Higgs production via vector-boson fusion at NNLO in QCD

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in collaboration with **P. Bolzoni** , **F. Maltoni** and **M. Zaro** on arXiv:1003.4451

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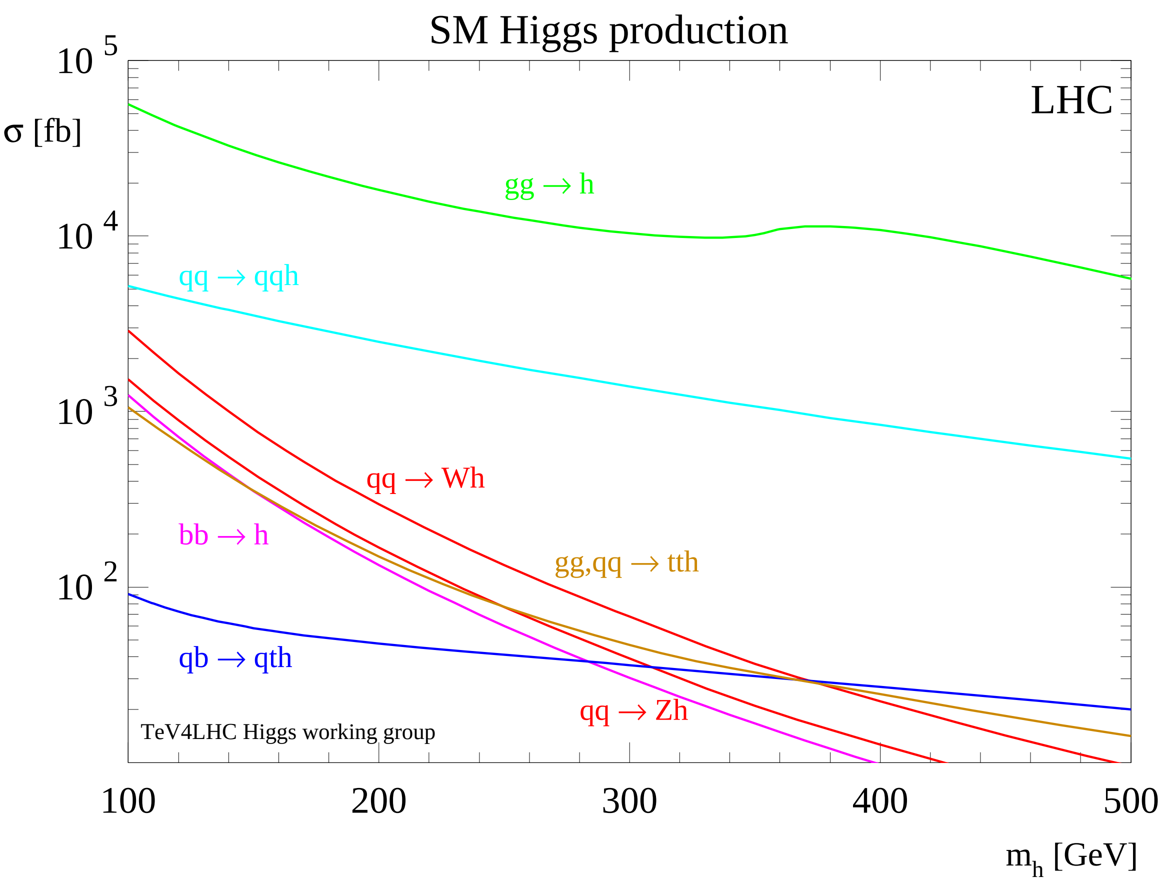
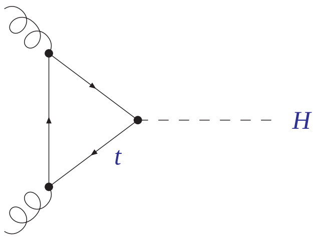
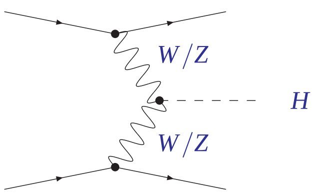
Cross section for Higgs production at the LHC

- Most important parton channels for Higgs boson production TeV4LHC '06

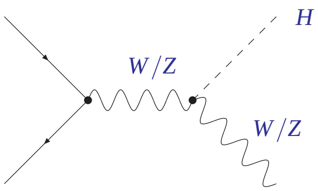




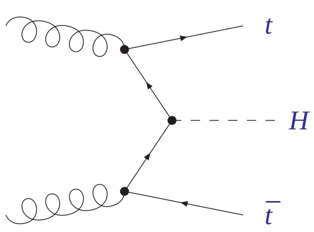
gg-fusion



weak boson fusion



Higgs strahlung



$t\bar{t}H$-channel

Why precision ?

- Standard approach to uncertainties in theoretical predictions
  - variation of factorization scale μ: $\dfrac{d}{d \ln \mu^2} \sigma_{pp \to X} = \mathcal{O}(\alpha_s^{l+1})$

$$\sigma_{pp \to X} = \sum_{ijk} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij \to k} \left(\alpha_s(\mu^2), Q^2, \mu^2 \right)$$

- Parton cross section $\hat{\sigma}_{ij \to k}$ calculable pertubatively in powers of α_s

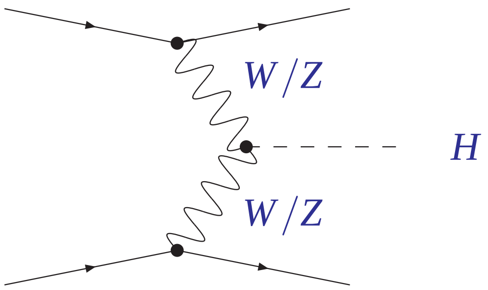
$$\hat{\sigma}_{ij \to k} \quad = \quad \underbrace{\hat{\sigma}^{(0)}_{ij \to k} + \alpha_s \, \hat{\sigma}^{(1)}_{ij \to k}}_{\text{NLO: standard approximation (large uncertainties)}} + \alpha_s^2 \, \hat{\sigma}^{(2)}_{ij \to k} + \dots$$

QCD predictions at NNLO

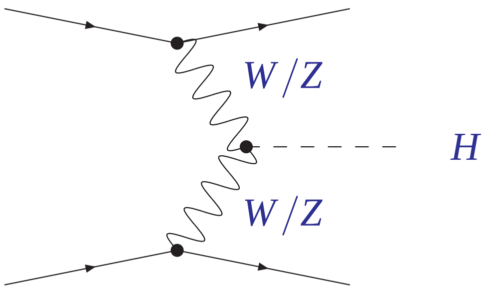
- Hadron colliders:
  NNLO QCD corrections required for accuracy better than $\mathcal{O}(10\%)$
  - LO $\to$ NLO: information on radiative corrections (K-factor)
  - NLO $\to$ NNLO: first reliable estimate of theoretical uncertainities

Vector-boson fusion

- Second largest rate (WWH coupling)



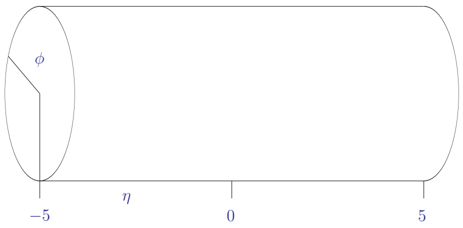
Vector-boson fusion

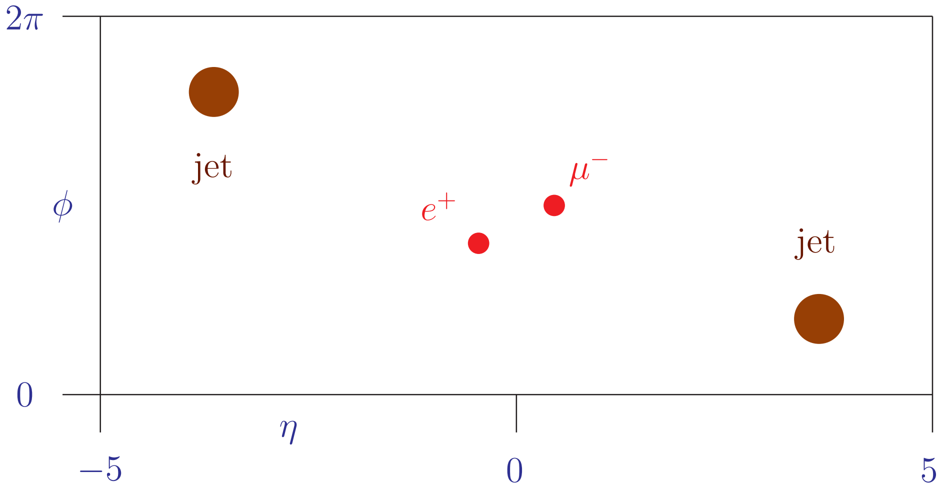


- Second largest rate (WWH coupling)

Signatures

- WW, ZZ fusion $\longrightarrow$ Higgs is color singlet
  - 2 hard (forward) tagging jets (visible in detector)
  - no (or small) hadronic activity between tagging jets
  - color connection between forward jet and proton remnant
  - Higgs decay in the central rapidity region

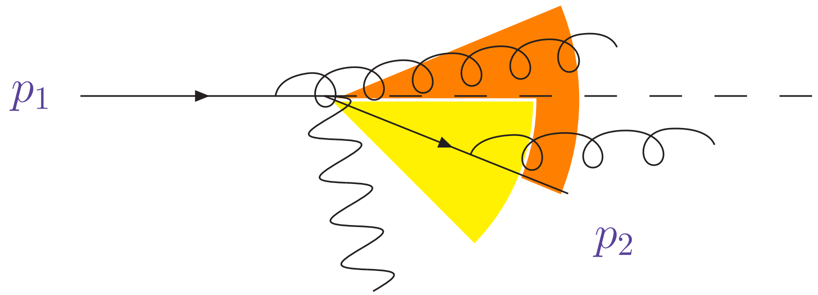




Perturbative QCD corrections

Where is the hadronic activity ?

- QCD radiation predominantly in direction of incoming partons (angular ordering)



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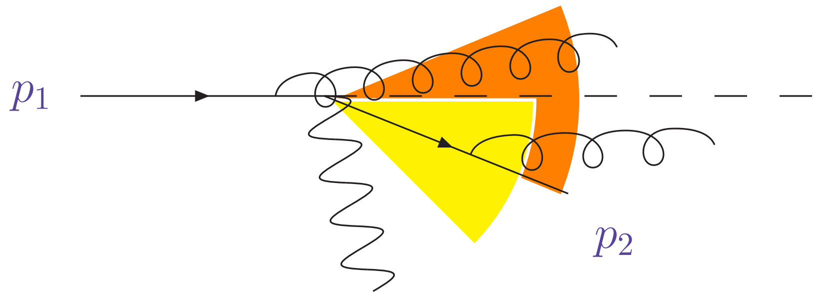
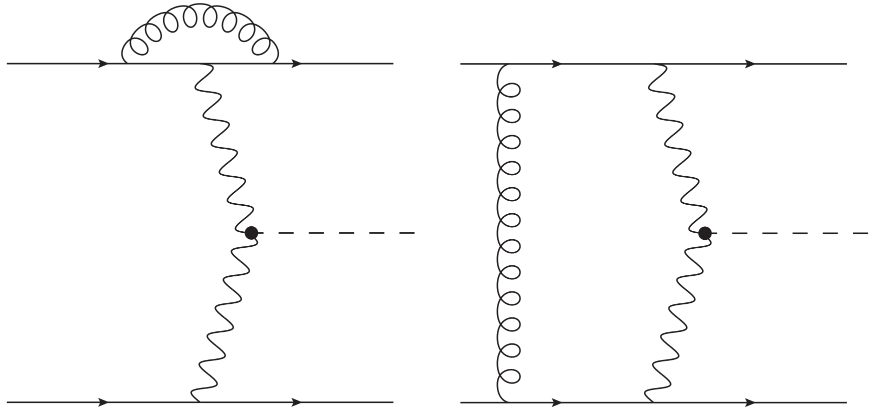


- NLO QCD corrections (vertex corrections and t-channel gluon)



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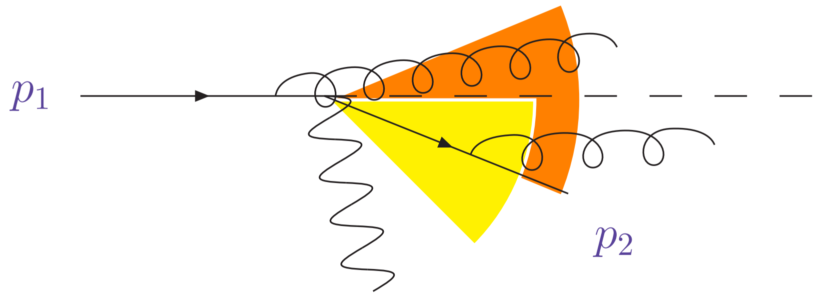
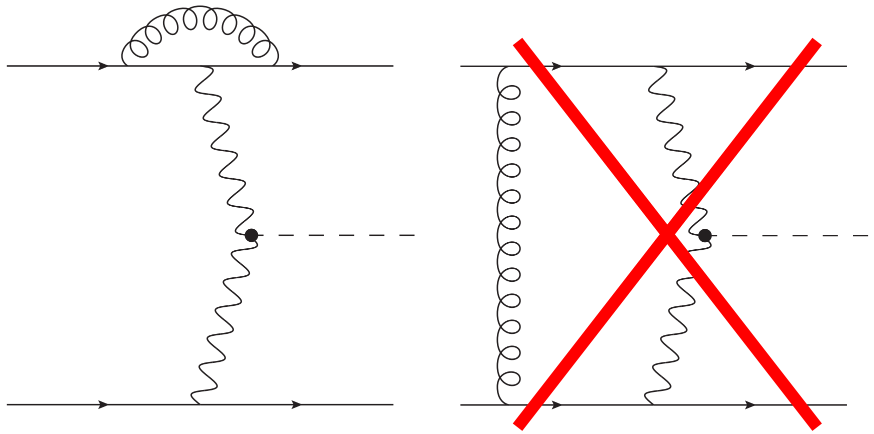
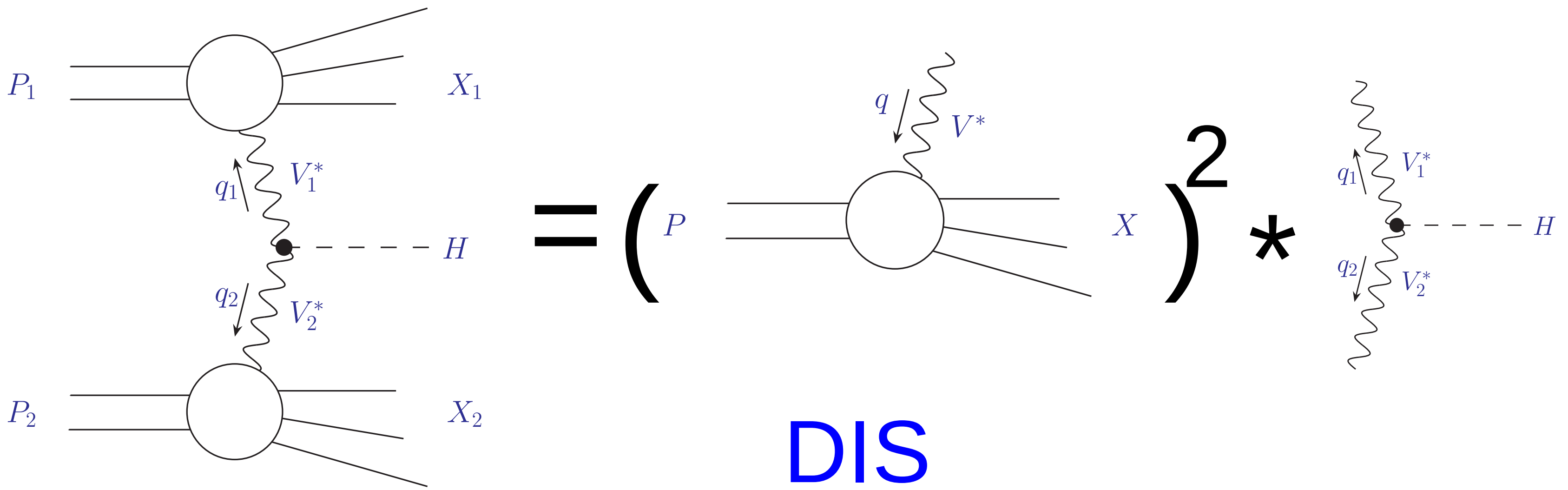


- Color conservation eliminates t-channel gluon exchange at NLO

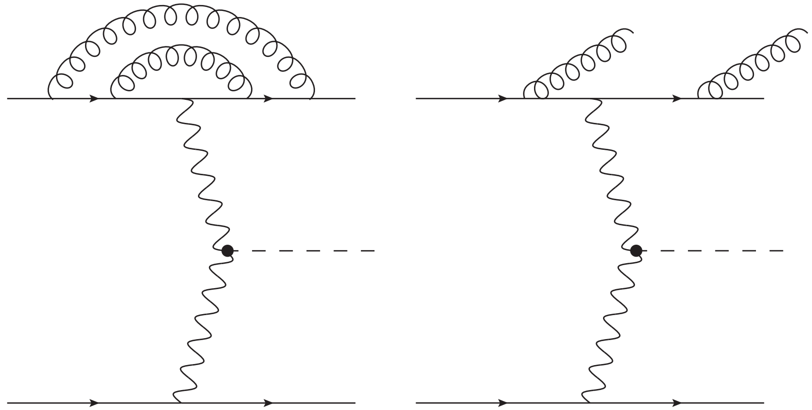


Exact factorization



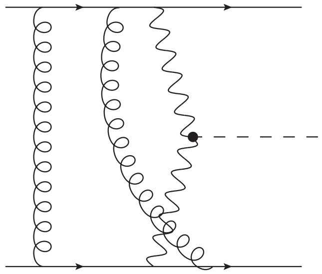
- Deep-inelastic scattering building block of cross section
- DIS structure functions F_1, F_2 and F_3 sufficient VBF cross section at NLO in QCD
- Exact factorization at NLO: so-called strucure function approach
  Han, Valencia, Willenbrock '92

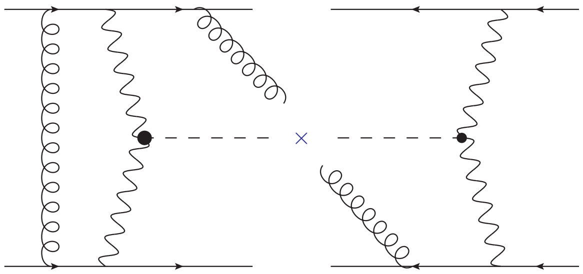
NNLO diagrams



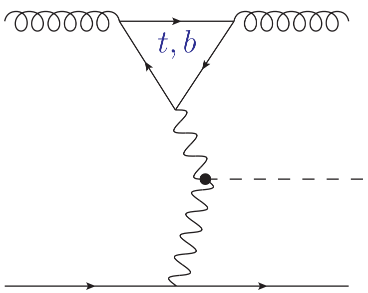
- Structure function approach is NOT exact at NNLO in QCD
  - but can be still considered a good approximation
- Dominant contributions are included through structure functions also at higher orders
  - F_1, F_2 and F_3
    long known at NNLO
    Kazakov, Kotikov '88; Zijlstra, van Neerven '92; S.M., Vermaseren '99
    and even at N^{3}LO
    Vermaseren, Vogt, S.M. '05; S.M., Rogal, Vogt '07; S.M., Vermaseren, Vogt '09

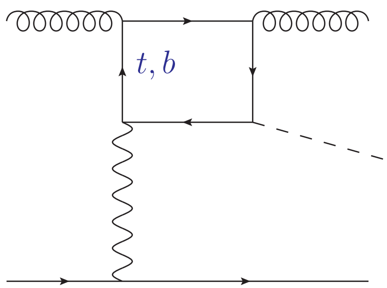
NNLO diagrams (cont’d)





- suppressed kinematically and by $1/N_c^2$ compared to DIS
- gauge invariant, UV finite



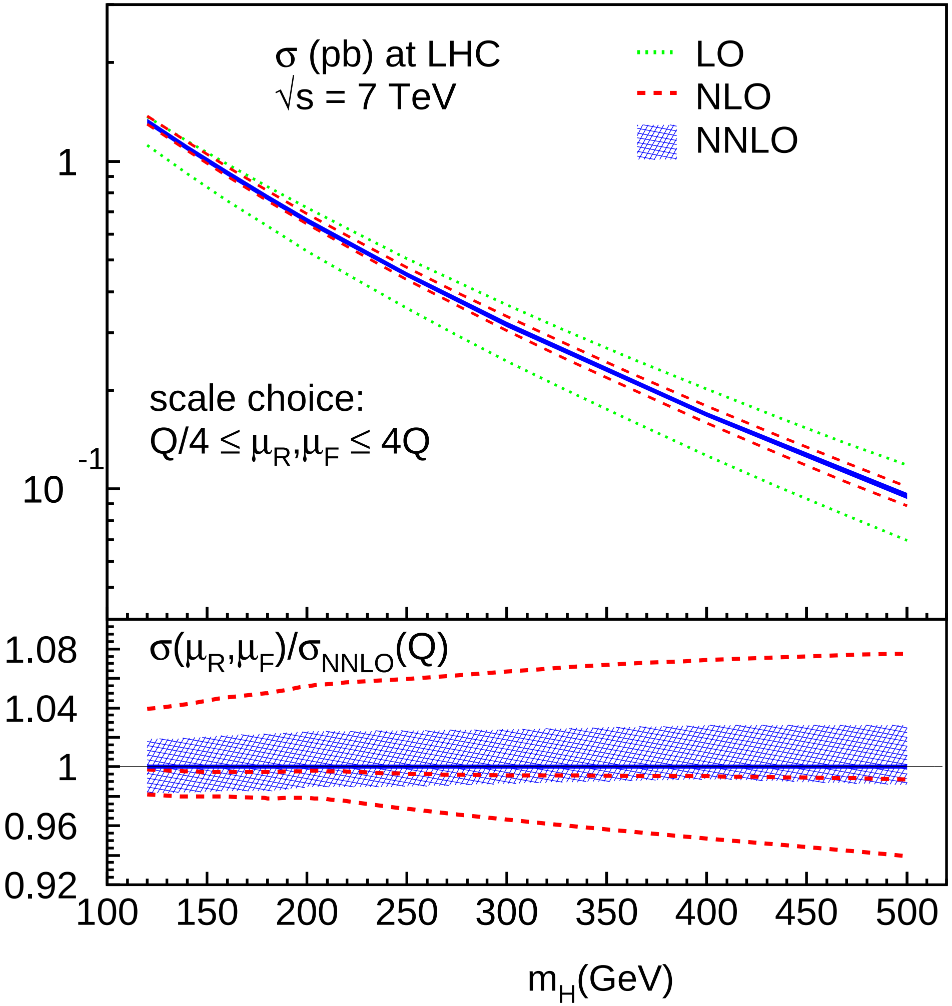


- negligible (estimated $\ll 1\%$)
- gauge invariant, destructive interference between box and triangle

Upshot

- Structure function approach at NNLO holds to $\mathcal{O}(1\%)$

Cross section for VBF at LHC



Bolzoni, Maltoni, S.M., Zaro '10

- QCD corrections at second order small
- NNLO results very stable at 2% against QCD scales variation (uniformly over the full mass range)

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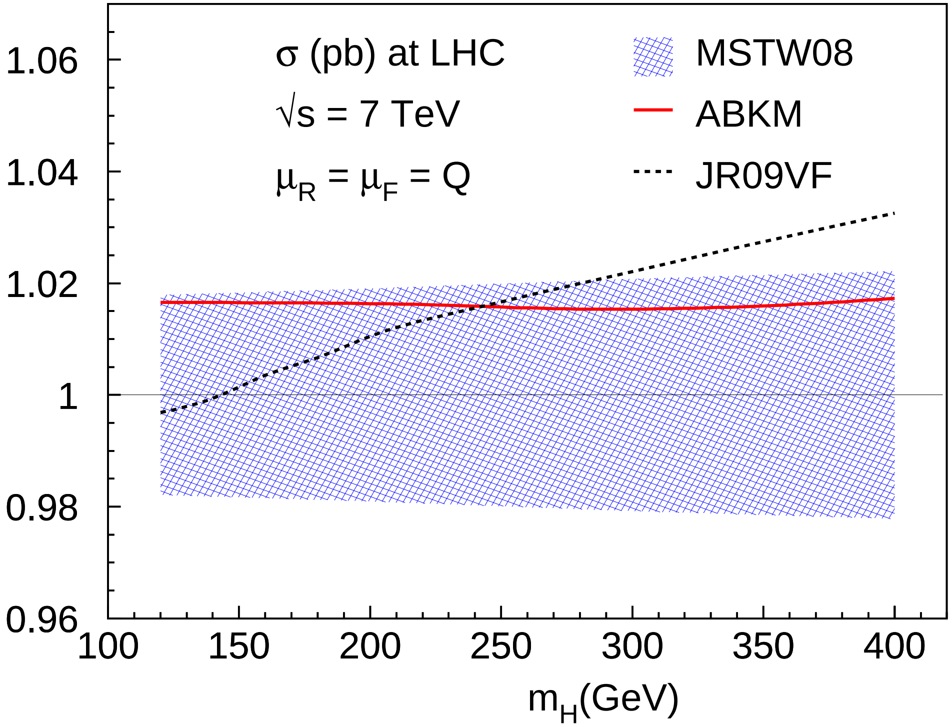


- QCD corrections at second order small
- NNLO results very stable at 2% against QCD scales variation (uniformly over the full mass range)

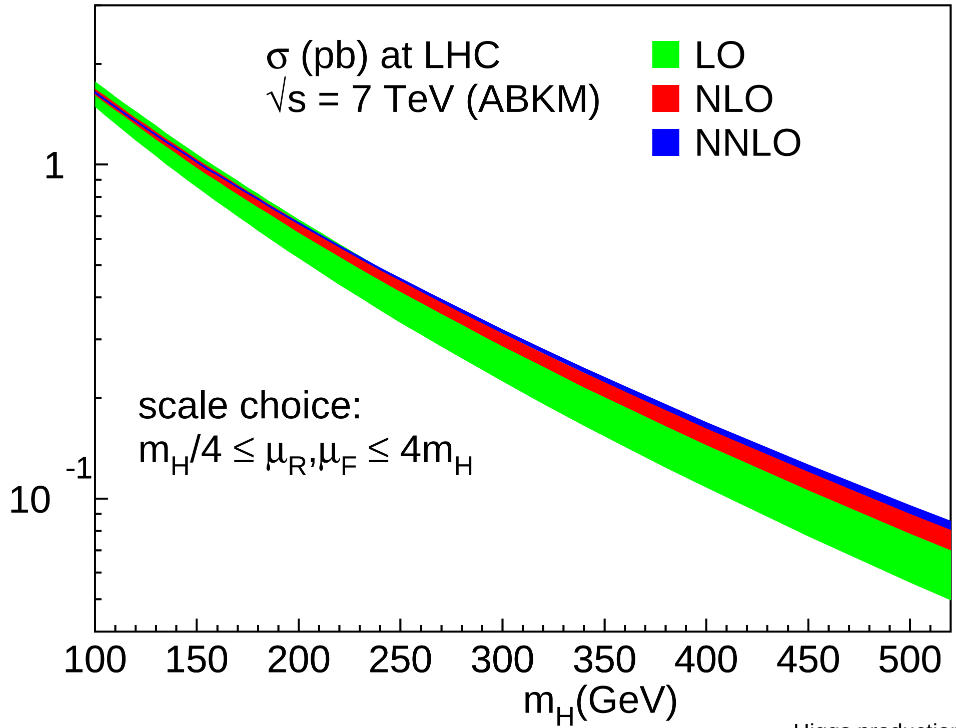
Upshot

- apparent convergence
- scale stability
- reduction of theoretical uncertainty
- PDF + α_s uncertainty generally small (improved at NNLO) $\Delta\sigma_{NLO} \gg \Delta\sigma_{NNLO}$

Bolzoni, Maltoni, S.M., Zaro '10

Comments on VBF

- Scale uncertainty
  - Potential choices for nominal scale $\mu_R, \mu_F = Q, M_W, M_H$
- Choice $\mu_R, \mu_F \in [Q/4, 4Q]$ physically motivated
  - t-channel dominance of VBF process: effective $\langle Q \rangle \simeq \mathcal{O}(20)$ GeV
  - improved apparent convergence for choice $\mu_R, \mu_F \in [Q/4, 4Q]$ (very small NNLO corrections at nominal scale)



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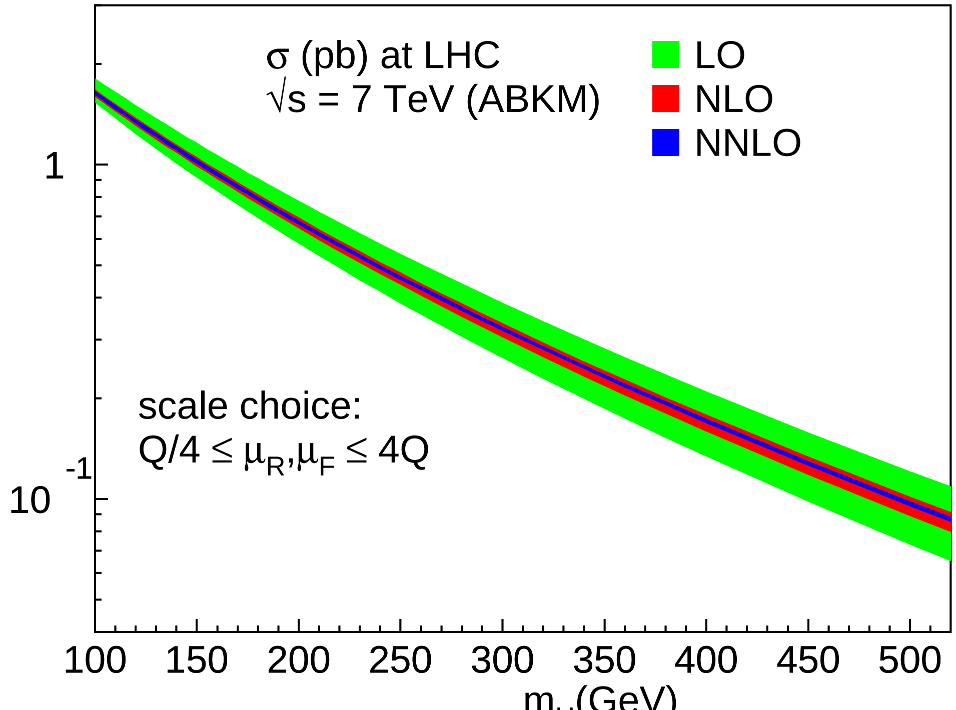

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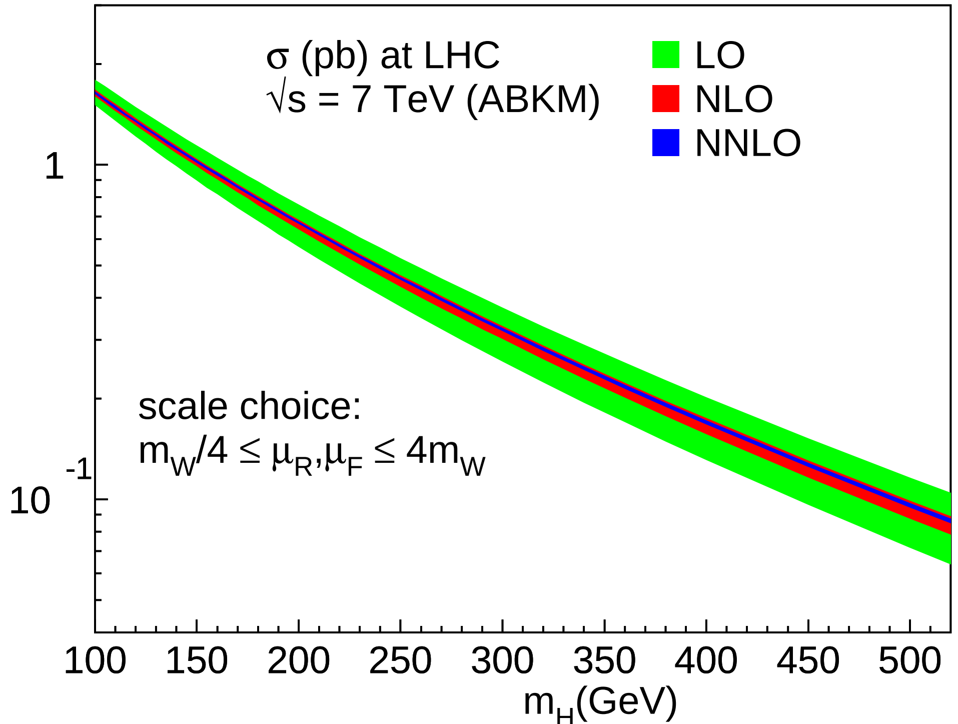


numbers ...

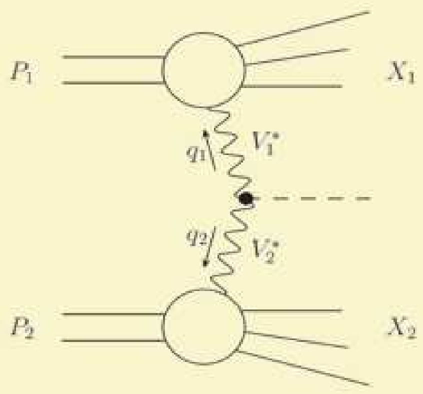
Higgs mass	LO±(scale)±(PDF)	NLO±(scale)±(PDF)	NNLO±(scale)±(PDF)
90.	1673.6 $^{+126.5}_{-125.4}$ $^{+20.7}_{-20.7}$	1782.2 $^{+58.9}_{-26.3}$ $^{+35.1}_{-35.1}$	1788.7 $^{+28.4}_{-32.8}$ $^{+31.6}_{-31.6}$
95.	1589[illegible] $^{+19.8}_{-19.8}$	1696.7 $^{+52.8}_{-33.1}$ $^{+33.6}_{-33.6}$	1696.8 $^{+27.0}_{-26.4}$ $^{+30.1}_{-30.1}$
100.	150[illegible] $^{+18.9}_{-18.9}$	1607.9 $^{+59.4}_{-29.4}$ $^{+32.0}_{-32.0}$	1615.8 $^{+25.2}_{-33.8}$ $^{+28.8}_{-28.8}$
105.	[illegible] $^{+18.1}_{-18.1}$	1530.5 $^{+58.9}_{-27.6}$ $^{+30.6}_{-30.6}$	1535.7 $^{+23.6}_{-33.2}$ $^{+27.5}_{-27.5}$
110.	[illegible] $^{+129.6}_{-120.2}$ $^{+17.4}_{-17.4}$	1455.8 $^{+55.4}_{-26.6}$ $^{+29.2}_{-29.2}$	1460.4 $^{+24.6}_{-26.6}$ $^{+26.3}_{-26.3}$
115.	[illegible] $^{+131.5}_{-117.7}$ $^{+16.6}_{-16.6}$	1386.2 $^{+53.4}_{-22.1}$ $^{+27.9}_{-27.9}$	1390.8 $^{+26.3}_{-28.2}$ $^{+25.1}_{-25.1}$
120.	[illegible] $^{+132.5}_{-117.2}$ $^{+16.0}_{-16.0}$	1319.9 $^{+54.9}_{-25.6}$ $^{+26.7}_{-26.7}$	1323.9 $^{+25.4}_{-22.7}$ $^{+24.0}_{-24.0}$
125[illegible]	[illegible] $^{+130.7}_{-115.5}$ $^{+15.3}_{-15.3}$	1258.0 $^{+57.4}_{-20.3}$ $^{+25.5}_{-25.5}$	1264.3 $^{+22.6}_{-23.4}$ $^{+23.1}_{-23.1}$
[illegible]	1126.5 $^{+130.3}_{-112.0}$ $^{+14.7}_{-14.7}$	1200.3 $^{+52.9}_{-20.3}$ $^{+24.5}_{-24.5}$	1203.3 $^{+25.7}_{-21.1}$ $^{+22.0}_{-22.0}$
[illegible]	1075.0 $^{+129.5}_{-109.8}$ $^{+14.1}_{-14.1}$	1144.1 $^{+52.8}_{-17.7}$ $^{+23.4}_{-23.4}$	1152.6 $^{+18.1}_{-22.9}$ $^{+21.2}_{-21.2}$
[illegible]	1026.5 $^{+128.8}_{-107.2}$ $^{+13.6}_{-13.6}$	1094.1 $^{+51.2}_{-17.7}$ $^{+22.5}_{-22.5}$	1098.8 $^{+24.0}_{-19.4}$ $^{+20.3}_{-20.3}$
[illegible]	981.8 $^{+126.4}_{-106.3}$ $^{+13.0}_{-13.0}$	1044.7 $^{+50.0}_{-17.7}$ $^{+21.5}_{-21.5}$	1049.9 $^{+21.5}_{-20.8}$ $^{+19.5}_{-19.5}$
[illegible]	938.3 $^{+124.6}_{-102.6}$ $^{+12.5}_{-12.5}$	999.8 $^{+48.6}_{-17.5}$ $^{+20.7}_{-20.7}$	1003.5 $^{+21.0}_{-15.6}$ $^{+18.7}_{-18.7}$
155.	898.6 $^{+120.4}_{-102.6}$ $^{+12.1}_{-12.1}$	957.0 $^{+46.3}_{-18.5}$ $^{+19.9}_{-19.9}$	959.9 $^{+20.9}_{-15.4}$ $^{+18.0}_{-18.0}$
160.	859.9 $^{+122.4}_{-99.7}$ $^{+11.6}_{-11.6}$	916.1 $^{+45.0}_{-16.3}$ $^{+19.1}_{-19.1}$	917.6 $^{+18.3}_{-13.3}$ $^{+17.3}_{-17.3}$
165.	823.3 $^{+119.9}_{-97.3}$ $^{+11.2}_{-11.2}$	876.5 $^{+44.3}_{-14.3}$ $^{+18.4}_{-18.4}$	880.9 $^{+18.4}_{-15.0}$ $^{+16.7}_{-16.7}$
170.	788.6 $^{+118.2}_{-95.5}$ $^{+10.8}_{-10.8}$	839.4 $^{+43.9}_{-15.1}$ $^{+17.6}_{-17.6}$	841.1 $^{+20.2}_{-12.6}$ $^{+16.0}_{-16.0}$
175.	755.8 $^{+115.6}_{-93.1}$ $^{+10.4}_{-10.4}$	803.7 $^{+43.5}_{-12.7}$ $^{+16.9}_{-16.9}$	808.5 $^{+17.4}_{-12.9}$ $^{+15.4}_{-15.4}$
180.	724.4 $^{+114.8}_{-90.3}$ $^{+10.0}_{-10.0}$	771.3 $^{+42.0}_{-13.1}$ $^{+16.3}_{-16.3}$	773.2 $^{+18.7}_{-10.5}$ $^{+14.8}_{-14.8}$
185.	695.6 $^{+112.3}_{-88.7}$ $^{+9.6}_{-9.6}$	739.8 $^{+41.1}_{-12.3}$ $^{+15.7}_{-15.7}$	741.2 $^{+18.5}_{-9.0}$ $^{+14.2}_{-14.2}$
190.	666.7 $^{+110.6}_{-85.4}$ $^{+9.3}_{-9.3}$	710.5 $^{+38.4}_{-13.6}$ $^{+15.1}_{-15.1}$	712.7 $^{+16.6}_{-10.2}$ $^{+13.7}_{-13.7}$
195.	640.4 $^{+109.3}_{-83.3}$ $^{+9.0}_{-9.0}$	682.2 $^{+38.3}_{-13.5}$ $^{+14.6}_{-14.6}$	685.6 $^{+14.6}_{-11.4}$ $^{+13.3}_{-13.3}$
200.	615.6 $^{+106.2}_{-81.7}$ $^{+8.7}_{-8.7}$	654.3 $^{+38.5}_{-11.6}$ $^{+14.0}_{-14.0}$	658.0 $^{+14.3}_{-9.6}$ $^{+12.8}_{-12.8}$
210.	568.3 $^{+102.9}_{-76.7}$ $^{+8.1}_{-8.1}$	604.9 $^{+35.1}_{-12.1}$ $^{+13.1}_{-13.1}$	608.1 $^{+13.7}_{-9.0}$ $^{+11.9}_{-11.9}$
220.	525.6 $^{+98.6}_{-73.7}$ $^{+7.5}_{-7.5}$	559.3 $^{+33.6}_{-11.3}$ $^{+12.1}_{-12.1}$	562.3 $^{+12.6}_{-7.5}$ $^{+11.1}_{-11.1}$
230.	487.1 $^{+94.2}_{-69.5}$ $^{+7.0}_{-7.0}$	518.4 $^{+32.2}_{-10.9}$ $^{+11.3}_{-11.3}$	521.3 $^{+11.4}_{-7.5}$ $^{+10.4}_{-10.4}$
240.	452.3 $^{+90.5}_{-67.2}$ $^{+6.6}_{-6.6}$	481.1 $^{+29.5}_{-11.8}$ $^{+10.6}_{-10.6}$	483.4 $^{+11.0}_{-6.4}$ $^{+9.7}_{-9.7}$
250.	420.0 $^{+86.8}_{-63.3}$ $^{+6.2}_{-6.2}$	445.7 $^{+29.8}_{-10.1}$ $^{+9.9}_{-9.9}$	448.8 $^{+10.7}_{-5.5}$ $^{+9.0}_{-9.0}$
260.	390.7 $^{+83.0}_{-60.1}$ $^{+5.8}_{-5.8}$	414.7 $^{+27.2}_{-10.2}$ $^{+9.2}_{-9.2}$	417.5 $^{+9.8}_{-5.2}$ $^{+8.5}_{-8.5}$
270.	363.8 $^{+79.6}_{-57.4}$ $^{+5.4}_{-5.4}$	386.0 $^{+25.8}_{-10.1}$ $^{+8.6}_{-8.6}$	388.6 $^{+9.8}_{-4.4}$ $^{+7.9}_{-7.9}$
280.	339.1 $^{+76.2}_{-54.5}$ $^{+5.1}_{-5.1}$	359.4 $^{+24.7}_{-9.8}$ $^{+8.1}_{-8.1}$	362.4 $^{+9.0}_{-4.3}$ $^{+7.5}_{-7.5}$
290.	316.2 $^{+73.1}_{-51.6}$ $^{+4.8}_{-4.8}$	336.0 $^{+22.6}_{-10.1}$ $^{+7.6}_{-7.6}$	338.0 $^{+8.6}_{-3.6}$ $^{+7.0}_{-7.0}$
300.	295.6 $^{+69.8}_{-49.2}$ $^{+4.5}_{-4.5}$	313.7 $^{+21.7}_{-10.0}$ $^{+7.1}_{-7.1}$	315.6 $^{+7.8}_{-3.1}$ $^{+6.6}_{-6.6}$
320.	258.7 $^{+64.0}_{-44.5}$ $^{+4.0}_{-4.0}$	274.0 $^{+19.8}_{-8.8}$ $^{+6.3}_{-6.3}$	276.2 $^{+7.3}_{-2.7}$ $^{+5.8}_{-5.8}$
340.	226.8 $^{+58.9}_{-39.9}$ $^{+3.5}_{-3.5}$	240.4 $^{+18.0}_{-8.1}$ $^{+5.6}_{-5.6}$	242.4 $^{+6.6}_{-2.2}$ $^{+5.2}_{-5.2}$
360.	199.8 $^{+53.8}_{-36.2}$ $^{+3.2}_{-3.2}$	211.9 $^{+16.1}_{-7.8}$ $^{+4.9}_{-4.9}$	213.6 $^{+5.7}_{-1.8}$ $^{+4.6}_{-4.6}$
380.	176.6 $^{+49.4}_{-32.9}$ $^{+2.8}_{-2.8}$	187.0 $^{+14.7}_{-7.4}$ $^{+4.4}_{-4.4}$	188.6 $^{+5.2}_{-1.4}$ $^{+4.1}_{-4.1}$
400.	156.5 $^{+45.3}_{-29.9}$ $^{+2.5}_{-2.5}$	165.7 $^{+13.1}_{-7.0}$ $^{+3.9}_{-3.9}$	167.1 $^{+4.5}_{-1.4}$ $^{+3.7}_{-3.7}$
450.	116.9 $^{+36.7}_{-23.6}$ $^{+2.0}_{-2.0}$	123.5 $^{+10.3}_{-5.8}$ $^{+3.0}_{-3.0}$	124.8 $^{+3.5}_{-1.3}$ $^{+2.8}_{-2.8}$
500.	88.5 $^{+29.6}_{-18.8}$ $^{+1.5}_{-1.5}$	93.4 $^{+8.1}_{-4.9}$ $^{+2.3}_{-2.3}$	94.4 $^{+2.7}_{-1.1}$ $^{+2.2}_{-2.2}$
550.	67.7 $^{+24.2}_{-14.9}$ $^{+1.2}_{-1.2}$	71.4 $^{+6.4}_{-4.0}$ $^{+1.8}_{-1.8}$	72.2 $^{+2.1}_{-1.0}$ $^{+1.7}_{-1.7}$
600.	52.3 $^{+19.7}_{-12.0}$ $^{+1.0}_{-1.0}$	55.2 $^{+5.1}_{-3.4}$ $^{+1.4}_{-1.4}$	55.8 $^{+1.6}_{-0.9}$ $^{+1.3}_{-1.3}$
650.	40.8 $^{+16.2}_{-9.7}$ $^{+0.8}_{-0.8}$	43.0 $^{+4.1}_{-2.9}$ $^{+1.1}_{-1.1}$	43.5 $^{+1.3}_{-0.7}$ $^{+1.1}_{-1.1}$
700.	32.0 $^{+13.3}_{-7.8}$ $^{+0.6}_{-0.6}$	33.7 $^{+3.3}_{-2.4}$ $^{+0.9}_{-0.9}$	34.1 $^{+1.1}_{-0.6}$ $^{+0.9}_{-0.9}$
750.	25.3 $^{+11.0}_{-6.4}$ $^{+0.5}_{-0.5}$	26.6 $^{+2.7}_{-2.0}$ $^{+0.7}_{-0.7}$	26.9 $^{+0.8}_{-0.5}$ $^{+0.7}_{-0.7}$
800.	20.1 $^{+9.1}_{-5.2}$ $^{+0.4}_{-0.4}$	21.1 $^{+2.2}_{-1.7}$ $^{+0.6}_{-0.6}$	21.4 $^{+0.7}_{-0.5}$ $^{+0.6}_{-0.6}$
850.	16.0 $^{+7.5}_{-4.3}$ $^{+0.3}_{-0.3}$	16.8 $^{+1.8}_{-1.4}$ $^{+0.5}_{-0.5}$	17.0 $^{+0.6}_{-0.4}$ $^{+0.4}_{-0.4}$
900.	12.8 $^{+6.2}_{-3.5}$ $^{+0.3}_{-0.3}$	13.5 $^{+1.5}_{-1.2}$ $^{+0.4}_{-0.4}$	13.6 $^{+0.4}_{-0.4}$ $^{+0.4}_{-0.4}$
950.	10.3 $^{+5.2}_{-2.9}$ $^{+0.2}_{-0.2}$	10.8 $^{+1.2}_{-1.0}$ $^{+0.3}_{-0.3}$	11.0 $^{+0.3}_{-0.3}$ $^{+0.3}_{-0.3}$
1000.	8.3 $^{+4.3}_{-2.4}$ $^{+0.2}_{-0.2}$	8.7 $^{+1.0}_{-0.8}$ $^{+0.2}_{-0.2}$	8.8 $^{+0.3}_{-0.3}$ $^{+0.2}_{-0.2}$

TABLE I: Cross sections (fb) at a $\sqrt{S} = 7$ TeV LHC at LO, NLO and NNLO in QCD with the uncertainties due to independent scale variations $\mu_R, \mu_F \in [Q/4, 4Q]$ and due to the PDF errors.

VBF @ NNLO : Cross-section Calculator

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

alpha version v0.3 -- 01 July 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.

Registration | Talks & Conferences | HNNLO web page (gg->H)

Up to order:	NNLO	
Collider type:	p-p	
Center of mass energy:	7000	GeV
Higgs boson mass:	120	GeV
PDF set:	MSTW08 68%cl (LO-NLO-NNLO)	Description
PDF uncertainities:	no	
Reference scale:	Q (recommended)	Description
Scale uncertainities:	no	Description

Submit

http://vbf-nnlo.phys.ucl.ac.be/vbf.html

This is an alpha version. Pleae send comments/requests/bug rep ... Marco.Zaro AT uclouvain.be).

Conclusions

Higgs production via VBF

- NNLO QCD corrections to total cross section (factorization approach)
- VBF "on par" with gluon fusion and Higgs strahlung
  - best present estimate
- Small residual scale uncertainty
  - important information about preferred scale choices

Outlook

- Precision predictions
  - combine with NLO EW corrections Dittmaier, Denner, Mück '10
- Factorization approach
  - improve estimate of neglected contributions
  - study effect of standard VBF cuts (e.g. rapidity)
- Future: fully differential distribution