

# Flavour physics of the top quark and projecting on the Higgs to light

Gilad Perez

Weizmann Inst.



Physics at the High-Luminosity LHC

# Flavor physics $\Leftrightarrow$ precision test $\Rightarrow$ good for HL

$$\text{mass reach} \propto (\text{Lumi})^{\frac{1}{7}}$$



- ◆ Slow progress in energy frontier, still conventional searches should push forward. (will be done in any case regardless of what we discuss today...)

More info' e.g: Salam-Weiler, <http://collider-reach.web.cern.ch/collider-reach/>

$$\text{mass reach} \propto (\text{Lumi})^{\frac{1}{2}, \frac{1}{4}}$$



- ◆ Faster progress in “precision frontier”, not too hard physics scale, relatively weak coupling  $\Leftrightarrow$  this talk ...

# Outline

---

- ◆ Intro: top and flavor.
  - ◆ The case for top FCNC & its challenge, lurking Standard Model (SM) background.
  - ◆ Top B-phys., alternative incl. & excl. way for precision flavor tests at the LHC.
  - ◆ Summary.
- .....
- ◆ HL Higgs-to-light projections:  
powerful inclusive (charm); miserable exclusive (post ATLAS  $h \rightarrow J/\psi\gamma$ ).

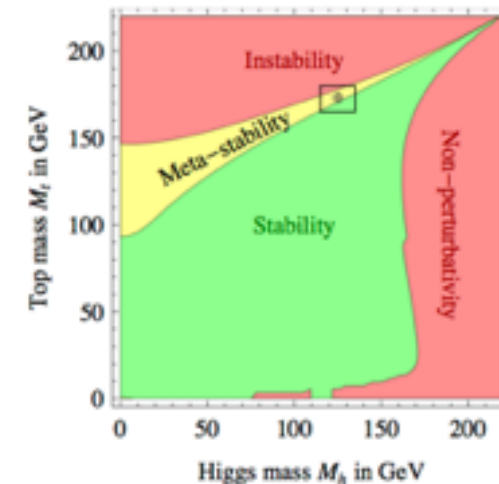
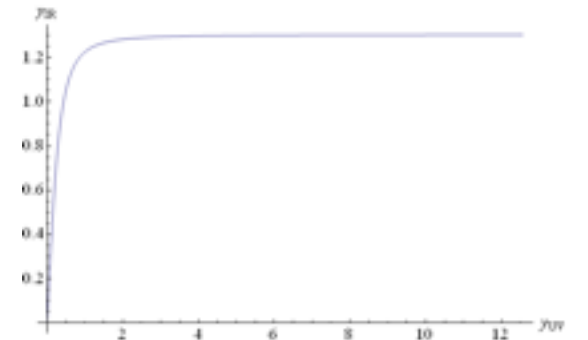
# Intro: top & flavor (post LHC1)

- ◆ The top is a quark, a part of the flavor sector. (not enough for a dedicated talk)
- ◆ Special among quarks, reinforced by LHC1:

SM: the largest Yukawa, but actually almost maximal because of perturbativity -

because of stability -

(raise of  $< 3\%$  in top Yukawa  $\Rightarrow$  weakless universe)



Degrassi, Vita, Elias-Miro, Espinosa, Giudice, Isidori & Strumia (12)

and, because it is the only quark  
w (proven) coupling to the Higgs -

$\mu$	ATLAS+CMS
$\tau$	$0.97 \pm 0.23$
$b$	$0.71 \pm 0.31$
$t$	$2.2 \pm 0.6$ (Moriond)

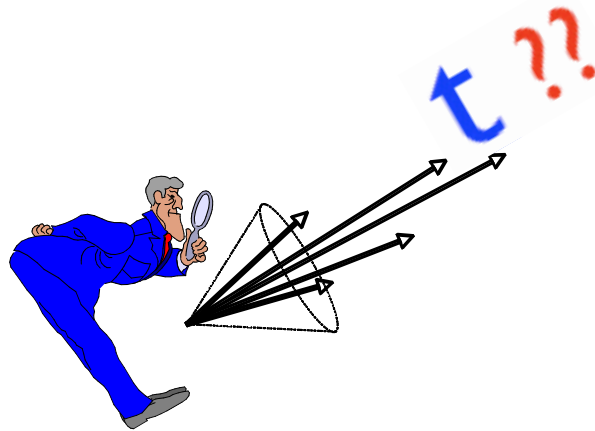
$$\mu_x = \frac{\sigma_h^x \text{BR}_x}{\sigma_h^{\text{x,SM}} \text{BR}_x^{\text{SM}}}$$

# Top and flavor, potential progress at the LHC & HL-LHC

---

- ◆ The (established) top-Higgs couplings suggests that it's linked to new physics (NP) related to electroweak sym' breaking and/or the hierarchy problem.
- ◆ There are many forms in which top-phys. probe NP scenario. The charge: not to discuss "top" as a signature of other  $B_{\text{eyondSM}}$  particles, but top in its own.  
Focus on 2 case studies, potentially relevant to HL-LHC:
  - (i) t-FCNC, clearly rare process but also well motivated theoretically (see below);
  - (ii) t-bphys: leptonically decaying top  $\Rightarrow$  flavor-tagging b-quark  $\Rightarrow$  flavor factory.

$t$ FCNC as new phys. probe,  
experimental challenges & opportunities



# $t$ FCNC status & EFT

- ◆ GIM+loop:  $t \rightarrow c, u \ Z/h/\gamma$ , SM null test.  $BR(t \rightarrow qZ, \gamma, G) \sim 10^{-12}$ .  
(Díaz-Cruz (89); Eilam, Hewett & Soni (90))

- $t \rightarrow qZ$ :  
 $Br(t \rightarrow qZ) < 0.05\%$  CMS-TOP-12-037
- $t \rightarrow qh$ :  
 $Br(t \rightarrow ch) < 0.56\%$  CMS-PAS-HIG-13-034
- $qg \rightarrow t$ :  
 $Br(t \rightarrow ug) < 3.1 \times 10^{-5}$ ,  $Br(t \rightarrow cg) < 1.6 \times 10^{-4}$  ATLAS-CONF-2013-063
- $qg \rightarrow t\gamma$ :  
 $Br(t \rightarrow u\gamma) < 0.0161\%$ ,  $Br(t \rightarrow c\gamma) < 0.182\%$   
(assuming  $tug$  vanishes) CMS-PAS-TOP-14-003

Cen Zhang, Top14.

RunII projections LHC (see HL below): LHC ( $100\text{fb}^{-1}$ ):  $BR(t \rightarrow qZ, \gamma) \gtrsim 10^{-5}$ .  
(Carvalho, et. al (05))

- ◆ Effective field theory (EFT), consider  $t \rightarrow cZ$  for simplicity:

$$\bar{t}_R \gamma^\mu c_R (H^\dagger \overleftrightarrow{D}_\mu H), \quad \bar{t}_L \gamma^\mu c_L (H^\dagger \overleftrightarrow{D}_\mu H) \quad \text{and} \quad \bar{t}_L \gamma^\mu \sigma_3 c_L (H^\dagger \sigma_3 \overleftrightarrow{D}_\mu H).$$

# $t$ FCNC status & EFT

- ◆ Effective field theory (EFT), consider  $t \rightarrow cZ$  for simplicity:

$$\bar{t}_R \gamma^\mu c_R (H^\dagger \overleftrightarrow{D}_\mu H), \quad \bar{t}_L \gamma^\mu c_L (H^\dagger \overleftrightarrow{D}_\mu H) \quad \text{and} \quad \bar{t}_L \gamma^\mu \sigma_3 c_L (H^\dagger \sigma_3 \overleftrightarrow{D}_\mu H).$$

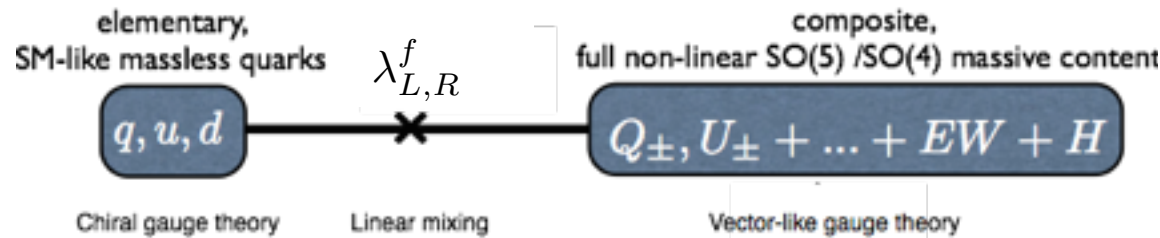
- ◆ Generic NP tale:

$$\begin{aligned} \text{BR}(t \rightarrow cZ)_{\text{dim 6}} &\sim \left( \frac{g}{2c_W} \right)^2 \times V_{23}^2 \times \frac{v^4}{M_*^4} \\ &\sim 10^{-5} \times (200, 0.3, 2) \times \left( \frac{V_{23}}{1}, \frac{V_{23}^L}{V_{cb}}, \frac{V_{23}^R}{\frac{m_c}{m_t V_{cb}}} \right)^2 \times \left( \frac{700 \text{ GeV}}{M_*} \right)^4 \\ &\quad \text{anarchy, LH-MFV, RH (flavor models)} \\ &\sim 10^{-5} \times \left( \frac{3 \text{ TeV}}{M_*} \right)^4 \\ &\quad \text{generic reach} \end{aligned}$$

- ◆ Model predictions:

- (i) almost impossible for loop induced NP;
- (ii) only  $< \text{TeV}$  NP can be probed, preferably w RH, non-MFV structure ...
- (iii) generically fulfilled by composite Higgs models, w no extra th' effort ...

# 2 slides on composite Higgs $\Rightarrow t \rightarrow cZ$



$$m^f \propto \lambda^f_L \times \lambda^f_R, \quad V^{\text{CKM}/L}, V^R \propto \frac{\lambda^i_L}{\lambda^j_L}, \frac{m_c}{m_t V_{ij}^{\text{CKM}}} \quad \text{same structure as in EFT}$$

see:

Gherghetta & Pomarol (00)  
Huber & Shafi (11)

♦  $t_R \rightarrow c_R Z$  in composite models could be **large**. Agashe GP & Soni (06)

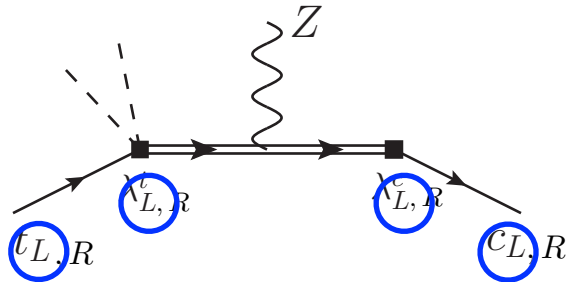
$$\text{BR}(t \rightarrow cZ)_{\text{dim 6}} \sim \left( \frac{g}{2c_W} \right)^2 \times V_{23}^2 \times \frac{v^4}{M_*^4}$$

$$\sim 10^{-5} \times (200, 0.3, 2) \times \left( \frac{V_{23}}{1}, \frac{V_{23}^L}{V_{cb}}, \frac{V_{23}^R}{\frac{m_c}{m_t V_{cb}}} \right)^2 \times \left( \frac{700 \text{ GeV}}{M_*} \right)^4$$

# Composite natural $t \rightarrow cZ$

- ♦  $t \rightarrow cZ$  in custodial composite models could be **small**.

Agashe, Contino, Da Rold & Pomarol (06)



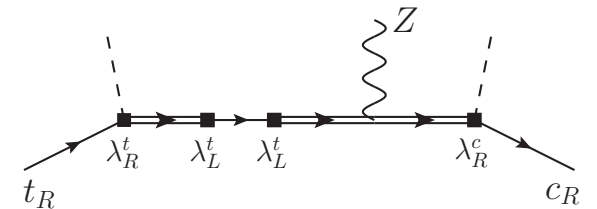
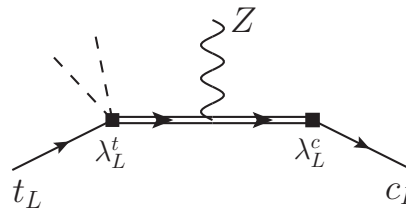
$$\text{BR}(t \rightarrow cZ)_{\text{dim } 6} \sim \left( \frac{g}{2c_W} \right)^2 \times V_{23}^2 \times \frac{v^4}{M_*^4}$$

$$\lesssim 10^{-5} \times (200, 0.3, 2) \times \left( \frac{V_{23}}{1} \frac{V_{23}^L}{V_{cb}}, \frac{V_{23}^R}{m_c V_{cb}} \right)^2 \times \left( \frac{700 \text{ GeV}}{M_*} \right)^4$$

- ♦  $t \rightarrow cZ$  in natural custodial composite models should be **large**.

As both LH & RH tops needs to be composite, Azatov, Panico GP & Soreq (14)

$$\text{BR}(t \rightarrow cZ) \sim 10^{-5} \left( \frac{700}{M_*} \right)^4.$$



- ♦ Two extra generic predictions:

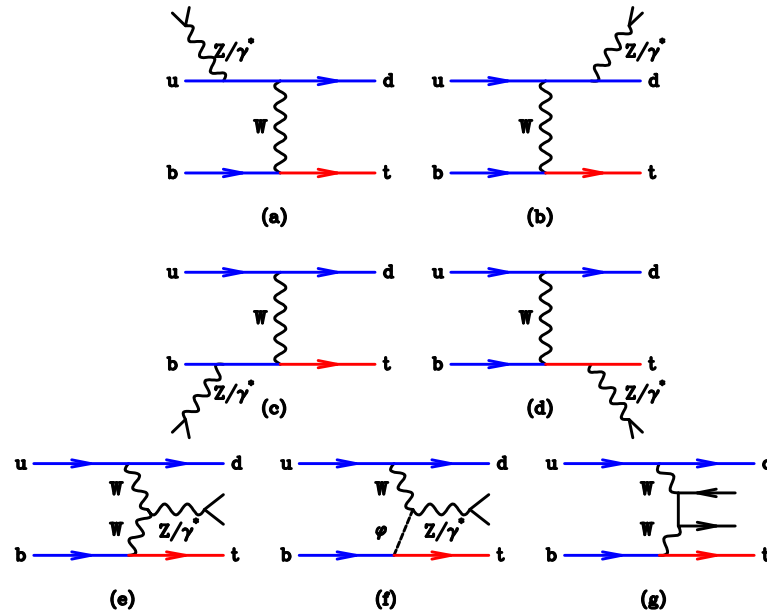
(i) tops should be RH polarized; (ii) should be a charm (tagger)

Azatov, Panico, GP & Soreq (14)

# The SM semi-irreducible background

- ♦  $tZj$  in the SM is important once  $\text{BR}(t \rightarrow cZ) < 10^{-5}$  is reached.

Campbell, Ellis & Rontsch (13)



- ♦ Current bound is  $\text{BR}(t \rightarrow cZ) \sim 5 \times 10^{-4}$ , more serious studies required before the experimentalists actually go below  $10^{-5}$  ...

I apologise if it exists but I failed to find it.

# The SM semi-irreducible background

- ◆ Similar story for  $\text{BR}(t \rightarrow ch)$  for NP, but with suppression:

Agashe & Contino (09)

$$\begin{aligned}
 y_{tc,L} &\sim \frac{\lambda_R^t \lambda_R^c}{M_*^2} \frac{v}{f^2} m_t \sim \frac{m_t m_c}{f M_* V_{cb}} \sim 4 \times 10^{-3} \left( \frac{700 \text{ GeV}}{f} \right) \left( \frac{700 \text{ GeV}}{M_*} \right), \\
 y_{tc,R} &\sim \frac{\lambda_L^t \lambda_L^c}{M_*^2} \frac{v}{f^2} m_t \sim \frac{m_t^2 V_{cb}}{f M_*} \sim 2 \times 10^{-3} \left( \frac{700 \text{ GeV}}{f} \right) \left( \frac{700 \text{ GeV}}{M_*} \right),
 \end{aligned}
 \Rightarrow
 \text{BR}(t \rightarrow ch) \sim 5 \times 10^{-6} \left( \frac{700 \text{ GeV}}{f} \right)^2 \left( \frac{700 \text{ GeV}}{M_*} \right)^2.$$

Azatov, Panico, GP & Soreq (14)

- ◆ HL projection:  $\text{BR}(t \rightarrow ch) \sim 10^{-4}$ .

ATL-PHYS-PUB-2013-012

- ◆ Background: similar story w  $thj$  being the BG w a twist:

Campbell, Ellis & Rontsch (13)

- (i) SM  $thj$  production is small due to cancellation.

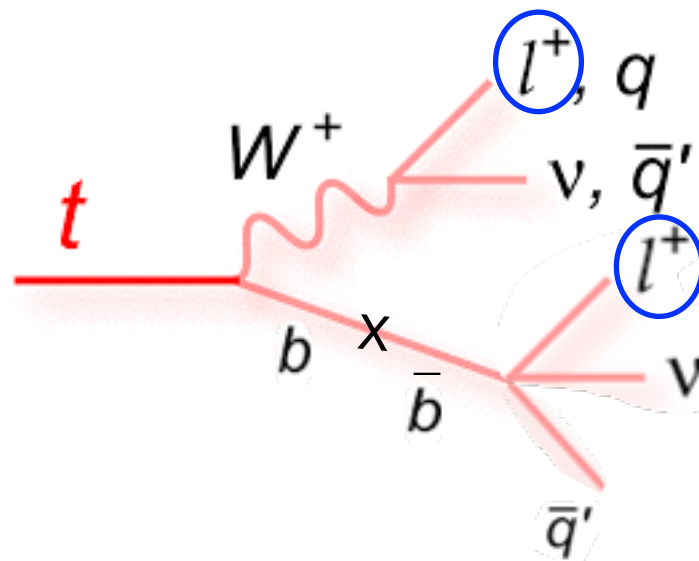
Tait & Yuan (00); Maltoni, Paul, Stelzer & Willenbrock (01)

- (ii)  $thj$  production  $\Rightarrow$  test for BSM (sign of  $y_t$ )  $\Rightarrow$  large enhancement.

Biswas, Gabrielli & Mele; Farina, Grojean, Maltoni, Salvioni & Thamm; Agrawal, Mitra & Shivaji (12)

- ◆ Would be good to check how much the  $t \rightarrow ch$  mix w  $thj$

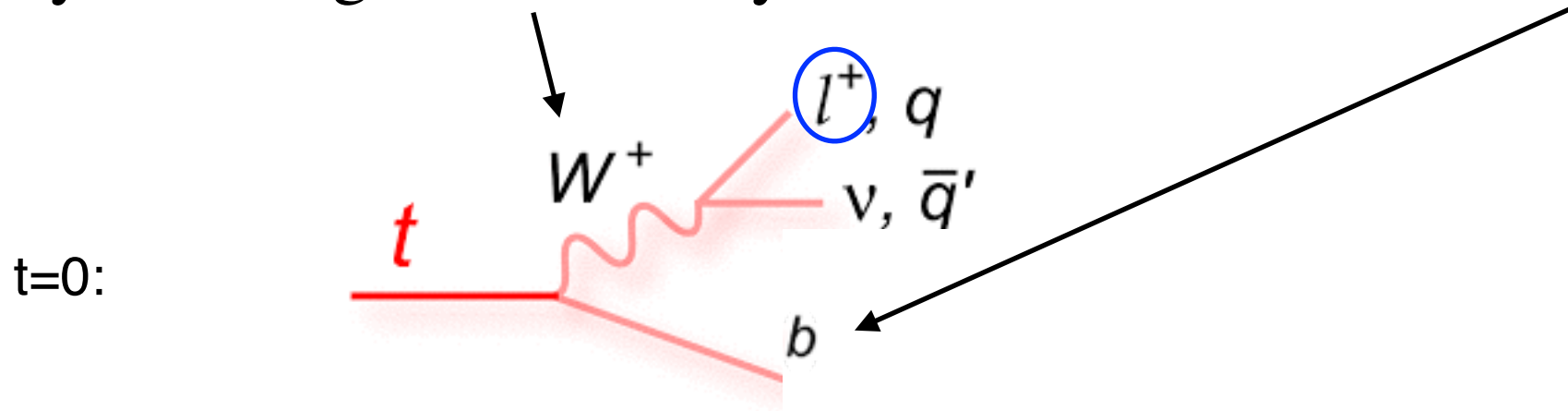
# top B-physics



# Top as a flavor factory, basic idea

Gedalia, Isidori, Maltoni, GP, Selvaggi & Soreq (12)

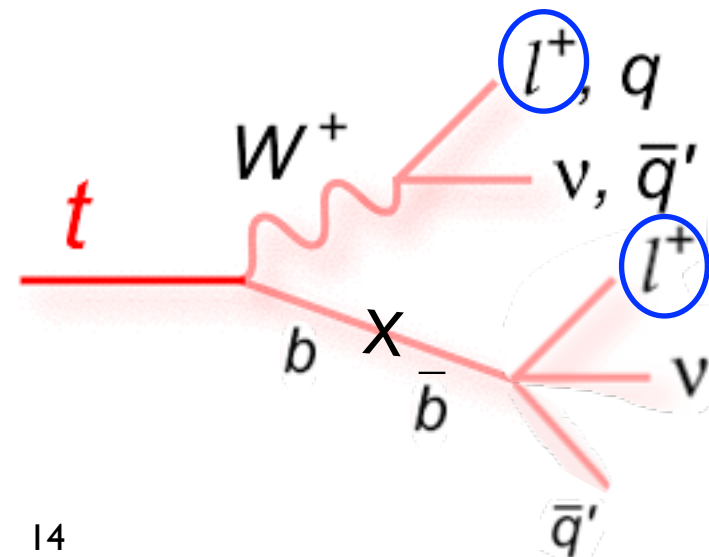
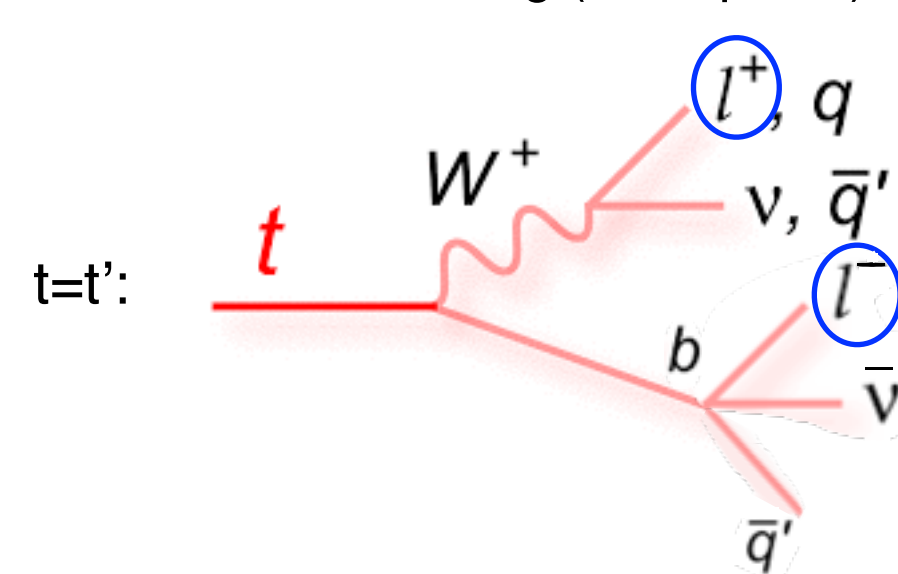
- ♦  $t$ -decay  $\Rightarrow$  charge of  $W$  is fully correlated w the flavor of  $b$ .



- ♦  $b$ -decay  $\Rightarrow$  charge of *lepton* is correlated w the flavor of  $b$ .

no mixing (OS leptons)

Ex.: w mixing (SS leptons)



# The observables & the asymmetries

Gedalia, Isidori, Maltoni, GP, Selvaggi & Soreq (12)

- Similar to  $b$ -factories define same-sign asymmetry but also opposite-sign asymm':

$$A^{ss} \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

$$A^{os} \equiv \frac{N^{+-} - N^{-+}}{N^{+-} + N^{-+}}$$

- Sensitive to two class of CP asymm':

(i) CPV in mixing; (ii) inclusive CPV in decay.

$$A^{ss} \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = r_b A_{\text{mix}}^{b\ell} + r_c (A_{\text{dir}}^{bc} - A_{\text{dir}}^{c\ell})$$

$\uparrow$   
 $b \rightarrow \bar{b} \rightarrow \ell^+$   
 0.16

$\uparrow$   
 $b \rightarrow c \rightarrow \ell^+$   
 0.82

$$A^{os} \equiv \frac{N^{+-} - N^{-+}}{N^{+-} + N^{-+}} = \tilde{r}_b A_{\text{dir}}^{b\ell}$$

$\uparrow$   
 $b \rightarrow \ell^-$   
 0.79

# top B-physics, projections

Flavor & Top at 100 TeV: Maltoni & Soreq (15)

Sensitivity for the Asymmetries:

$$\delta A^{ss} \sim \frac{9.0}{\sqrt{\sigma_{t\bar{t}}\mathcal{L}}} \sim 6(1) \times 10^{-4} \quad \delta A^{os} \sim \frac{7.6}{\sqrt{\sigma_{t\bar{t}}\mathcal{L}}} \sim 5(0.8) \times 10^{-4}$$

For CP violation only in mixing (no direct CPV):

$$\delta A_{\text{mix}}^{b\ell} \sim 3(0.5) \times 10^{-3}$$

$$\sqrt{s} = 14(100) \text{ TeV} \quad \mathcal{L} = 300 \text{ fb}^{-1}$$

Bounds on direct CP violation sources (95% CL):

	current	8TeV	14TeV, 50
$A_{\text{dir}}^{b\ell}$	1.2%	1%	0.3%
$A_{\text{dir}}^{c\ell}$	6%	1%	0.3%
$A_{\text{dir}}^{bc}$	?	1%	0.3%

# Conclusions

---

---

- ◆ HL-LHC order of  $10^{10}$  tops  $\Rightarrow$  truly precision frontier.
- ◆  $\text{BR}(t \rightarrow ch/Z) \sim 10^{-5,-6}$ , well motivated in composite Higgs.
- ◆ Polarization & charm tagging provide support.
- ◆  $th/Zj$  backgrounds are important & interfere w other searches?
- ◆ top- $B$ phys.: possible new way of doing precision flavor physics.

# Flavour physics of the top quark and projecting on the Higgs to light

Gilad Perez

Weizmann Inst.

GP, Soreq, Stamou & Tobioka (Feb/15)  
GP, Soreq, Stamou & Tobioka (May/15)



Physics at the High-Luminosity LHC

# Higgs & flavor physics within the SM

♦ Higgs in minimal SM, 2 roles:

- (i) induce electroweak (EW) gauge boson masses & unitarization (high-E consistency);
- (ii) induce fermion masses & unitarization (high-E consistency).

(i) was already tested in a quantitative way (ii) much less & mostly for 3rd gen'.  
Currently, clueless whether the Higgs mechanism is behind light fermion masses!

♦ What happens if we just write bare masses to fermions?

Unitarity violation:

$$q\bar{q} \rightarrow V_L V_L$$

(where  $V_L$  is the longitudinal boson)

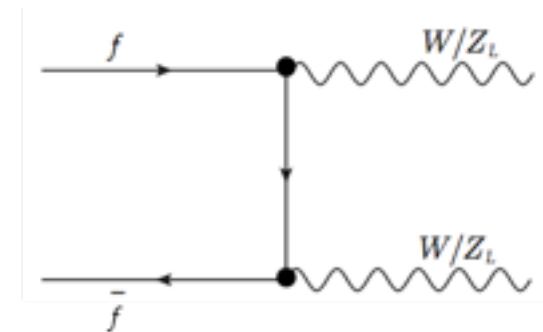
$$\begin{aligned} \sqrt{s} &\lesssim \frac{8\pi v^2}{\sqrt{6}m_{b,c,s,d,u}} \\ &\approx 200, 1 \times 10^3, 1 \times 10^4, 2 \times 10^5, 5 \times 10^5 \text{ TeV} . \end{aligned}$$

Appelquist & Chanowitz (87).

$$q\bar{q} \rightarrow nV_L$$

$$\sqrt{s} \lesssim 23, 31, 52, 77, 84 \text{ TeV} .$$

Maltoni, Niczyporuk & Willenbrock (01); Dicus and H.-J. He (05).



# Executive sum.: Constraining Higgs-charm univ.

GP, Soreq, Stamou & Tobioka (Feb/15)

## ◆ Existing data already constrain Higgs-quarks Univ..

(i) Direct constraint: recast  $VH(bb)$ , taking advantage of 2 working point  $C_c < 230$  ;

(ii) the recent ATLAS search to  $h \rightarrow J/\psi\gamma$  (see later) yield  $C_c < 220$  ;

(assumes Higgs coupling to two photons and/or four leptons is not significantly modified by new physics);

(iii) the direct measurement of the total width yield  $C_c < 140$  (ATLAS), 120 (CMS) ;

(iv) Global fit to the Higgs signal strength,  $C_c < 6$  ;

(v)  $tth$  data  $\Rightarrow C_t > 1.0$  (equivalence to  $C_c > 310$ ).



Higgs univ. excluded!

GP, Soreq, Stamou & Tobioka (Feb/15)

# #1 Direct constraint: recast $VH(bb)$

GP, Soreq, Stamou & Tobioka (Feb/15)

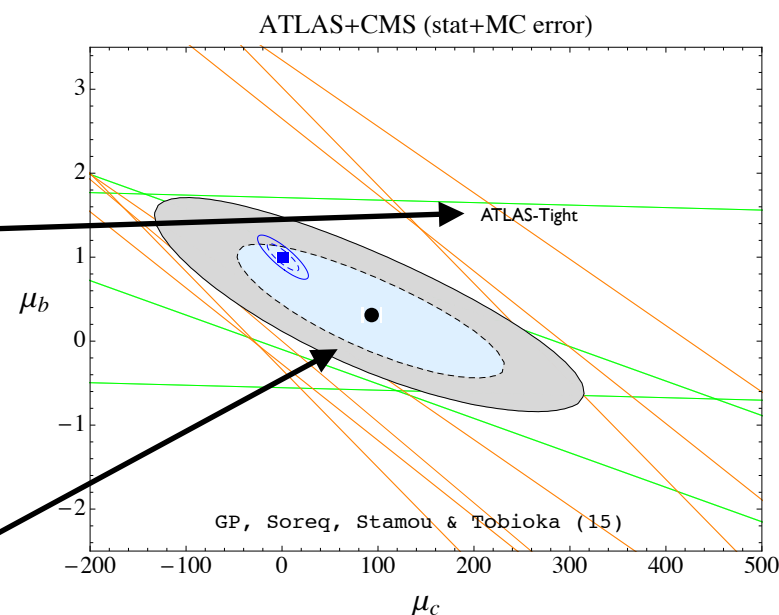
- ♦ Idea: use several charm-tagging working points of ATLAS & CMS in their  $VH(bb)$  analysis.

$$\mu_b = \frac{\sigma}{\sigma_{SM}} \frac{\text{BR}_{b\bar{b}}}{\text{BR}_{b\bar{b}}^{SM}} \rightarrow \mu_b + \frac{\text{Br}_c^{SM}}{\text{Br}_b^{SM}} \frac{\epsilon_{c1} \epsilon_{c2}}{\epsilon_{b1} \epsilon_{b2}} \mu_c$$

where  $\epsilon_{b1,2}$  and  $\epsilon_{c1,2}$  are efficiencies to tag jets originating from bottom and charm quark, respectively.  $\mu_c$  is normalized to be 1 in a case of the SM.

- ♦ Each working point yields flat direction:

ATLAS	Med	Tight	CMS	Loose	Med1	Med2	Med3
$\epsilon_b$	70%	50%	$\epsilon_b$	88%	82%	78%	71%
$\epsilon_c$	20%	3.8%	$\epsilon_c$	47%	34%	27%	21%

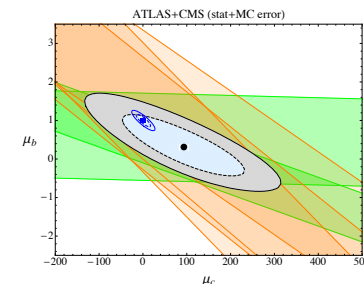


- ♦ However, combining points => bound. (reproducing ATLAS/CMS  $hbb$  bounds to 10-20%)

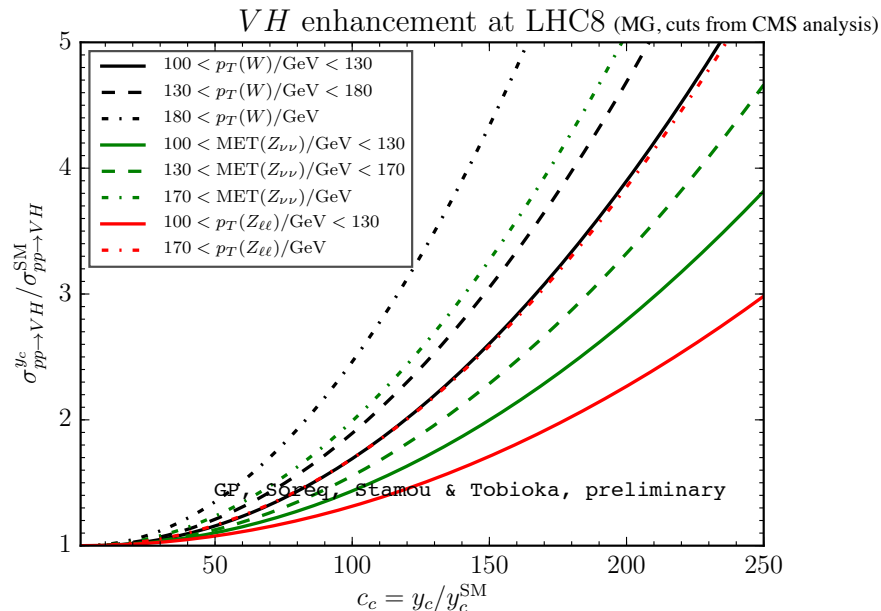
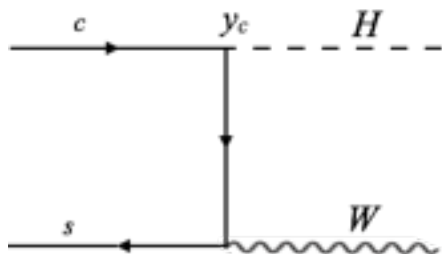
# New production mechanism $VH(bb)$

GP, Soreq, Stamou & Tobioka (Feb/15)

◆  $\mu_c = \frac{\sigma}{\sigma^{\text{SM}}} \frac{\text{Br}}{\text{Br}_c^{\text{SM}}} \Rightarrow \text{w SM } VH\text{-production } \mu_c < 30 \Rightarrow \text{no constraint on } y_c.$



◆ However  $\mu_c < 30$  for large  $c_c > 50$  new production mechanism:



No runaway for  $c_c$



$C_c < 250.$

# Constraining Higgs-quark universality #2+3

- ◆ Width bound:  $\Gamma_h < 2.6 \text{ GeV (ATLAS)}, \Gamma_h < 1.7 \text{ GeV (CMS)} \Rightarrow \boxed{C_c < 140, 120 .}$

GP, Soreq, Stamou & Tobioka (Feb/15)

- ◆ Interpretation of ATLAS recent  $h \rightarrow J/\psi\gamma$  (1501.03276):  $\sigma(pp \rightarrow h) \times \text{BR}_{h \rightarrow J\psi\gamma} < 33 \text{ fb}$ ,

- ◆ This implies (see later):  $\Gamma_{h \rightarrow J/\psi\gamma} = 1.42 (\kappa_\gamma - 0.087\kappa_c)^2 \times 10^{-8} \text{ GeV}$

Bodwin, Petriello, Stoynev & Velasco (13); Bodwin, Chung, Ee, Lee & Petriello (14)

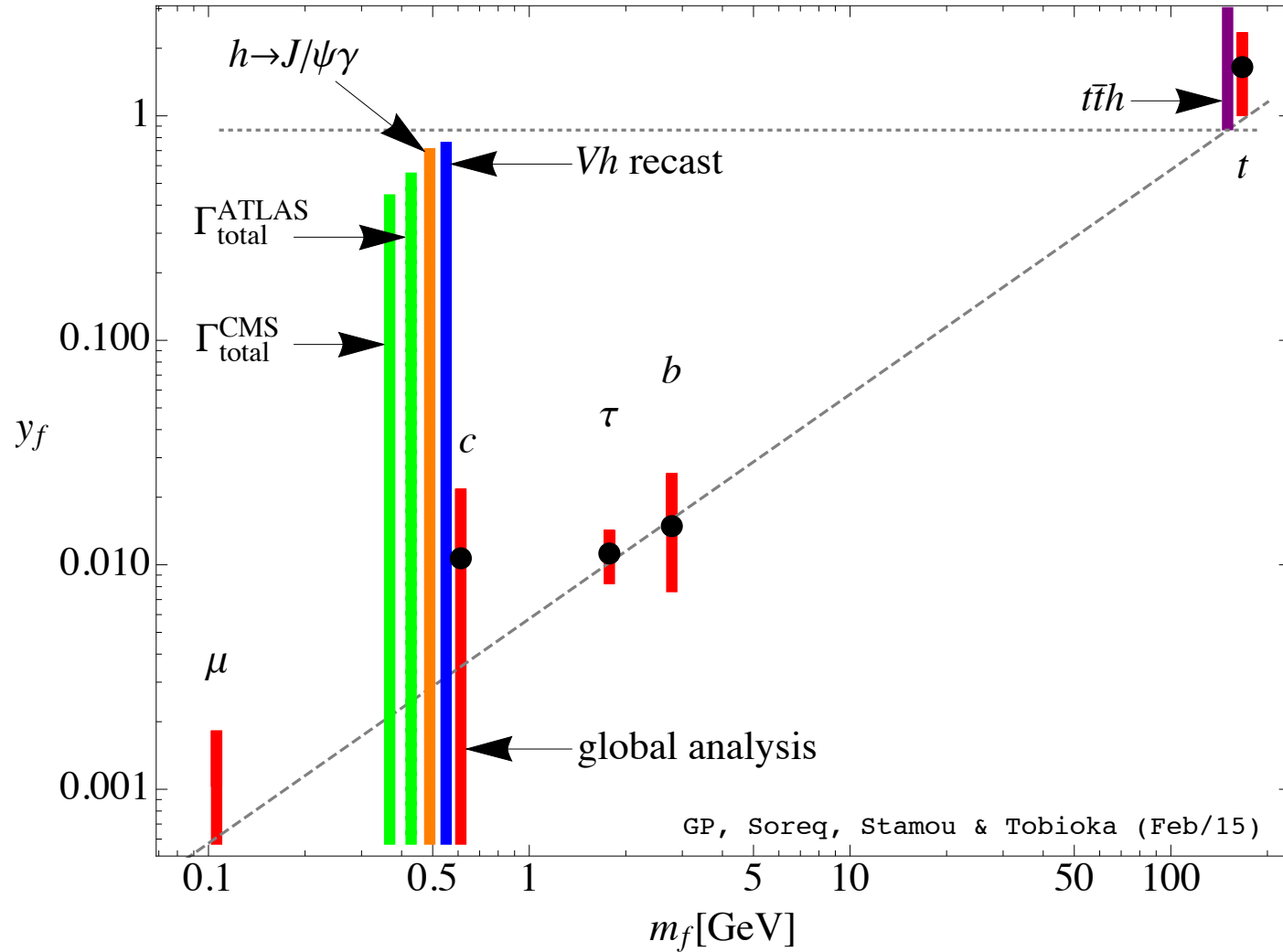
- ◆ Getting rid of production:  $\mathcal{R}_{J/\psi,Z} = \frac{\sigma(pp \rightarrow h) \times \text{BR}_{h \rightarrow J/\psi\gamma}}{\sigma(pp \rightarrow h) \times \text{BR}_{h \rightarrow ZZ^* \rightarrow 4\ell}} = \frac{\Gamma_{h \rightarrow J/\psi\gamma}}{\Gamma_{h \rightarrow ZZ^* \rightarrow 4\ell}} = 2.79 \frac{(\kappa_\gamma - 0.087\kappa_c)^2}{\kappa_V^2} \times 10^{-2},$

$$\mathcal{R}_{J/\psi,Z} = \frac{33 \text{ fb}}{\mu_{ZZ^*} \sigma^{\text{SM}} \text{BR}_{h \rightarrow ZZ^* \rightarrow 4\ell}^{\text{SM}}} < 9.32 \quad \Rightarrow \quad \boxed{c_c < 210c_V + 11c_\gamma .}$$

(LEP:  $c_V = 1.08 \pm 0.07$ )

GP, Soreq, Stamou & Tobioka (Feb/15)

# Summary plot, current situation



# Higgs to light quarks sensitivity - projections for HL-LHC

GP, Soreq, Stamou & Tobioka, to appear.

# Inclusive, charm-tagging

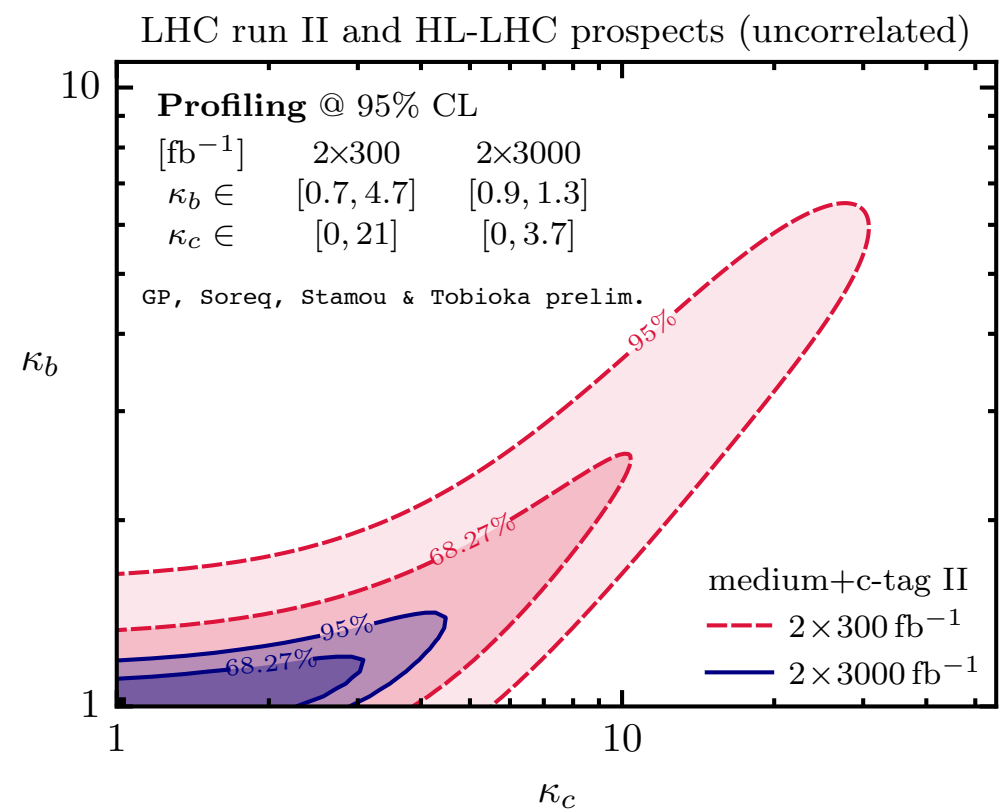
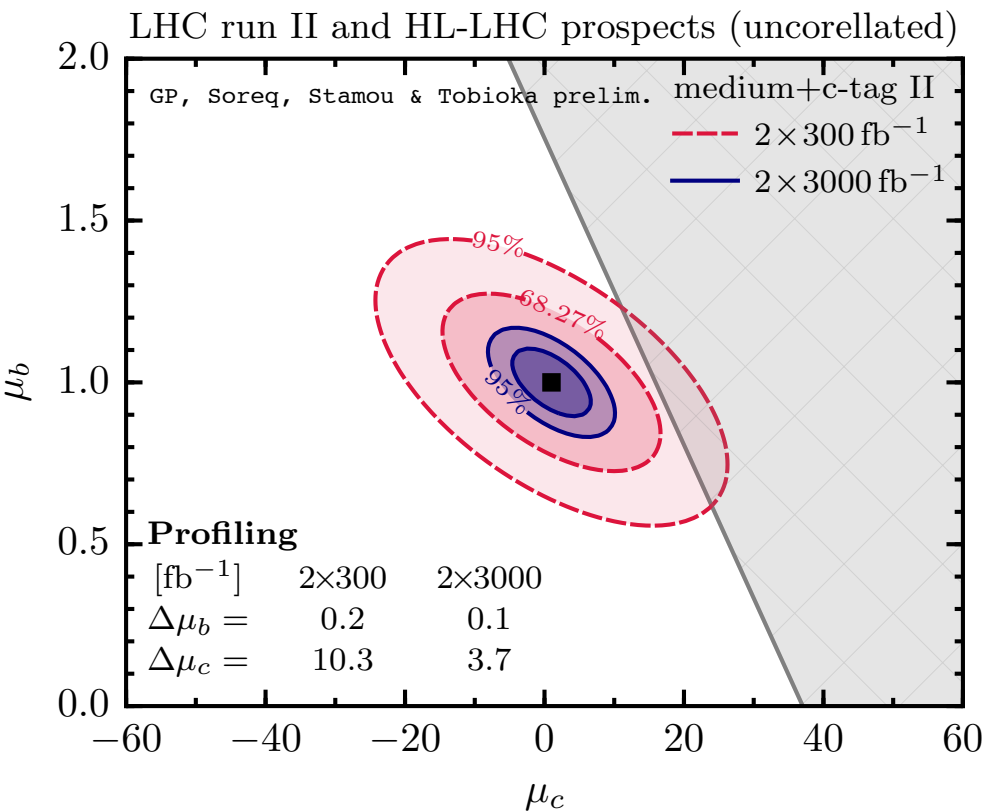
	$\epsilon_b$	$\epsilon_c$	$\epsilon_l$
<b><i>b</i>-tagging</b>	70%	20%	1.25%
<b><i>c</i>-tagging I</b>	13%	19%	0.5%
<b><i>c</i>-tagging II</b>	20%	30%	0.5%

ATLAS, arXiv:1501.01325.

$$\kappa_c \equiv y_c/y_c^{\text{SM}},$$

[fb<sup>-1</sup>]      2×300      2×3000

$\kappa_c \in$       [0, 21]      [0, 3.7]



# Exclusive projections

◆ ATLAS result, mapped out the dominant BG:  $\sigma_h \text{BR}_{J/\psi \gamma} < 33 \text{ fb}$  arXiv:1501.03276 [hep-ex]

◆ Useful to define ratio that is independent of the production:

GP, Soreq, Stamou & Tobioka (Feb/15)

$$\mathcal{R}_{M\gamma,Z} \equiv \frac{\sigma_h \text{BR}_{M\gamma}}{\sigma_h \text{BR}_{ZZ^* \rightarrow 4\ell}} \simeq \frac{\Gamma_{M\gamma}}{\Gamma_{ZZ^* \rightarrow 4\ell}} = \begin{cases} 2.8 \times 10^{-2} (\kappa_\gamma - 8.7 \times 10^{-2} \kappa_c)^2 / \kappa_V^2 & M = J/\psi \\ 2.4 \times 10^{-2} (\kappa_\gamma - 2.6 \times 10^{-3} \kappa_s)^2 / \kappa_V^2 & M = \phi \end{cases},$$

Bodwin, Petriello, Stoynev & Velasco (13); Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

$$\text{BR}_{J/\psi \gamma}^{\text{SM}} = 2.9 \times 10^{-6}, \text{BR}_{\phi \gamma}^{\hat{\text{SM}}} = 3.0 \times 10^{-6}, \text{BR}_{ZZ^* \rightarrow 4\ell}^{\text{SM}} = 1.25 \times 10^{-4}.$$

◆ For a given upper bound,  $\bar{\mu}_M$ , on an exclusive mode, we can write:

$$\mathcal{R}_{M\gamma,Z} < \frac{\bar{\mu}_M}{\mu_{ZZ^*}} \frac{\text{BR}_{M\gamma}^{\text{SM}}}{\text{BR}_{ZZ^* \rightarrow 4\ell}^{\text{SM}}}, \quad \bar{\mu}_M \equiv \frac{\bar{\sigma}_h \overline{\text{BR}}_{M,\gamma}}{\sigma_h^{\text{SM}} \text{BR}_{M,\gamma}^{\text{SM}}},$$

# Exclusive, deriving the bound

- ◆ For a given upper bound we find the following bound:

$$11\kappa_\gamma - 10\kappa_V \sqrt{\bar{\mu}_{J/\psi}/\mu_{ZZ^*}} < \kappa_c < 11\kappa_\gamma + 10\kappa_V \sqrt{\bar{\mu}_{J/\psi}/\mu_{ZZ^*}} ,$$

$$380\kappa_\gamma - 380\kappa_V \sqrt{\bar{\mu}_\phi/\mu_{ZZ^*}} < \kappa_s < 380\kappa_\gamma + 380\kappa_V \sqrt{\bar{\mu}_\phi/\mu_{ZZ^*}} .$$

GP, Soreq, Stamou & Tobioka (May/15)

- ◆ To project define the following ratios:

$$\bar{\mu}_{M,E} = \bar{\mu}_{M,8} \left( \frac{1}{R_{P,E} R_{\mathcal{L},E} R_{SB,E}} \right)^{1/2} ,$$

$$R_{SB,E} \equiv \frac{S_E^{\text{SM}}/B_E}{S_8^{\text{SM}}/B_8} , \quad R_{P,E} \equiv \frac{\sigma_{h,E}^{\text{SM}}}{\sigma_{h,8}^{\text{SM}}} , \quad R_{\mathcal{L},E} \equiv \frac{\mathcal{L}_E}{\mathcal{L}_8} ,$$

- ◆ Projection for  $J/\psi \gamma$  :

$$\boxed{\kappa_c < 11 + (75, 42) \left( \frac{1}{R_{SB,14}} \frac{2 \times (300, 3000) \text{ fb}^{-1}}{\mathcal{L}_{14}} \right)^{1/4}} , \quad \text{assuming } \mu_{ZZ^*} = \kappa_\gamma = \kappa_V = 1$$

# Exclusive, deriving the bound

◆ Ratio of signals:

$$\frac{S_\phi}{S_{J/\psi}} = \frac{\sigma_h \text{BR}(h \rightarrow \phi \gamma) \mathcal{L}}{\sigma_h \text{BR}(h \rightarrow J/\psi \gamma) \mathcal{L}} \frac{\text{BR}(\phi \rightarrow K^+ K^-)}{\text{BR}(J/\psi \rightarrow \mu^+ \mu^-)} \frac{\epsilon_\phi}{\epsilon_{J/\psi}}$$

where  $\epsilon_{J/\psi(\phi)}$  is the triggering and reconstruction efficiency

◆ Backgrounds: ATLAS=> dominant is jet -> photon + QCD  $J/\psi$  production.

Even more so expected for  $\phi$ : 
$$\frac{B_\phi}{B_{J/\psi}} = \frac{\sigma(pp \rightarrow \phi j) P(j \rightarrow \gamma) \mathcal{L}}{\sigma(pp \rightarrow J/\psi j) P(j \rightarrow \gamma) \mathcal{L}} \frac{\text{BR}(\phi \rightarrow K^+ K^-)}{\text{BR}(J/\psi \rightarrow \mu^+ \mu^-)} \frac{\epsilon_\phi}{\epsilon_{J/\psi}},$$

$$\bar{\mu}_\phi = \bar{\mu}_{J/\psi} \frac{\text{BR}_{J/\psi\gamma}^{\text{SM}}}{\text{BR}_{\phi\gamma}^{\text{SM}}} \sqrt{\frac{\sigma(pp \rightarrow \phi j)}{\sigma(pp \rightarrow J/\psi j)} \frac{\text{BR}(J/\psi \rightarrow \mu^+ \mu^-)}{\text{BR}(\phi \rightarrow K^+ K^-)} \frac{\epsilon_{J/\psi}}{\epsilon_\phi}} = 0.33 \bar{\mu}_{J/\psi} \sqrt{\frac{\sigma(pp \rightarrow \phi j)}{\sigma(pp \rightarrow J/\psi j)} \frac{\epsilon_{J/\psi}}{\epsilon_\phi}}$$

◆ For tight selection (ATLAS)  $P(j \rightarrow \gamma) \sim 2 \times 10^{-4}$  & using PYTHIA to simulate QCD BG, and rescaling from  $J/\psi \gamma$ : 
$$\left. \frac{\sigma(pp \rightarrow \phi j)}{\sigma(pp \rightarrow J/\psi j)} \right|_{\text{Pythia}} \sim 8.5.$$

◆ Projection for  $\phi\gamma$ :

$$\kappa_s < 380 + (2900, 1600) \left( \frac{1}{R_{SB,14}} \frac{2 \times (300, 3000) \text{ fb}^{-1}}{\mathcal{L}_{14}} \right)^{1/4}$$

GP, Soreq, Stamou & Tobioka (May/15)

# Summary

Inclusive (c-tagging):  $\kappa_c < 4$ ;

Exclusive ( $J/\psi\gamma$ ):  $\kappa_c < 40$ ;

Exclusive ( $\phi\gamma$ ):  $\kappa_s < 2000$ .

GP, Soreq, Stamou & Tobioka (May/15)

- ◆ C-tagging based analysis is just “waiting” for someone to dominate the field.
- ◆ To improve on the exclusive miserable situation, one needs to devise new methods, to use the “quiet” nature of the Higgs decay. (new class of jet substructure)
- ◆ What about CMS? Impact of ATLAS new IBL? LHCb?

