

Higgs production via vector-boson fusion at NNLO in QCD

Sven-Olaf Moch

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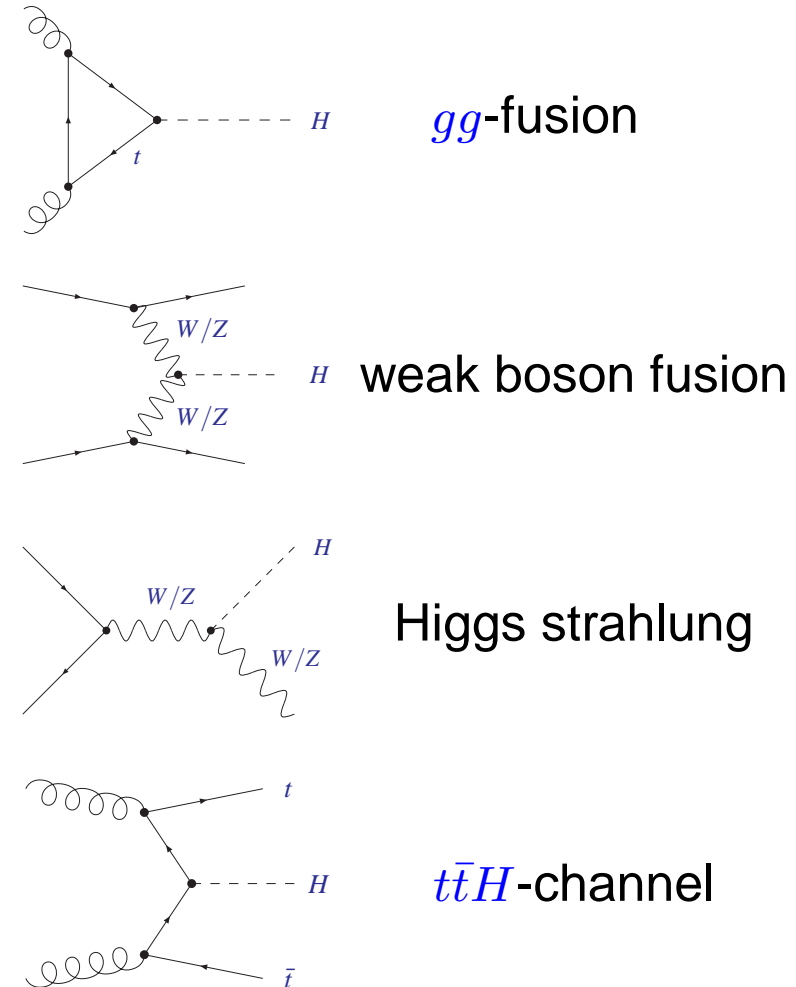
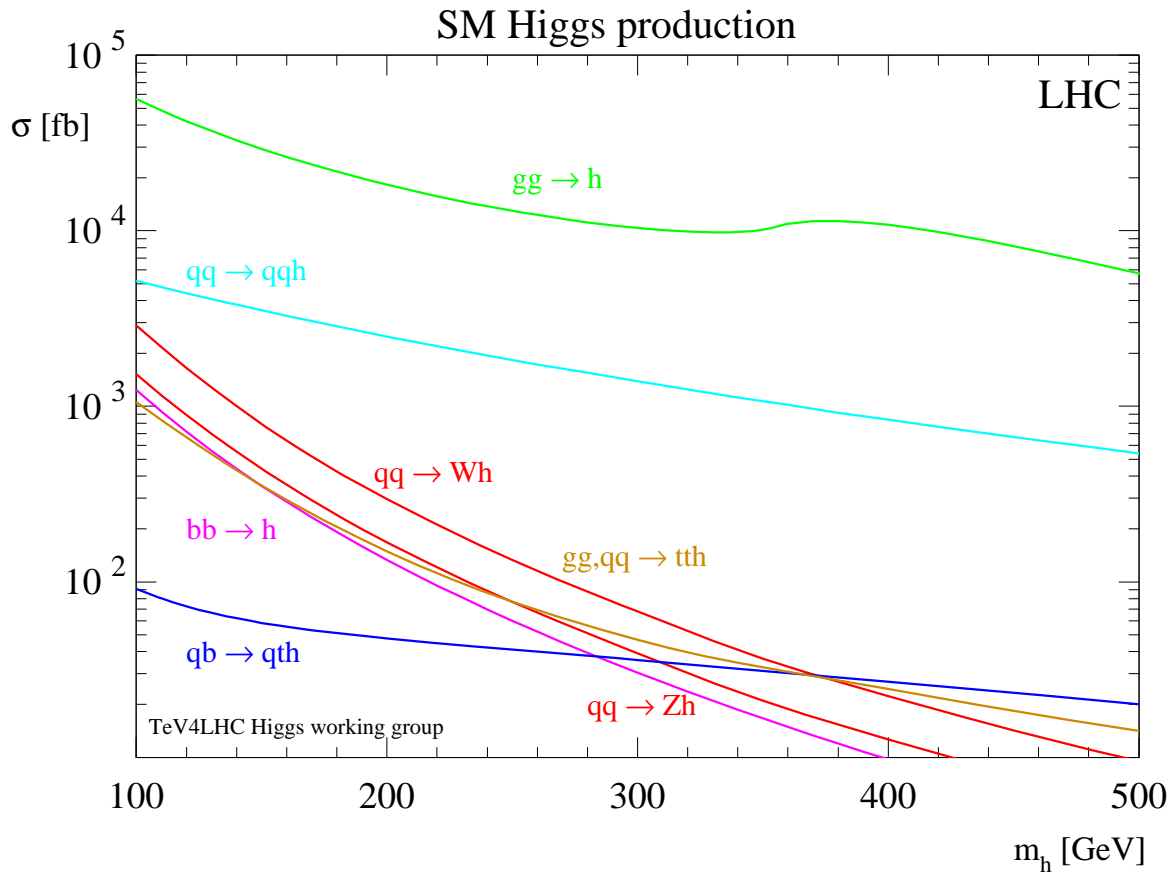
DESY, Zeuthen

in collaboration with **P. Bolzoni** , **F. Maltoni** and **M. Zaro** on [arXiv:1003.4451](https://arxiv.org/abs/1003.4451)

– *Workshop of the LHC Higgs Cross Section Working Group at CERN, Geneva, July 05, 2010* –

Cross section for Higgs production at the LHC

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



Why precision ?

- Standard approach to uncertainties in theoretical predictions

- variation of factorization scale μ : $\frac{d}{d \ln \mu^2} \sigma_{pp \rightarrow X} = \mathcal{O}(\alpha_s^{l+1})$

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

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

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

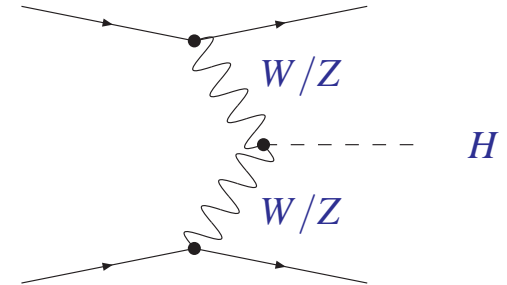
NLO: standard approximation (large uncertainties)

QCD predictions at NNLO

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

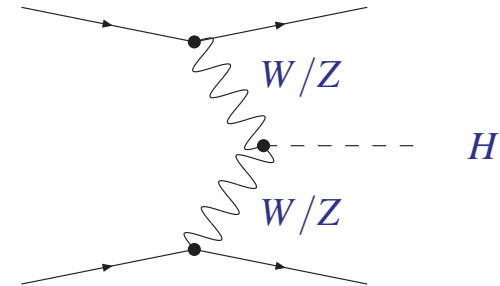
Vector-boson fusion

- Second largest rate (WWH coupling)



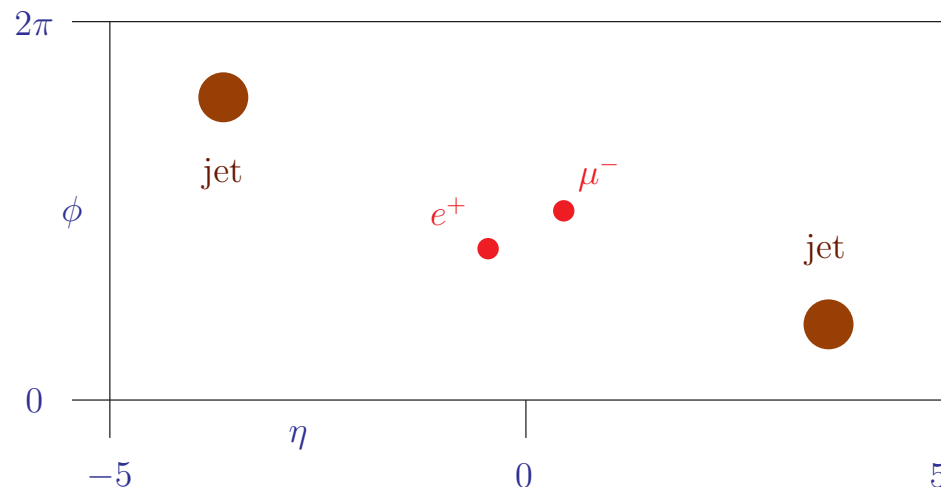
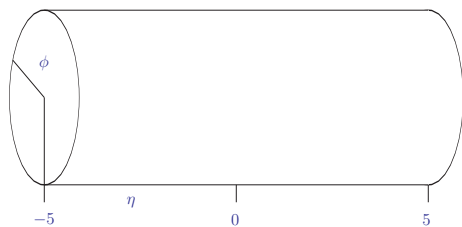
Vector-boson fusion

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Signatures

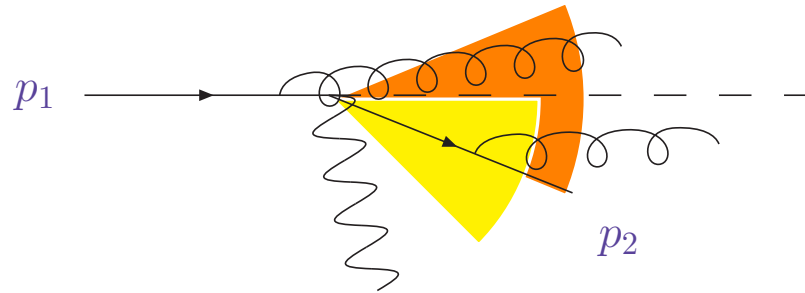
- WW, ZZ fusion \rightarrow Higgs is color singlet
 - 2 hard (forward) tagging jets (visible in detector)
 - no (or small) hadronic activity between tagging jets
 - color connection between forward jet and proton remnant
 - Higgs decay in the central rapidity region



Perturbative QCD corrections

Where is the hadronic activity ?

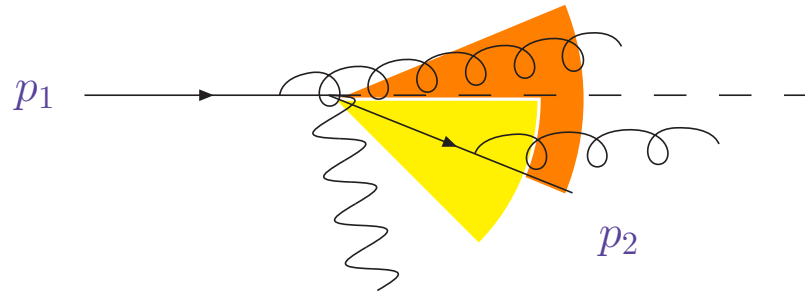
- QCD radiation predominantly in direction of incoming partons (angular ordering)



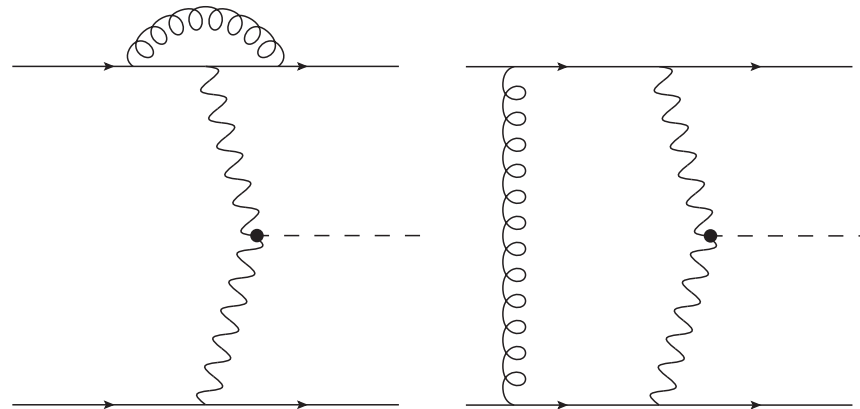
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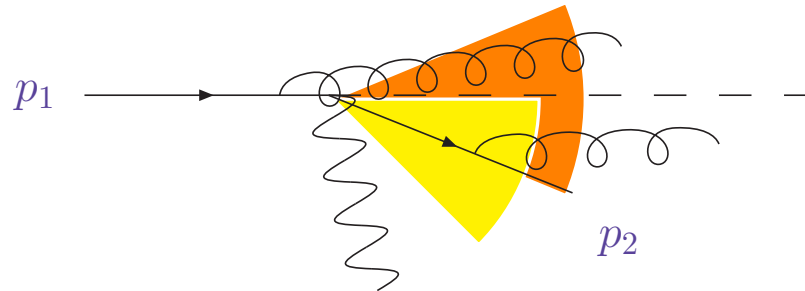
- NLO QCD corrections (vertex corrections and t -channel gluon)



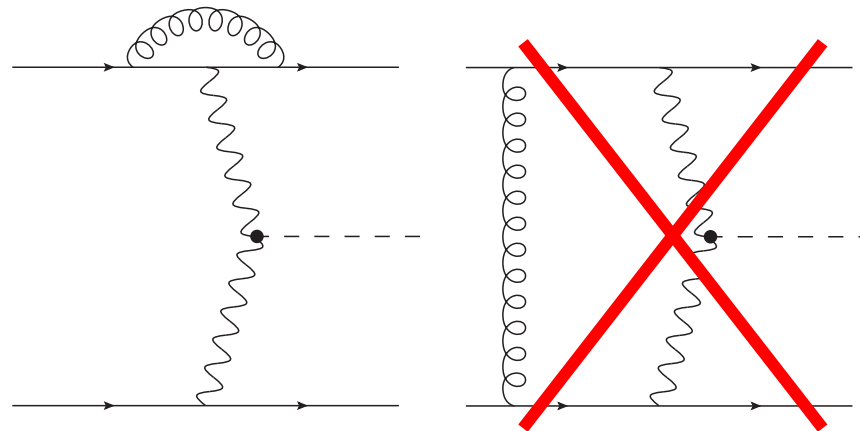
Perturbative QCD corrections

Where is the hadronic activity ?

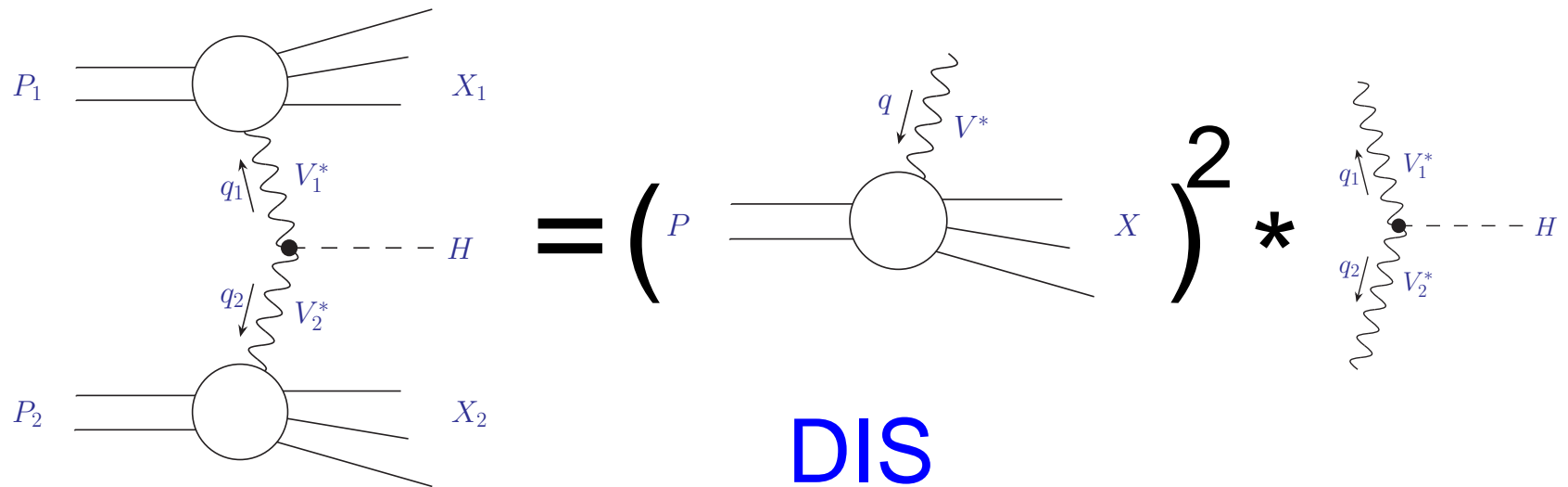
- QCD radiation predominantly in direction of incoming partons (angular ordering)



- Color conservation eliminates t -channel gluon exchange at NLO

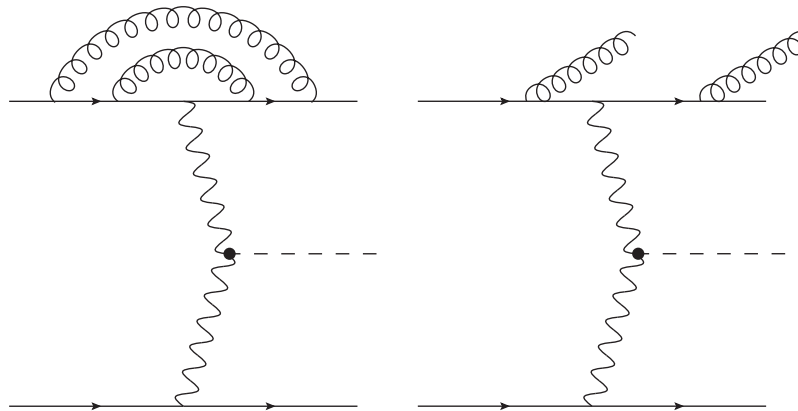


Exact factorization



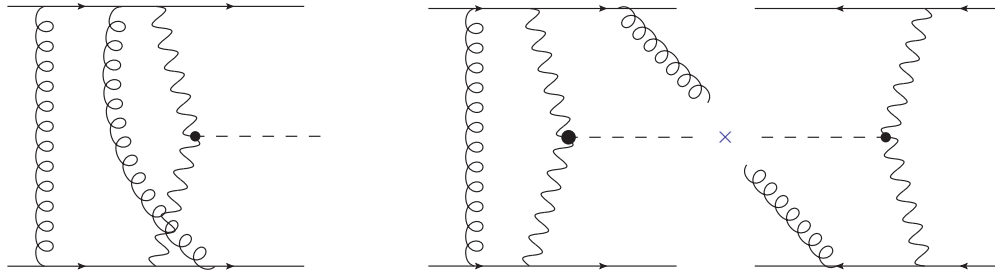
- Deep-inelastic scattering building block of cross section
- DIS structure functions F_1 , F_2 and F_3 sufficient VBF cross section at NLO in QCD
- Exact factorization at NLO: so-called structure function approach
Han, Valencia, Willenbrock '92

NNLO diagrams

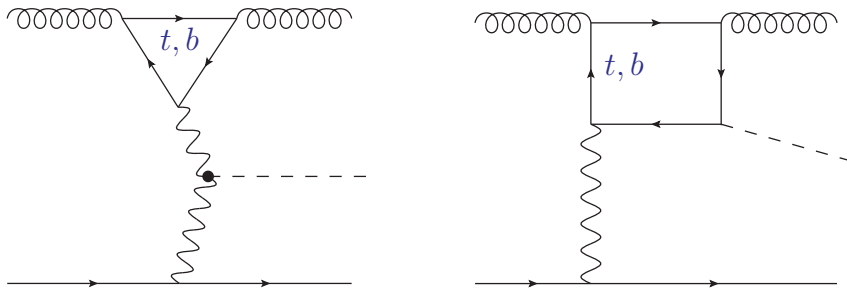


- Structure function approach is NOT exact at NNLO in QCD
 - but can be still considered a good approximation
- Dominant contributions are included through structure functions also at higher orders
 - F_1 , F_2 and F_3
long known at NNLO
Kazakov, Kotikov '88; Zijlstra, van Neerven '92; S.M., Vermaseren '99
and even at N³LO
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/IR finite

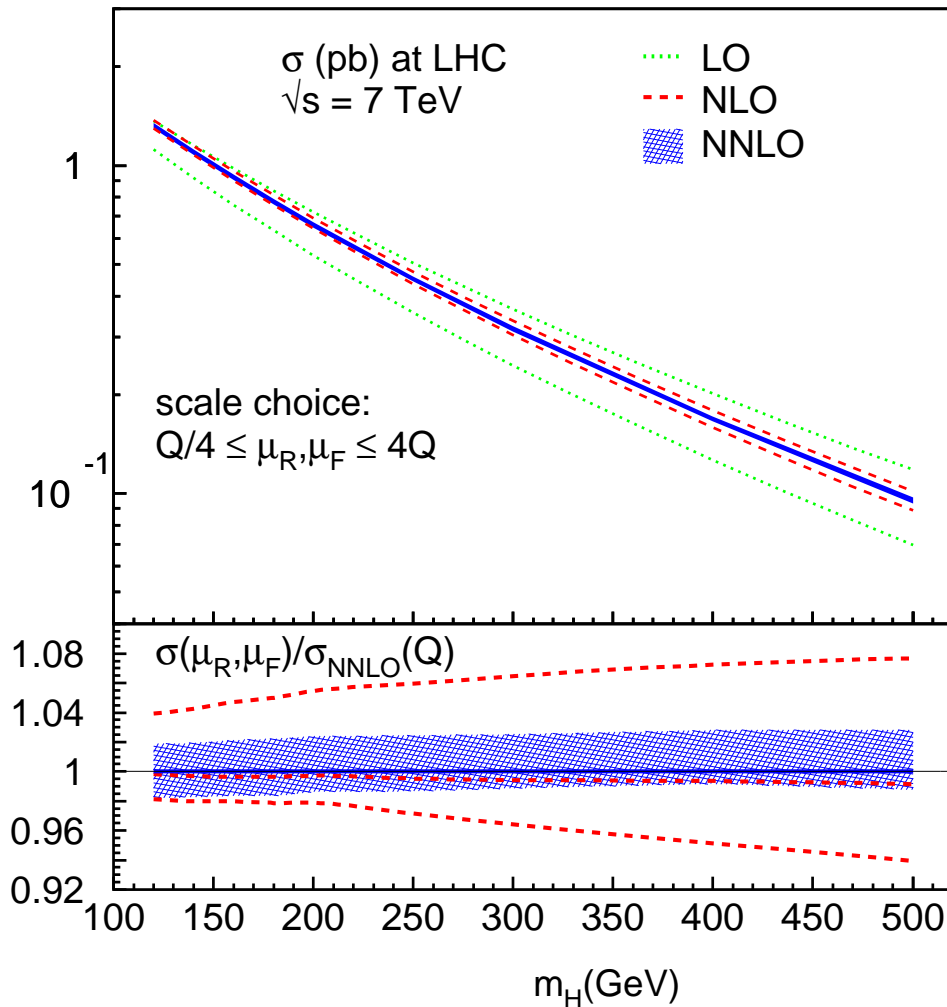


- negligible (estimated $\ll 1\%$)
- gauge invariant, destructive interference between box and triangle

Upshot

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

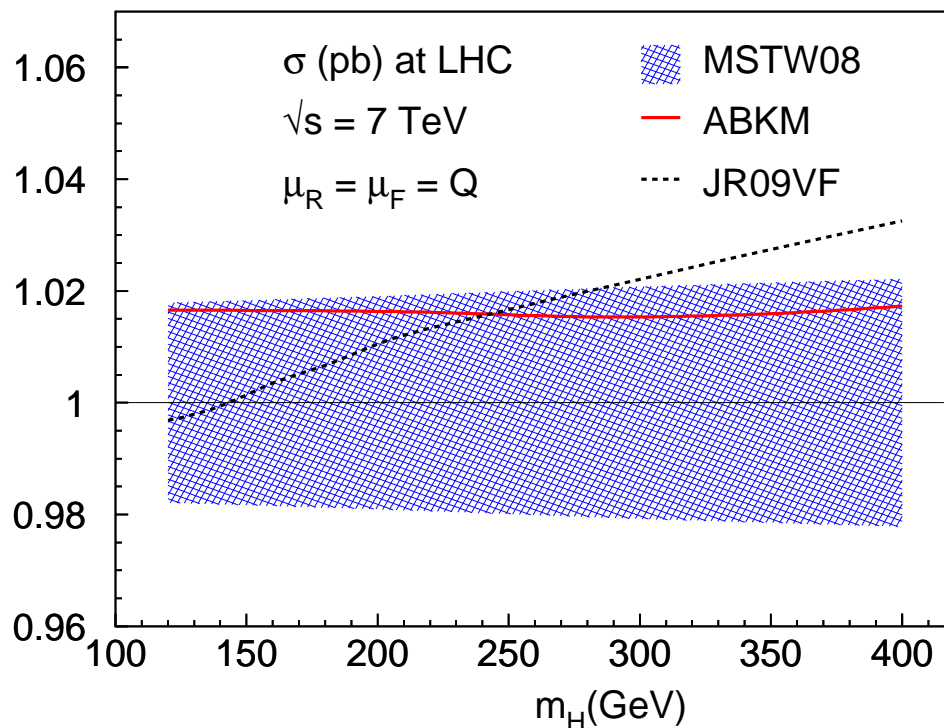
Cross section for VBF at LHC



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

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

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Upshot

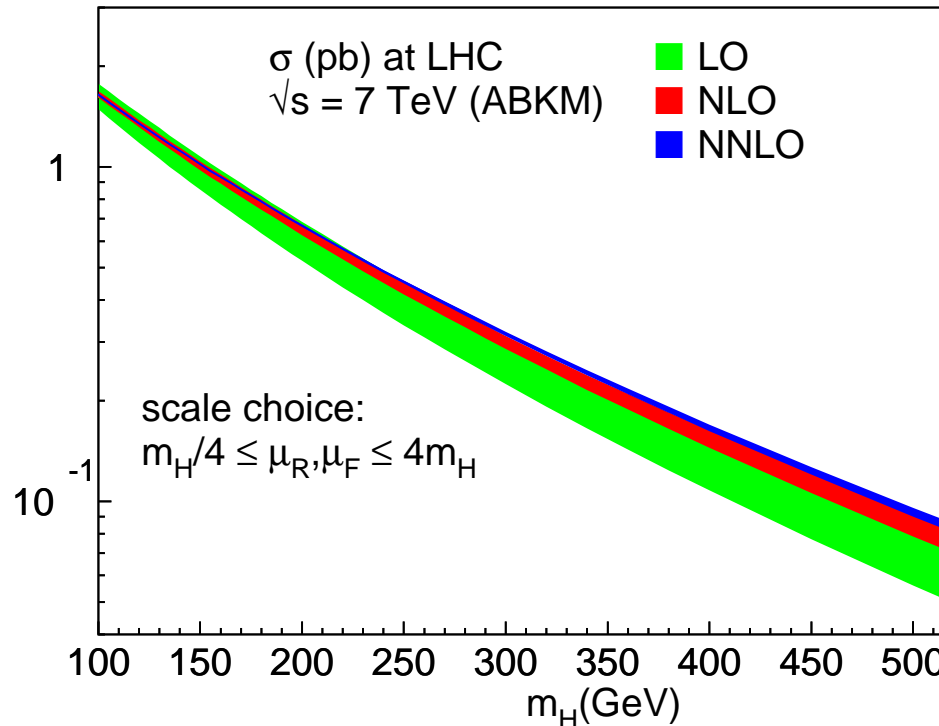
- apparent convergence
- scale stability
- reduction of theoretical uncertainty
- PDF + α_s uncertainty generally small (improved at NNLO)

$$\Delta\sigma_{NLO} \gg \Delta\sigma_{NNLO}$$

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

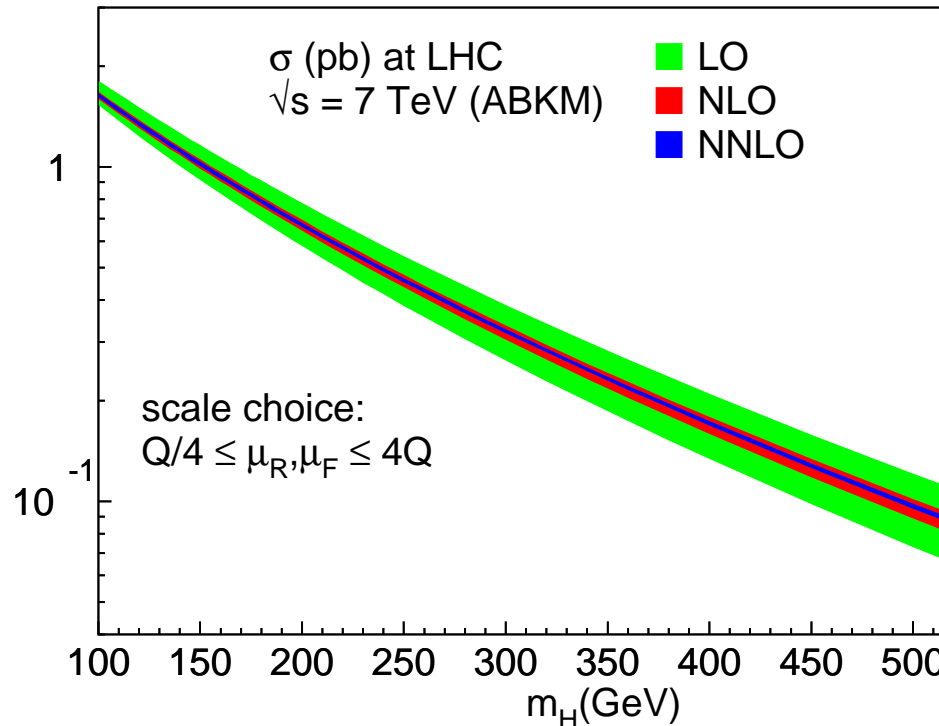
Comments on VBF

- 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)



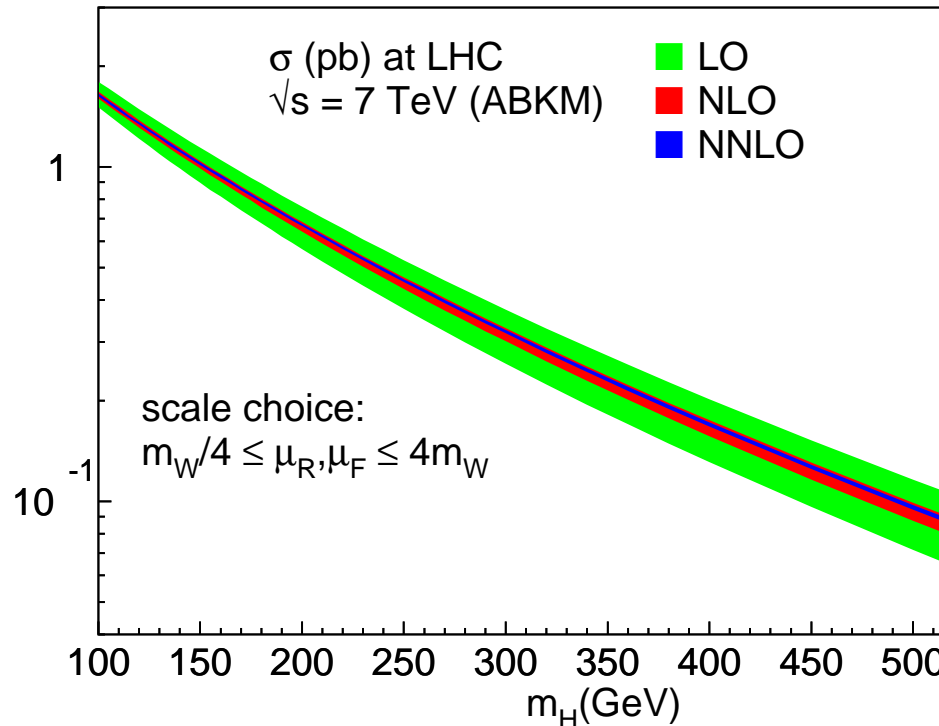
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Higgs mass	LO±(scale)±(PDF)	NLO±(scale)±(PDF)	NNLO±(scale)±(PDF)
90.	1673.6 +126.5 +20.7 -125.4 -20.7	1782.2 +58.9 +35.1 -26.3 -35.1	1788.7 +28.4 +31.6 -32.8 -31.6
95.	1589.4 +124.5 +19.8 -114.4 -19.8	1696.7 +52.8 +33.6 -33.1 -33.6	1696.8 +27.0 +30.1 -26.4 -30.1
100.	1507.7 +119.7 +18.9 -107.2 -18.9	1607.9 +59.4 +32.0 -29.4 -32.0	1615.8 +25.2 +28.8 -33.8 -28.8
105.	1429.4 +114.2 +18.1 -101.6 -18.1	1530.5 +58.9 +30.6 -27.6 -30.6	1535.7 +23.6 +27.5 -33.2 -27.5
110.	1352.6 +109.6 +17.4 -96.2 -17.4	1455.8 +55.4 +29.2 -26.6 -29.2	1460.4 +24.6 +26.3 -26.6 -26.3
115.	1275.8 +105.1 +16.6 -91.7 -16.6	1386.2 +53.4 +27.9 -22.1 -27.9	1390.8 +26.3 +25.1 -28.2 -25.1
120.	1200.2 +100.6 +16.0 -87.2 -16.0	1319.9 +54.9 +26.7 -25.6 -26.7	1323.9 +25.4 +24.0 -22.7 -24.0
125.	1125.2 +96.1 +15.3 -82.7 -15.3	1258.0 +57.4 +25.5 -20.3 -25.5	1264.3 +22.6 +23.1 -23.4 -23.1
130.	1050.2 +91.6 +14.7 -78.2 -14.7	1200.3 +52.9 +24.5 -20.3 -24.5	1203.3 +25.7 +22.0 -21.1 -22.0
135.	975.2 +87.1 +14.1 -73.7 -14.1	1144.1 +52.8 +23.4 -17.7 -23.4	1152.6 +18.1 +21.2 -22.9 -21.2
140.	900.2 +82.6 +13.6 -69.2 -13.6	1094.1 +51.2 +22.5 -17.7 -22.5	1098.8 +24.0 +20.3 -19.4 -20.3
145.	825.2 +78.1 +13.0 -64.7 -13.0	1044.7 +50.0 +21.5 -17.7 -21.5	1049.9 +21.5 +19.5 -20.8 -19.5
150.	750.2 +73.6 +12.5 -60.2 -12.5	999.8 +48.6 +20.7 -17.5 -20.7	1003.5 +21.0 +18.7 -15.6 -18.7
155.	675.2 +69.1 +12.1 -55.7 -12.1	957.0 +46.3 +19.9 -18.5 -19.9	959.9 +20.9 +18.0 -15.4 -18.0
160.	600.2 +64.6 +11.6 -51.2 -11.6	916.1 +45.0 +19.1 -16.3 -19.1	917.6 +18.3 +17.3 -13.3 -17.3
165.	525.2 +60.1 +11.2 -46.7 -11.2	876.5 +44.3 +18.4 -14.3 -18.4	880.9 +18.4 +16.7 -15.0 -16.7
170.	450.2 +55.6 +10.8 -42.2 -10.8	839.4 +43.9 +17.6 -15.1 -17.6	841.1 +20.2 +16.0 -12.6 -16.0
175.	375.2 +51.1 +10.4 -37.7 -10.4	803.7 +43.5 +16.9 -12.7 -16.9	808.5 +17.4 +15.4 -12.9 -15.4
180.	300.2 +46.6 +10.0 -33.2 -10.0	771.3 +42.0 +16.3 -13.1 -16.3	773.2 +18.7 +14.8 -10.5 -14.8
185.	225.2 +42.1 +9.6 -28.7 -9.6	739.8 +41.1 +15.7 -12.3 -15.7	741.2 +18.5 +14.2 -9.0 -14.2
190.	150.2 +37.6 +9.3 -24.2 -9.3	710.5 +38.4 +15.1 -13.6 -15.1	712.7 +16.6 +13.7 -10.2 -13.7
195.	75.2 +33.1 +9.0 -19.7 -9.0	682.2 +38.3 +14.6 -13.5 -14.6	685.6 +14.6 +13.3 -11.4 -13.3
200.	0.2 +28.6 +8.7 -15.2 -8.7	654.3 +38.5 +14.0 -11.6 -14.0	658.0 +14.3 +12.8 -9.6 -12.8
210.	-75.2 +24.1 +8.1 -10.7 -8.1	604.9 +35.1 +13.1 -12.1 -13.1	608.1 +13.7 +11.9 -9.0 -11.9
220.	-150.2 +19.6 +7.5 -6.2 -7.5	559.3 +33.6 +12.1 -11.3 -12.1	562.3 +12.6 +11.1 -7.5 -11.1
230.	-225.2 +15.1 +7.0 -1.7 -7.0	518.4 +32.2 +11.3 -10.9 -11.3	521.3 +11.4 +10.4 -7.5 -10.4
240.	-300.2 +10.6 +6.6 -2.8 -6.6	481.1 +29.5 +10.6 -11.8 -10.6	483.4 +11.0 +9.7 -6.4 -9.7
250.	-375.2 +6.1 +6.2 -8.3 -6.2	445.7 +29.8 +9.9 -10.1 -9.9	448.8 +10.7 +9.0 -5.5 -9.0
260.	-450.2 +1.6 +5.8 -13.8 -5.8	414.7 +27.2 +9.2 -10.2 -9.2	417.5 +9.8 +8.5 -5.2 -8.5
270.	-525.2 -2.9 +5.4 -19.3 -5.4	386.0 +25.8 +8.6 -10.1 -8.6	388.6 +9.8 +7.9 -4.4 -7.9
280.	-600.2 -8.4 +5.1 -24.8 -5.1	359.4 +24.7 +8.1 -9.8 -8.1	362.4 +9.0 +7.5 -4.3 -7.5
290.	-675.2 -13.9 +4.8 -30.3 -4.8	336.0 +22.6 +7.6 -10.1 -7.6	338.0 +8.6 +7.0 -3.6 -7.0
300.	-750.2 -19.4 +4.5 -35.8 -4.5	313.7 +21.7 +7.1 -10.0 -7.1	315.6 +7.8 +6.6 -3.1 -6.6
320.	-825.2 -24.9 +4.0 -41.3 -4.0	274.0 +19.8 +6.3 -8.8 -6.3	276.2 +7.3 +5.8 -2.7 -5.8
340.	-900.2 -30.4 +3.5 -46.8 -3.5	240.4 +18.0 +5.6 -8.1 -5.6	242.4 +6.6 +5.2 -2.2 -5.2
360.	-975.2 -35.9 +3.2 -52.3 -3.2	211.9 +16.1 +4.9 -7.8 -4.9	213.6 +5.7 +4.6 -1.8 -4.6
380.	-1050.2 -41.4 +2.8 -57.8 -2.8	187.0 +14.7 +4.4 -7.4 -4.4	188.6 +5.2 +4.1 -1.4 -4.1
400.	-1125.2 -46.9 +2.5 -63.3 -2.5	165.7 +13.1 +3.9 -7.0 -3.9	167.1 +4.5 +3.7 -1.4 -3.7
450.	-1275.2 -57.4 +2.0 -73.8 -2.0	123.5 +10.3 +3.0 -5.8 -3.0	124.8 +3.5 +2.8 -1.3 -2.8
500.	-1425.2 -67.9 +1.5 -84.3 -1.5	93.4 +8.1 +2.3 -4.9 -2.3	94.4 +2.7 +2.2 -1.1 -2.2
550.	-1575.2 -78.4 +1.2 -94.8 -1.2	71.4 +6.4 +1.8 -4.0 -1.8	72.2 +2.1 +1.7 -1.0 -1.7
600.	-1725.2 -88.9 +1.0 -105.3 -1.0	55.2 +5.1 +1.4 -3.4 -1.4	55.8 +1.6 +1.3 -0.9 -1.3
650.	-1875.2 -99.4 +0.8 -115.8 -0.8	43.0 +4.1 +1.1 -2.9 -1.1	43.5 +1.3 +1.1 -0.7 -1.1
700.	-2025.2 -109.9 +0.6 -126.3 -0.6	33.7 +3.3 +0.9 -2.4 -0.9	34.1 +1.1 +0.9 -0.6 -0.9
750.	-2175.2 -120.4 +0.5 -136.8 -0.5	26.6 +2.7 +0.7 -2.0 -0.7	26.9 +0.8 +0.7 -0.5 -0.7
800.	-2325.2 -130.9 +0.4 -147.3 -0.4	21.1 +2.2 +0.6 -1.7 -0.6	21.4 +0.7 +0.6 -0.5 -0.6
850.	-2475.2 -141.4 +0.3 -157.8 -0.3	16.8 +1.8 +0.5 -1.4 -0.5	17.0 +0.6 +0.4 -0.4 -0.4
900.	-2625.2 -151.9 +0.3 -168.3 -0.3	13.5 +1.5 +0.4 -1.2 -0.4	13.6 +0.4 +0.4 -0.4 -0.4
950.	-2775.2 -162.4 +0.2 -178.8 -0.2	10.8 +1.2 +0.3 -1.0 -0.3	11.0 +0.3 +0.3 -0.3 -0.3
1000.	-2925.2 -172.9 +0.2 -189.3 -0.2	8.7 +1.0 +0.2 -0.8 -0.2	8.8 +0.3 +0.2 -0.3 -0.2

numbers ...

July 4, 2010 (23:15)

Higgs production via vector-boson fusion at NNLO in QCD - p.11

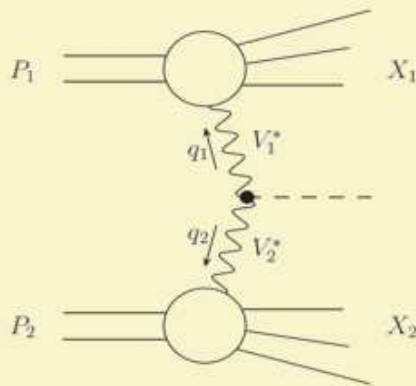
Sven-Olaf Moch

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 \[hep-ph\]](https://arxiv.org/abs/1003.4451).

This simple interface allows any [registered](#) user to obtain a cross section up to NNLO in QCD, including an estimate of the theoretical uncertainties coming from scale variation and PDF uncertainties.

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:	<input type="text" value="NNLO"/>	
Collider type:	<input type="text" value="p-p"/>	
Center of mass energy:	<input type="text" value="7000"/>	GeV
Higgs boson mass:	<input type="text" value="120"/>	GeV
PDF set:	<input type="text" value="MSTW08 68%cl (LO-NLO-NNLO)"/>	Description
PDF uncertainties:	<input type="text" value="no"/>	
Reference scale:	<input type="text" value="Q (recommended)"/>	Description
Scale uncertainties:	<input type="text" value="no"/>	Description

This is an alpha version. Please send comments/requests/bug reports to marco.zaro@uclouvain.be.

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

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

- Within *Higgs Cross Section Working Group*:
 - combine with HAWK (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