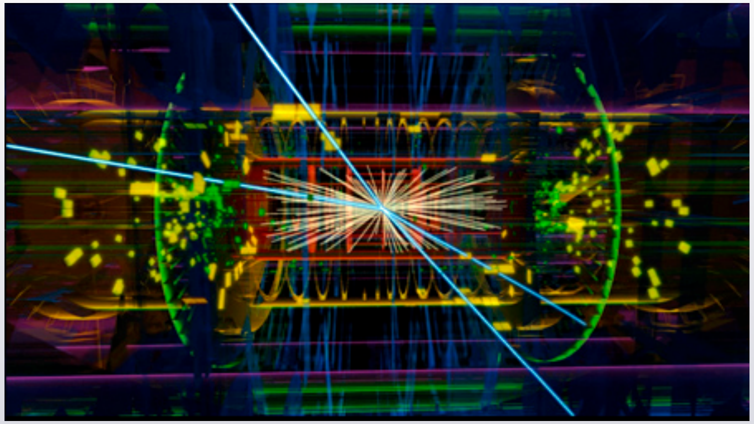
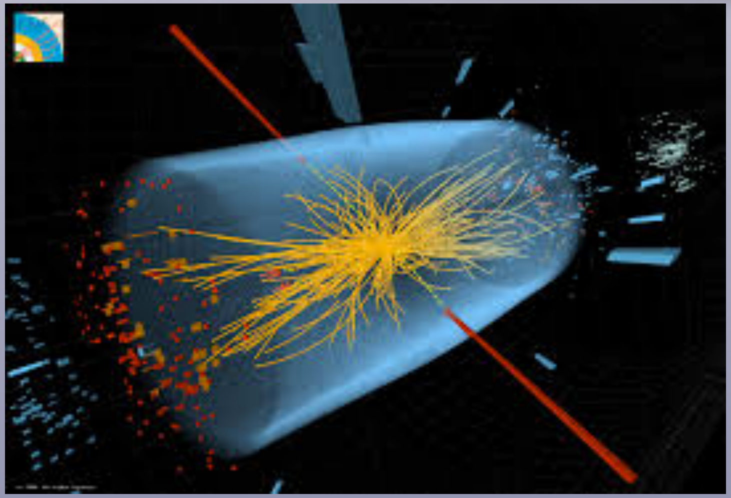
Parton Distributions and the search for New Physics at the LHC

Juan Rojo
STFC Rutherford Fellow
Rudolf Peierls Center for Theoretical Physics
University of Oxford

Theoretical Particle Physics & Cosmology seminar
King's College London
London, 23/09/2015

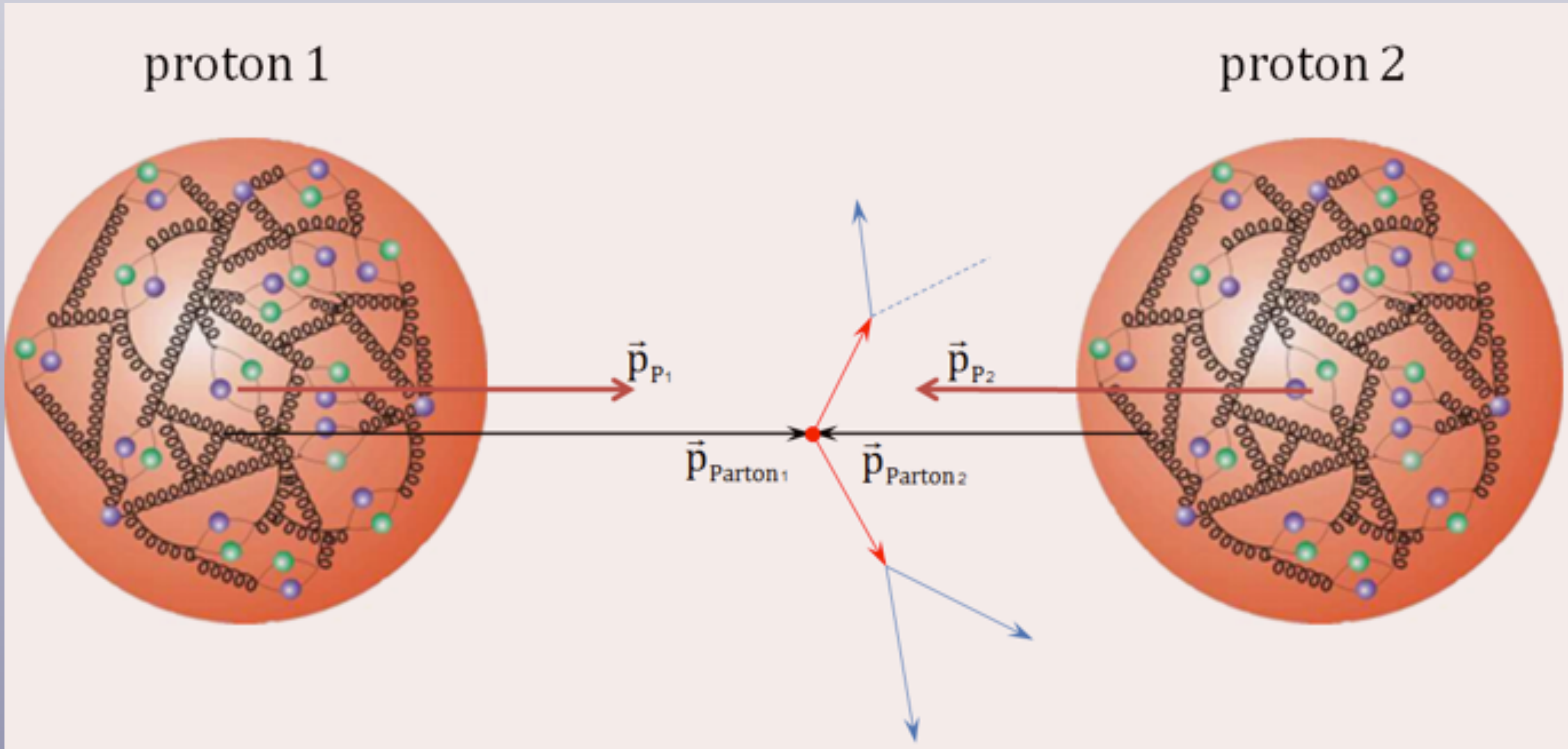


Parton Distributions and LHC phenomenology

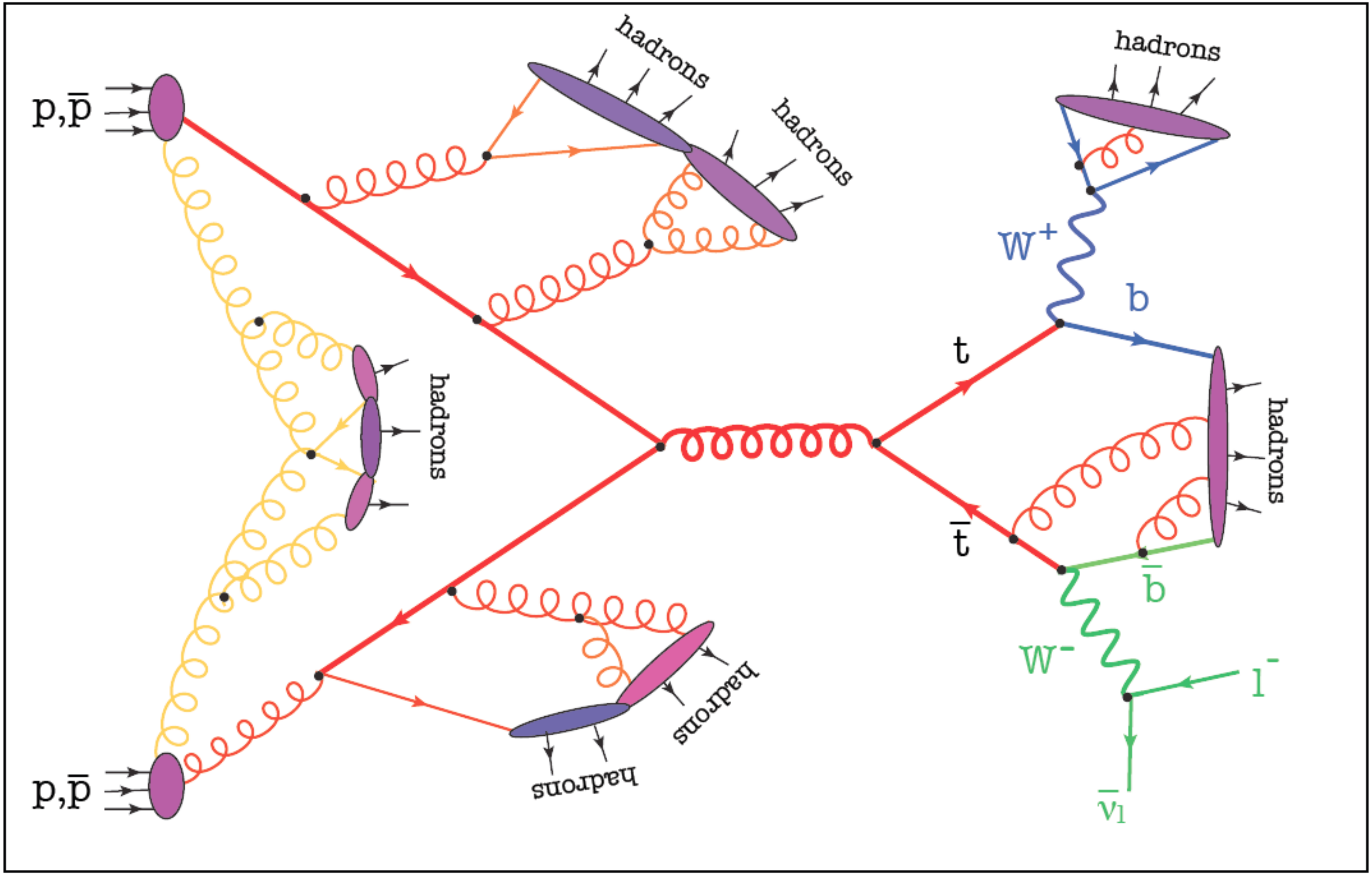


The inner life of the protons

- 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**

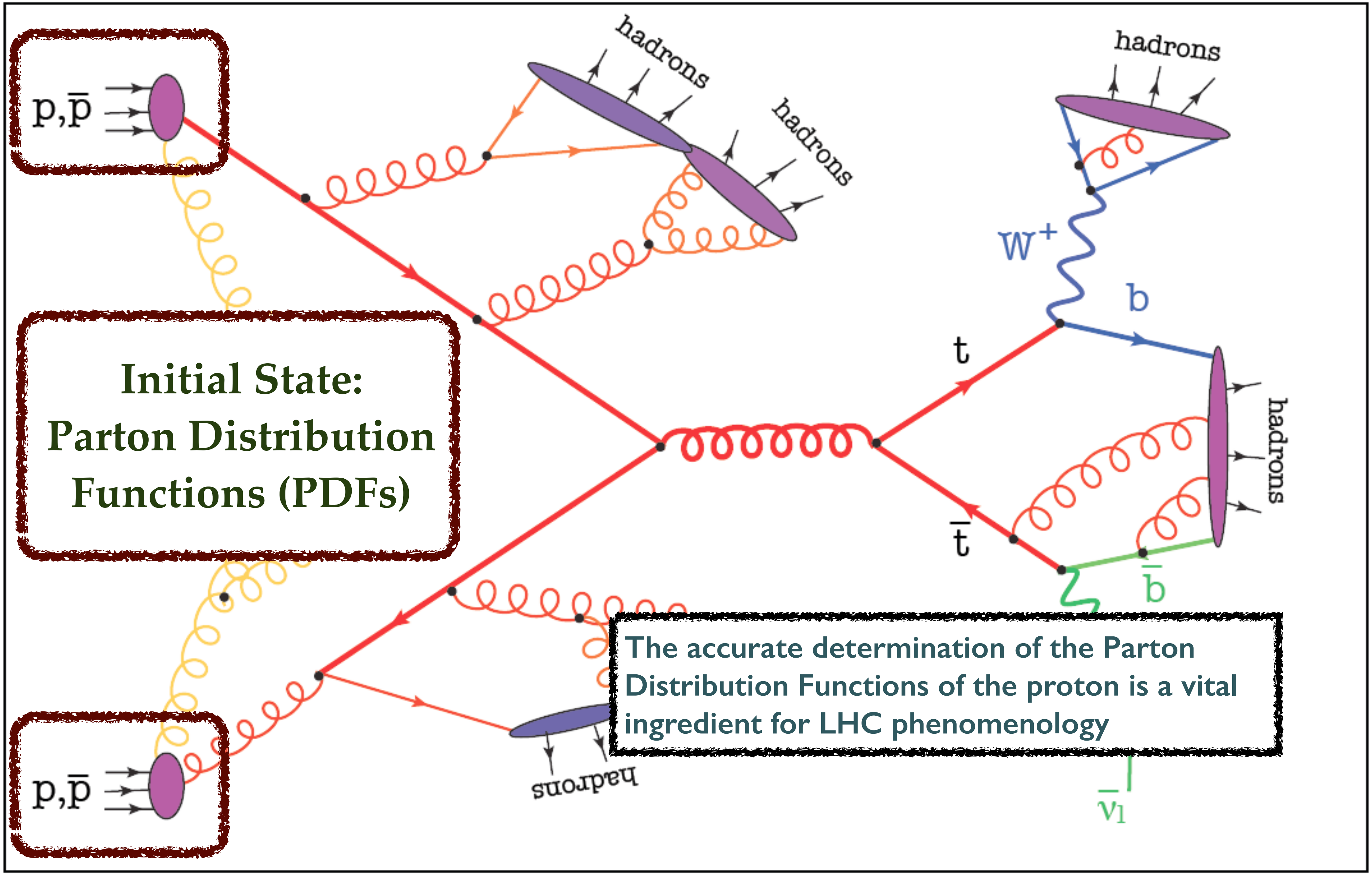


LHC collisions in a nutshell



Drawing by K. Hamilton

LHC collisions in a nutshell



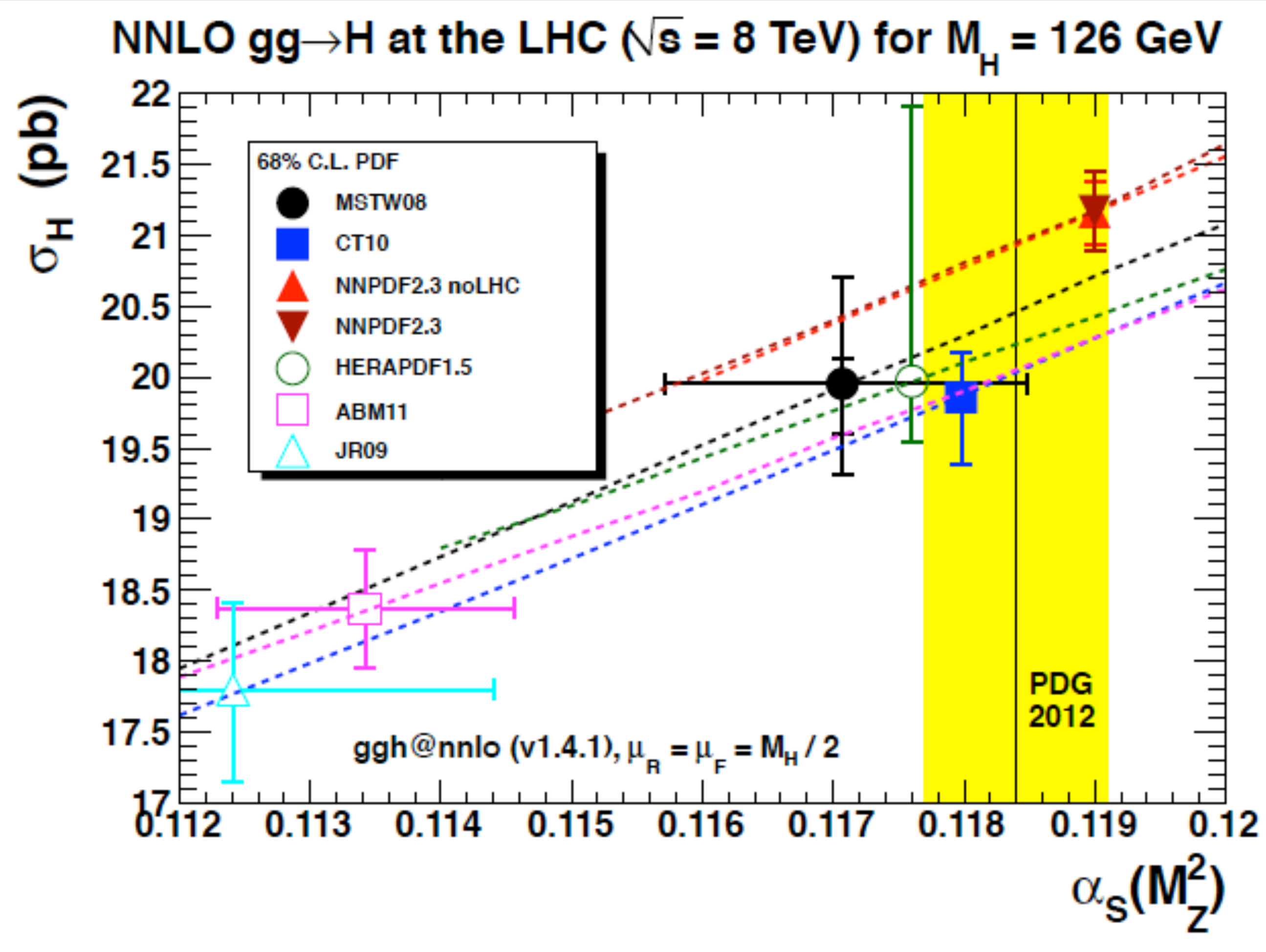
**Initial State:
Parton Distribution
Functions (PDFs)**

The accurate determination of the Parton Distribution Functions of the proton is a vital ingredient for LHC phenomenology

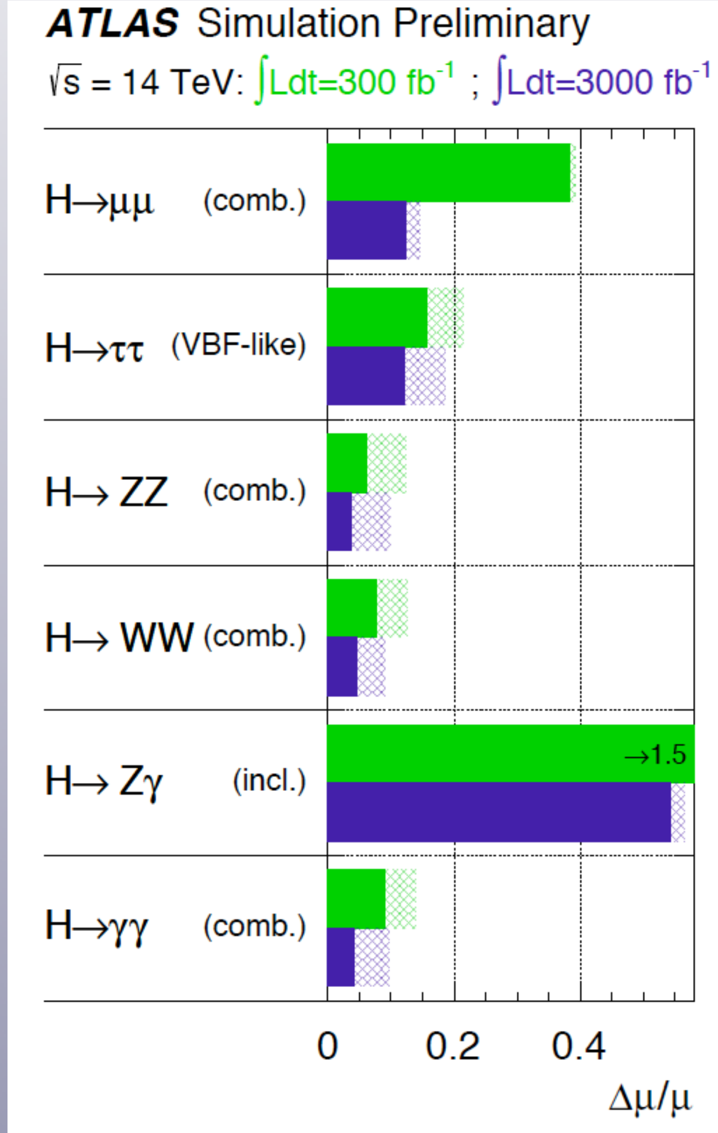
Drawing by K. Hamilton

Parton Distributions and LHC phenomenology

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

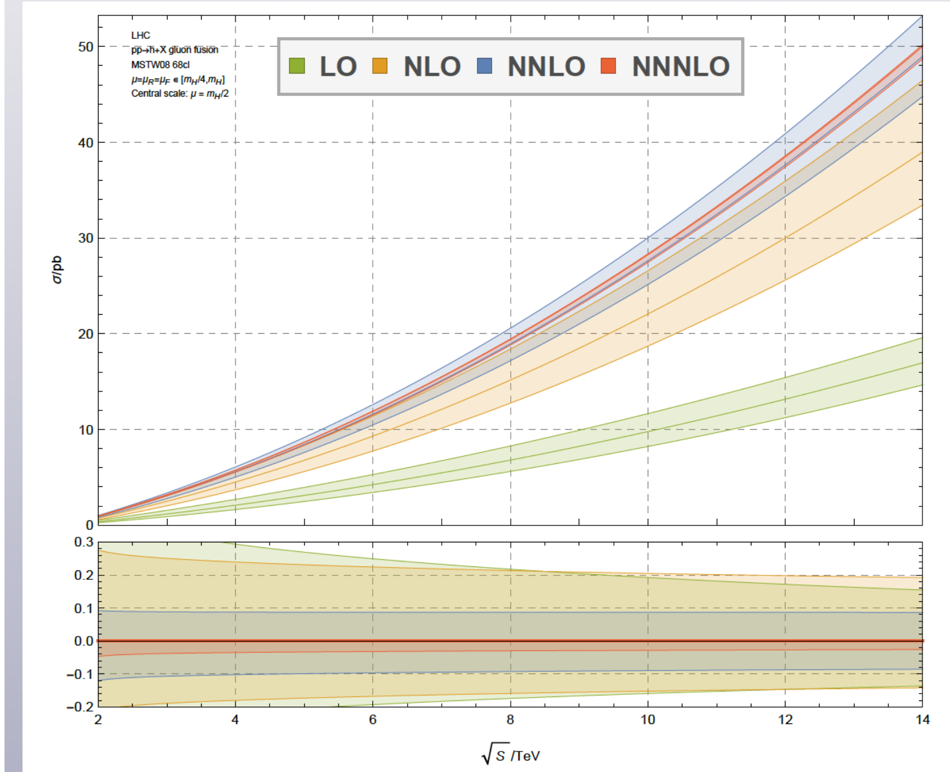


Solid: no TH unc
Hatched: with TH unc



Parton Distributions and LHC phenomenology

- Recently **massive development of NNLO higher-order calculations …**
- … now we even have the **Higgs gluon fusion xsec at N3LO! Scale uncertainties down to 2%!**



> Finally, the computation of the hadronic cross-section relies crucially on the knowledge of the strong coupling constant and the parton densities. After our calculation, the uncertainty coming from these quantities has become dominant. Further progress in the determination of parton densities must be anticipated in the next few years due to the inclusion of LHC data in the global fits and the impressive advances in NNLO computations, improving the theoretical accuracy of many standard candle processes.

Anastasiou et al, arxiv:1503.06056

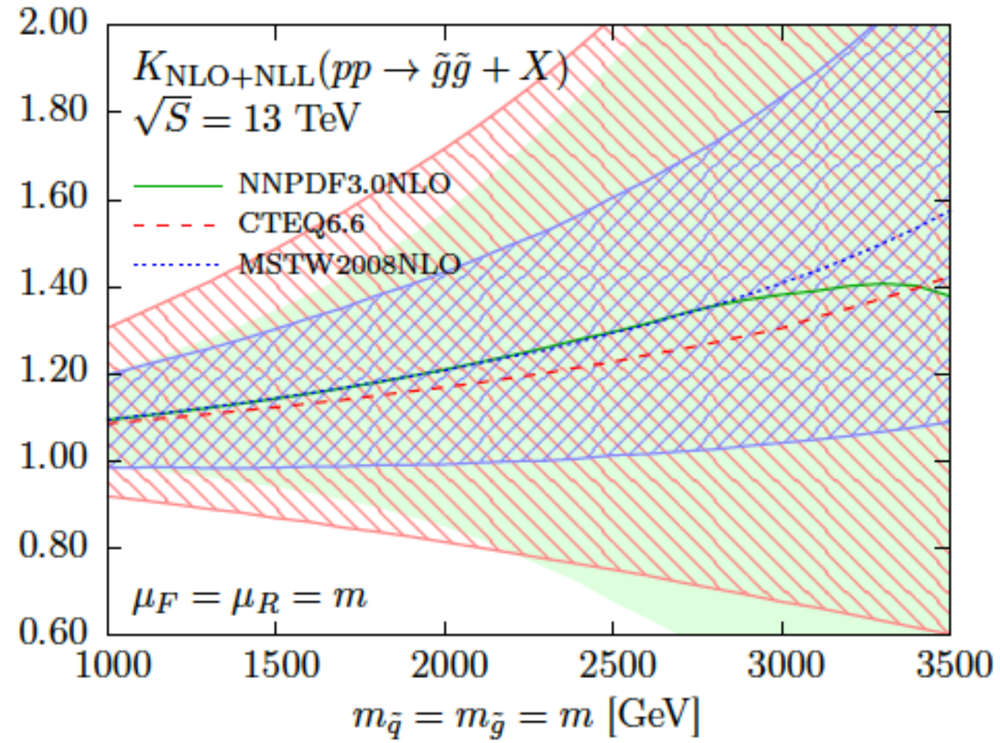
- PDF uncertainties are now **dominant** for a number of crucial LHC processes, and thus it is crucial to match the **accuracy of hard-cross section calculations** with that of the PDFs

Parton Distributions and LHC phenomenology

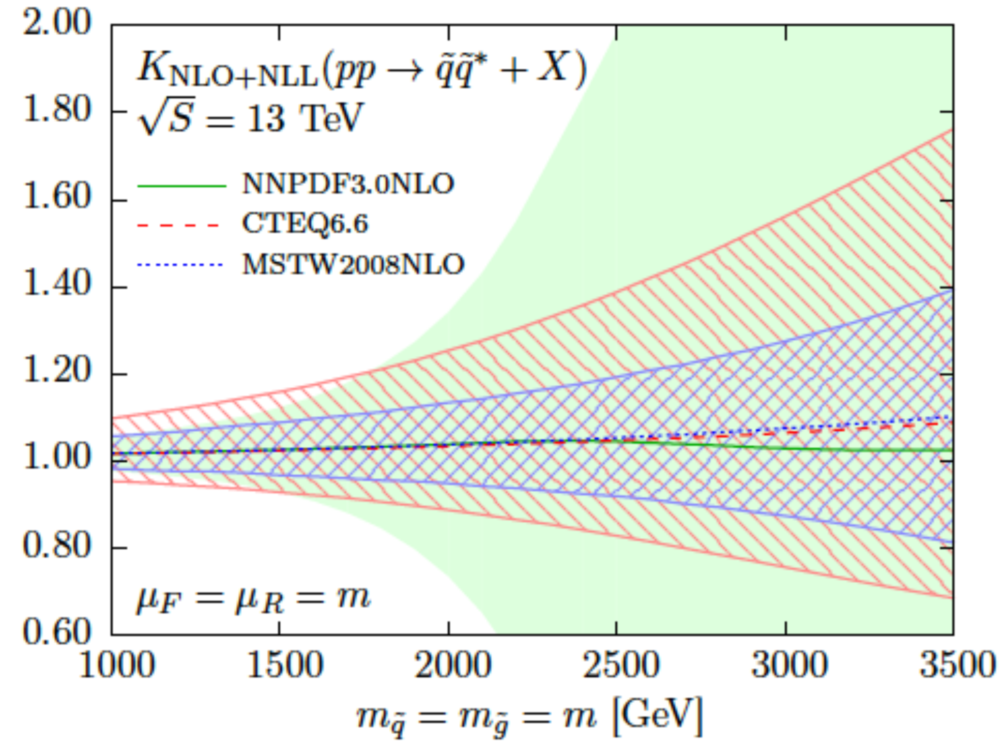
2) Very large PDF uncertainties (>100%) for BSM heavy particle production

$K_{NLO+NLL}$ = (NLO+NLL)/NLO

Gluino Pair Production



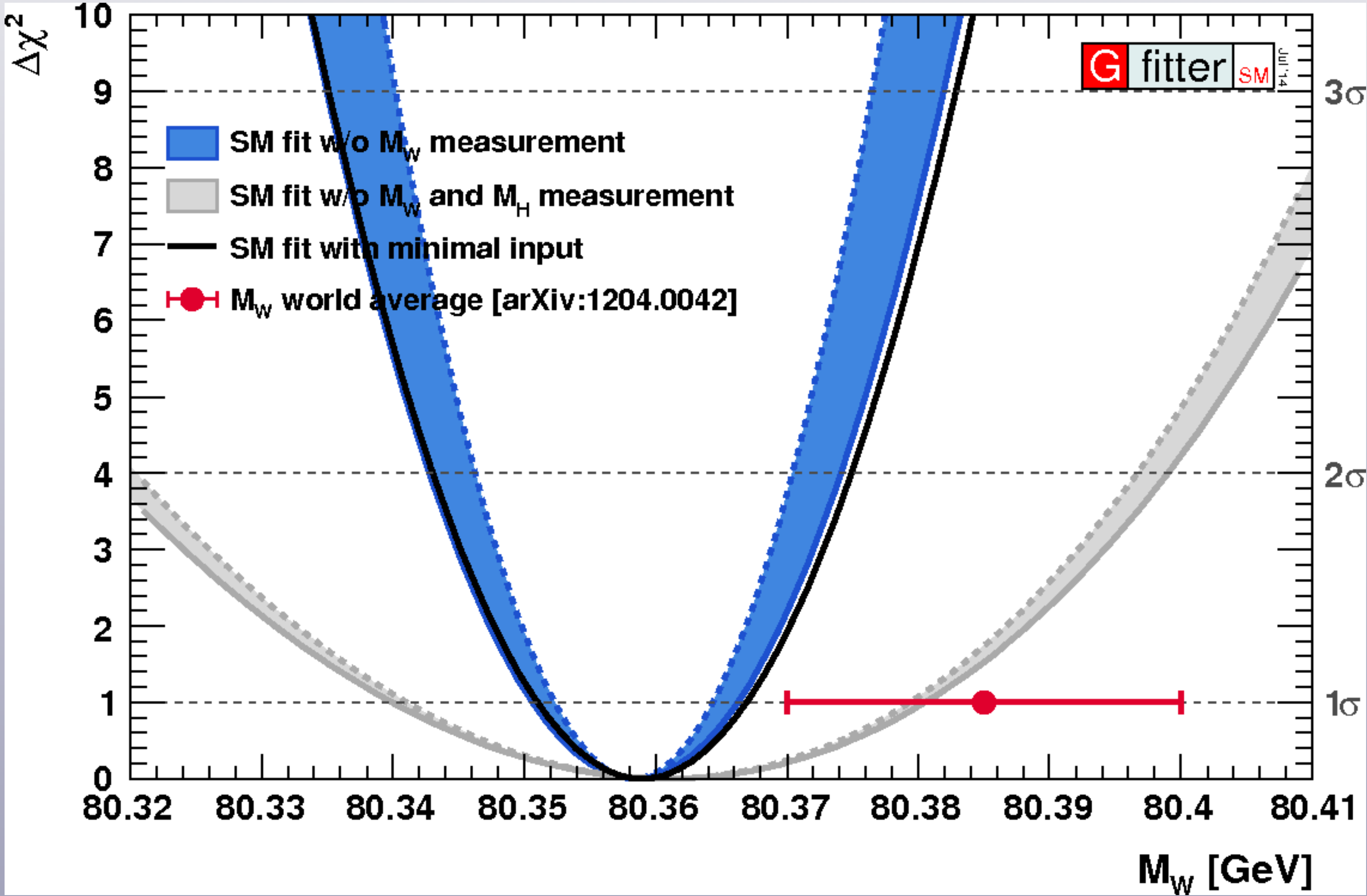
Squark-Antisquark Pair Production



Beenakker, Borschensky, Kramer, Kulesza, Laenen, Marzani, **JR,** arXiv:1509.aaaaa

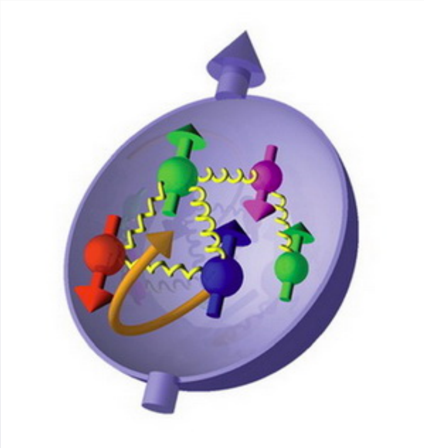
Parton Distributions and LHC phenomenology

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

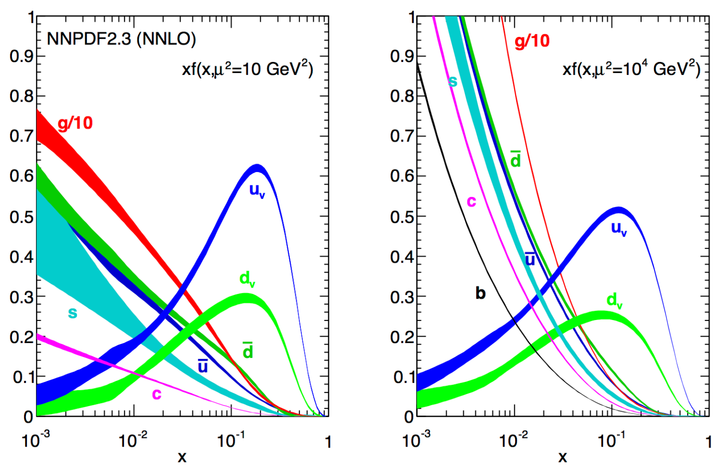


- Reducing TH systematics could lead to **indirect BSM discovery** from precision measurements
- Precision in M_W will **improve by a factor 3** in 10 years
- If SM confirmed, **ruled out a broad class of BSM scenarios**

1.8-sigma tension between direct M_W measurement and global EW fit

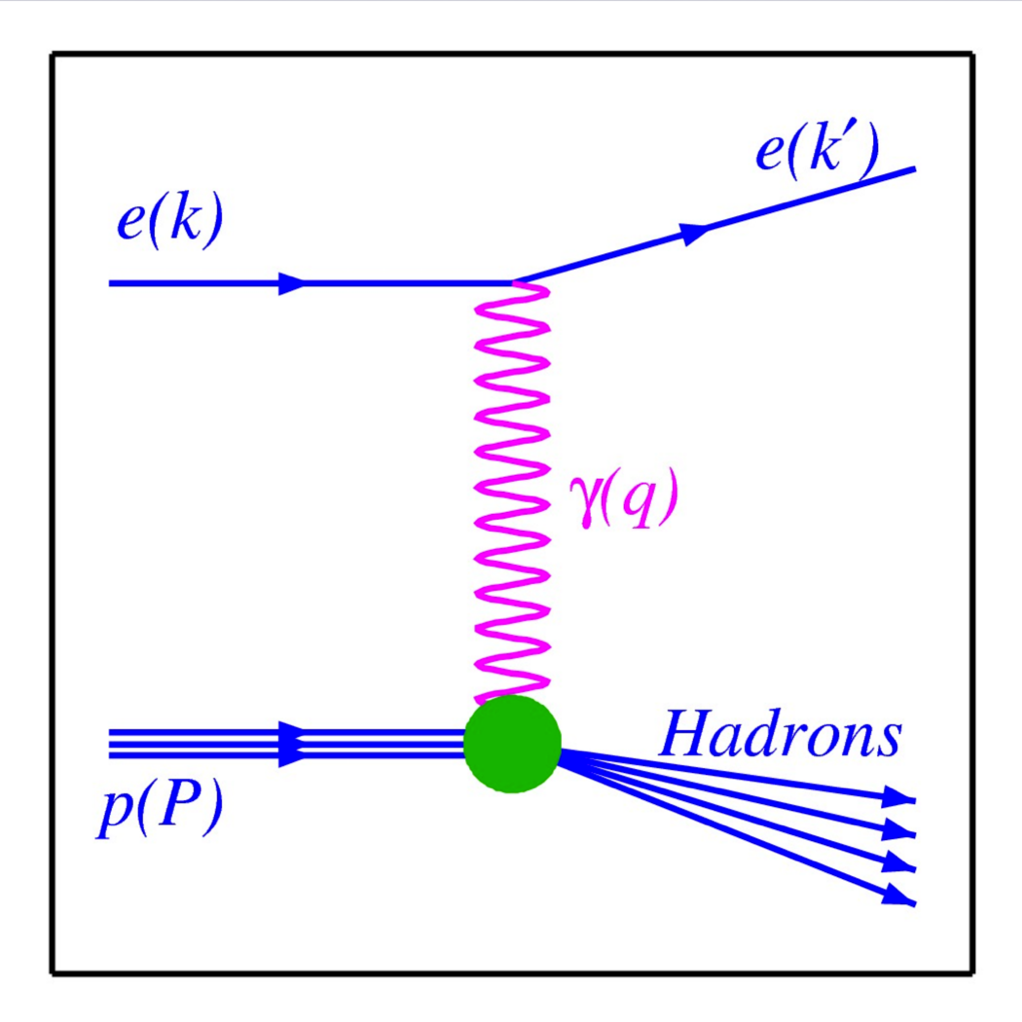


The inner life of protons : Parton Distribution Functions



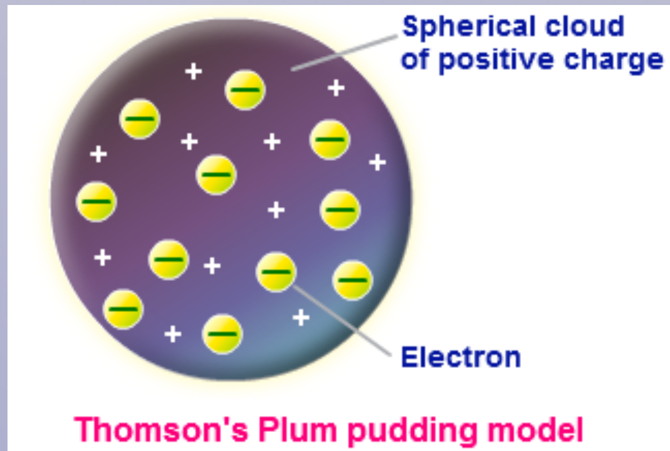
Deep-Inelastic scattering and the discovery of quarks

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



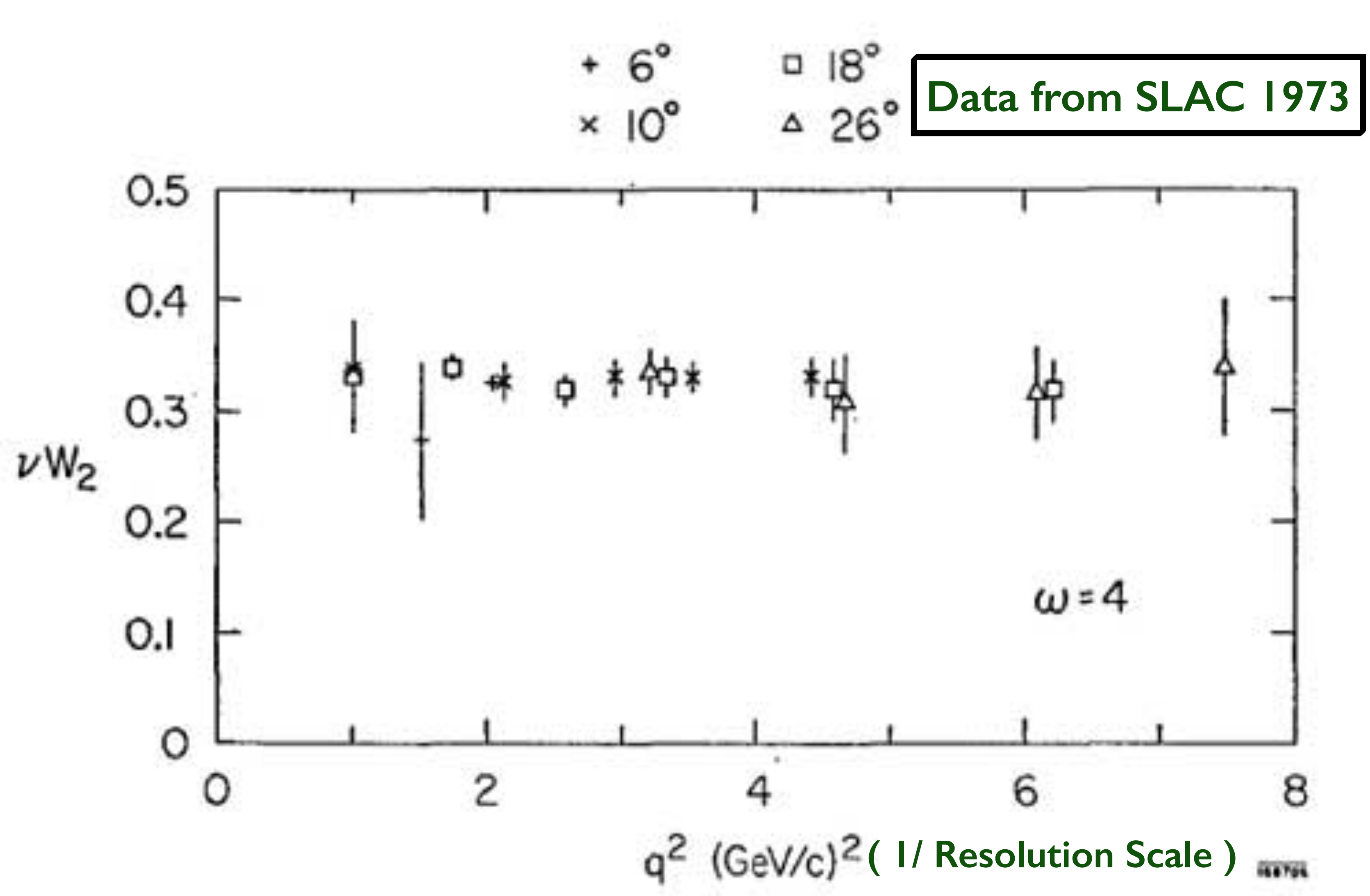
$$x_{\mathrm{Bj}} = \frac{Q^2}{2\,p\cdot q}, \quad Q^2 = -q^2 \quad y = \frac{q\cdot p}{k\cdot p}$$

- 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



Deep-Inelastic scattering and the discovery of quarks

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

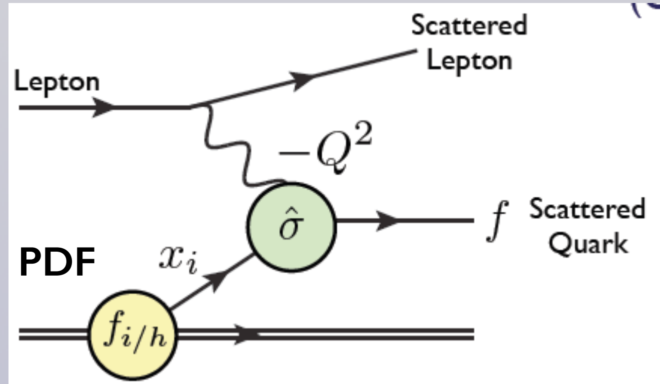


QCD Factorization and PDFs

- **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

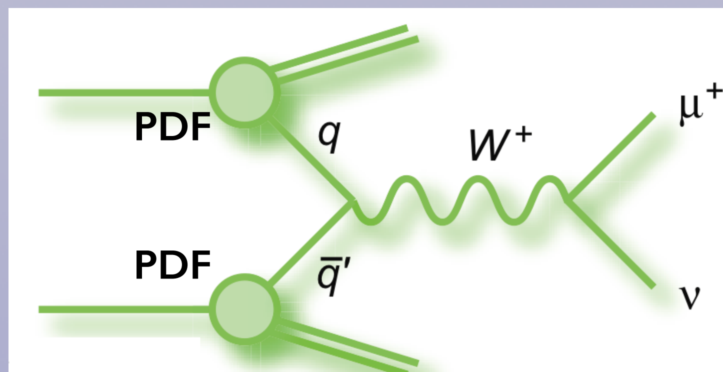


- The same **Factorization Theorem** allows to use the same **universal PDFs** to provide **predict ions for proton-proton collisions at the LHC:**

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

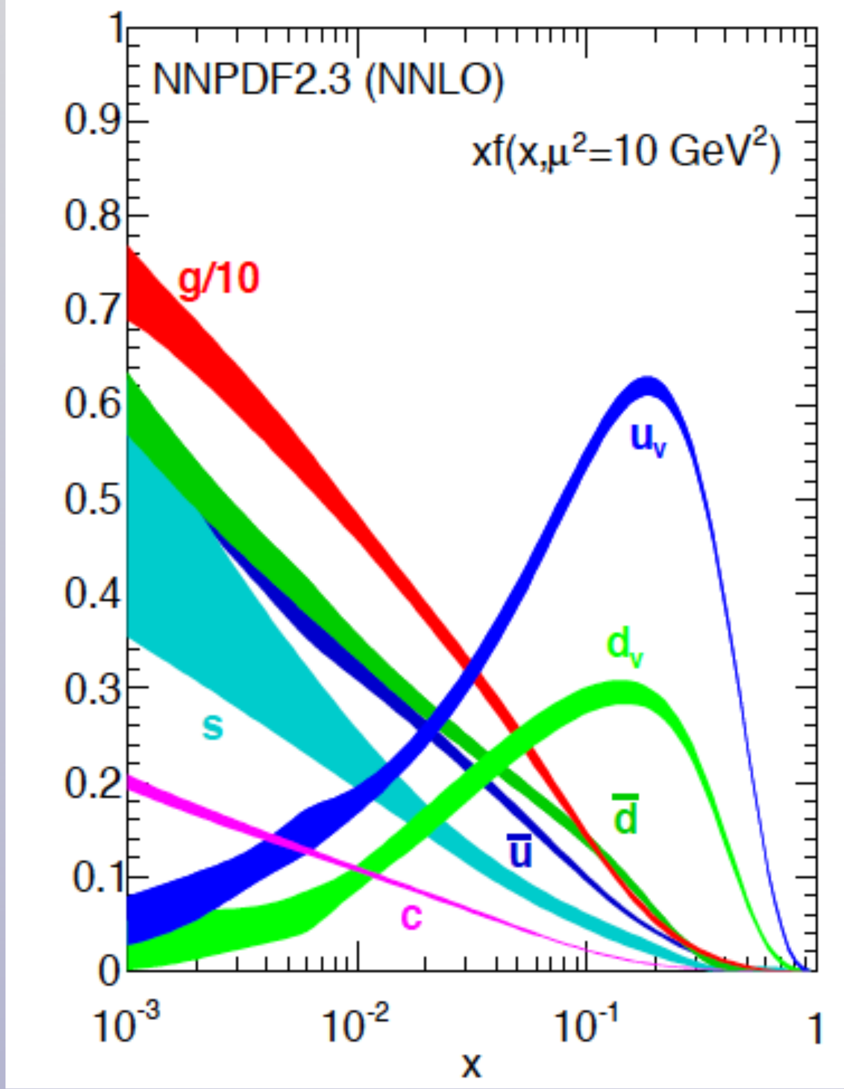
Hadron-level cross section   (2) Parton Distributions   Parton-level cross-section

- 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

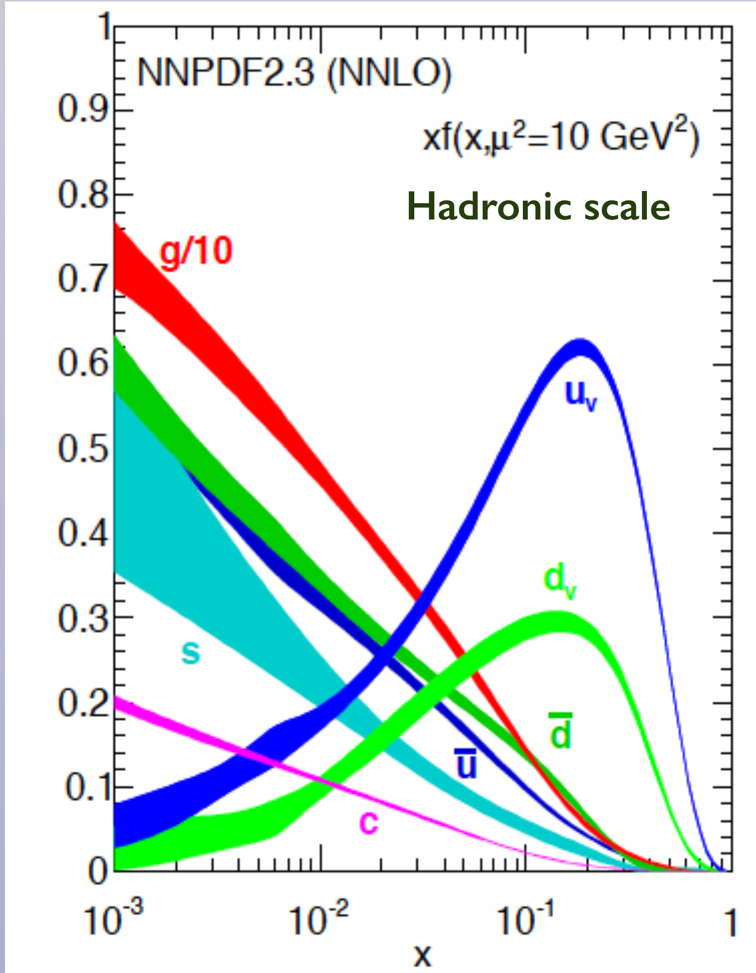
$$\int_0^1 dx\;\left(u(x)-\bar{u}(x)\right)=2\;,\qquad \int_0^1 dx\;\left(d(x)-\bar{d}(x)\right)=1$$

Perturbative evolution equations

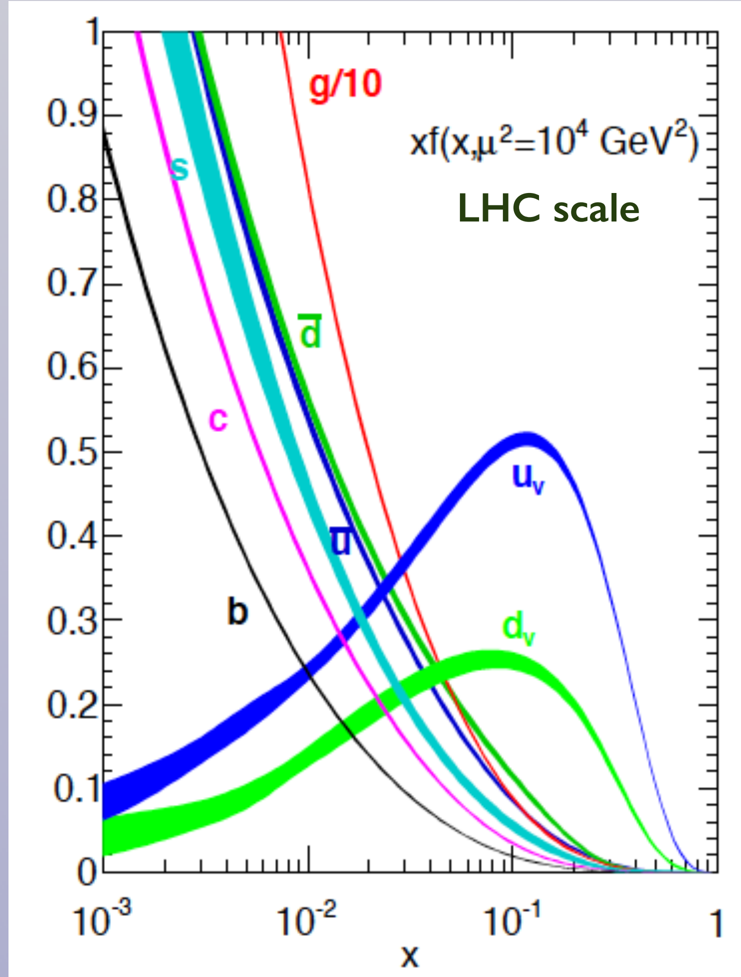
- The dependence of PDFs on **Bjorken-x (momentum fraction) is determined by non-perturbative QCD dynamics**, but that on the **scale Q^2 (resolution)** is instead known from perturbative QCD: the **DGLAP evolution equations**

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

- Once x-dependence $\mathbf{q(x,Q^2_0)}$ extracted from data, **pQCD determines PDFs** at other scales $\mathbf{q(x,Q^2)}$



Perturbative Evolution



Experimental data in global PDF fits

- 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**

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

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

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

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

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

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

- 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

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

Consistent error propagation to LHC xsecs
no Gaussian assumptions

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

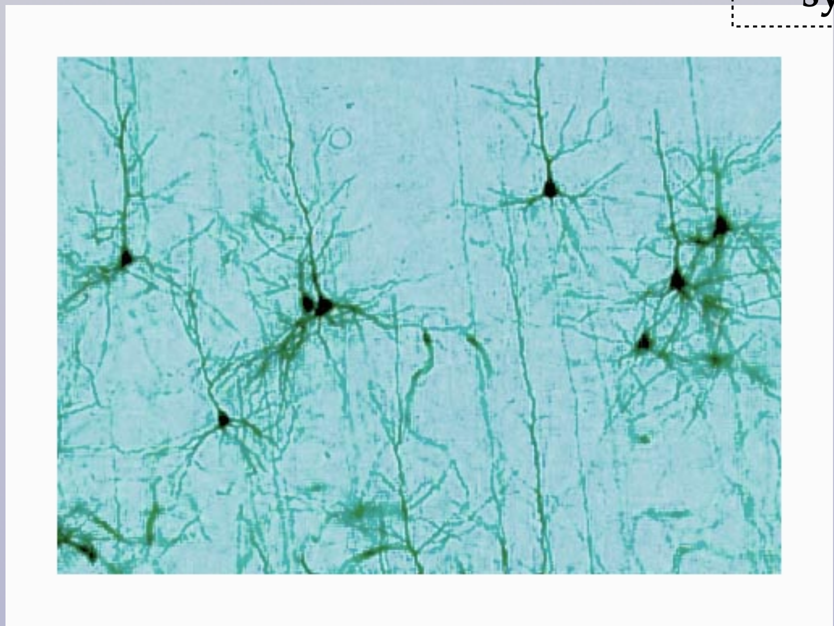
☑ NNPDF solution: Use **Genetic Algorithms** to be able to explore efficiently the vast parameter space

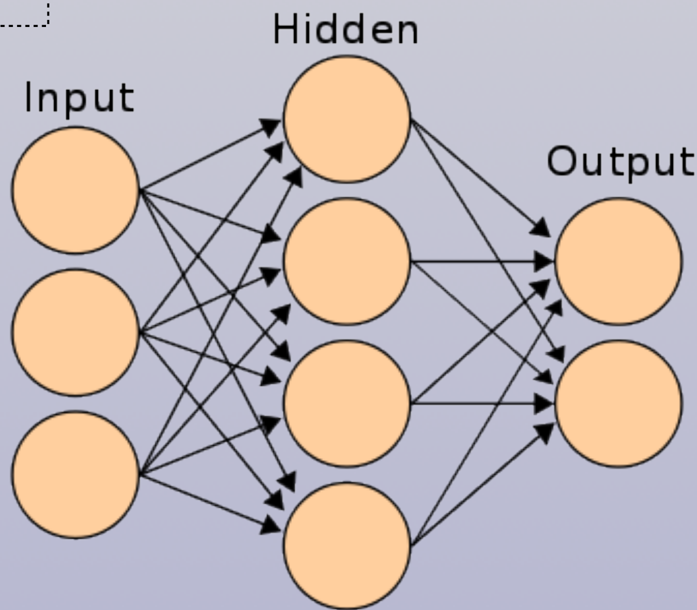
$$\chi^2 \;=\; \sum_{i=1}^{N_{\rm dat}}\sum_{i'=1}^{N_{\rm dat}}(D_i-T_i)\left(V^{-1}\right)_{ii'}(D_{i'}-T_{i'}).$$

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**





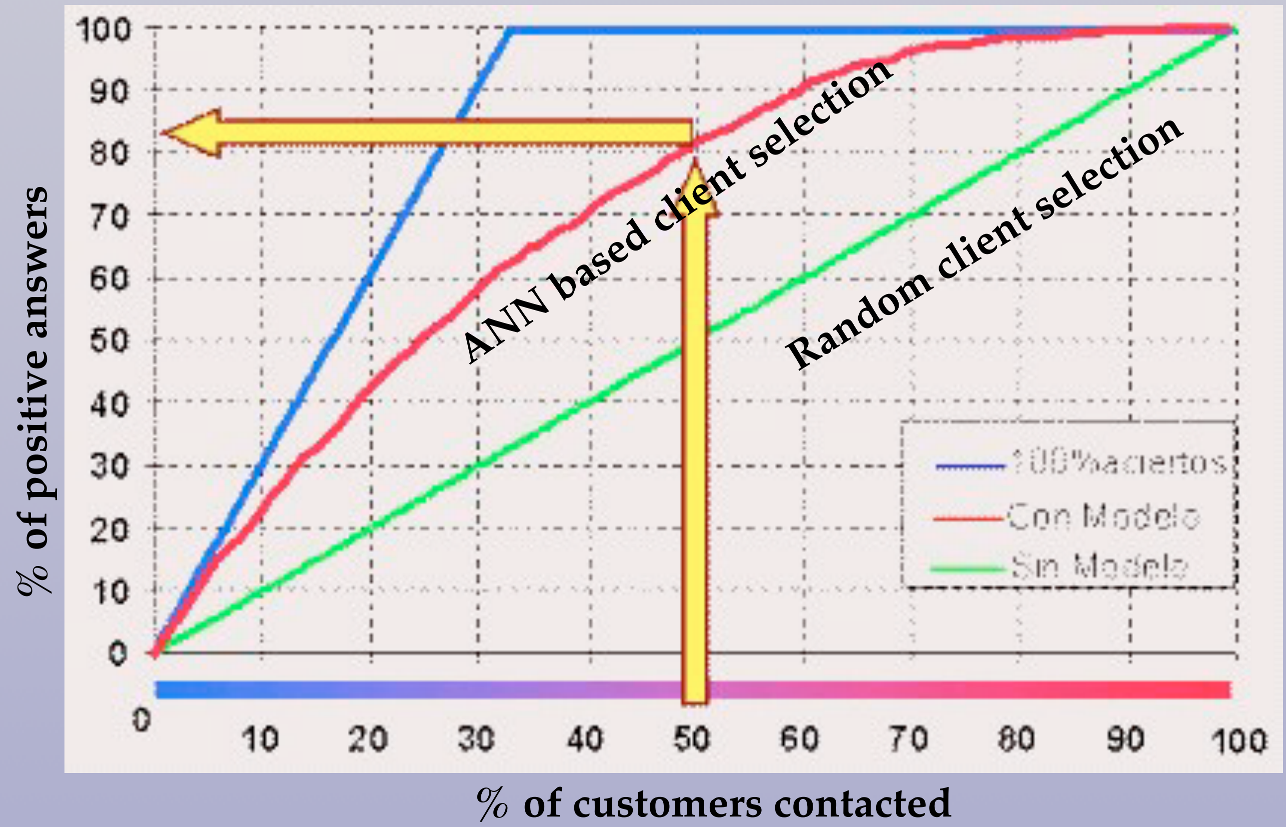
- Artificial neural networks aimed to excel in the same domains as their biological counterparts: **pattern recognition, forecasting, classification**, ... where our **evolution-driven biology** outperforms traditional algorithms

Artificial Neural Networks

Example 1: **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 output** (yes/no) and use the information to contact only clients likely to accept the offer

Cost-effective method to improve marketing performance



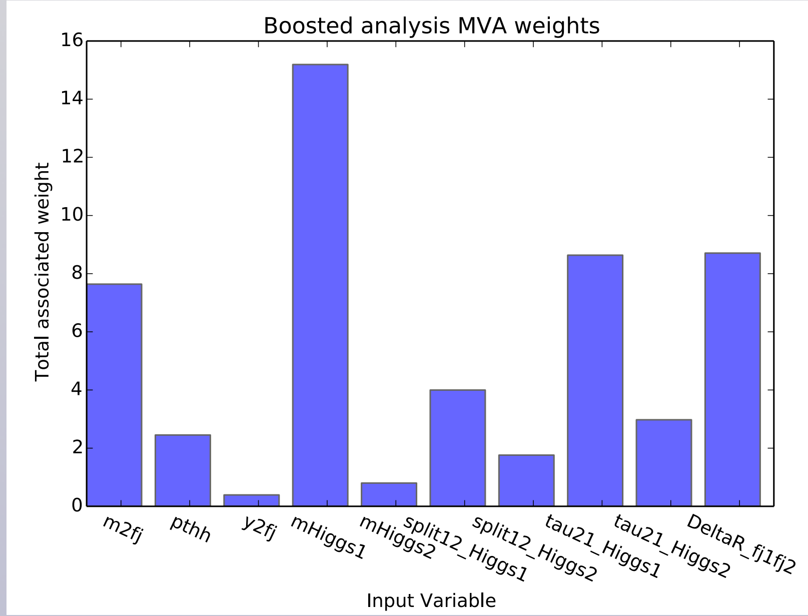
Artificial Neural Networks

Behr, Bortoletto, Frost, Hartland, Issever, JR, in prep

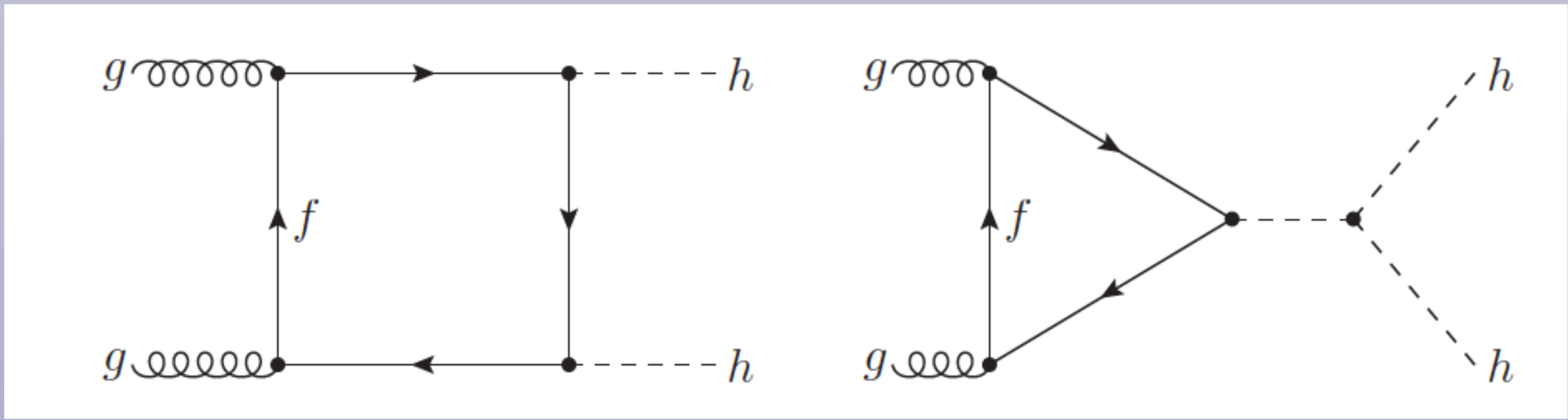
Example 2: **Classification.** Discriminate between signal and background events in complicated final states

- **Improve S/√B as compared to cut-based analyses**
- **Identify automatically** the kinematical variables with most discrimination power

Redundancy of **NN-based Multivariate Analysis** guarantees the optimisation of signal/background separation



HH->4b feasibility study



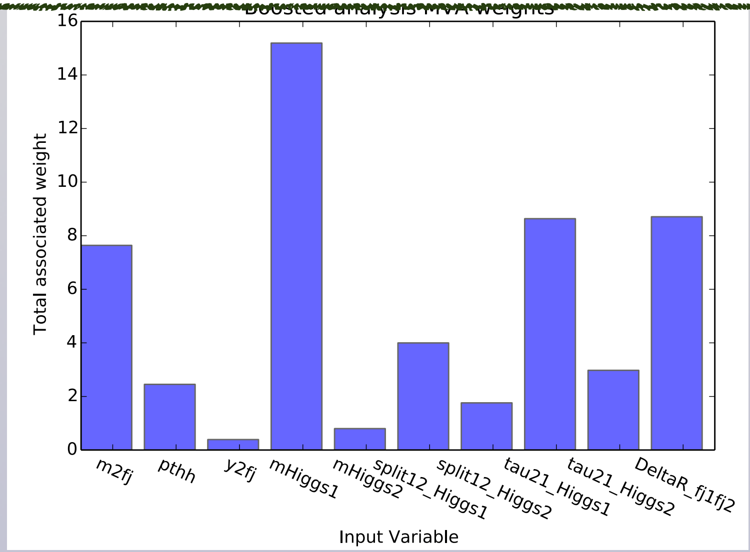
Artificial Neural Networks

Example 2: **Classification.** Discriminate between signal and background events in complicated final states

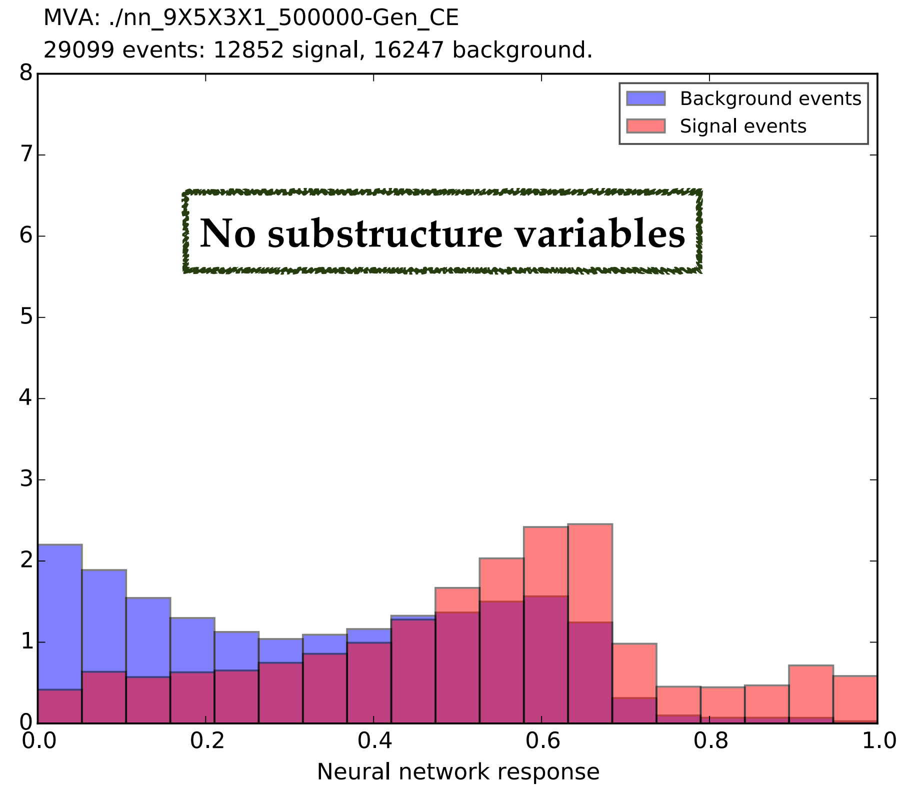
- **Improve S/√B as compared to cut-based analyses**
- **Identify automatically** the kinematical variables with most discrimination power

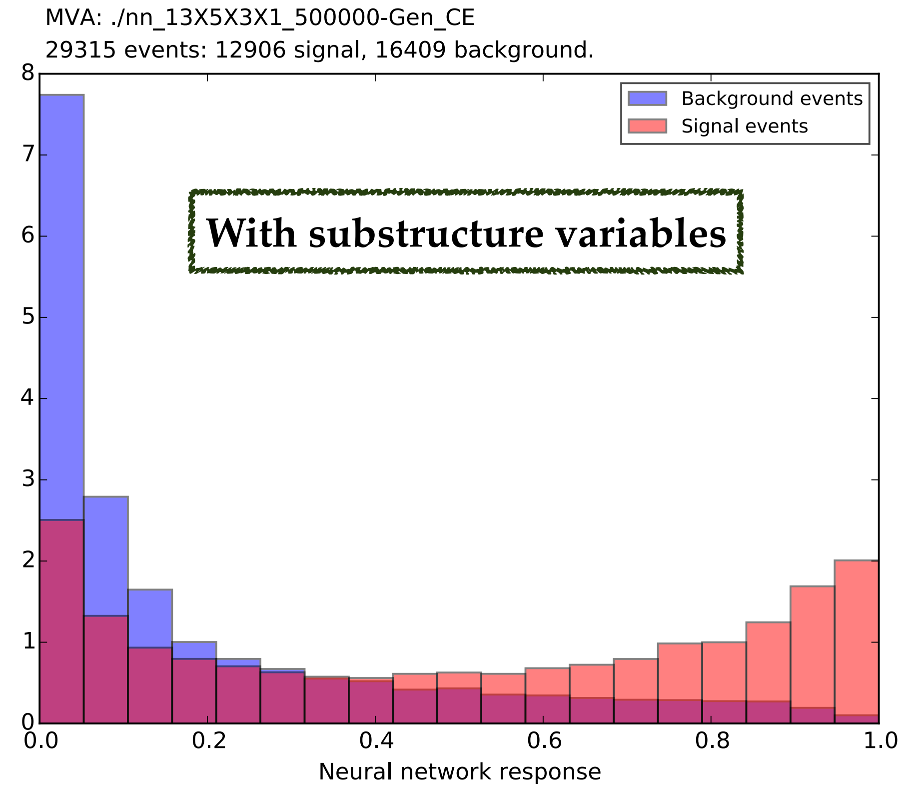
Redundancy of **NN-based Multivariate Analysis** guarantees the optimisation of signal/background separation

Behr, Bortoletto, Frost, Hartland, Issever, JR, in prep



HH->4b feasibility study



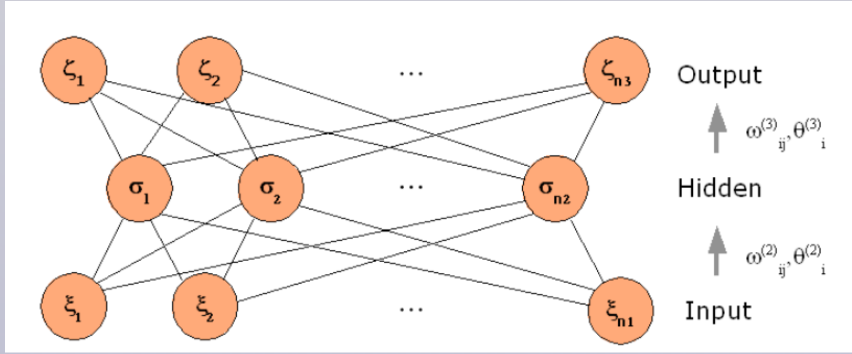


Artificial Neural Networks

- **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)



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

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

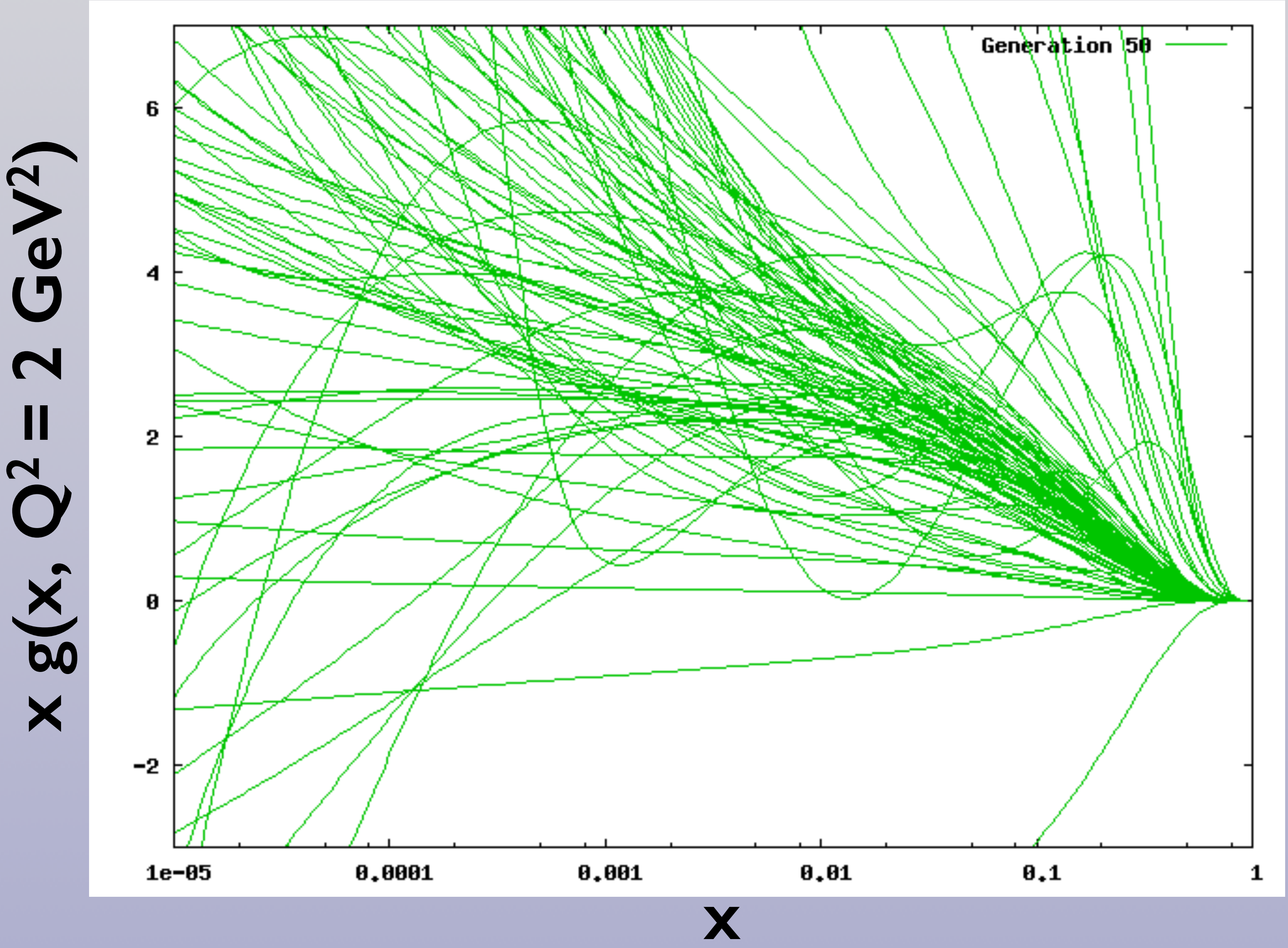
- In traditional PDF determinations, the input *ansatz* is a simple **polynomial**

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

- 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 Replica Neural Network Learning

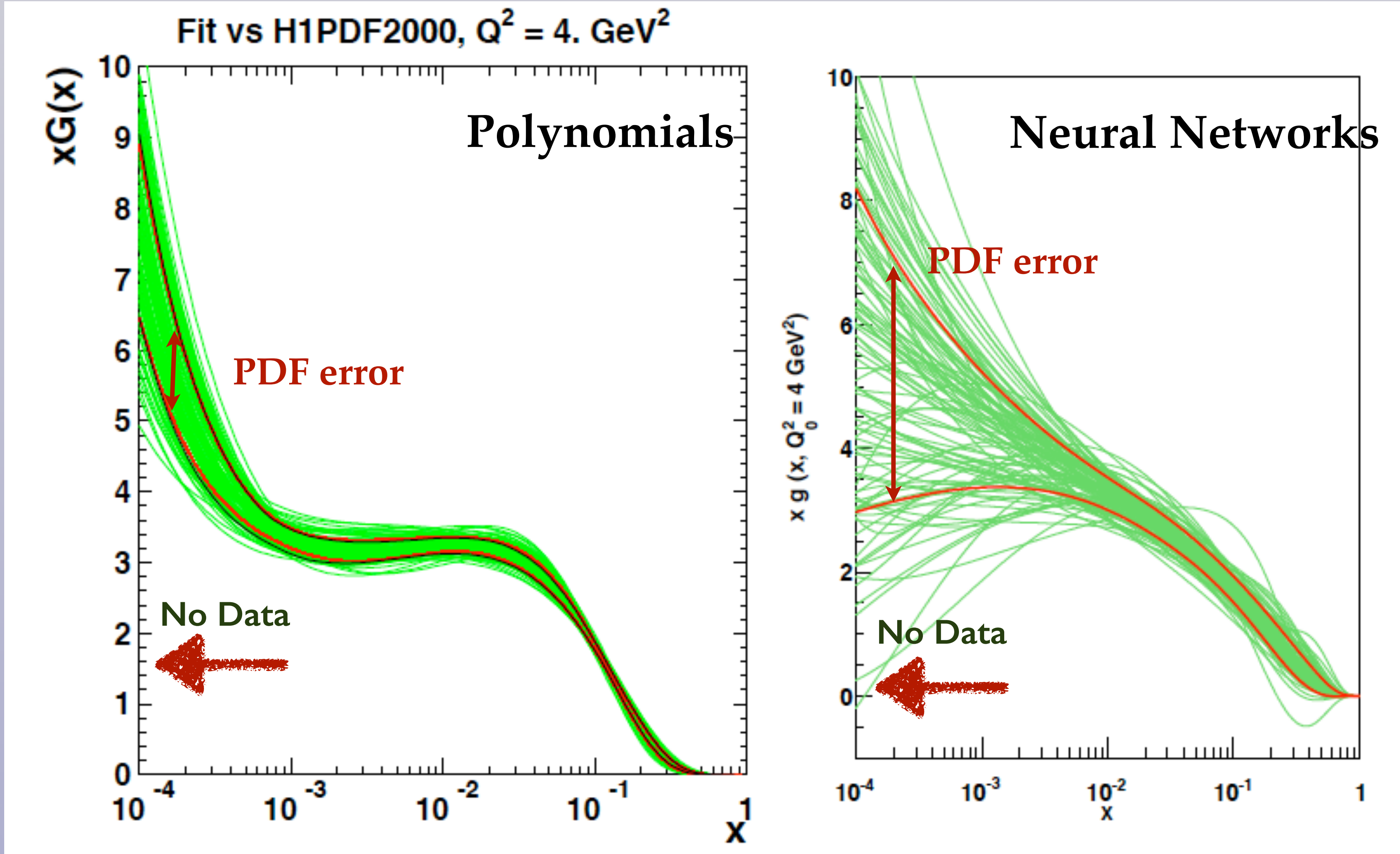
The minimisation of the **data vs theory χ^2** is performed using **Genetic Algorithms**
Each **green curve** corresponds to a **gluon PDF Monte Carlo** replica



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)

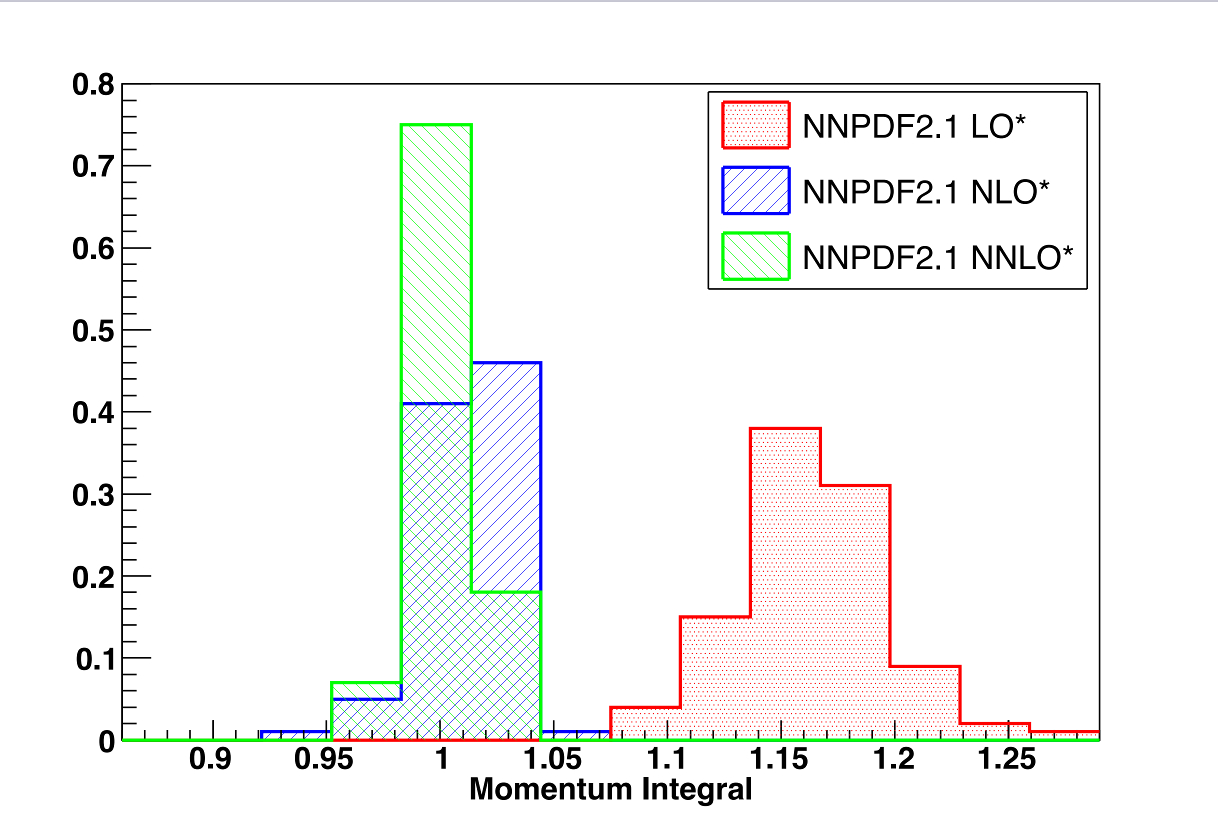


Precision tests of the Factorisation Theorem

- 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**



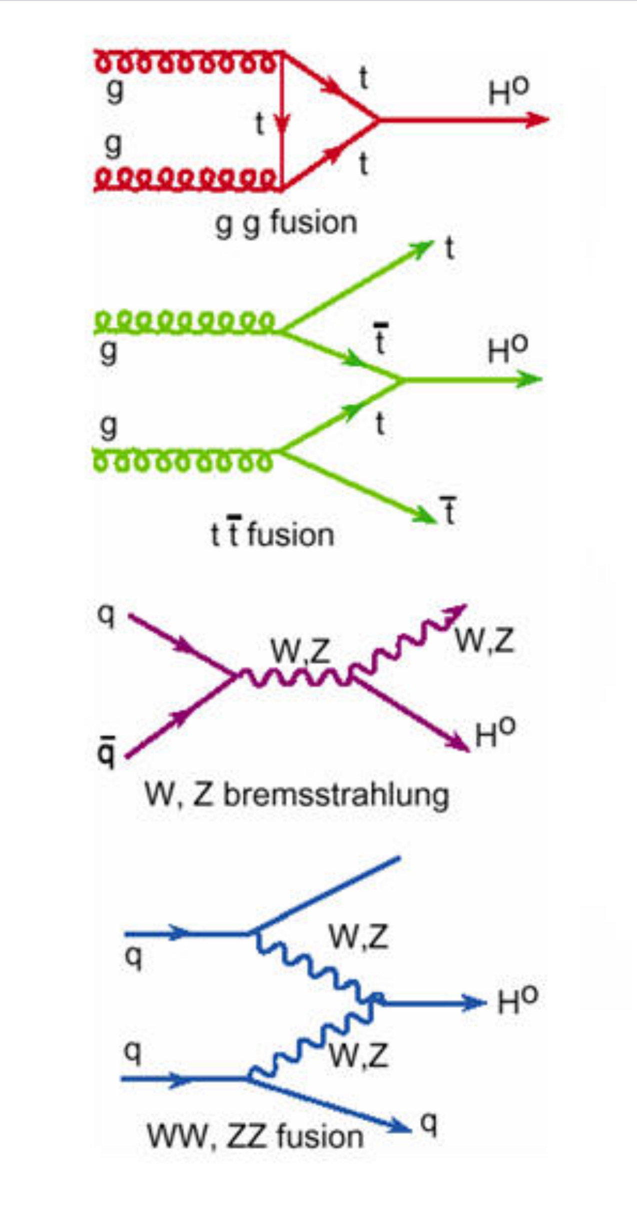
$$[M]_{\rm LO} = 1.161 \pm 0.032\,,$$
$$[M]_{\rm NLO} = 1.011 \pm 0.018\,,$$
$$[M]_{\rm NNLO} = 1.002 \pm 0.014\,.$$

- 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

PDFs and New Physics searches at the LHC

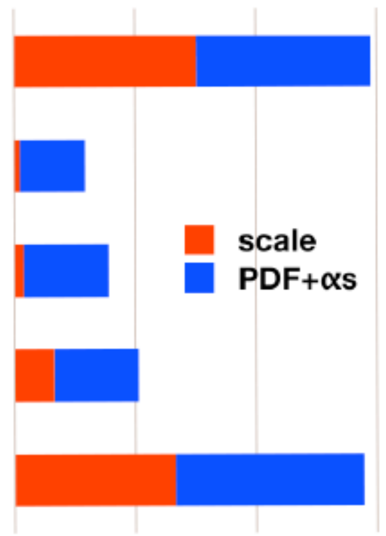
Higgs Boson Characterisation



- 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

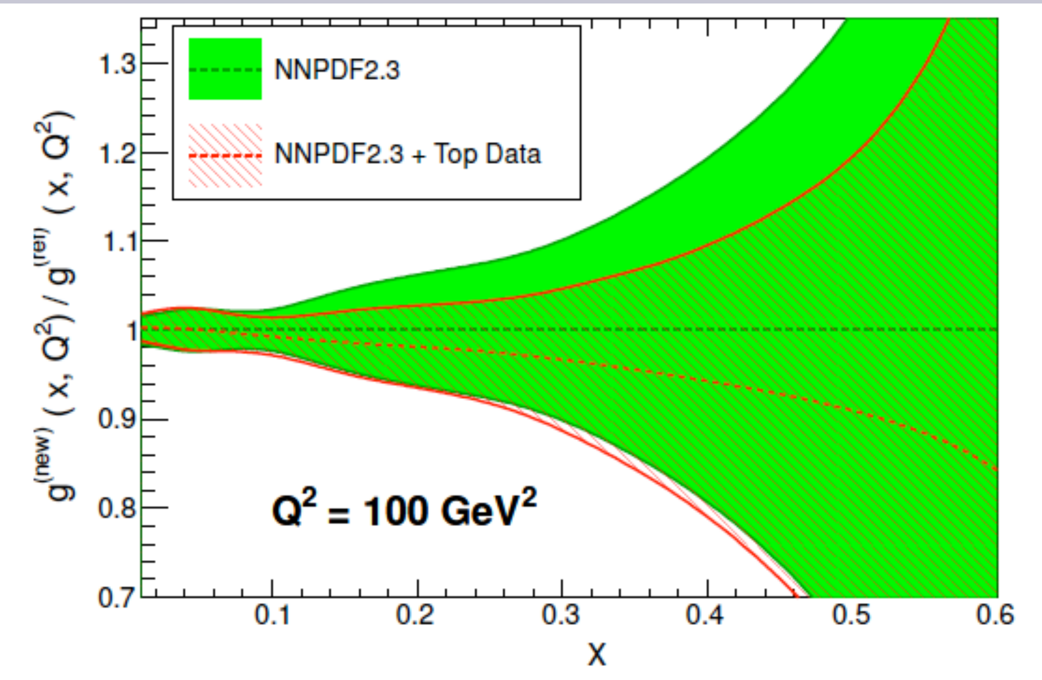
		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%

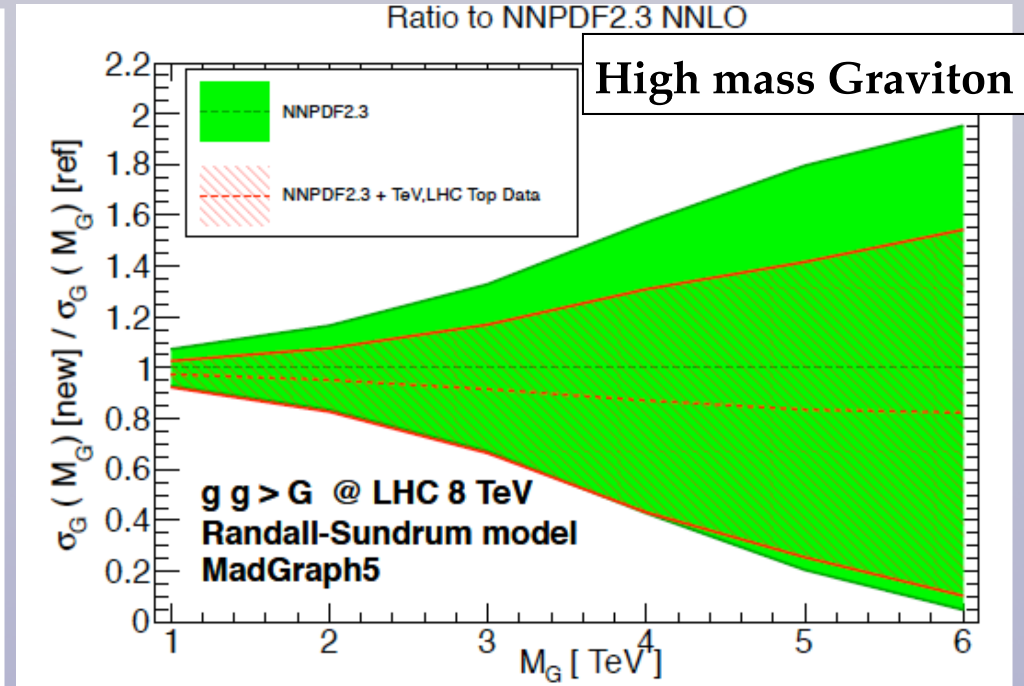


J. Campbell 12

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





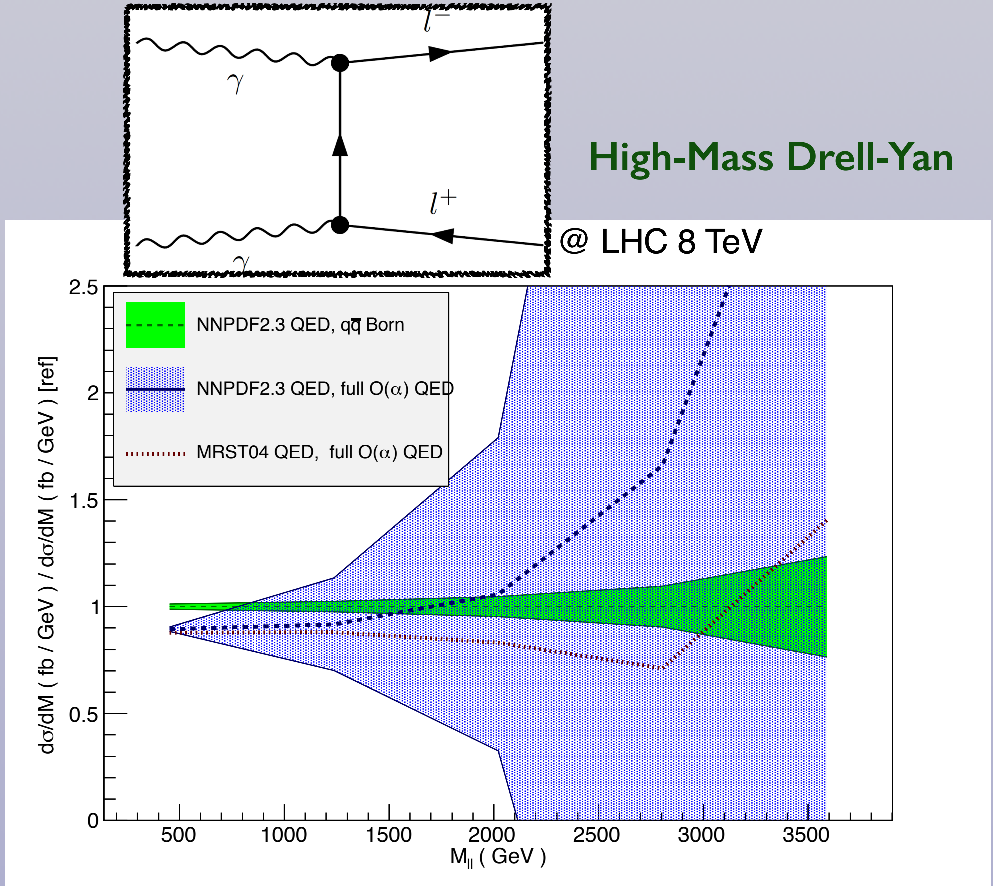
Czakon, Mangano, Mitov, J.R. 13

Top quark data now included in many global PDF fits: ABM12, MMHT14, HERAfitter ….

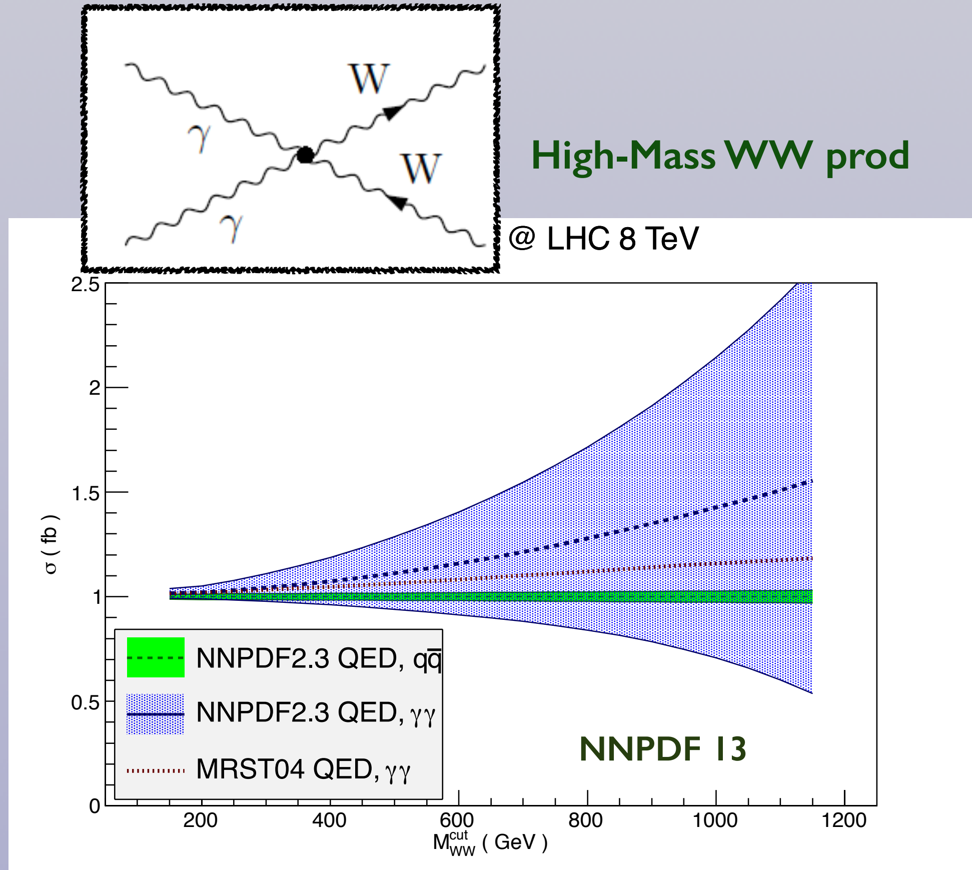
PDFs with QED corrections

- **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

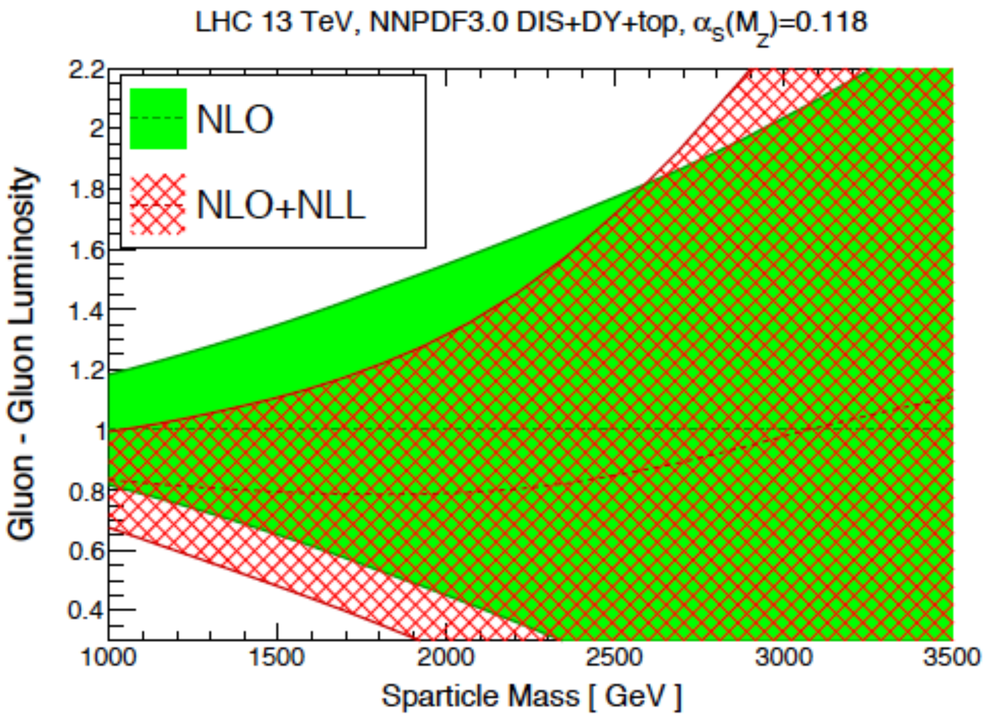


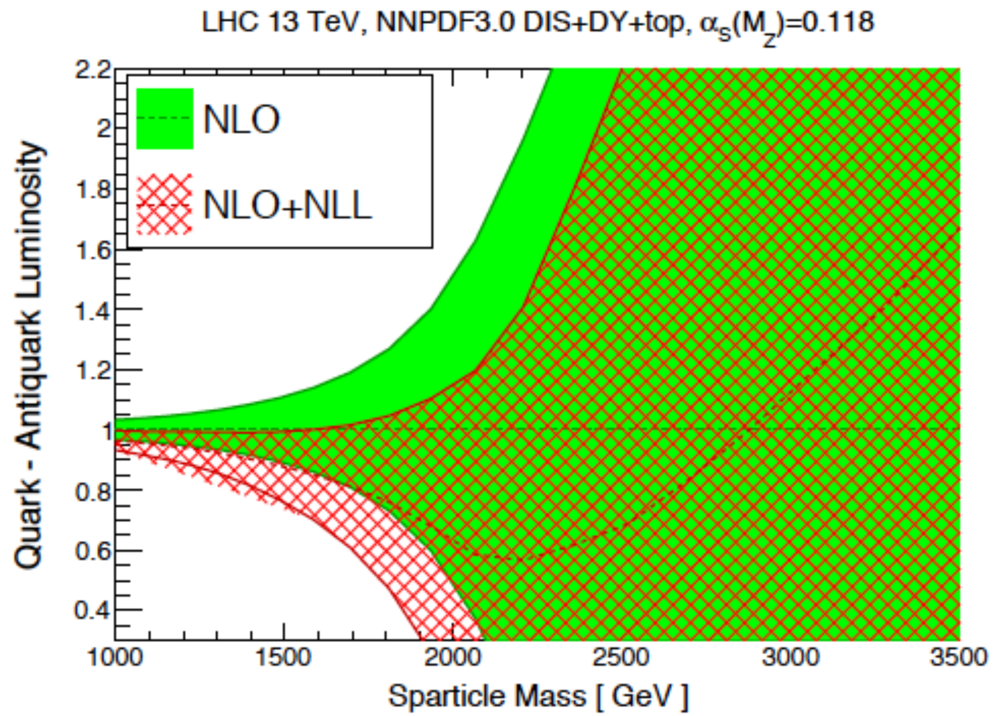
Updated squark and gluino cross-sections with threshold-improved PDFs

Bonvini, Marzani, JR, Rottoli, Ubiali, Ball, Bertone, Carrazza, Hartland, arXiv:1507.01006
Beenakker, Borschensky, Kramer, Kulesza, Laenen, Marzani, **JR,** arXiv:1509.aaaaa

PDFs with threshold resummation

- Many LHC calculations supplement **NLO and NNLO fixed-order results** with the **resummation of soft threshold logarithms to all orders**: Higgs, top pair production, high-mass supersymmetry ….
- NNPDF has produced for the first time **threshold-improved PDFs at NLO+NLL and NNLO+NNLL**

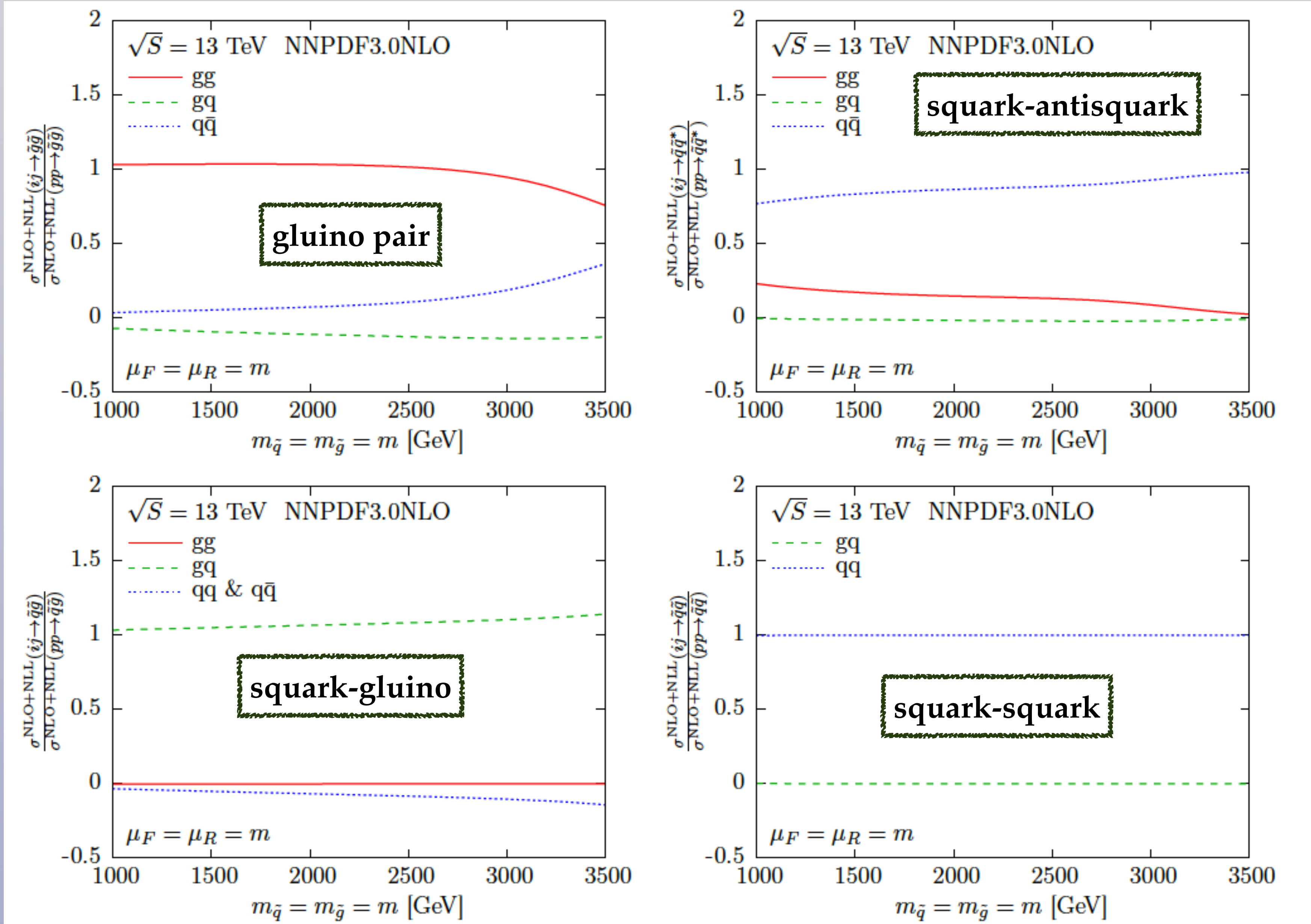




- **Threshold-improved PDFs** can differ substantially wrt fixed-order PDFs: **up to -20% for gg luminosity and -40% for quark-antiquark luminosity,** in the high-mass region relevant for new BSM heavy particles

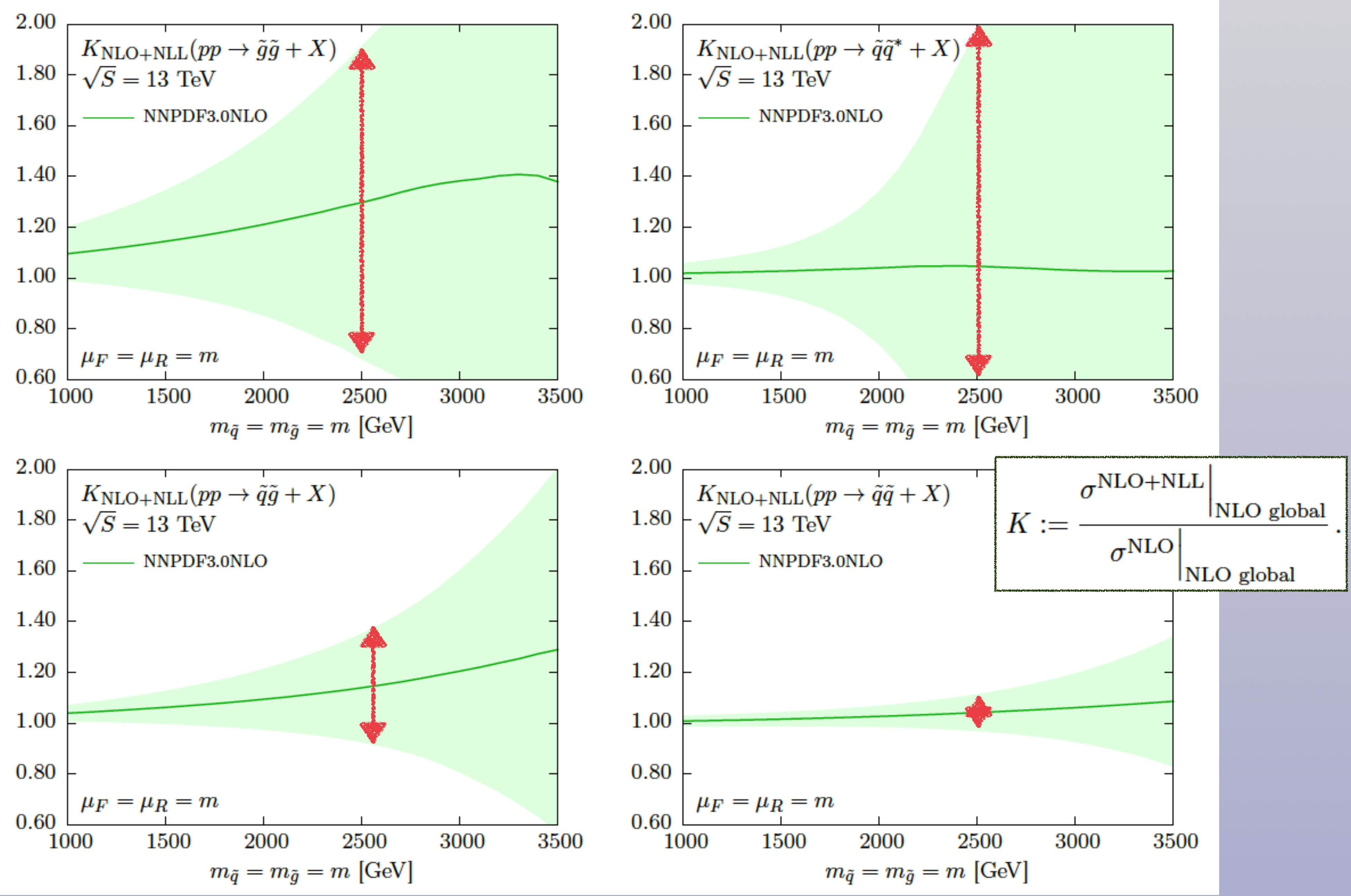
PDFs with threshold resummation

- PDF uncertainties in high-mass SUSY cross-sections are very large!
- This is because **large-x PDFs are being probed**, and these are affected by large errors due to the **lack of direct experimental constraints**



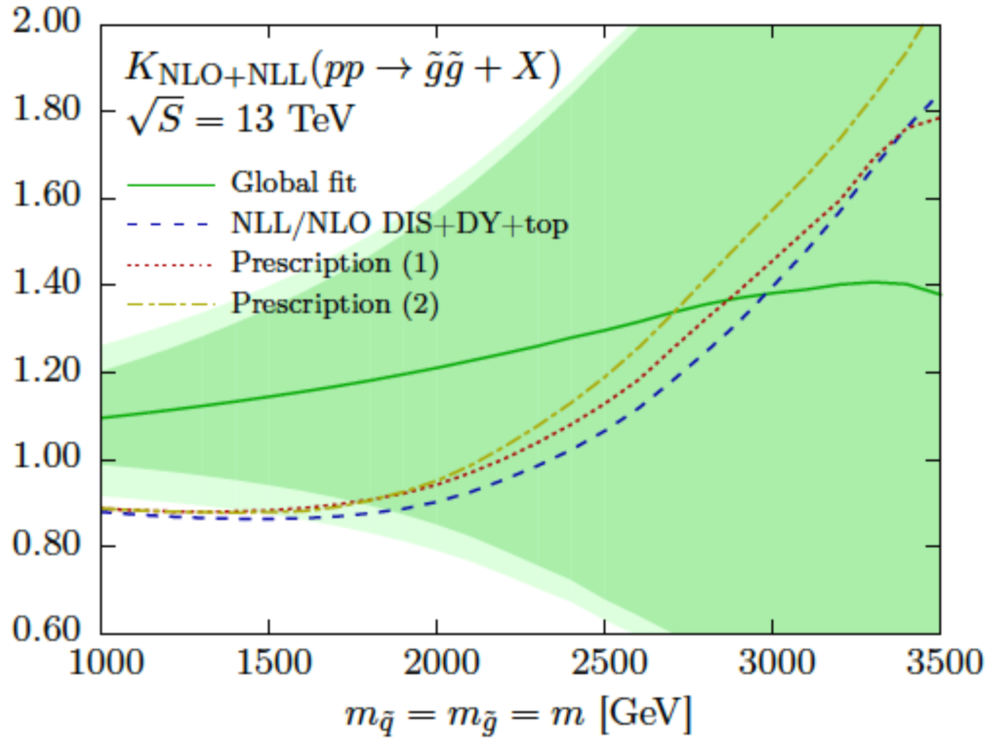
PDFs with threshold resummation

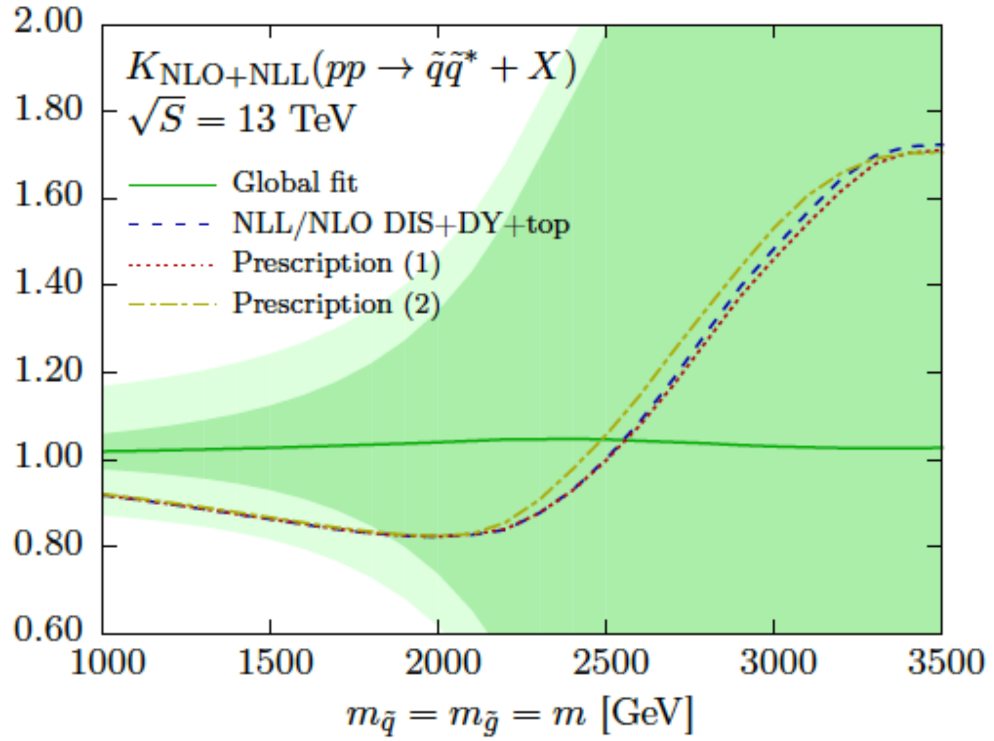
- How does this affect **existing limits on SUSY production** from LHC searches?
- First update **NLO+NLL cross-sections with NNPDF3.0NLO**



PDFs with threshold resummation

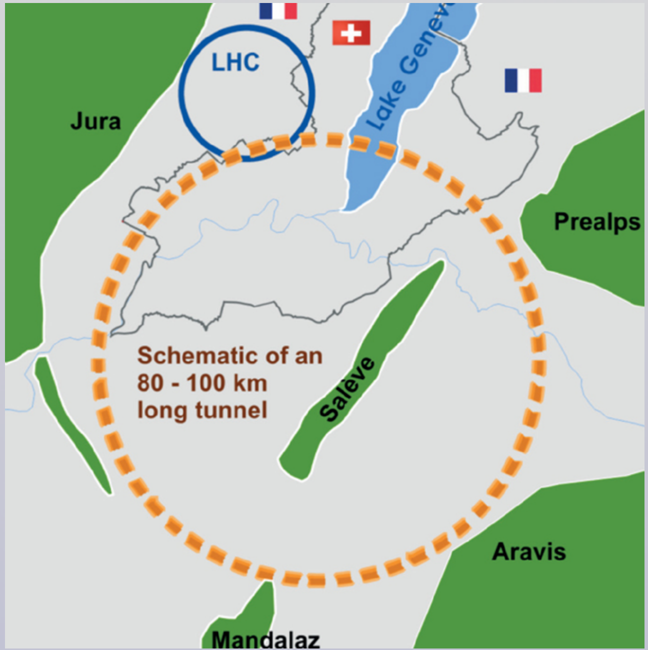
- Now include the effect of **NLO+NLL threshold-improved PDF**
- Substantial shift, changes qualitatively and quantitatively the behaviour of NLO+NLL SUSY xsecs
- Shift within total theory band, so **current exclusion limits unaffected**
- But will become crucial if we ever need to **characterise SUSY particles from LHC data**, much in the same way as we do for the Higgs boson



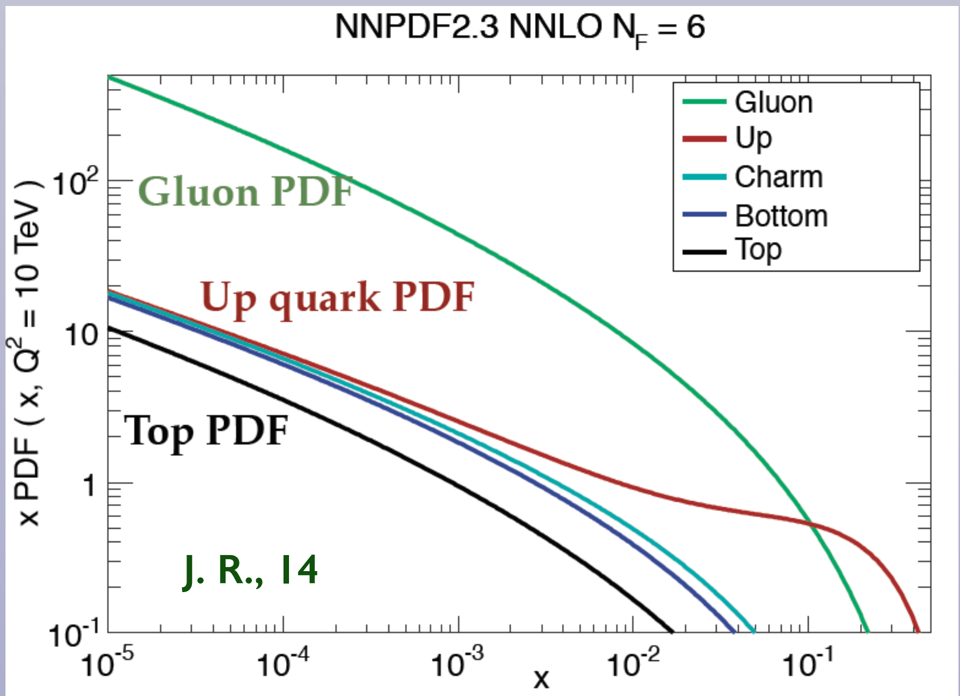


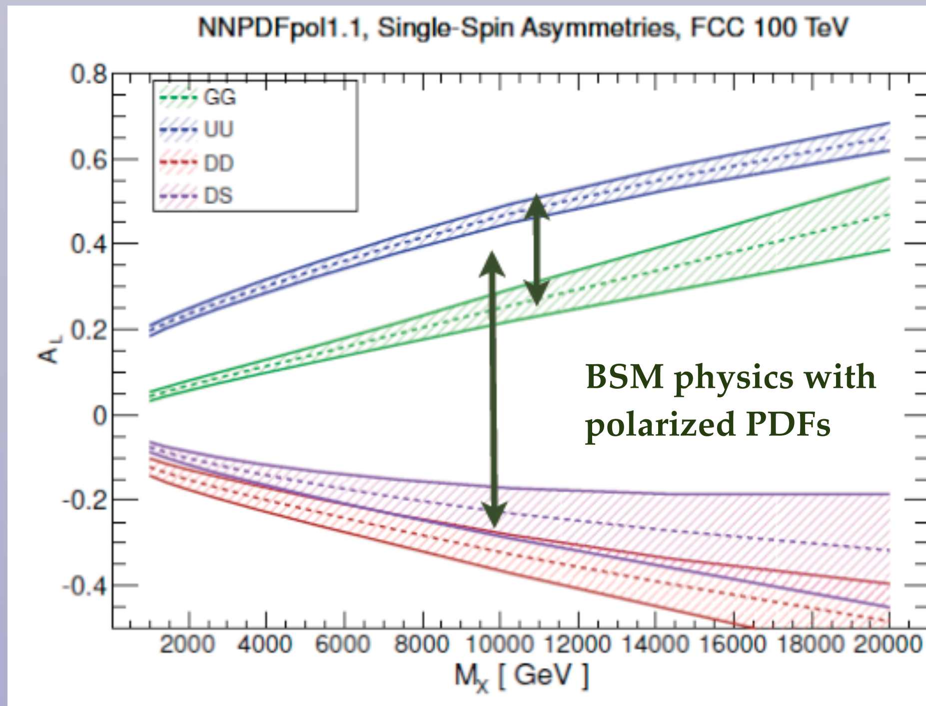
PDFs at Future Hadron Colliders

Going Beyond: PDFs at a 100 TeV collider

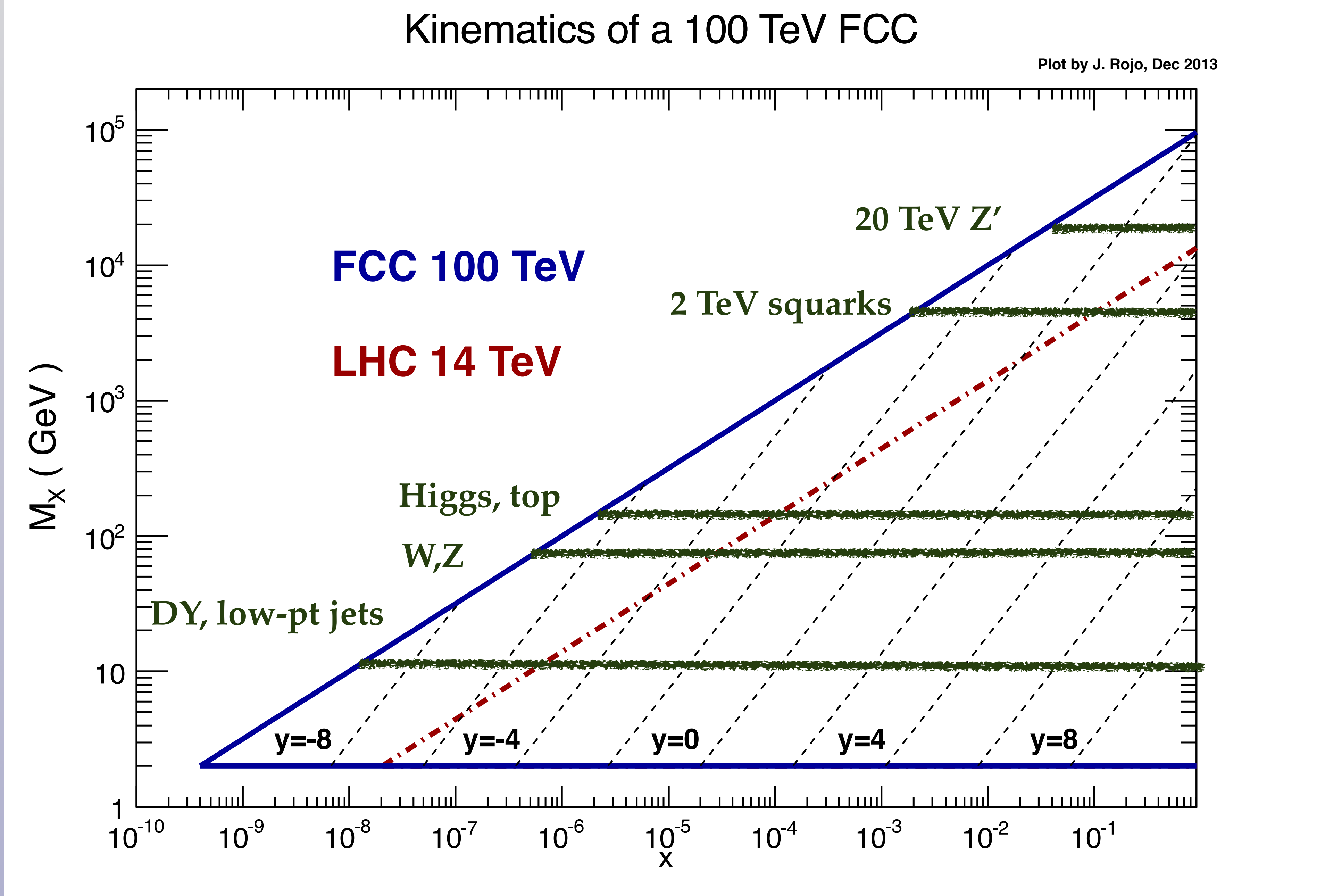


- Growing consensus that the next big machine more suitable to **explore the energy frontier** should be a **100 TeV hadron collider**, possibly with also **e+e-** and **ep** operation modes
- The **phenomenology of PDFs** at such extreme energies is very rich: **top quark PDFs**, electroweak effects 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**





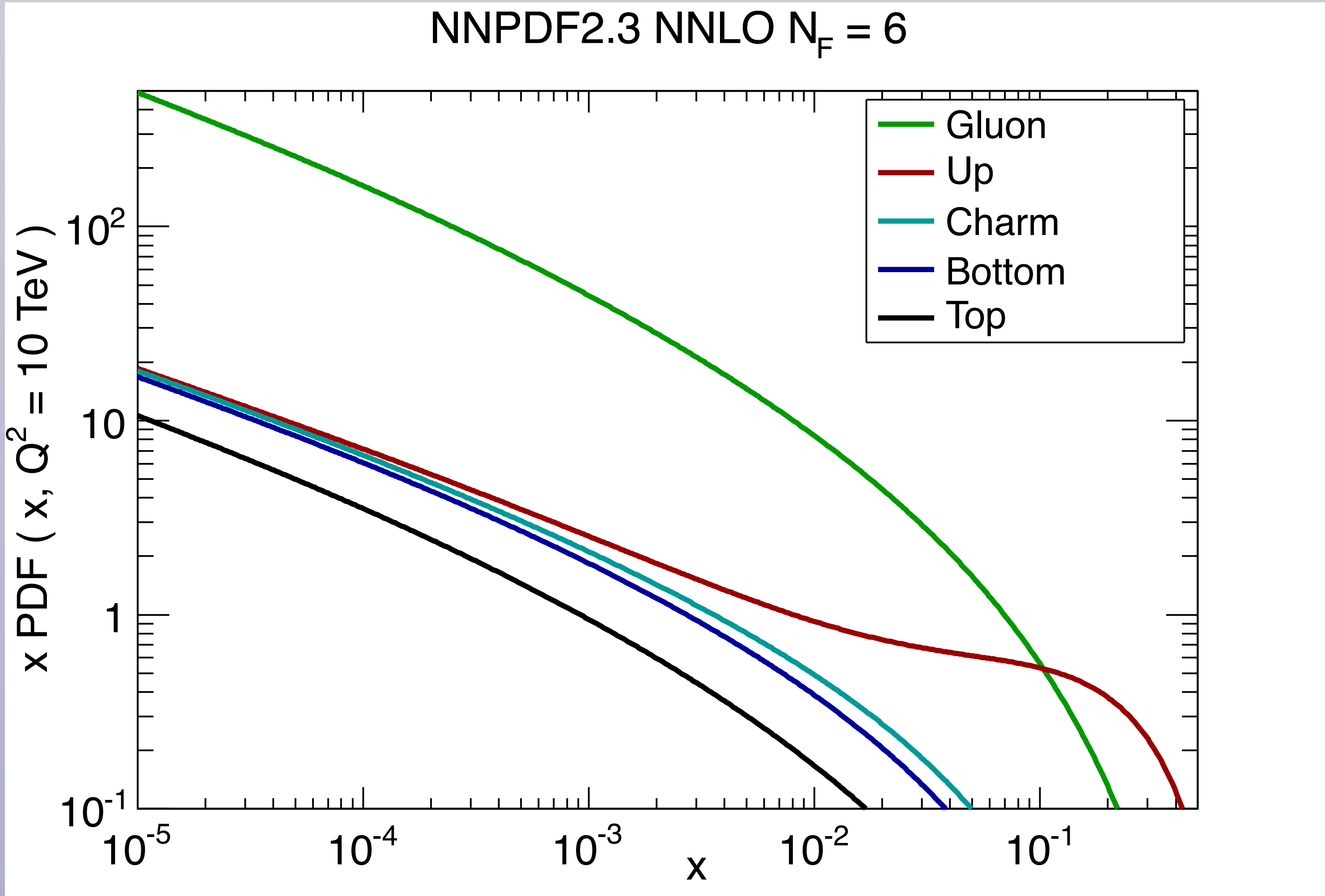
Kinematical coverage



The top quark PDF t(x,Q)

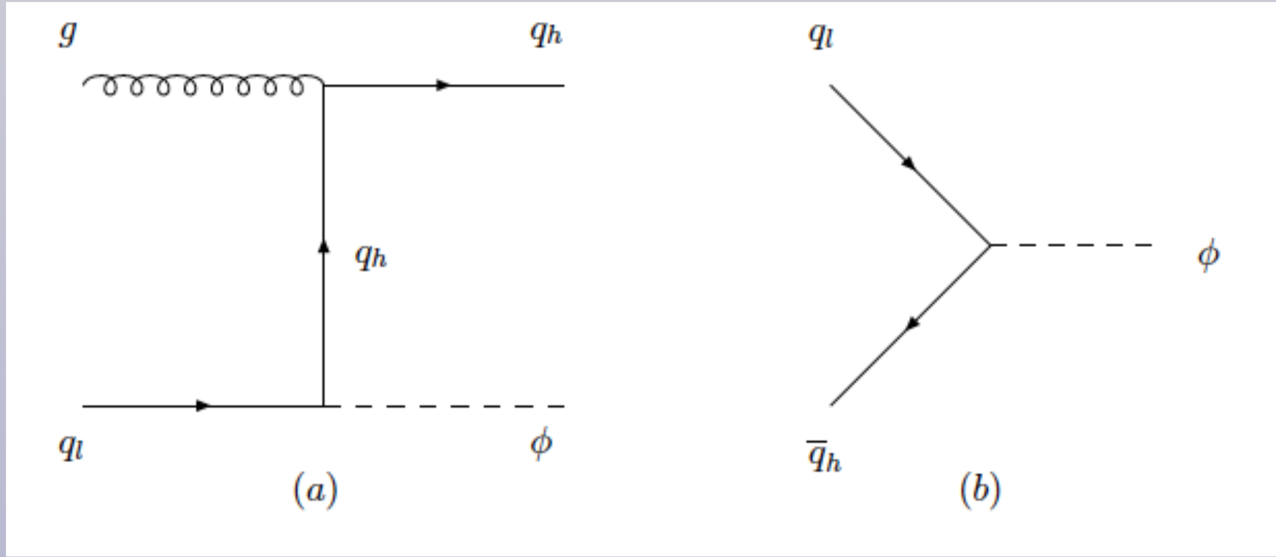
✦ At 10 TeV, the top quark PDF **t(x,Q)** is only a **factor 2 smaller that all other quark PDFs,** with charm and bottom essentially massless flavours there

✦ Shall we include top quarks in any FCC calculation? Yes, but it does not seem particularly useful to introduce a top PDF



The top quark PDF t(x,Q)

- **Heavy-quark PDFs** are constructed **perturbatively** from the resumption of multiple collinear emissions from initial-state light quarks and gluons
- They are only a convenient way to express a **theoretical calculation**, whose usefulness depends on the specific process. No intrinsic top sin the proton!
- At the FCC, **resummation of collinear logs** into a top PDFs is not necessary, since these are always small



Dawson, Ismail Low, **arXiv:1405.6211**
Han, Sayre, Westhoff, **arXiv:1411.2588**

$$\tilde{f}_q^{(1)}(x,\mu) = \frac{\alpha_s}{2\pi}\log\frac{\mu^2}{m_q^2}\int_x^1 \frac{dz}{z} P_{qg}(z)\, f_g(x/z,\mu) \,,$$

Heavy-quark PDF

Collinear log

Small for top at the FCC

Electroweak Parton Distributions at 100 TeV

- The analogous of **DGLAP** evolution equations in QCD can be derived in the **electroweak sector** of the Standard Model, but the resulting equations are very different **(Ciafaloni and Comelli 2002)**

Evolution equation for the structure function of W bosons

$$-\frac{\partial}{\partial t}\underset{g}{\mathcal{F}}_{AB} = \frac{\alpha_W}{2\pi}\left\{C_g \underset{g}{\mathcal{F}}_{AB} \otimes P^V_{gg} + (T^C_V \underset{g}{\mathcal{F}} T^C_V)_{AB} \otimes P^R_{gg} + \left(\sum_L \mathrm{Tr}\left[t^B \underset{L}{\mathcal{F}}\, {}^t t^A\right] + \sum_{\bar{L}} \mathrm{Tr}\left[t^A \underset{L}{\mathcal{F}}\, t^B\right]\right) \otimes P^R_{fg} + \mathrm{Tr}\left[T^B_L \underset{\phi}{\mathcal{F}}\, {}^t T^A_L\right] \otimes P^R_{\phi g}\right\}$$

- No **numerical implementation of EW evolution** equations exist. **Very different flavor/coupling structure** as compared to QCD evolution equations
- In addition, **EW must be combined with pure QED evolution**, and then combined with **QCD** into a **complete set of Standard Model PDF evolution equations**
- Striking new phenomena: **W and Z PDFs**, **internal polarisation of quarks** due to chiral couplings, resumption of multiple (massless) weak boson emission

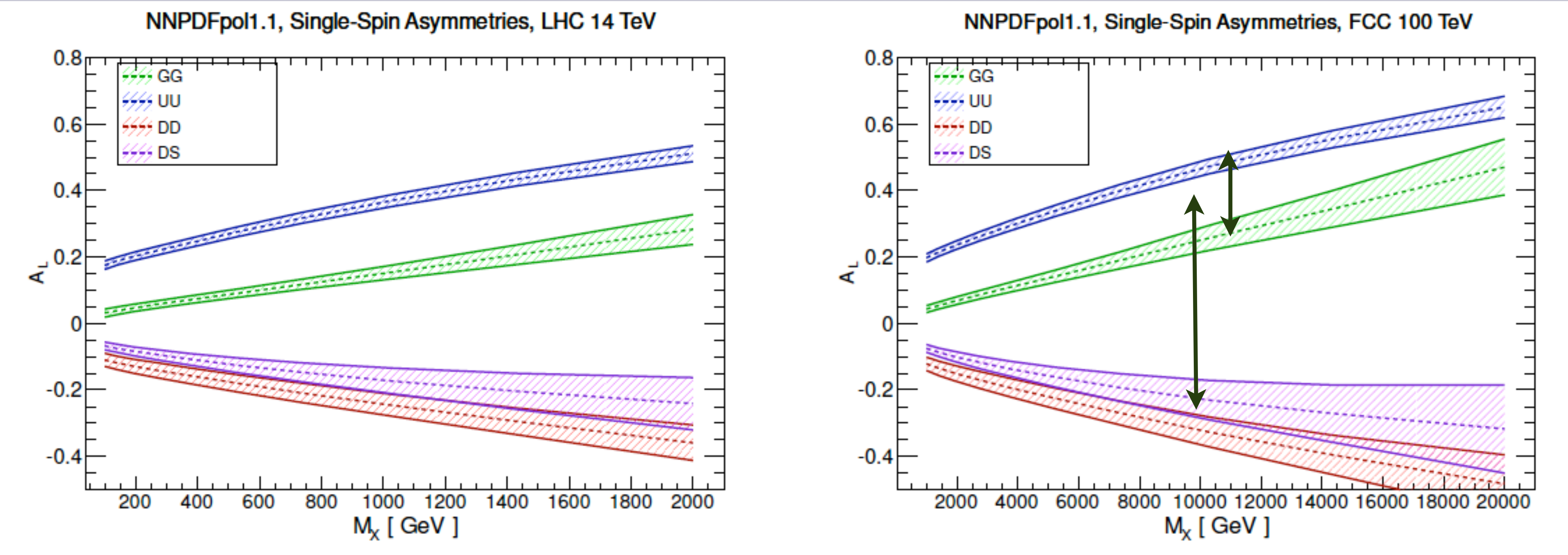
What can we do with polarised protons?

$$\mathcal{L}_{ij} = \frac{1}{s}\int_{\tau}^{1}\frac{dx}{x}\frac{1}{1+\delta_{ij}}\left[q_i\left(x,m_X\right)q_j\left(\frac{\tau}{x},m_X\right)+q_i\left(\frac{\tau}{x},m_X\right)q_j\left(x,m_X\right)\right]$$

$$\mathcal{L}_{ij}^{L} = \frac{1}{s}\int_{\tau}^{1}\frac{dx}{x}\frac{1}{1+\delta_{ij}}\left[\Delta q_i\left(x,m_X\right)q_j\left(\frac{\tau}{x},m_X\right)+q_i\left(\frac{\tau}{x},m_X\right)\Delta q_j\left(x,m_X\right)\right]$$

$$A_L = \frac{\sigma^{\uparrow\uparrow}-\sigma^{\downarrow\downarrow}-\sigma^{\uparrow\downarrow}+\sigma^{\downarrow\uparrow}}{\sigma^{\uparrow\uparrow}+\sigma^{\downarrow\downarrow}+\sigma^{\uparrow\downarrow}+\sigma^{\downarrow\uparrow}} \qquad A_L = \frac{\mathcal{L}_{ij}^{L}}{\mathcal{L}_{ij}}$$

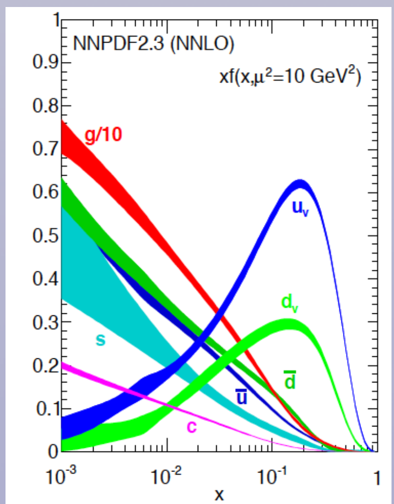
Fuks, Proudom, **JR**, Schienbein, **arXiv:1403.2383**

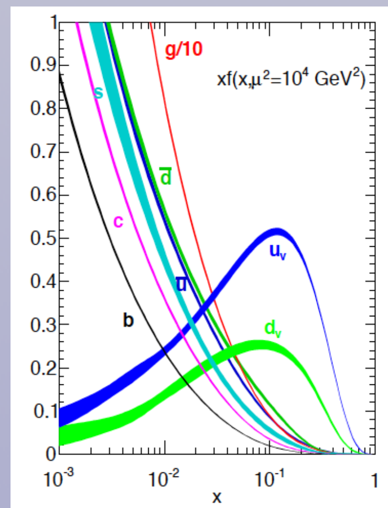


Measurement of spin-asymmetries discriminate between **different BSM scenarios** (different production modes) and would allow to **pin down couplings** and branching fractions of

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 benefits from improved PDFs
- PDFs are also a basic component for LO and NLO **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**





Extra Material

PDF Uncertainties: The Monte Carlo Method

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

sys errors stat error

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

lumi error random numbers

- 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

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

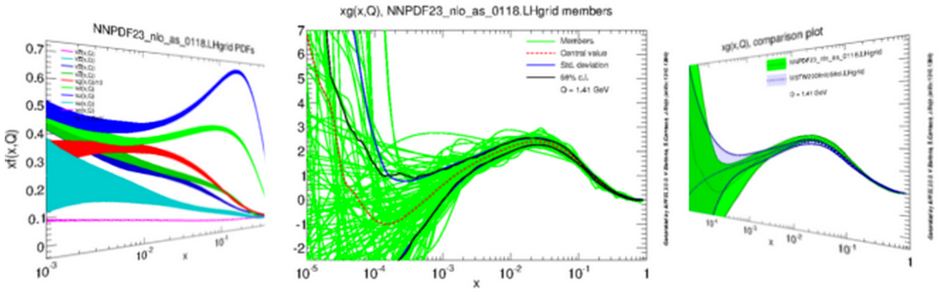
PDF comparisons made easy: APFEL-Web

- 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)

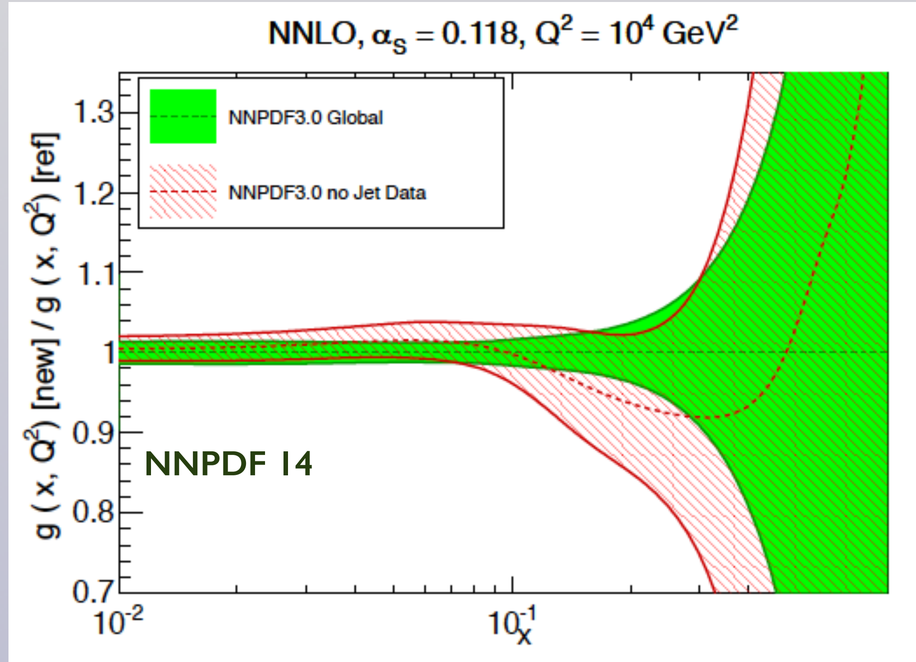
Bertone, Carrazza, J.R. 13

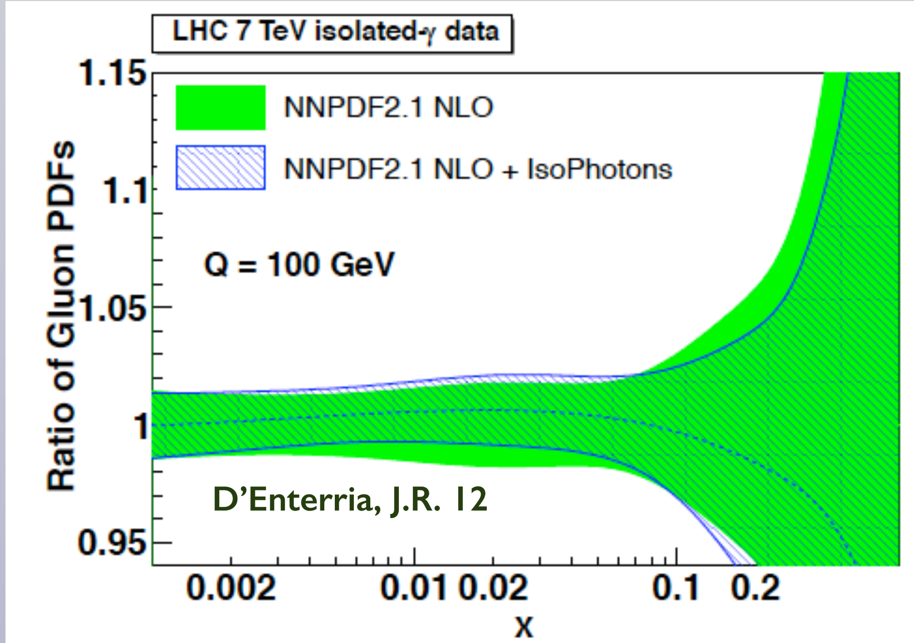
http://apfel.mi.infn.it/

Parton Distributions with LHC data

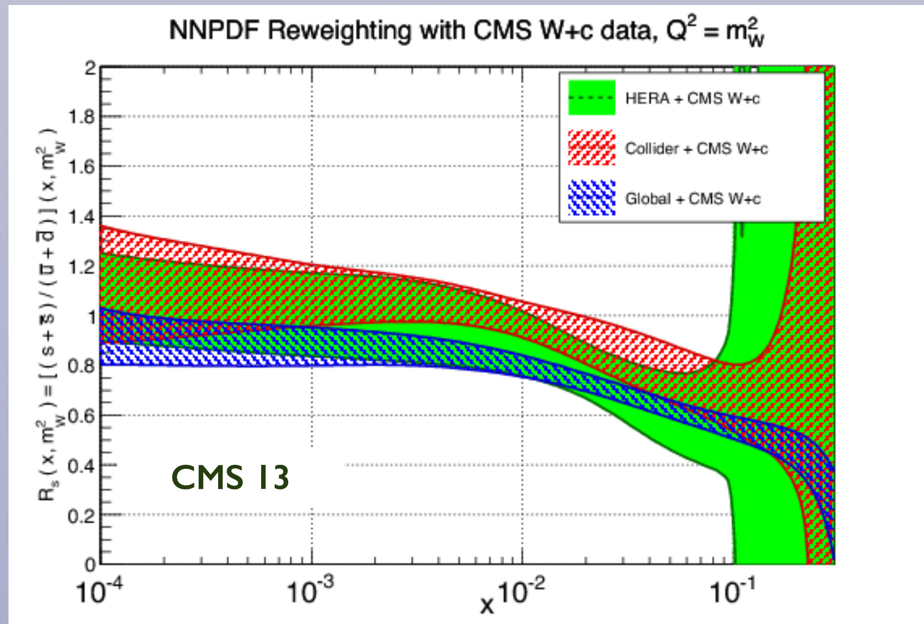
- A major breakthrough in the recent years has been the inclusion of **LHC data** into **global PDF fits**
- PDF constraints from a wide variety of LHC processes have been studied, many of which **for first time**

Large-x gluon from inclusive Jet production





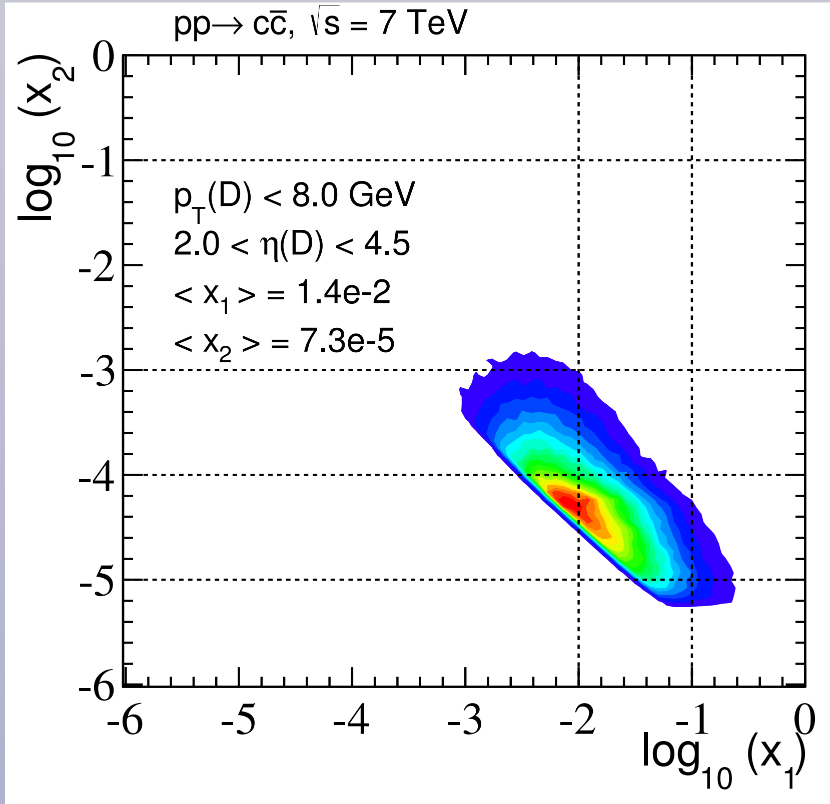
Isolated photon LHC data constraints **gluons at medium-x**: relevant for **Higgs production in gluon fusion**

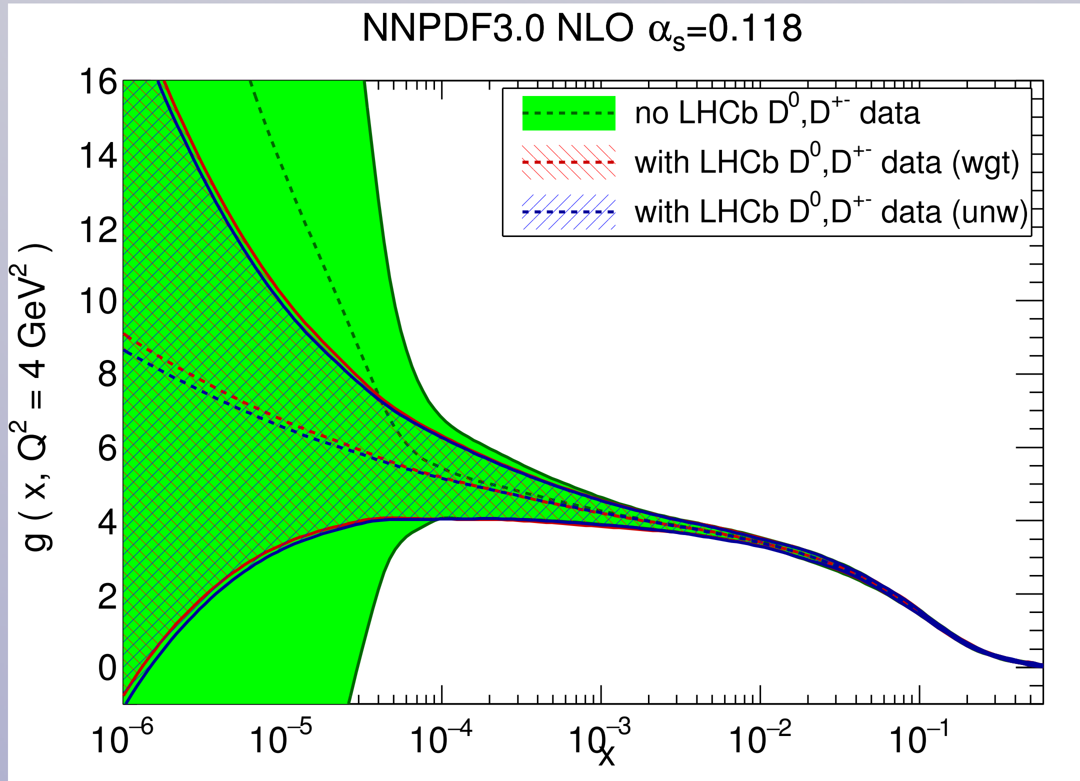


W production in association with charm quarks provides direct access to the proton strangeness

Charm production and the small-x gluon

- The production of **charm and bottom mesons in the forward region** is directly sensitive to the **small-x gluon**, where PDF uncertainties are huge from lack of direct constraints
- Using the FONLL calculation and **normalised LHCb 7 TeV D meson data**, we have included these measurements in **NNPDF3.0 NLO** and found a substantial reduction of PDF errors
- Semi-analytical **FONLL** results validated with **POWHEG** and **aMC@NLO** calculations
- Important implications for the calculations of **charm-induced prompt neutrino fluxes at IceCube**



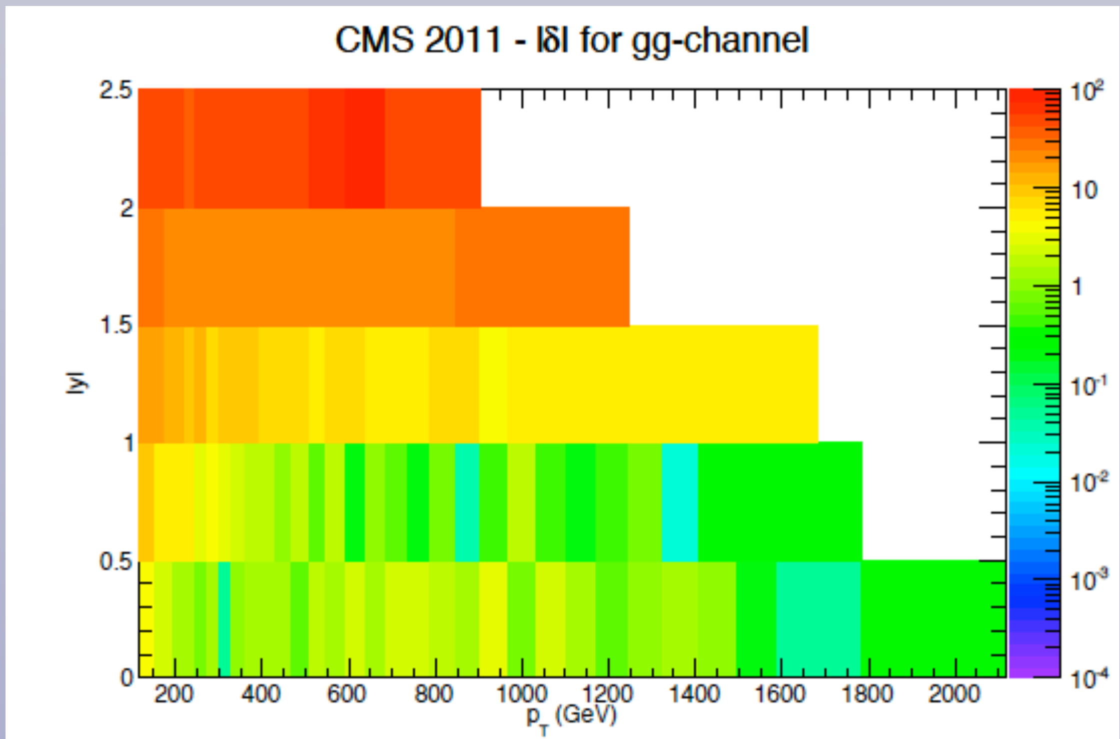


Gauld, J.R., Rottoli, Talbert in prep

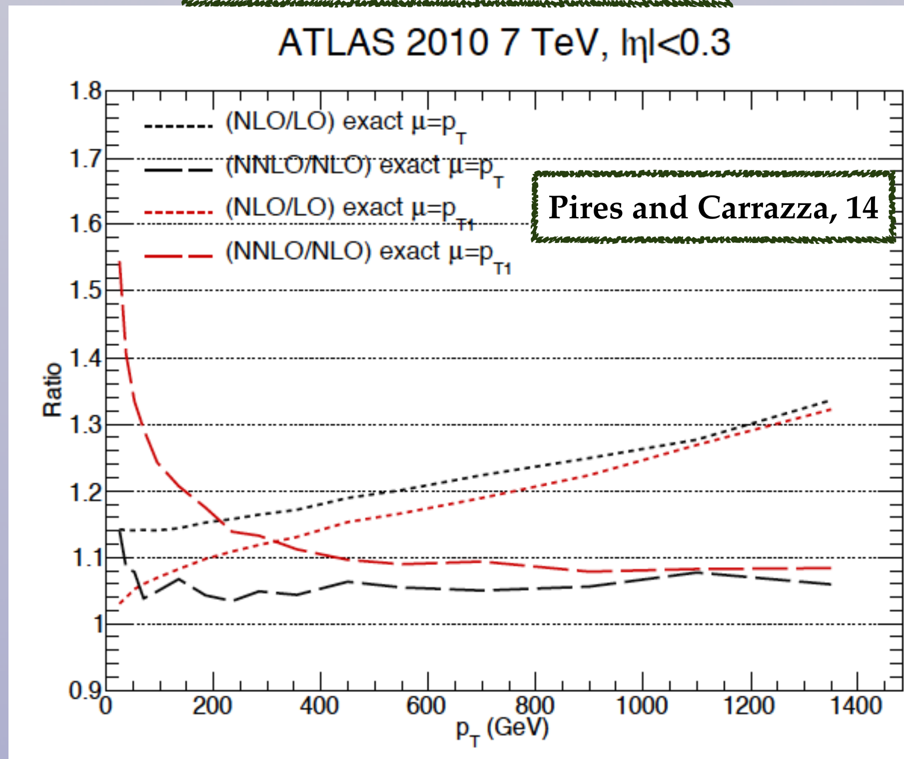
Jet data in NNLO PDF fits

- Jet data at NNLO included using **threshold calculation**, validated by **bin-by-bin comparison with the exact NNLO calculation** in the gg channel (Currie, Gehrmann, Glover, Pires 12-15)
- A substantial amount of data from **excluded from NNLO fit** at low $p_{T,jet}$ and forward rapidities
- Perturbative convergence improved if $\mathbf{p_{T,jet}}$ used as central scale, as opposed to $\mathbf{p_{T,leading}}$
- Validity of threshold calculation extended if **larger values of R used** (0.6 vs 0.4 for ATLAS data)

Difference between NNLO and NNLOthres in gg channel

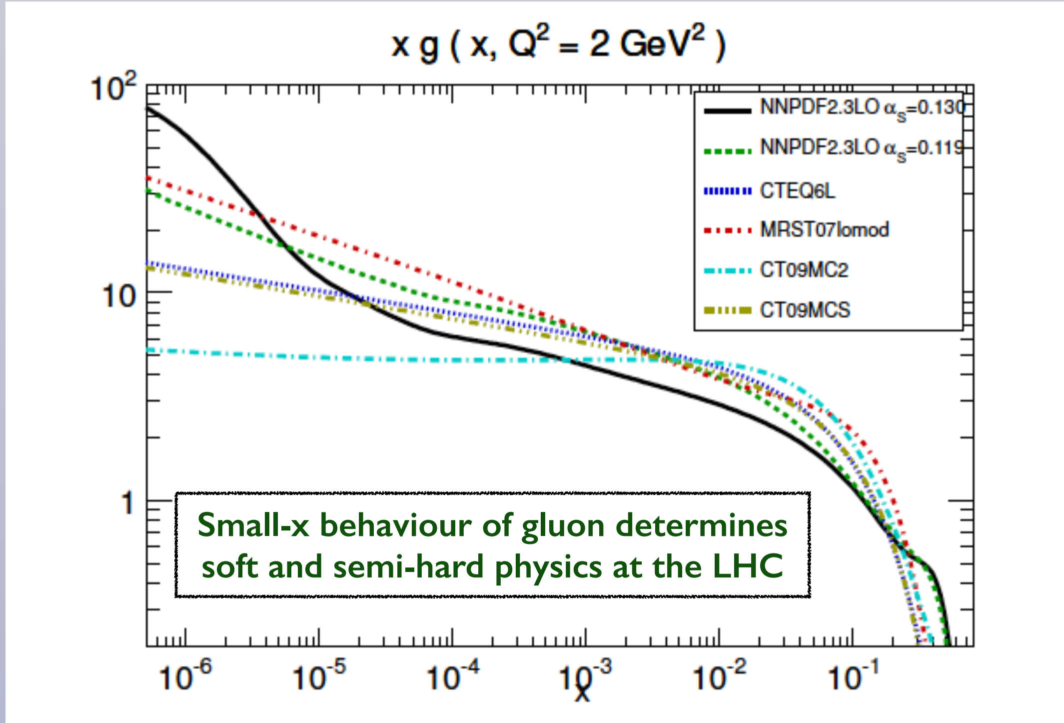


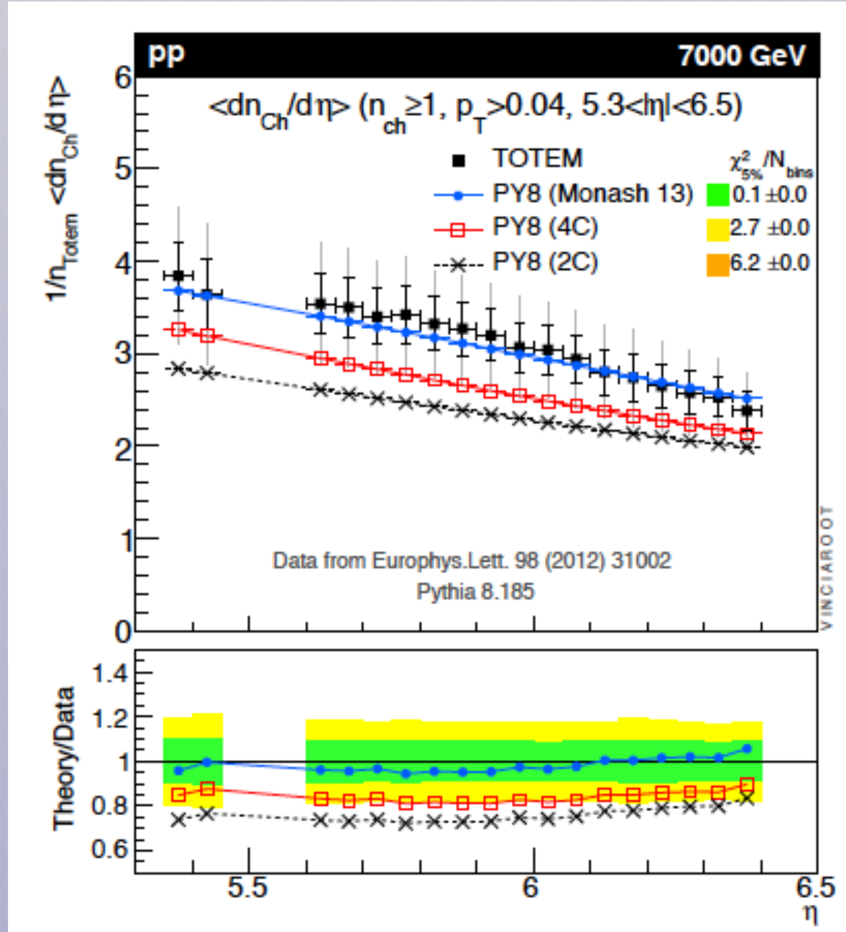
K-factor for different scale choices



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**



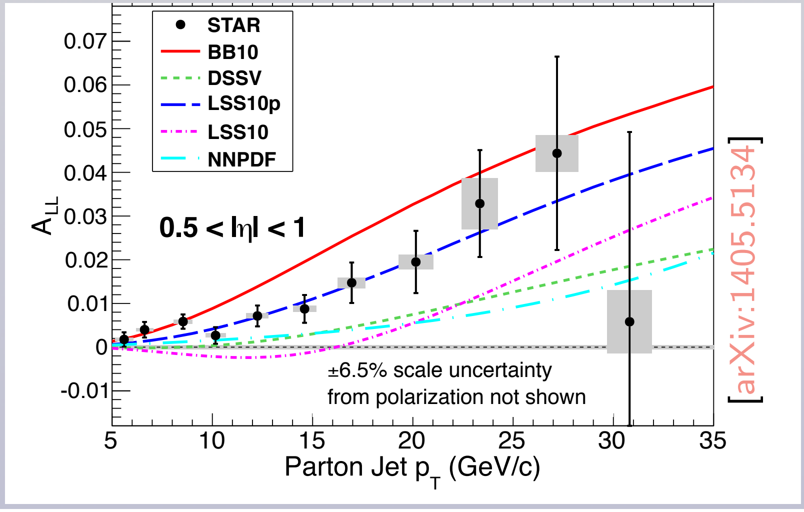


Skands, Carrazza, J.R. 14

- ☑ **NNPDF2.3** is the baseline PDF set in **MadGraph5_aMC@NLO** and in **Pythia8**
- ☑ **NNPDF3.0** is the baseline PDF in **Sherpa v2.2.0**

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



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


SCIENTIFIC AMERICAN™

Sign In | Register 0

Search ScientificAmerican.com

Subscribe | News & Features | Topics | Blogs | Videos & Podcasts | Education | Citizen Scie

More Science » News

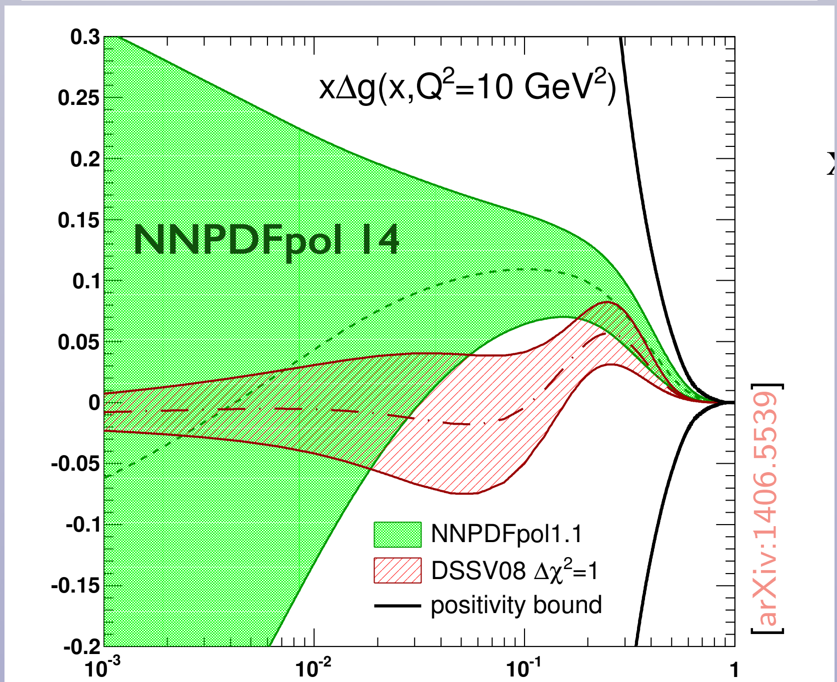
19 :: Email :: Print

Proton Spin Mystery Gains a New Clue

Physicists long assumed a proton's spin came from its three constituent quarks. New measurements suggest particles called gluons make a significant contribution

July 21, 2014 | By Clara Moskowitz

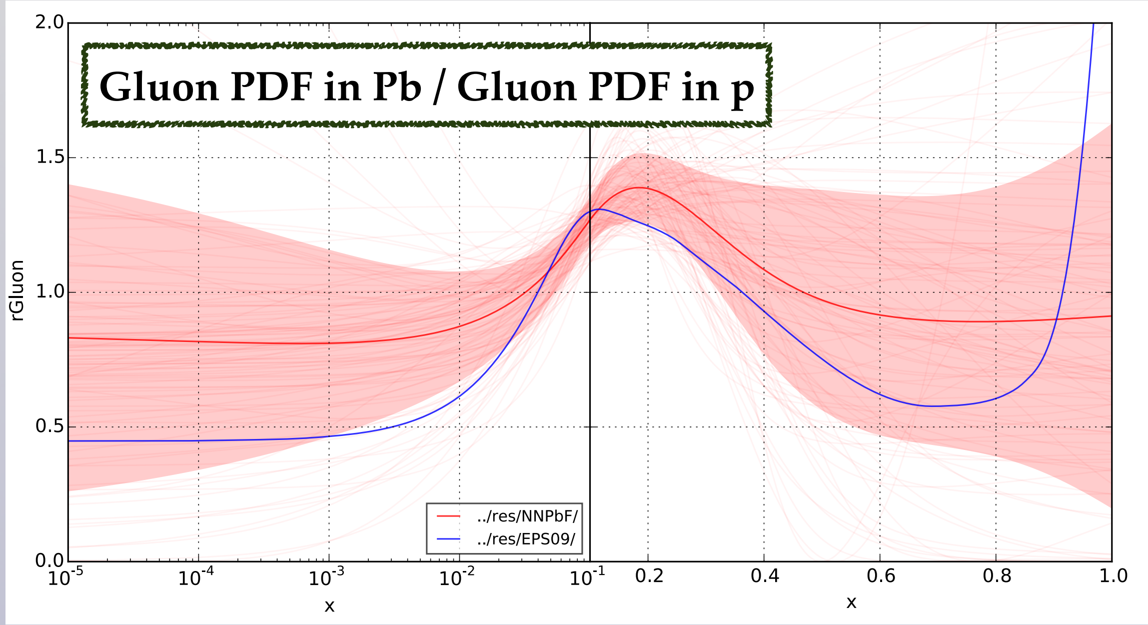
Protons have a constant spin that is an intrinsic particle property like mass or charge. Yet where this spin comes from is such a mystery it's dubbed the "proton spin crisis." Initially physicists thought a proton's spin was the sum of the spins of its three constituent quarks. But a 1987 experiment showed that quarks can account

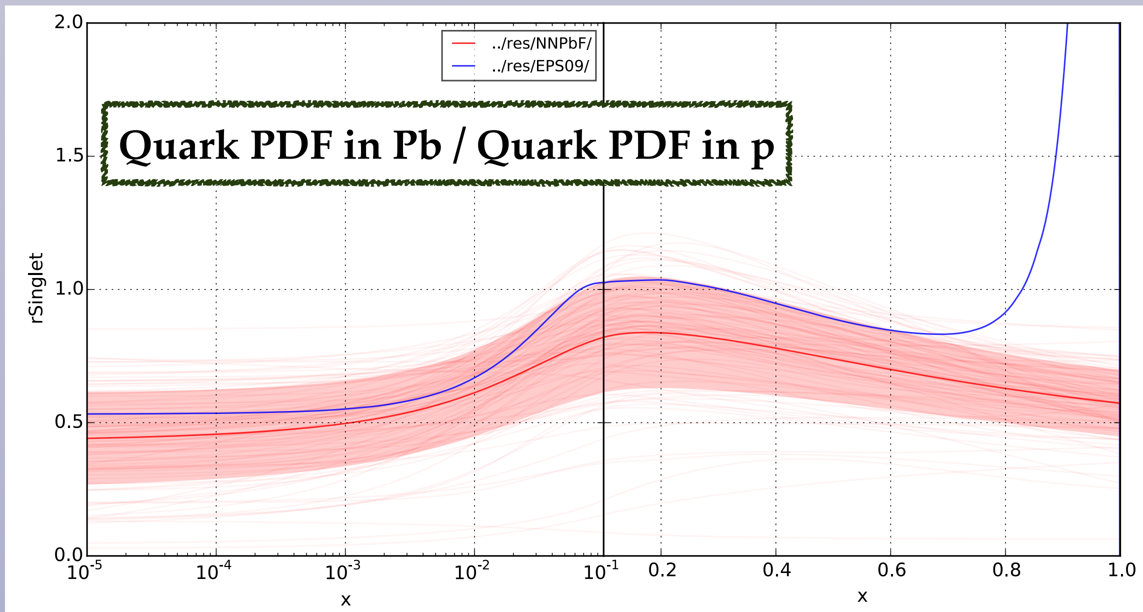


Total contribution of gluons to proton spin still unknown since **large uncertainties at small-x** from lack of data: need an **Electron-Ion Collider**

Unbiased determination of nuclear PDF

- **PDFs of nucleons inside nuclei** are modified as compared to **free proton PDFs**
- Knowledge of **nuclear PDFs** in lead is important to understand the **initial state of pPb and PbPb collisions at the LHC**
- Using the NNPDF technology, there is work in progress towards a **unbiased nuclear PDF fit, at NNLO** and including **heavy quark mass effects** for the first time
- Allows an essential cross-check for the nuclear models currently used for the LHC heavy ion program





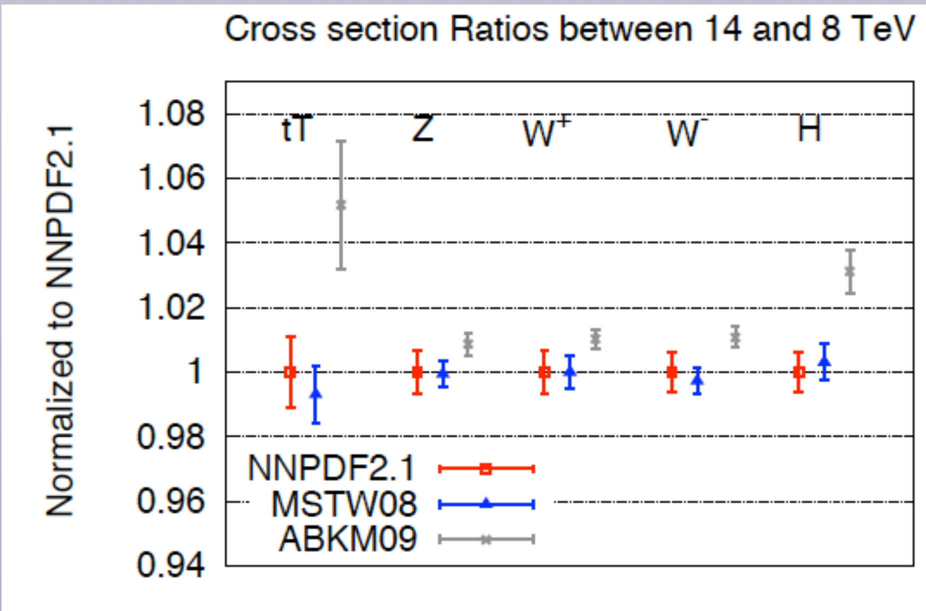
NNPDF in prep

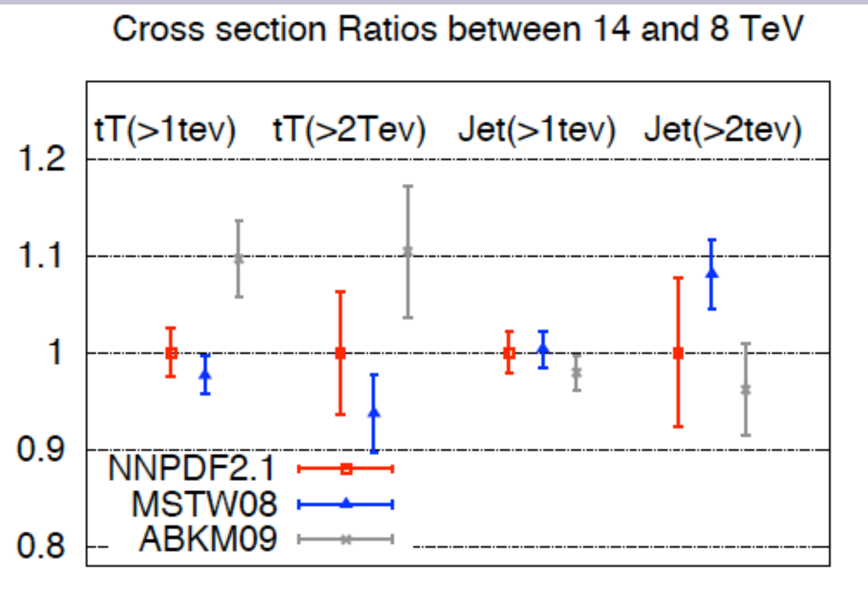
Cross section Ratios between 7, 8 and 14 TeV

- 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**



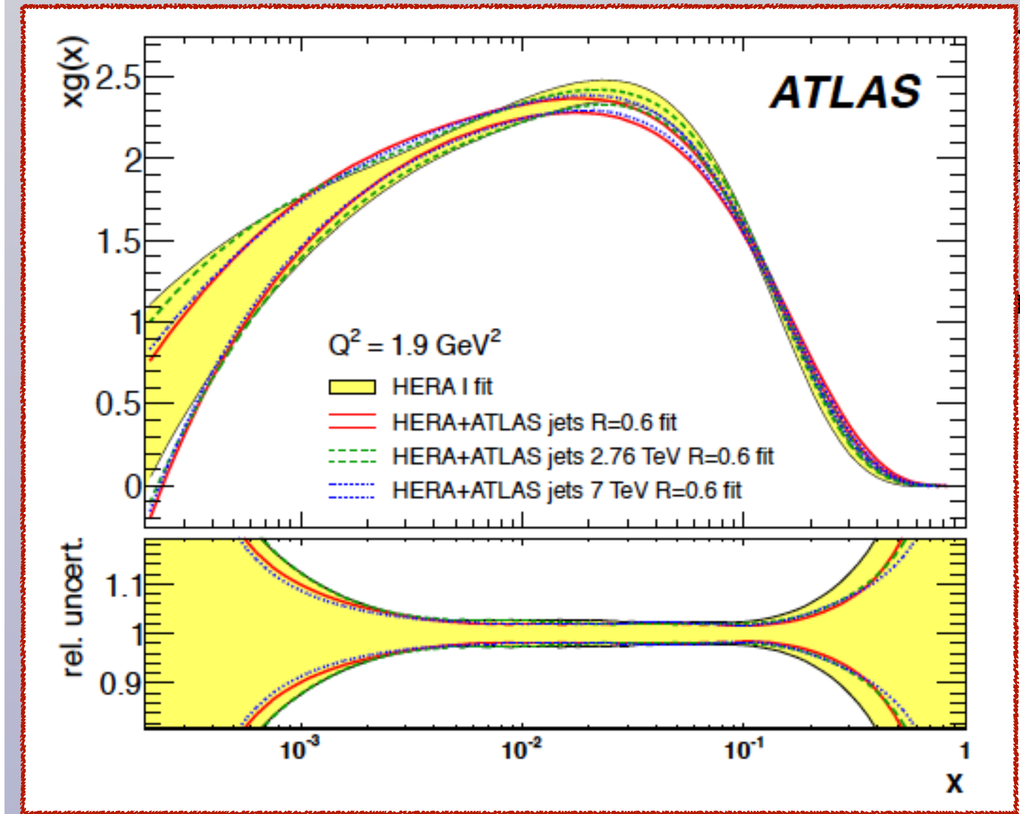


Mangano, J. R., 12

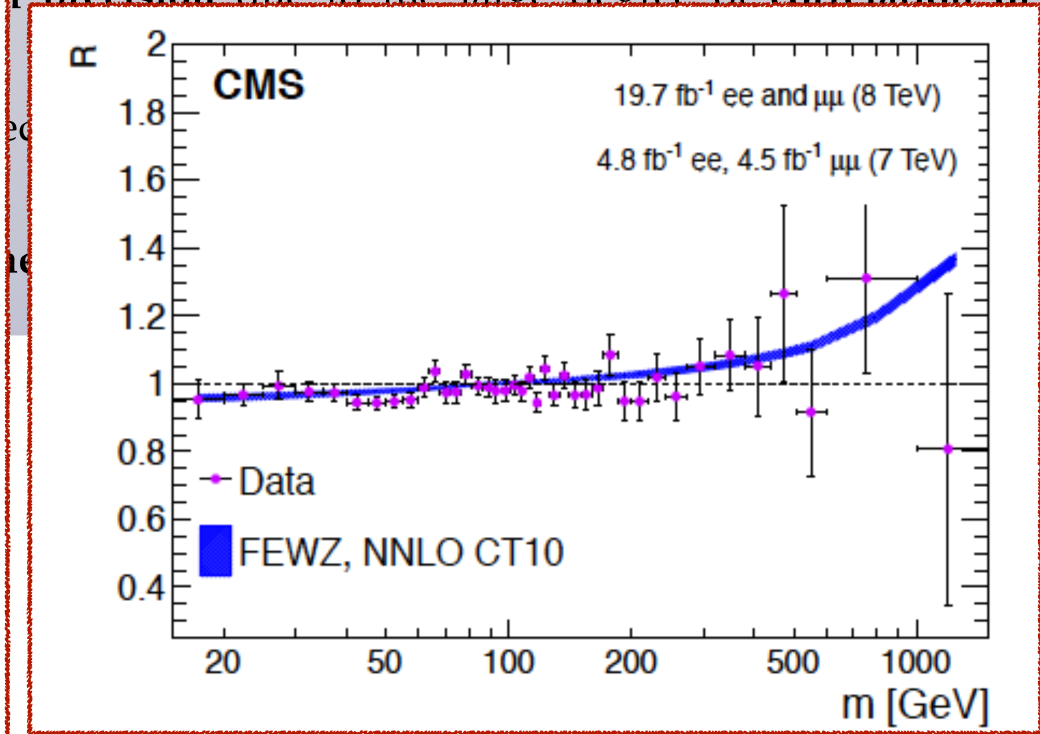
Cross section Ratios between 7, 8 and 14 TeV

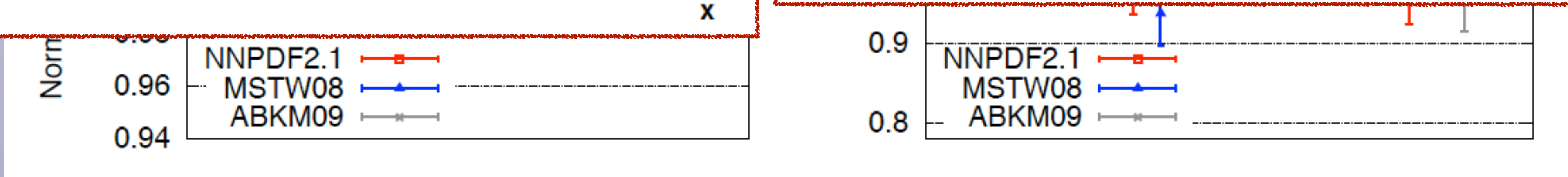
- The **staged increase of the LHC beam energy** provides a new class of interesting observables: **cross section ratios** for different beam energies

ATLAS: Gluon from 7 TeV / 2.76 TeV jet xsecs



CMS: Drell-Yan 8 TeV / 7 TeV ratio





Mangano, J. R., 12

Particle Physics in the headlines

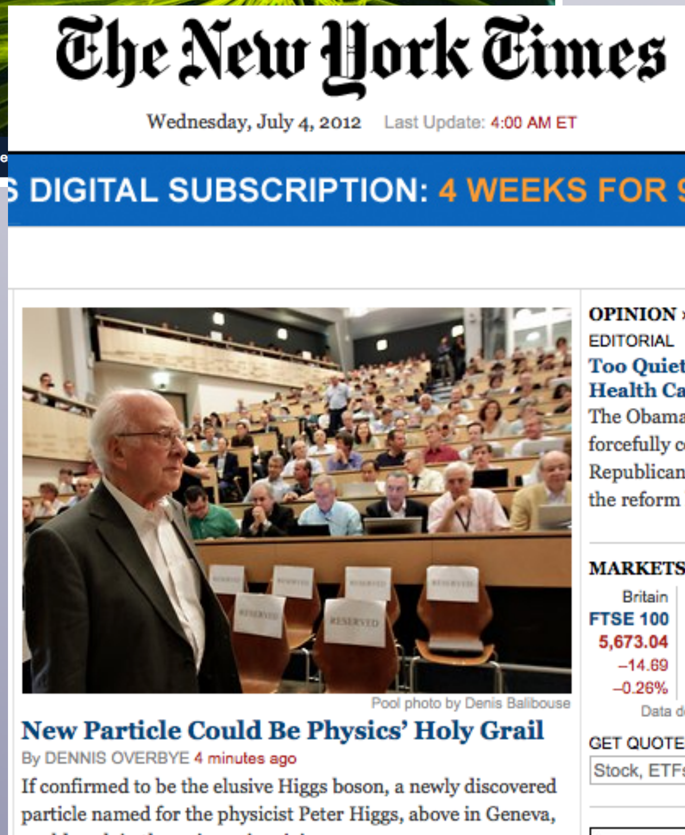
- The **Higgs Boson** is the **most important discovery in particle physics** in 25 years
- The Higgs completes the **extremely successful Standard Model of particle physics**, but at the same time **opens a number of crucial questions** for the field that we need to address
- The **LHC** will play a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

El CERN anuncia el descubrimiento de una partícula que podría ser el bosón de Higgs

El CERN anuncia el descubrimiento de una partícula que podría ser el bosón de Higgs, cuya existencia está predicha por el modelo estándar de la física de partículas

Ciencia | 04/07/2012 - 09:46h | Actualizado el 04/07/2012 - 11:27h

El bosón de Higgs podría se



The New York Times

Wednesday, July 4, 2012 Last Update: 4:00 AM ET

DIGITAL SUBSCRIPTION: 4 WEEKS FOR

OPINION
EDITORIAL
Too Quiet
Health Ca
The Obama
forcefully c
Republican
the reform

MARKETS
Britain
FTSE 100
5,673.04
−14.69
−0.26%
Data d

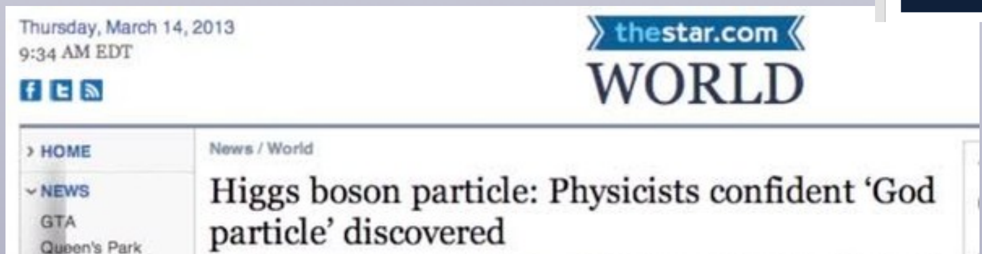
GET QUOTE
Stock, ETFs

Pool photo by Denis Balibouse

New Particle Could Be Physics' Holy Grail

By DENNIS OVERBYE 4 minutes ago

If confirmed to be the elusive Higgs boson, a newly discovered particle named for the physicist Peter Higgs, above in Geneva,



Thursday, March 14, 2013
9:34 AM EDT

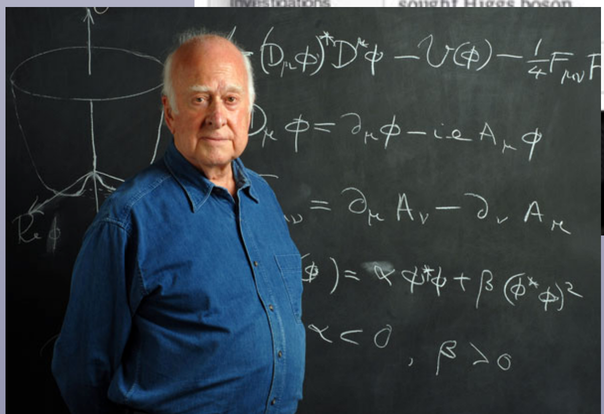
thestar.com
WORLD

HOME
NEWS
GTA
Queen's Park
Canada
World
Investigations

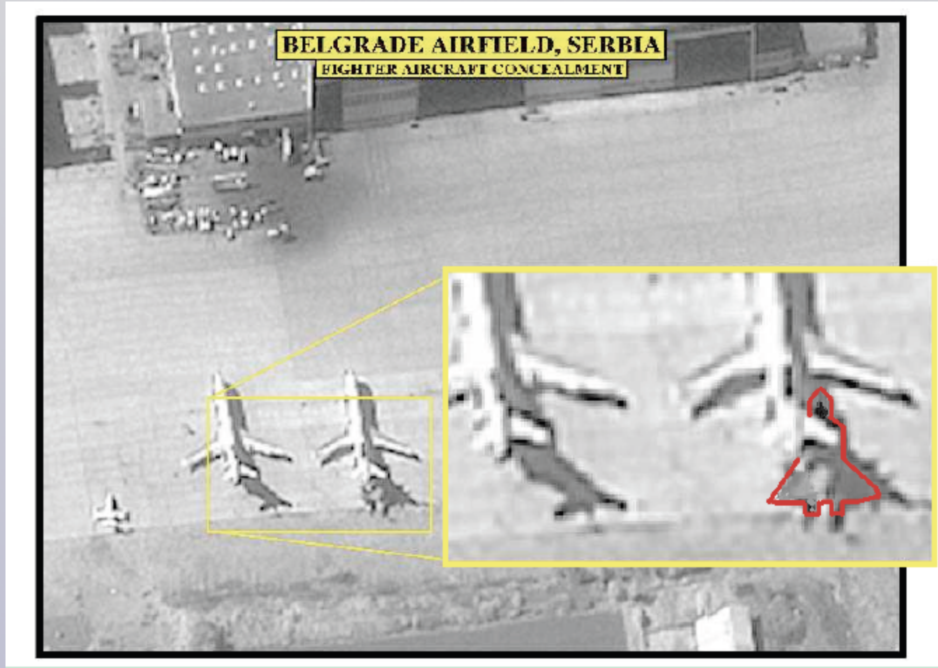
News / World

Higgs boson particle: Physicists confident 'God particle' discovered

Scientists announced Thursday that the parti
CMS experiments at the Large Hadron Collid
sought Higgs boson



Artificial Neural Networks



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

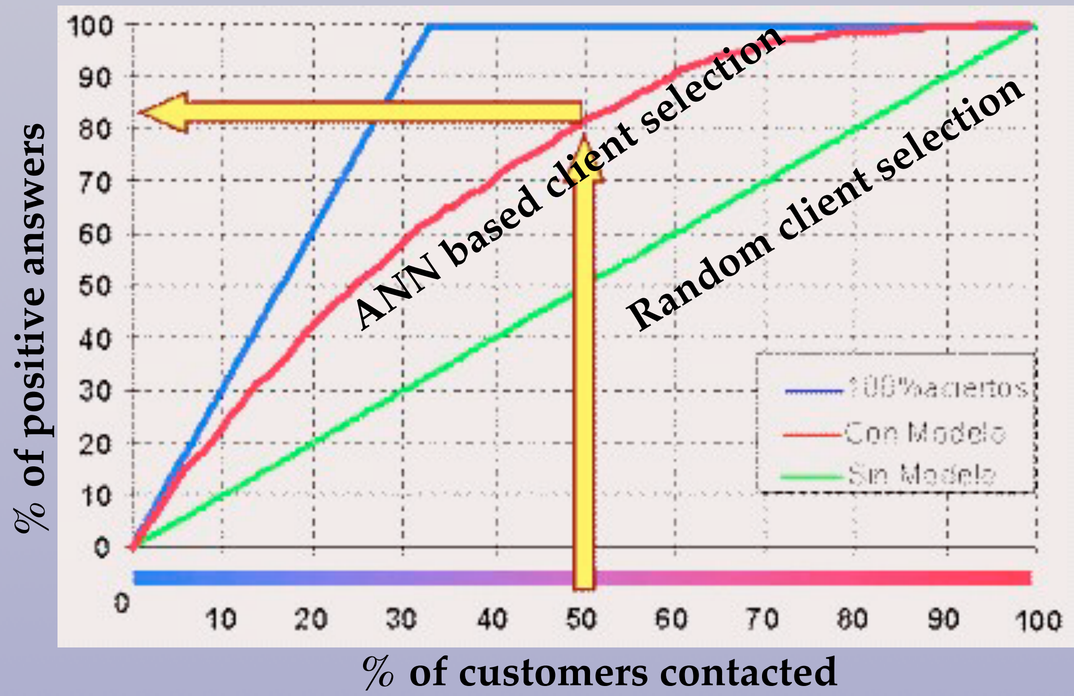
A military aircraft is identified, despite being hidden below a commercial plane.

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

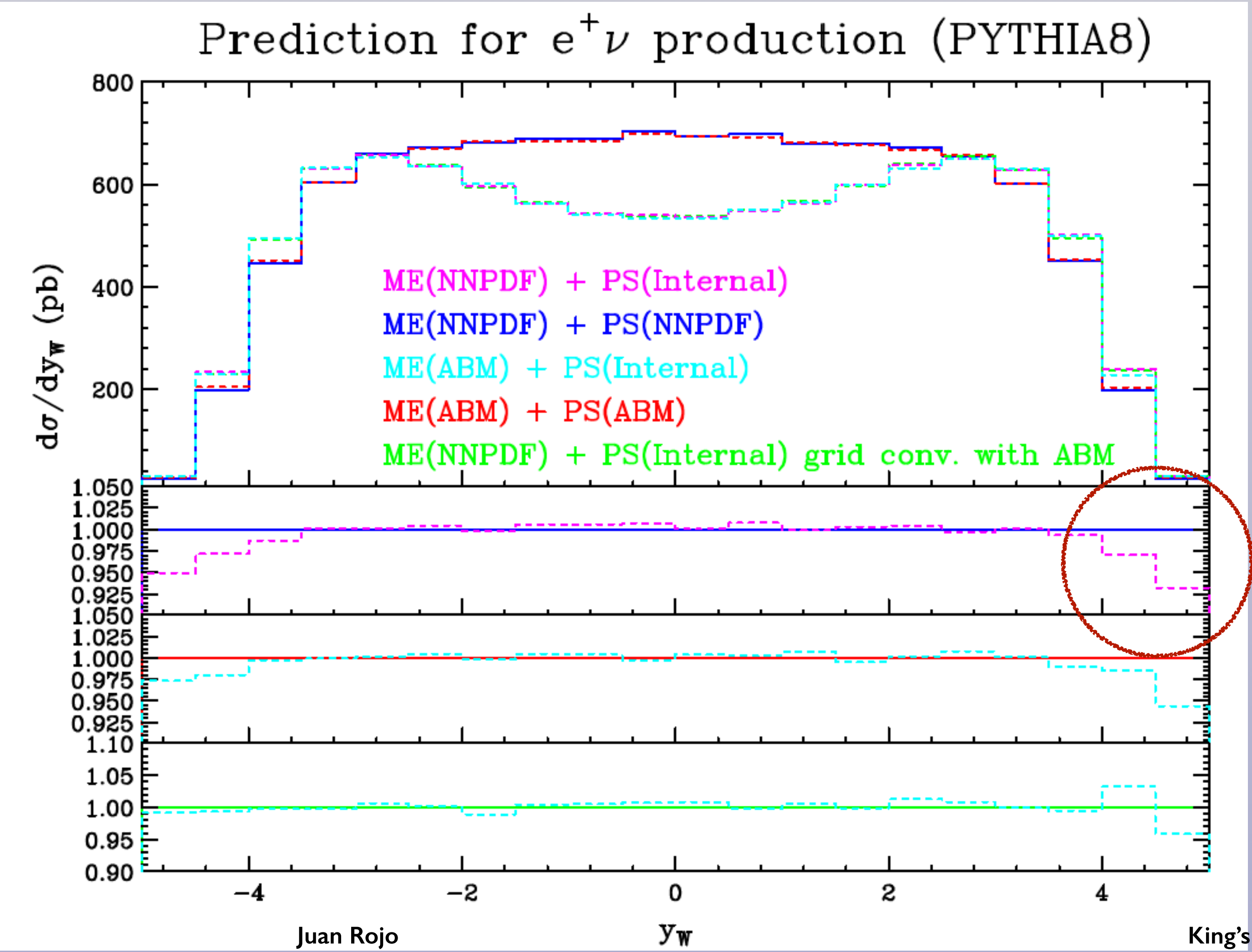


PDF fits at NLO+PS accuracy

- **NLO+PS** is current standard for LHC event simulation, and **improves in many directions over fixed-order NLO results**: improved pert. behaviour, direct relation with measured quantities, less need for kin cuts …

- Using **NLO+PS calculations** in global PDF fits should have many important applications, like for the **W mass** among others, and is now technically possible thanks to **aMCfast,** the fast interface to **MadGraph5_aMC@NLO** based on the **applgrid** library

aMCfast: Bertone, Frixione, Frederix, J.R., Sutton, arXiv:1406.7693 (for NLO), NLO+PS in preparation



- One crucial aspect to explore is the **role of the PDF used by the MC shower**, since this is fixed even in the fast NLO+PS grid

- Quite small effect in most observables, except **extreme kinematics** like forward rapidities

- **Future NNPDF releases could be performed at NLO+PS accuracy**

aMCfast makes possible to include easily **hadron-level measurements** directly into PDF fits

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

Outstanding Questions in Particle Physics *circa* 2014

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

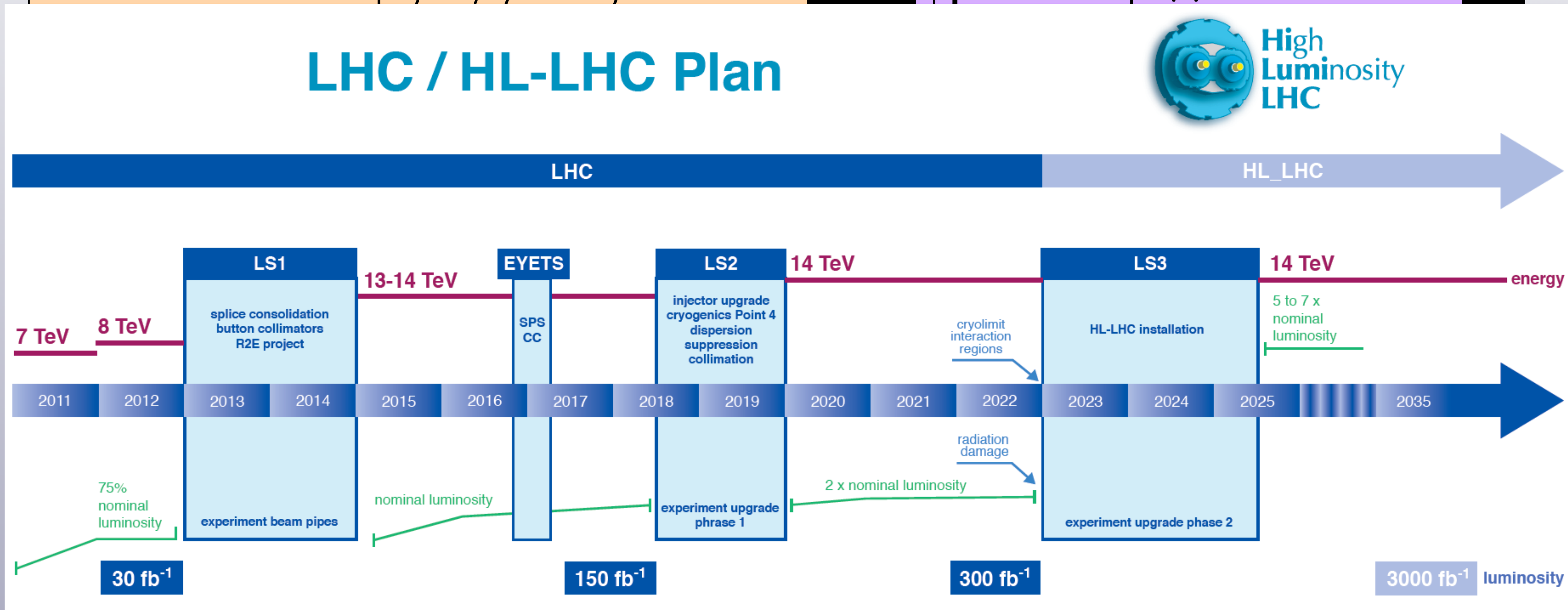
Higgs boson and EWSB

❑ Is m_H natural or fine-tuned ?

→ if natural: what new physics/symmetry ?

Quarks and leptons:

❑ why 3 families ?



❑ Majorana or Dirac ?

❑ *CP* violation

The two epochs of Universe's accelerated expansion:

❑ primordial: is inflation correct ? which (scalar) fields? role of quan

❑ today: dark energy (why is Λ so small?) or modification of gravity theory ?

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

List from Ian Shipsey