Probing CP-violation in the Higgs Sector

Texas A&M 2022 - 26th May 2022

Dorival Gonçalves

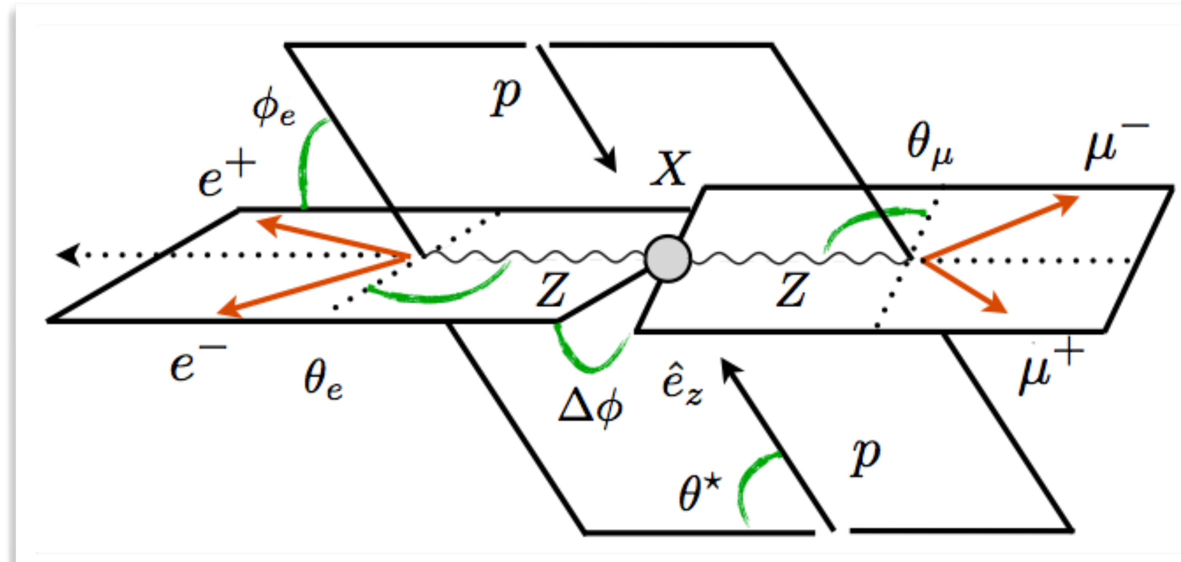
CP-violation

- 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

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



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

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

  → 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)

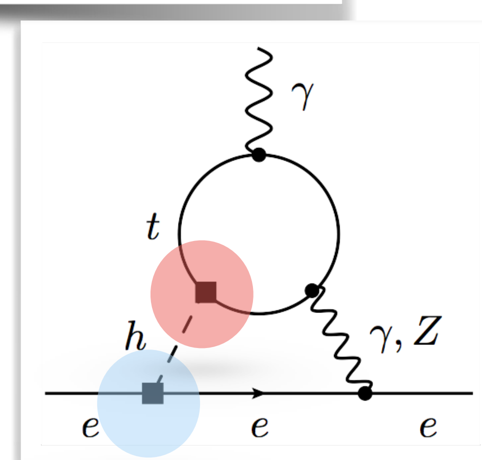
GF: Dolan, Harris, Jankowiak, Spannowsky 14’

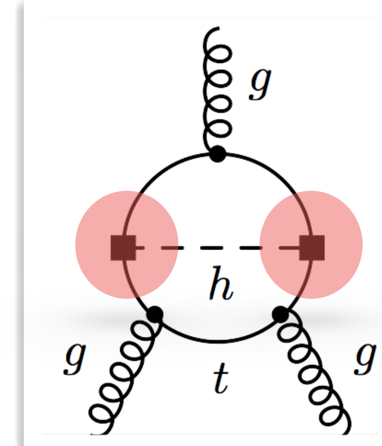
taus: Harnik, Martin, Okui, Primulando, Yu 13’

Indirect EDM constraints

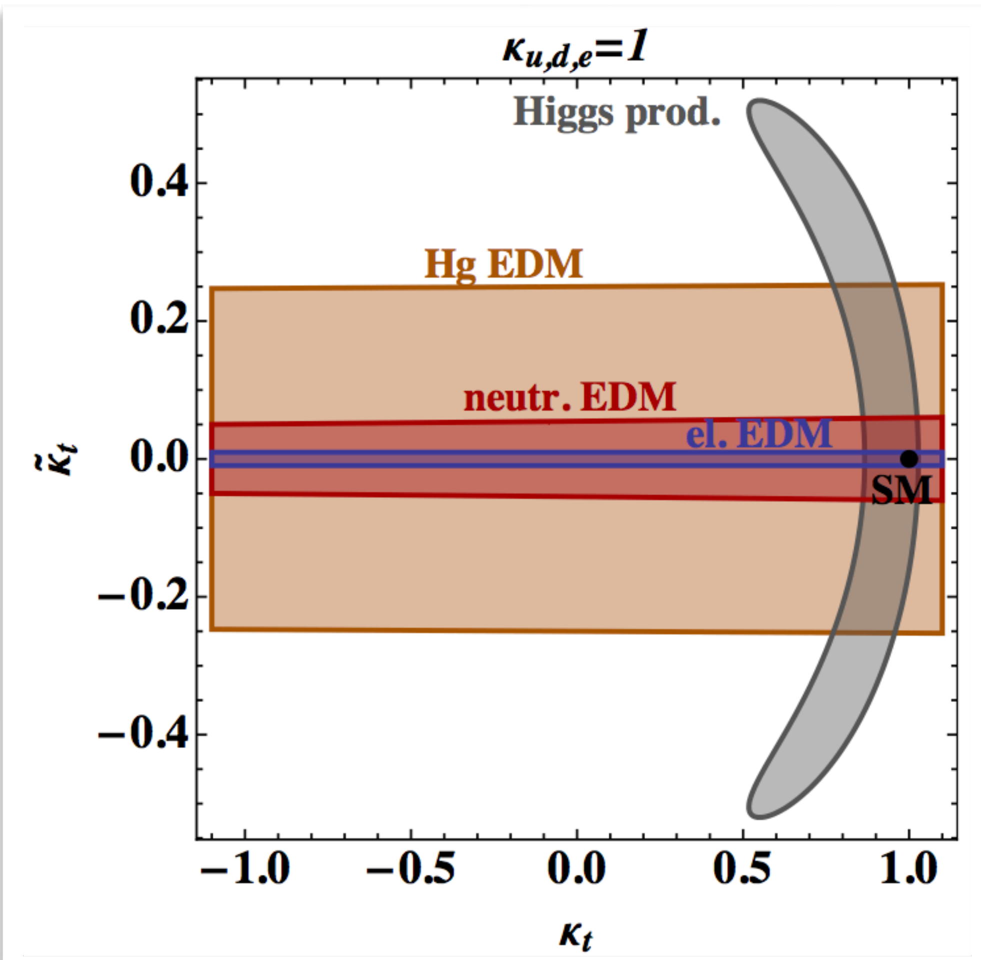
- Indirect constraints from eEDM very strong

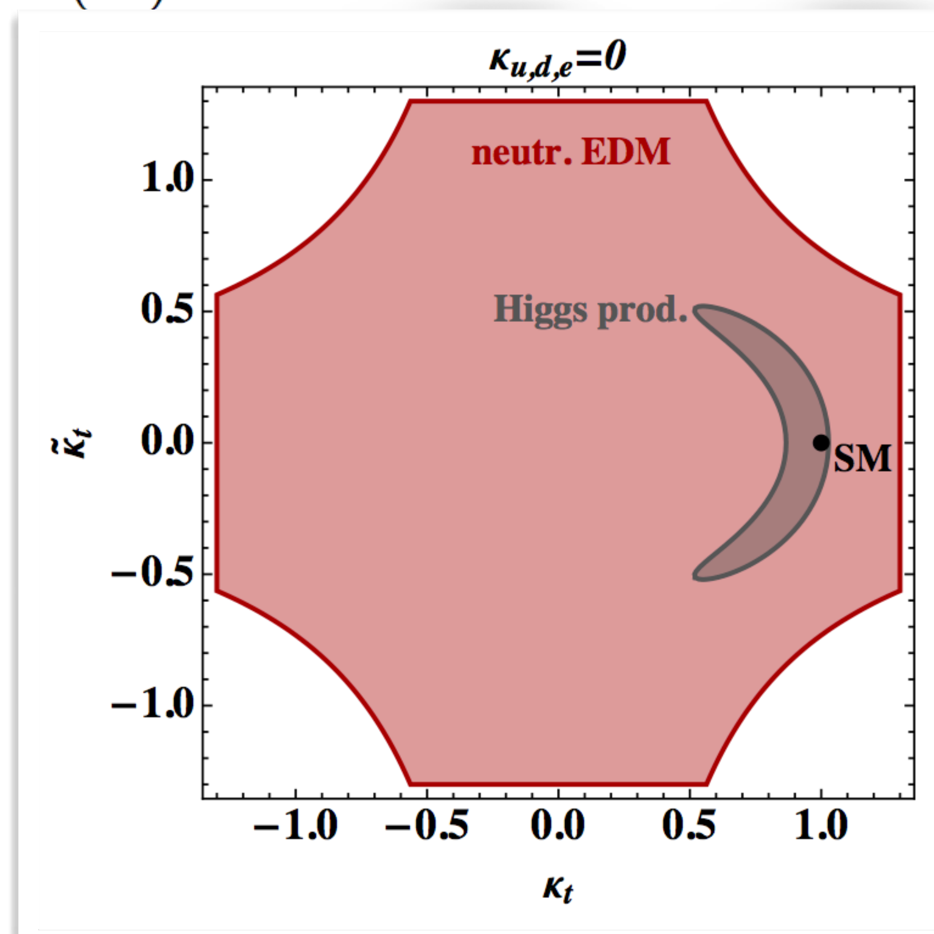
$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$





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



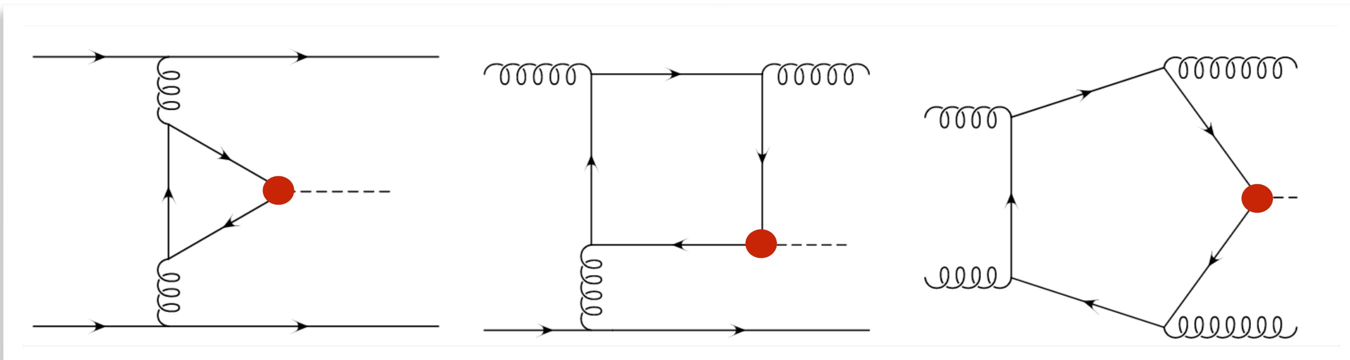


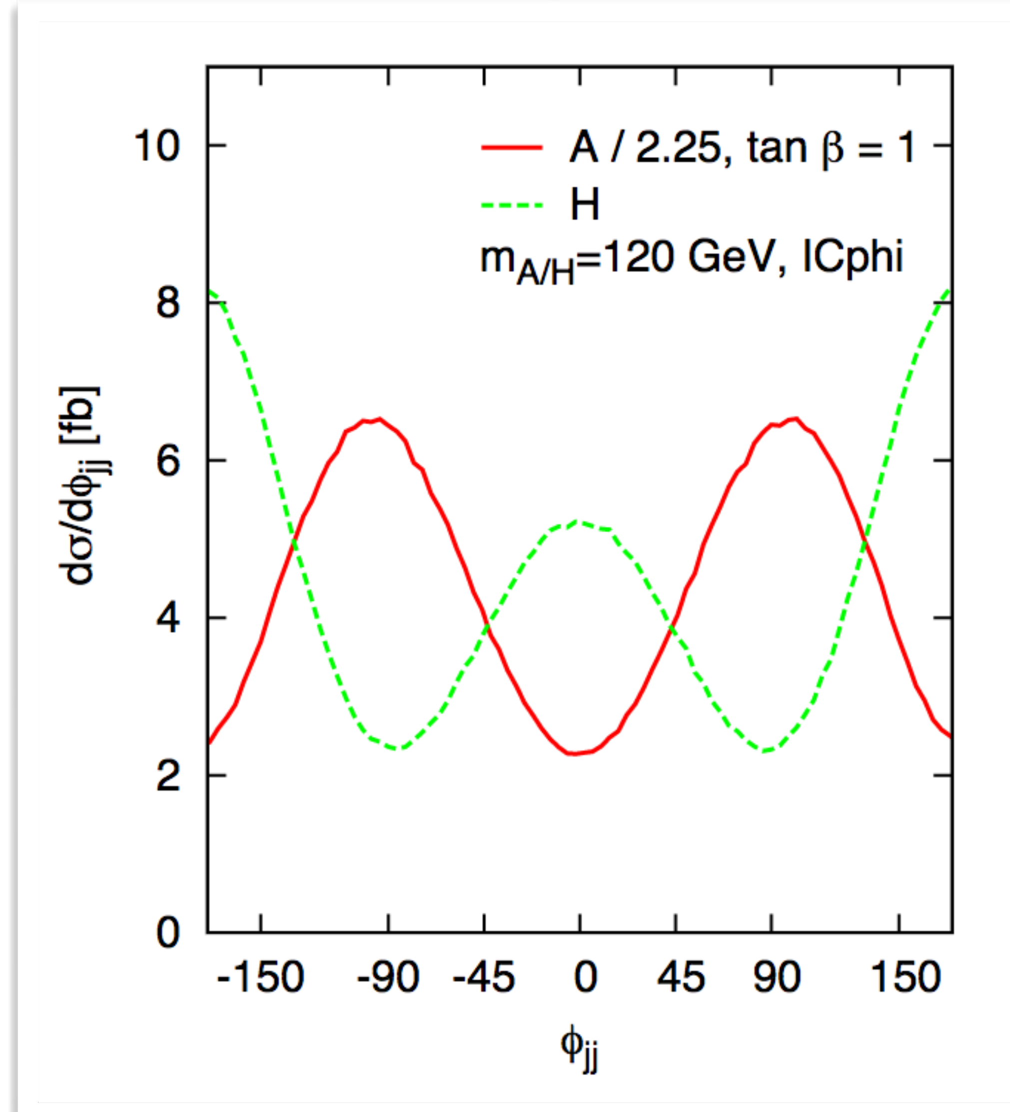
Brod, Haisch, Zupan (2013); Engel, Ramsey-Musolf, Kolck (2013); Cirigliano, Dekens, Vries, Mereghetti (2016)

Indirect collider constraints

- Complementary top-Higgs CP measurement at LHC:

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





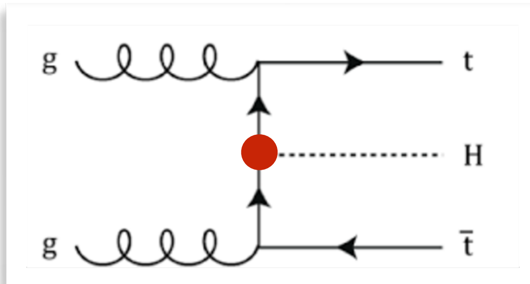
Plehn, Rainwater, Zeppenfeld (2001)
Zeppenfeld, Kubocz, Campanario (2010)
Englert, **DG**, Mawatari, Plehn (2012)
Dolan, Harris, Jankowiak, Spannowsky (2014)

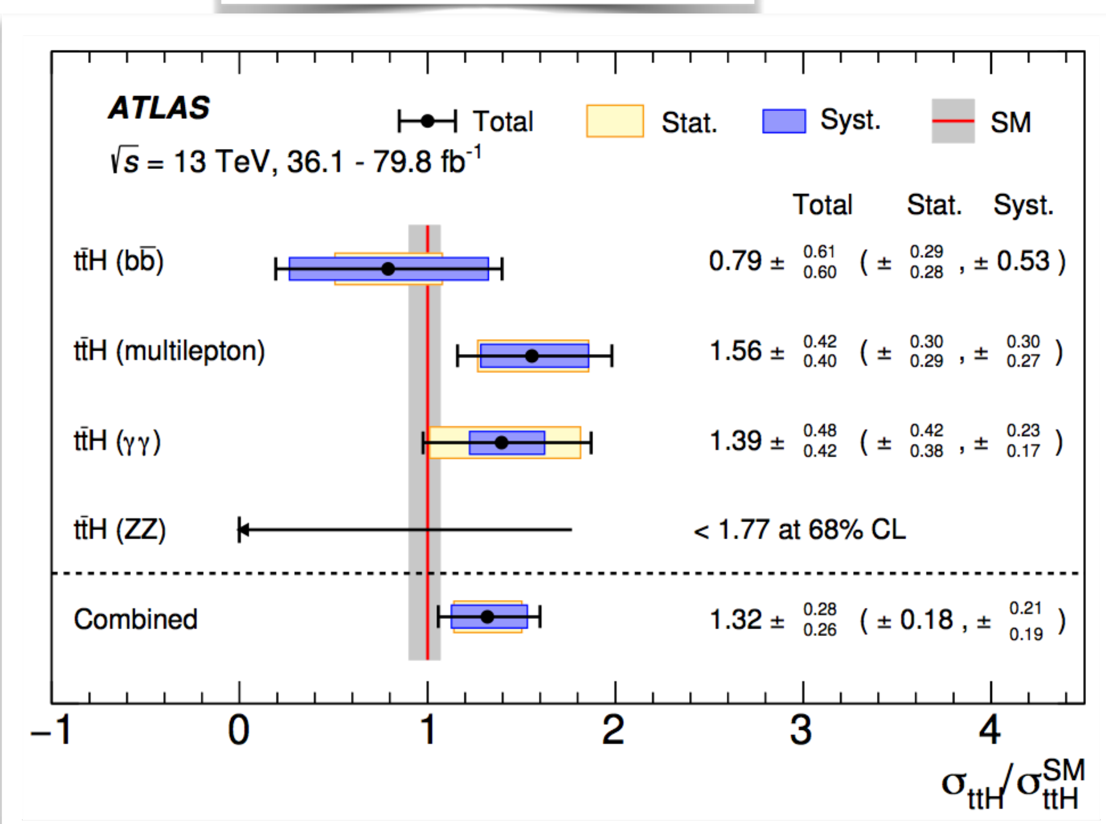
- Loop-induced: indirect constraints
- Bottom line:

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

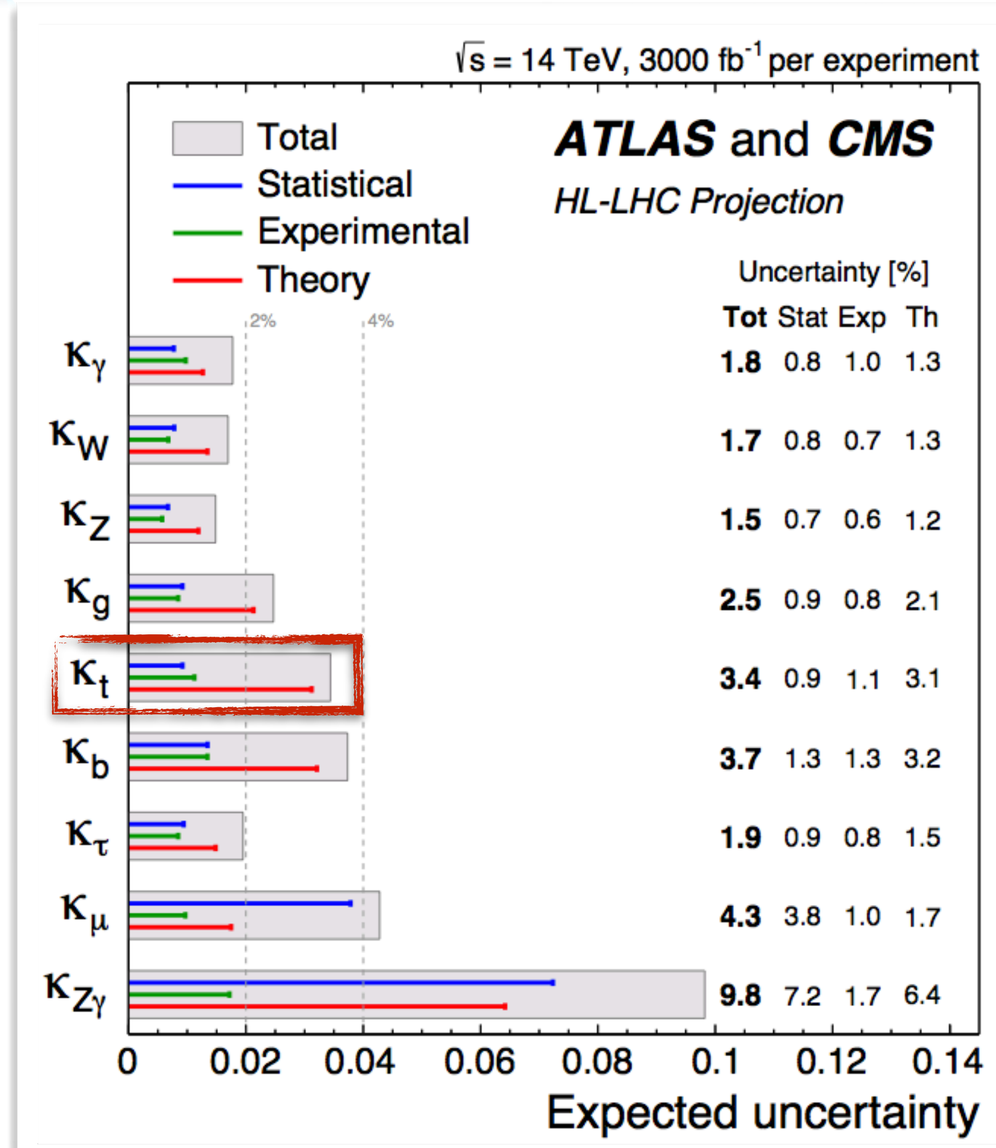
Direct CP measurement of Higgs-top coupling

- ttH channel observation (2018):





- Expected HL-LHC precisions:



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

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

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	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$
E (GeV)	14,000	14,000	250	350	500	1,000	125	125	≥ 500
$\mathcal{L}$ (fb^{-1})	300	3,000	250	350	500	1,000	250		
HZZ/HWW	$2{\cdot}10^{-4}$	$0.5{\cdot}10^{-4}$	$7{\cdot}10^{-4}$	$1.1{\cdot}10^{-4}$	$4{\cdot}10^{-5}$	$8{\cdot}10^{-6}$	✓	✓	✓
$H\gamma\gamma$	–	0.50	–	–	–	–	0.06	–	–
$HZ\gamma$	–	~ 1	–	–	–	–	–	–	–
Hgg	0.20	0.06	–	–	–	–	–	–	–
$Ht\bar{t}$	0.24	0.05	–	–	0.29	0.08	–	–	✓
$H\tau\tau$	0.07	0.008	0.01	0.01	0.02	0.06	✓	✓	✓
$H\mu\mu$	–	–	–	–	–	–	–	✓	–

arxiv:2205.07715

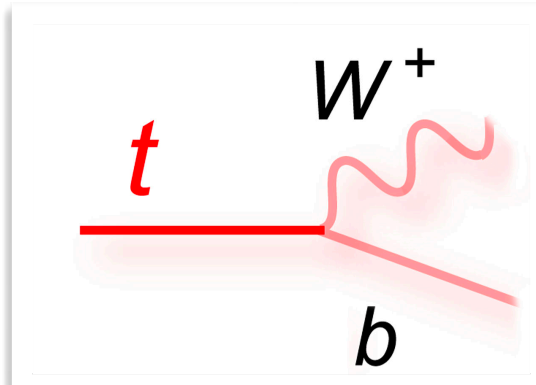
Top Quark is Unique

- 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

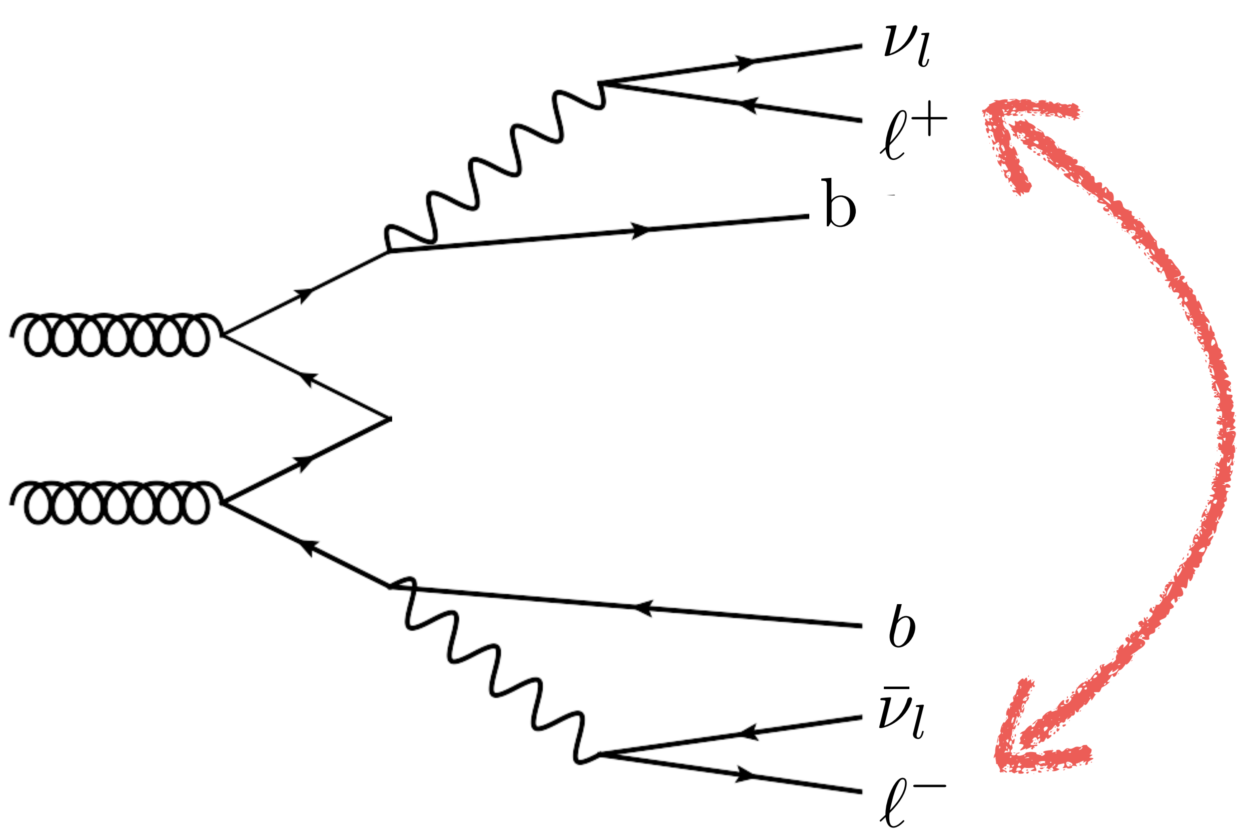
$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1+\omega_f\cos\theta_f)$$

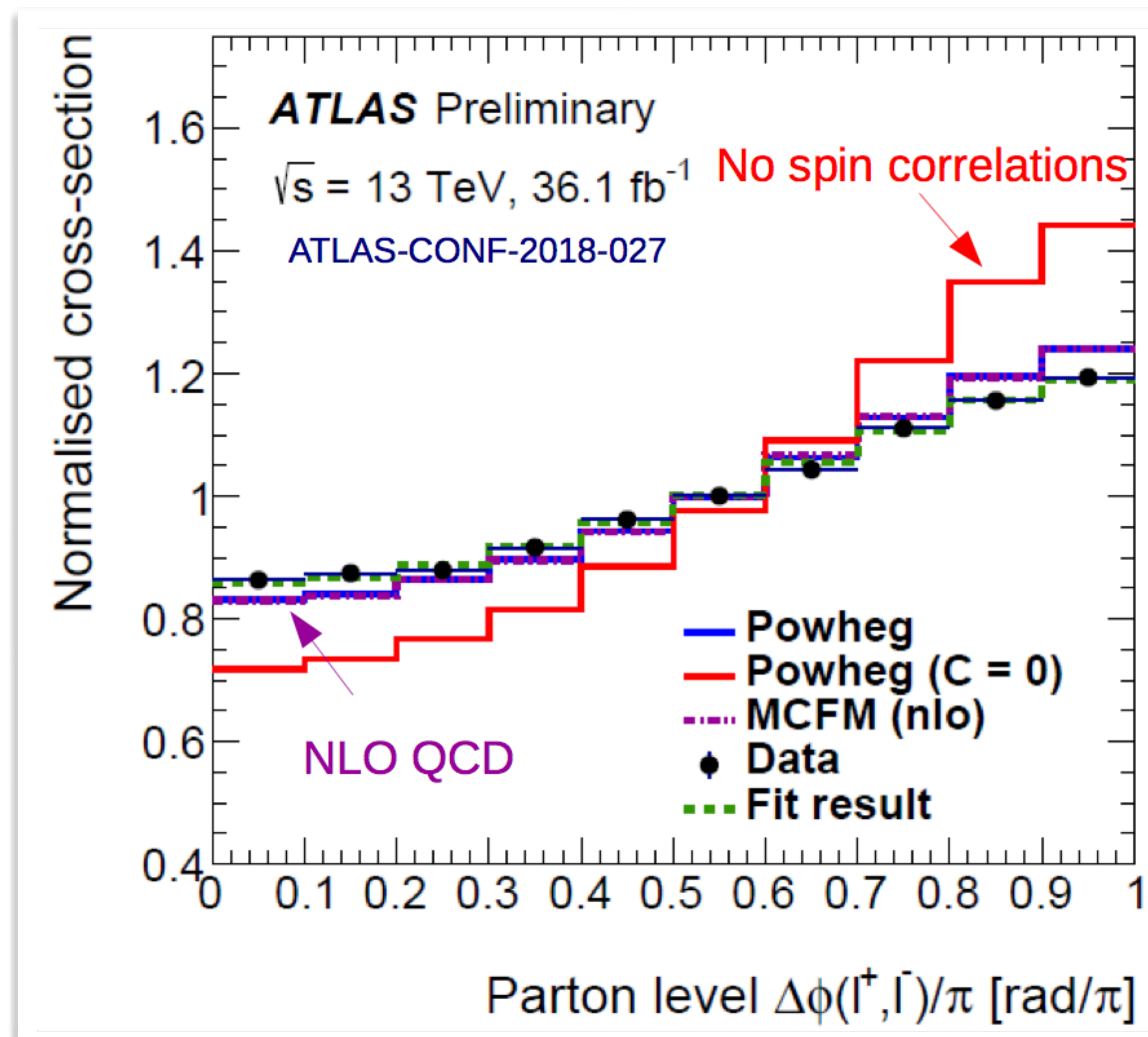
	$l^+, \bar{d}$	b	$\bar{\nu}, u$
ω_f	1	-0.4	-0.3

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

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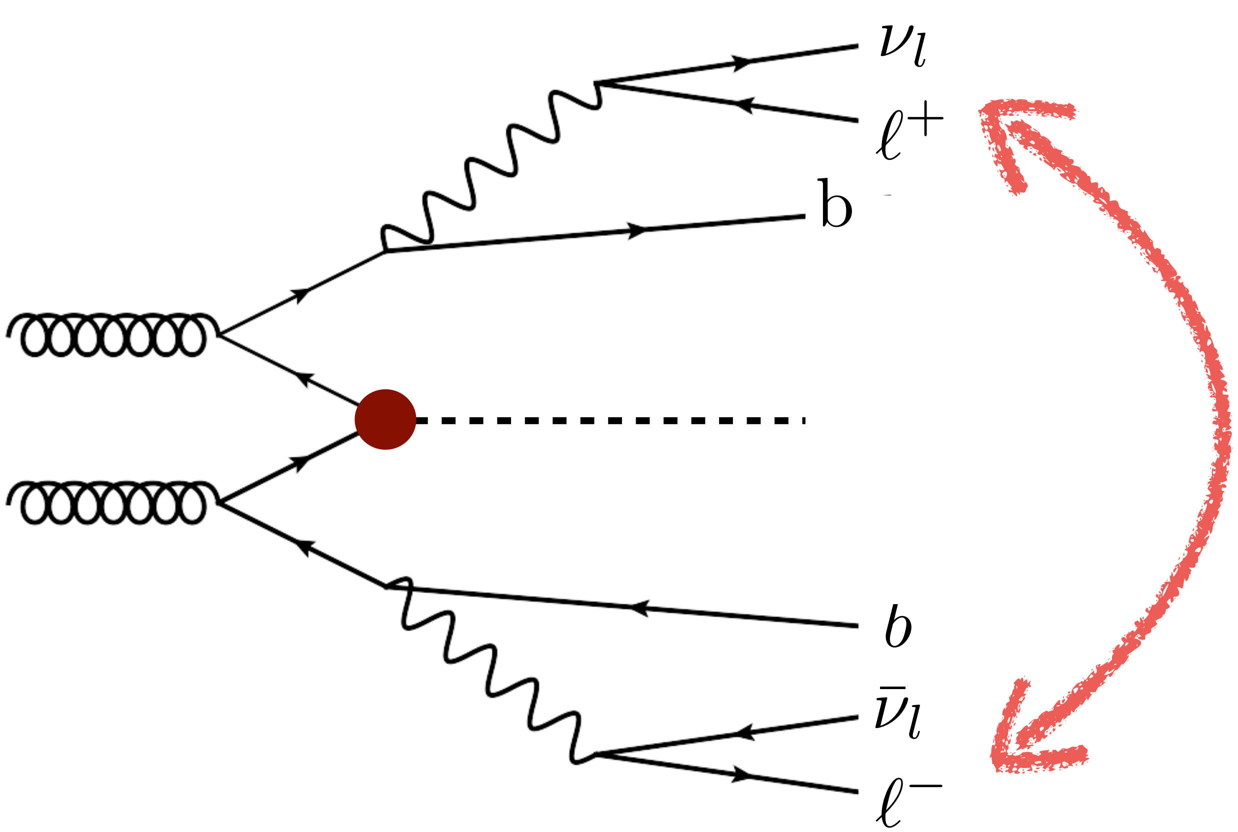
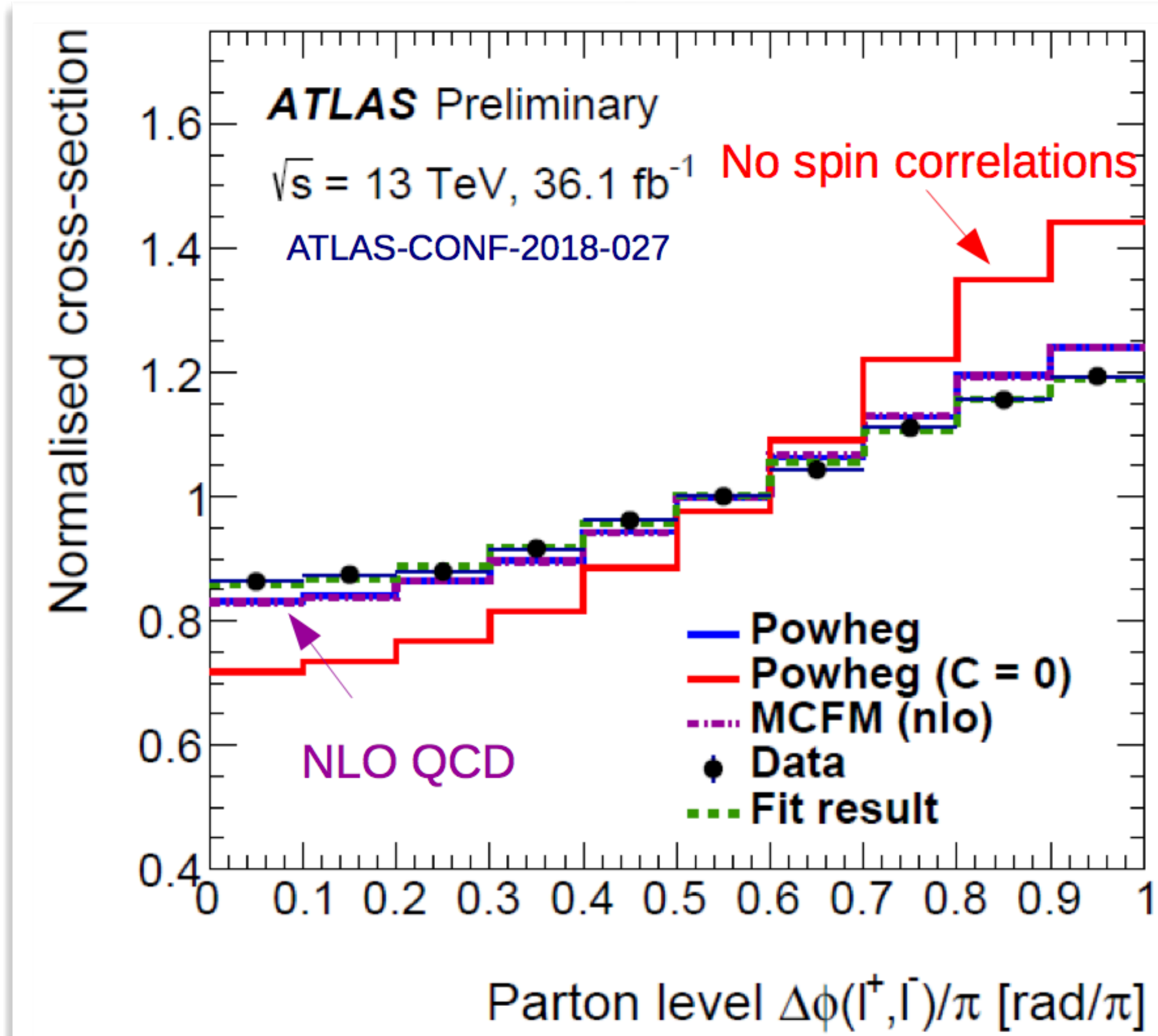


$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} (\cos\alpha + i\gamma_5 \sin\alpha) t \; H$$

Buckley, DG (PRL '15)



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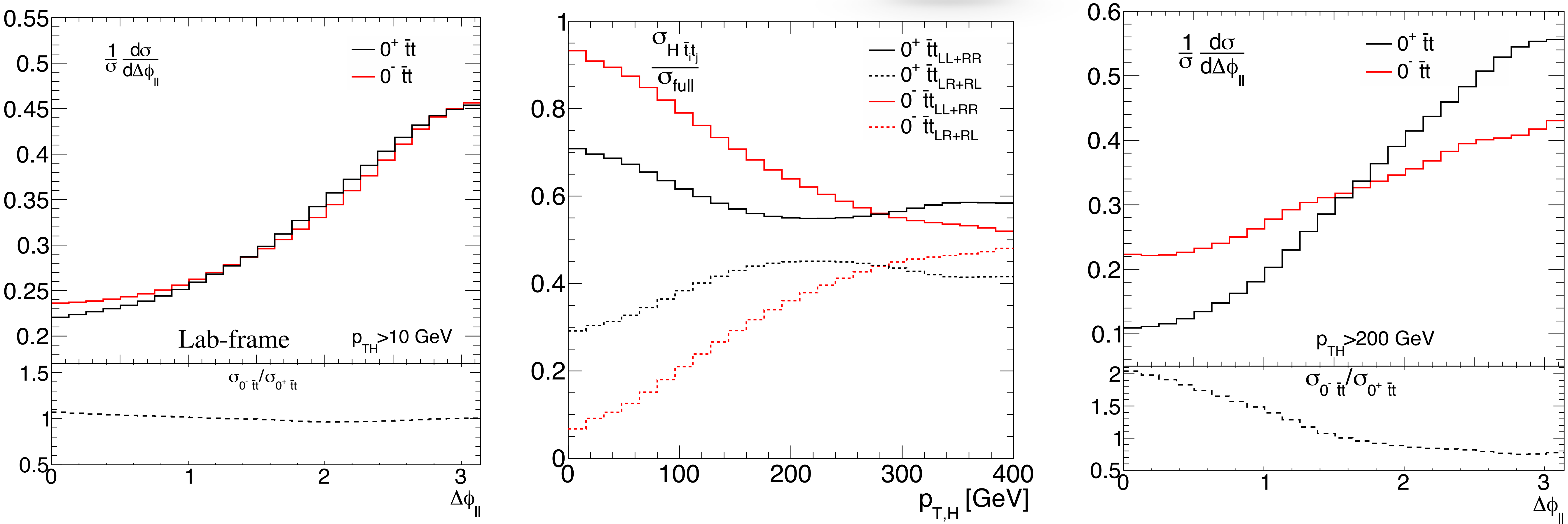

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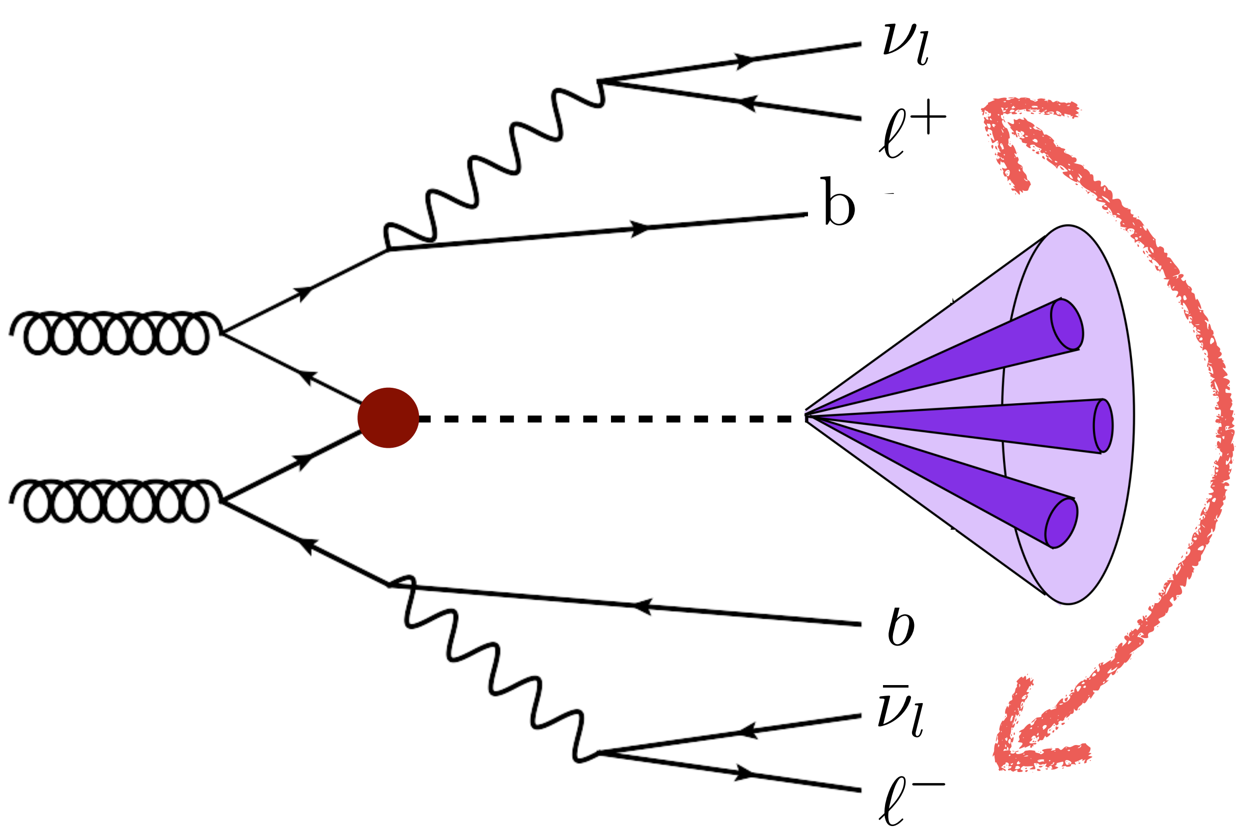
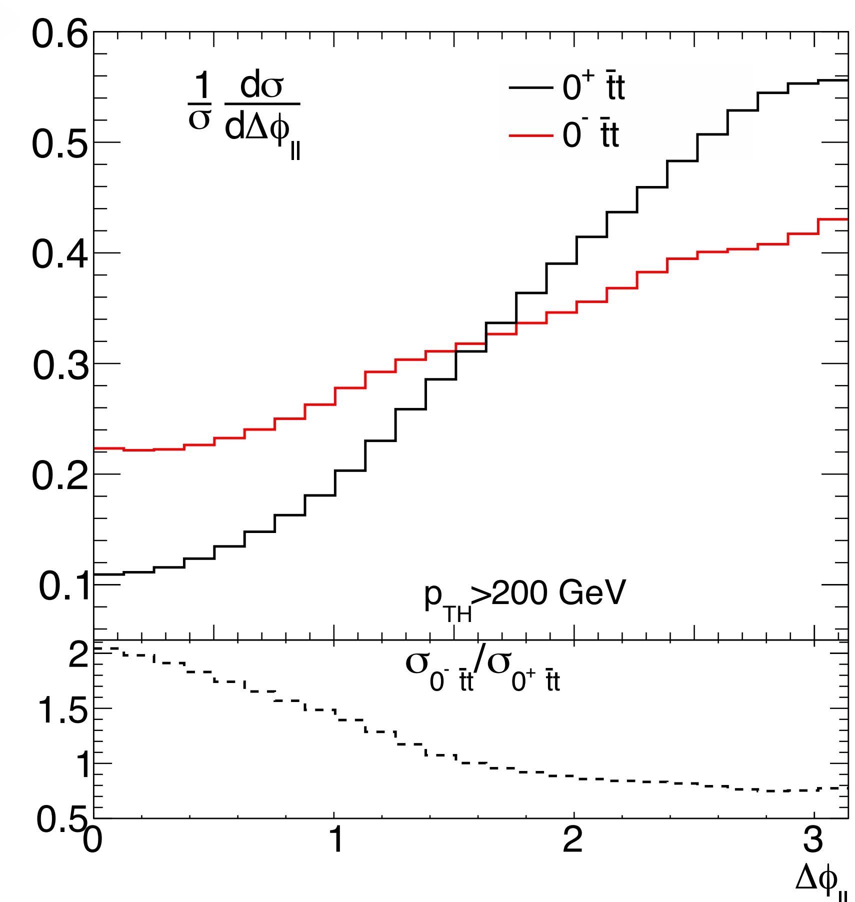




Buckley, DG (PRL '15)

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

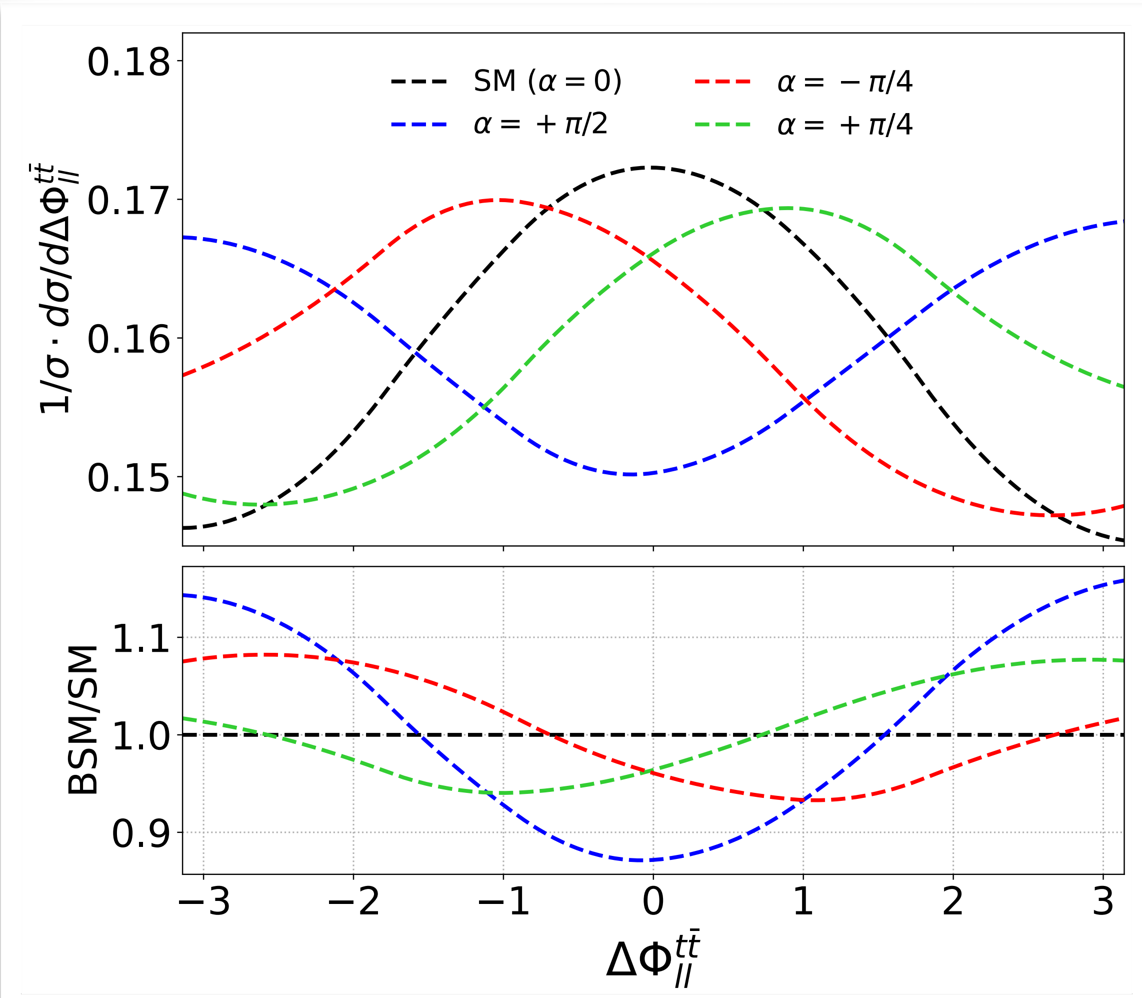
CP sensitive observables

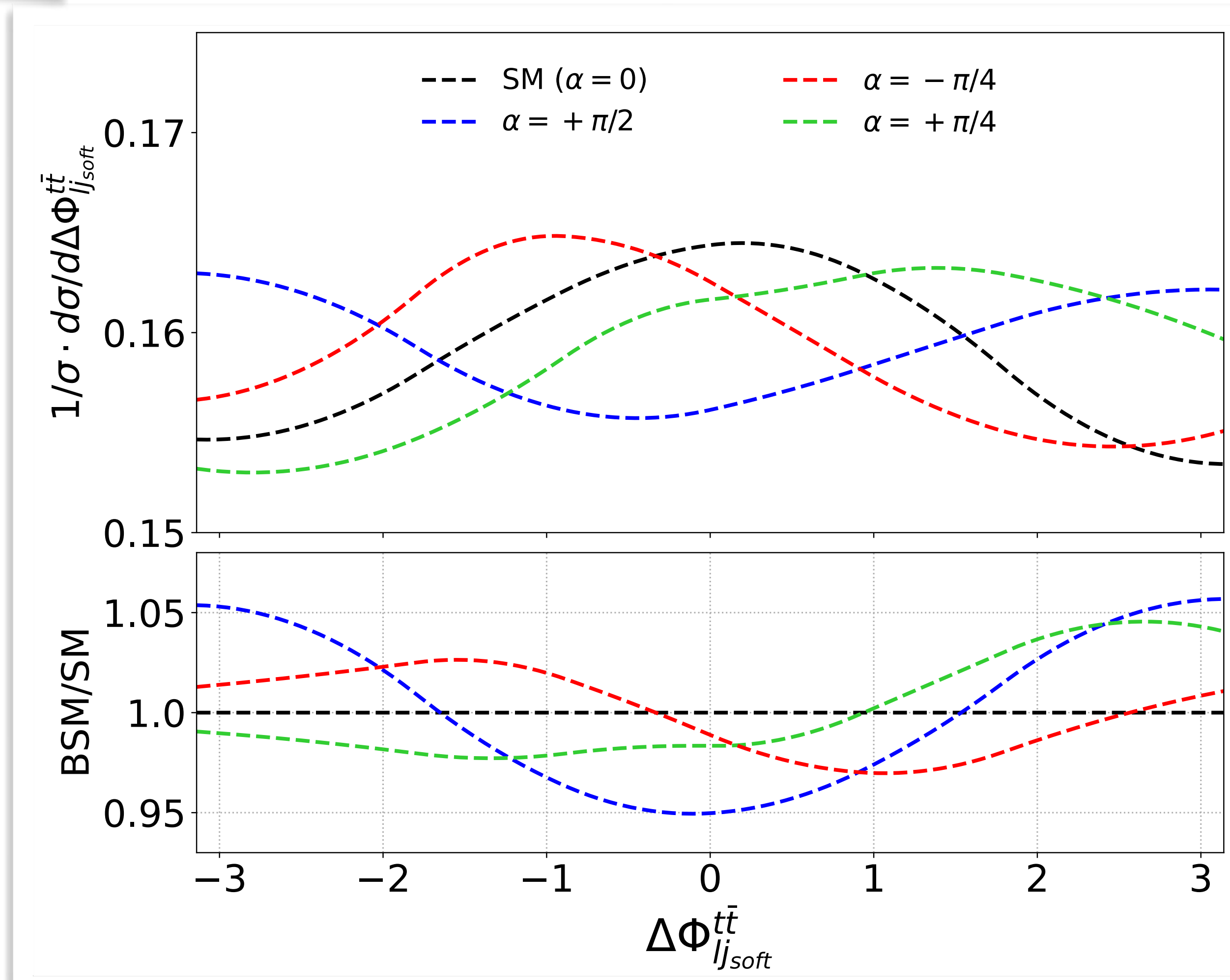
- CPV observables best defined at the top pair rest frame:

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

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

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





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

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

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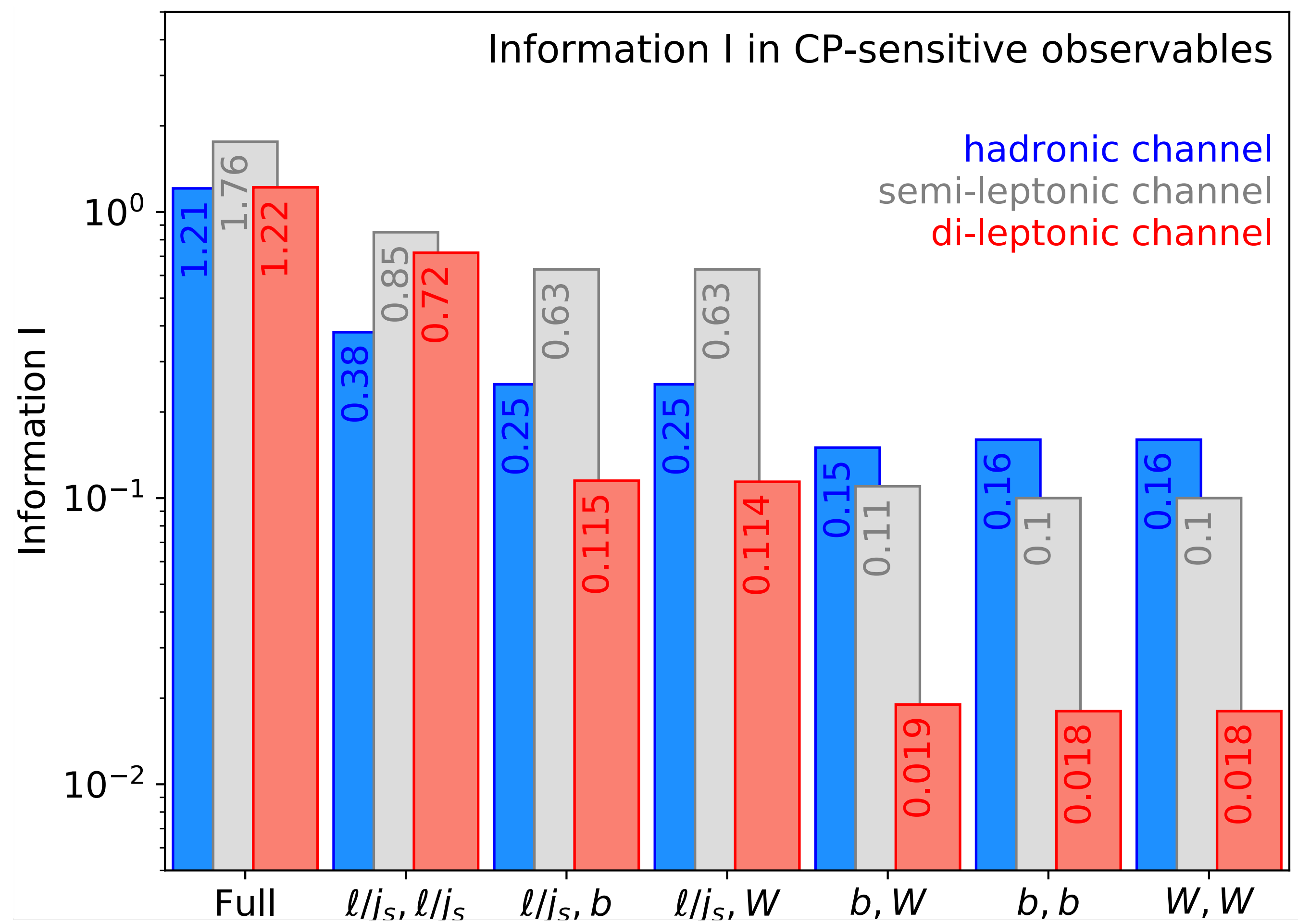
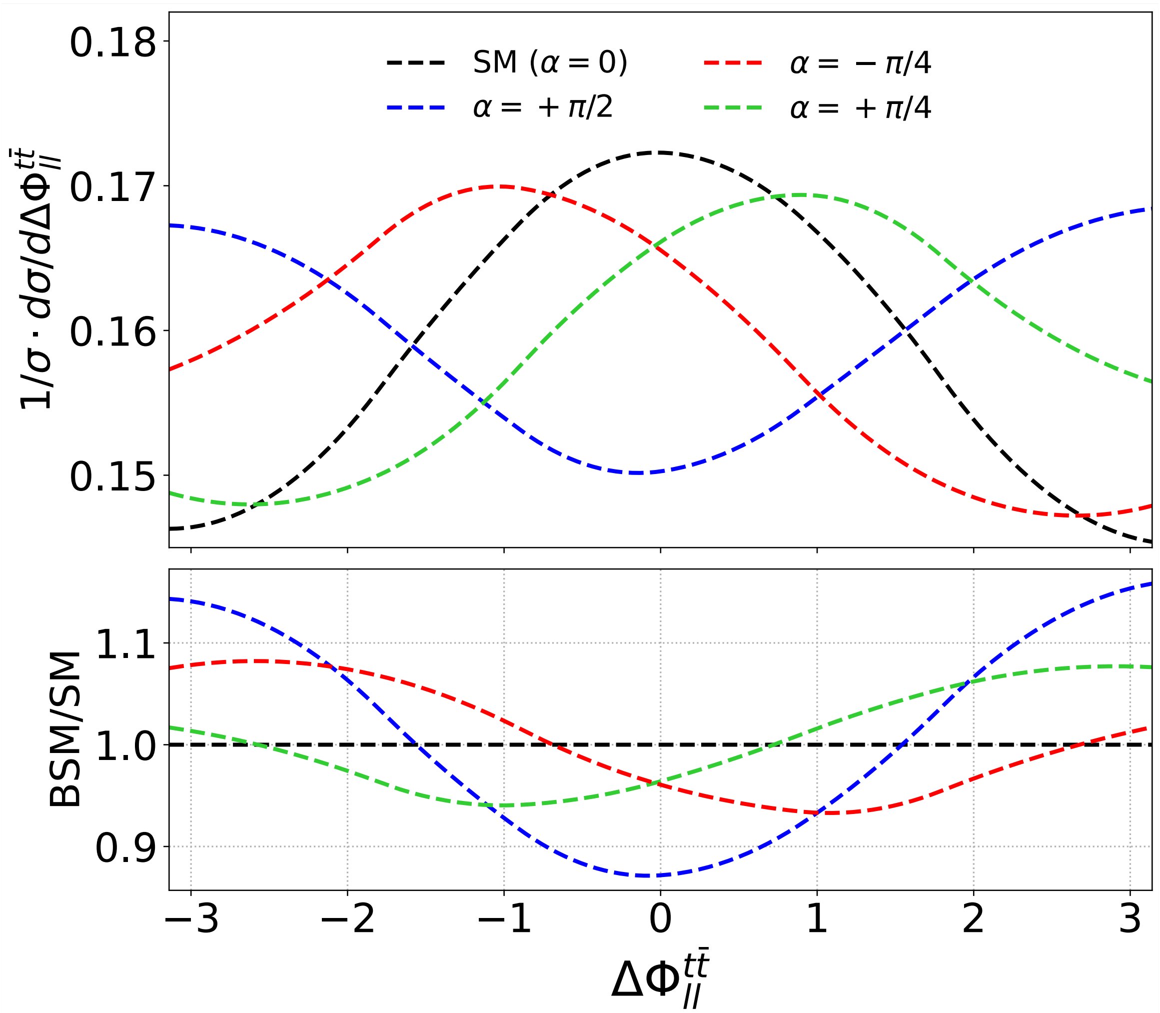
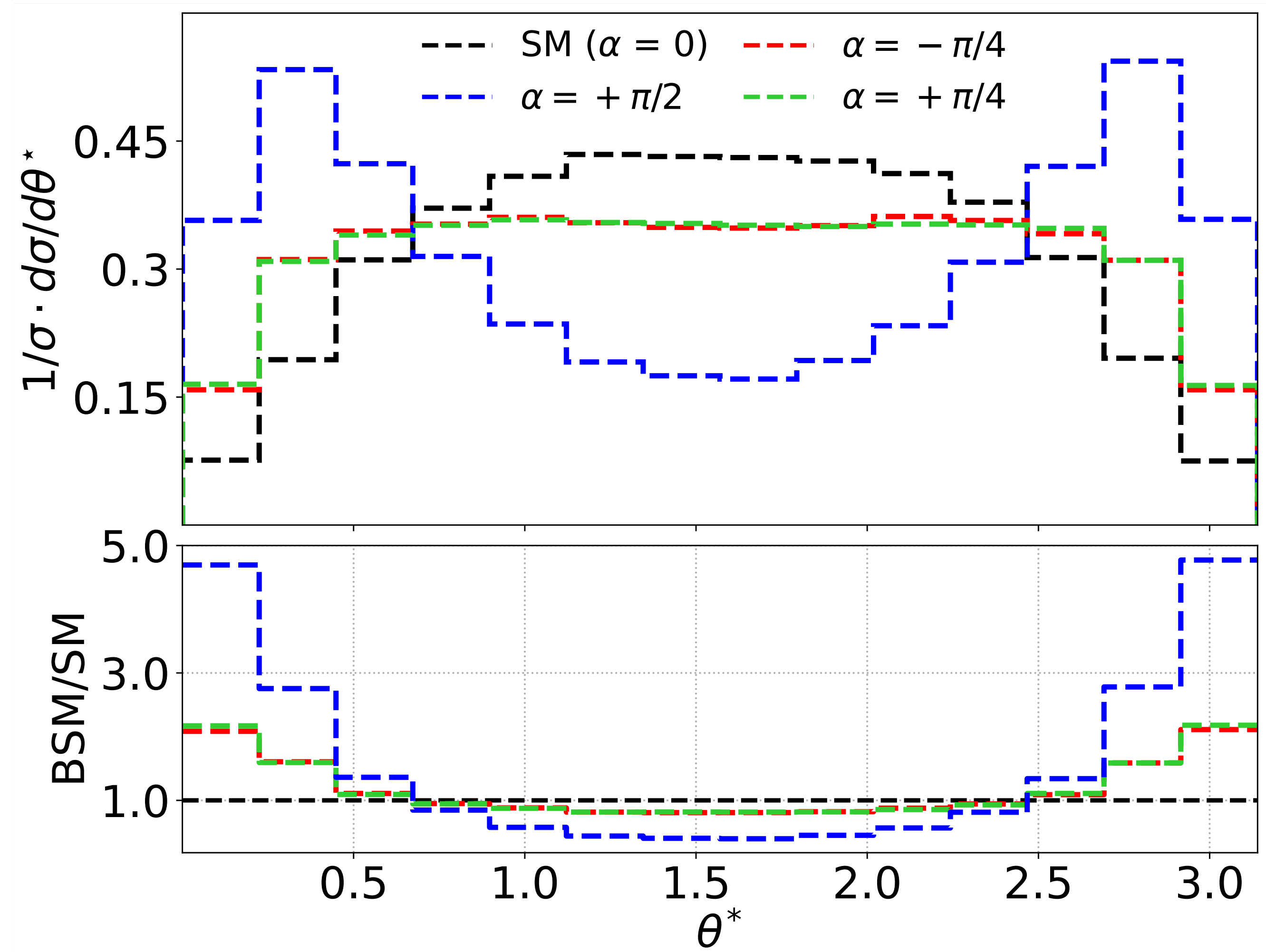


Barman, DG, Kling '21

Top Reconstruction

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



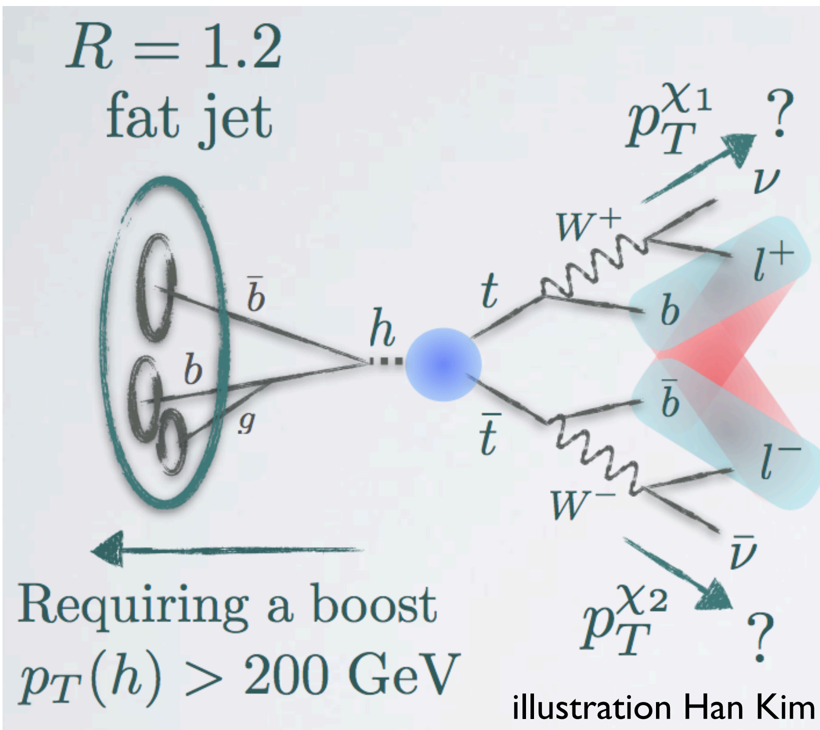


Combinatorial ambiguities and presence of up to two neutrinos makes reconstruction challenging

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

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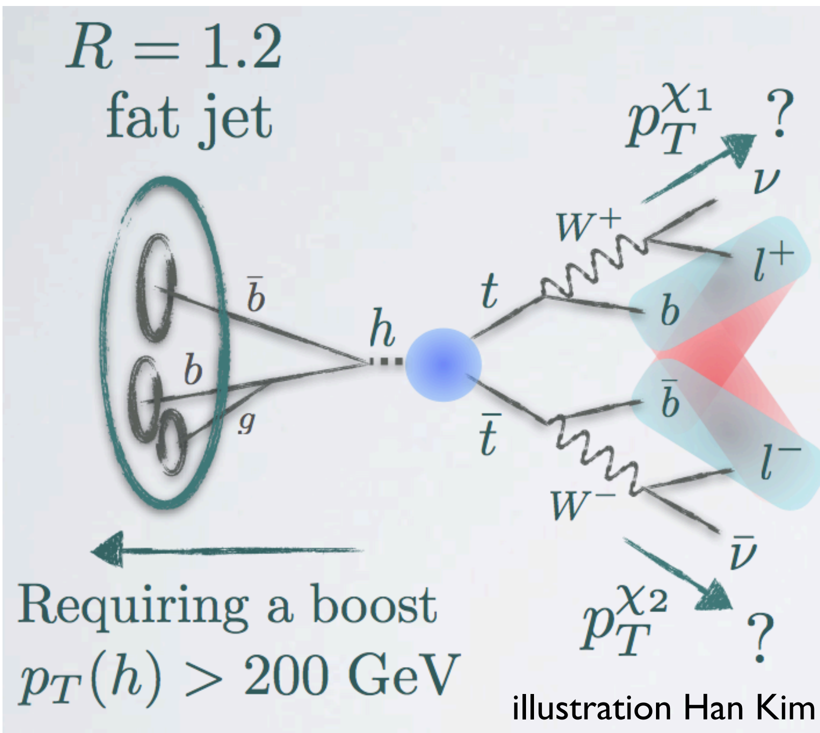

Debnath, Kim, Kong, Matchev '17

DG, Kong, Kim '18

→ **Reconstruction of the Higgs: BDRS**

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a) **guess neutrino momenta**

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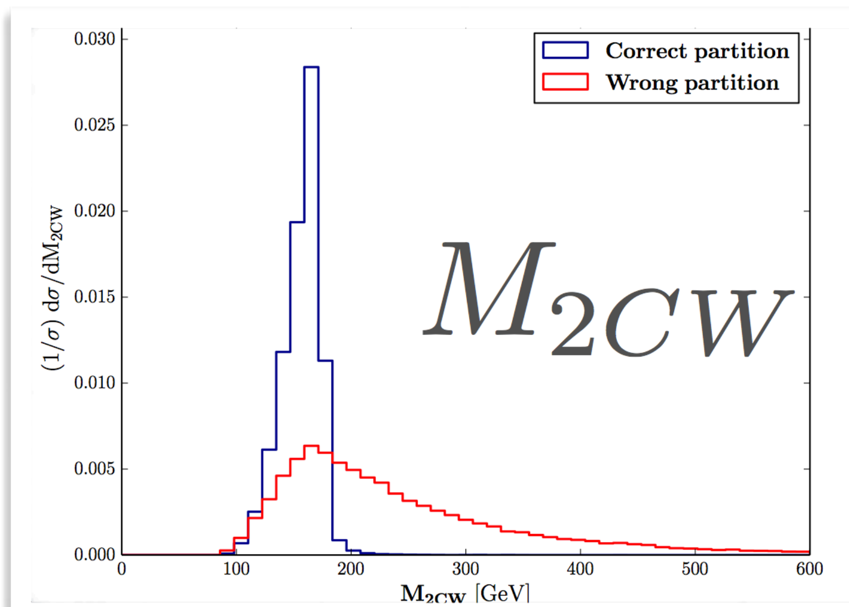
$M_{2CW}^{\text{correct}} \longrightarrow p_T^{\chi_1}(\text{correct}) \quad p_T^{\chi_2}(\text{correct})$

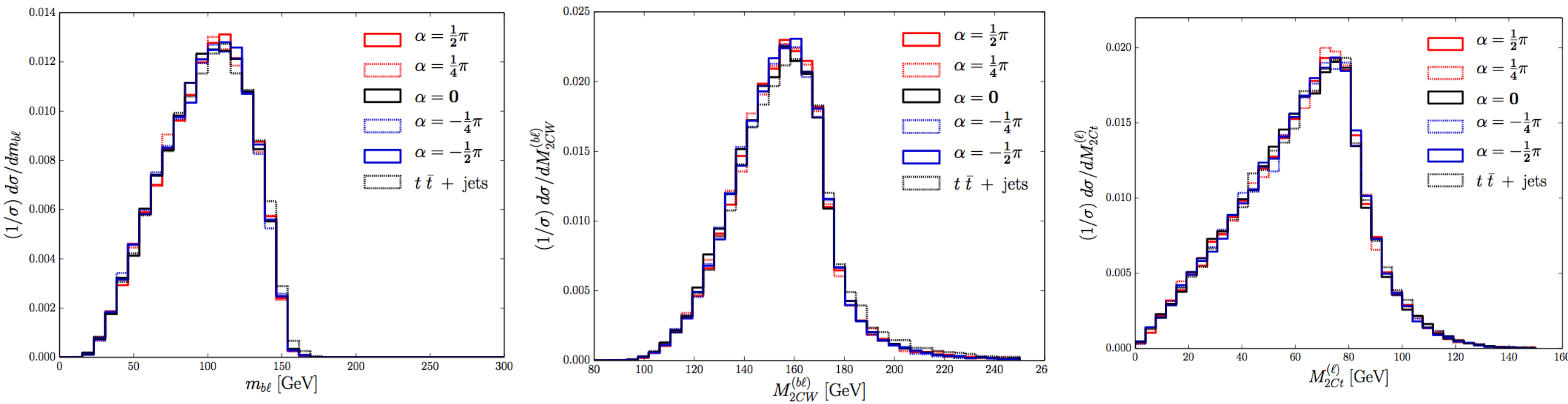
$M_{2CW}^{\text{wrong}} \longrightarrow p_T^{\chi_1}(\text{wrong}) \quad p_T^{\chi_2}(\text{wrong})$



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

Top Reconstruction

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



DG, Kong, Kim (2018)

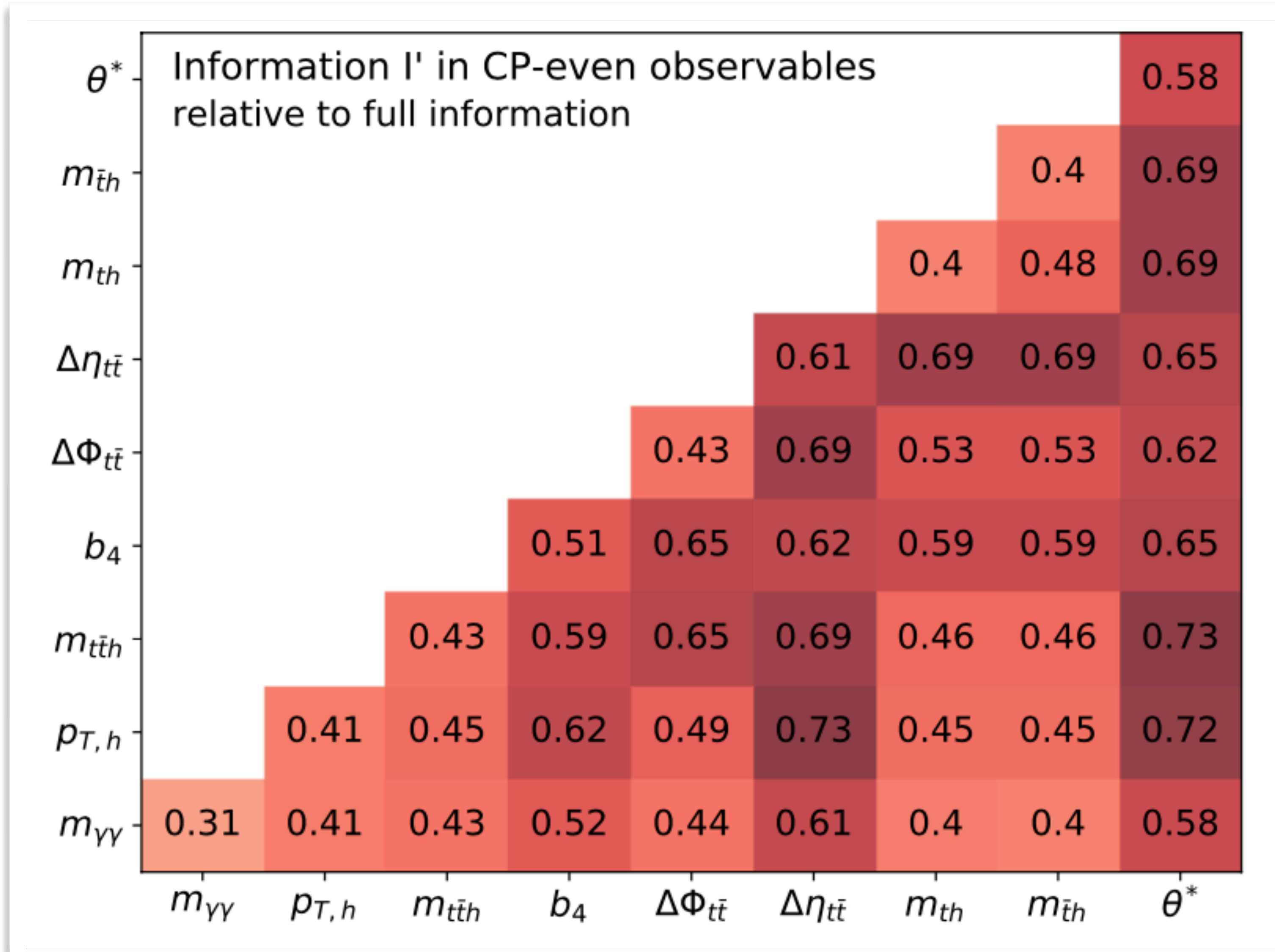
Machine Learning the Higgs-Top CP Phase

- 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.

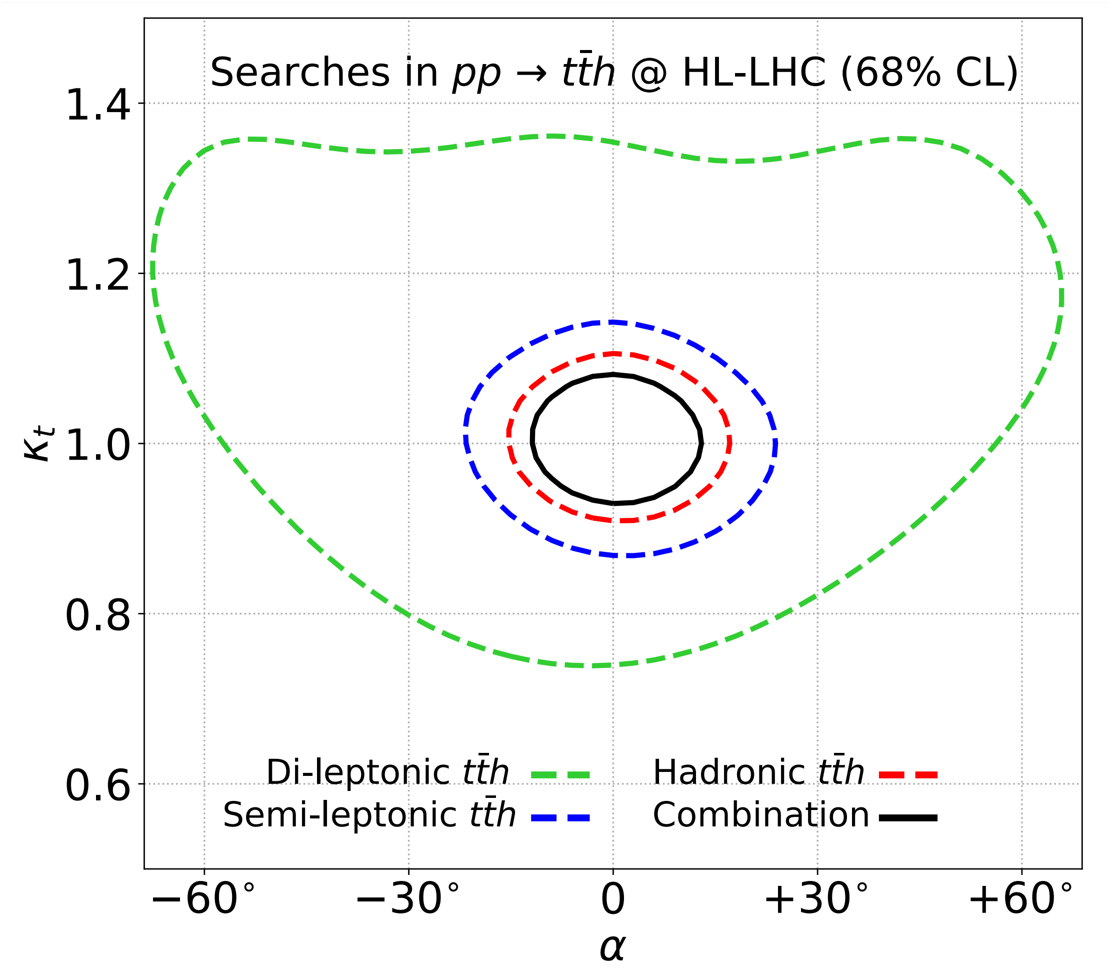


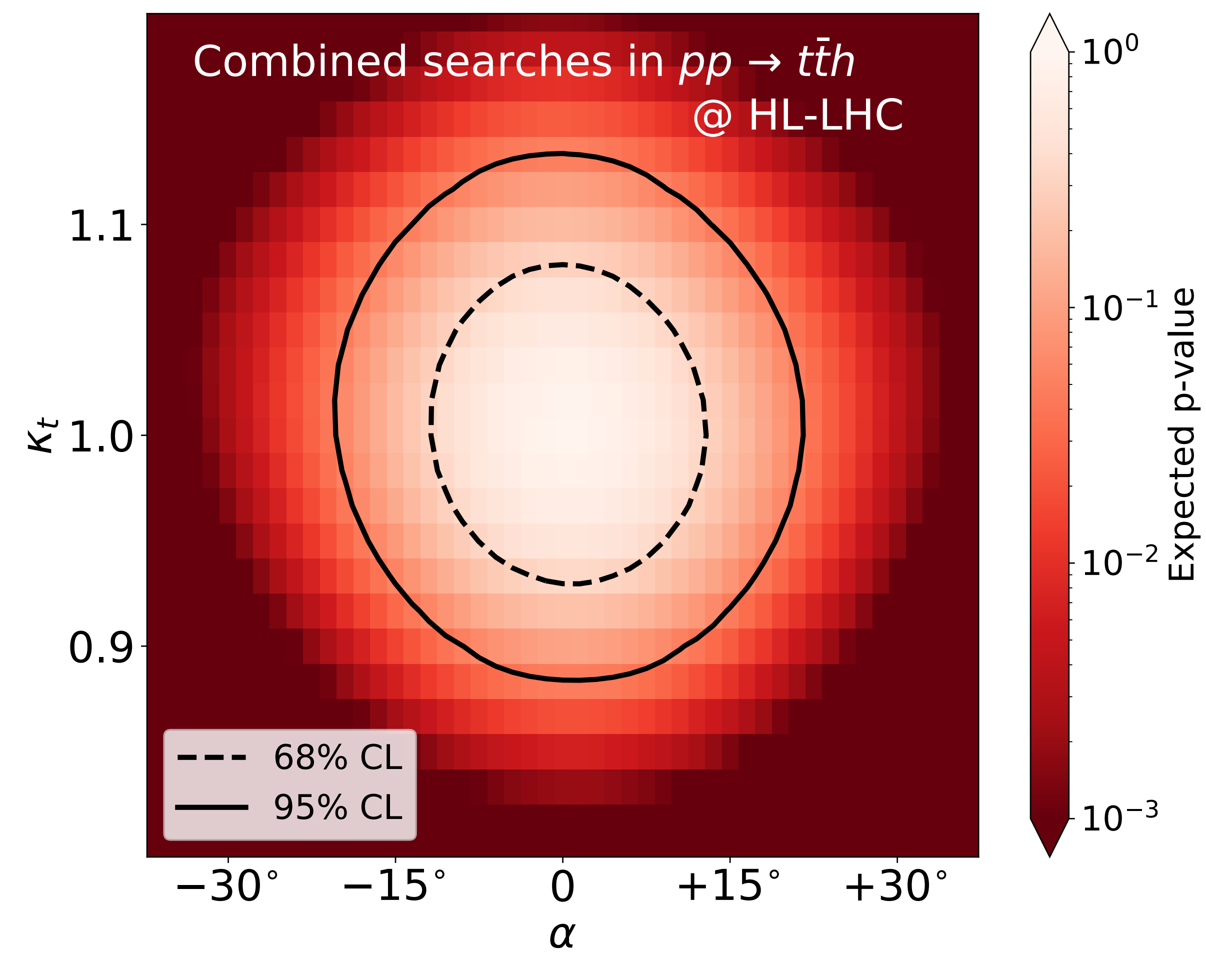
Barman, DG, Kling '21

Information increases with successive addition of observables ➡ Multivariate analysis problem

Machine Learning the Higgs-Top CP Phase

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



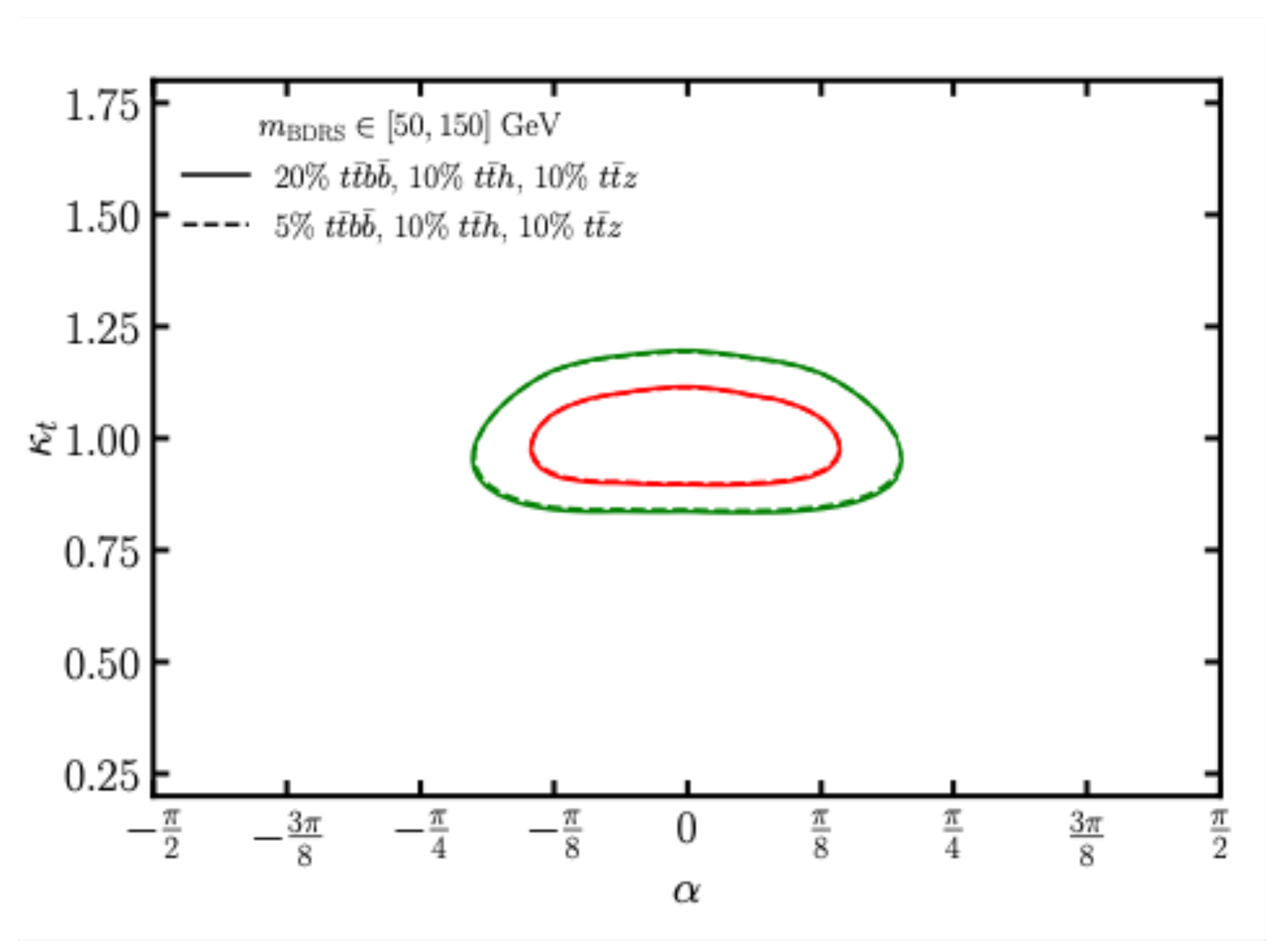


➡ Higgs-top CP phase could be probed up to $\alpha \lesssim 13^\circ$

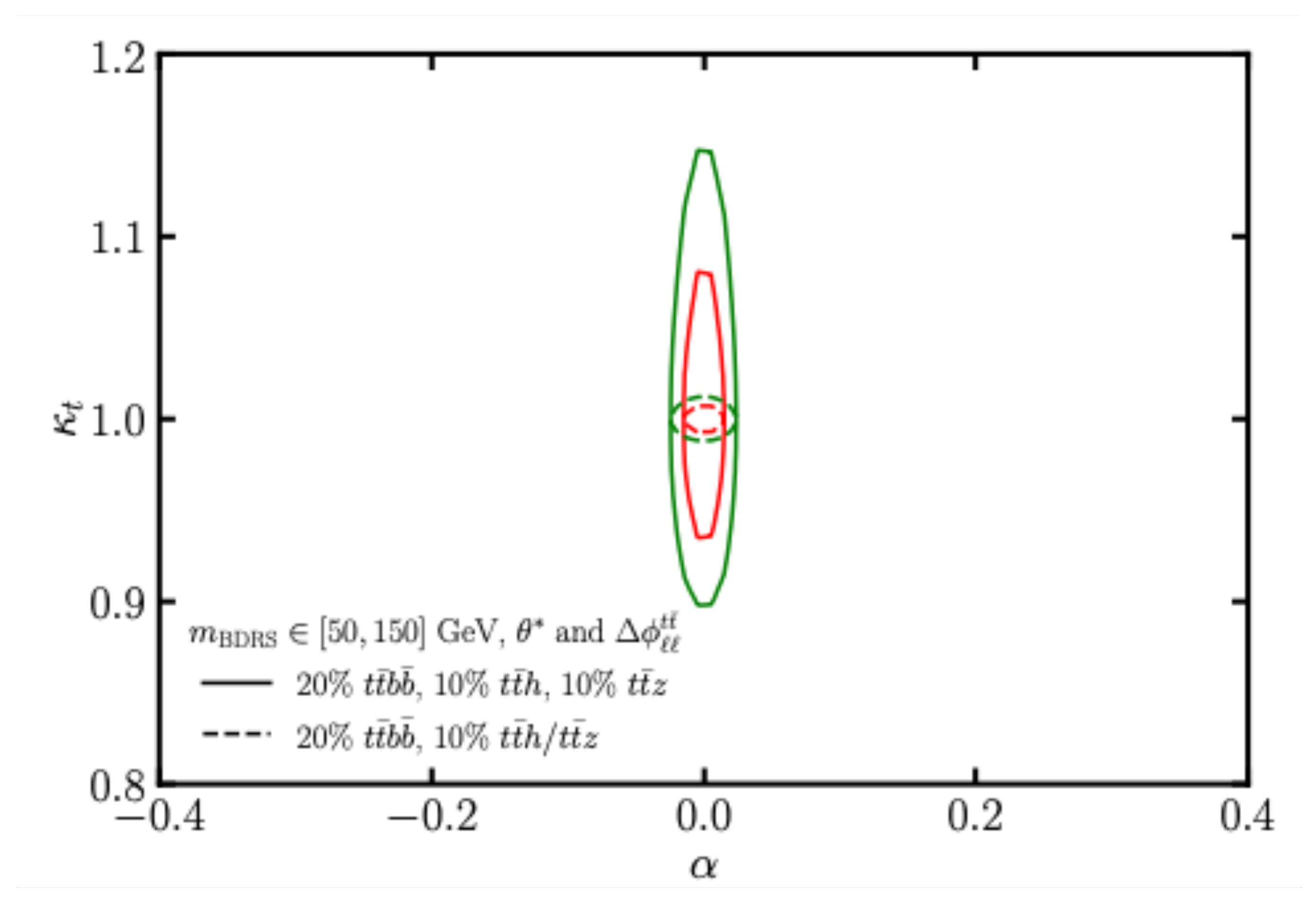
Barman, DG, Kling '21

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

Summary

The search for new sources of CPV is a cornerstones for the LHC program and forthcoming experiments, such as FCC, muon collider, …

- 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 uplifts analysis from raw rate to polarization study

Work in collaboration with

KC Kong (Kansas)

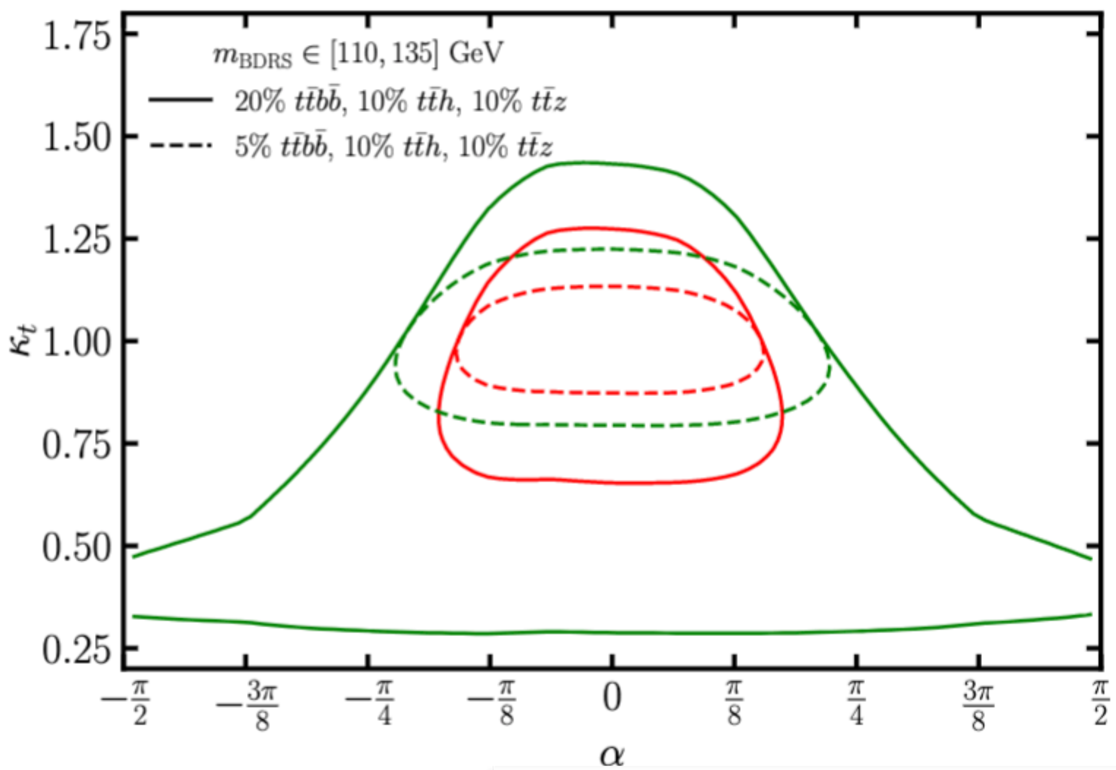
Felix Kling (DESY)

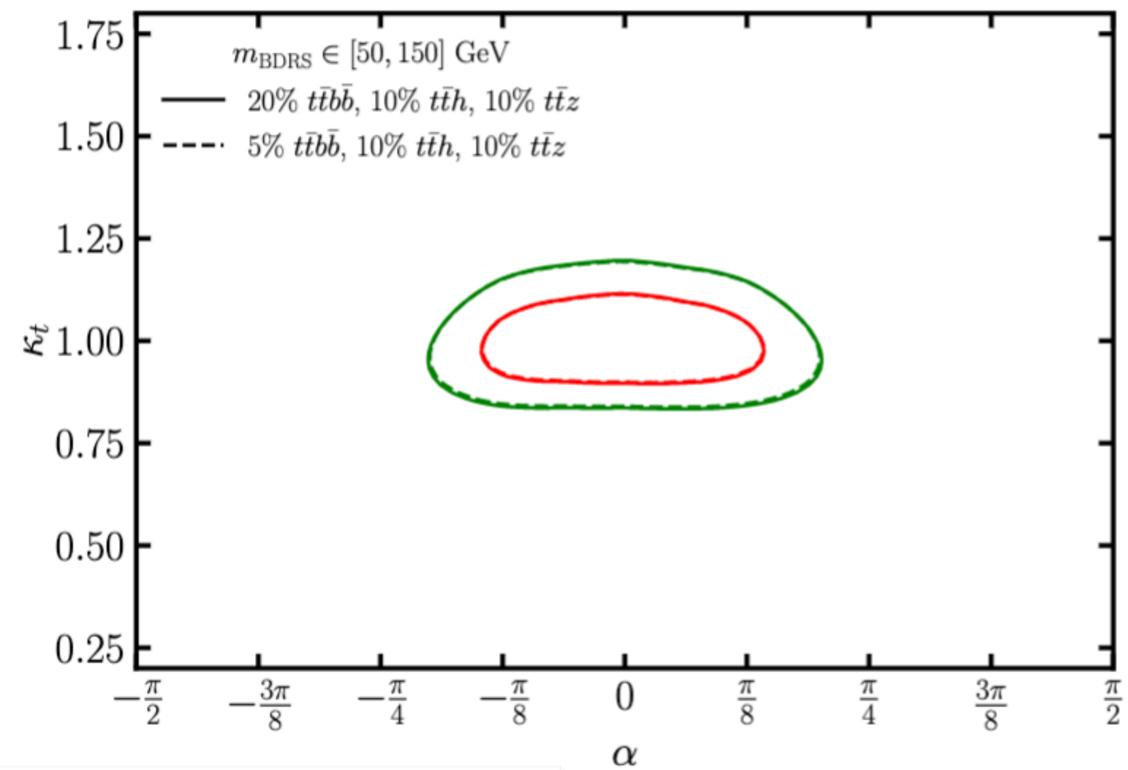
Kim Jeoghan (CBNU-Korea)

Rahool K. Barman (OSU)

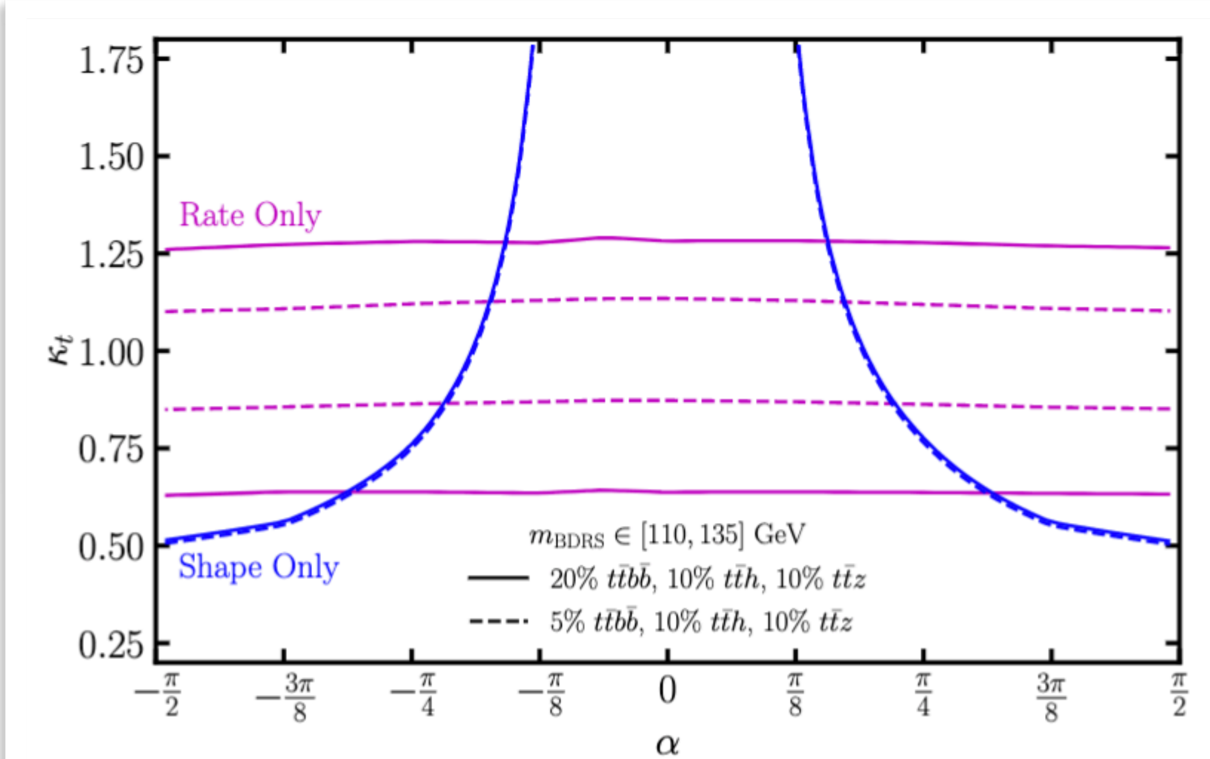
Yongcheng Wu (OSU -> Faculty Nanjing)

Backup





DG, Kong, Kim, Wu '21



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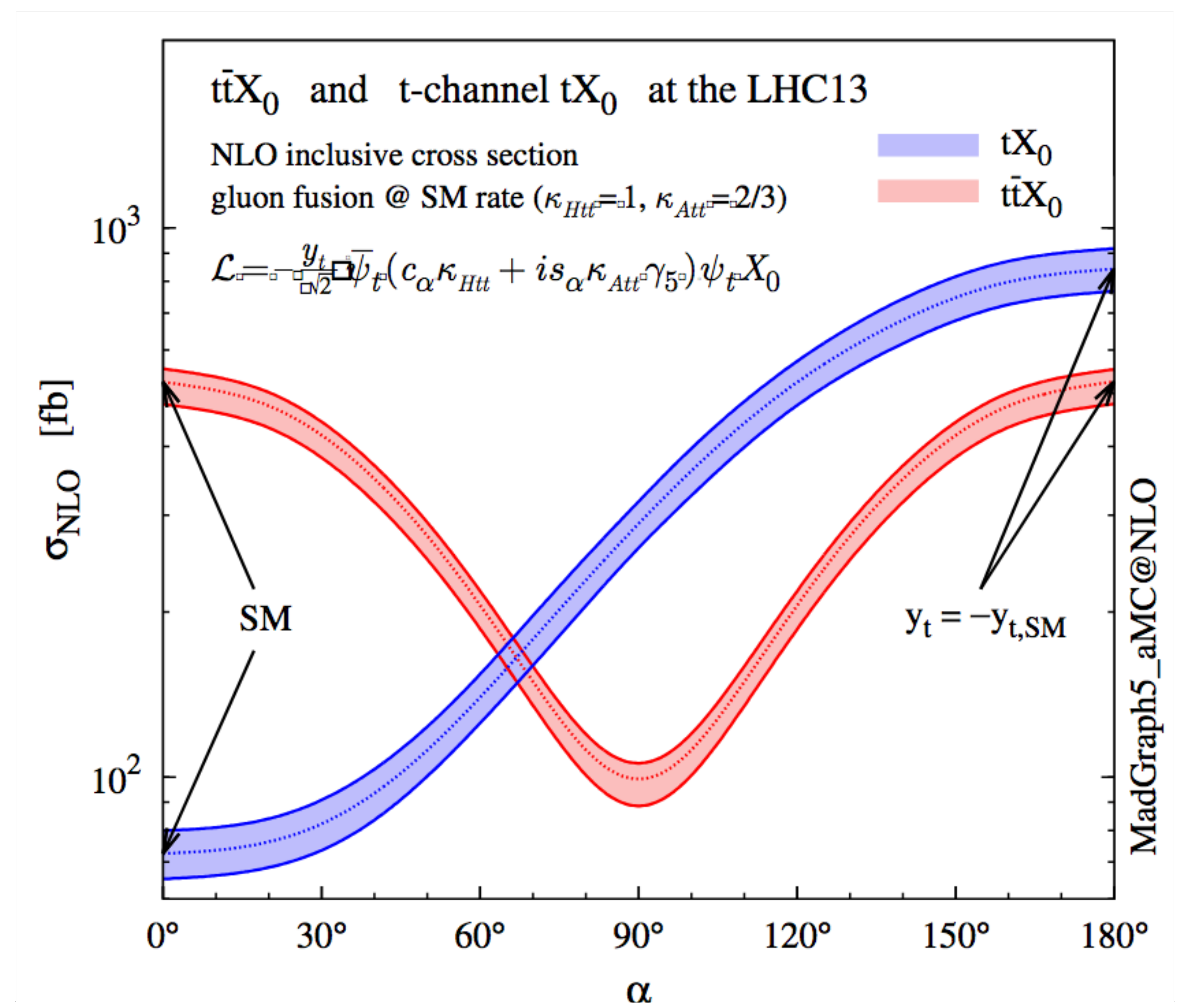
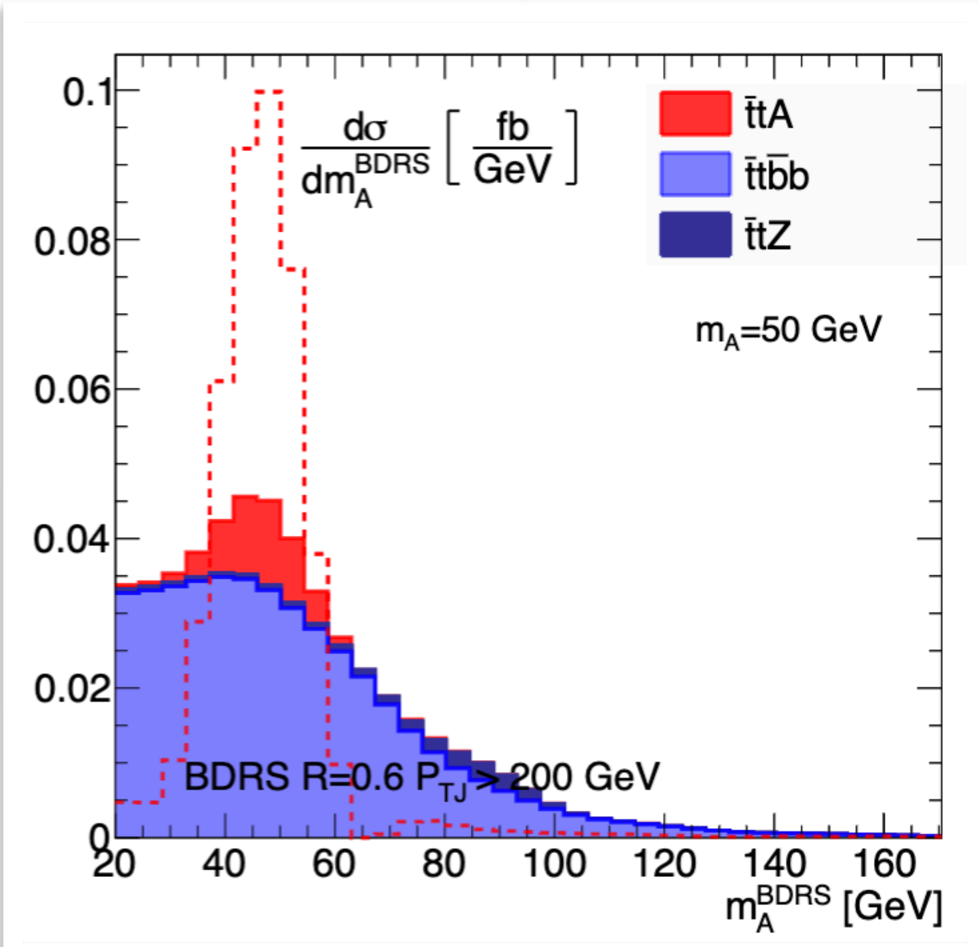
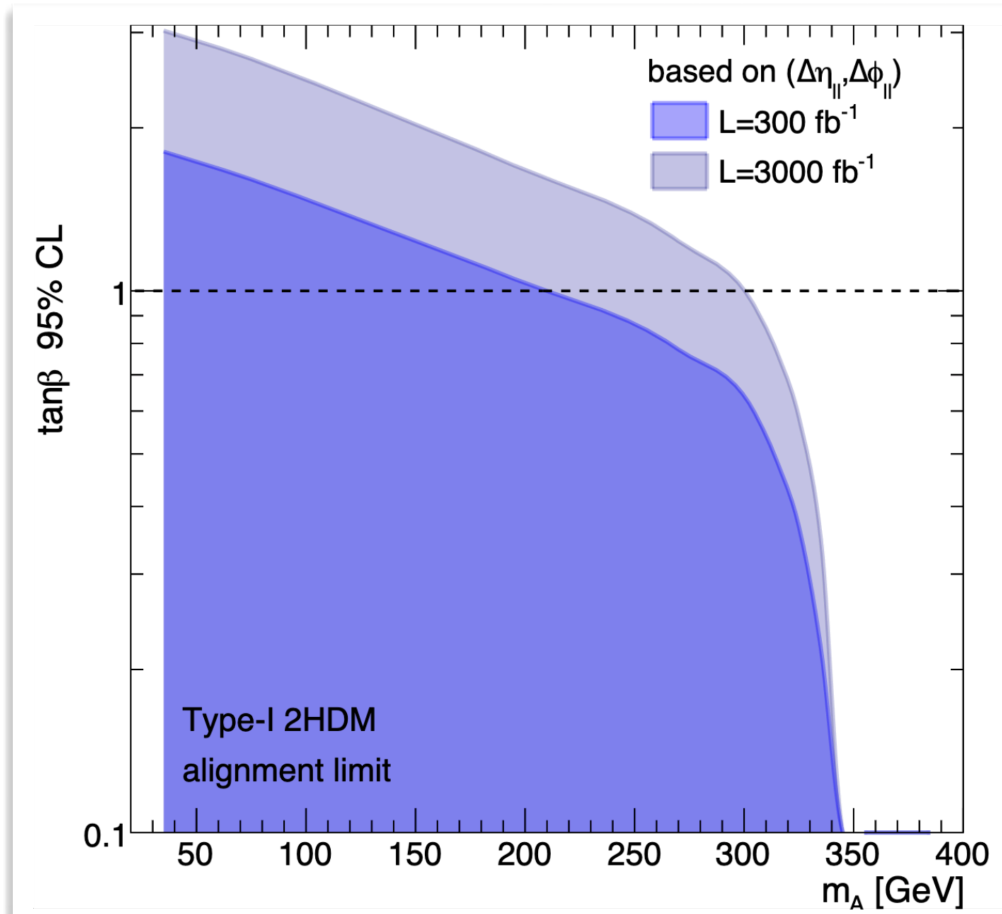


Demartin, Maltoni, Mawatari, Zaro (2015)
Englert, Re (2014)

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