The structure of the proton:

QCD at work from the LHC to IceCube

Juan Rojo

VU Amsterdam & Theory group, Nikhef

Nuclear Physics Seminar

University of California in Los Angeles (UCLA)

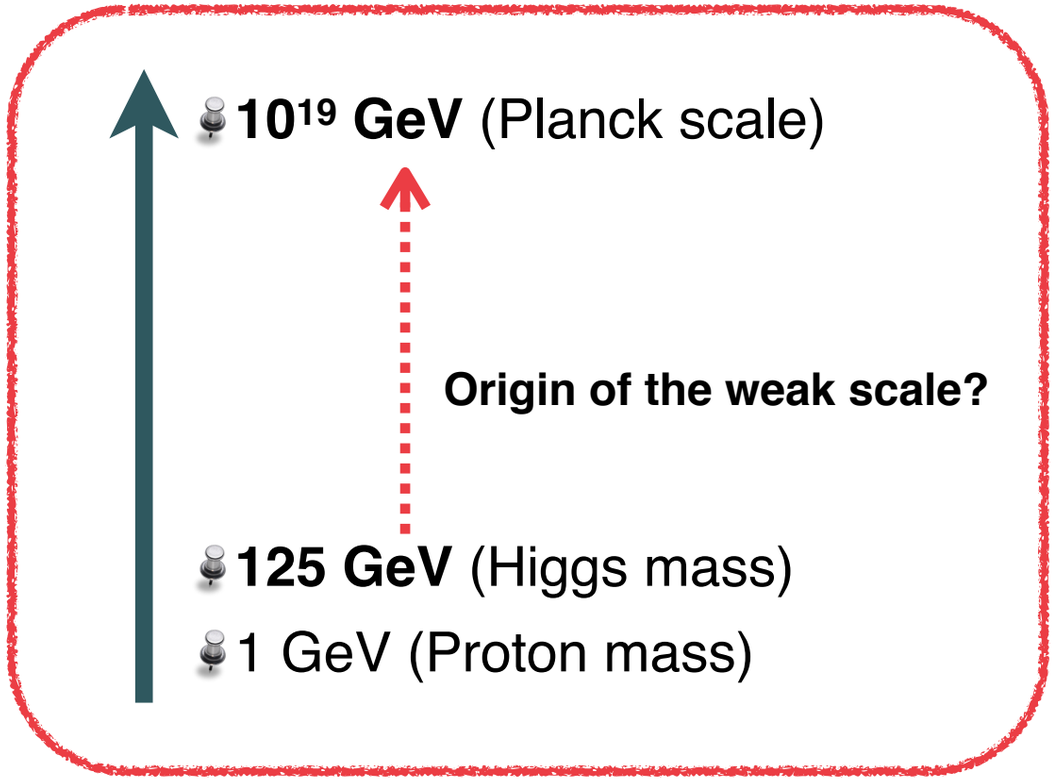
14/08/2019

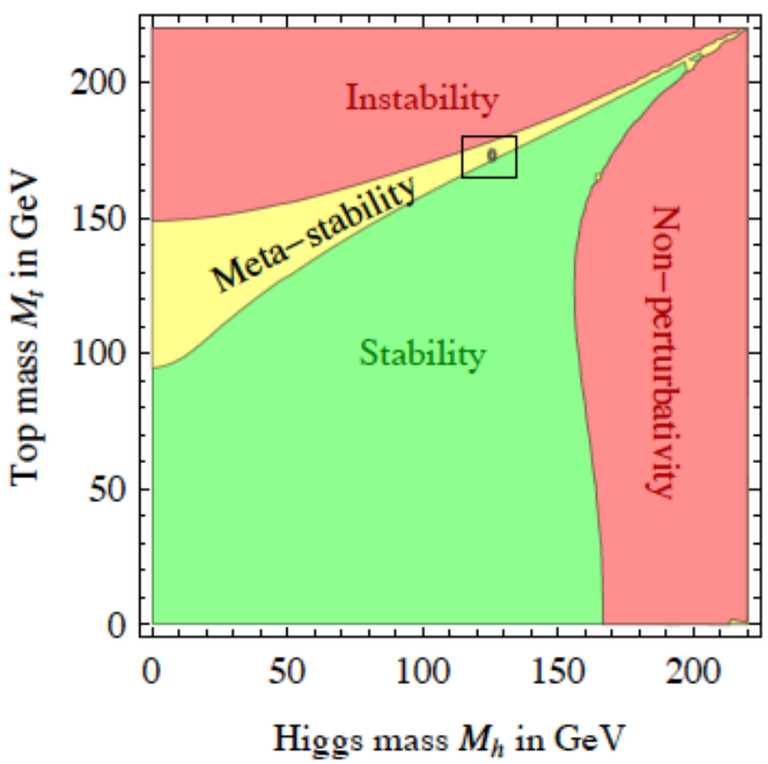
Particle Physics in the LHC precision era

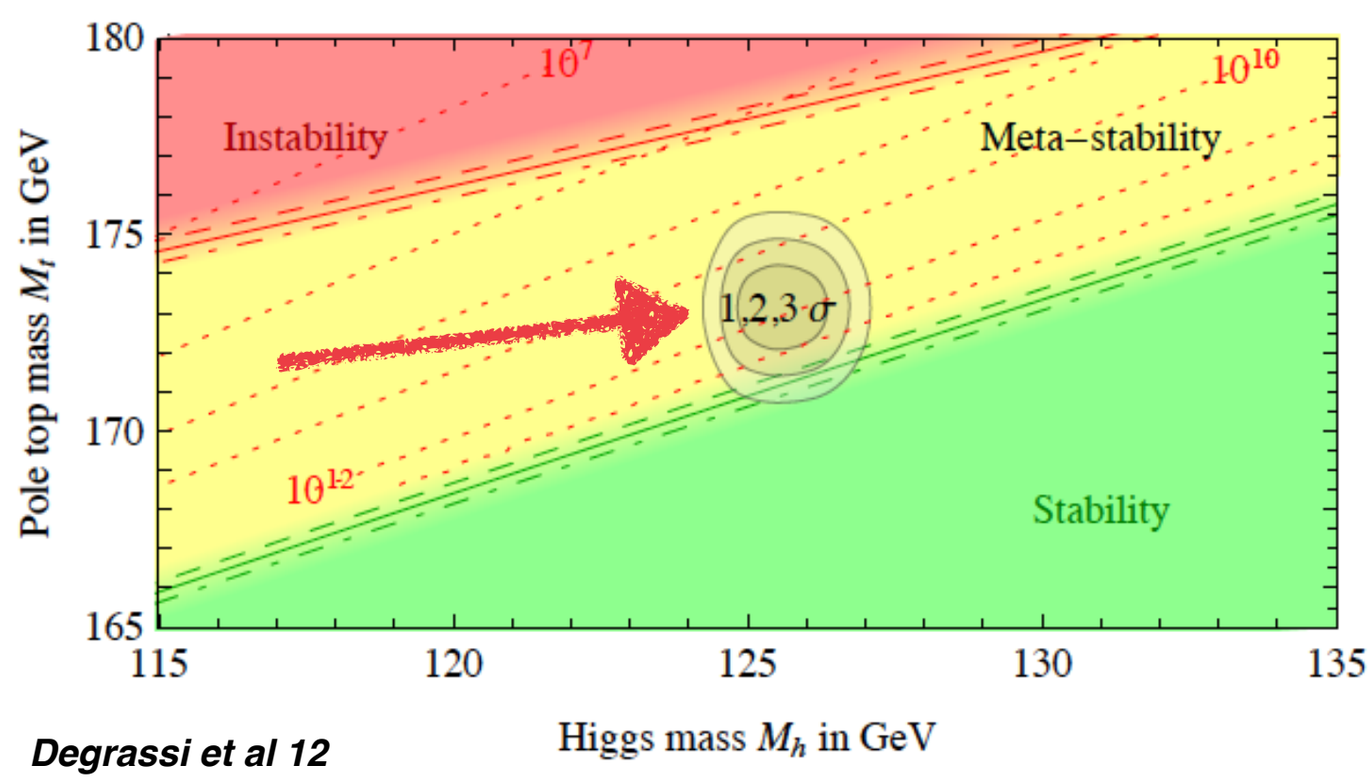
Open questions in particle physics

The Higgs boson

- Huge gap between **weak** and **Plank scales?**
- **Compositeness**? Non-minimal Higgs sector?
- Coupling to **Dark Matter**? Role in cosmological phase transitions?
- Is the **vacuum state of the Universe** stable?







Degrassi et al 12

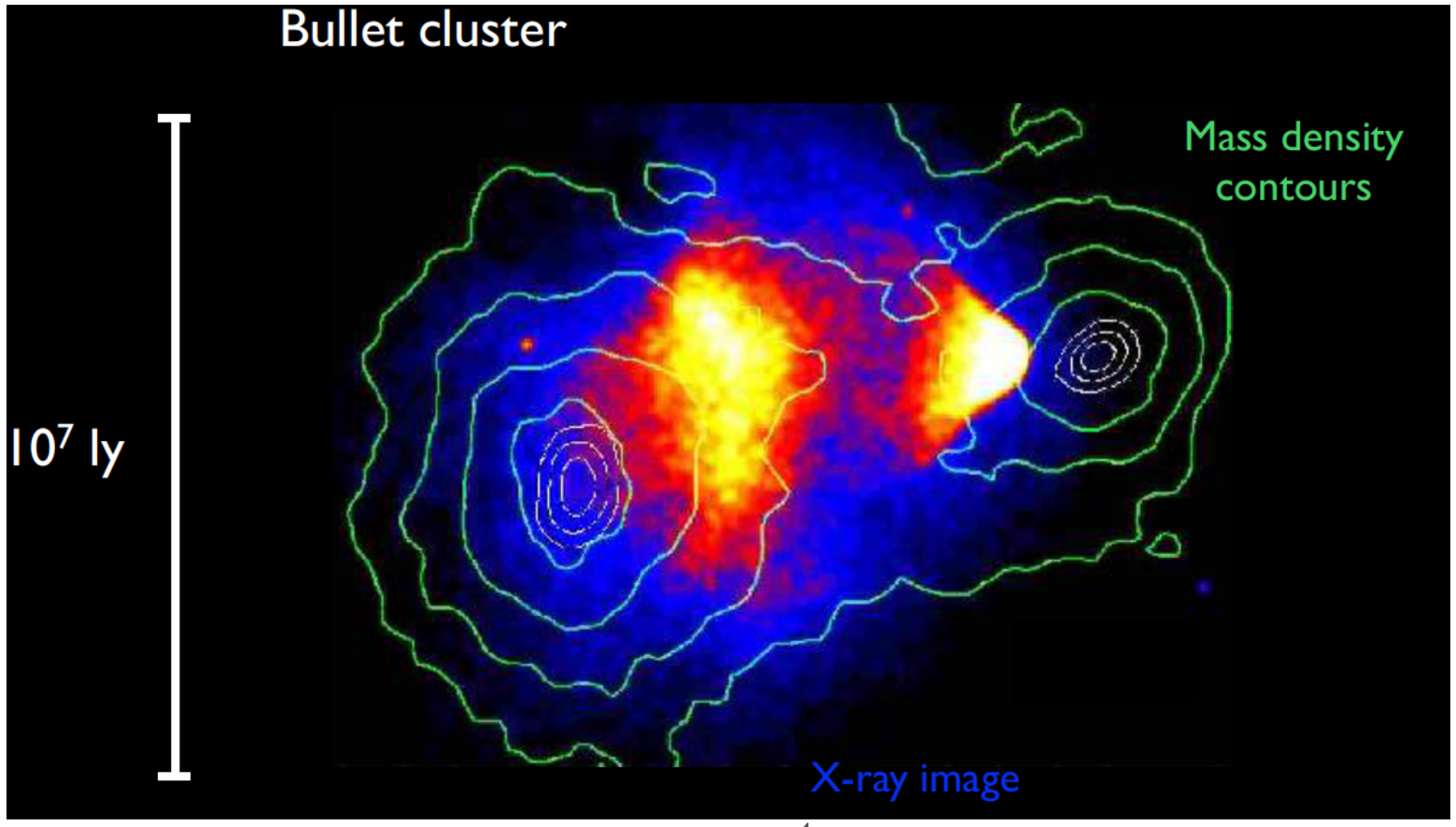
Open questions in particle physics

The Higgs boson

- Huge gap between **weak** and **Plank scales?**
- **Compositeness**? Non-minimal Higgs sector?
- Coupling to **Dark Matter**? Role in cosmological phase transitions?
- Is the **vacuum state of the Universe** stable?

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

The Higgs boson

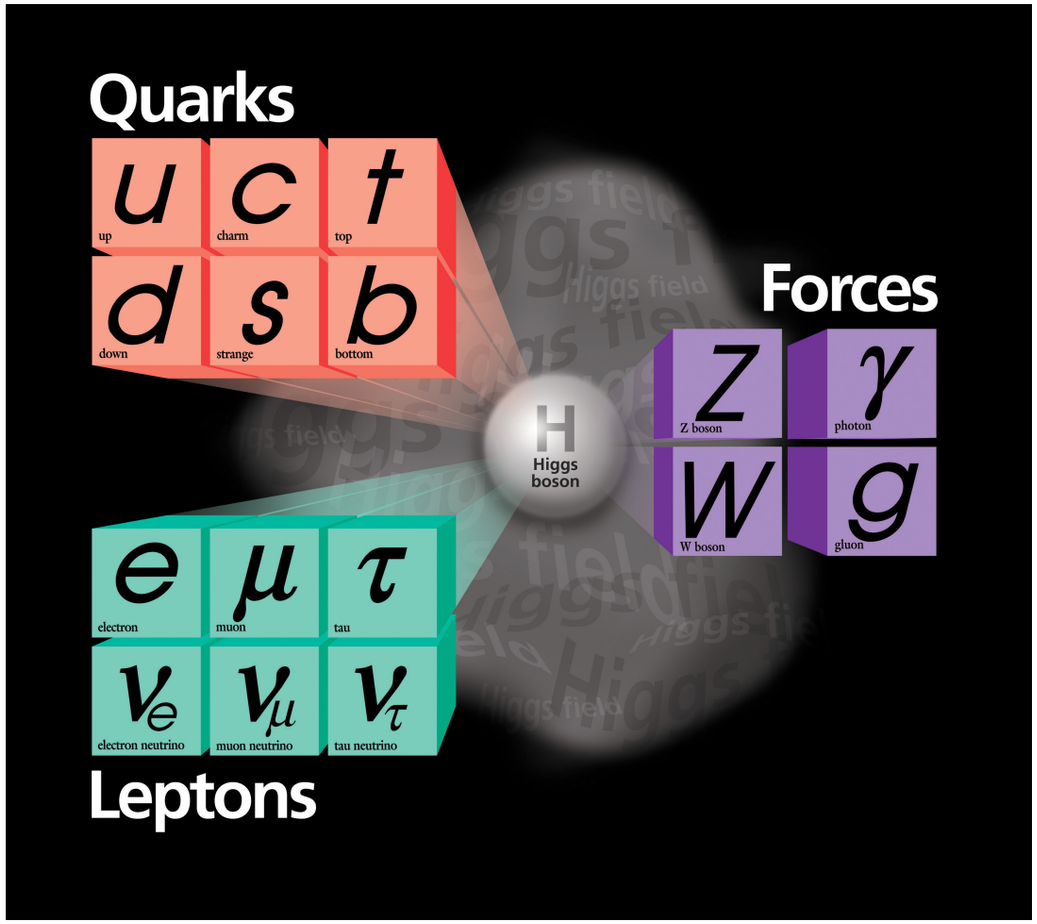
- Huge gap between **weak** and **Plank scales?**
- **Compositeness**? Non-minimal Higgs sector?
- Coupling to **Dark Matter**? Role in cosmological phase transitions?
- Is the **vacuum state of the Universe** stable?

Dark matter

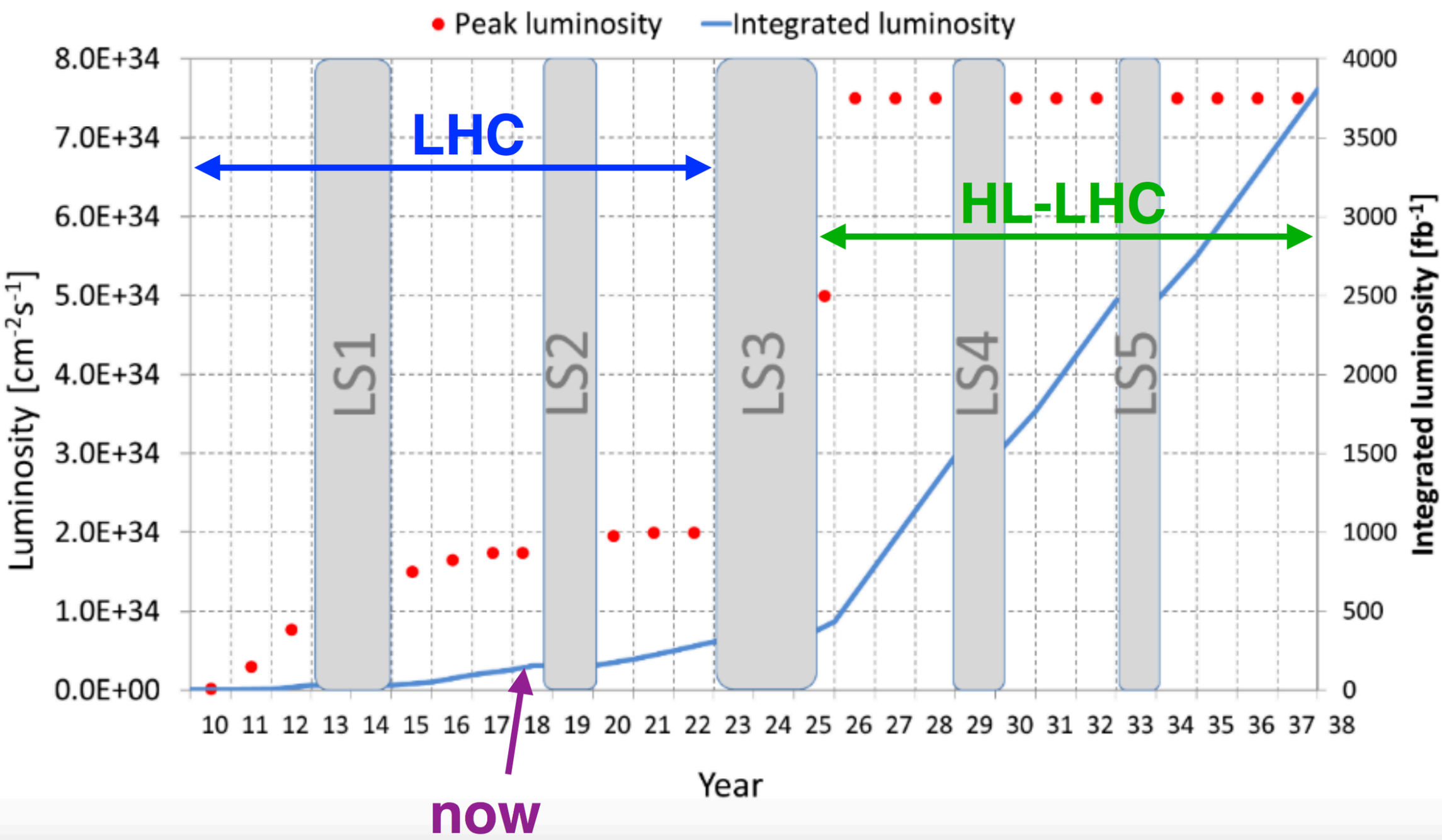
- **Weakly interacting massive particles**? Neutrinos? Ultralight particles (axions)?
- **Interactions** with SM particles? Self-interactions?
- **Structure** of the Dark Sector?

Quarks and leptons

- Why **3 families?** Origin of **masses, mixings**?
- Origin of **Matter-Antimatter asymmetry?**
- Lepton Flavour **Universality?**
- Origin of **neutrino masses?** Are neutrinos Majorana or Dirac?



Open questions in particle physics

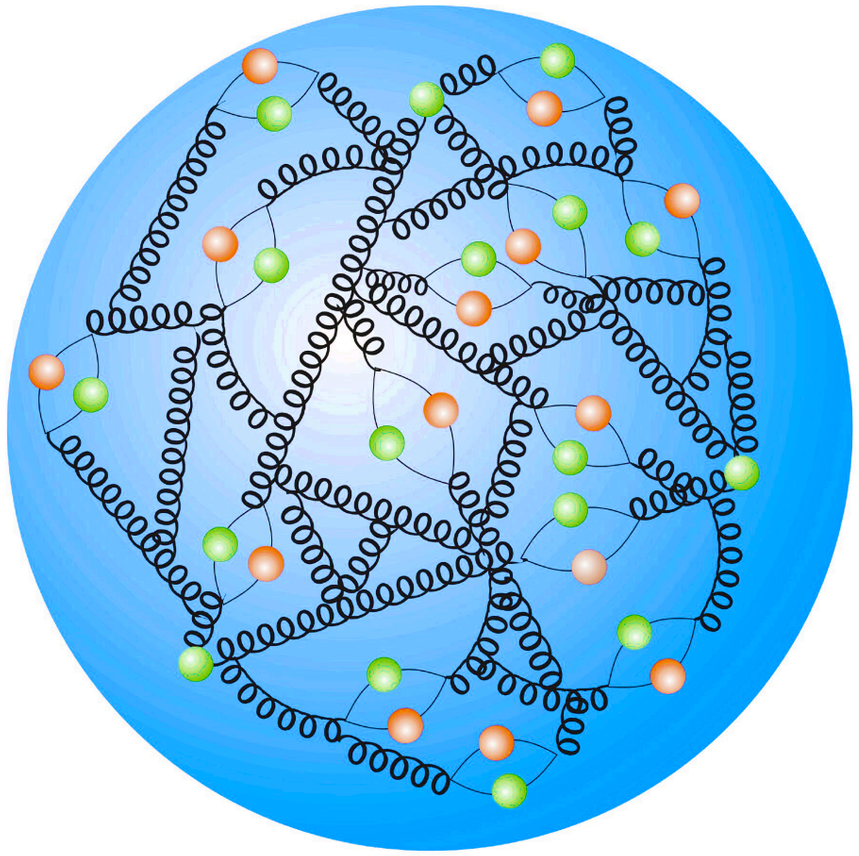


Crucial information on these fundamental questions will be provided by the LHC: the **exploration of the high-energy frontier** has just started!

The inner life of protons

The many faces of the proton

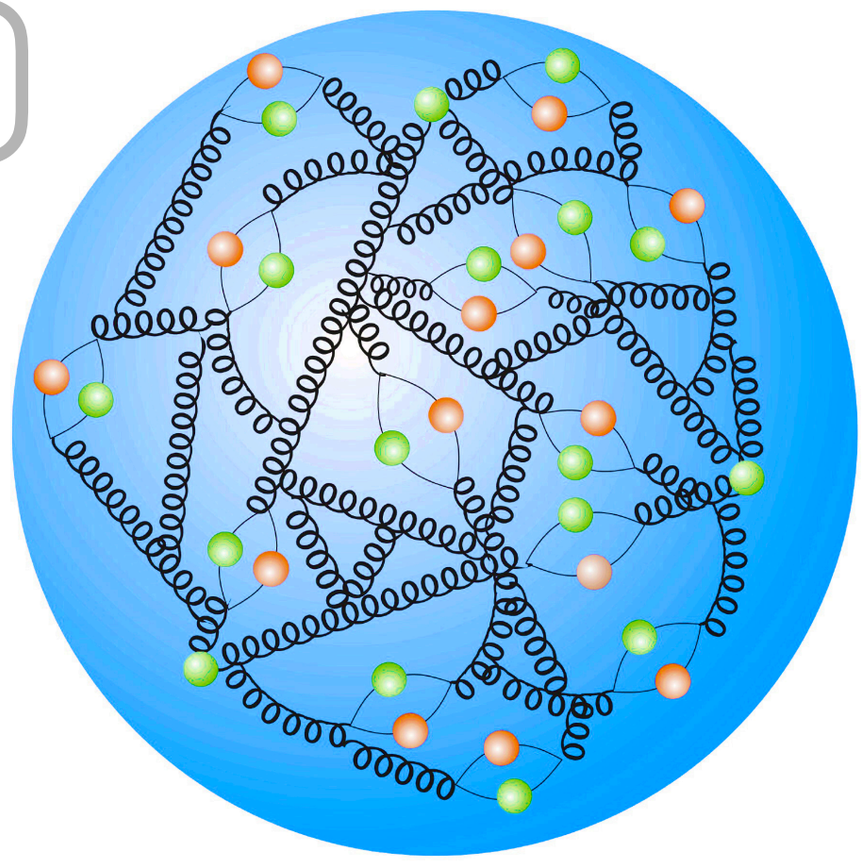
QCD bound state of **quarks** and **gluons**



The many faces of the proton

QCD bound state of **quarks** and **gluons**

Origin of mass?

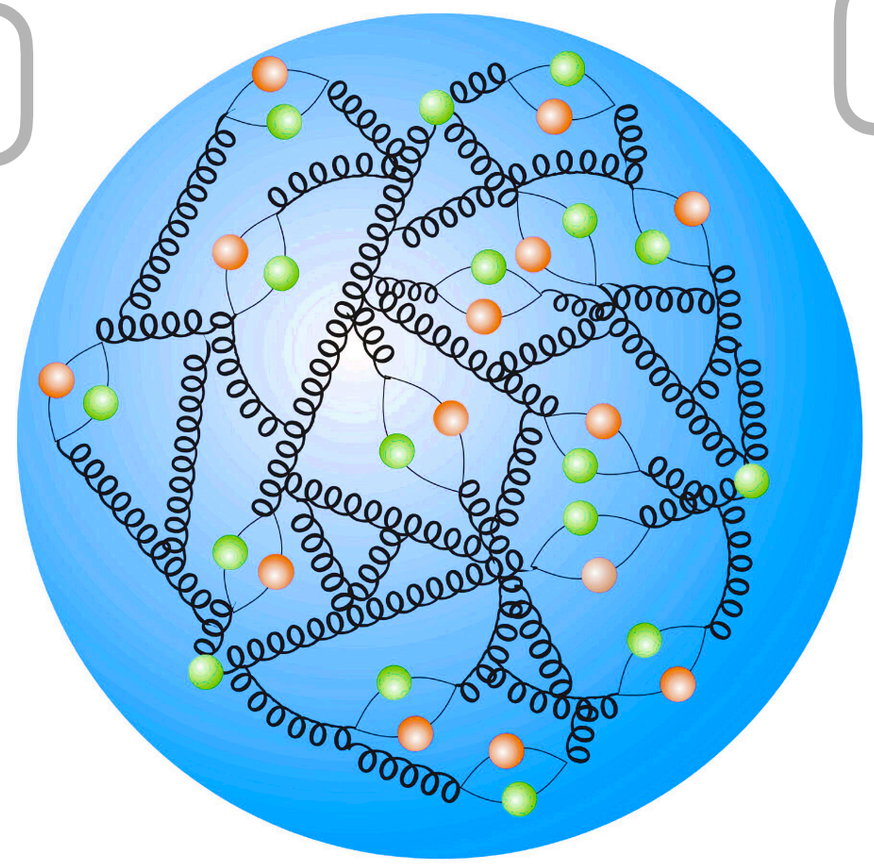


The many faces of the proton

QCD bound state of **quarks** and **gluons**

Origin of mass?

Origin of spin?

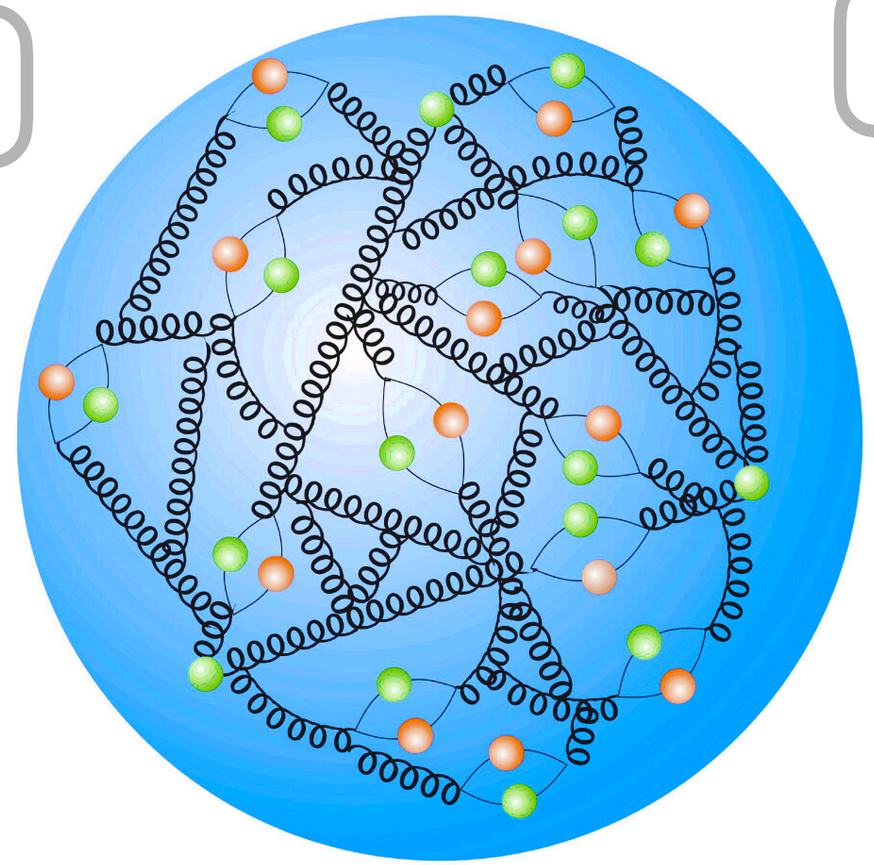


The many faces of the proton

QCD bound state of **quarks** and **gluons**

Origin of mass?

Origin of spin?



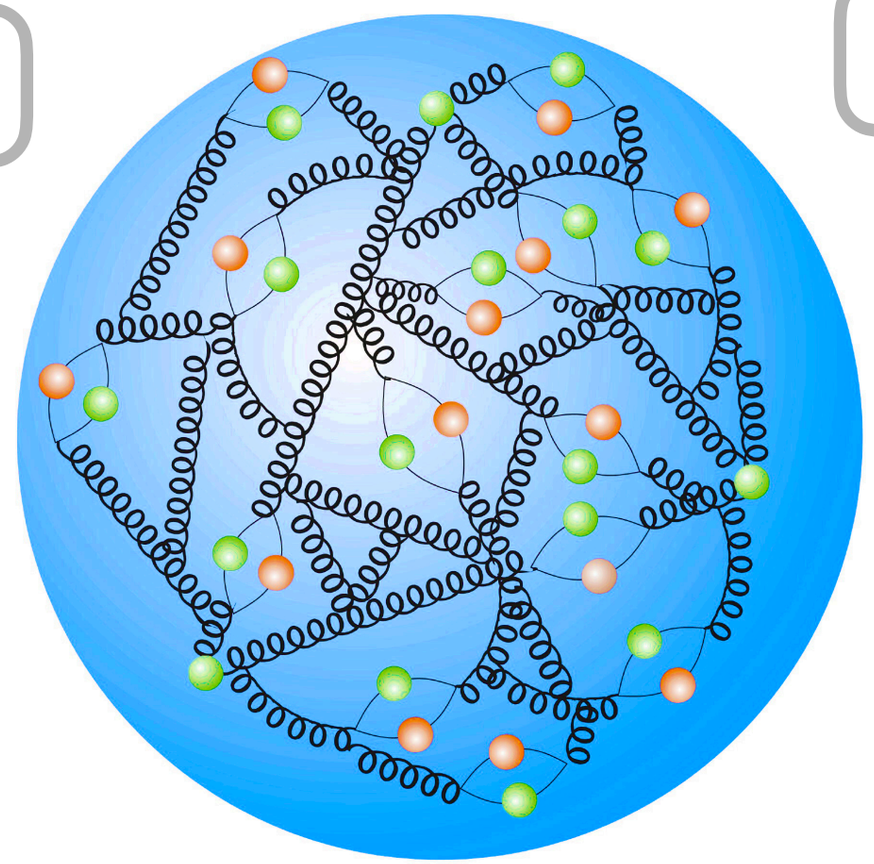
Gluon-dominated matter?

The many faces of the proton

QCD bound state of **quarks** and **gluons**

Origin of mass?

Origin of spin?



Gluon-dominated matter?

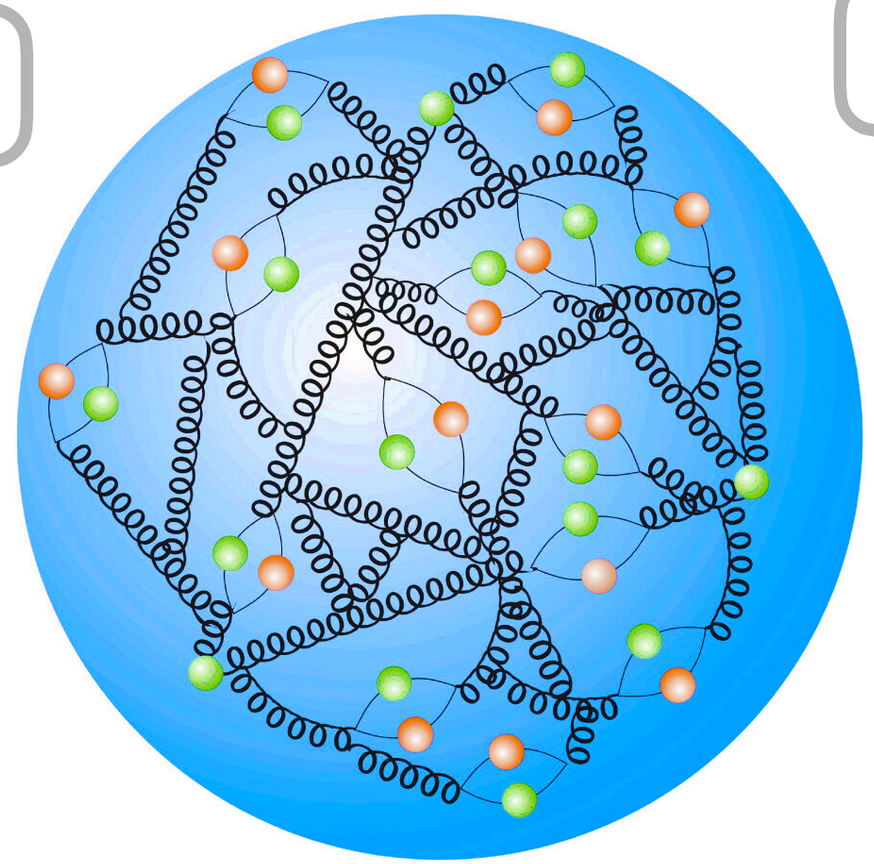
3D imaging?

The many faces of the proton

QCD bound state of **quarks** and **gluons**

Origin of mass?

Origin of spin?



Gluon-dominated matter?

3D imaging?

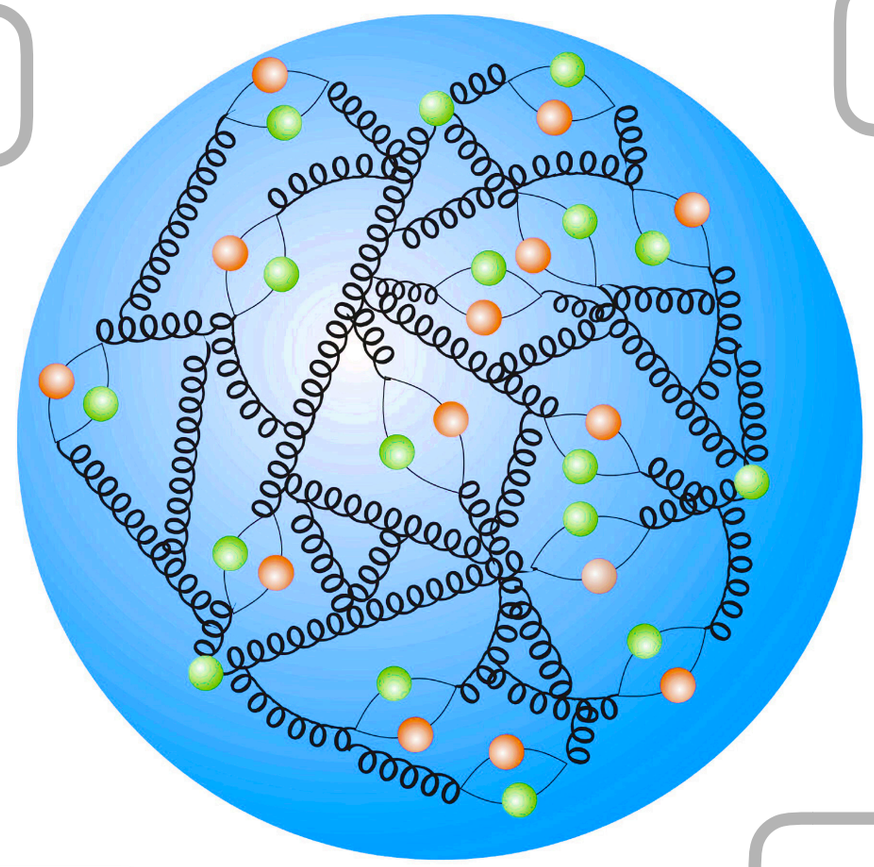
Heavy quark content?

The many faces of the proton

QCD bound state of **quarks** and **gluons**

Origin of mass?

Origin of spin?



Gluon-dominated matter?

3D imaging?

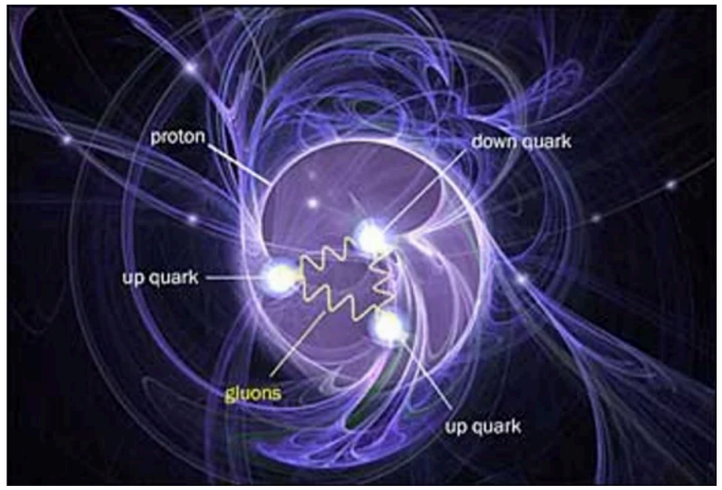
Heavy quark content?

Nuclear modifications?

The proton in the spotlight

THE SCIENCES

Proton Spin Mystery Gains a New Clue



Non-zero gluon polarisation

Scientific American (2014)

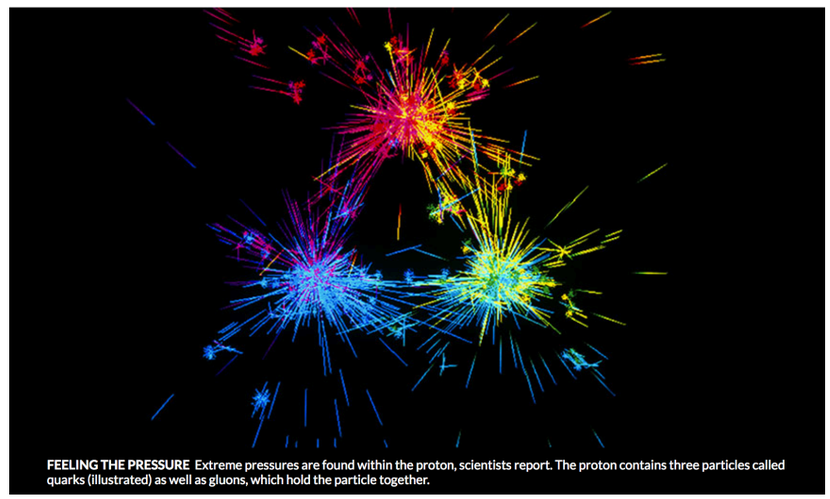
Nucleon pressure

NEWS PARTICLE PHYSICS

The inside of a proton endures more pressure than anything else we've seen

For the first time, scientists used experimental data to estimate the pressure inside a proton

BY EMILY CONOVER 1:18PM, MAY 16, 2018



FEELING THE PRESSURE Extreme pressures are found within the proton, scientists report. The proton contains three particles called quarks (illustrated) as well as gluons, which hold the particle together.

Science News (2018)

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

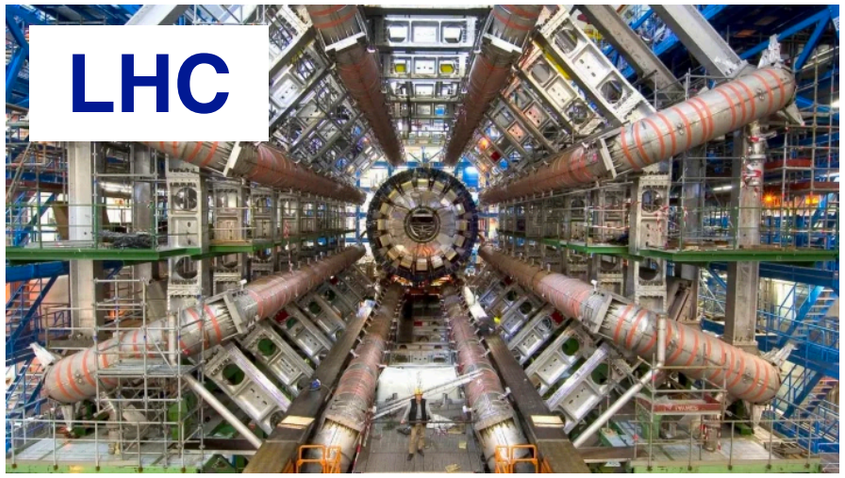
This was the year that analysis of data finally backed up a prediction, made in the mid 1970s, of a surprising emergent behaviour in the strong nuclear force

BFKL dynamics

The Guardian (2017)

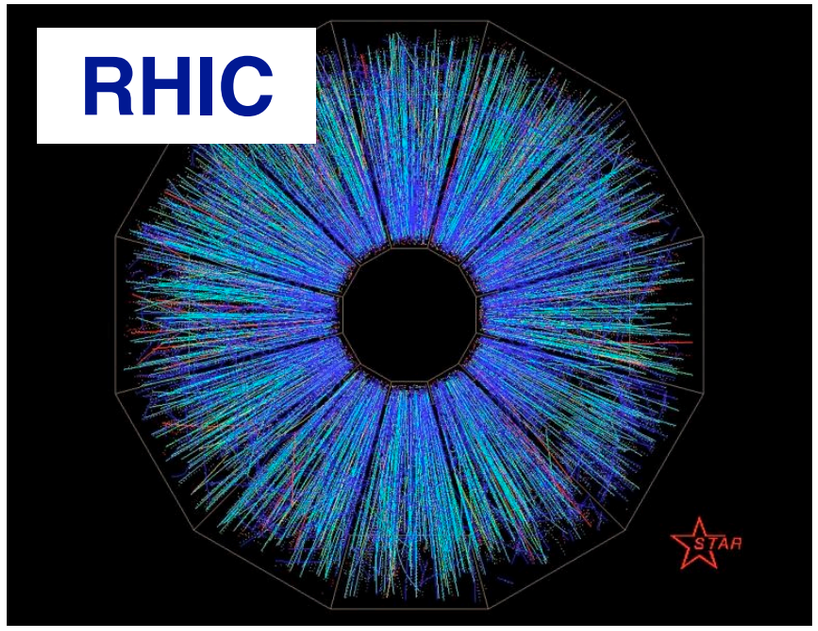
The proton keeps surprising us as an endless source of **fundamental discoveries**

From colliders to the cosmos



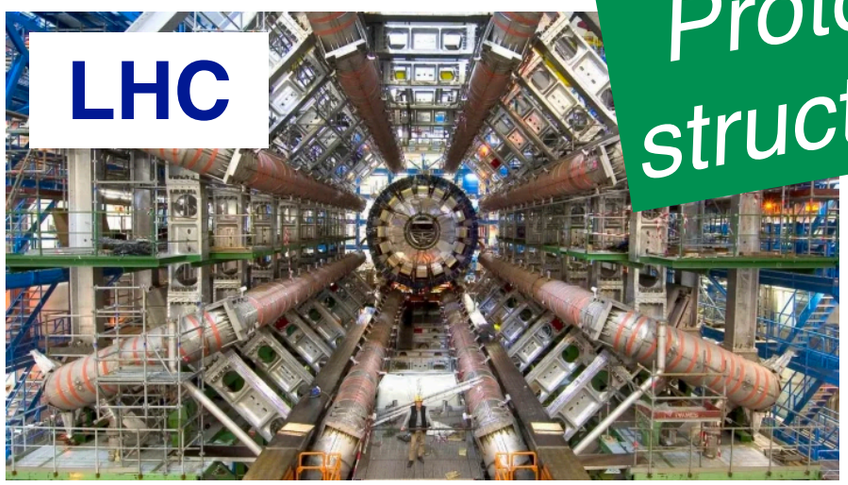
New **elementary particles** beyond the **Standard Model?**

Origins and properties of **cosmic neutrinos**?



Nature of **Quark-Gluon Plasma** in **heavy-ion collisions?**

From colliders to the cosmos

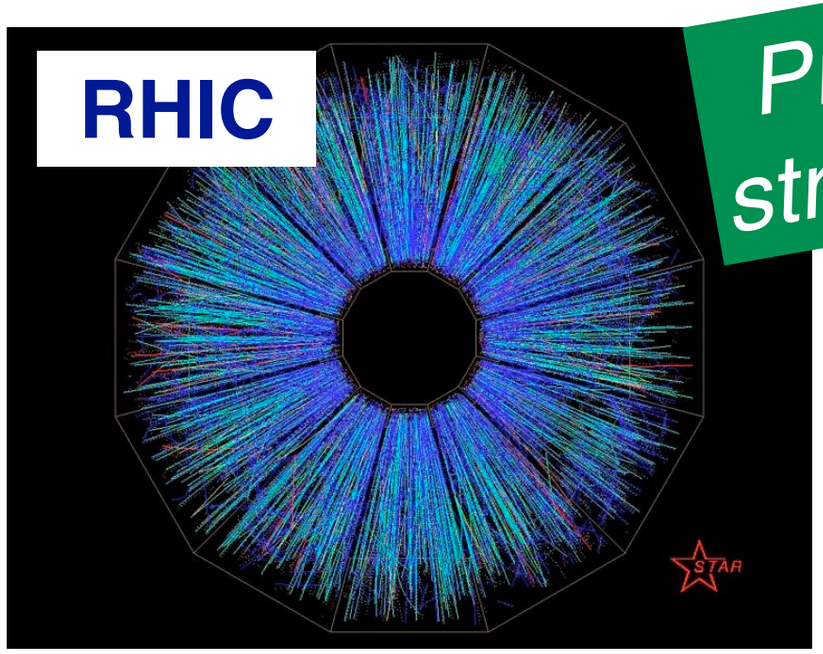


Proton structure

New **elementary particles** beyond the **Standard Model?**

Proton structure

Origins and properties of **cosmic neutrinos**?

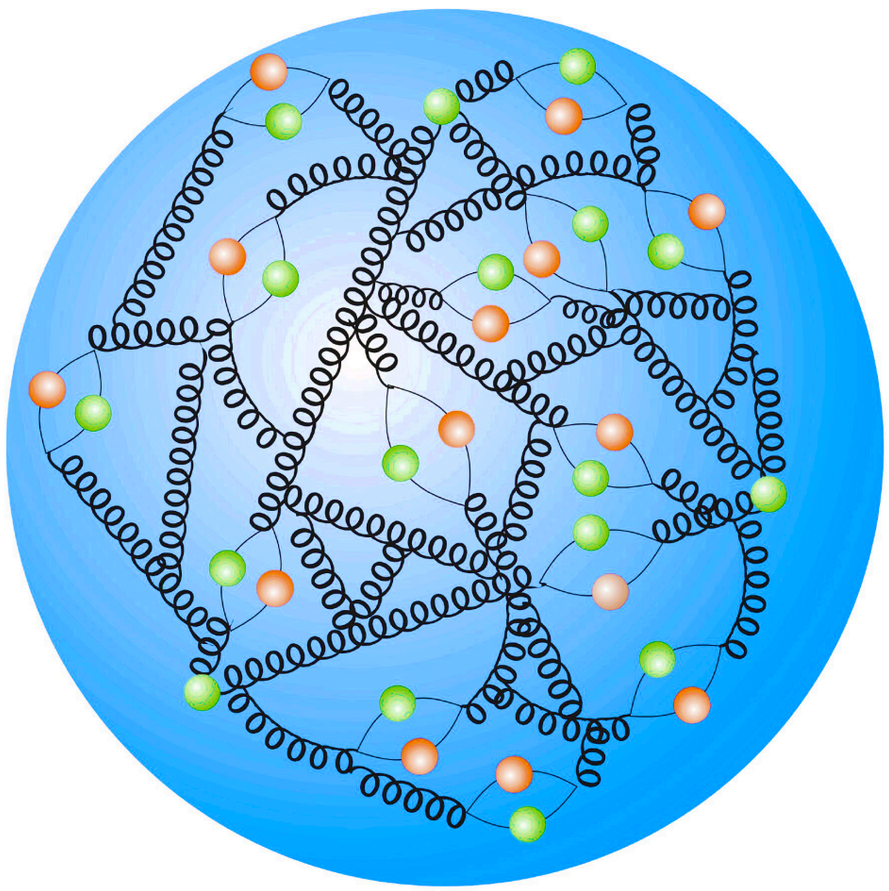


Proton structure

Nature of **Quark-Gluon Plasma** in **heavy-ion collisions?**

Parton Distributions

Proton energy divided among constituents: **quarks** and **gluons**



Parton Distribution Functions (PDFs)

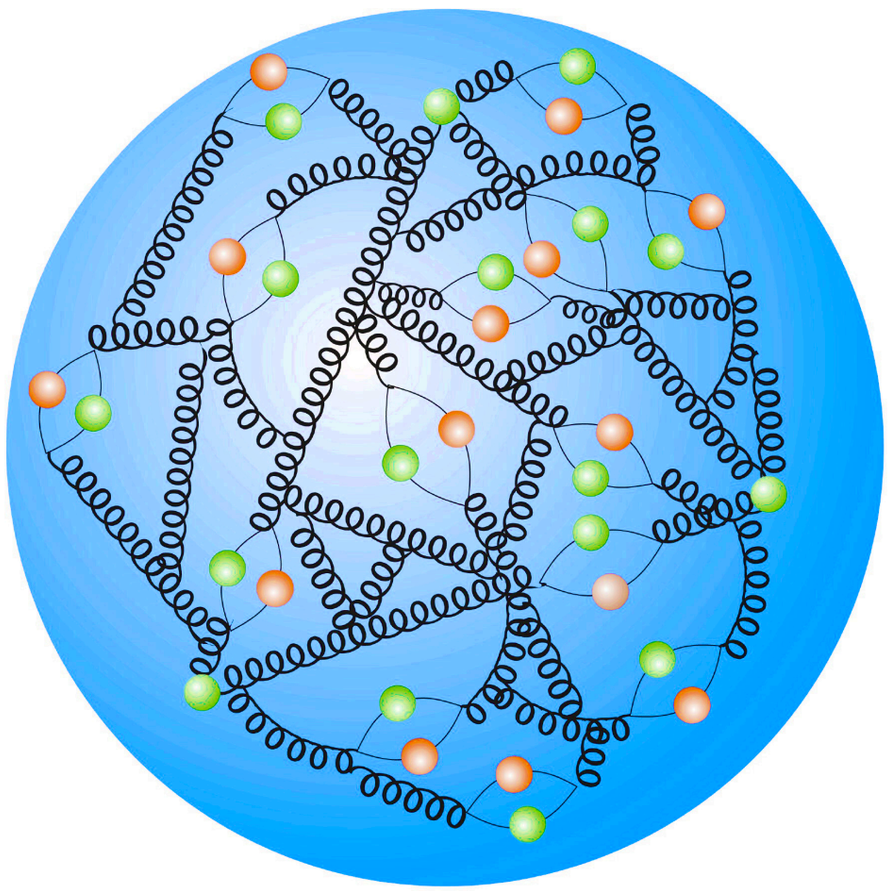
↓

Determine from **data:**

Global QCD analysis

Parton Distributions

Proton energy divided among constituents: **quarks** and **gluons**



Parton Distribution Functions (PDFs)

↓

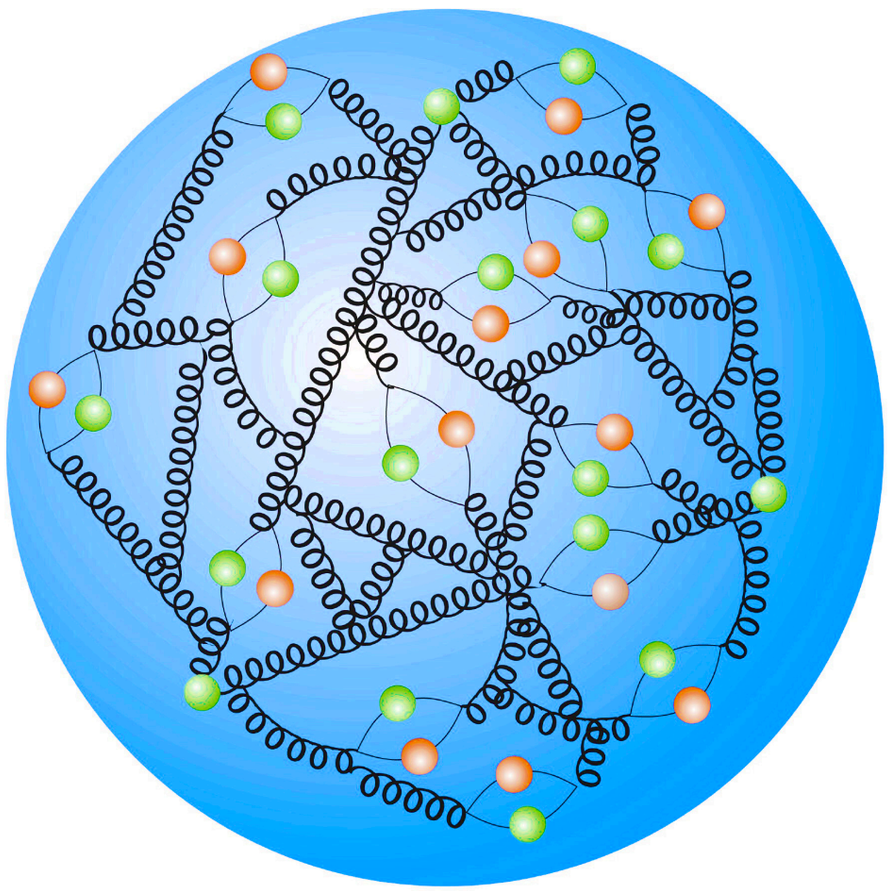
Determine from **data:**

Global QCD analysis

Lattice QCD starting to also make an impact

Parton Distributions

Proton energy divided among constituents: **quarks** and **gluons**



Parton Distribution Functions (PDFs)

Determine from **data:**

Global QCD analysis

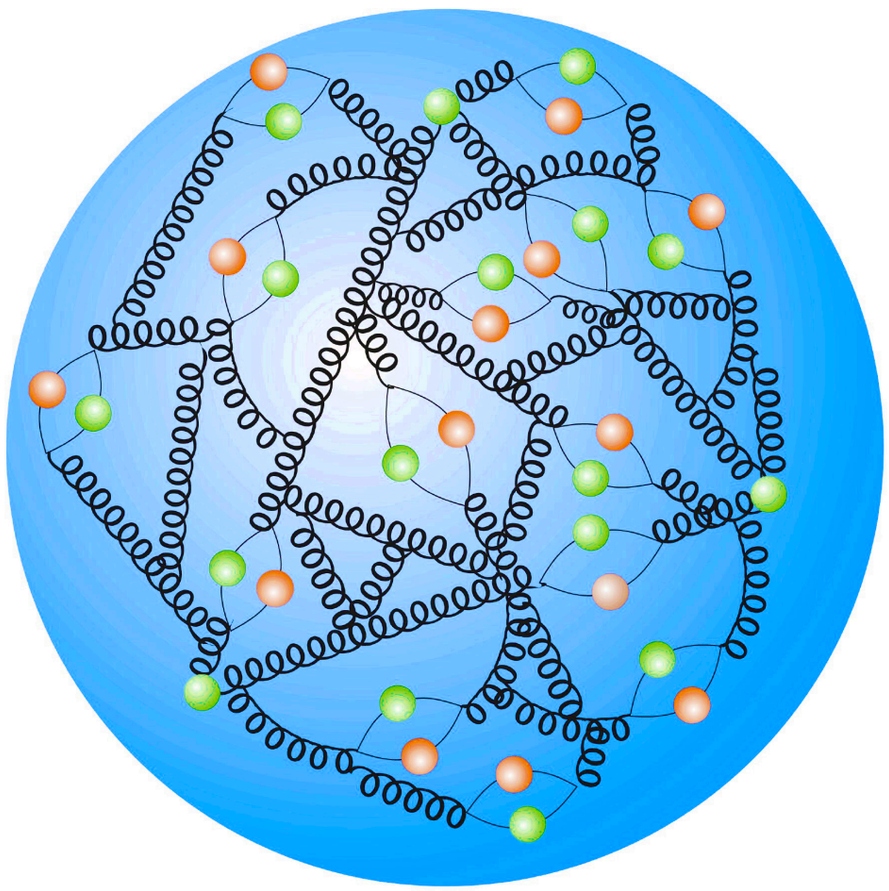
Mass? Spin?

Heavy quark content?

Novel QCD dynamics?

Parton Distributions

Proton energy divided among constituents: **quarks** and **gluons**



Parton Distribution Functions (PDFs)

Determine from **data:**

Global QCD analysis

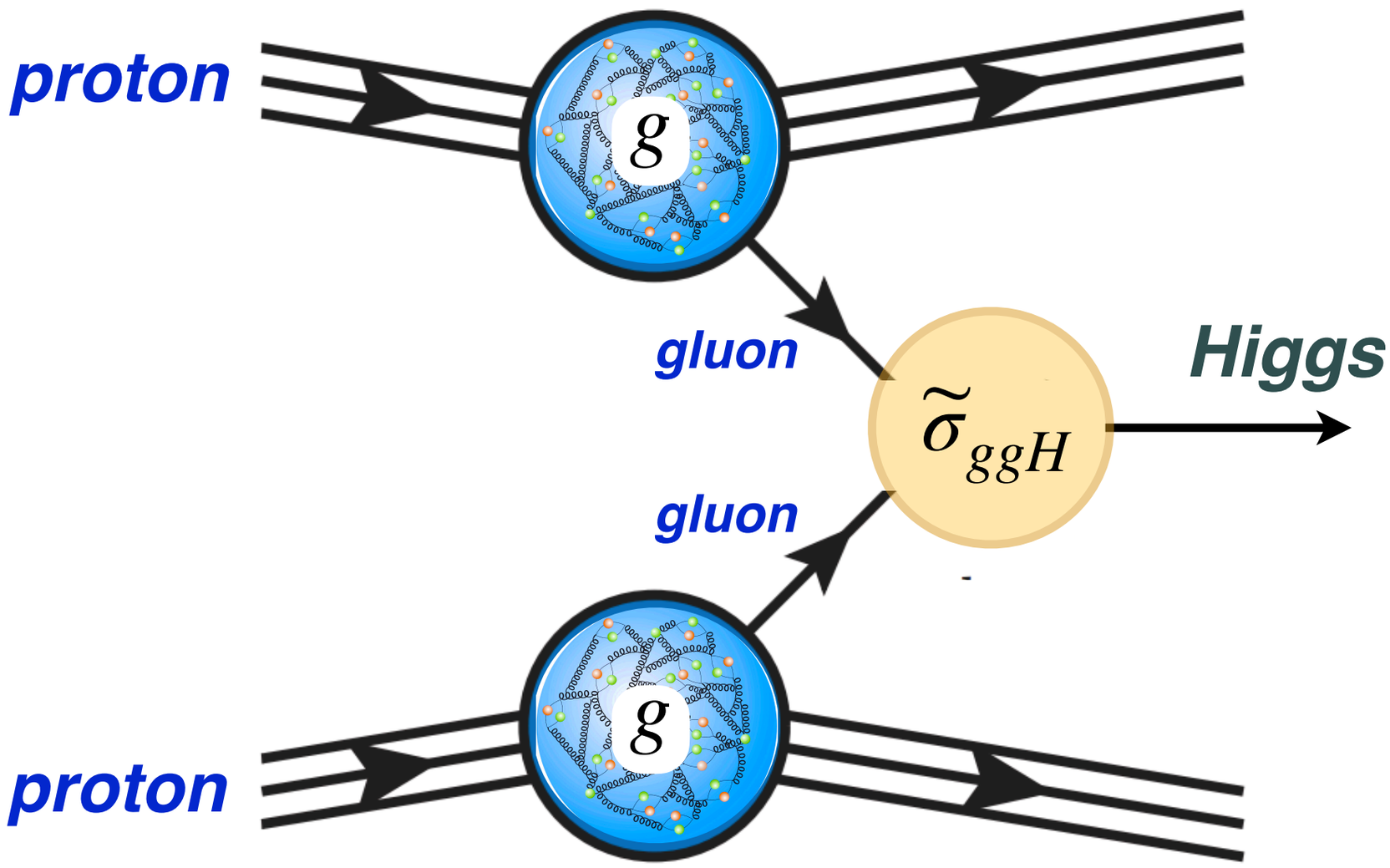
Mass? Spin?
Heavy quark content?
Novel QCD dynamics?

Theoretical predictions for LHC, RHIC, IceCube?

Parton Distributions

$$N_{\mathrm{LHC}}(H) \sim g \otimes g \otimes \widetilde{\sigma}_{ggH}$$

Parton Distributions



All-order structure: **QCD factorisation theorems**

Parton Distributions

$$g(x, Q)$$

Energy of hard-scattering reaction**:** inverse of resolution length

x: fraction of proton momentum carried by gluon

Probability of **finding a gluon inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

Dependence on *x* fixed by **non-perturbative QCD dynamics**: extract from experimental data

- **Energy conservation**: momentum sum rule

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

- **Quark number conservation**: valence sum rules

$$\int_0^1 dx\, \left(u(x, Q^2) + \bar{u}(x, Q^2) \right) = 2$$

Parton Distributions

$$g(x, Q)$$

Energy of hard-scattering reaction**:** inverse of resolution length

x: fraction of proton momentum carried by gluon

Probability of **finding a gluon inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

Dependence on ***Q*** fixed by **perturbative QCD dynamics**: computed up to $\mathcal{O}\left(\alpha_s^4\right)$

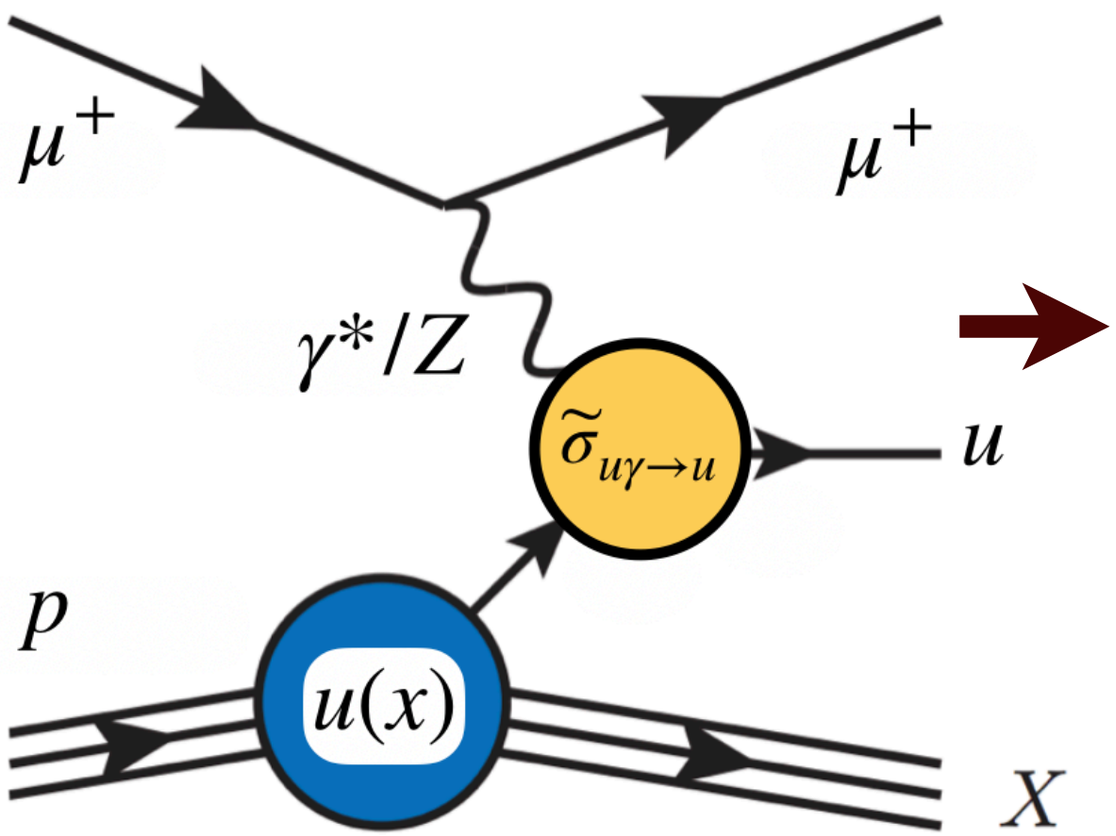
$$\frac{\partial}{\partial \ln Q^2} q_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) q_j(z, Q^2)$$

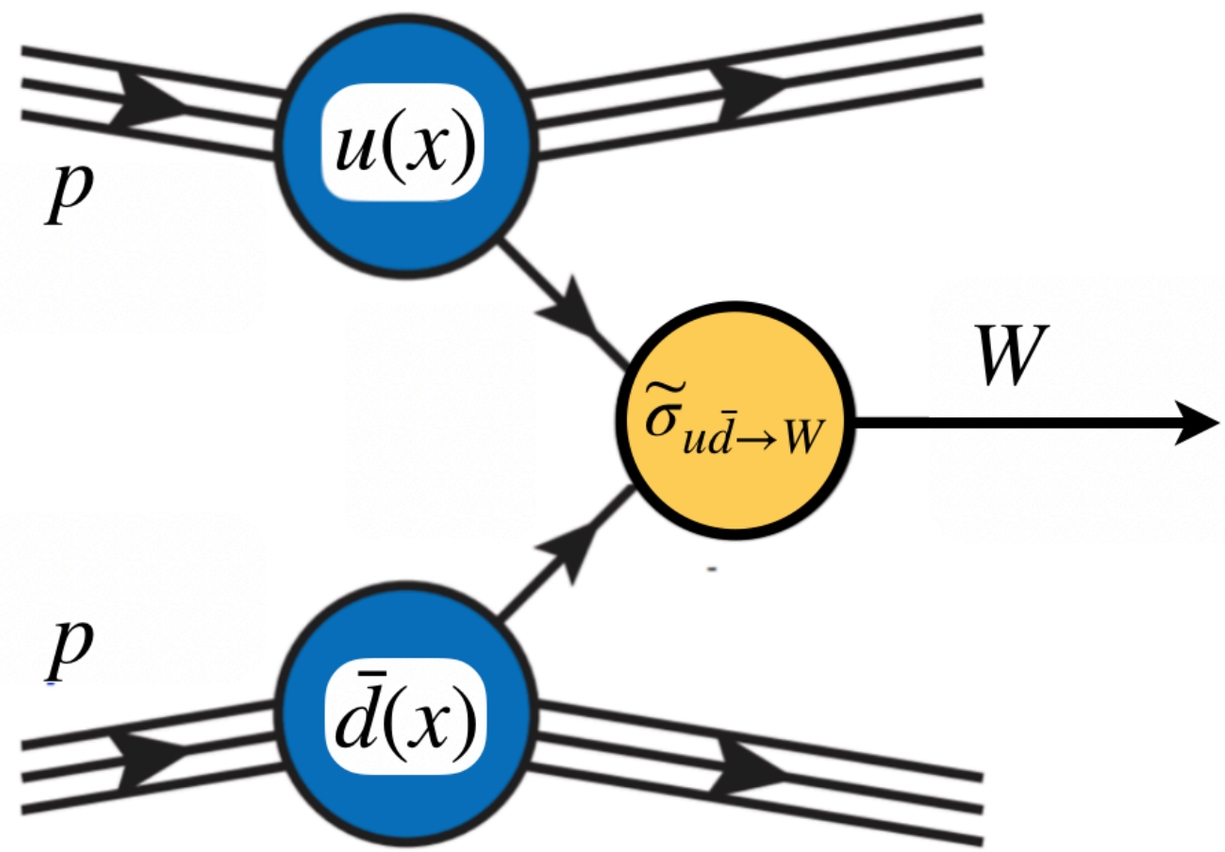
DGLAP *parton evolution equations*

The Global QCD analysis paradigm

QCD factorisation theorems**: PDF universality**

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

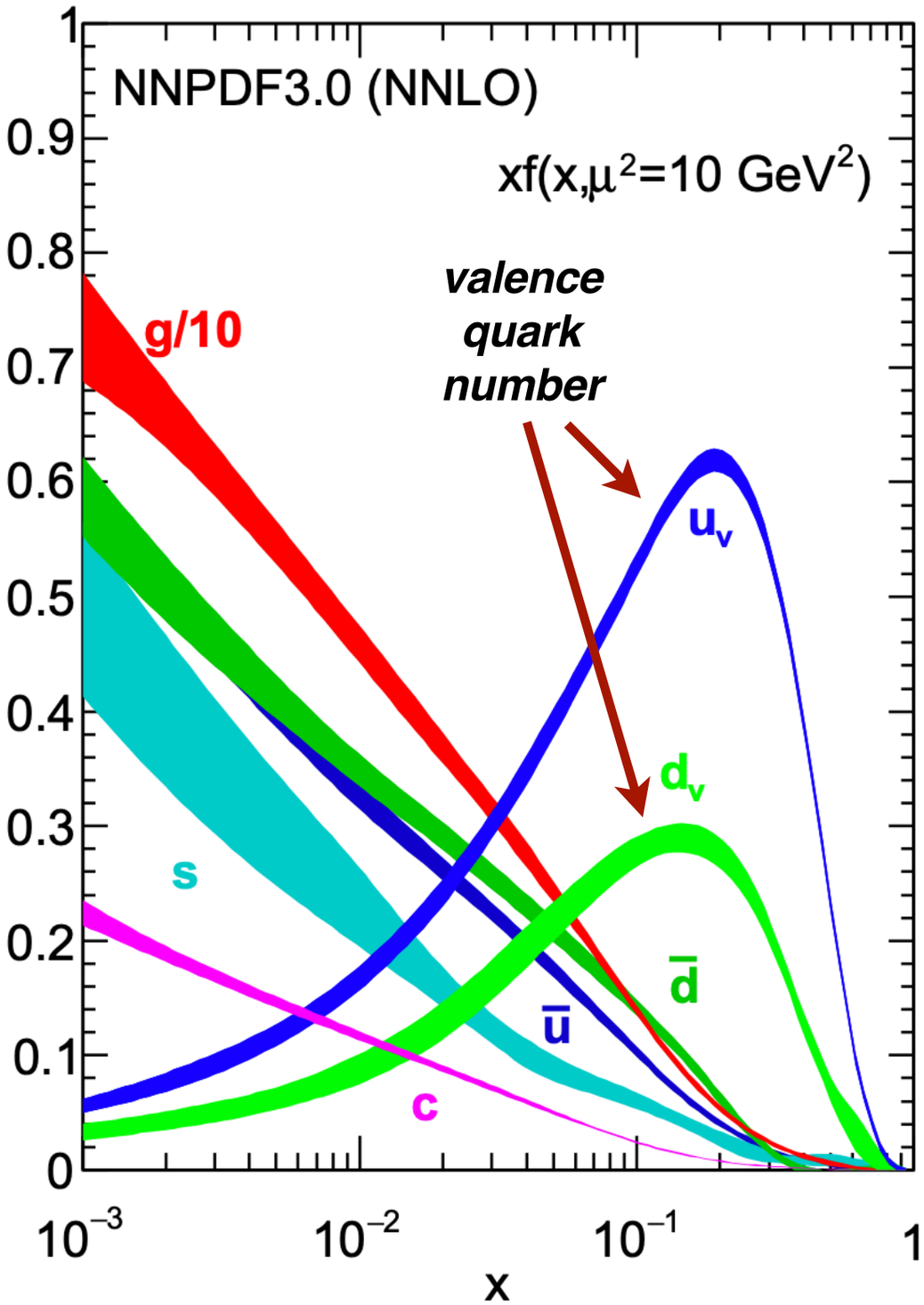


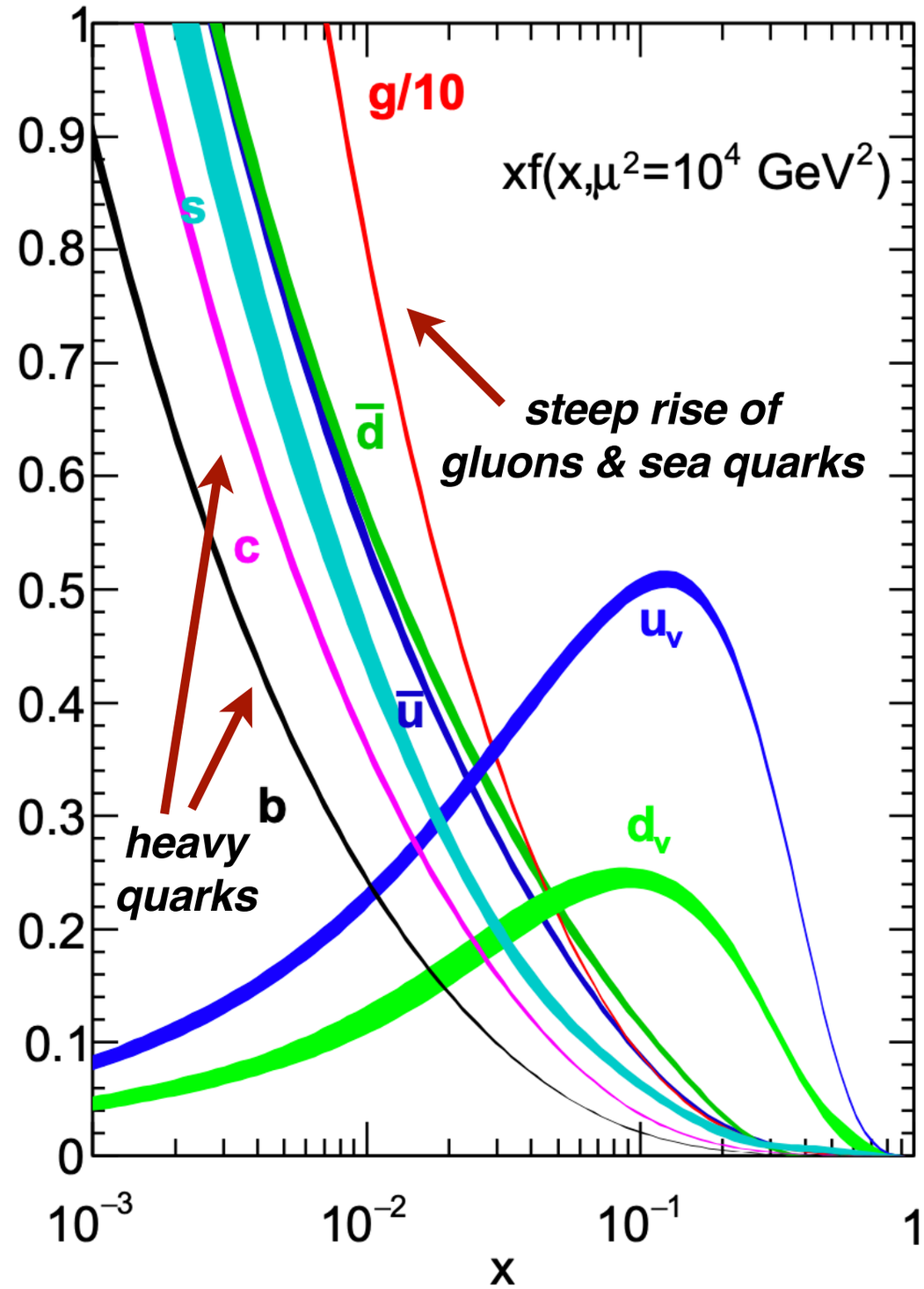


*Determine PDFs from **deep-inelastic scattering**…*

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

A proton structure snapshop





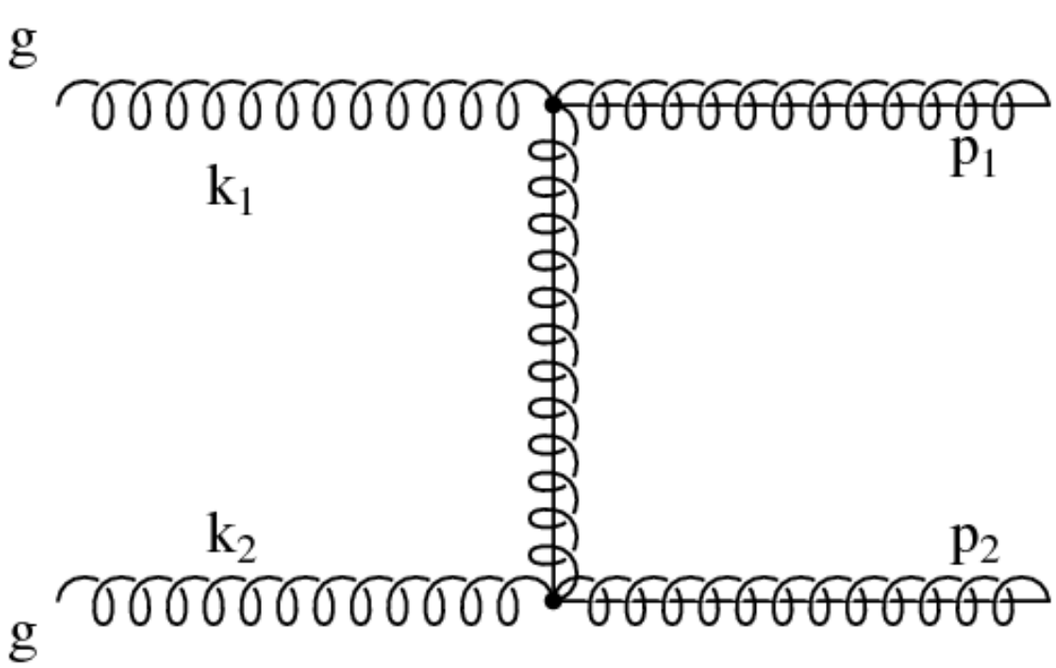
Why do we need better PDFs?

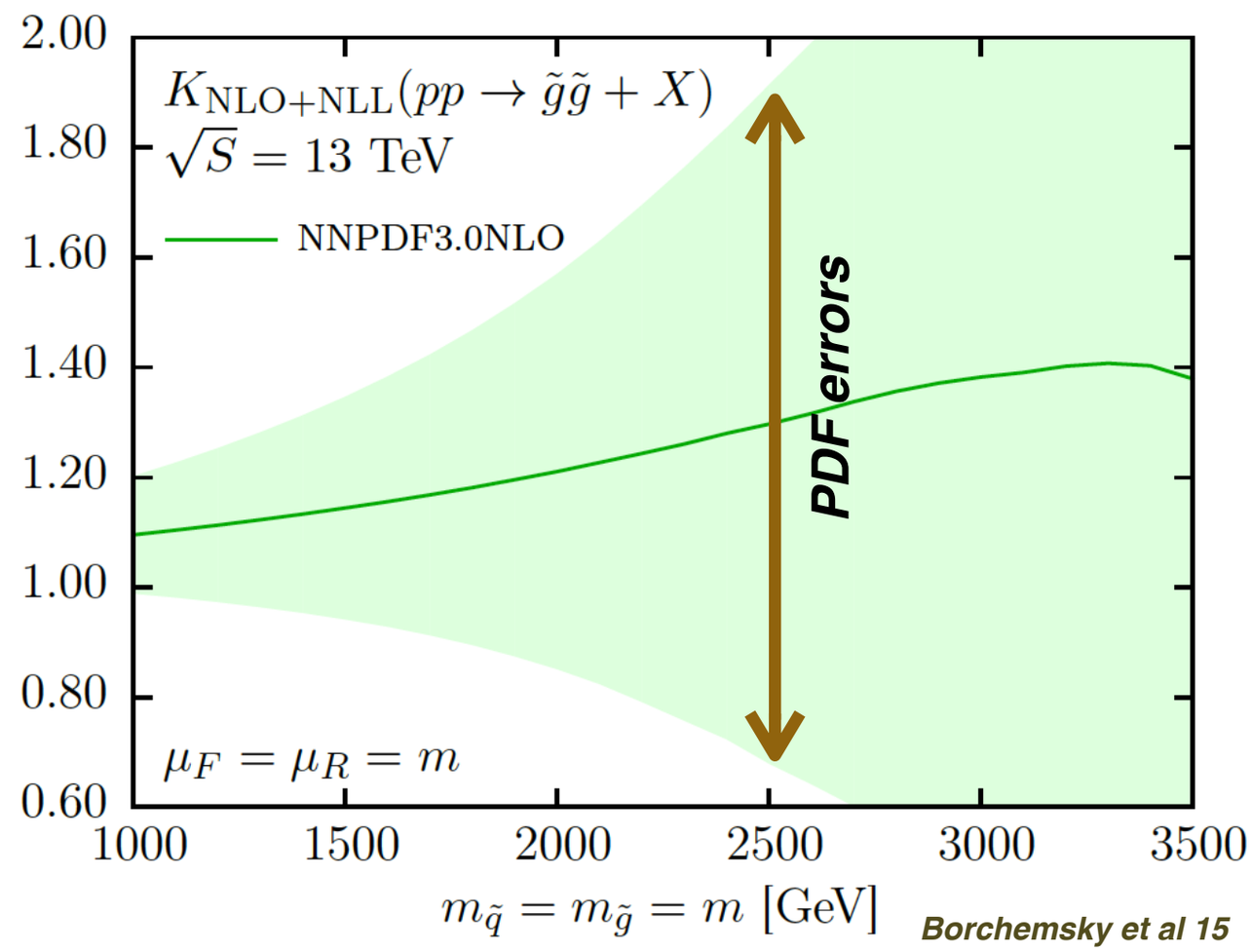
Why do we need better PDFs?

PDF uncertainties in the production of **New Physics heavy resonances** up to **100%**

Due to limited coverage of the **large Bjorken-*x* region**

gluino-pair production in supersymmetry





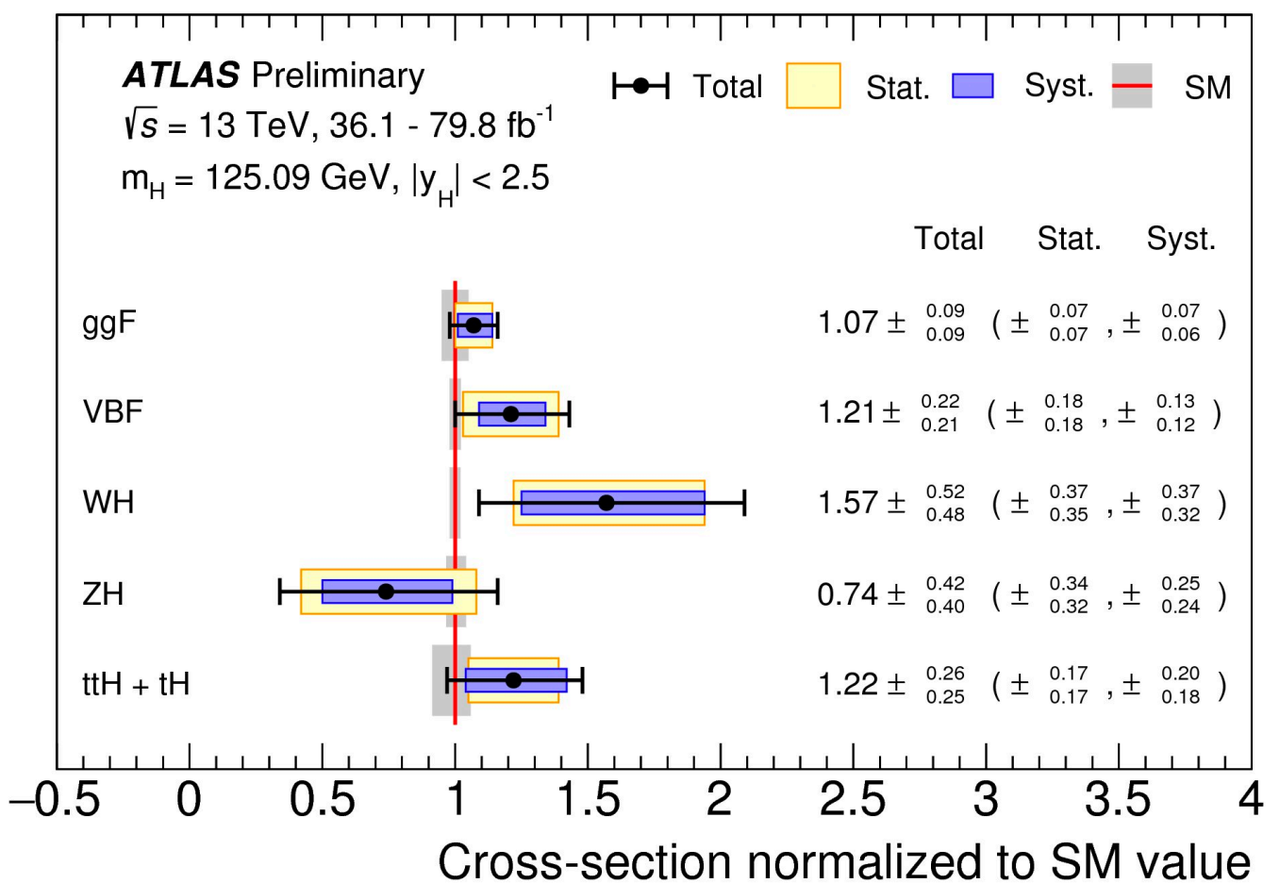
Borchemsky et al 15

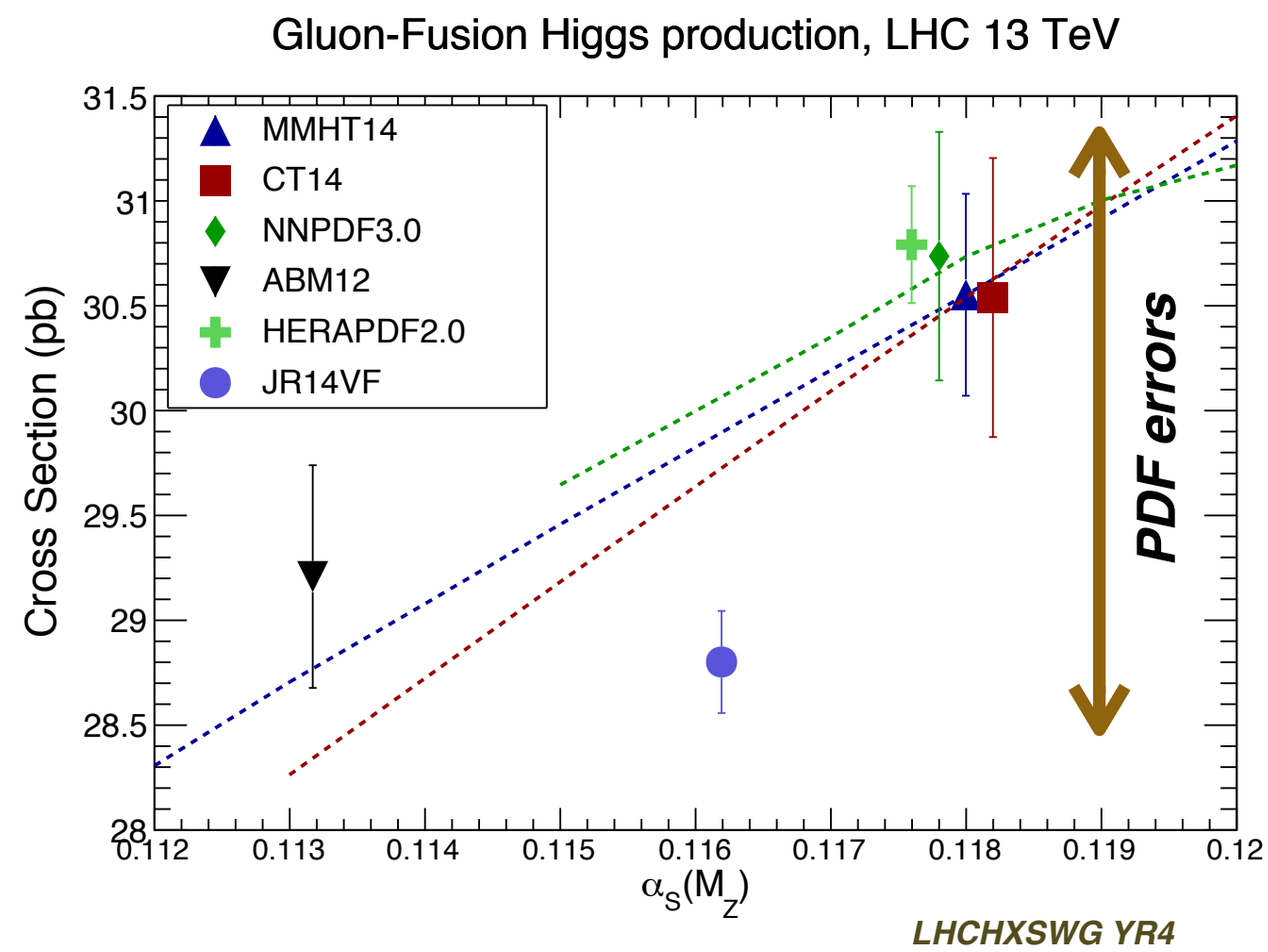
Why do we need better PDFs?

PDF uncertainties one of dominant theory errors in Higgs production cross-sections

any small **deviations of Higgs couplings** from SM predictions: **smoking gun for BSM**

Inclusive Higgs production rates

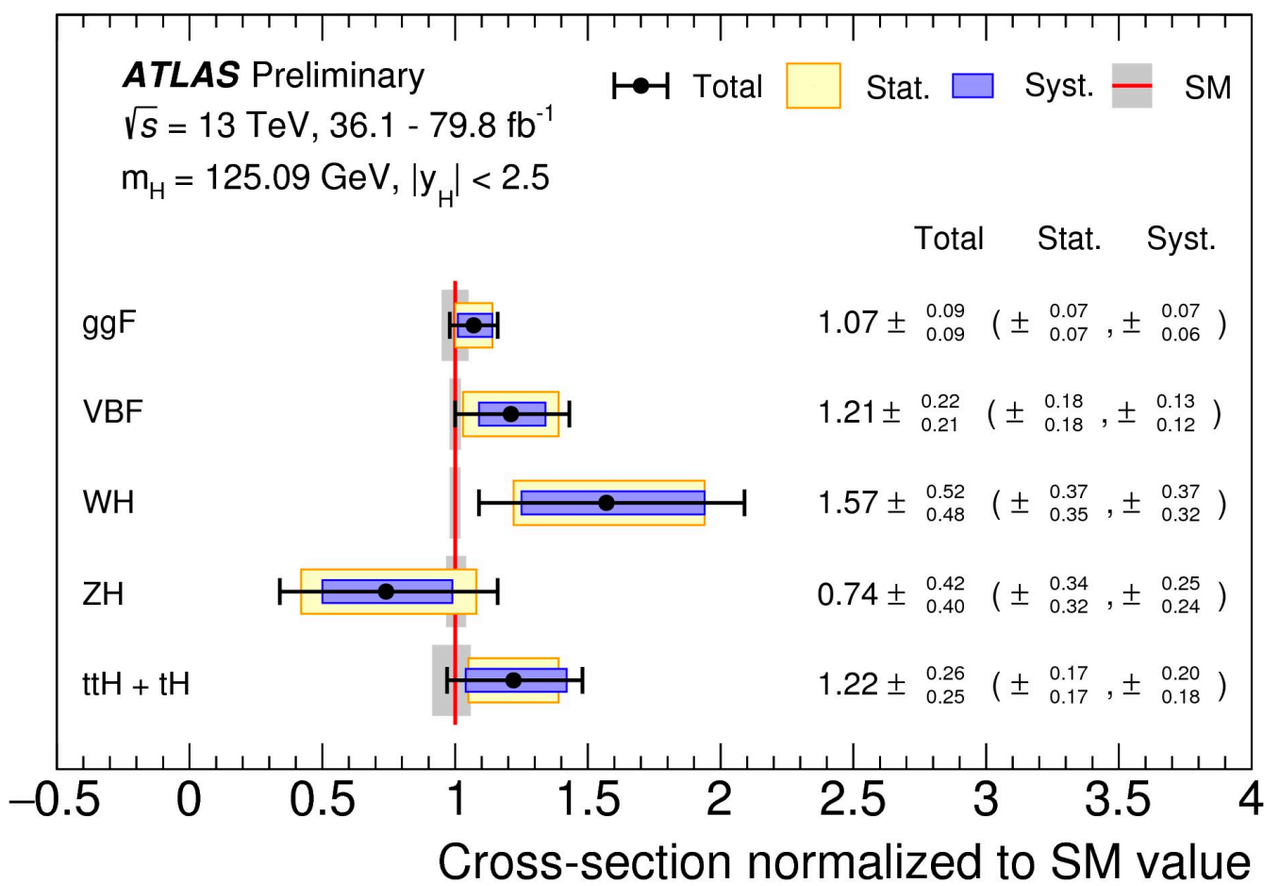




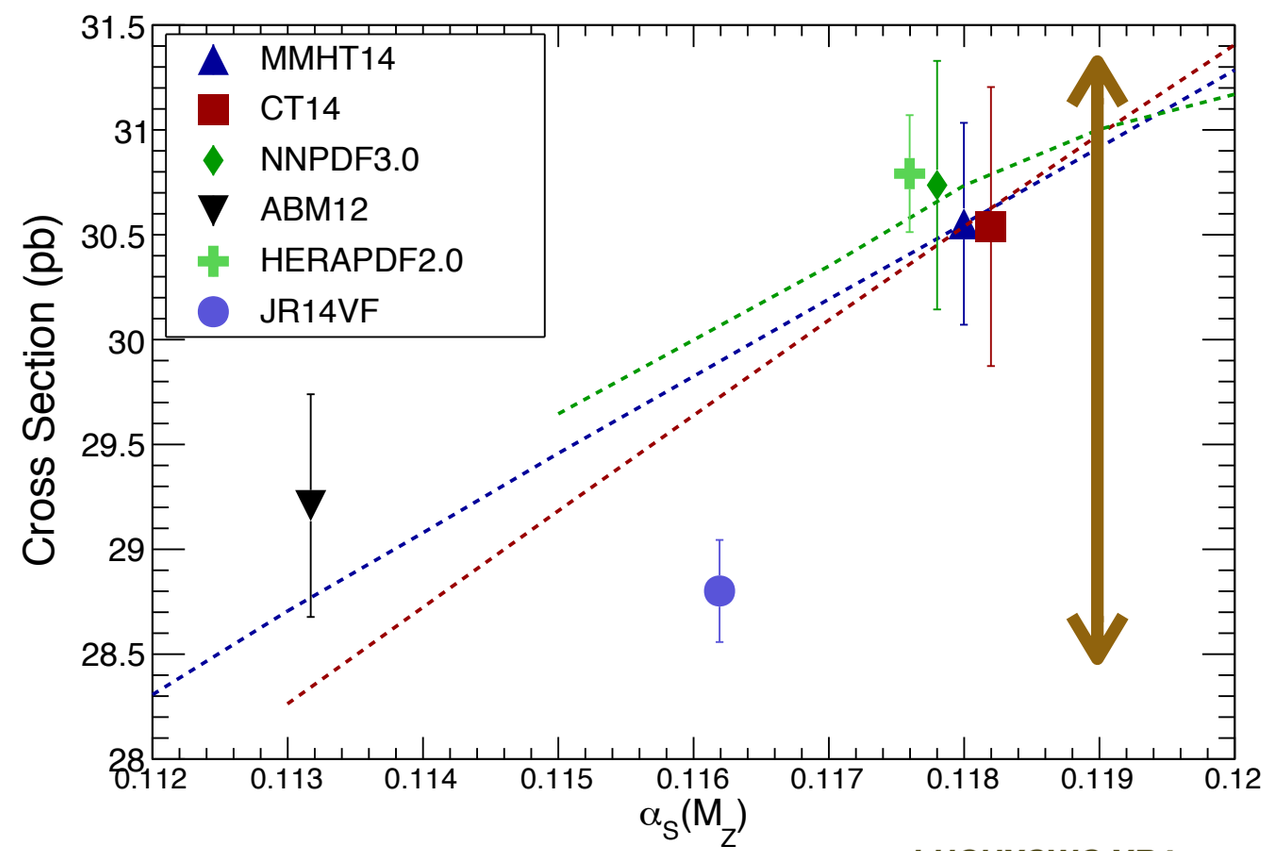
Why do we need better PDFs?

Snowmass 13

BSM model	Deviations in Higgs coupling to		
	W, Z weak bosons	bottom quarks	photons
New heavy Higgs boson	6%	6%	6%
Two-Higgs Doublet model	1%	10%	1%
Composite Higgs	-3%	-9%	-9%
New heavy top-like quark	-2%	-2%	+2%



Gluon-Fusion Higgs production, LHC 13 TeV



LHCHXSWG YR4

Why do we need better PDFs?

- Heavy bSM physics beyond the direct reach of the LHC can be **parametrised in a model-independent** in terms of a **complete** basis of higher-dimensional operators: this is the **Standard Model Effective Field Theory**

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

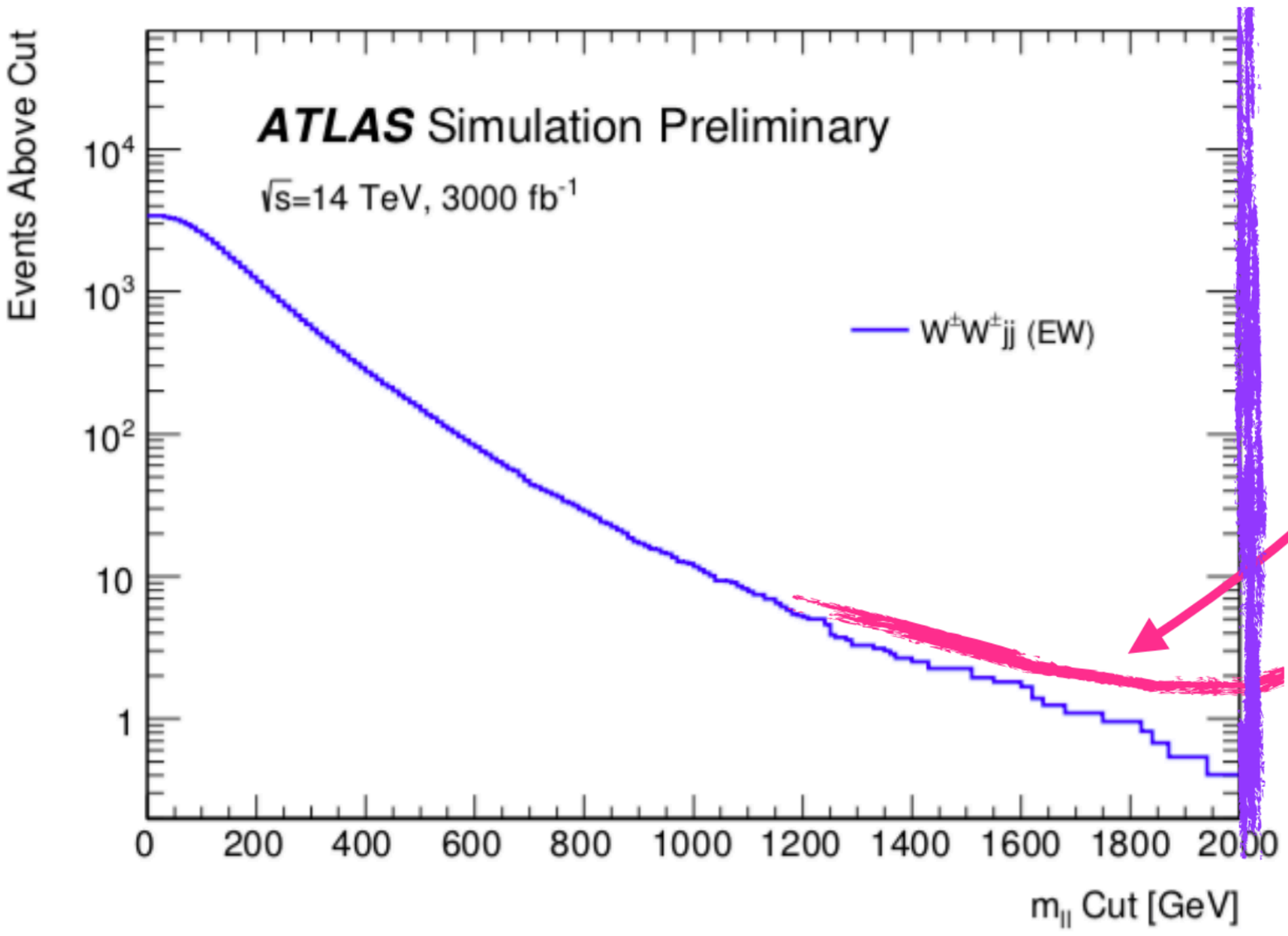
- Some operators induce **growth with the partonic centre-of-mass energy**: increased sensitivity in LHC cross-sections in the TeV region

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

*enhanced sensitivity from **TeV-scale processes:** unique feature of LHC*

Why do we need better PDFs?

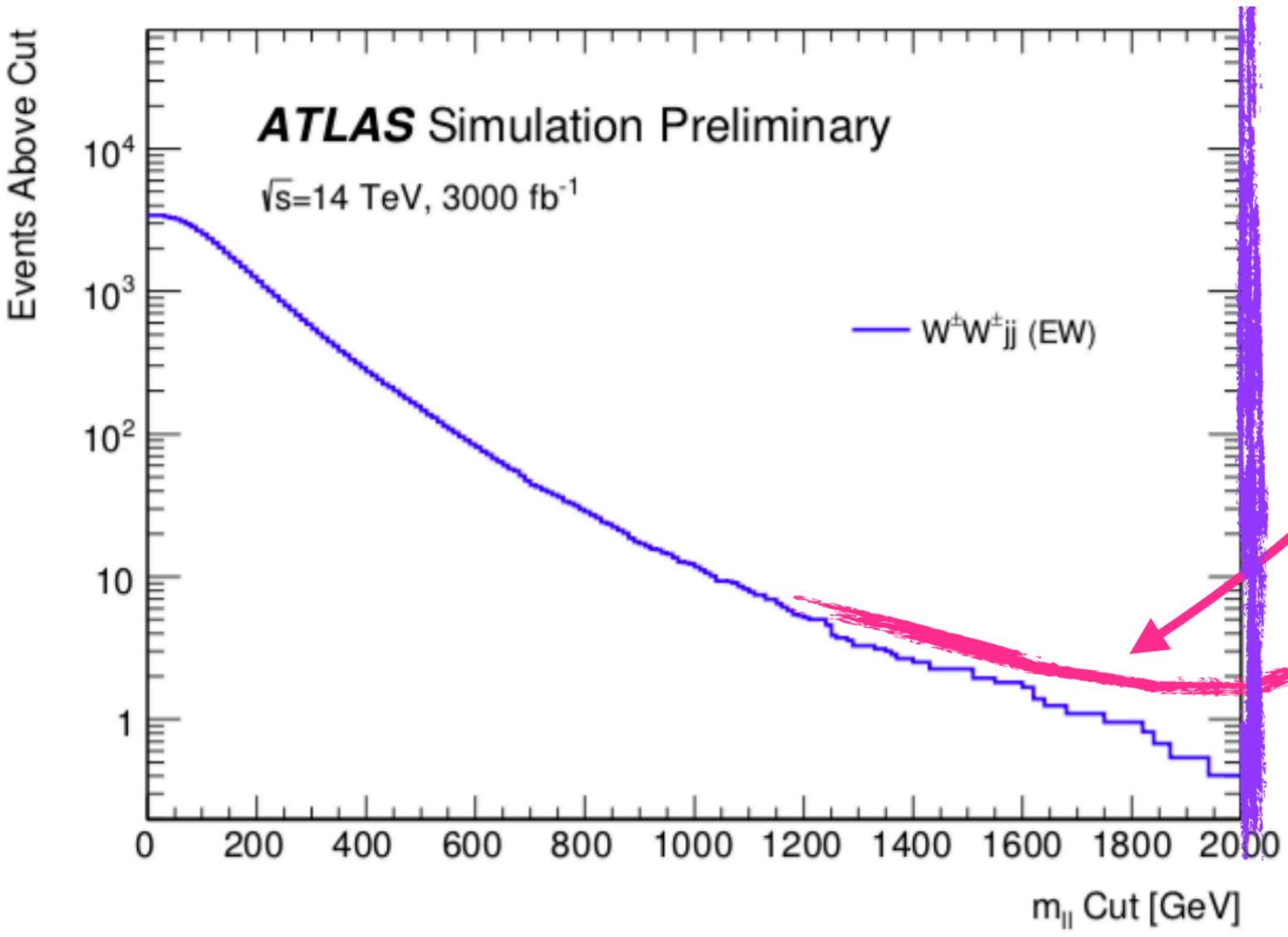
Deviation from SM prediction in high energy tails?



CA Lee, HL/HE-LHC Jamboree, 1 March 2019

Why do we need better PDFs?

Deviation from SM prediction in high energy tails?

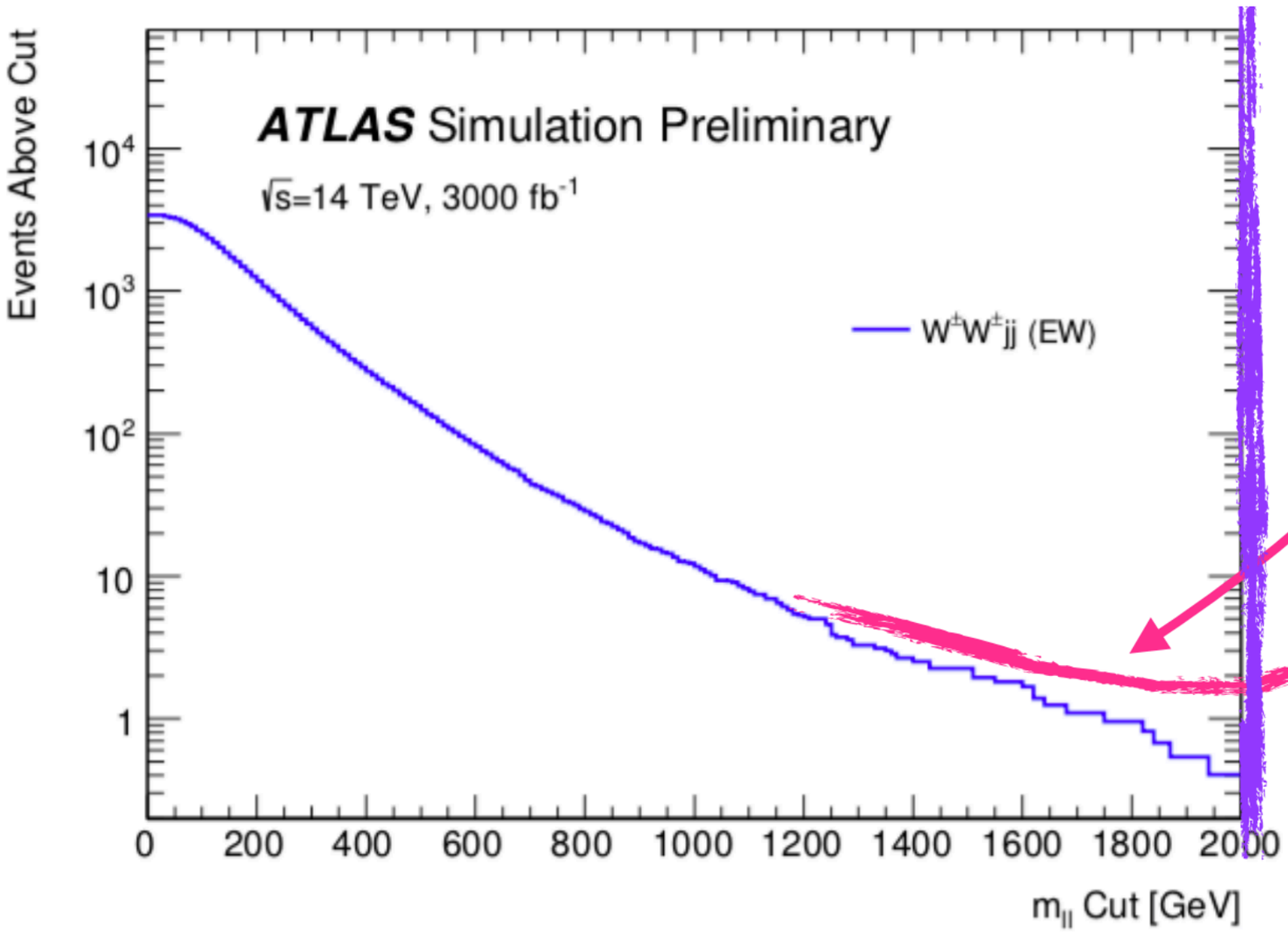


CA Lee, HL/HE-LHC Jamboree, 1 March 2019

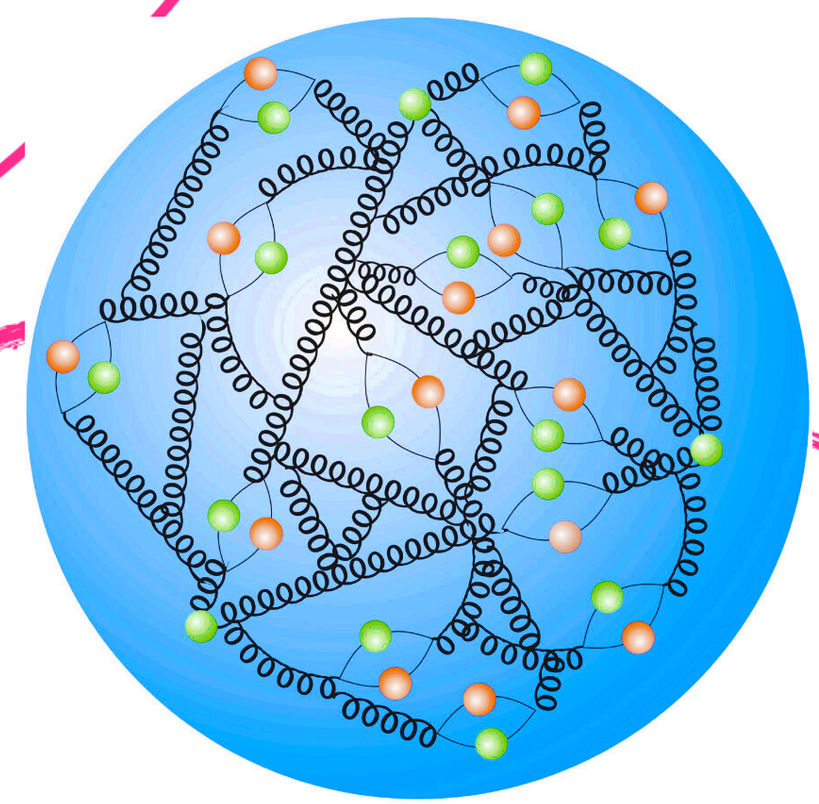
SMEFT interpretation: from a massive particle at high energies …

Why do we need better PDFs?

Deviation from SM prediction in high energy tails?



CA Lee, HL/HE-LHC Jamboree, 1 March 2019



…or reflecting our limited understating of proton structure?

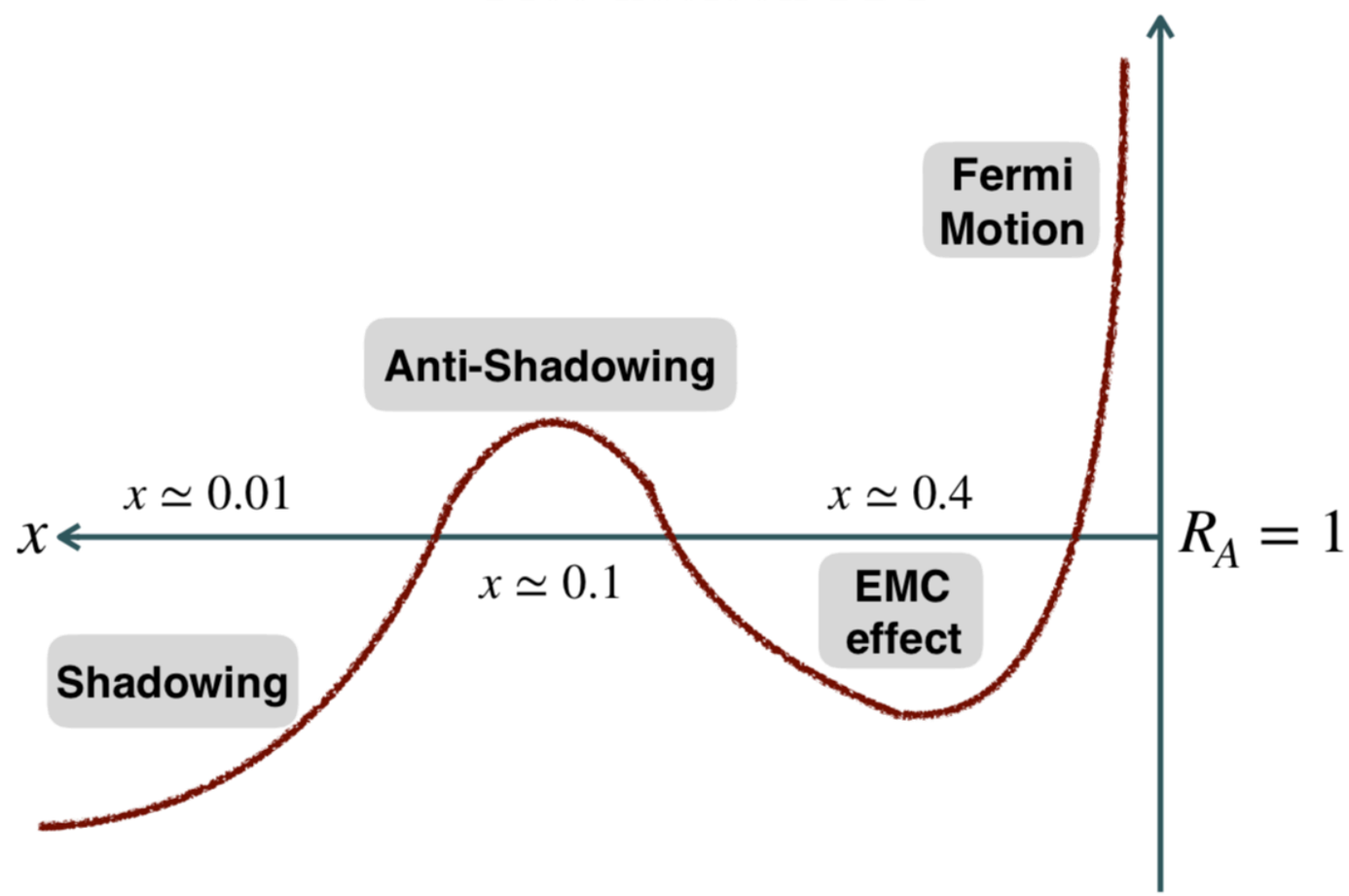
Hot and Cold Nuclear Matter

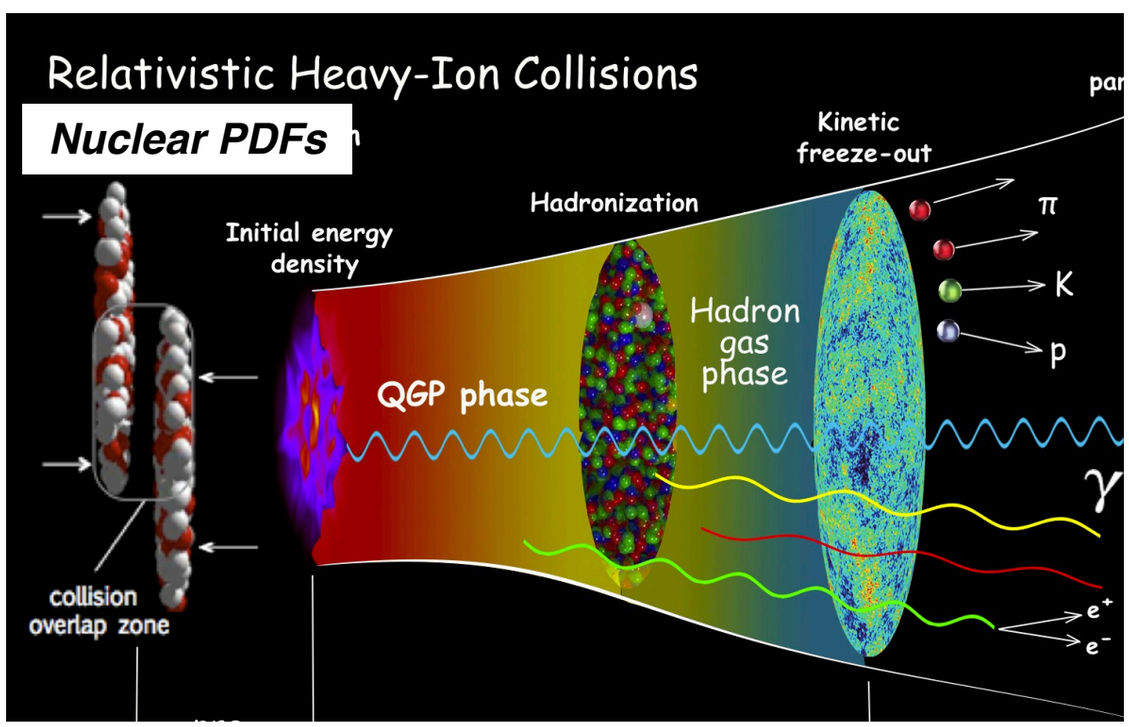
- Cold nuclear matter effects modify the **PDFs of bound nucleons** as compared to the **free-proton case**

- Rich **QCD phenomenology**: EMC effect, shadowing, non-linear evolution, ….

- Onset of **new gluon-dominated state of matter**: the Color Glass Condensate

$$R_A = \frac{\text{Bound Nucleon PDF in Nucleus } A}{\text{Free nucleon PDF}}$$



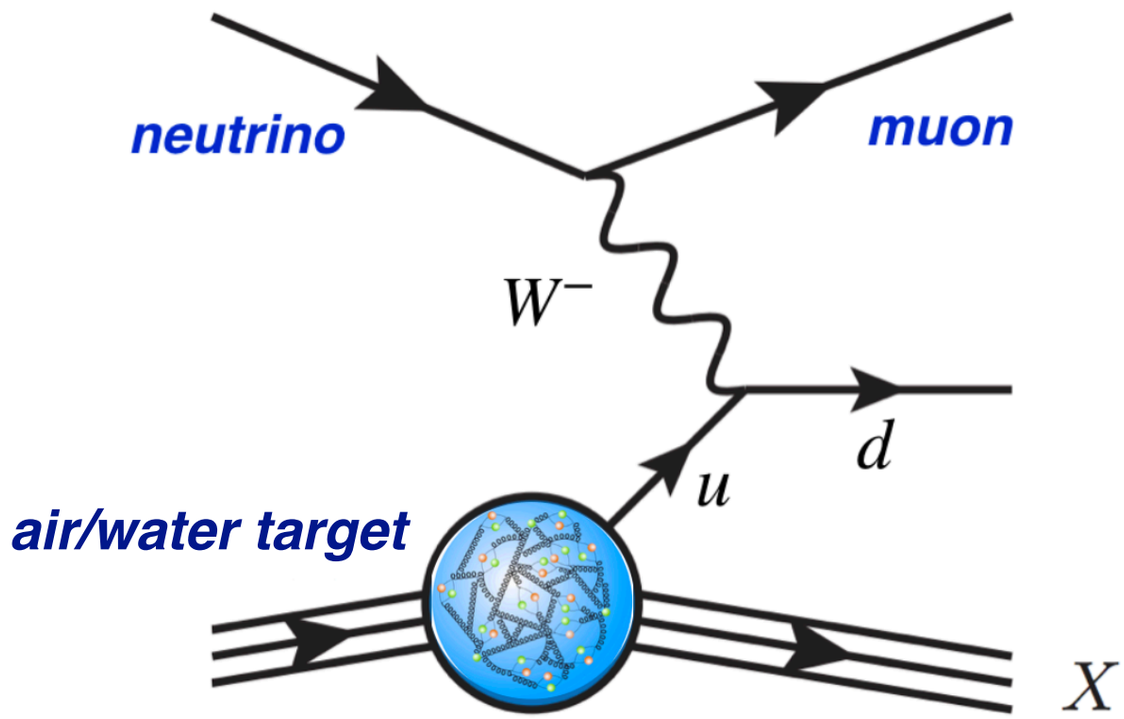


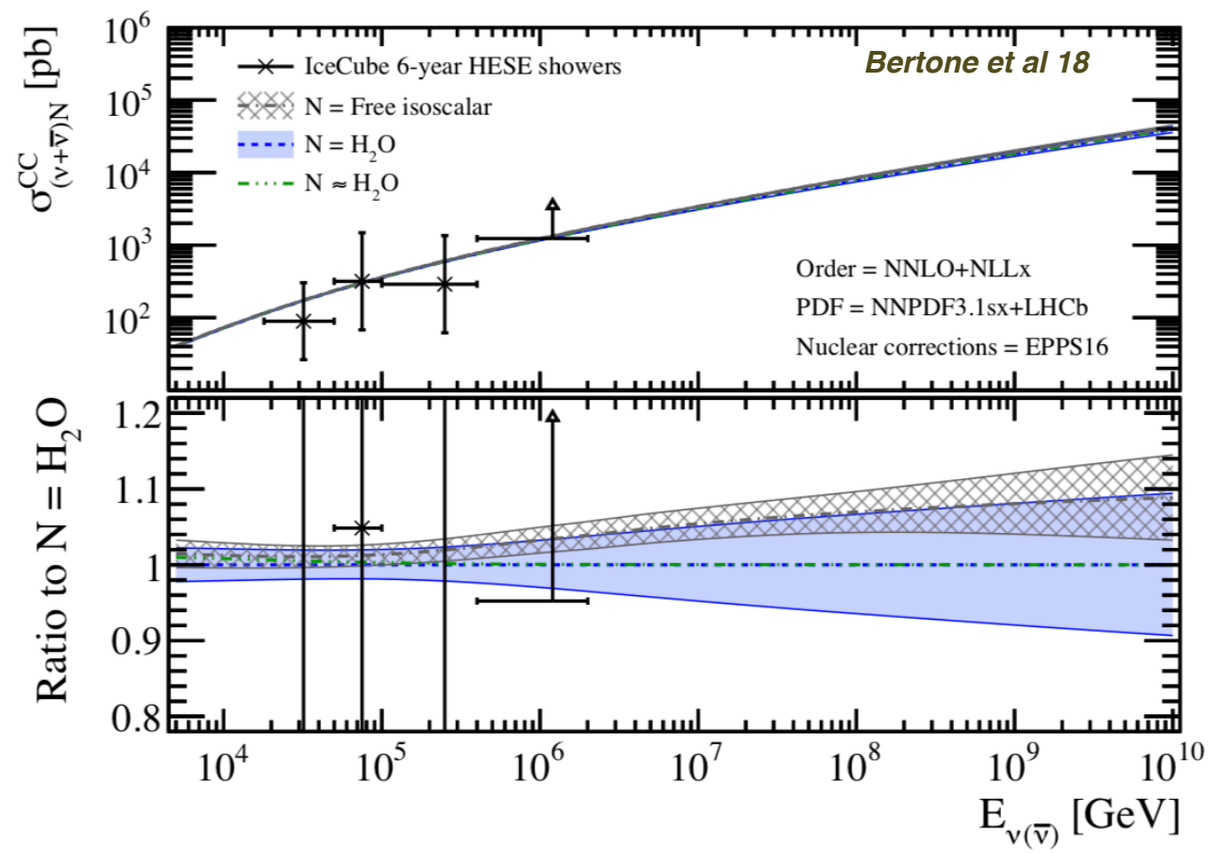
- **Initial state of heavy-ion collisions**: Quark-Gluon Plasma characterisation

- nPDFs also required for **ultra-high-energy astrophysics** e.g. neutrino telescopes

Neutrino telescopes as QCD microscopes

Ultra-high energy (cosmic) neutrino *- nucleus scattering:*
unique probe of ***small-x PDFs and QCD***





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

Bertone, Gauld, JR 18

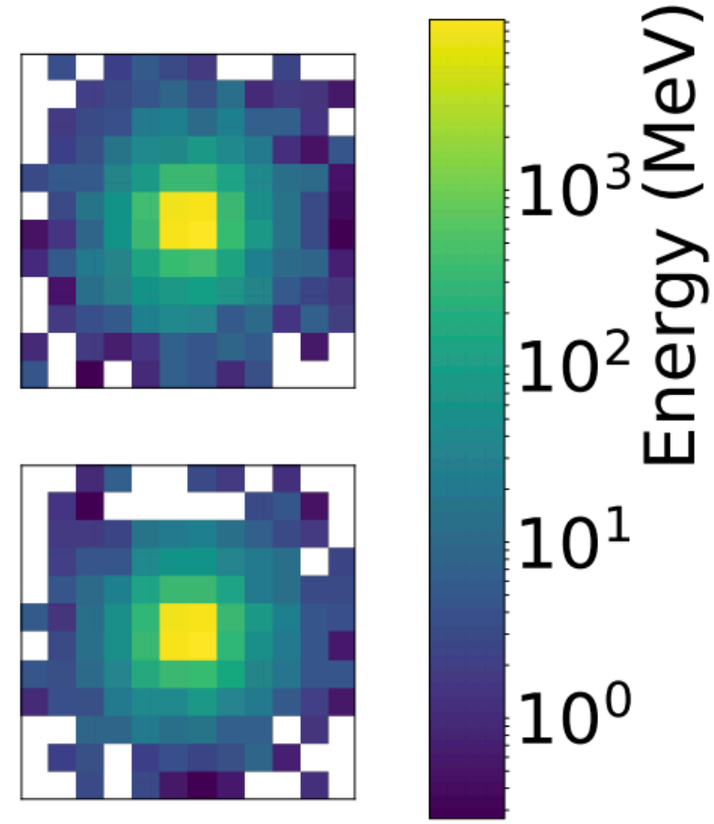
Machine Learning in particle physics

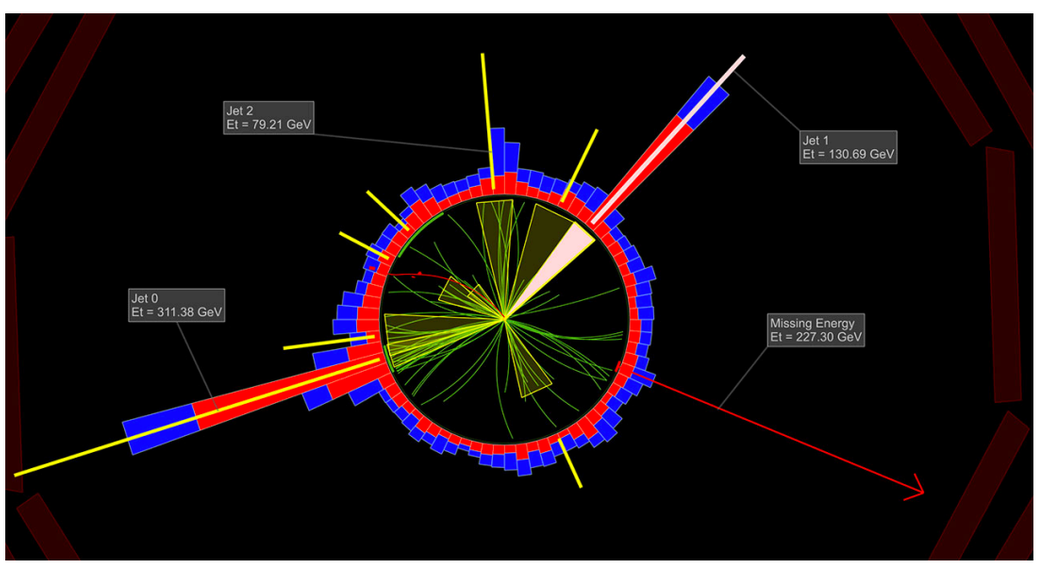
Machine Learning in Particle Physics

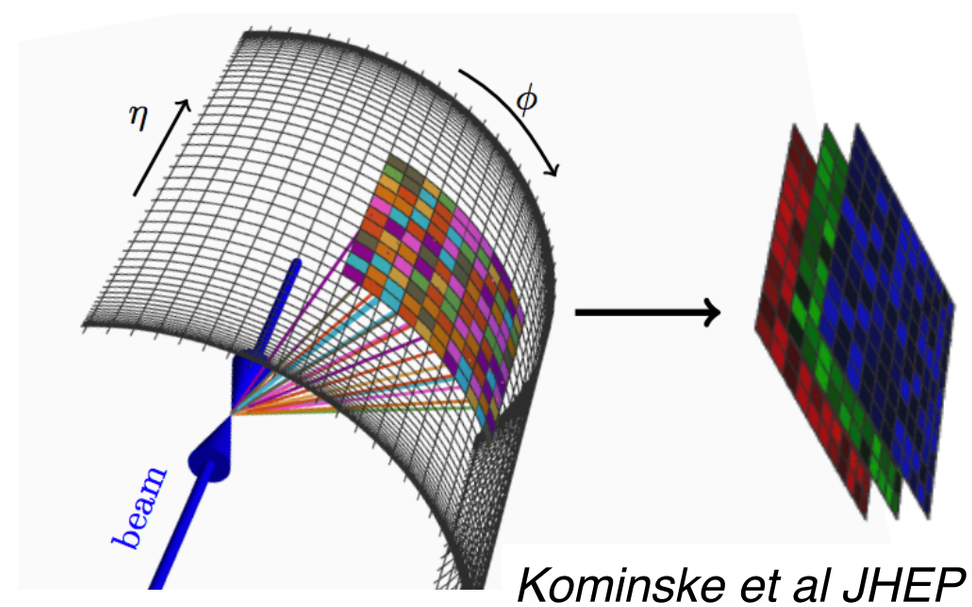
- **Machine Learning:** families of computer algorithms that **learn how to excel on a task** based on a **large sample of examples** rather than on some a priori fixed rules

- ML algorithms are nowadays ubiquitous, from **driverless cars** to **Amazon's purchase suggestions**, to **automated medical imaging recognition** to beating the words best players at Go and chess

- Nowadays a standard element of the **HEP toolbox** as well



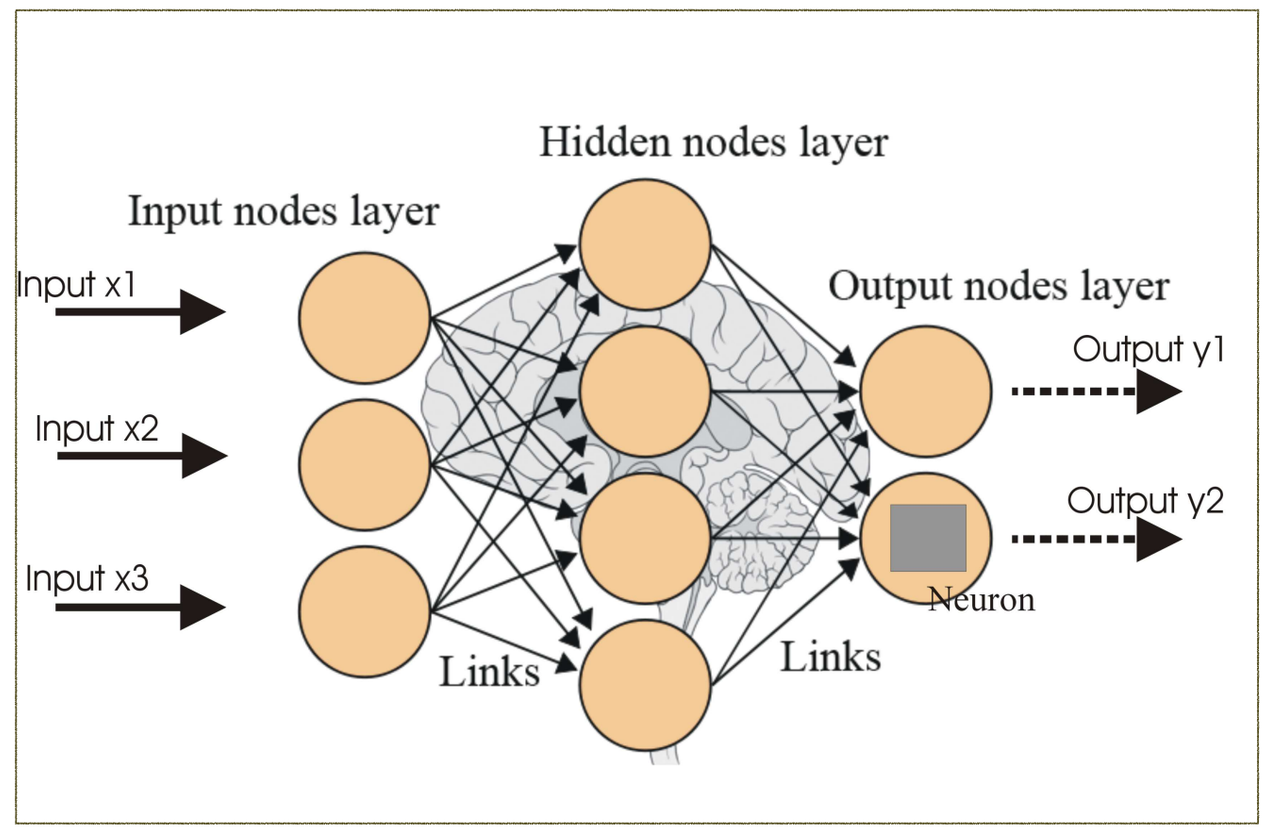




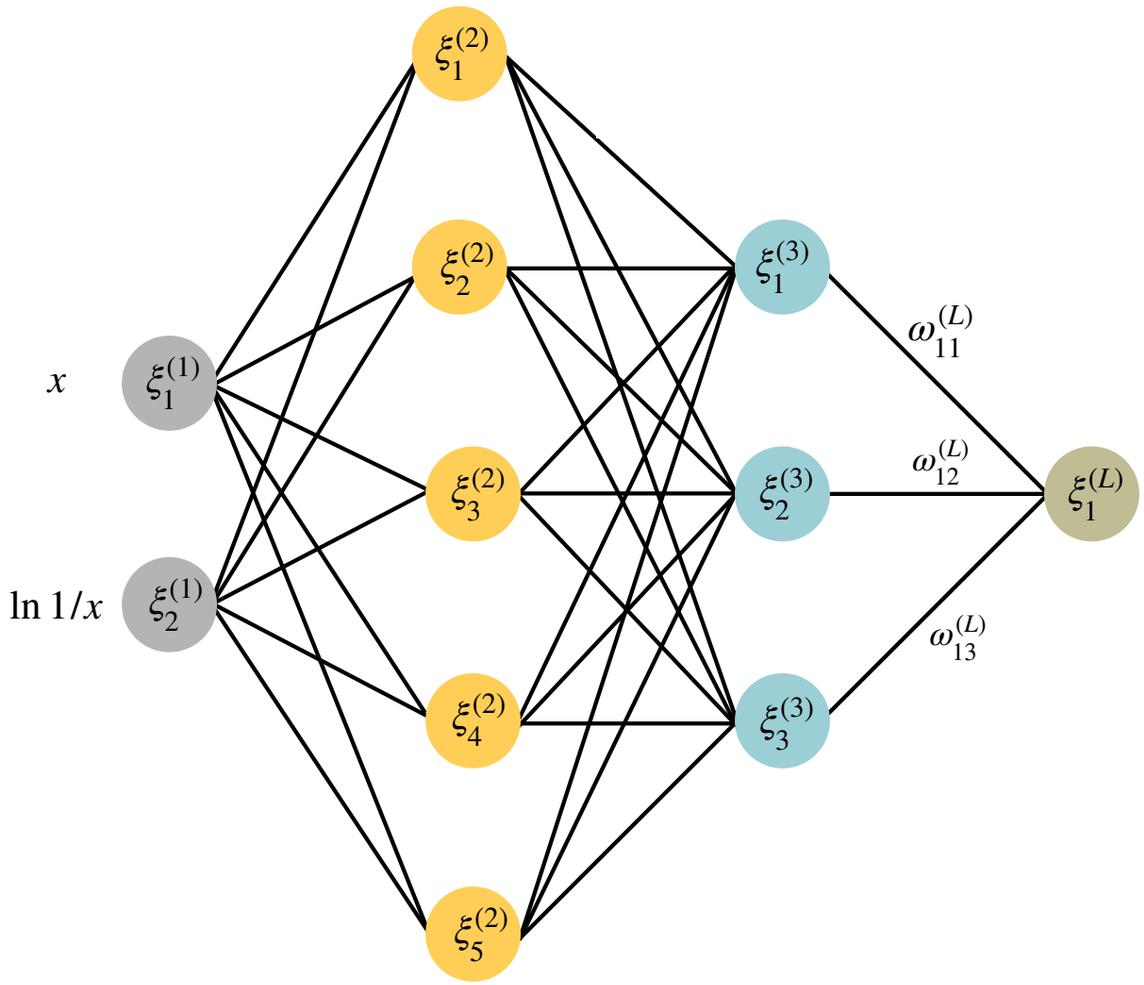
Kominske et al JHEP (2017)

Artificial Neural Networks

Inspired by **biological brain models**, **Artificial Neural Networks** (ANNs) are mathematical algorithms designed to excel where domains as their evolution-driven counterparts outperforms traditional algorithms in tasks such as **pattern recognition, forecasting, classification**, ...



Artificial Neural Networks and PDFs



- **Neural Networks** can be used universal unbiased interpolants to **parametrise PDFs**
- Removes model dependence: **unbiased learning** the physical laws from data
- Highly **redundant parametrisation:** identical results if O(10) increase in # free params

	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	$g(x) \simeq \mathrm{NN}(x)$	$R_g(x, A) \simeq \mathrm{NN}(x, A)$

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

A: *number of protons + neutrons*

Generative Adversarial Networks

- New architecture for an **unsupervised neural network training** (unlabelled samples)
- Based on two **independent nets** that work separately and act as **adversaries:**
  - the **Discriminator (D)** undergoes training and plays the role of classifier
  - the **Generator (G)** and is tasked to generate random samples that **resemble real samples** with a twist rendering them as fake samples.

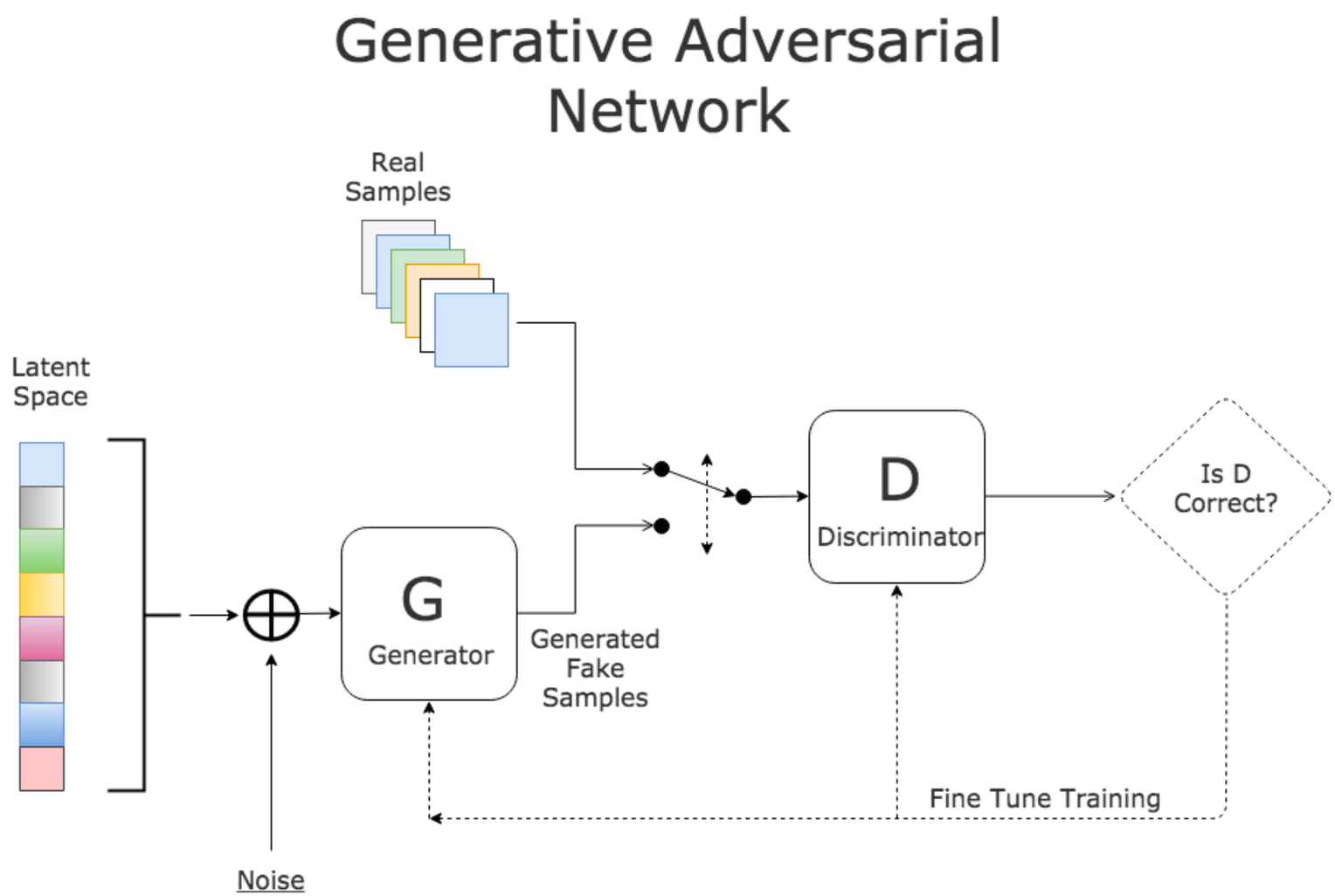
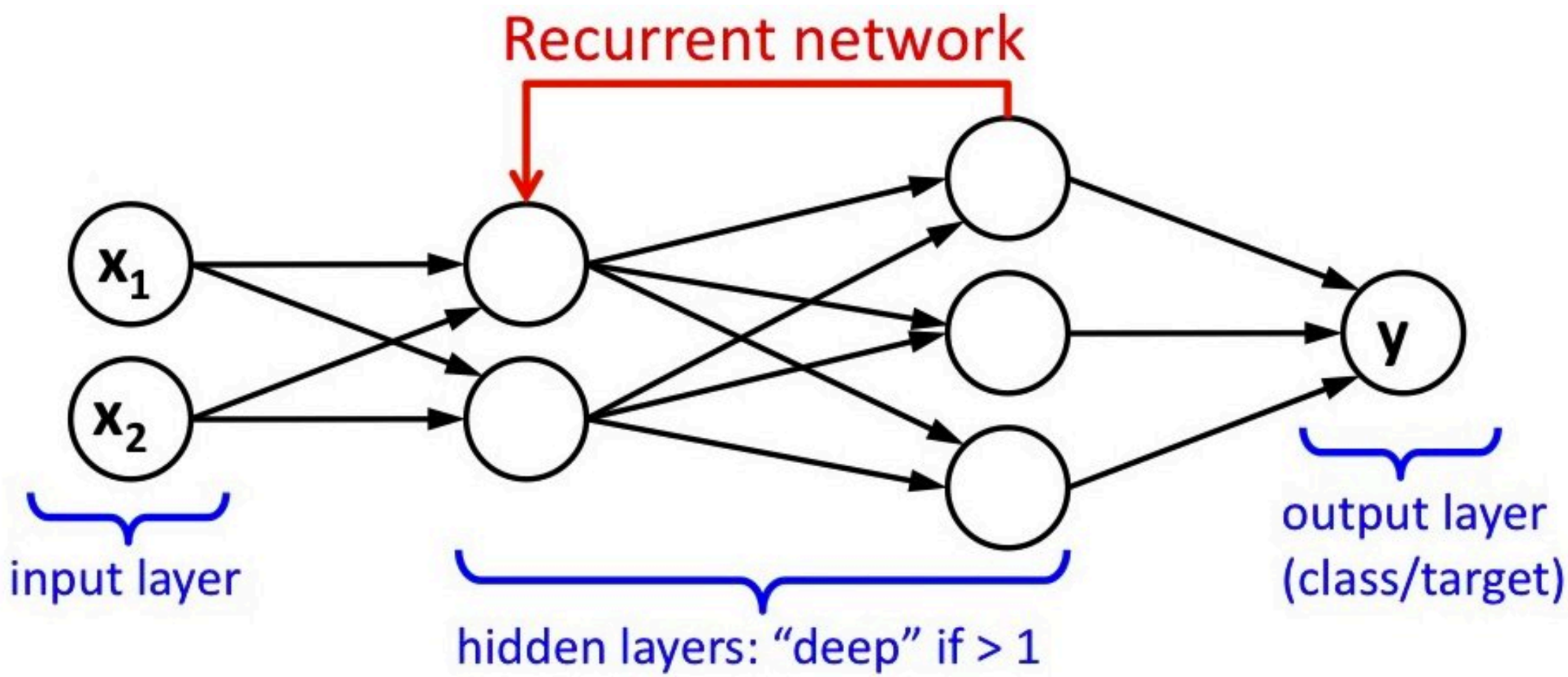


Image generation with GANs

https://thispersondoesnotexist.com/

Recurrent Neural Networks

RNNs use as inputs not just the current “training examples” but also what they have perceived previously: **built-in notion of time ordering** useful for time-dependent functions



The output of a RNN at time time, ***y(t),*** depends both on the current input example ***x(t)*** as well as of its previous output ***y(t-1)*** (or activation states of hidden neutrons at ***t-1***)

AI-based artificial text generation

SYSTEM PROMPT (HUMAN-WRITTEN)

In a shocking finding, scientist discovered a herd of unicorns living in a remote, previously unexplored valley, in the Andes Mountains. Even more surprising to the researchers was the fact that the unicorns spoke perfect English.

MODEL COMPLETION (MACHINE-WRITTEN, 10 TRIES)

The scientist named the population, after their distinctive horn, Ovid's Unicorn. These four-horned, silver-white unicorns were previously unknown to science.

Now, after almost two centuries, the mystery of what sparked this odd phenomenon is finally solved.

Dr. Jorge Pérez, an evolutionary biologist from the University of La Paz, and several companions, were exploring the Andes Mountains when they found a small valley, with no other animals or humans. Pérez noticed that the valley had what appeared to be a natural fountain, surrounded by two peaks of rock and silver snow.

https://openai.com/

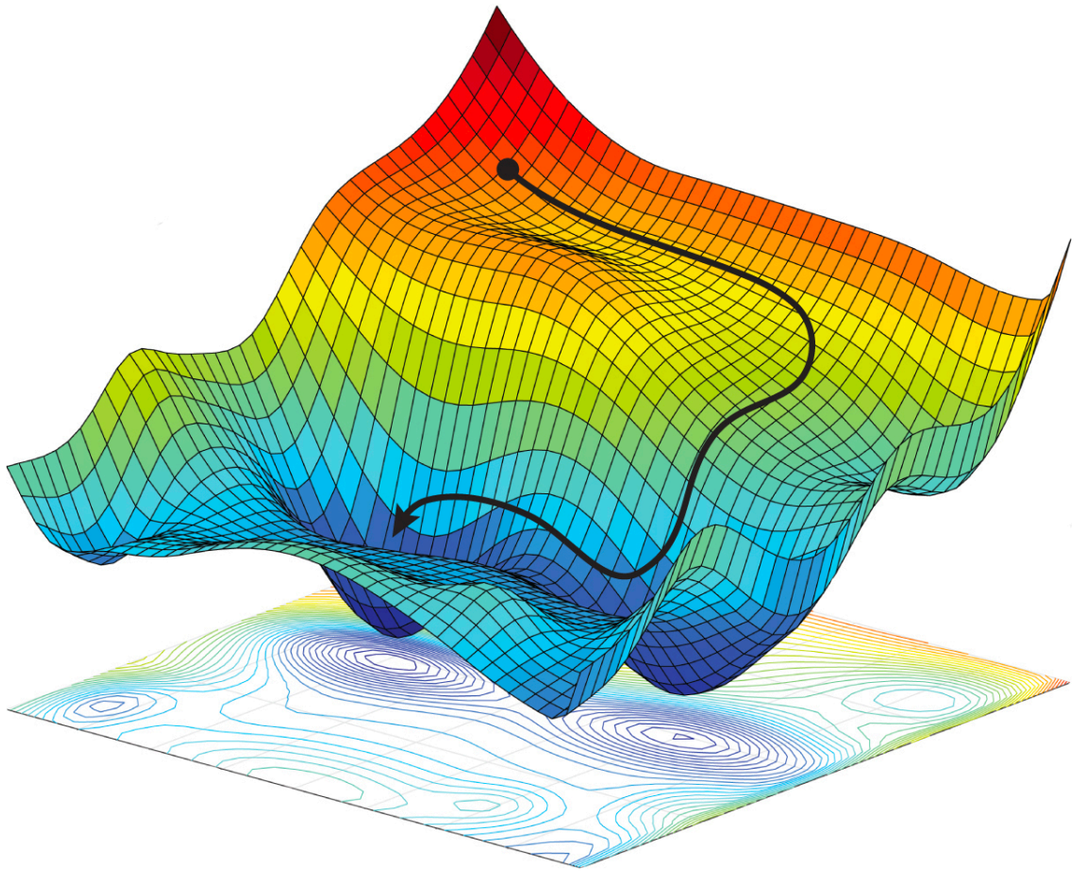
Pérez and the others then ventured further into the valley. "By the time we reached the top of one peak, the water looked blue, with some crystals on top," said Pérez.

Pérez and his friends were astonished to see the unicorn herd. These creatures could be seen from the air without having to move too much to see them – they were so close they could touch their horns.

While examining these bizarre creatures the scientists discovered that the creatures also spoke some fairly regular English. Pérez stated, "We can see, for example, that they have a common 'language,' something like a dialect or dialectic."

The optimisation conundrum

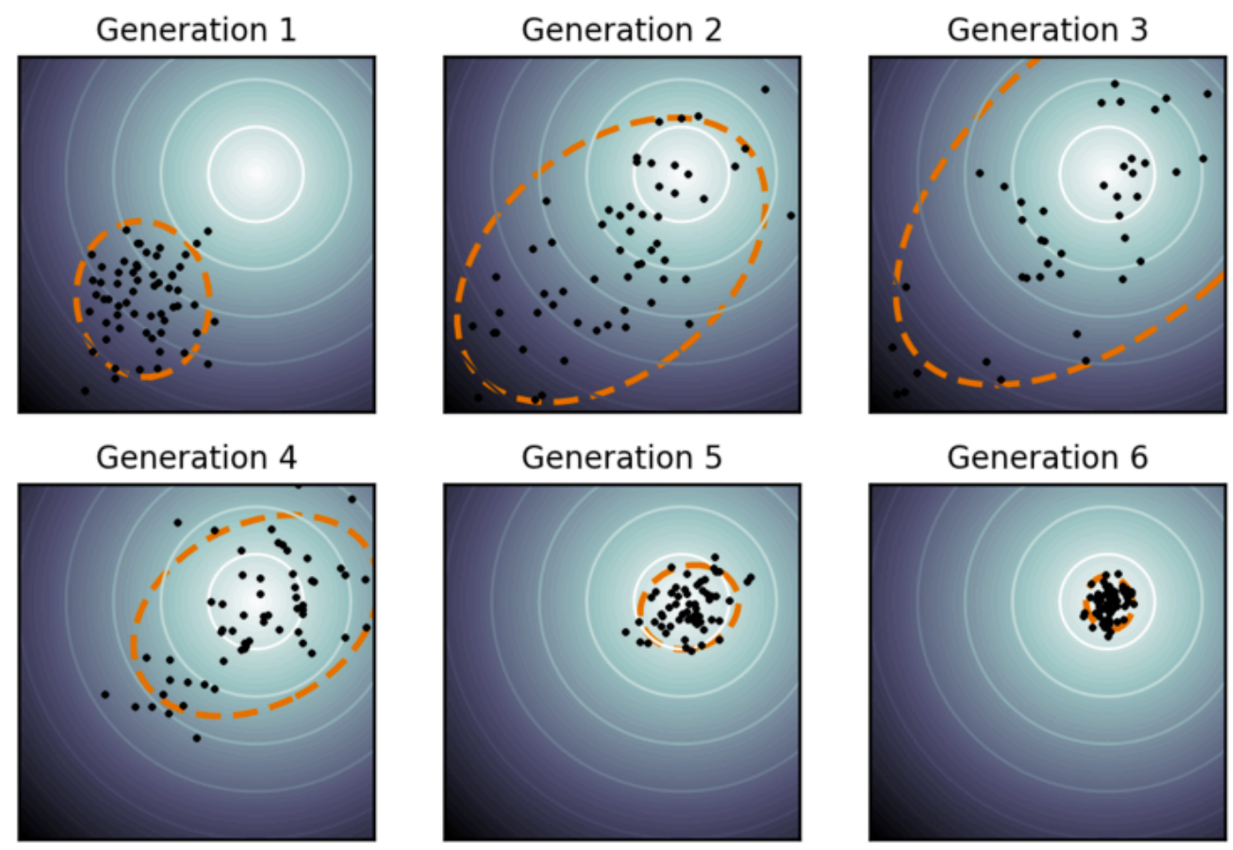
(Stochastic) Gradient Descent



- A challenge for any QCD global analysis is the efficient exploration of **huge parameter space** (hundreds/thousands free params)

- Several pitfalls to be avoided: under-fitting, over-fitting, **local minima**, saddle points, ….

Genetic Algorithms



- ***Deterministic algorithms***: follow the gradient of the cost function

- ***Evolutionary algorithms***: act on population of solutions with random mutations and selection

Parton Distributions with Theoretical Uncertainties

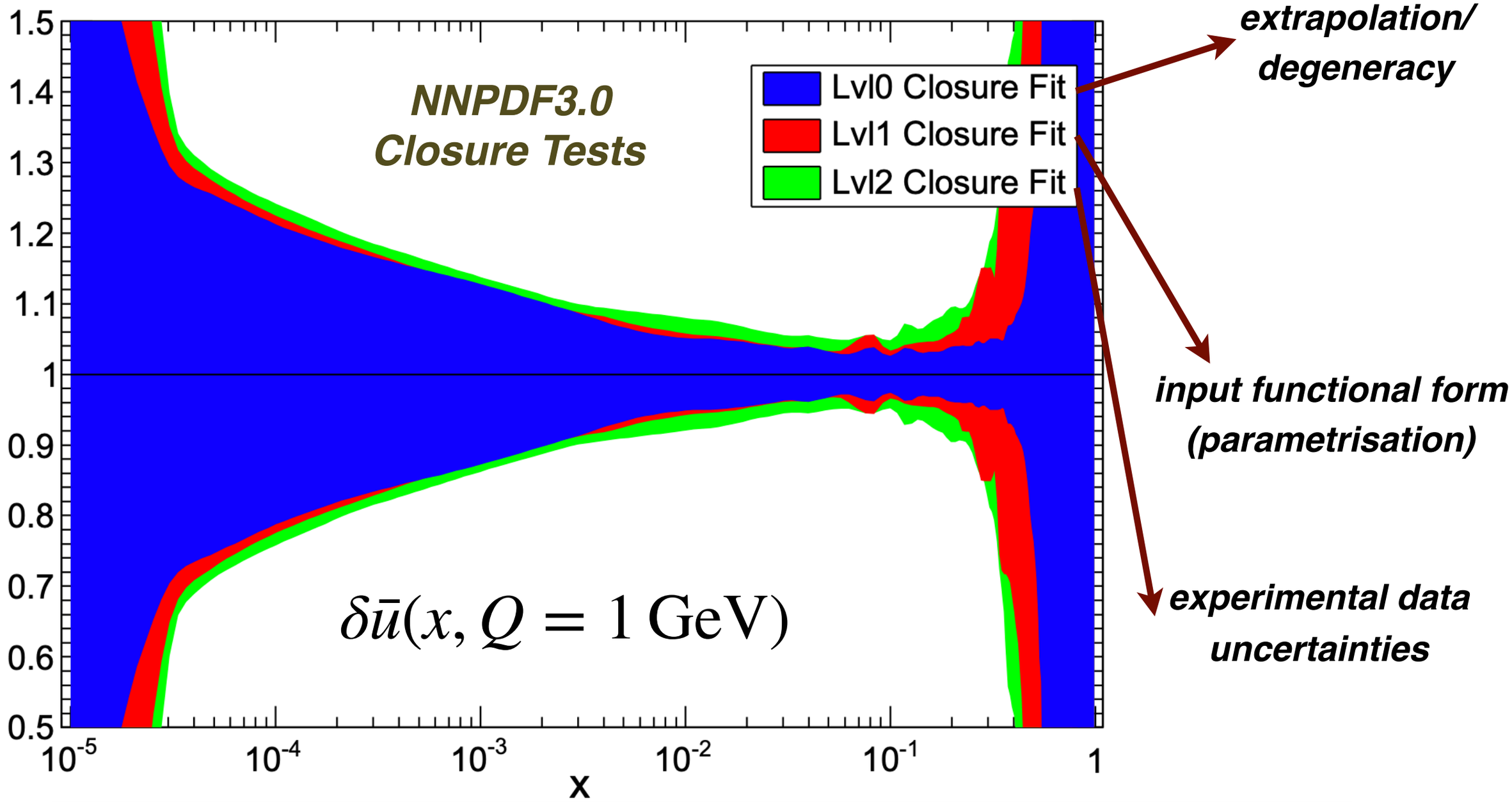
Based on ***NNPDF Collaboration:*** *R. Abdul Khalek, R. D. Ball, S. Carrazza, S. Forte, T. Giani, Z. Kassabov, R. L. Pearson, E. R. Nocera, J. Rojo, L. Rottoli, M. Ubiali, C. Voisey, M. Wilson*

arXiv:1905.04311, *submitted to PRL*

arXiv:1906.10698, *submitted to EPJC*

PDF uncertainties

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



What about **theory uncertainties**? Parametric theory errors from $\delta\alpha_S$, δm_c are routinely accounted for, but other relevant contributions are missing ….

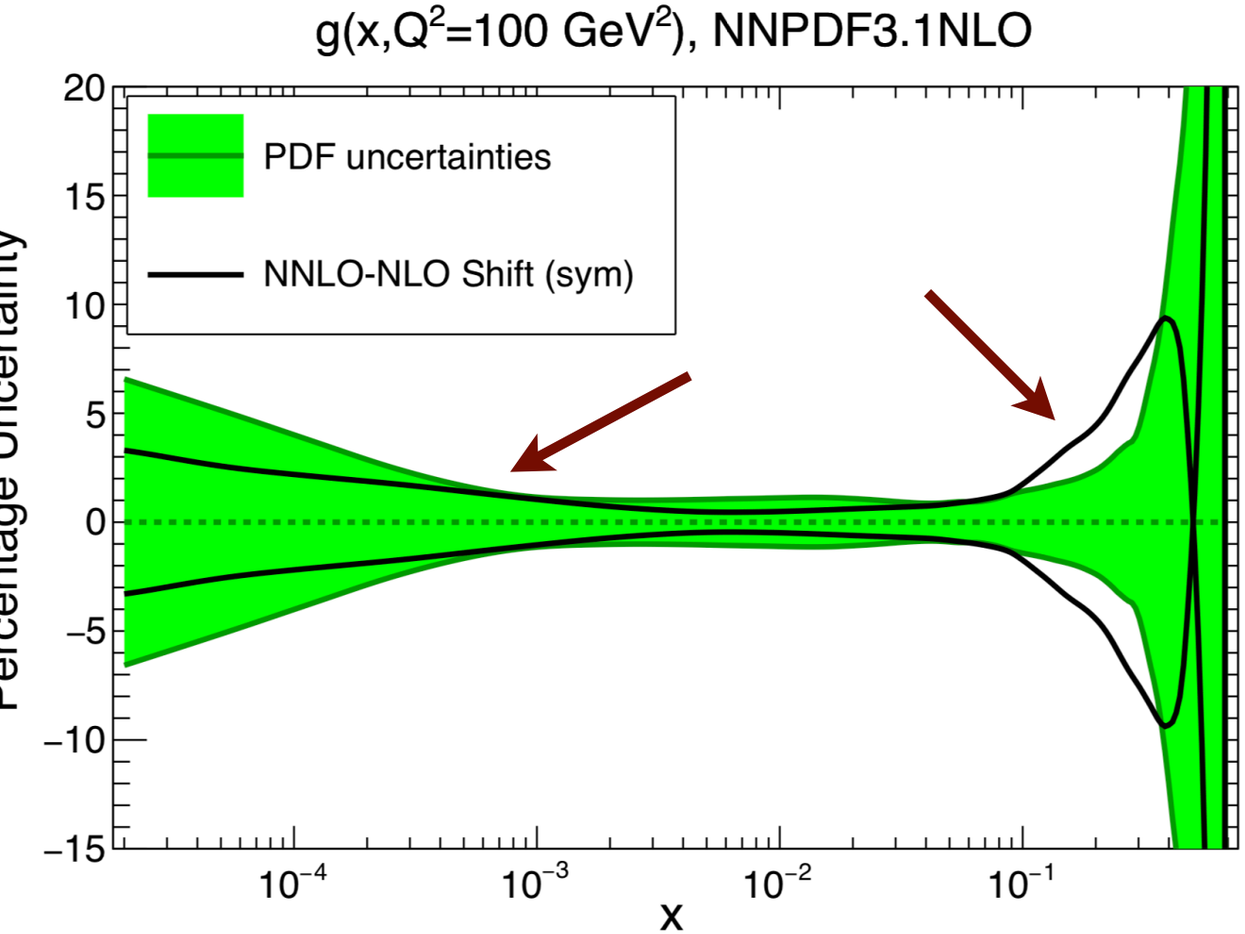
QCD uncertainties in PDF fits

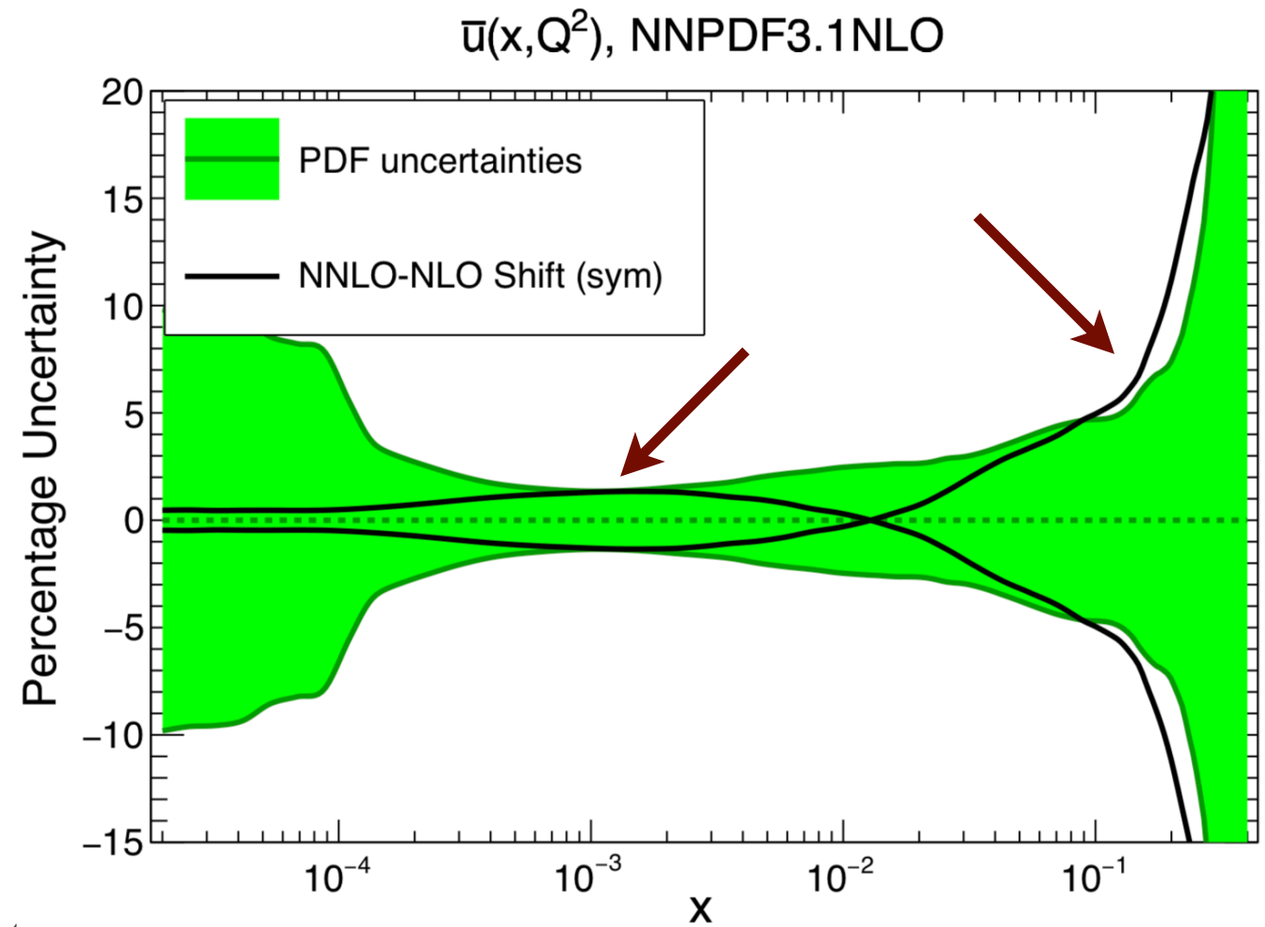
Standard global PDF fits are based on **fixed-order QCD calculations**

$$\sigma = \alpha_s^p \sigma_0 + \alpha_s^{p+1} \sigma_1 + \alpha_s^{p+2} \sigma_2 + \mathcal{O}(\alpha_s^{p+3})$$

The truncation of the perturbative series has associated a theoretical uncertainty: **Missing Higher Order (MHO)** uncertainty

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





A theoretical covariance matrix

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

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

experimental ***theoretical***

assumption: theory errors are **Gaussianly distributed** around **true value**

Formally the theory covariance matrix is defined as

$$S_{ij} = \left\langle (\mathcal{T}_i - T_i)(\mathcal{T}_j - T_j) \right\rangle \equiv \left\langle \Delta_i \Delta_j \right\rangle$$

true result *actual calculation*

How to estimate these **theory systematic shifts**?

A theoretical covariance matrix

Here we use **scale variations** to estimate the MHOUs

$$\Delta_{i_a}(\kappa_f, \kappa_{r_a}) \equiv T_{i_a}(\kappa_f, \kappa_{r_a}) - T_{i_a}(0,0)$$

theory shifts

labels data points in process a

$\kappa_{f(r_a)} = \ln \mu^2_{f(r_a)}/Q^2$

central prediction

note: renormalisation scale variations are only correlated within the *same* process

$$S_{ij} = n_m \sum_{V_m} \Delta_{i_a}(\kappa_f, \kappa_{r_a}) \Delta_{i_b}(\kappa_f, \kappa_{r_b})$$

theory covariance matrix

normalisation factor

sum over scale variations

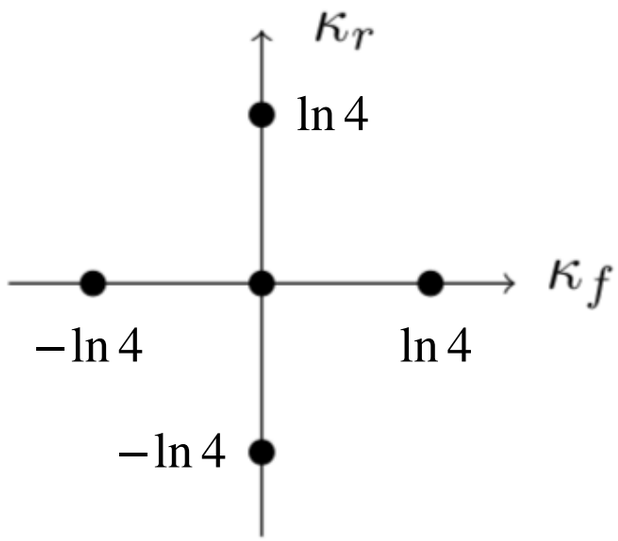
Different prescriptions for scale variations possible:

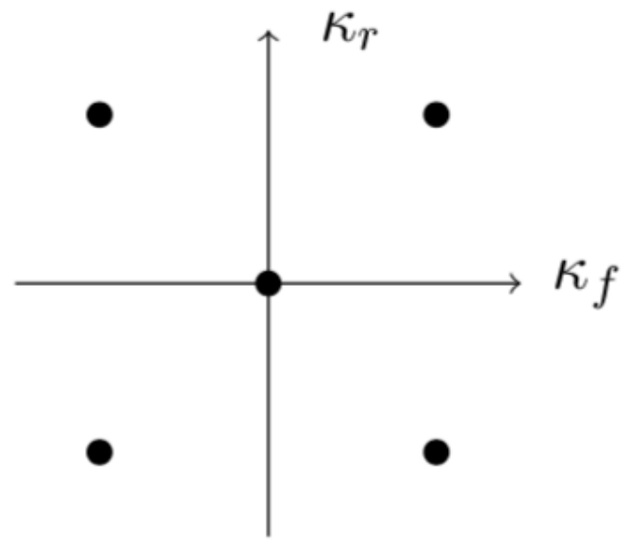
Need to validate which ones exhibit the best performance

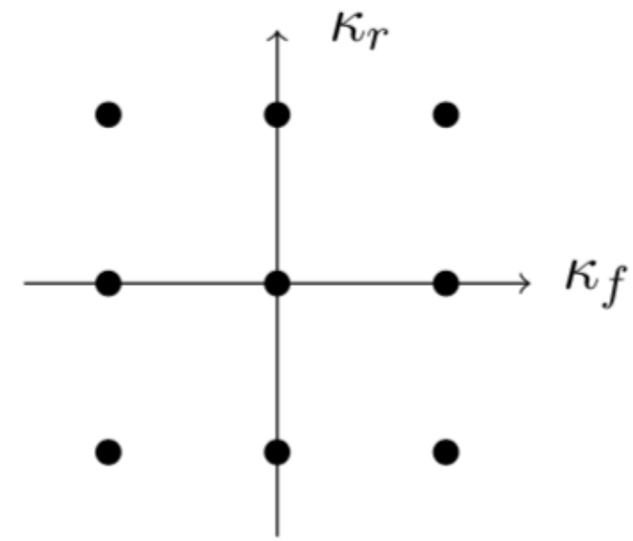
Point prescriptions

single process

symmetric prescriptions



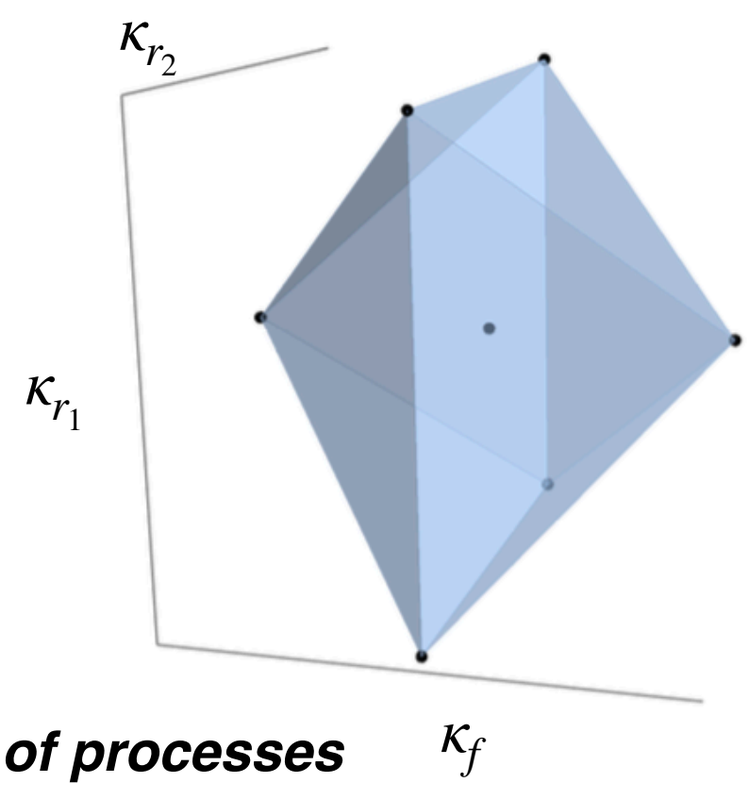


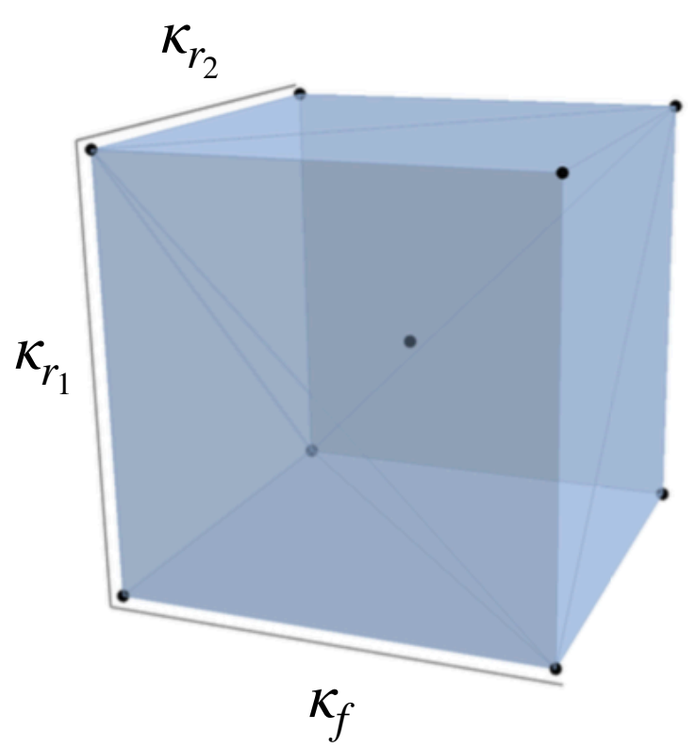


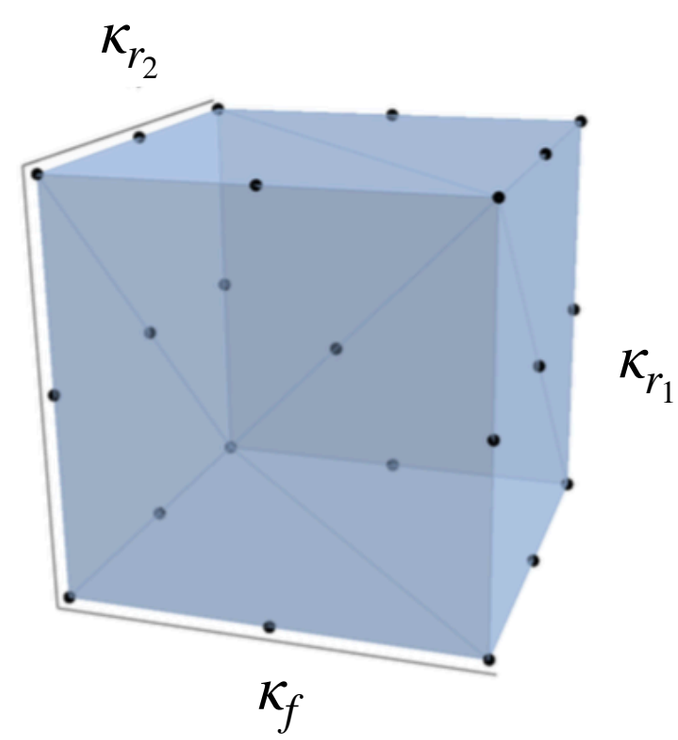
5-points

5bar-points

9-points



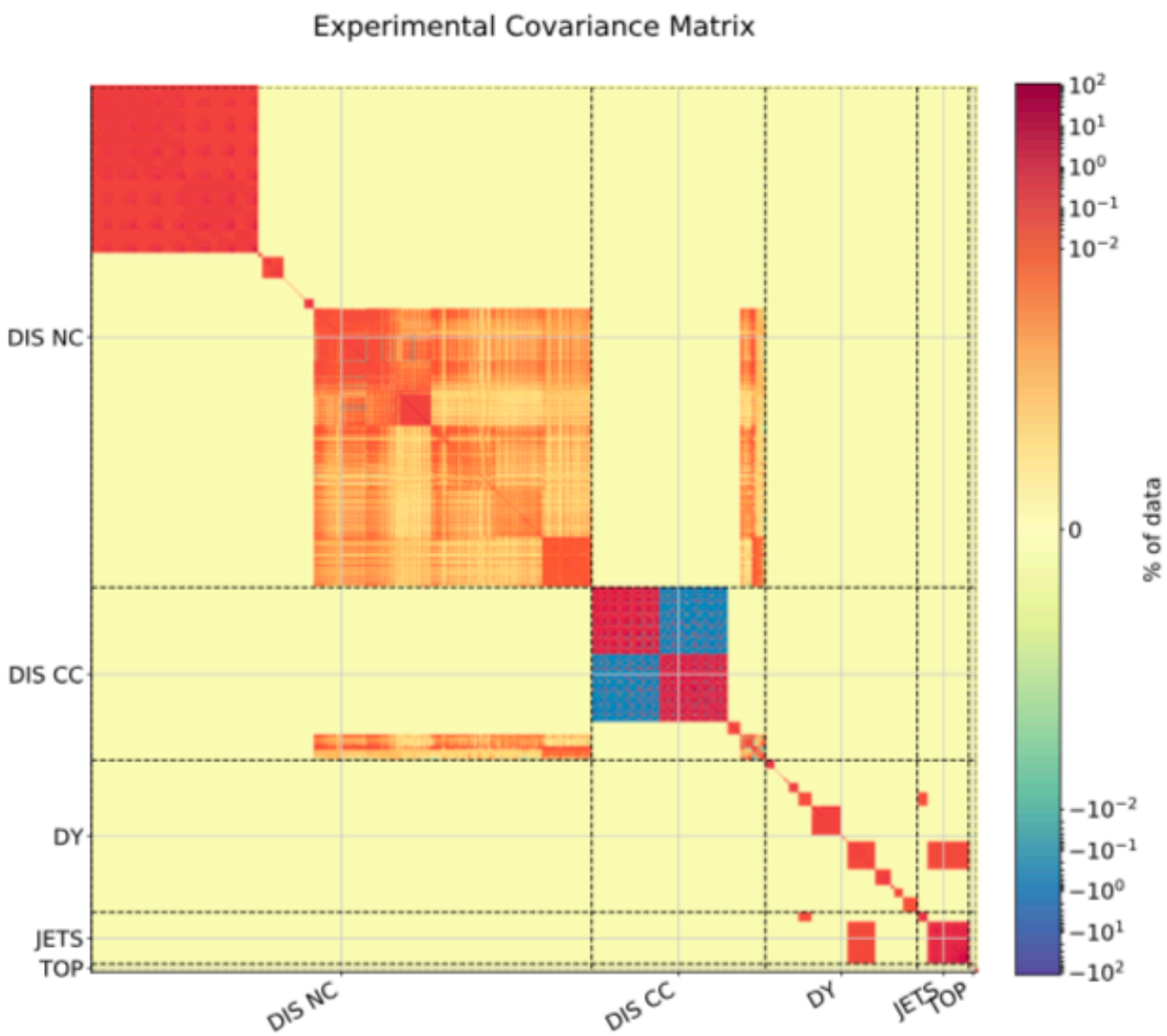


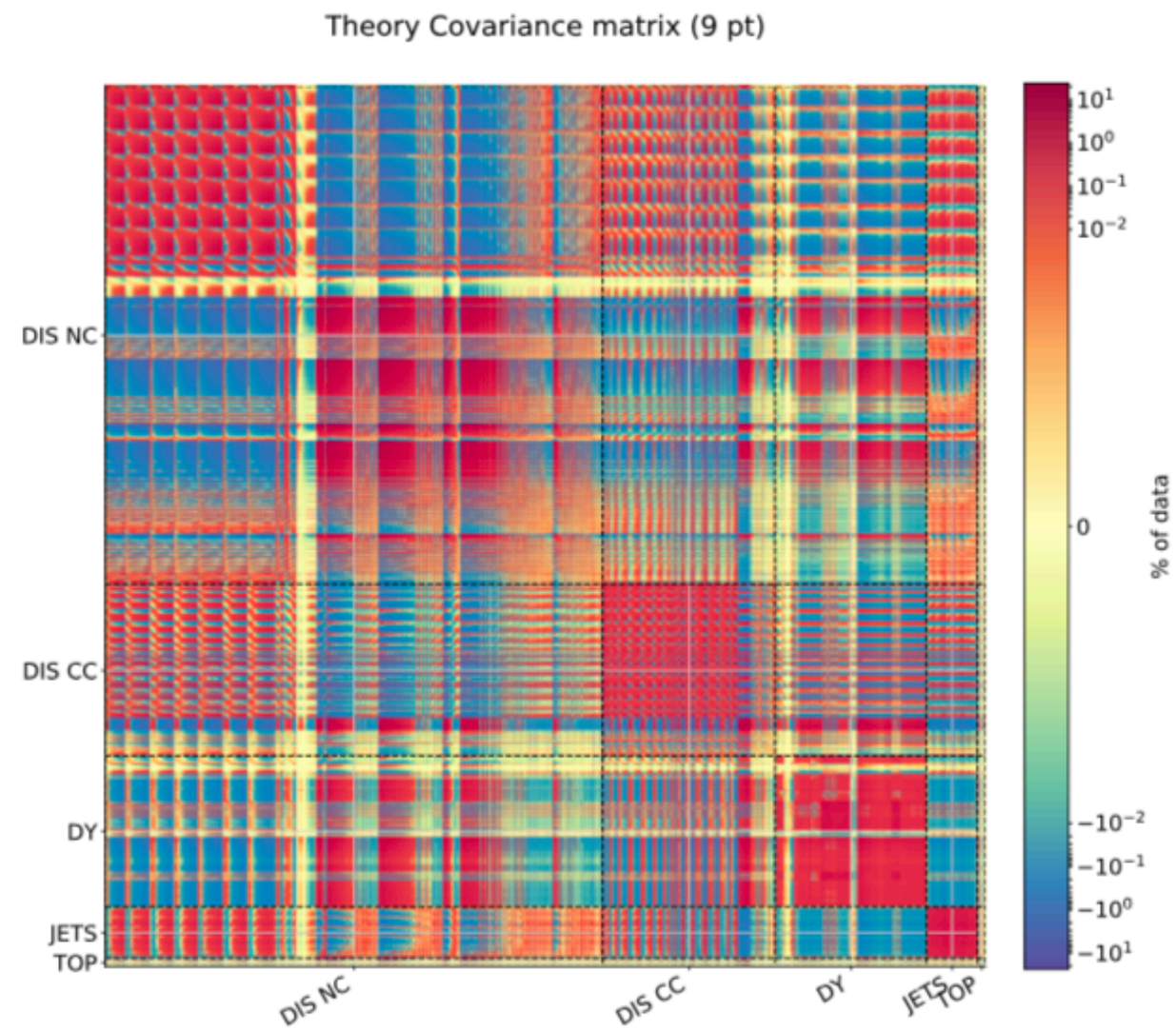


Pair of processes

The theory covariance matrix

covariance matrices

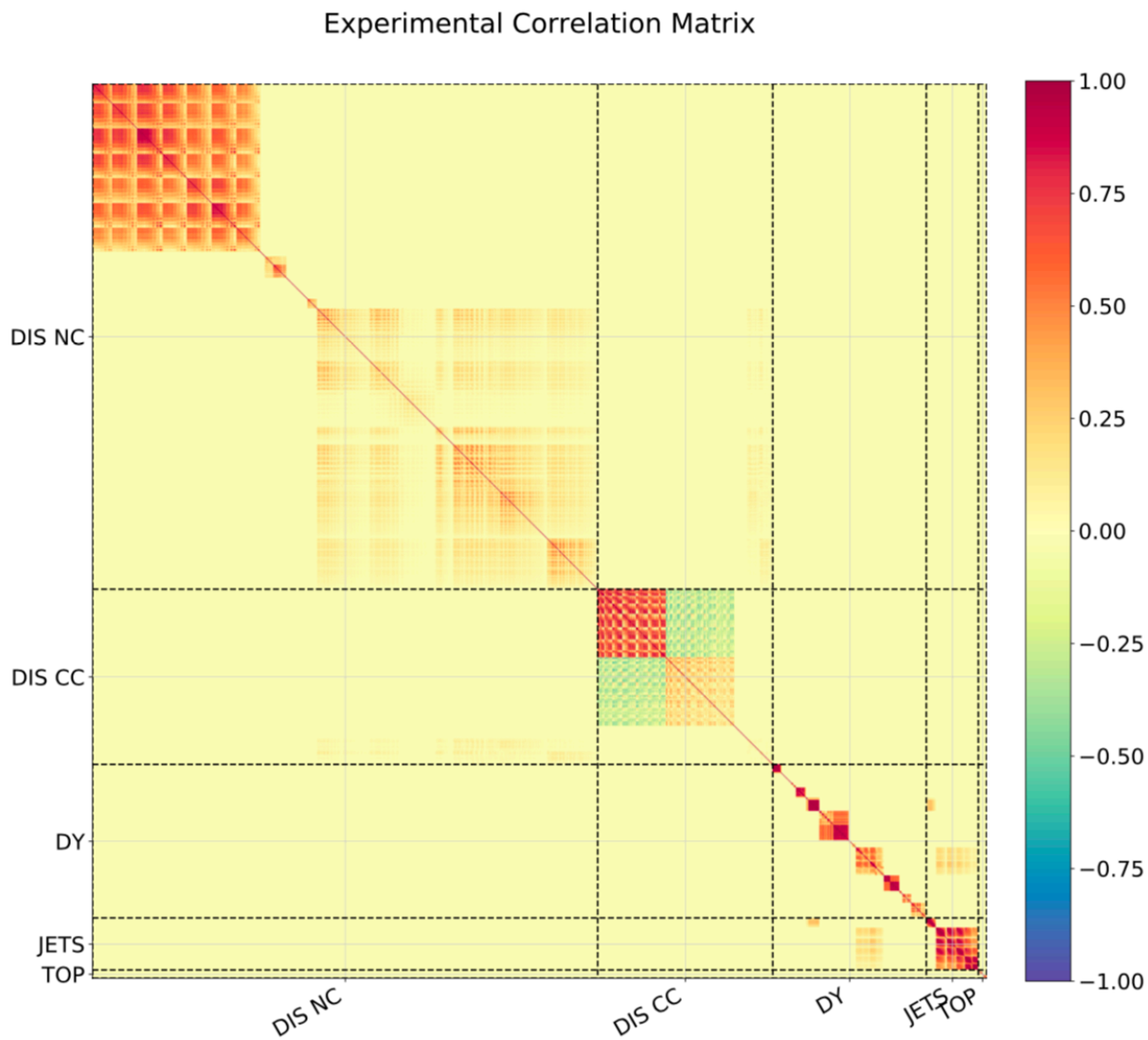


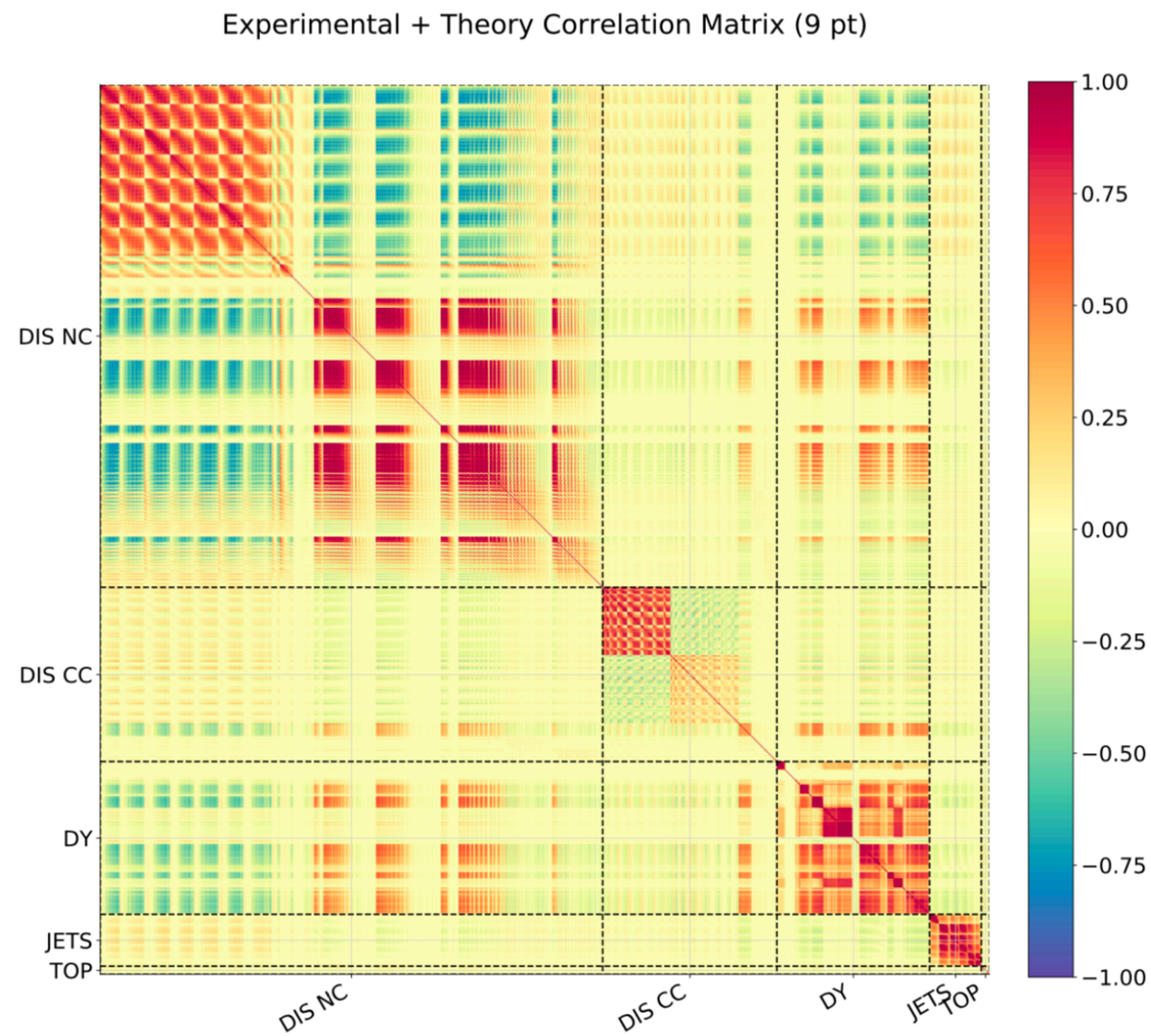


Rich pattern of **theory-induced correlations:**
Absent if only experimental errors considered

The theory covariance matrix

correlation matrices

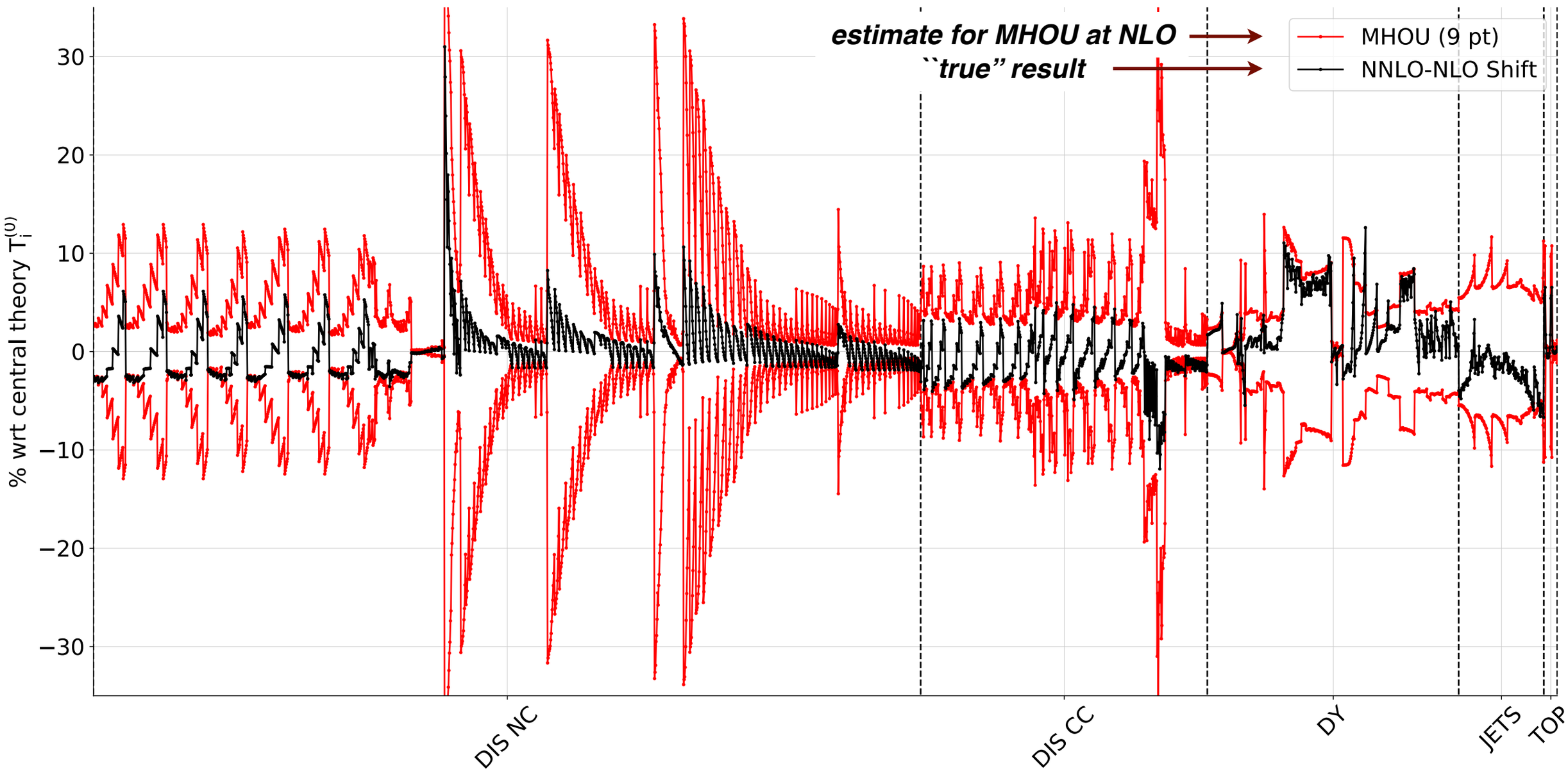




Rich pattern of **theory-induced correlations:**
Absent if only experimental errors considered

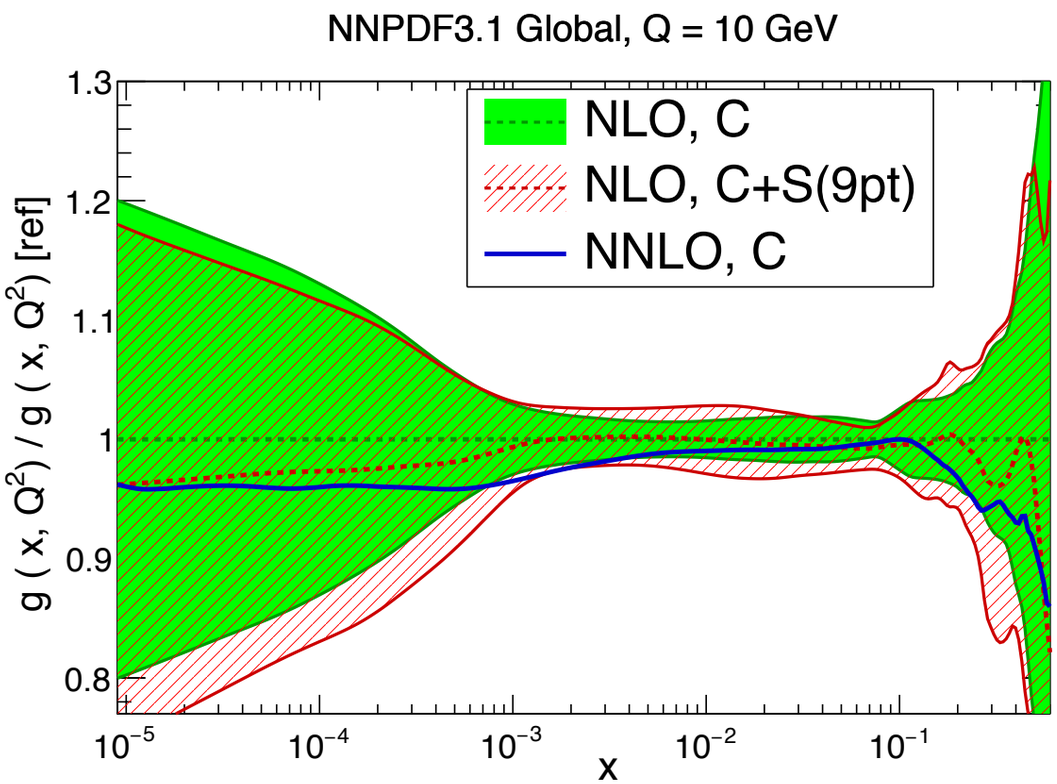
Validation

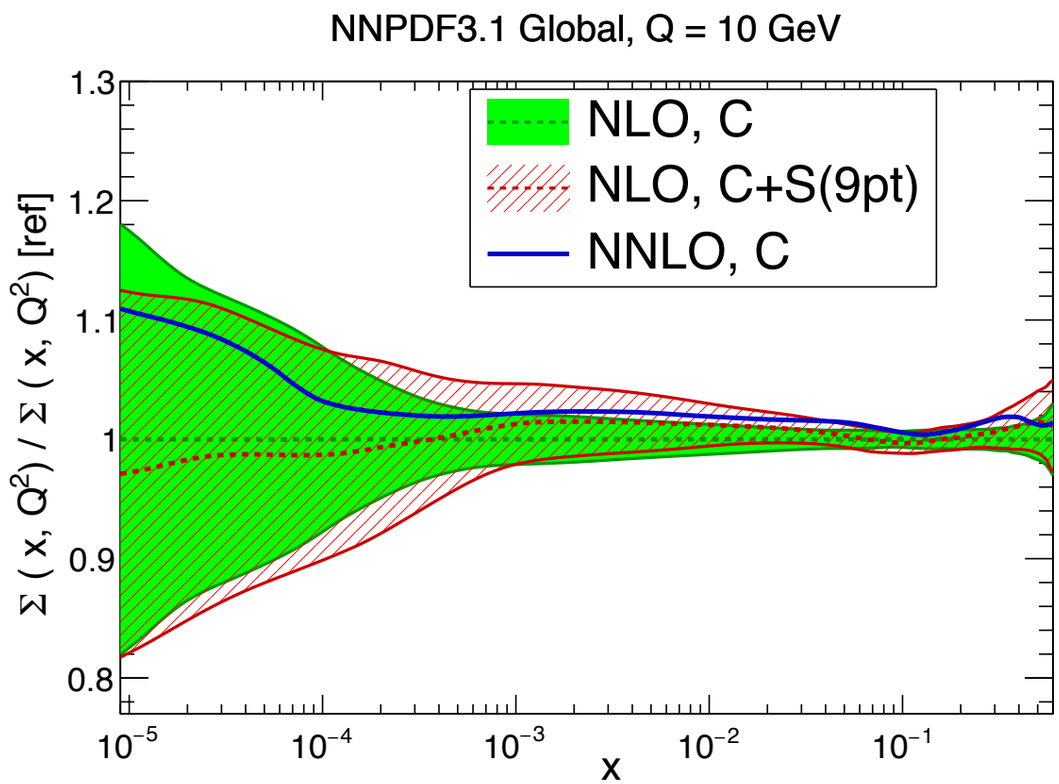
Systematic validation of NLO theory covariance matrix on the `exact' result, the **NLO=>NNLO shift**, for **O(3000) data points** of the global PDF fit

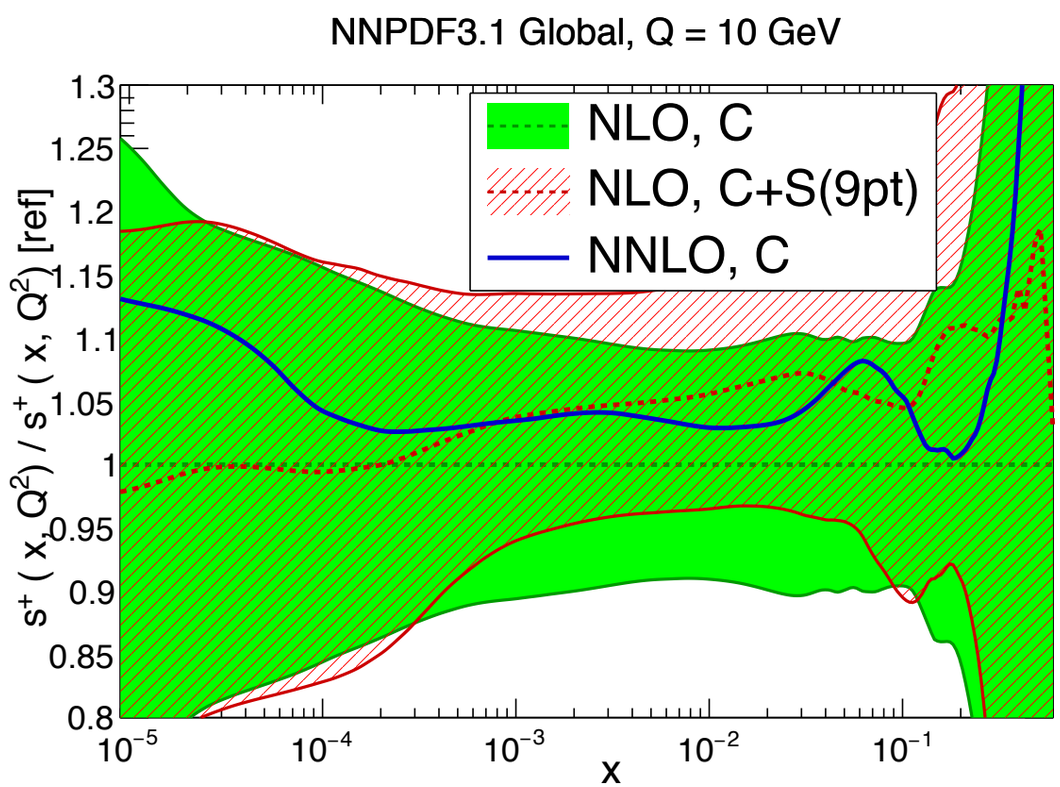


Scale variations: good estimate of MHOU for processes of relevance in PDF fits

Impact on PDFs

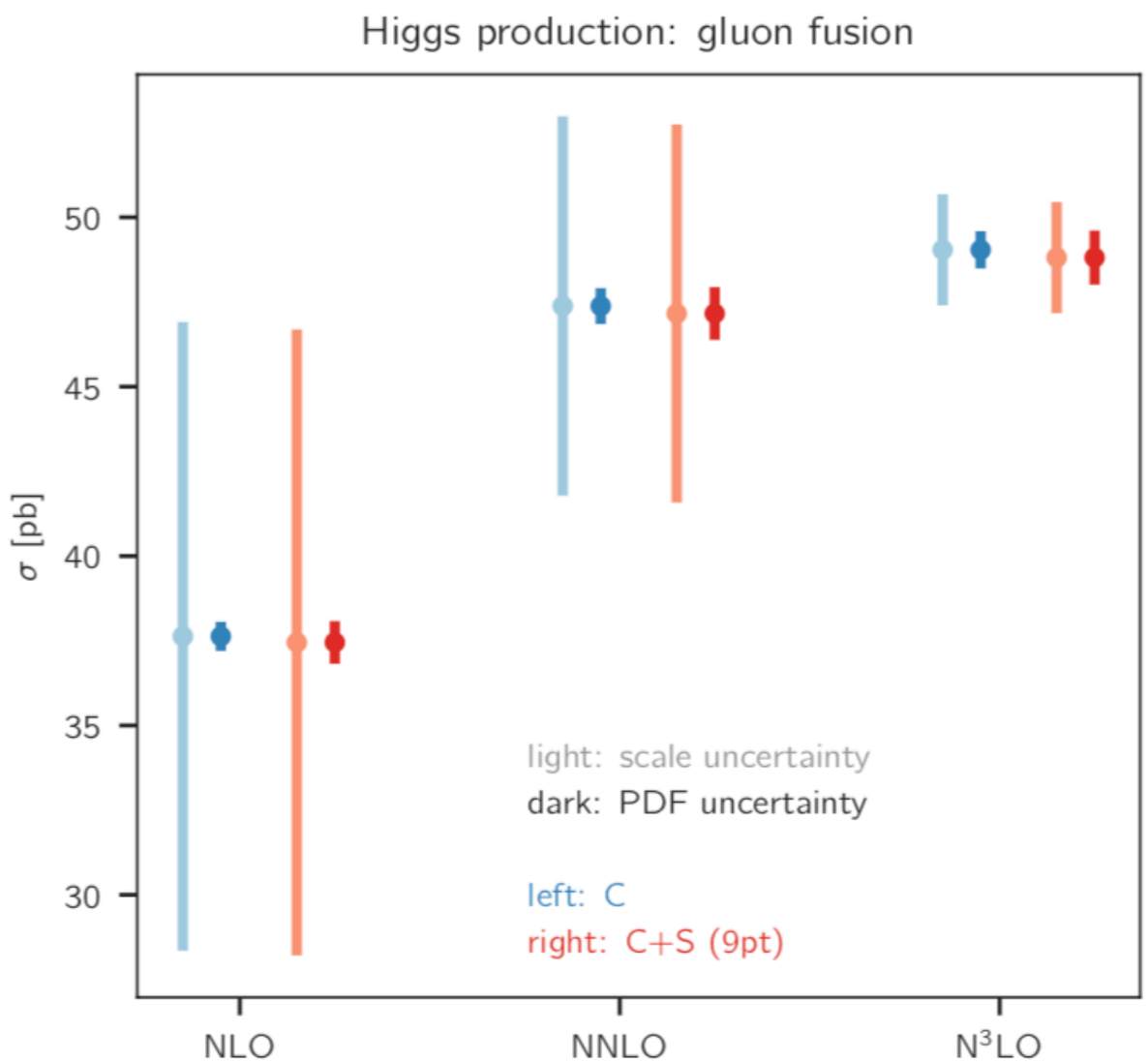


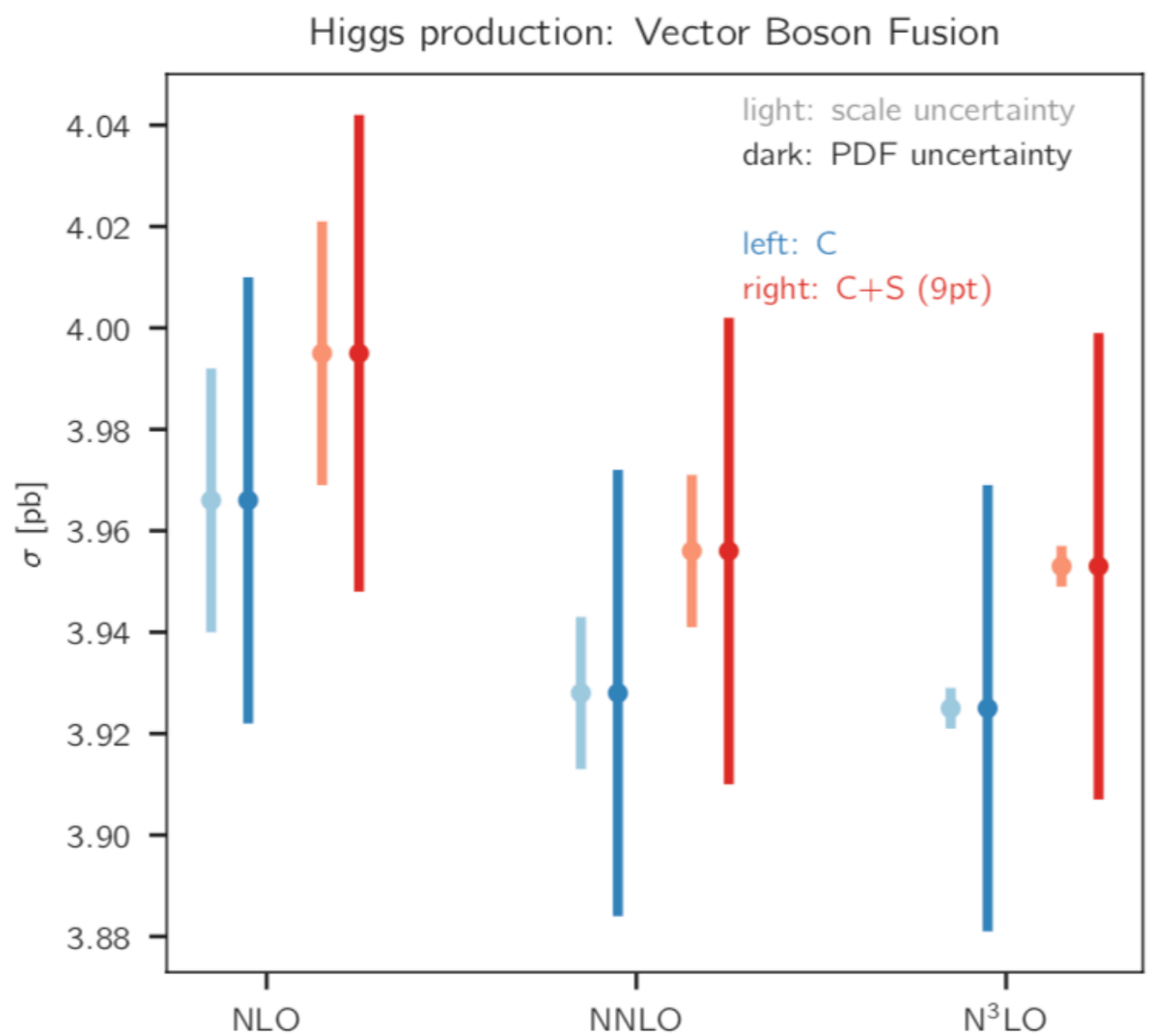




- **True result** (NLO to NNLO shift) contained within the NLO C+S band
- Central value of NLO C+S **shifts towards true result** in most cases
- Moderate (but not dramatic) **increase** in overall PDF uncertainties

Impact for LHC phenomenology





Depending on process, main consequence of **MHOUs in PDF fit for LHC pheno** is shift in central values, increase in overall PDF uncertainties, or both

Can New Physics Hide Inside the Proton?

Based on S. Carrazza, C. Degrande, S. Iranipour, J. Rojo, M. Ubiali

arXiv:1905.05215, *submitted to PRL*

SMEFT & PDFs

- Heavy bSM physics beyond the direct reach of the LHC can be **parametrised in a model-independent** in terms of a **complete** basis of higher-dimensional operators: this is the **Standard Model Effective Field Theory**

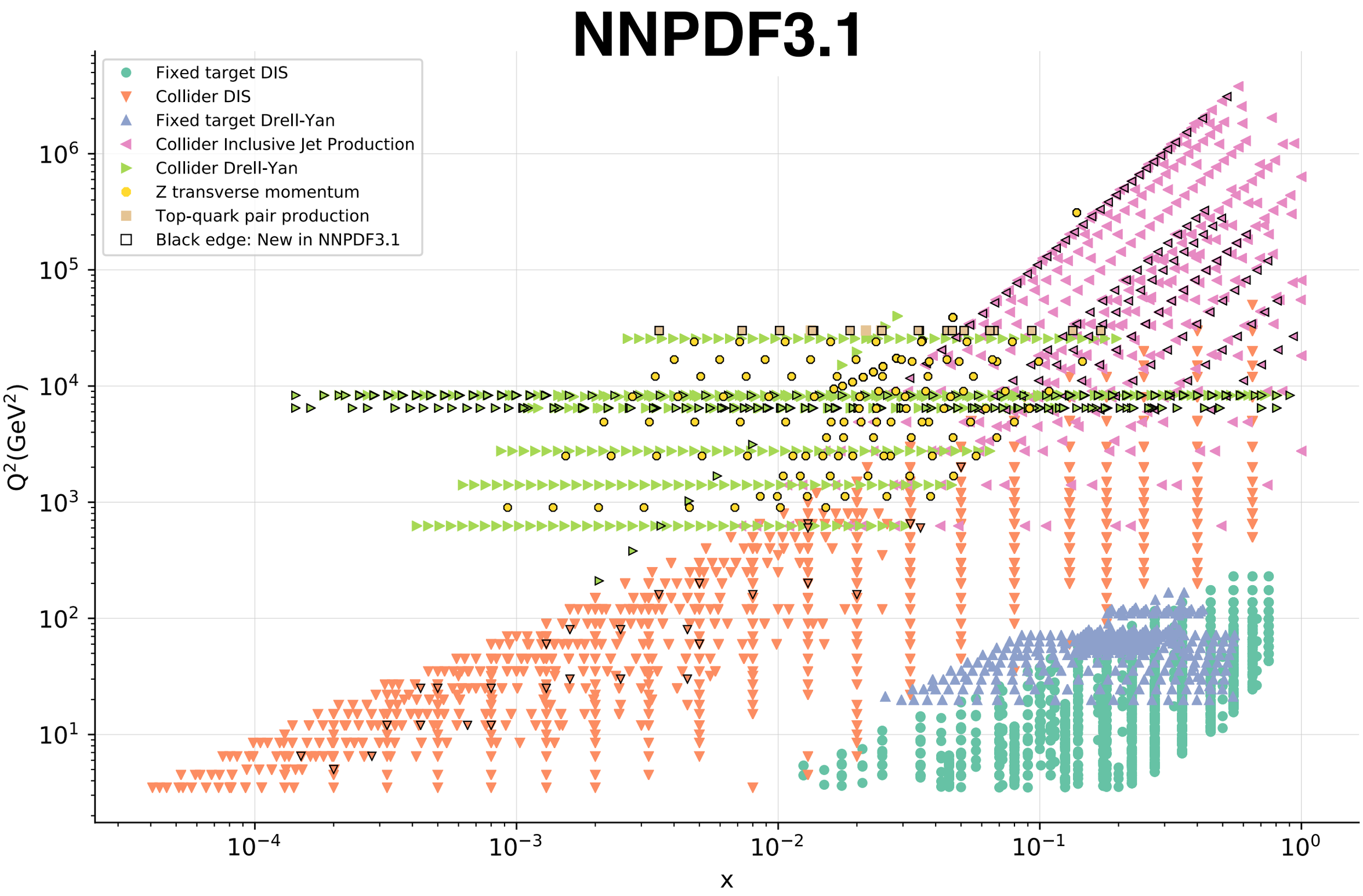
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \ldots ,$$

- Some operators induce **growth with the partonic centre-of-mass energy**: increased sensitivity in LHC cross-sections in the TeV region

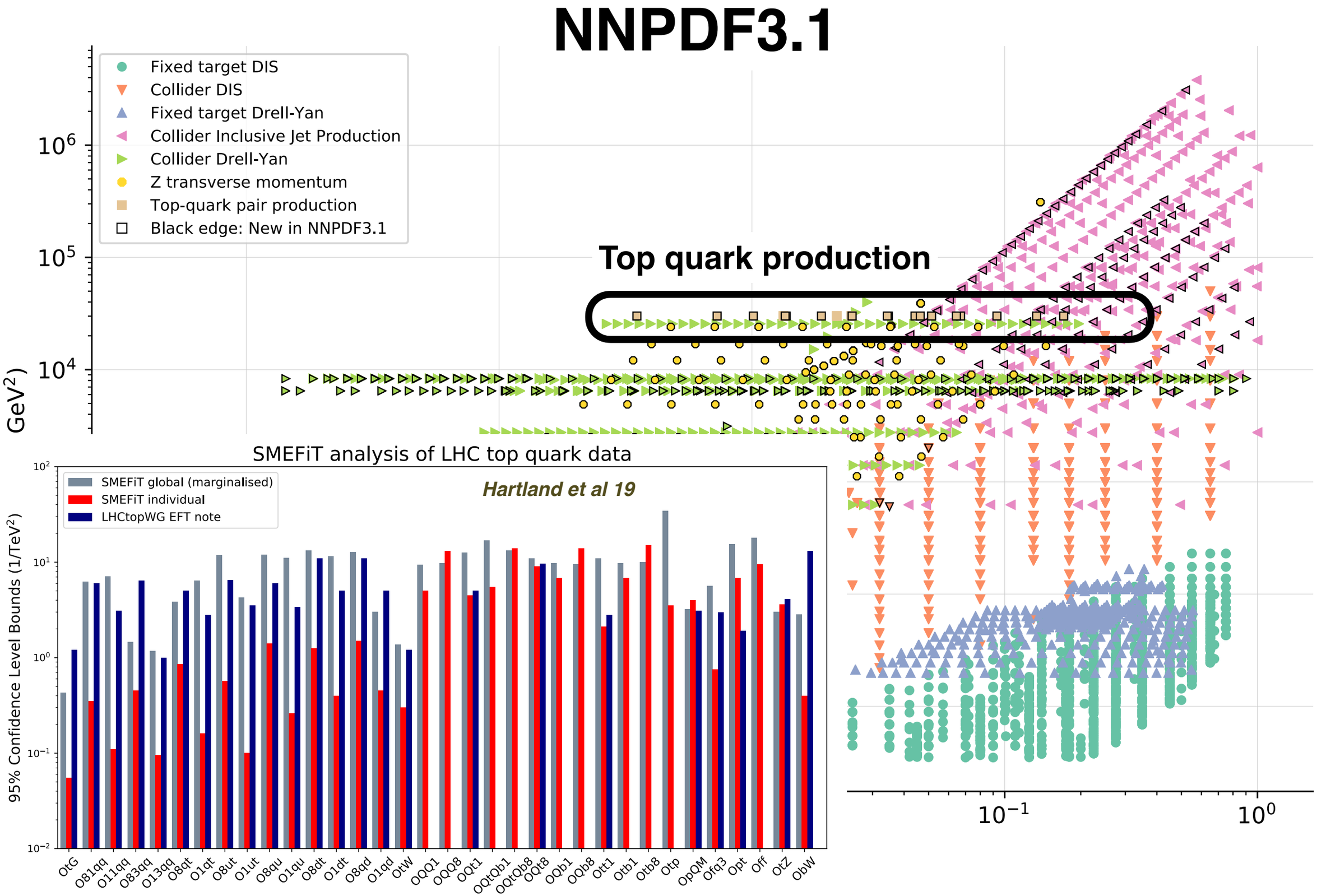
$$\sigma(E) = \sigma_{\rm SM}(E) \left(1 + \sum_i^{N_{d6}} \omega_i \frac{c_i\, m_{\rm SM}^2}{\Lambda^2} + \sum_i^{N_{d6}} \widetilde{\omega}_i \frac{c_i\, E^2}{\Lambda^2} + \mathcal{O}\left(\Lambda^{-4}\right) \right)$$

*enhanced sensitivity from **TeV-scale processes:** unique feature of LHC*

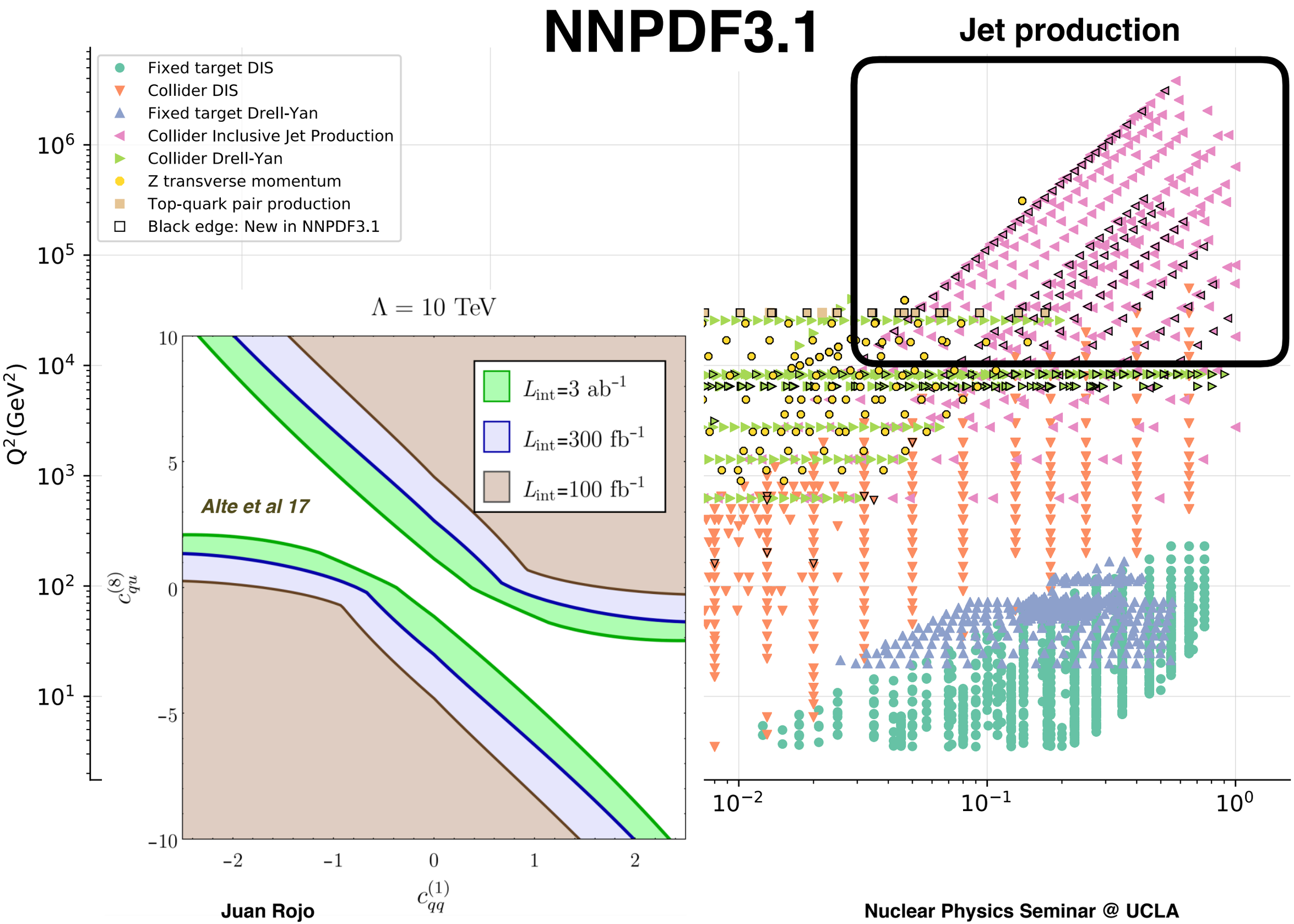
SMEFT & PDFs


NNPDF3.1
Fixed target DIS
Collider DIS
Fixed target Drell-Yan
Collider Inclusive Jet Production
Collider Drell-Yan
Z transverse momentum
Top-quark pair production
Black edge: New in NNPDF3.1
$Q^2(\mathrm{GeV}^2)$
10^1
10^2
10^3
10^4
10^5
10^6
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
x

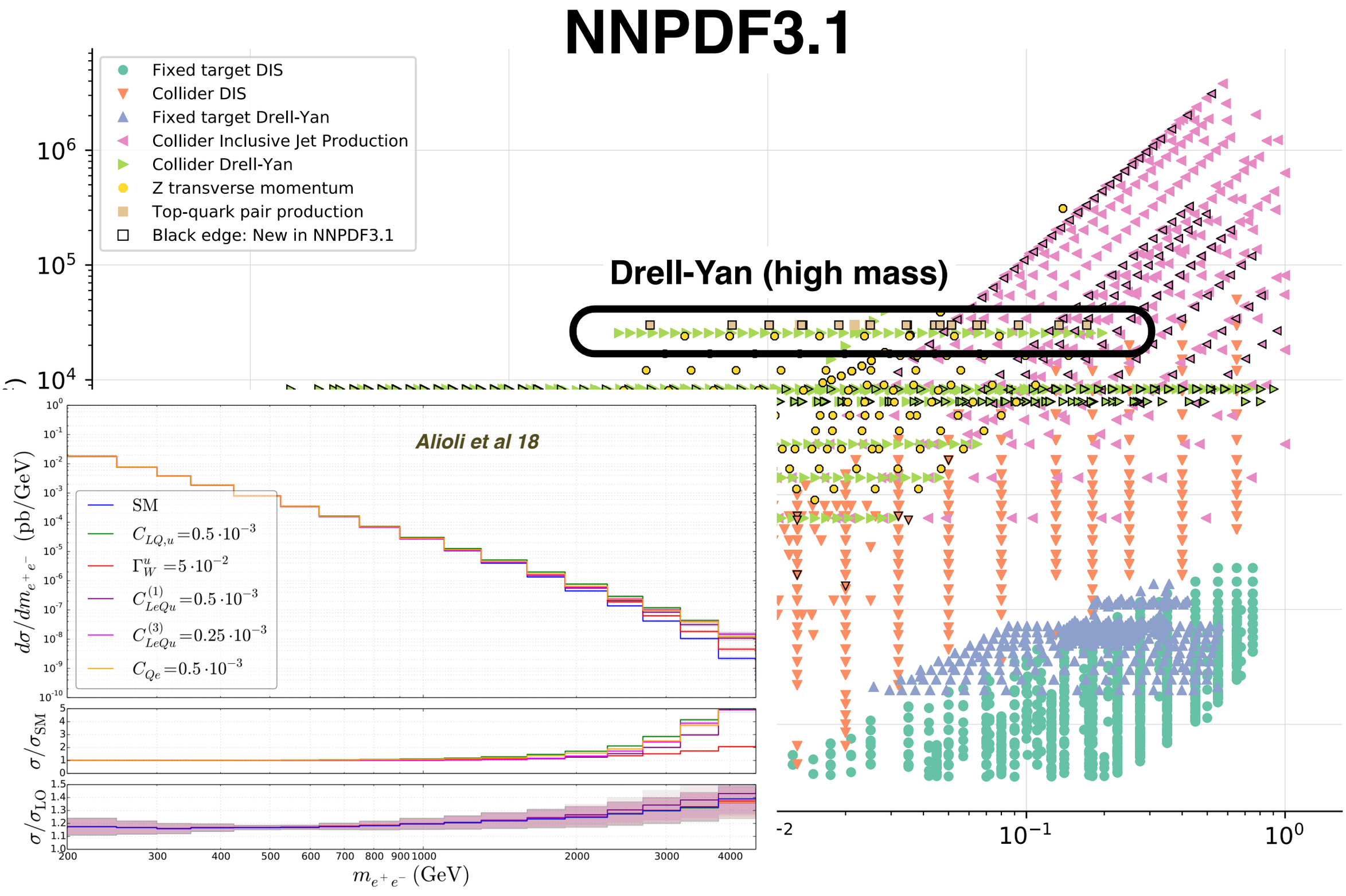
SMEFT & PDFs


NNPDF3.1
Fixed target DIS
Collider DIS
Fixed target Drell-Yan
Collider Inclusive Jet Production
Collider Drell-Yan
Z transverse momentum
Top-quark pair production
Black edge: New in NNPDF3.1
Top quark production
10^6
10^5
10^4
GeV^2)
10^{-1}
10^0
SMEFiT analysis of LHC top quark data
SMEFiT global (marginalised)
SMEFiT individual
LHCtopWG EFT note
Hartland et al 19
95% Confidence Level Bounds (1/TeV^2)
10^2
10^1
10^0
10^{-1}
10^{-2}
OtG
O81qq
O11qq
O83qq
O13qq
O8qt
O1qt
O8ut
O1ut
O8qu
O1qu
O8dt
O1dt
O8qd
O1qd
OtW
OQQ1
OQQ8
OQt1
OQtQb1
OQtQb8
OQt8
OQb1
OQb8
Ott1
Otb1
Otb8
Otp
OpQM
Ofq3
Opt
Off
OtZ
ObW

SMEFT & PDFs

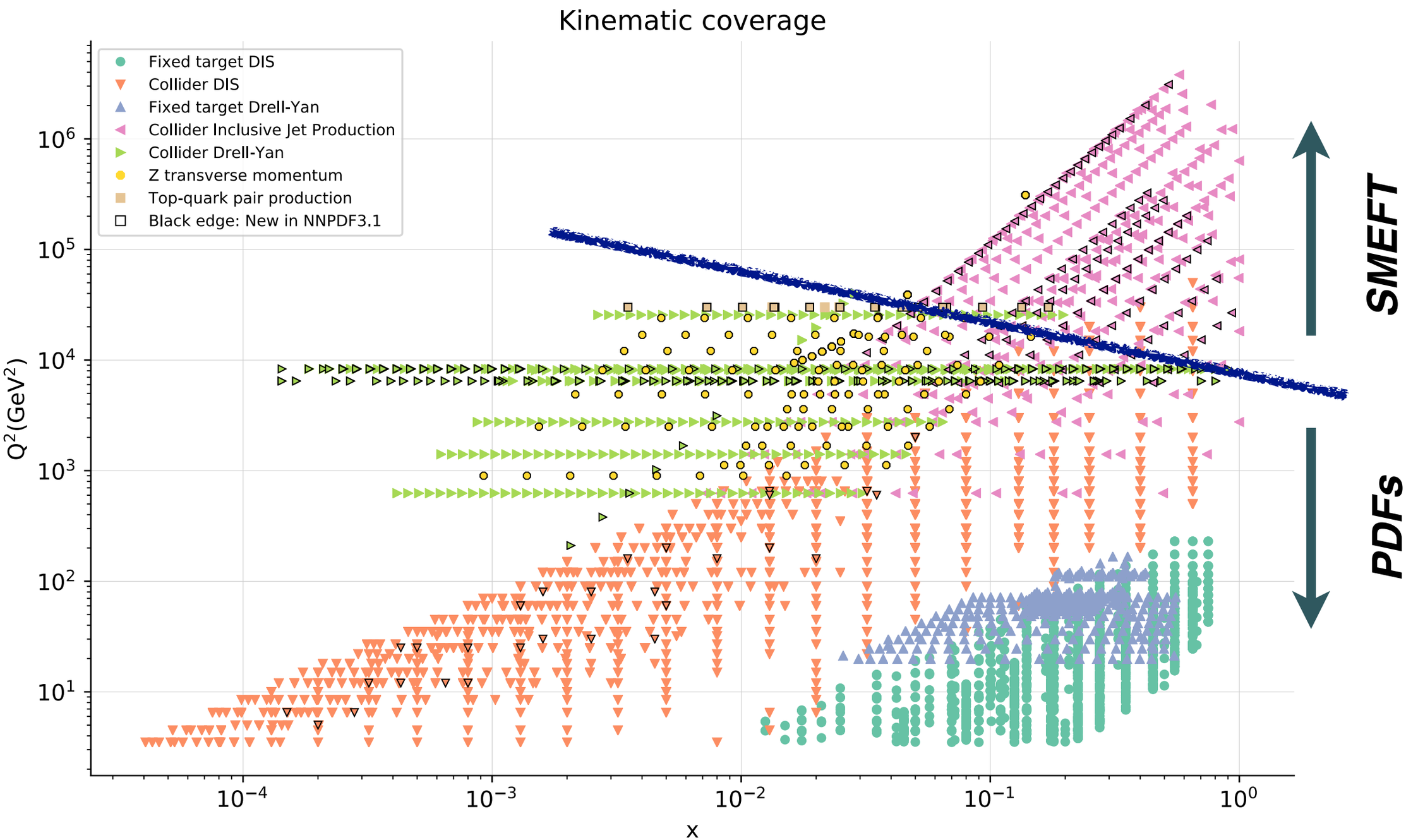

NNPDF3.1
Jet production
Fixed target DIS
Collider DIS
Fixed target Drell-Yan
Collider Inclusive Jet Production
Collider Drell-Yan
Z transverse momentum
Top-quark pair production
Black edge: New in NNPDF3.1
Q^2(GeV^2)
10^6
10^5
10^4
10^3
10^2
10^1
10^{-2}
10^{-1}
10^0
$\Lambda = 10$ TeV
$L_{\rm int}$=3 ab^{-1}
$L_{\rm int}$=300 fb^{-1}
$L_{\rm int}$=100 fb^{-1}
Alte et al 17
$c_{qu}^{(8)}$
$c_{qq}^{(1)}$
10
5
0
−5
−10
−2
−1
0
1
2

SMEFT & PDFs


NNPDF3.1
Fixed target DIS
Collider DIS
Fixed target Drell-Yan
Collider Inclusive Jet Production
Collider Drell-Yan
Z transverse momentum
Top-quark pair production
Black edge: New in NNPDF3.1
Drell-Yan (high mass)
Alioli et al 18
SM
$C_{LQ,u} = 0.5 \cdot 10^{-3}$
$\Gamma_W^u = 5 \cdot 10^{-2}$
$C_{LeQu}^{(1)} = 0.5 \cdot 10^{-3}$
$C_{LeQu}^{(3)} = 0.25 \cdot 10^{-3}$
$C_{Qe} = 0.5 \cdot 10^{-3}$
$d\sigma/dm_{e^+e^-}$ (pb/GeV)
σ/σ_{SM}
σ/σ_{LO}
$m_{e^+e^-}$ (GeV)

Naive approach

Separate LHC data into **input for PDF fits** and **input for SMEFT studies?**



Can we do better?

Simultaneous PDF+SMEFT fits

Our goal: constrain **simultaneously** both the PDFs and SMEFT degrees of freedom

Proof of concept: DIS-only fits where SM **augmented** by four *d=6* SMEFT operators

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{q=u,d,s,c} \frac{a_q}{\Lambda^2} \left(\bar{l}_R \gamma^\mu l_R\right) \left(\bar{q}_R \gamma_\mu q_R\right)$$

which can arise *e.g.* from a ***Z'* boson** with non-universal couplings to quarks

These SMEFT operators modify the DIS structure functions and thus **affect the PDF fit**

$$\Delta F_2^{\rm SMEFT} \supset \frac{x}{12e^4}\left(4a_u e^2 \frac{Q^2}{\Lambda^2}(1+4K_Z \sin^4\theta_W) + 3a_u^2 \frac{Q^4}{\Lambda^4}\right)\left(u+\bar{u}\right)$$

SMEFT effects enhanced by Q^2 : constrain from HERA data!

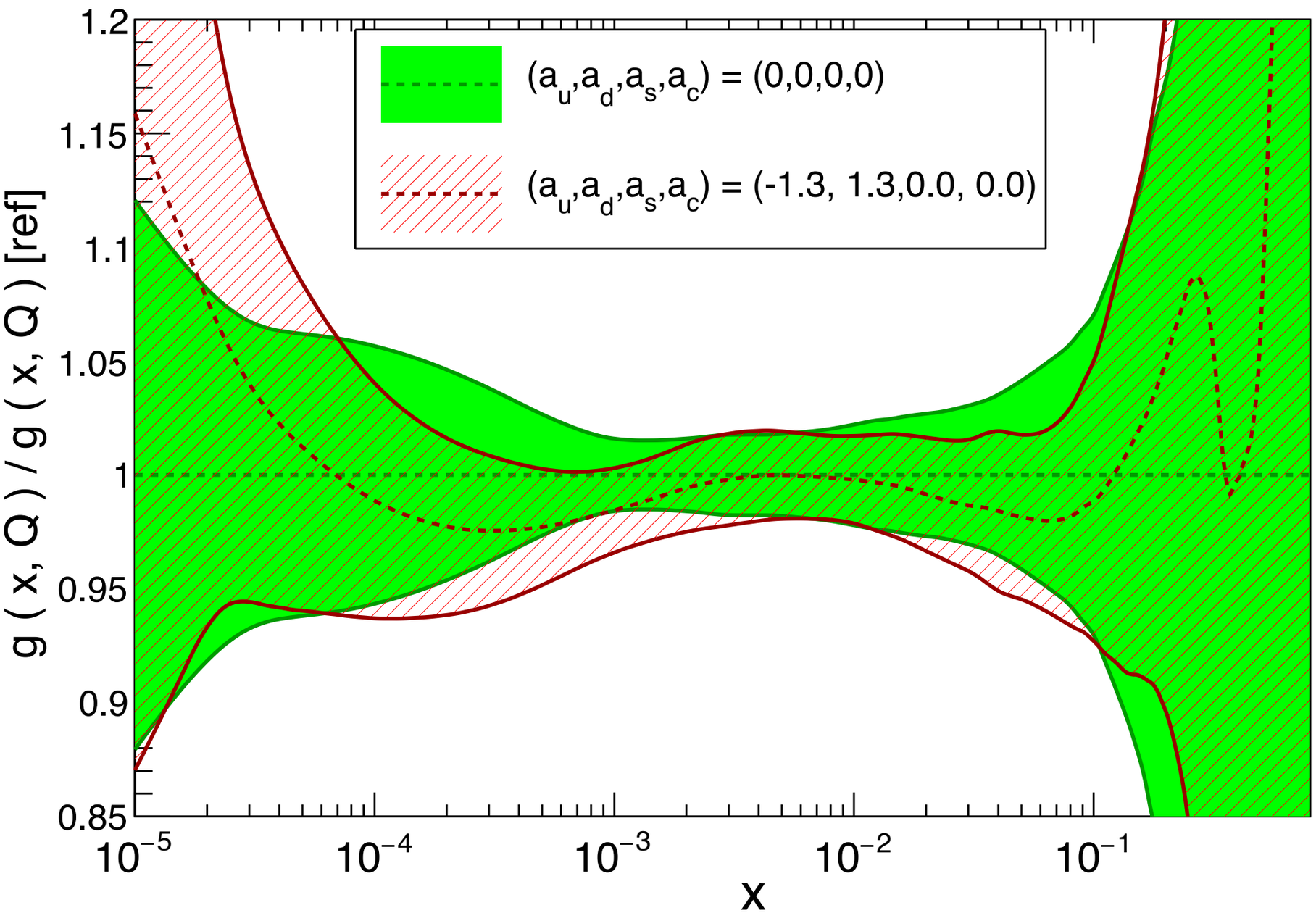
from interference with SM

from squared amplitude

Impact on the PDFs

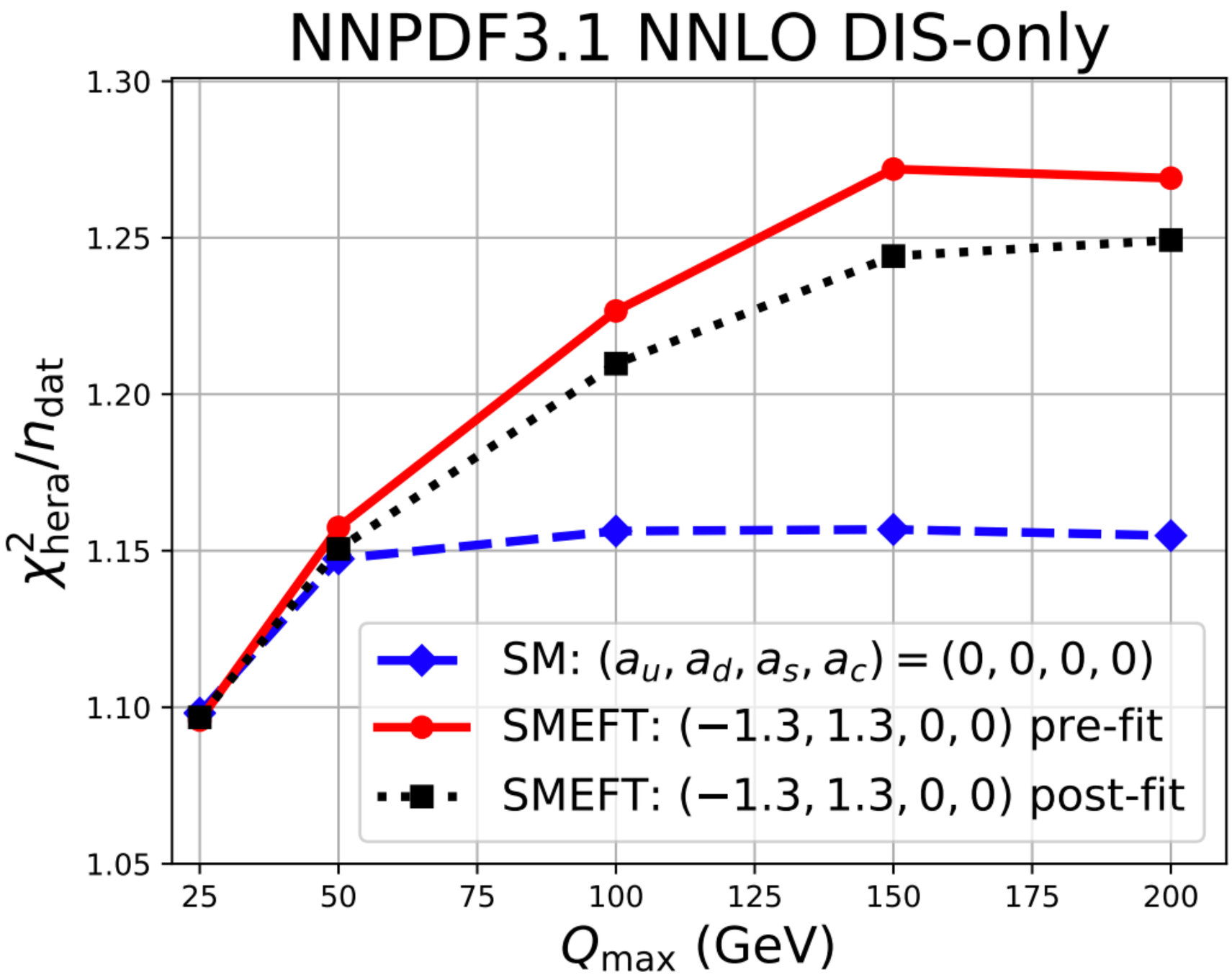
For a large region of the allowed parameter space,
SMEFT effects can be partially (but not completely) **reabsorbed into the PDFs**

NNPDF3.1 DIS-only, Q = 10 GeV



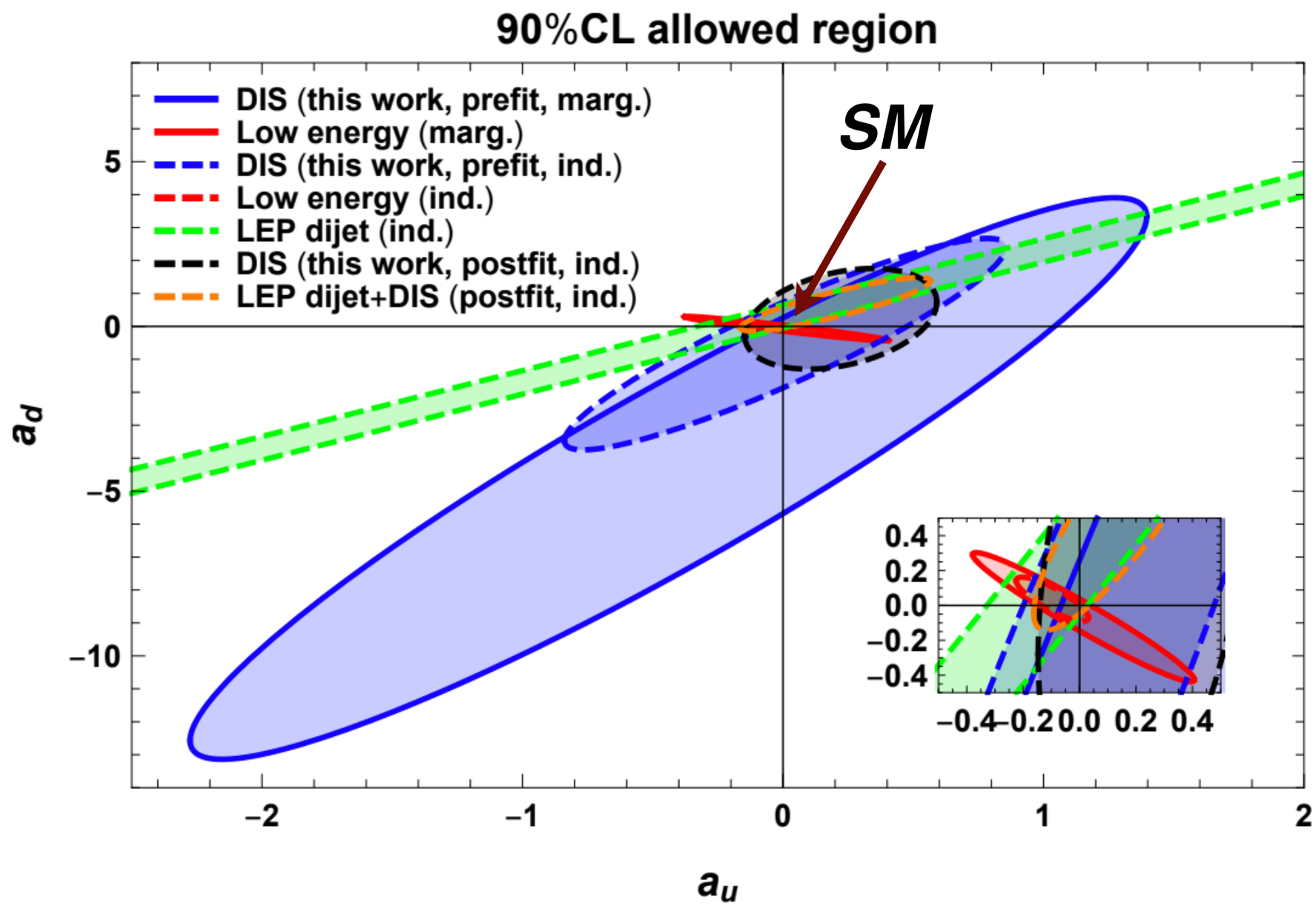
Fingerprinting BSM effects

Tell-tale sign of SMEFT effects: **rapid variation with *Q*** (DGLAP evolution slower)



Fingerprinting BSM effects

We can compare bounds on SMEFT degrees of freedom in the joint fit as compared to the usual approach where PDFs are kept fixed



Ultimate goal (HL-LHC timescale): **simultaneous PDF+SMEFT global analysis!**

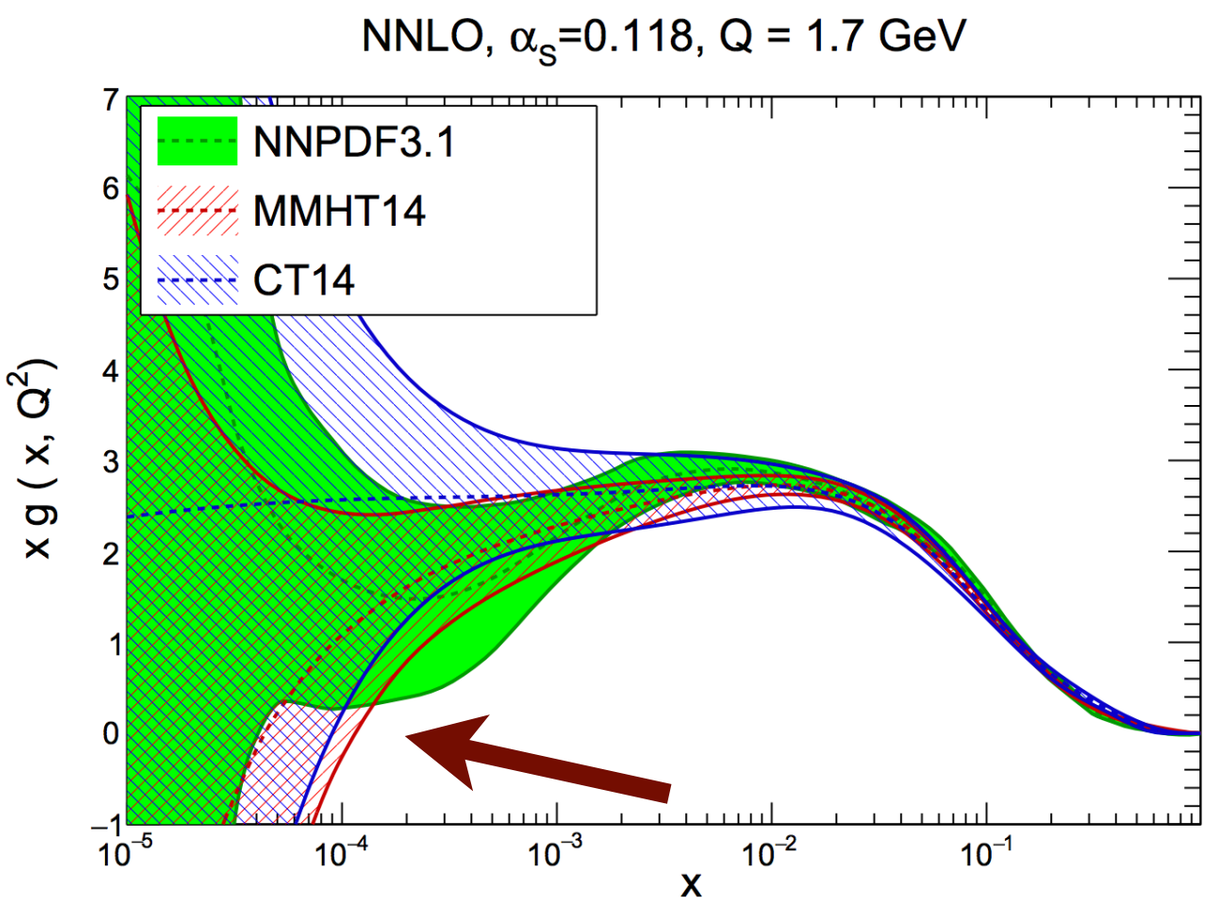
Neutrino Telescopes as QCD Microscopes

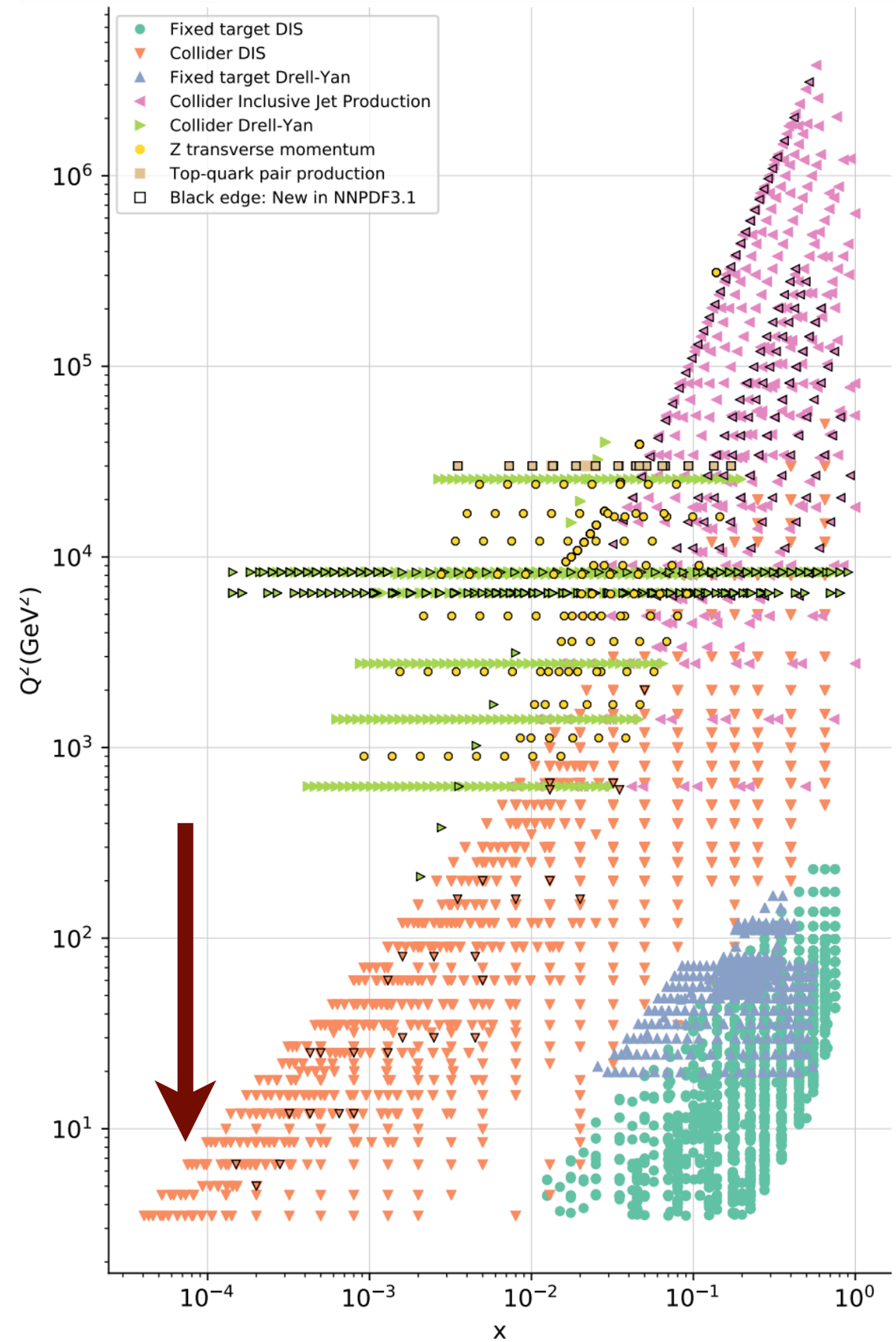
Based on V. Bertone, R. Gauld, J. Rojo

arXiv:1808.02034 *(JHEP)*

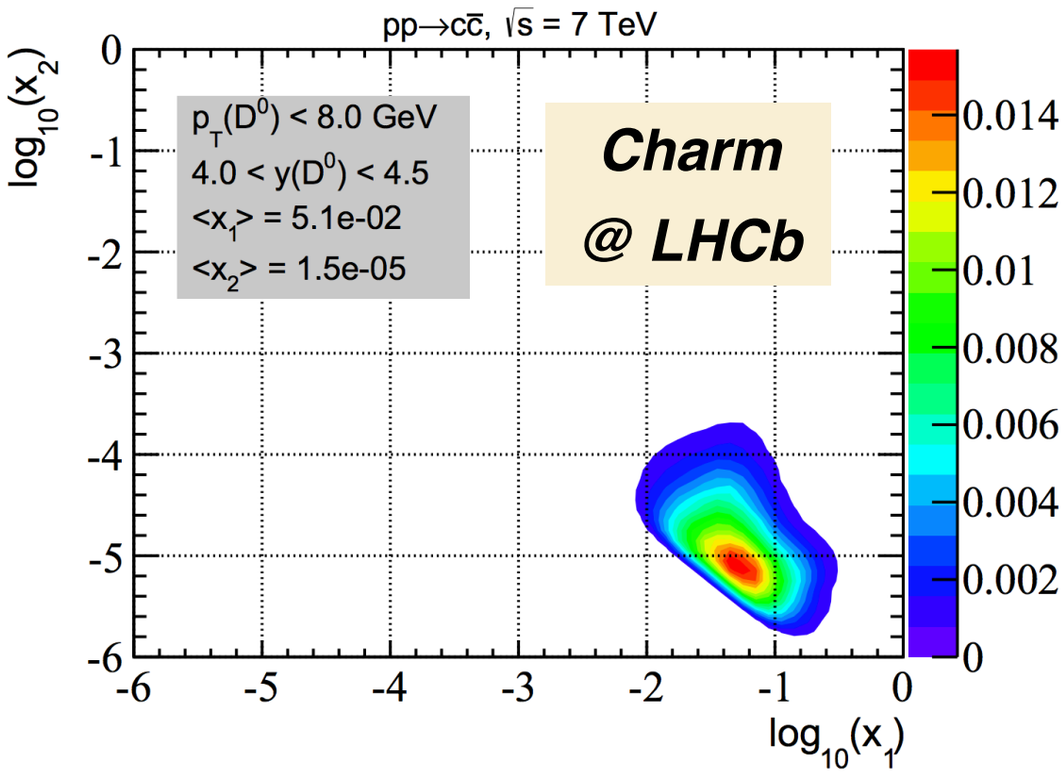
The small-x gluon from HERA data

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



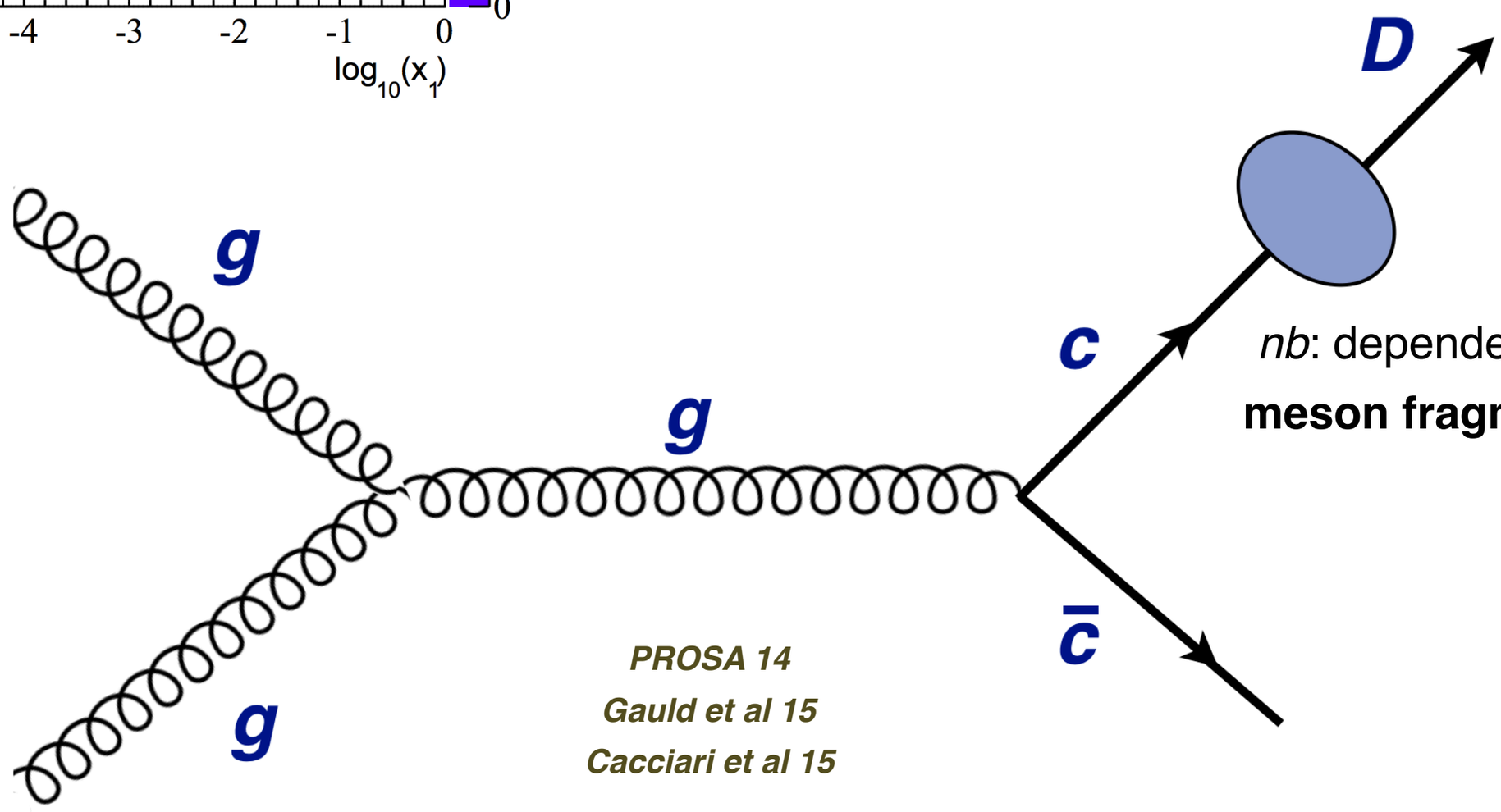


Forward charm production



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

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



nb: dependence on **D meson fragmentation**

PROSA 14
Gauld et al 15
Cacciari et al 15

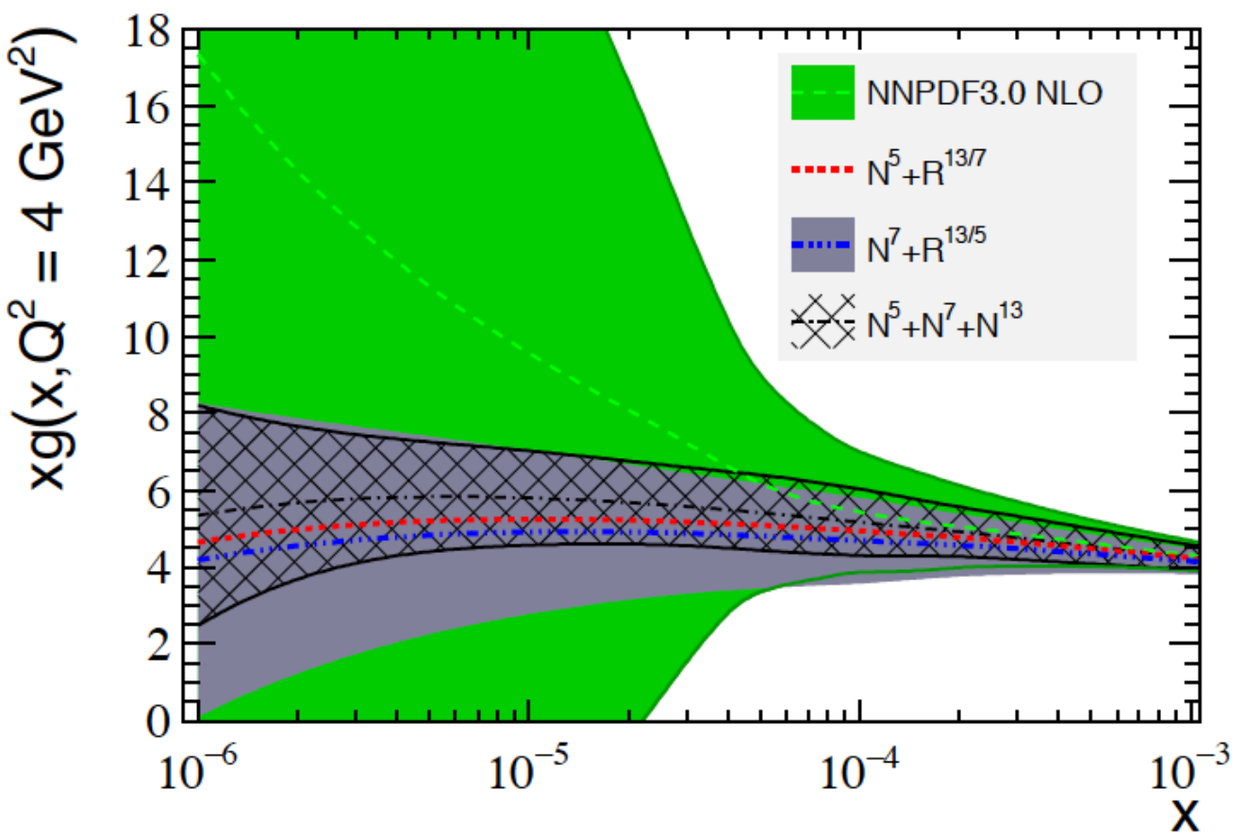
Forward charm production

- 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

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 Q²

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

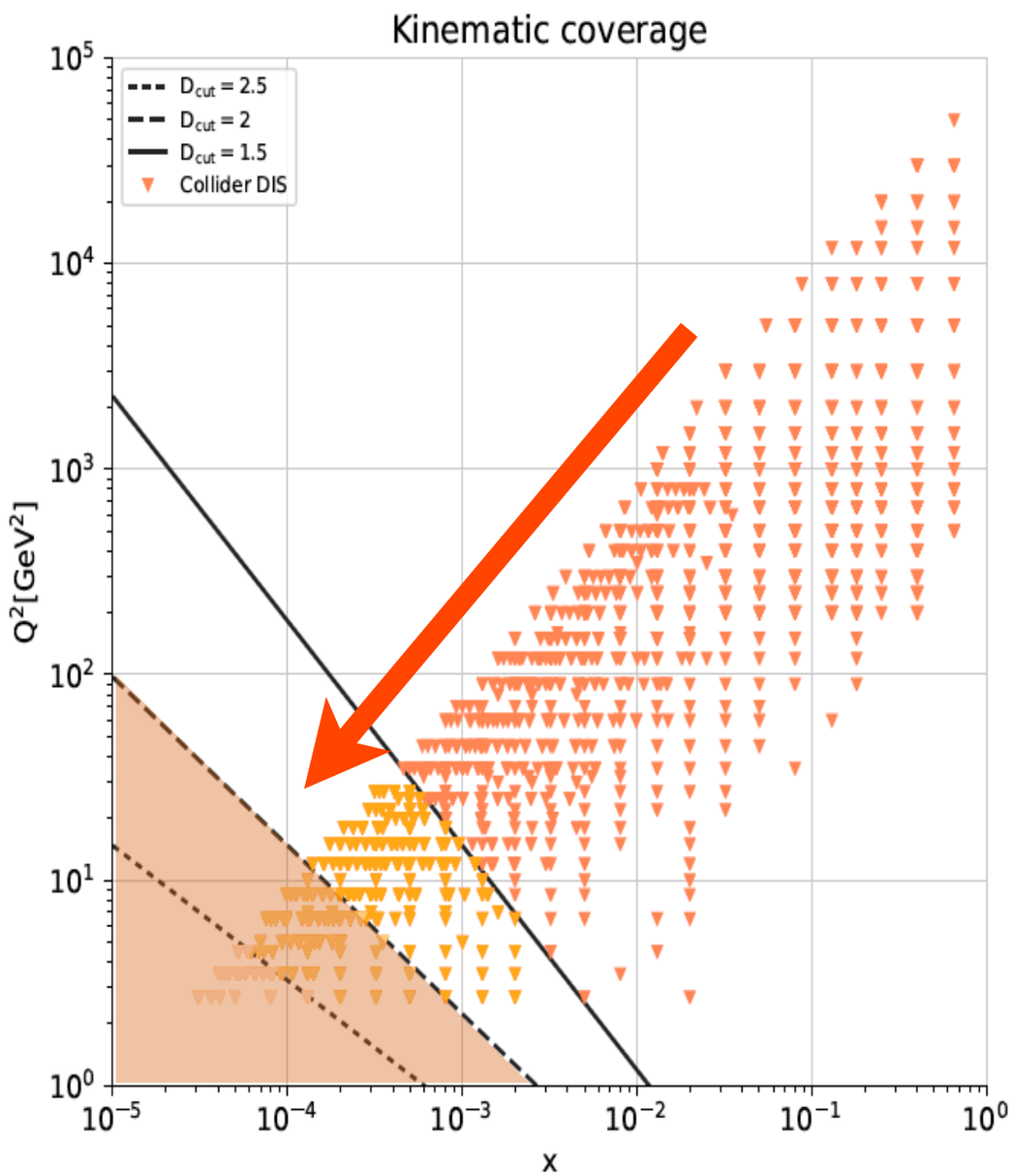
BFKL Evolution in x

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

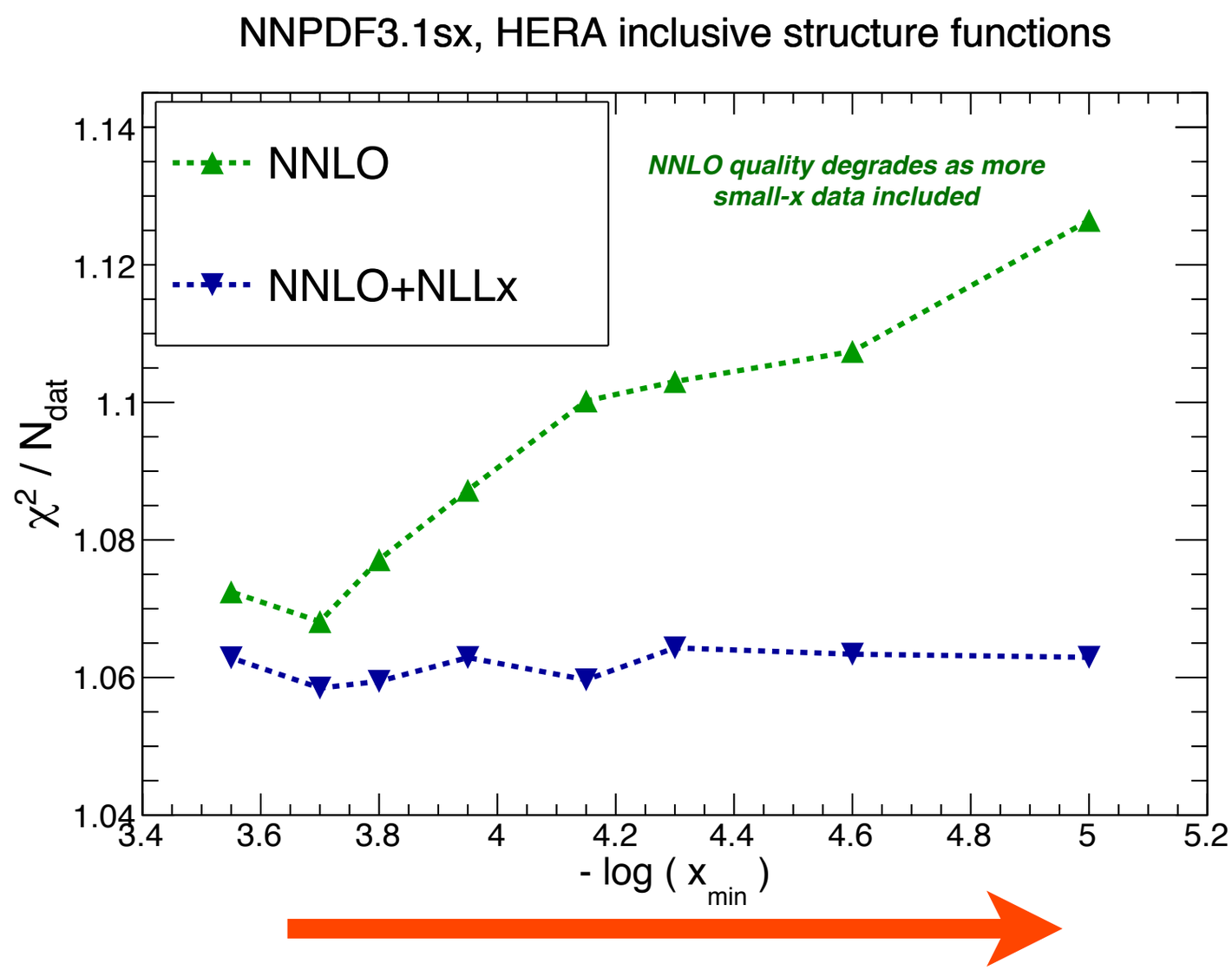
ABF, CCSS, TW + others, 94-08

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

BFKL dynamics at small-*x*



Ball et al 17, xFitter 18



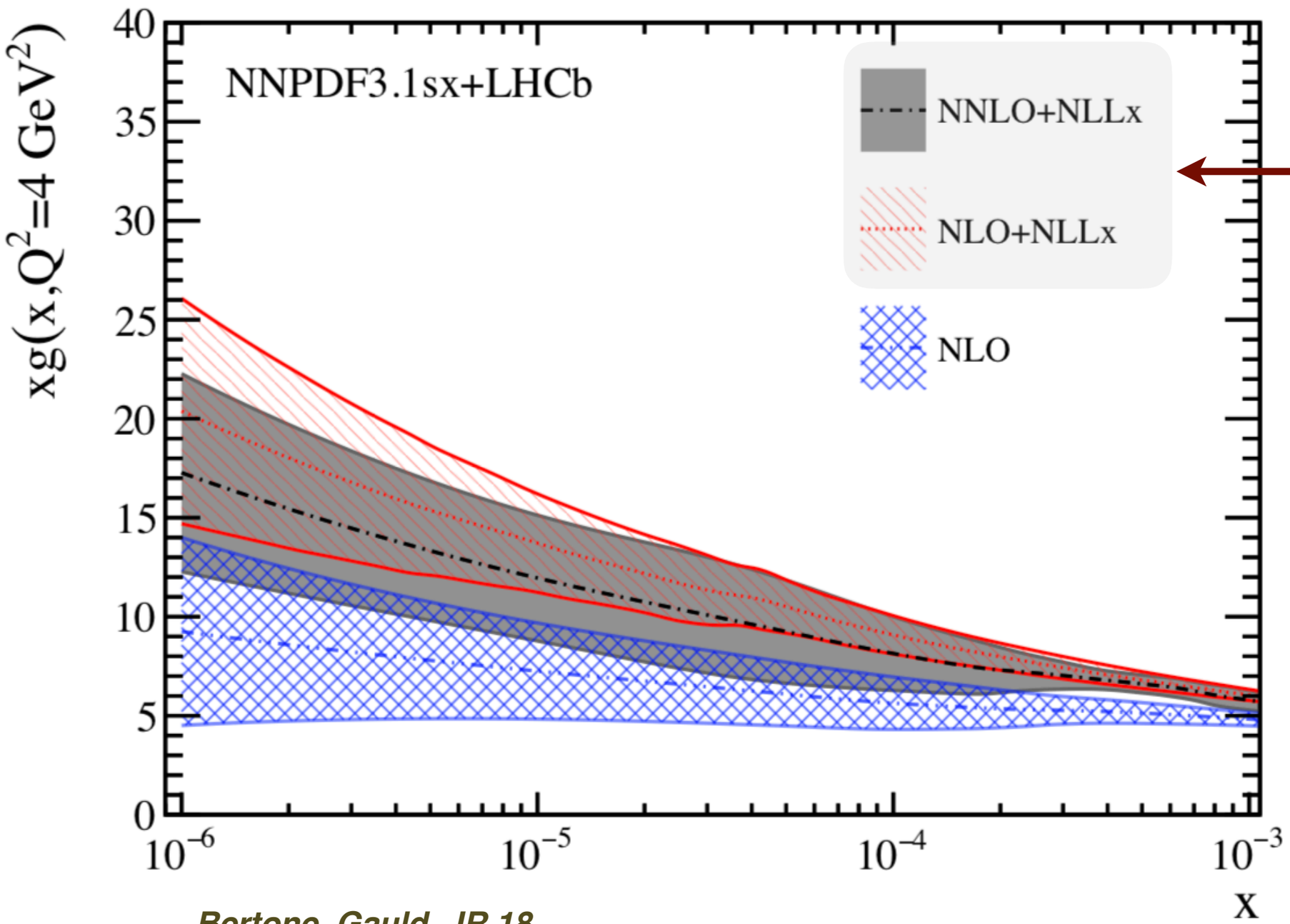
Monitor the **fit quality** as one includes more data from the **small-*x* region**

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**



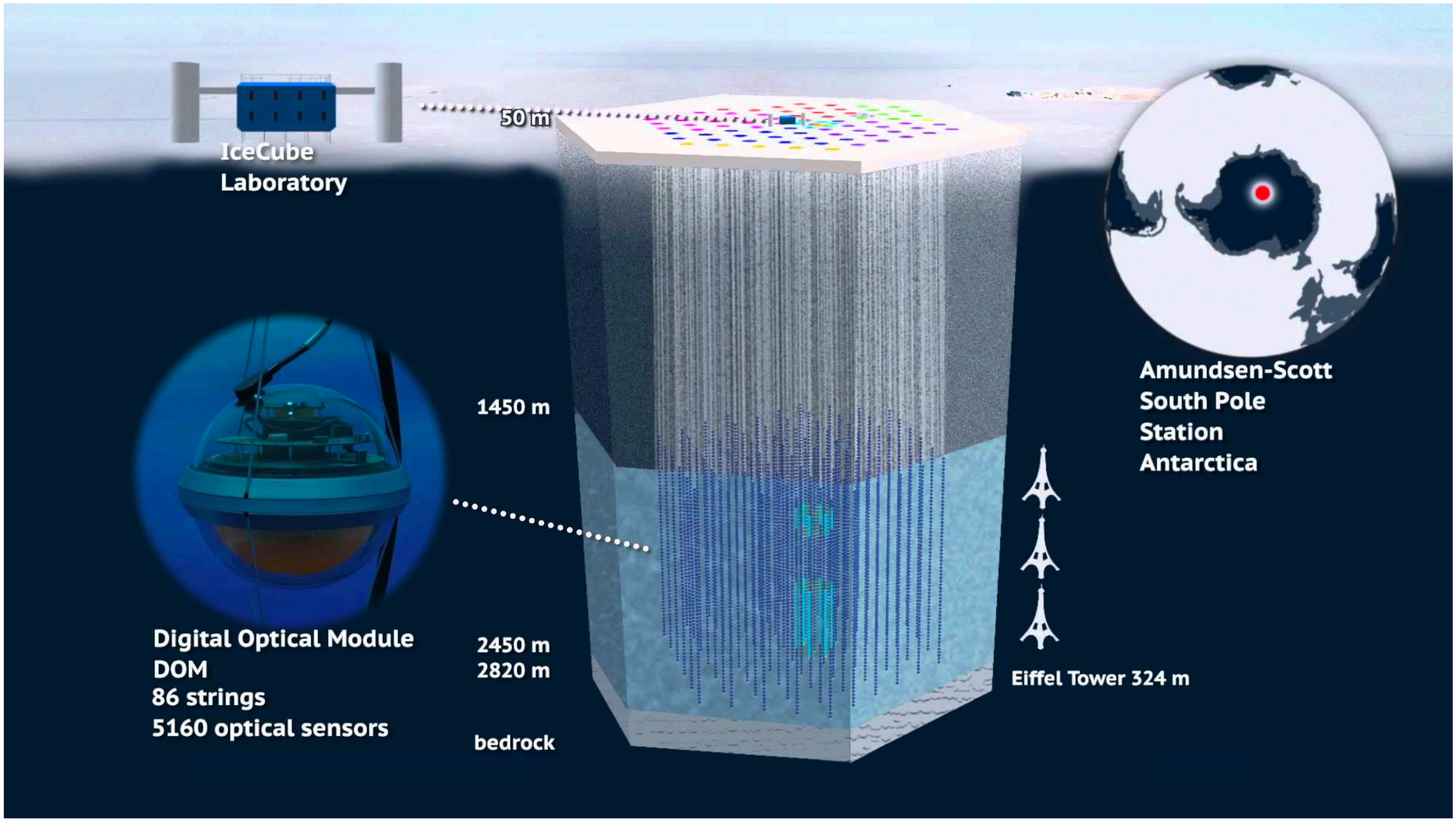
BFKL effects included

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

Bertone, Gauld, JR 18

Neutrino telescopes

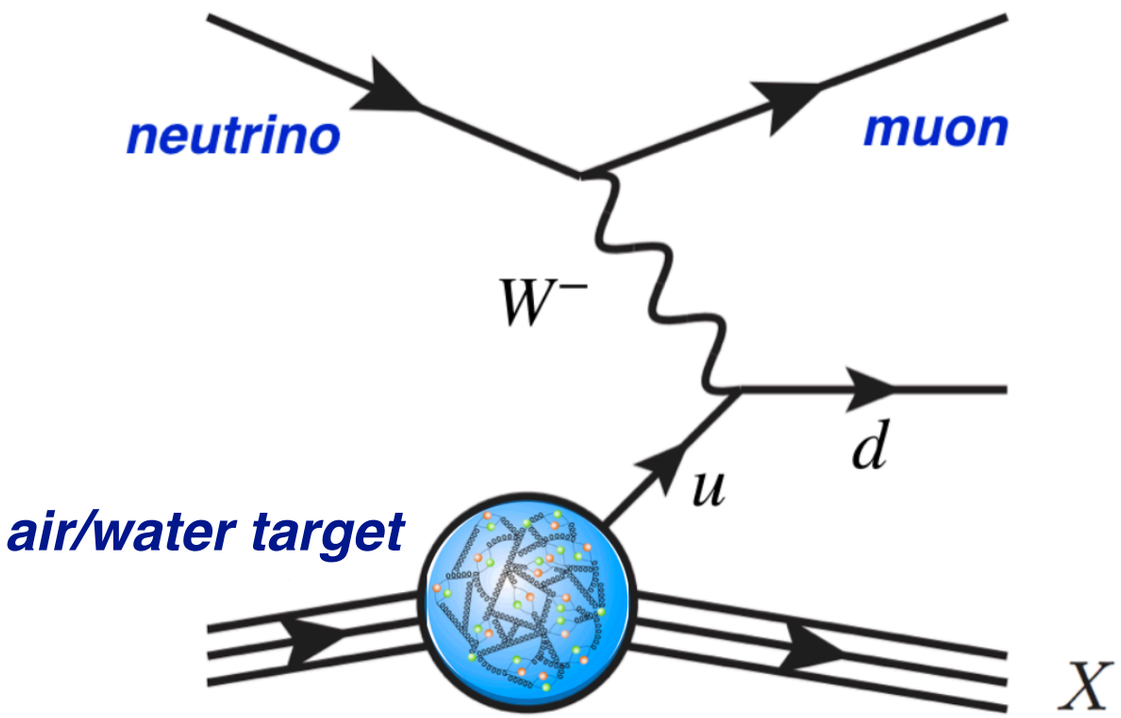
Ultra-high energy (UHE) neutrinos: novel window to the **extreme Universe**

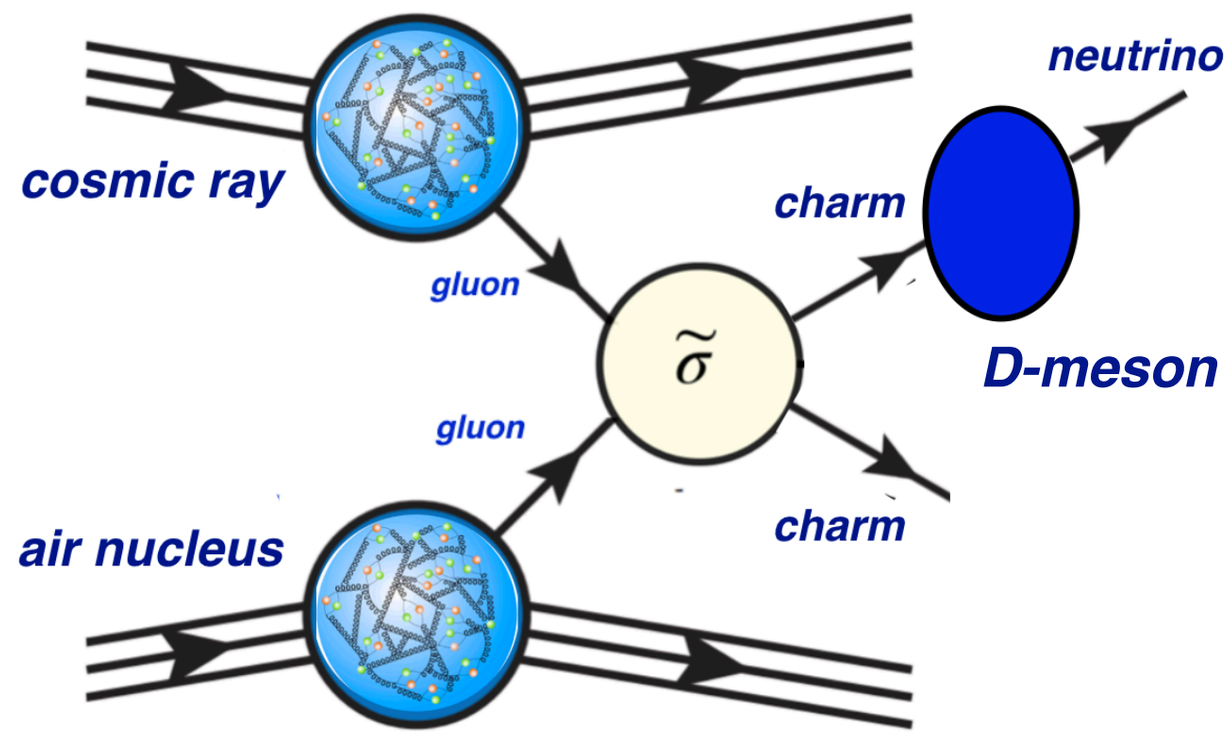


Neutrino telescopes as QCD microscopes

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

***background**: prompt charm production*



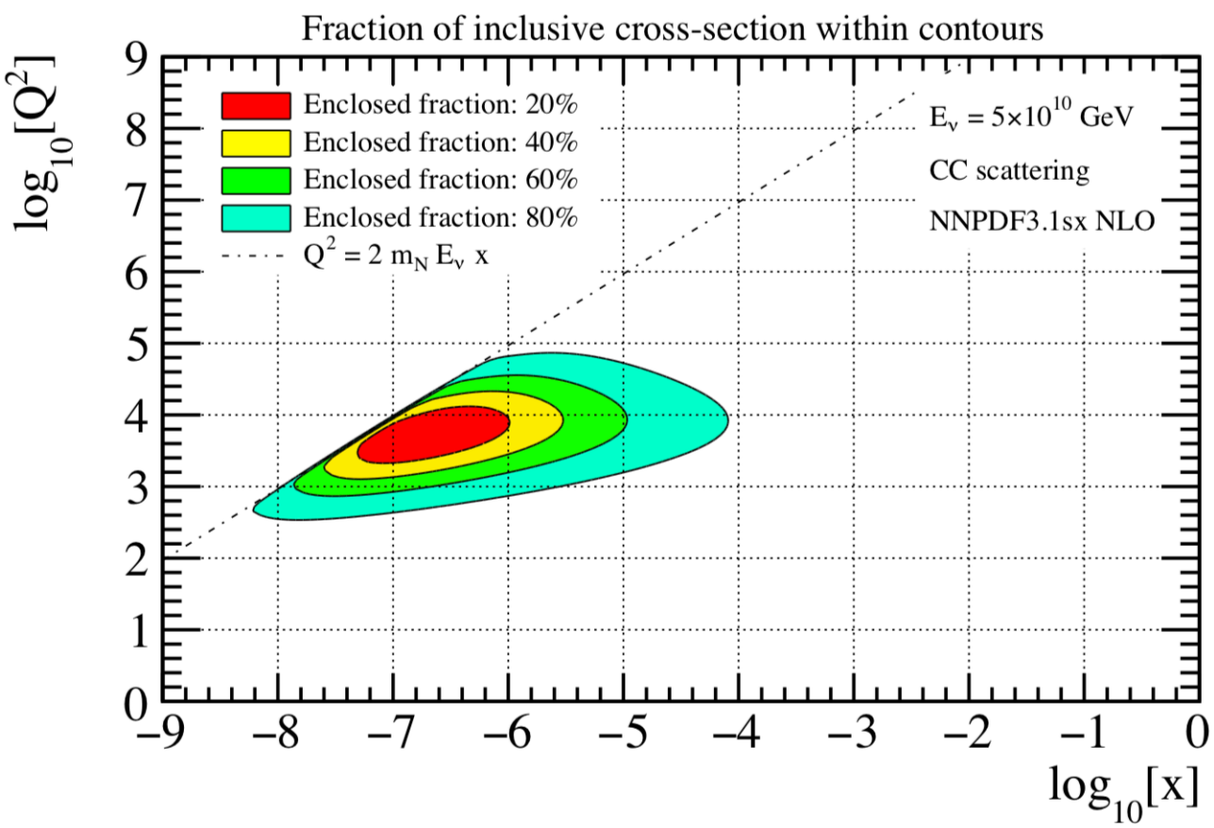


Sensitive to **small-*x* quarks** (and thus gluons via evolution) down to **x** ≃ **10^{-8}** and **Q** ≃ **M_W**

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

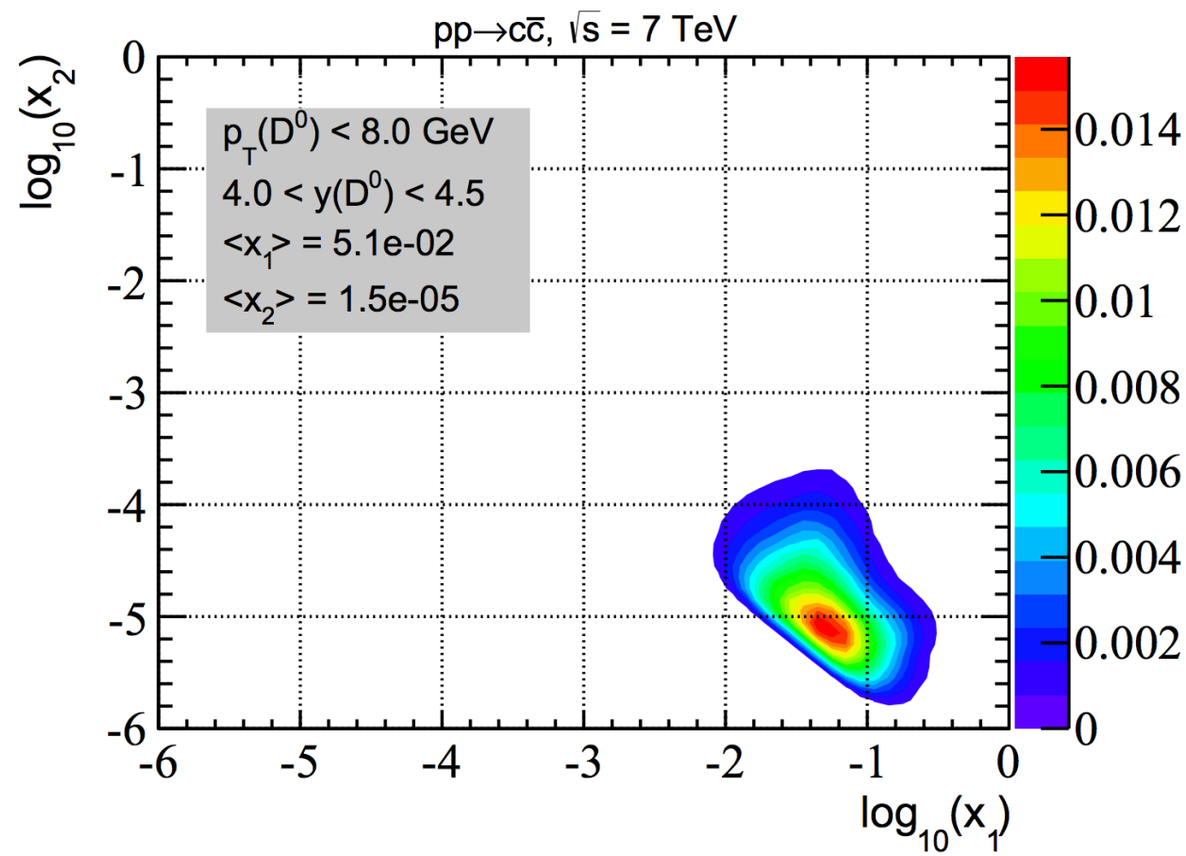
Neutrino telescopes as QCD microscopes

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



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

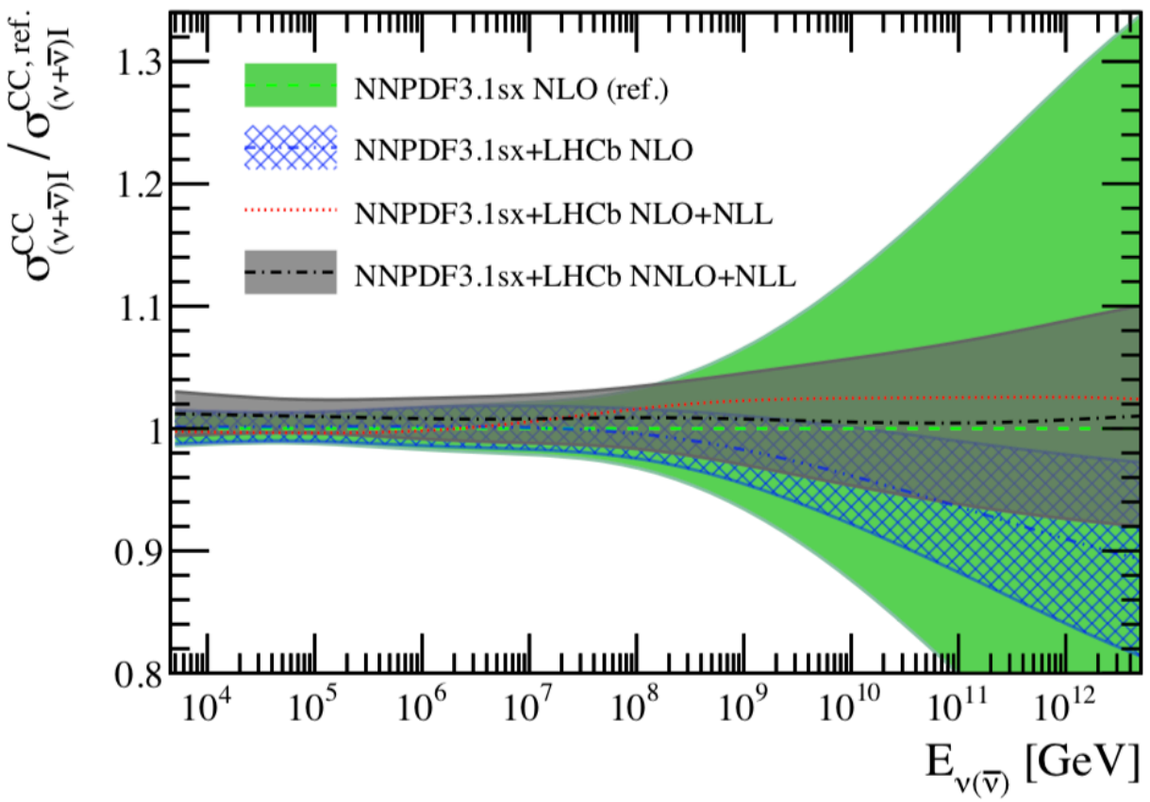
***background**: prompt charm production*

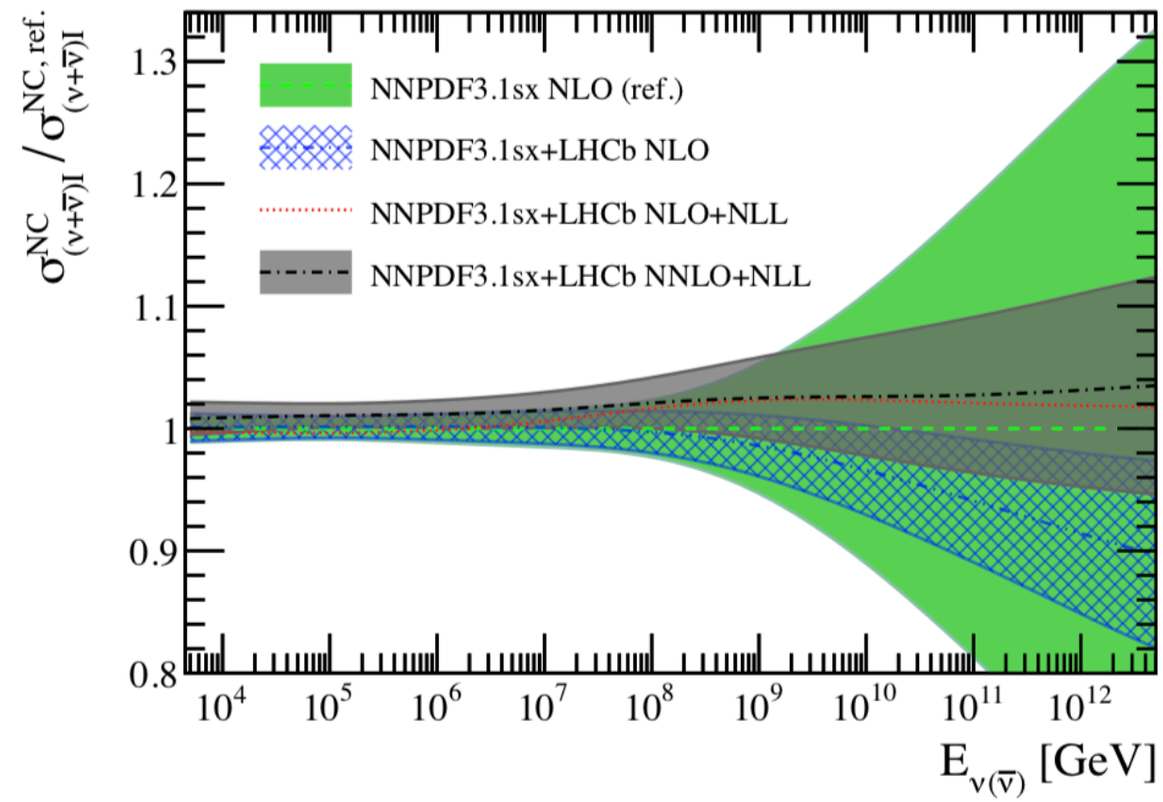


Sensitive to **small-*x* gluons** down to **x** ≃ **10^{-6}** and **Q** ≃ **M_{charm}** in the **centre-of-mass frame**

UHE neutrino-nucleus cross-section

Bertone, Gauld, JR 18



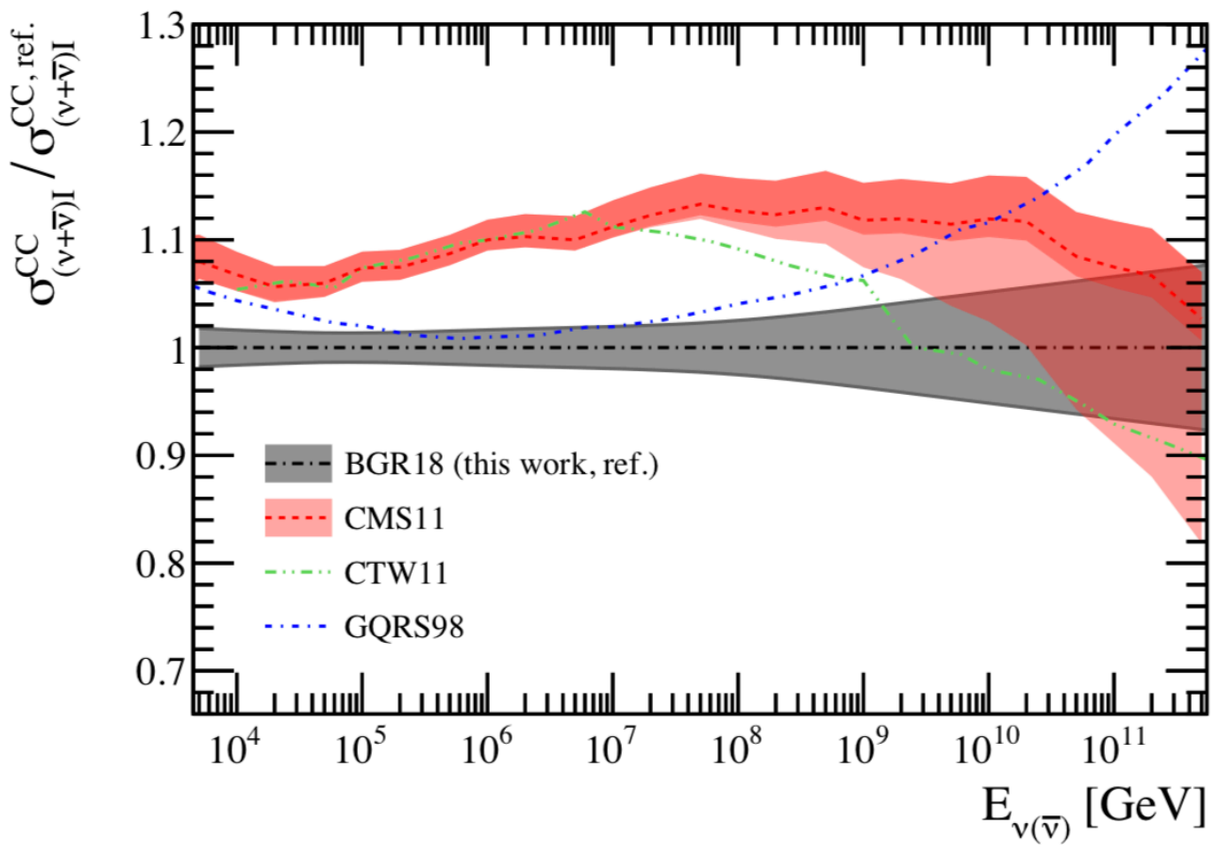


State-of-the-art predictions for **ultra-high energy** neutrino interactions

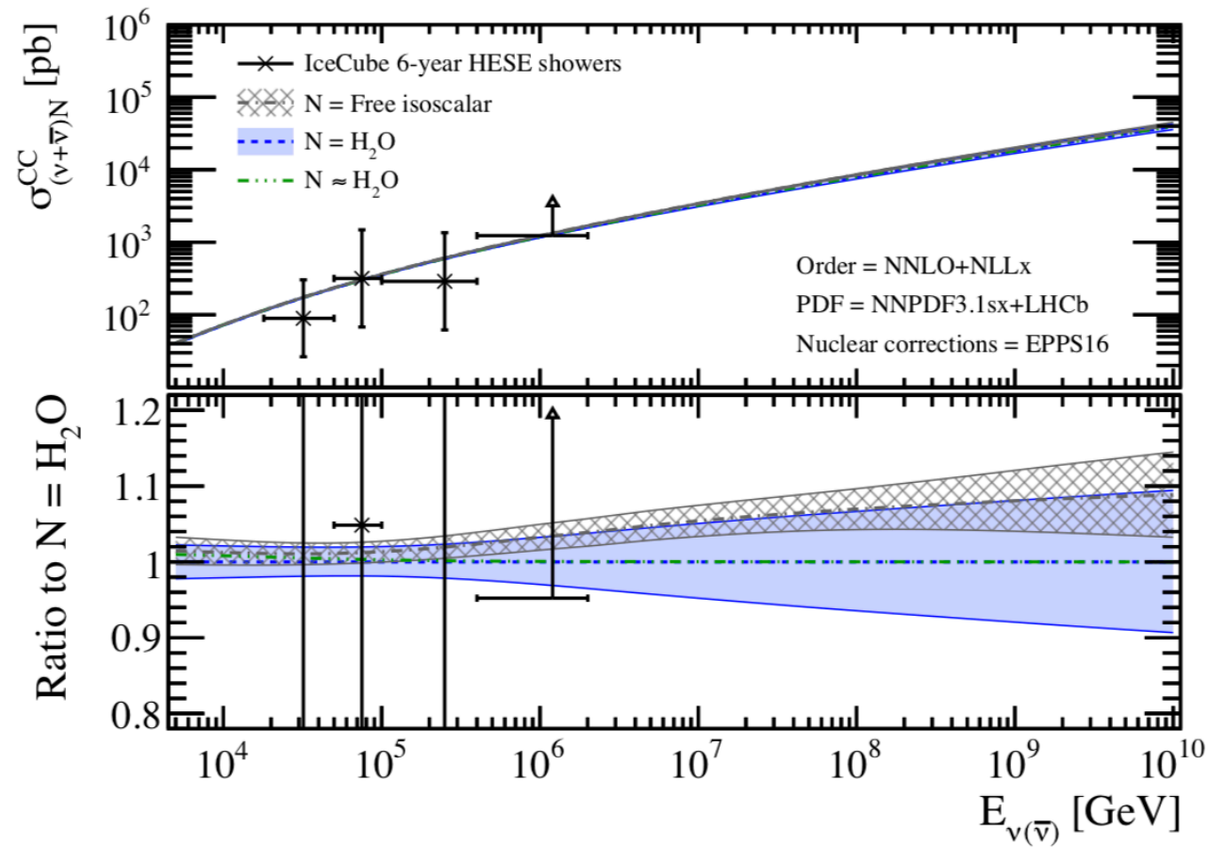
- **BFKL small-x effects** in PDFs and deep-inelastic structure functions
- Constraints on small-x PDFs from **LHCb charm production**
- Accounting for **nuclear corrections** and heavy-quark-initiated contributions

UHE neutrino-nucleus cross-section

*Comparison with **previous results***



*Comparison with **IceCube data***



- Differences both at **intermediate** (updated 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 from Collider Data

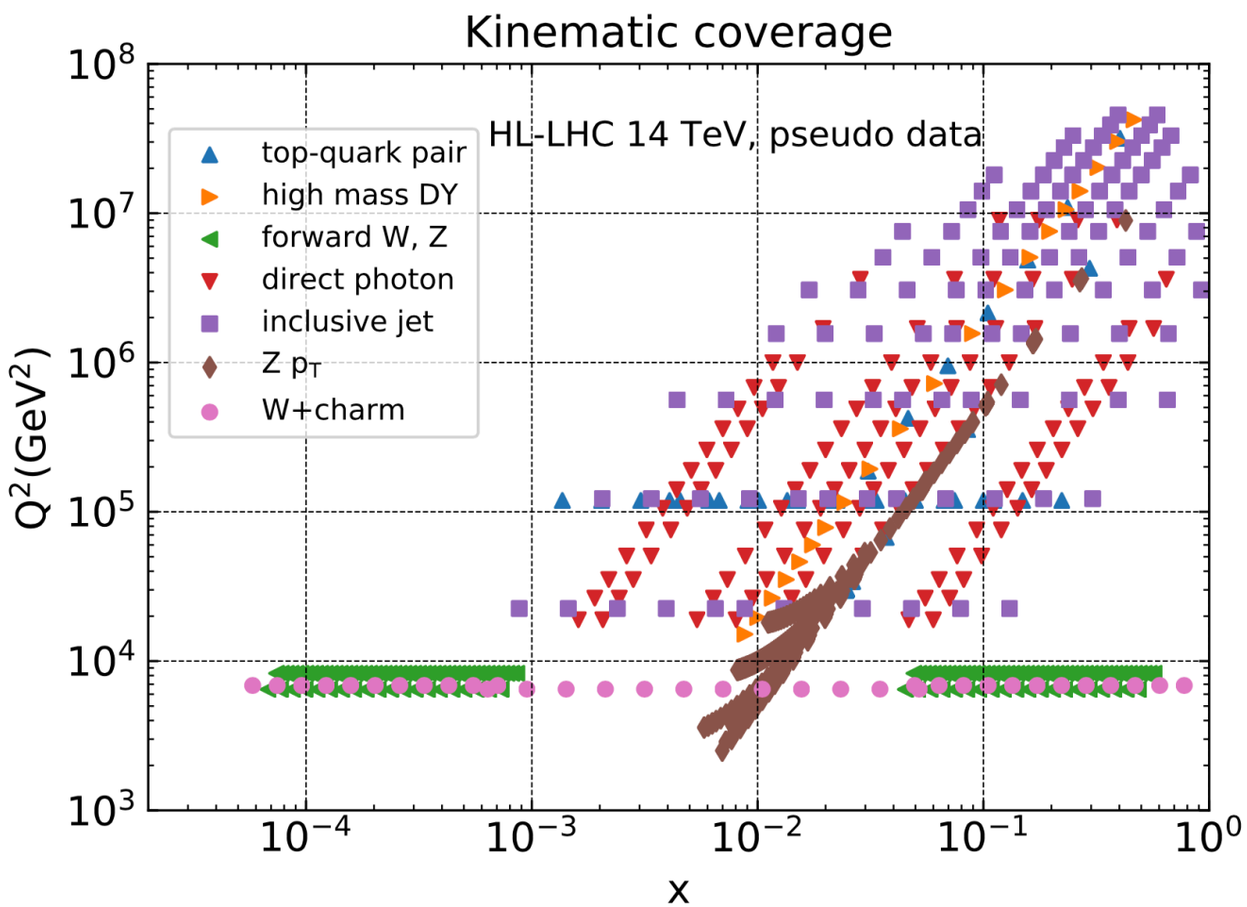
Based on R. Abdul Khalek, S. Bailey, J. Gao, L. Harland-Land, J. Rojo

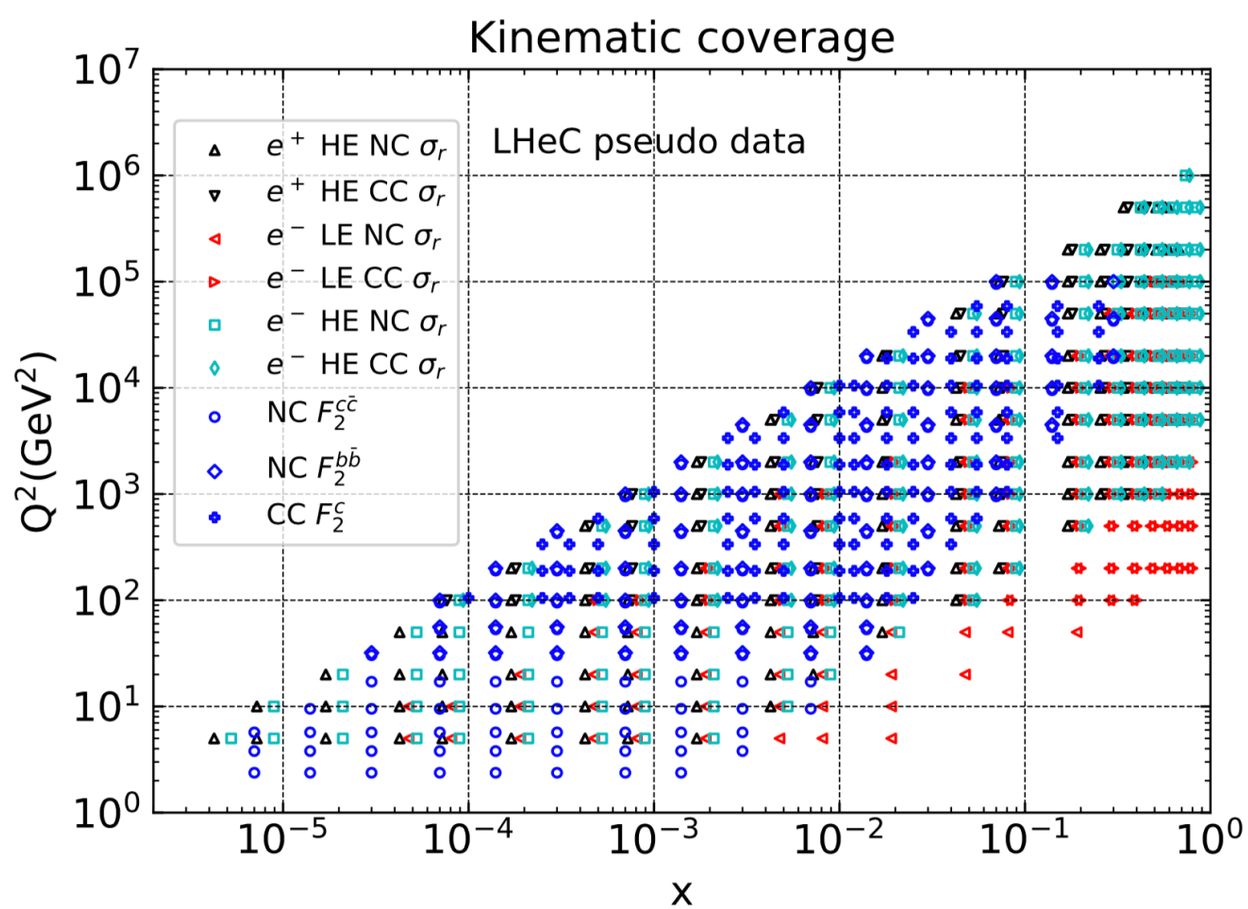
arXiv:1810.03639 (EPJC)

arXiv:1906.10127 (Submitted to SciPost)

Towards ultimate PDFs at the HL-LHC and LHeC

Exploit **novel facilities** for precision studies of the proton structure



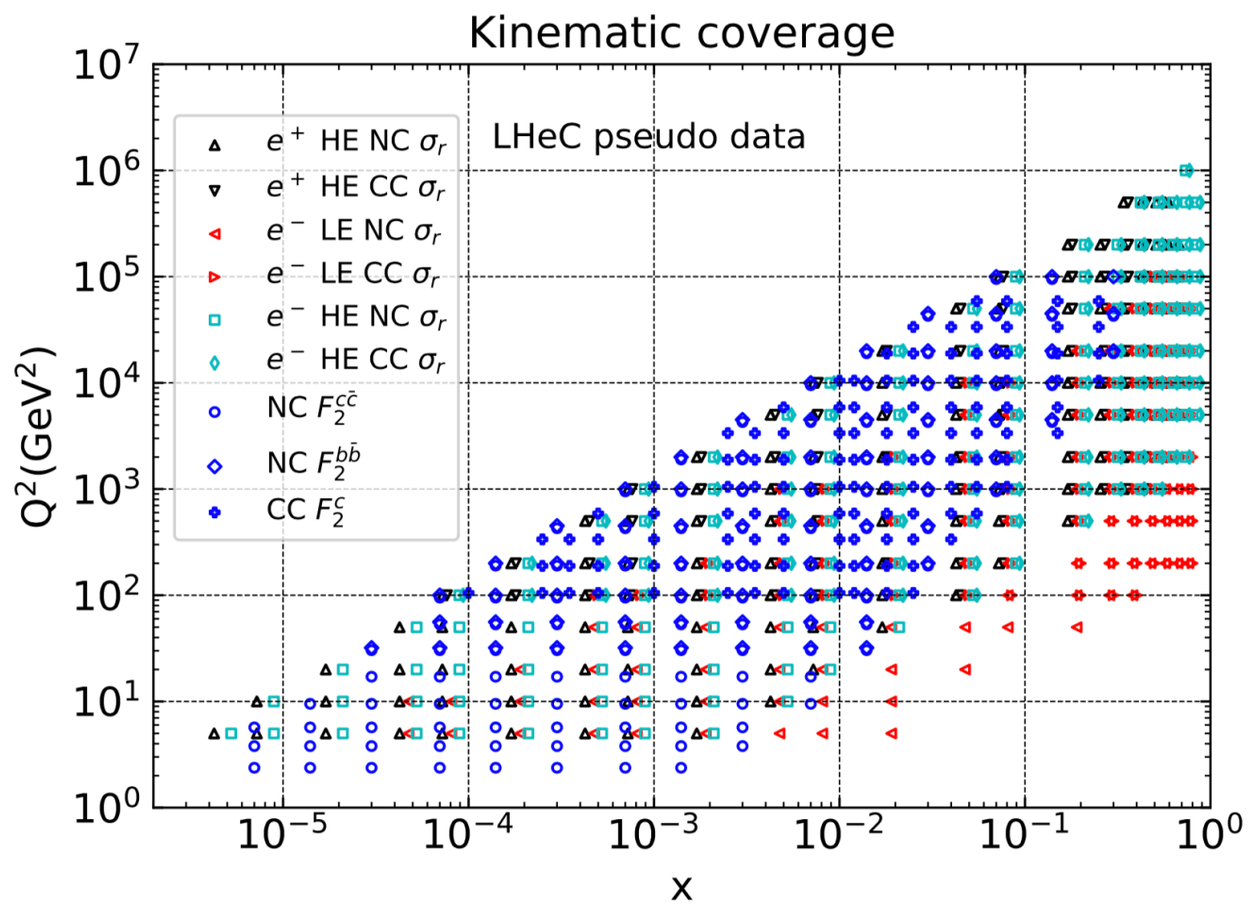


Fully **complementary** in terms of PDF constraints, possible synchronous operation

Towards ultimate PDFs at the HL-LHC and LHeC

Exploit **novel facilities** for precision studies of the proton structure

Process	Kinematics	$N_{\rm dat}$	$f_{\rm corr}$	$f_{\rm red}$	Baseline
$Z\ p_T$	$20\,\text{GeV} \leq p_T^{ll} \leq 3.5\,\text{TeV}$	338	0.5	(0.4, 1)	[52] (8 TeV)
	$12\,\text{GeV} \leq m_{ll} \leq 150\,\text{GeV}$				
	$\lvert y_{ll}\rvert \leq 2.4$				
High-mass Drell-Yan	$p_T^{l1(2)} \geq 40(30)\,\text{GeV}$	32	0.5	(0.4, 1)	[47] (8 TeV)
	$\lvert\eta^l\rvert \leq 2.5,\ m_{ll} \geq 116\,\text{GeV}$				
Top quark pair	$m_{t\bar{t}} \simeq 5\,\text{TeV},\ \lvert y_t\rvert \leq 2.5$	110	0.5	(0.4, 1)	[50] (8 TeV)
W+charm (central)	$p_T^{\mu} \geq 26\,\text{GeV},\ p_T^{c} \geq 5\,\text{GeV}$	12	0.5	(0.2, 0.5)	[24] (13 TeV)
	$\lvert\eta^{\mu}\rvert \leq 2.4$				
W+charm (forward)	$p_T^{\mu} \geq 20\,\text{GeV},\ p_T^{c} \geq 20\,\text{GeV}$	10	0.5	(0.4, 1)	LHCb projection
	$p_T^{\mu+c} \geq 20\,\text{GeV}$				
	$2 \leq \eta^{\mu} \leq 4.5,\ 2.2 \leq \eta^{c} \leq 4.2$				
Direct photon	$E_T^{\gamma} \lesssim 3\,\text{TeV},\ \lvert\eta_{\gamma}\rvert \leq 2.5$	118	0.5	(0.2, 0.5)	[55] (13 TeV)
Forward W, Z	$p_T^{l} \geq 20\,\text{GeV},\ 2.0 \leq \eta^{l} \leq 4.5$	90	0.5	(0.4, 1)	[49] (8 TeV)
	$60\,\text{GeV} \leq m_{ll} \leq 120\,\text{GeV}$				
Inclusive jets	$\lvert y\rvert \leq 3,\ R = 0.4$	58	0.5	(0.2, 0.5)	[61] (13 TeV)
Total		768			



HL-LHC: generate our own pseudo-data based on **extrapolations from Run II**

Hessian profiling

- **Hessian Profiling:** analytic minimisation of the figure of merit:

$$\chi^2(\beta_{\rm exp},\beta_{\rm th}) = \frac{1}{\left(\delta^{\rm exp}_{{\rm tot},i}\right)^2}\sum_{i=1}^{N_{\rm dat}}\left(\sigma_i^{\rm exp} + \sum_j \Gamma^{\rm exp}_{ij}\beta_{j,{\rm exp}} - \sigma_i^{\rm th} + \sum_k \Gamma^{\rm th}_{ik}\beta_{k,{\rm th}}\right)^2 + \sum_j \beta^2_{j,{\rm exp}} + T^2\sum_k \beta^2_{k,{\rm th}}$$

Exp data nuisance parameters ***Hessian PDF nuisance parameters*** ***Effective Tolerance***

- To mimic the effects of the correlation model for the HL-LHC pseudo-data, we **rescale the total experimental systematic error** by a suitable factor ***f_{corr}***

$$\delta^{\rm exp}_{{\rm tot},i} \equiv \left(\left(\delta^{\rm exp}_{{\rm stat},i}\right)^2 + \left(f_{\rm corr}\times f_{\rm red}\times \delta^{\rm exp}_{{\rm sys},i}\right)^2\right)^{1/2}$$

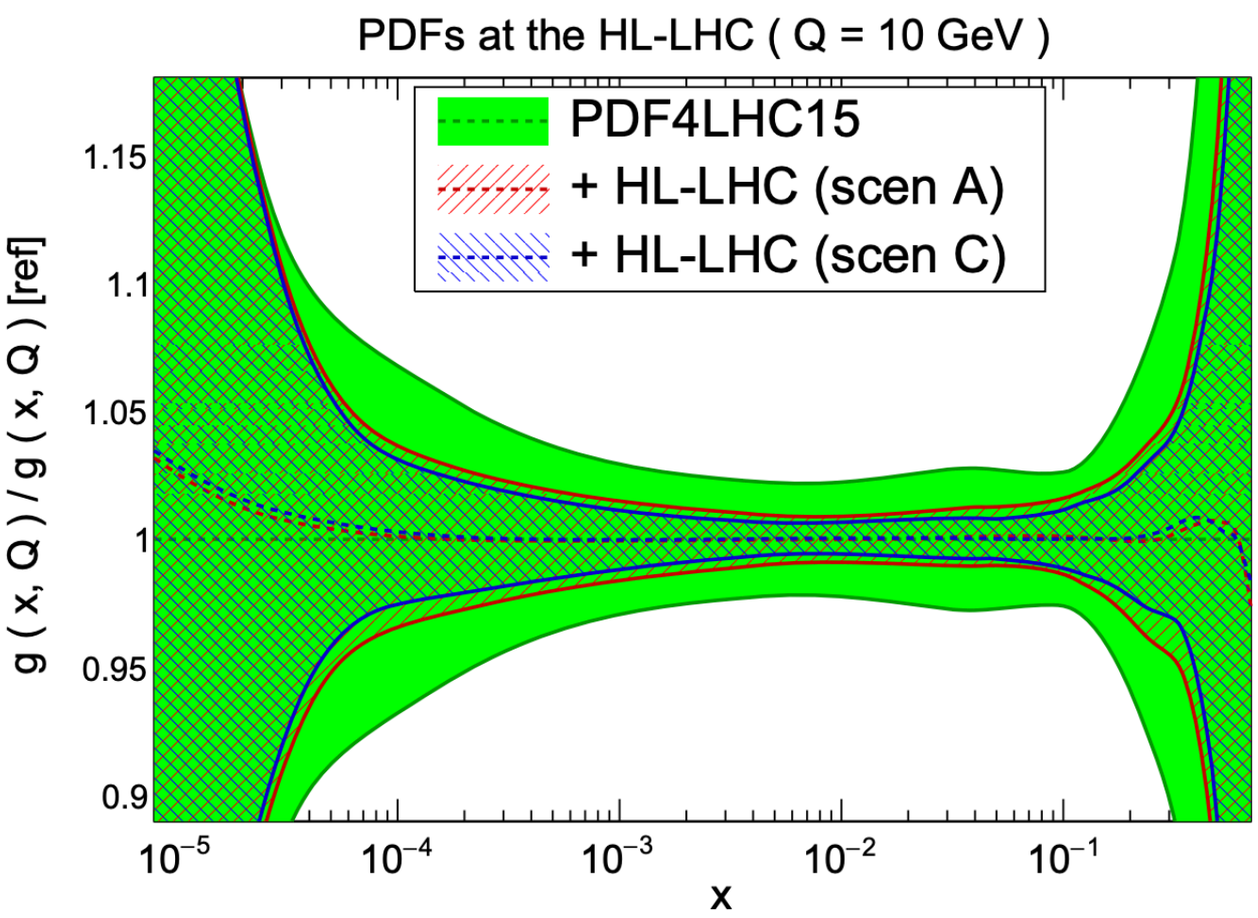
$$\delta^{\rm exp}_{{\rm stat},i} = \left(f_{\rm acc}\times N_{{\rm ev},i}\right)^{-1/2}$$

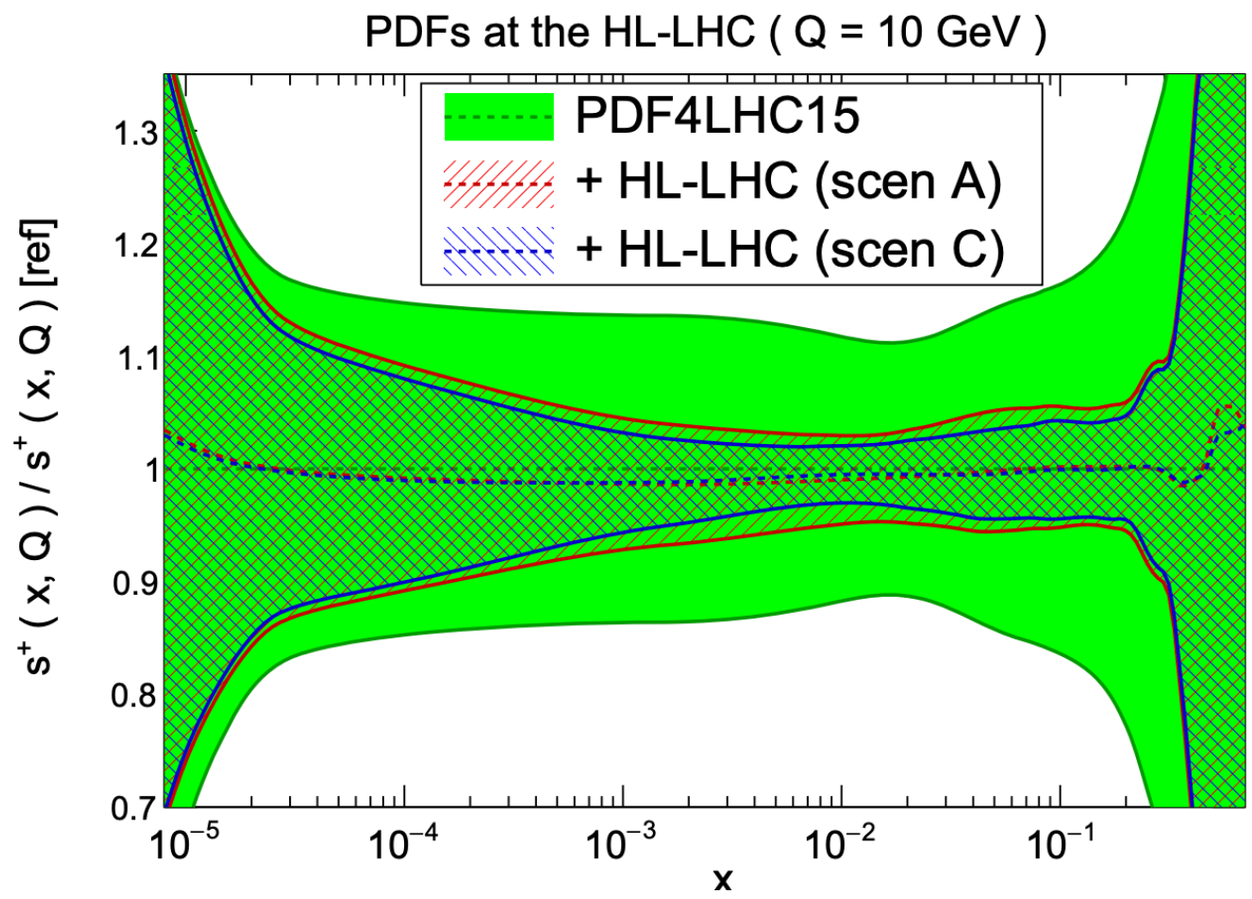
- For the LHeC pseudo-data the correlation model already available for **inclusive structure functions**

HL-LHC: focus on process where systematics are not already **limiting factor**

Towards ultimate PDFs at the HL-LHC and LHeC

Quantify the ultimate **PDF constraining power** of HL-LHC





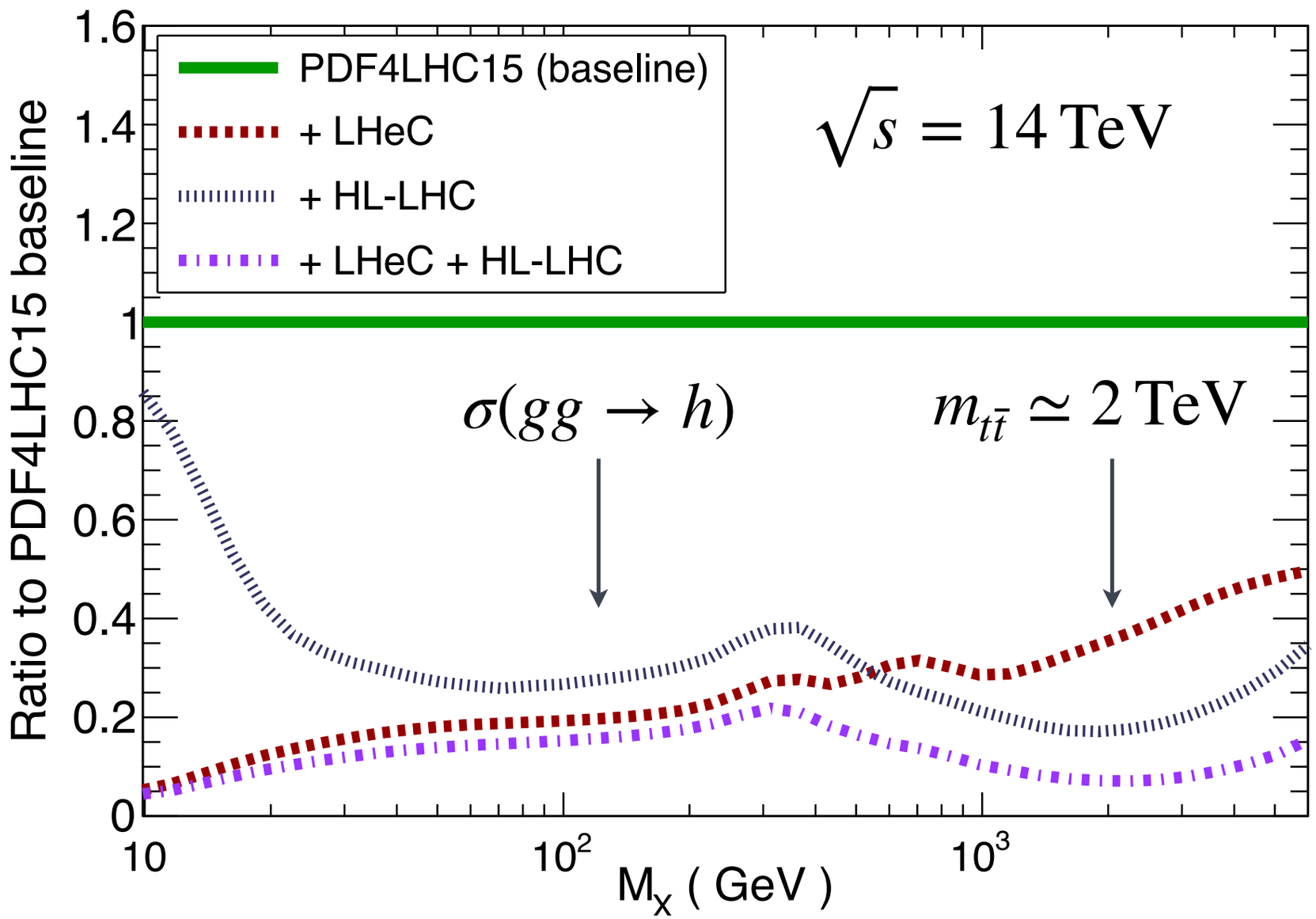
HL-LHC measurements will be specially useful to constrain **gluon** and **quark flavour separation**, including strangeness

Pinning down **antiquarks at large-*x*** seems challenging, suggestions welcome!

Towards ultimate PDFs at the HL-LHC and LHeC

Quantify the ultimate **PDF constraining power** of HL-LHC and LHeC

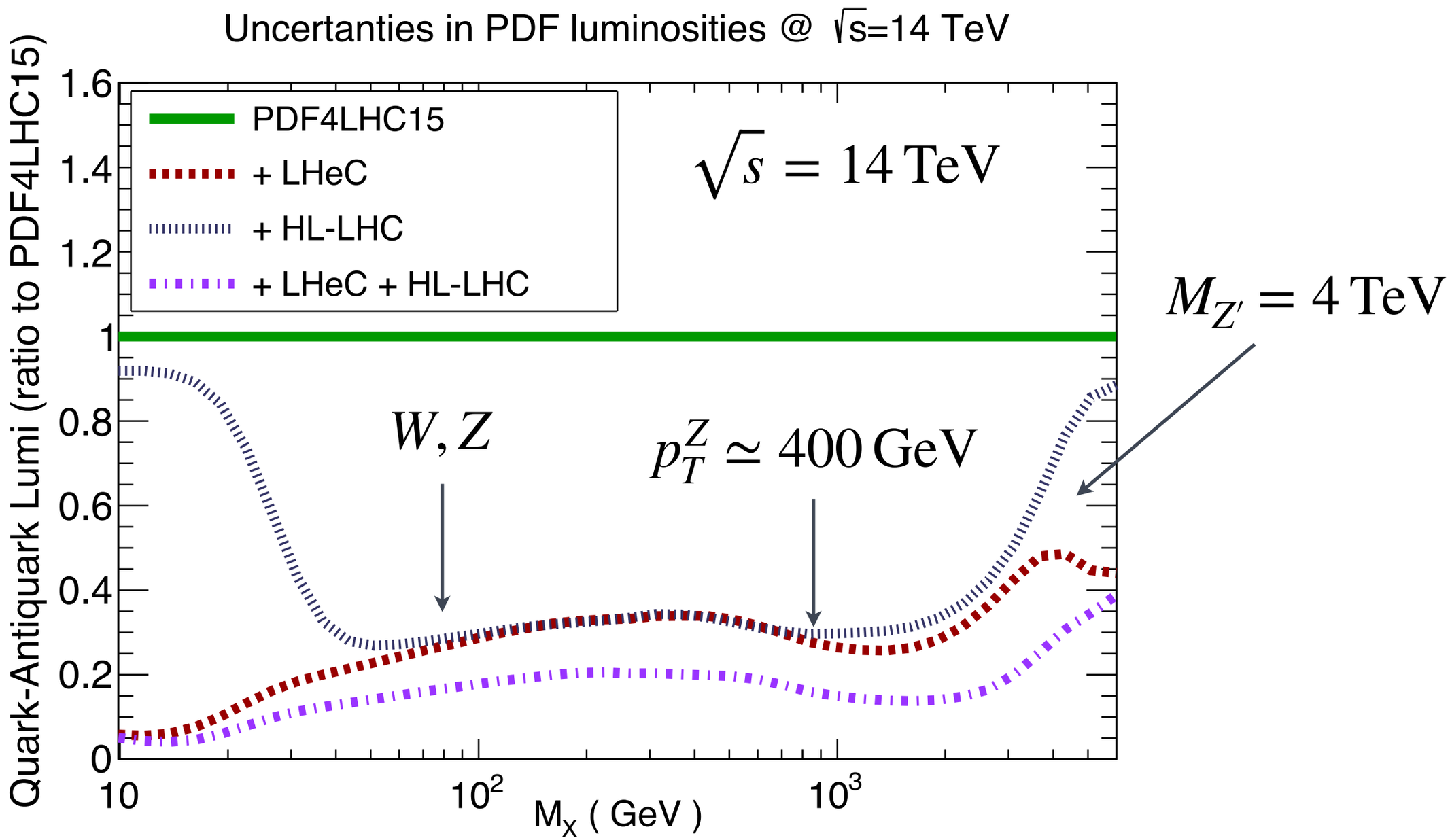
PDF uncertanties in gluon-gluon luminosity



A reduction of PDF uncertainties by **up to a factor 10** could be within reach

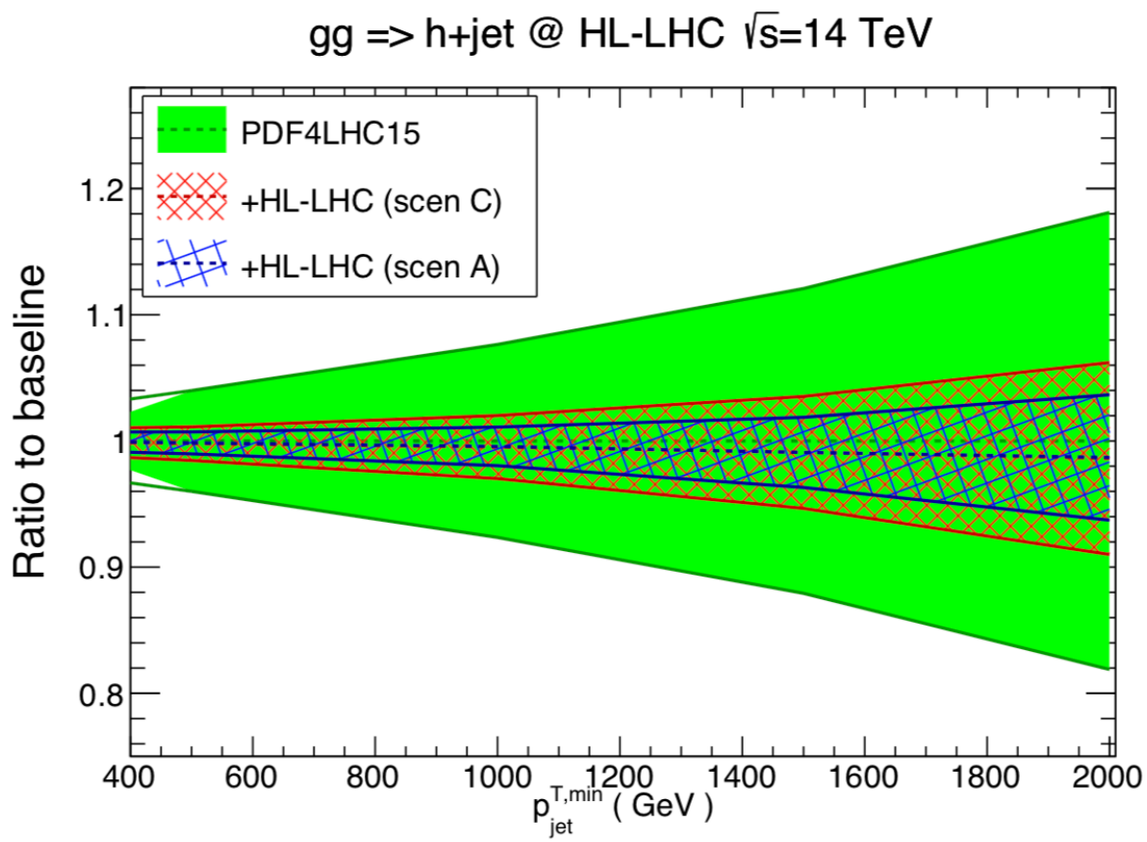
Towards ultimate PDFs at the HL-LHC and LHeC

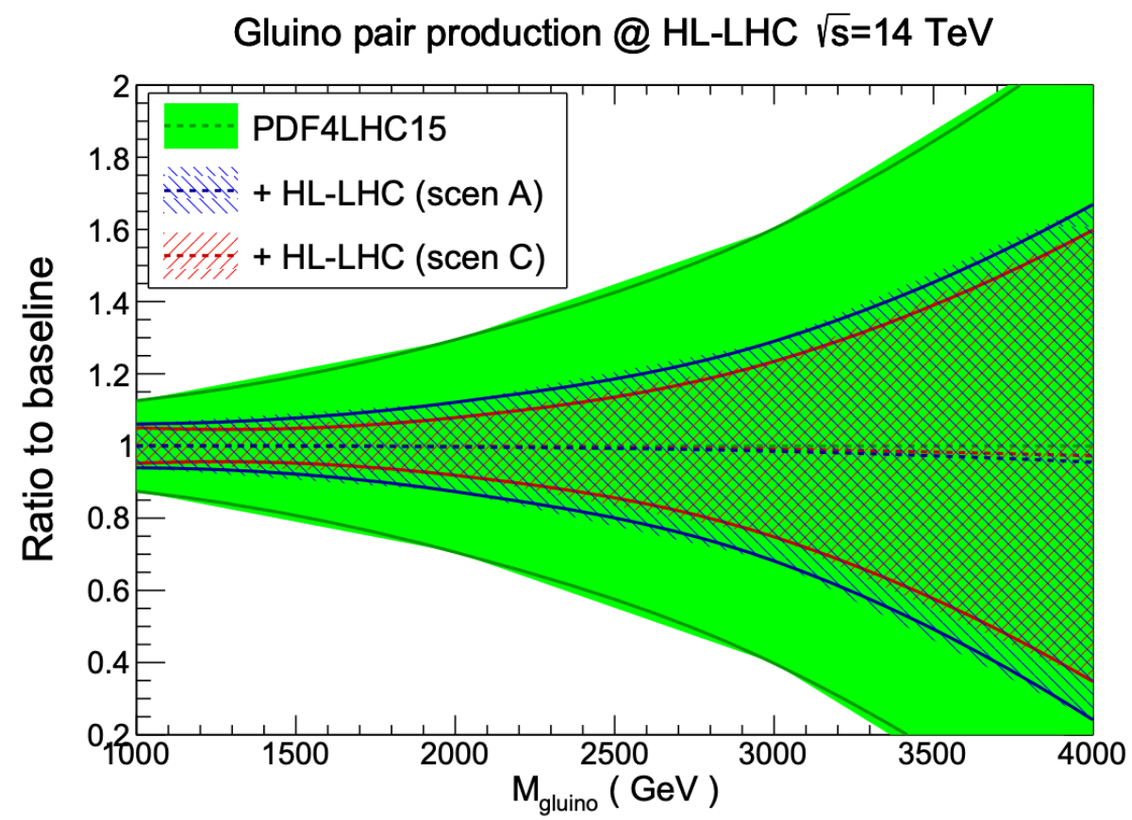
Quantify the ultimate **PDF constraining power** of HL-LHC and LHeC

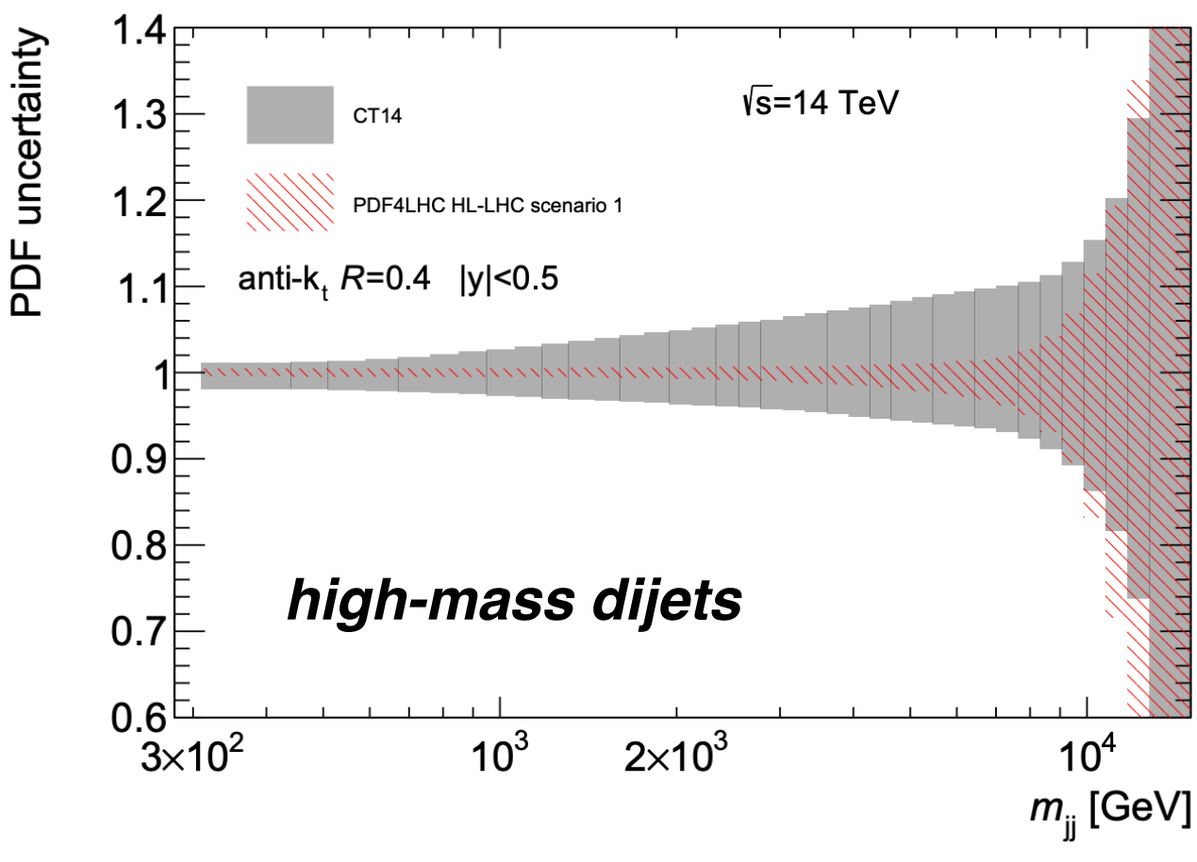


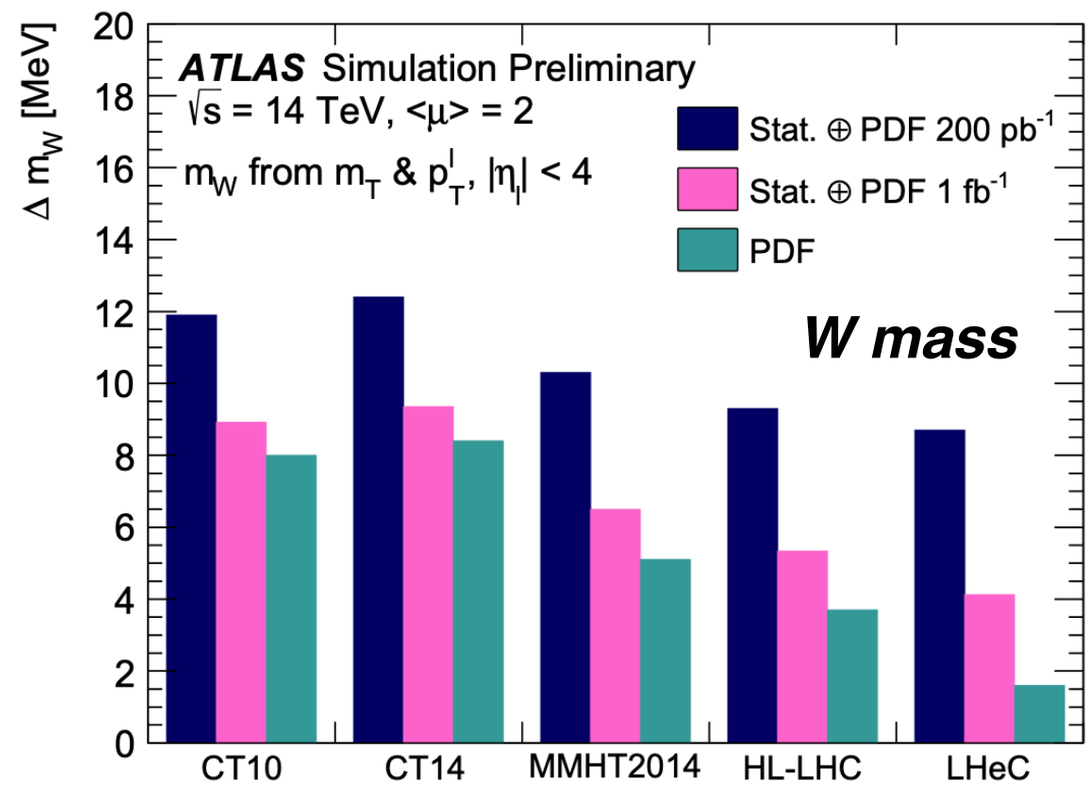
A reduction of PDF uncertainties by **up to a factor 10** could be within reach

Impact on phenomenology









Summary and outlook

The accurate determination of the **quark and gluon structure of the proton** is an essential ingredient for **LHC phenomenology** and **beyond**

- Recent progress in **longstanding issues**: QCD uncertainties on PDFs, lattice QCD constraints, strange and charm content of the proton, connection with astrophysics, …

- … but also **wrapping up**: QED effects on PDFs, BFKL dynamics in HERA data, ….

- Long-term goals of QCD analyses: **exploiting future facilities** (HL-LHC, LHeC, EIC) and **integrating its multiple dimensions**: joint fits of (p)PDFs + FFs + nPDFs + TMDs ….

- Simultaneous constraints of both **proton structure and BSM effects** will play a central role for the interpretation of the HL-LHC measurements

The fascinating study of the proton structure never stops surprising us, stay tuned!

Summary and outlook

The accurate determination of the **quark and gluon structure of the proton** is an essential ingredient for **LHC phenomenology** and **beyond**

- Recent progress in **longstanding issues**: QCD uncertainties on PDFs, lattice QCD constraints, strange and charm content of the proton, conn[illegible] physics, …
- … but also **wrapping up**: QED [illegible] ata, ….
- Long-t[illegible] **ities** (HL-LHC, LHeC, EIC) and **integrat**[illegible] ts of (p)PDFs + FFs + nPDFs + TMDs ….
- Simultane[illegible] straints of both **proton structure and BSM effects** will play a central role for the interpretation of the HL-LHC measurements

Thanks for your attention!

The fascinating study of the proton structure never stops surprising us, stay tuned!