Probing the CP nature of the top quark Yukawa at hadron colliders

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Motivation

- The only O(1) Yukawa in the SM → LHC

$$-y_{ij}\bar{Q}_i\tilde{H}u_j \to -\frac{y_t}{\sqrt{2}}\bar{t}th \qquad y_t = \sqrt{2}\frac{m_t}{v}$$

- SM + dim. 6 operator $|H|^2\bar{Q}\tilde{H}u$ can induce:

J. A. Aguilar-Saavedra., Nucl. Phys. B821 (2009) 215 [0904.2387]

$$-\frac{y_t}{\sqrt{2}}\bar{t}(\kappa + i\tilde{\kappa}\gamma_5)th$$

SM: $(\kappa, \tilde{\kappa}) = (1, 0)$

- CP-even quantities are sensitive to $\tilde{\kappa}^2$

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

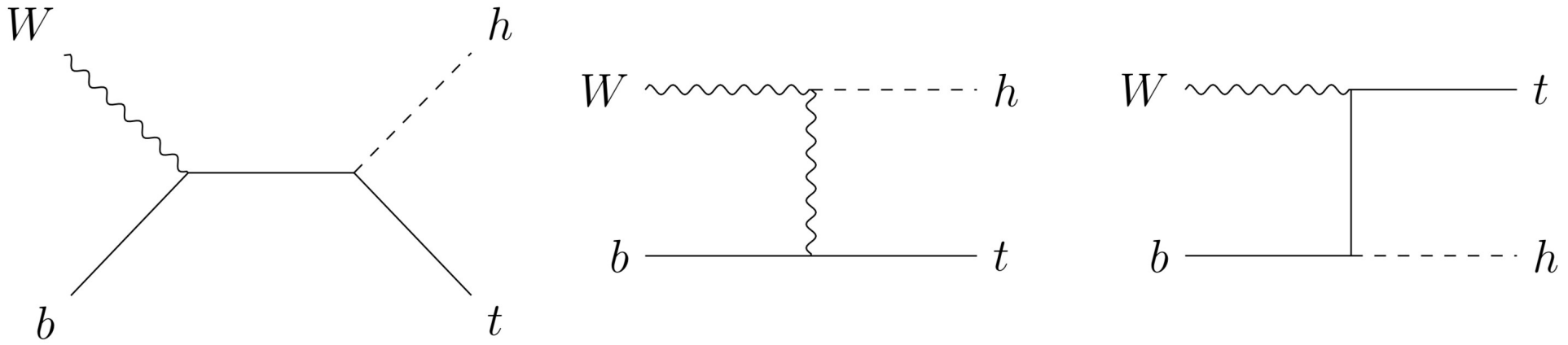
- Can we find observables with linear sensitivity to $\tilde{\kappa}$?

Polarization observables in th

Lab. frame observables in $t\bar{t}h$

Polarization observables in th

"Parton" level analysis:



Polarized cross section ⟶ Optimal top pol. vector

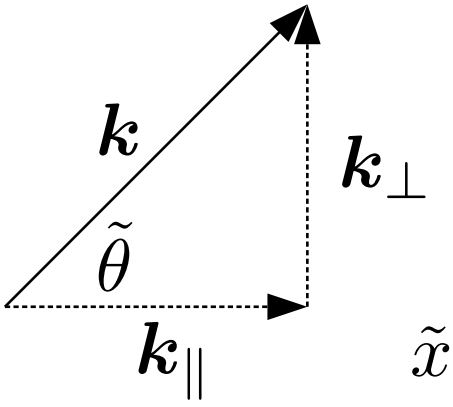
$$|\mathcal{M}|^2 = a + b_\mu s^\mu$$

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

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

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

Top always forward:

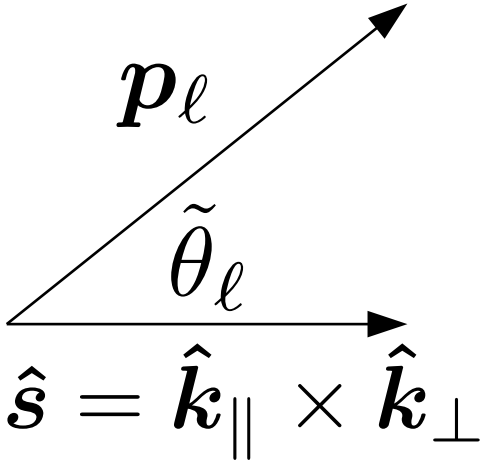


$$\tilde{x} = \cos\tilde{\theta}$$

Semileptonic top decay: $t \to b\ell\nu$

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

[1205.0264, hep-ph/0403035, ...]



Hadronic process $pp \to thj$

D. Atwood and A. Soni,
Phys. Rev. D45 (1992) 2405

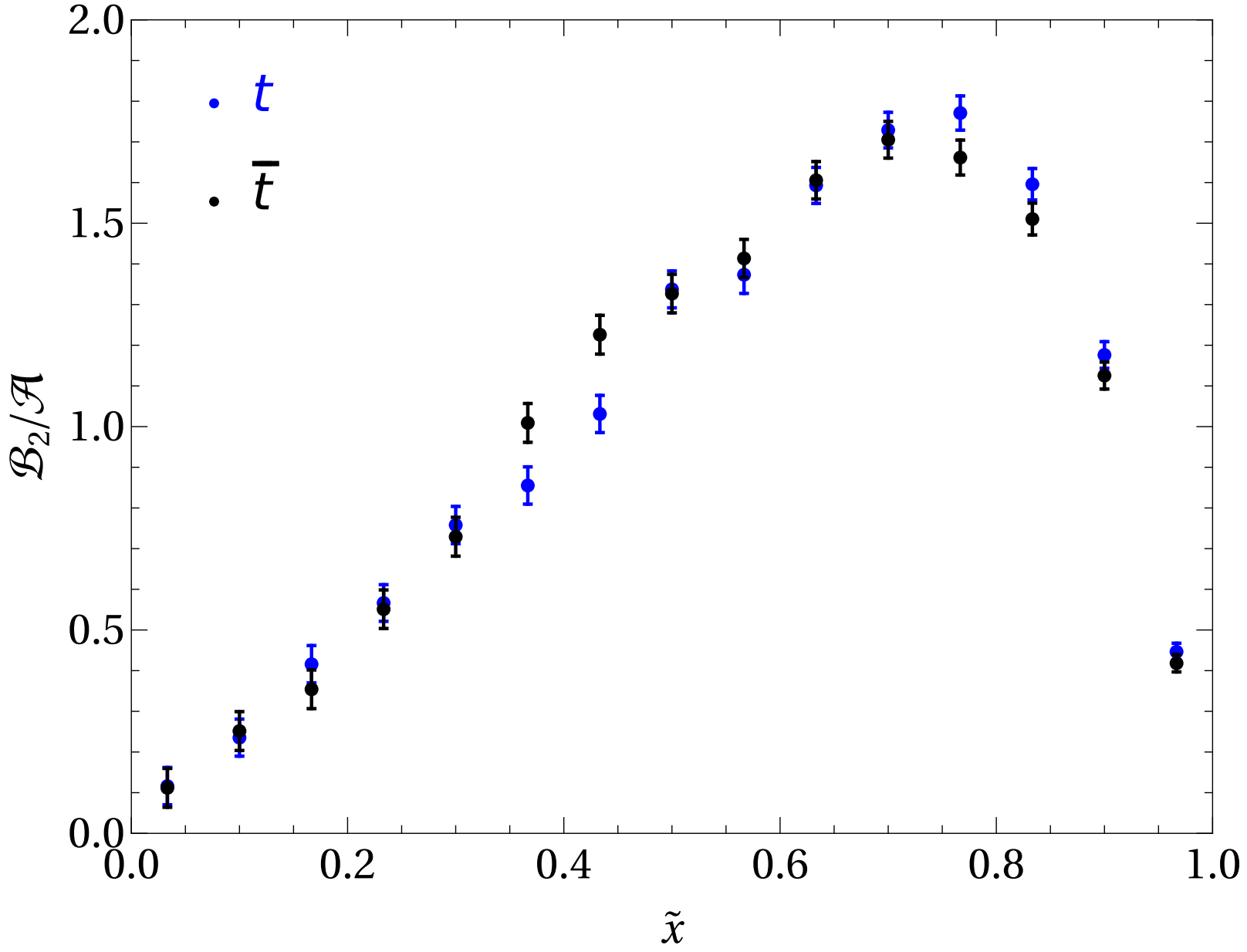
$$\frac{d^2\sigma^{pp\to thj}}{d\tilde{x}\, d\cos\tilde{\theta}_\ell} \sim \mathcal{A}(\tilde{x}) + \tilde{\kappa}\cos\tilde{\theta}_\ell \mathcal{B}_2(\tilde{x}) \qquad \mathrm{f}_{opt.} = \cos\tilde{\theta}_\ell \mathcal{B}_2/\mathcal{A}$$

$$O_{\mathrm{simp.}} \equiv \left\langle \cos\tilde{\theta}_\ell \right\rangle$$

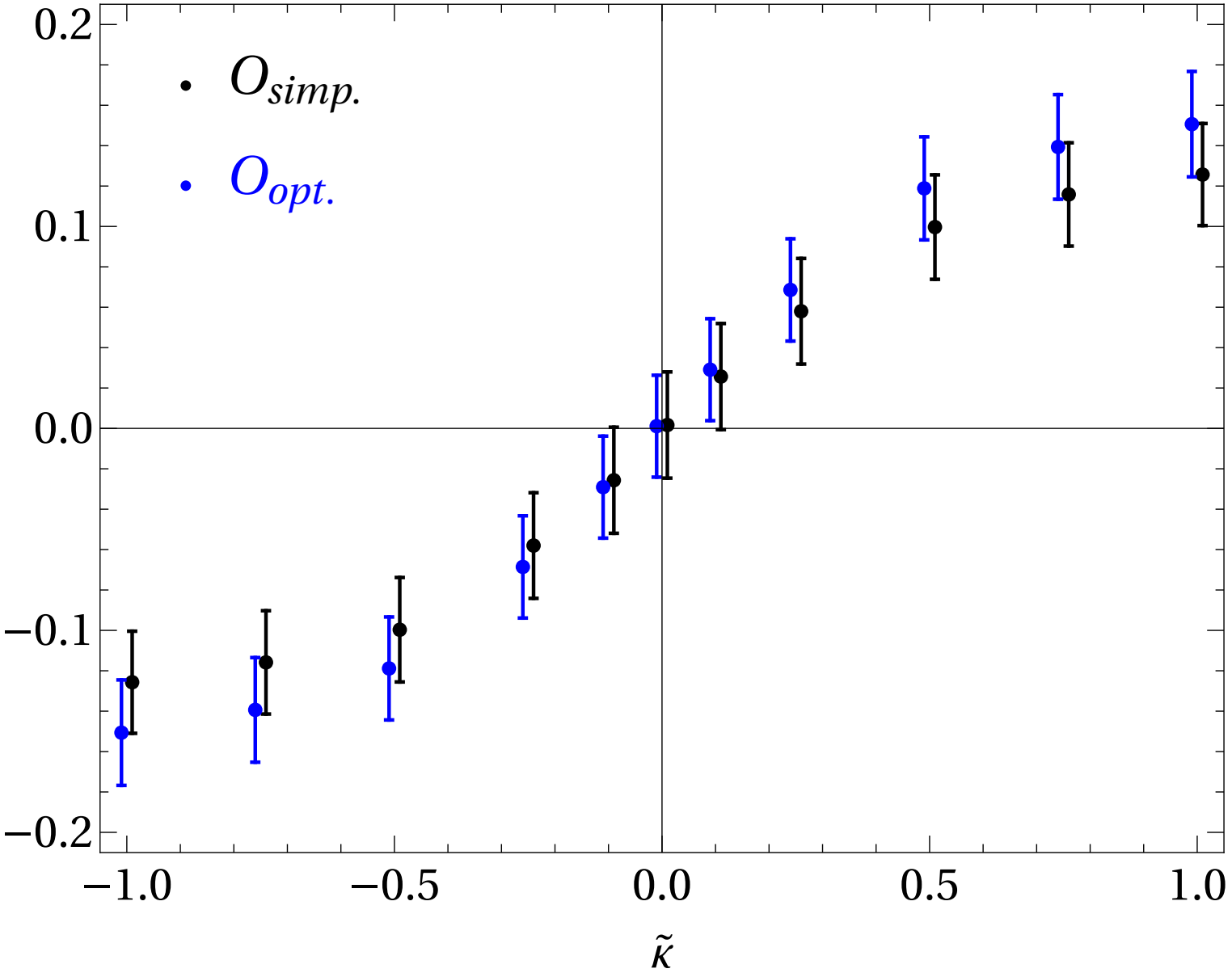
$$O_{\mathrm{opt.}} \equiv \left\langle \frac{\mathcal{B}_2(\tilde{x})}{\mathcal{A}(\tilde{x})} \cos\tilde{\theta}_\ell \right\rangle$$

weight can be extracted from MC

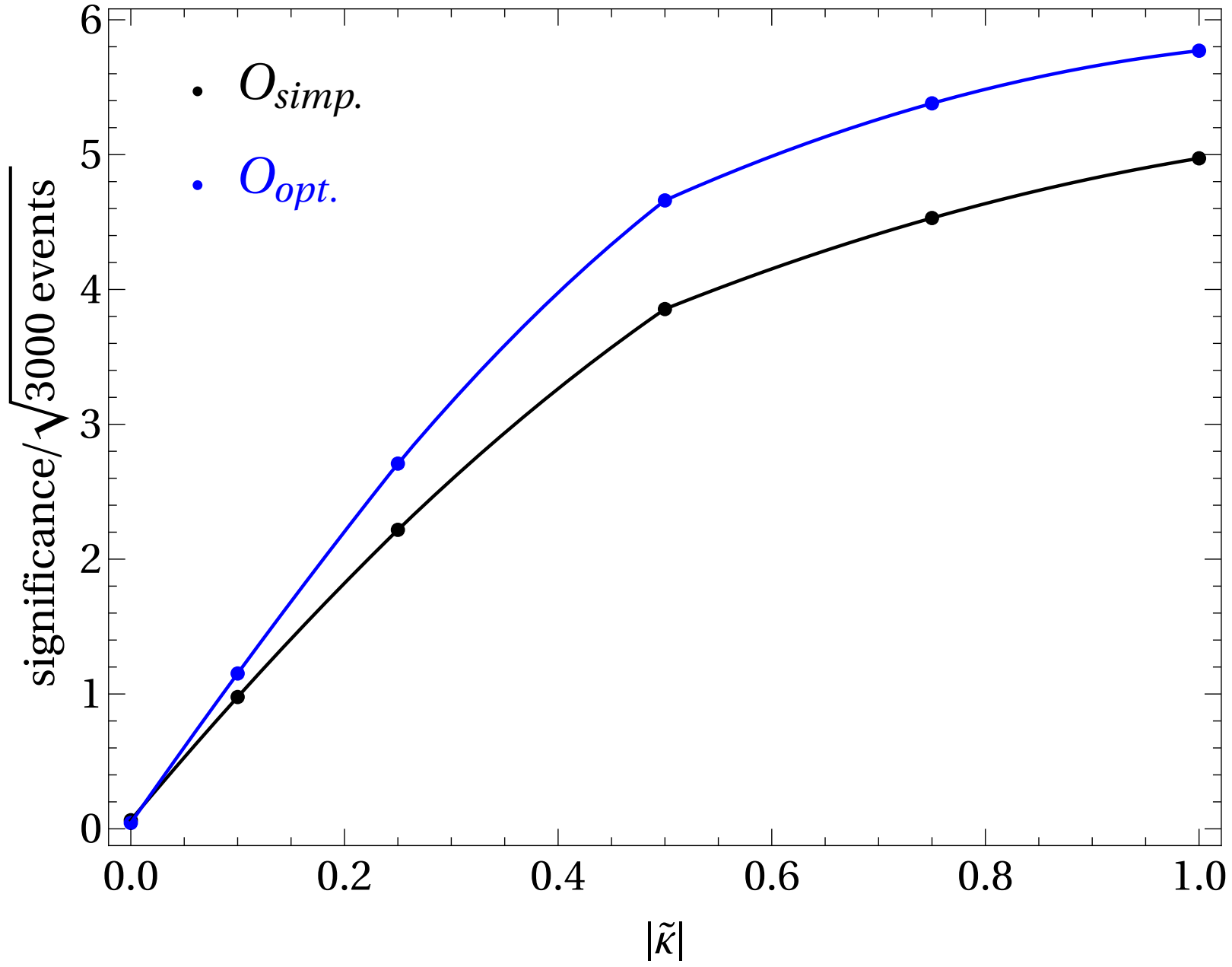
Extracted optimal weight – 10^6 MC events



Simp. vs opt. observable – 3000 evts./ $\tilde{\kappa}$



Simp. vs opt. observable – 3000 evts./ $\tilde{\kappa}$



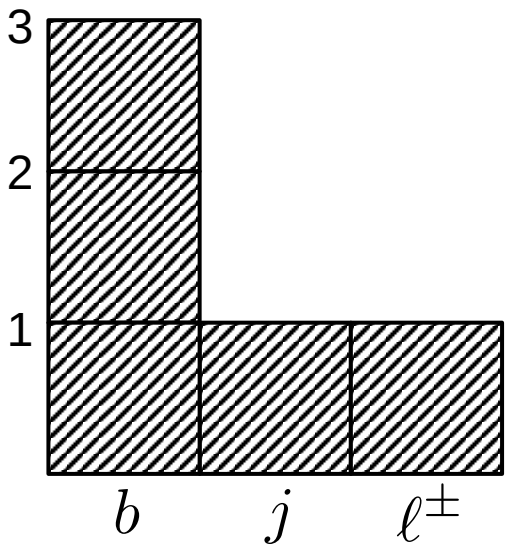
Event reconstruction analysis

Madgraph5 → Pythia8 → Delphes

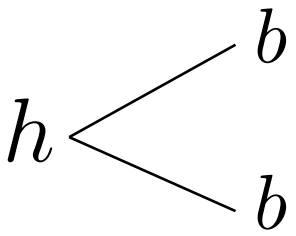
- event generation - - showering, hadronization - - detector simulation -

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

Event selection:



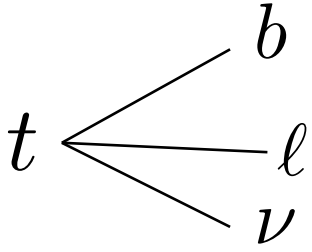
$$
\begin{aligned}
|\eta(b)| &< 5 & p_T(b) &> 20\ \text{GeV} \\
2 < |\eta(j)| &< 5 & p_T(j) &> 20\ \text{GeV} \\
|\eta(\ell)| &< 2.5 & p_T(\ell) &> 10\ \text{GeV}
\end{aligned}
$$



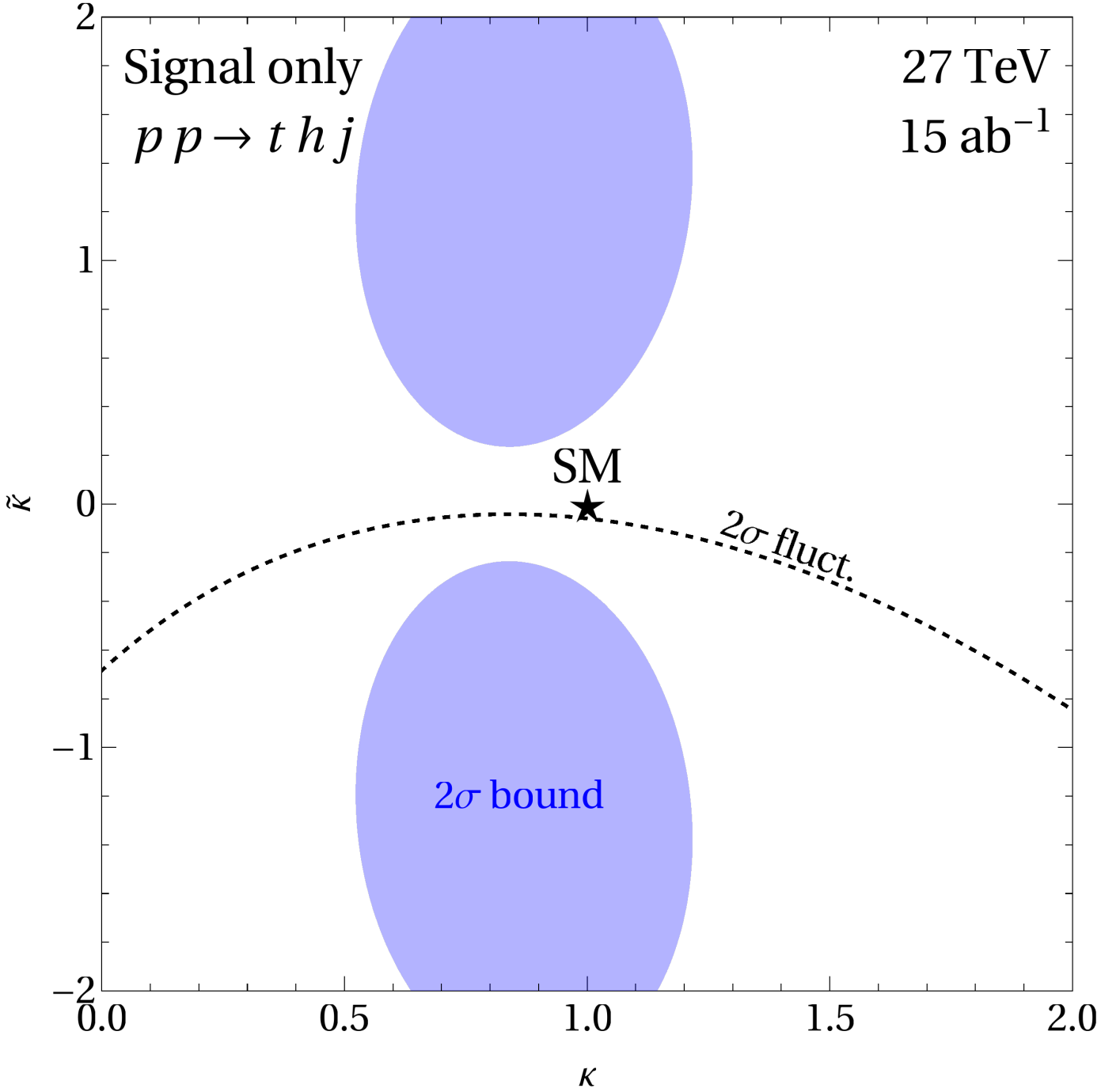
$$|m_{bb} - m_h| < 15\ \text{GeV}$$

$$m_{bbj} > 280\ \text{GeV}$$

Farina et al., JHEP 05 (2013) 022



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



… but signal is completely swamped by $pp \to t\bar{t}$ background

Lab. frame observables in $t\bar{t}h$

Similar approaches: F. Boudjema et al., Phys. Rev. D92 (2015)
W. Bernreuther et al., Phys. Rev. D49 (1994)

CP and P-odd observables, built from accessible final-state momenta

$\Rightarrow$ no $b, \bar{b}$ differentiation

Higgs and semi-leptonic top decay final state momenta:

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

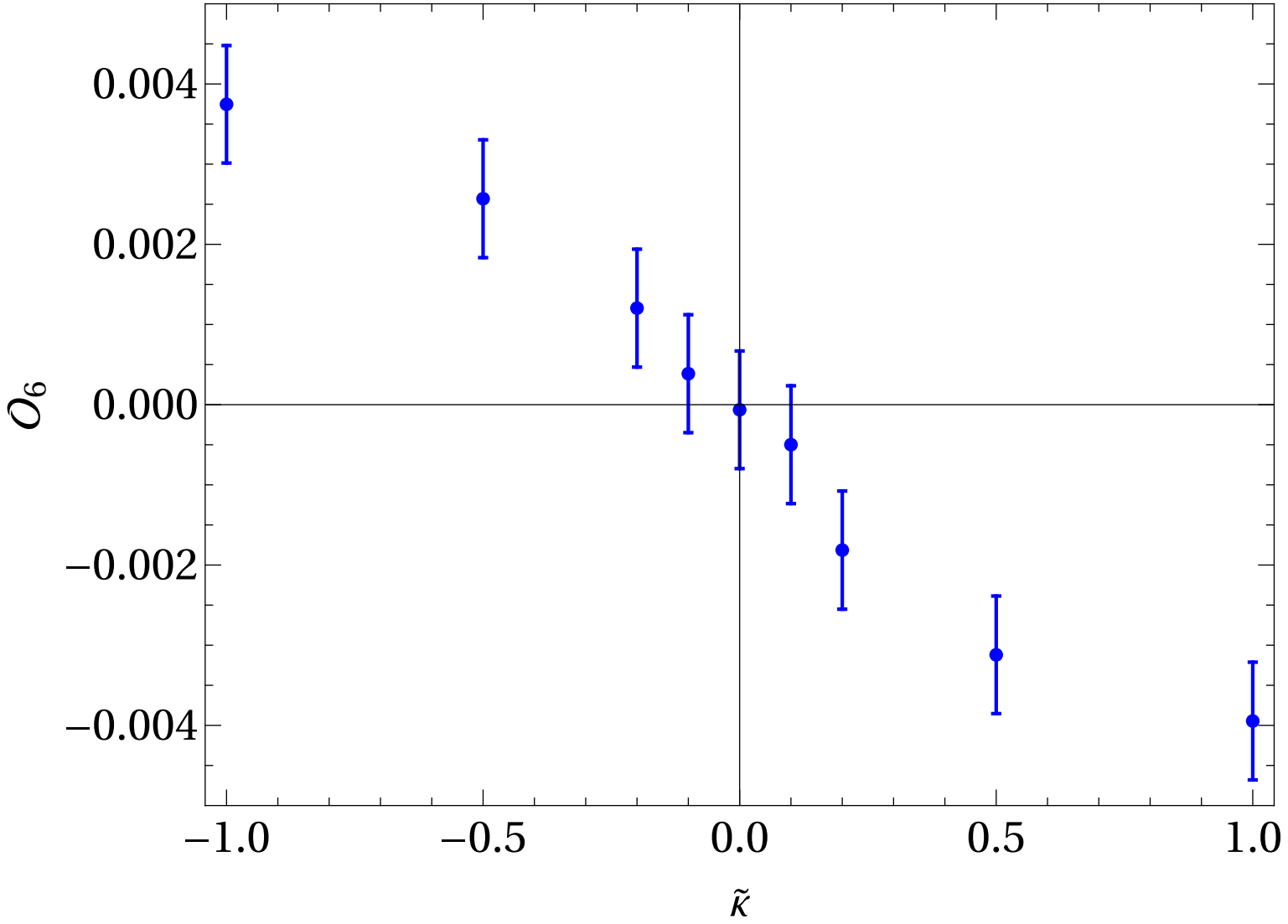
E.g.:

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

+ many more..

$$\frac{d^2\sigma}{dx d\omega} \sim A(x) + \kappa\tilde{\kappa}\gamma(x)\omega \longrightarrow O_6 = \frac{1}{\sigma} \int dx \, d\omega_6 \frac{d^2\sigma}{dx d\omega_6} \omega_6 = \frac{1}{N} \sum_{i=1}^{N} \omega_6^{(i)}$$

$$O_6 = \frac{1}{N}\sum_{i=1}^{N}\omega_6^{(i)}$$



$10^5\ t\bar{t}h$ events per $\tilde{\kappa}$

Event reconstruction analysis

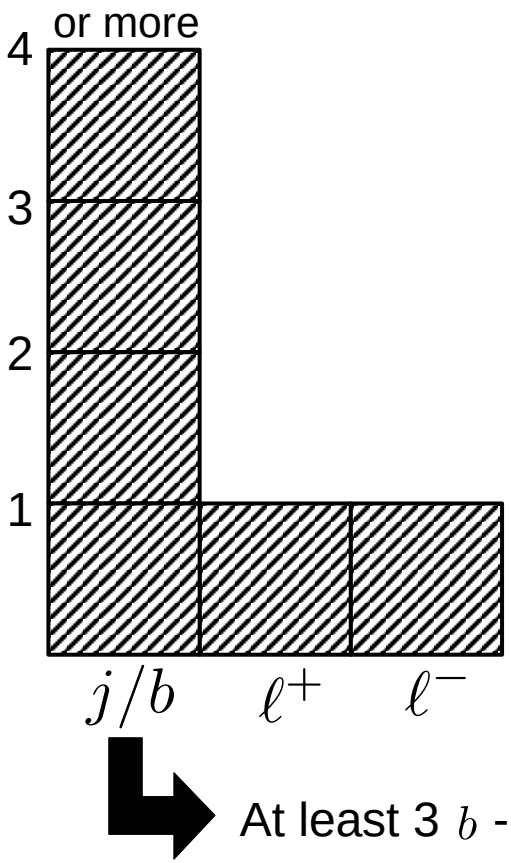
Madgraph5 → **Pythia8** → **Delphes**

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

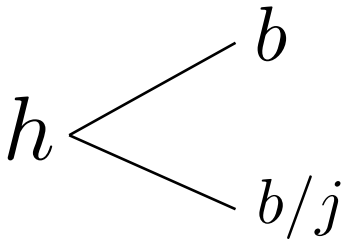
Signal: $pp \to t\bar{t}h(t \to b\ell^+\nu_\ell, \bar{t} \to \bar{b}\ell^-\bar{\nu}_\ell, h \to b\bar{b})$

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

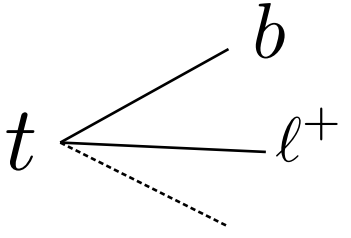
Event selection:

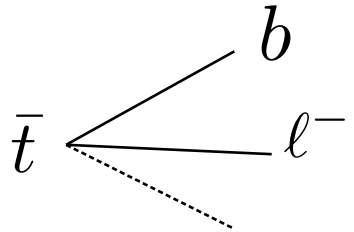


At least 3 b - tagged



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

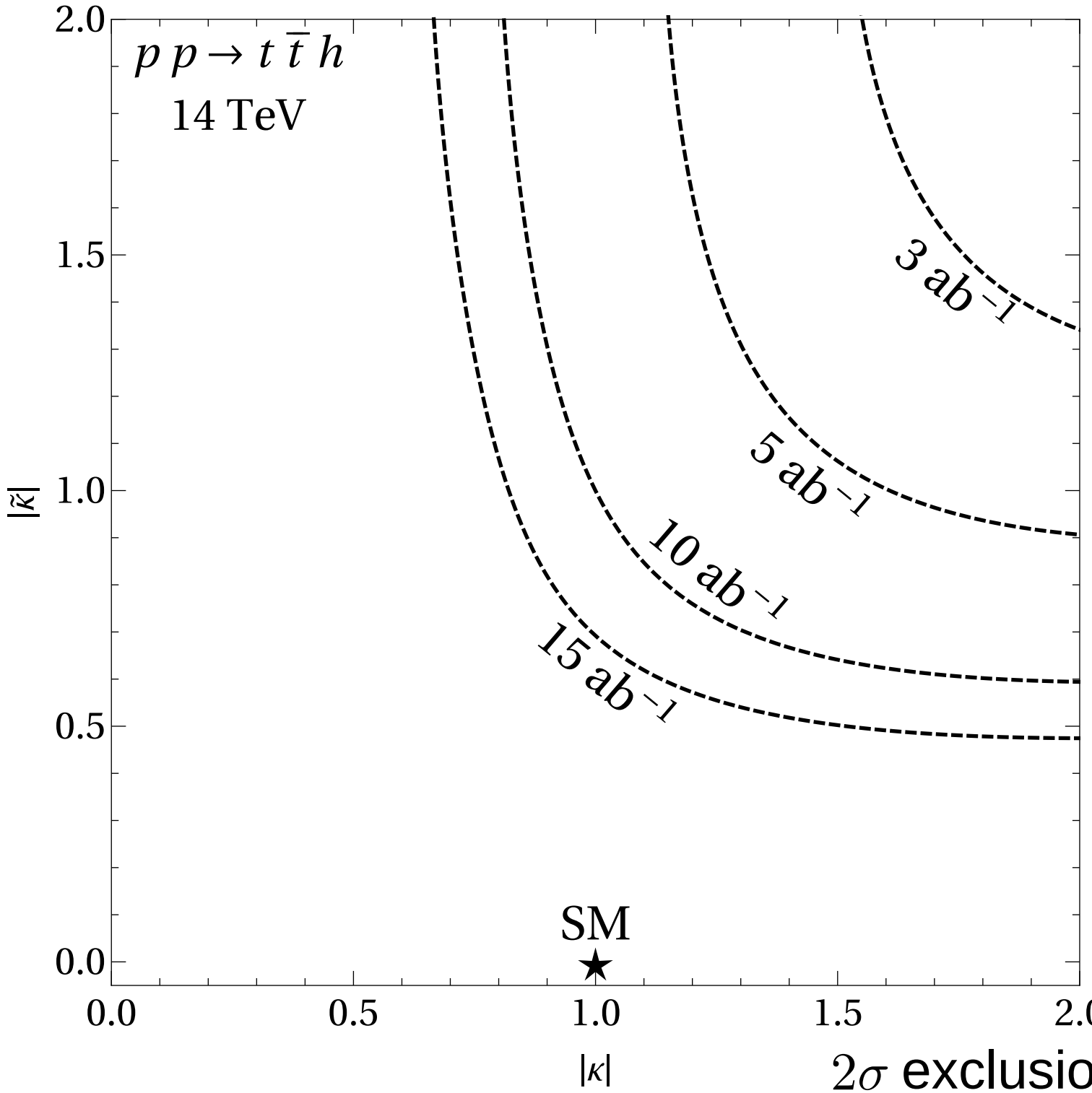




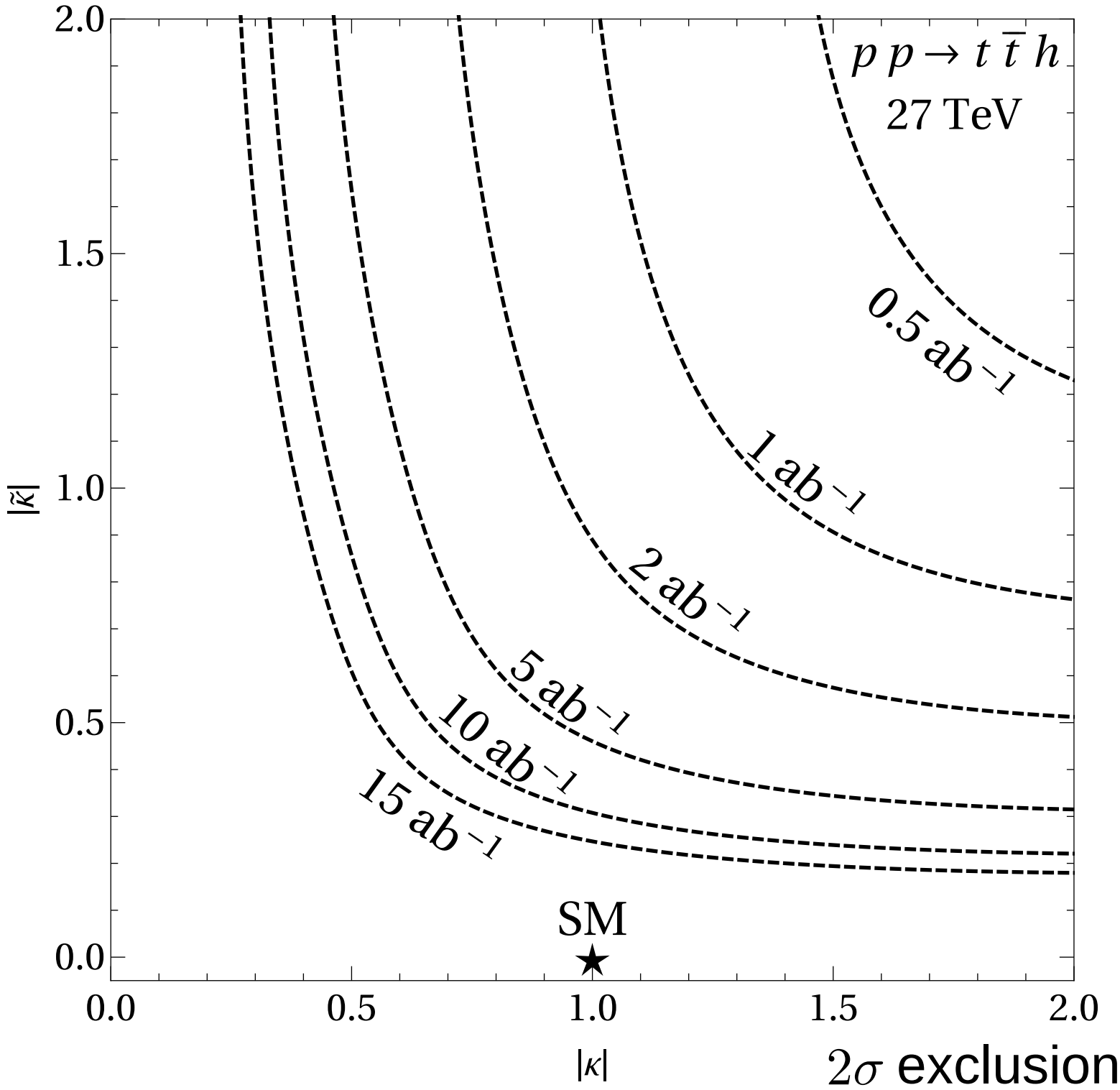
Highest p_T $b-$jets assumed to originate from tops

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

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

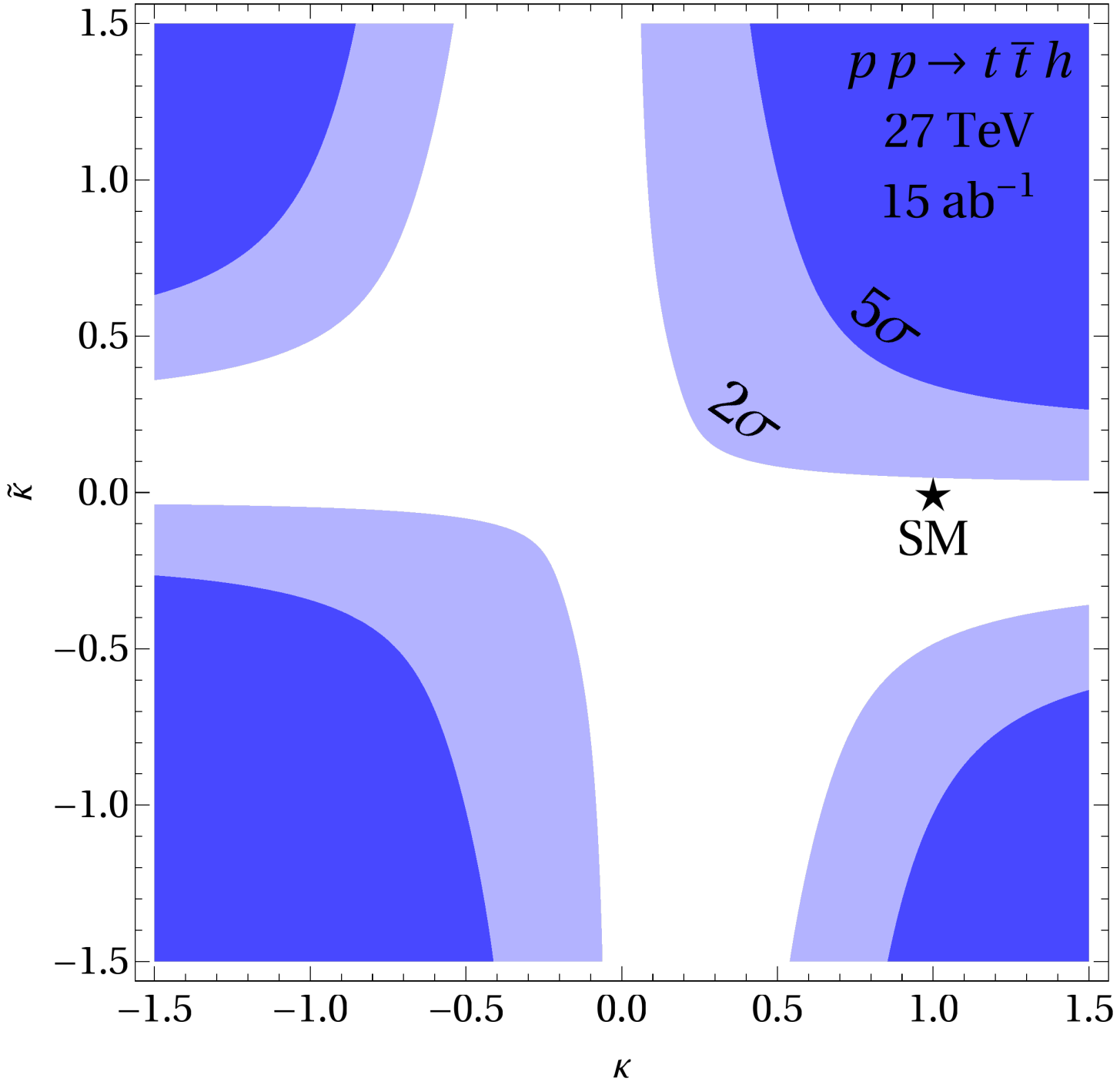


2σ exclusion regions



2σ exclusion regions

2σ positive fluctuation – asymmetric bounds



Conclusions

Studied manifestly CP-odd observables in thj and $t\bar{t}h$ production at HL/HE LHC

In th:

- Can reconstruct the top $\Rightarrow$ access to the top polarization
- Identified a pol. direction, perpendicular to the th plane
- Top polarization along this direction? $\Rightarrow$presence of $\tilde{\kappa}$
- In our analysis signal is swamped by background

$\Rightarrow$ potential for improvement

In $t\bar{t}h$:

- Focused on experimentally feasible lab. frame observables
- Much more favorable signal-to-background ratio
- HE-LHC with $15\,\mathrm{ab}^{-1}$ reaches $\tilde{\kappa} \sim \mathcal{O}(0.1)$ at 2σ level