ZPW2020

The Higgs boson and the Top quark

Probing New Physics with Top Quarks (Precisely)

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Zurich
14/01/2020

Scope

Top quark as NP probe - vast topic

Necessarily guided (biased) selection:

- ➤ guidance/complementarity from/with other (quark) flavor sectors
- ➤ testing/exploiting capabilities of future/upcoming experiments (HL-LHC & beyond)

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CPV & LFU

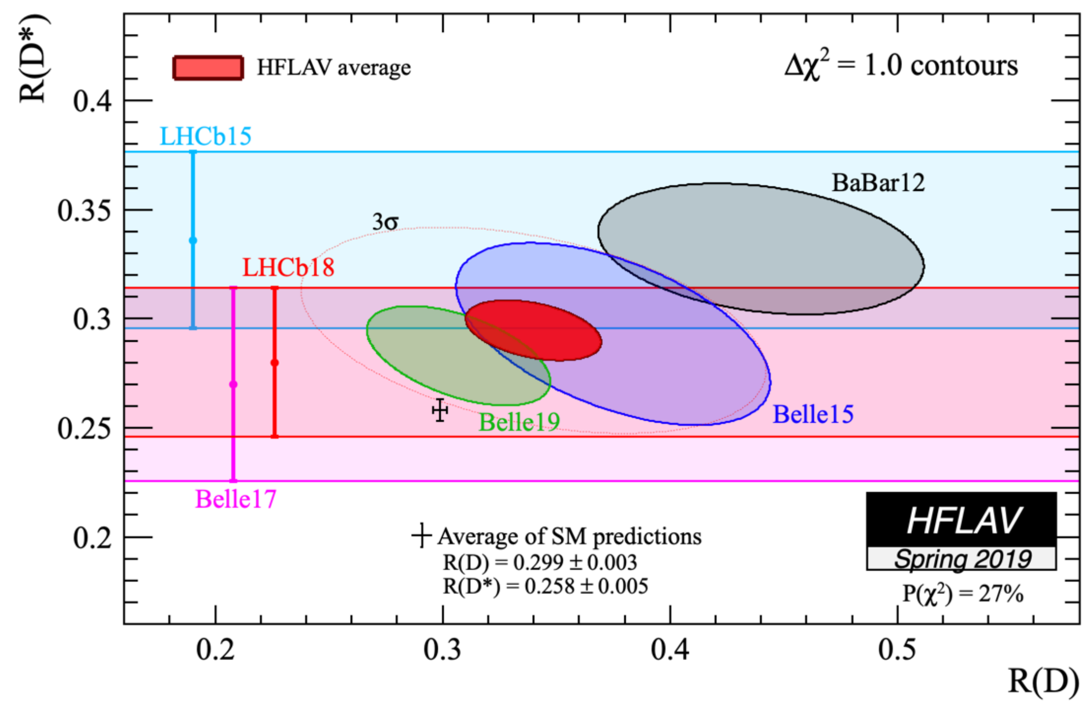
Probing LFU in top decays

with A. Katz & Daniel Stolarsky, 1808.00964

LFU in the top sector

LFU has been well tested in K, D, τ sectors $\mathcal{O}(1\% - 1‰)$

Recent intriguing results in semi-leptonic B decays:



$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

⇒ discrepancy at O(20%) level

In SM predicted to be purely due to mass effects (phase-space, chirality flips)

⇒ extremely small in main top decay $(m_\tau/m_W)^2 \sim 5 \times 10^{-4}$

+ constrained by LEP measurements: $\frac{\Gamma(W \to \tau\nu)}{\Gamma(W \to \mu\nu)} = 1.070 \pm 0.026$

LEP Colls., 1302.3415

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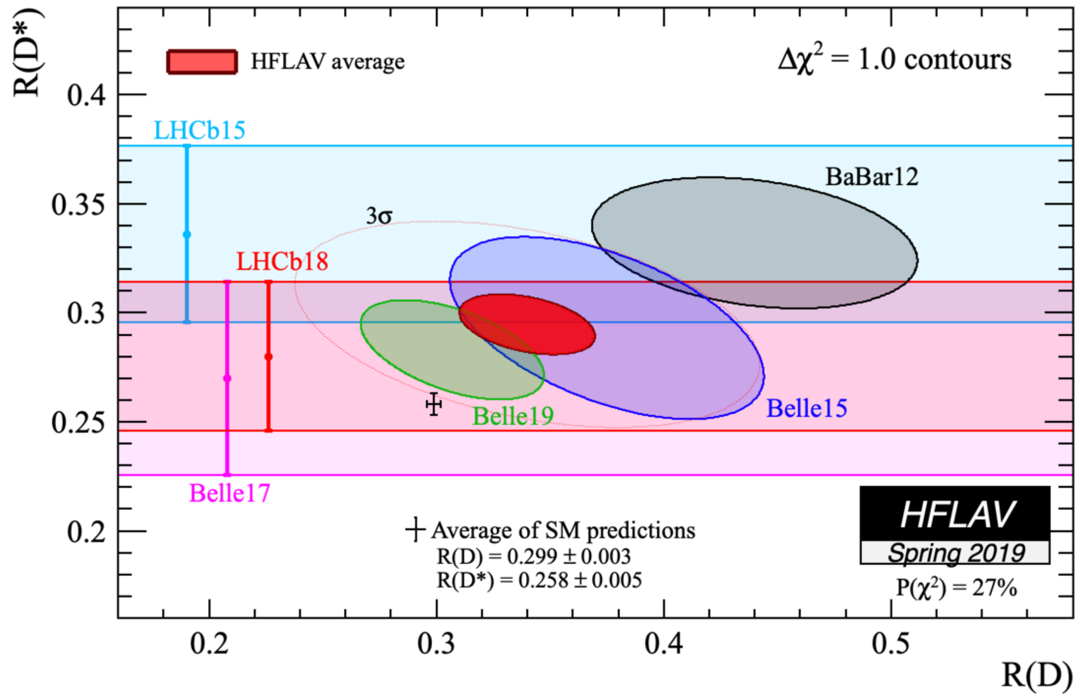

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What is the ultimate precision of LFU tests in top decays?

Probing LFU in top decays

Consider semitauonic mode $t \to b(W \to \tau\nu)$

If NP heavy ($m_{NP} > m_t$ - m_W), can parametrise NP in EFT

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_{i,q} C_i^q \mathcal{O}_i^q + \text{h.c.}$$

Relevant four-fermi ops: $\mathcal{O}_{VL}^q = (\bar{q}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)\,, \quad \mathcal{O}_{SL}^q = (\bar{q}P_L b)(\bar{\tau}P_L\nu_\tau),$

see e.g. Freytsis, Ligeti & Ruderman, 1506.08896

$$\mathcal{O}_{TL}^q = (\bar{q}\sigma_{\mu\nu}P_L b)(\bar{\tau}\sigma^{\mu\nu}P_L\nu_\tau)\,, \mathcal{O}_{SR}^q = (\bar{q}P_R b)(\bar{\tau}P_L\nu_\tau)\,,$$

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❊ Large top decay width ($|V_{tb}|$~1, 2-body dominant mode)

⇒ effects on total Br tiny:

$$\delta\mathcal{B}_\tau = 1.8 \times 10^{-5} \bar{C}^t_{VL} + 2.0 \times 10^{-5} (\bar{C}^t_{VL})^2\,, \qquad \bar{C}^q_i \equiv C^q_i (1\text{TeV}/\Lambda)^2$$

$$\delta\mathcal{B}_\tau = 5.1 \times 10^{-6} \left[(\bar{C}^t_{SL})^2 + (\bar{C}^t_{SR})^2\right]\,,$$

[$R(D)$ requires $\bar{C}^q_i \sim \mathcal{O}(1)$]

+ current exp. precision O(10%)

$$\mathcal{B}_e = 13.3(4)(4)\%\,, \mathcal{B}_\mu = 13.4(3)(5)\%\,, \mathcal{B}_{\tau_h} = 7.0(3)(5)\%\,,$$

ATLAS, 1506.05074

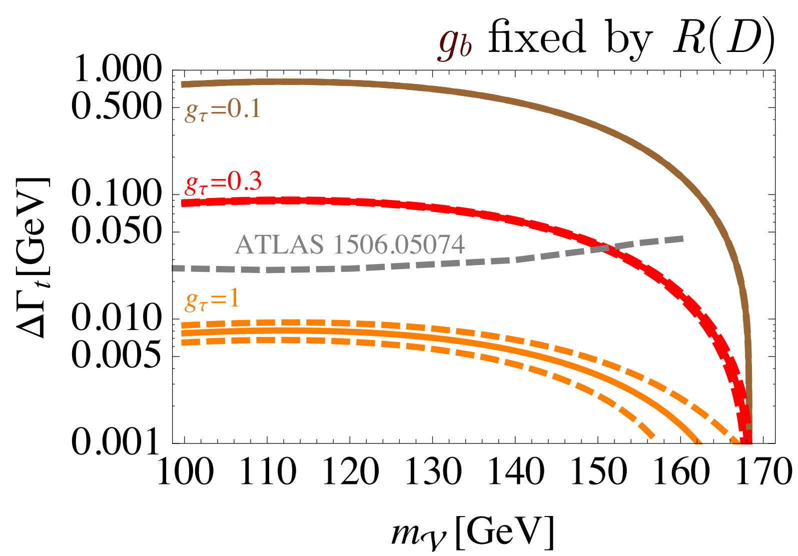
LFU probes beyond large top width?

1) *Light NP*: if top decays to on-shell new d.o.f.s in 2-body mode, can more easily compete with SM contributions

Examples:

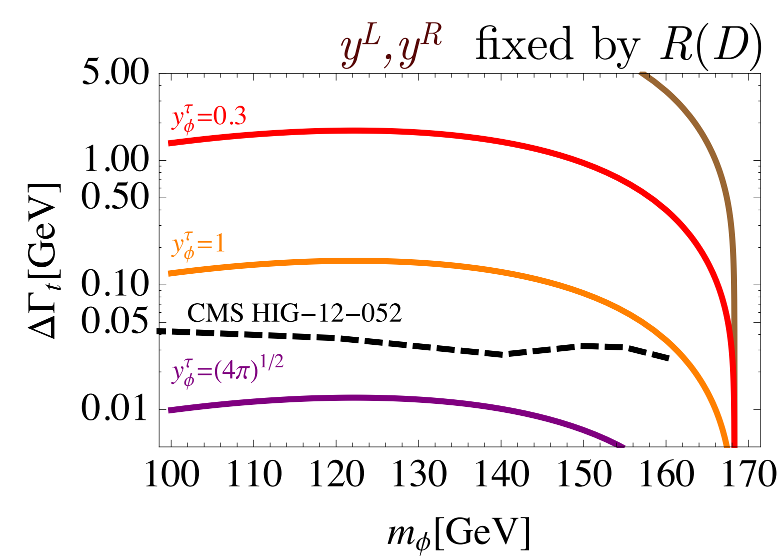
a) light charged vector

$$\mathcal{L}^{(a)} = \mathcal{L}_{\rm SM} + \frac{1}{4}\mathcal{V}^{+}_{\mu\nu}\mathcal{V}^{-\mu\nu} - m^2_{\mathcal{V}}\mathcal{V}^{+}_{\mu}\mathcal{V}^{-\mu} + \left[\boxed{g_b}\sum_q V_{qb}\bar{q}\,\not{\mathcal{V}}^{+}P_L b + \boxed{g_\tau}\bar{\tau}\,\not{\mathcal{V}}^{-}P_L\nu_\tau + \text{h.c.}\right],$$



b) light charged scalar

$$\mathcal{L}^{(b)} = \mathcal{L}_{\rm SM} + \partial_\mu\phi^+\partial^\mu\phi^- - m^2_\phi\phi^+\phi^- + \left[\sum_q V_{qb}\phi^+\left(\boxed{y^L_\phi}\bar{q}P_L b + \boxed{y^R_\phi}\bar{q}P_R b\right) + \boxed{y^\tau_\phi}\phi^-\bar{\tau}P_L\nu_\tau + \text{h.c.}\right],$$



R(D) explanations being tested, pushed to strong coupling

LFU probes beyond large top width?

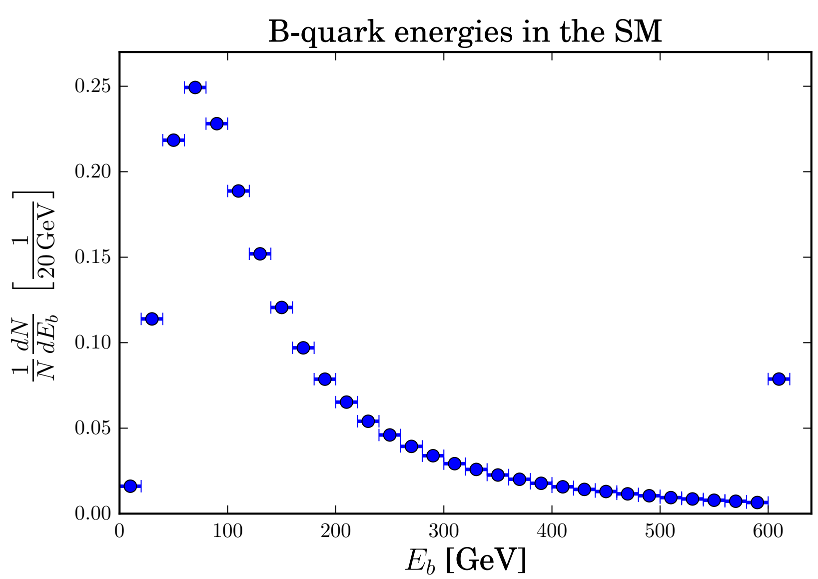
2) *Heavy NP*: exploit difference in 2-body (SM) and 3-body (NP) phase-space

Powerful observable: lab-frame b-jet energy spectrum

⇒ For (SM) 2-body decay, *peak* predicted with high accuracy:

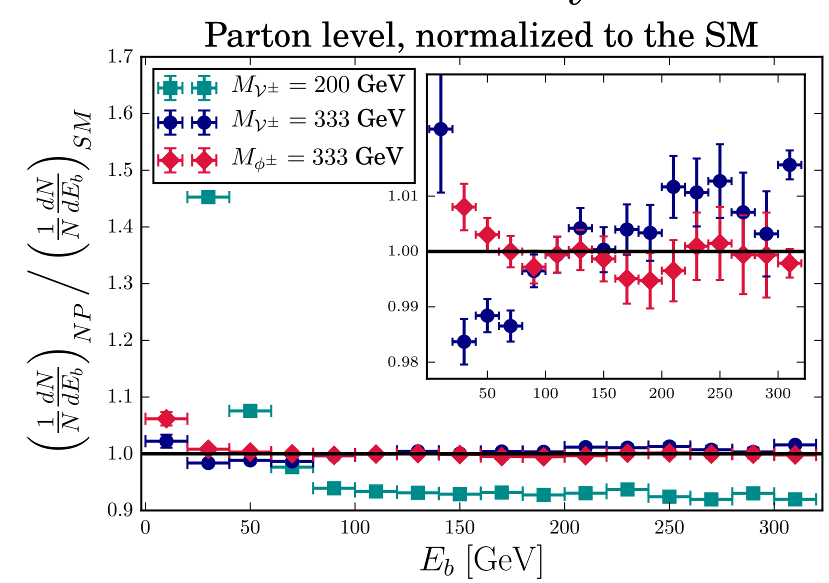
$$E_b^* = \frac{m_t^2 - m_W^2}{2m_t}$$

Agashe, Franceschini & Kim
1209.0772, 1309.4776



More generally:

$$E_b^* = \frac{m_t^2 - m_{l\nu}^2}{2m_t}$$

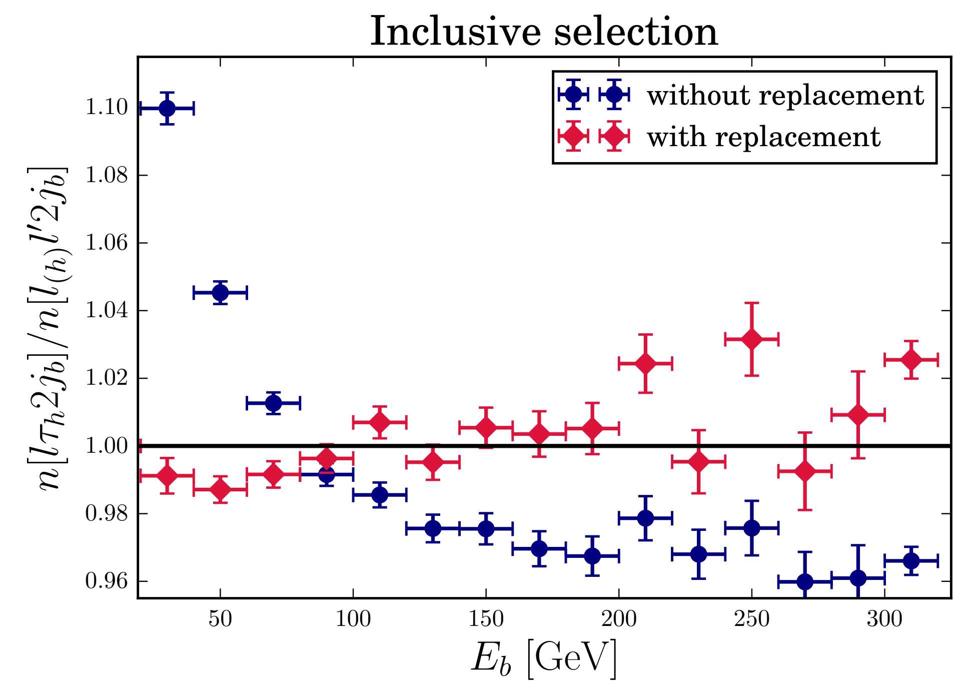


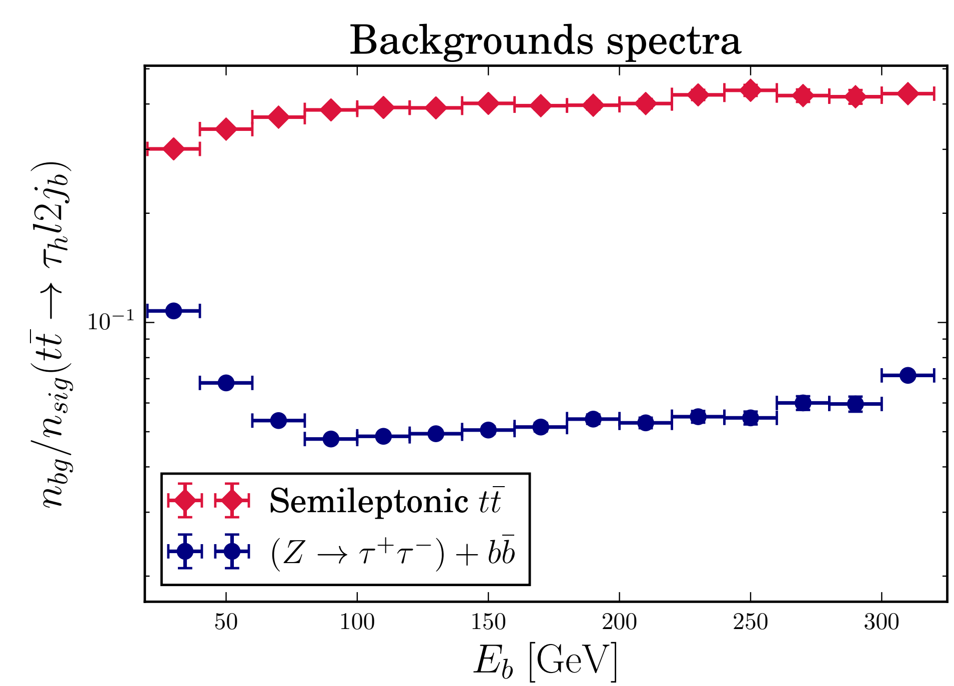
⇒ Probe ratio of differential energy spectra

A realistic analysis?

Test LFU by comparing E_b spectra in tauonic vs. muonic events

- Need to compensate for different selection and reconstruction efficiencies of muons vs. taus
  $\Rightarrow$ extract in data driven way with $\mu \rightarrow \tau$ replacement
- Small contaminations from semilep. $t\bar{t}(j \rightarrow \tau_h)$ and $(Z \rightarrow \tau^+\tau^-)b\bar{b}$
  $\Rightarrow$ different kinematics, can be controlled for using jet veto and $(Z \rightarrow \mu^+\mu^-)b\bar{b}$





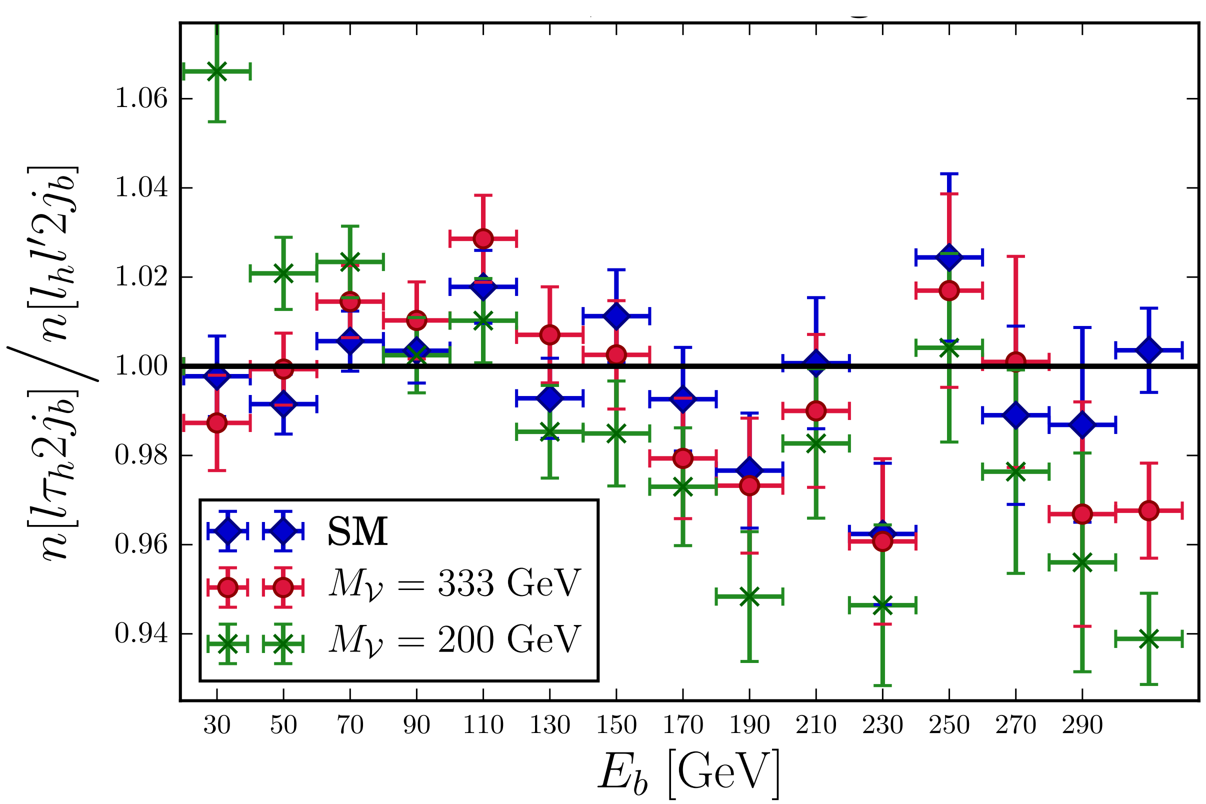
LHC prospects

Our final systematic error estimates are dominated by MC statistics

[O(100M) events simulated in total, corresponding up to O(100fb^{-1}) of LHC data]

⇒ at O(1%) per [20GeV] energy bin

<u>Example</u>:



(HL-)LHC prospects for testing (sub-)percent level top LFU

Probing CPV in the top-Higgs sector

with D. Faroughy, N. Košnik & A. Smolkovič, 1909.00007

CPV in quark sector

- CPV has been observed in *K* (1964,Cronin & Fitch), *B* (2002, Belle & Babar) and *D* (2019, LHCb) meson sectors
  ⇒ Good concordance with SM (CKM)

- Predicted to be vanishingly small in top sector (absence of significant GIM breaking, short *t*-lifetime, no neutral long-lived bound states)
  ⇒ “Null test” of SM

Best strategies to probe top CPV BSM?

CPV in the top sector

Parametrise heavy NP with EFT: leading dim-6 operators

see e.g. J. A. Aguilar-Saavedra, 0904.2387

$$Q^{(3)}_{\phi q,33} \equiv (\phi^\dagger i \overleftrightarrow{D}^a_\mu \,\phi)(\bar{Q}_{L,3}\gamma^\mu \sigma^a Q_{L,3})\,,$$

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'penguins'

$$Q_{Wd,33} \equiv \bar{Q}_{L,3}(\sigma \cdot W) b_R\, \phi\,,$$

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dipoles

$$Q_{Hu,33} \equiv \bar{Q}_{L,3} t_R\, \tilde{\phi}|\phi|^2\,,$$

yukawas

+ four-fermion ops.

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- Probed *directly* through (single, pair, associate) top production and decays at LHC
- Important complementarity with low energy *indirect* probes

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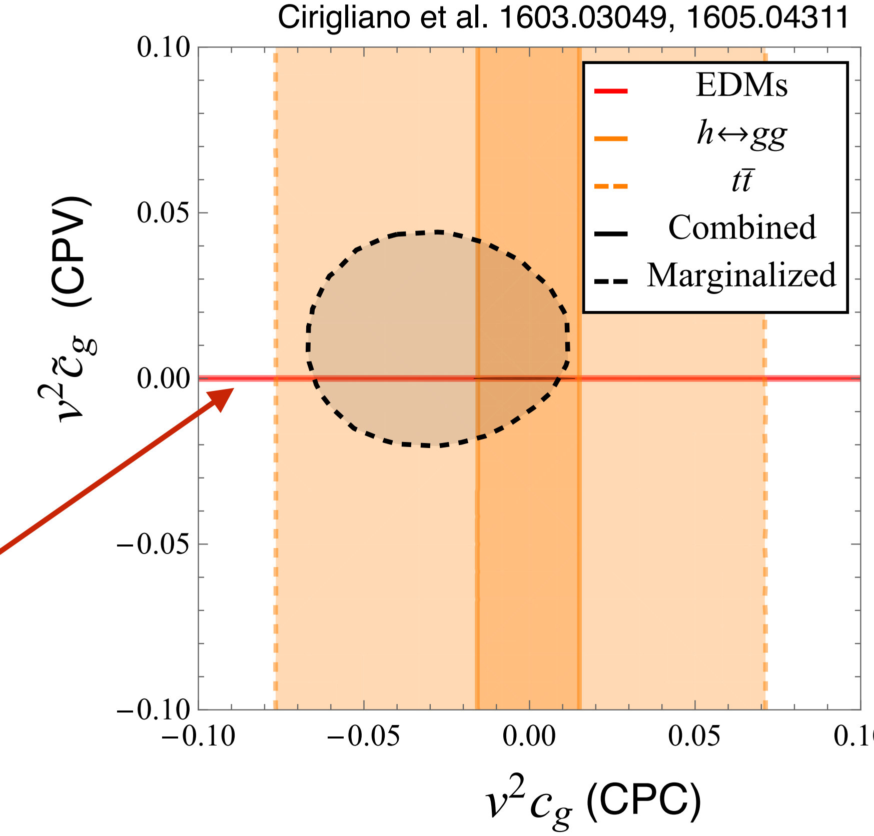
$$\boxed{\mathrm{Im}(\Lambda/\sqrt{C_{Gu,33}})_{\mathrm{EDM}} > 4.7\,\mathrm{TeV}}$$

J.F.K. et al. 1107.3143
C. Degrande et al. 1205.1065
Schulze & Soreq 1603.08911
Cirigliano et al. 1603.03049, 1605.04311



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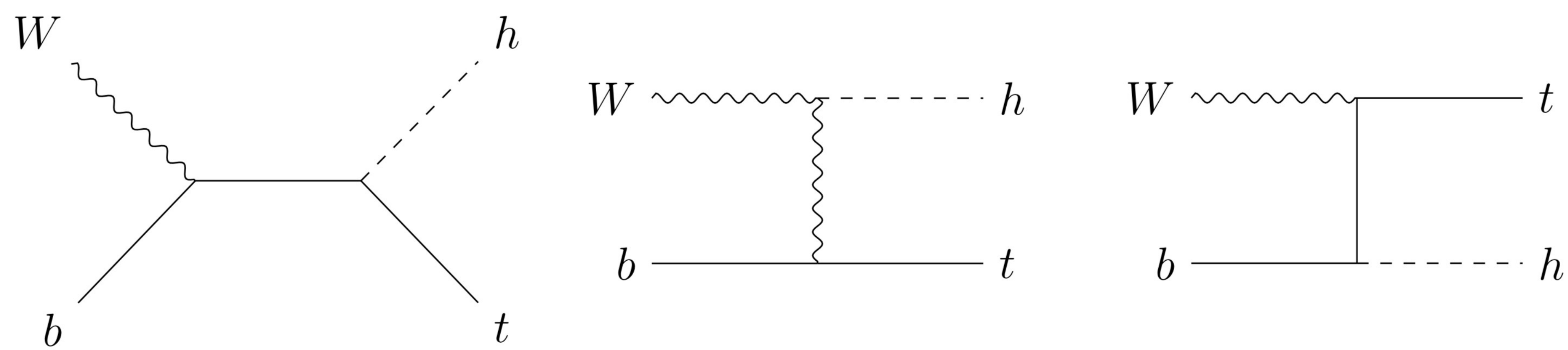
- After EWSB modifies top-Higgs coupling $-\frac{y_t}{\sqrt{2}}\bar{t}(\kappa + i\tilde{\kappa}\gamma_5)th$
- Currently most sensitive *direct* probes are CP-even, sensitive to $\tilde{\kappa}^2$, e.g.

$$\sigma(pp \to t\bar{t}h) \sim A\kappa^2 + B\tilde{\kappa}^2$$

Genuinely CPV probes? CP-odd observables, linear in $\tilde{\kappa}$

Toy example: top-polarisation in *th* production

“parton level” $Wb \to th$ scattering - tractable analytically



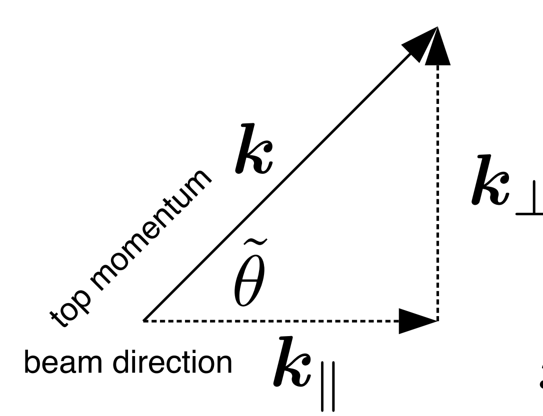
Polarised cross section ~ $|\mathcal{M}|^2 = a + b_\mu s^\mu$

see e.g. Fajfer, J.F.K. & Melic, 1205.0264

❊ important spin quantisation axis $s^\mu = \left(\frac{\boldsymbol{k}\cdot\hat{\boldsymbol{s}}}{m_t}, \hat{\boldsymbol{s}} + \frac{\boldsymbol{k}(\boldsymbol{k}\cdot\hat{\boldsymbol{s}})}{m_t(E_t+m_t)} \right)$

⇒ optimal for $\hat{\boldsymbol{s}} = \hat{\boldsymbol{k}}_\parallel \times \hat{\boldsymbol{k}}_\perp$

$$|\mathcal{M}|^2 = A(\tilde{x}) + B_i(\tilde{x})\hat{s}_i$$

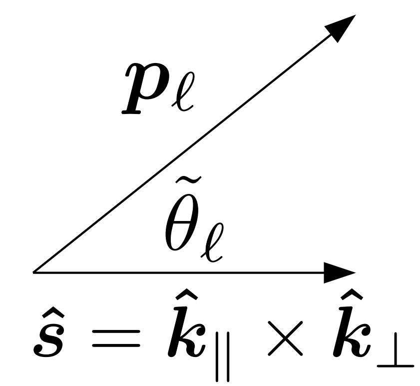


$\tilde{x} = \cos\tilde{\theta}$

Probing top polarization in semileptonic top decay

Charged lepton in $t \to b\ell\nu$ decay close to optimal top-spin analyser - directions (almost) 100% correlated see e.g. Bernreuther et al., hep-ph/0403035

$$\frac{1}{\Gamma_t}\frac{d\Gamma_t}{d\cos\tilde{\theta}_\ell} = \frac{1}{2}\left(1 + B_i \hat{s}_i \cos\tilde{\theta}_\ell\right)$$



In hadronic production thus

$$\frac{d^2\sigma^{pp\to thj}}{d\tilde{x}\, d\cos\tilde{\theta}_\ell} \sim \mathcal{A}(\tilde{x}) + \tilde{\kappa}\cos\tilde{\theta}_\ell \mathcal{B}_i(\tilde{x})\hat{s}_i$$

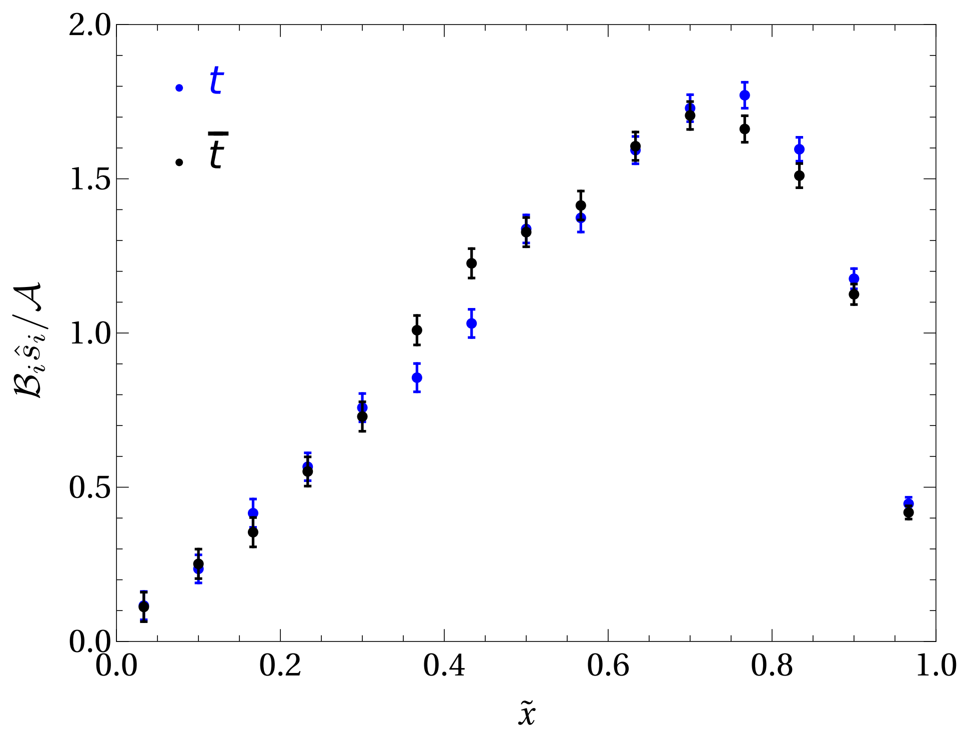
⇒ simplest CP-odd observable $O_{\mathrm{simp.}} \equiv \left\langle \cos\tilde{\theta}_\ell \right\rangle$

Optimal CPV sensitivity in $pp \to thj$

Sensitivity can be optimised by reweighing (by f) over phase-space ($\tilde{x}$):

Atwood & Soni, Phys. Rev. D45 (1992) 240

$$f_{\rm opt}(\tilde{x}) = \cos\tilde{\theta}_\ell \mathcal{B}_i(\tilde{x})\hat{s}_i/\mathcal{A}(\tilde{x})$$



⇒ optimal CP-odd observable $O_{\rm opt} = \langle\cos\tilde{\theta}_\ell \mathcal{B}_i\hat{s}_i/\mathcal{A}\rangle$

❊ Optimal weight must be extracted from MC

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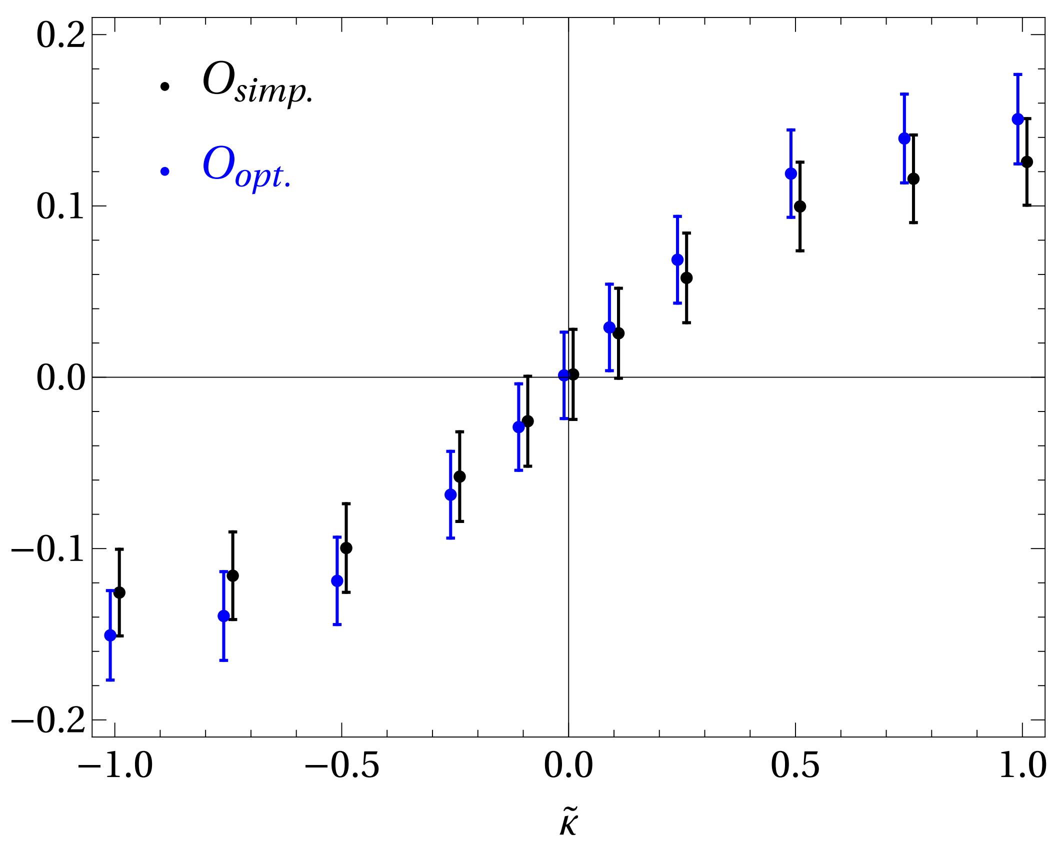
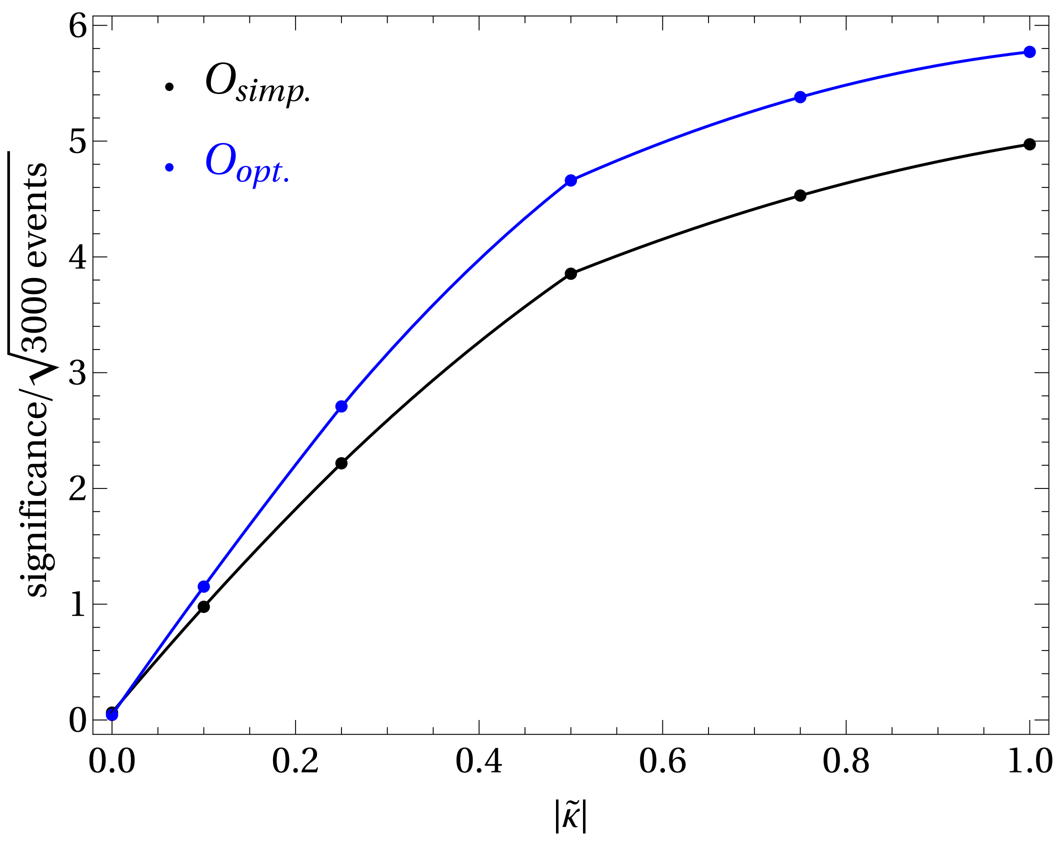




Marginal improvement of sensitivity compared to $O_{simp.}$

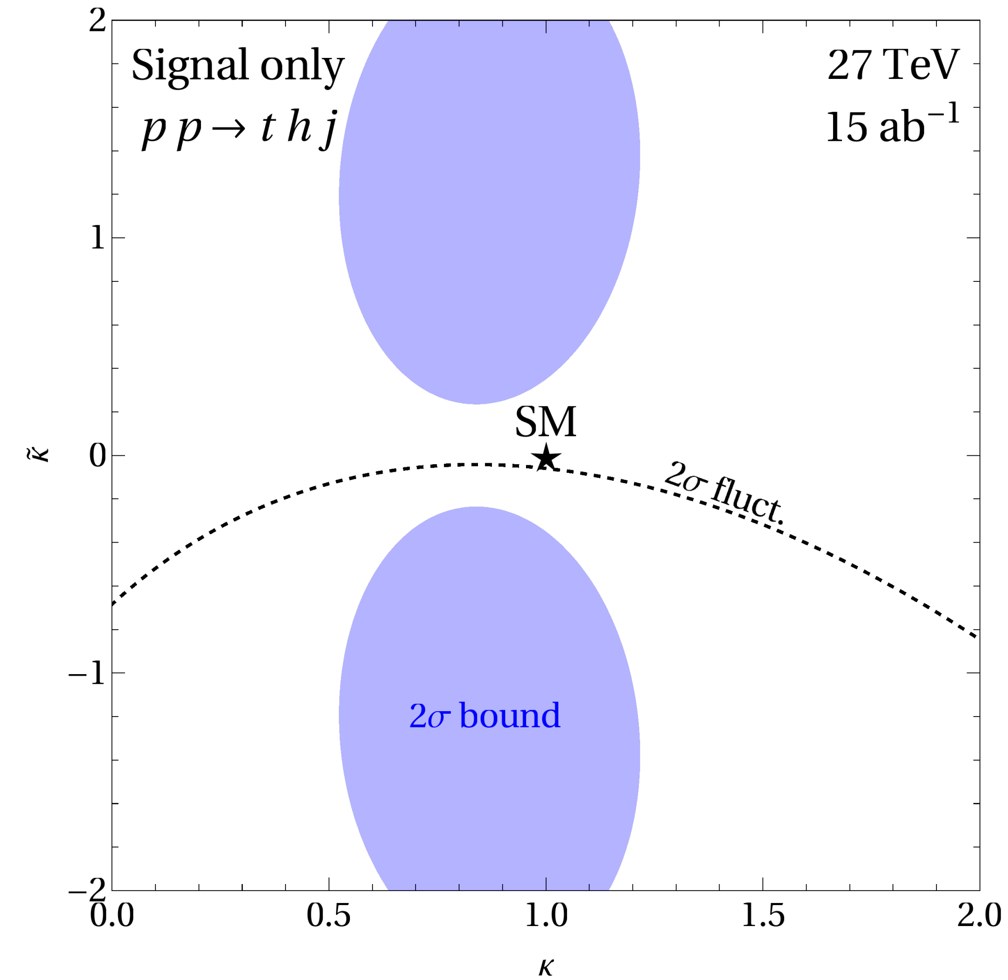
Realistic analysis?

see e.g. Farina et al., 1211.3736

Including realistic top, Higgs reconstruction, one can project bounds from prospective measurements

⇒ Not relevant at LHC due to tiny *th* x-section

Example at HE-LHC:



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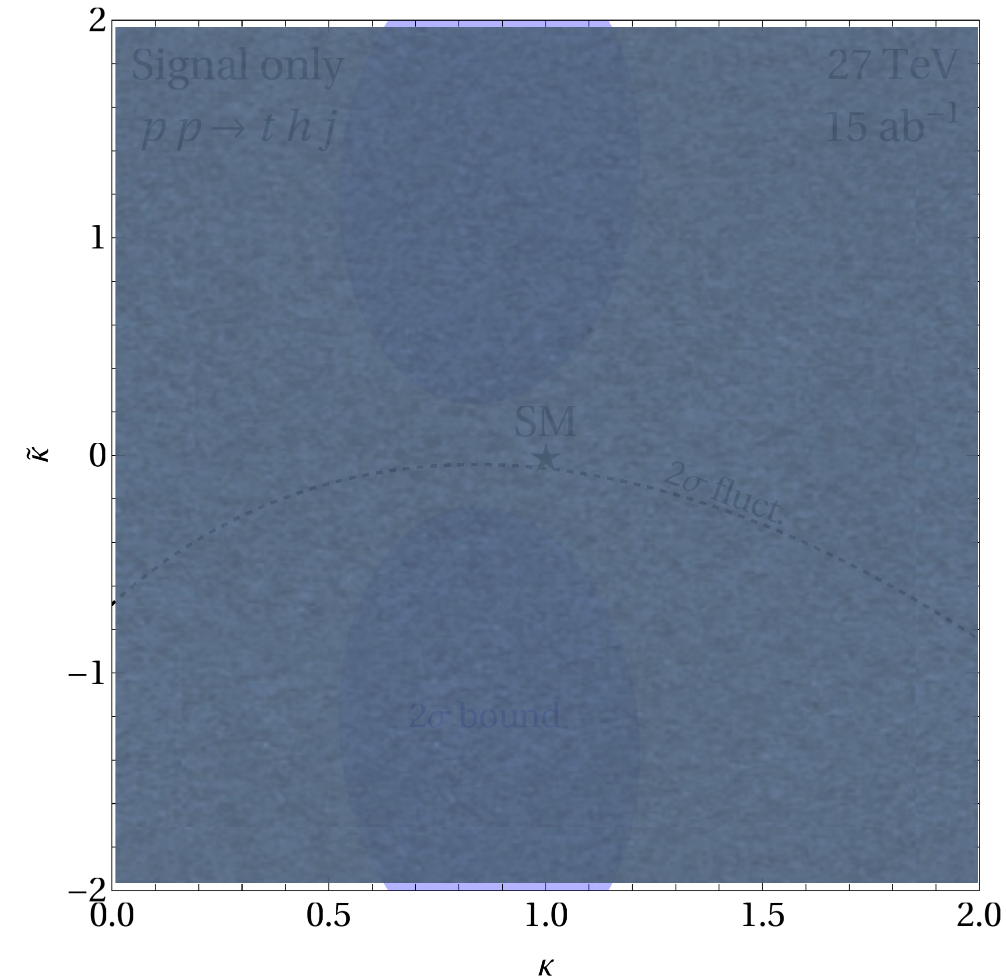
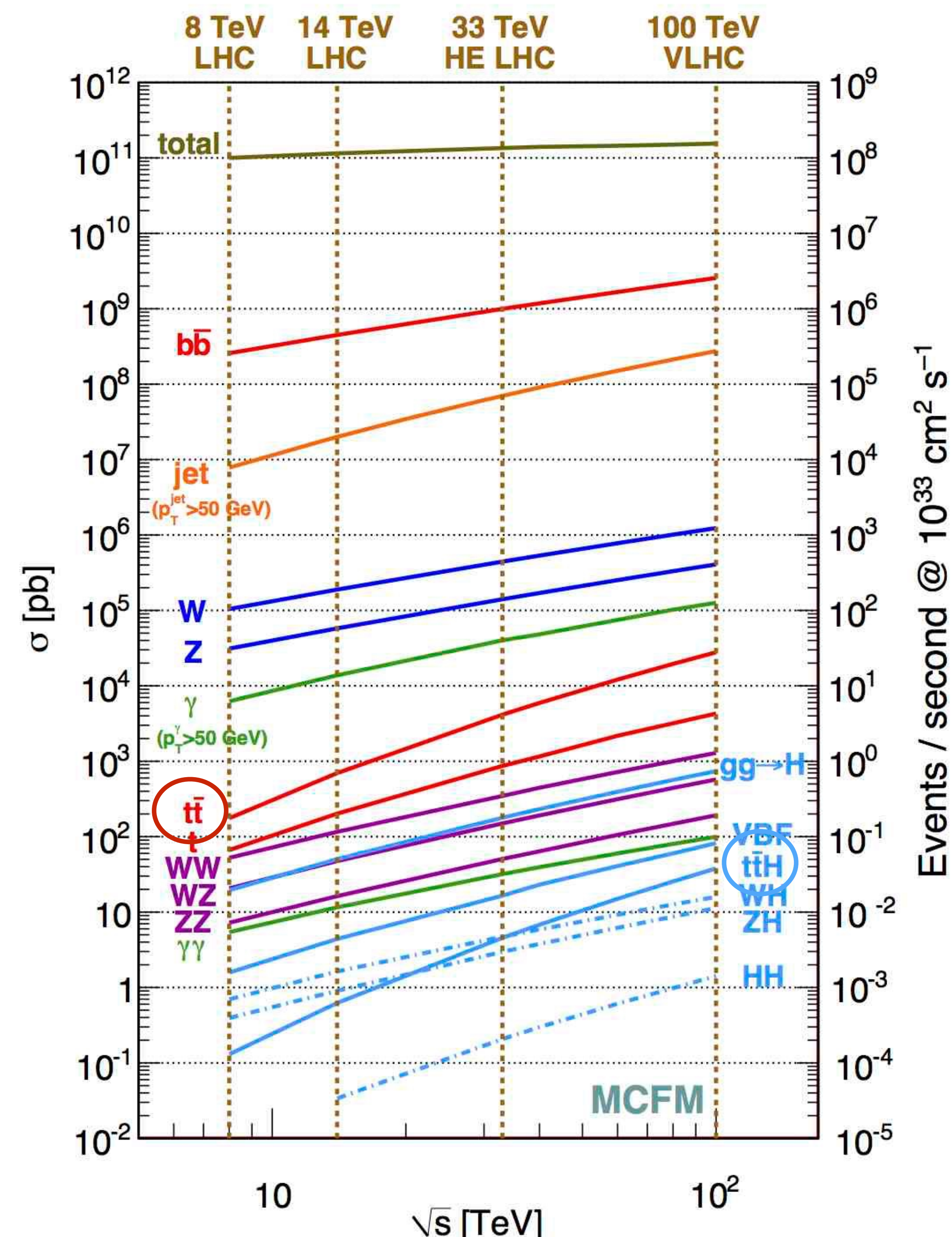


In practice signal swamped by dominant $t\bar{t}$+jets background

Lessons learned

- top spin only one example (pseudo)vector allowing to construct CP-odd observables
- optimal polarisation axis
  ⇒ maximises "triple product"
- charged leptons good proxies of top spin
- top-Higgs production is puny
  ⇒ CPV in *tth*?



CP-odd observables in $t\bar{t}h$ production

Clean dileptonic signature to suppress backgrounds

⇒ $t\bar{t}$ rest-frames not reconstructable

Lab-frame observables built from accessible final-state momenta

⇒ assume Higgs fully reconstructed ($\gamma\gamma$, $b\bar{b}$, ...)

[no b - $\bar{b}$ (charge) differentiation] see however Boudjema et al., 1501.03157

	$\boldsymbol{p}_h$	$\boldsymbol{p}_{\ell^-} + \boldsymbol{p}_{\ell^+}$	$\boldsymbol{p}_{\ell^-} - \boldsymbol{p}_{\ell^+}$	$\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}}$	$\boldsymbol{p}_{\ell^-} \times \boldsymbol{p}_{\ell^+}$	$\boldsymbol{p}_b \times \boldsymbol{p}_{\bar{b}}\,(\boldsymbol{p}_b - \boldsymbol{p}_{\bar{b}})$
C	$+$	$+$	$-$	$+$	$-$	$+$
P	$-$	$-$	$-$	$-$	$+$	$-$
CP	$-$	$-$	$+$	$-$	$-$	$-$

⇒ Suitable observables: triple-products, double-triple products, etc…

see also Bernreuther et al., Phys. Rev. D49 (1994)

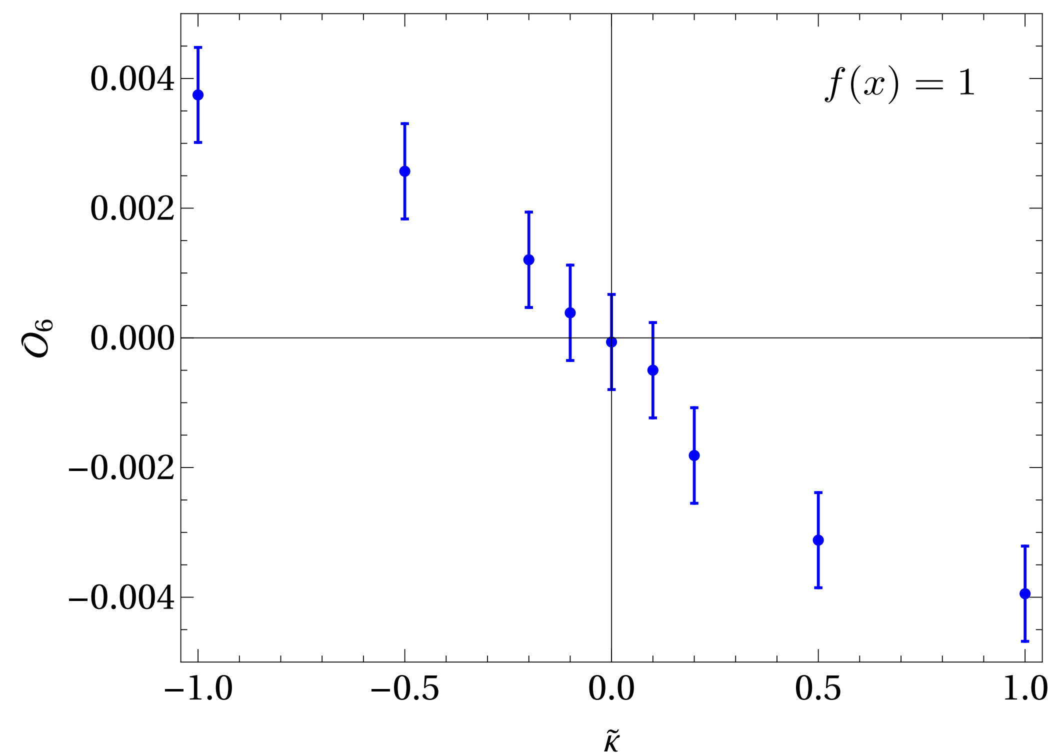
CP-odd observables in *tt̄h* production

Example: $$\omega_6 \equiv \frac{[(\boldsymbol{p}_{\ell^-} \times \boldsymbol{p}_{\ell^+}) \cdot (\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}})]\,[(\boldsymbol{p}_{\ell^-} - \boldsymbol{p}_{\ell^+}) \cdot (\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}})]}{|\boldsymbol{p}_{\ell^-} \times \boldsymbol{p}_{\ell^+}|\,|\boldsymbol{p}_{\ell^-} - \boldsymbol{p}_{\ell^+}||\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}}|^2}$$

Differential x-section $$\frac{d^2\sigma}{dx\,d\omega} \sim A(x) + \kappa\tilde{\kappa}\gamma(x)\omega$$ x - kinematical variables

⇒ can define CP-odd observable

$$\mathcal{O}_\omega = \frac{1}{\sigma}\int dx\, d\omega \frac{d^2\sigma}{dx d\omega} f(x)\omega$$



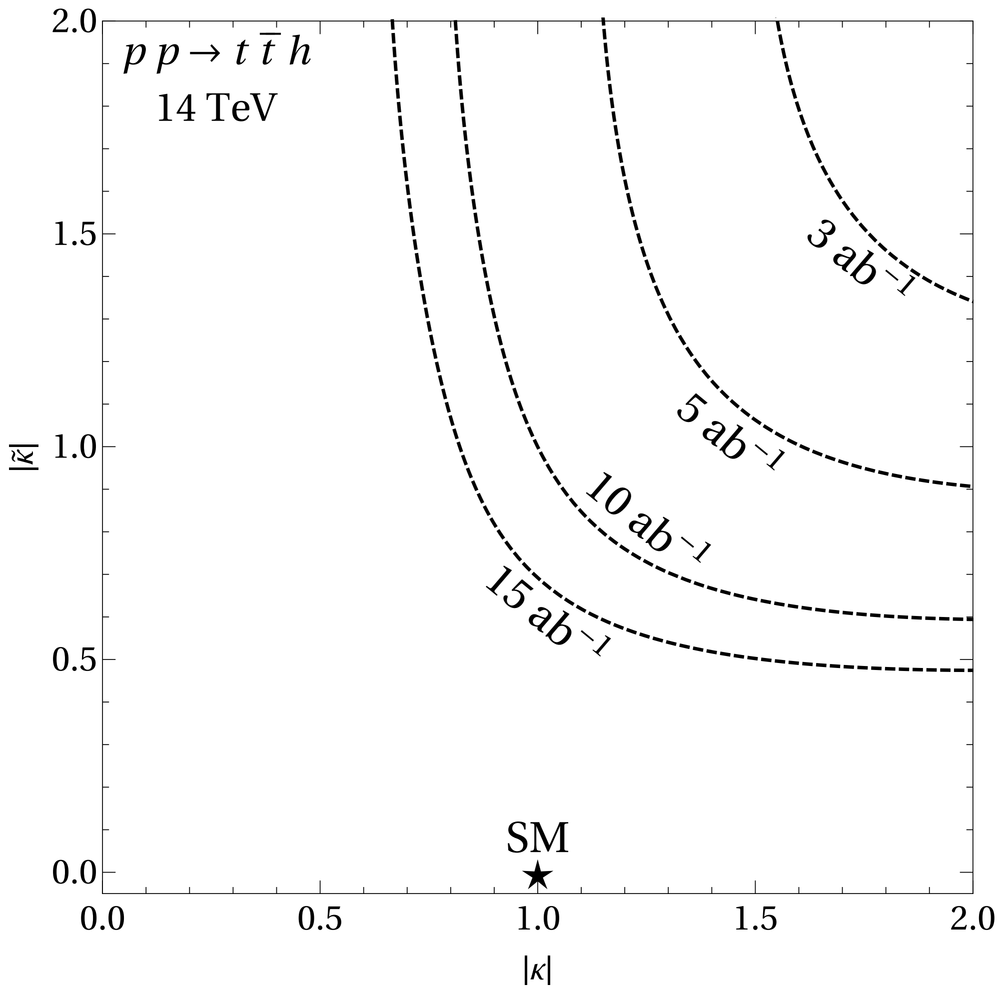
- Linear in $\tilde{\kappa}$ close to origin
- Tiny effect - can be optimised similar to *th*?
- $f_{\mathrm{opt.}}$ depends on whole 3-body phase space
- Case for ML…in progress

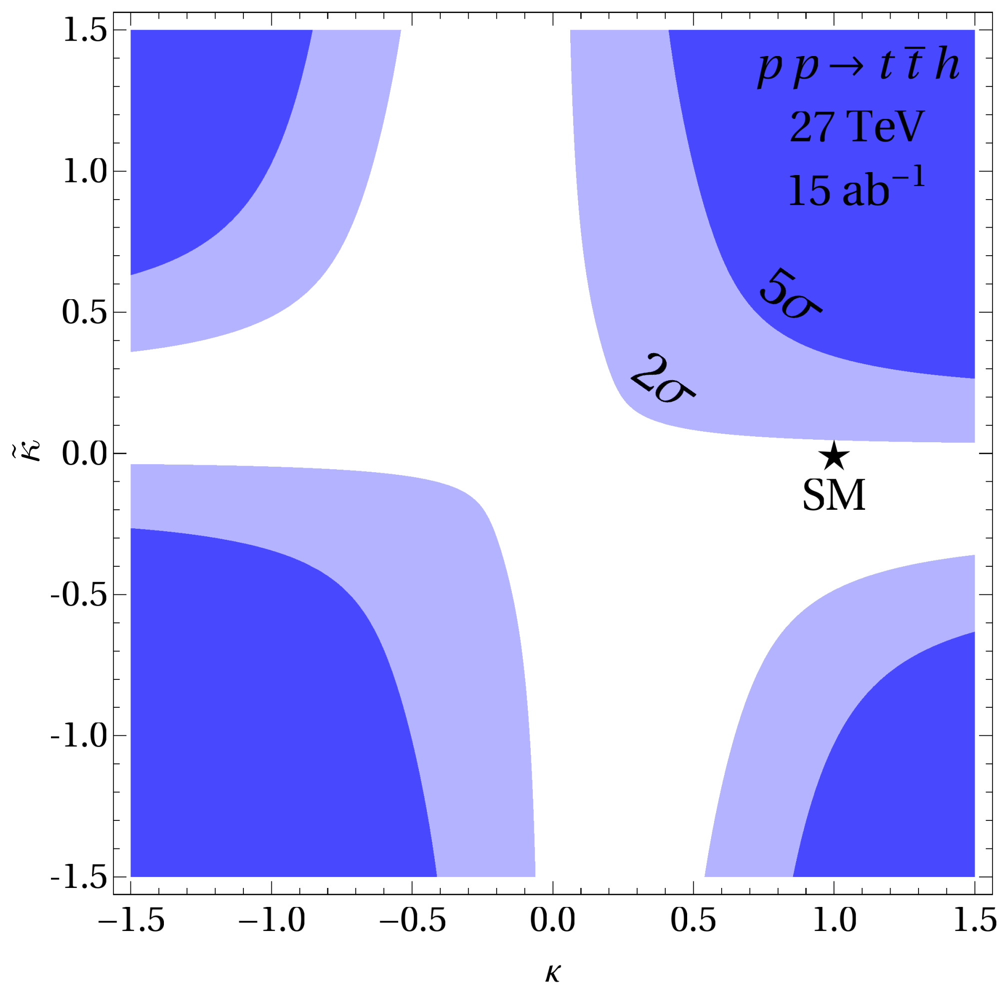
Realistic analysis?

Including realistic reconstruction of signal

$pp \to t\bar{t}h(t \to b\ell^+\nu_\ell, \bar{t} \to \bar{b}\ell^-\bar{\nu}_\ell, h \to b\bar{b})$ and main background

$pp \to t\bar{t}b\bar{b}, (t \to b\ell^+\nu_\ell, \bar{t} \to \bar{b}\ell^-\bar{\nu}_\ell)$





Non-trivial bounds or. signals possible at LHC upgrades

Conclusions

Top physics offers many important complementary probes of BSM in flavor (& Higgs) sectors

- ➤ Here covered examples in LFU & CPV
  - Practically null-tests of SM
  - Existing data can in some cases already yield non-trivial constraints on relevant BSM scenarios
  - Full exploration of NP sensitivity calls for ambitious new (Giga?) top-factories (HE-LHC, FCC)

Additional material

Lepton Flavor Universality in SM

SM gauge sector respects accidental flavor symmetry

$$G_F^{\rm SM} = U(3)_Q \times U(3)_U \times U(3)_D \times \underbrace{\boxed{U(3)_L \times U(3)_E}}_{\text{LFU}}$$

*neutrino masses

Broken by Higgs Yukawas

$$G_{\rm acc.}^{\rm SM} = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

⇒ Unique source of LFU breaking: $m_e \neq m_\mu \neq m_\tau$

Any LFU violation beyond lepton mass effects sign of NP!

*Higgs boson processes

th reconstruction

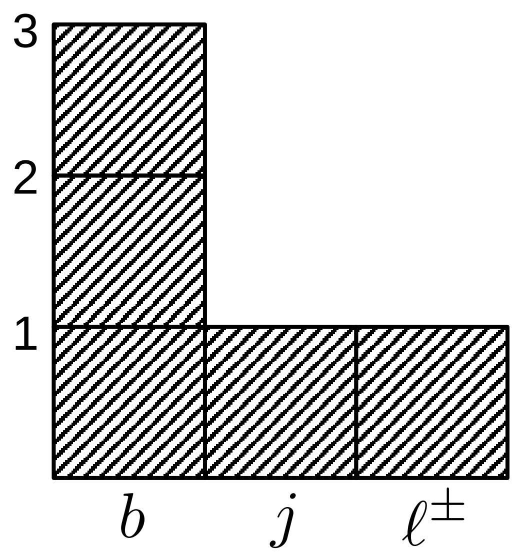
courtesy A. Smolkovic

Madgraph5 → **Pythia8** → **Delphes**

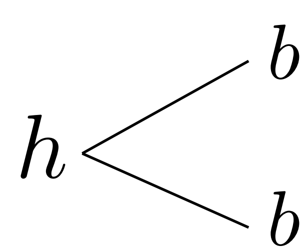
- event generation -   - showering, hadronization -   - detector simulation -

Signal: $pp \to t(\to b\ell\nu)h(\to b\bar{b})j$	Background: $pp \to t\bar{t}$ plus jets

Event selection:

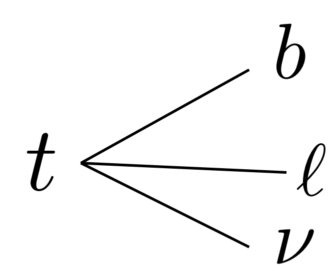


$$|\eta(b)| < 5 \qquad p_T(b) > 20\ \mathrm{GeV}$$
$$2 < |\eta(j)| < 5 \qquad p_T(j) > 20\ \mathrm{GeV}$$
$$|\eta(\ell)| < 2.5 \qquad p_T(\ell) > 10\ \mathrm{GeV}$$



$$|m_{bb} - m_h| < 15\ \mathrm{GeV}$$
$$m_{bbj} > 280\ \mathrm{GeV}$$

Farina et al.,
JHEP 05 (2013) 022



$$|m_{b\ell\nu} - m_t| < 35\ \mathrm{GeV}$$

$t\bar{t}h$ reconstruction

courtesy A. Smolkovic

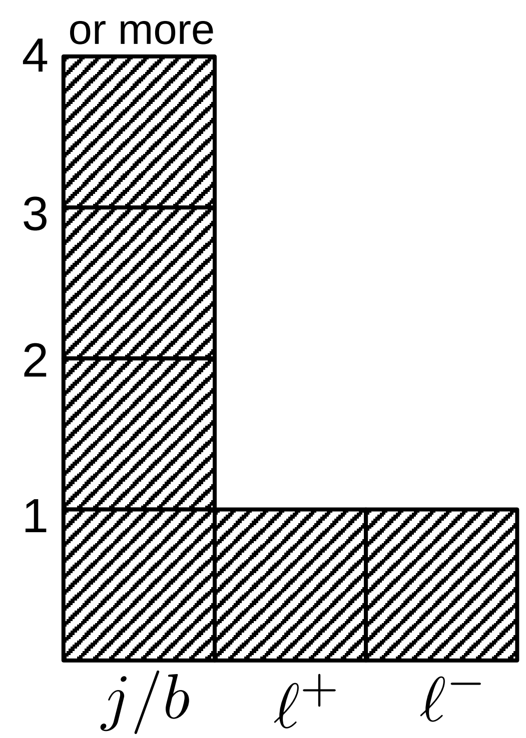
Madgraph5 → **Pythia8** → **Delphes**

- event generation - | - showering, hadronization - | - detector simulation -

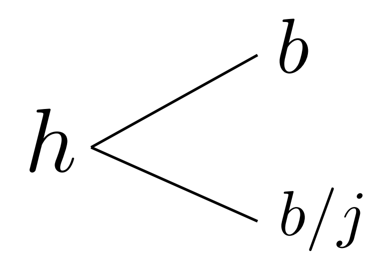
Signal: $pp \to t\bar{t}h\,(t \to b\ell^+\nu_\ell, \bar{t} \to \bar{b}\ell^-\bar{\nu}_\ell, h \to b\bar{b})$

Background: $pp \to t\bar{t}b\bar{b}, (t \to b\ell^+\nu_\ell, \bar{t} \to \bar{b}\ell^-\bar{\nu}_\ell)$

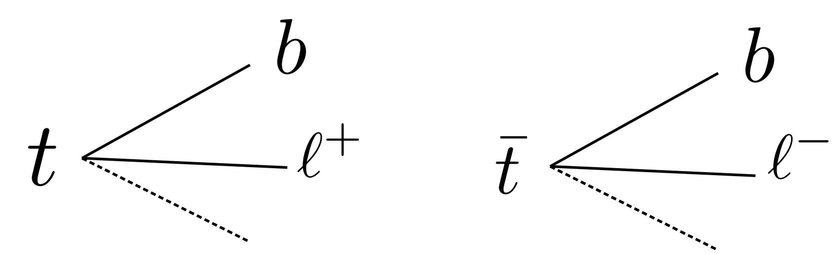
Event selection:



At least 3 b - tagged



$|m_{bb} - m_h| < 15\ \mathrm{GeV}$



Highest $p_T\ b-\mathrm{jets}$ assumed to originate from tops

$|\eta(j)| < 5 \qquad p_T(j) > 20\ \mathrm{GeV}$

$|\eta(\ell)| < 2.5 \qquad p_T(\ell) > 10\ \mathrm{GeV}$