Gluon-Gluon contributions to WW production and Higgs Interference Effects

1107.5569

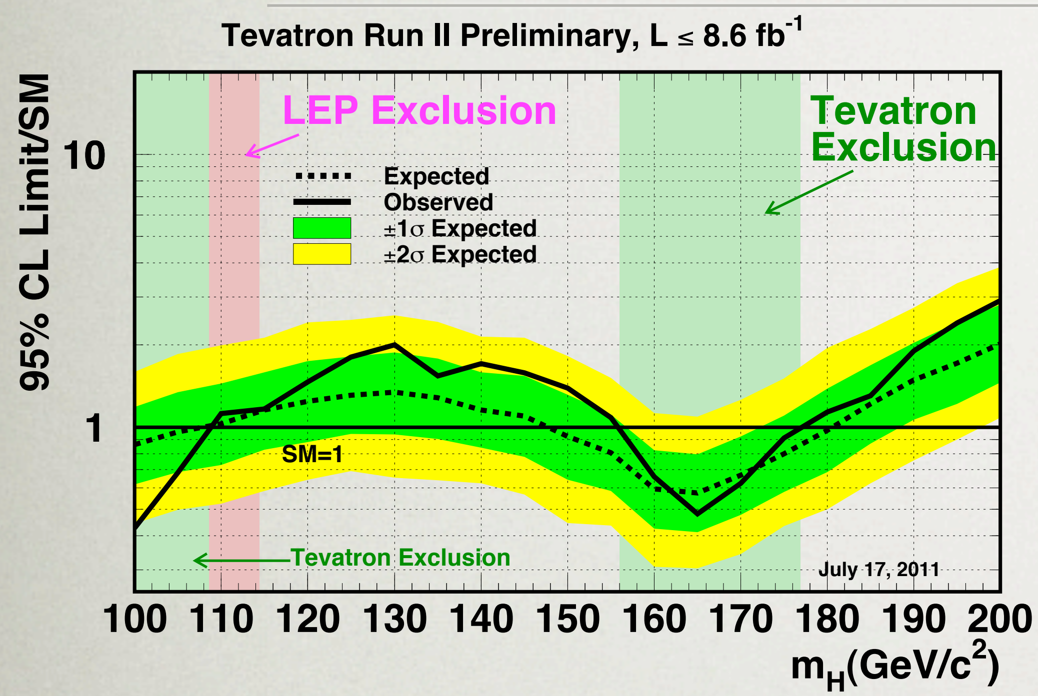
with John Campbell and Keith Ellis

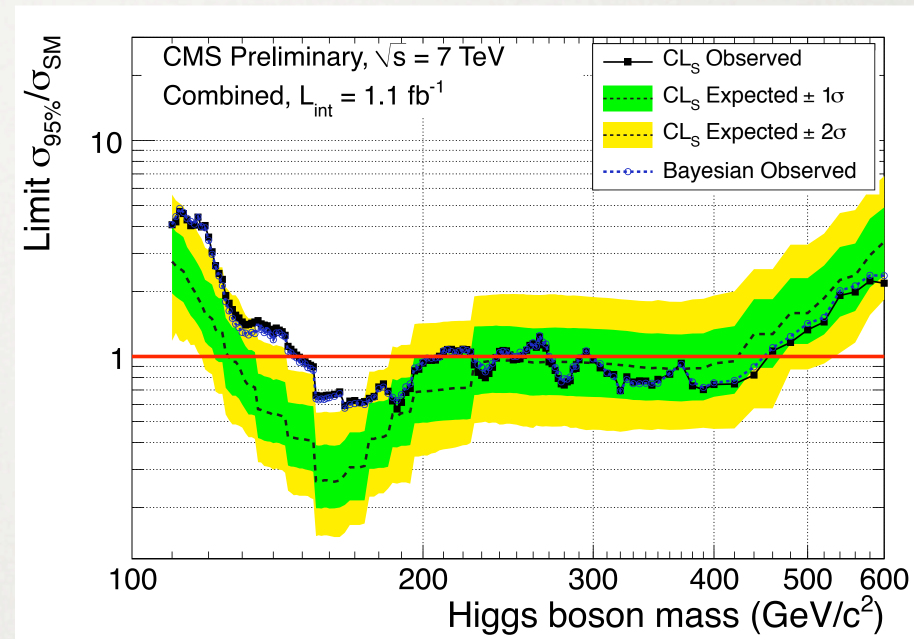
Ciaran Williams, Fermilab

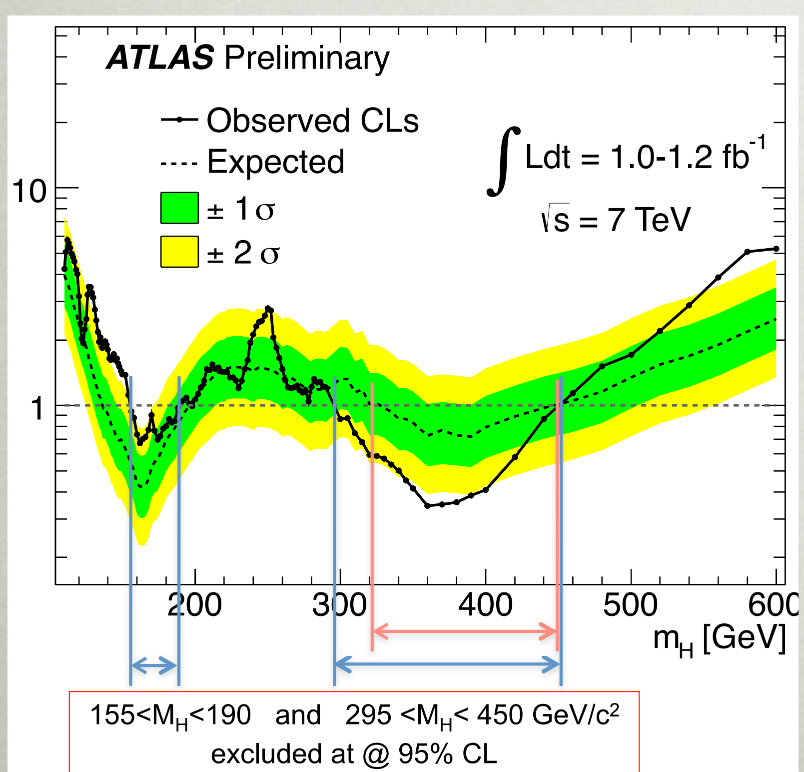
Outline

- Motivation
- Calculation of gg->WW (t,b) loops
- Interference at the LHC
- Interference at the Tevatron
- Summary

Motivation





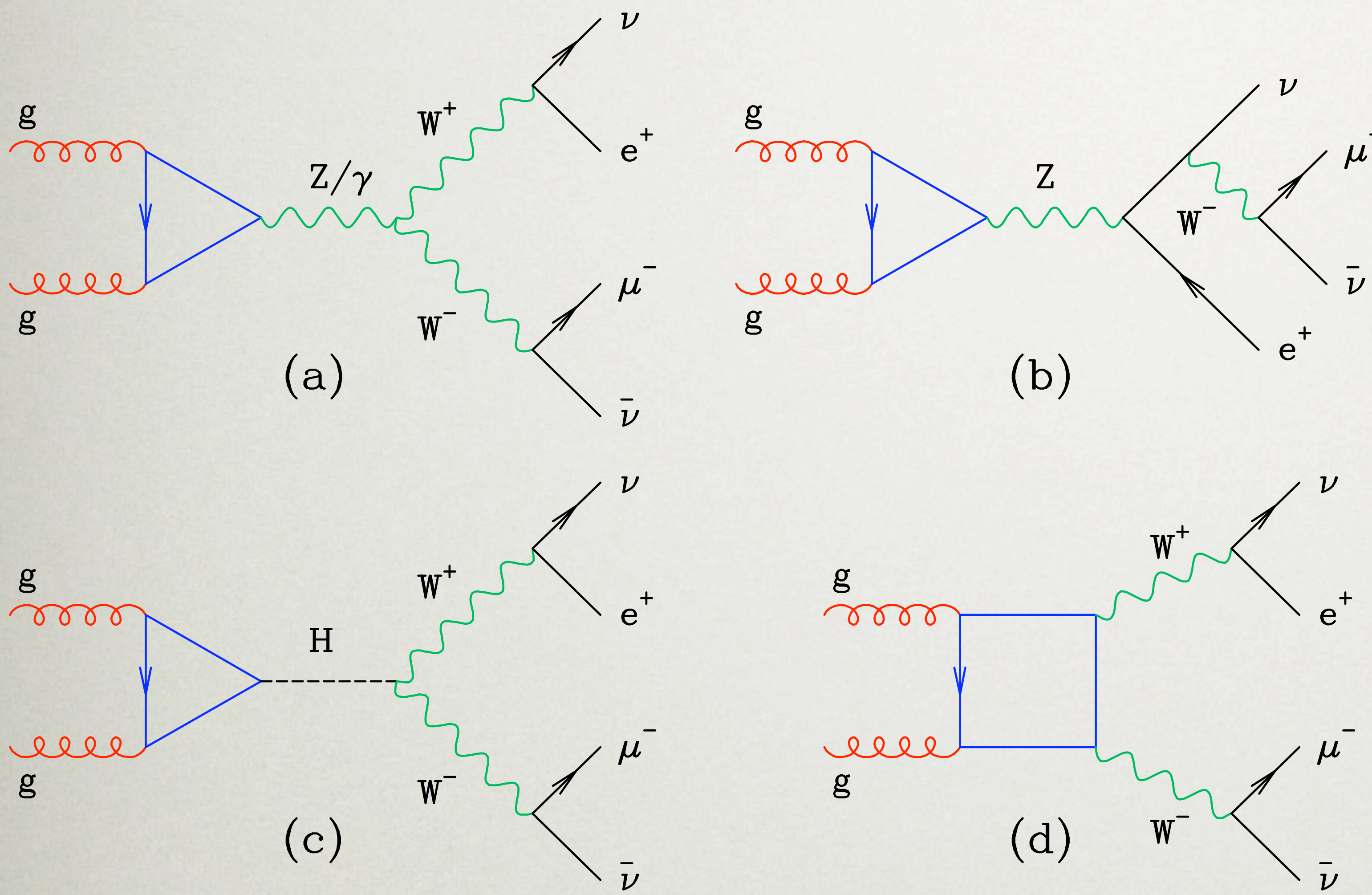


- Much theoretical work done on NNLO (and beyond) calculations see e.g. (Anastasiou, Melnikov 02; Ravindran Smith, van Neervan 03; Anastasiou, Melnikov, Petriello 04; Catani, Grazzini 07; Anastasiou, Dissertori,Stockli 09; Grazzini 09; Anastasiou, Buehler, Herzog, Lazopoulos 11.....)
- Currently used theory error is between 10-20 %. To be accurate we require that there are no neglected contributions of this order.
- Experimentalists typically neglect interference between Higgs and SM production of WW pairs......

Existing Calculations

- Many existing calculations of Diboson and Interference studies
- Brown, Mikaelian 79; Dicus, Kao, Repko 87; Glover, van der Bij 89; Ohnemus (91,94); Frixione 93; Dixon, Kunszt, Signer (98, 99); Campbell, Ellis 99; Dixon, Sofianatos 09; Melia, Nason, Roestch, Zanderighi 11;....
- In particular for this talk,
- Binoth, Ciccolini, Kauer, Kramer 05 (GG2WW) ; Dixon, Siu 03 (di-photon Higgs Interference); Campbell, Ellis CW 11 (MCFMv6).

GG Initiated WW Loops

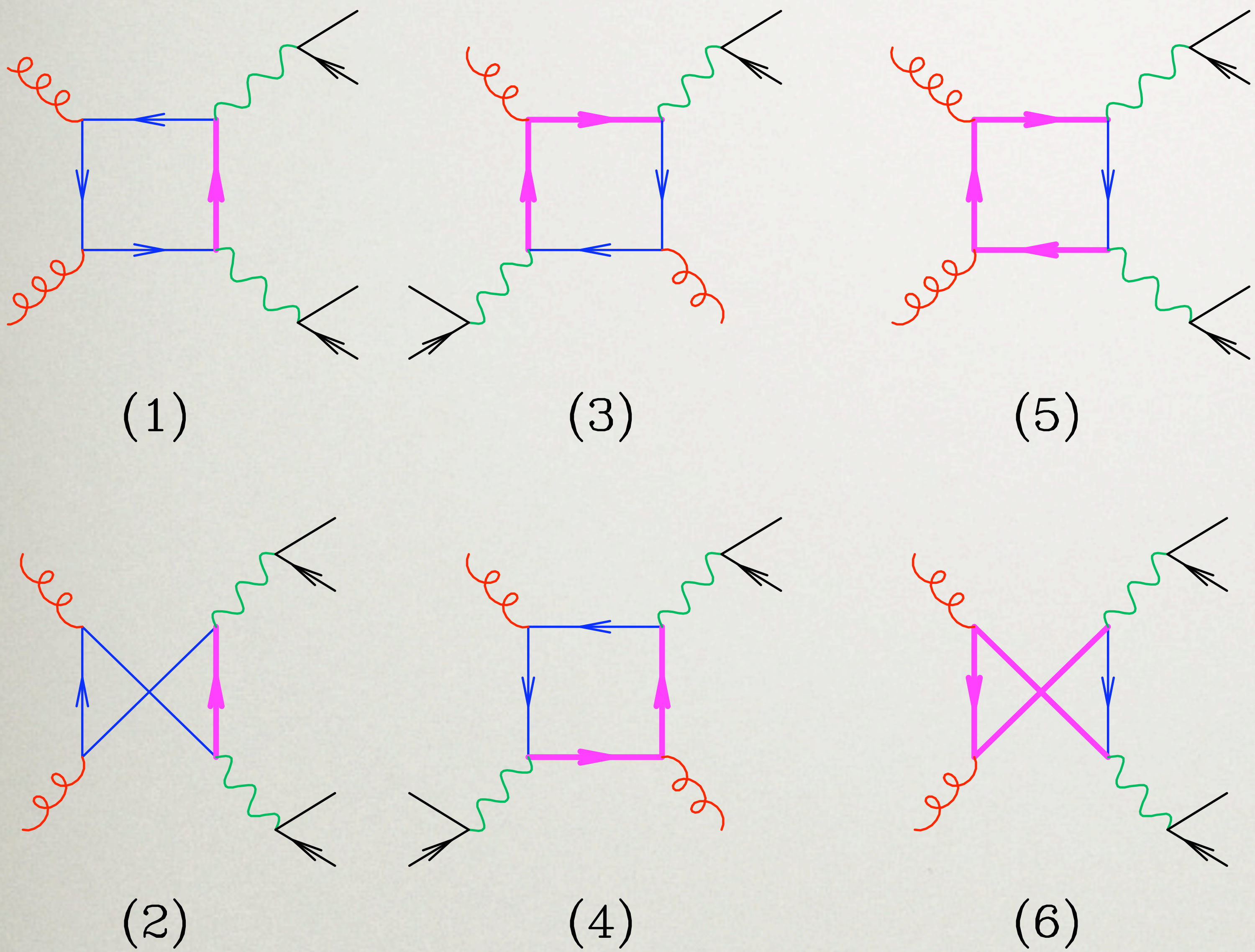


- Vector pieces of (a) and (b) vanish as a result of Furrys theorem.
- For the axial pieces there is a net cancellation between diagrams of topology (a) and (b) (Binoth, Ciccolini, Kauer, Kramer 05; Campbell, Ellis, Zanderighi 07)
- For massless isodoublets analytic results for (d) have been computed (Campbell, Ellis CW 11)
- These results are extracted from the Z+2 jet results of (Bern, Dixon, Kosower 98)

$$\mathcal{A}_{\text{massive}} = \sum_{i=1}^{6} d_i D^{(i)} + \sum_{i=1}^{12} c_i C^{(i)} + \sum_{i=1}^{6} b_i B^{(i)} + \mathcal{R}\,.$$

$$\mathcal{A}_{\text{full}} = \delta^{a_1 a_2} \left(\frac{g_w^4 g_s^2}{16\pi^2}\right) \mathcal{P}_W(s_{34}) \mathcal{P}_W(s_{56}) \; [2\,\mathcal{A}_{\text{massless}} + \mathcal{A}_{\text{massive}} + \mathcal{A}_{\text{Higgs}}]$$

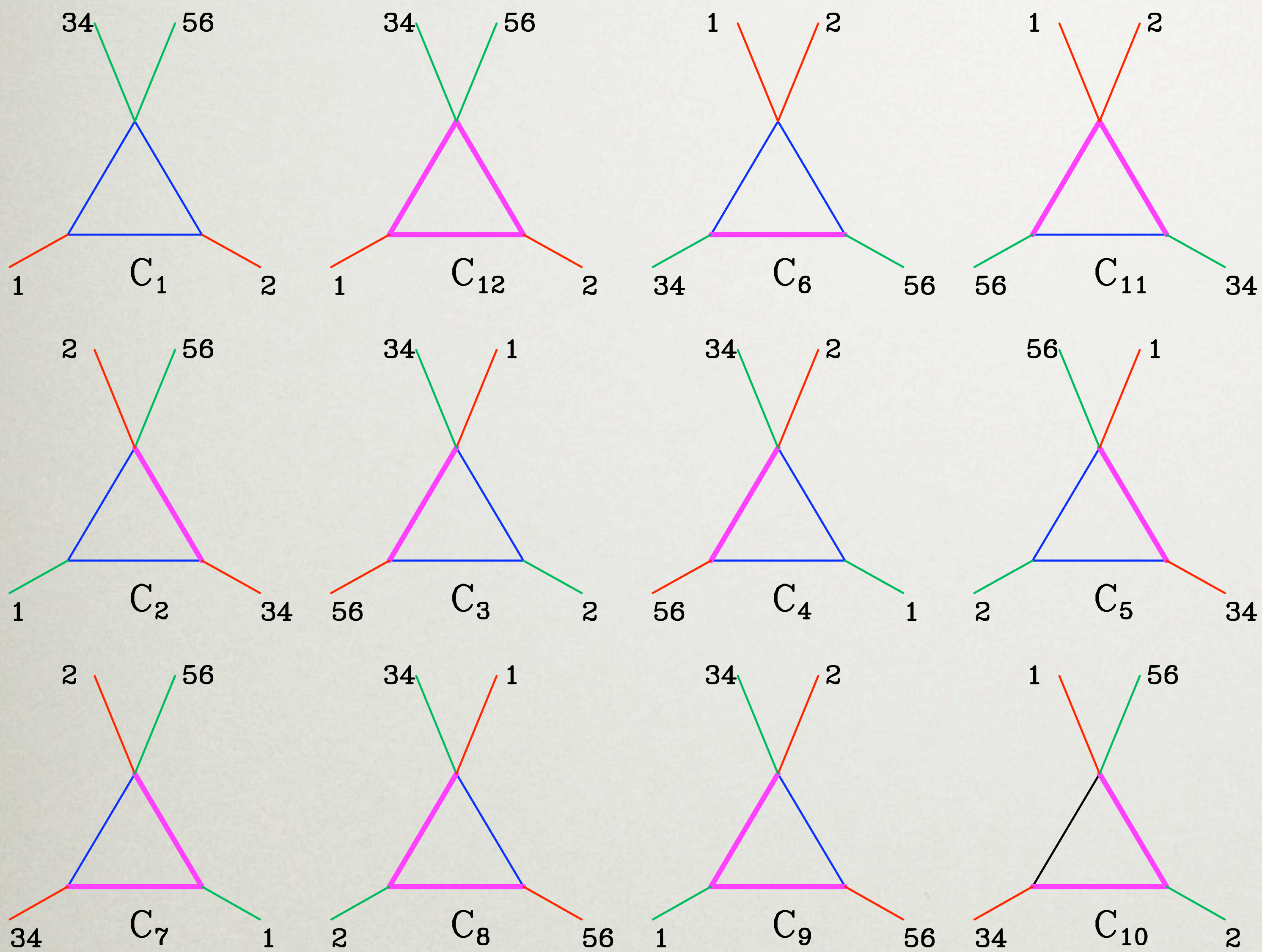
Third Gen. Loops



- Different helicity routings around the loop specify the number of massive propagators
- Box coefficients are calculated using quadruple cuts (Britto Cachazo Feng 04)
- Relatively simple final coefficients

$$d_3^{+-} = \frac{i}{2}\,\frac{1}{s_{34}s_{56}}\,\frac{m^2\left(s_{134}s_{156} - s_{56}s_{34} + m^2 s_{12}\right)[2\,6]}{s_{12}^2\langle 1|(5+6)|2]^2}\left(\langle 1\,2\rangle\,\langle 4\,3\rangle\,[1\,4] - \langle 1\,3\rangle\,\frac{m^2 s_{12}}{\langle 1|(5+6)|2]}\right)$$
$$\left(\langle 1\,2\rangle\,[1\,4]\,\langle 5|(3+4)|2] - \langle 1\,5\rangle\,[2\,4]\,\frac{m^2 s_{12}}{\langle 1|(5+6)|2]}\right)\,,$$

Triangle Coefficients



- Many different triangle topologies
- Thankfully some are constrained by IR safety
- Remaining triangles are calculated using triple cut method of Forde 07

$$\frac{d_1}{s_{134}-m^2}+\frac{d_2}{s_{156}-m^2}+c_1=0\,,$$
$$\frac{d_4}{\Delta}+\frac{d_1}{s_{12}(s_{134}-m^2)}+\frac{c_2}{s_{134}-s_{34}}=0\,,$$
$$\frac{d_3}{\Delta}+\frac{d_1}{s_{12}(s_{134}-m^2)}+\frac{c_3}{s_{134}-s_{56}}=0\,,$$
$$\frac{d_4}{\Delta}+\frac{d_2}{s_{12}(s_{156}-m^2)}+\frac{c_4}{s_{156}-s_{56}}=0\,,$$
$$\frac{d_3}{\Delta}+\frac{d_2}{s_{12}(s_{156}-m^2)}+\frac{c_5}{s_{156}-s_{34}}=0\,.$$

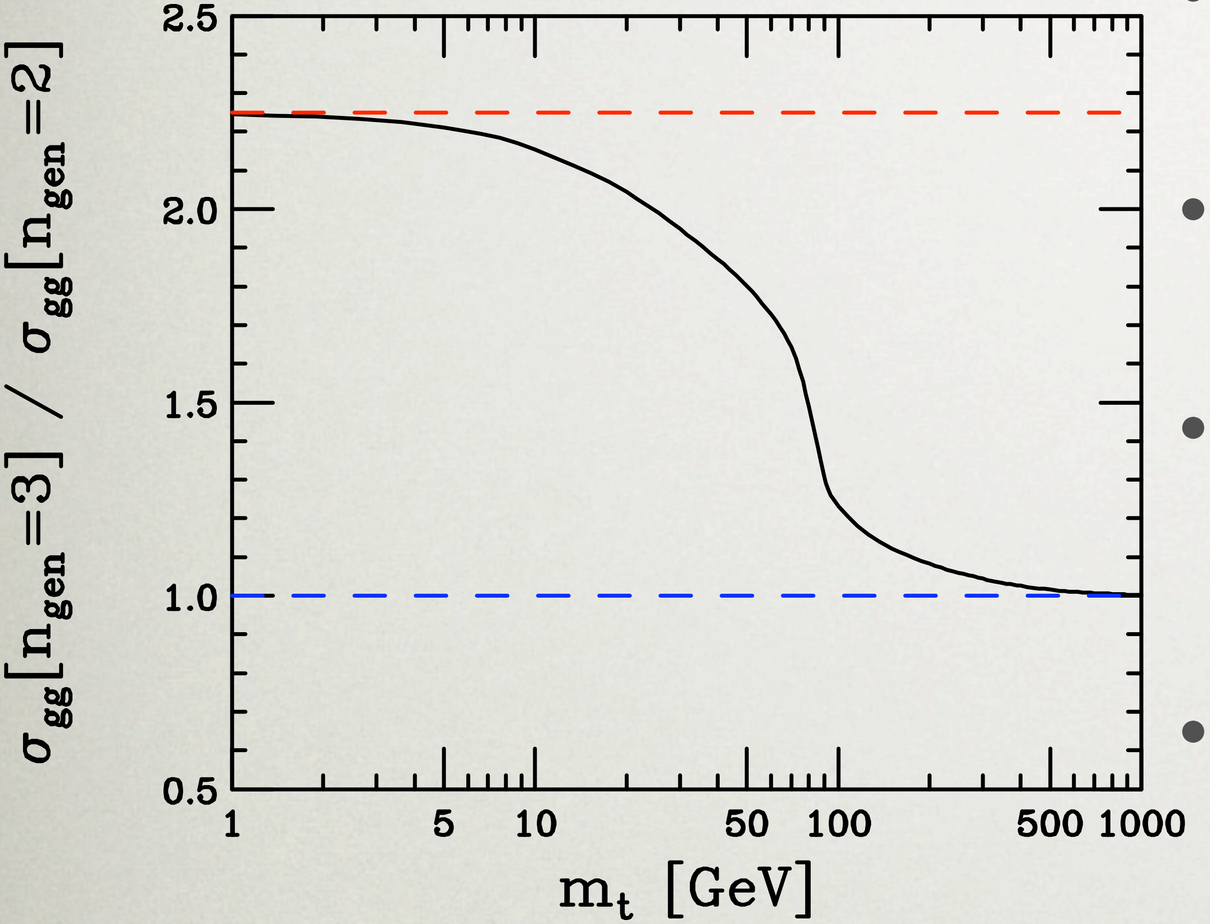
Bubble and Rational Terms

- We find that the rational terms are identical to the massless isodoublet, as a result of UV nature of rational terms
- For the bubble coefficients we find that the bubble topologies with one massive propagator are also identical to the massless isodoublet results
- For the like sign helicity amplitudes this is enough to calculate all bubble coefficients, for the opposite sign helicity amplitude one further bubble is needed, however the cancellation of UV poles informs us that

$$b^{(1)} + b^{(6)} = b^{(1)}_{\text{massless}}$$

- Therefore all bubbles bar one can be taken from massless results (Campbell, Ellis, CW 11; Bern, Dixon Kosower 98) remaining coefficient is calculated using the method of Mastrolia 09.
- Results verified against GG2WW (Binoth, Ciccolini, Kauer, Kramer 05) and an inhouse D-dim unitarity code.

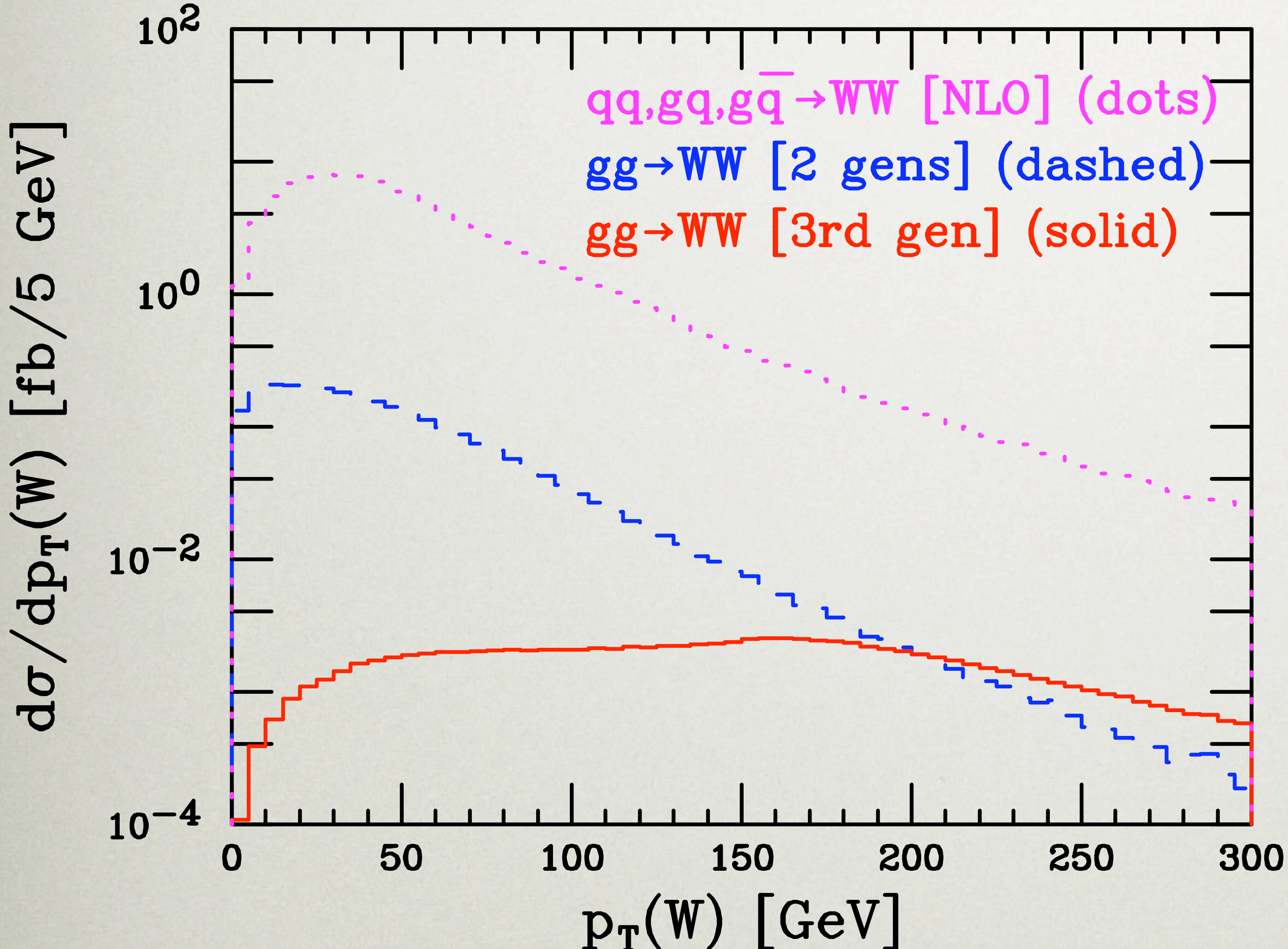
Results



- Basis integrals evaluated using QCDLoop library (Ellis, Zanderighi 08)
- Martin, Stirling, Thorne and Watt 2008 (NLO) PDF set
- Impact of third generation is sensitive to top mass, in the region around W mass changes rapidly
- Numerical instability associated with poles of the form $1/\langle 2|3+4|1]^n$, cut W such that p_T > 2. Lose 0.05 % of the cross section

$\sqrt{s}$ [TeV]	1.96 ($p\bar{p}$)	7	8	10	12	14
$\sigma_{gg}[n_{\rm gen}=2]$	0.460(0)	13.74(1)	18.19(1)	28.37(2)	40.06(3)	52.99(4)
$\sigma_{gg}[n_{\rm gen}=3]$	0.490(1)	15.16(1)	20.12(2)	31.61(3)	44.84(4)	59.59(4)
$\sigma_{gg}[n_{\rm gen}=3]/\sigma_{gg}[n_{\rm gen}=2]$	1.065	1.103	1.106	1.114	1.119	1.125
σ_{tot}^{NLO}	134.6(2)	539(1)	657(1)	904(1)	1162(1)	1429(2)
$\sigma_{gg}[n_{\rm gen}=3]/\sigma_{tot}^{NLO}$	0.0036	0.028	0.030	0.035	0.039	0.042

W Transverse Momentum



- The W transverse momentum associated with the third generation has a much harder spectrum than the massless generations and full NLO results.
- Peaks around top mass.
- Becomes dominant contribution to gg pieces at high transverse momentum.

Defining Interference Quantities

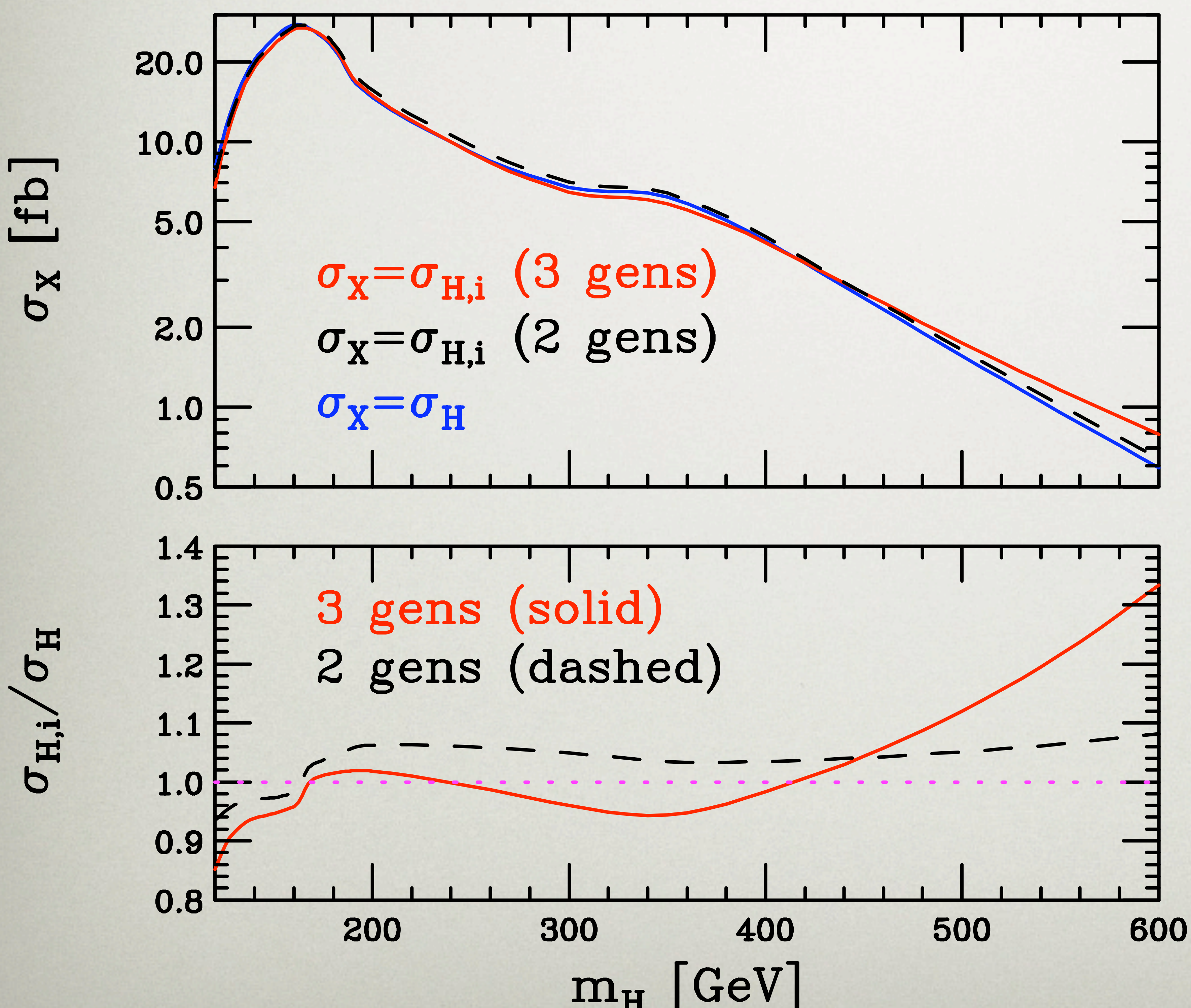
$$
\begin{aligned}
\sigma_B &\longrightarrow |\mathcal{A}_{\rm box}|^2 \ , \qquad \mathcal{A}_{\rm box} = 2\mathcal{A}_{\rm massless} + \mathcal{A}_{\rm massive} \ , \\
\sigma_H &\longrightarrow |\mathcal{A}_{\rm Higgs}|^2 \ , \\
\sigma_i &\longrightarrow 2{\rm Re}\left(\mathcal{A}_{\rm Higgs}\mathcal{A}^*_{\rm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

Typically experimental collaborations work with the first two quantities (with the Higgs cross section at NNLO)

Aim is to estimate the impact of neglecting the interference, i.e. we define the ratio of $\sigma_{H,i}$ to σ_H as the relative change in the expected signal (i.e. number of Higgs containing events) due to the interference

Higgs widths are calculated using HDECAY (Djouadi, Kalinowski, Spira 98)

Higgs Interference at the LHC



LHC at 7 TeV, no final state lepton cuts.

Clearly including only the first two generations does a miserable job of describing the full interference effects.

Interference is dynamic in Higgs mass with local maxima and minima at WW and tt thresholds.

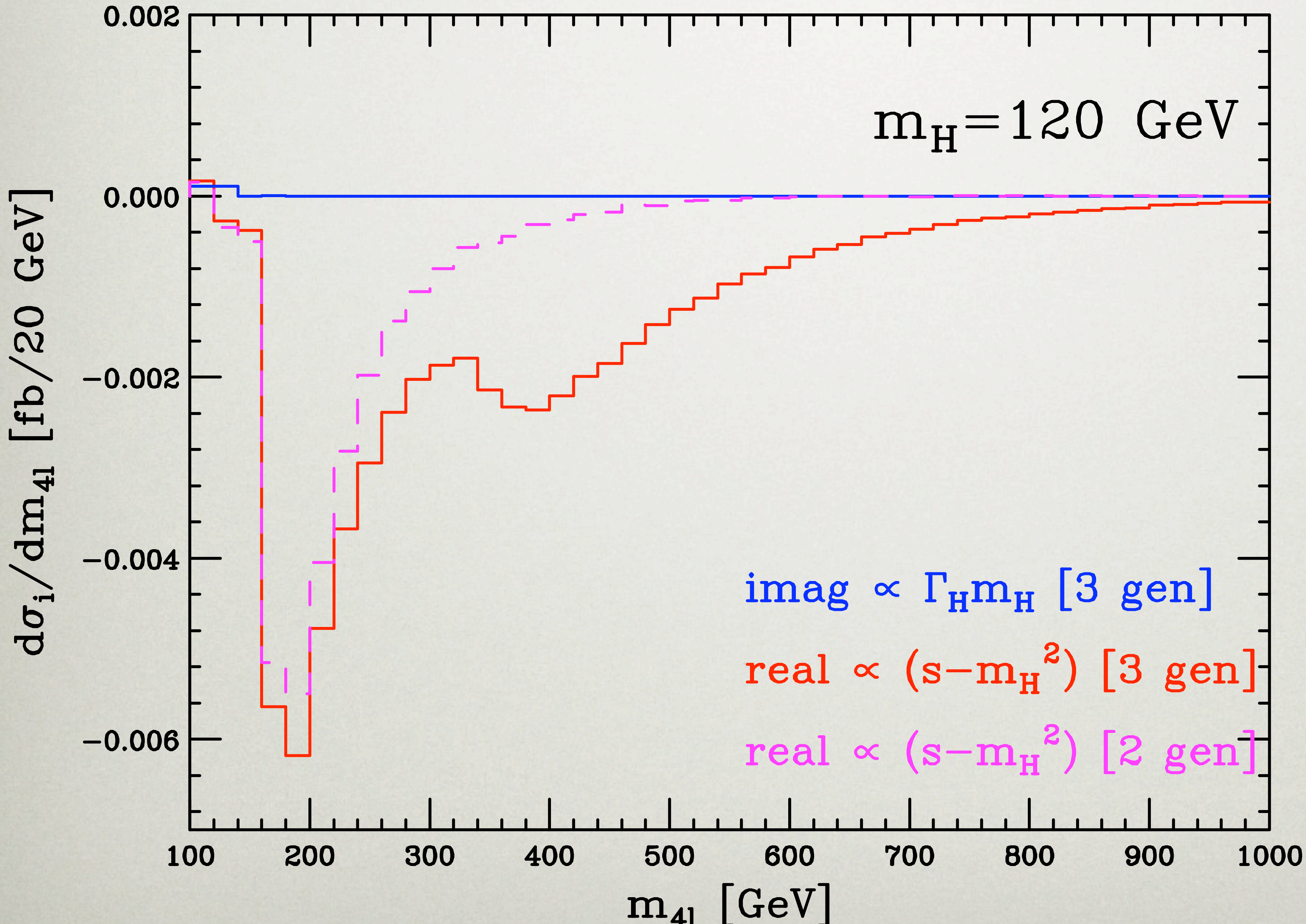
Hang on?

- Could have anticipated much smaller effects by assuming that the interference was proportional to the width i.e.

$$\delta\sigma_i = \frac{(\hat{s}-m_H^2)}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2}\,\mathfrak{Re}\left\{2\widetilde{\mathcal{A}}_{\text{Higgs}}\mathcal{A}^*_{\text{box}}\right\} + \frac{m_H\Gamma_H}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2}\,\mathfrak{Im}\left\{2\widetilde{\mathcal{A}}_{\text{Higgs}}\mathcal{A}^*_{\text{box}}\right\}$$

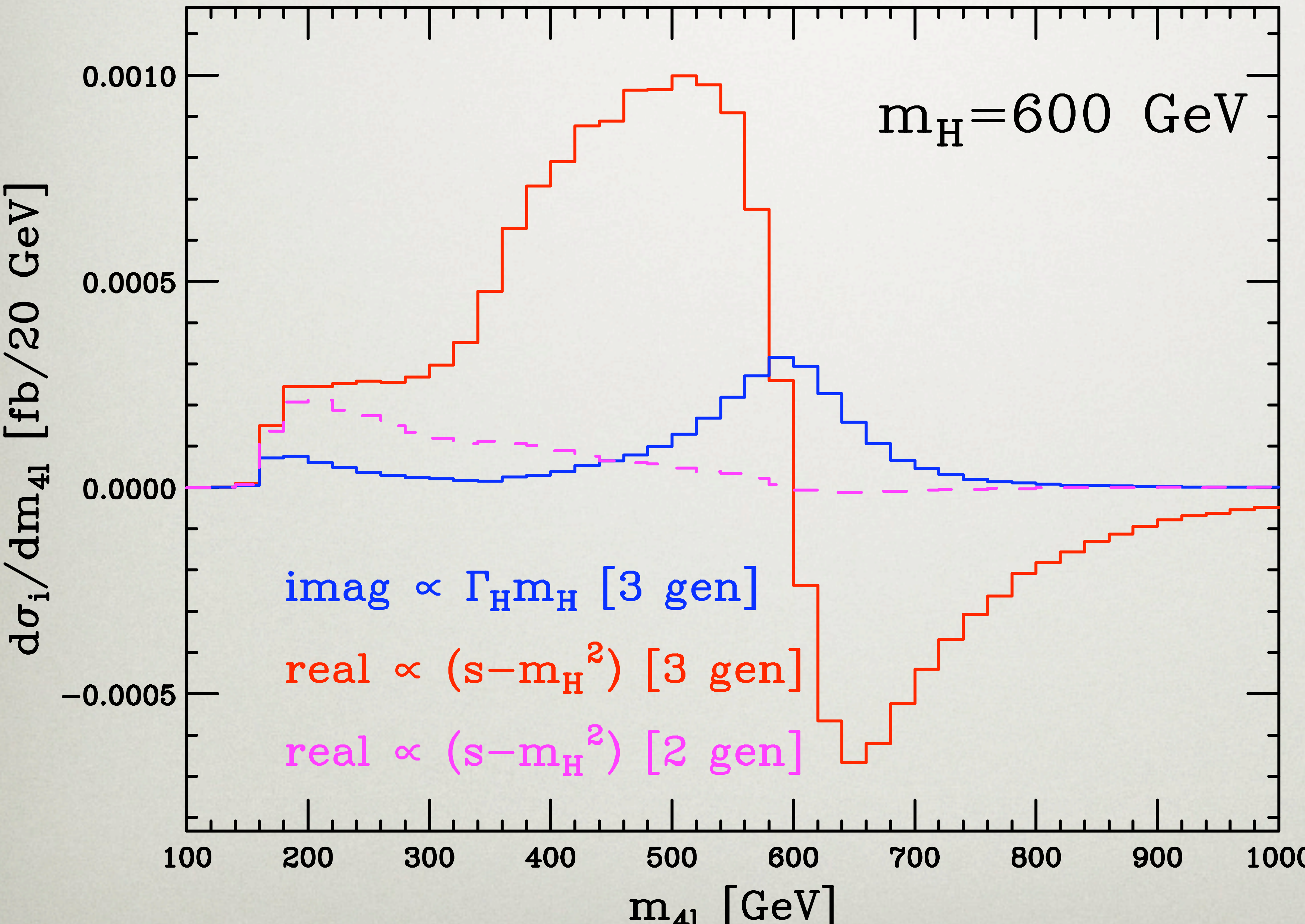
- Clearly first term in the above is odd (in s) around the Higgs mass, if we integrate in s there will be a net cancellation between regions above and below threshold
- This argument works provided that the functional form of s in the region we integrate over is fairly flat.
- This is the case for golden channel type modes e.g. Interference effects in di-photon channel (Dixon, Siu 03)

Real and Imaginary B.W.



Two pieces of the interference plotted separately. Results for 2 massless generations are shown in magenta for the real pieces

More Re and Im B.W.

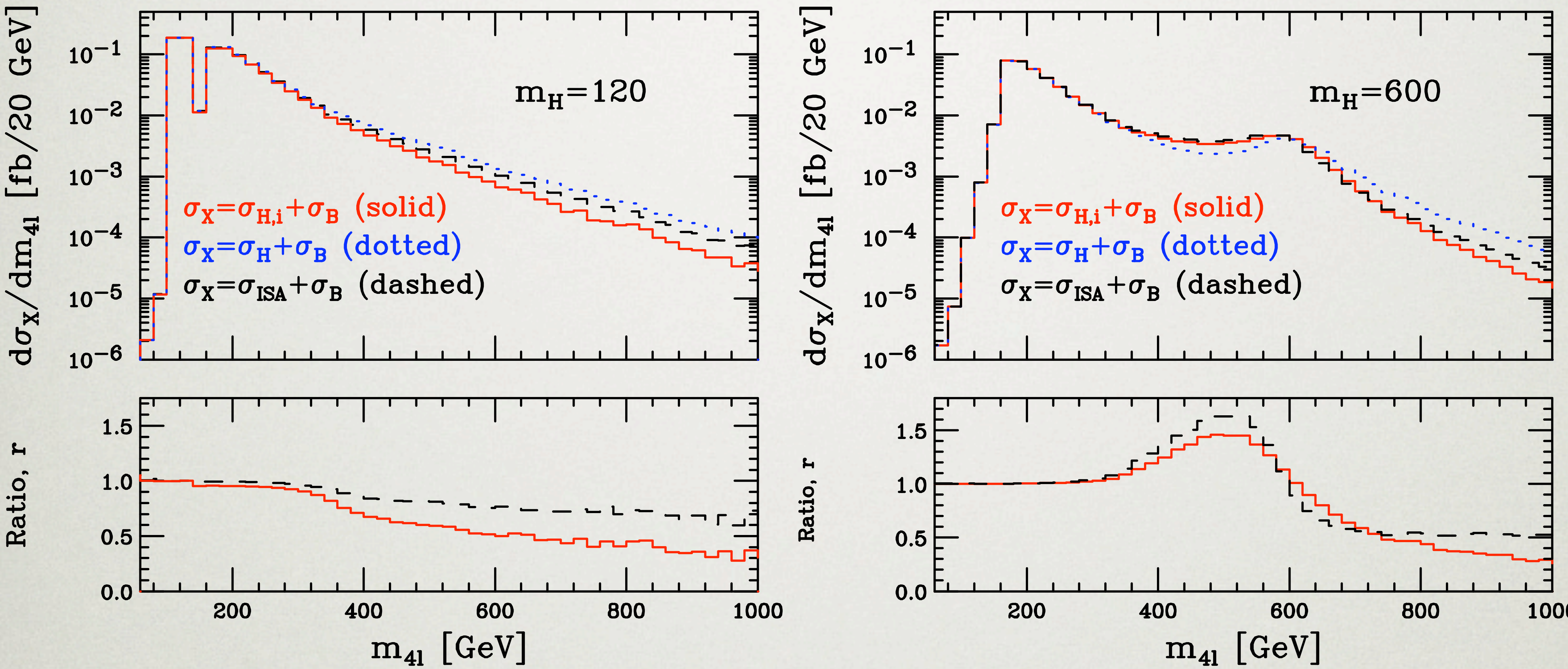


Although there is a net constructive effect the interference still has a destructive tail

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

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

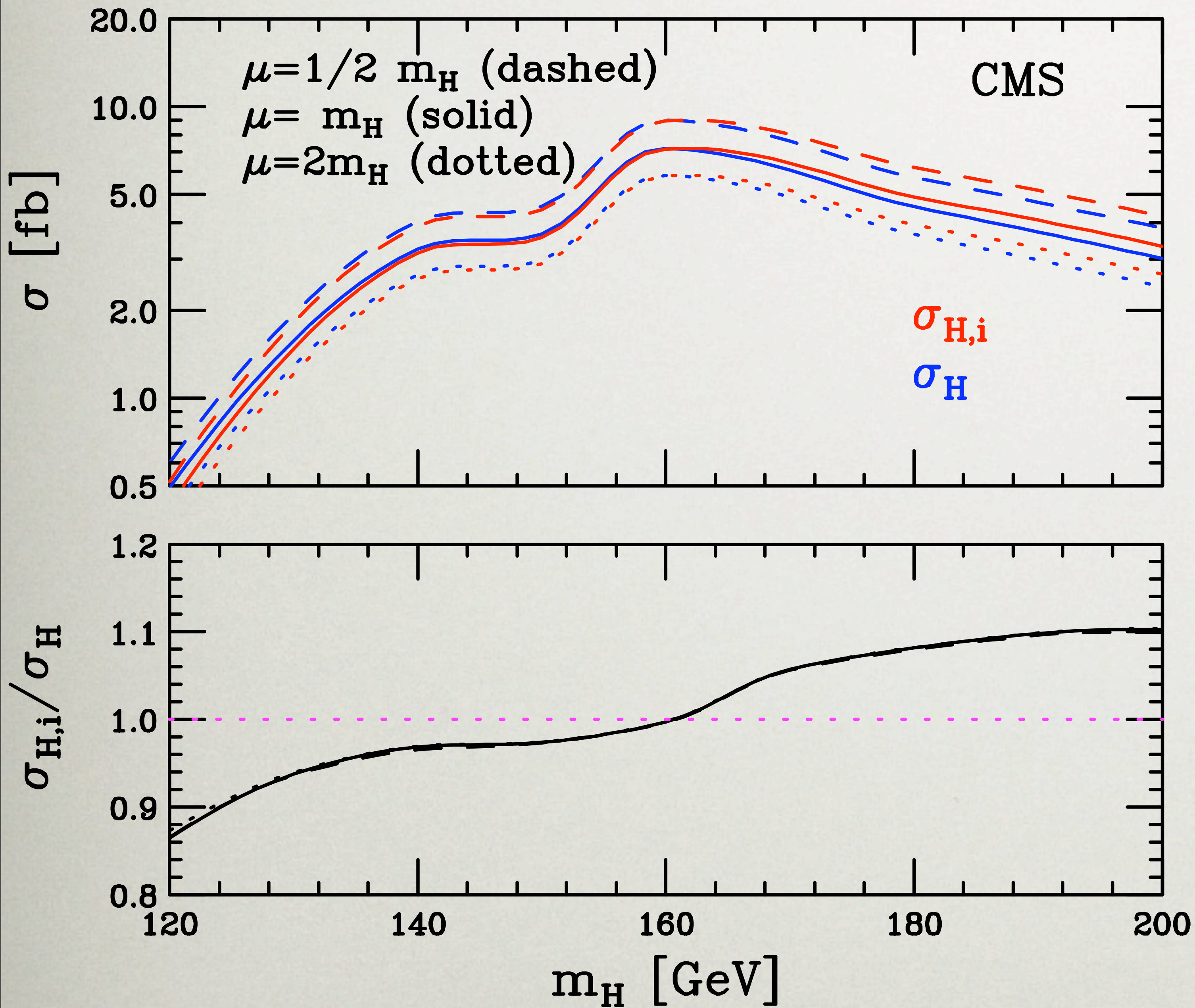
Invariant mass of the four leptons



For comparison we have also presented the results with no interference but with the improved s-channel approximation (Seymour 95)

$$\frac{i\hat{s}}{\hat{s}-m_H^2} \rightarrow \frac{im_H^2}{\hat{s}-m_H^2+i\Gamma_H(m_H)\frac{\hat{s}}{m_H}}$$

Interference @ CMS



2010 CMS Cuts

$$p_T^{\ell max} > p_T^h\ , \quad p_T^{\ell min} > p_T^s$$

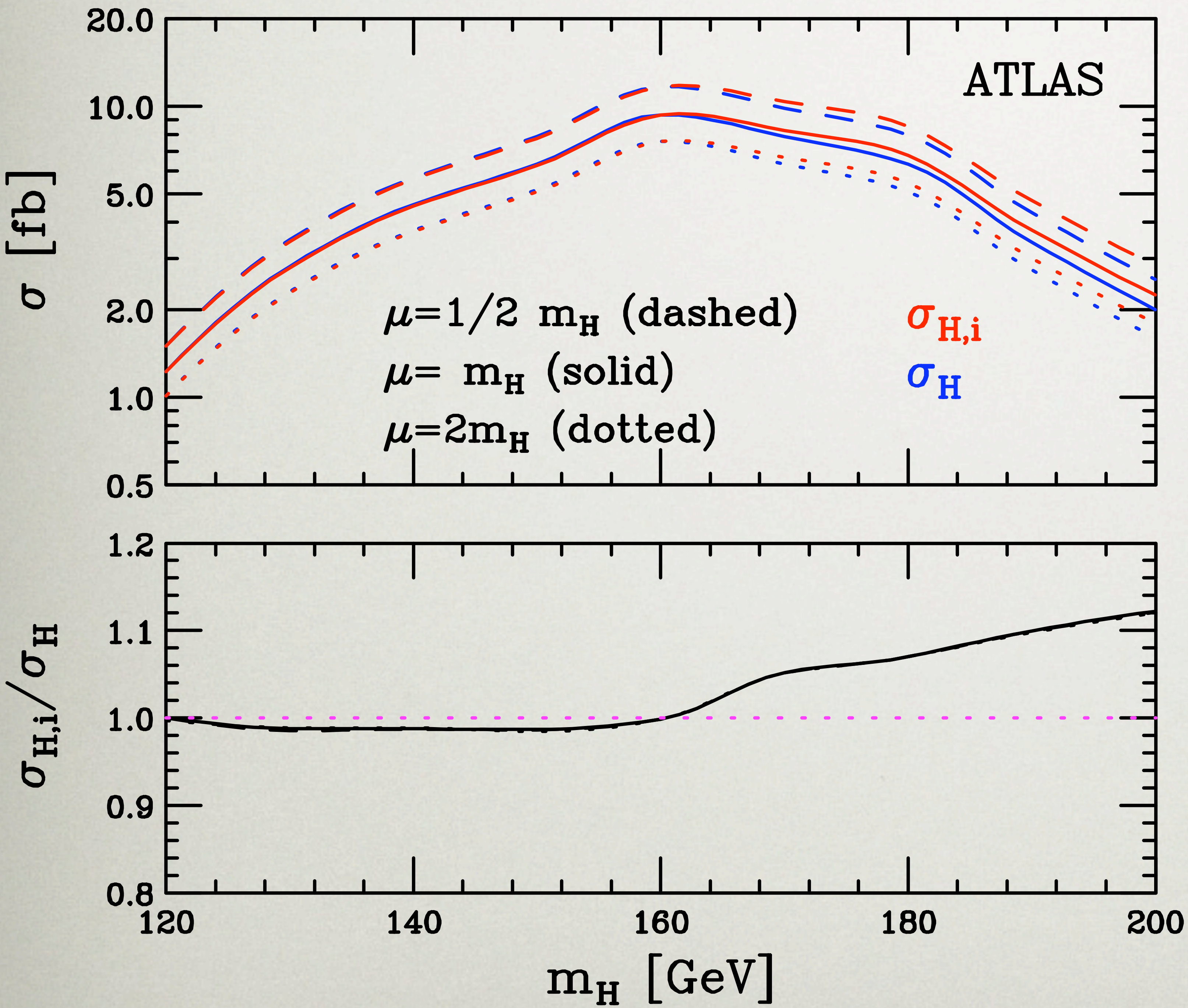
$$m_{\ell\ell} < m_{\rm cut}\ , \quad \Delta\phi_{\ell\ell} < \Delta\phi_{\rm cut}$$

m_H [GeV]	p_T^h [GeV]	p_T^s [GeV]	$m_{\rm cut}$ [GeV]	$\Delta\phi_{\rm cut}$
130	25	20	45	60°
160	30	25	50	60°
200	40	25	90	100°

$$\not{E}_t > 20\ \text{GeV}, \quad |\eta_\ell| < 2.5$$

Similar to the no-cuts results

Interference @ ATLAS



ATLAS 2010 Cuts

$$p_T^{\ell max} > 20 \text{ GeV}, \quad p_T^{\ell min} > 15 \text{ GeV}$$

$$\not{E}_t > 30 \text{ GeV}, \quad |\eta_\ell| < 2.5$$

$$m_{\ell\ell} < 50\ (60) \text{ GeV}, \quad \Delta\phi_{\ell\ell} < 1.3\ (1.8)$$

$$0.75\ m_H < M_T < m_H$$

Cuts change either side of 170 GeV (brackets >)

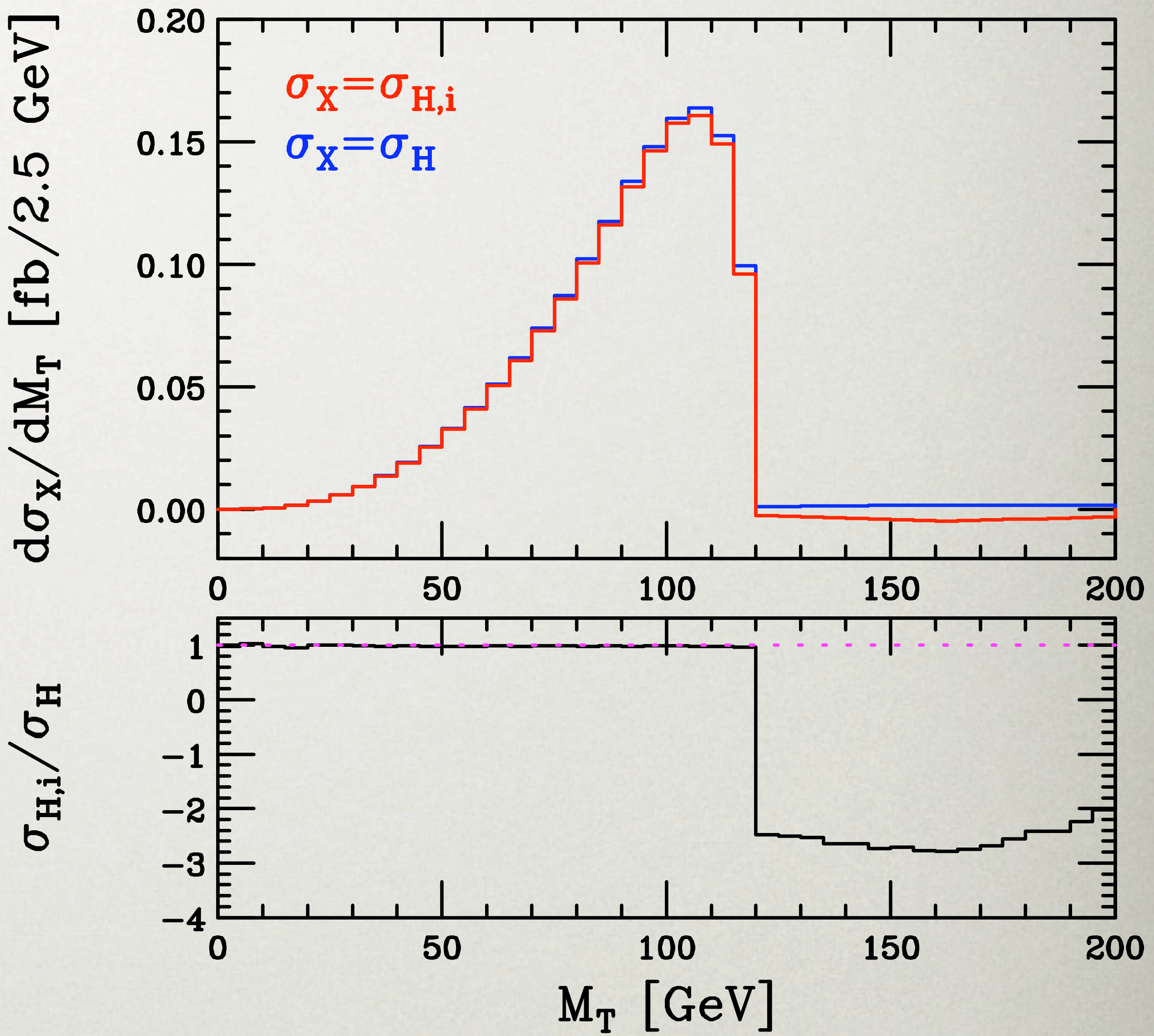
Different to CMS!

Transverse Mass cuts

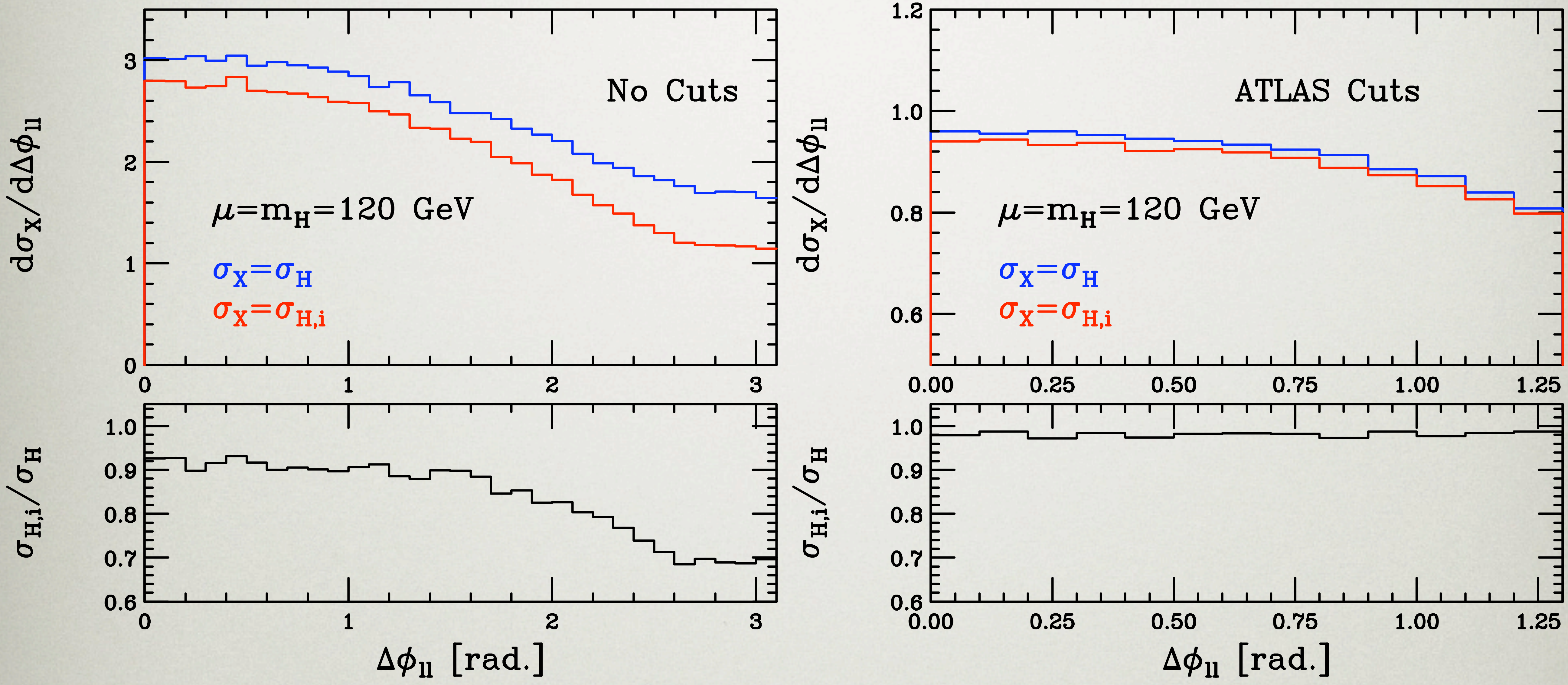
- ATLAS defines the transverse mass as,

$$M_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - (\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{\text{miss}})^2}$$

- Where $E_T^{\ell\ell} = \sqrt{(\mathbf{p}_T^{\ell\ell})^2 + m_{\ell\ell}^2}$.
- As a result the cut removes destructive region

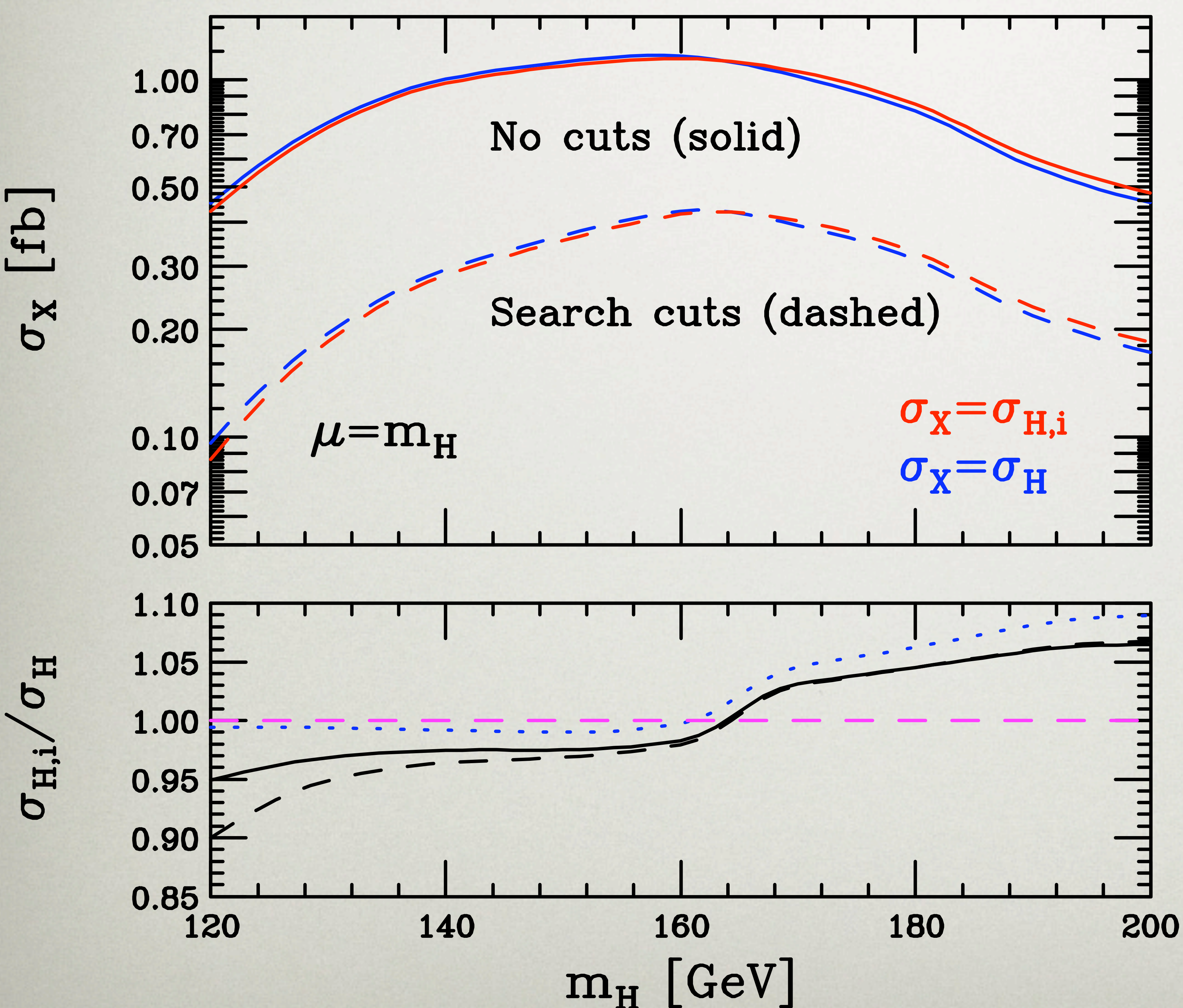


Effect on Other Distributions



Azimuthal angle between leptons is crucial discriminant, under ATLAS cuts interference effects are small

What About the Tevatron?



WW channel is also used extensively at the Tevatron, here search cuts are those used by CDF (see CDF note 9887)

$$p_T^{\ell max} > 20 \text{ GeV}, \quad |\eta^{\ell max}| < 0.8,$$
$$p_T^{\ell min} > 10 \text{ GeV}, \quad |\eta^{\ell min}| < 1.1,$$
$$m_{\ell\ell} > 16 \text{ GeV}$$
$$\not{E}_t \sin\left[\min\left(\Delta\phi, \frac{\pi}{2}\right)\right] > 25 \text{ GeV}$$

phi is angular separation between nearest lepton and MET.

Blue dotted line in lower panel indicates CDF cuts + transverse mass upper limit cut.

Consolidation with NNLO

- 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...)

Summary

- $gg \to W^+W^- \to \nu l^+ l^- \bar{\nu}$ with full top mass dependence now in MCFMv6.1 (http://mcfm.fnal.gov/ soon! - see table below for major updates.)
- Top loops calculated using analytic unitarity. Small effects on total cross section, increasing importance as function of W transverse momentum.
- Interference between box diagrams and Higgs triangles included as separate process in 6.1
- Interference is larger than one may have guessed, is extremely sensitive to cuts on s, which manifests as a sensitivity to transverse mass cuts.

Process	Notes
$gg \to WW(m_t)$	New process in 6.1
$pp \to \gamma j$	Fragmentation included, flexible isolation
$pp \to VH$	New Higgs decays included WW,ZZ,$\gamma\gamma$
$pp \to H + jets$	New Higgs decays included $\gamma\gamma$