Search for heavy Higgs bosons decaying to top quarks: status and prospects.

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Terascale Workshop

November 28, 2017

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An extended Higgs Sector

The Standard Model (SM) is incomplete

- Dynamic behind the Quark Mass Hierarchy?
- CP Violation
- Dark Matter (DM) candidates and etc.

Two-Higgs-Doublet Models (2HDMs)

- An minimal SM Extension
  just an extra complex scalar doublet Φ_2 in $\mathrm{SU}(2)_\mathrm{L}$
- Motivated by **MSSM** and **axion** models
- Our Benchmark model: **Type-II 2HDM**

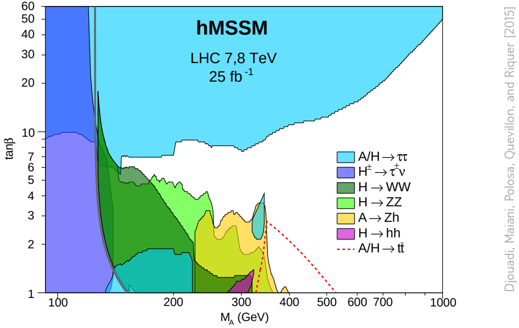
An extended Higgs Sector

Parameters	Higgs Bosons
m_h, m_H	CP-even: h, H
m_A	CP-odd: A
$m_{H^\pm}$	Charged: $H^\pm$
$\tan\beta$: $\langle\Phi_2\rangle/\langle\Phi_1\rangle$	
α: mixing angle between h and H	

Physical constraints
Softly broken $\Phi_1 \leftrightarrow \Phi_2$ $\mathbb{Z}_2$ symmetry
Alignment limit: $\sin(\beta - \alpha) = 1$
$m_h = 125\text{GeV}$

$t\bar{t}$: Last Piece of the Puzzle

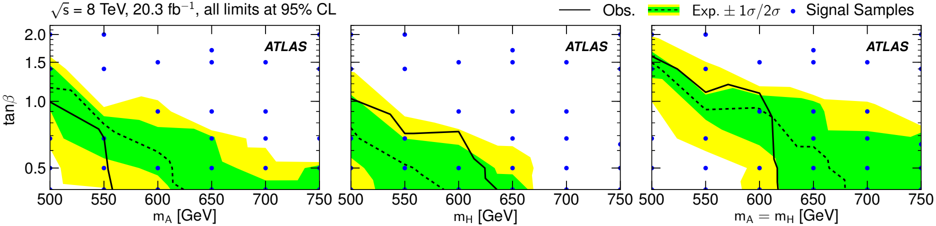
Cover the ($m_{A/H}$, $\tan\beta$) plane in a Type-II 2HDM-like model (e.g hMSSM)



- Yukawa couplings is proportional to fermion masses
- The lower $\tan\beta$ the higher coupling to up-type quarks
- Extraordinary sensitivity in $t\bar{t}$ channels for $m_{A/H} > 2m_t$ and $\tan\beta < 10$!
- Not least then why last?
  - Very challenging due to the interference effects

$t\bar{t}$: Last Piece of the Puzzle

Phys. Rev. Lett. 119 (2017) 191803 [arXiv:1707.06025 [hep-ex]]



$\sqrt{s} = 8$ TeV, 20.3 fb^{-1}

$e^{\pm}/\mu^{\pm}$+jets, N(jets) $\geq$ 4, N(b-jets) $\geq$ 1

Three different mass hierarchies

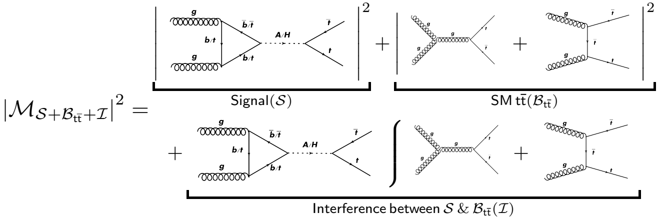
1. $m_A \ll m_H$ 2. $m_A \gg m_H$ 3. $m_A = m_H$

Benchmark: $\mu = 1$ limits for Generic Type-II 2HDM in the alignment limit

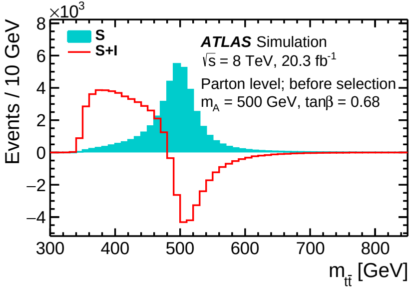
- No significant excesses or deficits
- Sensitivity & reliability enhanced by considering interference effects

Interference: the challenge and the opportunity

ggF A/H->$t\bar{t}$ strongly interferes with SM $t\bar{t}$

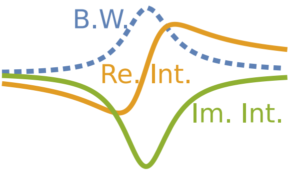


Signal-plus-interference $m_{t\bar{t}}$ distribution



Phys. Rev. Lett. 119 (2017) 191803

A dip-peak structure



M. Carena and Z. Liu [2016]

Interference: the challenge and the opportunity

1. Signal
   - MadGraph5_aMCatNLO
   - Leading order in QCD
   - QCD scale corrections: $k_{\mathcal{S}} = \sigma_{\mathcal{S}}^{\mathrm{SusHi}} / \sigma_{\mathcal{S}}^{\mathrm{MG5}}$

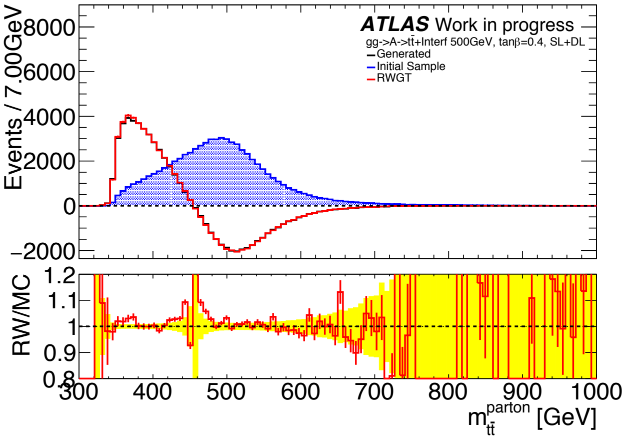
2. QCD Background
   - Powheg+Pythia6
   - > Currently most reliable $m_{t\bar{t}}$ shape

3. Signal-plus-interference
   Need to efficiently produce huge amount of samples
   - Event-by-event Reweighting at LO
     just need a few signal samples as inputs
   - Matrix Element Level Bkg. Removal
   - Event Matching using PDF info.
     in order to propagate the weight to higher level simulation

$$\mathcal{W}_{\mathcal{S}+\mathcal{I}} = \frac{|\mathcal{M}_{\mathcal{S}+\mathcal{I}+\mathcal{B}}|^2 - |\mathcal{M}_{\mathcal{B}}|^2}{|\mathcal{M}_{\mathcal{S}}|^2} \times \mathcal{W}_{\mathcal{S}}$$

   - QCD scale corrections: $k_{\mathcal{I}} = \sqrt{k_{\mathcal{S}} k_{\mathcal{B}}}$, $k_{\mathcal{B}} = \sigma_{t\bar{t}}^{\mathrm{NNLO+NNLL}} / \sigma_{t\bar{t}}^{\mathrm{MG5,LO}}$

Interference: the challenge and the opportunity



- Good agreement between generated & reweighted distribution
- Same approach can adapt to other models: 2HDM+a for example

A case study: 2HDM+a Dark Matter reinterpretation

Parameters	Particles
m_h, m_H	CP-even scalar: h, H
m_a, m_A	CP-odd scalar: a, A
$m_{H^\pm}$	Charged scalar: $H^\pm$
m_χ	Dark Matter: χ
$\tan\beta$: $\langle\Phi_2\rangle/\langle\Phi_1\rangle$	
α: mixing angle between h and H	
θ: mixing angle between a and A	

Physical constraints

Softly broken $\Phi_1 \leftrightarrow \Phi_2$ $\mathbb{Z}_2$ symmetry

Alignment limit: $\sin(\beta - \alpha) = 1$

$m_h = 125$ GeV

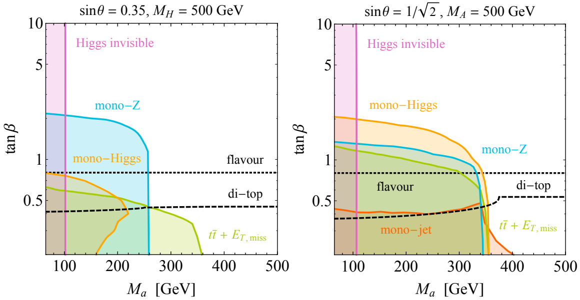
$\langle\sigma v\rangle = 1$ pb

7 "fixed" + 4 "impactful" + 3 "non-impactful" parameters

A case study: 2HDM+a Dark Matter reinterpretation

- One of DM Benchmark Model for LHC Run-2 Searches
- Rich LHC phenomenology
  Mono-V, Mono-h, Mono-jet, $t\bar{t}/b\bar{b} + E_T^{\text{miss}}$ and etc.
- $t\bar{t}$ resonance channel helps to constraint the model
  Here the di-top limit is computed by simply recasting our limit:

$$\mu_{\mathcal{S}+\mathcal{I}}^{\text{2HDM}+a} = \frac{\sigma_{\mathcal{S}}^{\text{2HDM}+a}}{\sigma_{\mathcal{S}}^{\text{2HDM}}} \mu_{\mathcal{S}+\mathcal{I}}^{\text{2HDM}}$$



M. Bauer, U. Haisch and F. Kahlhoefer [2017]

Some concerns as to 2HDM+a

How robust can this limit rescaling be?

- Would kinematic distributions change a lot?
- Is it neccessary to rerun anything?

Some Possible Sources causing scale & shape difference

1. Width Effects:

   Extra A/H decay channels: e.g. $\Gamma(H \to aZ)$ & $\Gamma(A \to ah)$ & $\Gamma(A \to \chi\bar{\chi})$

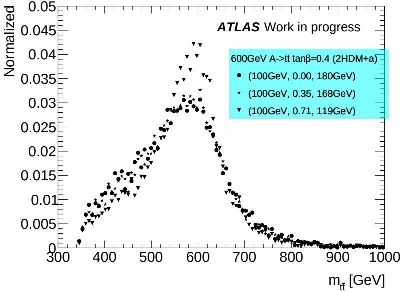
2. Interference Effects:

   Extra interference terms: $\mathcal{M}^*(gg \to A \to t\bar{t})\mathcal{M}(gg \to a \to t\bar{t}) + h.c.$

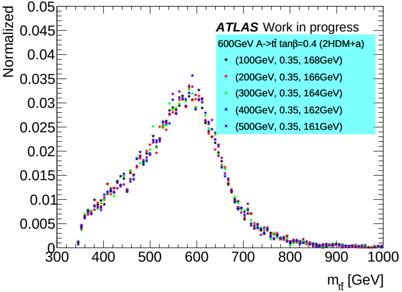
Width Effects

$A \to t\bar{t}$ In the legend: $(m_a, \sin(\theta), \Gamma(A/H \to X))$

Varies $\sin\theta$



Varies m_a



$\Gamma(A \to t\bar{t}) \propto \cos^2\theta$

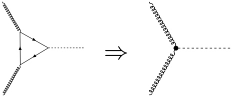
	$\Gamma(A \to X)$	$\Gamma(A \to t\bar{t})$	$\sigma(A \to t\bar{t})$
$\sin\theta \nearrow$	$\searrow$	$\searrow$	$\searrow$
$m_a \nearrow$	$\leadsto$	$\to$	$\leadsto$

- $\sim 1/2$ normalized height difference at pole mass for both A/H when varying $\sin\theta$ and m_a

MC Production for $t\bar{t}$+Interf in 2HDM+a

1. Current model can't simulate interf.: FormFactors Approach

   The only issue



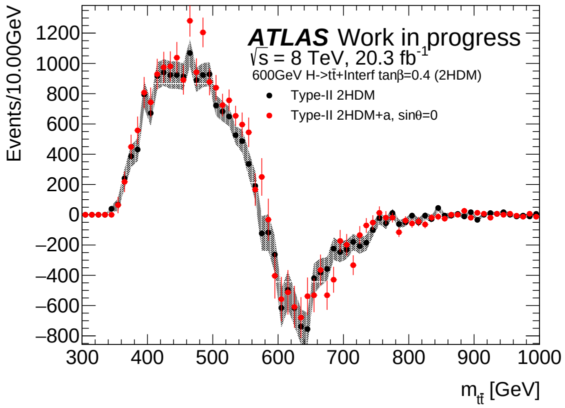
2. Reweighting from existing $\mathcal{S}^{\mathrm{2HDM}}$ samples
3. Standard analysis and limit-setting procedure

Caveats

- off-shell region are expected to be a little problematic
  Since their phase space is broader than the input samples due to the total width increase

Validation of FormFactors Approach

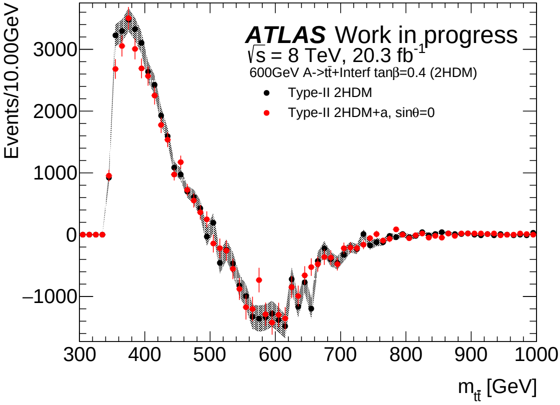
600 GeV $H\ m^{\mathcal{S}+\mathcal{I}}_{H\to t\bar{t}}$



- FormFactors Approach also works fine for 2HDM+a
- 2HDM+a fully agrees with 2HDM at decoupling limit of a: $\sin\theta = 0$ as expected

Validation of FormFactors Approach

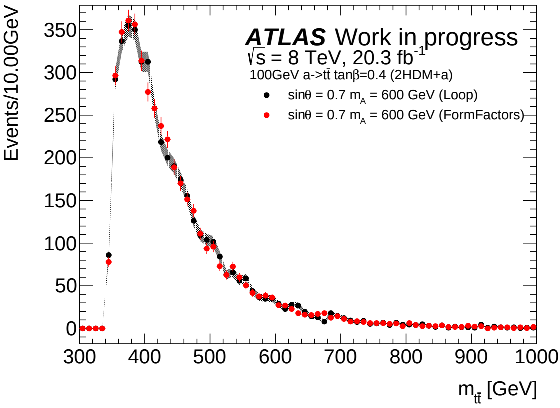
600 GeV $A\ m^{\mathcal{S}+\mathcal{I}}_{A\to t\bar{t}}$



- FormFactors Approach also works fine for 2HDM+a
- 2HDM+a fully agrees with 2HDM at decoupling limit of a: $\sin\theta = 0$ as expected

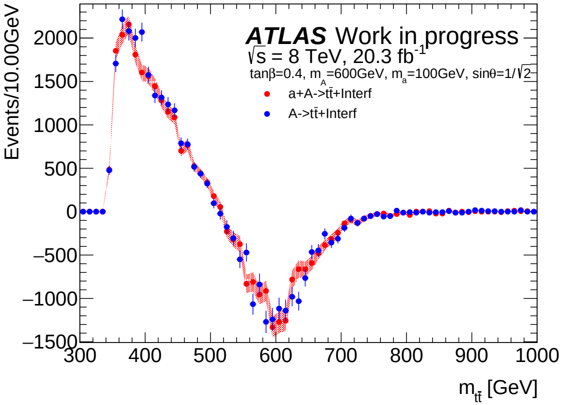
Validation of FormFactors Approach

100 GeV a $m^{\mathcal{S}}_{a\to t\bar{t}}$



- Due to the lack of understanding of how $m^{\mathcal{S}+\mathcal{I}}_{a\to t\bar{t}}$ would look, only $m^{\mathcal{S}}_{a\to t\bar{t}}$ shape is validated against the original model.
- Good Agreement as expected

Signal-plus-interference $m_{t\bar{t}}$ distribution in the 2HDM+a



σ_A^S	6.56×10^{-1} pb
$\sigma_A^{\mathcal{I}}$	-3.24×10^{-1} pb
σ_a^S	3.12×10^{-3} pb
$\sigma_a^{\mathcal{I}}$	-6.77×10^{-4} pb
$\sigma_{a\leftrightarrow A}^{\mathcal{I}}$	-1.25×10^{-4} pb
$\sigma_{a+A}^{\text{total}}$	3.16×10^{-1} pb

- Very little contribution from $a \to t\bar{t}$
- Still in contact with the phenomenologists to ensure that the shape is correct

Conclusions

- This FormFactors+Reweighting Approach is employed for signal MC production in 8 TeV search for A/H->$t\bar{t}$ in a type-II 2HDM.
- The same techniques developed for 2HDM can be easily transferred to 2HDM+a.
- Future look:
  1. New version of the 2HDM+a UFO which allows everyone to run interference samples is planned.
     > Already in touch with the authors of the 2HDM+a UFO
  2. Run-2 studies are in progress
  3. NLO signal shape

Outline

> Backup

Event Selection

Resolved semi-leptonic top pair: ℓ+jets

- N($\ell^{\pm}$)=1, τ-veto
  $p_T > 25$ GeV, $|\eta| < 2.5$
  Tight, mini-isolated
- $E_T^{\text{miss}} > 20$ GeV
- $m_T(W) + E_T^{\text{miss}} > 60$ GeV
- N(jets) ≥ 4
  anti-k_t R=0.4 jets
  $\text{p}_\text{T} > 25$ GeV, $|\eta| < 2.5$
- N(b-jets) ≥ 1
  MV1@70%

- Analytical Neutrino Reconstruction
  smaller $|p_z|$ working point
- Kinematic χ^2 $t\bar{t}$ Reconstruction
  $\log_{10}\chi^2 \leq 0.9$

$$\chi^2 = \left|\frac{m_{jj} - m_W}{\sigma_W}\right|^2 + \left|\frac{m_{jjb} - m_{jj} -}{\sigma_{th-V}}\right. \\ + \left|\frac{m_{j\ell\nu} - m_{tl}}{\sigma_{t\ell}}\right|^2 + \left|\frac{(p_{\text{T},jjb} - p_{\text{T},j\ell\nu}) - (p_{\text{T},th}}{\sigma_{diffp\text{T}}}\right.$$

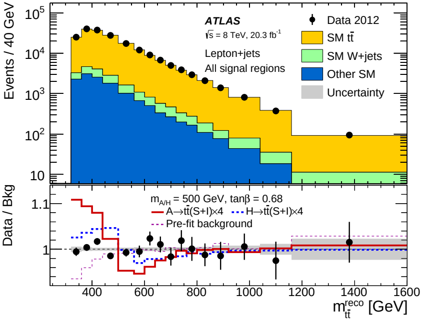
Six mutually exclusive signal regions

- Fit to data individually

> Combined fit to data in all regions are adopted in the end for better sensitivity

Flavours	$\text{t}_{\text{had.}}/\text{t}_{\text{lep.}}$ is b-labelled or not		
e+jets	✓ ✗	✗ ✓	✓ ✓
μ+jets	✓ ✗	✗ ✓	✓ ✓

Perform a fit



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Parameterised in terms of signal strength μ

$$\mu \cdot \mathcal{S} + \sqrt{\mu} \cdot \mathcal{I} + \mathcal{B} \Rightarrow \sqrt{\mu} \cdot (\mathcal{S} + \mathcal{I}) + (\mu - \sqrt{\mu}) \cdot \mathcal{S} + \mathcal{B}$$

Profit likelihood fit to $m_{t\bar{t}}$

- Hunts for the peak-dip structure
- Uncertainties taken into account as nuisance parameters

Consider only bins with $m_{t\bar{t}} > 320$ GeV

- To reduce threshold effects

Experimental resolution

- At most 8% (decreases with $m_{A/H}$ and $\tan\beta$)

Dominant Systematic Uncertainties

For $m_{A/H} = 500$ GeV, $\tan\beta = 0.68$

Systematic uncertainties [%]	Total bkg.	$\mathcal{S}$	$\mathcal{S}+\mathcal{I}$
Luminosity	1.7	1.9	1.9
PDF	2.5	2.1	12.3
$t\bar{t}$ initial-/final-state radiation	3.2	–	–
$t\bar{t}$ parton shower + fragmentation	4.9	–	–
$t\bar{t}$ normalization	5.7	–	–
$t\bar{t}$ generator	0.5	–	–
$t\bar{t}$ top quark mass	0.5	2.2	12.5
Jet energy scale	6.4	4.9	9.3
Jet energy resolution	1.3	1.6	1.7
b-tagging b-jet efficiency	1.5	1.3	1.1
b-tagging c-jet efficiency	0.2	0.2	0.8
Electron efficiency	0.3	0.4	0.7
Muon efficiency	0.9	1.0	1.0
Signal MC scales	–	7.3	7.3
Reweighting	–	–	5.0
MC statistical uncertainty	0.5	2.4	11.2
Total uncertainty	11.2	10.1	24.7

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- ± 1 GeV top mass

  has a large impact to signal shape for low $m_{A/H}$ and low $\tan\beta$ but decrease rapidly.

- Correlation between MC scales

  is disentangled assuming that they are anticorrelated in $m_{t\bar{t}}$ distribution

- Reweighting uncertainty

  for covering the difference between reweighted and generated distributions

2HDM

	Type I	Type II
ξ_h^u	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$
ξ_h^d	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)-\cos(\beta-\alpha)*\tan\beta$
ξ_h^l	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)-\cos(\beta-\alpha)*\tan\beta$
ξ_H^u	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$
ξ_H^d	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)+\sin(\beta-\alpha)*\tan\beta$
ξ_H^l	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)+\sin(\beta-\alpha)*\tan\beta$
ξ_A^u	$1/\tan\beta$	$1/\tan\beta$
ξ_A^d	$-1/\tan\beta$	$\tan\beta$
ξ_A^l	$-1/\tan\beta$	$\tan\beta$

gg->Scalar Vertices

$$H(p)g^{a,\mu}(p_1)g^{b,\nu}(p_2) : \frac{ig_s^2}{12\pi^2 v}\left(c_t A_S(\tau_t) + c_b A_S(\tau_b)\right)\left(p_1^\mu p_2^\nu - p_1 \cdot p_2 g^{\mu\nu}\right)\delta^{ab}$$

$$A(p)g^{a,\mu}(p_1)g^{b,\nu}(p_2) : \frac{ig_s^2}{8\pi^2 v}\left(c_t \frac{f(\tau_t)}{\tau_t} + c_b \frac{f(\tau_b)}{\tau_b}\right)\epsilon^{\mu\nu\rho\sigma} p_{1,\rho} p_{2,\sigma}\delta^{ab}$$

, where c_f is the reduced coupling. $\tau_f = \frac{p^2}{4m_f^2}$ and $\beta = (1 = \tau^{-1})^{1/2}$ is the velocity of the top quark and top antiquark in the center-of-momentum frame.

$$A_S(\tau) = \frac{3}{2\tau^2}(\tau + (\tau - 1)f(\tau))$$

$$f(\tau) = \begin{cases} \arcsin(\sqrt{\tau})^2, & \tau \leq 1 \\ -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}}\right) - i\pi\right]^2, & \tau > 1 \end{cases}$$

Matrix Element

Scalar

$$\frac{d\sigma}{ds} = \frac{\alpha_s^2 G_F^2 c_t^2 m_t^2 s^2}{1536\pi^3}\beta^3 \left|\frac{\sum_f c_f A_S(\tau_f)}{s - m_H^2 + i m_H \Gamma_H(s)}\right|^2$$

S

$$- \frac{\alpha_s^2 G_F c_t m^2}{66\pi\sqrt{2}}\beta^2 \log\left(\frac{1+\beta}{1-\beta}\right) \mathrm{Re}\left[\frac{\sum_f c_f A_S(\tau_f)}{s - m_H^2 + i m_H \Gamma_H(s)}\right]$$

I

$$+ \frac{d\sigma_{QCD}}{ds}$$

B

Pseudo-scalar

$$\frac{d\sigma}{ds} = \frac{3\alpha_s^2 c_t^2 G_F^2 m^2 s^2}{2048\pi^3}\beta \left|\frac{\sum_f c_f f(\tau_f)/\tau_f}{s - m_A^2 + i m_A \Gamma_A(s)}\right|^2$$

S

$$- \frac{\alpha_s^2 c_t G_F m^2}{64\pi\sqrt{2}} \log\left(\frac{1+\beta}{1-\beta}\right) \mathrm{Re}\left[\frac{\sum_f c_f f(\tau_f)/\tau_f}{s - m_A^2 + i m_A \Gamma_A(s)}\right]$$

I

$$+ \frac{d\sigma_{QCD}}{ds}.$$

B

Catastrophic Cancellation

1. $gg \to A \to t\bar{t} + \text{Interf}$
   $m(A)$ 500 GeV , $\tan\beta$ 0.40

   1M events, parton tops, after selections