Sixth LHC Higgs Cross Section Workshop
CERN, 24-25 May 2012

Heavy Higgs status and plans

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For the Heavy Higgs and BSM group

Outline

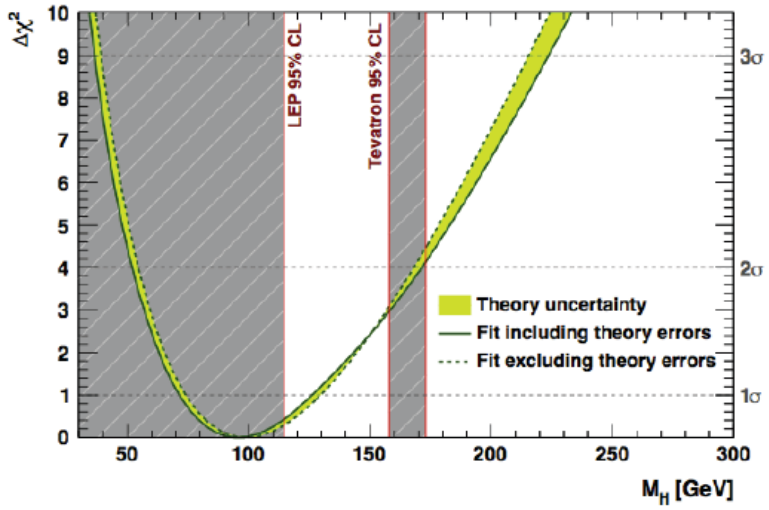
- Why heavy Higgs searches?
- Signal – background interference
- Higgs lineshape
- Conclusions
- Questions

Disclaimer:

-The "BSM group" is actually the BSM & Heavy Higgs group

-These are hot topics (and we are "just" experimentalists ☺)… please wait the end of the talk to throw stones

Why to search for heavy Higgs



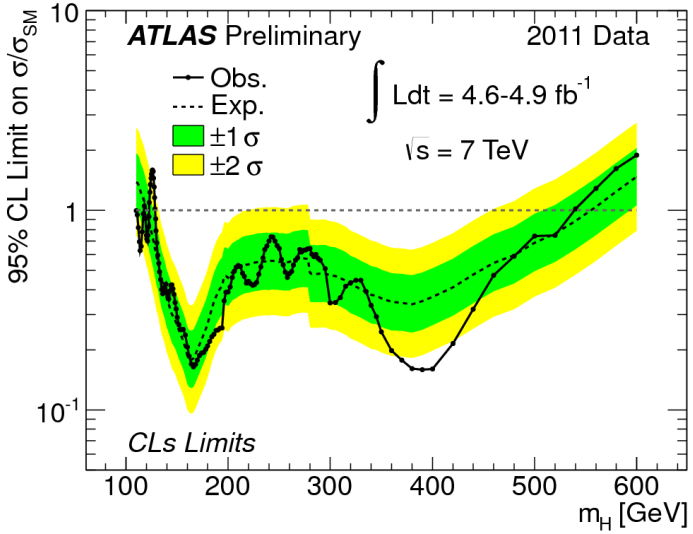
- SM Higgs unlikely to be heavy
- SM extension with **Higgs mass splitting**: light SM-like Higgs + heavy scalar resonance

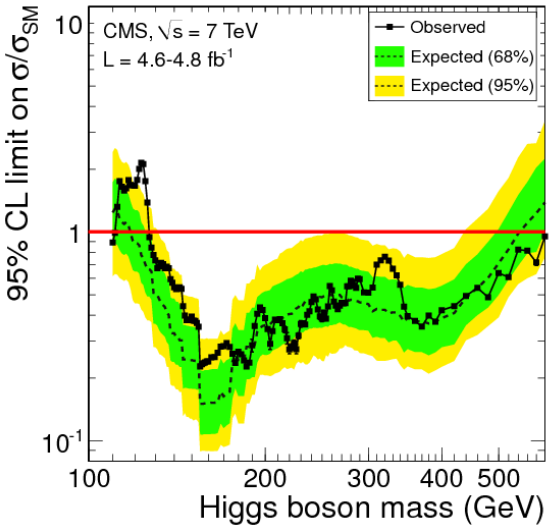
  (compatible with EWK fit and current exclusions, see [9],[10],[11])

- **Composite models:** SM-like Higgs with suppressed couplings + heavy vector resonance

  (LHC results reinterpreted in these models, see [8])

→ direct search: WE ARE COLLECTING VV EVENTS AT ~1TeV FOR THE FIRST TIME !!!!

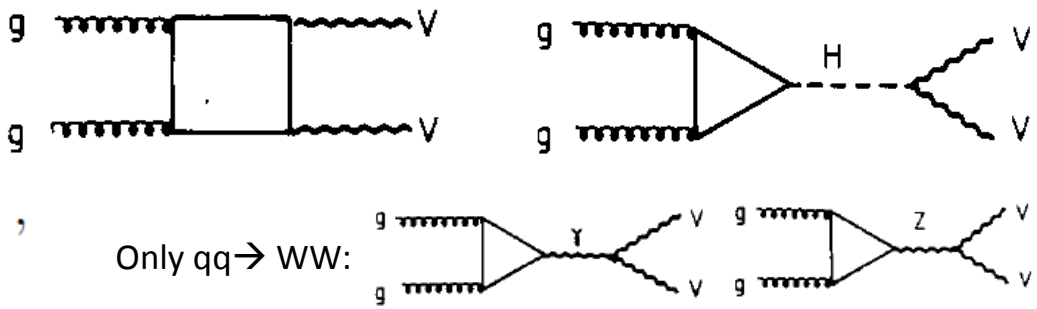




Interference in gg->VV

❑ **Large signal-background interference in gg→VV (especially at high mVV)**

$$\sigma_B \longrightarrow |\mathcal{A}_{\rm box}|^2 \ ,$$
$$\sigma_H \longrightarrow |\mathcal{A}_{\rm Higgs}|^2 \ ,$$
$$\sigma_i \longrightarrow 2{\rm Re}\left(\mathcal{A}_{\rm Higgs}\mathcal{A}^*_{\rm box}\right) \ ,$$
$$\sigma_{H,i} = \sigma_H + \sigma_i \ .$$



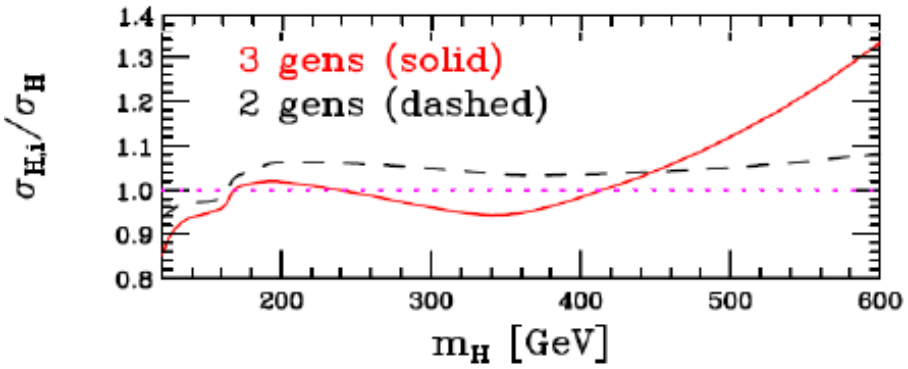
Typically experimental collaborations work with σB and σH at different perturbative orders

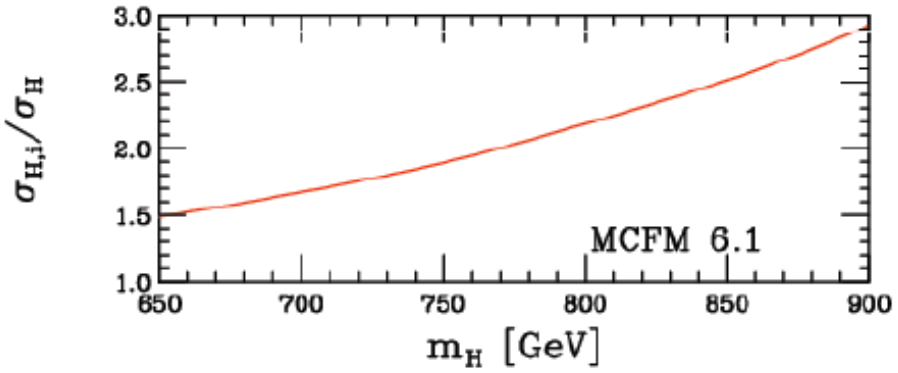
❑ Situation very similar in **VBF: interference btw resonant diagrams and EWK non-resonant**

How important is the interference @ LHC?

Campbell, Ellis, Williams 2011

LHC @ 7 TeV , gg→WW, No final state lepton cuts



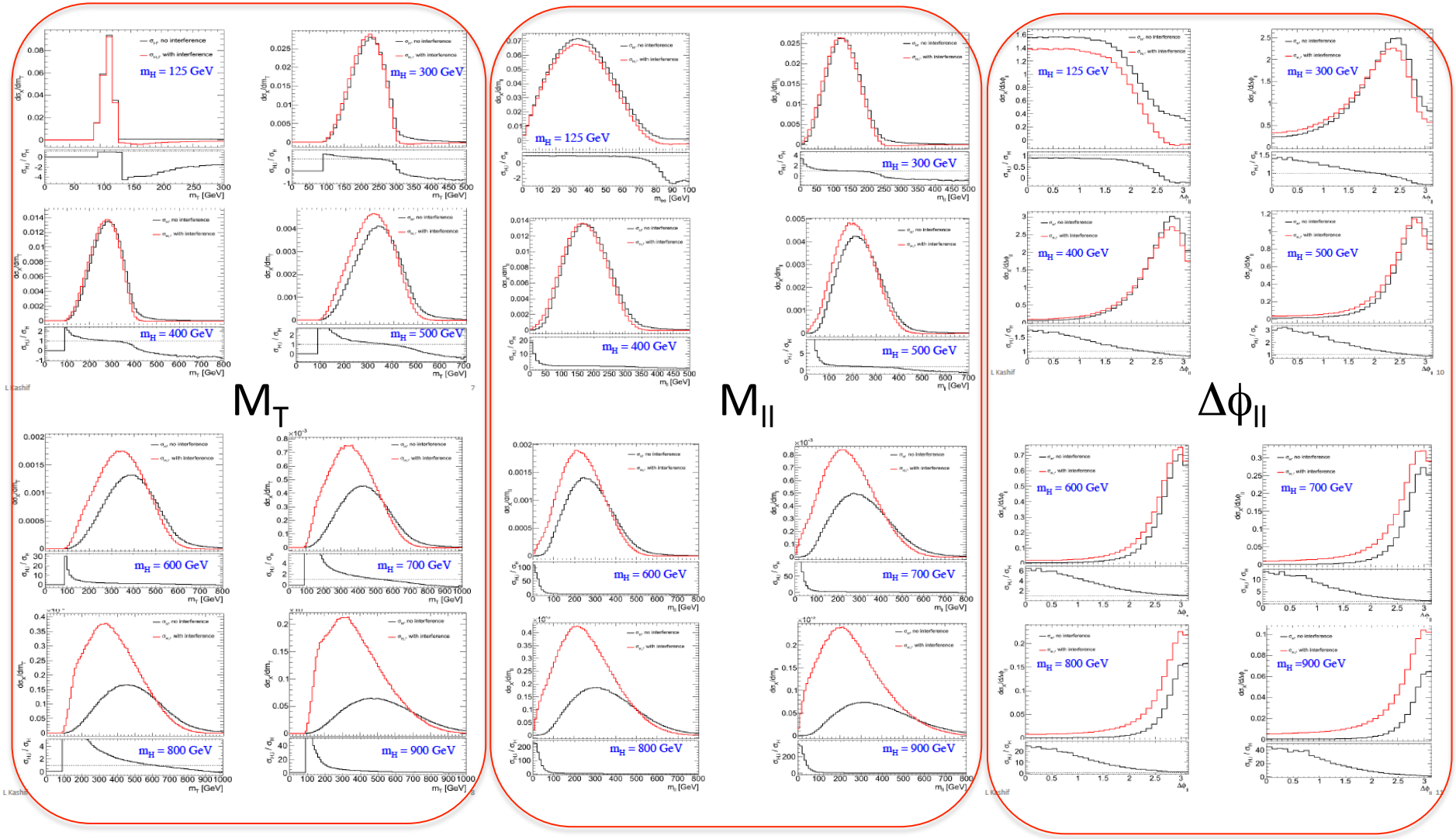


❑ Interference effects rise fast above 400 GeV

- net constructive effect on total xsec (destructive tail to preserve unitarity)
- above 600 (not yet explored) interference > "signal" xsec
- also shape effects ! → next slide

Effect of the interference on distributions (ATLAS studies)

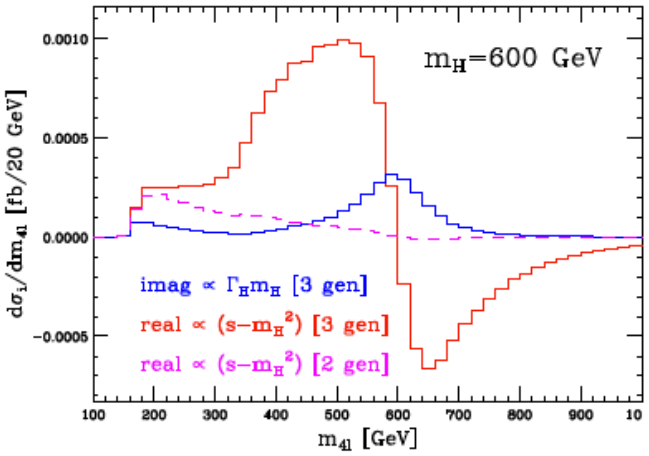
Lashkar Kashif
HSG3 Workshop, March 12-14

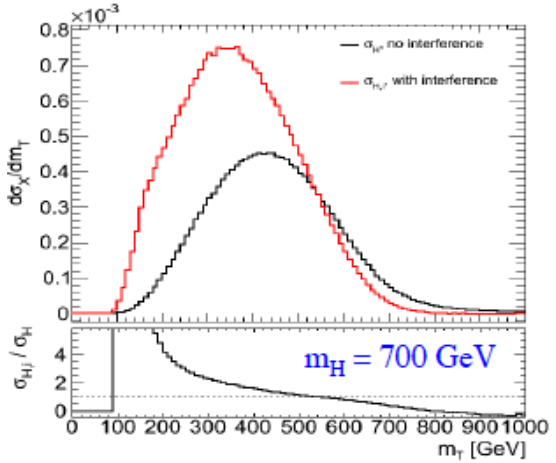


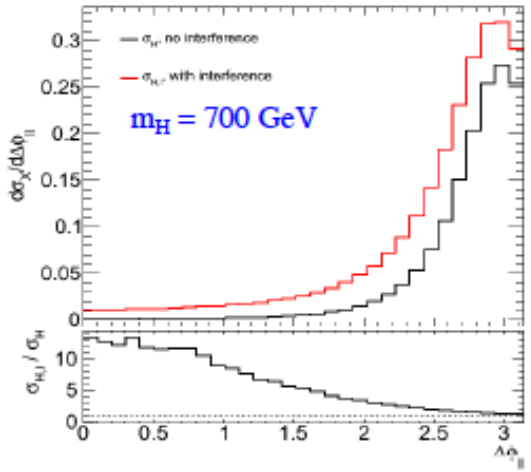
Zoom on M_T , $\Delta\phi_{ll}$

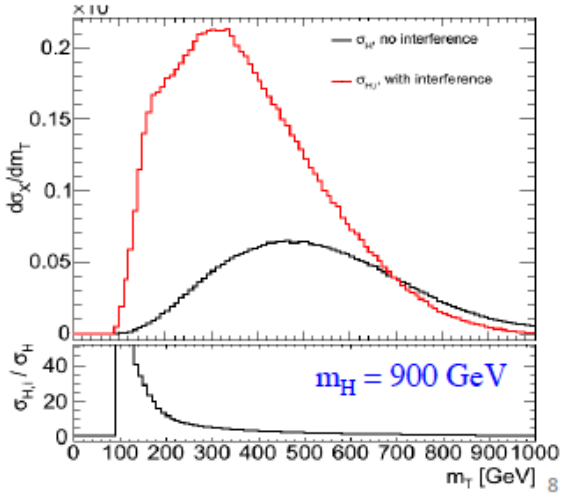
Lashkar Kashif
HSG3 Workshop, March 12-14

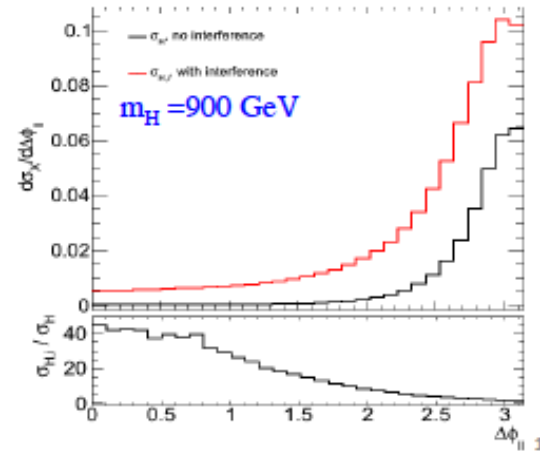
Campbell, Ellis, Williams 2011











- Affect lineshape:

→ constructive s<mH

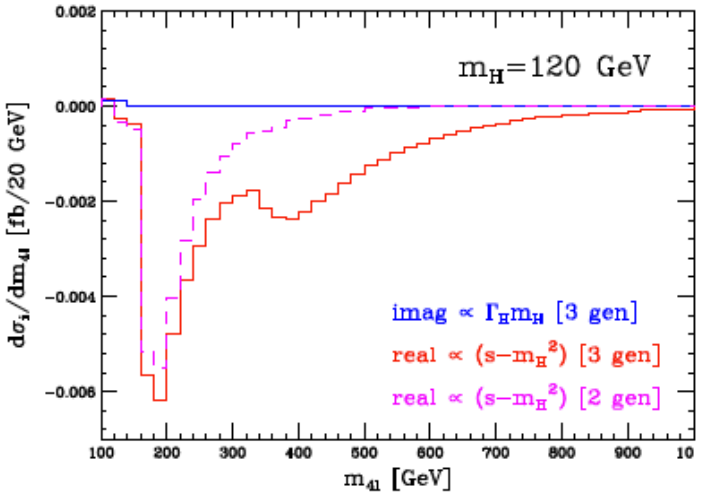
→ destructive s>mH

-> shape effect on mT

- **Shape effect on Δϕ**:

main cut to extract scalar signal over VV background !

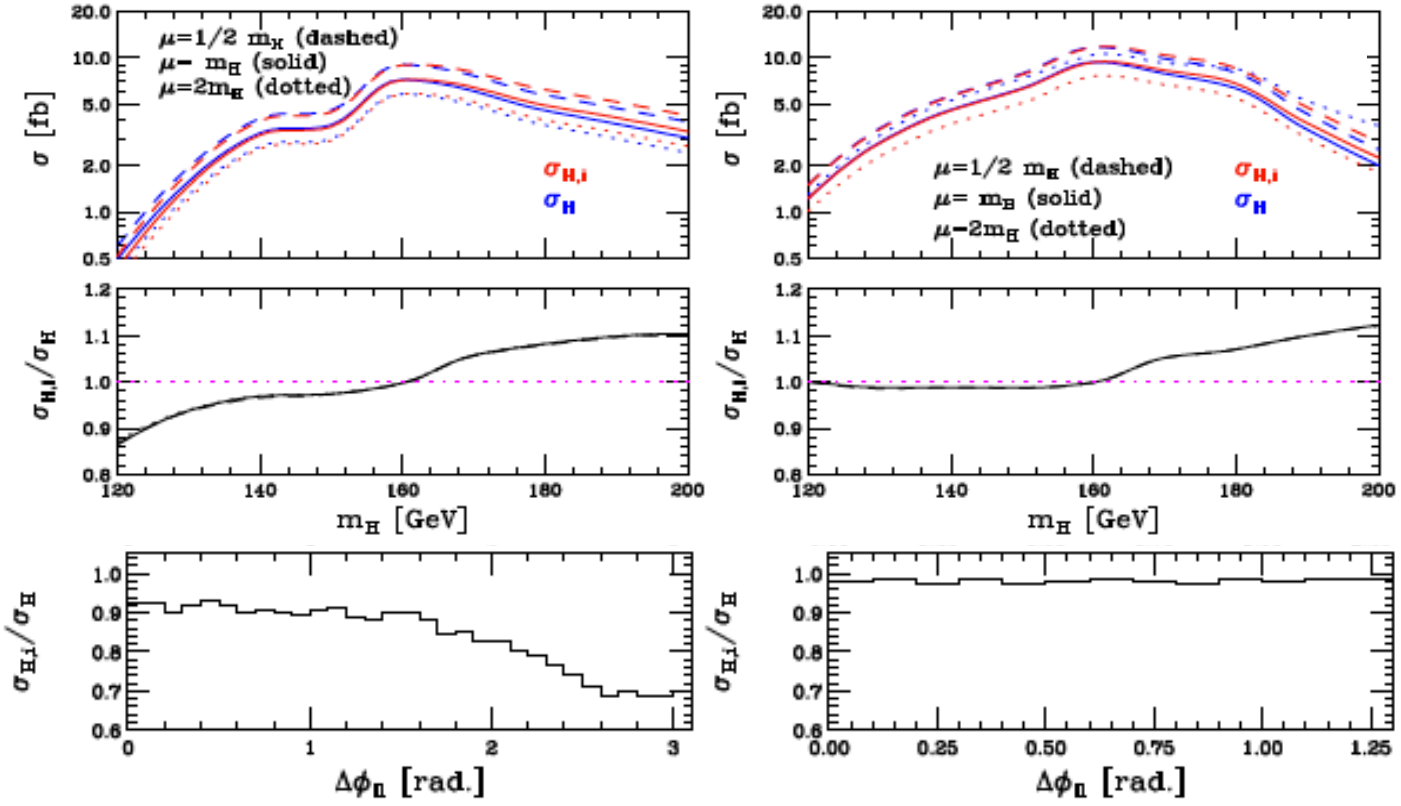
Interference at low mass and mT cut



Campbell, Ellis, Williams 2011

without MT cut

with MT cut: 0.75*mH < mT < mH



MC programs with interference included

- Interference in gg→VV
  - MCFM (J. Campbell, K. Ellis, C. Williams)
    - gg→WW (no gg->ZZ since missing 3rd generation)
  - gg2ZZ- gg2WW (N. Kauer)
    - gg→WW
    - gg→ZZ
  - aMC@NLO (S.Frixione, F.Maltoni, A. Laureys)
    - gg→ZZ
- Interference in VBF
  - HAWK
  - VBFNLO

MCFM

- MCFM is a parton level MC code
- Contains many EW + jets processes at NLO including :
  - gg→Higgs → (ZZ,WW, $\gamma\gamma$, bb) + 0,1,2 jets (NLO)
  - VBF, Associated Higgs production (NLO)
  - Diboson pp→ VV
- gg->WW interference calculation at LO
- No gg→ZZ interference: no top loop
- Possibility to change the Higgs propagator (eg, using ISA)

gg2ZZ – gg2WW

Nikolas Kauer
First BSM and Heavy Higgs kick off meeting

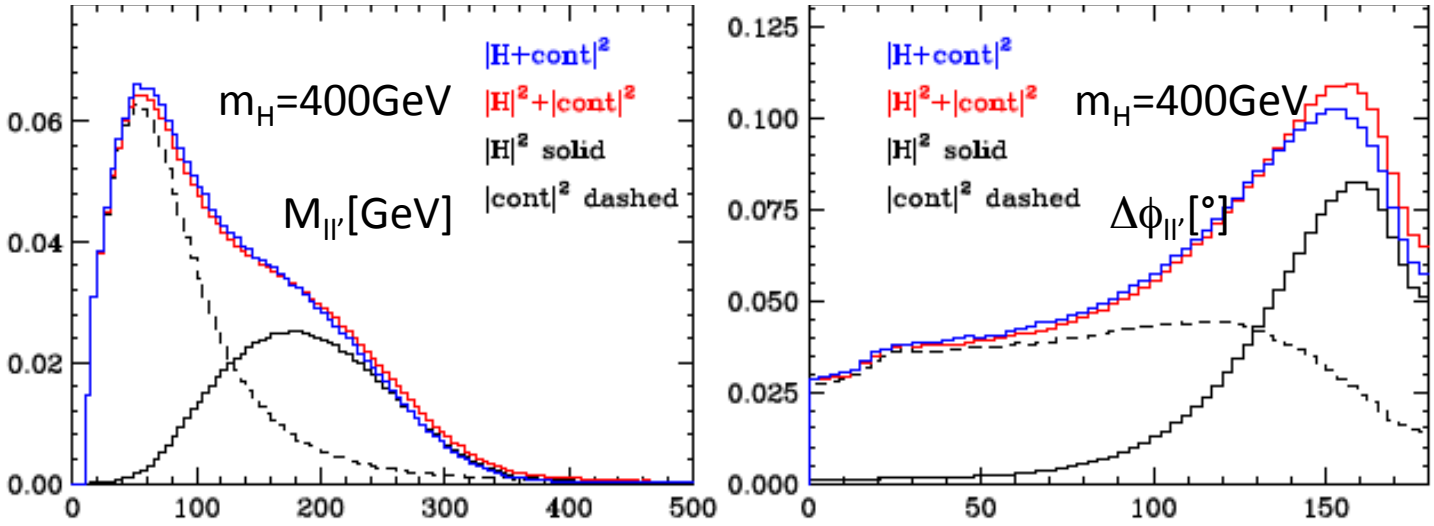
- Parton level integrator and event generator
- Off-shell weak boson and massless and massive quarks are taken into account
- simultaneous xsec calculation for multiple scales and PDF error
- BW with fixed width

gg2WW-3.0 public $gg\,(\to H) \to W^-W^+ \to l\bar{\nu}_l l'\bar{\nu}_{l'}$ in full PS; $l, l' = e, \mu, \tau$

gg2ZZ-2.0 public $gg \to ZZ \to l\bar{l}l'\bar{l}'$ in full PS; $l, l' = e, \mu, \tau; l \neq l'$

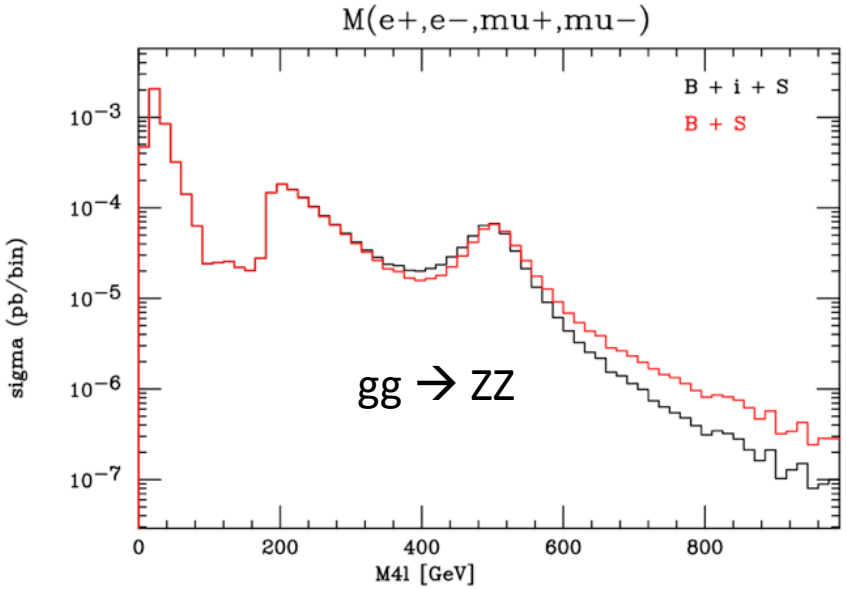
gg2ZZ-3.0 in preparation $gg\,(\to H) \to ZZ \to ll'l', llll, ll\nu_{l'}\bar{\nu}_{l'}, llq\bar{q};\ \ l, l' = e, \mu, \tau$

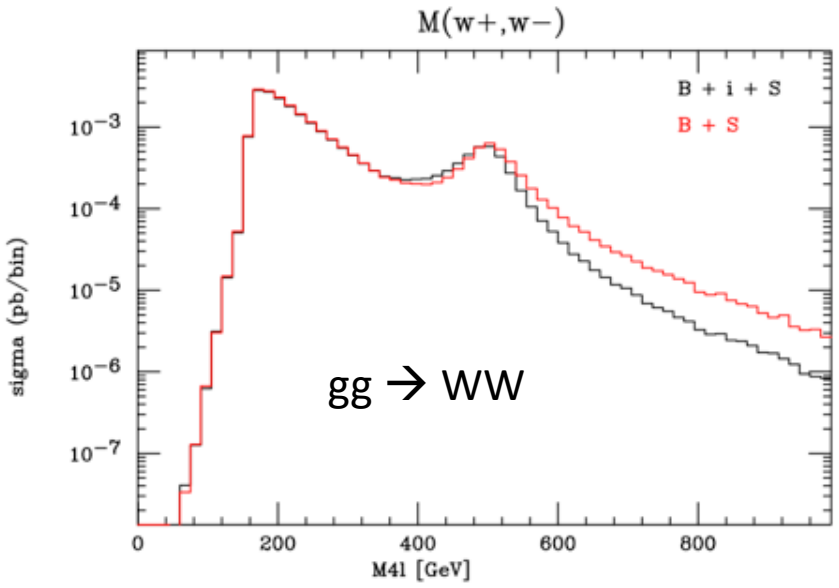
$gg\,(\to H) \to W^-W^+ \to l\bar{\nu}_l l'\bar{\nu}_{l'}$, LHC, 7 TeV, standard cuts



aMC@NLO

- gg → VV automatically generated by MadLoop and cross-checked at the matrix element level with MCFM
- Finite top mass effects, spin correlations, off-shell effects and interference with the Higgs signal
- Unweighted events produced (as usual) in MG and passed to PS **(**no matching is needed as these are LO processes**)**
- Codes to generate unweighted events are in preparation for:
  - B + i + S
  - B + i to be used in conjunction with MC@NLO gg → H → VV at NLO





How to deal with interference @LO and signal @(N)NLO?

Do we have to care? I'm not sure, since interference effects may be larger than these corrections. But let's assume we do

Call H whatever diagrams feature Higgs exchange, and nH all the others

Study impact of interference by comparing (as in MCFM)

$$|H+nH|^2 \qquad |H|^2+|nH|^2$$

Each of these three terms can be unweighted with MadLoop

If the interference is not so large, then get from MadLoop

$$|H+nH|^2-|H|^2$$

and add to this the "signal" computed with MC@NLO
(i.e., $|H|^2$ at $\mathcal{O}(\alpha_s^3)$)
In all the above, the Higgs can be given a real mass and a fixed width

- A natural question arises about how to incorporate the LO results presented here with the NNLO cross section
- Simplest thing to do is to merely add as an absolute correction to the total cross section

$$\sigma_{H,i}^{NNLO} = \sigma_H^{NNLO} + (\sigma_{H,i}^{LO} - \sigma_H^{LO})$$

- This is natural from a theory point of view, in which we are used to incomplete perturbation series. The K-factor going from LO to NNLO is large the resulting impact of the interference terms is reduced by a factor of two.
- Other option is to re-weight predictions by the ratio

$$\sigma_{H,i}^{NNLO} = \sigma_H^{NNLO}\left(\frac{\sigma_{H,i}^{LO}}{\sigma_H^{LO}}\right)$$

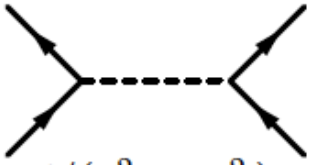
- Certainly if a conservative approach in limit setting is desired this is better to do in the destructive region (since the true NNLO interference terms are some way off...)

Stefano Frixione
The case of a large-mass Higgs

Ciaran Williams
The case of a large-mass Higgs

Lineshape: the problem

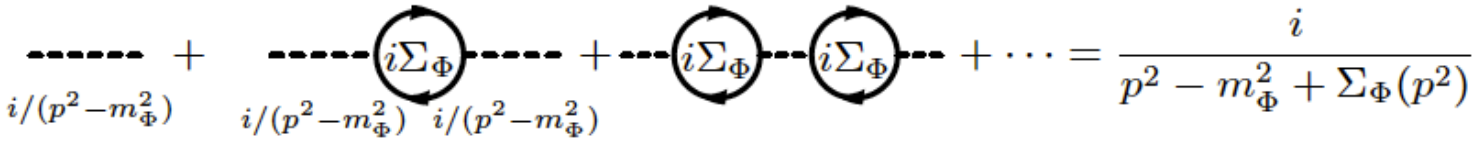
Conventional perturbation theory for scattering $f_1 f_2 \to \Phi \to f_3 f_4$:



usual wisdom

breaks down for for $p^2 \sim m_\phi^2 \Rightarrow$ on-shell decay $\Phi \to f_3 f_4$

Resummation of self-energy insertions in propagator



- **It mixes orders in perturbation theory and violates gauge invariance**
  - **→ justified only for p2~mH**
    - **→ suitable if small Γ → restrict the phase space around s~mH**

Possible solutions ?

❑ Usual solution: use propagator with **constant width** $\dfrac{i}{p^2 - M^2 + iM\Gamma}$

→ **production times decay** (violates gauge invariance but mostly harmless at tree level)

$$\sigma_{f_1 f_2 \to f_3 f_4} \Rightarrow \sigma_{f_1 f_2 \to \Phi} \times \frac{\Gamma_{\Phi \to f_3 f_4}}{\Gamma_\Phi}$$

($\sigma_{f_1 f_2 \to \Phi}$, $\Gamma_{\Phi \to f_3 f_4}$ usually known at NNLO, $\sigma_{f_1 f_2 \to f_3 f_4}$ only NLO)

- Accuracy $\sim \Gamma/m$
- Higgs boson:

$$\Gamma_H/m_H \begin{cases} \lesssim 5\% & m_H \lesssim 350\text{GeV} \\ \gtrsim 10\% & m_H \gtrsim 450\text{GeV} \end{cases}$$

→ **not suitable for mH~>500 GeV**

❑ Similar implementation but fully consistent: **complex mass scheme**

requires fixed-order calculation for full process -> practical limitations:

- **no above NLO for 2→4**
- **no signal/background separation,**

Let's try again…

- " There is only one thing that is uniquely defined: the complete calculation for pp → 4f "

  but very useful notion of

  - **Higgs production and Higgs decay** (eg, usually known at different orders)
  - **Higgs signal and non-resonant background** (eg, to optimize the analysis strategy for a given signal topology)

-> some conventional but gauge invariant splitting of Total into Signal and Background + Interference .

$$A(\zeta, \ldots) = V_{\rm prod}(\zeta, \ldots)\, \Delta_{\rm prop}(\zeta)\, V_{\rm dec}(\zeta) + N(\zeta, \ldots)\,.$$

Pole mass scheme (1)

$$A\left(\zeta,\ldots\right)=V_{\rm prod}\left(\zeta,\ldots\right)\,\Delta_{\rm prop}(\zeta)\,V_{\rm dec}(\zeta)+N\left(\zeta,\ldots\right).$$

❑ CPP fully consistent approach: compute signal with Higgs virtuality = pole (signal defined as the residual in the complex pole)

CPP

$$S\left(\zeta,\ldots\right)=V_{\rm prod}\left(s_{\rm H},\ldots\right)\,\Delta_{\rm prop}(\zeta)\,V_{\rm dec}(s_{\rm H}),\qquad \Delta_{\rm prop}(\zeta)=\text{propagator}.$$

but difficult to implement and require to shift to "background" the difference

$$A(s)=\frac{f(s)}{s-s_{\rm H}}+N(s)$$

$$A(s)=S(s)+B(s),\qquad S(s)=\frac{f(s_{\rm H})}{s-s_{\rm H}},\quad B(s)=\frac{f(s)-f(s_{\rm H})}{s-s_{\rm H}}+N(s).$$

❑ **Solution: OFFP** ie keep the production and decay as function of virtuality but preserving gauge invariance

OFFP

$$S\left(\zeta,\ldots\right)=V_{\rm prod}\left(\zeta,\ldots\right)\,\Delta_{\rm prop}(\zeta)\,V_{\rm dec}(\zeta),\qquad \Delta_{\rm prop}(\zeta)=\text{propagator},$$

Pole mass scheme (2)

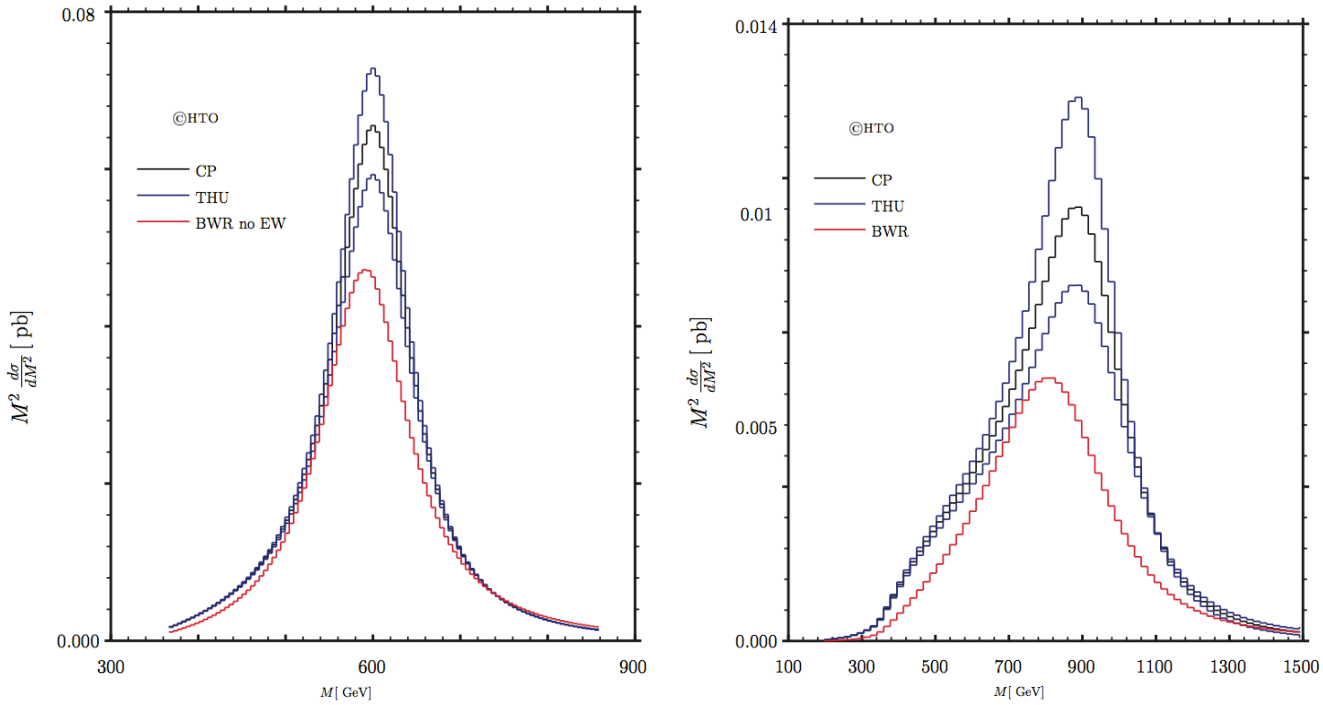
❑ **Consistent separation signal/background (→ including higher orders in signal) :**

what is in OFFP and not in CPP will be shifted to B + I

(the difference between two schemes should NOT be interpreted as theoretical uncertainty!!)

G.Passarino (Torino University)
http://personalpages.to.infn.it/~giampier/notes_HH.pdf

❑ Results at 8 TeV:



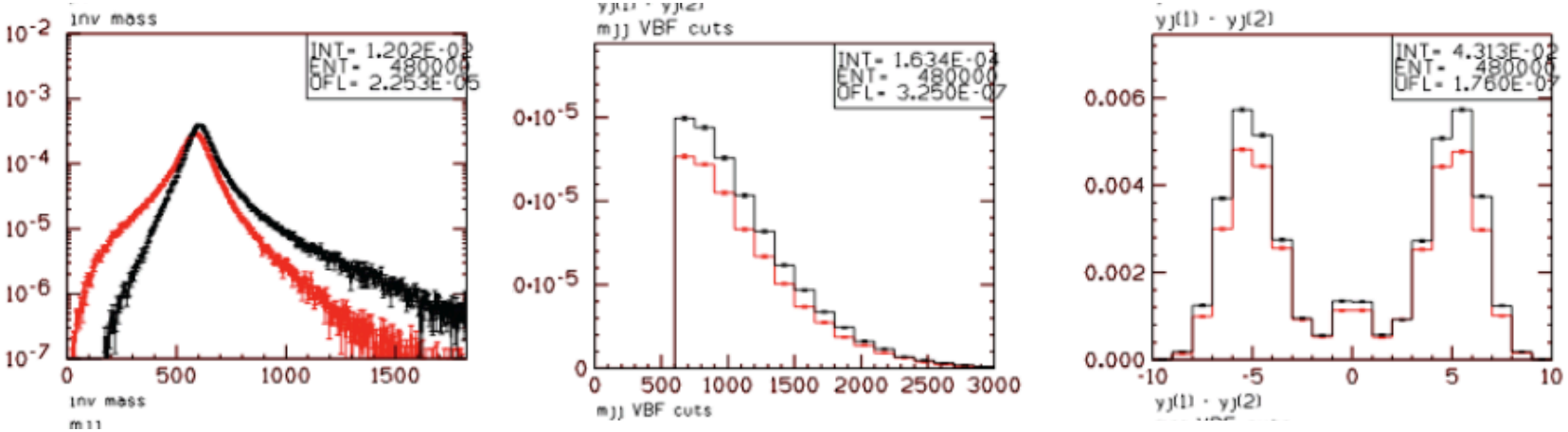
Pole mass scheme at work …

Usable recipe with associated uncertainties -> status of OFFP implementation:

- VBF in HAWK done
- ggF and VBF in Powheg in progress -> reweigthing available
- ggF in aMC@NLO in progress
- ggF (DeFlorian) in progress

eg, results from POWHEG reweighting in VBF

Oleari, Nason
Second BSM and Heavy Higgs kick off meeting



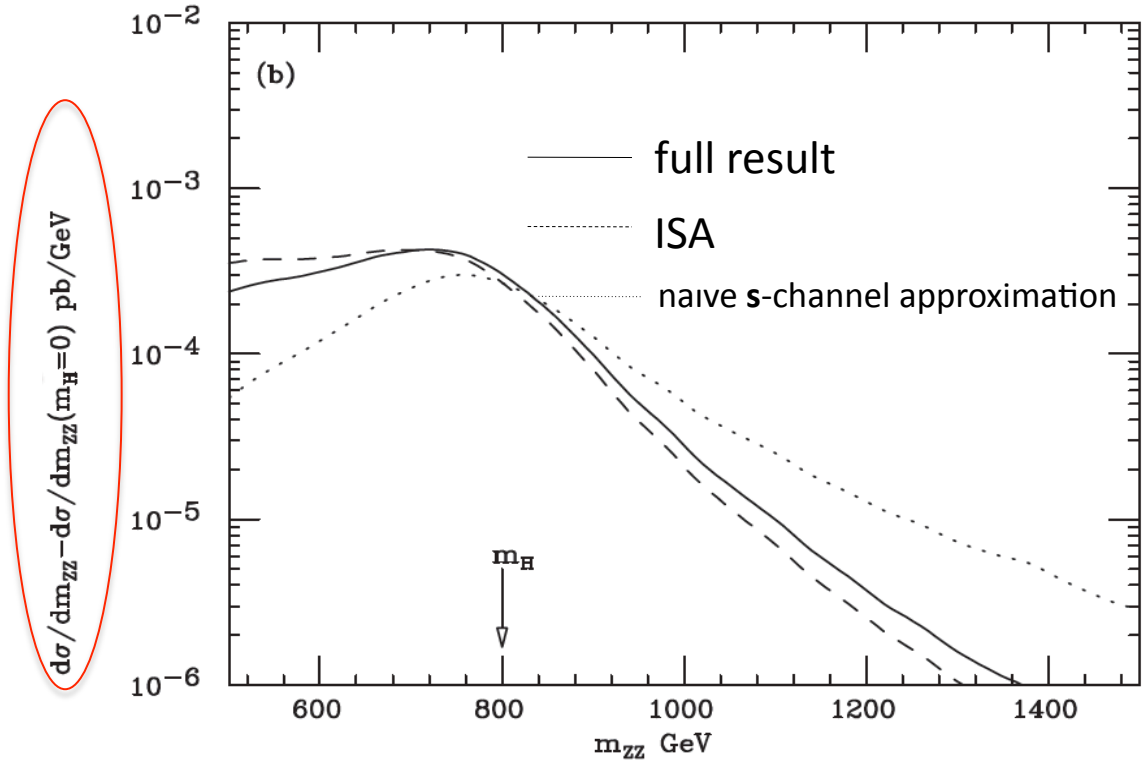
Improved s-channel Approximation

Different approach: find a way to combine resonant and non-resonant diagrams before the "self-energy" resummation (ie have a signal definition which does not break unitarity)

- If you want to make an *s*-channel calculation look as much like the full calculation as possible,

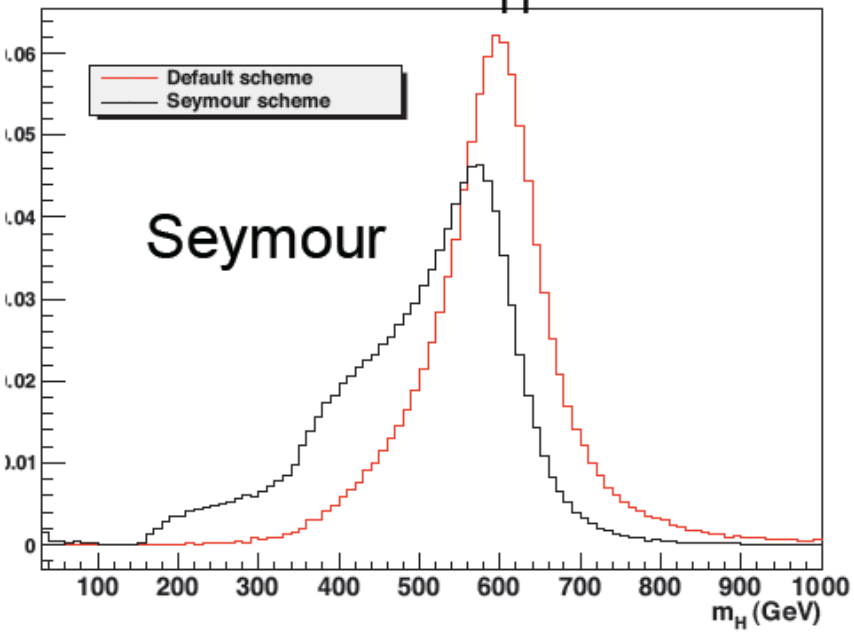
$$\frac{i}{s-m_H^2} \to \frac{im_H^2/s}{s-m_H^2+i\Gamma_H s/m_H}$$

"but beware: this is using the s-channel diagram to calculate non-resonant contributions! "

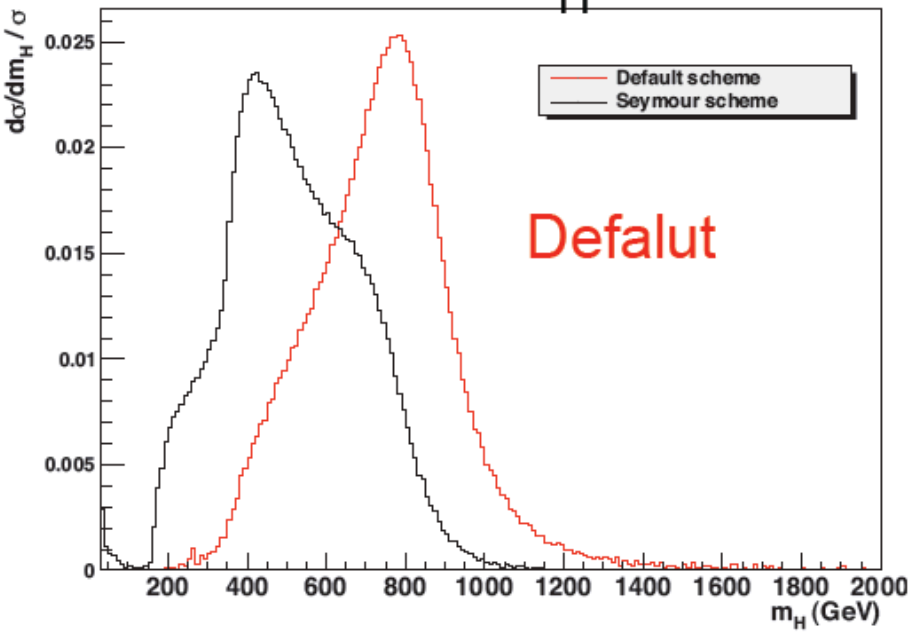


Abuses of the ISA...

M_H=600GeV



M_H=800GeV



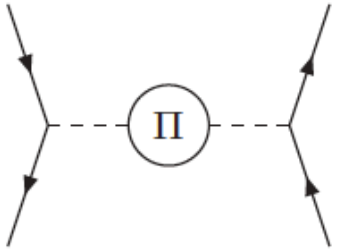
ISA includes non-resonant contributions, which "default" does not. Meaningless to compare shapes, but absolute σs should agree near resonance

x4 for m_H=800 GeV

x1.6 for m_H=500 GeV

Effective theory

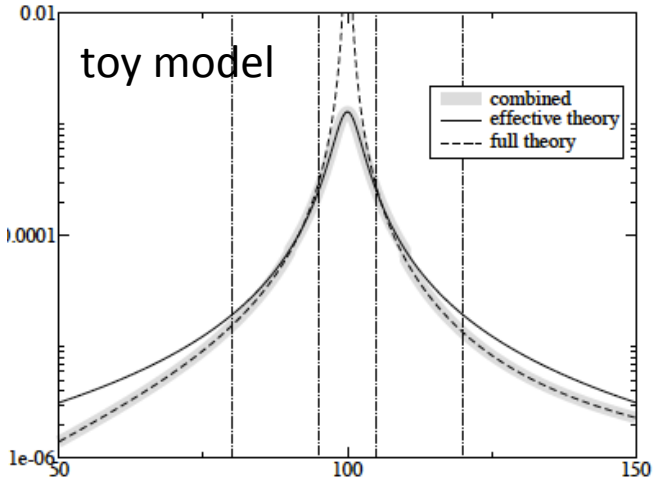
resummation of self-energy $\Pi(s, M_H^2, m_X^2)$



$$\sim \frac{1}{s - M_H^2}\,\Pi\,\frac{1}{s - M_H^2} \sim \frac{1}{\delta}\,\alpha\,\frac{1}{\delta}$$

expansion in α and δ:

$$\Pi(s, M_H^2, m_X^2) = \sum_{n=1} \alpha^n \sum_{m=0} \delta^m\, \Pi^{(n,m)}(M_H^2, m_X^2)$$



full range of $\sqrt{s}$: matching of resonant to off-resonant cross section

- this offers a complementary approach, useful for comparison and cross checks
- application of effective-theory methods to the full Standard Model in the case of Higgs production has a number of additional complications (on going)

valid only for small δ , ie near MH, not usable for heavy Higgs (>400 GeV) far from the peak

The battle field

- Up to which mH we can have a reasonable signal definition and a lineshape for it?

feasible up to 1 TeV !

do not go above 400 GeV !!!

- Above "that" limit everybody agrees that the only reasonable strategy is:

  - compare data with **pp→4l with mh = 0 (or 125 GeV)** → (see the proposal for VBF yesterday)
    ie, the only observable is s(VV) vs mVV

  - VV prediction with full interference effects expected in case of low Higgs
    → need MC which describes interference effects (see above)

  - cut and count analysis: no signal search, no signal lineshape
    → publish # events vs mVV

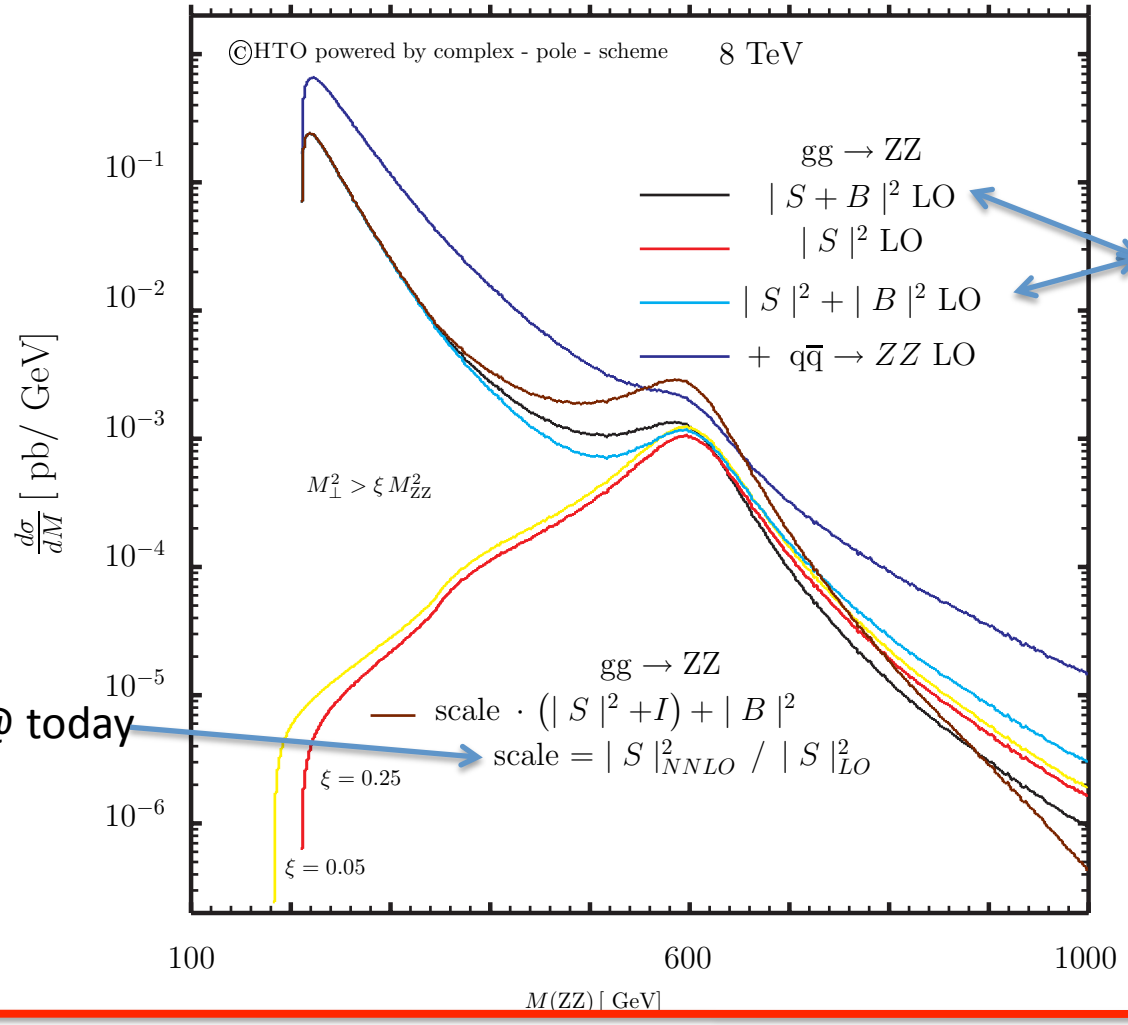
(… as has been always done in VV scattering studies …)

Conclusions

- We want to search for the Higgs beyond 600 GeV
- **Interference**
  - is large and constructive at high mass (with destructive tail)
  - dominates production for a heavy Higgs and modifies lineshape (and kinematic distributions) dramatically
  - we need a clear prescription on how to reweight the current available MC samples
  - WW available in MCFM, ZZ work is on-going
- **Lineshape:**
  - pole mass scheme (reweighting available)
  - effective theory approach can be a useful x-check (for s~mH) when ready
  - above "a certain" mass -> just measure s(VV) vs mVV

A step in a new world … ☺

Putting together interference and lineshape (gg->ZZ):



effect of the interference

"best" @ today

Questions

- **How to combine Higgs signal (with correct lineshape) and backgrounds taking into account the signal-background interference effects ?**
  - present plan: pole mass scheme + reweighting from MCFM/gg2ZZ/aMC@NLO for interference
  - reweigting: which prescription?

$$\sigma_{H,i}^{NNLO} = \sigma_H^{NNLO} + (\sigma_{H,i}^{LO} - \sigma_H^{LO}) \,. \qquad \sigma_{H,i}^{NNLO} = \sigma_H^{NNLO} \left(\frac{\sigma_{H,i}^{LO}}{\sigma_H^{LO}} \right).$$

  - NLO signal effects: do we have to care?

- Will it be possible to have **at least 2 MCs with both gg→WW and gg→ZZ** interference effects implemented in order to compare results?
  (also in view of recent gg2ZZ results at low mH !)
- Theory uncertainties to be assigned for heavy Higgs lineshape and interference effects after all corrections
  - lineshape uncertainty from pole mass scheme defined (they can be implemented in Powheg reweighting)
  - other lineshape approaches will be x-checked as well, when ready
- Up to which Higgs mass we should keep the same Higgs search strategy? When should we switch to simple cut-and-count analysis for s(VV) ?

[8] J. Espinosa, C. Grojean, and M. Muhlleitner, *Composite Higgs under LHC Experimental Scrutiny*, arXiv:1202.1286. 6 pages. Contribution to the proceedings of Hadron Collider Physics Symposium 2011, Paris Nov. 14-18.

[9] S. Kanemura, Y. Okada, H. Taniguchi, and K. Tsumura, *Indirect bounds on heavy scalar masses of the two-Higgs-doublet model in light of recent Higgs boson searches*, Phys.Lett. **B704** (2011) 303–307, arXiv:1108.3297 [hep-ph].

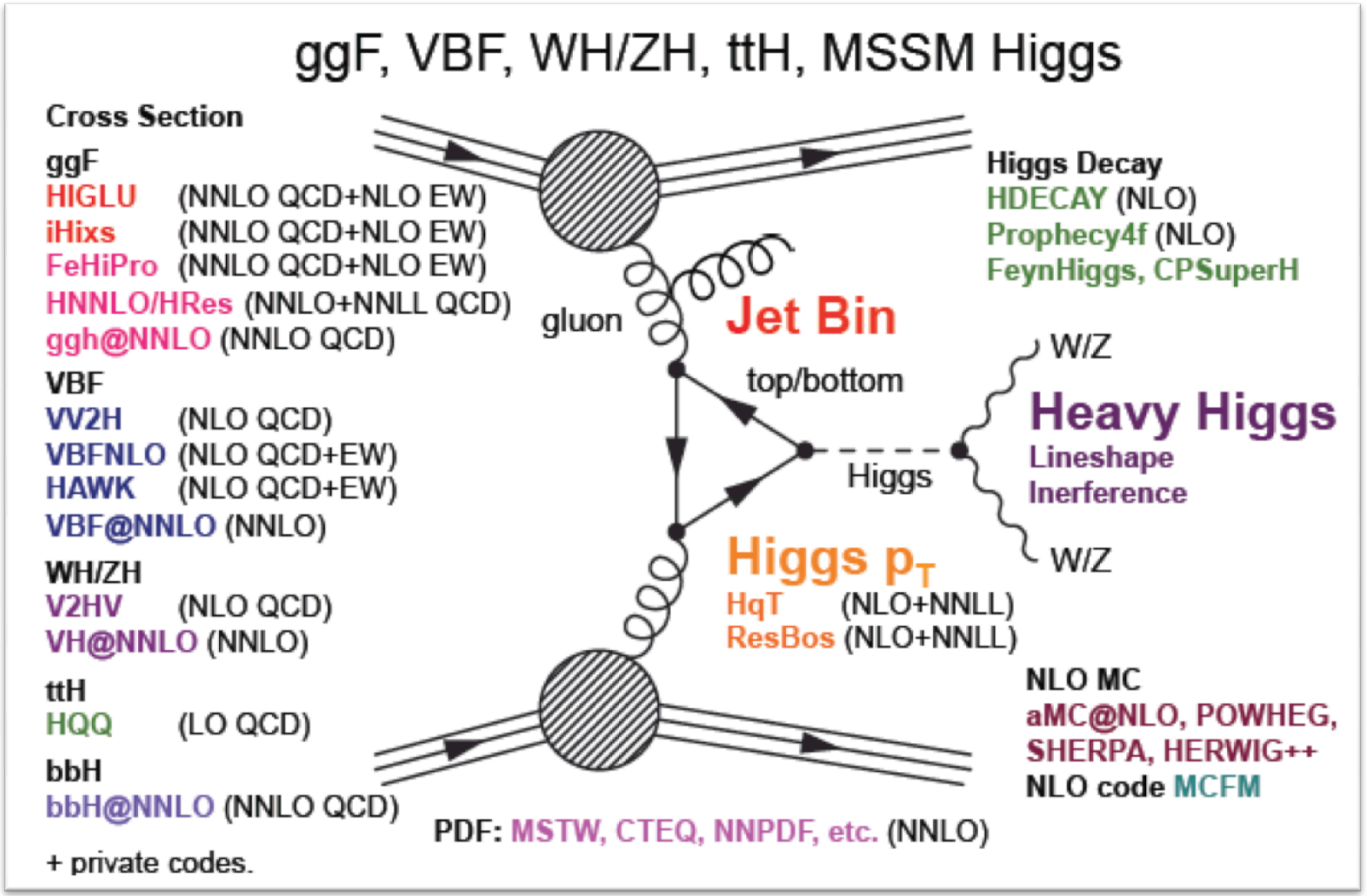
[10] Y. Bai, J. Fan, and J. L. Hewett, *Hiding a Heavy Higgs Boson at the 7 TeV LHC*, arXiv:1112.1964 [hep-ph].

[11] M. E. Peskin and J. D. Wells, *How can a heavy Higgs boson be consistent with the precision electroweak measurements?*, Phys.Rev. **D64** (2001) 093003, arXiv:hep-ph/0101342 [hep-ph].

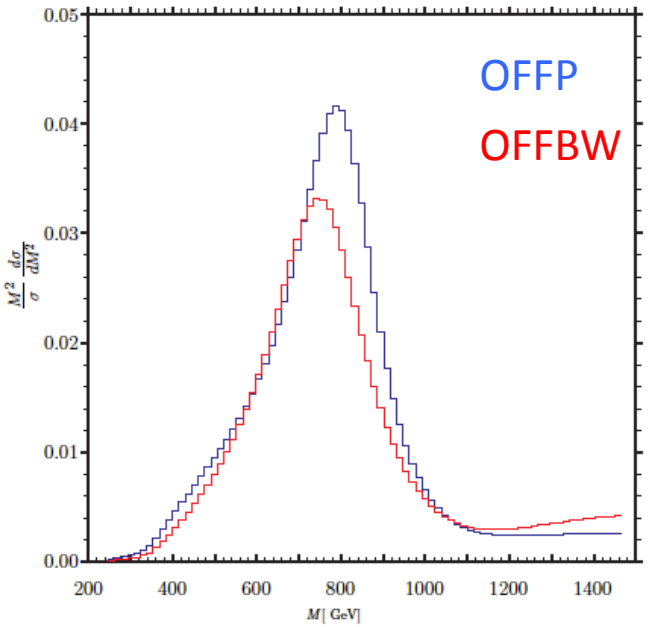
2. **The Higgs Boson Lineshape.**
Stefano Goria, Giampiero Passarino, Dario Rosco (Turin U. & INFN, Turin). Dec 2011. 27 pp. Note: 51 pages, 16 eps figures, v2 a major extension to our previous work
e-Print: **arXiv:1112.5517 [hep-ph]**

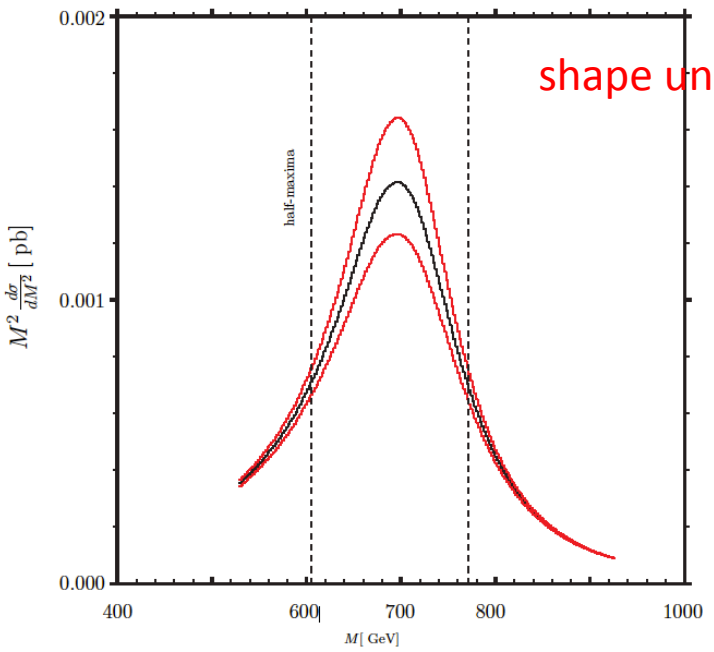
6. **Gluon-Gluon Contributions to W+ W- Production and Higgs Interference Effects.**
John M. Campbell, R.Keith Ellis, Ciaran Williams (Fermilab). Jul 2011.
FERMILAB-PUB-11-340-T.
Published in **JHEP 1110 (2011) 005**
e-Print: **arXiv:1107.5569 [hep-ph]**

Available tools



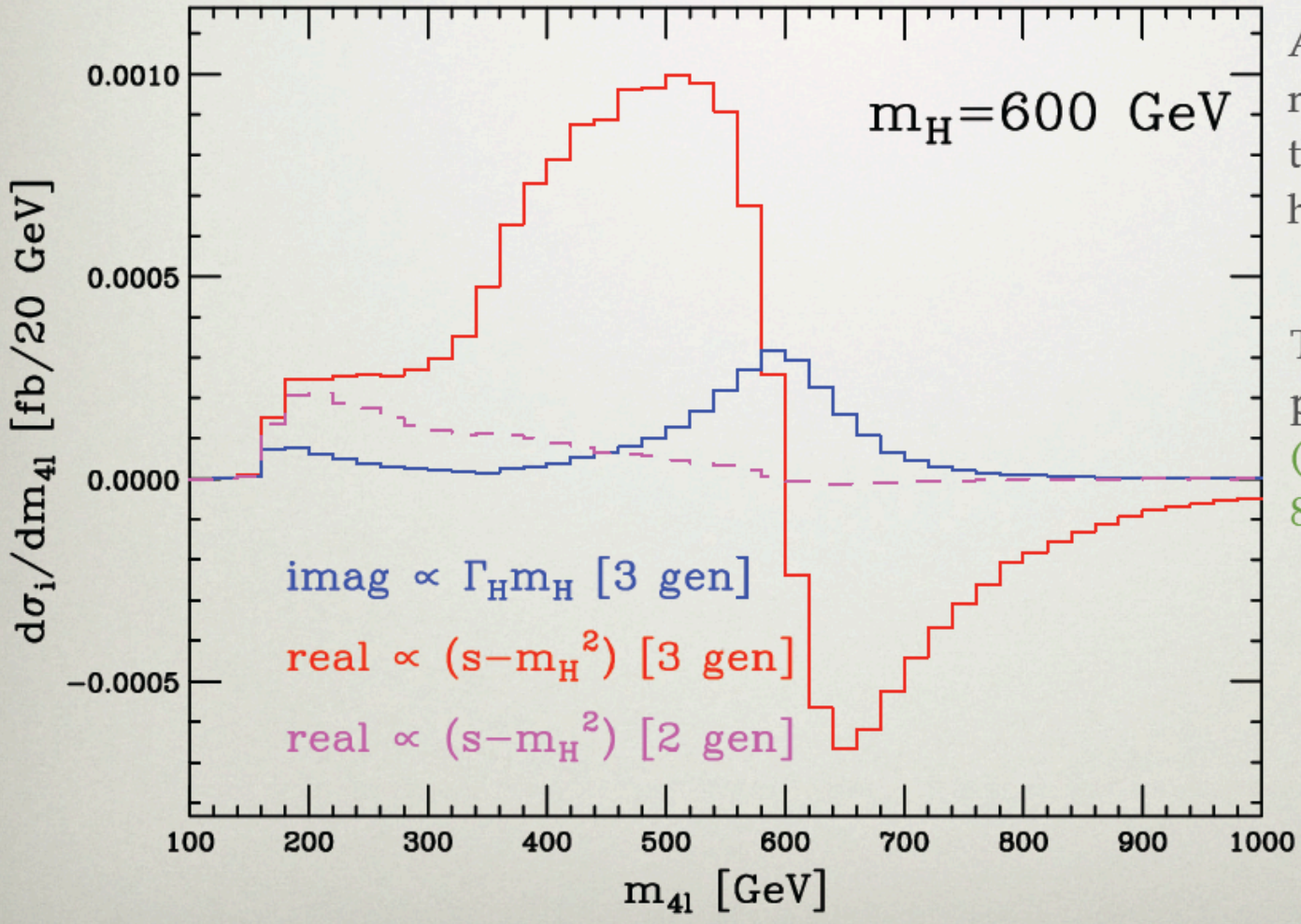
Backup





G.Passarino (Torino University)
http://personalpages.to.infn.it/~giampier/notes_HH.pdf

More Re and Im B.W.



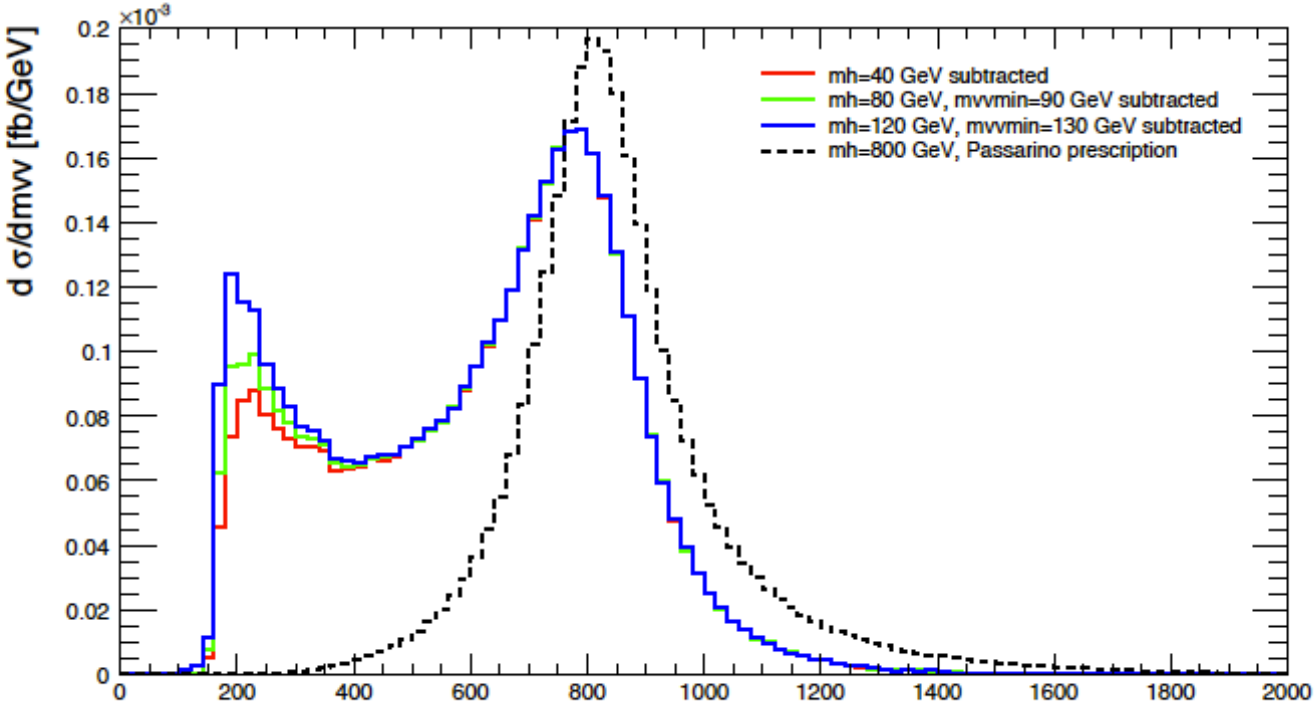
Although there is a net constructive effect the interference still has a destructive tail

This is essential to preserve unitarity (Glover, van der Bij 89)

Destructive interference ensures correct behaviour in $\log^2(s/m_t^2)$

Resonance shape for heavy Higgs: LO $WWjj$ case

PRELIMINARY



Notation:

$\mathcal{M}_X = \mathcal{M}_X(m_X) \sim \frac{s}{v^2}$ Signal amplitude for s-, t- and u-channel exchange of new particle X

$\mathcal{M}_B \sim \frac{-s}{v^2}$ continuum electroweak background amplitude

$\Longrightarrow B = \int d\Phi |\mathcal{M}_B|^2$ or $S = \int d\Phi \left[|\mathcal{M}_X|^2 + 2\mathrm{Re}\mathcal{M}_X\mathcal{M}_B^*\right]$ violate unitarity at large s

Compare to SM light Higgs scenario with $m_h = 125$ GeV or $m_h = 100$ GeV, i.e. define electroweak background: $B = \int d\Phi |\mathcal{M}_B + \mathcal{M}_h(m_h)|^2$ and signal: $S = \int d\Phi |\mathcal{M}_B + \mathcal{M}_X(m_X)|^2 - B$

Integrate over suitable mass range $[m_X - \Gamma_1, m_X + \Gamma_2]$