Accurate QCD predictions for the full exploitation of LHC Run II

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The LHC era
A truly exciting time

- SM of particle physics well consolidated but necessarily incomplete theory
- **LHC Run I**: Higgs boson, most important discovery in particle physics in 20 years! Its very existence & the extraordinary success of SM opens a number of compelling questions (G. Altarelli: The Higgs and the excessive success of the SM, 2014)
- **LHC Run II**: At the forefront of exploration of high energy frontiers
- Precise & Accurate theoretical predictions are key not to miss any opportunity

4th July 2012, CERN: Guido celebrating the discovery of the Higgs
Theory predictions
Divide et impera

Proton Proton $X$-section $= \sum_{I,J=1}^{n_f} \sum_{I,J=1}^{n_f} \text{Probabilities of finding partons } I,J \text{ with momenta } x_1, x_2 \times X$-section for partons with momenta $x_1, x_2$
Collinear factorisation

How did QCD evolve from a Lagrangian with property of asymptotic freedom to sophisticated tool for calculation of high energy processes?

Key work by G. Altarelli and G. Parisi (1977) by formulating the evolution of parton densities as a branching process with probabilities determined by the splitting functions and proving that the latter are a property of the theory and do not depend on the process.

G. Altarelli (2012) “The early days of QCD (as seen from Rome)”
K. Ellis (2016) “Guido Altarelli and the evolution of QCD”

LO  Dokshitzer; Gribov, Lipatov; Altarelli, Parisi, 1977

NLO - Floratos,Ross,Sachrajda; Floratos,Lacaze,Kounnas, Gonzalez-Arroyo,Lopez,Yndurain; Curci,Furmanski Petronzio, 1981

NNLO - Moch, Vermaseren, Vogt, 2004
Proton Proton X-section = \sum_{I,J=1}^{n_f} Proportions of finding partons I,J with momenta $x_1, x_2$ \times X-section for partons with momenta $x_1, x_2$

Parton Distribution Functions
The NNPDF approach
A new powerful approach

- **Monte Carlo** representation of Probability Density in PDF space
- **Neural Networks**: each independent PDF associated to unbiased and flexible parametrization given by NN

- Precise error estimate not driven by theoretical prejudice
- No need to add new parameters when new data are included
- Statistical interpretation of uncertainty bands
- Possibility to include data via re-weighting: no need to refit

The NNPDF adventure
It all began for me on a sunny day in Edinburgh

Maria Ubiali — SUPA Prize Student

Maria Ubiali, a SUPA Prize Student, comes from Italy. She graduated in Milan in July 2005, her final work in the area of perturbative quantum chromo dynamics. In particular she dealt with the Landau pole in the context of resummation of large enhanced contributions in the soft region. She is now researching this subject in depth in the field of the parton distributions functions with her supervisors, Richard Ball and Luigi Del Debbio.

Both Maria and her husband are doing their PhD in Scotland. They started to submit applications for studentships in January 2006 and were planning to get married in September 2006.
The NNPDF adventure
Baby delivered and taking his first steps

**NNPDF1.0:** First NNPDF set - only DIS data

**NNPDF1.2:** Determination of the proton strangeness: solved NuTeV anomaly

2008 **NNPDF1.0:**

2009 **NNPDF1.2:**
The NNPDF adventure
A fast-paced growth

2008

**NNPDF1.0**: First NNPDF set - only DIS data

2009

**NNPDF1.2**: Determination of the proton strangeness: solved NuTeV anomaly

2010

**NNPDF2.0**: First NNPDF global set

2011

**NNPDF2.1**: Heavy quark mass effects

2012

Reweighting PDFs

2013

**NNPDF2.3**: First PDF set with LHC data

2014

**NNPDF2.3QED**: First PDF set with fitted photon PDF

2015

**NNPDF3.0**: First NNPDF global set

2016

**NNPDF3.1**: First PDF set with fitted charm

2017

**NNPDF3.2**: First PDF set with threshold resummation

2018

**NNPDF3.3**: First PDF set with fitted charm

2019

**NNPDF4.0**: First PDF set validated with closure test

2020

**NNPDF4.1**: First PDF set with fitted charm
The NNPDF adventure
and the family gets bigger

2008
**NNPDF1.0:** First NNPDF set - only DIS data

2009
**NNPDF1.2:** Determination of the proton strangeness: solved NuTeV anomaly

2010
**NNPDF2.0:** First NNPDF global set

2011

2012
**NNPDF2.1:** Heavy quark mass effects

2013
**NNPDF2.3:** Determination of $\alpha_S^{f}$ from PDF fit

2014
**NNPDF2.3QED:** First PDF set with fitted photon PDF

2015

2016
**NNPDF3.0:** First PDF set validated with closure test

2017
**NNPDF3.1** and the family gets bigger
The PDF adventure
A not-so-obvious success

“The beautiful ‘naive’ parton model of Bjorken, Feynman and others has by now evolved into the ‘QCD improved’ parton model. This powerful language has become such a familiar and and widespread tool for everyday practice in high energy physics that one is led to take all its new successes as granted and in a way obvious.”

Plenary talk at a conference in Bari, 1985
Quoted by R. K. Ellis at “Guido Altarelli Memorial Symposium”, 2016
The PDF adventure
Looking at the future at the precision frontier

- Exploit precise **LHC data** to reduce PDF uncertainties
- Explore potential constraints from **future colliders**
- Reduce & measure residual **theory uncertainty** in PDF fits
- **Resummations** in PDF fits (large-$x$, small-$x$, $p_T$), PS effects
- If **new physics** is there, are we absorbing them in PDFs?

Issues so far ignored have now become crucial at the current precision frontier
Proton Proton X-section = \sum_{I,J=1}^{n_f} \text{Probabilities of finding partons } I,J \text{ with momenta } x_1, x_2 \otimes X\text{-section for partons with momenta } x_1, x_2

Heavy quark schemes
Heavy quarks
A path towards a deeper understanding

Proton Proton $X$-section

$$\sum_{I,J=1}^{n_f} \text{Probabilities of finding partons } I,J \text{ with momenta } x_1, x_2 \otimes X\text{-section for partons with momenta } x_1, x_2$$

- Heavy-quark-initiated processes crucial at the LHC, from flavour physics to Higgs searches and as a window to new physics
- Two ways or schemes of performing calculations: heavy quark may belong to proton or may be created as massive particles the final state

At LHC:

$$\Lambda_{\text{QCD}} \ll m_b \ll M (m_t, m_H, m_Z)$$

100 TeV collider top quark plays role of bottom
Heavy quarks
A path towards a deeper understanding

4F scheme

- It does not resum possibly large logs, yet it has them explicitly
- Computing higher orders is more difficult
- Mass effects are there at any order
- Straightforward implementation in MC event generators at LO and NLO

Collinear log
\[ \alpha_s(M^2) \log \left( \frac{M^2}{m_b^2} \right) \]

5F scheme

- It resums initial state large logs into b-PDFs leading to more stable predictions
- Computing higher orders is easier
- \( p_T \) of bottom enters at higher orders
- Implementation in MC depends on the gluon splitting model in the PS

\[ \sum_{k=1}^{\infty} \left[ \alpha_s(\mu_F) \log \left( \frac{\mu_F^2}{m_b^2} \right) \right]^k \]
Heavy quarks
A path towards a deeper understanding

➡ Why do the two schemes often lead to very different results?
➡ Why differences become smaller is a softer scale is used?
➡ For inclusive observables: how to reconcile/combine the two schemes to maximise the pros?
➡ For exclusive/differential observables: which one to use?
Heavy quarks
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Why differences become smaller is a softer scale is used?
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For exclusive/differential observables: which one to use?
Heavy quarks
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All these questions can be answered by taking into account two main results.

1. Resummation effects of initial state collinear logs into the b-PDFs are important only at large \( x \approx \frac{M^2}{S_{\text{had}}} \)

\[
b_{\text{approx}}(O(\alpha_s^2)) / b_{\text{NLO}}
\]

\[
b_{\text{approx}}(O(\alpha_s))
\]

\[
b(\xi, \mu^2) = \frac{\alpha_s}{2\pi} \log \left( \frac{\mu^2}{m_b^2} \right) \int_{\xi}^{1} \frac{dy}{y} \ P_{qqg} \left( \frac{\xi}{y} \right) \ g(y, \mu^2) + O(\alpha_s^2)
\]

F. Maltoni, G. Ridolfi, MU, JHEP 1207 (2012)
M. Lim, F. Maltoni, G. Ridolfi, MU, JHEP 1609 (2016)
Heavy quarks
A path towards a deeper understanding

All these questions can be answered by taking into account two main results.

1. The possibly large ratios $M^2/m_b^2$ are always accompanied by universal phase space factors that lead to their suppression.

For $V+b$ production,

$$\log \left( \frac{M_V^2}{m_b^2} \frac{(1 - z)^2}{z} \right)$$

$$z = \frac{M_V^2}{\hat{s}}$$

$F. Maltoni, G. Ridolfi, MU, JHEP 1207 (2012)$

$M. Lim, F. Maltoni, G. Ridolfi, MU, JHEP 1609 (2016)$
Heavy quarks
A simple explanation, a rich phenomenology

Heavy Charged Higgs boson production excellent case study for QCD

✓ Reconciled 4F and 5F scheme predictions for **total cross section** by choosing judicious scales
  Flechl, Klees, Kramer, Spira, **MU**
  Phys.Rev. D91 (2015) 7

✓ New 4FS calculation and thorough comparison between **differential distributions** in 4F and 5F schemes
  Degrande, **MU**, Wiesemann, Zaro
  JHEP 1510 (2015) 145

✓ NLO cross section for **intermediate mass** charged Higgs boson using complex mass scheme for top quark
  Degrande, Frederix, Hirschi, **MU**, Wiesemann, Zaro
  arXiv: 1607.05291

Example n.1:

- Many new physics models require two Higgs doublets, leading to five physical scalar Higgs bosons, among which mass degenerate $H^\pm$
- **2HDMs** represent the simplest extension of SM
- The discovery of a **charged Higgs** boson would be a clear evidence of an extended Higgs sector beyond the SM
Heavy quarks
A simple explanation, a rich phenomenology

Example n.2:

- Higgs production in bottom-quark fusion is relevant especially in BSM scenarios in which the bottom-Higgs Yukawa coupling is enhanced.
- Predictions in the 4F and 5F schemes consistently combined in consistent matching by extending the FONLL formalism.

Conclusions

MANY THANKS

After more than 40 years since its early days QCD is still the key to explore the precision frontiers and spot any hint for new physics.

In this talk I focussed on Parton distribution function analyses and the understanding of heavy quark schemes as a window to probe the precision frontier and looking for something unexpected.

First BIG thank to Guido: without his work we could not even talk of global QCD analyses, parton evolution and QCD phenomenology in general!

Thanks to my family and my scientific “fathers” and “big brothers” (Giovanni Ridolfi, Stefano Forte, Fabio Maltoni, Alberto Guffanti, Andrea Piccione, Juan Rojo, Richard D. Ball, Luigi Del Debbio, Bryan Webber) without whom I would not be here + thanks to my fantastic collaborators.

Finally thanks to the Selection Committee and the DIS International Advisory Committee for this award!

And thanks to you for your patience and for listening to me twice today!!