# Higgs production via vector-boson fusion at NNLO in QCD

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# Outline

Introduction: the quest for the Higgs boson

The Vector Boson Fusion (VBF) production channel

QCD corrections to VBF and the structure function approach

Results at colliders

Web interface

Conclusions

# The quest for the Higgs: why NNLO?

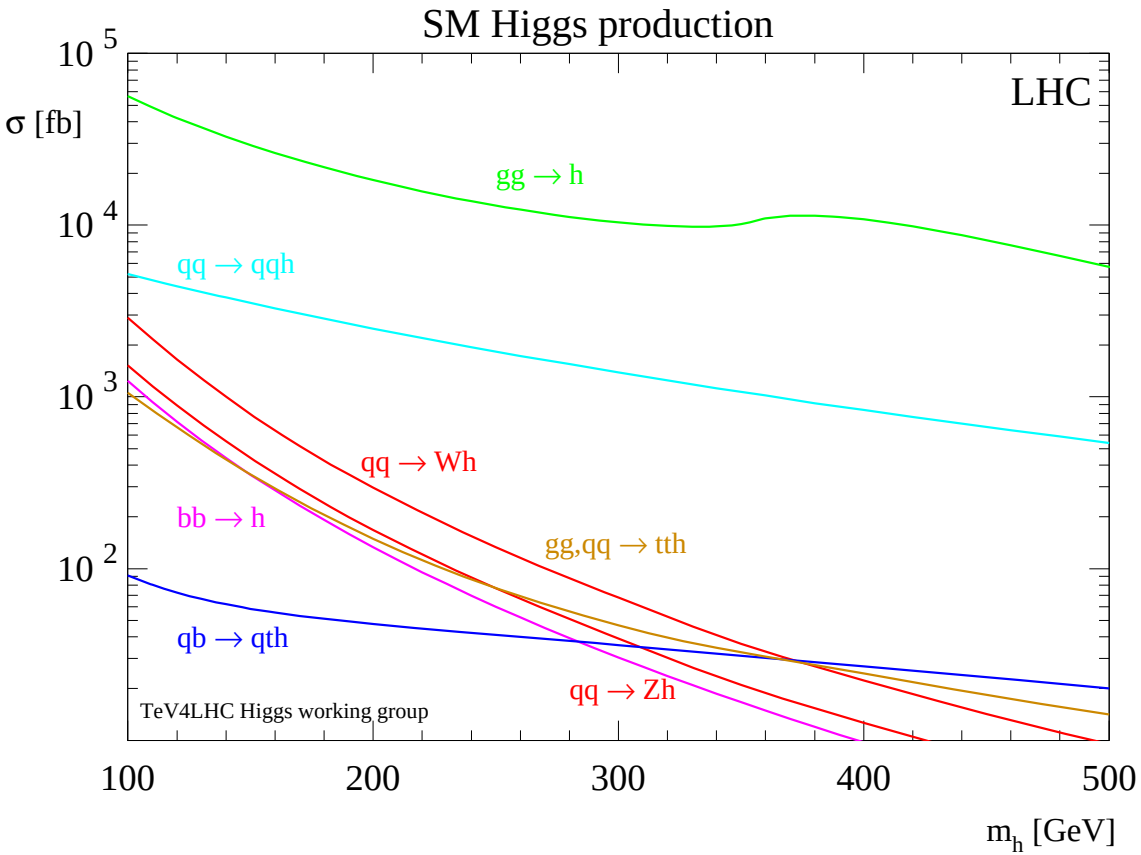
To find the Higgs in the QCD haystack you need:

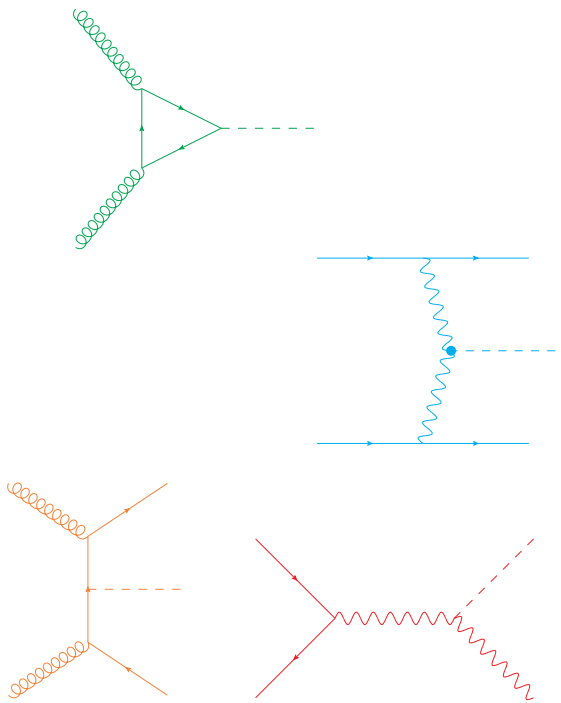
- The existence of the Higgs
- Rough estimate of number of expected events
- To reduce the background noise (specific signature, exp. cuts, ...)

To measure the Higgs properties (mass, couplings, ...) you need

- Precise estimate of the cross-section:
  LO $\rightarrow$ NLO: reliable info on cross-section value
  NLO $\rightarrow$ NNLO: improvement of theoretical uncertainities

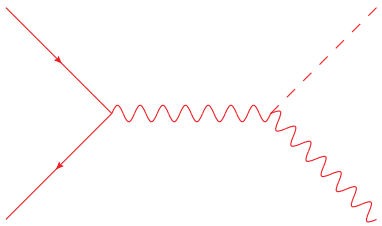
# The Higgs production channels



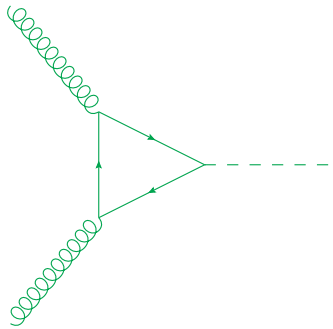
# The Higgs production channels @NNLO, on feb 2010

$q\bar{q} \to hV$



O. Brein, A. Djouadi and R. Harlander, Phys. Lett. B **579**, 149 (2004) [arXiv:hep-ph/0307206].

$gg \to h$

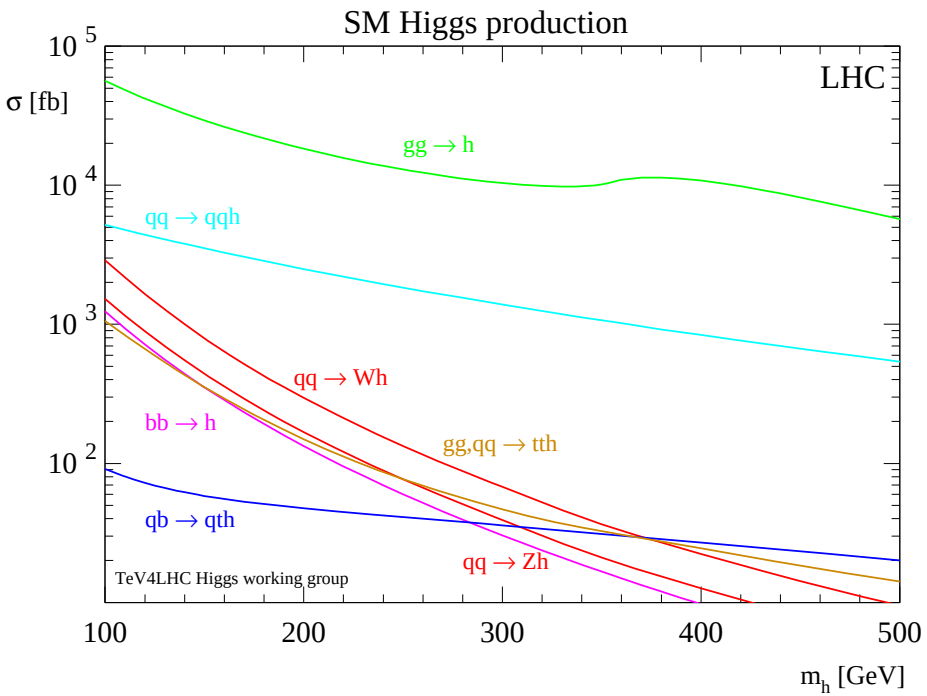


C. Anastasiou, K. Melnikov and F. Petriello, Phys. Rev. Lett. **93**, 262002 (2004) [arXiv:hep-ph/0409088].
R. V. Harlander, H. Mantler, S. Marzani and K. J. Ozeren, arXiv: 0912.2104 [hep-ph]

- No $2 \to 2$ process with in/out hadrons is available at NNLO
- VBF is an $2 \to 3$ process (need for some trick to compute it at NNLO)

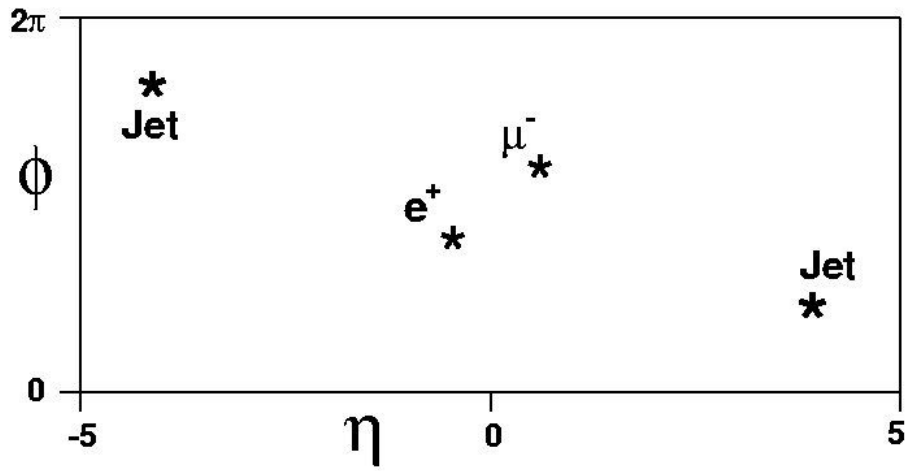
# The VBF production channel

VBF: $t$-channel color singlet exchange




- VBF is the second channel for Higgs production
- Soft Higgs mass dependence
- Negligible interference ($\mathcal{O}(10^{-3})$) with the other channels
- Clear experimental signature

# VBF signature

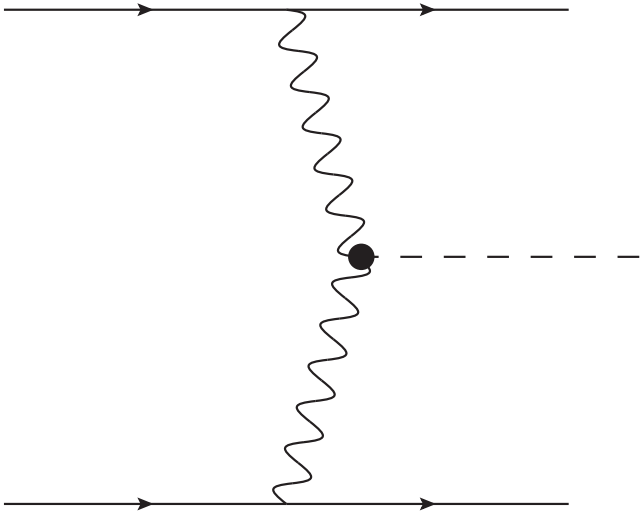



- 2 hard tagging jets
- large rapidity separation between jets
- no (or small) hadronic activity between jets
- Higgs decay in the central rapidity region

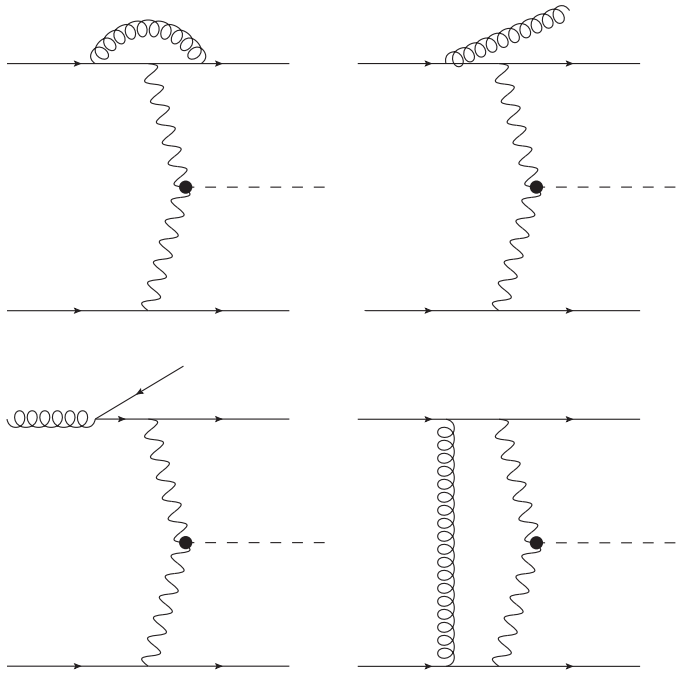
# QCD corrections to VBF and the structure function approach

# QCD corrections to VBF

## LO

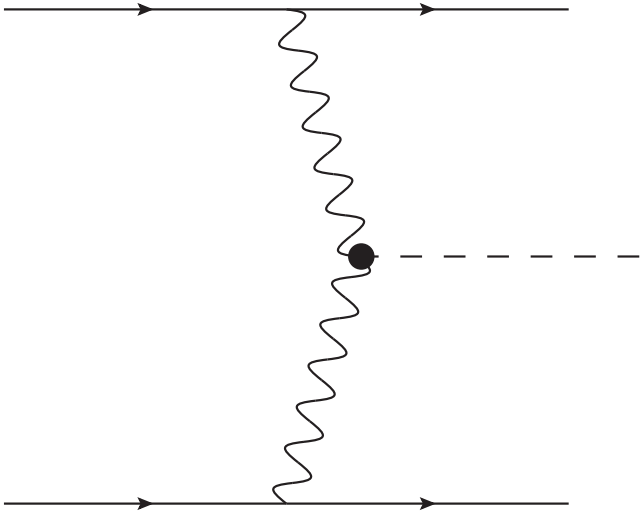


## NLO

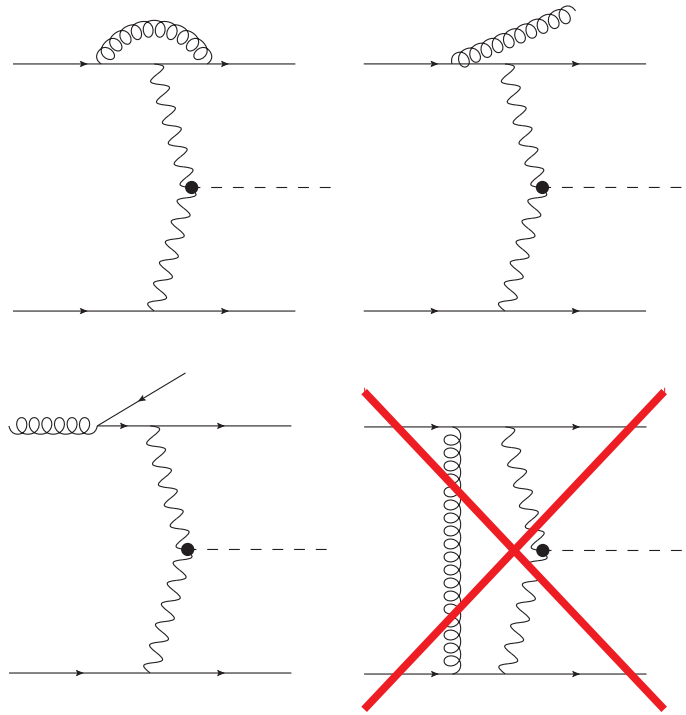


# QCD corrections to VBF

LO



NLO



# QCD corrections to VBF

At NLO

$$\text{VBF} = (\text{DIS})^2$$

Knowledge of NLO DIS structure functions $F_i$ $(i = 1, 2, 3)$

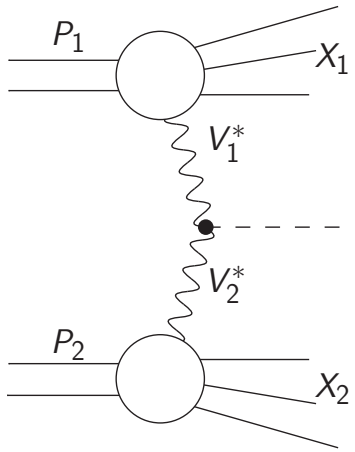
$$\Downarrow$$

Knowledge of VBF NLO cross-section

Structure function approach

T. Han, G. Valencia and S. Willenbrock, Phys. Rev. Lett. **69**, 3274 (1992) [arXiv:hep-ph/9206246]

# QCD corrections to VBF

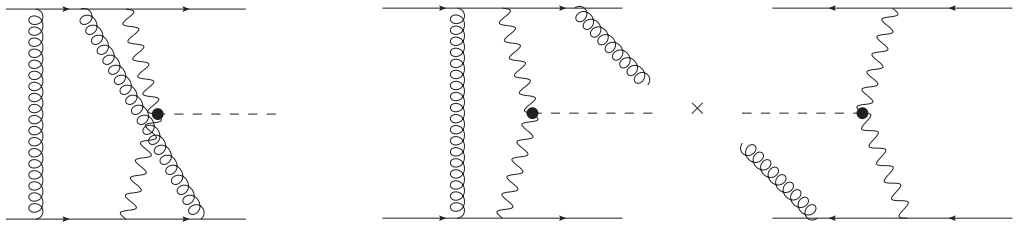



$$d\sigma = \frac{1}{S}\,\frac{G_F^2 M_{V_1}^2 M_{V_2}^2}{(Q_1^2+M_{V_1}^2)^2(Q_2^2+M_{V_2}^2)^2}\; W_{\mu\nu}^{DIS}\left(x_1,Q_1^2\right)\mathcal{M}_{VVH}^{\mu\rho}\mathcal{M}^{*\,\nu\sigma}_{VVH}\,W_{\rho\sigma}^{DIS}\left(x_2,Q_2^2\right)\times$$

$$\times\,\frac{d^3P_{X_1}}{(2\pi)^3\,2E_{X_1}}\,\frac{d^3P_{X_2}}{(2\pi)^3\,2E_{X_2}}\,ds_1\,ds_2\,\frac{d^3P_H}{(2\pi)^3\,2E_H}\,(2\pi)^4\,\delta^4\left(P_1+P_2-P_{X_1}-P_{X_2}-P_H\right)$$

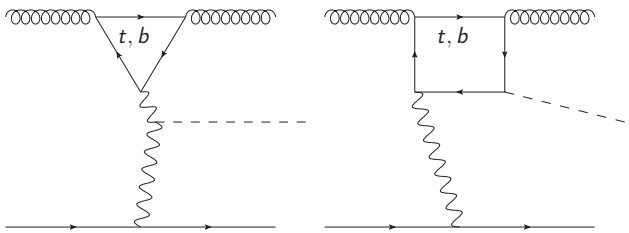
# The structure function approach to VBF @ NNLO

- structure function approach is not exact at NNLO
  - double gluon-exchange diagrams (real and virtual)



$\frac{1}{N_c^2}$ and kinematically suppressed

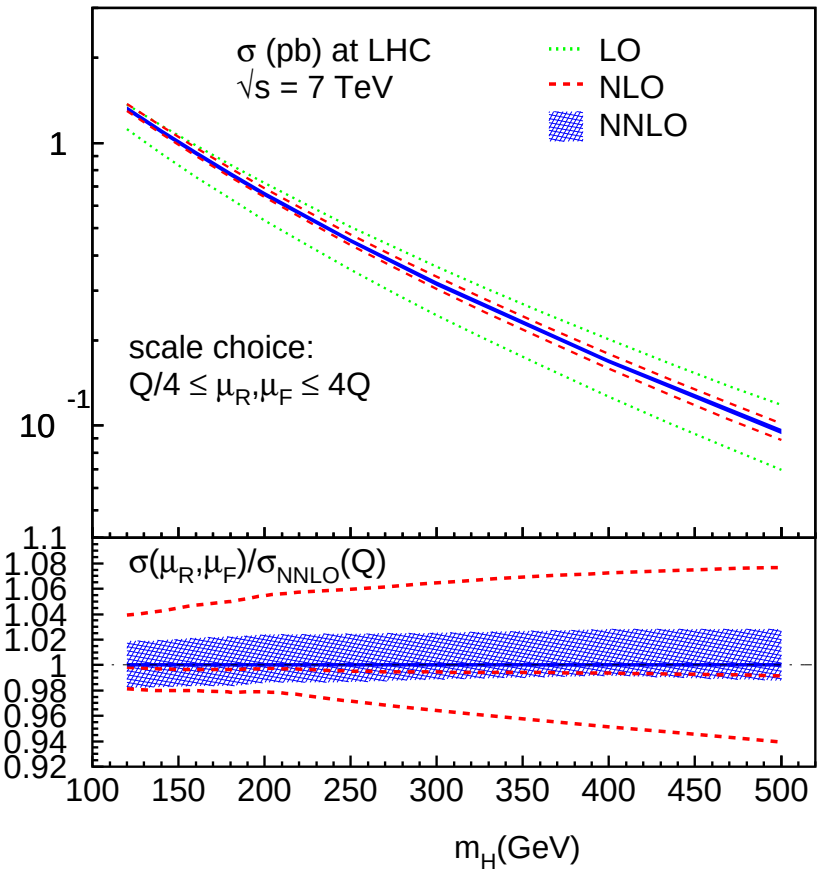
  - $t/b$ loop diagrams

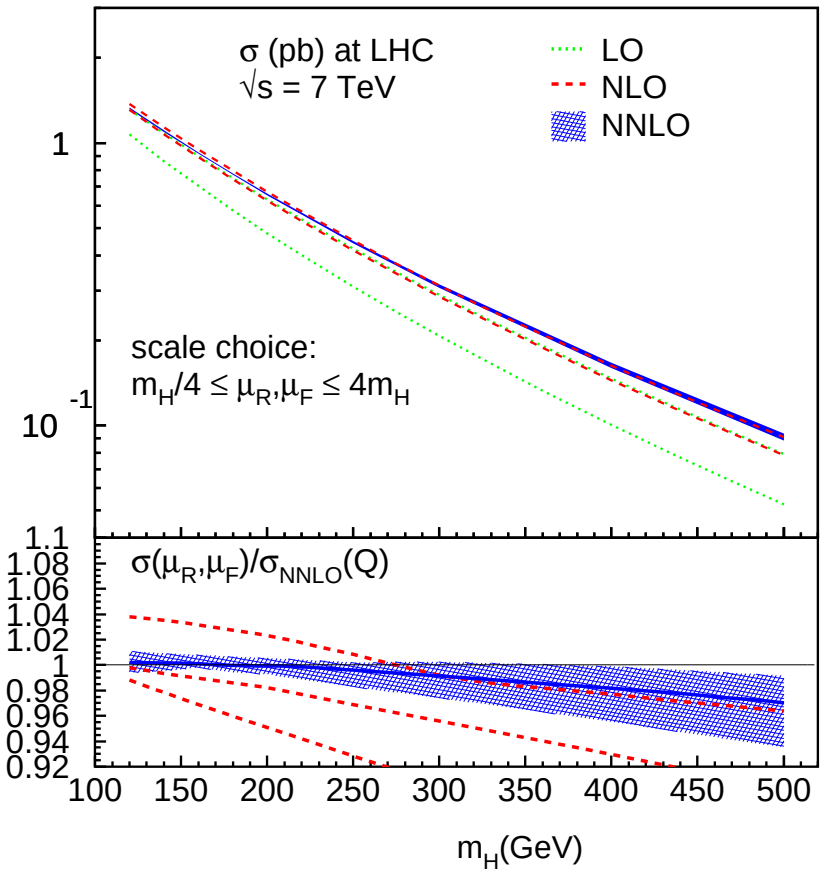



Destructive interference, upper bound at $\mathcal{O}(10^{-3})$

# Results at colliders

# Results at the LHC @7 TeV

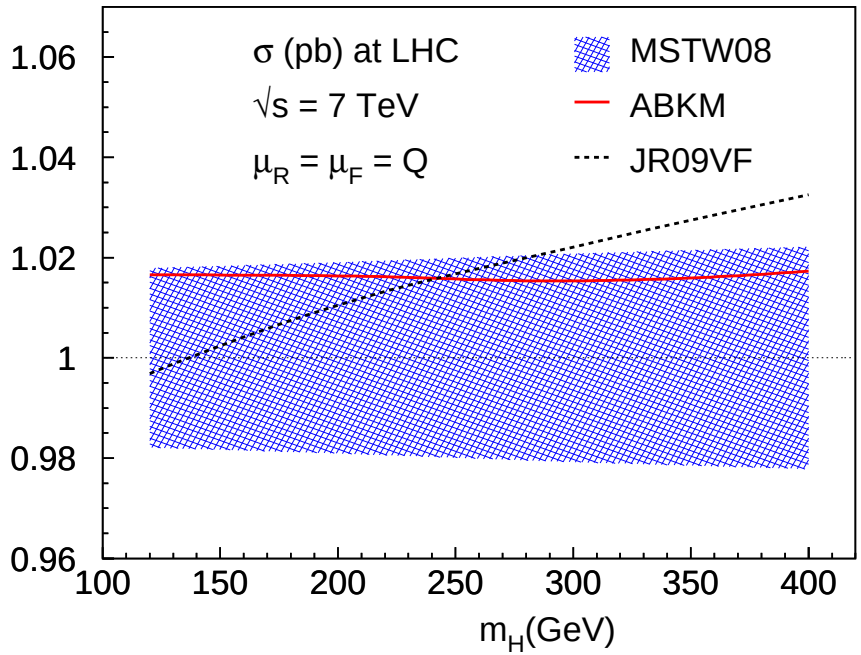


# Considerations:

- Clear convergence of perturbative series ($\Delta\text{NNLO}/\text{NLO} = \mathcal{O}(1\%)$)
- Theoretical uncertainities reduce at $1-2\%$ for the NNLO cross-section
- Reference scales $Q$ and $m_H$ become equivalent at NNLO
- Reference scale $Q$ looks more natural

# PDF uncertainities at the LHC @7 TeV



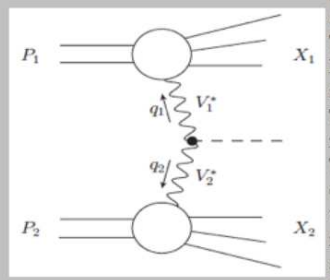

- PDF error band of MSTW08 set is uniformly $\pm 2\%$ (68% CL)
- ABKM, JR best fit PDF is compatible with MSTW08

# Web interface: http://madgraph.phys.ucl.ac.be/vbf.html

## VBF @ NNLO : Cross-section Calculator

by P. Bolzoni, F. Maltoni, S.-O. Moch and M. Zaro

alpha version v0.1 -- 10 April 2010




Higgs production in vector-boson fusion (VBF) is computed via a structure-function approach, as reported in ArXiv:1003.4451 [hep-ph].
This simple interface allows any registered user to obtain a cross section up to NNLO in QCD, including an estimate of the theoretical uncertaintes coming from scale variation and PDF uncertaintes.
The electro-weak parameters used for the cross-section computation are set to their respective PDG values (see the list here).
The code runs over the CP3-MadGraph cluster and might take up to a few hours depending on the actual request. An e-mail with the corresponding data file is sent to the user as soon as results are available. The possibility of requesting multiruns, i.e. runs corresponding to a series of Higgs mass values and/or collider energies, will be available soon upon e-mail request.
See the HNNLO web page by M. Grazzini for a similar tool for gg -> H.

New users are kindly asked to register here

| | | |
|---|---|---|
| Up to order: | NNLO | |
| Collider type: | p-p | |
| Center of mass energy: | 7000 | GeV |
| Higgs boson mass: | 120 | GeV |
| PDF set: | MSTW08 | |
| PDF uncertainities: | no | |
| Reference scale: | Q | Description |
| Scale uncertainities: | no | Description |

Submit

This is an alpha version. Pleae send comments/requests/bug reports to Marco Zaro (e-mail: Marco.Zaro AT uclouvain.be).

# Conclusions:

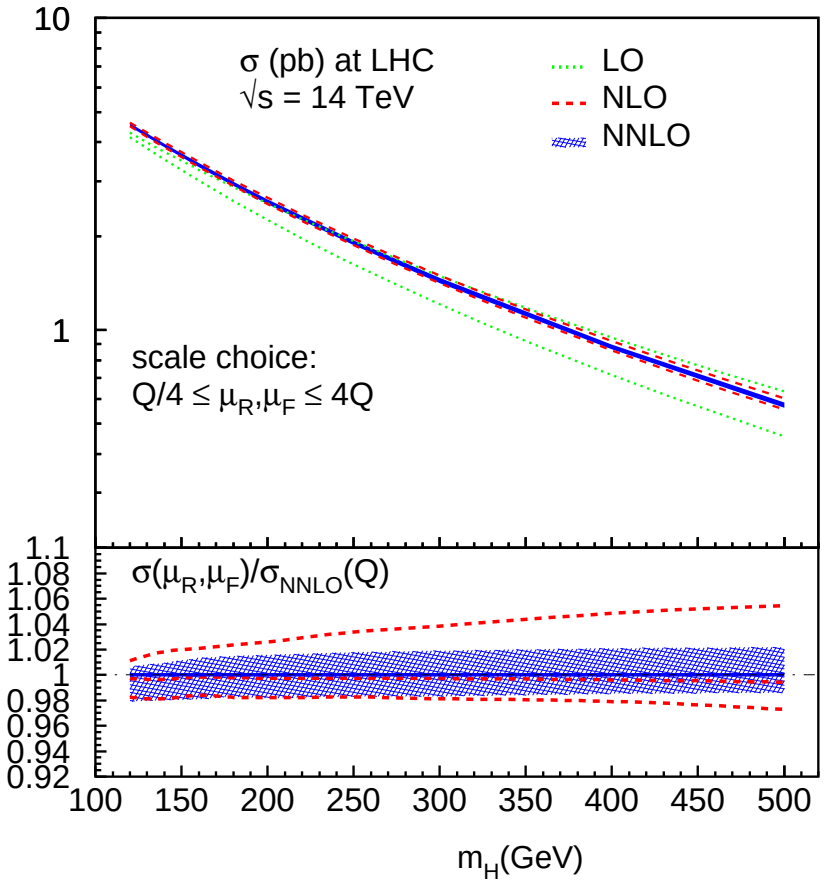
- LHC is finally ready to look for the Higgs
- VBF is a promising channel both for discovery and precision measurements
- First computation VBF cross-section @NNLO now available
- Theoretical uncertainities lowered at $1-2\%$ level
- Web interface available http://madgraph.phys.ucl.ac.be/vbf.html (still alpha version)

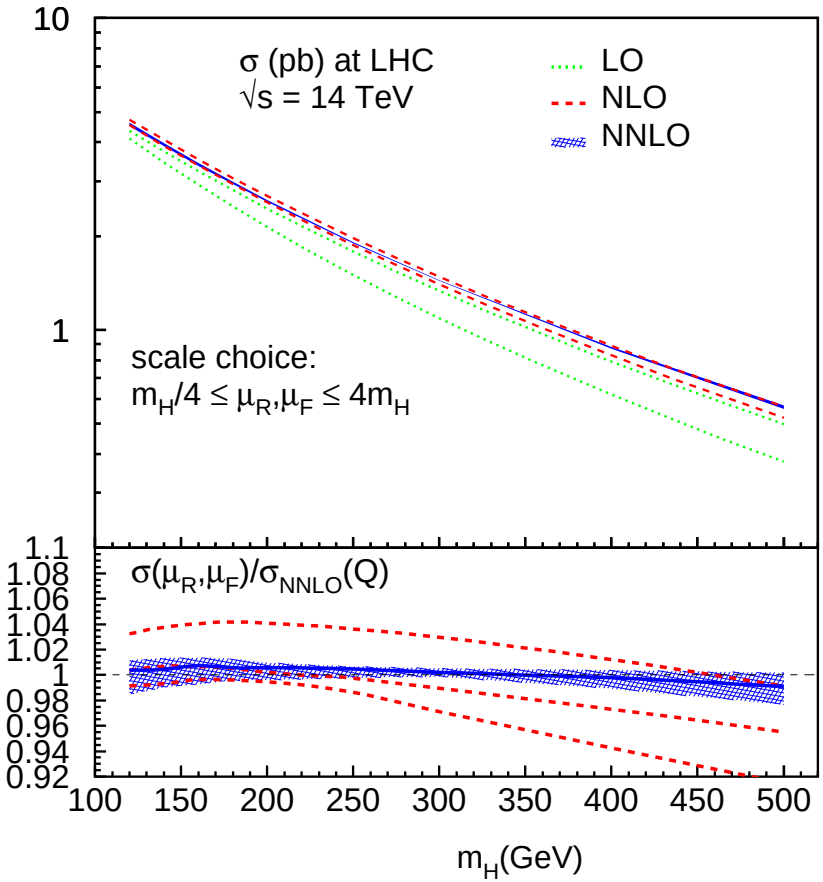
# Conclusions:

- Structure function approach is a powerful tool to compute NNLO cross-sections
- Structure function approach can be extended to $pp \to X\,jj$ process
- Need for a fully differential NNLO computation

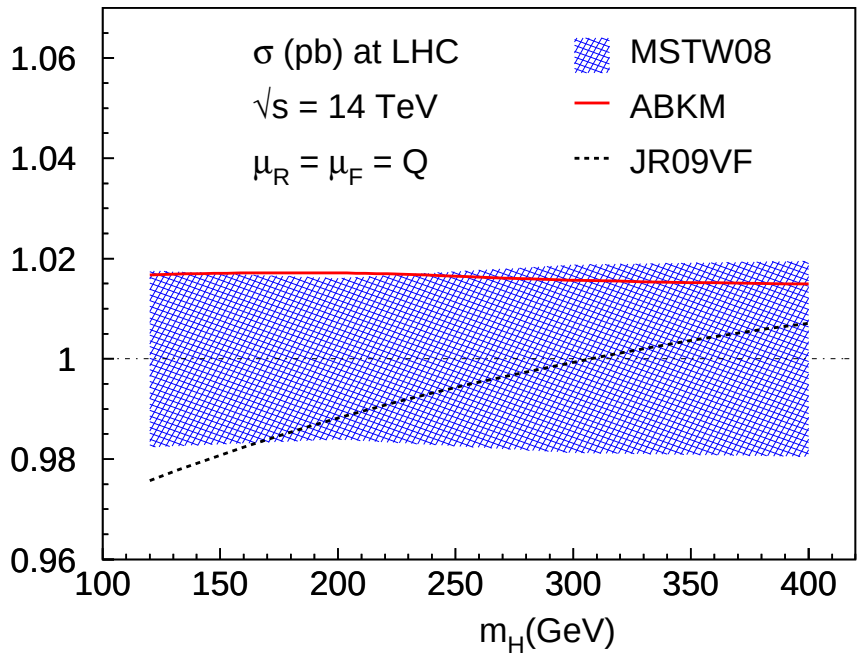
# Backup slides

# Results at the LHC @14 TeV

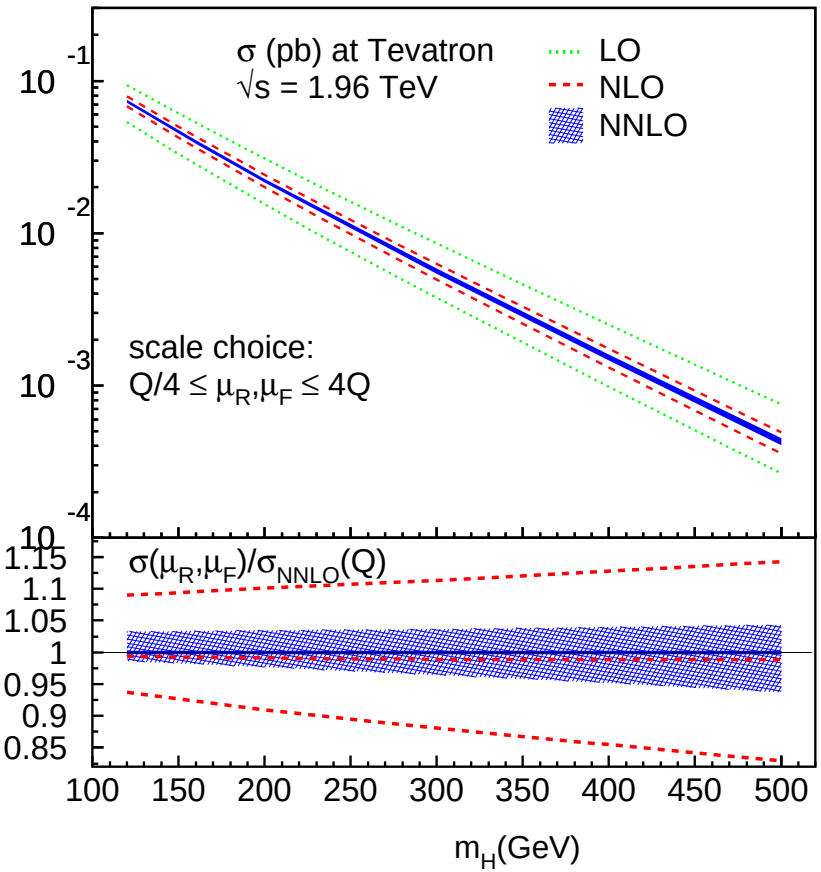


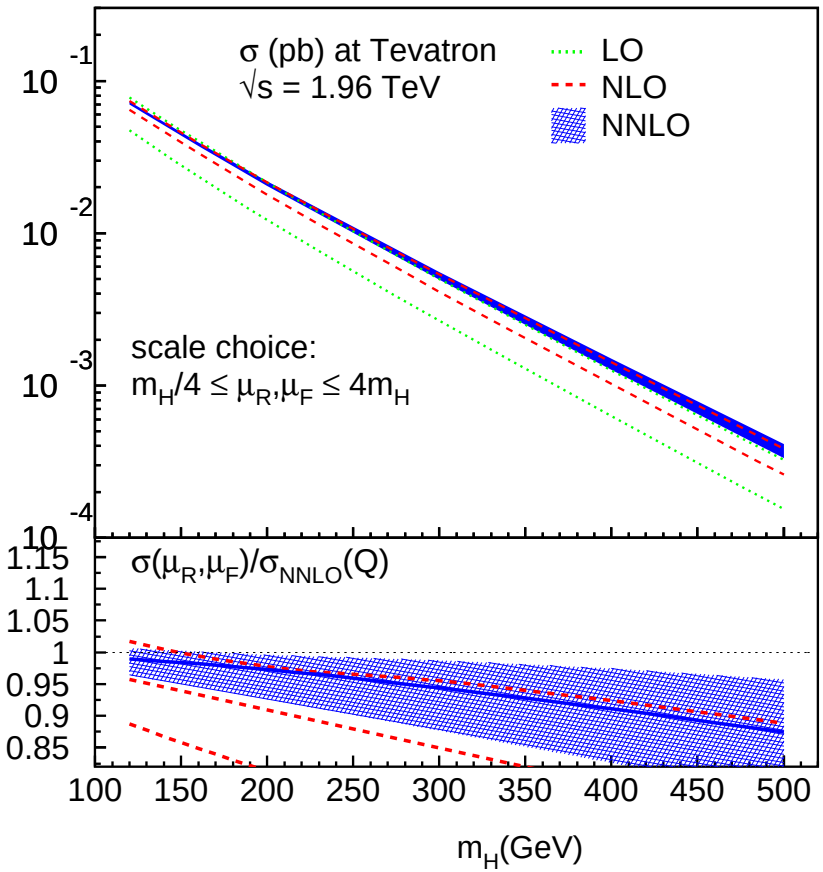



# PDF uncertainities at the LHC @14 TeV

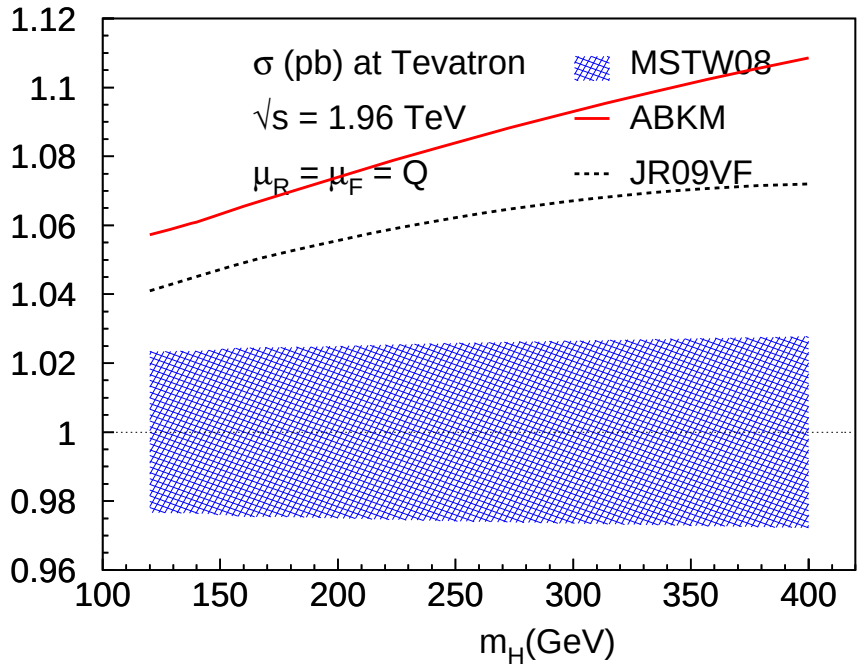


# Results at the Tevatron @1.96 TeV

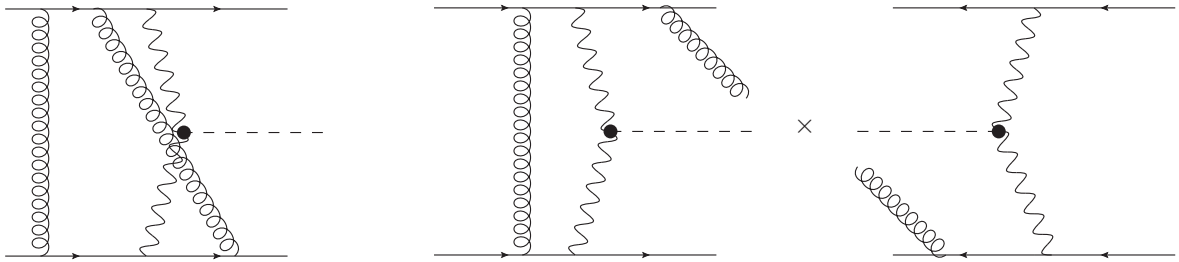


# PDF uncertainities at the Tevatron @1.96 TeV

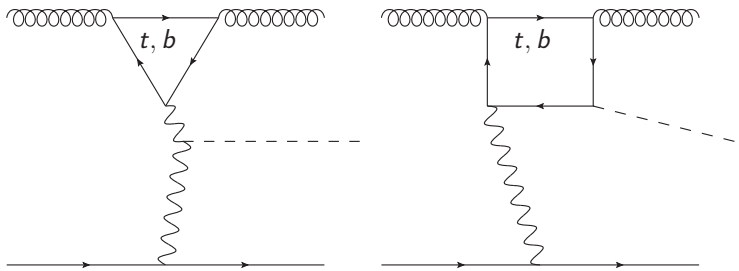


# Double gluon-exchange diagrams



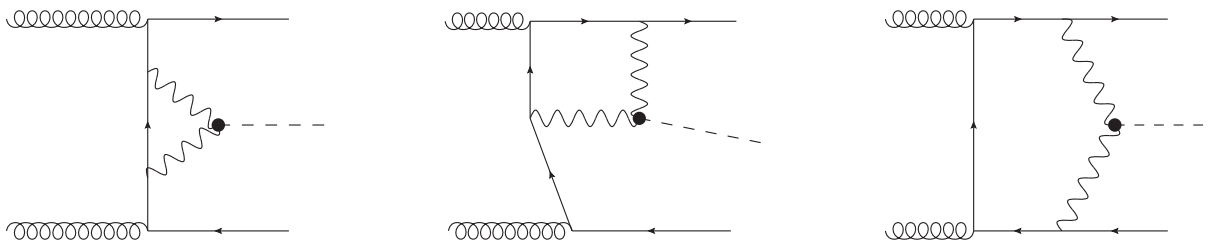
- Gauge invariant class
- No collinear divergencies
- $R + V$ is UV and IR finite
- Double quark trace: $1/N_c^2$ suppression with respect to DIS$^2$ diagrams
- Kinematic suppression
  T. Figy, V. Hankele and D. Zeppenfeld, JHEP **0802**, 076 (2008) [arXiv:0710.5621 [hep-ph]].

# $t/b$ loop diagrams



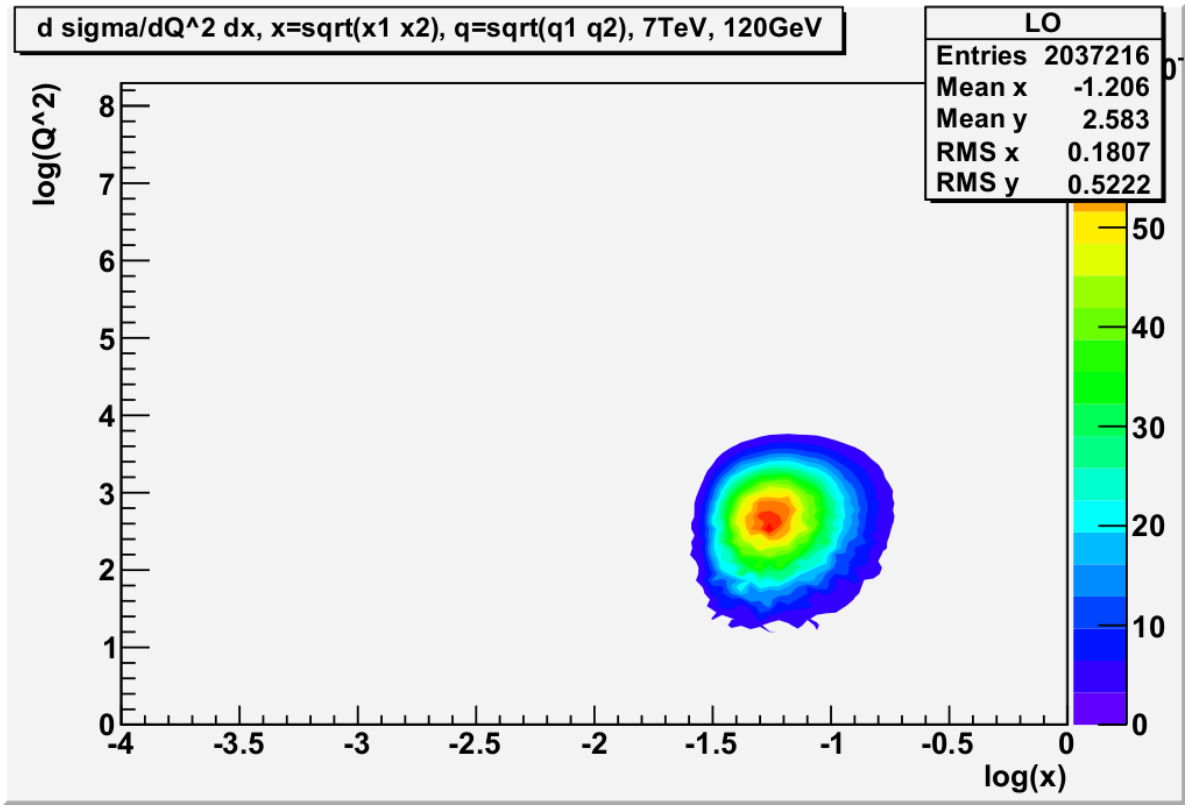

- Gauge invariant class
- Box and triangle interfere destructively
- Impact on cross-section estimated in the $m_t \to \infty$, $m_b \to 0$ limit, $<< 1\%$

# Single quark line (SQL) diagrams



- Gauge invariant class
- Not "pure" VBF process (colour exchanged between protons)
- Not IR-safe
- Studied by R. V. Harlander, J. Vollinga and M. M. Weber, Phys. Rev. D **77**, 053010 (2008) [arXiv:0801.3355 [hep-ph]]
- Impact on the VBF cross section (after VBF cuts) $\mathcal{O}(10^{-}3)$

# Kinematics in the $x$ vs. $Q^2$ plane

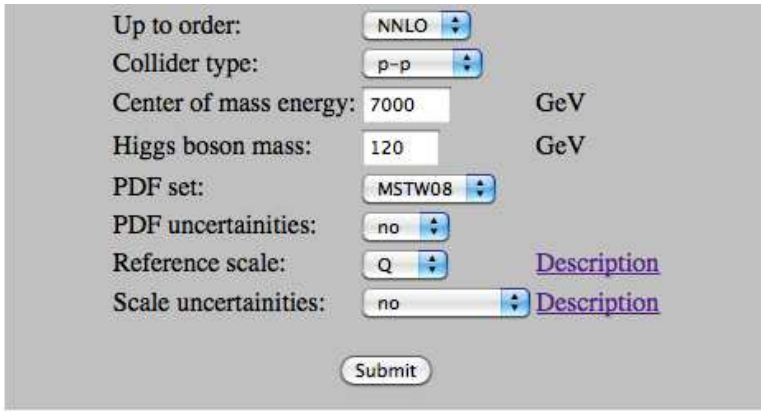



$$< Q^2 > \simeq (20\text{GeV})^2$$

$$< x > \simeq 6 \cdot 10^{-2}$$

# Web interface: how-to

- Register
- Choose run parameters




- The page checks wether the process has already been computed, if not it runs the code

# Web interface: how-to

- The link to the results will be sent to your e-mail address
- Incremental DB
- Each user has his own results folder

**VBF @ p-p collider**

Request sent on 2010-04-15

Process requested: mh=120 GeV, $\sqrt{s}$=7 TeV, up to NNLO

PDF set: MSTW08, PDF error: no

Scale reference: Q
Theoretical uncertainity: no

| | LO | NLO | NNLO |
|---|---|---|---|
| σ(pb): | 1.239 | 1.3216 | 1.3203 |
| theo err +: | 0 | 0 | 0 |
| theo err -: | 0 | 0 | 0 |
| pdf err +/-: | 0 | 0 | 0 |

You can find here the list of EW parameters used for the computation

Click here to go back to the VBF @ NNLO page