# Inclusive and Semi-Inclusive Constraints on the Parton Distributions at the LHC and the Study of Hard Processes

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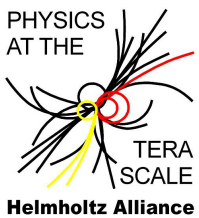
DESY

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# The Collaboration:

| | | | |
|---|---|---|---|
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S. Alekhin, F. Ellinghaus, A. Geiser, D. Hirschbühl, K. Lohwasser, + collaborators

# Main Research Objectives:

- Precise NNLO fits to the World DIS, DY, and di-muon data exist and serve as a first input for all LHC measurements.
- Several measurements at the LHC are by now that precise that they influence the PDFs and the value of $\alpha_s(M_Z^2)$ directly.
- It is timely to consistently include precision LHC data into the World QCD analysis of hadronic hard scattering processes, based on a fully consistent theoretical description.
- This requires close collaboration of experimental and theory groups working on the relevant processes.
- The analyses have to be performed using solid statistical methods and have to account for the experimental systematics as accurately as possible.
- The major goal consists in a thorough description of the
  - NNLO PDFs (supplemented by resummations)
  - NNLO $\alpha_s(M_Z^2)$ (perhaps even from LHC data only)
  - NNLO precision for $m_c, m_b, m_t$.
- Contribute to the physics at LHC as The Machine of the present era, also under the precision aspect.

# Hadronic $W^{\pm}$ production, charged current DIS

[DESY, CMS; Mainz, ATLAS, DESY, TH; Hamburg, TH]

- Allow stringent checks on the $u_v - d_v$ and $d/u$-distributions and are sensitive to the $s$-quark density; $Wc$ final state!
- The reactions have sensitivity also on the $c$- and $b$-distributions, requiring partly new calculations. Higher order corrections to charged current DIS will be provided to allow for an improved analysis of these data.
- The inclusive and differential $W^{\pm}$ cross sections measured at LHC will be incorporated into the fit.

# $Z$-production and off-resonance Drell-Yan

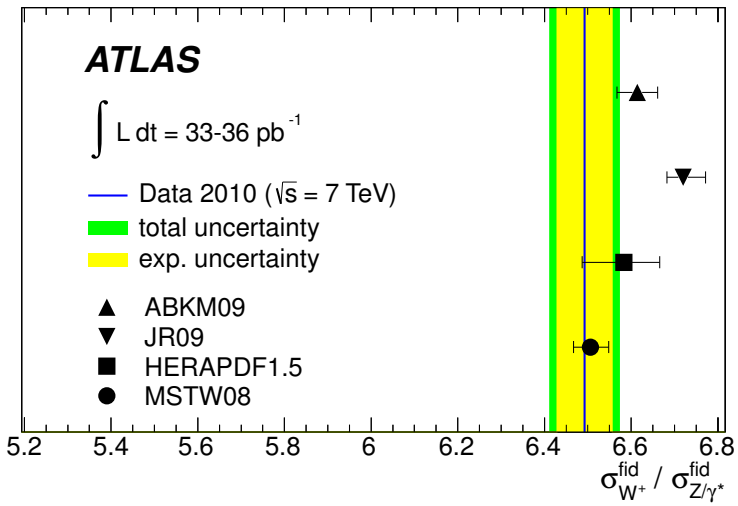
[DESY, CMS; Mainz, ATLAS, DESY, TH; Hamburg, TH]

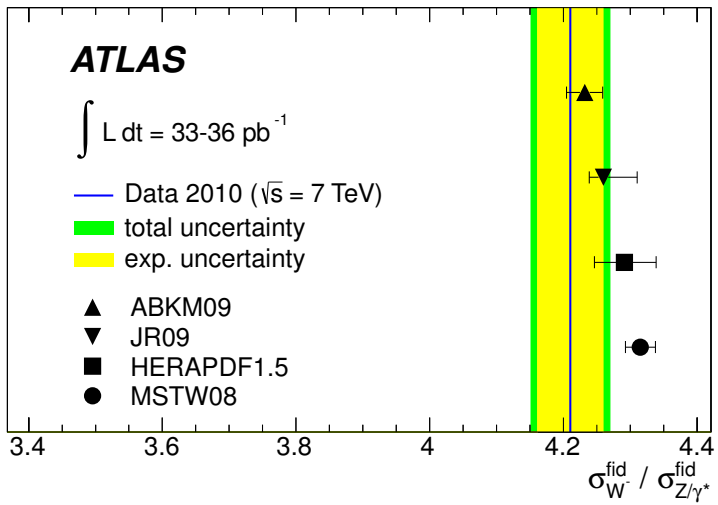
- Relevant for an improved determination of the $\bar{d} - \bar{u}$ distributions and the strange-quark distributions, also using the $W^{\pm}/Z$-ratios.
- Of key importance since together with the known valence quark distributions an important combination can be measured for which the 2nd moment can be determined on the lattice, allowing for an ab-initio QCD tests.
- Off-resonance Drell-Yan process allows to access the yet unexplored region of larger values of $x$ for the sea-quark distributions.
- Using the forward-backward asymmetry the weak mixing angle can be determined. Here the dominant experimental uncertainty is given by the PDF-errors.

# $W^{\pm}$ and $Z^0$ production cross sections at the LHC (NNLO)

## Sea Quarks:

Recent measurements of $W^{\pm}$ and $Z$-production cross sections at ATLAS arXiv:1109.5141: much improved systematics; use fiducial region only.



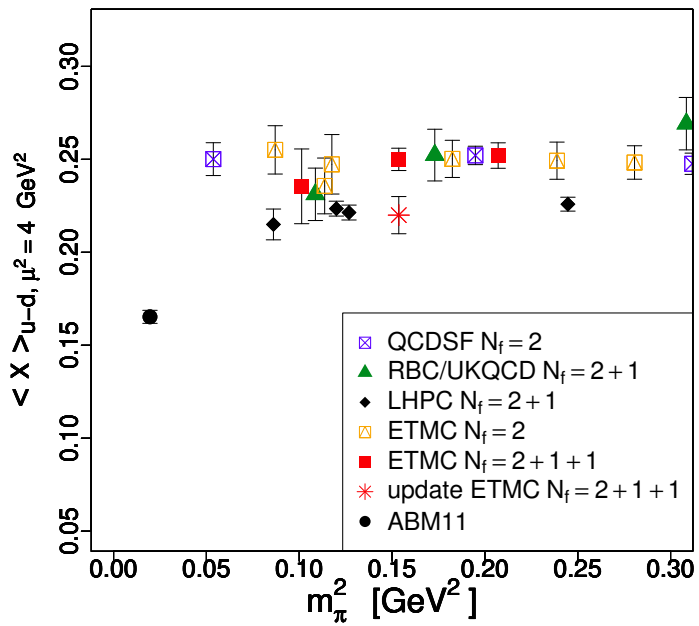




$W^{\pm}/Z$ cross section ratios will constrain parton distributions:
ATLAS, CMS, LHCb
Similarly, this is expected from off-resonance Drell-Yan data.
$\Longrightarrow$ quark, anti-quark sensitivity
$\Longrightarrow$ 5 $fb^{-1}$ on tape will lead to brilliant differential distributions.

# Moments of PDFs: perturbative extraction vs lattice

## Valence Quarks:

World Summary of the 2nd NS moment (Dinter, Drach et al.):




## Collaboration between NIC & Theory

Simulations at still smaller pion masses needed

Further NS moments

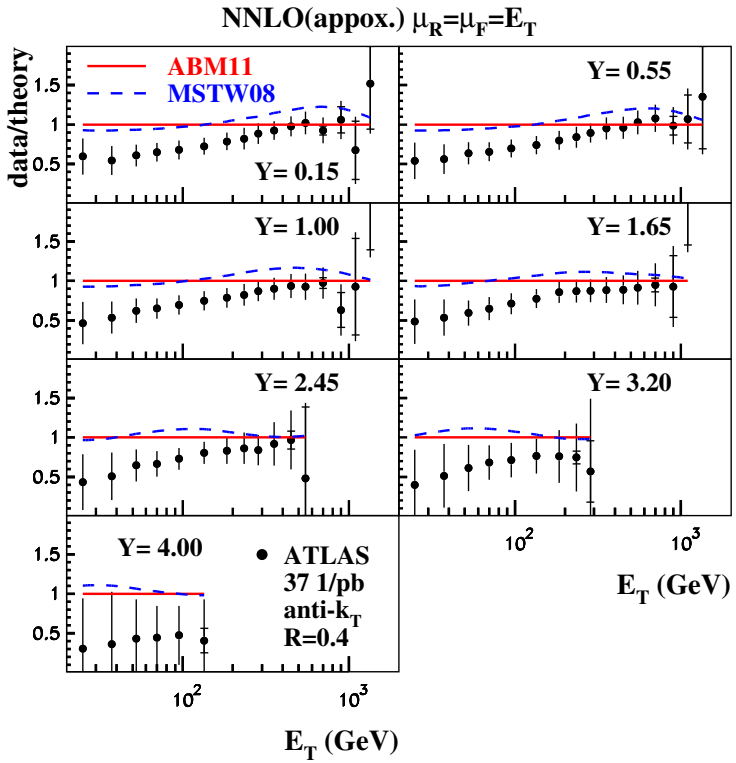
# Inclusive jets, di- and multijets

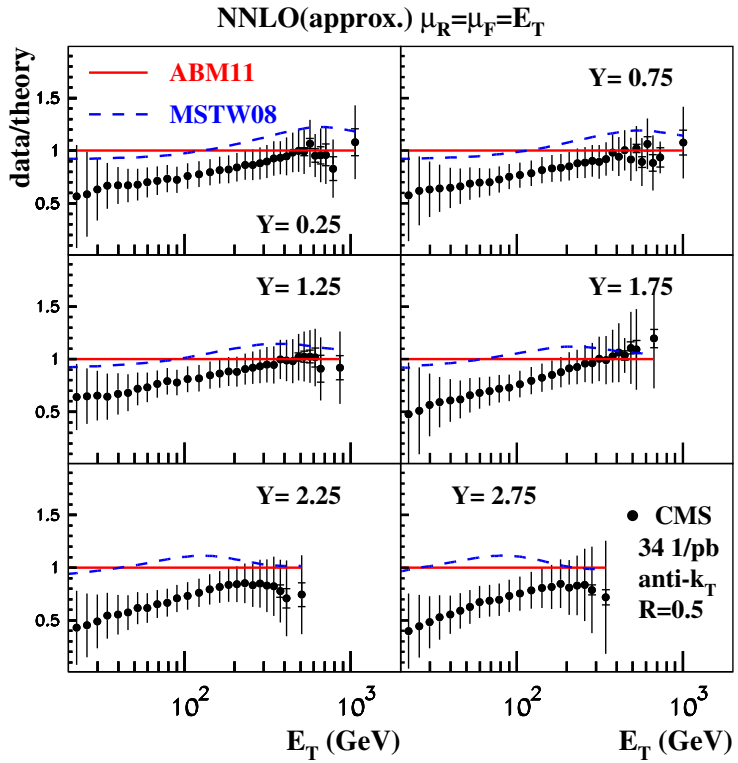
[Karlsruhe, CMS; Mainz, ATLAS; DESY, TH; Hamburg TH]

- The measurement of single, di- and multi-jet final states will improve the present knowledge of the gluon density and $\alpha_s(M_Z^2)$ significantly.
- LHC data are systematically better than those taken at Tevatron (much wider kinematic region)
- Concentrate on the hard part, $p_\perp > 100$ GeV
- NNLO production cross sections are not yet available, but upcoming.
- First goal: Sudakov-resummation of the NLO cross sections for large $E_T$
- Recent first NLO results: CMS 3/2- jet rates :

  $\alpha_s(M_Z^2) = 0.1135 \pm 0.0096,$ MSTW
  $\alpha_s(M_Z^2) = 0.1143 \pm 0.0064,$ NNPDF
  $\alpha_s(M_Z^2) = 0.1130 \pm 0.0080,$ CT10

# LHC jet data (NLO +resum.) and PDFs




- ATLAS and CMS data agree rather well.
- The jet data prefer a smaller gluon at large $x$.

# ATLAS jet data and ABM11

## Gluons:

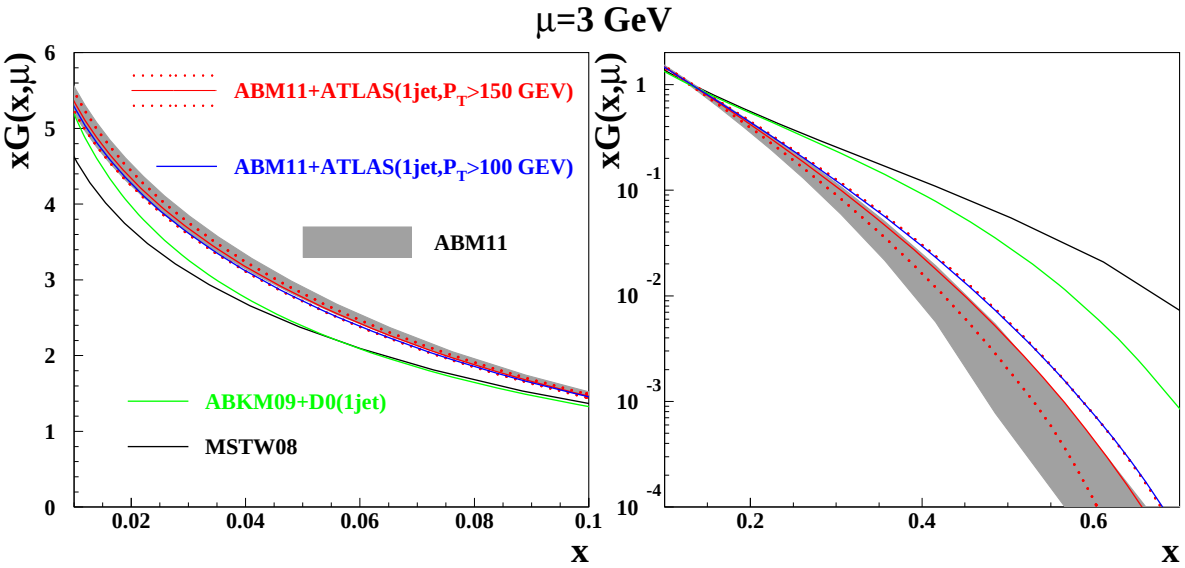



Figure 28: Gluon distribution obtained by including the ATLAS jet data into the ABM11 analysis.

$\chi^2/\text{NDP} = 55/55$; $p_\perp > 150$ GeV
$\alpha_s(M_Z) = 0.1134(11)$ ABM $\rightarrow 0.1141(8)$ + ATLAS jets

# Inclusive and differential $t\bar{t}$ production

[DESY CMS, Hamburg, TH]

- Sensitive to the gluon and inclusive sea quark densities, including larger values of $x$ (limited virtualities)
- Measurement of $m_t$, consistent with the RGE of QCD at highest precision.
- Some sensitivity to the $b$-quark density,
- Ongoing computation of the differential NNLO corrections.

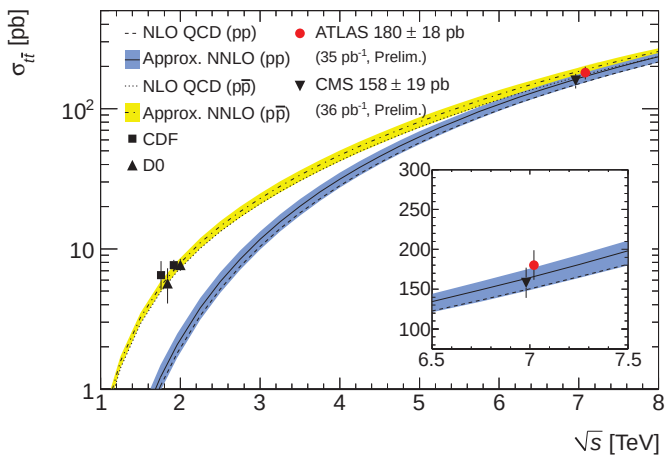



Figure 4: Measurements of $\sigma_{t\bar{t}}$ from ATLAS and CMS in $pp$ collisions, and CDF and D0 in $p\bar{p}$ collisions, compared to theoretical predictions assuming a top mass of 172.5 GeV as a function of $\sqrt{s}$. The present result is indicated by the red circle.

# Single top production

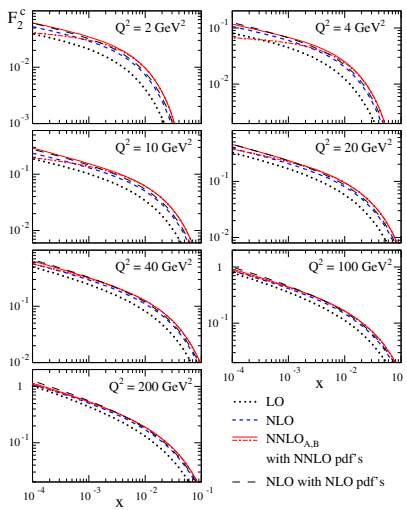
[Wuppertal, ATLAS; DESY, CMS]

- Sensitive to the gluon distribution in a mass range similar to the one for the present Higgs-boson search $\Longrightarrow$ direct constraints.
- By measuring the single top-quark and single top-antiquark cross sections separately and forming their ratio $R_t$ (expected to be roughly equal to two); sensitivity to the $u$-and $d$-quark at intermediate $x$.
- Extend the measurement to be differential in certain sensitive variables.
- Sensitivity to the cross the $b$-distribution and at high luminosities.

# Improved values for $m_c$ and $m_b$

[DESY, CMS; Wuppertal, ATLAS, DESY, TH; Hamburg, TH]

- $F_2^{c\bar{c}}, F_2^{b\bar{b}}$ will allow to measure $m_c$ and $m_b$ at a higher precision.
- Further sensitivity in analyses of the $Wb\bar{b}$ and $Zb\bar{b}$ final states at the LHC.
- The more accurate values of $m_c$ and $m_b$ will reduce the present uncertainties of the $W$- and $Z$-boson production cross sections.
- Alekhin, JB, Daum, Lipka, Moch :
  $m_c(m_c) = 1.24 \pm 0.03$ exp. $^{+0.03}_{-0.02}$ sc. $^{+0.00}_{-0.07}$ th



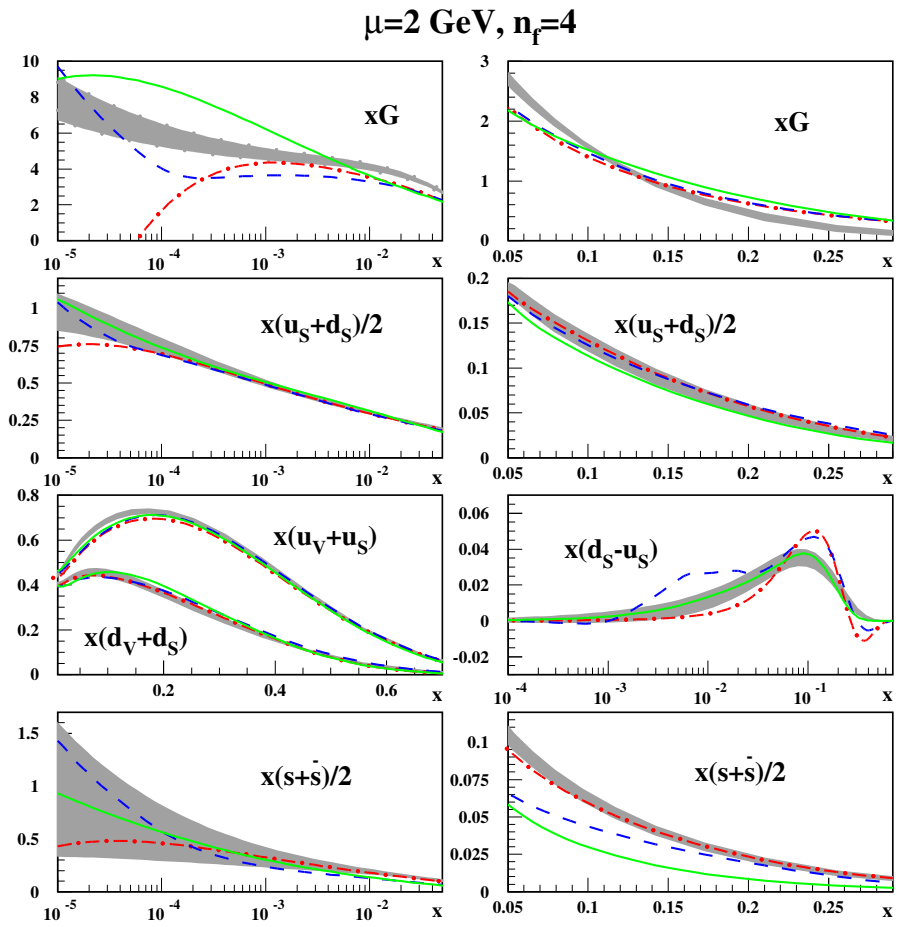

Theory: Ablinger, Bierenbaum, JB, De Freitas, Hasselhuhn, Klein, Round, Raab, Schneider, Wißbrock; Phenomenology: Kawamura, Lo Presti, Moch, Vogt [1205.5727]

# Global PDF-fits based on DIS and LHC data

[DESY, TH; Hamburg, TH]

- The code `OpenQCDRad` will be steadily extended; grid-processing of the various sets of LHC data.
- Implementation of $W, Z$- and Drell-Yan data and processing of jet-data from ATLAS and CMS.
- Here an important issue consists in the thorough account for the systematic errors.
- Analyses of this kind will be performed in close contact to the experimental groups.
- The newly obtained PDFs and $\alpha_s$-values, including correlated errors, will be made available to the participating groups continuously.

# PDFs for the LHC




ABM11 PDFset [1202.2281]: Comparison of ABM (grey) with MSTW (red), JR (green) NNPDF (blue).

# Measurement of $\alpha_s(M_Z)$

$\alpha_s(M_Z^2)$ from NNLO DIS(+) analyses

| | $\alpha_s(M_Z^2)$ | |
|---|---|---|
| BBG | $0.1134\ ^{+0.0019}_{-0.0021}$ | valence analysis, NNLO |
| GRS | $0.112$ | valence analysis, NNLO |
| ABKM | $0.1135 \pm 0.0014$ | HQ: FFNS $N_f = 3$ |
| JR | $0.1124 \pm 0.0020$ | dynamical approach |
| JR | $0.1158 \pm 0.0035$ | standard fit |
| MSTW | $0.1171 \pm 0.0014$ | |
| ABM | $0.1147 \pm 0.0012$ | FFNS, incl. combined H1/ZEUS data |
| $\text{ABM}_J$ | $0.1134 - 0.1149 \pm 0.0012$ | Tevatron jets (NLO) incl. |
| ABM11 | $0.1134 \pm 0.0011$ | |
| CTEQ | $0.118 \pm 0.005$ | |
| NNPDF | $0.1174 \pm 0.0006 \pm 0.0001$ | |
| Gehrmann et al. | $0.1131 \pm 0.0028 \pm 0.0022$ | $e^+e^-$ thrust |
| Abbate et al. | $0.1135 \pm 0.0011 \pm 0.0006$ | $e^+e^-$ thrust |
| BBG | $0.1141\ ^{+0.0020}_{-0.0022}$ | valence analysis, $\text{N}^3\text{LO}$ |

$$\Delta_{\text{TH}}\alpha_s = \alpha_s(\text{N}^3\text{LO}) - \alpha_s(\text{NNLO}) + \Delta_{\text{HQ}} = +0.0009 \pm 0.0006_{\text{HQ}}$$

Difference to MSTW and NNPDF understood: Singlet/NS HT and treatment of exp. systematics.

# $\alpha_s(M_Z^2)$

$\alpha_s(M_Z^2)$ from further processes

| | $\alpha_s(M_Z^2)$ | |
|---|---|---|
| 3 jet rate | $0.1175 \pm 0.0025$ | Dissertori et al. 2009 |
| $Z$-decay | $0.1190 \pm 0.0026$ | BCK 2008 |
| $\tau$ decays | $0.1212 \pm 0.0014$ | Pich 2010 |
| $\tau$ decays | $0.1202 \pm 0.0019$ | BCK 2008 |
| $\tau$ decays | $0.1180 \pm 0.0008$ | Beneke, Jamin 2008 |
| lattice | $0.1183 \pm 0.0008$ | HPQCD 2008 (more to come) |
| Average 2011 | $0.1185 \pm 0.0008$ | S. Bethke |

Despite the statistical and systematic errors are getting smaller, there is no final consensus on the value of $\alpha_s(M_Z^2)$ yet.

# Theory Technologies

- Various of the ongoing theory calculations require innovative technologies to achieve analytic and/or precise numerical results.
- Stückelberg-Feynman Project :
  Integrate as you integrate can (in analytic form).
- From the side of QFT : comparable to the Human Genome Project etc.: $\Longrightarrow$ Structural Spell of the Microcosm.
- New function classes are given birth.
- Close connections to : Modern summation theory, integration theory, function field creation, number theory, algebraic geometry, theory of motives, free Lie algebras, iterated integrals, cryptography, combinatorics, high performance computer algebra (reaching peta terms!), higher transcendental functions, new function classes ...
- Intense co-operation with mathematicians and computer-algebraists are of central importance.
- Feynman graphs create new mathematics.
- Results provide solutions also in other fields, e.g. String Theory.

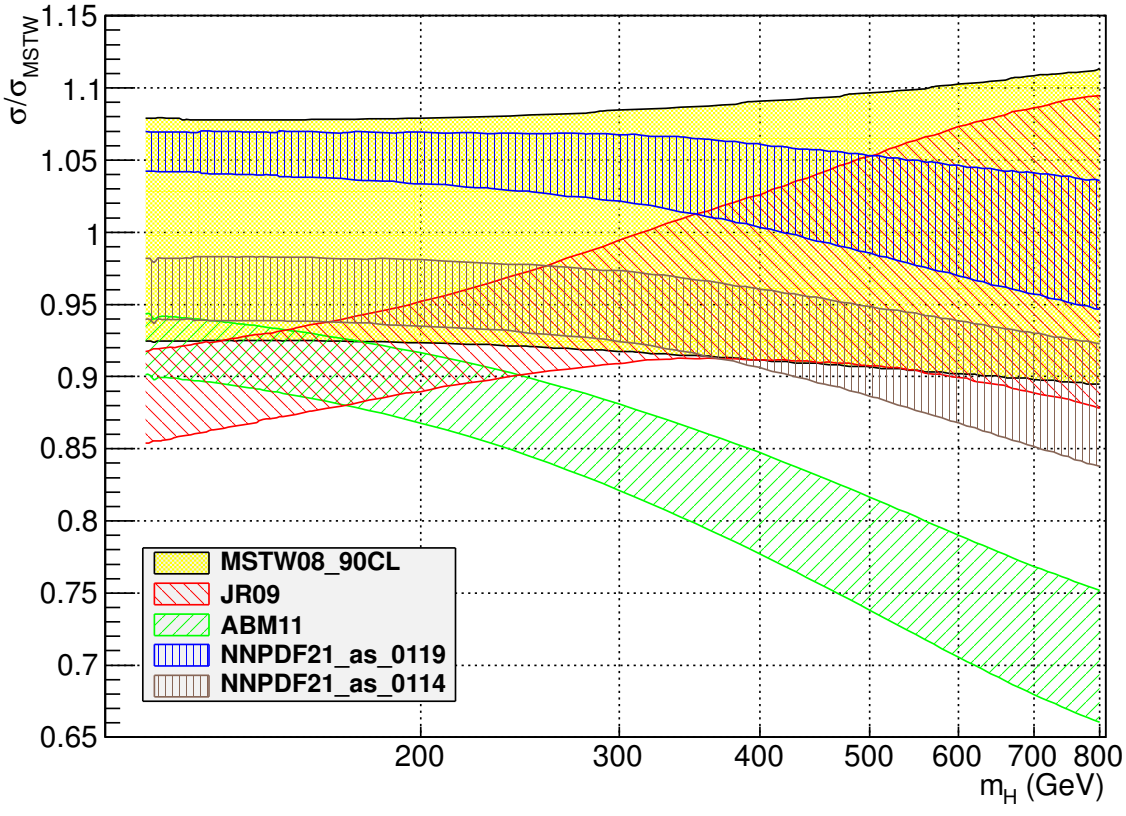
# Benchmarking at NNLO

- Continuous benchmarking with HERAPDF, JR, (M)MSTW(W), NNPDF, CTEQ(CT10), including thorough monitoring to assure the correct use of theoretical results for the scattering cross sections.
- At precisions of $O(1\%)$ enormous care is needed w.r.t.
  - high precision numerics
  - high precision implementation of reliable statistics methods
  - detailed treatment of systematic errors
  - detailed account of several non-perturbative effects:
    Higher twist, special small $x$ behaviour, other power corrections, nuclear wave functions etc.
- Comparisons have to include detailed correlated/uncorrelated error treatment and fit correlations.

  As well-known, simple uncorrelated variations of NNLO pdfs and $\alpha_s$ will therefore, at this precision, problematic. [1211.5142] $\Longrightarrow$ $\chi^2$-values are very different; $\Longrightarrow$ Strong biases.
- To be replaced by consistent analyses accounting for the above aspects.

# Higgs boson production

$\Longrightarrow$ Whatever the $\sim 125$ GeV particle may be, it should be described as precise as possible: $\propto \alpha_s^2(xG(x, M_H^2))^2$




Anastasiou et al. 2011.

Precision physics requests the close cooperation of experimenters and theorists, to get the utmost out of valuable data & to unravel new physics.

During the 2 years to come stringent improvements of QCD key distributions and parameters may be achieved.

Thank you for funding this initiative.