Heavy Higgs: SM exclusion and next steps

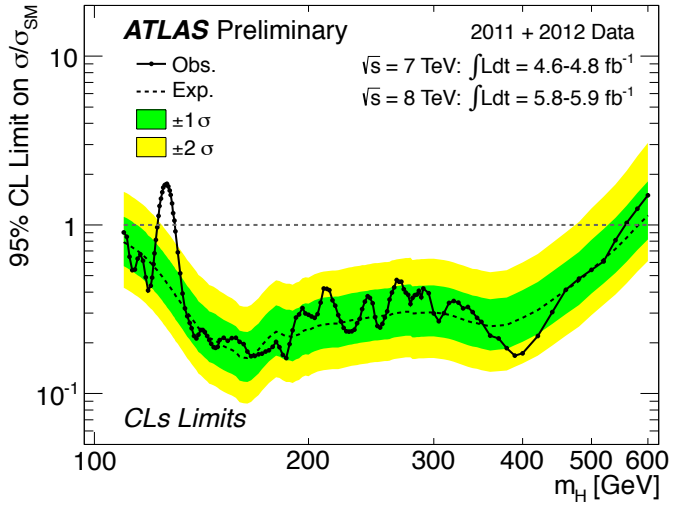
Sara Bolognesi[1], Sara Diglio[2]
[1] Johns Hopkins University (CMS)
[2]University of Melbourne (ATLAS)

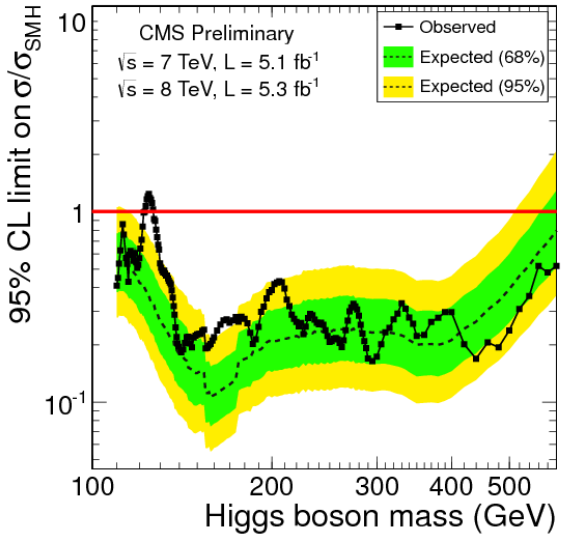
Outline

According to what we have learnt recently at ICHEP

- Standard Model like-Higgs:
  - Current exclusion limits
  - Higgs lineshape
  - Signal – Background interference
  - ATLAS/CMS plans
- BSM searches compatible with updated results

Standard Model Higgs exclusion





- An excess around 125 GeV has been confirmed by ATLAS and CMS →it will take time before establishing definitively the nature of the observed excess: is it the SM Higgs boson?
- <u>We want to explore the full available Higgs mass range up to 1 TeV</u>

What is different in High Mass region wrt light mass Higgs region?

In Heavy Higgs region we must account for:

- Lineshape effects
- Signal-Background interference effect

LHC XS working group "Heavy Higgs and BSM"
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsBSMMinutes

Talk @ **Sixth LHC Higgs Cross Section Workshop** : "Heavy Higgs status and plans"
https://indico.cern.ch/getFile.py/access?contribId=13&sessionId=4&resId=0&materialId=slides&confId=182952

Lineshape with complex pole

G.Passarino
arXiv:1112.5517v2

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

but very useful notions 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)
  → but strong interference between Higgs S and VV B at high masses

One possible solution proposed by Passarino: **OFFP**

keep the production and decay as a function of virtuality but preserving gauge invariance

OFFP

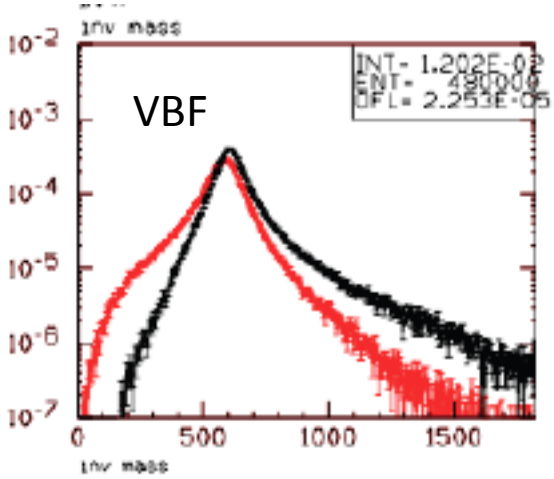
$$S(\zeta, \ldots) = V_{\rm prod}(\zeta, \ldots)\, \Delta_{\rm prop}(\zeta)\, V_{\rm dec}(\zeta), \qquad \Delta_{\rm prop}(\zeta) = \text{propagator},$$

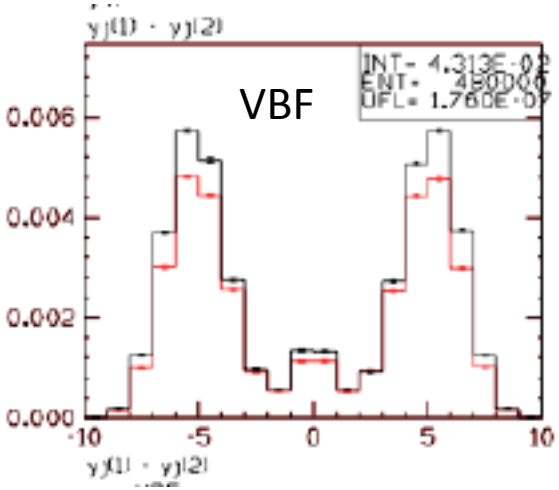
Results from complex pole reweighting

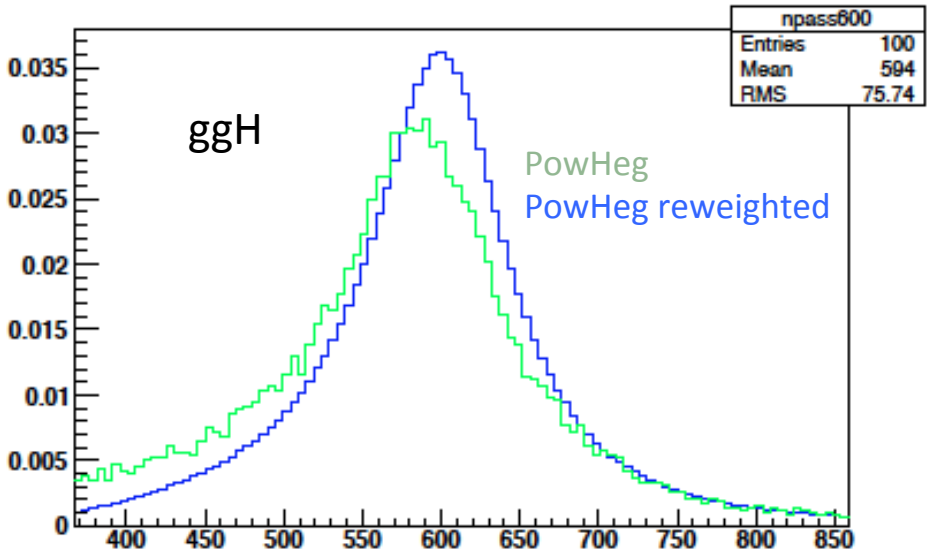
Oleari, Nason
Second BSM and Heavy Higgs kick off meeting

Black: Propagator scheme

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





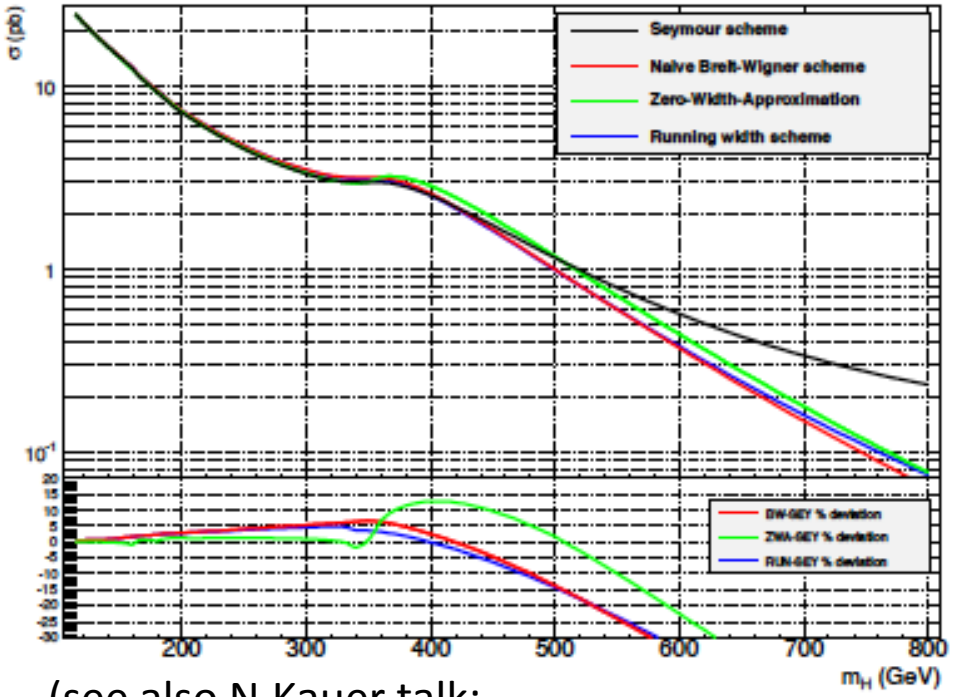


Rebuzzi, Steele
Second BSM and Heavy Higgs kick off meeting

Weights calculated as the ratio between HAWK with the correct propagator and POWHEG (with its default propagator)

Other available schemes

Anastasiou et al arXiv:1202.3638
M. Seymour Phys.Lett.B 354 (1995) 409 [hep-ph/9505211]
N.Kauer and G.Passarino arXiv:1206.4803v1



- **Zero width approximation** (ZWA):

$$\frac{1}{\Delta(Q, m_H)} \to \frac{\pi}{m_H \Gamma_H(m_H)} \delta\left(Q^2 - m_H^2\right) \tag{4.3}$$

This should be an adequate treatment for a light Higgs boson where the width of the Higgs boson is very small in comparison to its mass.

- **Naive Breit-Wigner** (BW):

$$\frac{1}{\Delta(Q, m_H)} = \frac{1}{(Q^2 - m_H^2)^2 + m_H^2 \Gamma_H^2(m_H)} \tag{4.4}$$

This corresponds to resumming leading width contributions for $Q \sim m_H$.

- **Breit-Wigner with running width**:

$$\frac{1}{\Delta(Q, m_H)} = \frac{1}{(Q^2 - m_H^2)^2 + Q^2 \Gamma_H^2(Q)} \tag{4.5}$$

- **Seymour scheme** [21]

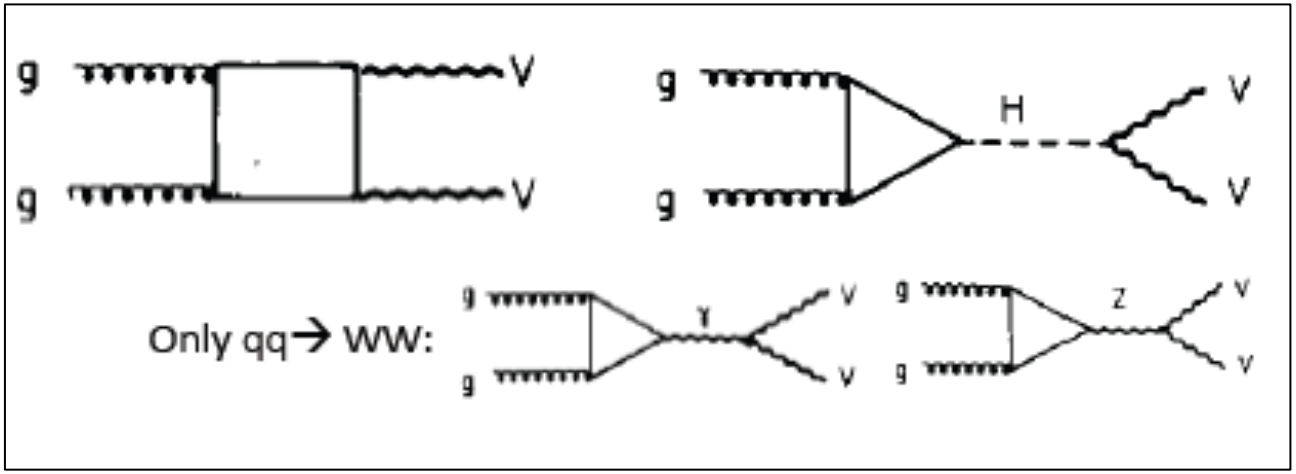
$$\frac{1}{\Delta(Q, m_H)} = \frac{m_H^4/Q^4}{(Q^2 - m_H^2)^2 + \Gamma_H^2(m_H^2)\frac{Q^4}{m_H^2}} \tag{4.6}$$

This scheme is a prescription to account for signal-background interference effects at the high energy limit and finite width resummation simultaneously.

(see also N.Kauer talk:
https://indico.cern.ch/getFile.py/access?contribId=54&sessionId=5&resId=0&materialId=slides&confId=173388)

Interference effects in gg→VV (I)

Interference effects between Higgs and SM backgrounds are strong in ZZ and WW production at high invariant masses due to the heavy Higgs boson large width



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

$$\sigma_B \longrightarrow |\mathcal{A}_{\rm box}|^2 \ , \qquad \mathcal{A}_{\rm box} = 2\mathcal{A}_{\rm massless} + \mathcal{A}_{\rm massive}$$

$$\sigma_H \longrightarrow |\mathcal{A}_{\rm Higgs}|^2 \ ,$$

$$\sigma_i \longrightarrow 2{\rm Re}\left(\mathcal{A}_{\rm Higgs}\mathcal{A}^*_{\rm box}\right) \ ,$$

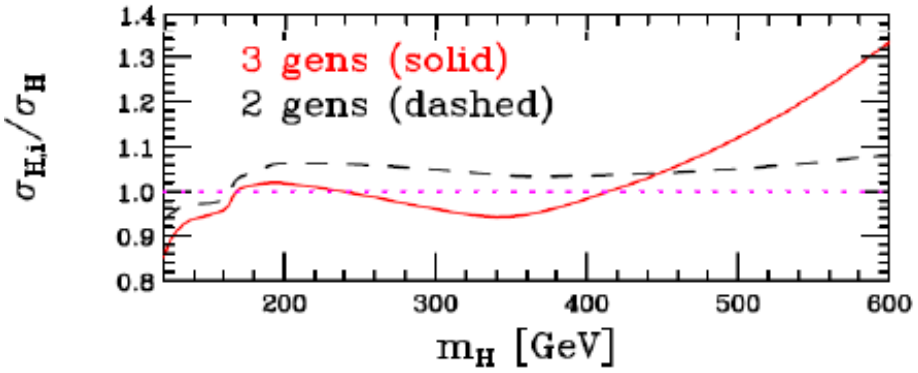
$$\sigma_{H,i} = \sigma_H + \sigma_i \ .$$

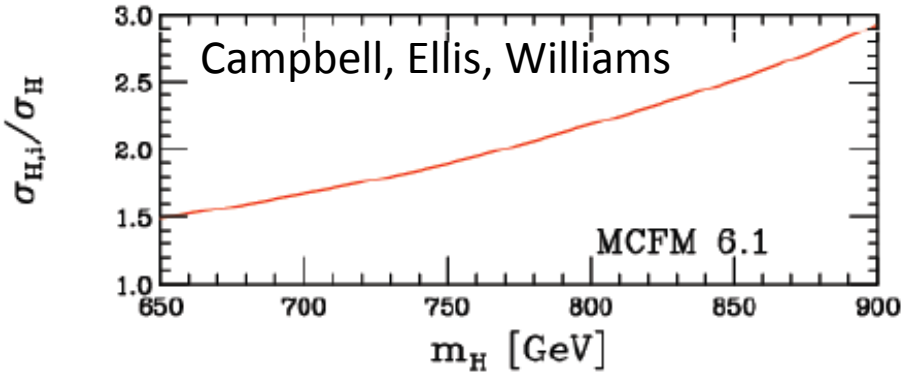
Typically experimental collaborations work with the first two quantities (with the Higgs x sec at NNLO)

Interference effects in gg→VV (II)

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

Ciaran Williams
Workshop: the case of a large-mass Higgs





MC programs with interference effect included:

- gg2VV (N. Kauer): gg→ZZ and gg →WW
- MCFM (J. Campbell, K. Ellis, C. Williams): gg→WW
- aMC@NLO (S.Frixione, F.Maltoni, A. Laureys) : gg→ZZ

NEW version:
It also includes OFFP propagator for the lineshape

Interference on X-sec

WW standard
$\mathbf{pT_l}$ > 20 GeV and $|\eta_l|$ < 2.5
$\mathbf{pT^{miss}}$ > 30 GeV
$\mathbf{M_{ll'}}$ > 12 GeV

WW Higgs
Standard cuts +
$\mathbf{pT_l^{min}}$ > 25 GeV
$\mathbf{pT_l^{max}}$ > 90 GeV
$\mathbf{M_{ll'}}$ < 300 GeV
$\Delta\phi_{ll'}$ < 175°

Relative measures for interference effect

$S+B$-inspired measure:

$$R_1 := \frac{\sigma(|\mathcal{M}_H + \mathcal{M}_{cont}|^2)}{\sigma(|\mathcal{M}_H|^2) + \sigma(|\mathcal{M}_{cont}|^2)}$$

$S/\sqrt{B}$-inspired measure:

$$R_2 := \frac{\sigma(|\mathcal{M}_H|^2 + 2\,\mathrm{Re}(\mathcal{M}_H \mathcal{M}^*_{cont}))}{\sigma(|\mathcal{M}_H|^2)}$$

ZZ standard
$\mathbf{pT_l}$ > 20 GeV and $|\eta_l|$ < 2.5
76 GeV < $\mathbf{M_{ll'}}$ < 106 GeV

ZZ Higgs
Standard cuts +
$|\mathbf{M_{ll'l'}} - \mathbf{M_H}| < \Gamma_H$

N.Kauer arXiv: 1201.1667v3

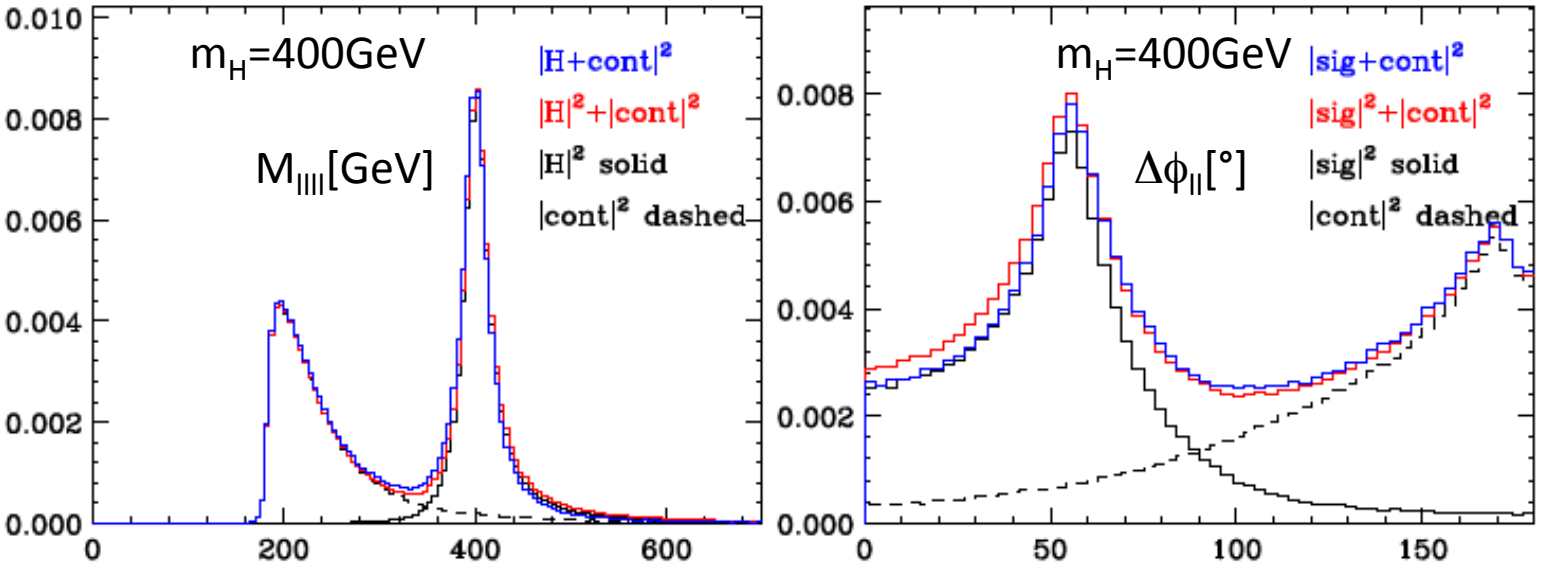
(see also N.Kauer talk)

		σ [fb], pp, $\sqrt{s} = 7$ TeV, $M_H = 400$ GeV			interference	
process	cuts	$\lvert\mathscr{M}_H\rvert^2$	$\lvert\mathscr{M}_{cont}\rvert^2$	$\lvert\mathscr{M}_H + \mathscr{M}_{cont}\rvert^2$	R_1	R_2
$gg\,(\to H) \to WW$	stand.	4.361(3)	6.351(4)	10.582(7)	0.9879(8)	0.970(2)
$gg\,(\to H) \to WW$	Higgs	2.502(2)	0.633(1)	3.007(3)	0.959(2)	0.949(2)
$gg\,(\to H) \to ZZ$	stand.	0.3654(4)	0.3450(4)	0.7012(8)	0.987(2)	0.975(3)
$gg\,(\to H) \to ZZ$	Higgs	0.2729(3)	0.01085(2)	0.2867(3)	1.010(2)	1.011(2)

- $\mathcal{O}(5\text{–}10\%)$ signal-background interference effects for $gg \to H \to VV$
- Experimental selection cuts (e.g. on M_T) allow to eliminate/mitigate effects

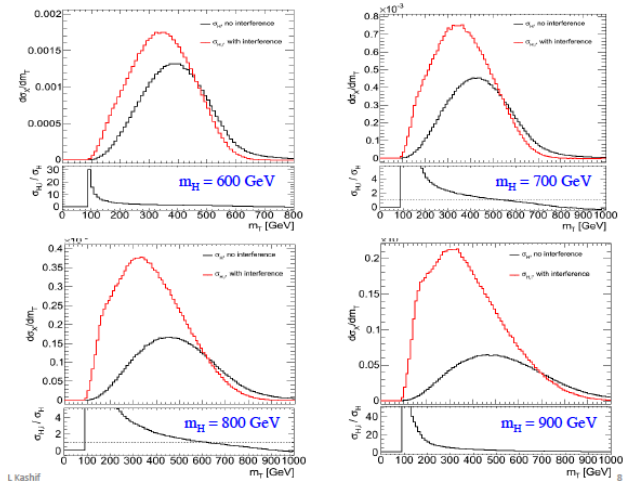
Interference on distributions

gg2ZZ:
studies by
N. Kauer

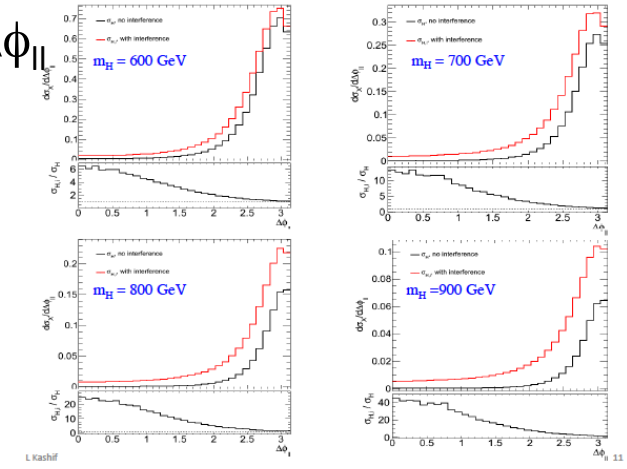


Effect is big on the lineshape for H→ZZ and on all the shapes (not just mH) for H→WW

M_T



$\Delta\phi_{ll}$

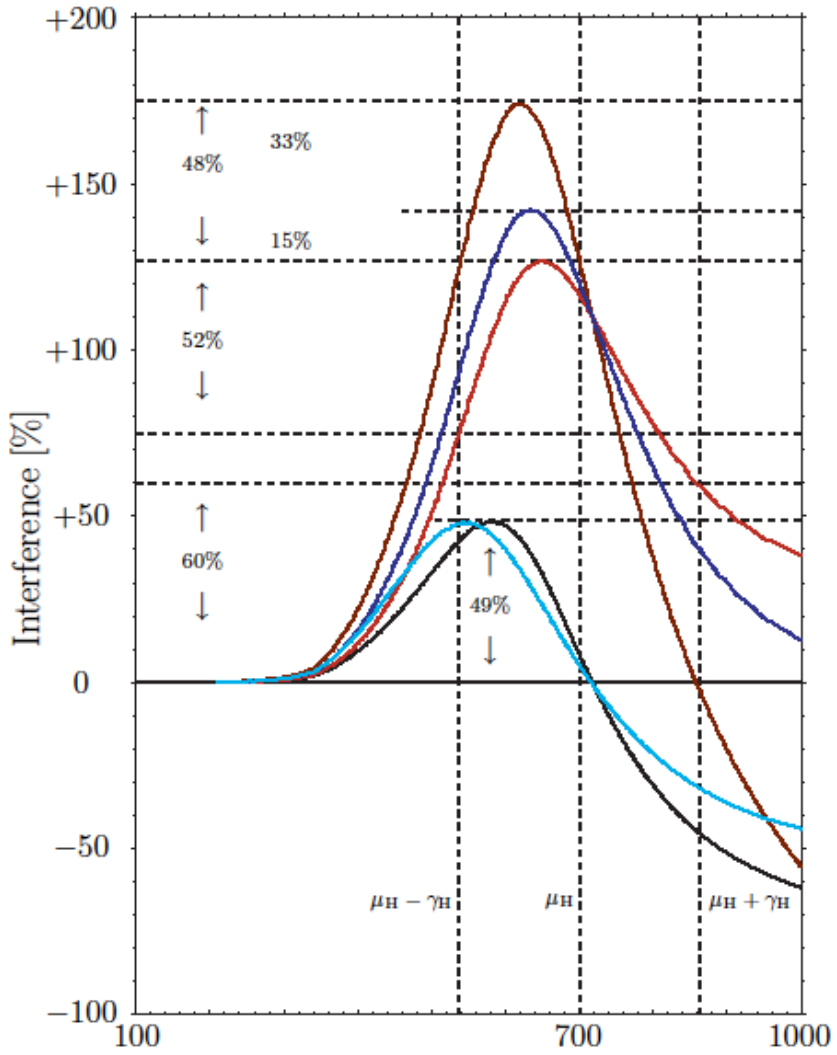


MCFM: studies in ATLAS
H→WW

Lashkar Kashif
HSG3
Workshop, ,March

Interference in H→ZZ [%]

New results from Passarino mH=700 GeV [arXiv:1206.3824v1]



S+B (LO)

S+B+I (LO)

S+B+I comparing different recipes to scale to NNLO ($K = S_{NNLO}/S_{LO}$)

multiplicative
(S+I)*K +B

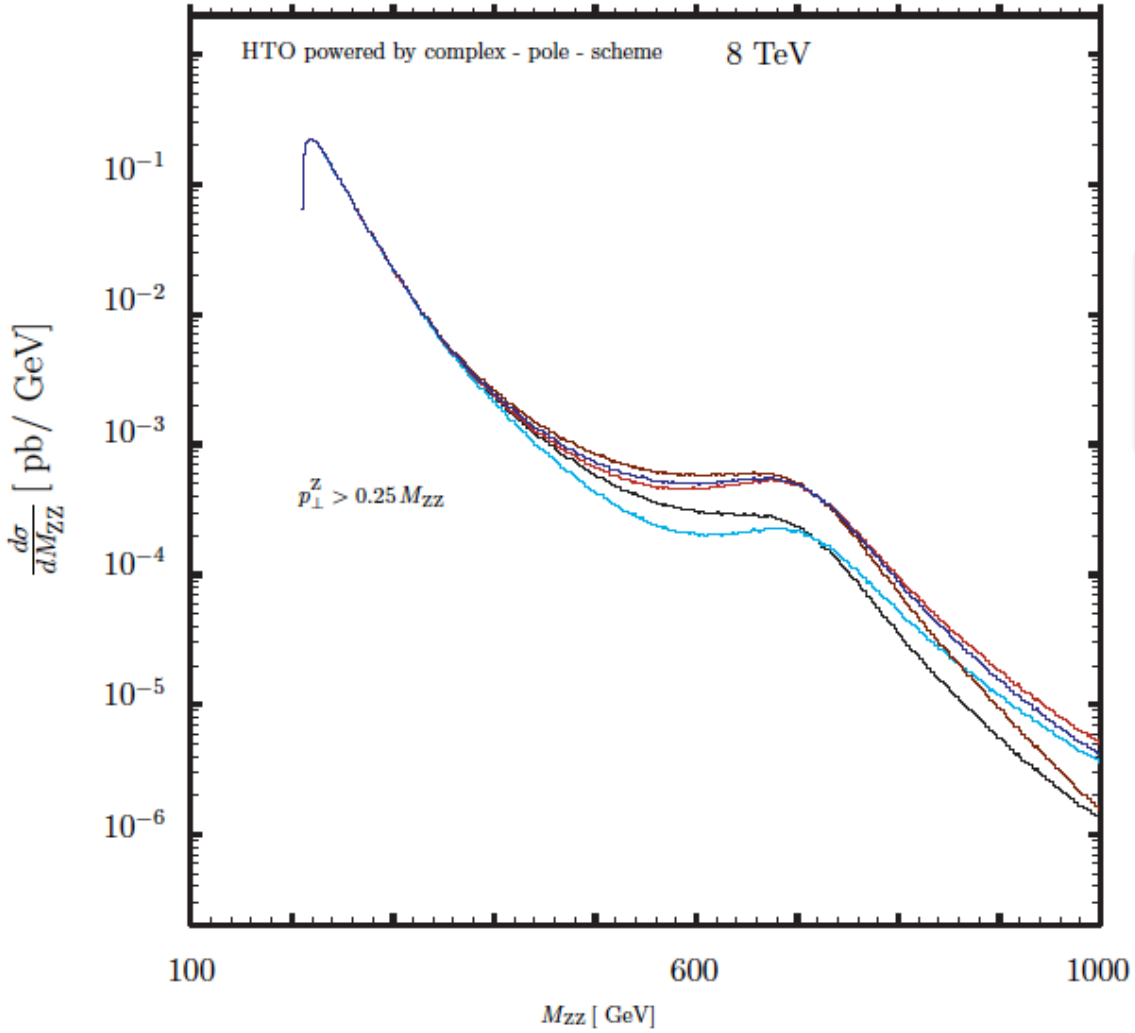
additive
(S*K) + I + B

intermediate:
S*K + I*K' + B

where K' just include gg initiated diagrams

Interference in H→ZZ: mZZ shape

New results from Passarino mH=700 GeV [arXiv:1206.3824v2]



S+B (LO)

S+B+I (LO)

S+B+I comparing different recipes to scale to NNLO ($K = S_{NNLO}/S_{LO}$)

multiplicative
(S+I)*K +B

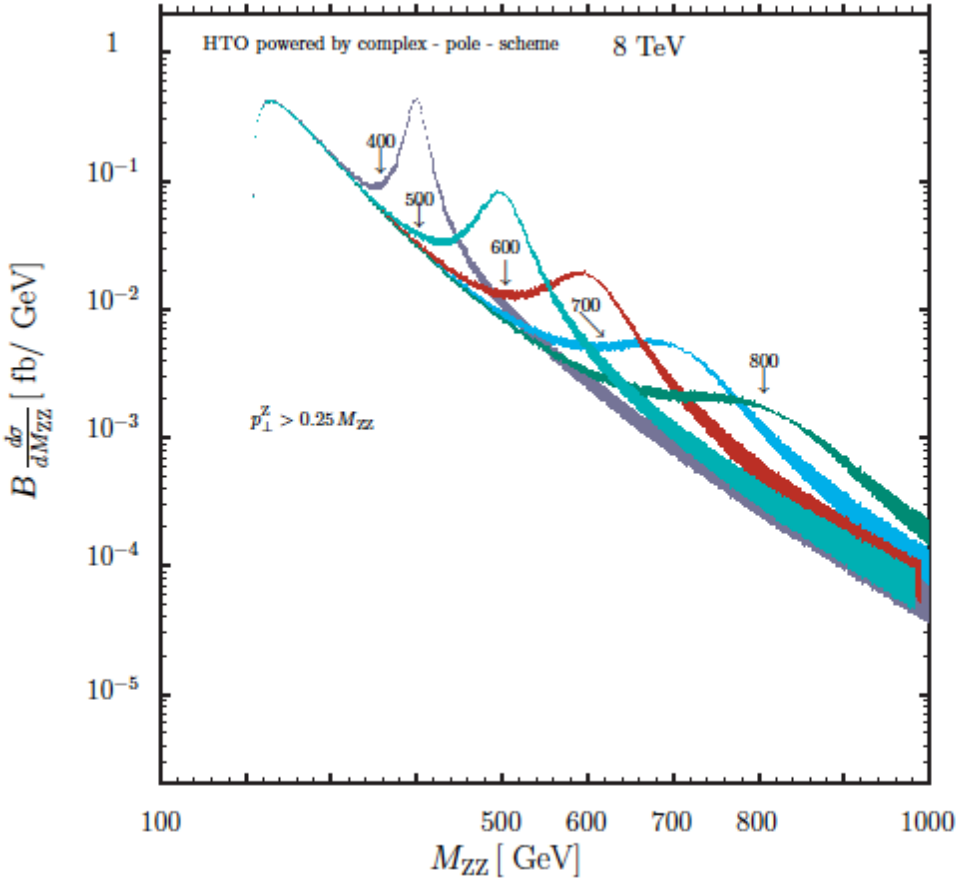
additive
(S*K) + I + B

intermediate:
S*K + I*K' + B

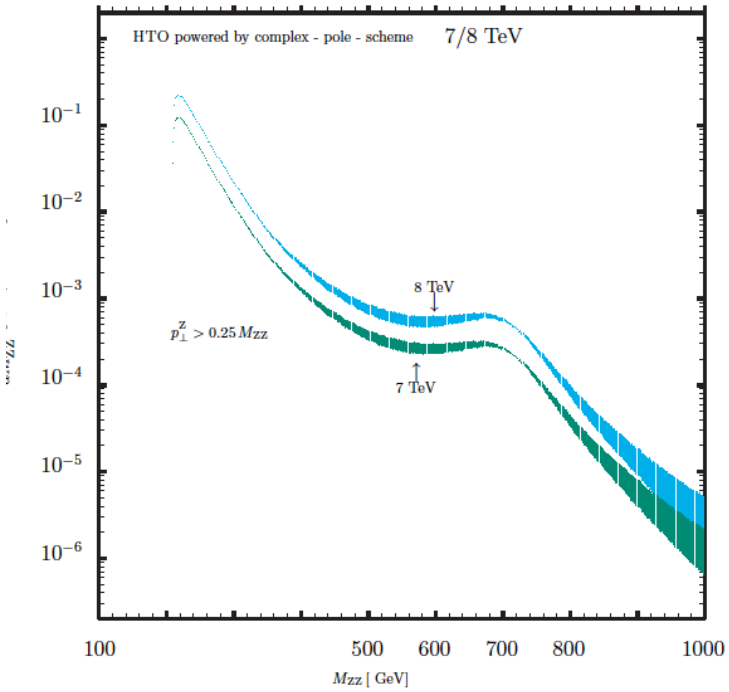
where K' just include gg initiated diagrams

Effective NNLO ZZ invariant mass including THU

New results from Passarino [arXiv:1206.3824v2]



Comparison 7 – 8 TeV for mH =700 GeV



How to go up to 1 TeV analysis

IDEAL APPROACH

- Use MC NNLO that include both OFFP lineshape and interference effect

How to go up to 1 TeV analysis

IDEAL APPROACH **NOT AVAILABLE**

- Use MC NNLO that include both OFFP lineshape and interference effect

FIRST FEASIBLE APPROACH

1. **Reweight our available MC samples to account for lineshape of the Higgs boson (using OFFP) → available tools:**
   - from P.Nason and C.Oleari
   - from D.Rebuzzi and G.Steele
   (https://svnweb.cern.ch/cern/wsvn/atlasusr/gsteele/Heavy_Higgs_Reweighting/trunk/)
2. **Associate an uncertainty to this lineshape reweighting**
   → Numbers from G.Passarino (http://personalpages.to.infn.it/~giampier/allheavy3.txt)
3. **Correct the result to include Signal-Background interference effect and associate an uncertainty (LO→NNLO) to this correction**
   → Numbers from G.Passarino (http://personalpages.to.infn.it/~giampier/int_summary_*.dat)

How to go up to 1 TeV analysis

IDEAL APPROACH **NOT AVAILABLE**

- Use MC NNLO that include both OFFP lineshape and interference effect

FIRST FEASIBLE APPROACH

1. **Reweight our available MC samples to account for lineshape of the Higgs boson (using OFFP) → available tools:**
   - from P.Nason and C.Oleari
   - from D.Rebuzzi and G.Steele
   (https://svnweb.cern.ch/cern/wsvn/atlasusr/gsteele/Heavy_Higgs_Reweighting/trunk/)
2. **Associate an uncertainty to this lineshape reweighting**
   → Numbers from G.Passarino (http://personalpages.to.infn.it/~giampier/allheavy3.txt)
3. **Correct the result to include Signal-Background interference effect and associate an uncertainty (LO→NNLO) to this correction**
   → Numbers from G.Passarino (http://personalpages.to.infn.it/~giampier/int_summary_*.dat)

SECOND FEASIBLE APPROACH

- **Use MC LO that include both OFFP lineshape and interference effect (LO)**
  → gg2VV from N. Kauer
- **Associate an uncertainty : LO → NNLO**

Plans from ATLAS/CMS

- H → ZZ

  Correct the available PowHeg MC sample for

  – Lineshape with complex pole
  – Signal-background interference

  } ATLAS and CMS **(FIRST APPROACH)**

- H→ WW
  – Keep the uncertainty on xsec as for 2011 data

    $1 + 1.5 * (m_H / \text{TeV})^3$ (→ CMS)

  – Generate new MC samples with gg2WW for

    $m_H > 300$ GeV (→ ATLAS) **(SECOND APPROACH)**

Lineshape with complex pole

http://personalpages.to.infn.it/~giampier/allheavy3.txt

- inclusive Xsec computed with OFFP
  - residual uncertainty after OFFP inclusion are smaller than PDF and scale uncertainty

- mH shape (same for WW and ZZ):
  - central values with OFFP + uncertainty bin by bin available
    - →central value bin by bin from POWHEG reweigthing
    - → % uncertainty bin by bin

Interference for ZZ

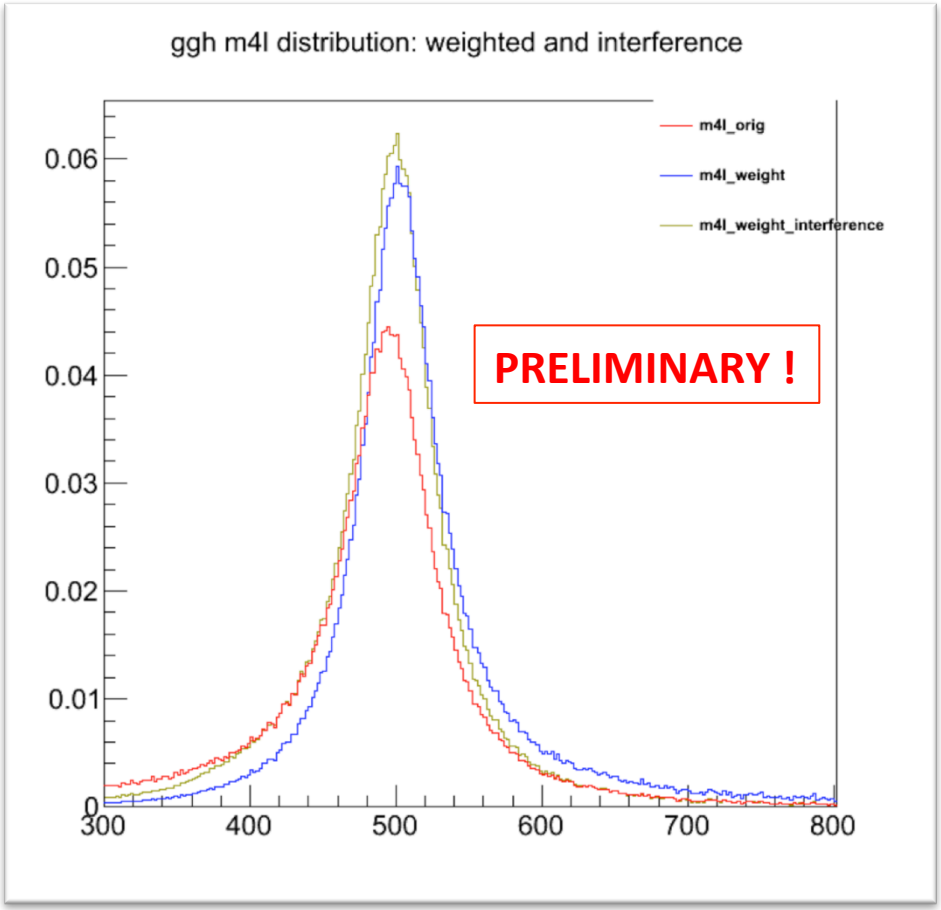
- Total Xsec
  - 8 TeV small effect: ~few% → we will neglect it
  - 7 TeV: we can assume $[I/(S+B)]_{7TeV} \sim [I/(S+B)]_{8TeV}$
- mZZ shape
  - Much larger effect

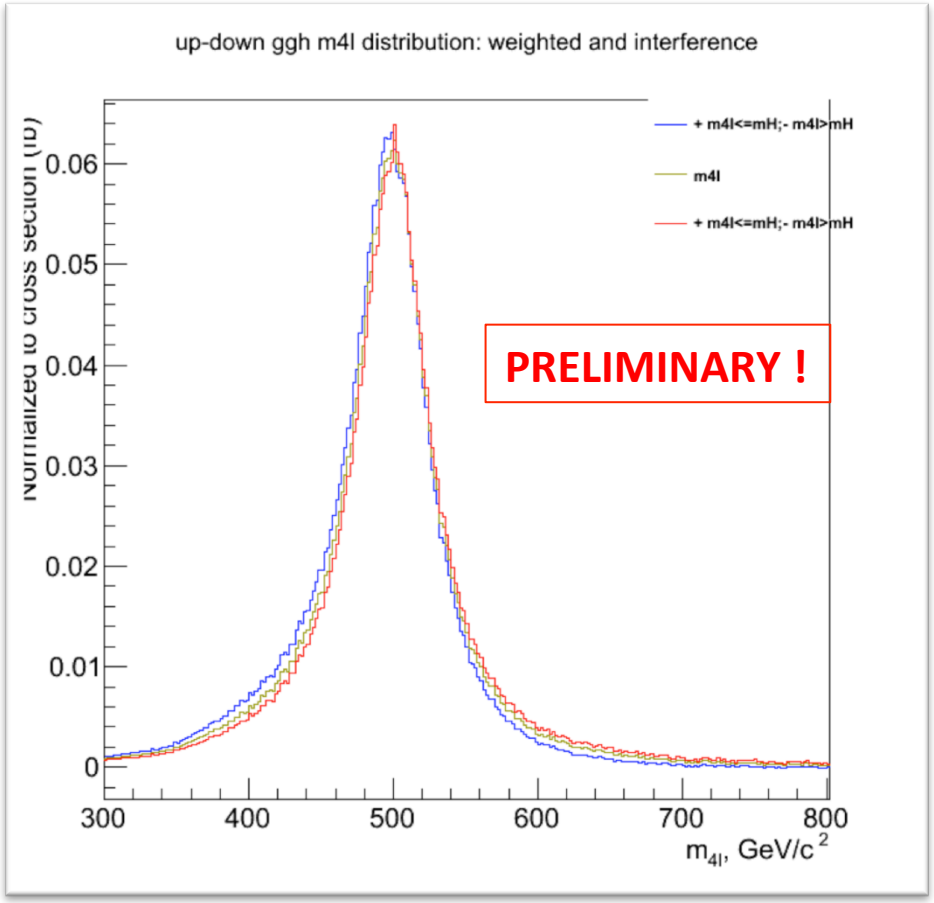
  →I/(S+B) central values from the intermediate prescription by Passarino (see slide 12)

  →uncertainty evaluated with the additive and multiplicative (see slide 12)

Preliminary results from CMS

Cheng Tongguang





BSM models

There are still models BSM compatible with a light 'SM-like Higgs' and EWK fit that do not exclude a heavy mass resonance:

- Higgs Composite models

  →Higgs=Pseudo-Goldstone boson (PGB)

See also C.Grojean talk:
https://indico.cern.ch/getFile.py/access?contribId=50&sessionId=4&resId=0&materialId=slides&confId=173388

- SM extension with Higgs mass splitting

S.Kanemura et al arXiv:1108.3297

Conclusions

- Both ATLAS and CMS aim to explore H→ZZ and H→WW channel up to 1 TeV

- We setup a procedure for both channels:

  H→ZZ

  – Reweight for lineshape and interference effect the PowHeg MC sample already available
  – Associate uncertainties to these reweighting procedures

  H→WW

  – Associate uncertainty as for 2011 data (CMS)
  – Generate new MC samples for mH>300 GeV with gg2WW (ATLAS)

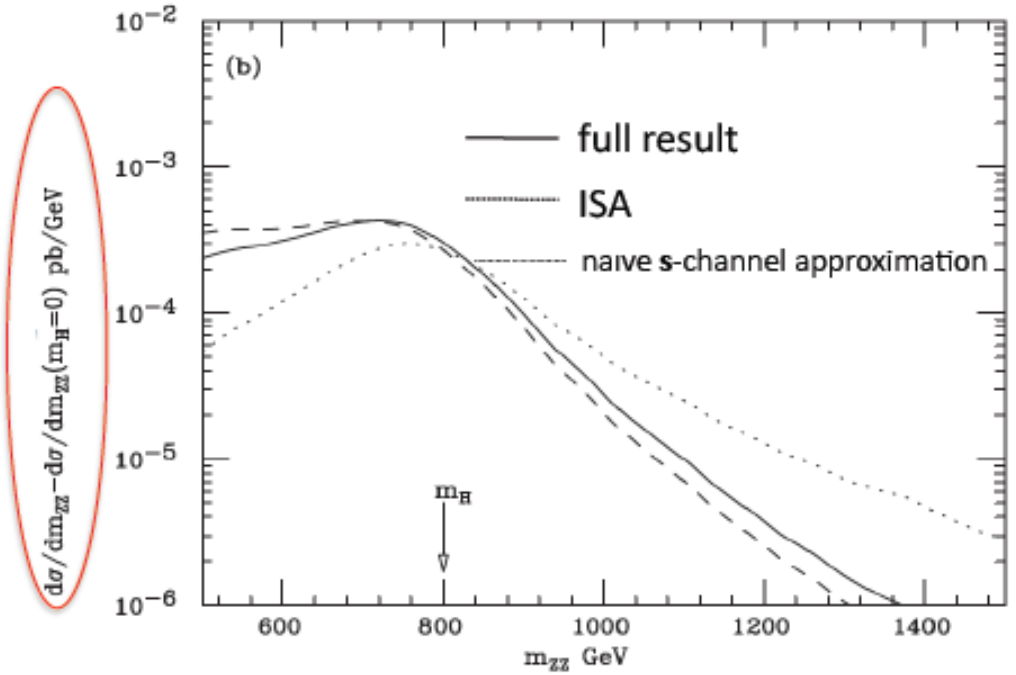
- Study BSM models compatible with a resonance ~ 125 GeV and an heavy resonance hypothesis

BACKUP

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! "