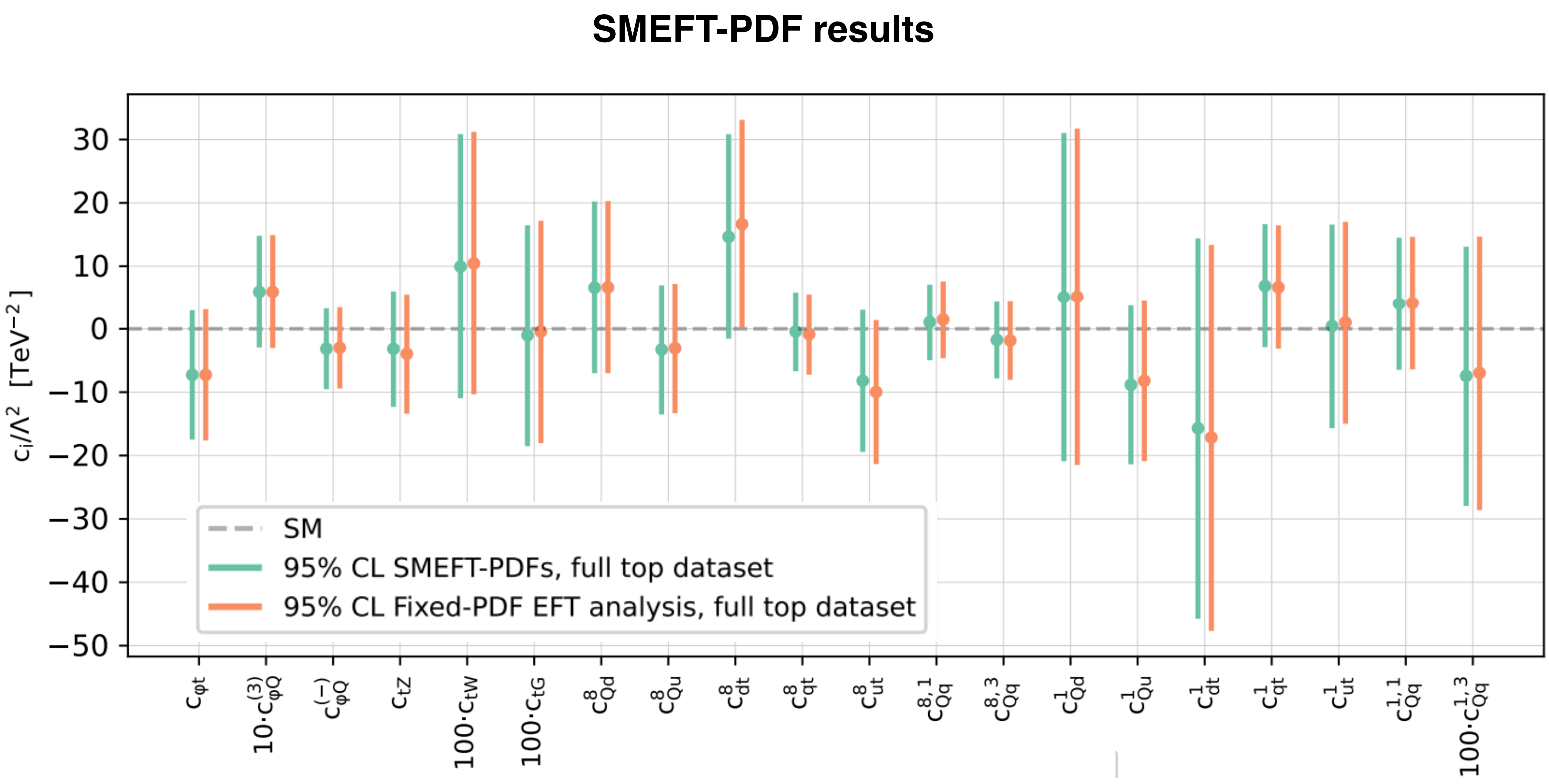


$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$

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

- Sensitivity to **small-x gluon** outside coverage of any other (laboratory) experiment
- Extend to full-fledged simulations with state-of-the-art QCD

SMEFT PDFs from top quark data



Despite differences between SMEFT-PDFs and SM-PDFs, **bounds on EFT coefficients stable**

PDF dependence **does not seem to affect** (for current data) EFT interpretations of top data