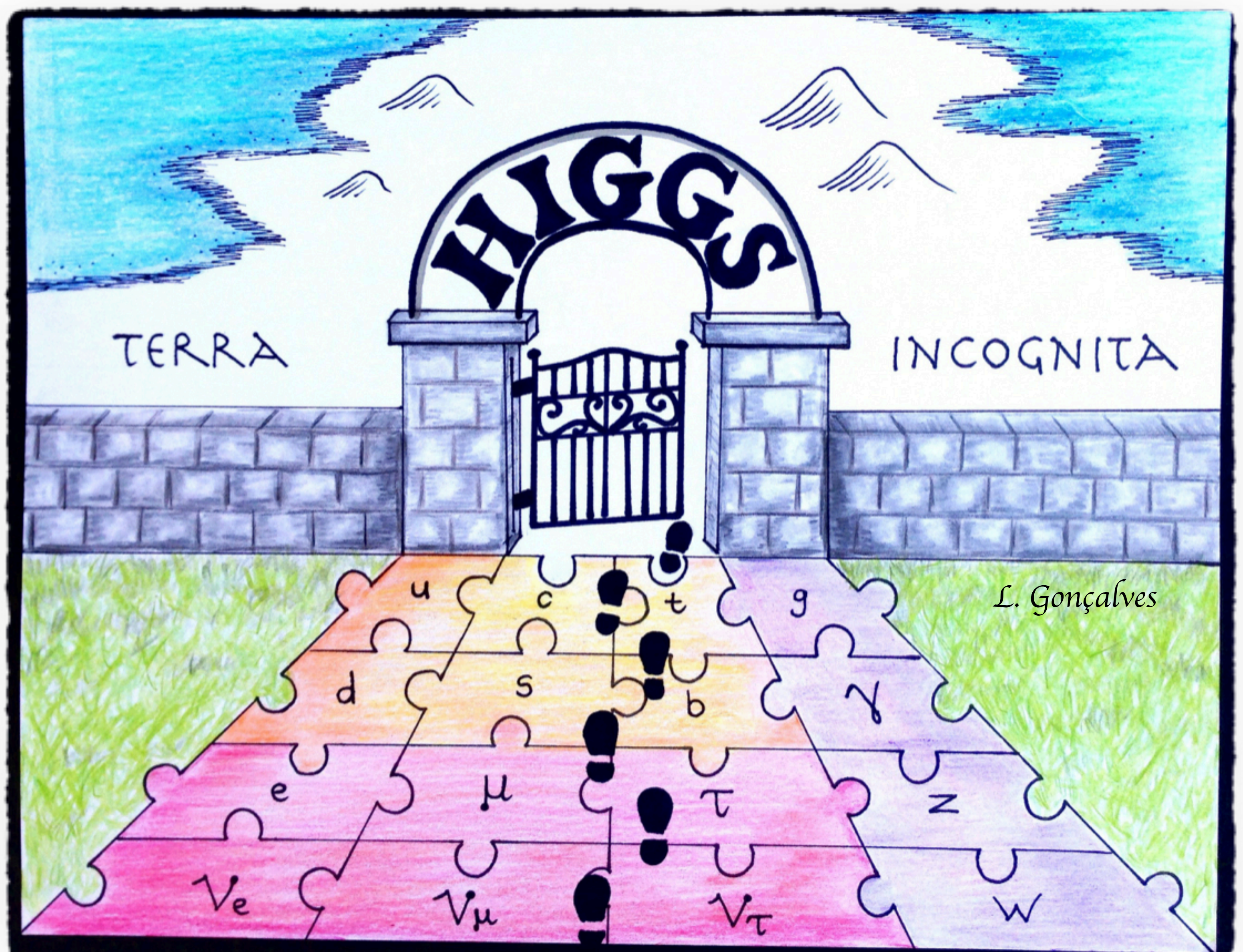
# Direct Higgs-top CP-phase Measurement

Dorival Gonçalves
Oklahoma State University

WG2: CP violation in Higgs interactions - 12.15.2021

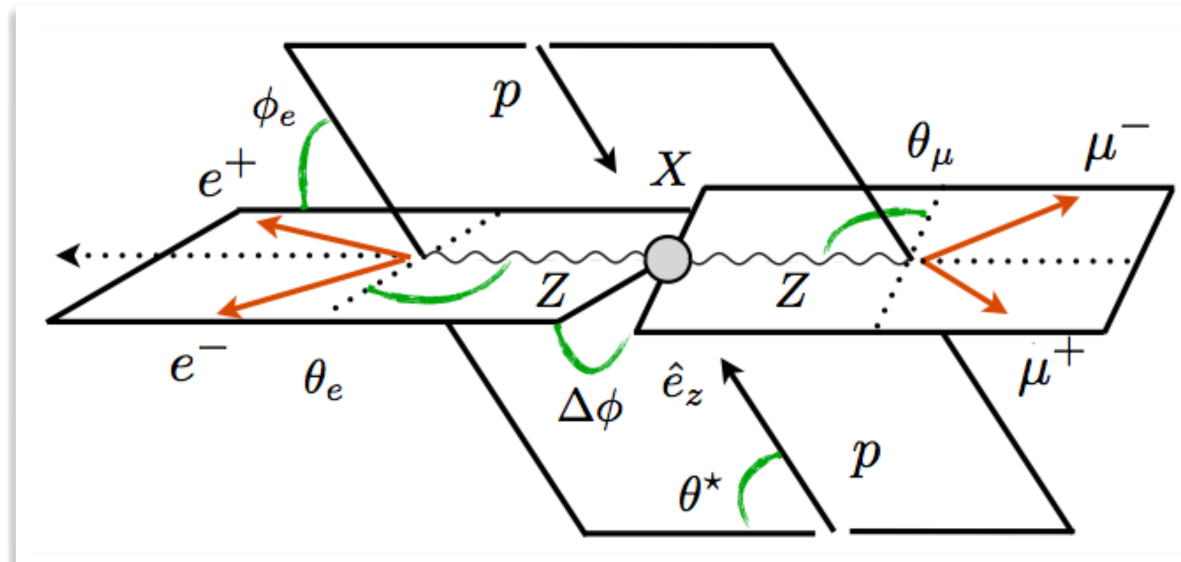


# CP-violation

- 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

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

See talk by Hualin Mei



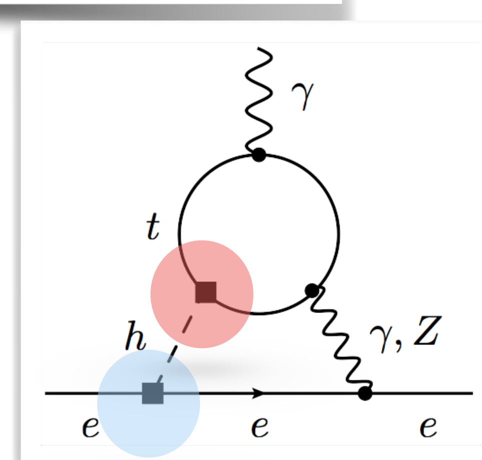

- While CP-odd HVV is loop suppressed, CP-odd Hff can manifest at tree-level:
  - ➡ Mixture possible in some models, e.g., 2HDM
  - ➡ Not excluded from Higgs measurements
  - ➡ Top quark is an obvious candidate

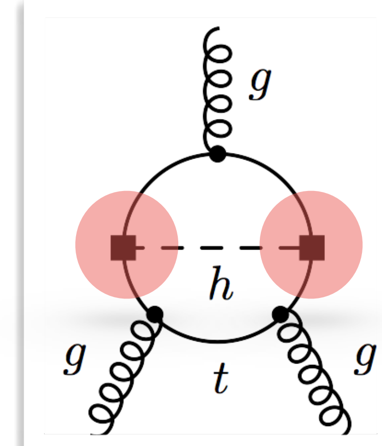
$$\mathcal{L} \supset -\frac{m_f}{v} K h \bar{f} (\cos\alpha + i\gamma_5 \sin\alpha) f$$

# Indirect EDM constraints

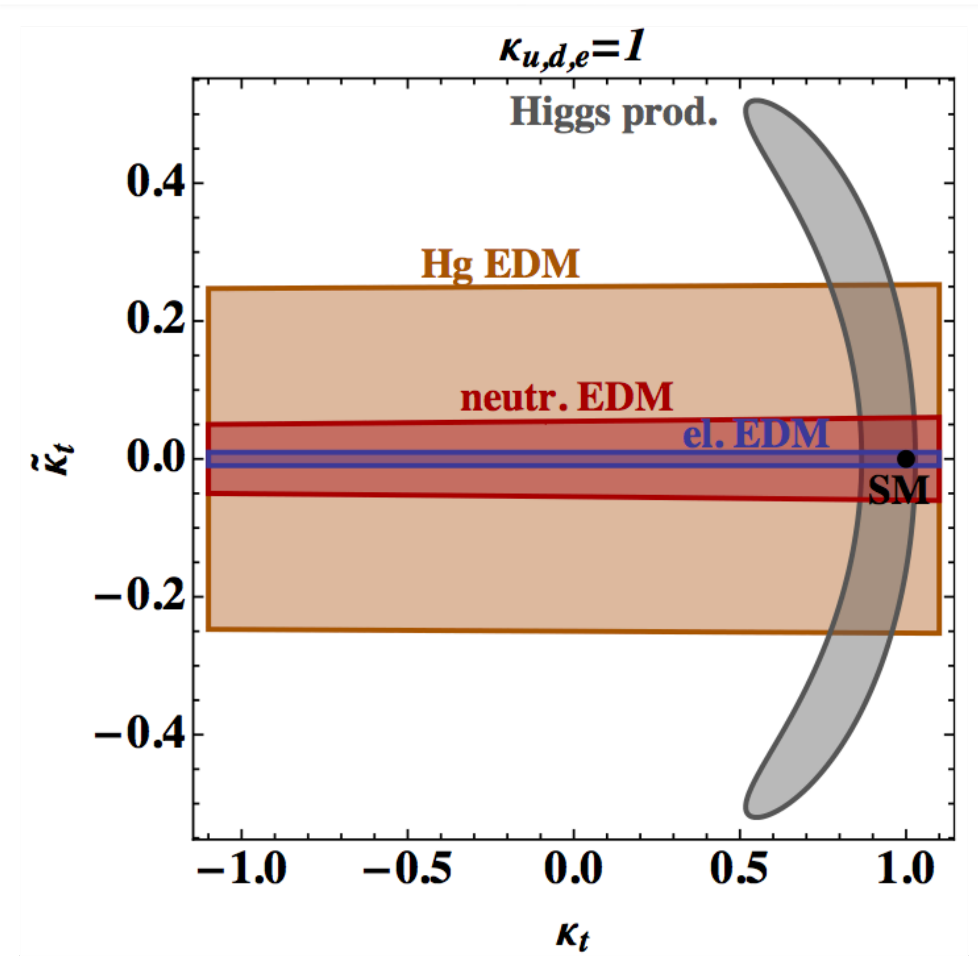
- Indirect constraints from eEDM very strong

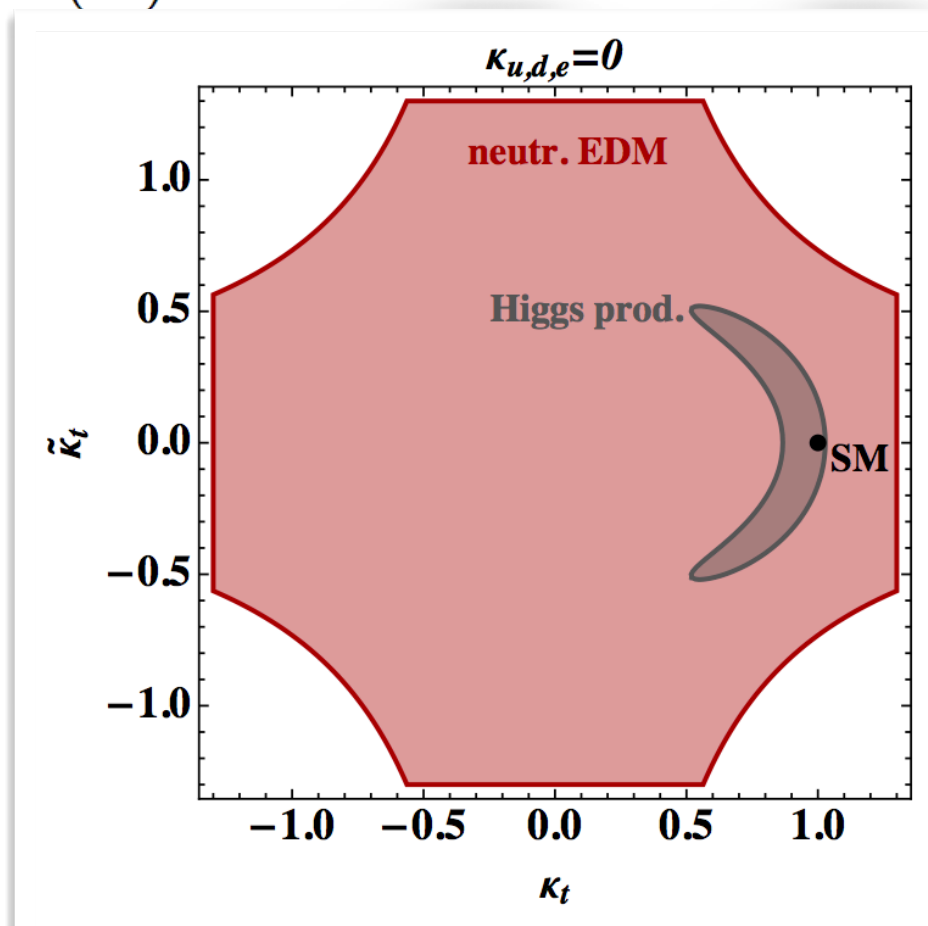
$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$




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



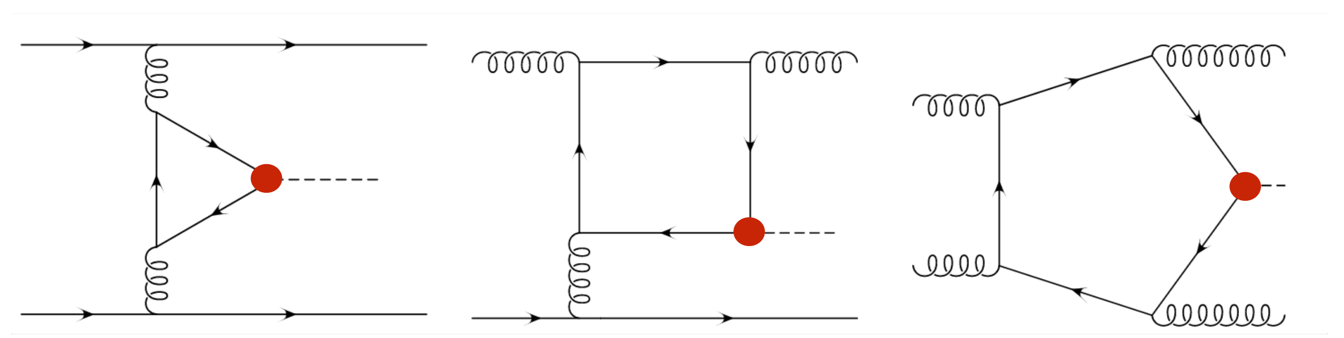



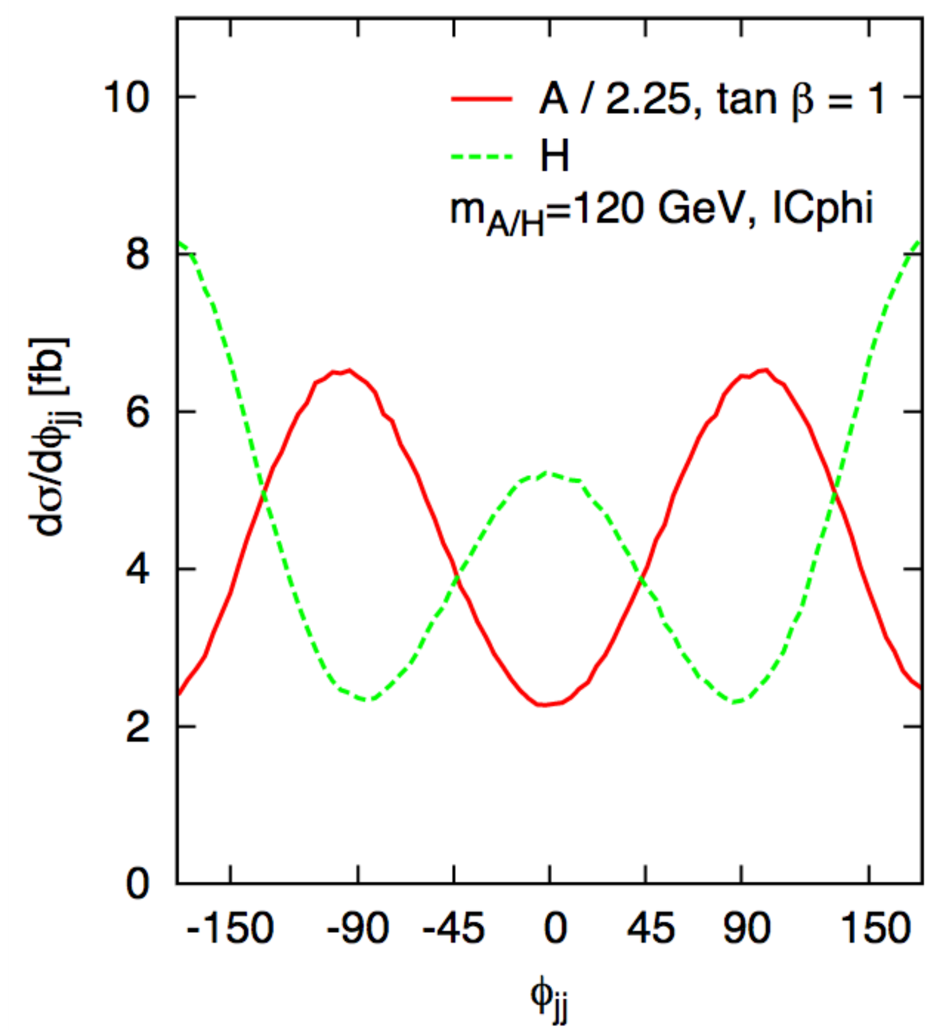

Brod, Haisch, Zupan (2013); Engel, Ramsey-Musolf, Kolck (2013); Cirigliano, Dekens, Vries, Mereghetti (2016)

# Indirect collider constraints

- Complementary top-Higgs CP measurement at LHC:

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






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

- Loop-induced: indirect constraints

- Bottom line:

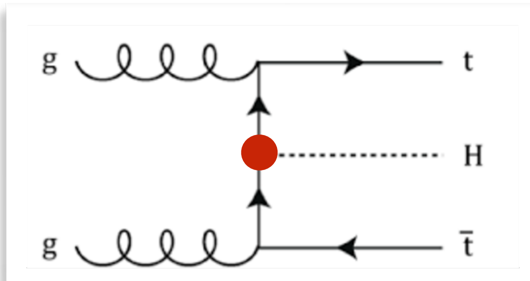
  Analogously to *direct* yt signal strength measurement,

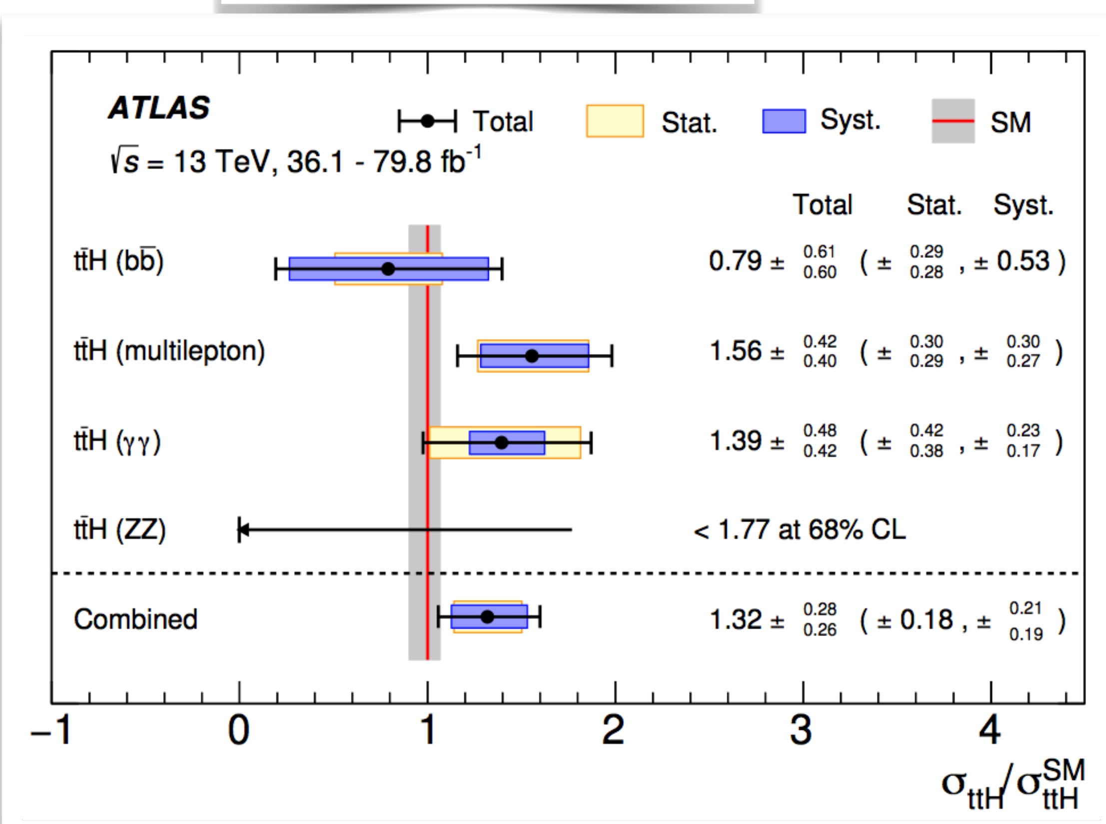
  the direct Higgs-top CP structure has in the ttH channel

  its most natural path

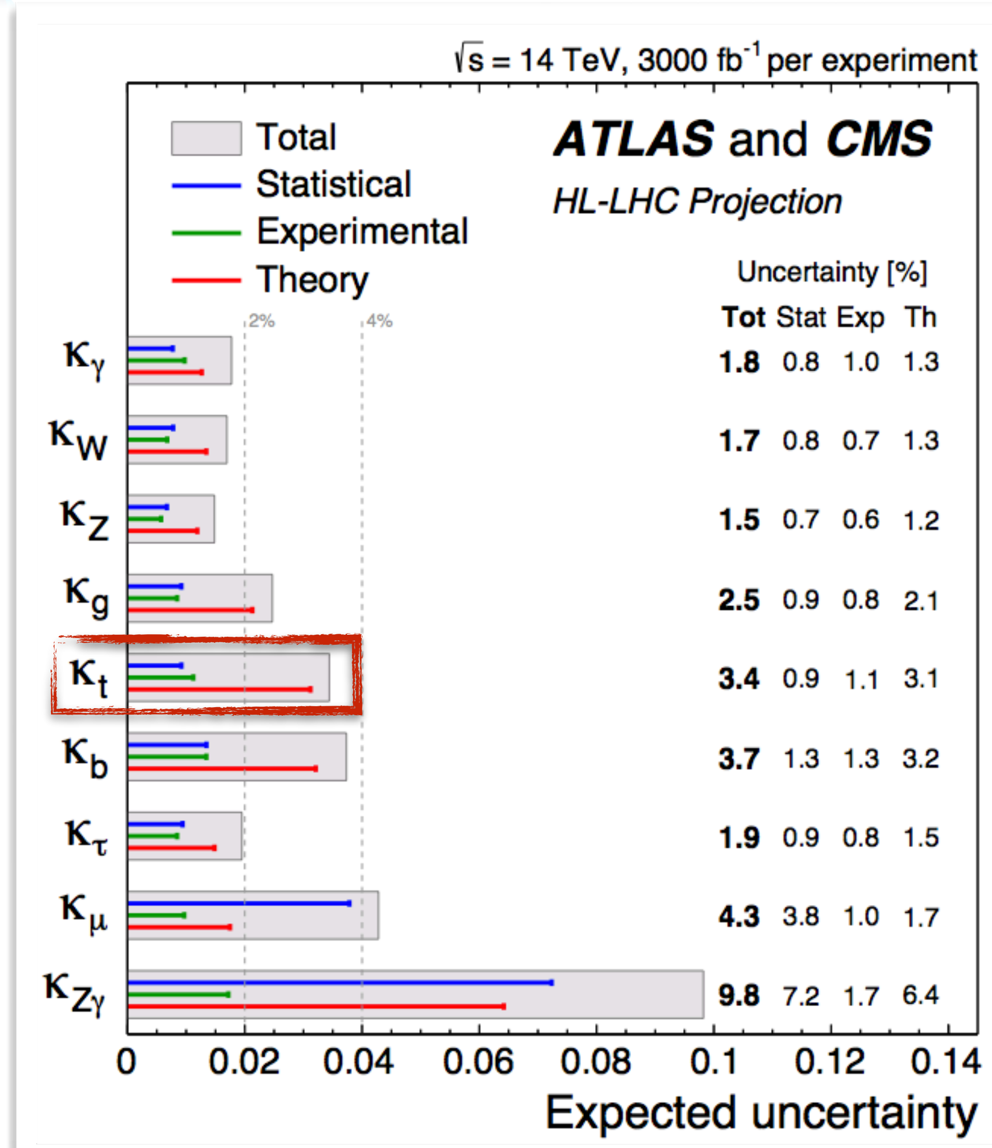
# Direct CP measurement of Higgs-top coupling

- ttH channel observation (2018):




- Expected HL-LHC precisions:

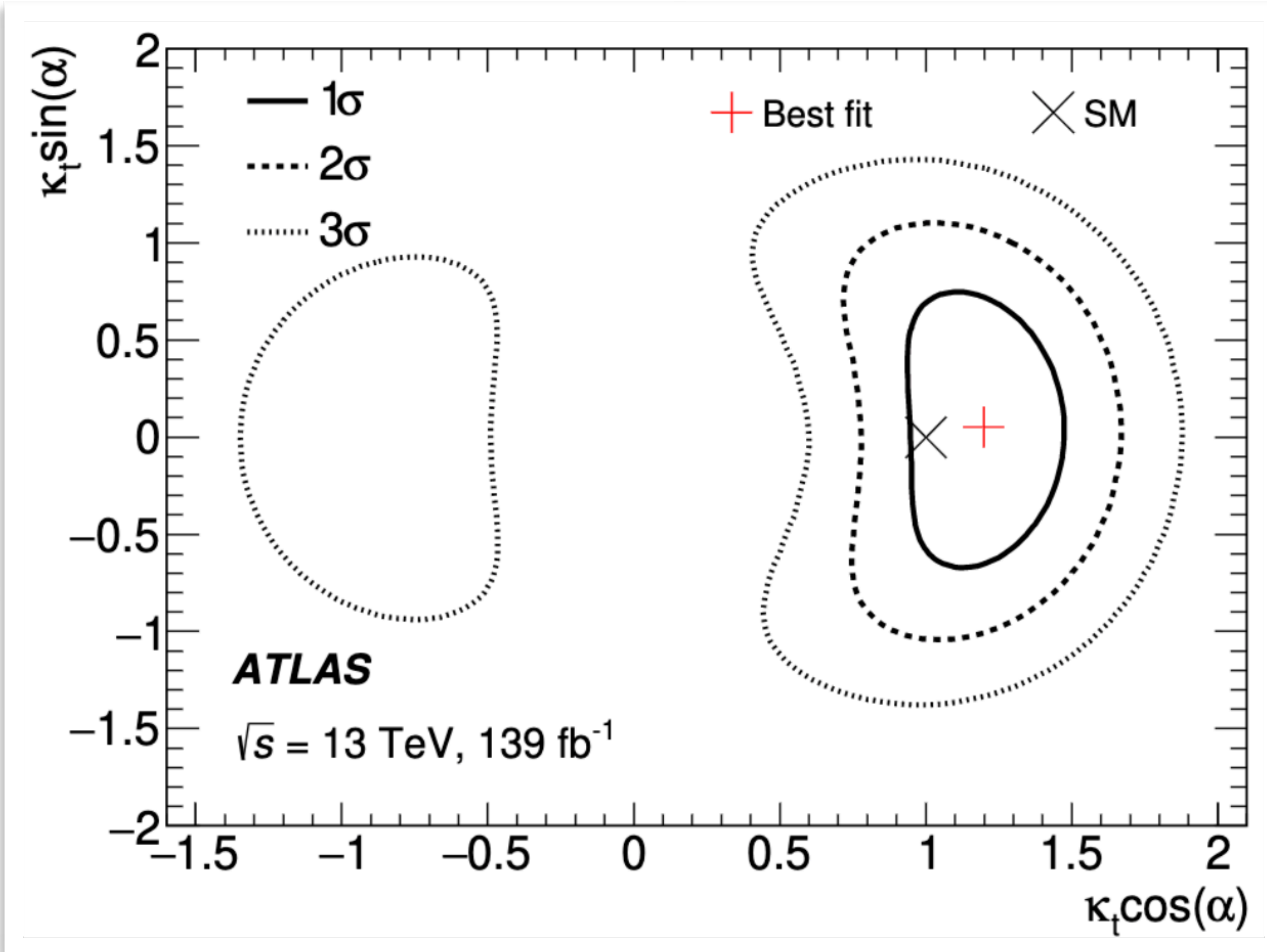



- Opportunity: direct measure Higgs-top CP structure at the LHC

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

# Direct CP measurement of Higgs-top coupling

- Current limits: $|\alpha| < 43°$ (ATLAS) and $|\alpha| < 55°$ (CMS)



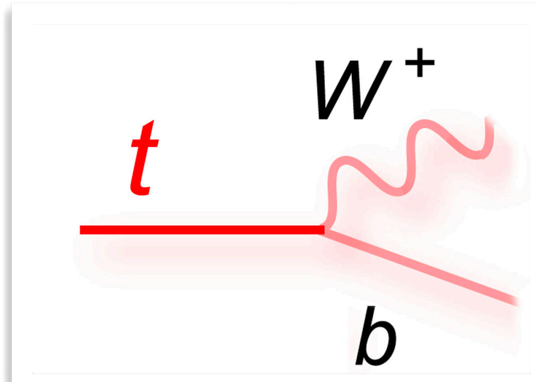

ATLAS – arxiv:2004.04545
CMS – arxiv:2003.10866

→ Improved rates at HL-LHC coupled with efficient kinematic reconstruction and machine learning techniques can lead to large sensitivity

# Top Quark is Unique

- Decays before hadronizing and significantly prior to spin flip by strong interactions:

$$\tau_{top} \approx 5 \times 10^{-25} s$$
$$\tau_{had} \approx 2 \times 10^{-24} s$$
$$\tau_{flip} \approx 10^{-21} s$$




Bottom quark is several orders of magnitude behind: $\tau_b \approx 10^{-12} s$

- Top polarization directly observable via angular distributions of its decay products

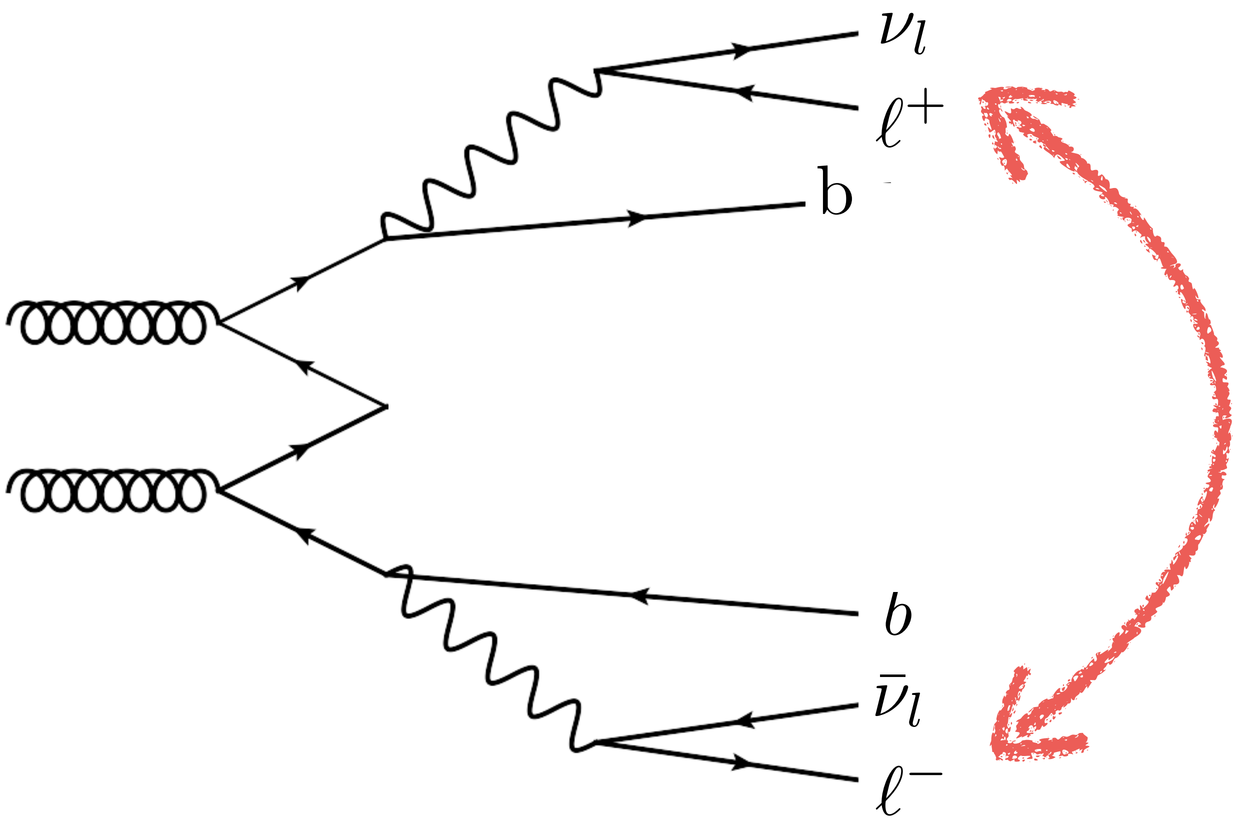
$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + \omega_f P_t \cos\theta_f)$$

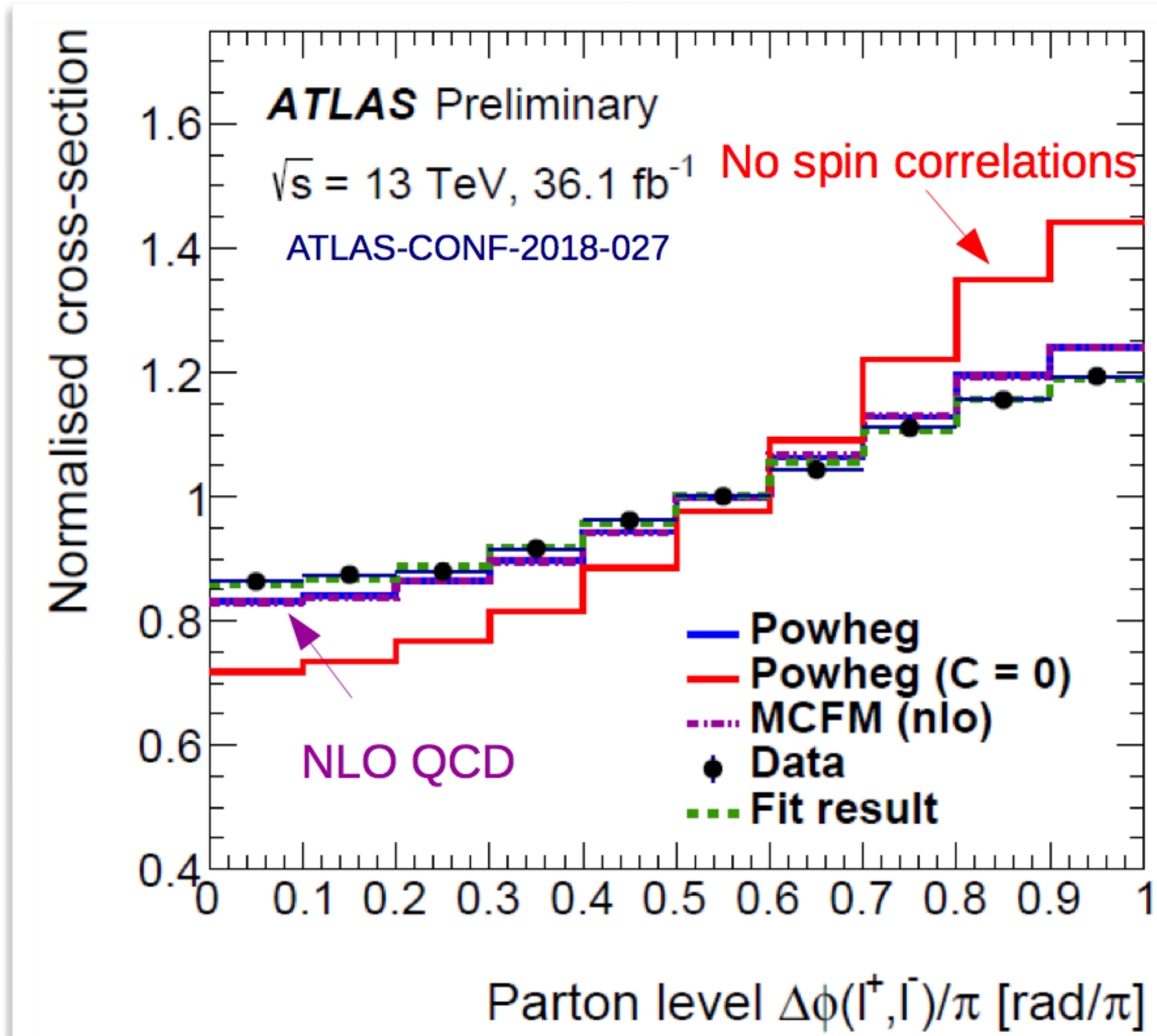
| | $l^+, d$ | $b$ | $\nu, u$ |
|---|---|---|---|
| $\omega_f$ | $1$ | $-0.4$ | $-0.3$ |

Spin analyzing power: maximum for charged leptons

# Top quark polarization

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




Parke, Mahlon '10

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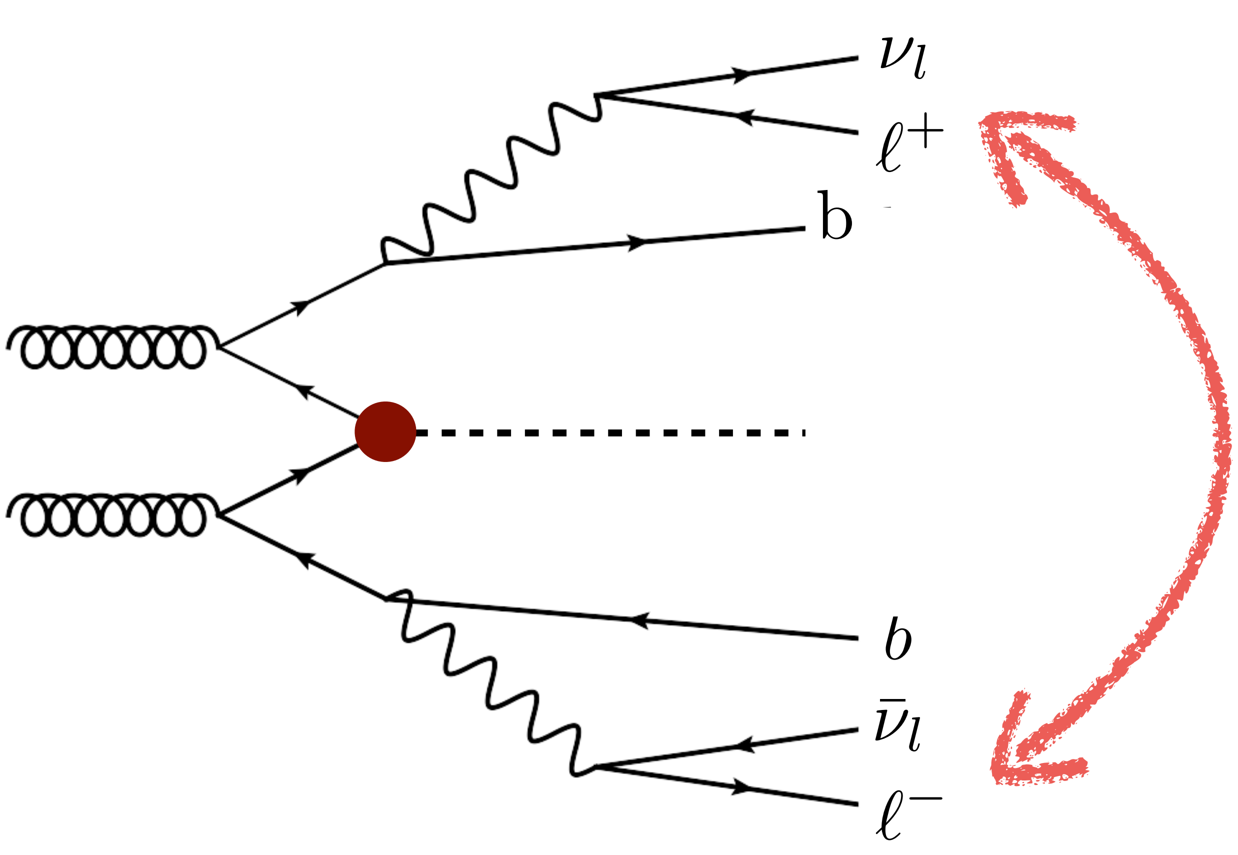
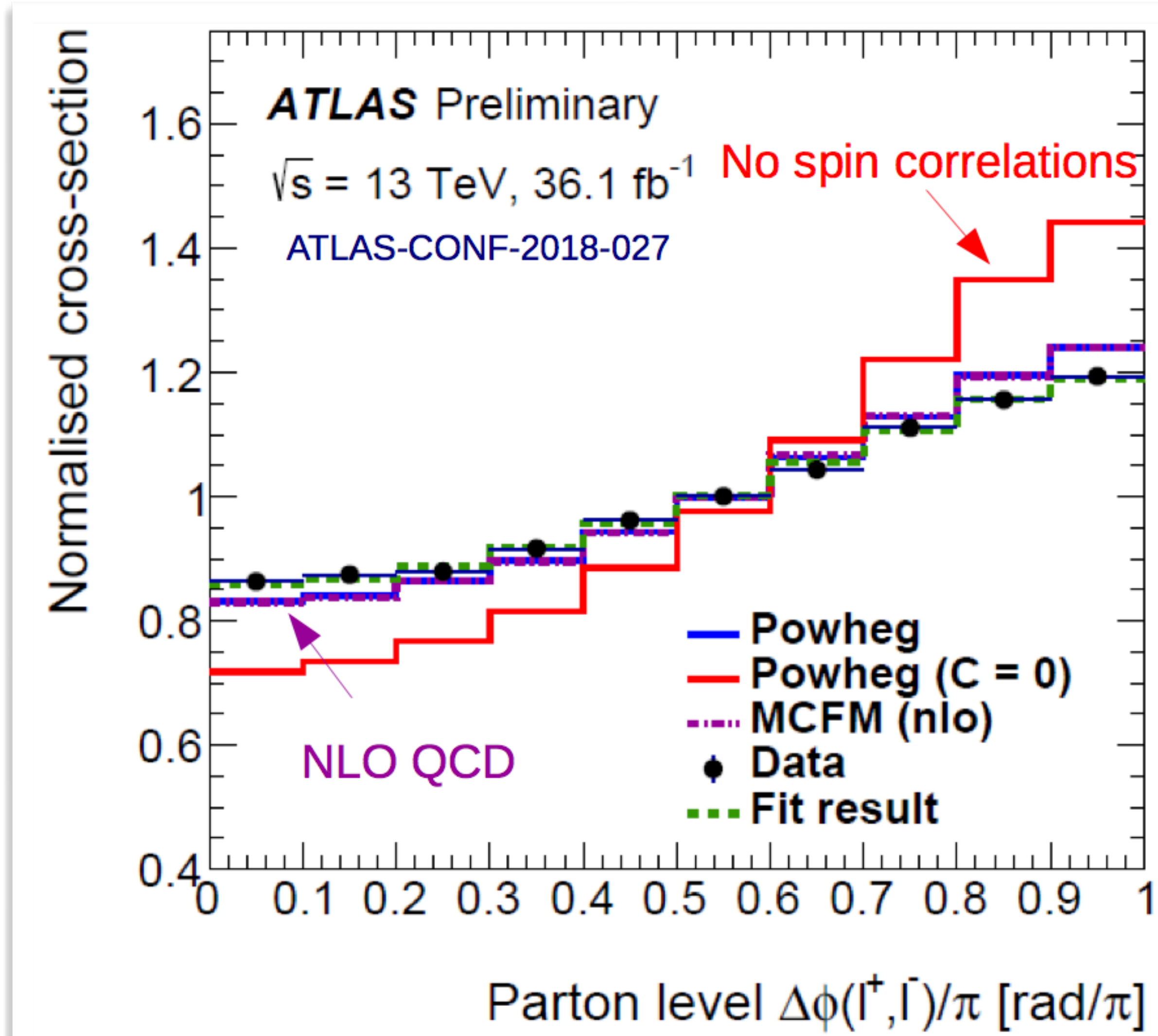



$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left( \cos\alpha + i\gamma_5 \sin\alpha \right) t \; H$$

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

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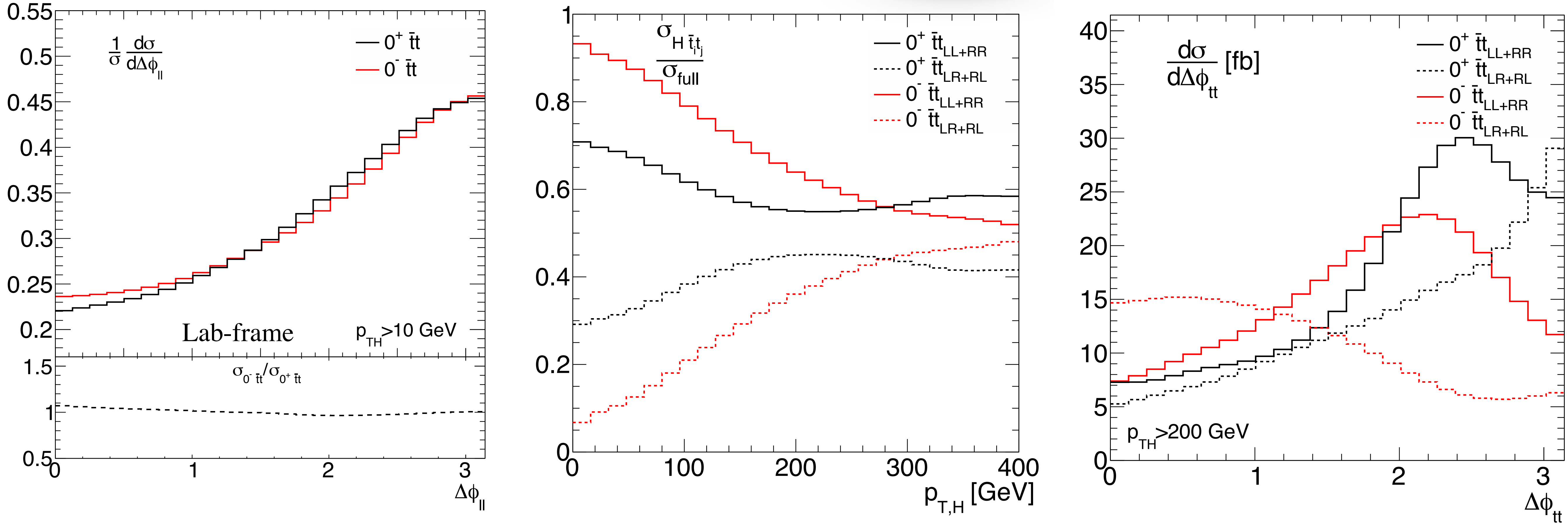


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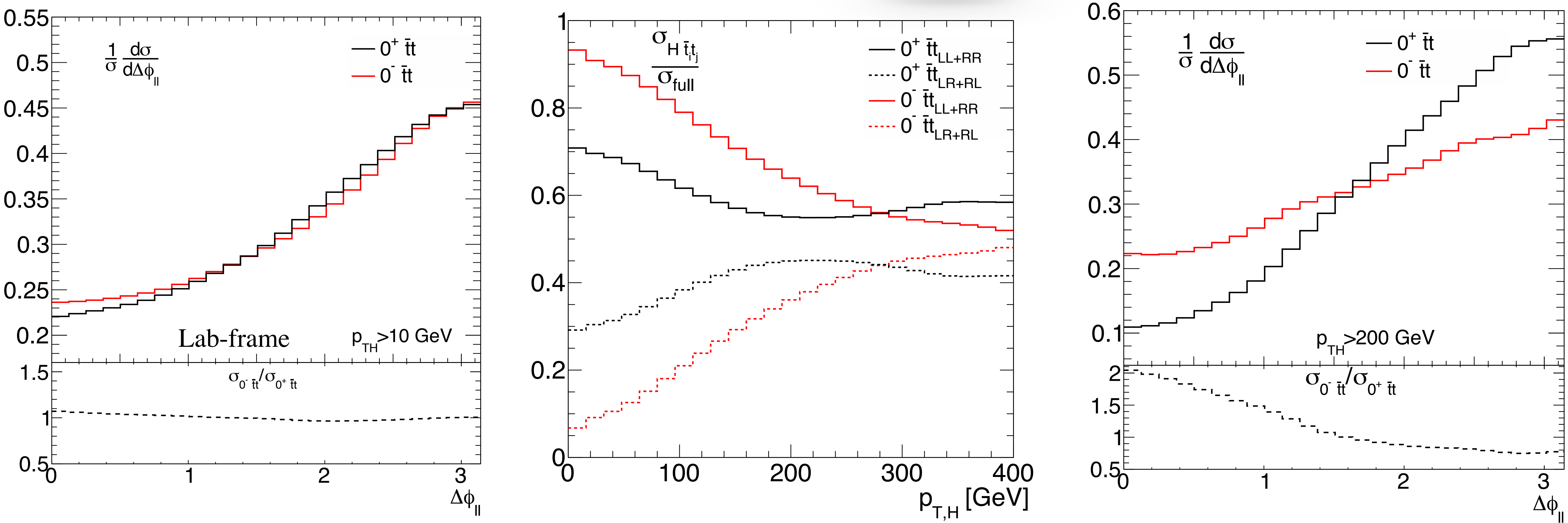


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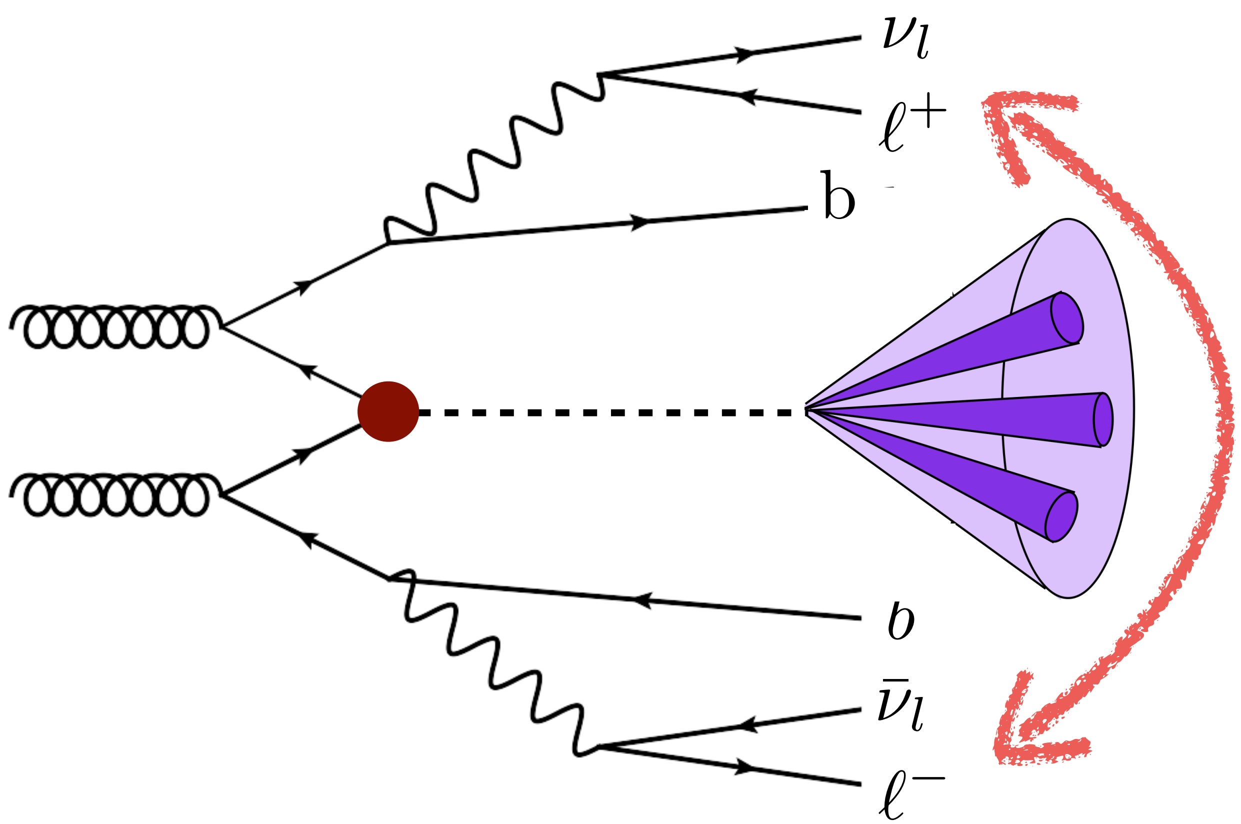
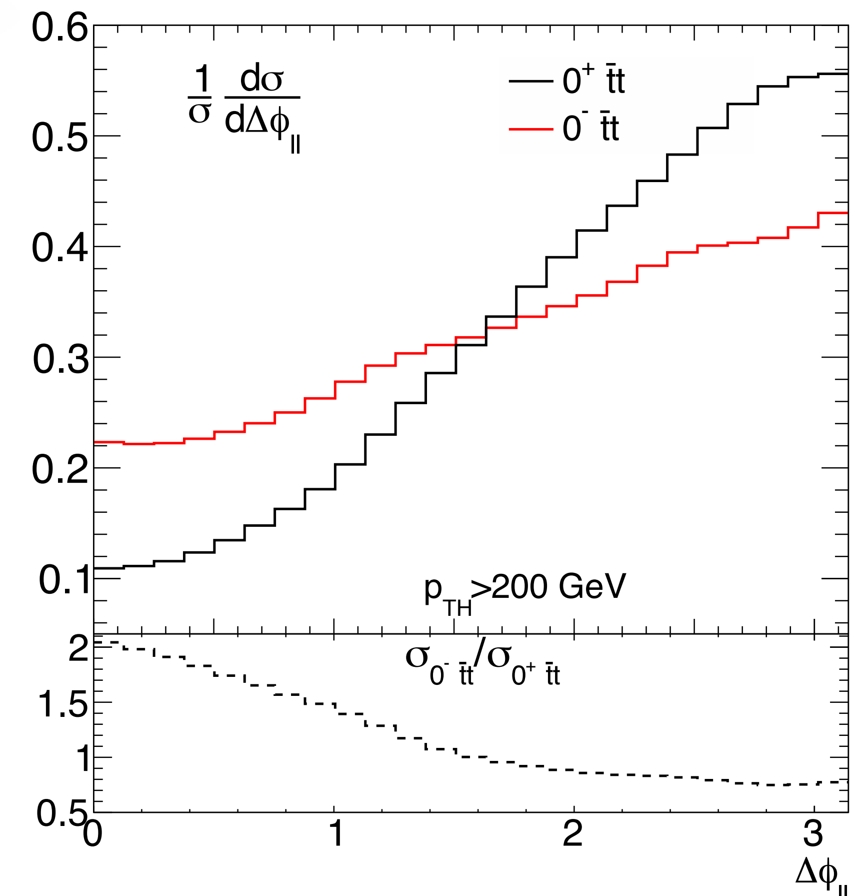



Buckley, **DG** (PRL '15)

- **Boosted Higgs** study nicely match with Higgs-top CP-measurement
  $h \to b\bar{b}$

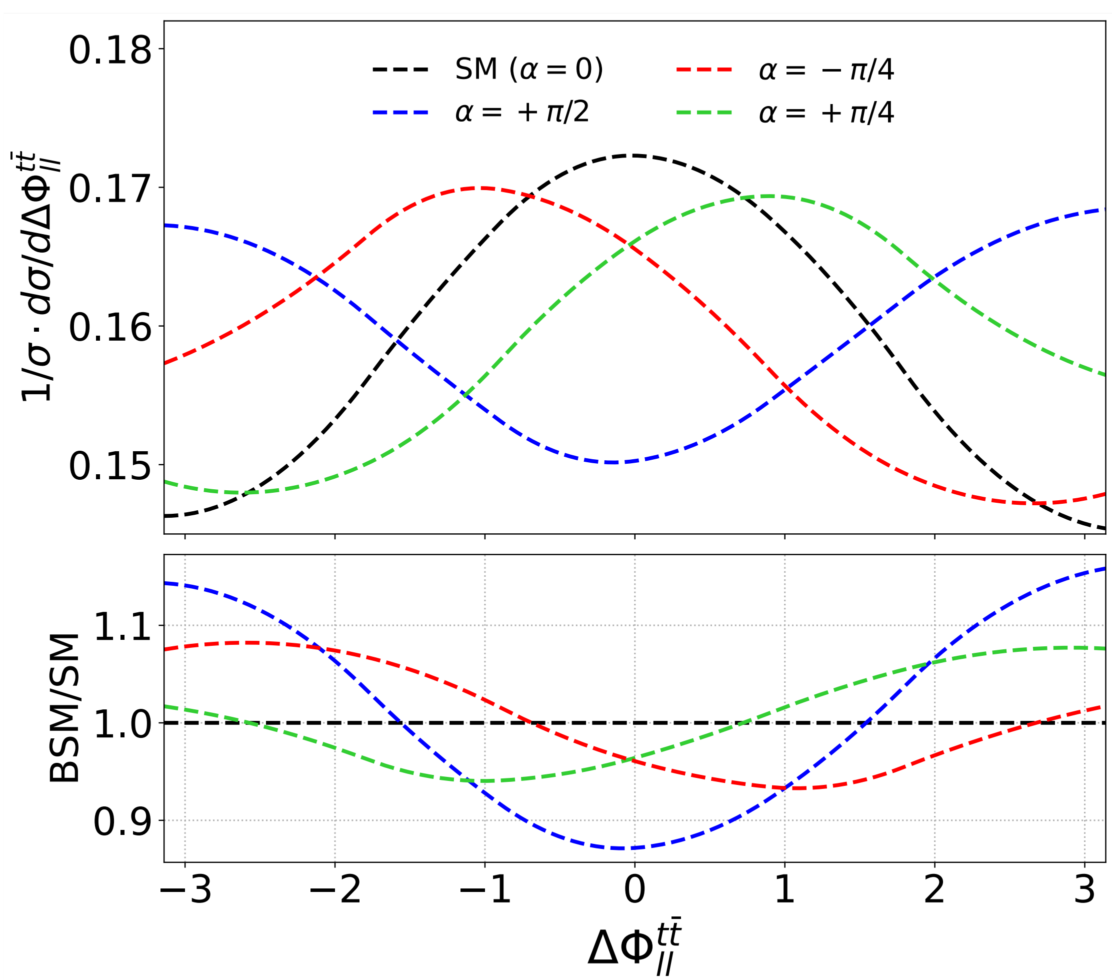
# CP sensitive observables

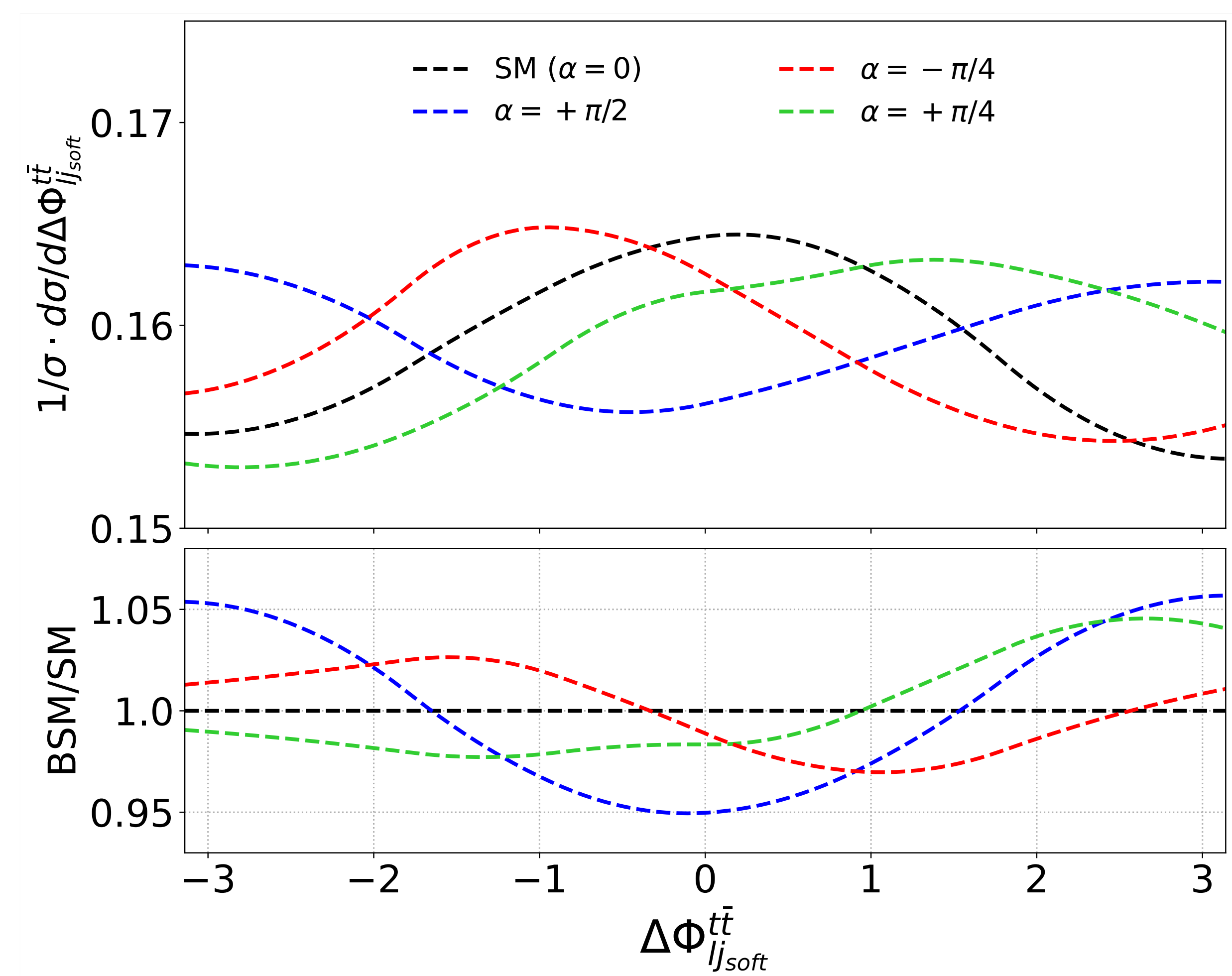
- CPV observables best defined at the top pair rest frame:

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

$$\epsilon_{\mu\nu\rho\sigma}p_a^\mu p_b^\nu p_c^\rho p_d^\sigma = E_a\, \vec{p_b}\cdot(\vec{p_c}\times\vec{p_d}) + E_c\, \vec{p_d}\cdot(\vec{p_a}\times\vec{p_b}) - E_b\, \vec{p_c}\cdot(\vec{p_d}\times\vec{p_a}) - E_d\, \vec{p_a}\cdot(\vec{p_b}\times\vec{p_c})$$

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




**DG**, Kong, Kim '18 & '21, Barman, **DG**, Kling '21

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$$\epsilon_{\mu\nu\rho\sigma}p_a^\mu p_b^\nu p_c^\rho p_d^\sigma = \quad E_a\, \vec{p_b}\cdot(\vec{p_c}\times\vec{p_d}) + E_c\, \vec{p_d}\cdot(\vec{p_a}\times\vec{p_b}) - E_b\, \vec{p_c}\cdot(\vec{p_d}\times\vec{p_a}) - E_d\, \vec{p_a}\cdot(\vec{p_b}\times\vec{p_c})$$

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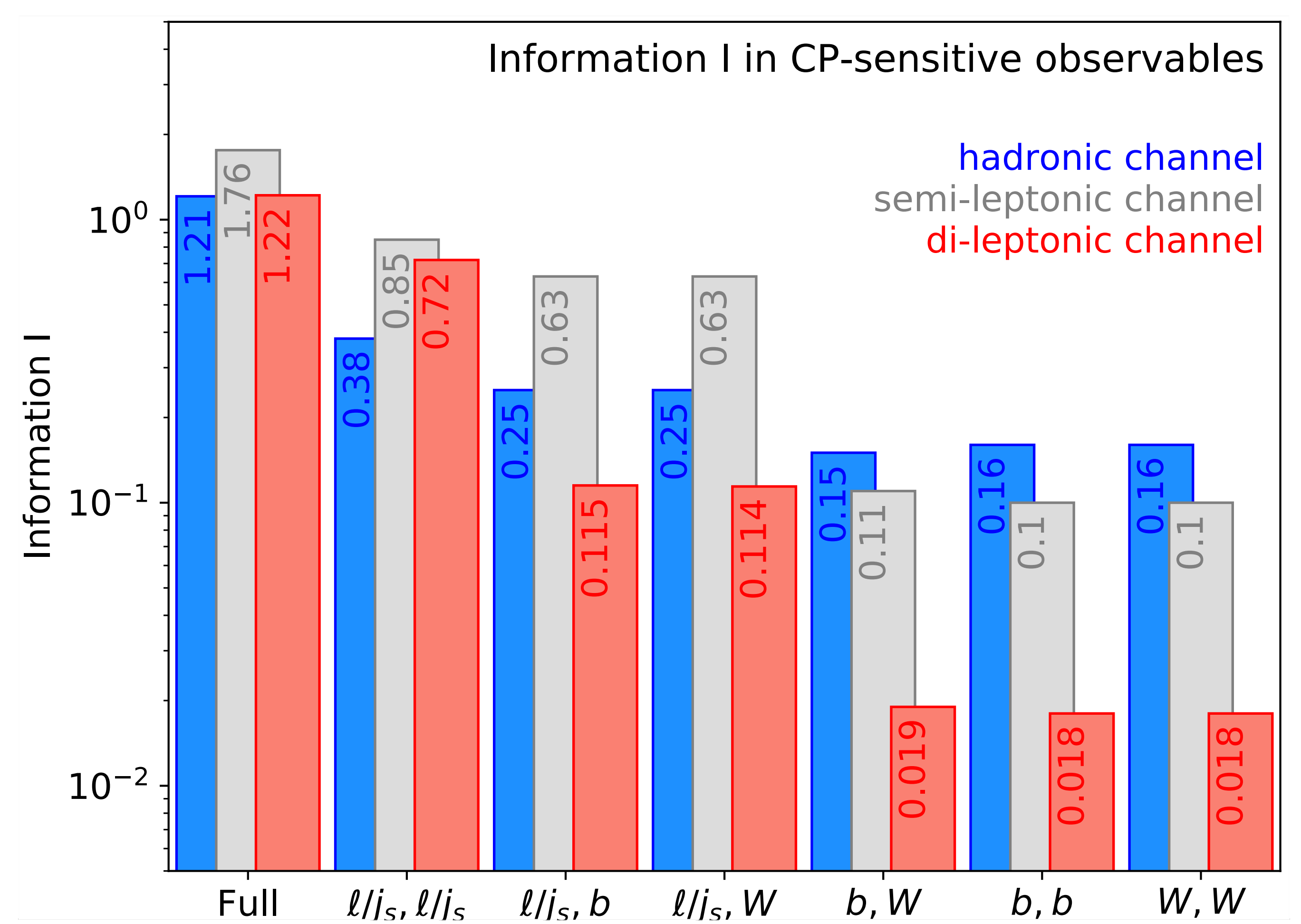


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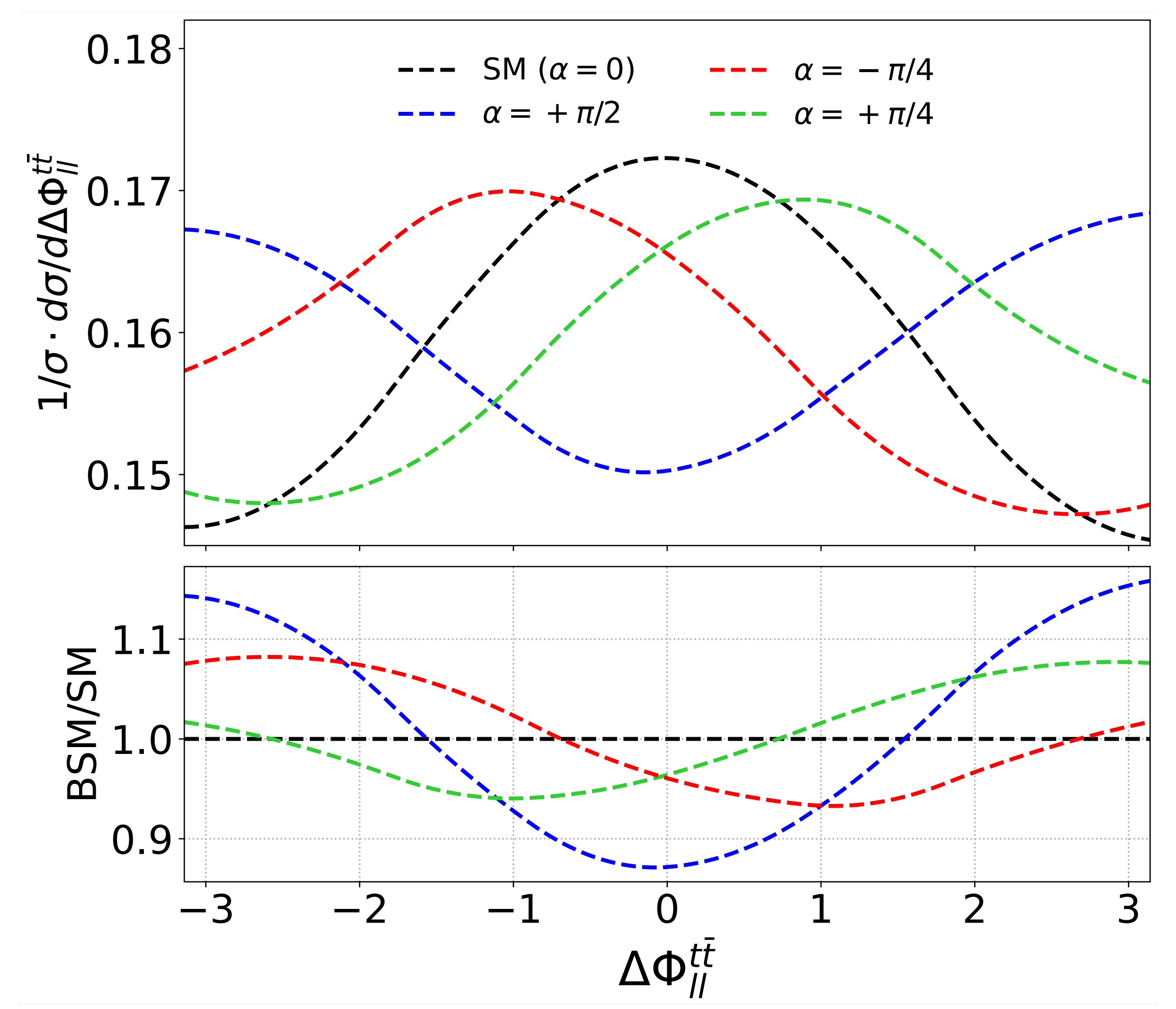
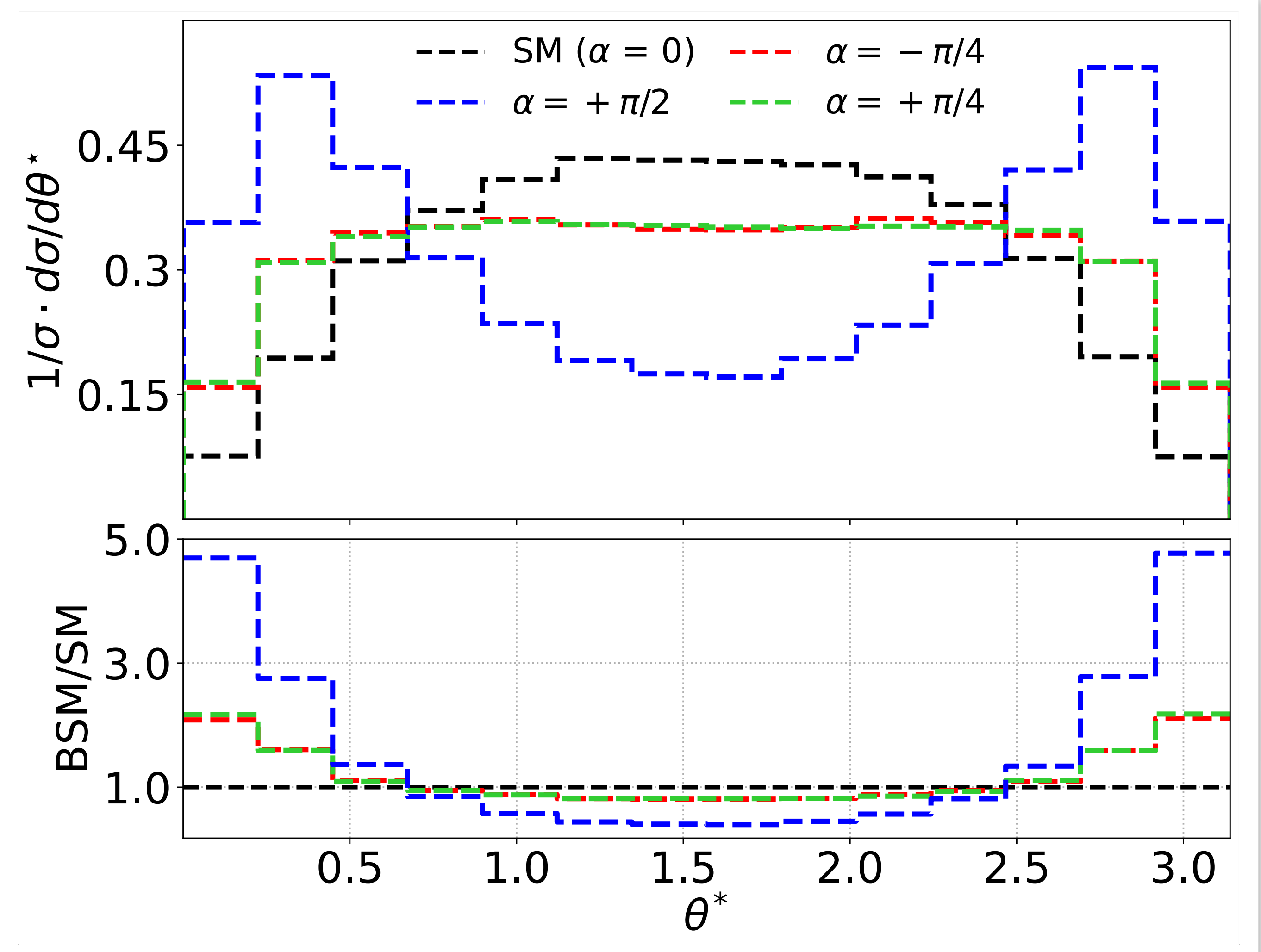
# Top Reconstruction

- Full reconstruction of the top pair system is required to maximize CP-sensitivity



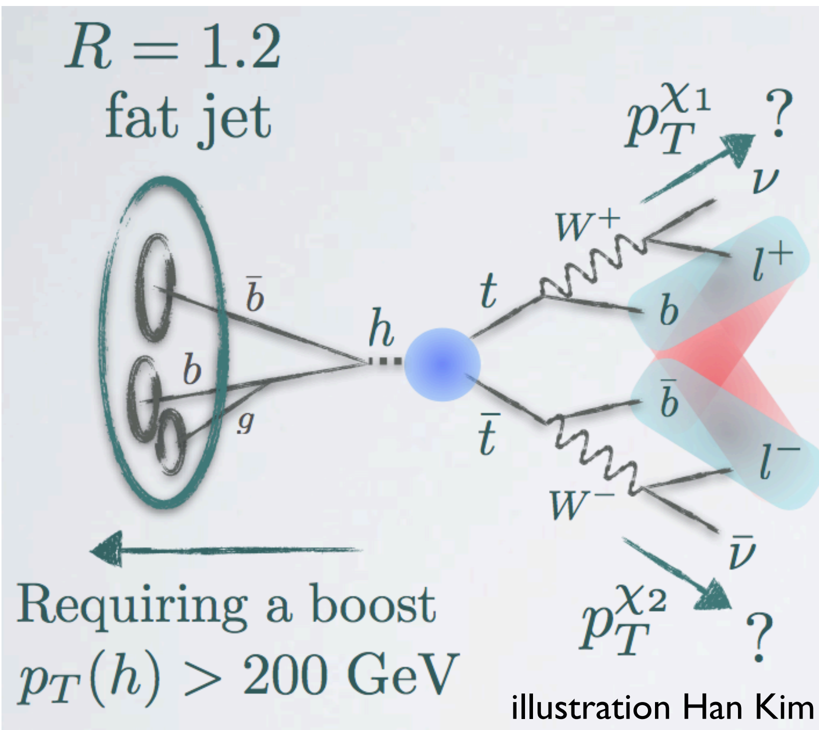




Combinatorial ambiguities and presence of up to two neutrinos makes reconstruction challenging

**DG**, Kong, Kim '18 & '21, Barman, **DG**, Kling '21

# Top Reconstruction

- 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**

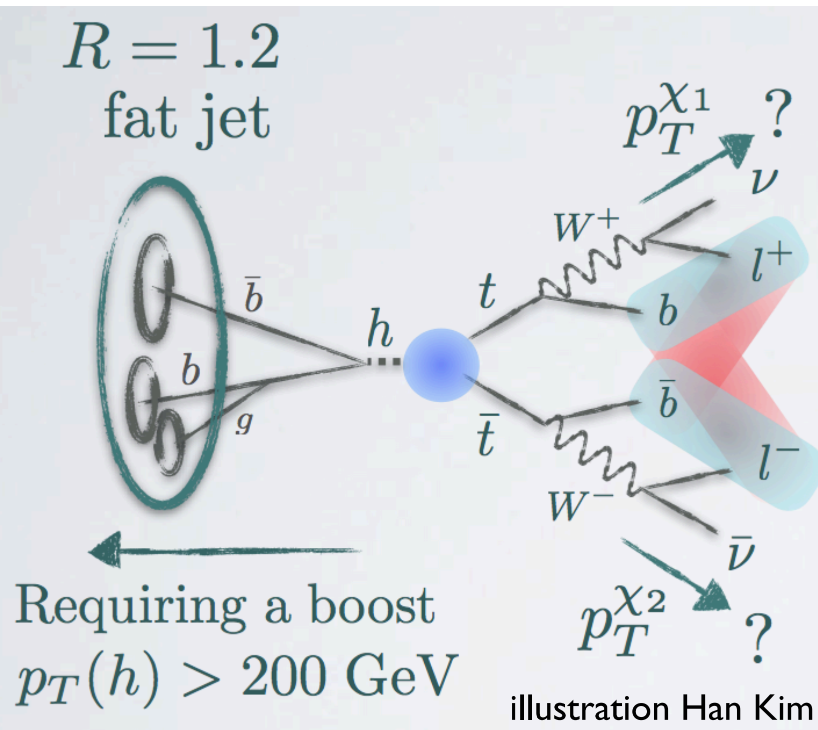
a) **guess neutrino momenta**
b) **solve combinatorial problem**

Generalization of MT2 with mass constraints:

$$
\begin{aligned}
M_{2CW}^{(b\ell)} &\equiv \min_{\vec{q}_1,\vec{q}_2} \{\max\left[M_{t_1}(\vec{q}_1,\tilde{m}),\ M_{t_2}(\vec{q}_2,\tilde{m})\right]\} \\
\vec{q}_{1T} + \vec{q}_{2T} &= \vec{\not{P}}_T \\
M_{t_1} &= M_{t_2} \\
M_{W_1} &= M_{W_2} = m_W
\end{aligned}
$$

# Top Reconstruction

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




Debnath, Kim, Kong, Matchev '17
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→ **Reconstruction of the Higgs: BDRS**

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a) **guess neutrino momenta**
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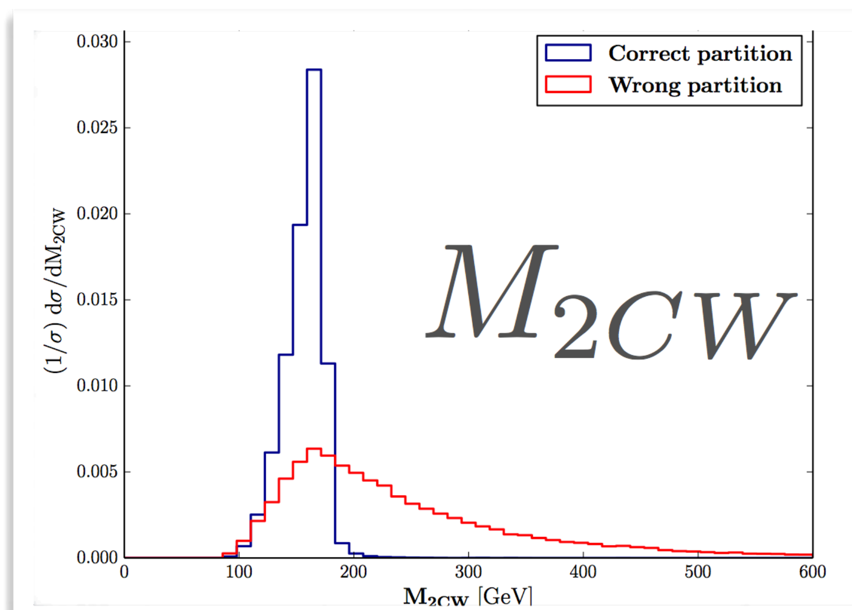
$M_{2CW}^{\text{correct}} \longrightarrow p_T^{\chi_1}(\text{correct}) \quad p_T^{\chi_2}(\text{correct})$

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



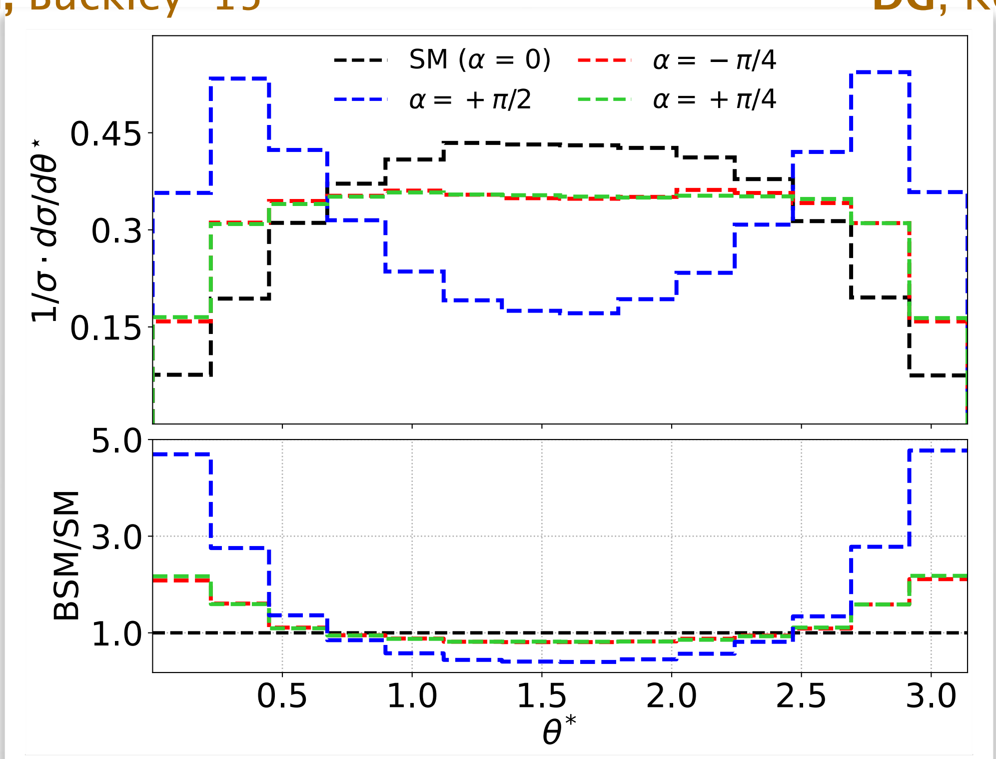

- The wrong partition often violates the end-points: Optimass uses it to pick up correct one

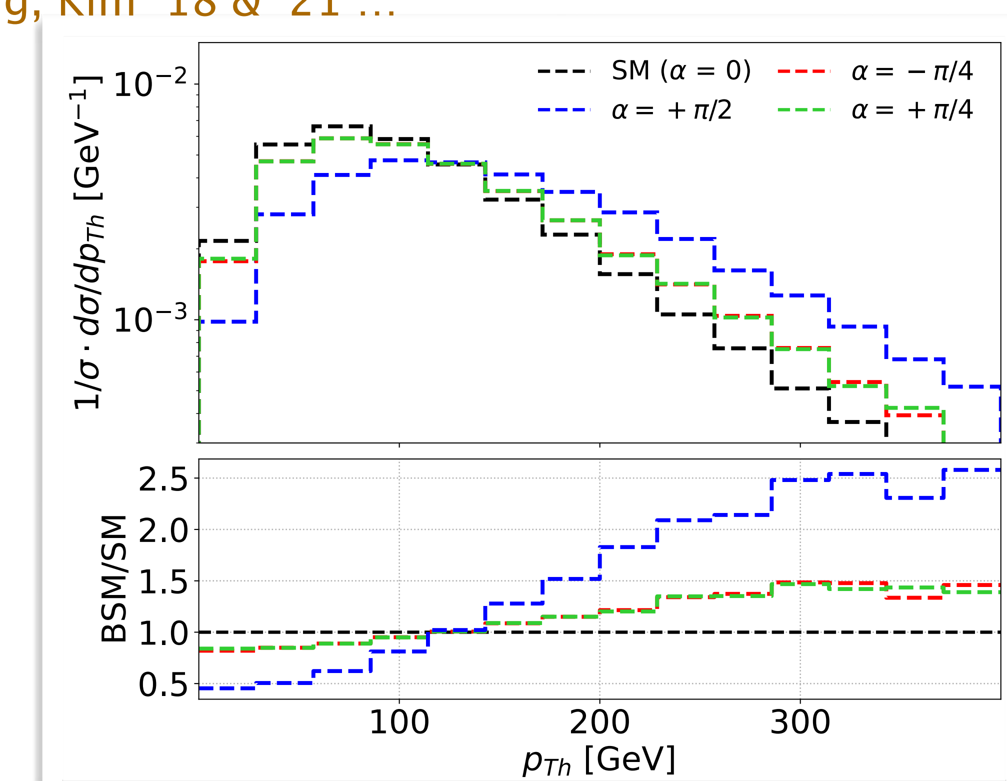
# Multivariate analysis problem

Numerous well-motivated observables have been explored in the literature

- $\theta^*$: angle between $t$ and beam direction in the $t\bar{t}$ CM frame.
- $b_4 = p^z_t p^z_{\bar{t}} / p_t p_{\bar{t}}$
- $m_{t\bar{t}}$: invariant mass of $t$ and $\bar{t}$.
- $p_{T,h}$: transverse momentum of $h$
- $\Delta\eta_{t\bar{t}}$: pseudorapidity difference between $t$ and $\bar{t}$.
- $m_{th}$: invariant mass of the $t$ and $h$.

Gunion, He '96
Ellis, Hwang, Samurai, Takeuchi '13
Demartin, Maltoni, Mawatari, Page, Zaro '14
**DG,** Buckley '15
Gritsan, Rontsch, Schulze, Xiao '16
Amor dos Santos et al. '17
Azevedo, Onofre, Filthaut, Gonçalo '17
**DG**, Kong, Kim '18 & '21 …

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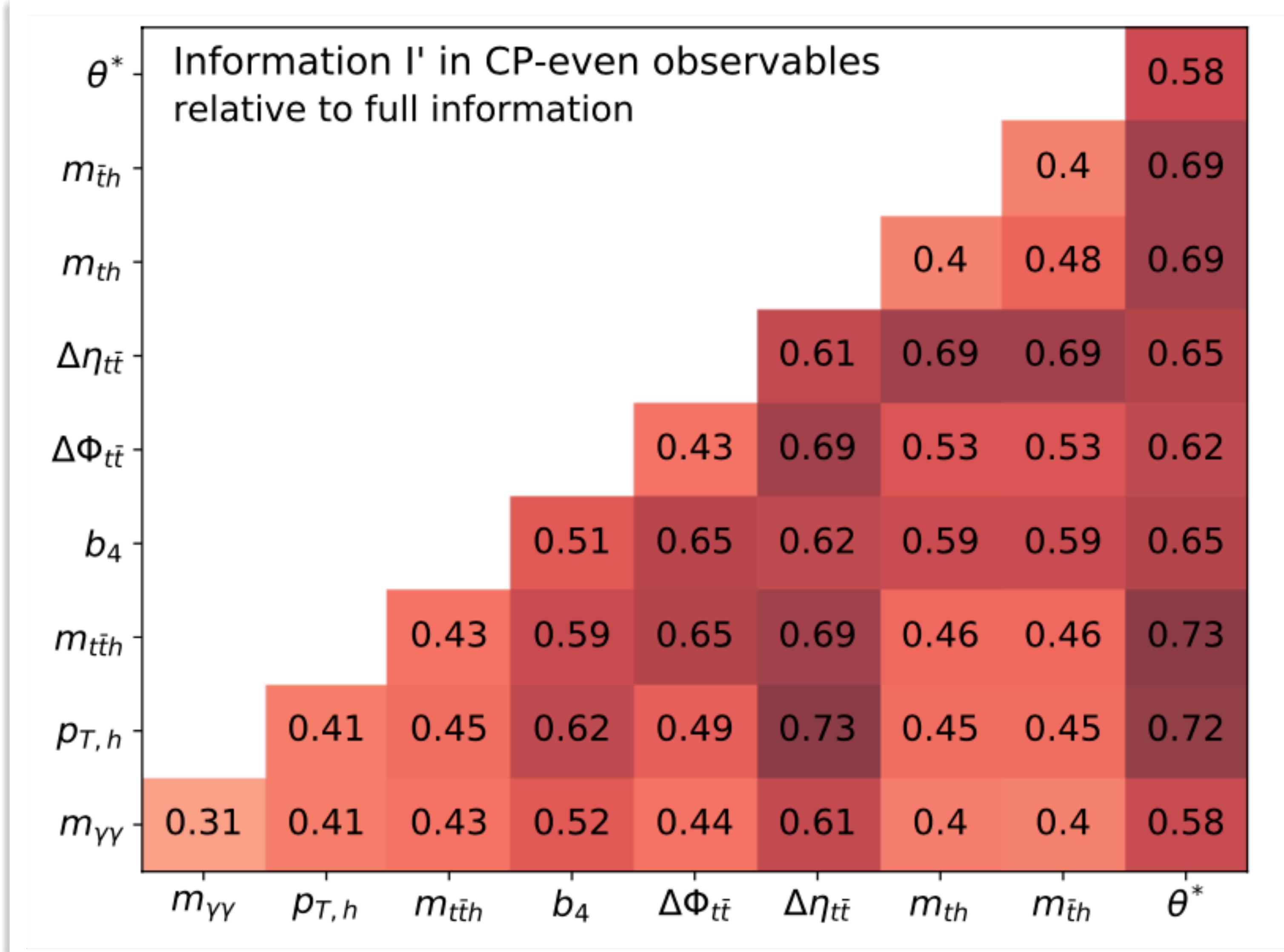
# Multivariate analysis problem

- Sensitivity on nonlinear BSM terms can be quantified through modified Fisher information:

  Brehmer, Dawson, Homiller, Kling, Plehn ‘19

$$I' = \mathbb{E}\left[\frac{\partial \log p(x|\kappa_t^2,\alpha^2)}{d\alpha^2}\frac{\partial \log p(x|\kappa_t^2,\alpha^2)}{d\alpha^2}\right]$$

$p(x|\kappa_t,\alpha)$ is the event likelihood, $\mathbb{E}[.]$ is the expectation value at SM.

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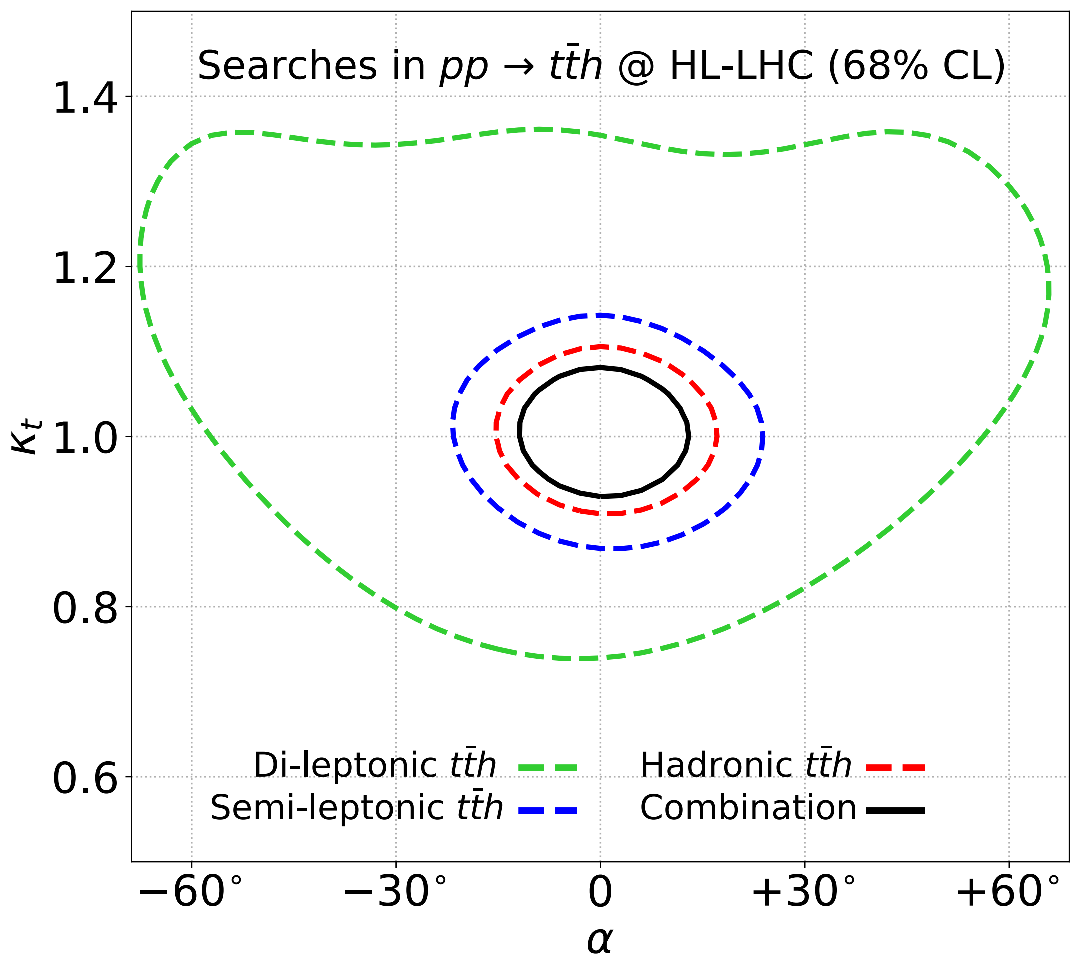
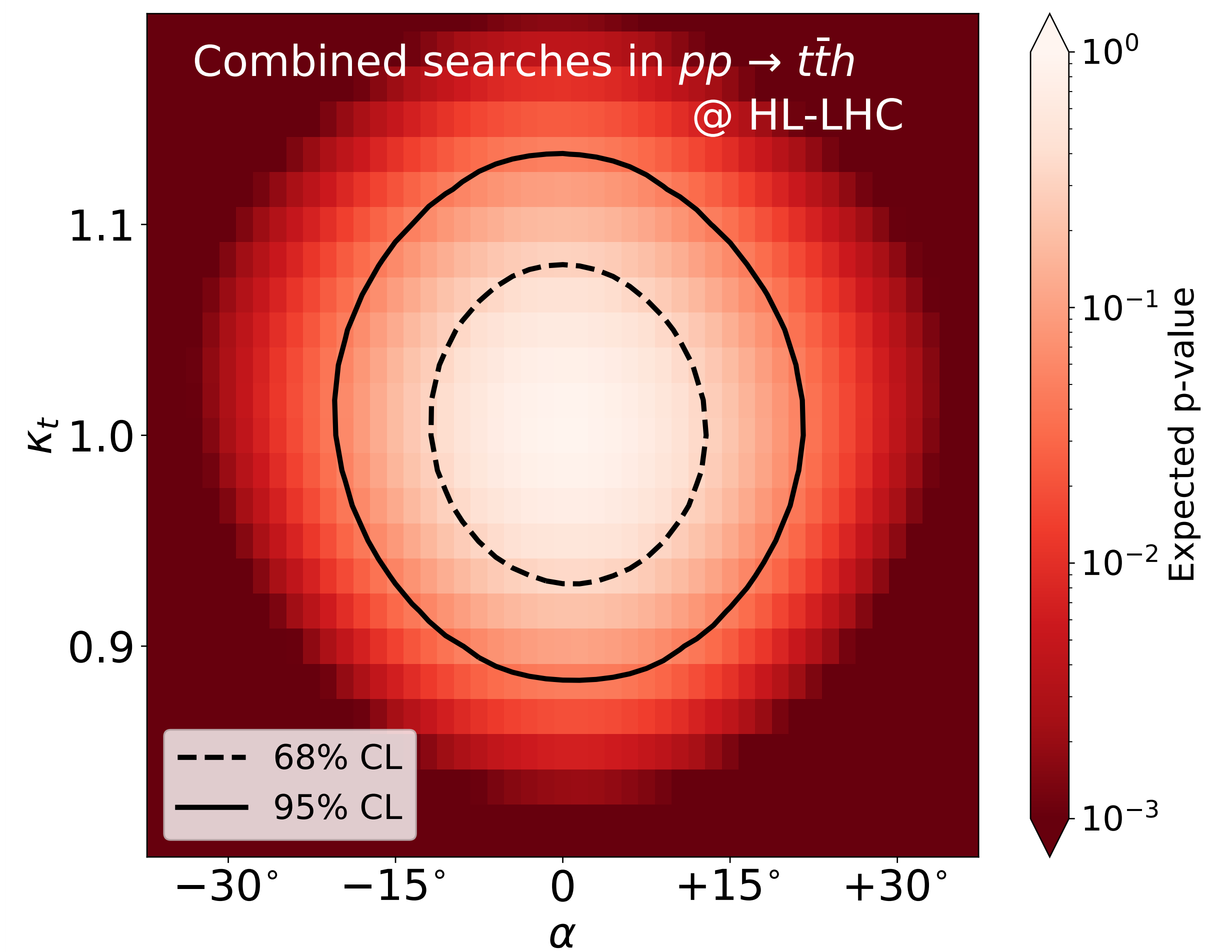
Information increases with successive addition of observables → Multivariate analysis problem

# HL-LHC Projections

- Recent $h \to \gamma\gamma$ study:



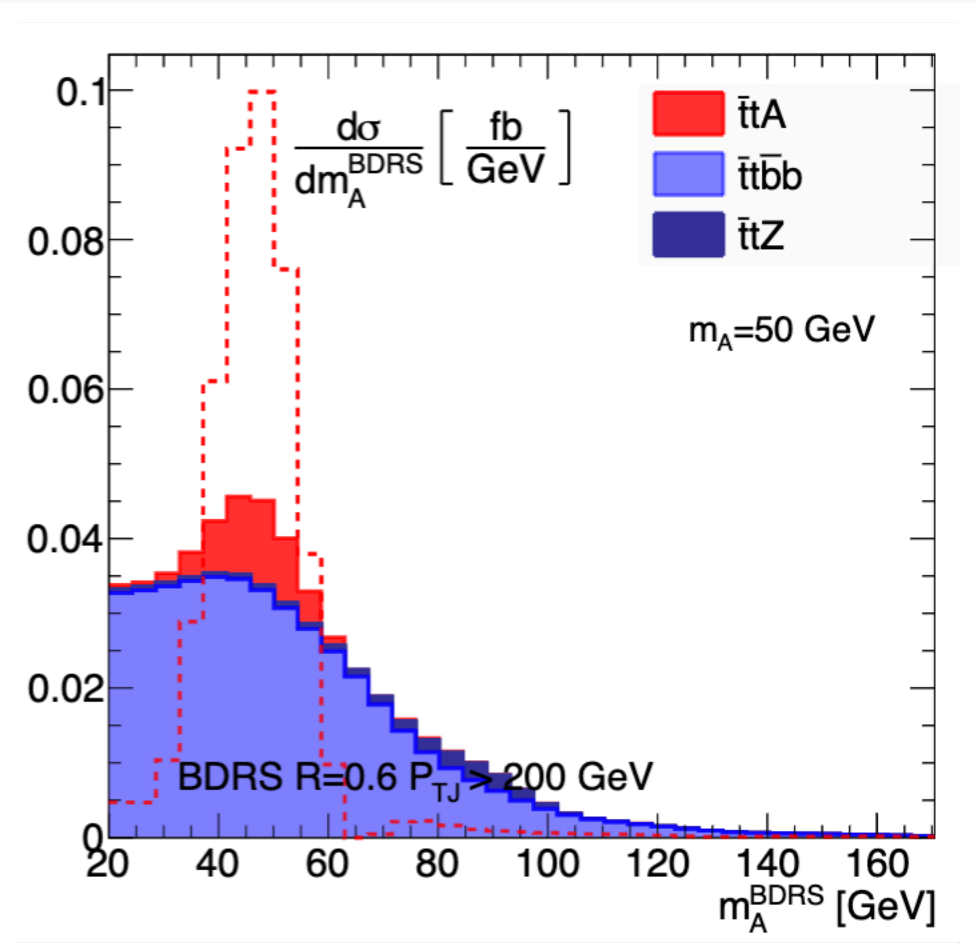



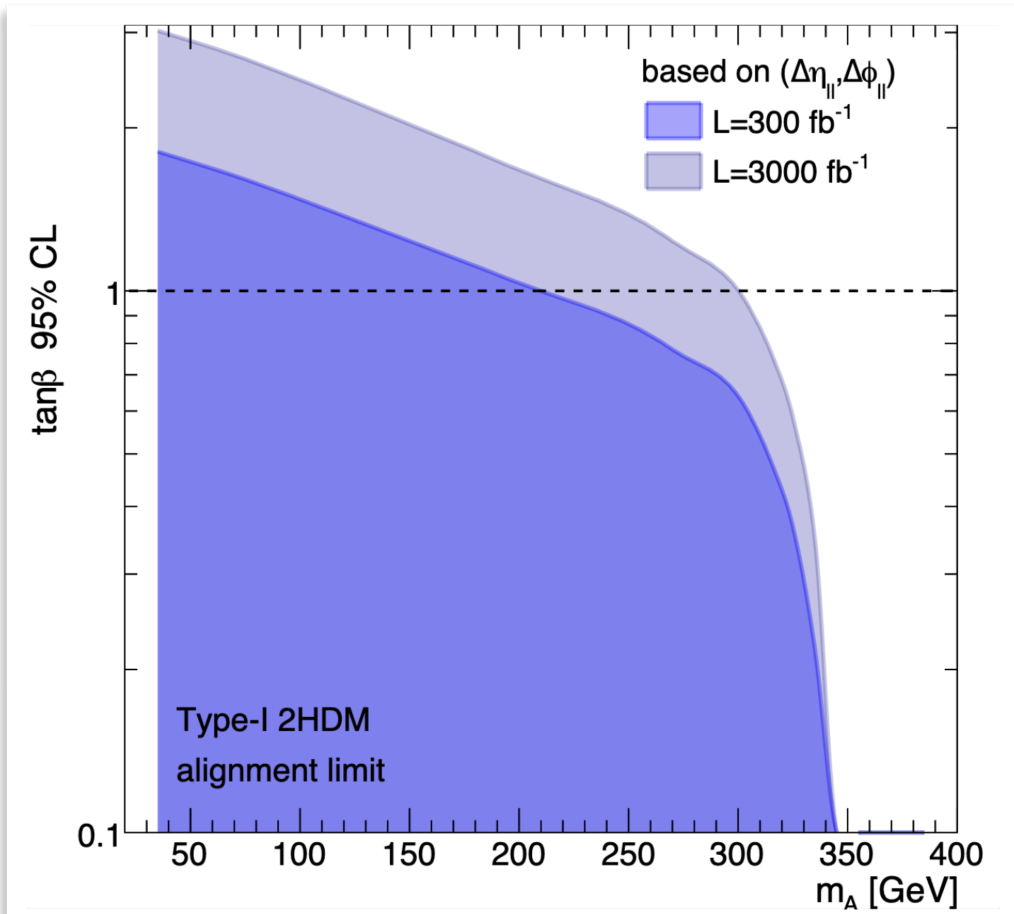

➡ Higgs-top CP phase could be probed up to $\alpha \lesssim 13^\circ$

Barman, **DG**, Kling '21

# Extended Scalar Sectors

- Seeking for light pseudoscalars: ttA(bb) can <u>direct</u> access the Yukawa and explore low $m_A$




➡ 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 coupling 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!