Higgs & Flavour

Bonus: on-shell interference as a probe of top-quark FCNCs

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Perspective: Higgs & Flavour at the LHC

Who cares?

- **Weak scale** does not have to be related to the **flavour scale**
- **Hierarchy Problem** more pressing than understanding Flavour
- We can always **evade flavour** constraints by "alignment"

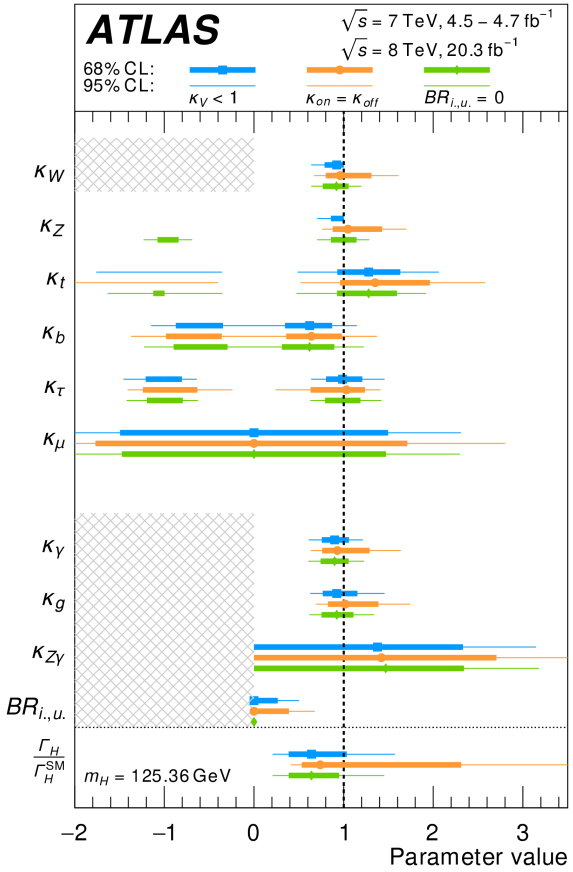
"No Donny, these men are nihilists, there's nothing to be afraid of.

[The Big Lebowski, 98]

Perspective: Higgs & Flavour at the LHC

Should we care?

- Higgs couplings to fermions **least constrained** quantities of the interactions among known particles
- Yukawas (and $\theta_{\rm QCD}$) only known sources of **CP violation** in SM (Baryogenesis)
- Major **opportunity** and **challenge** for the LHC program



The challenges

- SM-Higgs couples proportionally to mass
  ➜ **coupling to fermions small** (except for the top)
  ➜ Higgs **production/decay rates** from/to light-quarks small
  (except for the bottom)

- Challenging to distinguish (tag) light-quark flavours
  [Craik's talk]

- Standard rate measurements insensitive to CP violation
  ➜Interference effects, angular distributions, ...
  ➜Often penalised by small **statistics**
  [Martin's & Ojalvo's talk]

Outline

- Higgs–charm from c-**tagging**
- Higgs–fermions from **exclusive Higgs decays**
- Higgs–fermions from **Higgs kinematics**

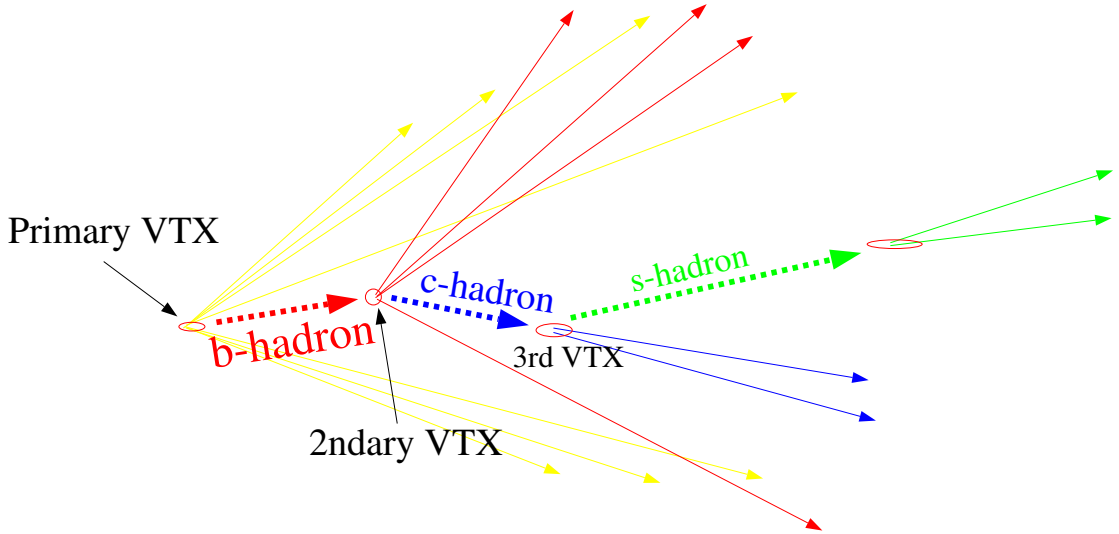
Bonus

- **Top-quark** FCNCs from **on-shell interference** with the W background

- Conclusions

Charm-tagging

- Statistically beneficial if we can stay "**inclusive**"
- This is **possible** for the ***c*-quarks** because they are **similar to *b*-quarks**



➜ B mesons are long-lived $\sim 440\mu m/c$
➜ b-tagging is based on looking for displaced vertices
➜ D mesons are also long-lived $\sim 110 - 310\mu m/c$
➜ c-tagging is possible at the LHC

Some *b*-jets are *c*-jets

Charm-tagging results

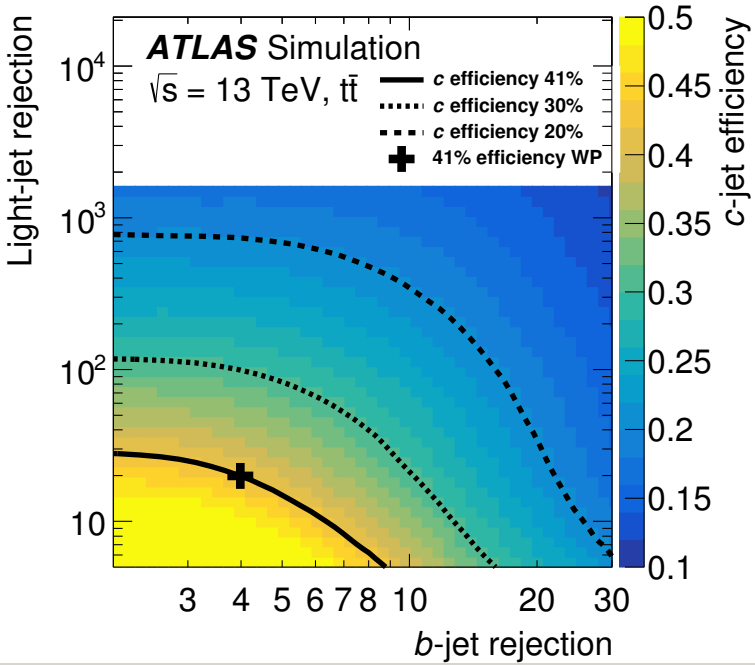
Recast of 8 TeV **ATLAS'** and **CMS'** $h \to \bar{b}b$ measurements **constrain the charm Yukawa**

$$\mu_c = 95^{+90(175)}_{-95(180)} \ @68.3(95)\% \ CL$$

Keypoint: need different tagging-working points to disentangle b's from c's

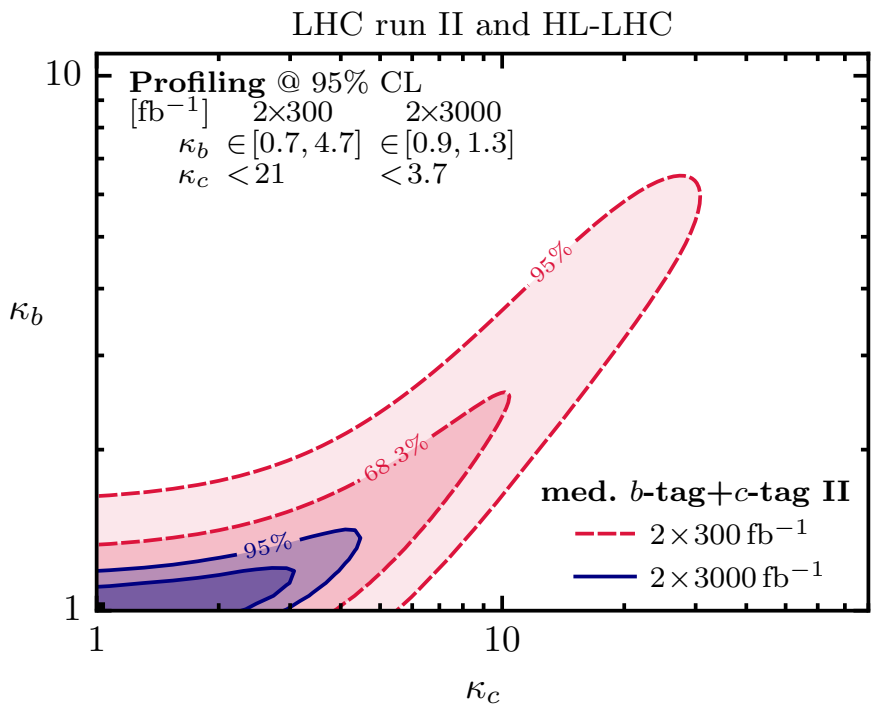
[Perez, Soreq, ES, Tobioka 15]

- **ATLAS performed the 13 TeV analysis** [ATLAS, 1802.04329]
- $\sigma(pp \to Zh)\mathrm{BR}(h \to \bar{c}c) = 3.9^{+2.1}_{-1.1} \ @95\% CL$
- $\mu_c = -69 \pm 101$ (without floating y_b)



Charm-tagging prospects at HL LHC

$$\epsilon_c = 30\% \qquad \epsilon_b = 20\%$$

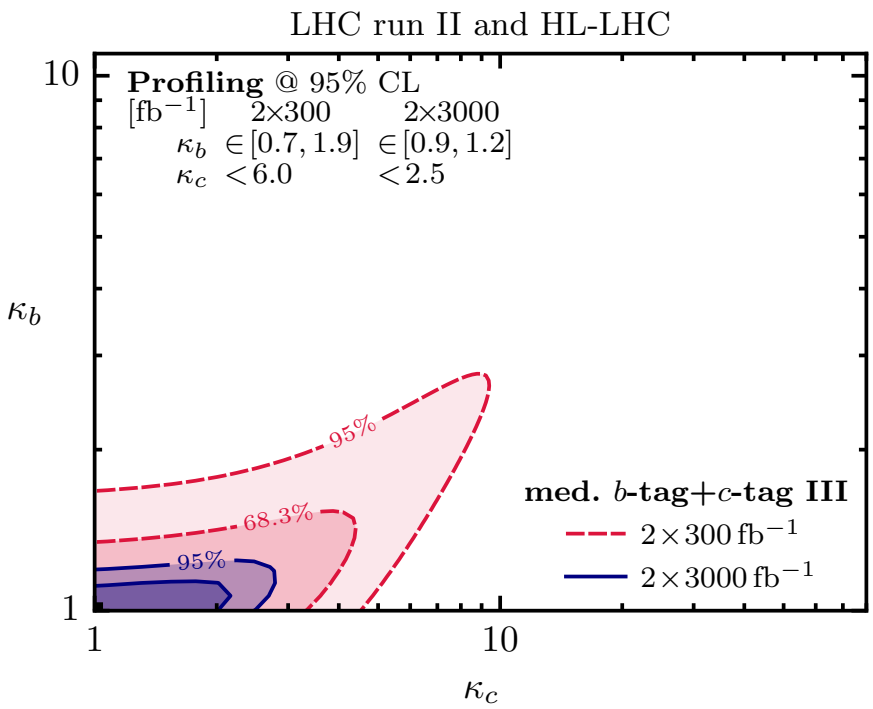


@95% CL $\quad |\boldsymbol{\kappa_c}| \equiv \left|\frac{\boldsymbol{y_c}}{\boldsymbol{y_c^{\rm SM}}}\right| < \pm\mathbf{21}, \pm\mathbf{3.7}$ at RunII, HL LHC

[Perez, Soreq, ES, Tobioka 15]

Charm-tagging prospects at HL LHC

$$\epsilon_c = 50\% \qquad \epsilon_b = 20\%$$



@95% CL $\quad |\boldsymbol{\kappa_c}| \equiv \left|\frac{\boldsymbol{y_c}}{\boldsymbol{y_c^{\mathrm{SM}}}}\right| < \pm\mathbf{6.0}, \pm\mathbf{2.5}$ at RunII, HL LHC

[Perez, Soreq, ES, Tobioka 15]

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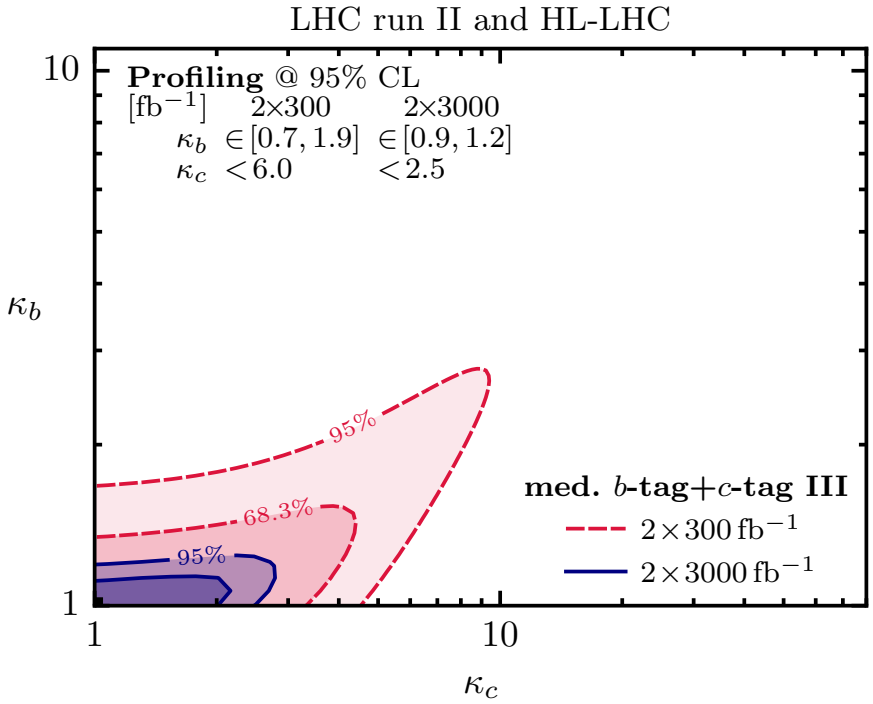

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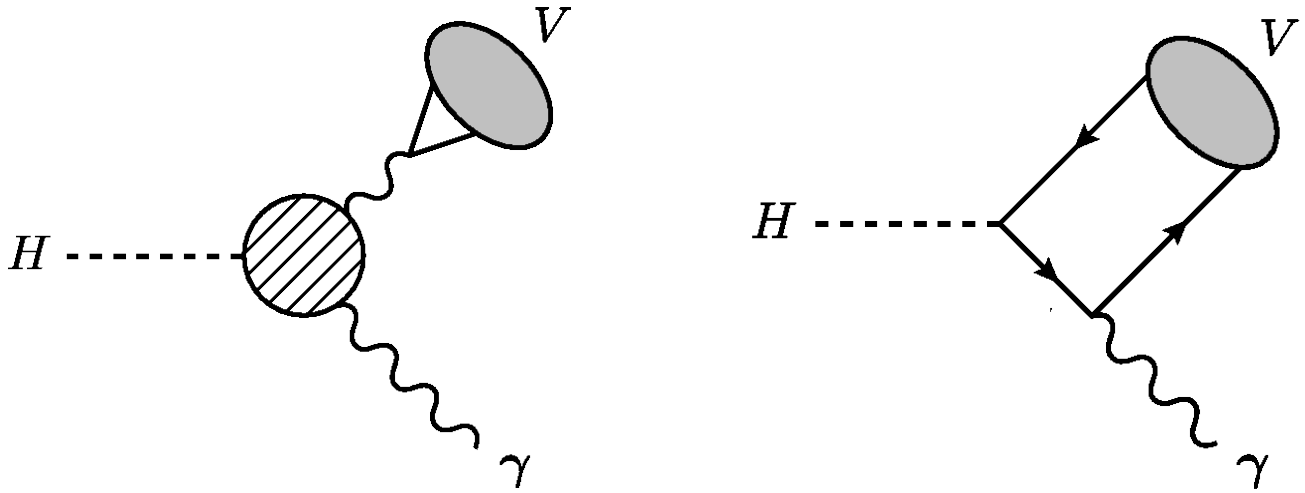
[Perez, Soreq, ES, Tobioka 15]

Disadvantages: ○ not possible for light quarks
○ insensitive to sign/CP properties

Exclusive Higgs decays: the exclusive "window"

Idea: tag the quark from the meson it hadronises into

[Bodwin et al 13]



$$\Gamma_{h\to J/\psi\,\gamma} = |(11.9 \pm 0.2)\kappa_\gamma - (1.04 \pm 0.14)\kappa_c|^2 \cdot 10^{-10}\ \text{GeV}$$

[Bodwin et al 13, 14, König, Neubert 15]

Highlights:

- two contributions: direct (κ_c) and indirect (κ_γ)
- main effect from **interference** (info about sign and CP properties)
- generalisation to the case of **light quark** Yukawas [Kagan et al, 14]

Exclusive Higgs decays: status and challenges

ATLAS

$\sigma \times \mathrm{BR}(h \to J/\psi\,\gamma) < 33$ fb @ 95% CL

[ATLAS, 1501.03276]

- Translates to $|\kappa_c| < 220$
- ATLAS measurement ➜ first measurement of QCD background

  (QCD + real photon and QCD with jet mistagged as a γ
- Expect similar backgrounds for other interesting modes

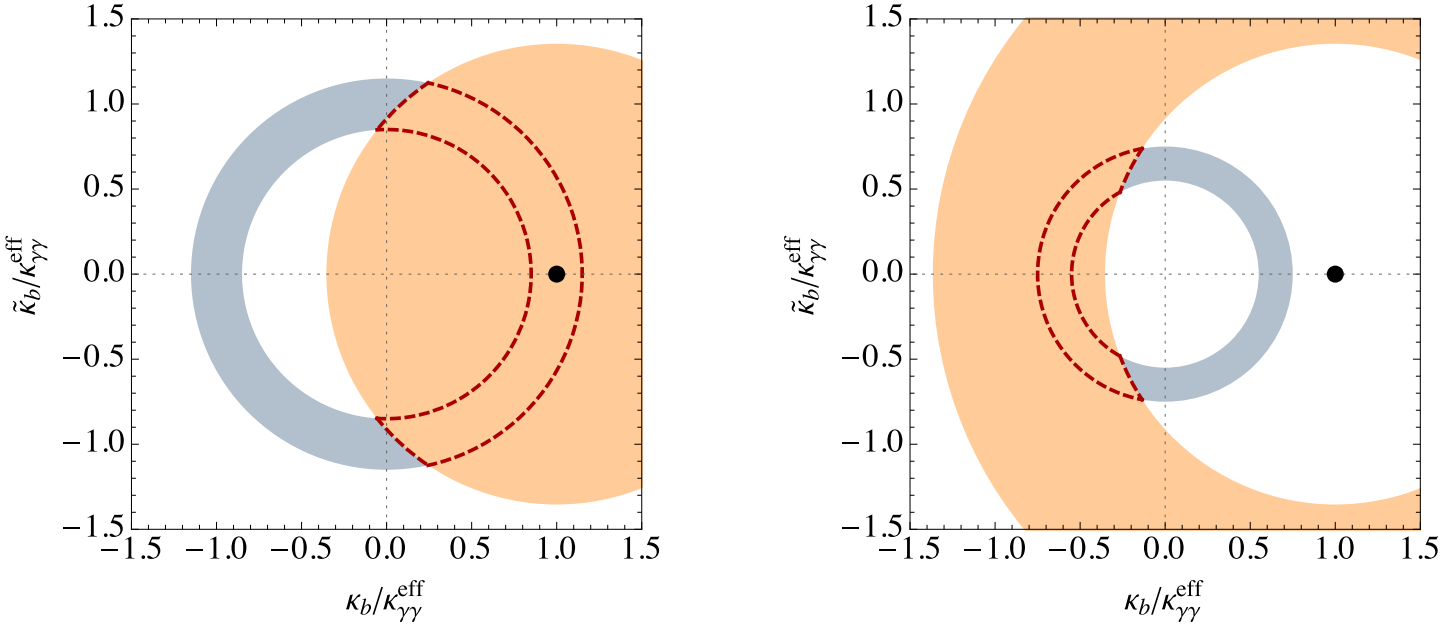
  $(h \to \phi\gamma, h \to \Upsilon\gamma, \ldots)$
- Unless reduced, @ HL-LHC with 2×3000 fb^{-1} $\boldsymbol{\kappa_c < 56}$

  (much weaker that c-tagging) [Perez, Soreq, ES, Tobioka 15]

However, if reduced ...

Exclusive Higgs decays: possibilities

The sign of the bottom Yukawa



[König, Neubert, 15]

The size of the strange Yukawa ($\bar{\kappa}_s \equiv y_s/y_b^{\rm SM}$)

$\sqrt{s}$ [TeV]	$\int \mathcal{L}\, dt$ [fb^{-1}]	# of events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\rm stat.} > (<)$
14	3000	770	0.39 (−0.97)	0.27 (−0.81)
33	3000	1380	0.36 (−0.94)	0.22 (−0.75)
100	3000	5920	0.34 (−0.90)	0.13 (−0.63)

[Kagan et al, 14]

Higgs couplings from kinematics

- Be less direct ➜ abandon strict flavour tagging
- Look for p_T/y distributions that are affected by Yukawa modifications

➜ bottom, charm, strange [Bishara et al, 16]

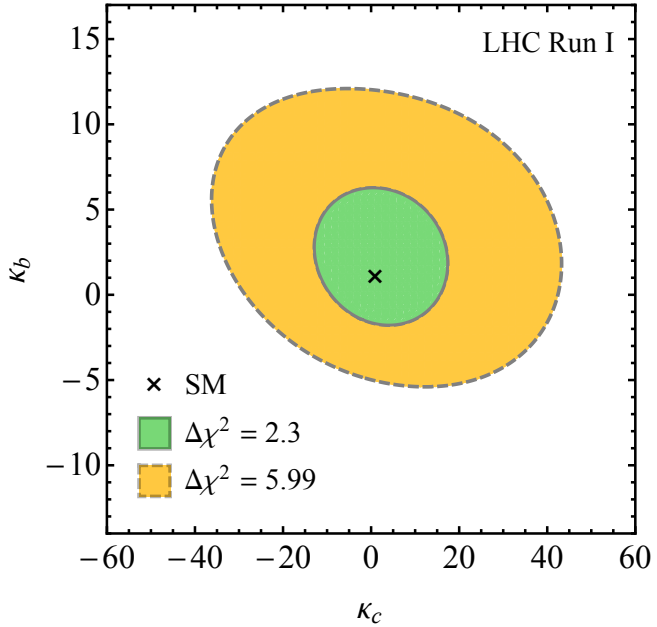
- Higgs + jet events
- Interference with top in gg-fusion (sign sensitivity)

➜ up, down, strange [Soreq et al, 16]

- Large light-quark Yukawas ➜ asymmetric rapidity distributions
- p_T spectrum peaks before gg fusion (different effective radiation strength)

Charm Yukawa from distributions

Racast of ATLAS's and CMS's $p_{T,j}$ and $p_{T,h}$ spectra

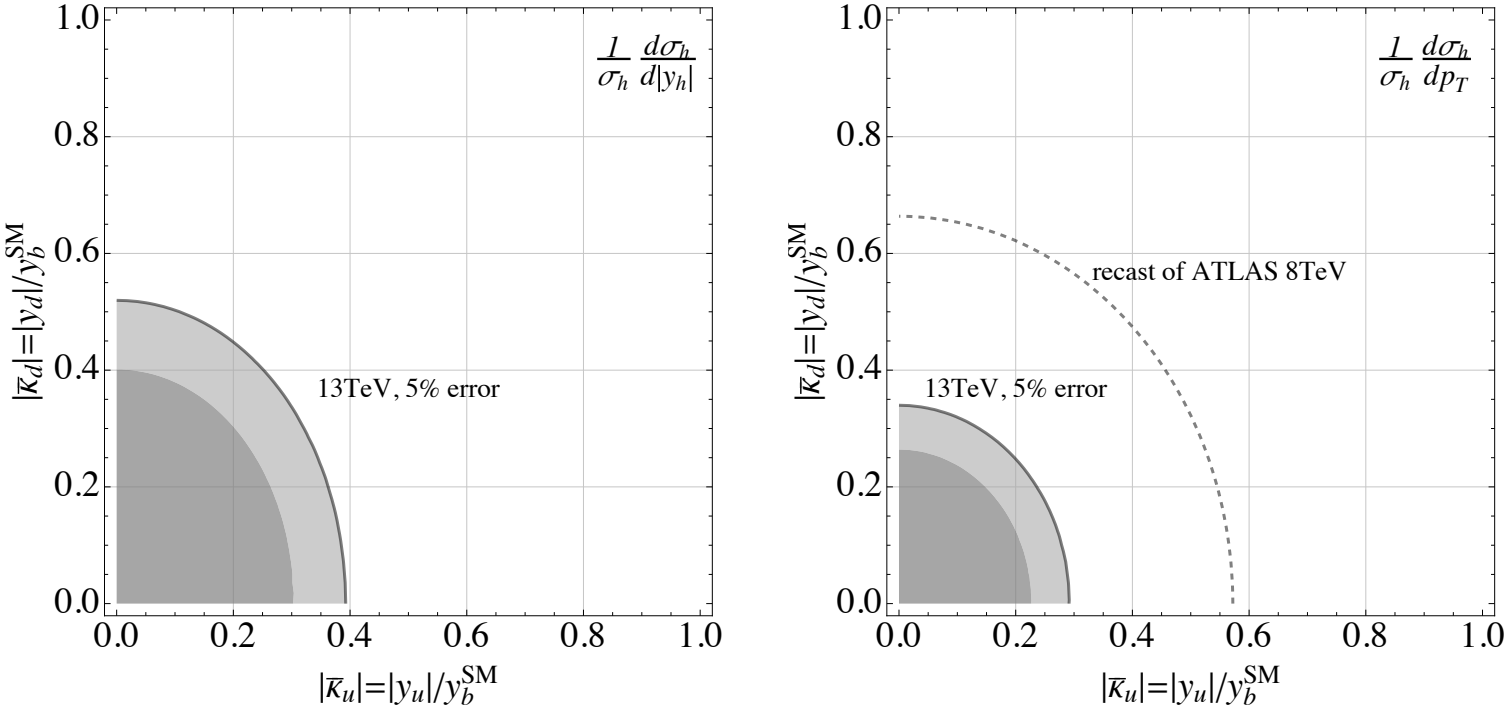


@LHC run II	$\kappa_c \in [-4.7, 5.5]$	at 95% CL, **projection**
@HL-LHC	$\kappa_c \in [-2.9, 4.2]$	at 95% CL, **projection**

[Bishara et al, 16]

u, d Yukawas from distributions

ATLAS and CMS recast and LHC13 projection



Bounds from p_T distributions:

$$\bar{\kappa}_u \equiv y_u/y_b^{\rm SM} < 0.46(0.27) \quad \text{@ LHC8 (LHC13 with 2ab}^{-1}\text{)}$$
$$\bar{\kappa}_d \equiv y_d/y_b^{\rm SM} < 0.54(0.31) \quad \text{@ LHC8 (LHC13 with 2ab}^{-1}\text{)}$$

Bounds stronger than inclusive fit

[Soreq et al, 16]

Bonus

Probing top FCNCs via on-shell interference with the W background

Work in progress, in collaboration with R. Harnik, C. Wagner, L. Wang

Top-quark FCNCs: status

- The **beyond-SM** couplings $\boldsymbol{t - Z - q}$ and $\boldsymbol{t - h - q}$ $(q = u, c)$ are among the **least protected** flavour violating couplings in MFV-type alignments of **New Physics** models

- Constraints from **indirect searches weak**, GIM/Yukawa suppressed

  (especially for the CP conserving case) [e.g., Fox et al, 08; Harnik et al, 12]

- Pursued measurements by LHC experiments, **excellent progress**

Limit	$\sqrt{s}$	$\mathcal{L}$	Exp.
BR$(t \to Zu) < 0.017\%$	13 TeV	36 fb^{-1}	ATLAS
BR$(t \to Zu) < 0.023\%$	13 TeV	36 fb^{-1}	ATLAS
BR$(t \to Zq) < 0.07\%$	8 TeV	20.3 fb^{-1}	CMS
BR$(t \to Zu) < 0.022\%$	8 TeV	19.7 fb^{-1}	ATLAS
BR$(t \to Zc) < 0.049\%$	8 TeV	19.7 fb^{-1}	ATLAS
BR$(t \to hu) < 0.24\%$	13 TeV	36.1 fb^{-1}	ATLAS
BR$(t \to hc) < 0.22\%$	13 TeV	36.1 fb^{-1}	ATLAS
BR$(t \to hu) < 0.45\%$	8 TeV	20.3 fb^{-1}	ATLAS
BR$(t \to hc) < 0.46\%$	8 TeV	20.3 fb^{-1}	ATLAS
BR$(t \to hu) < 1.92\%$	8 TeV	19.8 fb^{-1}	CMS
BR$(t \to hc) < 1.16\%$	8 TeV	19.8 fb^{-1}	CMS

Top-quark FCNCs: prospects

Limit	$\sqrt{s}$	$\mathcal{L}$
$\mathrm{BR}(t \to Zq) < 0.022\%$	14 TeV	$300\,\mathrm{fb}^{-1}$
$\mathrm{BR}(t \to Zq) < 0.007\%$	14 TeV	$3000\,\mathrm{fb}^{-1}$
$\mathrm{BR}(t \to hq) < 0.05\%$	14 TeV	$300\,\mathrm{fb}^{-1}$
$\mathrm{BR}(t \to hq) < 0.02\%$	14 TeV	$3000\,\mathrm{fb}^{-1}$

[Top Quark Working Group, 13]

- For Z case present constraint stronger than the expectations.
- How do these bounds **scale with** the integrated **luminosity**?

$$\frac{\mathrm{S}}{\sqrt{\mathrm{B}}} = \frac{\mathcal{L}\,\sigma^{\mathrm{S}}\,\epsilon^{\mathrm{S}}}{\sqrt{\mathcal{L}\,\sigma^{\mathrm{B}}\,\epsilon^{\mathrm{B}}}} \quad \longrightarrow \quad \mathrm{coupling}\Big|_{95\%} \propto \frac{1}{\mathcal{L}^{\frac{1}{4}}}$$

- **Can we do better?**

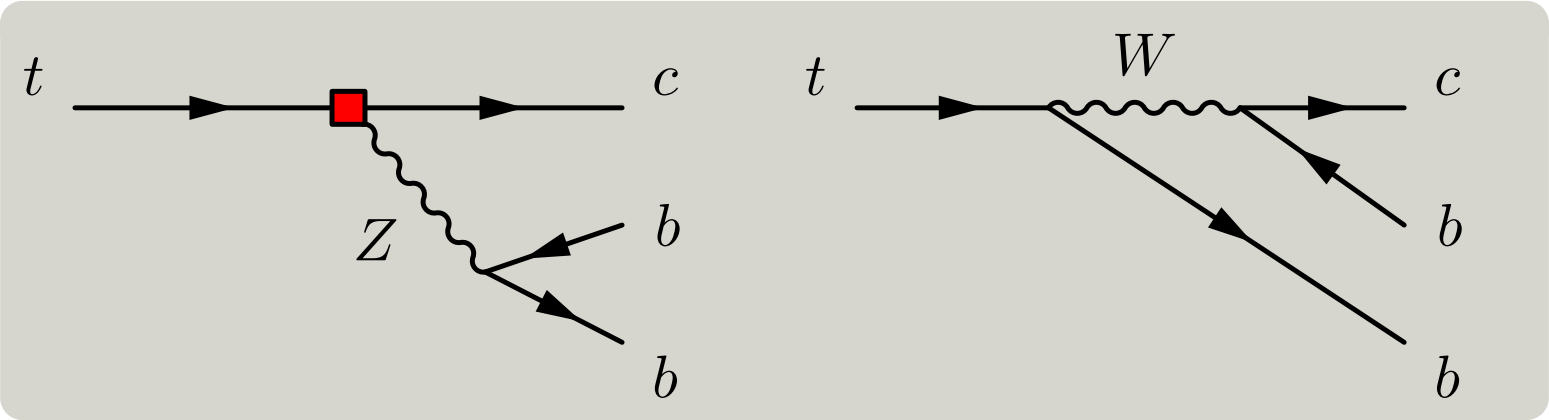
Top-quark FCNCs from on-shell interference (work in progress)

Idea:

- The **luminocity-scaling changes** if there is a large background to **interfere** with
  ➜SM background of $t \to Wb$
- Keep both "signal" and "background" to be **on-shell**
  ➜mantain enough events to be sensitive
- Interference sensitive also to **CP-violating phases**
  ➜top-decay asymmetries

Top-quark FCNCs from on-shell interference (work in progress)

Interference only for same final states (3-body decay)



Can both the Z and the W be simultaneously on-shell? Yes

(two independent Dalitz variables)

Both propagators (Breit-Wigner's) must go on-shell:

$$\frac{1}{q_Z^2 - m_Z^2 + i m_Z \Gamma_Z} \longrightarrow \frac{1}{i m_Z \Gamma_Z}$$

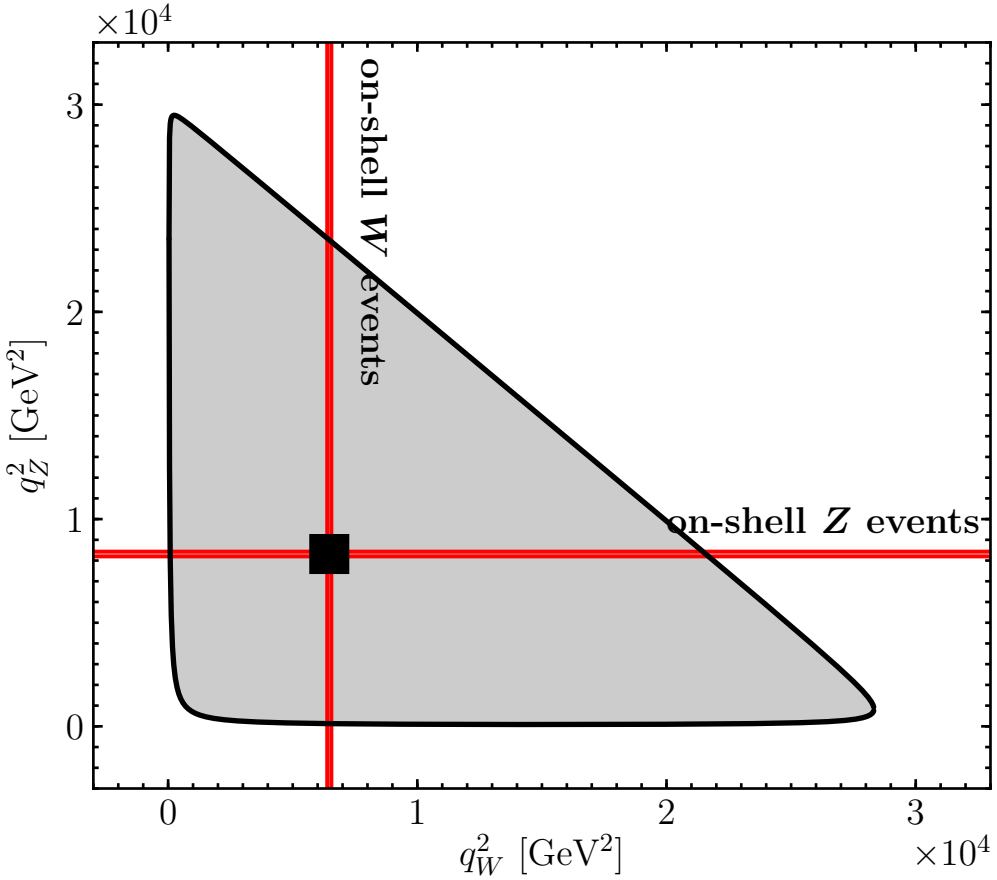
$$\frac{1}{q_W^2 - m_W^2 + i m_W \Gamma_W} \longrightarrow \frac{1}{i m_W \Gamma_W}$$

(these two i's correspond to socalled "strong phases")

Onshell interference on the Dalitz spot

$t \to b\bar{b}c$ at the Dalitz spot:

$$\mathrm{BR_B} \propto \frac{m_t}{\Gamma_t}\frac{m_W}{\Gamma_W}\frac{\Gamma_{Z/h}}{m_{Z/h}} \qquad \mathrm{BR_S} \propto \frac{m_t}{\Gamma_t}\frac{m_{Z/h}}{\Gamma_{Z/h}}\frac{\Gamma_W}{m_W}\,g^2 \qquad \mathrm{BR_I} \propto \frac{m_t}{\Gamma_t}\,g$$



- Onshell interference only on the **Dalitz spot** (square)
- Small phase space (around widths of Z/h and W)
- However, at HL LHC $\sim 10^{10} ts$
- Still, **higgs too narrow** and **interference suppressed by m_b**, not enough events ✘
- But, Z broad, more promising✓

$t - Z - q$ sensitivity from on-shell interference (work in progress)

A first (very preliminary) "back-on-the-slide" estimate for $t\bar{t}$ events:

$$\frac{\mathrm{S}}{\sqrt{\mathrm{B}}} = \frac{\mathcal{L}\, 2\sigma_{t\bar{t}}\, \mathrm{BR}^{\mathrm{S+I}}(t \to b\bar{b}c)\epsilon}{\sqrt{\mathcal{L}\, 2\sigma_{t\bar{t}}\, \mathrm{BR}^{\mathrm{B}}(t \to b\bar{b}c)\epsilon + \mathcal{L}\, \sigma_{\mathrm{other}}\epsilon'}}$$

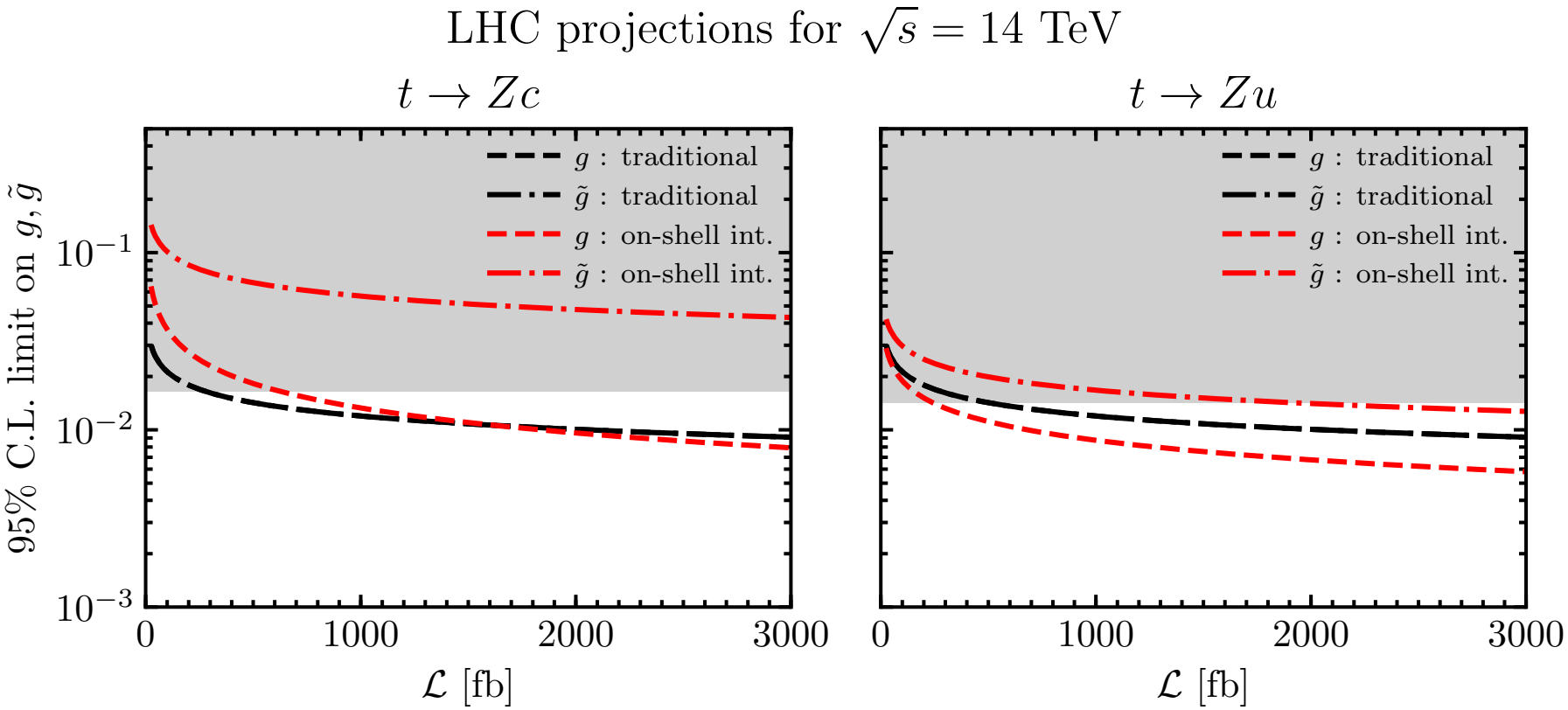
- Demand 3 b-tags and a leptonically decaying top
- Efficiency: $\epsilon \sim \mathrm{BR}(t \to b(W \to \ell\nu)) \times \epsilon_b^3 \times 10\%$
- σ_{other} expected to be negligible (small phase-space, 3 b-jets, 1 lepton)
- For small enough coupling, **interference dominates**

$$\frac{\mathrm{S}}{\sqrt{\mathrm{B}}} \propto \sqrt{\mathcal{L}}\,\mathrm{coupling} \longrightarrow \mathrm{coupling}\Big|_{95\%} \propto \frac{1}{\sqrt{\mathcal{L}}}$$

- **Interference analysis will "win" for high enough luminocity.**

But when?

$t - Z - q$ sensitivity from on-shell interference (work in progress)



- g ($\tilde{g}$) left-handed (right-handed) $t - Z - c$ coupling
- gray region excluded by present measurements
- **Black:** Top Working Group projection, **Red:** our interference analysis
- For $t - Z - c$ crossover $\mathcal{L}$ at $1.5\,\text{ab}^{-1}$, for $t - Z - u$ already important

Top FCNCs and CP properties

Parametrising anomalous $t - Z - q$ couplings

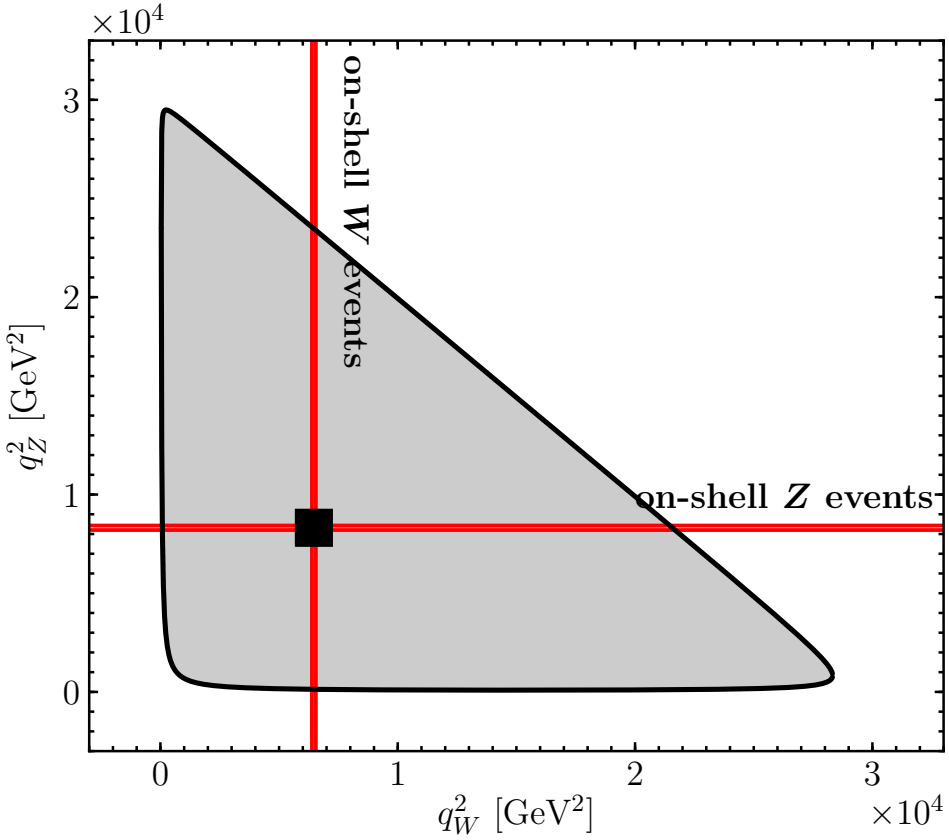
$$\mathscr{L}_{Z-t-c} = \frac{1}{2}\bar{t}\left(ge^{+i\theta}\gamma^{\mu}P_L + \tilde{g}e^{+i\tilde{\theta}}\gamma^{\mu}P_R\right)cZ_{\mu} + \text{c.c}$$

(with $g, \tilde{g} > 0$ and $0 \leq \theta,\ \tilde{\theta} < 2\pi$)

- Can the LHC probe the two weak CP violating phases?
- *"To probe a weak phase you need a strong phase."* [Citation needed]
- Interference with on-shell W has all ingredients
  ➜Keep the background on-shell, i.e.,
  strong phase from W propagator
  ➜Probe the weak phases from top-decay asymmetries
- Similar setup as in determination of CKM angle γ from multibody decays [Giri et al, 03]

Top-decay asymmetries

(work in progress)



- Contruct **asymmetries** from events with on-shell W

$$\mathcal{A} = \frac{N^t(q_Z^2 < m_Z^2) - N^t(q_Z^2 > m_Z^2)}{N^t + N^{\bar{t}}} + \frac{N^{\bar{t}}(q_Z^2 < m_Z^2) - N^{\bar{t}}(q_Z^2 > m_Z^2)}{N^t + N^{\bar{t}}} = \frac{\mathbf{I}}{\mathbf{B} + \mathbf{S}} \propto \sin\theta\cos\theta$$

- Applicable also to single-top events.

- Complements searches for couplings g ($\tilde{g}$)
- Possibly difficult to compete with indirect constraints from EDMs

Conclusions & Outlook

Higgs & Flavour

- **Various** interesting and/or realistic **ideas** to probe Higgs couplings to fermions (c-tagging, exclusive decays, kinematics,...)
- Advantages and disadvantages of the methods are **complementary**
- The **HE/HL LHC** will probe $\mathcal{O}(1)$ modifications of some parameters (charm Yukawa) for the **first time**

Top-quark FCNCs with on-shell interference

- When NP effects small, interferences can be powerful
- For top FCNCs the SM W decay provides such an interfering bkg
- Promising for $t - Z - q$ (not for $t - H - q$)
- Conceptually interesting beyond this top-FCNC application

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