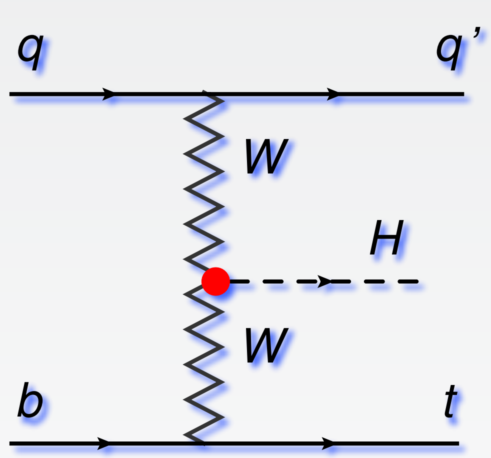
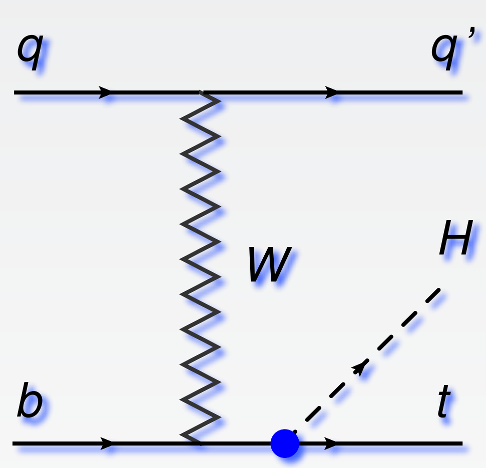
2nd CMS Single-Top Workshop

4-5 December 2014, Palazzo Alabardieri, Napoli, Italy

Single top + Higgs (theory)





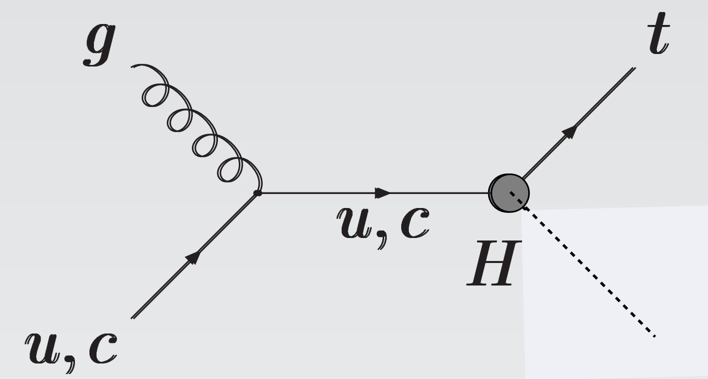
Istituto Nazionale di Fisica Nucleare Sezione di Roma

Barbara Mele

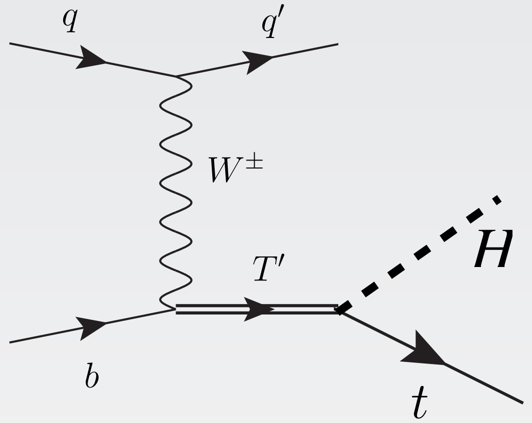
Napoli, 4 December 2014

Why to look at t+H final states ?

- probe FCN couplings tuH, tcH



- search for singly-produced tH resonances



- test structure of g_{Htt} coupling
  (beyond what can be achieved by gg → H, ttH)
- . . . . .

in this talk focus on g_{ttH} tests
(including g_{ttH} CP properties !)

ttH interaction beyond the SM

$$\mathcal{L}_t^{SM} = -\frac{1}{\sqrt{2}} Y_t^{SM}\, \bar{t}\, t\, H$$ **Yukawa interaction**

$$Y_t^{SM} = \frac{\sqrt{2}\, m_t}{v} \simeq \sqrt{2}\, \frac{173}{246} \simeq 0.995 \simeq 1 \quad !!!$$

→ **special role of top in EWSB ?**

- **beyond the SM (scalar + pseudo-scalar coupling)**

$$\mathcal{L}_t = -\frac{1}{\sqrt{2}} Y_t^{SM} (\kappa_t\, \bar{t}\, t + i\, \tilde{\kappa}_t\, \bar{t} \gamma_5 t) H$$

Part 1:

real g_{ttH} (→ CP conserving)

$$Y_t^{SM}\,\bar{t}\,t\,H \rightarrow Y_t\,\bar{t}\,t\,H$$

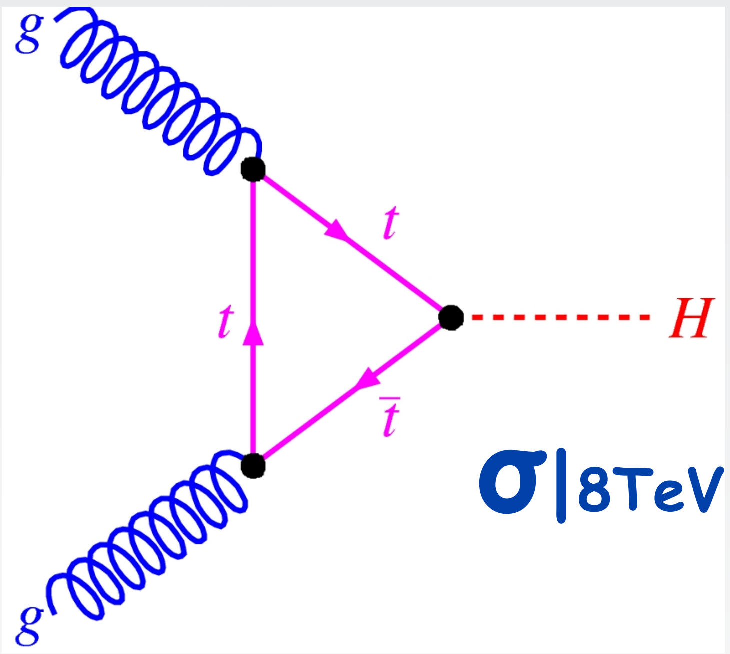
notation :

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

C_f modifier of Hff couplings

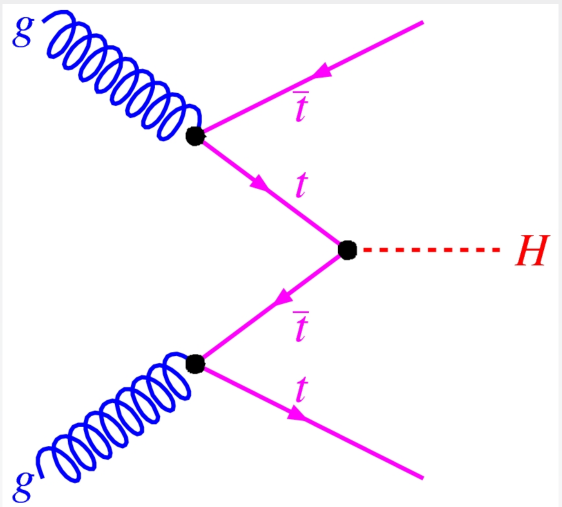
main sensitivity to g_{Htt} (~C_t)

- dominant but indirect (top quark not observed → C_t effects could be faked by New Virtual contributions)



$\sigma|_{8TeV}$ ~ 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 !

BSM theories can predict $c_f < 0$!

- example : Minimal Composite Higgs Models SO(5) -> SO(4)

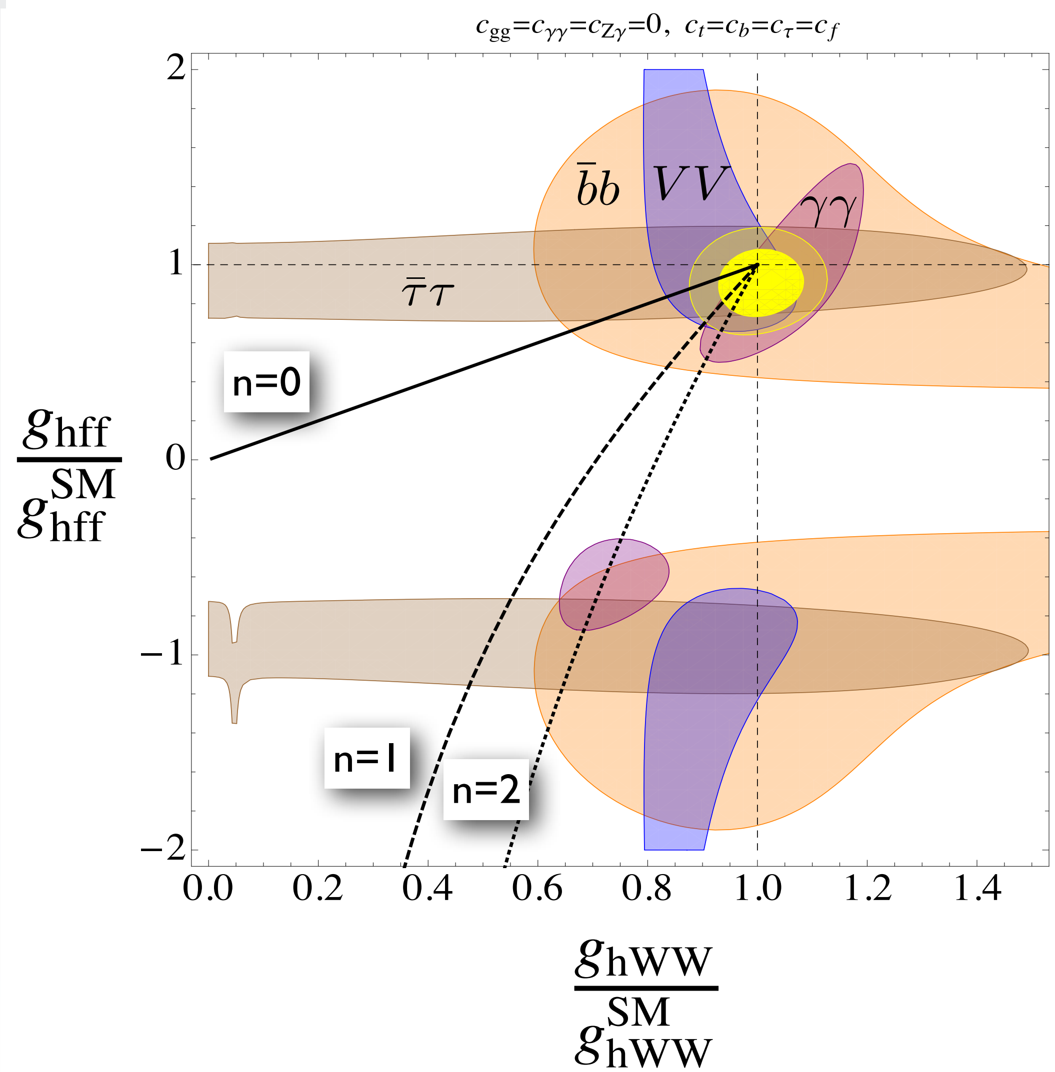
global symmetry in a strong sector broken at a scale $f_H > v$

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

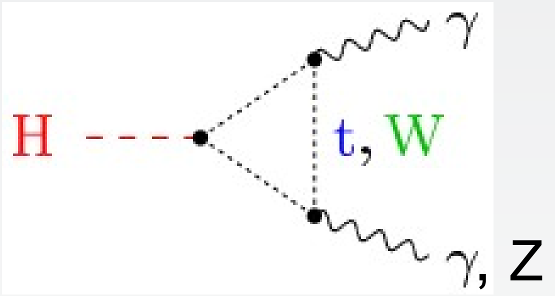
$$\rightarrow f_H \gtrsim 700\,\mathrm{GeV}$$

Falkowski, Riva, Urbano, [1303.1812]

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

- linear terms in C_f needed → look for interferences in squared amplitudes

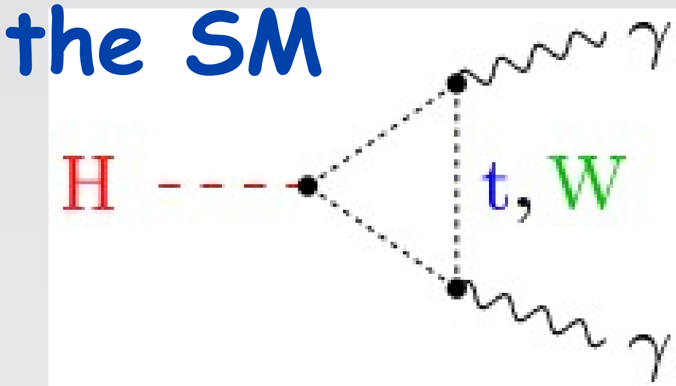
- in decays: mainly in loop channels



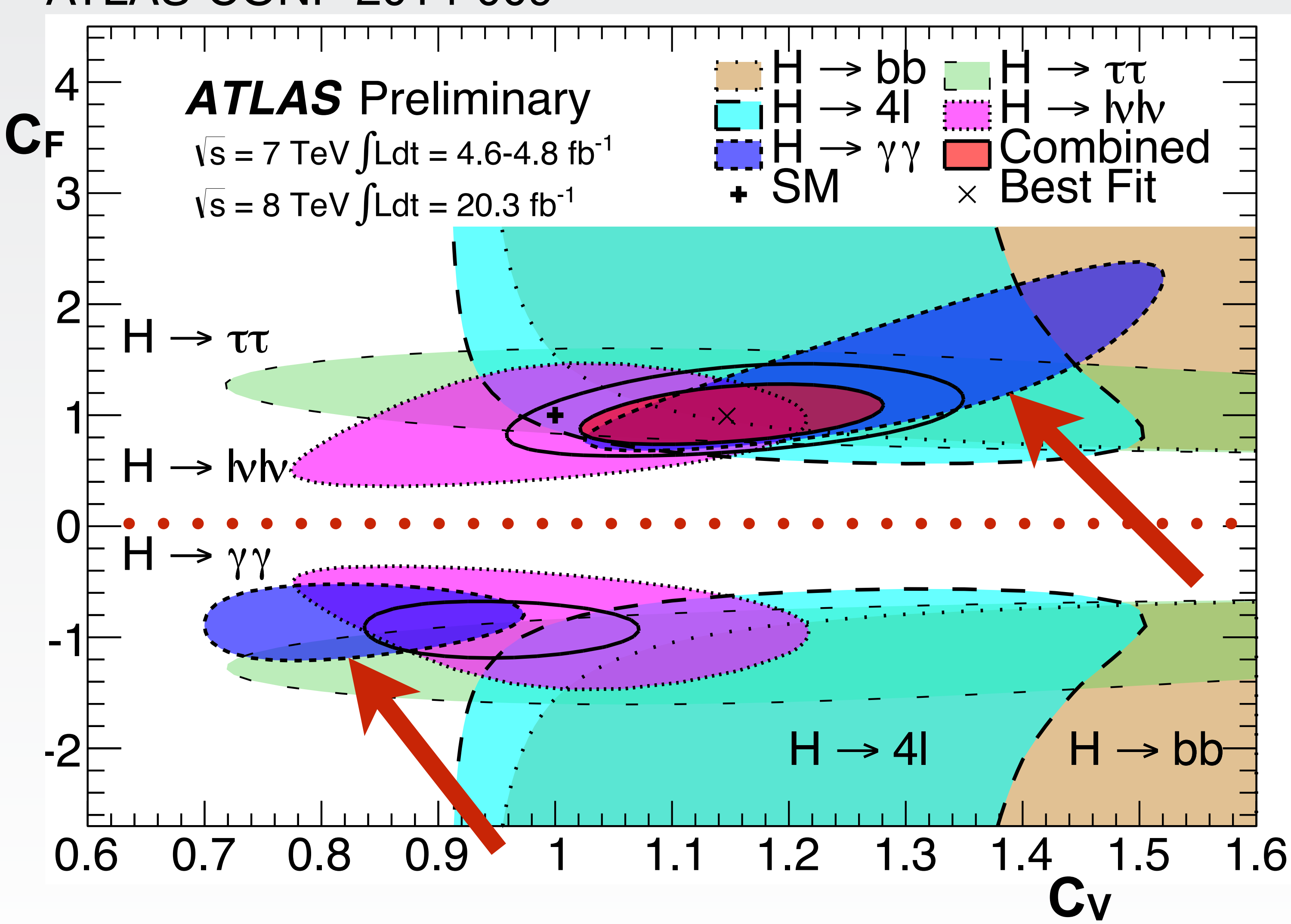
- what about production mechanisms ???

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

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



ATLAS-CONF-2014-009



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

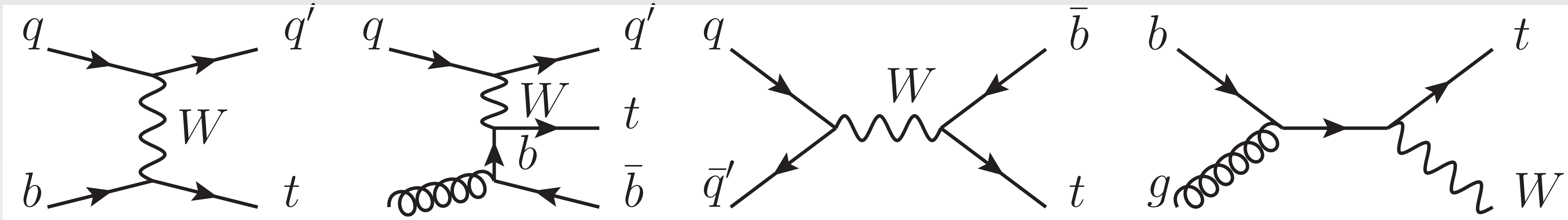
note !
two solutions for any $\sigma^{\gamma\gamma}$

$$\sigma^{\gamma\gamma}_{SM} = \sigma^{\gamma\gamma}(C_V = C_t = 1)$$
$$\simeq \sigma^{\gamma\gamma}(C_V = -C_t = 0.66)$$

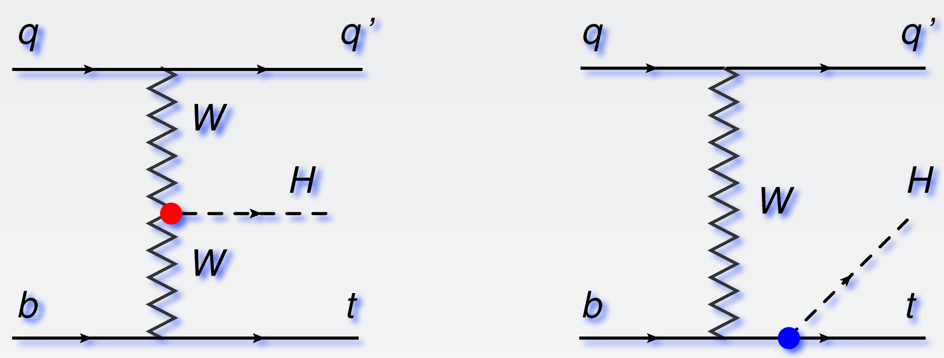
Single top + Higgs production

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

- ask for an extra Higgs in single-top production



(t-channel)



(same for tb and tW channels)

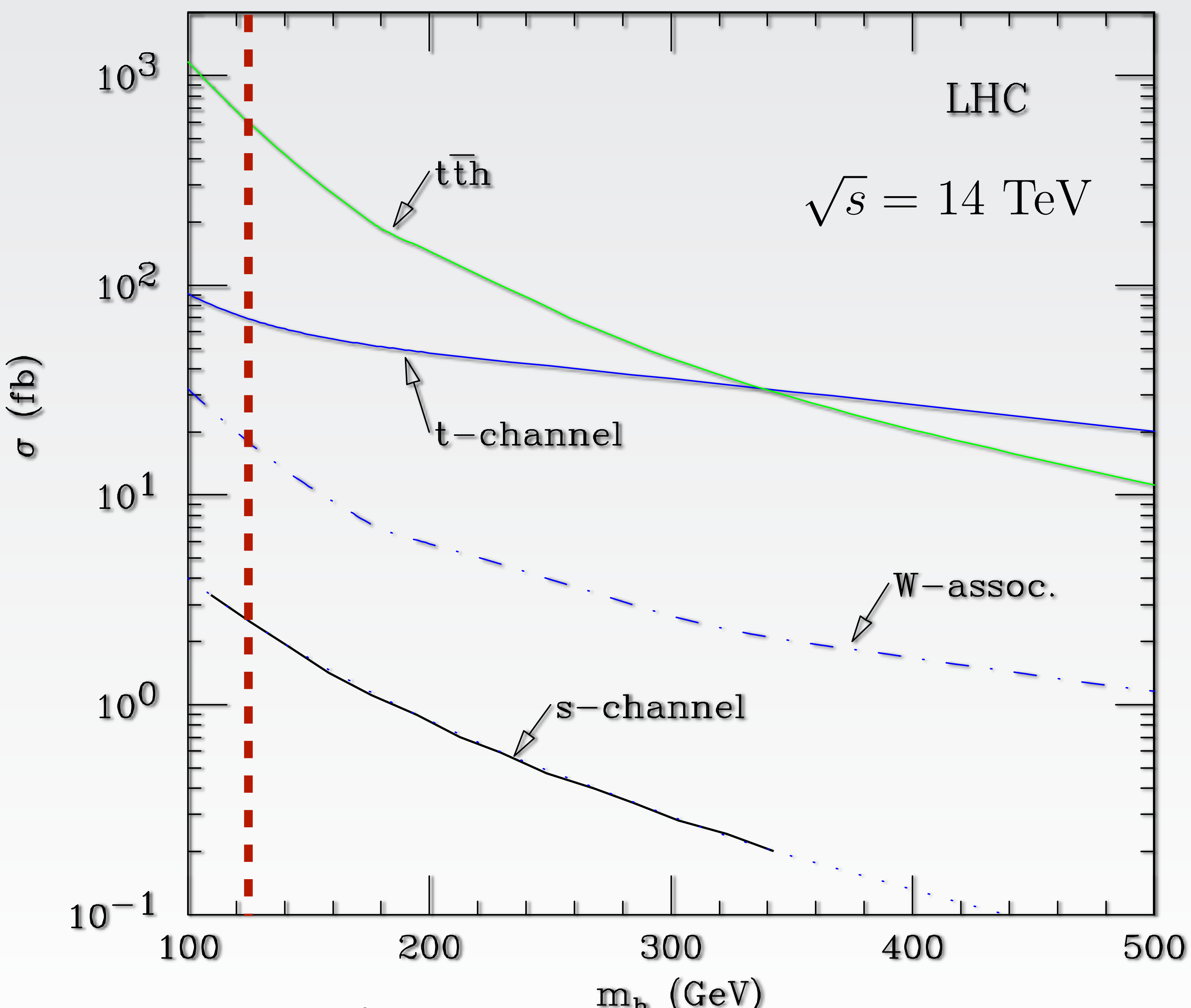
- EW process where Higgs emission from a W interferes with Higgs emission from a top-quark :

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

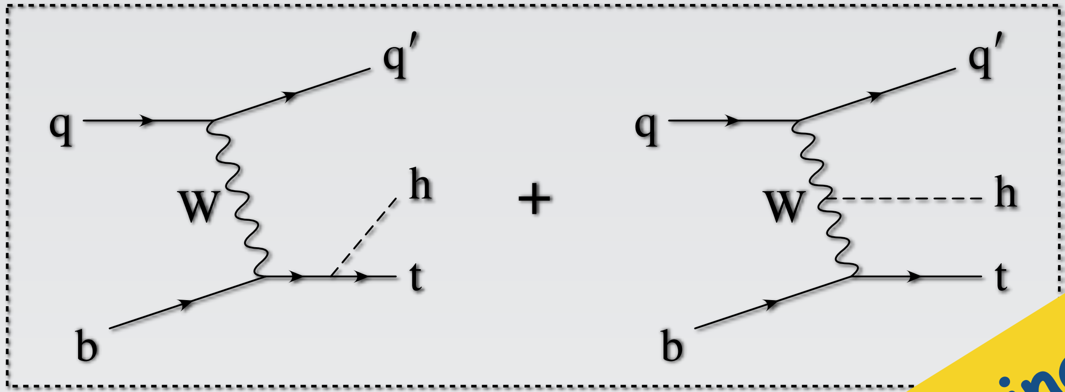
interference term in σ_{tot} sensitive to C_t sign !

σ(pp→ t H + X) in the SM: 3 channels

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

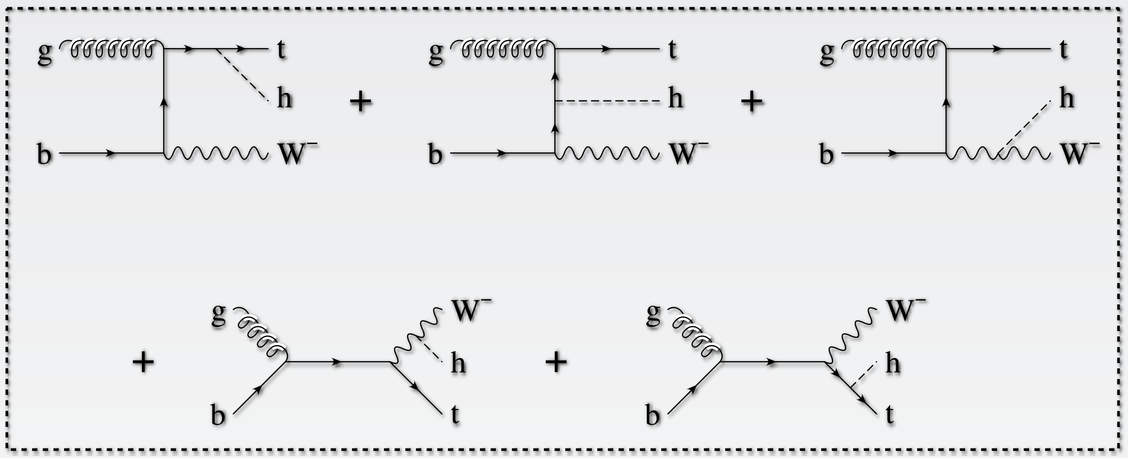


Maltoni et al,hep-ph/0106293

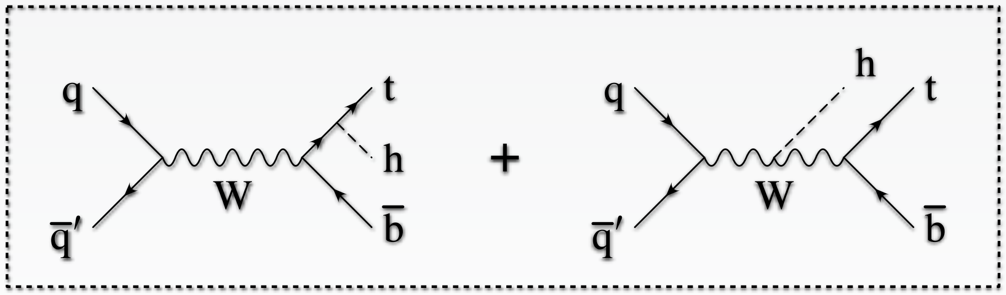


(t-channel)

(dominant !)



(W-assoc.)



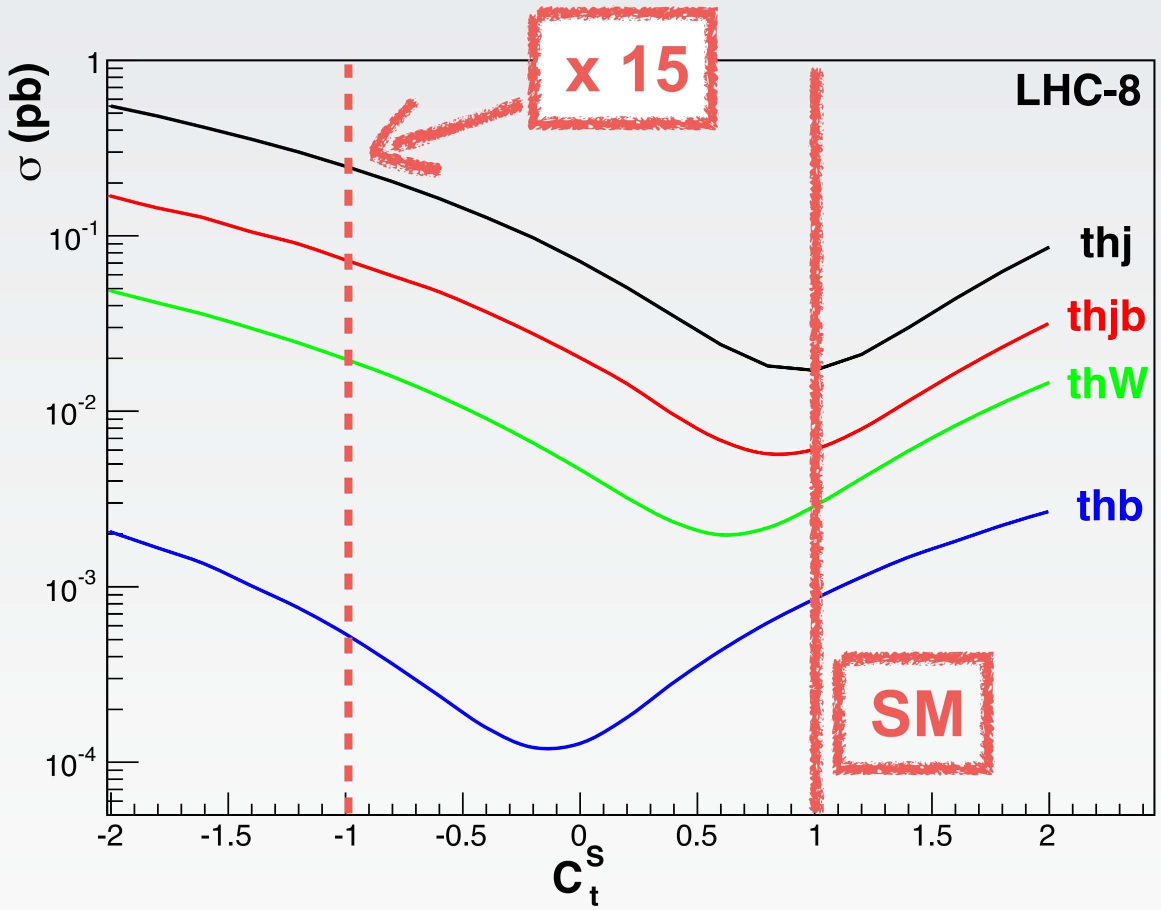
(s-channel)

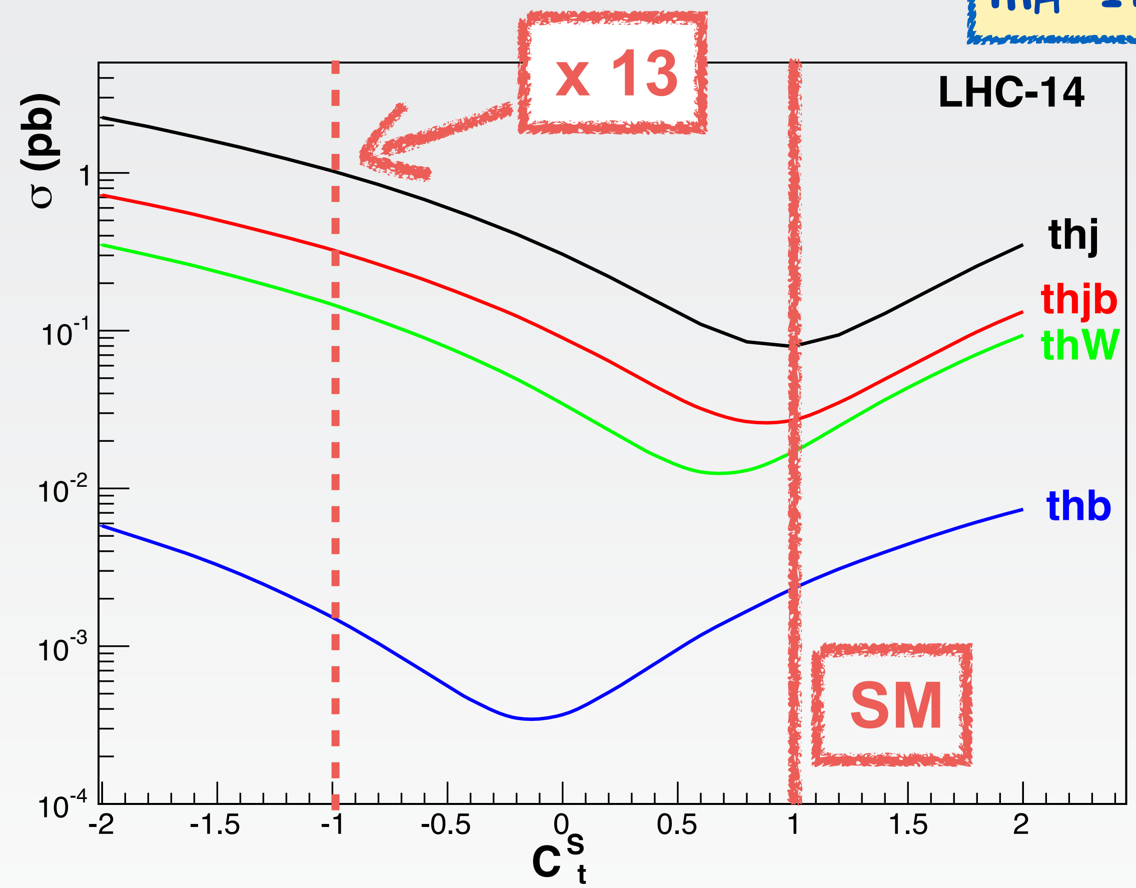
σ(pp→ t H X) [fb] vs C_t at 14 TeV (8 TeV)

	$X=j$	$X=j+b$	$X=W$	$X=b$
$C_t^S=+1$ (SM)	79.4 (17.1)	27.1 (5.95)	17.0 (2.89)	2.32(0.833)
$C_t^S=0$	305 (71.4)	90.0 (19.8)	34.4 (4.66)	0.368 (0.126)
$C_t^S=-1$	1030 (249)	325 (72.8)	146 (19.8)	1.52 (0.536)

Chang et al, arXiv:1403.2053

m_H=125 GeV





destructive (constructive) interference in tHj,tHW (tHb) channels for C_t = 1

prompted dedicated studies → → →

a few references on tHq sensitivity to C_t at LHC

Tait and Yuan, *Phys.Rev.* D63 (2000) 014018 [hep-ph/0007298]

Maltoni et al, *Phys.Rev.* D64 (2001) 094023 [hep-ph/0106293]

Barger et al, *Phys.Rev.* D81 (2010) 034020 [arXiv:0911.1556]

Biswas et al , *JHEP* 01 (2013) 088 [arXiv:1211.0499] ($H \to \gamma\gamma$ + (had) top)

Farina et al , *JHEP* 05 (2013) 022 [arXiv:1211.3736] ($H \to bb$ + (lep) top)

Biswas et al , *JHEP* 07 (2013) 073 [arXiv:1304.1822] ($H \to \gamma\gamma$, WW, $\tau\tau$)

Ellis et al , *JHEP* 1404 (2014) 004 [arXiv:1312.5736]

Englert and Re, *Phys.Rev.* D89 (2014) 073020 [arXiv:1402.0445]

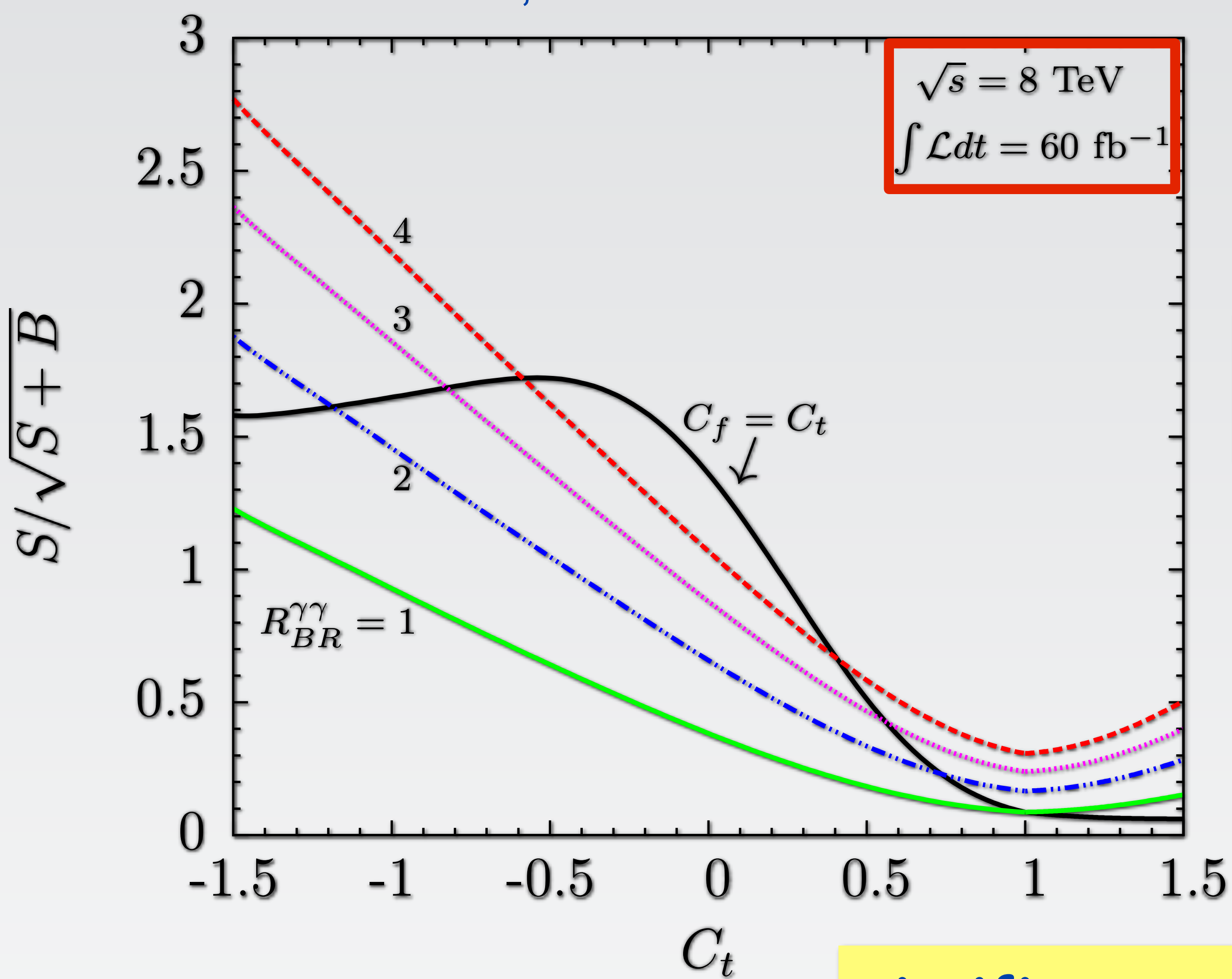
Chang et al, *JHEP* 1405 (2014) 062 [arXiv:1403.2053]

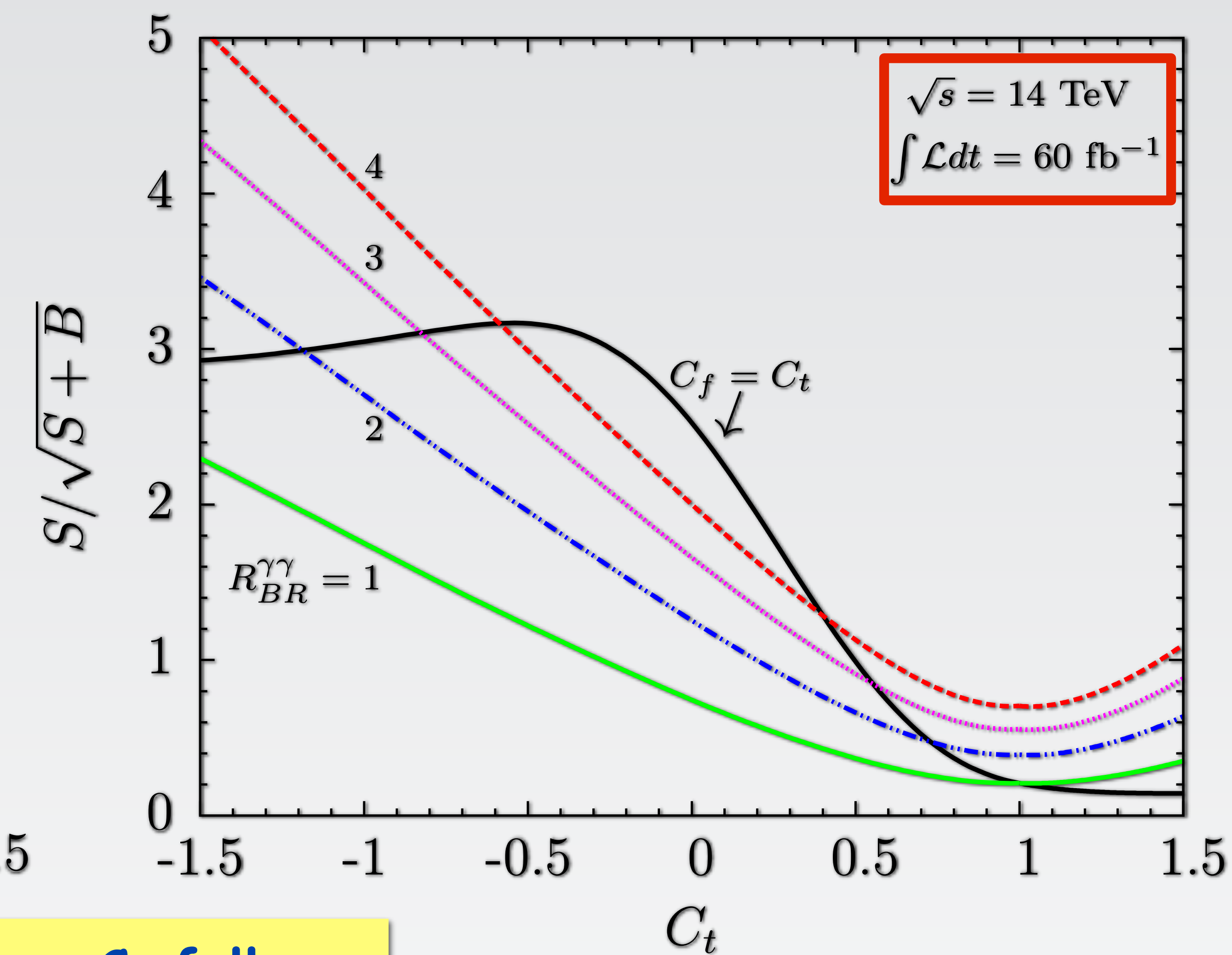
Kobakhidze et al, arXiv:1406.1961

Yue, arXiv:1410.2701

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

Biswas et al,arXiv:1211.0499



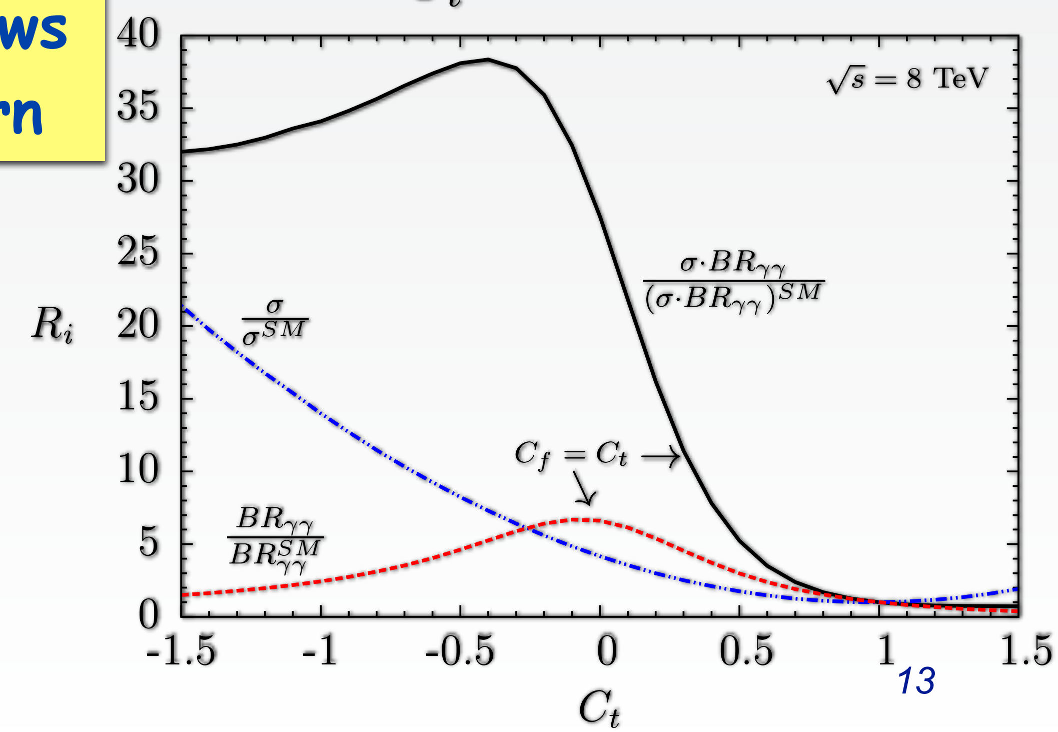


$$\frac{BR_{\gamma\gamma}(C_t = -1)}{BR^{SM}_{\gamma\gamma}} \simeq 2.4$$

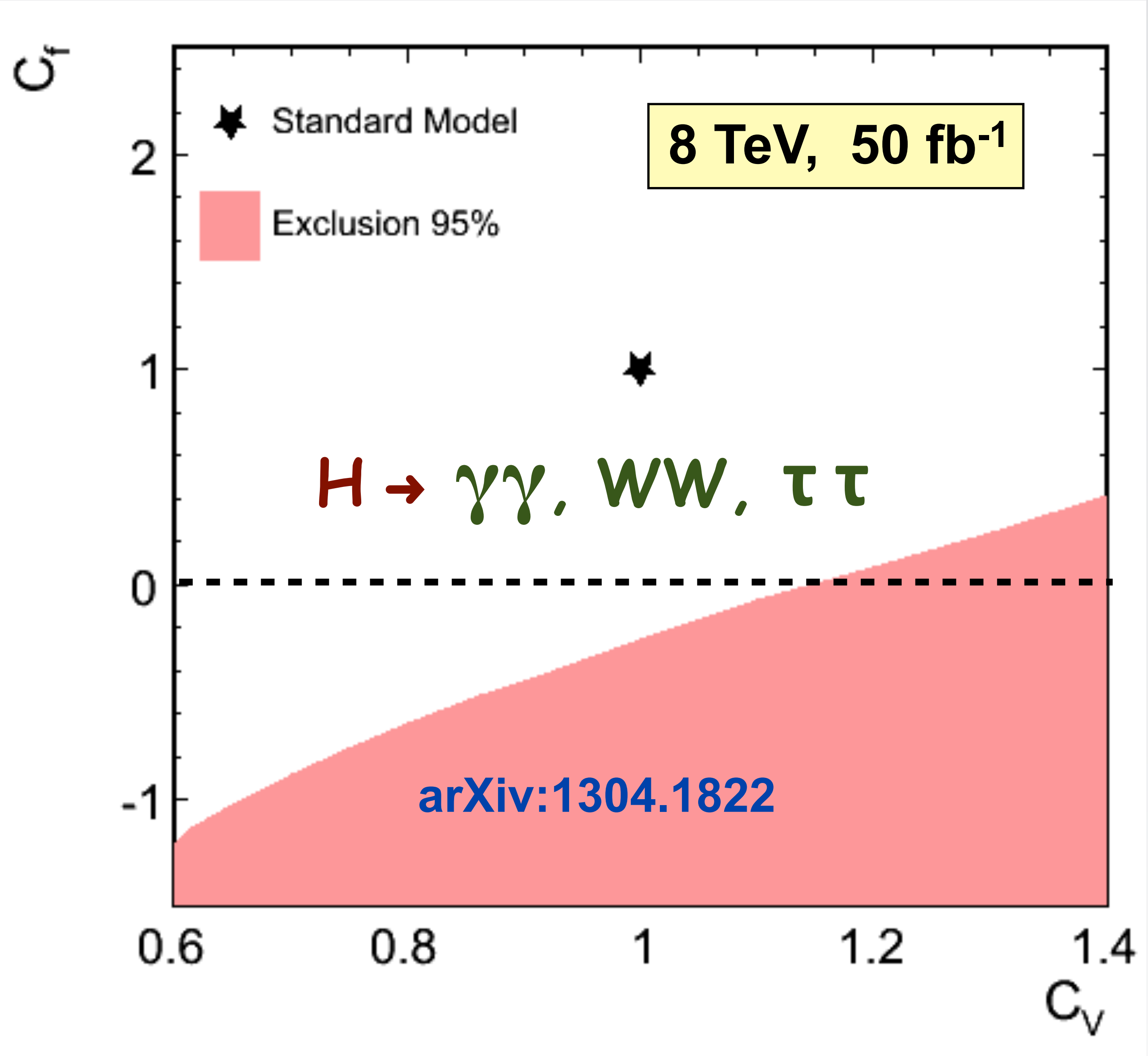
significance vs C_t follows signal strength pattern

2 benchmark scenarios :

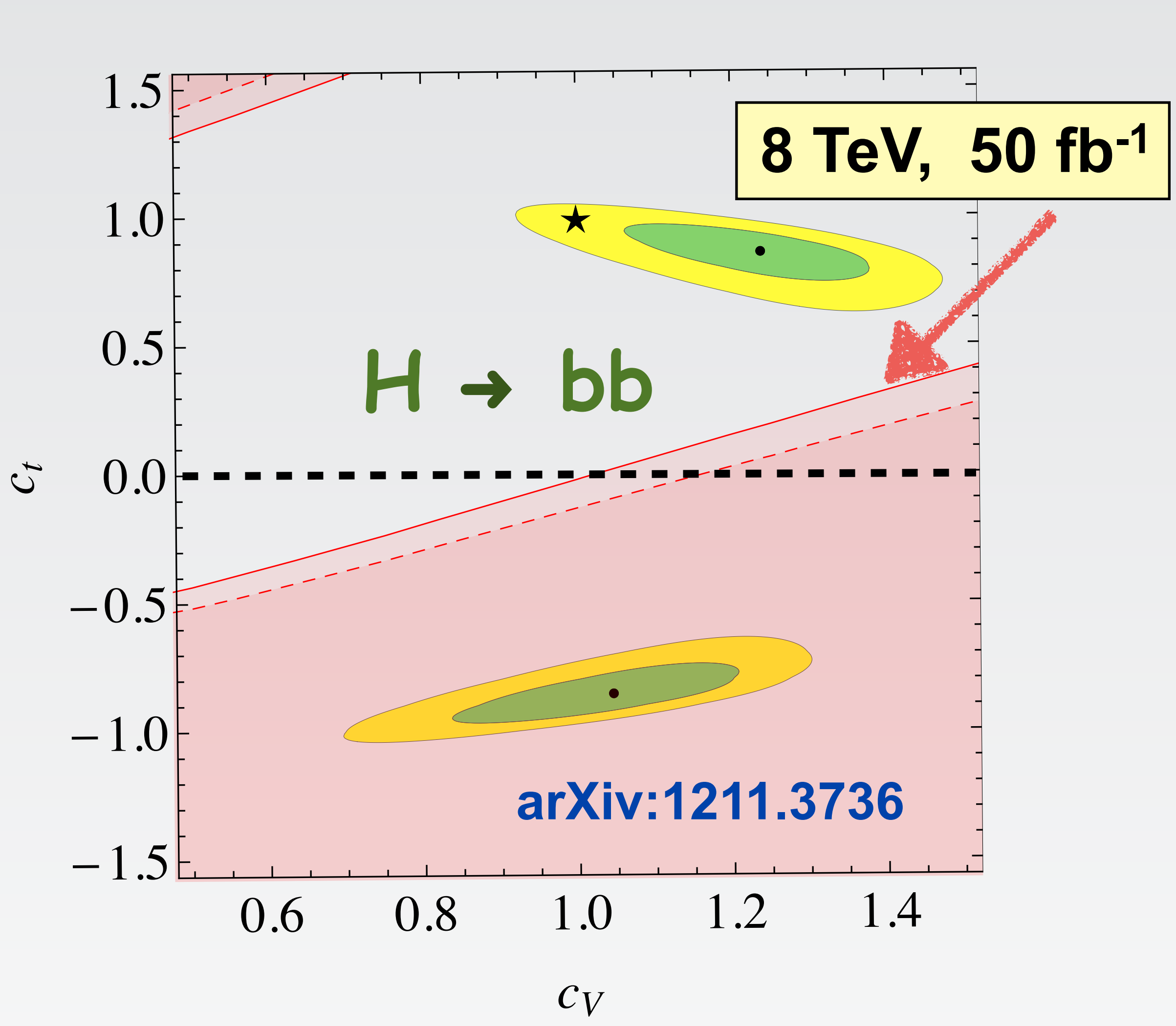
- universal C_f (=C_t) ⟶
- free C_t ,and SM-like C_b=C_c=C_τ= 1



exclusion potential in (C_V,C_t) plane at 8 TeV



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

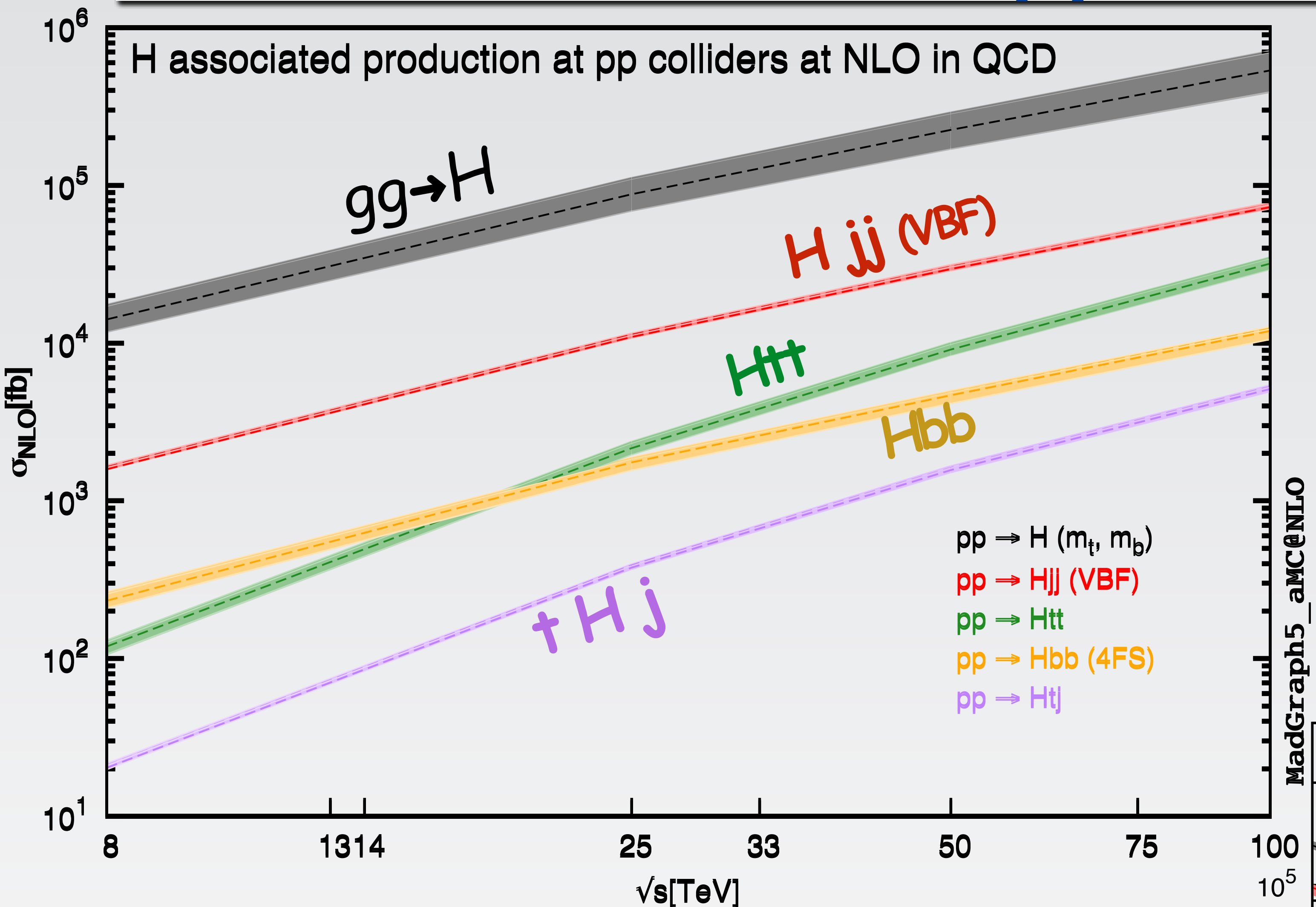


can now be compared with real analyzes ! (see next talk…)

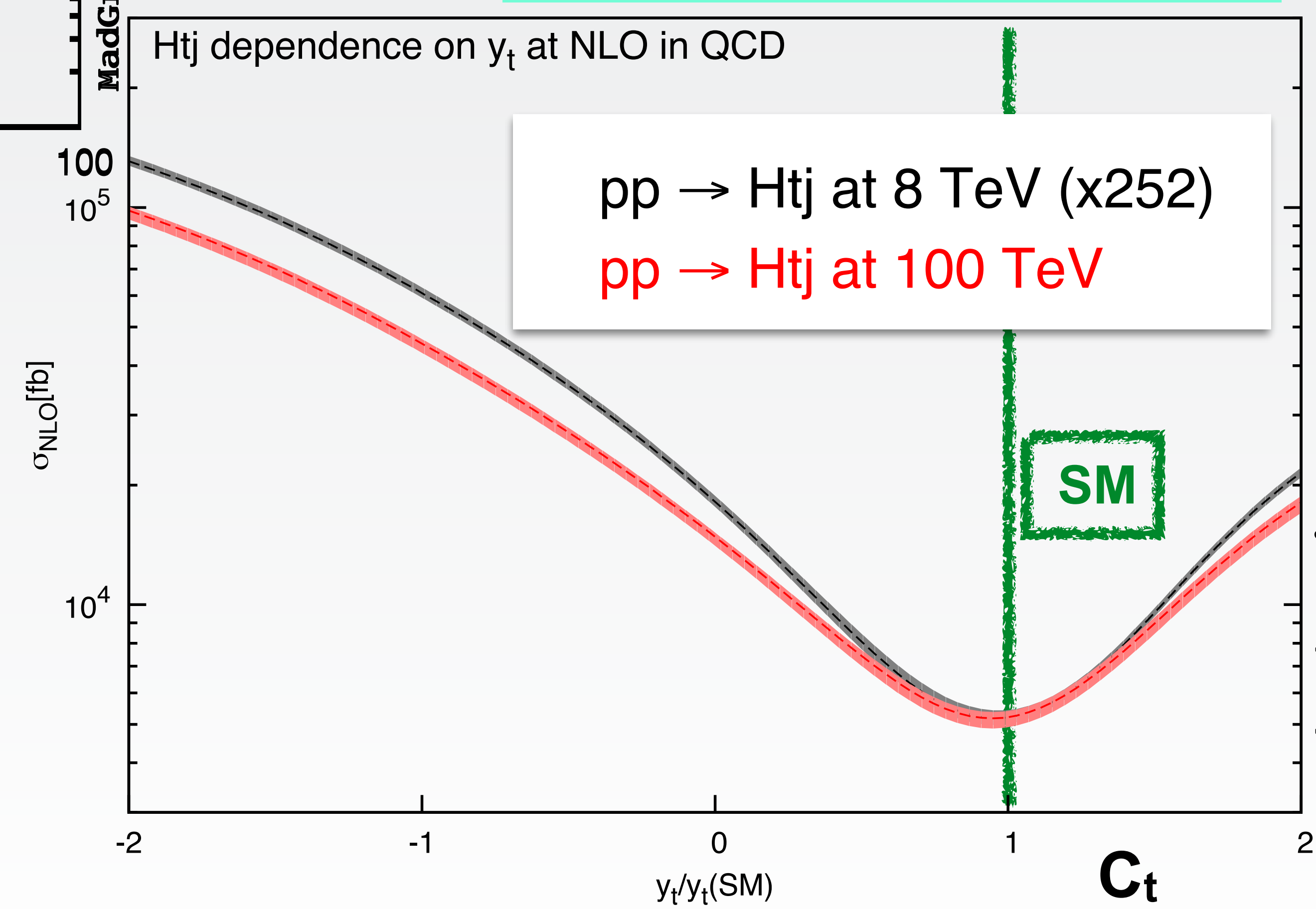
- H → γγ CMS-PAS-HIG-14-001; (ATLAS) CERN-PH-EP-2014-179
- H → bb CMS-PAS-HIG-14-015

present data-set not yet sensitive to C_t ~ -1

(NLO) SM $\sigma(pp \to t\,H\,j)$ vs $\sqrt{S}$



tHJ sensitivity to C_t



$\sigma(Htt)$ and $\sigma(tHj)$ have similar (fast) increase vs E_{cm}

Torrielli, arXiv:1407.1623

(NLO) SM σ(pp→ t H j) vs √S

σ(100TeV) / σ(8TeV)

	Process	$\sigma_{\rm NLO}(8\ \rm TeV)$ [fb]	$\sigma_{\rm NLO}(100\ \rm TeV)$ [fb]	ρ
$pp \rightarrow$	$H\ (m_t, m_b)$	$1.44 \cdot 10^4\ {}^{+20\%}_{-16\%}\ {}^{+1\%}_{-2\%}$	$5.46 \cdot 10^5\ {}^{+28\%}_{-27\%}\ {}^{+2\%}_{-2\%}$	38
$pp \rightarrow$	Hjj (VBF)	$1.61 \cdot 10^3\ {}^{+1\%}_{-0\%}\ {}^{+2\%}_{-2\%}$	$7.40 \cdot 10^4\ {}^{+3\%}_{-2\%}\ {}^{+2\%}_{-1\%}$	46
$pp \rightarrow$	$Ht\bar{t}$	$1.21 \cdot 10^2\ {}^{+5\%}_{-9\%}\ {}^{+3\%}_{-3\%}$	$3.25 \cdot 10^4\ {}^{+7\%}_{-8\%}\ {}^{+1\%}_{-1\%}$	269
$pp \rightarrow$	$Hb\bar{b}$ (4FS)	$2.37 \cdot 10^2\ {}^{+9\%}_{-9\%}\ {}^{+2\%}_{-2\%}$	$1.21 \cdot 10^4\ {}^{+2\%}_{-10\%}\ {}^{+2\%}_{-2\%}$	51
$pp \rightarrow$	Htj	$2.07 \cdot 10^1\ {}^{+2\%}_{-1\%}\ {}^{+2\%}_{-2\%}$	$5.21 \cdot 10^3\ {}^{+3\%}_{-5\%}\ {}^{+1\%}_{-1\%}$	252
$pp \rightarrow$	$HW^{\pm}$	$7.31 \cdot 10^2\ {}^{+2\%}_{-1\%}\ {}^{+2\%}_{-2\%}$	$1.54 \cdot 10^4\ {}^{+5\%}_{-8\%}\ {}^{+2\%}_{-2\%}$	21
$pp \rightarrow$	HZ	$3.87 \cdot 10^2\ {}^{+2\%}_{-1\%}\ {}^{+2\%}_{-2\%}$	$8.82 \cdot 10^3\ {}^{+4\%}_{-8\%}\ {}^{+2\%}_{-2\%}$	23

Torrielli, arXiv:1407.1623

√S = 8 TeV → σ(tHj) ~ 10^{-3} σ(H)

√S = 100 TeV → σ(tHj) ~ 10^{-2} σ(H)

Part 2:

complex g_{ttH} (→ CP violating)

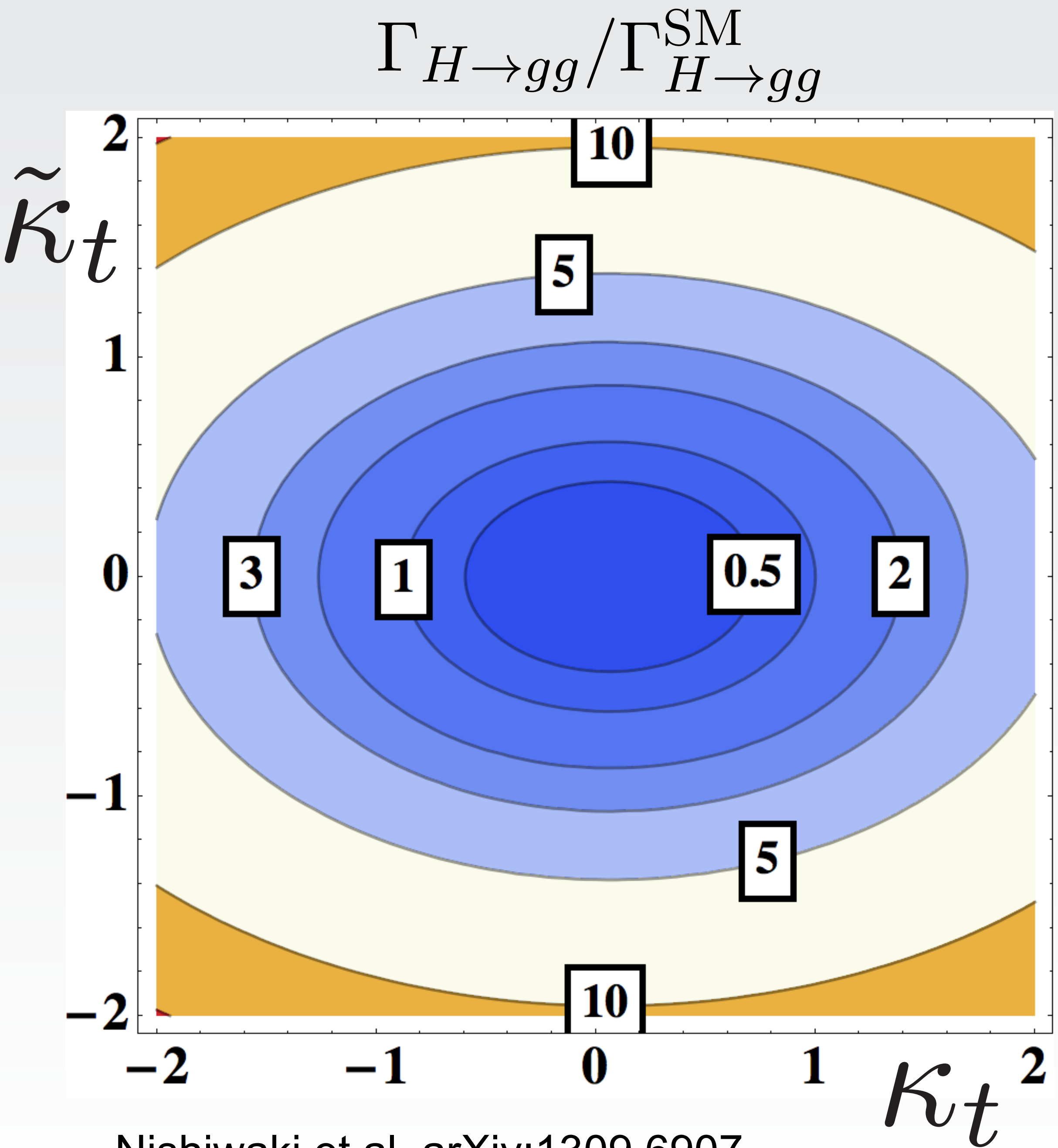
$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

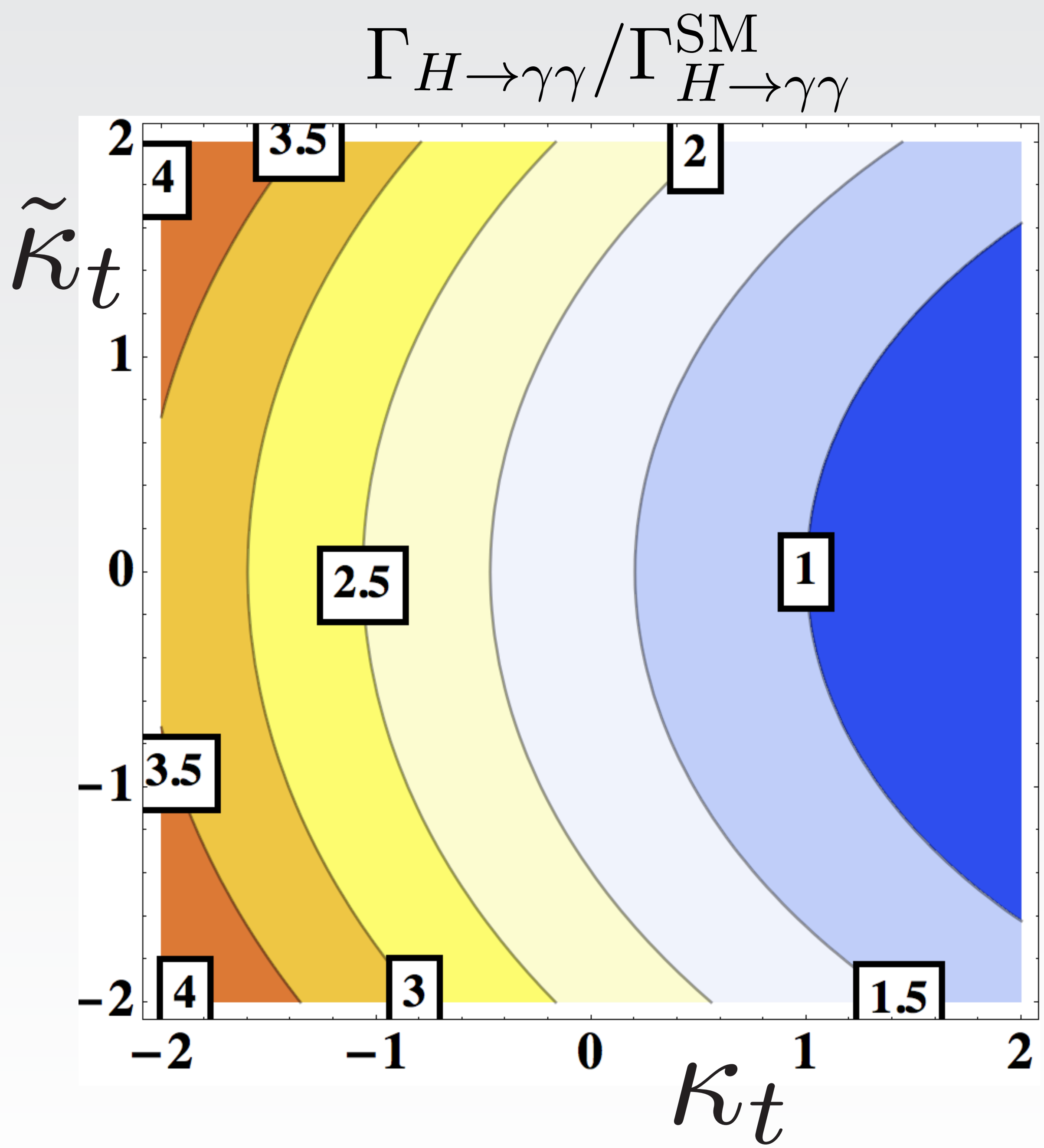
$$\kappa_t \equiv C_t \quad (\tilde{\kappa}_t = 0)$$

great sensitivity in tHj features also to pseudo-scalar coupling $\tilde{\kappa}_t$!

indirect constrains on (κ_t , $\tilde{\kappa}_t$) from C_g and C_γ

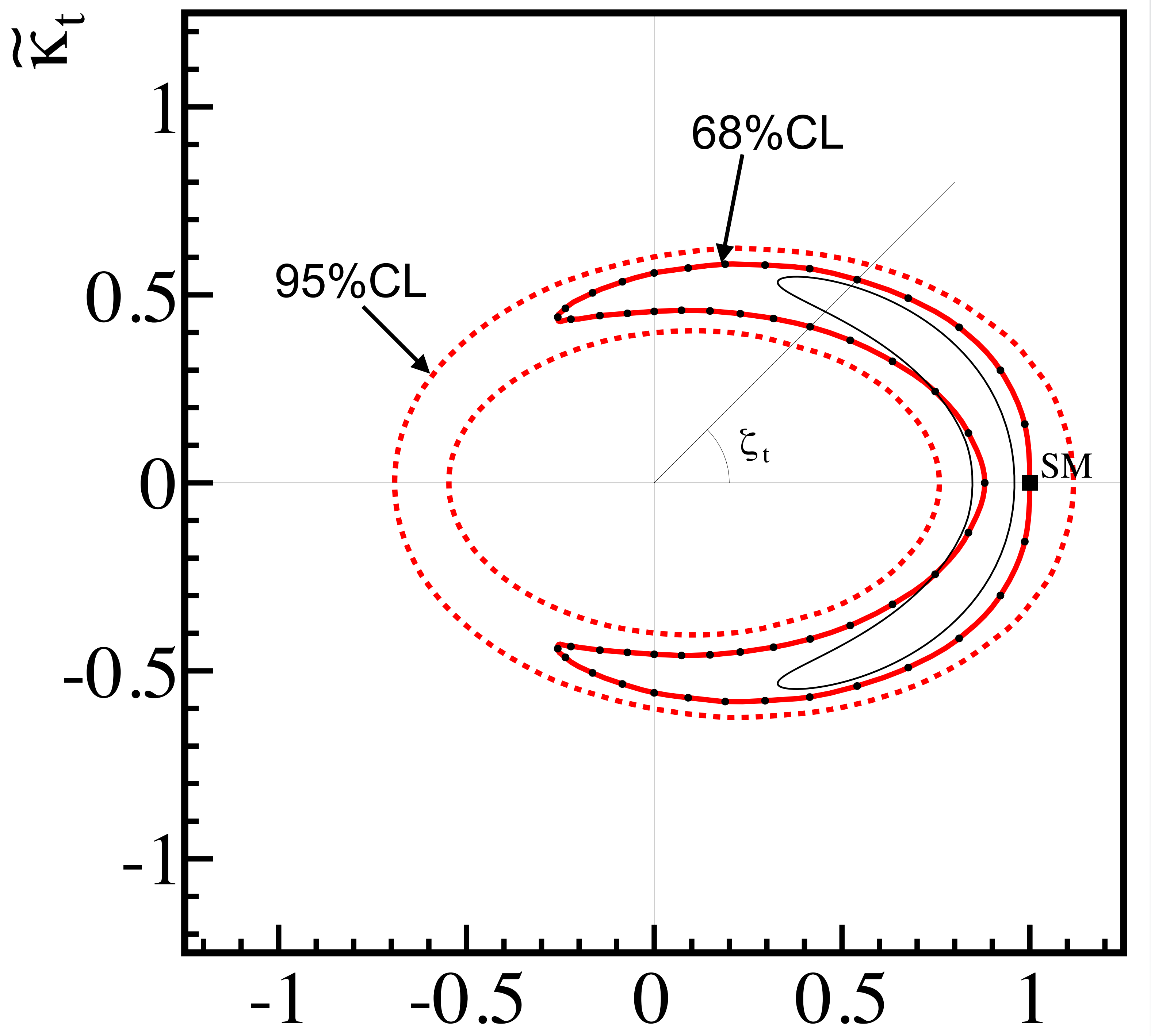
$$c_g^2 = \mu_{gg} \simeq \kappa_t^2 + 2.6\tilde{\kappa}_t^2 + 0.11\kappa_t(\kappa_t - 1)$$
$$c_\gamma^2 = \mu_{\gamma\gamma} \simeq (1.28 - 0.28\kappa_t)^2 + (0.43\tilde{\kappa}_t)^2$$





Nishiwaki et al, arXiv:1309.6907

by combining LHC constrains on C_g and C_γ :



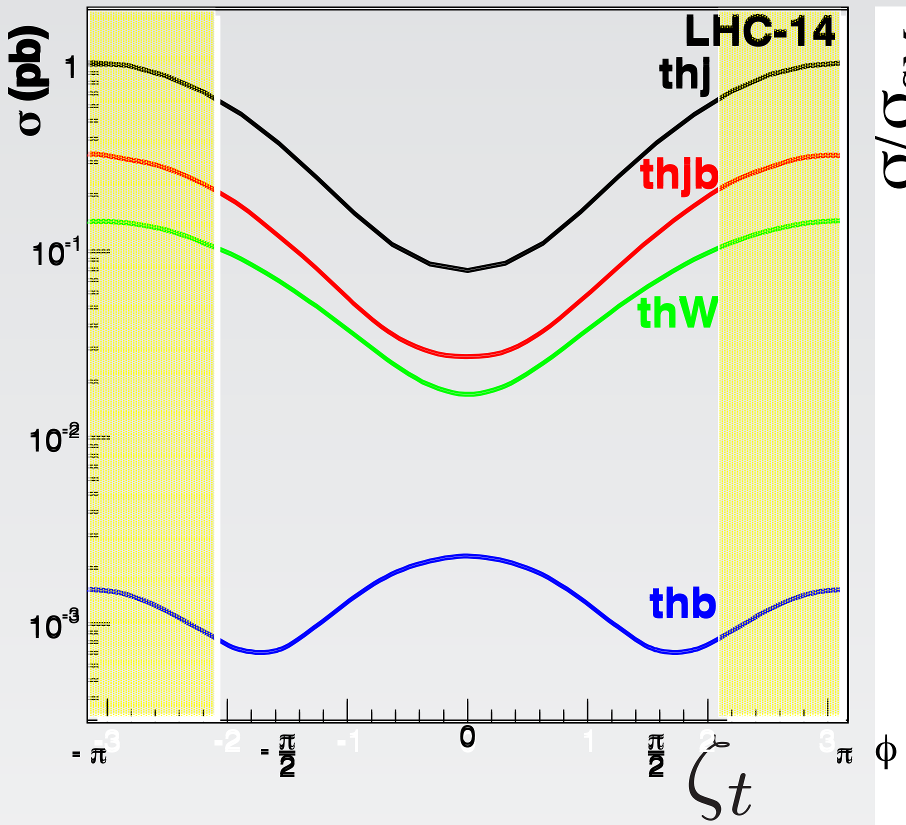
Ellis et al, arXiv:1312.5736

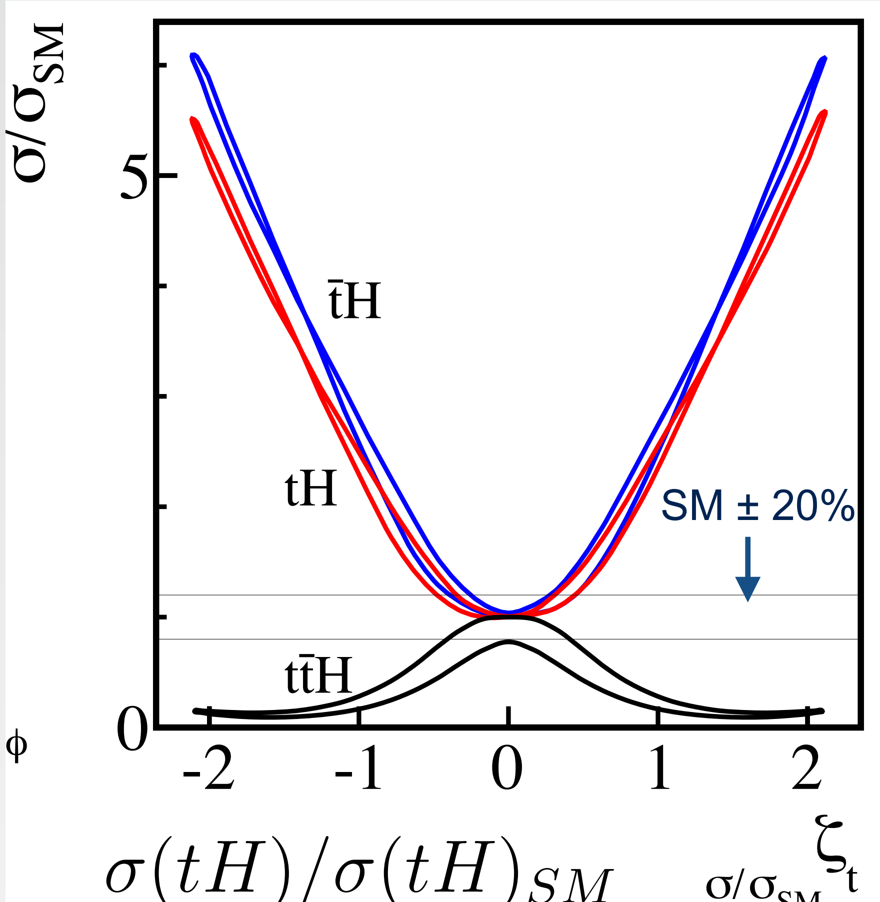
CP-violation phase in g_{ttH} :

$$\zeta_t \equiv \arctan\left(\frac{\tilde{\kappa}_t}{\kappa_t}\right)$$

low-energy bounds on electric dipole moments
$|\tilde{\kappa}_t| < 0.01 \quad \text{if} \quad \kappa_e = 1$
(model dependent !)
Brod et al, arXiv:1310.1385

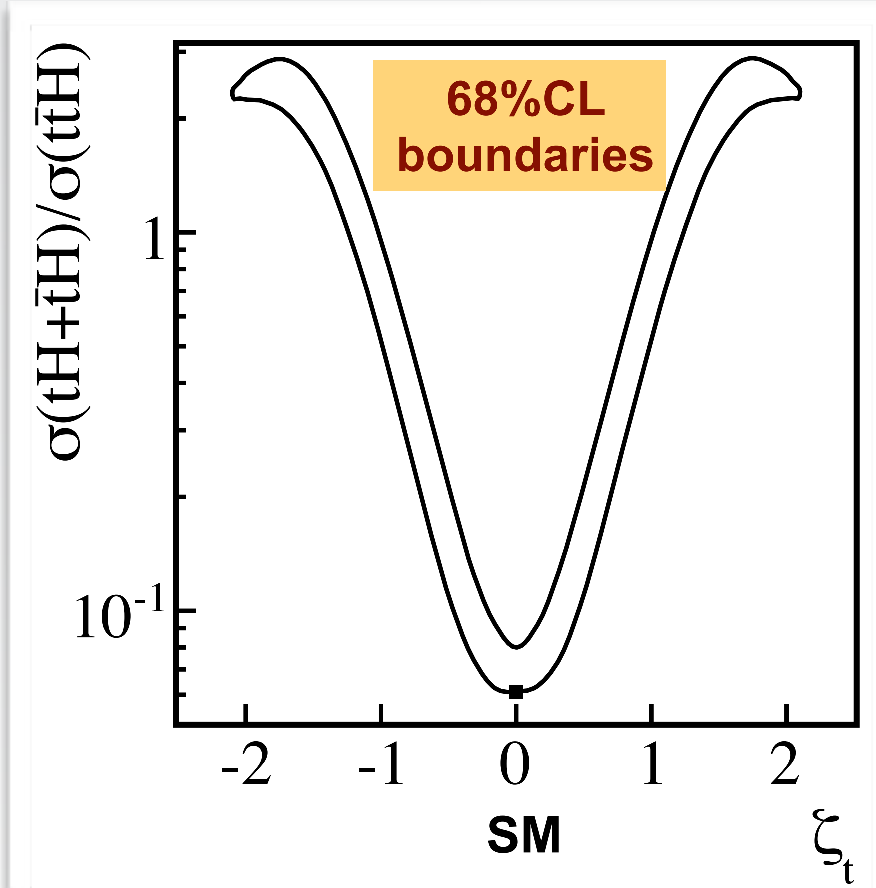
tHj and Htt cross sections versus (κ_t , $\tilde{\kappa}_t$, ζ_t)

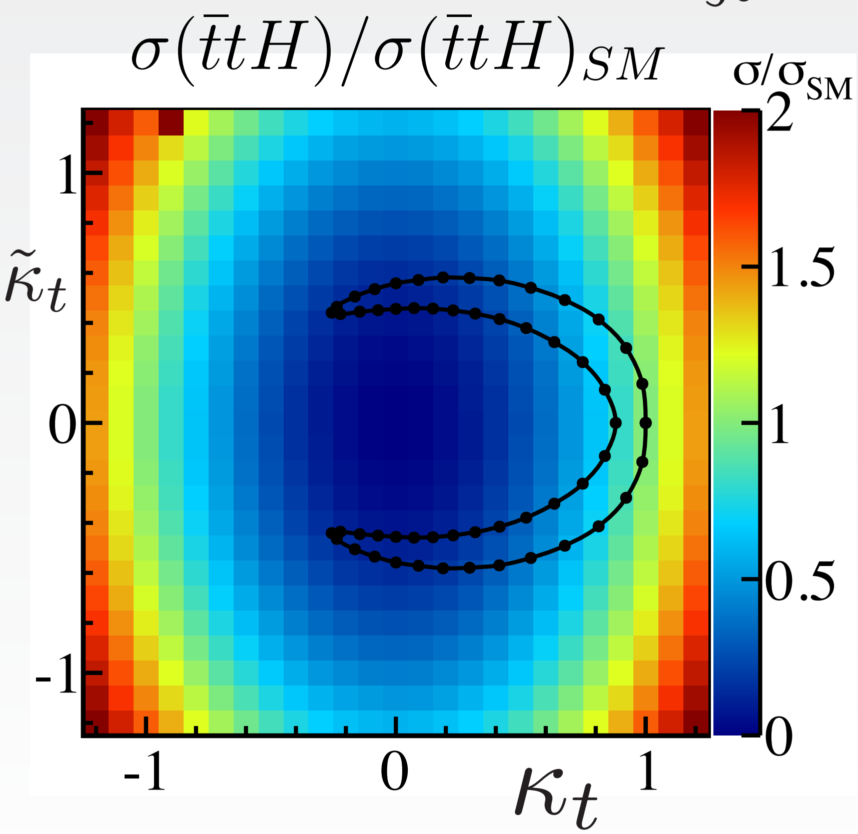


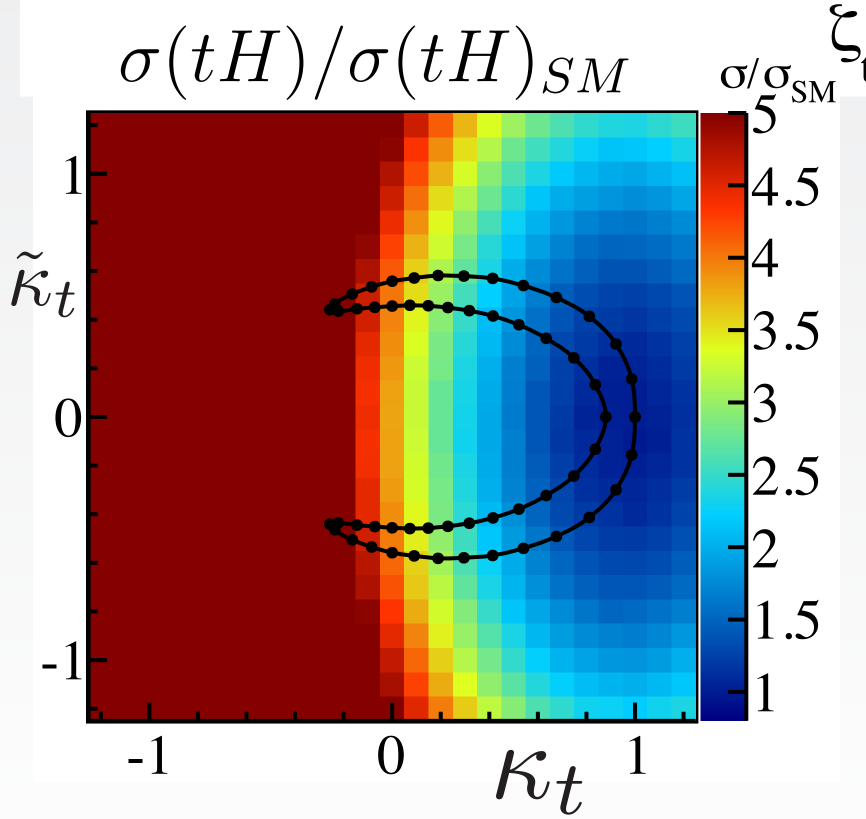


Ellis et al, arXiv:1312.5736

σ(tH)/σ(ttH) increased up to ~ 20







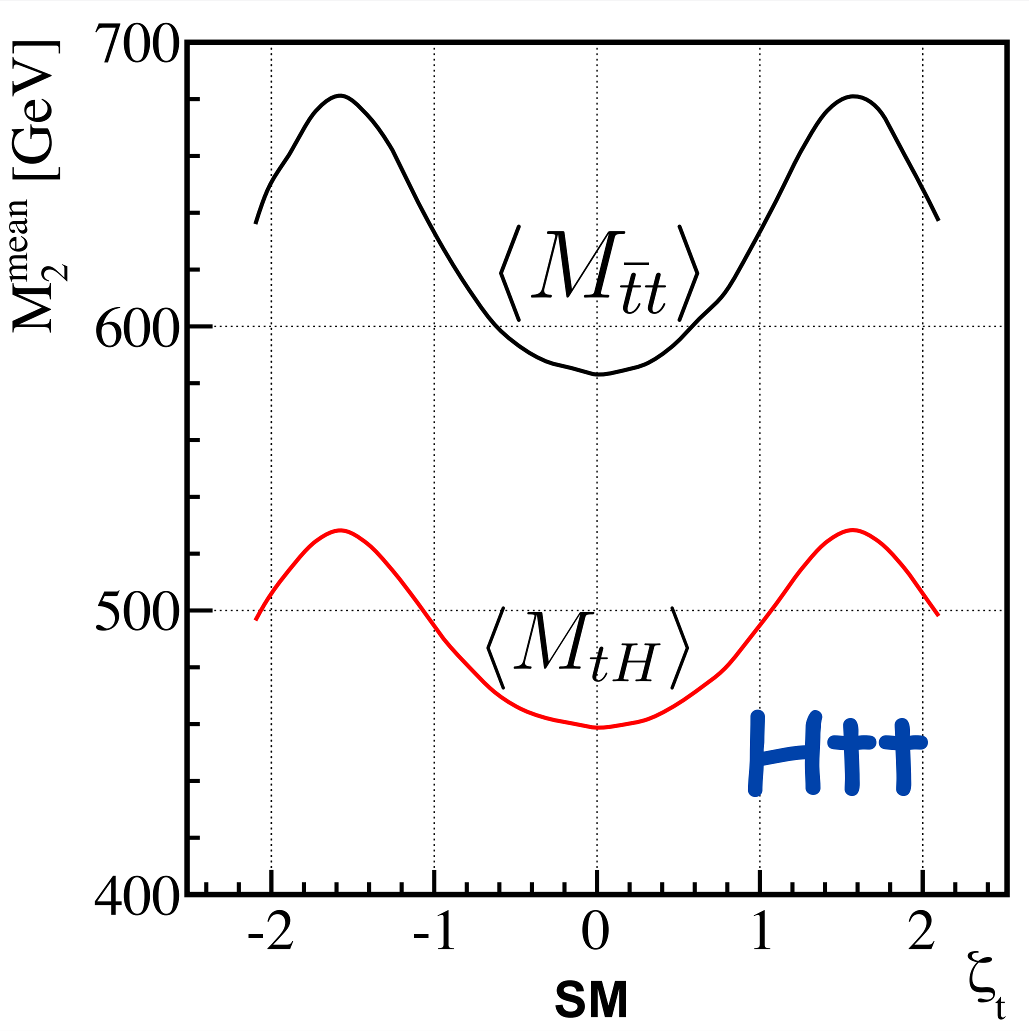
σ(tH)/σ(ttH)|$_{SM}$~0.06

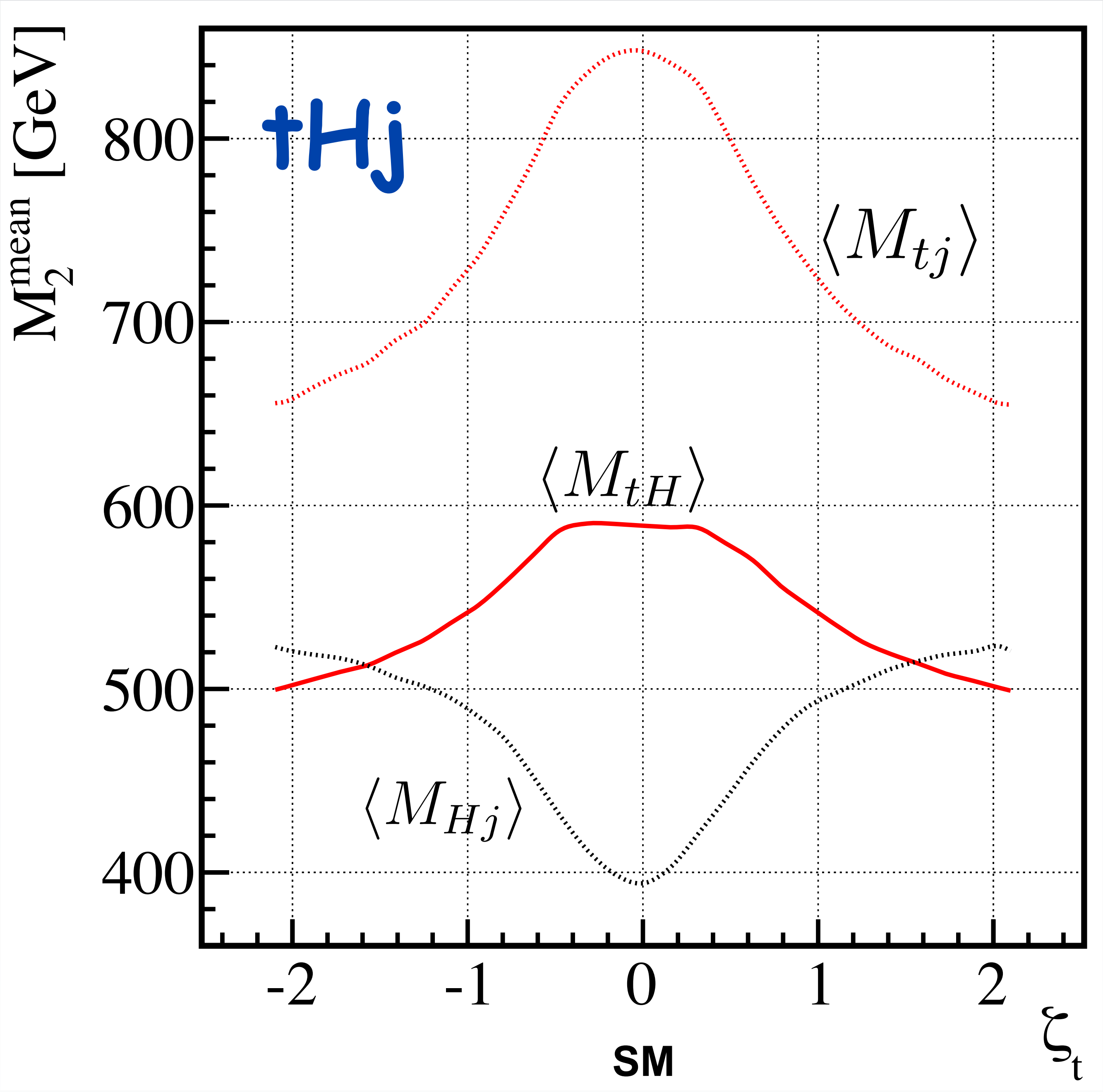
(see also Khatibi Najafabadi, arXiv:1409.6553)

tHj and Htt invariant-mass distributions

(along a contour passing trough the middle of 68%CL crescent-shape allowed region)

sensitive variables for all sub-systems !





lepton angle in [t(→ℓvb) H j] and $|\tilde{\kappa}_t/\kappa_t|$

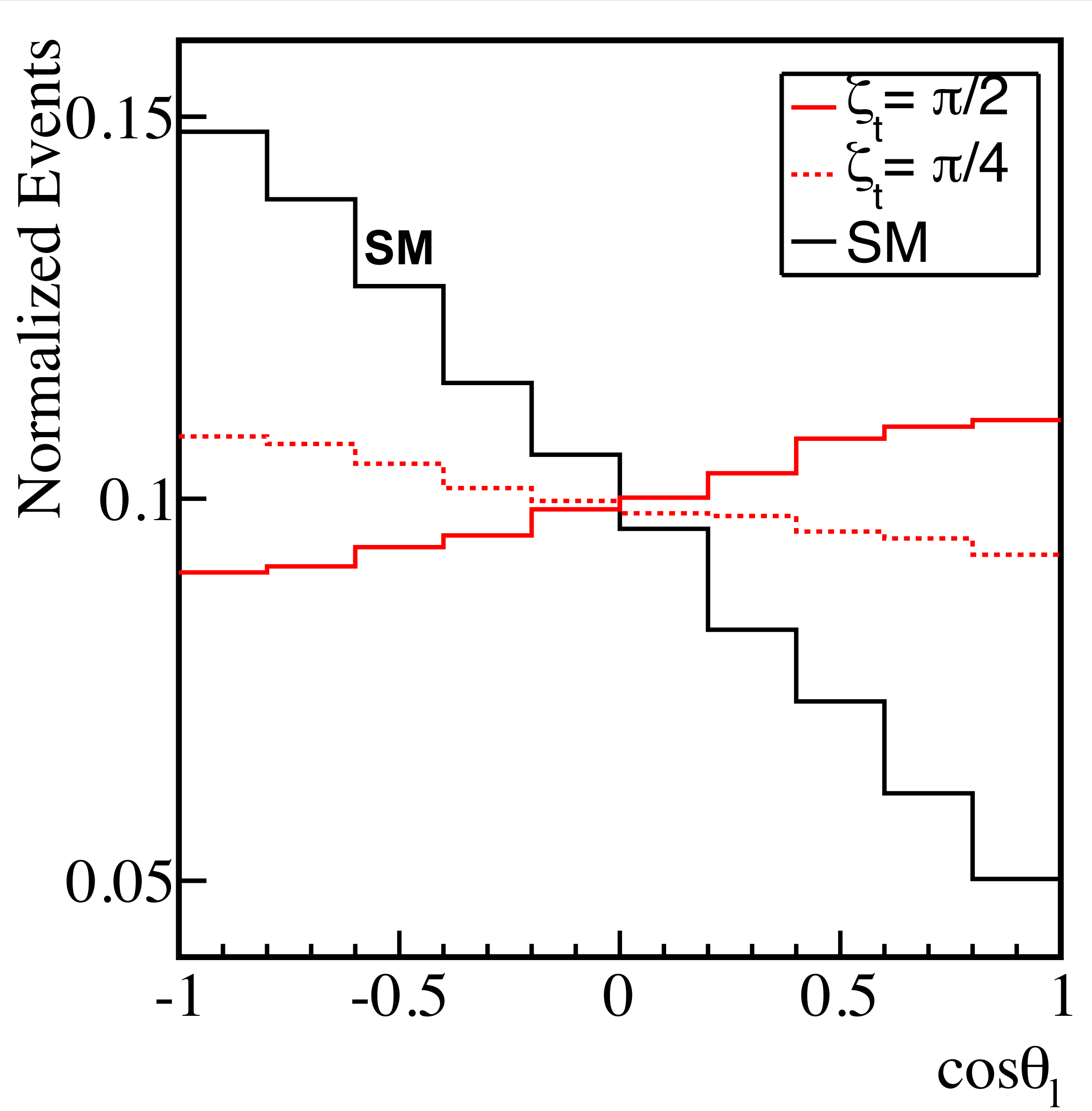
$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1+\omega_f P_t \cos\theta_f)$$

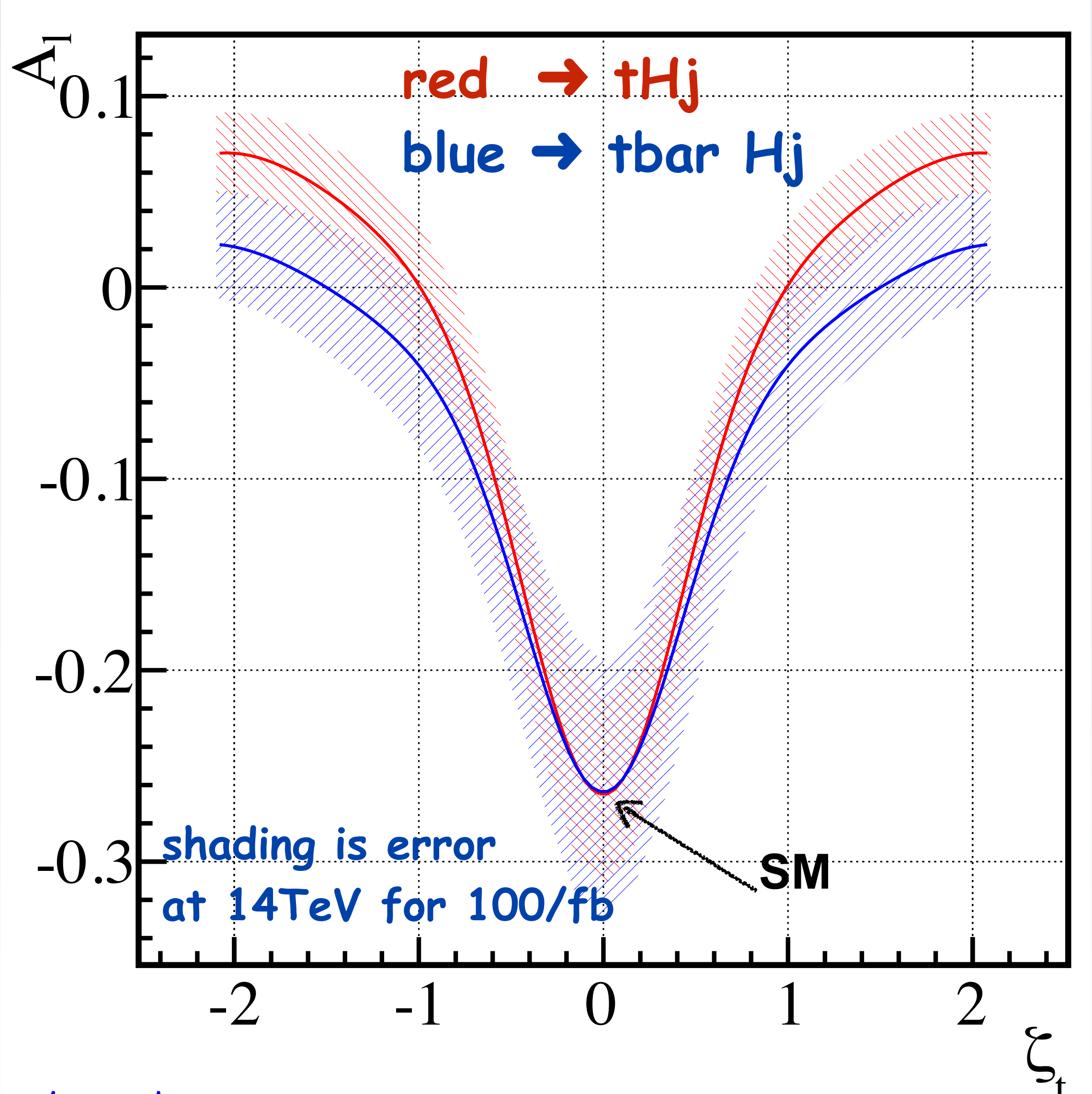
top spin quantization axis
in top rest frame
(angle wrt top boost direction)

top in tHj highly polarized in the SM

large $P_t = \frac{N(\uparrow)-N(\downarrow)}{N(\uparrow)+N(\downarrow)}$ ➜ large asymmetry

$$A_\ell = \frac{N(\cos\theta_\ell>0)-N(\cos\theta_\ell<0)}{N(\cos\theta_\ell>0)+N(\cos\theta_\ell<0)}$$





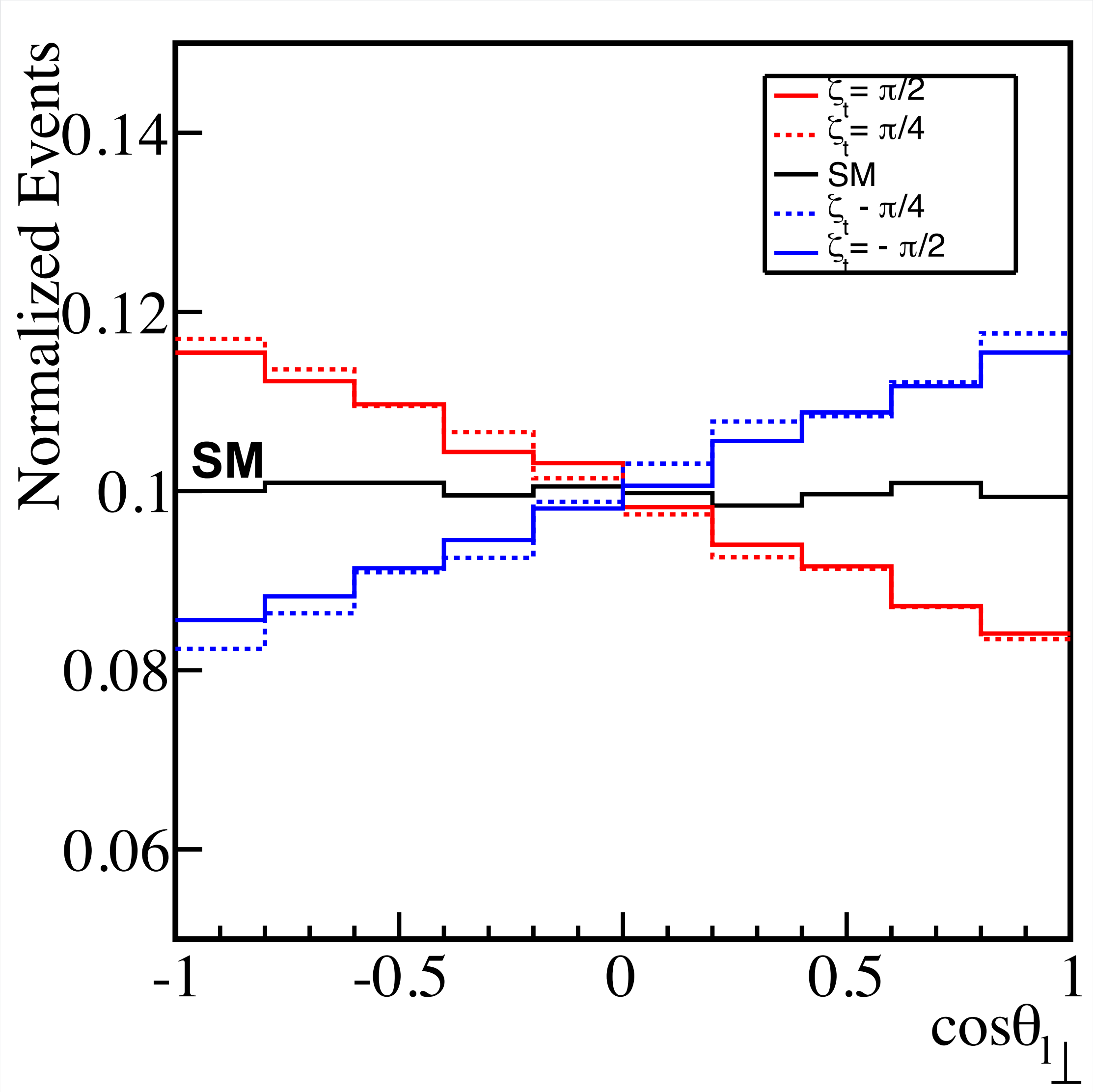
$|\tilde{\kappa}_t/\kappa_t| \neq 0$ decreases Asymmetry !

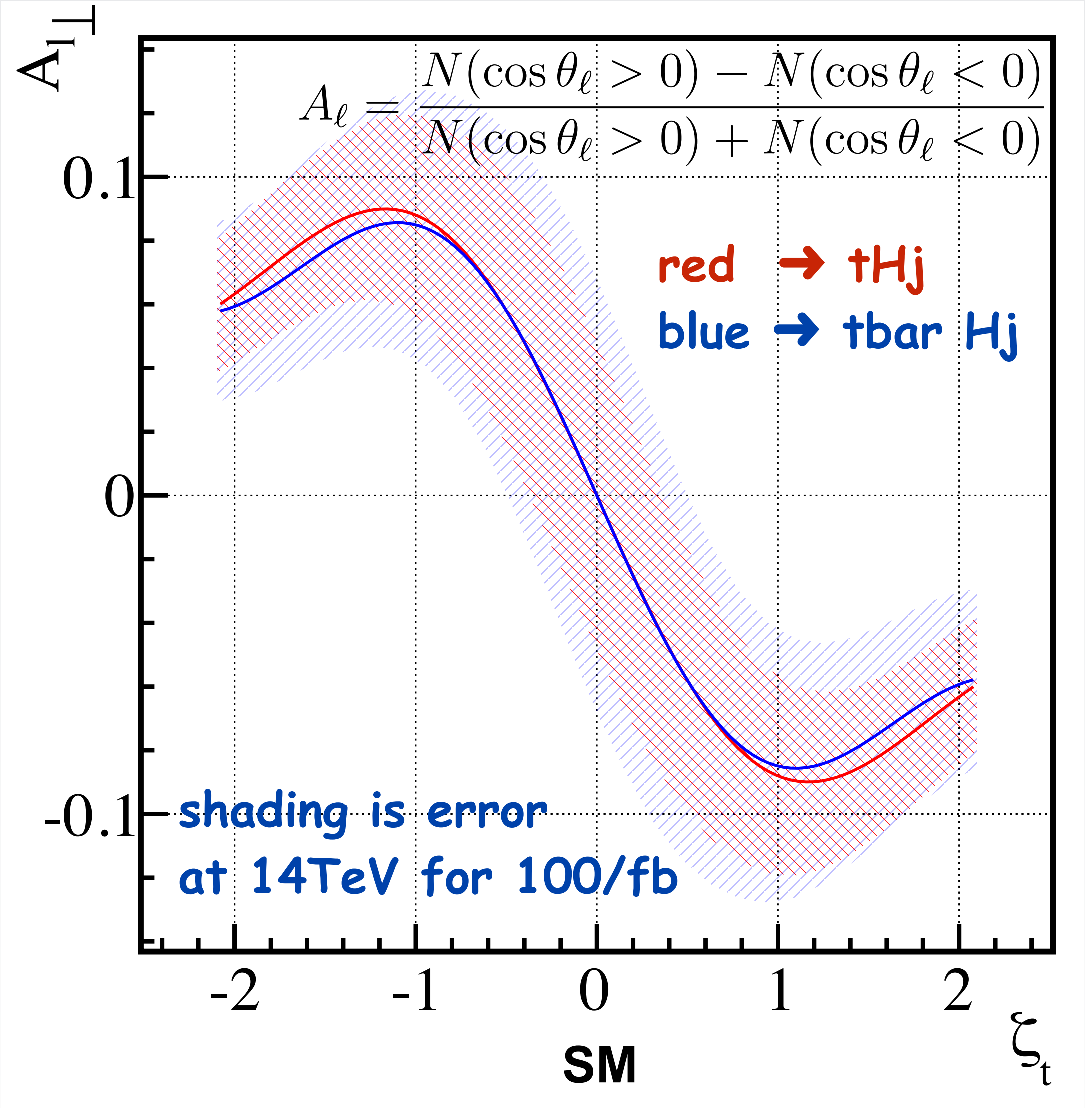
t(→ℓνb) H j and sign of $\tilde{\kappa}_t/\kappa_t$

lepton decay angle out of tHj production plane sensitive to sign of $\tilde{\kappa}_t/\kappa_t$

$\vec{p}_j \times \vec{p}_H$ ➜ top spin quantization axis perpendicular to production plane in top rest frame

$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1+\omega_f P_t \cos\theta_f)$$

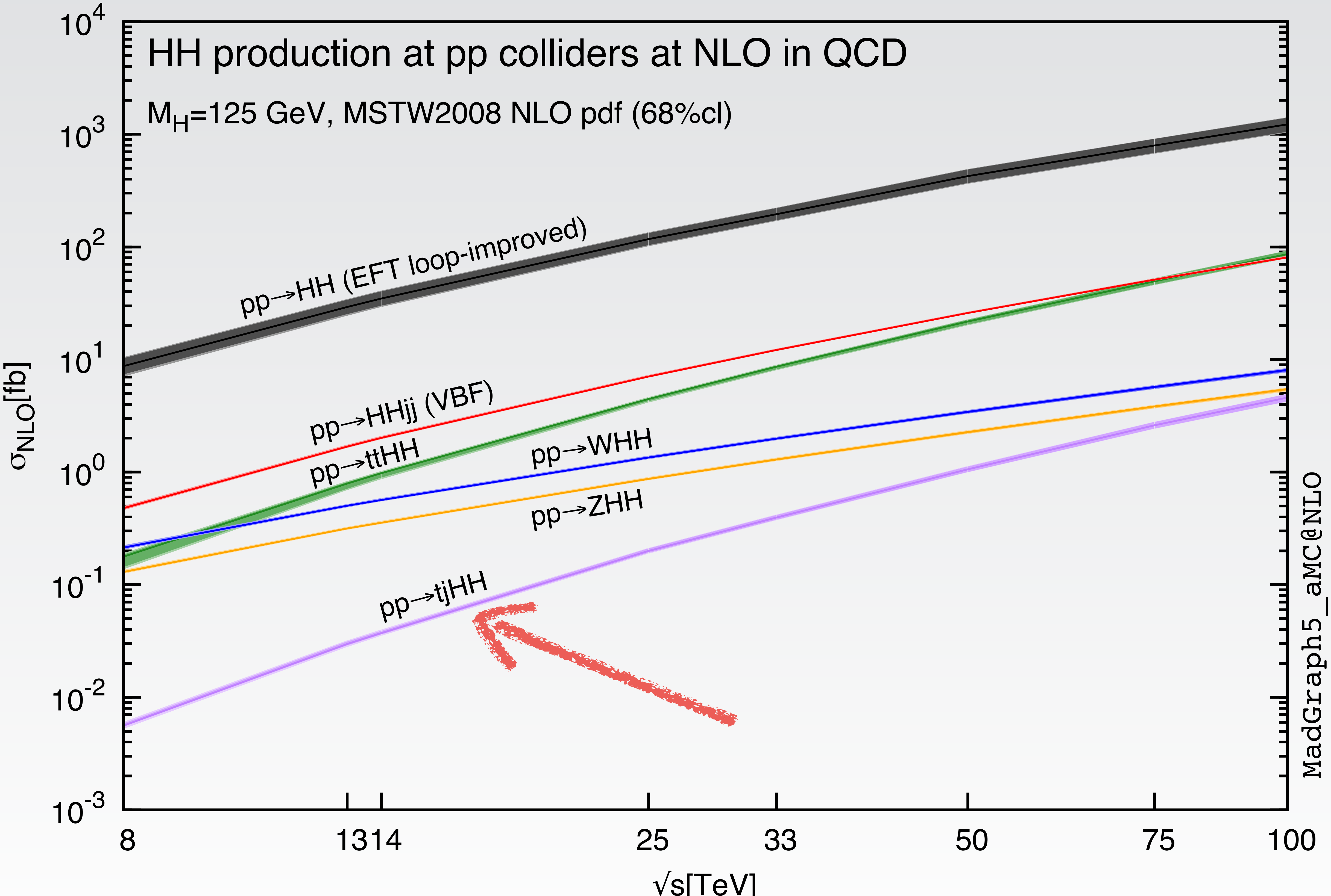




Ellis et al, arXiv:1312.5736

just a look to the far future of t+H…

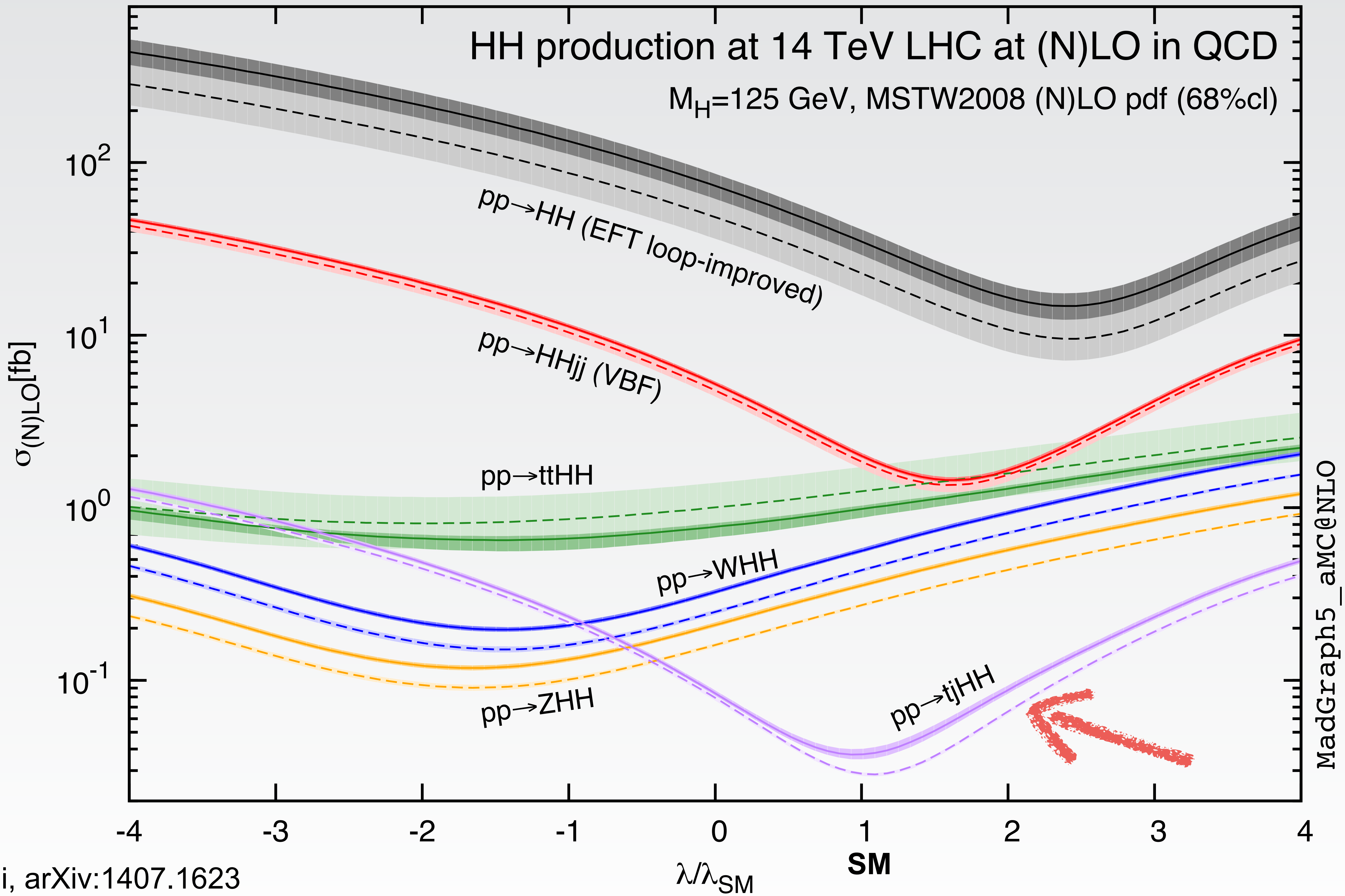
t+HH production



Torrielli, arXiv:1407.1623

nice sensitivity to trilinear coupling λ H^3

$[\lambda^{SM} = (m_H/v)^2/2 = 0.13]$



Torrielli, arXiv:1407.1623

Outlook

- g_{Htt} coupling tightly connected to EWSB mechanism
- crucial to probe it in a direct way
- p p → H tt major role, but not sensitive to g_{Htt} sign
- p p → t H q production excellent test of g_{Htt} sign
- p p → t H q also sensitive to pseudo-scalar g_{Htt} components (in a complementary way to Htt production); kinematical distributions and asymmetries crucial !
- SM tHq cross sections hard to probe in near future
- 13-TeV run expected to reach sensitivity needed for testing the $C_t \sim -1$ hypothesis through p p → t H q !