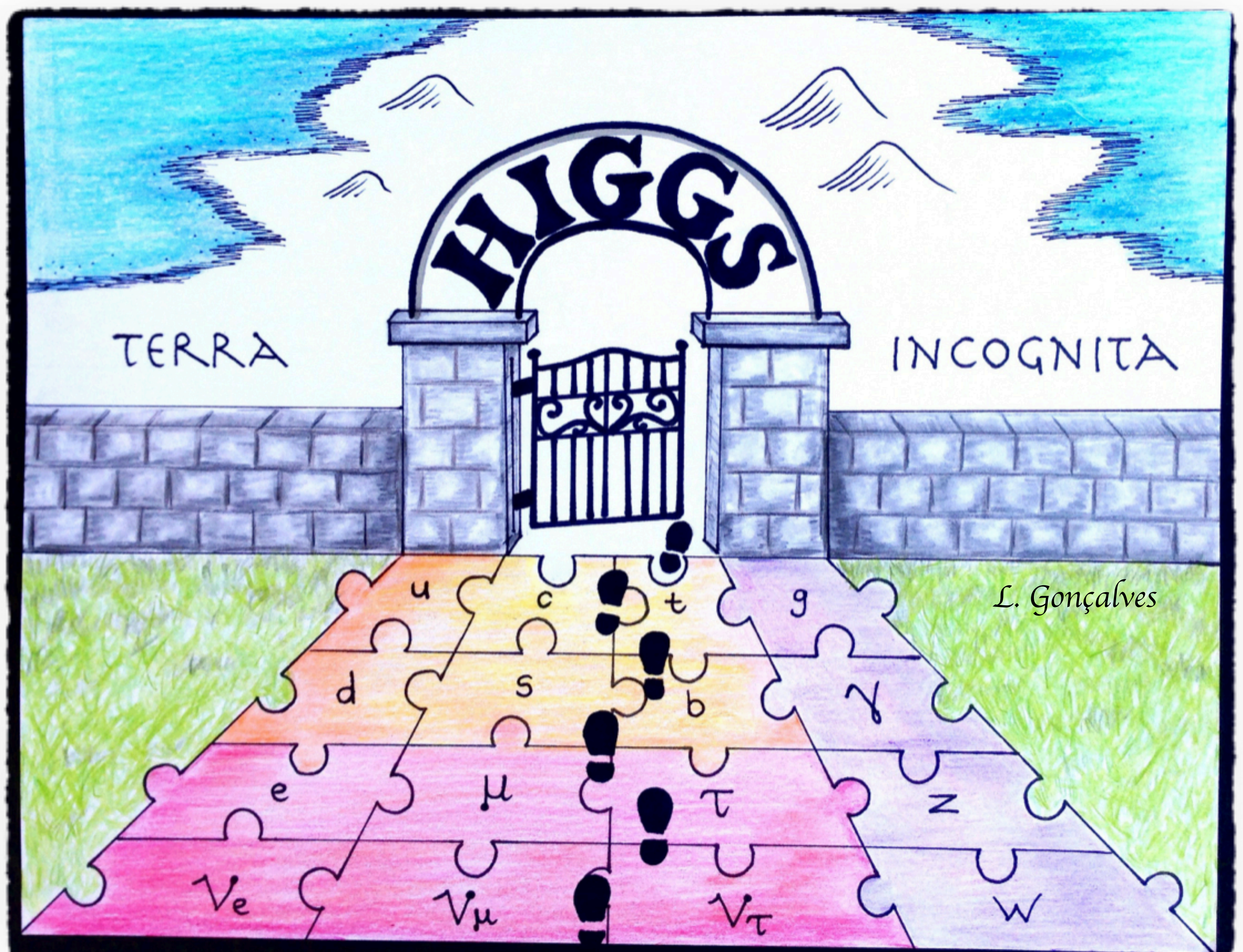
Prospects for CP measurements in ttH

Dorival Gonçalves

LHC Higgs Working Group - Nov 29, 2022



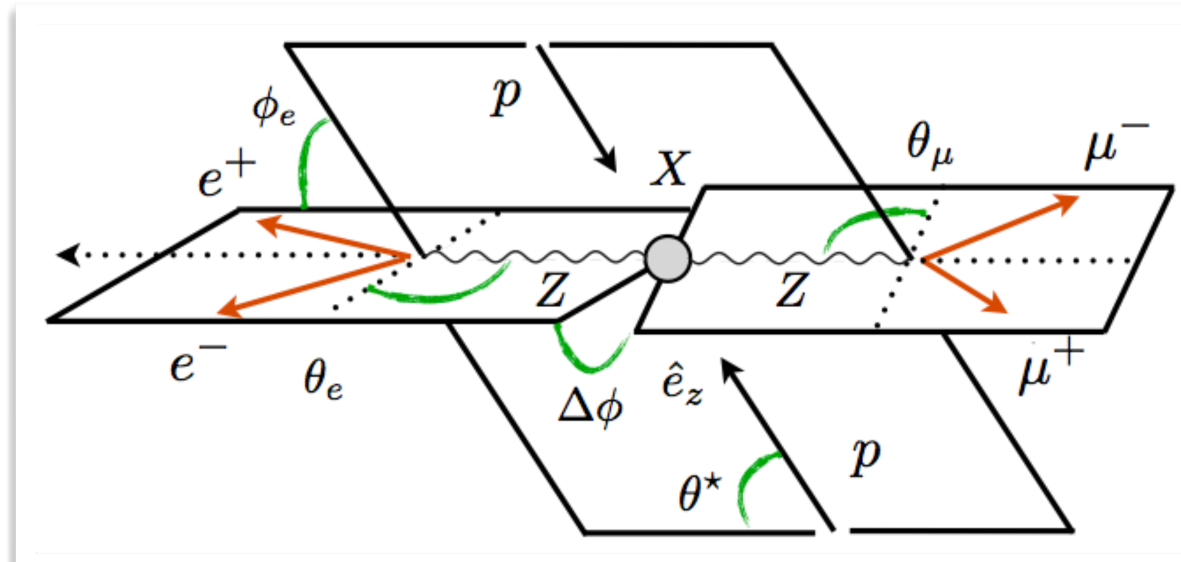
CP-violation

- 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

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



- While CP-odd HVV is loop suppressed, CP-odd Hff can manifest at tree-level:

→ Mixture possible in some models, e.g., 2HDM

→ Not excluded from Higgs measurements

→ Top quark is an obvious candidate

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

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

GF: Anderson, Bolognesi, Caola, Gao, Gritsan et al 13'

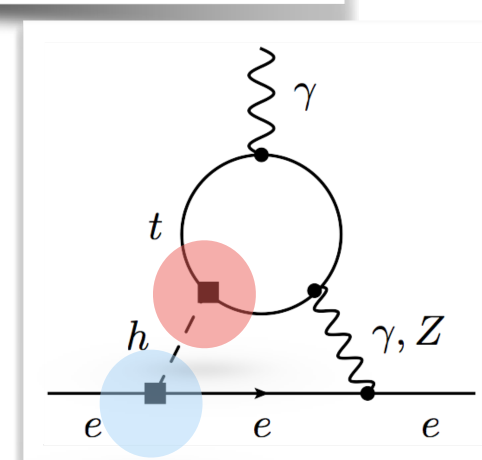
Dolan, Harris, Jankowiak, Spannowsky 14'

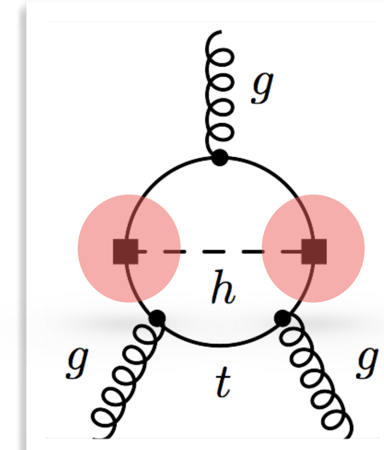
taus: Harnik, Martin, Okui, Primulando, Yu 13'

Indirect EDM constraints

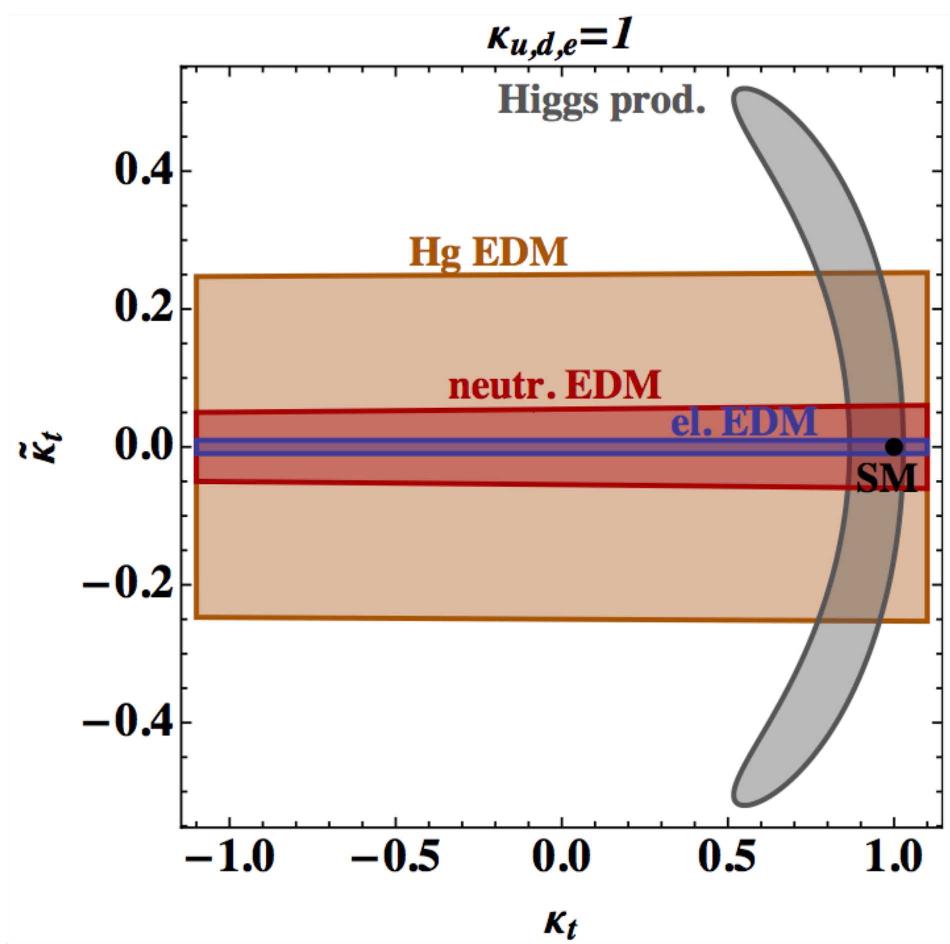
- Indirect constraints from eEDM very strong

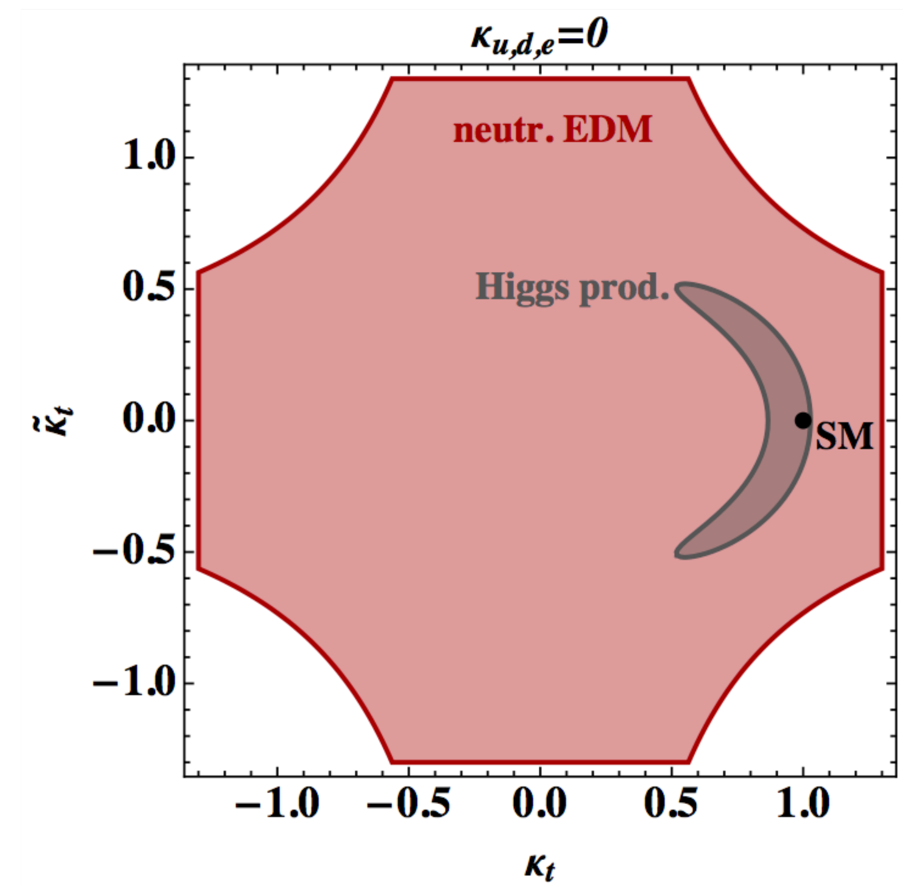
$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$





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



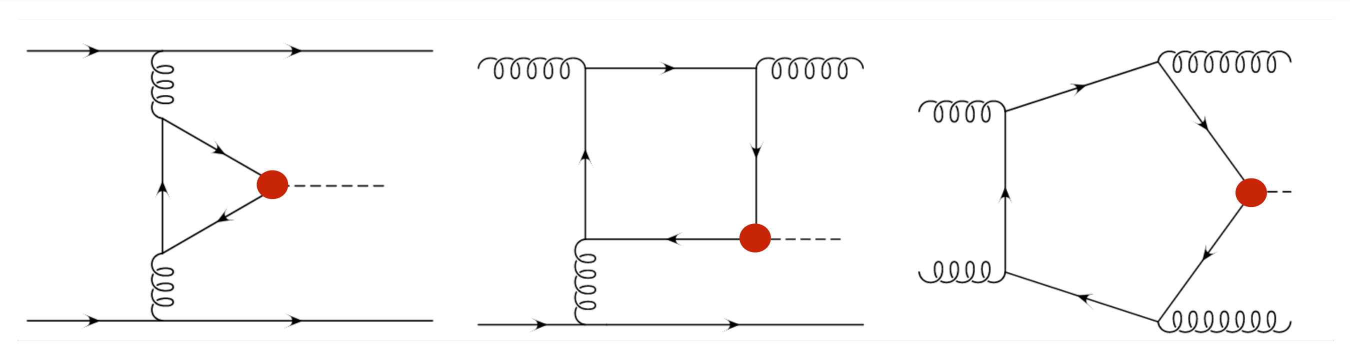


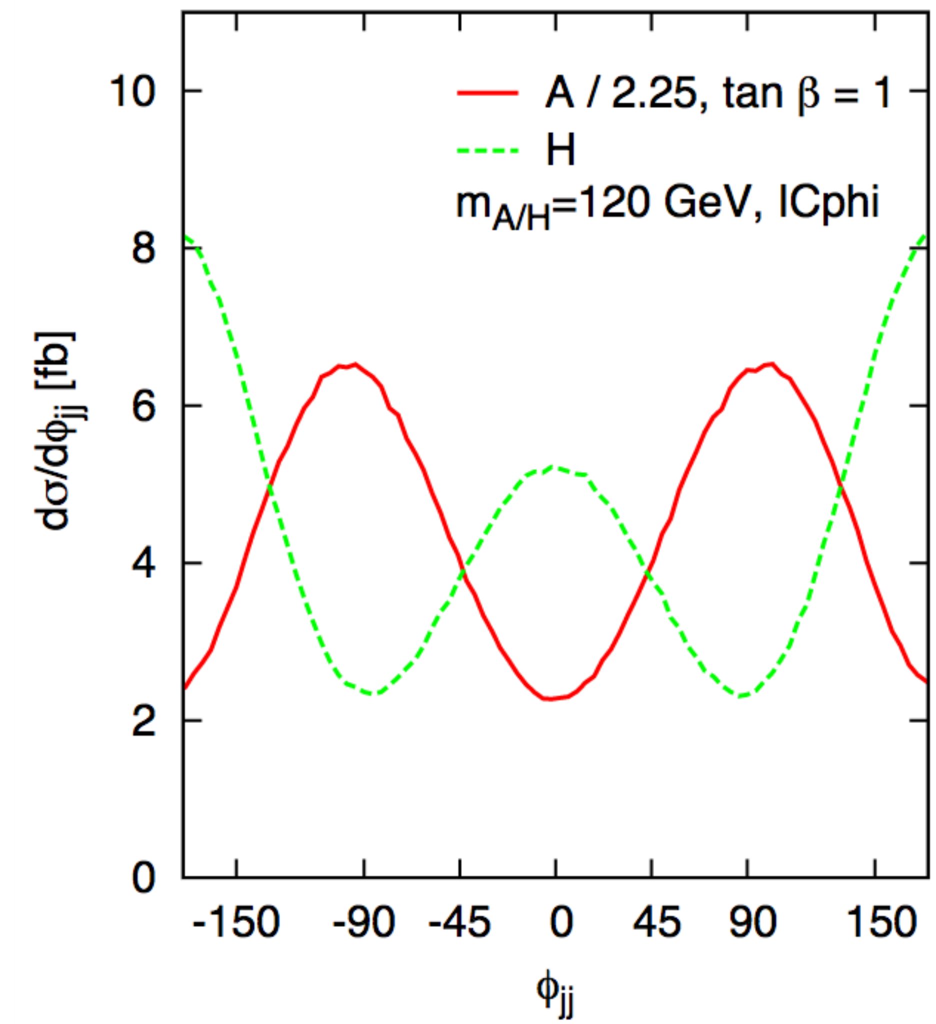
Brod, Haisch, Zupan (2013); Engel, Ramsey-Musolf, Kolck (2013); Cirigliano, Dekens, Vries, Mereghetti (2016)

Indirect collider constraints

- Complementary top-Higgs CP measurement at LHC:

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





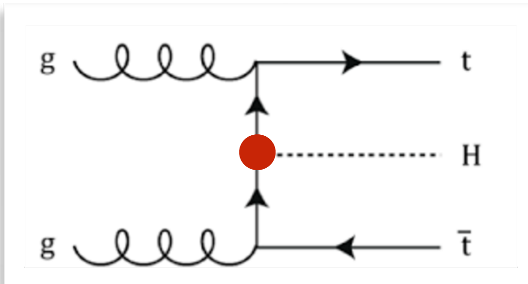
- Loop-induced: indirect constraints
- Bottom line:

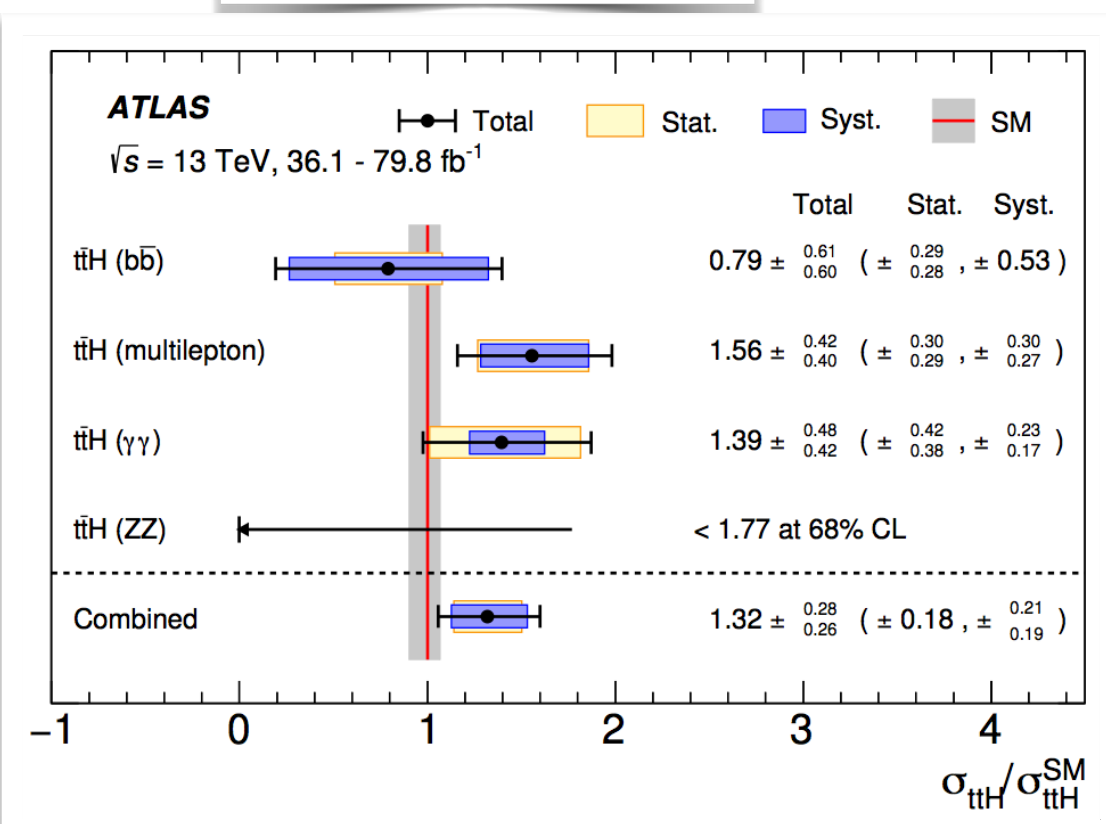
Analogously to direct yt signal strength measurement the direct top-Higgs CP structure has in the ttH channel its most natural path

Plehn, Rainwater, Zeppenfeld (2001)
Zeppenfeld, Kubocz, Campanario (2010)
Englert, **DG**, Mawatari, Plehn (2012)
Anderson, Bolognesi, Caola, Gao, Gritsan et al (2013)
Dolan, Harris, Jankowiak, Spannowsky (2014)
Bahl, Bechtle, et al (2020)

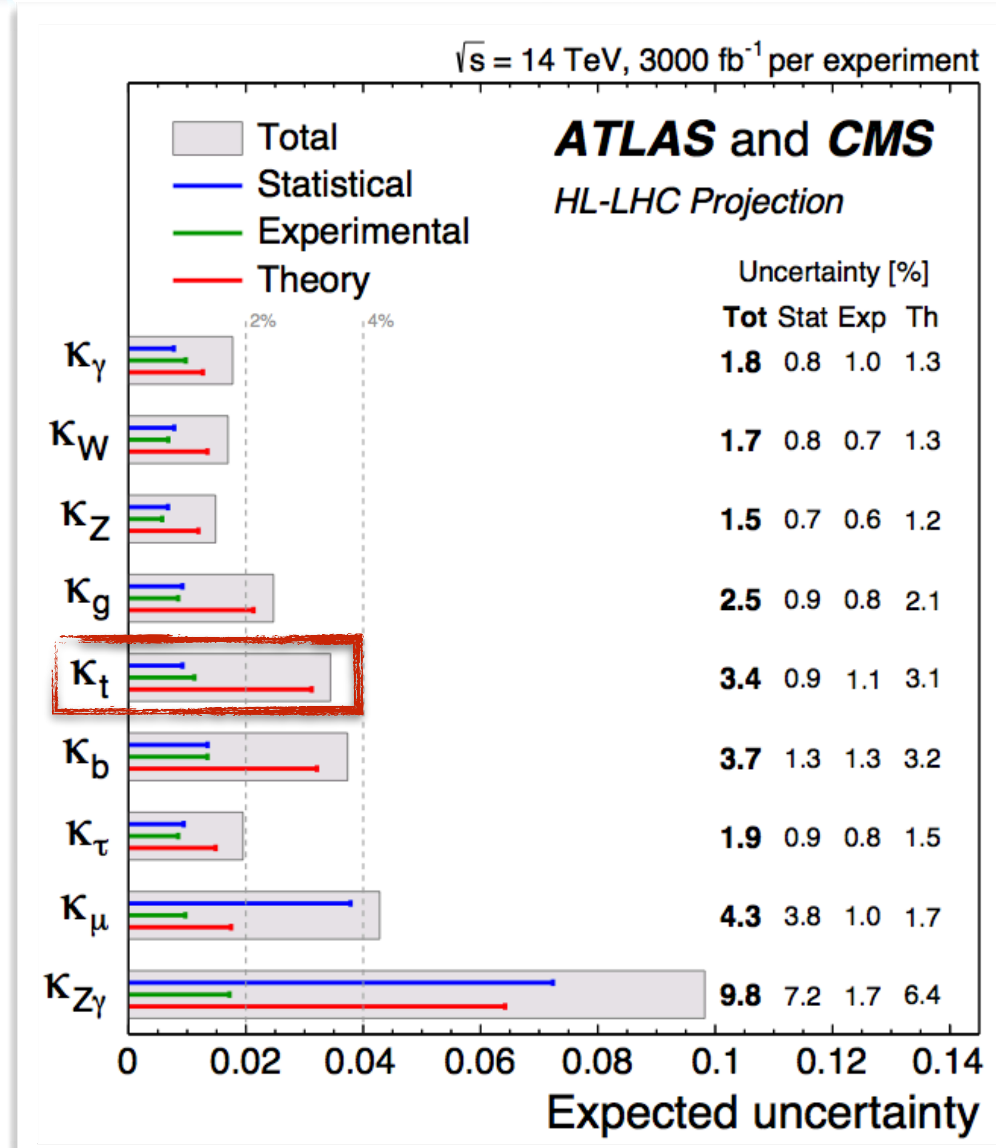
Direct CP measurement of Higgs-top coupling

- ttH channel observation (2018):





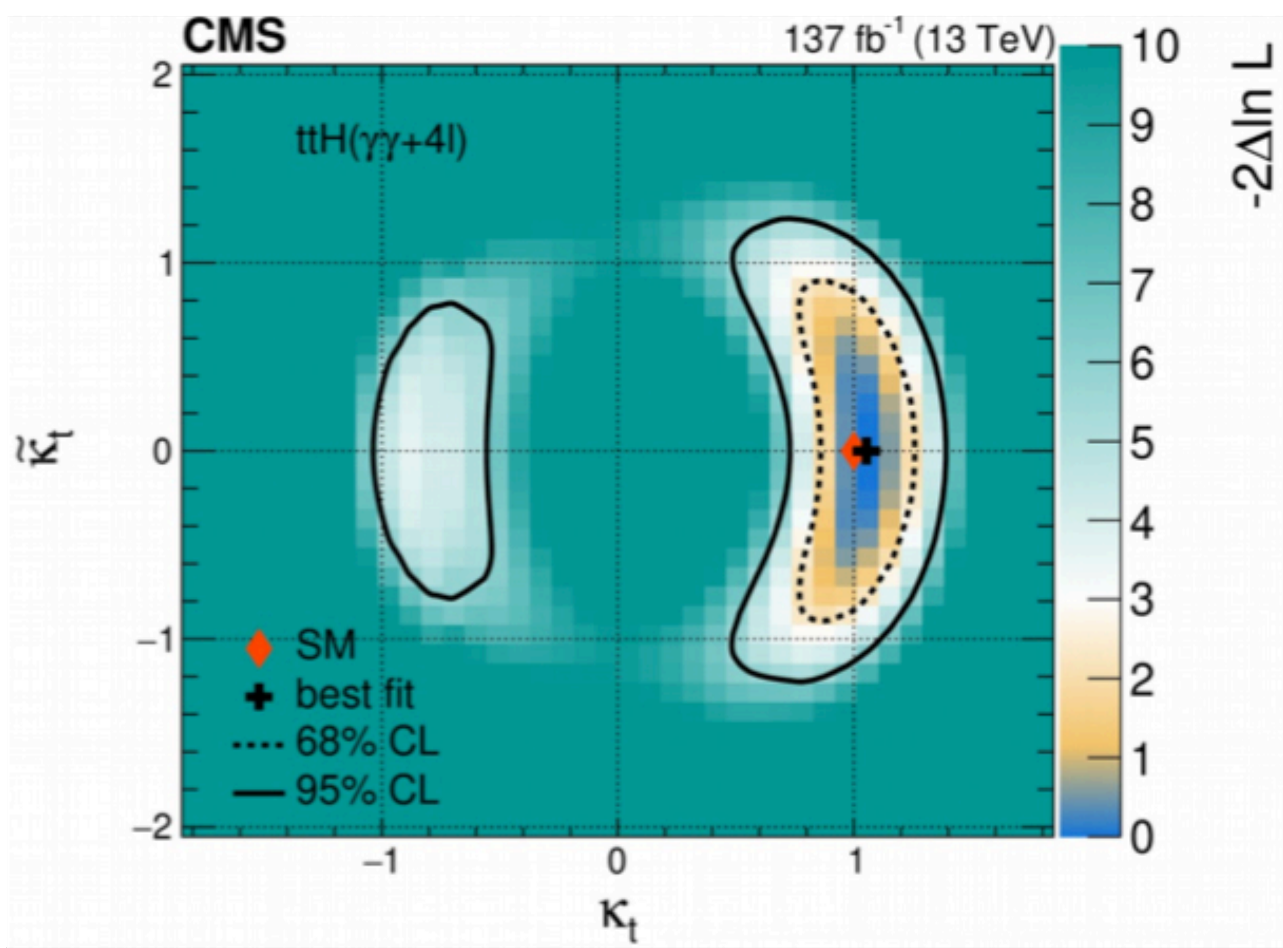
- Expected HL-LHC precisions:

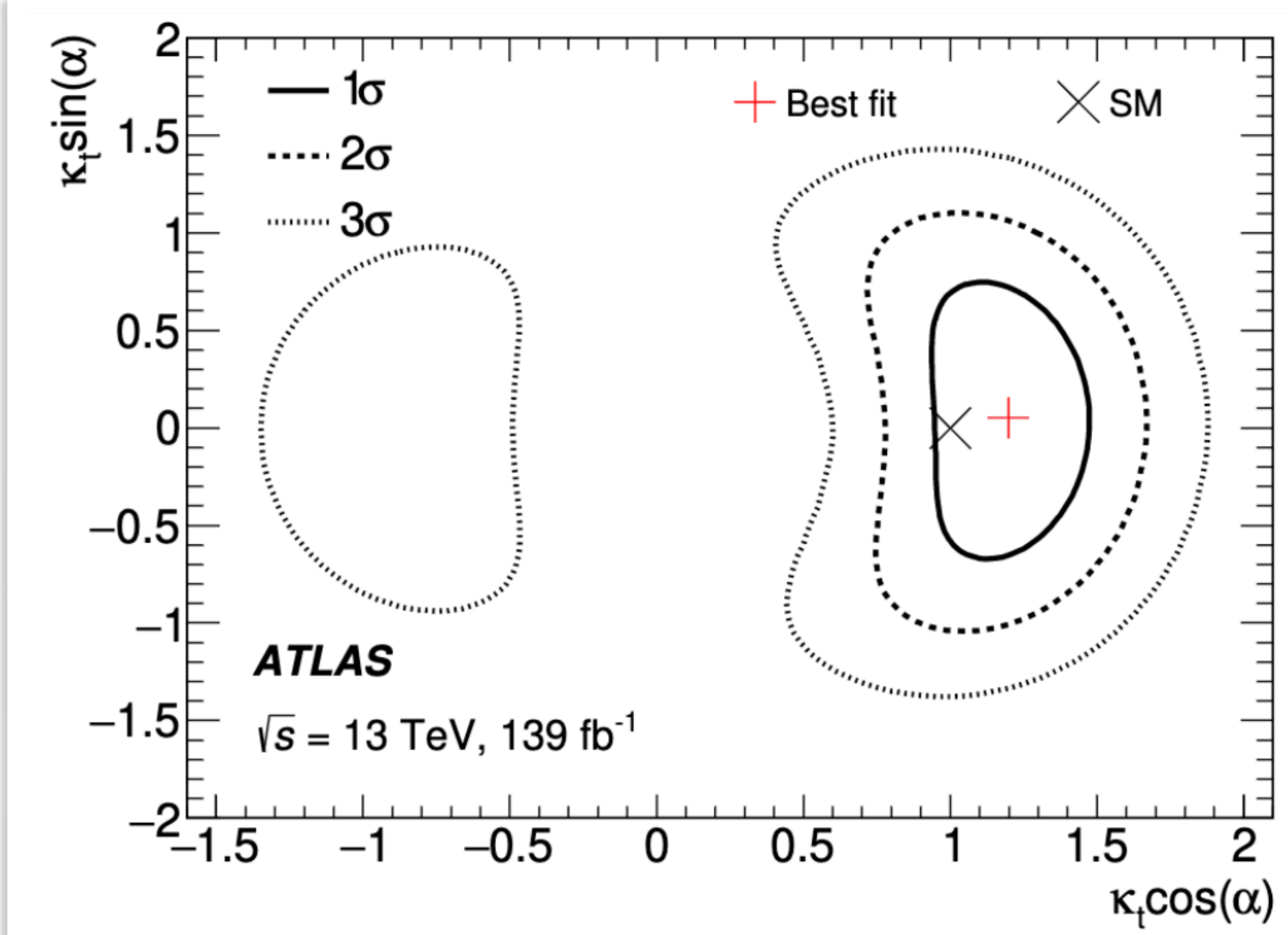


- Opportunity: direct measure Higgs-top CP structure at the LHC

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

Direct CP measurement of Higgs-top coupling





Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Directly Probing the CP-structure of the Higgs-Top Yukawa at HL-LHC and Future Colliders

Rahool Kumar Barman,[1] Morgan E. Cassidy,[2] Zhongtian Dong,[2]
Dorival Gonçalves,[1] Jeong Han Kim,[3] Felix Kling,[4] Kyoungchul Kong,[2]
Ian M. Lewis,[2] Yongcheng Wu,[1] Yanzhe Zhang,[2] and Ya-Juan Zheng[2]

Bounds on α at 95% CL ($\kappa_t = 1$)	Channel	Collider	Luminosity
$\lvert\alpha\rvert \lesssim 36^\circ$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	HL-LHC	3 ab^{-1}
$\lvert\alpha\rvert \lesssim 25^\circ$ [2]	$t\bar{t}(h \to \gamma\gamma)$ combination	HL-LHC	3 ab^{-1}
$\lvert\alpha\rvert \lesssim 3^\circ$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	100 TeV FCC	30 ab^{-1}
$\lvert\alpha\rvert \lesssim 9^\circ$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	10 TeV $\mu^+\mu^-$	10 ab^{-1}
$\lvert\alpha\rvert \lesssim 3^\circ$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	30 TeV $\mu^+\mu^-$	10 ab^{-1}

arXiv:2203.08127

Snowmass White Paper: Prospects of CP-violation measurements with the Higgs boson at future experiments

TABLE I: List of expected precision (at 68% C.L.) of CP-sensitive measurements of the parameters f_{CP}^{HX} defined in Eq. (2). Numerical values are given where reliable estimates are provided, ✓ mark indicates that feasibility of such a measurement could be considered.

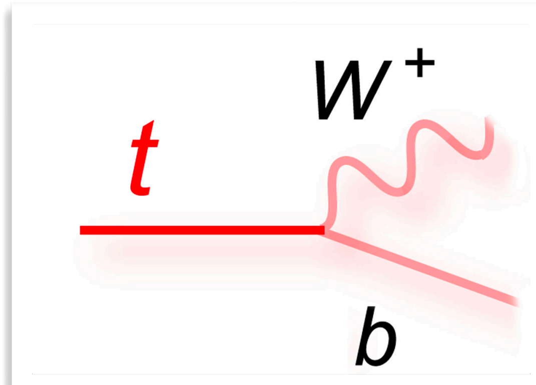
Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000		125	125	≥ 500	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	20,000	250	350	500	1,000		250			
HZZ/HWW	$4\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.4\cdot10^{-4}$	$1.1\cdot10^{-4}$	$4\cdot10^{-5}$	$8\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~ 1	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	–	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

arxiv:2205.07715

Top Quark is Special

- Decays before it hadronizes or its spin flips

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



Bottom quark is several orders of magnitude behind

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

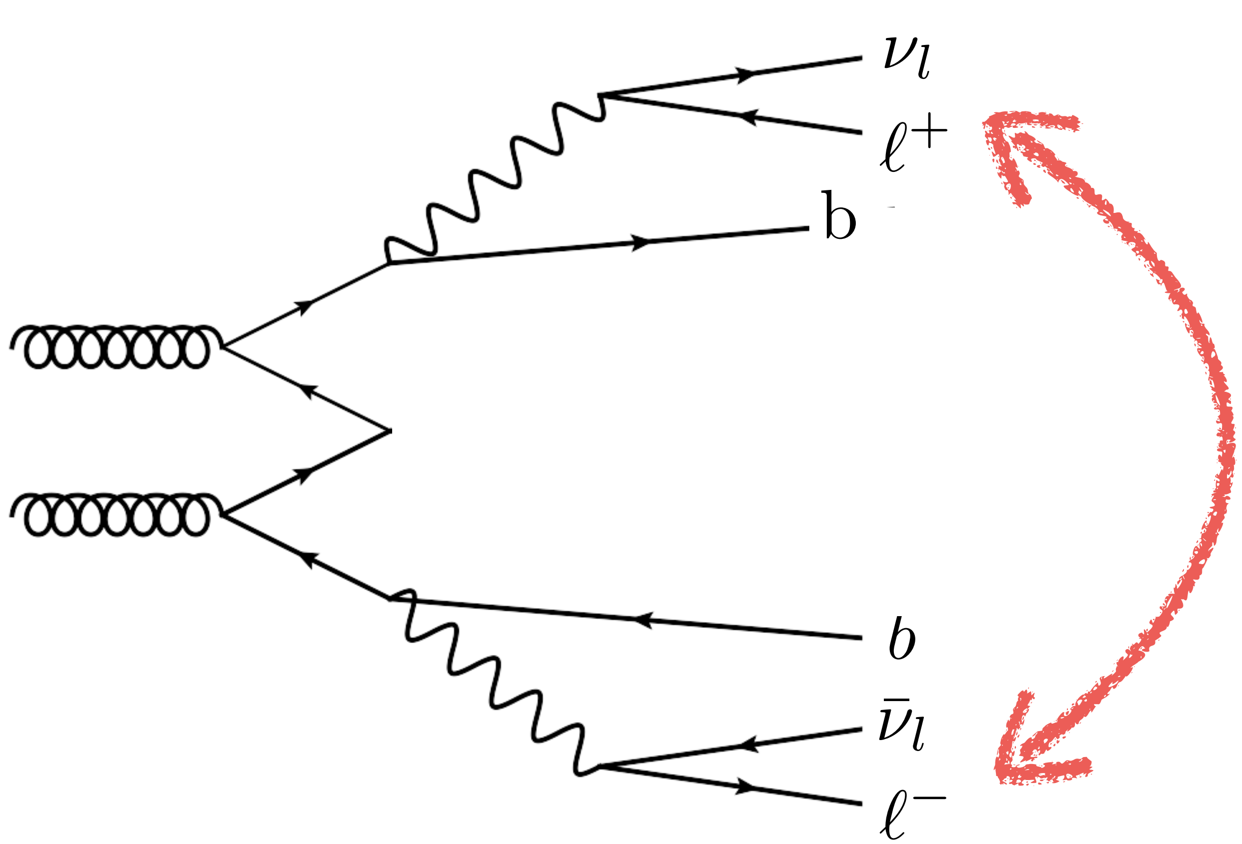
$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + \omega_f \cos\theta_f)$$

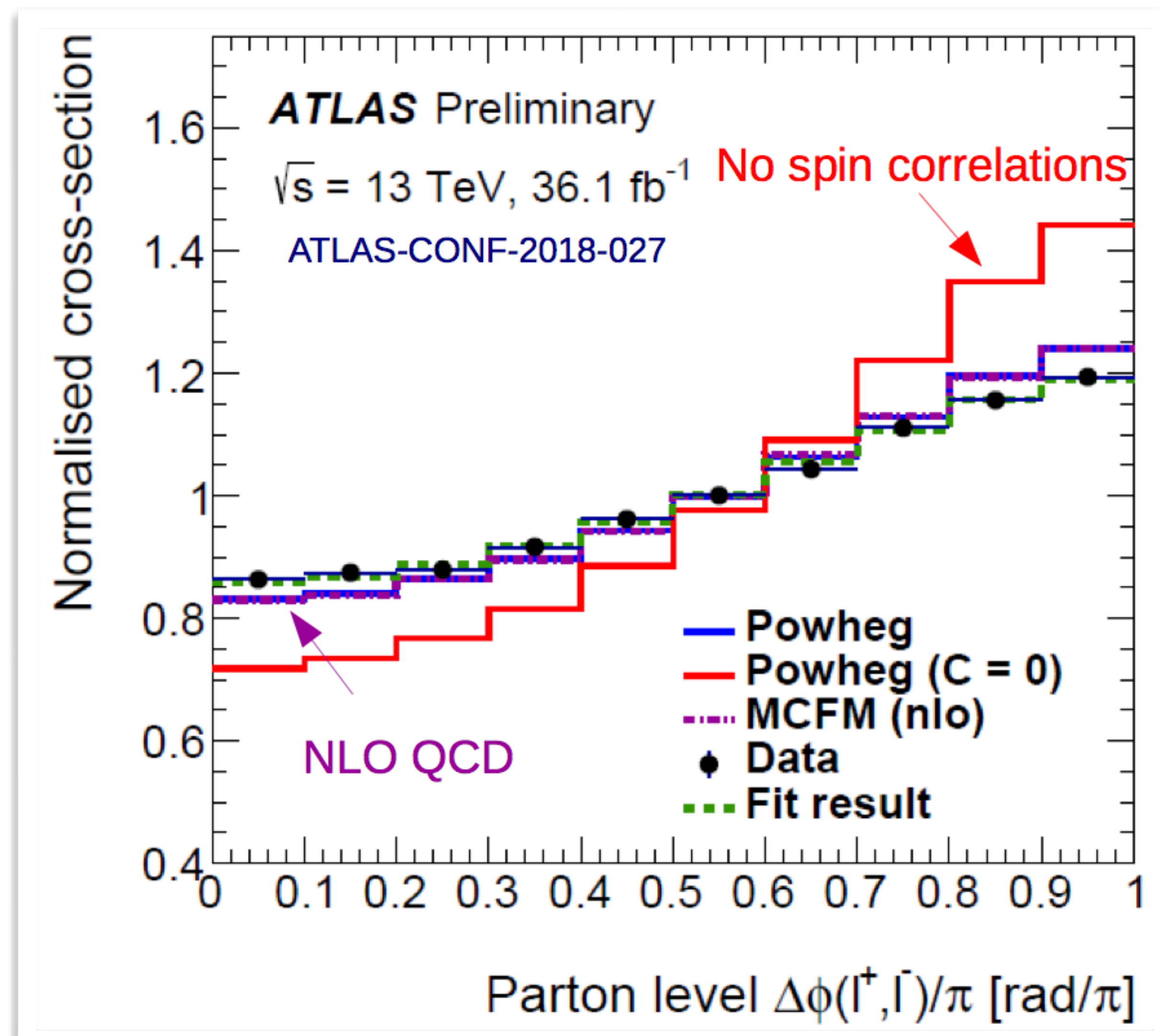
	$l^+, \bar{d}$	b	$\bar{\nu}, u$
ω_f	1	-0.4	-0.3

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

Top quark polarization

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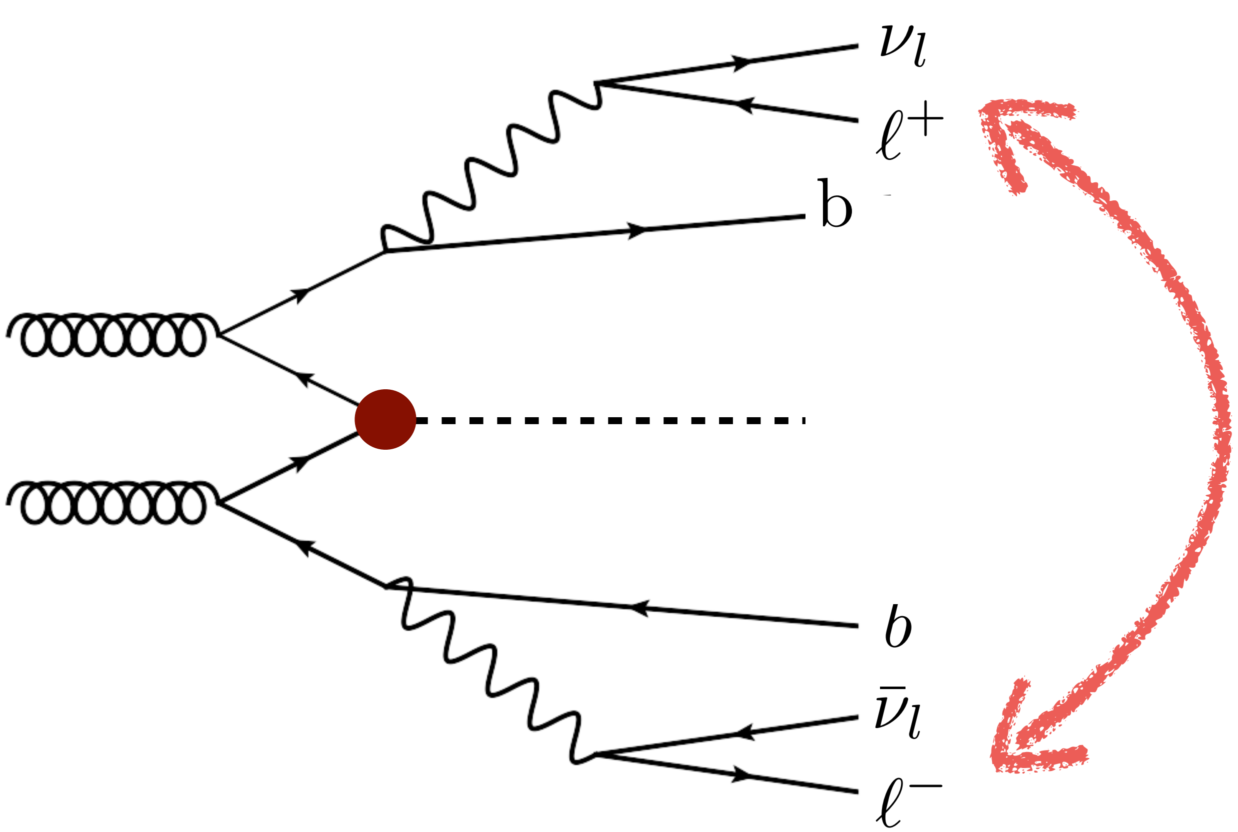
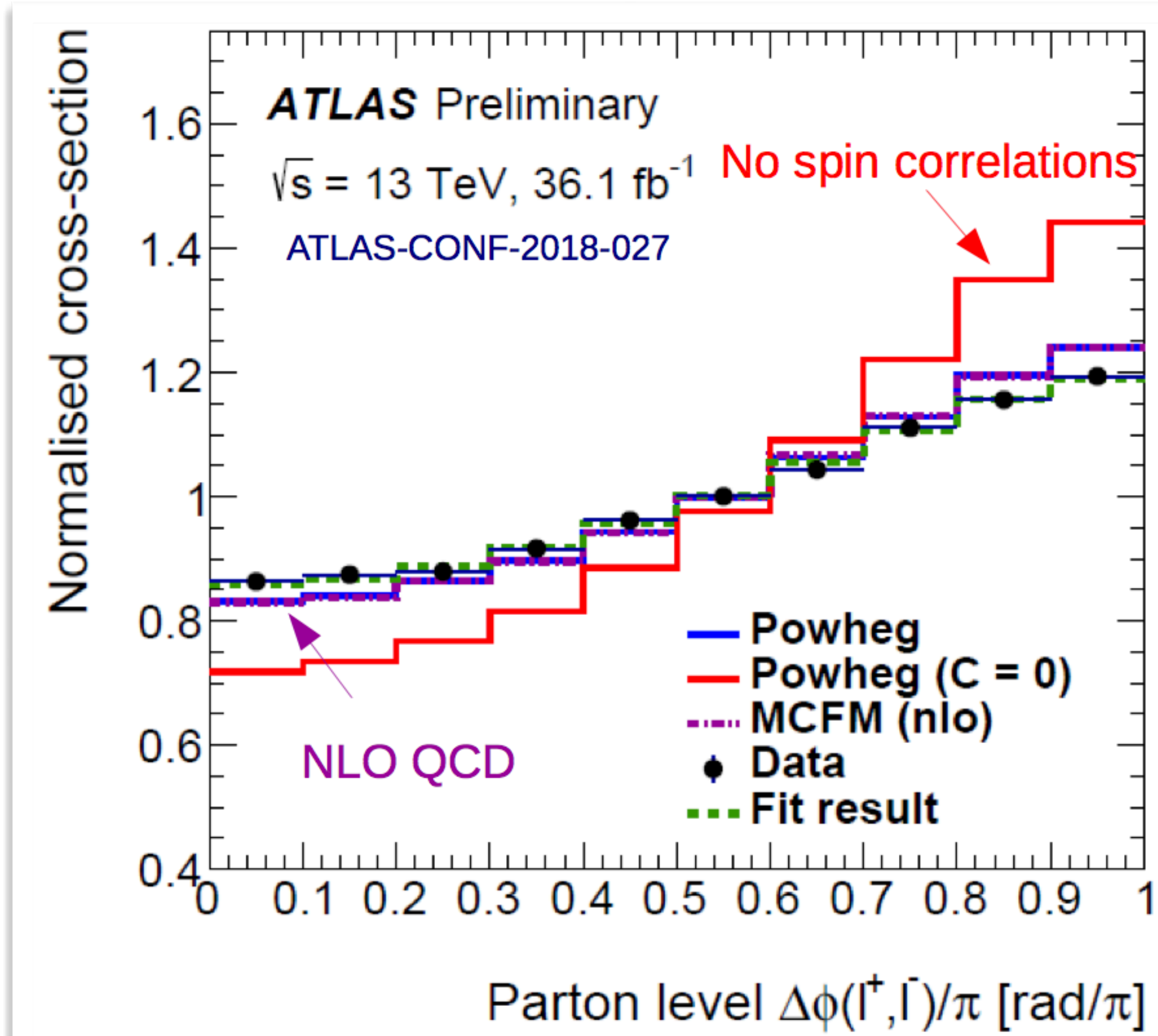


$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha \right) t \; H$$

Buckley, DG (PRL '15)



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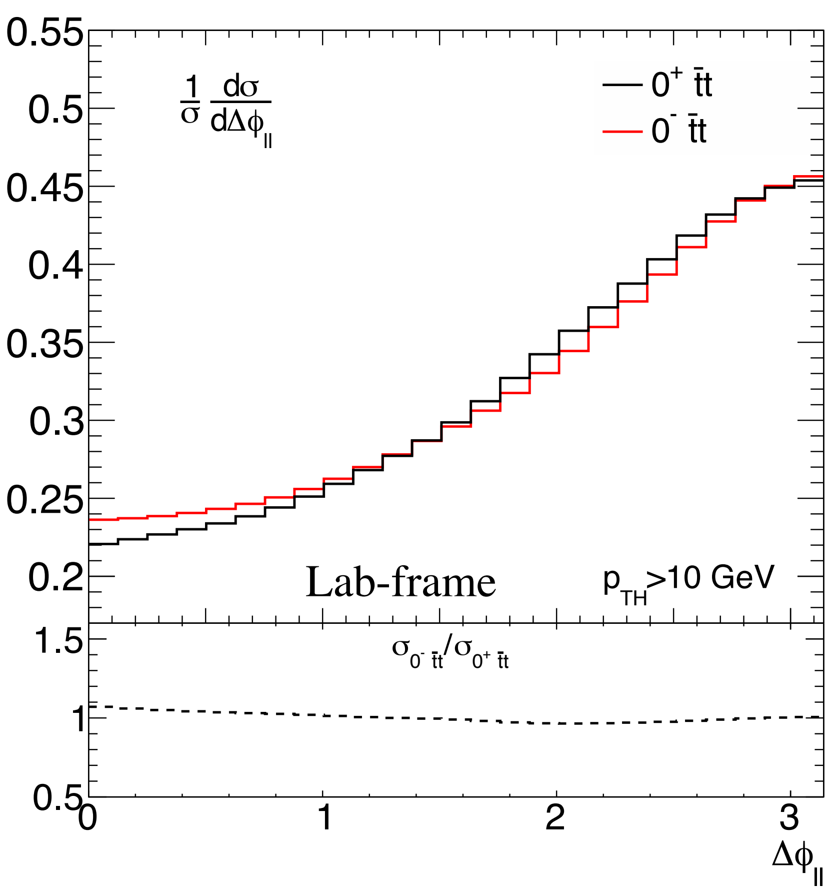

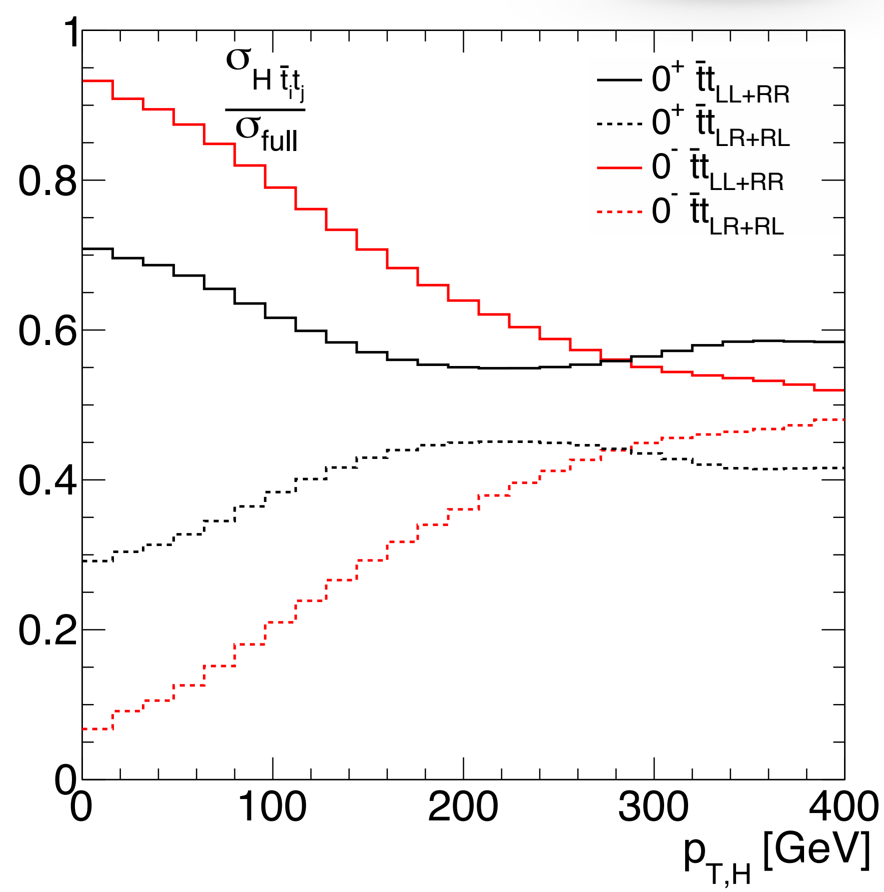

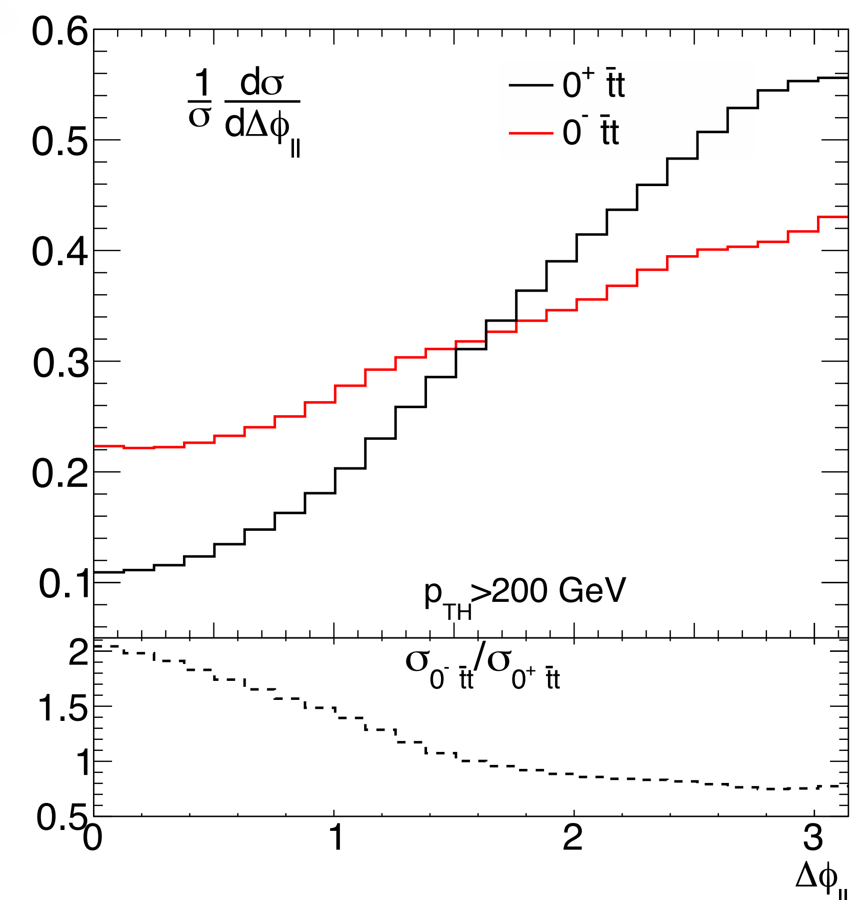

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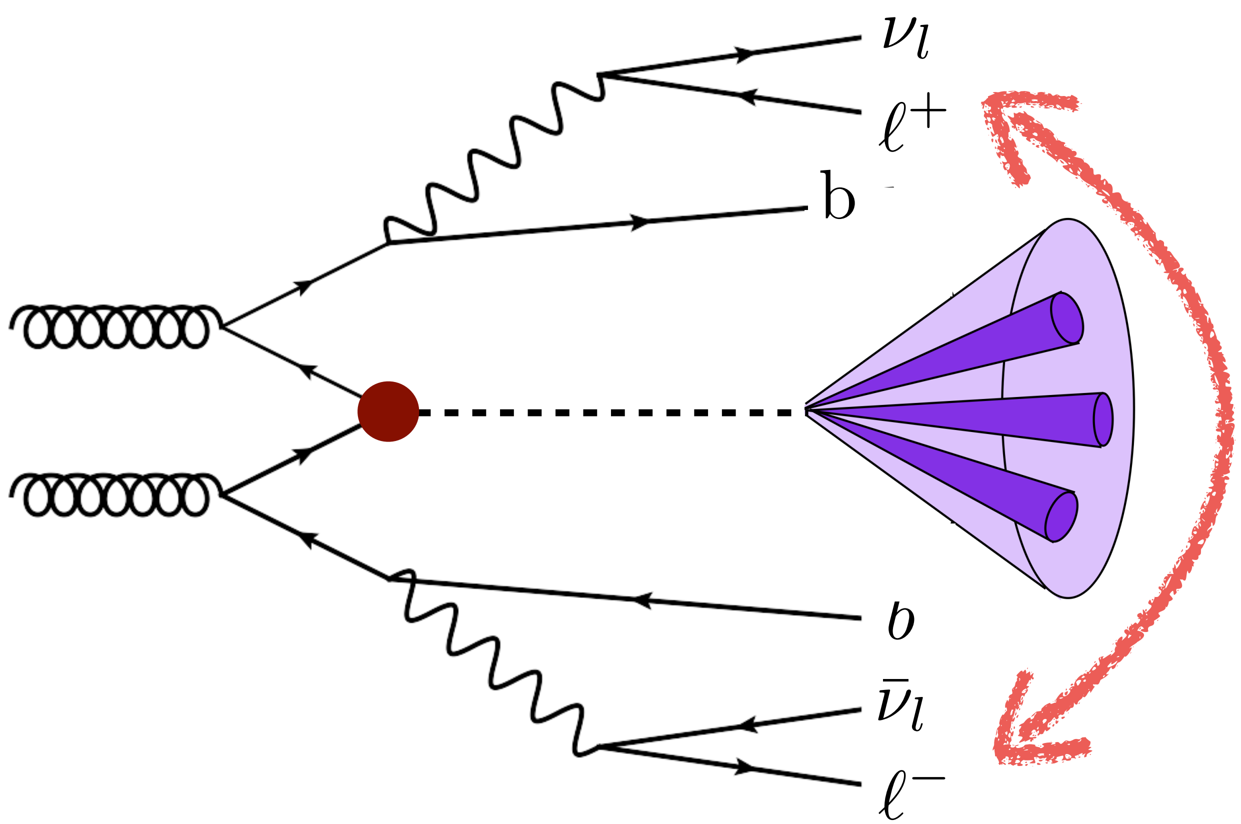
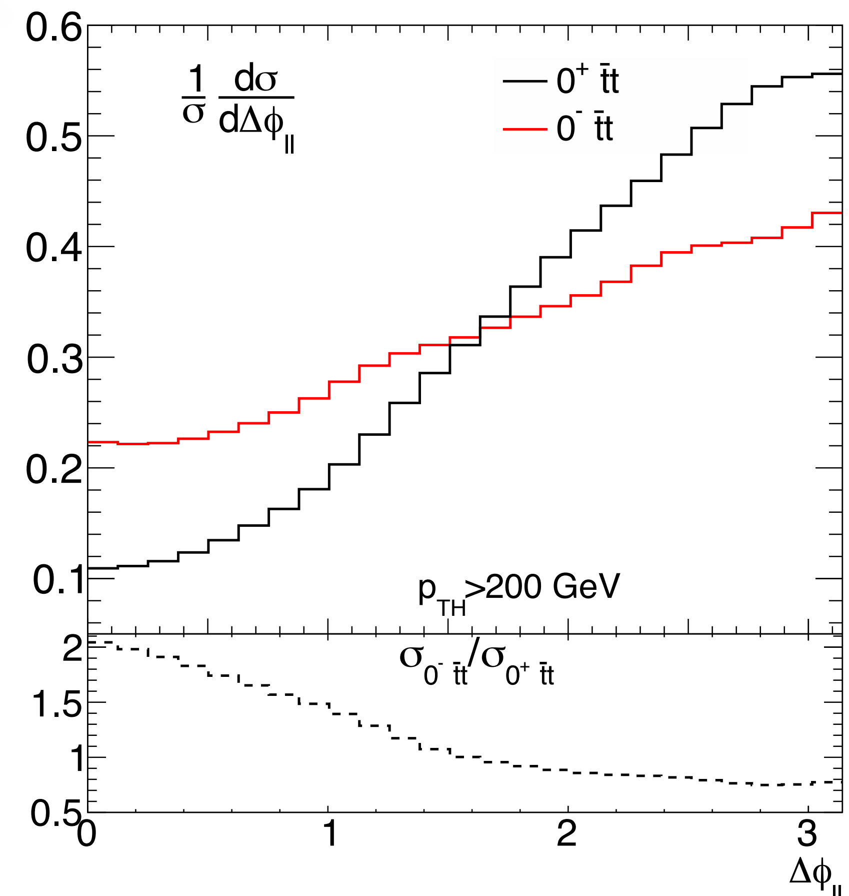




Buckley, DG (PRL '15)

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

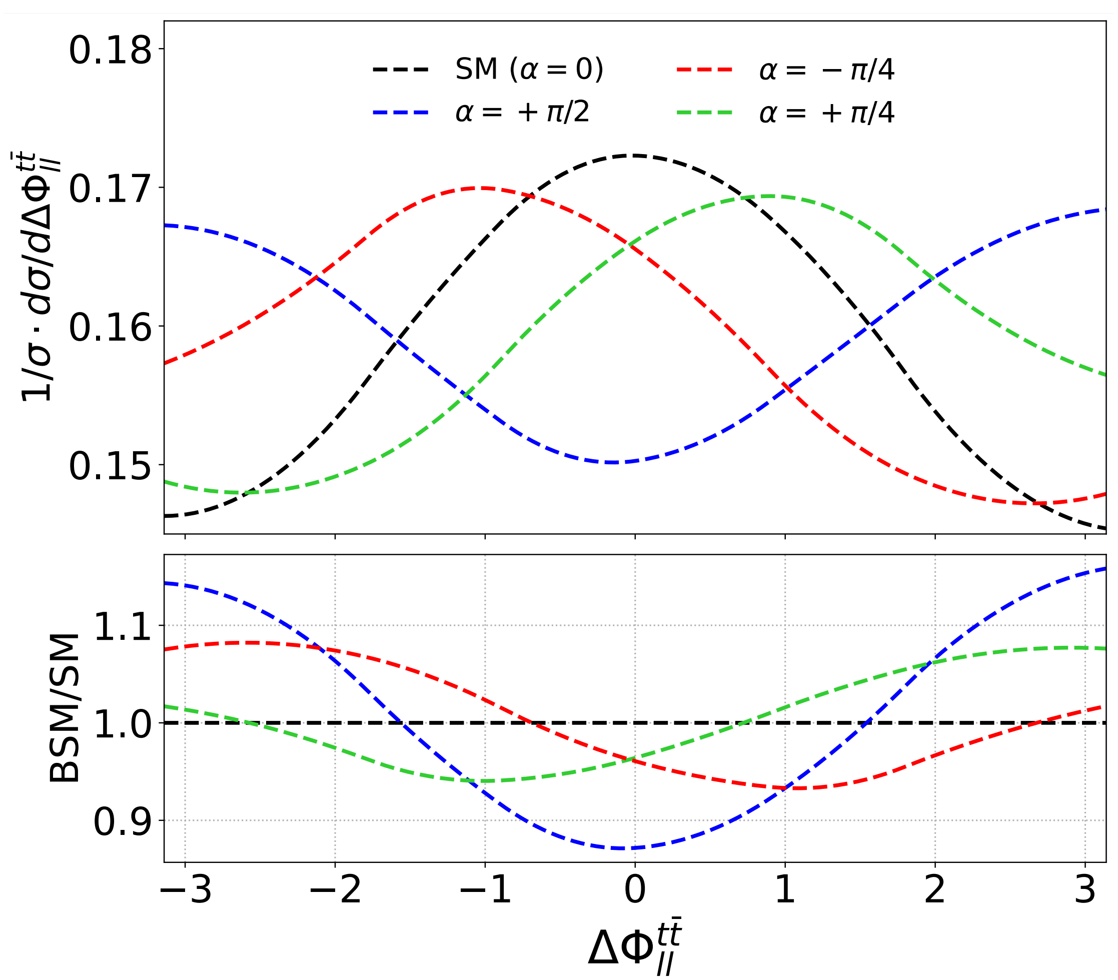
CP sensitive observables

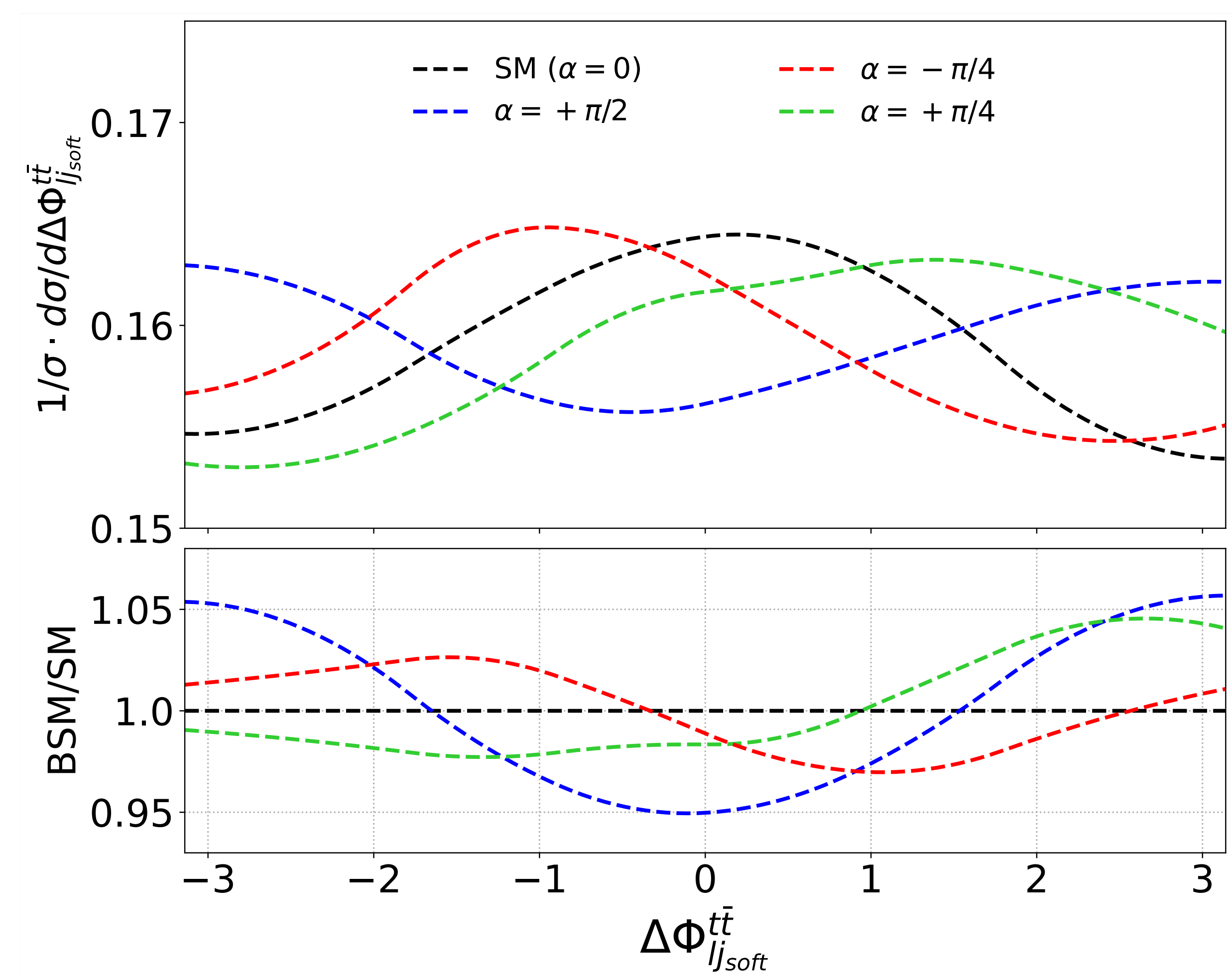
- CPV observables best defined at the top pair rest frame:

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

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

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





DG, Kong, Kim ’18 & ’21, Barman, DG, Kling ‘21

CP sensitive observables

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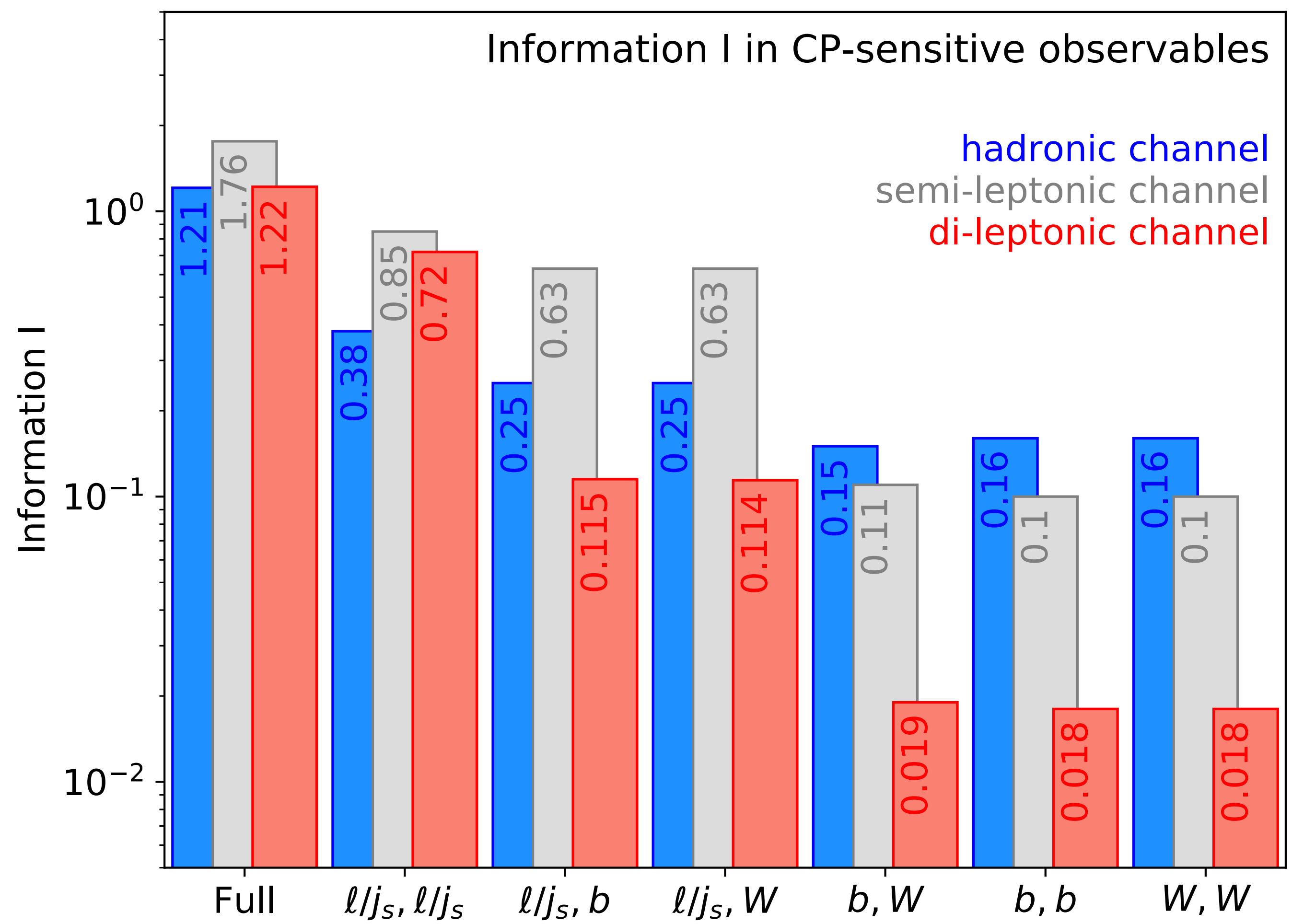
$$\begin{aligned}\epsilon_{\mu\nu\rho\sigma}p_a^\mu p_b^\nu p_c^\rho p_d^\sigma = \quad & E_a\,\vec{p_b}\cdot(\vec{p_c}\times\vec{p_d}) + E_c\,\vec{p_d}\cdot(\vec{p_a}\times\vec{p_b}) \\ & -E_b\,\vec{p_c}\cdot(\vec{p_d}\times\vec{p_a}) - E_d\,\vec{p_a}\cdot(\vec{p_b}\times\vec{p_c})\end{aligned}$$

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



Barman, DG, Kling '21

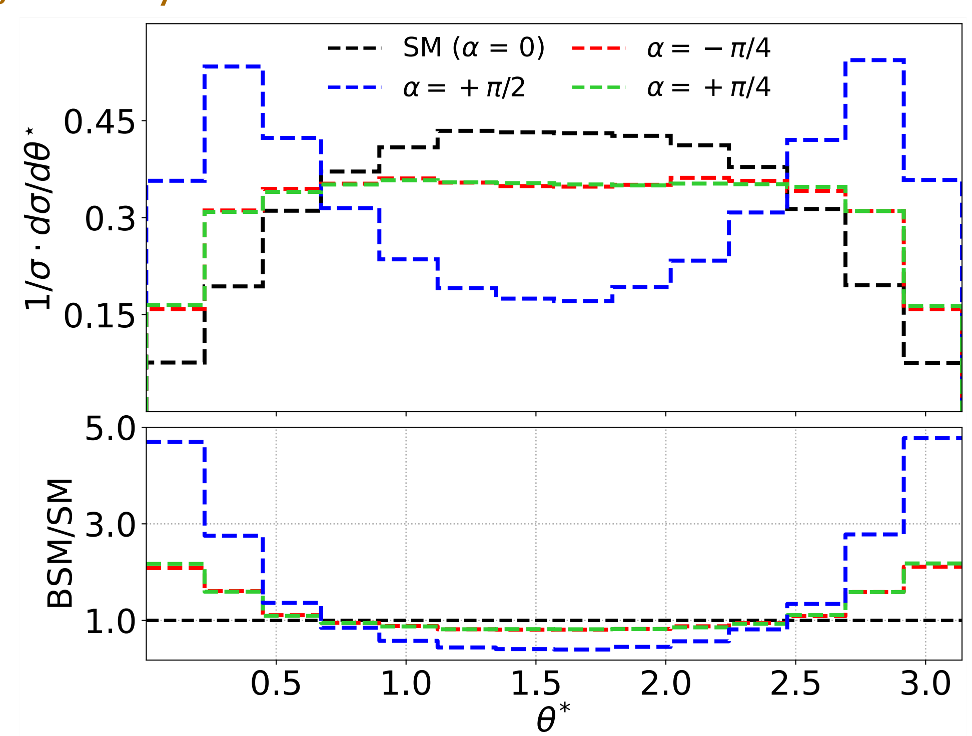
Multivariate analysis problem

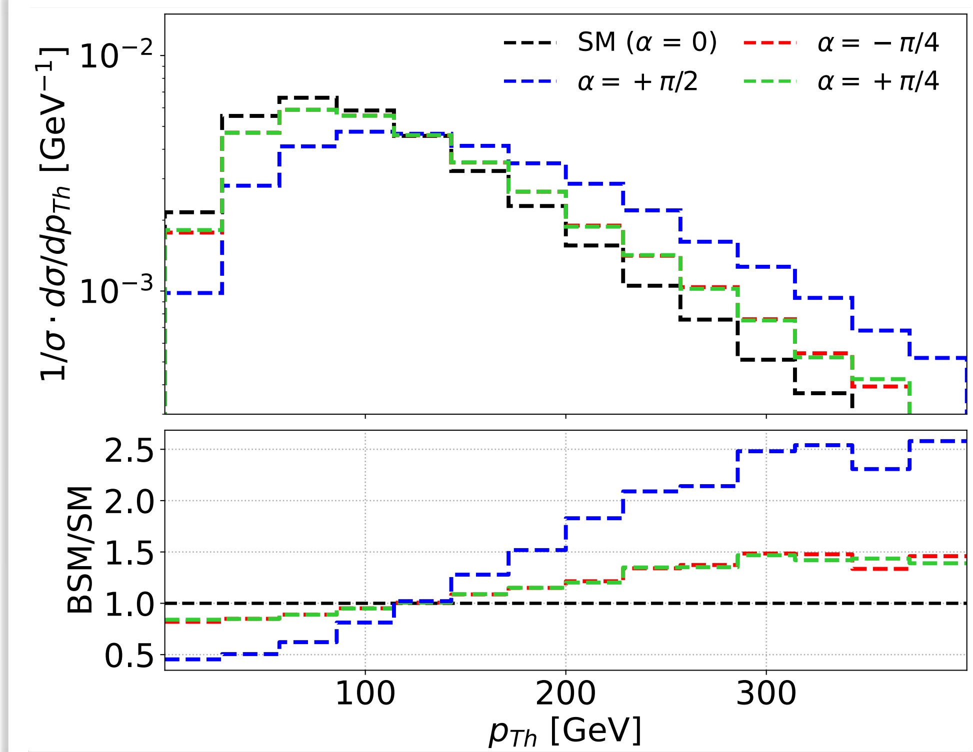
Numerous well-motivated observables have been explored in the literature

- θ^*: angle between t and beam direction in the $t\bar{t}$ CM frame.
- $b_4 = p_t^z p_{\bar{t}}^z / p_t p_{\bar{t}}$
- $m_{t\bar{t}}$: 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; Barman, **DG,** Kling 21'; Bahl, Brass '21





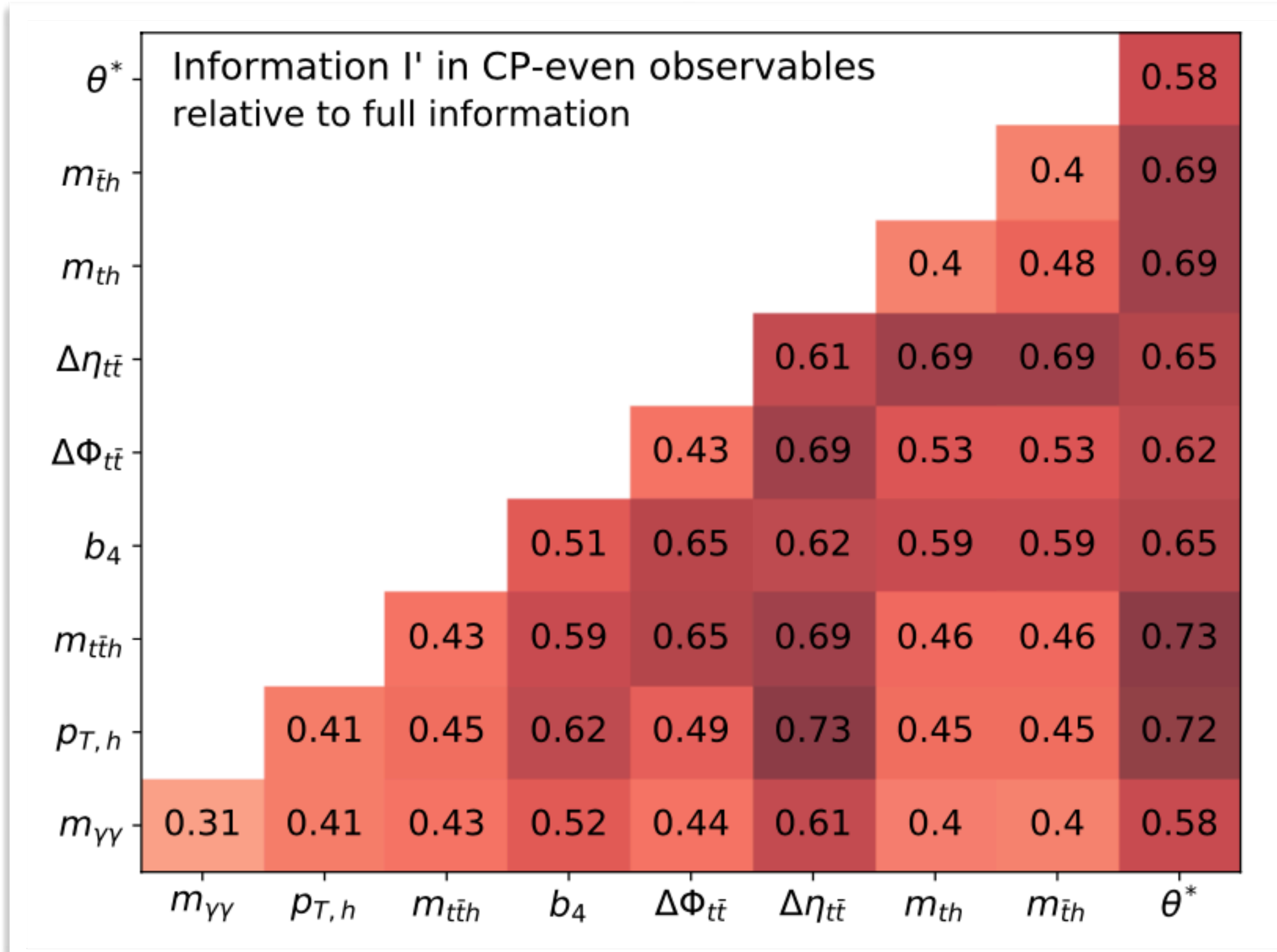
DG, Kong, Kim '18 & '21, Barman, **DG**, Kling '21

Machine Learning the Higgs-Top CP Phase

- 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.

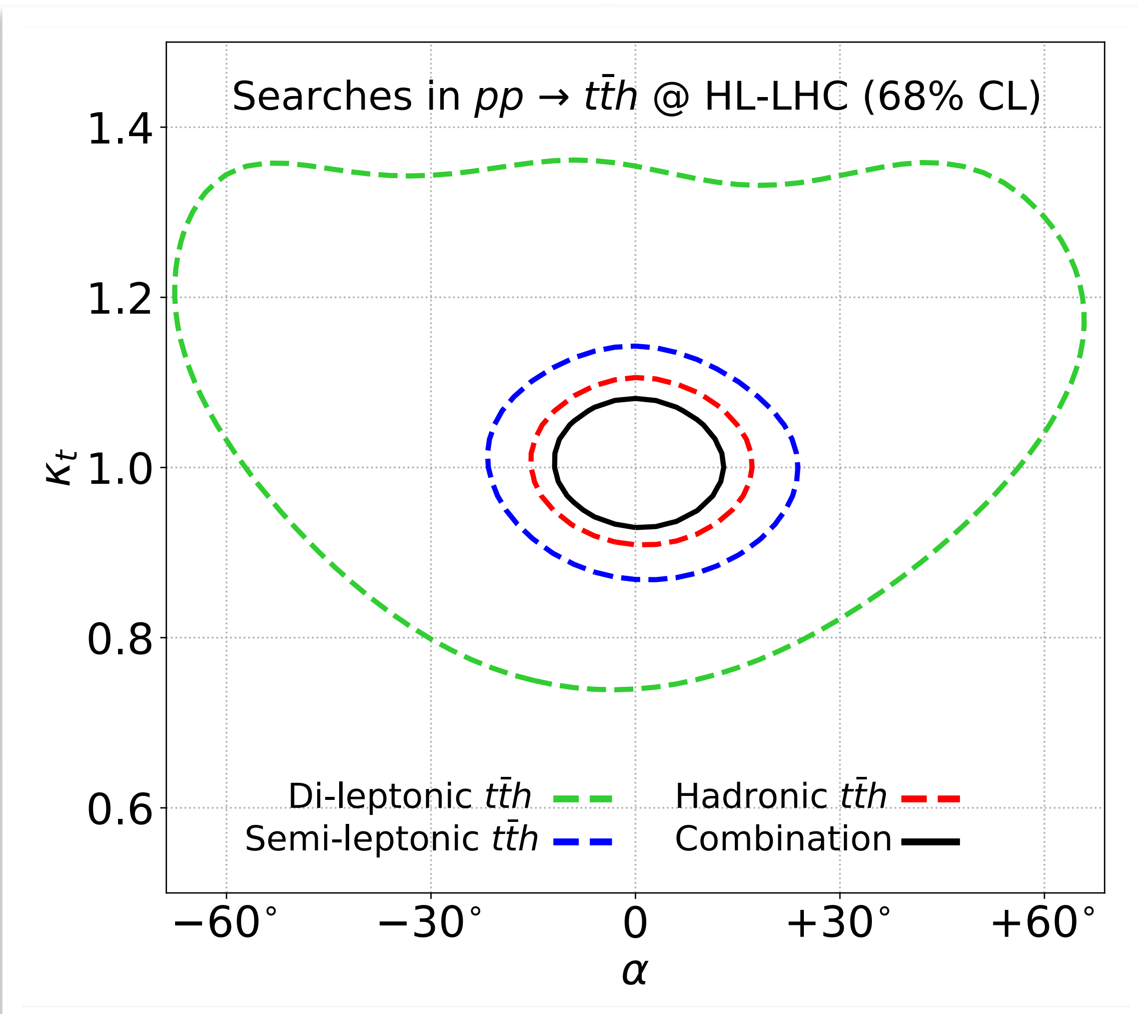


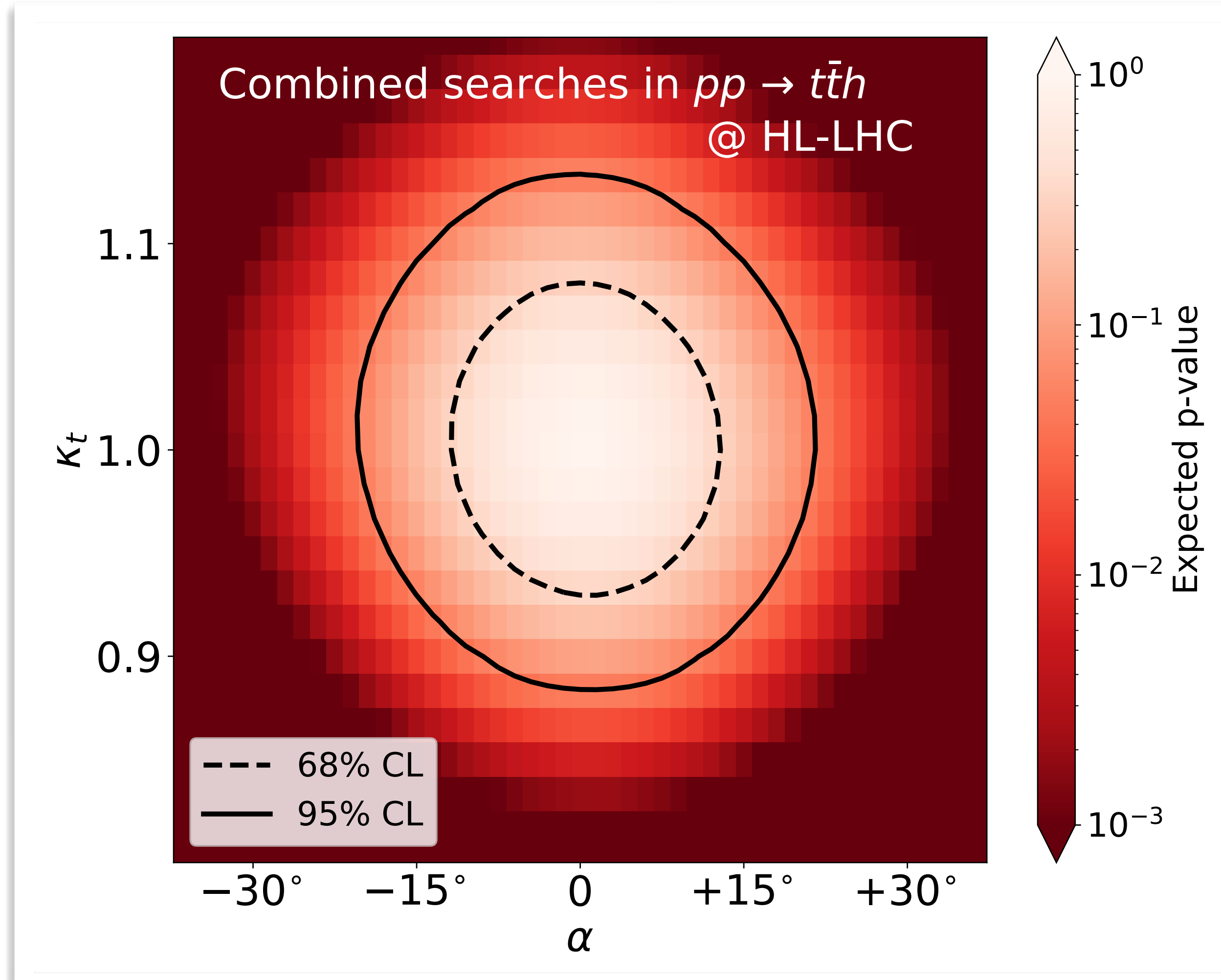
Barman, **DG**, Kling '21

Information increases with successive addition of observables → Multivariate analysis problem

Machine Learning the Higgs-Top CP Phase

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



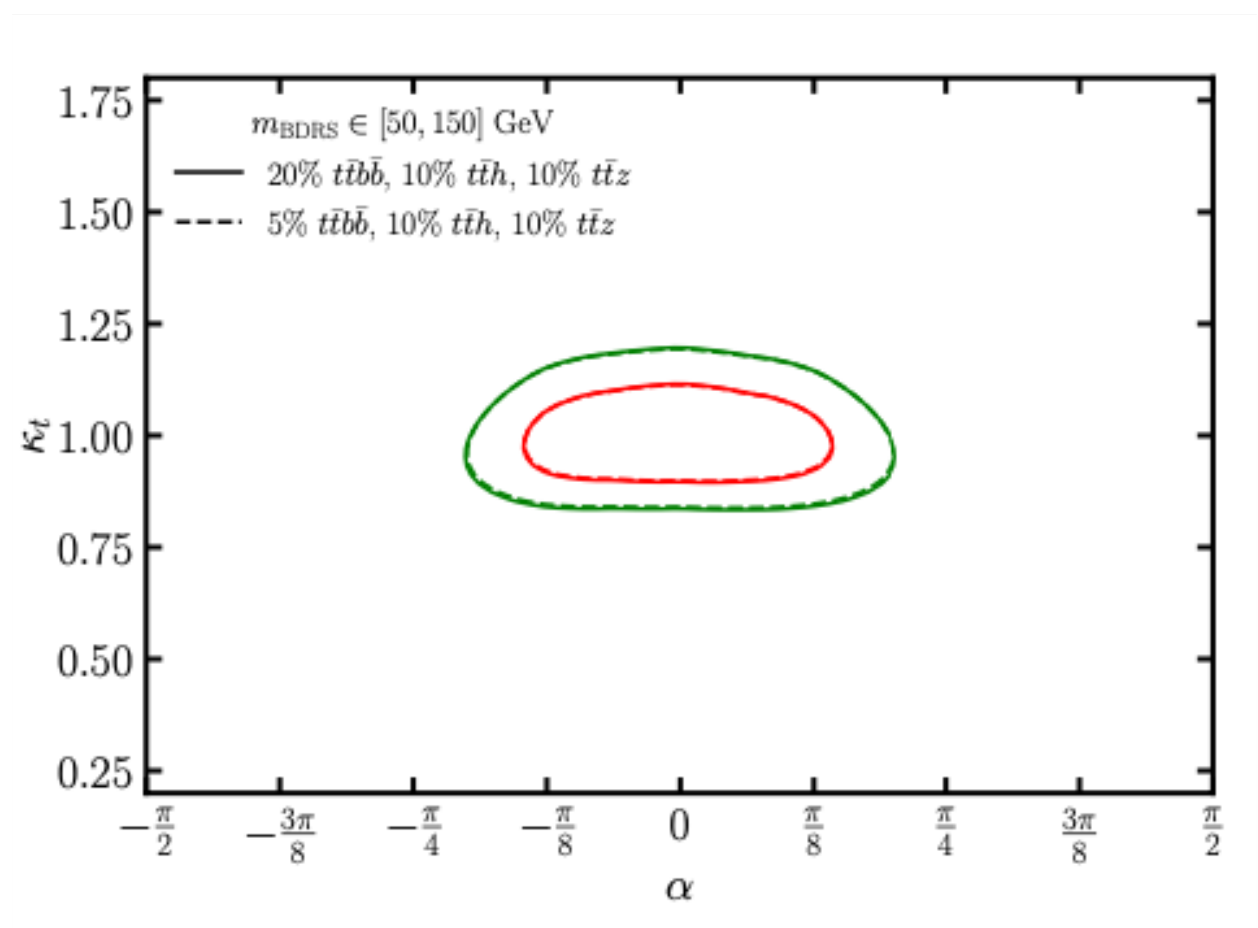


→ Higgs-top CP phase could be probed up to $\alpha \lesssim 13°$

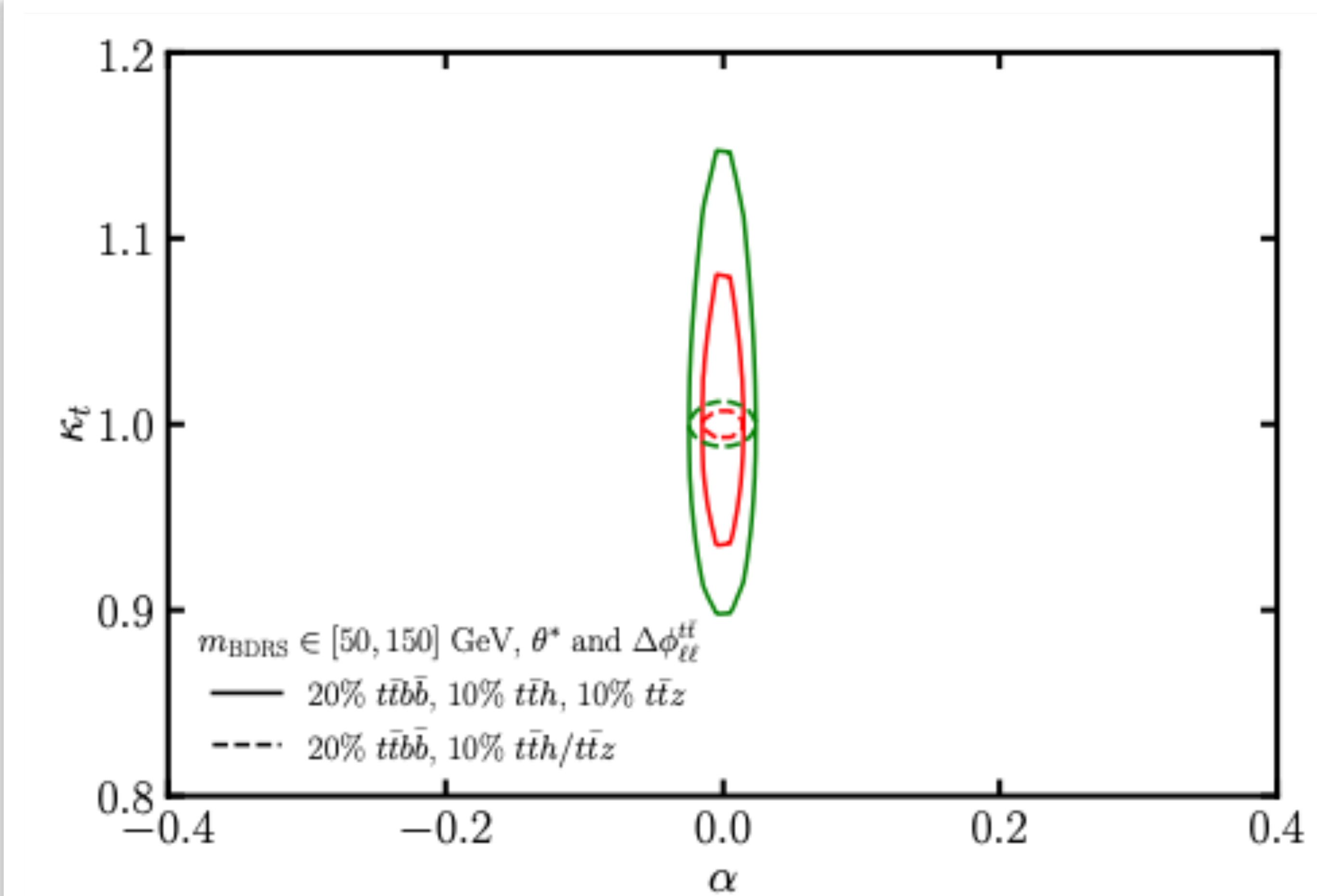
Barman, DG, Kling '21

HL-LHC & FCC-hh Projections

- Recent $h \to b\bar{b}$ study:



HL-LHC: $\alpha \lesssim 22°$



FCC-hh: $\alpha \lesssim 1°$

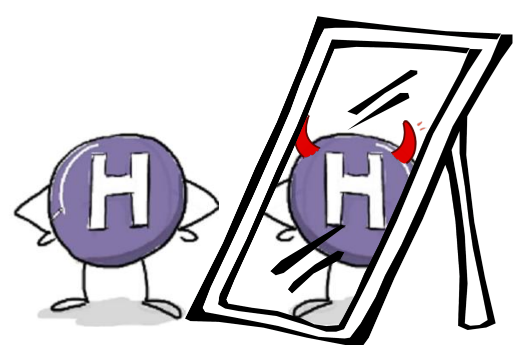
DG, Kong, Kim, Wu ’21
Mangano, Plehn, Reimitz, Schell, Shao ‘15

WG2 CPV Activities

Summary of WG2 CPV activity

Daniele Barducci, Nicolas Berger, Mauro Donega, Sarah Heim, Ken Mimasu & Giacomo Ortona

19th Workshop of the LHC Higgs Working Group



28th November 2022

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Summary & next steps

CPV in Higgs is a core WG2 activity for 2023

- Common parametrisation & benchmarks
  - Note in preparation, contributors welcome
  - Will define framework for future CPV activities
- ttH pheno
  - Established 2 directions for concrete studies
  - Any interested parties welcome to join effort
- WG2/WG3 joint activity
  - Round table meeting planned for early 2023
- EDMs
  - On the backburner for now

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Slides from K. Mimasu during "The 19th Workshop of the LHC Higgs Working Group"

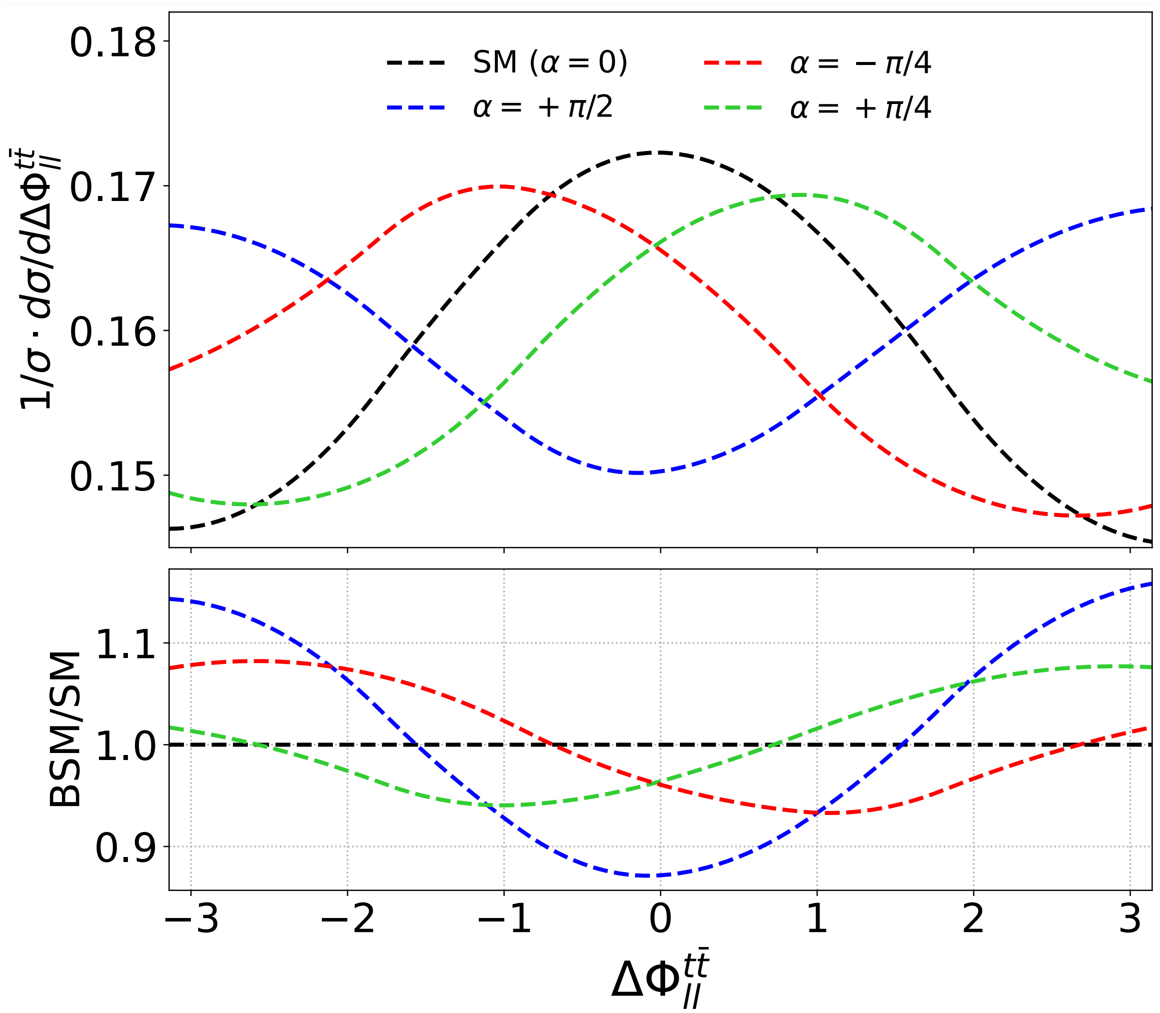
Summary

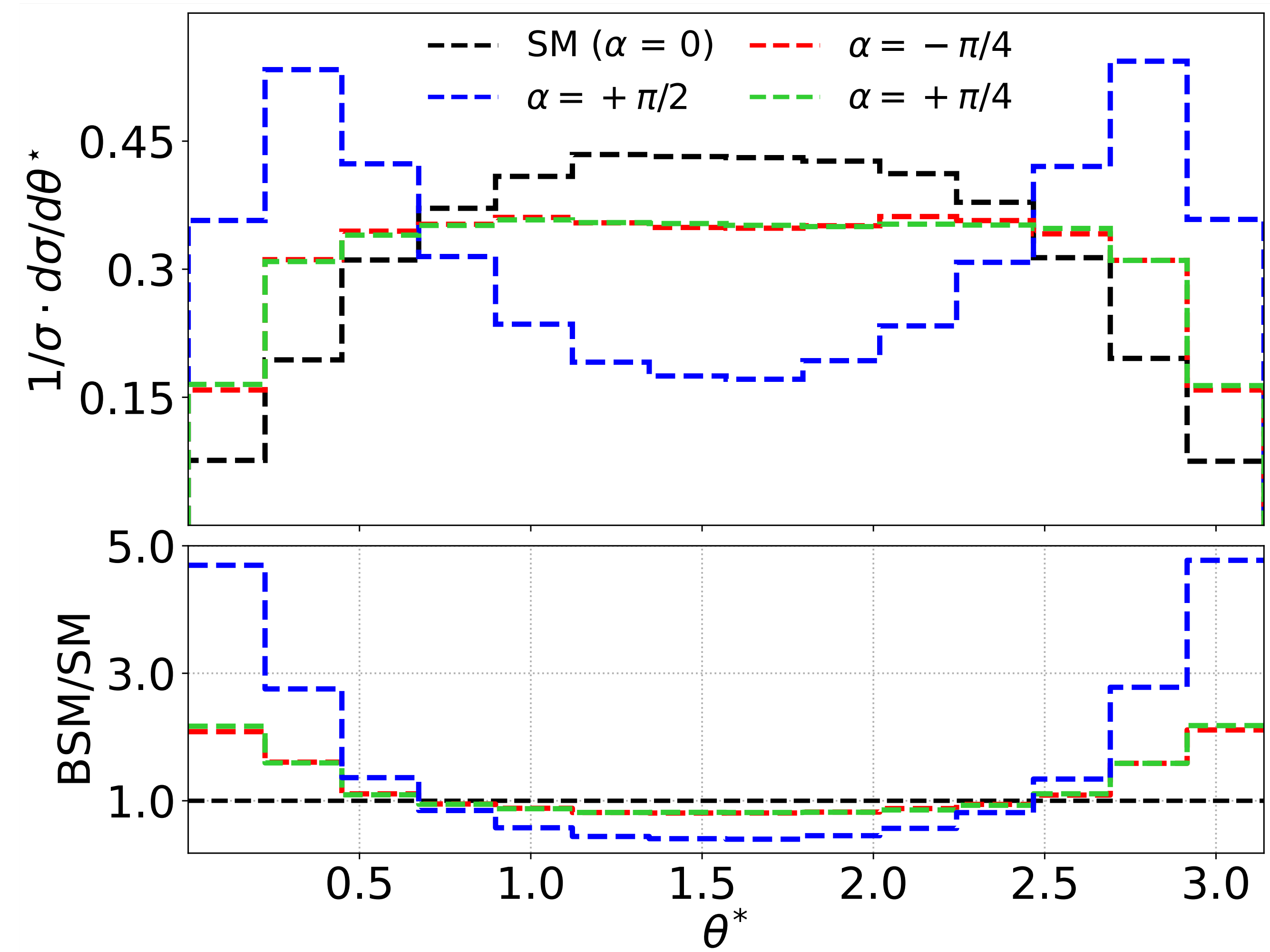
The search for new sources of CPV is one of the cornerstones of the Higgs program

- Higgs-top coupling can naturally display larger CP-phases than HVV
  - ➡ Direct probe: ttH channel
- Boosted Higgs analysis nicely match with CP-measurement
- “Machine learning problem”
- t-quark polarization and spin correlations uplift analysis from raw rate to polarization study

Top Reconstruction

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



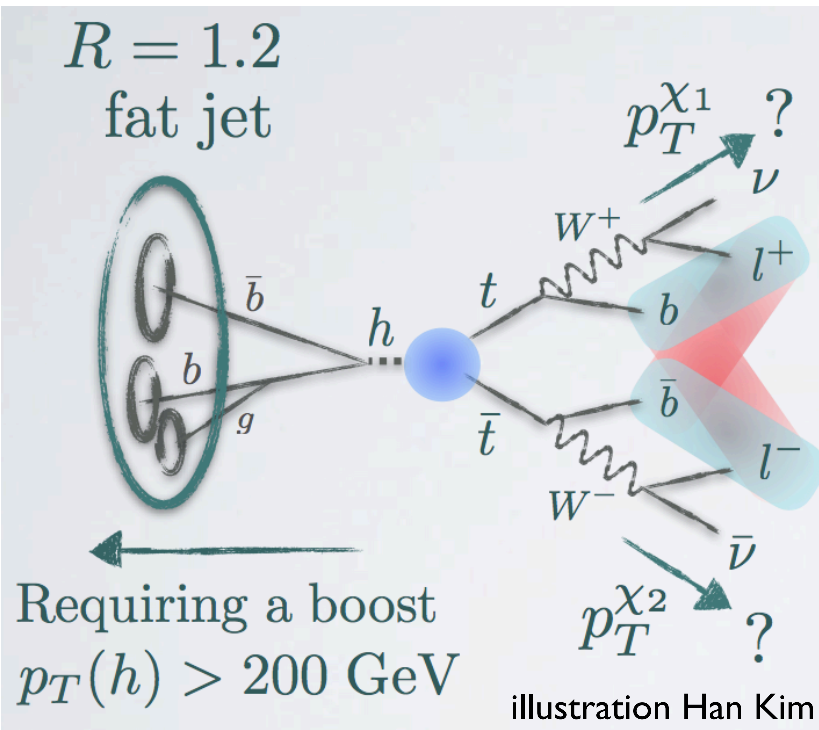


Combinatorial ambiguities and presence of up to two neutrinos makes reconstruction challenging

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:

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

Top Reconstruction

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

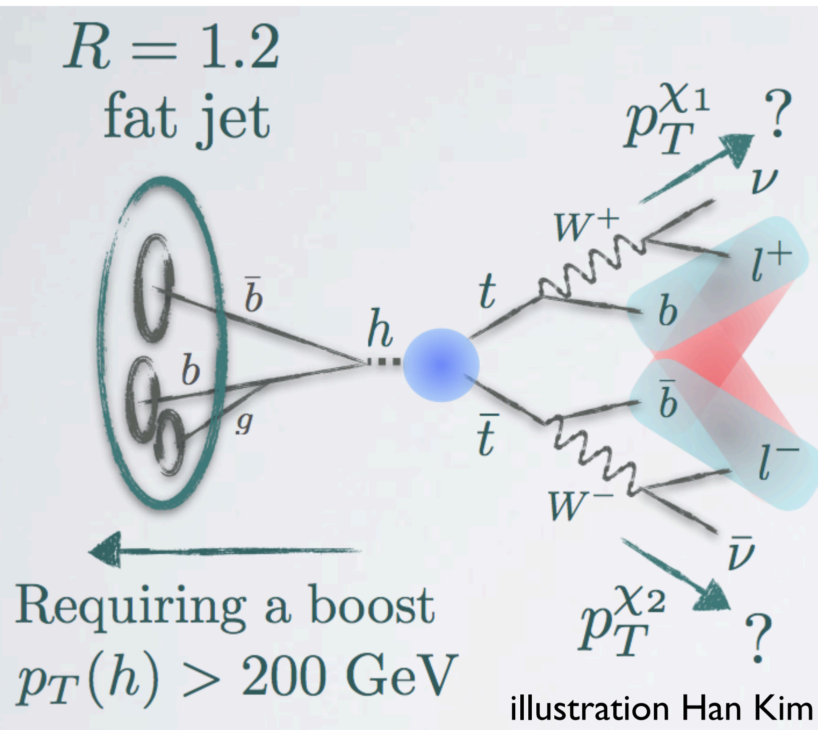


illustration Han Kim

Debnath, Kim, Kong, Matchev '17

DG, Kong, Kim '18

→ **Reconstruction of the Higgs: BDRS**

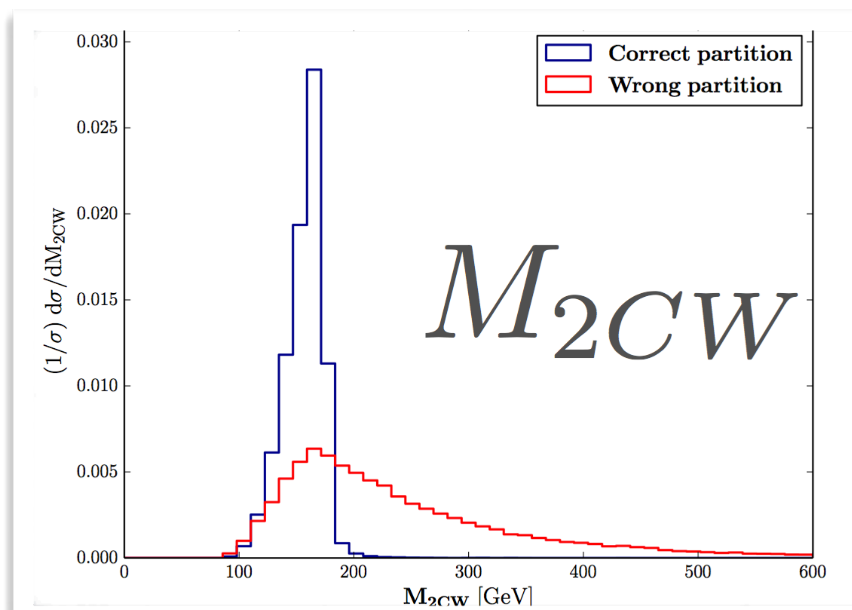
→ **Reconstruction of top momenta: Optimass**

a) **guess neutrino momenta**

b) **solve combinatorial problem**

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

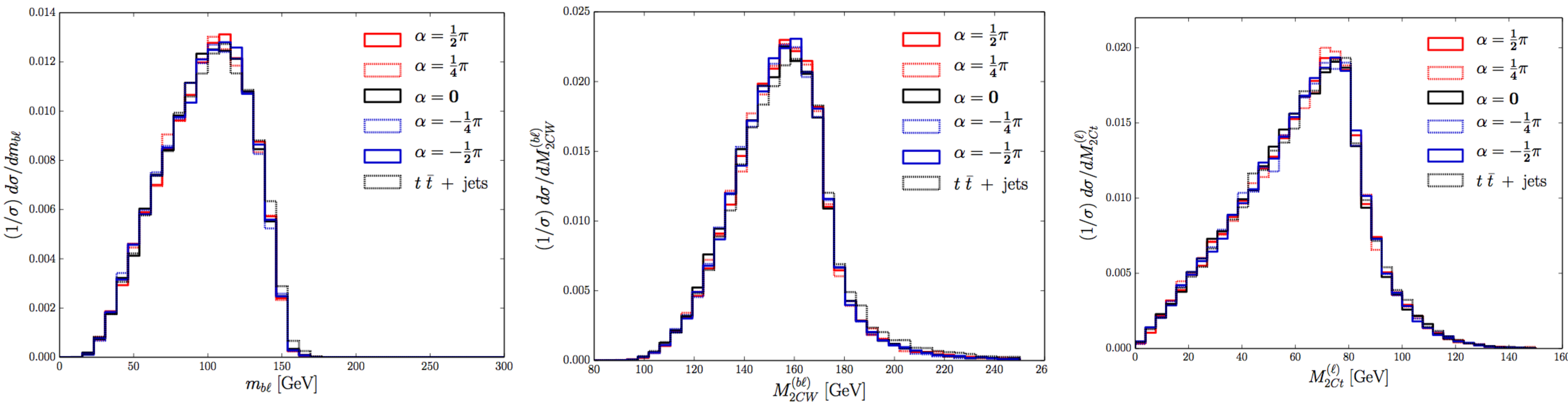
$M_{2CW}^{\text{wrong}} \longrightarrow p_T^{\chi_1}(\text{wrong}) \quad p_T^{\chi_2}(\text{wrong})$



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

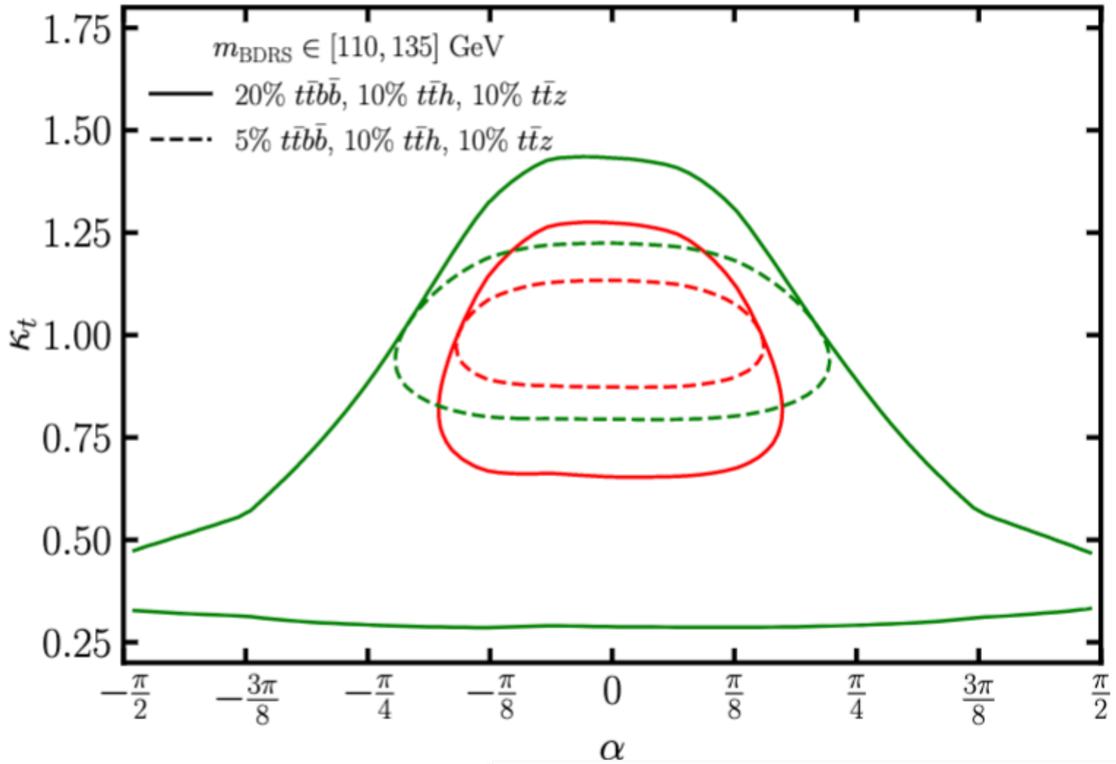
Top Reconstruction

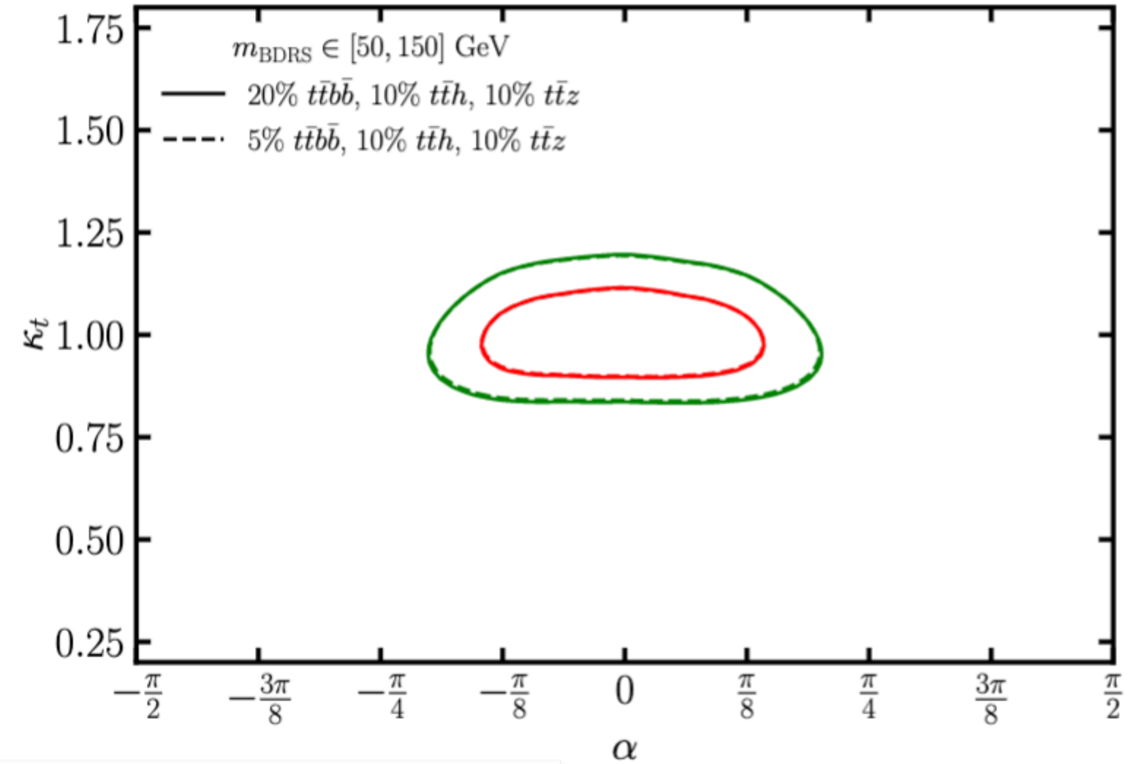
- Reconstruction method is purely based on mass minimization: It is less sensitive to BSM modifications



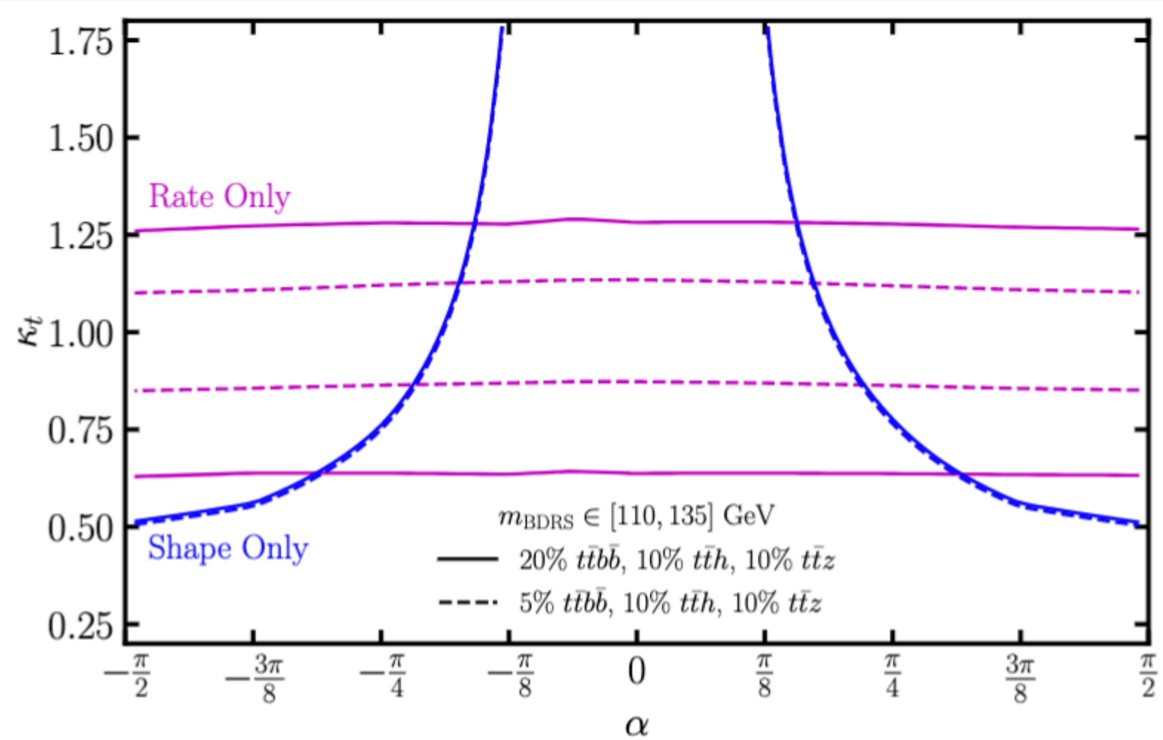
DG, Kong, Kim (2018)

Backup

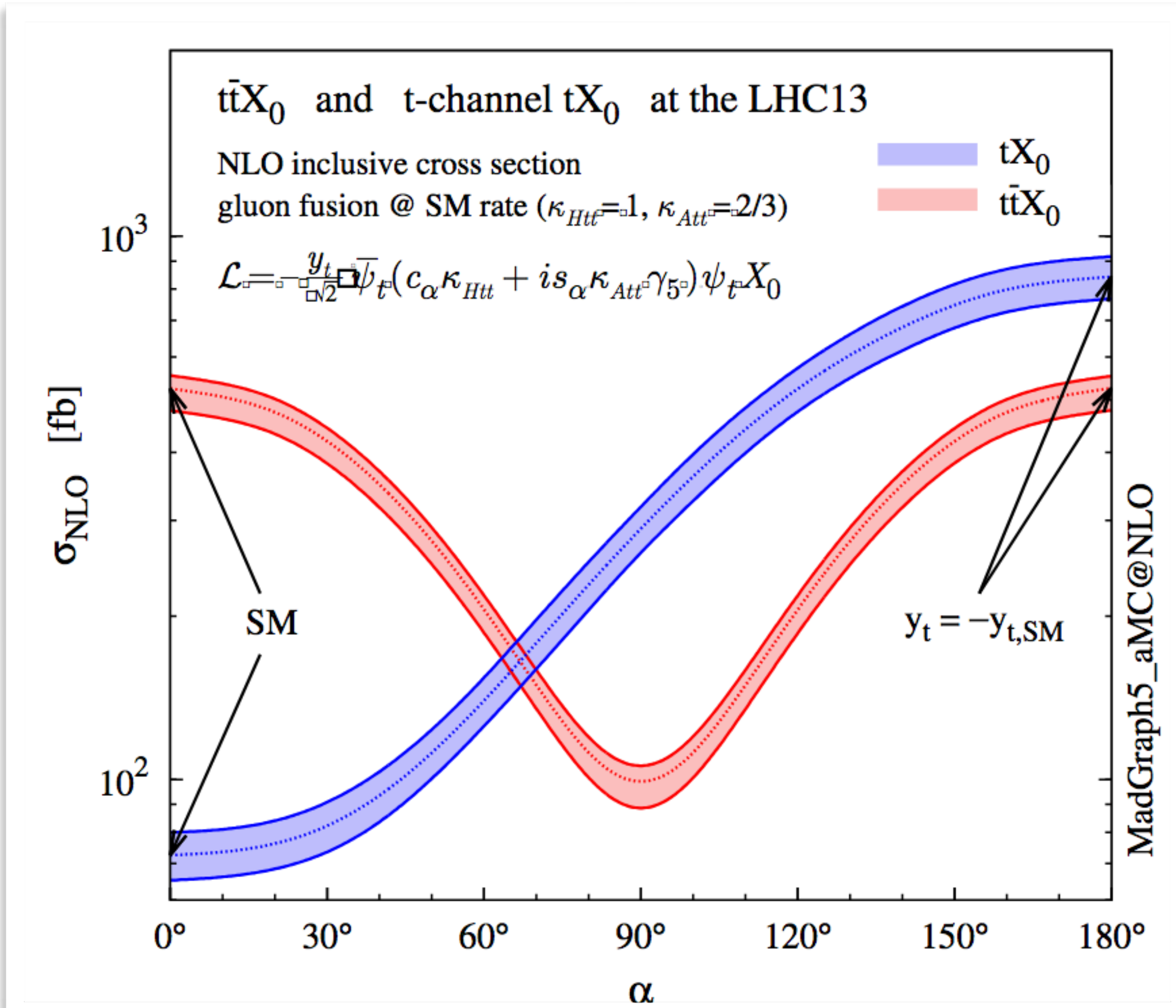




DG, Kong, Kim, Wu '21



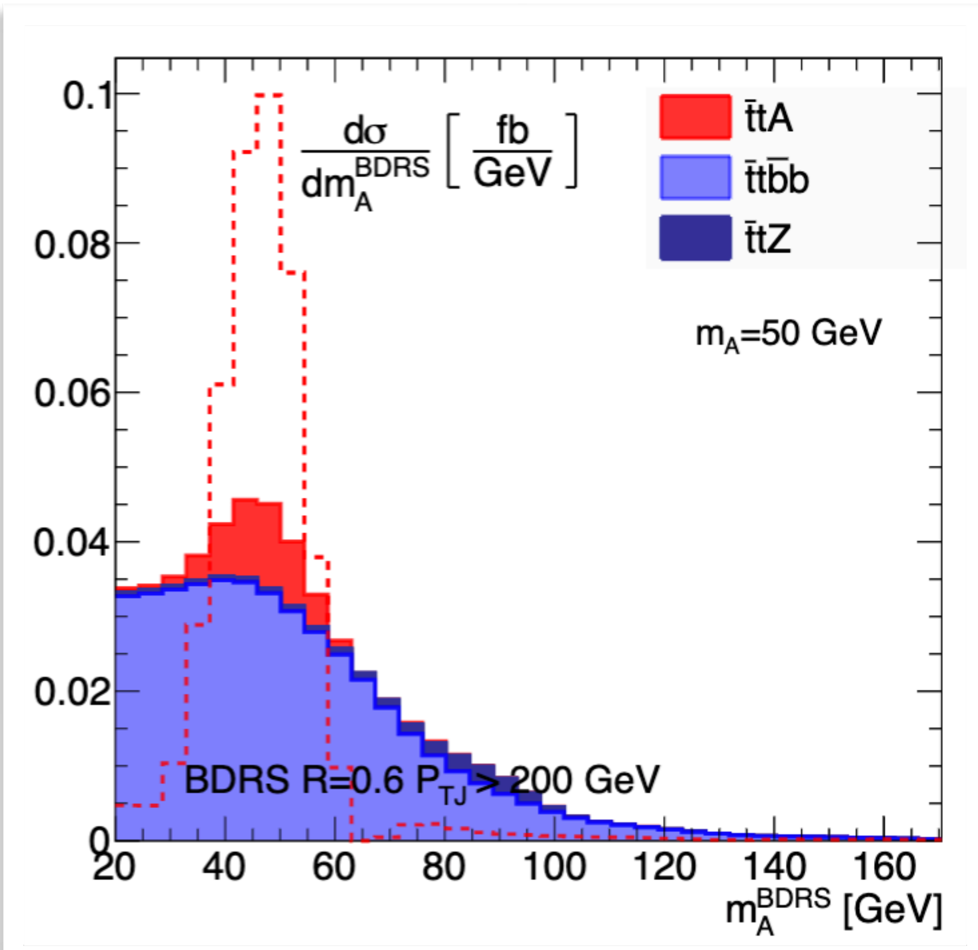
Backup

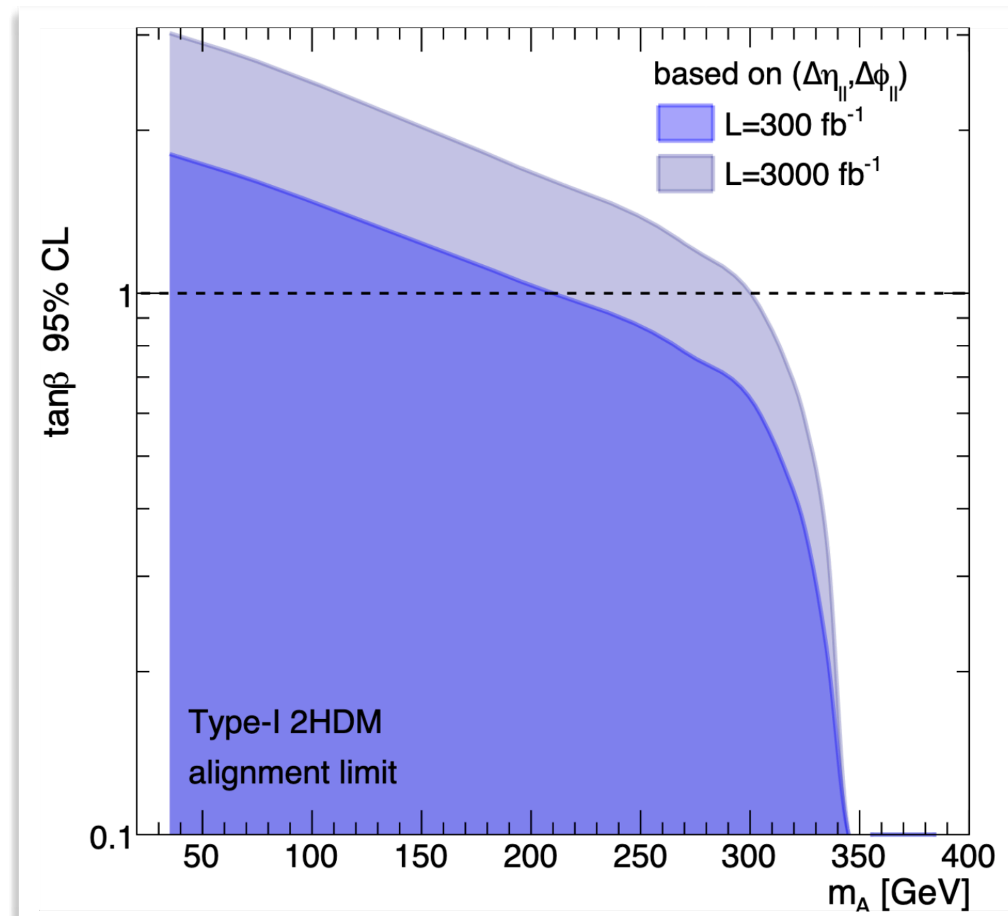


Demartin, Maltoni, Mawatari, Zaro (2015)
Englert, Re (2014)

Extended Scalar Sectors

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





Lopez-val, **DG** (2016)

Azevedo, Capucha, Gouveia, Onofre, Santos (2020)

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