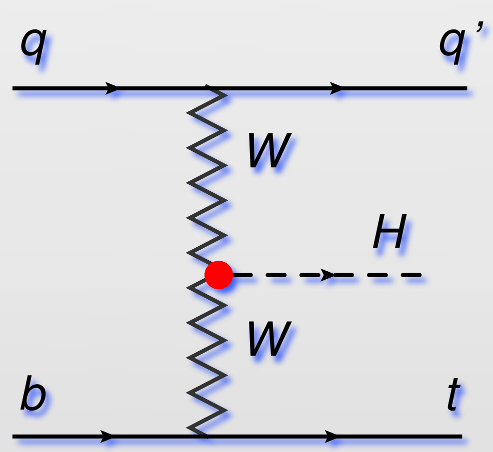
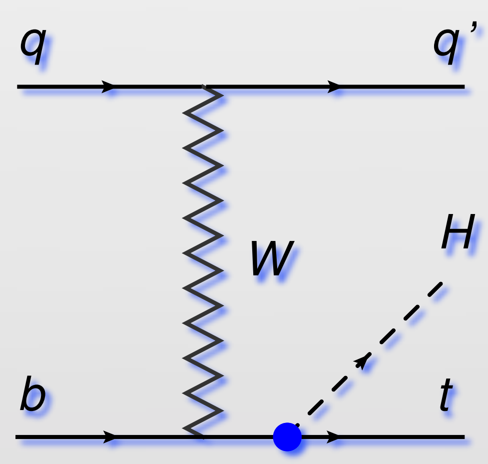
LC13 Workshop :

Exploring QCD from the infrared regime to heavy flavour scales at B -factories, the LHC and a Linear Collider, 16-20 September 2013, ECT*, Villa Tambosi, Trento, Italy

Solving the sign ambiguity in the Higgs coupling measurements at the LHC





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Sezione di Roma

Trento, 18 September 2013

Outline

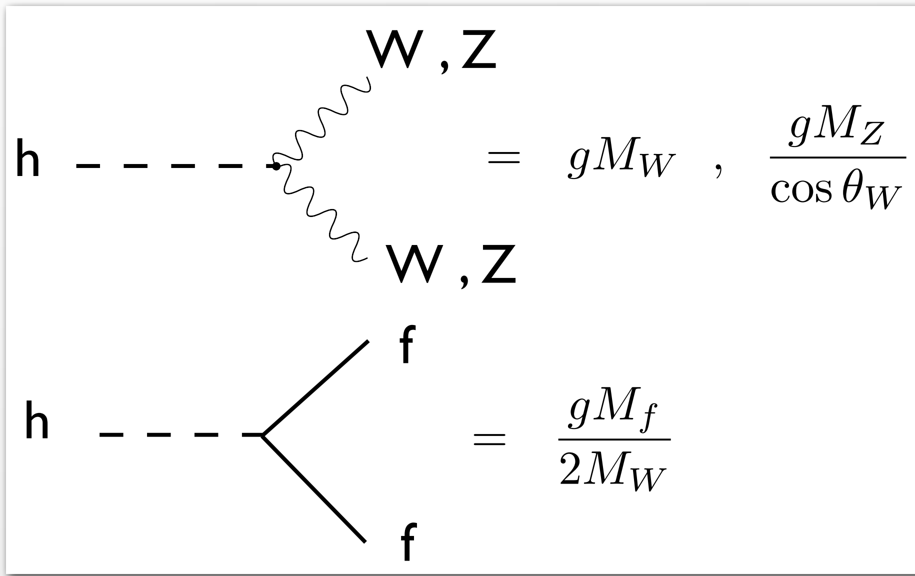
- 2012: "Higgs" discovery

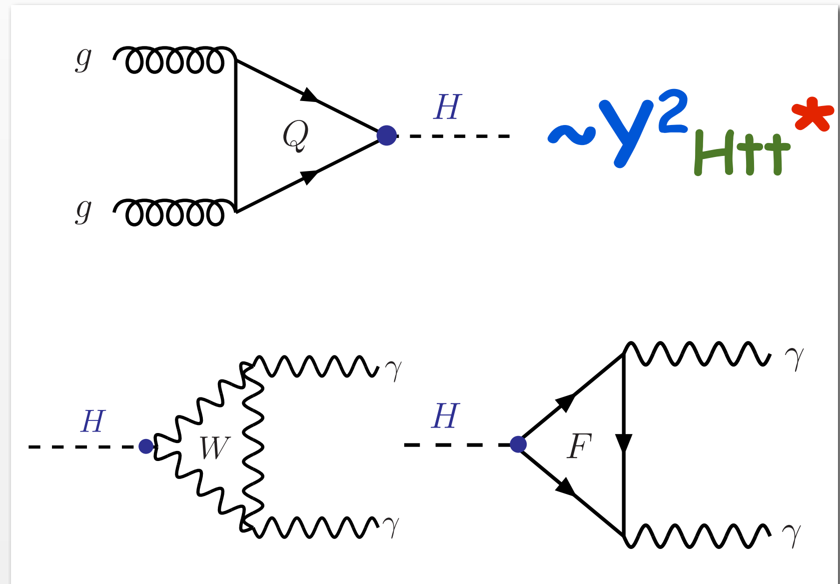
  → we now have to get acquainted with it !

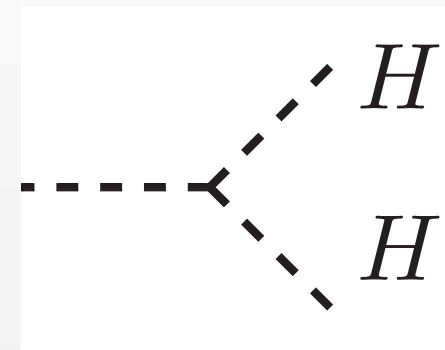
- fits of g_{HXX} and sign degeneracies
- production channels with direct sensitivity to the top-Higgs coupling g_{Htt}
- prod. channels with direct sensitivity to g_{Htt} sign
- single-top plus Higgs production :
  - the t-channel $pp \to t\,H\,q$: sensitivity to g_{Htt} sign
  - $pp \to t\,H\,q$ ($H \to \gamma\gamma$, WW, $\tau\tau$) : S vs B vs (C_V, C_f)
  - exclusion potential in the (C_V, C_f) space at 8 TeV

is the LHC signal really a SM Higgs ?

- test g_{HXX} (magnitude and structure) to vector bosons (EWSB), to fermions and self-couplings







$\sim \lambda v$

$m_H \sim 126$ GeV

$\Gamma_H = 4.2$ MeV

$\lambda = (m_H/v)^2/2 = 0.131$

$H \to WW^*$ 23%*

$H \to ZZ^*$ 2.9%*

$H \to bb$ 56%*

$H \to cc$ 2.8%

$H \to \tau\tau$ 6.2%*

$H \to \mu\mu$ 0.21‰

$H \to gg$ 8.5%*

$H \to \gamma\gamma$ 2.3‰*

$H \to \gamma Z$ 1.6 ‰*

new set of reference SM parameters

many couplings accessible at LHC (*) !

in-direct g_{HXX} determination : what we knew before LHC data !

Let's assume :

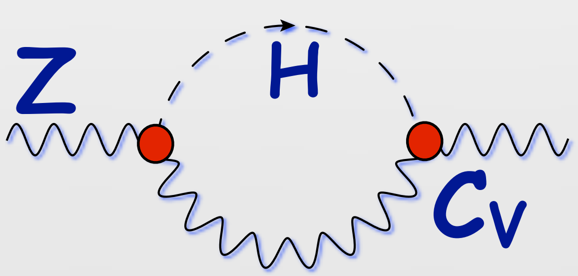
$$g_{HVV} = C_V \, g_{HVV}^{SM}$$

universal modifier of HWW and HZZ couplings

$$Y_f = C_f \, Y_f^{SM}$$

universal modifier of Hff couplings

- EWPT's highly constrain (C_V, m_H) through (indirect) loop effects :

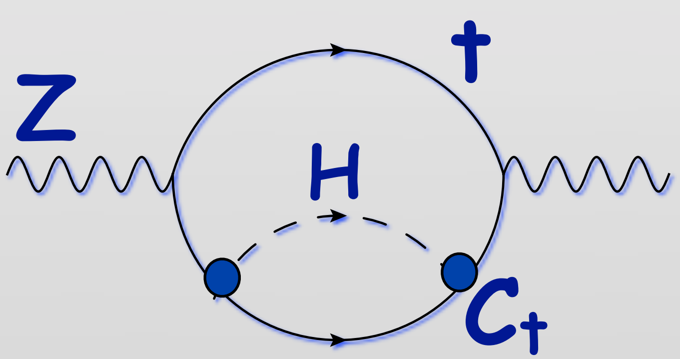


for m_H = 125 GeV

C_V = 1.01 ± 0.06 (95% CL)

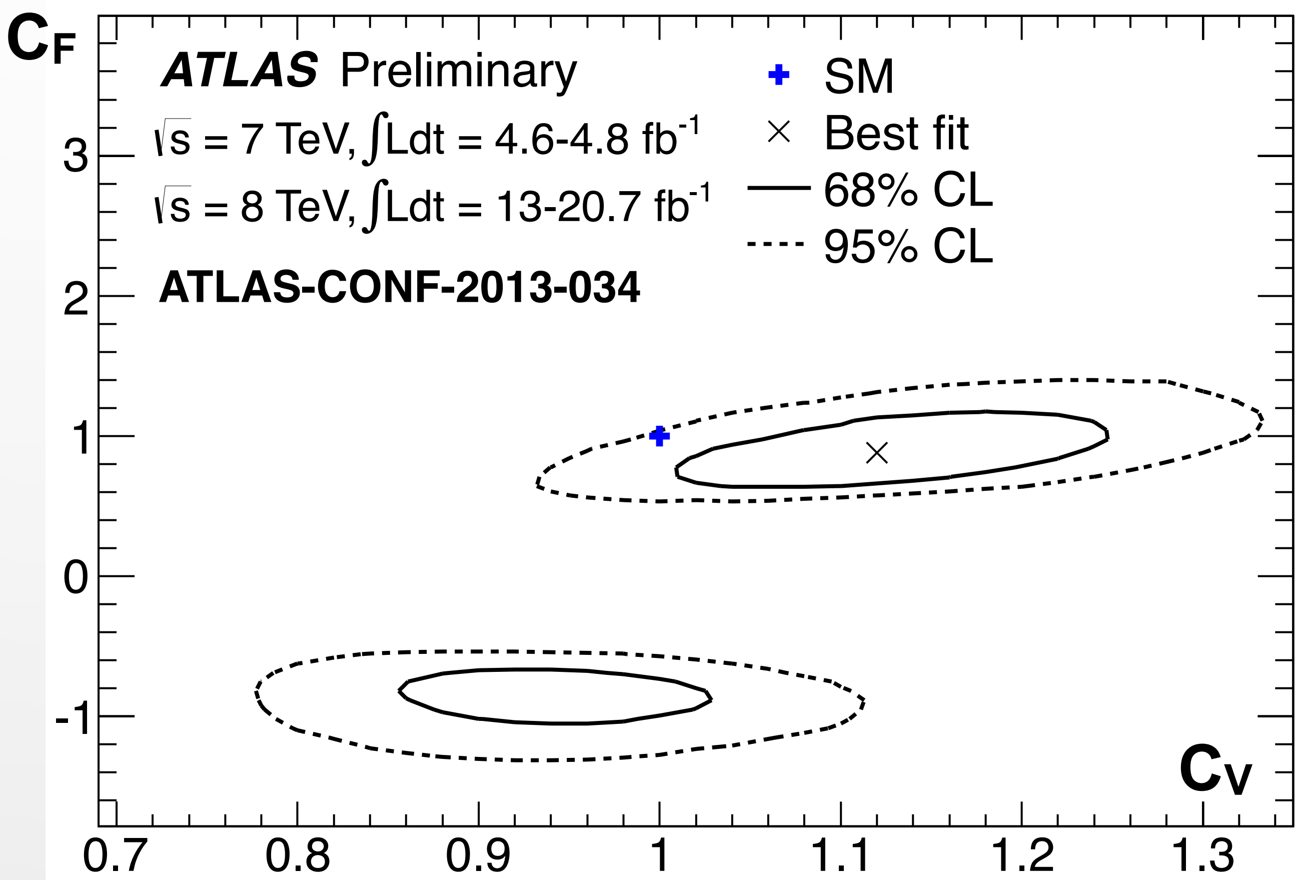
Azatov, Galloway

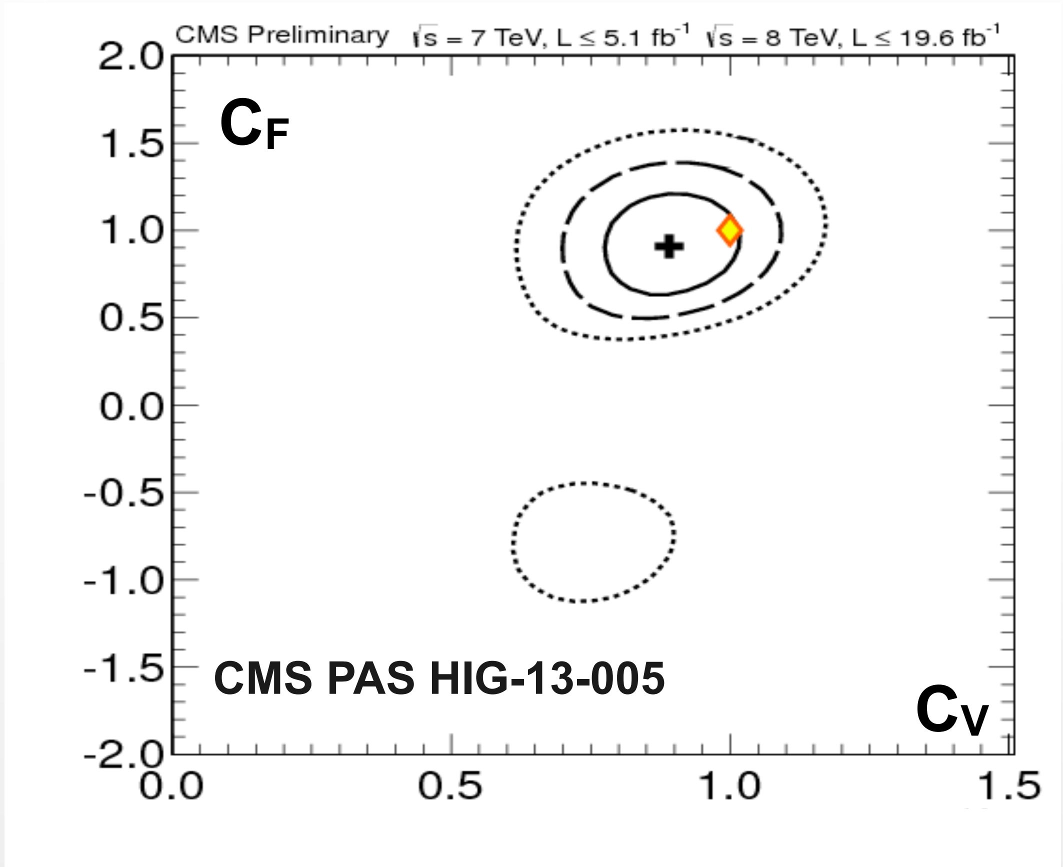
- no constrain on C_f (enter only at two loops in EWPT's)



C_f = ???

direct g_{HXX} determination : what we know today !





both agree with SM Higgs at 95%CL

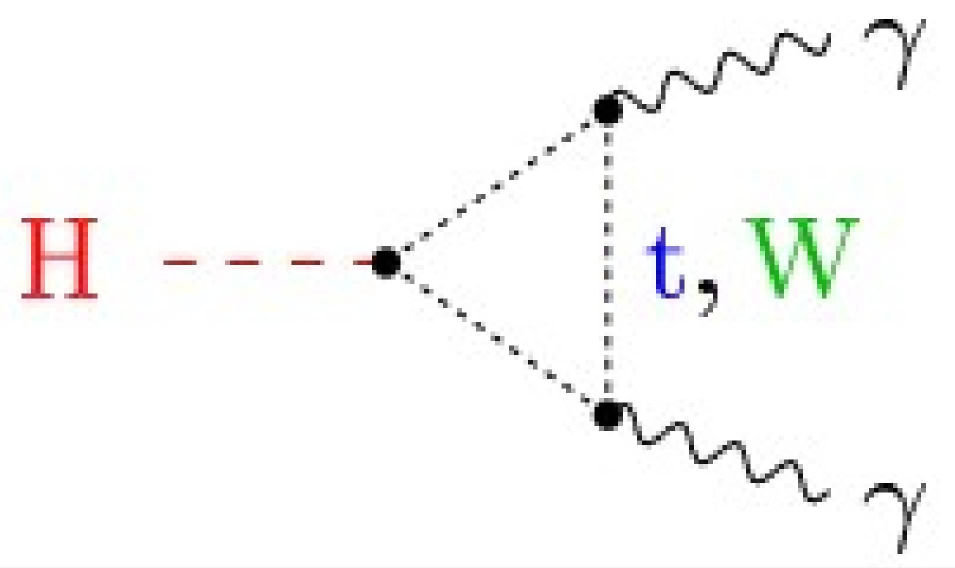
- starting point of new exciting chapter of experimental measurements (regardless of possible further new-state discoveries at the LHC !)

note: one-loop decays (H→γγ) and production (gg→H) are very sensitive to new heavy degrees of freedom that do not decouple !

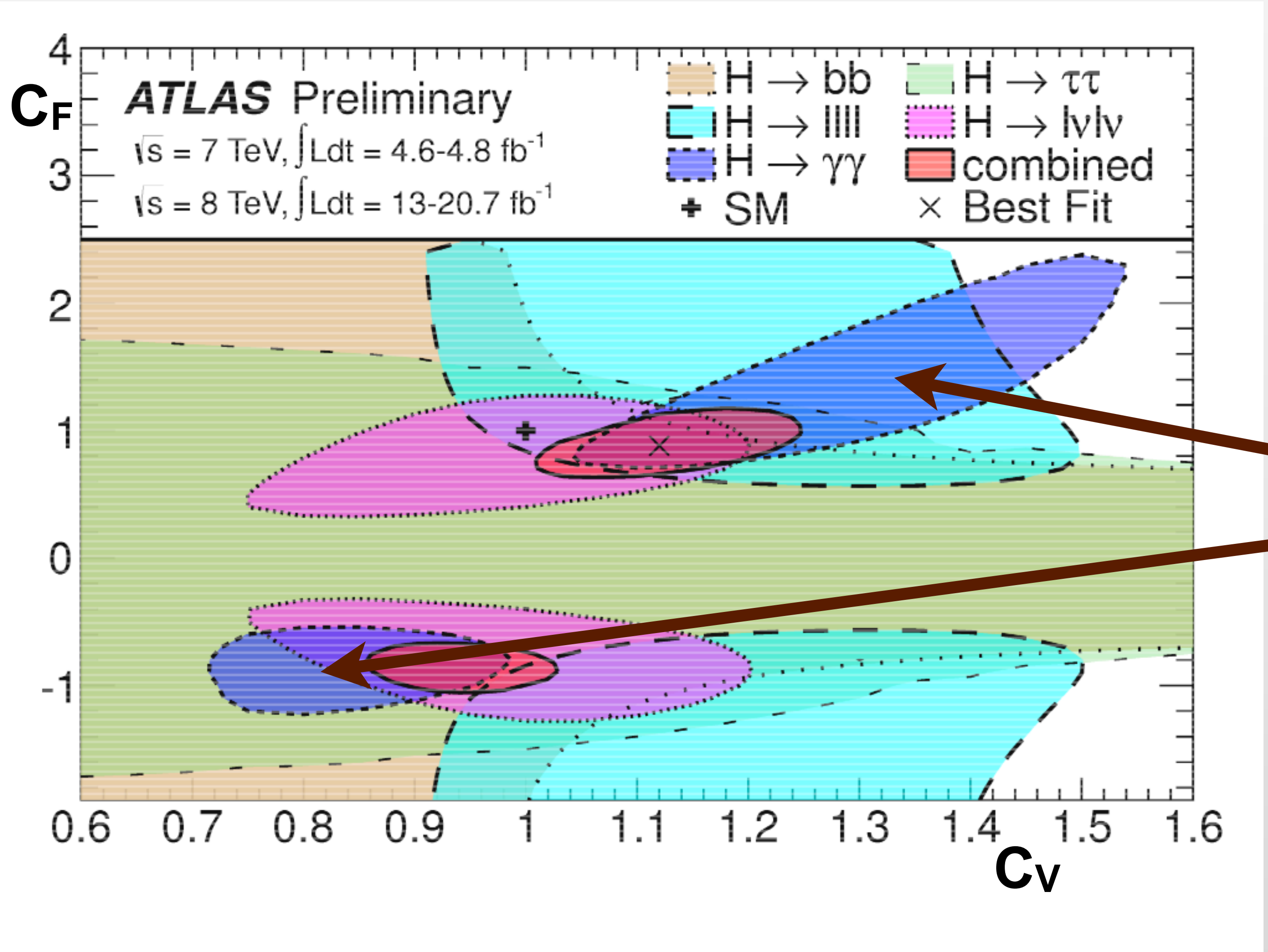
- new generation of Precision Tests opened up with excellent sensitivity to BSM effects (→ cf. EWPT's at LEP)
- ability to reach accuracies on g_{HXX}'s as large as possible is crucial !

$H \to \gamma\gamma$ breaks $C_f \to -C_f$ degeneracy

- W and top loops interferes destructively in the SM
- $C_t \sim +1$(SM) $\to$ $C_t \sim -1$ enhances $BR_{\gamma\gamma}$



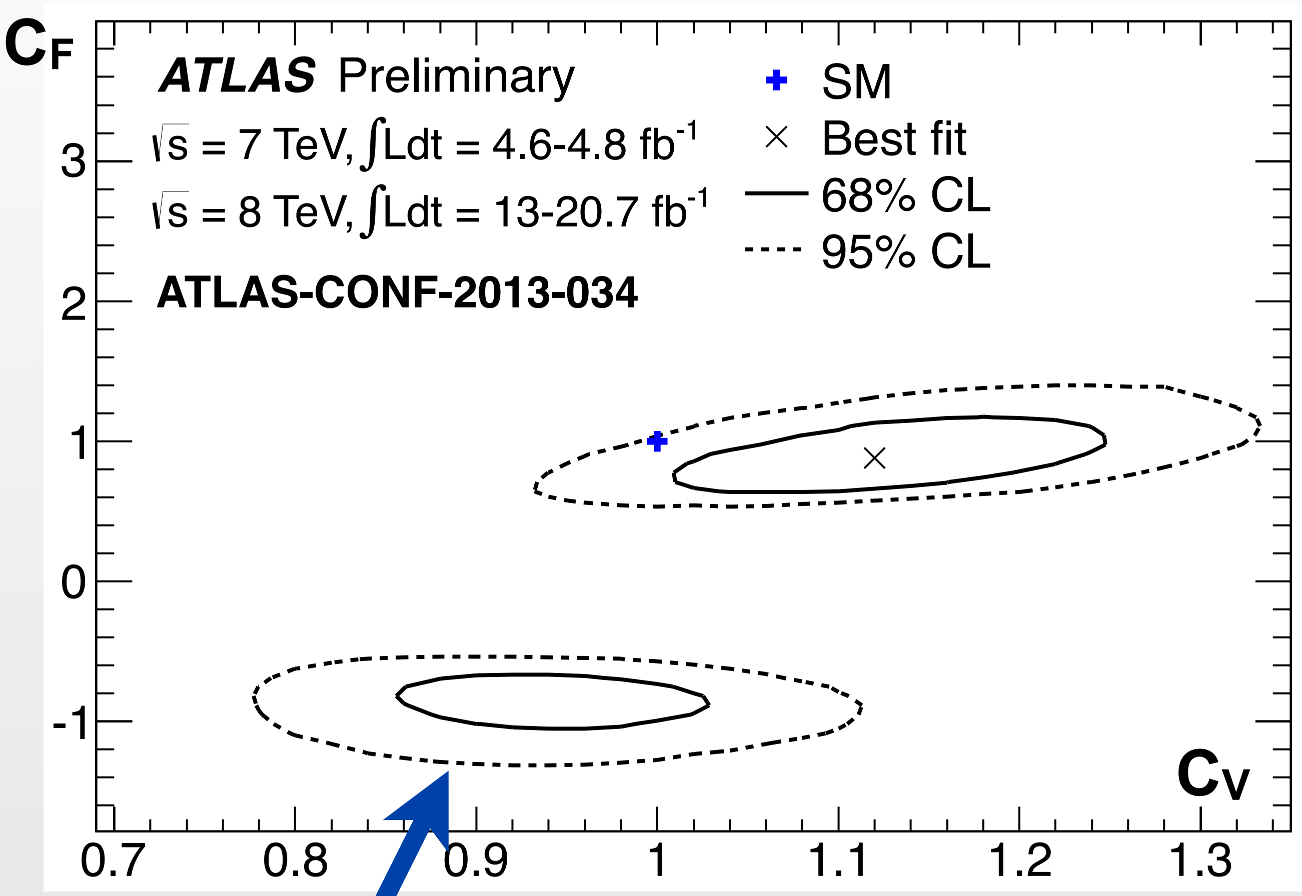
ATLAS-CONF-2013-034

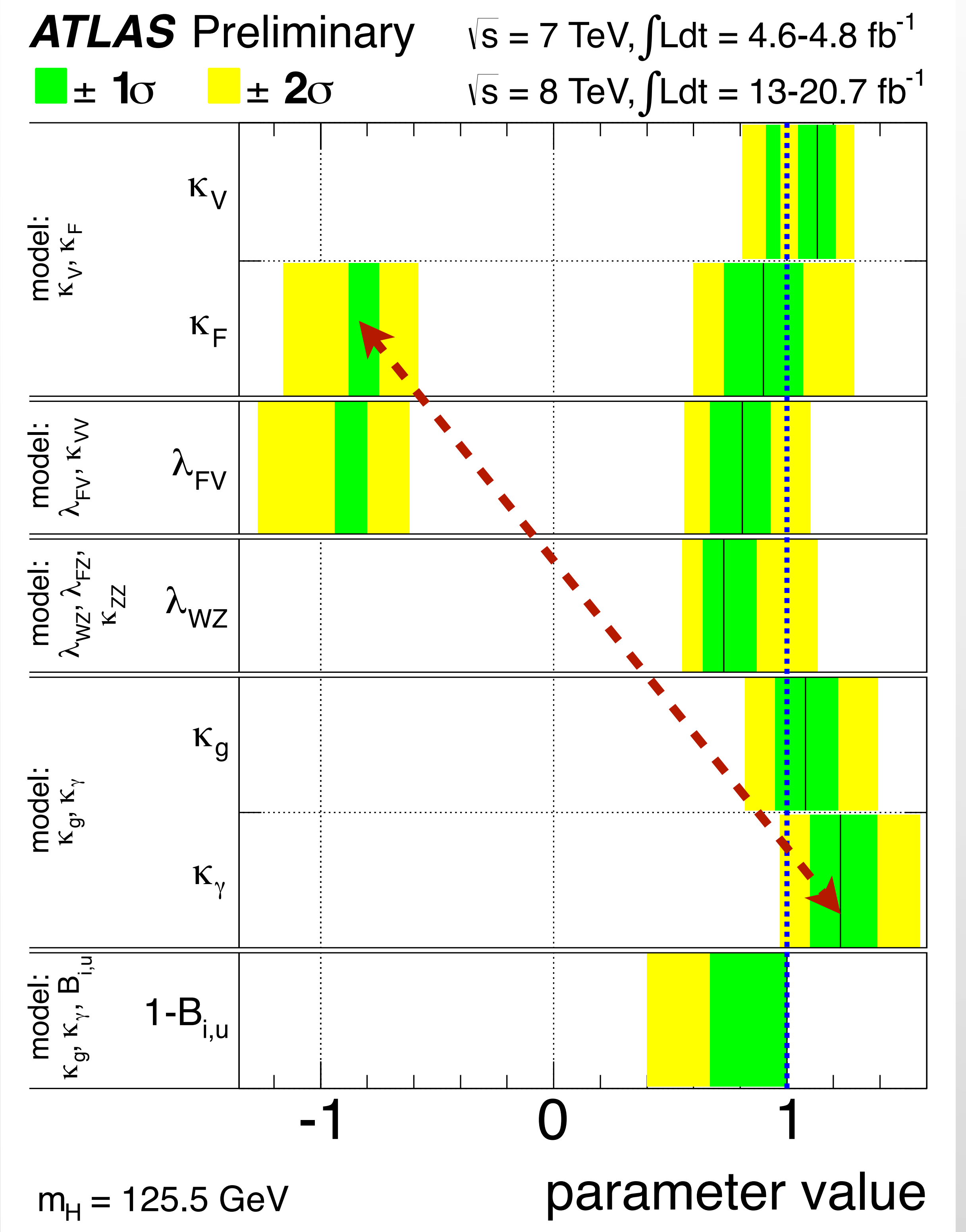


- $\sigma(H \to \gamma\gamma) \sim (5C_V - C_t)^2$ gives asymmetric constraints for $C_t \to -C_t$
- enhanced $\sigma_{\gamma\gamma}$ rates favor $C_f < 0$ ranges

g_{HXX} global fits

- enhanced $\sigma_{\gamma\gamma}$ rates favor $C_f < 0$ ranges





how much data do we still need to exclude the non-SM $C_f < 0$ region ?

BSM theories can predict $c_f < 0$!

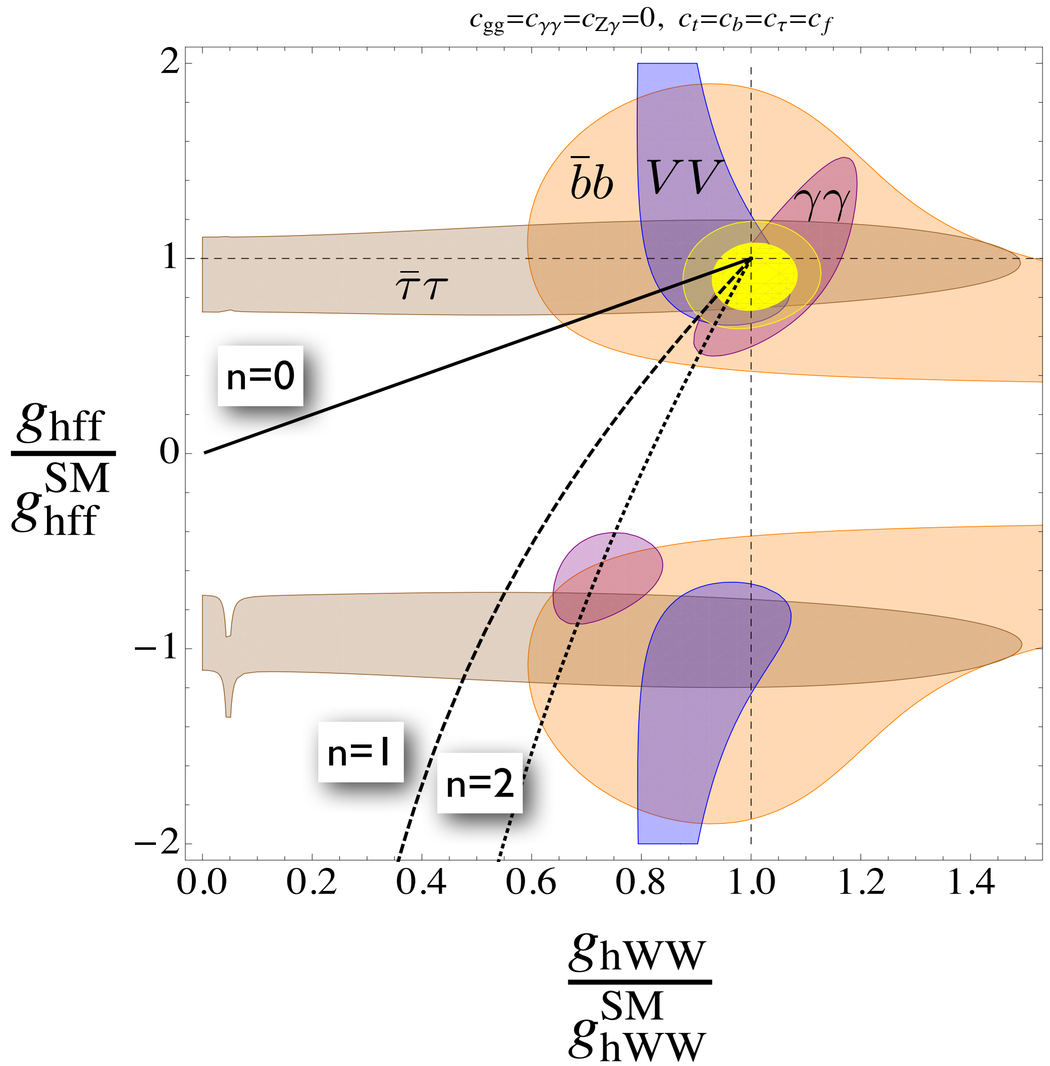
- example : Minimal Composite Higgs Models SO(5) -> SO(4) global symmetry in a strong sector broken at a scale $f_H > v$

Agashe, Contino, Pomarol, [hep-ph/0412089]

$$\xi = \frac{v^2}{f_H^2}$$

$$\frac{g_{hWW}}{g_{hWW}^{SM}} = \sqrt{1-\xi} \qquad \frac{g_{hff}}{g_{hff}^{SM}} = \frac{1-(1+n)\xi}{\sqrt{1-\xi}} \qquad n = 0, 1, 2, \ldots$$

Depending on realization

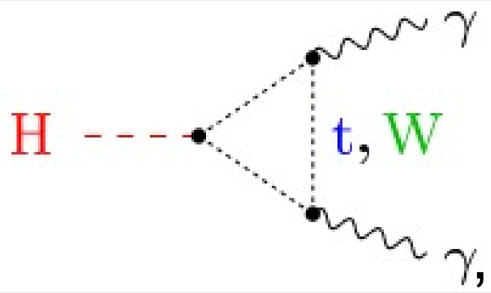


- MCHM limit

$$\to f_H \gtrsim 700\,\mathrm{GeV}$$

Falkowski, Riva, Urbano, [1303.1812]

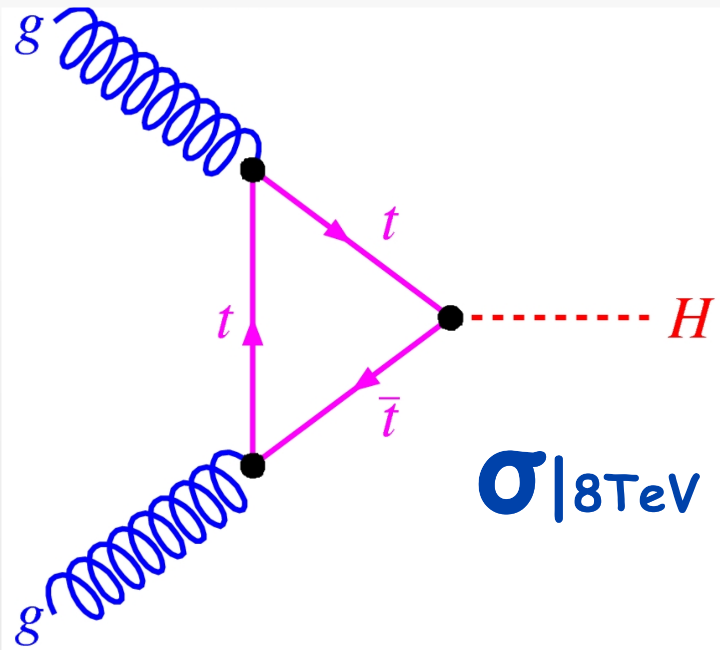
Looking for some way to experimentally discriminate the C_f sign .....

- linear terms in C_f needed → look at interferences in squared amplitudes
- in **decays**: mainly in loop channels 

- what about **production** mechanisms ???

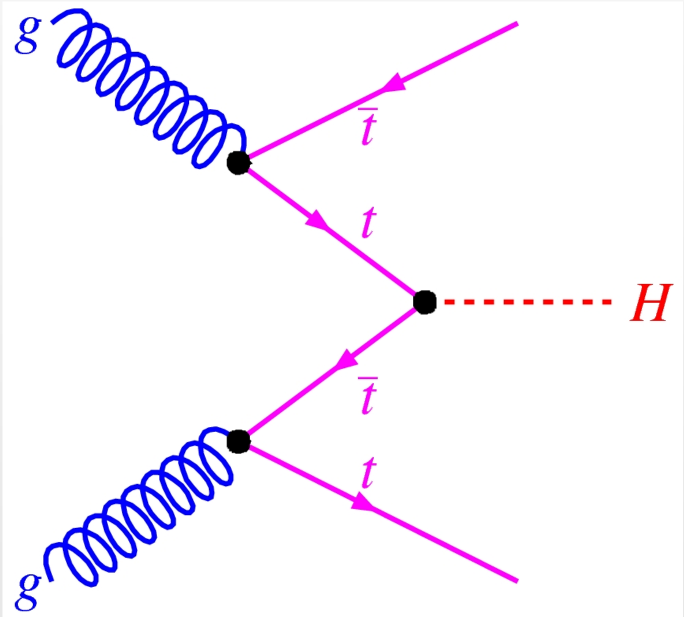
main sensitivity to C_f through g_{Htt}

- indirect (→ top quark not observed) and dominant



$\sigma|_{8TeV}$ ~ 20 pb

- direct (top quark observed) but not yet quite at reach



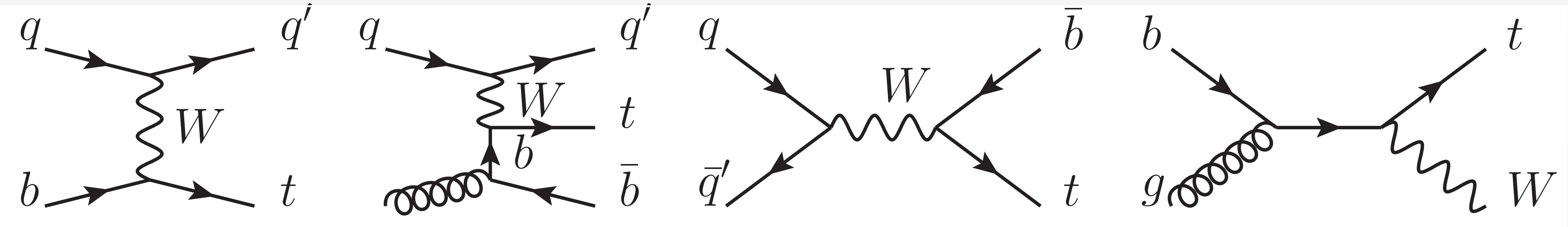
$\sigma|_{8TeV}$ ~ 130 fb

both σ's depend on C_t^2 :
no sensitivity to g_{Htt} sign !

Single top-quark + Higgs production

$$p\,p \rightarrow t\,H\,x \qquad (x = q, W, b)$$

- ask for an extra Higgs in single top production



- EW process, where Higgs emission from a top-quark interferes with Higgs emission from a W :

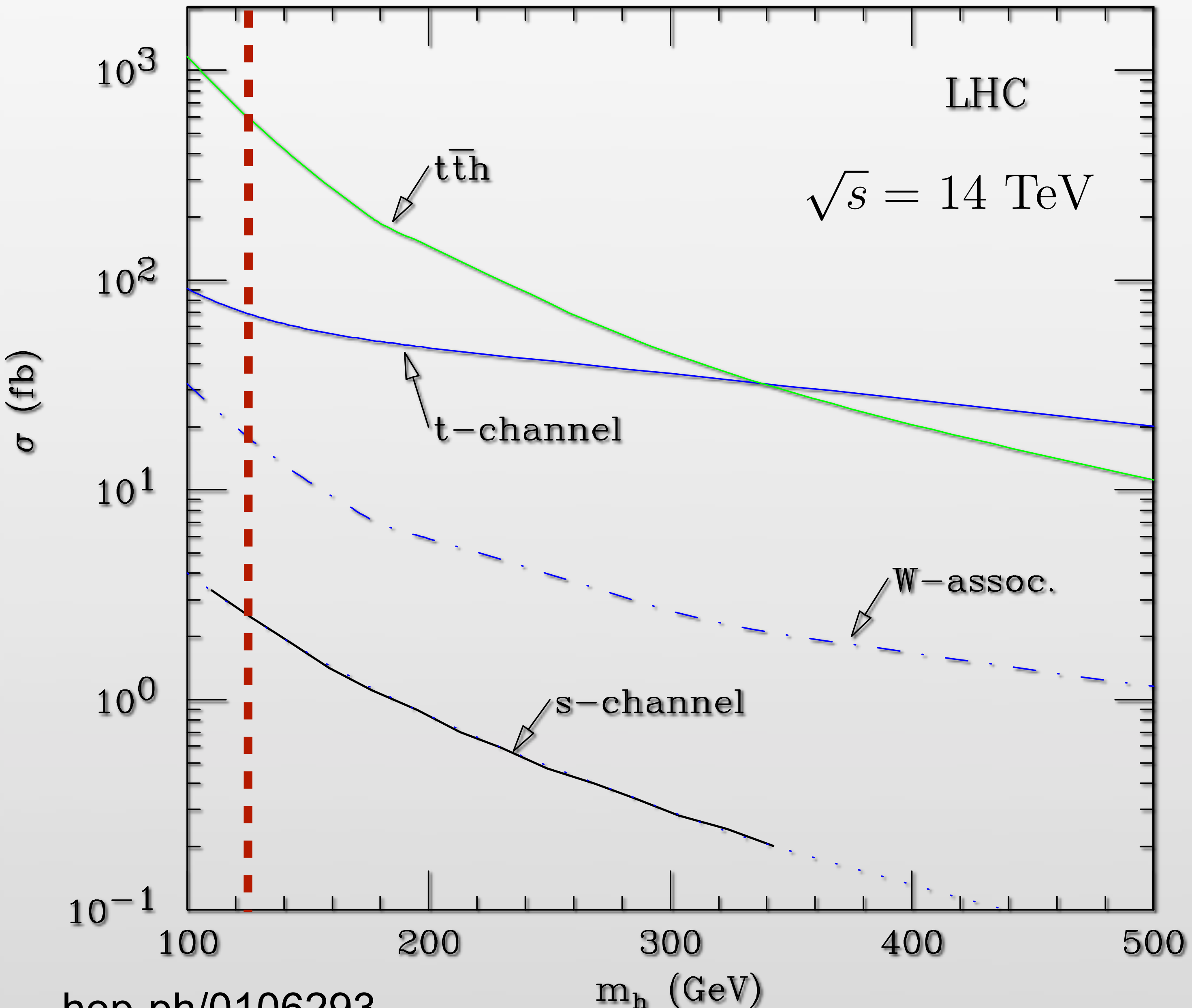
$$\sigma \sim C_t^2\, a \;+\; C_W^2\, b \;+\; C_t\, C_W\, c$$

sensitivity to C_t sign

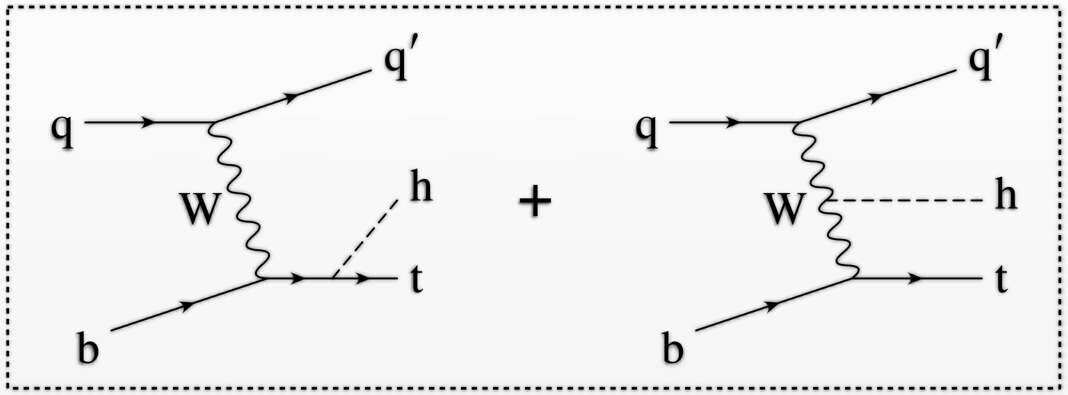
σ(pp→ t H + X) in the SM: 3 channels

- sensitive to g_{Htt} and g_{HWW}
- σ(t-channel) ~ 1/10 σ(ttH)

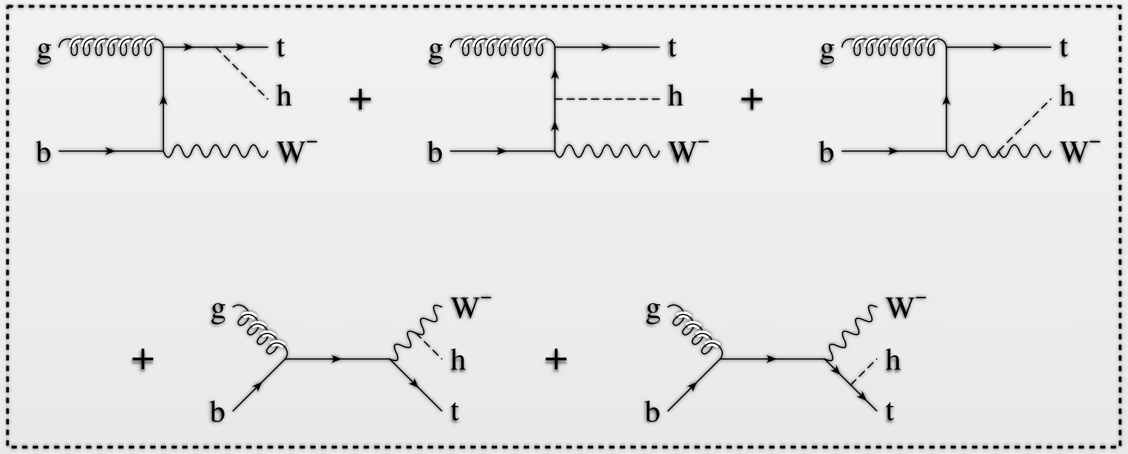
(dominant !)



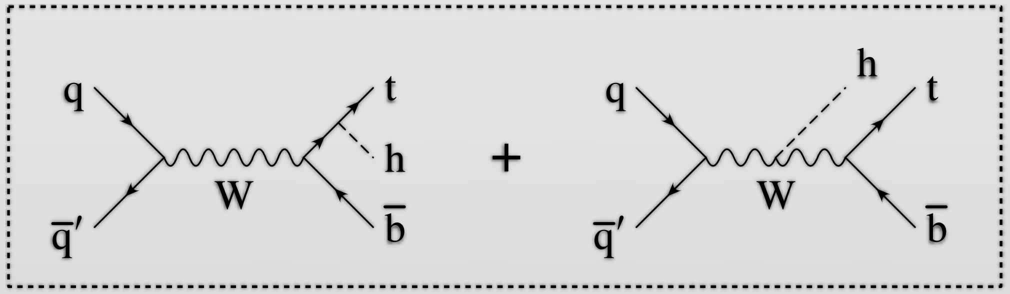
hep-ph/0106293



(t-channel)

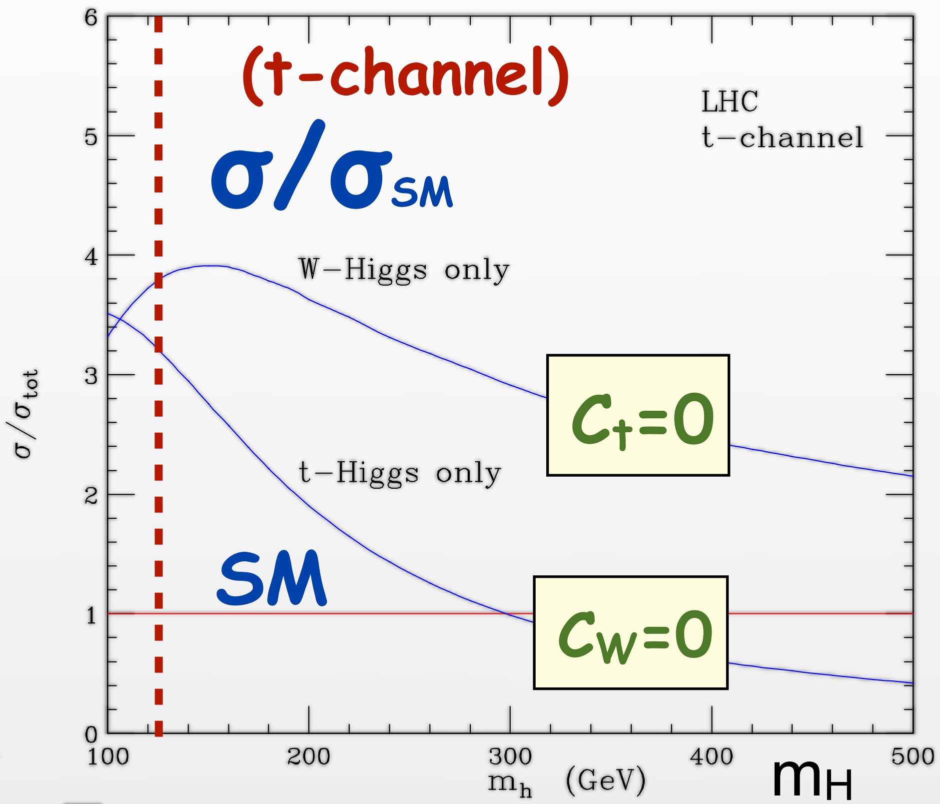


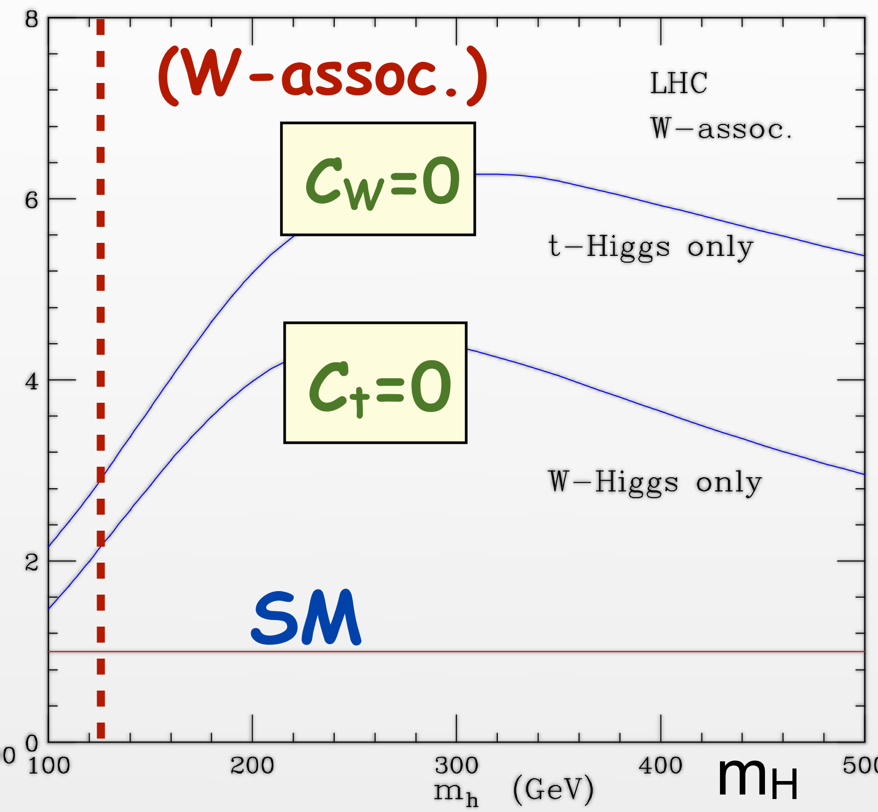
(W-assoc.)

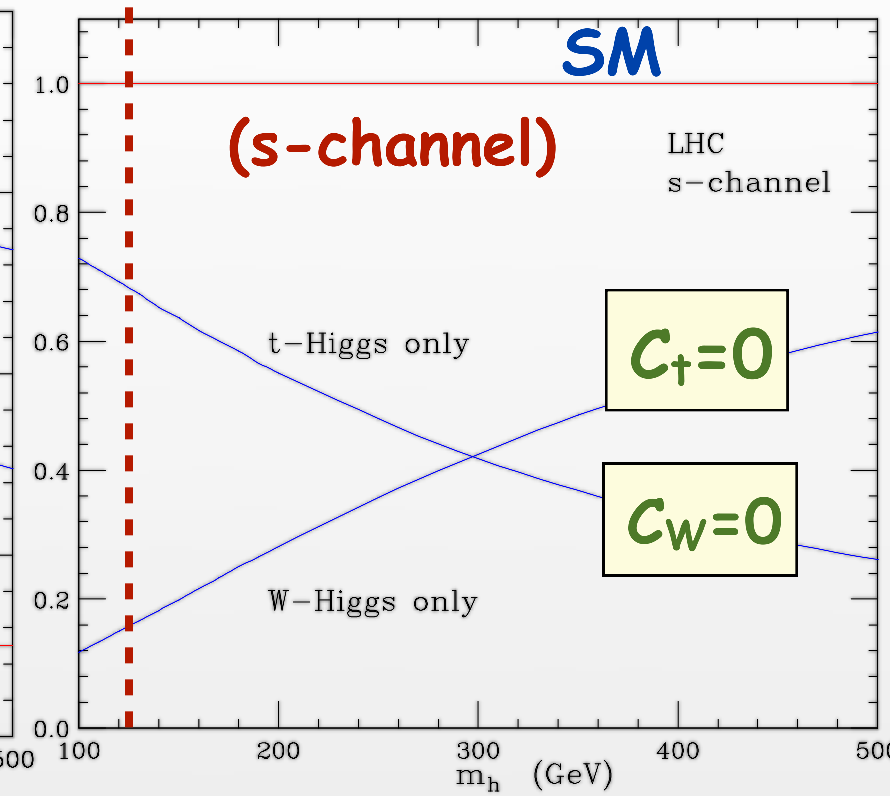


(s-channel)

switching off either g_{Htt} $C_t=0$ or g_{HWW} $C_W=0$







hep-ph/0106293

$\sqrt{s} = 14$ TeV

SM → ($C_W=1$)

σ^t (Ct= 1) = 72 fb
σ^t (Ct= 0) = 280 fb
σ^t (Ct=-1) = 890 fb

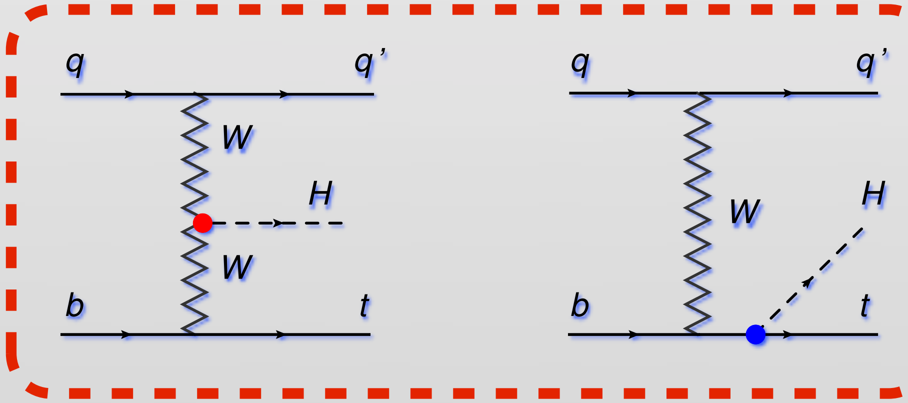
SM → ($C_W=1$)

σ^W (Ct= 1) = 16 fb
σ^W (Ct= 0) = 35 fb
σ^W (Ct= -1)= 140 fb

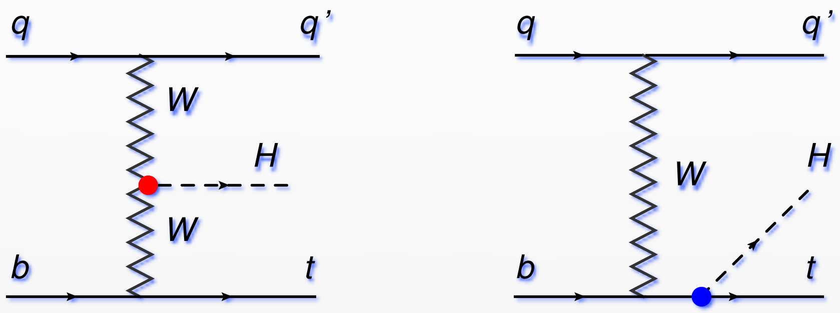
SM → ($C_W=1$)

σ^s (Ct= 1) = 2.3 fb
σ^s (Ct= 0) = 0.39 fb
σ^s (Ct= -1)= 1.5 fb

- t-channel ($pp \to tHq$) most sensitive to g_{Htt} and g_{HWW} variations
- largest cross sections !

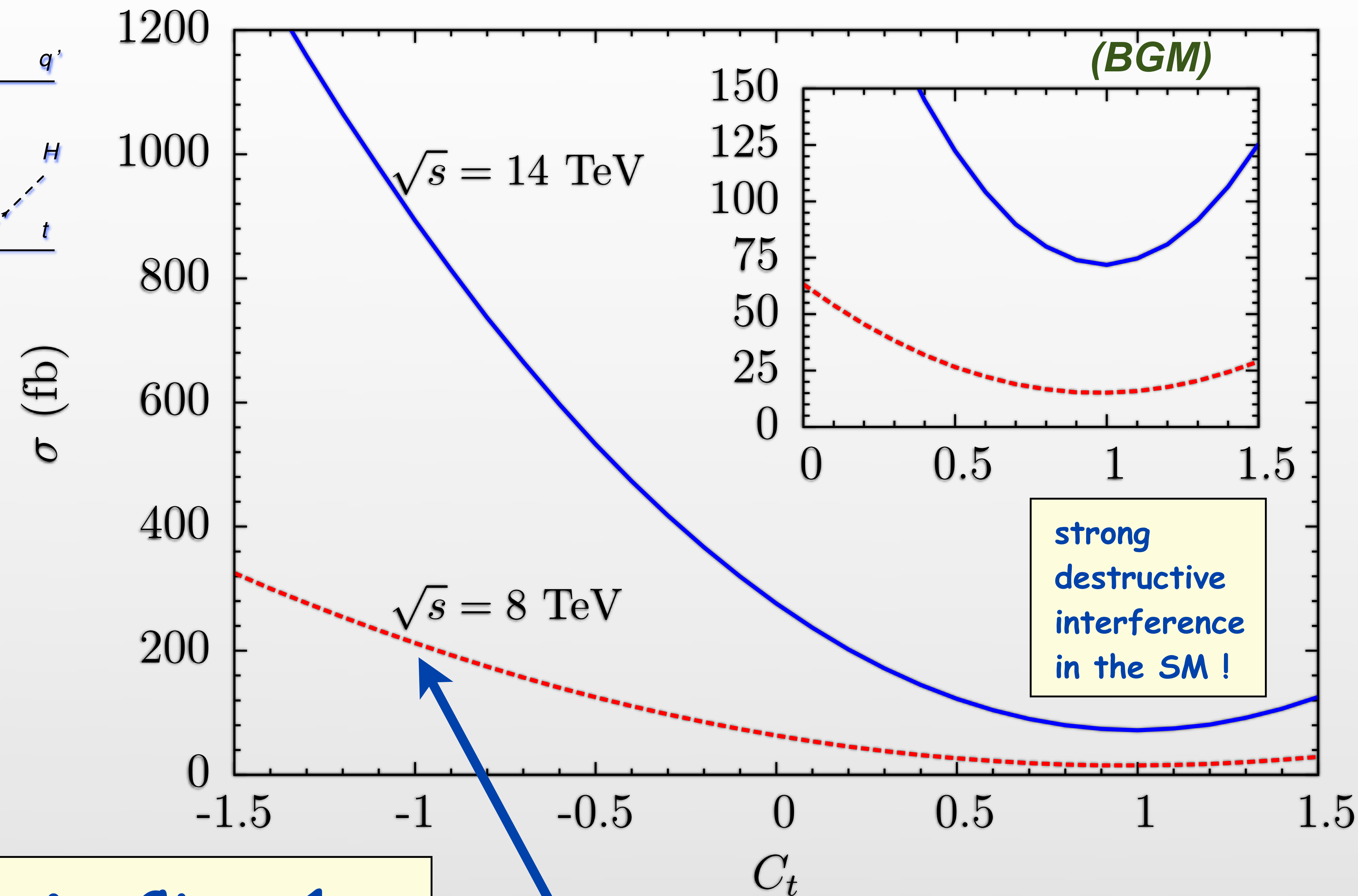


$\sigma(pp \to tHq)$ vs C_t



σ^t (SM) = 15 fb

$\sqrt{s} = 8$ TeV



- Ct =+1 (SM) ➜ Ct =-1 increases tHq production rates by factor ~ 13

prompted dedicated studies !

main references on tHq sensitivity to C_f sign

S. Biswas, E. Gabrielli, B.M. (*BGM*) ($H \to \gamma\gamma$ + top (had))

"Single top and Higgs associated production as a probe of the Htt coupling sign at the LHC", *JHEP* 01 (2013) 088 [arXiv:1211.0499]

M.Farina, C.Grojean, F.Maltoni, E.Salvioni, A.Thamm, ($H \to$ bb+top (lep))

"Lifting degeneracies in Higgs couplings using single top production in association with a Higgs boson", *JHEP* 05 (2013) 022 [arXiv:1211.3736]

S. Biswas, E. Gabrielli, F. Margaroli, B.M. (*BGMM*) ($H \to \gamma\gamma$, WW, $\tau\tau$)

"Direct constraints on the Htt coupling from the 8 TeV LHC data", *JHEP* 07 (2013) 073 [arXiv:1304.1822]

main focus here on *BGMM* results :
sensitivity to C_t sign
of present 7 + 8 TeV data set !

premise

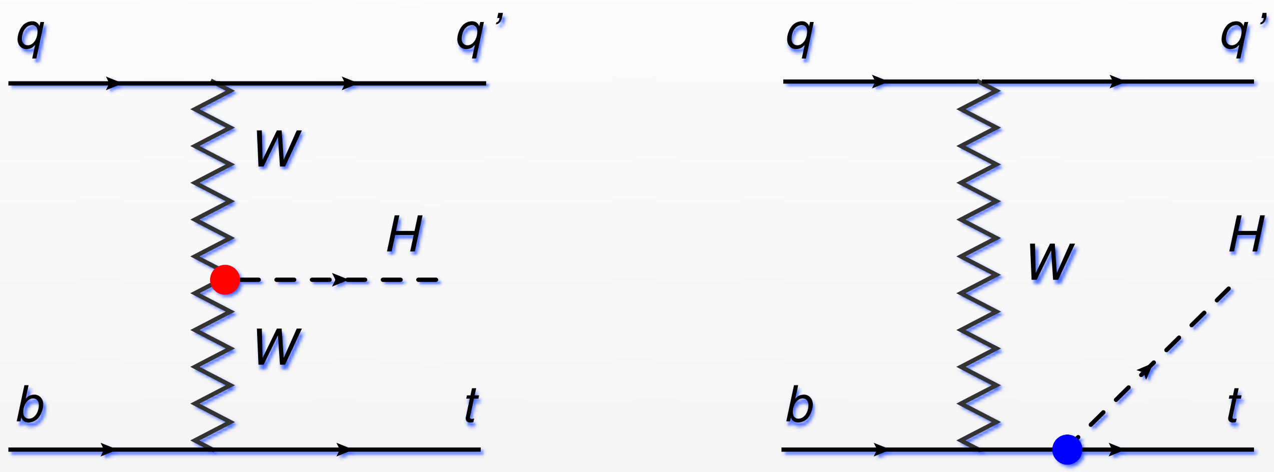
- most of plots in the following shows C_t dependence (at fixed C_V=1)
- easy to see that in (single-top + Higgs) production :

$$d\,\sigma = d\,\sigma(C_W, C_t) = |C_W|^2\, d\,\sigma(1, C_t/C_W)$$

➜ straightforward to get C_V- from C_t-dependence !

- what is physical is the relative sign of g_{Hff} and g_{HVV}
- we will assume C_V > 0 following exp.s' fits
- 2 benchmark scenarios :
  - universal C_f (=C_t) (described first, and more extensively)
  - free C_t , and SM-like C_b=C_c=C_τ= 1

tHq signatures under scrutiny



$H \to \gamma\gamma,\ WW,\ \tau\tau$

- combination of 3-object products:
  - forward light jet (→ rapidity-cut)
  - t → W (had, lept) + b-jet (tagged)
  - $H \to \gamma\gamma$

$$\to WW^* \to \ell\nu\ell'\nu,\ \ell\nu\, qq'$$

$$\to \tau\tau \to \ell\nu\nu\,\ell'\nu\nu,\ \ell\nu\nu + had(s)$$

Higgs most robust signatures at reach at 8 TeV !

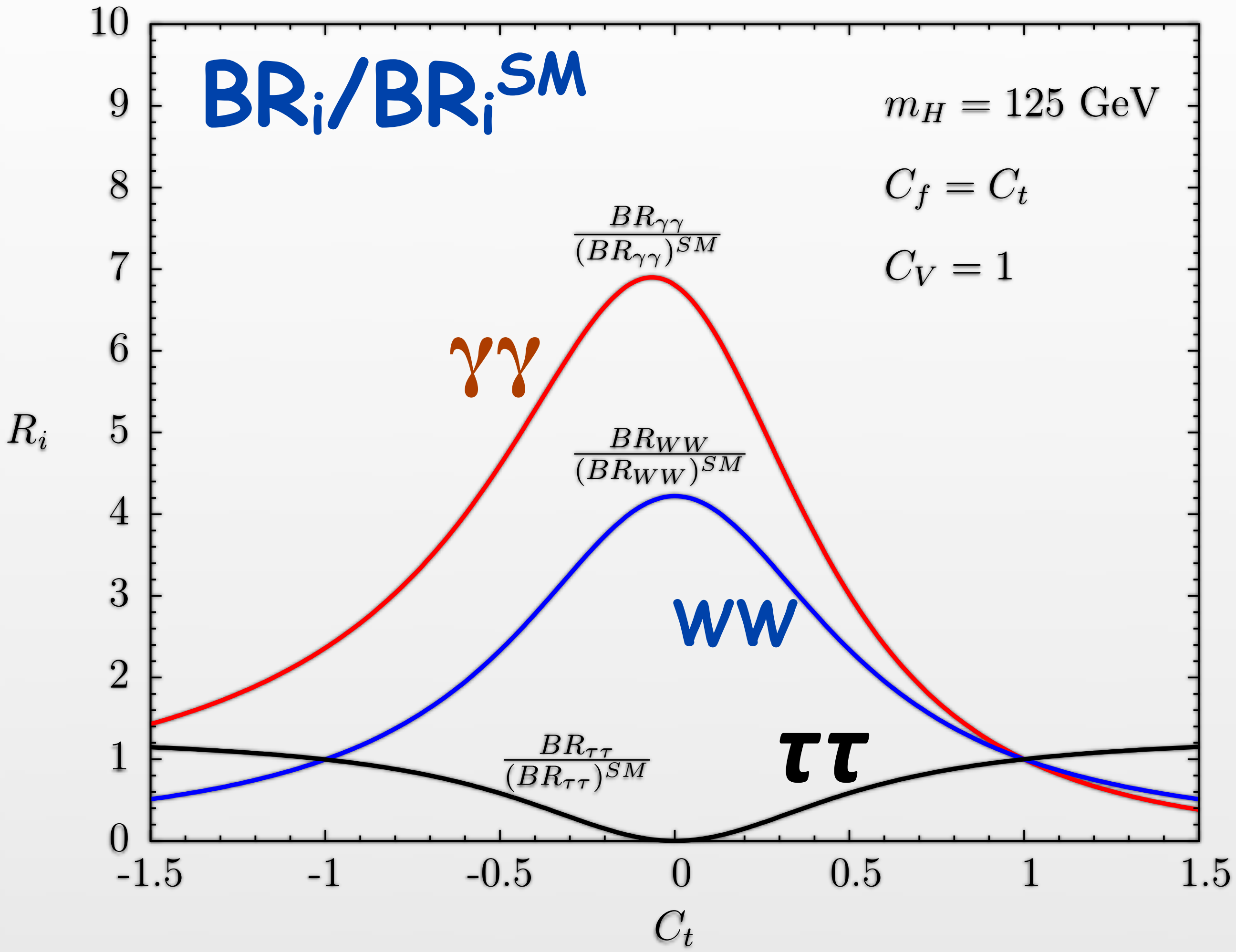
pheno mostly ruled by σ/σ^{SM} and BR_i/BR_i^{SM} behavior versus C_t

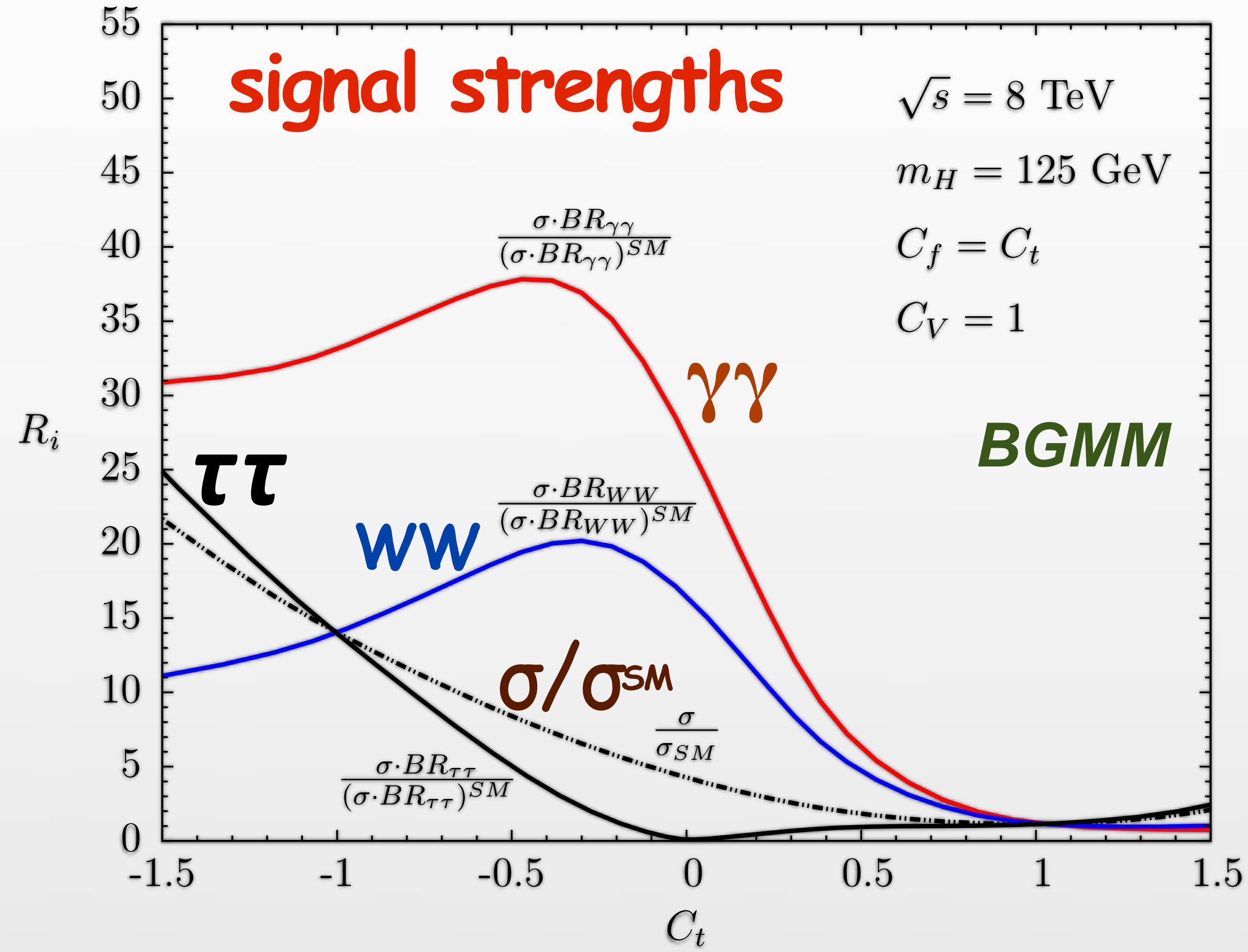
$$R_\sigma = \frac{\sigma}{\sigma^{SM}} \qquad R_{BR_{\gamma\gamma,WW,\tau\tau}} = \frac{BR_{\gamma\gamma,WW,\tau\tau}}{(BR_{\gamma\gamma,WW,\tau\tau})^{SM}}$$

signal strength vs C_t :

$$R_{\sigma\cdot BR_{\gamma\gamma,WW,\tau\tau}} = \frac{\sigma \cdot BR_{\gamma\gamma,WW,\tau\tau}}{(\sigma \cdot BR_{\gamma\gamma,WW,\tau\tau})^{SM}}$$

BR_i/BR_i^{SM} and σ_i/σ_i^{SM} vs Ct



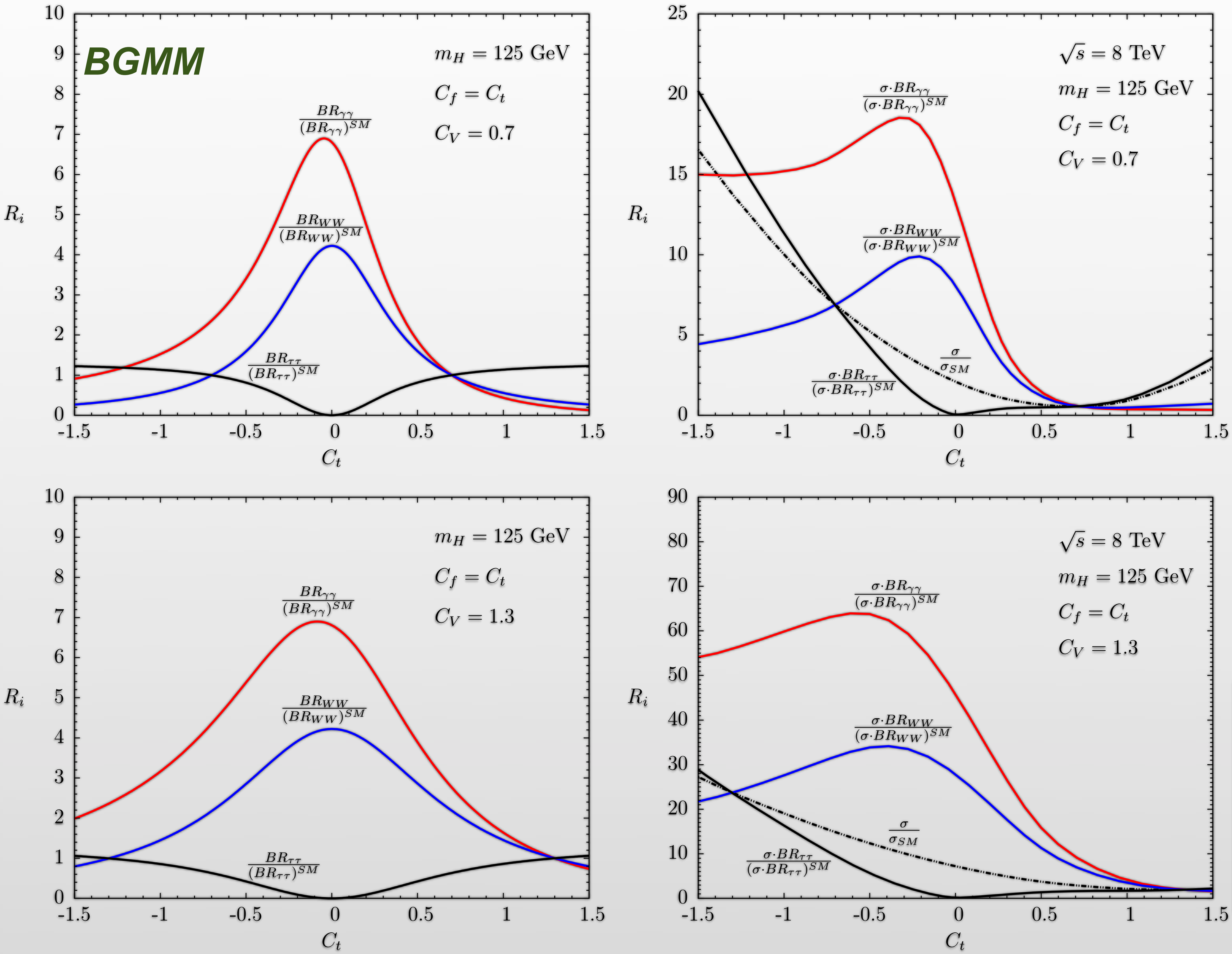


$BR_{\gamma\gamma}$ and BR_{WW} mostly ruled by $1/\Gamma_H \sim 1/(\Gamma_b + \Gamma_\tau) \sim 1/C_t^2$

→ enhancement for $|Ct| \to 0$ in (asym.) $BR_{\gamma\gamma}$ and BR_{WW}

σ/σ^{SM} levels up corresponding signal strengths for $Ct < 0$!

changing Cv in BR_i/BR_i^{SM} and σ_i/σ_i^{SM}



Cv = 0.7

Cv = 1.3

affects both normalization and shapes

tHq signal ($H \to \gamma\gamma$, WW, $\tau\tau$) vs bckgr

BGMM

- parton level study (MadGraph 5)
- includes mostly irreducible bckgr's
  → fair approx. for multi-photon / multi-lepton final states
- list of included signal final states :
  - 2 photons + jet (forward) + b-jet + jets
  - 2 photons + lepton + jet (forward) + b-jet + jet
  - 3 leptons + jet (forward) + b-jet
  - 2 Same-Sign leptons + jet (forward) + b-jet + jets
- always requires a forward light-jet and a b-jet tagging
- no requirement on E_T^{miss} from neutrinos
- studies (combined) $S/\sqrt{(S+B)}$ versus (C_V, C_t)
  at $\sqrt{S} = 8$ TeV for 50 fb^{-1} (~ present ATLAS + CMS data set)

bckgr studies : H → γγ + top (had)

(universal C_f scenario)

- $pp \to 2\,\gamma + t + j;$
- $pp \to H(\to \gamma\gamma) + t\bar{t};$
- $pp \to 2\,\gamma + \bar{t}\,t;$
- $pp \to 2\,\gamma + b + 3\,j.$

$$\Delta R_{i,j} = \sqrt{\Delta\eta^2_{i,j} + \Delta\phi^2_{i,j}} > 0.4$$

for any photon/ lepton/ parton pair in all channels

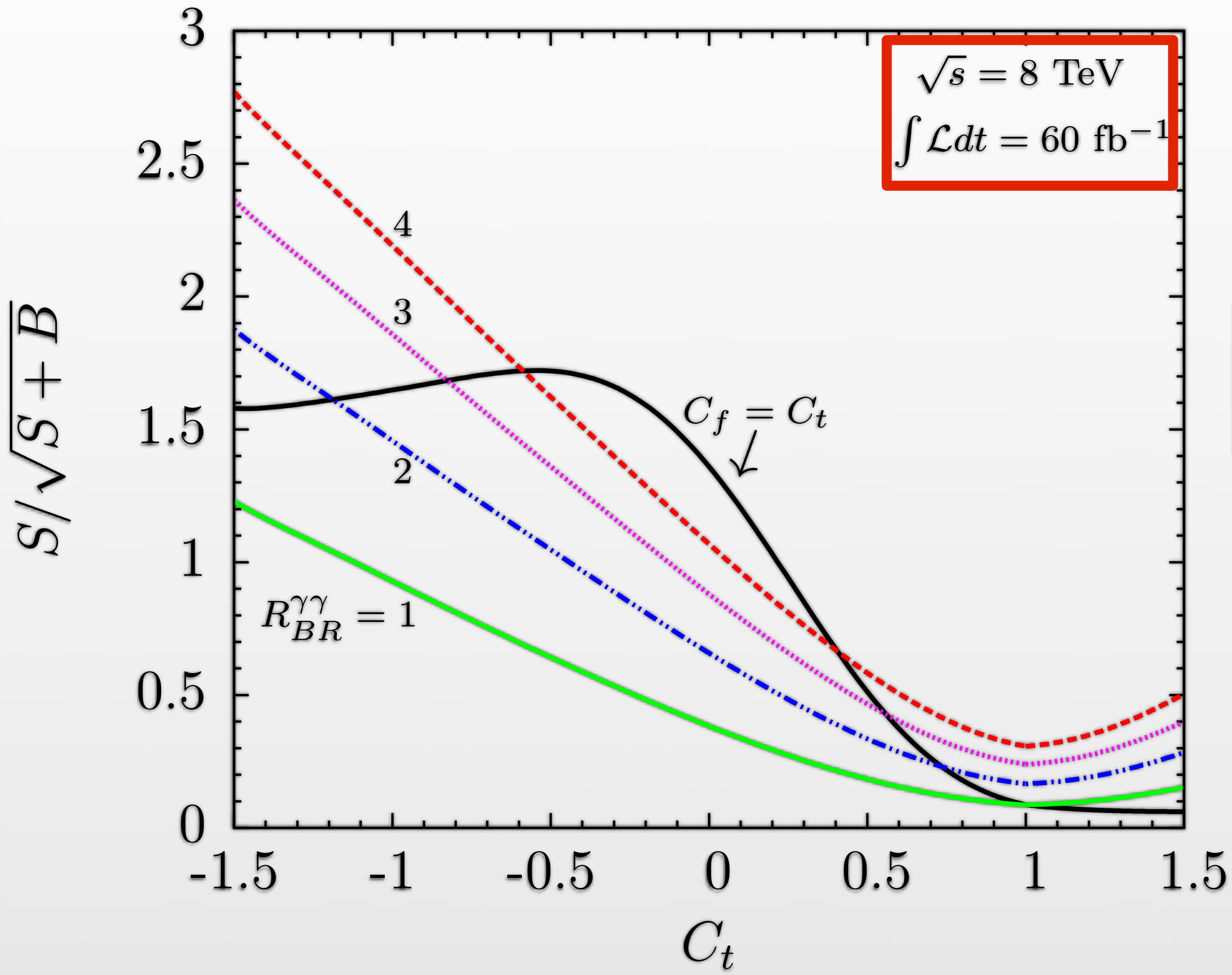
event numbers

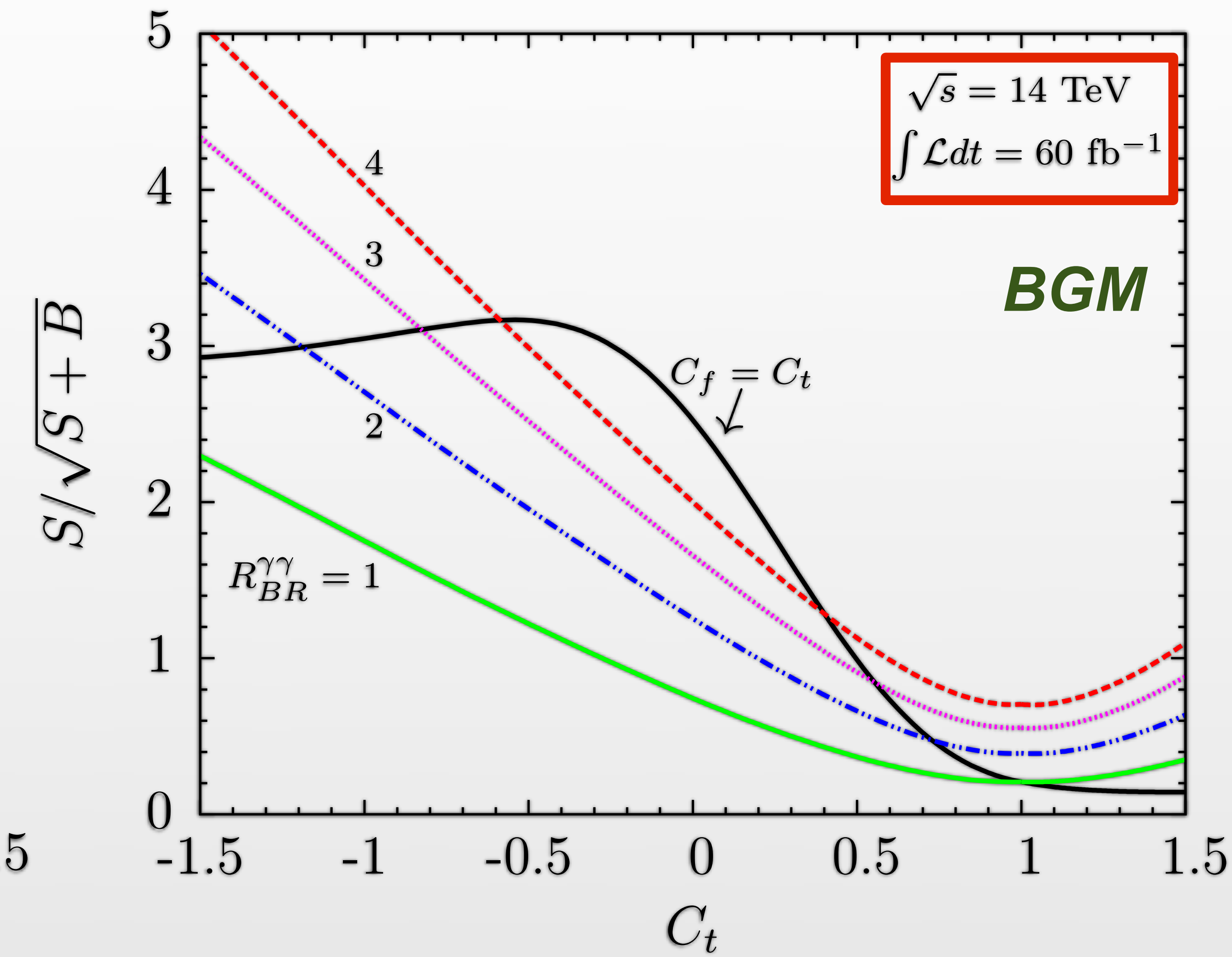
$\sqrt{s} = 8$ TeV (50 fb^{-1})	*Signal (S)*			*Background (B)*				
Cut	$C_t = -1$	$C_t = 0$	$C_t = 1$	$2\gamma\, tj$	$2\gamma\, t\bar{t}$	$t\bar{t}H$	$2\gamma\, b\, 3j$	*Total*
$2\gamma + b + (\geq 3\,j)$	6.4	5.1	0.18	8.2	9.2	1.6	249	268
$\lvert\eta_{j_F}\rvert > 2.5$ & $p_{T_{j_F}} > 30$ GeV	3.0	2.5	0.08	3.3	0.32	0.06	22	26
$\lvert M_{bjj} - m_t\rvert < 20$ GeV	3.0	2.4	0.08	2.8	0.20	0.02	4.5	7.5
$\lvert M_{jj(top)} - M_W\rvert < 15$ GeV	2.8	2.3	0.07	3.2	0.19	0.02	1.8	5.2
$\lvert M_{\gamma\gamma} - m_H\rvert < 3$ GeV	2.8	2.3	0.07	0.12	0.02	0.02	0.57	0.73
$S/\sqrt{S+B}$	1.5	1.3	0.08					

BGMM

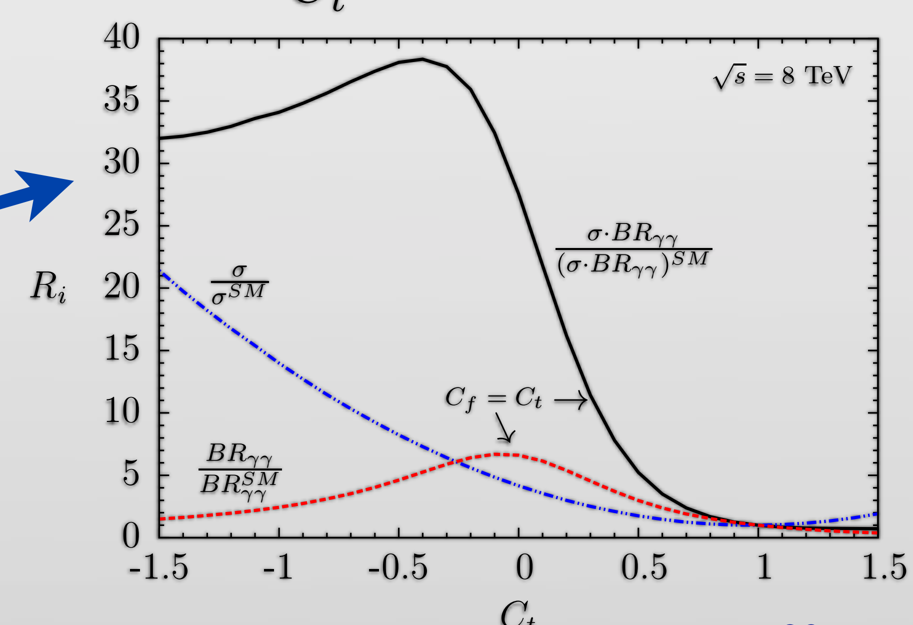
$$p_T^{\gamma_1} > 40 \text{ GeV}, \quad p_T^{\gamma_2} > 30 \text{ GeV}, \quad p_T^{j,b} > 25 \text{ GeV}, \quad |\eta_{\gamma,b}| < 2.5, \quad |\eta_j| < 4.5.$$

bckgr studies : $H \to \gamma\gamma$ + top (had)





significance vs C_t follows signal strength pattern



bckgr studies : H → γγ + top (lept)

- $pp \to 2\,\gamma + t + j;$
- $pp \to H(\to \gamma\gamma) + t\bar{t};$
- $pp \to 2\,\gamma + \bar{t}\,t;$
- $pp \to 2\,\gamma + W + b + \ j.$

event numbers

$\sqrt{s} = 8$ TeV (50 fb^{-1})	*Signal (S)*			*Background (B)*				
Cut	$C_t = -1$	$C_t = 0$	$C_t = 1$	$2\gamma\,tj$	$2\gamma\,t\bar{t}$	$t\bar{t}H$	$2\gamma\,W\,bj$	*Total*
$2\gamma + \ell + b\,(\geq ,\mathrm{j})$	3.01	2.35	0.08	7.0	6.5	0.8	5.0	19.3
$\|M_{\gamma\gamma} - m_H\| < 3$ GeV	3.01	2.35	0.08	0.16	0.18	0.77	0.09	1.20
$\|\eta_{j_F}\| > 1.5$	2.54	2.01	0.06	0.12	0.04	0.15	0.03	0.34
$S/\sqrt{S+B}$	1.5	1.4	0.09					

BGMM

$p_T^{\gamma} > 20$ GeV, $\quad p_T^{\mu} > 20$ GeV, $\quad p_T^{e,j,b} > 25$ GeV, $\quad |\eta_{\gamma,l,b}| < 2.5, \quad |\eta_j| < 4.5.$

bckgr studies : $H \to \ell\nu(\nu)\ell\nu(\nu)$ $\quad t \to b\ell\nu$

(H → WW, τ τ   3 leptons)

- $pp \to t\bar{t} + W$;
- $pp \to t\bar{t} + Z$;
- $pp \to t\bar{t} + H$;
- $pp \to t + WW + j$;
- $pp \to t + WZ + j$;
- $pp \to b + WZ + j$;
- $pp \to b + WWZ$.

2 compl.ry sets :

$e^\pm e^\pm \mu^\mp$ $\quad \mu^\pm \mu^\pm e^\mp$

$\ell_i^\pm \ell_i^\pm \ell_j^\mp + b + jets$ (no Z → $\ell^+\ell^-$ bckgr)

$\ell_i^\pm \ell_j^\pm \ell_j^\mp + b + jets$ (Z → $\ell^+\ell^-$ bckgr)

$\sqrt{s} = 8$ TeV (50 fb^{-1})	*Signal (S)*			*Background (B)*				
Cut	$C_t = -1$	$C_t = 0$	$C_t = 1$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$tWWj$	*Total*
$\ell_i^\pm \ell_i^\pm \ell_j^\mp bq$	0.96	0.81	0.06	3.69	0.14	1.07	0.04	4.94
$\lvert\eta_j^F\rvert > 1.5$	0.81	0.70	0.05	0.64	–	0.18	0.01	0.83
$S/\sqrt{S+B}$	0.63	0.57	0.05					
	Signal (S)			*Backgrounds (B)*				
	$C_t = -1$	$C_t = 0$	$C_t = 1$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$tWWj$	*Total*
$\ell_i^\pm \ell_j^\pm \ell_j^\mp bq$	3.11	2.58	0.18	12.2	43.5	3.3	0.2	59.2
$\lvert\eta_j^F\rvert > 1.5$	2.72	2.22	0.14	2.6	11.0	0.6	0.1	14.3
$M_{\ell_j^+\ell_j^-} \notin [86.2, 96.2]$ GeV	2.16	1.76	0.11	2.0	0.2	0.4	-	2.6
$S/\sqrt{S+B}$	0.99	0.88	0.07					

$N_\ell = 3 \qquad p_T^\ell > 20$ GeV, $\qquad p_T^{(j,b)} > 20$ GeV $\qquad |\eta_{\ell,b}| < 2.5, \qquad |\eta_j| < 4.5$

bckgr studies : $H \to \ell\nu\, qq', \ell\nu\nu + had(s) \quad t \to b\ell\nu$

(H → WW, ττ ; 2SS leptons)

- $pp \to t\bar{t} + W;$
- $pp \to t\bar{t} + Z;$
- $pp \to t\bar{t} + H;$
- $pp \to t + WW + j;$
- $pp \to t + W + jjj.$

$\sqrt{s} = 8\,\text{TeV}$ (50 fb^{-1})	*Signal (S)*			*Backgrounds (B)*					
Cut	$C_t = -1$	$C_t = 0$	$C_t = 1$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$tWWj$	$tW\,3j$	*Total*
$\ell^\pm\ell^\pm bqqq$	7.8	6.3	0.53	45.1	3.7	8.4	0.5	0.3	57.9
$\lvert\eta_j^F\rvert > 1.5$ GeV	6.6	5.4	0.42	11.3	0.6	1.8	0.2	0.1	13.9
$S/\sqrt{S+B}$	1.5	1.3	0.11						

$N_\ell = 2 \qquad p_T^\ell > 20$ GeV, $\qquad p_T^{(j,b)} > 20$ GeV $\qquad \lvert\eta_{\ell,b}\rvert < 2.5, \qquad \lvert\eta_j\rvert < 4.5$

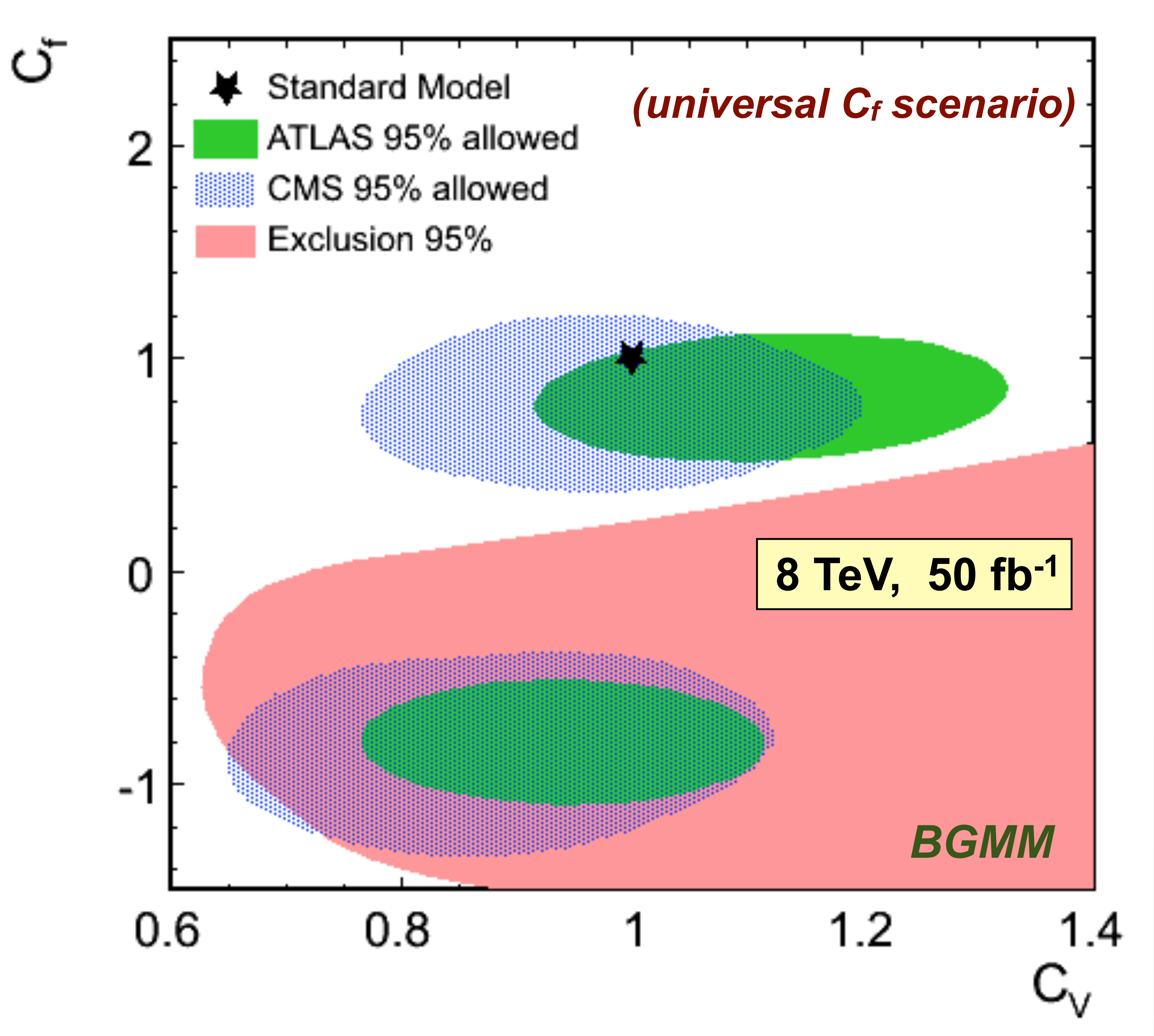
combination

	Channels					Total
Process	$\gamma\gamma bqqq'$	$\gamma\gamma b\ell q'$	$\ell_i^\pm \ell_i^\pm \ell_j^\mp bq'$	$\ell_i^\pm \ell_j^\pm \ell_j^\mp bq'$	$\ell^\pm \ell^\pm bqqq'$	
$C_t = -1.5$						
S	2.6	2.4	0.91	2.4	3.6	11.9
B	0.78	0.69	0.86	2.7	14.3	19.3
$S/\sqrt{S+B}$	1.4	1.4	0.68	1.1	0.85	2.5
$C_t = -1$						
S	2.8	2.5	0.81	2.2	6.6	14.9
B	0.76	0.56	0.83	2.6	14.0	18.8
$S/\sqrt{S+B}$	1.5	1.4	0.63	1.0	1.5	2.8
$C_t = 0$						
S	2.3	2.0	0.70	1.8	5.4	12.2
B	0.71	0.19	0.65	2.2	12.2	15.9
$S/\sqrt{S+B}$	1.3	1.4	0.60	0.90	1.3	2.5
$C_t = 0.3$						
S	1.0	0.80	0.33	0.84	2.5	5.5
B	0.72	0.25	0.70	2.3	12.7	16.7
$S/\sqrt{S+B}$	0.76	0.78	0.33	0.47	0.64	1.4

BGMM

- $S/\sqrt{S+B}$ close to 3 at $C_t \sim -1$; > 2.5 for $-1.5 < C_t < 0$
- best single channels : 2 photons and SS leptons

exclusion potential in (C_V,C_t) plane



$H \to \gamma\gamma$, WW, $\tau\tau$

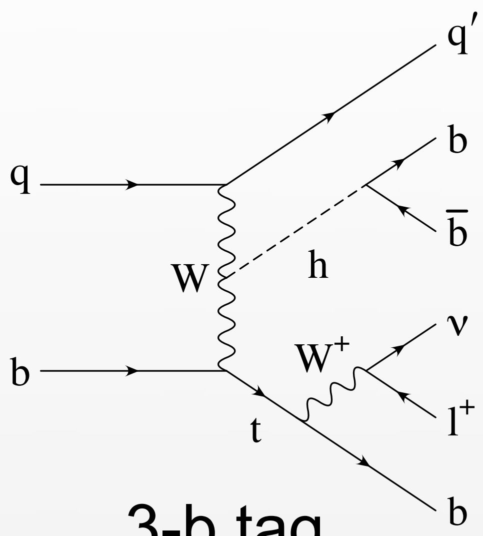
covers all critical Cf < 0 region !

ATLAS-CONF-2013-034 CMS PAS HIG-12-045

comparison with H → bb potential (8TeV)

(universal C_f scenario)

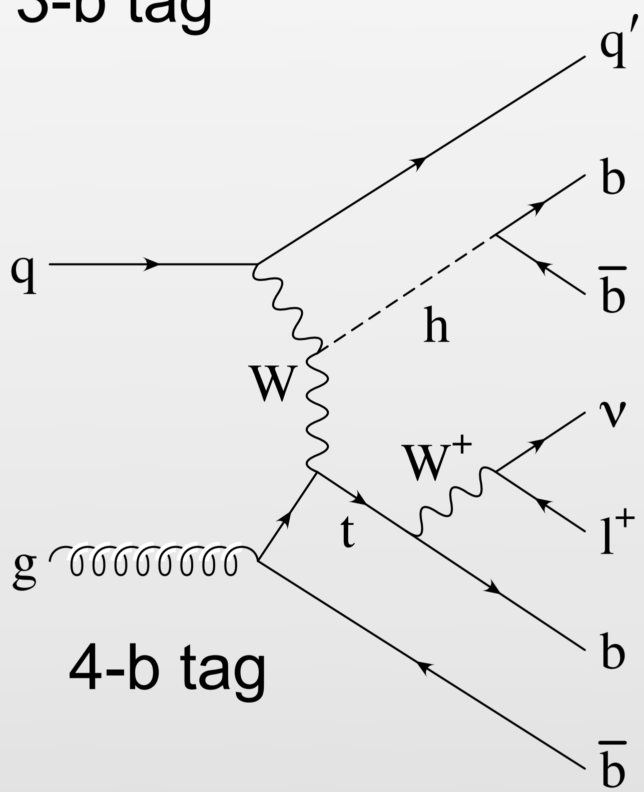
arXiv:1211.3736



3-b tag

	Signal		Backgrounds				
Cuts	$c_F = 1$	$c_F = -1$	Total	tZj	$tb\bar{b}j$	$t\bar{t}$	$t\bar{t}j$
Acceptance Cuts + ϵ	0.18	2.88	600.81	0.61	1.01	456.40	142.80
$\|m_{bb} - m_h\| < 15$ GeV	0.15	2.55	245.95	0.02	0.11	184.2	61.65
$m_{bbj} > 270$ GeV	0.10	2.02	31.78	0.01	0.08	0.	30.68
$\|\eta^j\| > 1.7$	0.08	1.70	17.98	0.01	0.06	0.	17.24
Events at 25 fb^{-1}	1.9	42.5	449.4				

fb for the 3 b-tag case at 8 TeV.



4-b tag

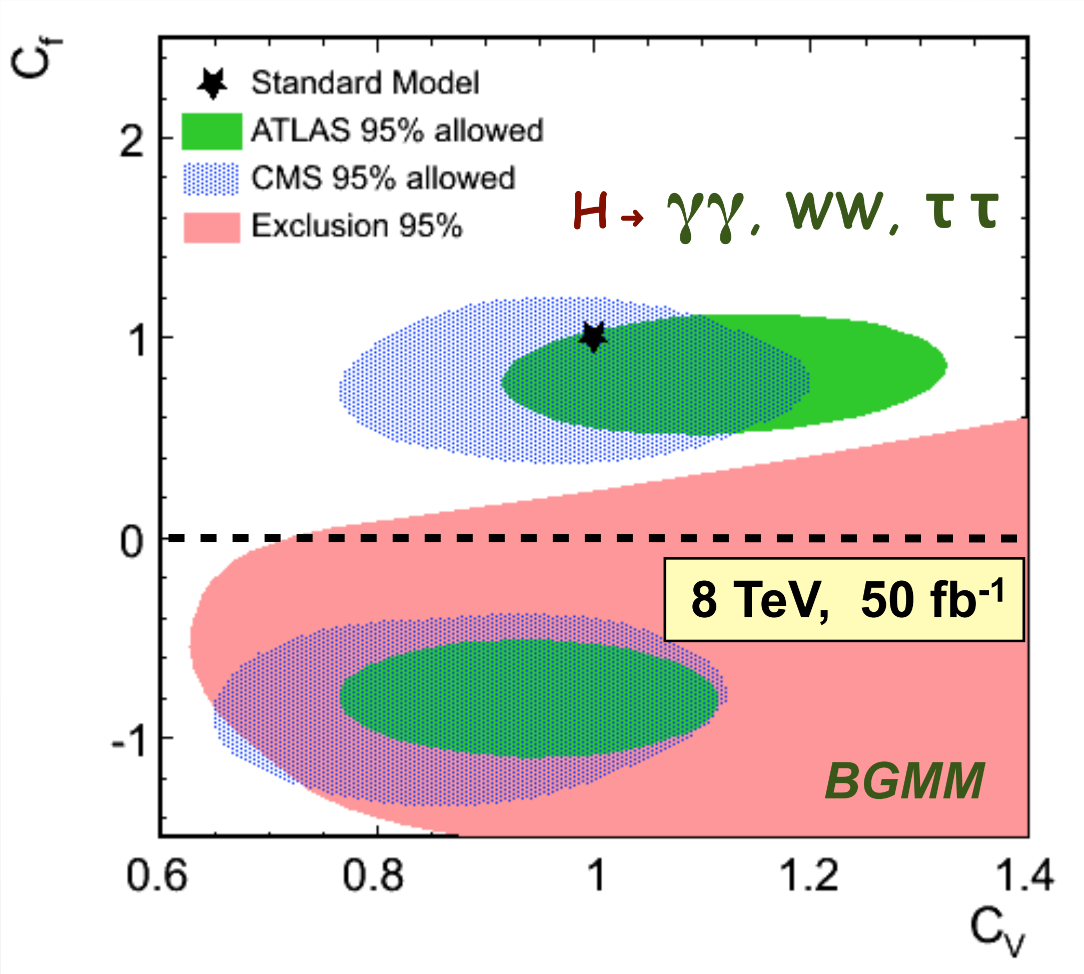
	Signal		Backgrounds					
Cuts	$c_F = 1$	$c_F = -1$	Total	$tZ\bar{b}j$	$tb\bar{b}\bar{b}j$	$t\bar{t}b\bar{b}$	$t\bar{t}b\bar{b}$ (mis)	$t\bar{t}j$
Acceptance Cuts + ϵ	0.043	0.63	7.81	0.11	0.26	2.66	2.25	2.54
$\|m_{bb} - m_h\| < 15$ GeV	0.039	0.58	4.06	0.03	0.08	0.94	1.29	1.71
min $m_{bb} > 110$ GeV	0.023	0.30	0.67	0.002	0.015	0.20	0.44	0.
min $m_{bj} > 180$ GeV	0.008	0.15	0.014	0.	0.007	0.002	0.004	0.
Events at 25 fb^{-1}	0.2	3.8	0.4					

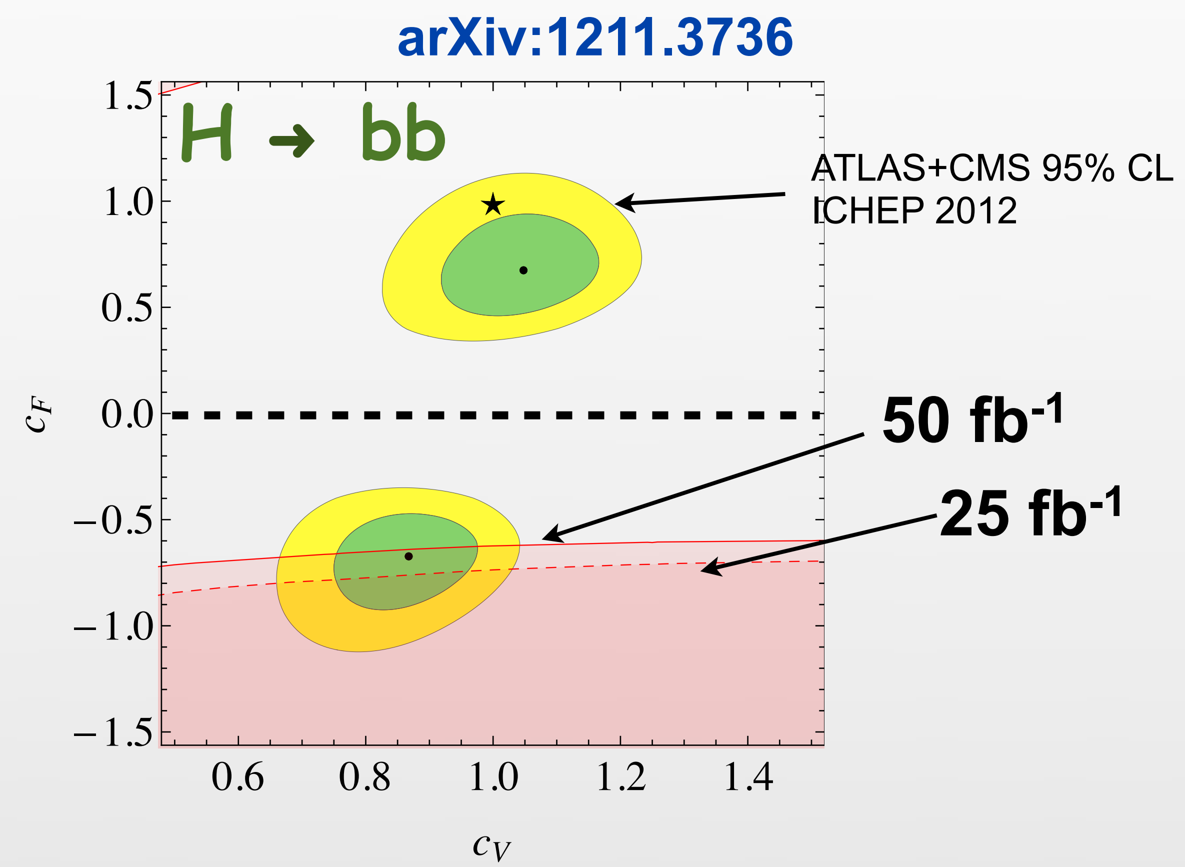
fb for the 4 b-tag case at 8 TeV

challenging !

comparison with H → bb potential (8TeV)

(universal C_f scenario)





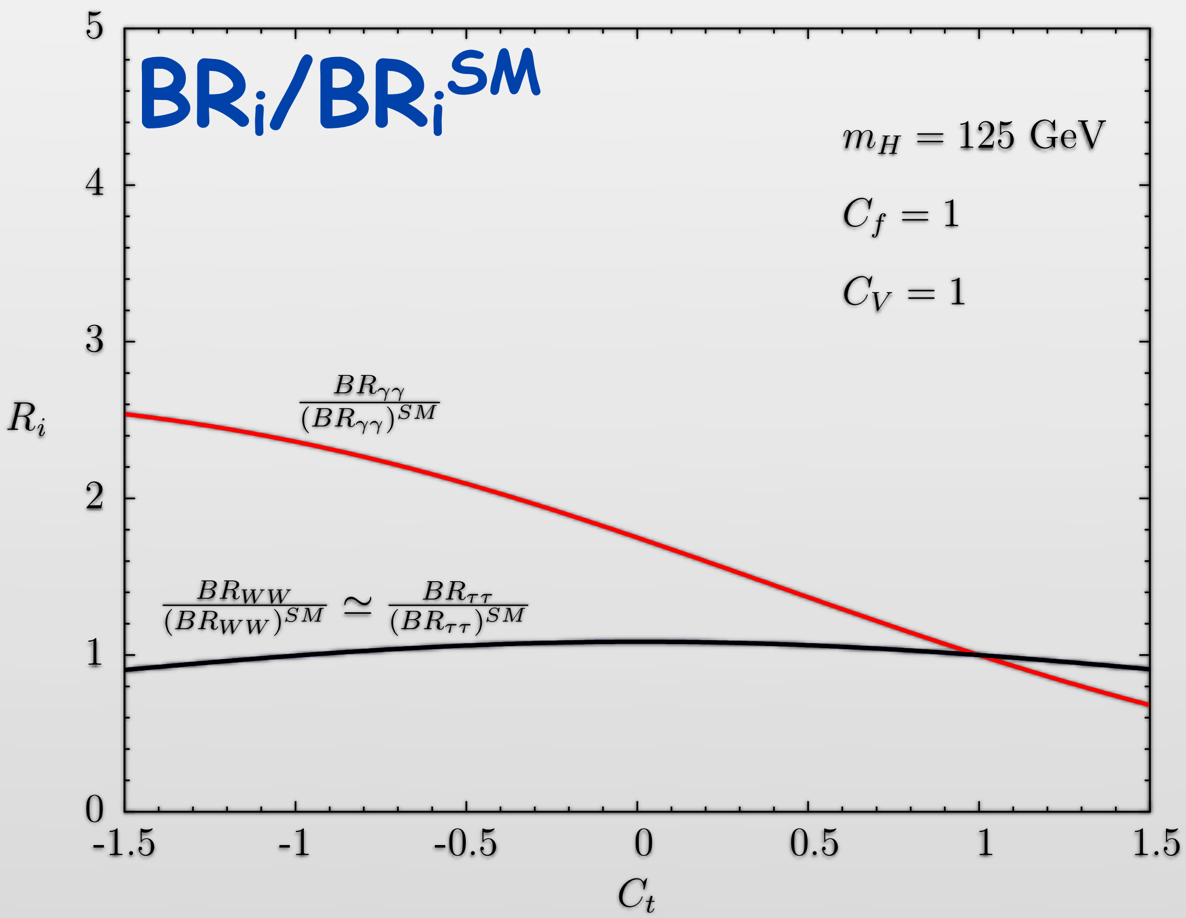
- some complementarity, since H → bb drops at small |Cf| where γγ and WW are enhanced
- at this stage H → γγ, WW, ττ looks more promising !

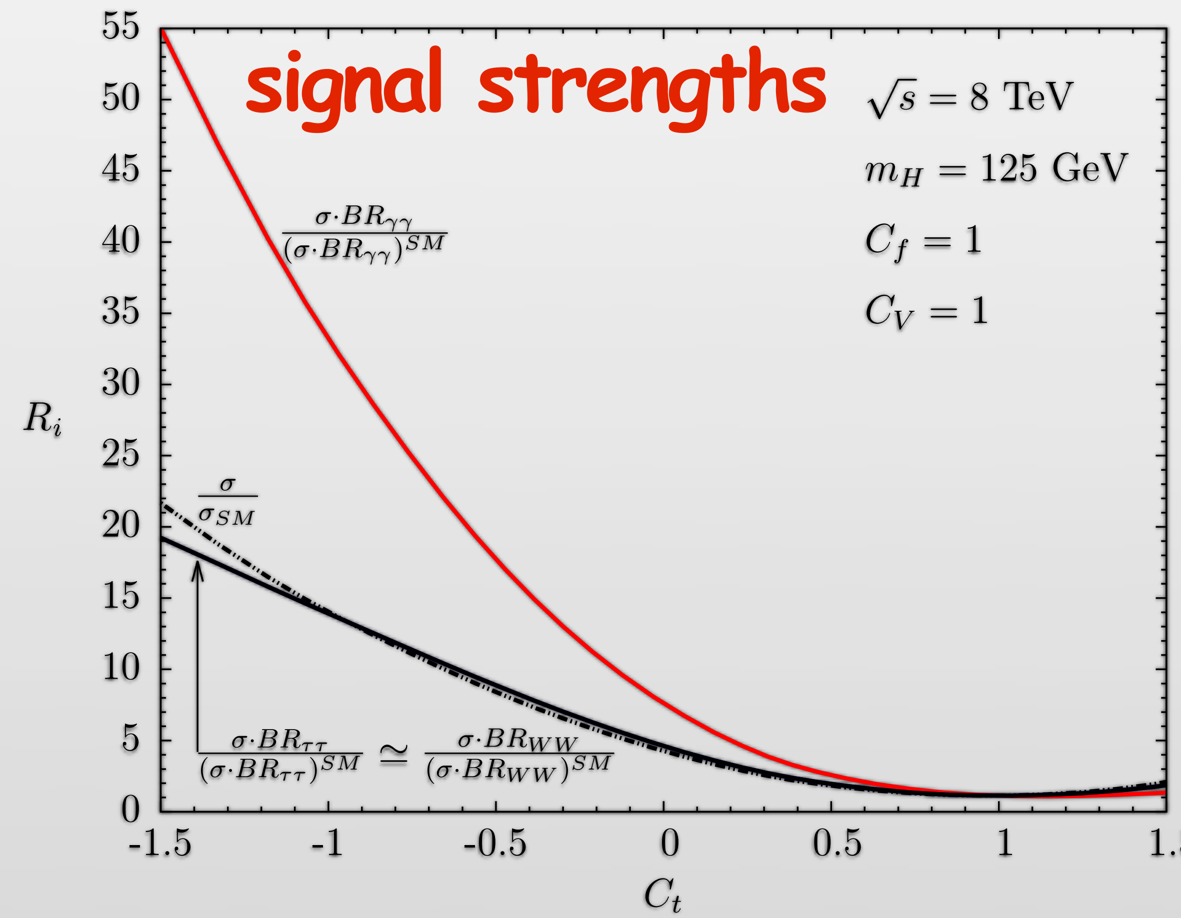
BR_i/BR_i^{SM} and σ_i/σ_i^{SM} vs C_t $(C_{f\neq t}=1)$

- choose a different benchmark scenario :

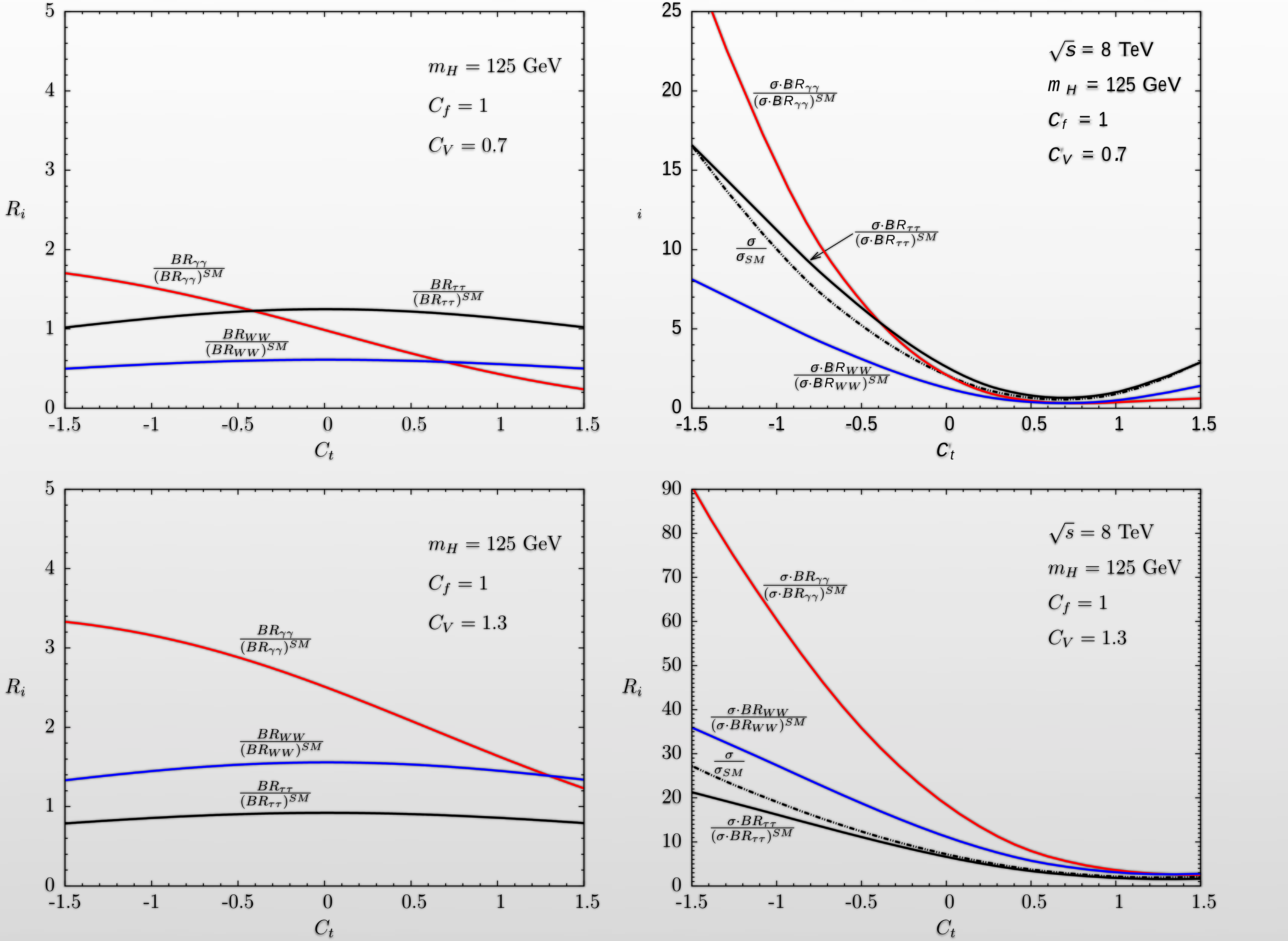
  " free C_t with SM-like $C_{f\neq t}=1$ "

- main impact of C_t just on $BR_{\gamma\gamma}$ and σ/σ^{SM}



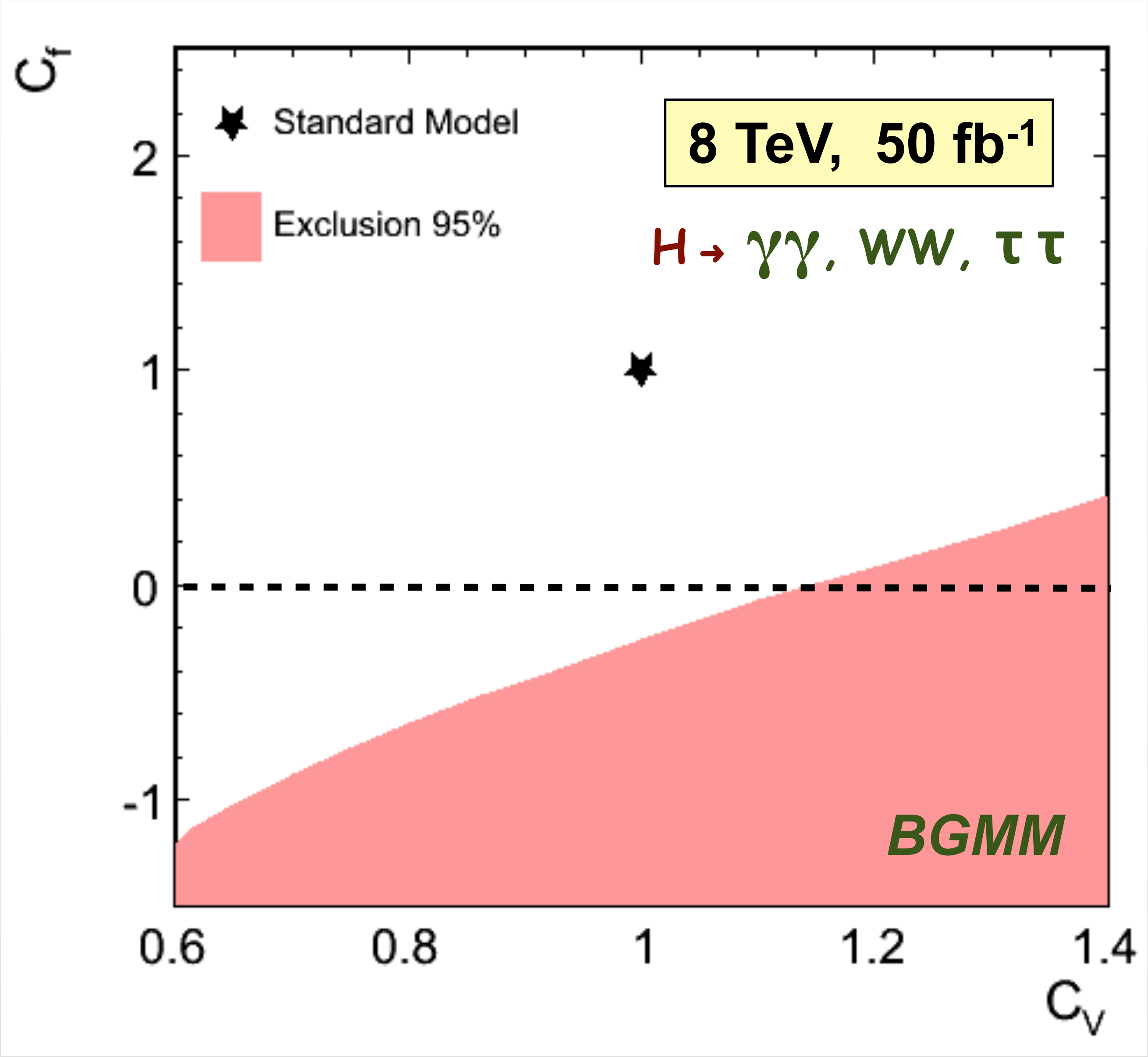


changing Cv in BR_i/BR_i^{SM} and σ_i/σ_i^{SM}

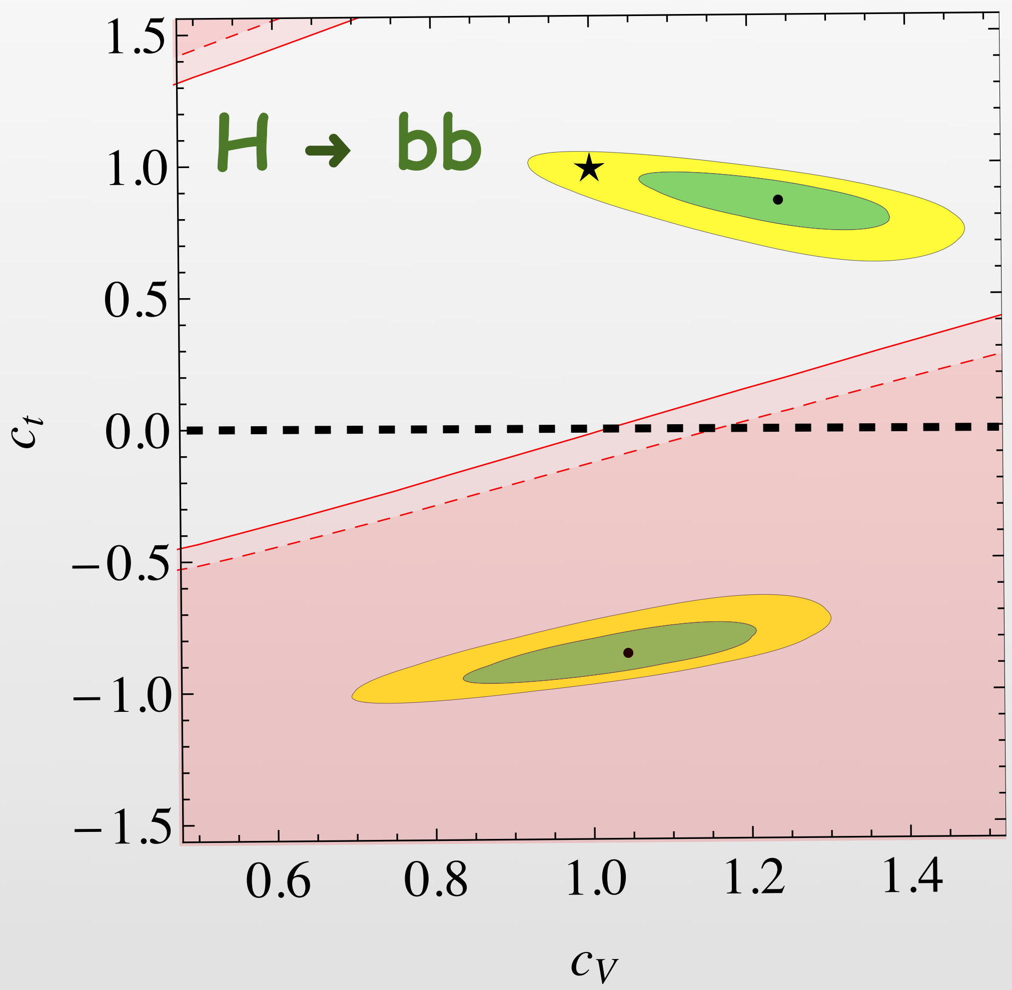


comparison with H → bb potential (8TeV)

free C_t with $C_{f \neq t} = 1$ scenario



arXiv:1211.3736



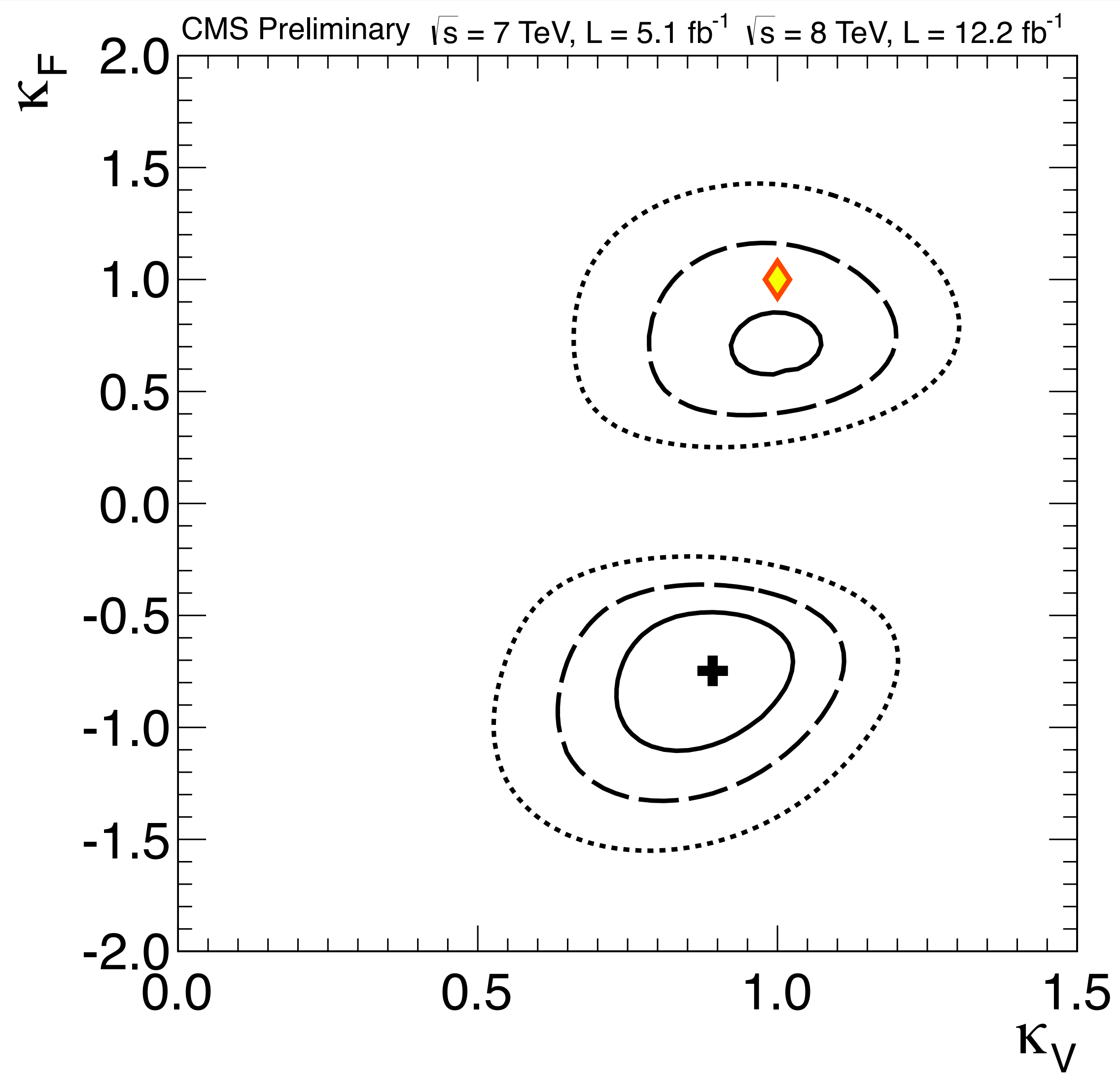
- H → bb keeps now good rates at small $|C_f|$
- H → γγ, WW, ττ weaker at $C_V < 1$!

Outlook

- Higgs coupling fits still subject to substantial fluctuations (see this-year CMS update ...)
- not yet clear when the (BSM) $C_f < 0$ region will be excluded by "traditional" fits
- $p\,p \to t\,H\,q$ production seems to be an excellent probe of the negative C_f region
- combining multi-photon and multi-lepton channels could have a great potential even with the present data set
- full simulation plus possible improvements (ex. hadronic tau decays) needed to realistically assess the $p\,p \to t\,H\,q$ potential at 8 TeV and beyond !

CMS g_{HXX} fit

(universal C_f scenario)



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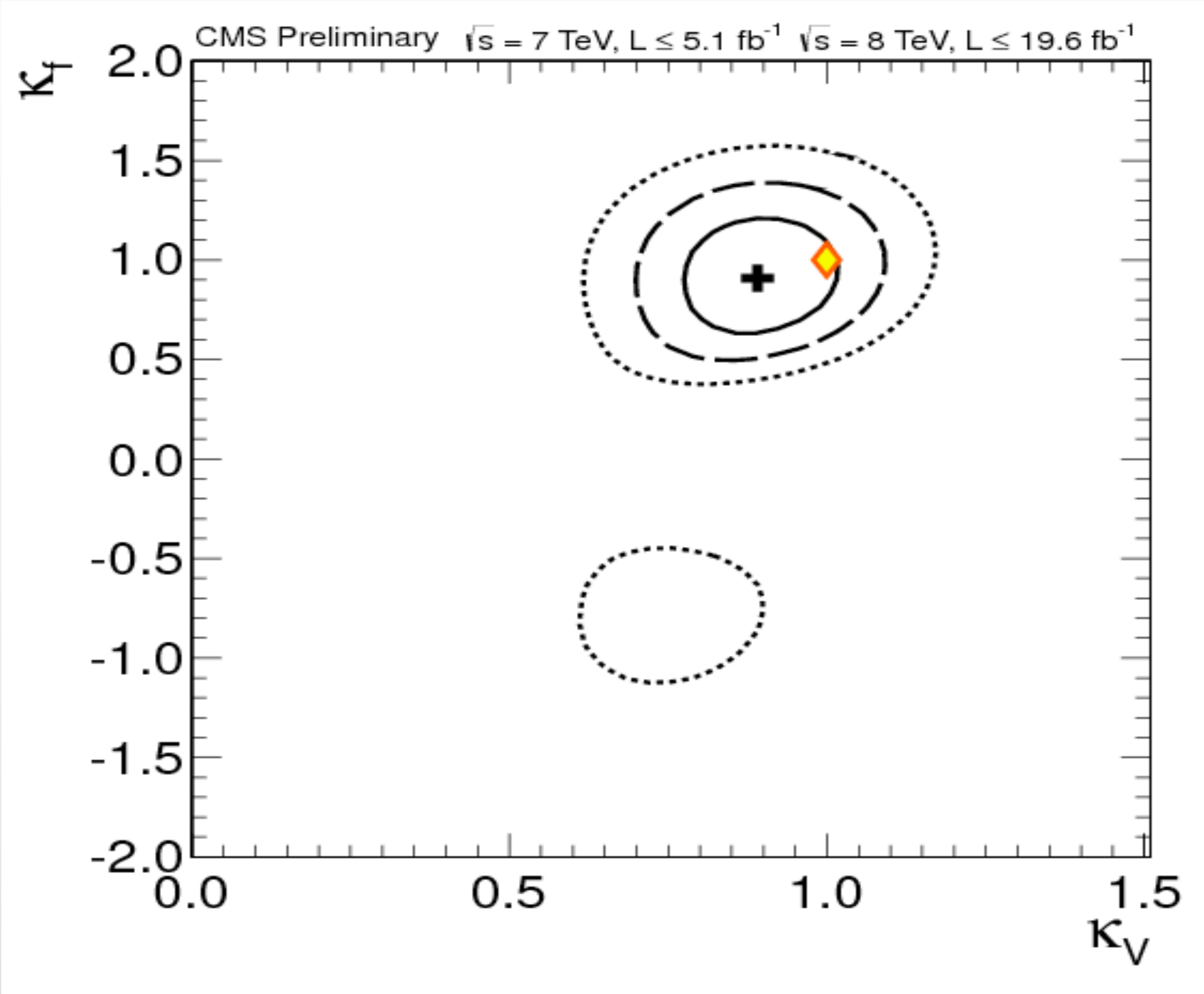

CMS PAS HIG-13-005 *(18 April)*