Higgs => WW Interference Effects in MCFM.

see 1107.5569

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Outline

- Calculation of gg->WW (t,b) loops
- Interference at the LHC
- Approximating propagators.
- Summary

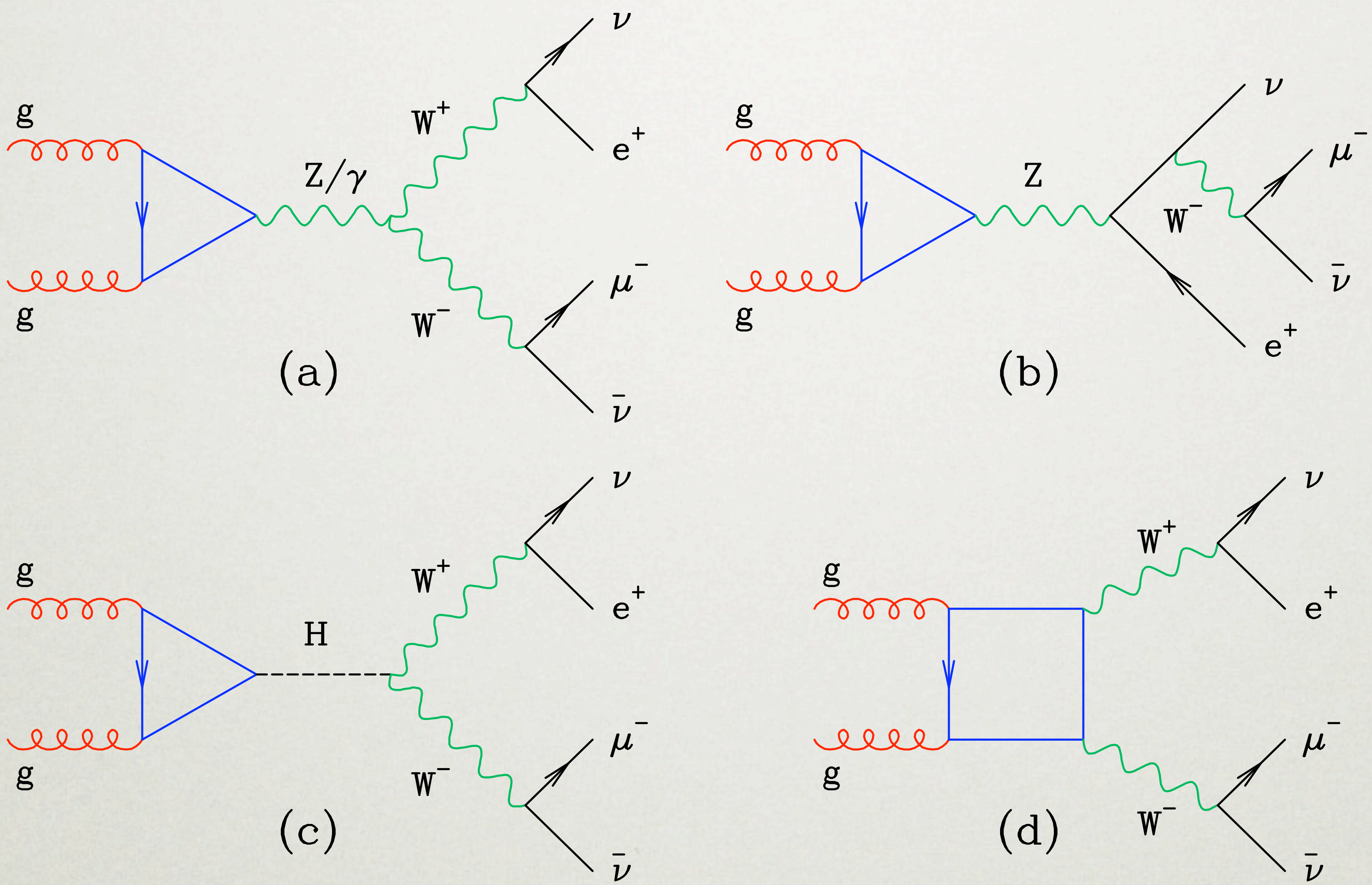
Higgs boson Processes in MCFM

- MCFM is a parton level MC code.
- Contains many EW + jets processes at NLO including :
- gg=>Higgs => (ZZ,WW, 2 gamma, bb) + 0,1,2 jets (NLO)
- VBF, Associated Higgs production (NLO)
- Diboson pp=> VV (including gg initiated loops WW full result, ZZ 5 massless flavours.

Whats Not in MCFM?

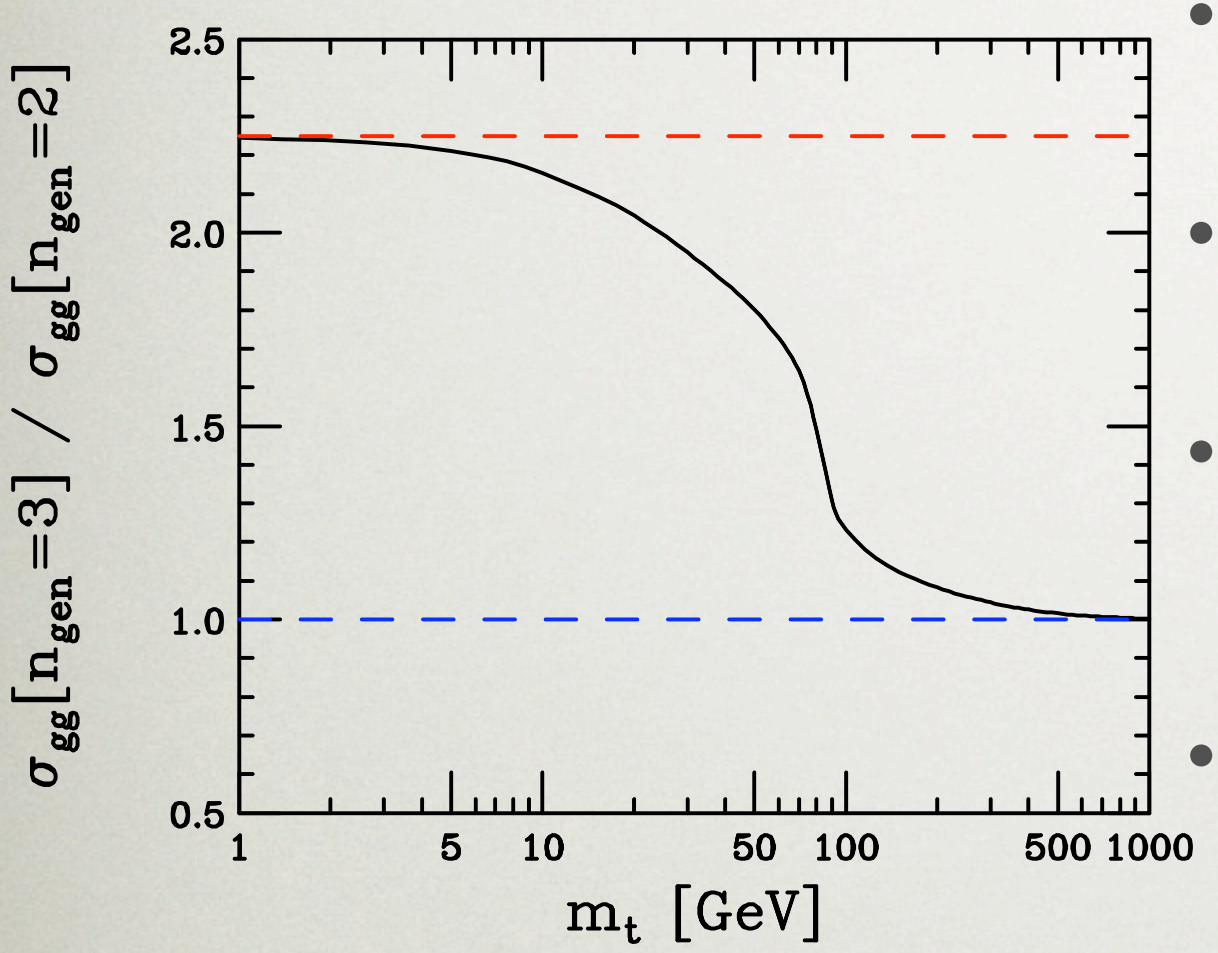
- Of course MCFM doesn't do everything!
- Compared to some dedicated Higgs codes we are an order in perturbation theory behind (i.e. no NNLO or resummation in Higgs production). Note no NLO interference calculation yet.
- No gg=>ZZ * gg=> H=>ZZ interference, for reasons I will discuss in this talk. We don't have the top loop so including the interference may be unreliable...

GG Initiated WW Loops



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

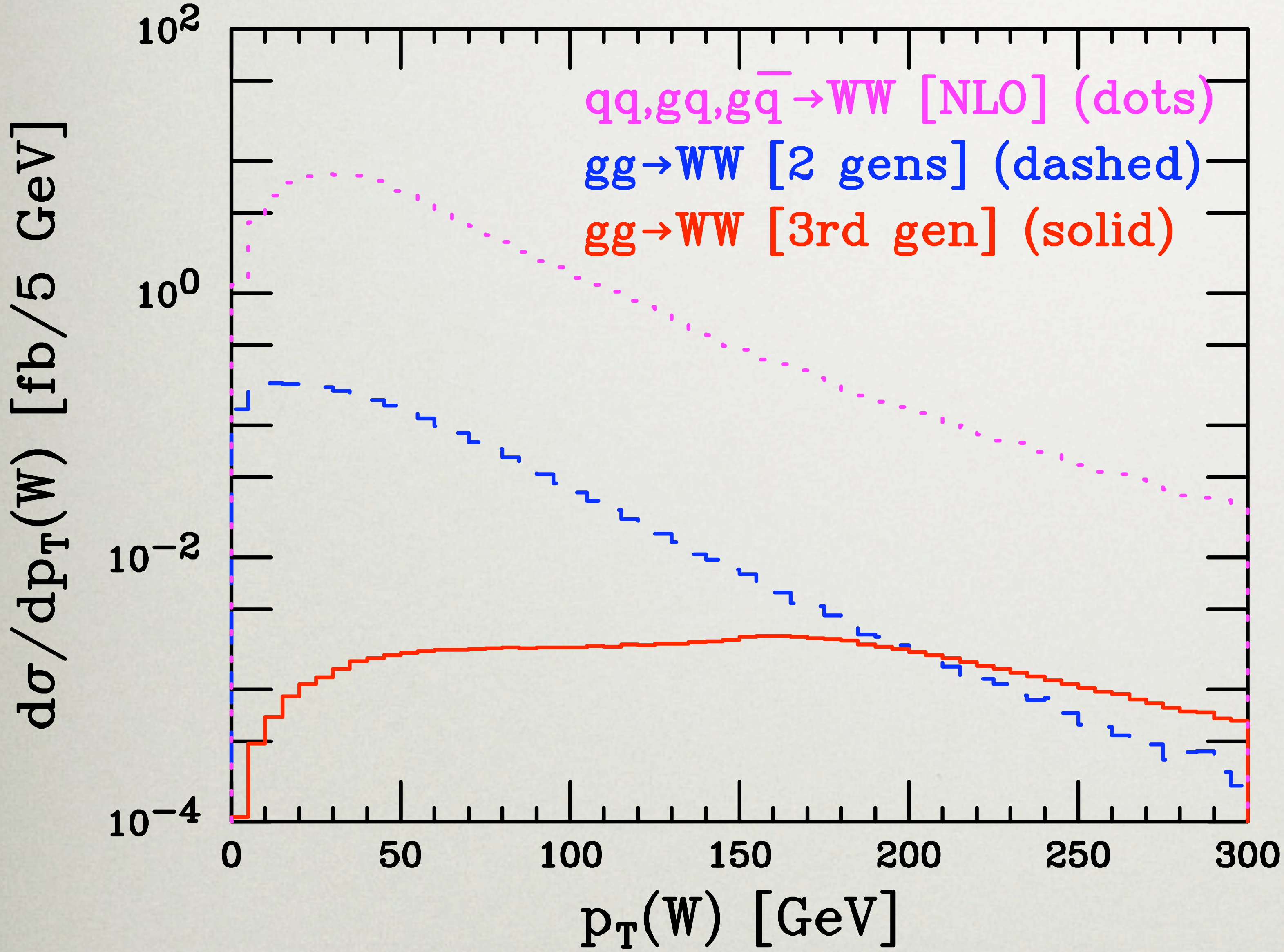
Results



- 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

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

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

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

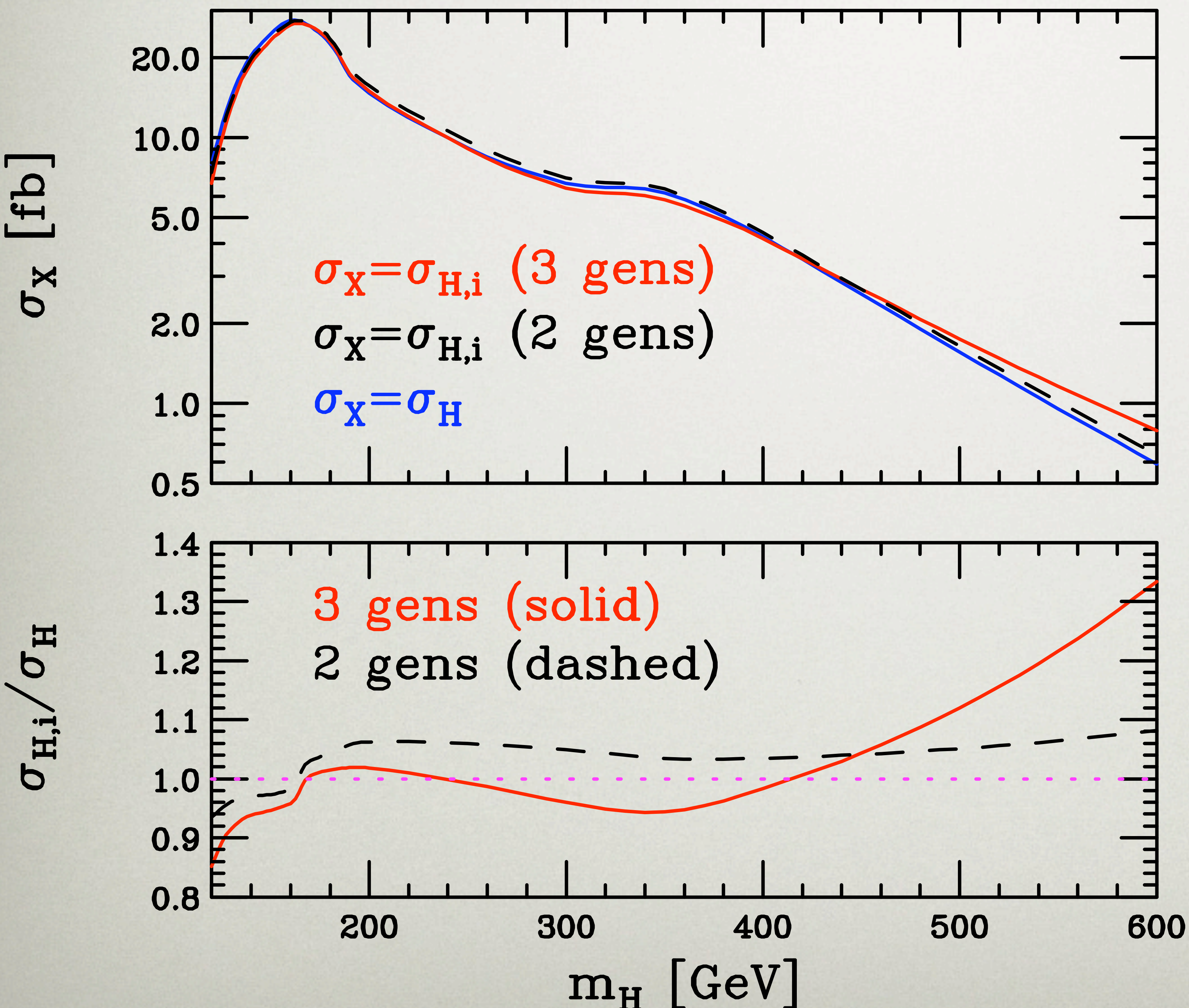
$$\sigma_{H,i} \;=\; \sigma_H + \sigma_i \;.$$

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

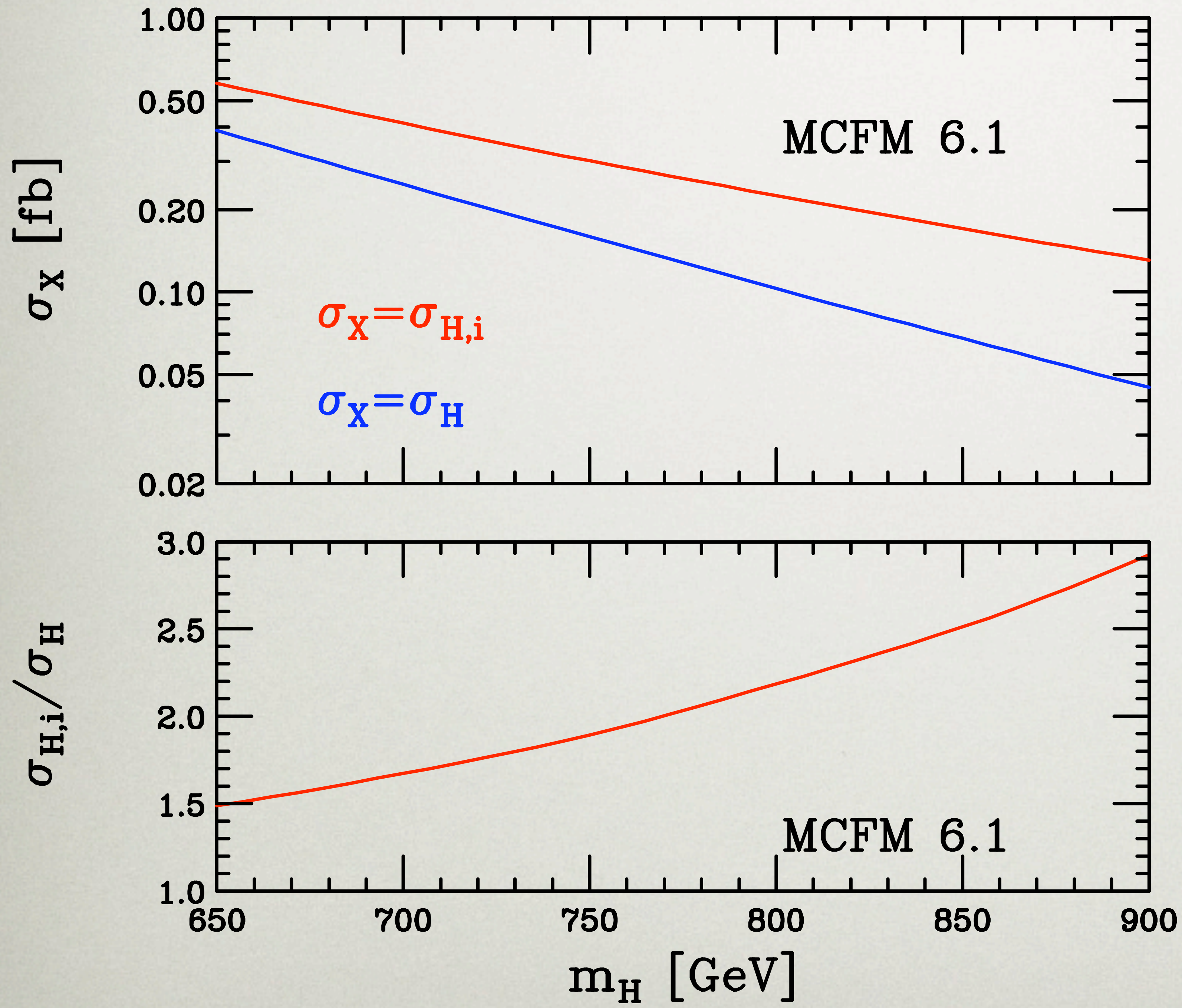


LHC at 7 TeV, no final state lepton cuts.

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

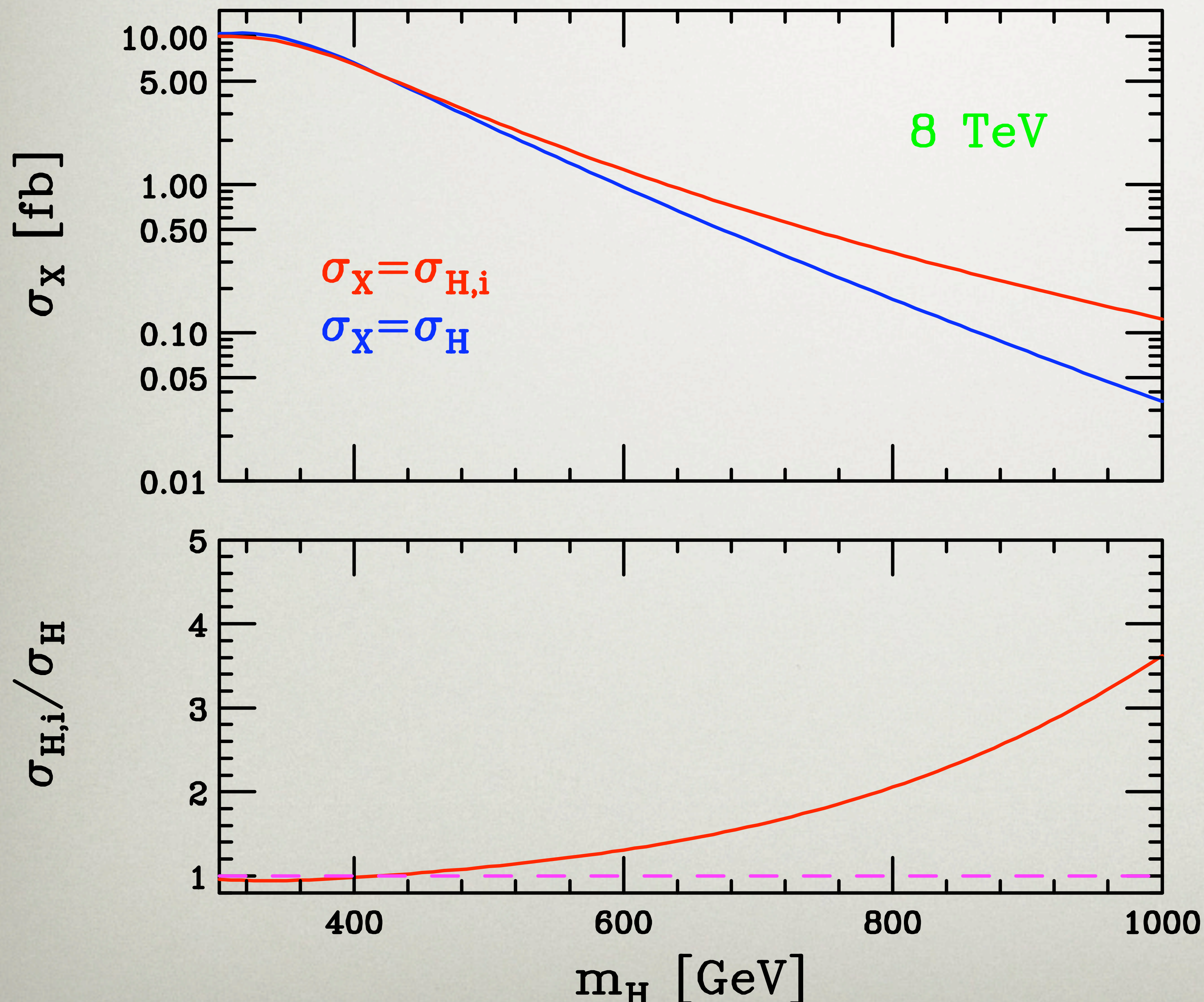
Interference is dynamic in Higgs mass with local maxima and minima at WW and tt thresholds.

The (very) Heavy Higgs Realm.



- For a very heavy Higgs the interference term dominates in the "signal" part of the cross section.
- Note the effect on the total cross section is always constructive.

Heavy Higgs at 8 TeV



- Unsurprisingly very similar to 7 TeV!
- Large (net) constructive interference for total cross section at heavy Higgs masses.

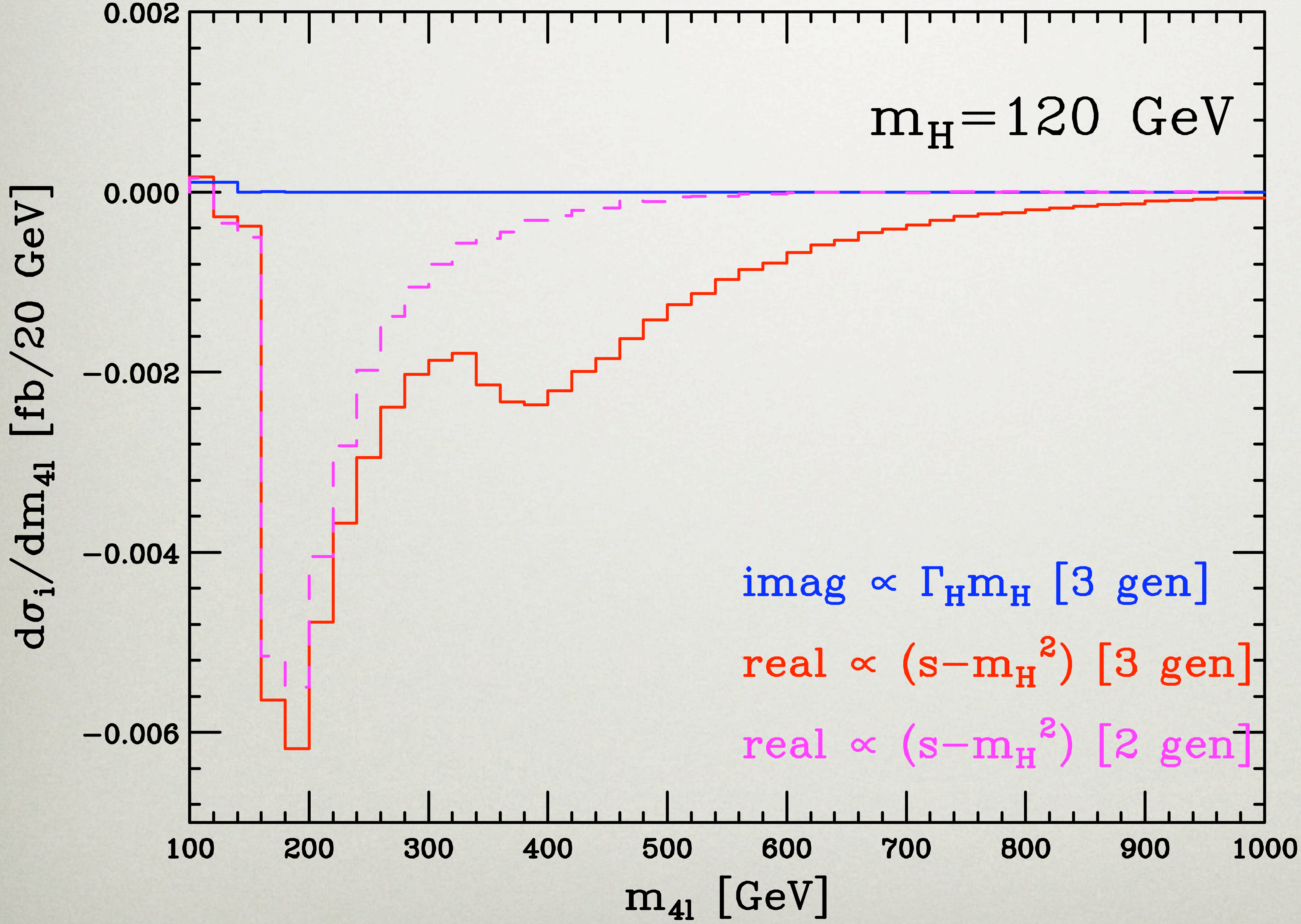
Interference Physics

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

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

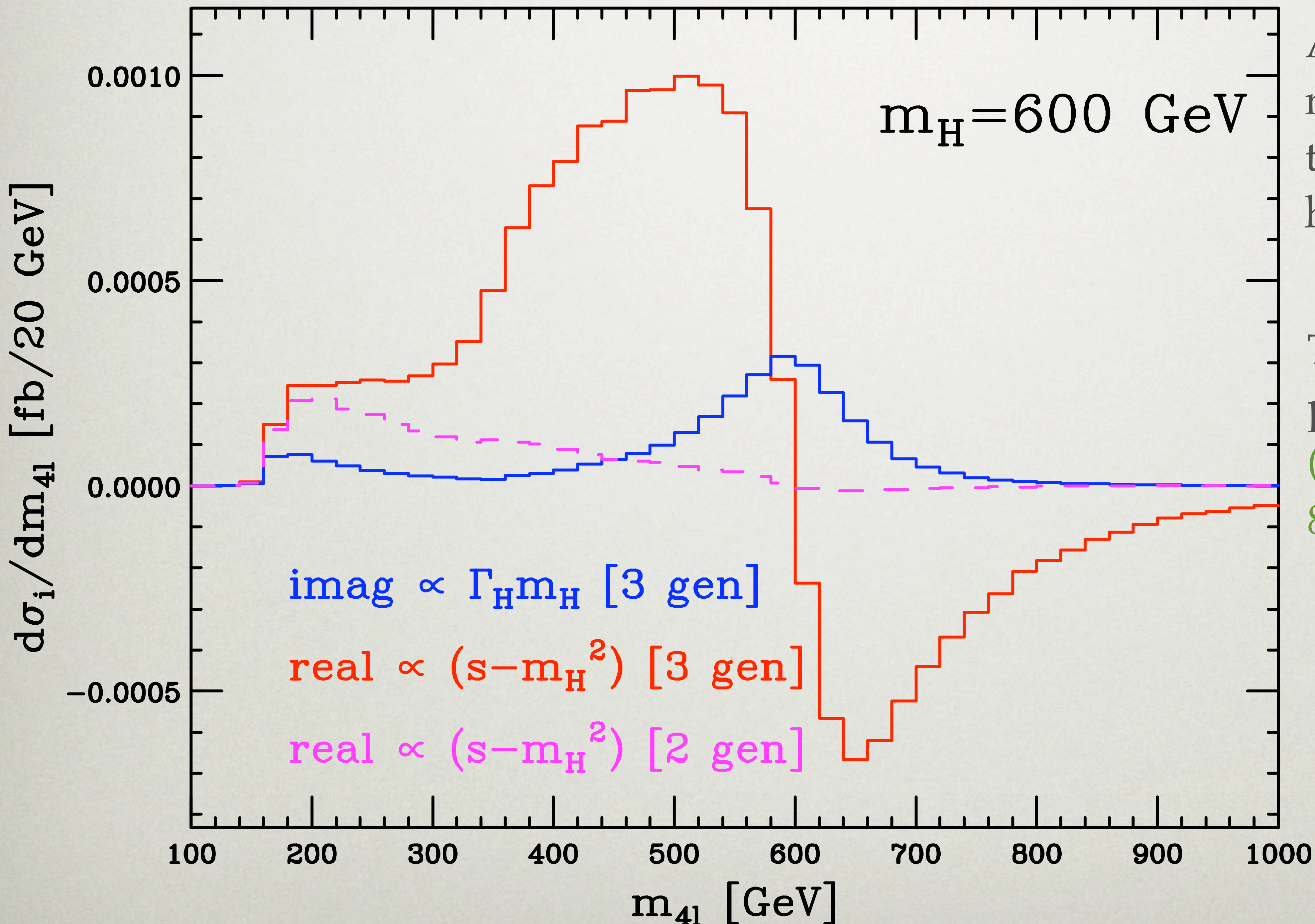
- Clearly first term in the above is odd (in s) around the Higgs mass, if we integrate in s there will be a net cancellation between regions above and below threshold
- This argument works provided that the functional form of s in the region we integrate over is fairly flat.
- This is the case for golden 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.

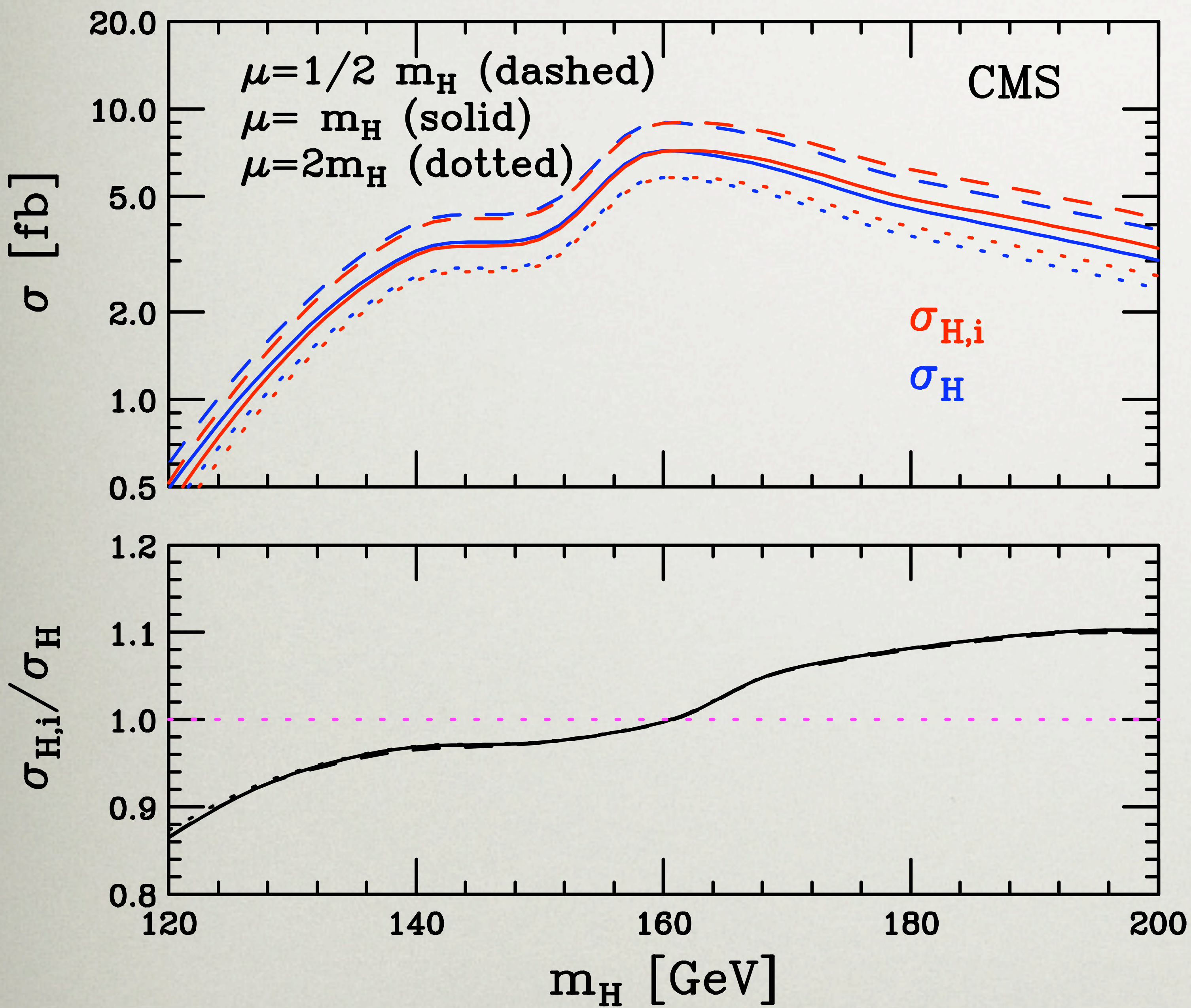


Although there is a net constructive effect the interference still has a destructive tail

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

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

Interference @ CMS



2010 CMS Cuts

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

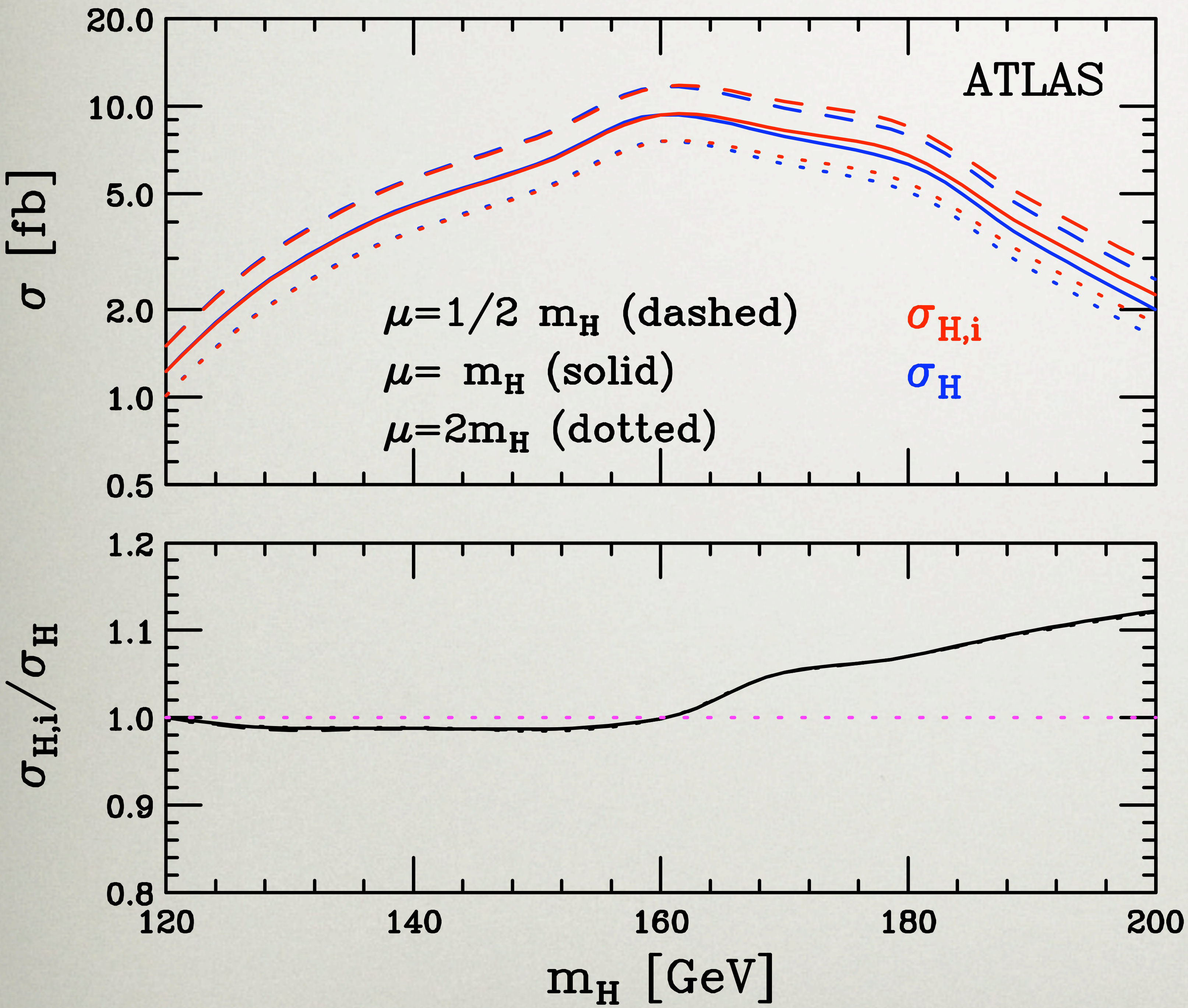
$$m_{\ell\ell} < m_{\rm cut} \ , \quad \Delta\phi_{\ell\ell} < \Delta\phi_{\rm cut}$$

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 >)

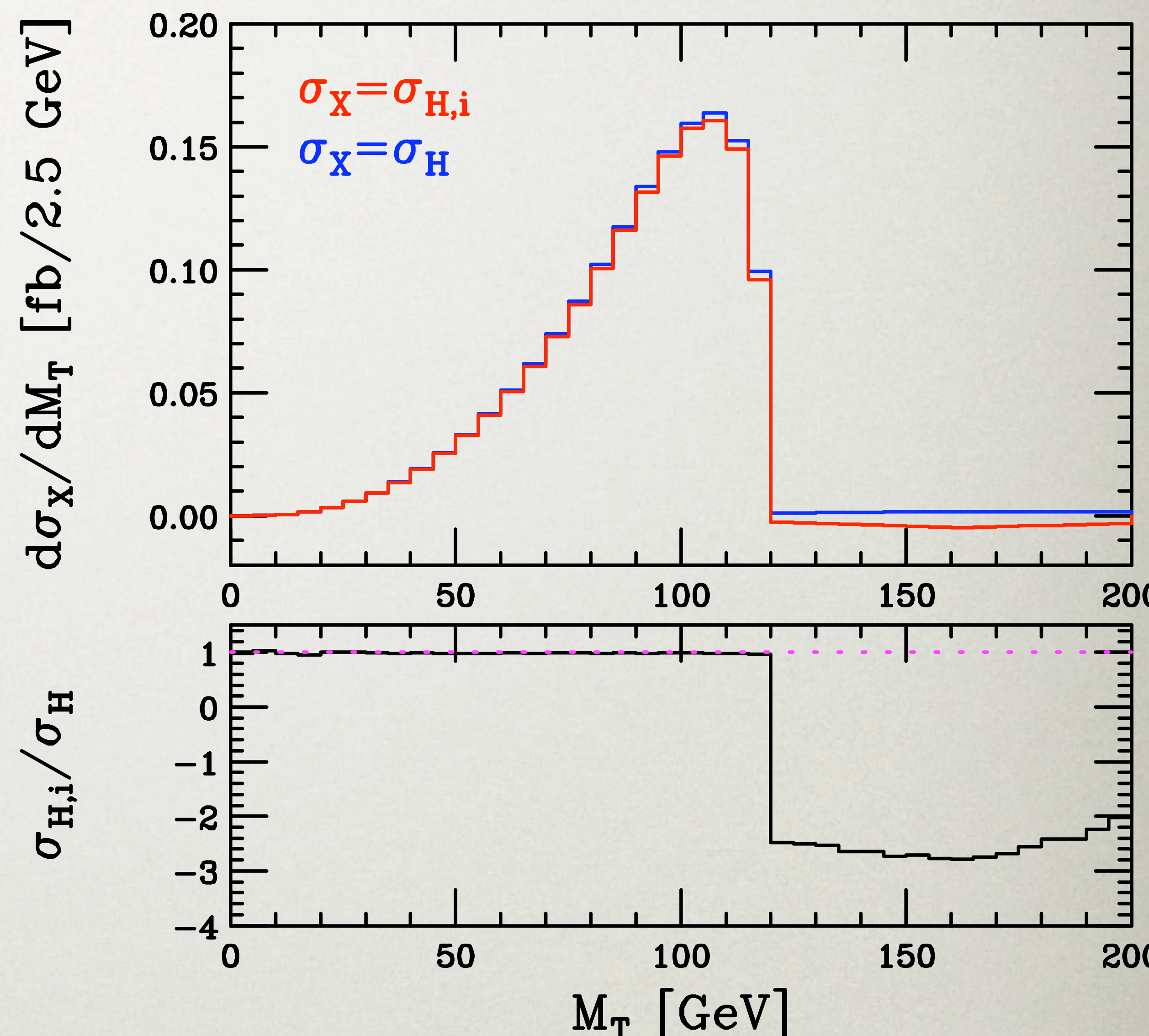
Different to CMS!

Transverse Mass cuts

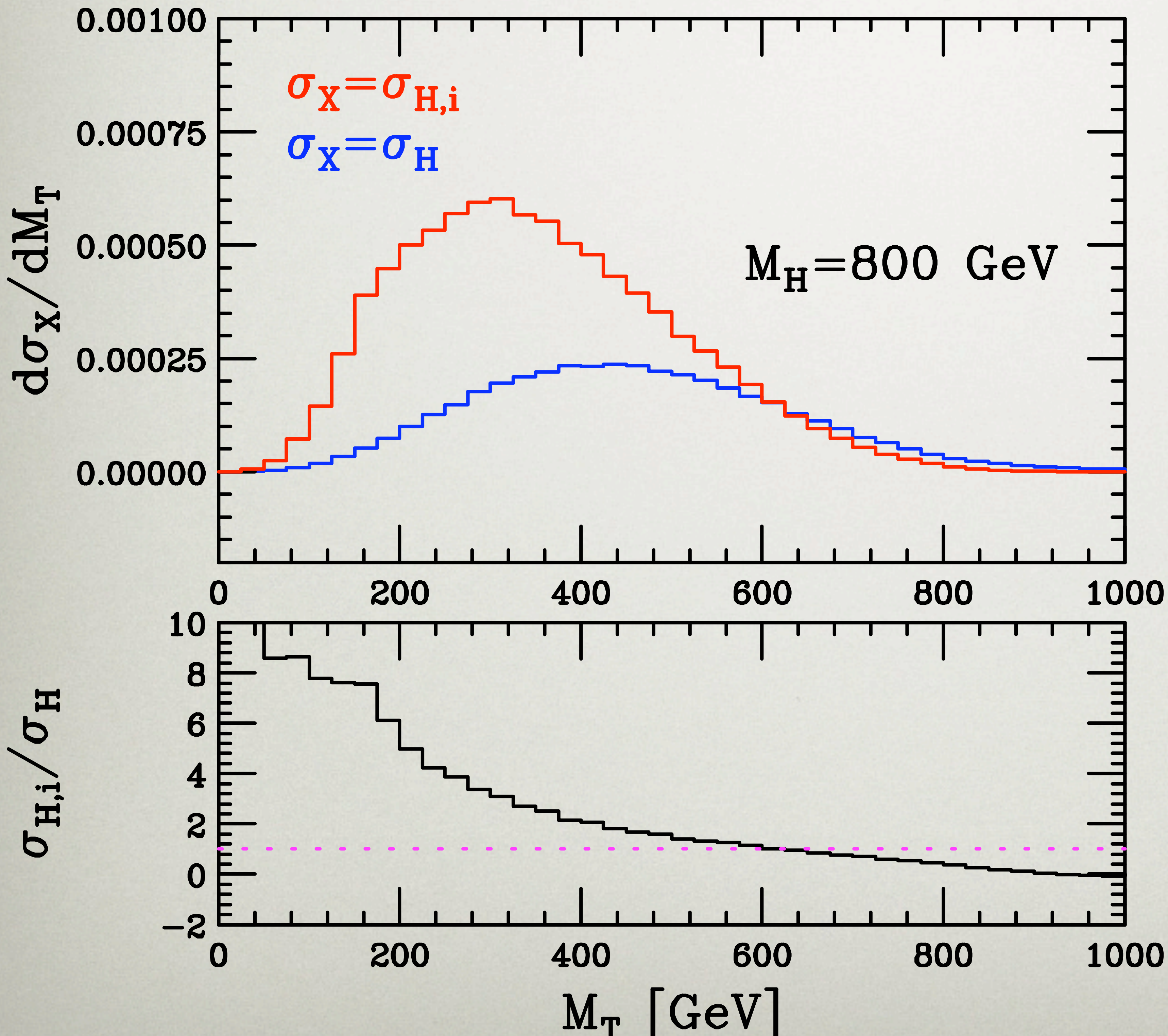
- ATLAS defines the transverse mass as,

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

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

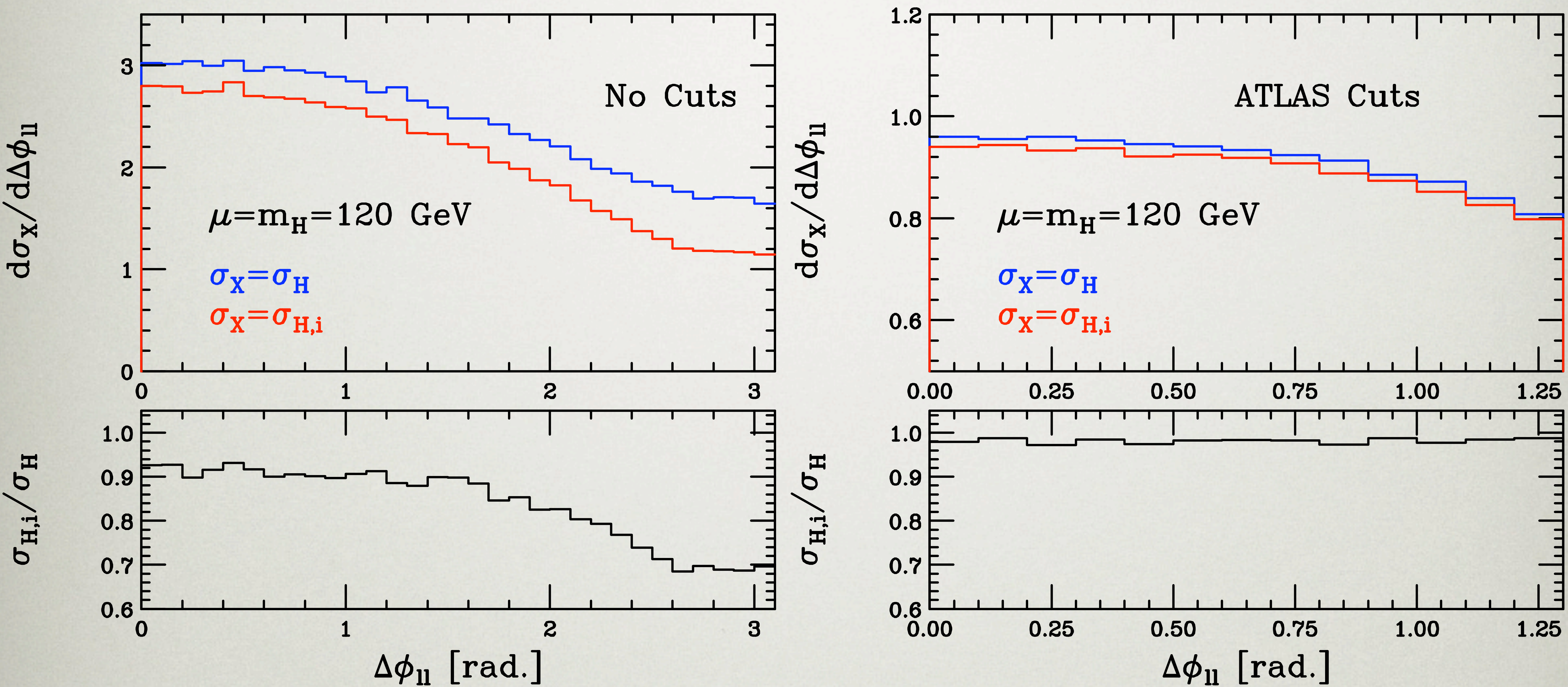


Transverse mass for Heavy Higgs



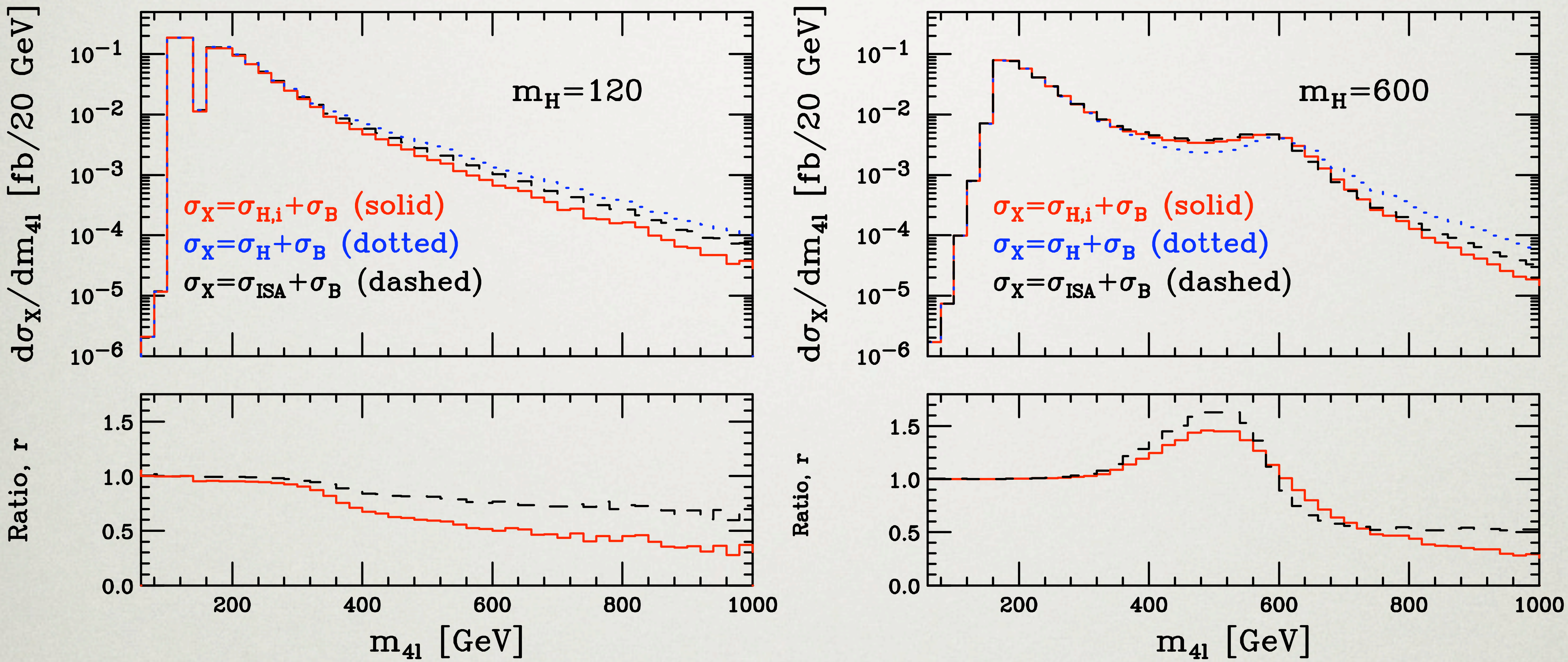
- Again tail is destructive (mandatory)
- Lower region shows considerable enhancement, (dwarfs NLO and NNLO K-factor in < 200 GeV).

Effect on Other Distributions



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

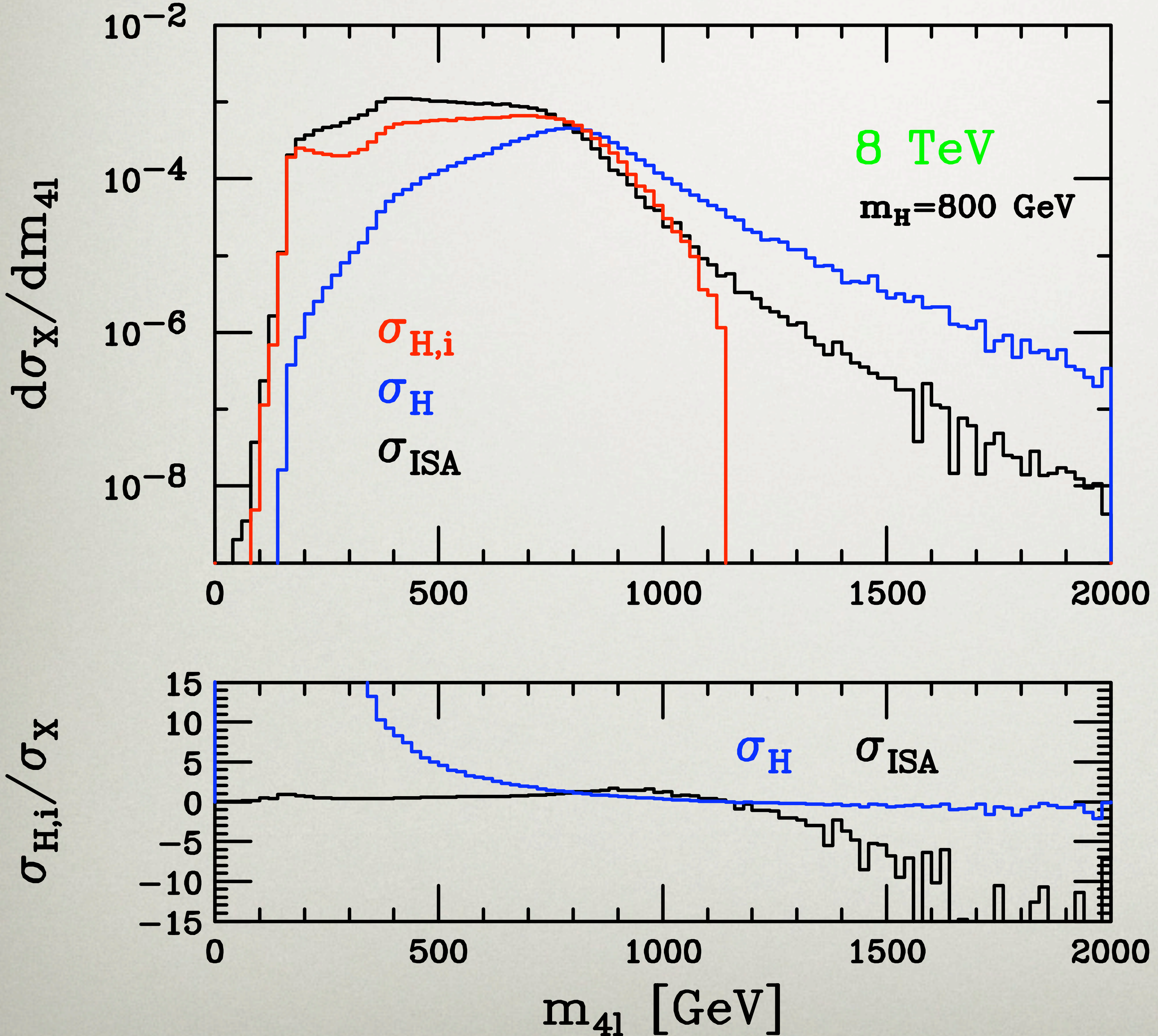
Modifying The Higgs propagator.



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

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

ISA FOR HEAVY HIGGS @ 8 TEV



- ISA does a better job than using the normal propagator. Gets the extreme tail wrong.
- Also misses features associated with the top kinematics in the background.

Changing The Higgs Prop in MCFM

```
Emacs@ciaran-williamss-macbook-2.local

      double precision p(mxpart,4),msq(fn:nf,fn:nf),msqgg,fac
      double precision mfsq,tau,tauinv,rt,p1(4),p2(4),p3(4),p4(4),pttwo
      double complex Ahiggs(2,2),Agen3(2,2),fachiggs,amphiggs,f,e3De4
      double complex num_c

      do j=-nf,nf
      do k=-nf,nf
      msq(j,k)=0d0
      enddo
      enddo

      call spinoru(6,p,za,zb)

c--- fill amplitudes with contributions of Higgs: top loop
      mfsq=mt**2
      tau=s(1,2)/(4d0*mfsq)
      tauinv=1d0/tau
!------ default prop
      fachiggs=cone/dcmplx(s(1,2)-hmass**2,hmass*hwidth)

!======== SEYMOUR ISA APPROX
!------- numerator correction
      num_c=dcmplx(hmass**2/s(1,2))
      fachiggs=num_c/dcmplx(s(1,2)-hmass**2,s(1,2)*hwidth/hmass)


      if (tau .le. 1d0) then
         f=dcmplx(dasin(sqrt(tau))**2)
      elseif (tau .gt. 1d0) then
         rt=sqrt(1d0-tauinv)
         f=-0.25d0*(dcmplx(log((1d0+rt)/(1d0-rt)))-im*pi)**2
      else
         f=czip
      endif
      e3De4=2d0*za(3,5)*zb(6,4)/(s(3,4)*s(5,6))
      amphiggs=mfsq*(cone+(cone-dcmplx(tauinv))*f)*im*e3De4
      Ahiggs(1,1)=fachiggs*amphiggs*za(1,2)/zb(2,1)
      Ahiggs(1,2)=czip
--:**  qqb_hww_tb.f    18% L40    (Fortran)------------------------------------------
```

- Get a clean copy of MCFM. (http://mcfm.fnal.gov)
- For interference studies modify the file src/HWW/qqb_hww_tb.f
- Introduce your numerator correction.
- After default declaration of propagator introduce your new version.
- make, and run process 121.
- To compare to original undo your changes and run process 122 (incs interference.

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...)

Conclusions

- I discussed the implementation of Higgs interference in MCFM.
- Interference dominates production for a heavy Higgs and modifies the lineshape dramatically.
- Probably one of the best uses of MCFM going forward is to use its speed and public nature to test modified propagators. These could then be used in NNLO /PS codes to make predictions most useful for experimentalists.