Parton Distribution Functions at the Large Hadron Collider

Theory Group Retreat

Emanuele R. Nocera

Università degli Studi di Torino and INFN, Torino

11 November 2023

Since I am *new* . . . me, in one slide

Scientific path

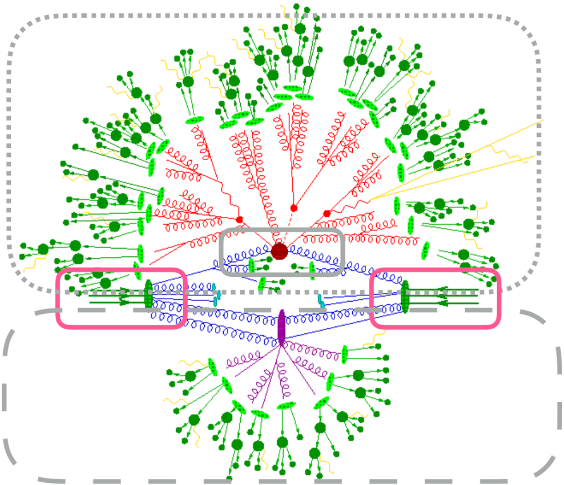
- Born in Aosta, Italy
- B.Sc. (Torino, 2008), M.Sc. (Torino, 2010), Ph.D. (Milano, 2014)
- Postdoctoral experience: Oxford (2015–2017), Edinburgh (2017–2022)
- Marie-Curie (on leave from Edinburgh), Nikhef Theory Group, Amsterdam (2018–2020)
- Rita Levi-Montalcini, back to (and stay) where everything started, Torino (2022–now)

Research interests

- Parton distribution functions for LHC phenomenology
  how can we improve PDF accuracy and precision for LHC discoveries?
- Spin physics and 3D-imaging of the proton
  how do quarks and gluons contribute to the proton spin?
- The hadronisation of partons: fragmentation functions
  how do quarks and gluons fragment into final-state particles?
- Nonperturbative QCD methods and their interface to perturbative QCD
  what can we learn about the nucleon structure from nonperturbative QCD methods?

1. What are PDFs and why are they important at the LHC?

A laboratory for Quantum Chromodynamics



Hard scattering of partons (Perturbative QCD+EW)

Parton Distribution Functions

Parton Showering and Hadronisation

Multi-Parton Interactions Underlying Events

[Plot by courtesy of SHERPA]

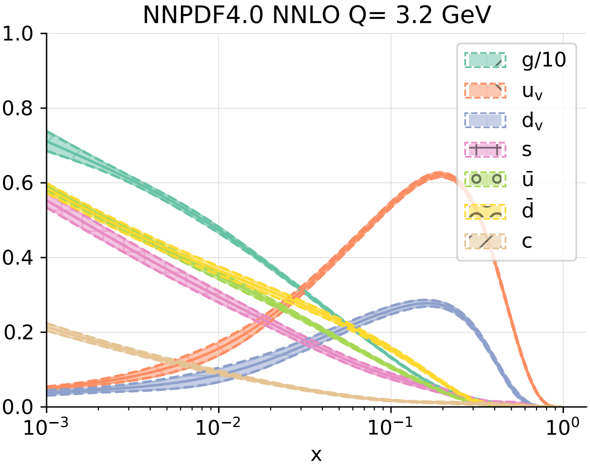
$$\sigma(Q^2, \tau, \mathbf{k}) = \sum_{ij} \int_{\tau}^{1} \frac{dz}{z} \mathcal{L}_{ij}(z, Q^2) \hat{\sigma}_{ij} \left(\frac{\tau}{z}, \alpha_s(Q^2), \mathbf{k} \right) \quad \mathcal{L}_{ij}(z, Q^2) = (f_i^{h_1} \otimes f_j^{h_2})(z, Q^2)$$

Parton Distribution Functions

PDFs express the likelihood of a quark or gluon (partons) to enter a collision

That is, $x\times$PDFs are momentum fraction distributions for each parton

Dependence on x is non-perturbative (fit); dependence on Q is perturbative (DGLAP)



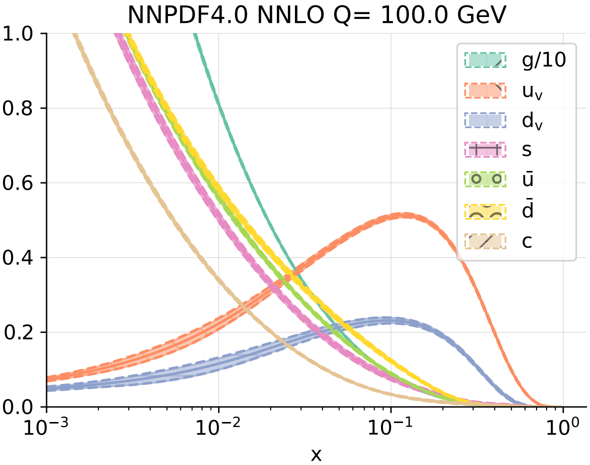
[Plot from the PDG Review of Particle Physics]

Parton Distribution Functions

PDFs express the likelihood of a quark or gluon (partons) to enter a collision

That is, $x\times$PDFs are momentum fraction distributions for each parton

Dependence on x is non-perturbative (fit); dependence on Q is perturbative (DGLAP)



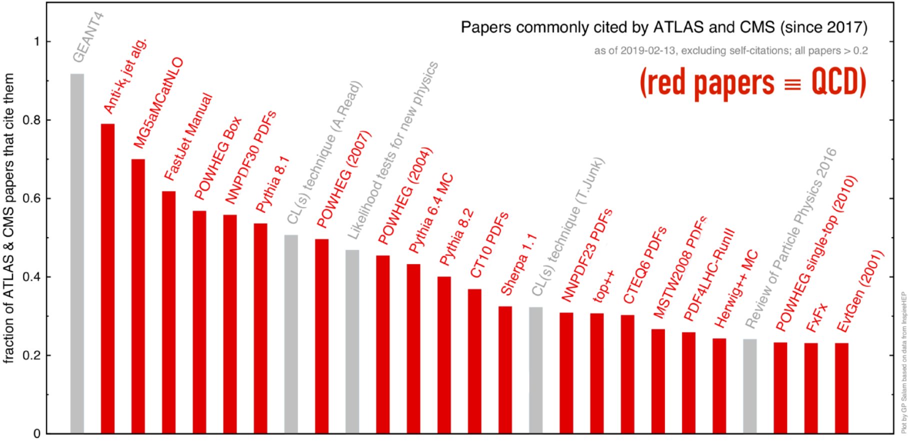
[Plot from the PDG Review of Particle Physics]

LHC, QCD and PDFs

The LHC is a Proton Collider – Any interaction contains a strong interaction

Quantum Chromodynamics (QCD) is the main actor

Within QCD, Parton Distribution Functions (PDFs) play a leading role



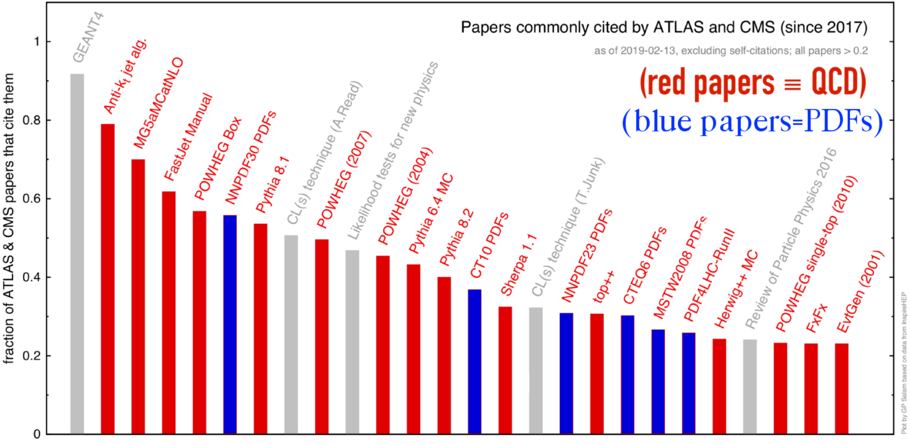
[Plot by courtesy of G. Salam]

LHC, QCD and PDFs

The LHC is a Proton Collider – Any interaction contains a strong interaction

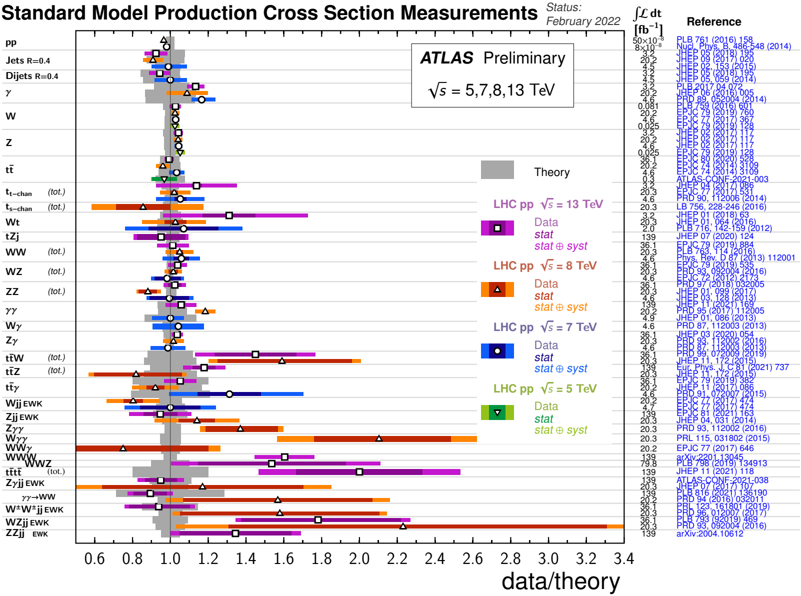
Quantum Chromodynamics (QCD) is the main actor

Within QCD, Parton Distribution Functions (PDFs) play a leading role



[Plot by courtesy of G. Salam]

Physics at the LHC as Precision Physics



[Plot from ATLAS Collaboration web page]

Making predictions with PDFs

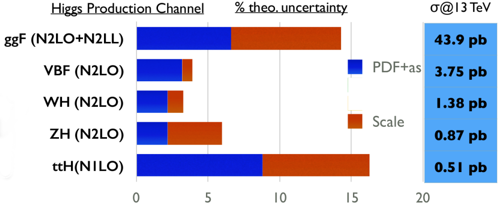
PDF uncertainty is often the dominant source of uncertainty in LHC cross sections

Higgs boson characterisation

Determination of SM parameters, such as the mass of the W boson

Searches for beyond SM physics at large invariant mass of the final state

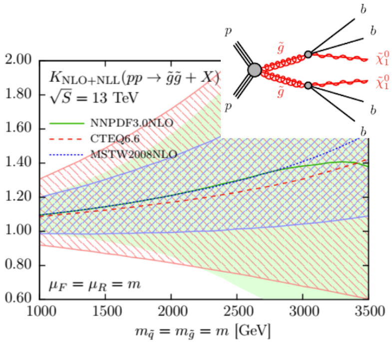
Precision



Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

[Plot from the CERN Yellow Report 2016]

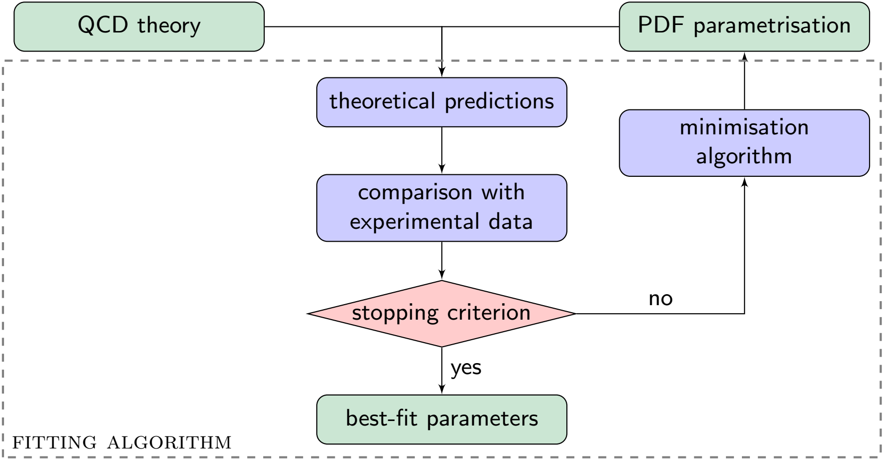
Discovery



[EPJC 76 (2016) 53]

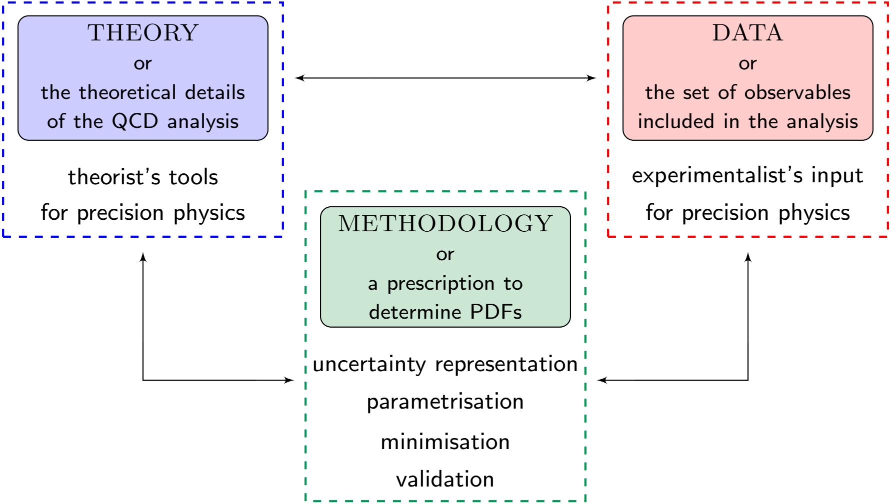
Determining PDFs from (LHC) experimental data

$$\sigma(Q^2,\tau,\mathbf{k}) = \sum_{ij}\int_\tau^1 \frac{dz}{z}\mathcal{L}_{ij}(z,Q^2)\hat{\sigma}_{ij}\left(\frac{\tau}{z},\alpha_s(Q^2),\mathbf{k}\right) \quad \mathcal{L}_{ij}(z,Q^2) = (f_i^{h_1}\otimes f_j^{h_2})(z,Q^2)$$



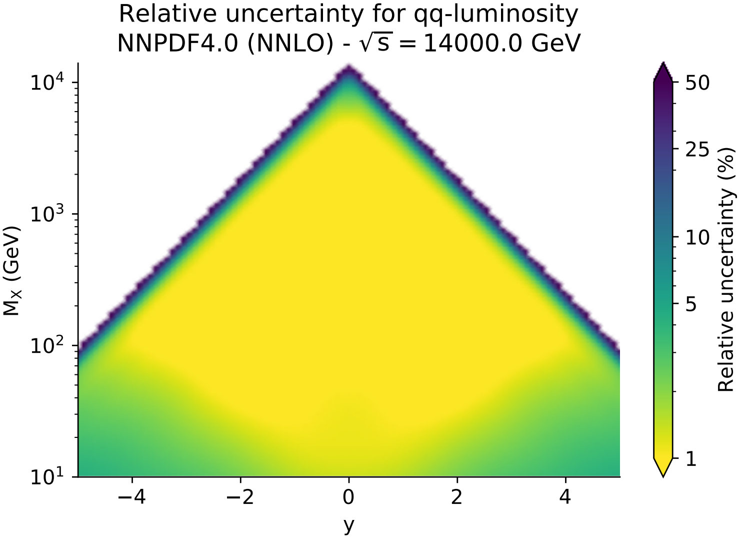
$$\chi^2 = \sum_{i,j}^{N_{\rm dat}}[T_i[\{\vec{a}\}]-D_i](\mathrm{cov}^{-1})_{ij}[T_j[\{\vec{a}\}]-D_j]$$ with $\{\vec{a}\}$ the set of parameters

The ingredients of PDF determination



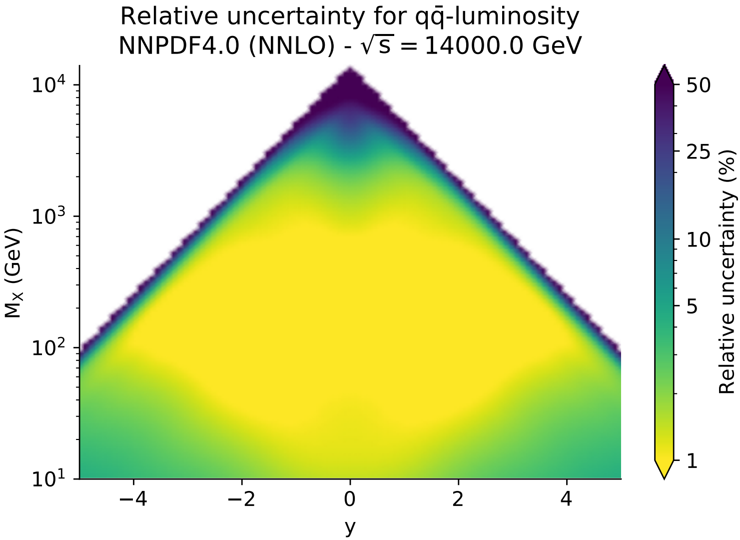
Each of these ingredients is a source of uncertainty in the PDF determination

How well do we know PDF uncertainties?



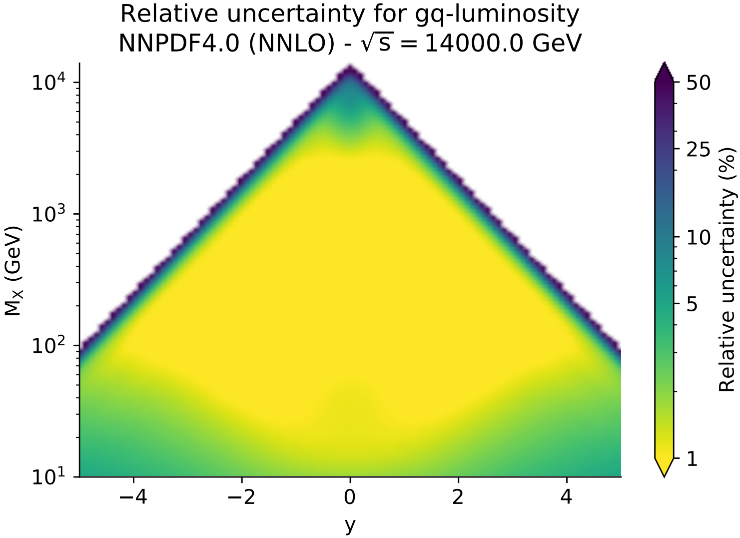
We are approaching 1% uncertainties

How well do we know PDF uncertainties?



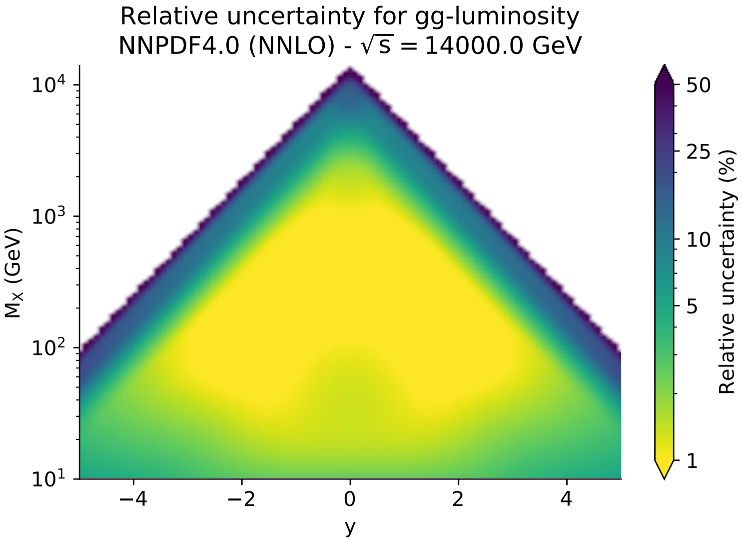
We are approaching 1% uncertainties

How well do we know PDF uncertainties?



We are approaching 1% uncertainties

How well do we know PDF uncertainties?

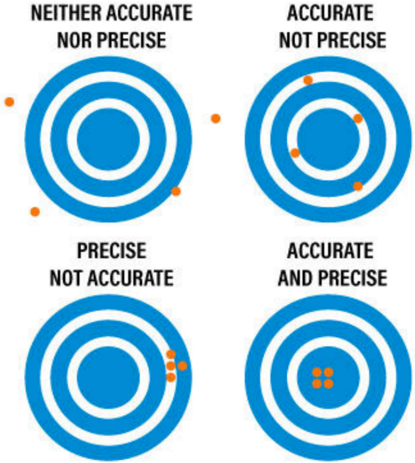


We are approaching 1% uncertainties

2. What does 1%-accurate PDFs imply?

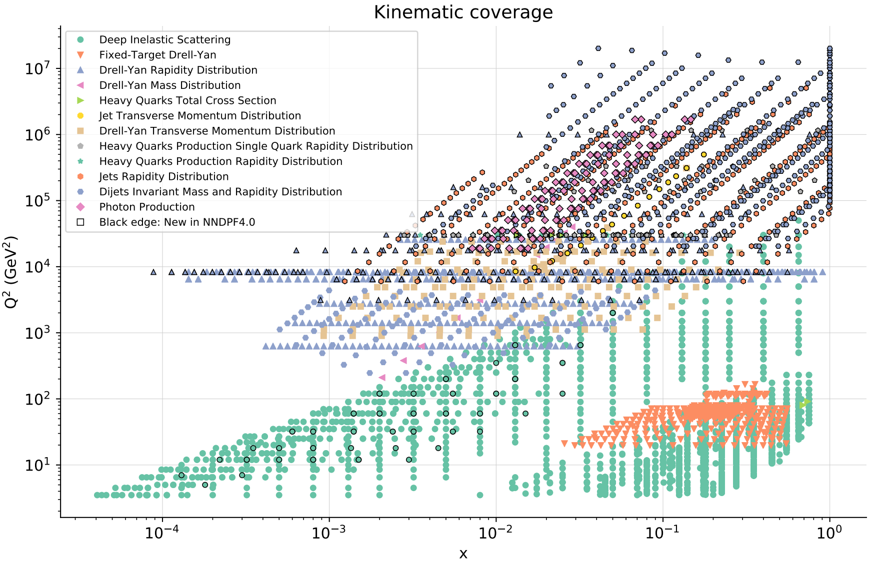
Bias-variance trade-off

Precision is not everything, we must also aim for accuracy



1% PDF accuracy goes through data, theory and methodology

Which data?



$$N_{\rm dat} = 4618 \qquad \chi^2/N_{\rm dat} = 1.16$$

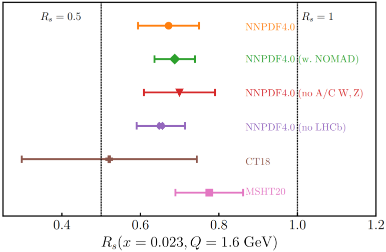
Are data consistent?

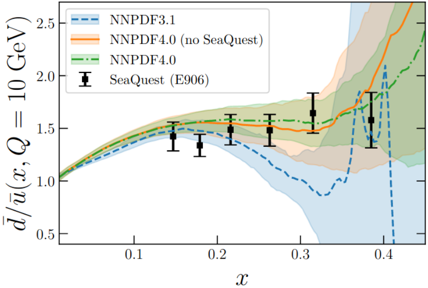
Strange in the proton [EPJ C80 (2020) 1168]

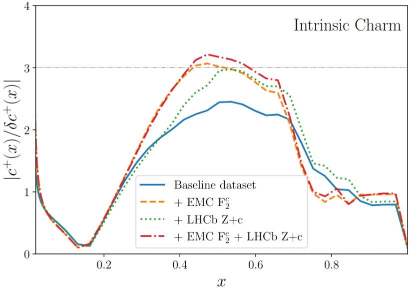
$$R_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)}$$

The d/u ratio in the proton [EPJ C82 (2022) 428]

Charm in the proton [Nature 608 (2022) 7923 483]





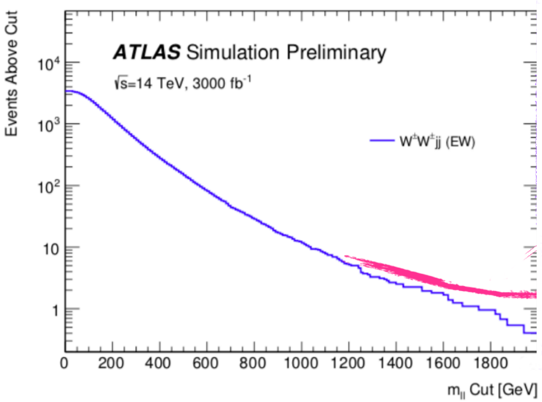


There may be tensions between data sets (correlations, missing higher orders, . . .)

Which theory?

PDFs are determined *assuming* the SM and fixed-order theory

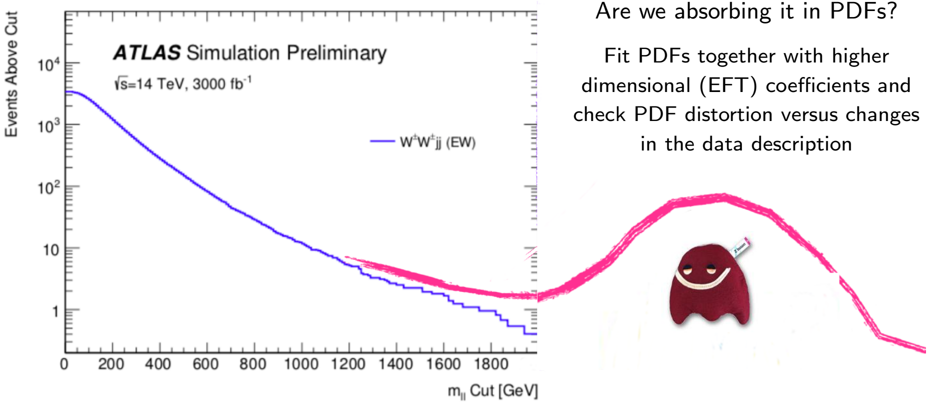
Deviation(s) from SM prediction in high energy tails?



Which theory?

PDFs are determined *assuming* the SM and fixed-order theory

Deviation(s) from SM prediction in high energy tails?



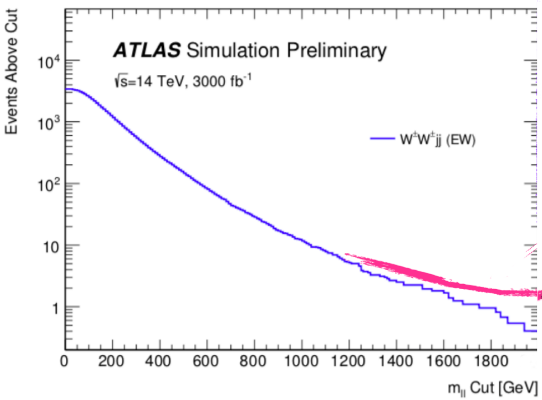
A) New Physics?
Are we absorbing it in PDFs?

Fit PDFs together with higher dimensional (EFT) coefficients and check PDF distortion versus changes in the data description

Which theory?

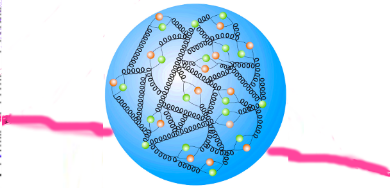
PDFs are determined *assuming* the SM and fixed-order theory

Deviation(s) from SM prediction in high energy tails?



B) Limited PDF accuracy?
How shall we improve it?

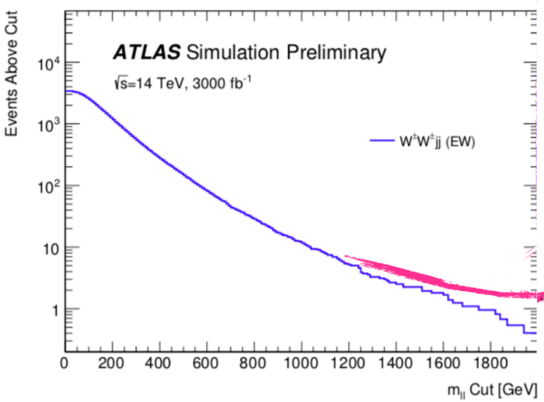
Inclusion of higher order corrections
Inclusion of electroweak effects
Inclusion of theory uncertainties



Which theory?

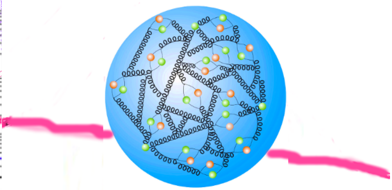
PDFs are determined *assuming* the SM and fixed-order theory

Deviation(s) from SM prediction in high energy tails?



B) Limited PDF accuracy?
How shall we improve it?

Inclusion of higher order corrections
Inclusion of electroweak effects
Inclusion of theory uncertainties



In both cases, there is a lot of work to do

Which accuracy?

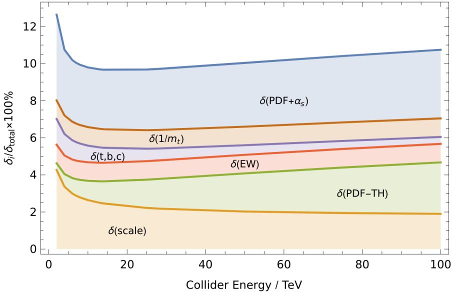
NNLO is the precision frontier for PDF determination

N3LO is the precision frontier for partonic cross sections

Mismatch between perturbative order of partonic cross sections and accuracy of PDFs is becoming a significant source of uncertainty

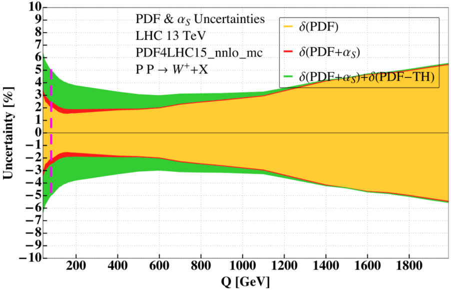
$$\hat{\sigma} = \alpha_s^p \hat{\sigma}_0 + \alpha_s^{p+1}\hat{\sigma}_1 + \alpha_s^{p+2}\hat{\sigma}_2 + \mathcal{O}(\alpha_s^{p+3}) \qquad \delta(\mathrm{PDF}-\mathrm{TH}) = \frac{1}{2}\left|\frac{\sigma^{(2)}_{\mathrm{NNLO-PDFs}} - \sigma^{(2)}_{\mathrm{NLO-PDFs}}}{\sigma^{(2)}_{\mathrm{NNLO-PDFs}}}\right|$$

Higgs production in gluon-gluon fusion



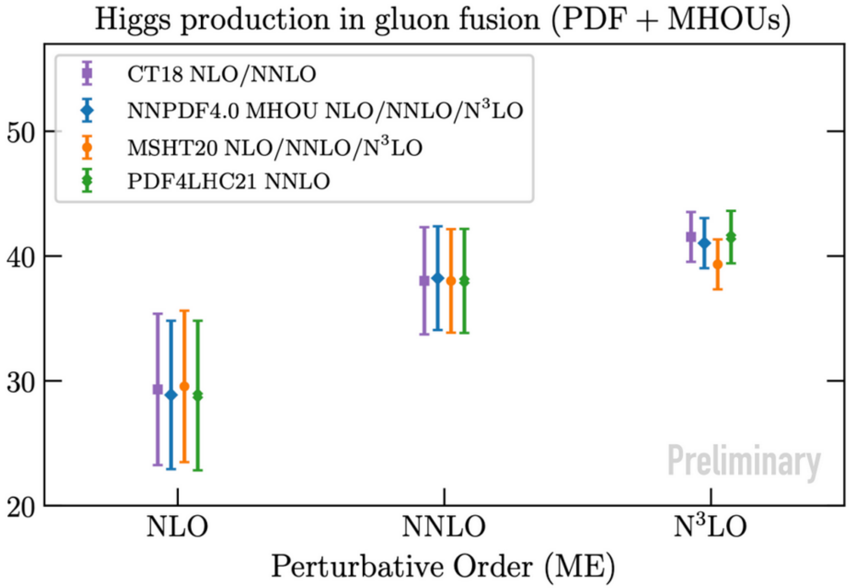
[CERN Yellow Rep.Monogr. 7 (2019) 221]

W$^+$ boson production in CC Drell-Yan



[JHEP 11 (2020) 143]

Towards PDFs at (approximate) N^3LO



[NNPDF, in preparation]

Which methodology? The NNPDF methodology!

Why does the NNPDF methodology stand out?

uncertainty representation
bootstrap of experimental uncertainties
unambiguous statistical characterisation of uncertainties

parametrisation
neural network(s)
reduction of parametrisation bias

minimisation
adaptive gradient descent
efficient exploration of the parameter space

validation
closure tests (what happens if I know in advance the underlying law that I am fitting?)
characterisation of the interpolation and extrapolation uncertainties

benchmark
PDF4LHC working group
are PDFs obtained independently by various groups equivalent?

PDF uncertainties are statistically sound, minimally biased, and completely characterised
Machine learning plays a crucial role

The NNPDF methodology is public

NNPDF

Tests passing | DOI 10.5281/zenodo.6542572

NNPDF: An open-source machine learning framework for global analyses of parton distributions

The NNPDF collaboration determines the structure of the proton using Machine Learning methods. This is the main repository of the fitting and analysis frameworks. In particular it contains all the necessary tools to reproduce the NNPDF4.0 PDF determinations.

Documentation

The documentation is available at https://docs.nnpdf.science/

Install

See the NNPDF installation guide for the conda package, and how to build from source.

Please note that the conda based workflow described in the documentation is the only supported one. While it may be possible to set up the code in different ways, we won't be able to provide any assistance.

We follow a rolling development model where the tip of the master branch is expected to be stable, tested and correct. For more information see our releases and compatibility policy.

NNPDF

Search docs

- Getting started
- Fitting code: `n3fit`
- Code for data: validphys
- Handling experimental data: Buildmaster
- Storage of data and theory predictions
- Theory
- Chi square figures of merit
- Contributing guidelines and tools
- Releases and compatibility policy
- Continuous integration and deployment
- Servers
- External codes
- Tutorials

https://github.com/NNPDF
http://nnpdf.mi.infn.it/

[EPJ C81 (2021) 958]

3. To conclude

The work of many people

The work of many people

Thank you