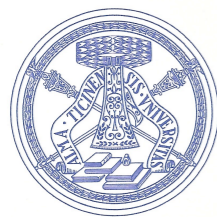


LHC Higgs Cross Section WG: VBF Status Report



Daniela Rebutti, *Pavia University and INFN*
on behalf of the LHC Higgs Cross Section VBF subgroup

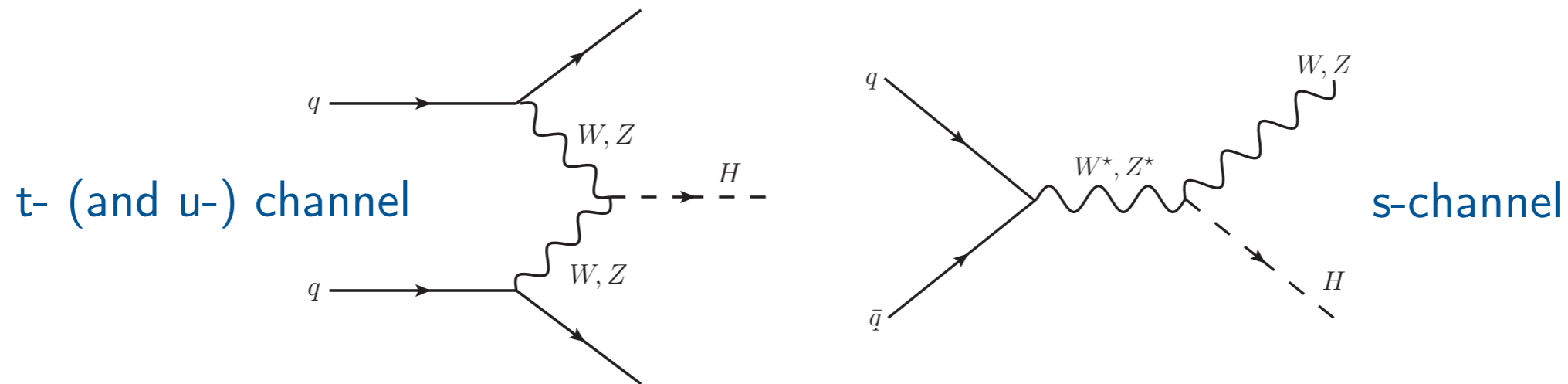


Co-contacts: A. Denner (*Würzburg*), P. Govoni (*Milano*), C. Oleari (*Milano-Bicocca*)

Collaborators: P. Bolzoni, S. Dittmaier, B. Quayle, F. Maltoni, C. Mariotti, S.-O. Moch, A. Mueck, P. Nason, S. Palmer, G. Passarino, R. Tanaka, G. Steele, M. Zaro



VBF Calculations and Programs



Available calculations and programs:

- VV2H [M. Spira]: only t-channel, NLO QCD
- • **VBFNLO** [D. Zeppenfeld *et al.*]: only t-channel, NLO QCD + NLO EW
- MCFM [J. M. Campbell, R. K. Ellis, C. Williams]: only t-channel, NLO QCD hep-ph/0403194
- • **HAWK** [M. Ciccolini, A. Denner, A. Dittmaier, A. Mück]: NLO QCD and NLO EW, s- and t-channel included (s-channel may be switched off)
- • **VBF@NNLO program** [P. Bolzoni, F. Maltoni, S.-O. Moch, M. Zaro]
- • **POWHEG** [C. Oleari, P. Nason]: only t-channel, NLO QCD + PS

- Pythia/Fortran-Herwig: simulate only t-channel
- Sherpa: automatically includes s-channel

VBF Cross Sections at 8 TeV

- **Central Values:** Inclusive calculations 'à la YR1', i.e.:

NNLO QCD (structure function approach) + NLO EW (HAWK)

- **QCD scale uncertainty:** estimated by changing μ_R and μ_F independently by a factor 2 and 1/2 (at NNLO QCD)
 - **PDF+ α_s uncertainties:** PDF4LHC prescription for 7 TeV \rightarrow 8 TeV to avoid the recalculation of the PDF+ α_s envelope *not really valid for VBF*:
 - for $M_H > 300$ GeV we do not have numbers at 7 TeV for off-shell Higgs \rightarrow at least for $M_H > 300$ GeV we have to do new runs
 - for VBF the factorization scale is M_W and not \sqrt{s} and this makes the argument of PDF4LHC partly invalid
 - changing prescription at 300 GeV is probably creating a non-physical kink/discontinuity
- ➔ *We opted for the full envelope recalculation at 8 TeV*

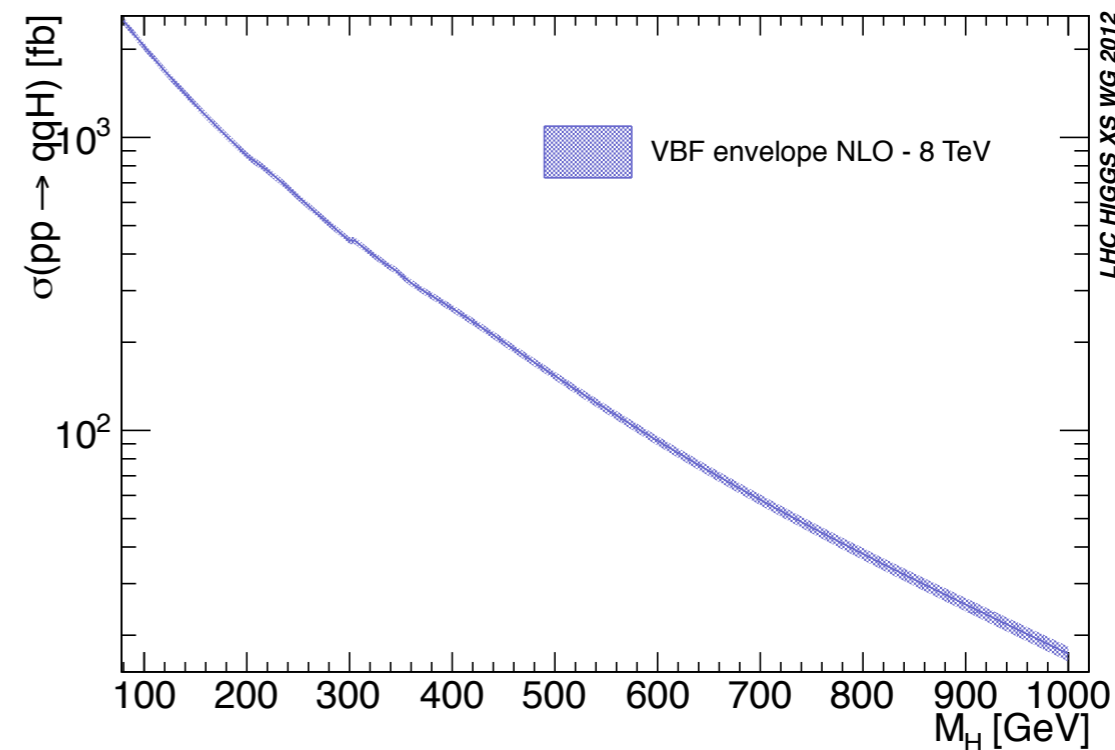
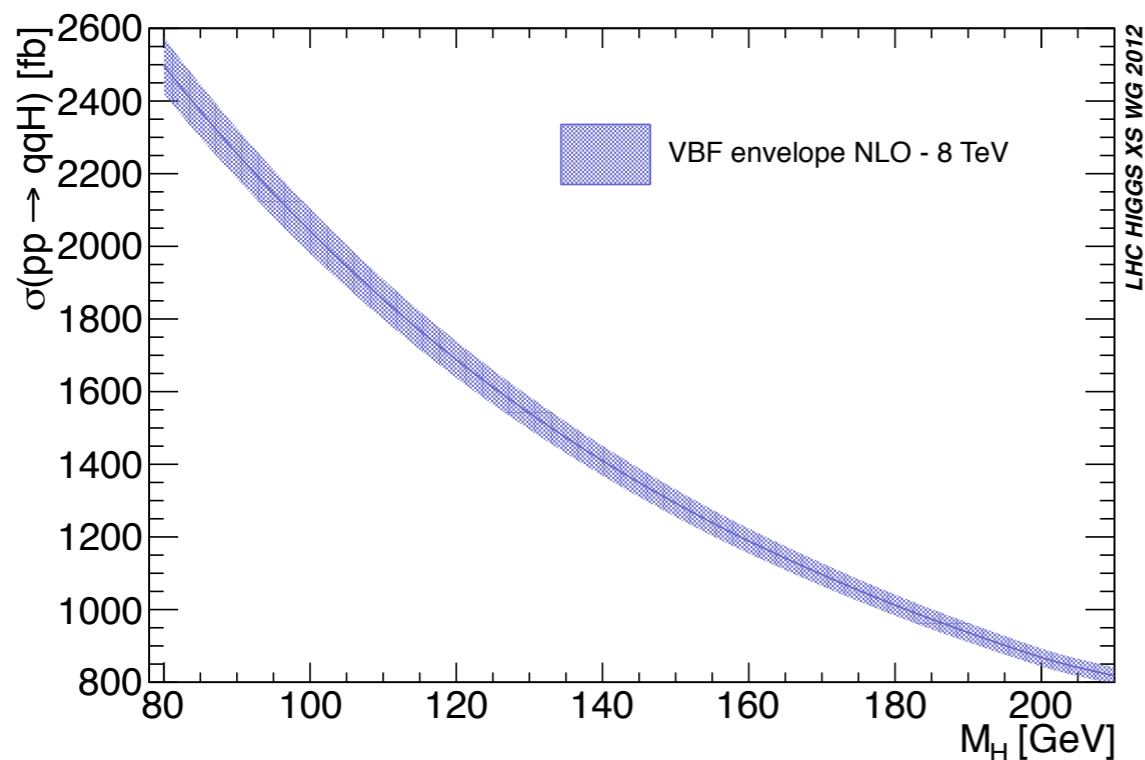
VBF Cross Sections at 8 TeV - results

[to appear at <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV>]

M_H [GeV]	$\sigma_{VBF@NNLO}^{NNLO}$ [fb]	$\sigma^{NNLO+EW}$ [fb]	δ_{HAWK}^{EW} [%]	PDF4LHC [%]	QCD Scale [%]
80.0	2527	2410	- 4.6	± 3.1	+0.2 - 0.3
81.0	2500	2384	- 4.6	± 3.1	+0.4 - 0.3
82.0	2475	2360	- 4.6	± 3.1	+0.3 - 0.3
83.0	2449	2336	- 4.6	± 3.1	+0.4 - 0.2
84.0	2424	2311	- 4.6	± 3.1	+0.3 - 0.2
85.0	2400	2289	- 4.6	± 3.1	+0.3 - 0.2
86.0	2375	2265	- 4.6	± 3.1	+0.3 - 0.2

[.....]

233 mass points (see Backup Slides for mass grid)



VBF Cross Sections at 8 TeV - comments

1. A problem in the complex mass scheme implementation has been found:

- VBF@NNLO numbers recalculated
- HAWK cross sections (temporary) corrected a posteriori using scaling factors G_OS/ γ_H (*)

Validity of rescaling for NLO QCD cross section

M_H [GeV]	$\sigma_{rescaled}^{NLO-QCD}$ [fb]	$\sigma_{correct}^{NLO-QCD}$ [fb]	error[%]
400	250.0(1)	249.8(1)	0.08
600	93.69(3)	94.68(4)	-1.1
900	28.69(2)	30.54(2)	-6.1

rescaling is not really fine at large M_H

Validity of the corrections at NLO EW

M_H [GeV]	$\delta_{EW}(ONS)$ [%]	$\delta_{EW}(CMS)$ [%]	error[%]
400	-3.29(1)	-3.28(1)	0.01(1)
600	3.42(2)	3.39(2)	-0.03(2)
900	17.33(6)	17.42(6)	-0.09(6)

δ_{EW} depends mildly on the rescaling, same for α_s+PDF bands

- Agreement after the correct complex mass scheme implementation
as good as before with the wrong Higgs width

	8TeV - $M_H = 600$ GeV - MSTW2008	
	LO	NLO
HAWK	87.93(2)	91.68(3)
VBF@NNLO	87.94	91.56
VBFNLO	87.87(4)	91.68(6)

2. Envelope PDF4LHC calculated at NLO, to be correct for NNLO [The PDF4LHC Working Group (**)
Interim Report, <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSectionsCalc>]

(*) calculations will be redone for Winter Conf (**) will be done by next week

VBF Cross Sections for the ES

[<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy2012>]

European Strategy (ES) scenario: high-luminosity LHC collecting 3 ab^{-1} at 14 and 33 TeV

- Higgs physics *important*: Higgs coupling measurements, self-coupling, rare decay, etc.
- Working points: $M_H = 125$ (Higgs couplings) and 800 GeV (heavy Higgs - 800 GeV is chosen to avoid unitarity problem at $s \rightarrow \infty$)
- We have to provide (VBF) cross sections and associated uncertainties

• **First results:**

33 TeV - $M_H = 120 \text{ GeV}$ - MSTW2008nlo <i>on shell Higgs</i>			
	HAWK [fb]	VBF@NNLO [fb]	VBF@NLO [fb]
LO	17561(5)	17563(9)	17565(2)
NLO QCD	16688(14)	16669(9)	16683(3)
NLO QCD+EW	15557(14)	-	15546(15)

33 TeV - $M_H = 125 \text{ GeV}$ *on shell Higgs*

	VBFNLO-MSTW [fb]	HAWK-MSTW [fb]	HAWK-CT10 [fb]	POWHEG-CT10 [fb]
LO	16976(2)	16980(7)	17167(7)	-
NLO QCD	16145(3)	16154(19)	16368(18)	16770(67)
NLO QCD+EW	-	15030(23)	15232(20)	-

33 TeV - $M_H = 800 \text{ GeV}$ *complex mass scheme*

	VBFNLO-MSTW [fb]	HAWK-MSTW [fb]	HAWK-CT10 [fb]	POWHEG-CT10 [fb]
LO	2304(1)	2306(1)	2337(1)	-
NLO QCD	2294(2)	2298(5)	2326(5)	2368(10)
NLO QCD+EW	2480(6)	2489(5)	2520(5)	-

The complex mass scheme should also be taken into account *in the existing ggF and VBF samples* (already processed in ATLAS and CMS), especially for high masses → **Reweighting of NLO MC** with the ‘corrected’ Higgs invariant mass spectrum (including associated shape uncertainty) for both ggF and VBF processes

1. Tool A [G.Steele and DR]

ggF

Weights calculated as:

$$\mathbf{factor} = \text{Passarino}(\text{complex mass scheme, EW corr}) / \text{Passarino}(\text{POWHEG propagator, no EW corr})$$

VBF

Weights calculated as:

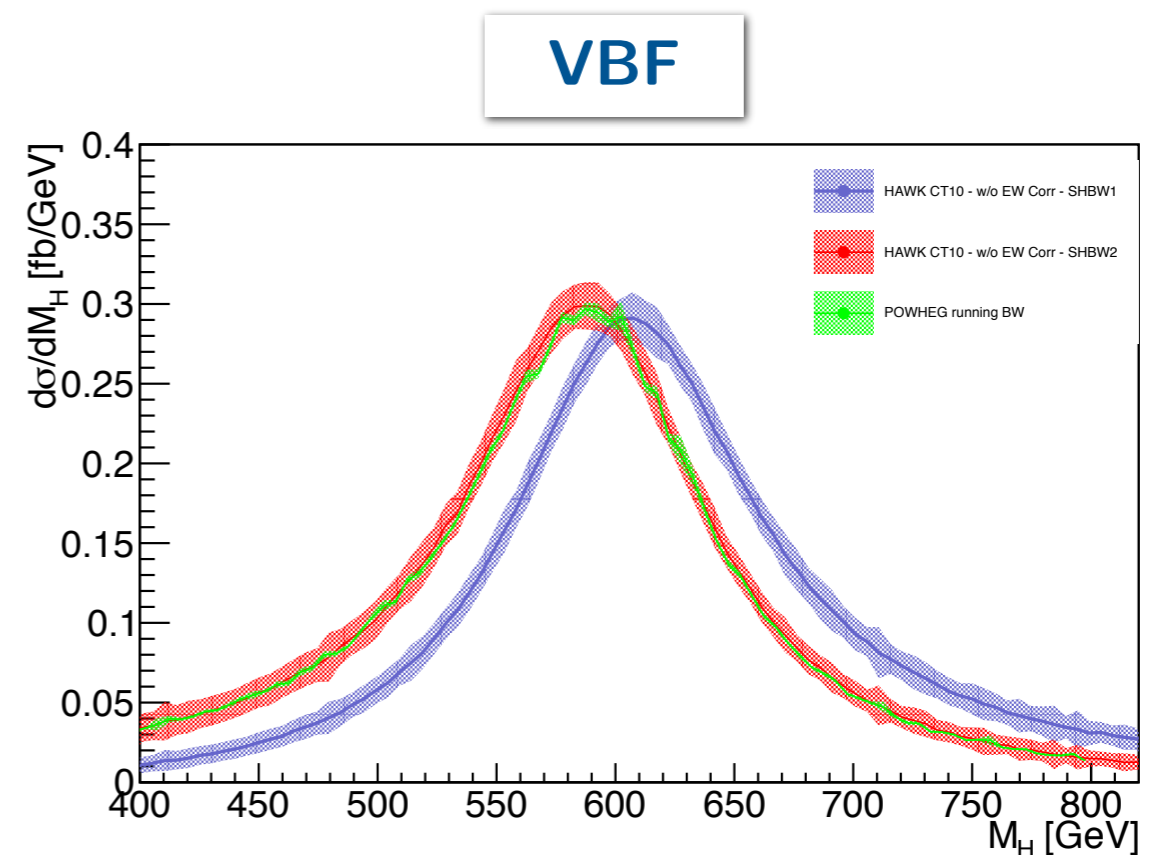
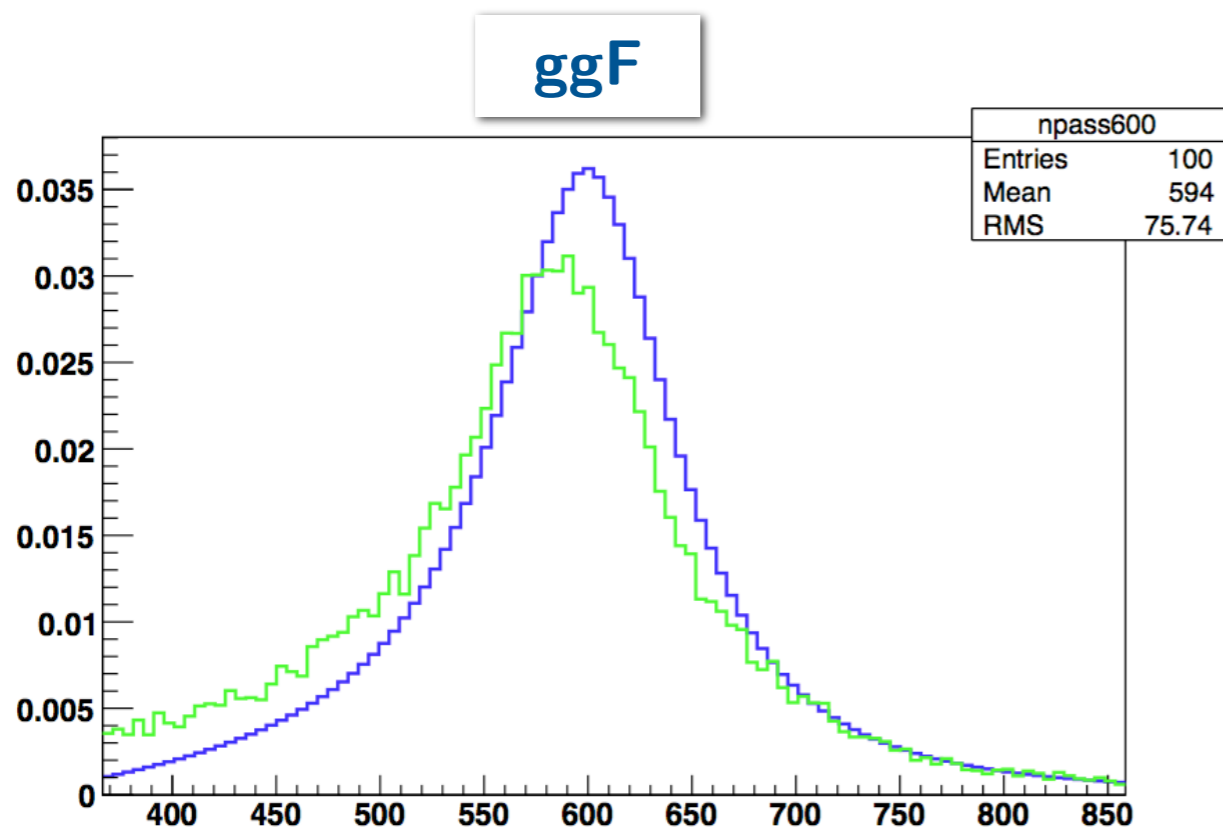
$$\mathbf{factor} = \text{HAWK}(\text{complex mass scheme, EW corr}) / \text{HAWK}(\text{POWHEG propagator, no EW corr})$$

- **Factors** are used to reweight POWHEG M_H distribution *No full event reweighting*
- Reweighting procedure implemented in a ROOT-python code which provides the weights for each mass bin, given an input mass
- **Status:** ready but need to recompute HAWK complex mass scheme for VBF

Advantages: also corrects for EW NLO - Disadvantages: corrects only M_H distribution

VBF Reweighting Tools

- $M_H = 600$ GeV comparison plots - existing POWHEG shown in green, complex mass scheme prescription shown in blue



Code: svn.cern.ch/repos/atlasphys/Physics/Higgs/HSG2/ConfNotes/NoteZZllnunu_Winter2012/InternalMaterial/HeavyHiggs

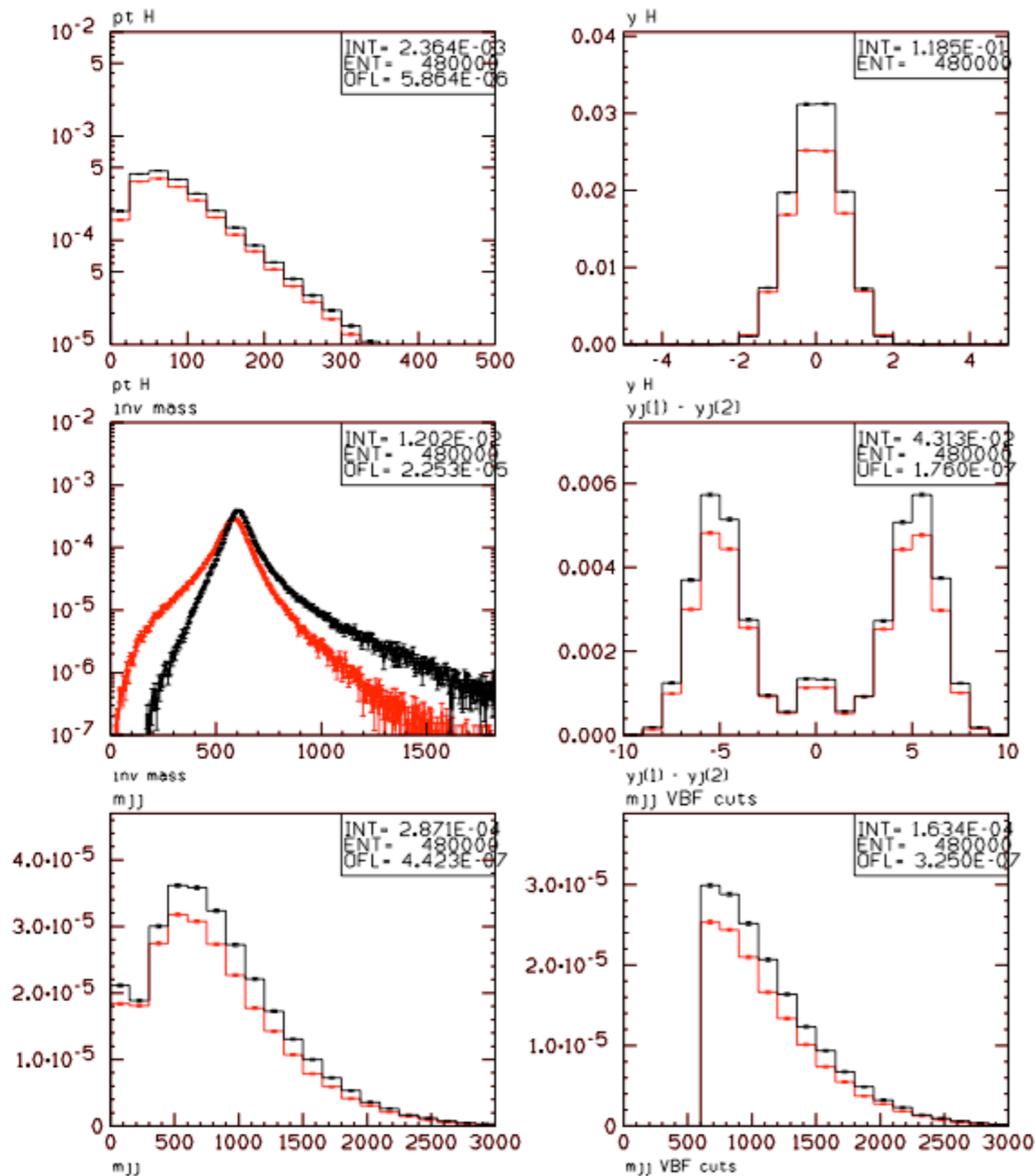
TWiki: https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/HiggsCrossSection#3_Heavy_Higgs_Lineshape_and_VV_s

2. Tool B [C. Oleari and P. Nason]

- Fortran subroutine to *reweight events* generated with POWHEG BOX to implement the complex mass scheme prescription
 - Can be used to reweight both ggH and VBF events - procedure correct at NLO+PS order
 - For each POWHEG BOX event with a given weight, a subroutine is called passing:
 - the Higgs boson mass and width used in the generation with the POWHEG BOX
 - the mass of the top quark and BWflag set accordingly
 - the Higgs boson virtuality of the event
- ➔ A POWHEG BOX version that implements complex scheme prescription has been already released (since svn revision 1818", for both VBF and ggF)

Advantages: reweights events, not only M_H - Disadvantages: does not correct for EW NLO

VBF Reweighting Tools



Black: Complex mass scheme

Red: BW with running width
(default in POWHEG BOX)

Other VBF Issues Recently Discussed

- Interfacing HAWK (NLO QCD+EW) to parton shower MC:
 - *not in the immediate future*: printing events from HAWK is non-trivial - it would mean combining HAWK with POWHEG/PYTHIA for EW corrections as well
 - *Proposal*: reweighting technique as done in arXiv:1003.1241, page 89 - HAWK is used to calculate EW corrections for given distribution and these corrections are used to reweigh events of some other MonteCarlo
- Interfacing Prophecy4f to (ggF and) VBF NLO MC for $H \rightarrow VV \rightarrow 4f$ decays:
 - including important interference effects, NLO QCD+EW effects for precise Higgs property measurements [https://twiki.cern.ch/twiki/bin/view/LHCPhysics/BRs#Validity_of_H_4f_branching_ratio]
 - Prophecy4f v2.0 (August 2011) can generate unweighted events
 - CMS working on that already, analyzing interference effect for ME angular analysis [<https://indico.cern.ch/getFile.py/access?contribId=34&sessionId=18&resId=0&materialId=slides&confId=162621>]

M. Duehrssen and DR working on this with BR subgroup and Prophecy4f authors, item in common with LM subgroup
- Follow up of the studies about uncertainties on the cross sections and efficiencies after the jet veto cut which appeared on the YR2 *to appear on the VBF TWiki soon, B. Quayle*

VBF Items to be Discussed/Followed Up

- Interference in VBF between resonant diagrams and EW non-resonant

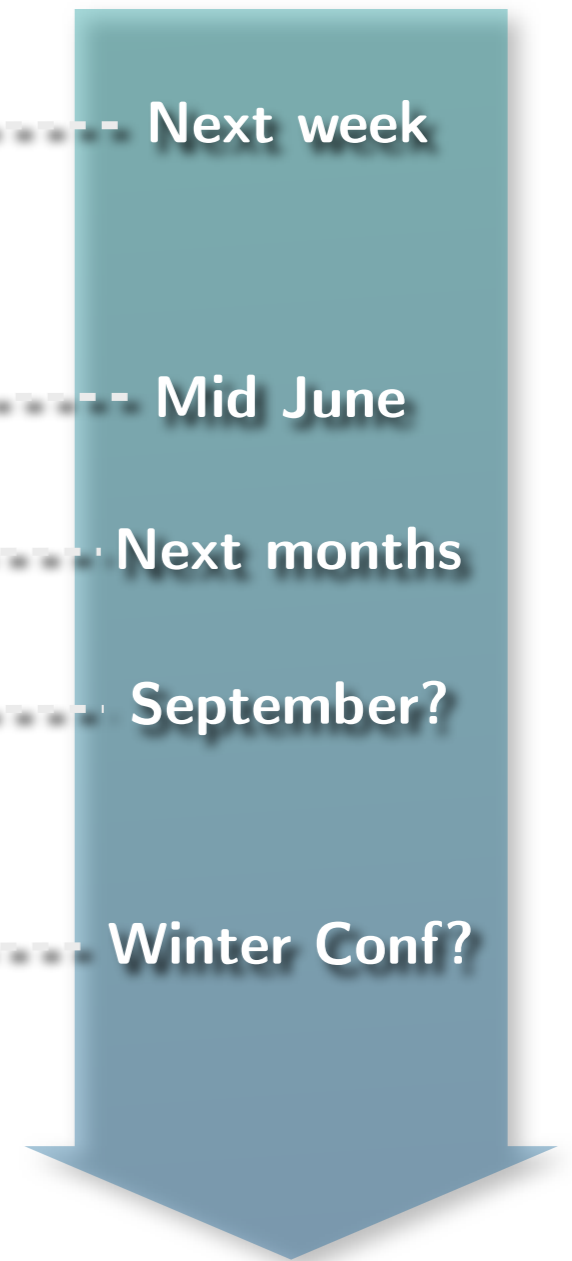
*topic in common with new Heavy Mass Higgs subgroup
See Dieter's talk later and
see S. Bolognesi and S. Diglio's talk on Heavy Higgs for ggF interference*

- ggF contamination in VBF

- some work already done for the YR2 (see section 10.3): ggF cross section of Higgs + 2j @ NLO with MCFM, after VBF cuts (typical of the $H > WW$ analysis)

topic in common with new Jet subgroup

- Complete the calculation of the VBF numbers at 8 TeV ('rescale' PDF4LHC envelope at NNLO) and make results public **Next week**
- 33 TeV cross sections with uncertainties for the ES **Mid June**
- Recalculate the envelope with HAWK+complex pole scheme **Next months**
- Prophecy4f interfaced to (ggF and) VBF NLO MC for $H \rightarrow VV \rightarrow 4f$ decays **September?**
- Differential studies at 8 TeV? **Winter Conf?**



HAWK: MC integrator for $pp \rightarrow H+2\text{jets}$ - version 1.1 (last updates 20.07.2011)

- **New features**: optional off-shell Higgs boson distributed according to Breit-Wigner (BW), with isotropic decay into a pair of singlets - cuts on decay singlets possible - parallel, multithread execution - simultaneous evaluation of the cross section for all members of a given PDF set - leading 2-loop heavy Higgs corrections included

VBFNLO: Parton level MC program dedicated to VBF processes

- **New features**: NLO QCD and EW corrections (since version 2.5) - Higgs and vector boson decays with full spin correlations and off-shell effects - production of a Higgs via VBF in association with a photon - extension of VBF Higgs production to MSSM - full $WWjj$ and $ZZjj$ processes, including the background and interference

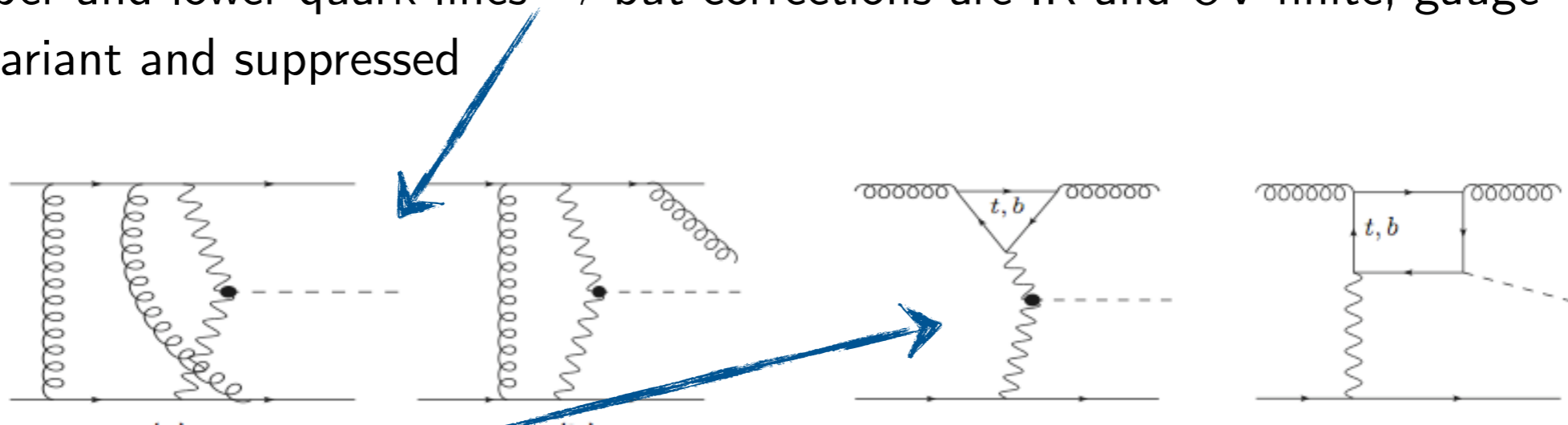
POWHEG BOX: General framework for interfacing NLO calculations to PS generators

- **Features**: VBF Higgs boson production at NLO QCD plus PS - Higgs distributed according to BW with s -dependent width

VBF NNLO QCD Calculations

[P. Bolzoni, F. Maltoni, S.-O. Moch, M. Zaro, arXiv:1003.4451v1]

- Calculations for t-channel (interference with s-channel at the order of per mil)
- Performed in *structure function approach*: VBF treated as a double DIS process
 - cross section computed as $M_{VBF} \otimes W_{DIS}$ hadronic tensor
- This factorization is still exact up to NLO (neglecting a small interference effects)
- At NNLO the factorization breaks down because of corrections connecting upper and lower quark lines \rightarrow but corrections are IR and UV finite, gauge invariant and suppressed



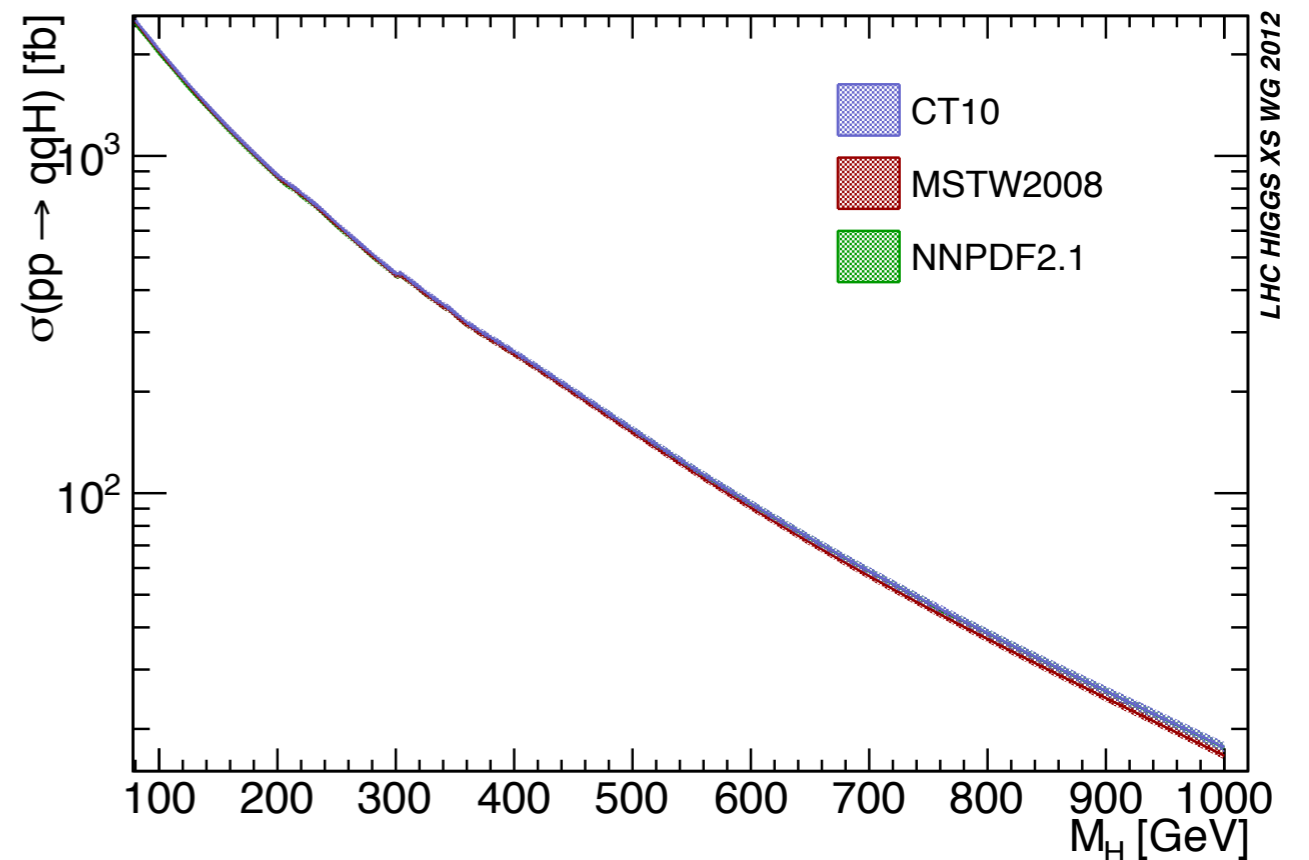
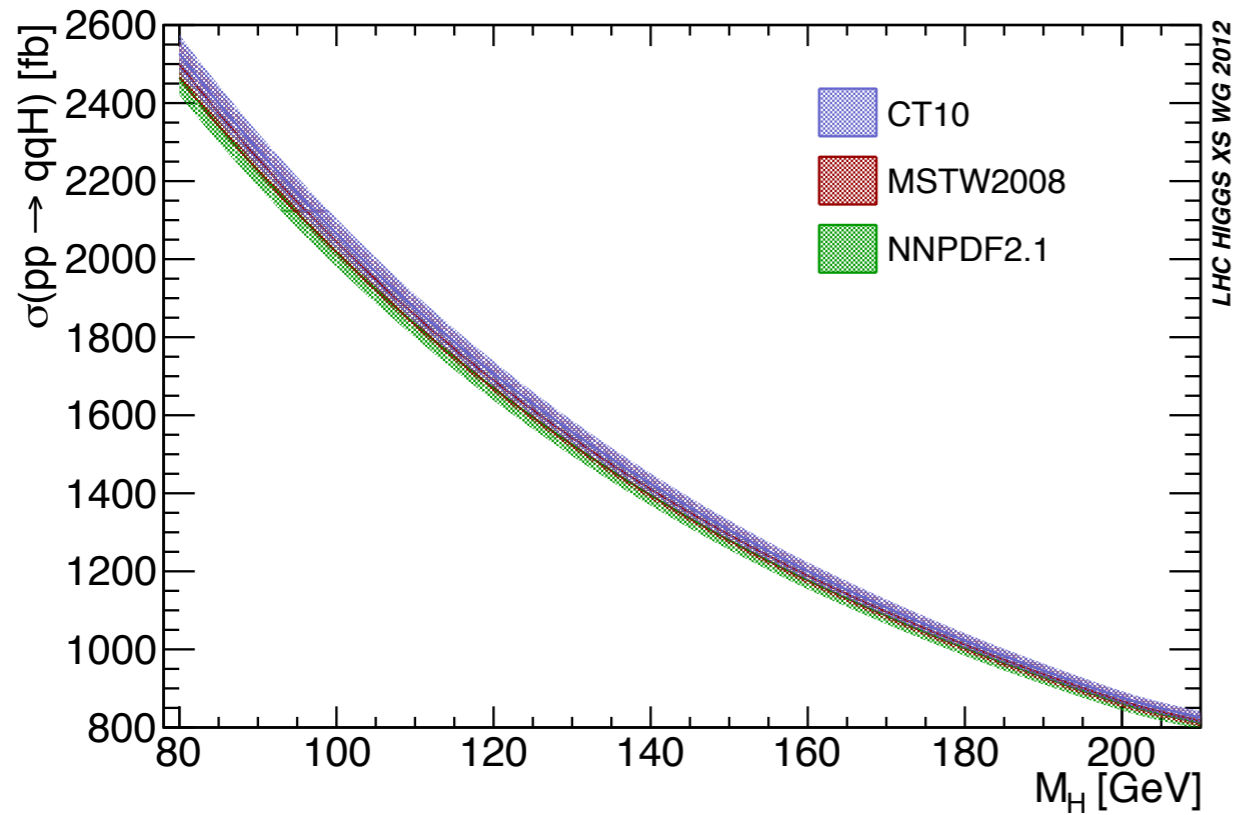
- Other corrections $O(\alpha_{EW}^3 \alpha^2)$ included and computed in $m_b \rightarrow 0$, $m_t \rightarrow \infty$ limit \rightarrow they contribute *below the percent level* to the total cross section

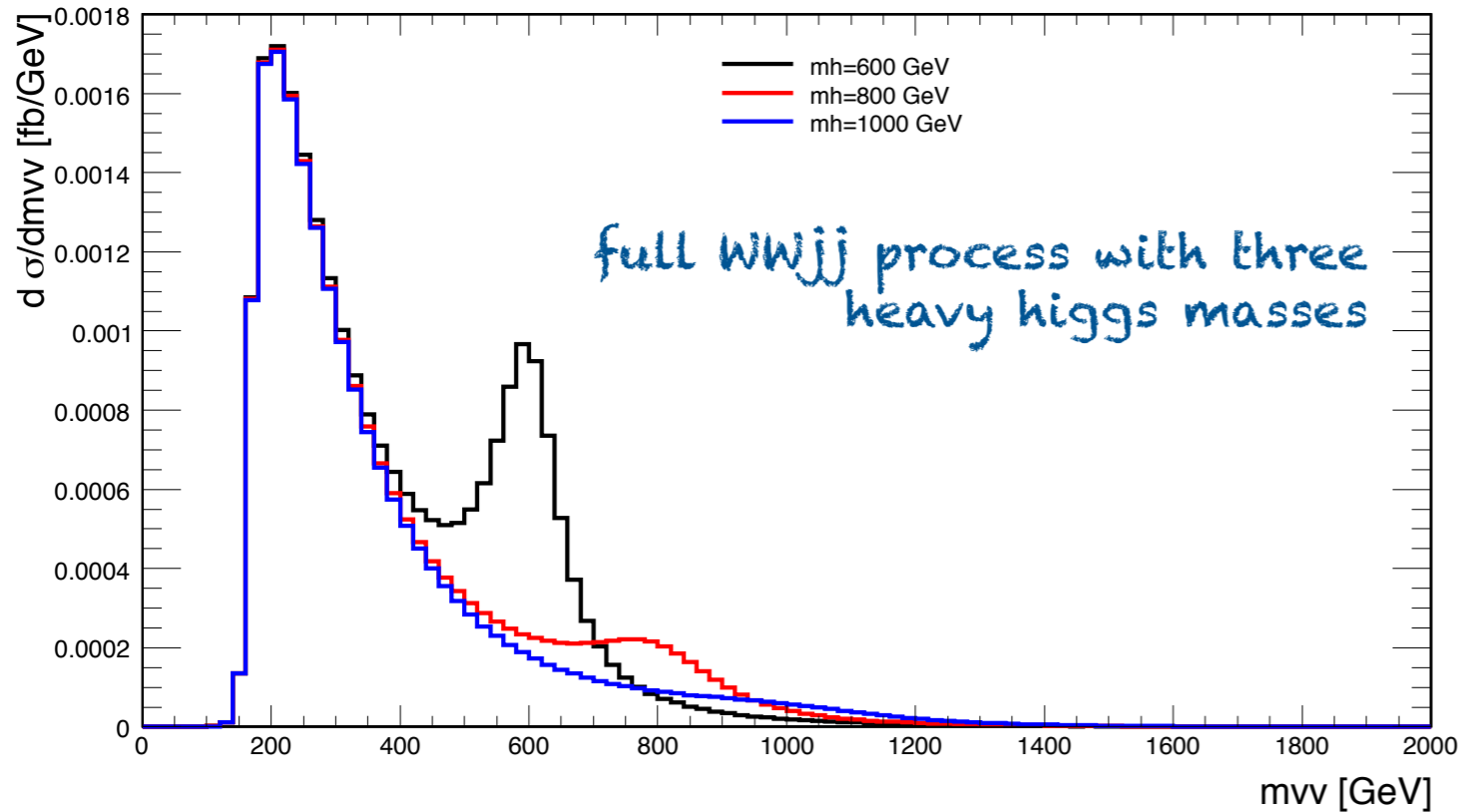
8 TeV Calculations Mass Grid

M_H range [GeV]	Step	# points
80,110	1 GeV	31 points
110,140	0.5 GeV	60 points
140,160	1 GeV	20 points
160,290	2 GeV	65 points
290,350	5 GeV	12 points
350,400	10 GeV	5 points
400,1000	20 GeV	30 points
+ 450, 550, 650, 750, 850, 950 GeV		6 points
+ 165, 175, 185, 195 GeV		4 points
Total		233 points

VBF PDF4LHC at 8 TeV - plots

[to appear at <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV>]





- Using the full VV_{jj} process with a heavy Higgs from VBFNLO and subtracting the VV_{jj} process with a very light Higgs in order to separate out the background
- Results for 7 TeV, CT10

solid lines = WW_{jj} process with $m_h=800$ various light higgs masses subtracted
black dashed line = VBF Higgs production, $H \rightarrow WW$, Passarino's prescription

