The structure of the proton and precision LHC phenomenology

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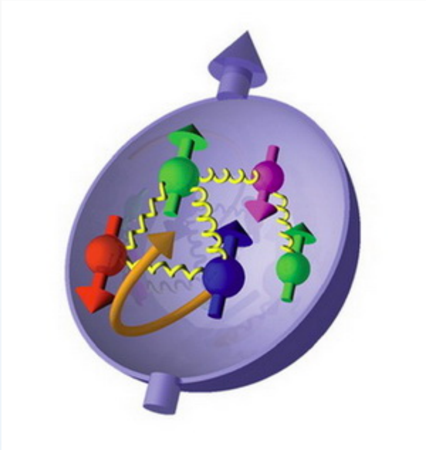
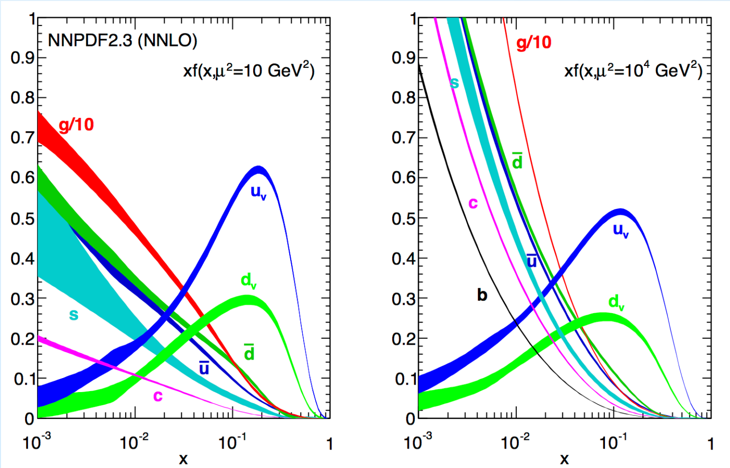
High Energy Physics & Cosmology Seminar
SUNY Buffalo, 30/11/2016

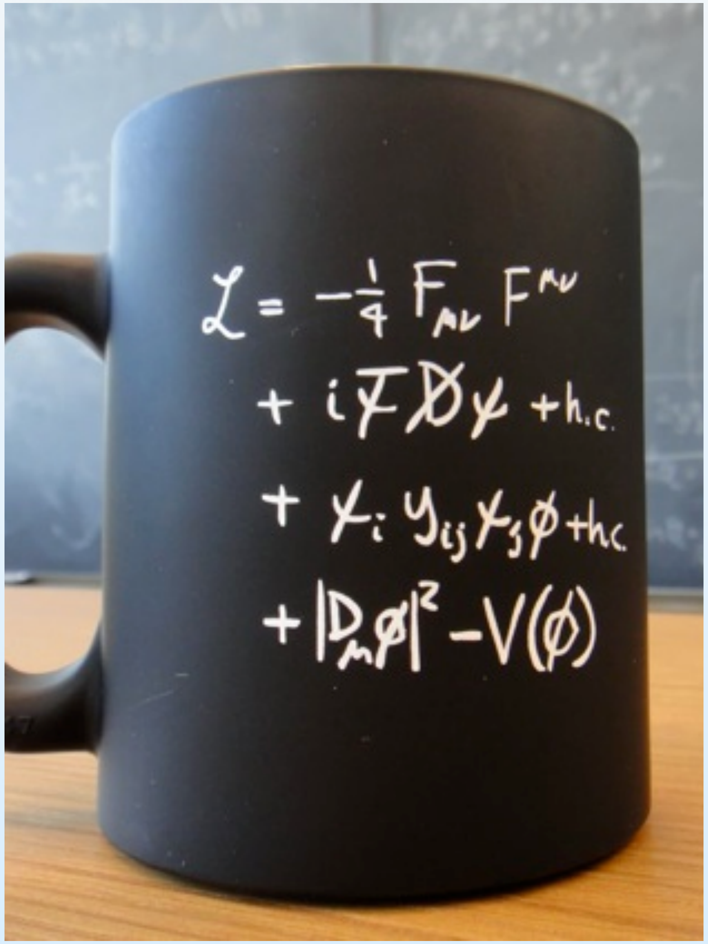


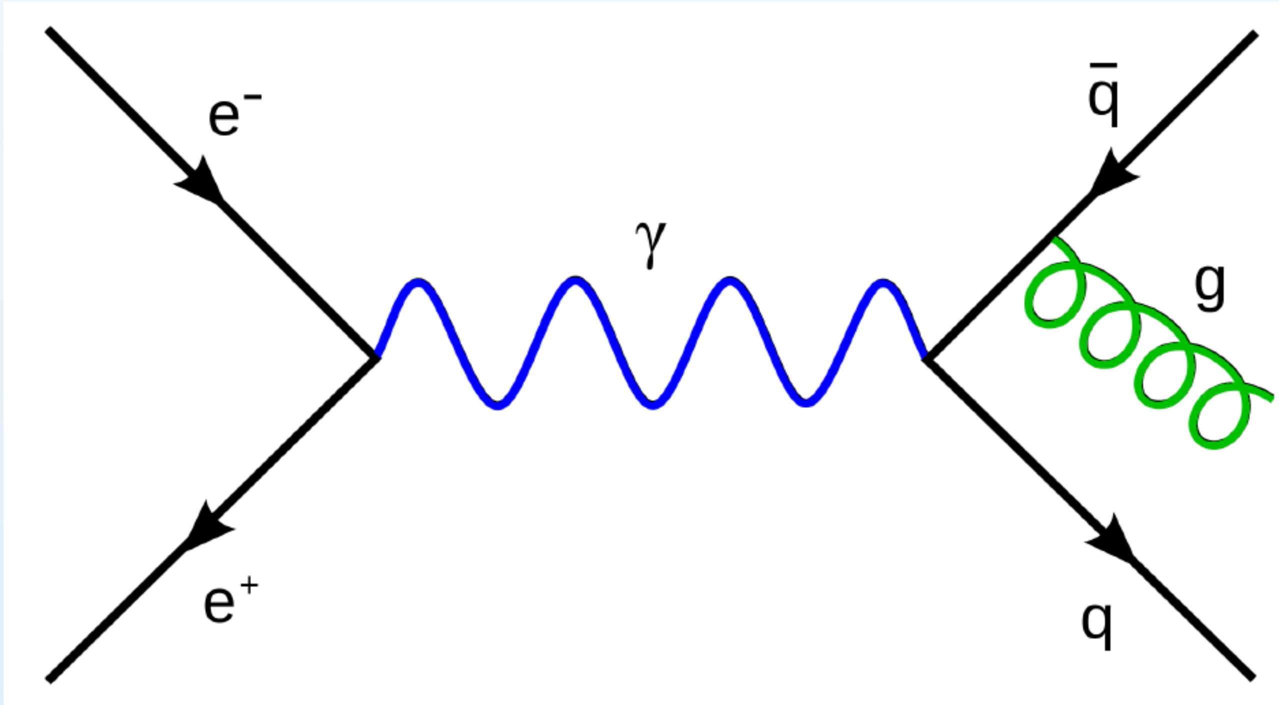
The inner life of protons : Parton Distribution Functions



Lepton vs Hadron Colliders

In high-energy **lepton colliders**, such as the **Large Electron-Positron Collider** (LEP) at CERN, the collisions involve **elementary particles** without substructure

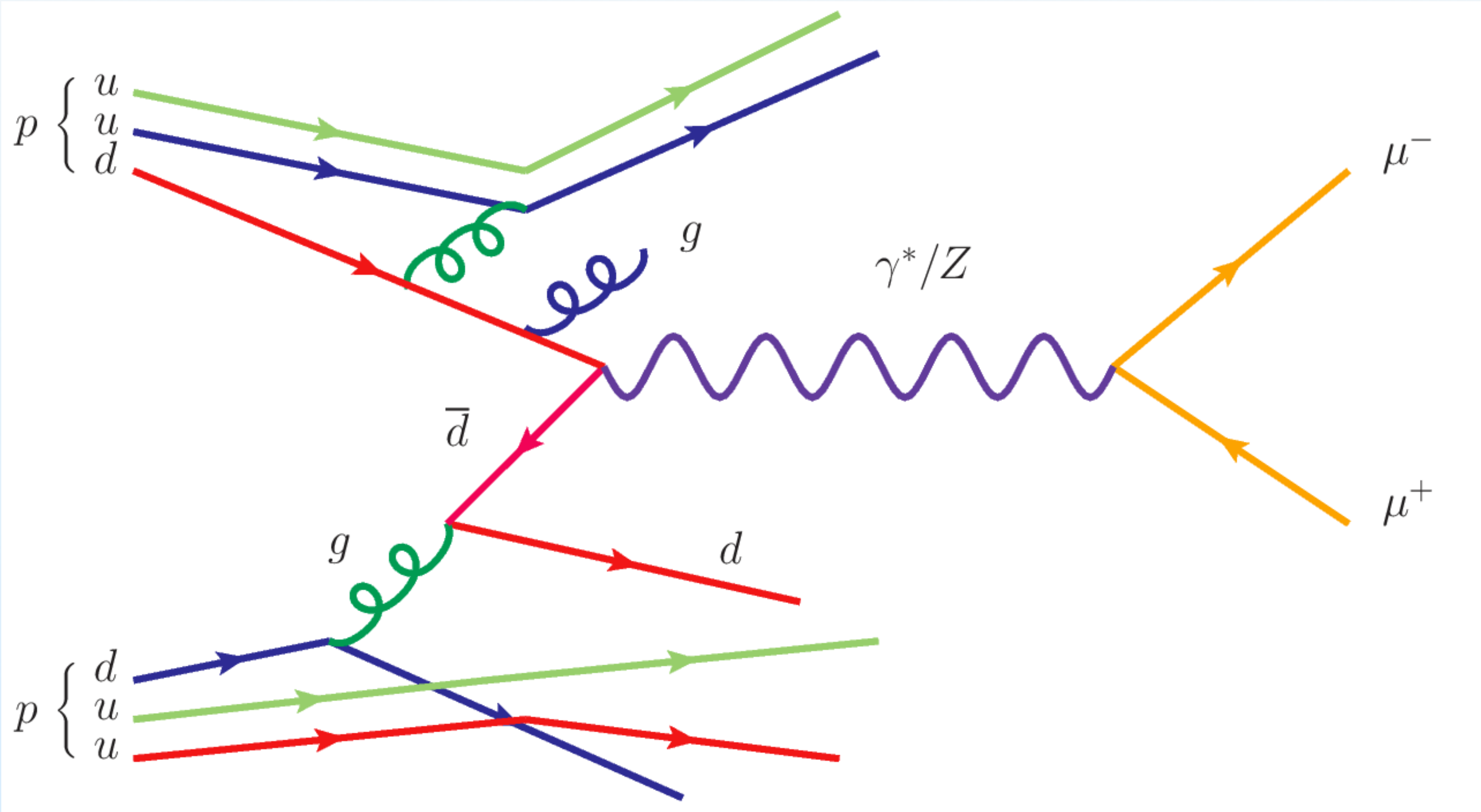




Cross-sections in lepton colliders can be computed in perturbation theory using the **Feynman rules of the Standard Model Lagrangian**

Lepton vs Hadron Colliders

In high-energy **hadron colliders**, such as the LHC, the collisions involve **composite particles** (protons) with internal structure (quarks and gluons)



Lepton vs Hadron Colliders

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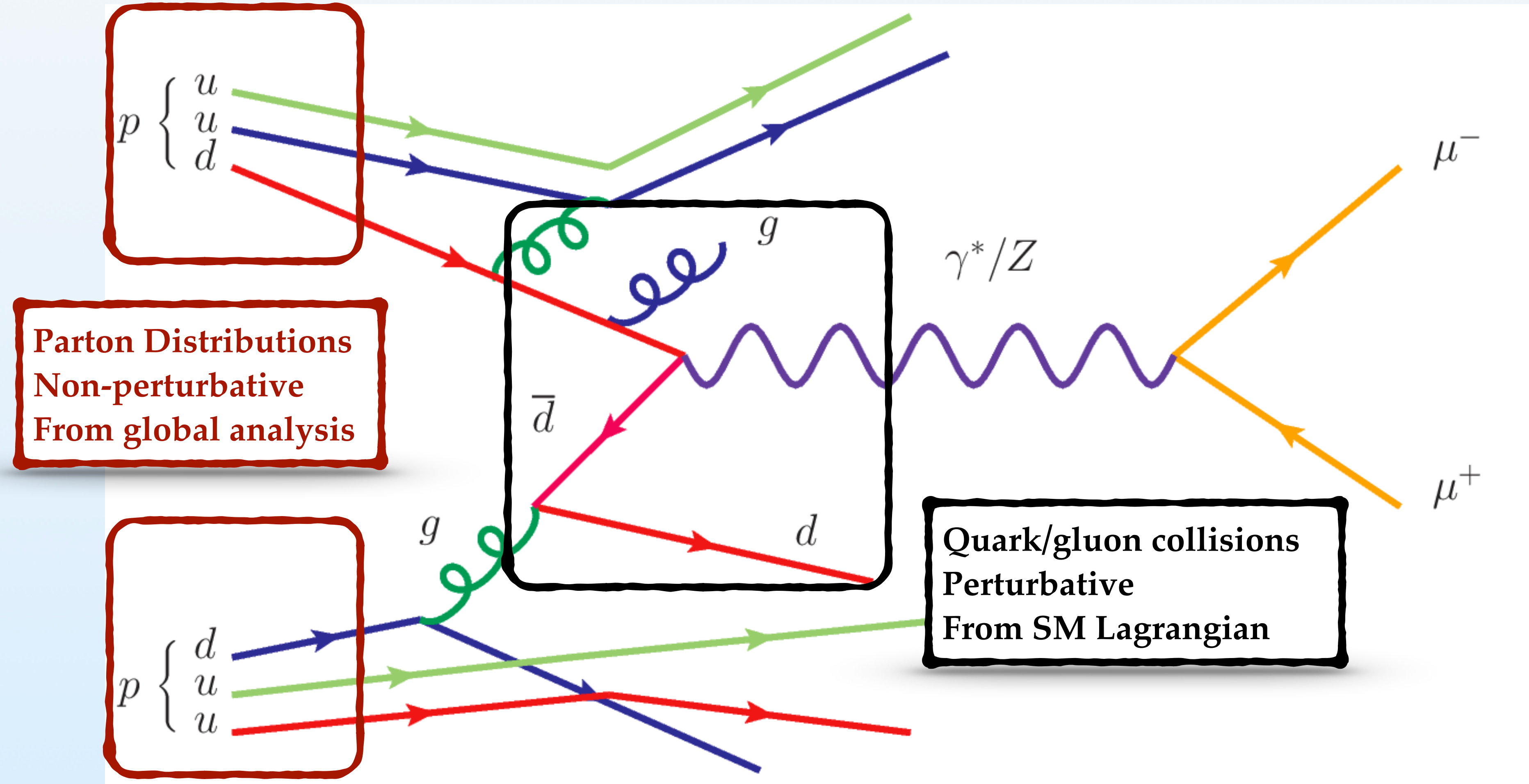

Calculations of **cross-sections** in hadron collisions require the combination of **perturbative, quark/gluon-initiated processes**, and **non-perturbative, parton distributions**, information

Parton Distributions

The distribution of energy that **quarks and gluons carry inside the proton** is quantified by the **Parton Distribution Functions (PDFs)**

$$g(x, Q)$$

Q: **Energy of the quark/gluon collision**
Inverse of the resolution length

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

x: Fraction of the proton's momentum

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- **Energy conservation** $$\int_0^1 dx \left(g(x,Q) + \sum_q q(x,Q) \right) = 1$$

- **Dependence with quark/gluon collision energy Q** determined in perturbation theory

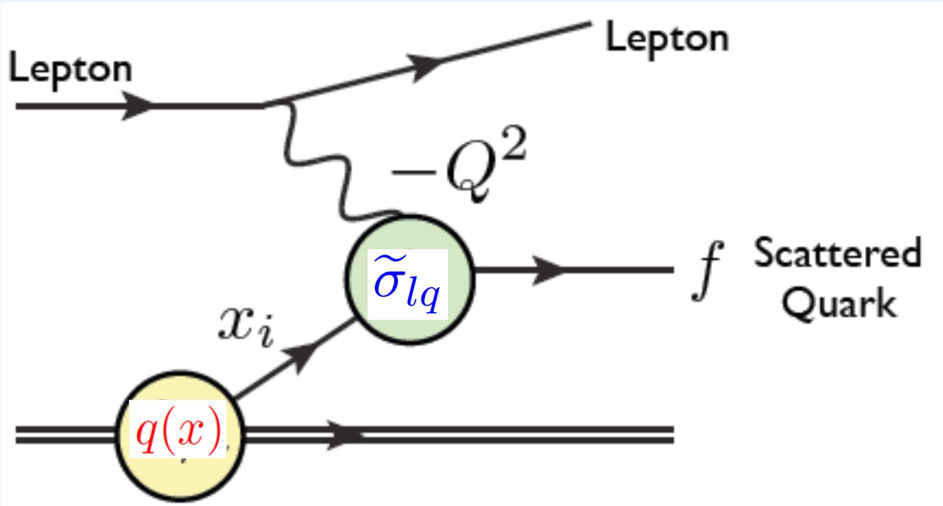
$$\frac{\partial g(x,Q)}{\partial \ln Q} = P_g\left(\alpha_s\right) \otimes g(x,Q) + P_q\left(\alpha_s\right) \otimes q(x,Q)$$

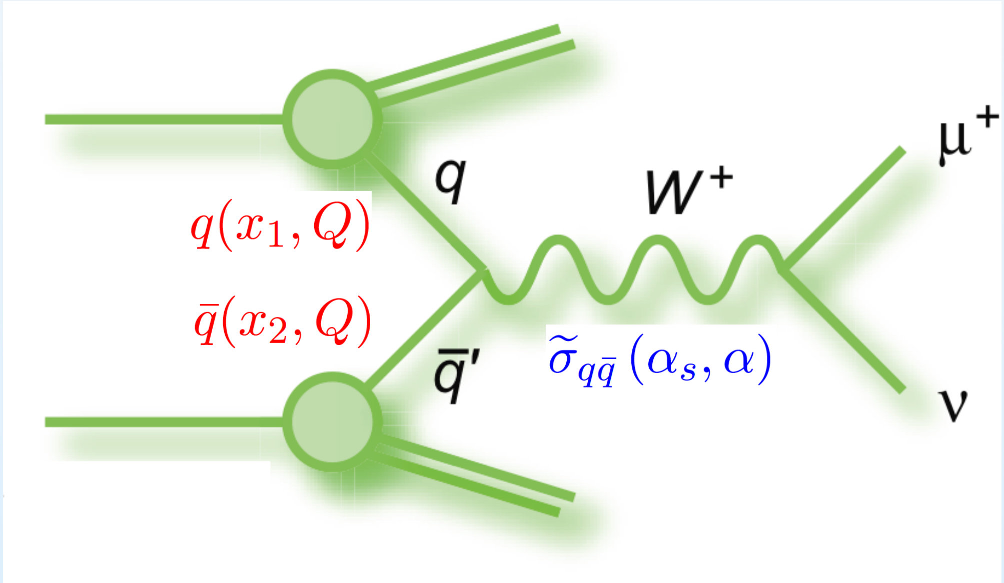
The QCD Factorization Theorem

The **QCD factorization theorem** guarantees **PDF universality: extract them from a subset of** process and use them to provide pure predictions for new processes

$$\sigma_{lp} \simeq \widetilde{\sigma}_{lq}\left(\alpha_s, \alpha\right) \otimes q(x, Q)$$

$$\sigma_{pp} \simeq \widetilde{\sigma}_{q\bar{q}}\left(\alpha_s, \alpha\right) \otimes q(x_1, Q) \otimes \bar{q}(x_2, Q)$$



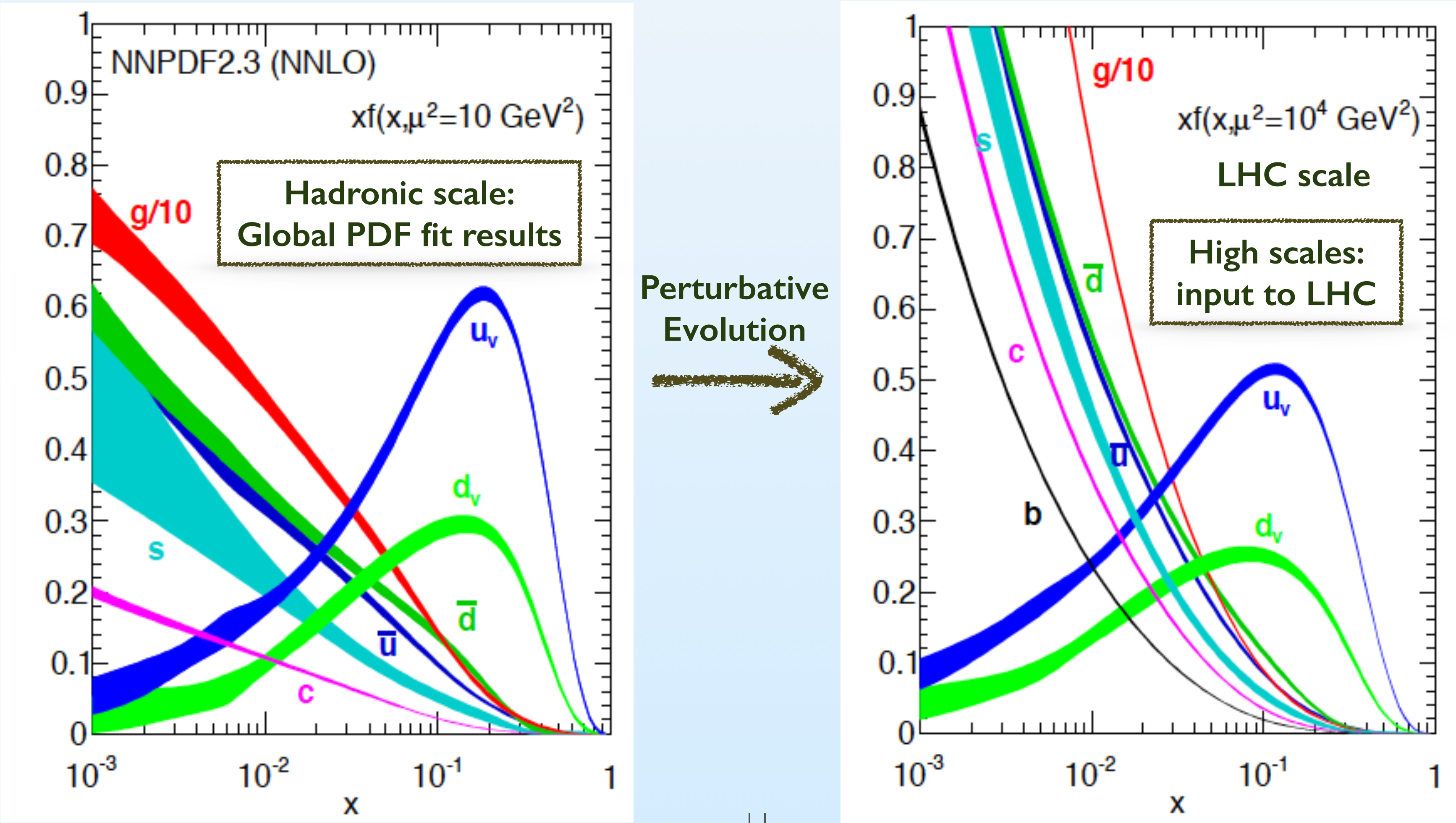


Determine PDFs in lepton-proton collisions ….

And use them to compute cross-sections in proton-proton collisions at the LHC

The global PDF analysis

- Combine **state-of-the-art theory calculations,** the **constraints from PDF-sensitive measurements** from different processes and colliders, and a **statistically robust fitting methodology**
- **Extract Parton Distributions** at hadronic scales of **a few GeV,** where non-perturbative QCD sets in
- Use **perturbative evolution** to compute PDFs at high scales as **input to LHC predictions**



The NNPDF approach

A **novel approach to PDF determination**, improving the limitations of the traditional PDF fitting methods with the use of **advanced statistical techniques** such as **machine learning** and **multivariate analysis**

Non-perturbative PDF parametrization

- **Traditional approach**: based on **restrictive functional forms** leading to strong theoretical bias
- **NNPDF solution**: use **Artificial Neural Networks** as universal unbiased interpolants

PDF uncertainties and propagation to LHC calculations

- **Traditional approach**: limited to Gaussian/linear approximation
- **NNPDF solution**: based on the **Monte Carlo replica method** to create a probability distribution in the space of PDFs. Specially critical in **extrapolation regions** (**i.e.** high-x) for New Physics searches

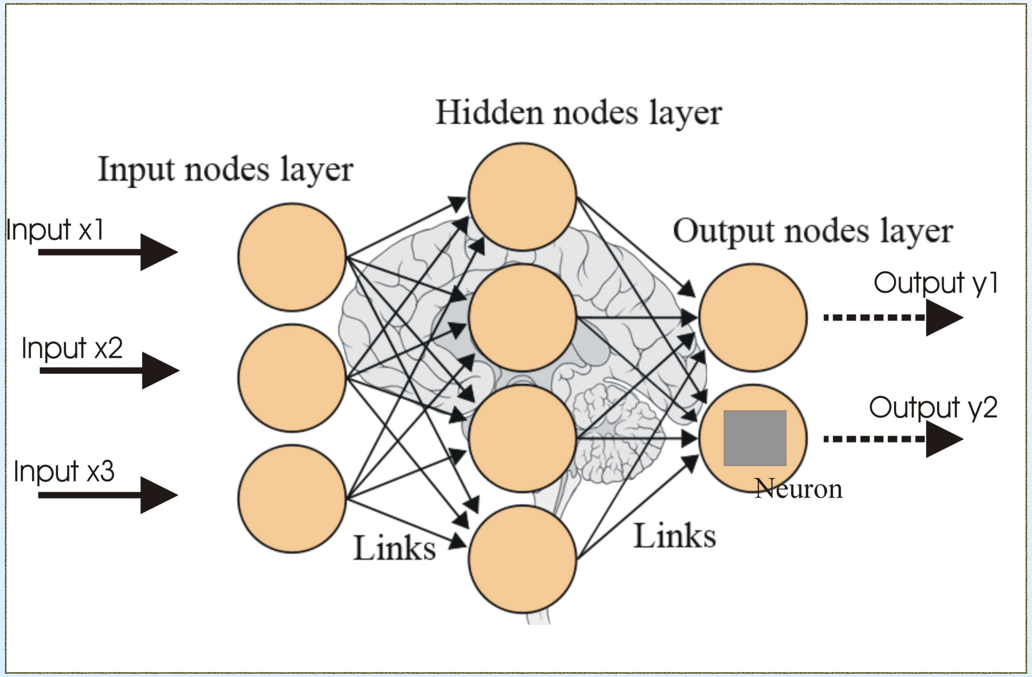
Fitting technique

- **Traditional approach**: deterministic minimization of χ^2, **flat directions** problem
- **NNPDF solution**: **Genetic Algorithms** to explore efficiently the vast parameter space, with **cross-validation** to avoid fitting stat fluctuations

Artificial Neural Networks

Inspired by **biological brain models**, **Artificial Neural Networks** are **mathematical algorithms** widely used in a wide range of applications, from **high energy physics** to **targeted marketing** and **finance forecasting**

From Biological to Artificial Neural Networks



Artificial neural networks aim to excel in the same domains as their biological counterparts: **pattern recognition, forecasting, classification**, ... where our **evolution-driven biology** outperforms traditional algorithms

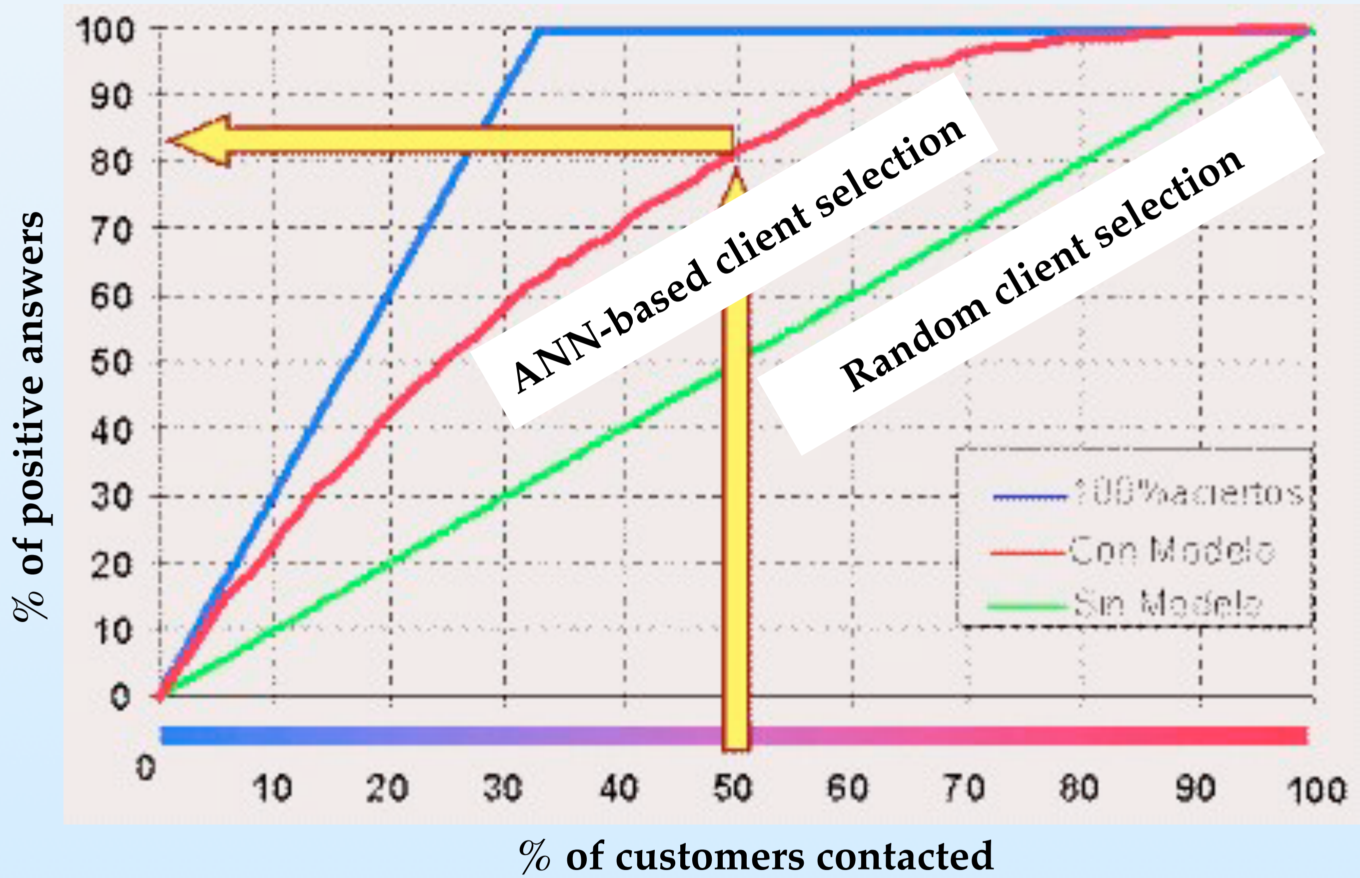
Artificial Neural Networks

Application in **Marketing**

A bank wants to offer a new credit card to their clients. Two possible strategies:

- **Contact all customers**: slow and costly
- Contact **5%** of the customers, **train a ANN with their input** (gender, income, loans) and **their output** (yes/no) and use the information to **contact only clients likely to accept the product**

Cost-effective method to improve marketing performance



ANN in high-energy physics

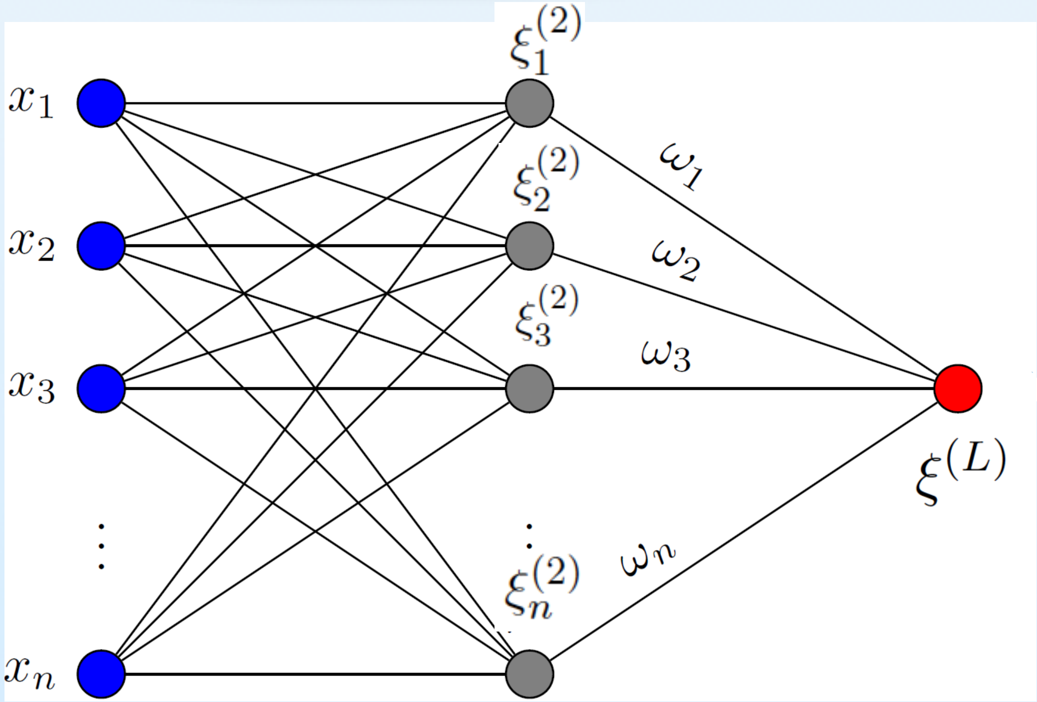
- ANNs are routinely exploited in **high-energy physics**, in most cases as **classifiers** to separate between interesting and more mundane events
- **ANNs also** provide **universal unbiased interpolants** to parametrize the non-perturbative dynamics that determines the **size and shape of the PDFs** from experimental data

Traditional approach

$$g(x,Q_0) = A_g(1-x)^{a_g}x^{-b_g}\left(1+c_g\sqrt{s}+d_g x+\ldots\right)$$

NNPDF approach

$$g(x,Q_0) = A_g \mathrm{ANN}_g(x)$$



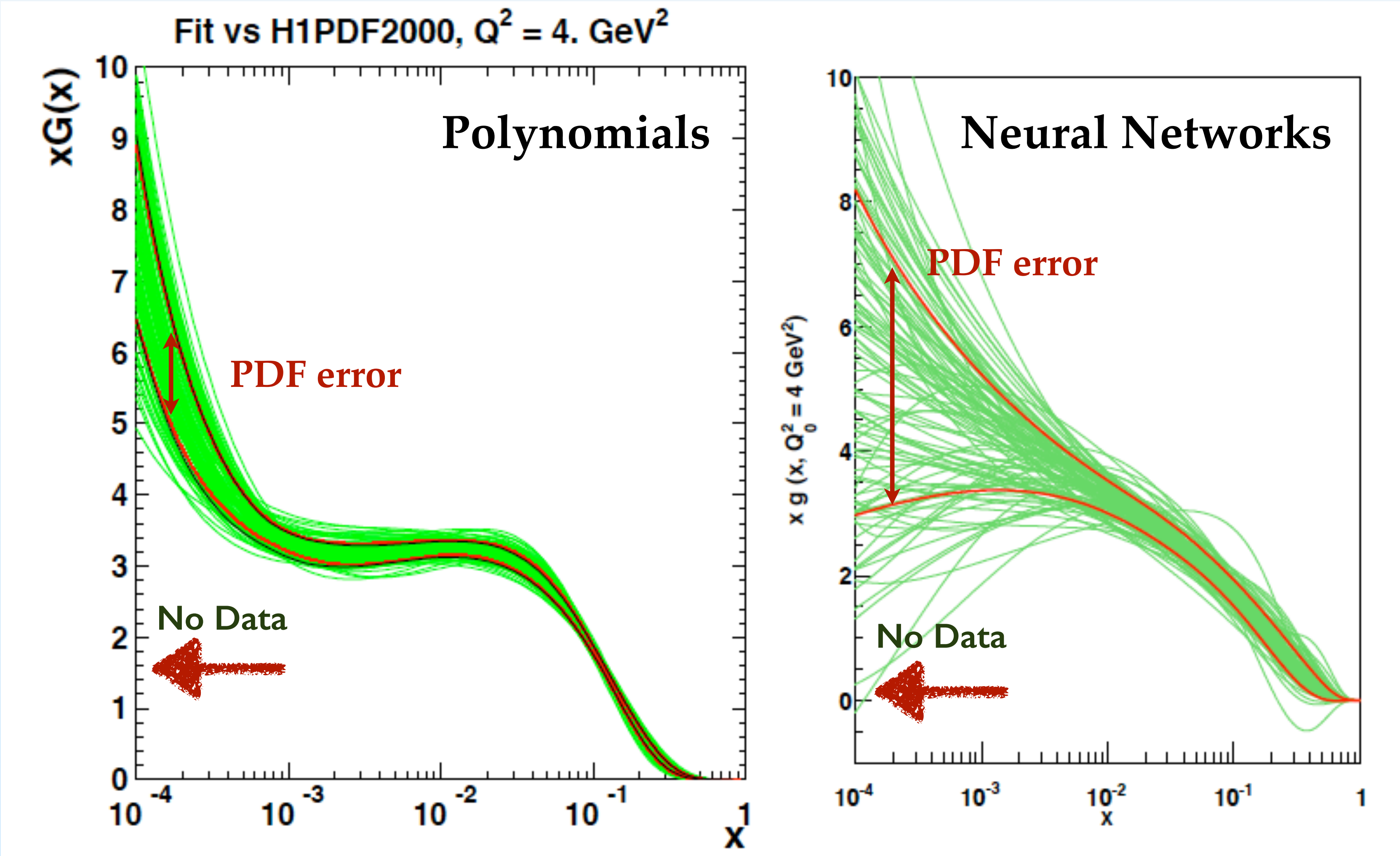
$$\mathrm{ANN}_g(x) = \xi^{(L)} = \mathcal{F}\left[\xi^{(1)},\{\omega_{ij}^{(l)}\},\{\theta_i^{(l)}\}\right]$$

$$\xi_i^{(l)} = g\left(\sum_{j=1}^{n_{l-1}}\omega_{ij}^{(l-1)}\xi_j^{(l-1)} - \theta_i^{(l)}\right)$$

- ANNs eliminate **theory bias** introduced in PDF fits from choice of *ad-hoc* functional forms
- NNPDF fits used **O(400) free parameters**, to be compared with **O(10-20) in traditional fits**. Results stable if **O(4000) parameters used!**
- **Faithful extrapolation**: PDF uncertainties **blow up** in regions with scarce experimental data

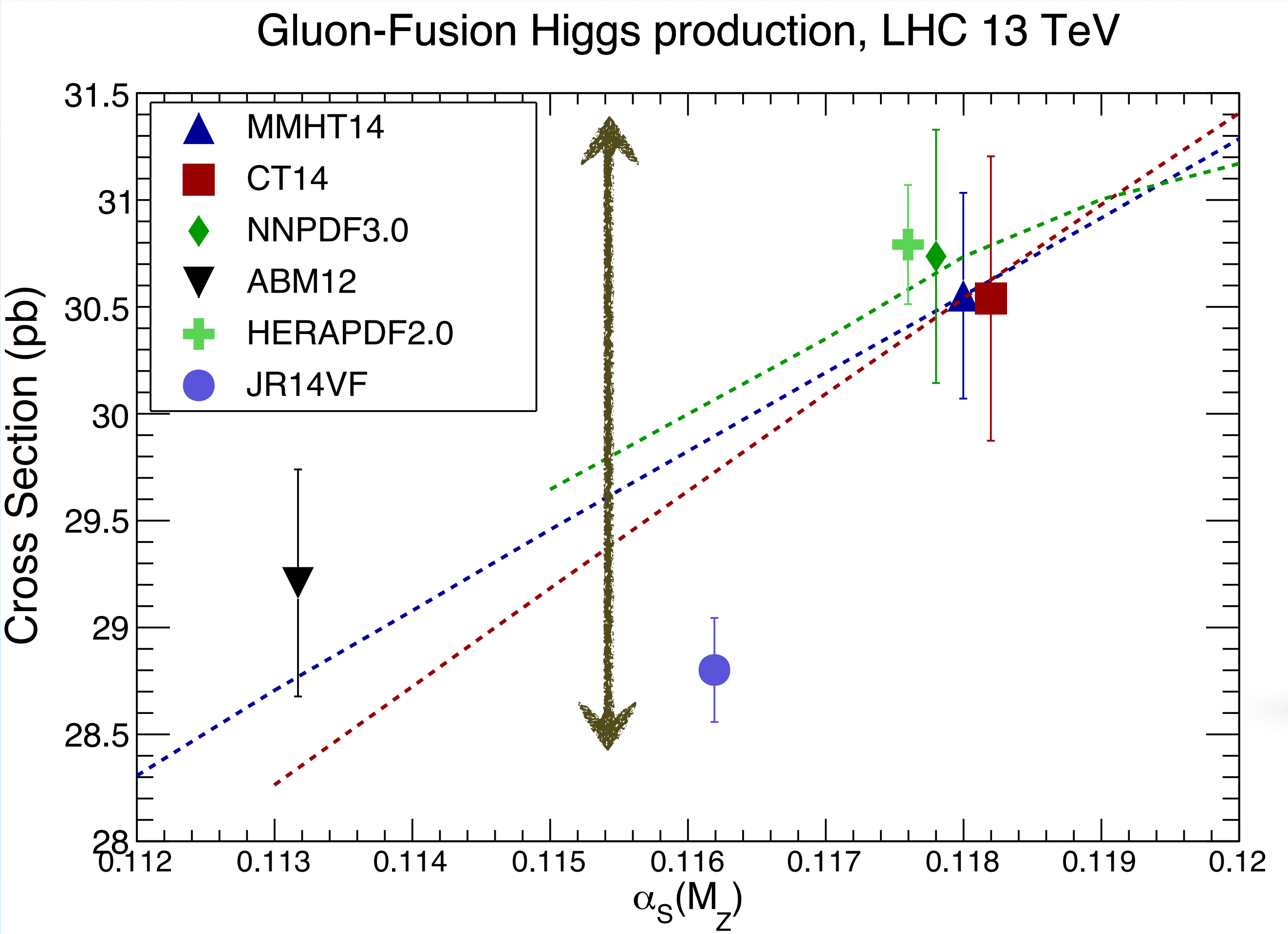
Artificial Neural Networks vs Polynomials

- Compare a **benchmark PDF analysis** where **the same dataset** is fitted with **Artificial Neural Networks** and with **standard polynomials,** other settings identical)
- **ANNs** avoid biasing the PDFs, **faithful extrapolation at small-x** (very few data, thus error blow up)

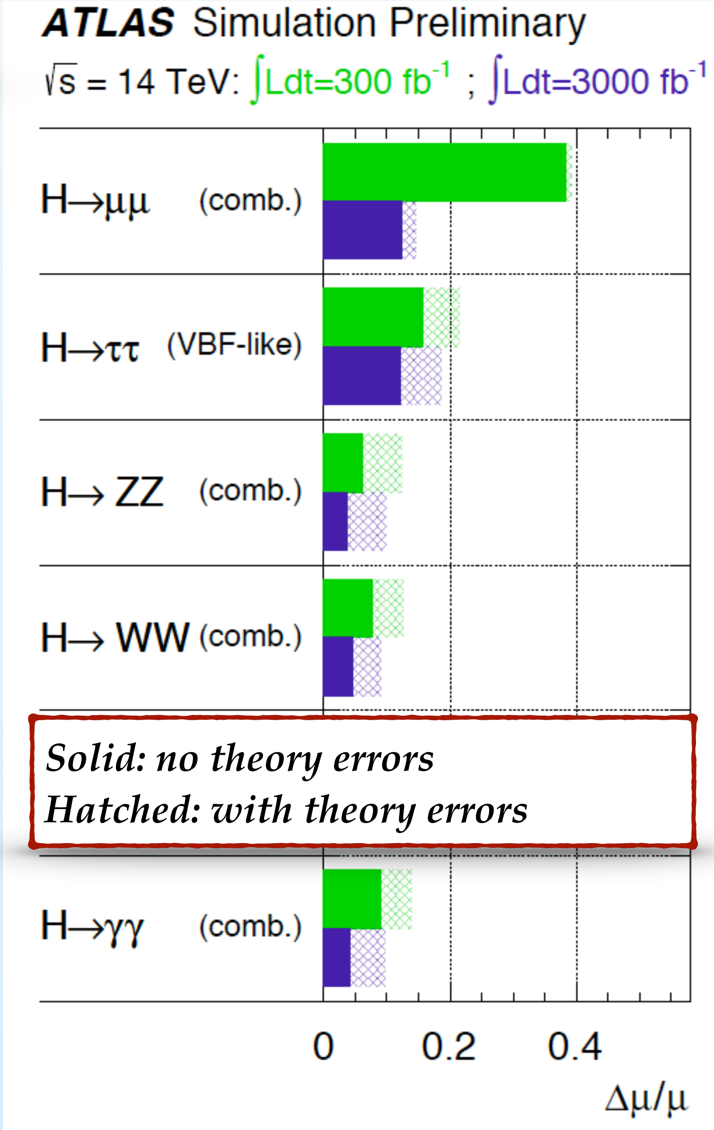


Fingerprinting the Higgs sector

Uncertainties from Parton Distributions *are one of the limiting factors of theory predictions of Higgs production,* ***degrading the exploration of the Higgs sector***



Higgs Cross-Section Working Group YR4 16

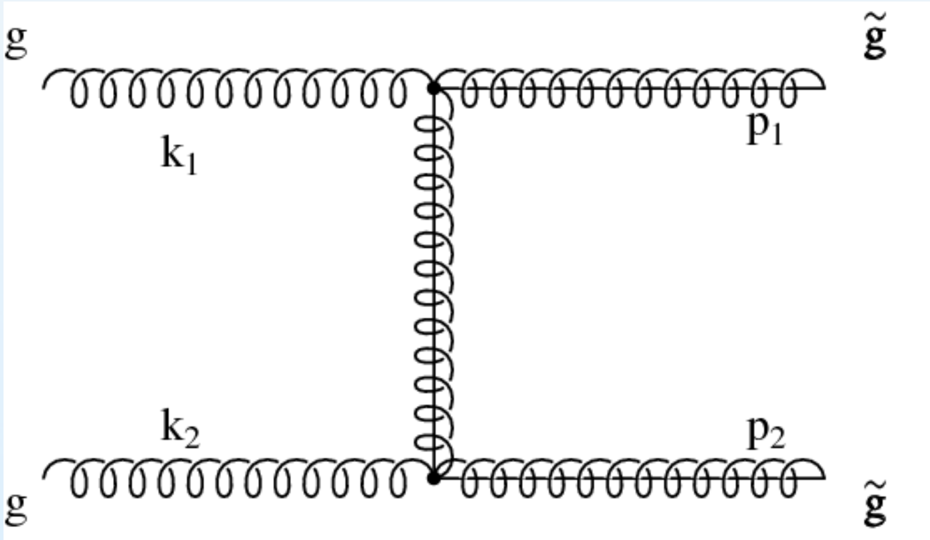


Solid: no theory errors
Hatched: with theory errors

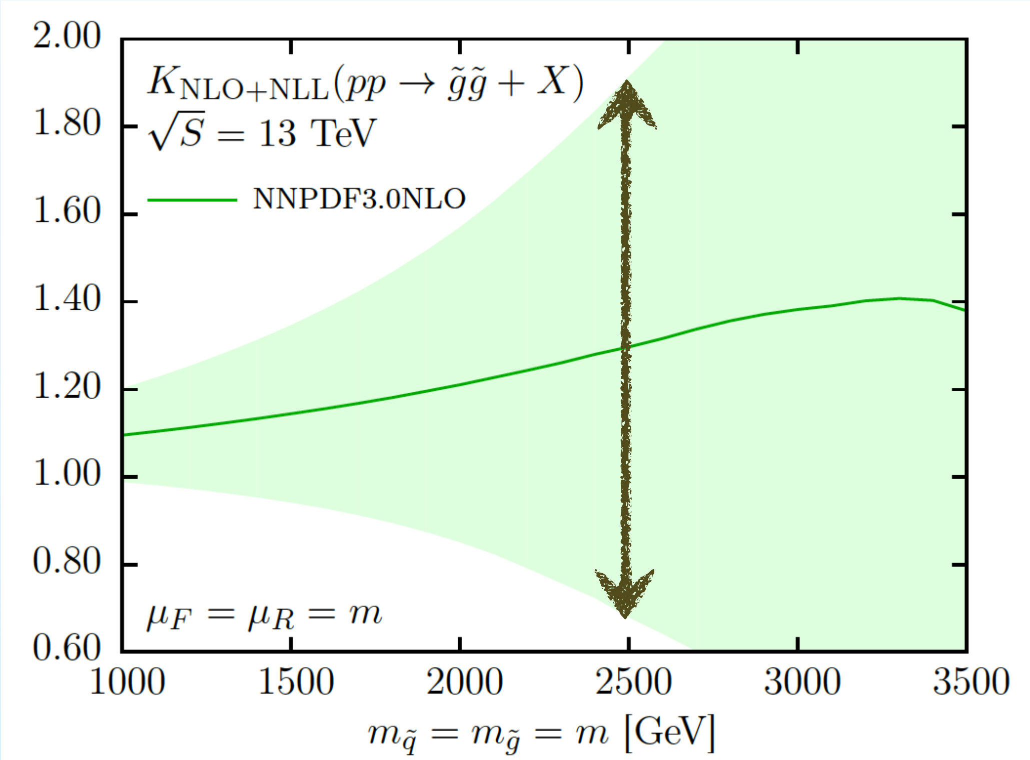
Characterising Heavy New Physics

PDF uncertainties in the production of **New Physics heavy resonances** can be al large as **100%**

The reason is that massive particle production probes **large-x PDFs**, which are poorly known due to very limited direct experimental constraints



Gluino pair production at the LHC

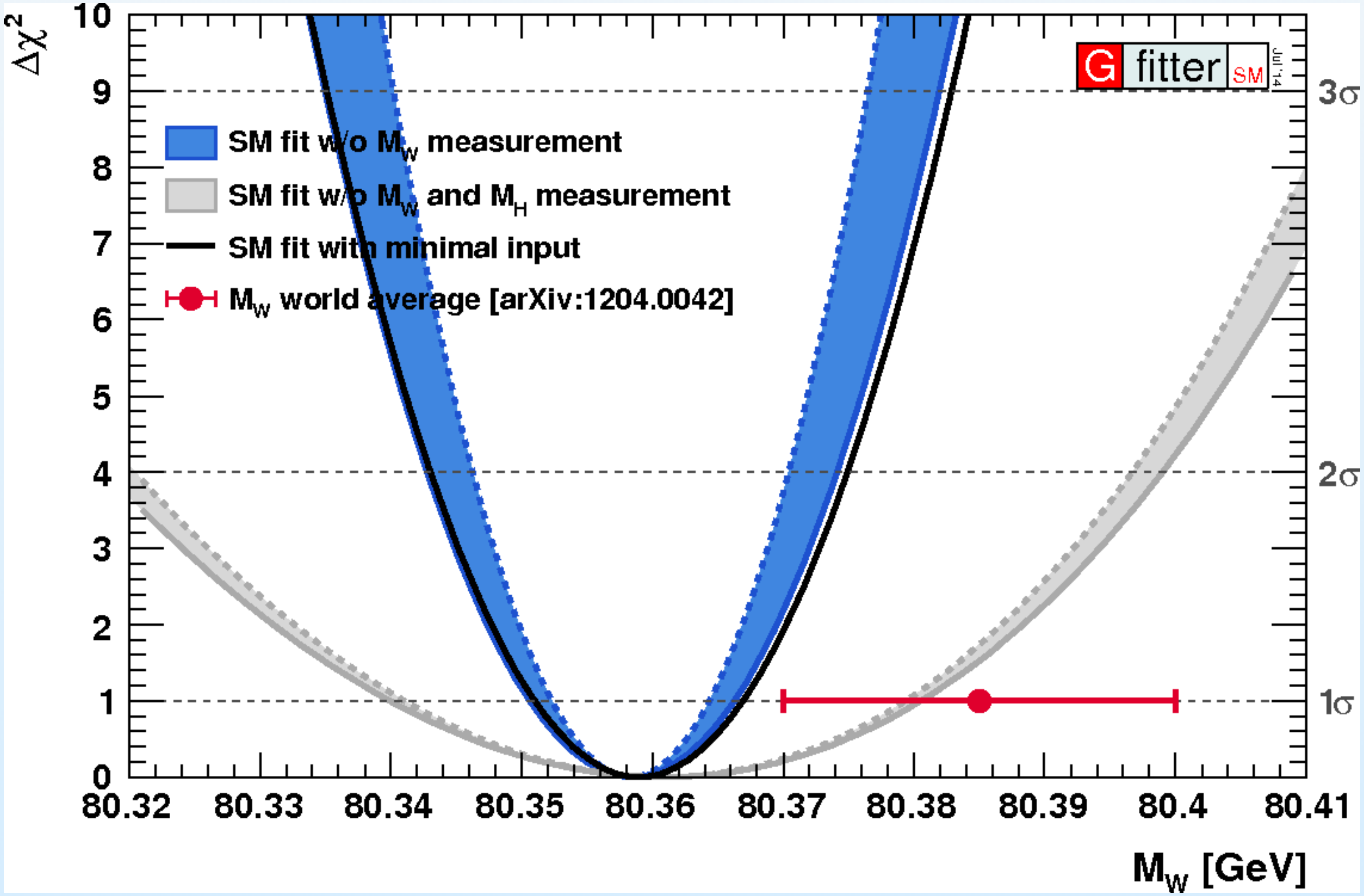


Beenakker, Borchensky, Kramer, Kulesza, Laenen, Marzani, Rojo 15

*Unless we **improve PDF uncertainties**, even if we discover New Physics, it will be extremely **difficult to characterise the underlying dynamics***

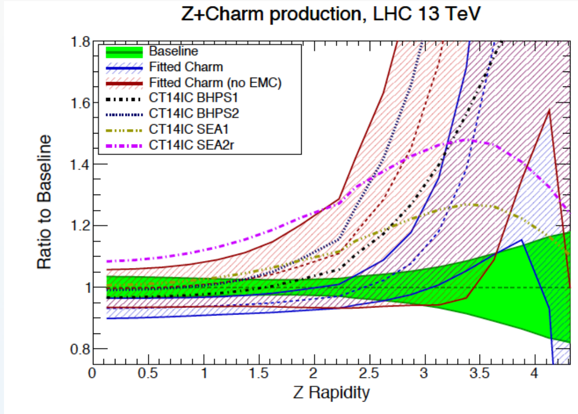
PDFs and precision determination of SM parameters

PDFs dominant systematic for precision measurements, like W boson mass, that provide stringent consistency stress-tests of the Standard Model

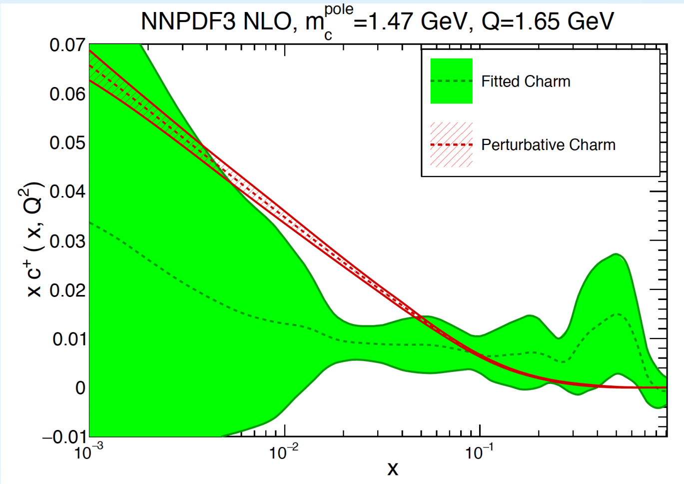


GFitter collaboration 16

- Reducing TH systematics could lead to **indirect BSM discovery** from precision measurements
- Precision in M_W will **improve by a factor 3** in 10 years
- If SM confirmed, **ruled out a broad class of BSM scenarios**
- First measurements from ATLAS and CMS to be presented soon!



A first unbiased determination of the charm content of the proton



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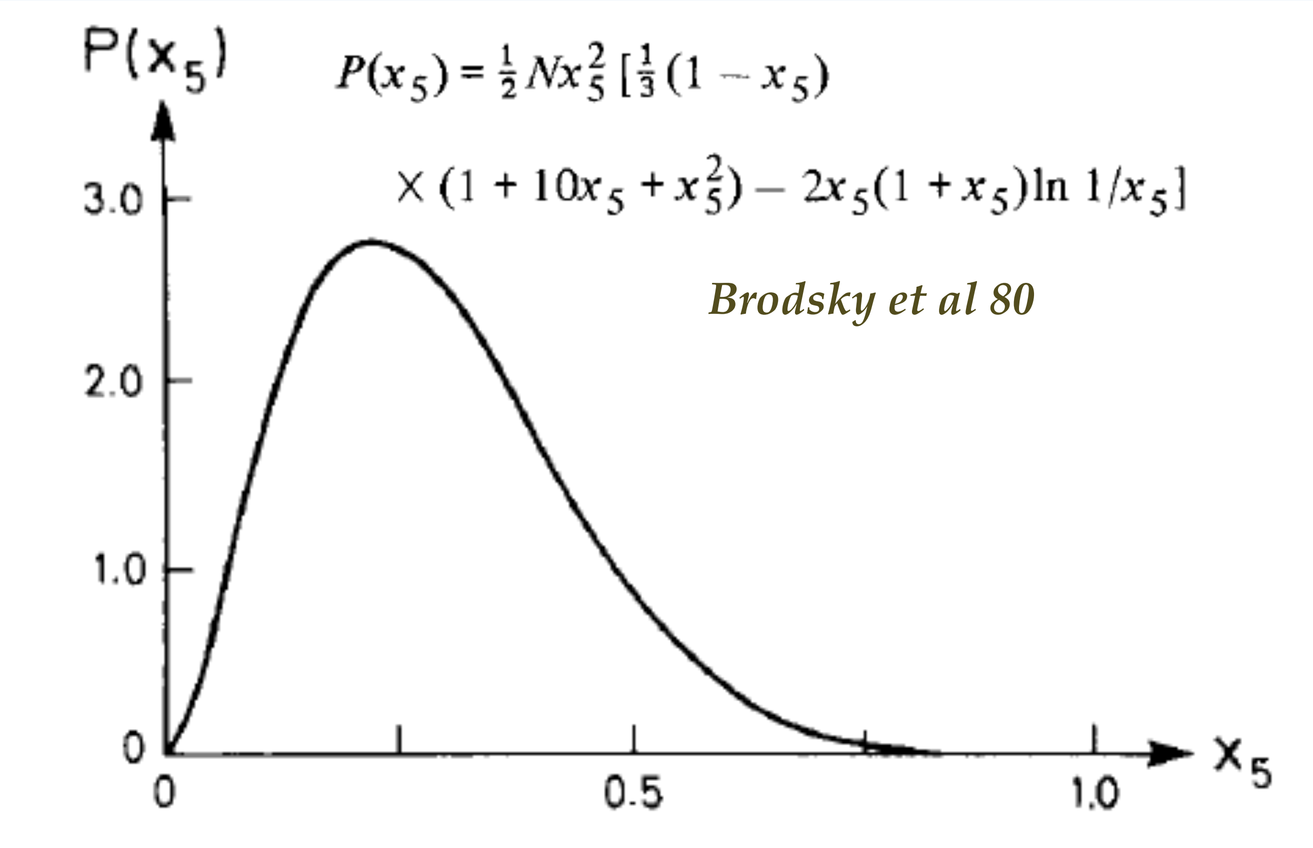
The charm content of the proton

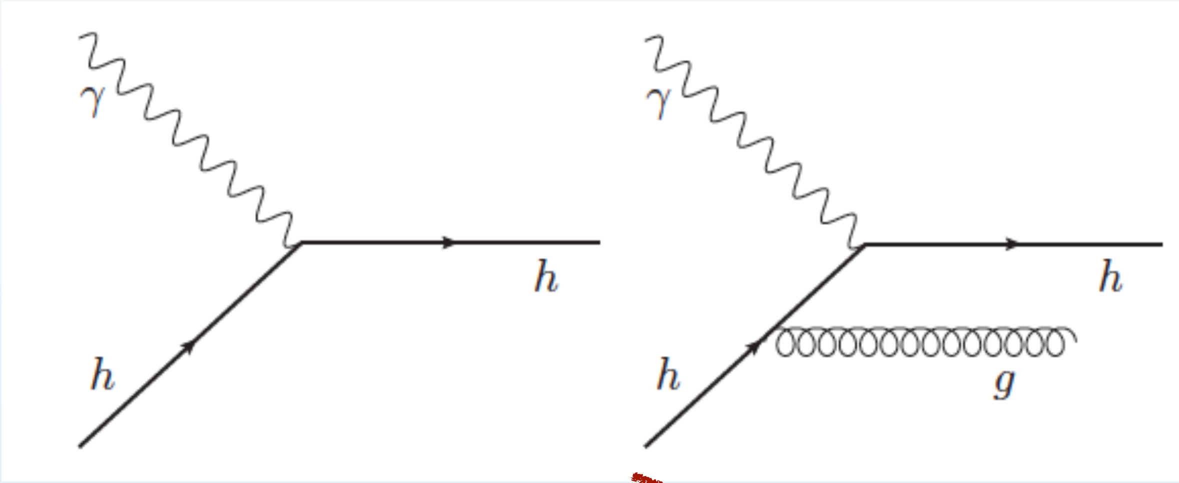
- The motivation **to fit a charm PDF** in a global analysis is **two-fold:**
  - ☑ Stabilise the dependence of **LHC calculations** with respect to **value of the charm mass**
  - ☑ Quantify the **non-perturbative charm component in the proton** and compare with models



A 30-years old conundrum of QCD!

Global QCD analysis with fitted charm

General-mass VFN scheme **heavy quark deep-inelastic structure functions** are modified to account for **massive charm-initiated diagrams**



$$F(x,Q^2) = F^{\mathrm{FLNR}}(x,Q^2) + \Delta F(x,Q^2)$$

Forte, Laenen, Nason, Rojo 10

Ball, Bertone, Bonvini, Forte, Groth-Merrild, Rojo and Rottoli 15

Parametrize the charm PDF $c(x,Q_0)$ on an equal footing to light quarks: **ANN with 37 params**

Fit quality improvement when **charm is fitted** as compared to the traditional **dynamical charm:** χ^2/N_{dat} from **1.18 to 1.15**

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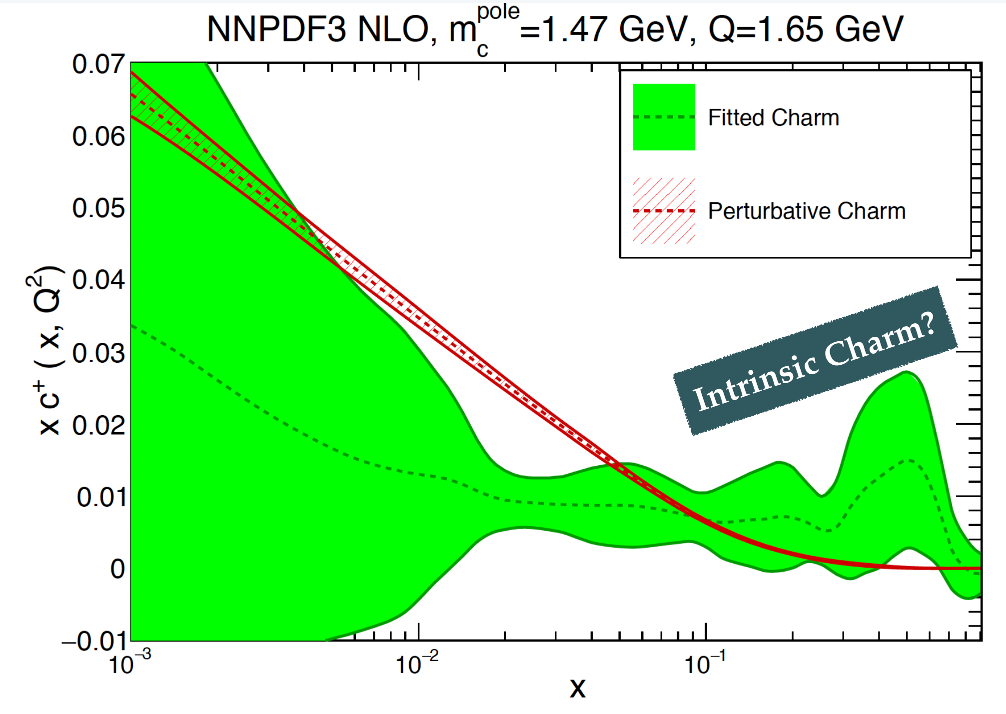
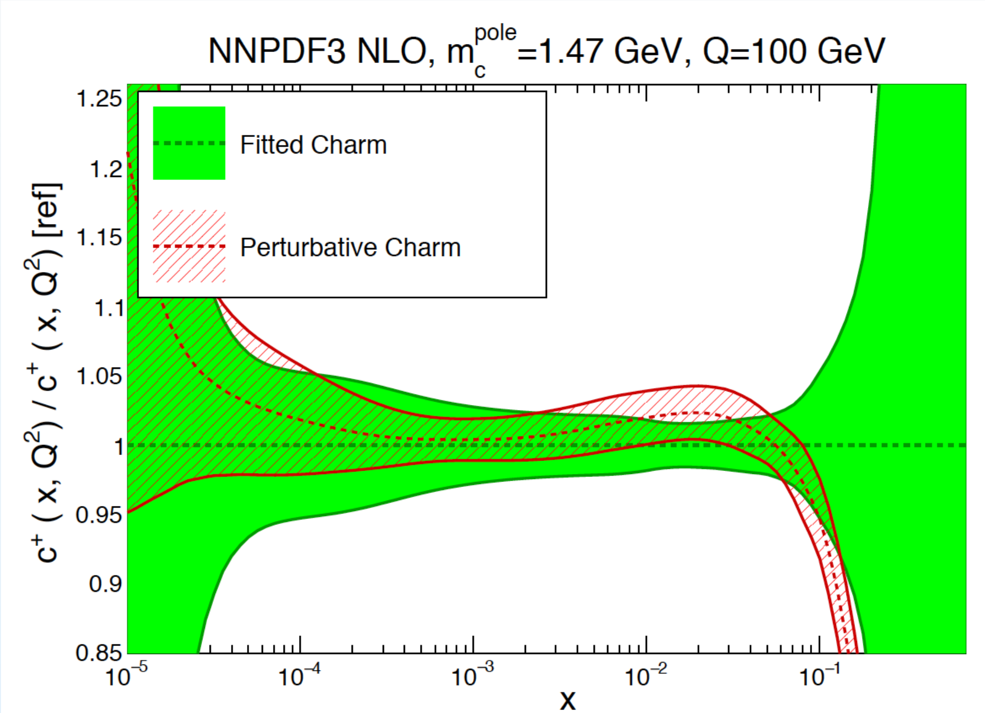
Global QCD analysis with fitted charm





At low scales, hints of a **non-perturbative charm component**, though PDF errors still large

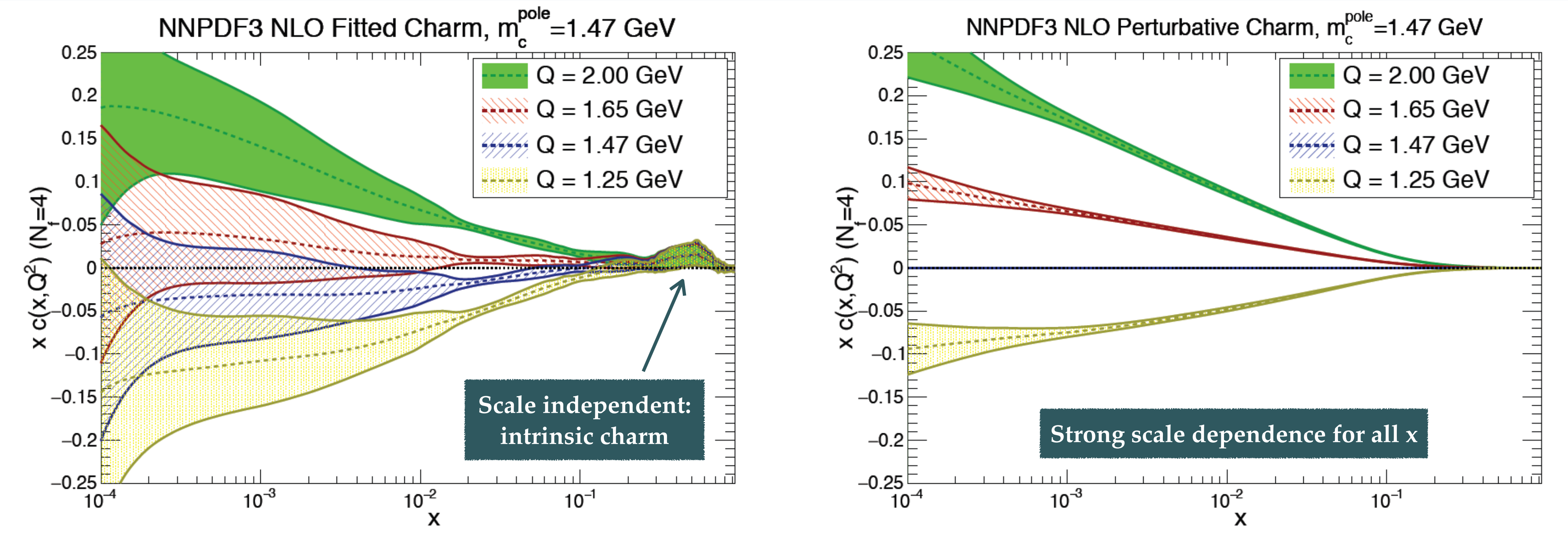
At LHC scales, **fitted and perturbative charm in good agreement** for x < 0.08

Charm can account up to **1% of the total proton momentum** at low scales

Charm momentum fraction

PDF set	$C(Q = 1.65\ \mathrm{GeV})$
NNPDF3 perturbative charm	$(0.239 \pm 0.003)\%$
NNPDF3 fitted charm	$(0.7 \pm 0.3)\%$
NNPDF3 fitted charm (no EMC)	$(1.6 \pm 1.2)\%$

Disentangling perturbative and intrinsic charm



The fitted charm PDF is, by construction, the **sum of the intrinsic and perturbative components**

These can be disentangled from the **scale dependence** of the fitted charm PDF

Intrinsic charm is scale independent, while perturbative charm has strong scale dependence

The perturbative component vanishes for $Q \simeq$ **m_{charm}** $\simeq$ **1.5 GeV** as expected since for **Q** $\lesssim$ **m_{charm}** the perturbative description of the charm PDF breaks down

Fitted and perturbative charm very similar for **x** $\lesssim$ **0.1**

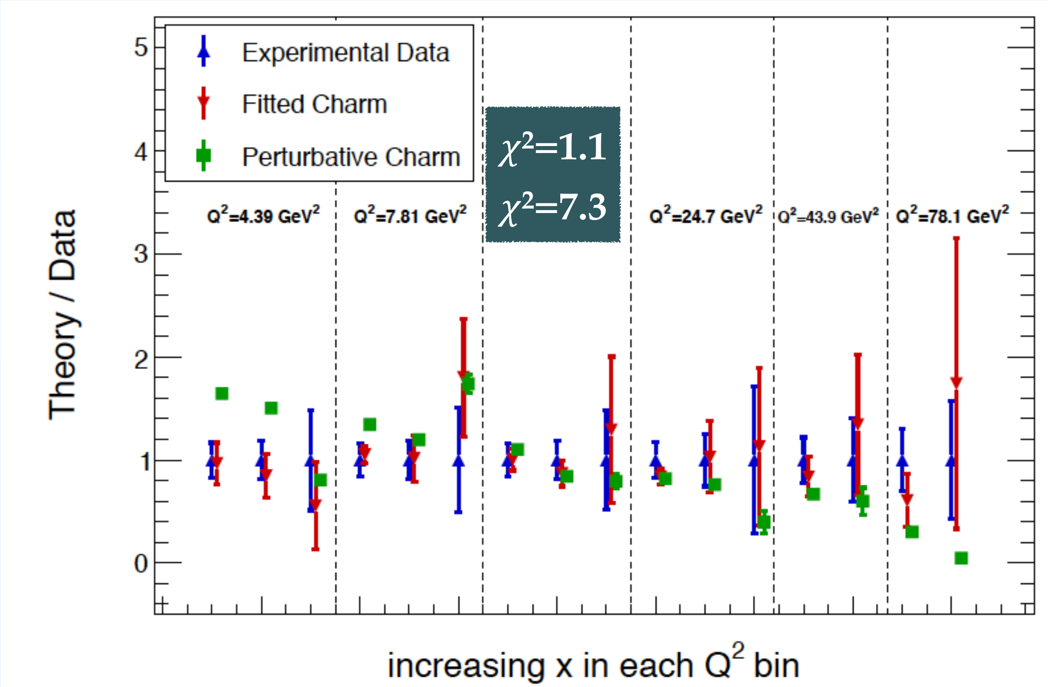
The EMC charm mystery solved?

The **EMC measurements of charm production** in the early 80s have since then been advocated as *smoking gun* for intrinsic charm, but **including them in a global PDF fit** had been impossible

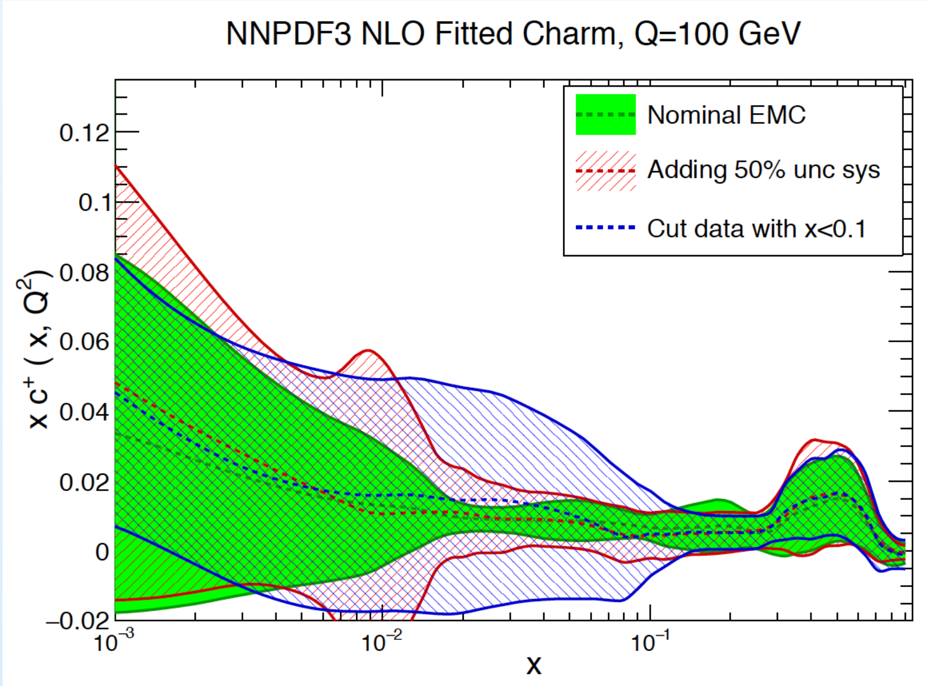
This NNPDF analysis with fitted charm includes EMC data, leading to an **excellent fit quality**

Our results stable upon **variations of the EMC data** (such as cutting data for $x < 0.1$)

Theory/data ratio for EMC charm production



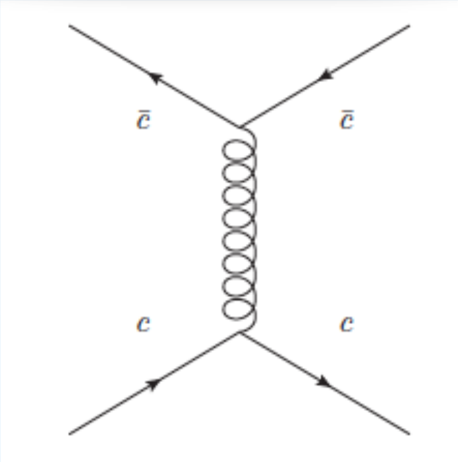
Fitted charm stability

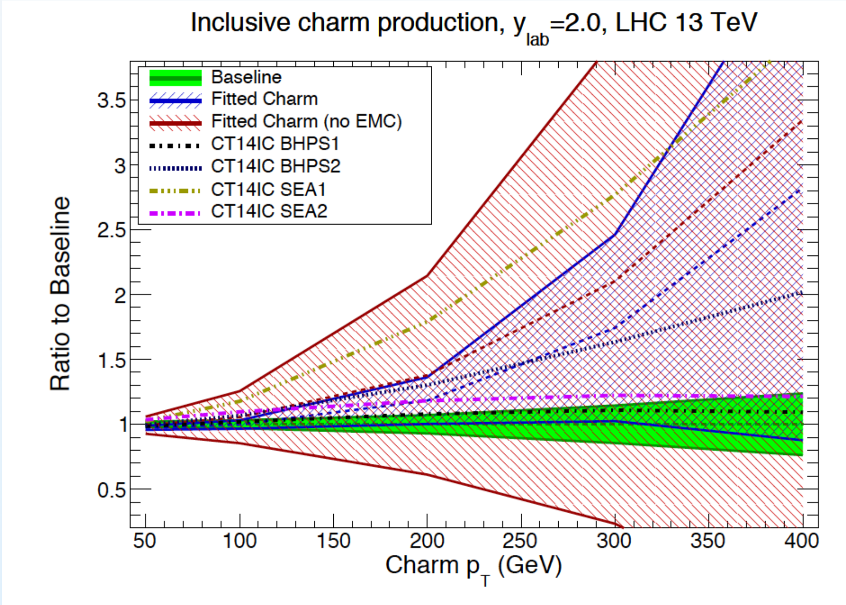


intrinsic charm: implications for the LHC

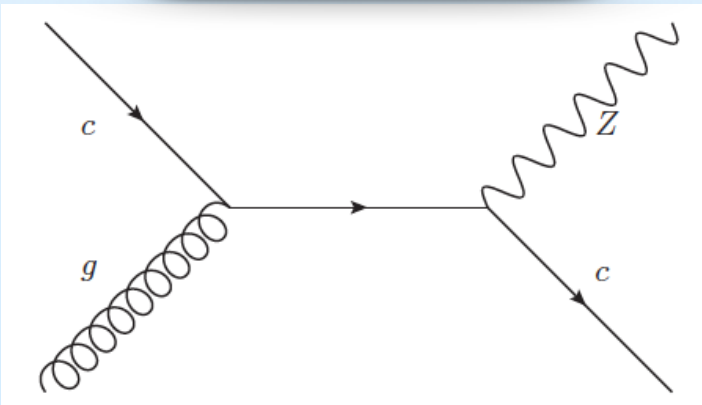
- A number of LHC processes are sensitive to the **charm content of the proton**
- To probe **large-x charm** we need either **large p_T** or **forward rapidities** production
- Within the **reach of the LHC** at Run II+III

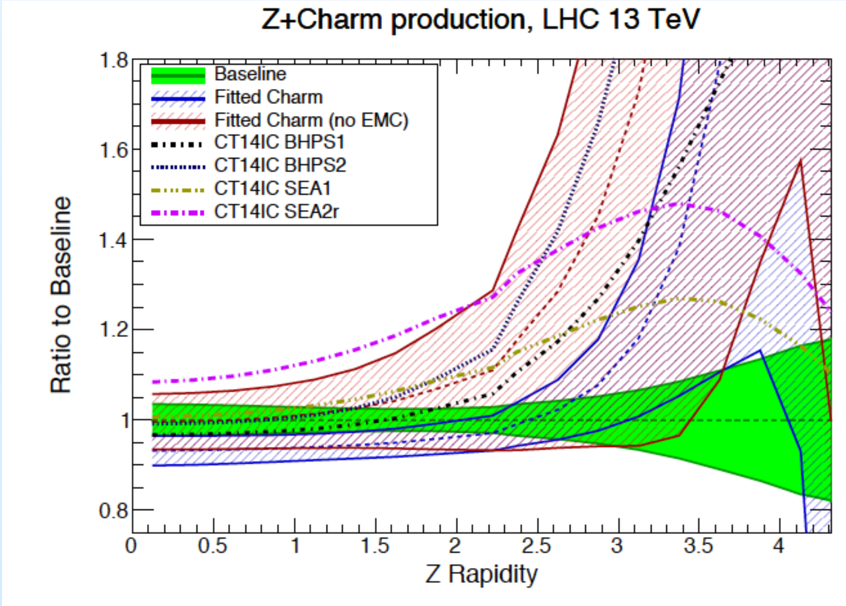
D meson production

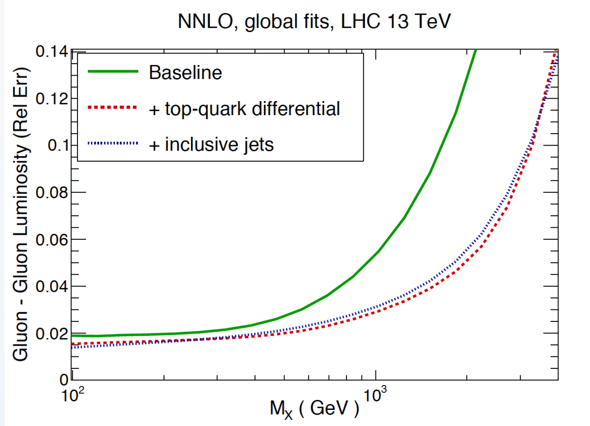




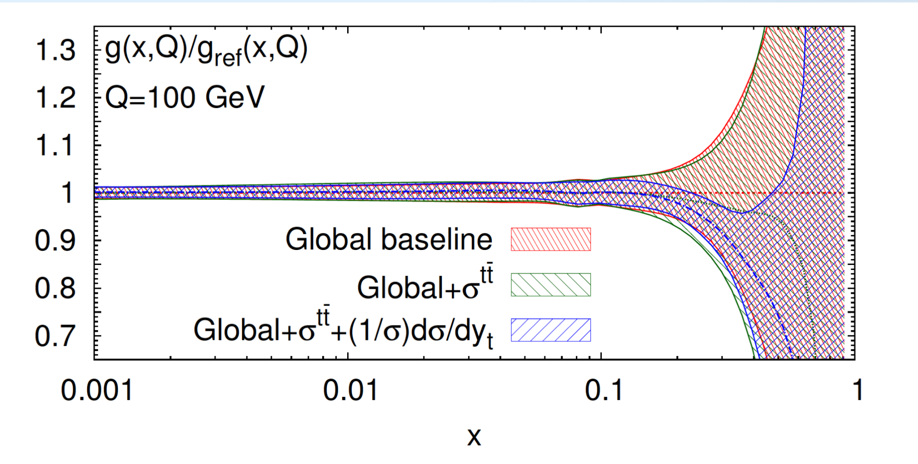
Z+charm production







Pinning down the large-x gluon with NNLO top differential distributions



Czakon, Hartland, Mitov, Nocera, Rojo 16

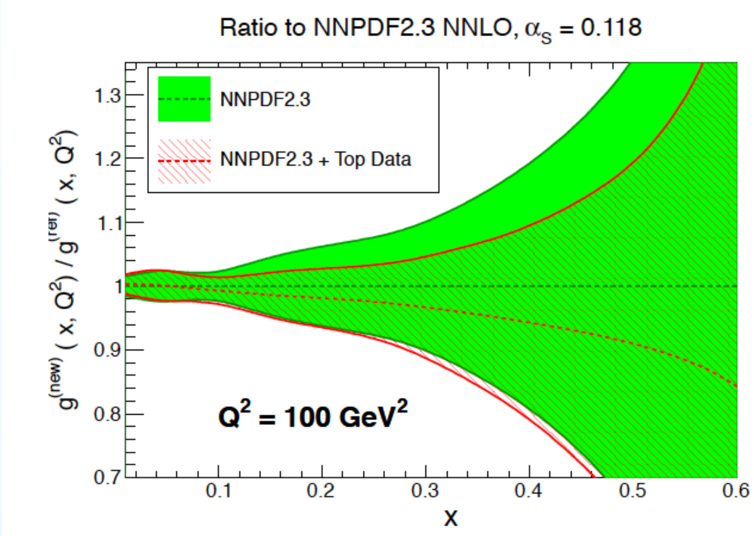
Why top-pair differential data in PDF fits?

- **Total cross-sections already used** in some PDF fits, using **differential measurements** will only increase constraining power

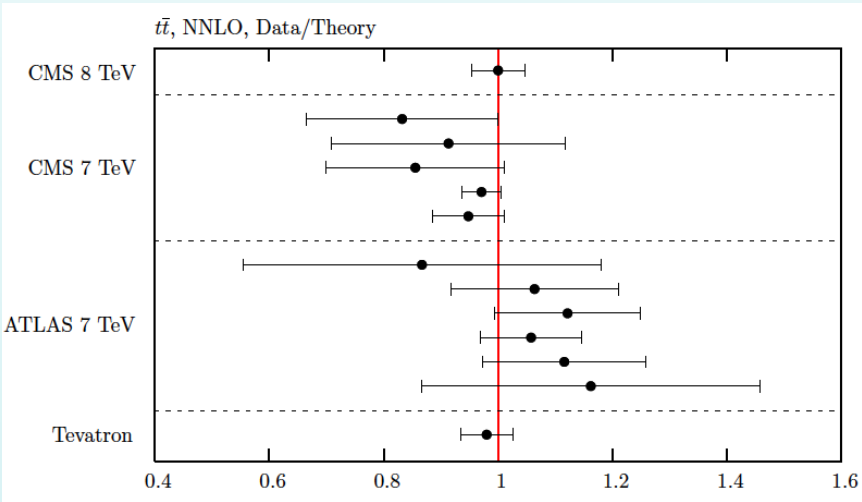
- **NNLO calculation for stable top quarks** available, together with **scale optimization,** allows for the use of state-of-the art theory for top data in global PDF fits

- Available p**recise data from ATLAS and CMS at 8 TeV** with full breakdown of statistical and systematic uncertainties

- Study **interplay with inclusive jet production** measurements (NNLO calculation very recently completed)



Czakon, Mangano, Mitov, Rojo 13



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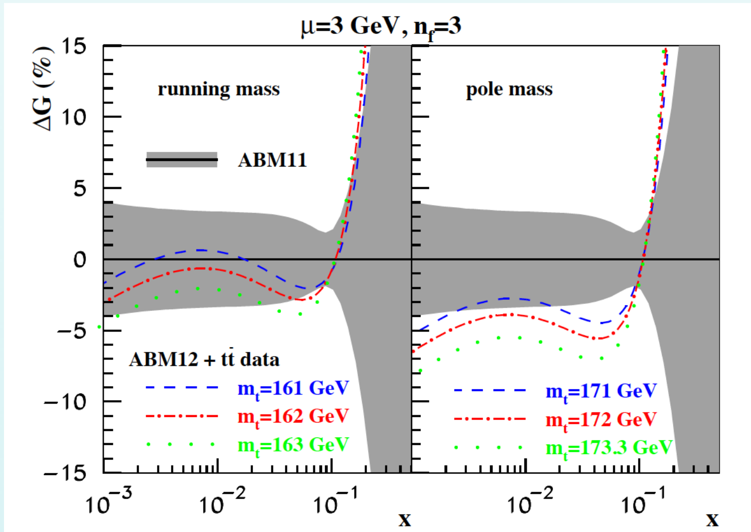


ABM12

PDF fit settings

NNPDF Collaboration 14-16

- Based on the **NNPDF3 global analysis framework**
- Baseline fit based on the **same dataset as in NNPDF3.0**, except for:
  - ☑ Separate H1 and ZEUS data from HERA-II replaced by **final HERA combination**
  - ☑ **Jet data excluded** (since NNLO for inclusive jets only very recently available) *Currie, Glover, Pires 16*
- **NNLO theory,** with $\alpha_S(m_Z)$ =0.118, $\mathbf{m_{top}}$**=173.3 GeV**, m_{charm} =1.51 GeV, m_{bottom}=4.92 GeV
- Optimized choice of **factorization and renormalization scales**

Czakon,Heines, Mitov 16

For y_t, y_{tt}, m_{tt}

$$\mu_R = \mu_F = \mu = H_T/4\,, \qquad H_T \equiv \sqrt{m_t^2 + \left(p_T^t\right)^2} + \sqrt{m_t^2 + \left(p_T^{\bar{t}}\right)^2}$$

For p^t_T

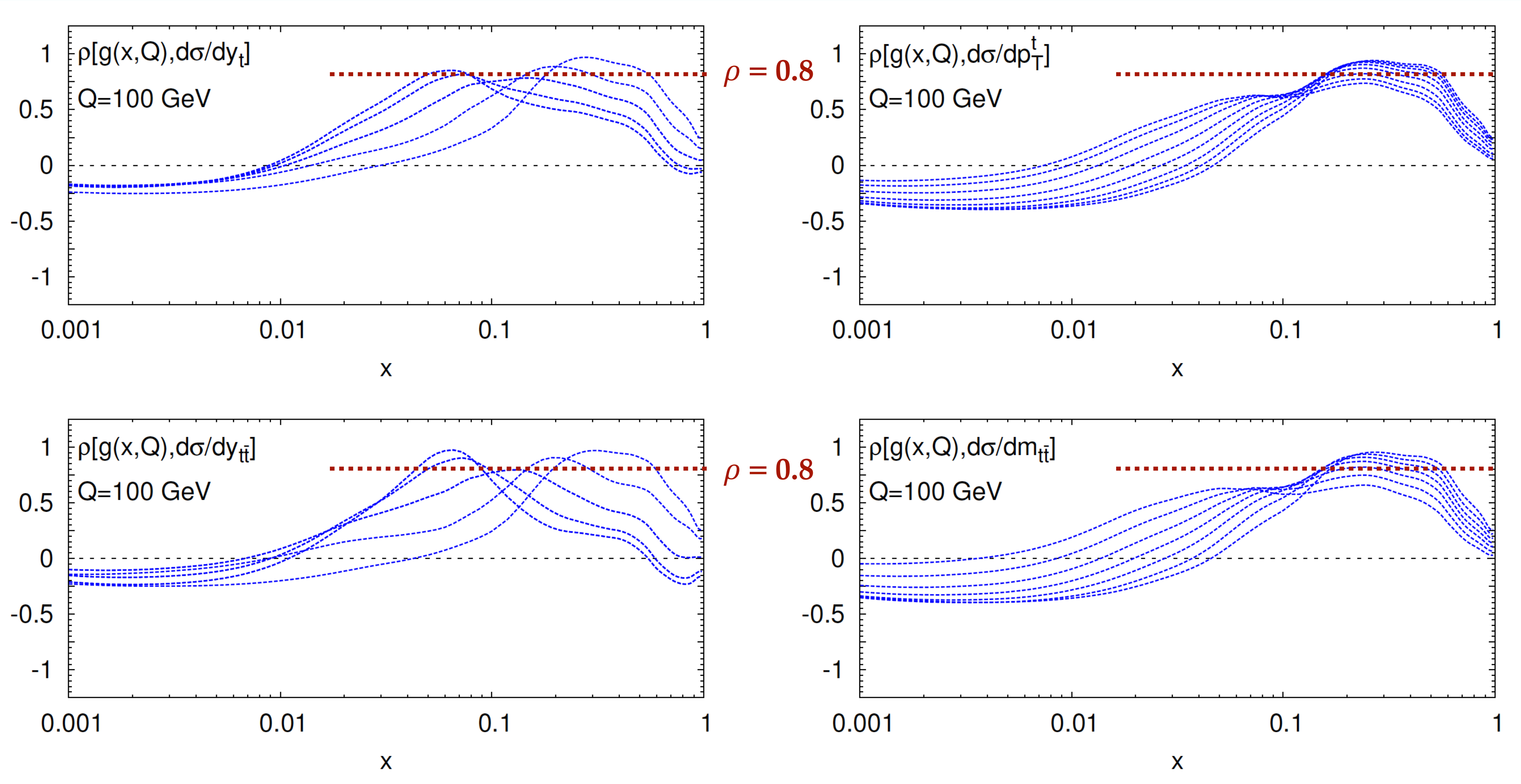
$$\mu'_R = \mu'_F = \mu' = \sqrt{m_t^2 + \left(p_T^t\right)^2}\Big/2$$

- Fast NLO calculations based on **Sherpa/MCgrid**, supplemented by bin-by-bin **NNLO/NLO K-factors**
- All available sources of **statistical and systematic correlated uncertainties** accounted for

Sensitivity to the large-x gluon

- The **correlation coefficient** between the gluon PDF and each of the bins of the four kinematic distributions determines the region of Bjorken-x where **available data has sensitivity**

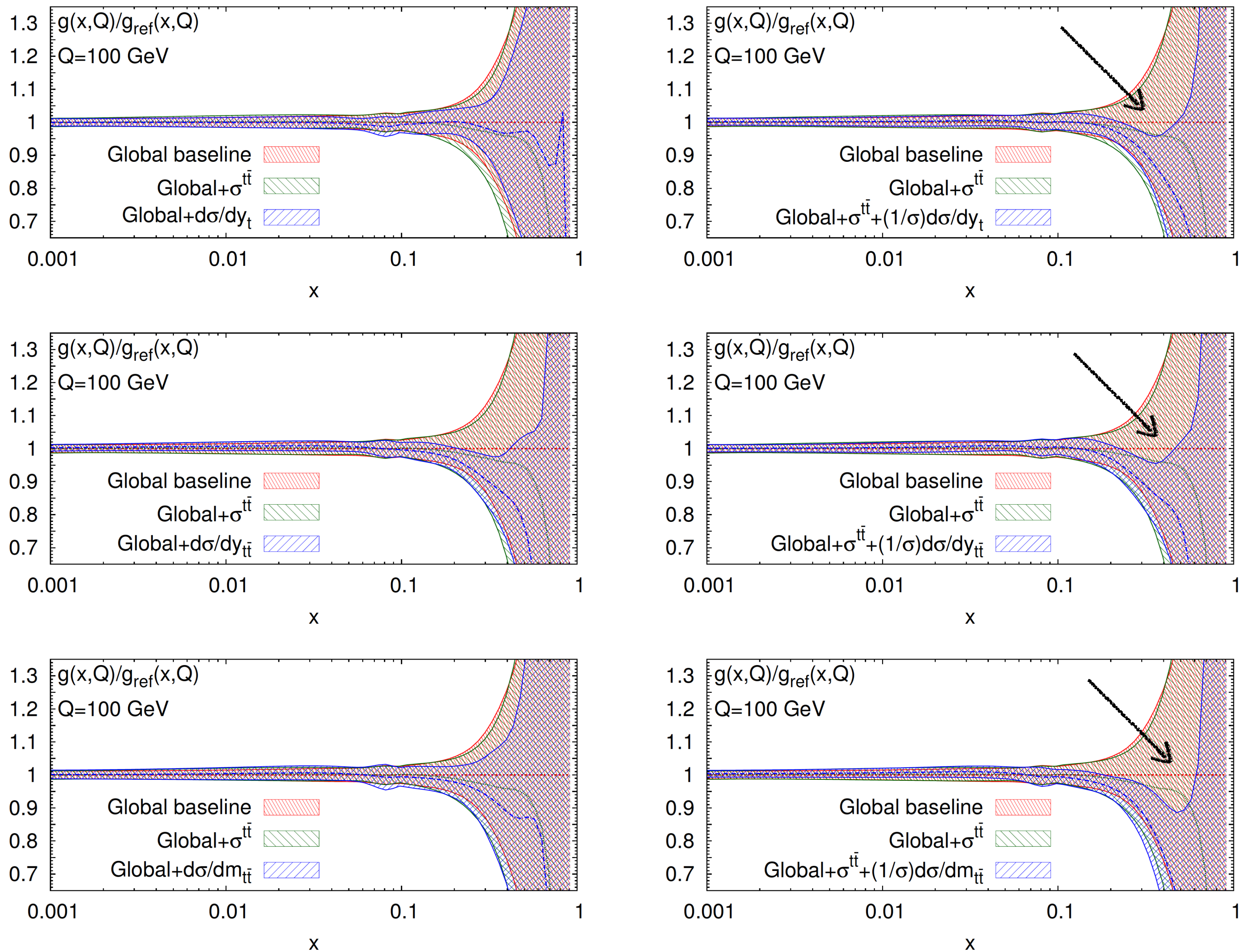
- Large values, $\rho \geq$ **0.8**, of the correlation for **0.07 < x < 0.6,** representing a significant improved over the **coverage in x of inclusive cross-section measurements**



Impact on the large-x gluon

Absolute

Normalized



Which top-quark differential data to fit?

- Fit **normalized distributions**, which exhibit somewhat enhanced constraining power

- Among these, select the distributions with which lead to **larger reduction of PDF uncertainties**

- Require **good agreement between data and theory, $\chi^2/N_{dat} \sim 1$,** to avoid distorting the fit in the case of (still not understood) tensions between ATLAS and CMS

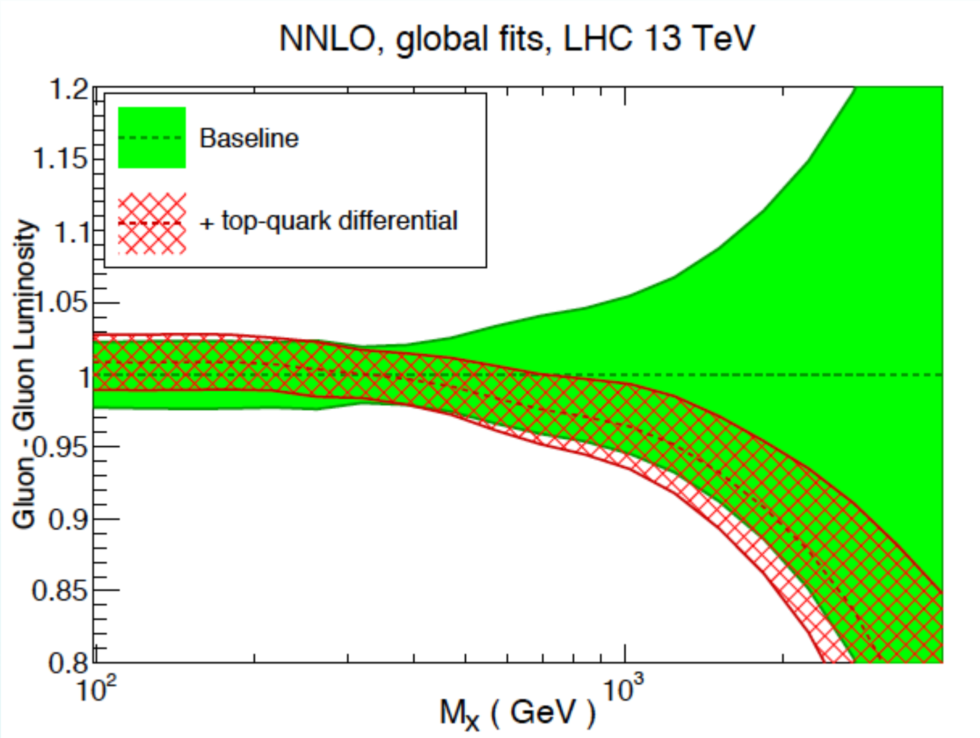
- Include **one kinematic distribution from ATLAS** and **a different one from CMS**, to achieve better kinematical coverage on the gluon PDF

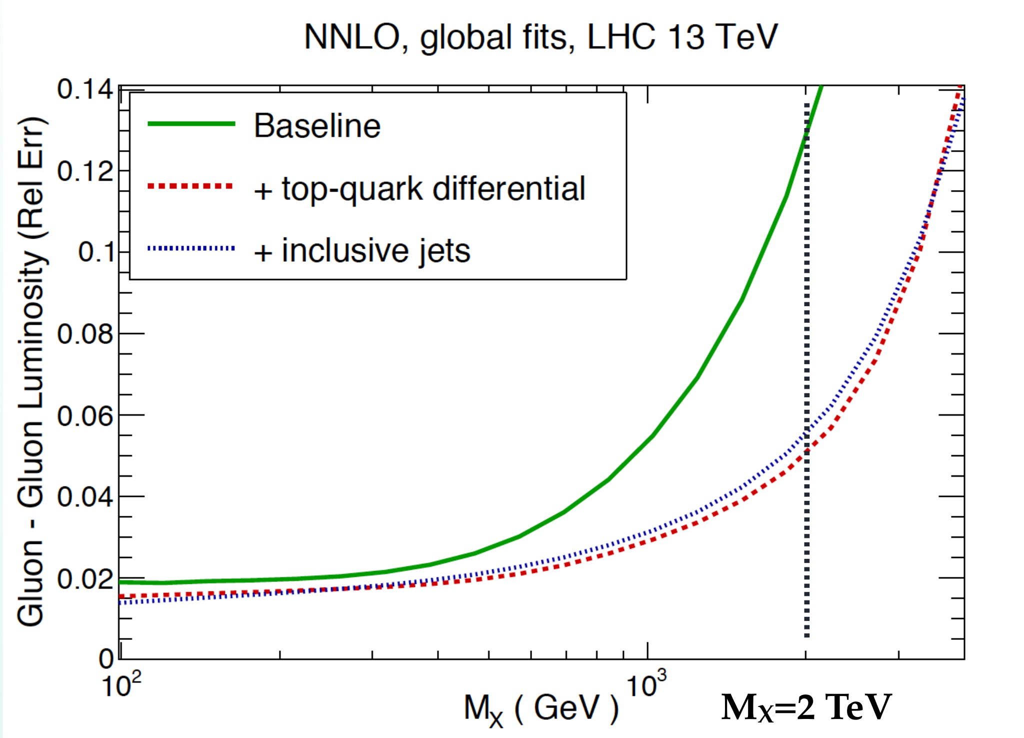
Our recommendation for the 8 TeV lepton+jets differential distributions:

- the normalized top-quark rapidity distribution $(1/\sigma)d\sigma/dy_t$ from ATLAS;
- the normalized top-quark pair rapidity distribution $(1/\sigma)d\sigma/dy_{t\bar{t}}$ from CMS;
- and the total inclusive cross-section $\sigma_{t\bar{t}}$ from ATLAS and CMS at $\sqrt{s} = 8$ TeV.

Other possible choices, within the above guidelines, would lead to consistent results, since the **pull on the large-x gluon is similar for all the ATLAS and CMS distributions** (even when $\chi^2/N_{dat} \gg 1$)

Impact on the large-x gluon





- Significant reduction of PDF uncertainties in the **gluon-gluon luminosity at high invariant masses**
- For instance, for **M_X=2 TeV**, the PDF uncertainties decrease **from 13% to 5%**
- Remarkably, the **constraints from top differential data** in the global fit are comparable to those from **inclusive jets**, despite coming from much fewer data points: **N_{dat} =17 for top vs N_{dat} =470 for jets**

Impact on differential distributions

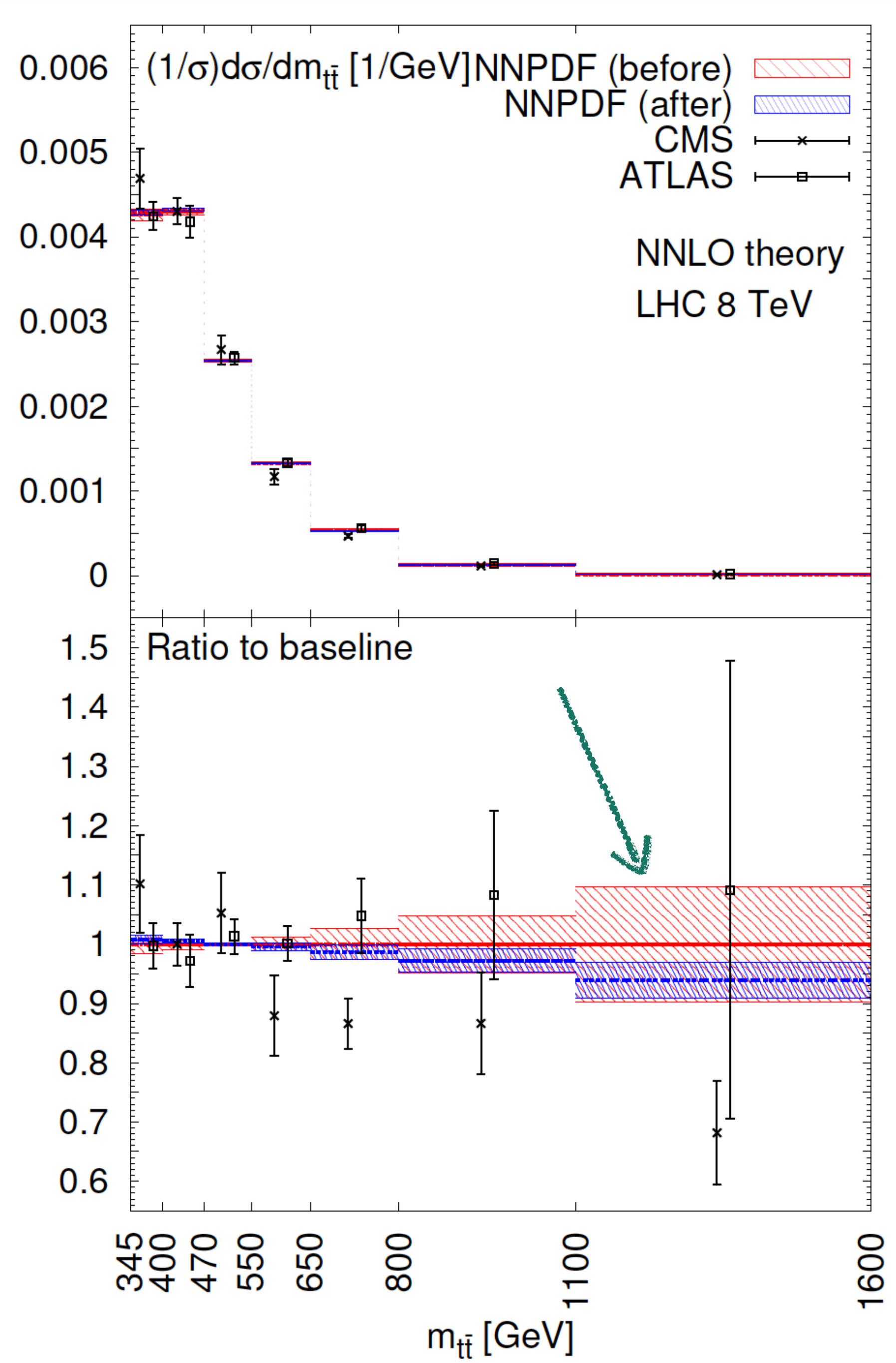
- PDF uncertainties reduced by more than a factor two for **$m_{tt} \gtrsim$ 500 GeV**

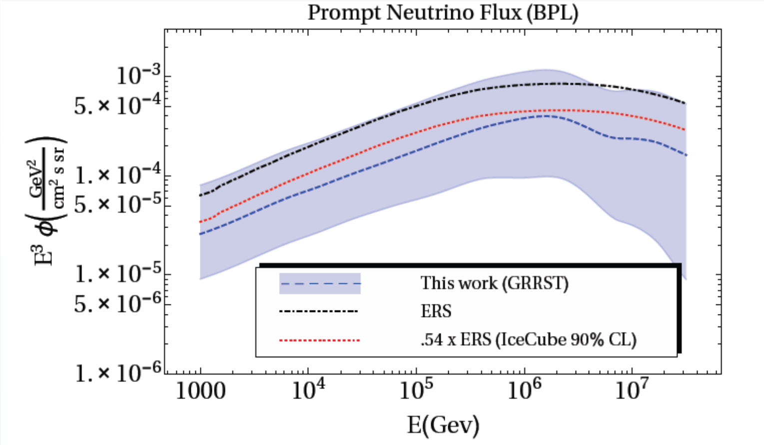
- Similar improvements for **gluon-driven processes,** either SM or BSM, at high masses

- Self-consistent program to **use top data to provide improved theory predictions**

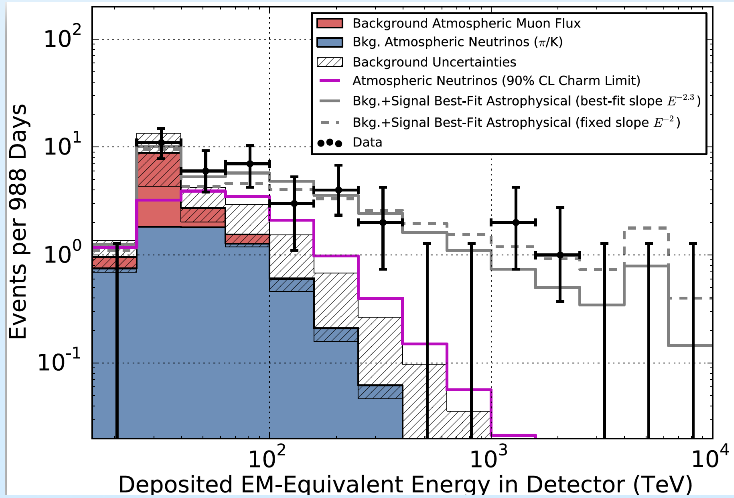
- Our **choice of fitted distributions** (y_t and y_{tt}) reduce the **risk of *BSM contamination*** (kinematical suppression of heavy resonances) which can show up instead in the tails of the m_{tt} and p^t_T distributions (whose PDF uncertainties are now greatly reduced)

Improved sensitivity to BSM dynamics with top-quark final states





From hadron colliders to neutrino telescopes



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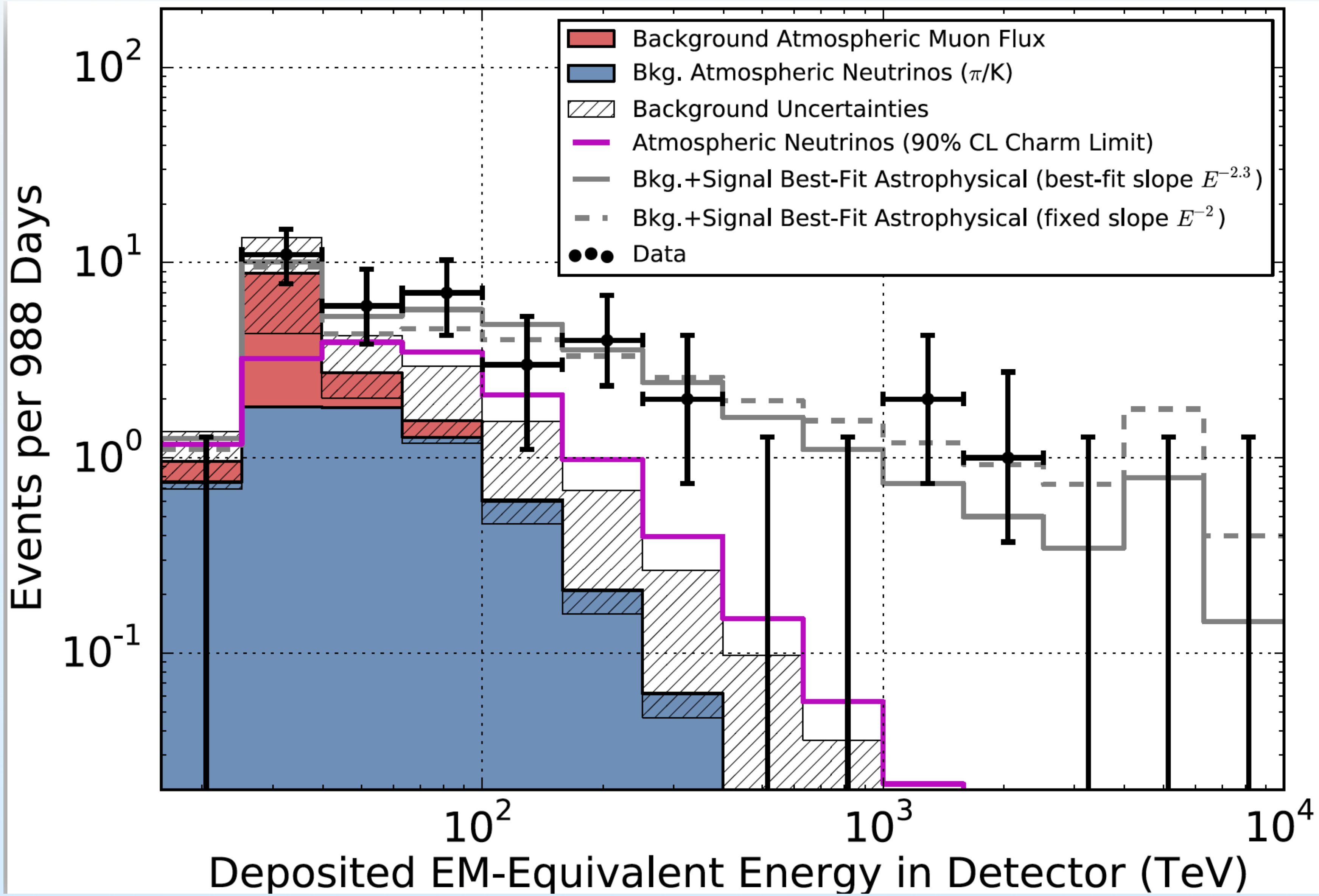
From the LHC to Neutrino Telescopes

Observation of Ultra-High Energy (UHE) neutrino events at IceCube heralds start of **Neutrino Astronomy**

New window to the Universe, but interpretation of IceCube data requires **control over backgrounds**



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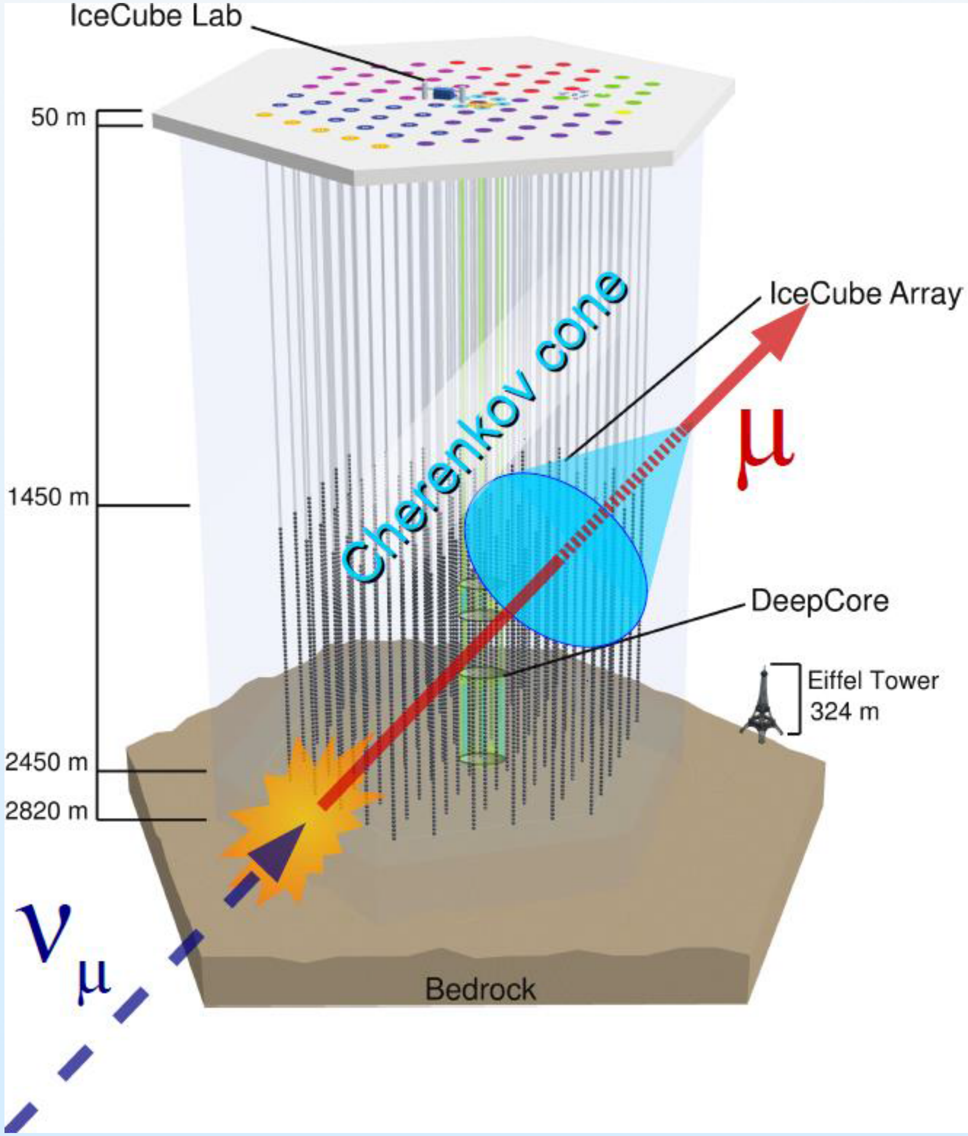
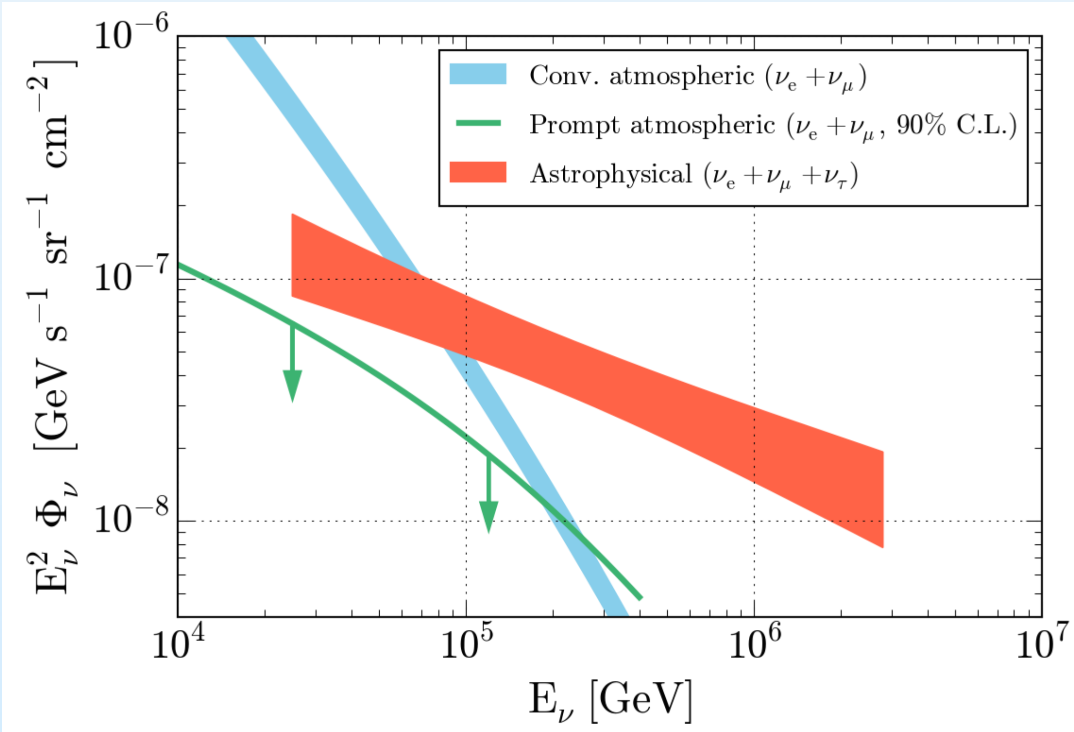


- The main **background for astrophysical neutrinos at IceCube** is the flux of neutrinos from the **decays of charm mesons** in cosmic ray collisions in atmosphere
- Theoretically, this **prompt neutrino flux** is affected by large uncertainties: very small-x PDFs, very low scales - can pQCD be applied?
- Use **LHC data itself** to pin down this prompt flux



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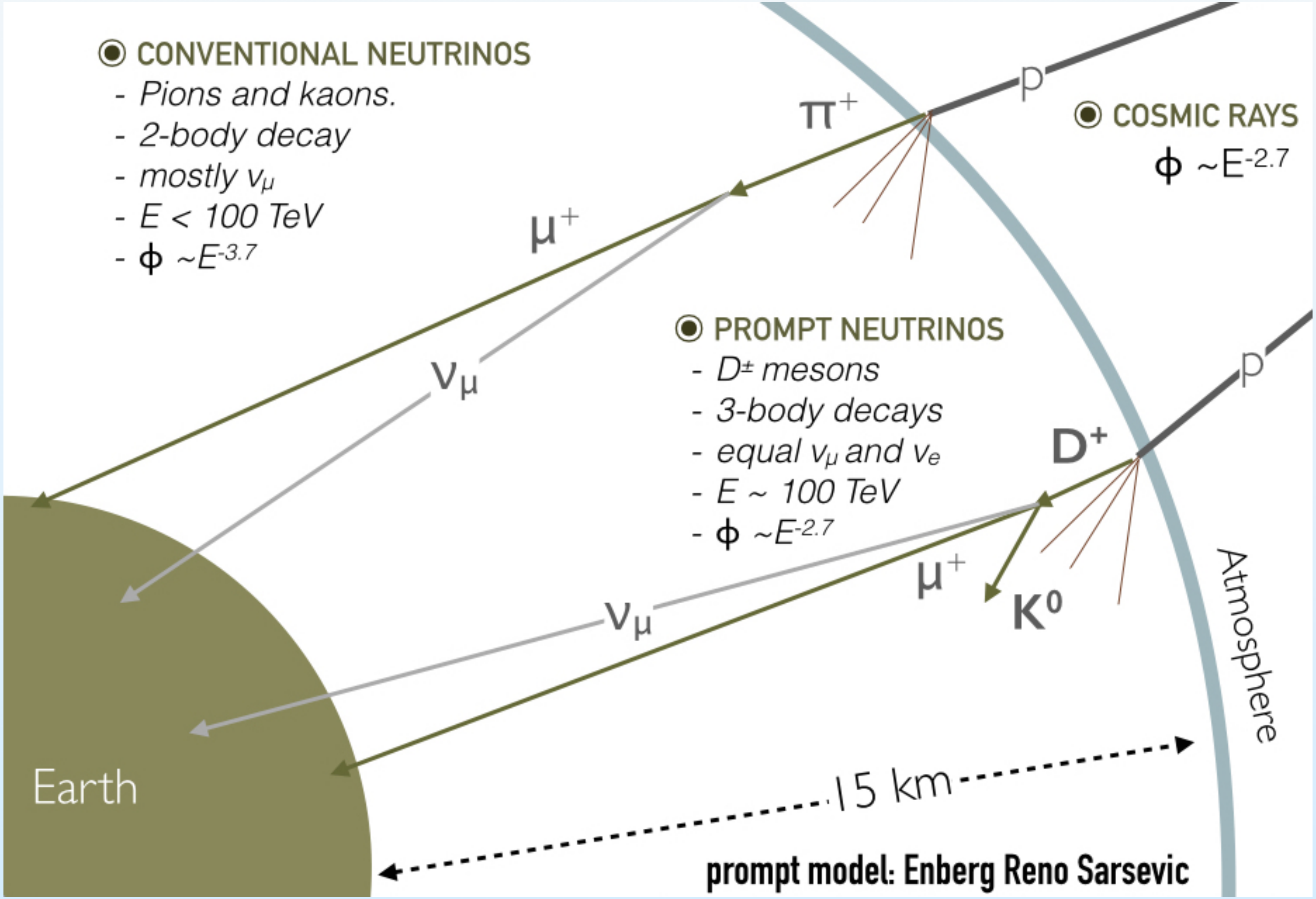

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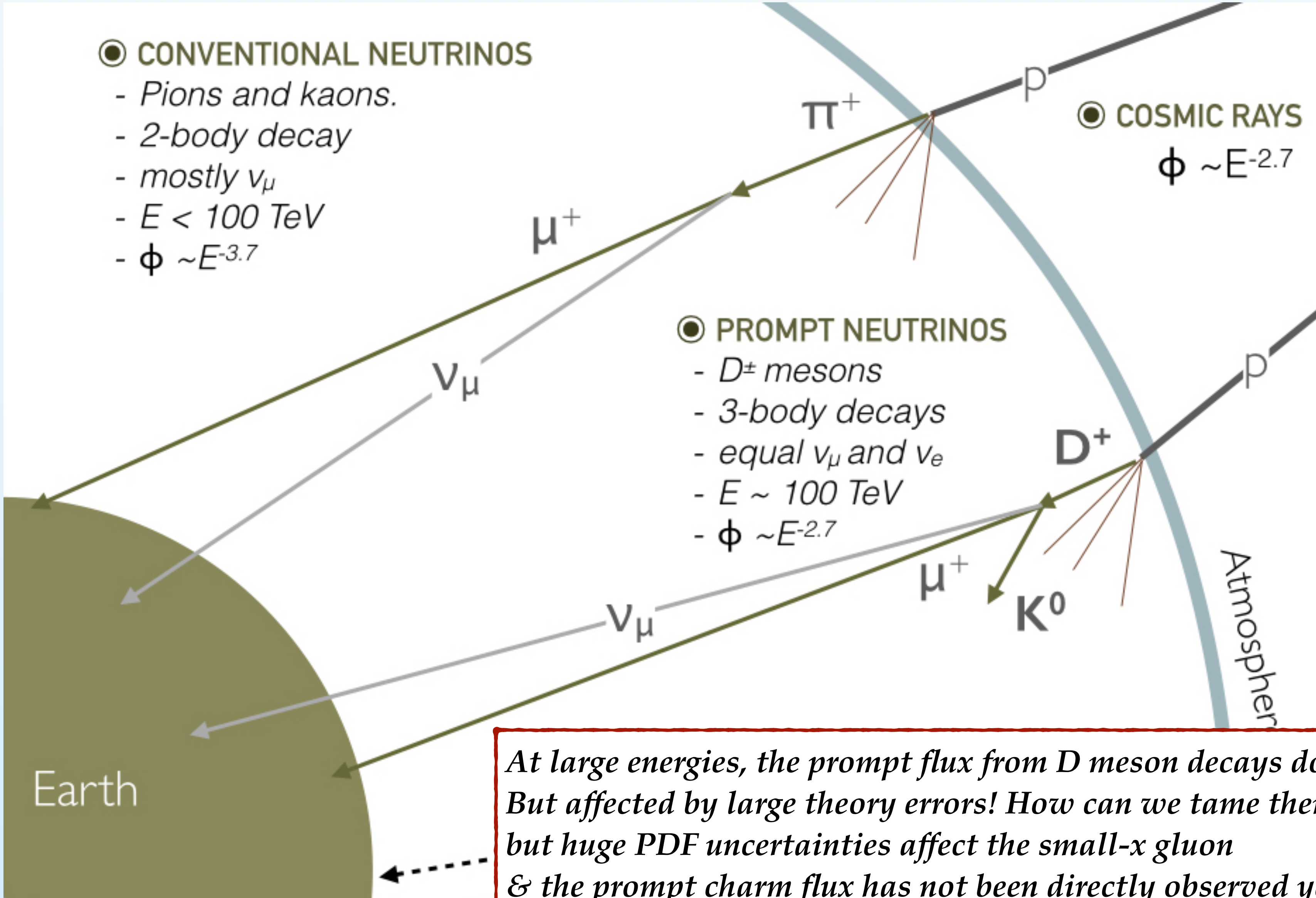


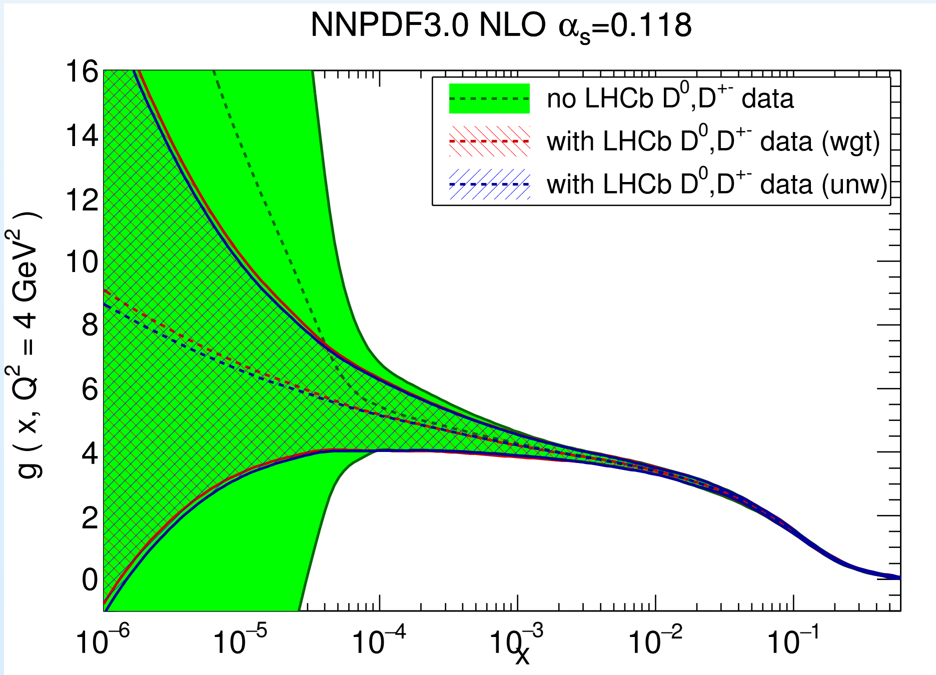
At large energies, the prompt flux from D meson decays dominates
But affected by large theory errors! How can we tame them?
but huge PDF uncertainties affect the small-x gluon
& the prompt charm flux has not been directly observed yet …

From the LHC to Neutrino Telescopes

Use **collider data** to provide state-of-the-art **predictions for backgrounds at Neutrino Telescopes**

The **LHCb forward charm production data** at 7 TeV cover the **same kinematical region** as prompt neutrino production in high-energy cosmic rays

- ☑ Include **7 TeV LHCb forward charm production data** in the global fit
- ☑ Validate **perturbative QCD calculations** on collider data, and **constrain the small-x gluon**
- ☑ Compute optimised predictions for **prompt neutrino fluxes at high energies**



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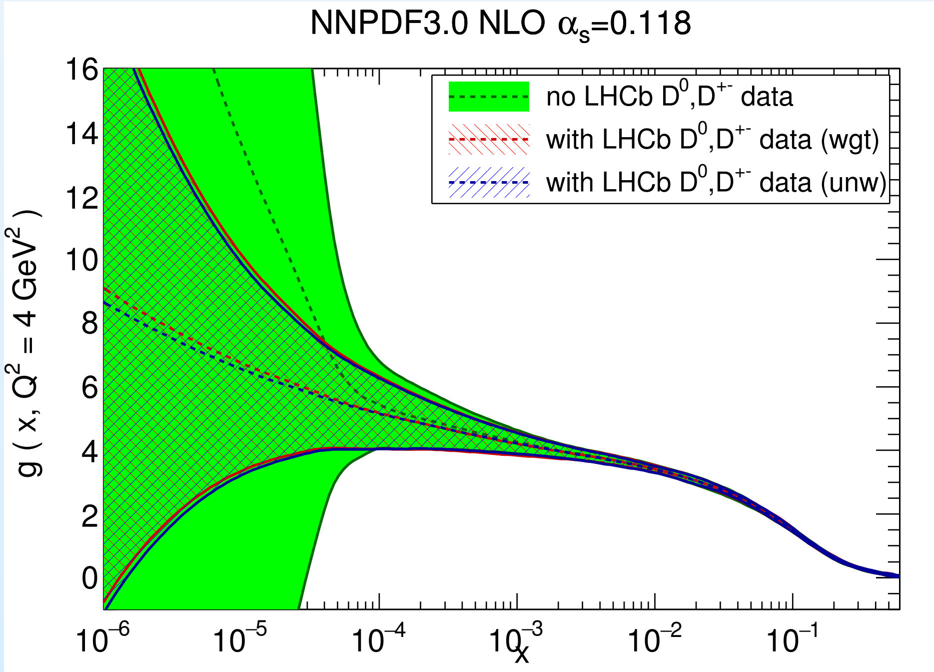

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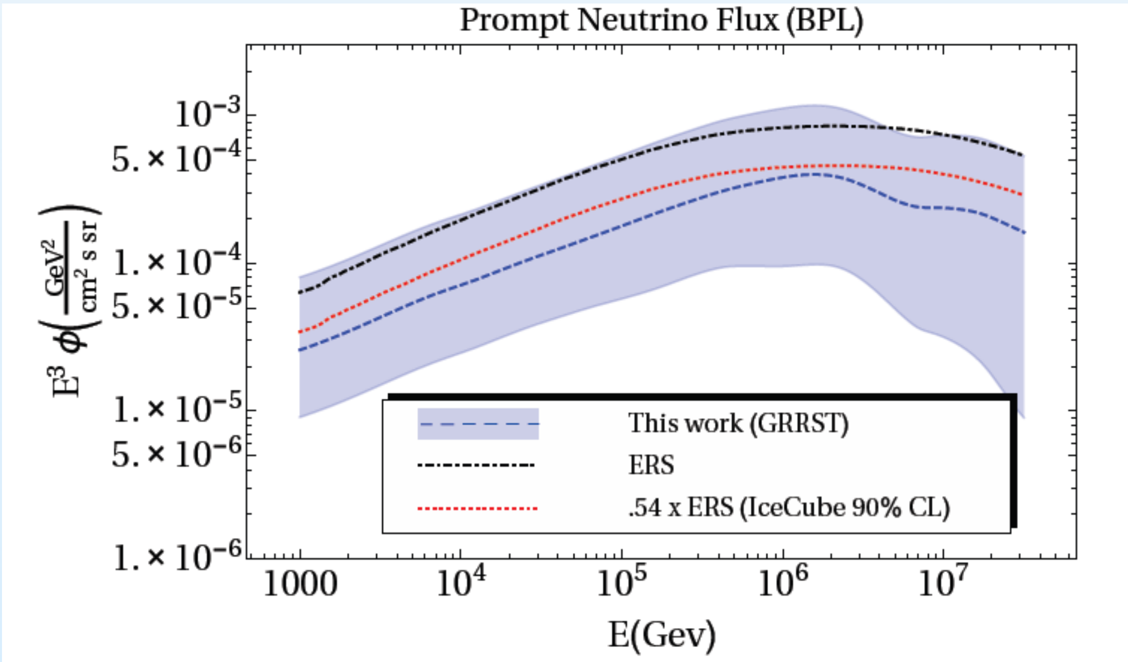

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We predict that detection of the prompt neutrino flux should be within IceCube reach

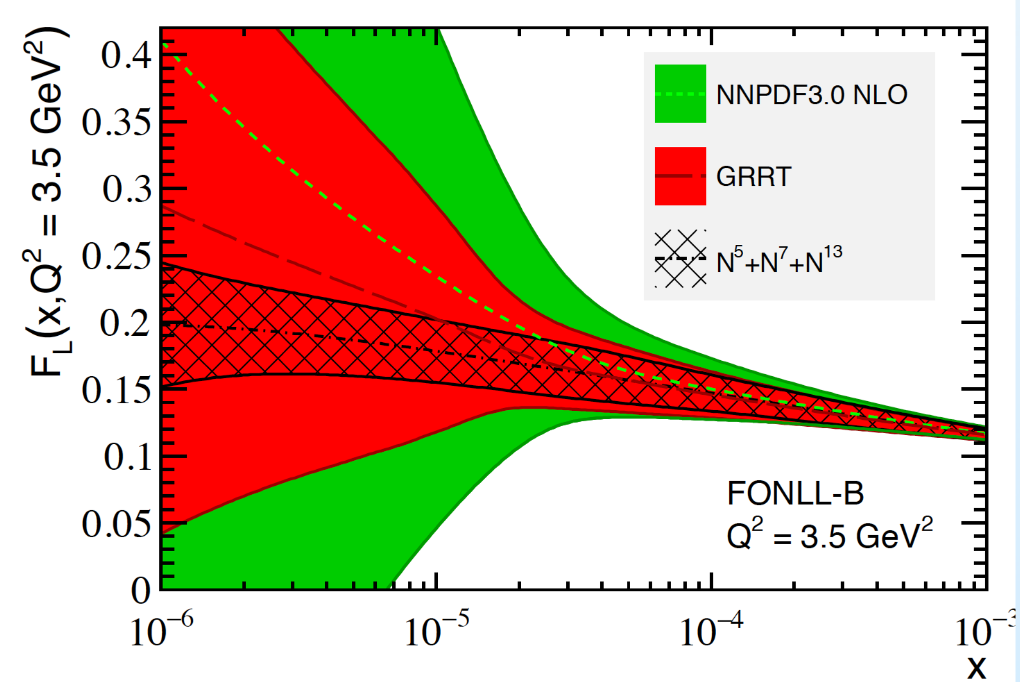
Precision determination of the small-x gluon

- Recently LHCb presented charm production data at **5 and 13 TeV**
- Different options to fit data, either normalised distributions or cross-section ratios (13 TeV / 7 TeV and 13 TeV / 5 TeV)
- As compared to NNPDF3.0, we achieve up to a **factor 10 reduction on the small-x gluon** uncertainties down to **x ≲ 10^{-6}**
- High-precision predictions of UHE neutrino-nucleus cross section for energies up to **$E_\nu \simeq 10^6$ PeV**

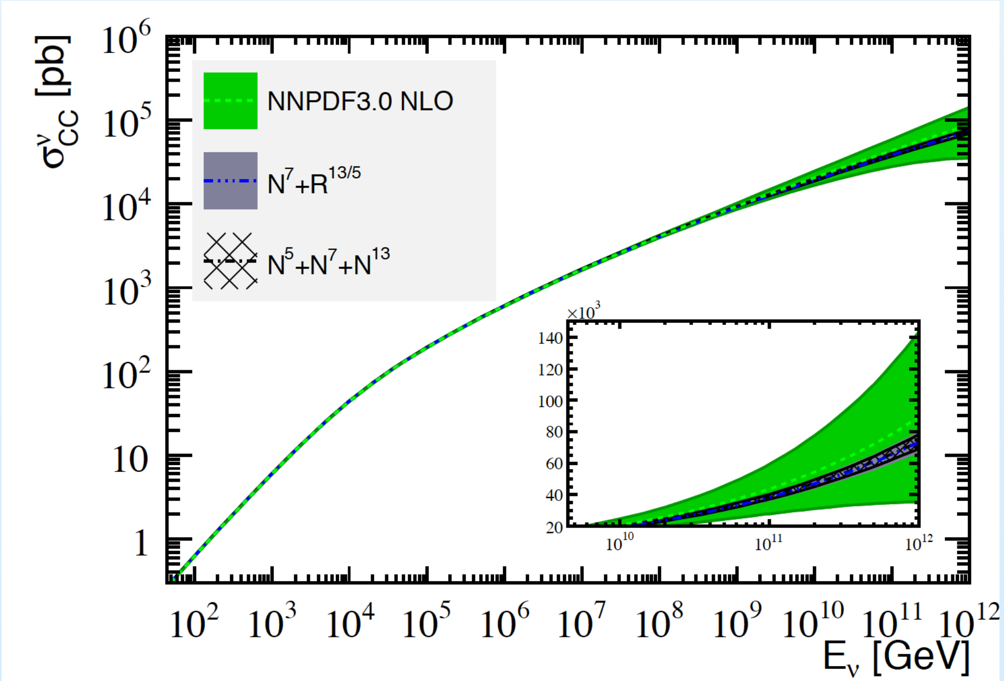
$$N_X^{ij} = \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_{\mathrm{ref}}^D d(p_T^D)_j}$$

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

F_L at future high-energy lepton-proton colliders



Ultra-high energy neutrino-nucleus cross-section



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Summary and outlook

- **Parton Distributions** are an essential ingredient for **LHC phenomenology**

- **At the LHC,** accurate PDFs are required for

  - ☑ **Precision SM measurements** and determination of **fundamental parameters** like **W mass**

  - ☑ **The characterisation of the Higgs sector**

  - ☑ **Searches for New Physics** beyond the Standard model

  - ☑ **Monte Carlo event generators** and higher-order **perturbative calculations**

- The NNPDF approach provides state-of-the art Parton Distributions based on a **robust, unbiased methodology,** the most updated **theoretical information** and all the relevant experimental information **including LHC data**

- The recent years have seen a **revolution** in PDF fits: PDFs with **LHC data**, PDFs with **QED corrections**, PDFs with **all-order resummations**, PDFs tailored for **neutrino telescopes,** and much more

Beyond unpolarized (NN)PDFs

Unpolarized proton structure: *NNPDF3.0*
LHC phenomenology
Higgs boson characterisation
New Physics searches

Polarized proton structure: *NNPDFpol1.1*
The proton spin puzzle
The polarization of gluons

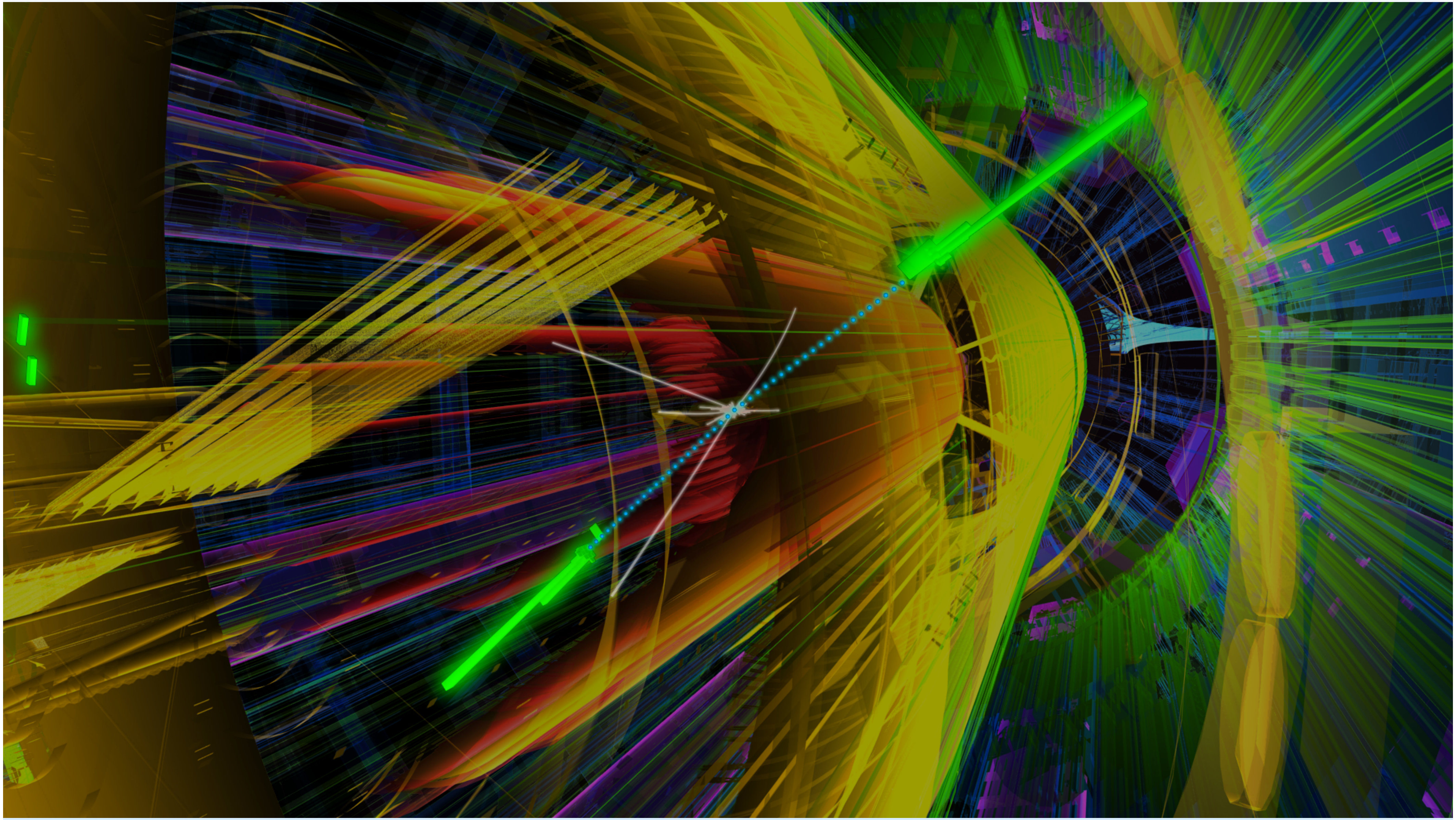
Fragmentation Functions: *NNFF1.0*
inclusive hadron production
in DIS, pp, p+Pb, Pb+Pb collisions
in preparation

Nucleon Structure

Hadron Fragmentation

Nuclear parton distributions: *nNNPDF1.0*
from nuclear DIS and LHC p+Pb data
QCD in the high density regime
Quark-Gluon Plasma characterisation
in preparation

Fascinating times ahead at the high-energy frontier!



we should stay tuned for news from the LHC!

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