The gluon PDF: from LHC heavy quark production to neutrino astrophysics

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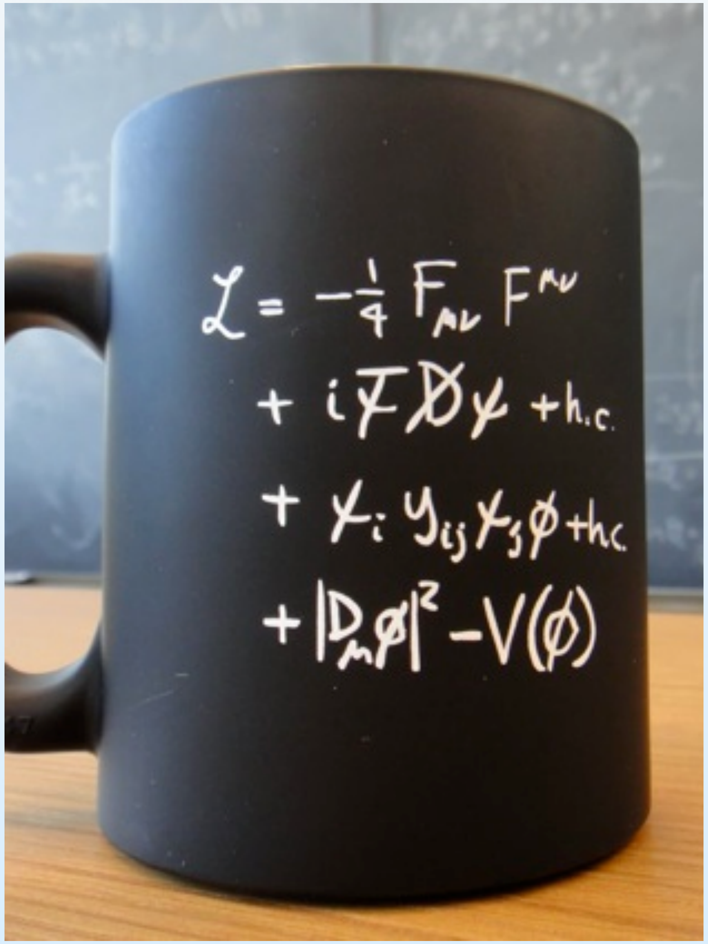
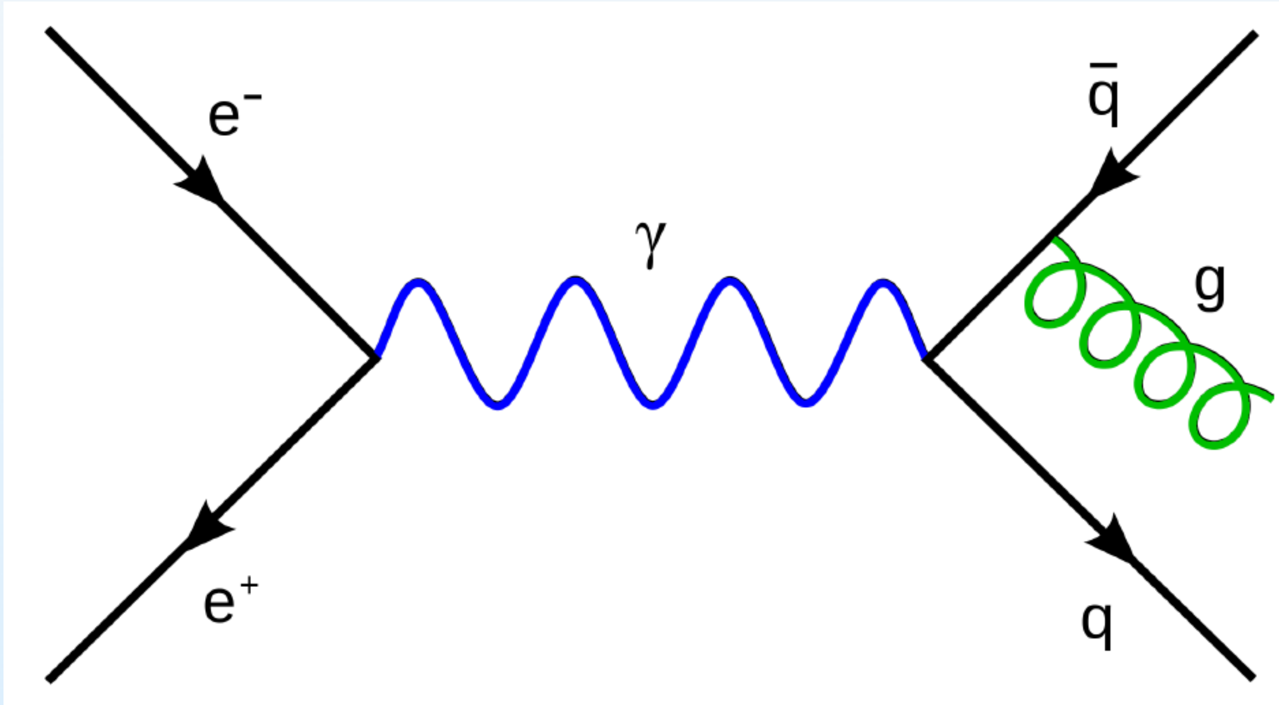
Lepton vs Hadron Colliders

High-energy **lepton colliders** such as **LEP** involve **elementary particles** without substructure

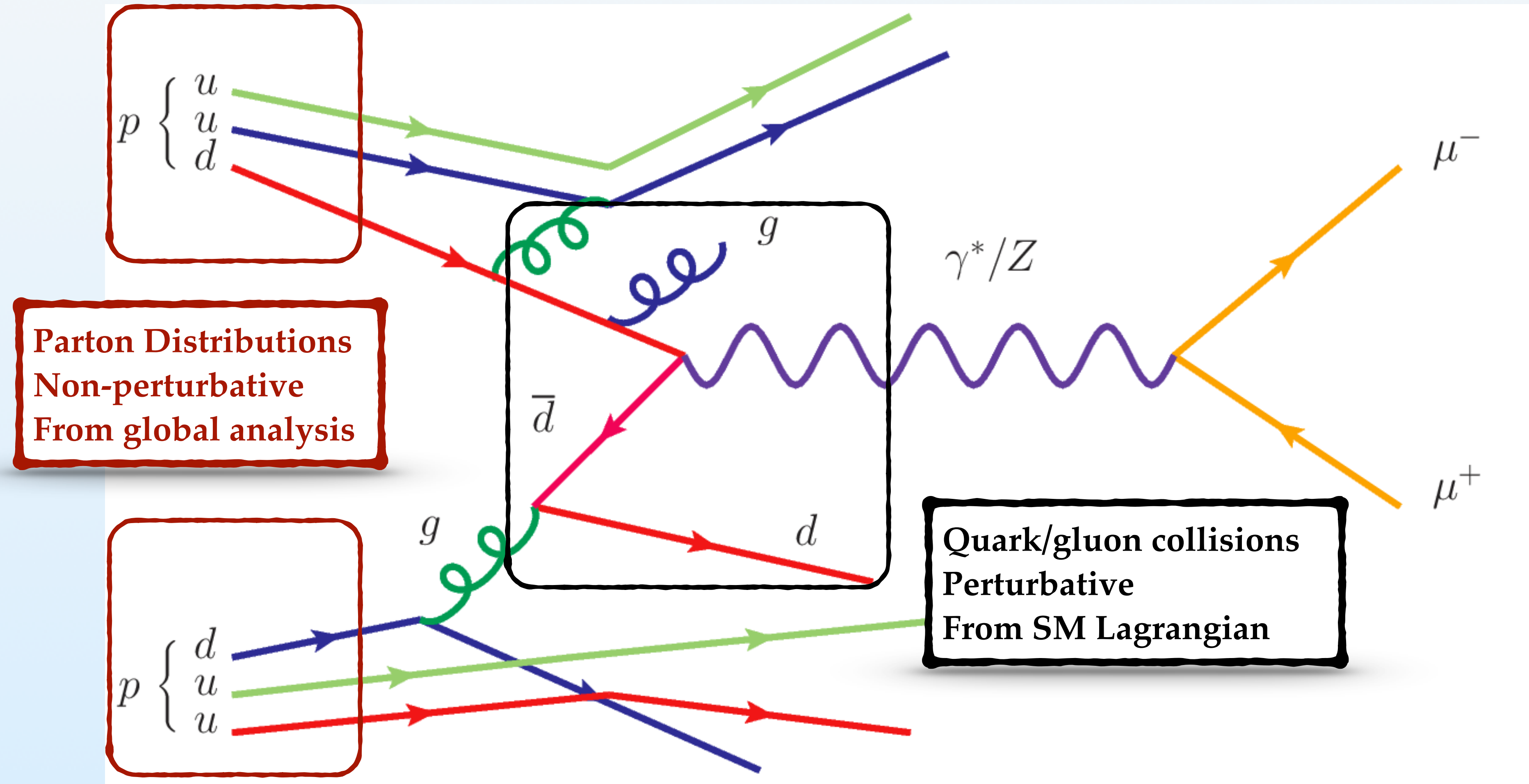




Cross-sections in lepton colliders can be computed in perturbation theory using the **Feynman rules of the Standard Model Lagrangian**

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)



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**

PDFs are determined by **non-perturbative QCD dynamics,** cannot be computed from first principles, and need to be **extracted from experimental data** with a **global analysis**

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

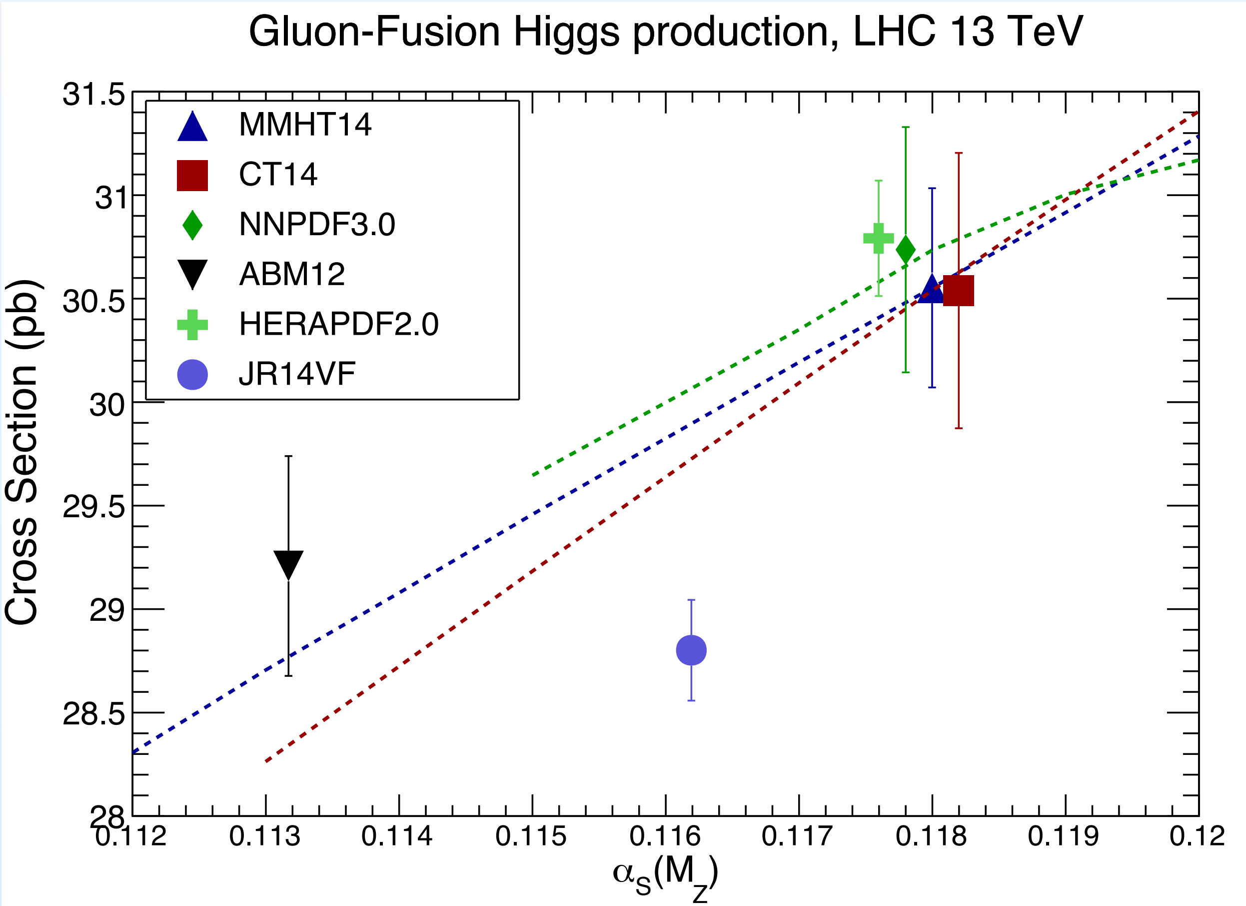
- **Dependence with quark/gluon collision energy Q** determined in perturbation theory

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

PDFs and LHC phenomenology

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

$$\sigma_{exp} = \mu_{bsm} \cdot \sigma_{SM} = \boxed{\mu_{bsm}} \cdot \sigma_{gg\to h} \cdot \boxed{g(x_1, m_h) \cdot g(x_2, m_h)}$$



Higgs Cross-Section Working Group Yellow Report 4, 16

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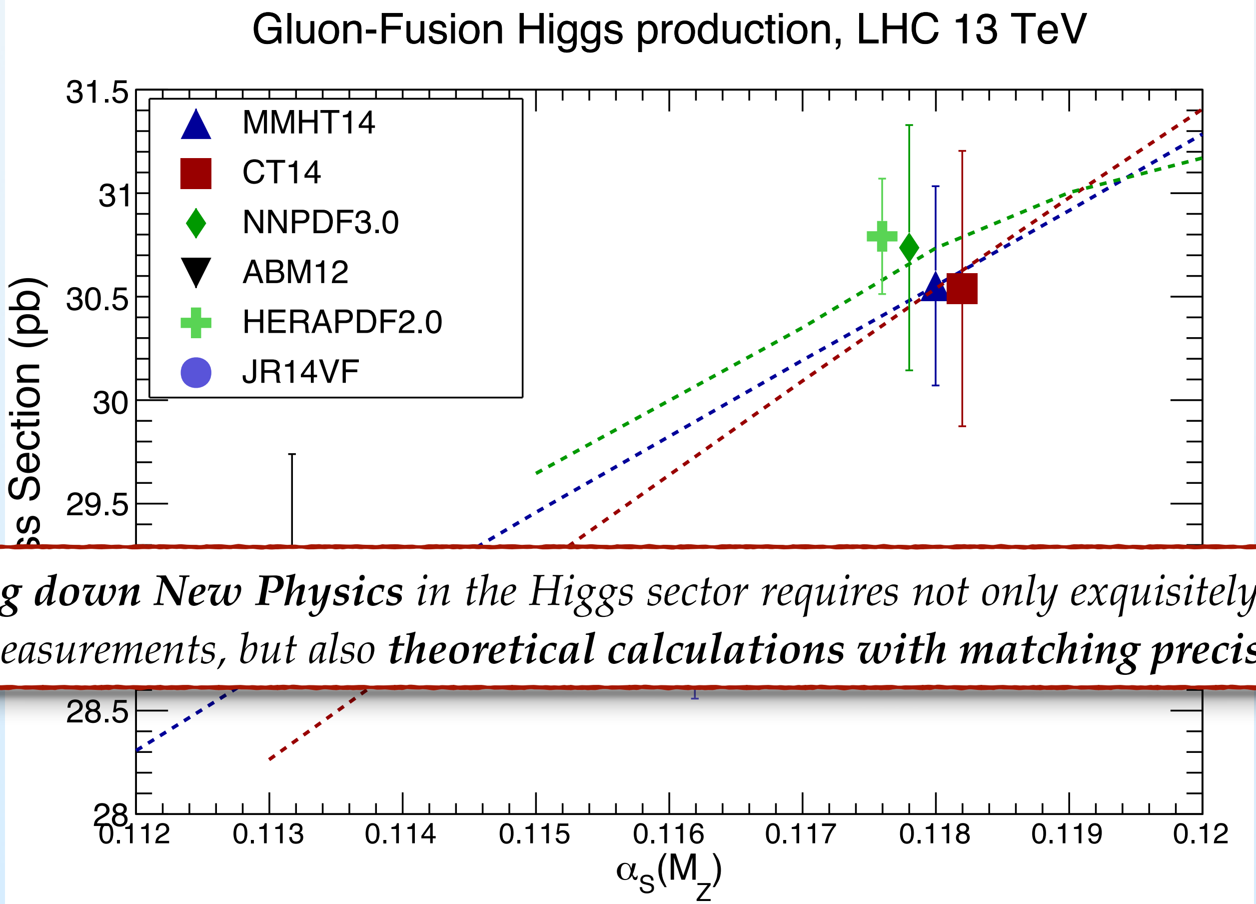

Pinning down New Physics *in the Higgs sector requires not only exquisitely precise LHC measurements, but also* ***theoretical calculations with matching precision***

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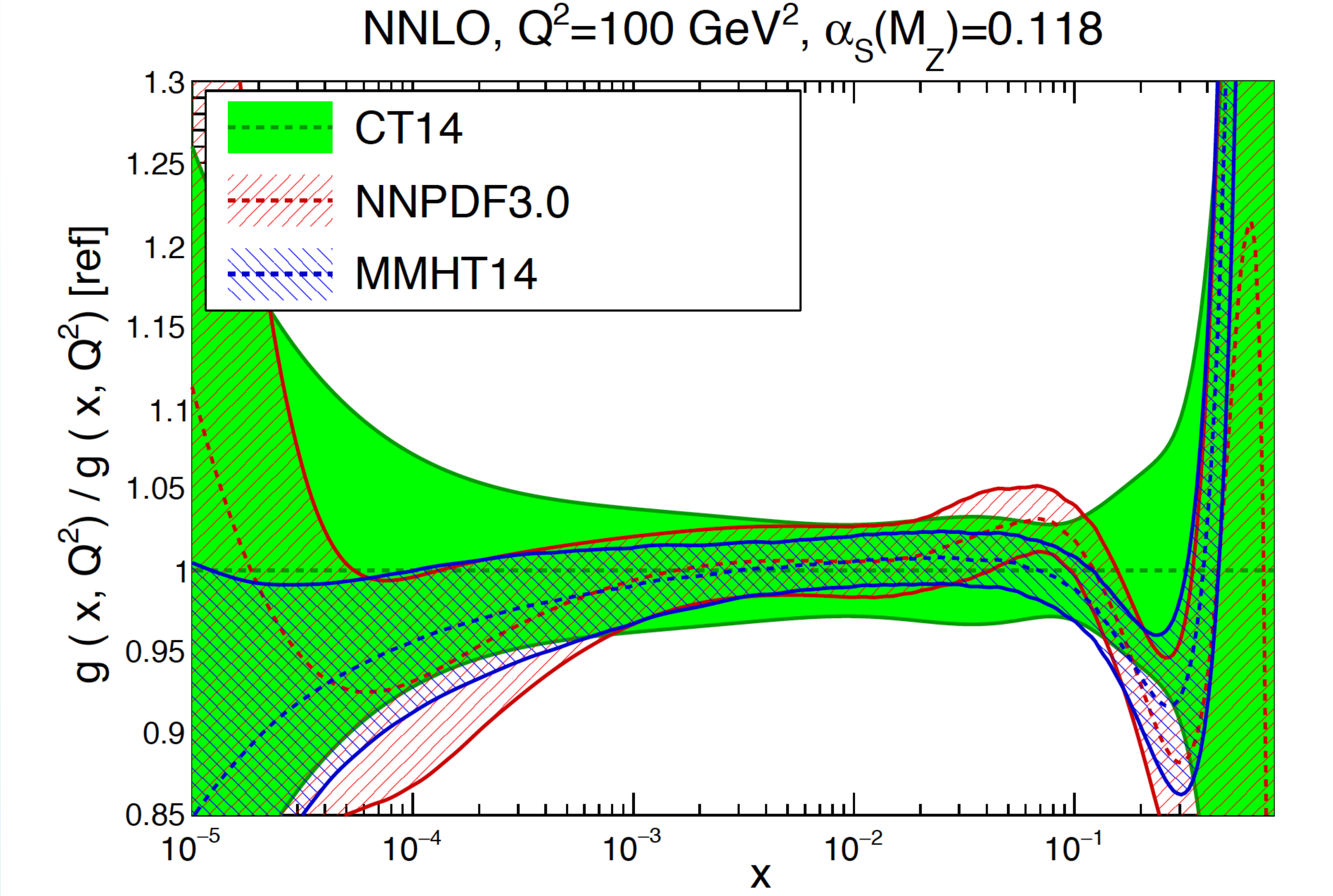
One glue to bind them all



A *family portrait* of the gluon, circa 2015

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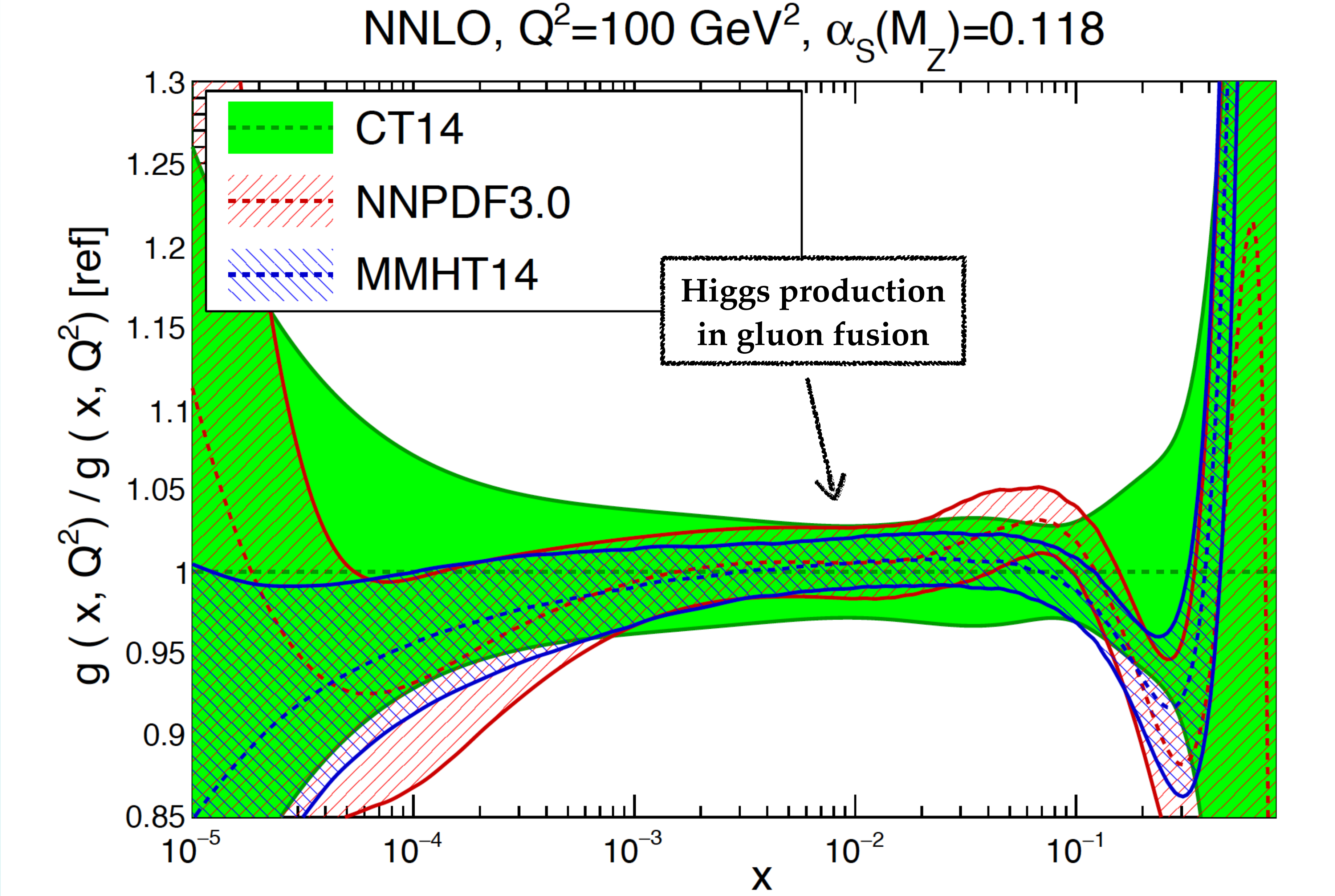

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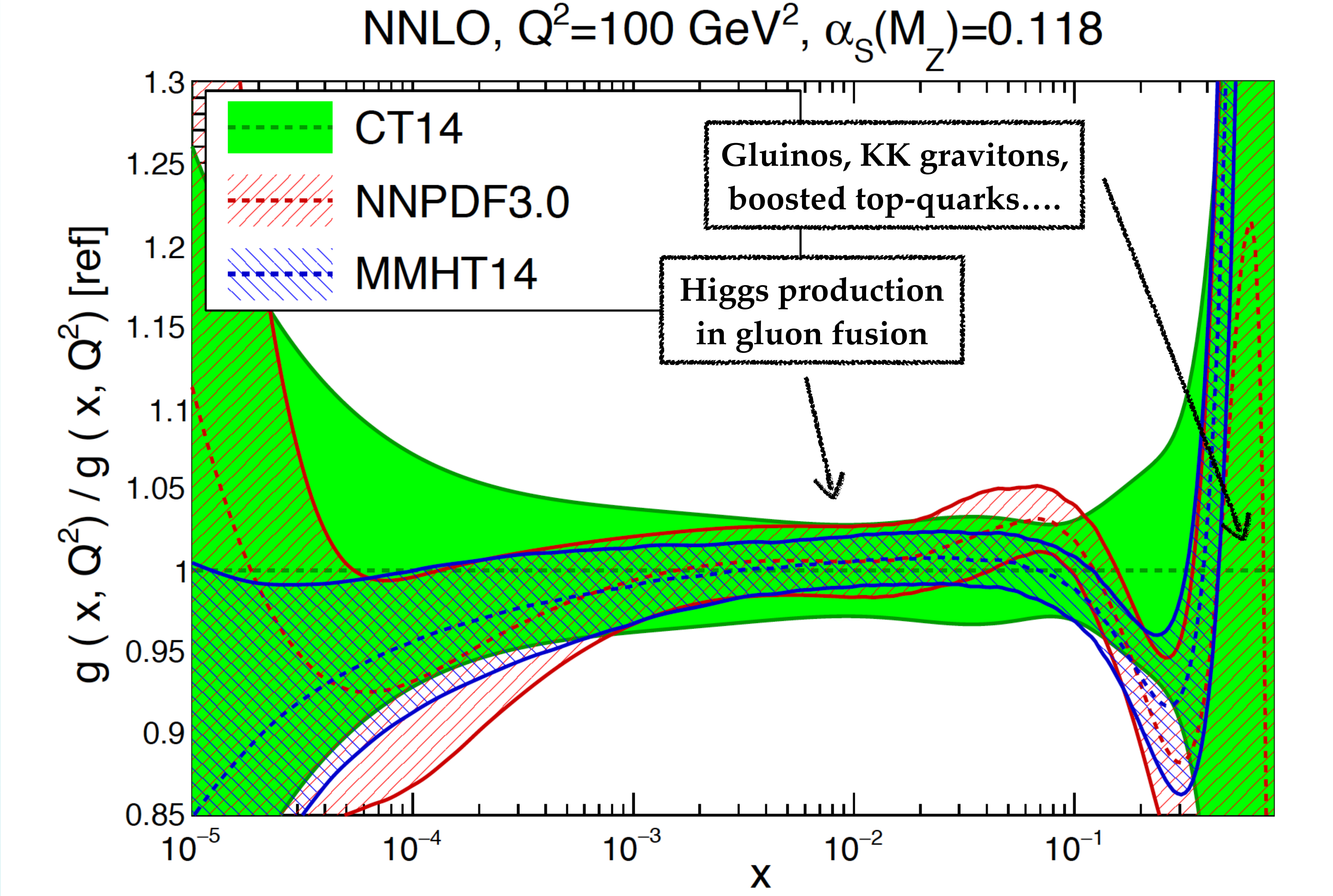

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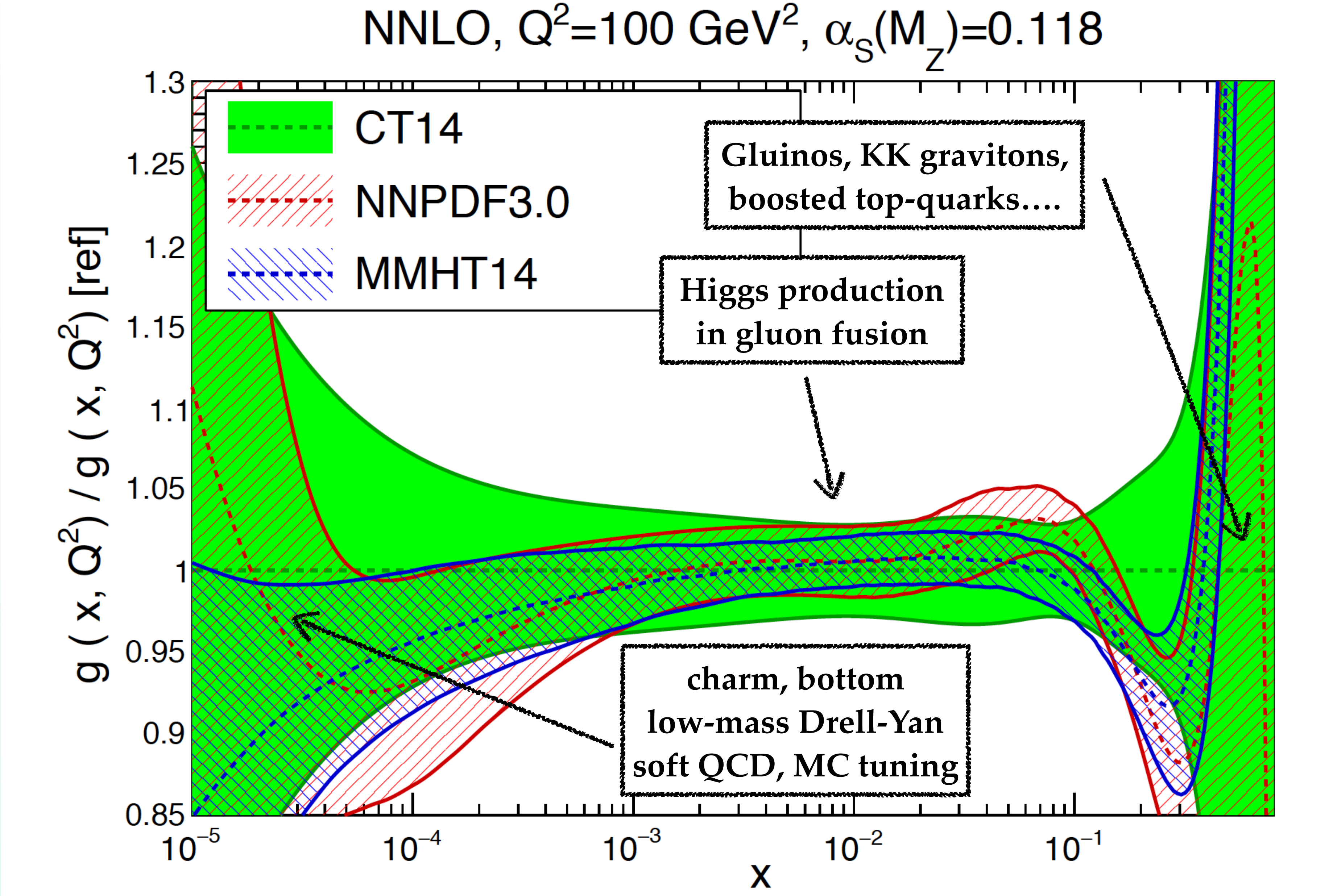

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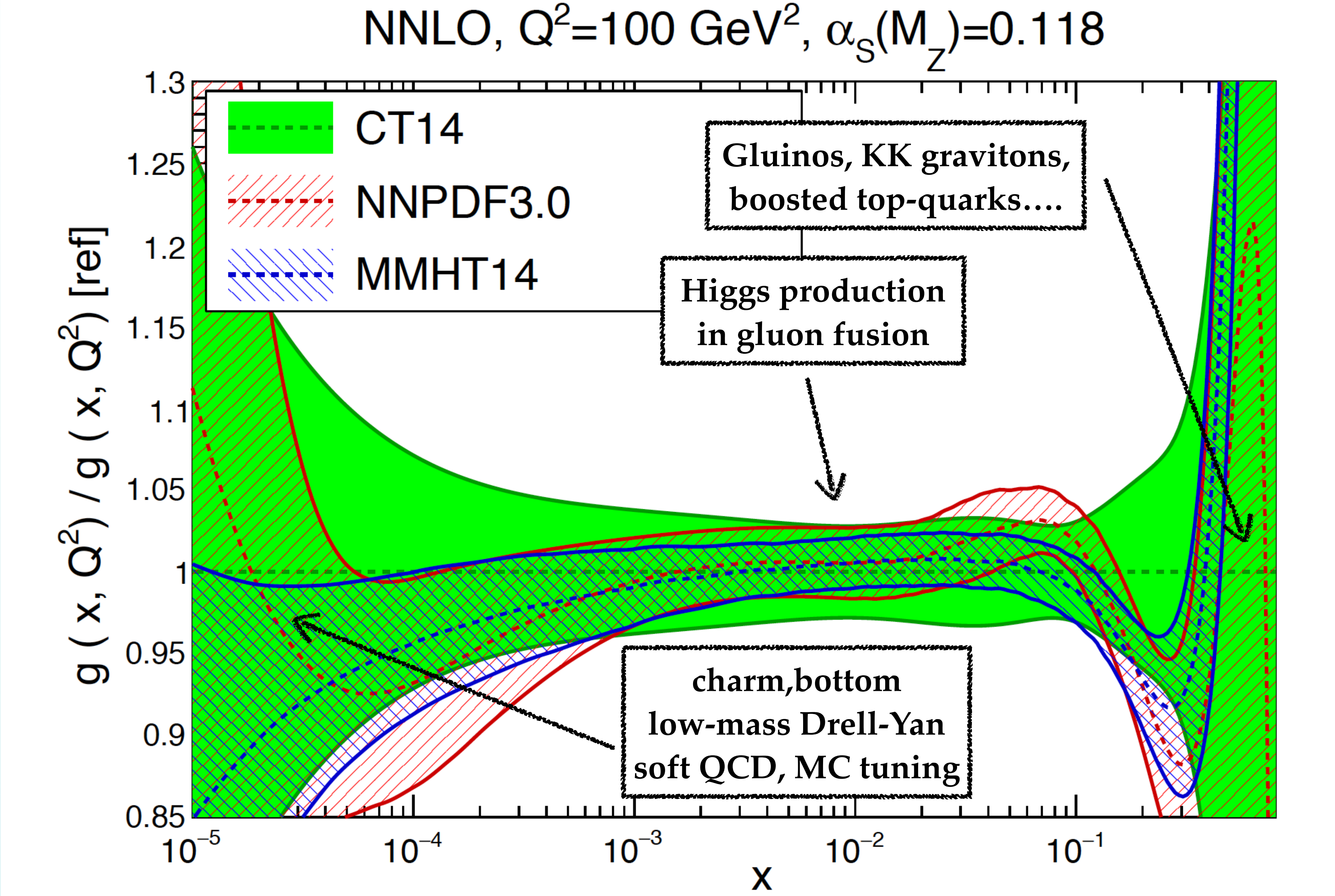

Exploit PDF-sensitive LHC measurements to **constrain the gluon from small to large-x!**

The large-x gluon from top-quark production

- Top-quark pair production driven by the **gluon-gluon luminosity**

- **NNLO calculations for stable top quarks** available (with decays in the pipeline)

- Recent **precision data from ATLAS and CMS at 8 TeV** with full breakdown of statistical and systematic uncertainties

- For the first time, included ATLAS+CMS 8 TeV differential top measurements into the **global PDF fit**

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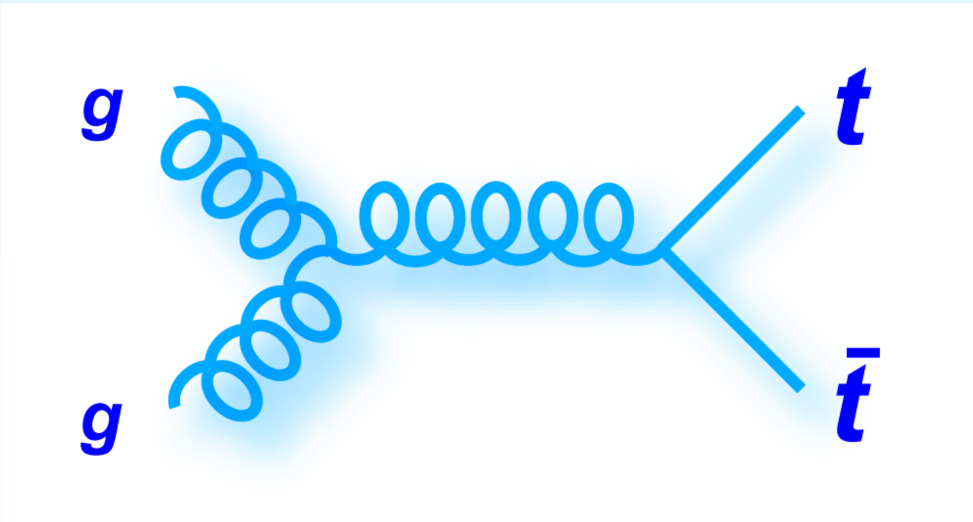
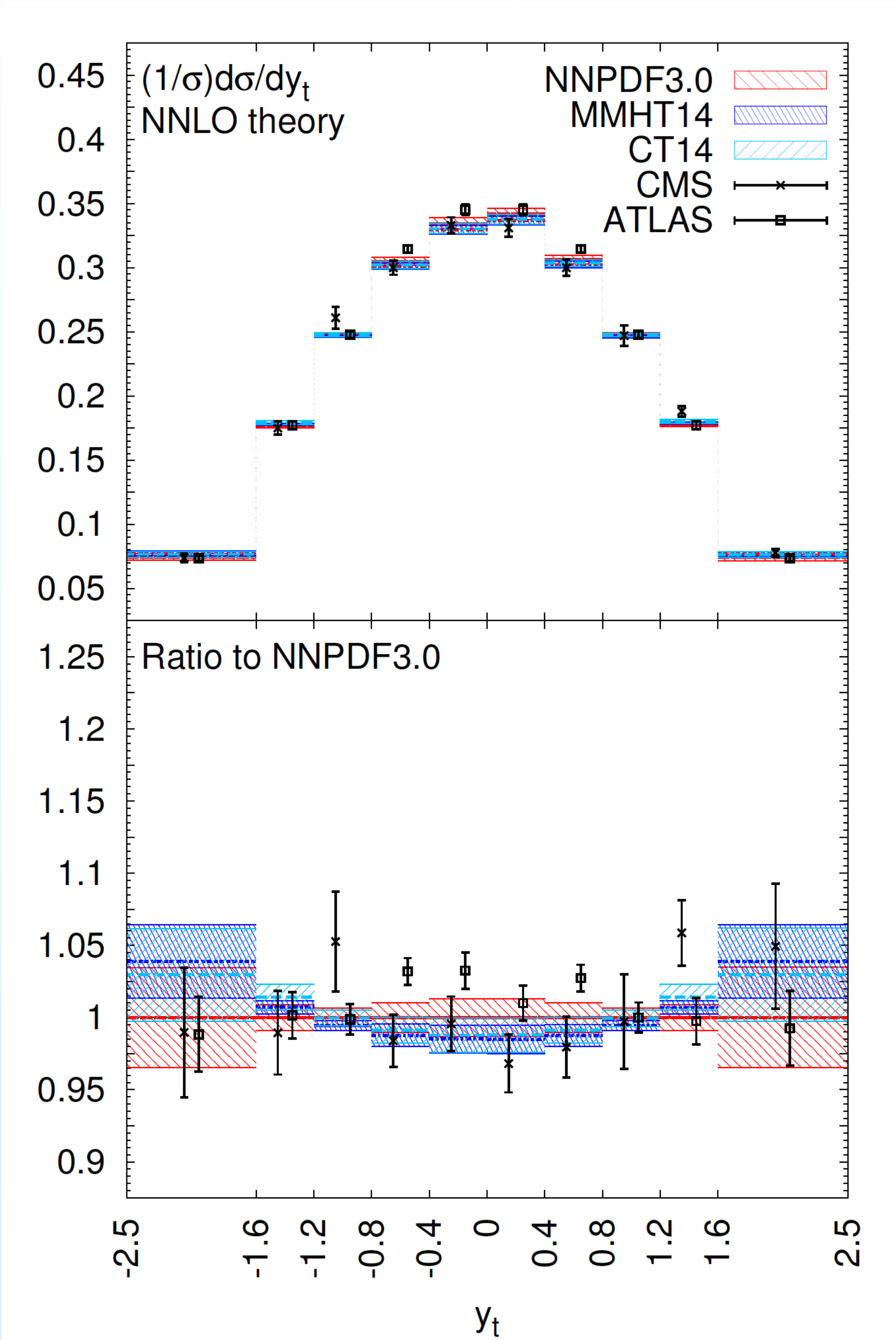
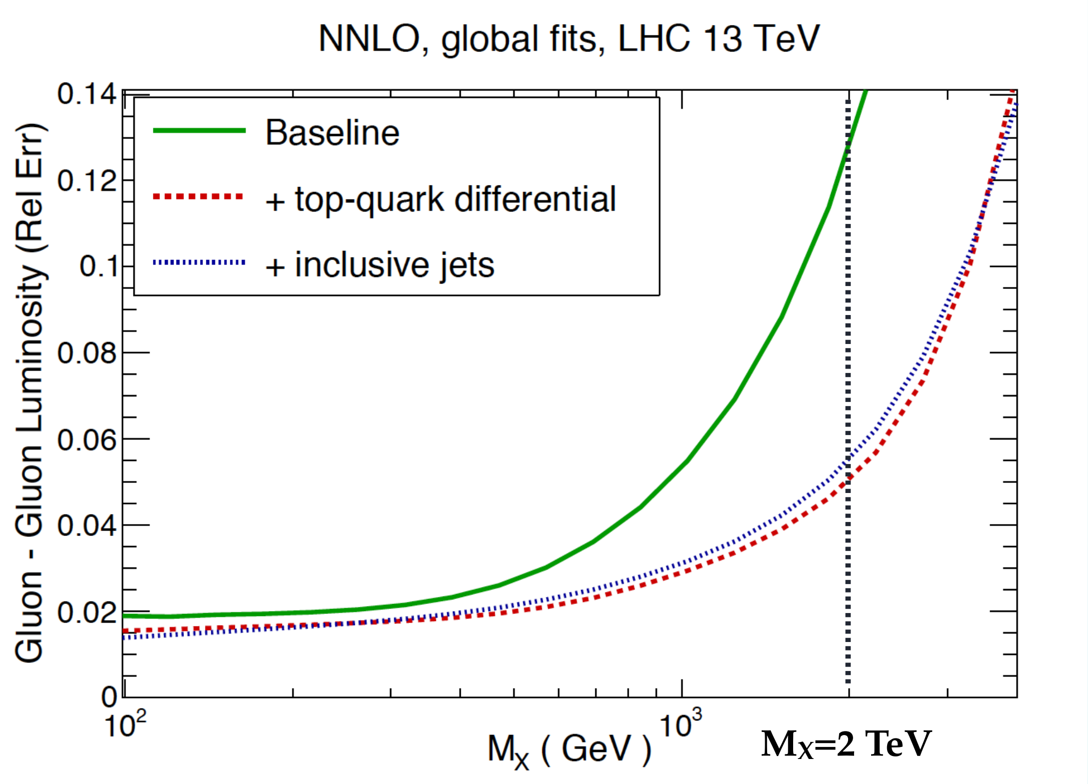




The large-x gluon from top-quark production

$$\Phi_{ij}\left(M_X^2\right) = \frac{1}{s}\int_{\tau}^{1} \frac{dx_1}{x_1} f_i\left(x_1, M_X^2\right) f_j\left(\tau/x_1, M_X^2\right)$$



- Significant reduction of PDF uncertainties in **gluon-gluon luminosity at high invariant masses (**from large-x gluon**).** For **M_X=2 TeV**, improvement **from** ≃13% **to** ≃5%

- **Constraints from top differential data** in global fit comparable to those from **inclusive jets**, despite much fewer data points: **N_{dat} =17 for top vs N_{dat} =470 for jets**

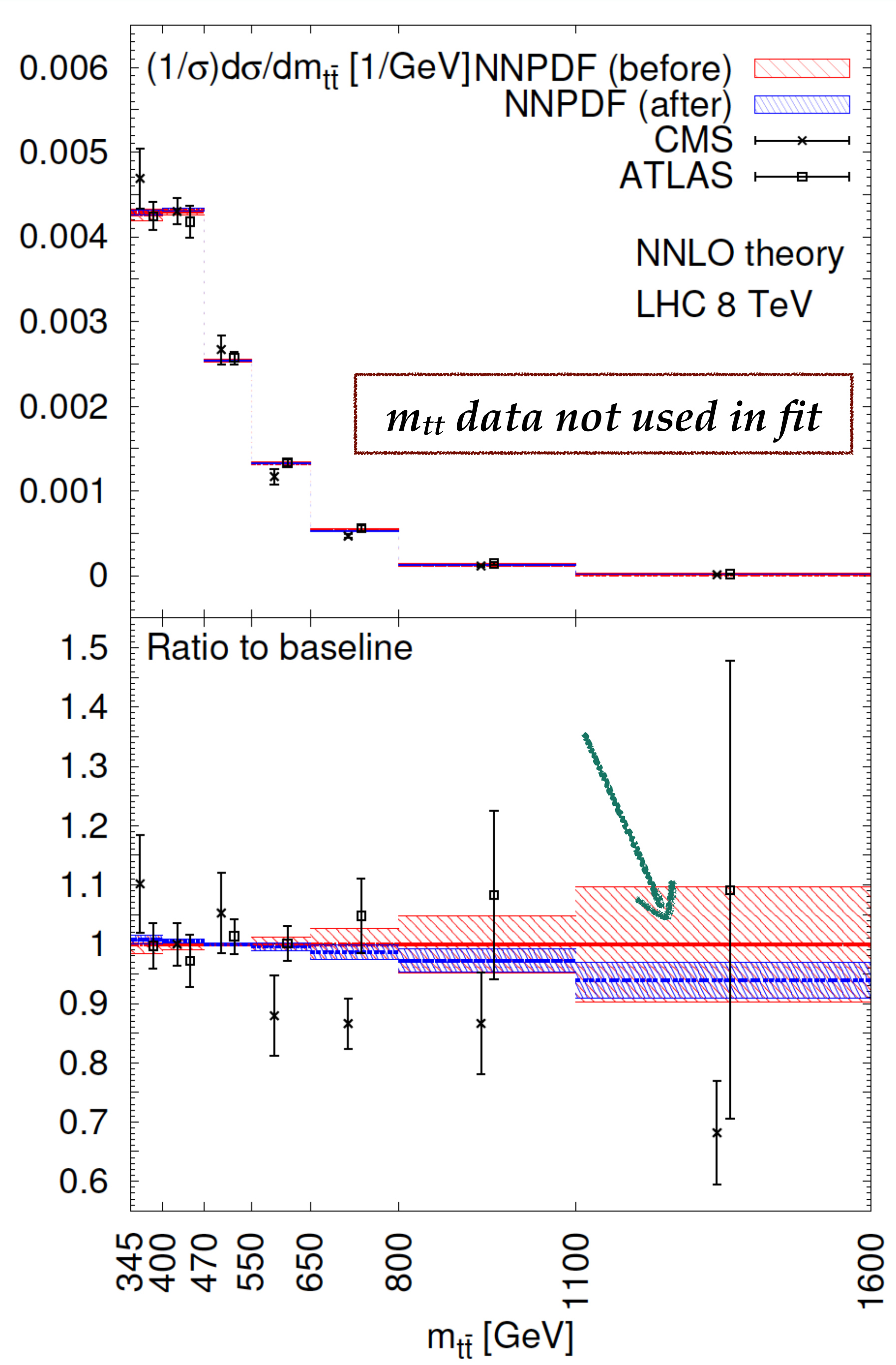
The large-x gluon from top-quark production

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

- Our choice of fitted distributions, $\mathbf{y_t}$ and $\mathbf{y_{tt}}$, reduces the **risk of *BSM contamination*** (kinematical suppression of resonances), which might show up instead in $\mathbf{m_{tt}}$ and $\mathbf{p^t_T}$, where PDF uncertainties are now much smaller

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

Improved sensitivity to BSM dynamics with top-quark final states!

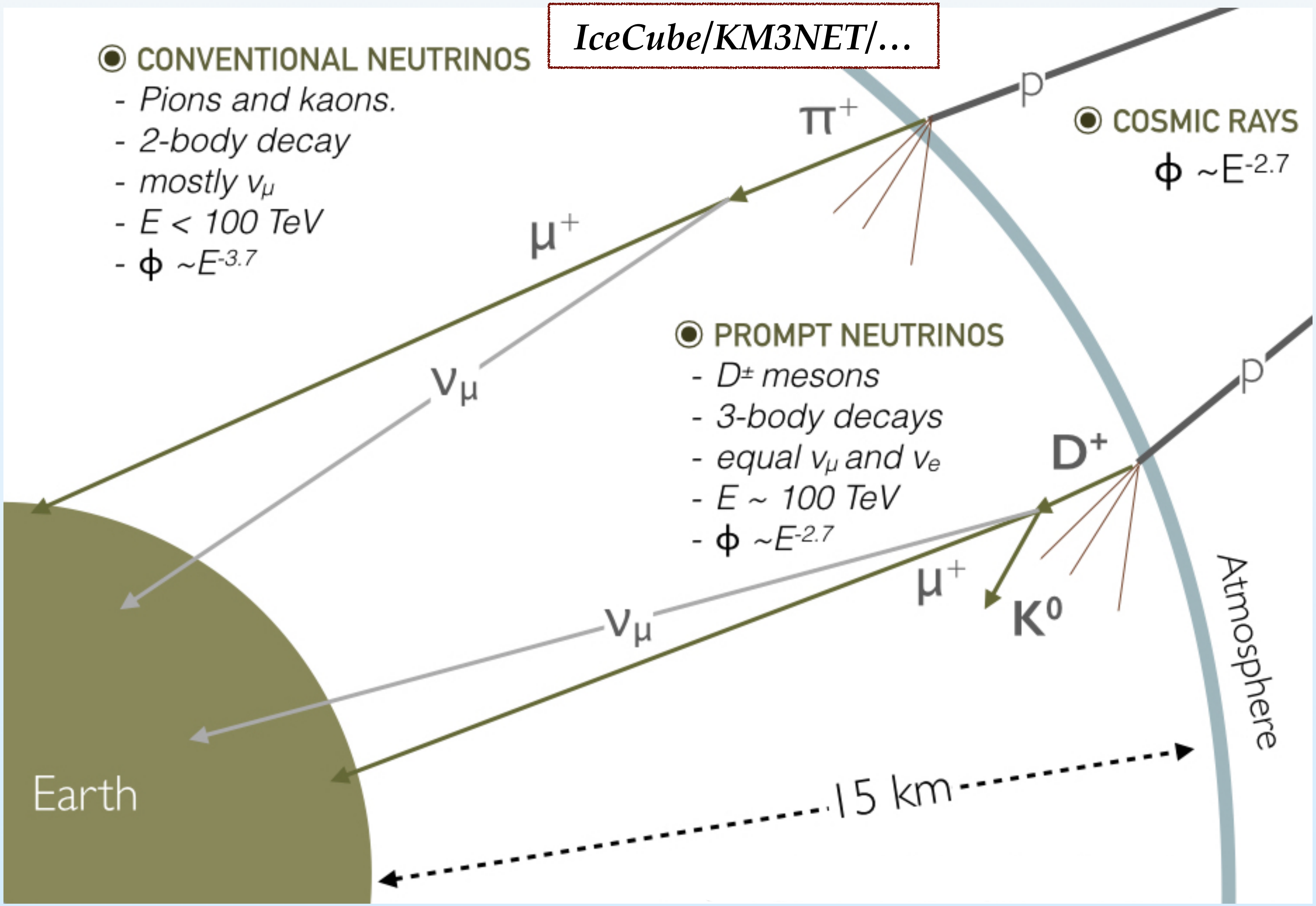


The prompt flux at neutrino telescopes

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

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

IceCube/KM3NET/…



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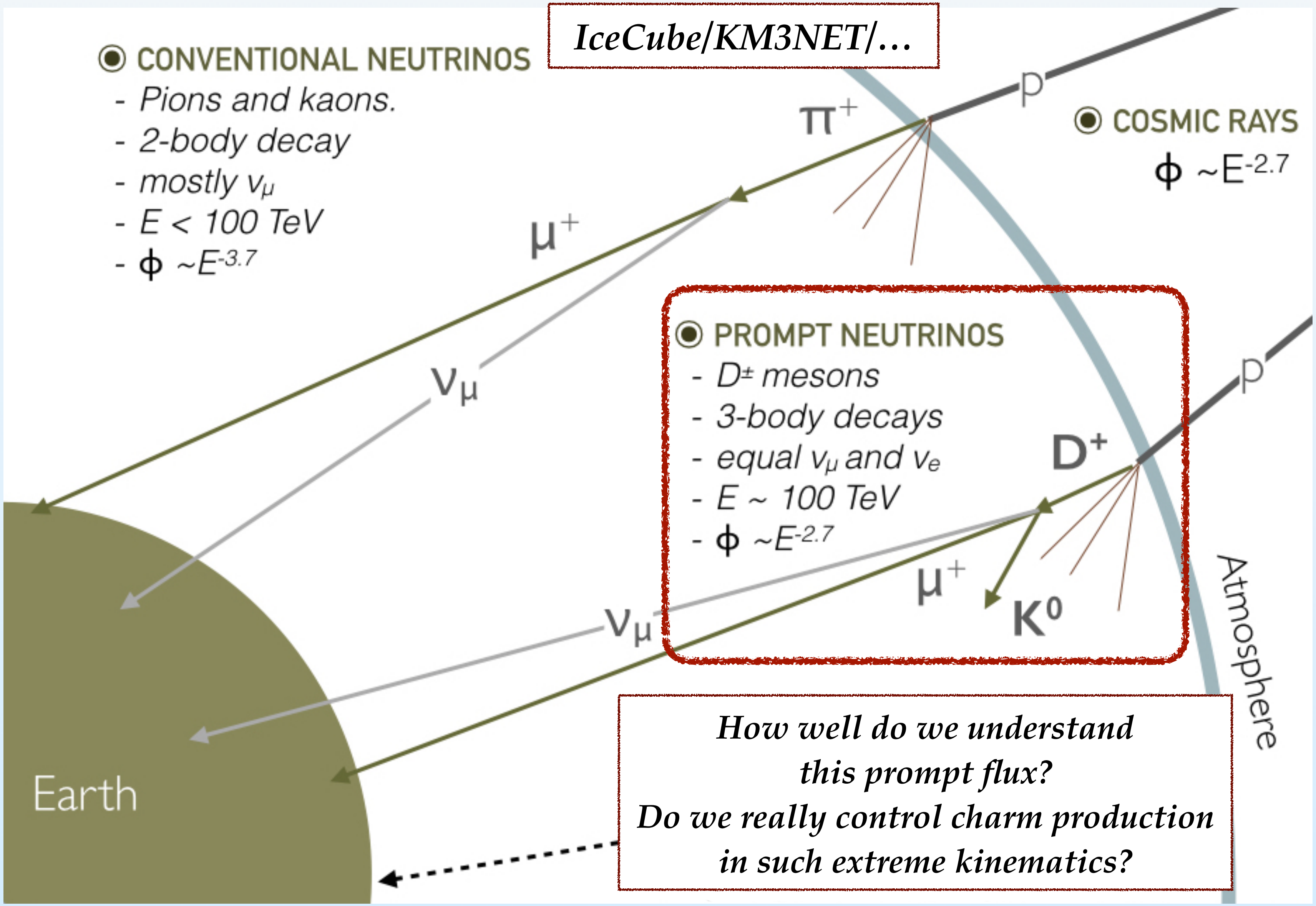
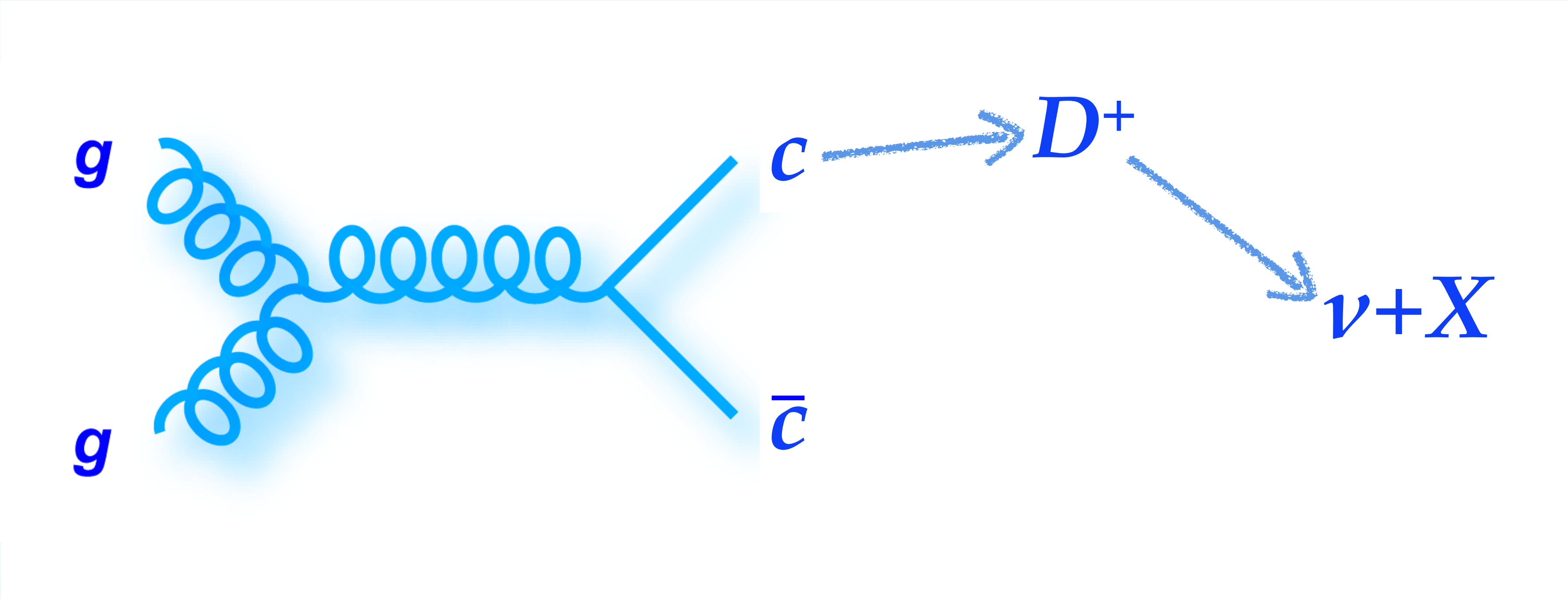
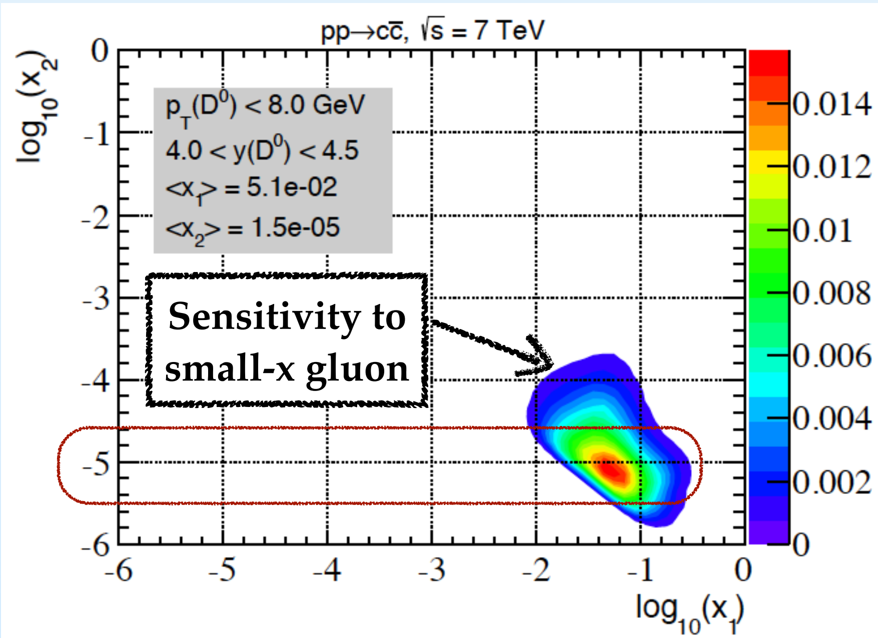


The low-x gluon from charm production





Lab frame $E_{lab} = (2m_p E_{CR})^{1/2}$

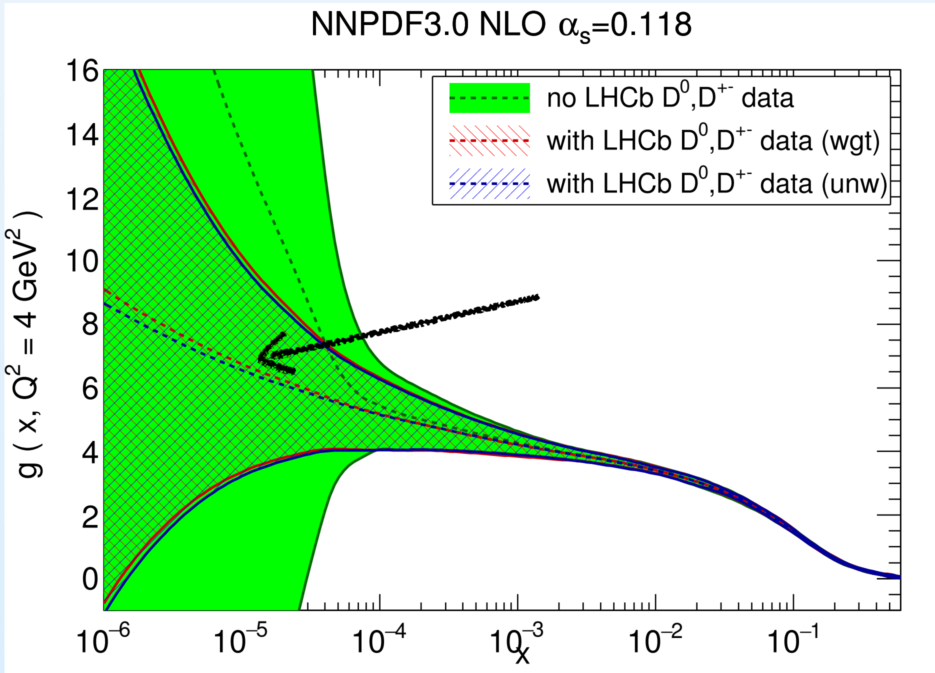
$E_{CR} = 100$ *PeV* $\longrightarrow E_{lab} \approx 14$ *TeV*

Overlap kinematics between charm production in UHE cosmic rays and at the LHC

The low-x gluon from charm production

Strategy: use **LHC data** to provide state-of-the-art **predictions for backgrounds at neutrino telescopes**

- ☑ 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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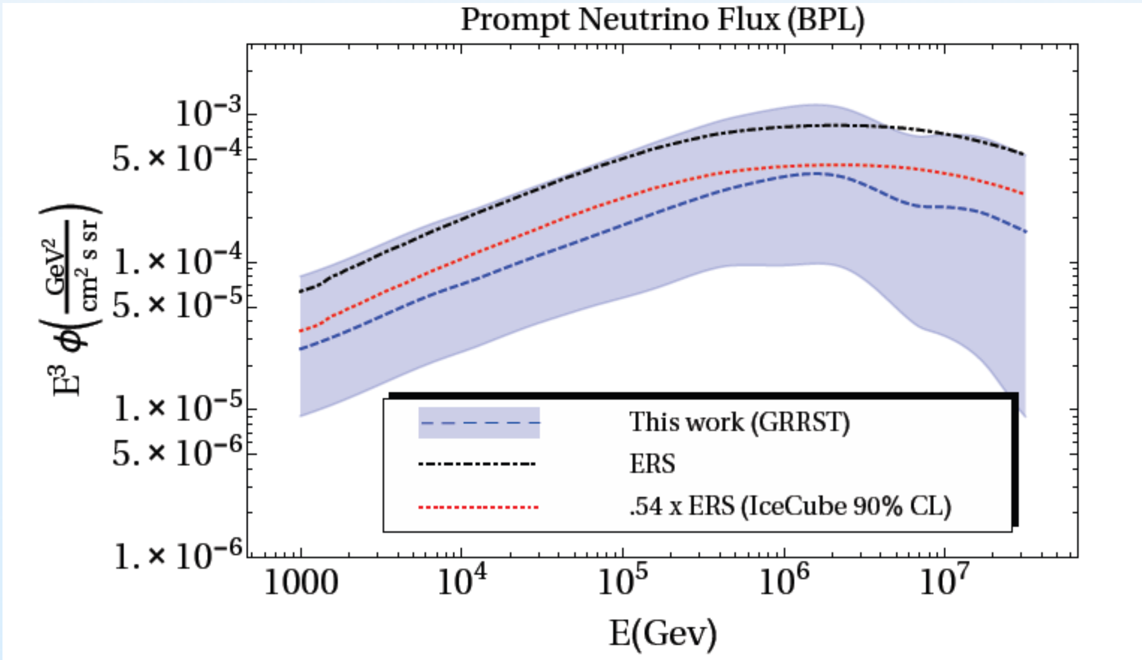

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We predict that detection of the prompt neutrino flux should be within reach

UHE neutrino-nucleus cross-sections

- Updated analysis combining **LHCb 5 TeV and 13 TeV with 7 TeV** leads to a reduction of gluon PDF errors **by an order of magnitude at $x=10^{-6}$**

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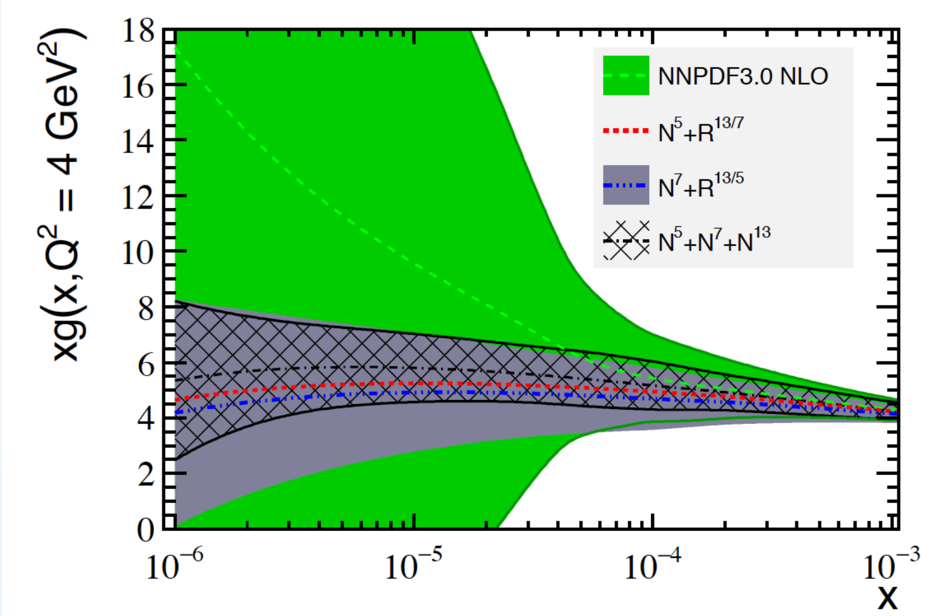
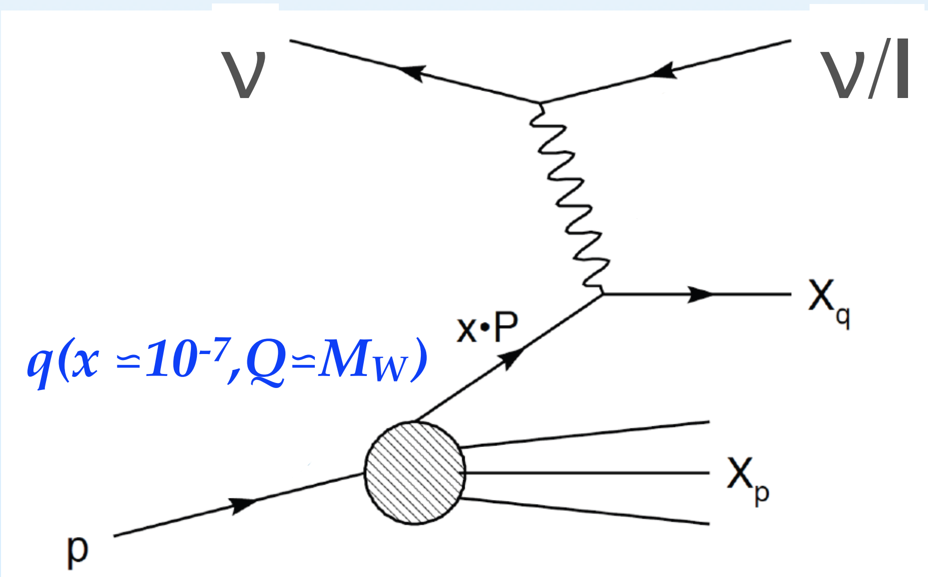
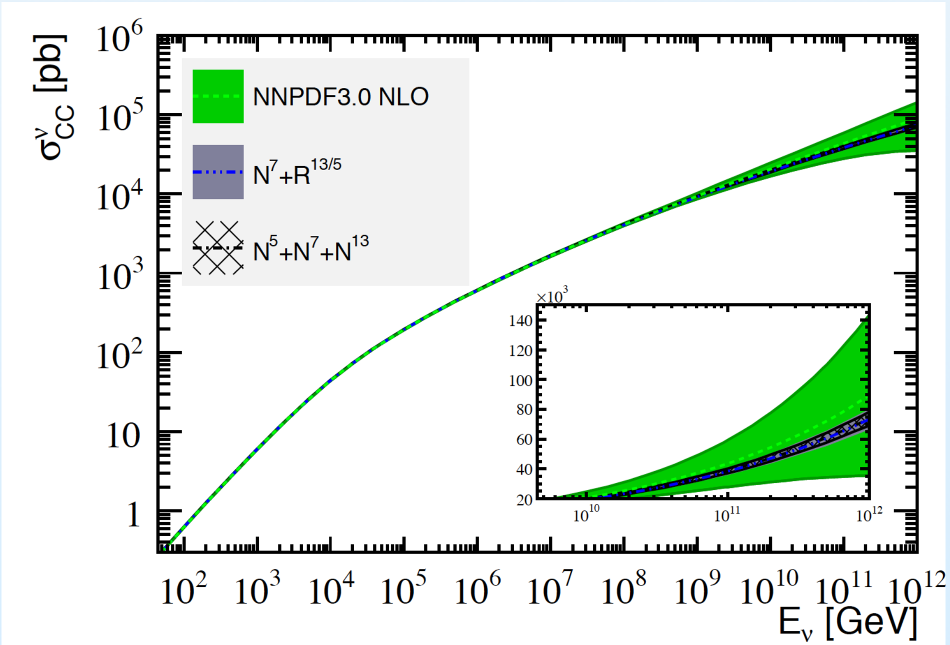
- High-precision QCD predictions of **neutrino-nucleus cross-section up to 10^6 PeV** (low-x sea quarks driven by gluon through DGLAP evolution)



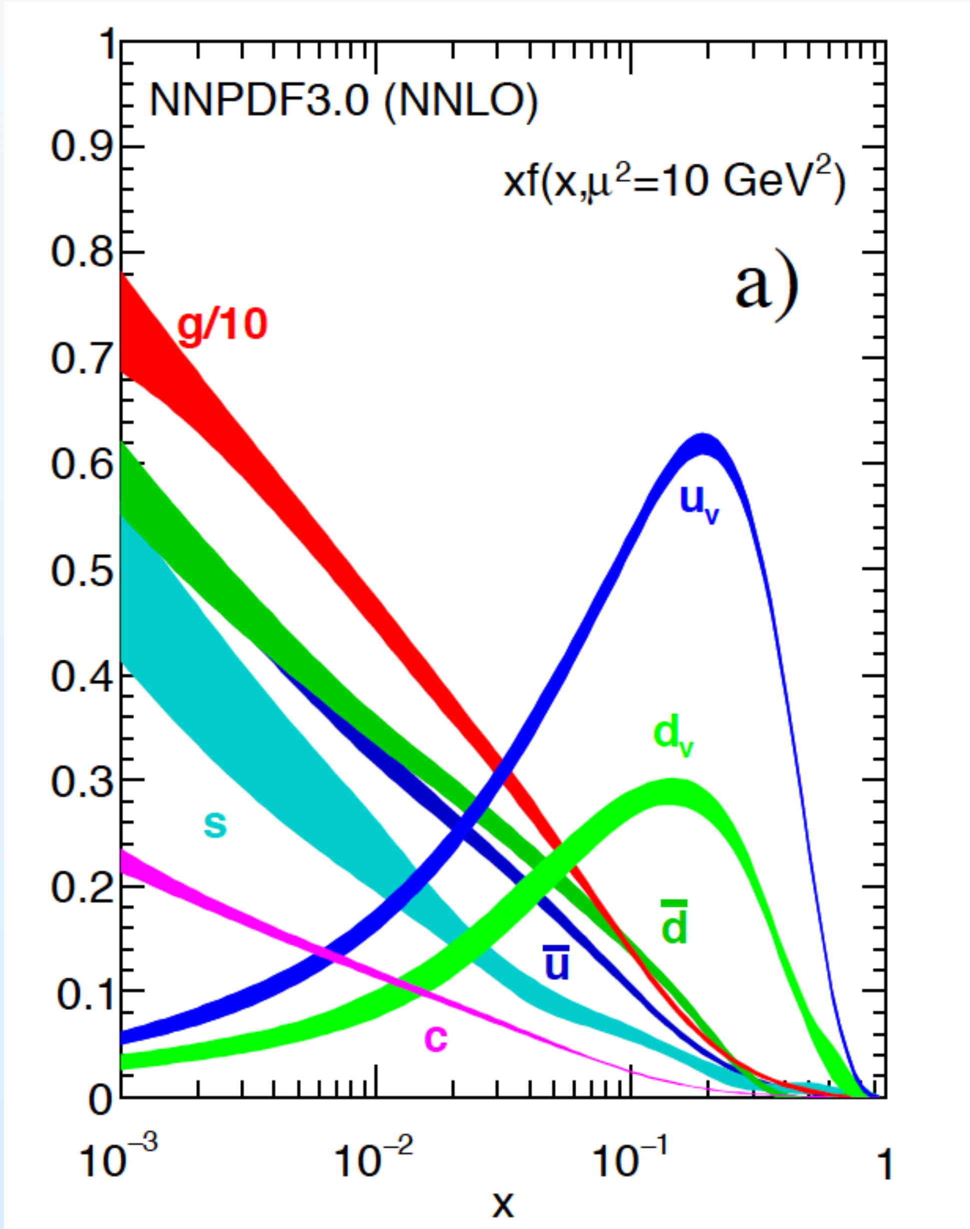




Precision studies of **extreme QCD** with **IceCube/KM3NET: the ultimate DIS experiments!**

PDFs from BSM searches to astrophysics

- **Parton Distributions** are an essential requirement for **LHC phenomenology**
- Important for **precision SM measurements** (like M_W), characterisation of **Higgs sector**, Monte Carlo event generators, and also for many **BSM searches**
- Recent years have seen a **revolution in global PDF analyses**: PDFs with LHC data, PDFs with QED corrections, PDFs with all-order resummations, PDFs tailored for neutrino telescopes, model-independent intrinsic charm fits, ….



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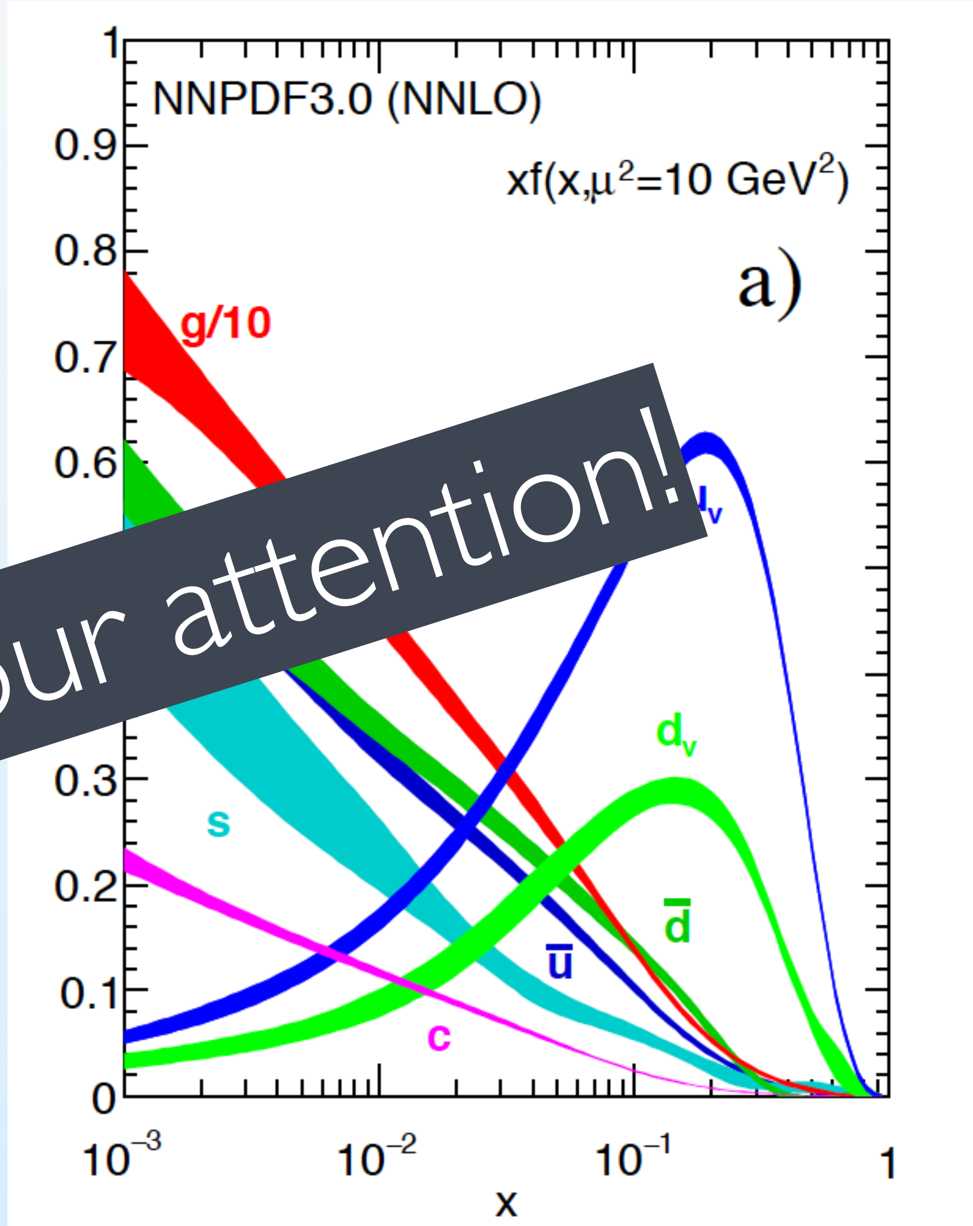
Thanks for your attention!



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