The Structure of the Proton in the Higgs Boson Era

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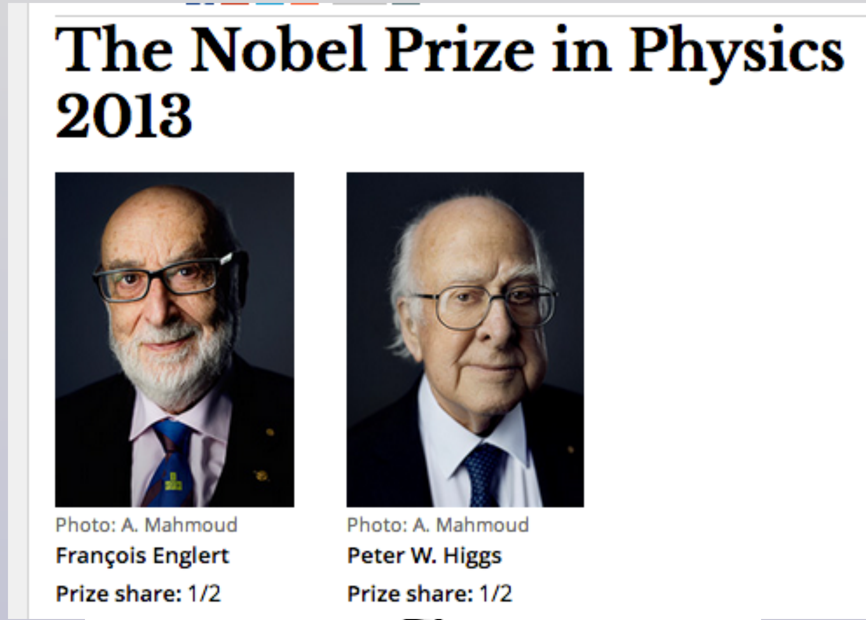
High-Energy Physics in the Higgs Boson Era

- The **Higgs Boson discovery** is the most important breakthrough in particle physics in 25 years
- The Higgs discovery at **Large Hadron Collider** (LHC) marks the start of a new era in particle physics
- **New particle discoveries** are within the LHC reach in the next years


The Nobel Prize in Physics 2013

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François Englert
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Photo: A. Mahmoud
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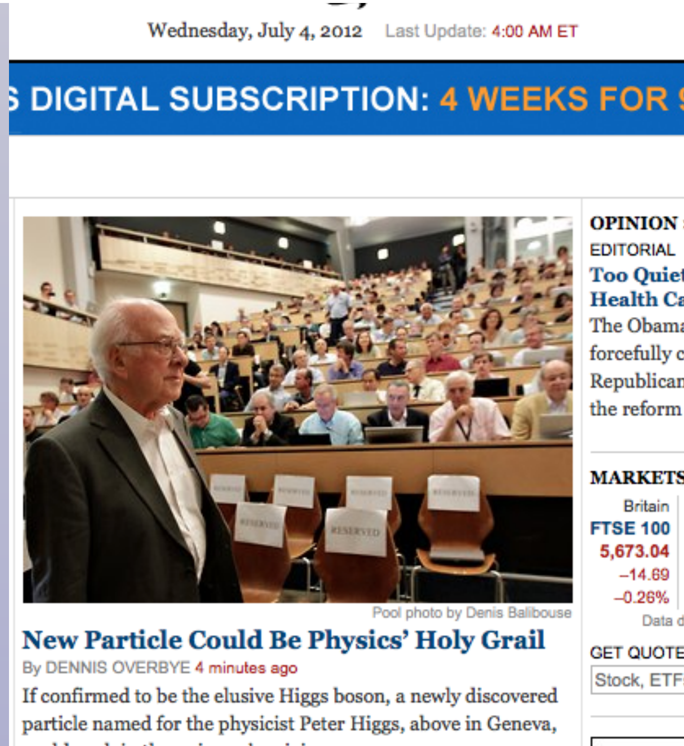
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New Particle Could Be Physics' Holy Grail

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,

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News / World

Higgs boson particle: Physicists confident 'God particle' discovered

Scientists announced Thursday that the particle discovered through the ATLAS and CMS experiments at the Large Hadron Collider last summer is, in fact, the long-sought Higgs boson.

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THE TORONTO STAR

High-Energy Physics in the Higgs Boson Era

- Higgs Boson: last missing ingredient of successful **Standard Model** of particle physics

- The Standard Model is **not a complete theory of nature**: a substantial amount of experimental data and theoretical arguments require **New Physics Beyond the Standard Model**:

  Dark Matter and Dark Energy

  Huge gap (10^{16}) between Higgs mass and Plank scale

  Unification of Gravity and Quantum Mechanics

  Inflation

  Flavor physics and Neutrino masses and mixings

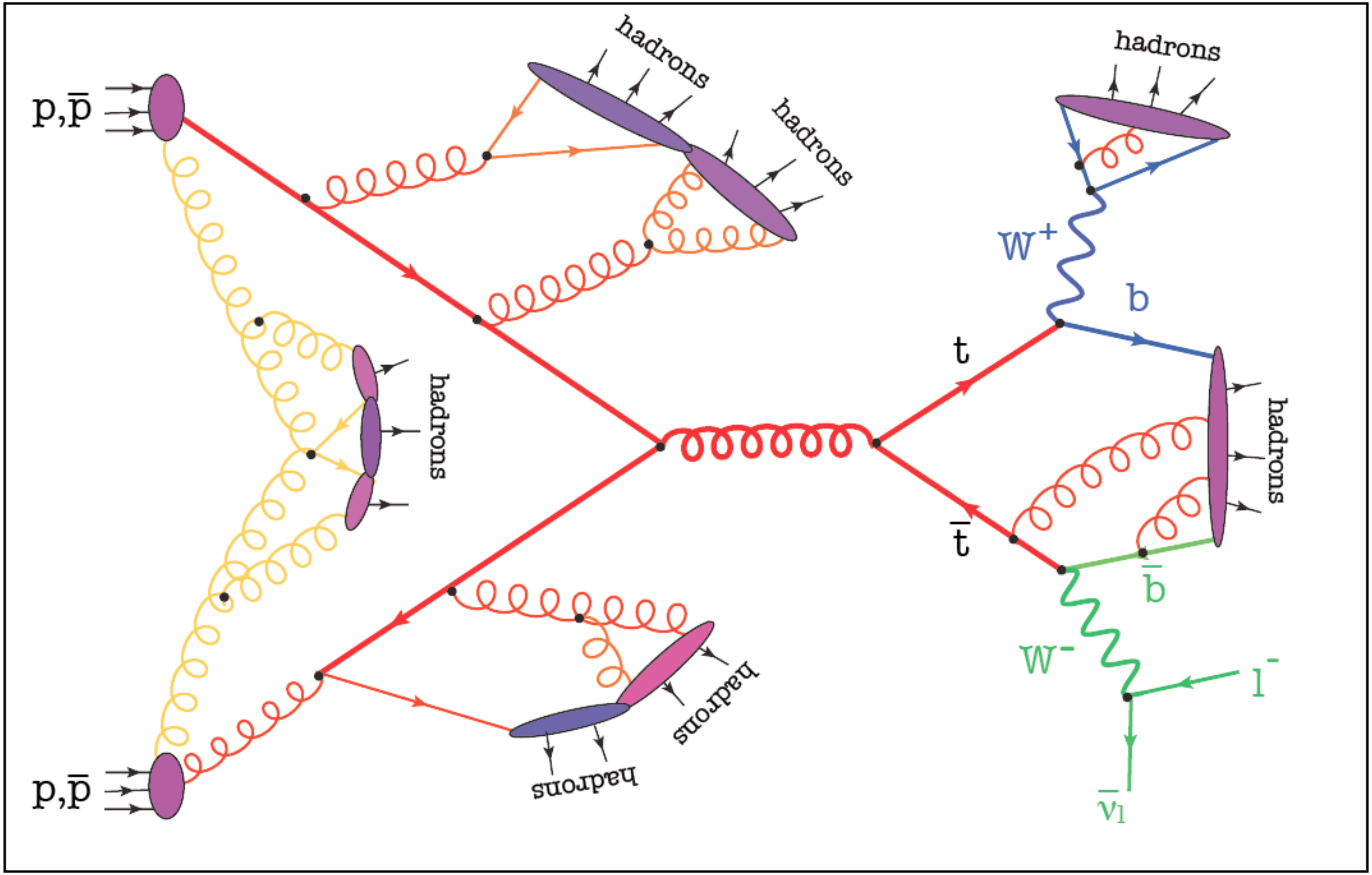
- The LHC program for the coming decade is based on the **detailed characterization of the properties of the Higgs Boson** and the **search of Physics Beyond the Standard Model**:

  Direct searches: new heavy particle production, supersymmerty, extra dimensions

  Indirect searches: Higgs couplings and branching ratios, Higgs compositeness

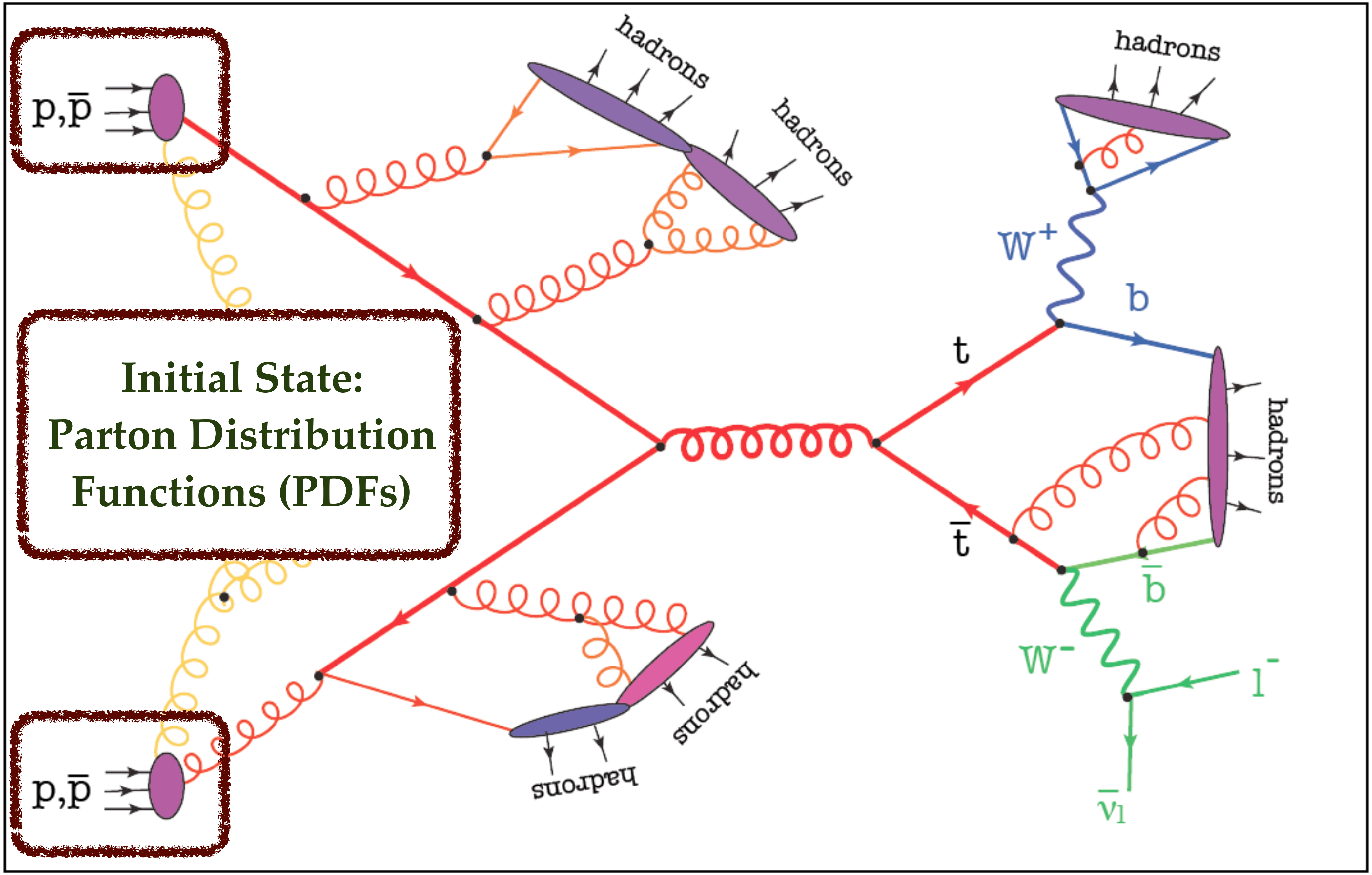
  Consistency tests: precision electroweak data

LHC collisions in a nutshell



Drawing by K. Hamilton

LHC collisions in a nutshell



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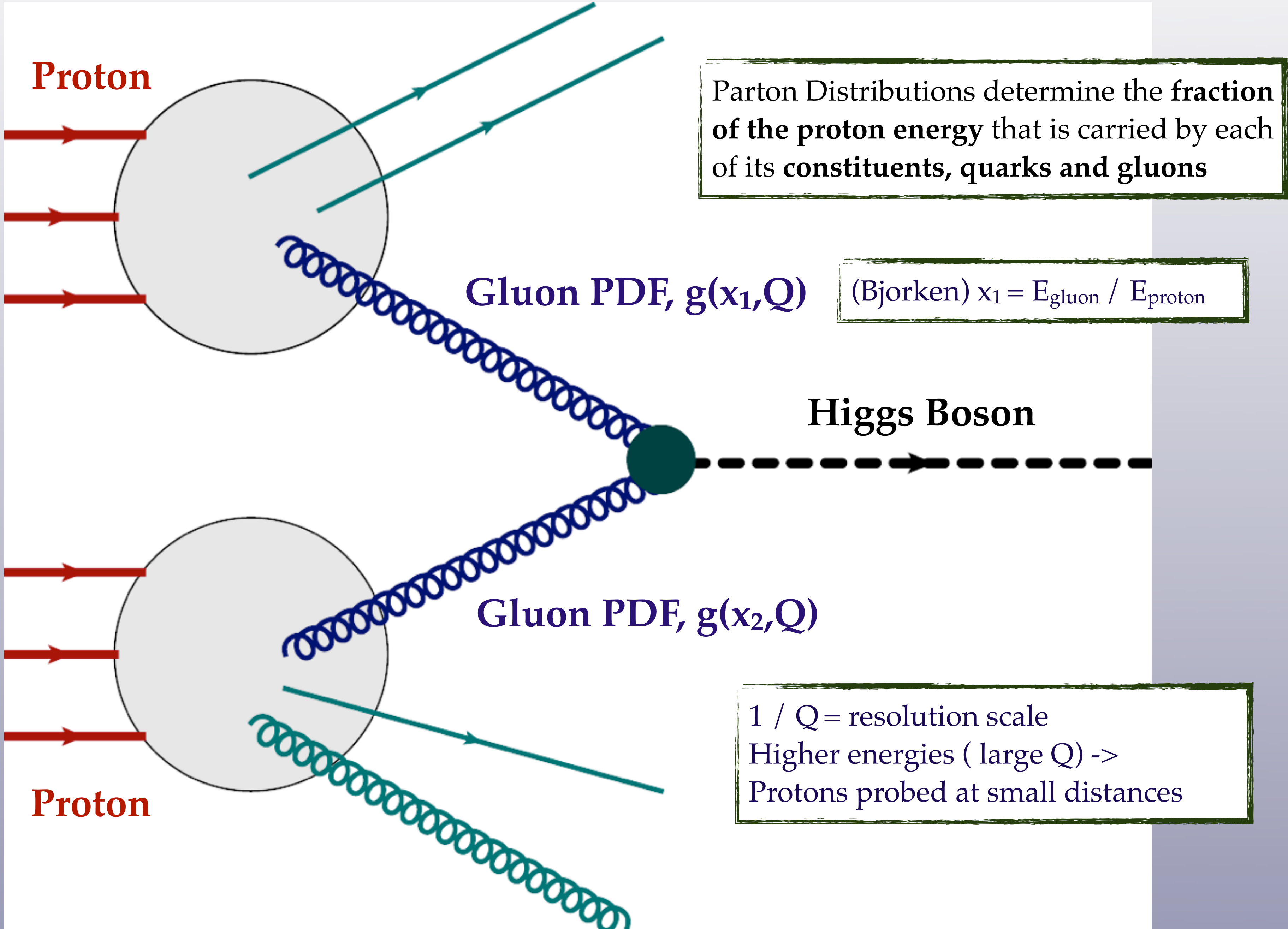
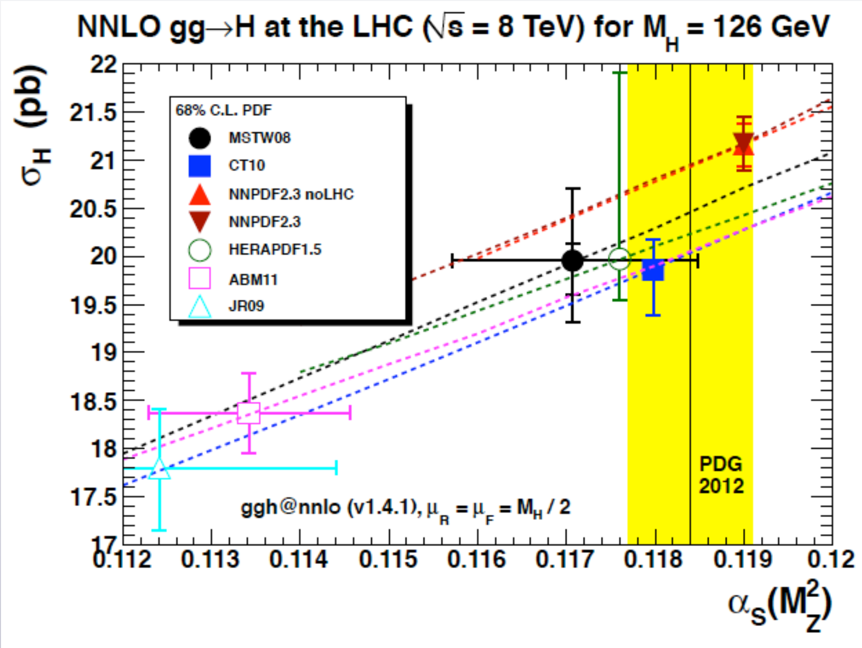
Parton Distribution Functions - I

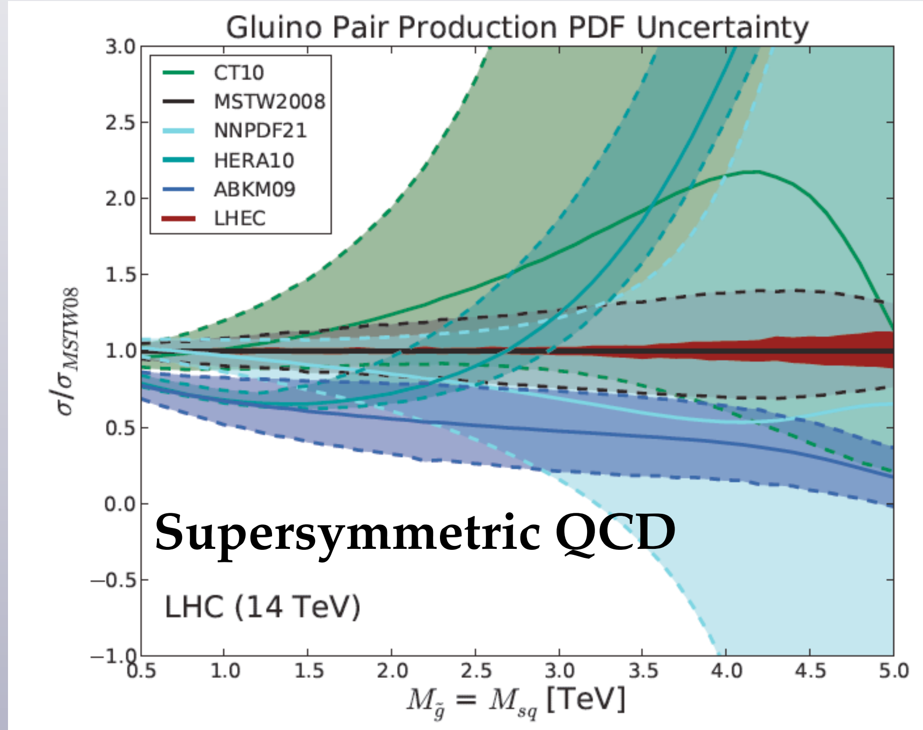


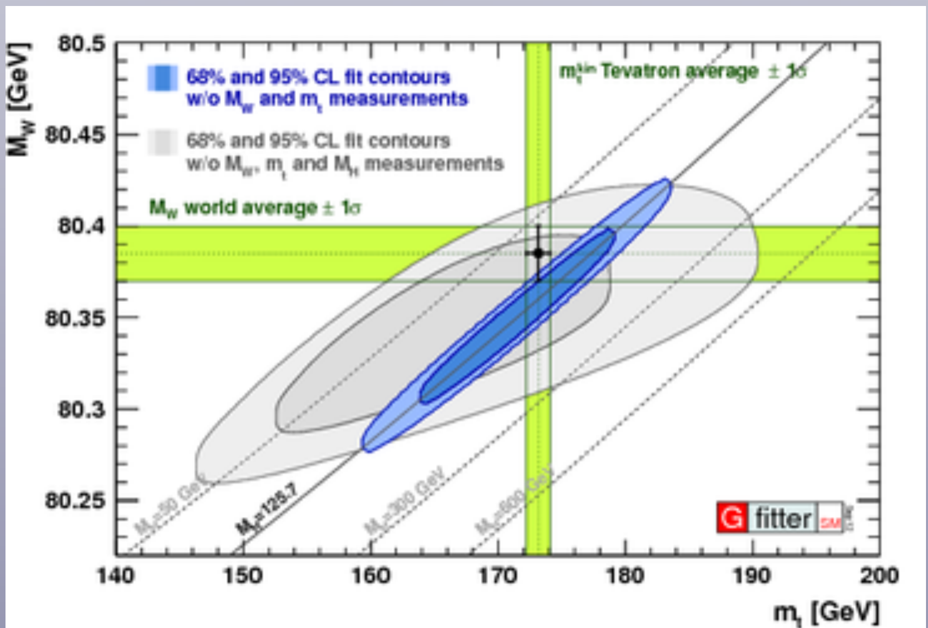
Parton Distributions and LHC phenomenology



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

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





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

Parton Distribution Functions - II

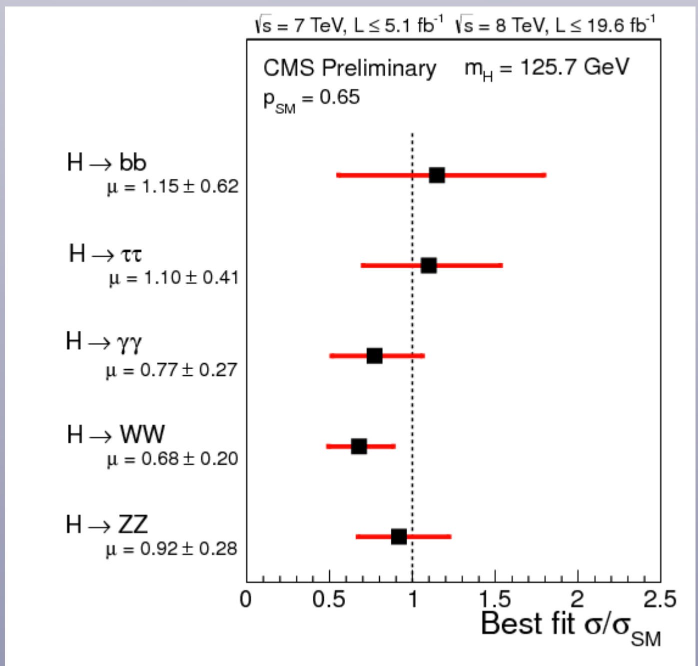
LHC cross-sections can be written as a convolution of **Parton Distributions** and **partonic cross-sections:**

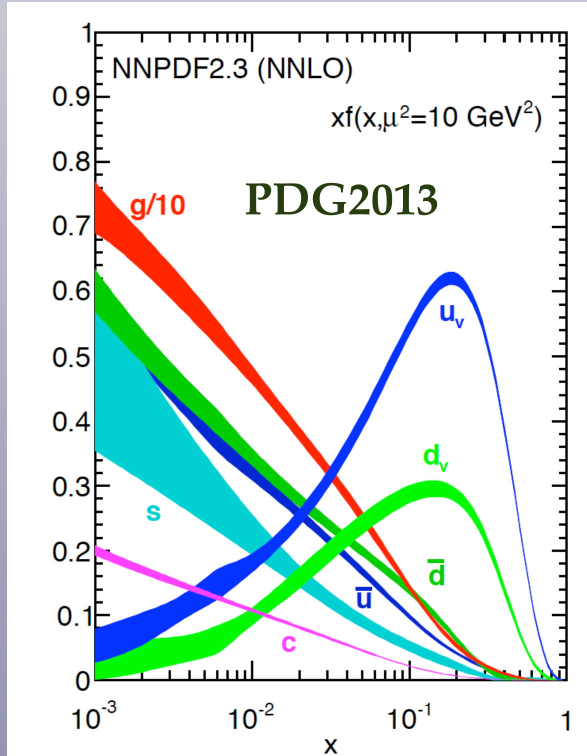
$$\sigma_X(s, M_X^2) = \sum_{a,b} \int_{x_{\min}}^1 dx_1\, dx_2\, f_{a/h_1}(x_1, M_X^2)\, f_{b/h_2}(x_2, M_X^2)\, \hat{\sigma}_{ab\to X}\left(x_1 x_2 s, M_X^2\right)$$

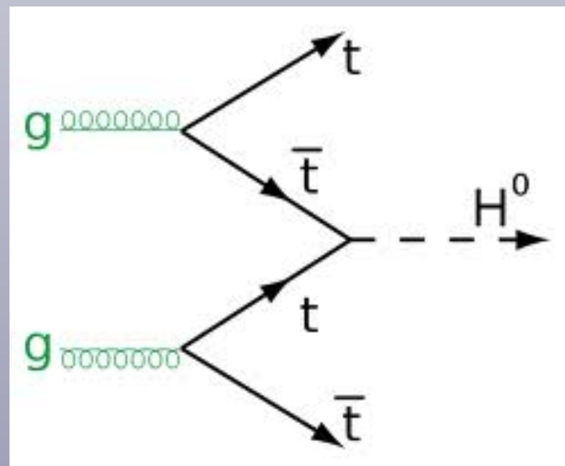
Hadronic cross-section to be compared with exp data
eg Higgs coupling extraction

Parton Distributions are intrinsically non-perturbative quantities to be extracted from experimental data

Partonic cross-sections: perturbatively calculable as an expansion in the QCD and electroweak couplings







Global PDF analysis

Parton Distributions need to be determined from a **global QCD analysis** of all relevant hard-scattering data
Highly complex procedure that requires to combine the **most precise experimental data** and the most **advanced theoretical calculations** into a **statistically robust analysis framework**

Experimental data → **Lepton-proton structure functions**, heavy quark production, jet production, Drell-Yan pair production, electroweak bosons, isolated photons, ...

↓

QCD Theory → **NNLO DGLAP evolution, NLO and NNLO hard scattering cross sections**, heavy quark treatment, strong coupling, electroweak effects, hadronic production, PDF flavor separation,...

↓

Methodology → ***Ansatze* for the x-dependence of PDFs $q(x,Q_0)$**, propagation of **experimental errors from data to PDFs**, model uncertainties, minimization, definition of the **figure of merit χ^2** , parallel computing, ...

↓

Parton Distributions → **LHC phenomenology**, predictions for LHC processes, PDF and Higgs production, ...

Global PDF analysis

Parton Distributions need to be determined from a **global QCD analysis** of all relevant hard-scattering data
Highly complex procedure that requires to combine the **most precise experimental data** and the most **advanced theoretical calculations** into a **statistically robust analysis framework**

In this talk focus on one crucial aspect:
How to determine, in a fully unbiased way, the **dependence with Bjorken-x of the PDFs**

$$f_{a/h_1}(x_1, M_X^2)$$

In other words: how can we learn a **underlying physical law** from data without imposing any **ad hoc theoretical bias?**

Methodology

Ansatze **for the x-dependence of PDFs q(x,Q_0)**, propagation of **experimental errors from data to PDFs**, model uncertainties, minimization, definition of the **figure of merit χ^2** , parallel computing, ...

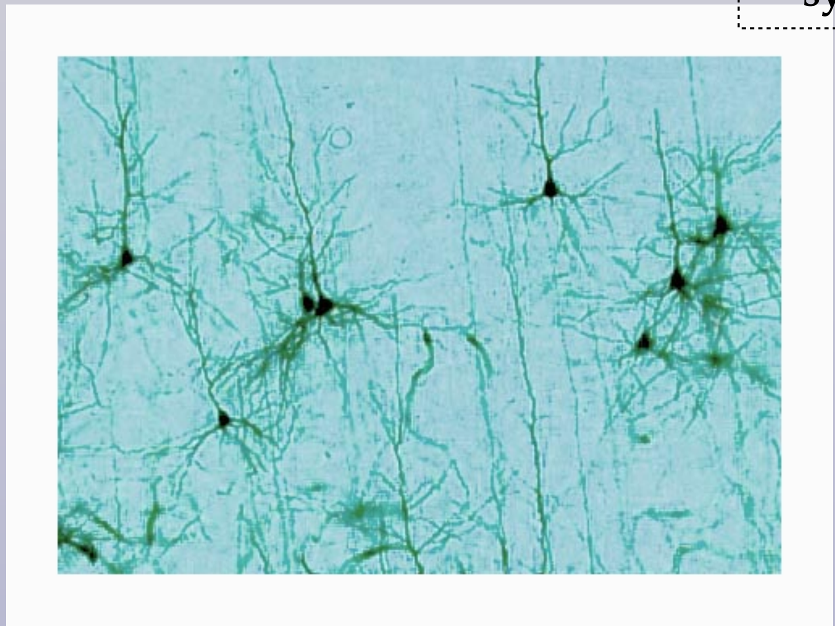
Parton Distributions

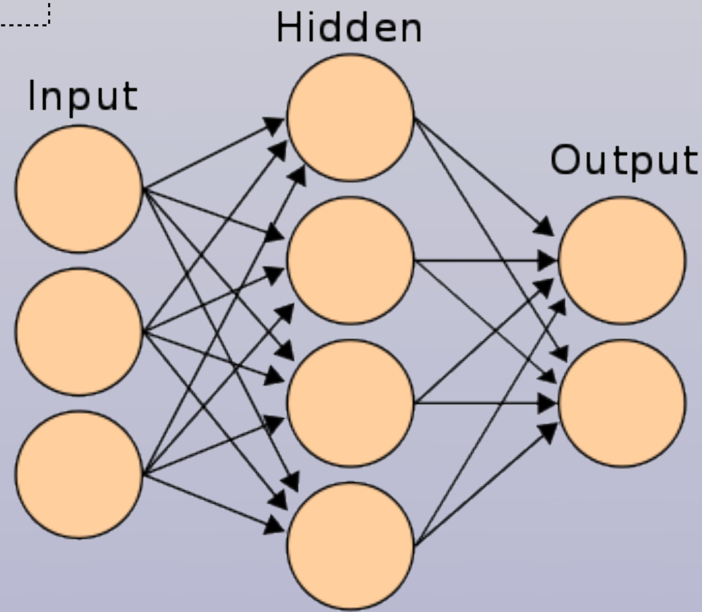
LHC phenomenology, predictions for LHC processes, PDF and Higgs production, ...

Artificial Neural Networks

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

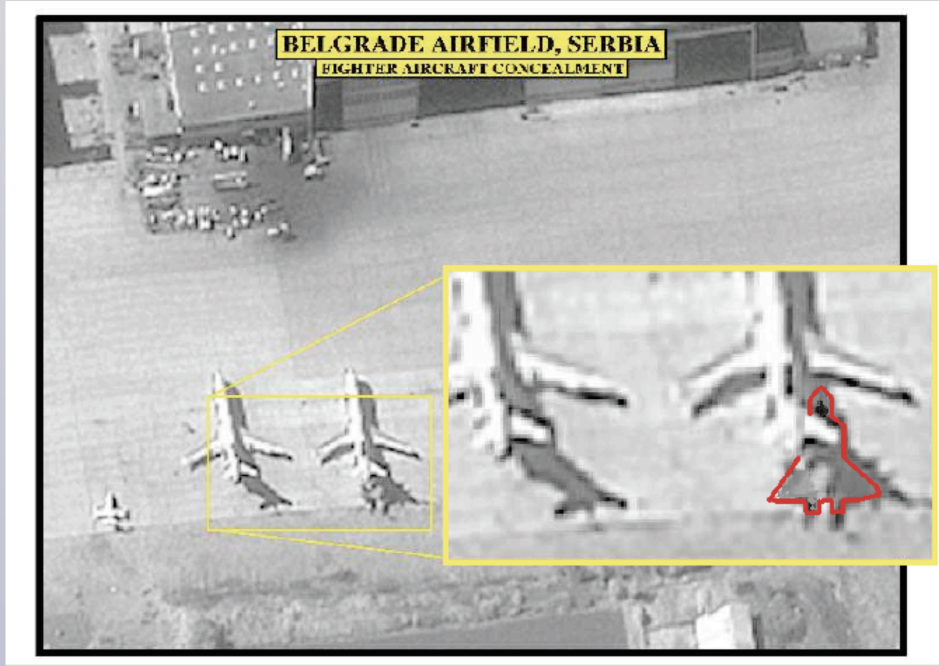
Biological NeuralNets → Neurons, axions, synapses, ... ← **Artificial NeuralNets**





- 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 recognize hidden military vehicles

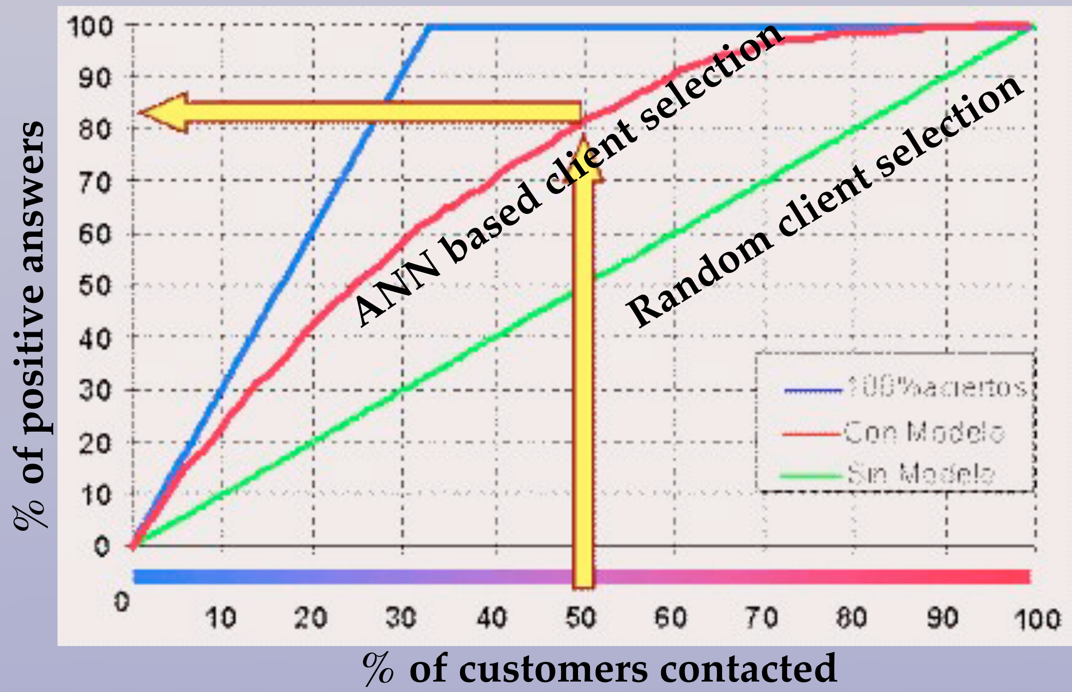
A military aircraft is identified, despite being hidden below a commercial plane.

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

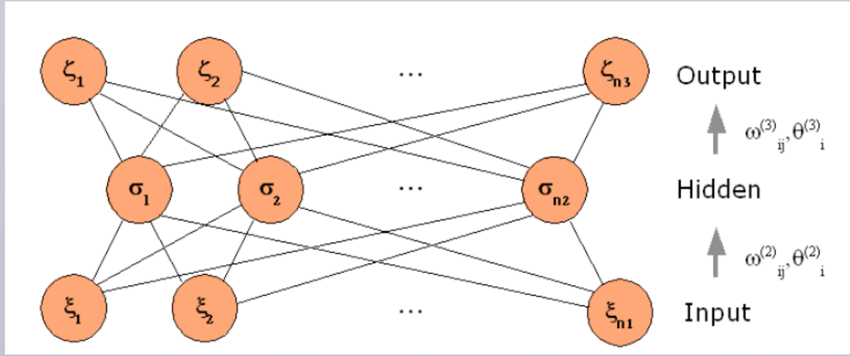


Artificial Neural Networks

- **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)



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

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

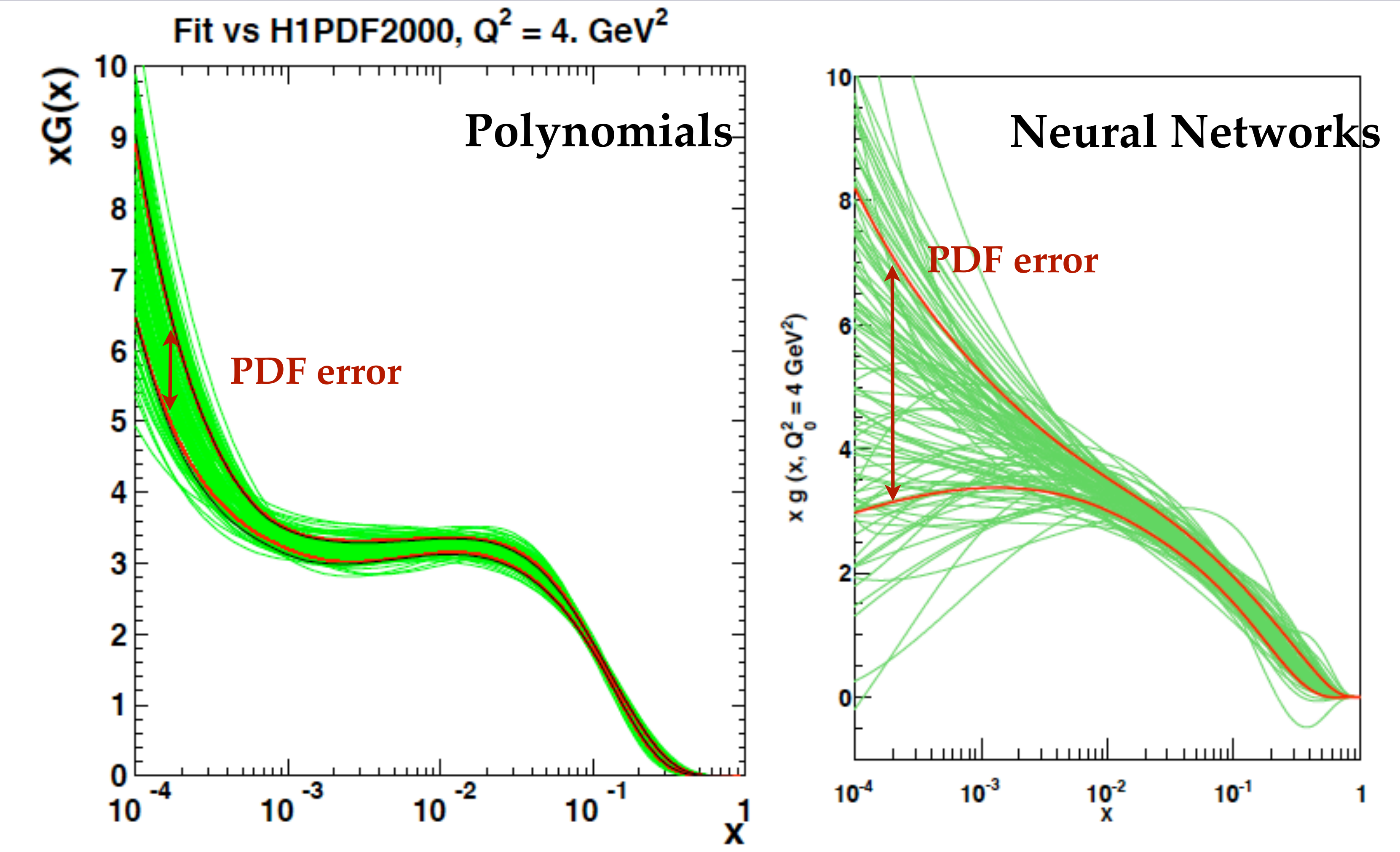
- In traditional PDF determinations, the input *ansatz* is a low-order **polynomial**

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

- The use of 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

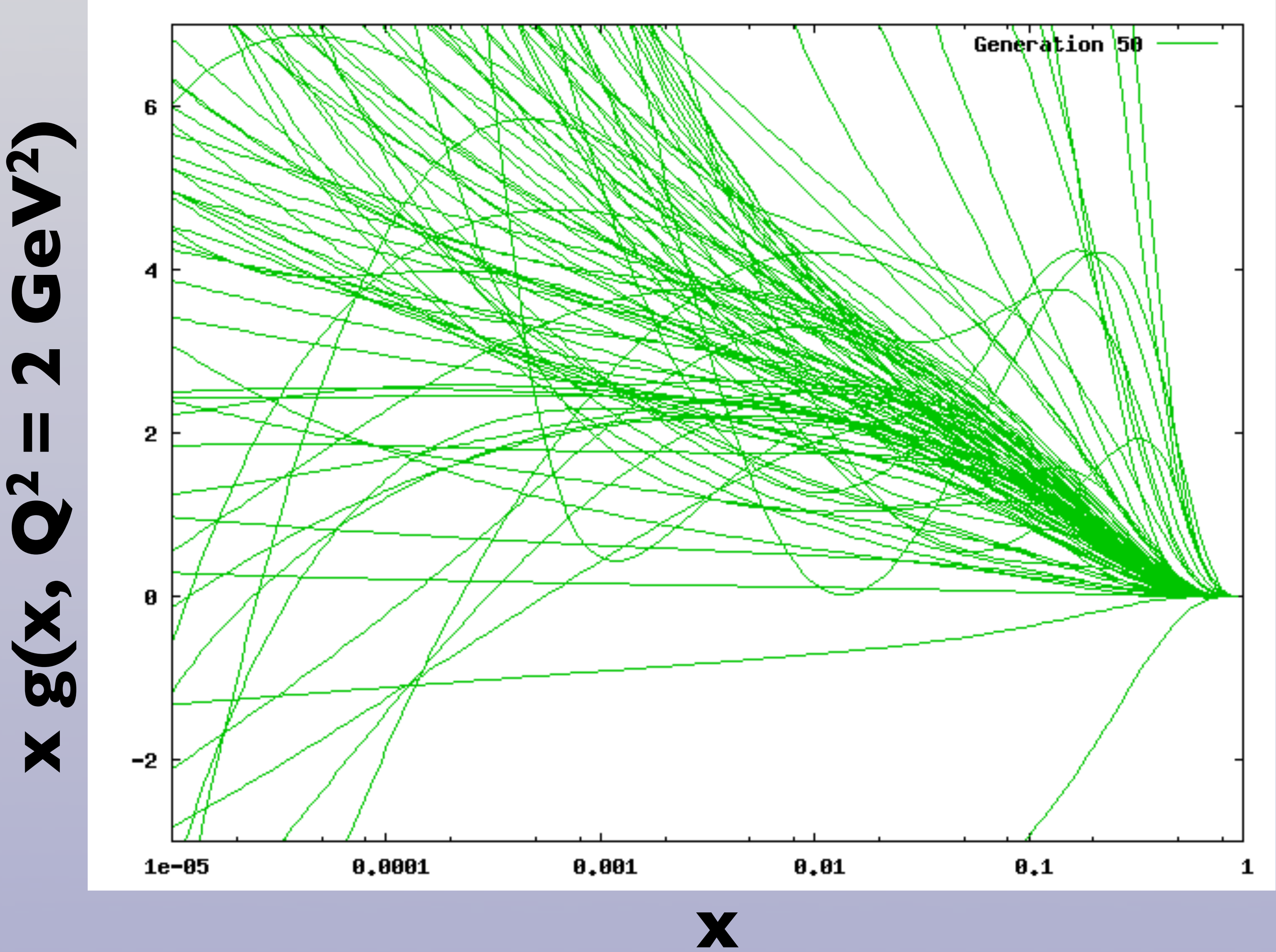
Artificial Neural Networks vs. Polynomials

- 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)



PDF Replica Neural Network Learning

Each **green curve** corresponds to a **gluon PDF Monte Carlo replica**

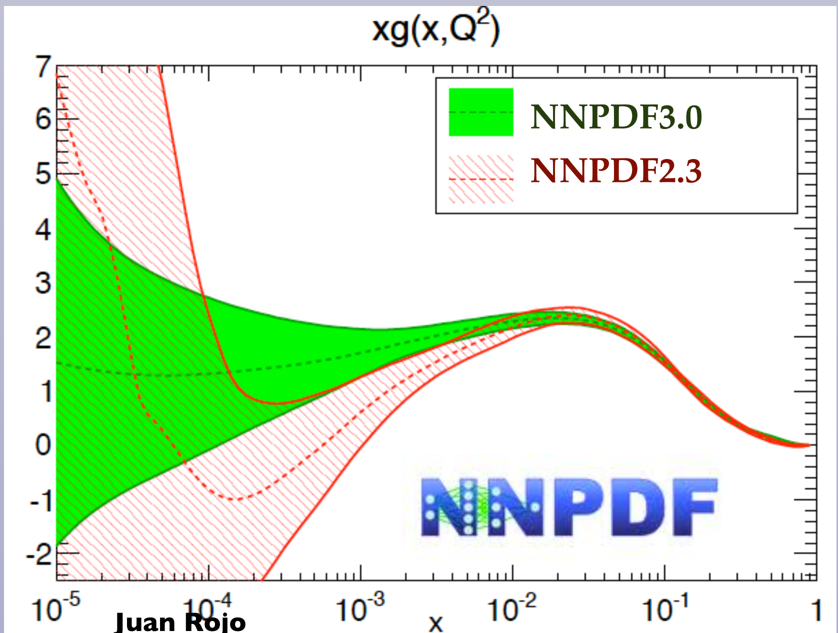


The next NNPDF generation

- Upcoming new release: **NNPDF3.0,** based on a complete rewriting of the NNPDF framework in **C++** (more than **70K** lines of code)

Language	files	blank	comment	code
C++	106	6993	6048	26551
Fortran 77	113	115	10161	20872
C/C++ Header	134	1183	857	3920
make	34	792	447	1699
ASP.Net	1	511	0	1390
Bourne Shell	23	261	202	802
Python	8	187	168	565
Fortran 90	1	32	43	117
Bourne Again Shell	3	7	11	34
SUM:	423	10081	17937	55950

- More than **1000 new data points** from **HERA-II and the LHC**, including jet cross-sections, W+charm production, top quark data, low and high mass Drell-Yan, W lepton asymmetries.....



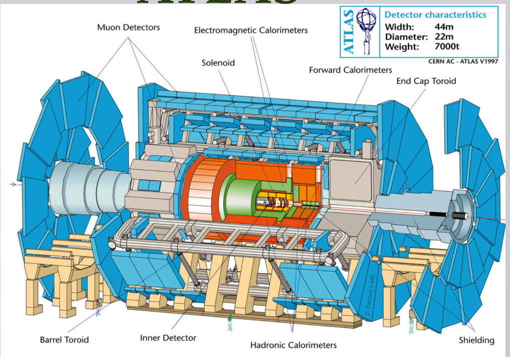
- Completely redesigned fitting methodology based on **closure tests** with known underlying physical laws
- Substantially improved **Genetic Algorithms minimization** with new **Weight Penalty method** for fitting (iterative Bayesian regularization)

Experiment	Dataset	DOF
NMC		356
	NMCPD	132
	NMC	224
SLAC		74
	SLACP	37
	SLACD	37
BCDMS		581
	BCDMSP	333
	BCDMSD	248
CHORUS		862
	CHORUSNU	431
	CHORUSNB	431
NTVDMN		79
	NTVNUDMN	41
	NTVNBDMN	38
HERA1AV		592
	HERA1NCEP	379
	HERA1NCEM	145
	HERA1CCEP	34
	HERA1CCEM	34
ZEUSHERA2		252
	Z06NC	90
	Z06CC	37
	ZEUSHERA2NCP	90
	ZEUSHERA2CCP	35
H1HERA2		511
	H1HERA2NCEM	139
	H1HERA2NCEP	138
	H1HERA2CCEM	29
	H1HERA2CCEP	29
	H1HERA2LOWQ2	124
	H1HERA2HGHY	52
HERAF2CHARM		47
DYE886		199
	DYE886R	15
	DYE886P	184
DYE605		119
CDF		105
	CDFZRAP	29
	CDFR2KT	76
D0		138
	D0ZRAP	28
	D0R2CON	110
ATLAS		179
	ATLASWZRAP36PB	30
	ATLASR04JETS36PB	90
	ATLASR04JETS2P76TEV	59
CMS		95
	CMSWEASY840PB	11
	CMSWMASY47FB	11
	CMSJETS11	63
	CMSWCHARMTOT	5
	CMSWCHARMRAT	5
	CMSDY2D11	132
LHCB		19
	LHCBW36PB	10
	LHCBZ940PB	9
TOP		6
Total (exps)		4214

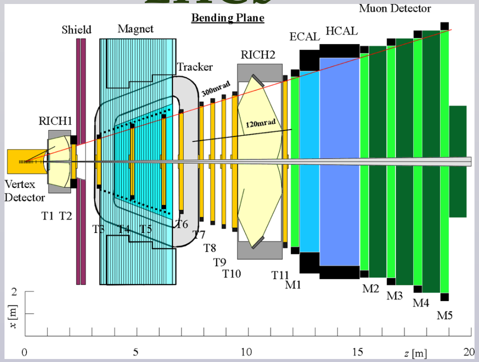
Connecting Research

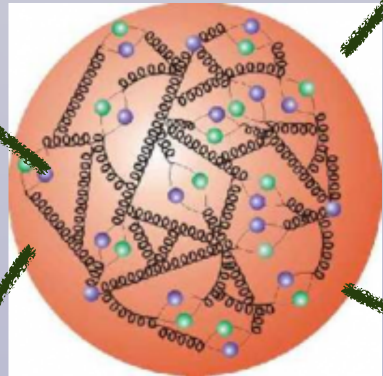
The **determination of the proton's structure** has direct connections with related research from our Dept

ATLAS



LHCb

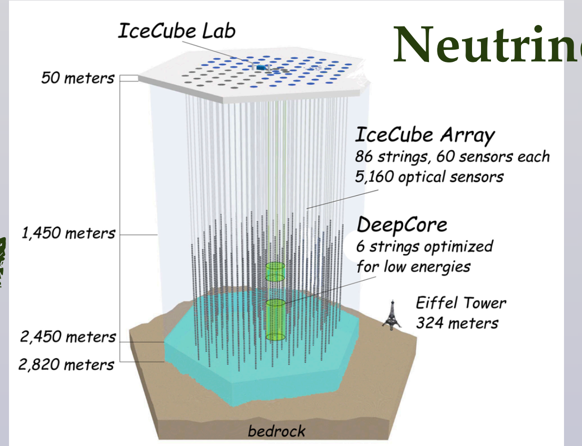




The data from **ATLAS** and **LHCb** provides **important constraints on PDFs**, with new measurements only available at LHC: top quarks, Z with jets, W with charm quarks, ...

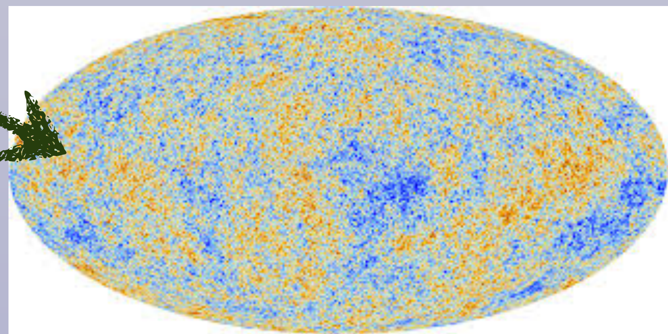
The ATLAS group is part of the **HERAfitter** developement, an open-source framework for PDF analysis

Neutrinos



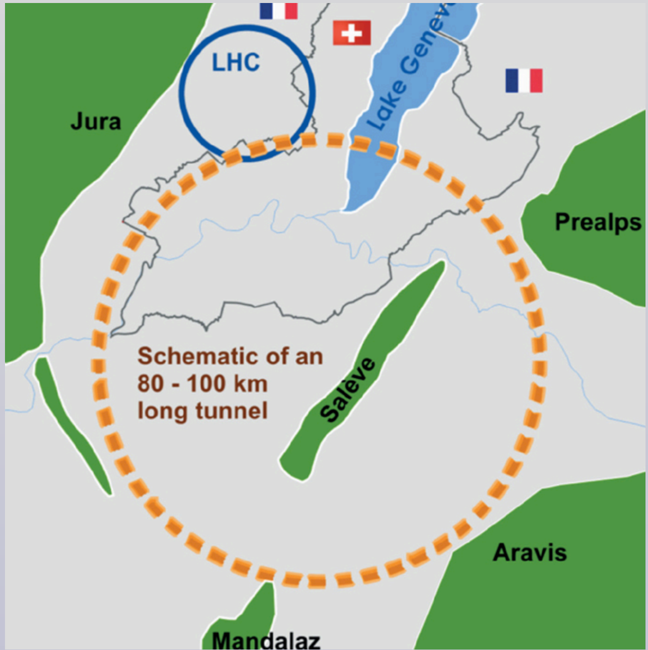
Ultra-high energy neutrino-nucleus interactions depend crucially on PDFs at small Bjorken-x and on departures from linear QCD evolution

Cosmology

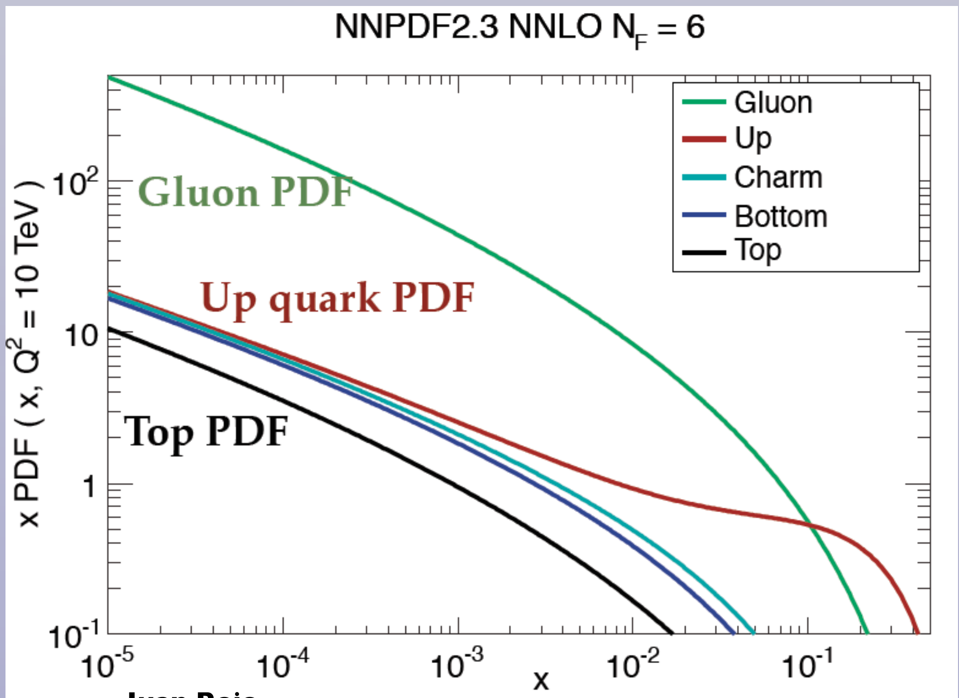


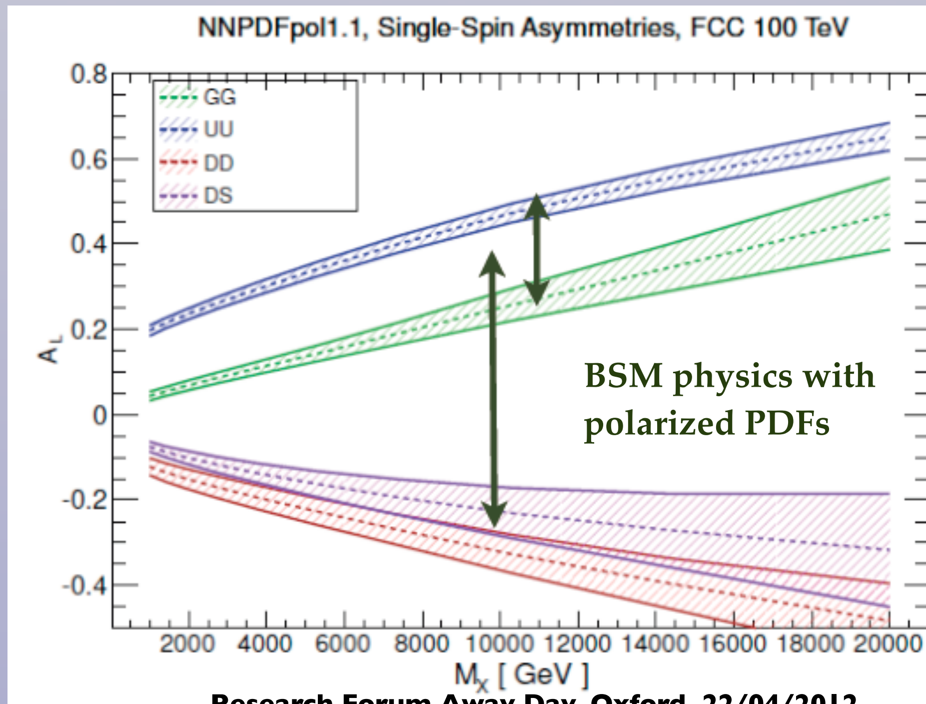
Advanced statistical tools, like artificial neural networks, genetic algorithms and Bayesian inference are important in cosmology to extract the values of **cosmological parameters** from data

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, ...
- First studies being now performed in the context of the **CERN FCC working group**





Summary

- **Parton Distributions** are an essential ingredient for precision phenomenology at the Large Hadron Collider
- Accurate PDFs are required for **precision Standard Model measurements, Higgs Boson characterization** 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
- The s**tatistical methodology** used in the NNPDF framework can be used in many other applications, from physics (like cosmology) to financial applications

E.g. Ongoing collaboration between **physicists** and **economists** towards a **quantitative cost/benefit analysis in the research and innovation sectors**

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Thanks for your attention!