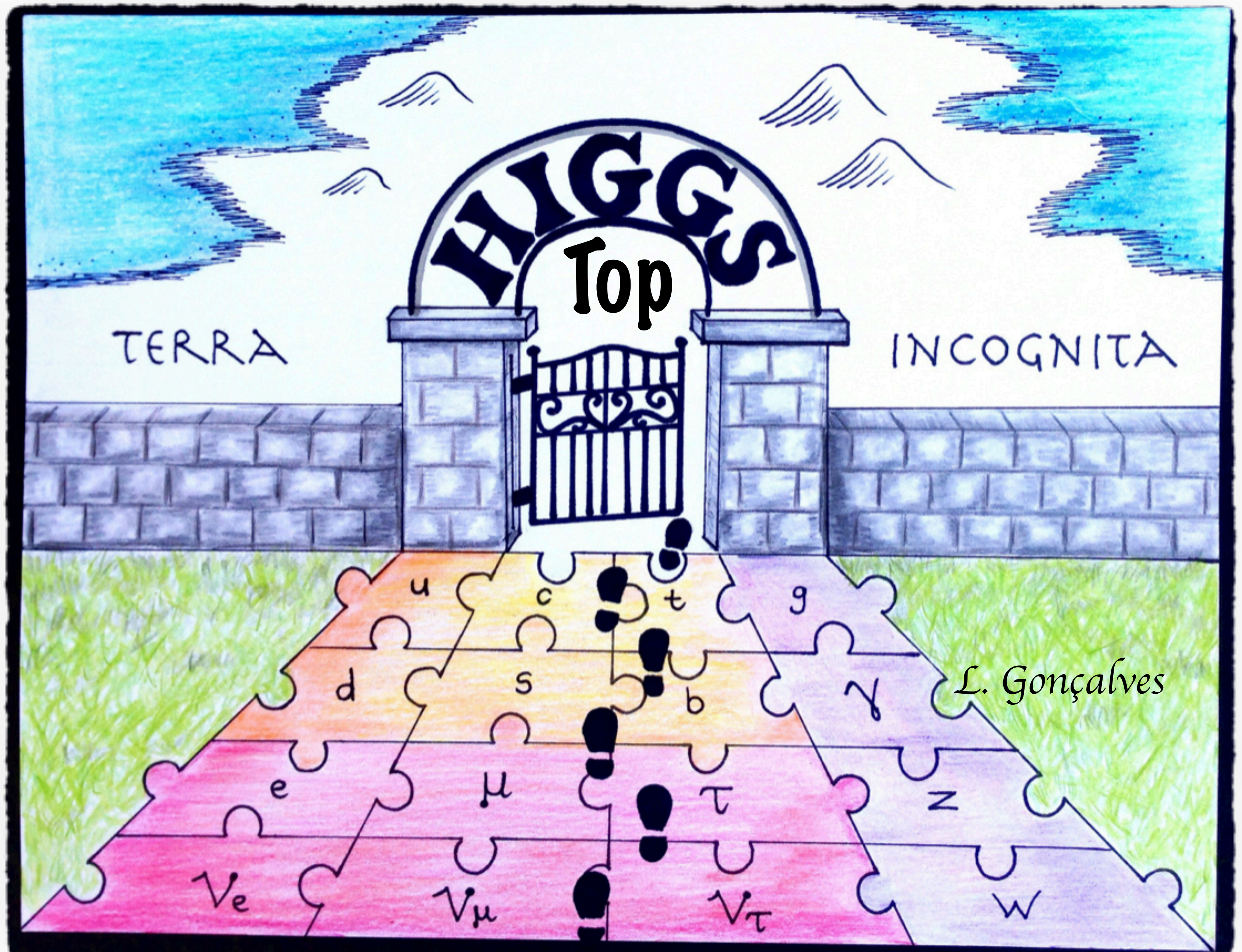
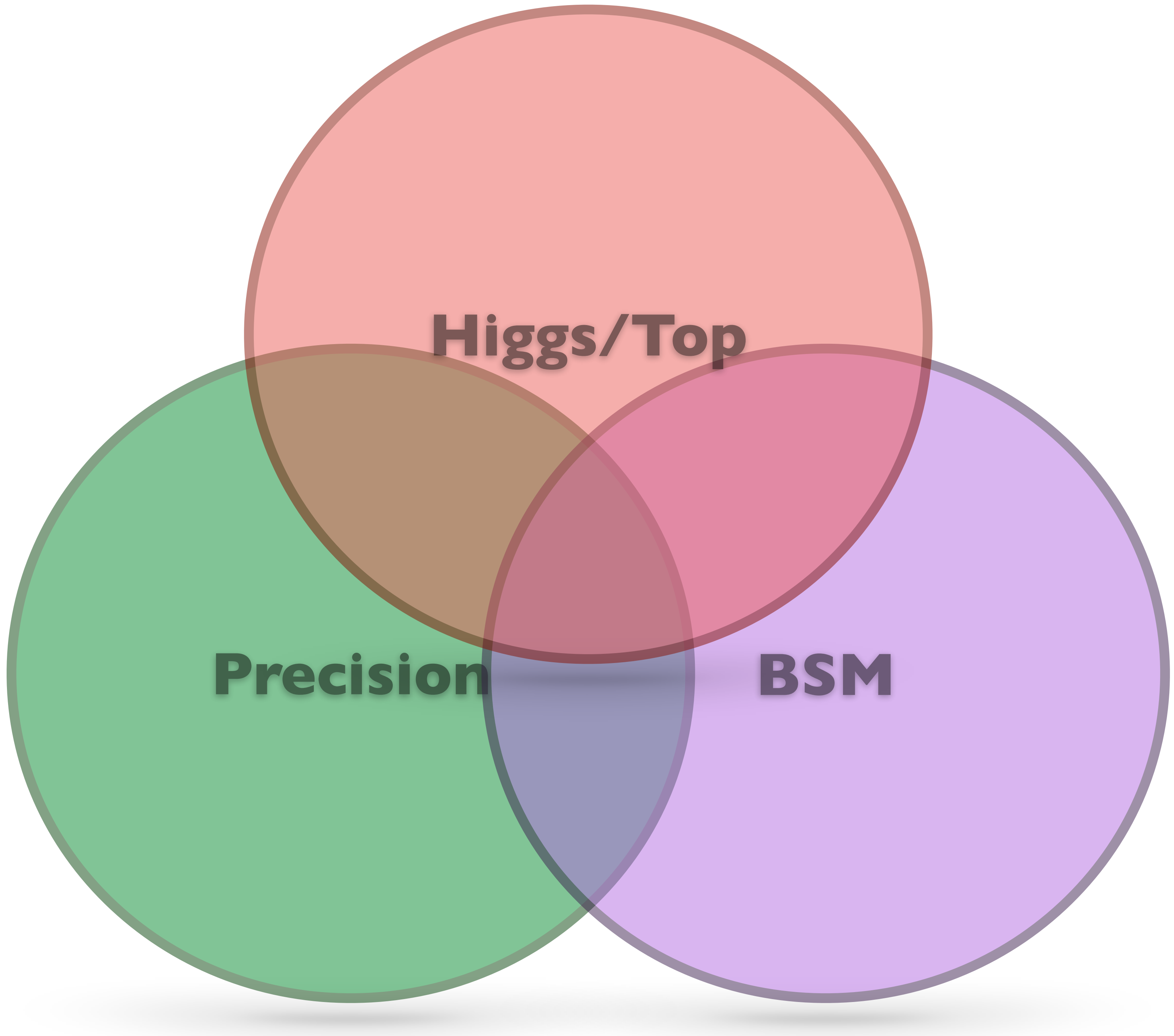
The Higgs-top gateway to new physics

HET Seminar, BNL - Oct 26, 2023

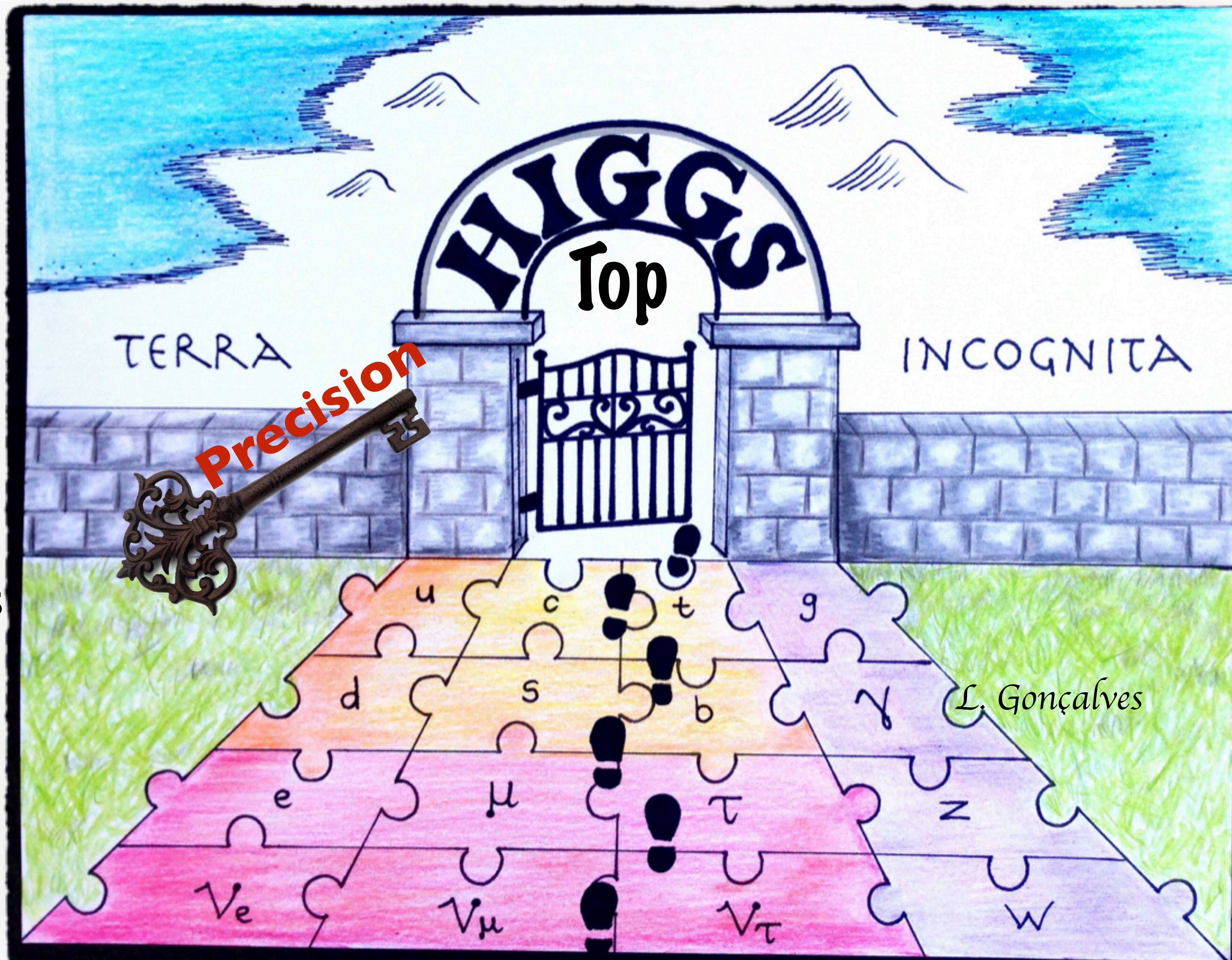
Dorival Gonçalves




Higgs/Top
Precision
BSM

Big Questions

- Is it elementary or composite?
- What is the new physics scale?
- Are there more Higgs bosons?
- Are there top partners?
- Is it natural?
- Is it a portal to a dark sector?
- Is it responsible for the masses of all fundamental particles?
- Can it help explain matter antimatter-asymmetry?
- What is the order of EWPT?



- Can we use their phenomenology to probe QIS questions?

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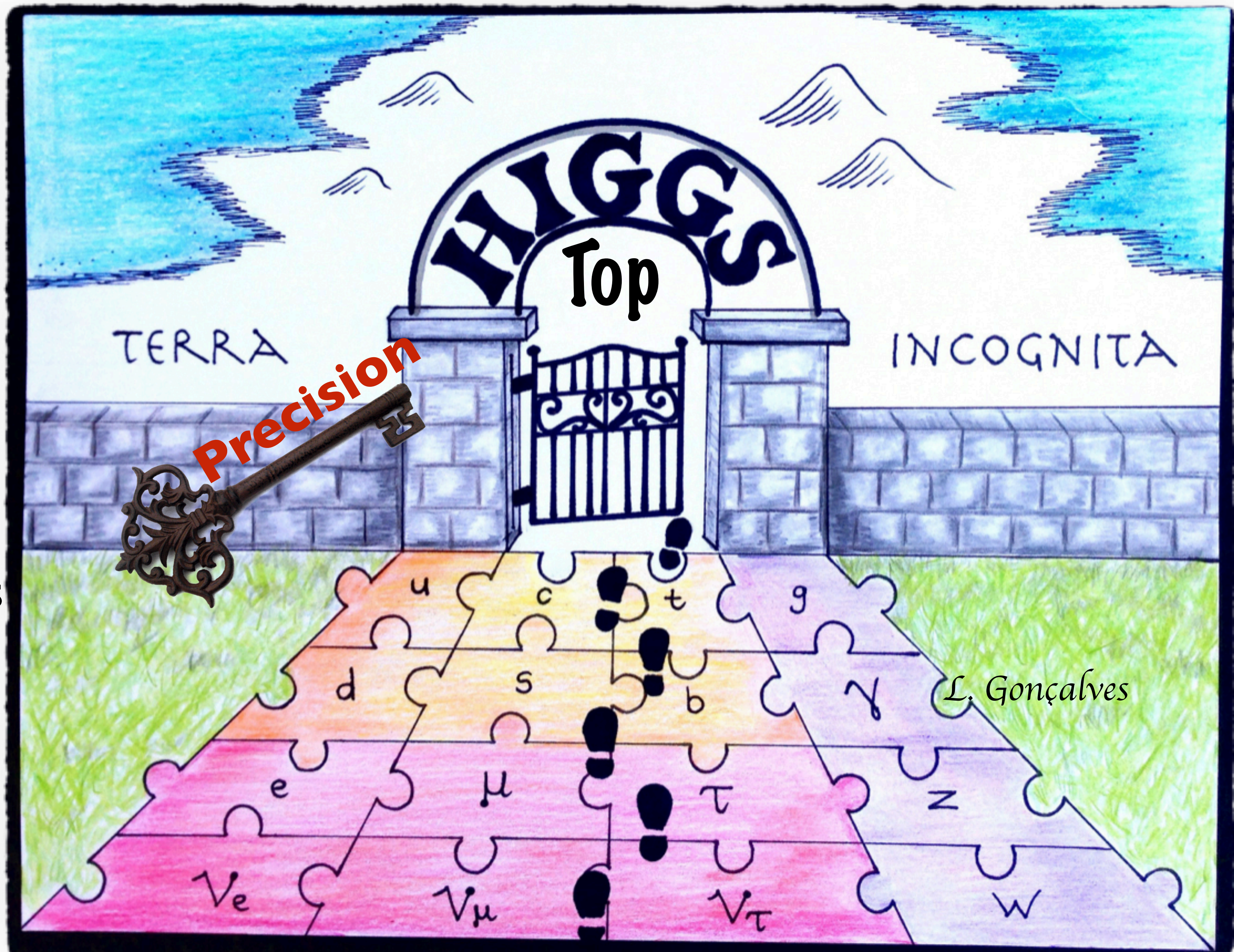


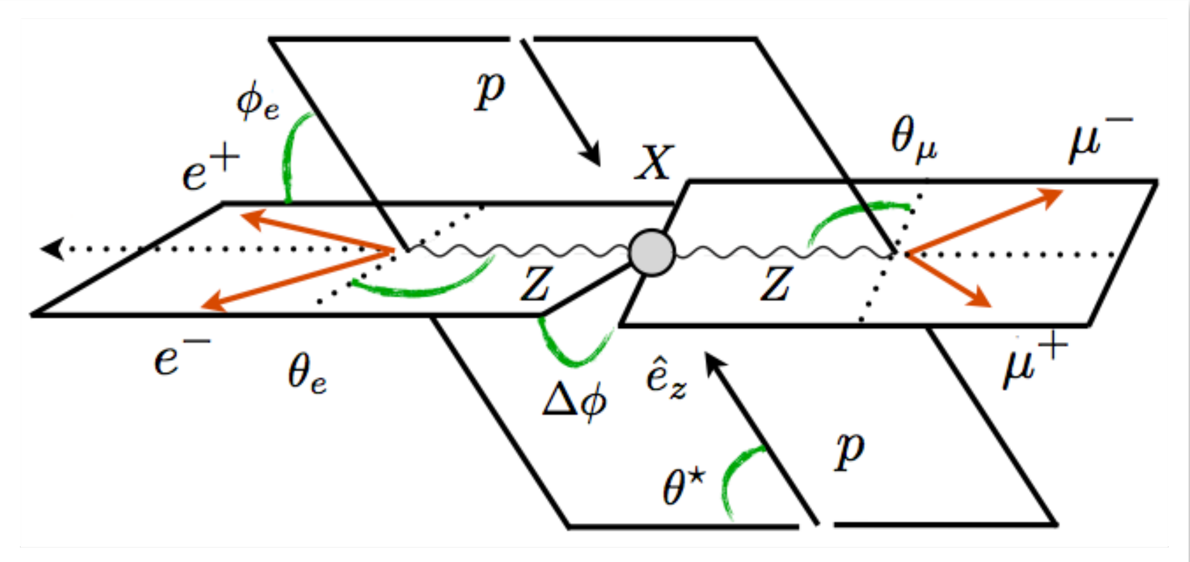
CP-violation

- 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

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

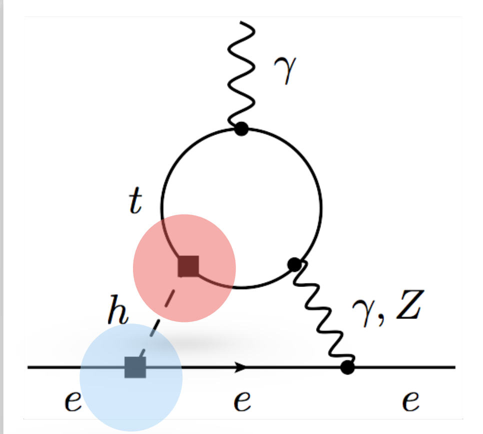
Buckley, **DG** (PRL '15)

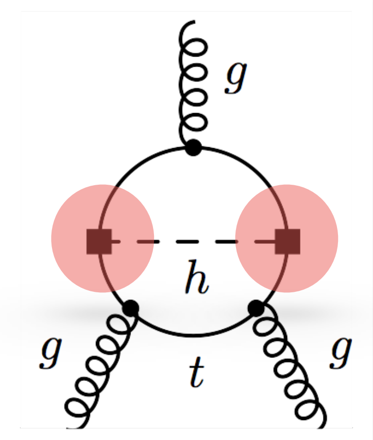
Atwood, Shalom, Eilam, Soni '00

Indirect EDM constraints

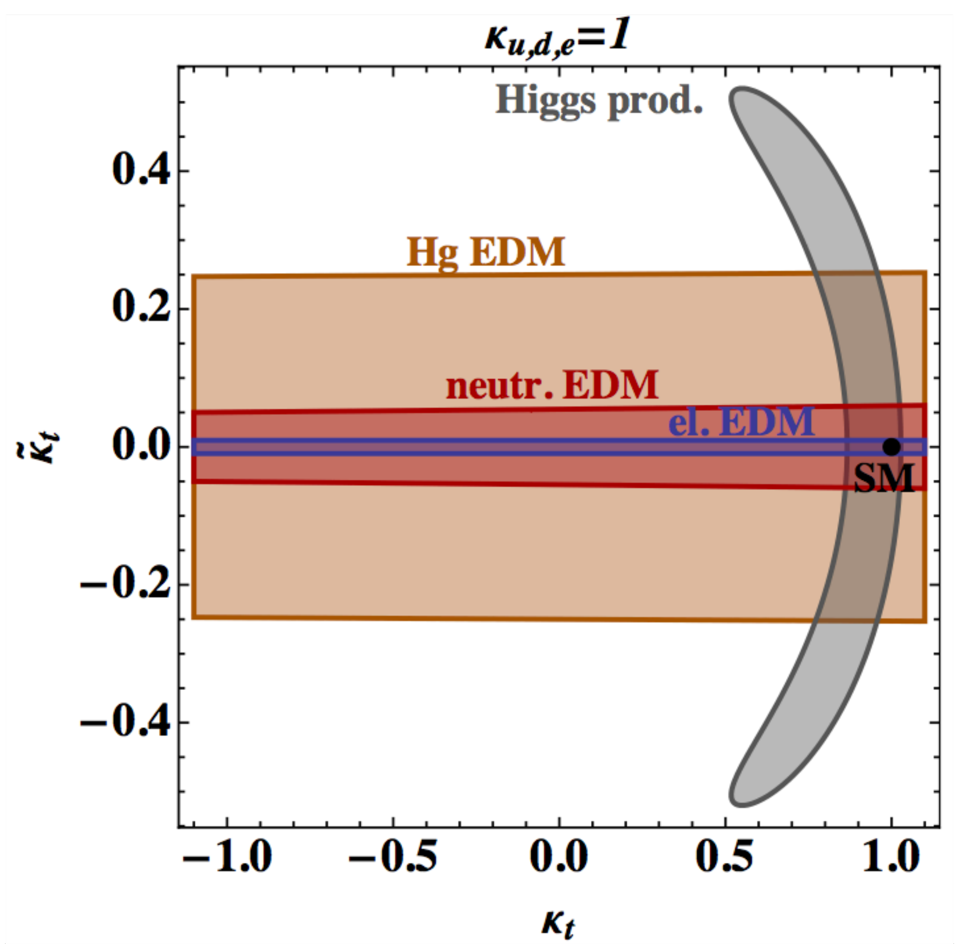
- Indirect constraints from eEDM very strong

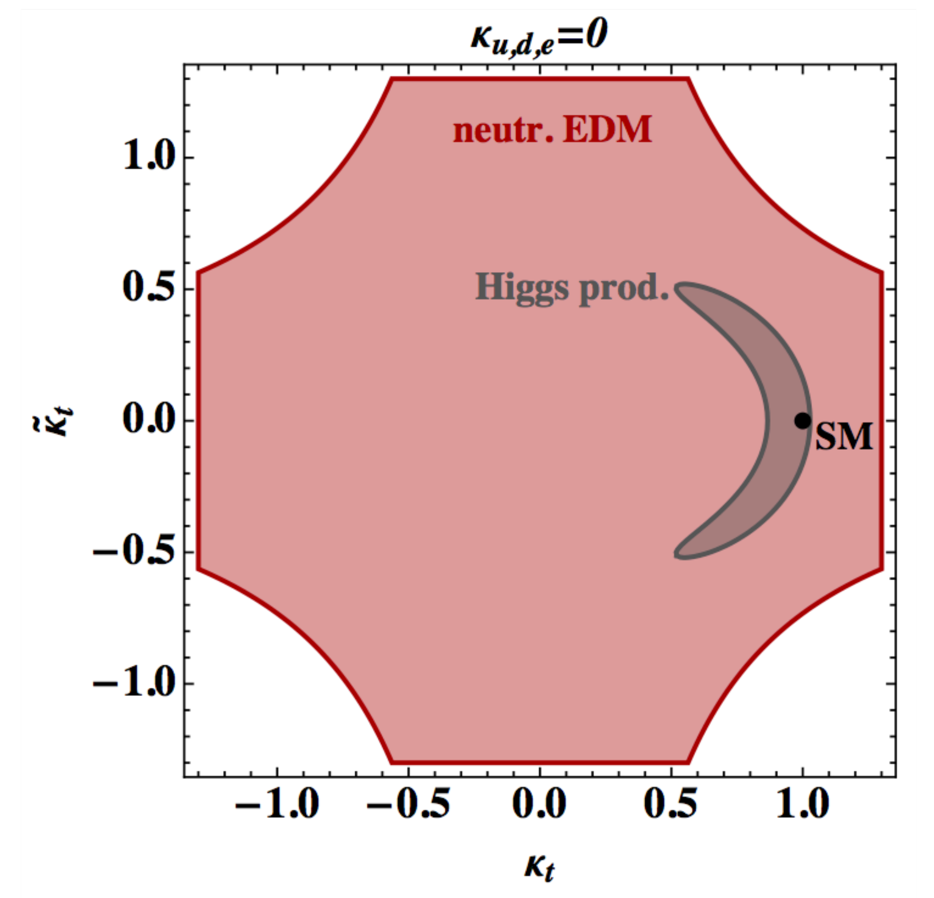
$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$





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



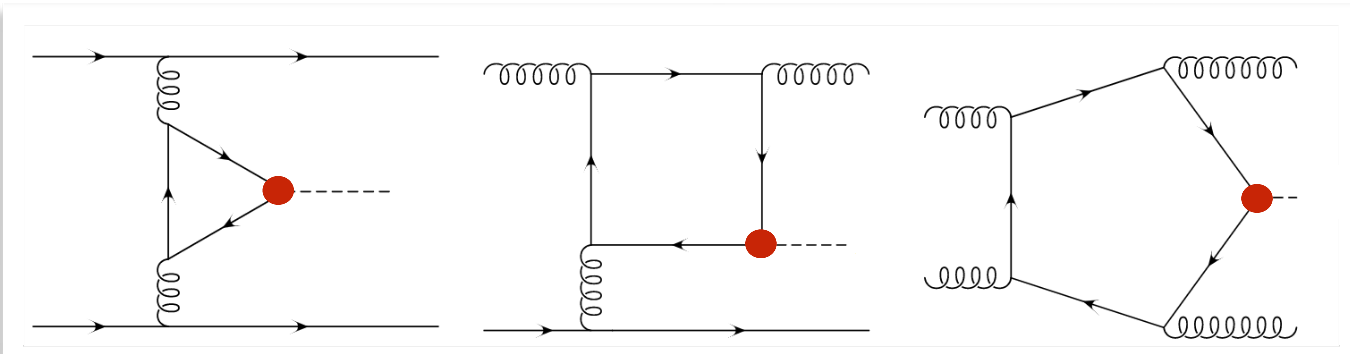


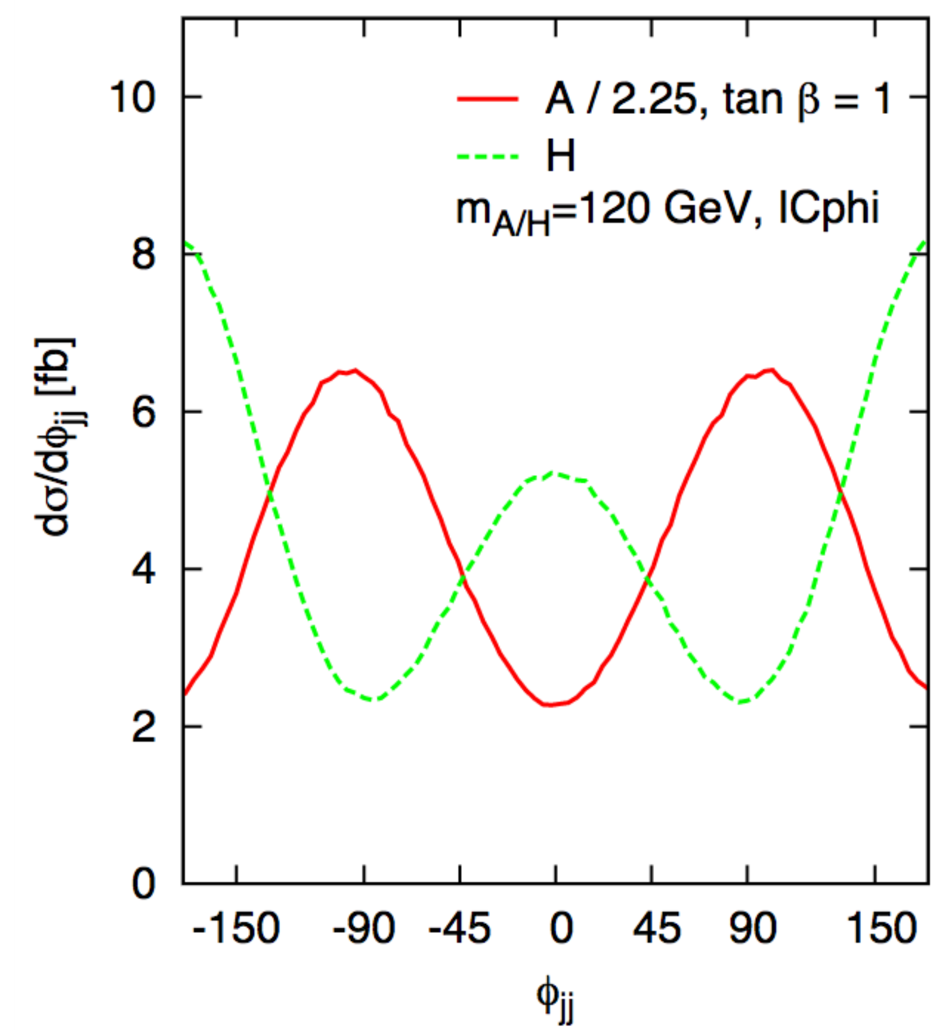
Brod, Haisch, Zupan (2013); Engel, Ramsey-Musolf, Kolck (2013); Cirigliano, Dekens, Vries, Mereghetti (2016)

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)
Anderson, Bolognesi, Caola, Gao, Gritsan et al (2013)
Dolan, Harris, Jankowiak, Spannowsky (2014)

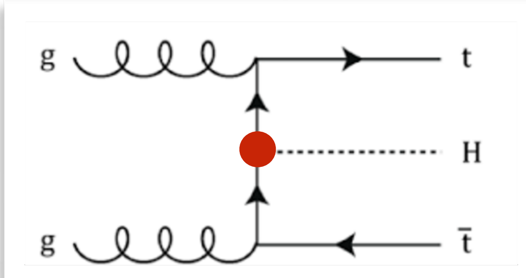
- Loop-induced: indirect constraints

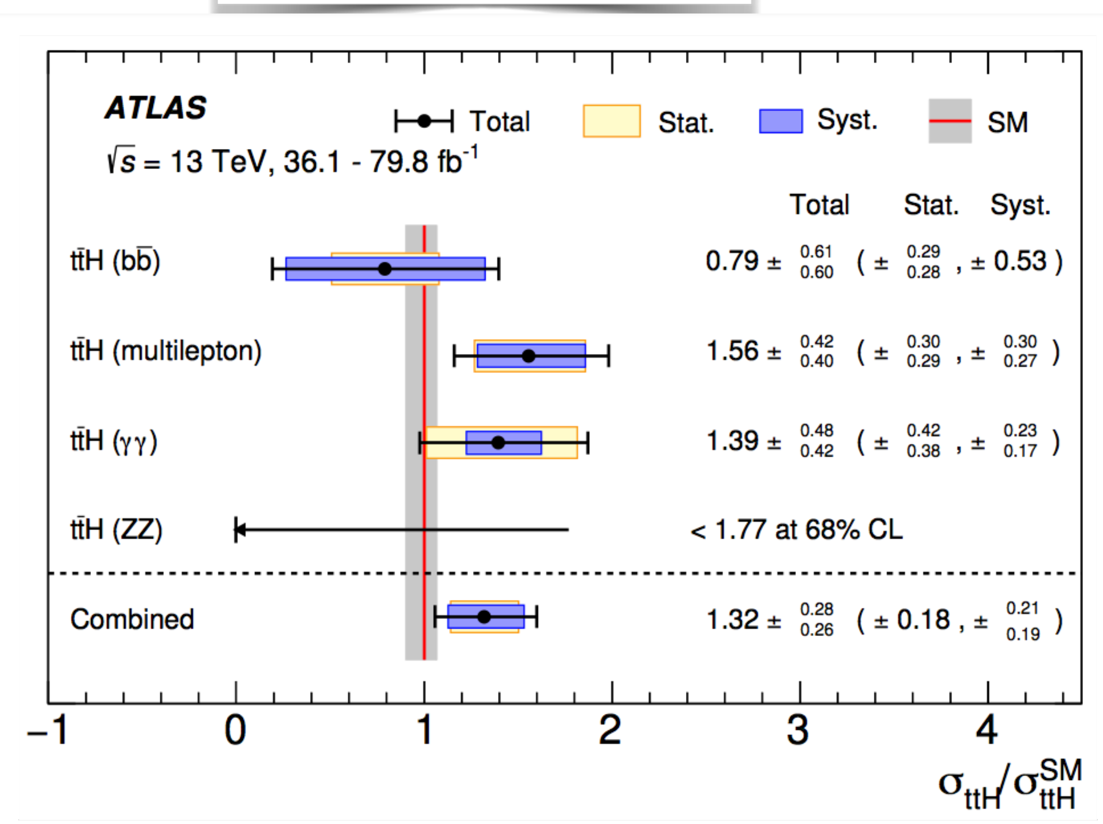
- Bottom line:

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

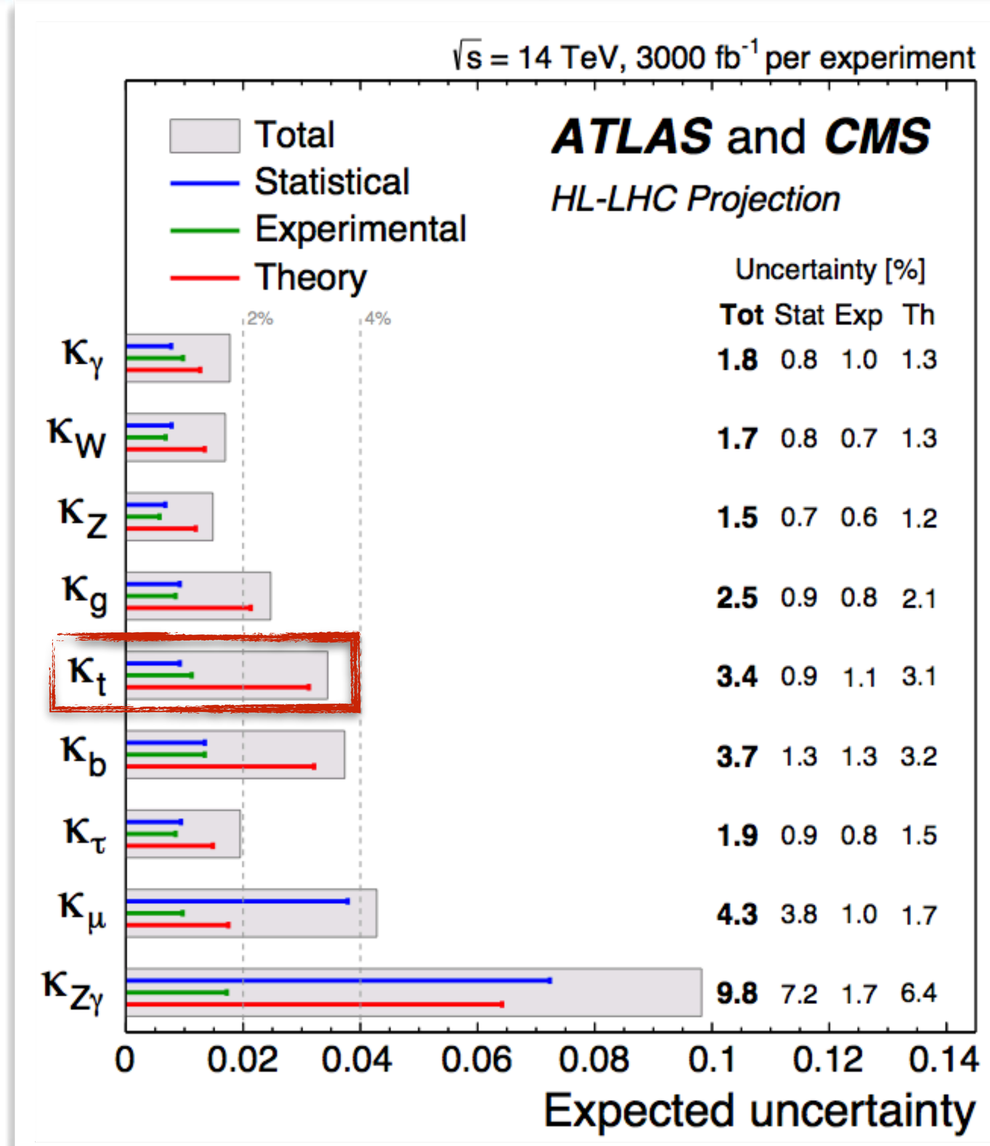
Direct CP measurement of Higgs-top coupling

- ttH channel observation (2018):





- Expected HL-LHC precisions:



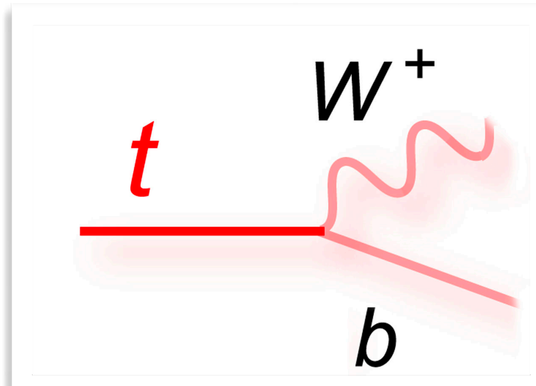
- Opportunity: direct measure Higgs-top CP structure at the LHC

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

Top Quark is Unique

- Decays before it hadronizes or its spin flips

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



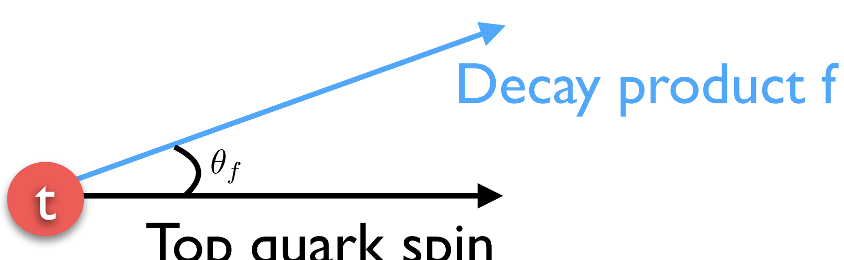
Bottom quark is several orders of magnitude behind

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

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

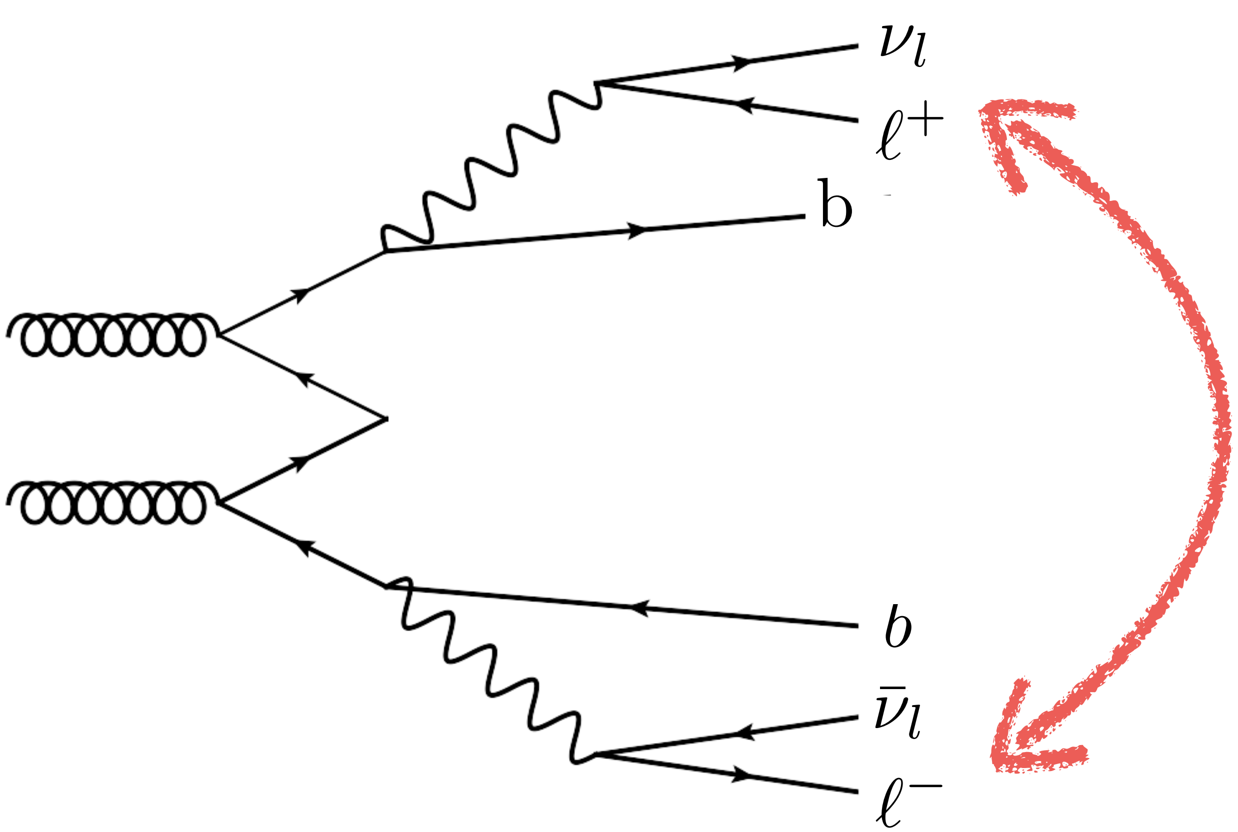
	$l^+, \bar{d}$	b	$\bar{\nu}, u$
ω_f	1	-0.4	-0.3

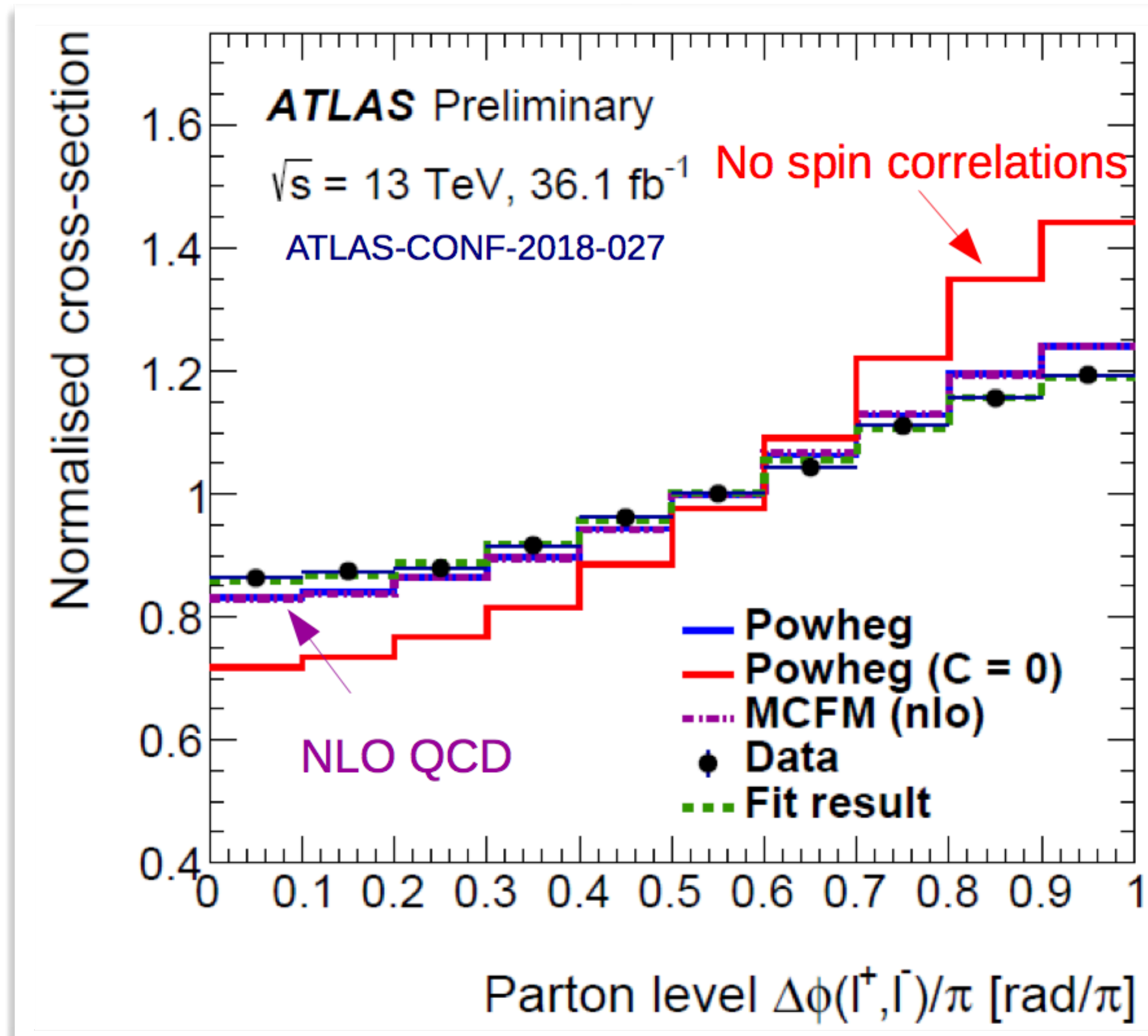
Spin analyzing power: maximum for charged leptons



Top quark polarization

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





Parke, Mahlon '95

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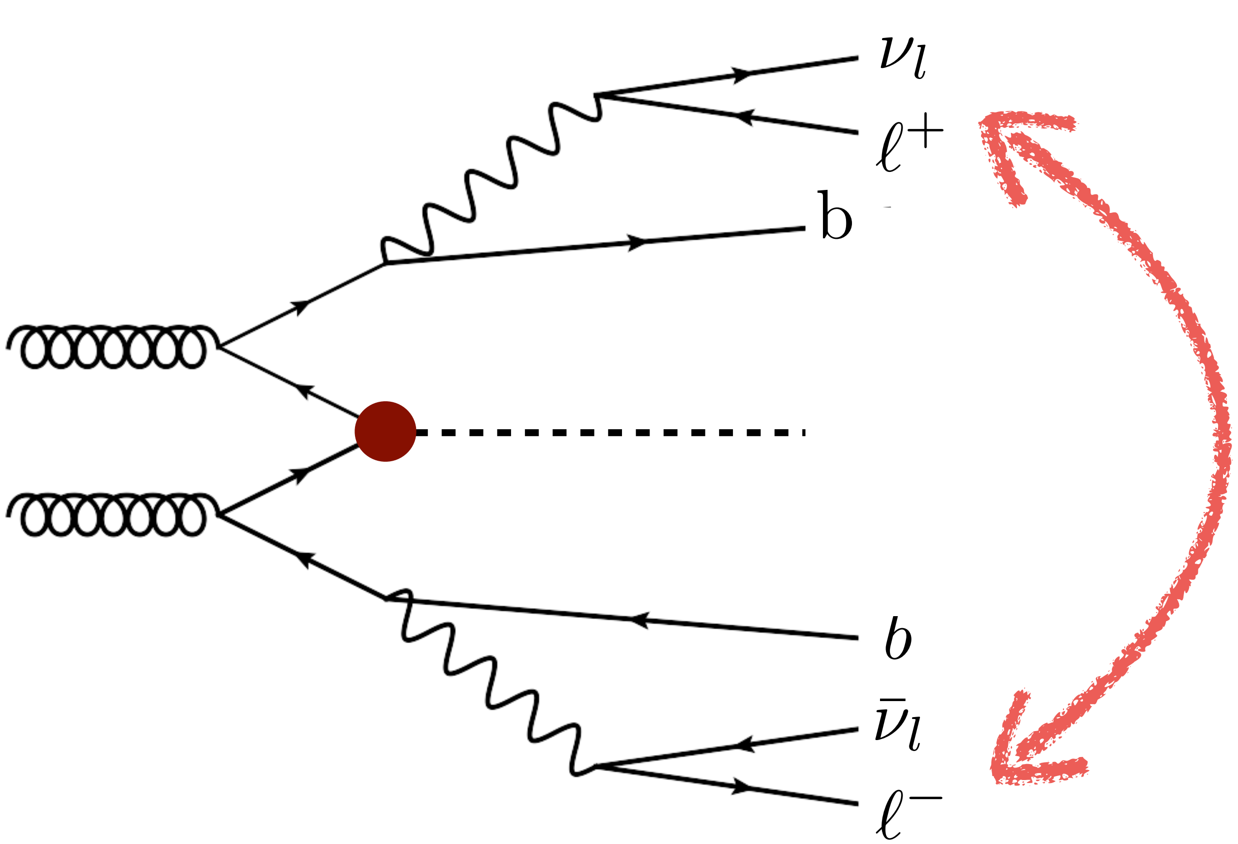
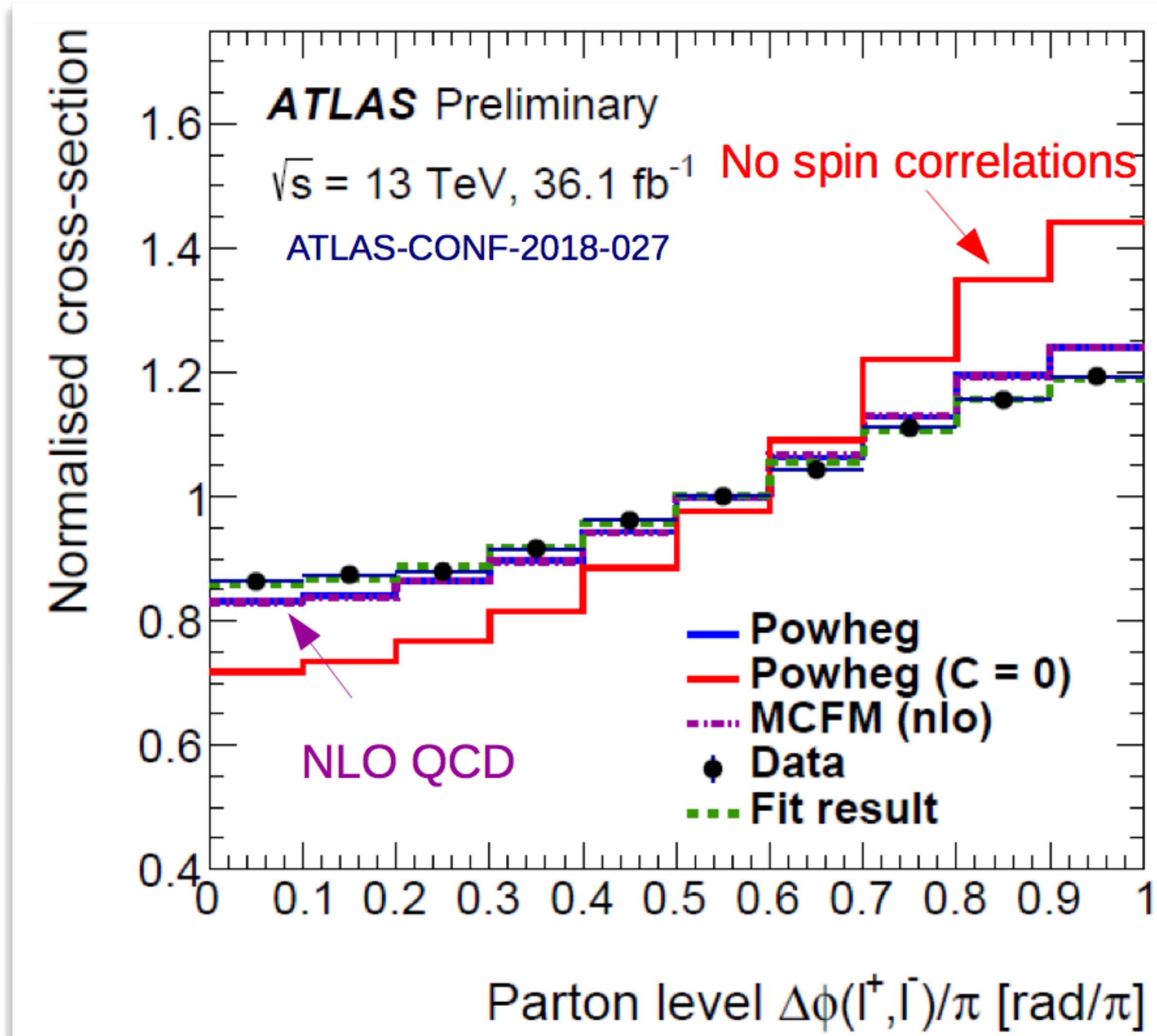


$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha \right) t \; H$$

Buckley, DG (PRL '15)



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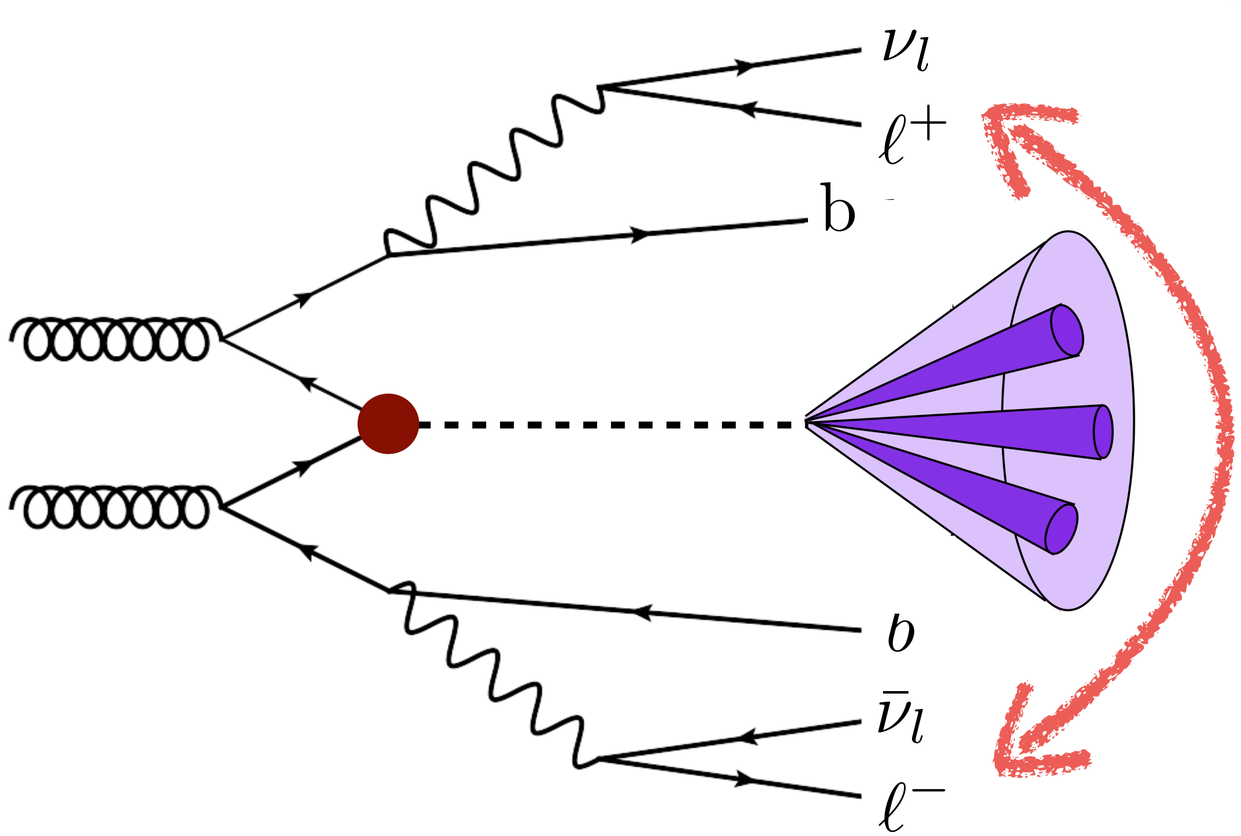
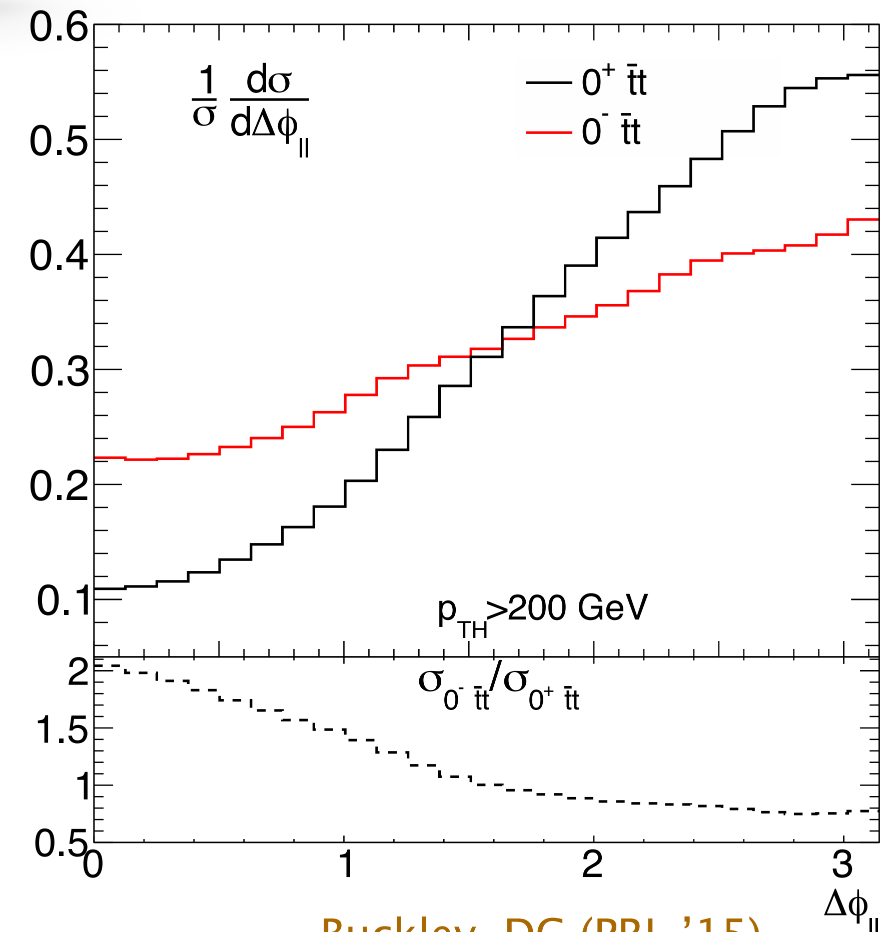




Buckley, DG (PRL '15)

DG, Kong, Kim '21

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

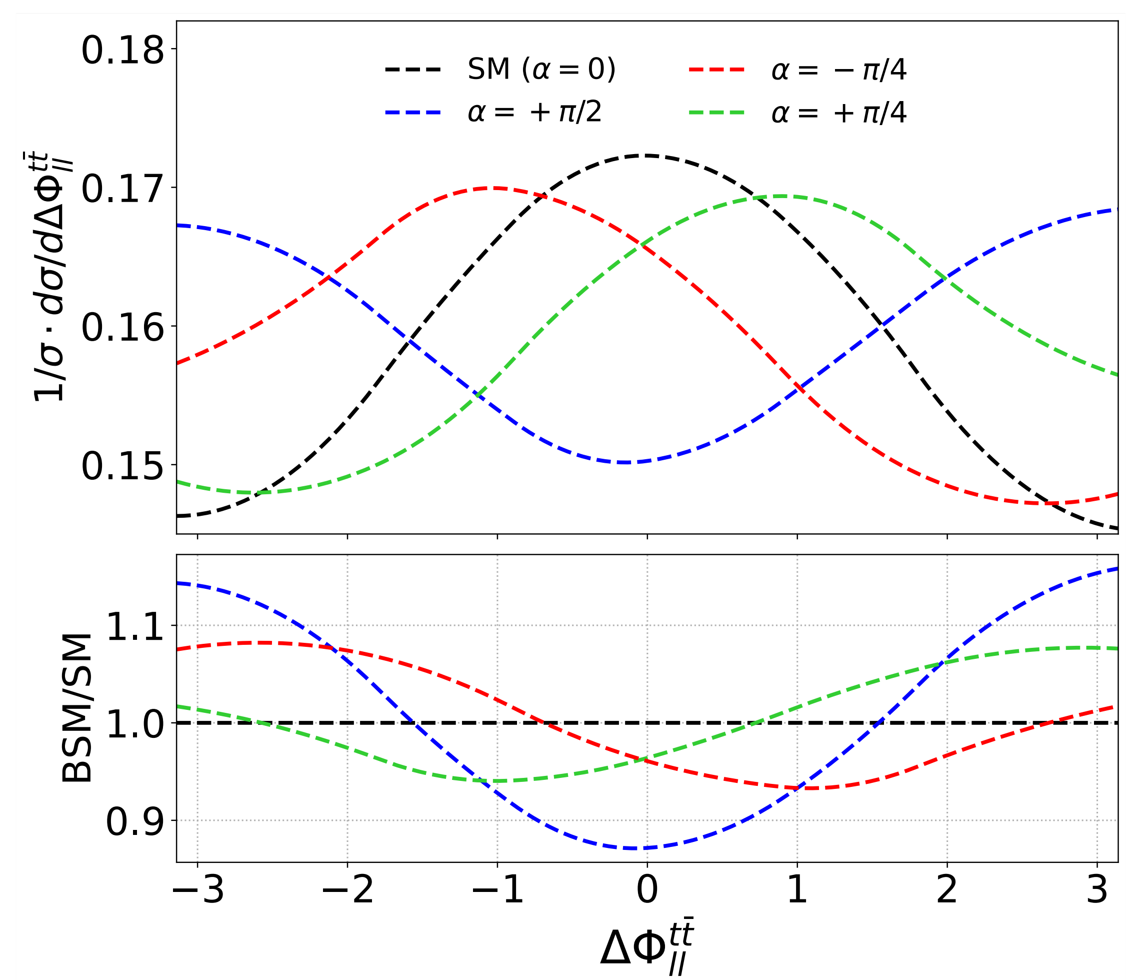
CP sensitive observables

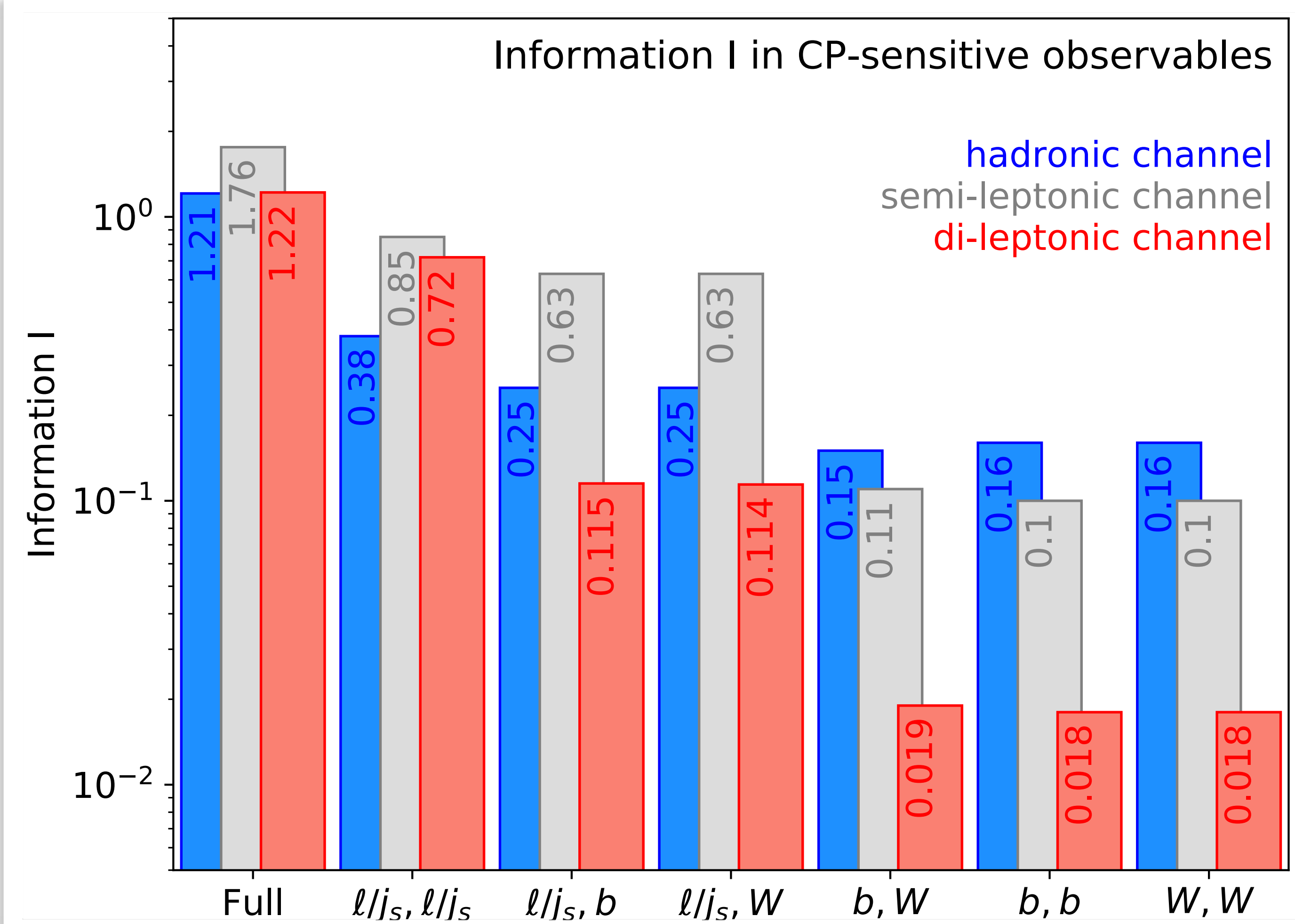
- CPV observables best defined at the top pair rest frame:

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

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

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

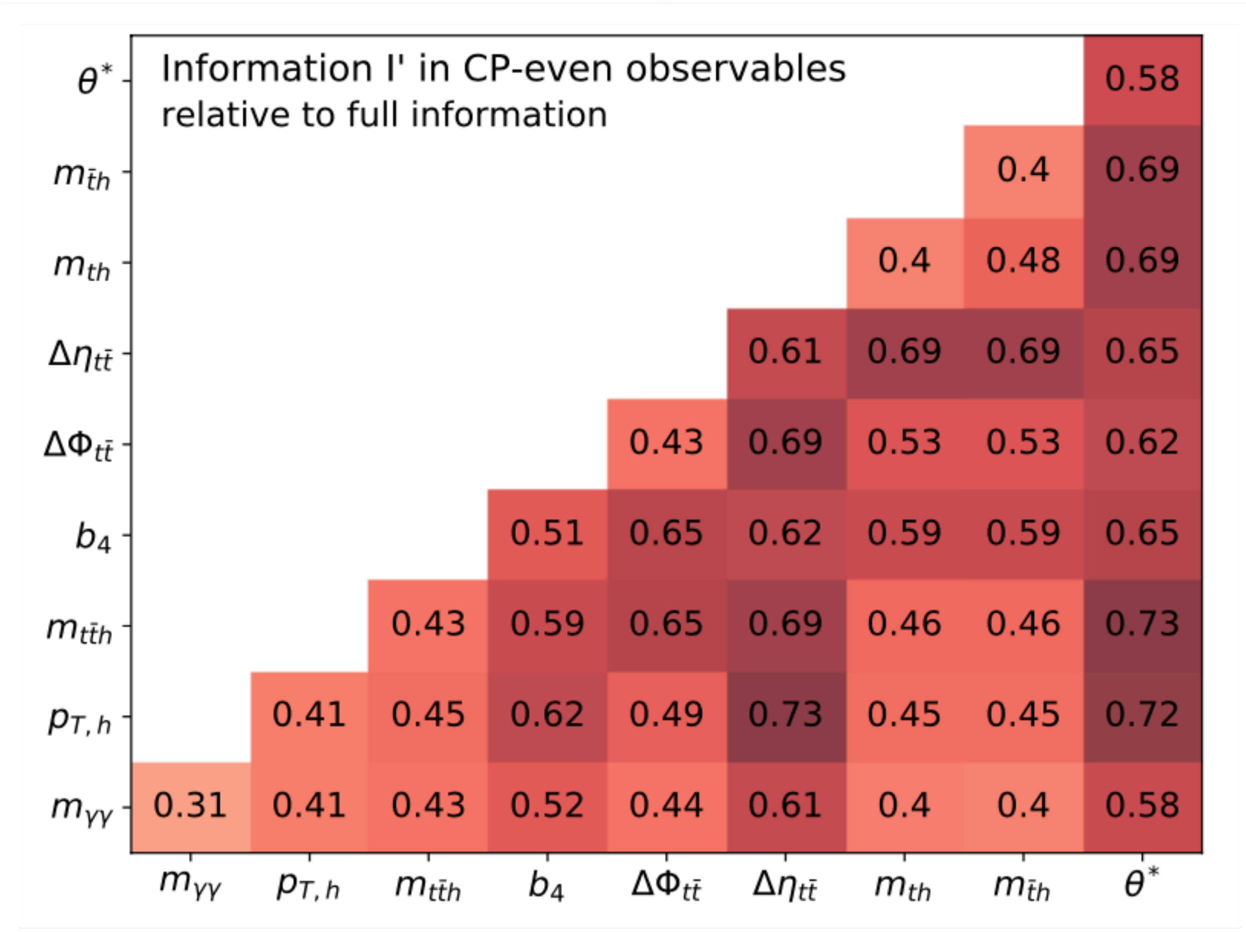




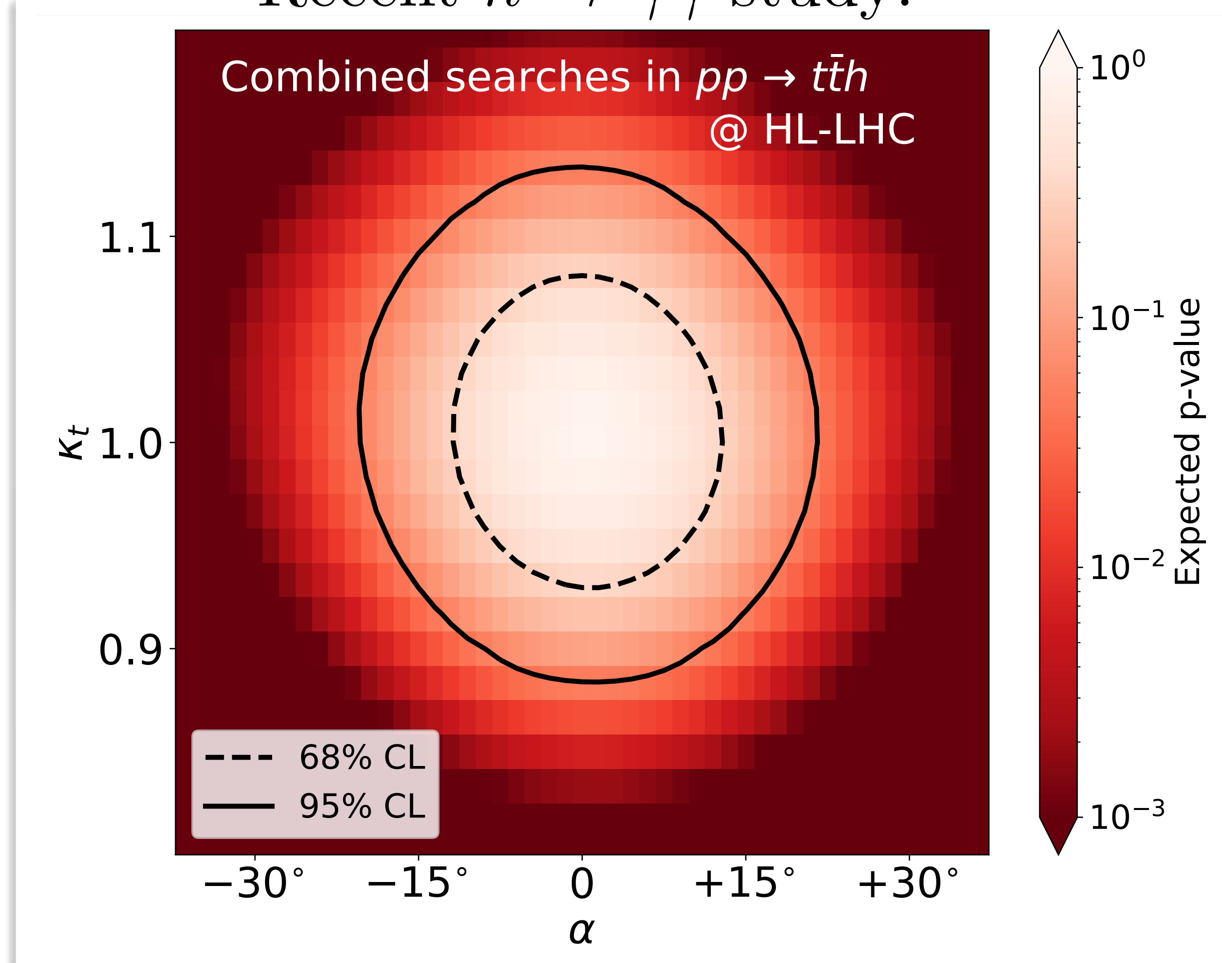
DG, Kong, Kim '18 & '21, Barman, DG, Kling '21, Atwood, Shalom, Eilam, Soni '00

Machine learning the Higgs-top CP-phase

Multivariate analysis problem: Information increases with successive addition of observables



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

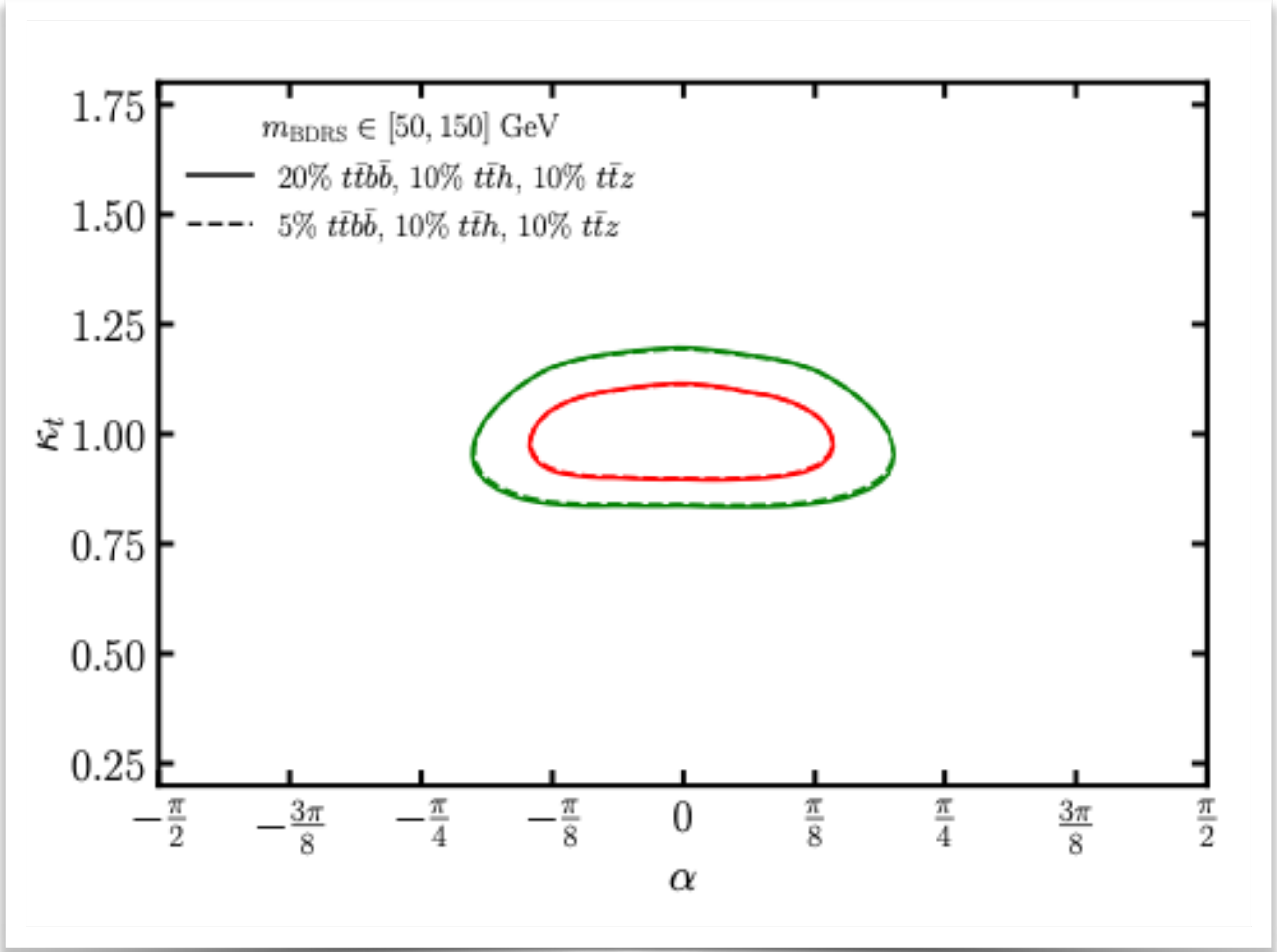


➡ Higgs-top CP phase could be probed up to $\alpha \lesssim 13^\circ$

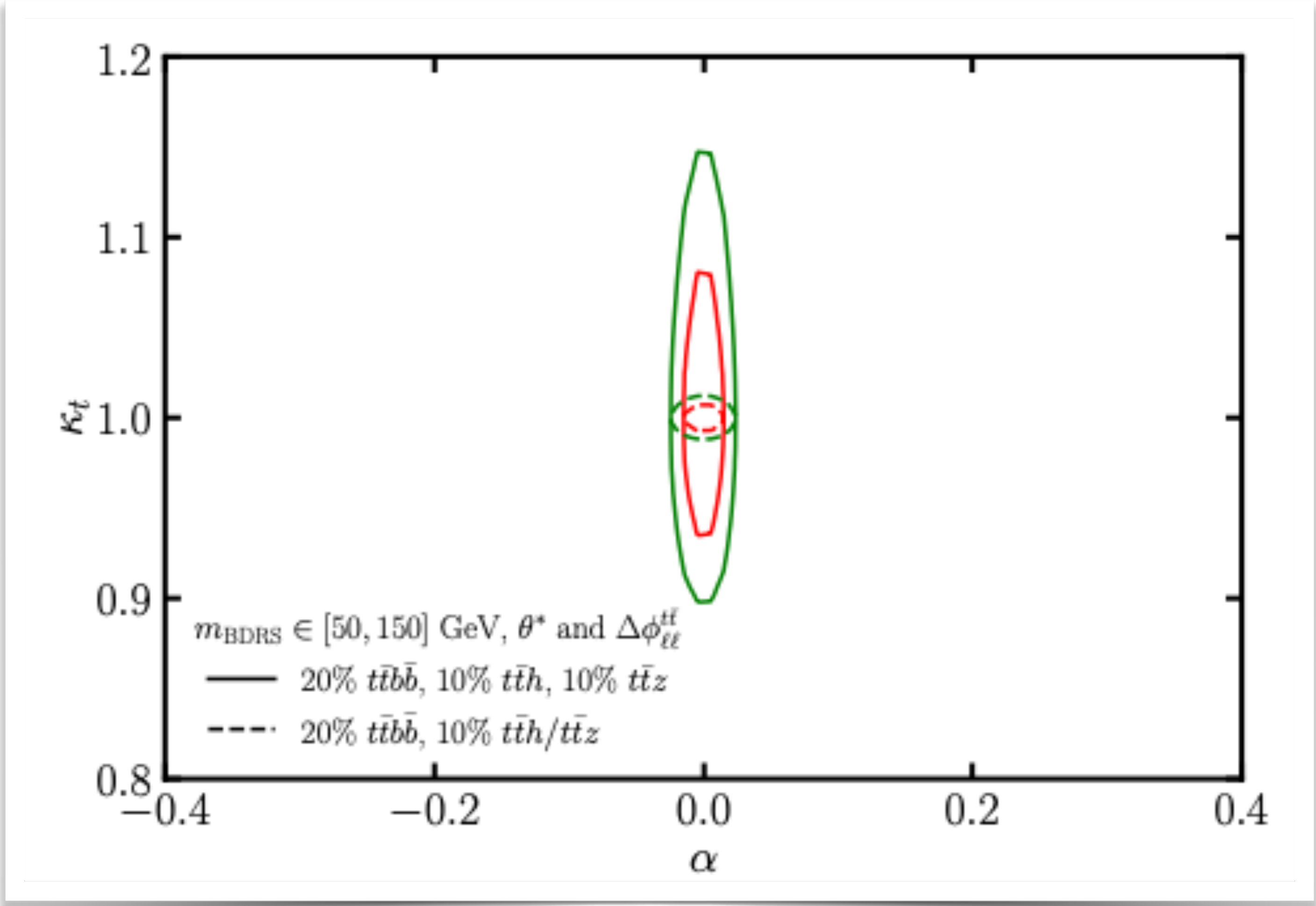
Barman, DG, Kling '21
Ackerschott, Barman, DG, Heimel, Plehn '23
Bhardwaj, Englert, DG, Navarro '23
Brehmer, Dawson, Homiller, Kling, Plehn '19

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

SMEFT vs. HEFT

While CPV effects can arise at the dim-4, it is also relevant to study how they can appear within EFTs. In this context, there exist two fundamentally different choices:

- **SMEFT:** Higgs boson is a component of an electroweak doublet. Lagrangian contains all possible operators invariant under $SU(3)_c X SU(2)_L X U(1)_Y$. Ordering by operator dimension and suppression $(1/\Lambda)^n$

- **HEFT:** Higgs transforms as a gauge singlet. Based on chiral perturbation theory. Ordering of operators is not unique.

Cohen, Craig, Lu, Sutherland ’21
Ambrosio, Estrada, Bernardez, Cillero ‘22
Dawson, Fontes, Calonge, Cillero ’23

$$\text{HEFT} \supset \text{SMEFT} \supset \text{SM}$$

→ How sensitive the LHC can be to sources of non-linear CPV? How correlated CPV is across different Higgs multiplicities?
Bhardwaj, Englert, DG, Navarro ’23

SMEFT vs. HEFT Higgs-top CPV

- **SMEFT** $\mathcal{O}_{t\Phi} = |\Phi|^2 \bar{Q}_L \Phi^c t_R$

$$\mathcal{L}_{\text{SMEFT}} \supset -\frac{m_t}{v}\,\kappa_t\,\bar{t}(\cos\alpha + i\gamma^5 \sin\alpha)\,t\,h - \frac{3m_t}{2v^2}\,\bar{t}(\{\kappa_t\cos\alpha - 1\} + i\kappa_t\gamma^5\sin\alpha)\,t\,h^2$$

$$\Rightarrow \left.\frac{\Gamma_{\bar{t}th}}{\Gamma_{\bar{t}th^2}}\right|_{\gamma^5,\text{SMEFT}} = \frac{v}{3}$$

- **HEFT:** Owing to the singlet character of the Higgs boson in HEFT, the operator can be dressed with a “flare” function”

$$Y_t(h) = 1 + c^{(1)}\frac{h}{v} + c^{(2)}\frac{h^2}{2v^2} + \dots$$

$$\mathcal{L}_{\text{HEFT}} \supset -\frac{m_t}{v}\,\kappa_t\,\bar{t}(\cos\alpha + i\gamma^5 \sin\alpha)\,t\,h - \frac{m_t}{2v^2}\,\kappa_{tt}\,\bar{t}(\cos\beta + i\gamma^5\sin\beta)\,t\,h^2$$

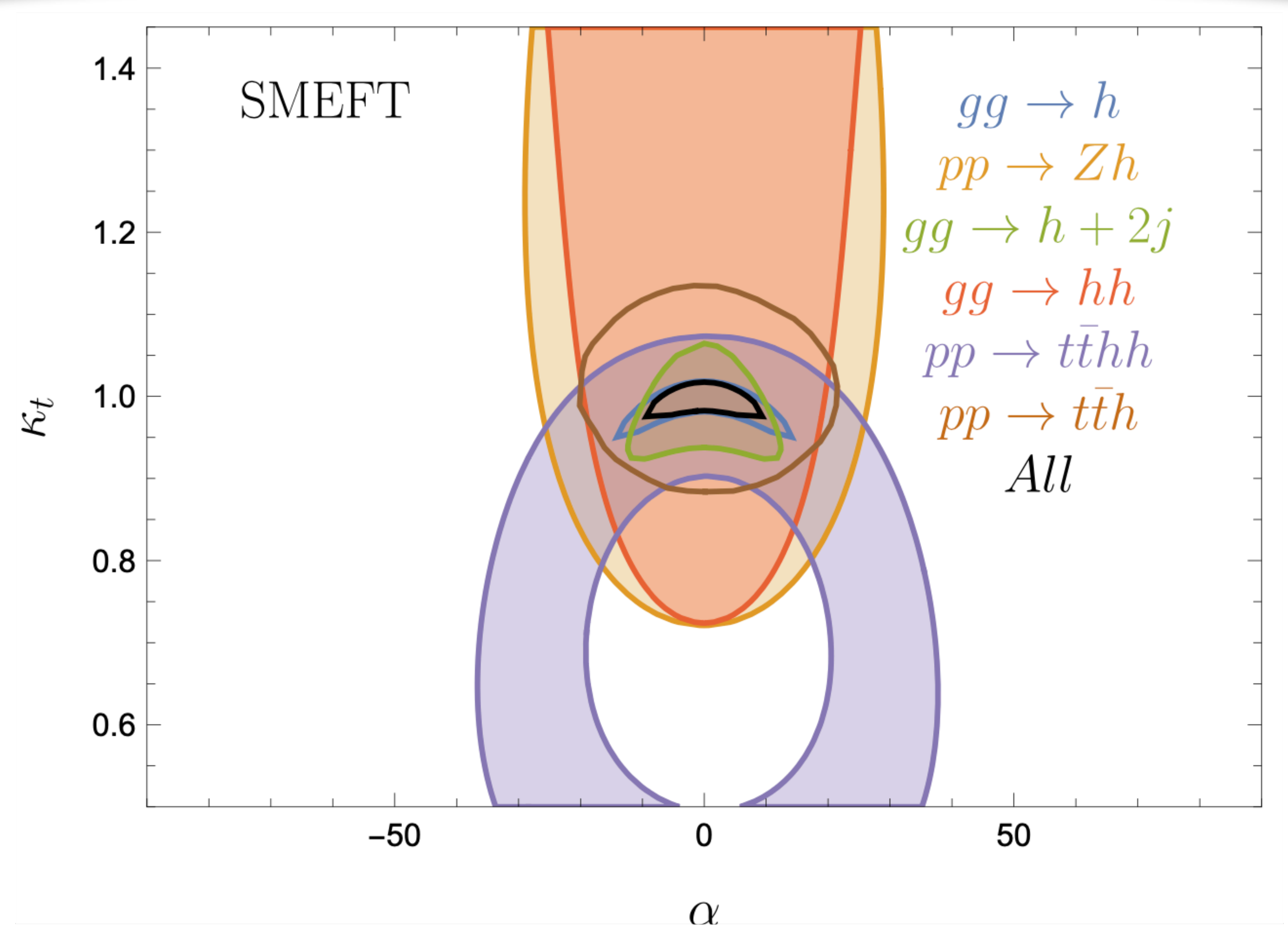
$$\Rightarrow \left.\frac{\Gamma_{\bar{t}th}}{\Gamma_{\bar{t}th^2}}\right|_{\gamma^5,\text{HEFT}} = \frac{\kappa_t}{\kappa_{tt}}\frac{\sin\alpha}{\sin\beta}\,v$$

SMEFT trajectory can be recovered by the HEFT choices:

$$\kappa_{tt}^2 = 9(1 - 2\kappa_t\cos\alpha + \kappa_t^2)$$
$$\tan\beta = \frac{\kappa_t\sin\alpha}{\kappa_t\cos\alpha - 1}\,.$$

Bhardwaj, Englert, DG, Navarro ’23

SMEFT vs. HEFT Higgs-top CPV

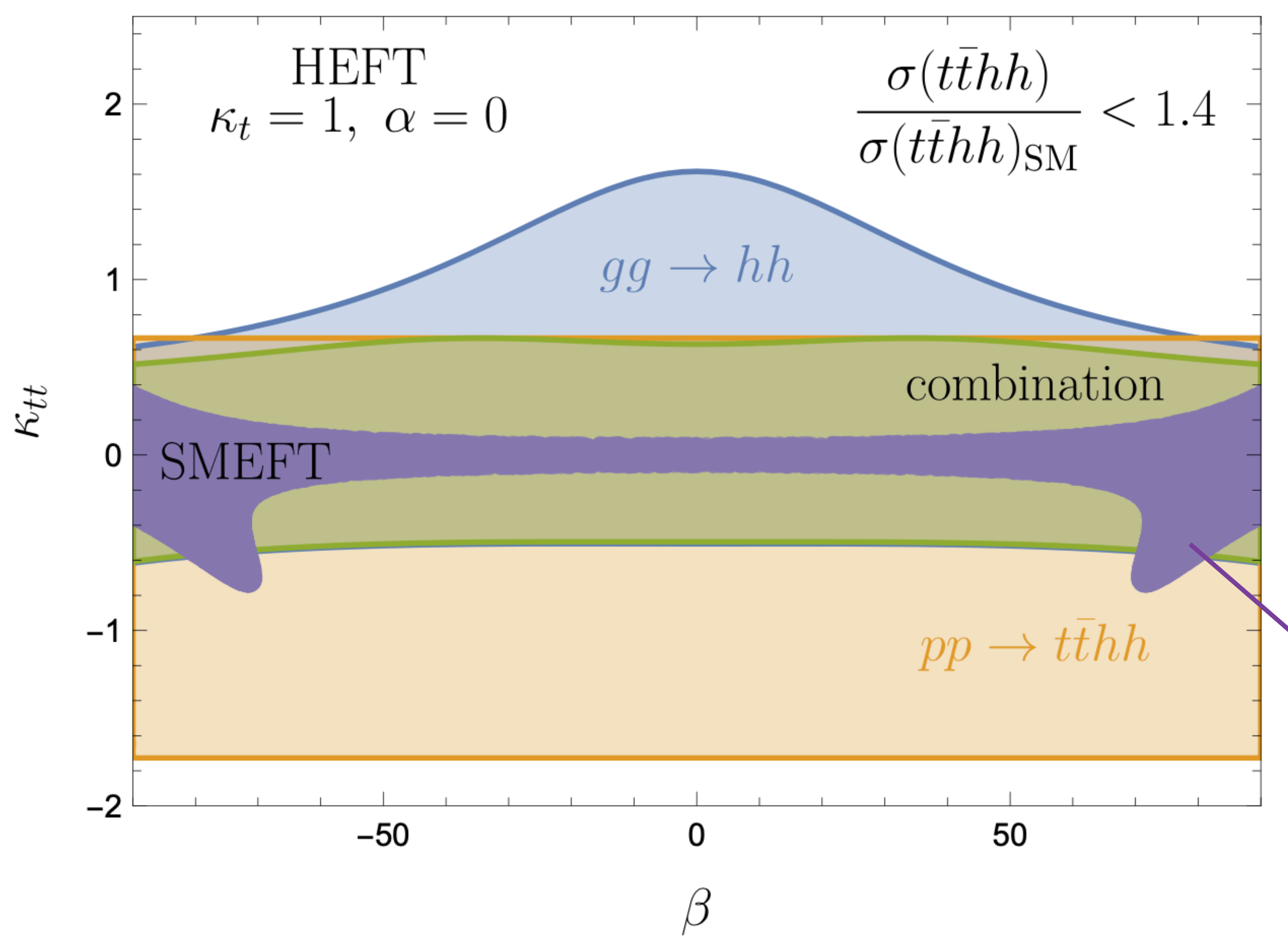


- Higgs-top CPV manifest predominantly in single Higgs physics in the SMEFT
  - → Single Higgs production has larger event rate than double Higgs at the LHC
  - → $\left.\frac{\Gamma_{\bar{t}th}}{\Gamma_{\bar{t}th^2}}\right|_{\gamma^5,\mathrm{SMEFT}} = \frac{v}{3}$

Bhardwaj, Englert, DG, Navarro '23

SMEFT vs. HEFT Higgs-top CPV

- Assuming a SM value in HEFT for the single Higgs modes, $(k_t, \alpha) = (1, 0)$, the expected constraints from purely non-linear CPV are obtained from multi-Higgs production



Bhardwaj, Englert, DG, Navarro '23

- Even if optimistic tthh constrain is relaxed, gg→hh production is still sensitive to significant quartic tthh vertices and associated CPV in HEFT

- SMEFTy extensions select a subspace of HEFT:

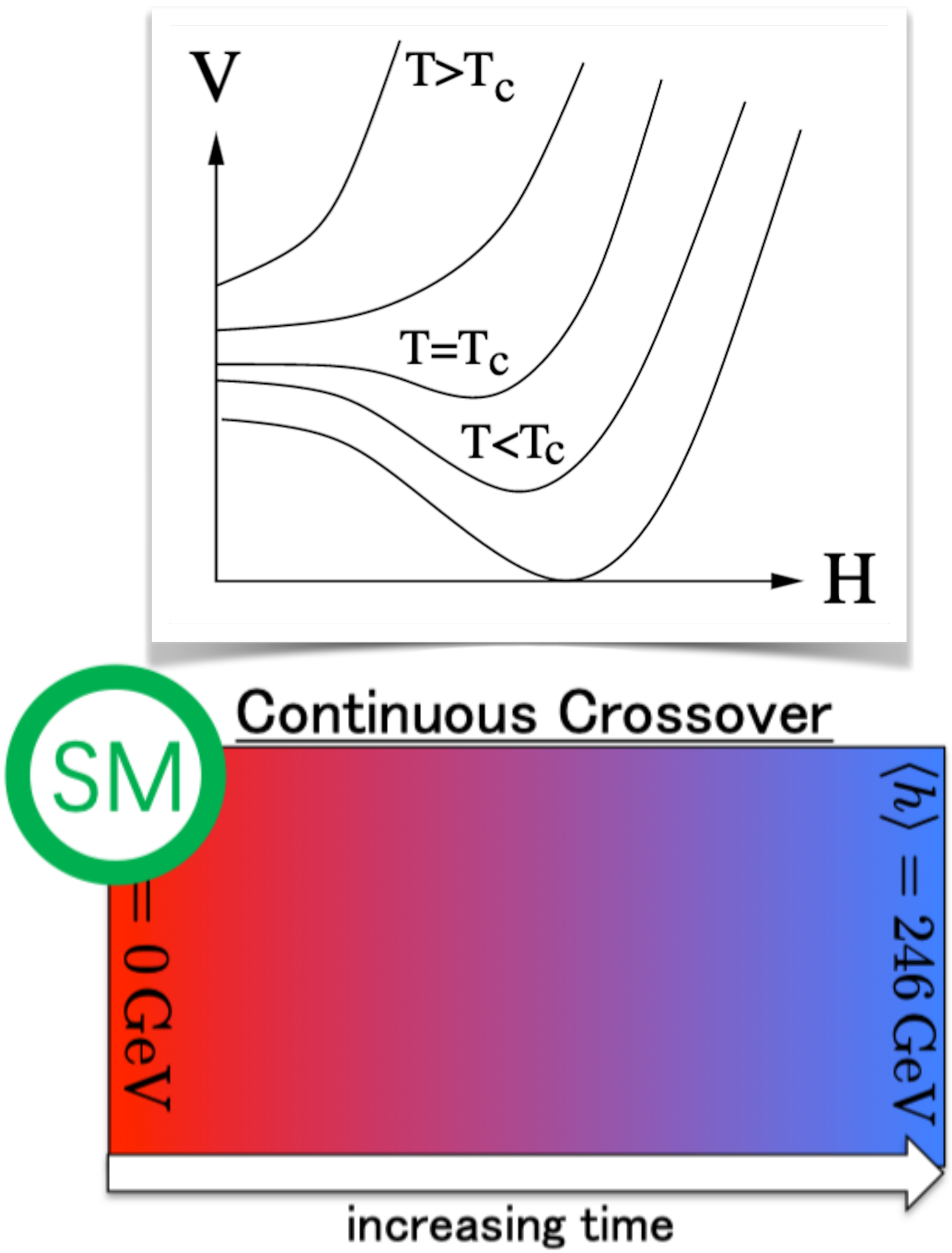
$$\kappa_{tt}^2 = 9(1 - 2\kappa_t \cos\alpha + \kappa_t^2)\,,$$
$$\tan\beta = \frac{\kappa_t \sin\alpha}{\kappa_t \cos\alpha - 1}\,.$$

SMEFT region selected from a fit to single Higgs data

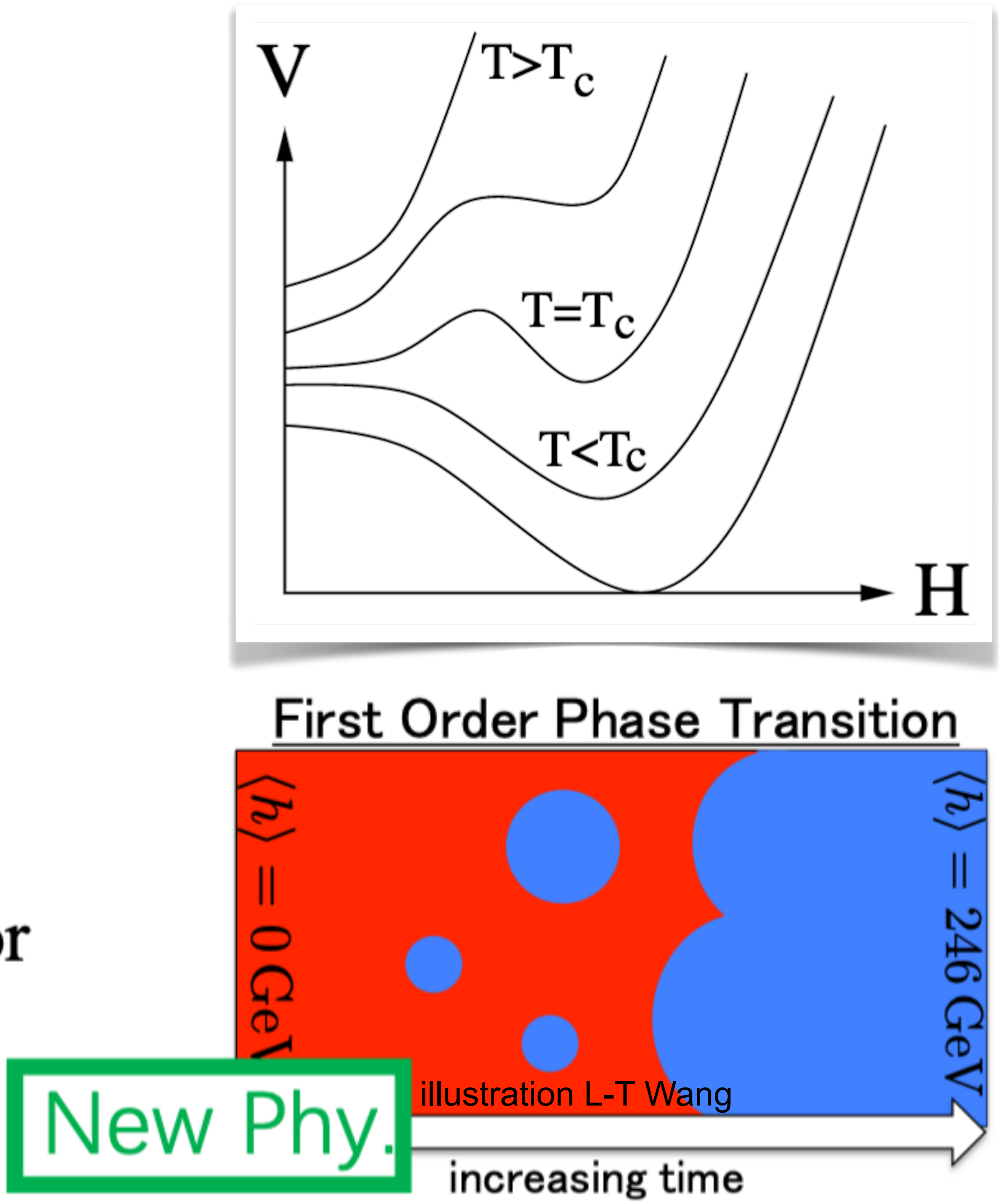
SM-like outcome of single Higgs measurements renders the available parameter space in the di-Higgs couplings relatively limited in SMEFT

Thermal history of our Universe

- What is the order of the Electroweak Phase Transition?



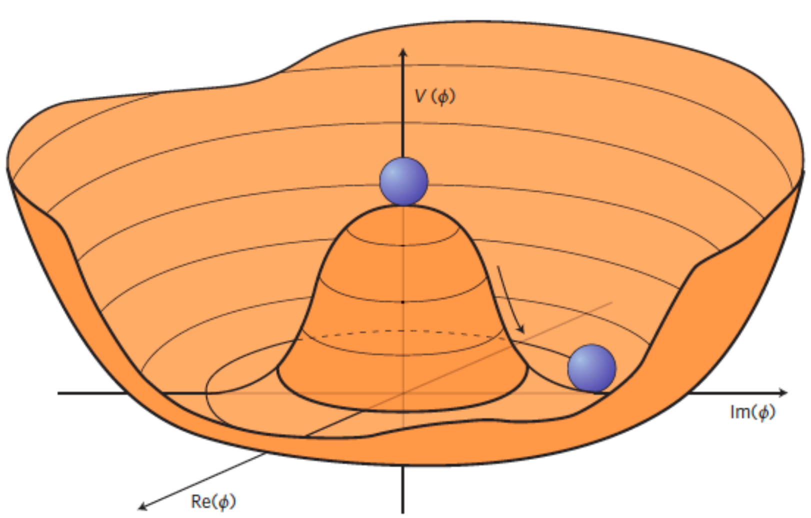
or

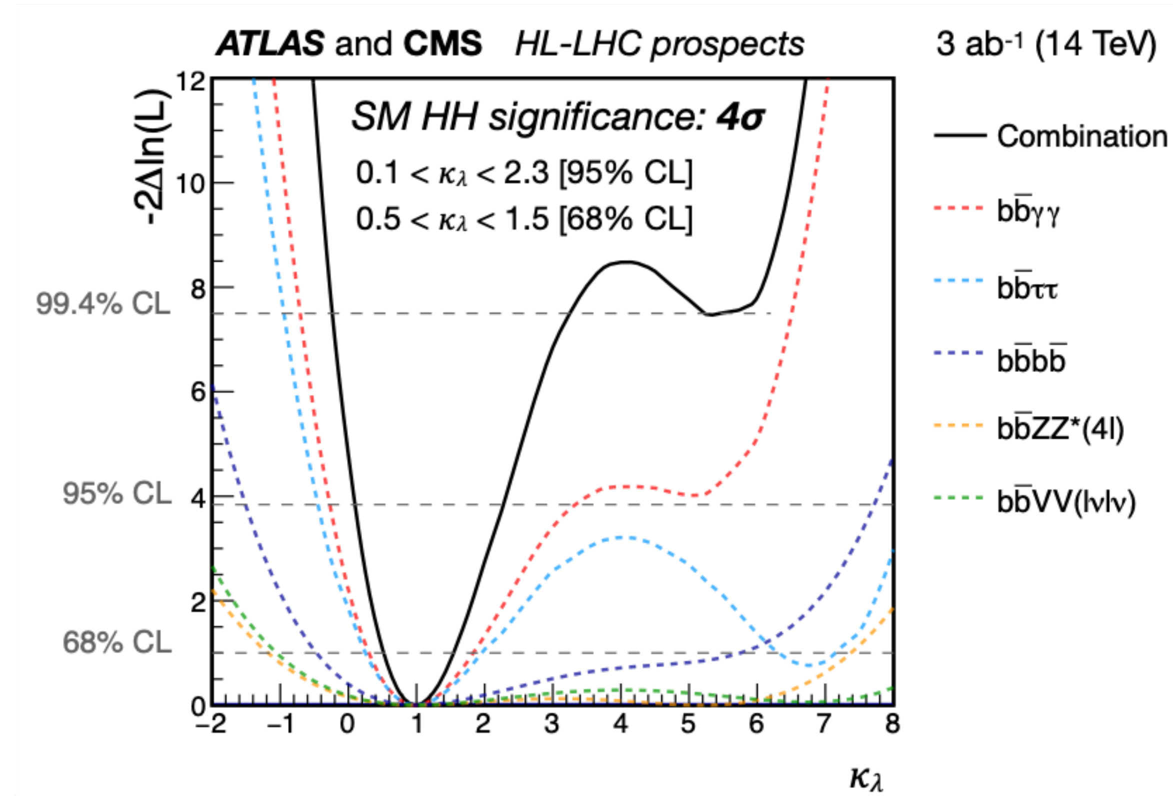


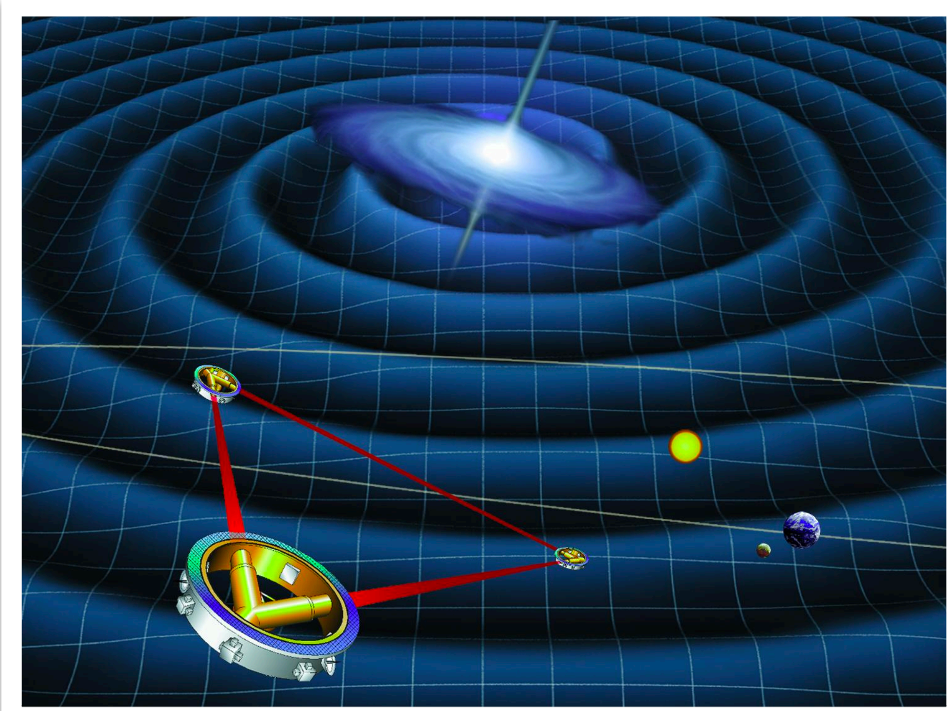
Higgs Potential: Collider & GW Complementarity

- Strong first order phase transition at EW scale typically requires novel degrees of freedom close to EW scale, displaying sizable interactions with the Higgs boson

  LHC searches: di-Higgs or heavy resonant searches







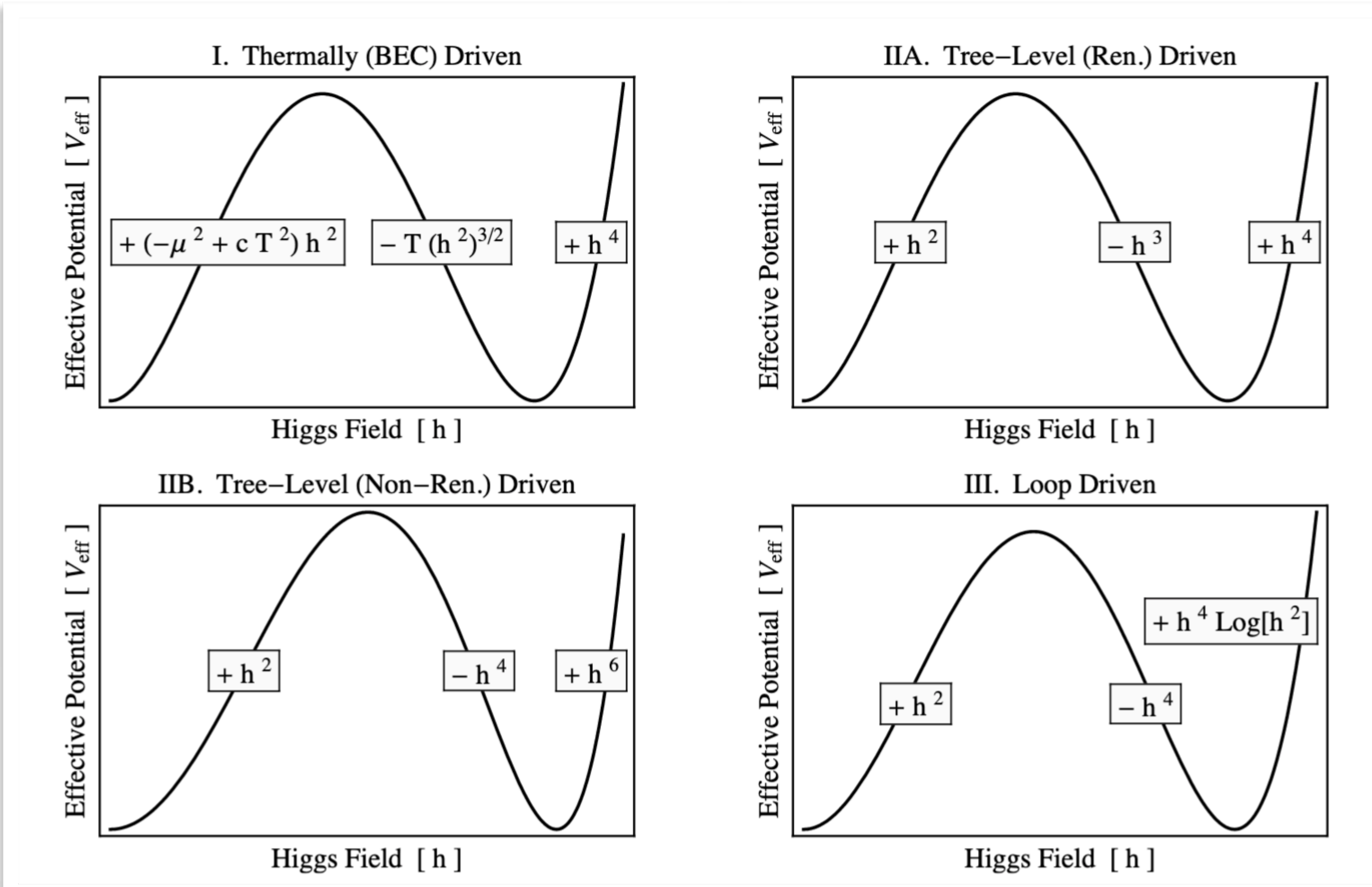
For T_* ~ 100 GeV, GW frequency (redshifted to today) ~ mHz

Signal in sensitivity band of future space-based GW detector **LISA**

The Shape of the Higgs Potential

$$V_{\rm eff} = V_0 + V_1 + V_T$$

- **Barrier formation:** tree vs. one-loop vs. thermally induced barrier

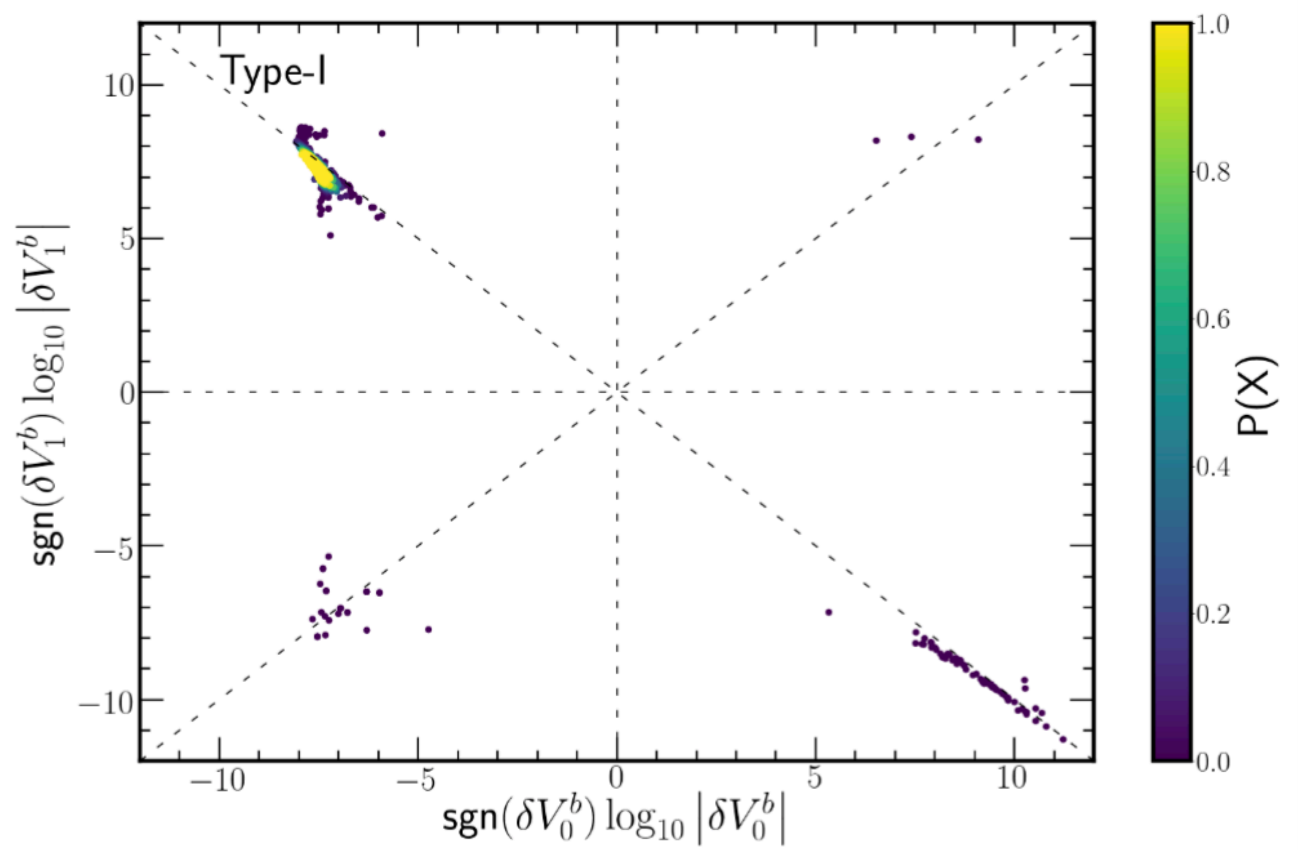


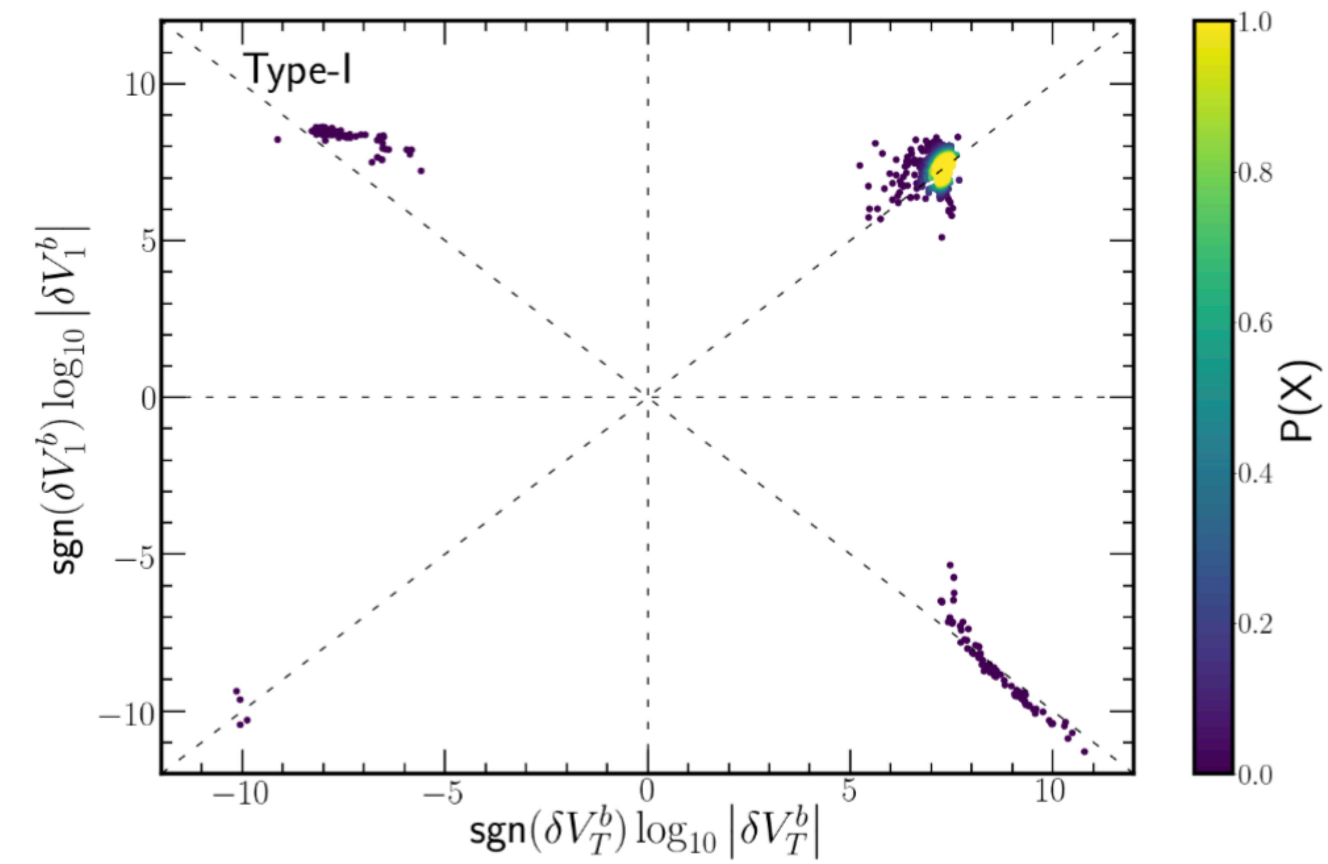
Chung,Long, L–T Wang '12

The Shape of the Higgs Potential

$$V_{\text{eff}} = V_0 + V_1 + V_T$$

- **Barrier formation:** tree vs. one-loop vs. thermally induced barrier
- 2HDM





DG, Kaladharan, Wu '21

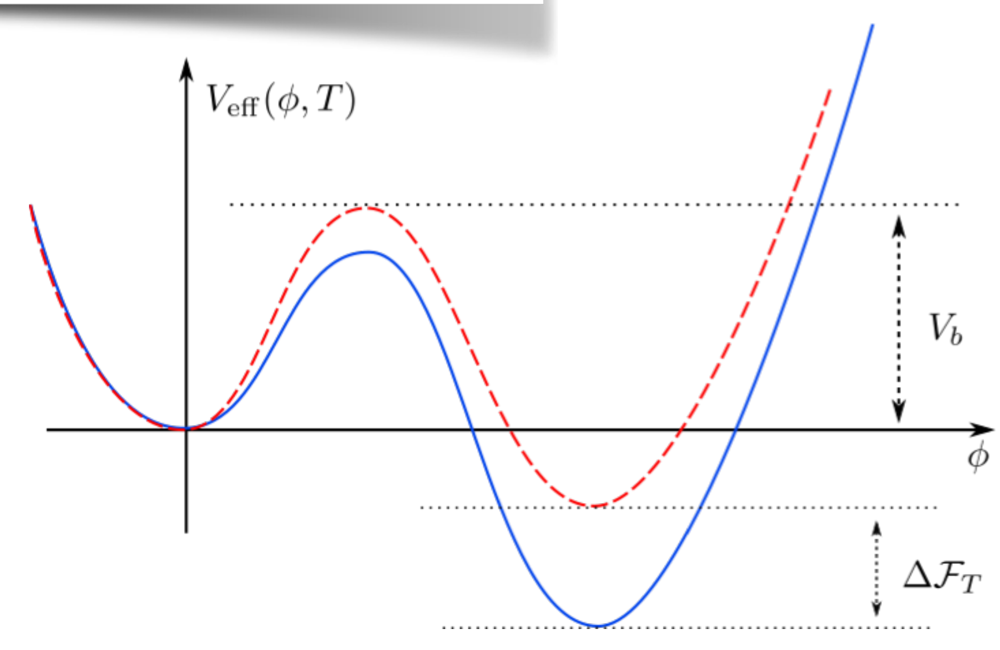
➡ Potential barrier induced by one-loop+thermal effects for more than 99% of points

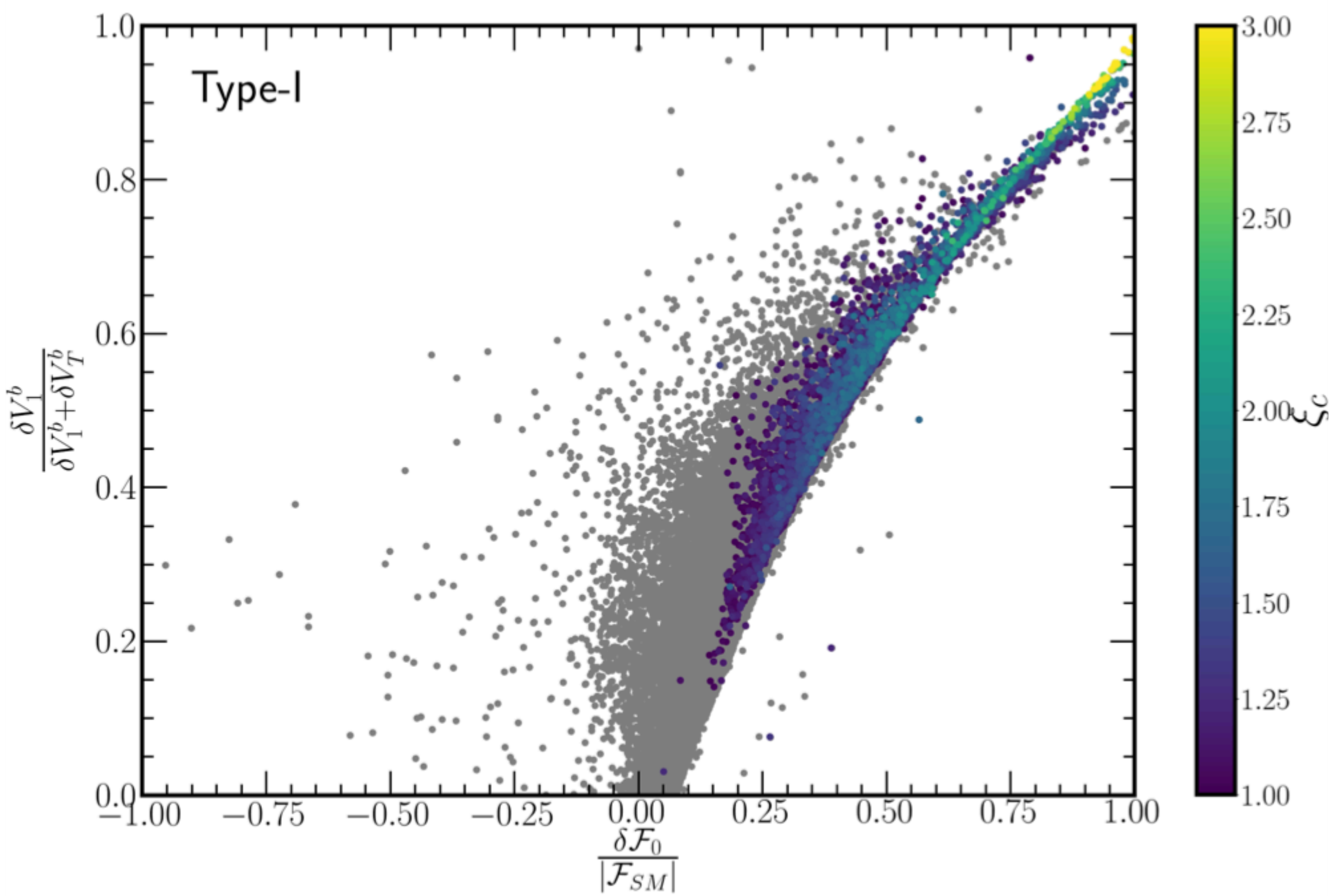
The Shape of the Higgs Potential

Vacuum Upliftment:

$$\frac{\Delta\mathcal{F}_0}{|\mathcal{F}_0^{SM}|} \equiv \frac{\mathcal{F}_0 - \mathcal{F}_0^{SM}}{|\mathcal{F}_0^{SM}|}$$

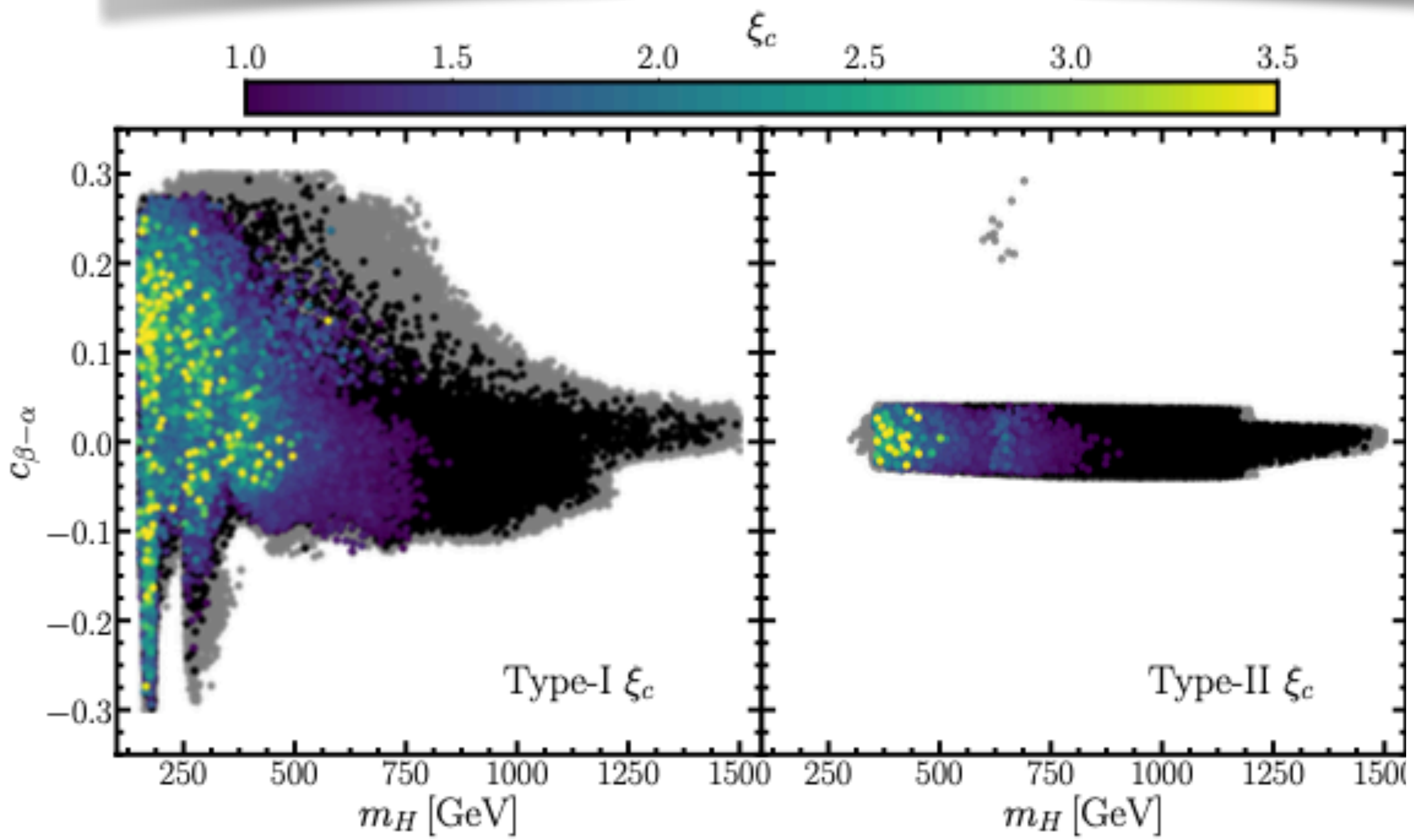
$$\mathcal{F}_0 \equiv V_{\rm eff}(v_1, v_2, T=0) - V_{\rm eff}(0,0,T=0)$$





DG, Kaladharan, Wu ’21; Dorsch, Huber, Mimasu, No ’17

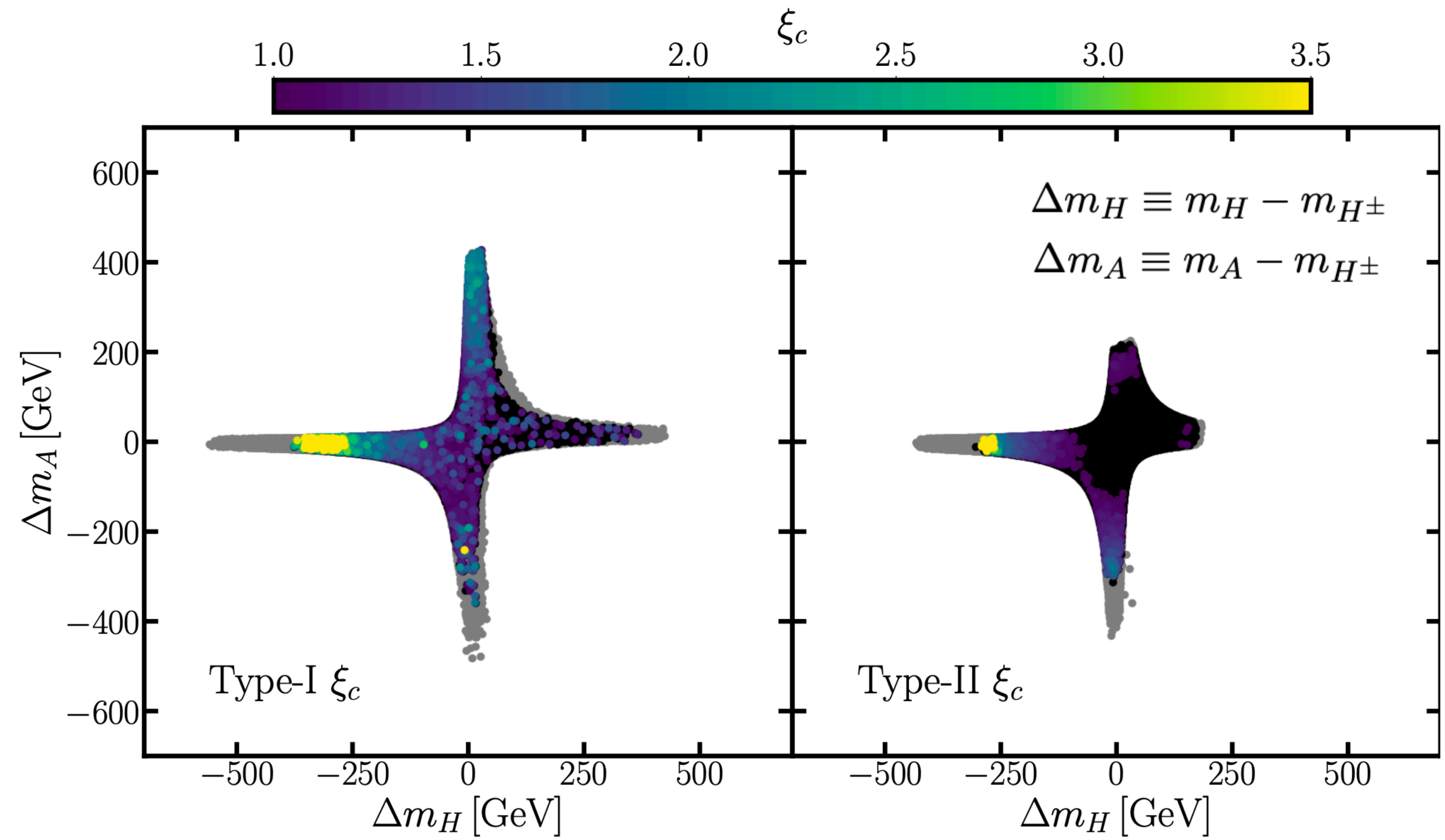
Strong first-order phase transition in the 2HDM



DG, Kaladharan, Wu '21
Dorsh, Huber, No 13'; Ramsey-Musolf '19

- Typically: the lighter the resonance, the higher the order parameter
  $\xi > 1 \;\rightarrow\; m_H \lesssim 750$ GeV
- Strong extra motivation for scalar searches at the LHC

Strong first-order phase transition in the 2HDM



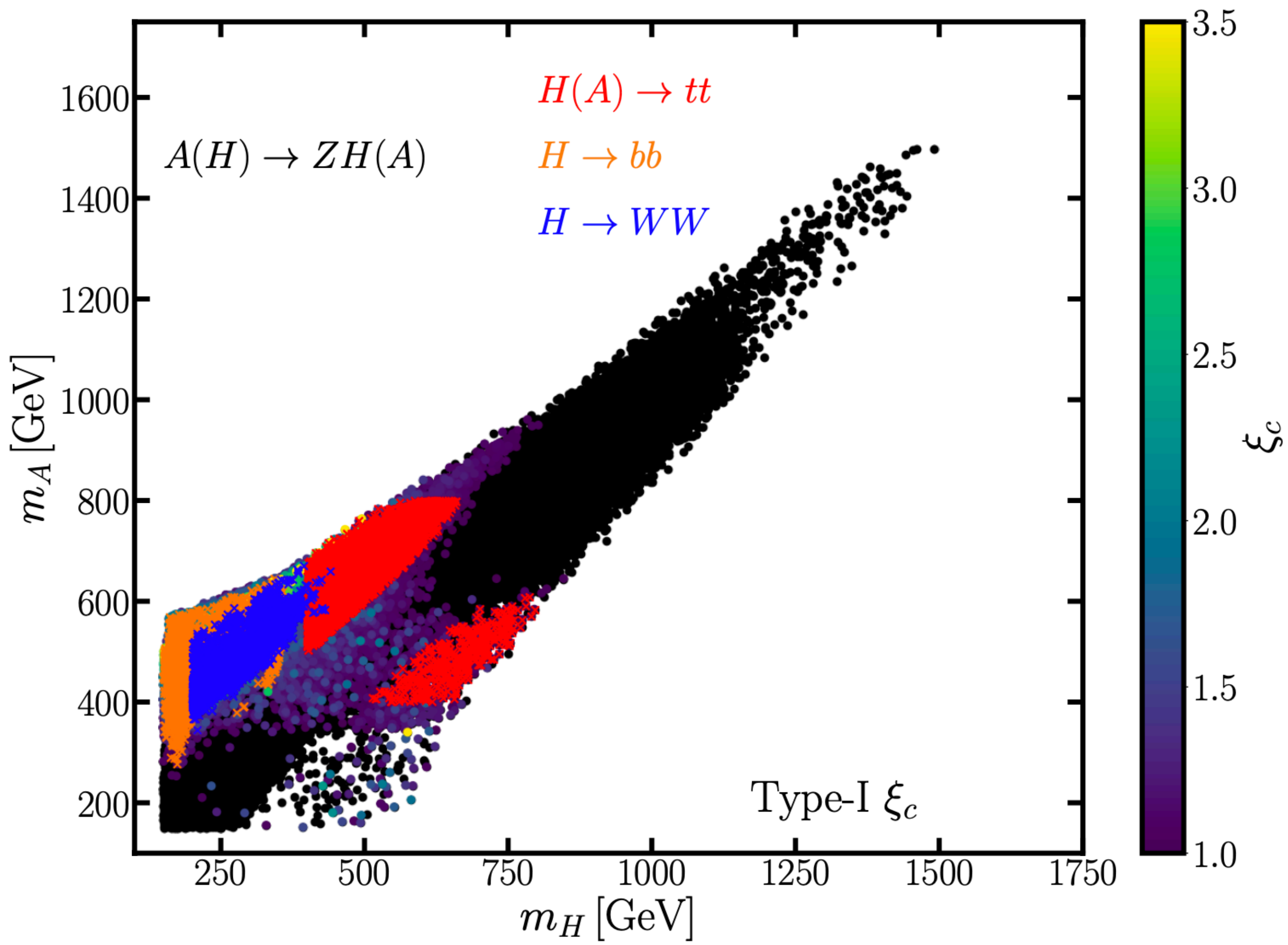
DG, Kaladharan, Wu '21; Dorsh, Huber, No 13'

- Due to the preference for large mass hierarchy among the scalar modes, it is likely that at least one of the scalar states be above the top-quark pair threshold: Favors gg→H/A→tt searches
- $m_H < m_{H^\pm} \approx m_A$: most favorable region for SFOEWPT
  Favors BSM searches via $A \to ZH$ channel

Top Pair Resonant Searches via pp→ZH/A

- Current pp→ZH/A searches mostly account for H/A→bb and H→WW (sensitivity $m_{H,A}$ < 350 GeV)
  See e.g., arXiv:2011.05639 and arXiv:1911.03781

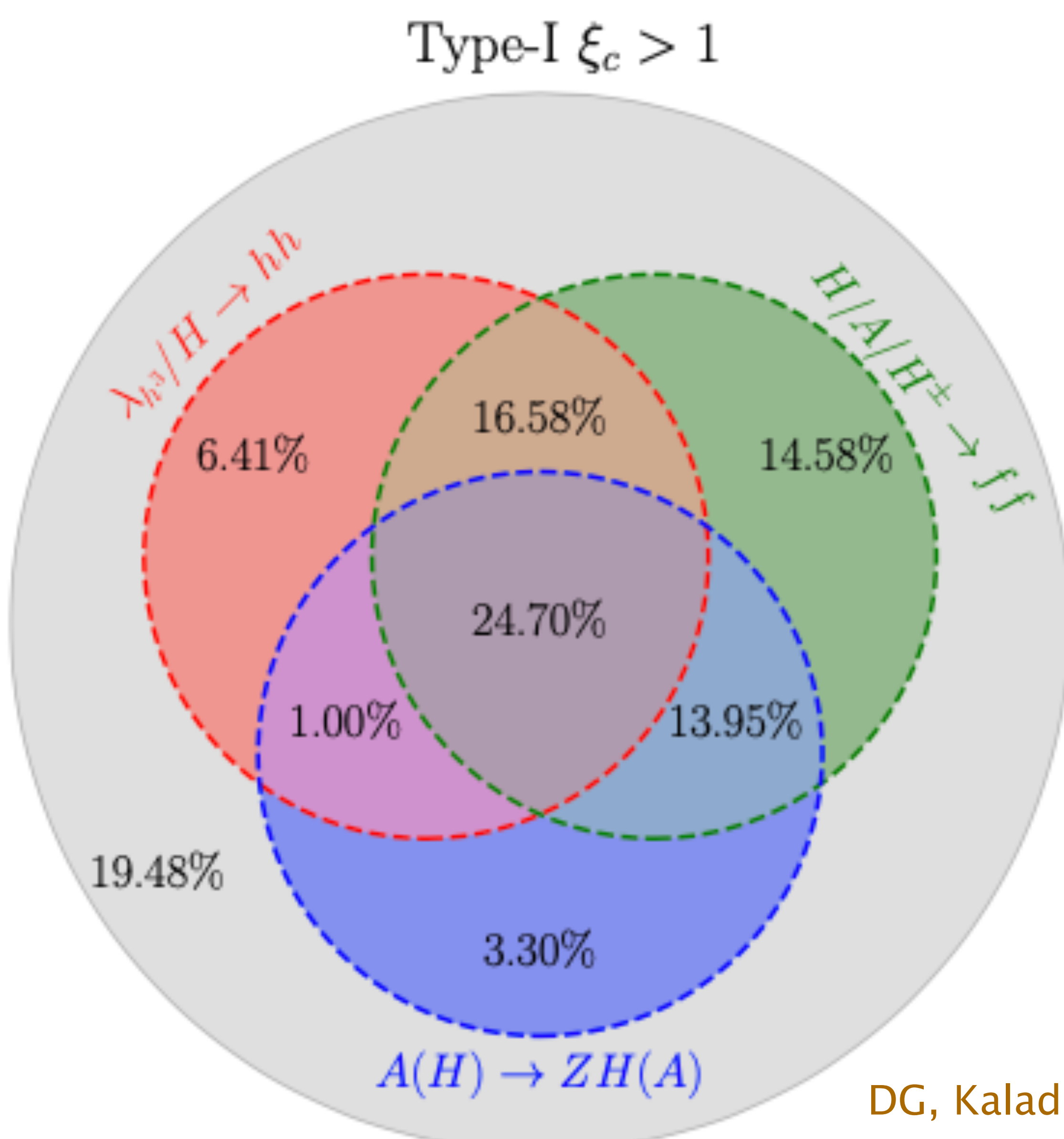
→ Above top-quark pair threshold the H/A → tt is typically dominant decay, leading to strong limits, and extending the sensitivity to strong first-order phase transition regime



DG, Kaladharan, Wu '22

Combined results

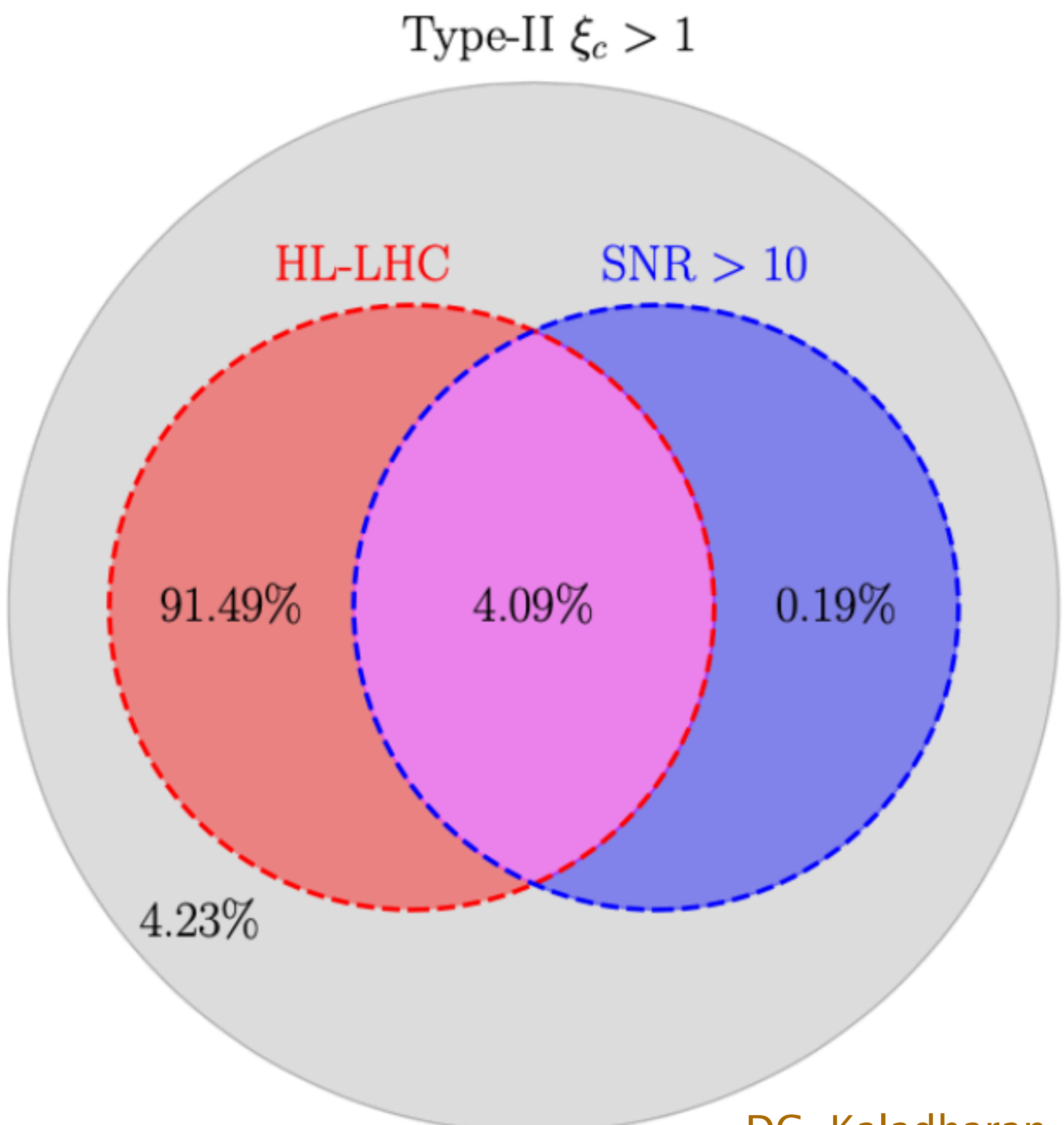
- Complementarity of the Higgstrahlung searches with other relevant classes of searches at the HL-LHC



DG, Kaladharan, Wu '22

$$\tan\beta \in (0.8, 25)\,, \quad m_{12}^2 \in (10^{-3}, 10^5)\,\mathrm{GeV}^2\,, \quad m_H \in (150, 1500)\,\mathrm{GeV}\,,$$
$$\cos(\beta-\alpha) \in (-0.3, 0.3)\,, \quad m_A \in (150, 1500)\,\mathrm{GeV}\,, \quad m_{H^\pm} \in (150, 1500)\,\mathrm{GeV}.$$

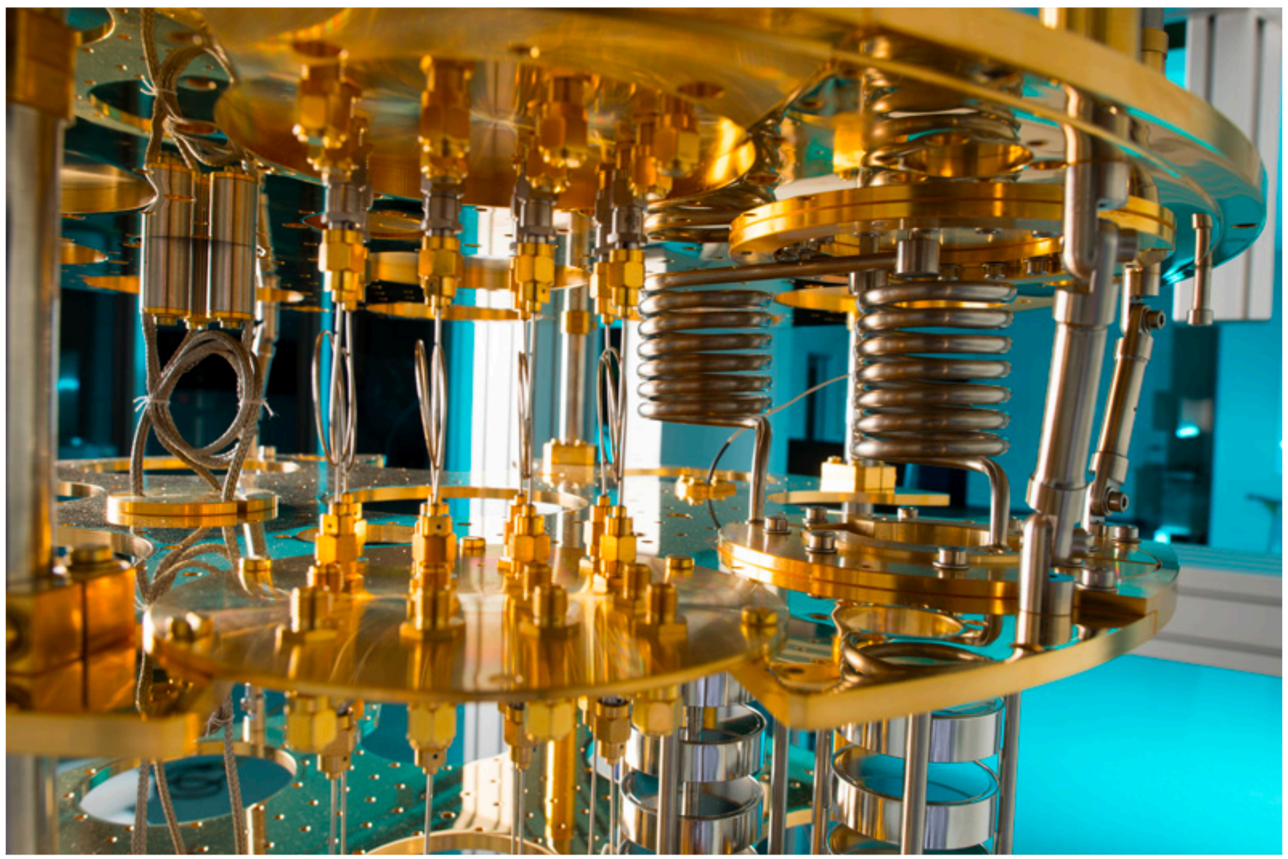
Collider & GW complementarity

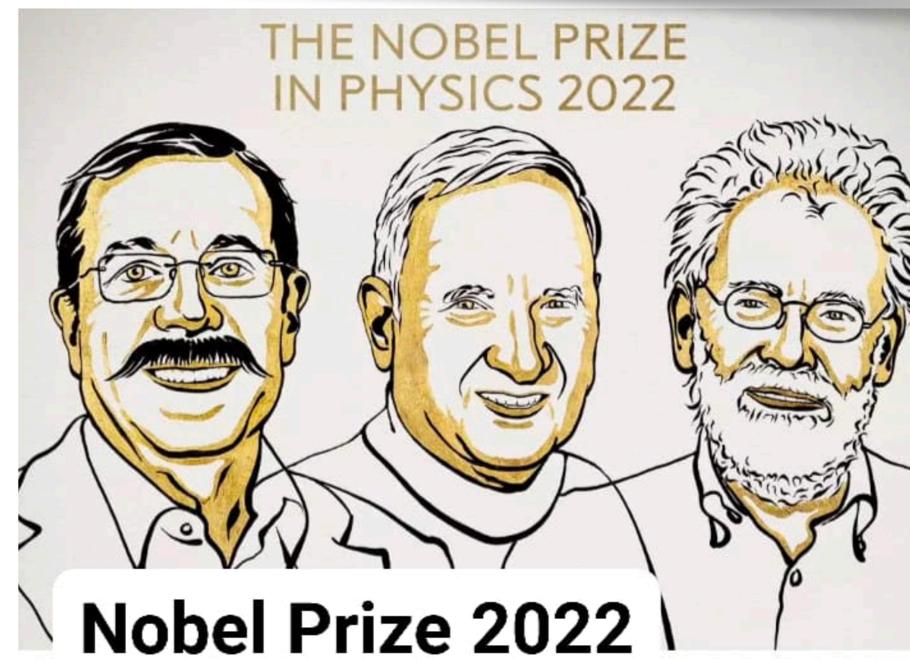


DG, Kaladharan, Wu '21

➡ In contrast to HL-LHC, LISA is going to be sensitive to a significantly smaller parameter space region, whereas it renders to complementary sensitivities where correspondent LHC cross-section is suppressed

Entanglement and Bell's Inequalities with Boosted Top Quarks





Nobel Prize 2022

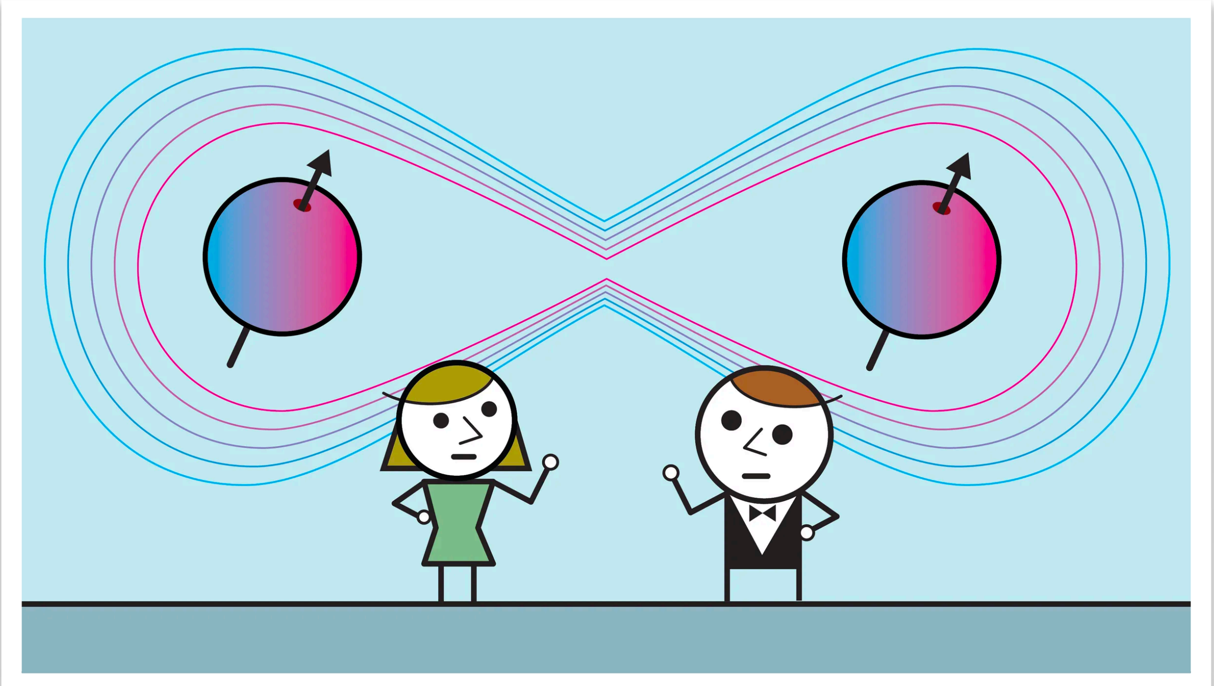
Nobel Prize in Physics awarded to Aspect, Clauser and Zeilinger for work in quantum mechanics

The Royal Swedish Academy of Sciences has decided to award the 2022 Nobel Prize in Physics to Alain Aspect, John F Clauser and Anton Zeilinger, according to an official tweet. They have been awarded the Nobel Prize for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science.

- QI theory provides a set of tools designed to probe the inner behavior of QM. While these phenomena have been widely tested at low energies, their study at higher energy scales has not be undertaken

Entanglement and Bell's Inequalities with Boosted Top Quarks

- LHC can provide a unique environment to study entanglement and violation of Bell's inequalities at the highest energy available today



- Top quark pair production is an optimal candidate for these studies

See as well talks by Claudio Severi, Kun Cheng, Oliver Baker, Giulia Negro (CMS), Yoav Afik (ATLAS)

Top quark as a one qubit system

- As a spin-1/2 particle, the most general spin density matrix for the top quark is

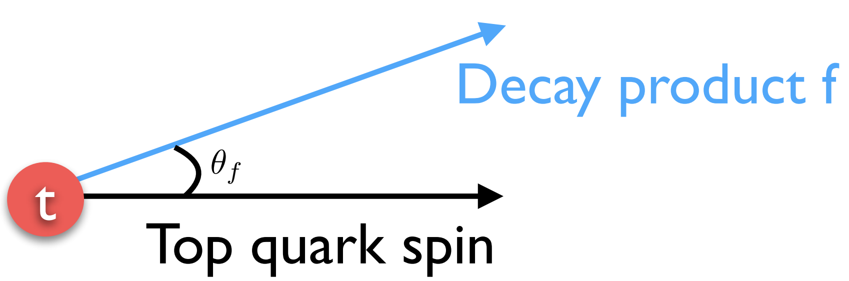
$$\rho = \frac{\mathbb{I} + B_i \sigma_i}{2}$$

- Characterized by three parameters: $B_i = \langle \sigma_i \rangle = tr(\sigma_i \rho)$

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

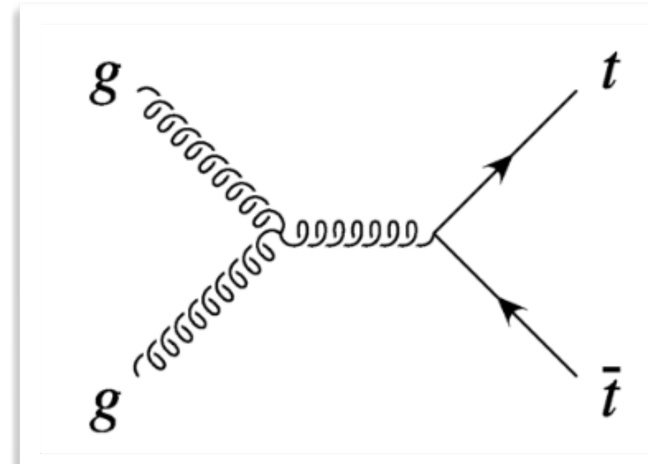
	$l^+, \bar{d}$	b	$\bar{\nu}, u$
ω_f	1	-0.4	-0.3

Spin analyzing power: maximum for charged leptons and down-type quarks



Top quark pair production as a two qubit system

- The most general two-qubit system can be represented by



$$\rho = \frac{\mathbb{I}\otimes\mathbb{I} + \left(B_i \sigma_i \otimes \mathbb{I} + \bar{B}_i \mathbb{I}\otimes\sigma_i\right) + C_{ij}\sigma_i\otimes\sigma_j}{4}$$

- Characterized by 15 parameters parameters: B_i, $\bar{B}_i$, and C_{ij}

$B_i = \langle \sigma_i \otimes \mathbb{I} \rangle$ → Polarizations

$\bar{B}_i = \langle \mathbb{I} \otimes \sigma_i \rangle$ → Polarizations

$C_{ij} = \langle \sigma_i \otimes \sigma_j \rangle$ → Spin correlations

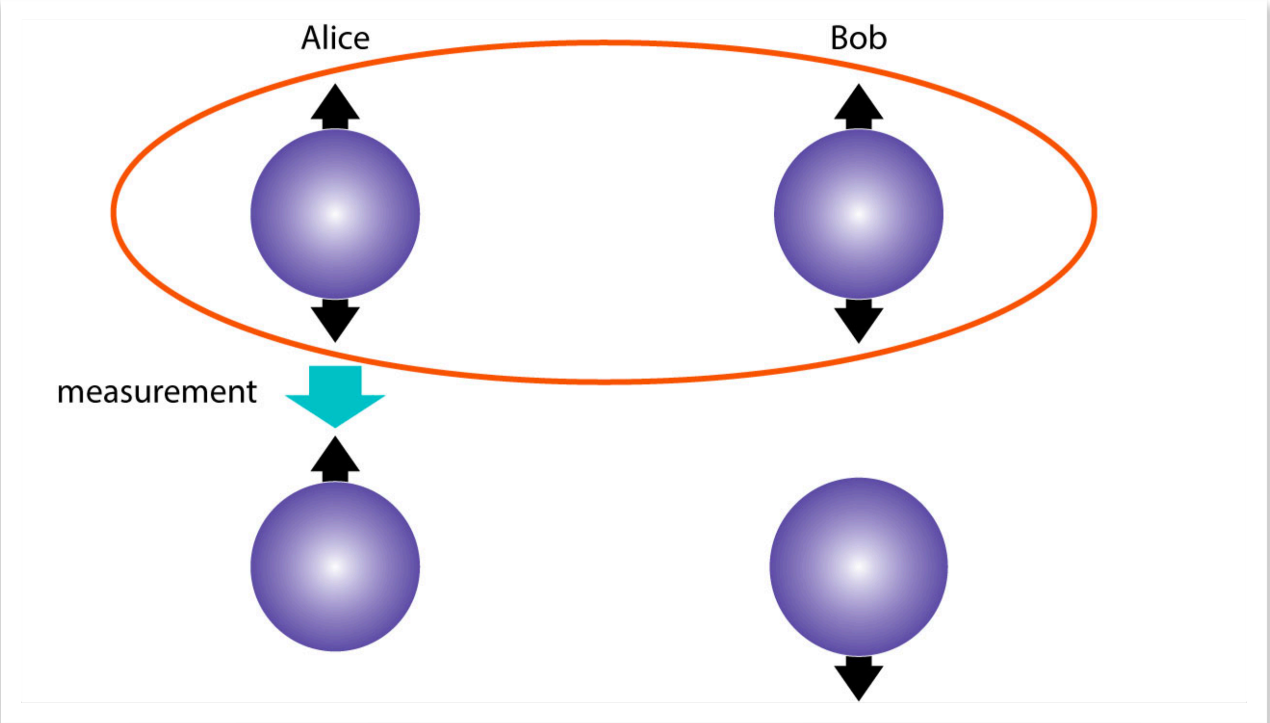
- P and CP invariance under $t\bar{t}$ production $\rightarrow B_i = \bar{B}_i = 0$ and $C_{ij} = C_{ji}$
- Things further simplify in the helicity basis: only non-vanishing parameters are the diagonal terms C_{ii} and one off-diagonal term $C_{12} \simeq C_{21}$ Bernreuther, Heisler, Si '15 Frederix, Tsinikos, Vitos '21

Quantum Entanglement

- A quantum state of two subsystems A and B is separable when its density matrix ρ can be expressed as a convex sum

$$\rho = \sum_i p_i \rho_A^i \otimes \rho_B^i$$

→ If the state is not separable, it is named *entangled*



Measurement in one subsystem immediately affect the other, even if they are causally disconnected

Quantum Entanglement

- A quantum state of two subsystems A and B is separable when its density matrix ρ can be expressed as a convex sum

$$\rho = \sum_i p_i \rho_A^i \otimes \rho_B^i$$

➡ If the state is not separable, it is named *entangled*

- The Peres-Horodecki criterion provides a necessary and sufficient condition for entanglement in two-qubit systems:

Peres '96; Horodecki '97

Take the transpose of indices associated only to Bob (or Alice)

$$\rho^{T2} = \sum_i p_i \rho_A^i \otimes (\rho_B^i)^T$$

For a separable system, ρ^{T2} results in a non-negative operator

➡ If ρ^{T2} displays at least one negative eigenvalue, the system is entangled

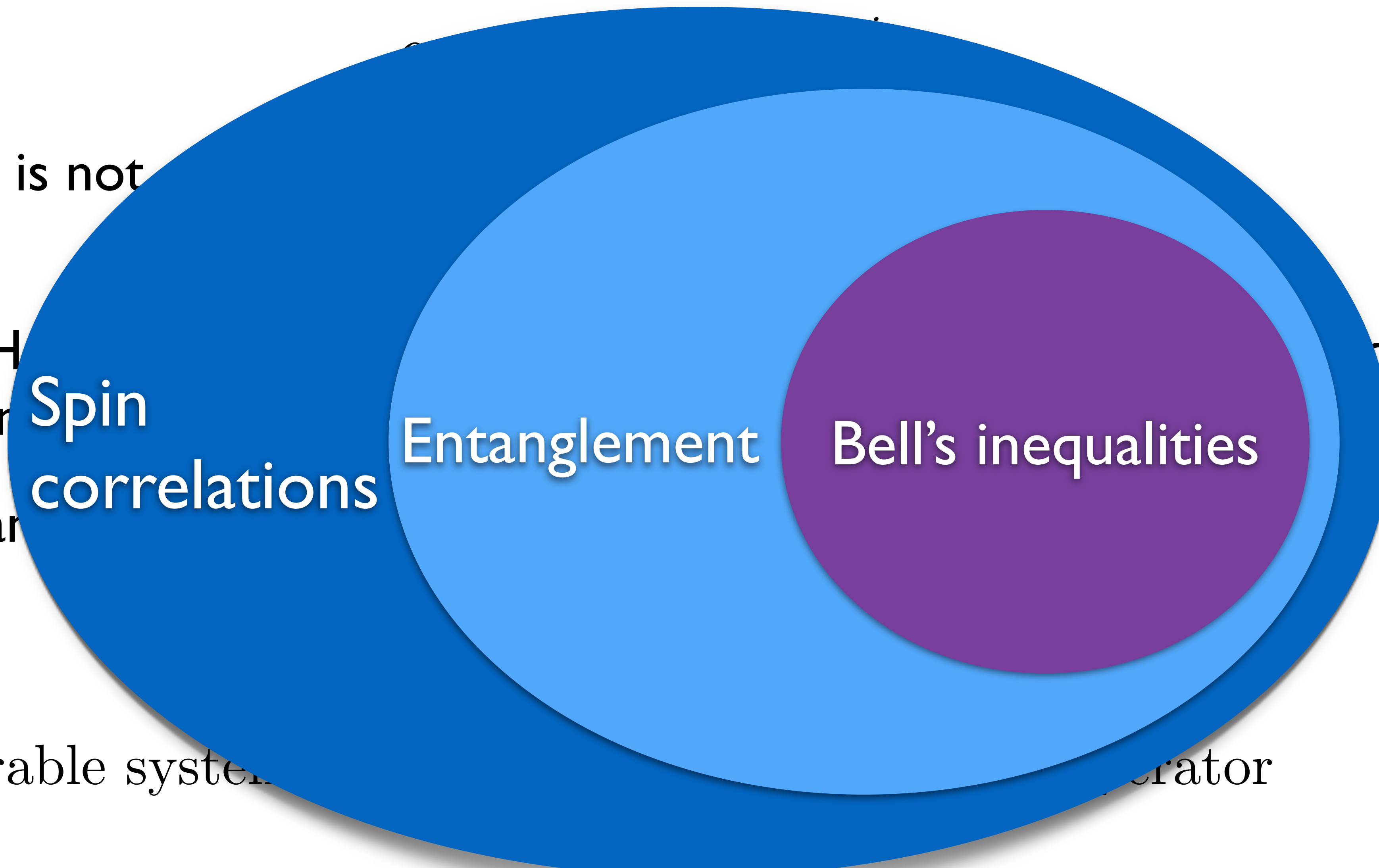
Quantum Entanglement

- A quantum state of two subsystems A and B is separable when its density matrix ρ can be expressed as a convex sum

→ If the state is not

- The Peres-H … dition for entanglemer … orodecki '97

Take the trar



For a separable syste … rator

→ If ρ^{T2} displays at least one negative eigenvalue, the system is entangled

Quantum Entanglement

- Since for the $t\bar{t}$ system $B_i = \bar{B}_i = 0$ and $C_{ij} = C_{ji}$ (P and CP) and $C_{13} \simeq C_{23} \simeq 0$ (helicity basis), we obtain some simple sufficient conditions for entanglement

Afik, Nova '20
Severi, Boschi, Maltoni, Sioli '21
Saavedra, Casas '22

$$|C_{kk} + C_{rr}| - C_{nn} - 1 > 0$$

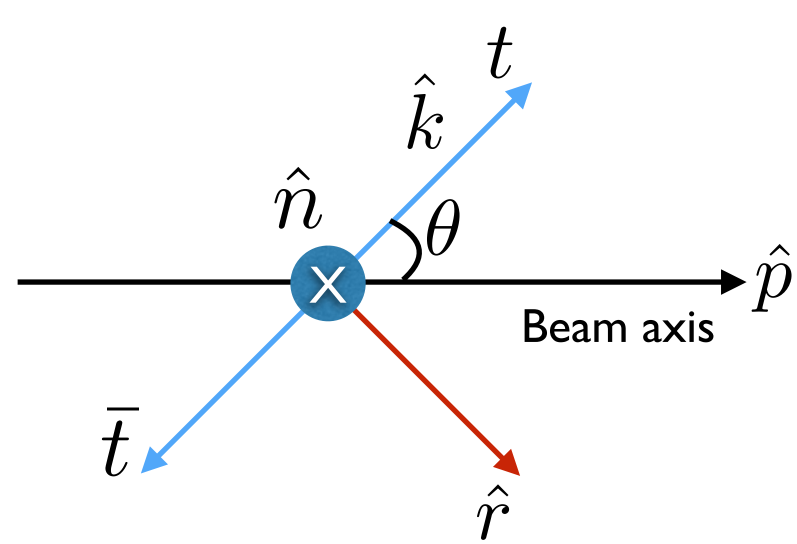
$$|C_{kk} - C_{rr}| + C_{nn} - 1 > 0$$

- Helicity basis

$\hat{k}$ = top quark direction

$\hat{r} = \text{sign}(\cos\theta)(\hat{p} - \cos\theta\hat{k})/\sin\theta$

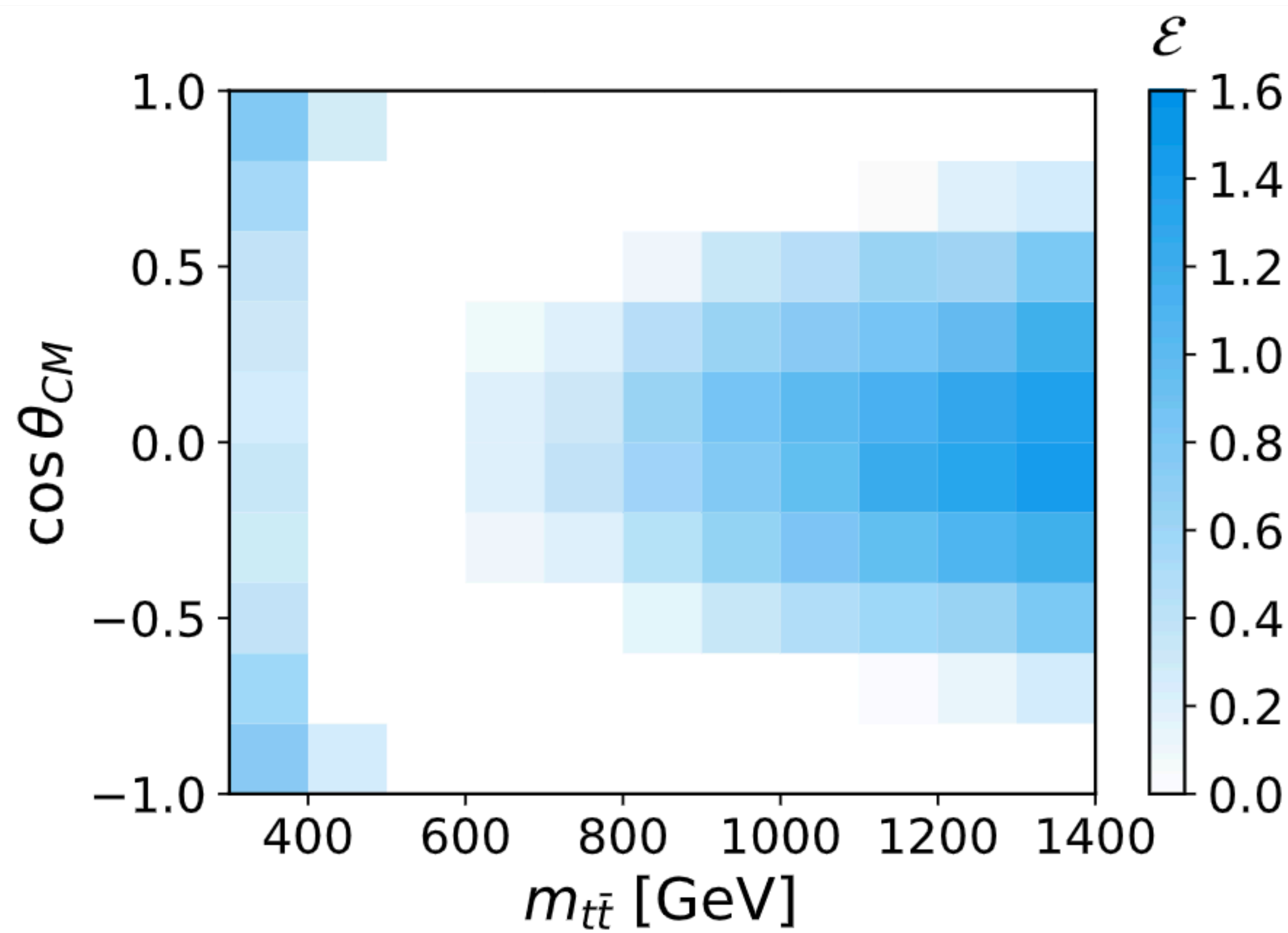
$\hat{n} = \hat{k} \times \hat{r}$



$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_a^i\, d\cos\bar{\theta}_b^j} = \frac{1}{4}\left(1 + \beta_a\beta_b C_{ij}\cos\theta_a^i\cos\bar{\theta}_b^j\right)$$

Quantum Entanglement

$$\mathcal{E} \equiv |C_{kk} + C_{rr}| - C_{nn} - 1 > 0$$



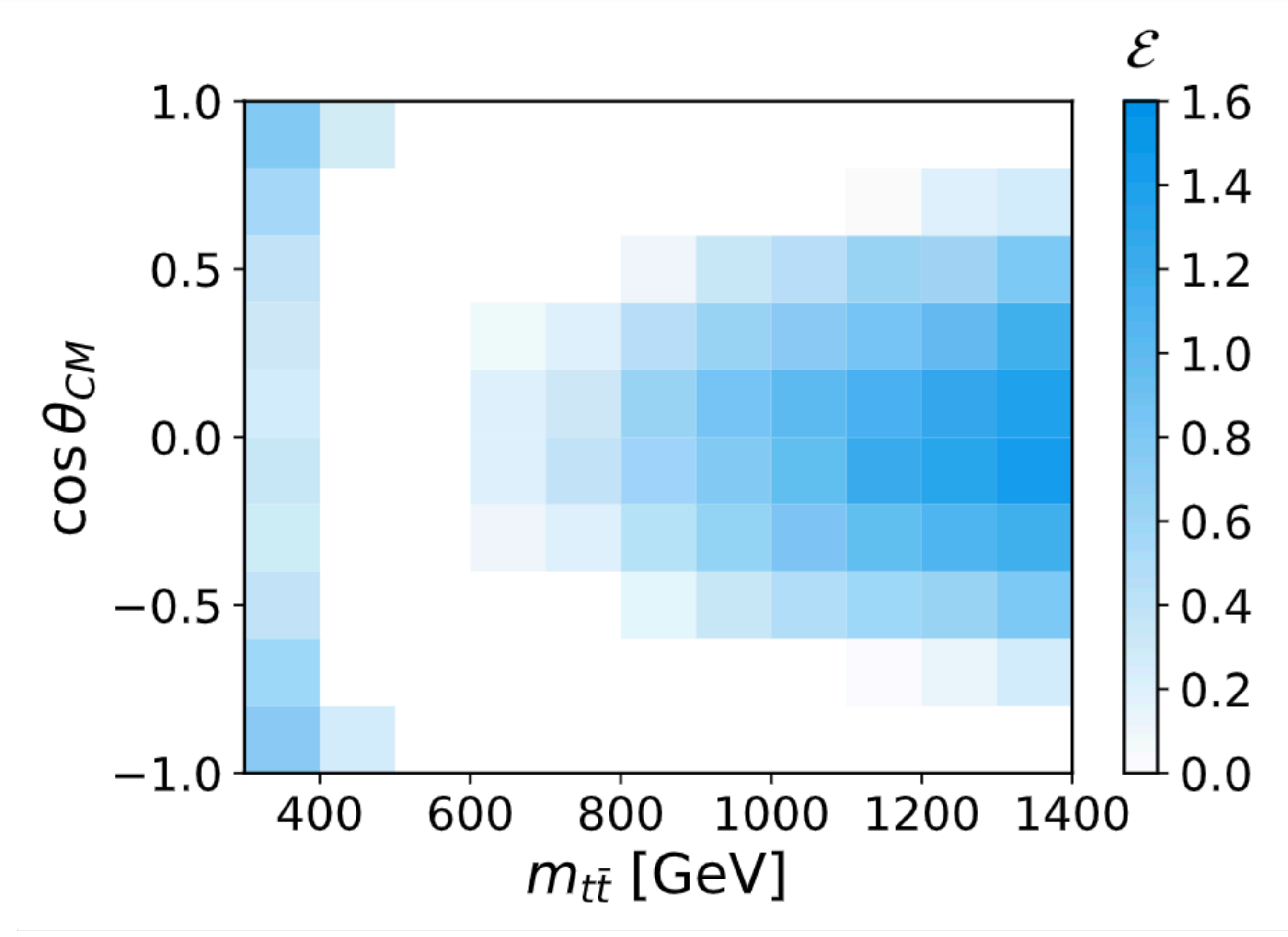
Dong, DG, Kong, Navarro ‘23

- Top pair displays entanglement in two disconnected regimes: **threshold** and **boosted** regions

Three reasons to study the boosted semileptonic tt final state

- i) Semi-leptonic top pair has an event rate higher than that of the dileptonic process, making it a more effective probe for the high-energy regime

$$\mathcal{E} \equiv |C_{kk} + C_{rr}| - C_{nn} - 1 > 0$$

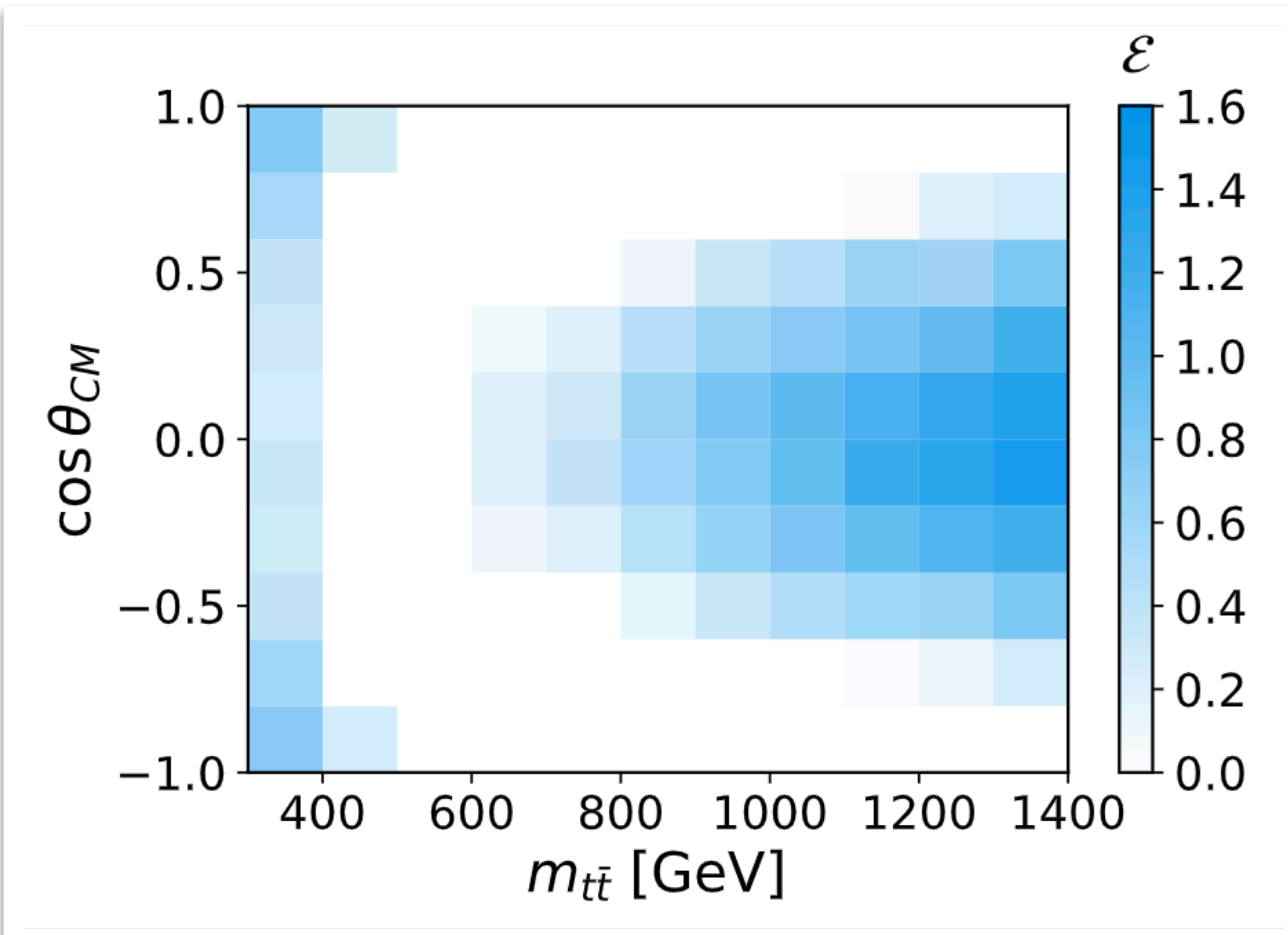


Dong, DG, Kong, Navarro '23

Three reasons to study the boosted semileptonic tt final state

- ii) Boosted top quark regime nicely matches with both entanglement and CHSH probes. High transverse momentum results in large top tagging efficiency and small fake rate for top tagging (e.g., HEPTopTagger)

$$\mathcal{E} \equiv |C_{kk} + C_{rr}| - C_{nn} - 1 > 0$$



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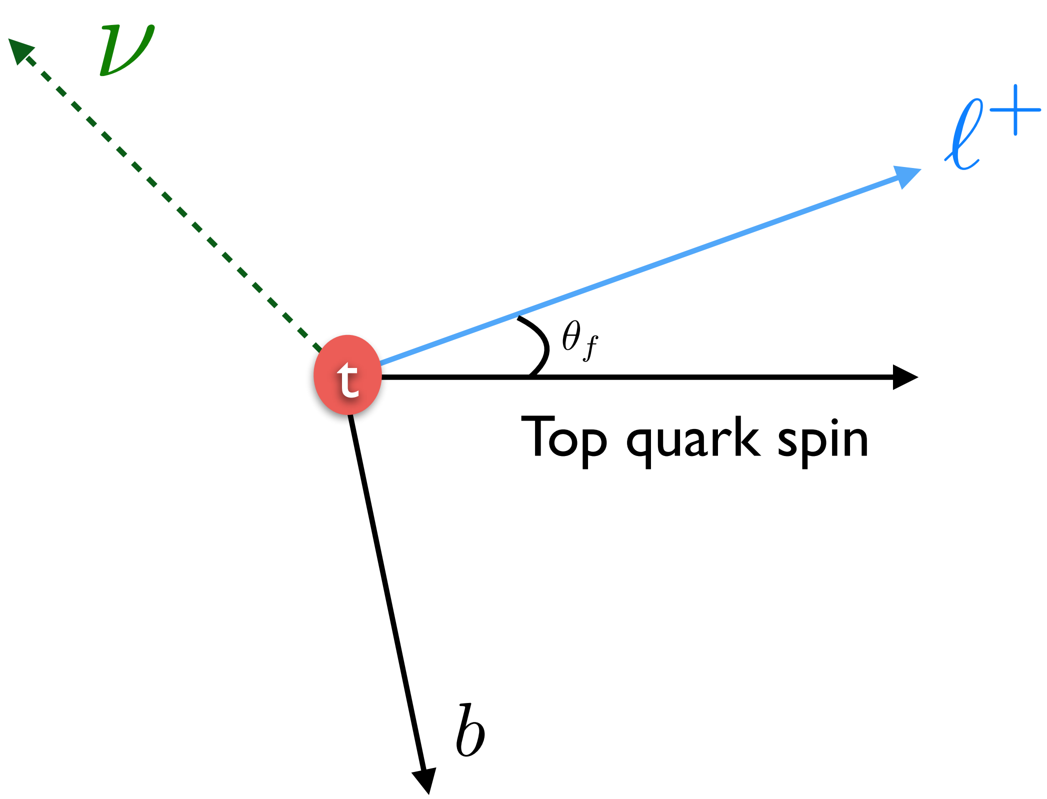
Three reasons to study the boosted semileptonic tt final state

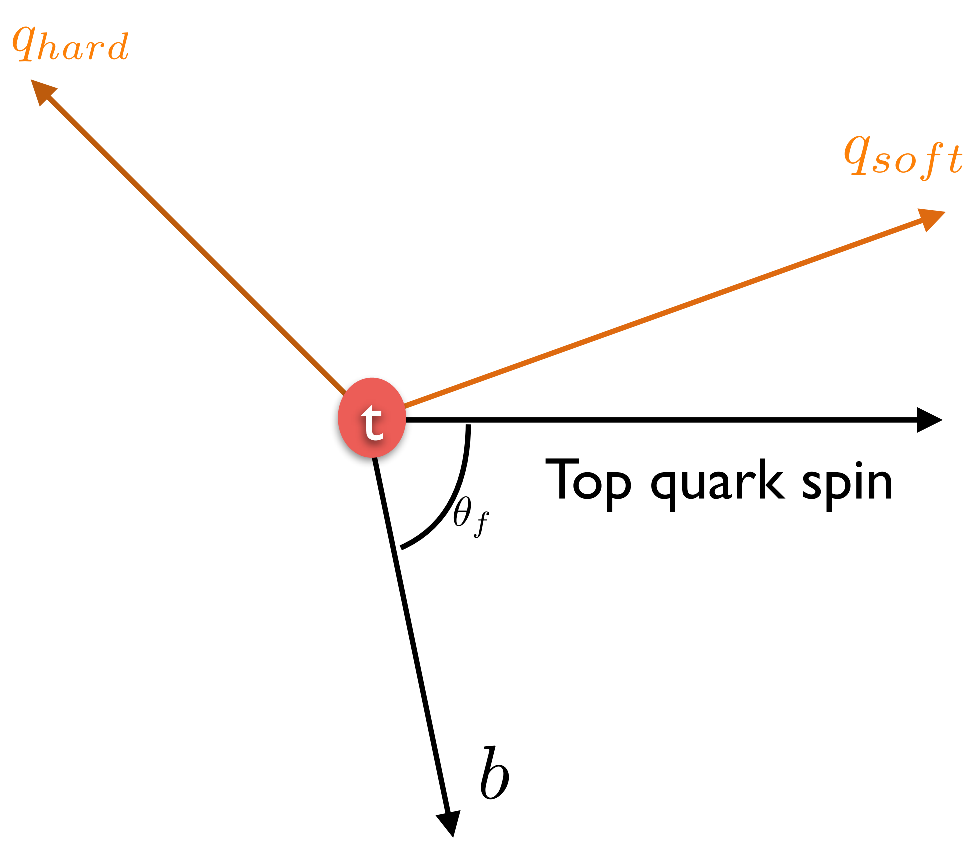
- iii) In the high-energy regime, boosted techniques can be employed to tag the hadronic top and efficiently identify the optimal hadronic direction



$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + \mathbf{1.0}\,\cos\theta_f)$$

Three reasons to study the boosted semileptonic tt final state

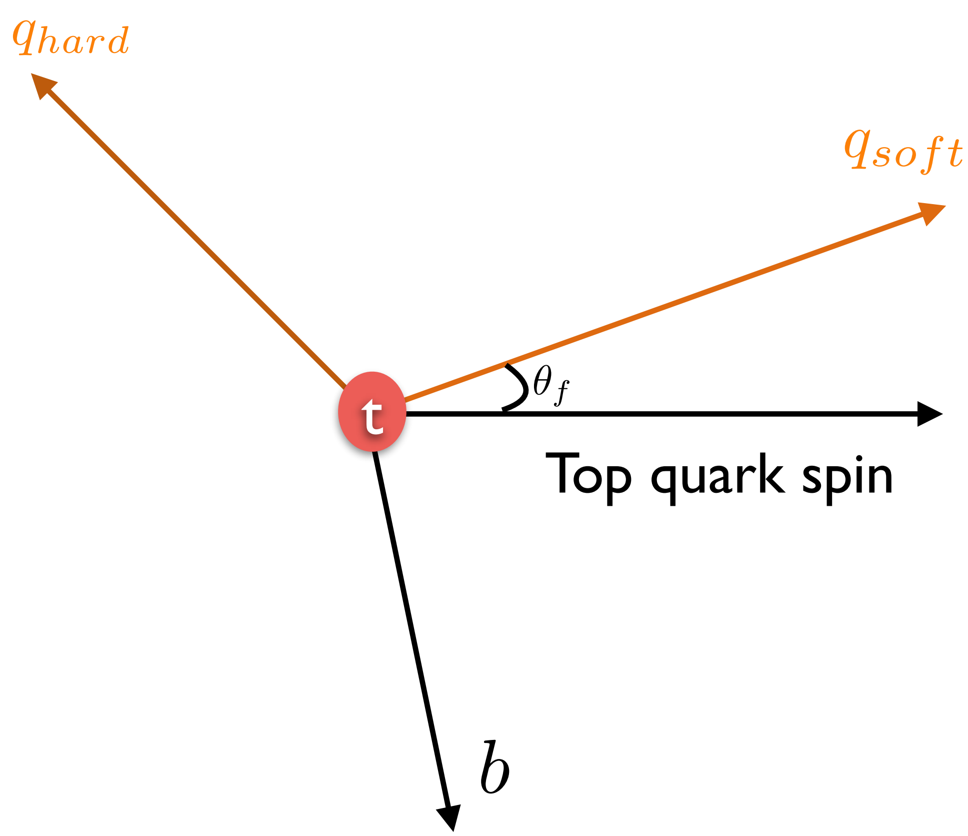
- iii) In the high-energy regime, boosted techniques can be employed to tag the hadronic top and efficiently identify the optimal hadronic direction



$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 \;\; \mathbf{-0.4} \;\; \cos\theta_f)$$

Three reasons to study the boosted semileptonic tt final state

- iii) In the high-energy regime, boosted techniques can be employed to tag the hadronic top and efficiently identify the optimal hadronic direction

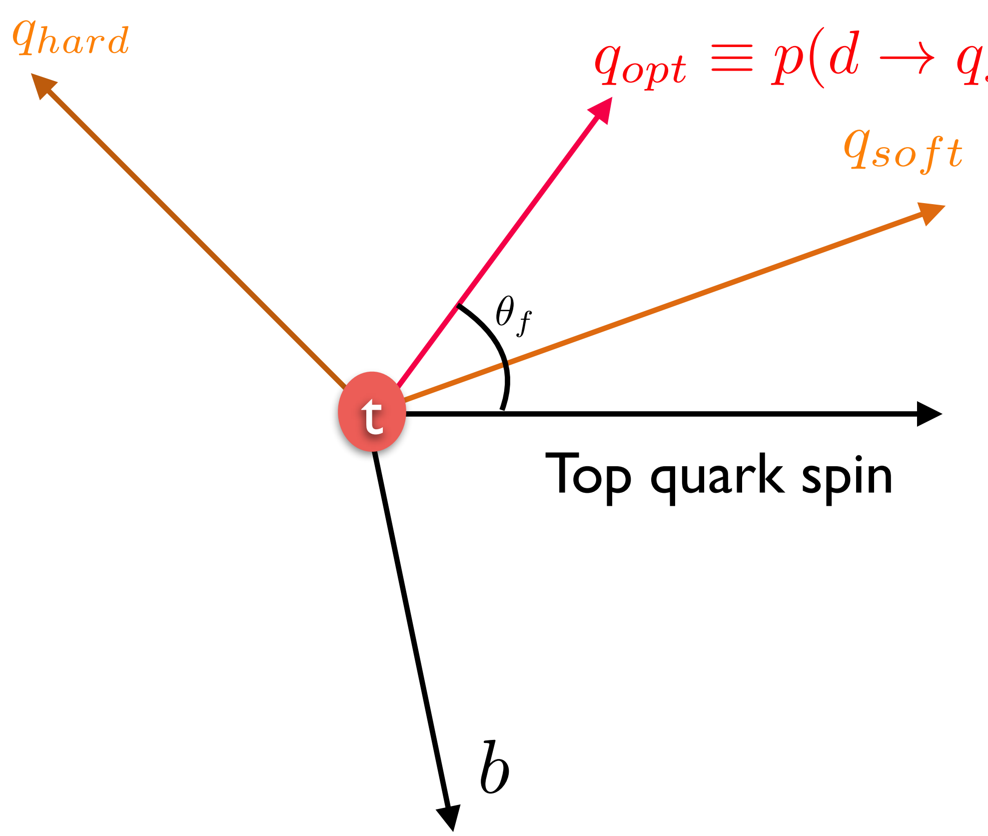


$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + \mathbf{0.5}\,\cos\theta_f)$$

Three reasons to study the boosted semileptonic tt final state

- iii) In the high-energy regime, boosted techniques can be employed to tag the hadronic top and efficiently identify the optimal hadronic direction

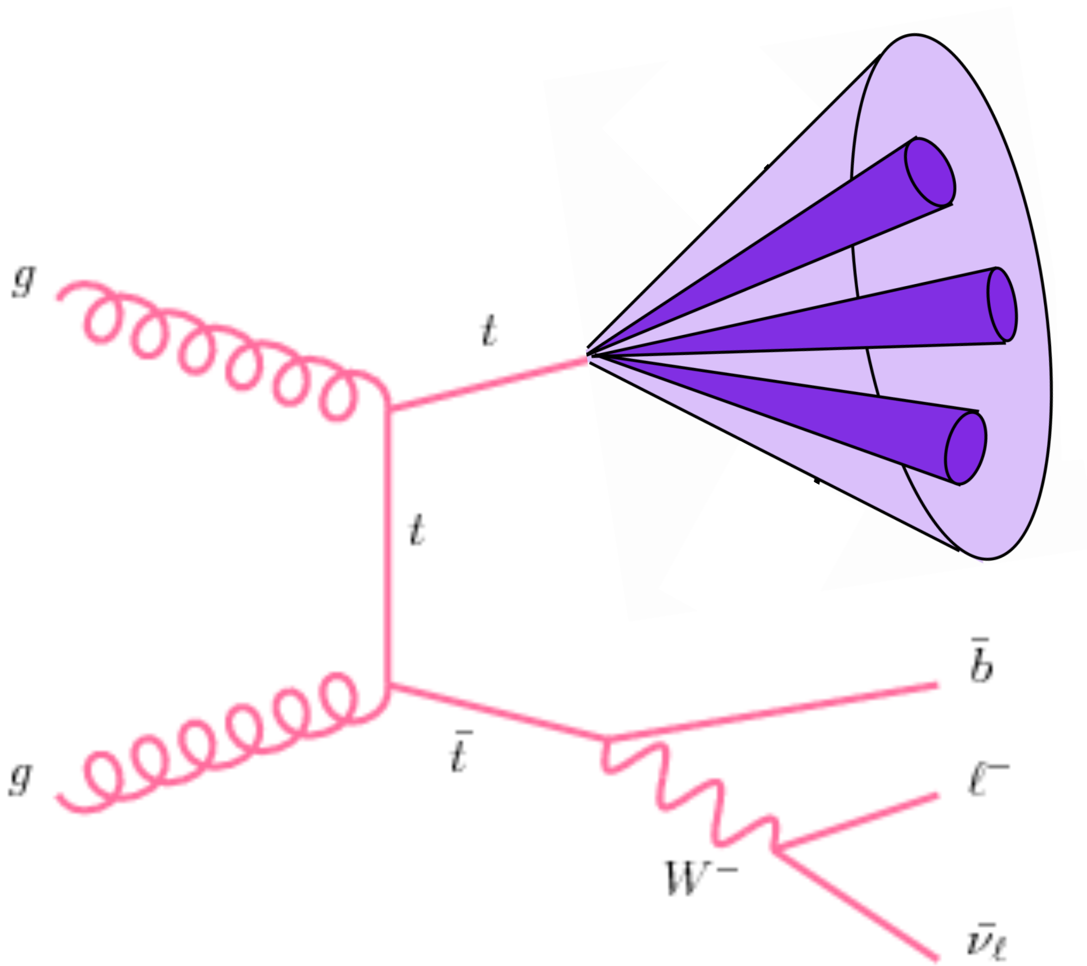
$$q_{opt} \equiv p(d \to q_{soft})\hat{q}_{soft} + p(d \to q_{hard})\hat{q}_{hard}$$



$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + \mathbf{0.64}\cos\theta_f)$$

Analysis

- Some key ingredients for the analysis:

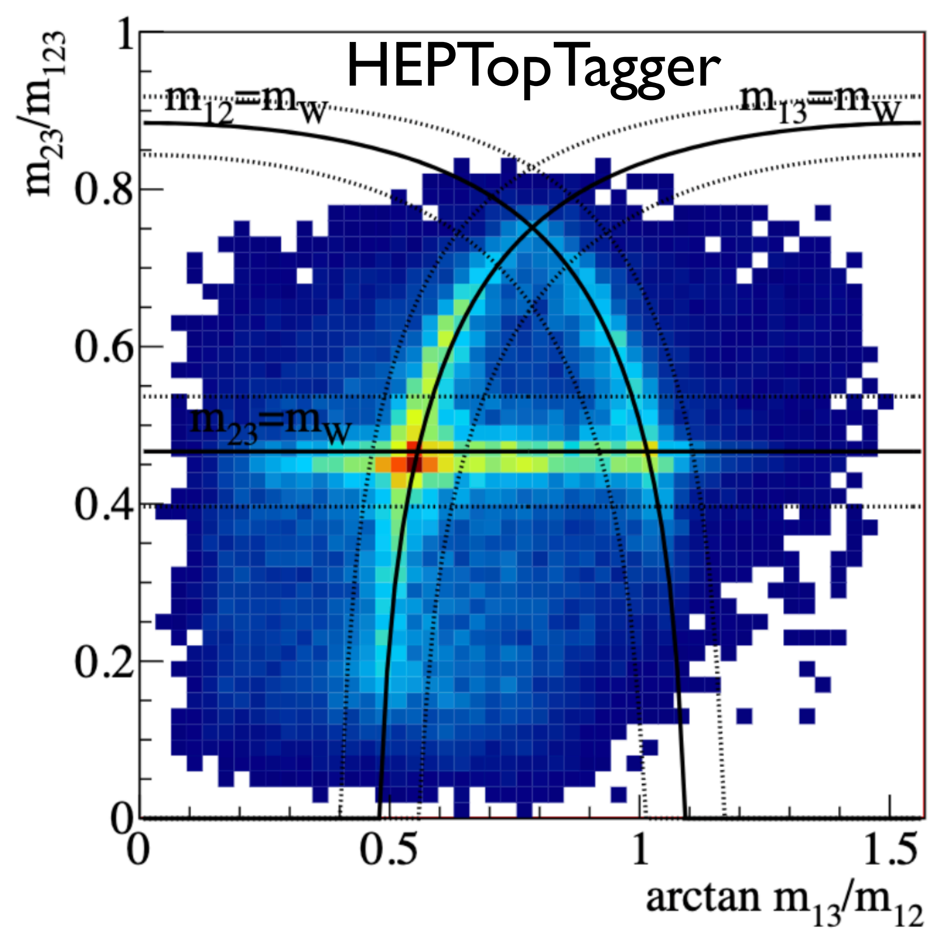


- Boosted top tagging (HEPTopTagger)

  Plehn, Spannowsky, Takeuchi, Zerwas '10

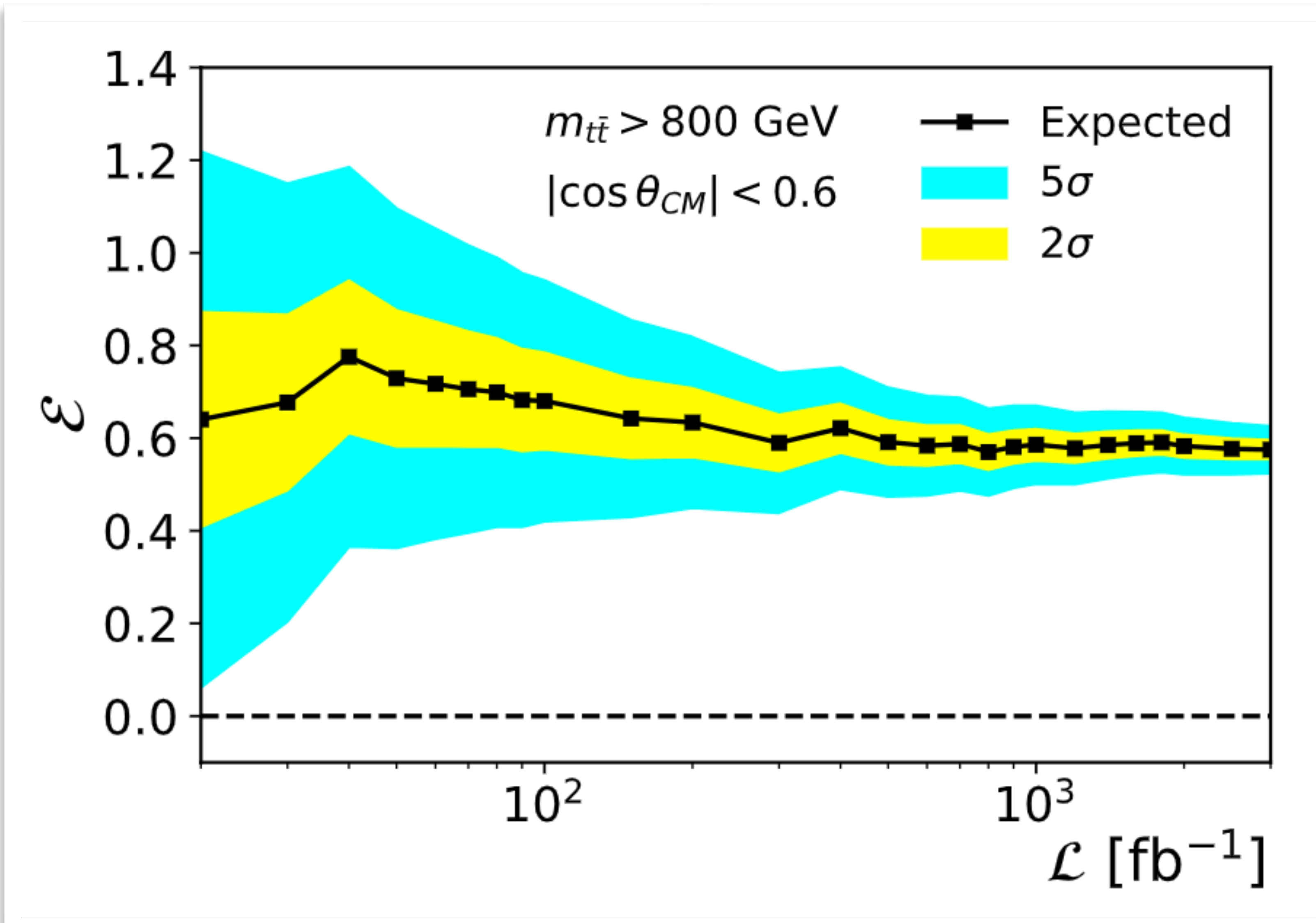
- Lorentz Boost Network: determines which of the subjects is b-tagged

- Proxy for down-quark: optimal hadronic polarimeter



LHC Projections

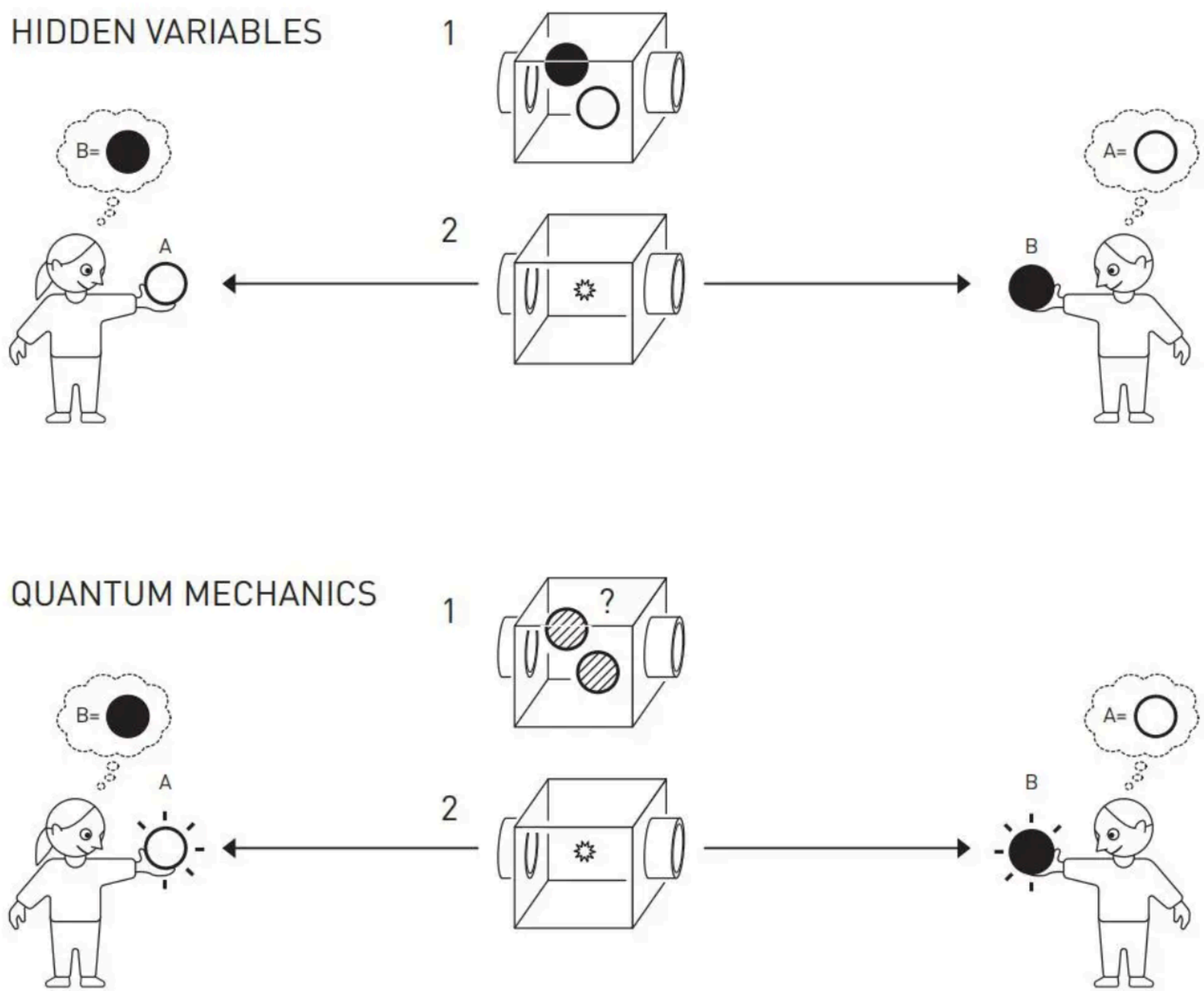
- Entanglement: $\mathcal{E} \equiv |C_{kk} + C_{rr}| - C_{nn} - 1 > 0$



Dong, DG, Kong, Navarro '23

➡ Current dataset can probe entanglement at 5-sigma level!

Bell's Inequalities



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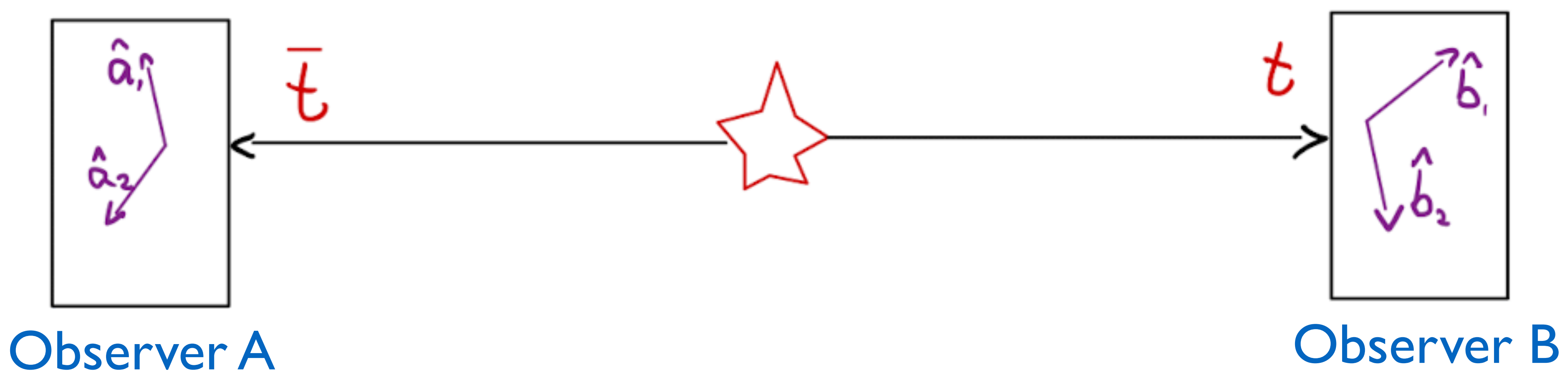
Bell's Inequalities

- Violation of Bell-type inequalities demonstrates that there is no hidden variable theory capable of encoding the generated entanglement. QM cannot be explained by classical laws
- Bell's inequality can be distilled in a simpler form: CHSH inequality

Clauser, Horne, Shimony, Holt '69

$$|\langle A_1 B_1\rangle + \langle A_2 B_1\rangle + \langle A_1 B_2\rangle - \langle A_2 B_2\rangle| \leq 2$$

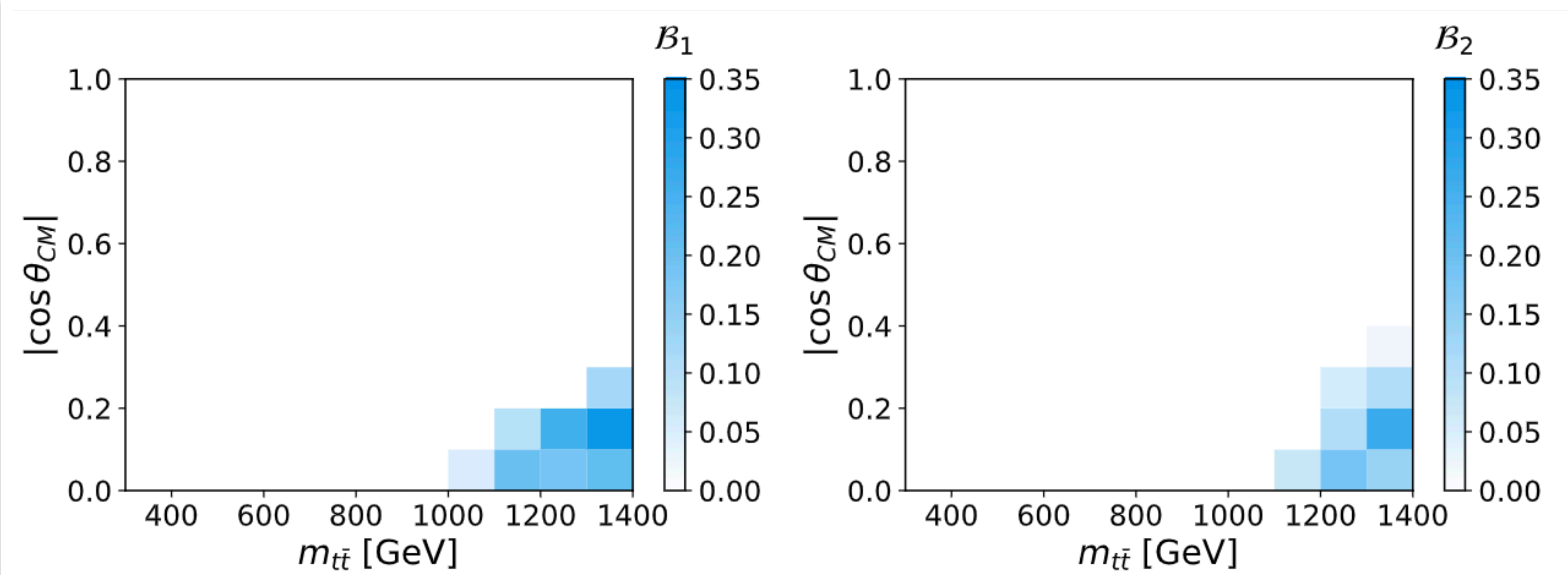


Bell's Inequalities

- Bell/CHSH inequalities:

$$\mathcal{B}_1 \equiv |C_{rr} - C_{nn}| - \sqrt{2} > 0$$
$$\mathcal{B}_2 \equiv |C_{kk} + C_{rr}| - \sqrt{2} > 0,$$

Afik, Nova '20
Severi, Boschi, Maltoni, Sioli '21
Saavedra, Casas '22



Dong, DG, Kong, Navarro '23

→ Bell/CHSH violation studies well match **boosted** top pair searches

LHC Projections

- Bell/CHSH inequalities: $\mathcal{B}_1 \equiv |C_{rr} - C_{nn}| - \sqrt{2} > 0$
  $\mathcal{B}_2 \equiv |C_{kk} + C_{rr}| - \sqrt{2} > 0,$

Afik, Nova '20
Severi, Boschi, Maltoni, Sioli '21
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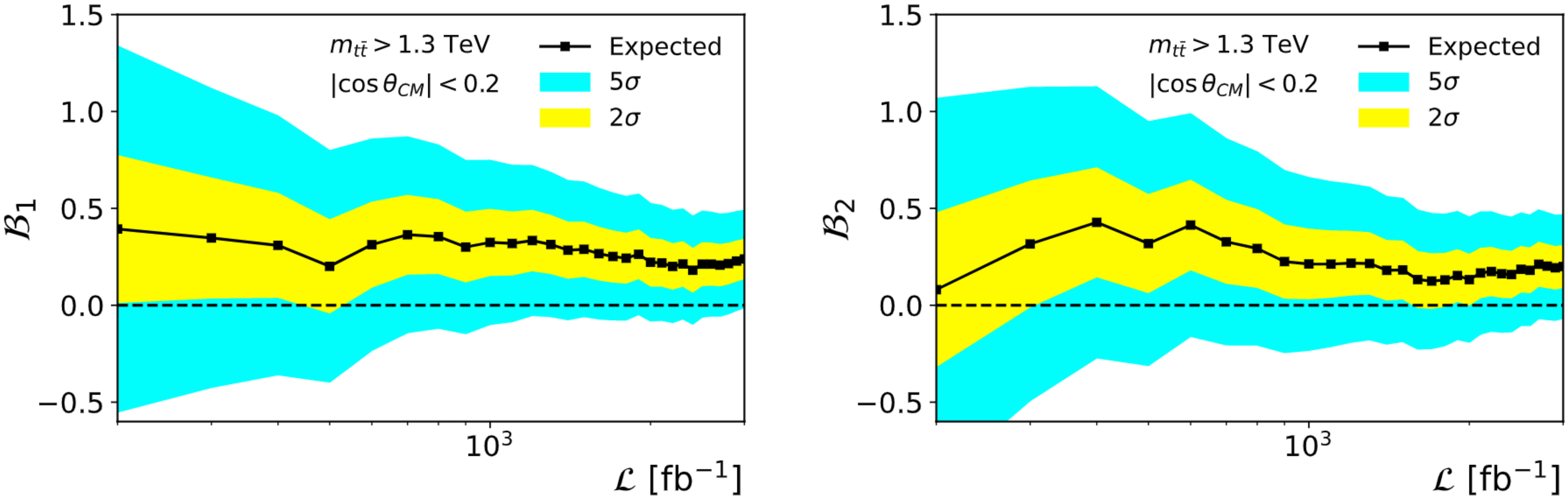


Dong, DG, Kong, Navarro '23

We are just at the beginning

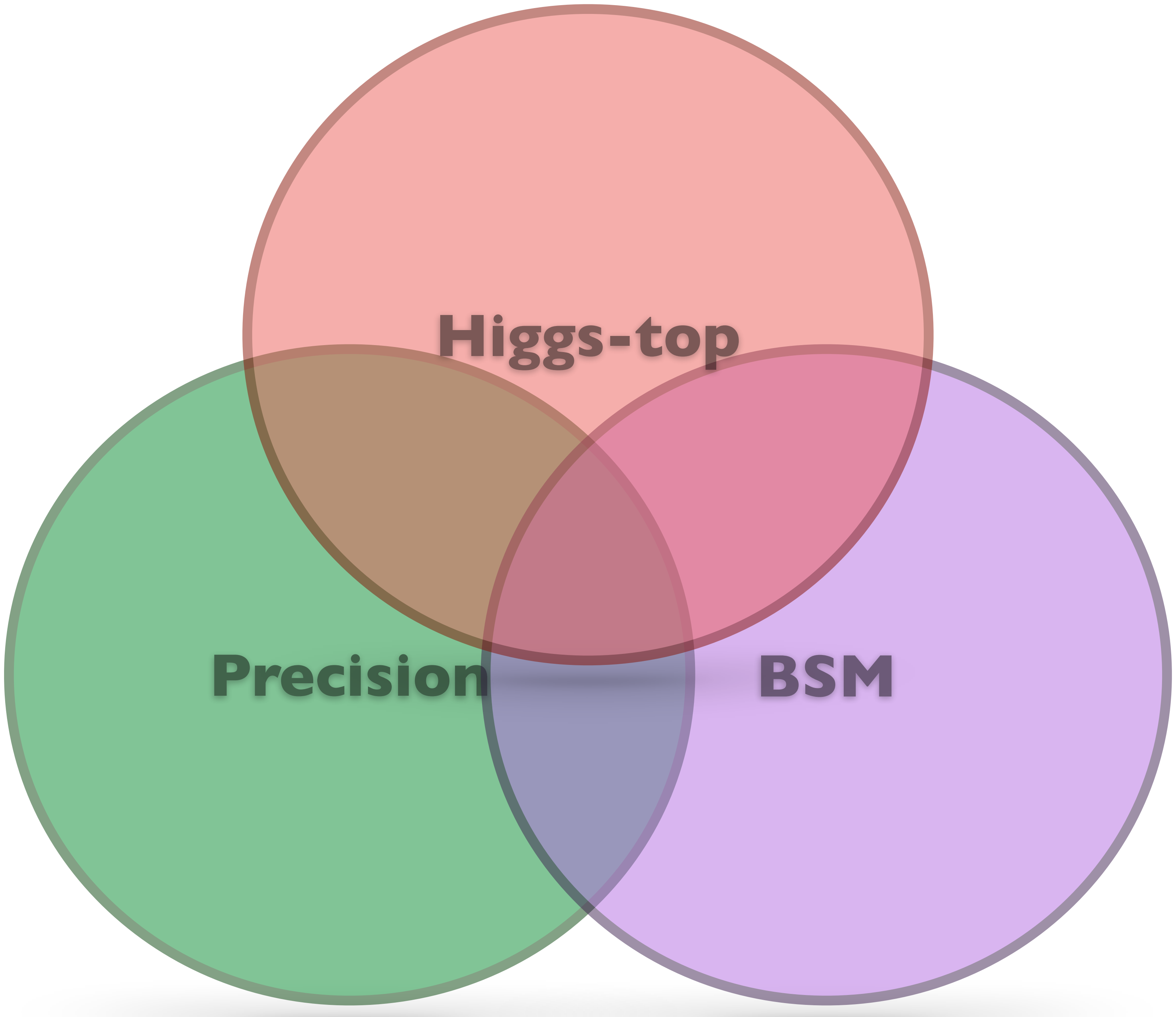
Observation of quantum entanglement in top-quark pair production using pp collisions of $\sqrt{s} = 13$ TeV with the ATLAS detector

28th September 2023

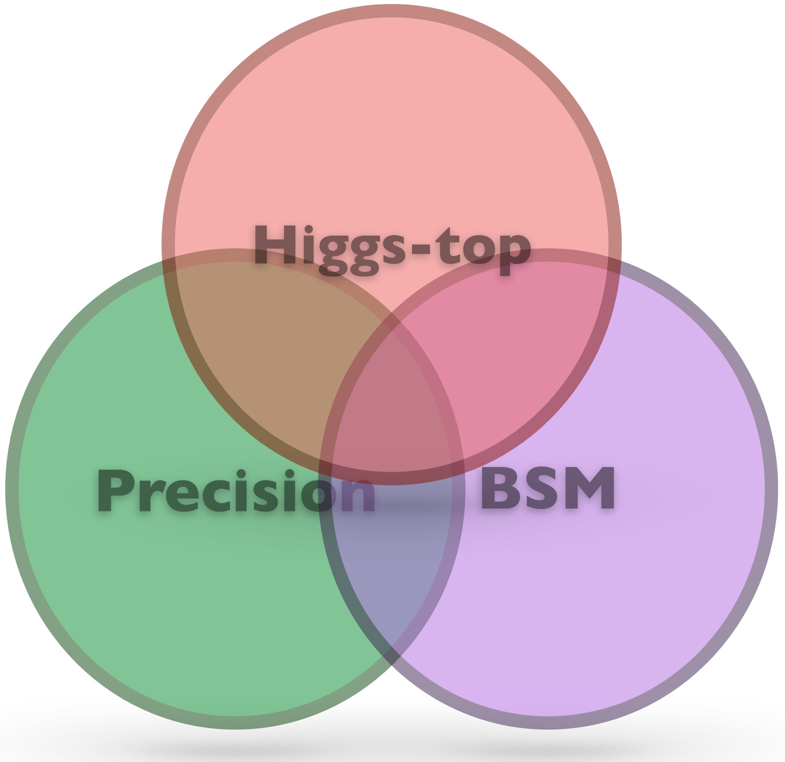
The ATLAS Collaboration

We report the highest-energy observation of entanglement so far in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision data set with a centre-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 140 fb^{-1}. Spin entanglement is detected from the measurement of a single observable D, inferred by the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured on a narrow interval around the top-quark–antitop-quark production threshold, where the entanglement detection is expected to be significant. The entanglement observable is measured in a fiducial phase-space with stable particles. The entanglement witness is measured to be $D = -0.547 \pm 0.002$ (stat.) $\pm$ 0.021 (syst.) for $340 < m_{t\bar{t}} < 380$ GeV. The large spread in predictions from several mainstream event generators indicates that modelling this property is challenging. The predictions depend in particular on the parton-shower algorithm used. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes the first observation of entanglement in a pair of quarks, and the observation of entanglement at the highest energy to date.

Summary



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. Multivariate analysis problem. Top quark polarization observables uplift analysis from a raw rate to a polarization study
  - ➡ LHC shows sensitivity when discriminating between SMEFT and HEFT CPV in top-Higgs sector
- Well-motivated 2HDM leads to rich phase transition, favoring SFOEWPT below TeV scale

➡ H, A→ tt: smoking gun signature for SFOEWPT at HL-LHC with gluon fusion and Higgstrahlung production

- LHC provides a unique opportunity to study entanglement and violation of Bell's inequalities at high energy scales

➡ We are just at the beginning. ATLAS announced last month the measurement of entanglement at LHC
➡ Bell/CHSH violation may be probed at 4-5 sigma level at the HL-LHC