The Structure of the Proton in the Higgs Boson Era

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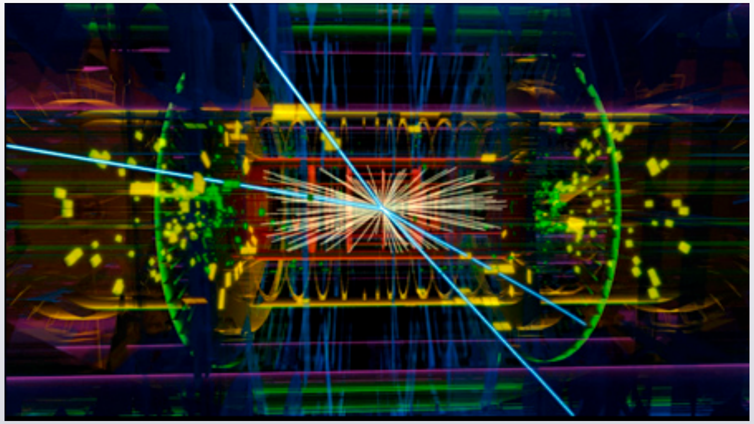
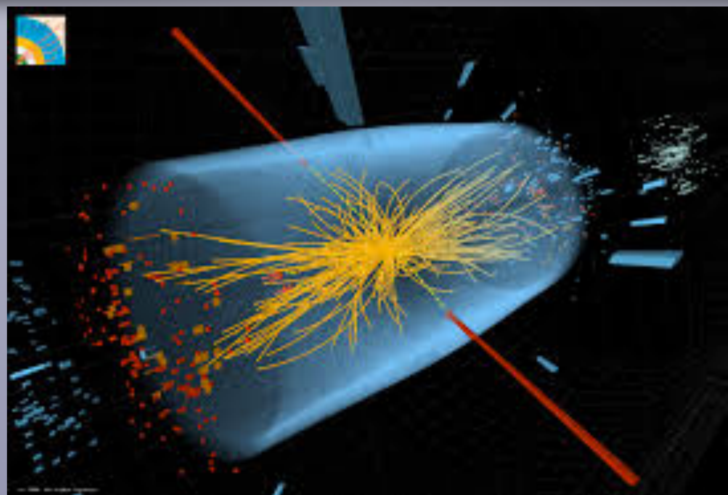
Theory Seminar
NIKHEF, 22/01/2015

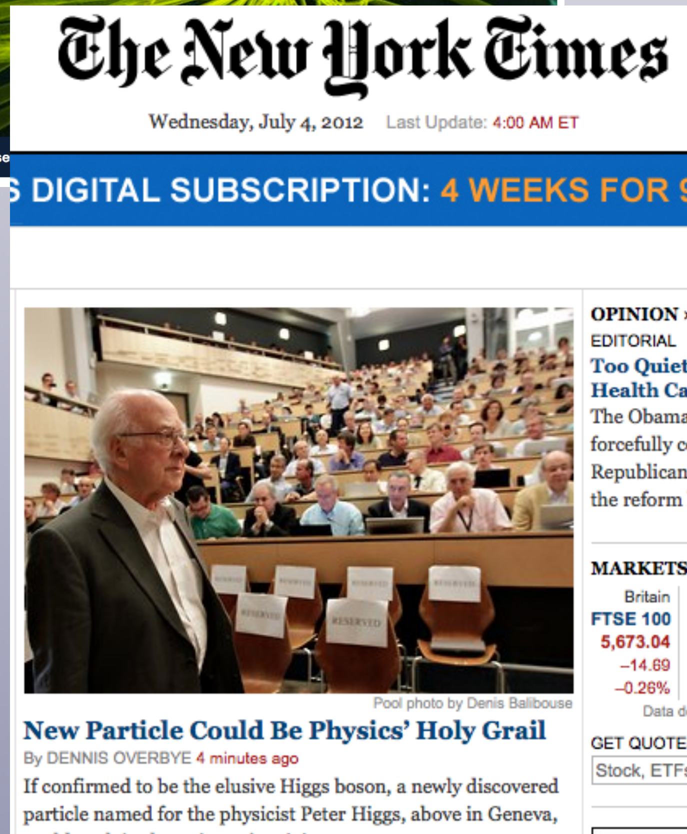


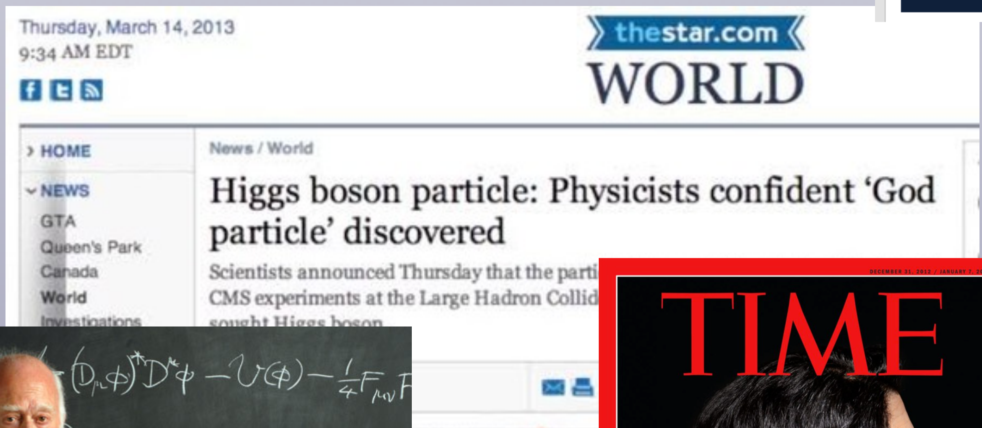
Exploring the high-energy frontier: The Large Hadron Collider

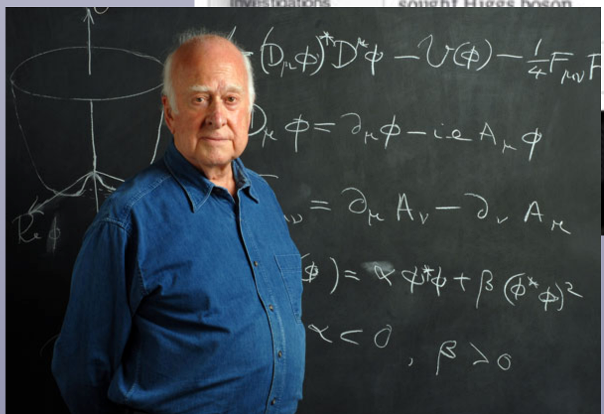


Particle Physics in the headlines

- The **Higgs Boson** is the **most important discovery in particle physics** in 25 years
- The Higgs completes the **extremely successful Standard Model of particle physics**, but at the same time **opens a number of crucial questions** for the field that we need to address
- The **LHC** will play a crucial role in **exploring the energy frontier in the next 20 years**







Outstanding Questions in Particle Physics *circa* 2014

... there has never been a better time to be a particle physicist!

Higgs boson and EWSB
- ❑ Is m_H natural or fine-tuned ?
- → if natural: what new physics/symmetry ?
- ❑ does it regularize the divergent $W_L W_L$ cross-section at high $M(W_L W_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate *CP* ?
- ❑ cosmological EW phase transition

Quarks and leptons:
- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation

Physics at the highest E-scales:
- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

Dark matter:
- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:
- ❑ ν masses and and their origin
- ❑ what is the role of $H(125)$?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation

The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ? which (scalar) fields? role of quantum gravit
- ❑ today: dark energy (why is Λ so small?) or modification of gravity theory ?

Many of these crucial questions can be addressed at the Large Hadron Collider

List from Ian Shipsey

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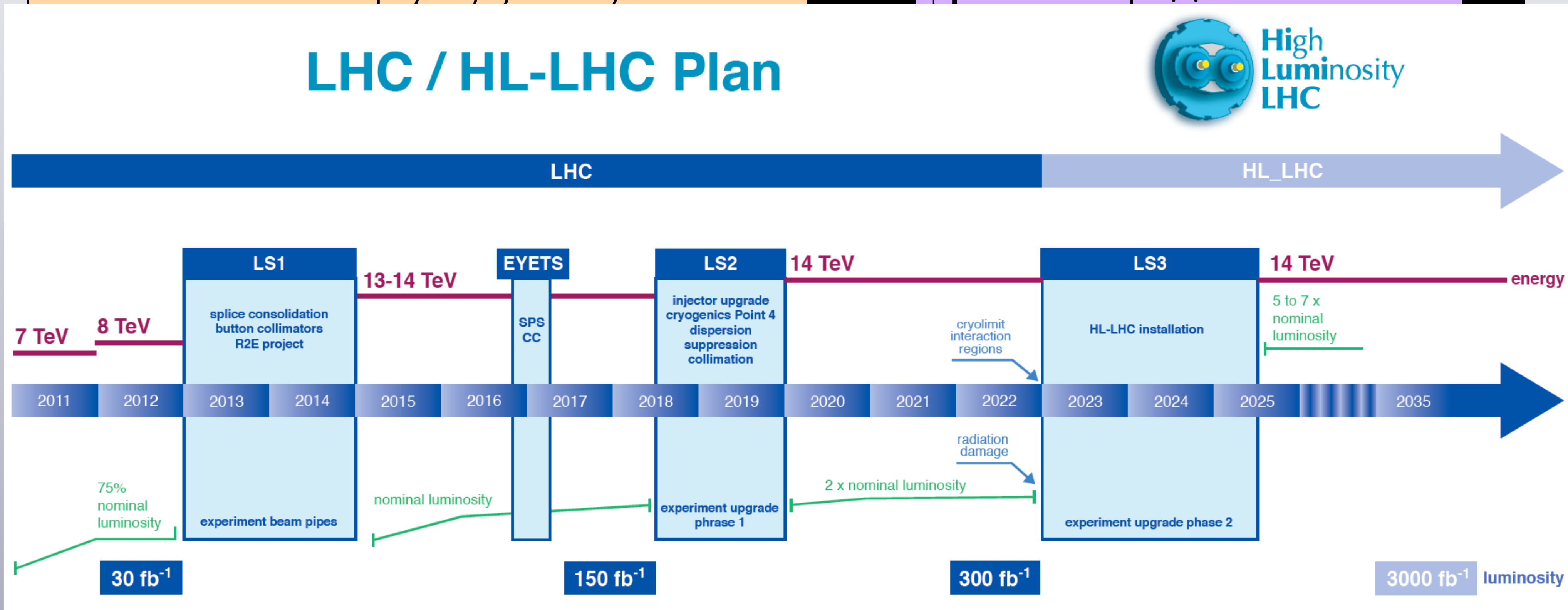
Quarks and leptons:

- ❑ why 3 families ?



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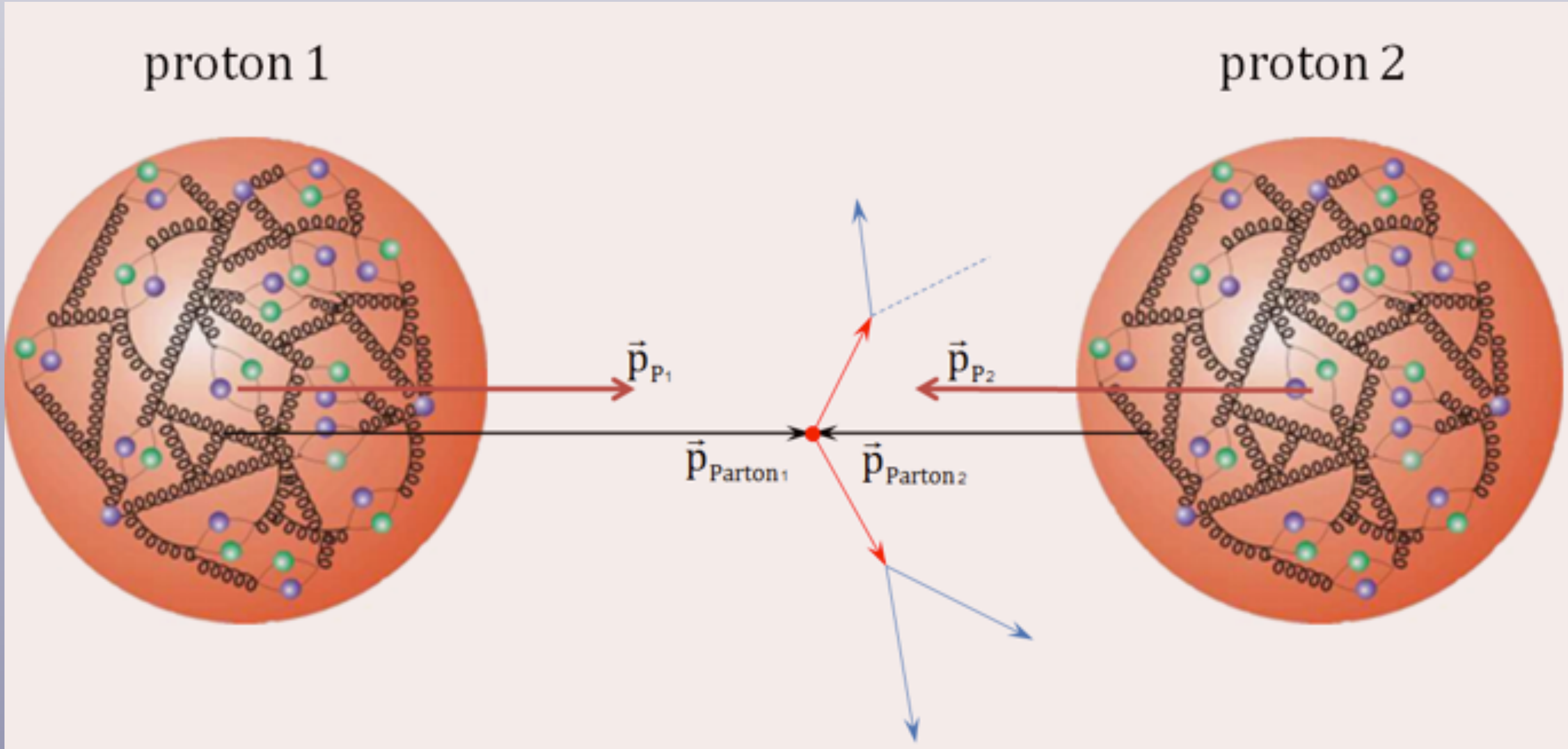
For the next 20 years, LHC will be at the forefront of the exploration of the high-energy frontier

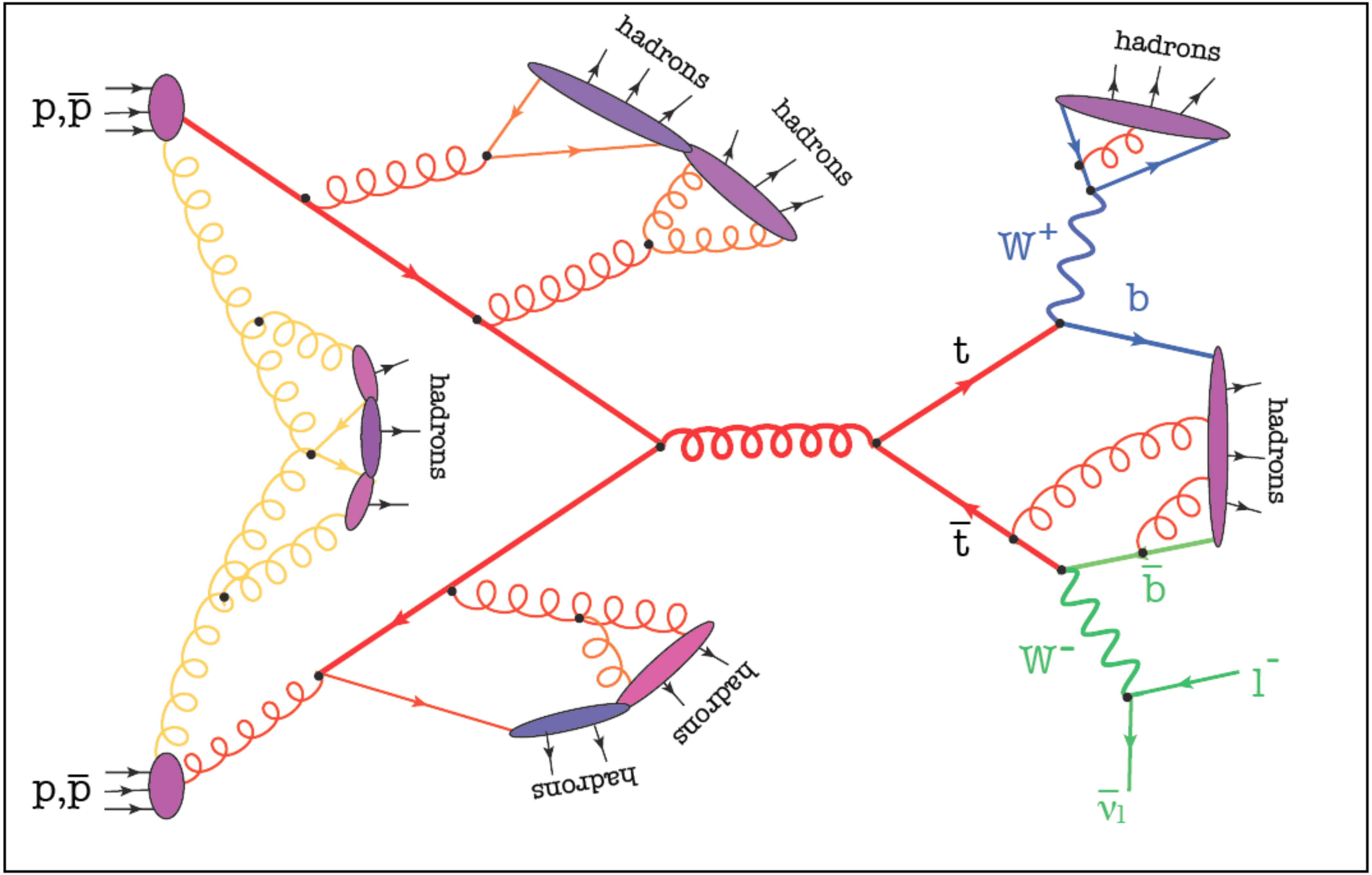
List from Ian Shipsey

The inner life of the protons

- The **Large Hadron Collider** collides proton, but these are not fundamental particles: really what the LHC is doing is colliding **quarks and gluons**
- The distribution of momentum that the quarks and gluons carry is quantified by the **Parton Distribution Functions (PDFs),** determined by **non-perturbative dynamics:** cannot be computed from first principles and need to be **extracted from experimental data**
- An **accurate determination of PDFs** is of paramount importance to be able to do **precision physics at hadronic colliders as the LHC**



LHC collisions in a nutshell



Drawing by K. Hamilton

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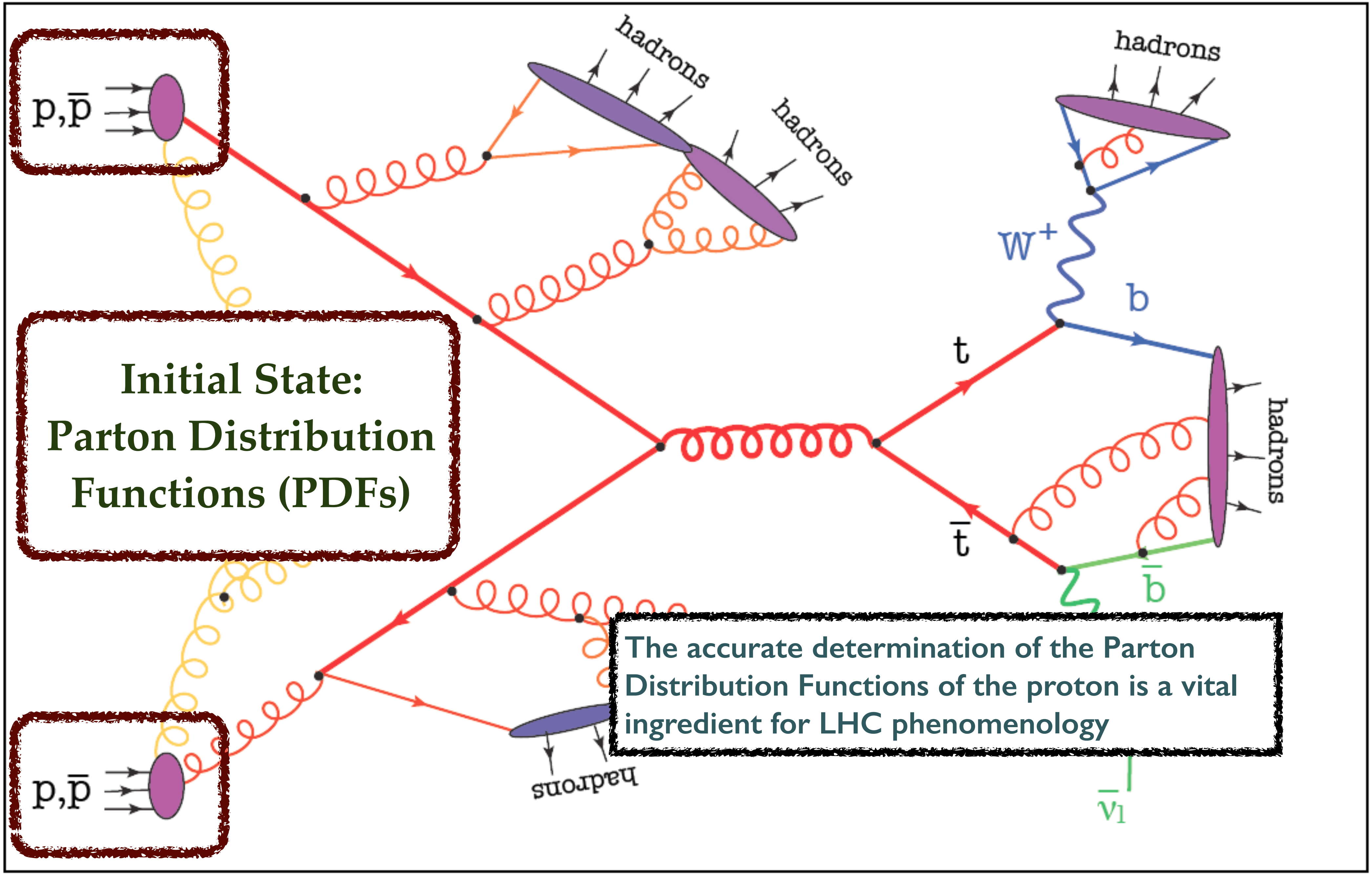


Drawing by K. Hamilton

QCD: The Toolbox for Discoveries at the LHC

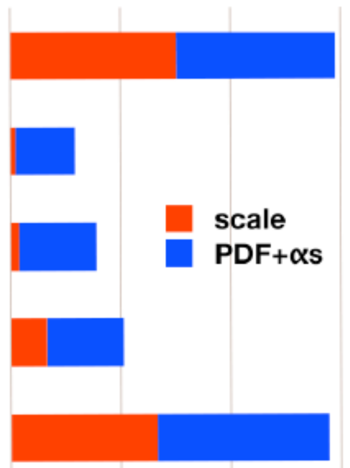
The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....

.... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...) Mangano, Aspen14

This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

Improving our **quantitative understanding of the Standard Model** is essential in this new era for HEP, where we need to hunt, unbiased, **for answers to the big questions of our field**
Now, more than ever, **sharpening our QCD tools** could be the **key for new discoveries at the LHC**

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



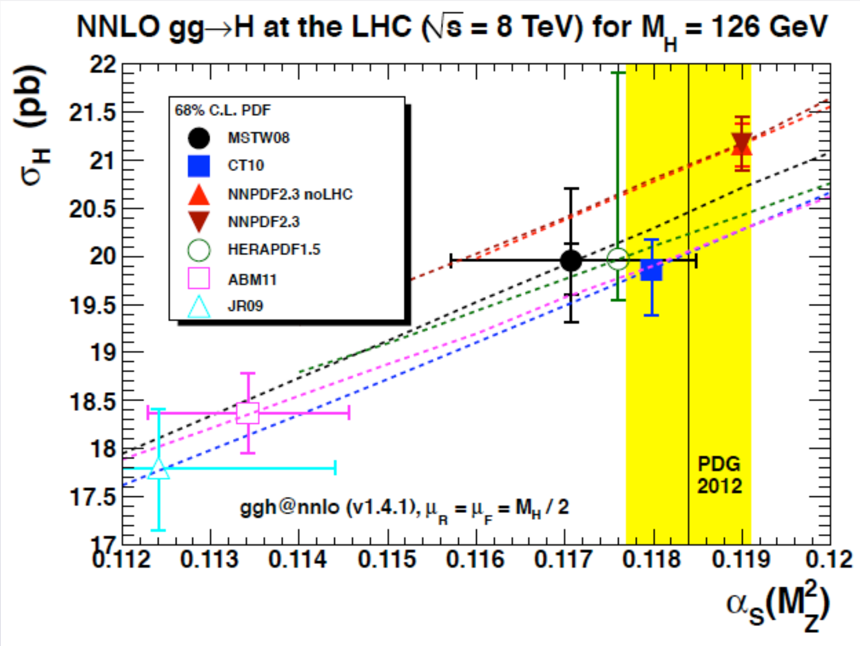
Campbell, ICHEP12

Prime example: **extraction of Higgs couplings** from LHC data soon to be **limited by QCD uncertainties**

More accurate determination of PDFs

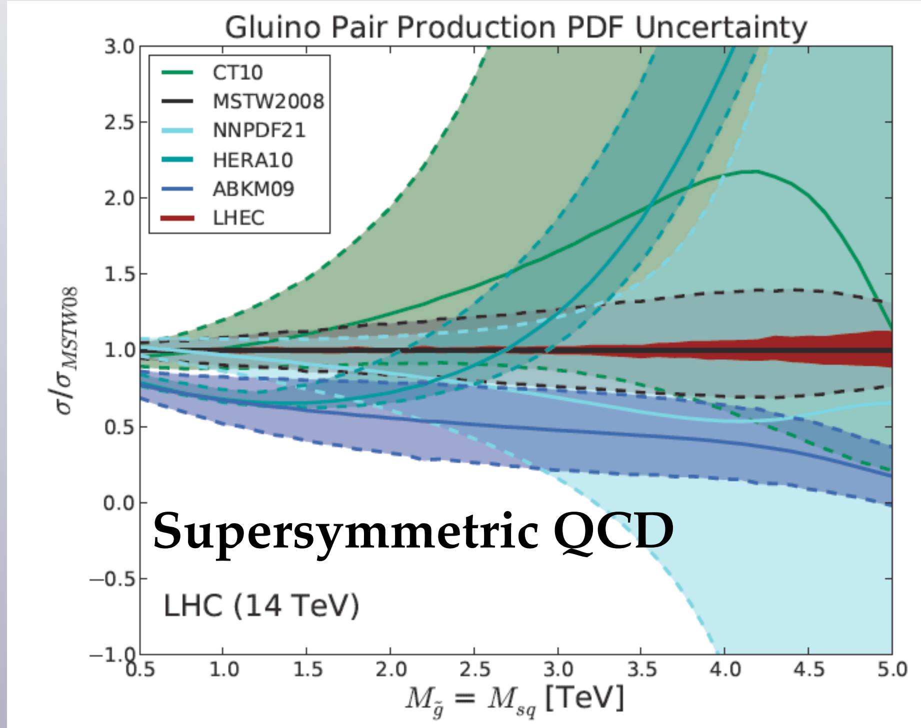
Improved indirect **sensitivity to New Physics** via deviations of Higgs couplings from SM expectations

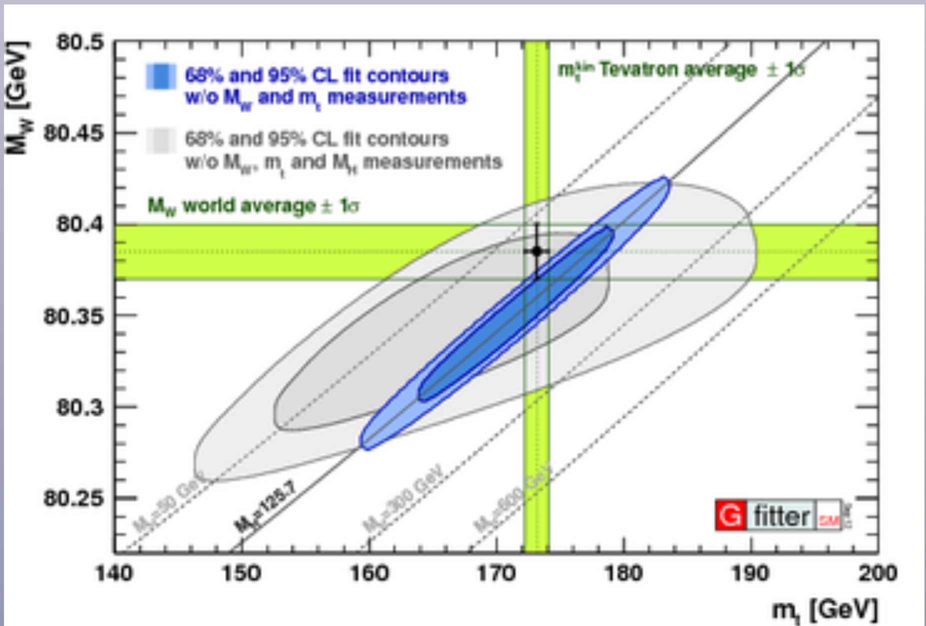
Parton Distributions and LHC phenomenology



1) PDFs fundamental limit for Higgs boson characterization in terms of couplings

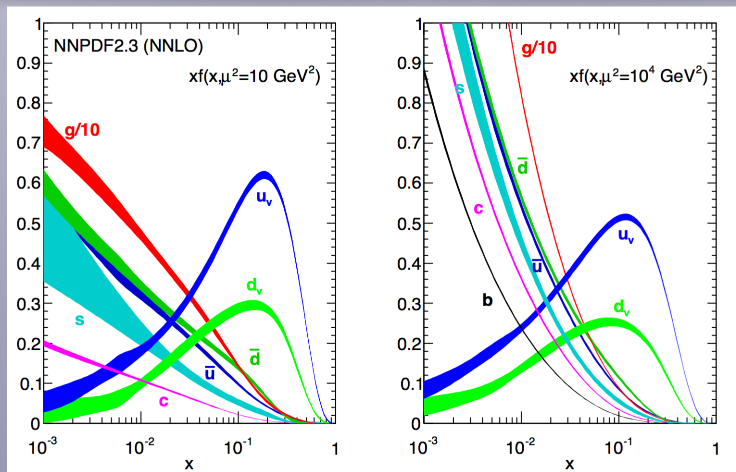
2) Very large PDF uncertainties (>100%) for new heavy particle production





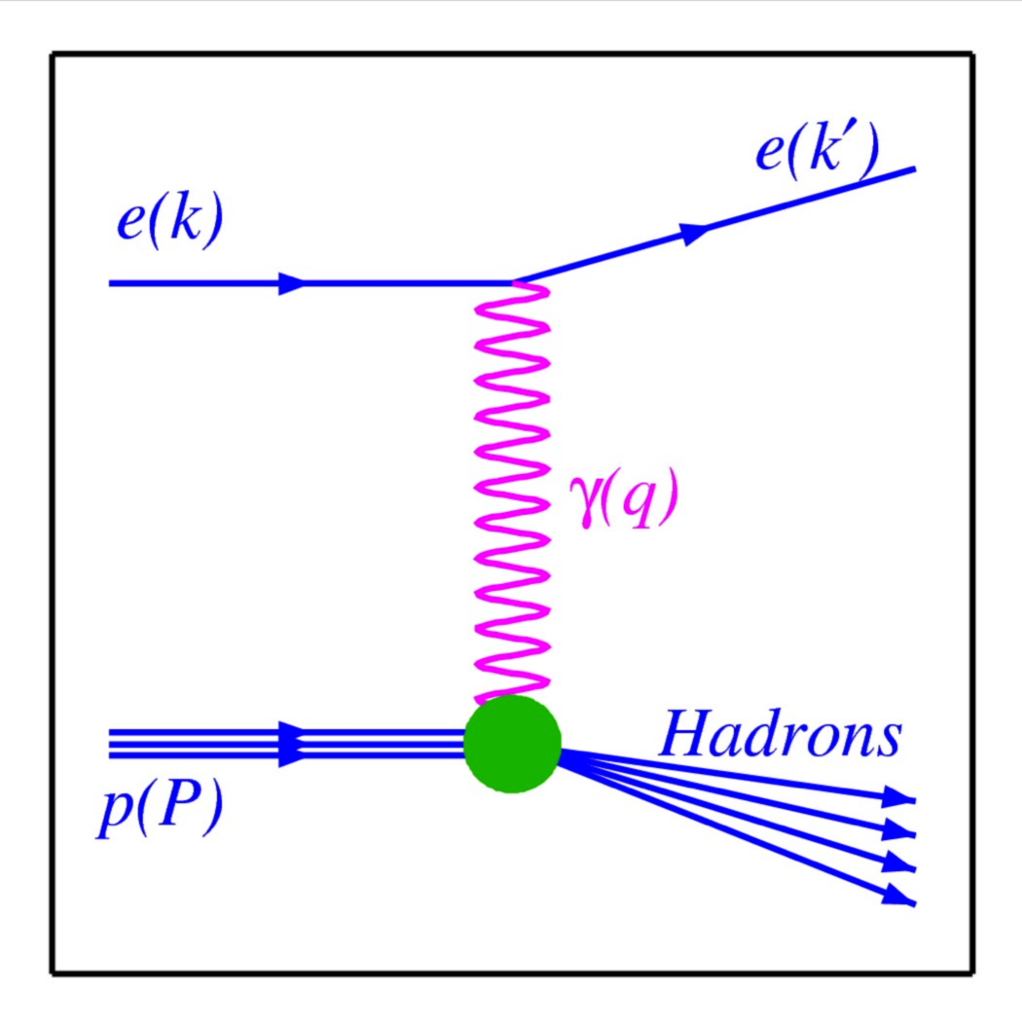
3) PDFs dominant systematic for precision measurements, like W boson mass, that test internal consistency of the Standard Model

The inner life of protons : Parton Distribution Functions



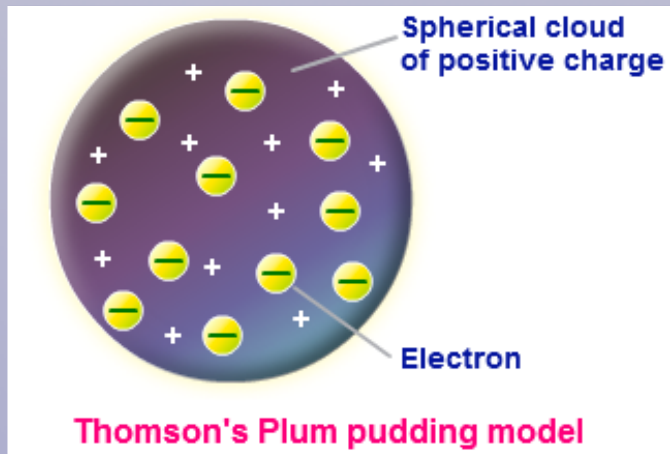
Deep-Inelastic scattering and the discovery of quarks

- Deep-inelastic **lepton-proton scattering**: First evidence for **proton structure** (SLAC, 70s)
- Measured scattering cross-section constant as **resolution scale 1/Q decreases.**
- Evidence for **point-like constituents in the proton: the quarks**



$$x_{\rm Bj} = \frac{Q^2}{2\,p\cdot q}, \quad Q^2 = -q^2 \quad y = \frac{q\cdot p}{k\cdot p}$$

- If the proton had a different structure, a **form factor F(Q)** would be expected
- Analogous to **Rutherford's discovery of the point-like atomic nucleus**, while expecting Thomson's Plum model



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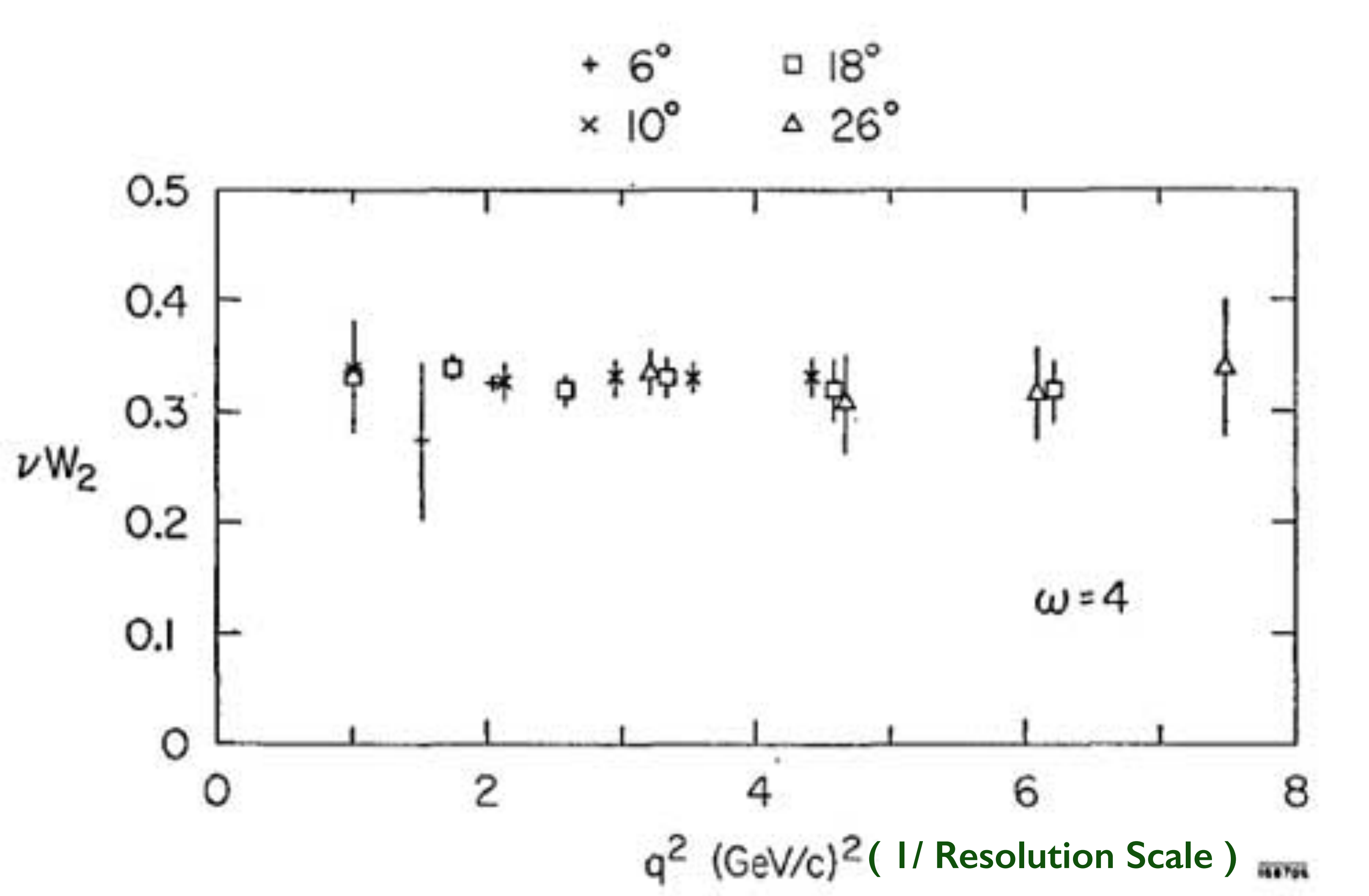
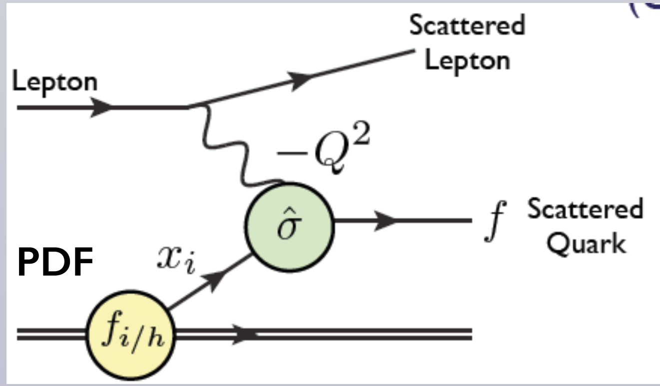


QCD Factorization and PDFs

- **QCD Factorization Theorem:** separate the hadronic cross section into a **perturbative, process dependent partonic cross section** and **non-perturbative, process independent Parton Distributions.** In DIS we have:

$$F_i(x,Q^2) = x\sum_i \int_x^1 \frac{dz}{z} C_i\left(\frac{x}{z}, \alpha_s(Q^2)\right) f_i(z,Q^2).$$

Hadron-level cross section Parton-level cross-section Parton Distribution

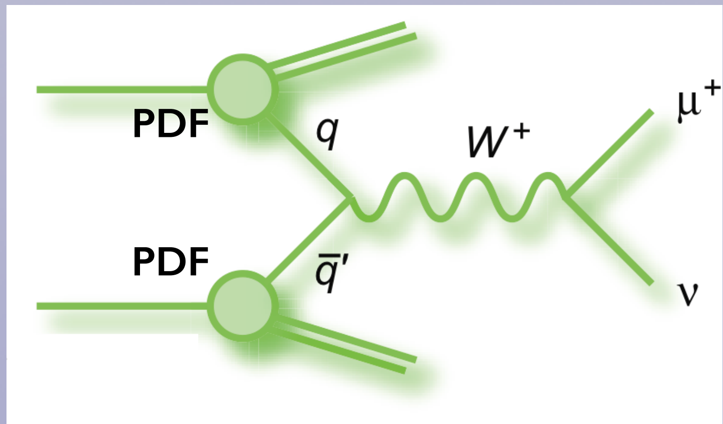


- The same **Factorization Theorem** allows to use the same **universal PDFs** to provide **predict ions for proton-proton collisions at the LHC:**

$$\sigma_X(s, M_X^2) \quad = \quad \sum_{a,b} \int_{x_{\min}}^1 dx_1\, dx_2\, f_{a/h_1}(x_1, M_X^2) f_{b/h_2}(x_2, M_X^2) \hat{\sigma}_{ab\to X}\left(x_1 x_2 s, M_X^2\right)$$

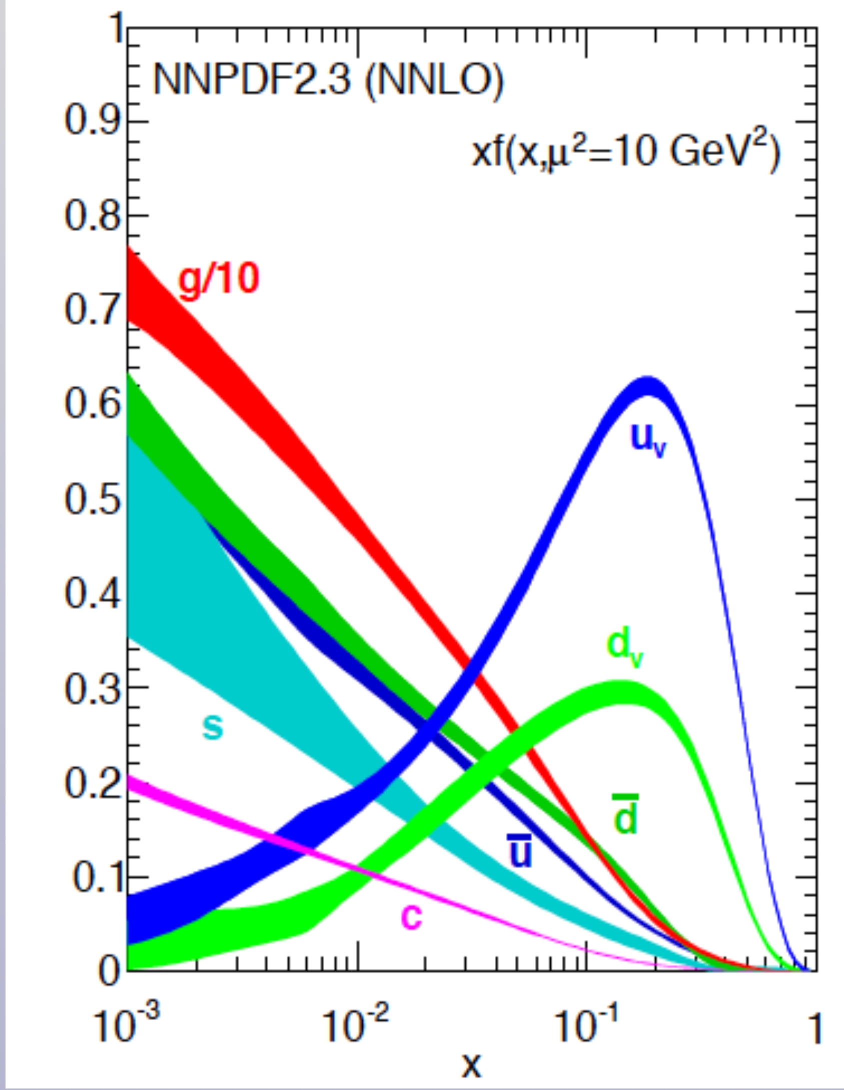
Hadron-level cross section (2) Parton Distributions Parton-level cross-section

- To make sense of **LHC collisions**, we need first of all to **determine the parton distributions of the proton** with good precision!



Parton Distributions

- There is one independent PDF **for each parton in the proton**: **u(x,Q²)**, **d(x,Q²)**, **g(x,Q²)**, …
- A total of **13 PDFs,** but **heavy quark PDFs generated radiatively** from gluon and light quarks
- At Leading Order, PDFs understood as the **probability of finding a parton of a given flavor that carries a fraction x** of the total proton's momentum
- Once QCD corrections included, PDFs become scheme-dependent and have no probabilistic interpretation
- **Shape and normalization** of PDFs are very different for each flavor, reflecting the different underlying **dynamics** that determine each PDF flavor
- QCD imposes **valence** and **momentum** sum rules **valid to all orders** in perturbation theory



PDG Review 2014

Momentum Sum Rule

$$\int_0^1 dx\, x\left[\Sigma(x) + g(x)\right] = 1$$

Valence Sum Rules

$$\int_0^1 dx\, \left(u(x) - \bar{u}(x)\right) = 2 \,, \qquad \int_0^1 dx\, \left(d(x) - \bar{d}(x)\right) = 1$$

Perturbative evolution equations

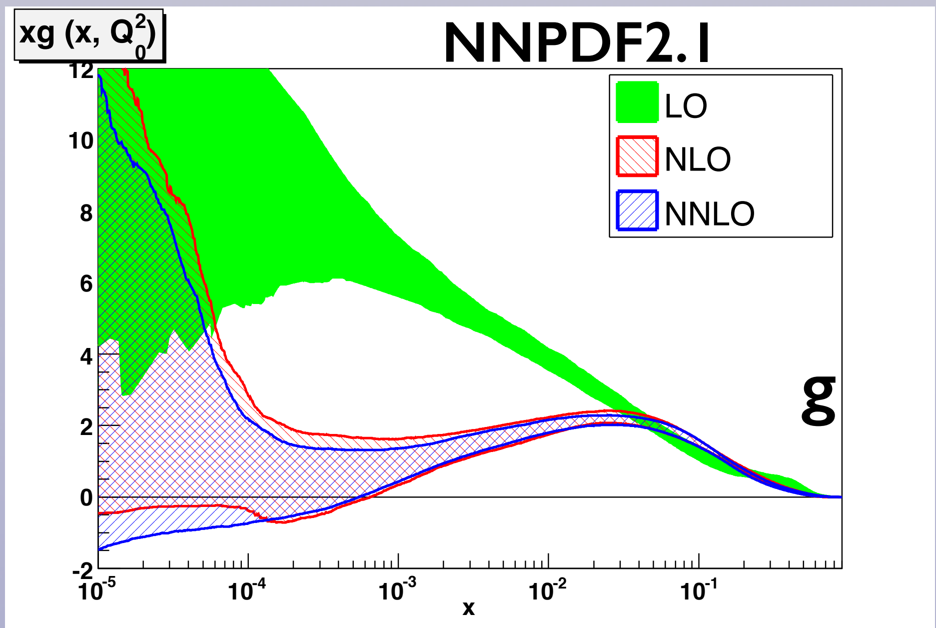
- The dependence of PDFs on **Bjorken-x (momentum fraction) is determined by non-perturbative QCD dynamics**, but that on the **scale Q² (resolution)** is instead known from perturbative QCD: the **DGLAP evolution equations**

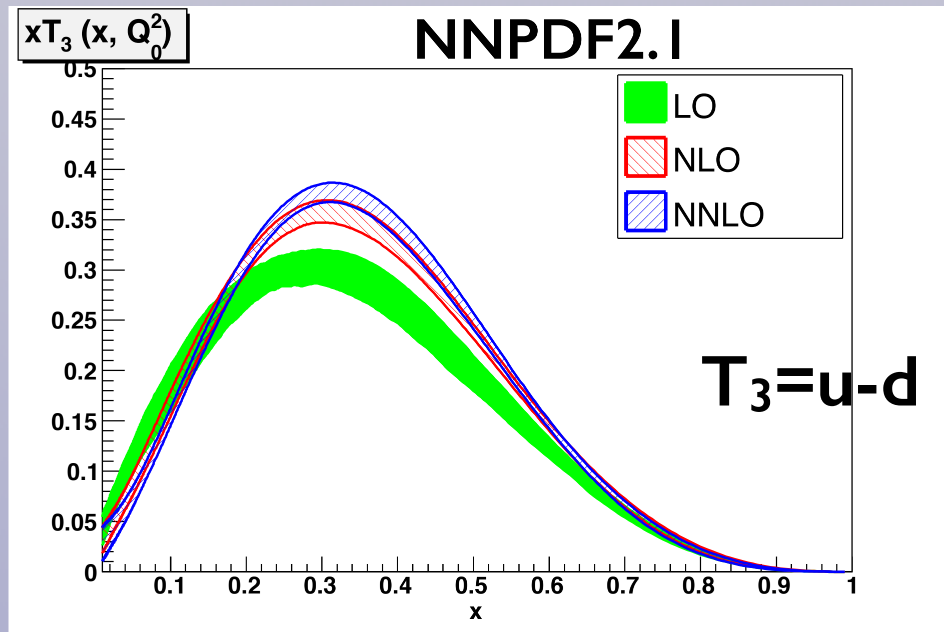
$$\frac{\partial q_i(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dz}{z} P_{ij}\left(z,\alpha_s\left(Q^2\right)\right) q_j\left(\frac{x}{z},Q^2\right)$$

- Once x-dependence $\mathbf{q(x,Q^2_0)}$ extracted from data, **pQCD determines PDFs** at other scales $\mathbf{q(x,Q^2)}$
- **Evolution kernels** have been computed up to next-to-next-to-leading order (NNLO):

$$P(z,\alpha_s(Q^2)) = P^{(0)}(z) + \frac{\alpha_s(Q^2)}{2\pi}P^{(1)}(z) + \left(\frac{\alpha_s(Q^2)}{2\pi}\right)^2 P^{(2)}(z)$$

- Reasonable **convergence of the perturbative expansion** of PDFs up to NNLO





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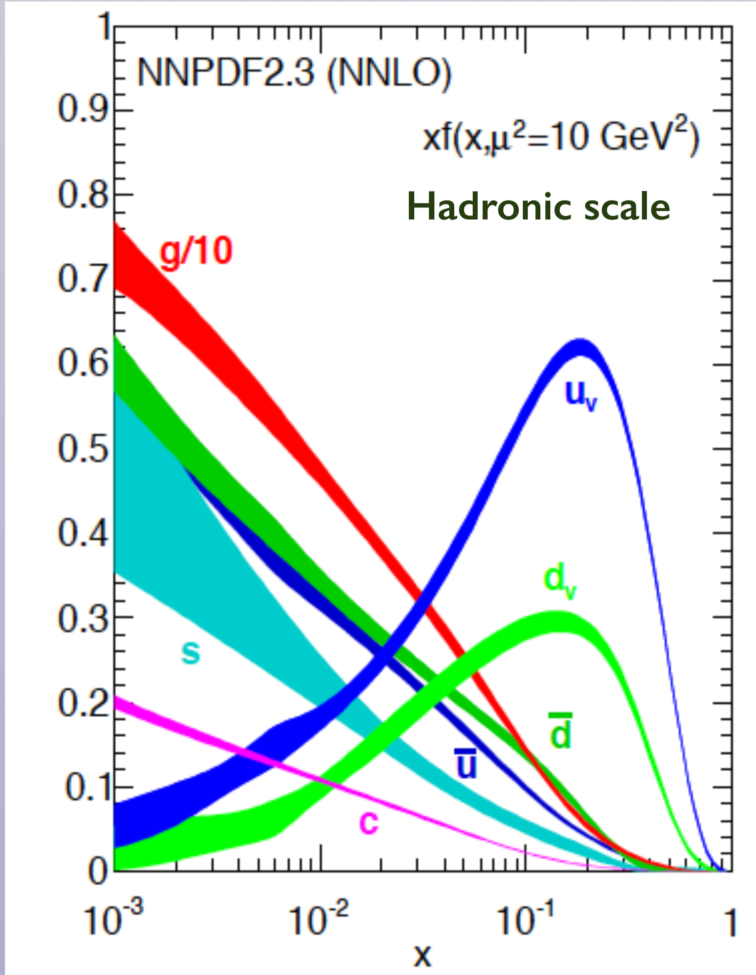
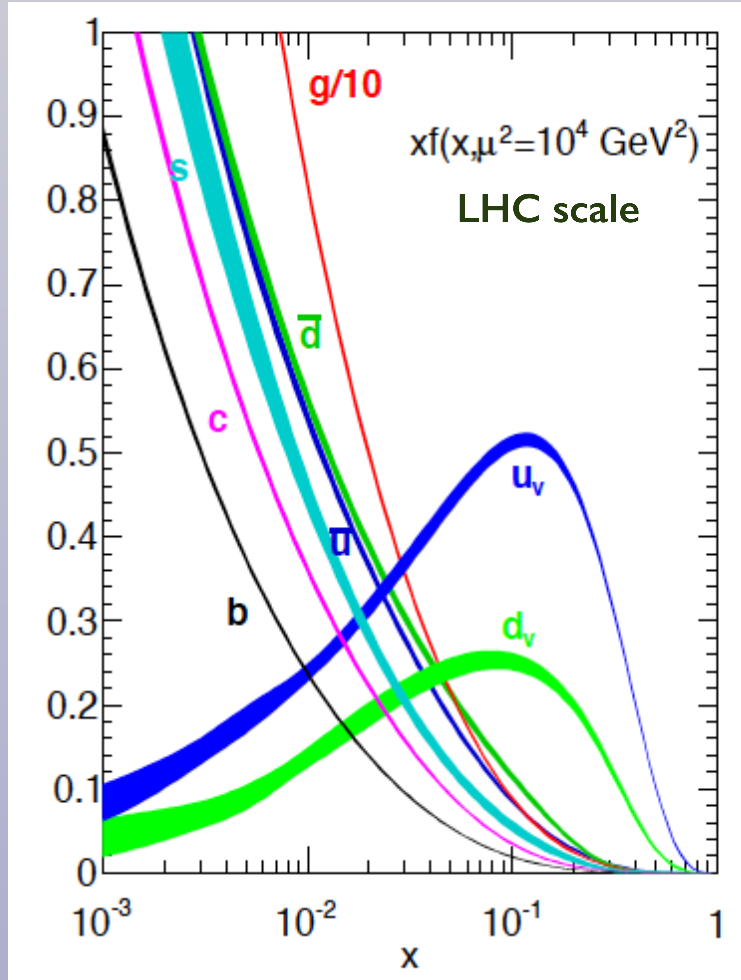


Perturbative Evolution



Global PDF analysis

Parton Distributions, and their associated **uncertainties**, need to be determined from a **global analysis of hard-scattering data** that requires as input the most updated **theory calculations**, precise and varied **experimental data** and robust **statistical methodology**

Theory

- ☑ Partonic cross-sections
- ☑ DGLAP evolution
- ☑ Heavy quark treatment
- ☑ Fast interfaces to NLO calculations
- ☑ NNLO QCD effects
- ☑ QED and electroweak corrections

Data

- ☑ Deep-inelastic scattering structure functions
- ☑ DIS charm production
- ☑ DIS Neutrino production
- ☑ Jets at pp colliders
- ☑ Drell-Yan (dilepton pair) production at pp colliders
- ☑ Top quark data

Methodology

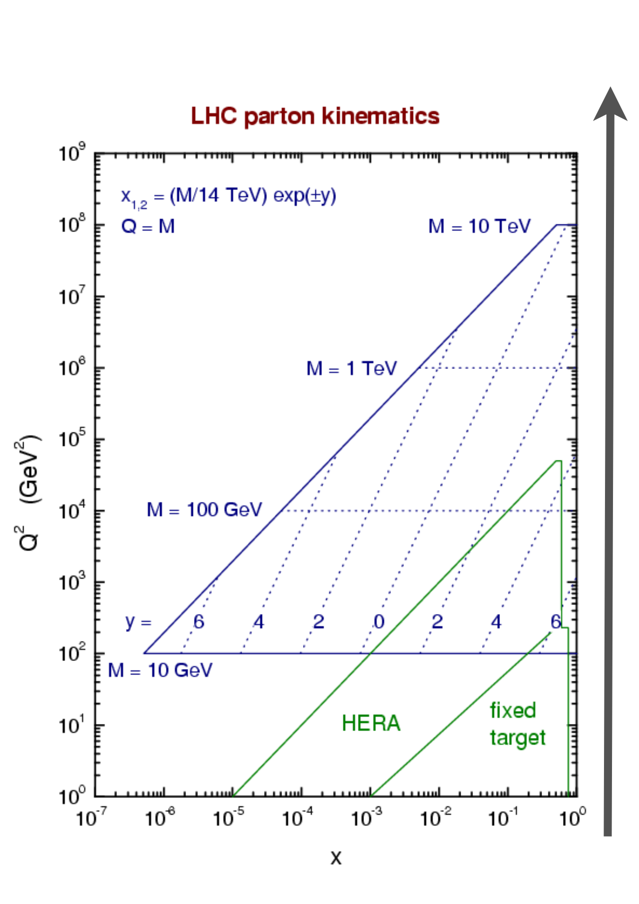
- ☑ PDF parametrisation
- ☑ PDF uncertainty estimation and error propagation to LHC cross-sections
- ☑ Theoretical uncertainties
- ☑ Minimisation strategy

Parton Distributions for the LHC

- Higgs cross-sections
- BSM New Physics searches
- Precision Standard Model measurements

Experimental data in global PDF fits

Q^2 dependence of PDFs: determined by pQCD



x dependence of PDFs: determined from data

- A **global dataset** covering a wide set of hard-scattering observables is required to constrain **all possible PDF combinations** in the **whole range of Bjorken-x**

- For example, **inclusive jets** are sensitive to the **large-x gluon**, while **HERA neutral current** data pins down the **small-x quarks**

- **LHC data** is introducing completely new observables to be used for PDF constraints

Process	Subprocess	Partons	x range
$\ell^\pm\{p,n\} \to \ell^\pm X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
$\ell^\pm n/p \to \ell^\pm X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
$pp \to \mu^+\mu^- X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
$pn/pp \to \mu^+\mu^- X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
$\nu(\bar{\nu})N \to \mu^-(\mu^+)X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
$\nu N \to \mu^-\mu^+ X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
$\bar{\nu} N \to \mu^+\mu^- X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
$e^\pm p \to e^\pm X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
$e^+ p \to \bar{\nu} X$	$W^+\{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$
$e^\pm p \to e^\pm c\bar{c} X$	$\gamma^* c \to c$, $\gamma^* g \to c\bar{c}$	c, g	$0.0001 \lesssim x \lesssim 0.01$
$e^\pm p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
$p\bar{p} \to (W^\pm \to \ell^\pm\nu)X$	$ud \to W$, $\bar{u}\bar{d} \to W$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
$p\bar{p} \to (Z \to \ell^+\ell^-)X$	$uu, dd \to Z$	d	$x \gtrsim 0.05$

MSTW08, arXiv:0901.0002

The Neural Network Approach to Parton Distributions

The NNPDF approach

- The **limitations of available PDF sets circa 2005**, and the requirements of **precision physics at the upcoming LHC,** prompted us to develop a completely novel approach to PDF determination

- PDF sets typically based on **restrictive functional forms** leading to strong theoretical bias

$$g(x,Q_0^2) \;=\; A_g(1-x)^{m_\Sigma}x^{-n_\Sigma}\left(1+a_g\sqrt{x}+b_g x+\ldots\right)$$

✅NNPDF solution: use **artificial neural networks** as universal unbiased interpolants

$$g(x,Q_0^2) \;=\; A_g(1-x)^{m_\Sigma}x^{-n_\Sigma}\mathrm{NN}_g(x)$$

- PDF sets often rely on the the **Gaussian/linear approximation** for error estimation and propagation

$$F_0 = F(S_0), \quad \sigma_F = \sqrt{\sum_{i=1}^{N_{\rm par}}\left[F(S_i)-F(S_0)\right]^2}.$$

✅NNPDF solution: Use the **Monte Carlo method** to create a probability distribution in the space of PDFs

$$F_{I,p}^{(\mathrm{art})(k)} = S_{p,N}^{(k)}F_{I,p}^{(\mathrm{exp})}\left(1+\sum_{l=1}^{N_c}r_{p,l}^{(k)}\sigma_{p,l}+r_p^{(k)}\sigma_{p,s}\right)\ ,\ k=1,\ldots,N_{\rm rep}$$

Consisteny error propagation no LHC xsecs
no Gaussian assumptions

- Traditional PDF analyses based on **deterministic minimisation** of the χ^2 to reach convergence in the fit

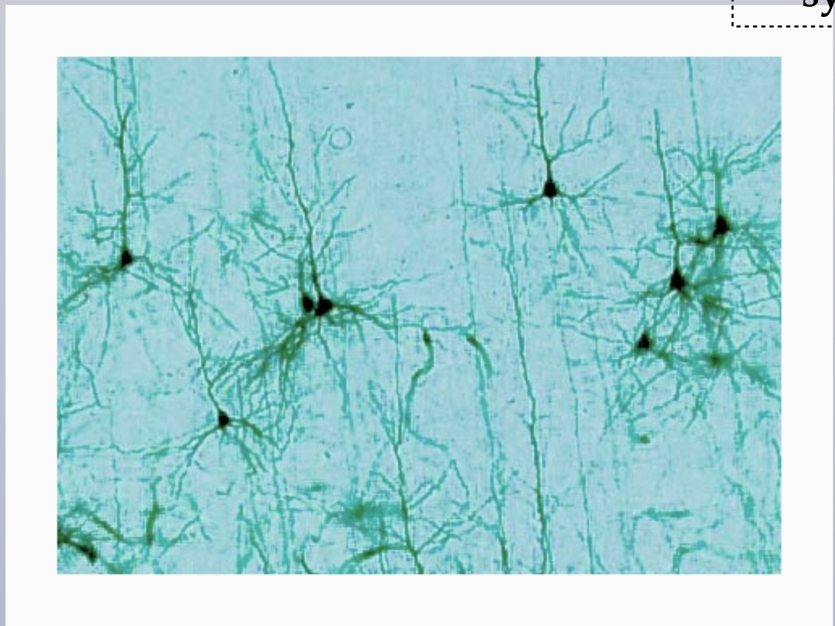
✅NNPDF solution: Use **Genetic Algorithms** to be able to explore efficiently the vast parameter space

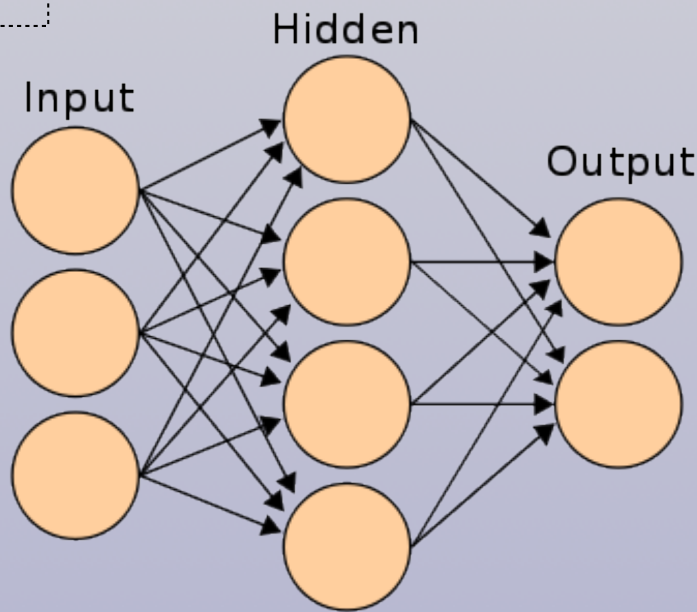
$$\chi^2 \;=\; \sum_{i=1}^{N_{\rm dat}}\sum_{i'=1}^{N_{\rm dat}}(D_i-T_i)\left(V^{-1}\right)_{ii'}(D_{i'}-T_{i'}).$$

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**

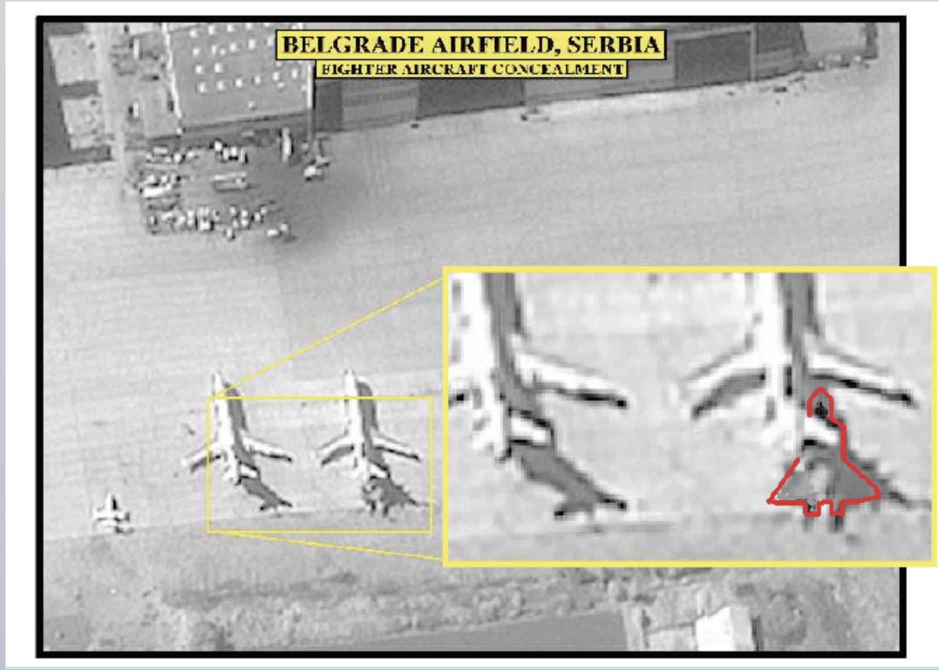
Biological NeuralNets → Neurons, axions, synapses, ... ← **Artificial NeuralNets**





- Artificial neural networks aimed 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



Example 1: **Pattern recognition.** During the Yugoslavian wars, the NATO used ANNs to recognise hidden military vehicles

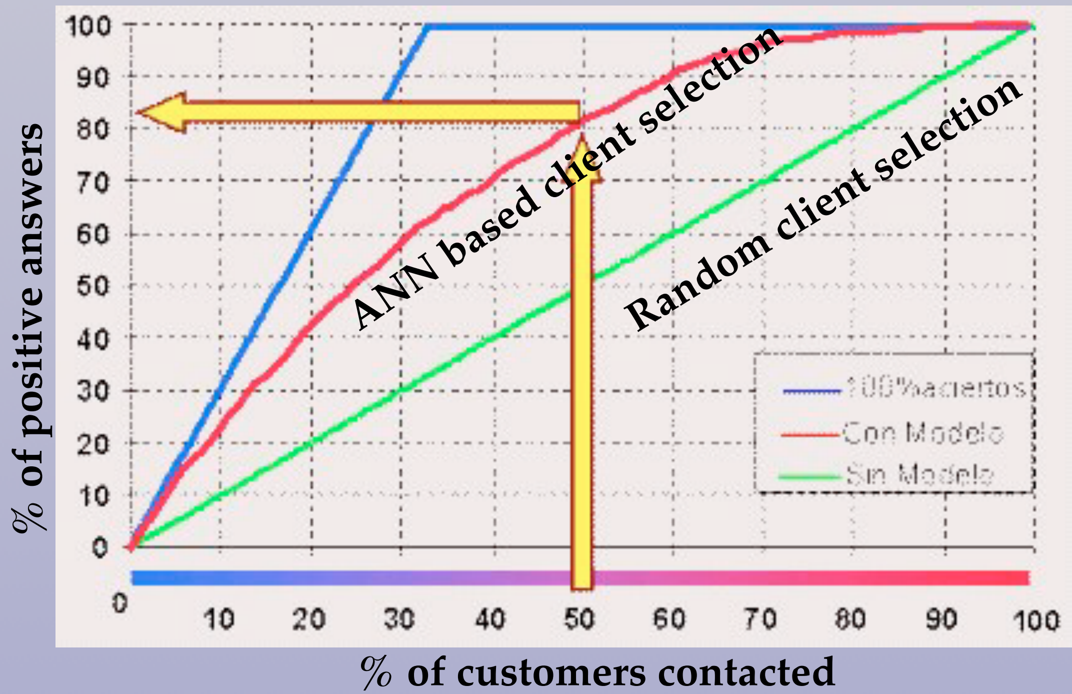
A military aircraft is identified, despite being hidden below a commercial plane.

Many other applications of ANN in **pattern recognition**: OCR software, hand writing recognition, automated anti-plagiarism software, ...

Example 2: **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** (sex, income, loans) and **their ourput** (yes/no) and use the information to contact only clients likely to accepy the offer

Cost-effective method to improve marketing performance

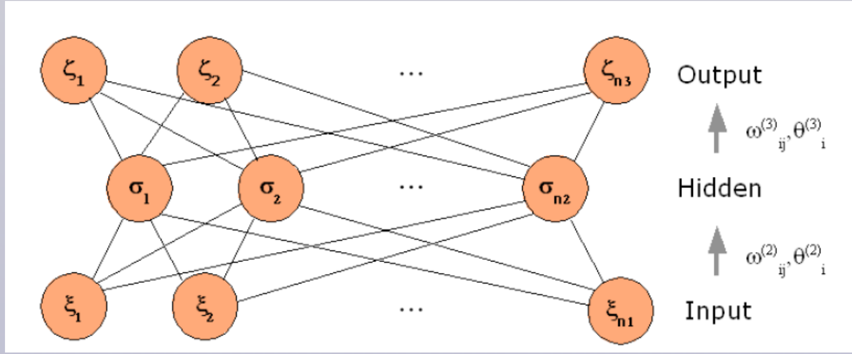


Artificial Neural Networks

- **Artificial Neural Networks** (ANNs) provide **universal unbiased interpolants** to parametrize PDFs at low input scales

$$\begin{aligned} \Sigma(x,Q_0^2) &= (1-x)^{m_\Sigma} x^{-n_\Sigma} \mathrm{NN}_\Sigma(x) \\ g(x,Q_0^2) &= A_g (1-x)^{m_\Sigma} x^{-n_\Sigma} \mathrm{NN}_g(x) \end{aligned}$$

- The ANN class that we adopt are **feed-forward multilayer neural networks** (perceptrons)



$$\xi_i^{(l)} = g\left(h_i^{(l)}\right) \ , \quad i=1,\ldots,n_l \ , \qquad l=2,\ldots,L$$

$$h_i^{(l)} = \sum_{j=1}^{n_{l-1}} \omega_{ij}^{(l)} \xi_j^{(l-1)} - \theta_i$$

- In traditional PDF determinations, the input *ansatz* is a simple **polynomial**

$$\begin{aligned} \Sigma(x,Q_0^2) &= (1-x)^{m_\Sigma} x^{-n_\Sigma} \left(1 + a_\Sigma\sqrt{x} + b_\Sigma x + \ldots\right) \ , \\ g(x,Q_0^2) &= A_g (1-x)^{m_\Sigma} x^{-n_\Sigma} \left(1 + a_g\sqrt{x} + b_g x + \ldots\right) \end{aligned}$$

- The use of Artificial Neural Networks allows:
  - **No theory bias** introduced in the PDF determination by the choice of *ad-hoc* functional forms
  - The use of very flexible parametrizations for all PDFs - regardless of the dataset used. The NNPDF analysis allow for **O(400) free parameters**, to be compared with **O(10-20) in traditional PDFs**
  - **Faithful extrapolation**: PDF uncertainties **blow up** in regions with scarce experimental data

PDF Uncertainties: The Monte Carlo Method

- Generate a **large number of Monte Carlo replicas of the experimental data** with the same underlying probability distribution

$$\underbrace{S_{p,N}^{(k)}}_{\text{lumi error}} \quad F_{I,p}^{(\mathrm{art})(k)} = S_{p,N}^{(k)} F_{I,p}^{(\mathrm{exp})} \left(1 + \sum_{l=1}^{N_c} r_{p,l}^{(k)} \sigma_{p,l} + r_p^{(k)} \sigma_{p,s} \right) \quad , \; k = 1, \ldots, N_{\mathrm{rep}} \gg 1$$

sys errors: $\sigma_{p,l}$; stat error: $\sigma_{p,s}$; random numbers: $r_{p,l}^{(k)}$, $r_p^{(k)}$; lumi error: $S_{p,N}^{(k)}$

- Perform a **PDF determination** on each of these MC replicas

- The set of PDF replicas form a **representation of the probability density in the space of parton distribution functions**

- PDF uncertainties can be propagated to physical cross sections using **textbook statistics**, no need of linear/gaussian assumptions

Central PDF prediction = Expectation Value of MC sample

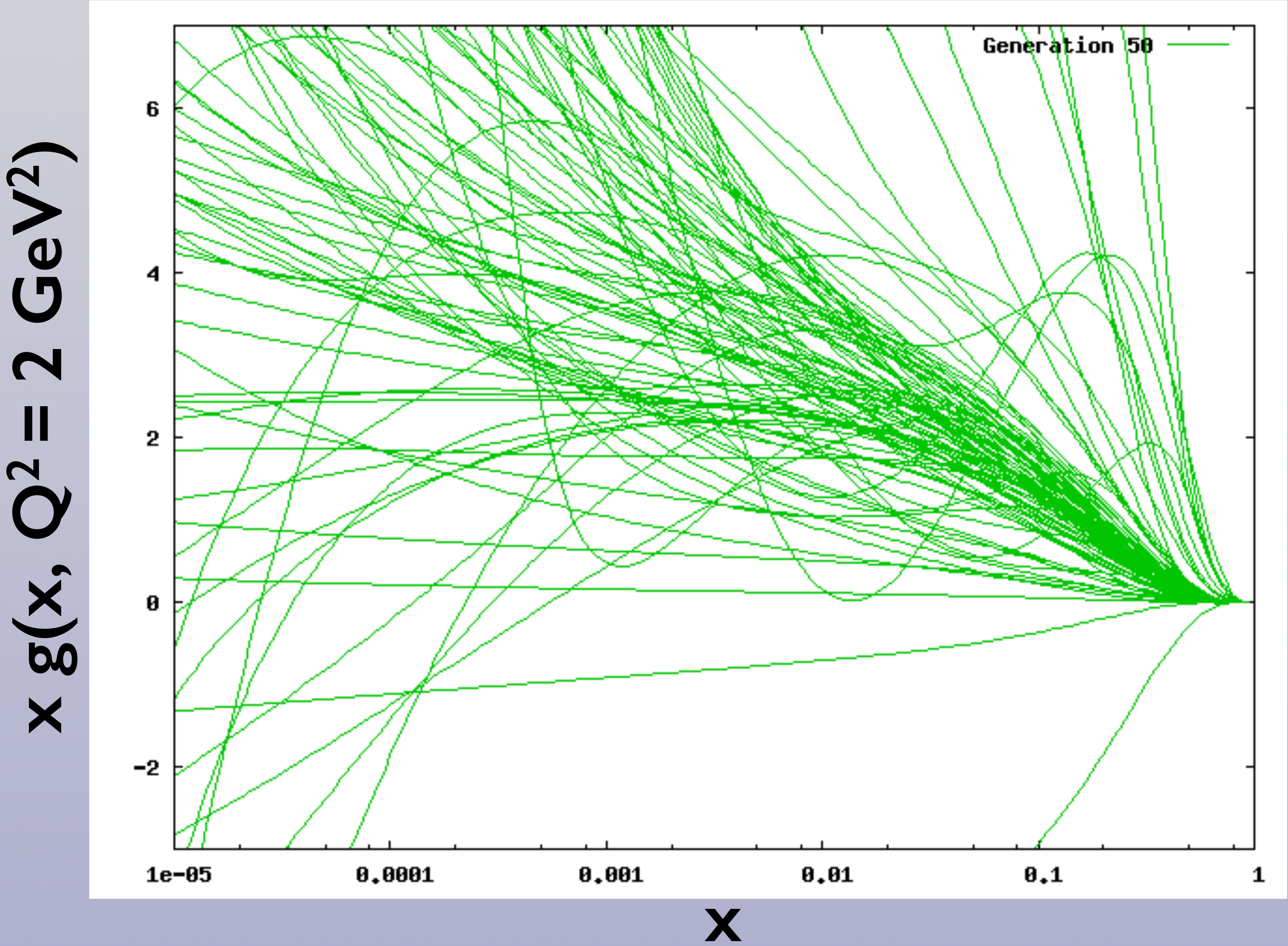
$$\langle \mathcal{O} \rangle = \int \mathcal{O}[f]\, \mathcal{P}(f)\, Df = \frac{1}{N} \sum_{k=1}^{N} \mathcal{O}[f_k]$$

PDF Uncertainty = Standard Deviation of MC sample

$$\Delta f = \sqrt{\frac{1}{N} \sum_{k=1}^{N} f_k^2 - \left(\frac{1}{N} \sum_{k=1}^{N} f_k \right)^2}$$

PDF Replica Neural Network Learning

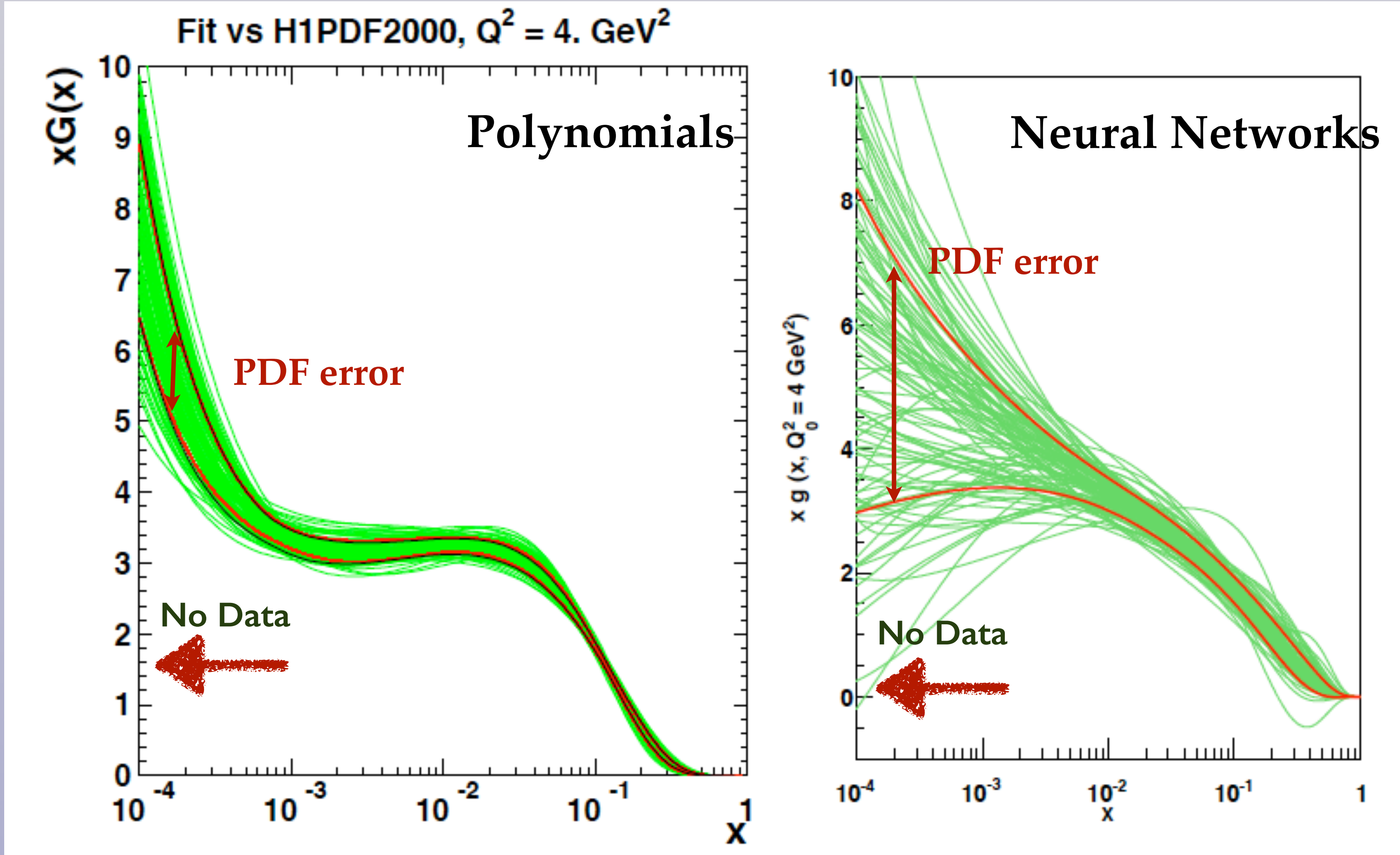
The minimisation of the **data vs theory chi2** is performed using **Genetic Algorithms**
Each **green curve** corresponds to a **gluon PDF Monte Carlo** replica



Artificial Neural Networks vs. Polynomials

- Compare a **benchmark PDF analysis** where **the same dataset** is fitted with **Artificial Neural Networks** and with **standard polynomials** (everything else identical)

- **ANN** avoid biasing the PDFs, **faithful extrapolation at small-x** (very few data, thus error blow up)

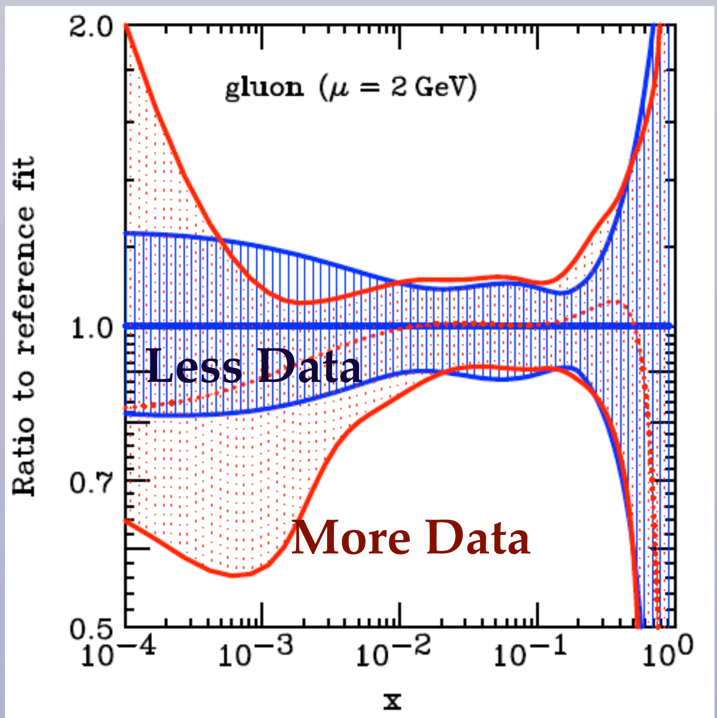


Adding more data: better or worse?

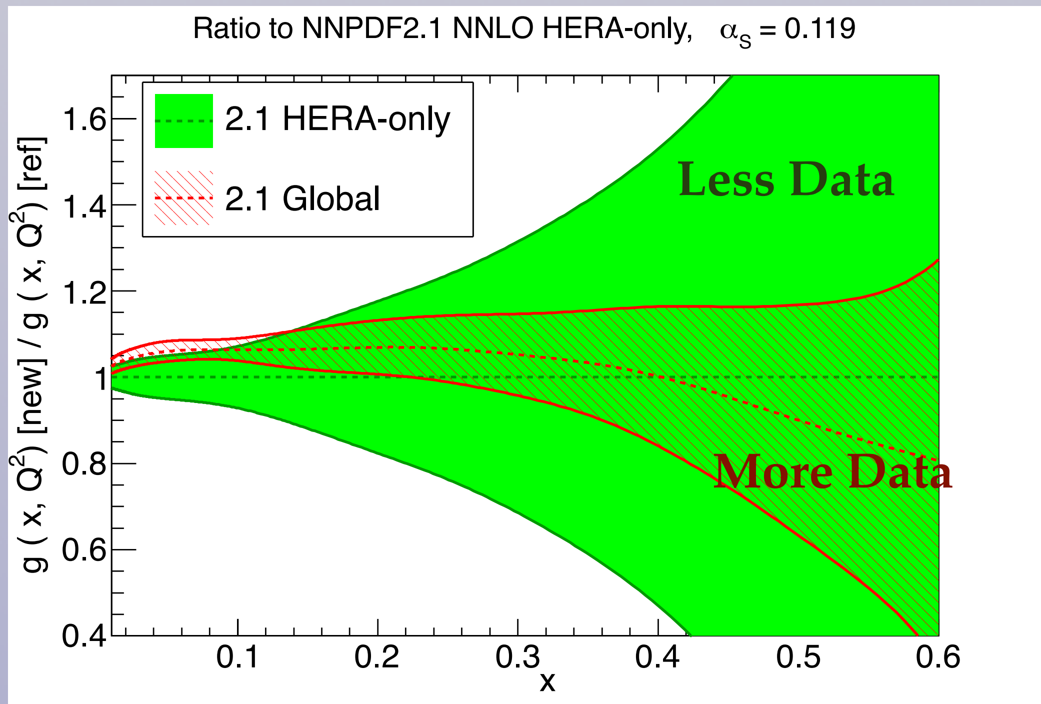
- In traditional **Hessian** PDF approach, **unexpected behaviors** might arise when data added

New data → **Need more flexible PDFs to fit data: increase # of params** → **More directions in Hessian space to explore** → **Larger PDF uncertainties?**

- In the **NNPDF approach**, more data always leads to an **improvement of PDF uncertainties**



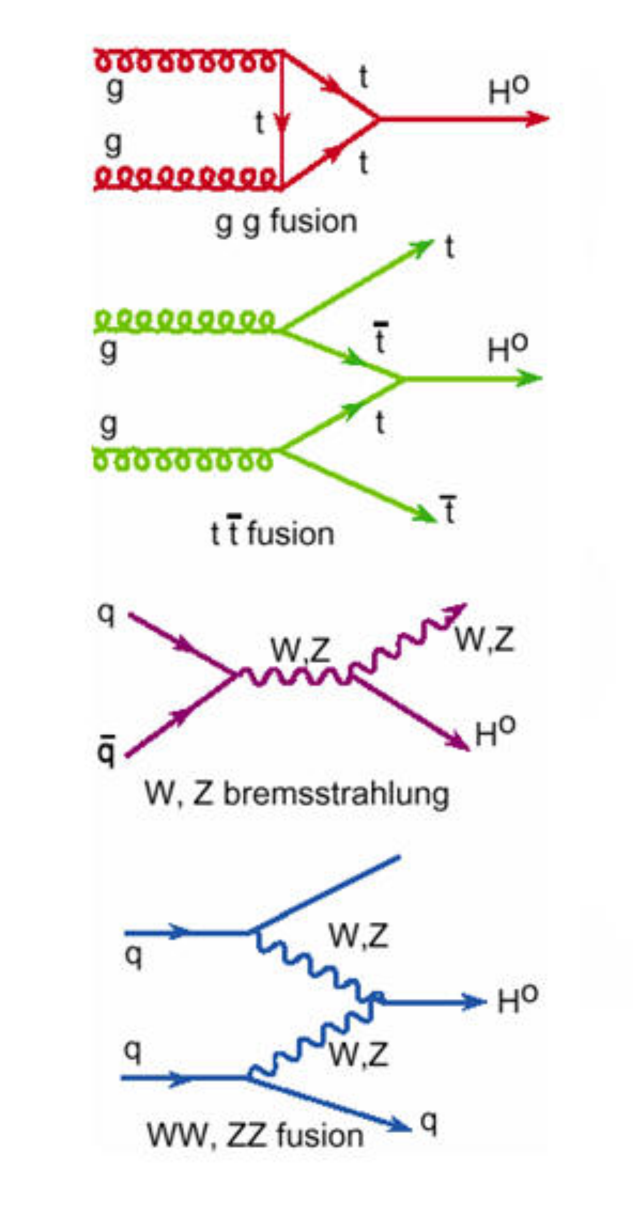
CT10 (Traditional approach)



NNPDF approach

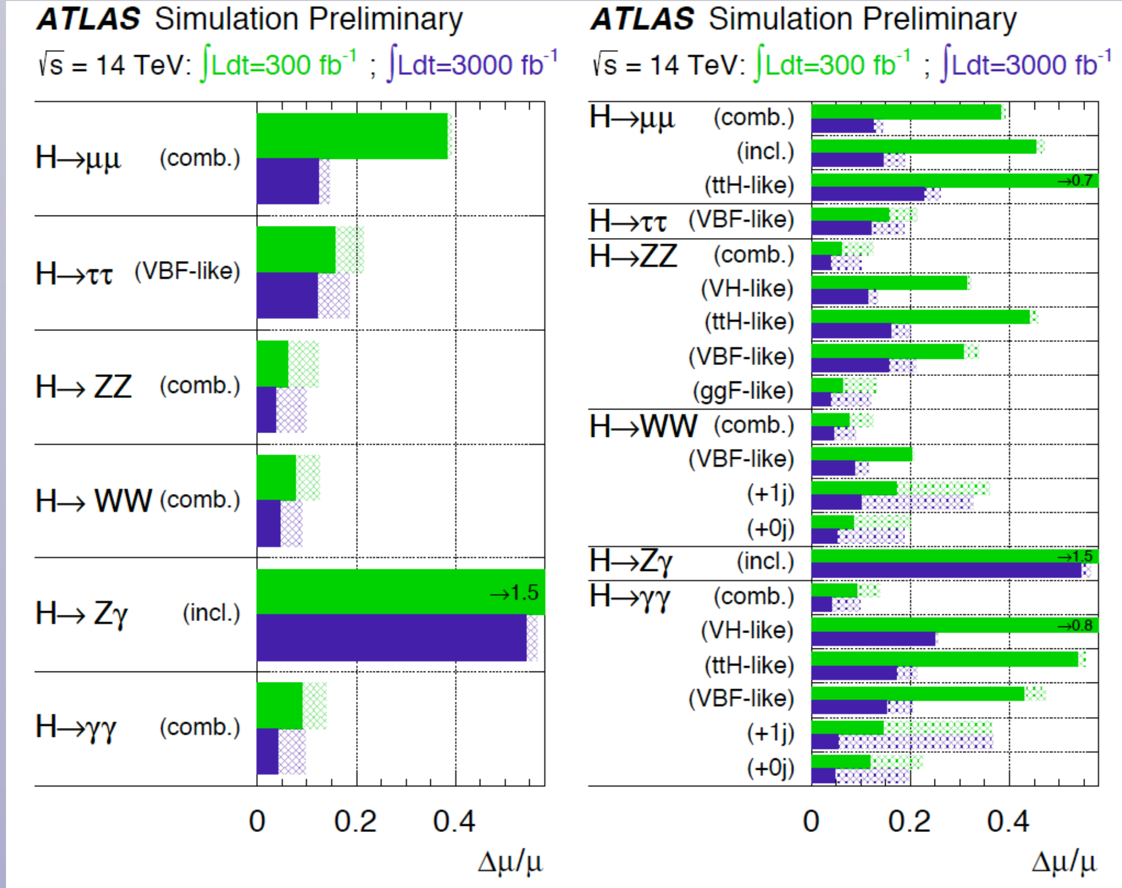
PDFs at the LHC:
From Higgs and SM to BSM searches

Higgs Boson Characterisation



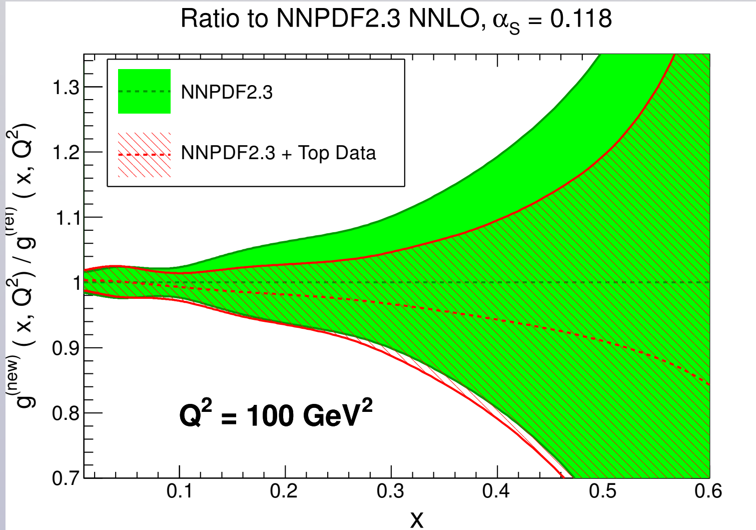
- The study of the Higgs boson properties is a cornerstone of the LHC program. **All production cross sections** require accurate knowledge of PDFs
    - **gg fusion, ttH**: gluon luminosity
    - **vector-boson fusion**: quark-quark luminosity
    - **associated production with W/Z**: quark-antiquark luminosity

For many crucial channels, **QCD uncertainties, including PDFs, hatched areas,** limit the accuracy of **Higgs coupling extraction** form LHC data

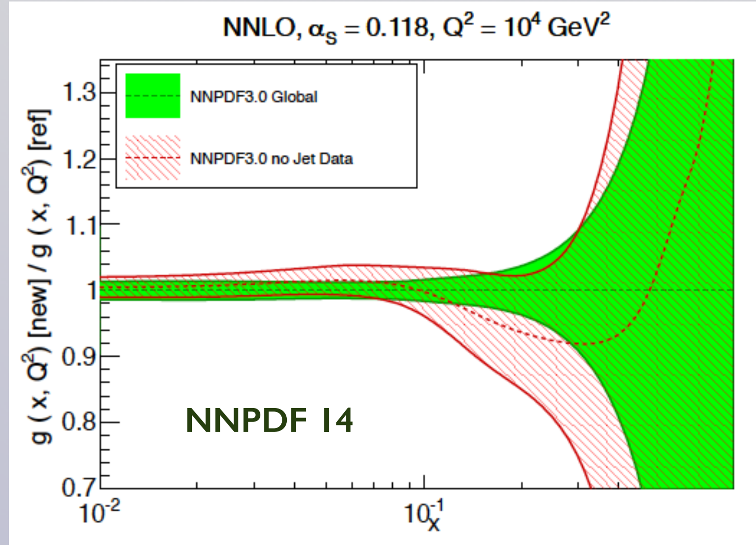


Parton Distributions with LHC data

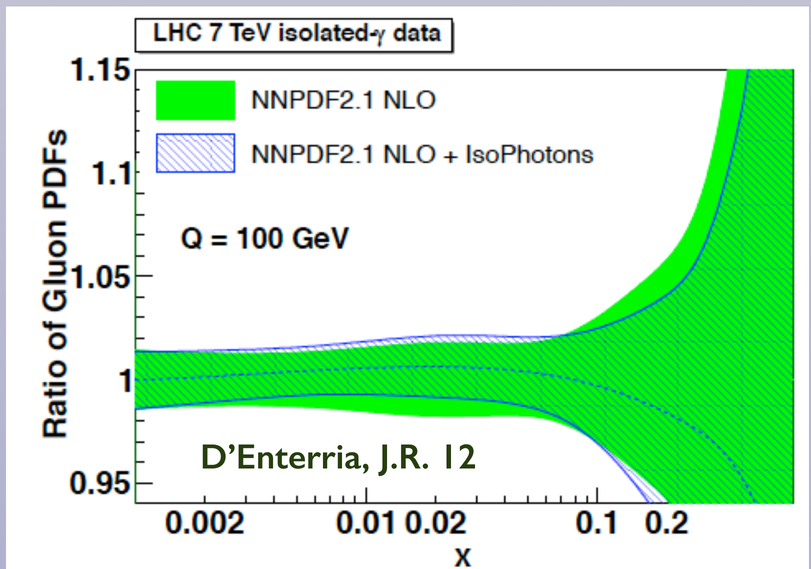
- A major breakthrough in the recent years has been the inclusion of **LHC data** into **global PDF fits**
- PDF constraints from a wide variety of LHC processes have been studied, many of which **for first time**



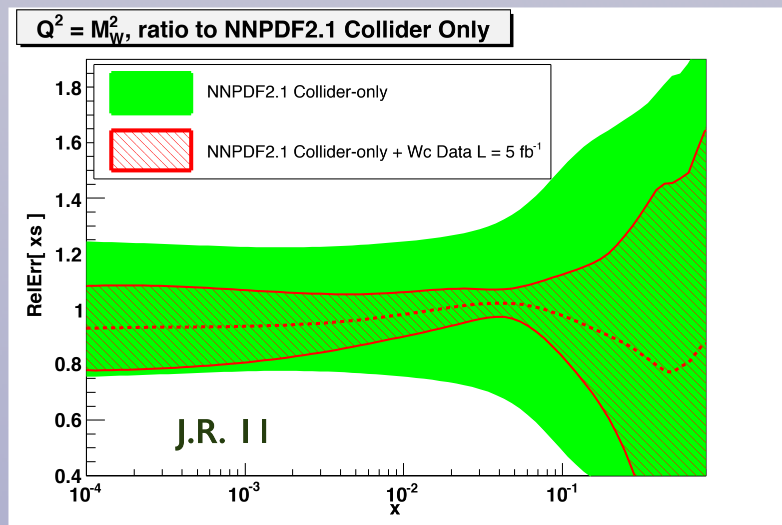
Large-x gluon from top quark data



Large-x gluon from inclusive Jet production



Isolated photon LHC data constraints **gluons at medium-x**: relevant for **Higgs production in gluon fusion**



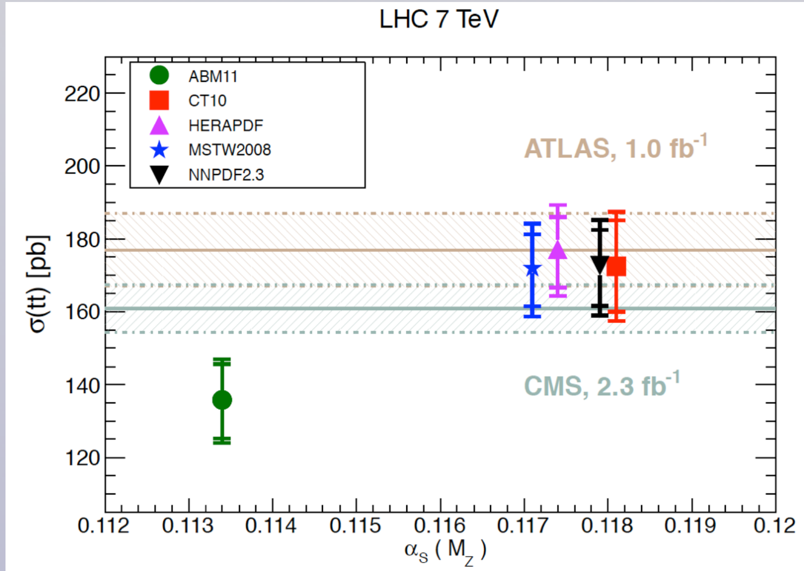
W production in association with charm quarks provides direct access to the proton strangeness

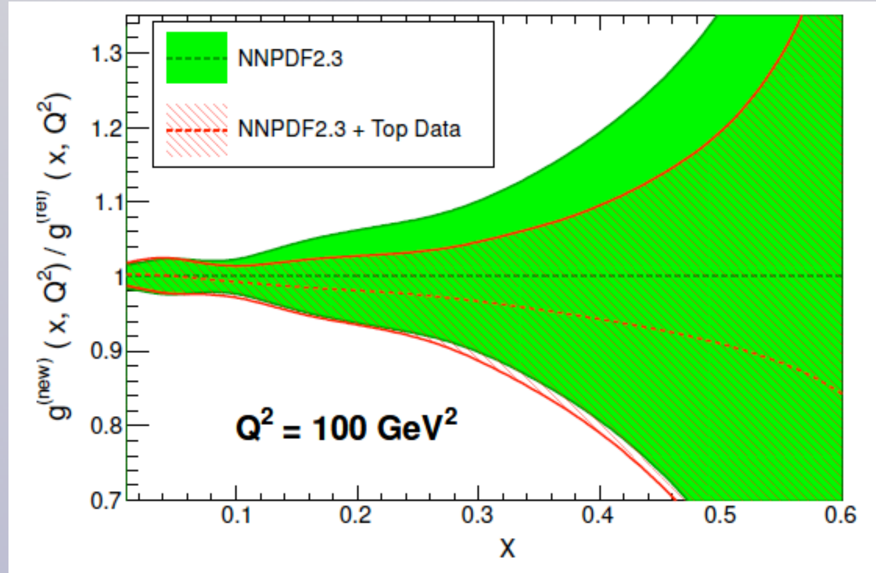
Top quarks as gluon luminometers

- The recent **NNLO top quark cross section** make top data the **only LHC observable** that is both **directly sensitive to the gluon PDF** and can be included consistently in a **NNLO global analysis**

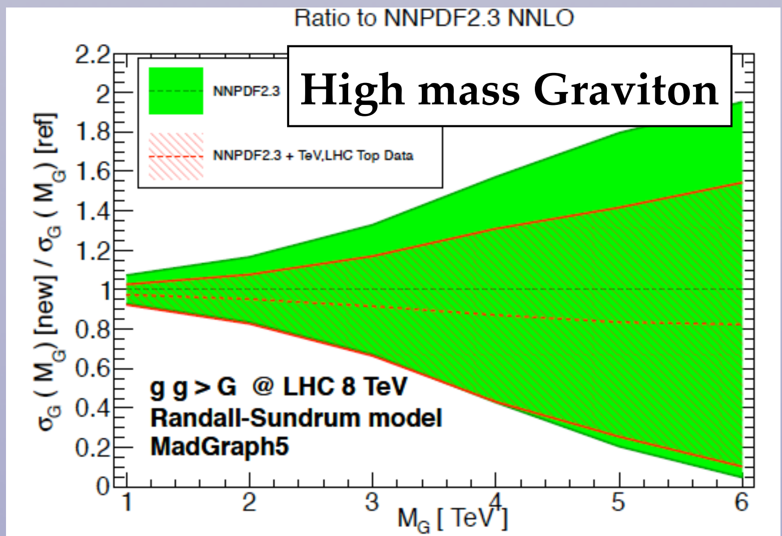
- The precise 7 and 8 TeV LHC data can be used to **discriminate between PDF sets** and **to reduce the PDF uncertainties on the poorly known large-x gluon**

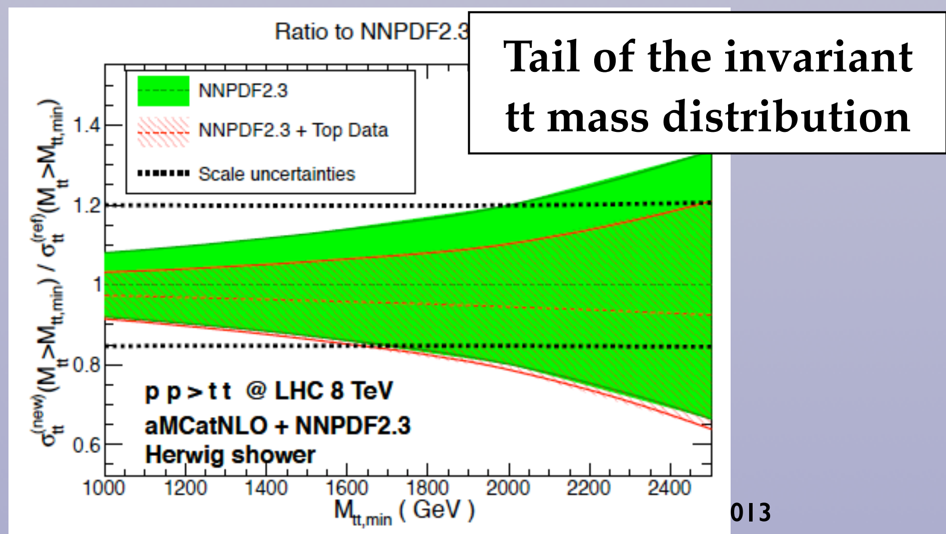
Czakon, Mangano, Mitov, J.R. 13





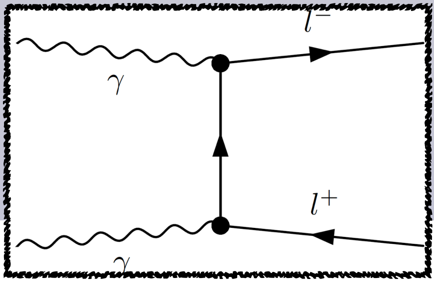
- The **improved large-x gluon** leads to more accurate theory predictions for **BSM searches**



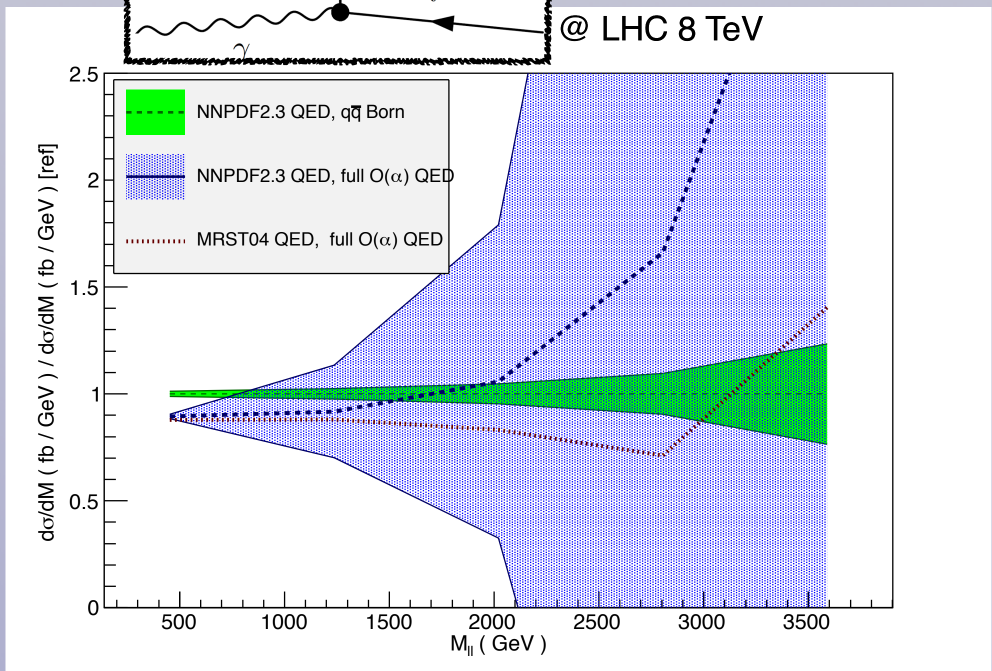


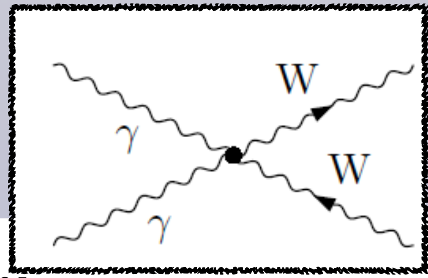
PDFs with QED corrections

- **QED** and **electroweak corrections** are essential for **precision LHC phenomenology**: **W and Z production**, **W mass determination**, **WW boson pair** production, **TeV scale** jet and top quark pair production, searches for new **W′, Z′ bosons**
- Consistent inclusion of electroweak effects require PDFs with **QED corrections** and a **photon PDF**
- **NNPDF2.3 QED:** first-ever determination of the **photon PDF** from **LHC data**
- Neglecting **photon-initiated contributions** leads to systematically underestimating theory errors in **crucial BSM search channels**

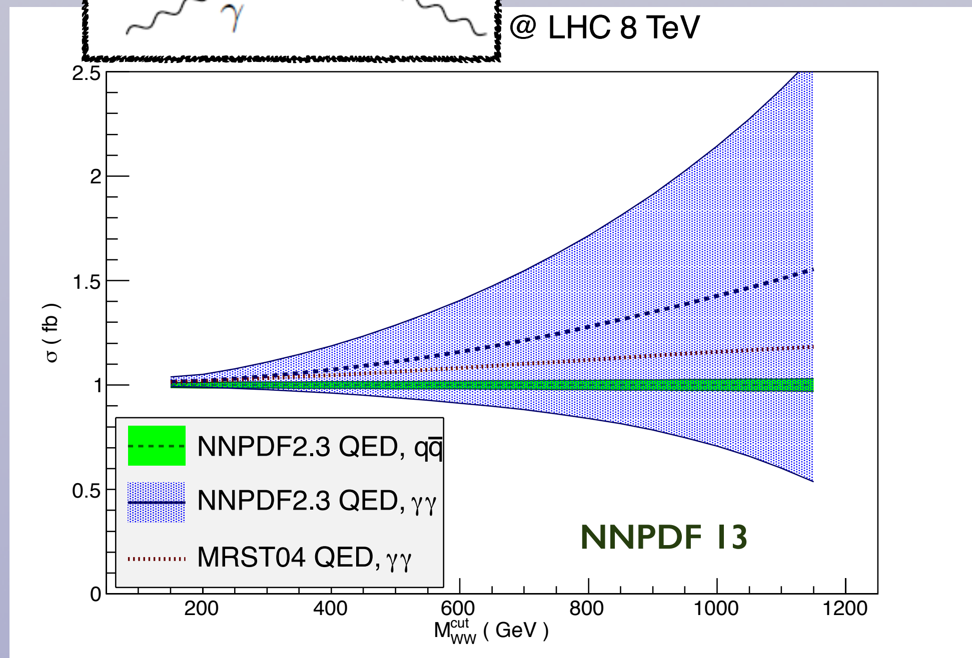


High-Mass Drell-Yan



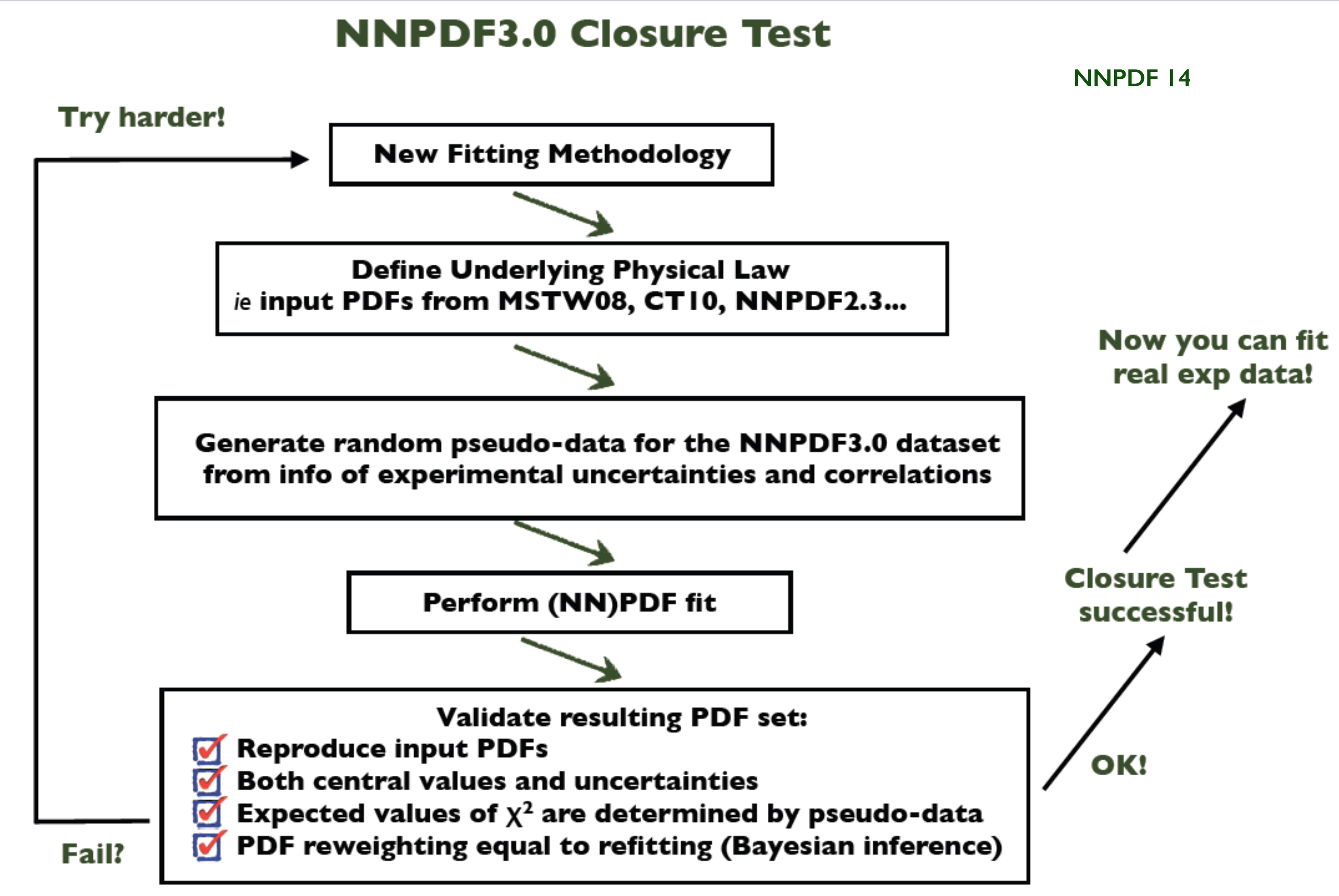


High-Mass WW prod



Closure Testing of Parton Distributions

- **PDF uncertainties** have been often criticised by a **potential lack of statistical interpretation**
- In the recent NNPDF3.0 paper, we performed a systematic **closure tests analysis** based on pseudo-data, and verified that **PDF uncertainties** show **a statistically robust behaviour**

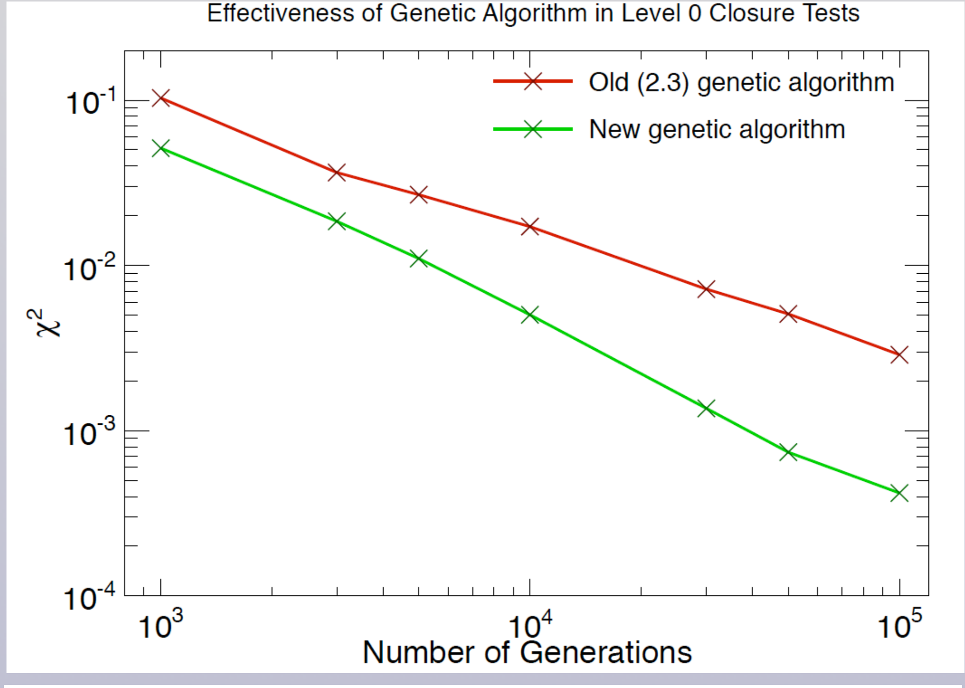


Closure Testing of Parton Distributions

Level 0 Closure Tests: Pseudo data = Theory

☑ **Central values of input PDF** reproduced with arbitrary accuracy

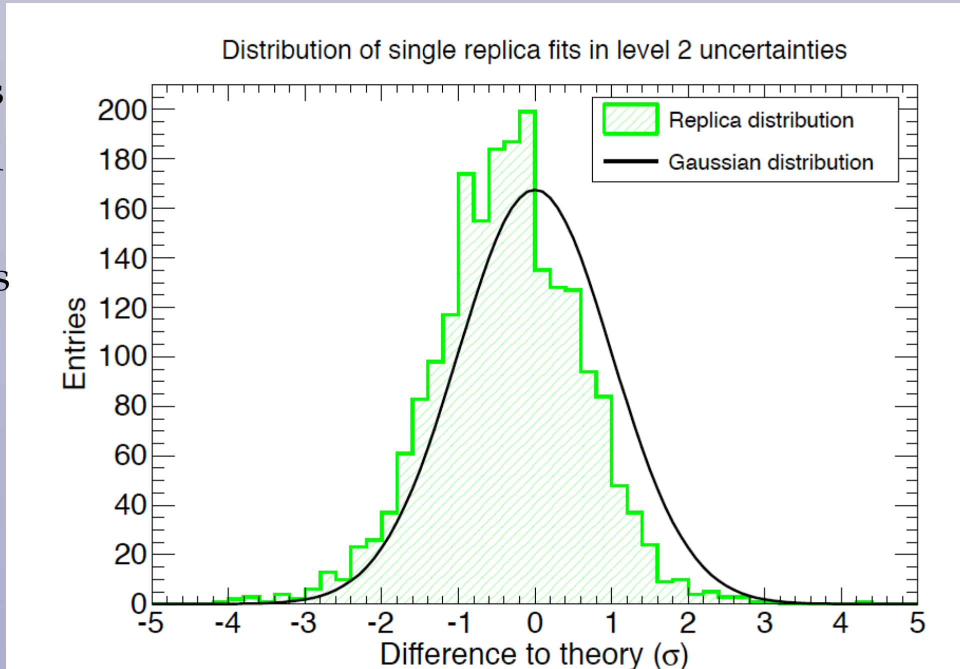
☑ **PDF uncertainties on the fitted data points** can become arbitrarily small



Level 2 Closure Tests: Pseudo data with "exp" fluctuations

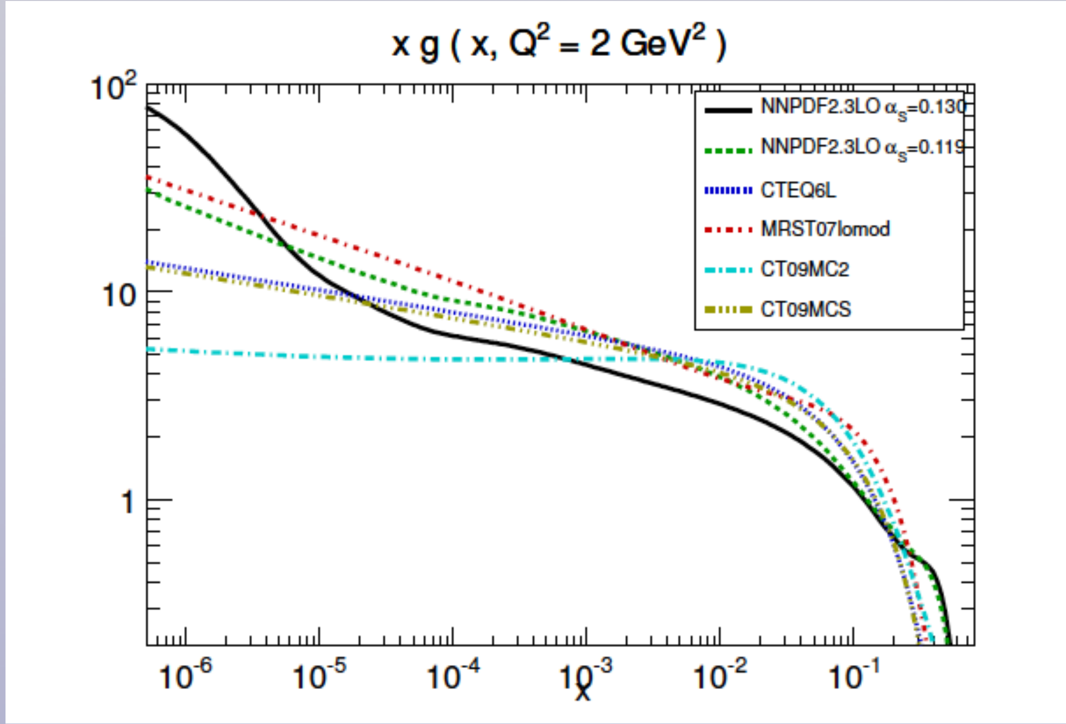
☑ Reproduced **χ^2 of input PDF** - both total and individual experiments

☑ **Fitted PDF central values** fluctuate around input values by the same amount as expected from the **size of the PDF uncertainties ->** PDF errors indeed correspond to **68% Confidence Levels**

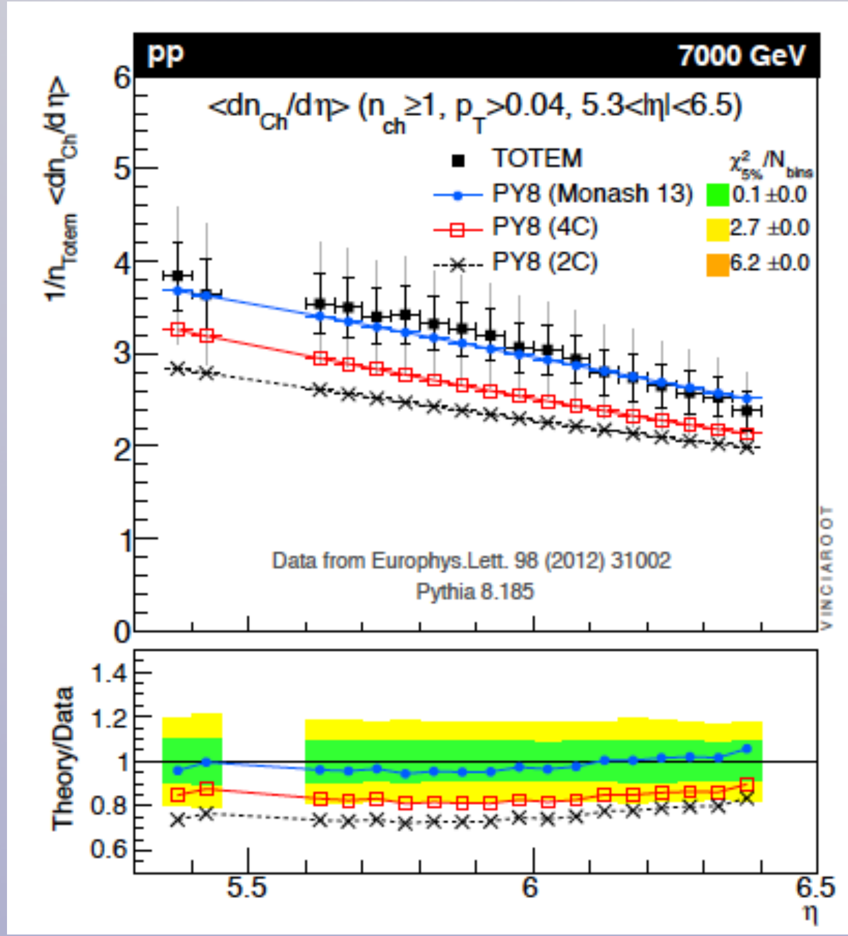


PDFs and Monte Carlo generators

- **PDFs** are an essential ingredient for the **tuning of soft and semi-hard physics** in LO Monte Carlo event generators like **Pythia8**, **Herwig++** or **Sherpa**
- Most updated tune of **Pythia8**, the **Monash 2013 Tune,** is based on the **NNPDF2.3LO** set
- The **harder small-x gluon in NNPDF2.3LO** is essential to improve the description of the LHC **forward data**
- Next step: specific tunes for NLO Monte Carlo event generators



Small-x behaviour of gluon determines soft and semi-hard physics at the LHC



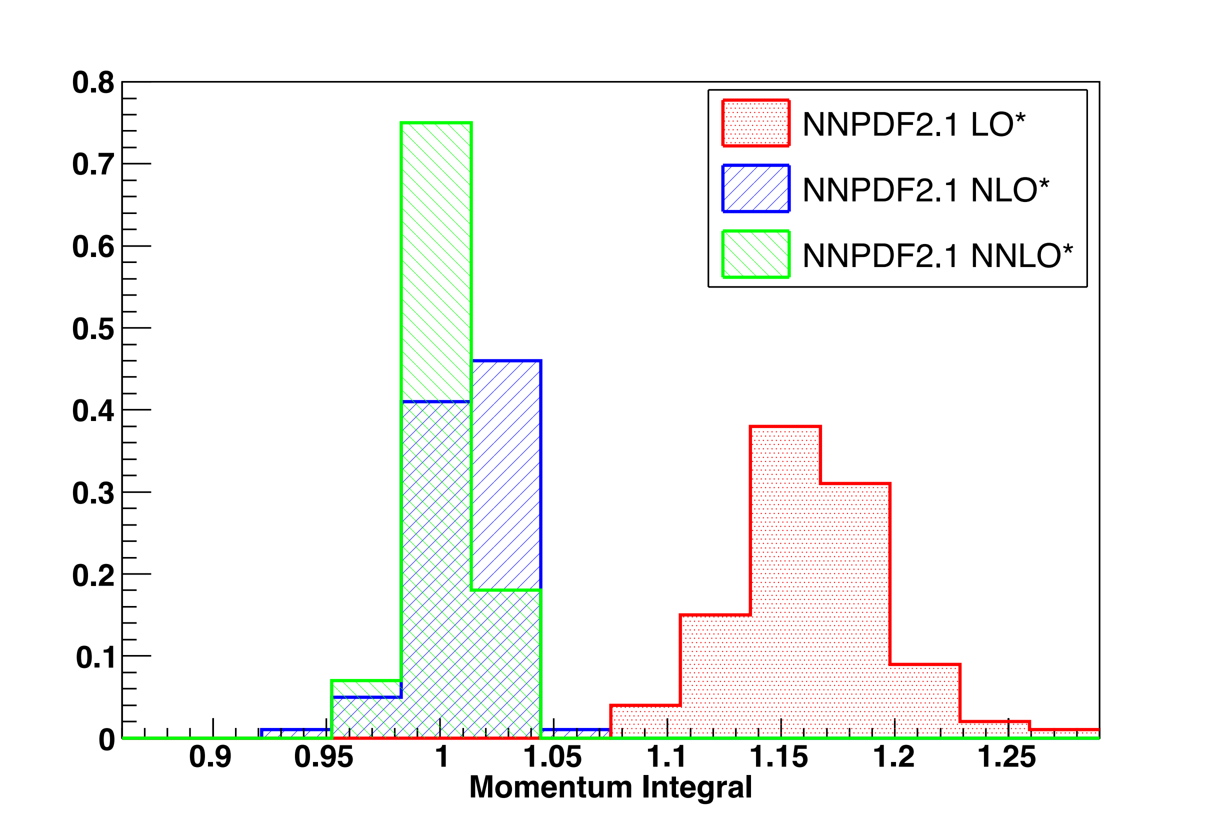
Skands, Carrazza, J.R. 14

Precision tests of the Factorisation Theorem

- Perturbative QCD requires that the **momentum integral** should be unity to all orders

$$[M]\left(Q^2\right) \equiv \int_0^1 dx \left(xg\left(x,Q^2\right) + x\Sigma\left(x,Q^2\right)\right)$$

- Is it possible to **determine** the value of the momentum integral from the global PDF analysis, rather than **imposing it?** Check in LO*, NLO* and NNLO* fits **without setting M=1**



$$[M]_{\rm LO} = 1.161 \pm 0.032\,,$$
$$[M]_{\rm NLO} = 1.011 \pm 0.018\,,$$
$$[M]_{\rm NNLO} = 1.002 \pm 0.014\,.$$

- Experimental data beautifully **confirms the pQCD expectation**
- **Extremely non trivial test** of the global analysis framework and the **factorization hypotheses**
- Very good convergence of the QCD perturbative expansion

NNPDF, 11

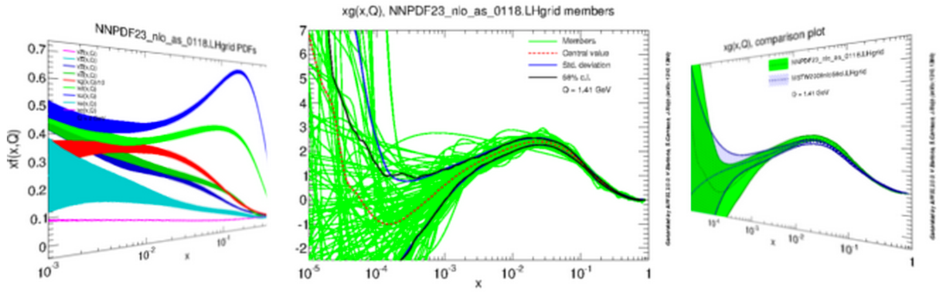
PDF comparisons made easy: APFEL-Web

- Comparing different PDF sets is now really easy thanks to the new **APFEL-Web online PDF plotter**
- Just log in, select the PDF sets that you want to compare, the plotting settings, and have fun!

Welcome to **APFEL** online cluster!

This web-application is a tool designed for High Energy Physics by providing a simple and intuitive interface to plot and compute the most common observables with Parton Distribution Functions (PDFs).

To begin to produce on-line plots, please register and login!



The APFEL library

APFEL, a PDF evolution library, is a computer library specialized in the solution of DGLAP evolution equations up to NNLO in QCD and to LO in QED, both with Pole and $\overline{\mathrm{MS}}$ masses. With APFEL you can replace the evolution of LHAPDF sets and check the impact on the choice of evolution parameters. APFEL also computes deep-inelastic scattering processes using multiple schemes.

Web developers: D. Palazzo, S. Carrazza, A. Ferrara
APFEL developers: V. Bertone, S. Carrazza, J. Rojo. (Contact)

Bertone, Carrazza, J.R. 13

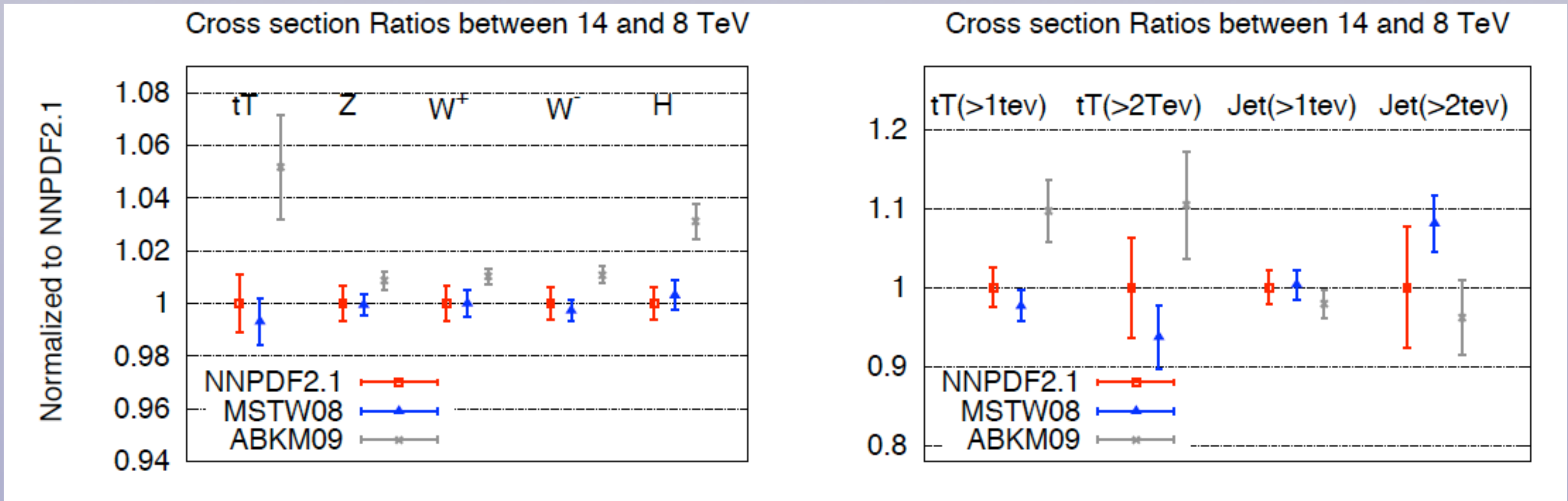
http://apfel.mi.infn.it/

Cross section Ratios between 7, 8 and 14 TeV

- The **staged increase of the LHC beam energy** provides a new class of interesting observables: **cross section ratios** for different beam energies

$$R_{E_2/E_1}(X) \equiv \frac{\sigma(X,E_2)}{\sigma(X,E_1)} \qquad R_{E_2/E_1}(X,Y) \equiv \frac{\sigma(X,E_2)/\sigma(Y,E_2)}{\sigma(X,E_1)/\sigma(Y,E_1)}$$

- These ratios can be computed with **very high precision** due to the large degree of **correlation of theoretical uncertainties** at different energies
- **Experimentally** these ratios can also be measured accurately since many systematics, like luminosity or jet energy scale, **cancel partially in the ratios**
- These ratios allow **stringent precision tests of the SM**, like **PDF discrimination**



Mangano, J. R., 12

Cross section Ratios between 7, 8 and 14 TeV

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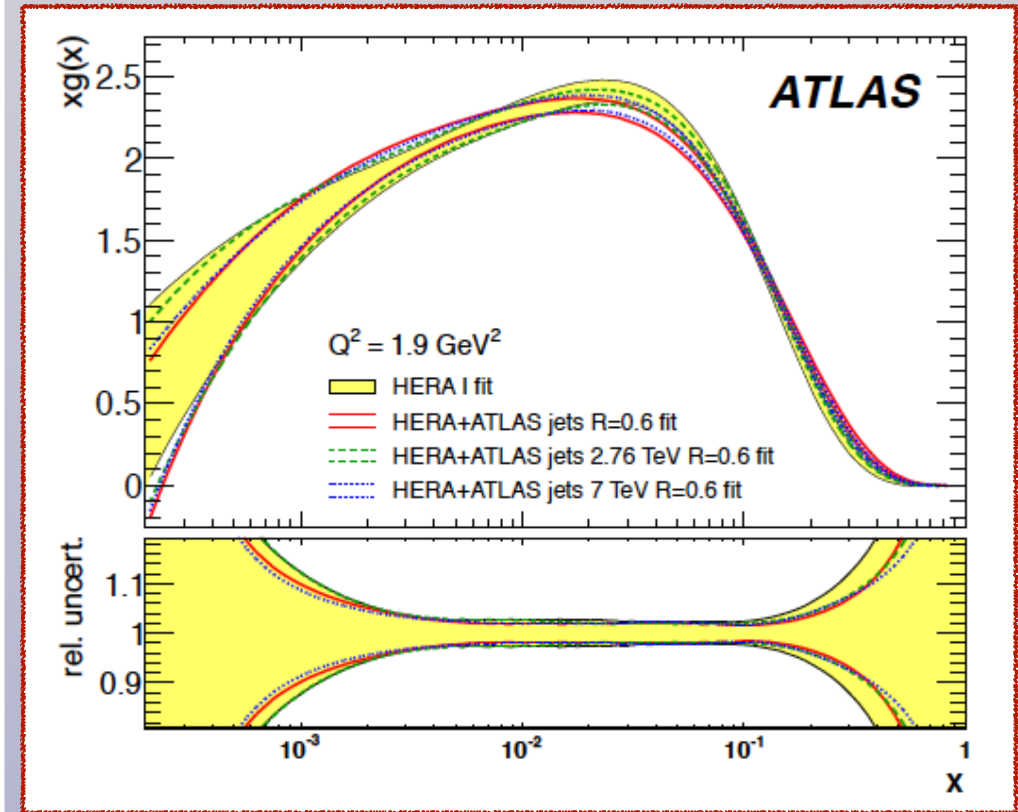
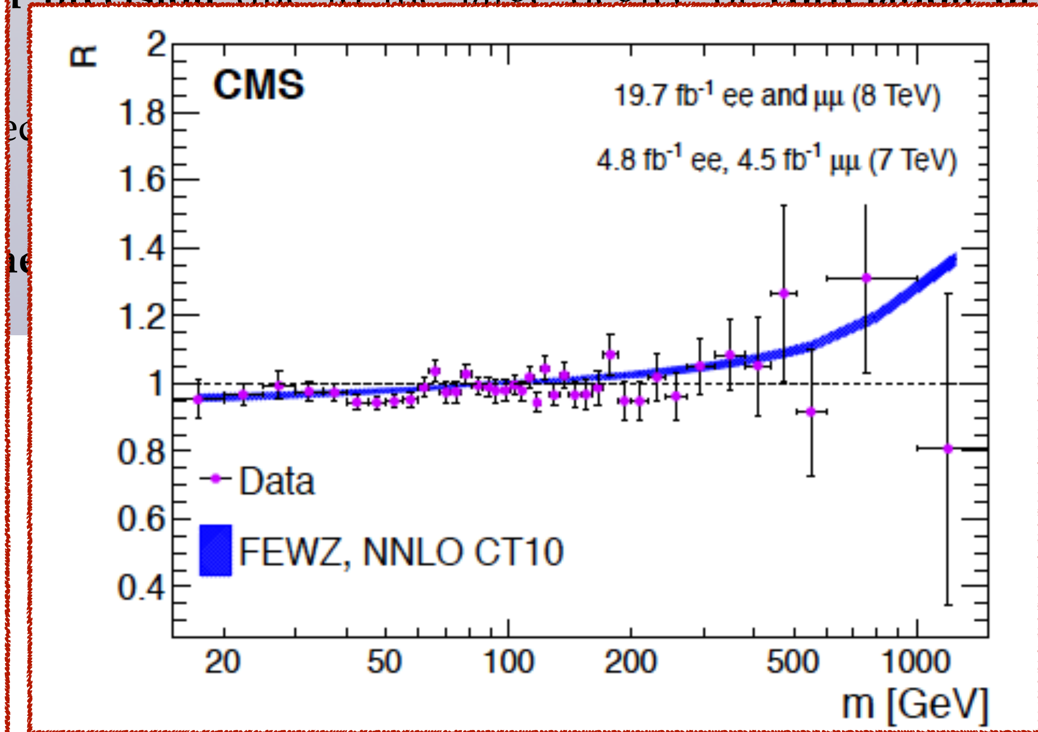
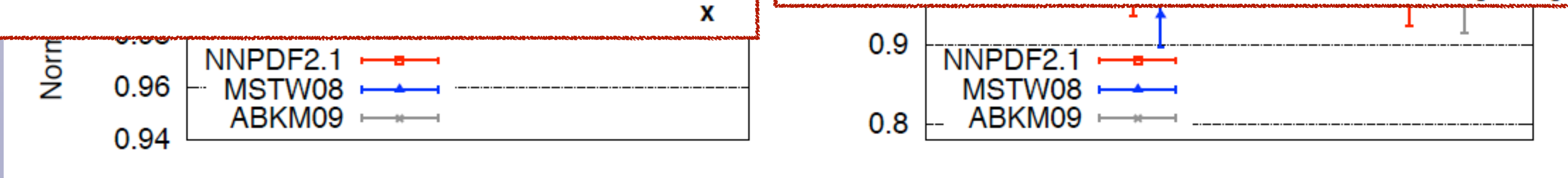
$$R_{E_2/E_1}(X,Y) \equiv \frac{\sigma(X,E_2)/\sigma(Y,E_2)}{\sigma(X,E_1)/\sigma(Y,E_1)}$$

ATLAS: Gluon from 7 TeV / 2.76 TeV jet xsecs



CMS: Drell-Yan 8 TeV / 7 TeV ratio





Mangano, J. R., 12

Cross section Ratios between 7, 8 and 14 TeV

- If SM theory systematics under control, these cross section ratios can provide an **improved sensitivity to New Physics** than absolute cross sections

$$\sigma(pp \to X) = \sigma^{SM}(pp \to X) + \sigma^{BSM}(pp \to X)$$

- The **visibility of a BSM contribution** in the **evolution with energy** of the cross section requires that it evolves in Q2 **differently from the SM contribution**

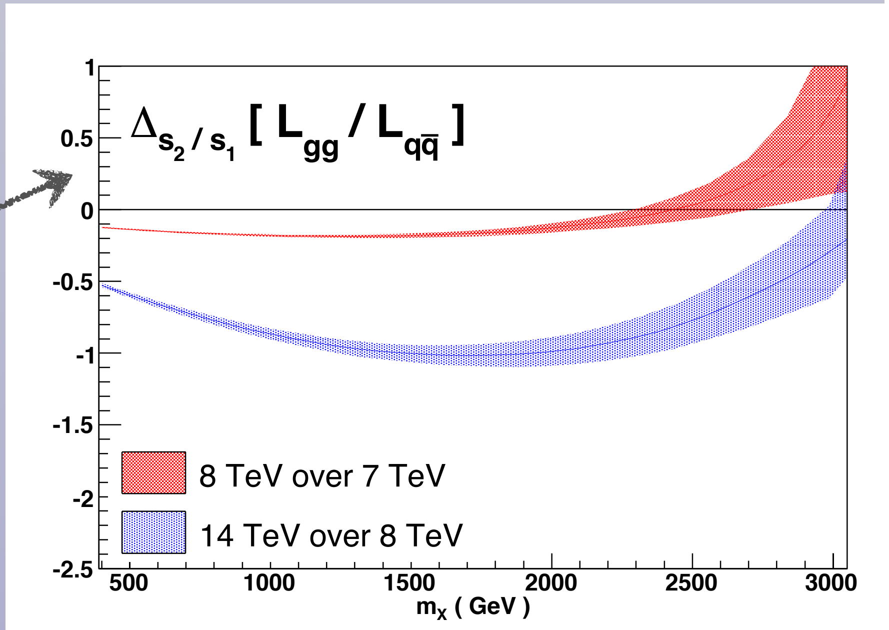
$$R^X_{E_1/E_2} \sim \frac{\sigma_X^{SM}(E_1)}{\sigma_X^{SM}(E_2)} \times \left\{ 1 + \frac{\sigma_X^{BSM}(E_1)}{\sigma_X^{SM}(E_1)} \Delta_{E_1/E_2} \left[\frac{\sigma_X^{BSM}}{\sigma_X^{SM}} \right] \right\}$$

$$\Delta_{E_1/E_2}(A) = 1 - \frac{A(E_2)}{A(E_1)}$$

Example: a **gluon-gluon initiated BSM** contribution to **high-mass Z production**. The cross section ratio enhanced by:

$$\frac{\sigma_Z^{\rm BSM}(m_X)}{\sigma_Z^{\rm SM}(m_X)} \Delta_{E_1/E_2} \left[\frac{\mathcal{L}_{gg}(m_X)}{\mathcal{L}_{q\bar{q}}(m_X)} \right]$$

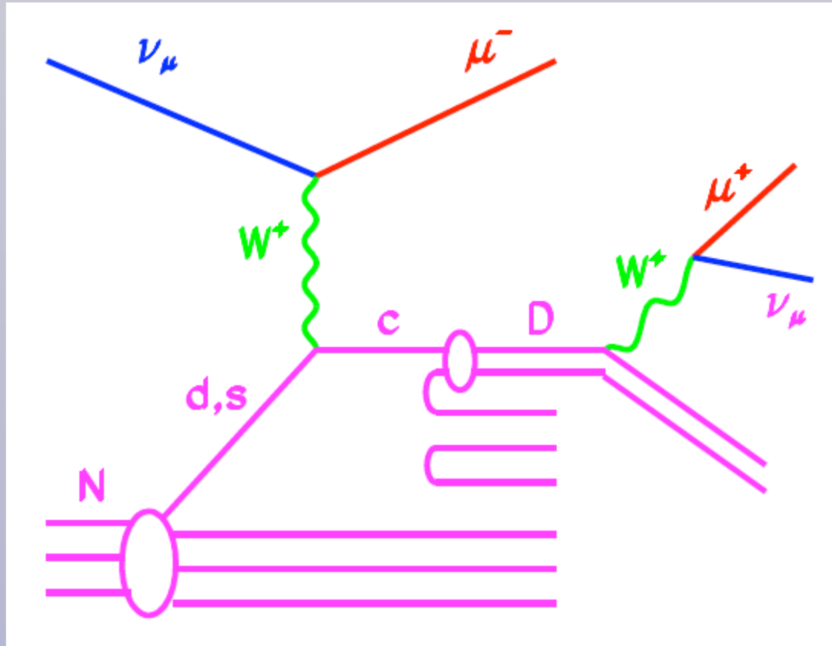
With greatly reduced experimental and theoretical uncertainties



But **theory systematics, mostly PDFs**, need to be known accurately for this new approach to show its **full potential**

Determination of Standard Model parameters

- **Accurate PDFs** are required for **precision determination of fundamental Standard Model parameters** in processes involving initial state hadrons
- These include, among many others, the **strong coupling constant** α_S, the **W boson mass**, the effective **lepton mixing angle**, **CKM** matrix elements, ...
- The **unbiased** nature of the NNPDF approach approach to **faithfully disentangle** PDF uncertainties from other parametric uncertainties. One example in neutrino DIS:



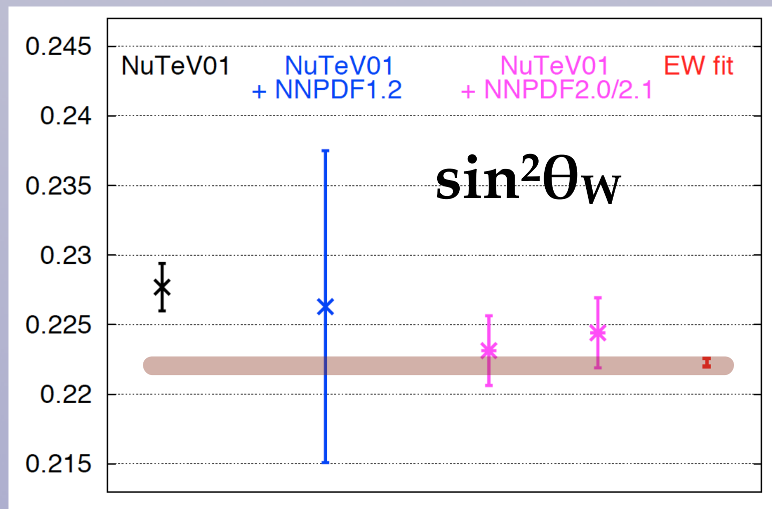
CKM matrix element $\mathbf{V_{cs}}$ can be determined from **neutrino DIS data** - but large uncertainties from **strange PDF**

NNPDF analysis manages to obtain the **most accurate ever determination** of $\mathbf{V_{cs}}$ from a single process:

$V_{cs} = 1.04 \pm 0.06$ (PDG average)
$V_{cs} = 0.96 \pm 0.07$ (NNPDF from NuTeV data)

The same analysis shows that the **strangeness asymmetry** in the proton has just the right size to **cancel the NuteV anomaly**

$$
\begin{aligned}
R_{\rm PW} &\equiv \frac{\sigma(\nu\mathcal{N}\to\nu X)-\sigma(\bar\nu\mathcal{N}\to\bar\nu X)}{\sigma(\nu\mathcal{N}\to\ell X)-\sigma(\bar\nu\mathcal{N}\to\bar\ell X)} \\
&= \frac{1}{2}-\sin^2\theta_W+\left[\frac{([U^-]-[D^-])+([C^-]-[S^-])}{[Q^-]}\frac{1}{6}\left(3-7\sin^2\theta_W\right)\right]
\end{aligned}
$$



NNPDF, arXiv:0906.1958

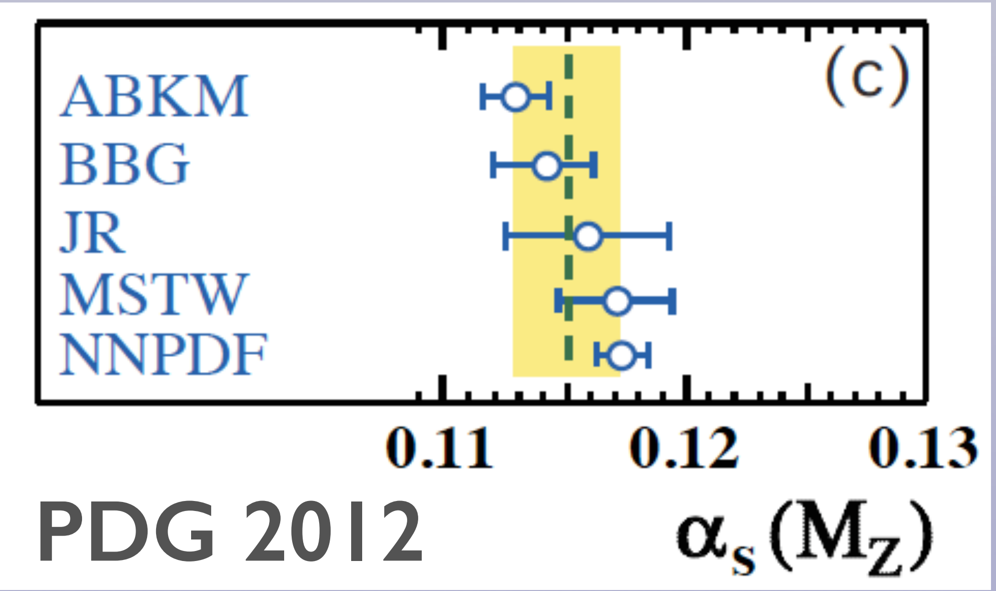
Determination of Standard Model parameters

- **Accurate PDFs** are required for **precision determination of fundamental Standard Model parameters** in processes involving initial state hadrons
- The **strong coupling constant** α_S can be determined from a global PDF analysis, mostly from scaling violations in Deep-Inelastic Scattering and in inclusive jet production
- The NNPDF result is the **most accurate determination** of α_S from a QCD global fit, and nicely consistent with the latest PDG average, to which is one of the dominant contributions
- In the pipeline: α_S determinations from LHC data at the **higher scale**s ever probed

PDG 2013 average

$$\alpha_s(M_Z^2) = 0.1184 \pm 0.0007$$

PDG average from PDF fits



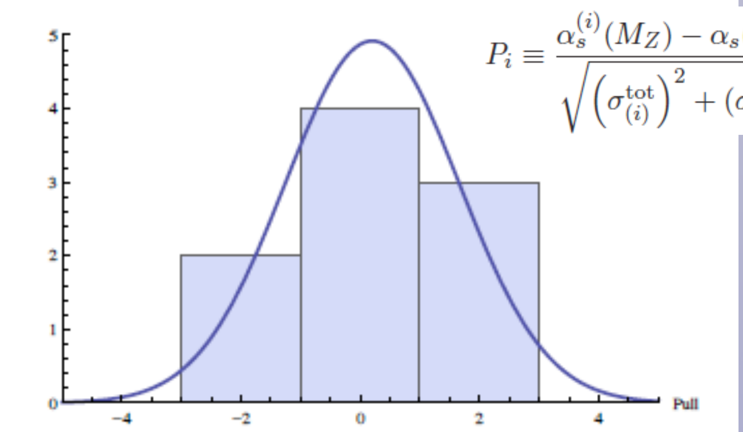
NNPDF2.1 NNLO

$$\alpha_s^{\rm NNLO}(M_Z) = 0.1173 \pm 0.0007^{\rm stat} \pm 0.0001^{\rm proc}$$

NNPDF, 11

- **Consistency check of the global PDF framework**: the distributions of pulls for α_S fitted to **individual experiments** follows a Gaussian distribution

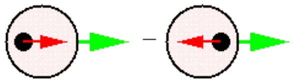
$$P_i \equiv \frac{\alpha_s^{(i)}(M_Z) - \alpha_s(M_Z)}{\sqrt{\left(\sigma^{\rm tot}_{(i)}\right)^2 + \left(\sigma^{\rm tot}\right)^2}}$$



Polarised PDFs:
Unraveling the origin of the proton spin

Polarised Parton Distributions

- Up to know in this talk everything was valid for **unpolarised protons**
- **The polarised case is also** extremely interesting: unique windows on the **spin structure of the proton.**
- How the **proton spin is distributed among its constituents** is a crucial issue for our understanding of **non-perturbative QCD and confinement**



$$\Delta f(x,Q^2) = f^{\Rightarrow\rightarrow}(x,Q^2) - f^{\Rightarrow\leftarrow}(x,Q^2)$$

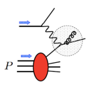
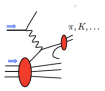
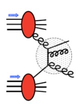
How do quarks (including sea quarks) and gluons carry the proton spin

$$\mathcal{S}(\mu) = \frac{1}{2} = \sum_f \left\langle P;S|\hat{J}^z_f(\mu)|P;S\right\rangle = \frac{1}{2}\int_0^1 dx\Delta\Sigma(x,\mu) + \int_0^1 dx\Delta g(x,\mu) + L_z$$

Quarks? **Gluons?** **Angular Mom?**

Nocera, SPIN14

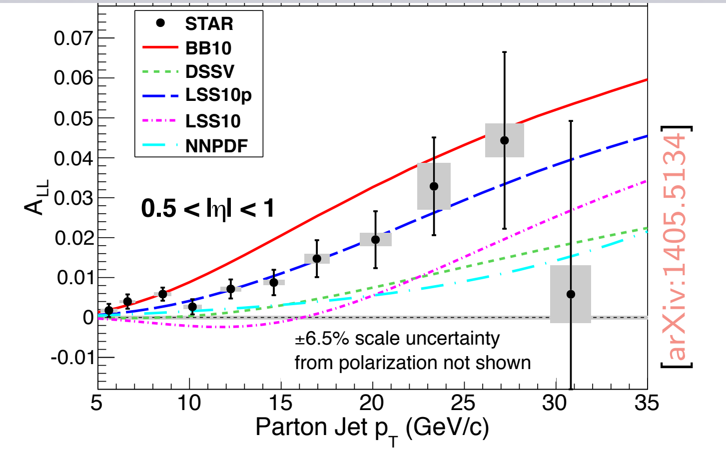
e.g. DIS $\quad d\Delta\sigma = \sum_{q,\bar{q},g} \Delta f(x,Q^2)\otimes d\Delta\hat{\sigma}_{\gamma^* f}(xP,\alpha_s(Q^2)) \quad d\Delta\hat{\sigma}_{\gamma^* f} = \sum_{n=0}^{\infty}\left(\frac{\alpha_s}{4\pi}\right)^n d\Delta\hat{\sigma}^{(n)}_{\gamma^* f}$

	Reaction	Partonic subprocess	PDF probed	x	Q^2 [GeV^2]
 DIS	$\ell^\pm\{p,d,n\}\to\ell^\pm X$	$\gamma^* q\to q$	$\Delta q+\Delta\bar{q}$ Δg	$0.003\lesssim x\lesssim 0.8$	$1\lesssim Q^2\lesssim 70$
 SIDIS	$\ell^\pm\{p,d\}\to\ell^\pm hX$	$\gamma^* q\to q$	$\Delta u\ \Delta\bar{u}$ $\Delta d\ \Delta\bar{d}$ Δg	$0.005\lesssim x\lesssim 0.5$	$1\lesssim Q^2\lesssim 60$
	$\ell^\pm\{p,d\}\to\ell^\pm DX$	$\gamma^* g\to c\bar{c}$	Δg	$0.06\lesssim x\lesssim 0.2$	~ 10
 pp	$\vec{p}\vec{p}\to jet(s)X$	$gg\to qg$ $qg\to qg$	Δg	$0.05\lesssim x\lesssim 0.2$	$30\lesssim p_T^2\lesssim 800$
	$\vec{p}p\to W^\pm X$	$u_L\bar{d}_R\to W^+$ $d_L\bar{u}_R\to W^-$	$\Delta u\ \Delta\bar{u}$ $\Delta d\ \Delta\bar{d}$	$0.05\lesssim x\lesssim 0.4$	$\sim M_W^2$
	$\vec{p}\vec{p}\to\pi X$	$gg\to qg$ $qg\to qg$	Δg	$0.05\lesssim x\lesssim 0.4$	$1\lesssim p_T^2\lesssim 200$

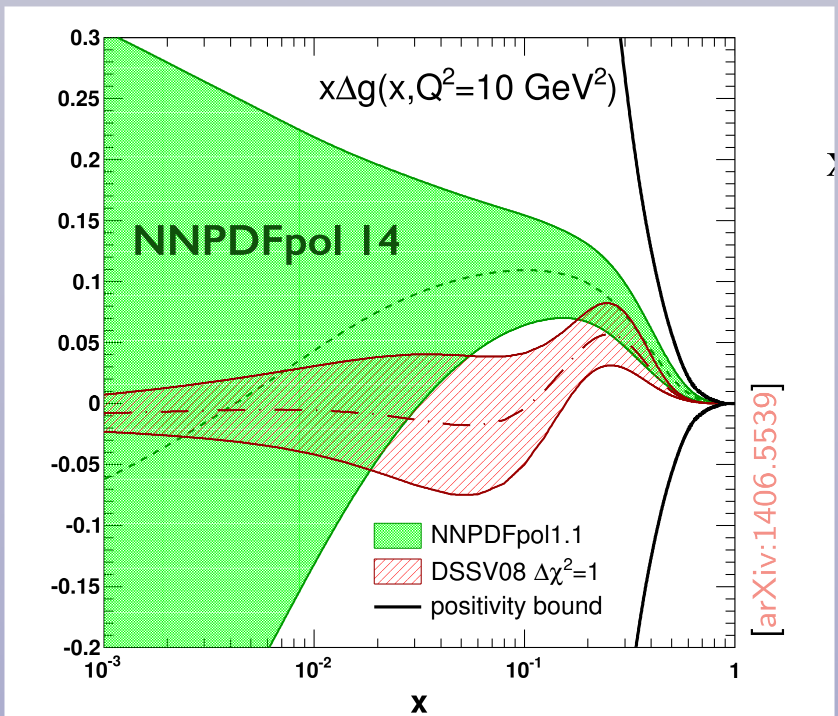
- First measurements with polarised DIS (80s) showed that **quark contribution much smaller than expected** (*proton spin crisis*)
- With the availability of polarised hadronic and semi-inclusive data, **global polarised PDF fits possible**
- The NNPDF framework has also been applied here: **NNPDFpol sets**

Unraveling the gluon polarisation

- Contribution of **gluon polarisation to the proton spin** has been of the **big unknowns** in the last 30 years
- The analysis of recent **RHIC polarised jet data** in the **NNPDFpol** and **DSSV** frameworks has provided **first ever evidence for positive (non-zero) polarisation** of the gluon in the proton
- Importance of this important result recognised by the popular media, *i.e.* Scientific American



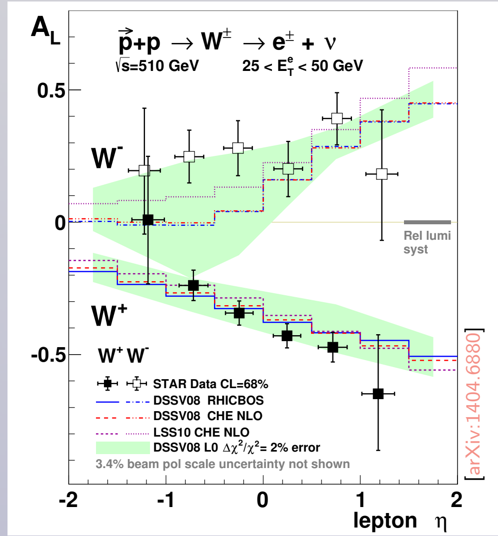
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$



Total contribution of gluons to proton spin still unknown since **large uncertainties at small-x** from lack of data: need an **Electron-Ion Collider**

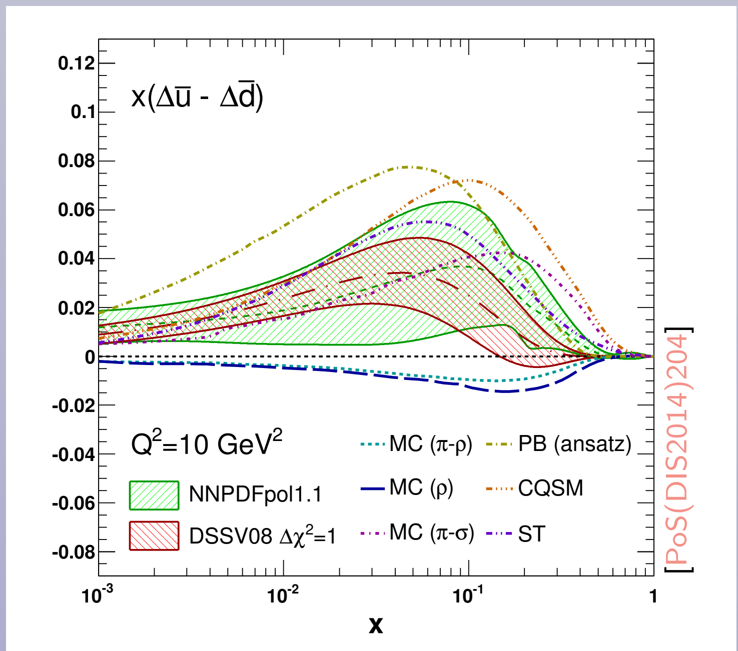
The polarised quark sea

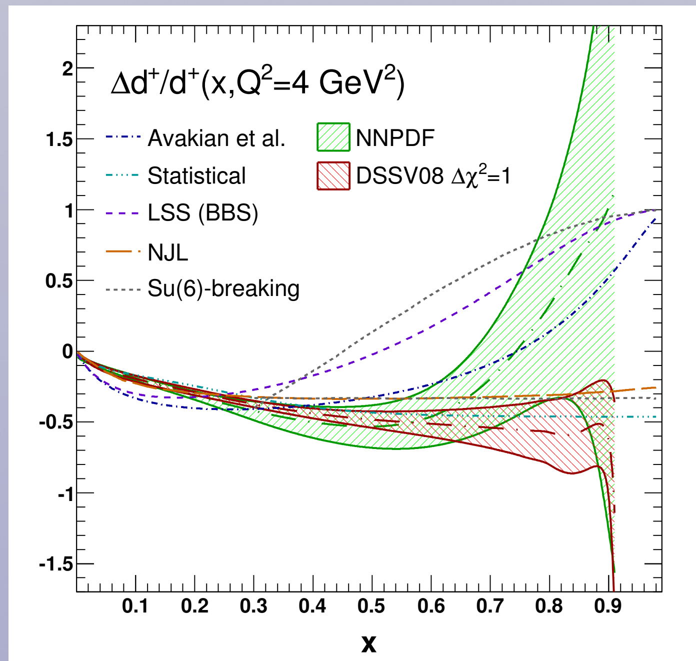
- Inclusive DIS data does not allow to separate polarised quarks from antiquarks
- Recent data on polarised **semi-inclusive DIS** and **hadronic *W* production** allow this separation for first time
- Stringent constraints on **non-perturbative models of the proton**



NNPDFpol 14

Nocera 14

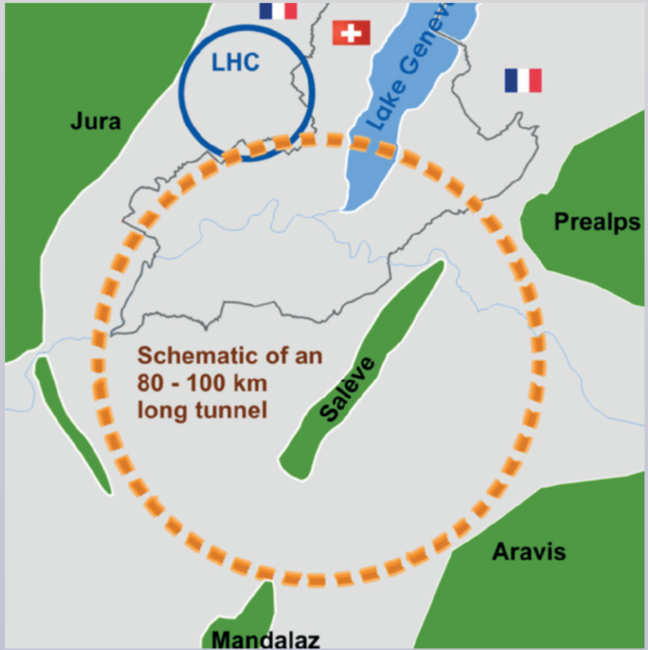




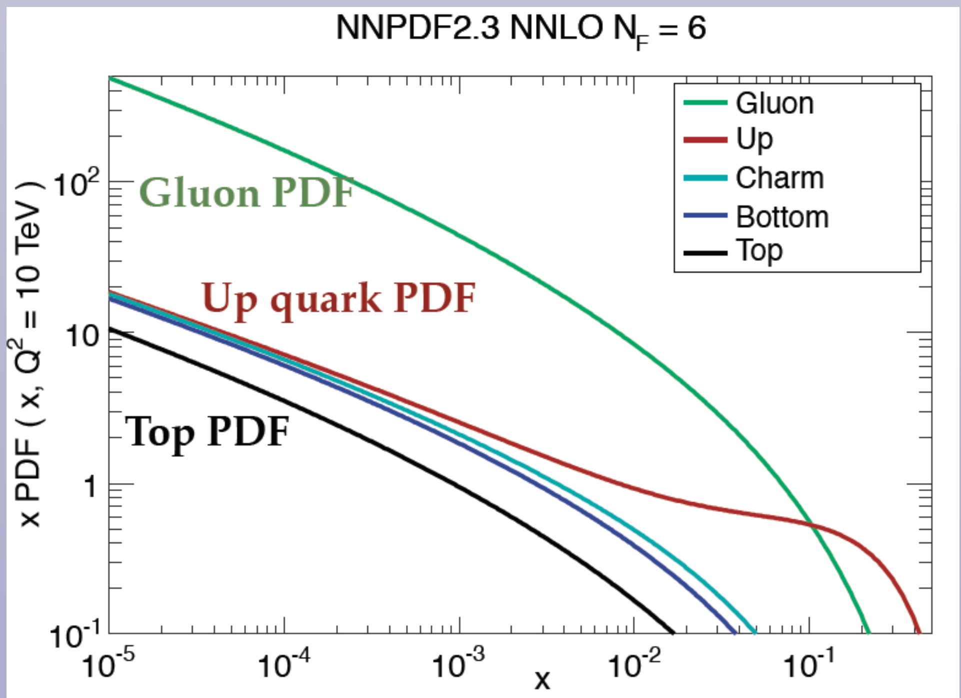
Summary

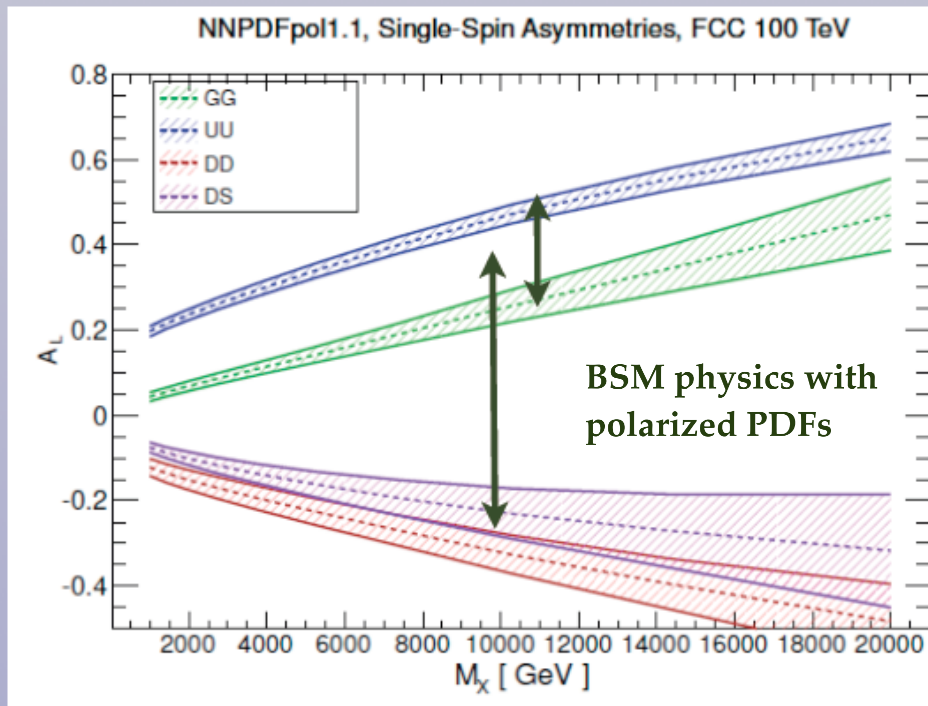
- **Parton Distributions** are an essential ingredient for LHC phenomenology
- Accurate PDFs are required for **precision SM measurements, Higgs characterisation** and **New Physics searches**
- The determination of **fundamental SM parameters** like the **W mass** or α_S **from LHC data** also greatly benefit from improved PDFs
- PDFs are also a basic component for Monte Carlo event generators
- The NNPDF approach provides parton distributions based on a **robust, unbiased methodology,** the most updated **theoretical information** and all the relevant hard scattering data **including LHC data**
- Near future developments in **NNPDF** include
  - **Inclusion of more HERA and LHC data**
  - Tailored PDFs for **NLO Monte Carlo event generators** at the LHC
  - PDFs with **threshold** and **high energy resummation,** impact on Higgs and top physics
  - PDFs with and **electroweak effects** (both in evolution and in partonic xsecs)
  - PDFs with **Intrinsic Charm**

Going Beyond: PDFs at a 100 TeV collider

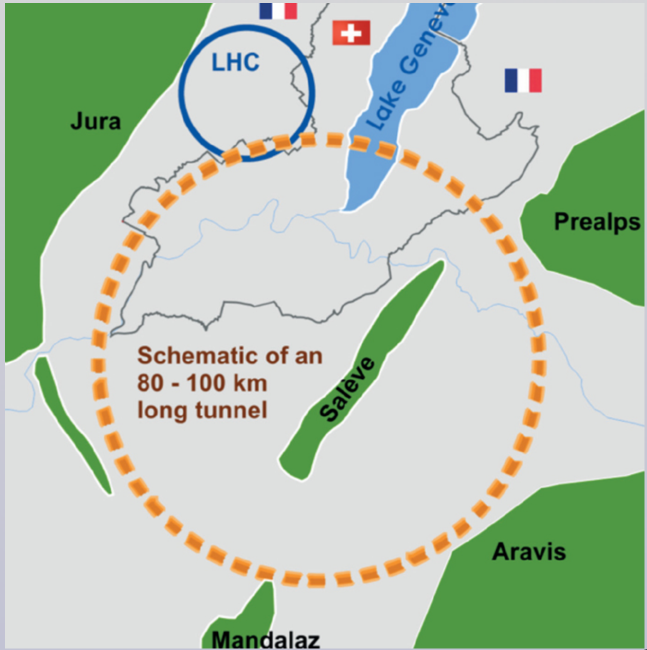


- Growing consensus that the next big machine more suitable to **explore the energy frontier** should be a **100 TeV hadron collider**, possibly with also **e+e-** and **ep** operation modes
- The **phenomenology of PDFs** at such extreme energies is very rich: **top quark PDFs**, electroweak effects on PDFs and **W/Z boson PDFs**, ultra-low-x physics, **BFKL dynamics**, BSM physics with polarized PDFs, ..., **lots of fun**!
- First studies being now performed in the context of the **CERN FCC working group**





Going Beyond: PDFs at a 100 TeV collider



- Growing consensus that the next big machine more suitable to **explore the energy frontier** should be a **100 TeV hadron collider**, possibly with also **e+e-** and **ep** operation modes

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- First studies ... the context of the **CERN FCC** ...

Thanks for your attention!