

# Developments in parton distribution functions of the proton

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# Motivation

Efforts in investigating the structure of the nucleon are crucial for a multitude of current and future high-energy physics programs.

Interpretation of experimental measurements at hadron colliders relies to large extent on the precise knowledge of fundamental QCD parameters and of **parton distribution functions (PDFs)** of the proton.

- ▶ Global QCD analysis of PDFs is a vast topic: I'll focus on general aspects and show few recent results

# Making a long story short...

**Parton distribution functions (PDFs) of the proton are essential ingredients of factorization theorems in QCD:**

The general structure of the inclusive cross section for high-energy collisions involving hadron-hadron beams, lepton-hadrons, or hadron targets, is a convolution product where long-distance non-perturbative contributions (PDFs) and short-distance infrared-safe perturbatively calculable quantities (hard scatterings) are separated. For **Drell-Yan** we have (Collins Soper Sterman (1984), (1985))

$$\begin{aligned} \sigma(h_1 h_2 \rightarrow l^+ l^- + X) = & \\ \sum_{a,b} \int_{x_1}^1 d\xi_1 \int_{x_2}^1 d\xi_2 f_{h_1 \rightarrow a}(\xi_1, \alpha_s(\mu_R), \mu_R, \mu_F) f_{h_2 \rightarrow b}(\xi_2, \alpha_s(\mu_R), \mu_R, \mu_F) & \\ \times \hat{\sigma}^{ab}\left(\frac{x_1}{\xi_1}, \frac{x_2}{\xi_2}; \alpha_s(\mu_R), Q, \mu_F, \mu_R\right) + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right), & \end{aligned} \quad (1)$$

# Complicated objects

The formal definition of PDFs in QCD, contains all the complications of “real life”: UV regulator in DR, gauge invariance Collins (2011)

$$f_{(0)j/h}(\xi) = \int \frac{dw^-}{2\pi} e^{-i\xi P^+ w^-} \langle P | \overline{\psi}_j^{(0)}(0, w^-, \mathbf{0}_T) W(w^-, 0) \frac{\gamma^+}{2} \psi_j^{(0)}(0) | P \rangle_c, \quad (2)$$

that is for quarks, where the Wilson-line factor is

$$W(w^-, 0) = P \left[ e^{-ig_0 \int_0^{w^-} dy^- A_{(0)\alpha}^+(0, y^-, \mathbf{0}_T) t_\alpha} \right]. \quad (3)$$

Similarly to the case of renormalization scheme, a set of rules has to be provided in order to define the PDFs when a cross section calculation is performed, e.g.  $\overline{\text{MS}}$  scheme.

# Scale dependence

In the collinear picture, the use of RG invariance tells us how to predict scale dependence or “evolution” of PDFs by renormalization group equations (RGE’s) once the “initial conditions” are given.

Parton evolution is obtained in terms of integro-differential equations known as DGLAP

(Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) equations

$$\frac{d f_i(x, \mu_R, \mu_F)}{d \log \mu_F} = \sum_{j=q\bar{q},g} \int_x^1 \frac{dy}{y} P_{ij} \left( \frac{x}{y}; \alpha_s, \mu_R, \mu_F \right) f_j(y, \mu_R, \mu_F), \quad (4)$$

The evolution kernels or “splitting functions”  $P_{ij}$  are known at 3-loop for the unpolarized case. Moch, Vermaseren, Vogt (2004)

# Universal objects

Gluons, quarks and antiquarks are the known constituents of the proton. Their distributions as a function of  $x$  and generic scale  $\mu$ , at which partons are probed, are universal quantities that do not depend on the specific hard process under consideration.

Differently from the hard-scattering cross section, the analytic structure of the PDFs cannot be predicted by perturbative QCD, but has to be determined by comparing standard sets of cross sections, such as Eq. 1, to experimental measurements by using a variety of analytical methods.

For this reason PDFs are “data-driven” quantities.

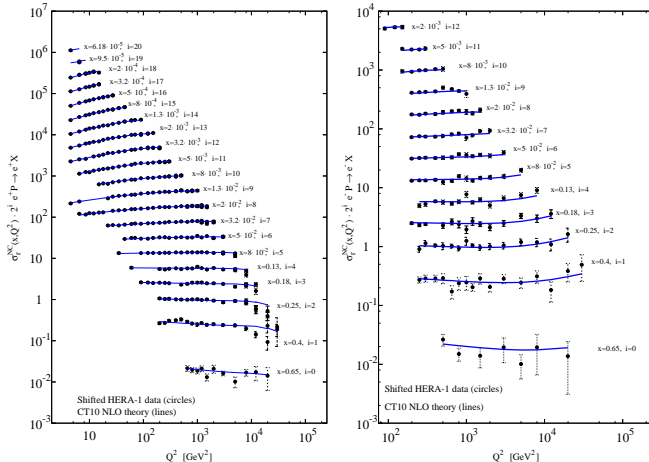
# LHC and PDFs in the NNLO QCD era

The increasing accuracy of the current data and the LHC unprecedented energies pushed the high-energy physics community towards a new realm of precision calculations:

- ▶ Enormous progress in perturbative NNLO QCD calculations (e.g. unitarity based methods ),
- ▶ semi-automated calculations of multi-leg NLO processes,
- ▶ NLO calculation of complex multi-leg processes such as for the production of vector boson plus 5 jets (e.g.  $W + 5 \text{ jets}$ ;  $H + 3 \text{ jets}$ ),
- ▶ theoretical progress in the combination of the fixed-order results with a parton shower codes,
- ▶ rapid developments of very sophisticated tools for phenomenology (I will briefly discuss the HERAFITTER platform at the end of this talk.),
- ▶ ....

# Very high precision HERA data

Measurements of lepton-proton deep-inelastic-scattering (DIS) at HERA are the most important data sets in PDFs determination



New (more precise!) measurements from HERA are planned to be released in the next fall. **More details in Hayk Pirumov's talk**

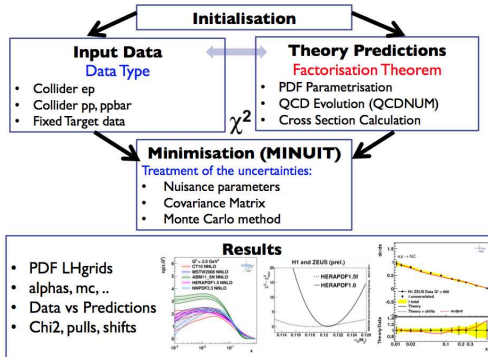
# Progress in PDFs determination: global QCD analyses at NNLO

In the past years, quite a lot of (non-trivial) efforts went in updating QCD analyses to determine PDFs from NLO to NNLO.

Several groups of high-energy physicists (from theory and experiments) are involved in global QCD analyses to determine PDFs of the proton at LO, NLO, and NNLO: CTEQ-TEA, MSTW, HERAPDF, NNPDF, ABM, JR, CTEQ-JLab.

Different groups use different approaches and methodologies

- ▶ smaller/larger/different data sets considered,
- ▶ heavy-flavor treatment,
- ▶ different values of  $\alpha_s(M_Z)$ ,
- ▶ different parametrization for input PDFs at  $Q_0$ ,
- ▶ ....



In global PDF fits a large number of iterations of the theory calculation programs (NLO, NNLO) is required to evaluate cross sections:

some of these computations are CPU time consuming!

Advanced tools have been developed to speed up calculations

⇒ **FastNLO** and **APPLgrid**

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- ▶ different parametrization for input PDFs at  $Q_0$ ,
- ▶ ....

⇒ it leads to different predictions for physical observables

let's see few examples

# Results for $F_2^c(x, Q^2)$ in DIS at NLO/NNLO

At NNLO and  $Q \approx m_c$ :

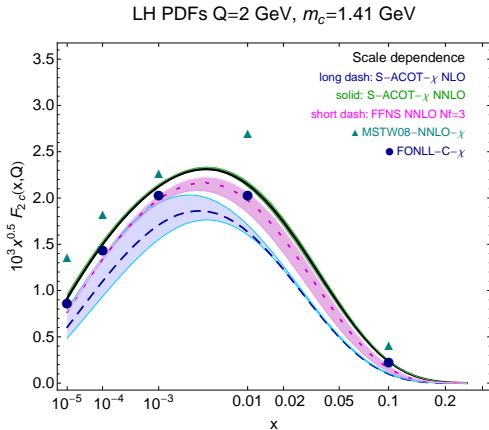
■ S-ACOT- $\chi \approx$   
FFN( $N_f = 3$ )  
without tuning

■ It is close to other  
NNLO schemes

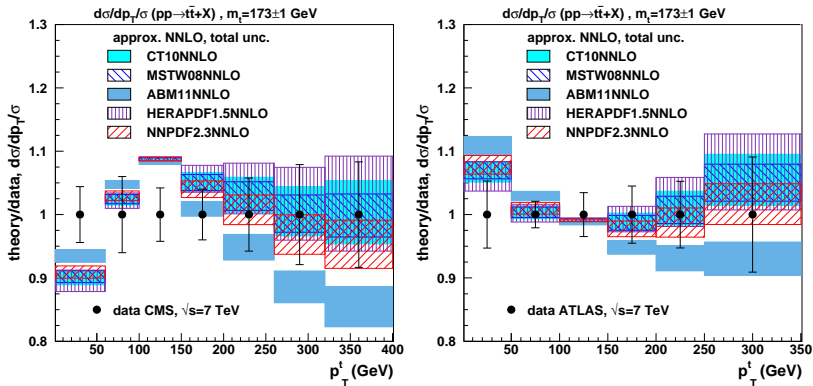
■ S-ACOT- $\chi$  predictions  
are for a physically  
motivated rescaling  
variable

$$\zeta = x(1 + 4m_c^2/Q^2).$$

Dependence on the form  
of  $\zeta$  is also reduced



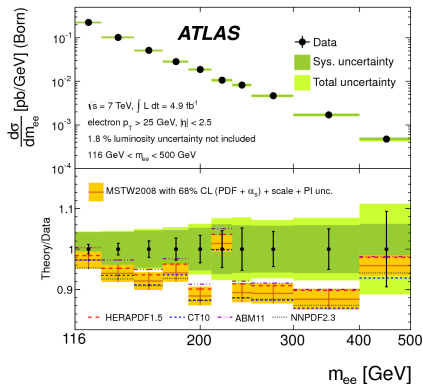
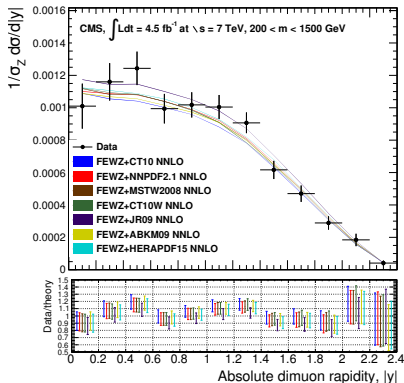
# The $p_T^t$ spectrum at approx NNLO in $t\bar{t}$ production



CMS (left) and ATLAS (right) collaborations

approx NNLO theory  $\mathcal{O}(\alpha_s^4)$ : **DIFFTOP**, threshold resummation code, M.G., K.Lipka, S.Moch (2014)

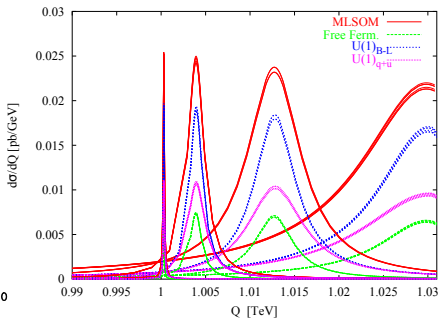
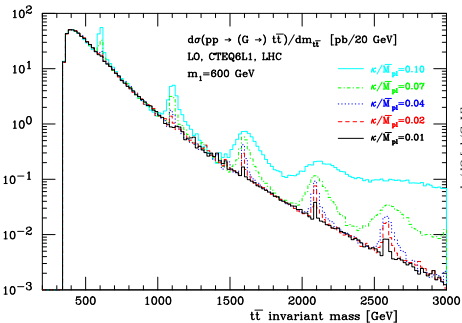
# Drell-Yan distributions: rapidity and large invariant mass at NNLO: Standard candle observables



FEWZ 3.1  $\rightarrow$  fully differential calculation at NNLO QCD  $\mathcal{O}(\alpha_s^2)$ .  
 CMS (left) and ATLAS (right) collaborations (2013)

# PDFs are important for BMS searches at the LHC

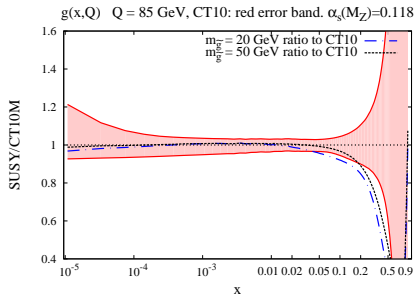
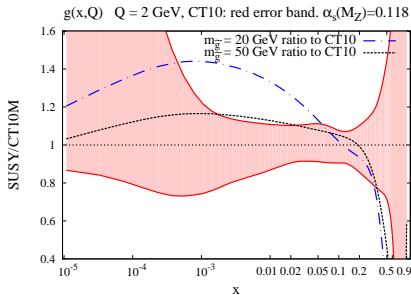
All theory predictions for BMS searches at the LHC are affected



**Left:** F.Maltoni and R.Frederix (2009):  
Spin-2 resonances in the  $t\bar{t}$  invariant mass

**Right:** R.Armillis, C. Corianò, M.G., S.Morelli (2009):  
Extra  $Z'$ 's in Drell-Yan invariant mass

# Constraining SUSY parameters at the LHC



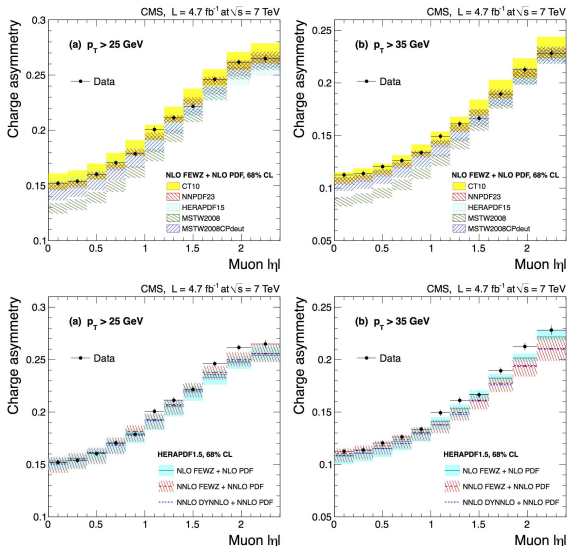
Ratios of  $g(x, Q)$  distribution in SUSY fits with fixed  $\alpha_s(M_Z) = 0.118$  and the CT10 fit at  $Q = 2$  GeV (left) and  $Q = 85$  GeV (right), for gluino mass  $m_{\tilde{g}}$  of 20 and 50 GeV.

M.G., E.Berger, H.-L. Lai, P.Nadolsky, F.I.Olness (2010)

**Now we might ask:**

# is it better when going from NLO to NNLO ?

Not trivial...



**Recent results from CTEQ:**  
**CT10 NNLO and CT1X<sup>1</sup> NNLO PDFs**

for the CTEQ-TEA group

S. Dulat, J. Gao, M.G., T.J. Hou, J. Huston, H.-L. Lai, Z. Li, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump, C.-P. Yuan

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<sup>1</sup>CT1X=CT14 ?

# CT10 NNLO and CT1X NNLO PDFs

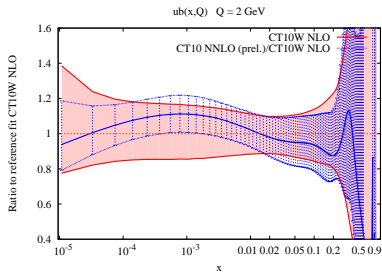
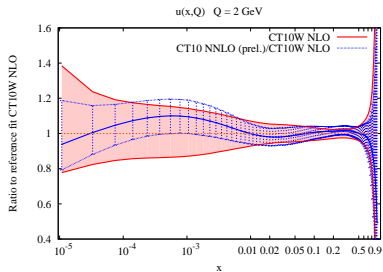
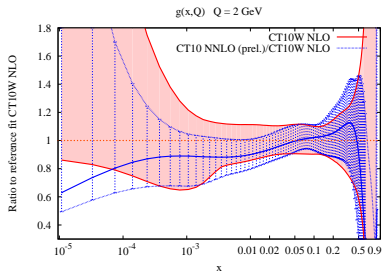
## PRE LHC

**CT10 NNLO:** officially published in [arXiv:1302.6246](#), is an NNLO counterpart to either CT10 NLO or CT10W NLO

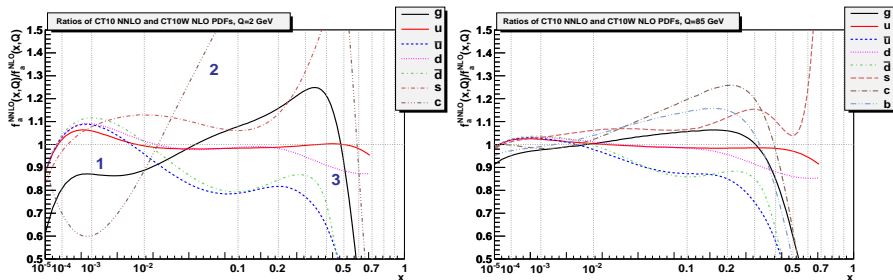
In good agreement with early LHC data

**CT1X NNLO:** – a preliminary extension of CT10 NNLO that includes latest HERA data on  $F_L(x, Q)$  and  $F_{2c}(x, Q)$ , LHC 7 TeV data (ATLAS  $W$  &  $Z$ , ATLAS jets, CMS  $W$  asymmetry). So far, the new data provide minor improvements compared to the CT10 data set. We investigate its agreement with the CT10 data sets and await for more precise LHC data and new theory calculations to be included in the CT1X public release.

# CT10 NNLO error PDFs (compared to CT10W NLO)



# CT10 NNLO central PDFs, as ratios to NLO, $Q=2$ and $85$ GeV



1. At  $x < 10^{-2}$ ,  $\mathcal{O}(\alpha_s^2)$  evolution suppresses  $g(x, Q)$ , increases  $q(x, Q)$
2.  $c(x, Q)$  and  $b(x, Q)$  change as a result of the  $\mathcal{O}(\alpha_s^2)$  GM VFN scheme
3. At  $x > 0.1$ ,  $g(x, Q)$  and  $d(x, Q)$  are reduced by revised EW couplings, alternative treatment of correlated systematic errors, scale choices

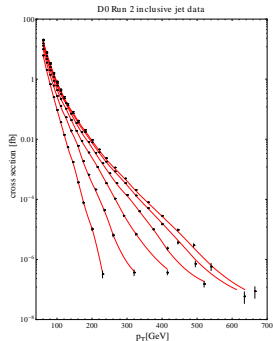
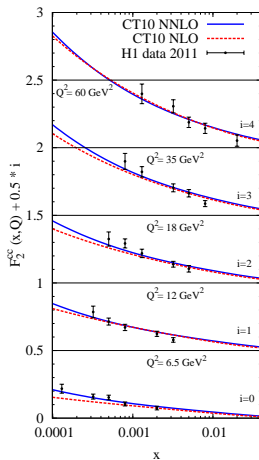
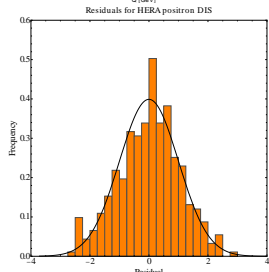
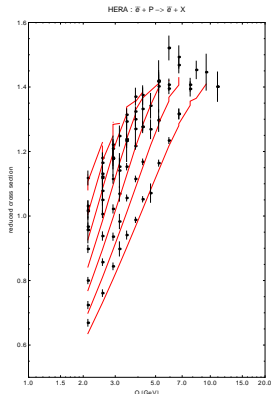
# CT10 NNLO: agreement with data

For the final CT10  
NNLO,  $\chi^2/N_{pt} =$   
2950/2641 = 1.11  
– slightly better  
than at NLO

Experimental data set	$N_{pt}$	CT10NNLO	CT10W
Combined HERA1 NC and CC DIS [60]	579	1.07	1.17
BCDMS $F_2^p$ [61]	339	1.16	1.14
BCDMS $F_2^d$ [62]	251	1.16	1.12
NMC $F_2^p$ [63]	201	1.66	1.71
NMC $F_2^d/F_2^p$ [63]	123	1.23	1.28
CDHSW $F_2^p$ [64]	85	0.83	0.66
CDHSW $F_3^p$ [64]	96	0.81	0.75
CCFR $F_2^p$ [65]	69	0.98	1.02
CCFR $xF_3^p$ [66]	86	0.40	0.59
NuTeV neutrino dimuon SIDIS [67]	38	0.78	0.94
NuTeV antineutrino dimuon SIDIS [67]	33	0.86	0.91
CCFR neutrino dimuon SIDIS [68]	40	1.20	1.25
CCFR antineutrino dimuon SIDIS [68]	38	0.70	0.78
H1 $F_2^c$ [69]	8	1.17	1.26
H1 $\sigma_c^c$ for $c\bar{c}$ [70, 71]	10	1.63	1.54
ZEUS $F_2^c$ [72]	18	0.74	0.90
ZEUS $F_2^c$ [73]	27	0.62	0.76
E605 Drell-Yan process, $\sigma(pA)$ [74]	119	0.80	0.81
E866 Drell-Yan process, $\sigma(pd)/(2\sigma(pp))$ [75]	15	0.65	0.64
E866 Drell-Yan process, $\sigma(pp)$ [76]	184	1.27	1.21
CDF Run-1 $W$ charge asymmetry [77]	11	1.22	1.24
CDF Run-2 $W$ charge asymmetry [78]	11	1.04	1.02
DØ Run-2 $W \rightarrow e\nu_e$ charge asymmetry [79]	12	2.17	2.11
DØ Run-2 $W \rightarrow \mu\nu_\mu$ charge asymmetry [80]	9	1.65	1.49
DØ Run-2 Z rapidity distribution [81]	28	0.56	0.54
CDF Run-2 Z rapidity distribution [82]	29	1.60	1.44
CDF Run-2 inclusive jet production [83]	72	1.42	1.55
DØ Run-2 inclusive jet production [84]	110	1.04	1.13
<b>Total:</b>	<b>2641</b>	<b>1.11</b>	<b>1.13</b>

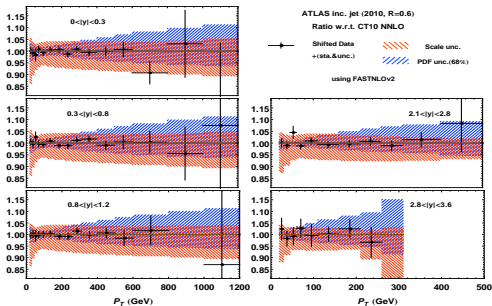
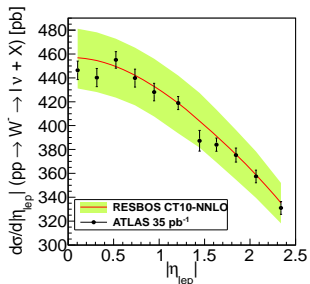
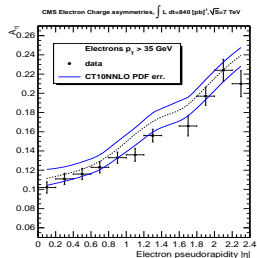
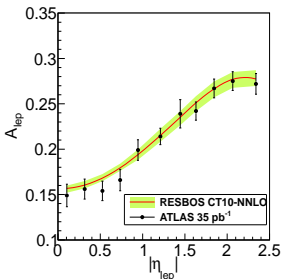
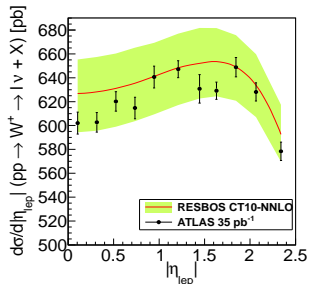
TABLE I: Experimental data sets examined in the CT10NNLO and CT10W NLO analyses, together with their  $\chi^2$  values.

# CT10 NNLO vs. fitted experiments



Good general  
agreement

# CT10 NNLO describes well LHC 7 TeV experiments



# Post-CT10 analysis

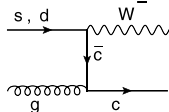
## Investigate

- ▶ impact of LHC data on quark flavor decomposition, gluon PDF (e.g.  $t\bar{t}$ , Higgs, Jets)
- ▶ dependence on correlated systematic effects (both of theoretical and experimental origin)
- ▶ photon PDFs in the proton.
- ▶ heavy-flavor mass dependence, impact of combined HERA  $F_{2c}(x, Q)$  data, update intrinsic charm PDFs.
- ▶ Strangeness with new LHC data.

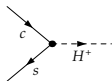
**Remaining part of this talk:**  
**recent analyses on strangeness;**  
**the HERAFITTER platform**

# strange quark: important for SM and BSM physics

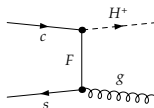
- Associated production of  $W$  and a  $c$ -quark at hadron coll.



- Charged Higgs production:  $c + \bar{s} \rightarrow H^+$ ;  $c + \bar{s} \rightarrow H^+ + 1\text{-jet}$ :  
2HDM, SUSY searches,...



(a)



(b)

- strange asym.  $[s(x) - \bar{s}(x)] \rightarrow$  "NuteV Anomaly"

$$R^- = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \frac{1}{2} - \sin^2 \theta_W \quad (5)$$

$$\text{NuteV} \Rightarrow \sin^2 \theta_W = 0.2277 \pm 0.0016$$

$$\text{LEP} \Rightarrow \sin^2 \theta_W = 0.2227 \pm 0.00037$$

# The Paschos-Wolfenstein ratio

SM corrections

$$R^- = \frac{1}{2} - s_W^2 - \left[ \delta N \frac{\int x(u_v - d_v) dx}{\int x(u_v + d_v) dx} + \frac{\int x(\textcolor{red}{s} - \textcolor{red}{\bar{s}}) dx}{\int x(u_v + d_v) dx} \right] \left[ 1 - \frac{7}{3} s_W^2 + \frac{4\alpha_s}{9\pi} \left( \frac{1}{2} - s_W^2 \right) \right]$$

1st term: Neutron excess  $\delta N \equiv (A - 2Z)/A$

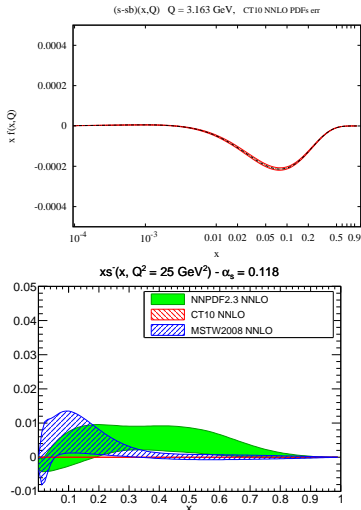
2nd term: strange asymmetry

3rd term: NLO corrections

These corrections were carefully investigated by many authors (Barone et. al.), Davidson et al. (also including scenarios of new physics)

# Strangeness asymmetry

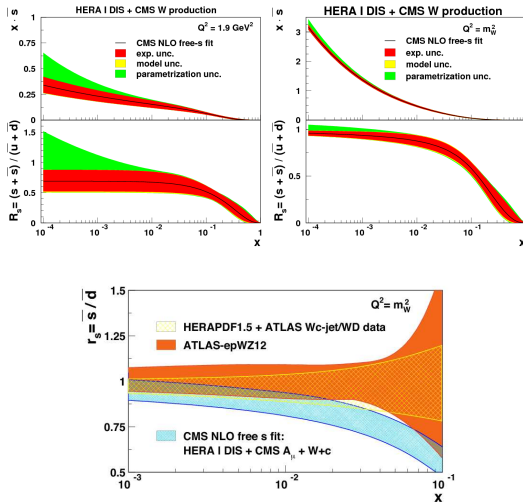
- ▶ QCD evolution tells us that  $s(x) - \bar{s}(x) \neq 0$ , but it's small
- ▶ CTEQ6.5 analysis: no experimental evidence for asymmetric strangeness inside the proton.
- ▶ recent (pre-LHC) NNPDF study: still large uncertainty in the asymmetric strangeness.
- ▶ new LHC data on differential  $W + c$  distribution will put more constraints on strangeness.



Sufficient to eliminate NuTeV anomaly

# New measurements from LHC 7 TeV

The CMS and ATLAS collaboration recently released two measurements for the  $W + c$  total and differential cross section together with two different analyses for the determination of  $r_s(x, Q^2) = \bar{s}/\bar{d}$ : arXiv:1312.6283 (CMS); arXiv:1402.6263 (ATLAS)

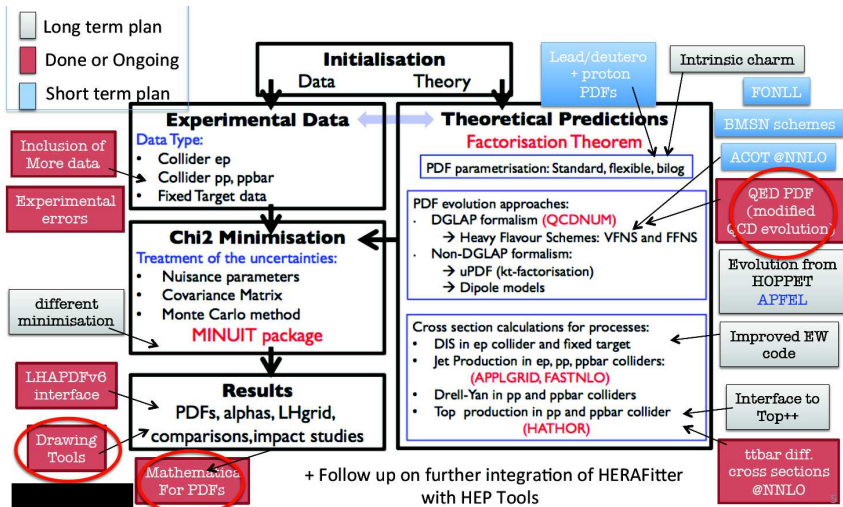


## Tools development: HERAFITTER

- ▶ HERAFITTER is an **open-source** package which provides a framework for the determination of PDFs of the proton and for multifold analyses in Quantum Chromodynamics (QCD)
- ▶ Measurements of lepton-proton DIS and of proton-proton (proton-antiproton) collisions at hadron colliders are included and used to probe and constrain the partonic content of the proton.
- ▶ Currently is extensively used by experimental collaborations HERA, CMS, ATLAS.
- ▶ broad choice of options for the treatment of the experimental uncertainties,
- ▶ represents a common environment where a large number of theoretical calculations and methods can be used to perform detailed QCD analyses.

# The HERAFITTER platform

A large number of analyses



# The HERAFITTER platform

**Provides users with a common environment where a large number of theoretical calculations and methods can be used to perform detailed QCD analyses.**

**It's under continuous development and everyone can contribute.**

**Quantitative analysis by the HERAFitter developers' team Collaboration is on the market: [arXiv:1404.4234](#)**

**“The HERAFitter paper” will be out soon.**

# Conclusions

- ▶ LHC unprecedented energies brought us in a new precision era
- ▶ A lot of efforts are ongoing to pin down PDFs uncertainties which still remain among the major sources of systematical theory uncertainties
- ▶ future looks promising but challenging at the same time: more data will be on the market, higher precision will be reached  $\Rightarrow$  more challenges on theory calculation side!
- ▶ Surprises from new physics might be behind the corner!

# Backup

# PDF evolution Codes

Most widely used codes implementing state-of-the-art DGLAP evolution at NNLO in QCD:

- ▶ **PEGASUS** - A. Vogt (2005): brute-force, Mellin space.
- ▶ **CANDIA** - A. Cafarella C. Corianò and M.G. (2006, 2008): iterative algorithm,  $x$ -space.
- ▶ **HOPPET** - G. Salam and J. Rojo (2009) brute-force,  $x$ -space.
- ▶ **QCDNUM** - M. Botje (2011): Polynomial interpolation,  $x$ -space.

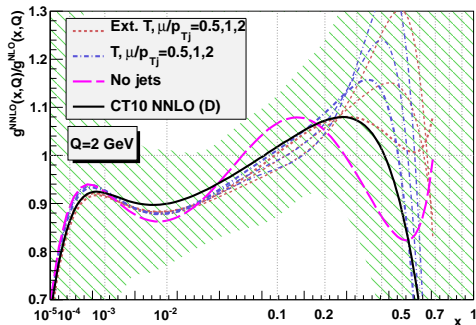
# Accuracy definition

According to the Les Houches 2014 agreement (arXiv:1405.1067) the accuracy in perturbative calculations is given by

- ▶ LO  $\equiv \mathcal{O}(1)$
- ▶ NLO QCD  $\equiv \mathcal{O}(\alpha_s)$
- ▶ NNLO QCD  $\equiv \mathcal{O}(\alpha_s^2)$
- ▶ NNLO QCD + EW  $\equiv \mathcal{O}(\alpha_{em}\alpha_s)$
- ▶ NNNLO QCD  $\equiv \mathcal{O}(\alpha_s^3)$

# Systematic effects in NNLO fits and the gluon PDF

$g(x, Q)$  at  $x > 0.1$  is sensitive to systematic effects from...



■ **theory:** QCD scale dependence of NLO inclusive jet cross sections

■ **experiment:** interpretation of correlated systematic errors for inclusive jet production

Both types of effects were explored. The CT10 NNLO gluon error sets are constructed so as to span the full range of uncertainty due to experimental errors, corr. syst. errors, and various scale choices

# Definitions of the covariance matrix

*arXiv:1302.6246, appendix in R. Ball et al., arXiv:1211.5142*

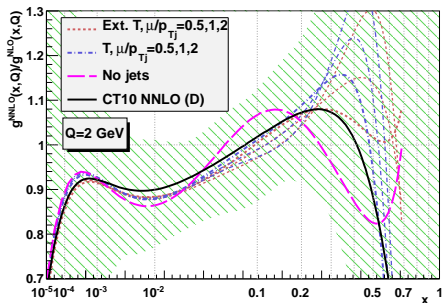
$$\chi^2 = \sum_{\{\text{exp.}\}} \left[ \sum_{k=1}^{N_{\text{pts}}} \frac{1}{s_k^2} \left( D_k - T_k(\{a\}) - \sum_{\alpha=1}^{N_\lambda} \lambda_\alpha \beta_{k\alpha} \right)^2 + \sum_{\alpha=1}^{K_e} \lambda_\alpha^2 \right]$$

The experimental correlated systematic errors  $\beta_{k\alpha}$  are often published as percentages. It can be taken to be a percentage of the theoretical prediction  $T_k$  ("truth") or the experimental datum  $D_k$ .

1. **Experimental ( $D$ ) prescription:** normalize all  $\beta_{k\alpha}$  to  $D_k$
2.  **$T$  ( $T_0$ ) prescription:** normalize luminosity & other multiplicative errors to (fixed)  $T_k$ , additive errors to  $D_k$
3. **Extended  $T$  ( $T_0$ ) prescription:** normalize all errors to (fixed)  $T_k$

The methods are numerically equivalent if  $T_k$  is close to  $D_k$ . Additive (multiplicative) errors are to be normalized to  $T_k$  ( $D_k$ ) to avoid/reduce biases. The available experimental data usually do not specify if the errors are additive or multiplicative.

# Impact on the gluon PDF



The central CT10 NNLO uses the  $D$  method,  $\mu = p_T$  for Tevatron jets, which softens large- $p_T$  jet cross sections and may compensate for the missing NNLO correction.

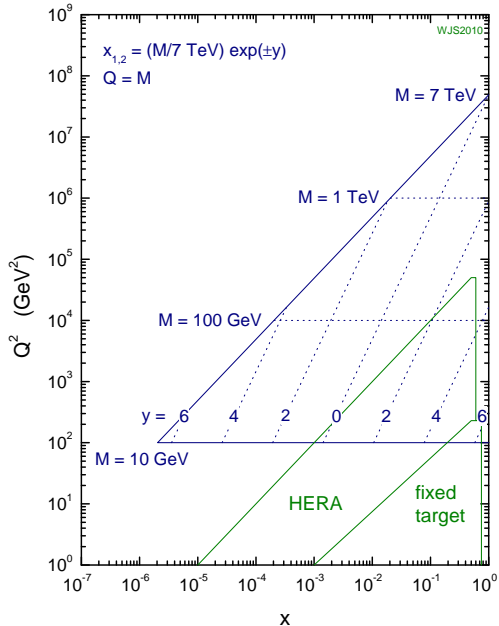
Extended  $T$  method is used for other experiments (which have the NNLO correction).

CT10 NLO cross sections use the ext.  $T$  method throughout.

The NNLO error band encloses parametrizations obtained with the extended  $T$  method for all expts., other QCD scales for jets, and no jets in the fit. No d'Agostini's bias was detected for fixed  $\alpha_s(M_Z)$ . [Some downward bias may exist with method  $D$  and free  $\alpha_s(M_Z)$ ].

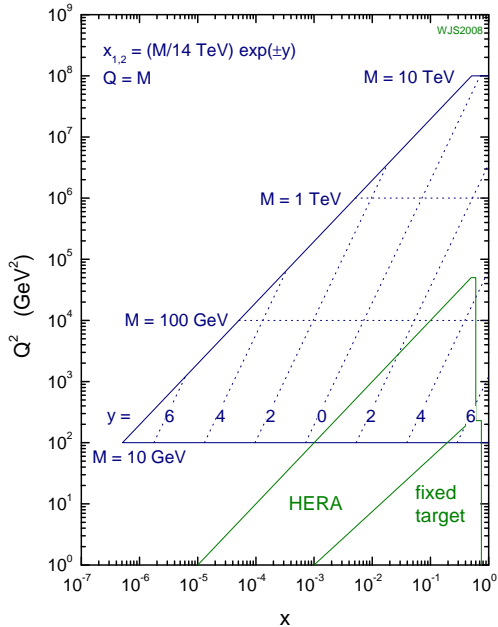
# Kinematics: LHC 7 TeV

7 TeV LHC parton kinematics



# Kinematics: LHC 14 TeV

LHC parton kinematics



# Kinematics: LHeC 14 TeV

## LHC parton kinematics

