Direct Higgs-top CP-measurement at LHC

Dorival Gonçalves
Oklahoma State University

BSM2021- 02.04.2021

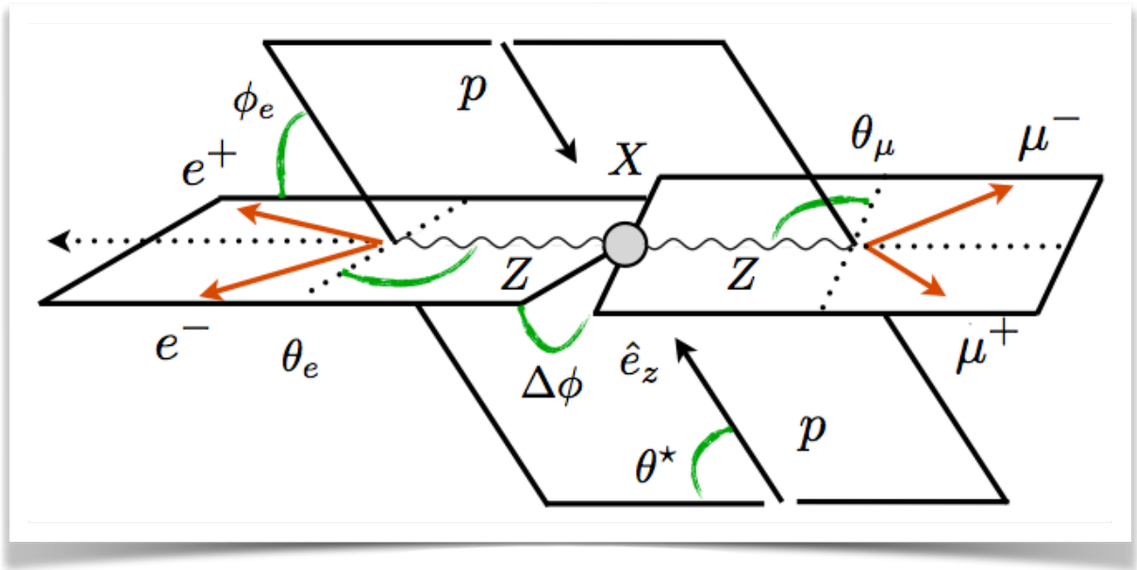
CP-violation

- Matter-antimatter unbalance requires new sources of CPV
- At LHC CPV HVV interaction is already extensively tested (clean target H→4leptons)

4l: Gritsan, Melnikov, Schulze, et al '12

WBF: Englert, **DG**, Mawatari, Plehn '12

$$\mathcal{L}_0 = g_1^{(0)}\, HV_\mu V^\mu - \frac{g_2^{(0)}}{4}\, H\, V_{\mu\nu} V^{\mu\nu} - \frac{g_3^{(0)}}{4}\, A\, V_{\mu\nu}\tilde{V}^{\mu\nu}$$



- While CP-odd HVV is loop suppressed, CP-odd Hff can manifest at tree-level:
  - → Mixture possible in some models, e.g., 2HDM

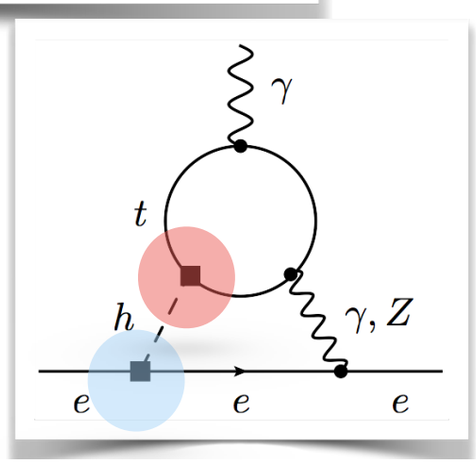
    see R. Santos talk @BSM2021
  - → Not excluded from Higgs measurements
  - → Top quark is an obvious candidate

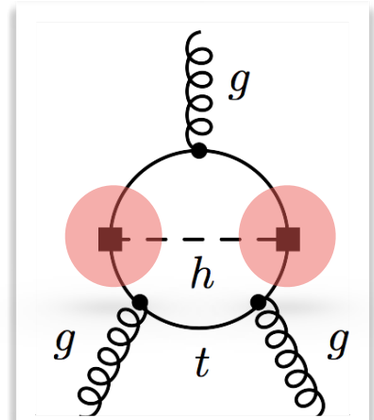
$$\mathcal{L} \supset -\frac{m_f}{v} K h \bar{f} (\cos\alpha + i\gamma_5 \sin\alpha) f$$

Indirect EDM constraints

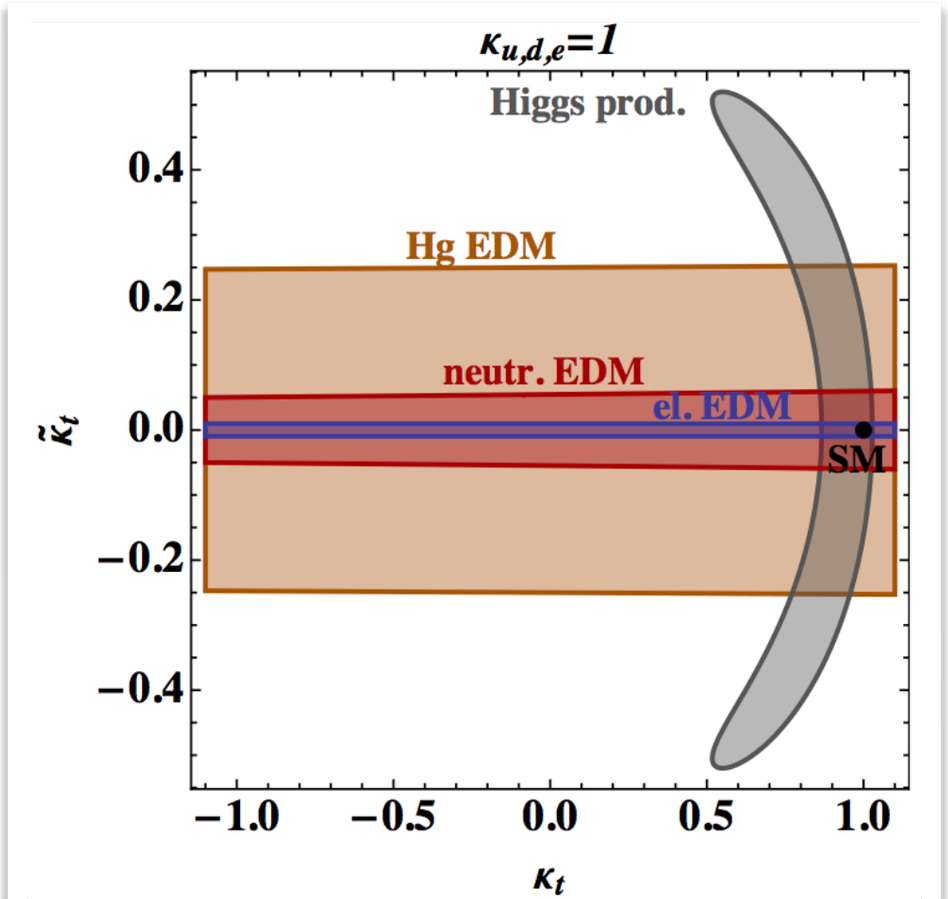
- Indirect constraints from eEDM very strong

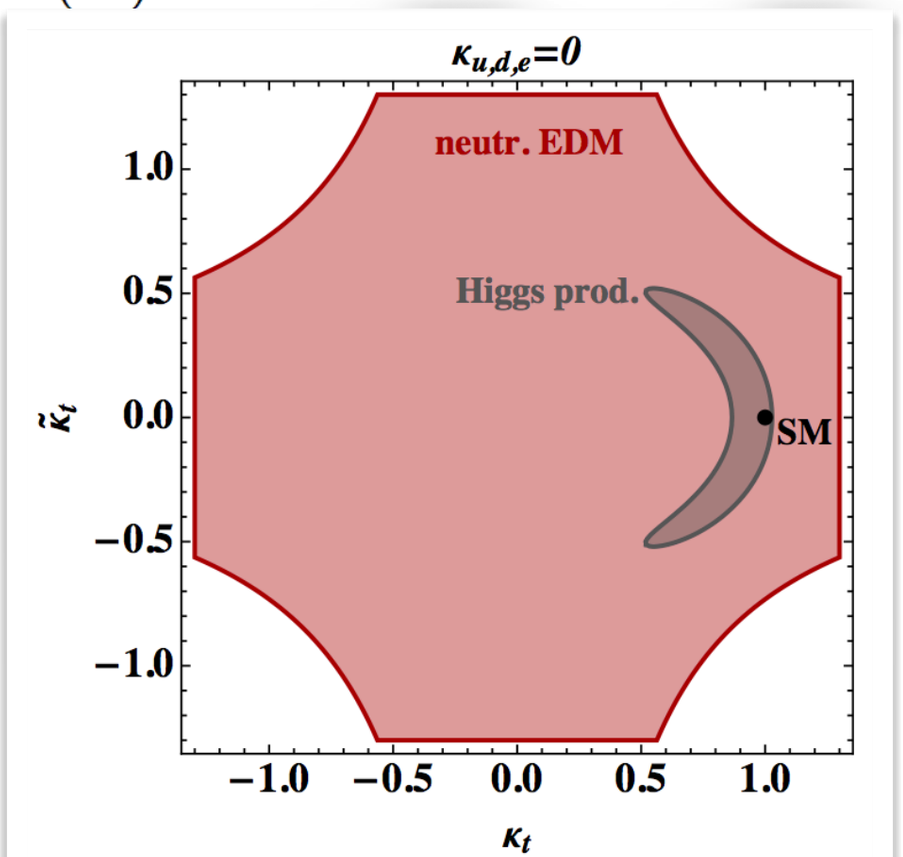
$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}}\left(\kappa_f\,\bar{f}f + i\tilde{\kappa}_f\,\bar{f}\gamma_5 f\right)h$$





$$\frac{d_e}{e} = \frac{16}{3}\frac{\alpha}{(4\pi)^3}\sqrt{2}G_F m_e\left[\kappa_e\tilde{\kappa}_t\, f_1(x_{t/h}) + \tilde{\kappa}_e\kappa_t\, f_2(x_{t/h})\right]$$



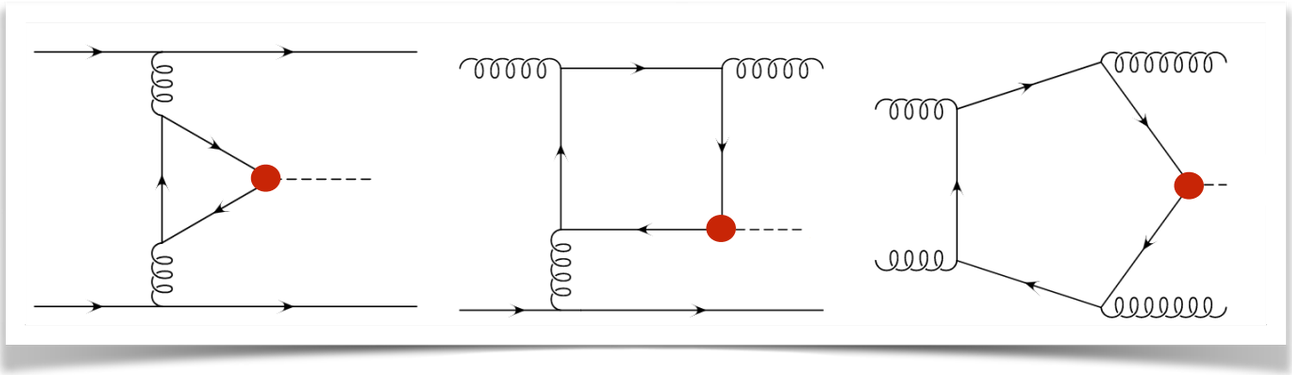


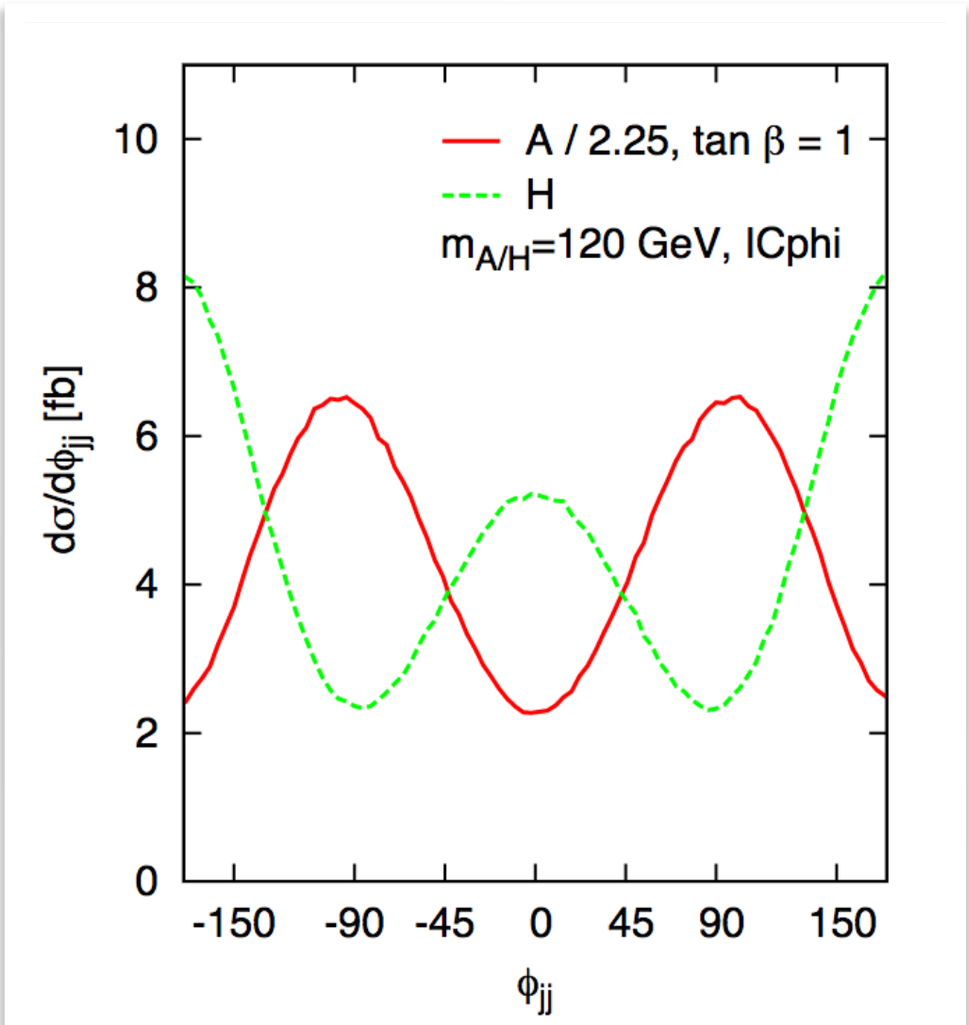
Brod, Haisch, Zupan (2013); Engel, Ramsey-Musolf, Kolck (2013); Cirigliano, Dekens, Vries, Mereghetti (2016)

Indirect collider constraints

- Complementary top-Higgs CP measurement at LHC:

$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t \; H$$





- Loop-induced: indirect constraints
- Bottom line:

  Analogously to *direct* yt signal strength measurement,

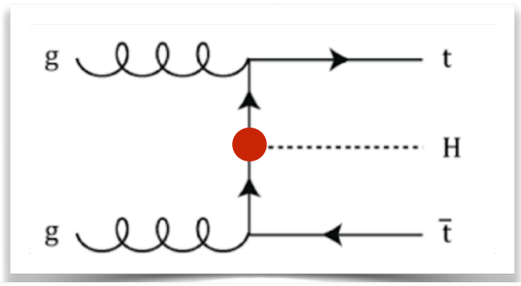
  the direct Higgs-top CP structure has in the ttH channel

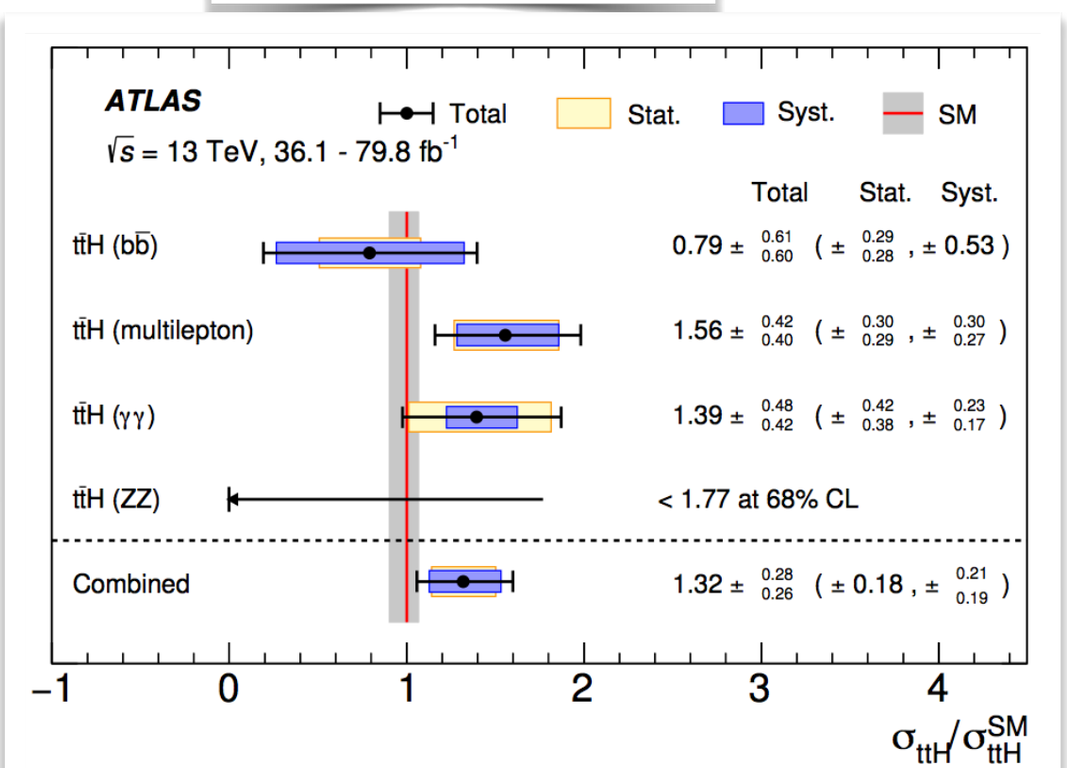
  its most natural path

Plehn, Rainwater, Zeppenfeld (2001)
Zeppenfeld, Kubocz, Campanario (2010)
Englert, **DG**, Mawatari, Plehn (2012)
Dolan, Harris, Jankowiak, Spannowsky (2014)

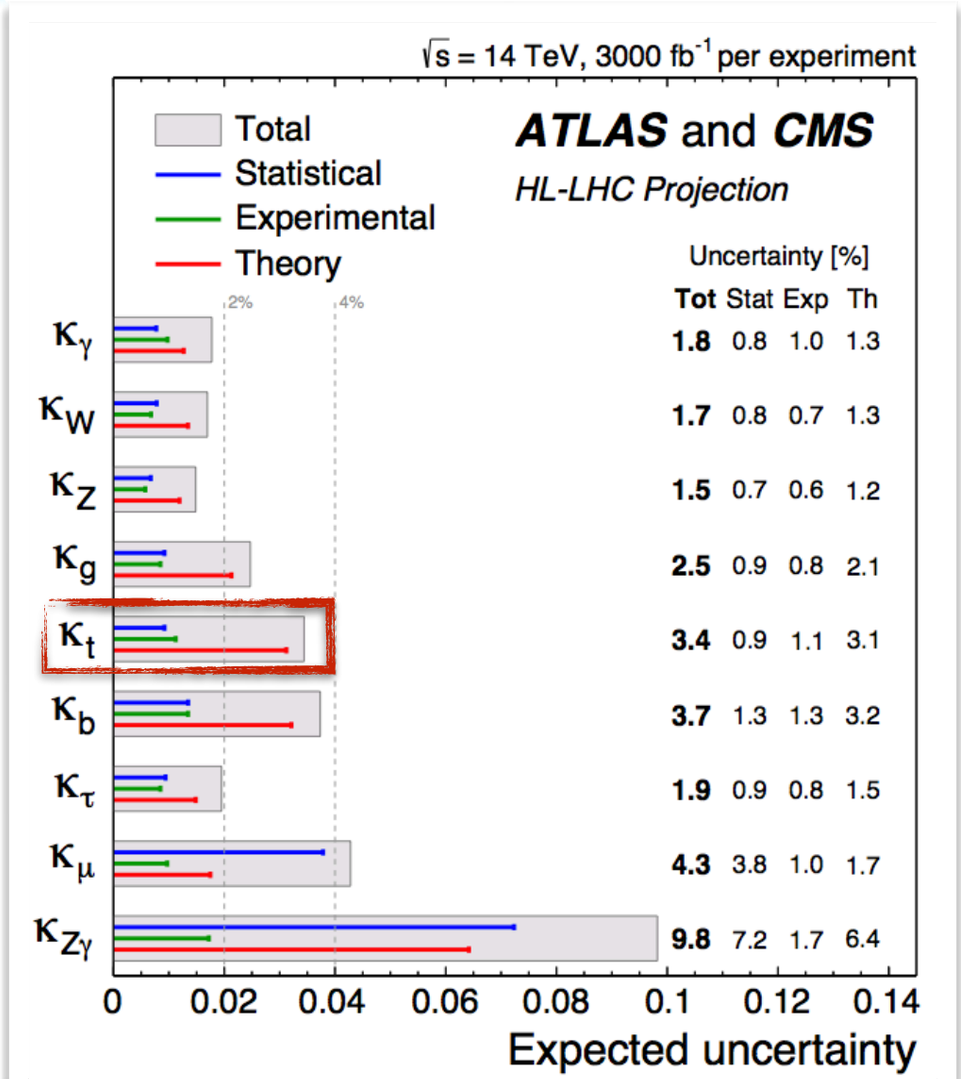
Direct CP measurement of Higgs-top coupling

- ttH channel observation (2018):





- Expected HL-LHC precisions:



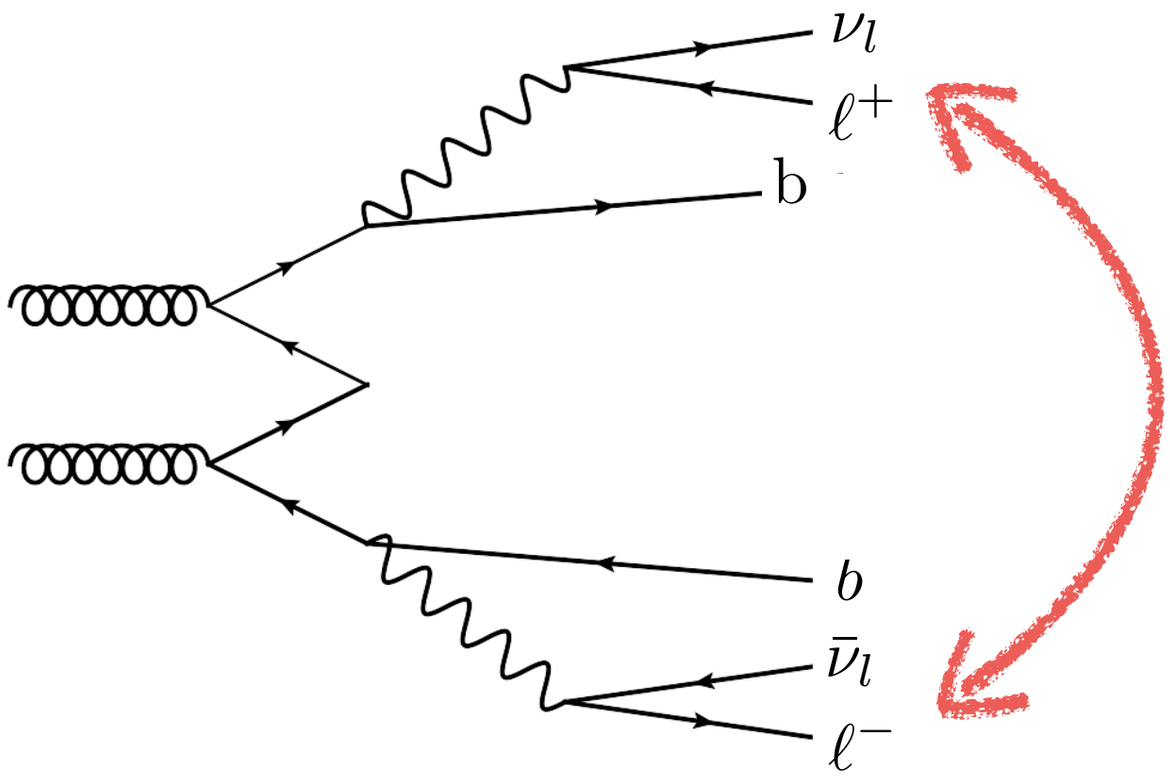
- Opportunity: direct measure Higgs-top CP structure at the LHC

$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t \; H$$

Direct CP measurement of Higgs-top coupling

- $\Delta\phi_{tt}$ distribution directly reflects on $\Delta\phi_{ll}$

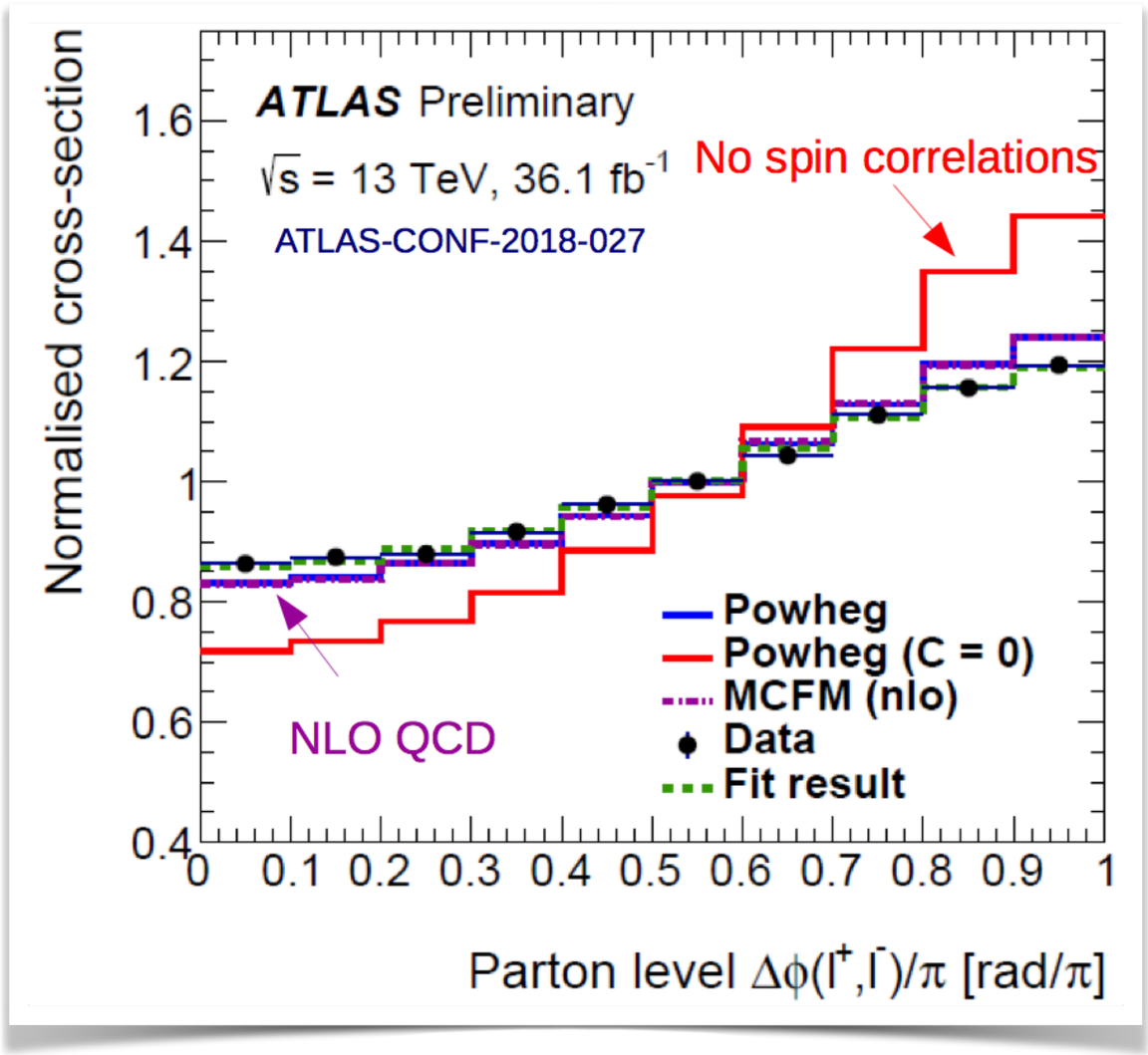
  Parke, Mahlon '10



$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1+\omega_f P_t \cos\theta_f)$$

	l^+, d	b	ν, u
ω_f	1	−0.4	−0.3

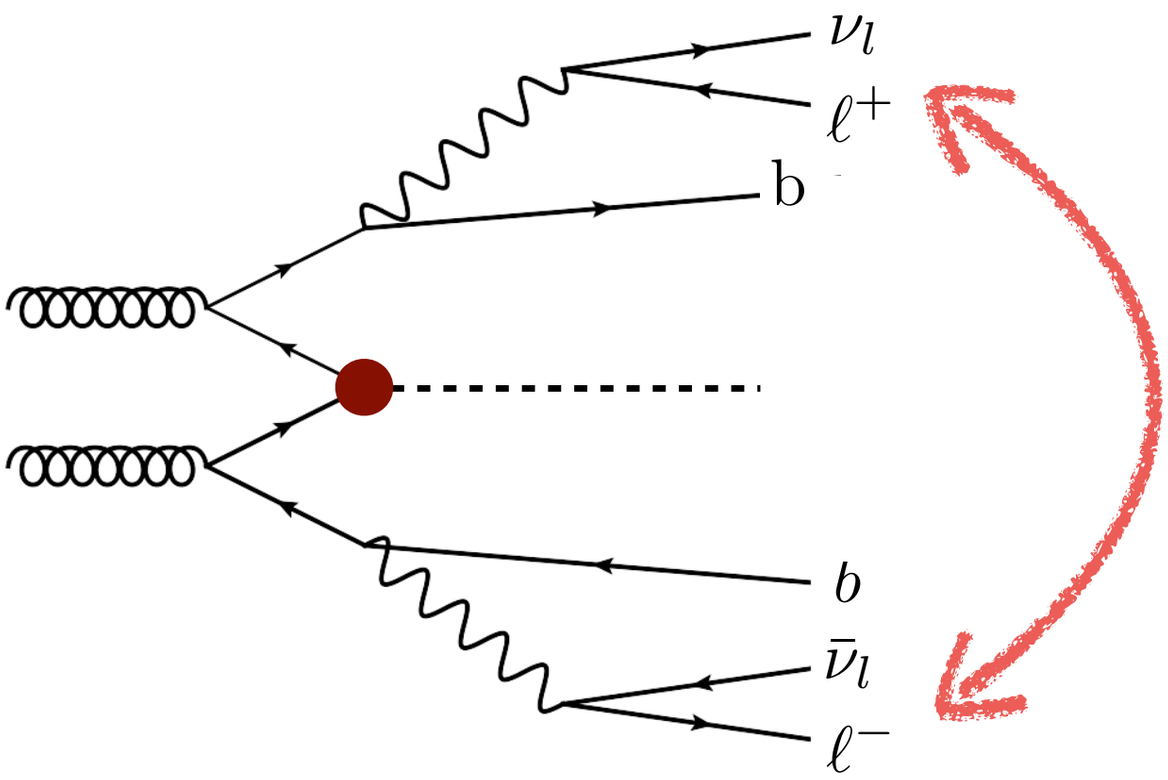
Spin analysing power: maximum for charged leptons



Direct CP measurement of Higgs-top coupling

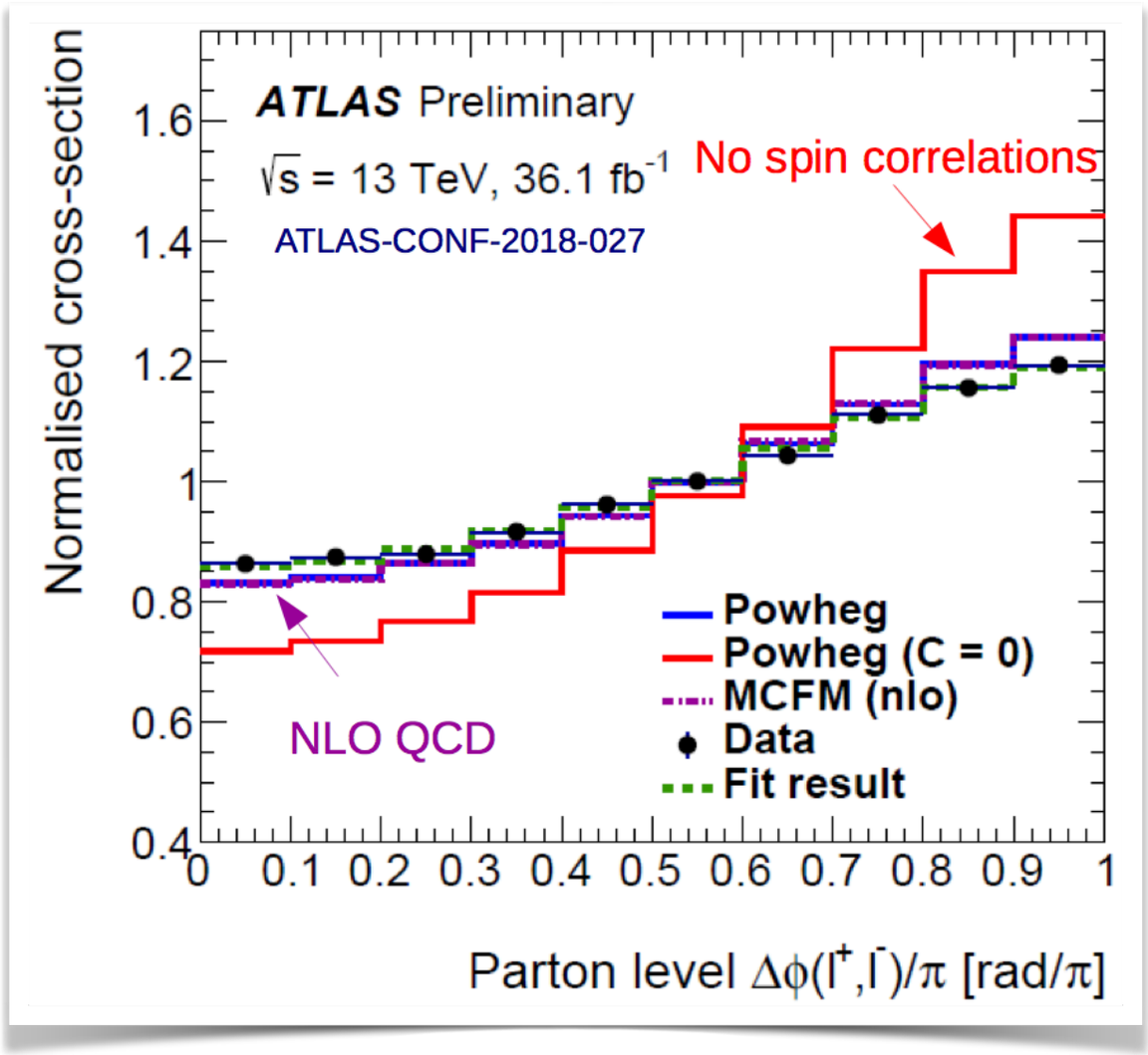
- $\Delta\phi_{tt}$ distribution directly reflects on $\Delta\phi_{ll}$

  Spin correlations of top and anti-top affected by nature of interaction



$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t\, H$$

Buckley, **DG** (PRL '15)

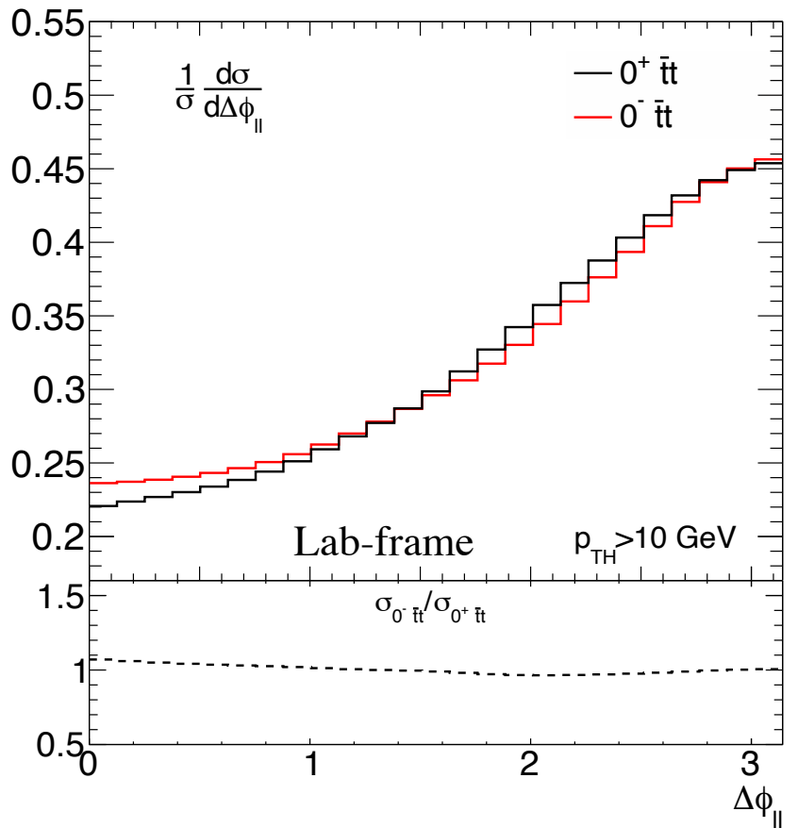


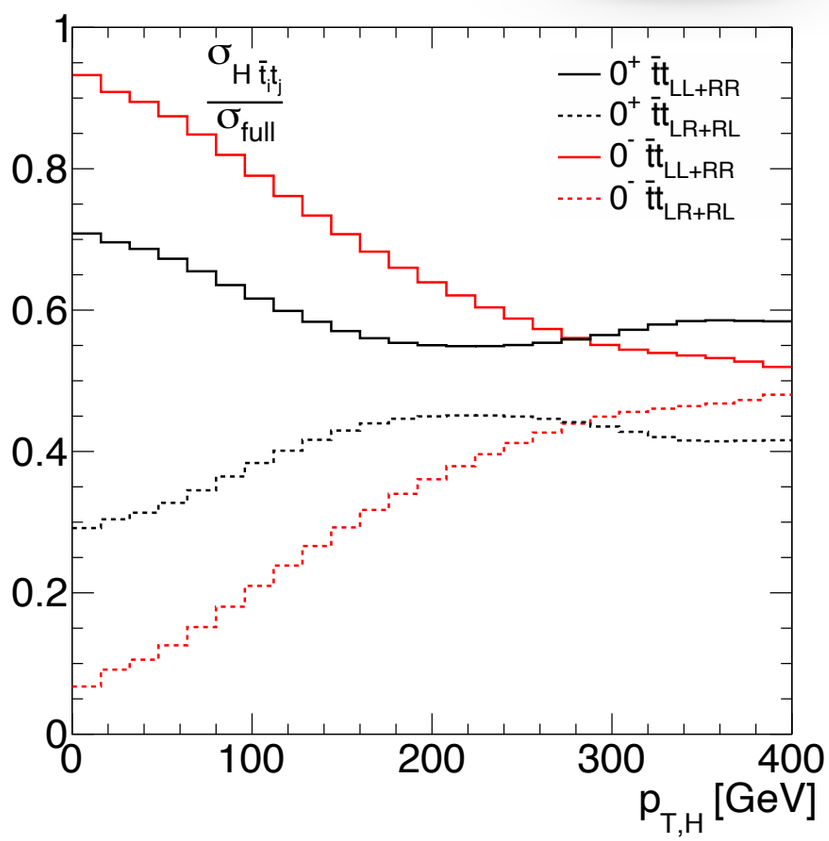
Direct CP measurement of Higgs-top coupling

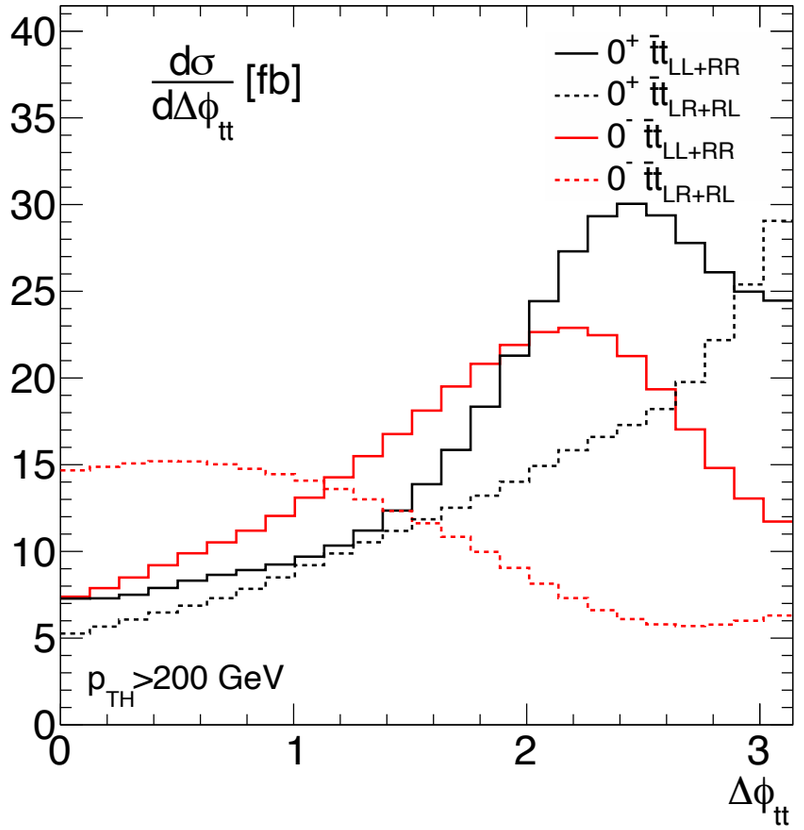
- $\Delta\phi_{tt}$ distribution directly reflects on $\Delta\phi_{ll}$

  Spin correlations of top and anti-top affected by nature of interaction

$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t\ H$$







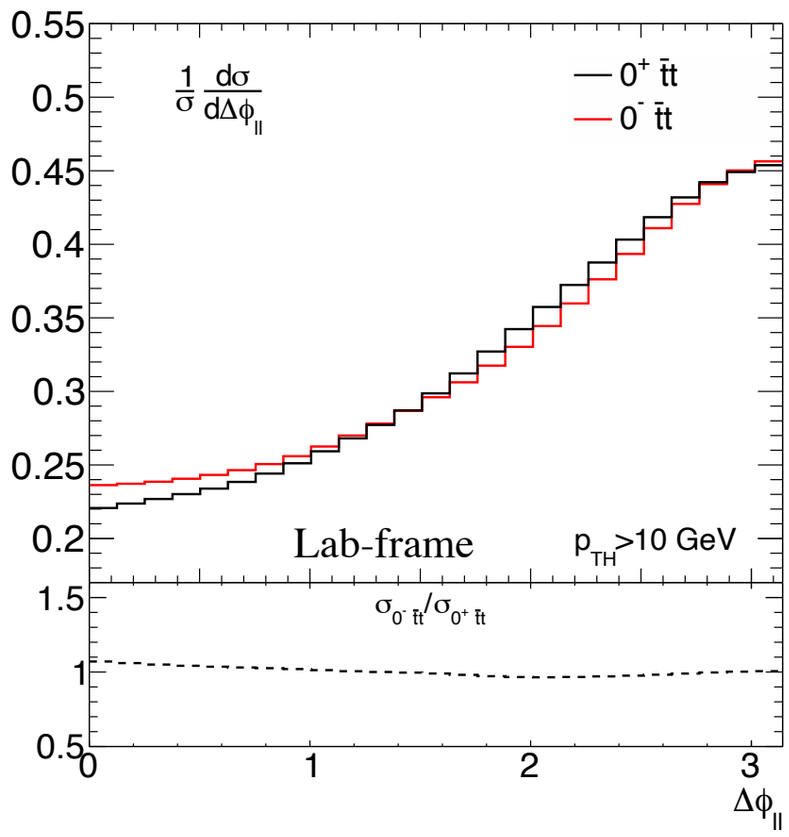
Buckley, **DG** (PRL '15)

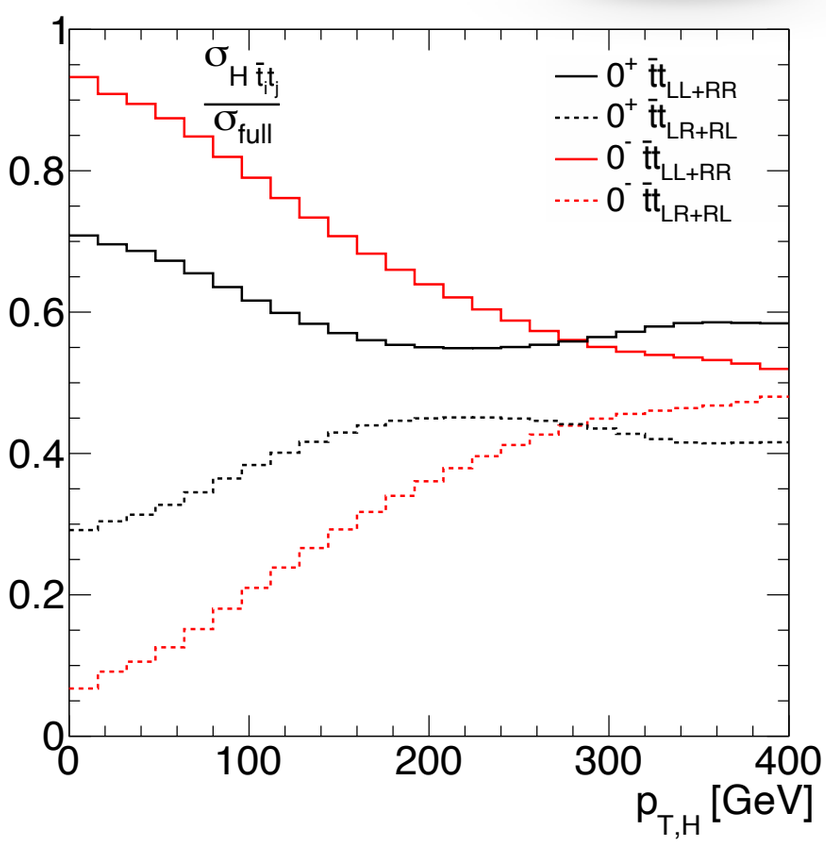
Direct CP measurement of Higgs-top coupling

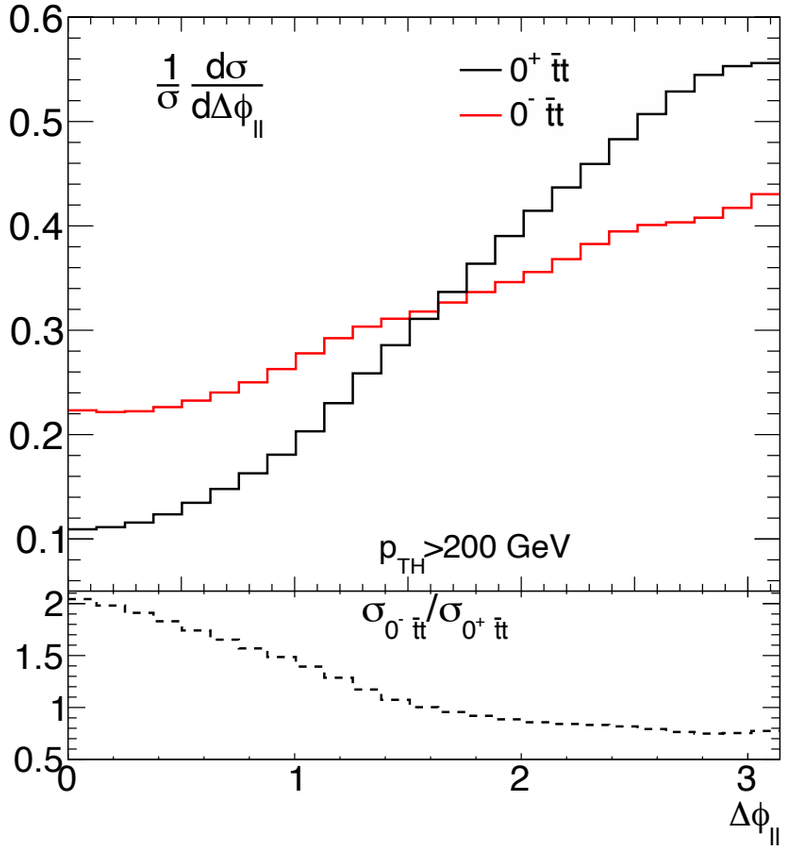
- $\Delta\phi_{tt}$ distribution directly reflects on $\Delta\phi_{ll}$

  Spin correlations of top and anti-top affected by nature of interaction

$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t\ H$$







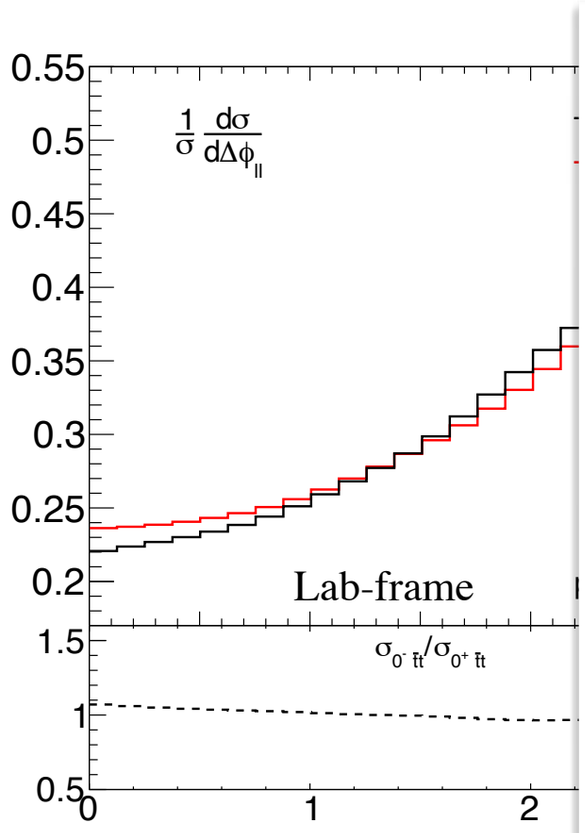
Buckley, **DG** (PRL '15)

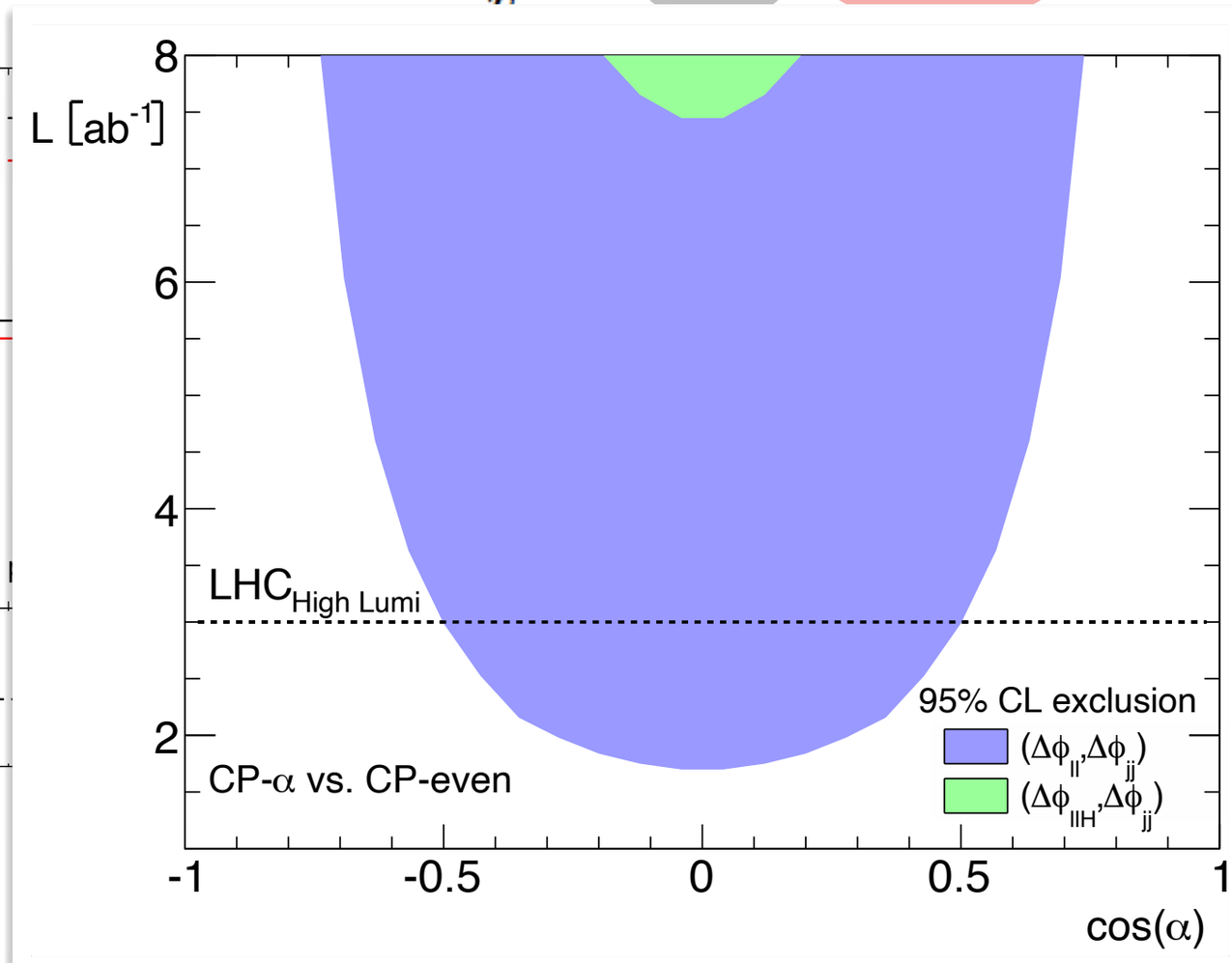
Direct CP measurement of Higgs-top coupling

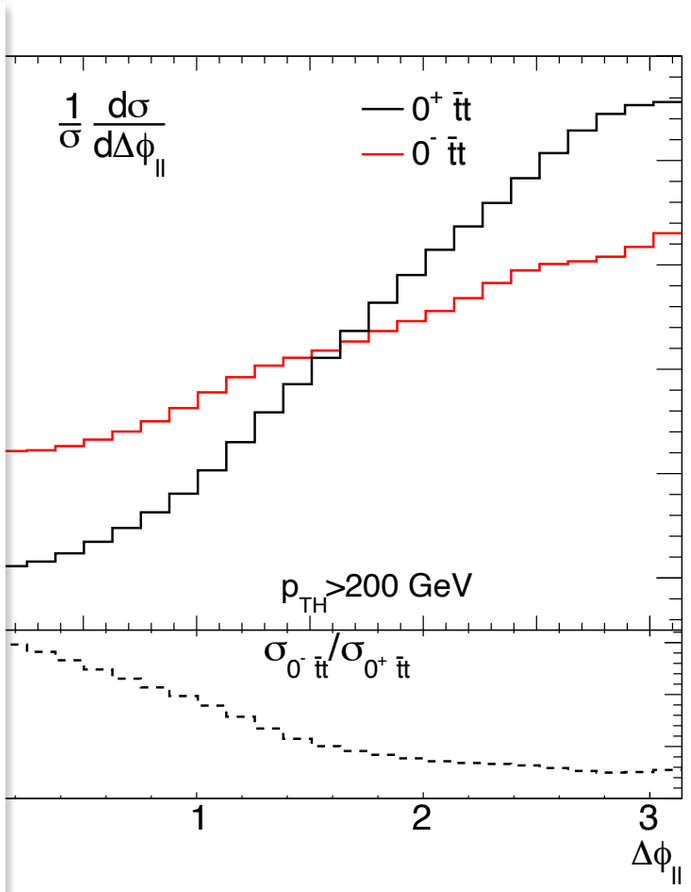
- $\Delta\phi_{tt}$ distribution directly reflects on $\Delta\phi_{ll}$

  Spin correlations of top and anti-top affected by nature of interaction

$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t\, H$$





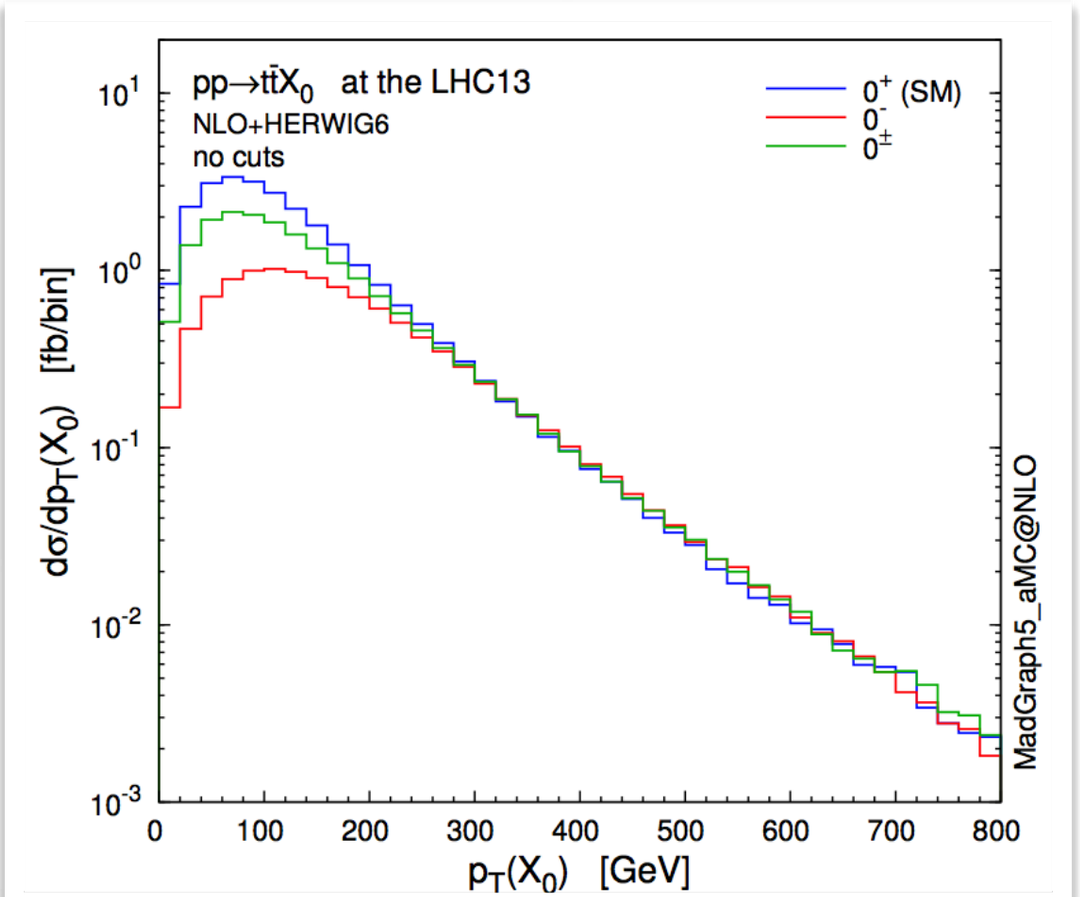


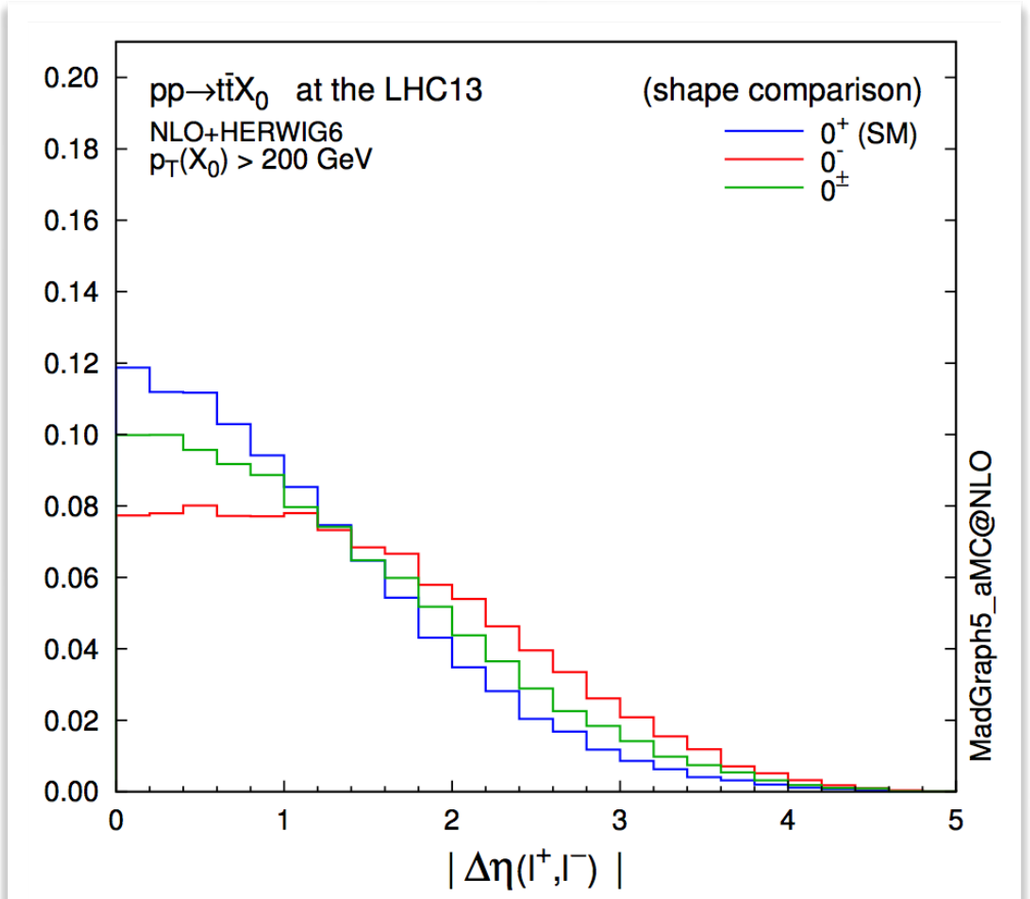
Buckley, **DG** (PRL '15)

➡ **Boosted Higgs** study nicely match with Higgs-top CP-measurement

Multivariate analysis problem

- Rich final state with many relevant observables:





Demartin, Maltoni, Mawatari, Page, Zaro ’14
Gritsan, Rontsch, Schulze, Xiao ’16
Amor dos Santos et al. ’17
Azevedo, Onofre, Filthaut, Gonçalo ’17
Brehmer Dawson, Homiller, Kling, Plehn ‘19

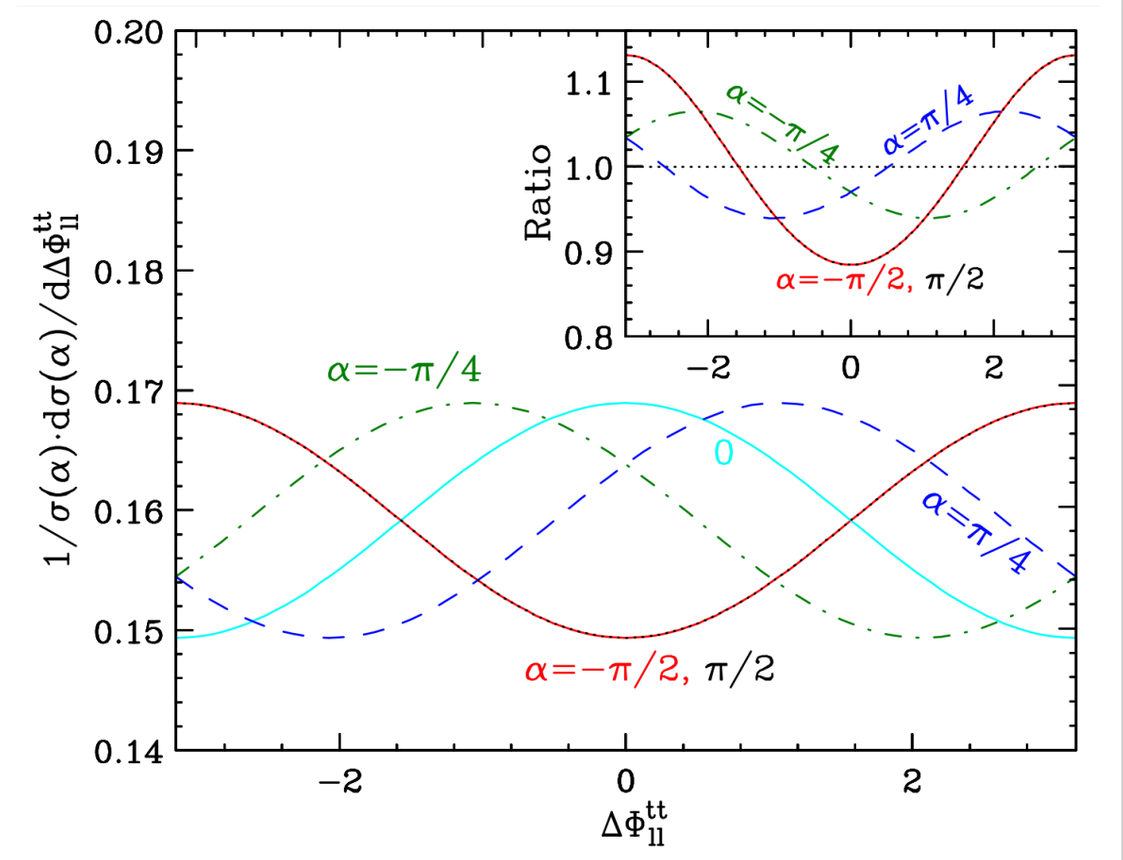
CPV Higgs-top measurement

- CPV observable best defined at the ttbar rest frame:

$$d\sigma(gg \to t(n_t)\bar{t}(n_{\bar{t}})H) = \sin^2\alpha f_1(p_i.p_j) + \cos^2\alpha f_2(p_i.p_j) + \sin\alpha\cos\alpha \sum_l g(p_i.p_j)\epsilon_l$$

$$\epsilon_{\mu\nu\rho\sigma}p_a^\mu p_b^\nu p_c^\rho p_d^\sigma = \begin{aligned} & E_a\ \overrightarrow{p_b}\cdot(\overrightarrow{p_c}\times\overrightarrow{p_d}) + E_c\ \overrightarrow{p_d}\cdot(\overrightarrow{p_a}\times\overrightarrow{p_b}) \\ & -E_b\ \overrightarrow{p_c}\cdot(\overrightarrow{p_d}\times\overrightarrow{p_a}) - E_d\ \overrightarrow{p_a}\cdot(\overrightarrow{p_b}\times\overrightarrow{p_c}) \end{aligned}$$

$$\epsilon(p_t, p_{\bar{t}}, p_{\ell+}, p_{\ell-})|_{t\bar{t}\ CM} \propto p_t \cdot (p_{\ell+} \times p_{\ell-})$$

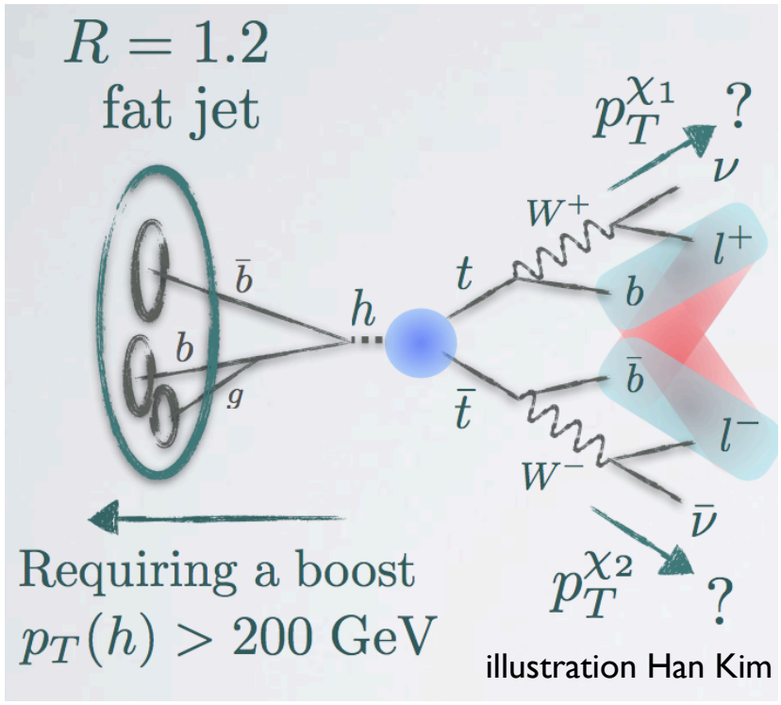


DG, Kong, Kim '18

➡ We need an efficient method to reconstruct the top momenta

CPV Higgs-top measurement

To obtain top momenta M2 method: based on mass minimization, being more flexible for BSM studies



Debnath, Kim, Kong, Matchev '17

DG, Kong, Kim '18

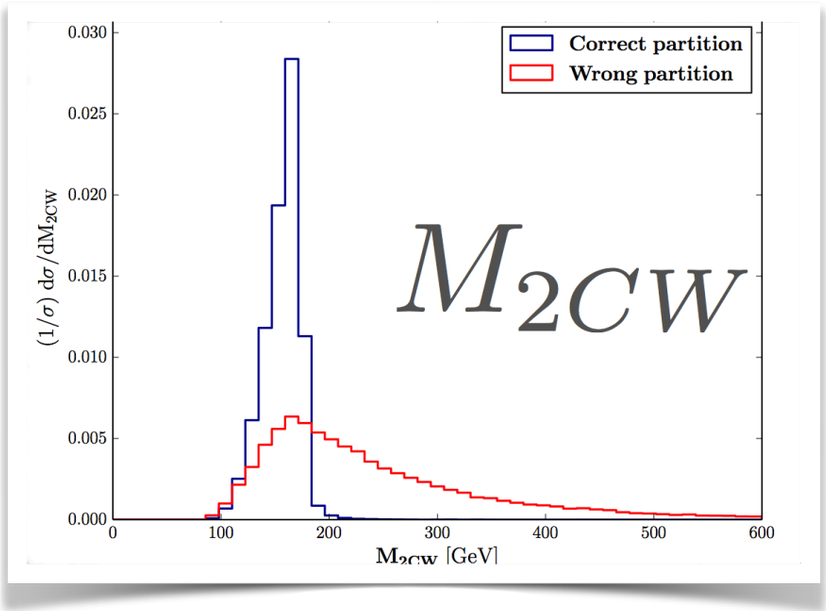
Reconstruction of the Higgs: BDRS

Reconstruction of top momenta: Optimass

a) guess neutrino momenta
b) solve combinatorial problem

$M_{2CW}^{\text{correct}} \longrightarrow p_T^{\chi_1}(\text{correct}) \quad p_T^{\chi_2}(\text{correct})$

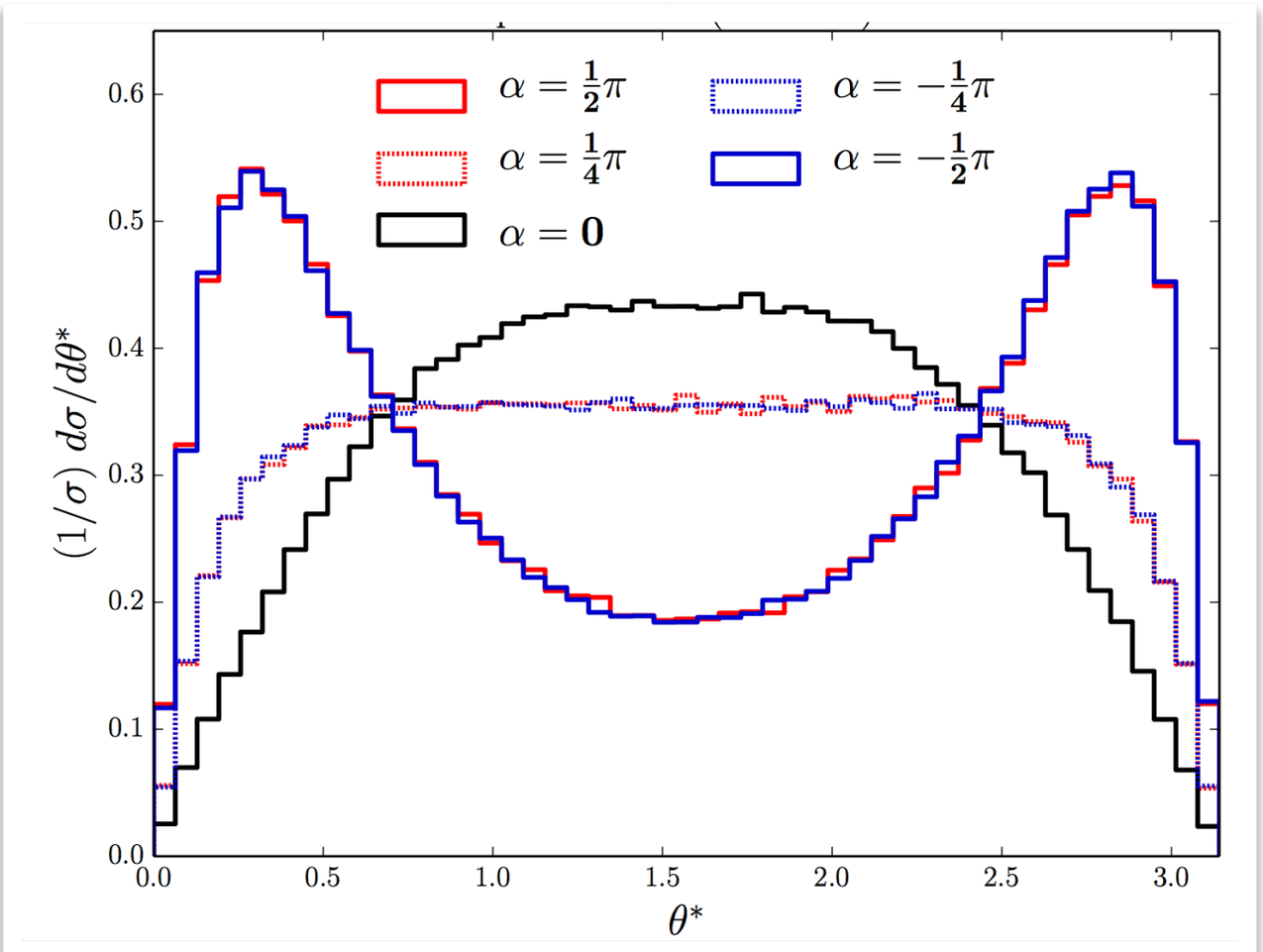
$M_{2CW}^{\text{wrong}} \longrightarrow p_T^{\chi_1}(\text{wrong}) \quad p_T^{\chi_2}(\text{wrong})$

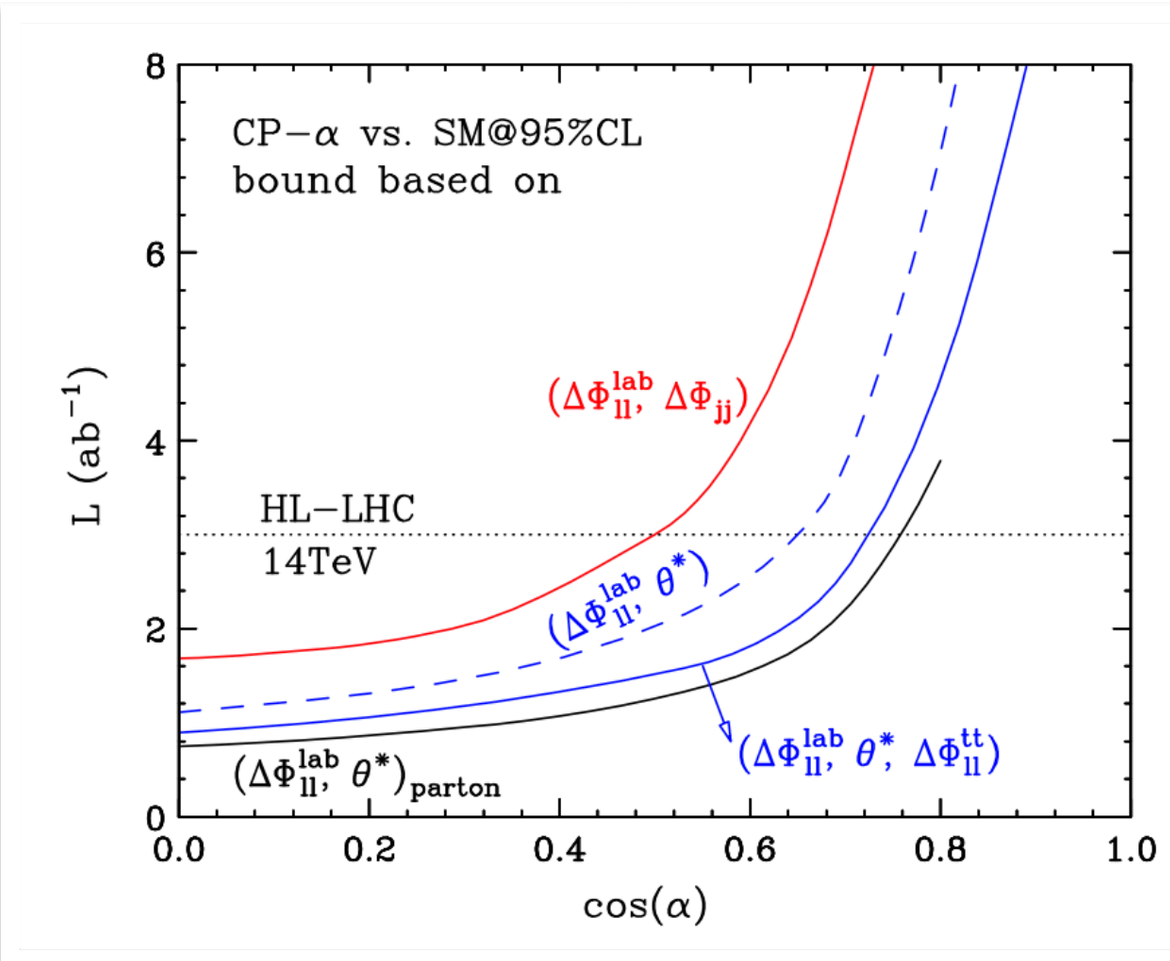


The wrong partition often violates the end-points: Optimass uses it to pick up correct one

CPV Higgs-top measurement

- Multivariate analysis problem
- tt-rest frame: new powerful observables, e.g., θ*



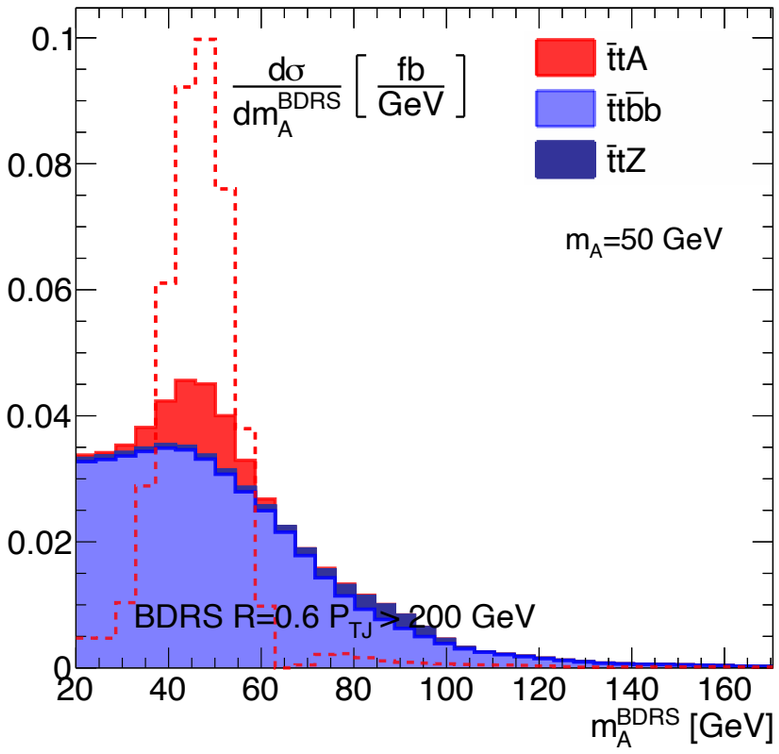


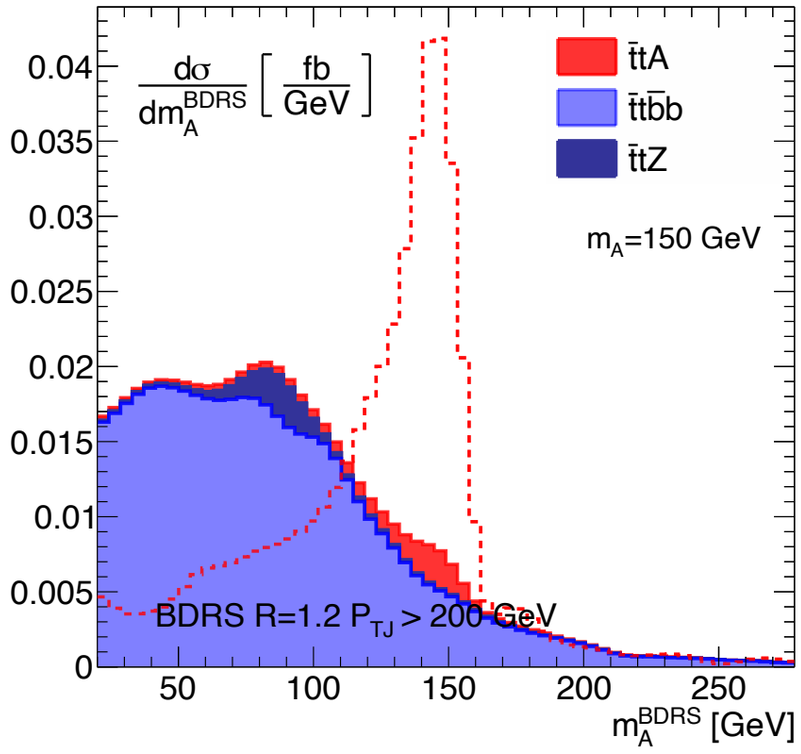
DG, Kong, Kim '18

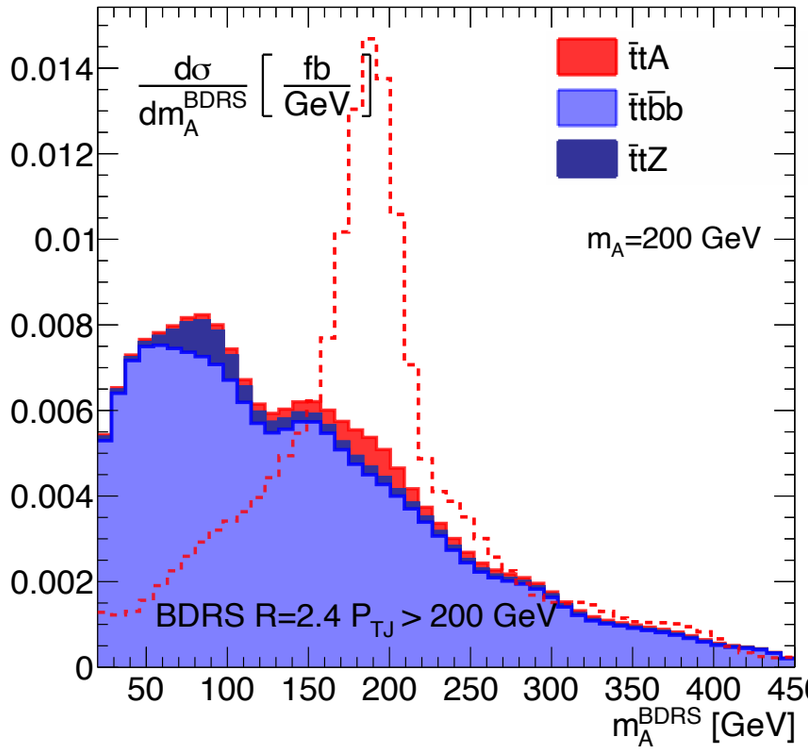
Extended Scalar Sectors

- Seeking for light pseudoscalars: ttA(bb) can direct access the Yukawa and explore low m_A

  Tailoring the BDRS analysis for different m_A ranges: $R \sim 2m_A/p_{TA}$







- We can probe the CP structure in a similar fashion to the 125 GeV particle

  Lopez-val, **DG** (2016) Azevedo, Capucha, Gouveia, Onofre, Santos (2020)

Summary

The search for new sources of CPV is one of the cornerstones of the Higgs program

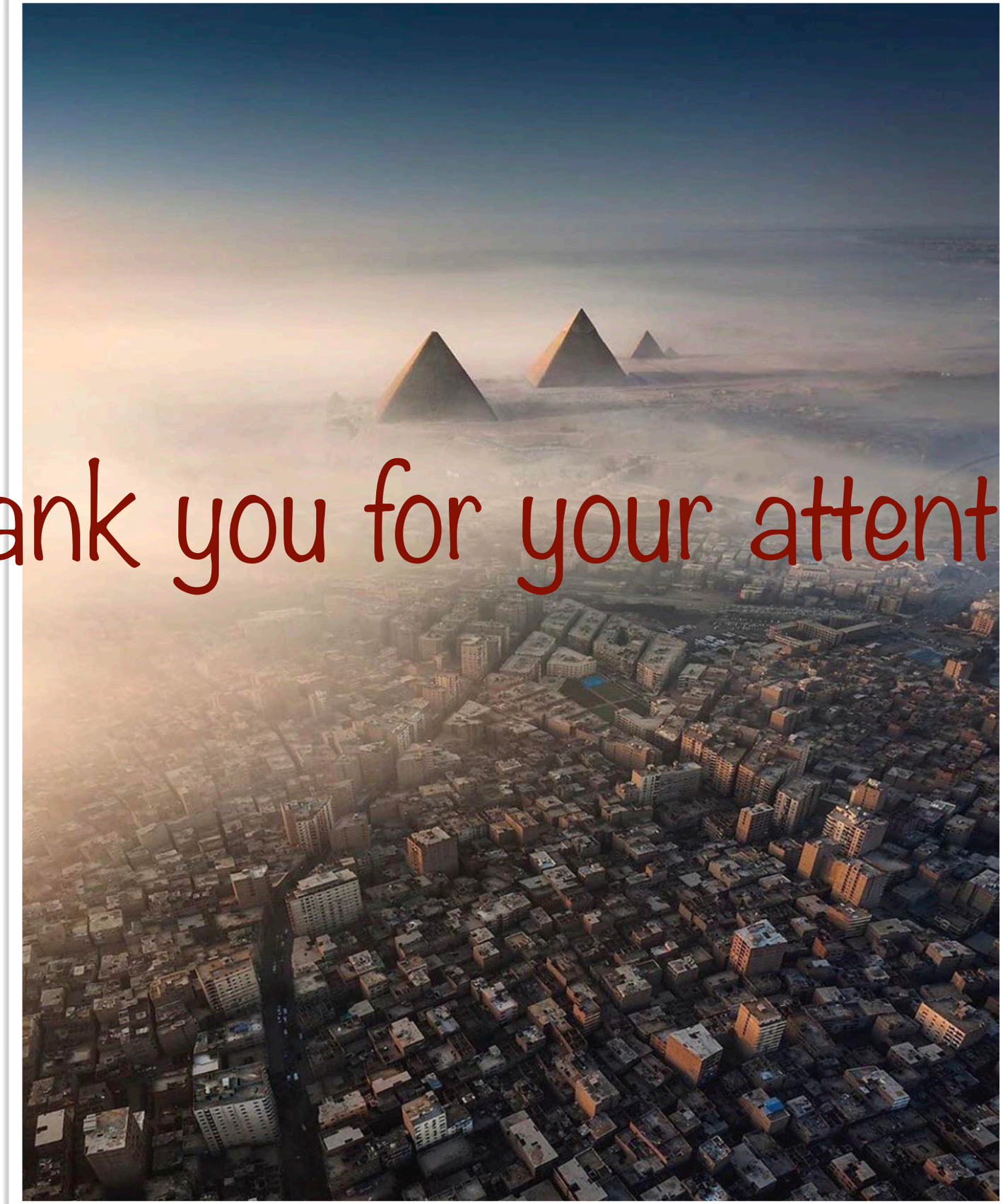
- Higgs-top coup can naturally display larger CP-phases than HVV

→ Direct probe: ttH channel

- Boosted Higgs analysis nicely match with CP-measurement
- Multivariate analysis problem

→ Observables at the top rest frame boost CPV sensitivity

- Works for both the 125 GeV Higgs and possible extra Higgses



Thank you for your attention!