The structure of the proton in the LHC high-precision era

Juan Rojo
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Theoretical High-Energy Physics seminar

Lund University, 19/10/2018

The inner life of protons

See also ``The structure of the proton in the LHC precision era''

Gao, Harland-Lang, JR (Physics Reports 17)

Open questions in particle physics

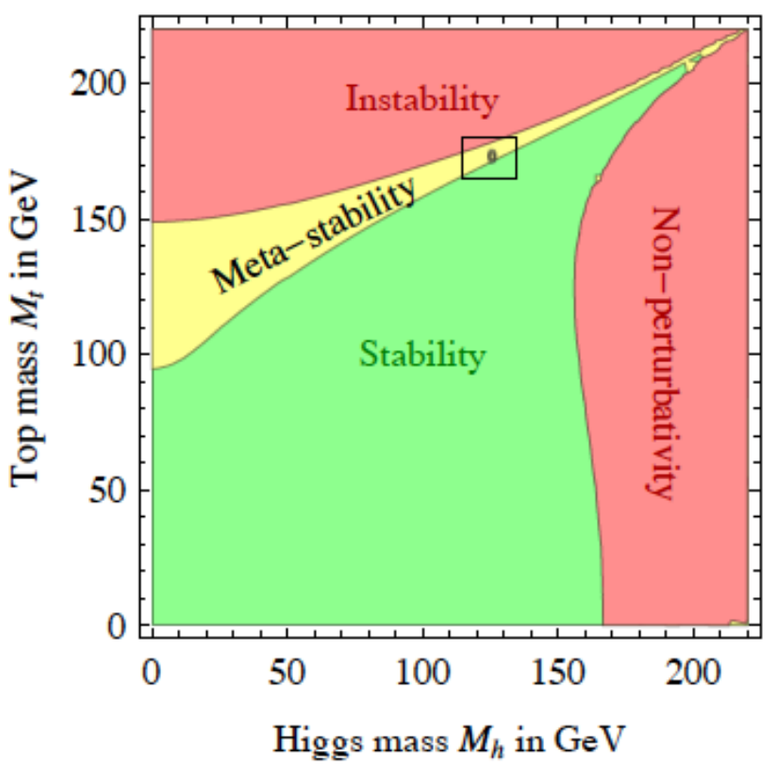
The Higgs boson

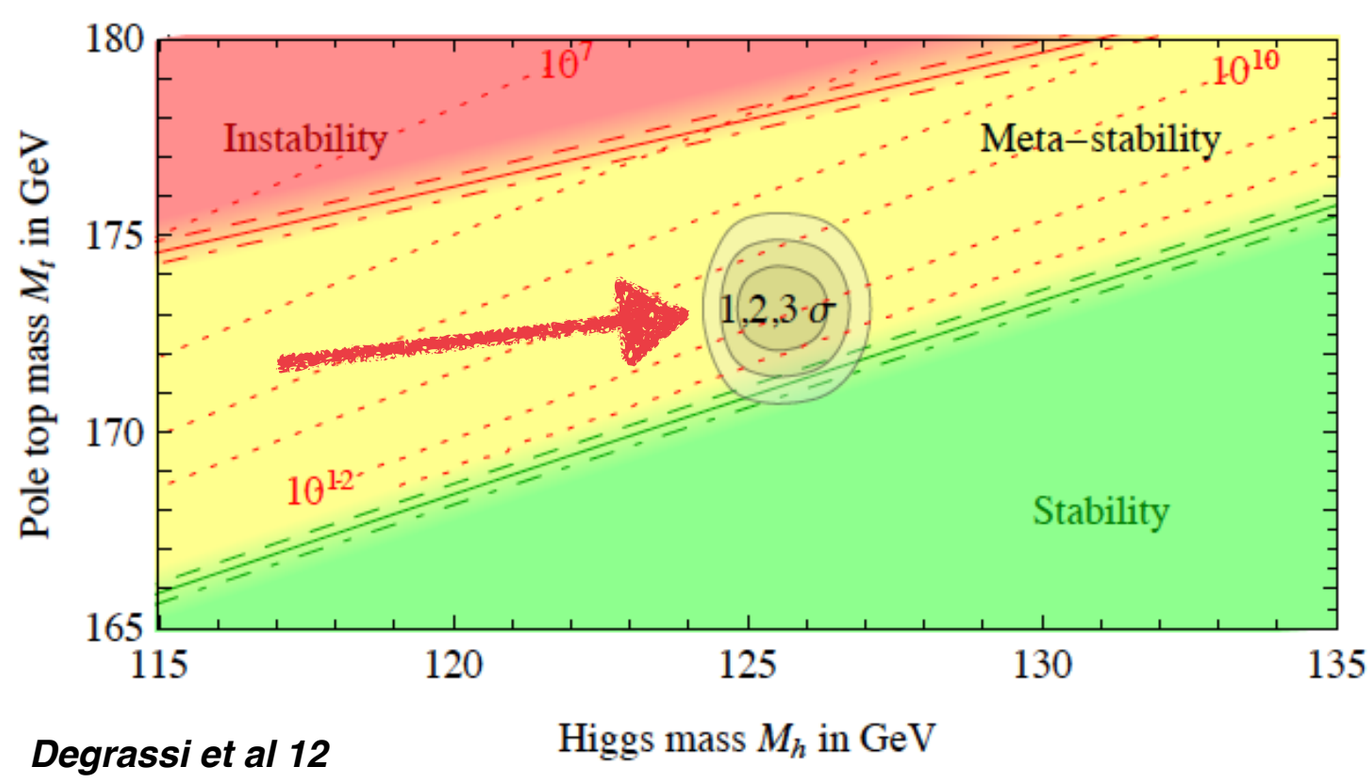
- Huge gap between **Higgs and Plank scales?**
- **Elementary or composite**? More Higgs bosons?
- Coupling to **Dark Matter**? Role in cosmological phase transitions?
- Is the **vacuum state of the Universe** stable?

- **10^{19} GeV** (Planck scale)

With radiative corrections, the natural value of the Higgs mass is Planck scale

- **125 GeV** (Higgs mass)
- 1 GeV (Proton mass)





Degrassi et al 12

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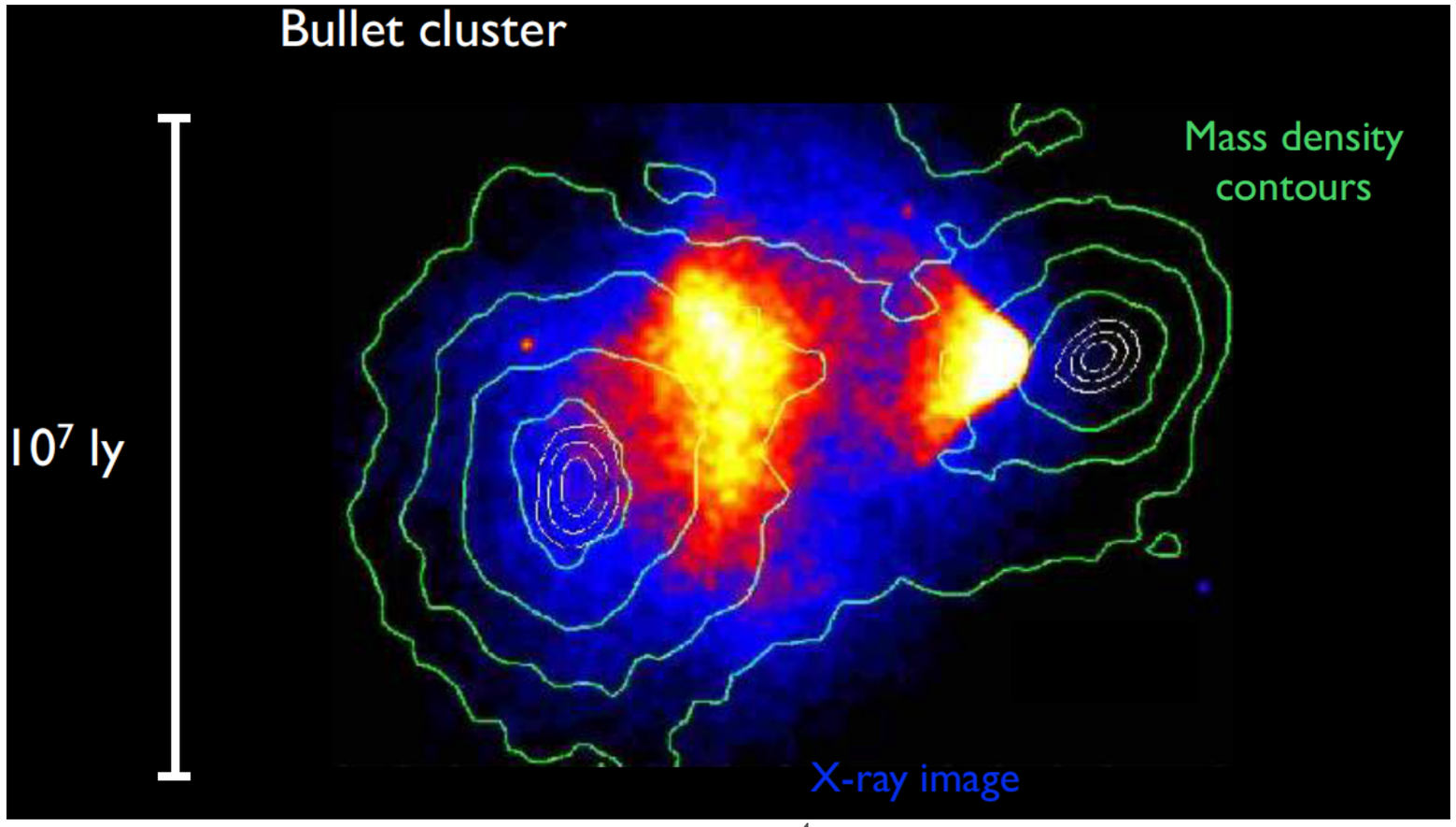
Dark matter

- **Weakly interacting massive particles**? Neutrinos? Ultralight particles (axions)?
- **Interactions** with SM particles? Self-interactions?
- **Structure** of the Dark Sector?



Open questions in particle physics

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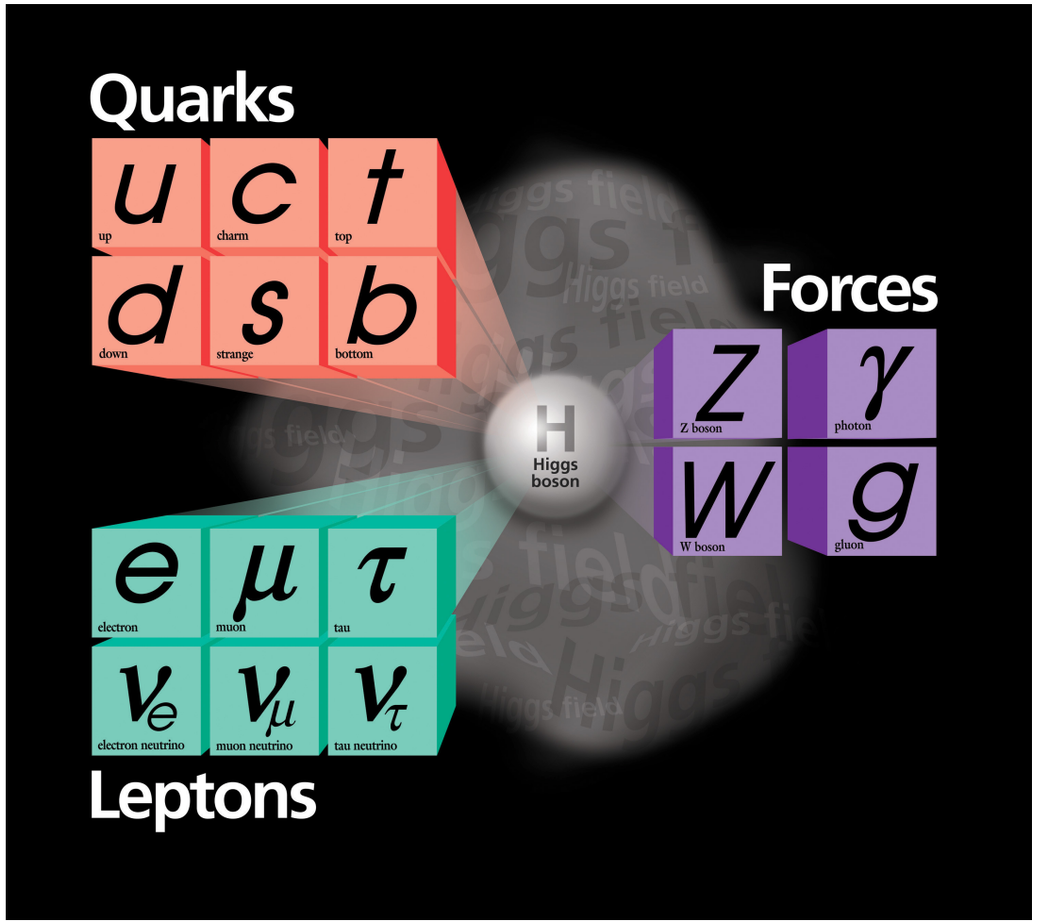
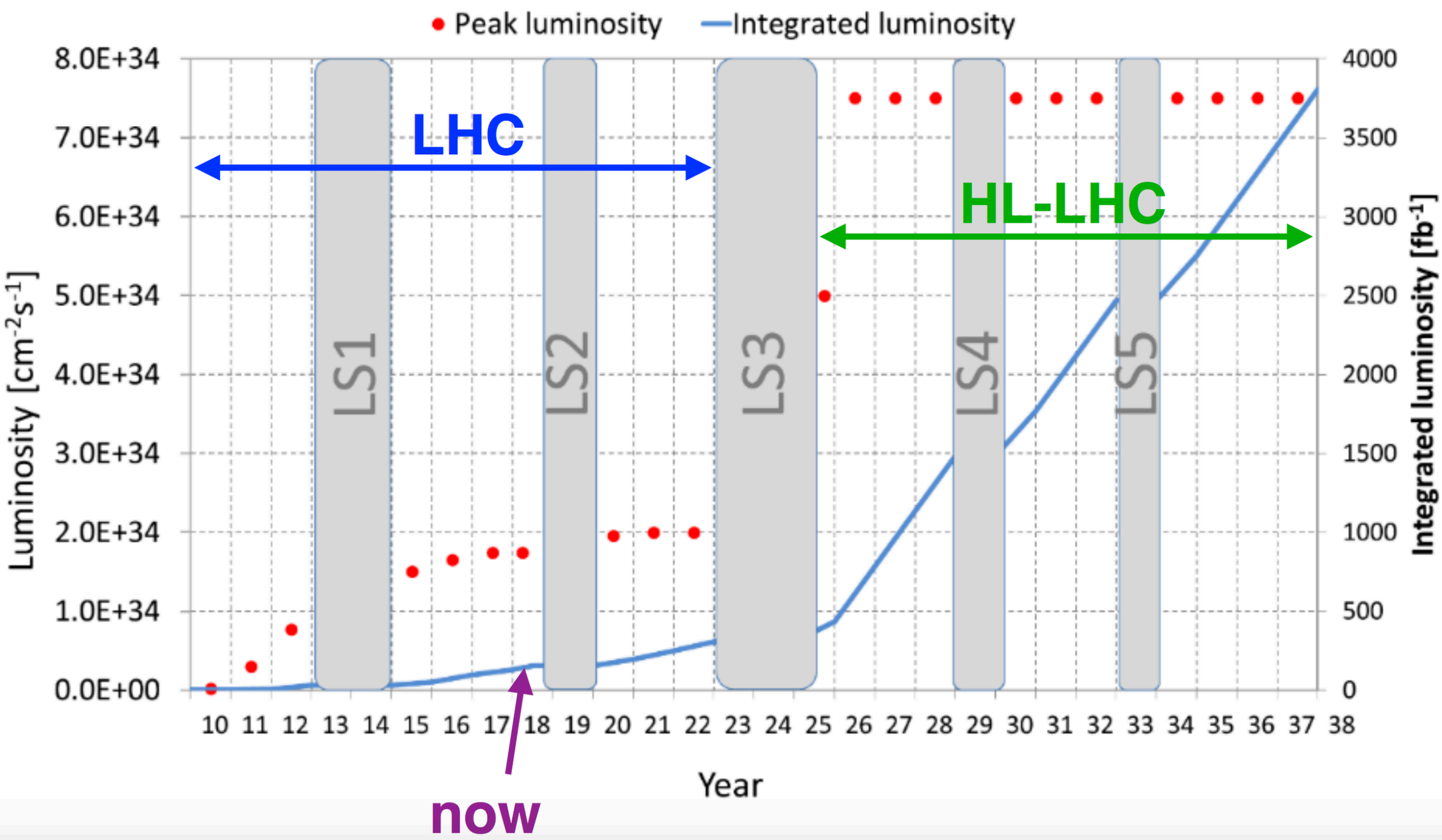
Quarks and leptons

- Why **3 families?** Origin of **masses, mixings**?
- Origin of **Matter-Antimatter asymmetry?**
- Are **neutrinos Majorana or Dirac**? CP violation in the lepton sector?



Open questions in particle physics



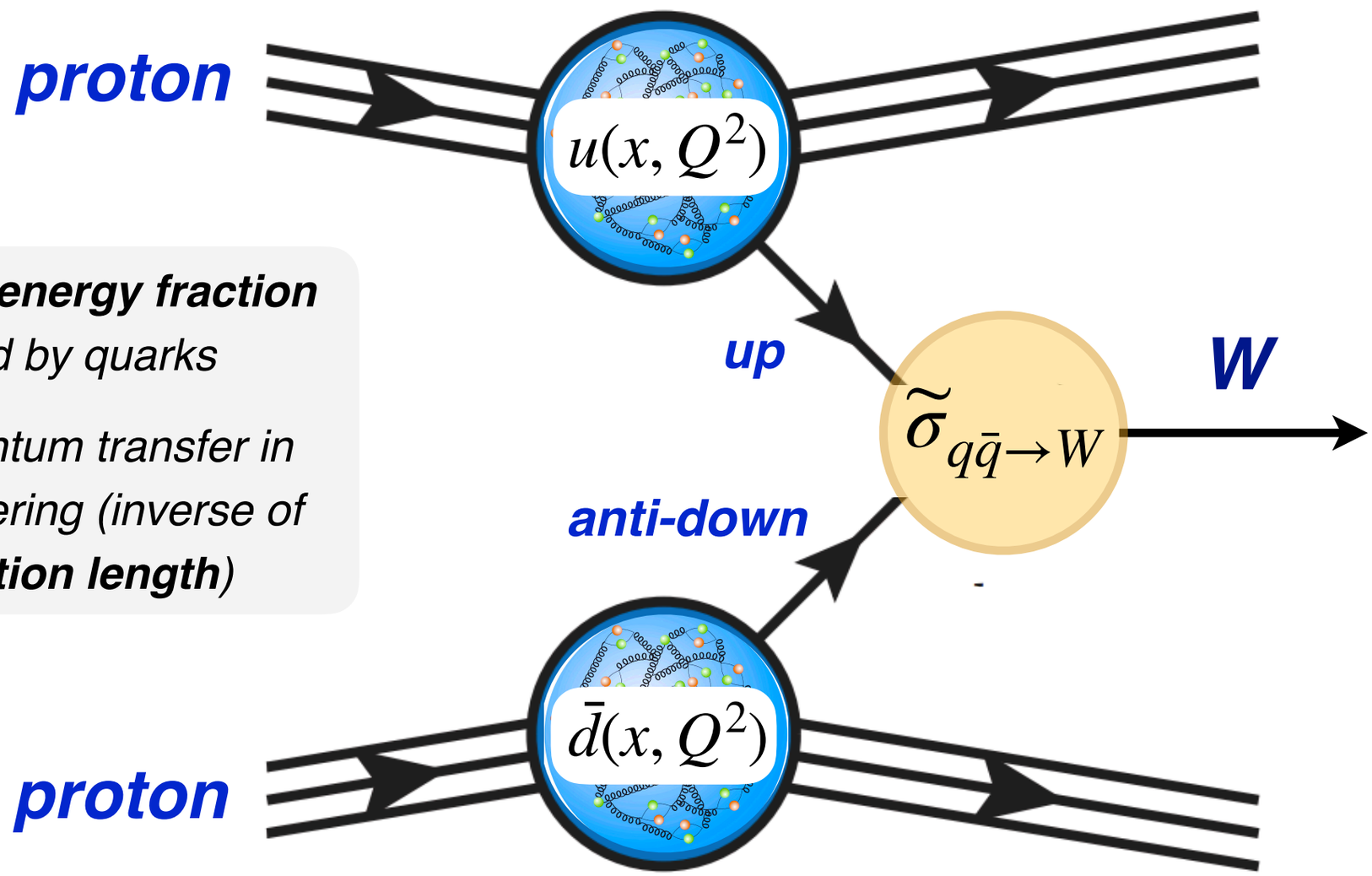
Crucial information on these fundamental questions will be provided by the LHC: the **exploration of the high-energy frontier** has just started!

Parton distributions @ LHC

QCD Factorisation theorem:

Event rates = **parton distributions** + hard-scattering partonic cross-sections

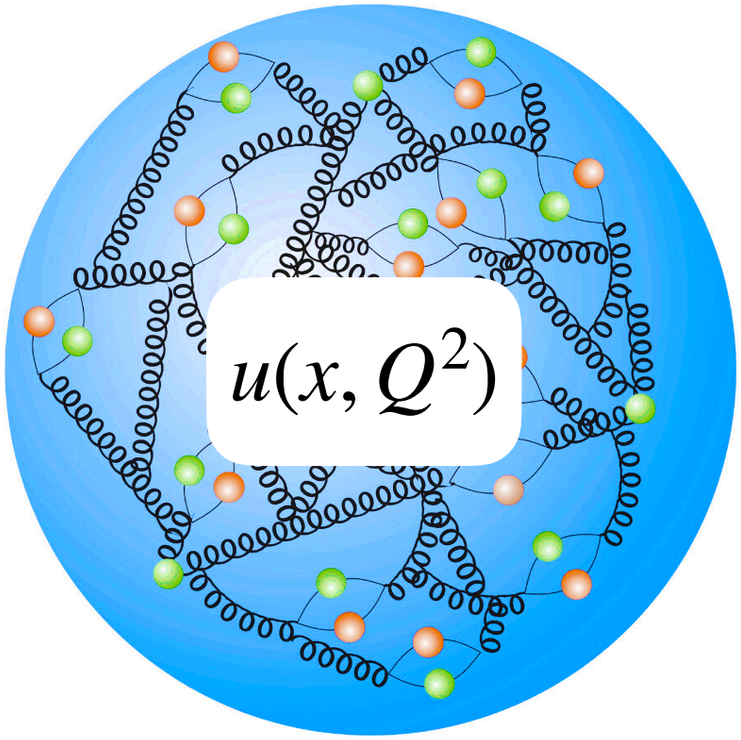
$$N_{\rm LHC}(W) \sim q \otimes \bar{q} \otimes \widetilde{\sigma}_{q\bar{q}\to W} + \mathcal{O}(\alpha_s)$$



x: *proton's* ***energy fraction*** *carried by quarks*

Q: *momentum transfer in hard scattering (inverse of* ***resolution length****)*

Parton distributions @ LHC



Challenging to compute **from first principles**

Determine from data:

Global QCD analysis

Mass? Spin?

Heavy quarks?

Event rates LHC,

RHIC, IceCube?

DGLAP evolution

(*upwards in Q*)

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

Momentum sum rule

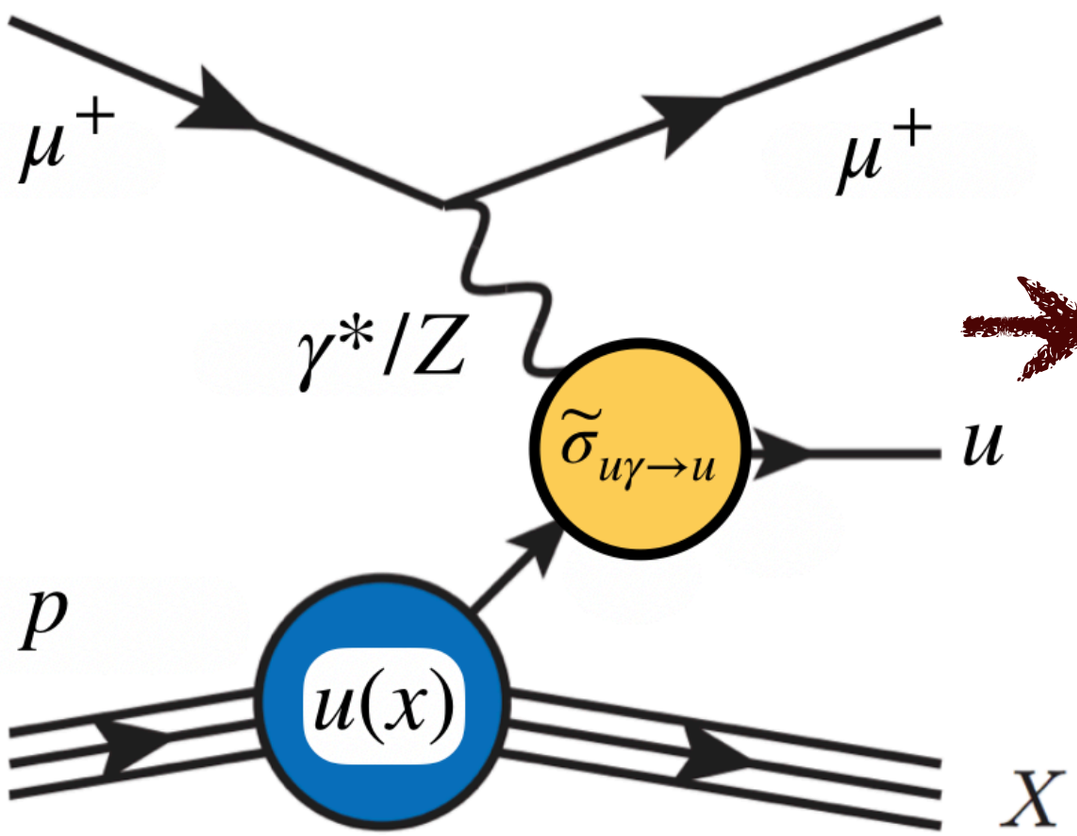
(*energy conservation*)

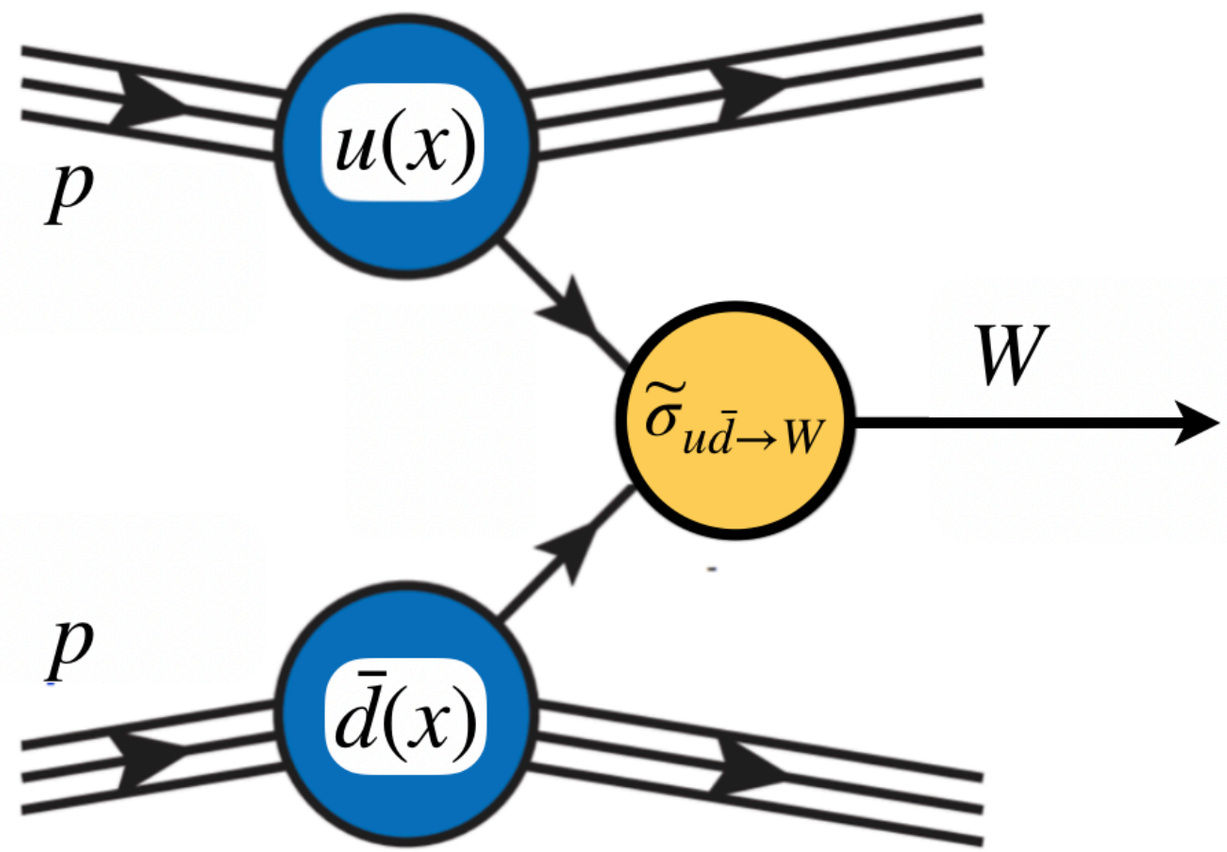
$$\int_0^1 dx\, x \left(\sum_{i=1}^{n_f} (q_i((x, Q^2) + \bar{q}_i(x, Q^2)) + g(x, Q^2) \right) = 1$$

QCD factorisation

The **QCD factorization theorems** guarantees **PDF universality**

$$\sigma_{l\,p\to\mu\,X} = \widetilde{\sigma}_{u\gamma\to u} \otimes u(x) \;\rightarrow\; \sigma_{p\,p\to W} = \widetilde{\sigma}_{u\bar{d}\to W} \otimes u(x) \otimes \bar{d}(x)$$





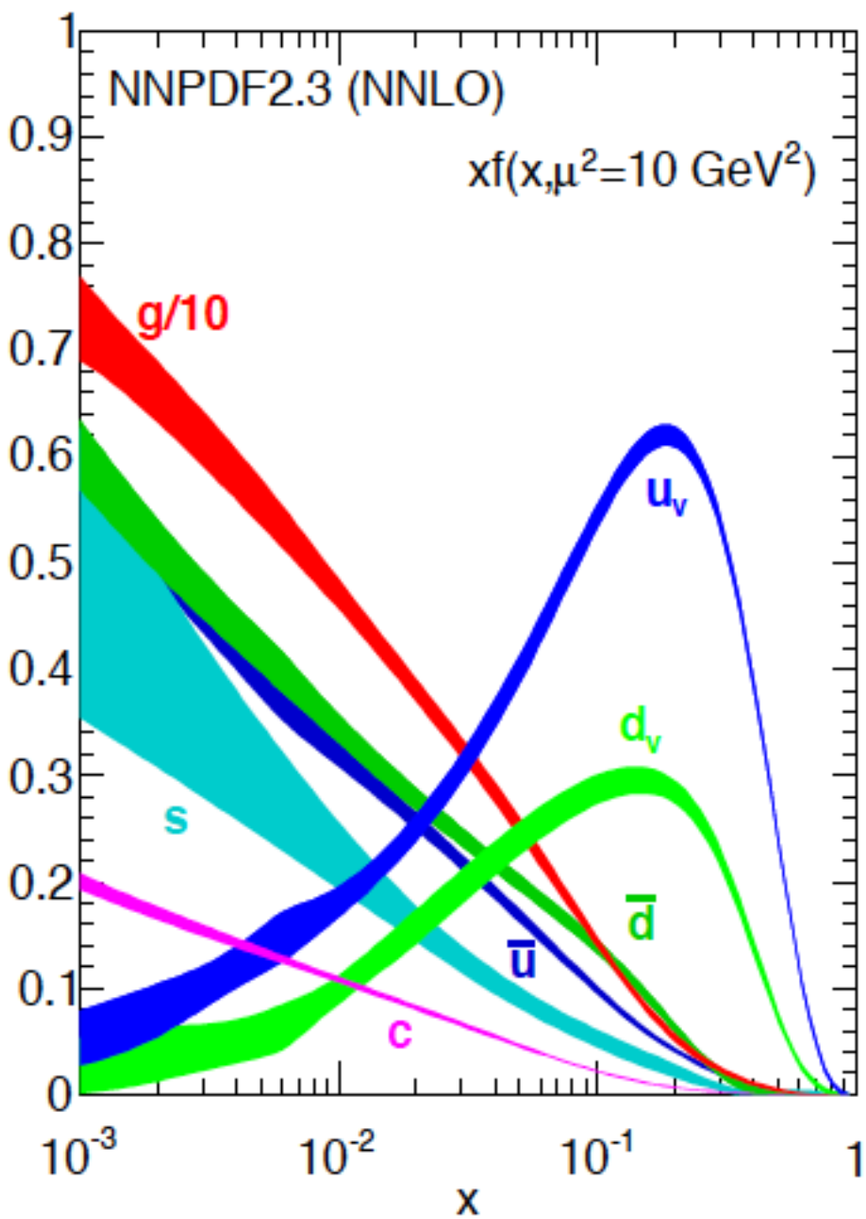
*Determine PDFs in **lepton-proton collisions** (deep-inelastic scattering) …*

*… and use them to compute predictions for **proton-proton collisions***

From the proton mass to the LHC

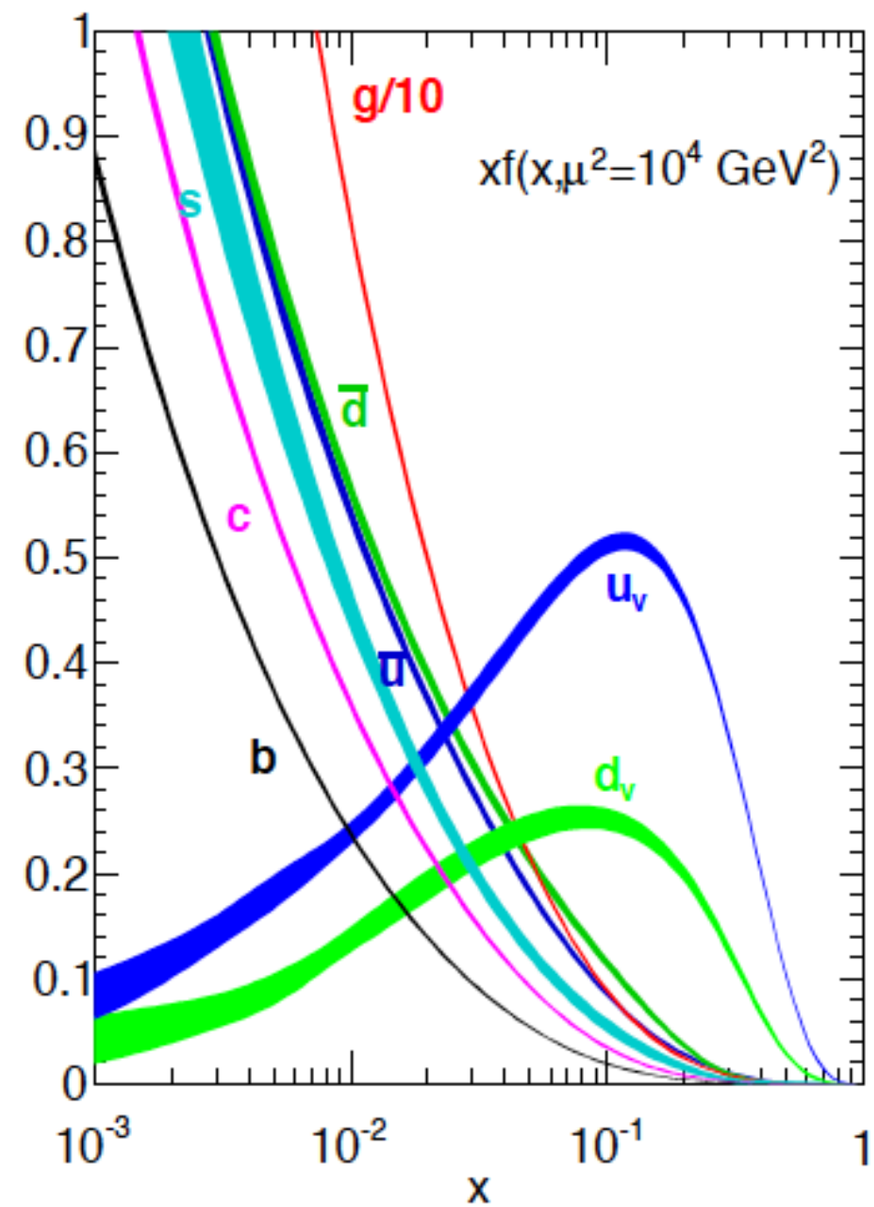
- **Extract PDFs** at hadronic scales (few GeV**),** where **non-perturbative QCD** sets in
- Use **perturbative evolution** to compute PDFs at high scales as **input to LHC predictions**

Hadronic scale:
Global PDF fit results

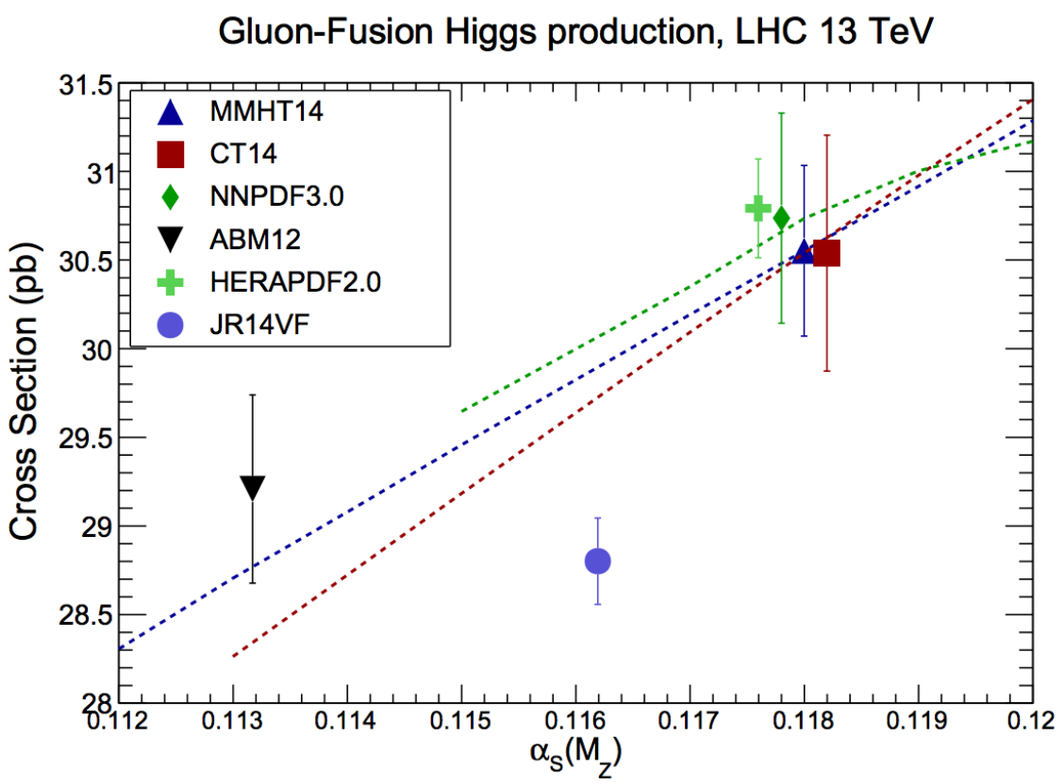


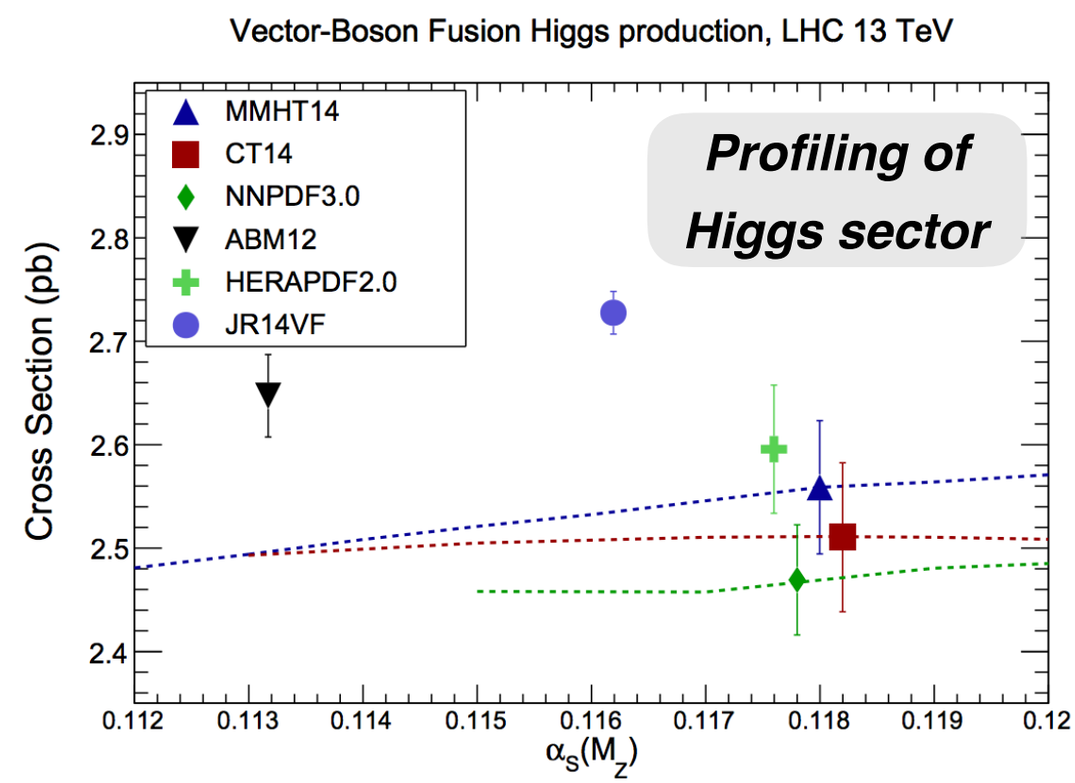
Evolution

High scales:
input to LHC

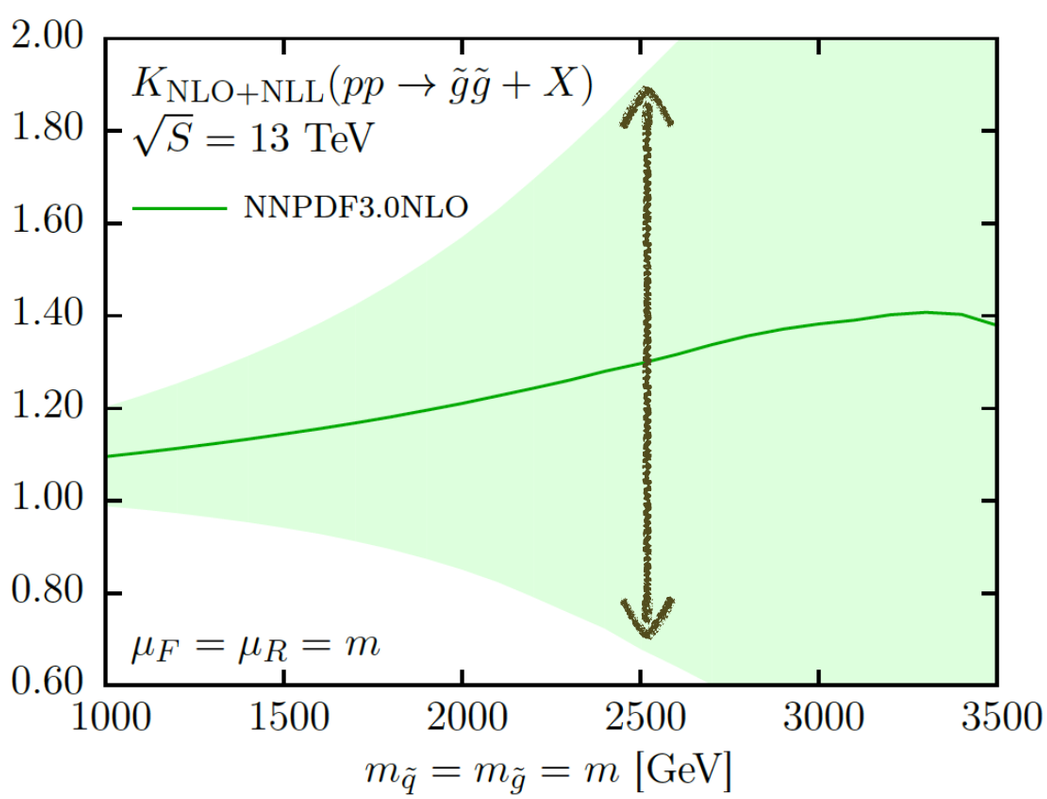


Why better PDFs?

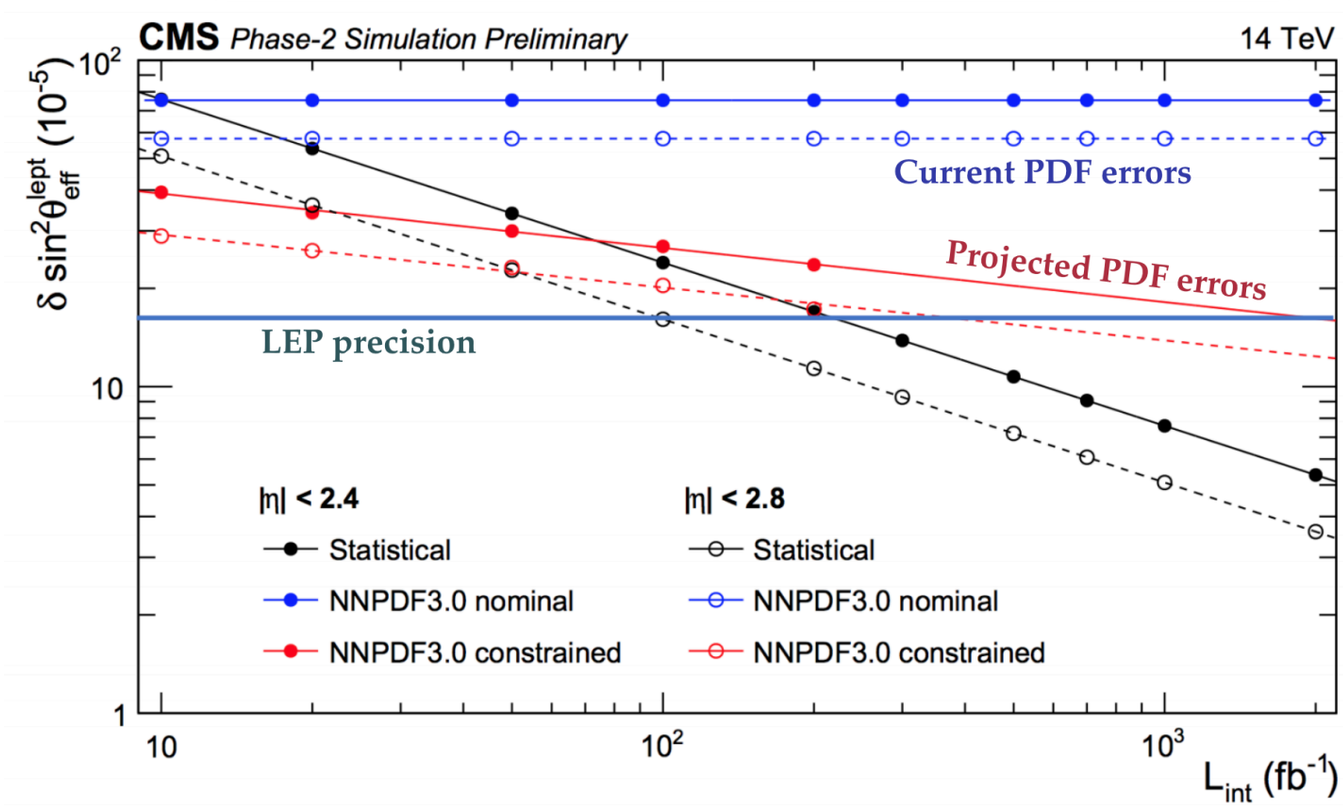




High-mass bSM searches



Precision electroweak measurements



Parton Distributions and the SMEFT

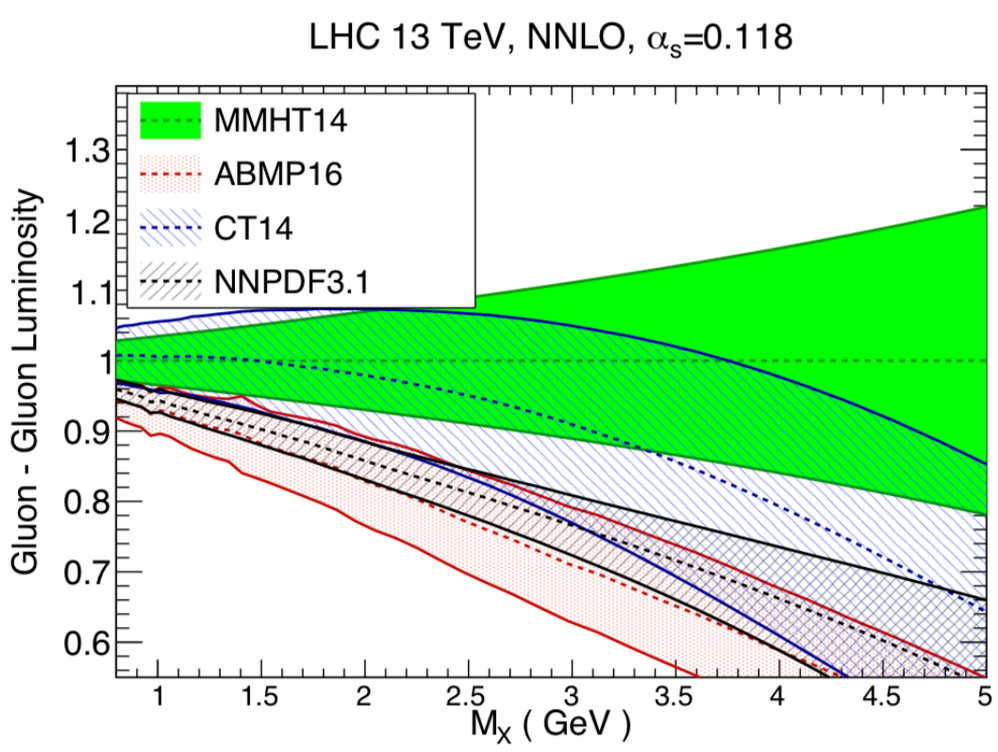
Heavy bSM states **beyond direct reach** can still modify LHC cross-sections

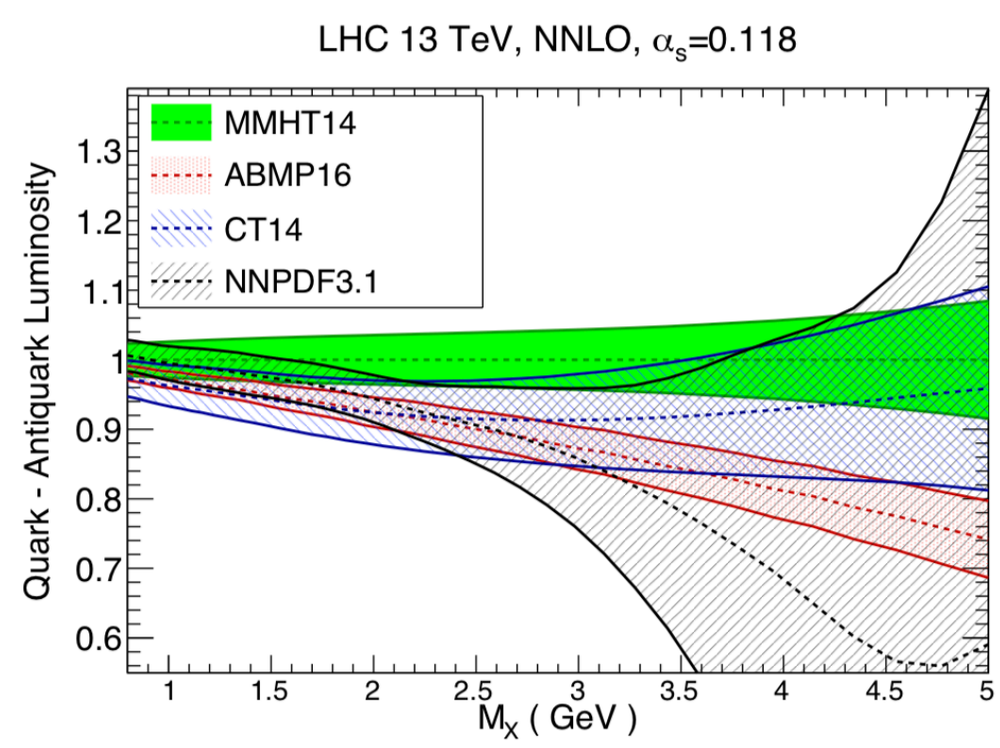
$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4}\mathcal{O}_j^{(8)} + \ldots$$

Some operators induce **energy-growing effects**: exploit unique LHC kinematic reach

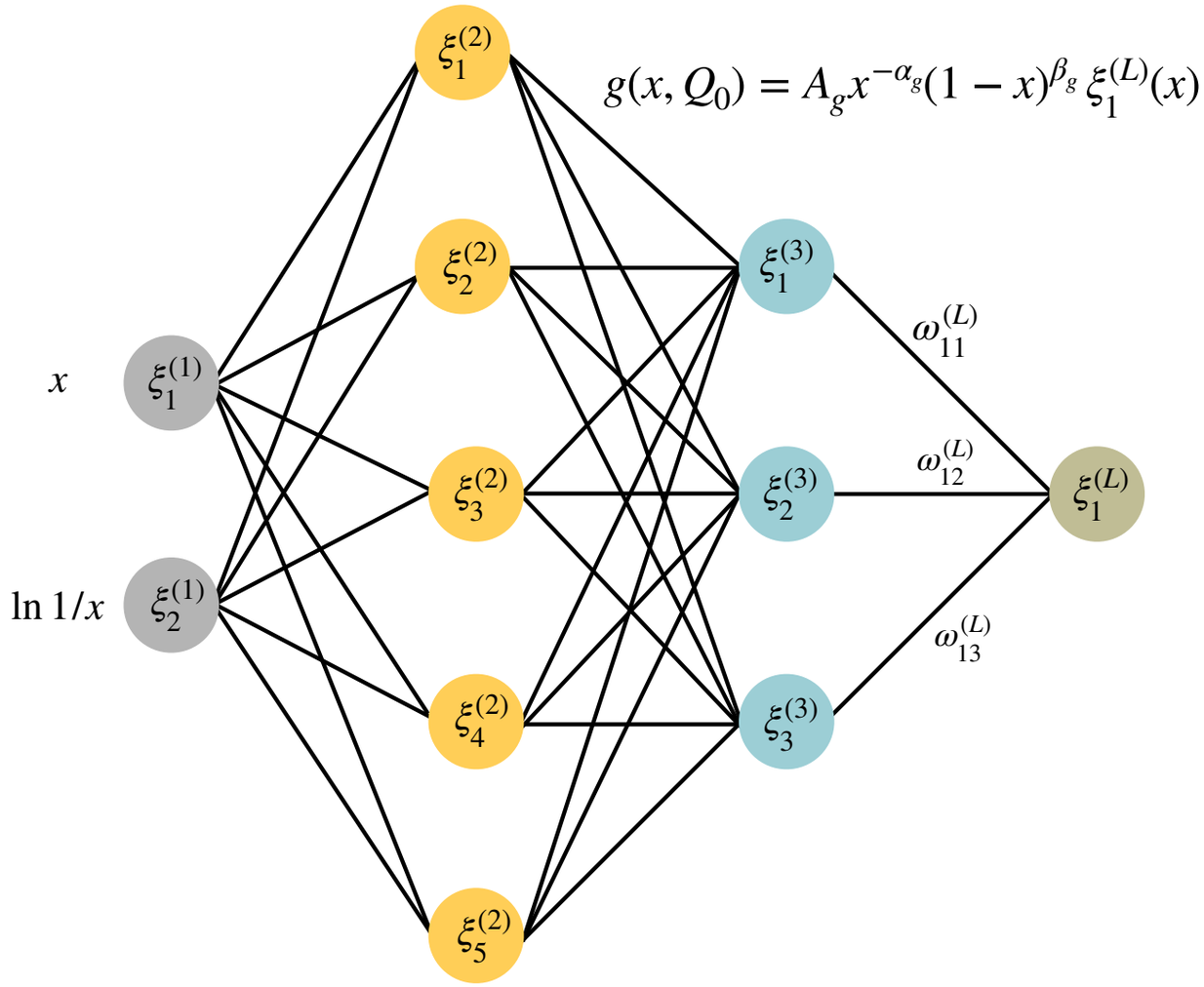
$$\sigma(E) = \sigma_{\rm SM}(E)\left(1 + \sum_i^{N_{d6}} \omega_i \frac{c_i\, m_{\rm SM}^2}{\Lambda^2} + \sum_i^{N_{d6}} \widetilde{\omega}_i \frac{c_i\, E^2}{\Lambda^2} + \mathcal{O}\left(\Lambda^{-4}\right)\right)$$

*but PDF errors blow up at **large masses!***





The NNPDF approach to PDF fits



- **Neural Networks** as universal unbiased interpolants to **parametrise PDFs:** eliminate model assumptions
- **Monte Carlo replicas** to propagate uncertainties wo Gaussian assumptions
- **Genetic algorithms** and **Machine Learning** to explore parameter space

	Proton PDFs	***Nuclear PDFs***
Traditional	$g(x) \simeq x^{-b}(1-x)^c$	$R_g(x, A) \simeq (1 + bx + cx^2) \times A^d$
Neural Nets	$g(x) \simeq \mathrm{NN}(x)$	$R_g(x, A) \simeq \mathrm{NN}(x, A)$

The NNPDF approach to PDF fits

Experimental data

Fixed-target & collider DIS
Tevatron and LHC measurements
Jets, DY, top, Z pT, ...

Statistical framework

PDF parametrisation,
PDF uncertainties and propagation
Model and theory uncertainties

Theory calculations

The global QCD fit

Minimise figure of merit (*) and determine PDF parameters

fit validation, statistical estimators, diagnosis tools

APFEL WEB

http://apfel.mi.infn.it/
on-line plotting toolbox

LHAPDF

lhapdf.hepforge.org

standard interface for public PDF delivery

$$^{(*)}\chi^2\left(\{a_i\}\right) = \sum_{m,n=1}^{N_{\rm dat}} \left(\sigma_m^{(\rm exp)} - \sigma_m^{(\rm th)}\left(\{a_i\}\right)\right) \left(\rm cov_{\rm exp} + \rm cov_{\rm th}\right)^{-1}_{mn} \left(\sigma_n^{(\rm exp)} - \sigma_n^{(\rm th)}\left(\{a_i\}\right)\right)$$

APPLgrid, FastNLO, aMCfast....

NNLO DGLAP evolution
DIS structure functions

APFEL, HOPPET, QCDNUM, ...

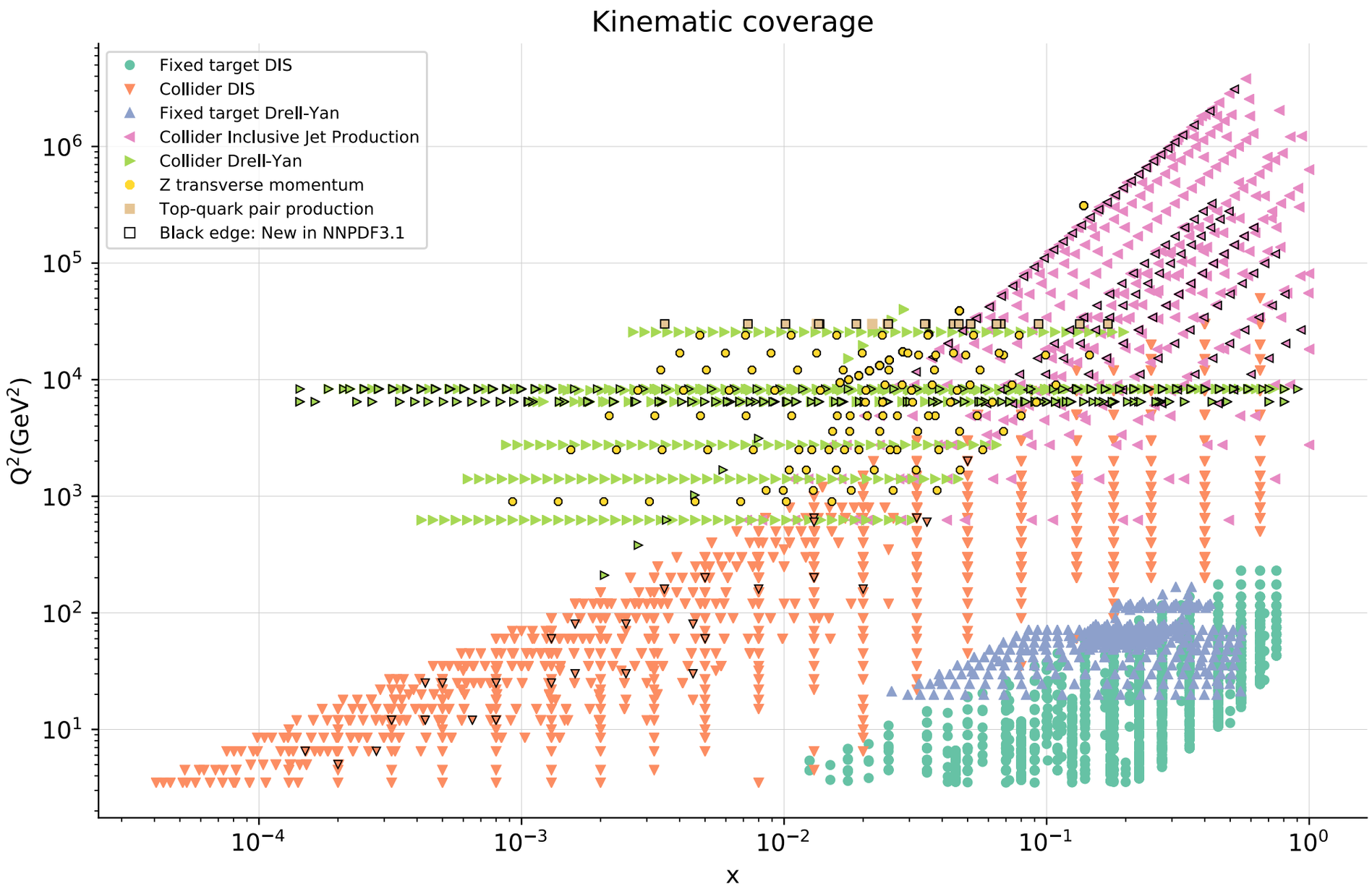
Fast NLO grids
NNLO QCD &
NLO EW K-factors

External (N)NLO codes

MCFM, NLOjet++, FEWZ, DYNNLO, private codes...

*Combine **precision measurements** and **state-of-the-art theory** within robust statistical framework*

The NNPDF approach to PDF fits



Highly non-trivial validation of the **QCD factorisation framework**:

Including **O(5000) data** points, from **O(40) experiments**, some of them with ≲**1% errors**,

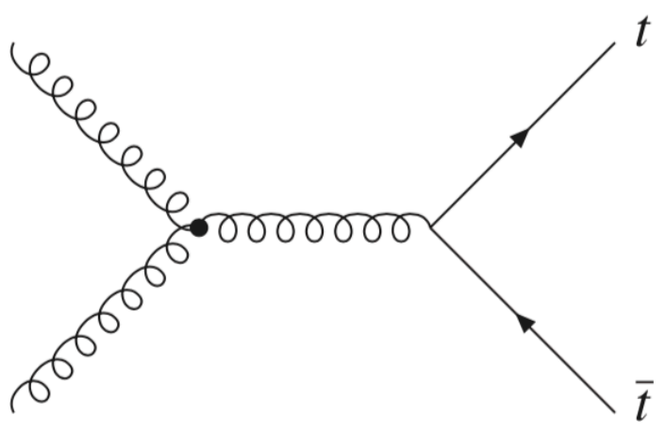
yet the global PDF fit achieves $\chi^2/N_{dat} \approx 1$!

PDF constraints from precision LHC data

PDF information from p+p collisions

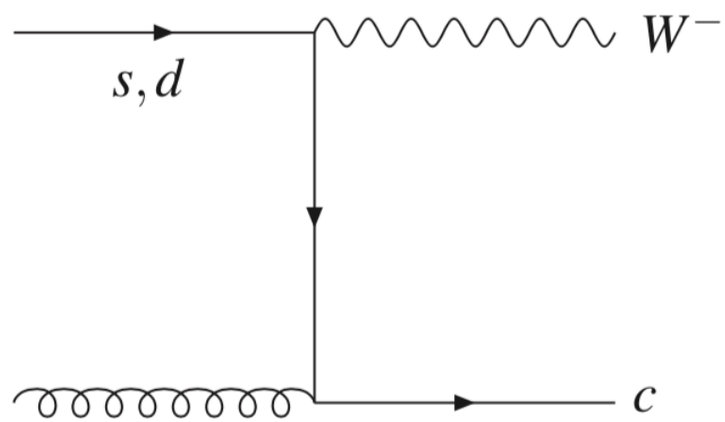
large-x gluon

Top quark pair production



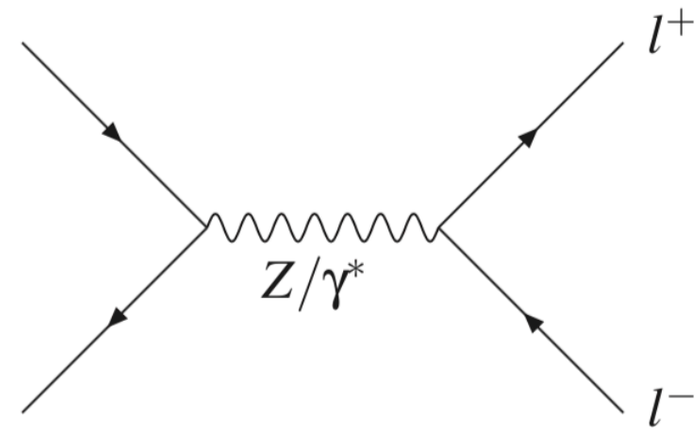
strangeness

$W + c$ production

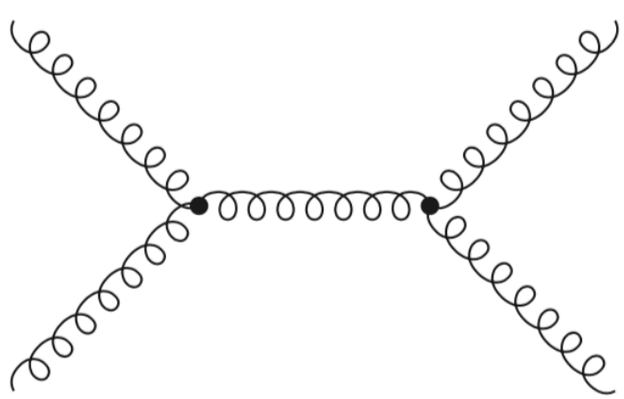


antiquarks

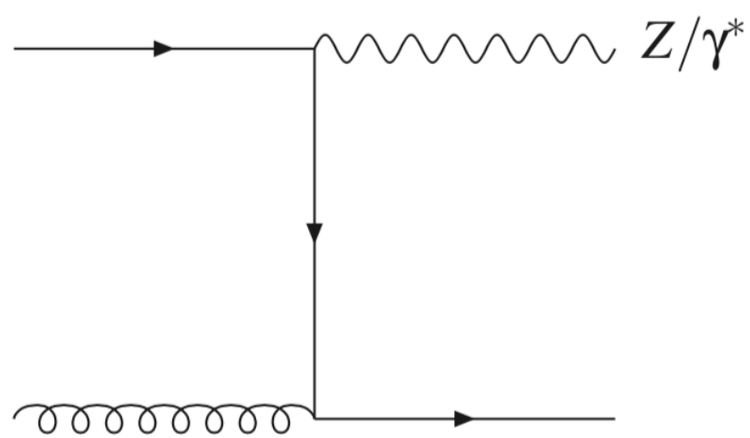
Drell–Yan production



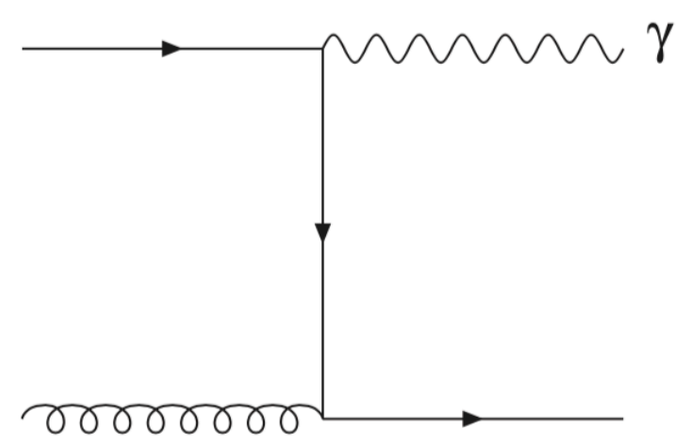
Jet production



$Z\ p_T$



Direct photon production

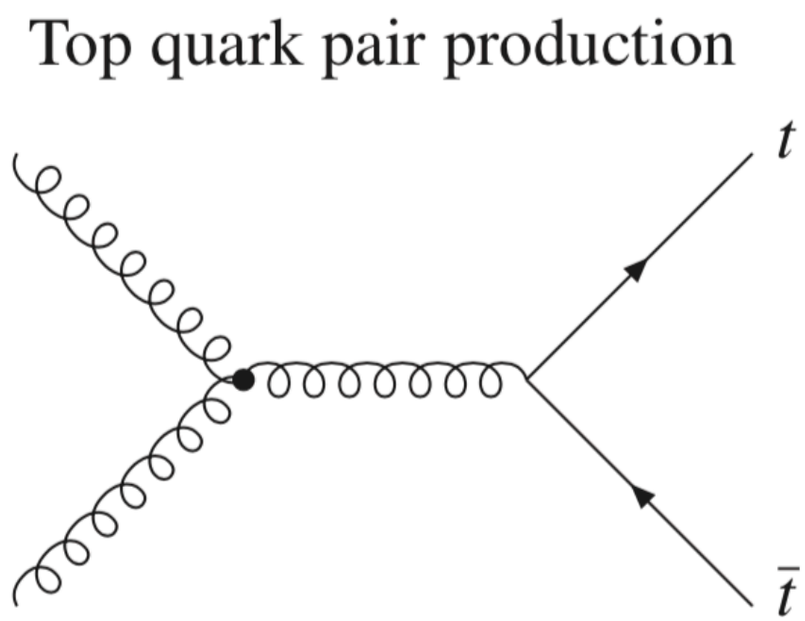


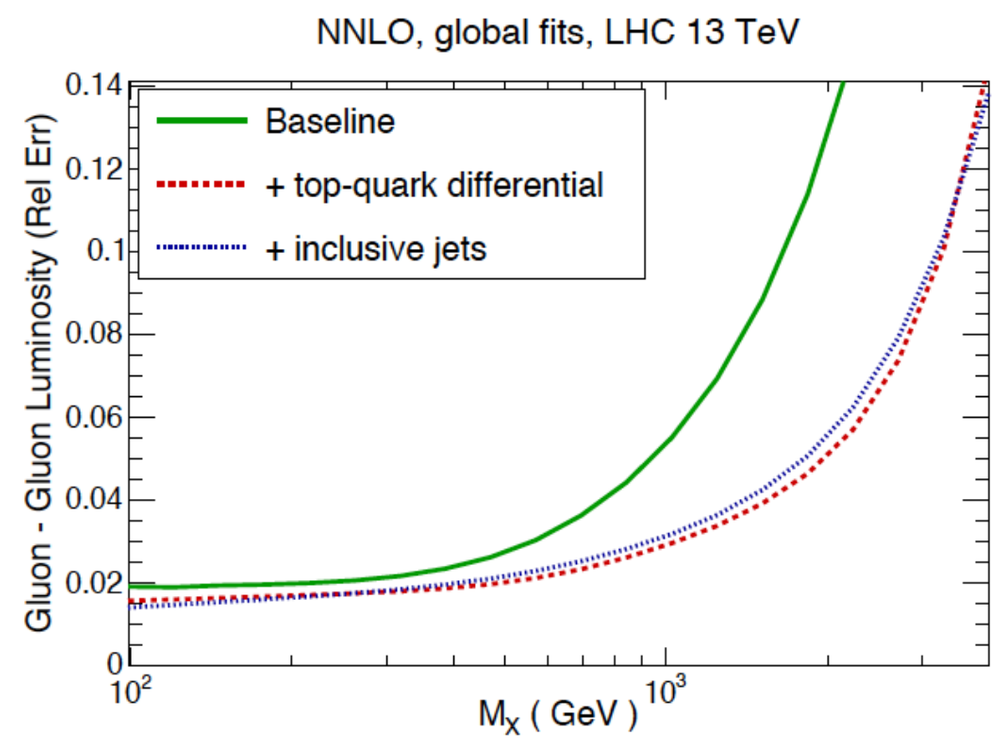
large-x gluon

medium-x gluon

medium-x gluon

Gluon PDF from top quarks

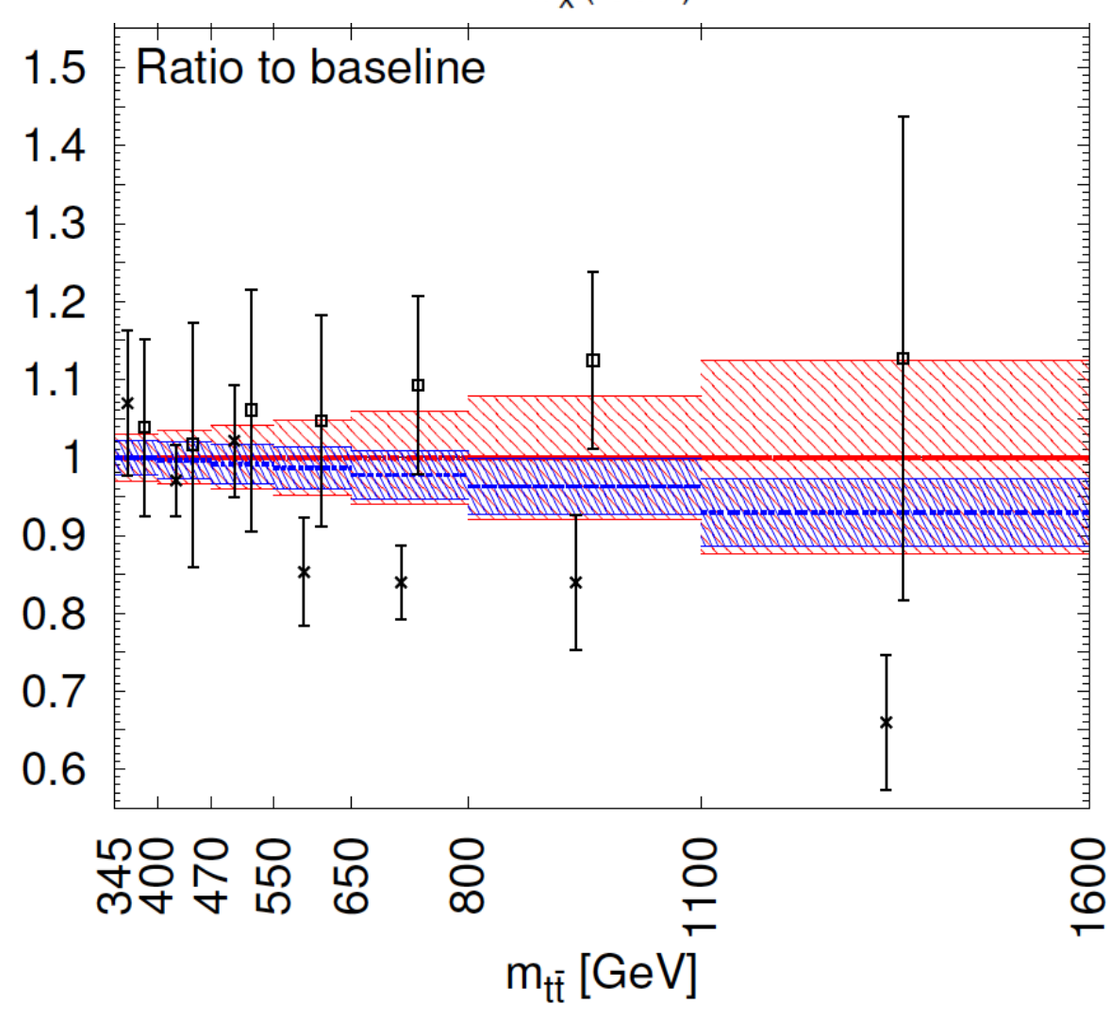




- Complementary probe of the **large-x gluon**

- Included **differential top distributions in NNPDF3.0 NNLO**: constraints on **large-*x* gluon** comparable to inclusive jet production

- Improved theory uncertainties in regions crucial for **BSM searches**, *i.e.*, **m_{tt} > 1 TeV** (while fitting only **y_t** and **y_{tt}**)



Czakon, Hartland, Mitov, Nocera, JR 16

Gluon PDF from direct photons

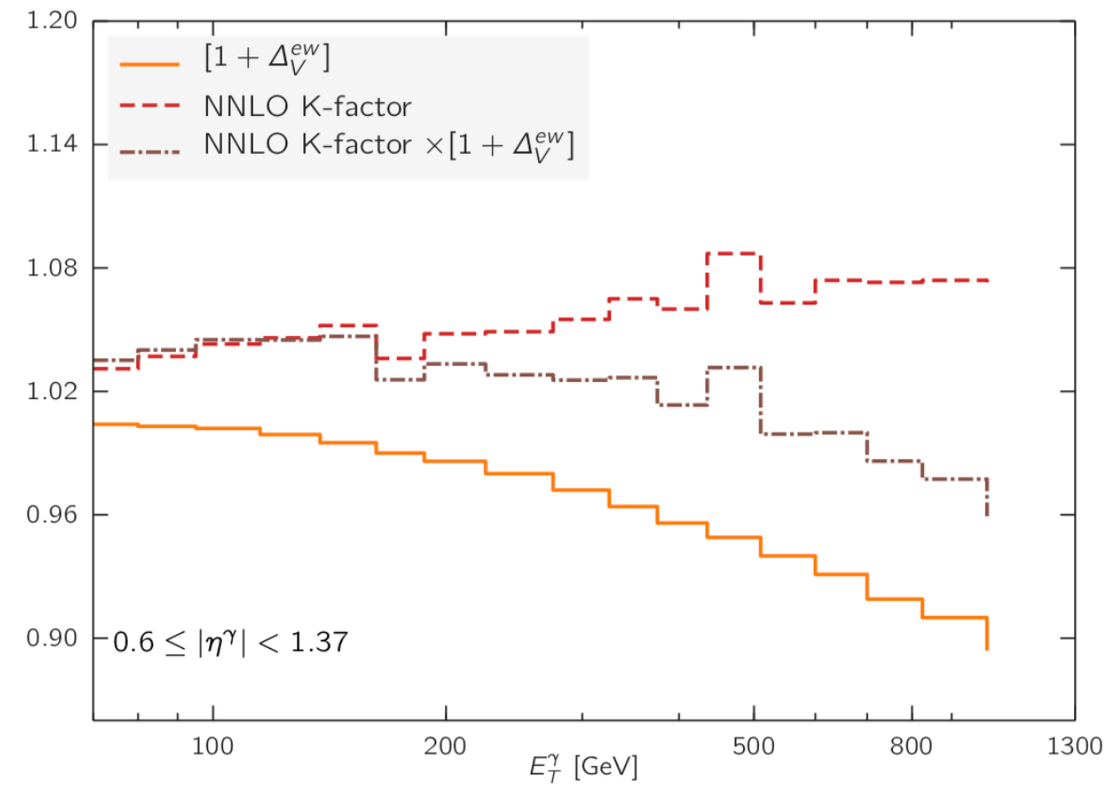
- Revisited the impact of LHC **direct photon data** into the global PDF fit

  Campbell, JR, Slade, Williams 18

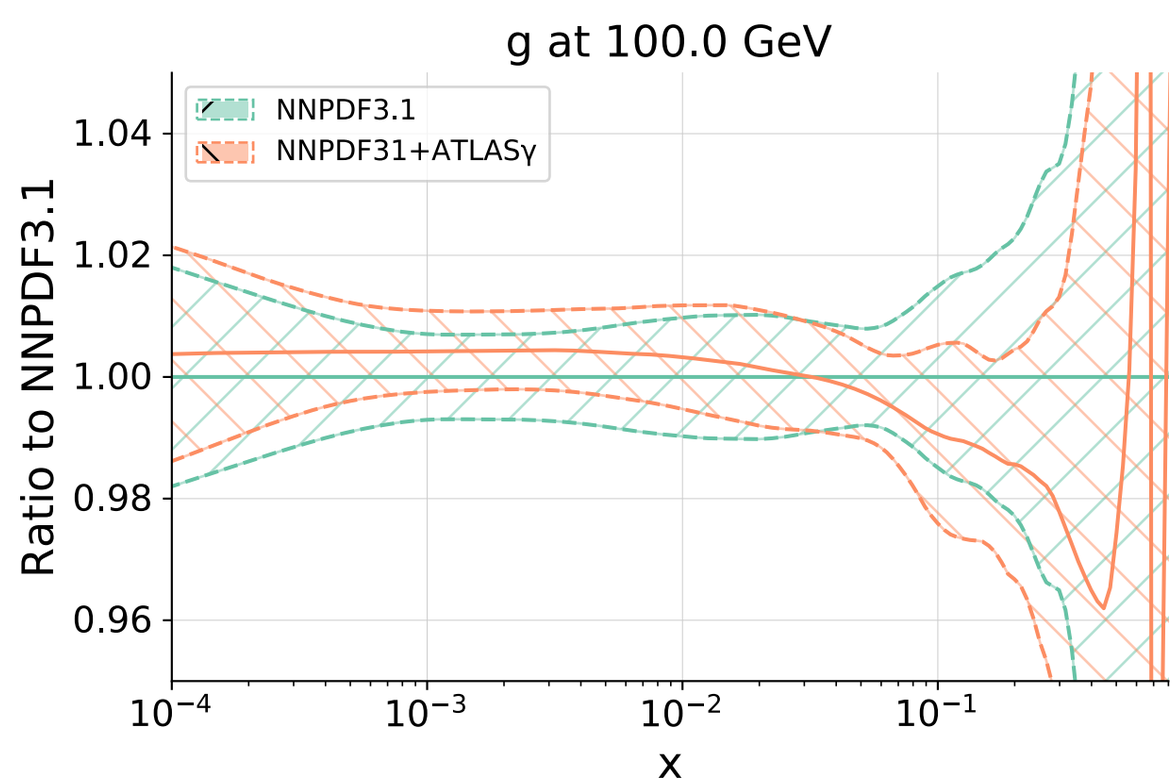
- Theory based on **NNLO QCD** and **LL electroweak** calculations

- Moderate impact on medium-*x* gluon

- Good **consistency** with other gluon-sensitive experiments in NNPDF3.1



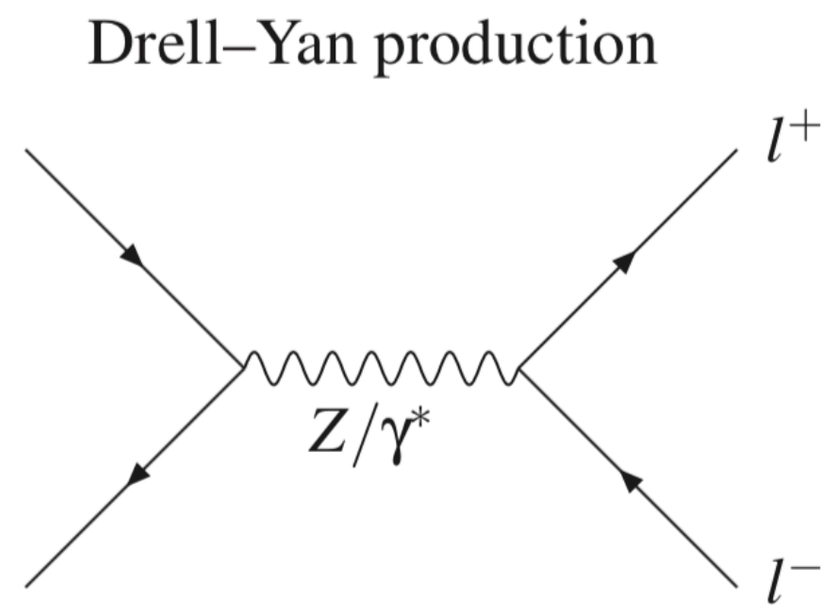
	NNPDF3.1	NNPDF3.1+ATLASγ
Fixed-target lepton DIS	1.207	1.203
Fixed-target neutrino DIS	1.081	1.087
HERA	1.166	1.169
Fixed-target Drell-Yan	1.241	1.242
Collider Drell-Yan	1.356	1.346
Top-quark pair production	1.065	1.049
Inclusive jets	0.939	0.915
Z p_T	0.997	0.980
Total dataset	**1.148**	**1.146**



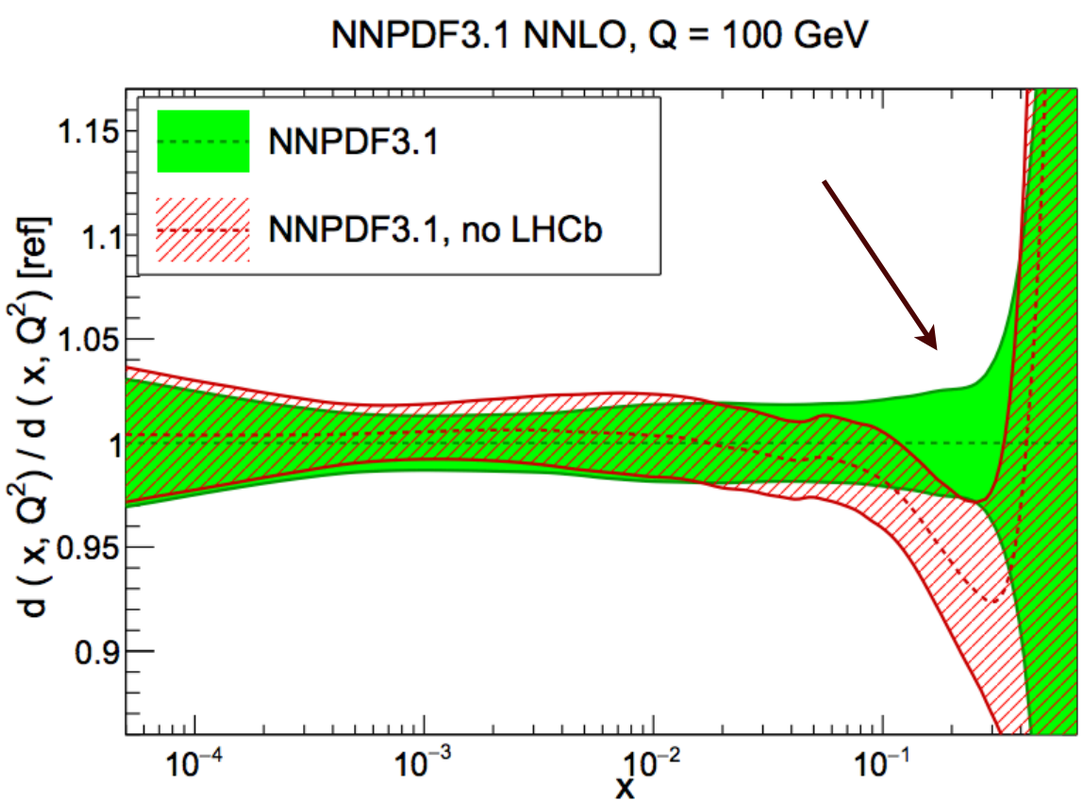
Flavour separation from forward W,Z

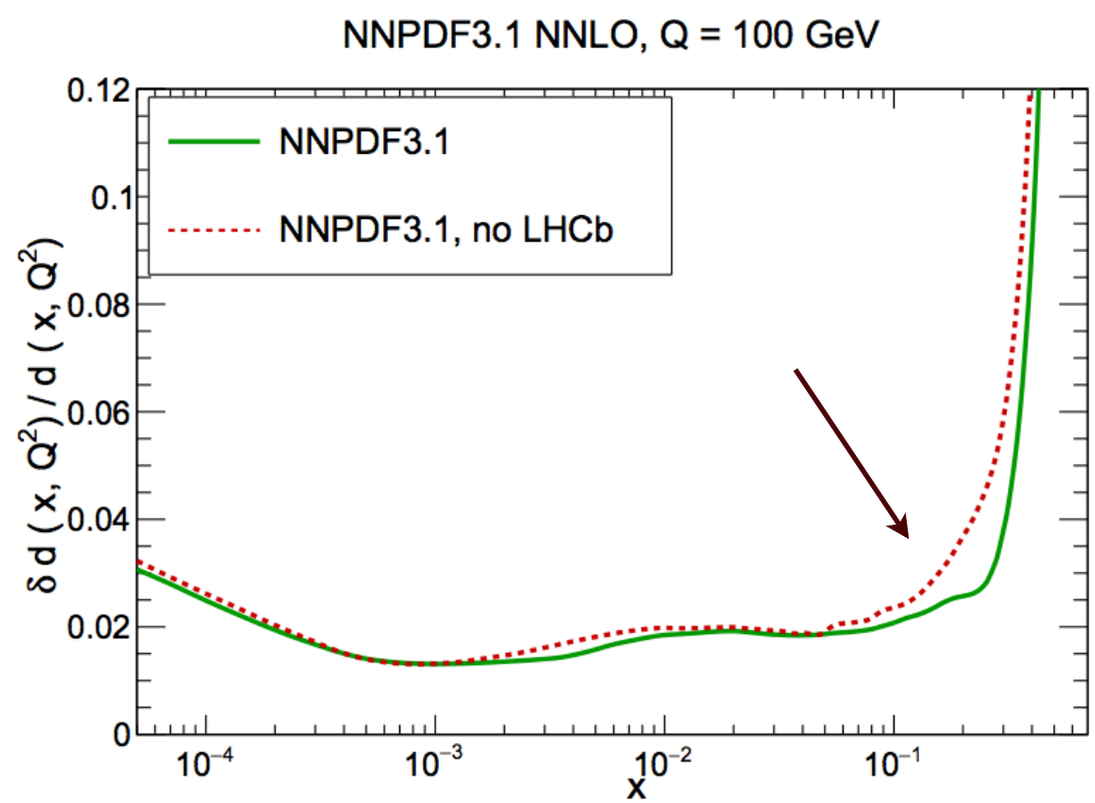
- **Forward coverage** of LHCb: unique sensitivity to small-*x* and large-*x* regions beyond that of ATLAS/CMS

- Specially important to disentangle **quark flavour at large-*x***



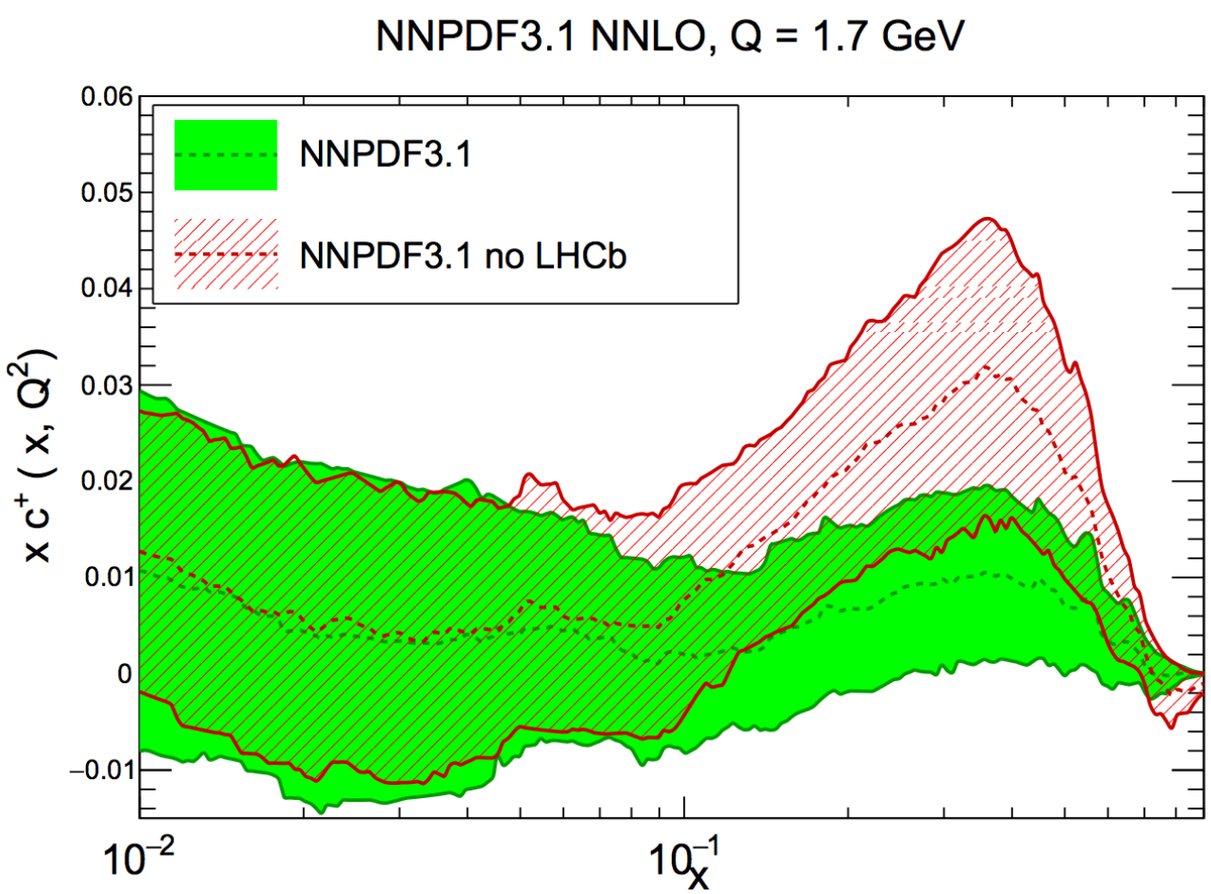
NNPDF 17

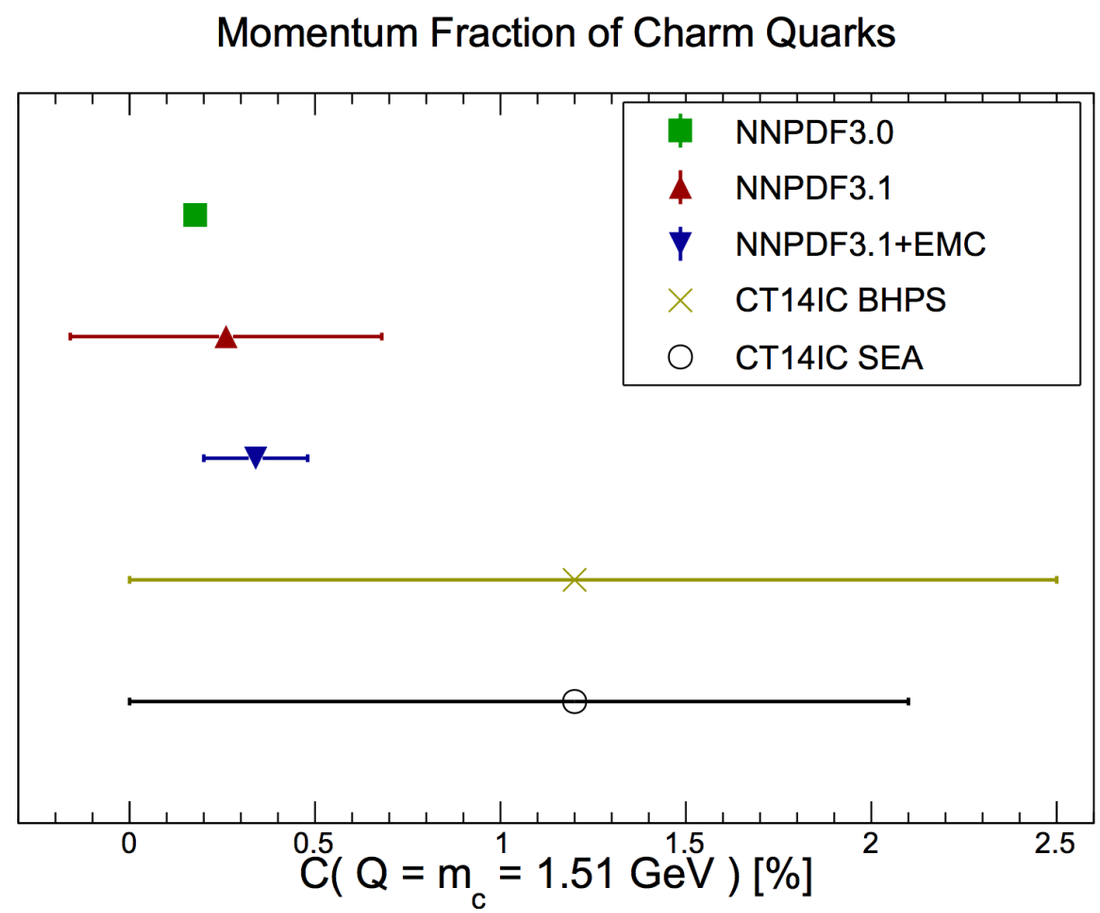




Impact on the charm PDF

***NNPDF3.1**: independent parametrisation for **charm PDF**, constrained from data*





- LHC electroweak data provide important info on **charm content of protons**
- **'Intrinsic' charm** (IC) bounded to < 0.7% of proton momentum from LHC data
- Indications of a **small but non-zero IC**

$$C(Q^2) \equiv \int_0^1 dx\, x \left(c(c, Q^2) + \bar{c}(x, Q^2) \right)$$

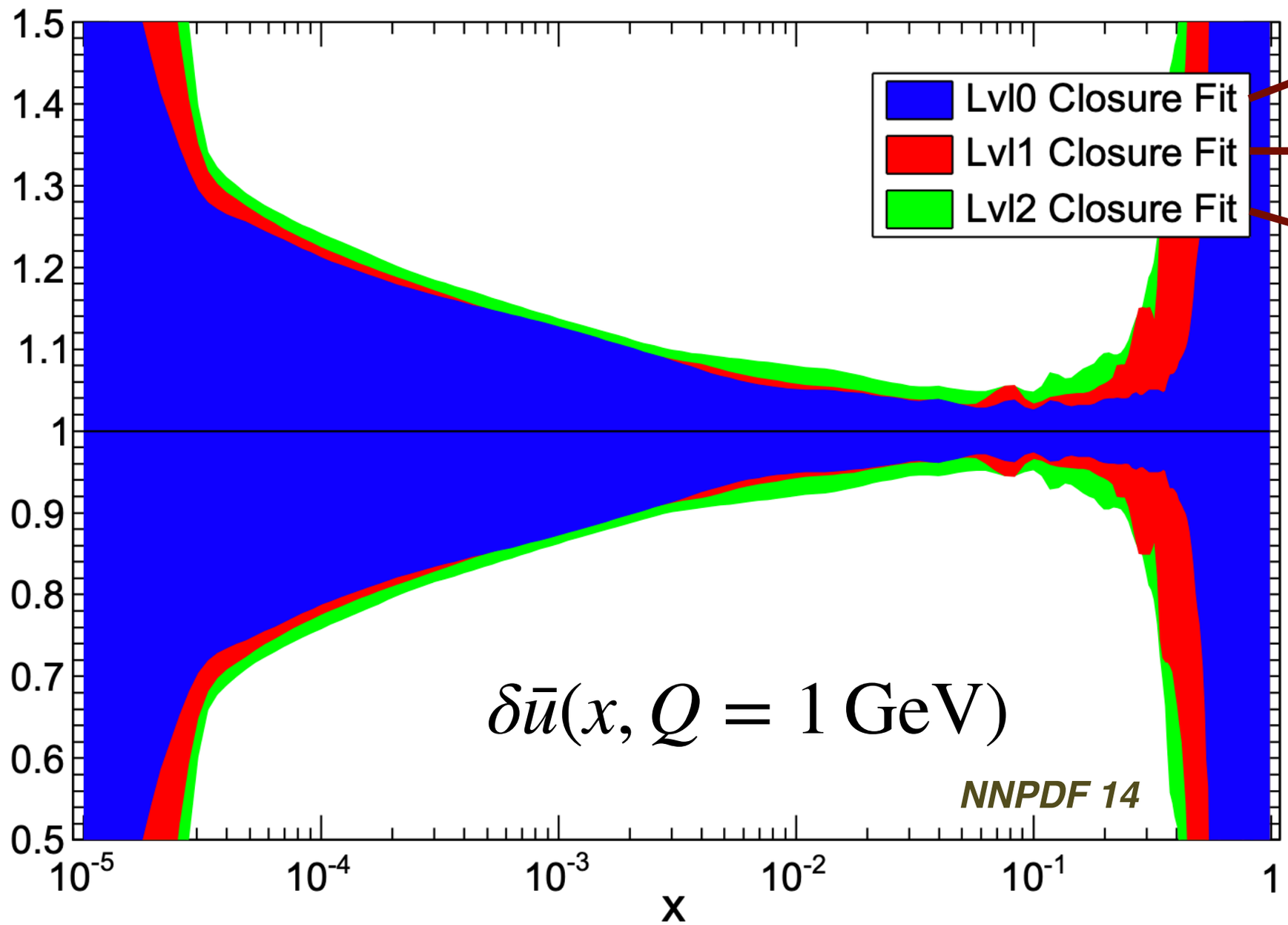
Large intrinsic charm allowed in CT14IC **disfavoured** by LHC data

Parton Distributions and theoretical uncertainties

NNPDF, in preparation

PDF uncertainties

PDF uncertainties receive contributions from **different sources**:



extrapolation/ degeneracy

functional form

exp data uncertainties

Parametric theory errors from $\delta\alpha_S$, δm_c accounted in modern fits

Theory uncertainties on PDFs from **Missing Higher Orders** (MHOs) never quantified!

Theory uncertainties from MHOs

At any finite order, perturbative QCD calculations depend on the unphysical **renormalisation** and **factorisation scales**

$$\sigma(\mu_R, \mu_F) = \sum_{k=0}^{n} \sum_{i,j}^{n_f} \alpha_s^{p+k}(\mu_R)\, \widetilde{\sigma}^{(k)}(\mu_R, \mu_F) \otimes q_i(\mu_F) \otimes q_j(\mu_F) + \mathcal{O}\left(\alpha_s^{p+n+1}\right)$$

In PDF fits, both scales are set to a fixed value, the typical **momentum transfer of the process *Q*,** and the MHOUs are ignored

$$\sigma(\mu_R = Q, \mu_F = Q) = \sum_{k=0}^{n} \sum_{i,j}^{n_f} \alpha_s^{p+k}(Q)\, \widetilde{\sigma}^{(k)}(Q) \otimes q_i(Q) \otimes q_j(Q)$$

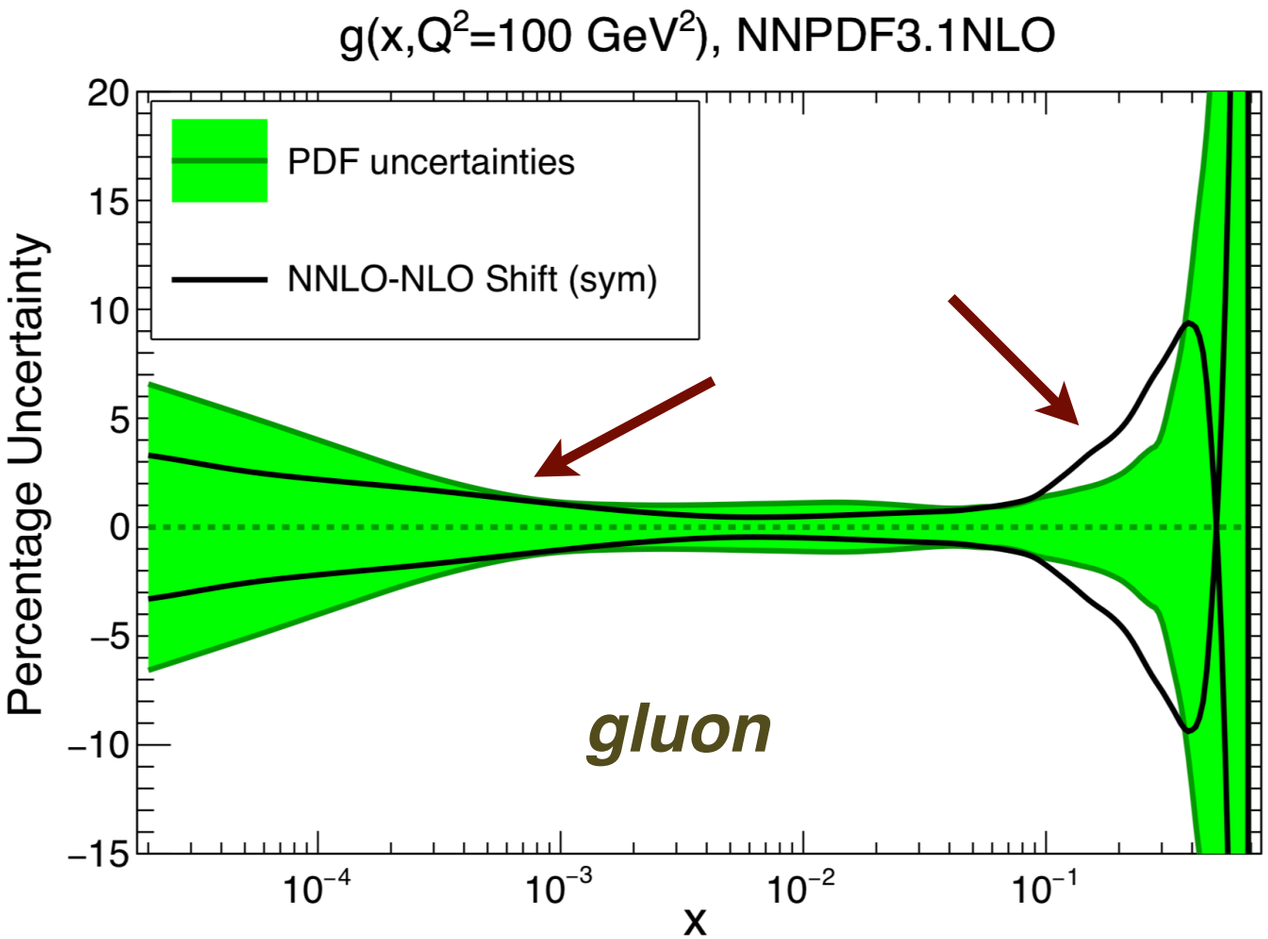
At order **N^{k}LO**, the dependence on the two scales is determined by the **N^{k-1}LO** splitting functions and partonic cross-sections by imposing:

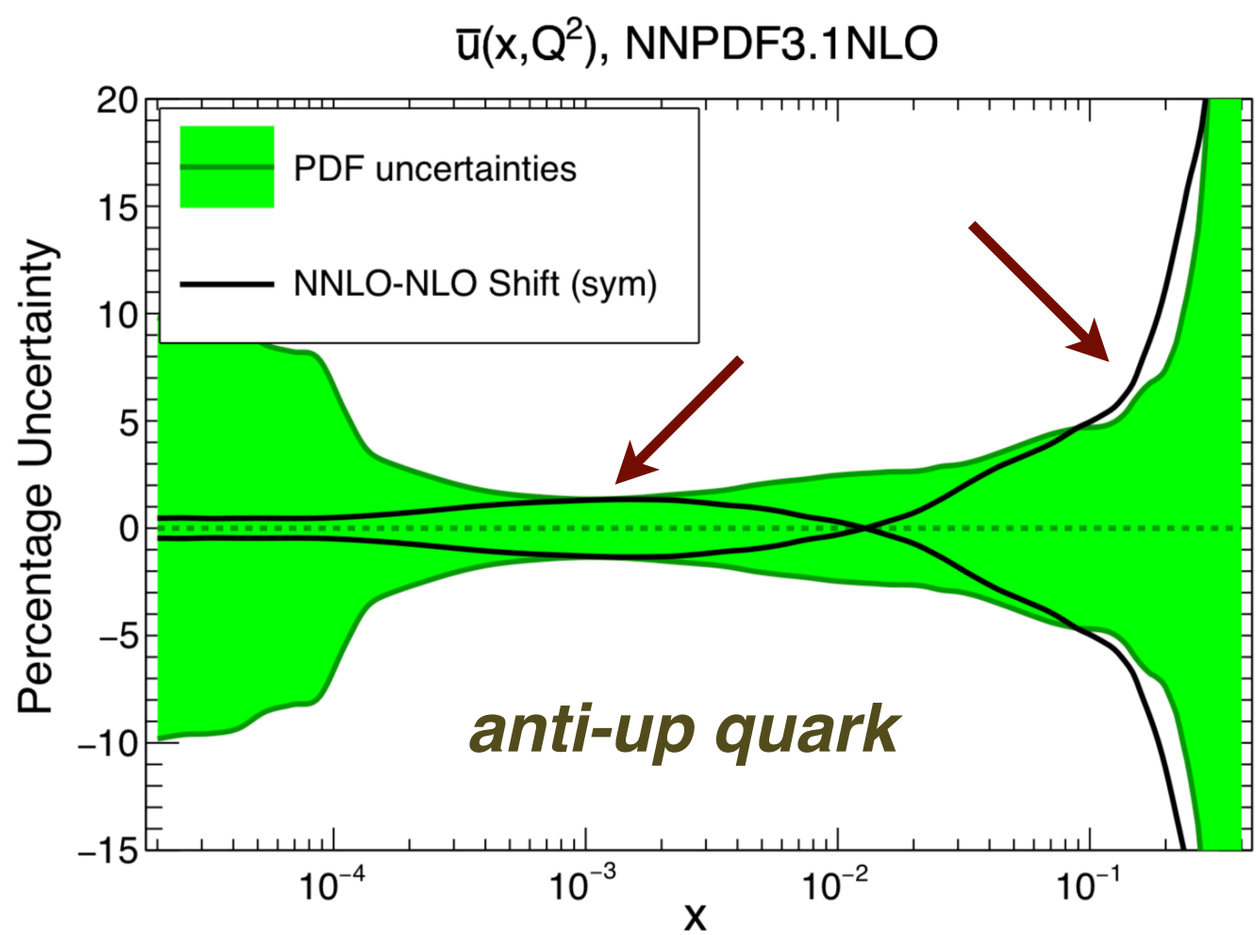
$$\sigma(\mu_R, \mu_F) = \sigma(Q, Q) + \mathcal{O}\left(\alpha_s^{p+n+1}\right)$$

*Scale variations provide an **estimate of the perturbative MHOs***

Theory uncertainties from MHOs

How severe is **ignoring MHOUs** in modern global PDFs fits?





Shift between **NLO and NNLO PDFs** comparable or larger than PDF errors

Given the high precision of modern PDF determinations, **accounting for MHOUs** is most urgent

Option #1: PDF fits with scale variations

Perform PDF fits where **theory calculations** are constructed by exploring a range of values for the **renormalisation** and **factorisation scales**

3-points

$$\sigma(\mu_R = Q, \mu_F = Q)$$ central scales

$$\sigma(\mu_R = 2Q, \mu_F = 2Q) \qquad \sigma(\mu_R = Q/2, \mu_F = Q/2)$$

7-points

$$\sigma(\mu_R = 2Q, \mu_F = Q) \qquad \sigma(\mu_R = Q, \mu_F = 2Q)$$

$$\sigma(\mu_R = Q/2, \mu_F = Q) \qquad \sigma(\mu_R = Q, \mu_F = Q/2)$$

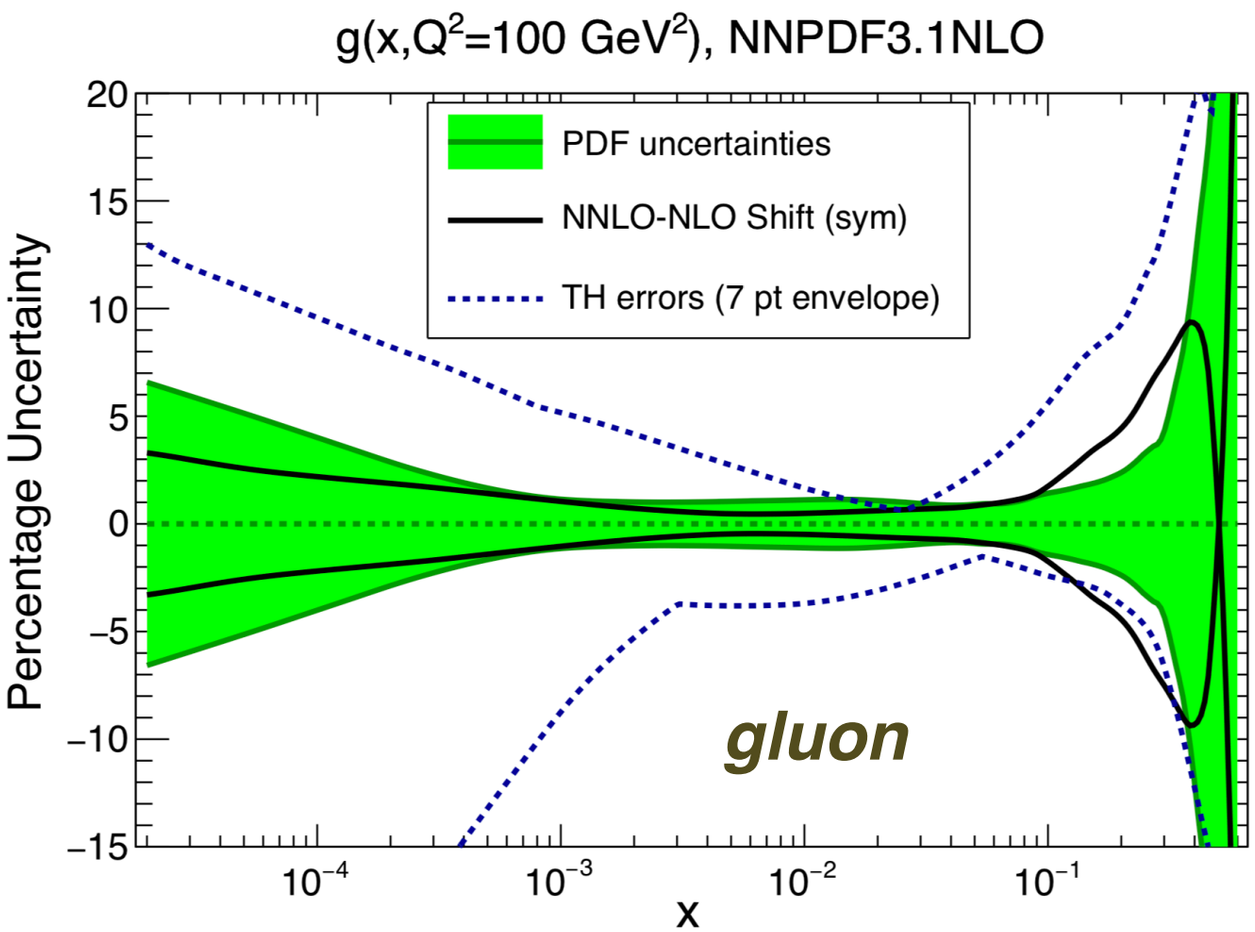
9-points

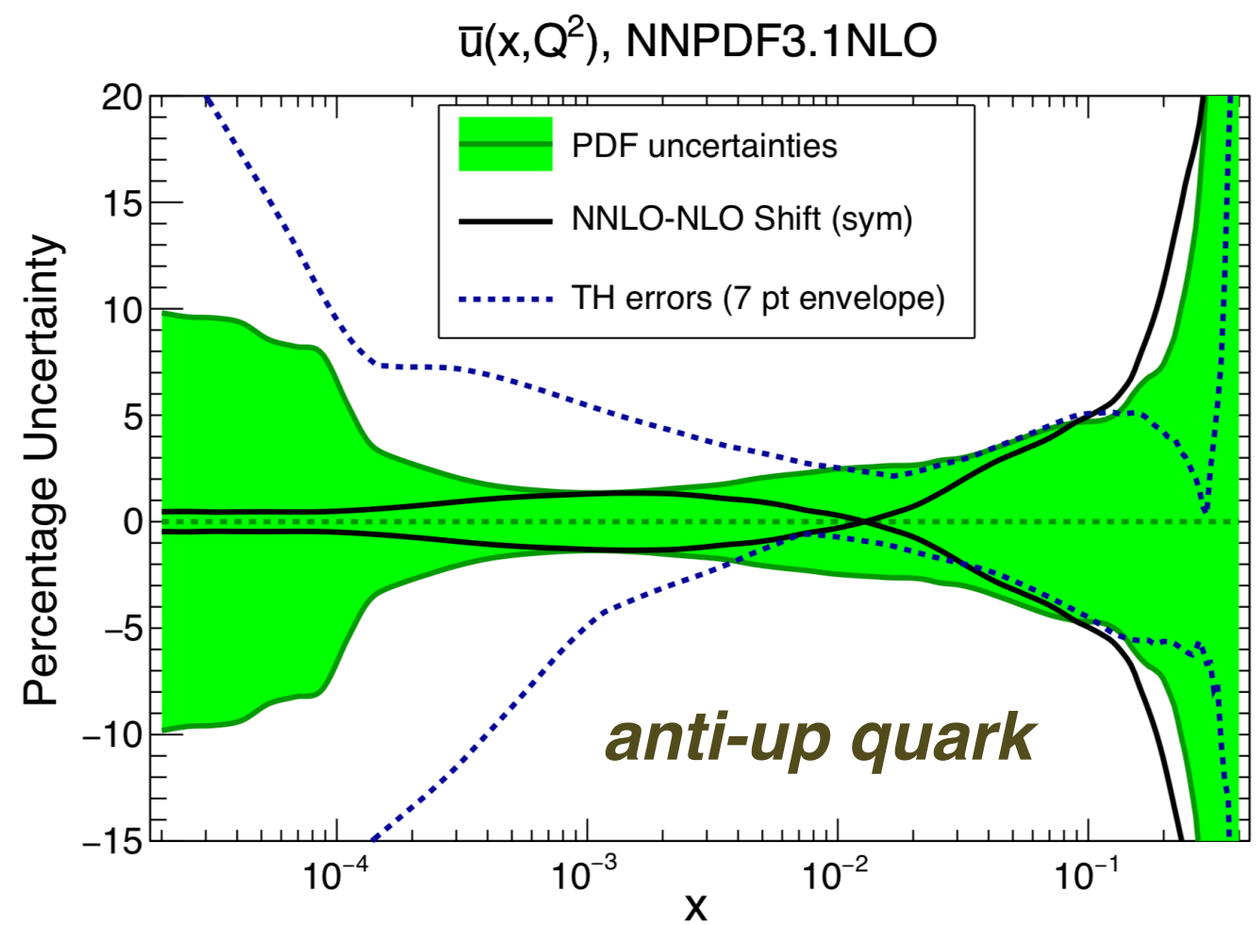
$$\sigma(\mu_R = 2Q, \mu_F = Q/2) \qquad \sigma(\mu_R = Q/2, \mu_F = 2Q)$$

Define the theory error due to MHOUs from **envelope of the scale-varied PDFs**

Option #1: PDF fits with scale variations

Perform PDF fits where **theory calculations** are constructed by exploring a range of values for the **renormalisation** and **factorisation scales**





- The 7pt envelope seems to work fine in most cases (perhaps too conservative?)
- Non-trivial **theory-induced correlations** between e.g. DIS and collider processes
- **CPU-intensive**, and cumbersome or LHC applications - can we do better?

Option #2: theory covariance matrix

Construct a theory covariance matrix from **scale-varied cross-sections** and combine it with the experimental covariance matrix

$$\chi^2 = \frac{1}{N_{\rm dat}} \sum_{i,j=1}^{N_{\rm dat}} \left(D_i - T_i\right) \left(\mathrm{cov}^{(\rm exp)} + \mathrm{cov}^{(\rm th)}\right)^{-1}_{ij} \left(D_j - T_j\right)$$

Different scale variation prescriptions possible, e.g, the **5-point prescription**

$$\mathrm{cov}^{(\rm th)}_{ii} = \frac{1}{2}\left(\Delta_i(+,0)^2 + \Delta_i(-,0)^2 + \Delta_i(0,+)^2 + \Delta_i(0,+)^2\right)$$

$$\mathrm{cov}^{(\rm th)}_{jj} = \frac{1}{2}\left(\Delta_i(+,0)\Delta_j(+,0) + \Delta_i(-,0)\Delta_j(-,0) + \frac{1}{4}(\Delta_i(0,+) + \Delta_i(0,-))(\Delta_j(0,+) + \Delta_j(0,-))\right)$$

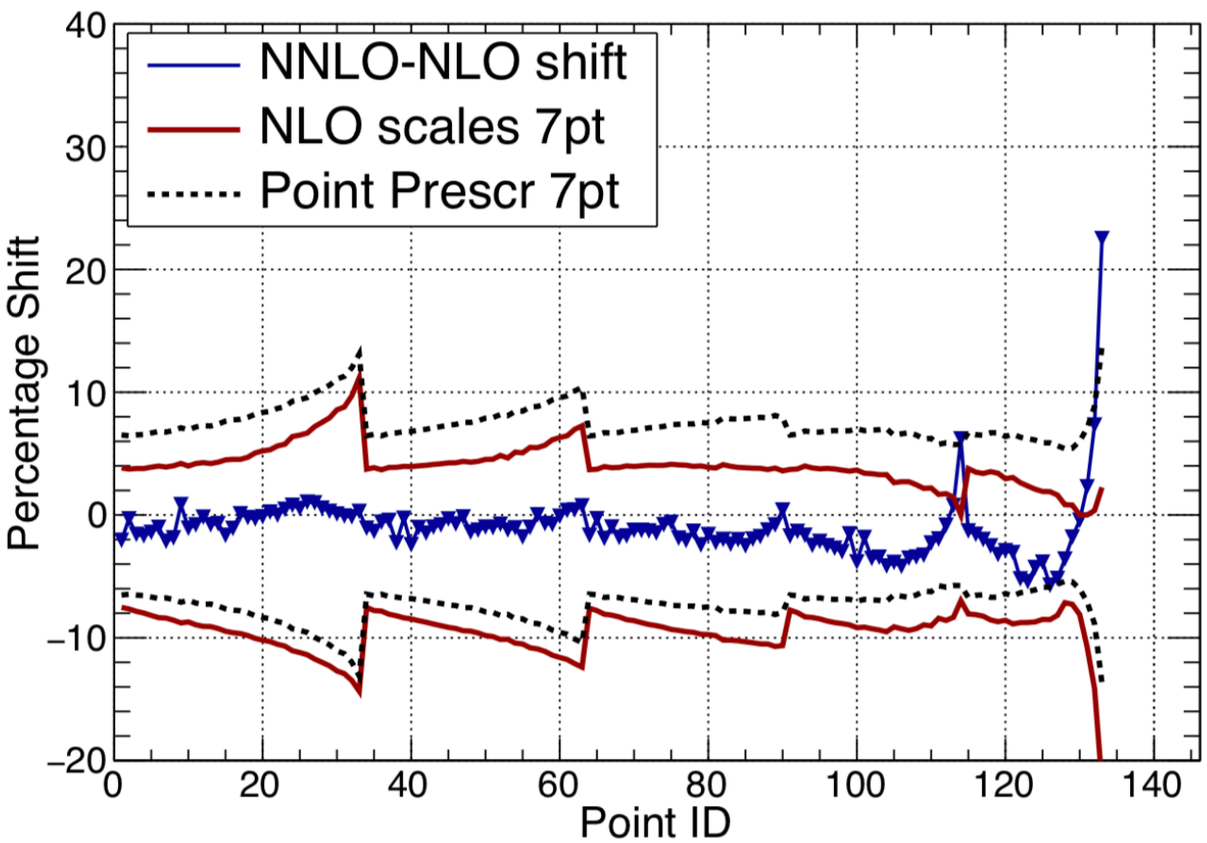
$$\Delta_i(-,0) \equiv \sigma(\mu_R = Q/2, \mu_F = Q) - \sigma(\mu_R = Q, \mu_F = Q)$$

$$\Delta_i(+,+) \equiv \sigma(\mu_R = 2Q, \mu_F = 2Q) - \sigma(\mu_R = Q, \mu_F = Q)$$

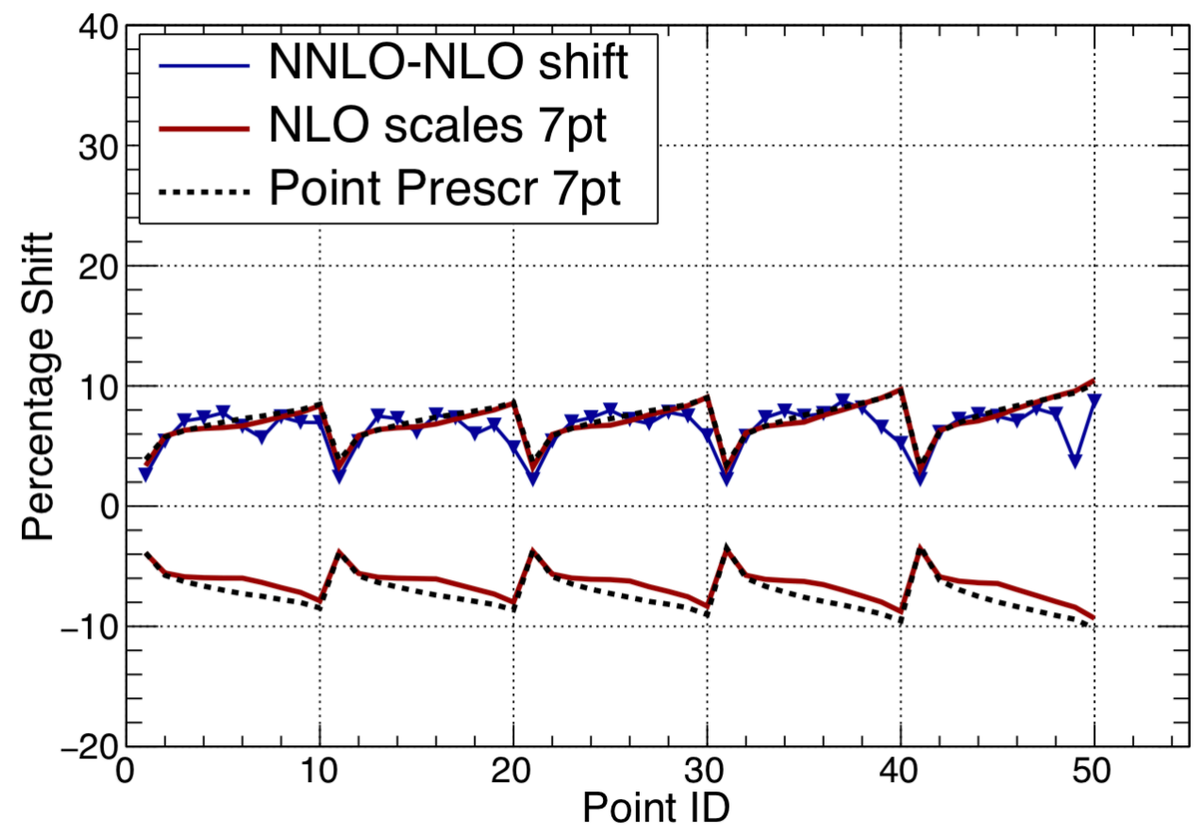
Option #2: theory covariance matrix

Construct a theory covariance matrix from **scale-varied cross-sections** and combine it with the experimental covariance matrix

ATLAS jets 7 TeV 2011

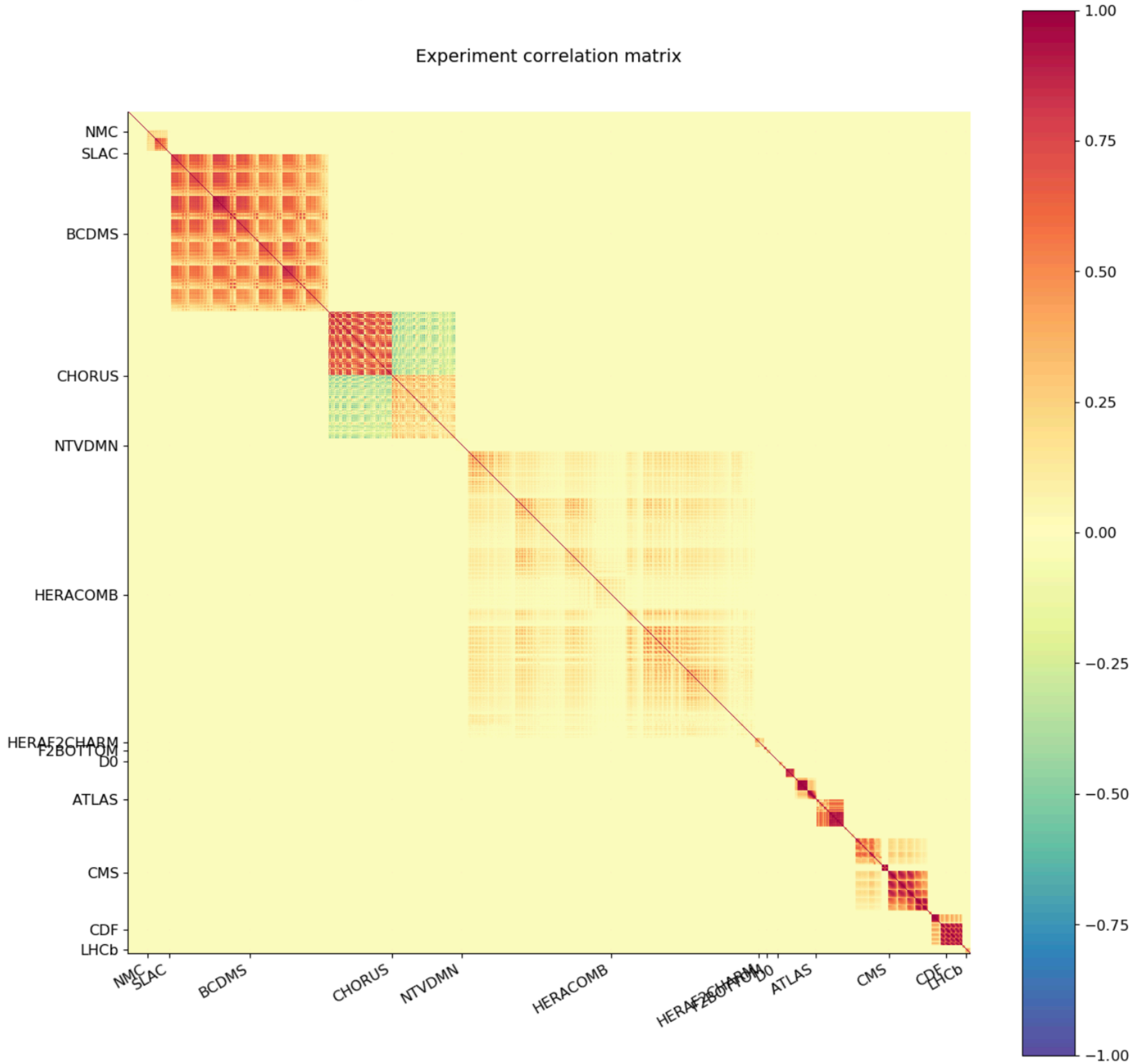


CMS Z pT 8 TeV



Systematic validation of the theory covariance matrix on the `exact' result, the **NNLO-NLO shift**, with the **O(5000) data points** of the global fit

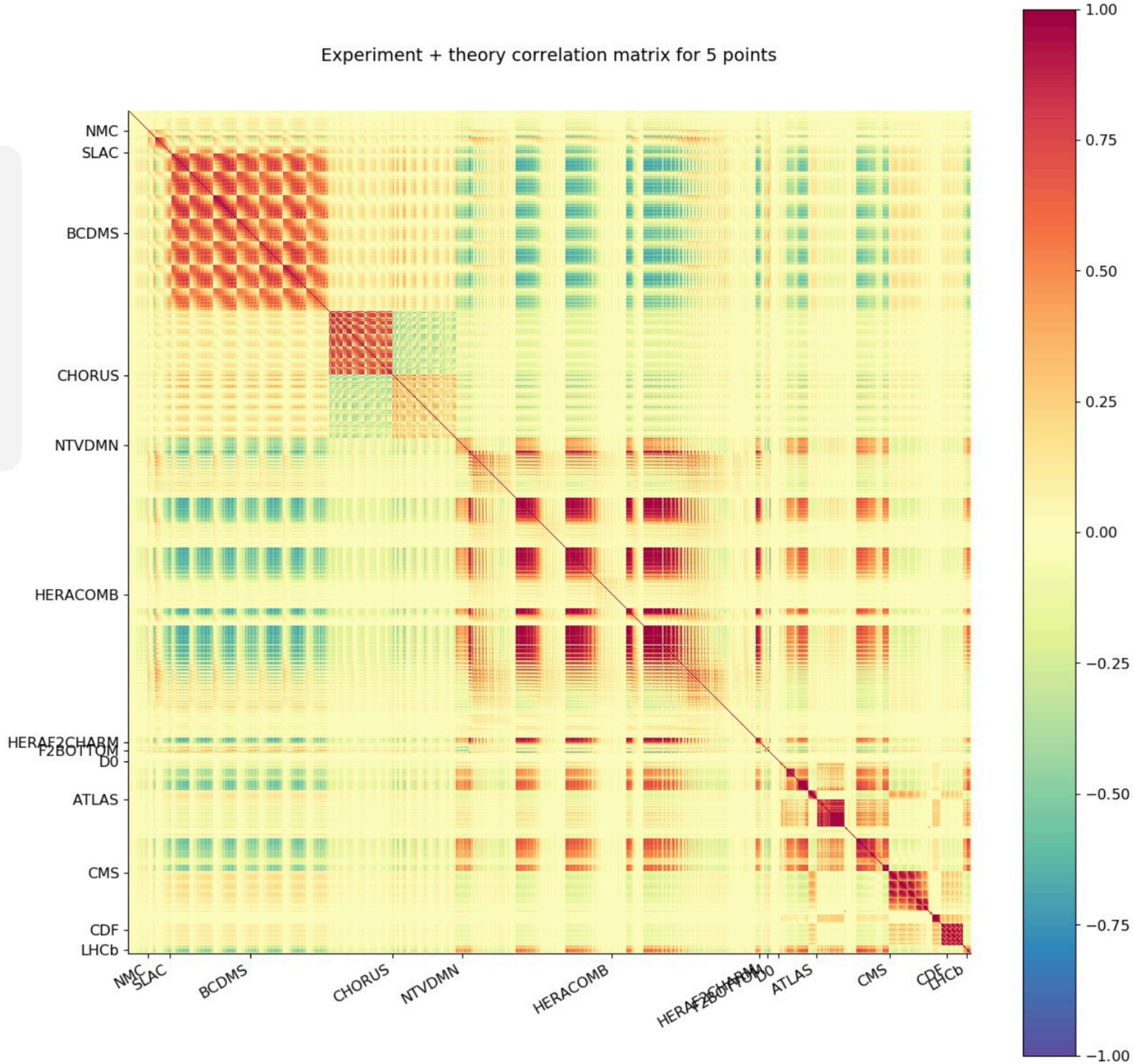
Option #2: theory covariance matrix



Option #2: theory covariance matrix

Theory-induced correlations between different experiments *e.g.* DIS and LHC

NNPDF fits with theory uncertainties in preparation

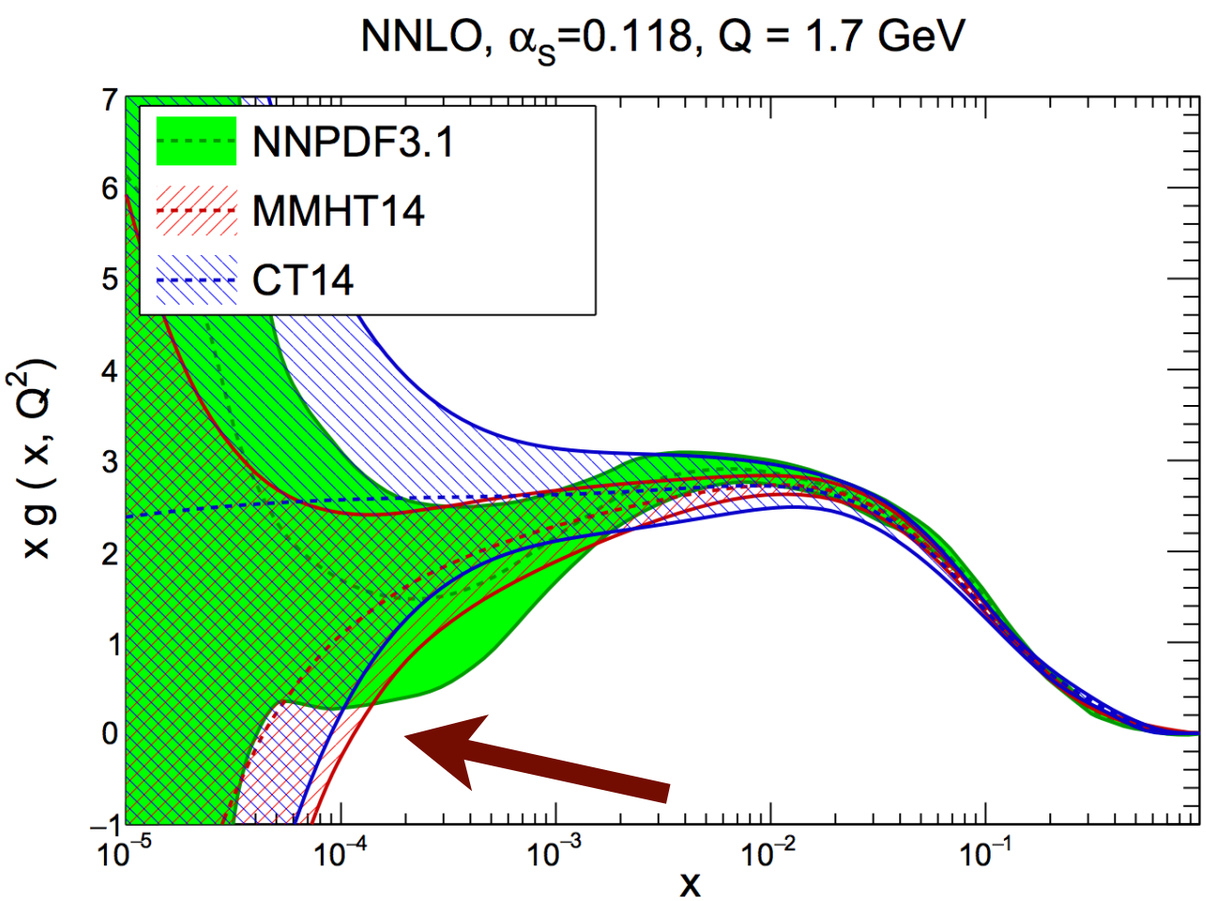


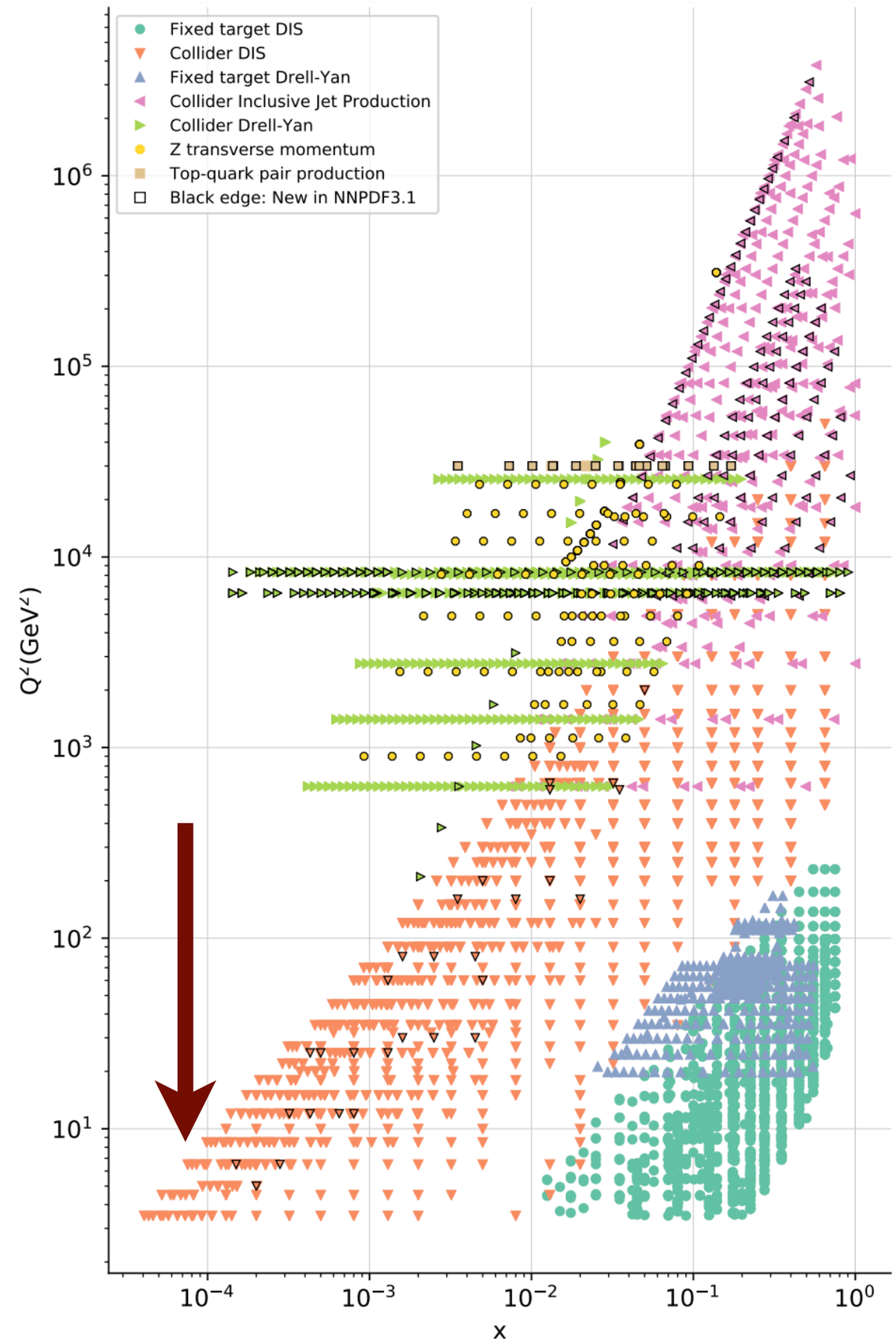
The small-x gluon and neutrino astronomy

Gauld, JR, Rottoli, Talbert 15
Gauld, JR, Rottoli, Sarkar, Talbert 15
Gauld, JR 17
Bertone, Gauld, Rojo 18

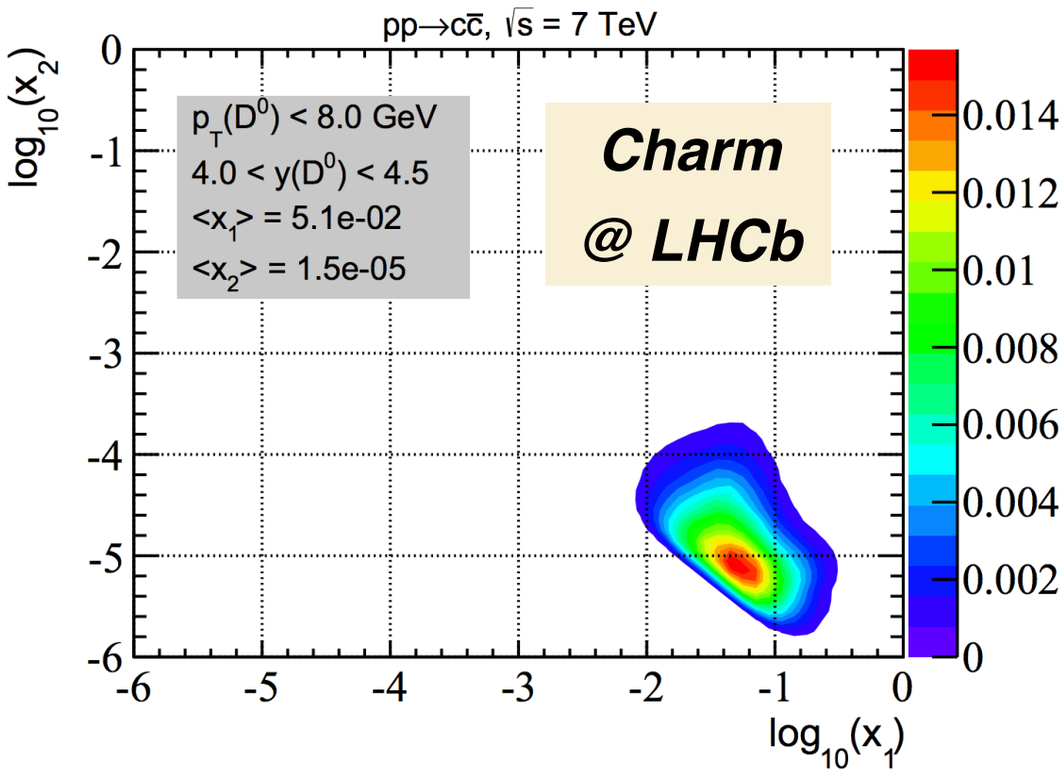
The small-x gluon from HERA data

- Small-x gluon unconstrained: information from HERA **ends for x<10^{-4}**
- Very large uncertainties in global fits
- Need processes covering **x<10^{-4} region**



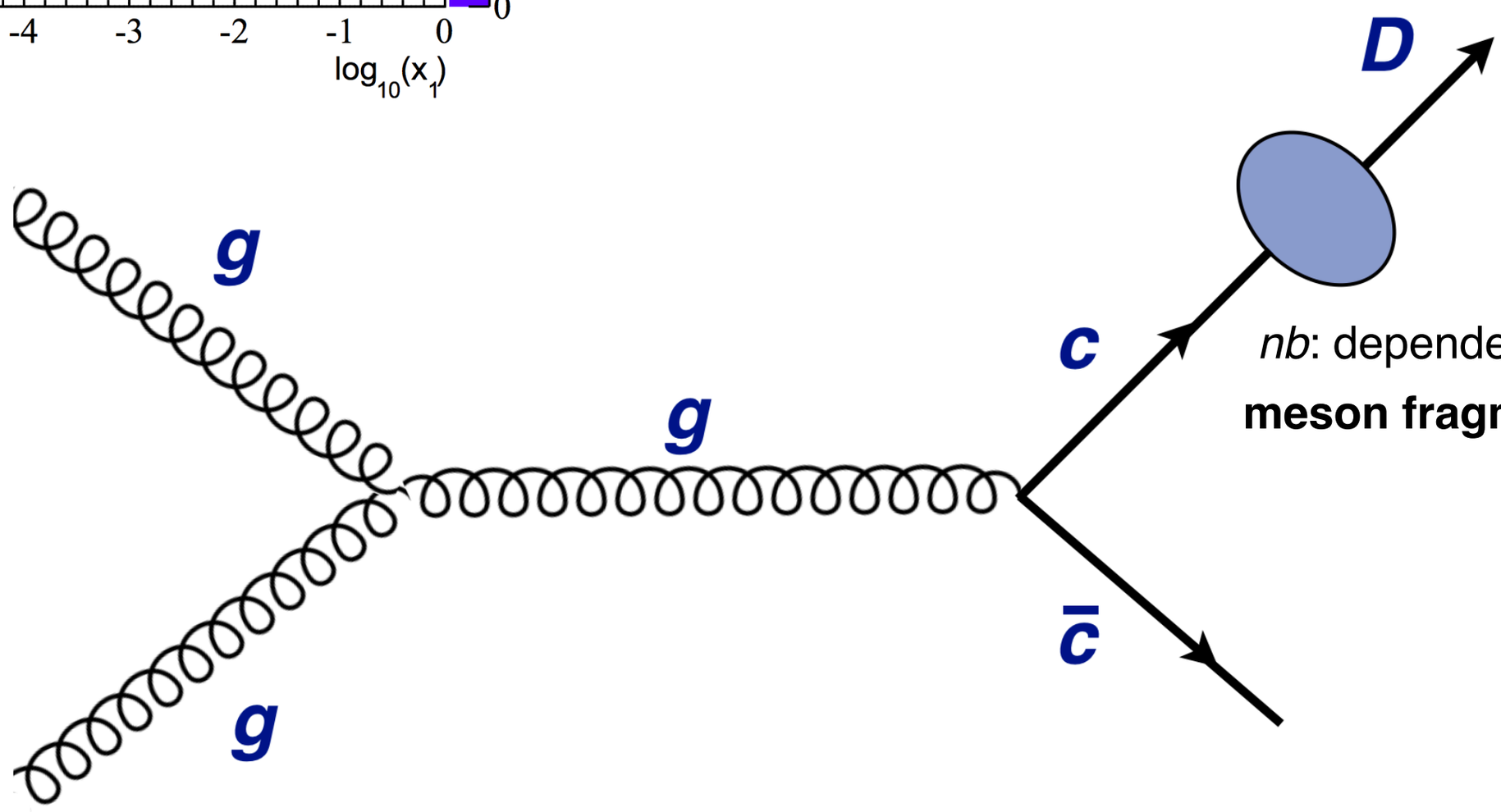


Forward charm production



LHC: charm production from **gluon-gluon scattering**

LHCb: forward coverage, Charm probes down to **x** ≃ **10^{-6}** !



nb: dependence on **D meson fragmentation**

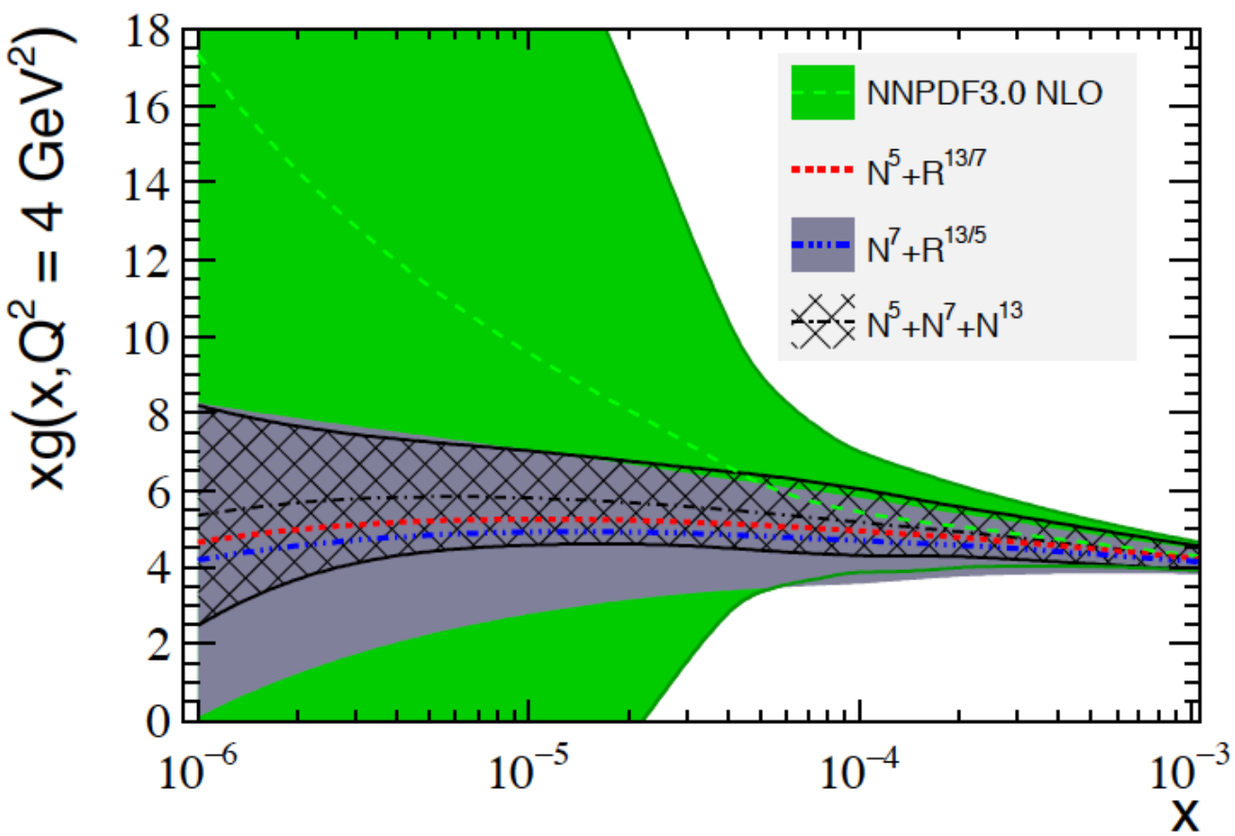
Forward charm production

- Include LHCb D meson production at **5, 7, 13 TeV**
- Fit **normalised distributions** & **ratios between CoM energies** to reduce MHOUs

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

$$R_{13/X}^{ij} = \frac{d^2\sigma(13\ \mathrm{TeV})}{dy_i^D\, d(p_T^D)_j} \Big/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_{\mathrm{i}}^D\, d(p_T^D)_j}$$

gluon PDF uncertainties reduced by **factor 10** at **x** ≃ **10^{-6}**



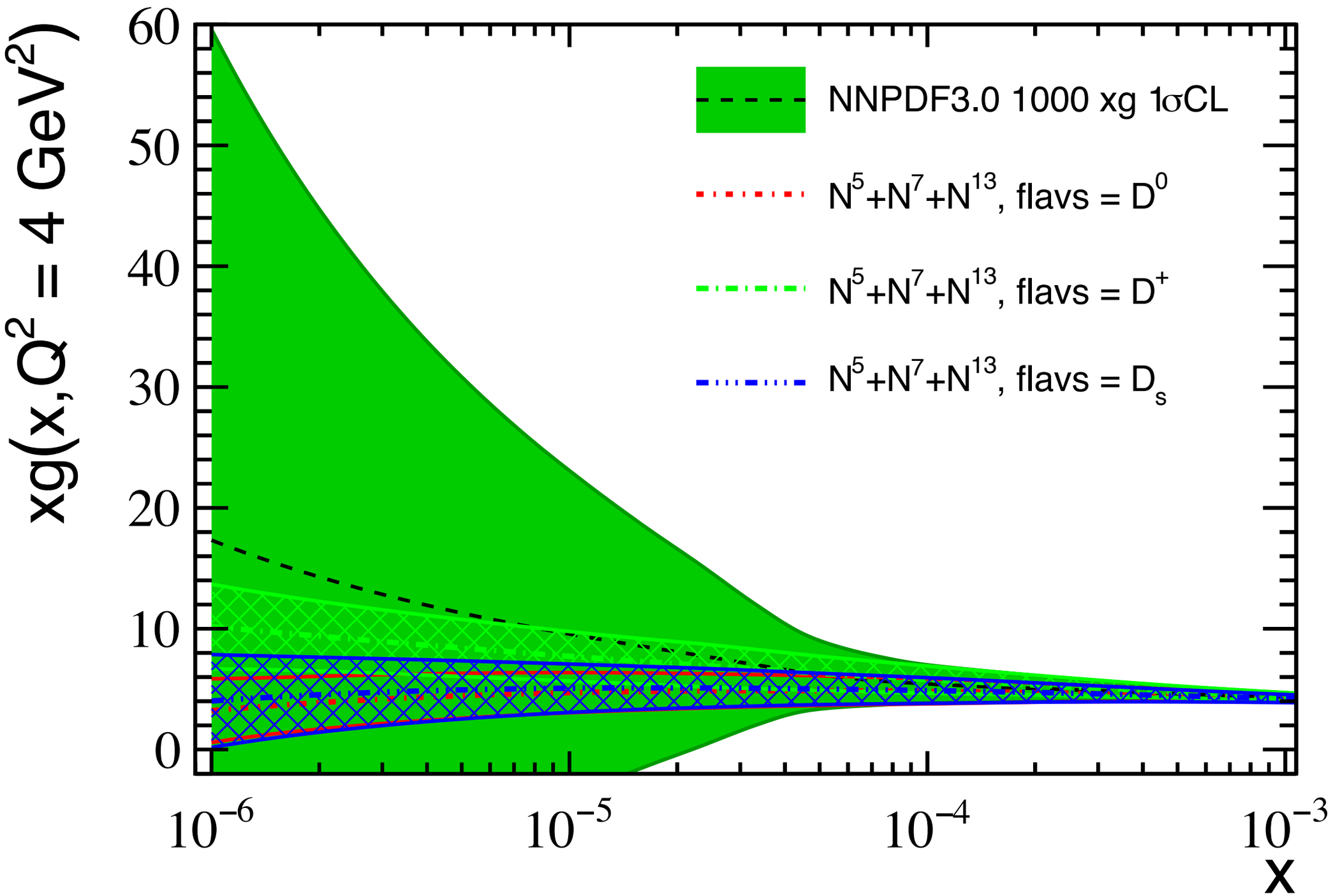
Gauld, JR 16

Excellent description of all LHCb datasets and ratios (after **errata** corrected)

$N_5(84)$	$N_7(79)$	$N_{13}(126)$	$R_{13/5}(107)$	$R_{13/7}(102)$
1.97	1.21	2.36	1.36	0.80
0.86	0.72	1.14	1.35	0.81
1.31	**0.91**	1.58	1.36	0.82
0.74	0.66	**1.01**	1.38	0.80
1.08	0.81	1.27	**1.29**	0.80
1.53	0.99	1.73	1.30	**0.81**
1.07	0.81	1.34	1.35	**0.81**
0.82	**0.70**	1.07	**1.35**	0.81
0.84	**0.71**	**1.10**	1.36	0.81

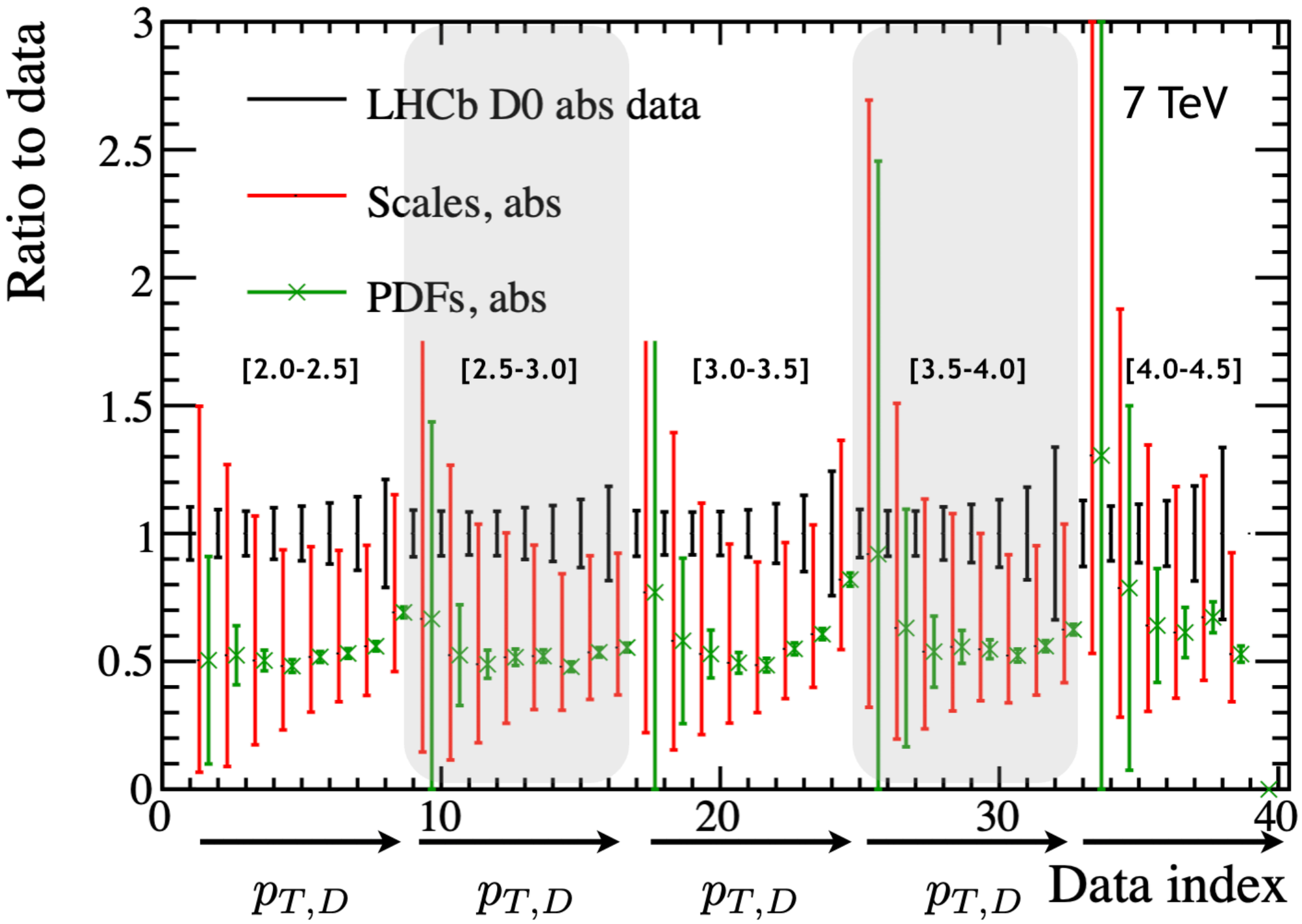
Forward charm production

Results stable wrt choice of **fitted D meson species**



Forward charm production

Cross-section ratios: improved perturbative stability



Forward charm production

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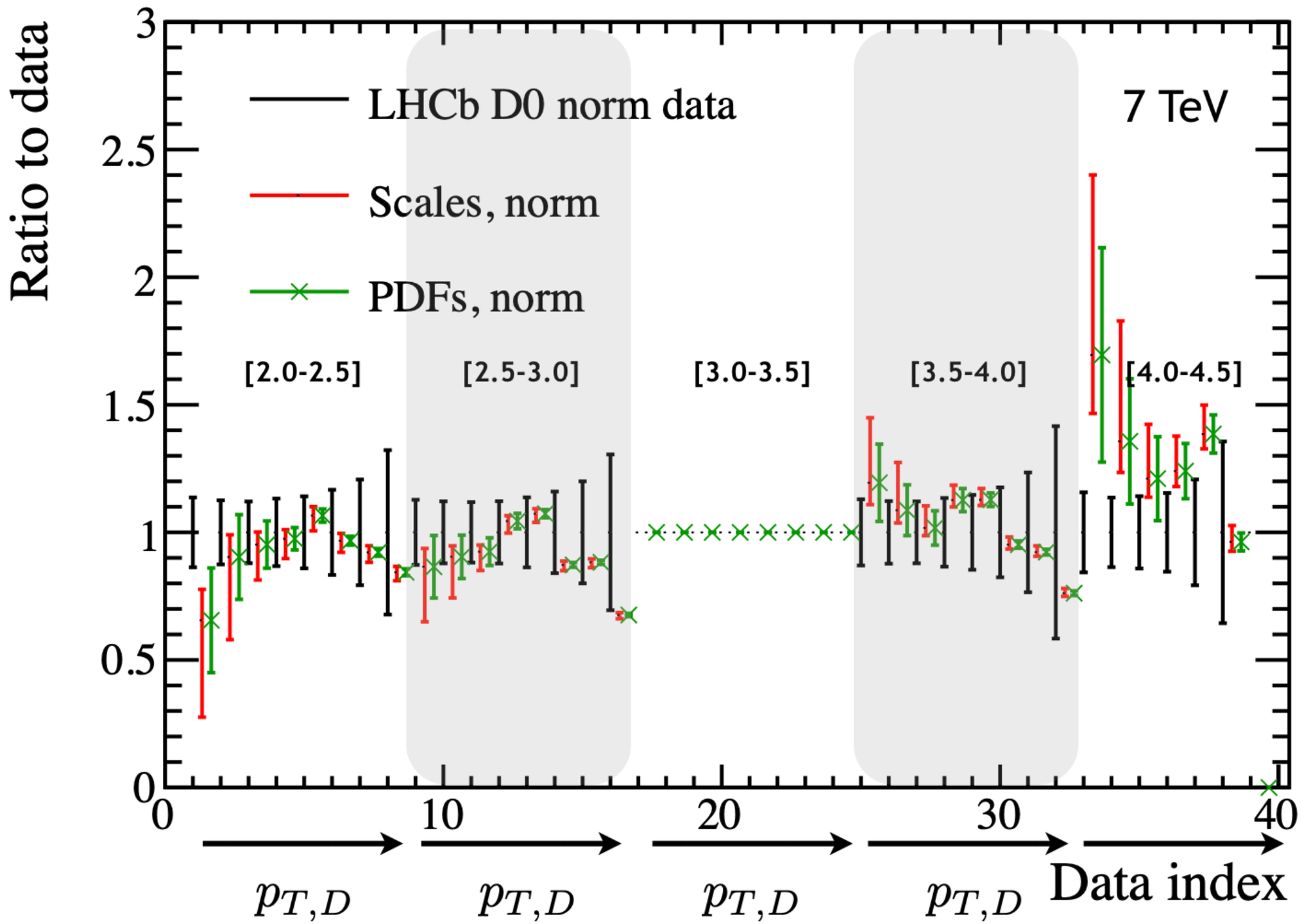


‘New Physics’ within QCD

Science
Life and Physics

The Guardian

Jon Butterworth

@jonmbutterworth
Thu 28 Dec 2017 17.30 GMT

529 | 59

After 40 years of studying the strong nuclear force, a revelation

This was the year that analysis of data finally backed up a prediction, made in the mid 1970s, of a surprising emergent behaviour in the strong nuclear force

In the mid 1970s, four Soviet physicists, Batlisky, Fadin, Kuraev and Lipatov, made some predictions involving the strong nuclear force which would lead to their initials entering the lore. “BFKL” became a shorthand for a difficult-to-

BFKL dynamics at small-*x*

- **QCD calculations in the DGLAP factorisation framework** successful in describing data from proton-proton and electron-proton collisions
- Need to go **beyond DGLAP**: at small-x, logarithmically enhanced terms in *1/x* become dominant and need to be **resummed to all orders**
- **BFKL (high-energy, small-*x*) resummation** can be matched to DGLAP collinear framework and included into PDF fits

DGLAP
Evolution in Q^2

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

BFKL
Evolution in x

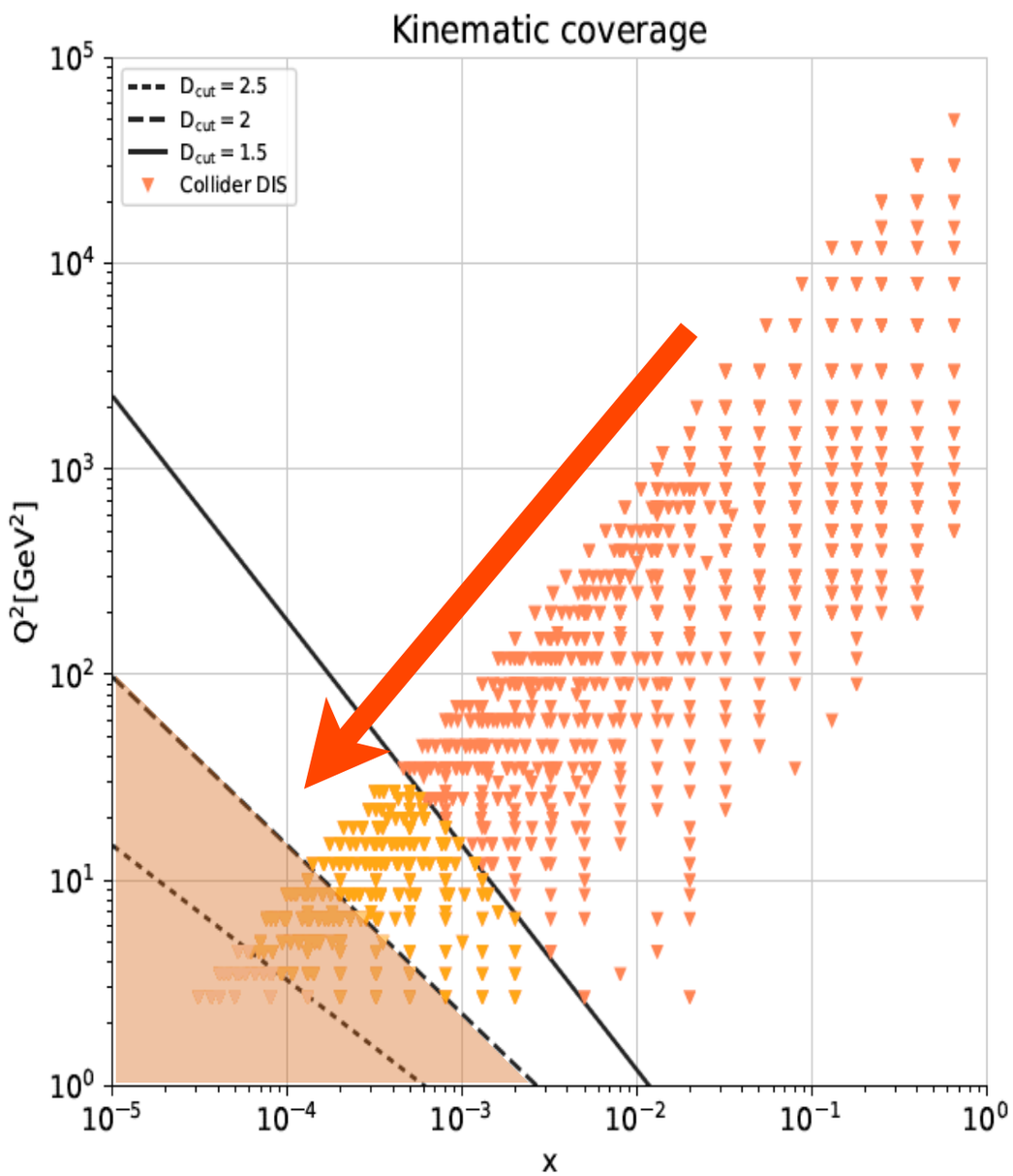
$$\frac{\partial}{\partial \ln 1/x} f_+(x, Q^2) = \int_0^\infty \frac{d\nu^2}{\nu^2} K\left(\frac{Q^2}{\nu^2}, \alpha_s(Q^2)\right) f_+(x, \nu^2)$$

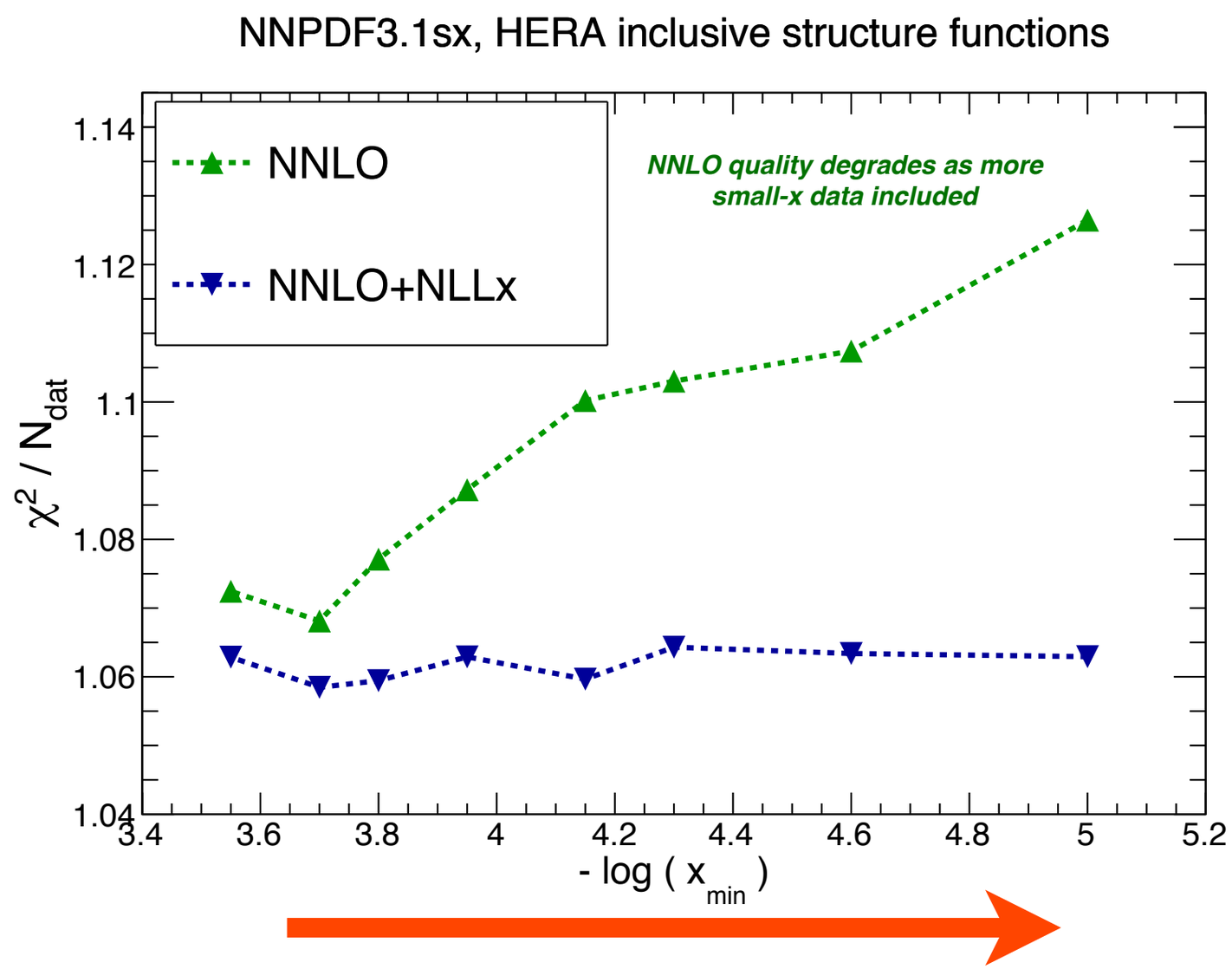
ABF, CCSS, TW
+ others, 94-08

$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x)$$

BFKL dynamics at small-*x*

Ball, Bertone, Bonvini, Marzani, JR, Rottoli 17





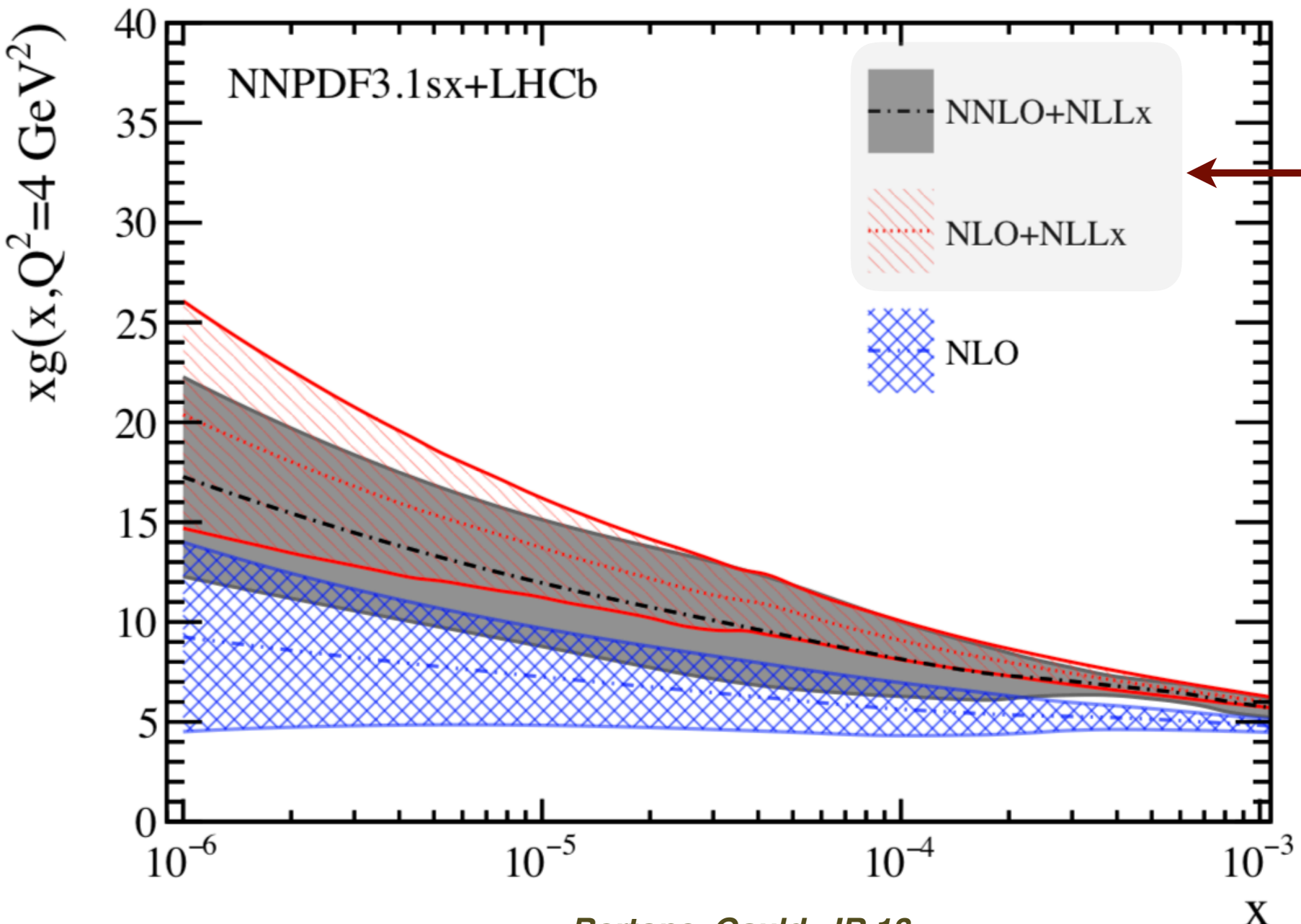
Monitor the **fit quality** as one includes more data from the **small-*x* region**

Best description of **small-*x* HERA data** only possible with **BFKL effects!**

Forward charm production revisited

LHCb D meson production included in **NNPDF3.1sx (N)NLO+NLL*x*** fits

Similar reduction of gluon PDF errors at **small-*x*** + **increase in central value**



BFKL effects included

small-x resummation: excellent **perturbative convergence** even for **x ≃ 10⁻⁶**

Bertone, Gauld, JR 18

Forward charm production revisited

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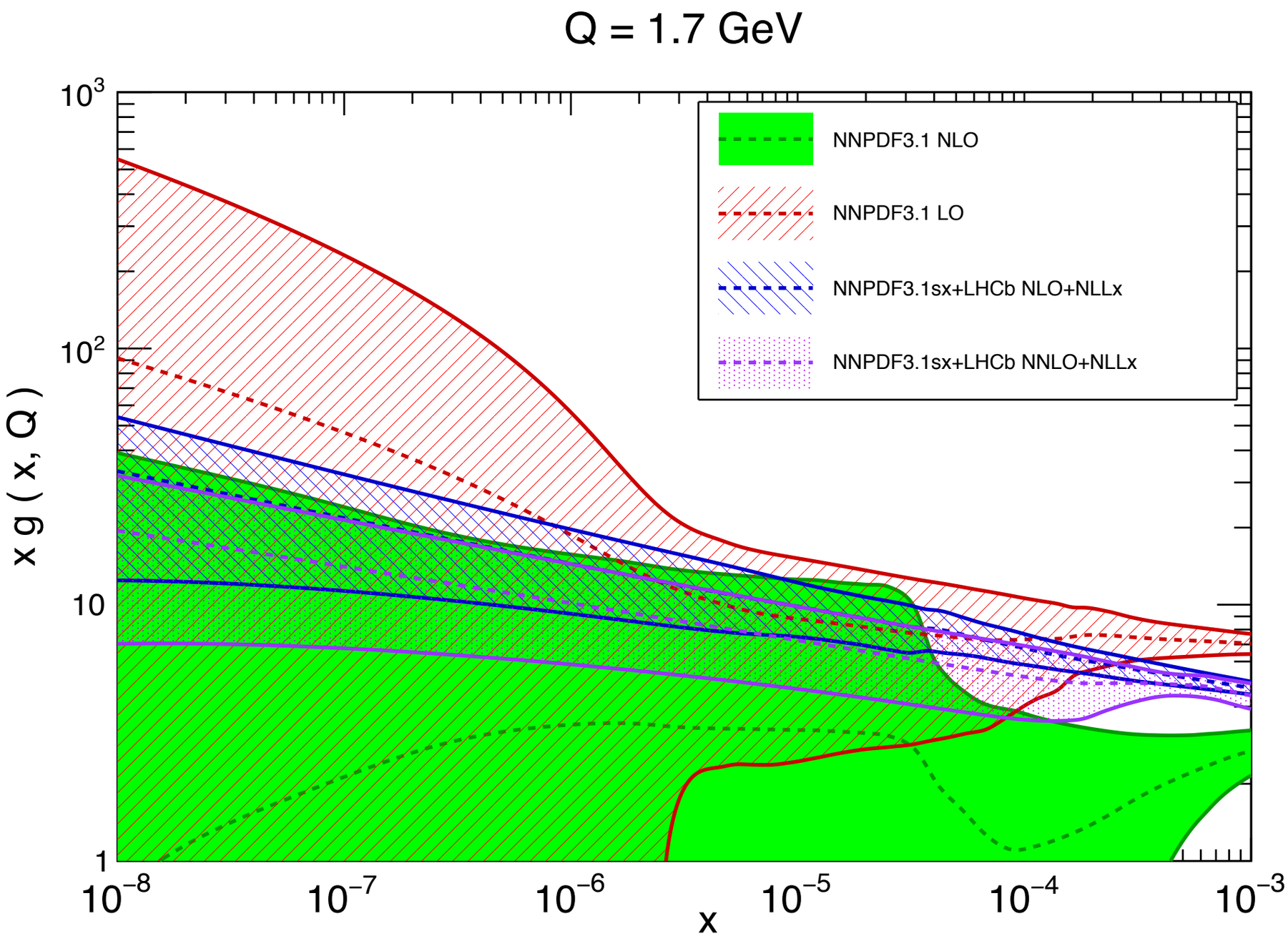


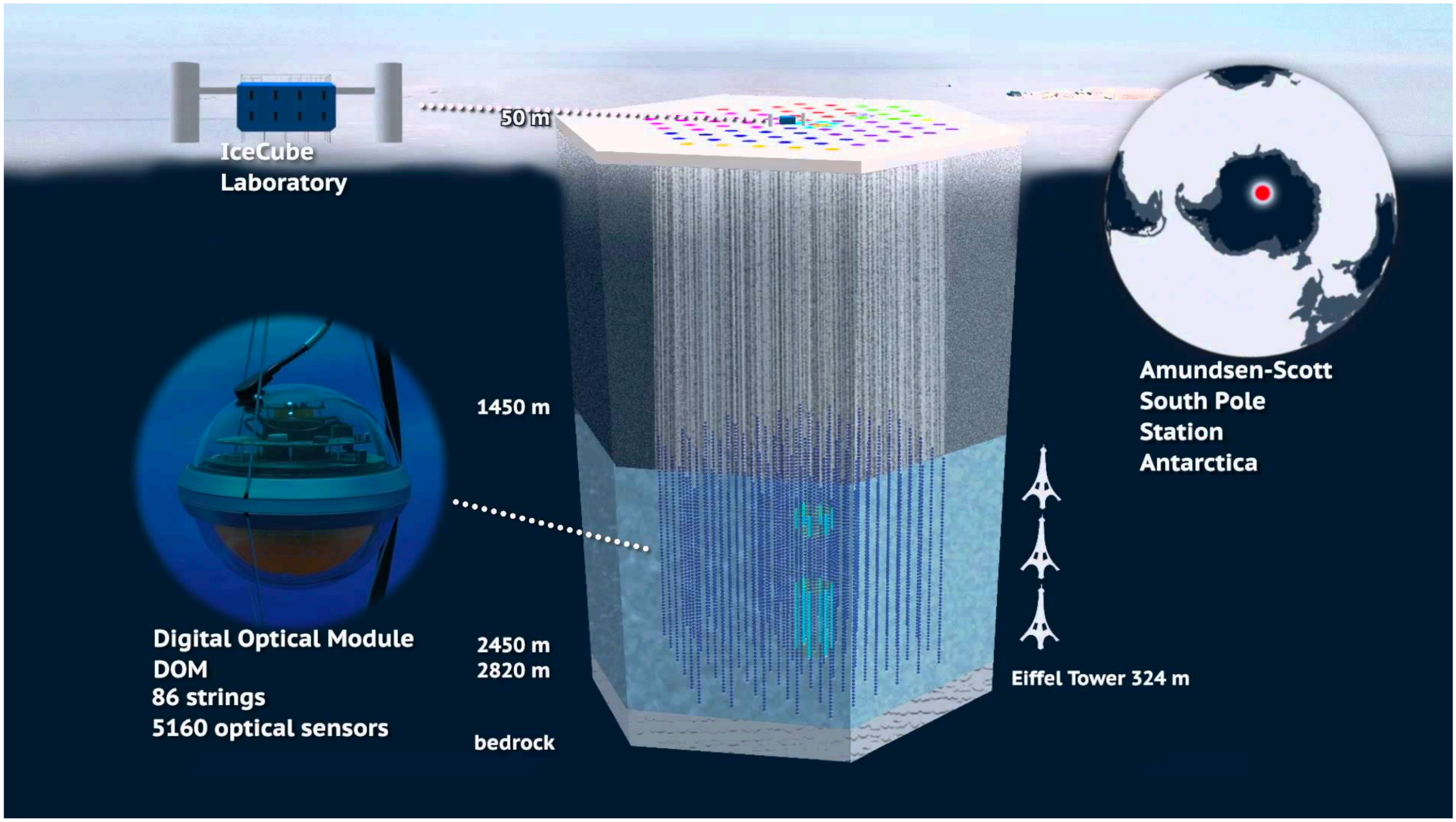
small-x resummation: excellent **perturbative convergence** even for **x ≃ 10^{-8}**

Neutrino telescopes

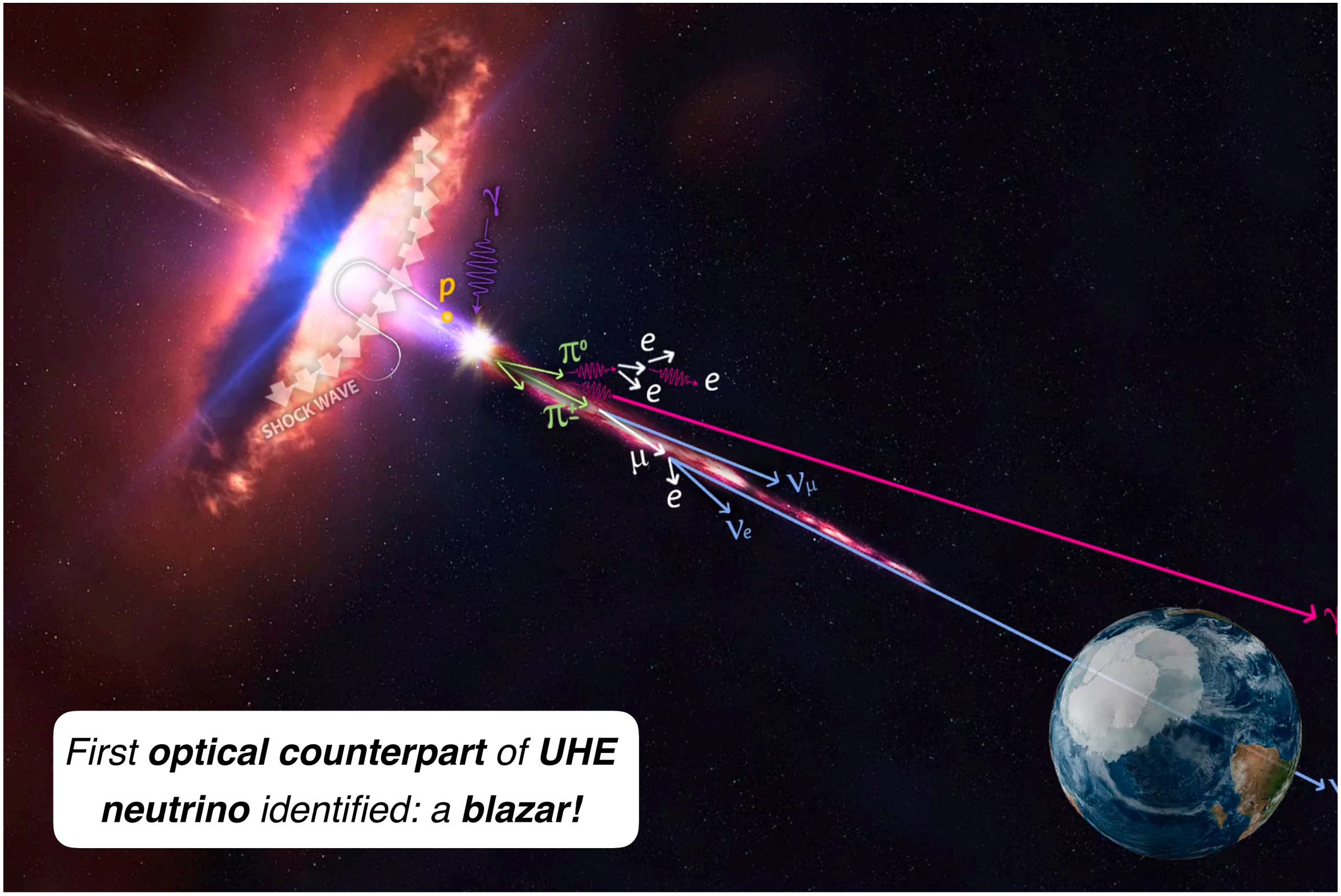
Ultra-high energy (UHE) neutrinos: novel window to the **extreme Universe!**

Neutrino telescopes

Ultra-high energy (UHE) neutrinos: novel window to the **extreme Universe!**



Unveiling cosmic neutrino origin

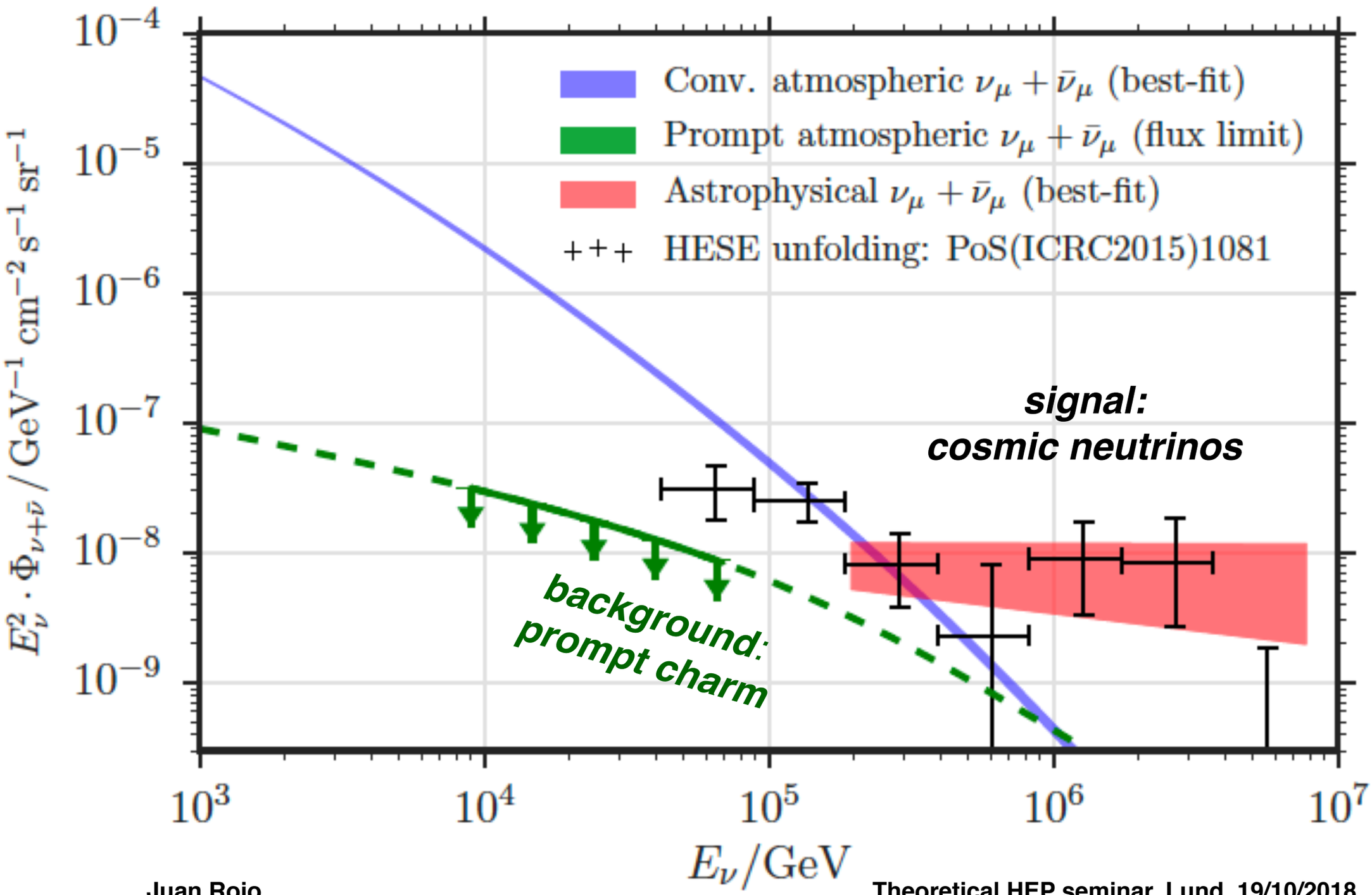


*First **optical counterpart** of **UHE neutrino** identified: a **blazar!***

Neutrino telescopes as QCD microscopes

***signal**: cosmic neutrino - nucleus scattering*

***background**: prompt charm production*



Neutrino telescopes as QCD microscopes

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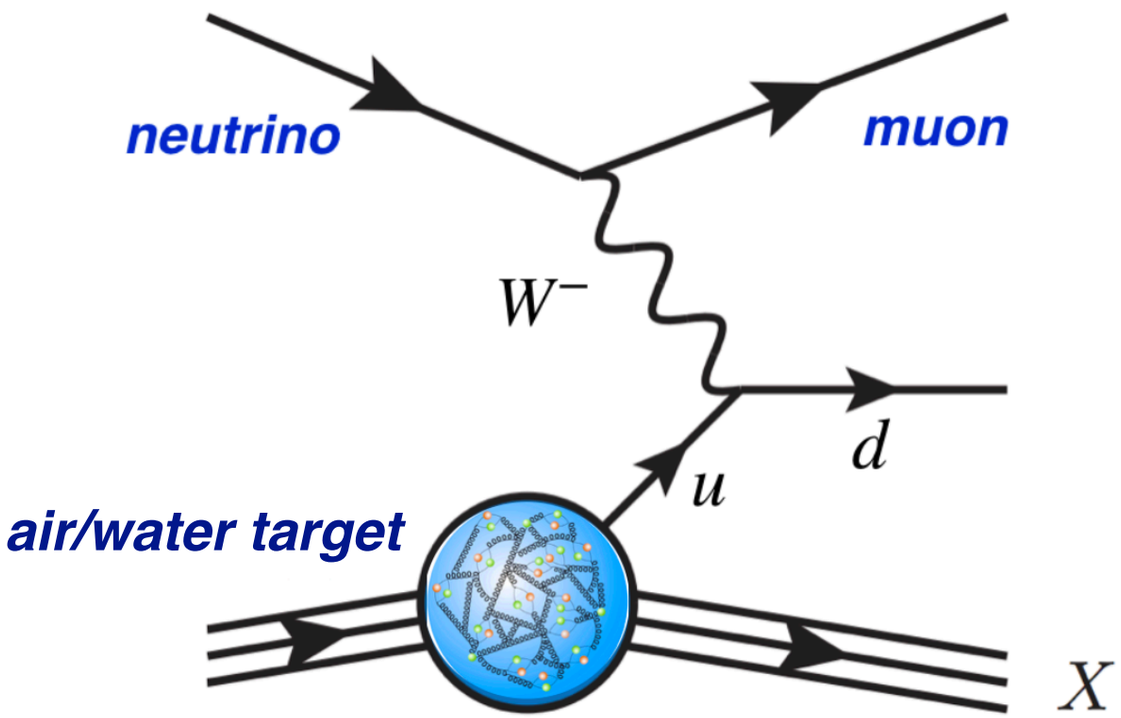
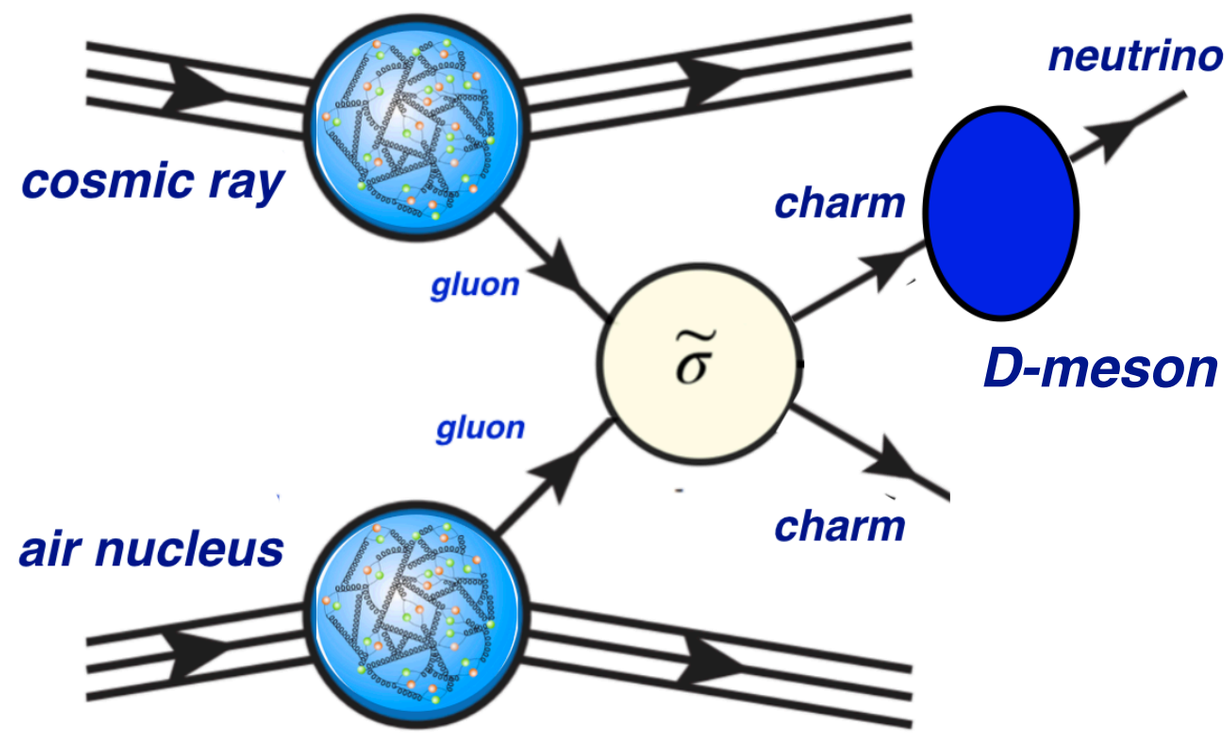


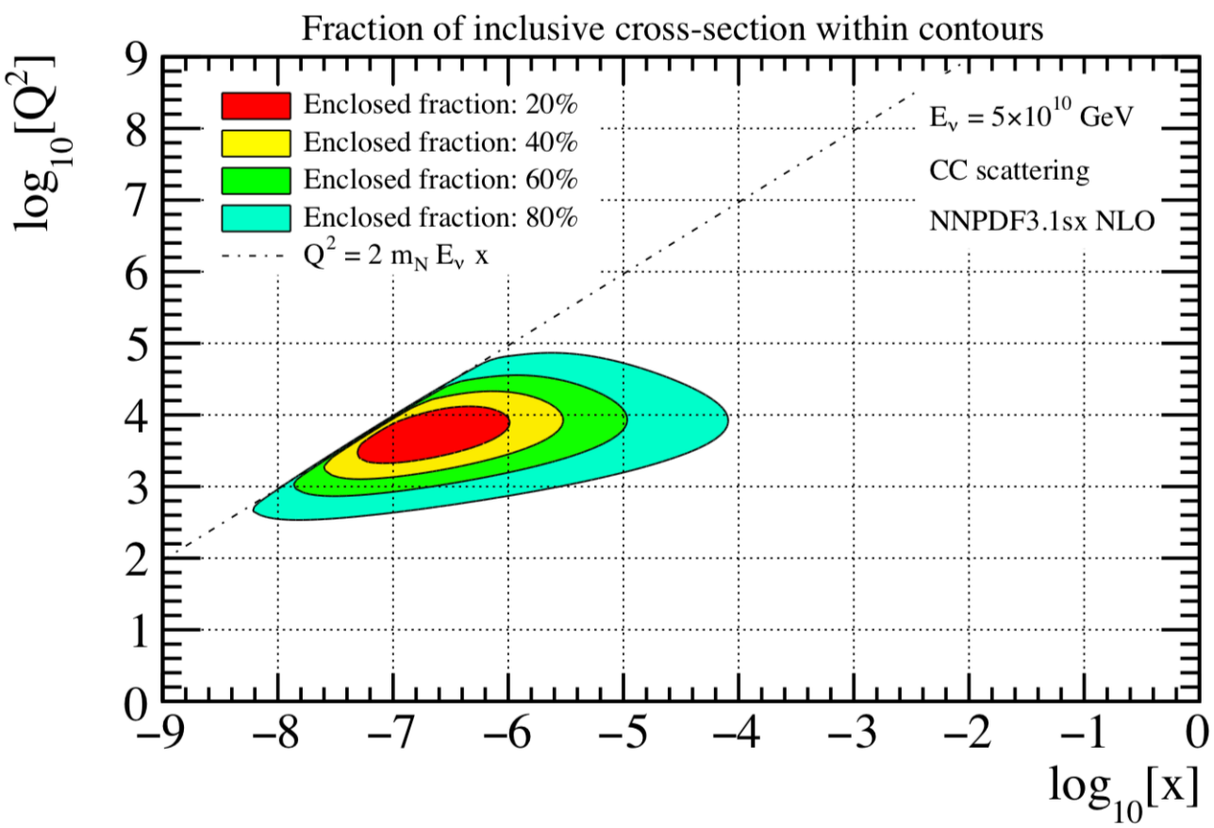


Sensitive to **small-*x* quarks** (and thus gluons via evolution) down to **x** ≃ **10^{-8}** and **Q** ≃ **M_W**

Sensitive to **small-*x* gluons** down to **x** ≃ **10^{-6}** and **Q** ≃ **M_{charm}** in the **centre-of-mass frame**

Neutrino telescopes as QCD microscopes

***signal**: cosmic neutrino - nucleus scattering*



Sensitive to **small-*x* quarks** (and thus gluons via evolution) down to **x** ≃ **10^{-8}** and **Q** ≃ **M_W**

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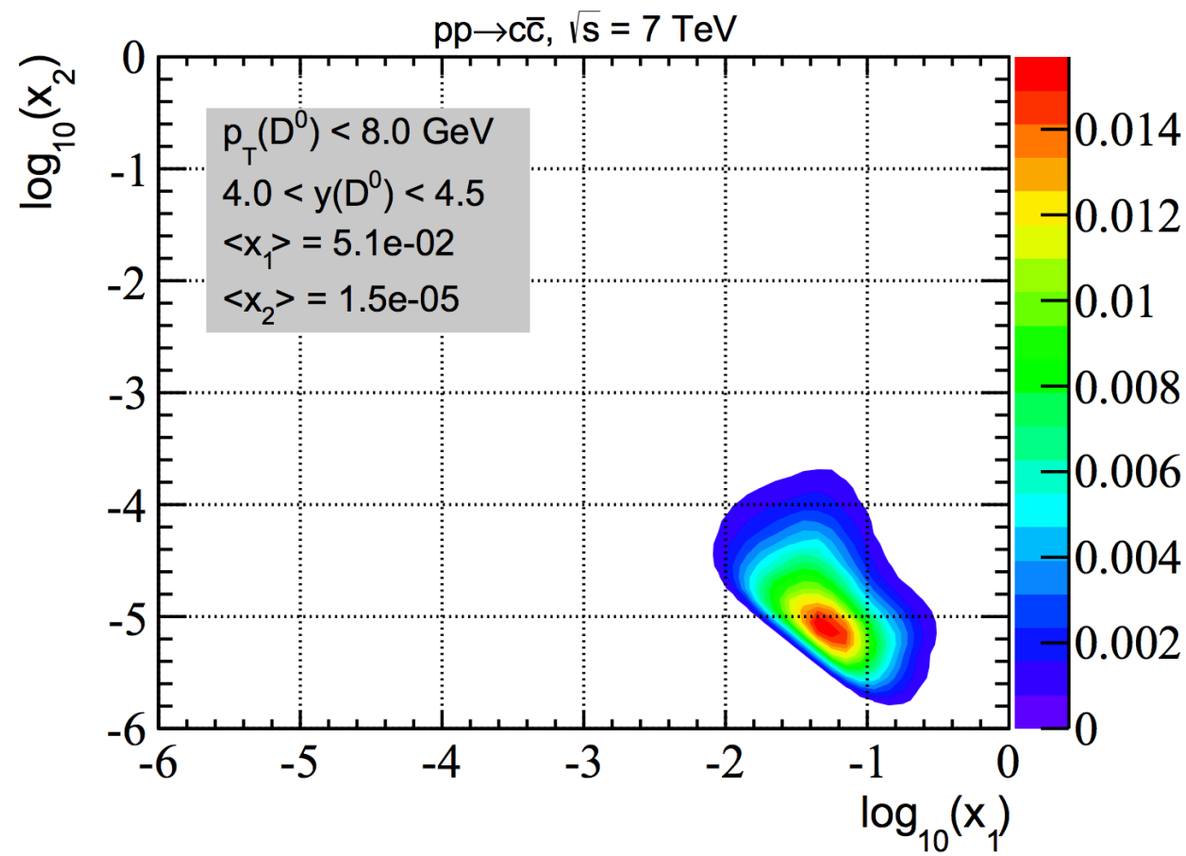
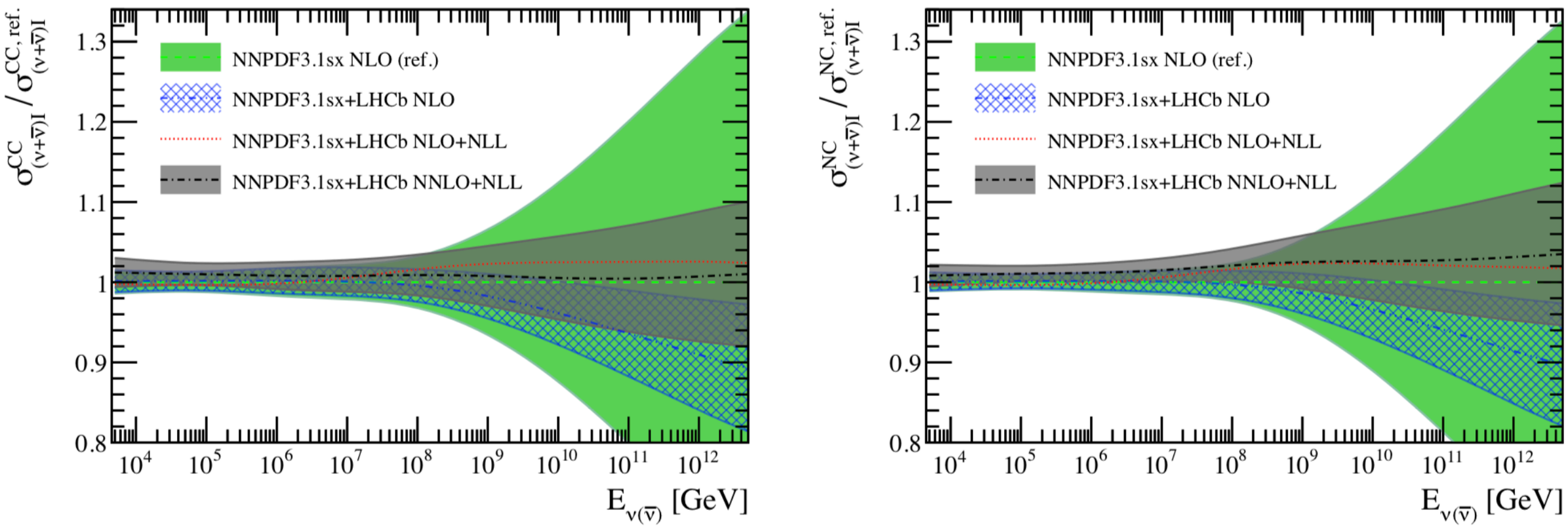


Sensitive to **small-*x* gluons** down to **x** ≃ **10^{-6}** and **Q** ≃ **M_{charm}** in the **centre-of-mass frame**

UHE neutrino-nucleus cross-section

Bertone, Gauld, JR 17

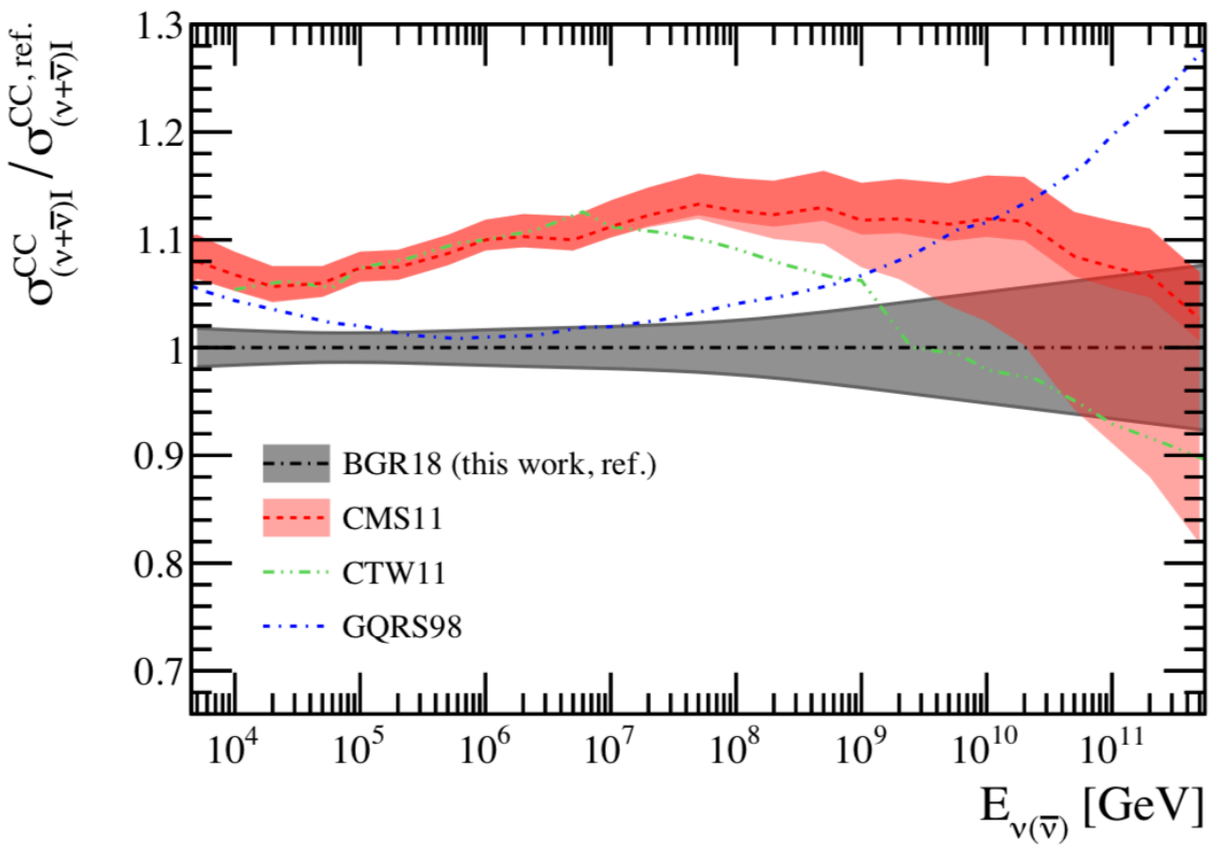


State-of-the-art predictions for **ultra-high energy** neutrino interactions

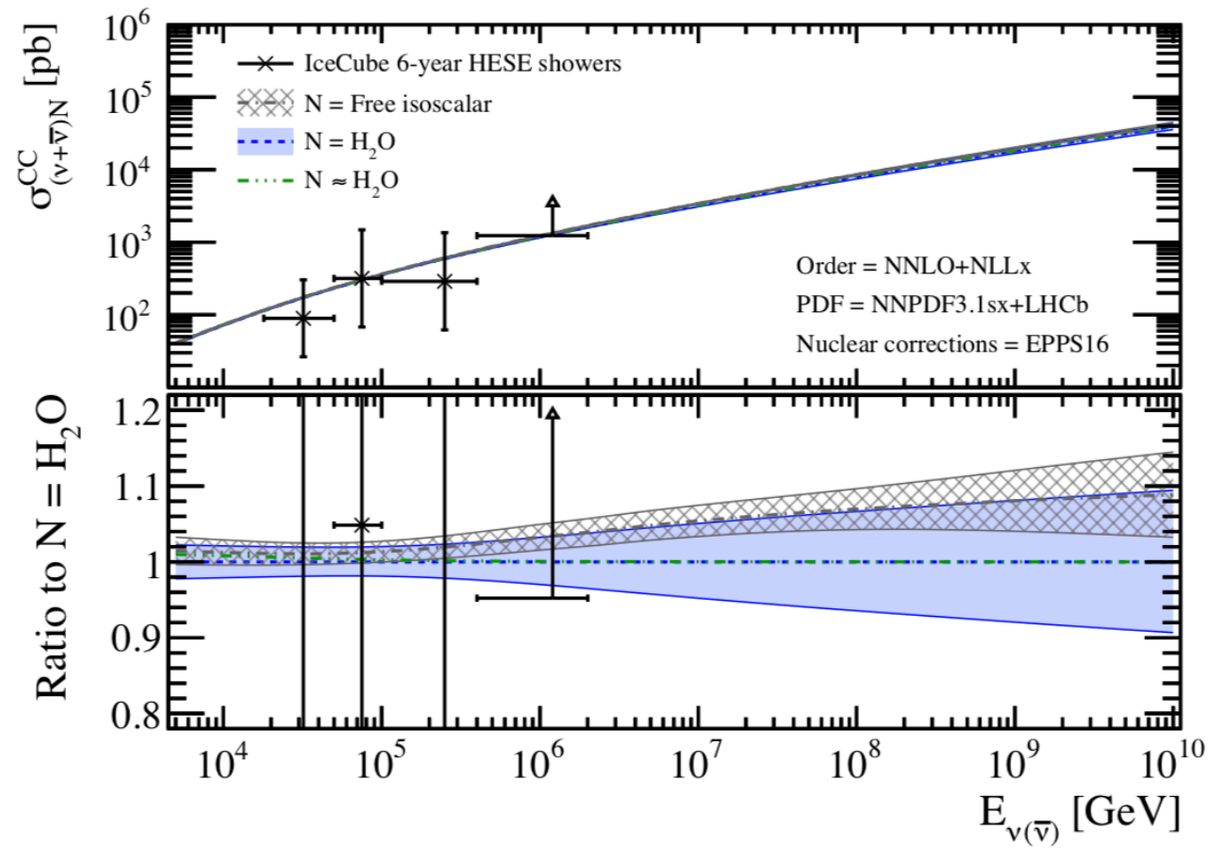
- **BFKL small-x effects** in PDFs and deep-inelastic structure functions
- Constraints on small-x PDFs from **LHCb charm production**
- Accounting for **nuclear corrections** and heavy-quark-initiated contributions

UHE neutrino-nucleus cross-section

*Comparison with **previous results***



*Comparison with **IceCube data***



- Differences both at **intermediate** (better PDFs, improved treatment of heavy quarks) and **high energies** (LHCb constraints, BFKL effects)
- Nuclear effects important: constrain them with LHCb **charm production in p+Pb**
- IceCube and other neutrino telescopes are the **ultimate QCD microscopes!**

Towards Ultimate PDFs at the High Lumi LHC

Abdul-Khalek, Bailey, Gao, Harland-Lang, JR 18
+ HL/HE-LHC Yellow Report, to appear

A luminous future

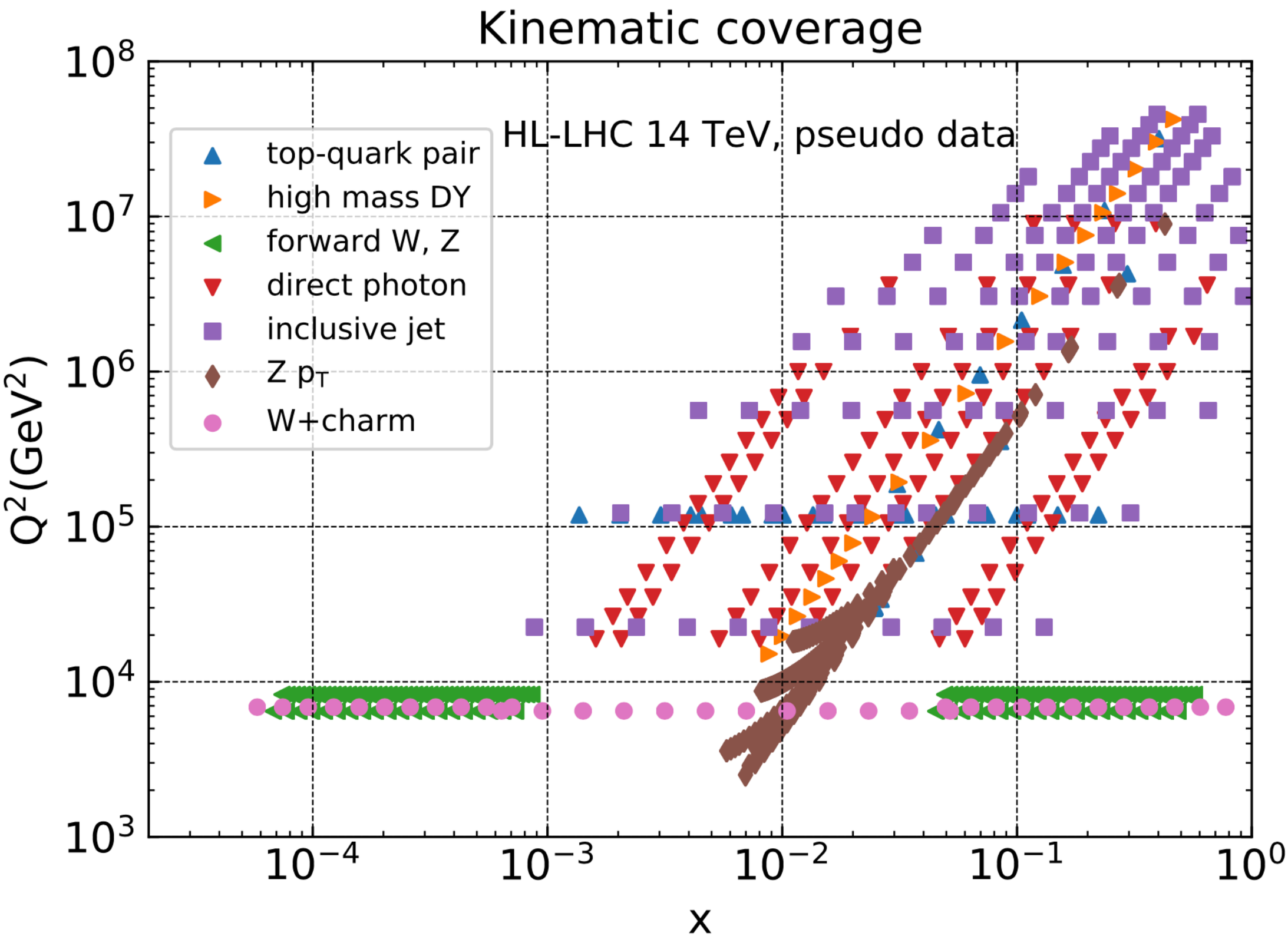
- In the framework of the update of the **European Strategy for Particle Physics**, a CERN Yellow Report will evaluate the physics potential of the **HL-LHC** (to appear in Dec 2018)

- We have studied the **impact of HL-LHC data on PDFs**, including projections with (future) LHCb measurements.

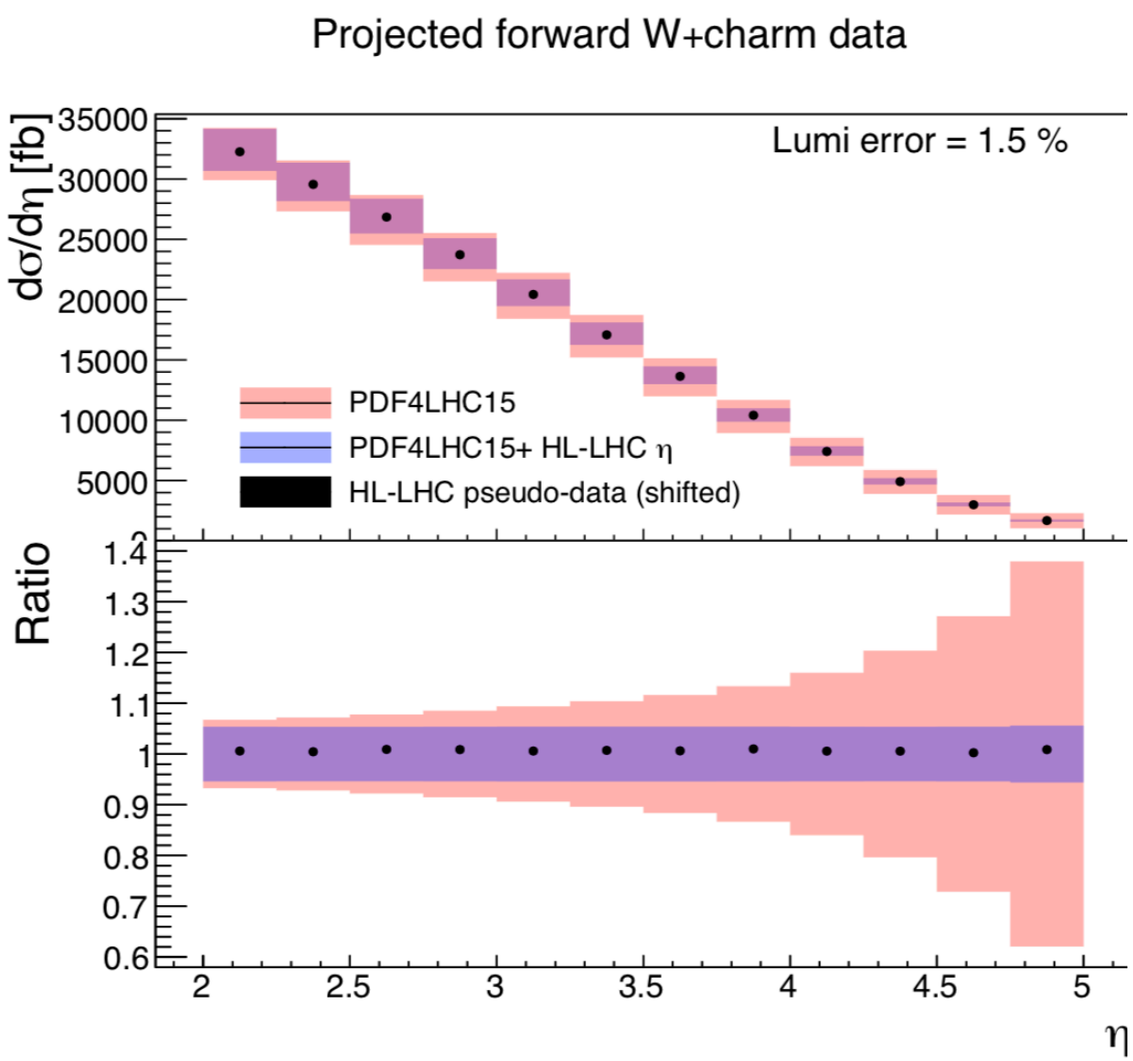
*What is the **ultimate precision** that can be expected for PDFs from **hadron collider data?***

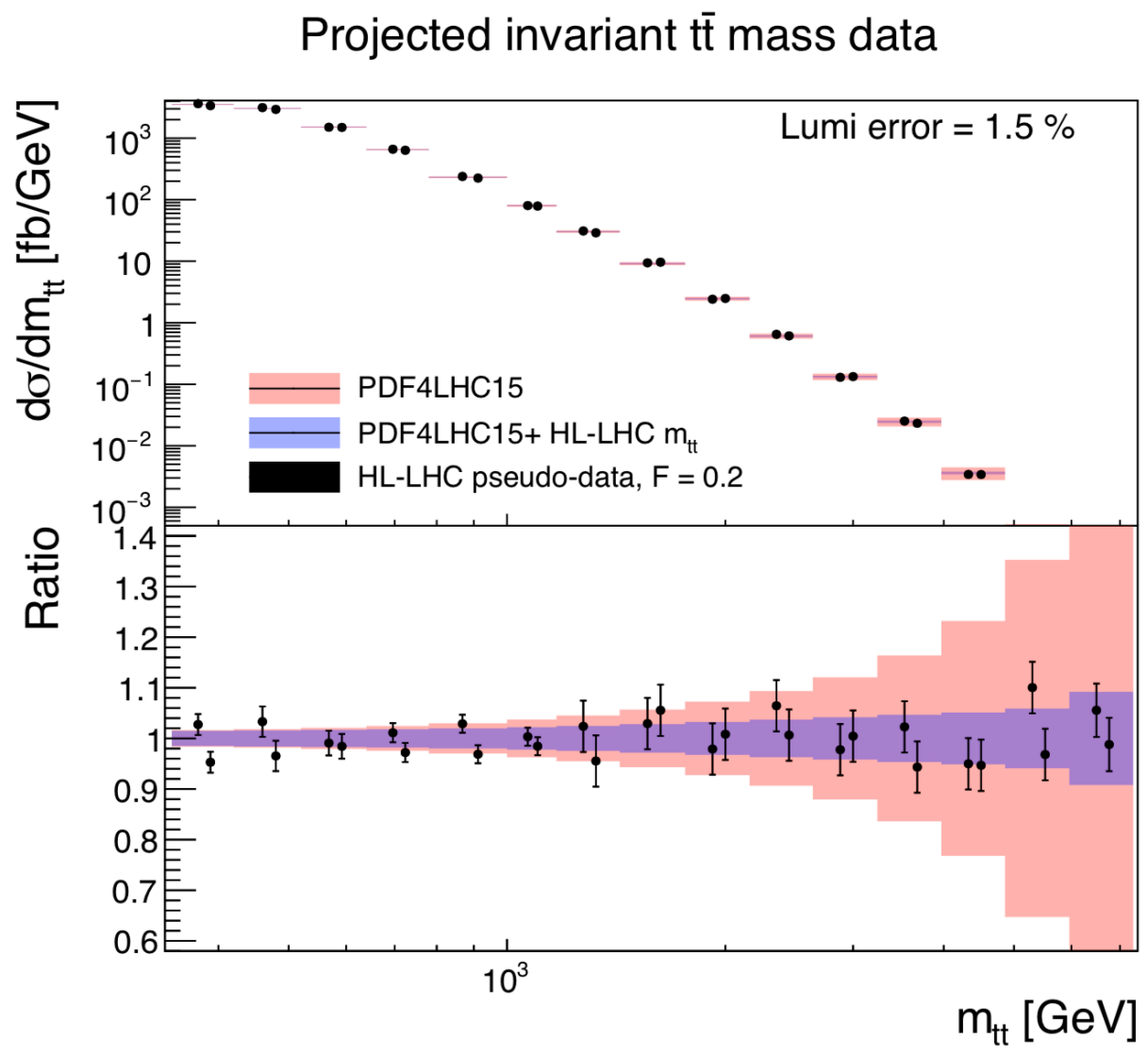
Process	Kinematics	$N_{\rm dat}$
Z p_T	$20\,\text{GeV} \leq p_T^{ll} \leq 3.5$ TeV $12\,\text{GeV} \leq m_{ll} \leq 150$ GeV $\lvert y_{ll}\rvert \leq 2.4$	162
high-mass Drell-Yan	$p_T^{l1(2)} \geq 40(30)\,\text{GeV}$ $\lvert\eta^l\rvert \leq 2.5,\ m_{ll} \geq 116\,\text{GeV}$	21
top quark pair	$m_{t\bar{t}} \simeq 5$ TeV, $\lvert y_t\rvert \leq 2.5$	26
W+charm (central)	$p_T^{\mu} \geq 26\,\text{GeV},\ p_T^{c} \geq 5\,\text{GeV}$ $\lvert\eta^{\mu}\rvert \leq 2.4$	6
W+charm (forward)	$p_T^{\mu} \geq 20\,\text{GeV},\ p_T^{c} \geq 20\,\text{GeV}$ $p_T^{\mu+c} \geq 20\,\text{GeV}$ $2 \leq \eta^{\mu} \leq 5,\ 2.2 \leq \eta^{c} \leq 4.2$	12
Direct photon	$E_T^{\gamma} \lesssim 3$ TeV, $\lvert\eta_{\gamma}\rvert \leq 2.5$	53
Forward W, Z	$p_T^{l} \geq 20\,\text{GeV},\ 2.0 \leq \eta^{l} \leq 4.5$ $2.0 \leq y_{ll} \leq 4.5$ $60 \leq m_{ll} \leq 120\,\text{GeV}$	90
Inclusive jets	$\lvert y\rvert \leq 3,\ R = 0.4$	54
Total		424

A luminous future



HL-LHC constraints from LHCb





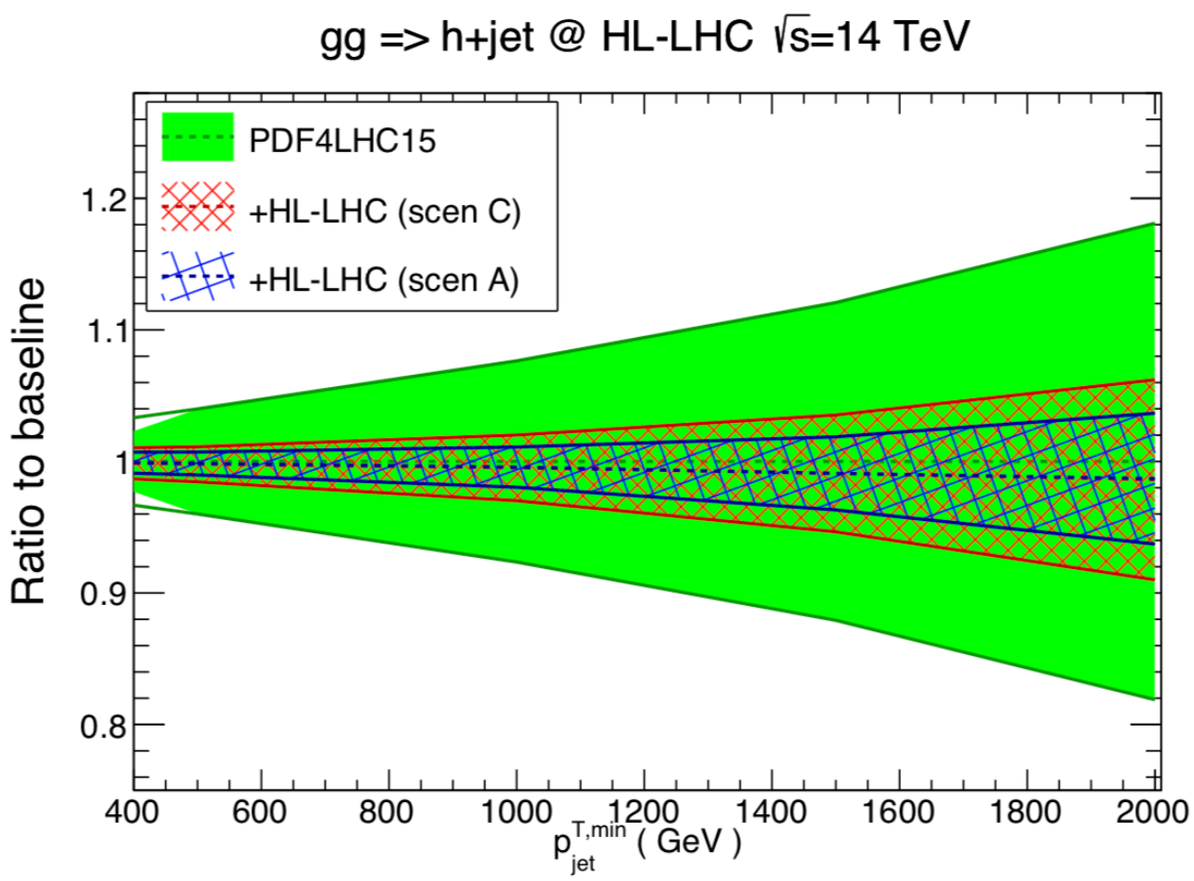
Forward W+charm

Top quark pair production

HL-LHC measurements will be specially useful to constrain the **gluon** and **quark flavour separation** in the large-*x* region, including strangeness

HL-LHC constraints on PDFs

PDF uncertainties HLLHC / Current	10 GeV < M_X < 40 GeV	40 GeV < M_X < 1 TeV	1 TeV < M_X < 6 TeV
g-g luminosity	0.58 (0.49)	0.41 (0.29)	0.38 (0.24)
q-g luminosity	0.71 (0.65)	0.49 (0.42)	0.39 (0.29)
quark-quark luminosity	0.78 (0.73)	0.46 (0.37)	0.60 (0.45)
quark-antiquark luminosity	0.73 (0.70)	0.40 (0.30)	0.61 (0.50)



HL-LHC data will lead to **stringent constraints on PDFs**, reducing uncertainties by up to a **factor 4**, and making possible precise predictions of central processes such as **Higgs p_T**

Summary and outlook

- Quark/gluon structure of the proton: essential ingredient for LHC phenomenology
- LHC data provides **stringent constraints on PDFs**, from the small-x gluon to the large-x antiquarks and to intrinsic charm
- PDFs with **theoretical uncertainties**: the next milestone for global QCD analyses
- **Neutrino astrophysics** requires direct input from small-x QCD
- Precision determination of the small-x gluon and the UHE neutrino-nucleon cross-section thanks to **LHCb charm data + BFKL resummation**
- At the **HL-LHC**, theory calculations with 1% PDF uncertainties are within reach