Israeli Joint Particle Physics Meetings

Optimised CP probes of top quark Yukawa at hadron colliders

Jernej F. Kamenik

with D. Faroughy, N. Košnik & A. Smolkovič, 1909.00007
with B. Bortolato, N. Košnik & A. Smolkovič, 2005.xxxxx

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Zoom
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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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$$Q_{\phi,33} \equiv (\tilde{\phi}^\dagger i \overleftrightarrow{D}_\mu \, \phi)(\bar{t}_R\gamma^\mu b_R) \,,$$

'Z-penguins'

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

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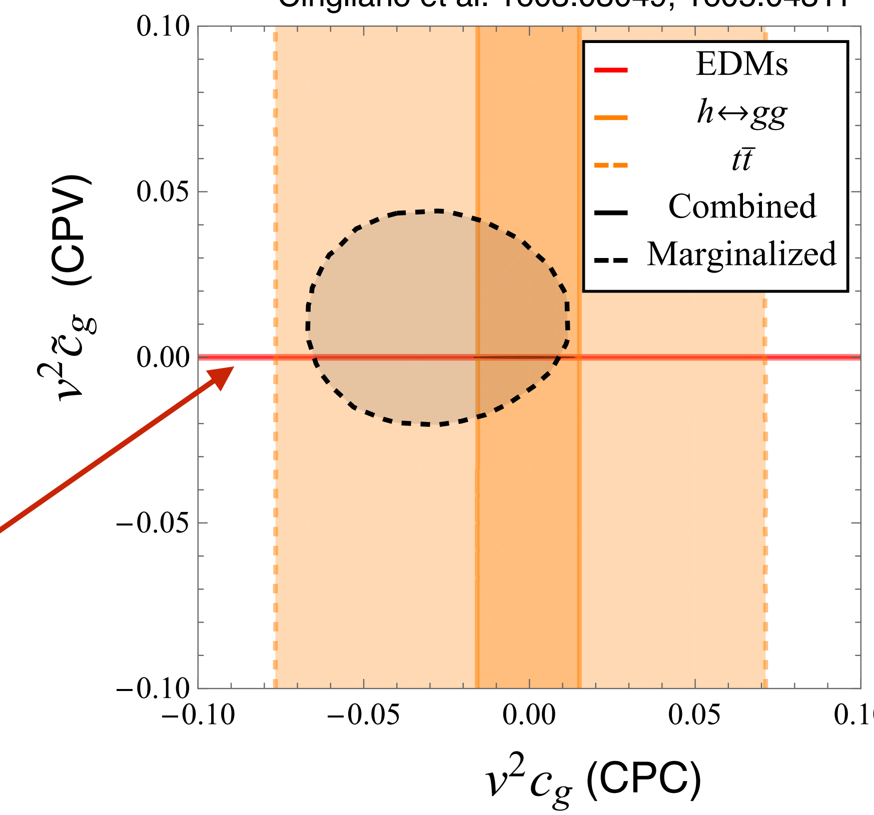
J.F.K. et al. 1107.3143
C. Degrande et al. 1205.1065
Schulze & Soreq 1603.08911
Cirigliano et al. 1603.03049, 1605.04311

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

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



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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.

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

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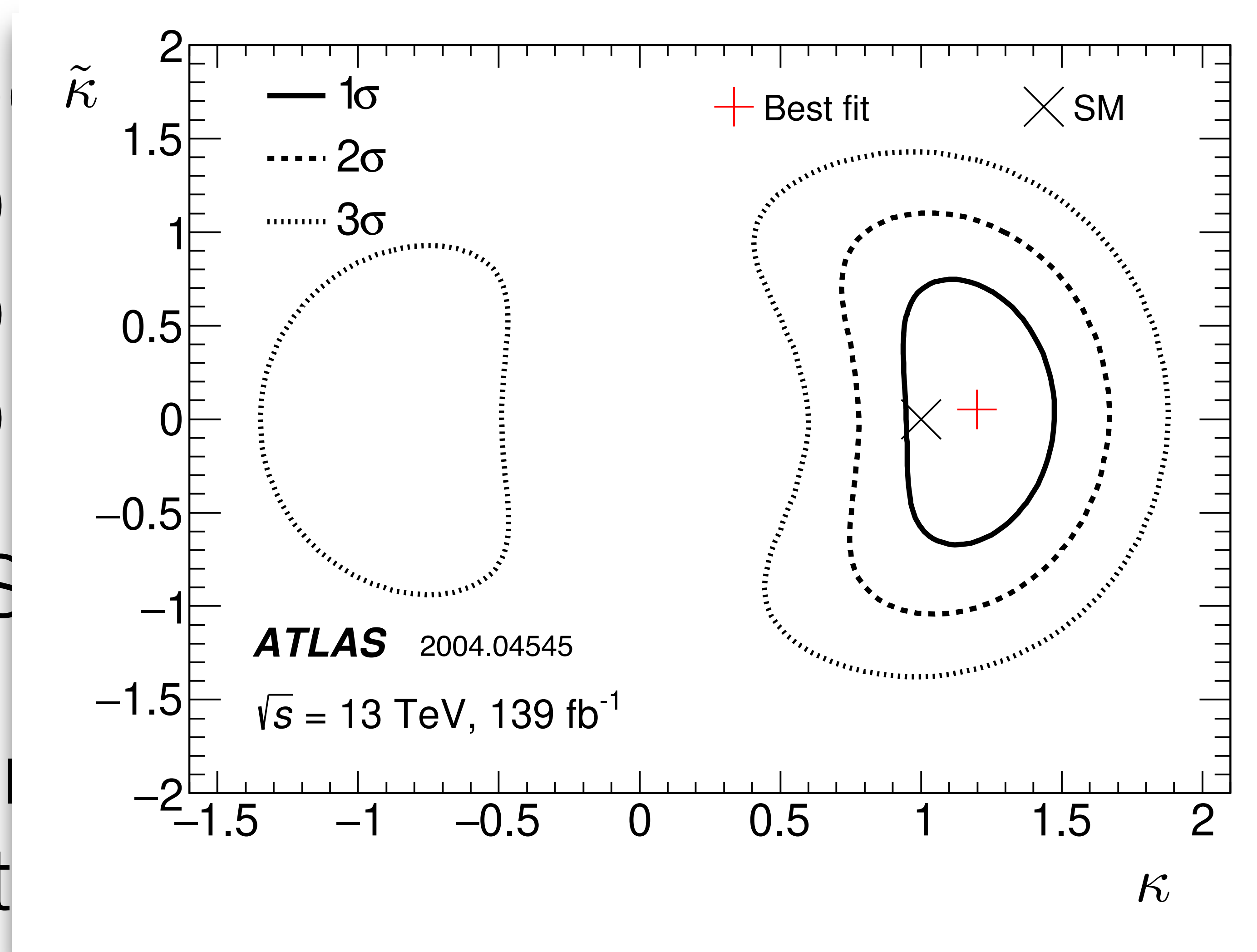

- After EWS $\dfrac{y_t}{\sqrt{2}}\bar{t}(\kappa + i\tilde{\kappa}\gamma_5)th$
- Currently P-even, sensitive t

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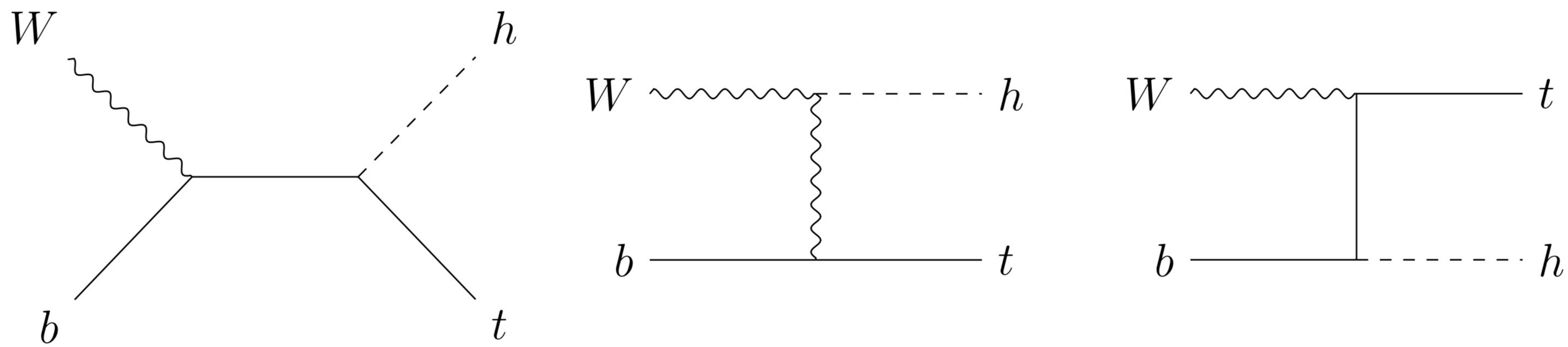
Genuinely CPV probes? CP-odd observables, linear in $\tilde{\kappa}$

Toy example: top-polarisation in *th* production

"parton level" $Wb \to th$ scattering - tractable analytically



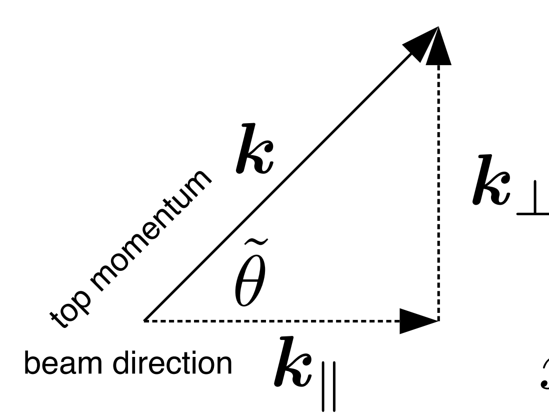
Polarised cross section ~ $|\mathcal{M}|^2 = a + b_\mu s^\mu$

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

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

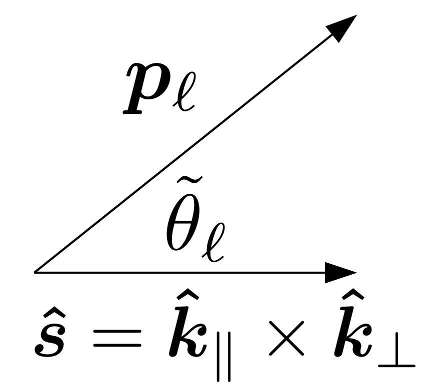


$\tilde{x} = \cos\tilde{\theta}$

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

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

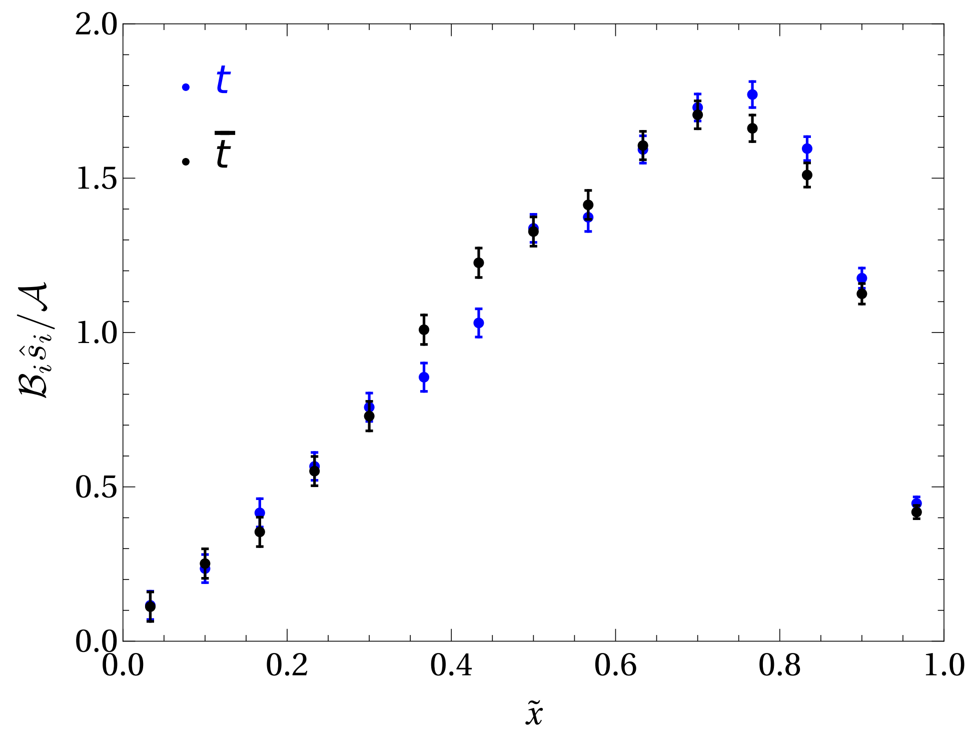
⇒ simplest CP-odd observable $O_{\mathrm{simp.}} \equiv \left\langle \cos\tilde{\theta}_\ell \right\rangle$

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 simulation

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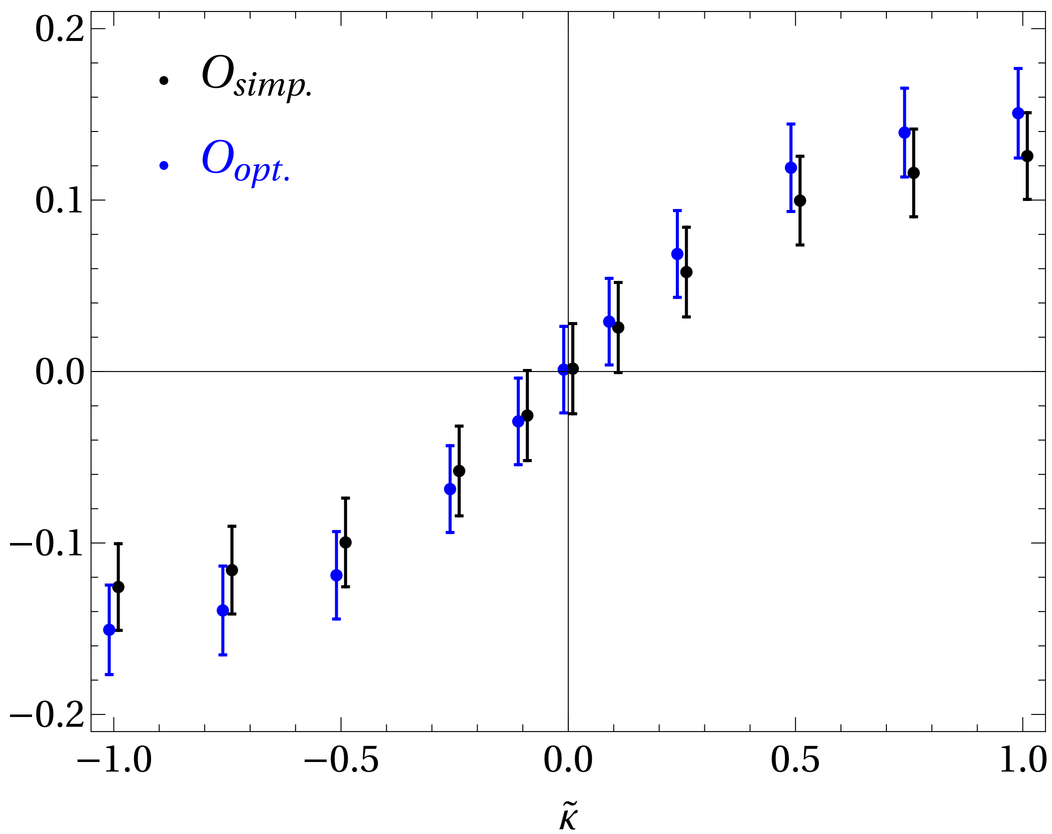
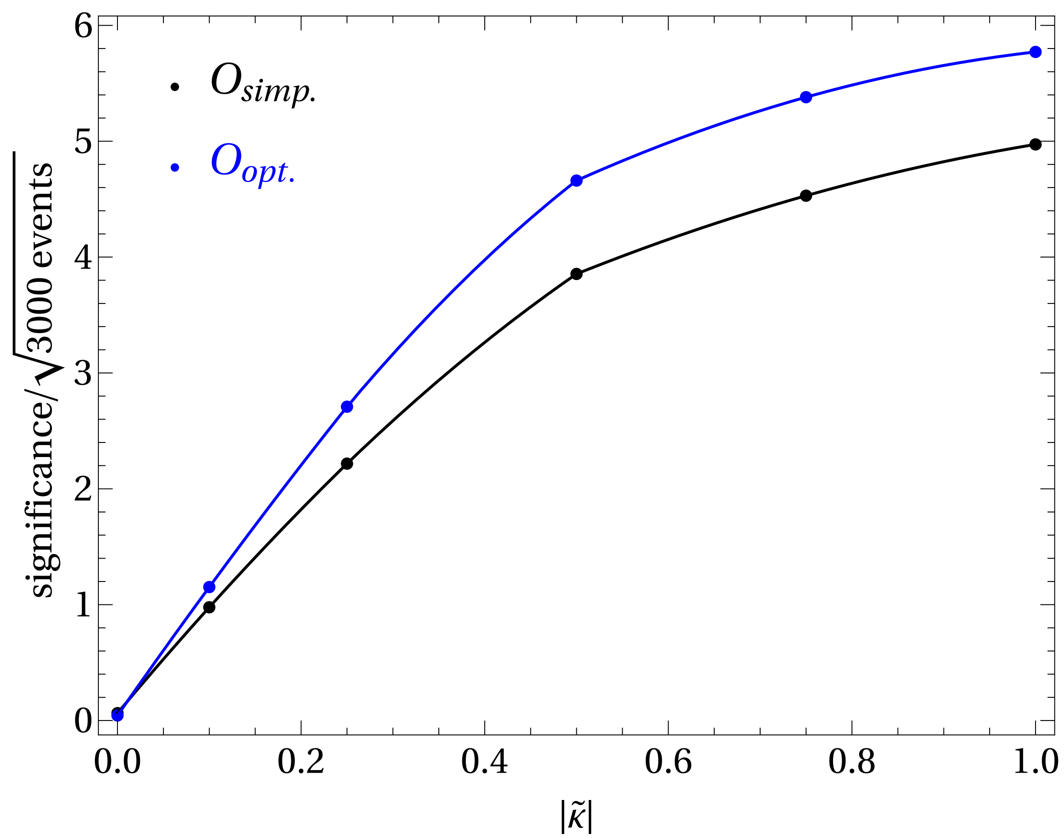




Marginal improvement of sensitivity compared to $O_{simp.}$

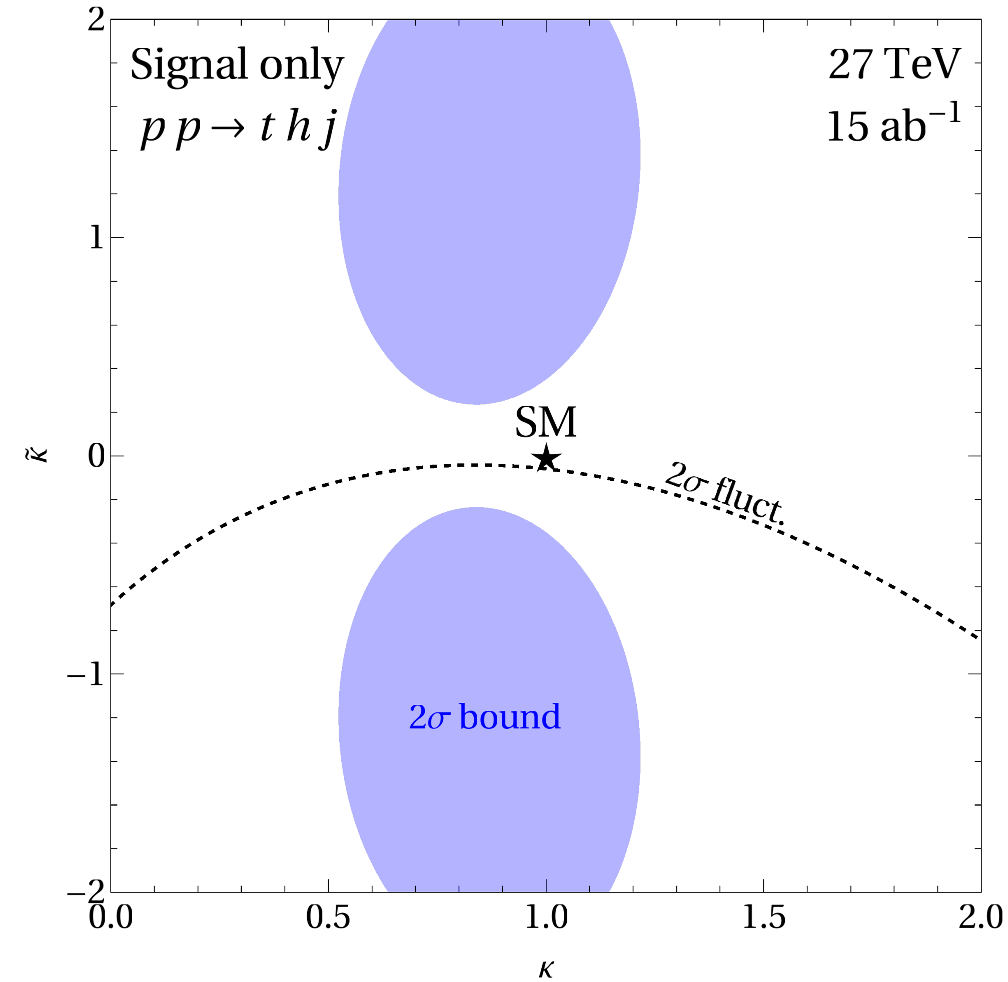
Realistic analysis?

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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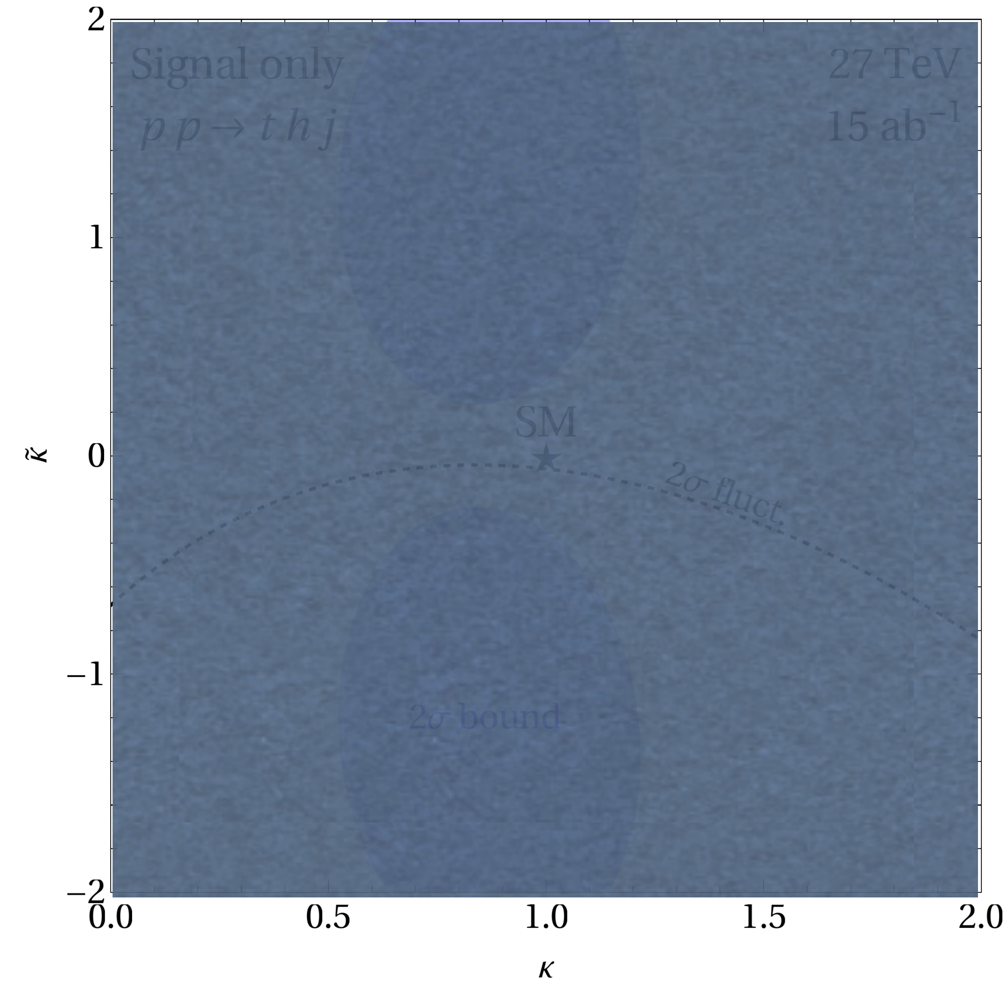
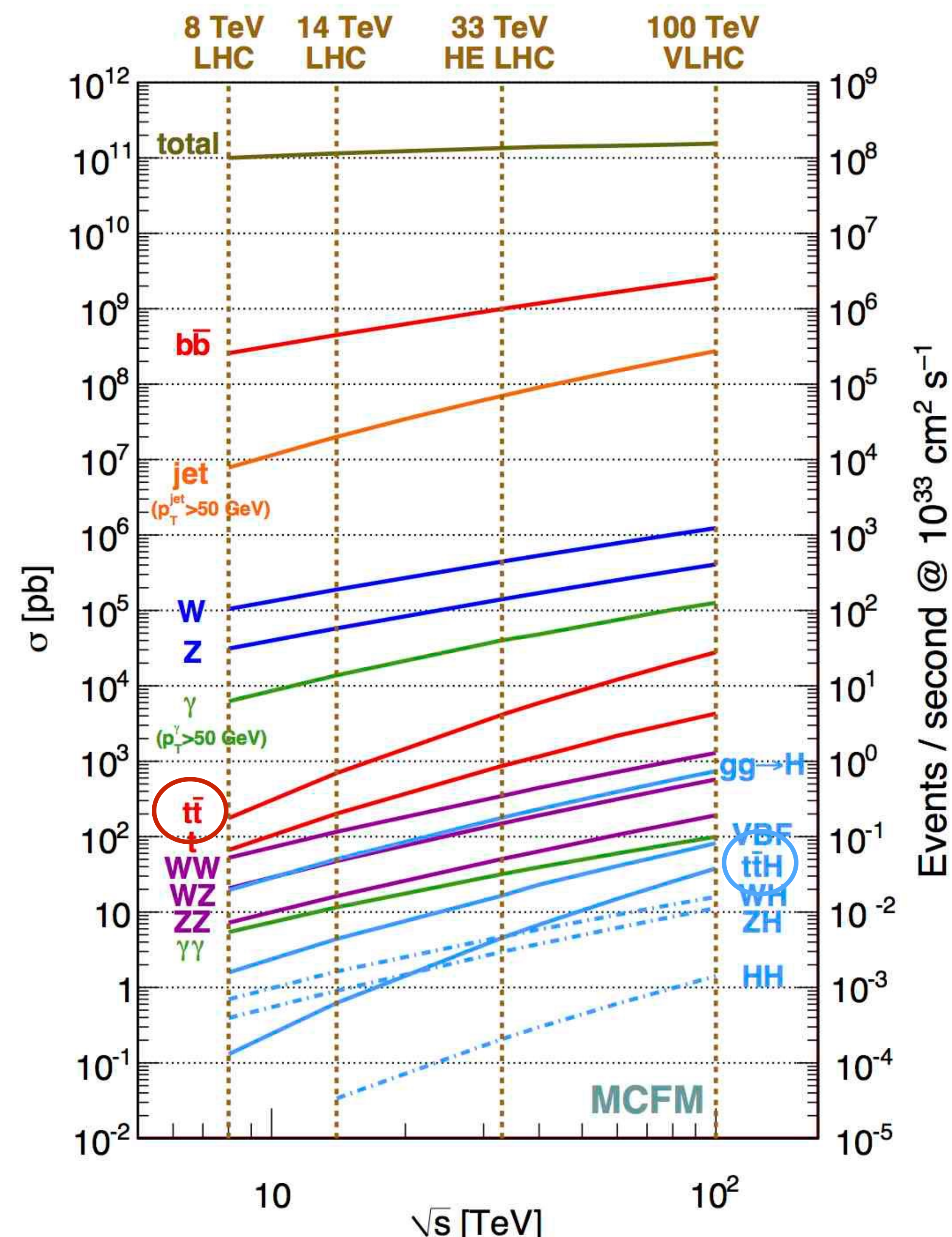


In practice signal swamped by dominant $t\bar{t}$+jets background

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 *tt̄h* production

Clean dileptonic signature to suppress backgrounds
⇒ *tt̄* rest-frames not easily reconstructable

Lab-frame observables built from accessible final-state momenta

⇒ assume Higgs fully reconstructed ($\gamma\gamma$,…) (can be relaxed)

[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 $t\bar{t}h$ production

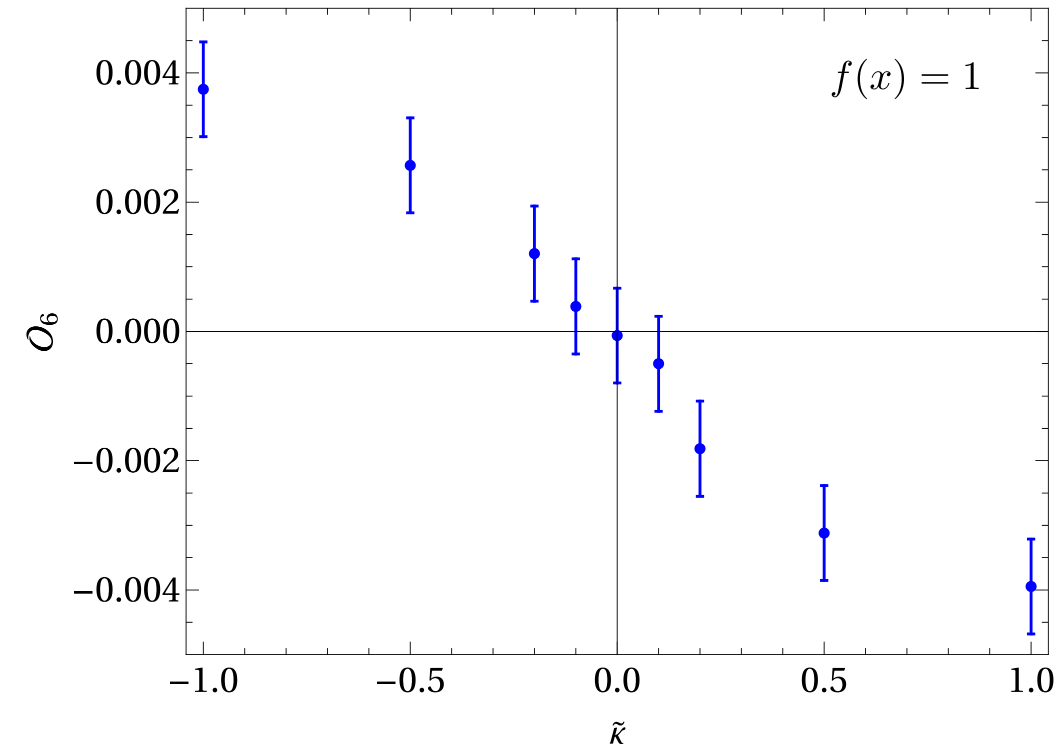
Example: $$\omega_6 \equiv \frac{[(\boldsymbol{p}_{\ell^-} \times \boldsymbol{p}_{\ell^+}) \cdot (\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}})]\,[(\boldsymbol{p}_{\ell^-} - \boldsymbol{p}_{\ell^+}) \cdot (\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}})]}{|\boldsymbol{p}_{\ell^-} \times \boldsymbol{p}_{\ell^+}|\,|\boldsymbol{p}_{\ell^-}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

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…? (see below)

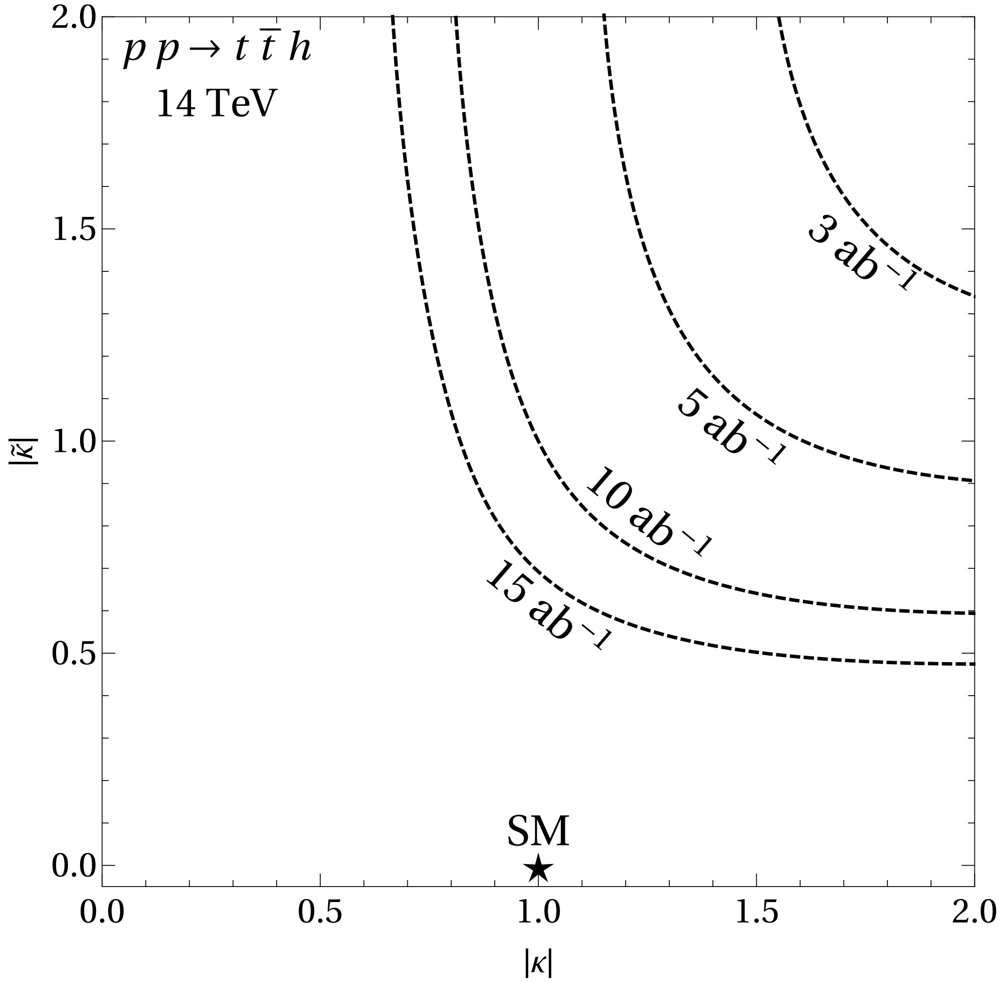


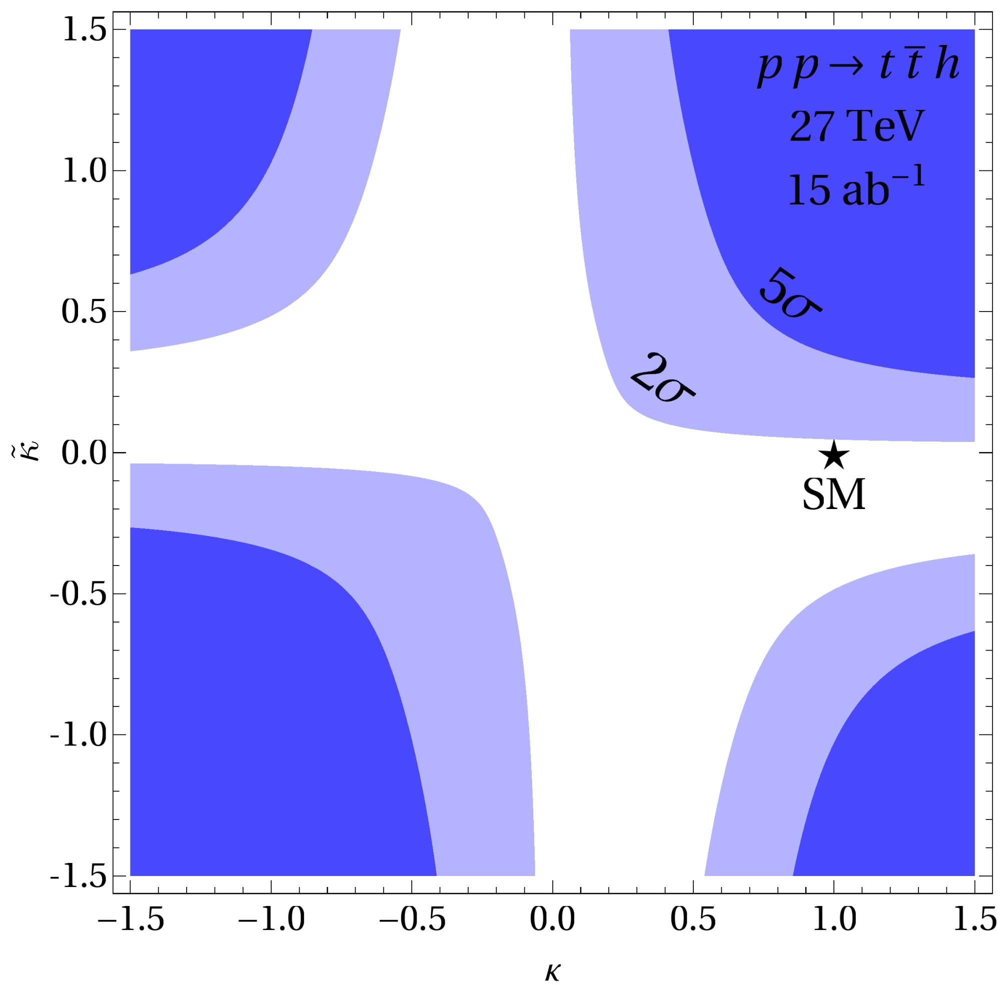
Realistic analysis?

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

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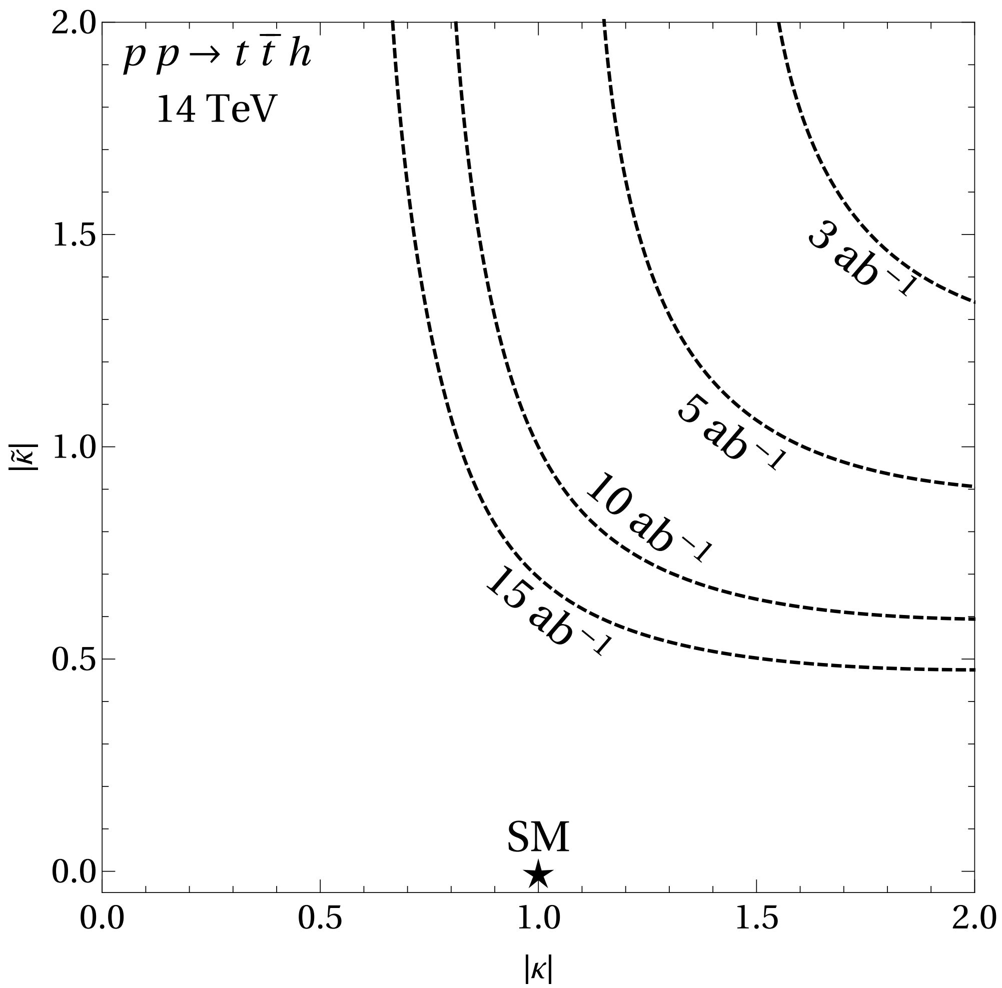

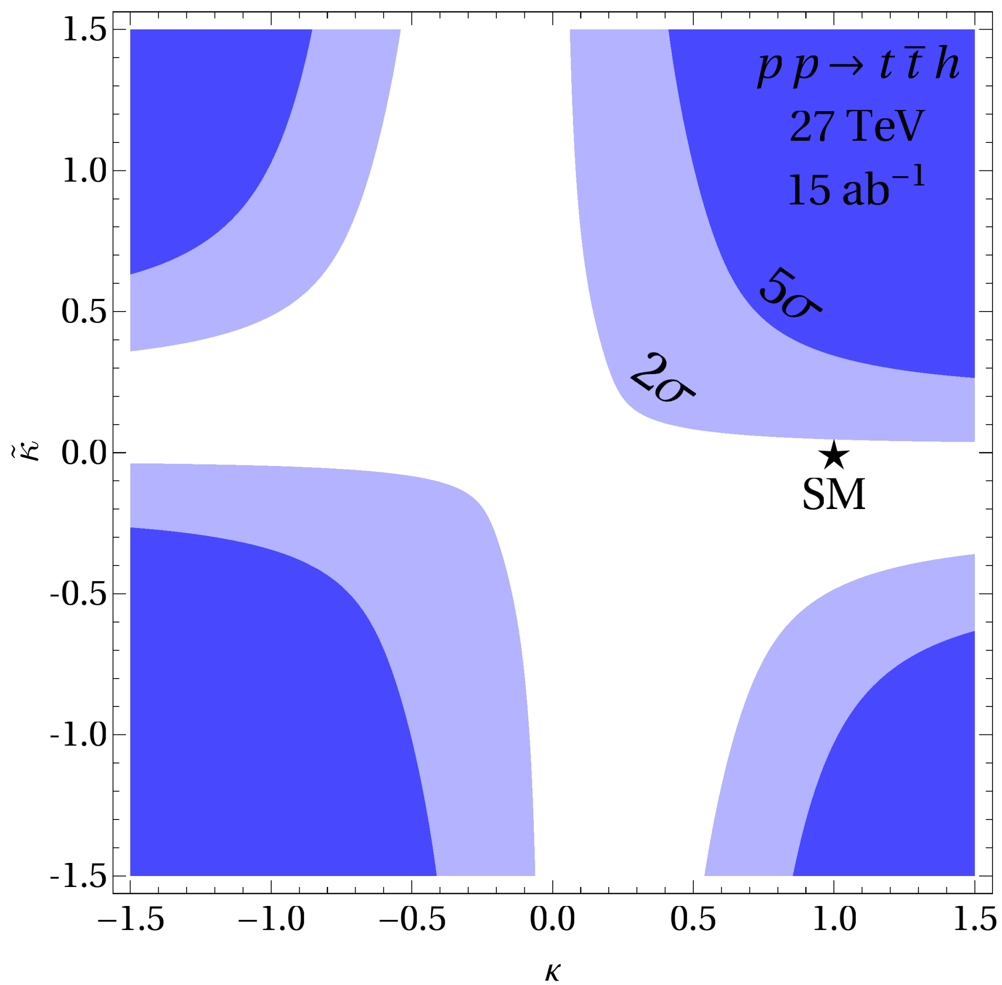

Can one improve upon this - make (HL)LHC relevant?

Multivariate optimisation of CP observables in $t\bar{t}h$

Two possible directions:

- phase space optimisation of O_ω (f_{opt}):
  - not tractable analytically, highly non-linear dependence on kinematical variables
    $\Rightarrow$ ML approach using NNs,
  - based on th experience, improvements beyond O(1) not expected
- combining several O_ω:
  - in the linear regime might improve upon O_6 by O(1)
  - exploration of non-linear regime using NNs.

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Neural network setup

Crucial to define optimization cost function preserving CP-odd symmetry of O_ω,

✓ significance on the training/validation dataset

$$\mathrm{cost}(\boldsymbol{\alpha}) = \left(\frac{\mathrm{mean}(\mathcal{F}(\boldsymbol{x};\boldsymbol{\alpha}))}{\mathrm{std}(\mathcal{F}(\boldsymbol{x};\boldsymbol{\alpha}))/\sqrt{N}}\right)^{-2}$$

NN parameters

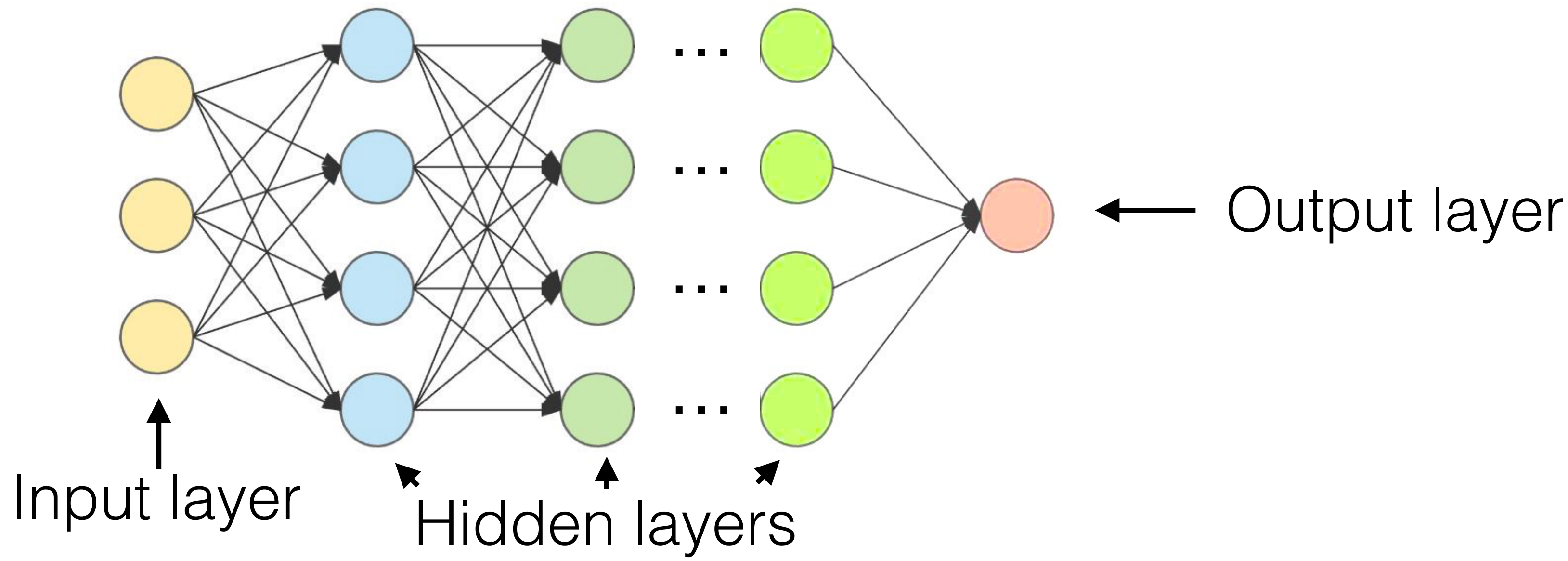
Number of events in training/validation sample

- needs to be odd function of kappa. In general for CP-even x: $f(x) = C(x) + \tilde{\kappa}^2 D(x) + \mathcal{O}(\tilde{\kappa}^4).$

$$\boxed{\Rightarrow\ \mathcal{F}(\boldsymbol{x};\boldsymbol{\alpha}) = f(x^{(i)};\boldsymbol{\alpha})\ \omega_6}$$

- Cost function can cannot be evaluated event by event ⇒ modification of NN back-propagation.

Neural network optimisation



Size of input layer determined by dimensionality of x:

$$
\begin{aligned}
x^{(i)} \in \{ & (\boldsymbol{p}_{\ell+} + \boldsymbol{p}_{\ell-}) \cdot \boldsymbol{p}_h, \\
& (\boldsymbol{p}_{\ell+} + \boldsymbol{p}_{\ell-}) \cdot (\boldsymbol{p}_b + \bar{\boldsymbol{p}}_b), \\
& (\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}}) \cdot \boldsymbol{p}_h, \\
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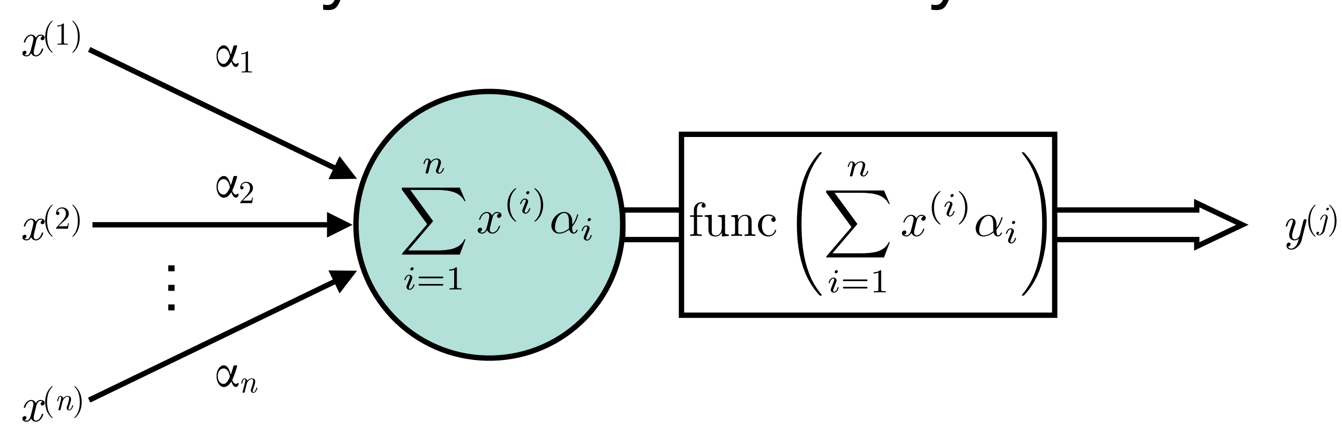
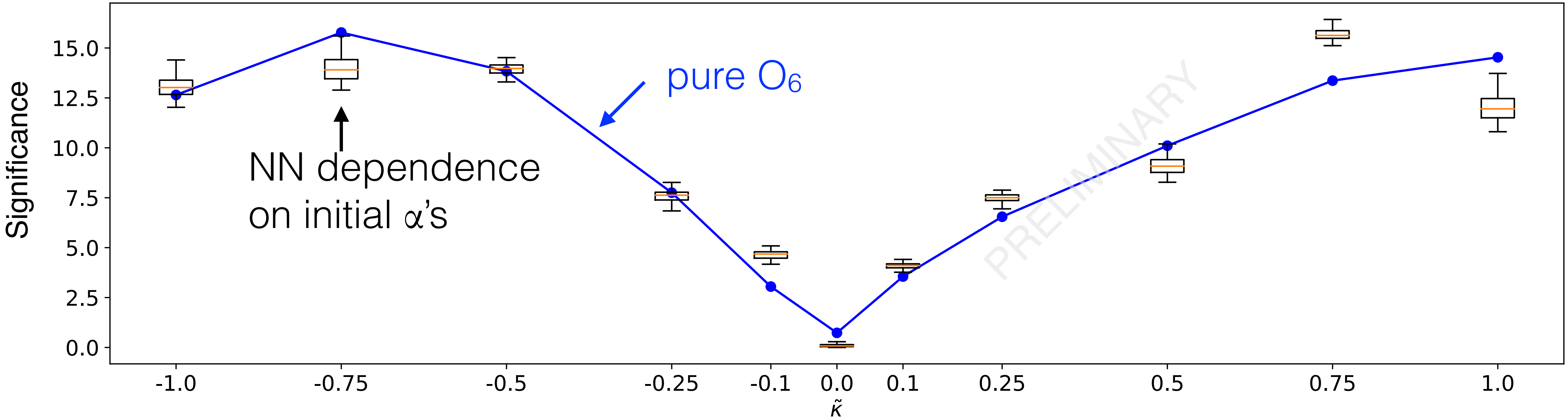
\end{aligned}
$$



Number {0-2} and size {1-15} of hidden layers & choice of transfer functions {sigmoid, tanh, …} optimised using Hyperopt (also x-checked manually).

Neural network optimisation

Phase-space optimisation of O_6 on 1M simulated events (at parton level)



No significant improvement compared to pure ω_6!

Combining multiple ω's

CP-odd optimisation - cost function condition $\mathcal{F}(-\boldsymbol{\omega}) = -\mathcal{F}(\boldsymbol{\omega})$

- Linear approximation: $\mathcal{F}(\boldsymbol{\omega}) = \sum_j \alpha_j \omega_j + \mathcal{O}(\omega^3)$

$$\Rightarrow \quad \mathcal{O}_\alpha = \langle \sum_j \alpha_j \omega_j \rangle \,.$$

⇒ Optimisation equations can be solved semi-analytically

$$\frac{\partial}{\partial \alpha_j} \frac{\mathcal{O}_\alpha}{\mathrm{std}(\mathcal{O}_\alpha)} = 0 \;\; \Rightarrow \boxed{\alpha^T M^{(j)} \alpha = 0 \;; \quad M^{(j)}_{ik} = \langle \omega_i \omega_j \rangle \langle \omega_k \rangle - \langle \omega_i \omega_k \rangle \langle \omega_j \rangle .}$$

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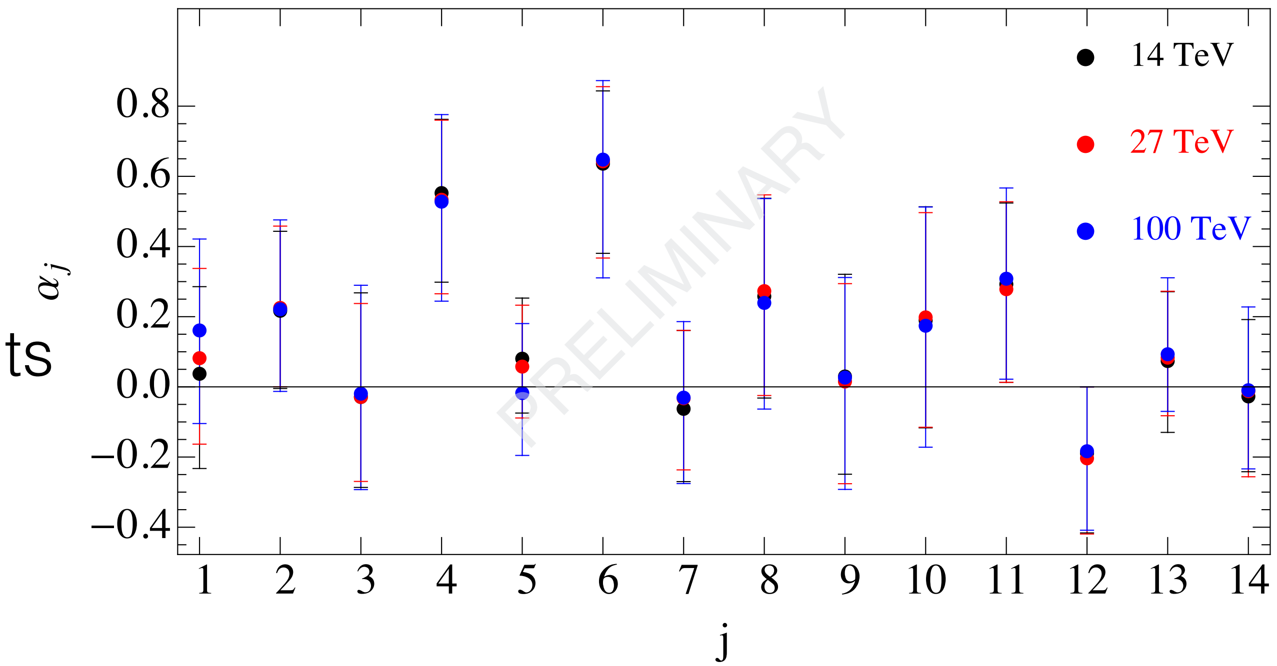
Parton level results:

- not all w's significant

MC uncertainties for 1M events



Combining multiple ω's

CP-odd optimisation - cost function condition $\mathcal{F}(-\boldsymbol{\omega}) = -\mathcal{F}(\boldsymbol{\omega})$

- Linear approximation: $\mathcal{F}(\boldsymbol{\omega}) = \sum_j \alpha_j \omega_j + \mathcal{O}(\omega^3)$

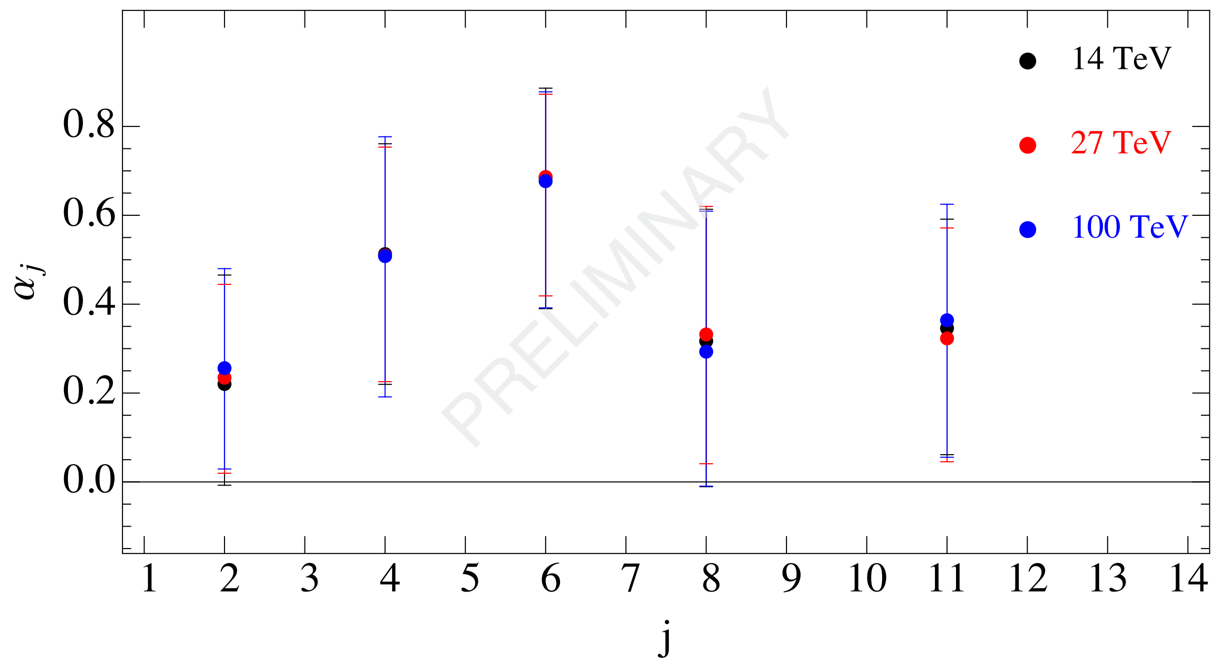
$$\Rightarrow \quad \mathcal{O}_\alpha = \langle \sum_j \alpha_j \omega_j \rangle \,.$$

$\Rightarrow$ Optimisation equations can be solved semi-analytically

$$\frac{\partial}{\partial \alpha_j} \frac{\mathcal{O}_\alpha}{\mathrm{std}(\mathcal{O}_\alpha)} = 0 \quad \Rightarrow \boxed{\alpha^T M^{(j)} \alpha = 0 \;; \quad M^{(j)}_{ik} = \langle \omega_i \omega_j \rangle \langle \omega_k \rangle - \langle \omega_i \omega_k \rangle \langle \omega_j \rangle .}$$

Parton level results:

- not all w's significant
- robust wrsp energy



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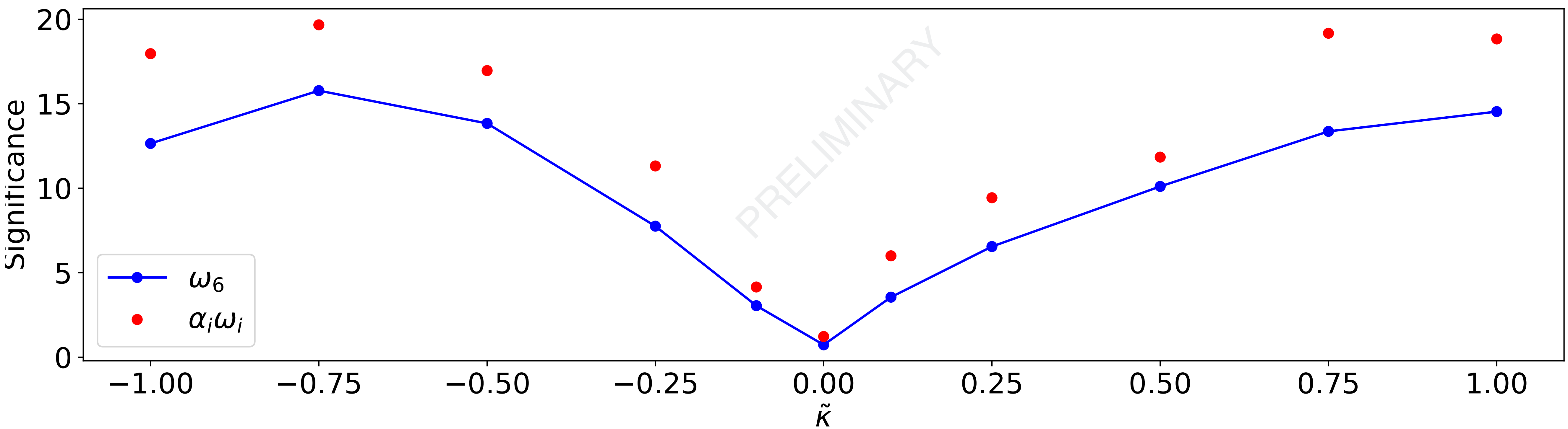
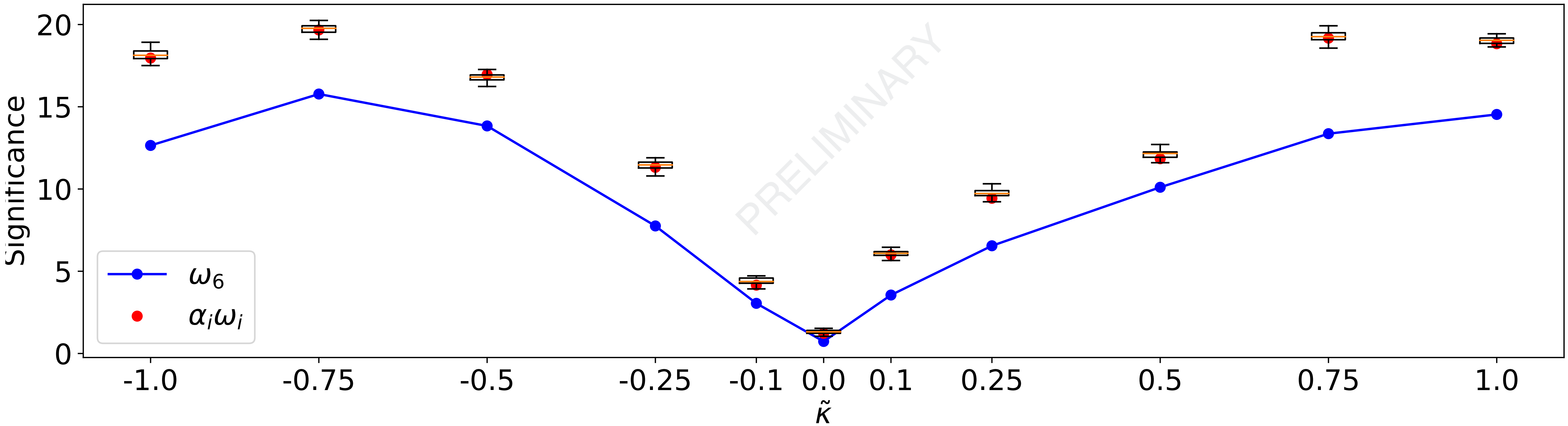


Significant improvement compared to pure ω_6!

Combining multiple ω's

CP-odd optimisation - cost function condition $\mathcal{F}(-\boldsymbol{\omega}) = -\mathcal{F}(\boldsymbol{\omega})$

- Linear approximation: $\mathcal{F}(\boldsymbol{\omega}) = \sum_j \alpha_j \omega_j + \mathcal{O}(\omega^3)$
- Full nonlinear dependence again via NNs: $\mathcal{F}(\boldsymbol{\alpha}, \boldsymbol{\omega})$

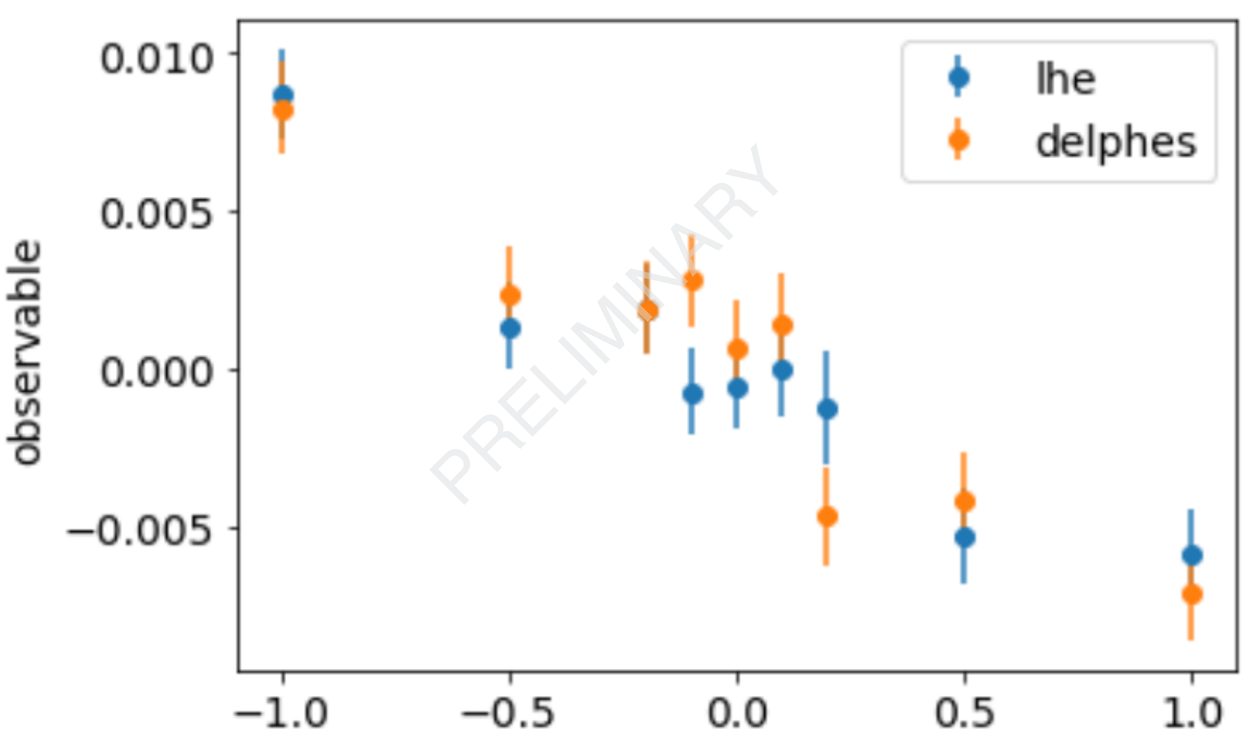


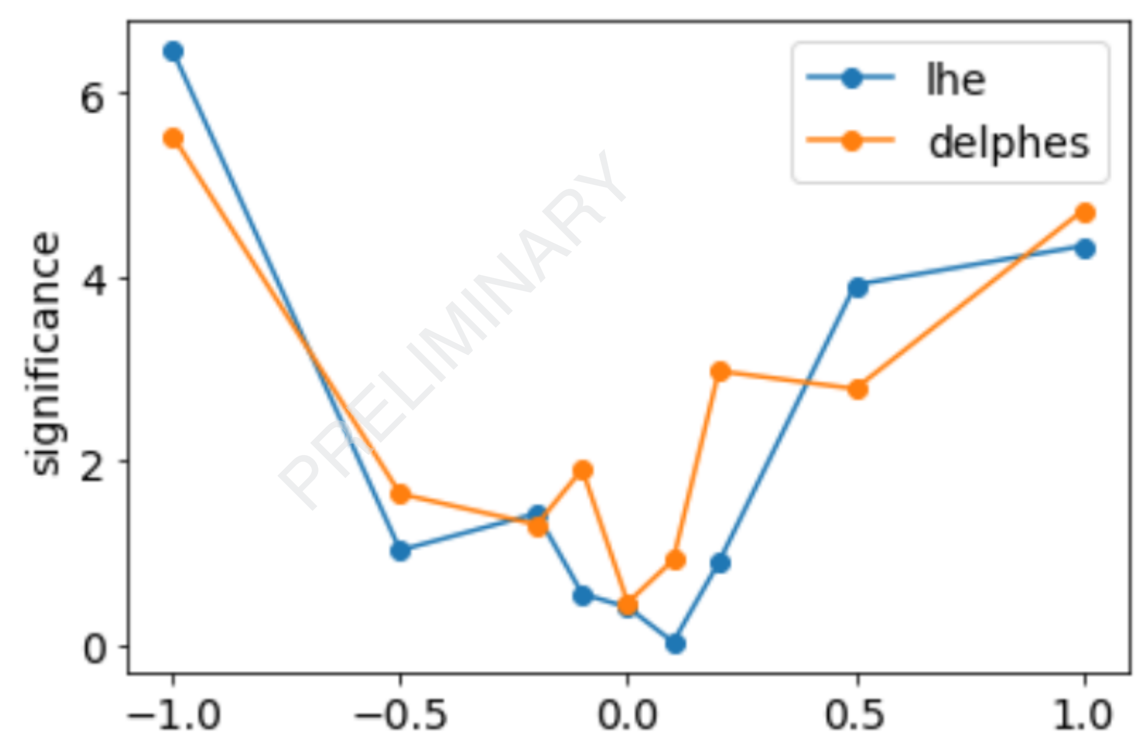
No significant improvement compared to linear regime!

Impact on realistic analyses

How do observables optimised on parton level simulations translate to more realistic analyses including detector & reconstruction effects?

➡ Fast simulation based results encouraging





$$\mathcal{O}_\alpha = \langle \sum_j \alpha_j \omega_j \rangle$$

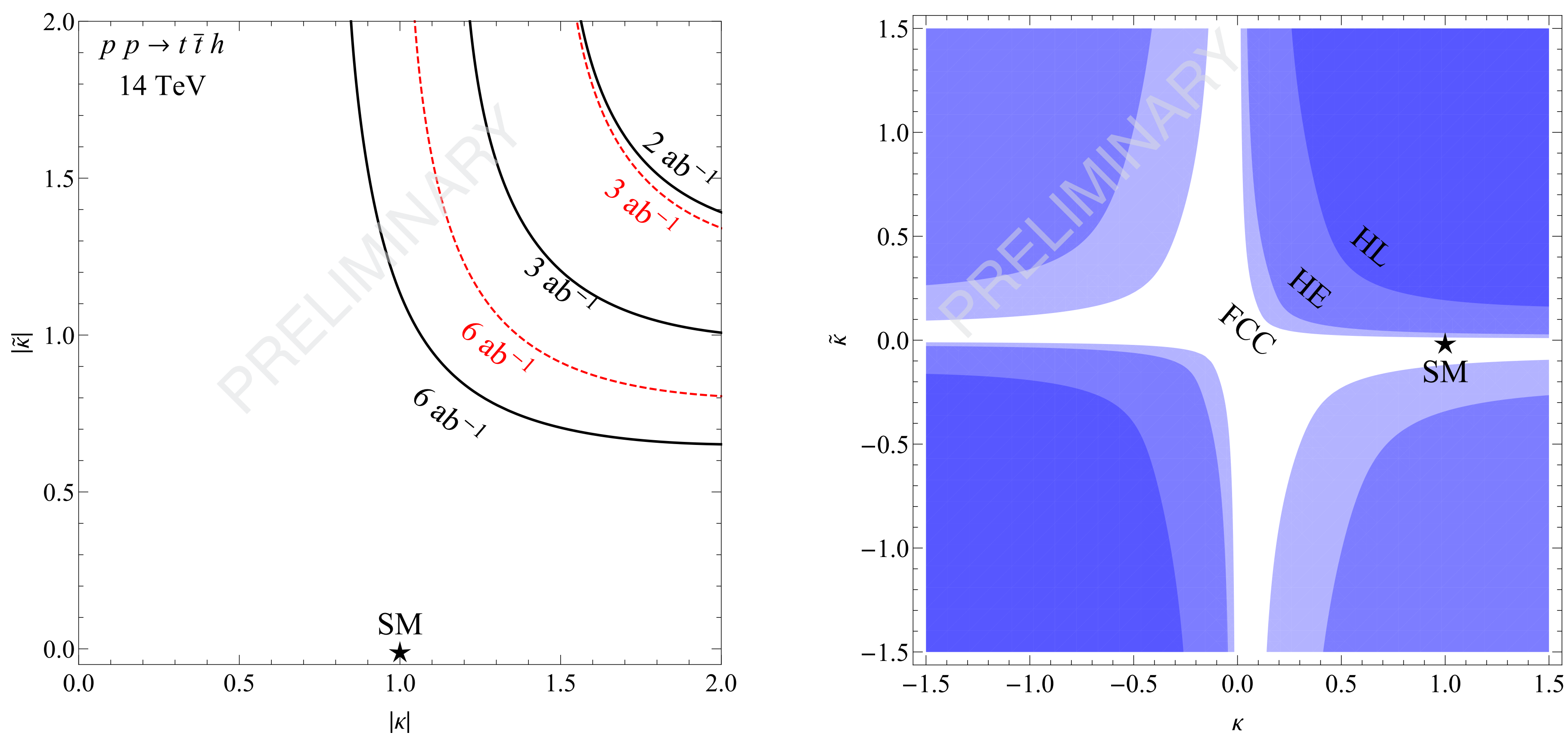
optimised on parton-events, applied to reconstruction level

Impact on realistic analyses

How do observables optimised on parton level simulations translate to more realistic analyses including detector & reconstruction effects?

➡ Fast simulation based results encouraging

➡ Substantial improvement of significance, especially at (HL)LHC



Conclusions

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

- Here covered example of CPV
  - Practically null-test of SM
  - Challenging reconstruction, high-dimensional phase-space
  - Linearised CP-odd observables close to optimal probes
  - Full exploration of NP sensitivity calls for ambitious new (Tera?) top-factories (HE-LHC, FCC)

Additional material

th reconstruction

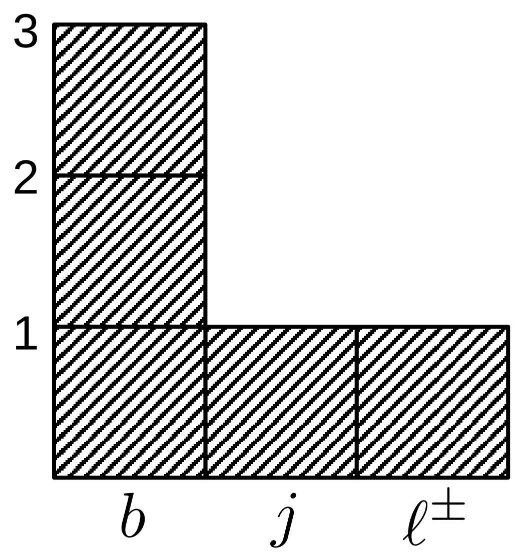
courtesy A. Smolkovic

Madgraph5 → **Pythia8** → **Delphes**

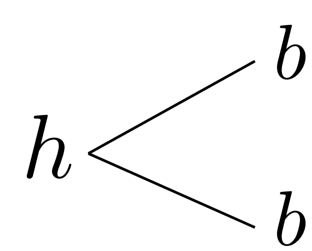
- event generation -   - showering, hadronization -   - detector simulation -

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

Event selection:

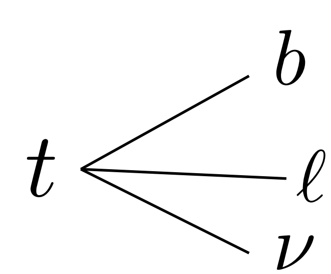


$$|\eta(b)| < 5 \qquad p_T(b) > 20\ \mathrm{GeV}$$
$$2 < |\eta(j)| < 5 \qquad p_T(j) > 20\ \mathrm{GeV}$$
$$|\eta(\ell)| < 2.5 \qquad p_T(\ell) > 10\ \mathrm{GeV}$$



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

Farina et al.,
JHEP 05 (2013) 022



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

$t\bar{t}h$ reconstruction

courtesy A. Smolkovic

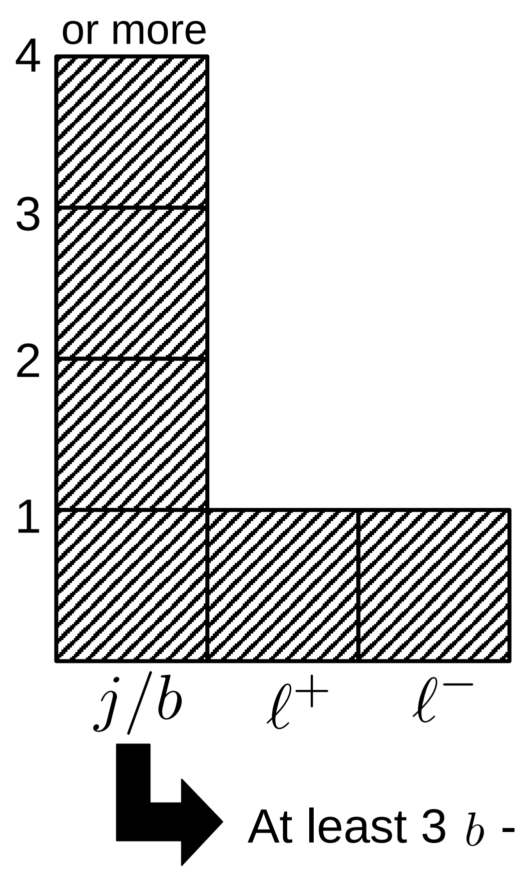
Madgraph5 → **Pythia8** → **Delphes**

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

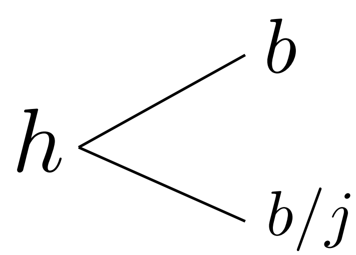
Signal: $pp \to t\bar{t}h\,(t \to b\ell^+\nu_\ell, \bar{t} \to \bar{b}\ell^-\bar{\nu}_\ell, h \to b\bar{b})$

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

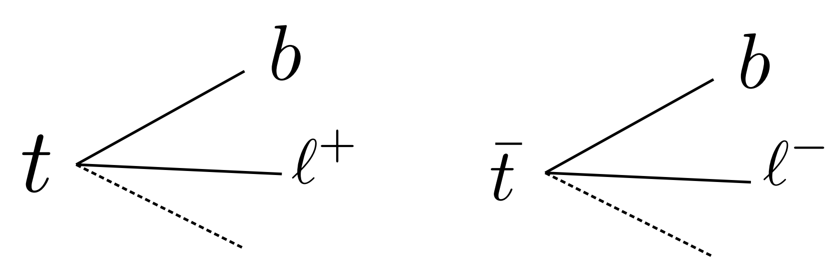
Event selection:



At least 3 b - tagged



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



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

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

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