Higgs: the view from the Top

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Tuesday, the view from the ~~top~~ air

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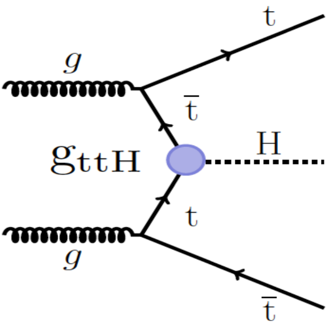
$pp \to t\bar{t}H$

Work done with Rohini Godbole, Diego Guadagnoli and Kirtimaan Mohan,

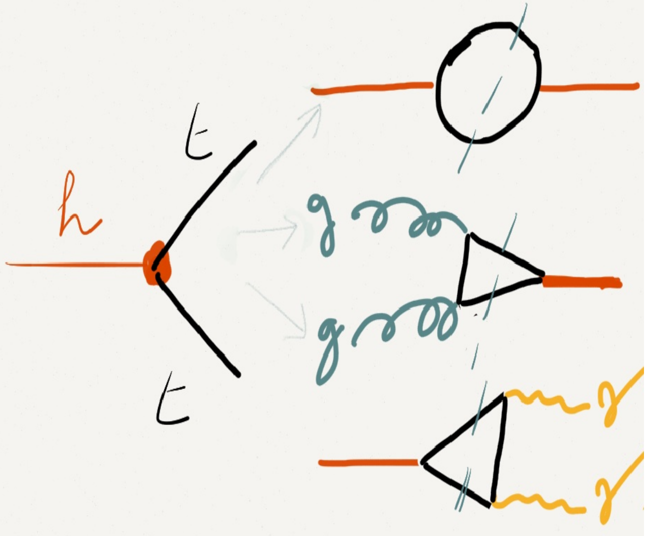
[arXiv:1501.03157]

Preliminary results, Les Houches Proceedings, in arXiv: 1405.1617



some work in arXiv: 1312.5736 (J. Ellis, D.S. Hwang, K. Sakurai, M. Takeuchi)

The Higgs and the Top



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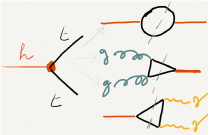

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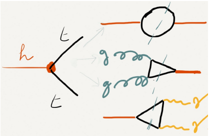

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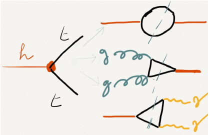

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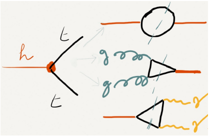

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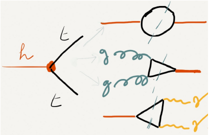

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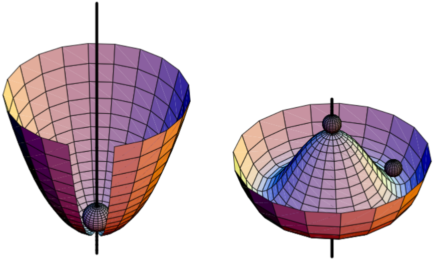
Higgs in the SM model

Higgs Kibble Mechanism



$$V = \lambda(|\Phi|^2 - v^2/2)^2$$

$(\lambda > 0)$

$$\langle 0|\phi|0\rangle = v/\sqrt{2}$$

$$Q_{em}|0\rangle = |0\rangle$$

$$y_\Phi = Y_\Phi = \frac{1}{2}$$

$$\Phi = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+H) \end{pmatrix} e^{i\frac{\omega^j \tau^j}{2v}}$$

$$\mathcal{L}_{\text{Higgs}} = (D^\mu\Phi)^\dagger(D_\mu\Phi) - V(\Phi^\dagger\Phi), \quad V(\Phi^\dagger\Phi) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2$$

$$\mathcal{L}_{m_f} = -\left(y_u \bar{u}_R \tilde{\Phi}^\dagger Q_L +^{y}_{d} \bar{d}_r \Phi^\dagger Q_L\right) + h.c, \quad \tilde{\Phi} = i\tau_2\Phi^* \quad m_{d,u} = y_{d,u}\frac{v}{\sqrt{2}}$$

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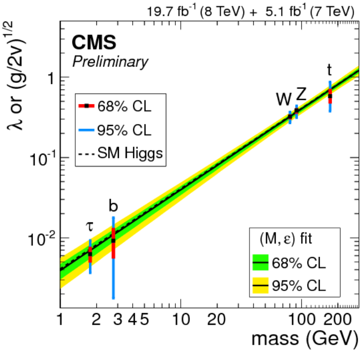
- Goldstones ω^i and H combine to form a linear representation of $SU(2) \times U(1)$

in the SM, Higgs and Mass are "ONE"

- Goldstones ω^i and H combine to form a linear representation of $SU(2) \times U(1)$
- $\hat{H} = H + v = v(1 + H/v)$, coupling of H is to the mass. Factor the mass out, the coupling is *universal* (tree-level). This must be verified precisely

Coupling proportional to mass? LHC early *evidence*



Mass and the Higgs, mass without a Higgs

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-

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- Dynamical mass from strong dynamics
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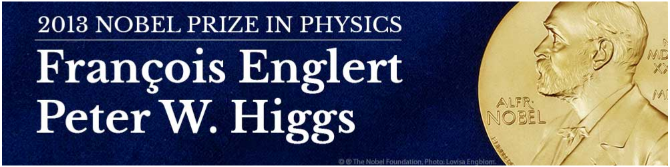
- Technicolour revamped, larger symmetries (modern parlance Composite Higgs)
- $H_{\rm SM}$ most economical set-up to unitarise the $WW, \cdots$,.. cross sections



Press Release

8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert
Université Libre de Bruxelles, Brussels, Be

and

Peter W. Higgs
University of Edinburgh, UK

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Mechanism...Spontaneous Symmetry Breaking

The Nobel Prize in Physics 2008

Photo: University of Chicago

Yoichiro Nambu

© The Nobel Foundation Photo: U. Montan

Makoto Kobayashi

© The Nobel Foundation Photo: U. Montan

Toshihide Maskawa

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

Masses in a Gauge Invariant Way without Higgs

The W, Z, γ kinetic pure gauge term still of the same origin but

mass and longitudinals through a system of Goldstones without the Higgs (still gauge invariant): Non-Linear realisation of SB

$$\Sigma = exp(\frac{i\omega^i \tau^i}{v}) \;\; (v = 246\; GeV \text{ is the vev}) \;\; \text{and} \;\; \mathcal{D}_\mu \Sigma = \partial_\mu \Sigma + \frac{i}{2}\left(g\boldsymbol{W}_\mu \Sigma - g' B_\mu \Sigma \tau_3\right)$$

$$\mathcal{L}_M = \frac{v^2}{4}\mathrm{Tr}(\mathcal{D}^\mu \Sigma^\dagger \mathcal{D}_\mu \Sigma) \equiv -\frac{v^2}{4}\mathrm{Tr}\left(\mathcal{V}_\mu \mathcal{V}^\mu\right) \quad \text{with} \;\; \mathcal{V}_\mu = \left(\mathcal{D}_\mu \Sigma\right)\Sigma^\dagger$$

Replaces all of the Higgs sector, potential and all.

Not renormalisable? and so what...!

The "chirally coupled" Higgs, composite Higgs

Chivukula and Koulovassilopoulos ('93,94)
FB+Chopin, '95
Grojean et al.

Coupling the Higgs X, to the chiral Lagrangian

$$\begin{aligned}
\Sigma &= exp(\frac{i\omega^i\tau^i}{v}) \\
\mathcal{L}_{M,X} &= \frac{1}{2}(\partial_\mu X)^2 - \frac{1}{2}M_X^2 X^2 \\
&+ \frac{v^2}{4}\mathrm{Tr}(\mathcal{D}^\mu\Sigma^\dagger\mathcal{D}_\mu\Sigma)\left(1+2a\frac{X}{v}+b\frac{X^2}{v^2}+\cdots\right) - Y_{ij}\overline{\psi}_L^i\Sigma\psi_R^j\left(1+c_{ij}\frac{X}{v}+\cdots\right) \\
&- \frac{1}{2}M_X^2X^2\frac{X}{v}\left(h_3+h_4\frac{X}{4v}\right)+\cdots \\
\text{for}\quad X &= H, \qquad a=b=c=1, \qquad h_3=h_4=1 \\
\text{Composite } X & \qquad \text{better have } c_{ij}=c \text{ else FCNC}
\end{aligned}$$

The Chiral Higgs

$$W^+W^- \to W^+W^- \Longrightarrow \mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s - M_X^2}\right) \to a = \pm 1$$

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$a \to W^+W^-H \qquad b \to W^+W^-HH \qquad c \to f\bar{f}H; t\bar{t}H$

The potential: Stability up to which scale?

the Higgs boson self-coupling $\lambda = M_H^2/2v^2$

$\lambda = M_H^2/2v^2 = 0.118(M_H = 125GeV) \quad \lambda^2/4\pi \sim 1/900 \ll \alpha_{\rm em}$

$\lambda = M_H^2/2v^2 = 4.9(M_H = 800GeV).$

$\lambda > 0.$

Behaviour of $\lambda(Q^2)$?

$$y_t = \sqrt{2}m_t/v \simeq 1$$

Running of couplings in the SM, remember running of gauge couplings?

At M_Z $g_i = \{0.46, 0.65, 1.2\}$

$$
\begin{aligned}
g_1 &= \sqrt{\frac{5}{3}}\frac{\sqrt{4\pi\alpha(m_Z)}}{\cos\theta_W} \simeq 0.46 \\
g_2 &= \frac{\sqrt{4\pi\alpha(m_Z)}}{\sin\theta_W} \simeq 0.65 \\
g_3 &= g_s = \sqrt{4\pi\alpha_3(m_Z)} \simeq 1.2
\end{aligned}
$$

the top Yukawa coupling $y_t = \sqrt{2}m_t/v \simeq 1$,

$$
\begin{aligned}
\frac{dg_1}{dt} &= \frac{41}{10}\frac{g_1^3}{16\pi^2}, \quad \frac{dg_2}{dt} = -\frac{19}{6}\frac{g_2^3}{16\pi^2}, \quad \frac{dg_3}{dt} = -7\frac{g_3^3}{16\pi^2} \\
\frac{dy_t}{dt} &= \frac{y_t}{16\pi^2}\left(-\frac{17}{20}g_1^2 - \frac{9}{4}g_2^2 - 8g_s^2 + \frac{9}{2}y_t^2\right)
\end{aligned}
$$

$$
t \equiv \ln(Q/Q_0)
$$

Running of couplings in the SM

$$\frac{d\lambda}{dt} = \frac{1}{16\pi^2}\left\{ \begin{array}{l} +24\lambda^2 - \lambda\left(\frac{9}{5}g_1^2 + 9g_2^2 + 12y_t^2\right) \\ -6y_t^4 \\ +\frac{9}{8}\left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2g_2^2 + g_2^4\right) \end{array}\right\}$$

Again importance of top, Higgs (self-coupling), gauge bosons

Running of the quartic coupling (one-loop)

$\lambda = M_H^2/2v^2 = 0.118(M_H = 125GeV); 4.9(M_H = 800GeV).$

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$+ \Rightarrow$ Coupling will increase until very large values and will no longer be perturbative.

$+ \Rightarrow$ like with em coupling, breaks at the Landau pole, Q_{LP}

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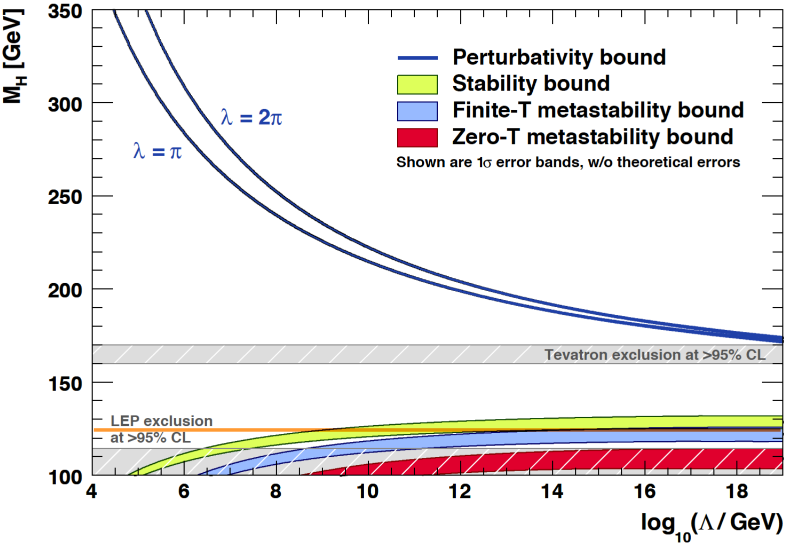
– ⇒ Coupling will decrease and may turn negative!

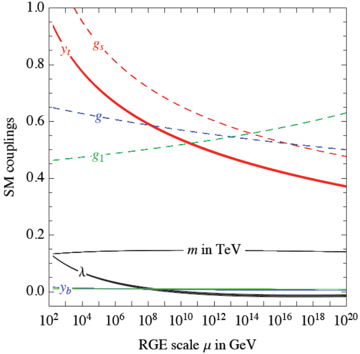
– ⇒ the Higgs potential will be unbounded from below: vacuum is no longer stable

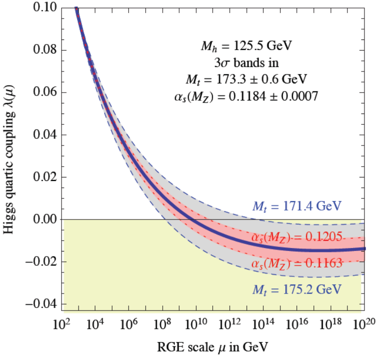
Stability and Perturbativity



J. Ellis, Espinosa, Giudice, Hoecker and Riotto '09

Stability: The Miracle (Degrassi et al ’12,)





Also Bezrukov, Shaposhnikov,..., Buttazzo,...

λ turns negative but "not too much" : it levels out ... β_λ vanishes over a wide range, starting from $\mu > 10^8$GeV.

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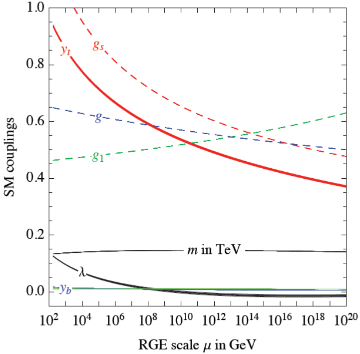

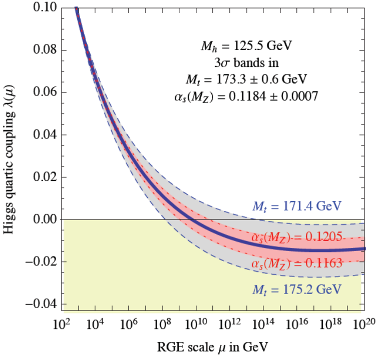

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some new physics contribution could easily move us to a stable region and perhaps give gauge coupling unification

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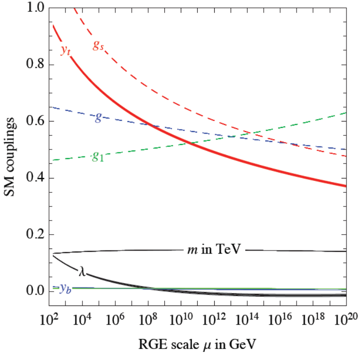

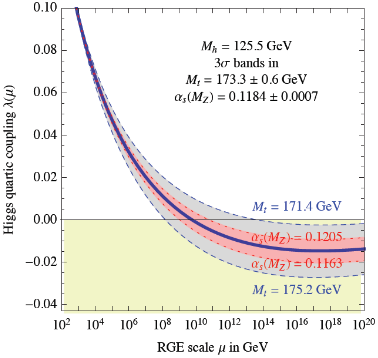

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Is there any meaning in this? M_h *vs* Planck Scale. **Higgs as inflaton?**

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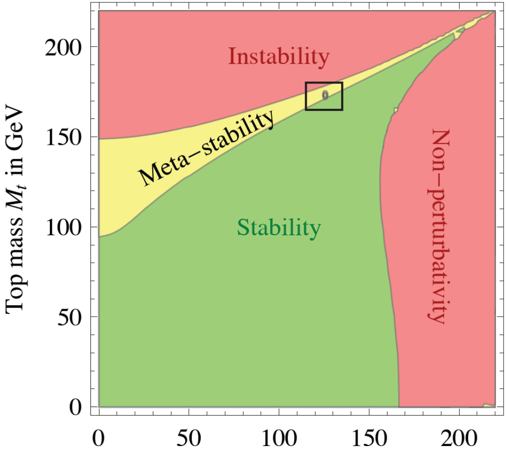

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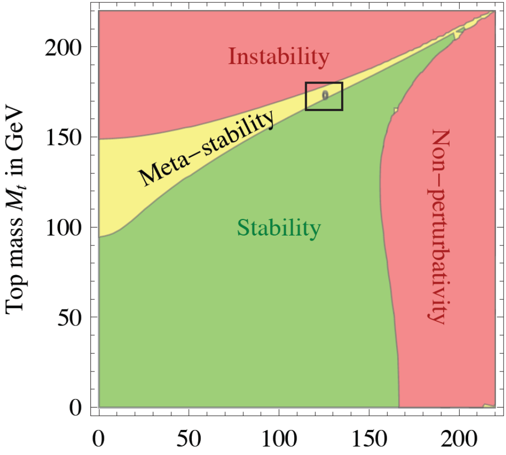
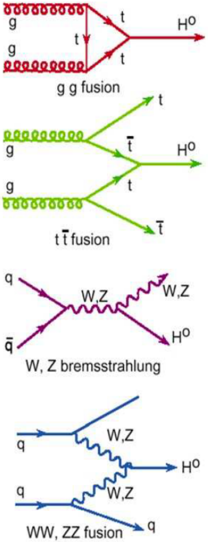


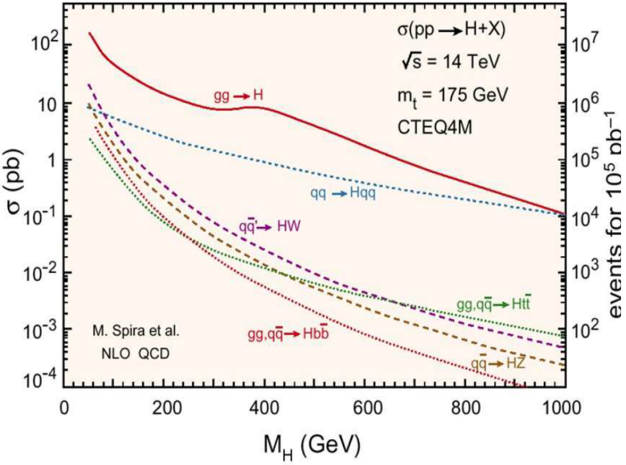
some new physics contribution could easily move us to a stable region

m_t essential (which m_t?)

Production at LHC, rôle of the top

Production mechanisms





Production at LHC

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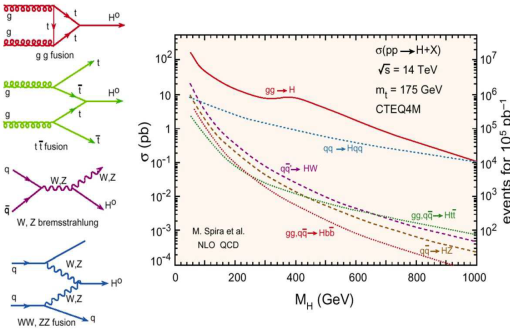

The largest cross section is the loop induced channel $gg \to h$

Production at LHC

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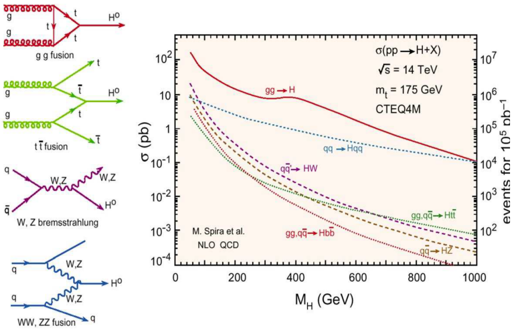

This *presumably* goes through tops

Production at LHC

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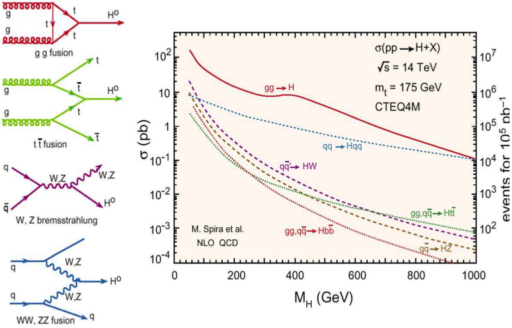
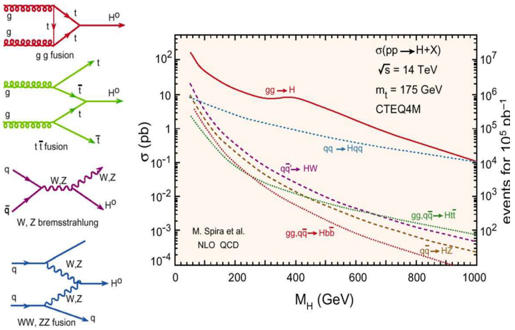


$gg \to H$ alone can not probe the "inside" of the process. Kinematics.

Sensitive to scale inside? can hardly tell between $m_t = 170$GeV and $m_t = \infty$

Production at LHC

Production mechanisms



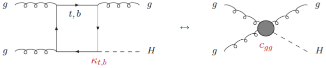
(one-) Loop function controlled by $A_t^a(\tau) = 4/3\,(1 + \tau/4 + \cdots)\quad \tau = m_h^2/4m_t^2 \sim 0.1 \ll 1$

$$\sigma(gg \to H) \propto \Gamma(H \to gg)$$

$$\sigma(gg \to H)_{m_t=170GeV}/\sigma(gg \to H)_{m_t=\infty} = 1 + 5\%$$

Boosted Higgs, P_T of the Higgs

$$\mathcal{L} = \quad -\sum_{\psi=u,d,l} m_{\psi^{(i)}} \bar{\psi}^{(i)} \psi^{(i)} \left(1 + \kappa_\psi \frac{h}{v} + \ldots\right) + \frac{c_{gg}}{2} G^a_{\mu\nu} G^{a\mu\nu} \frac{h}{v} + \ldots$$



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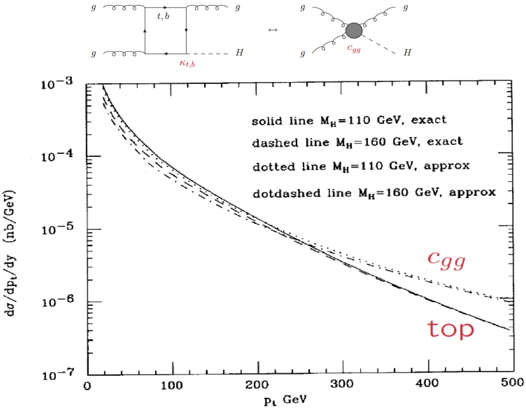

$m_t = 160$GeV (Ellis, Hinchliffe, Soldate, van der Bij [1987])

Tremendous drop in cross section when P_T large. This is the region where distinction may be made ($p_T > 500$GeV)

Boosted Higgs, P_T of the Higgs

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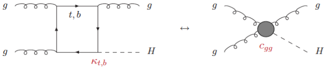
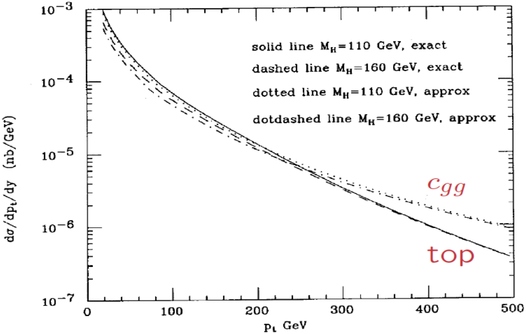




$m_t = 160\text{GeV}$ (Ellis, Hinchliffe, Soldate, van der Bij [1987])

$$\sigma_{P_T}/\sigma^{SM}_{P_T} = (k_t + k_g)^2 + \delta\ k_t k_g + \epsilon\ k_g^2$$

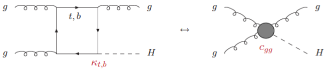
for $p_T = 100GeV$, $\sigma = 2pb$, $\delta = 0.003$; $\epsilon = 0.03$

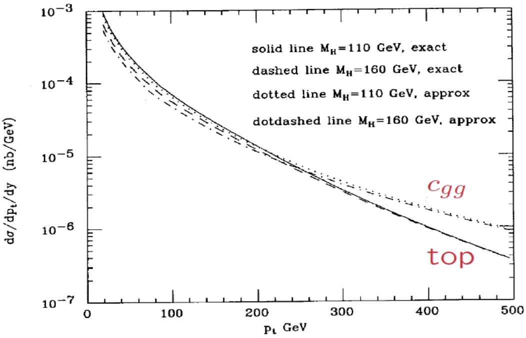
for $p_T = 500GeV$, $\sigma = 6fb$; $\delta = 1.7$; $\epsilon = 2.9$

Christophe (Grojean) and others for probe of the top origin of the process **Almost 3 orders of magnitude loss**

Boosted Higgs, P_T of the Higgs

$$\mathcal{L} = \; -\sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \overline{\psi}^{(i)}\psi^{(i)} \left(1+\kappa_\psi \frac{h}{v}+\dots\right) + \frac{c_{gg}}{2} G^a_{\mu\nu}G^{a\mu\nu}\frac{h}{v}+\dots$$

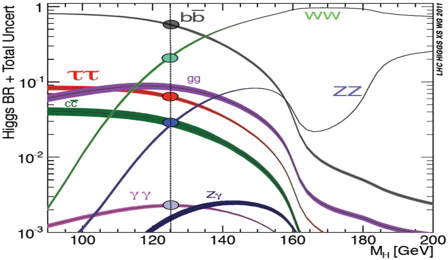




$m_t = 160$GeV (Ellis, Hinchliffe, Soldate, van der Bij [1987])

AND
NLO corrections known only for
$m_t \gg m_H, P_T^h$

Signatures



Though very small, $H \to \gamma\gamma$ is an essential signature

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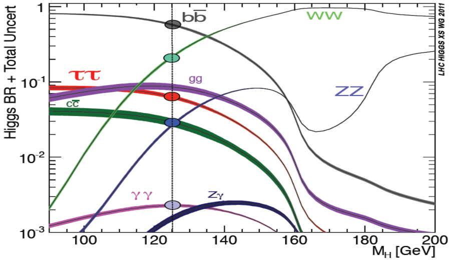

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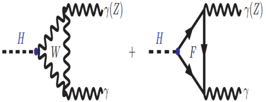

$$\mathcal{L}_{H\gamma\gamma} = c\frac{\alpha}{4\pi} F_{\mu\nu}F^{\mu\nu}\frac{H}{v}$$

$$\Gamma(H \to \gamma\gamma) = \frac{G_\mu M_H^3}{\sqrt{2}} \frac{\alpha^2}{128\pi^3} \sum_i |Q_i^2 N_{C,i} F_i|^2, \qquad F_i = \begin{cases} +7 \; (W^\pm) \\ -\frac{4}{3} \; \text{fermion} \\ -\frac{1}{3} \; \text{scalar} \end{cases}$$

Related to the β function.
4th generation reduces the rate by 15%.

Again $h \to \gamma\gamma$ is loop induced, the top plays a crucial role

Aside: amazing, number of channels accessed

Need a more direct access to the $t\bar{t}H$ coupling

What do we know about the $t\bar{t}h$ vertex ?

For all fermions

$$\mathcal{L}_{hf\bar{f}} = -\sum_f \frac{m_f}{v} h\, \bar{f}(a_f + i b_f \gamma_5) f,$$

$t\bar{t}H$ vertex and " parity"

$$\mathcal{L}_{tth} \; = \; -\frac{m_t}{v}\, h\, \bar{t}\, (\mathbf{a_t} \; + \; i\mathbf{b_t}\, \gamma_5)\, t \; ,$$

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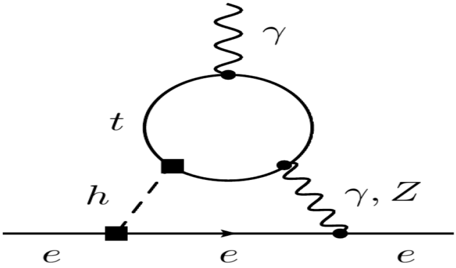
$$\mathcal{L}_{tth} \;=\; -\frac{m_t}{v}\,h\,\bar{t}\,(\mathbf{a_t} \;+\; i\mathbf{b_t}\,\gamma_5)\,t\;,$$

one can also check

$$\mathcal{L}_{hVV} = \frac{g}{2}\kappa_V m_W h \left(W^\mu W_\mu + \frac{1}{\cos\theta_W^2} Z^\mu Z_\mu \right).$$

Indirect constraints, low energy CP violation (Pre-LHC)

edm of the electron



$$\mathcal{L}^{e}_{\rm EDM} = -d_e \frac{i}{2} \overline{e}\, \sigma^{\mu\nu}\gamma_5\, e\, F_{\mu\nu}$$

$$d_e \propto b_t\, a_e\, f_1(m_t^2/m_h^2) + a_t\, b_e\, f_2(m_t^2/m_h^2)$$

$$|d_e/e| < 8.7\cdot 10^{-29}{\rm cm}(90\%{\rm CL}) \Longrightarrow b_t < 0.01\ ((a_e, b_e) = (1,0))$$

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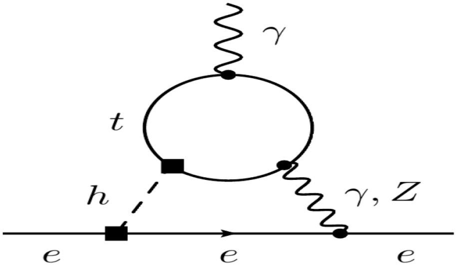

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Very model dependent, again an indirect loop induced argument: assumes we know *hee* coupling very well and that *hee* has both a scalar and a pseudo-scalar component

Less Indirect limits; Higgs Production and Decays at LHC

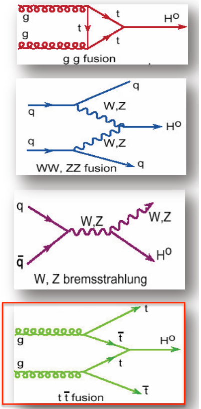
87%

7.1%

4.9%

0.6%

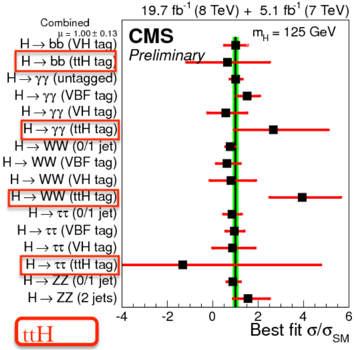
⇕

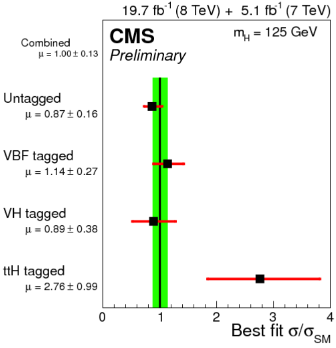


σ/σ_{tot} (M_H = 125 GeV)

The most direct one is by far the smallest!

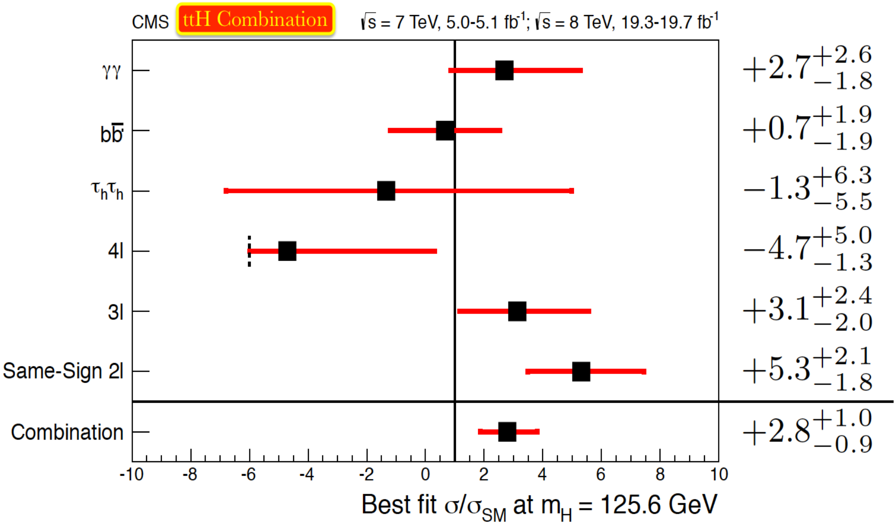
The data; constraining but !





$$\mu_{\text{combined}} = 1.00 \pm 0.13$$

ttH very loose



Most constraining from present data $\sigma(gg \to h)$ and $\Gamma(h \to \gamma\gamma)$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)^{\rm SM}} = \frac{|\kappa_V A_W^a(\tau_W) + a_t \frac{4}{3} A_t^a(\tau_t)|^2 + |b_t \frac{4}{3} A_t^b(\tau_t)|^2}{|A_W^a(\tau_W) + \frac{4}{3} A_t^a(\tau_t)|^2} \,.$$

For $\tau = m_h^2/4M^2 \ll 1$ $(M = m_t, M_W, ..)$

$$\begin{aligned} A_t^a(\tau) &= 4/3\,(1 + \tau/4 + \cdots) \\ A_W^a(\tau) &= -7\,(1 + \tau/5 + \cdots) \\ A_t^b(\tau) &= 2\,(1 + \tau/3 + \cdots) \end{aligned}$$

Most constraining from present data $\sigma(gg \to h)$ and $\Gamma(h \to \gamma\gamma)$

$$
\begin{aligned}
\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)^{\rm SM}} &\sim 1.6 \left((\kappa_W - 0.21\ a_t)^2 + (0.34\ b_t)^2 \right) \\
\frac{\sigma(gg \to h)}{\sigma(gg \to h)^{\rm SM}} &\sim a_t{}^2 + 2.29 b_t{}^2 \ .
\end{aligned}
$$

Most constraining from present data $\sigma(gg \to h)$ and $\Gamma(h \to \gamma\gamma)$

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$$pp \to t\bar{t}h$$

$$\sigma_{\rm 8TeV}/\sigma_{\rm 8\ TeV}^{\rm SM} \simeq a_t^2 + 0.31\ b_t^2\ .$$

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Less stronger relative dependence of b_t in direct production

Fits from Higgs observables

ATLAS and CMS have performed an analysis to measure a_t:

$$a_t \in [-1.2, -0.6] \cup [0.6, 1.3] \qquad \text{ATLAS}$$

$$a_t \in [0.6, 1.2] \qquad \text{CMS} .$$

Fits from Higgs observables

We extend the analysis to include b_t, combine both ATLAS and CMS data, making sure we recover (for $b_t = 0$, both ATLAS and CMS data).

As customary, the signal strength measured in a particular channel i at the LHC

$$\hat{\mu}_i = \frac{n^i_{\rm exp}}{(n^i_S)^{\rm SM}}$$

where $n^i_{\rm exp}$ is the number of events observed in the channel i and $(n^i_S)^{\rm SM}$ is the expected number of events as predicted in the SM.

For specific models, define

$$\mu_i = \frac{n^i_S}{(n^i_S)^{\rm SM}} = \frac{\Sigma_p \sigma_p \epsilon^i_p}{\Sigma_p \sigma^{SM}_p \epsilon^i_p} \times \frac{{\rm BR}_i}{{\rm BR}^{\rm SM}_i}\,.$$

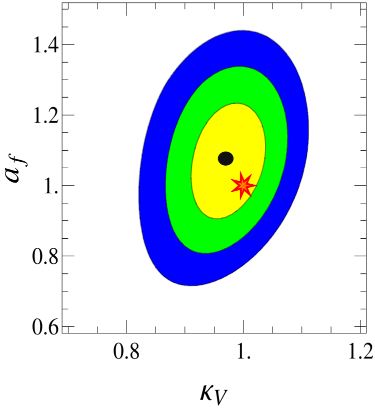
The fit is performed by minimizing the χ^2 function

$$\chi^2 = \sum_i \left(\frac{\mu_i - \hat{\mu}_i}{\sigma^{\rm exp}_i} \right)^2 ,$$

When correlations are given, we modify the χ^2 function to take correlations into account.

Fits from Higgs observables (Validation of our calculations)

Here like ATLAS and CMS we fit a_f (all fermions) and hVV. $b_f = 0$

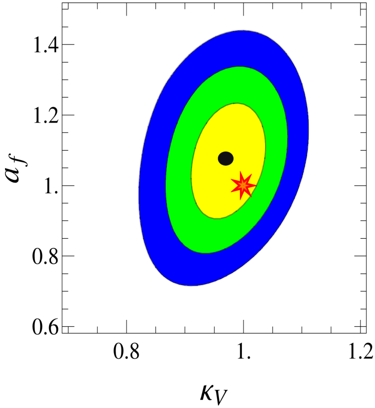


The ● indicates the best-fit value: $(\kappa_V, a_f) = (0.96, 1.06)$

68% , 95%, 99.7% CL

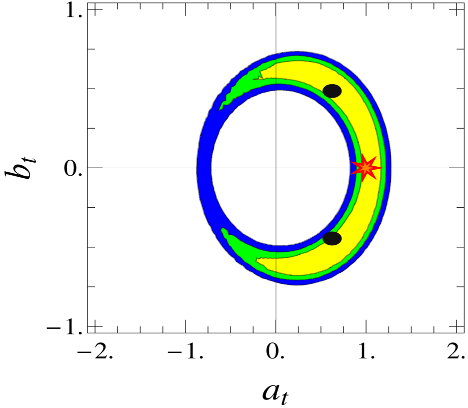
$\star$ SM, $(\kappa_V, a_f) = (1, 1)$.

Fits, *Fits*$(\kappa_V, a_f), b_f = 0$: *P* Properties (Pseudoscalar content in *hVV*)



If parity of Higgs measured as $\kappa_{\rm CP} = 1 - \kappa_V^2$, then very little is left for a parity-odd Higgs. (Djouadi-Moreau 1303.6591)

Fits to a_t, b_t from present data. All other couplings standard



The ● indicates the best-fit value $(a_t, b_t) = (0.67, +0.46)$ and $(a_t, b_t) = (0.67, -0.46)$.
68% , 95%, 99.7% CL
$\star$ SM
Note the $b_t \leftrightarrow -b_t$ degeneracy. as expected form total inclusive cross sections

Loopholes in constraints from loop-induced

In general, BSM models allow for additional interactions not present in the SM to both the scalar and pseudo-scalar components of the Higgs. Higher order operators (heavy states, ...) :

$$hG^{\mu\nu}G_{\mu\nu} \rightarrow \kappa_{gg}$$
$$hG^{\mu\nu}\tilde{G}_{\mu\nu} \rightarrow \tilde{\kappa}_{gg}$$
$$hF^{\mu\nu}F_{\mu\nu} \rightarrow \kappa_{\gamma\gamma}$$
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$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)^{\rm SM}} \sim 1.6\left((\kappa_W - 0.21\,(a_t+\kappa_{\gamma\gamma})\,)^2 + (0.34\,(b_t+\tilde{\kappa}_{\gamma\gamma})\,)^2\right)$$
$$\frac{\sigma(gg\to h)}{\sigma(gg\to h)^{\rm SM}} \simeq (a_t\;+\;\kappa_{gg})^2 + 2.29(b_t\;+\;\tilde{\kappa}_{gg})^2\;.$$

Total degeneracy. But

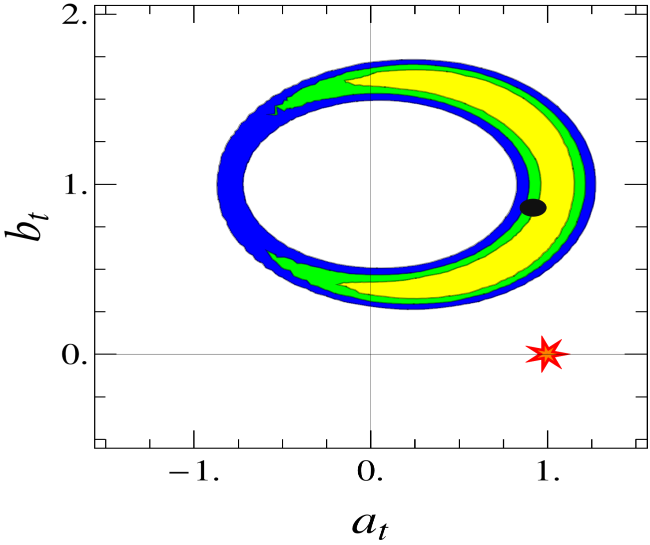
$$pp \to t\bar{t}h$$

$$\sigma_{8\rm TeV}/\sigma^{\rm SM}_{8\;\rm TeV} \simeq a_t^2 + 0.31\;b_t^2\;.$$

unfortunately weight of $pp \to t\bar{t}h$ is very small, still

Lifting the degeneracy: $\tilde{\kappa}_{gg} = \tilde{\kappa}_{\gamma\gamma} = -1$

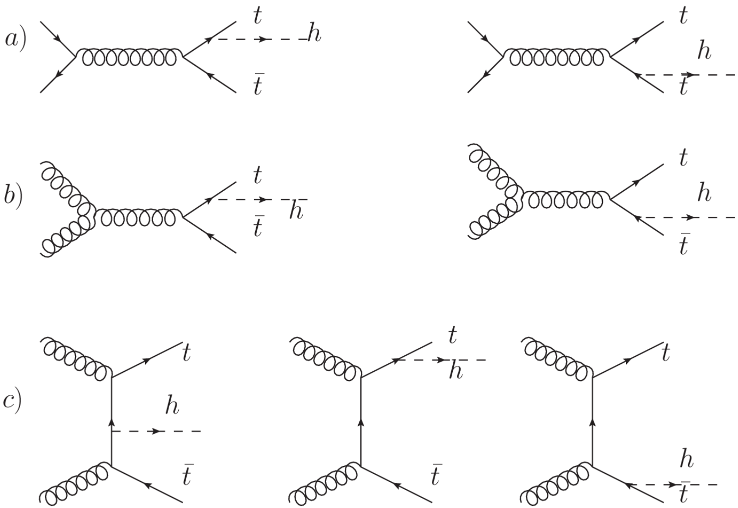
SM excluded but ...



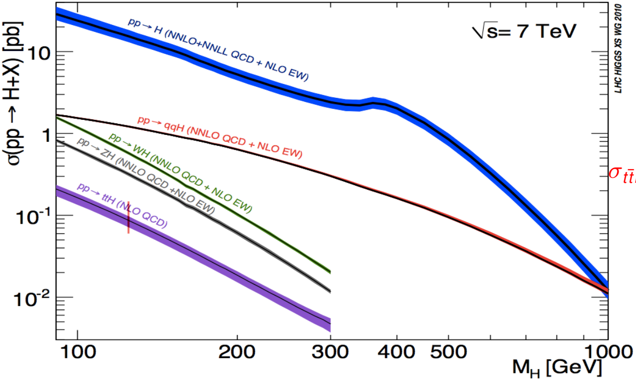
Direct Probe of the $t\bar{t}h$ coupling

$$pp \to t\bar{t}h$$

Feynman diagrams



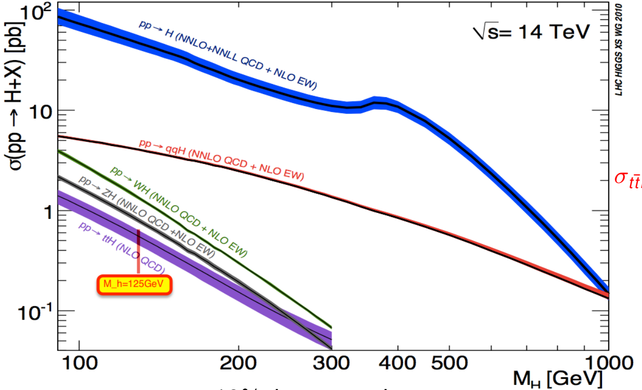
$t\bar{t}H$ SM cross sections



$\sigma_{t\bar{t}H}$(@7TeV)=137fb

10% th. uncertainty on $\sigma_{t\bar{t}H}$

$t\bar{t}H$ SM cross sections



$\sigma_{t\bar{t}H}$(@14TeV)=630fb

10% th. uncertainty on $\sigma_{t\bar{t}H}$

$t\bar{t}H$ SM cross sections: difficult

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process	incl. σ	efficiency	$\sigma^{\rm rec}$
$t\bar{t}h$, single-lepton	111 fb	0.0485	5.37 fb
$t\bar{t}h$, di-lepton	17.7 fb	0.0359	0.634 fb
$t\bar{t}$+jets, single-lepton	256 pb	0.463×10^{-3}	119 fb
$t\bar{t}$+jets, di-lepton	40.9 pb	0.168×10^{-3}	6.89 fb

Artoisenet *et al.*, arXiv: 1304.6414

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Artoisenet *et al.*, arXiv: 1304.6414

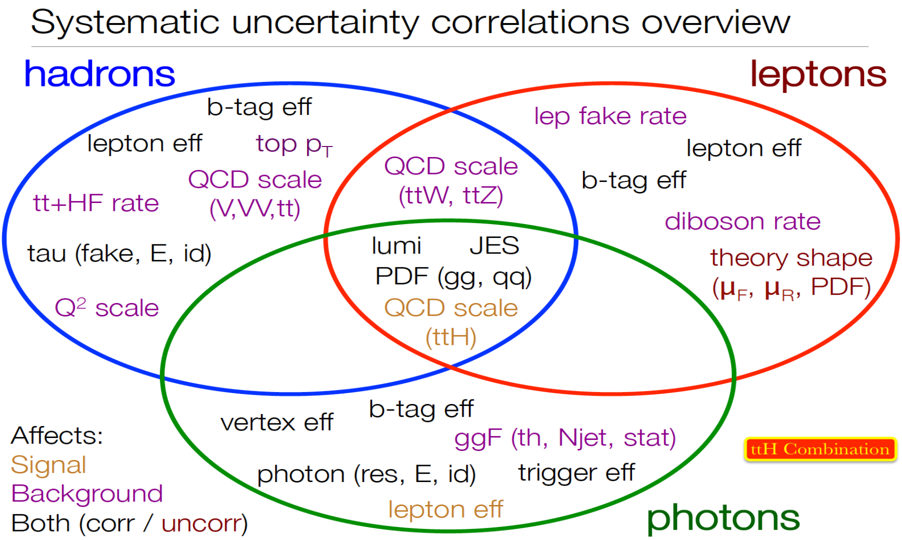
● Difficult, but the 3 body final state with each state decaying offers a large number of observables to study

$t\bar{t}H$ SM cross sections: difficult but a lot of progress

ATLAS and CMS have performed searches in this channel even in the rarest channel $H \to \gamma\gamma$ with present data, this help set a limit (with $\sim$ 25fb$^-1$) $\sigma_{tth}^{\rm obs.} < 5\sigma_{tth}^{SM}$ (assuming SM branching ratios!),

CMS has even newer results combining $H \to b\bar{b}, \tau\tau, \gamma\gamma$ $\sigma_{tth}/\sigma_{tth}^{SM} = 2.8^{+1.0}_{-0.9}$

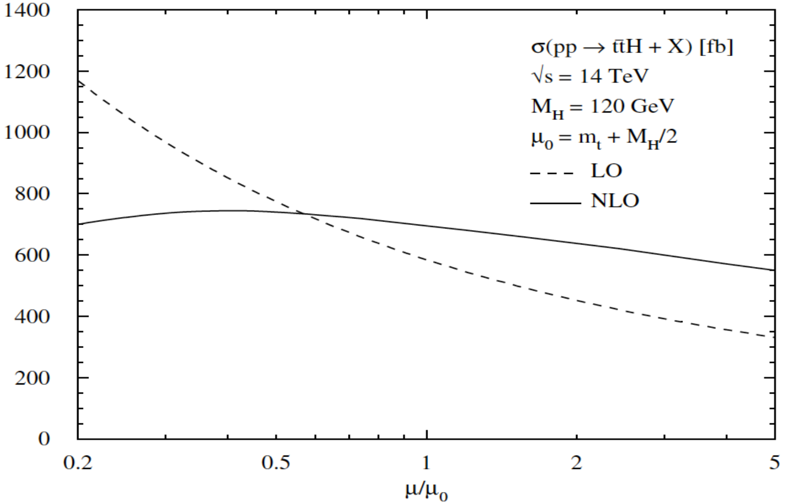
From experimental side, big effort



Equaly large effort from THEORY: Get the Standard Model $t\bar{t}H$ under control

Difficult process, but a lot of progress; NLO $t\bar{t}H$ cross section

2001: (QCD) NLO corrections ($\mathcal{O}(\alpha_s^3)$) to $t\bar{t}H$; (analytical) Beenakker et al., Reina and Dawson



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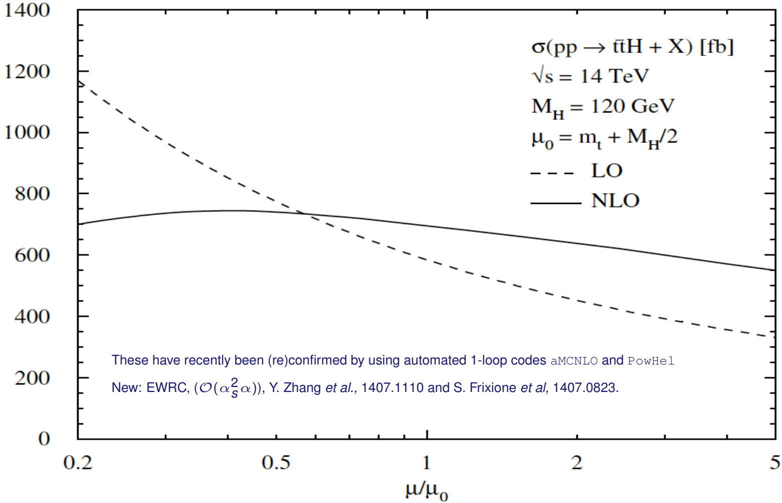

These have recently been (re)confirmed by using automated 1-loop codes `aMCNLO` and `PowHel`

New: EWRC, ($\mathcal{O}(\alpha_s^2\alpha)$), Y. Zhang *et al.,* 1407.1110 and S. Frixione *et al,* 1407.0823.

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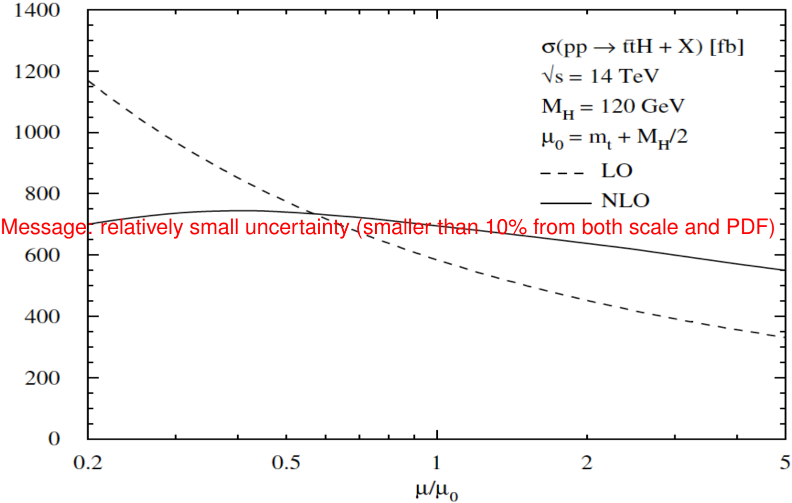

Message: relatively small uncertainty (smaller than 10% from both scale and PDF)

Implementation in NLO+PS tools

MadGraph5_aMC@NLO
Powhel samples (2011)
Powheg Box (Jaeger et al., 1501.04498)
Interface Sherpa+OpenLoops or GoSam
10% uncertainty from inclusive observables (more if sensitive to jet radiation)

What I will show on how to exploit $pp \to tth$...

May look (too) optimistic, however with the progress achieved there is hope AND

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A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

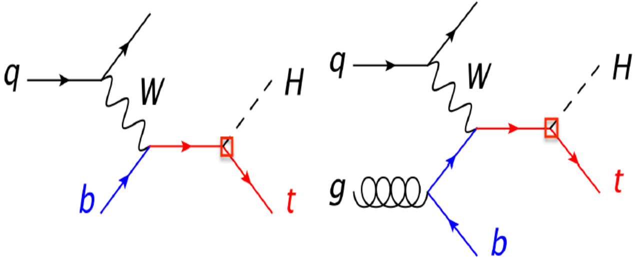
Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

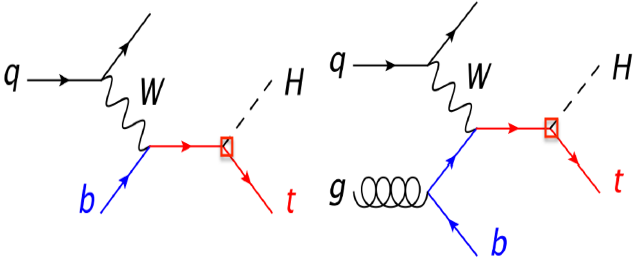
when this paper appeared there were about a dozen papers discussing the phenomenology of the Higgs

$pp \to tH + \bar{t}H$: Another probe, I will not discuss

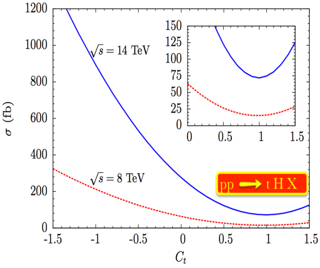


$(Wb \to th)$

$pp \to tH + \bar{t}H$: Another probe, I will not discuss

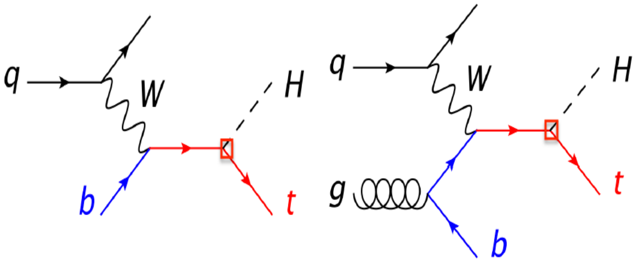


$(Wb \to th)$



$\sigma_{th} \sim$ 100fb @14TeV LHC

$pp \to tH + \bar{t}H$: Another probe, I will not discuss



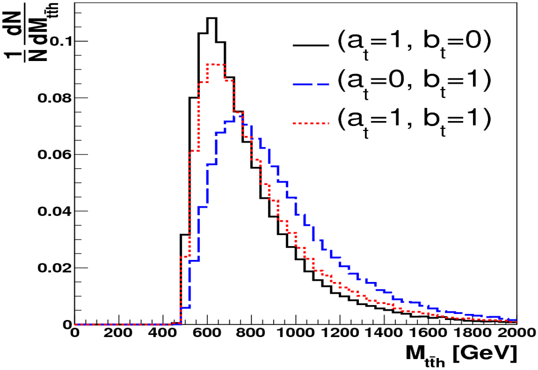
$(Wb \to th)$

- Maltoni; Paul; Stelzer ; Willenbrock [arXiv:hep-ph/0106293] (LO, sig+bkg)
- Biswas; Gabrielli ; Mele [arXiv:1211.0499] (LO, $H \to \gamma\gamma$ sig+bkg)
- Farina; Grojean; Maltoni; Salvioni; Thamm [arXiv:1211.3736]
  (NLO xsect 5F, LO distr, $H \to b\bar{b}$ sig+bkg)
- Ellis;Hwang; Sakurai;Takeuchi [arXiv:1312.5736]
  J. Yue, [arXiv:1410.2701]
- Chang; Cheung; Lee; Lu [arXiv:1403.2053]

$t\bar{t}H$: Total cross sections / All inclusive 1.

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{\rm SM}_{t\bar{t}H}} \sim a_t^2 + 0.42\ b_t^2 \qquad \sigma(p_T^h > 100GeV)/\sigma^{\rm SM}(p_T^h > 100GeV) = a_t^2 + 0.60\ b_t^2$$

$$\sigma_{8\rm TeV}/\sigma^{\rm SM}_{8\,\rm TeV} \simeq a_t^2 + 0.31\ b_t^2\ .$$



More rapid increase with energy ($\hat{s}$) in the case of the scalar

$t\bar{t}H$: Total cross sections / All inclusive 2.

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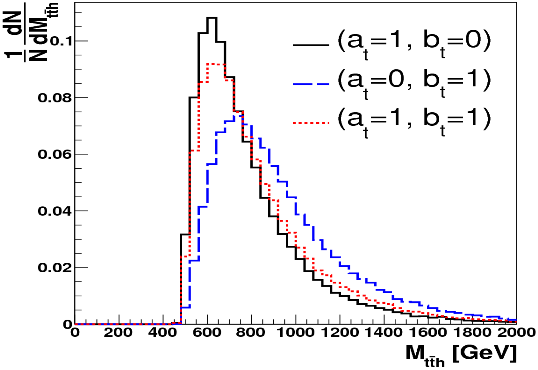
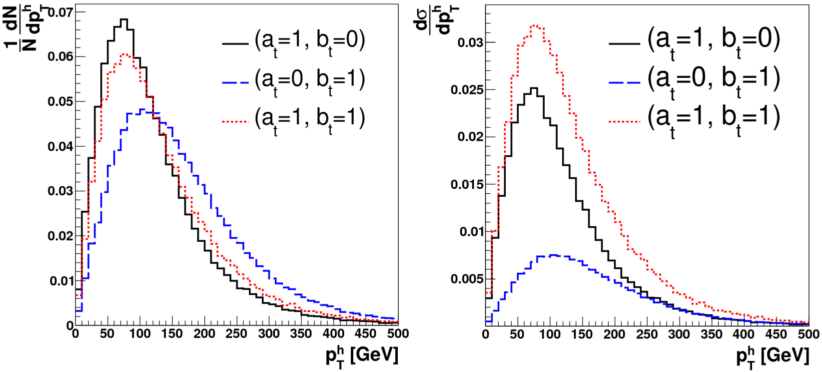


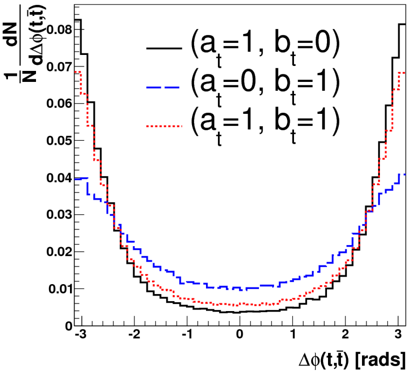
One single measurement can not make a difference between a_t and b_t.
Combine measurements at 2 energies or with 2 cuts, indirect probe of CP.

p_t^h distributions



p_T^h is a good discriminating variable. Easier to measure, requires to determine p_T^h, ($h \to b\bar{b}$, beware of combinatorics though ($4b$)).

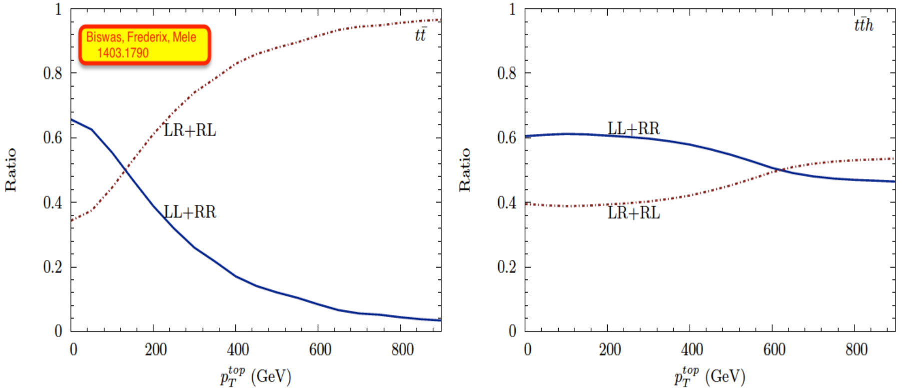
Azimuthal angle between the 2 tops



$$\cos(\Delta\phi(t\bar{t})) = \frac{(\hat{z}\times\vec{p}^{\,\bar{t}})\cdot(\hat{z}\times\vec{p}^{\,t})}{|\vec{p}^{\,\bar{t}}|\ \ |\vec{p}^{\,t}|}$$

Distributions understood from P_T^h distributions. At threshold where P_T small, $t\bar{t}$ back to back. More pronounced for scalar. Only needs reconstruction of both the direction of the top and anti-top.

$t\bar{t}h$ vs $t\bar{t}$ at LHC, SM



from arXiv: 1403.1790 (S. Biswas, R. Frederix, E. Gabrielli and B. Mele)

Polarised tops

A measure of the spin correlations can be defined through the following spin-correlation asymmetry in the lab frame

$$\begin{aligned}\zeta_{\text{lab}} &= \frac{\sigma(pp \to t_L\bar{t}_L h) + \sigma(pp \to t_R\bar{t}_R h) - \sigma(pp \to t_L\bar{t}_R h) - \sigma(pp \to t_R\bar{t}_L h)}{\sigma(pp \to t_L\bar{t}_L h) + \sigma(pp \to t_R\bar{t}_R h) + \sigma(pp \to t_L\bar{t}_R h) + \sigma(pp \to t_R\bar{t}_L h)} \\ &= 0.22\frac{1 + 0.86\; b_t^2/a_t^2}{1 + 0.42\; b_t^2/a_t^2} \quad \text{(LHC 14TeV)} \\ &= 0.22(b_t = 1), \quad 0.46\;\; \text{max. value}(a_t = 0), \quad 0.29(a_t = b_t)\end{aligned}$$

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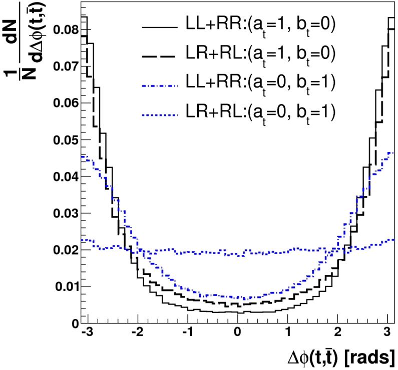
A pure pseudo-scalar has the largest $\zeta_{\rm lab}$, ~ 0.5

Theoretically a value which deviates from 0.22 or 0.46 corresponds to both a_t and b_t non zero and hence to a source of CP.

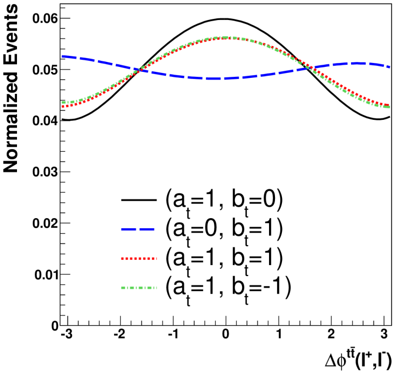

$\frac{1}{N}\frac{dN}{d\Delta\phi(t,\bar{t})}$
LL+RR:(a_t=1, b_t=0)
LR+RL:(a_t=1, b_t=0)
LL+RR:(a_t=0, b_t=1)
LR+RL:(a_t=0, b_t=1)
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-3
-2
-1
0
1
2
3
$\Delta\phi(t,\bar{t})$ [rads]

Spin correlations, density matrix

Using correlations with the final decay products

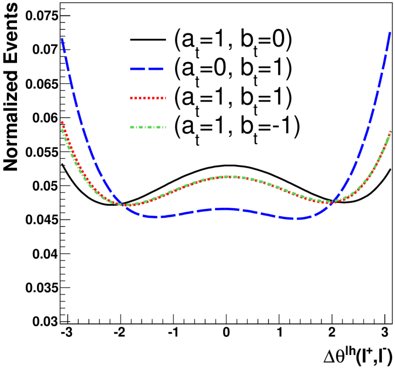
distributions for $\Delta\phi^{t\bar{t}}(\ell^+,\ell^-)$, $t,\bar{t}$ rest frames

- Dileptonic decay of the top. Beware cross section small...
- But it is also known that the lepton angular distribution in the decay of the top is not affected by non SM effect in the decay vertex. Hence all happens at production.
- Try to reconstruct observables as if we were in $t\bar{t}$production: observables **in rest frame** of the tops for example. This requires reconstruction of the top momenta, difficult with the missing enegy/$p_T$from the 2 neutrinos.



$$\cos(\Delta\phi^{t\bar{t}}(\ell^+,\ell^-)) = \frac{(\hat{z}\times\vec{p}^{\,\bar{t}}_{\ell-})\cdot(\hat{z}\times\vec{p}^{\,t}_{\ell+})}{|\vec{p}^{\,\bar{t}}_{\ell-}|\,|\vec{p}^{\,t}_{\ell+}|},$$

$\Delta\theta^{\ell h}(\ell^-, \ell^+)$, substitute in lab. frame



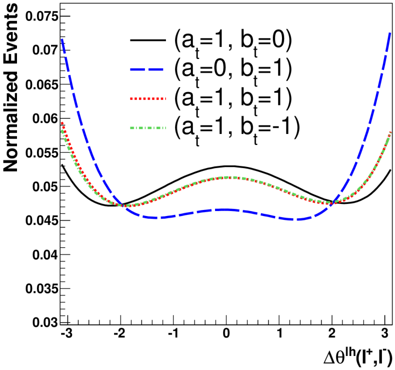
$$\cos(\Delta\theta^{\ell h}(\ell^-, \ell^+)) = \frac{(\vec{p}_h \times \vec{p}_{\ell -}) \cdot (\vec{p}_h \times \vec{p}_{\ell +})}{|\vec{p}_h \times \vec{p}_{\ell -}| \ \ |\vec{p}_h \times \vec{p}_{\ell +}|} \ .$$

Now all momenta in lab. frame. (could have used p_W instead of p_l and use the full hadronic samples).

CP-violating observables, 1-$t\bar{t}$ rest frame (Ellis et al.;)

$$\alpha \equiv \mathrm{sgn}\left(\vec{p}_t^{\;t\bar{t}} \cdot (\vec{p}_{\ell^-}^{\;t\bar{t}} \times \vec{p}_{\ell^+}^{\;t\bar{t}})\right).$$

$\Delta\theta^{t\bar{t}}(\ell^+, \ell^-)$ is the angle between the two lepton momenta projected onto the plane perpendicular to the t direction in the center-of-mass frame of the $t\bar{t}$ system.

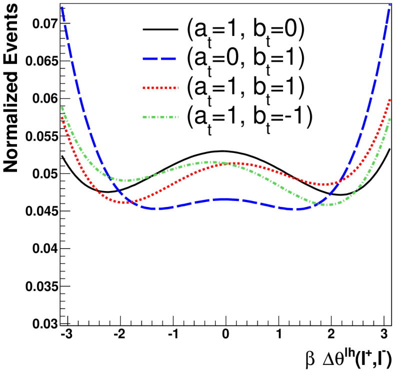


distributions for $\alpha \times \Delta\theta^{t\bar{t}}(\ell^+, \ell^-)$

CP-violating observables, 2- lab. frame

take the b's from the quark decays. One of these must be tagged (reconstruct either t or $\bar{t}$)

$$\beta \equiv \mathrm{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell-} \times \vec{p}_{\ell+}) \right) .$$



distributions for $\beta \times \Delta\theta^{\ell h}(\ell^-, \ell^+)$

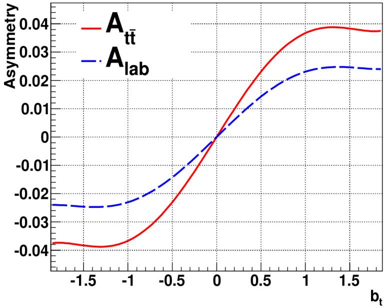
Asymmetries

$\alpha \times \Delta\theta^{t\bar{t}}(\ell^+, \ell^-)$ and $\beta \times \Delta\theta^{\ell h}(\ell^-, \ell^+)$ it is useful to define CP asymmetries as follows:

$$A_{t\bar{t}} = \frac{\sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+, \ell^-) > 0) - \sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+, \ell^-) < 0)}{\sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+, \ell^-) > 0) + \sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+, \ell^-) < 0)}$$

and

$$A_{\text{lab}} = \frac{\sigma(\beta \times \Delta\theta^{\ell h}(\ell^-, \ell^+) > 0) - \sigma(\beta \times \Delta\theta^{\ell h}(\ell^-, \ell^+) < 0)}{\sigma(\beta \times \Delta\theta^{\ell h}(\ell^-, \ell^+) > 0) + \sigma(\beta \times \Delta\theta^{\ell h}(\ell^-, \ell^+) < 0)}.$$



Conclusions

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- drawback: cross section small, even smaller if one wants to access spin correlation observables
- drawback: Large background
- More realistic studies are being done or are under way
- $pp \to t/\bar{t}h$ may be another handle, but cross sections even tinier