Accurate QCD predictions for the full exploitation of LHC Run II

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Guido Altarelli Award - DIS 2017

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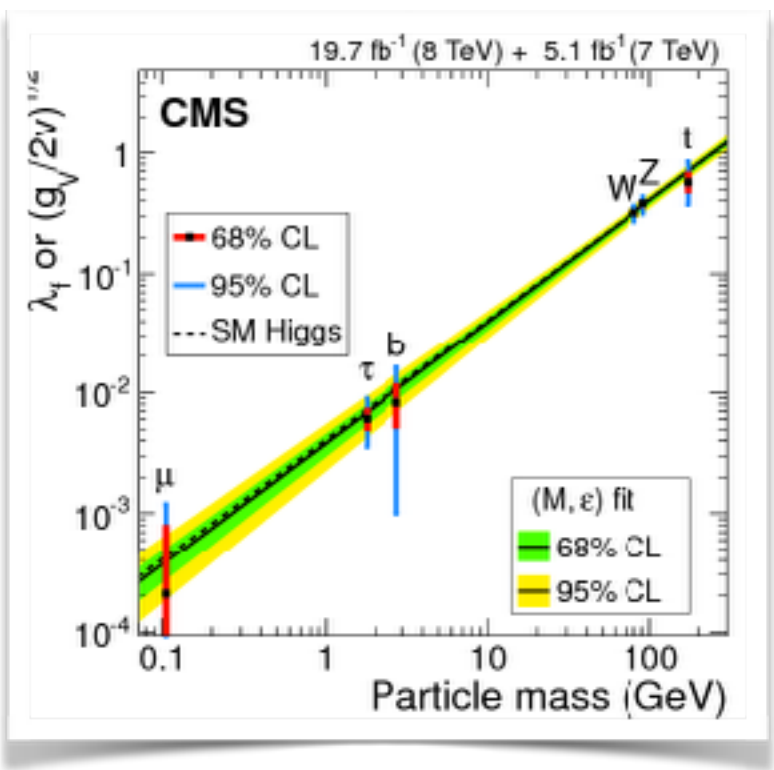
The LHC era

A truly exciting time

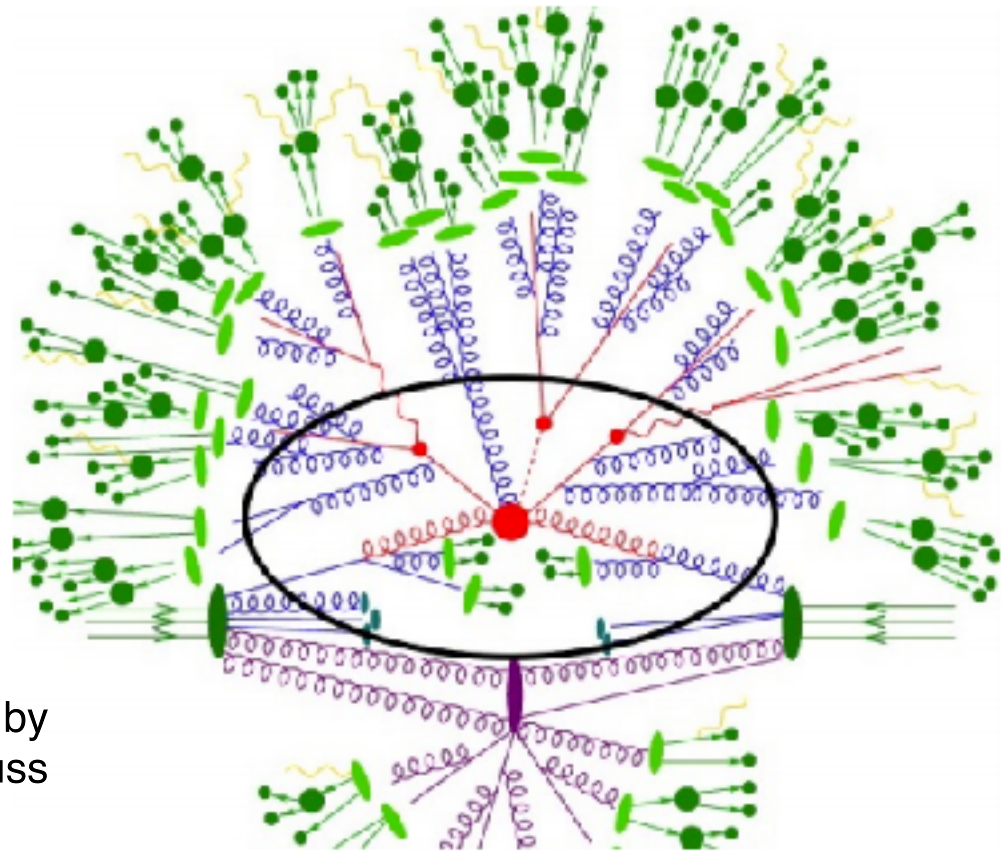
- SM of particle physics well consolidated but necessarily incomplete theory
- LHC Run I: Higgs boson, most important discovery in particle physics in 20 years! Its very existence & the extraordinary success of SM opens a number of compelling questions **(G. Altarelli: The Higgs and the excessive success 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



Picture by
F. Krauss

Factorization: Can isolate independent phases of the collision

- Parton distribution functions
- Hard scattering
- Parton shower
- Fragmentation
- Hadronisation, UE…

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

Collinear factorisation

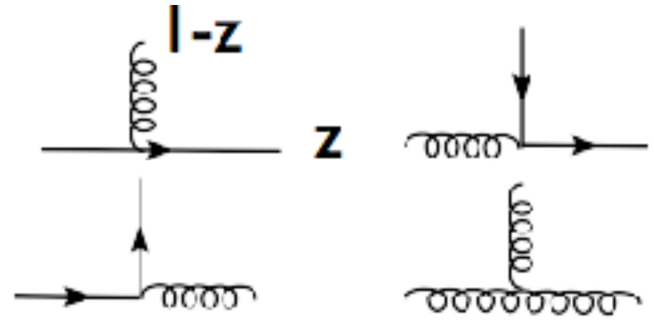
The Altarelli - Parisi (DGLAP) equations

- 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”

$$\frac{d}{dt}\begin{pmatrix} q_i(x,t) \\ g(x,t) \end{pmatrix} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \sum_{j=q,\bar{q}} \frac{d\xi}{\xi} \begin{pmatrix} P_{ij}\left(\frac{x}{\xi},\alpha_s(t)\right) & P_{ig}\left(\frac{x}{\xi},\alpha_s(t)\right) \\ P_{gj}\left(\frac{x}{\xi},\alpha_s(t)\right) & P_{gg}\left(\frac{x}{\xi},\alpha_s(t)\right) \end{pmatrix} \otimes \begin{pmatrix} q_j(\xi,t) \\ g(\xi,t) \end{pmatrix}$$

$$t = \log\frac{Q^2}{\mu^2}$$



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

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

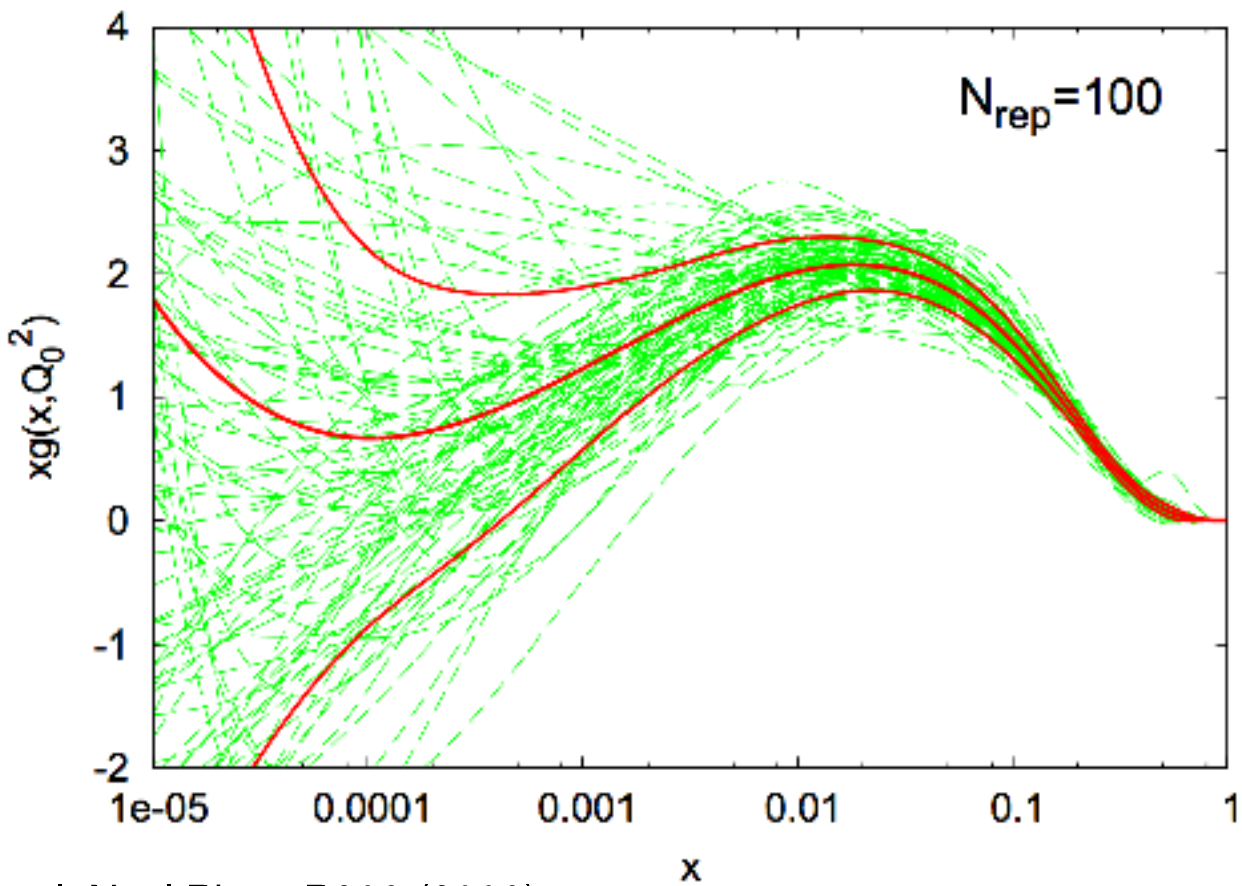
NNLO - Moch, Vermaseren, Vogt, 2004

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

Parton Distribution Functions

The NNPDF approach

A new powerful approach



R. Ball et al, Nucl.Phys. B809 (2009)

- **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

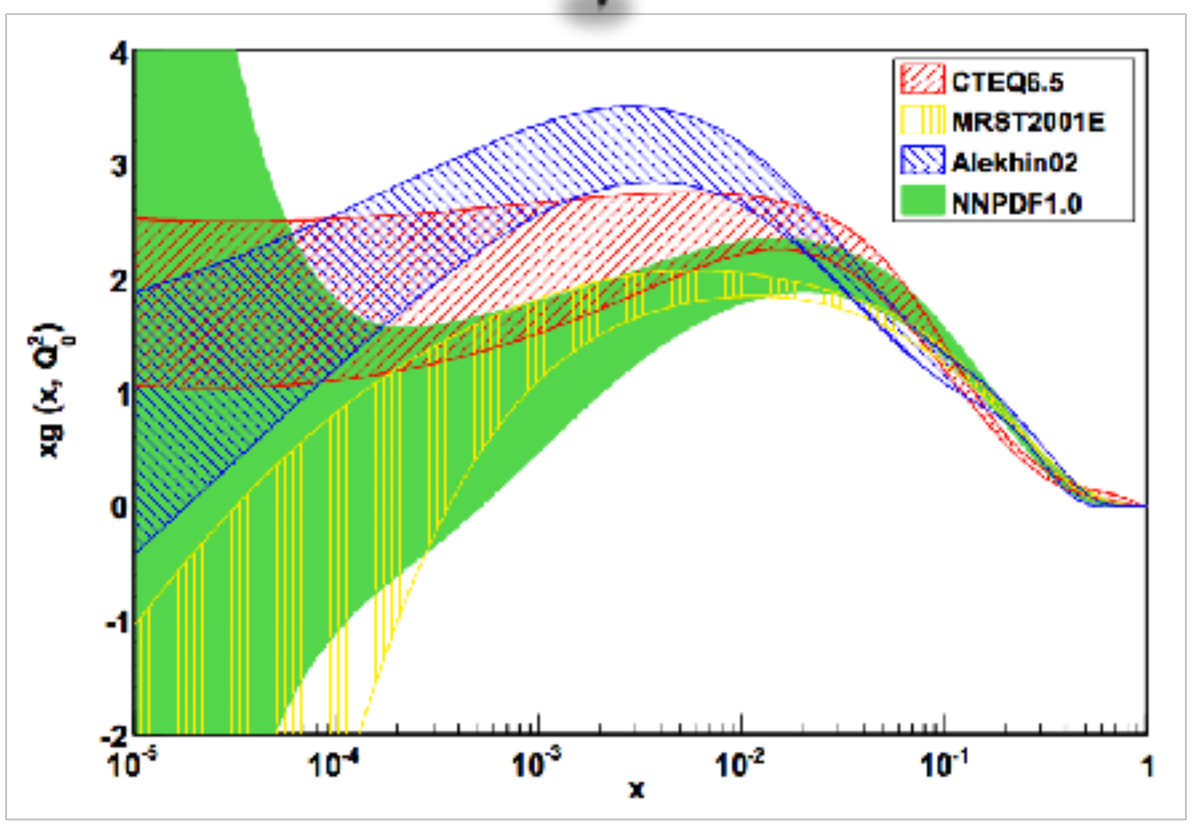
Maria and her husband are both studying for PhDs in Edinburgh

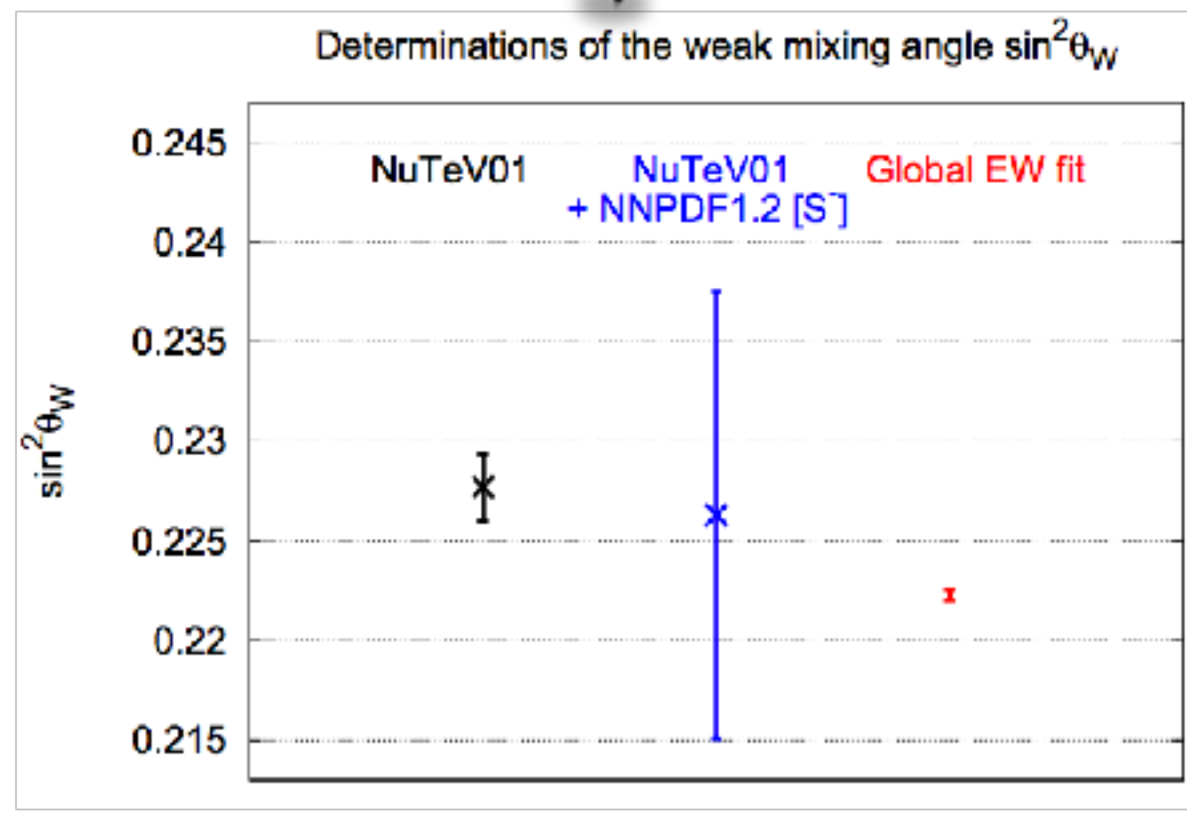
Maria Ubiali, a SUPA Prize Student, comes from Italy. She graduated in Milan in July 2005, her final work in the area of perturbative quantum chromo dynamics. In particular she dealt with the Landau pole in the context of resummation of large enhanced contributions in the soft region. She is now researching 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





2009 <u>**NNPDF1.2:**</u> Determination of the proton strangeness: solved NuTeV anomaly

2008 <u>**NNPDF1.0:**</u> First NNPDF set - only DIS data

The NNPDF adventure

A fast-paced growth

2017	NNPDF3.1 First PDF set with fitted charm
2016	First PDF set with threshold resummation
2015	NNPDF3.0: first PDF set validated with closure test
2014	NNPDF2.3QED: first PDF set with fitted photon PDF
2013	NNPDF2.3: first PDF set with LHC data
2012	Reweighting PDFs
	NNPDF2.1:Heavy quark mass effects
2011	Determination of α_S from PDF fit
2010	NNPDF2.0: First NNPDF global set
2009	NNPDF1.2: Determination of the proton strangeness: solved NuTeV anomaly
2008	NNPDF1.0: First NNPDF set - only DIS data

$$\sigma = \sum_{i,j}^{n_f} \sum_{\alpha,\beta}^{n_x} W_{ij\alpha\beta}\, f_i(x_\alpha, Q_0^2) f_j(x_\beta, Q_0^2)$$

The NNPDF adventure

and the family gets bigger

2017 **NNPDF3.1** Fi

2016 First PDF set

2015 **NNPDF3.0:** f

2014 **NNPDF2.3Q**

2013 **NNPDF2.3**: fir

2012 Reweighting PI

NNPDF2.1: He

2011 Determination

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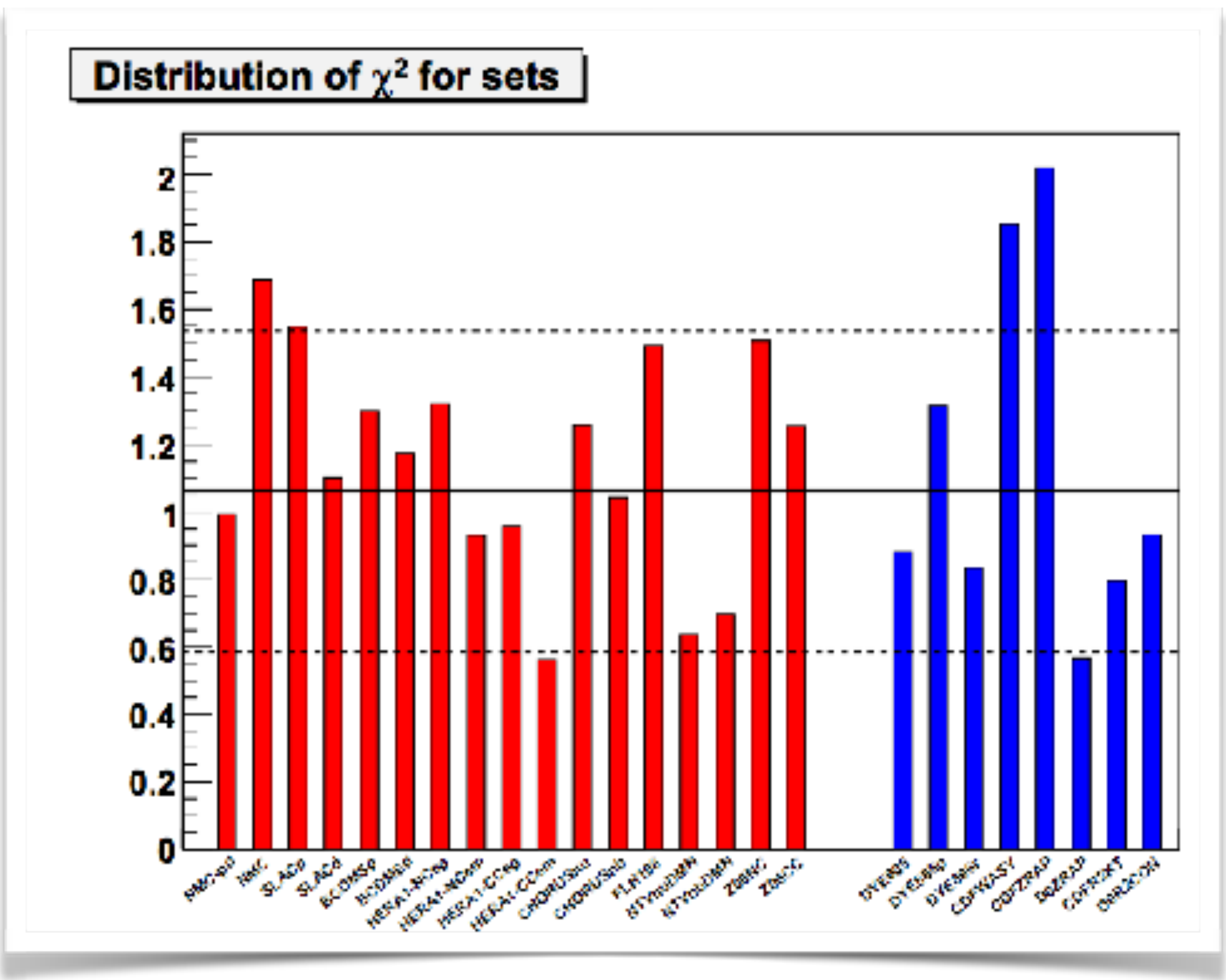
2009 **NNPDF1.2:** Determination of the proton strangeness: solved NuTeV anomaly

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

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

Reduce & measure residual **theory uncertainty** in PDF fits

Resummations in PDF fits (large-x, small-x, pT), PS effects

Explore potential constraints from **future colliders**

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

Heavy quark schemes

Heavy quarks

A path towards a deeper understanding

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

5F

4F

- 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

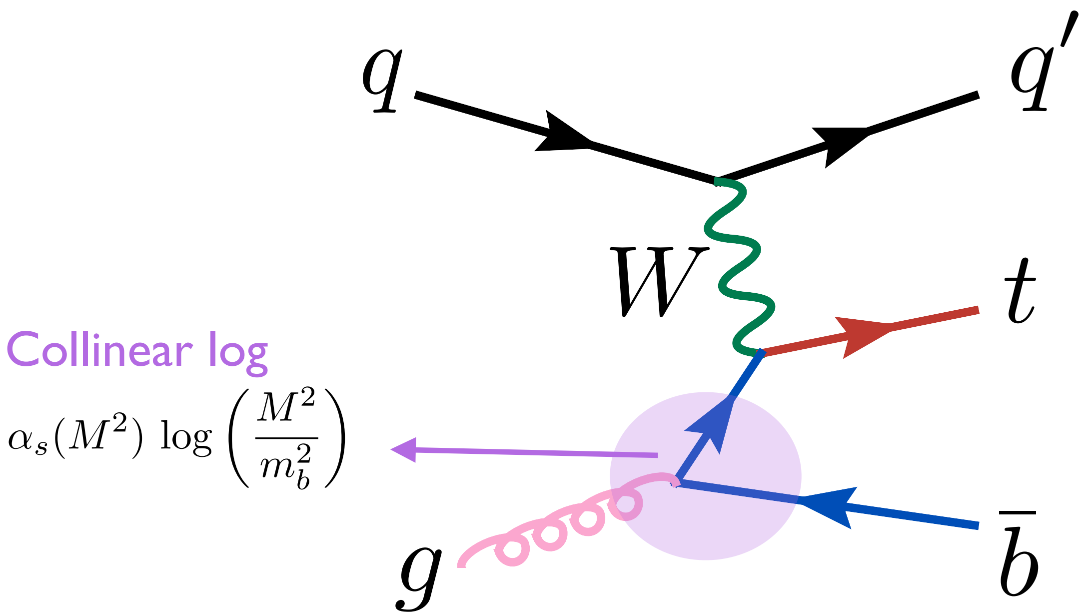
At LHC:

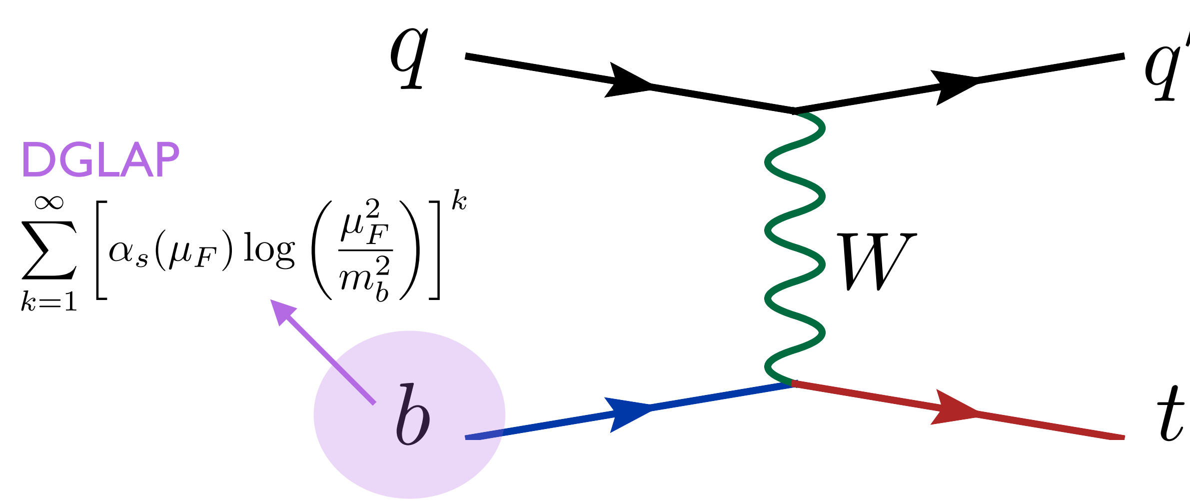
$\Lambda_{QCD} \ll m_b \ll M\ (m_t, m_H, m_Z)$

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

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

Heavy quarks

A path towards a deeper understanding

4F scheme

✗ It does not resum possibly large logs, yet
it has th
✗ Comp
✔ Mass
✔ Straig
event ge

5F scheme

✔ It resums initial state large logs into b-
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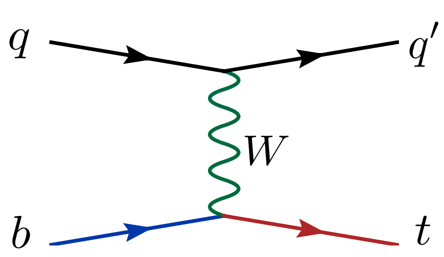
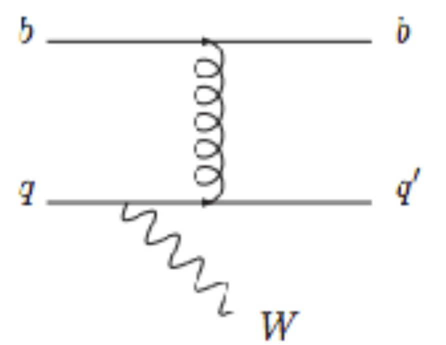
➡ Why do the two schemes often lead to very different results?
➡ Why differences become smaller is a softer scale is used?
➡ For inclusive observables: how to reconcile/combine the two schemes to maximise the pros?
➡ For exclusive/differential observables: which one to use?

Heavy quarks

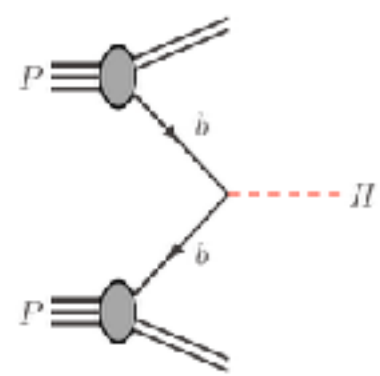
A path towards a deeper understanding



single top



b+V production



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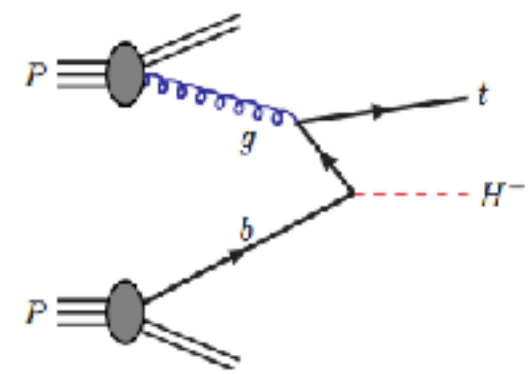

charged Higgs

4F scheme

5F scheme

✘ It does not resum possibly large logs, yet it has th…

✘ Comp…

✔ Mass…

✔ Straig… event ge…

✔ It resums initial state large logs into b- …ons …ers …n the

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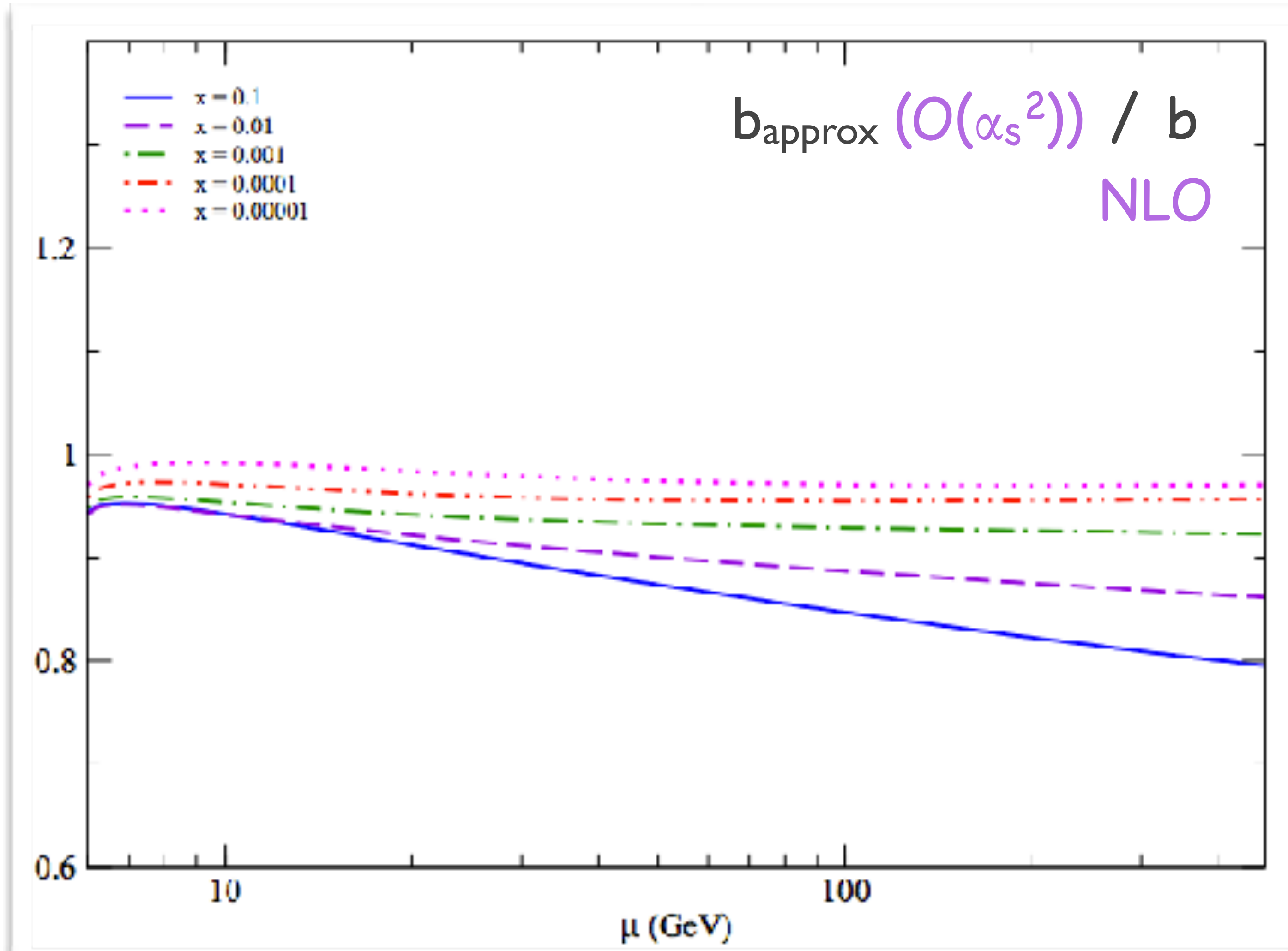
Heavy quarks

A path towards a deeper understanding

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

❶ Resummation effects of initial state collinear logs into the b-PDFs are important only at large $x \approx M^2 / S_{had}$



b_{approx} $(O(\alpha_s))$

$$b(\xi,\mu^2) = \frac{\alpha_S}{2\pi}\log\left(\frac{\mu^2}{m_b^2}\right)\int_\xi^1 \frac{dy}{y} P_{qg}\left(\frac{\xi}{y}\right) g(y,\mu^2) + \mathcal{O}(\alpha_S^2)$$

resummed logs in DGLAP evolution

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

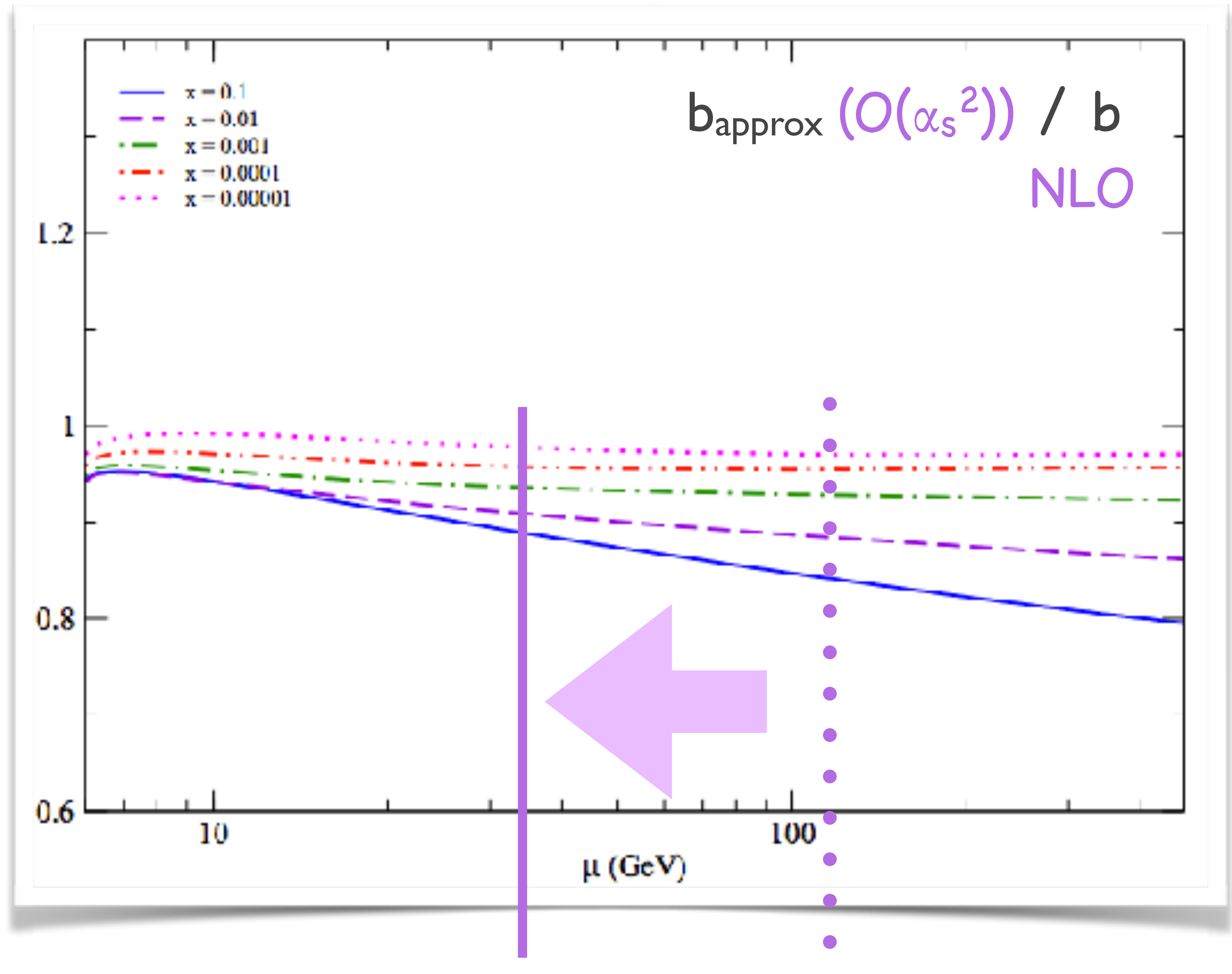
All these questions can be answered by taking into account two main results

❷ 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

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

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



$$\tilde{\mu}=M_V\sqrt{\left\langle\frac{(1-z)^2}{z}\right\rangle}$$

M_V

F. Maltoni, G. Ridolfi, <u>MU</u>, JHEP 1207 (2012)
M. Lim, F. Maltoni, G. Ridolfi, <u>MU</u>, 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

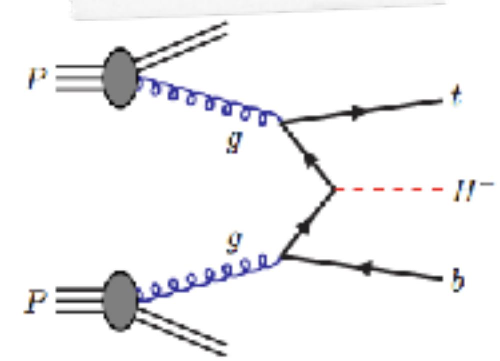
✓ New 4FS calculation and thorough comparison between **differential distributions** in 4F and 5F schemes
Degrande, MU, Wiesemann, Zaro
JHEP 1510 (2015) 145

✓ 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

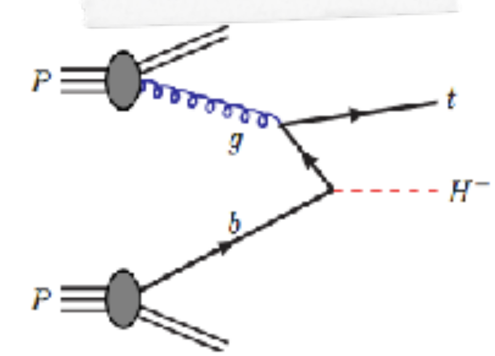
Example n.1:

- 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

4F scheme

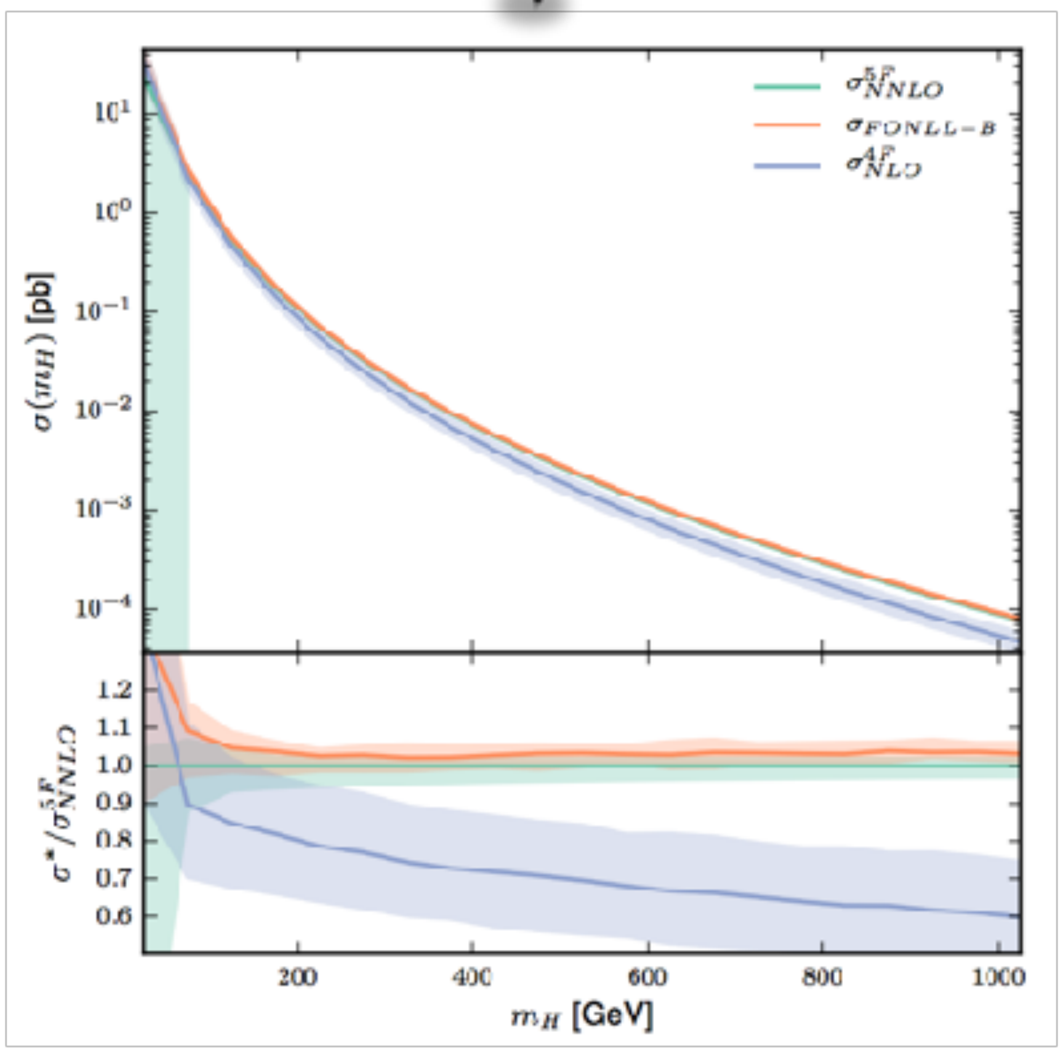


5F scheme



Heavy quarks

A simple explanation, a rich phenomenology

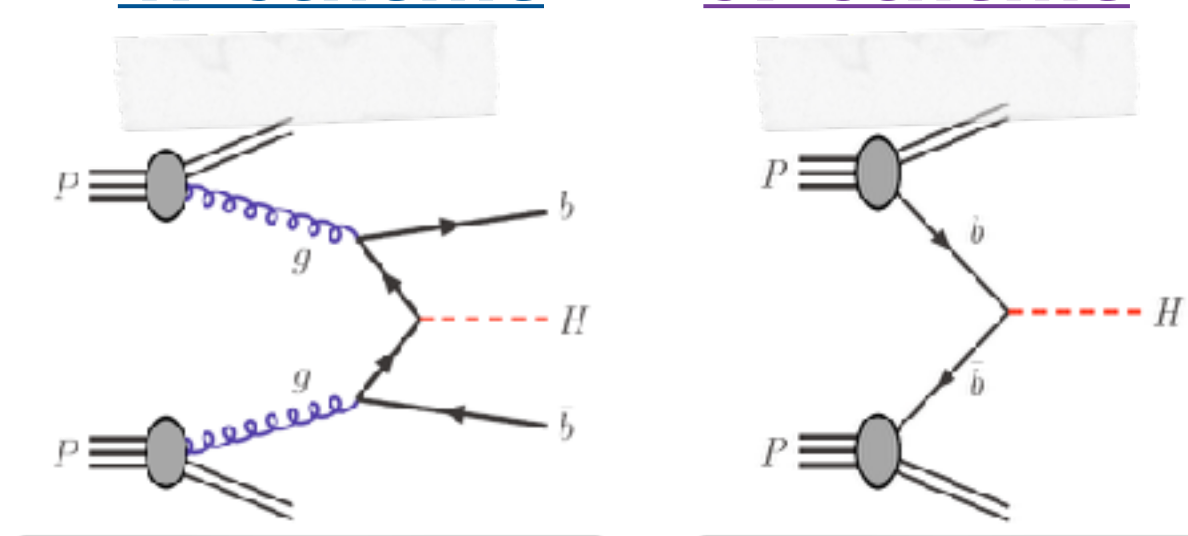


Forte, Napoletano, MU, Phys.Lett. B751 (2015)
Forte, Napoletano, MU, Phys. Lett. B763 (2016)

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

4F scheme **5F scheme**



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!!