Hadron production at the LHC: predictions for long-lived particles at forward facilities

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FNSNF
Swiss National Science Foundation

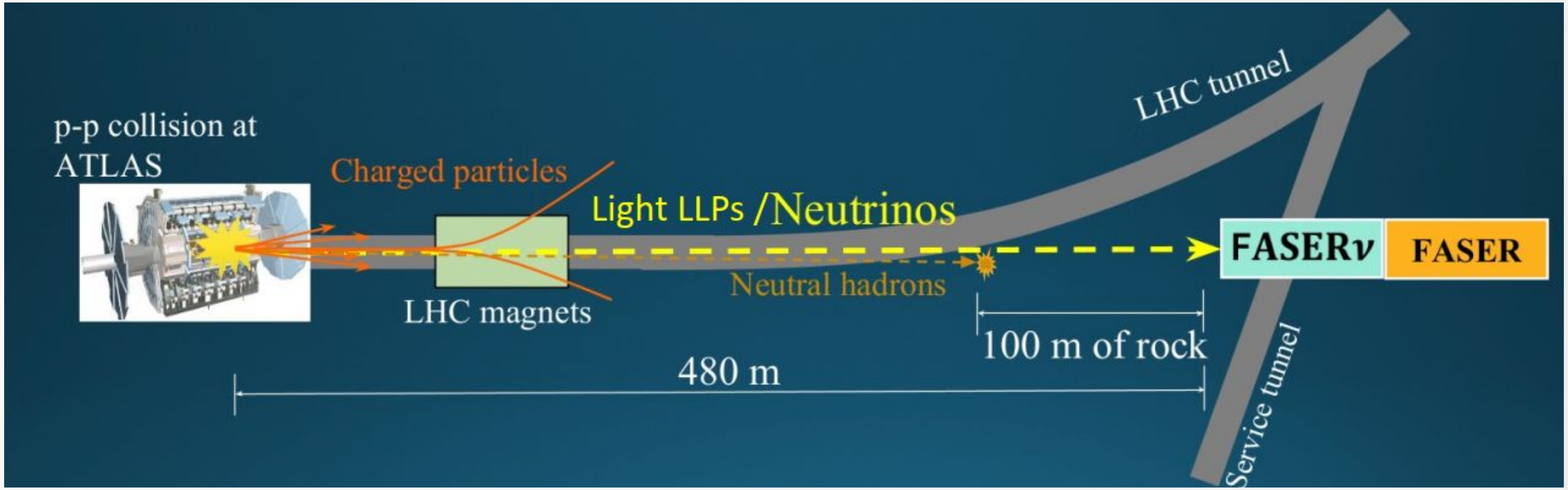
Based on 2309.12793 in collaboration with Luca Buonocore, Felix Kling and Jonas Sominka

Forward physics programme at the LHC

Long-lived particles (LLP), neutrinos and possibly new BSM particles, are copiously produced in the decay of SM mesons

Relatively small detectors close to the line of sight can have good sensitivity: detectors such as FASER and SND@LHC complement the experiments focussed on processes at high transverse momentum

Strong physics case emerging to house a suite of experiments during the HL-LHC era in the proposed **Forward Physics Facility** (**FPF**)



Forward hadron production

Reliable estimates of the relevant particle fluxes needed, notably precise predictions for **forward hadron fluxes** and associated uncertainties

- **Light hadron production:** simulated using event generators (often originally developed for **cosmic ray physics)**
- **Heavy hadron production** can be described by pQCD methods, achieving a reliable estimate of uncertainties

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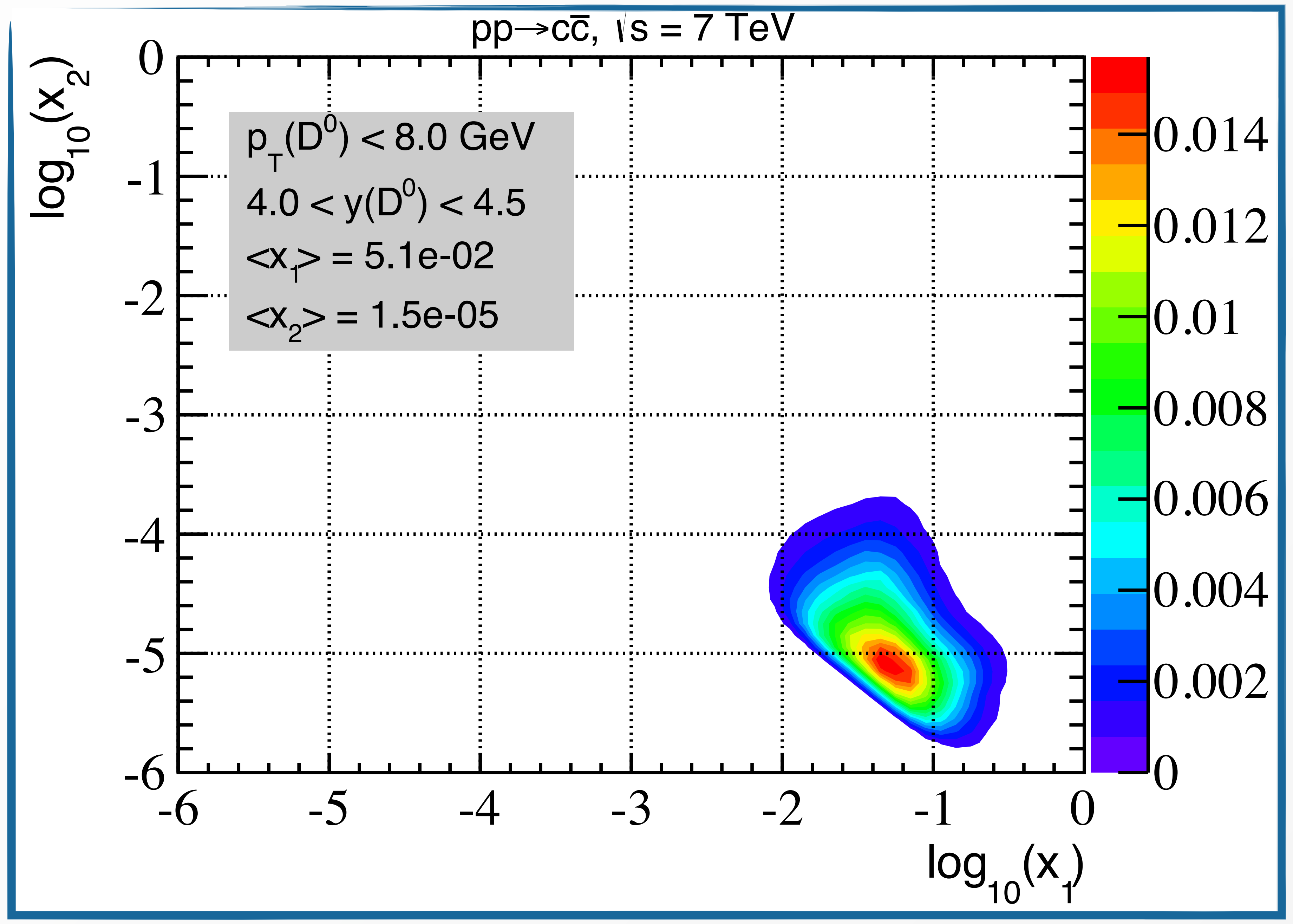
Current predictions in FASER kinematics often entail approximate descriptions of either the hard scattering or the hadronisation that may affect their reliability

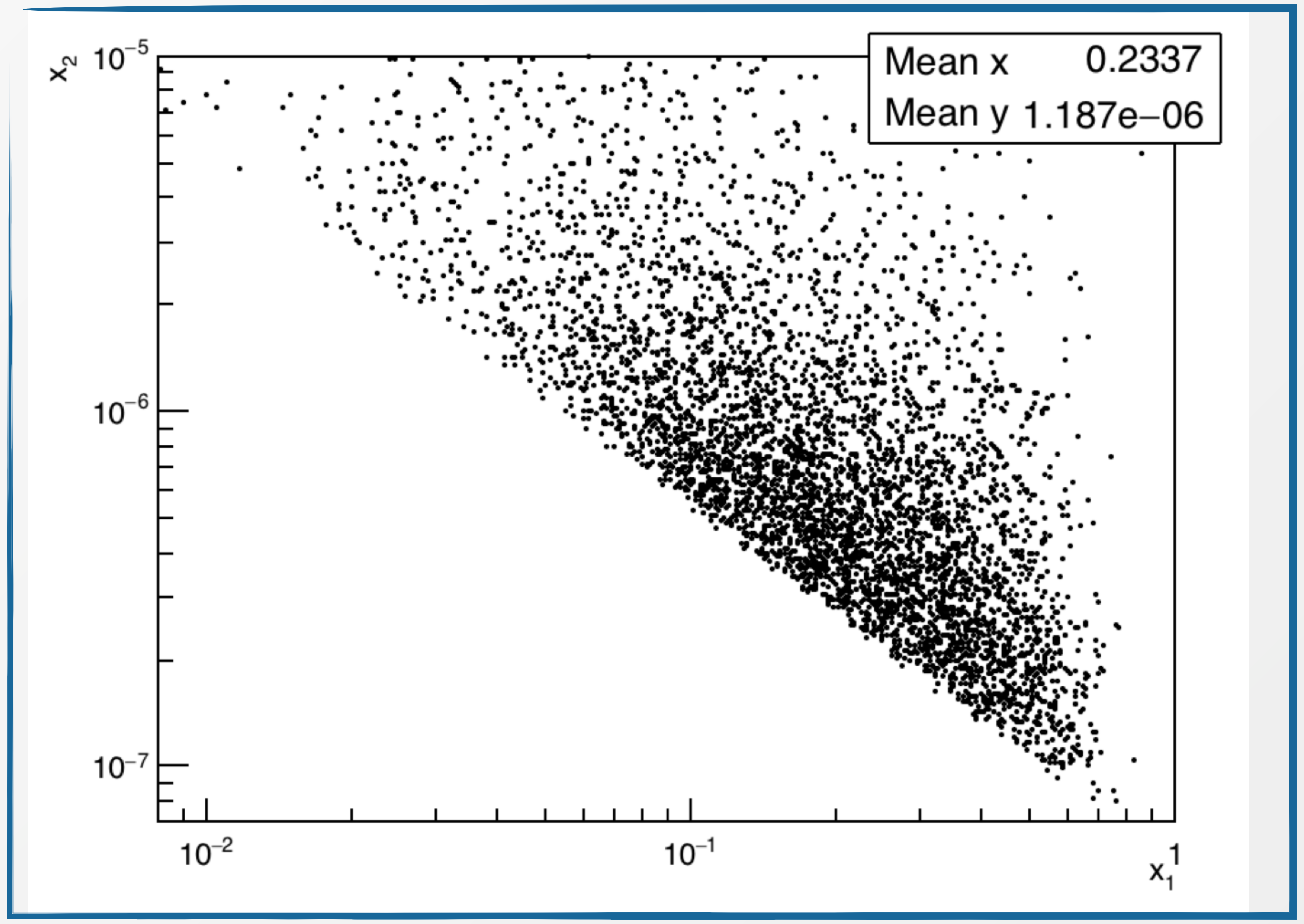
This talk: application of **state-of-the-art pQCD predictions** for **forward fluxes** for LLP

Forward heavy quark production: kinematics

Heavy quark production at the LHC is driven by the *gg* luminosity



[Gauld, Rojo, LR, Talbert '15]



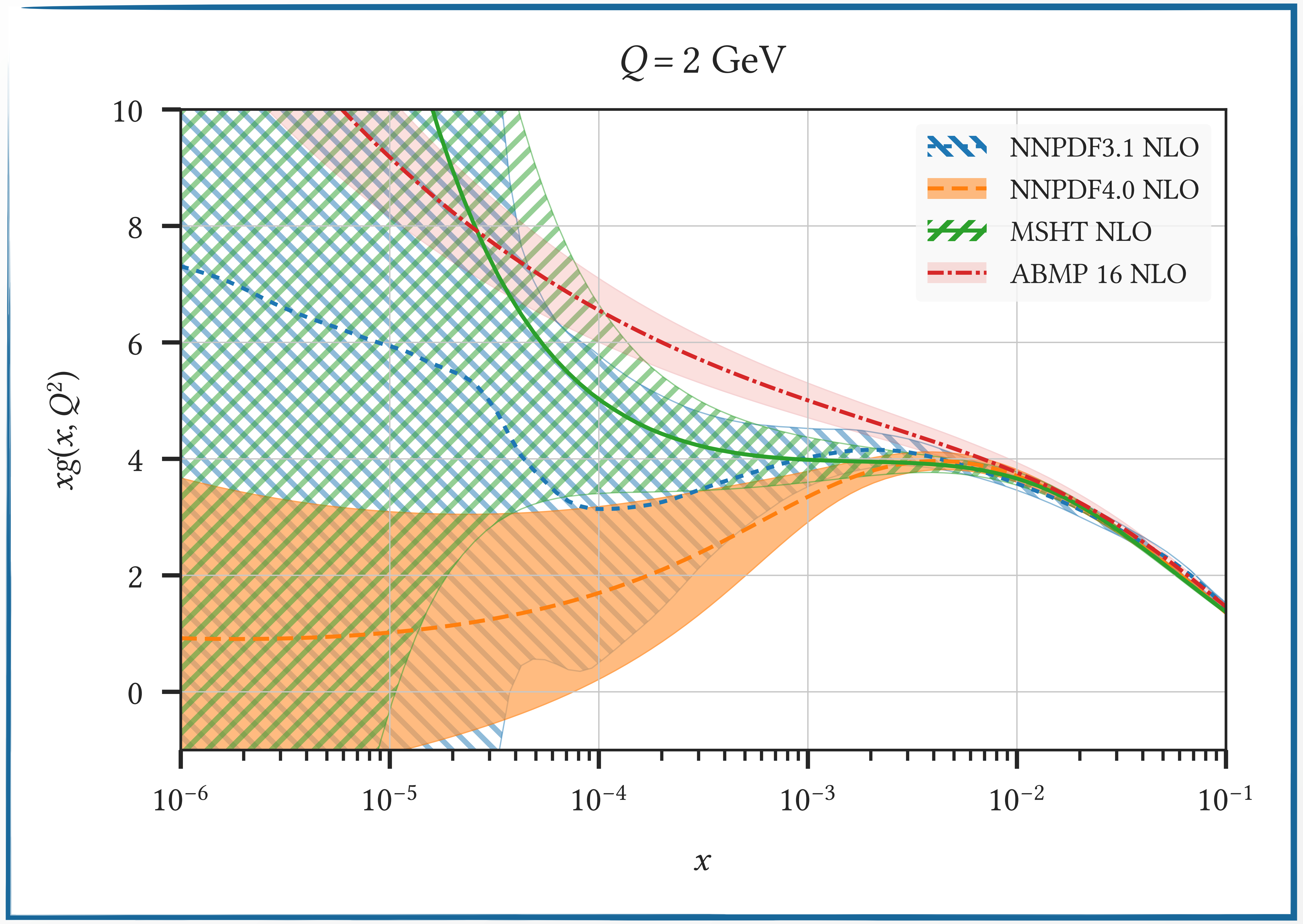
[Buonocore, LR, Tramontano, for the SND@LHC Technical Proposal]

Measurements of charm production probe average of Bjorken-*x* ~5x10^{-5}

Values of *x* even lower are probed in forward kinematics ($\eta_c \gtrsim 7.5$) probed in forward facilities

Knowledge of the **gluon PDF** for values below *x* ~10^{-5} is required

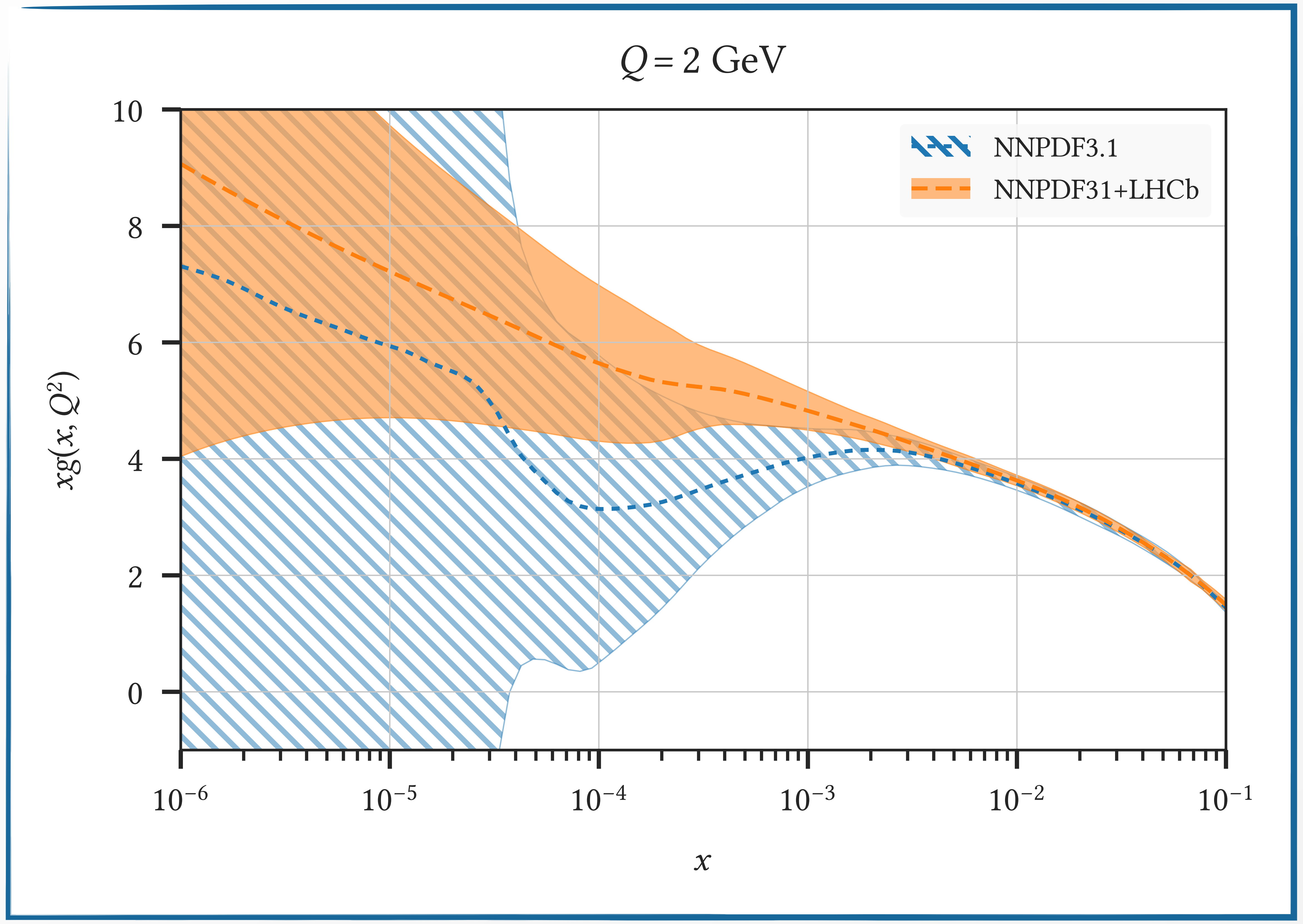
PDFs and the small-*x* region: taming PDF uncertainties



Gluon PDF at small *x* characterised by **relatively large uncertainties**

Different PDF sets may predict quite different low-*x* gluon PDFs (albeit within typically large uncertainties)

PDFs and the small-x region: taming PDF uncertainties



Gluon PDF at small x characterised by **relatively large uncertainties**

Different PDF sets may predict quite different low-x gluon PDFs (albeit within typically large uncertainties)

Charm and beauty production data have been used to provide additional information on the small-x gluon, **constraining the gluon PDF at small-x**

[PROSA coll. '15][Gauld, Rojo, LR, Talbert '15][Gauld, Rojo, Bertone '18]

Reducing PDF uncertainties thanks to LHCb data makes **PDF errors moderate** at relatively low value of x

PDFs and the small-x region: high-energy resummation

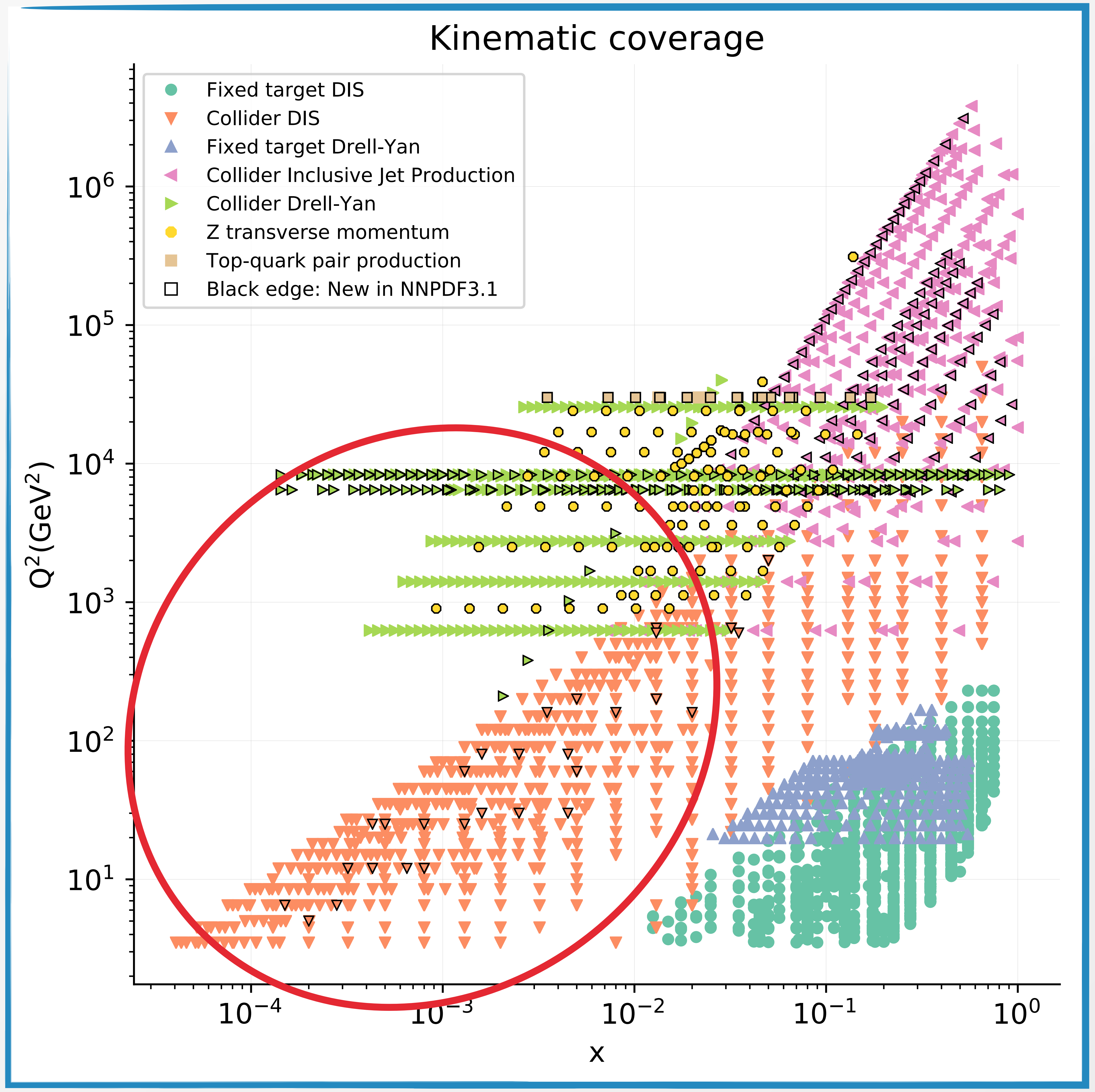
The kinematic coverage in global PDF fits probes Bjorken x values down to few 10^{-5}

In the small x region, **high energy** resummation may be relevant for phenomenology

Appearance of **single** logs due to high-energy gluon emission

$$\frac{1}{x}\ln^k x$$

Hints towards the importance of small-x resummation comes from a **poorer description of HERA data** when data points at smaller values of x are included and fixed-order theory is used



(brief and incomplete) recap of small-x resummation milestones

→Federico Silvetti's talk

Small-x resummation based on ***k_t*-factorization** and **BFKL formalism**. Developed mostly in the 90s-00s

[Catani,Ciafaloni,Colferai,Hautmann,Salam,Stasto][Altarelli,Ball,Forte] [Thorne,White]

Affects both **evolution** (LL*x*, NLL*x*) and **coefficient functions** (NLL*x*, lowest logarithmic order) in the singlet sector

ABF (Altarelli,Ball,Forte) procedure has been revived and further improved

[Bonvini, Marzani, Peraro, Muselli, '16, '17]

Two extractions of **small-*x* resummed PDFs** using this formalism have been performed (NNPDF3.1sx, xFitter)

[Ball, Bertone, Bonvini, Marzani, Rojo, LR '17][xFitter '18]

Resummed splitting functions and coefficient functions available through public code **HELL** www.ge.infn.it/~bonvini/hell

Use in PDF fits possible thanks to the interface with **APFEL** apfel.hepforge.org

NNPDF31sx: PDFs with small-x resummation

All ingredients for a PDF fit to **DIS data** available

In principle, one should add additional processes:

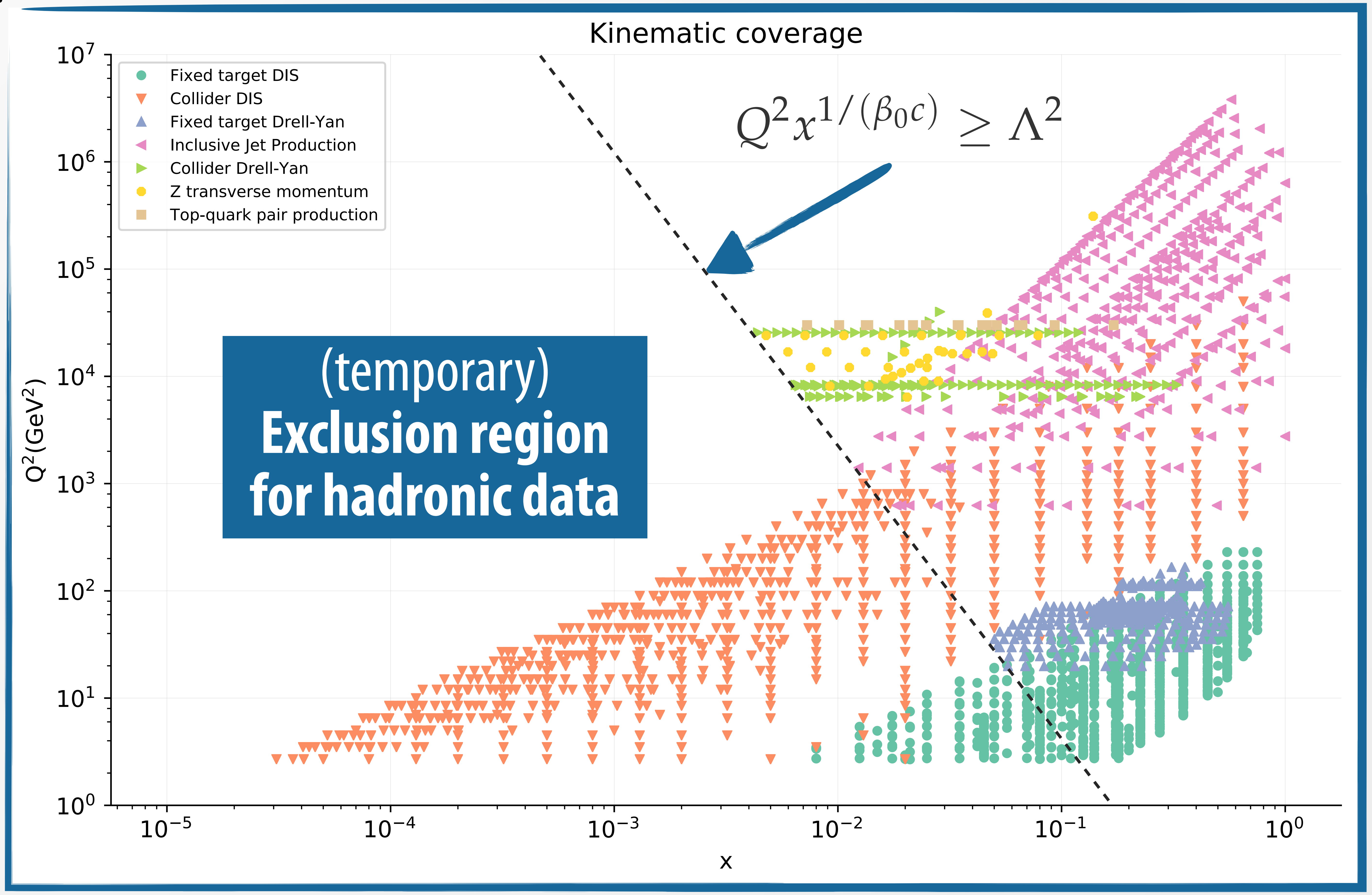
- DY
- Jets
- top
- …

For which only partial results were available

However, a global fit was performed applying **conservatives cuts** on hadronic data and excluding points which may feature small-x enhancement

$$\alpha_s(Q^2)\log\frac{1}{x} \geq c \sim 1$$

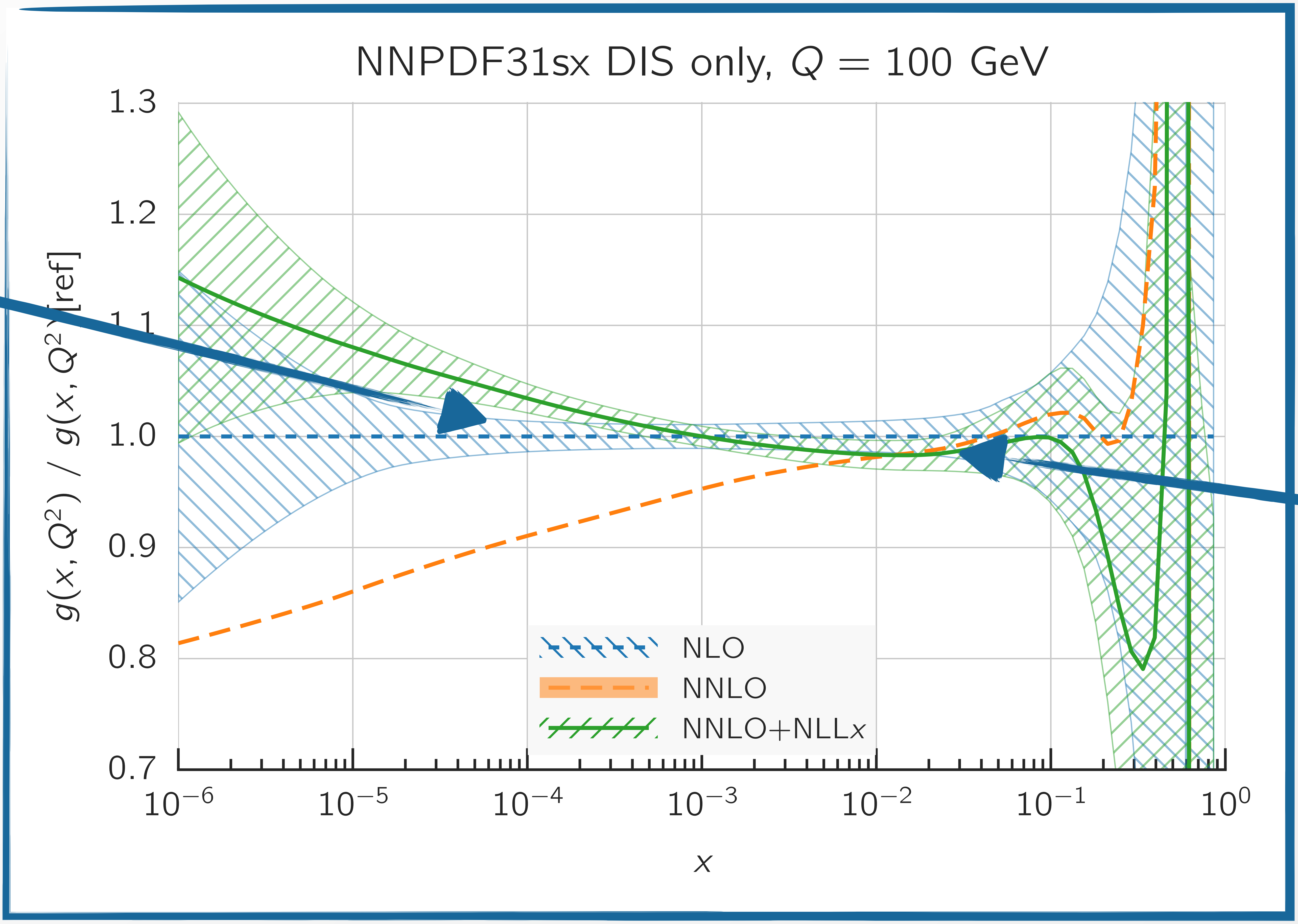
Value of c (slope of the line) selects the exclusion region



[Ball, Bertone, Bonvini, Marzani, Rojo, LR ’17]

NNPDF31sx: impact on PDFs

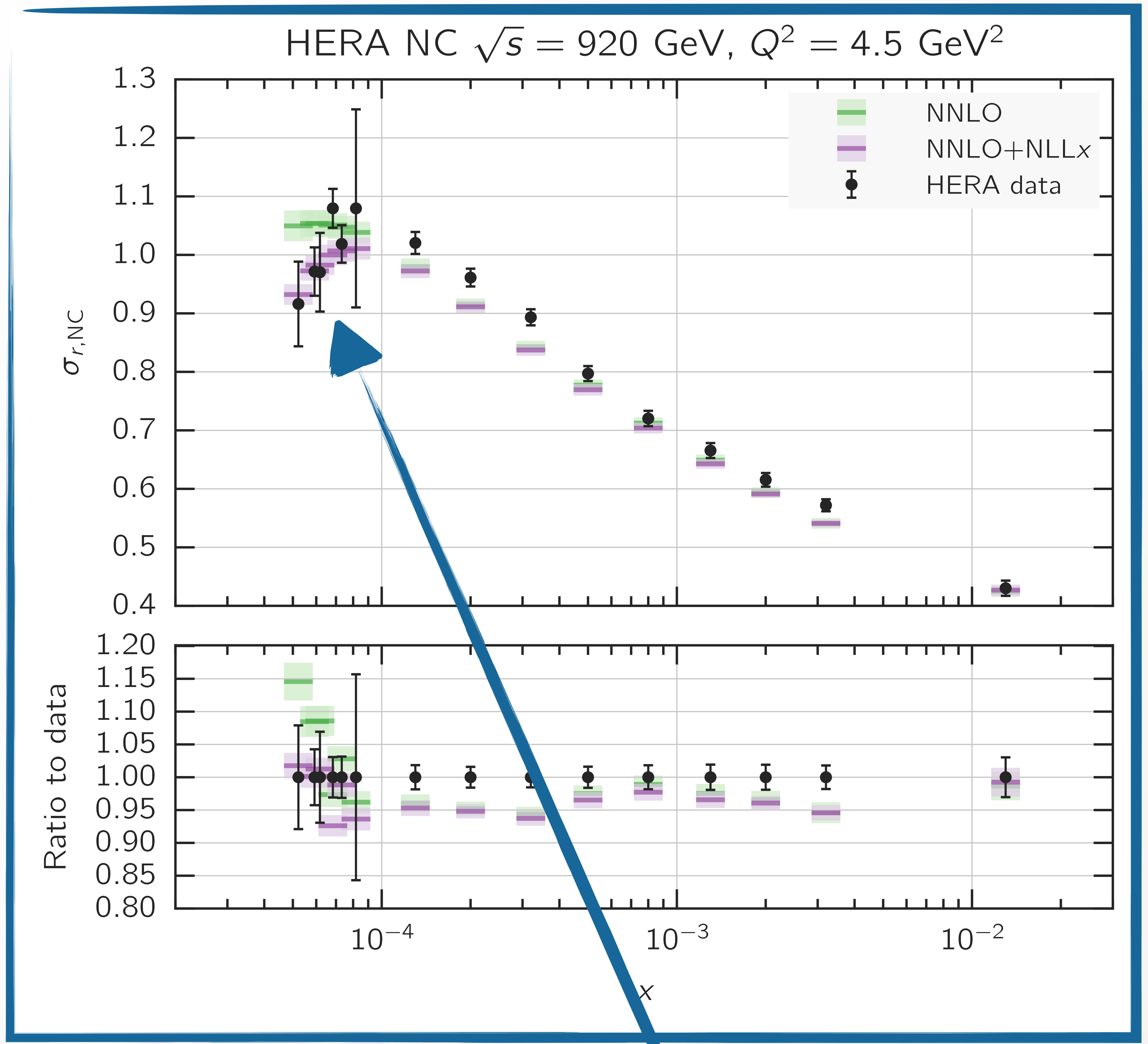
stabilisation of the gluon with respect to the perturbative order

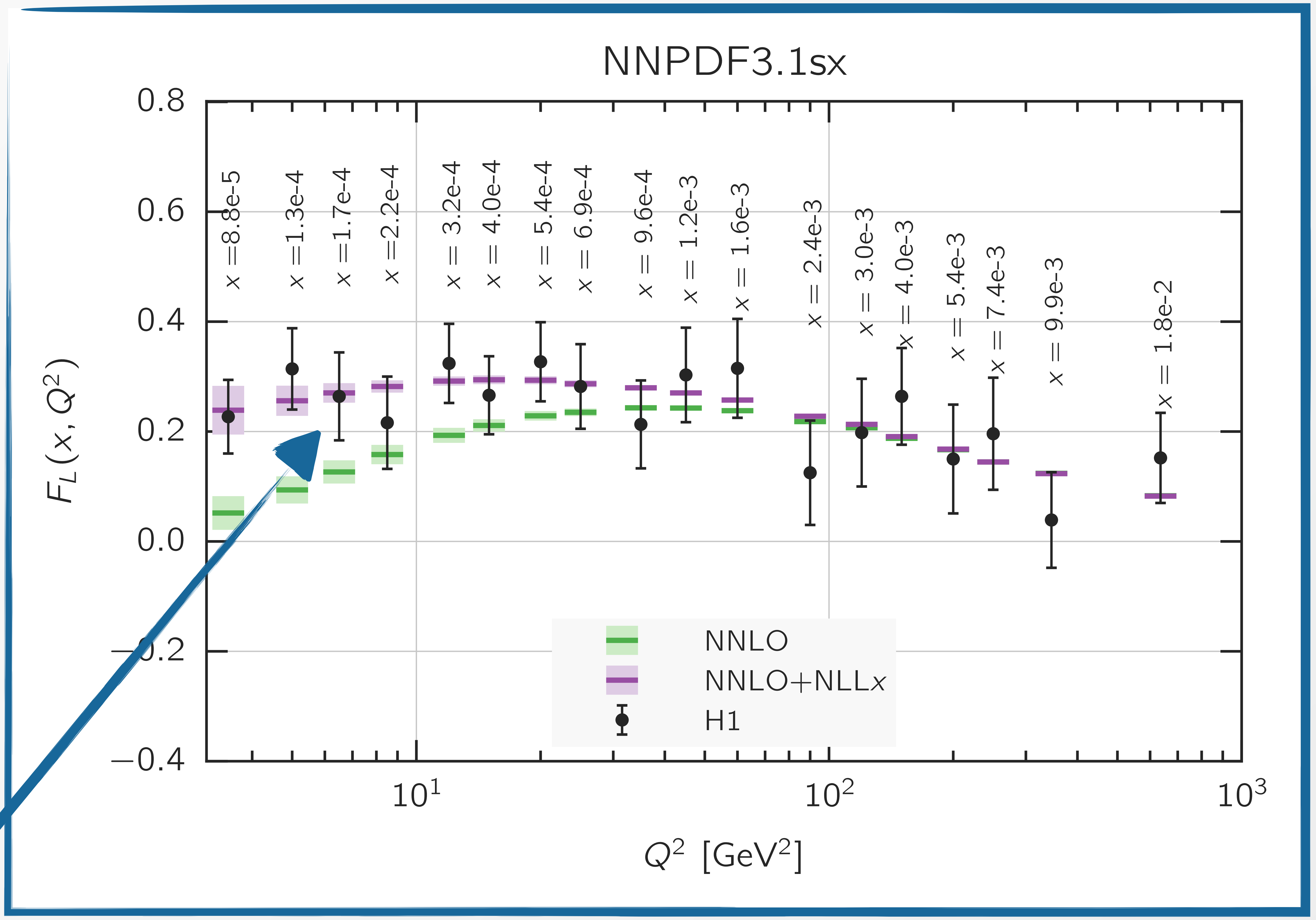


PDFs compatible within error at medium and large x

[Ball, Bertone, Bonvini, Marzani, Rojo, LR '17]

Small-x resummation and HERA data





[Ball, Bertone, Bonvini, Marzani, Rojo, LR '17]

Much improved description of data at small-x and their slope

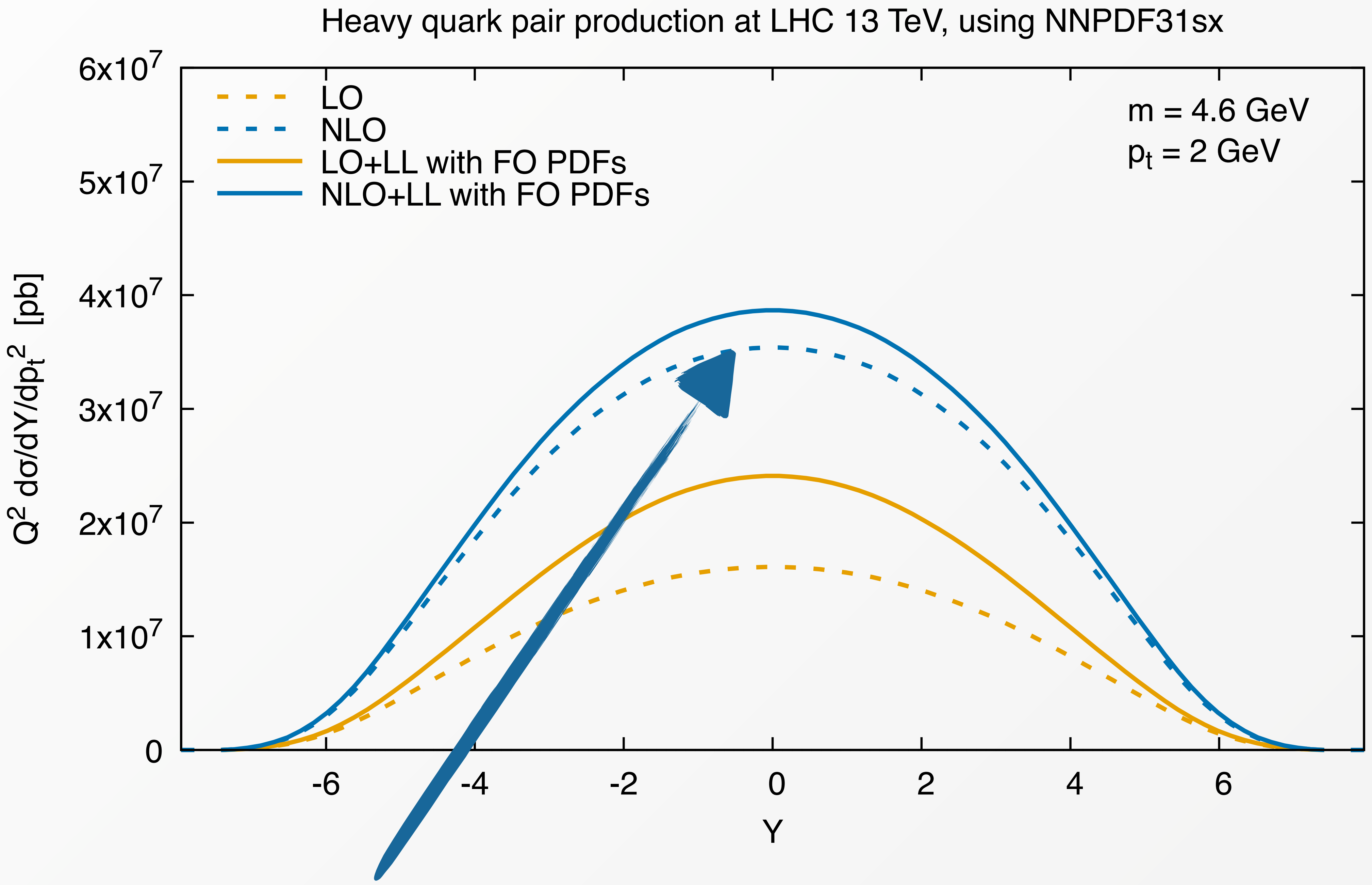
Confirmed by the **sensible improvement** in the χ^2 when resummation effects are included, coming primarily from the small-x region

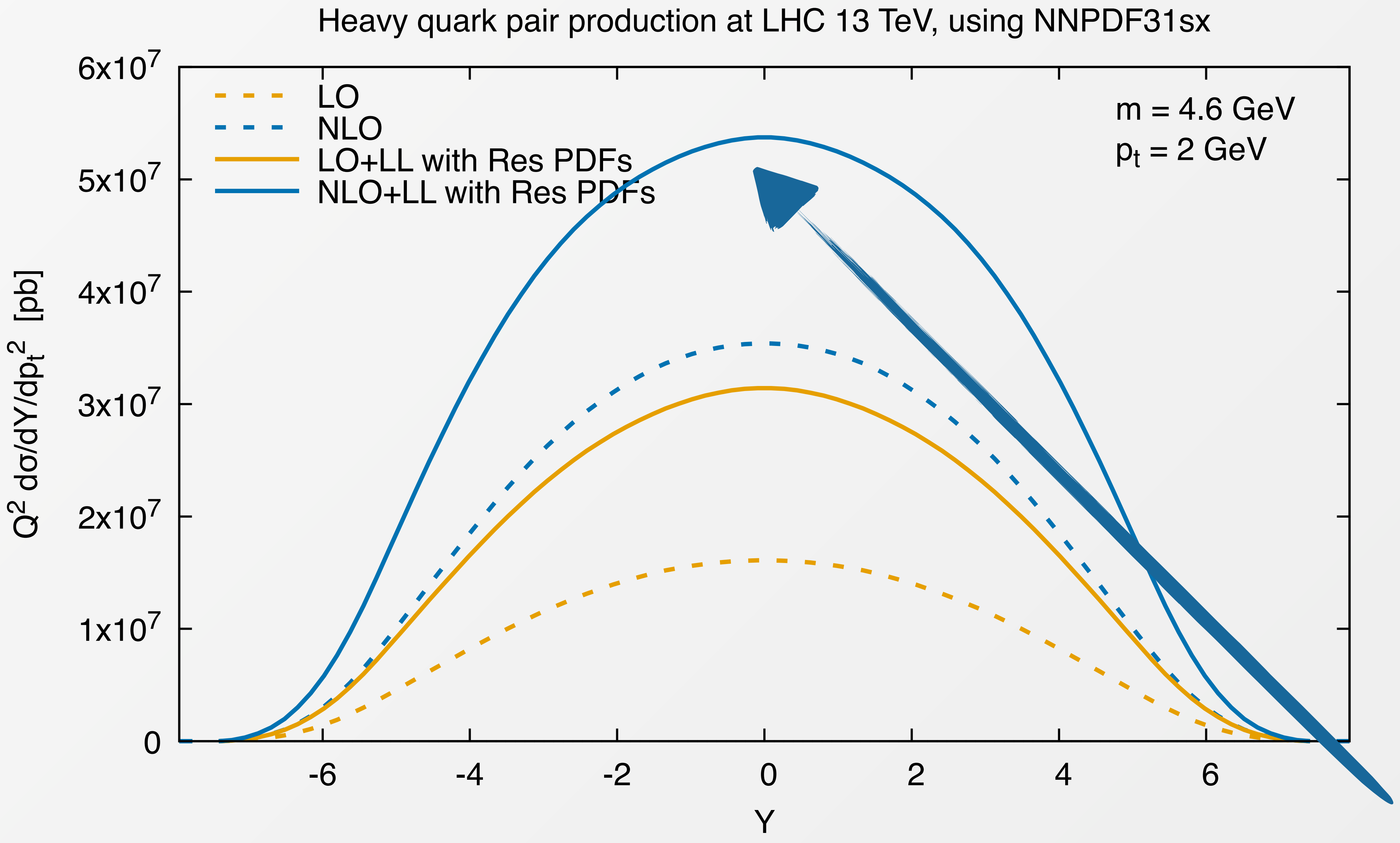
$(\chi^2_{\mathrm{NNLO}} - \chi^2_{\mathrm{NNLO+NLLx}})$ = **-121**

Small-*x* resummation for heavy-quark production

Small-x resummed PDFs **necessary but not sufficient** to achieve formal NLL_x resummation for heavy-hadron production (resummed coefficient function needed)

Coefficient functions for heavy quark production only recently available, though not yet in a form fully amenable for phenomenology. However: [Bonvini, Silvetti '22]





Effect of resummation in the **coefficient function relatively mild**

Largest effect come from the use of **resummed PDFs**

In first approximation, the use of resummed PDFs for forward charm production captures the **bulk of small-*x* resummation effects**

Forward charm production at NLO+NLL$_x$: default setup

We compute theoretical predictions at NLO+NLL$_x$ matched with parton showers with the POWHEG method using the **hvq** code [Frixione, Nason, Ridolfi '07]

We use NNPDF3.1sx + LHCb data, which include **small-*x* resummation at NLL$_x$** and include **LHCb *D*-meson** production data to **reduce PDF uncertainties at small-*x***

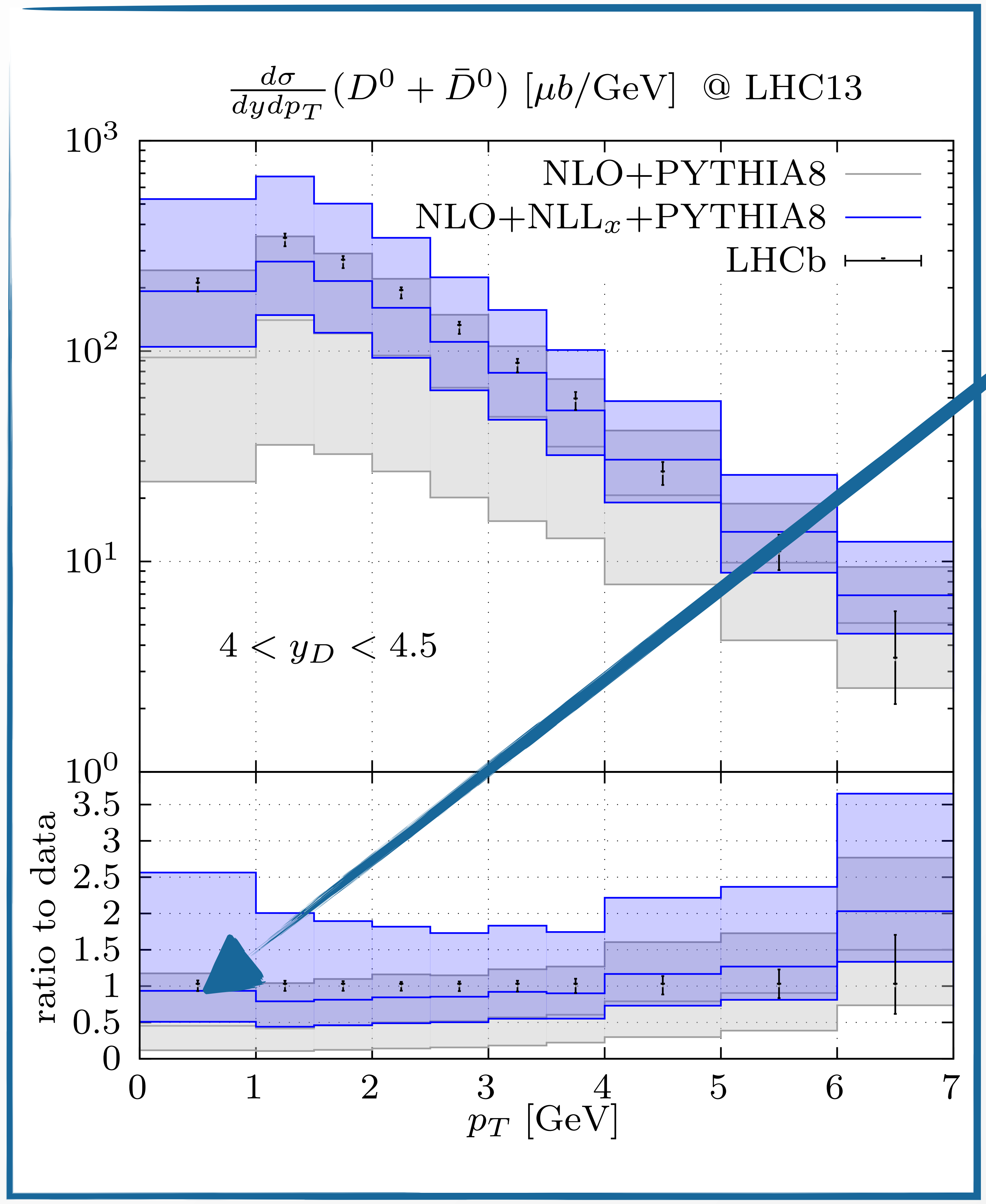
Central scale set to $\mu_R = \mu_F = \sqrt{m^2_{Q\bar{Q}} + p^2_{T,Q\bar{Q}}}$

Nominal charm and beauty mass m_c=1.5 GeV, m_b=4.5 GeV

Event showered with Pythia 8.245 using default Monash tune

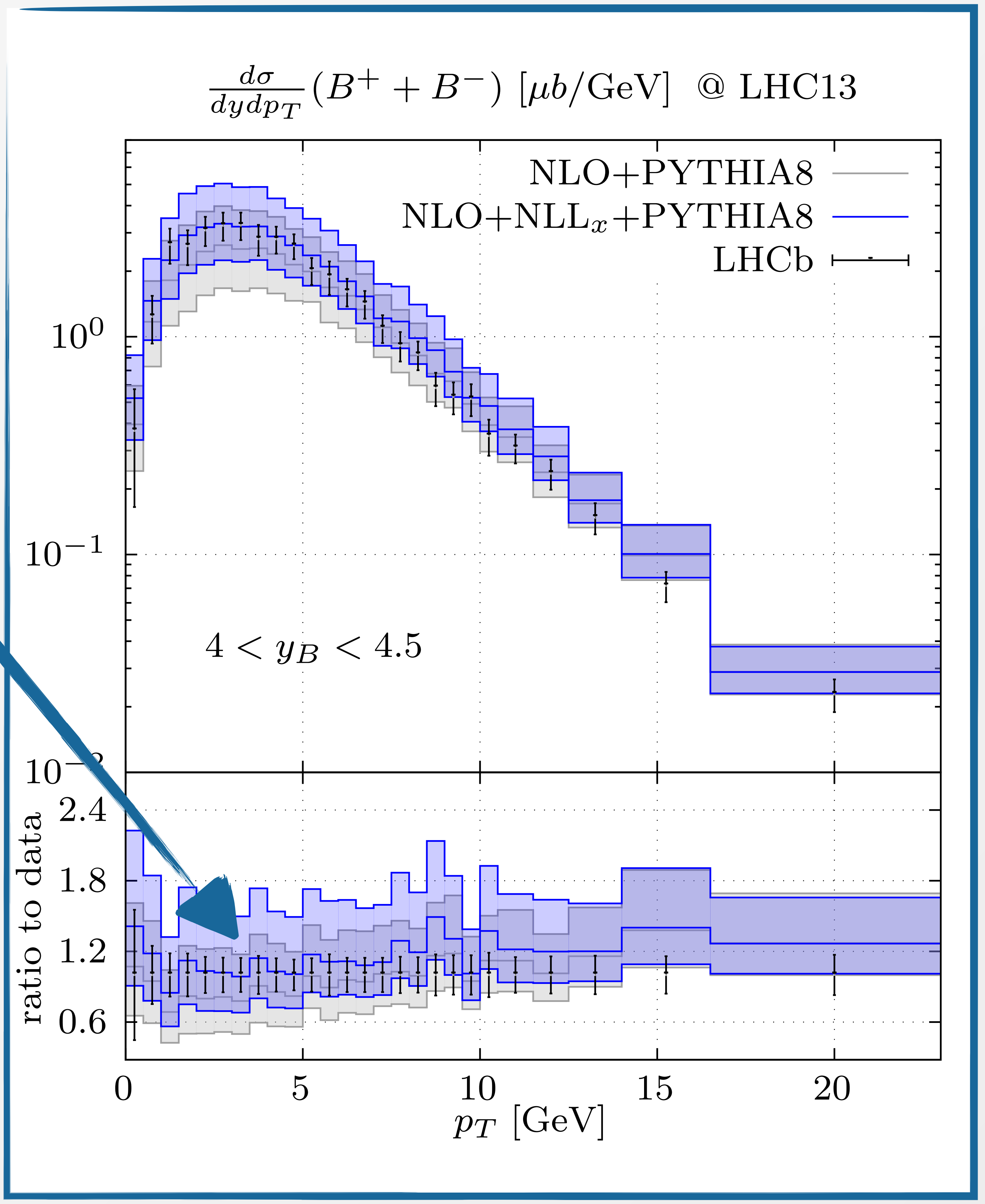
Forward charm production at NLO+NLL$_x$: results

Validation of the setup by comparing our default prediction with forward LHCb data for charmed and beauty hadrons



small-*x* resummation beneficial: improved description of the shape, **especially in the small-p_T region**

Scale uncertainties rather large, at the 30-40% level or larger at this order



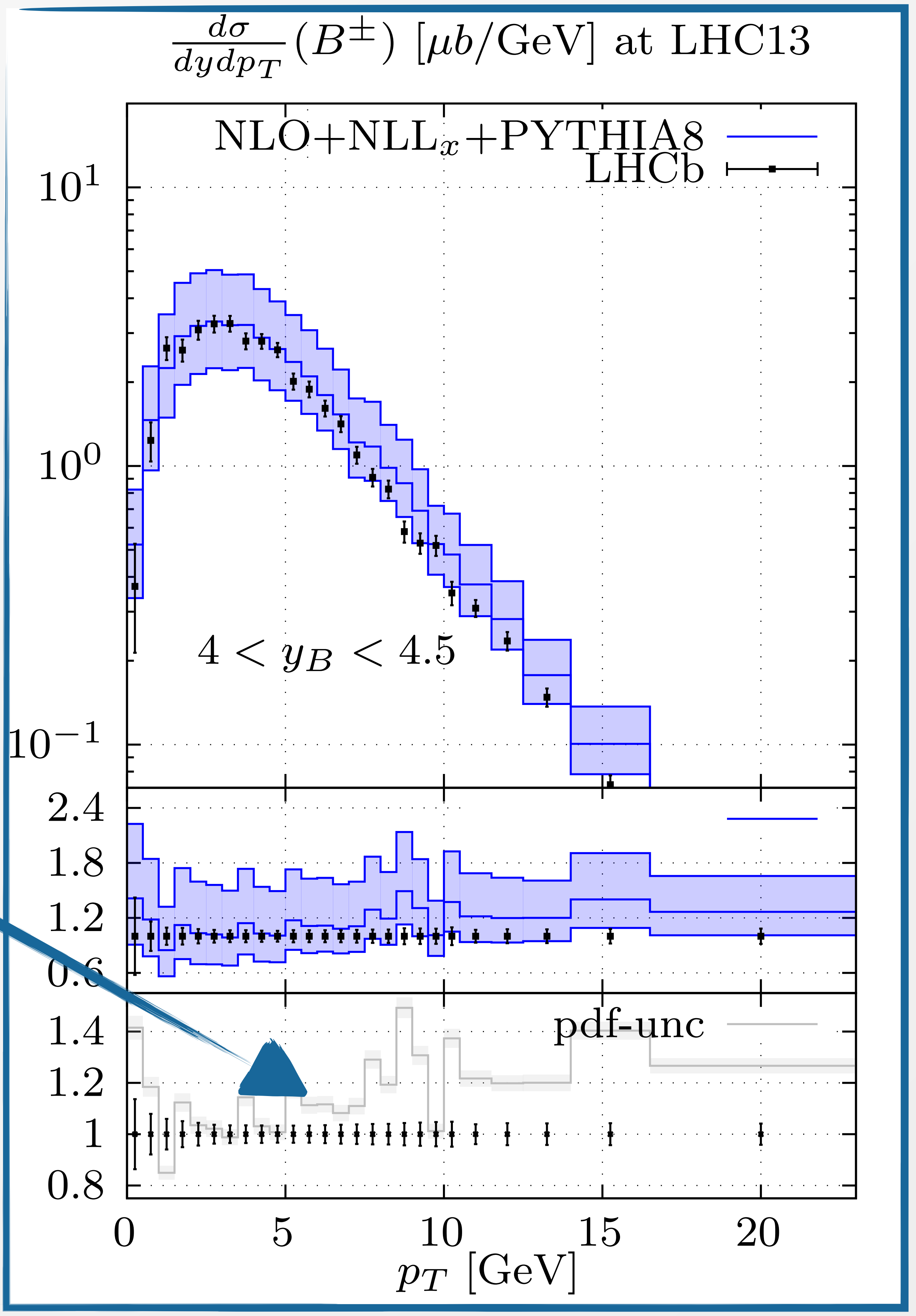
Forward charm production at NLO+NLL$_x$: results

The large scale uncertainties at this order allow us to neglect other uncertainties in the fixed-order calculation (PDF, quark mass) which are subdominant

Use of **LHCb-improved PDF** crucial to reduce PDF uncertainty

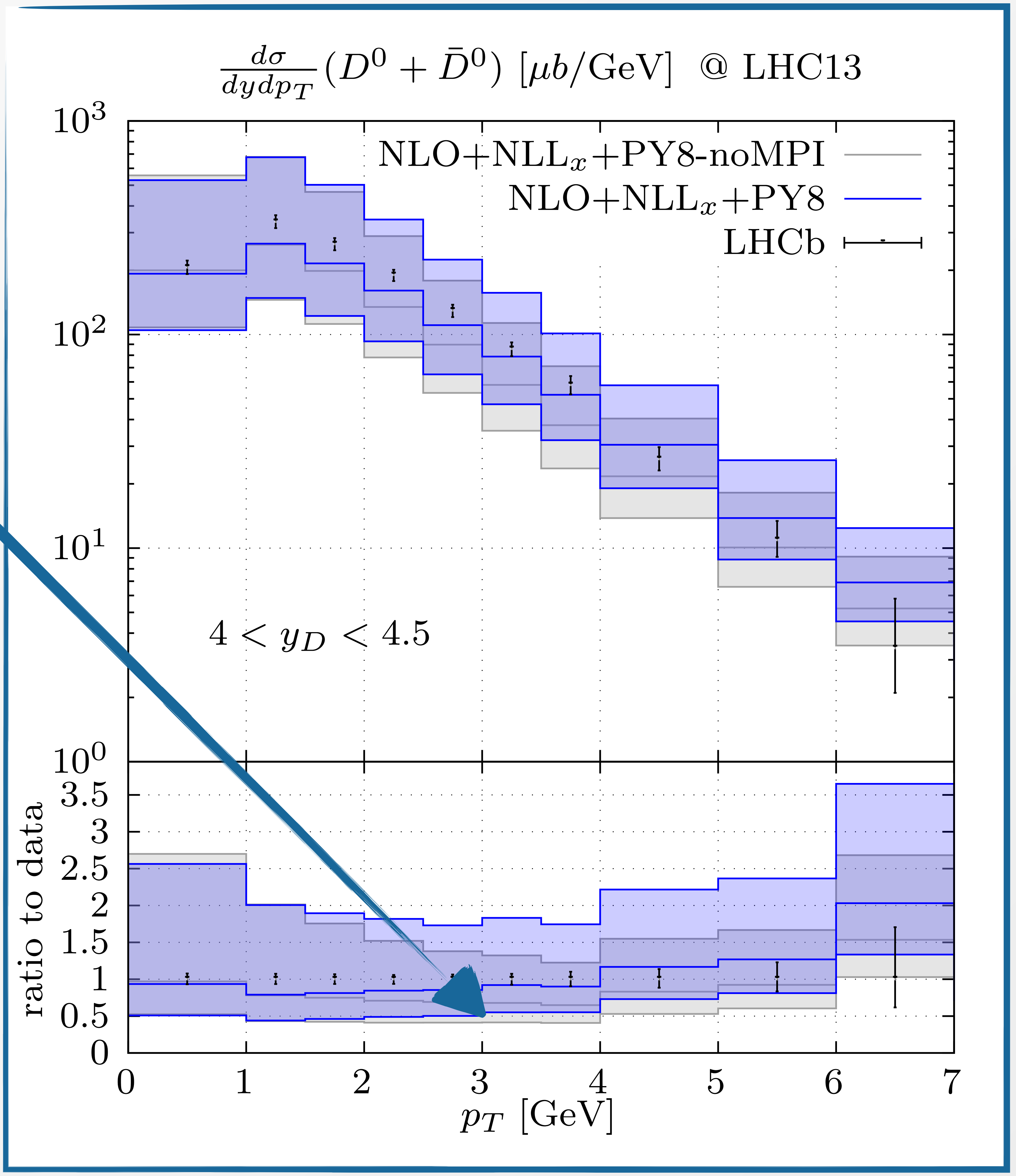
Scale uncertainties can be reduced (by a factor of two) recurring to **recent NNLO(+PS) calculation**, with some caveats: [Mazzitelli, Ratti, Wiesemann, Zanderighi '23]

- Charm hadron production not yet publicly available
- Other uncertainties no longer negligible
- Matching of NLL$_x$ with NNLO required (not currently available)



Forward charm production at NLO+NLL$_x$: MPI effects and shower dependence

Moderate effect of **removing MPI** from our default predictions with PYTHIA8



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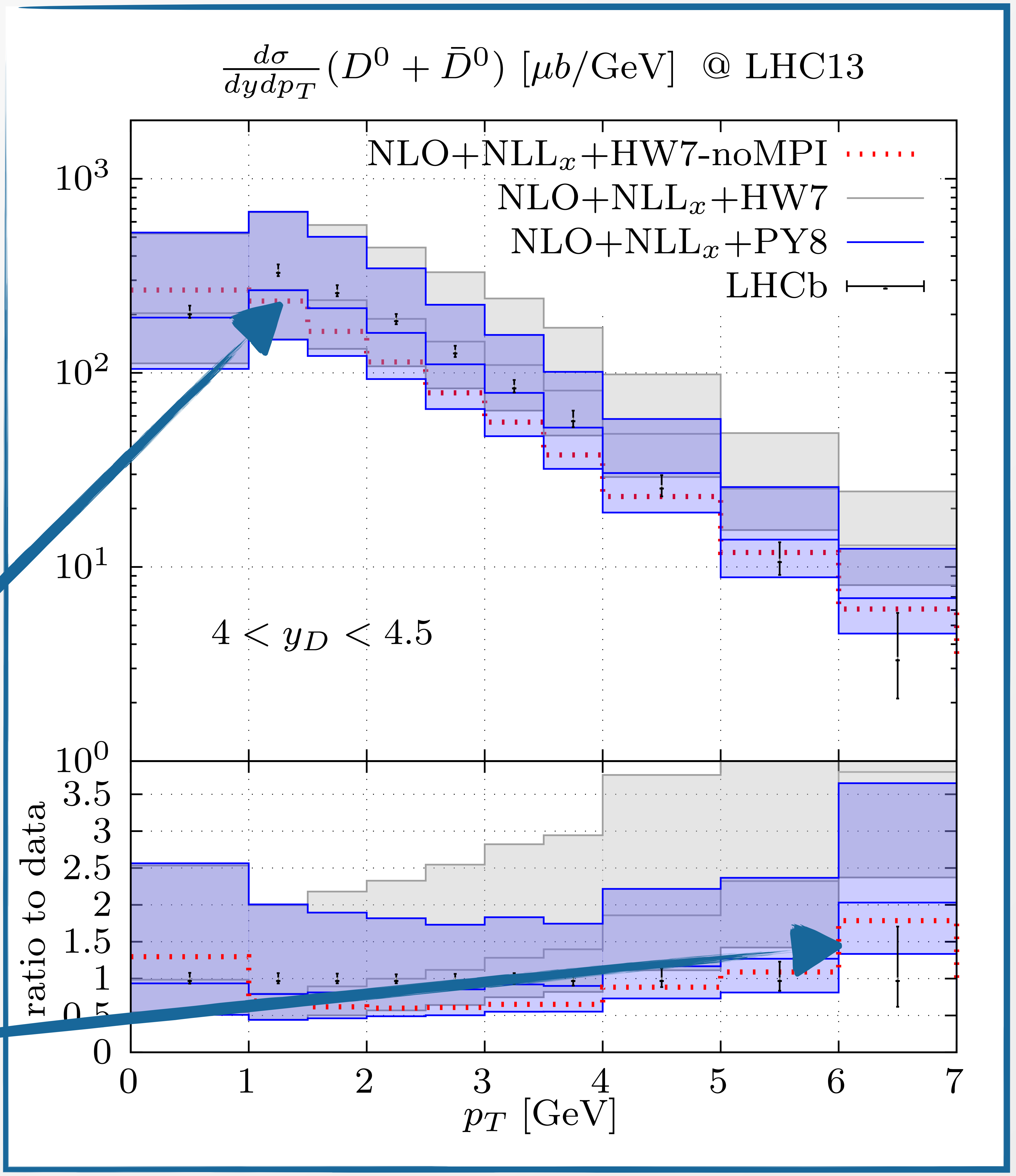
Much more pronounced effect with HERWIG 7.2

Without MPI, POWHEG+HERWIG **does not seem to reproduce the peak** in the *D*-meson distribution

Removal of MPI **soften considerably the spectrum** and brings it closer to the LHCb data at high p_T, while with MPI the predictions tend to overshoot the data



Application 1: Neutrino fluxes at FASERν

Study of high-energy collider neutrino is one of the **main objectives** of FASER experiment

Neutrinos detected by the FASERν detector, a 25cm x 25cm x 1m tungsten target with ~ 1.2 tons target mass, allowing the identification of the neutrino flavour and energy

13.6 TeV centre-of-mass energy with 150 fb^{-1} and we fold neutrino fluxes with interaction cross-section obtained through the GENIE code

Predictions for neutrinos from charm hadron decays obtained using our **pQCD NLO+NLL$_x$** compared with DPMJET and SIBYLL, which employ **phenomenological models** and have been historically used to describe forward charm production (with some known limitations)

- SIBYLL models forward charm production phenomenologically by replacing the production of a strange pair with a charm pair with a probability fitted to data

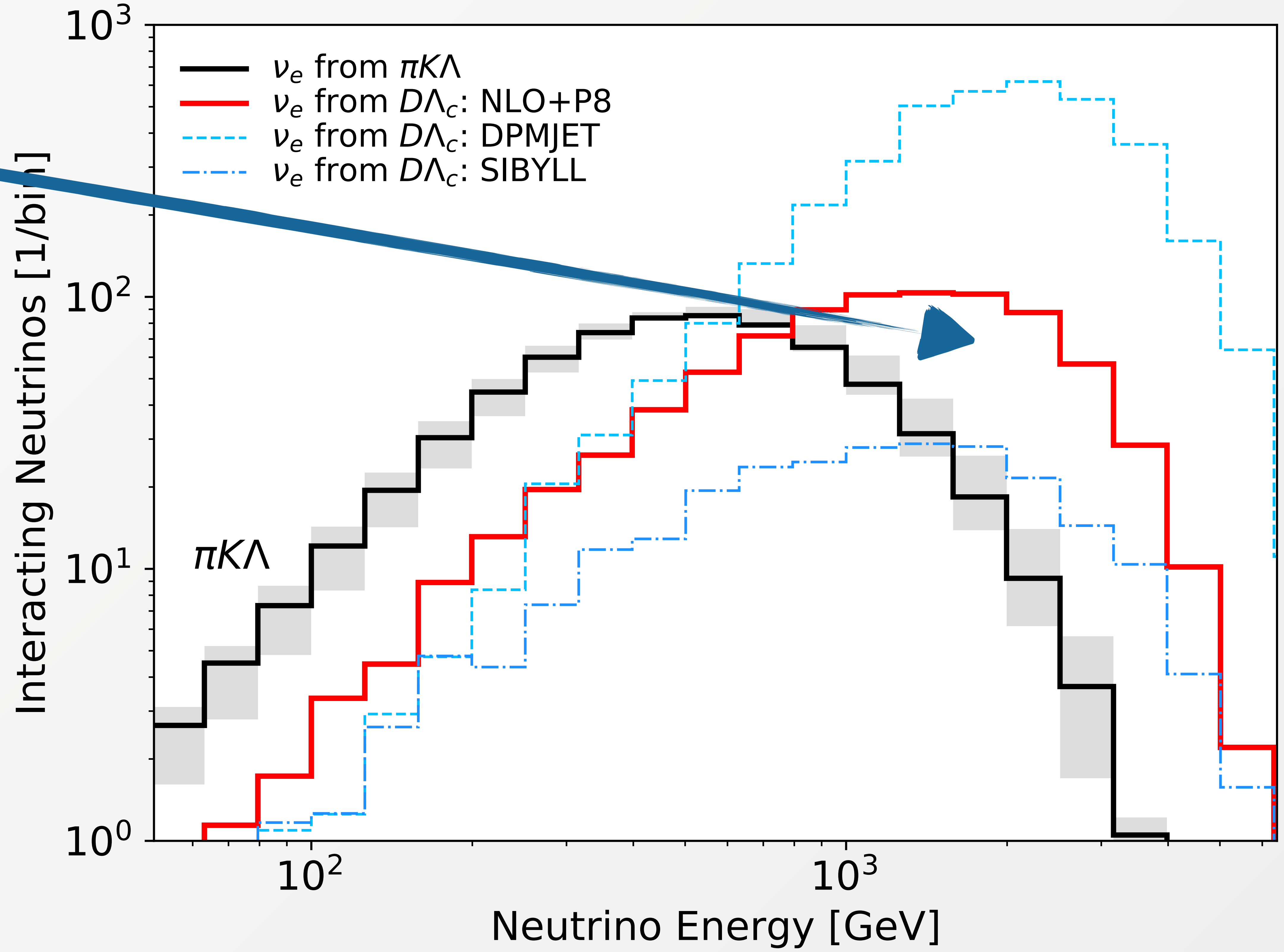
- DPMJET is part of the FLUKA package and is based on the dual parton model for the description of soft physics

Application 1: Neutrino fluxes at FASERν

Neutrino flux component from charm decay provides the **leading contribution for electron neutrinos** with energies above roughly 1 TeV

pQCD predictions error dominated by **scale uncertainties** of about a factor of two across the whole neutrino energy range

SIBYLL and DPMJET yield considerably smaller and larger predictions, respectively, which are **not covered** by the large uncertainties of the NLO+NLL$_x$ result



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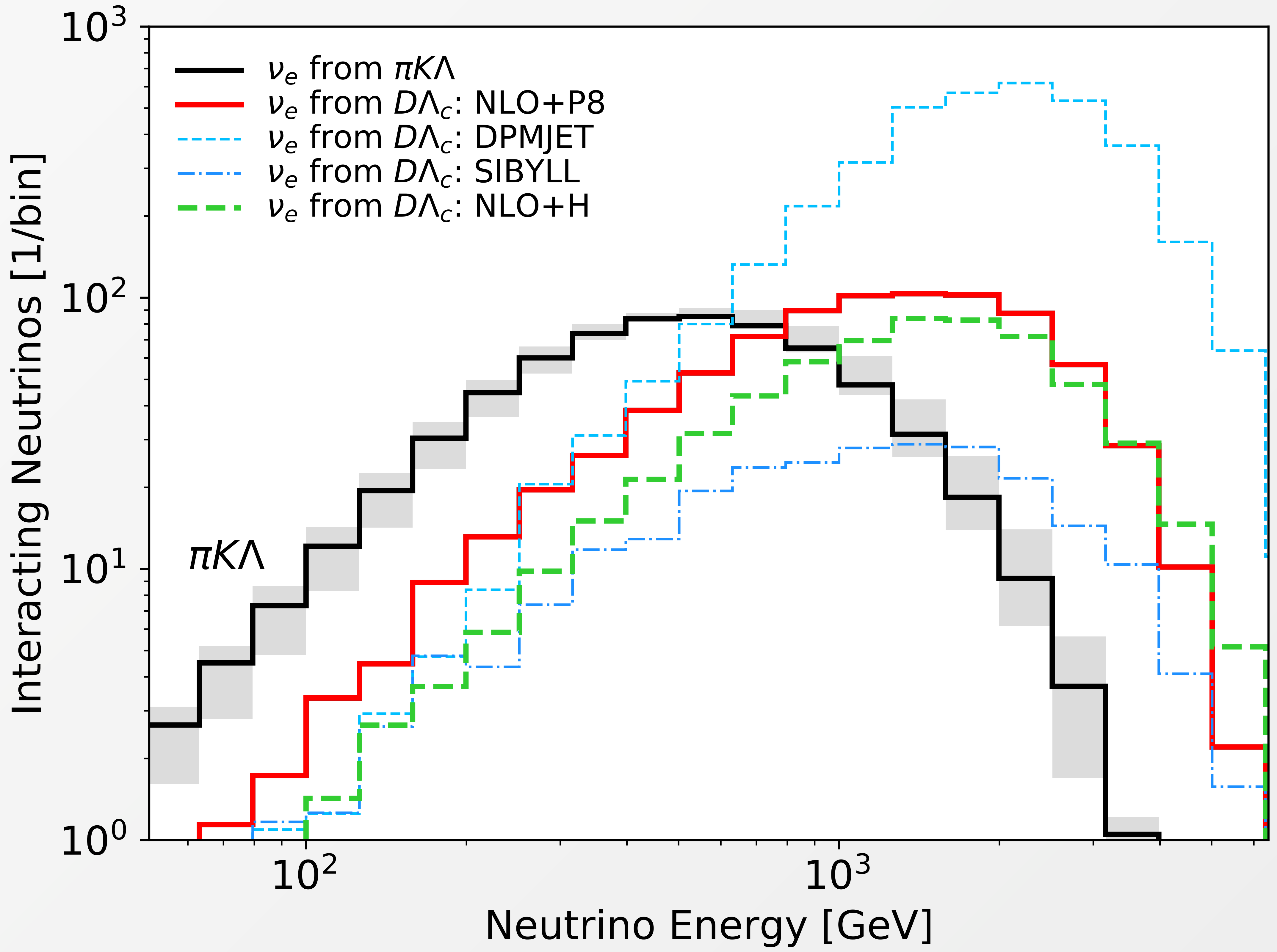
pQCD prediction relatively stable upon

- use of a different parton shower (PYTHIA vs HERWIG)



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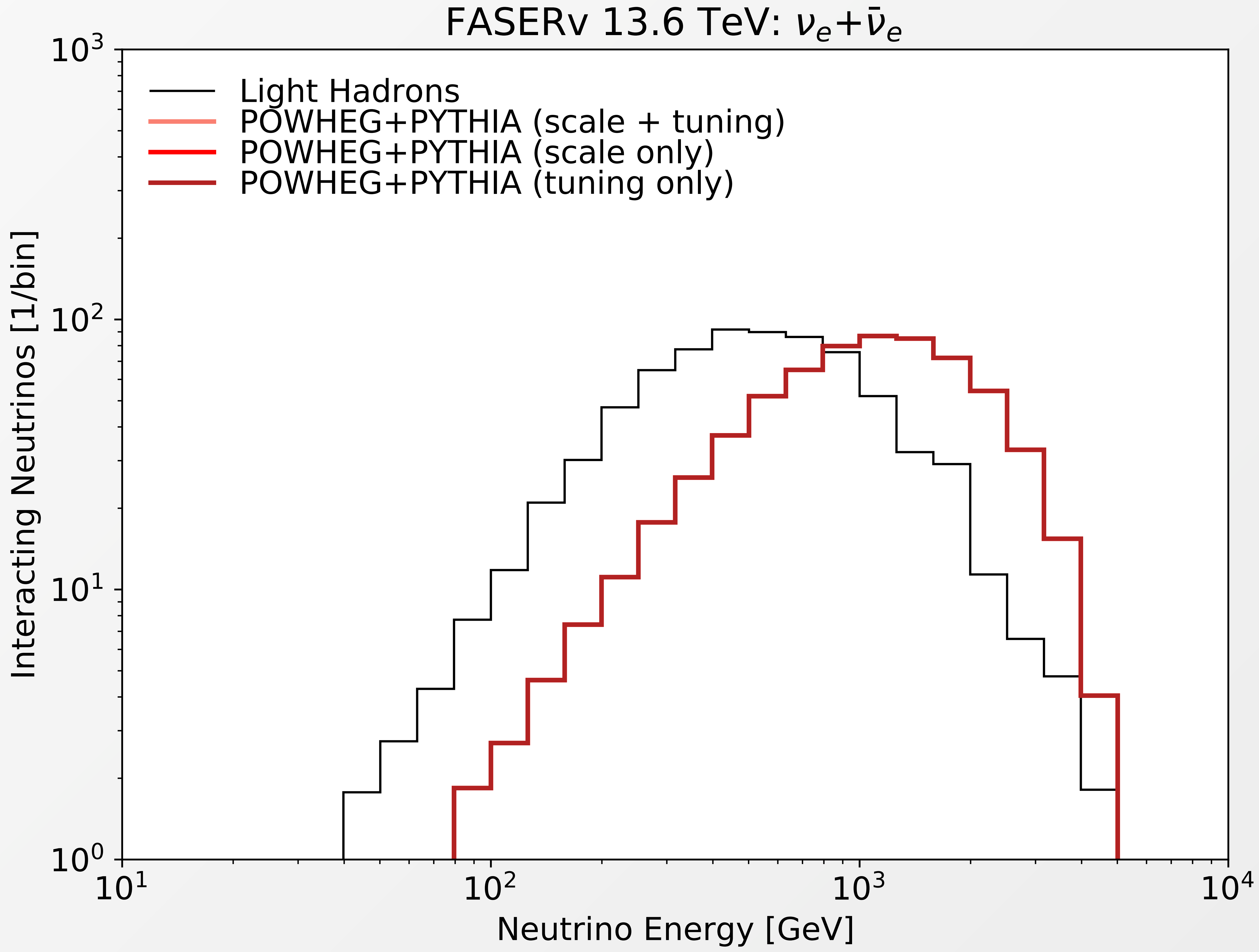
pQCD prediction relatively stable upon

- use of a different parton shower (PYTHIA vs HERWIG)
- Variation of the PYTHIA tune

Including recent forward tune [Fieg, Kling, Schulz, Sjöstrand '23]



Application 2: Electrophilic ALPs at FASER and FASER2

Other main objective of FASER is the search for light long-lived particles predicted by BSM models, notably ALPs

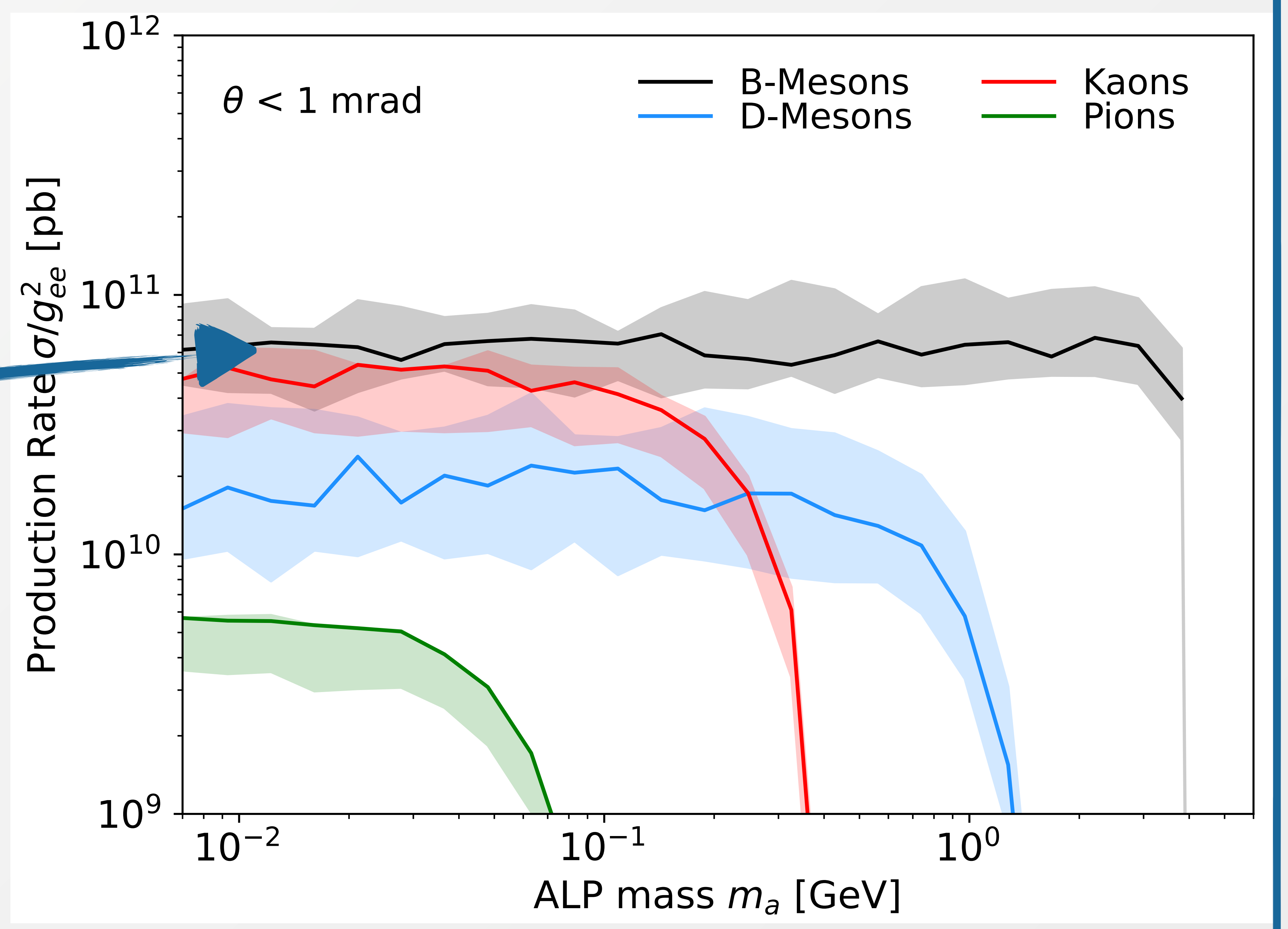
We consider an ALP with a dominant coupling to electrons (electrophilic ALP) with Lagrangian [Altmannshofer, Dror, Gori '22]

$$\mathscr{L} = \frac{g_{ee}}{2m_e}\partial_\mu a\bar{e}\gamma^\mu\gamma_5 e$$

For sufficiently small couplings g_{ee}, the ALP becomes long-lived, allowing it to travel a macroscopic distance before decaying in FASER

The ALP acquires couplings to the weak gauge bosons through the chiral anomaly which implies that it can be produced in flavor-changing hadron decays

In the forward region of the LHC, the dominant production channel of such are **rare *B*-meson** decays as well as kaon decays*



* light hadron production uncertainty obtained by computing the envelope of several MC generators originally developed for cosmic ray physics: EPOS-LHC (central), SYBILL, QGSJET

Application 2: Electrophilic ALPs at FASER and FASER2

For sufficiently small couplings g_{ee}, the ALP becomes long-lived, allowing it to travel a macroscopic distance before decaying in FASER

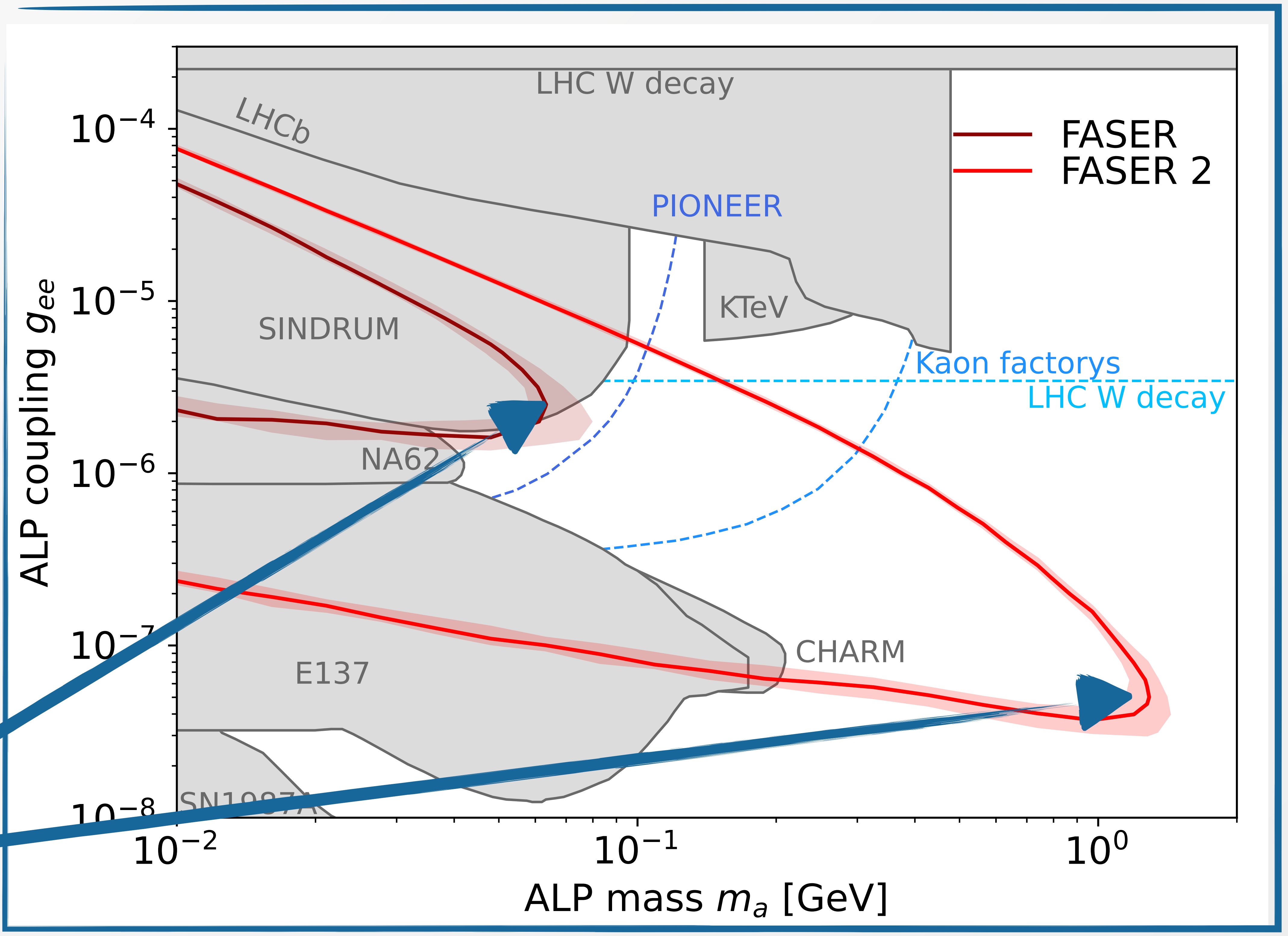
We assume that FASER and FASER2 can detect the signal with full efficiency and negligible background and we study the sensitivity to the ALP with the FORESEE package

We consider two scenarios:

FASER @LHC Run3 with 200 fb^{-1}

FASER2 @ HL-LHC with 3 ab^{-1}

Overall impact of the flux uncertainties remains relatively small and predominantly affect the reach at the high-mass end



FASER bound **competitive** with constraints from existing searches; FASER2 will extend this reach drastically, and be able to probe y**et unconstrained parameter-regions** up to ALP masses of 1 GeV

Conclusion and discussion

Precise predictions for **forward hadron fluxes** and associated uncertainties are essential ingredients for physics studies at present and future forward experiments

Kinematics in the forward region requires understanding of QCD in the small-*x* region and the assessment of relevant uncertainties

- PDF behaviour at small-*x*
- Interplay with high-energy resummation

State-of-the-art pQCD results @ NLO+NLL$_x$+PS used for reliable predictions of **neutrino fluxes** and searches for new particles produced predominantly in heavy meson decays

Prospects: ingredients for NNLO predictions for hadro-production and matching with NLL$_x$ resummation are becoming available, allowing for pushing further the precision frontier in the forward region

Backup

Electrophilic ALPs

$$\mathcal{L}_a = a g_{ee} \left(\bar{e} i \gamma_5 e + \frac{e^2}{16\pi^2 m_e} \left[\frac{1}{4 s_W^2} W^+_{\mu\nu} \tilde{W}^{-,\mu\nu} - F_{\mu\nu} \tilde{F}^{\mu\nu} \right] + \frac{ig}{2\sqrt{2} m_e} \bar{e} \gamma^\mu P_L \nu W^-_\mu + \ldots \right) .$$

ALP can be produced in two- and three-body meson decays

$$\begin{aligned}
\mathrm{BR}_{K^\pm \to \pi^\pm a} &= 45 \times g_{ee}^2 \times \lambda^{1/2}_{m_{K^+}, m_{\pi^+}, m_a} \,, \\
\mathrm{BR}_{K_L \to \pi^0 a} &= 27 \times g_{ee}^2 \times \lambda^{1/2}_{m_{K^0}, m_{\pi^0}, m_a} \,, \\
\mathrm{BR}_{K_S \to \pi^0 a} &= 0.3 \times g_{ee}^2 \times \lambda^{1/2}_{m_{K^0}, m_{\pi^0}, m_a} \,, \\
\mathrm{BR}_{B \to X_s a} &= 1.6 \cdot 10^5 \times g_{ee}^2 \times \lambda_{m_B, 0, m_a} \,.
\end{aligned}$$

$$\frac{d\mathrm{BR}(P^\pm \to e \nu_e a)}{dE_a} = C_P \, g_{ee}^2 (E_a^2 - m_a^2)^{\frac{3}{2}} ,$$

$$C_P = \frac{\mathrm{BR}(P^\pm \to \ell'^+ \nu_{\ell'})}{24\pi^2 m_e^2 m_{\ell'}^2} \lambda^{-1}_{P,\ell',0} ,$$

Electrophilic ALPs

$$\Gamma_{a\to ee} = \frac{g_{ee}^2 m_a}{8\pi}\sqrt{1 - \frac{4m_e^2}{m_a^2}}$$

$$\Gamma_{a\to\gamma\gamma} = \frac{\alpha^2 g_{ee}^2 m_a^3}{64\pi^3 m_e^2}.$$

ALPs in the sensitivity region of FASER will predominantly decay into electron pairs. Decay into photons will only become relevant at FASER2.

Electrophilic ALPs

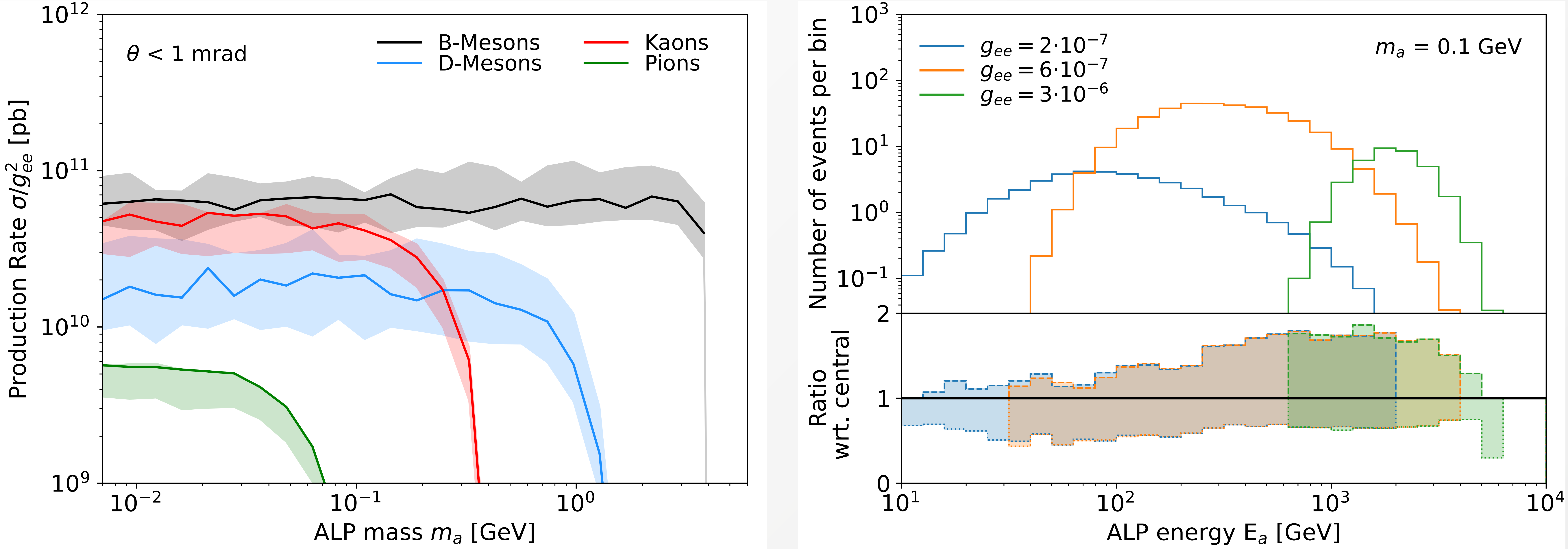


FIG. 5. **Left:** ALP production rate via decay of various mesons as a function of ALP mass m_a at a angular acceptance $\theta < 1$ mrad. The lines show the sum of all production channels of the respective meson. The uncertainty band was derived by varying the scales for charm and beauty mesons, and by varying the generators for pions and kaons as discussed in Sec. II. **Right:** Expected energy spectrum of ALPs decaying in the FASER2 decay volume for three different ALP benchmark models. The shaded band corresponds to the flux uncertainty. The lower panel shows the same flux normalized by the central predictions.

ALP production in beauty hadron decays

$$g_{asb} = -\frac{g_{ee}}{m_l}\frac{3m_W^2 m_b m_t^2 V_{ts}^* V_{tb}}{128\pi^4 v^4}\, f\left(\frac{m_t^2}{m_W^2}\right)$$

Spectator Model

Used in B-physics experiments; not expected to be valid close to the kinematic end-point

$$\mathrm{BR}_{B\to X_s a} = \frac{1}{\Gamma_B}\frac{(m_B^2 - m_a^2)^2}{32\pi\, m_B^3}\left|g_{asb}\right|^2$$

Exclusive Model

expected to underestimate the inclusive decay width at lower masses

sum over the exclusive branching fractions for decays of the type $B \to K_i\, a$

Rescaled Model

not expected to capture the right mass dependence

$$\mathrm{BR}_{B\to X_s a} \;\approx\; 5 \times (\mathrm{BR}_{B\to K a} + \mathrm{BR}_{B\to K^* a})$$

ALP production in beauty hadron decays