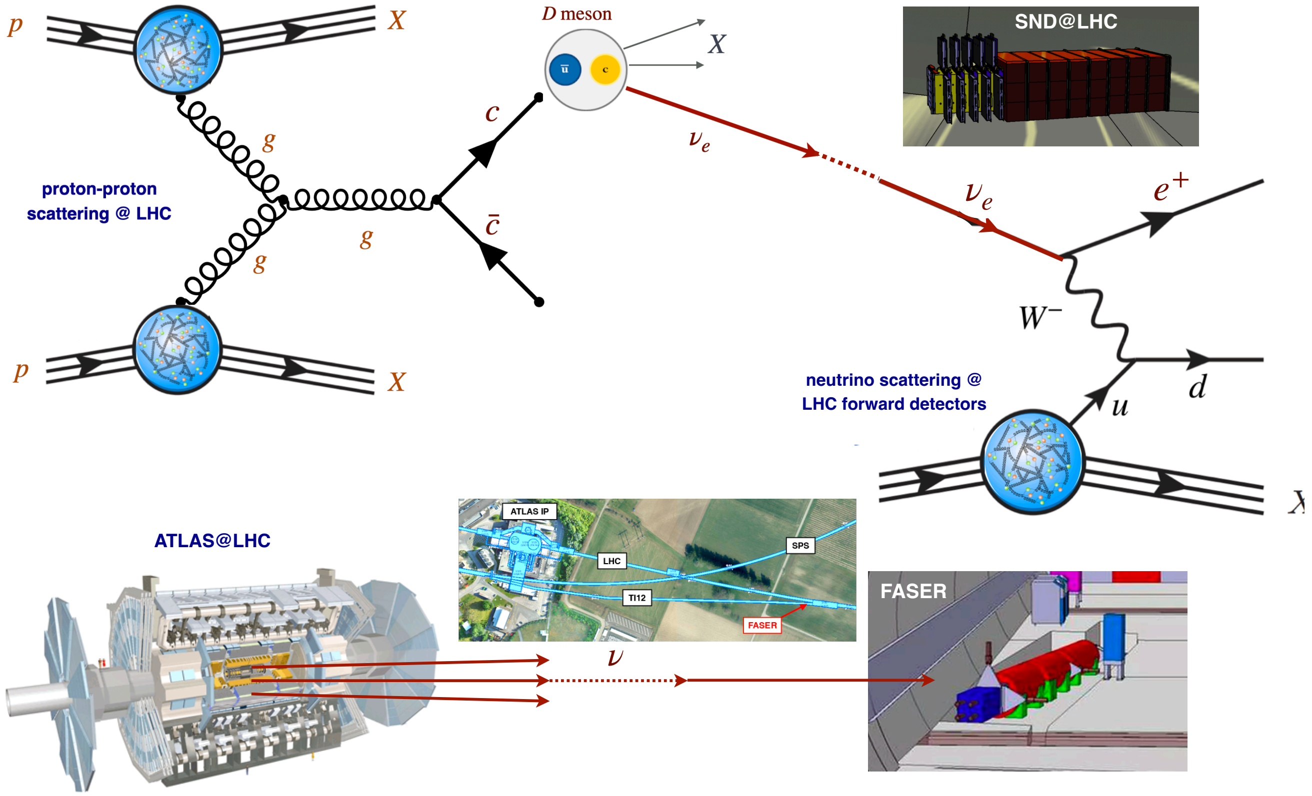
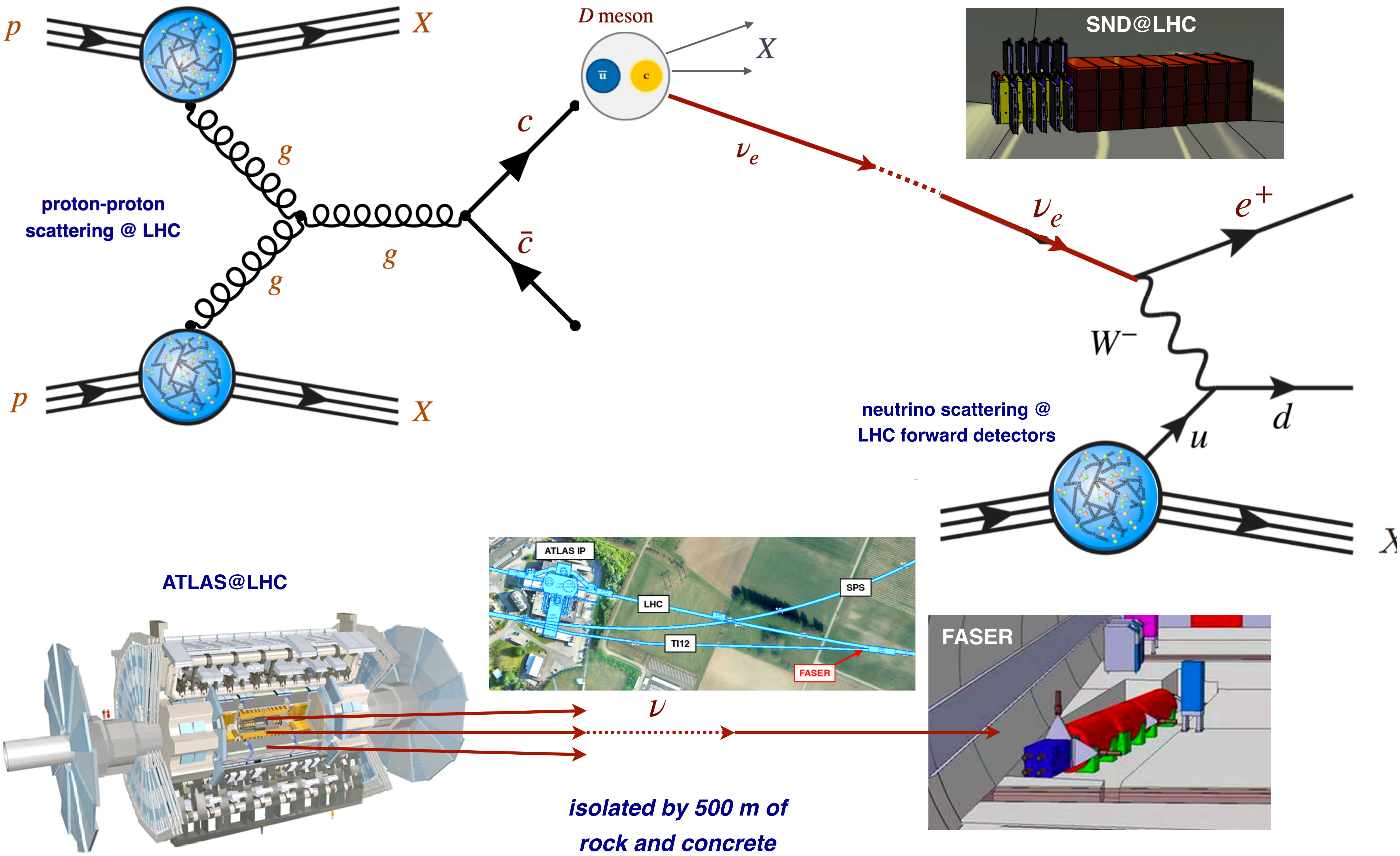
Requirements for Experiments: SM physics (QCD, neutrinos, astroparticle physics)

Juan Rojo, VU Amsterdam & Nikhef



FPF Convener Meeting, 09.11.2023

QCD Studies with LHC neutrinos



proton-proton scattering @ LHC

SND@LHC

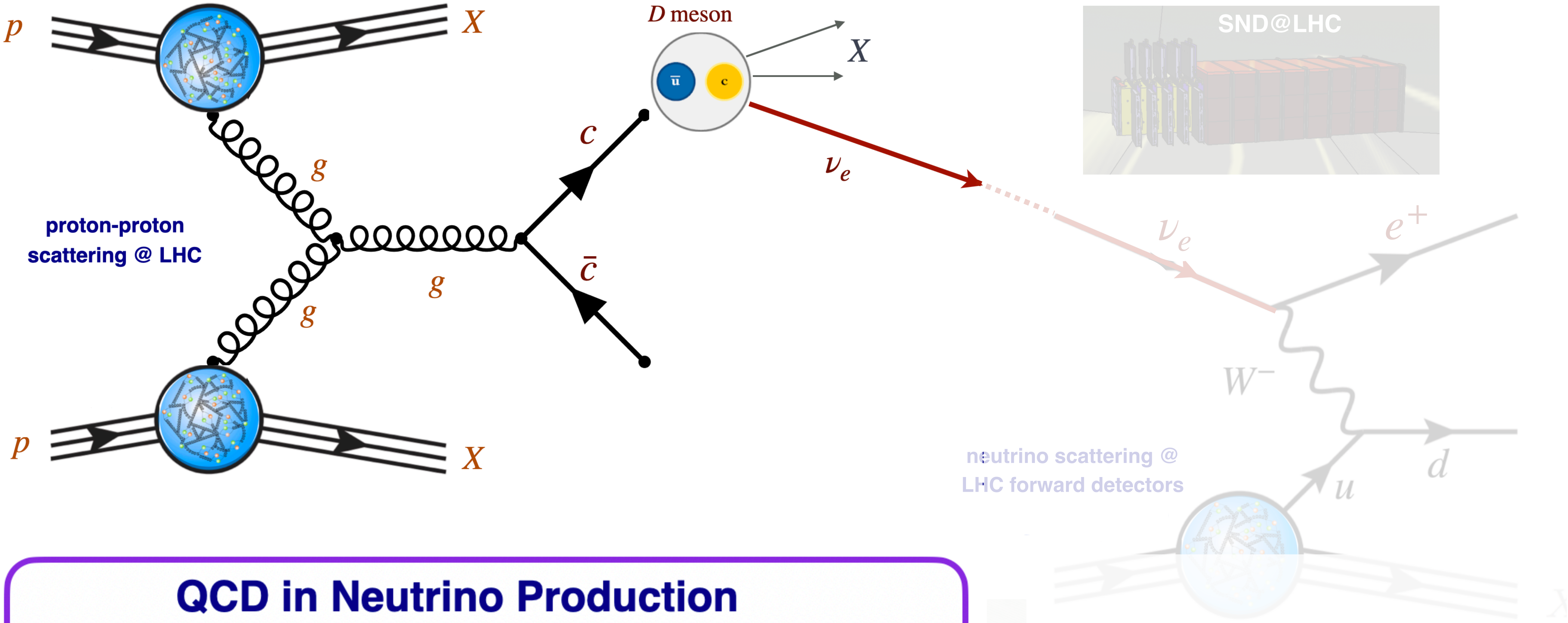
neutrino scattering @ LHC forward detectors

ATLAS@LHC

FASER

isolated by 500 m of rock and concrete

QCD Studies with LHC neutrinos

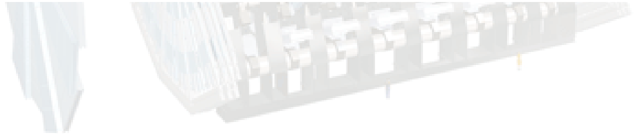


proton-proton scattering @ LHC

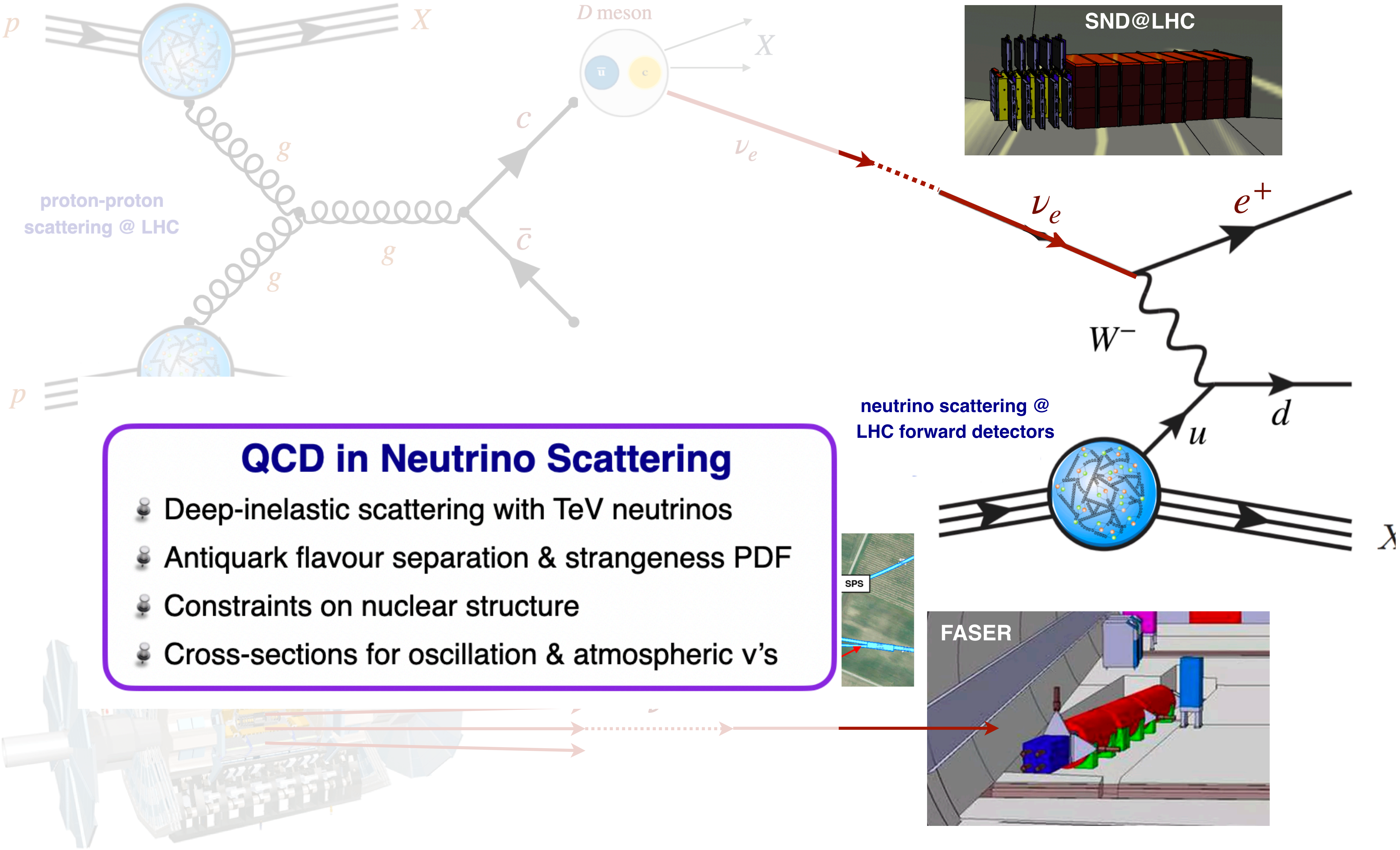
neutrino scattering @ LHC forward detectors

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



QCD Studies with LHC neutrinos



QCD in Neutrino Scattering

- Deep-inelastic scattering with TeV neutrinos
- Antiquark flavour separation & strangeness PDF
- Constraints on nuclear structure
- Cross-sections for oscillation & atmospheric ν's

The FPF Master Formula

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

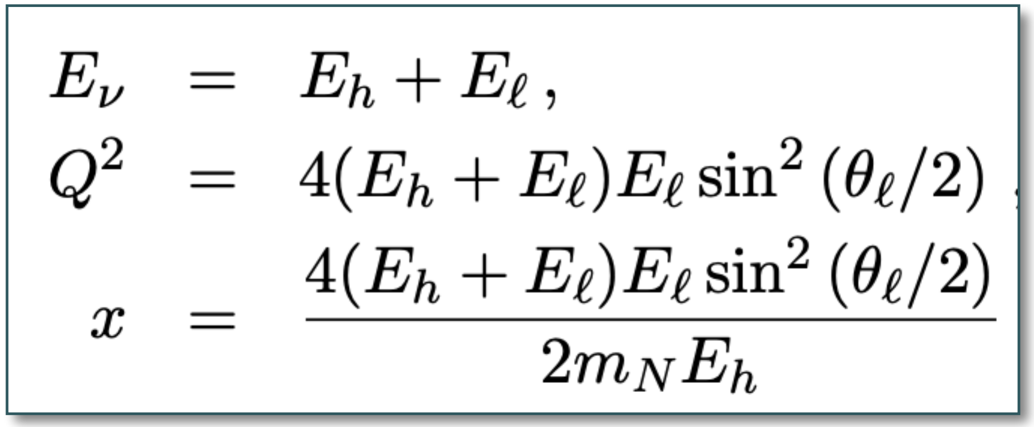
Binning

neutrino fluxes (include rapidity coverage)

DIS differential cross-section

Acceptance

- **Measured event rates** are primarily determined by detector geometry and acceptance
- Each detector covers a given rapidity range, hence receives a **different effective neutrino flux**
- *Trivial* increase in event rates by making the detector **deeper** (L_T) or **broader** (increasing effective fluxes)



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

Which of these parameters can be optimised for **specific physics targets?**

The FPF Master Formula

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

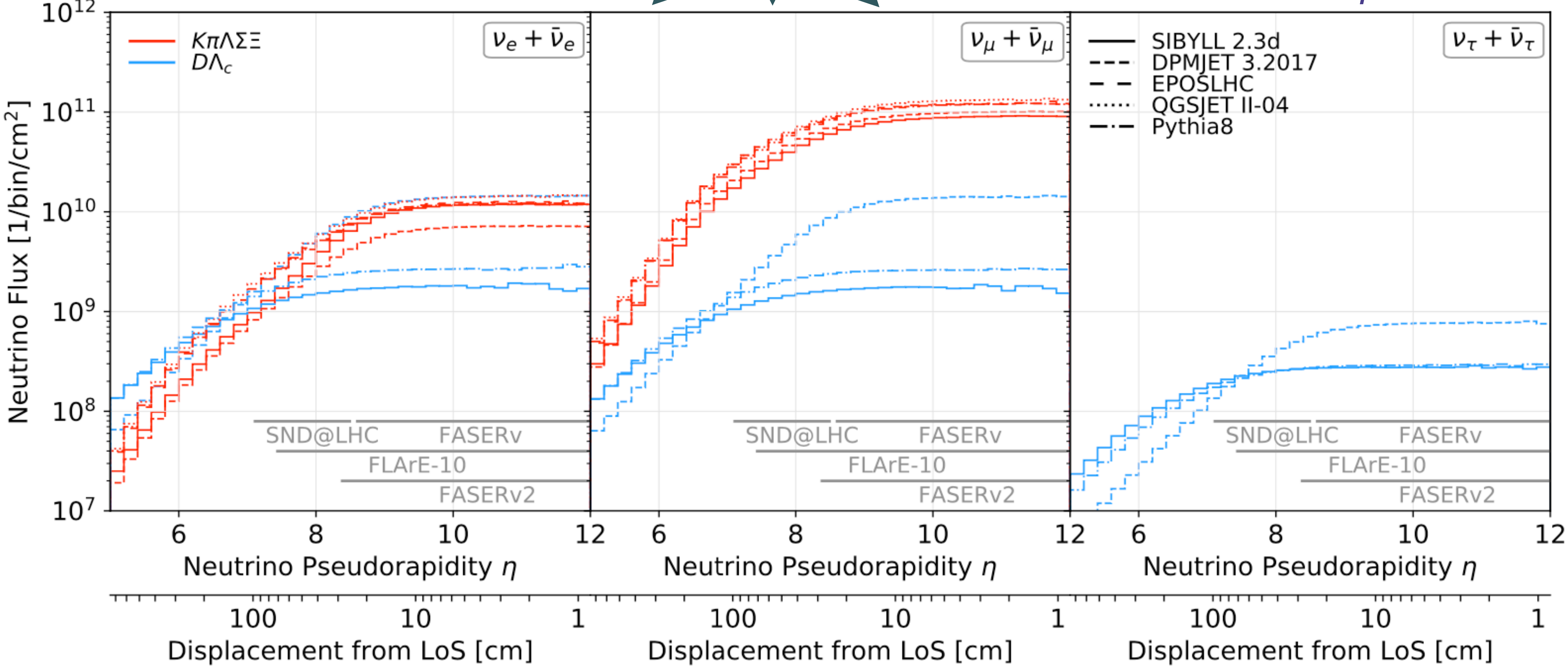
Binning

neutrino fluxes (include rapidity coverage)

DIS differential cross-section

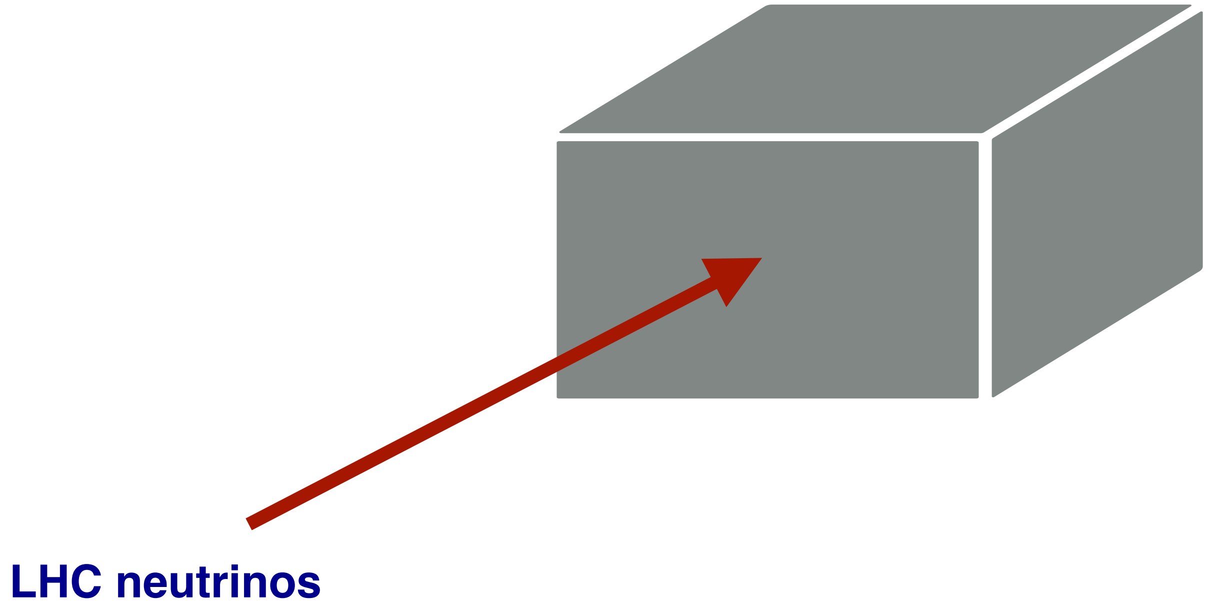
Acceptance

Rapid decrease of flux towards less forward rapidities



Experimental handles on physics targets

Start from a baseline FPF detector: which handles can you play with to **enhance physics reach?**



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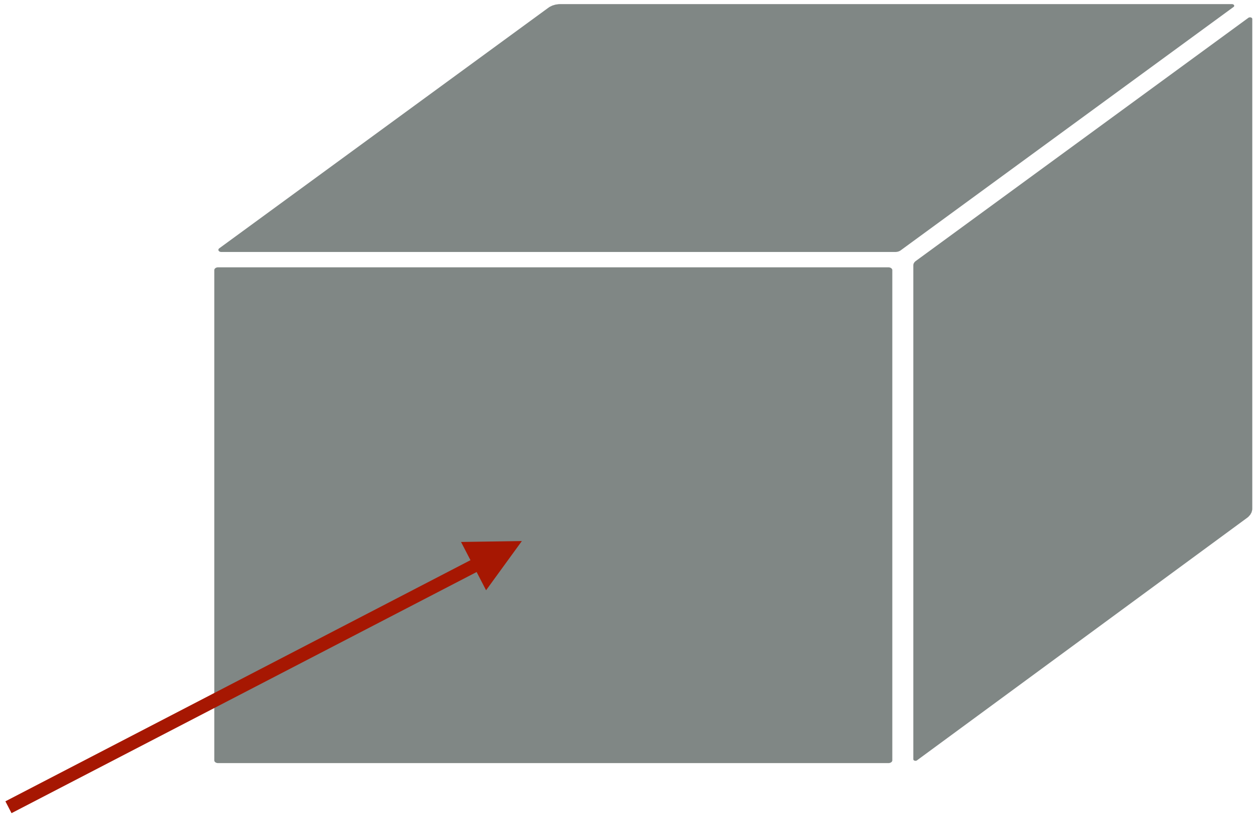


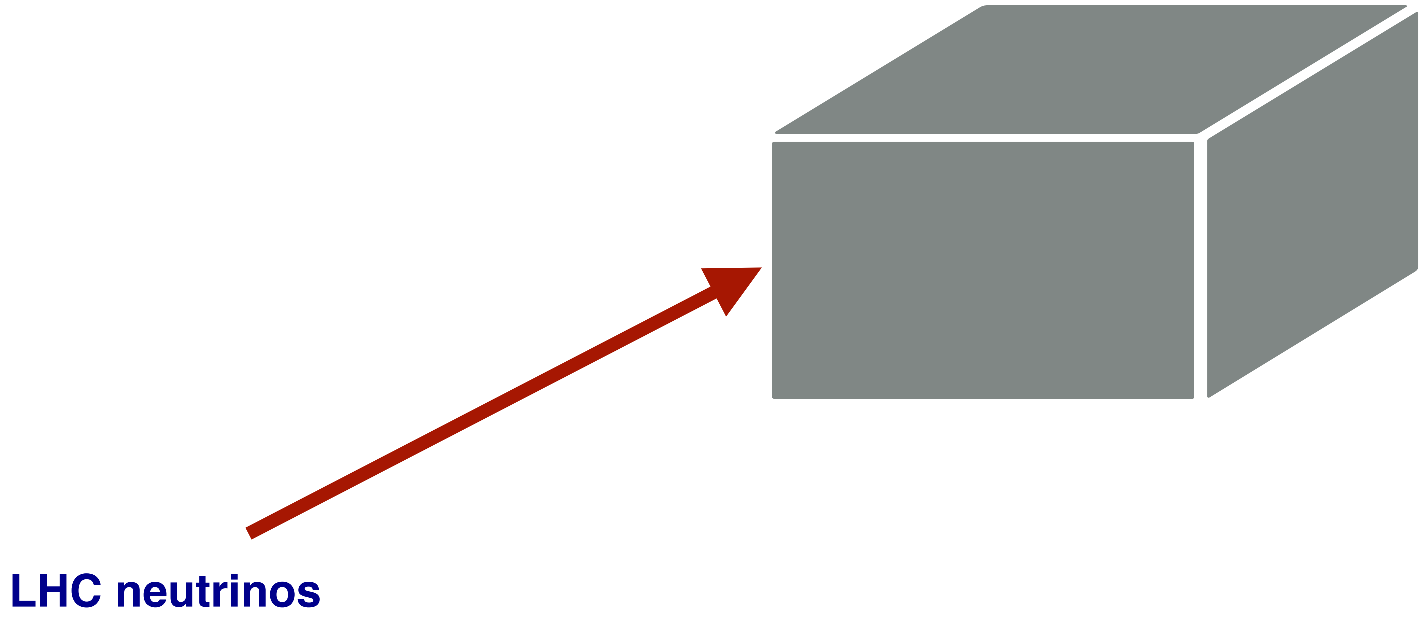
LHC neutrinos

you can make it bigger, to **increase event rates**

actually, the only thing you need is to make it **deeper** (if total event rates is all you care about)

Experimental handles on physics targets

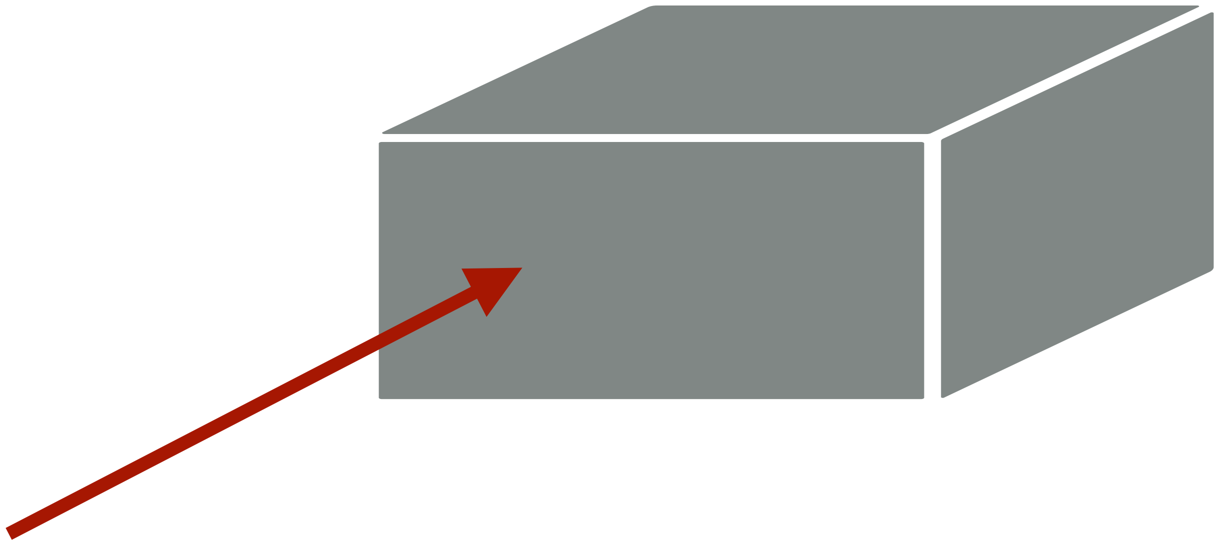
Start from a baseline FPF detector: which handles can you play with to **enhance physics reach?**



you can shift it **off axis** to cover a different region of **neutrino rapidity**

Experimental handles on physics targets

Start from a baseline FPF detector: which handles can you play with to **enhance physics reach?**



LHC neutrinos

you can shift it **off axis** to cover a different region of **neutrino rapidity**

actually, you can achieve the same with a **broader (one sided), on-axis detector**

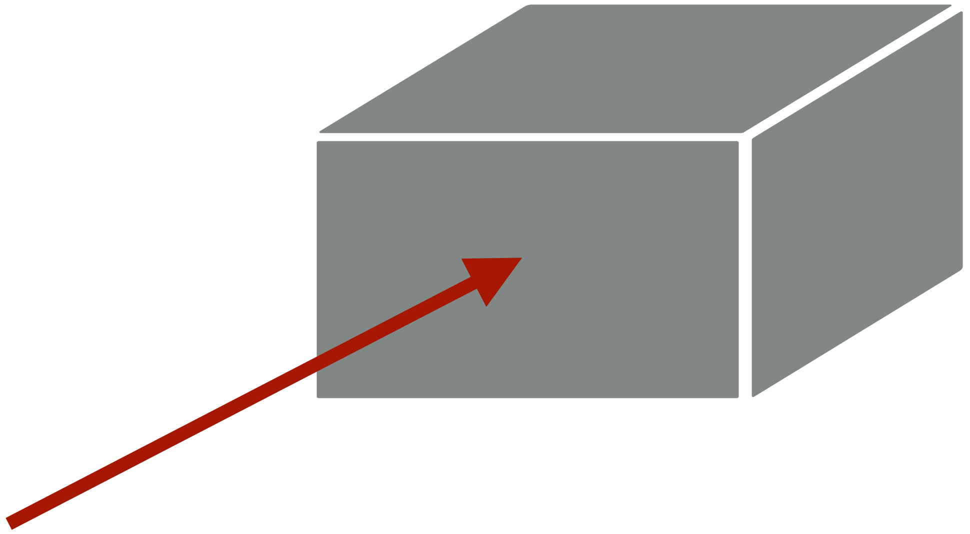
(provided you have sufficient granularity to **tell apart neutrinos with different rapidities**)

$$\frac{dN_{\rm ev}^{e,\mu,\tau}(E_\nu, y_\nu)}{dE_\nu dy_\nu}$$

All information about production encoded in this double differential cross-section!

Experimental handles on physics targets

Start from a baseline FPF detector: which handles can you play with to **enhance physics reach?**



LHC neutrinos

For the same geometry, improve **its performance** by

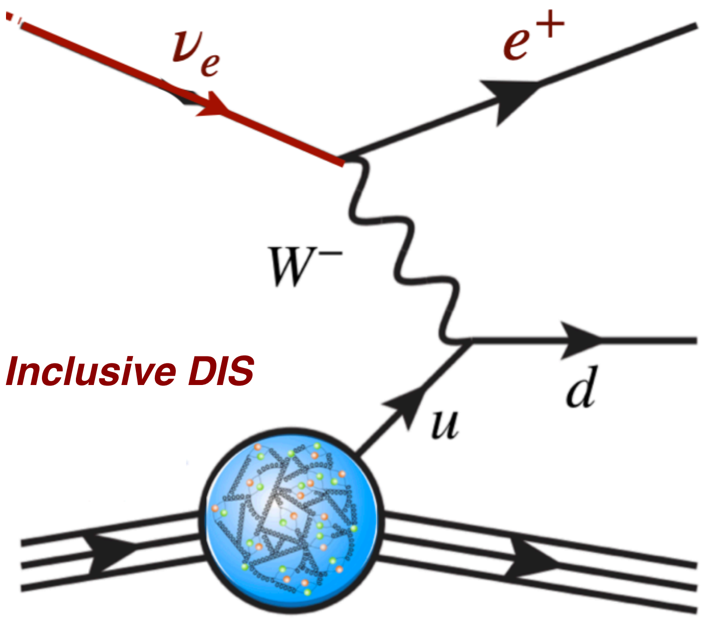
- Reduce systematic errors on **charged-lepton energy and scattering angle** and **hadronic energy** as much as possible (limiting factor for physics at the FPF)
- Better reconstruct **hadronic final state** (exclusive measurements), in particular **charm-tagging**
- Improve granularity so that **double differential event-rate measurements** in (Enu, ynu) within a single detector as possible

Detector optimisation depends on physics targets

SM physics in neutrino scattering

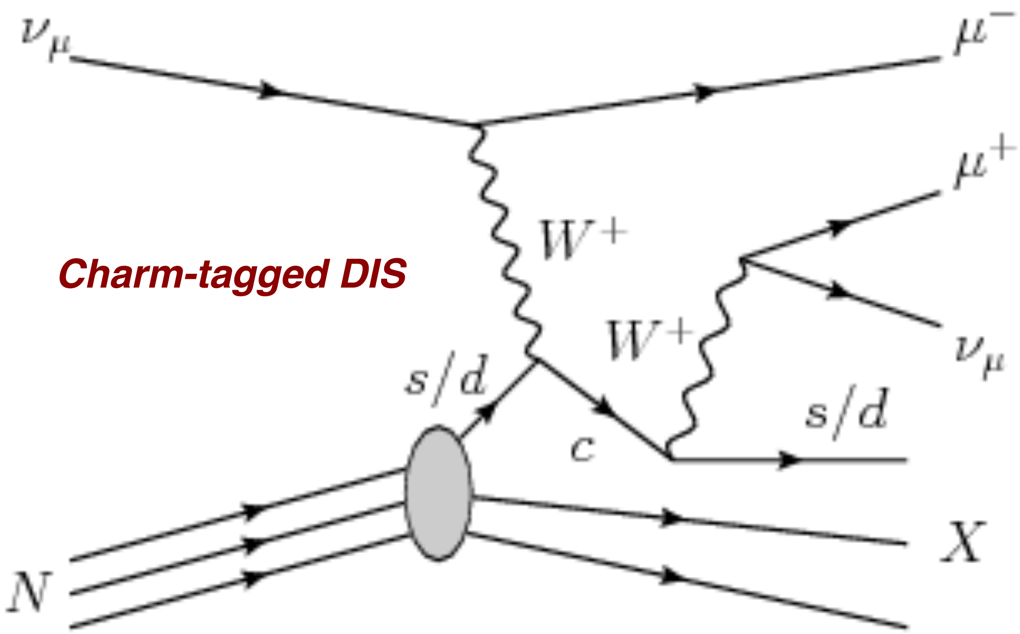
Integrated event rates for DIS kinematics for **inclusive (charm-tagged)** production

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	LoS	116k (17k)	56k (9.9k)	170k (27k)	380k (53k)	133k (23k)	510k (76k)
AdvSND-far	off-LoS	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	LoS	290k (35k)	130k (19k)	420k (54k)	440k (60k)	232k (30k)	670k (90k)



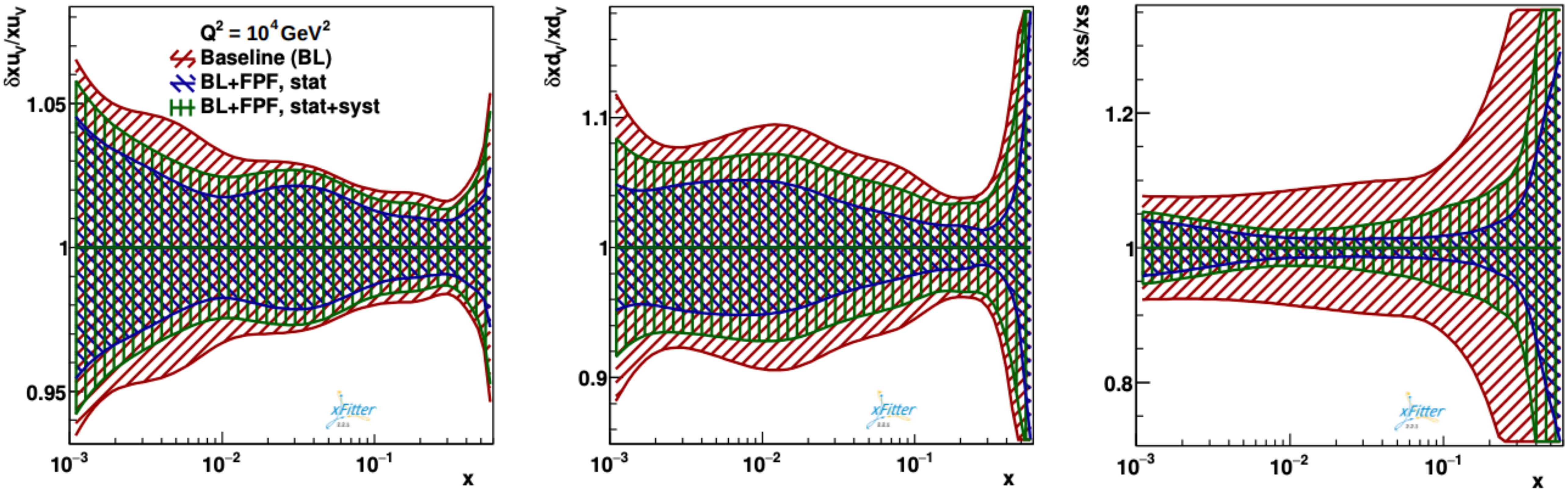
Inclusive DIS

- 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

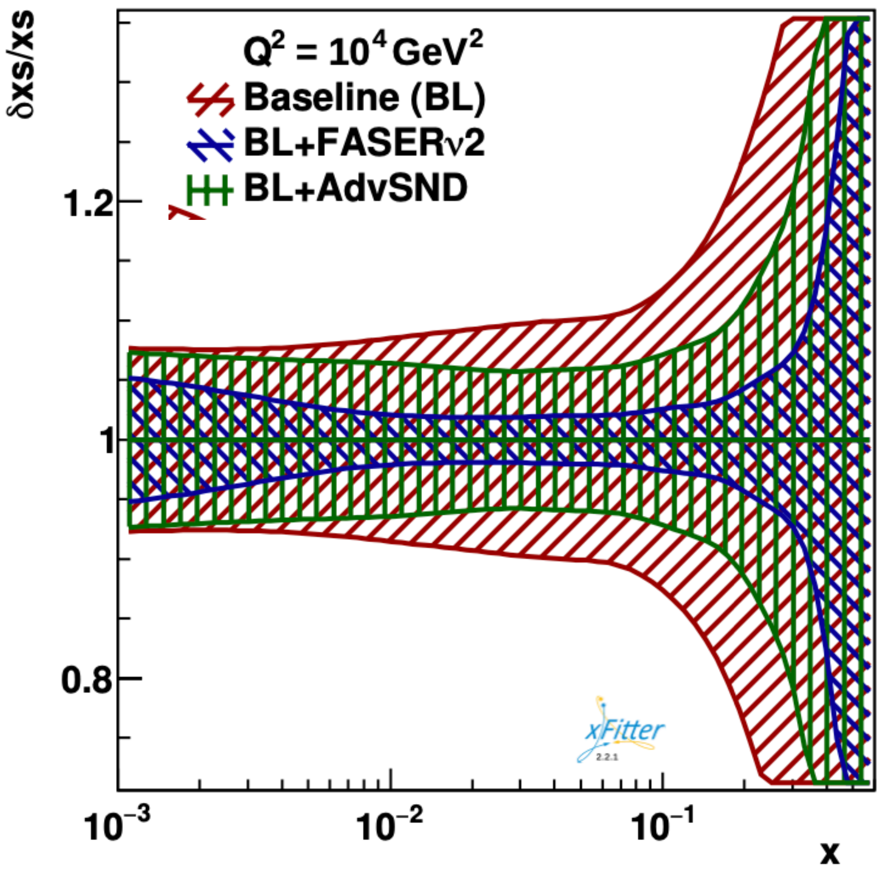
SM physics in neutrino scattering



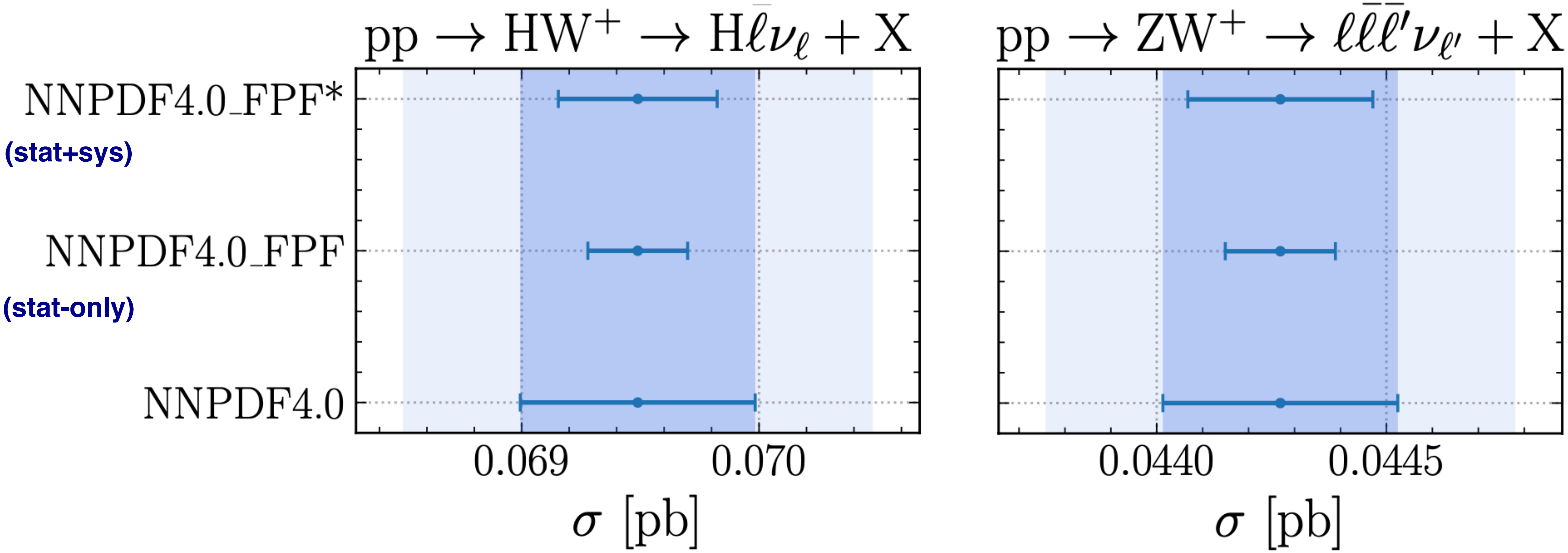
- Impact on proton PDFs quantified by the **Hessian profiling of PDF4LHC21** (xFitter) and by direct inclusion in the global **NNPDF4.0 fit**

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

- PDFs improved with LHC neutrino data **enhance precision HL-LHC measurements like *W* mass**

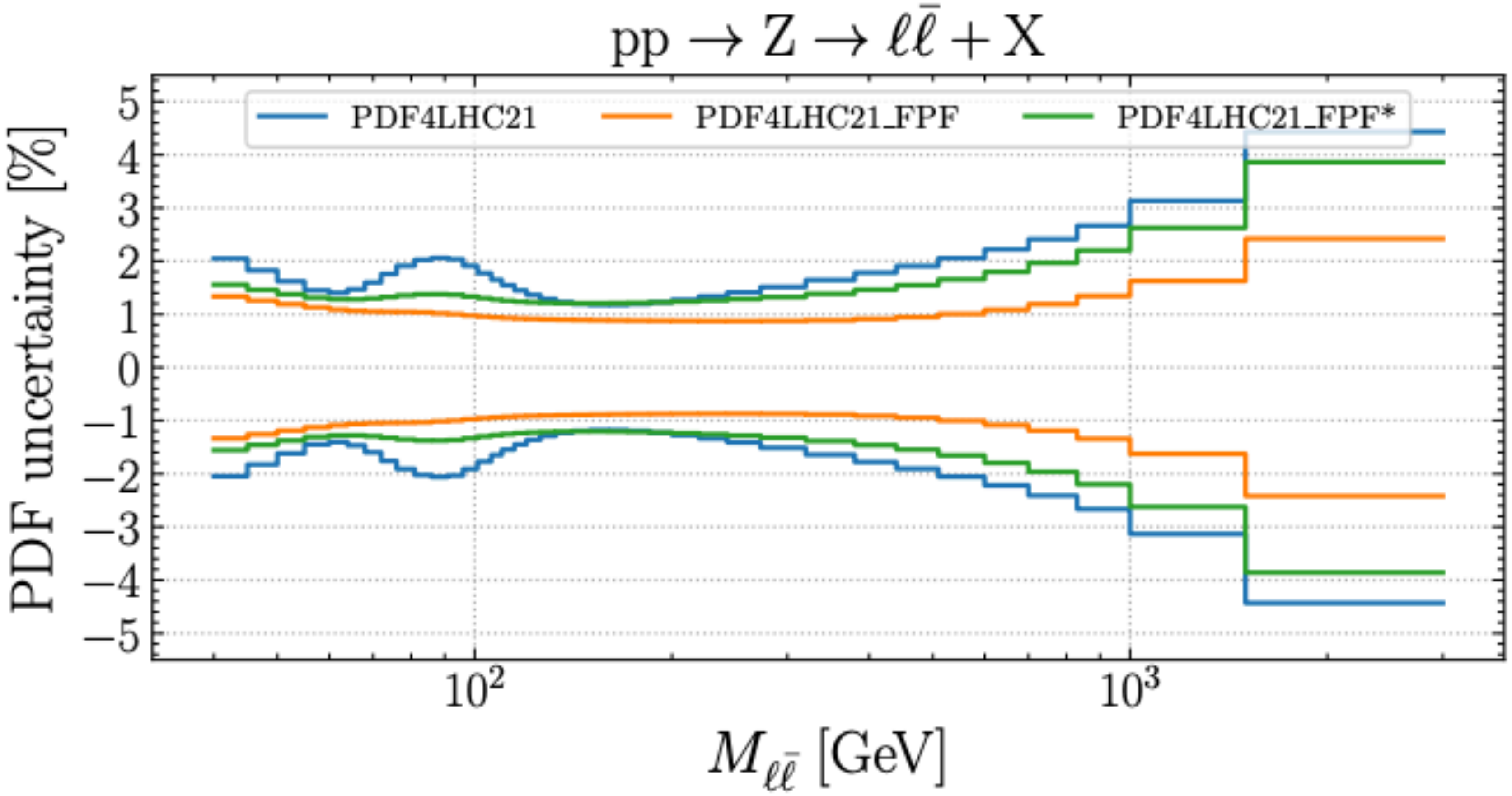


SM physics in neutrino scattering



(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

SM physics in neutrino scattering

- For physics applications related to **neutrino scattering,** what is relevant for detector design is
    - **Largest event rates** possible (central detector preferred)
    - Exclusive reconstruction of hadronic final state (& **charm-tagging**), incl **tau neutrinos**
    - Reduce **systematic errors** on final-state kinematic measurements as much as possible

- For physics applications related to **neutrino scattering,** what is **not relevant** is
    - Broad/different **rapidity coverage** (integrated out in event rates!)
    - High granularity on **neutrino energy**

QCD in Neutrino Scattering

- Deep-inelastic scattering with TeV neutrinos
- Antiquark flavour separation & strangeness PDF
- Constraints on nuclear structure
- Cross-sections for oscillation & atmospheric ν's

$$
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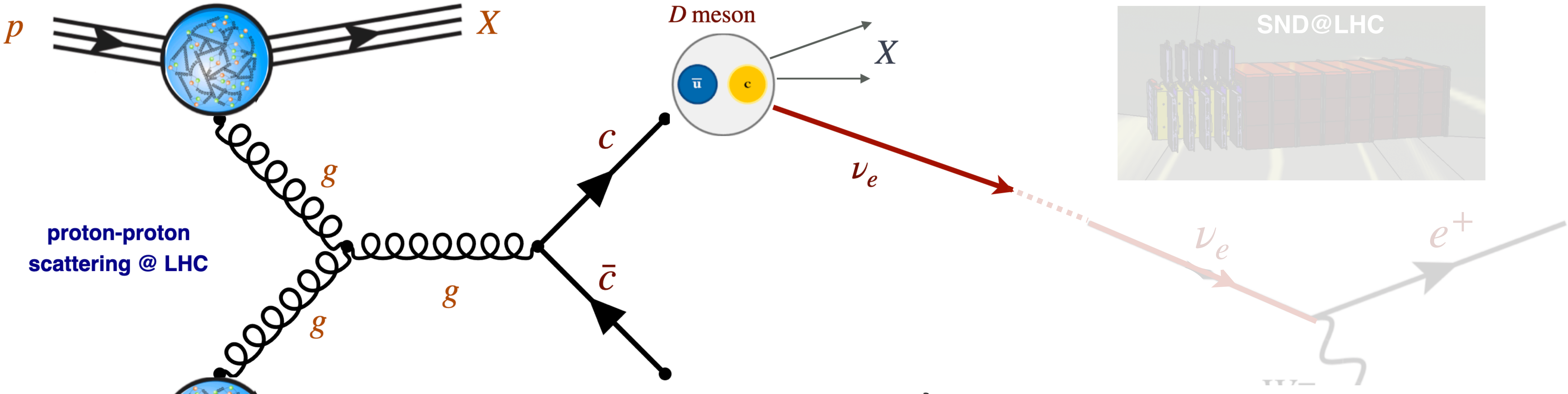
\end{aligned}
$$

SM physics in neutrino production



QCD in Neutrino Production

- Small-x gluon & large-x charm PDFs
- BFKL, non-linear QCD, cross-sections for UHE neutrinos
- *D*-meson fragmentation
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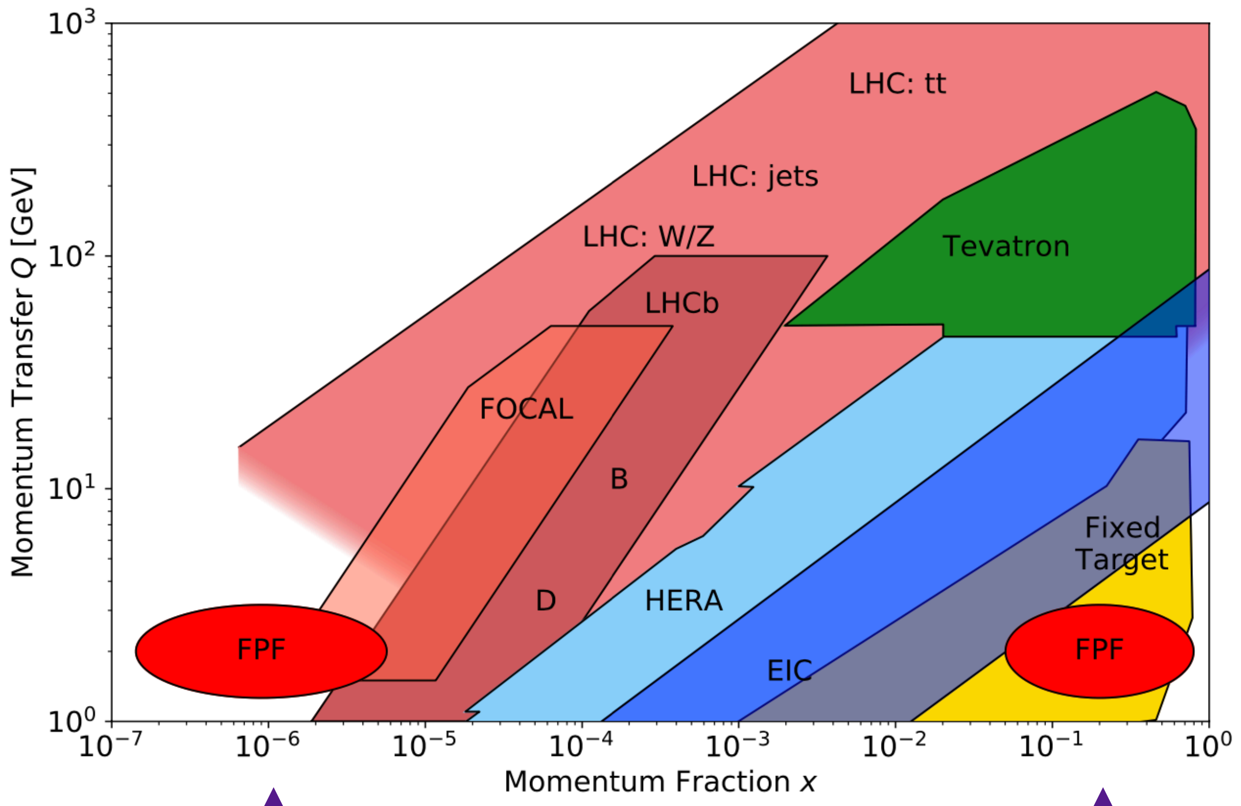


small-x gluon

large-x

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

SM physics in neutrino production

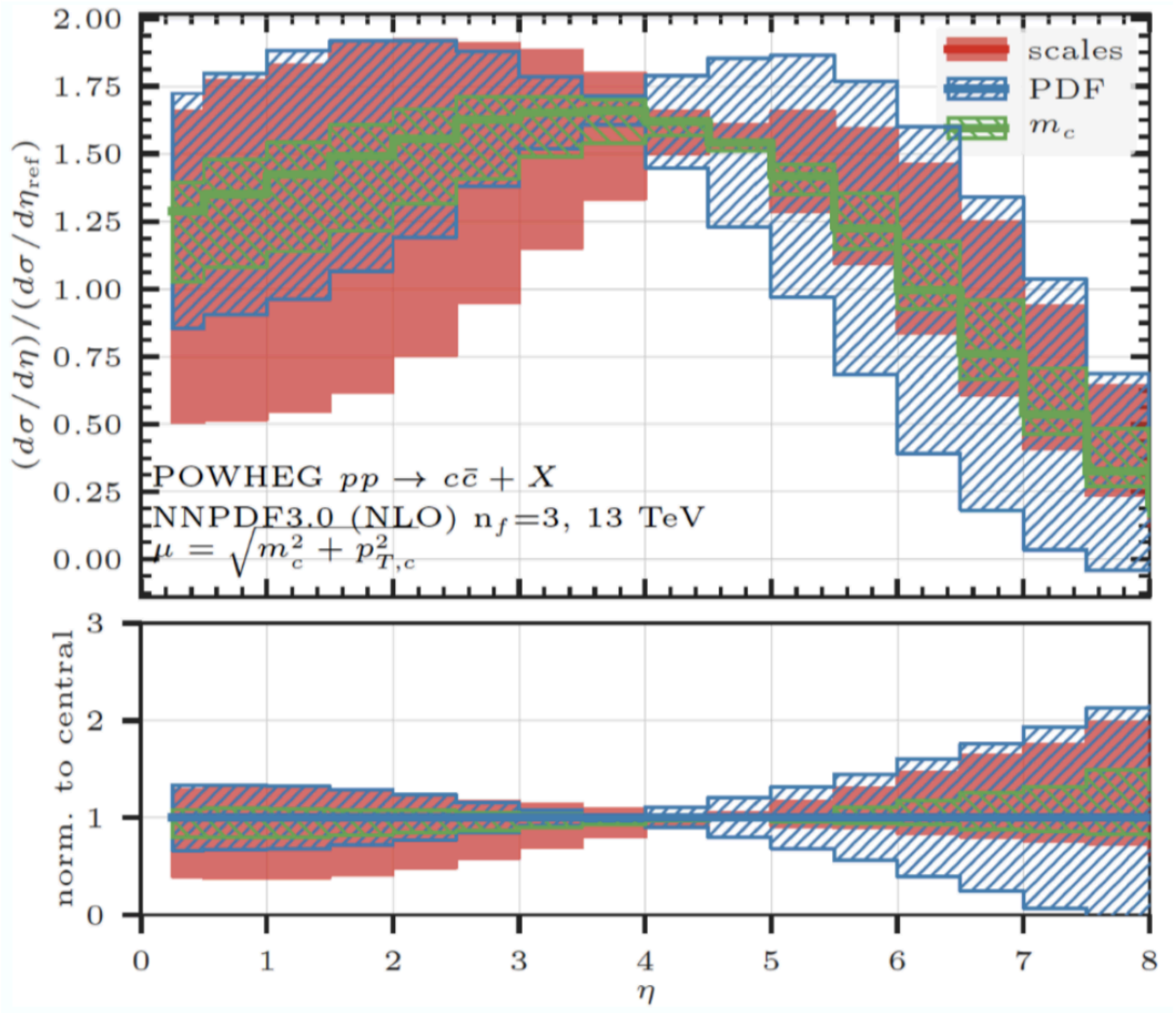
$$\frac{d^2\sigma(\mathrm{pp}\to D(\to\nu)+X)}{p_T^\nu y_\nu} \propto f_g(x_1,Q^2)\otimes f_g(x_2,Q^2)\otimes \frac{d^2\widehat{\sigma}(gg\to c\bar{c})}{p_T^c y_c}\otimes D_{c\to D}(z,Q^2)\otimes \mathrm{BR}(D\to\nu+X)$$

Extract from measured neutrino fluxes

Constrain from LHC neutrino data

QCD prediction: NLO + PS large theory uncertainties

QCD prediction/models + non-perturbative physics



Di Crescenzo, FPF6 workshop

- **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

SM physics in neutrino production

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

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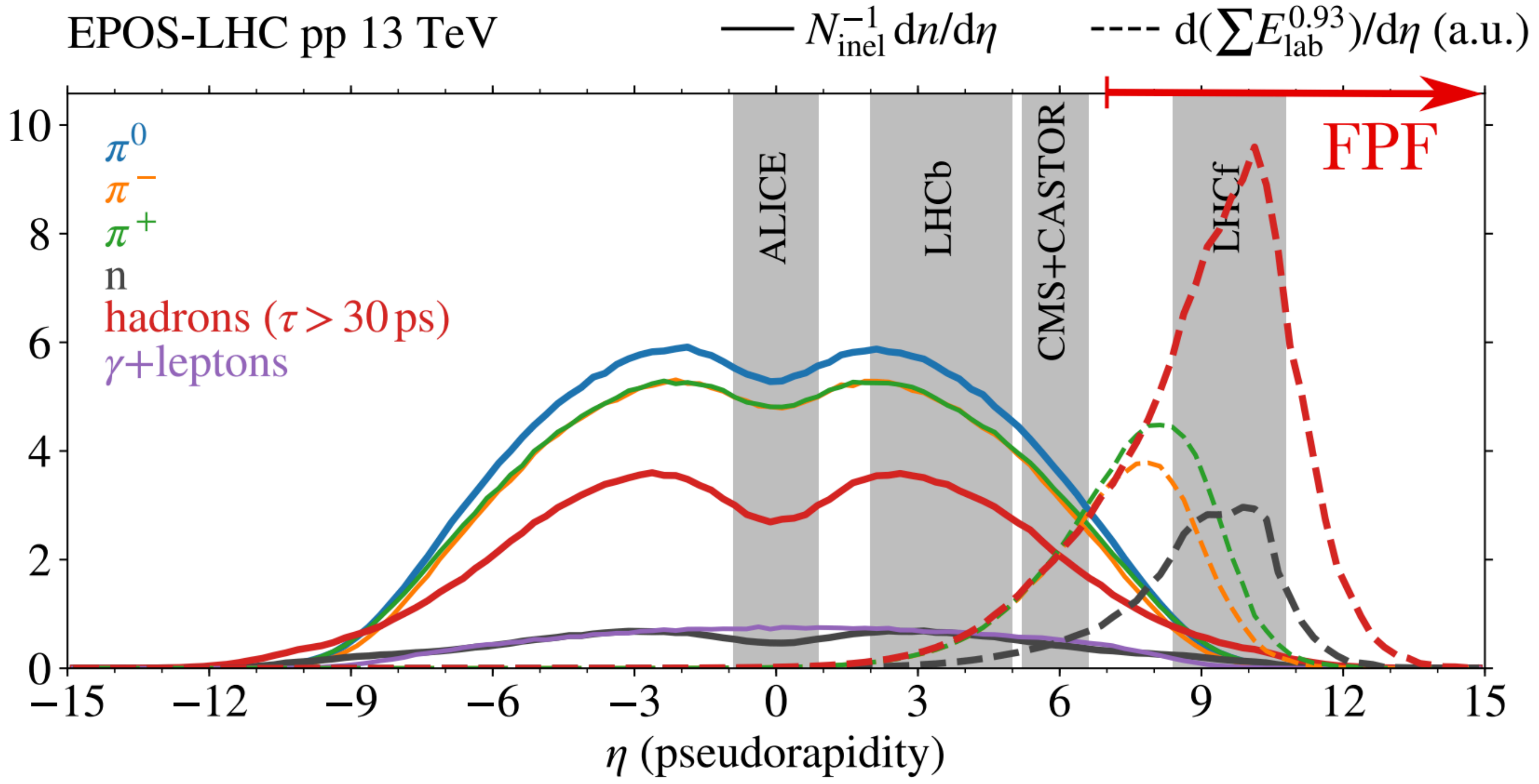
$$\frac{dN_{\mathrm{ev}}^{e,\mu,\tau}(E_\nu,y_\nu)}{dE_\nu dy_\nu}$$

The dependence of event rates in neutrino rapidity proves different Bjorken-x regions in light and heavy meson production

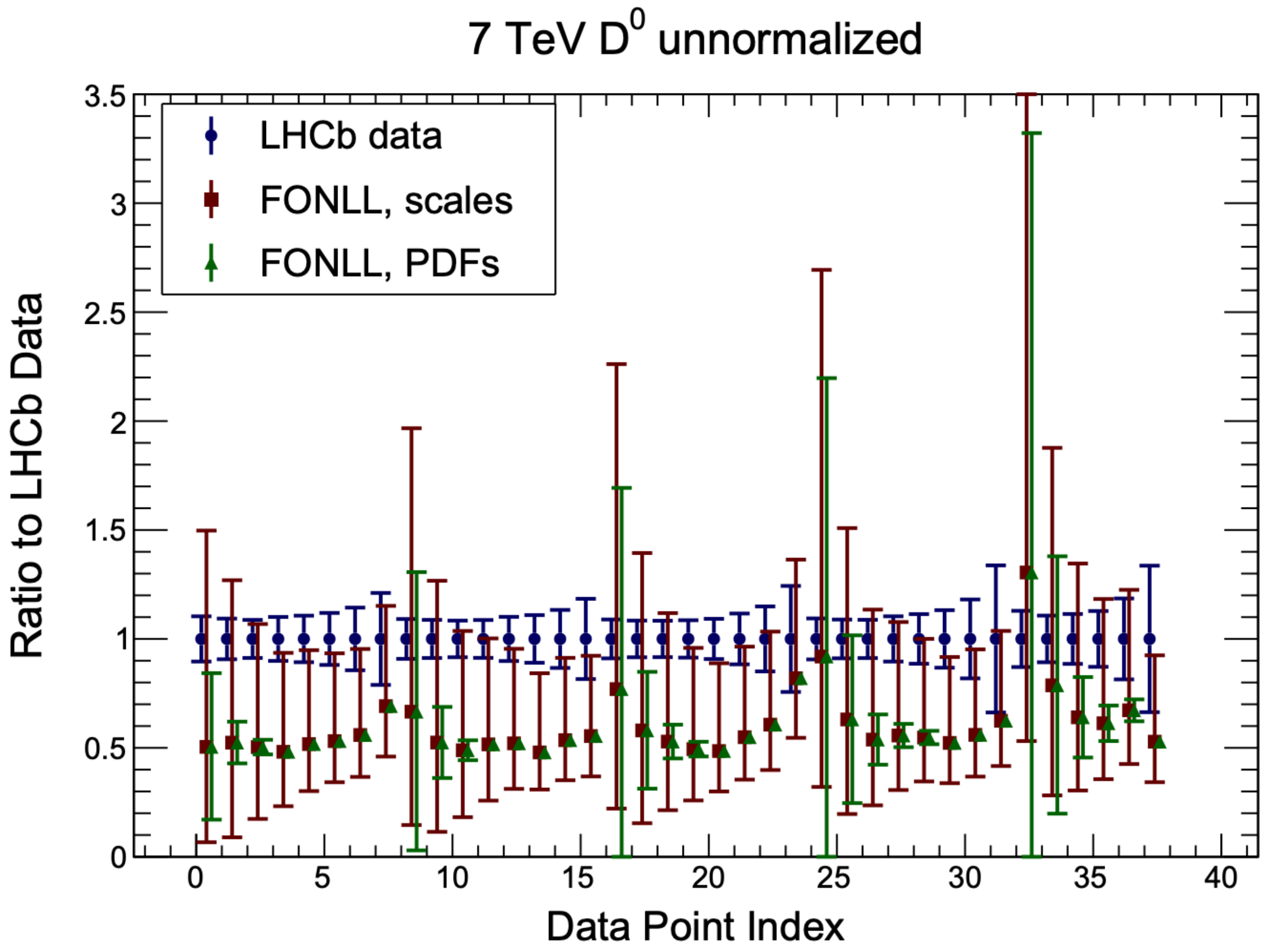


The dependence of event rates in neutrino rapidity key input for astroparticle physics applications

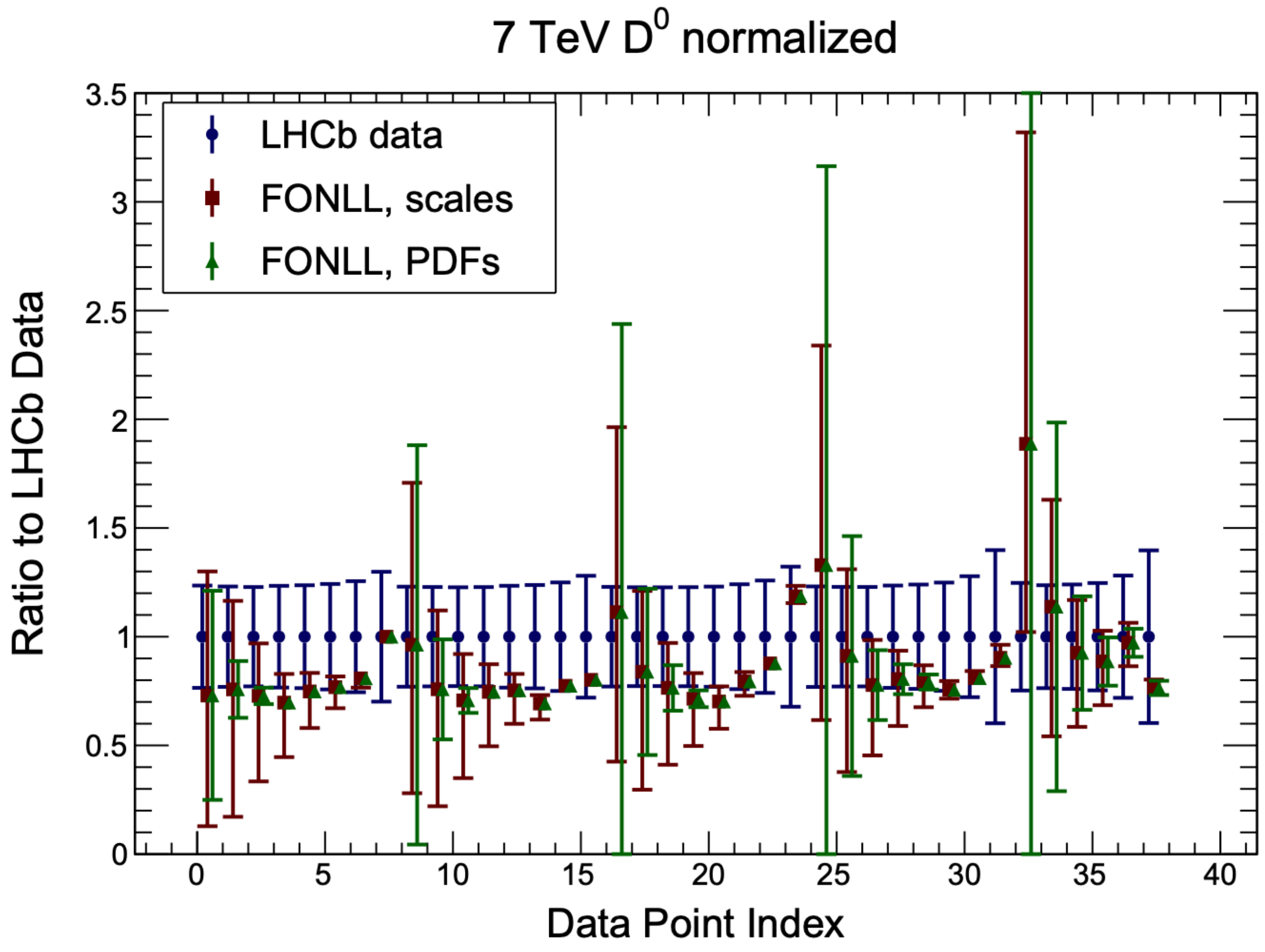
SM physics in neutrino production

Lever arm in neutrino rapidity crucial to reduce the dominant theory uncertainties

forward D-meson production has large MHOUs



markedly reduce when normalising to central rapidity bin

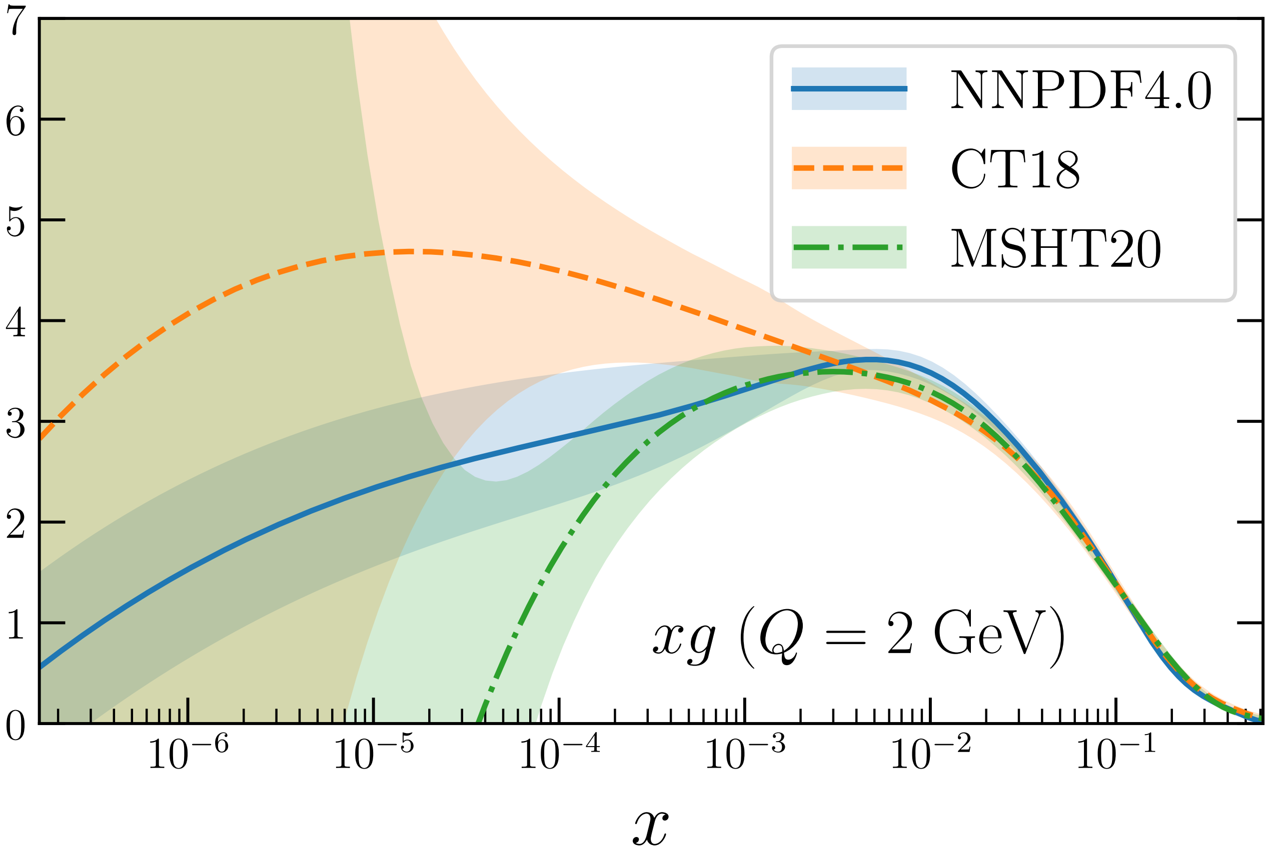


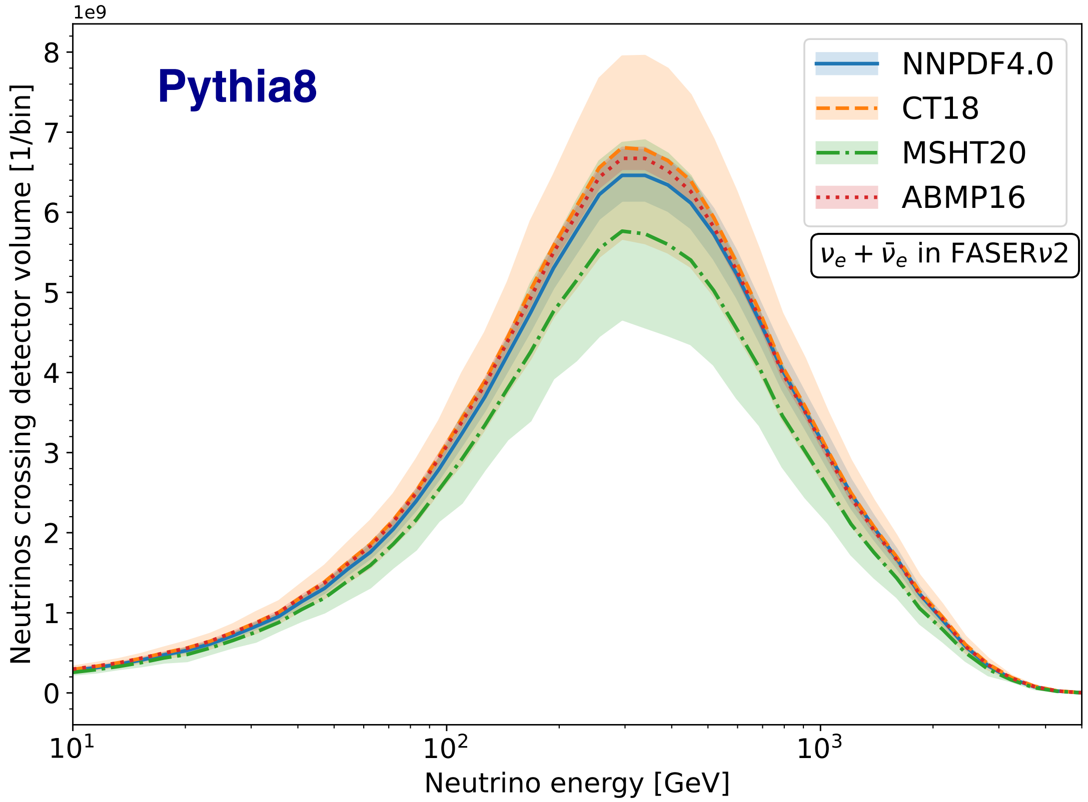
MHOUs are flat in *D*-meson rapidity, while PDF sensitivity is enhanced at forward rapidities

$$N_X^{ij} = \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_{\mathrm{ref}}^D d(p_T^D)_j}$$

Gauld et al 15

SM physics in neutrino production





- 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

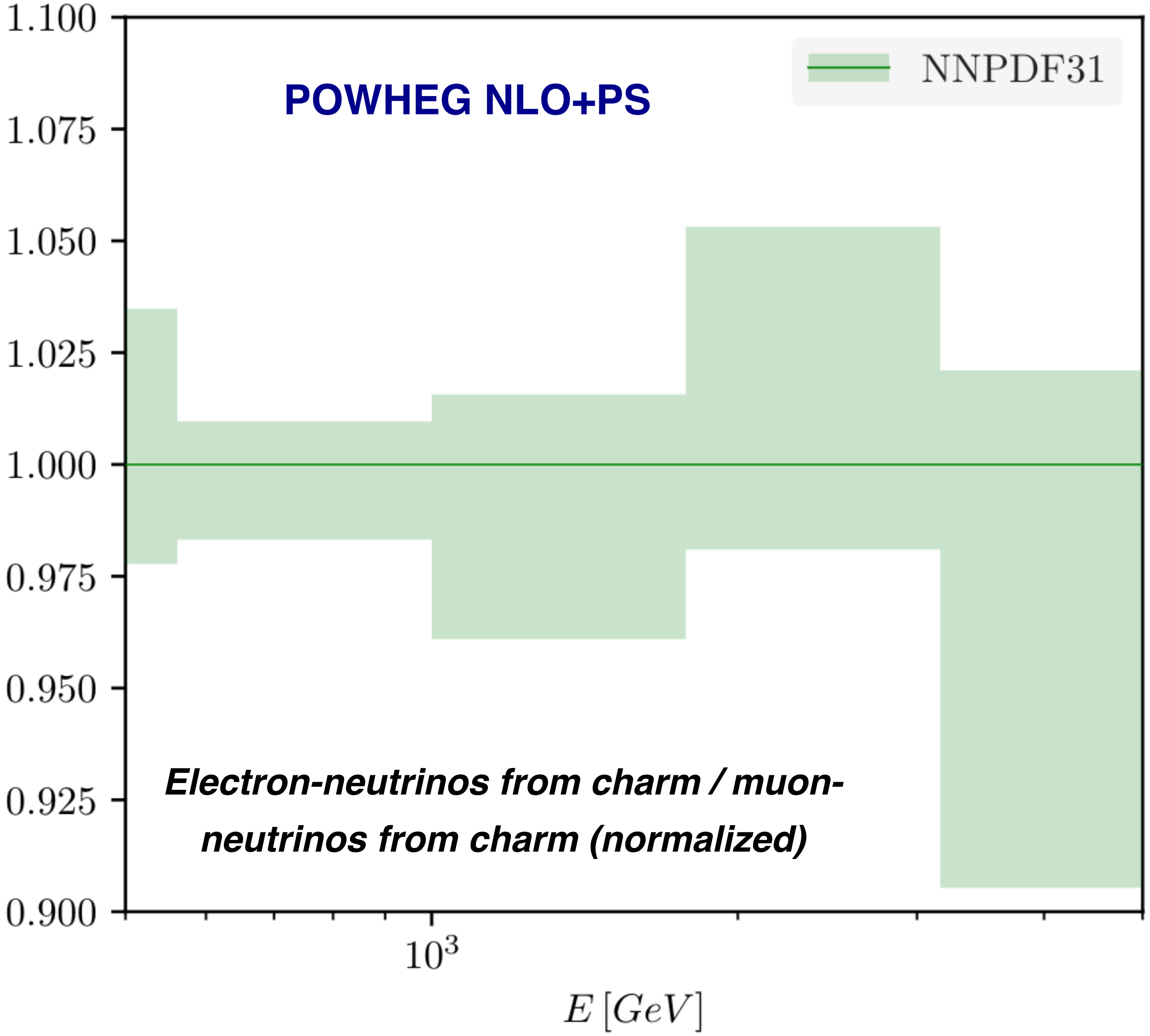
$$R_{\tau/e}(E_\nu) \equiv \frac{N(\nu_\tau + \bar{\nu}_\tau; E_\nu)}{N(\nu_e + \bar{\nu}_e; E_\nu)},$$

$$R^{\nu_e}_{\rm exp}(E_\nu) = \frac{N_{\rm FASER\nu}(\nu_e + \bar{\nu}_e E_\nu)}{N_{\rm SND@LHC}(\nu_e + \bar{\nu}_e; E_\nu)}$$

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

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

SM physics in neutrino production



POWHEG NLO+PS

Electron-neutrinos from charm / muon-neutrinos from charm (normalized)

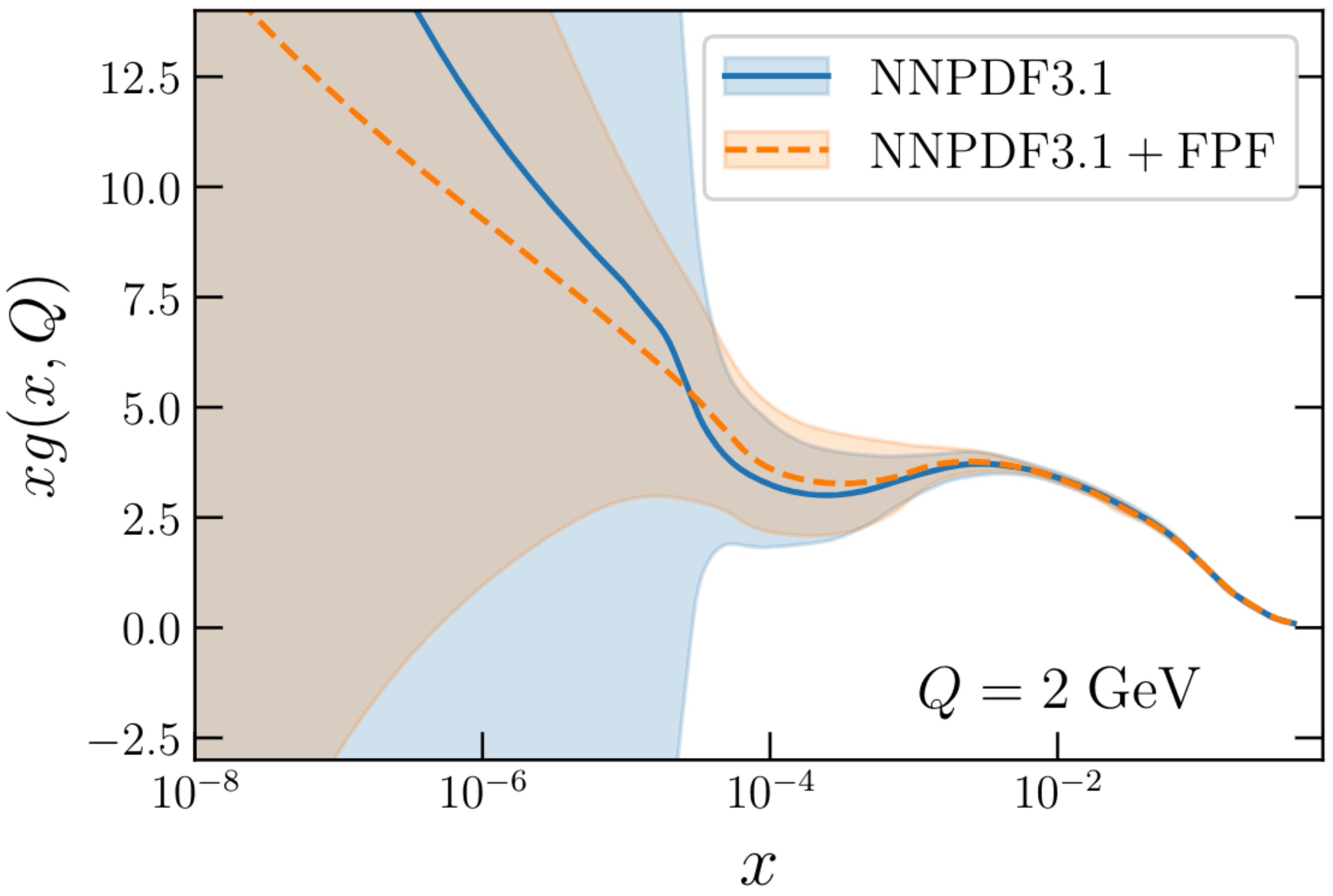
- When taking **ratios of event rates** (e.g. charm electron neutrinos vs charm muon neutrinos), QCD uncertainties reduced to O(few %)
- Strategy: assume a measurement of **inclusive event rates** as a function of neutrino energy with a given precision, quantify impact on PDFs via **Bayesian reweighting**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

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

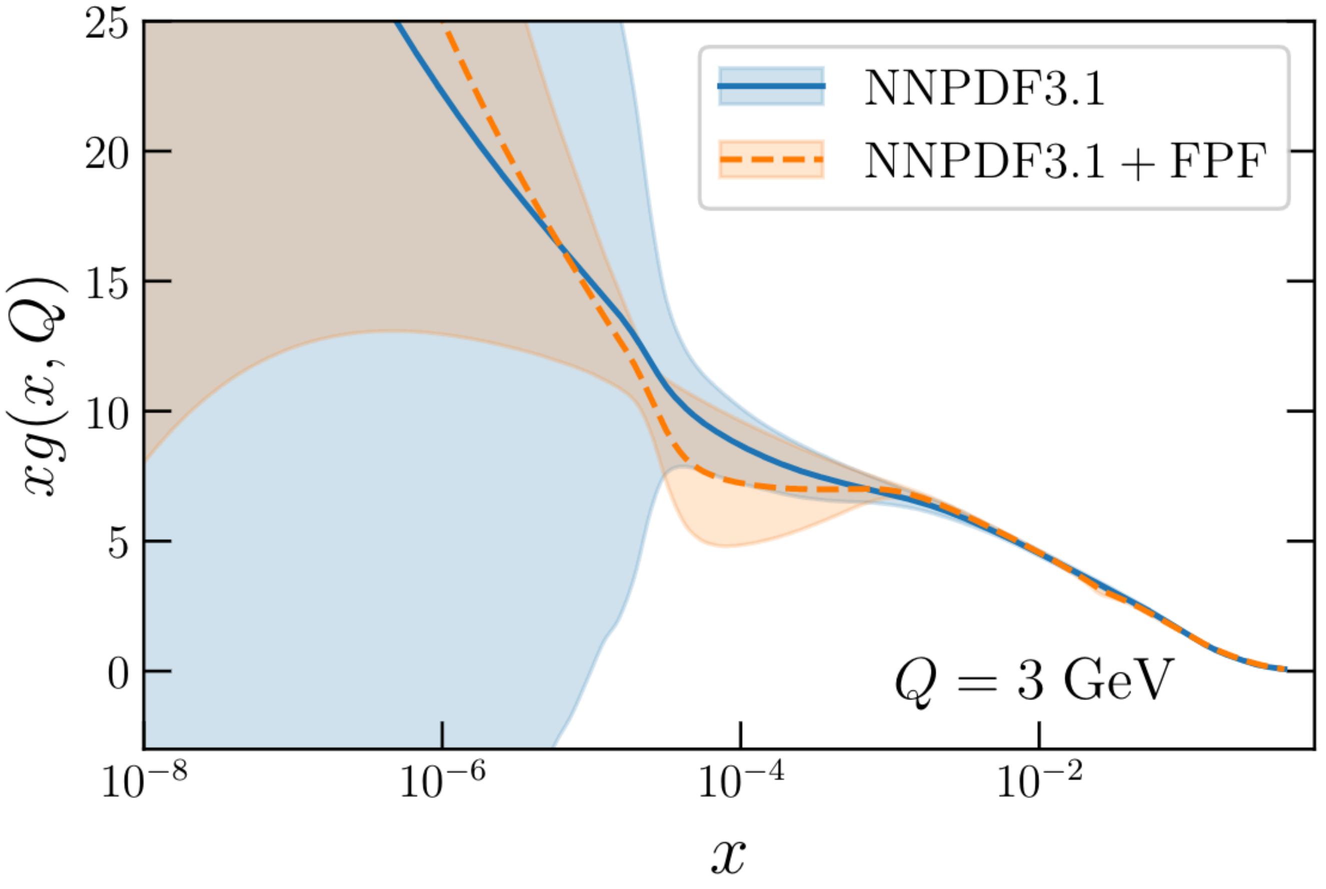
Proxy for “SND@LHC over FASER” ratio

SM physics in neutrino production

Electron neutrinos, 2% uncertainty in inclusive event rates



Tau neutrinos, 2% uncertainty in inclusive event rates

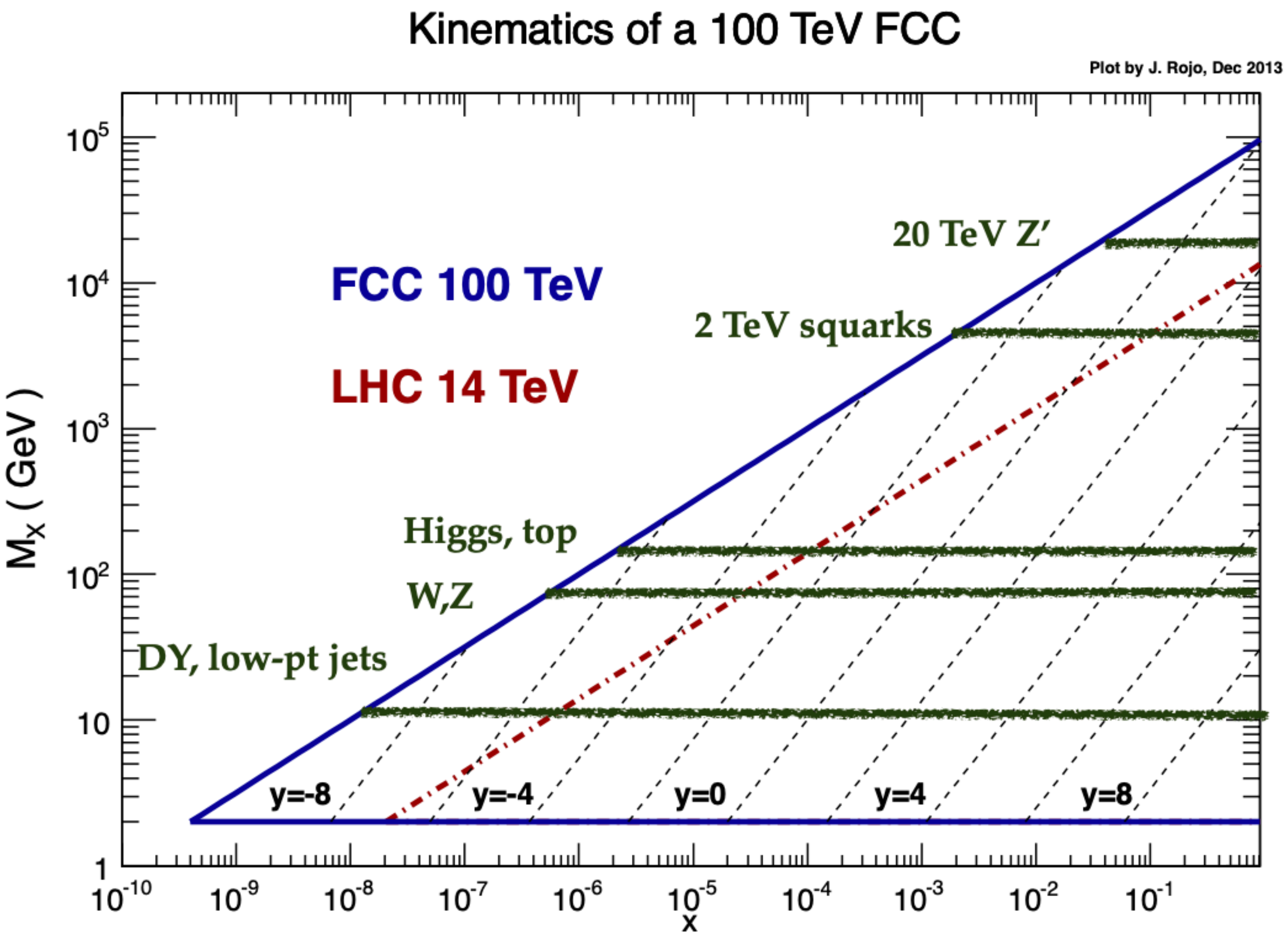


$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$

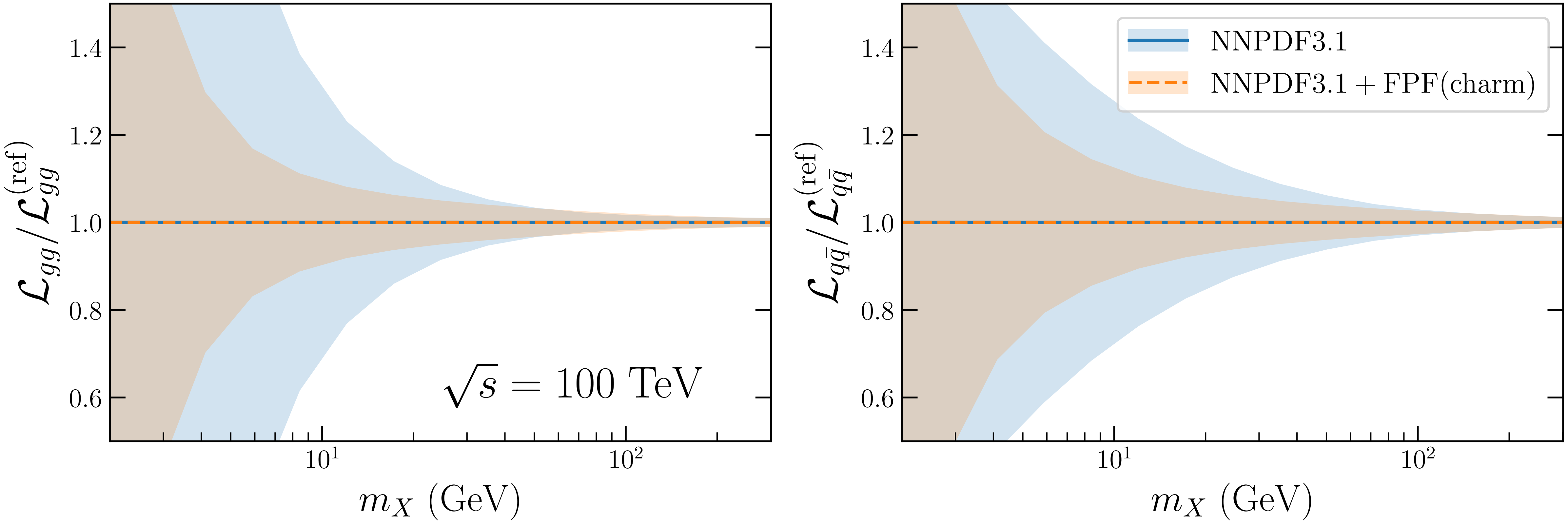
$$R_y^{(\tau)} \equiv \frac{N_{\nu_\tau}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_\tau}(E_\nu, 8.5 < y_\nu < 9.0)}$$

- 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

SM physics in neutrino production



- 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



SM physics in neutrino production

- For physics applications related to **neutrino production,** what is relevant for detector design is
  - Broad/different **rapidity coverage** (to test different production mechanisms & to cancel systematic errors)
  - High granularity on **neutrino energy**

- For physics applications related to **neutrino production,** what is **not relevant** is
  - **Largest event rates** possible (systematics dominated)
  - Exclusive reconstruction of hadronic final state (just event rate tagging sufficient)
  - Reduce **systematic errors** on final-state kinematic measurements

QCD in Neutrino Production

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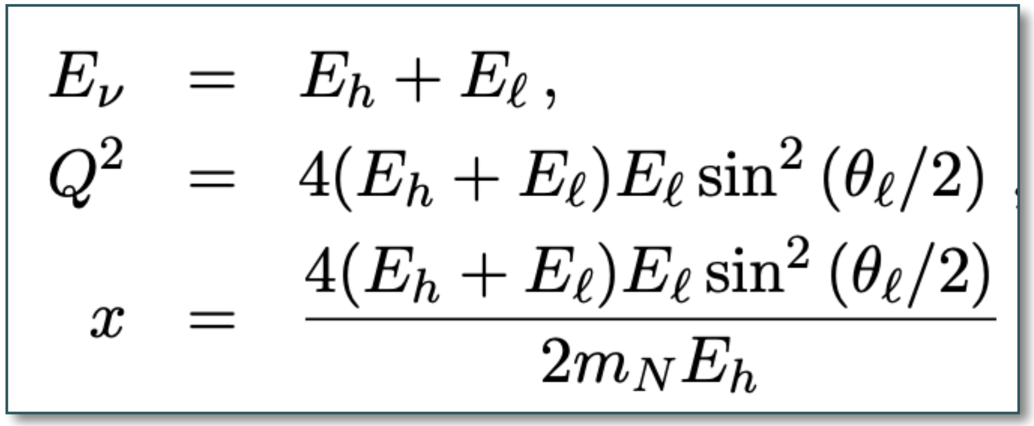

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The best of both worlds

to achieve the best physics reach for SM/QCD/neutrino studies, while fitting in the cavern and minimising costs, ideally one needs:

- A detector covering the LoS and **extended laterally** (one side!) up to 2 meters, covering rapidities < 6 , as **deep as possible** to increase total event rates
- High granularity on **neutrino energy and neutrino rapidity**
- Exclusive r**econstruction of hadronic final state (charm tagging!)**
- Reduce **systematic errors** on final-state kinematic measurements

of course, the same physics outputs can be achieved by combining different detectors with complementary performances