Deciphering the Nature of the Higgs boson

CP and beyond

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HEP seminar, Northwestern University, 1/22/2024

The Higgs discovery

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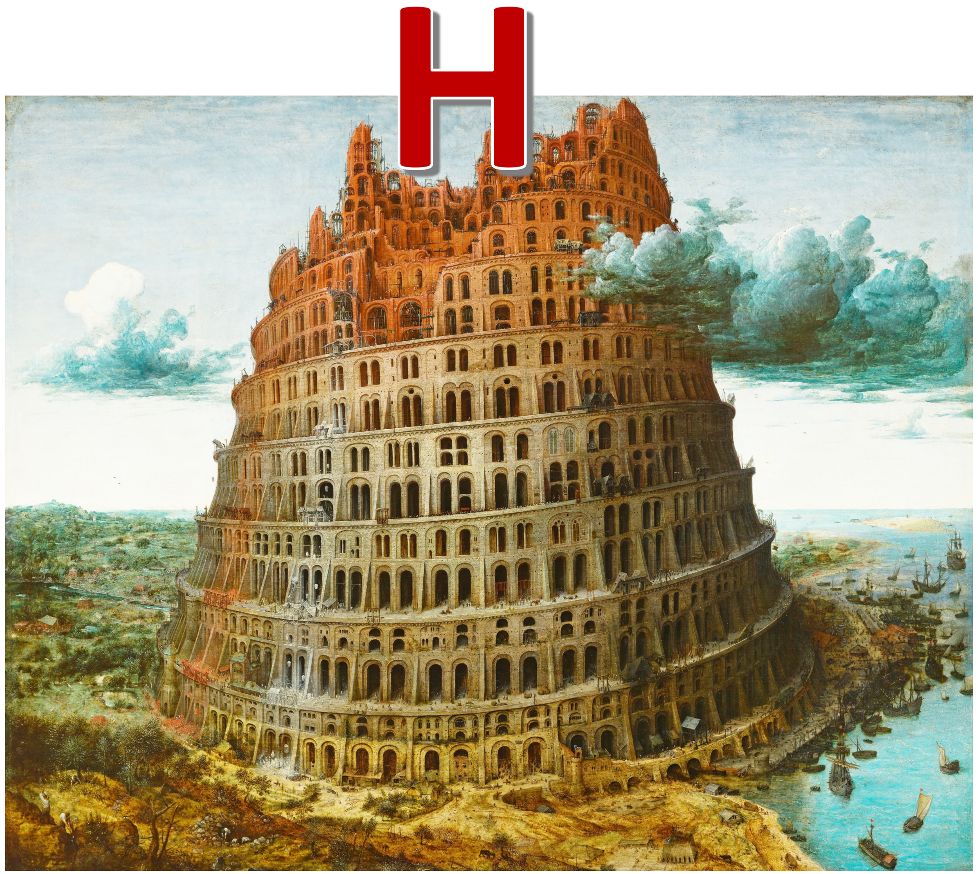

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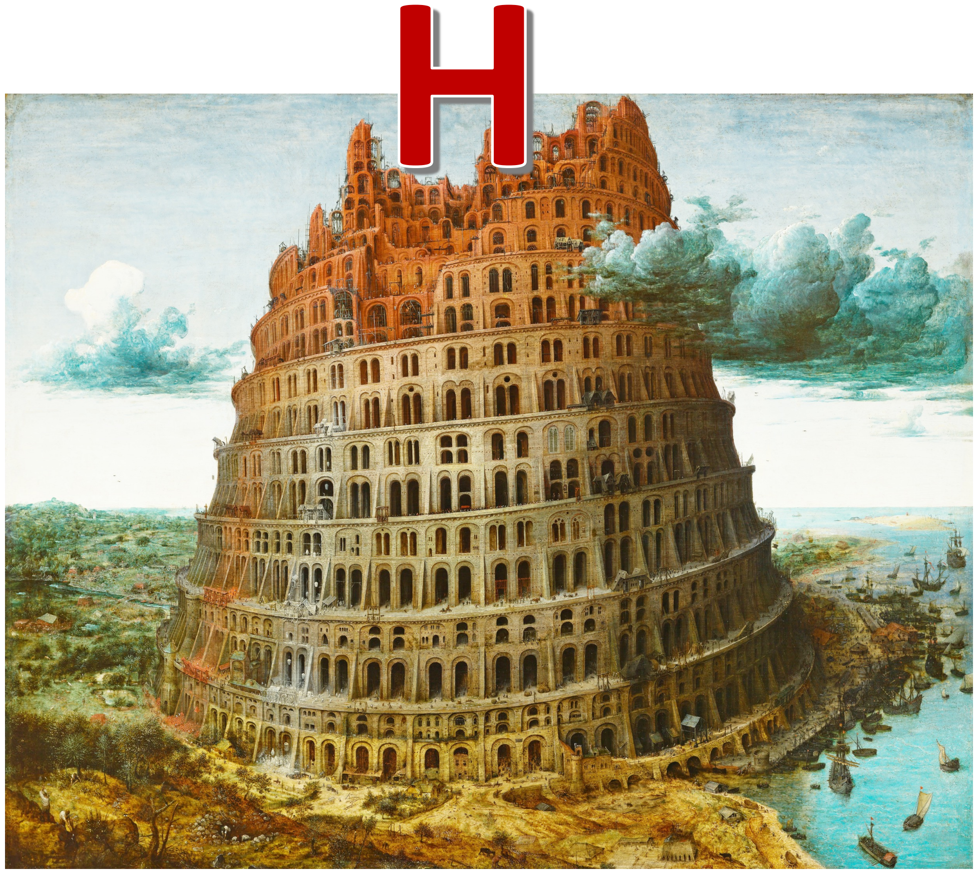

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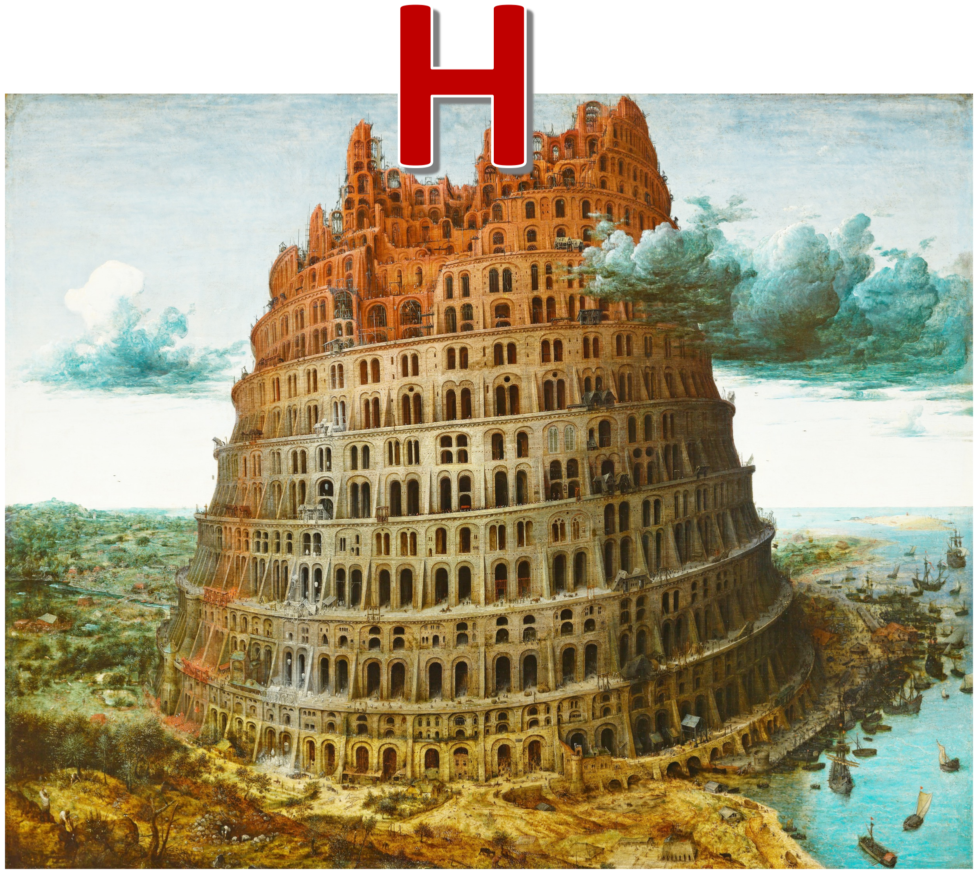

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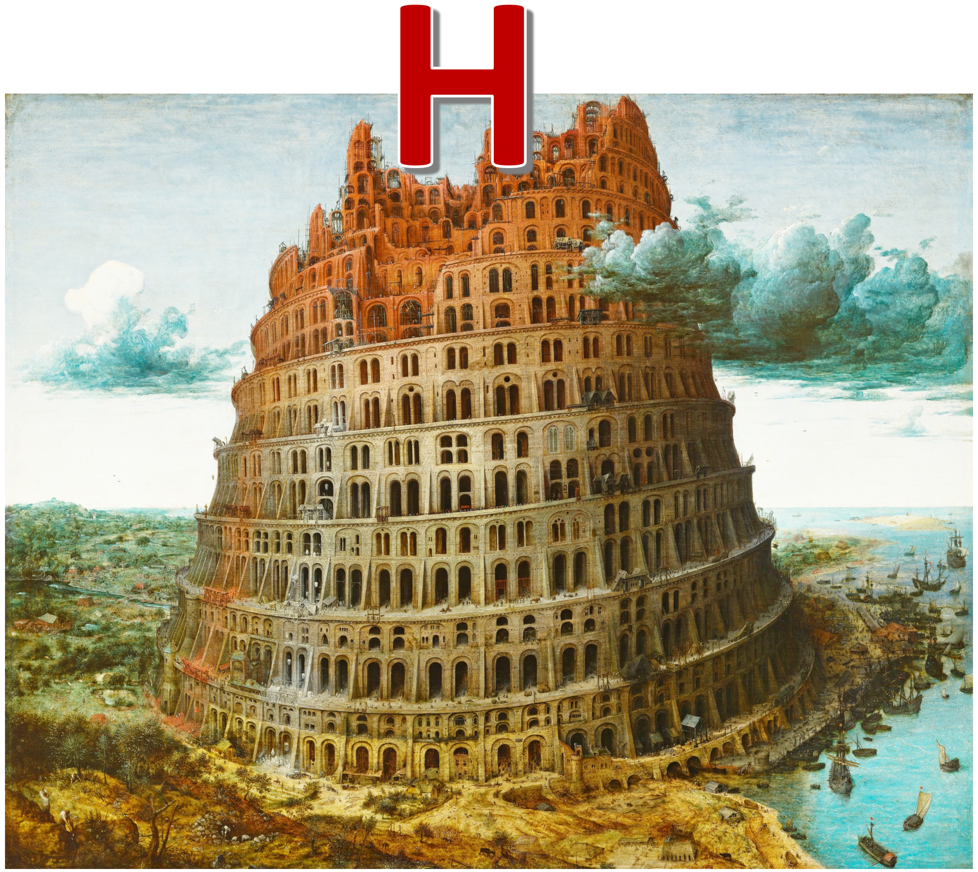

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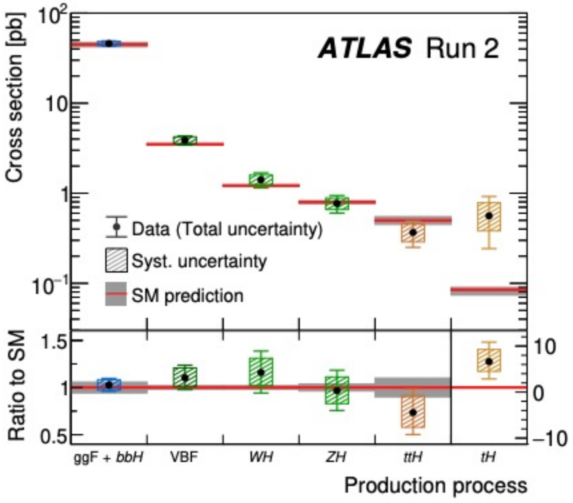
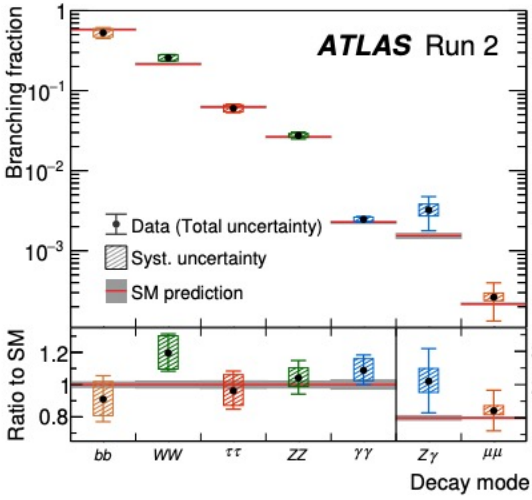
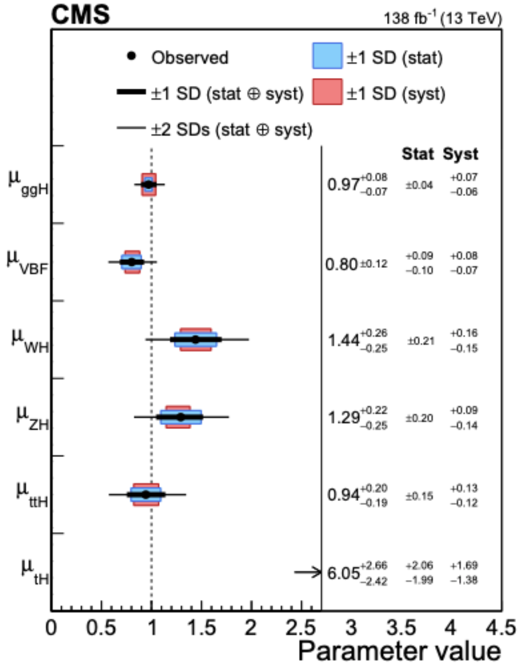
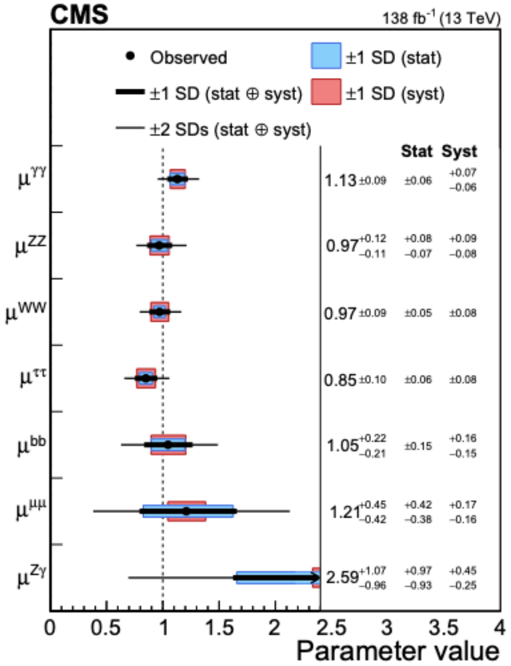
The Higgs 10 years later

[ATLAS 2207.00092, CMS 2207.00043]









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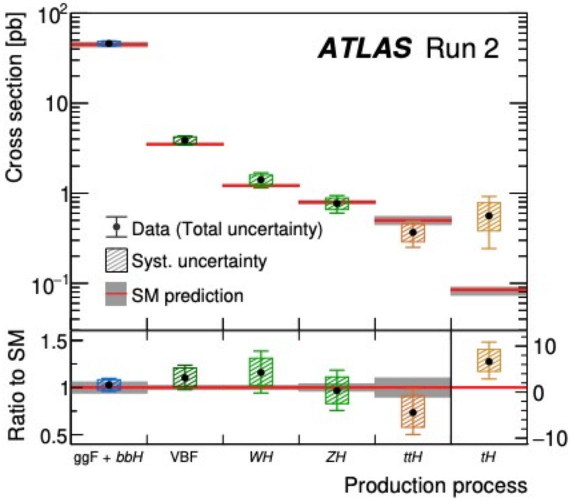

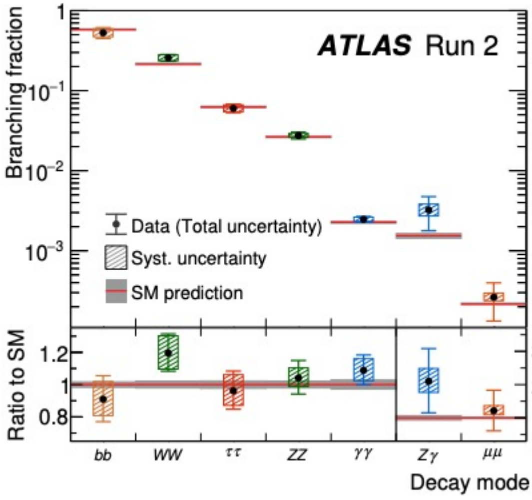

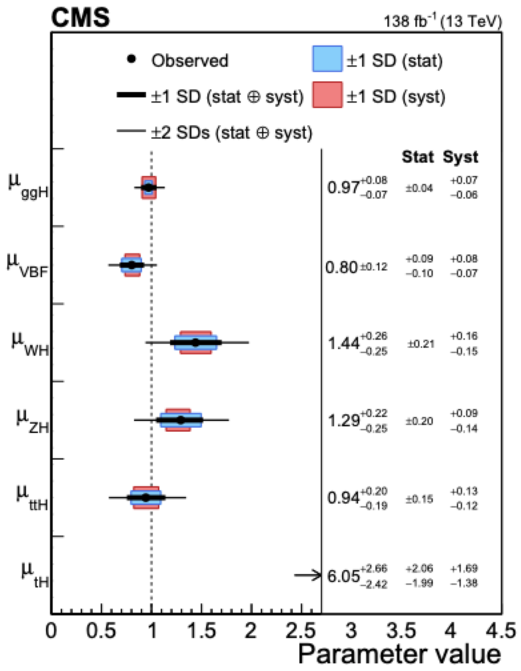

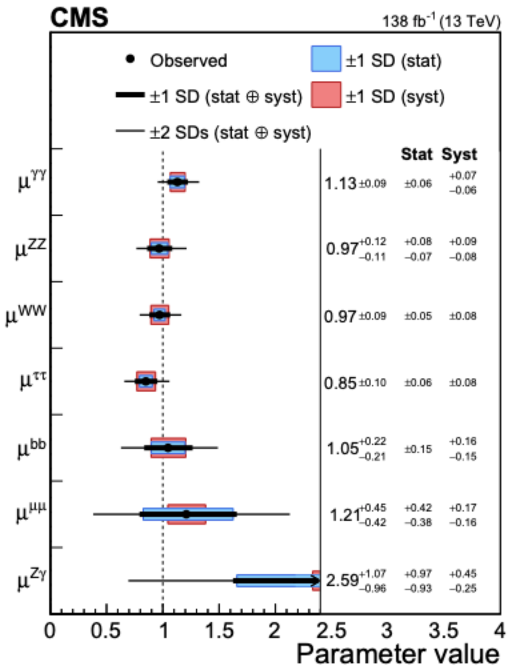

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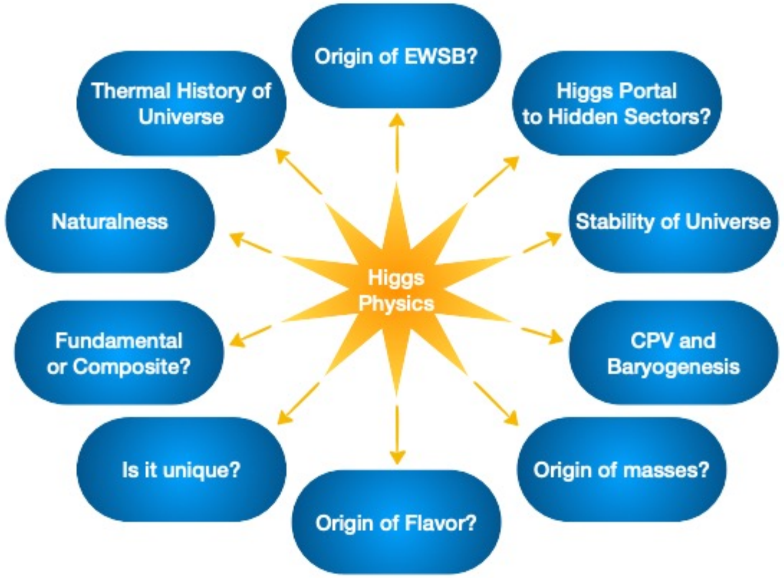

[Snowmass 2209.07510]

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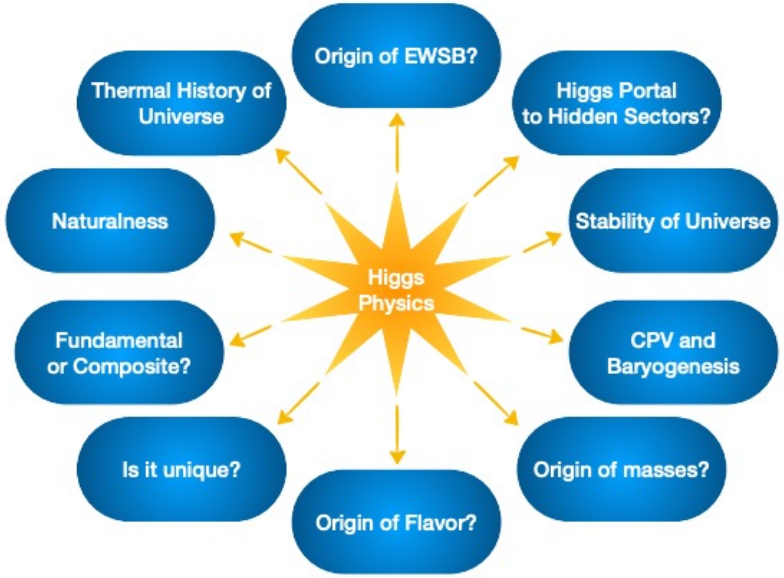


[Snowmass 2209.07510]

⇒ Strong motivation for on-going and future Higgs precision programs.

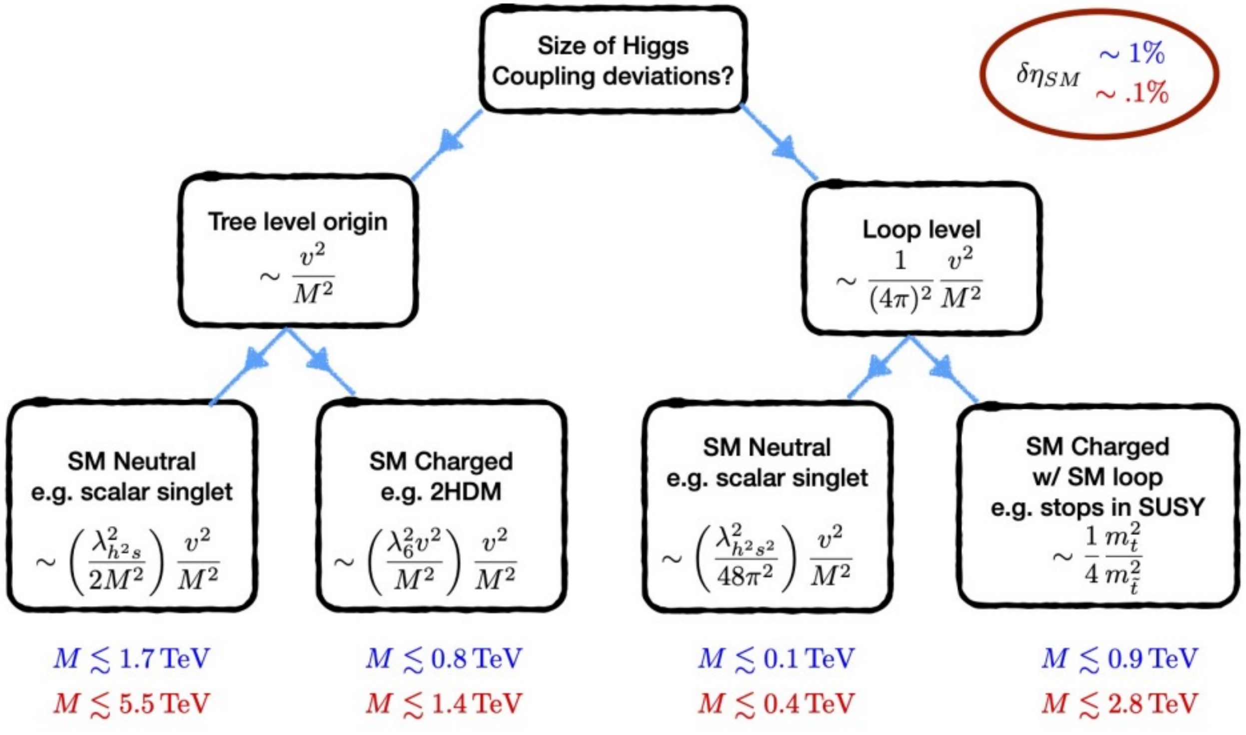
What can we learn from existing measurements?

What can we learn from Higgs precision measurements?

- Higgs precision measurements put stringent constraints on many BSM scenarios.

Simplified scaling analysis:

- 1% precision level can constrain BSM particles with mass from 100 GeV to several TeV (within reach of the LHC or future colliders).



Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

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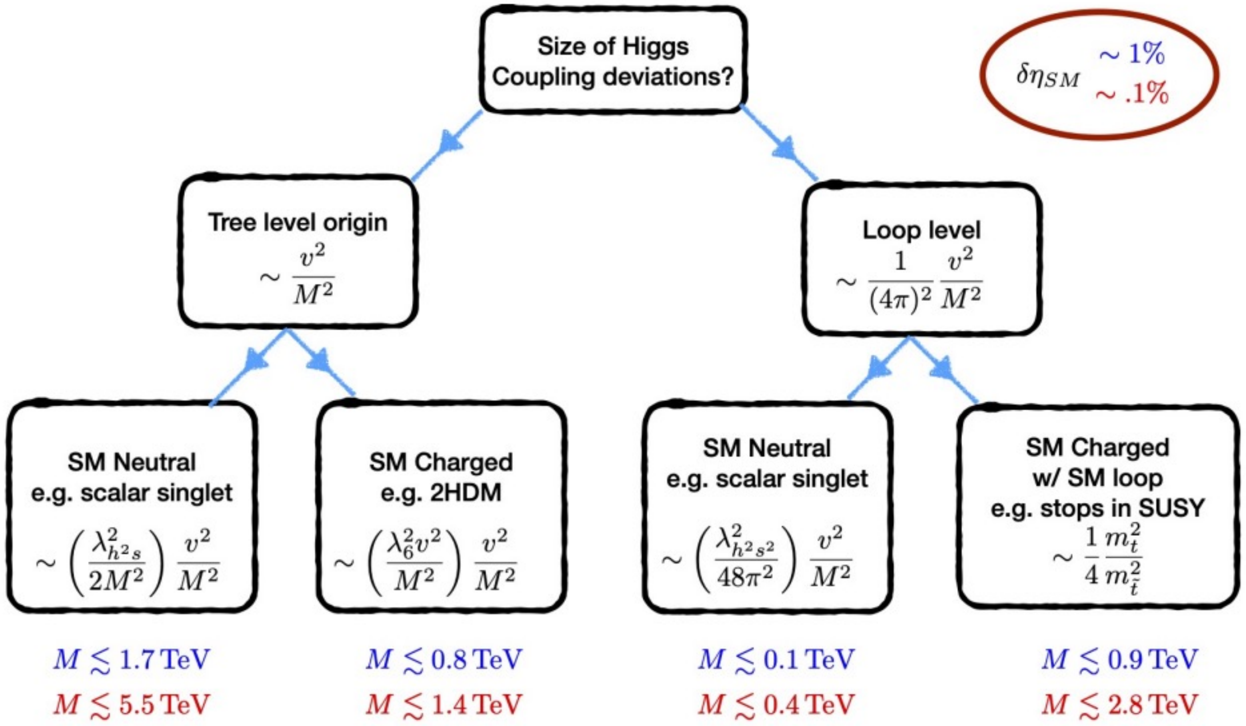

Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

[Snowmass 2209.07510]

We also shouldn't forget about the interplay with direct searches!

Interplay with direct searches

- Important interplay between Higgs precision measurements and direct searches for BSM particles.
- Cannot be captured in EFT framework
  → use 2HDM here as a benchmark model.
- Searches for BSM scalars ϕ:
  a) CMS: $pp \to \phi \to h_{125}h_{125}$
  b) CMS: $pp \to \phi_1 \to h_{125}\phi_2 \to bb\tau\tau$
  c) CMS: $pp \to \phi \to Zh_{125}$
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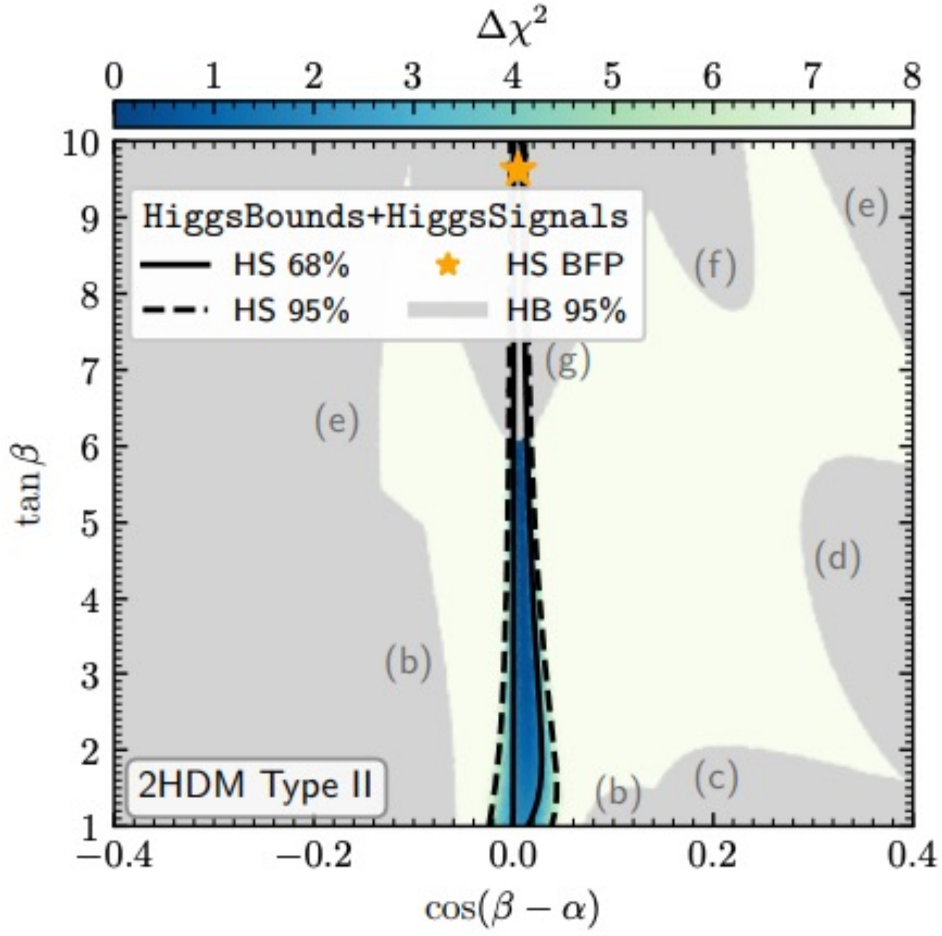
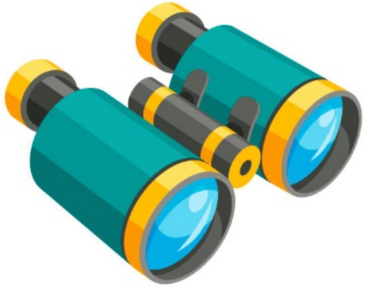


$$m_H = m_A = m_{H^\pm} = \sqrt{m_{12}^2/(\sin\beta\cos\beta)} = 800\ \text{GeV}$$

[HB et al. 2210.09332]



What is still left to explore?

Have we found the SM Higgs?

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We should test all these predictions!

What do we know about the Higgs potential?

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    - the location of the EW minimum: $v = 246$ GeV,
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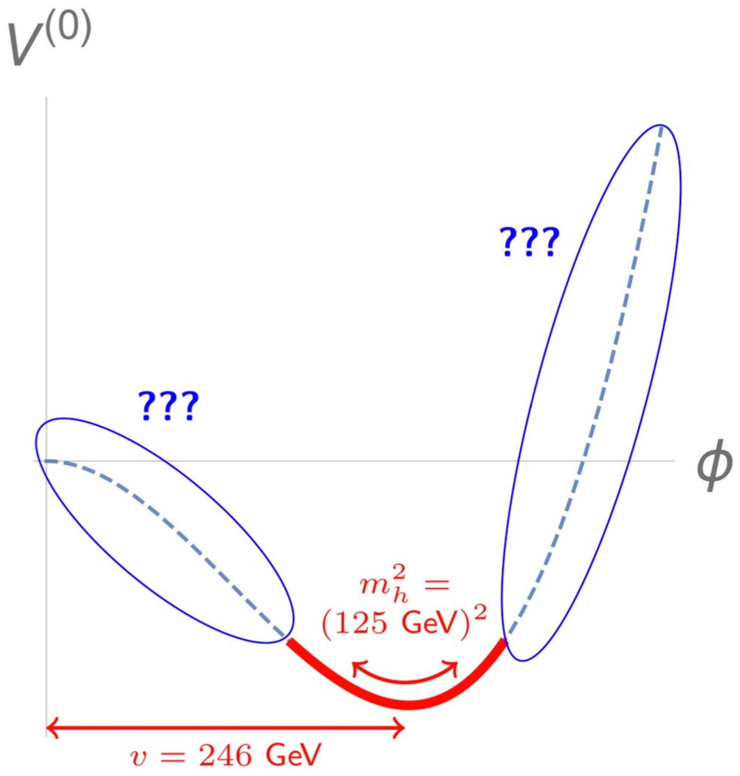

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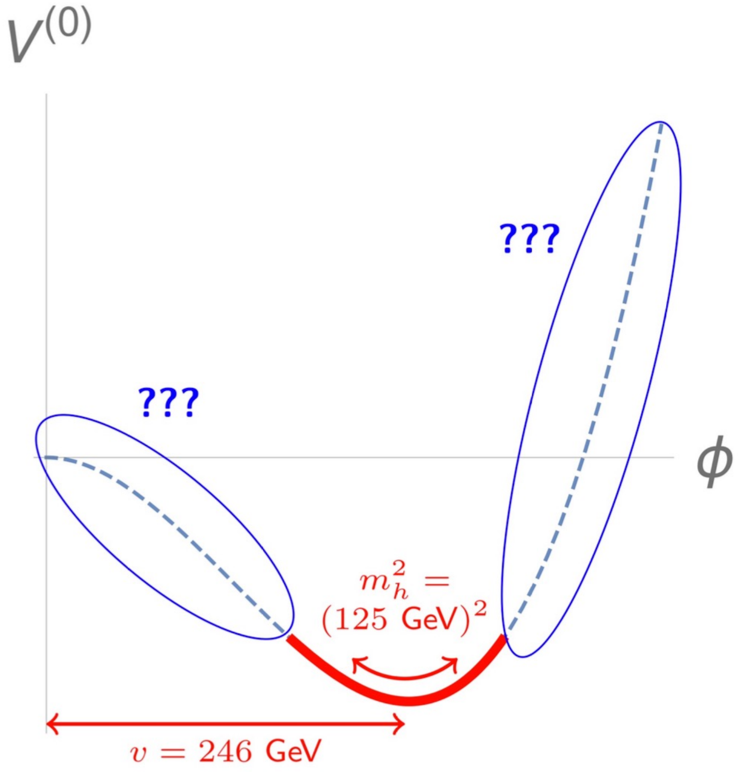

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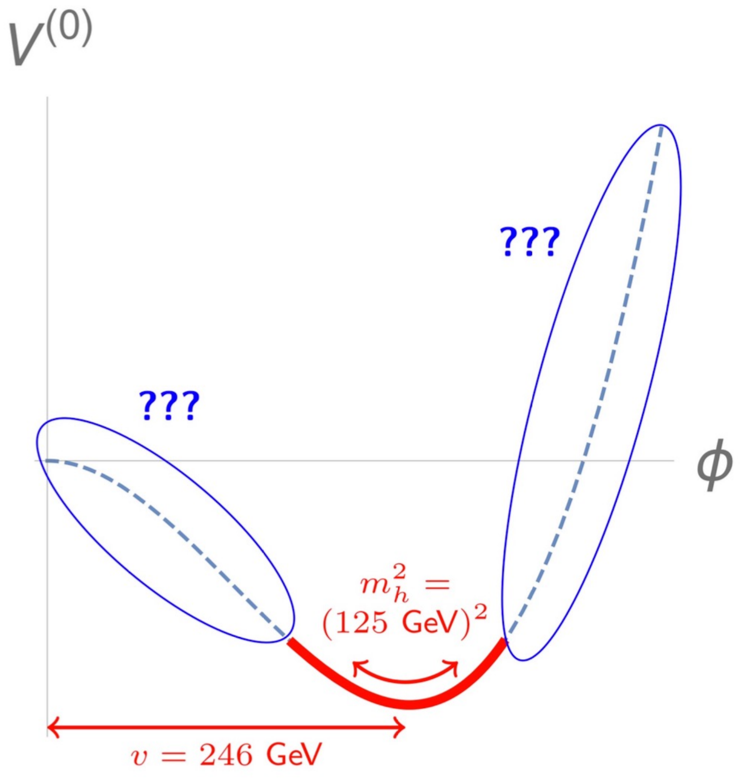

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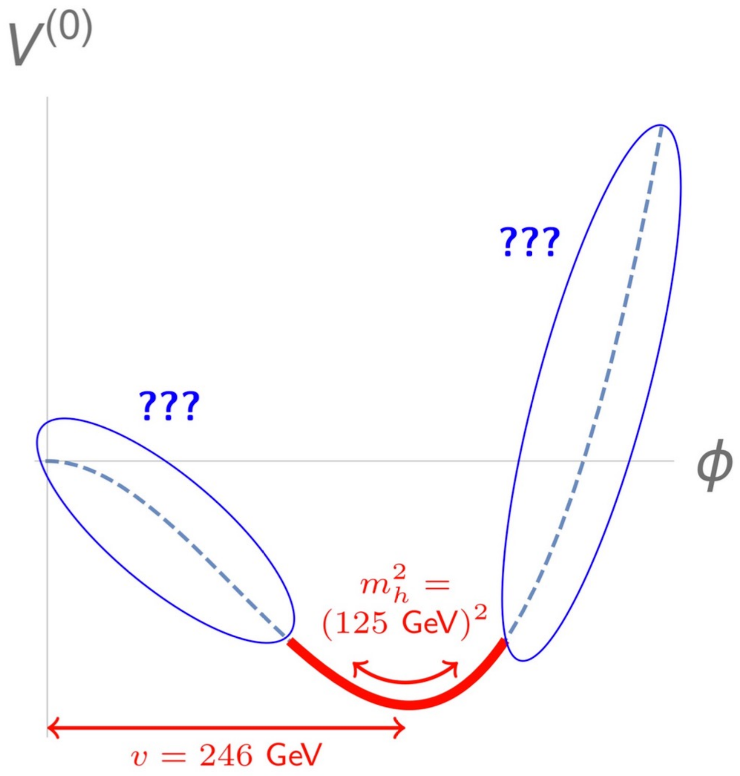
➡ Is the Higgs trilinear also a discovery tool?



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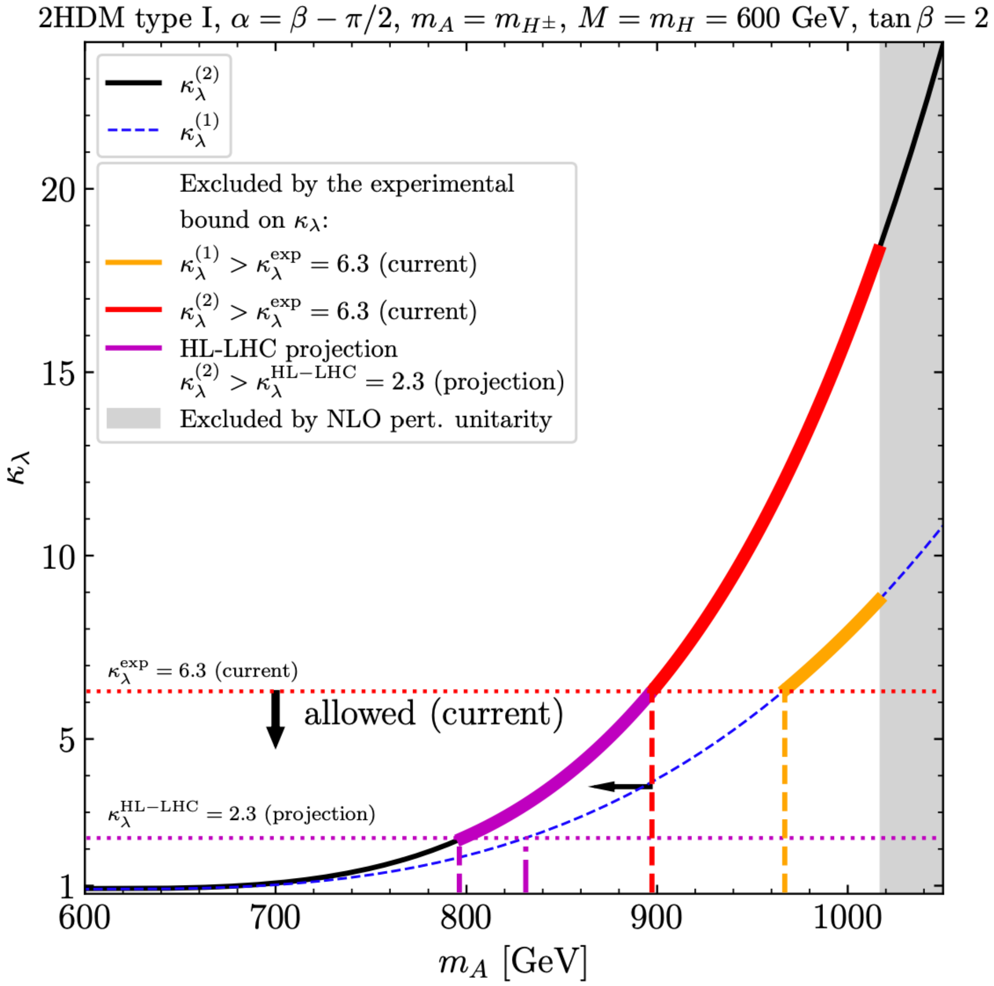
$-0.4 < \kappa_\lambda < 6.3$ at 95% CL [ATLAS, 2211.01216]



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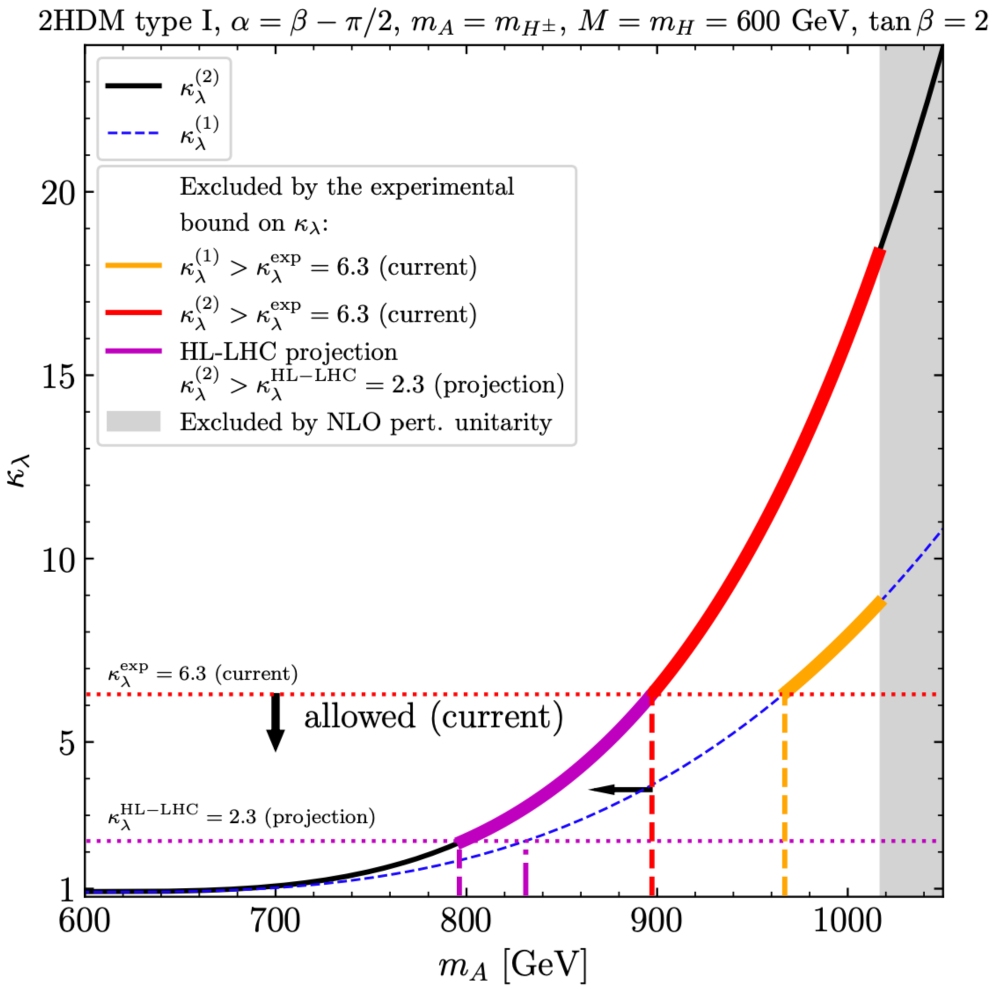
Already current experimental limits on κ_λ probe so-far unconstrained BSM parameter space!



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Consider toy model:

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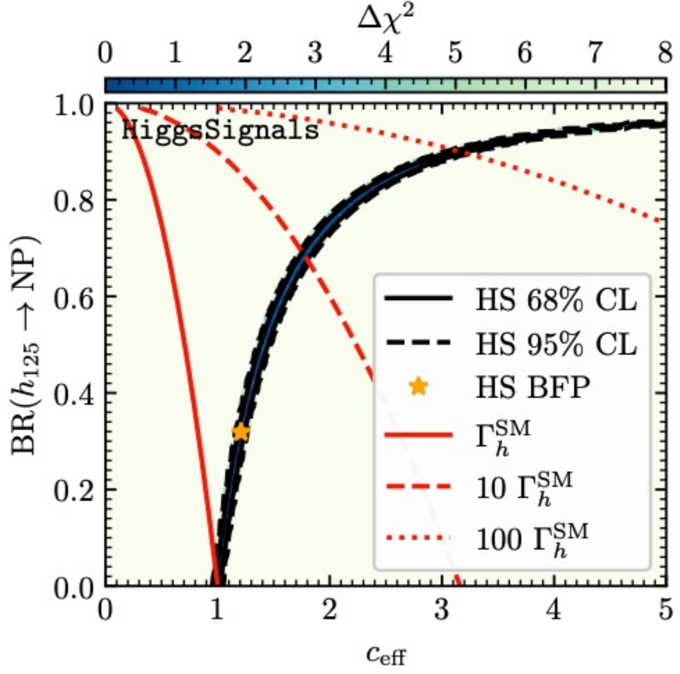

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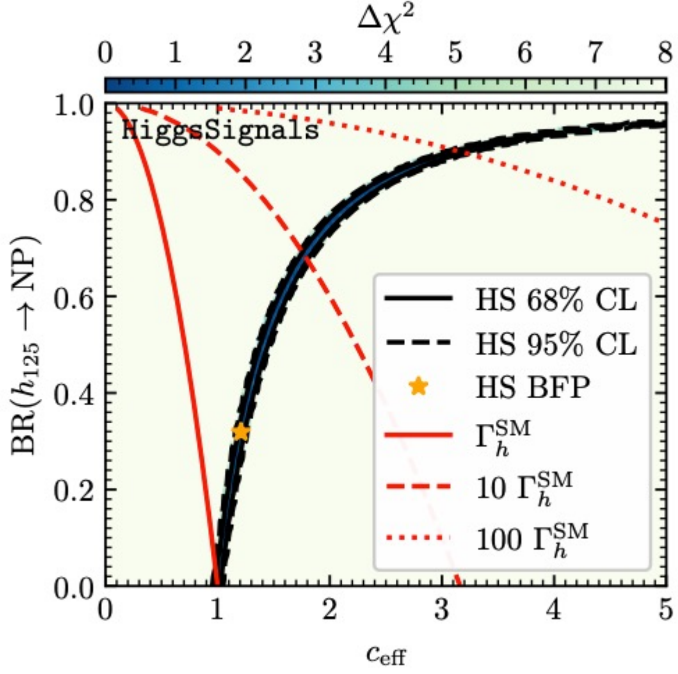

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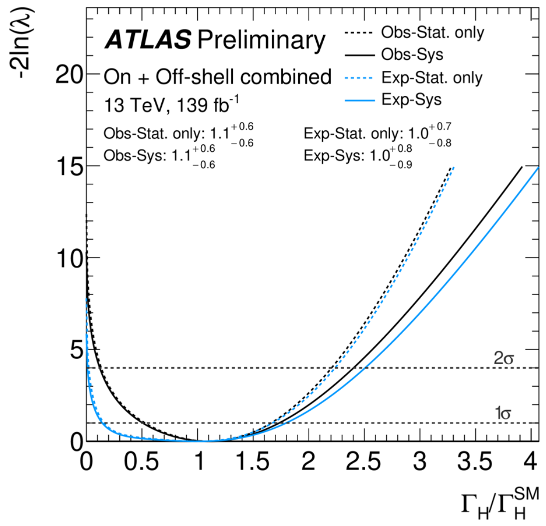
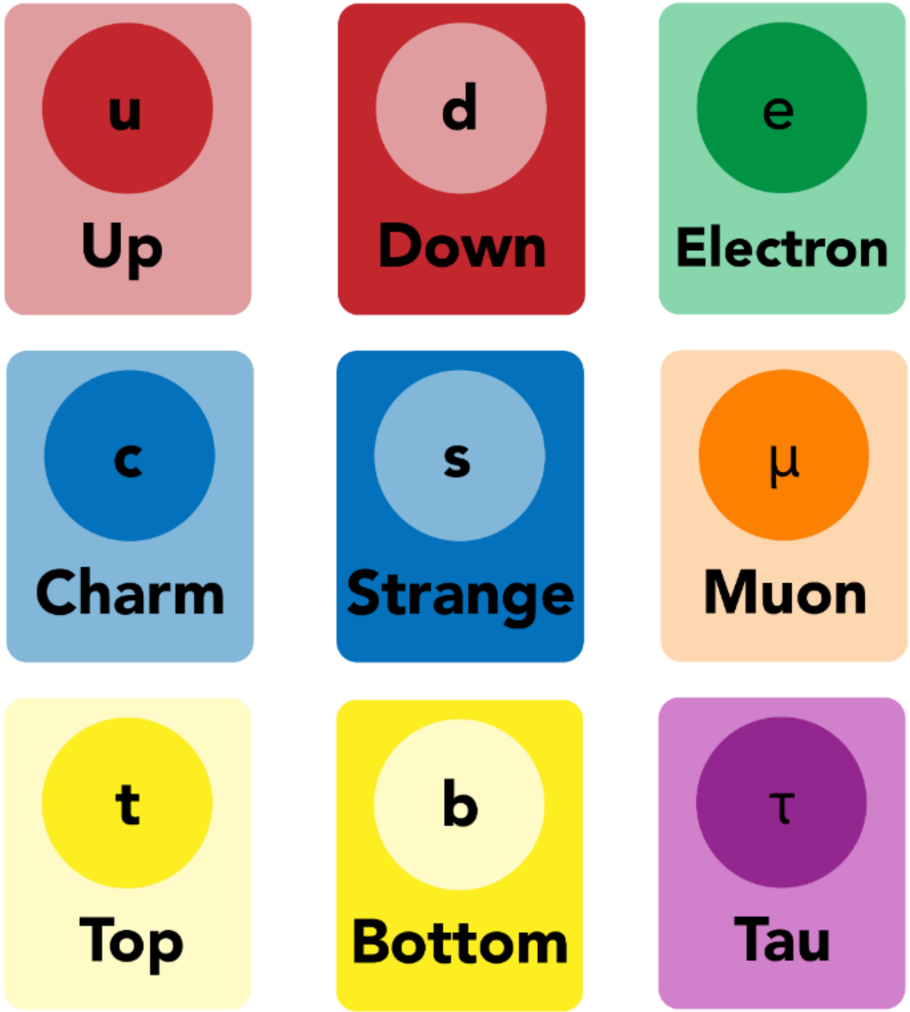
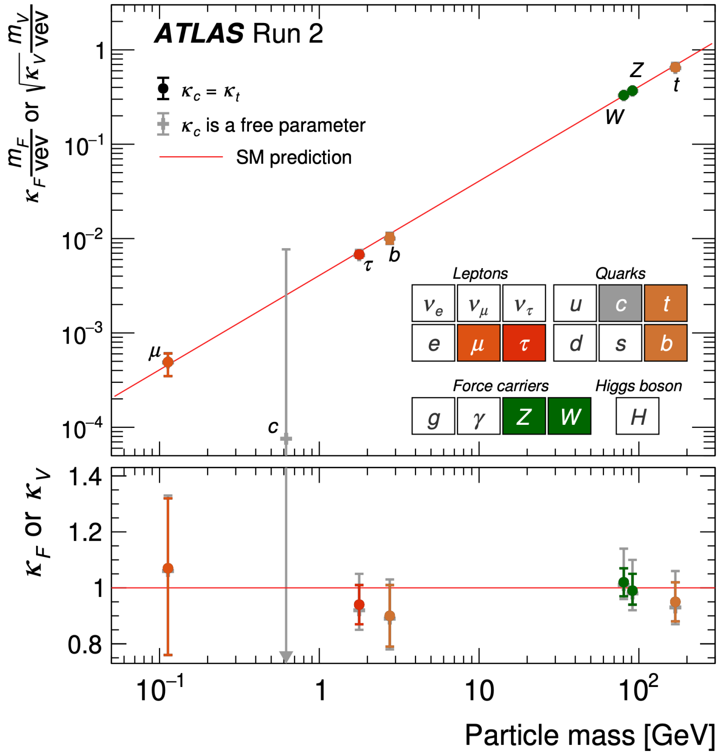


[ATLAS-CONF-2022-068]

- $\mathcal{O}(\mathrm{MeV})$ constraints on Γ_H.
- But depends on assumption that there is no other BSM contribution to $H \to ZZ$ production.

Light Yukawa couplings





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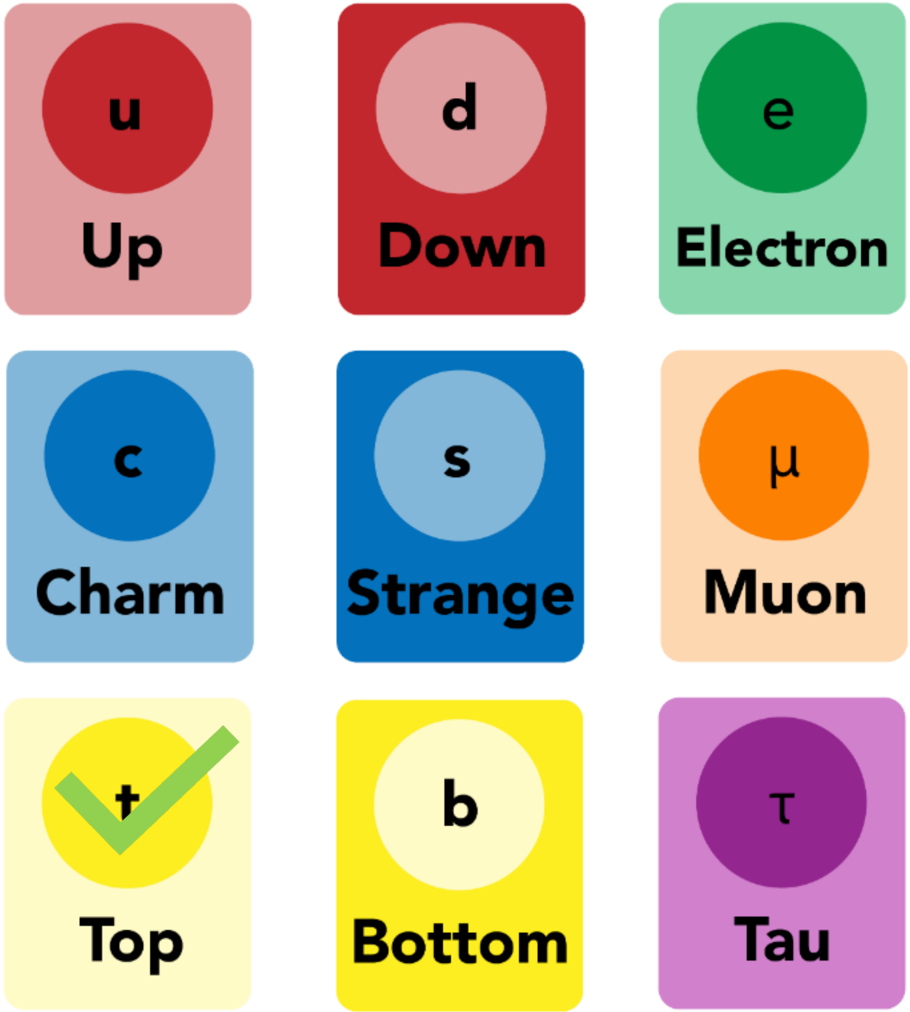

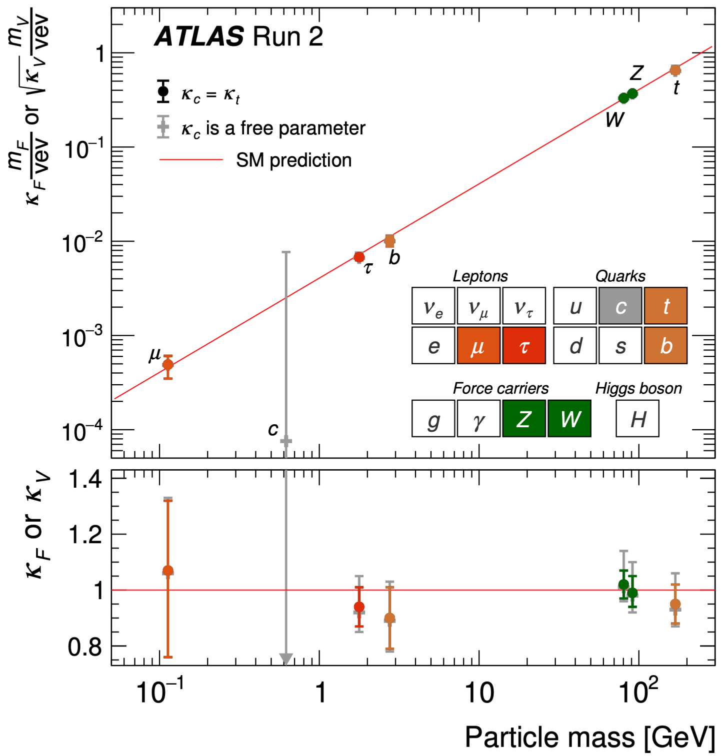

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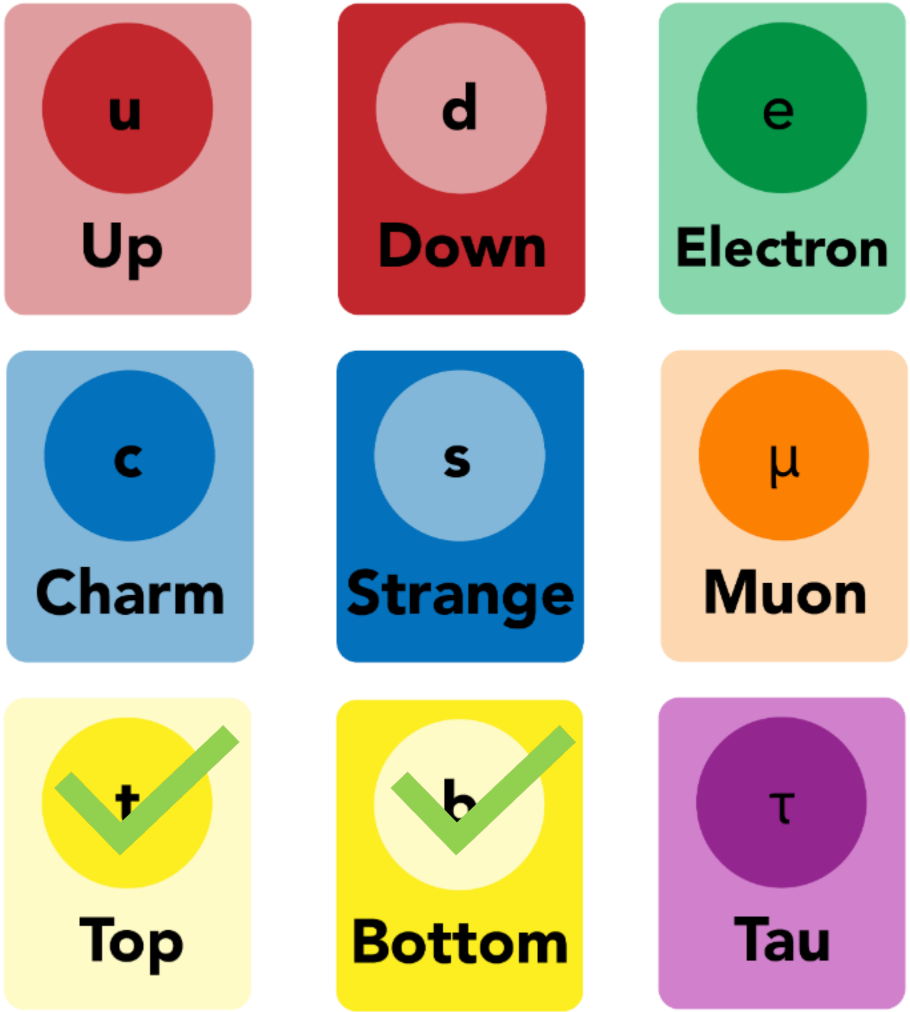

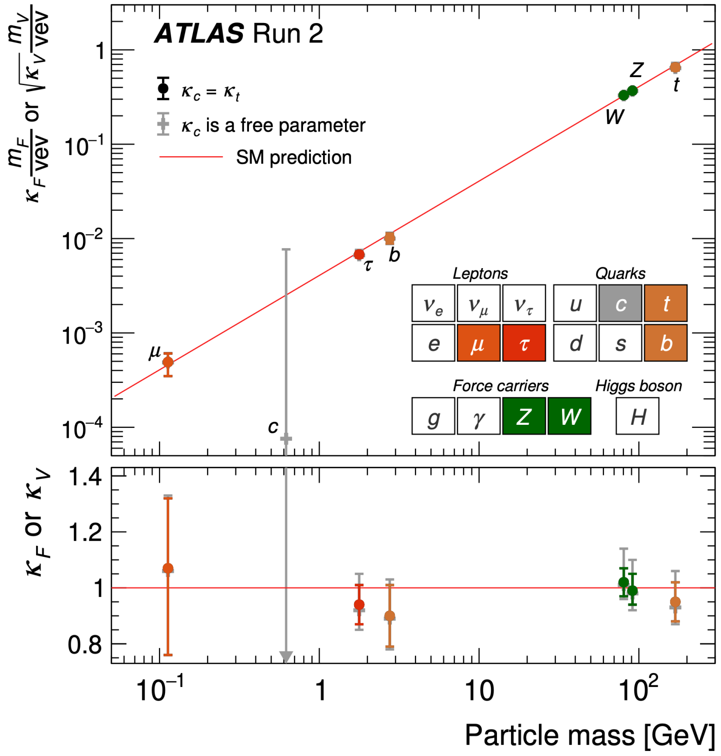

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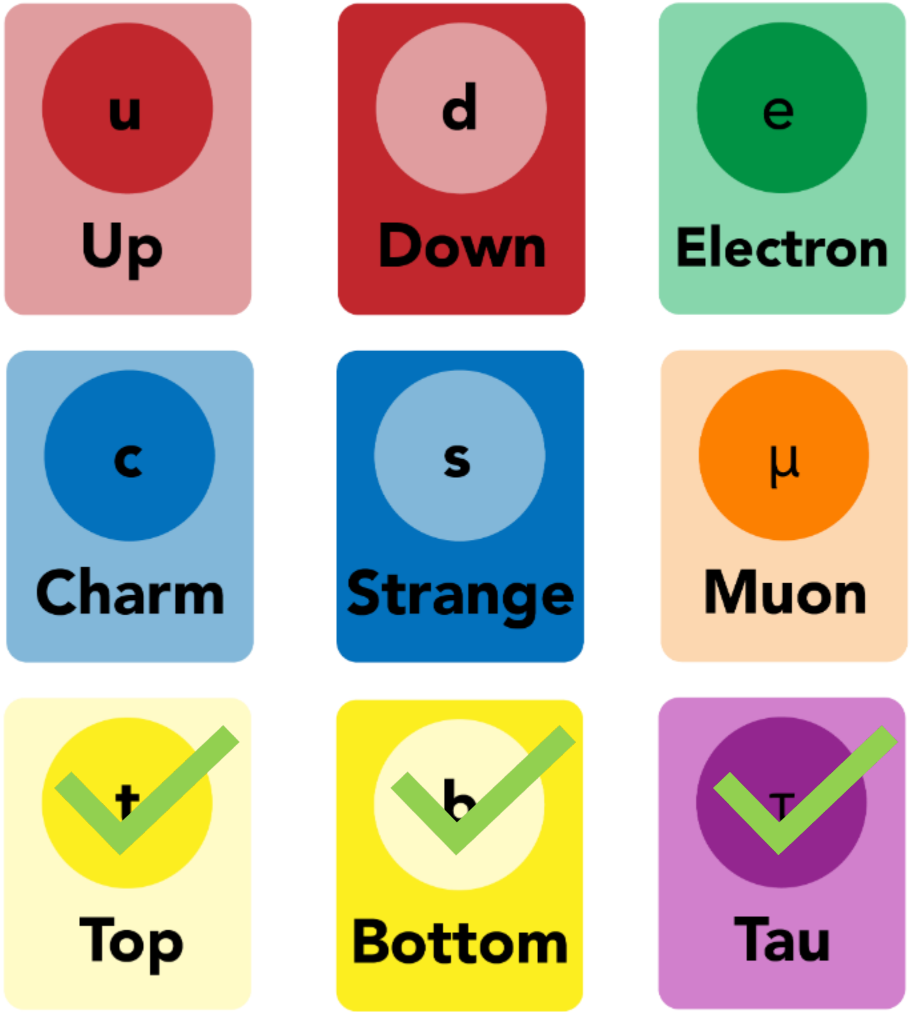

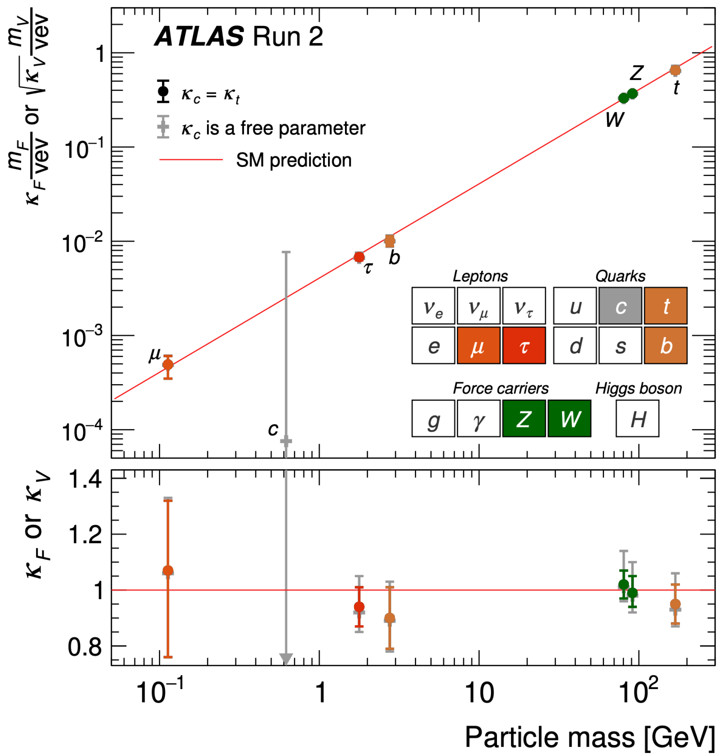

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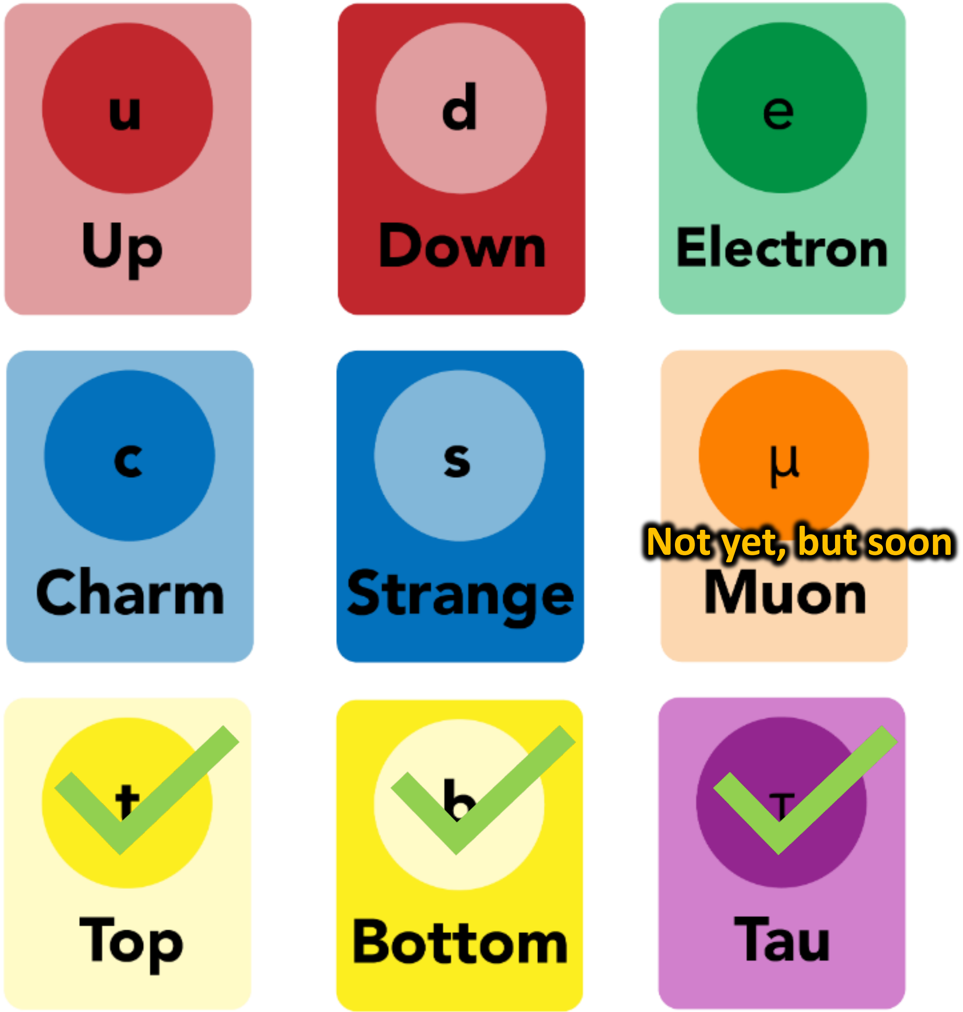

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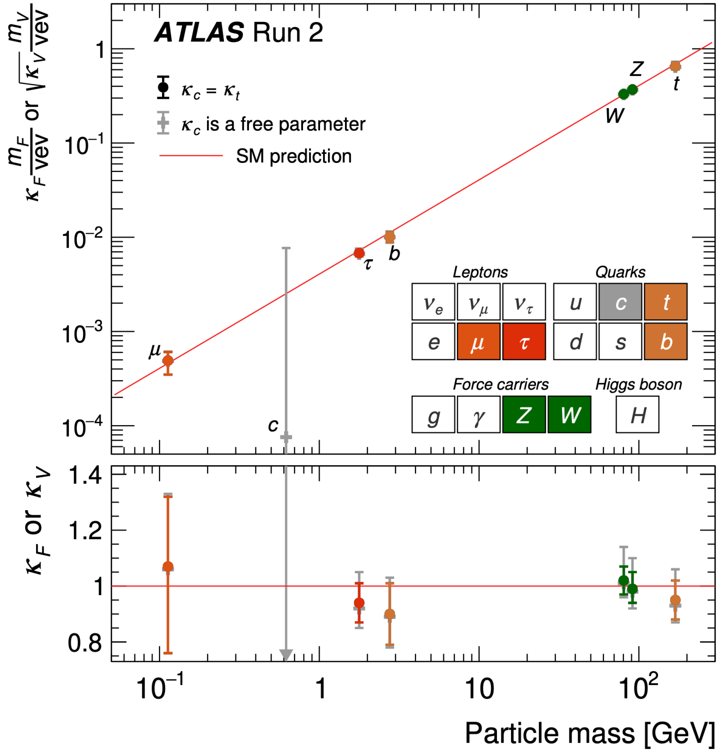

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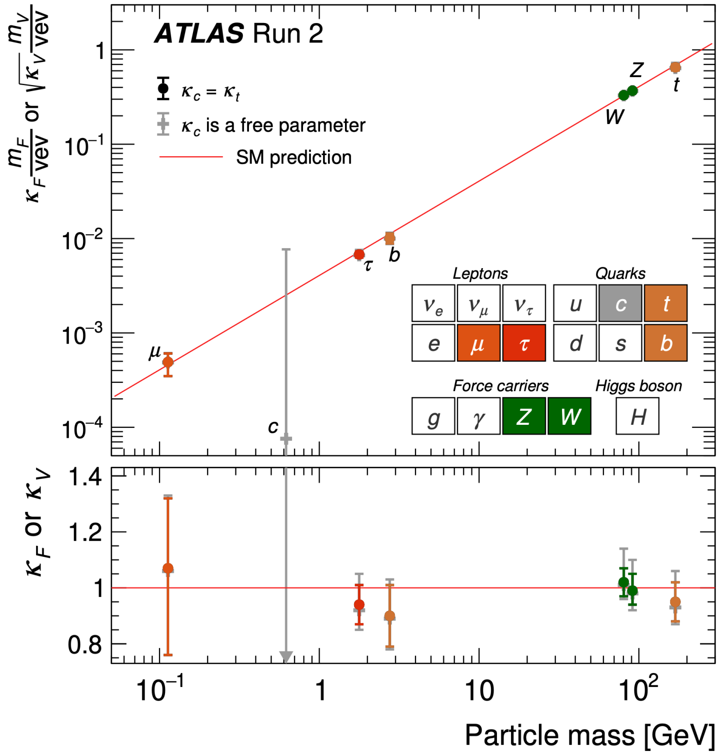

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Future collider?

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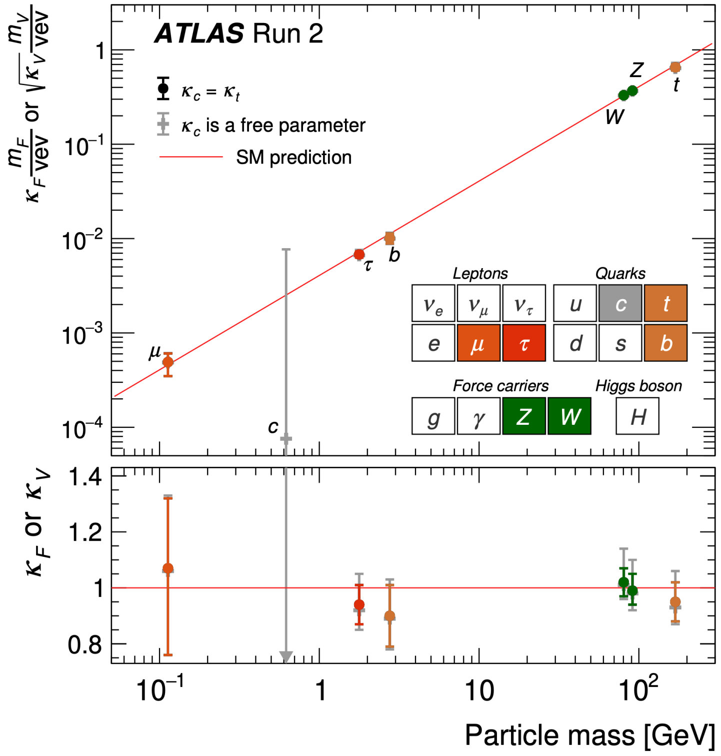

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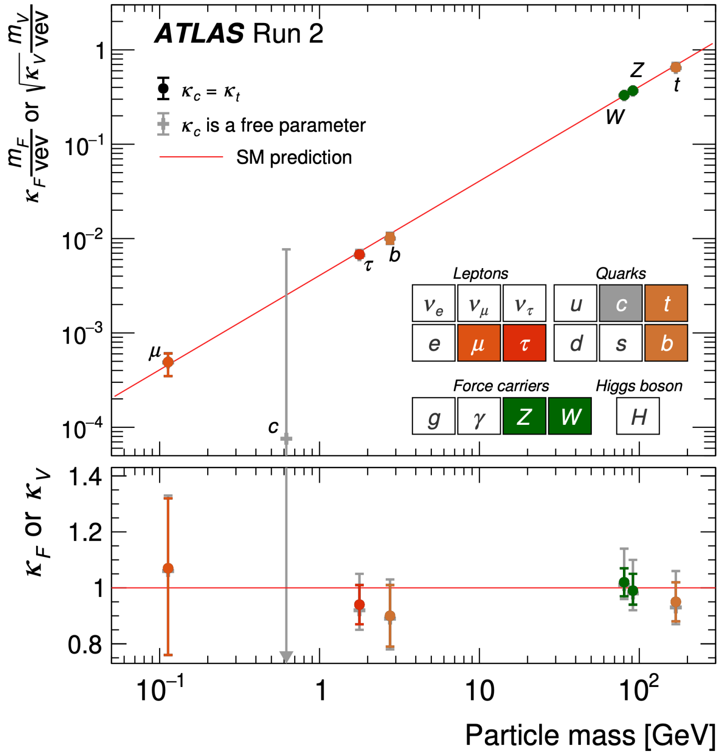

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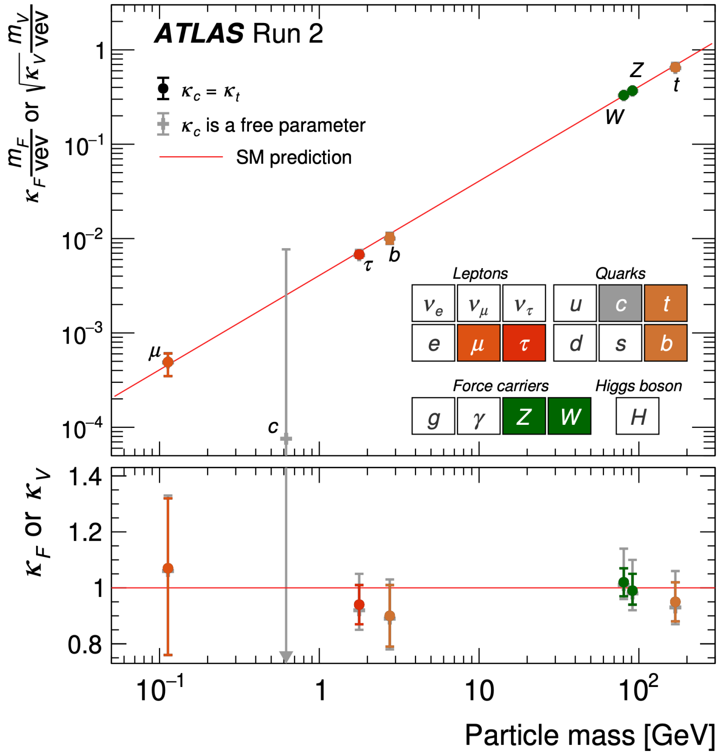
Future collider? (Electron)

Future collider? (Charm)

Future collider? (Strange)

Not yet, but soon (Muon)



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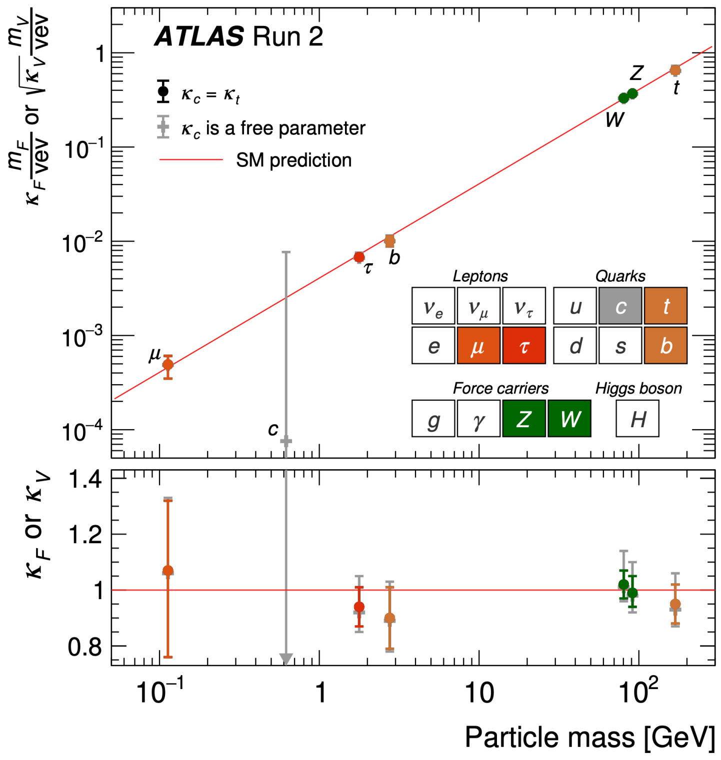

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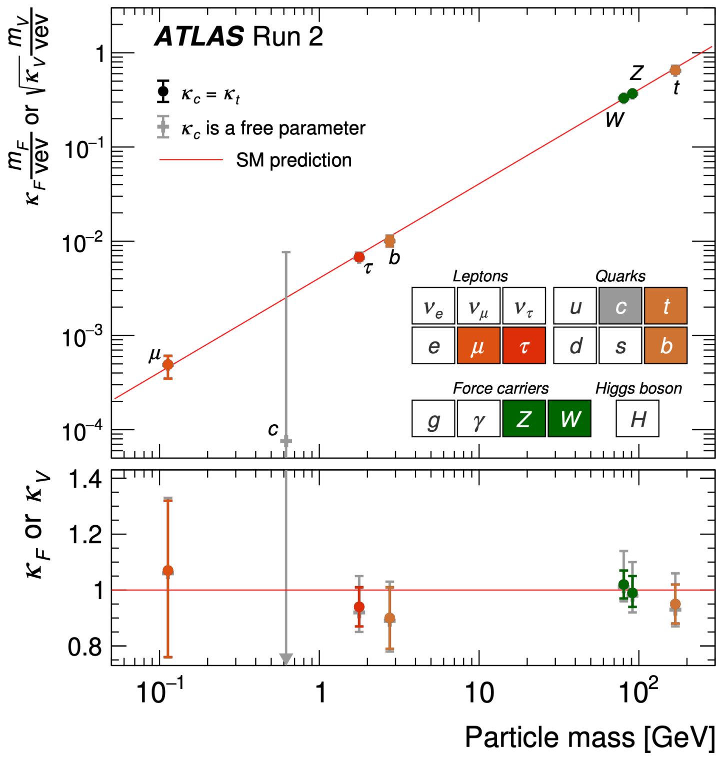

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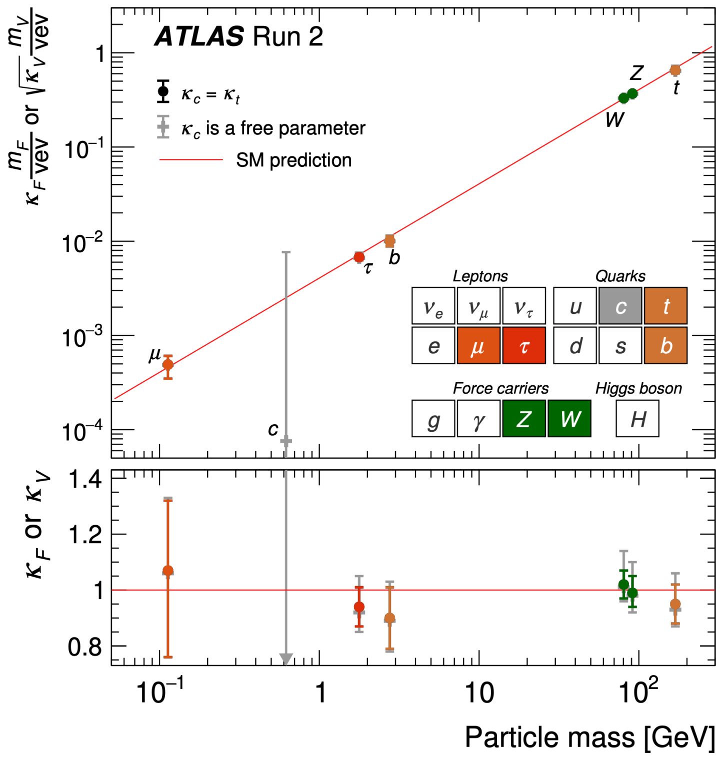

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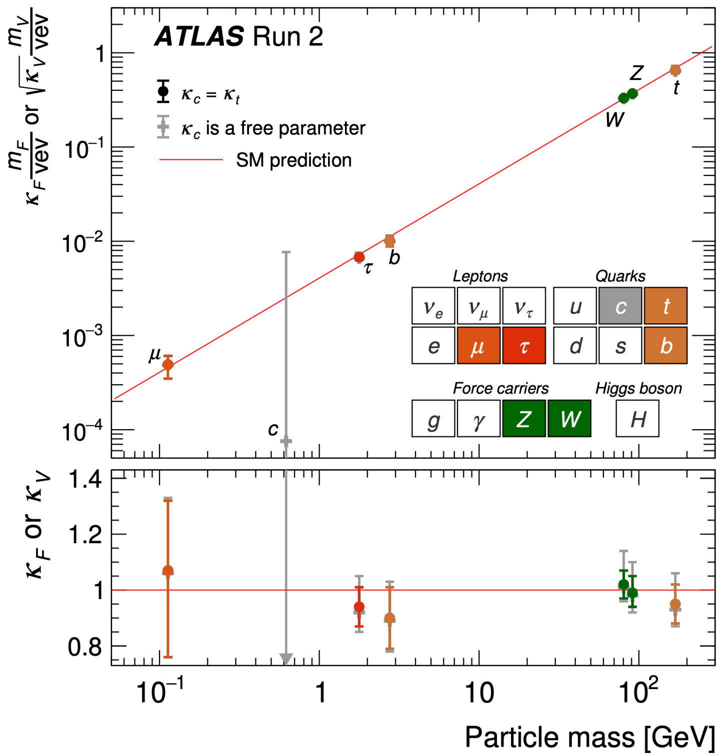

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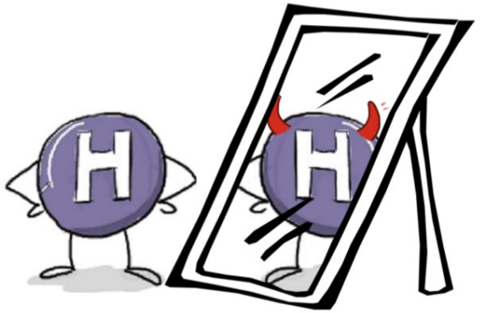
➡ CP provides an ”additional dimension”



The CP nature of the Higgs boson

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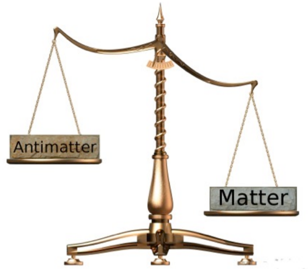

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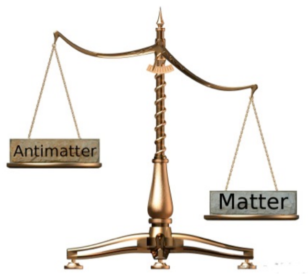

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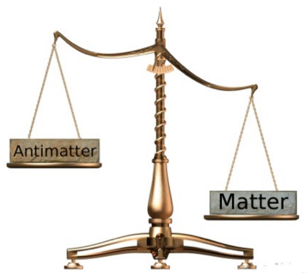

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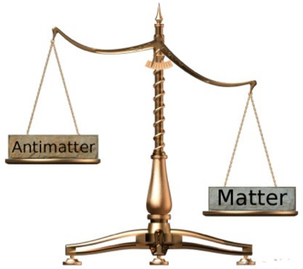

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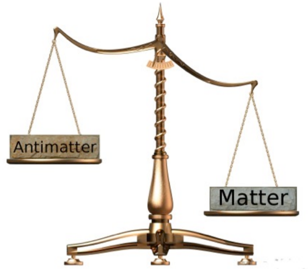

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Rewrite: $$\mathcal{L}_{\text{yuk}} = - \sum_{f=u,d,c,s,t,b,e,\mu,\tau} \frac{y_f^{\text{SM}}}{\sqrt{2}} \bar{f} \left(c_f + i \gamma_5 \tilde{c}_f\right) f H,$$

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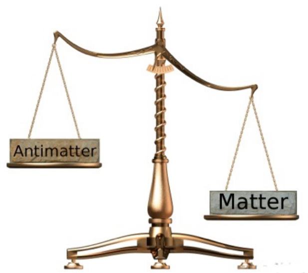

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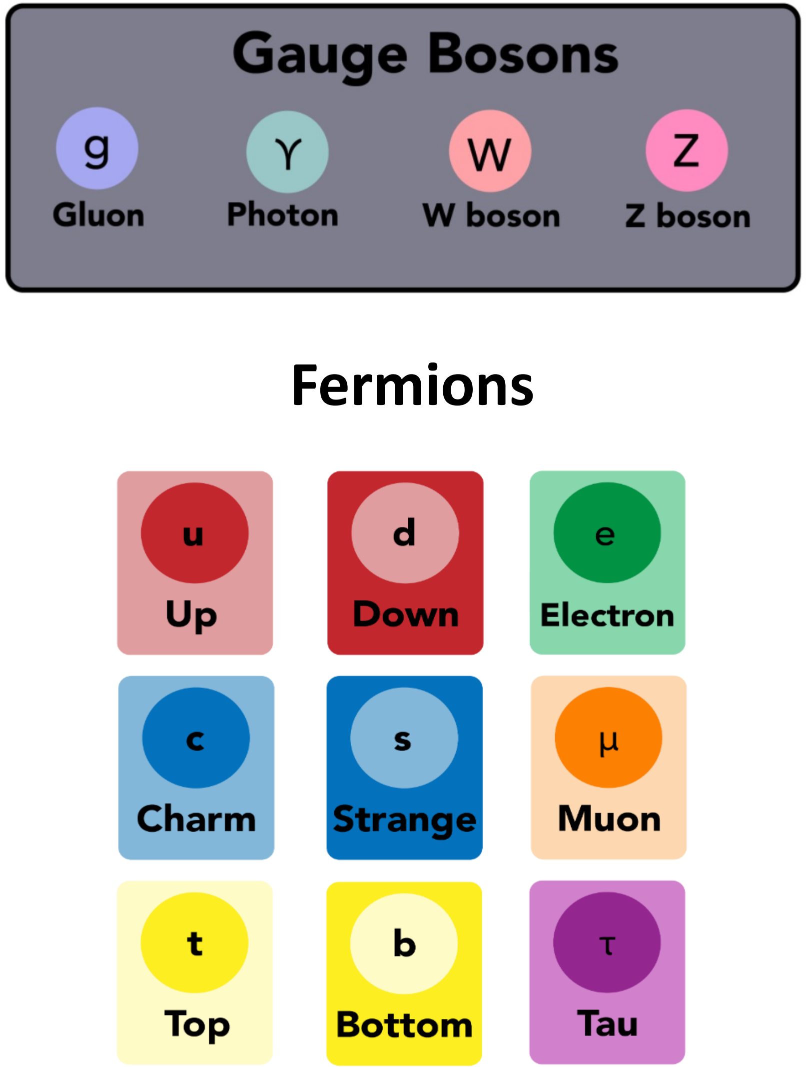
What is the current status?

Which CP structures are accessible at the LHC?



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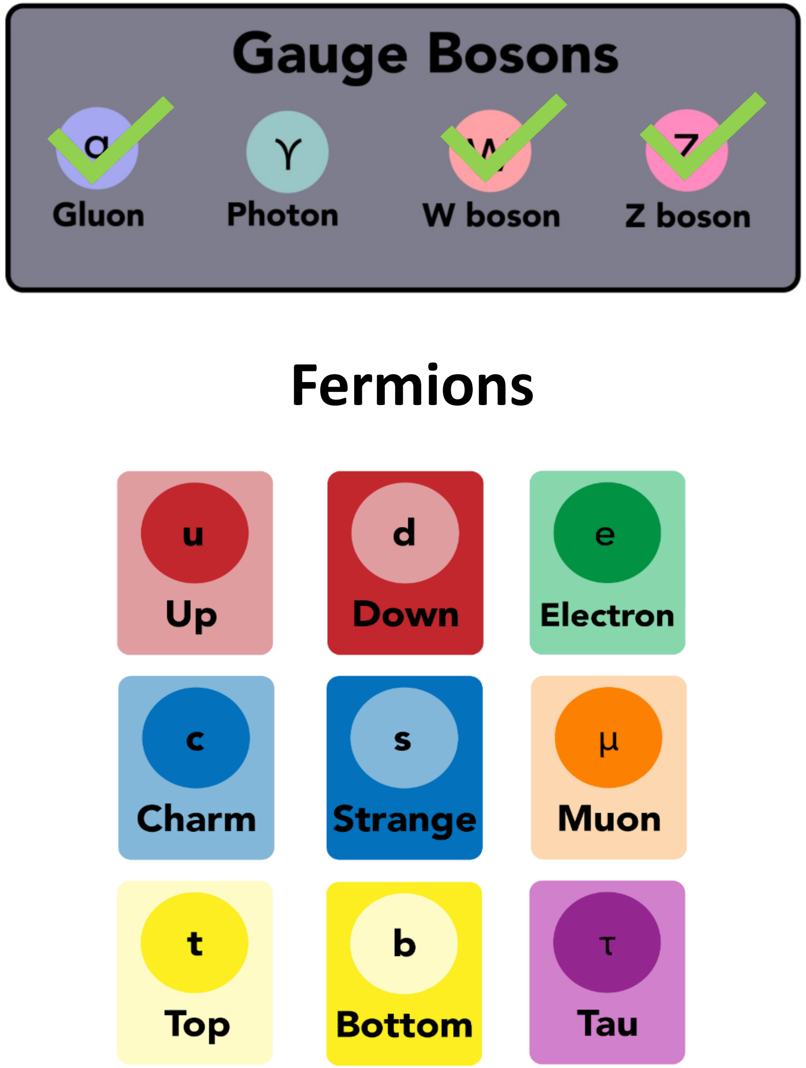

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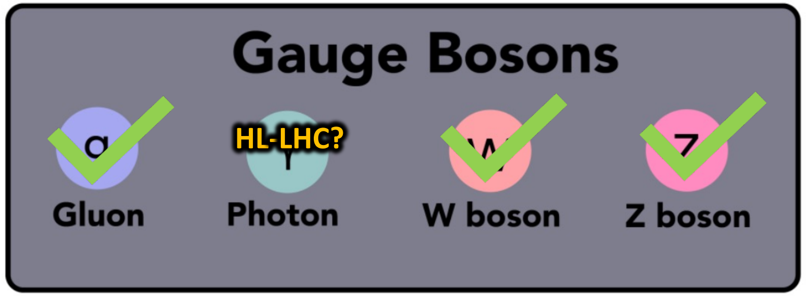
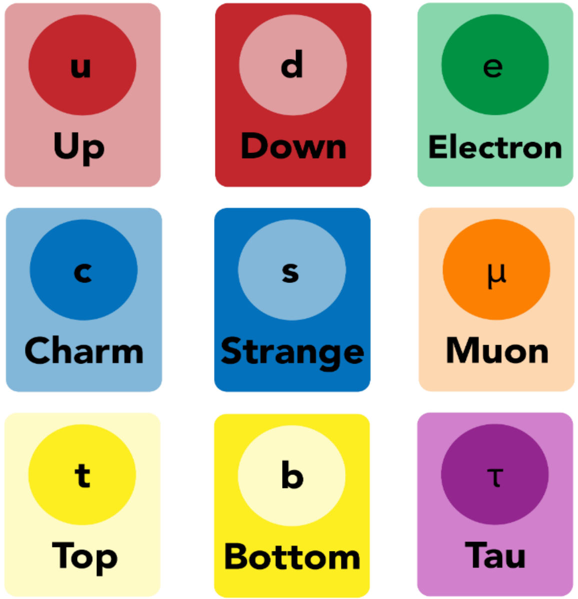


Fermions



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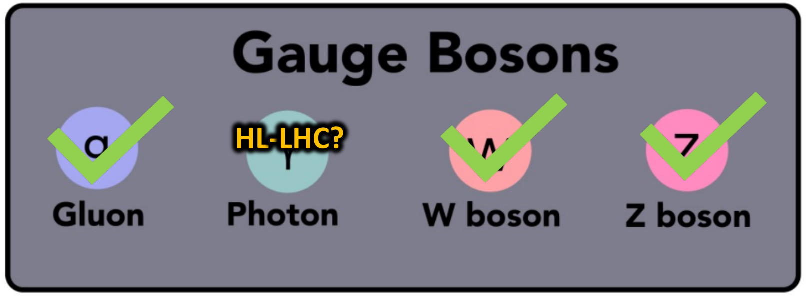

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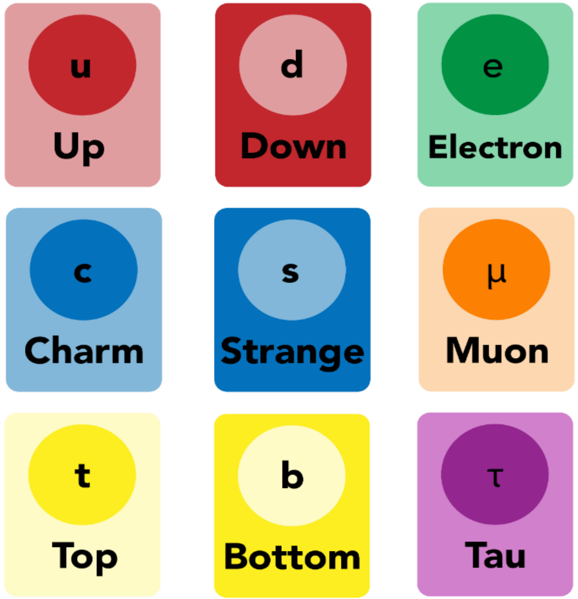

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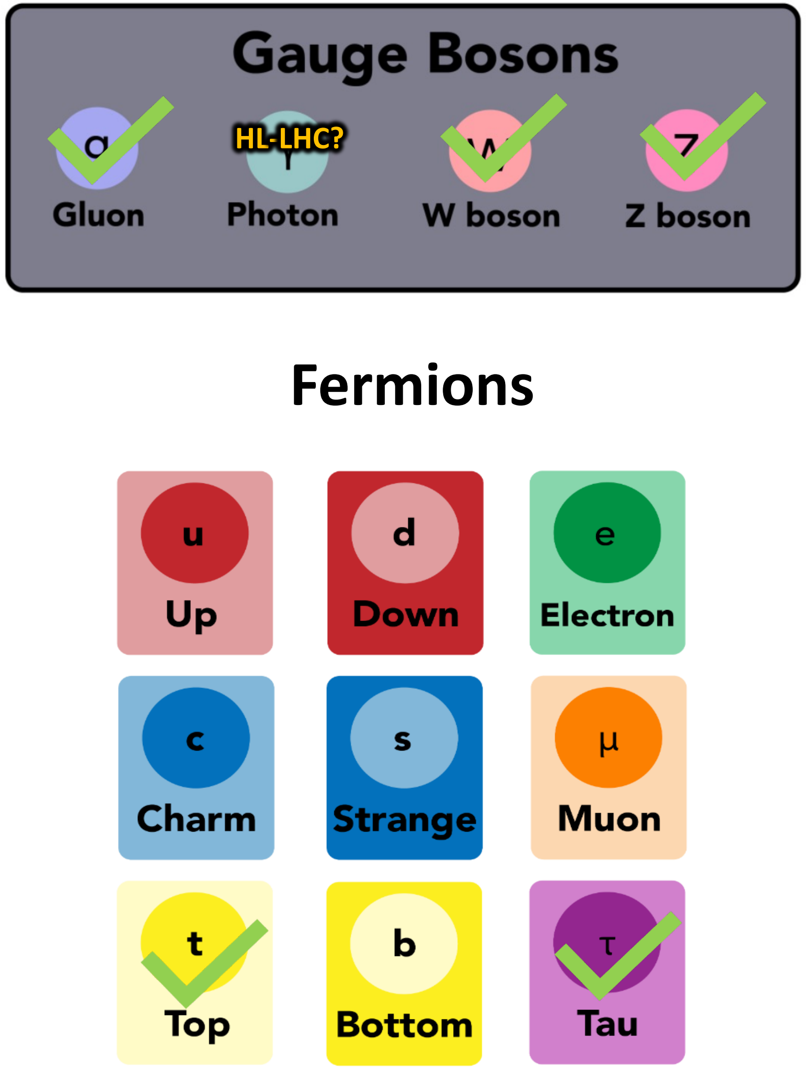

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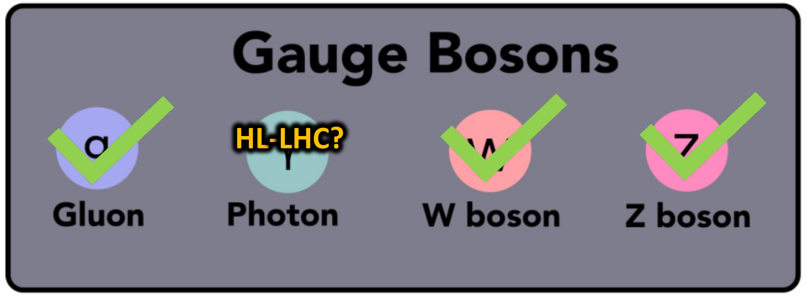

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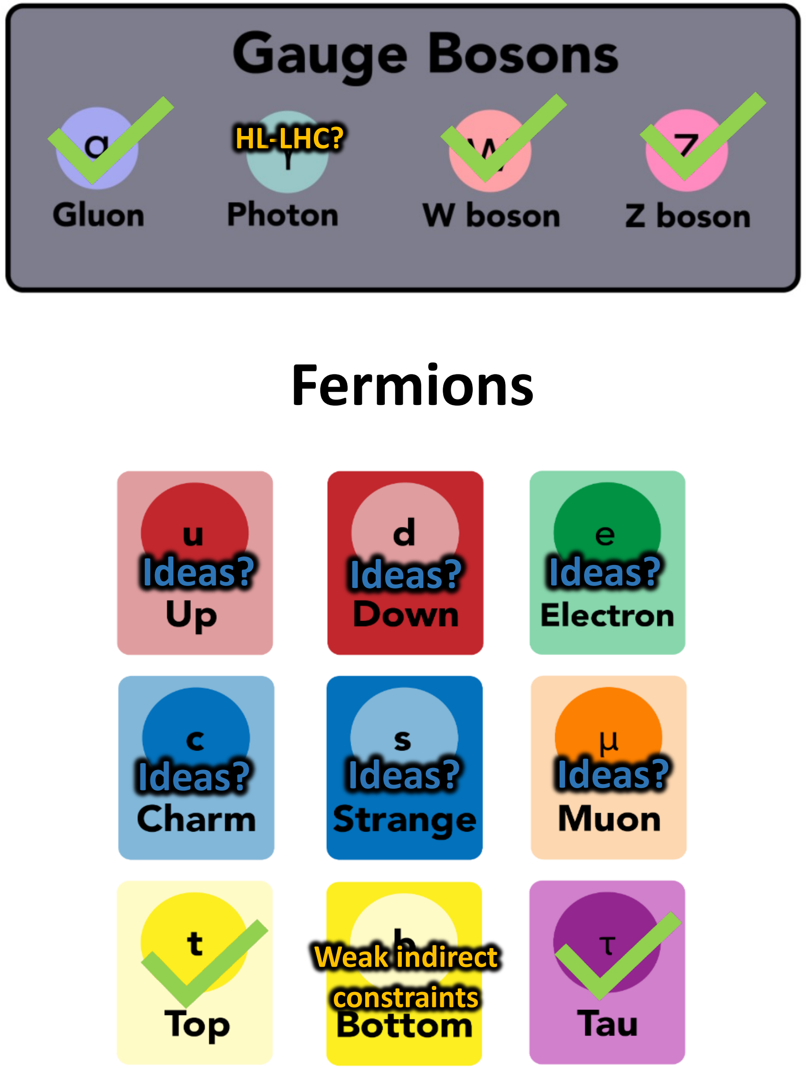

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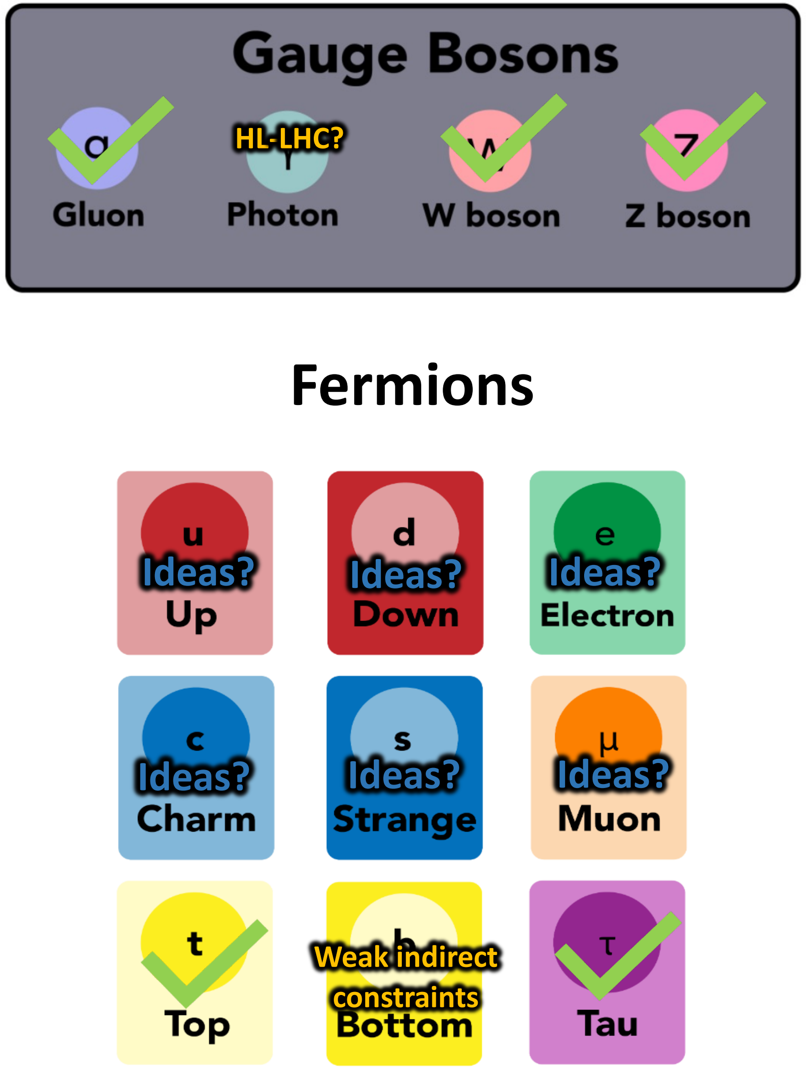

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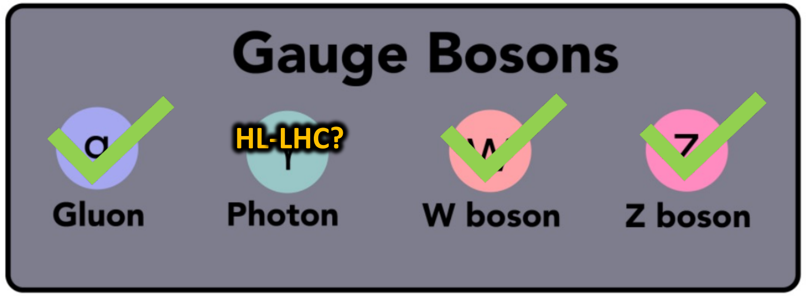

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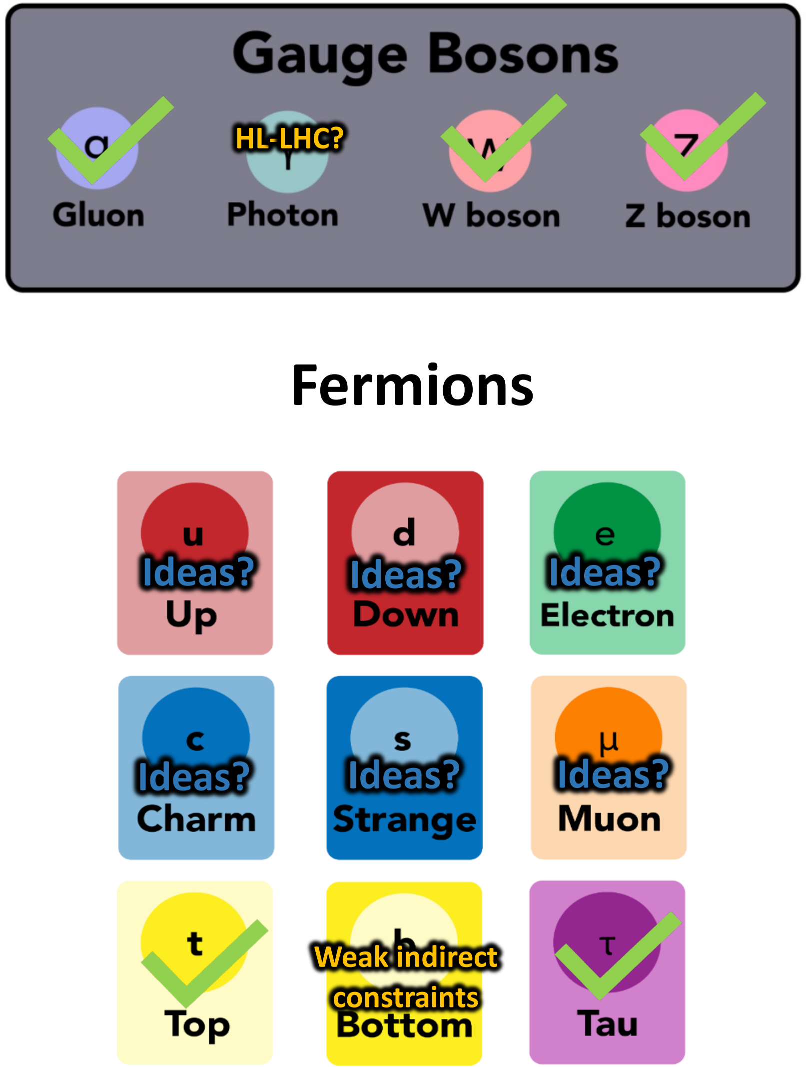

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➡ What about future colliders?

Future collider outlook

[Snowmass Higgs CP report, 2205.07715]

Limits set on: $f_{CP}^{HX} \equiv \frac{\Gamma^{CP\,\mathrm{odd}}_{H\to X}}{\Gamma^{CP\,\mathrm{odd}}_{H\to X} + \Gamma^{CP\,\mathrm{even}}_{H\to X}}$

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	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	$\sim$1	✓	–	–	–	$\sim$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	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

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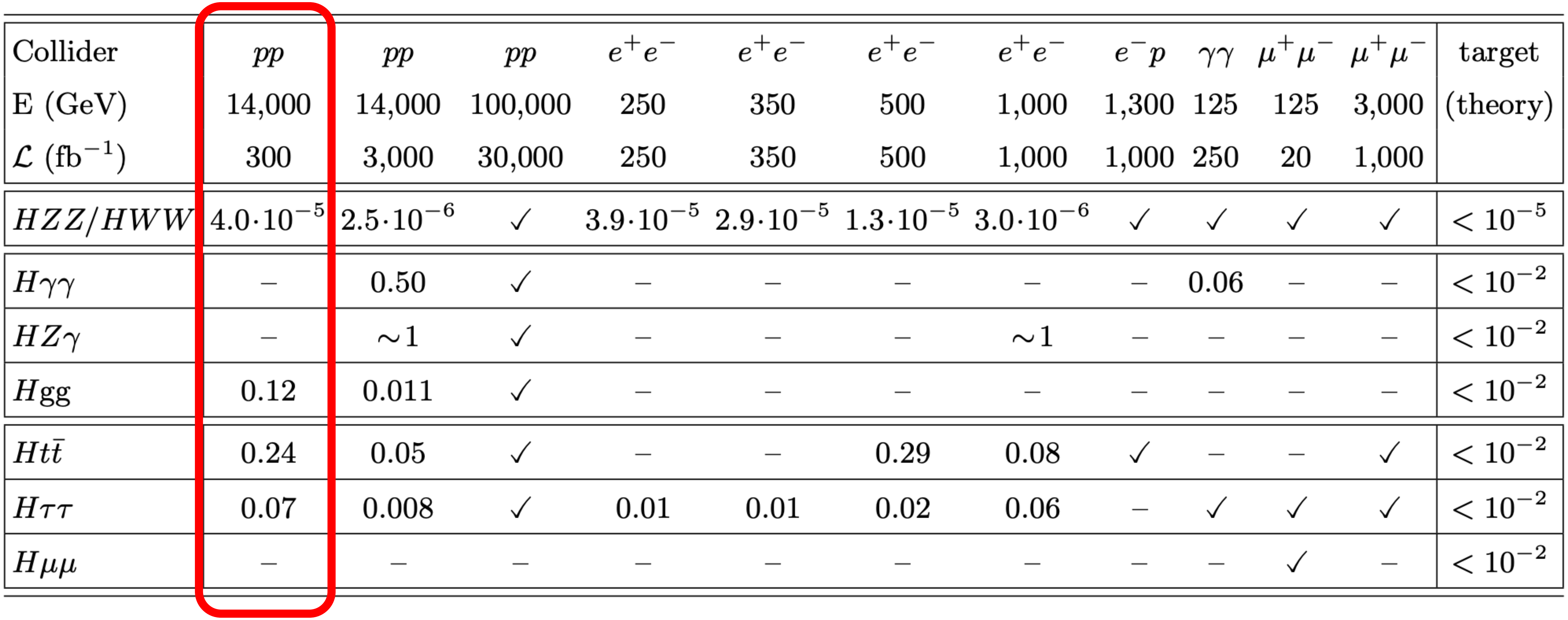

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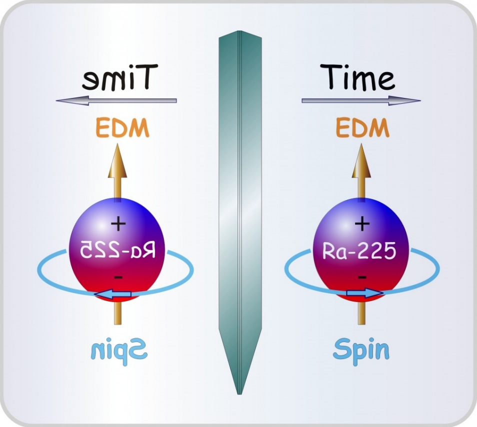
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

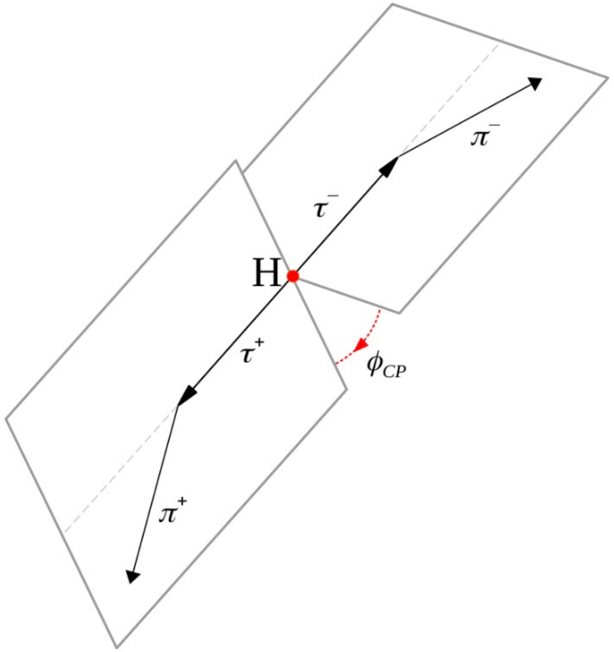
New ideas/techniques are needed to make the most of current and future data!

Constraining CP violation

CP violation in the Higgs sector can be constrained using:

- **Pure CP-odd observables**:
  - Unambiguous markers for CP violation: e.g.
    - EDM measurements,
    - decay angle in $H \to \tau^+\tau^-$.
  - Typically requires to access polarization of particles coupling to the Higgs.
  - Experimentally difficult for many LHC processes (i.e., top-associated Higgs production).
  - Almost impossible for $H \to b\bar{b}$ or $H \to \mu^+\mu^-$

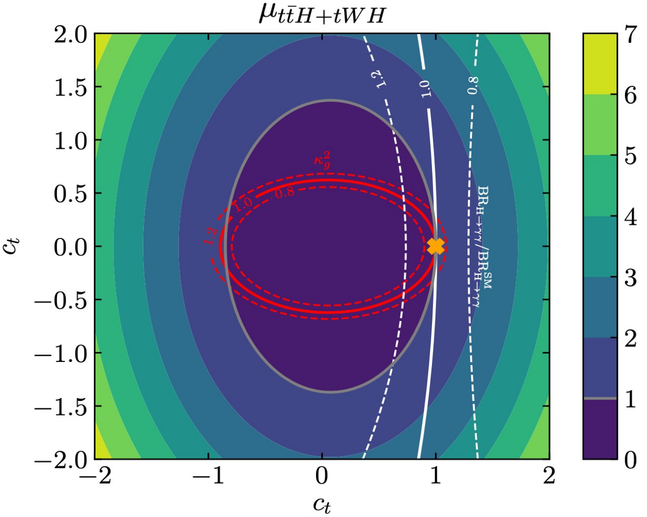




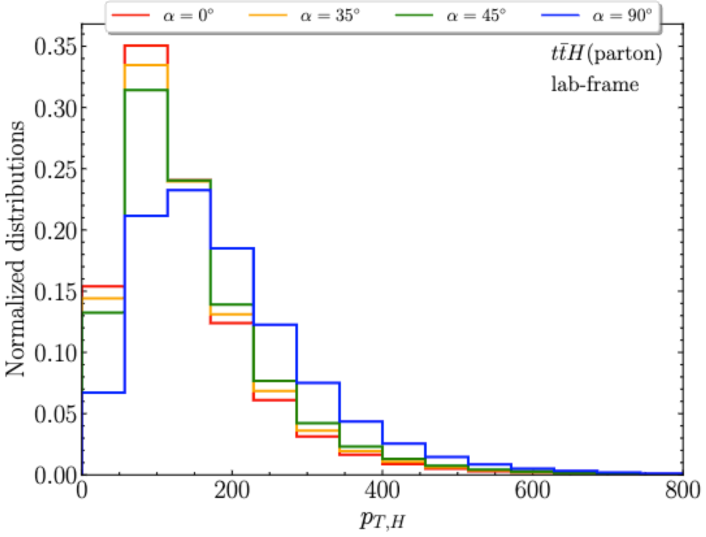
Constraining CP violation

CP violation in the Higgs sector can be constrained using:

- **Pure CP-even observables**:
    - Many rate measurements are indirectly sensitive: e.g. ggH.
    - Decay rates: e.g., $\Gamma_{H\to b\bar b} \propto c_b^2 + \tilde c_b^2$.
    - Subtle effects in kinematic distributions of CP-even observables (e.g. $p_{T,H}$ in $t\bar tH$).
    - Deviations from SM need not be due to CP violation → degeneracies with non-CPV BSM effects.



[HB et al., 2007.08542]

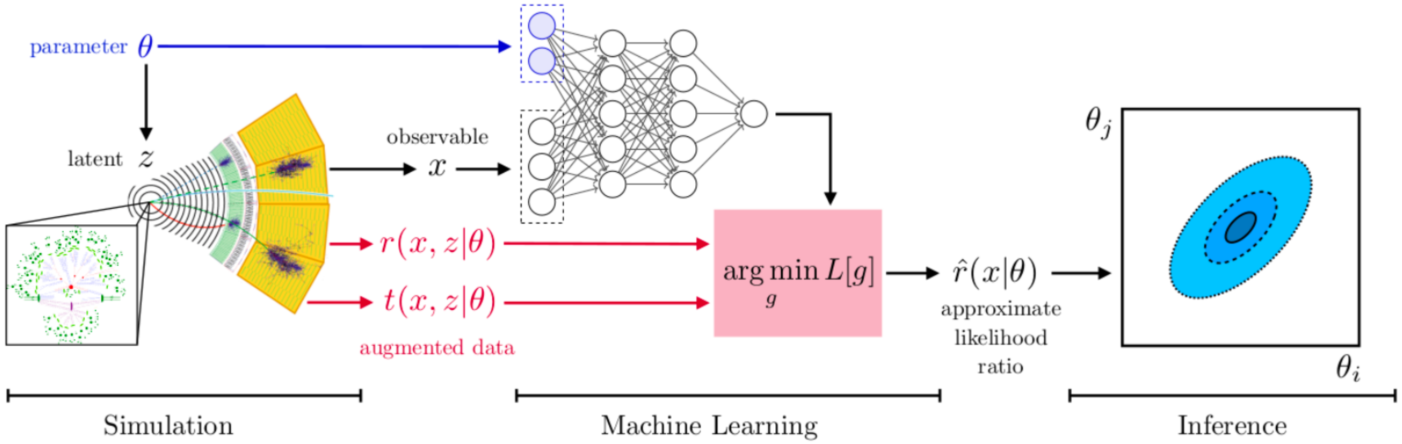


[HB et al., to appear]

Constraining CP violation

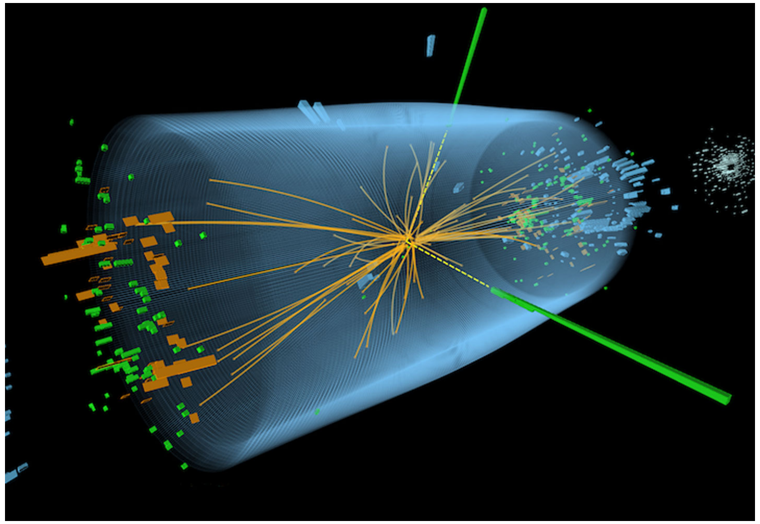
CP violation in the Higgs sector can be constrained using:

- **Multivariate analyses:**
  - Exploit full kinematic information using machine learning.
  - Often mixes CP-even and CP-odd observables.
  - High sensitivity.
  - Can be difficult to reinterpret.



[e.g. simulation-based inference, Brehmer et al.,1805.00013, …]

→ Exploit and combine all three complementary approaches to learn as much as possible!



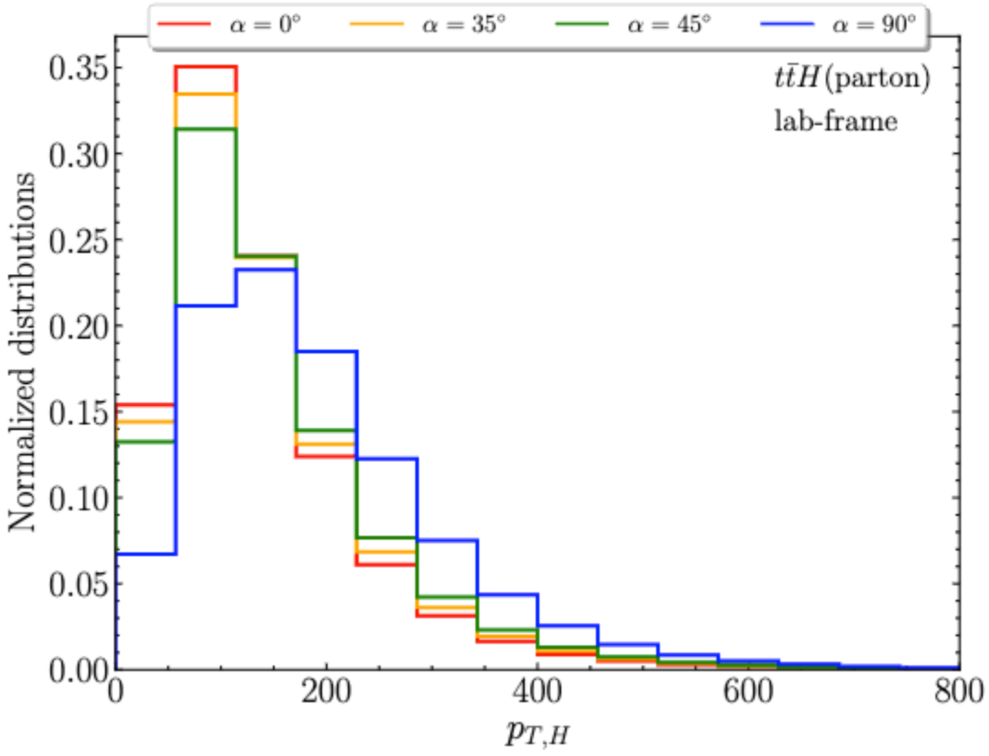
Improving LHC CP measurements I

CP-sensitive STXS extension for $t\bar{t}H$

[HB,Carnelli,Deliot,Fuchs,Kotsokechagia,Marsault,Menen,Schoeffel,Saimpert; to appear]

Current $t\bar{t}H$ STXS binning

- STXS is a common framework to provide differential results for various Higgs production channels combining different decay modes.
- Current $t\bar{t}H$ STXS binning: six bins in $p_{T,H}$.



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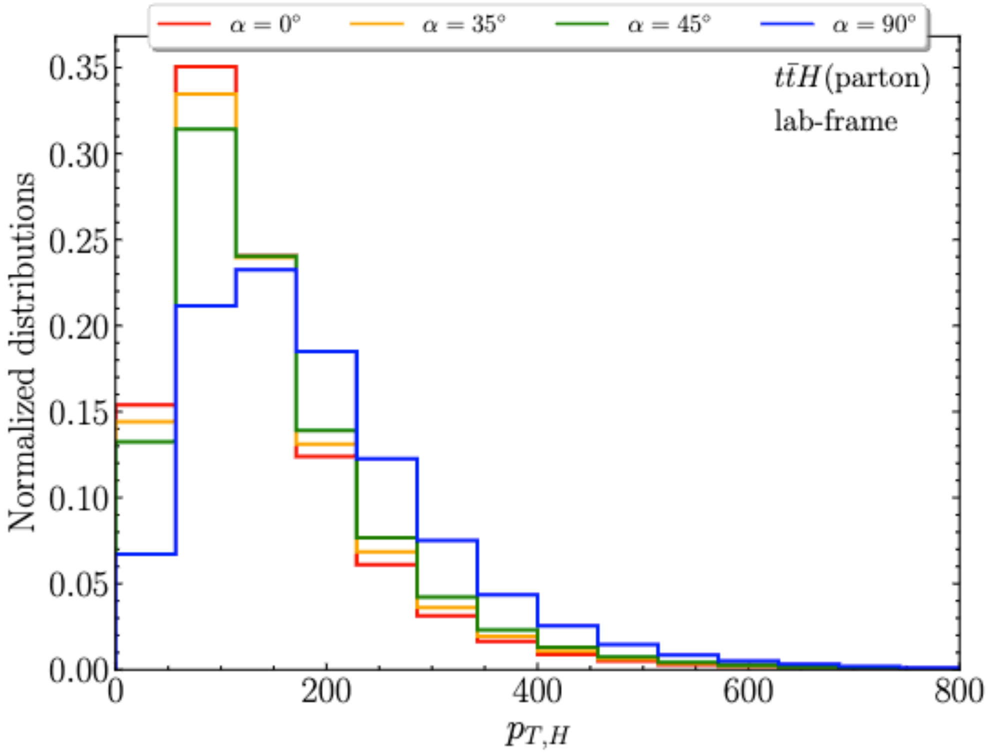

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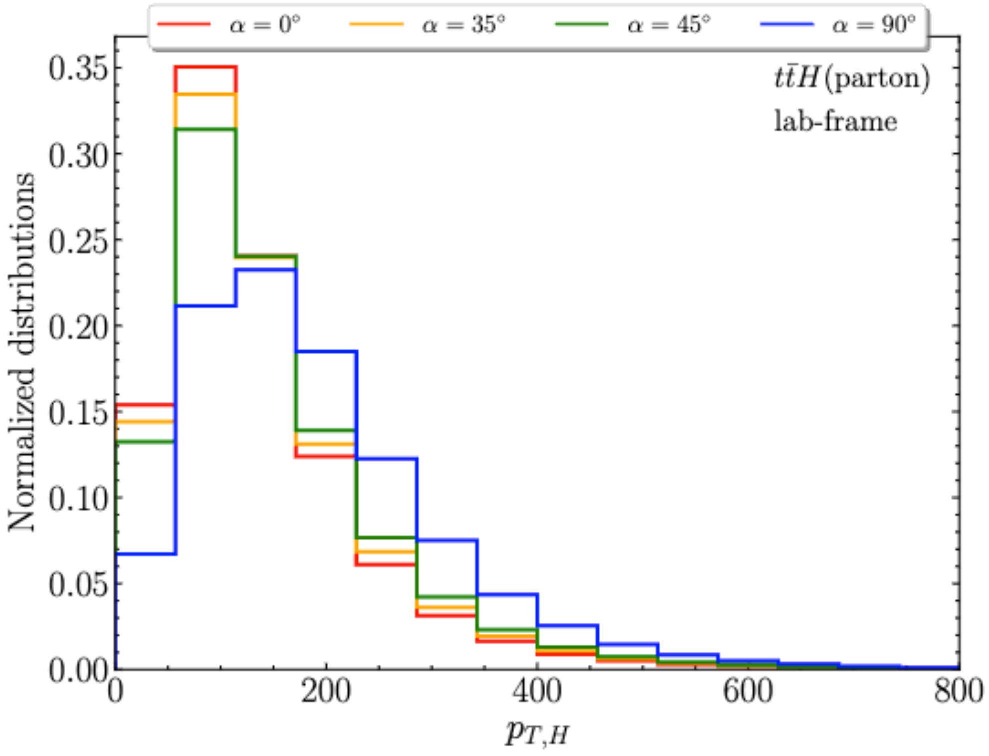

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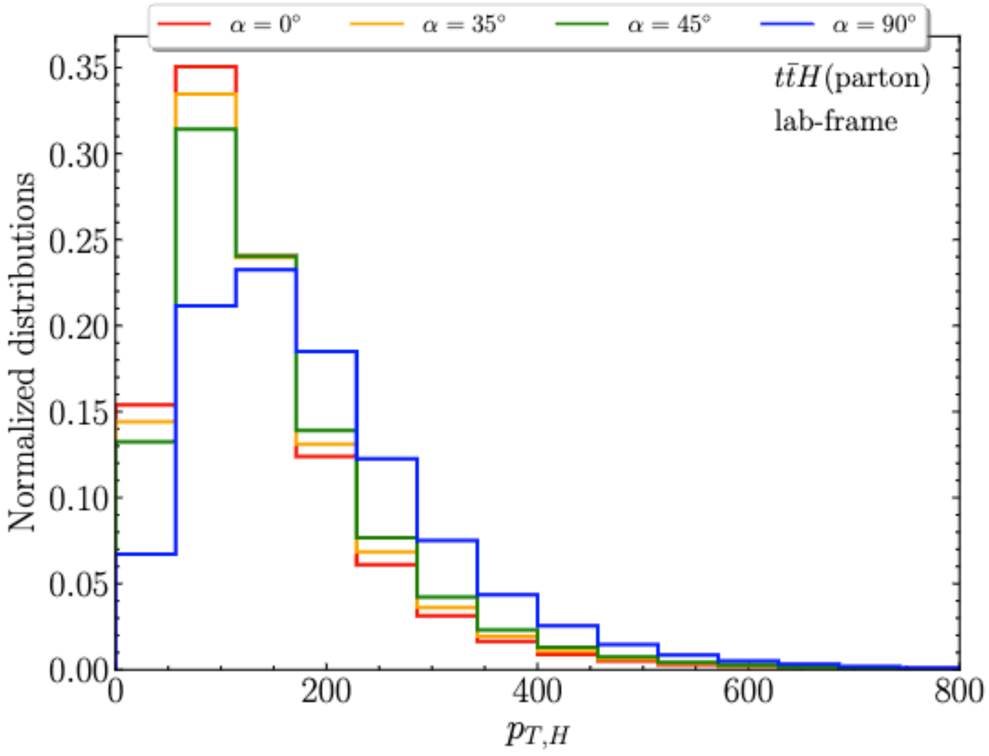
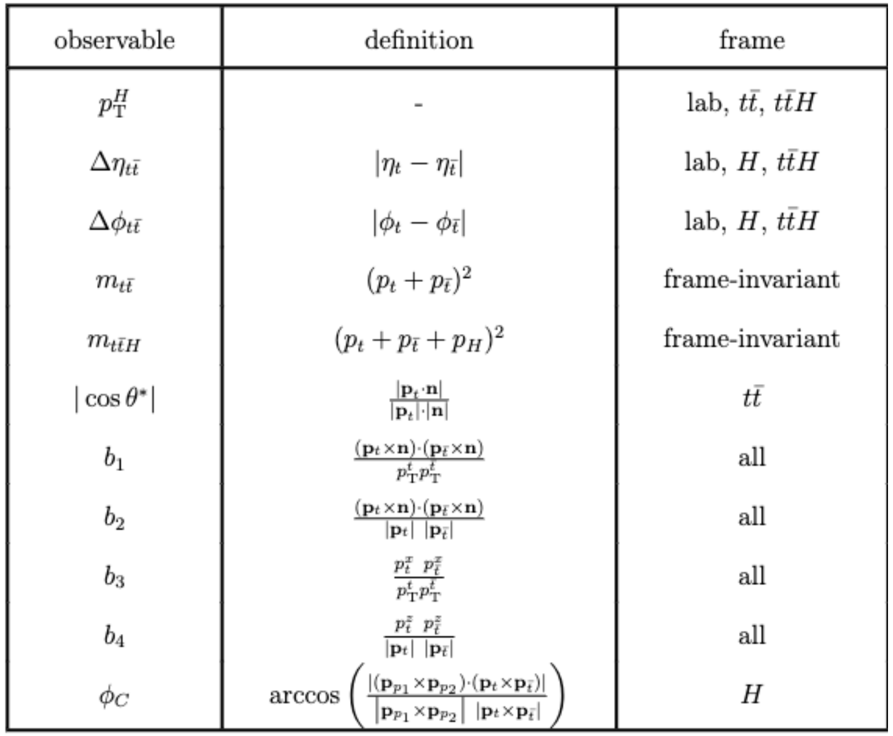
- Many CP-sensitive observables have been proposed in the literature.
- Test them against each other for
  - $H \to \gamma\gamma$
  - $H \to b\bar{b}$
  - $H \to$ multi-lepton



Investigated observables

- Tested 11 observables (1D) in different reference frames and their 2D combinations.
- In total, 465 different combinations
- Apply channel-specific smearing factors and reconstruction efficiencies to mimic existing experimental analysis.
- Removed rate information for $H \to b\bar{b}$,multi-lepton because of large backgrounds.
- Parameterize top Yukawa as $\mathcal{L}_{\text{top-Yuk}} = \frac{y_t^{\text{SM}} g_t}{\sqrt{2}} \bar{t} \left(\cos\alpha_t + i\gamma_5 \sin\alpha_t\right) tH$

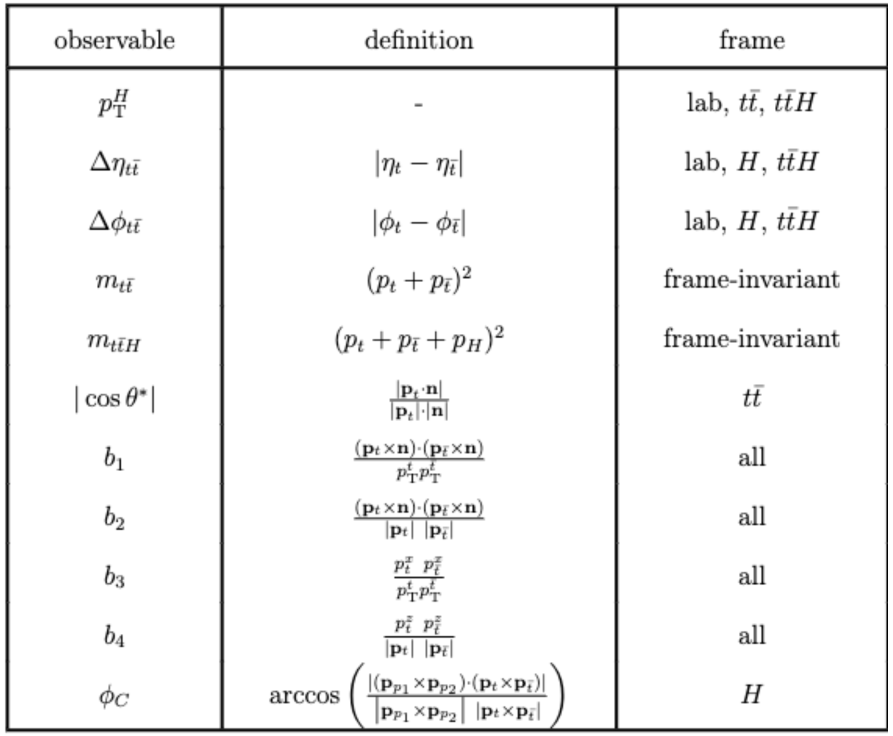


observable	definition	frame
p_{T}^H	-	lab, $t\bar{t}$, $t\bar{t}H$
$\Delta\eta_{t\bar{t}}$	$\lvert\eta_t - \eta_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$
$\Delta\phi_{t\bar{t}}$	$\lvert\phi_t - \phi_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$
$m_{t\bar{t}}$	$(p_t + p_{\bar{t}})^2$	frame-invariant
$m_{t\bar{t}H}$	$(p_t + p_{\bar{t}} + p_H)^2$	frame-invariant
$\lvert\cos\theta^*\rvert$	$\frac{\lvert\mathbf{p}_t \cdot \mathbf{n}\rvert}{\lvert\mathbf{p}_t\rvert \cdot \lvert\mathbf{n}\rvert}$	$t\bar{t}$
b_1	$\frac{(\mathbf{p}_t \times \mathbf{n}) \cdot (\mathbf{p}_{\bar{t}} \times \mathbf{n})}{p_{\mathrm{T}}^t p_{\mathrm{T}}^{\bar{t}}}$	all
b_2	$\frac{(\mathbf{p}_t \times \mathbf{n}) \cdot (\mathbf{p}_{\bar{t}} \times \mathbf{n})}{\lvert\mathbf{p}_t\rvert\ \lvert\mathbf{p}_{\bar{t}}\rvert}$	all
b_3	$\frac{p_t^x\ p_{\bar{t}}^x}{p_{\mathrm{T}}^t p_{\mathrm{T}}^{\bar{t}}}$	all
b_4	$\frac{p_t^z\ p_{\bar{t}}^z}{\lvert\mathbf{p}_t\rvert\ \lvert\mathbf{p}_{\bar{t}}\rvert}$	all
ϕ_C	$\arccos\left(\frac{\lvert(\mathbf{p}_{p_1} \times \mathbf{p}_{p_2}) \cdot (\mathbf{p}_t \times \mathbf{p}_{\bar{t}})\rvert}{\lvert\mathbf{p}_{p_1} \times \mathbf{p}_{p_2}\rvert\ \lvert\mathbf{p}_t \times \mathbf{p}_{\bar{t}}\rvert}\right)$	H

Investigated observables

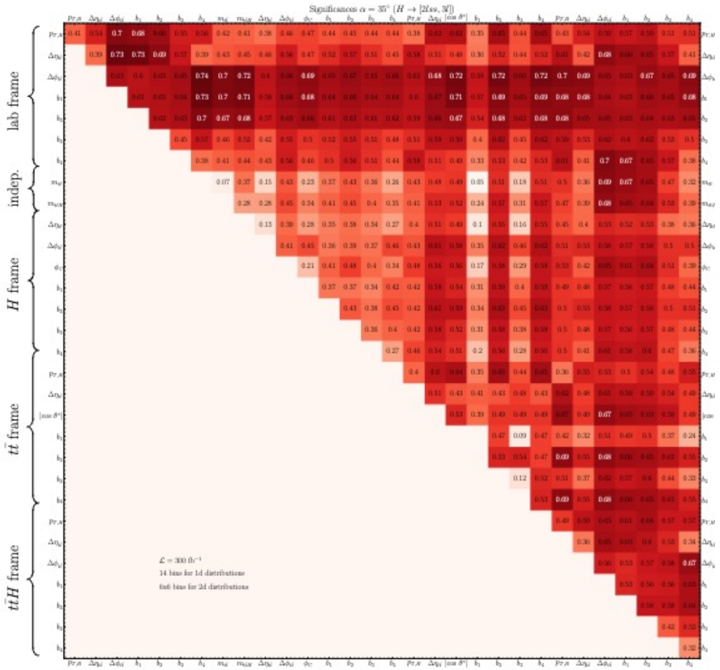
- Tested 11 observables (1D) in different reference frames and their 2D combinations.
- In total, 465 different combinations
- Apply channel-specific smearing factors and reconstruction efficiencies to mimic existing experimental analysis.
- Removed rate information for $H \to b\bar{b}$,multi-lepton because of large backgrounds.
- Parameterize top Yukawa as $\mathcal{L}_{\text{top-Yuk}} = \frac{y_t^{\text{SM}} g_t}{\sqrt{2}} \bar{t} \left(\cos\alpha_t + i\gamma_5 \sin\alpha_t\right) tH$

Use significance S to exclude $\alpha_t = 35°$ as performance metric.

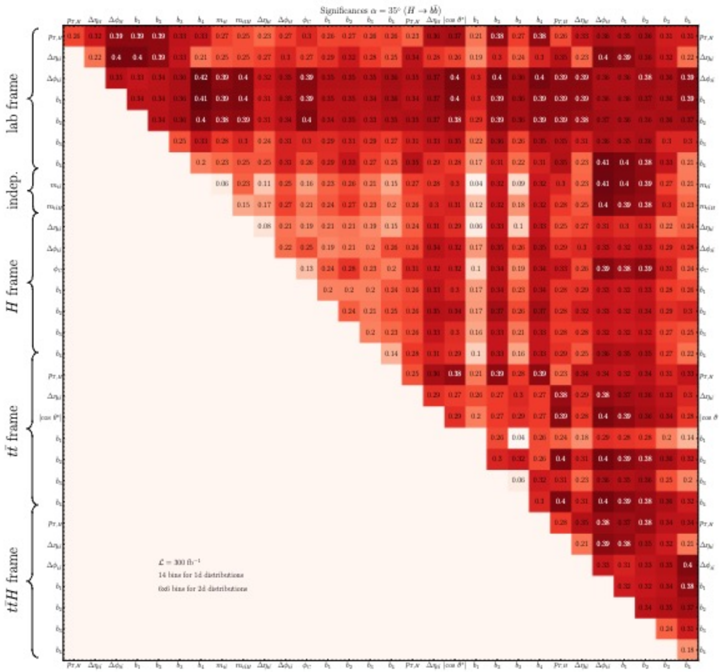


observable	definition	frame
p_{T}^{H}	-	lab, $t\bar{t}$, $t\bar{t}H$
$\Delta\eta_{t\bar{t}}$	$\lvert\eta_t - \eta_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$
$\Delta\phi_{t\bar{t}}$	$\lvert\phi_t - \phi_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$
$m_{t\bar{t}}$	$(p_t + p_{\bar{t}})^2$	frame-invariant
$m_{t\bar{t}H}$	$(p_t + p_{\bar{t}} + p_H)^2$	frame-invariant
$\lvert\cos\theta^*\rvert$	$\frac{\lvert\mathbf{p}_t \cdot \mathbf{n}\rvert}{\lvert\mathbf{p}_t\rvert \cdot \lvert\mathbf{n}\rvert}$	$t\bar{t}$
b_1	$\frac{(\mathbf{p}_t \times \mathbf{n}) \cdot (\mathbf{p}_{\bar{t}} \times \mathbf{n})}{p_{\mathrm{T}}^{t} p_{\mathrm{T}}^{\bar{t}}}$	all
b_2	$\frac{(\mathbf{p}_t \times \mathbf{n}) \cdot (\mathbf{p}_{\bar{t}} \times \mathbf{n})}{\lvert\mathbf{p}_t\rvert \; \lvert\mathbf{p}_{\bar{t}}\rvert}$	all
b_3	$\frac{p_t^x \; p_{\bar{t}}^x}{p_{\mathrm{T}}^{t} p_{\mathrm{T}}^{\bar{t}}}$	all
b_4	$\frac{p_t^z \; p_{\bar{t}}^z}{\lvert\mathbf{p}_t\rvert \; \lvert\mathbf{p}_{\bar{t}}\rvert}$	all
ϕ_C	$\arccos\left(\frac{\lvert(\mathbf{p}_{p_1} \times \mathbf{p}_{p_2}) \cdot (\mathbf{p}_t \times \mathbf{p}_{\bar{t}})\rvert}{\lvert\mathbf{p}_{p_1} \times \mathbf{p}_{p_2}\rvert \; \lvert\mathbf{p}_t \times \mathbf{p}_{\bar{t}}\rvert}\right)$	H

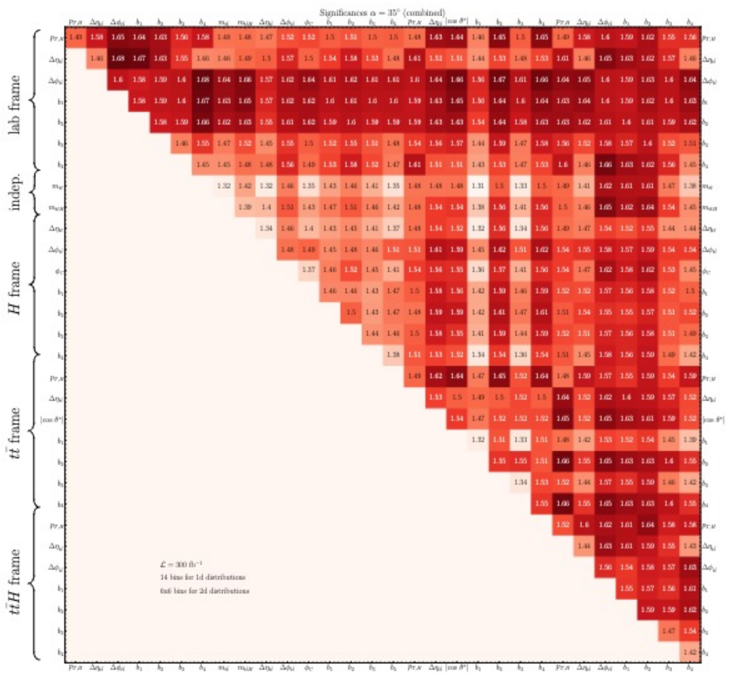
Significance tables



$H \to \gamma\gamma$

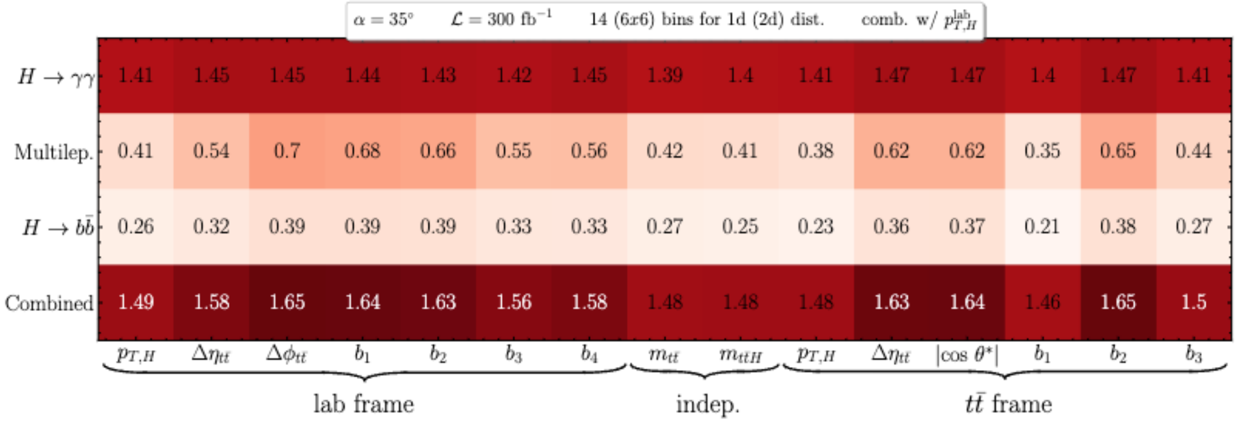


$H \to b\bar{b}$



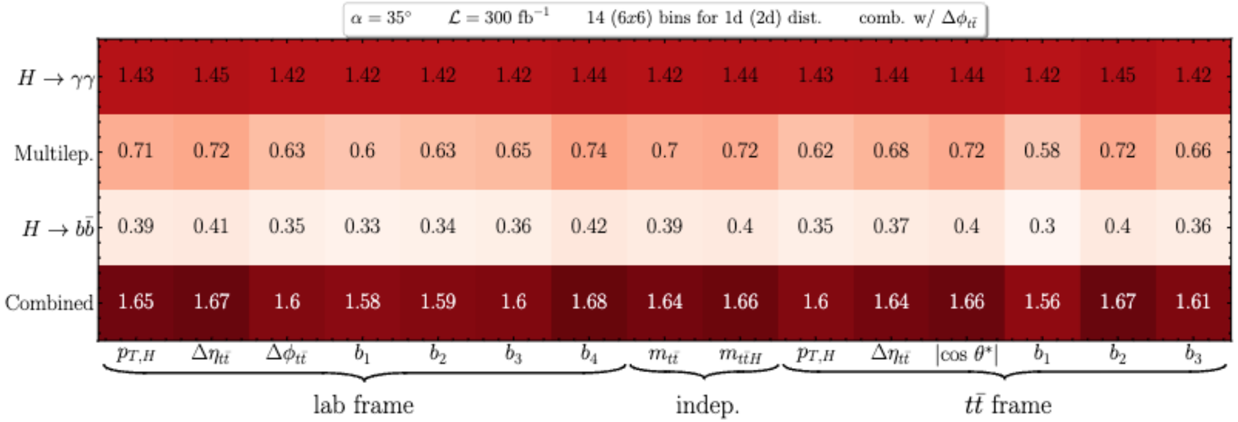
$H \to$ multi-lepton

Significance tables



$\alpha = 35^\circ$ $\mathcal{L} = 300\ \text{fb}^{-1}$ 14 (6x6) bins for 1d (2d) dist. comb. w/ $p_{T,H}^{\text{lab}}$

	lab frame							indep.		$t\bar{t}$ frame					
	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\Delta\phi_{t\bar{t}}$	b_1	b_2	b_3	b_4	$m_{t\bar{t}}$	$m_{t\bar{t}H}$	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\lvert\cos\theta^*\rvert$	b_1	b_2	b_3
$H \to \gamma\gamma$	1.41	1.45	1.45	1.44	1.43	1.42	1.45	1.39	1.4	1.41	1.47	1.47	1.4	1.47	1.41
Multilep.	0.41	0.54	0.7	0.68	0.66	0.55	0.56	0.42	0.41	0.38	0.62	0.62	0.35	0.65	0.44
$H \to b\bar{b}$	0.26	0.32	0.39	0.39	0.39	0.33	0.33	0.27	0.25	0.23	0.36	0.37	0.21	0.38	0.27
Combined	1.49	1.58	1.65	1.64	1.63	1.56	1.58	1.48	1.48	1.48	1.63	1.64	1.46	1.65	1.5



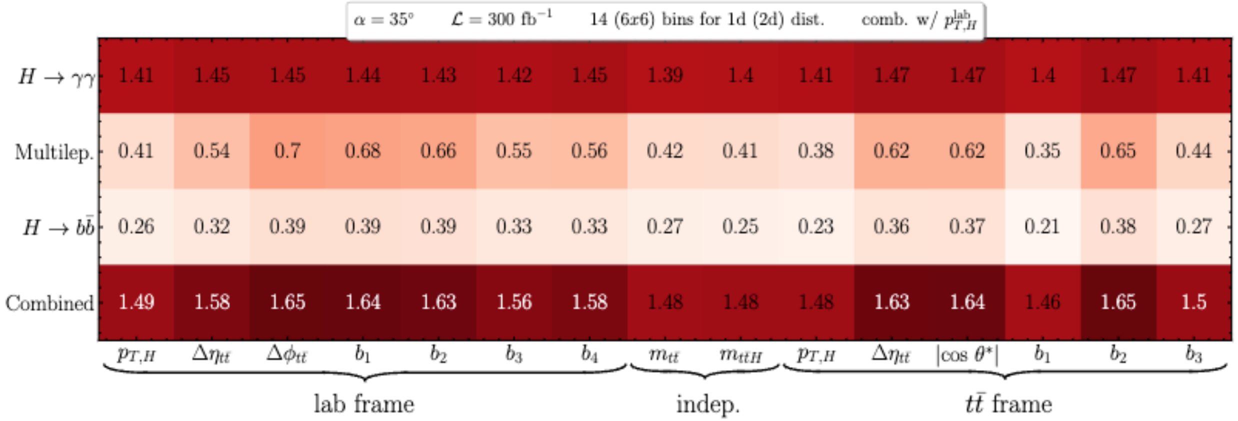
$\alpha = 35^\circ$ $\mathcal{L} = 300\ \text{fb}^{-1}$ 14 (6x6) bins for 1d (2d) dist. comb. w/ $\Delta\phi_{t\bar{t}}$

	lab frame							indep.		$t\bar{t}$ frame					
	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\Delta\phi_{t\bar{t}}$	b_1	b_2	b_3	b_4	$m_{t\bar{t}}$	$m_{t\bar{t}H}$	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\lvert\cos\theta^*\rvert$	b_1	b_2	b_3
$H \to \gamma\gamma$	1.43	1.45	1.42	1.42	1.42	1.42	1.44	1.42	1.44	1.43	1.44	1.44	1.42	1.45	1.42
Multilep.	0.71	0.72	0.63	0.6	0.63	0.65	0.74	0.7	0.72	0.62	0.68	0.72	0.58	0.72	0.66
$H \to b\bar{b}$	0.39	0.41	0.35	0.33	0.34	0.36	0.42	0.39	0.4	0.35	0.37	0.4	0.3	0.4	0.36
Combined	1.65	1.67	1.6	1.58	1.59	1.6	1.68	1.64	1.66	1.6	1.64	1.66	1.56	1.67	1.61

- Most sensitive combination: $(\Delta\phi_{t\bar{t}}^{\text{lab}}, b_2^{t\bar{t}})$ with $S = 1.67$

- Most sensitive combination with $p_{T,H}$: $(p_{T,H}^{\text{lab}}, b_2^{t\bar{t}})$ with $S = 1.65$

Significance tables



$\alpha = 35^\circ$ $\mathcal{L} = 300$ fb^{-1} 14 (6x6) bins for 1d (2d) dist. comb. w/ $p_{T,H}^{\mathrm{lab}}$

	lab frame							indep.		$t\bar{t}$ frame					
	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\Delta\phi_{t\bar{t}}$	b_1	b_2	b_3	b_4	$m_{t\bar{t}}$	$m_{t\bar{t}H}$	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\lvert\cos\theta^*\rvert$	b_1	b_2	b_3
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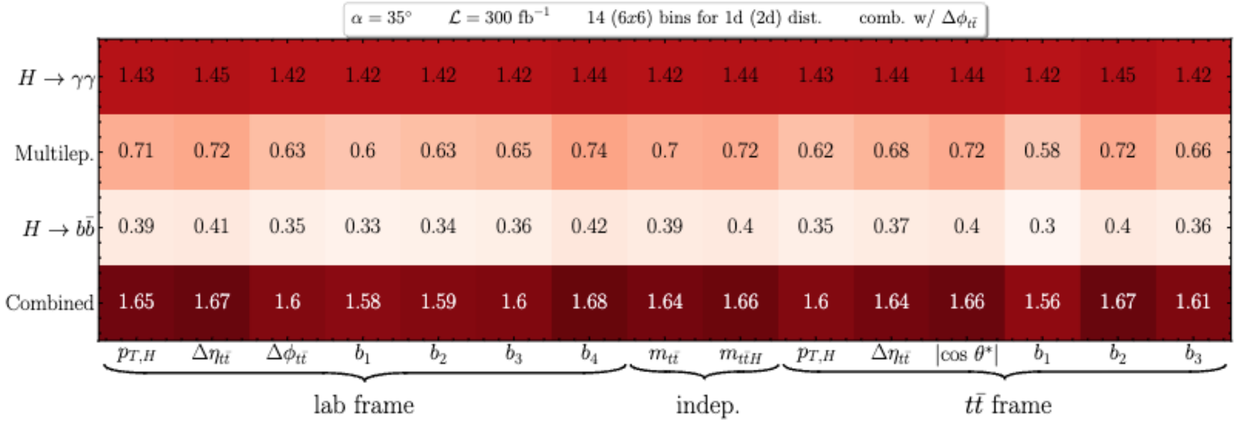

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	lab frame							indep.		$t\bar{t}$ frame					
	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\Delta\phi_{t\bar{t}}$	b_1	b_2	b_3	b_4	$m_{t\bar{t}}$	$m_{t\bar{t}H}$	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\lvert\cos\theta^*\rvert$	b_1	b_2	b_3
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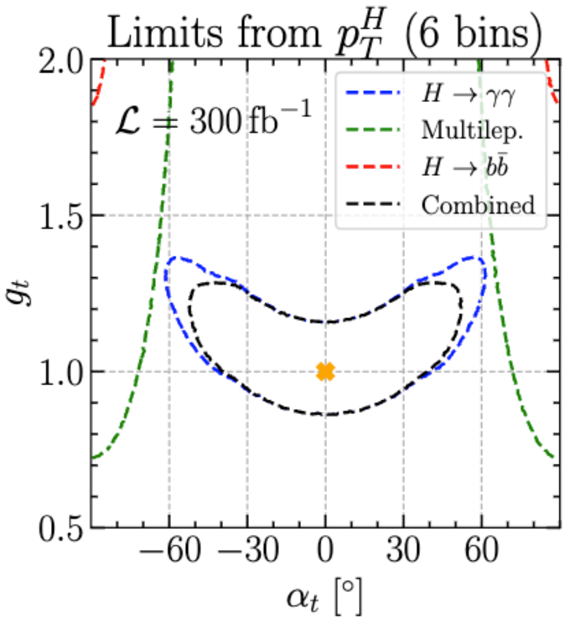
- Most sensitive combination with $p_{T,H}$: $(p_{T,H}^{\mathrm{lab}}, b_2^{t\bar{t}})$ with $S = 1.65$

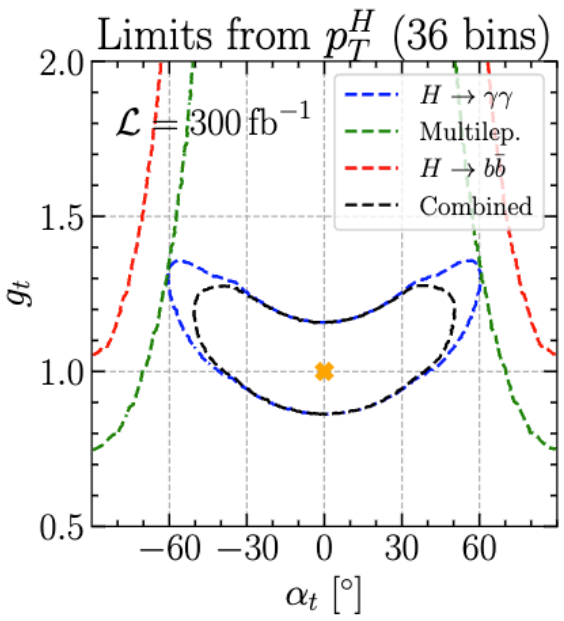
⬇

Extending the current STXS by a second dimension provides near optimal sensitivity!

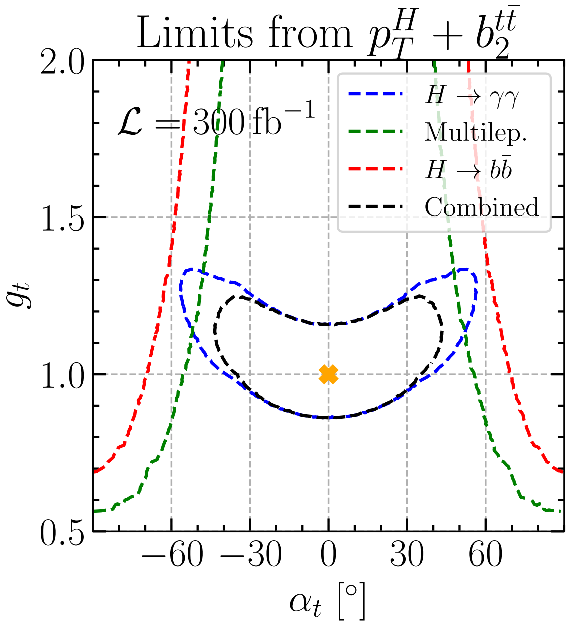
Expected limits



$|\alpha_t| < 60°$

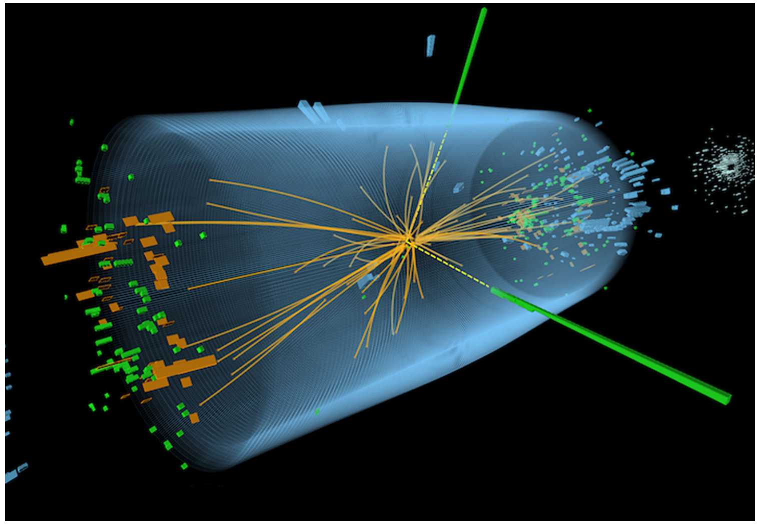


$|\alpha_t| < 48°$



$|\alpha_t| < 42°$

Adding second dimension helps to boost sensitivity!

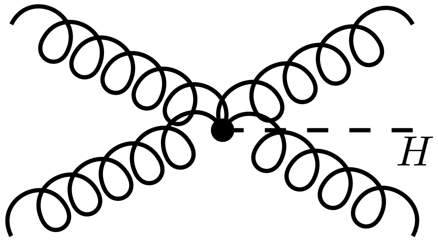


Improving LHC CP measurements

Classifying the CP nature of Higgs + 2 jet production

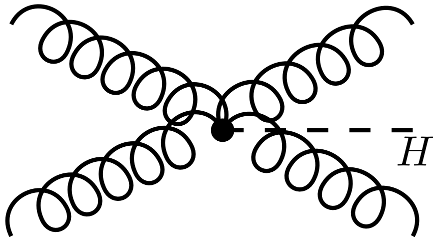
[HB,Hannig,Menen,Fuchs,2309.03146]

Higgs + 2jet production (ggF2j)



Why is ggF2j production interesting for Higgs CP tests? [Hankele, Klamke, Zeppenfeld `06,`07, …]

Higgs + 2jet production (ggF2j)



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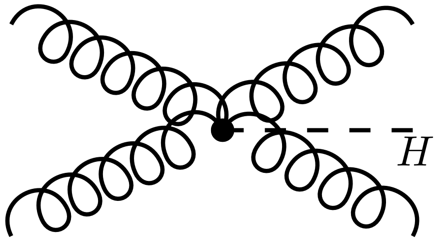
- Gluon fusion is the largest Higgs production channel → wealth of data.

Higgs + 2jet production (ggF2j)

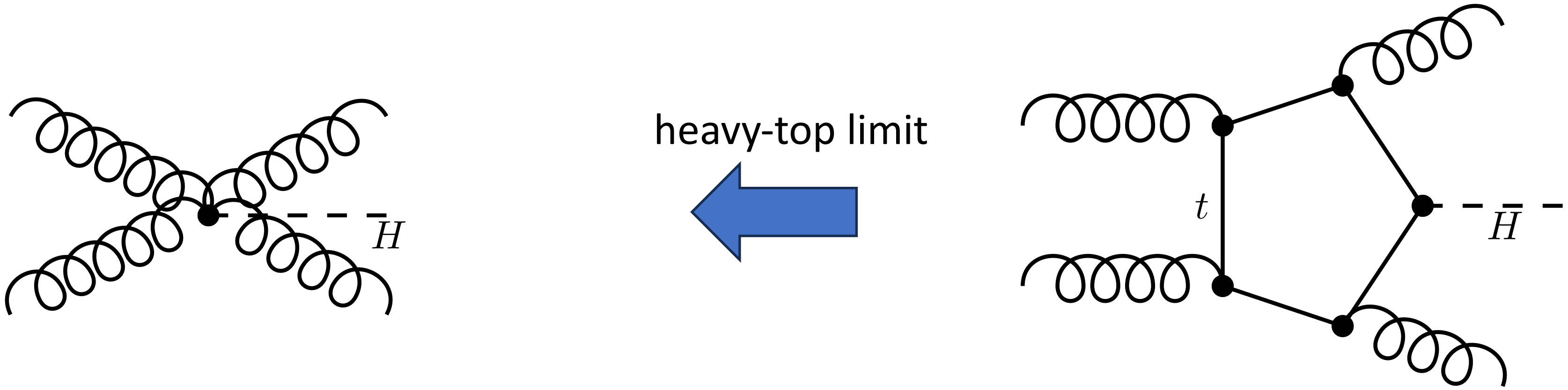


Why is ggF2j production interesting for Higgs CP tests? [Hankele, Klamke, Zeppenfeld `06,`07, …]

- Gluon fusion is the largest Higgs production channel → wealth of data.
- Two additional jets in the final state allow to construct CP-odd observables

  → direct CP test.

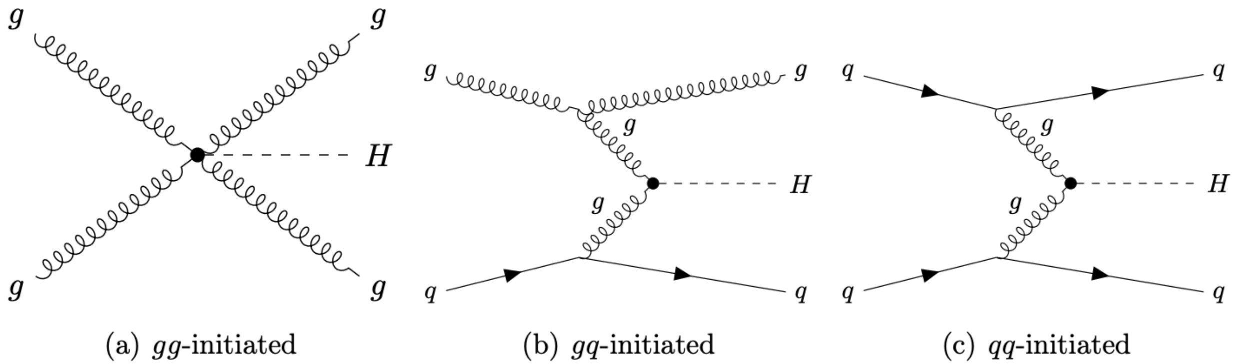
Higgs + 2jet production (ggF2j)



Why is ggF2j production interesting for Higgs CP tests? [Hankele, Klamke, Zeppenfeld `06,`07, …]

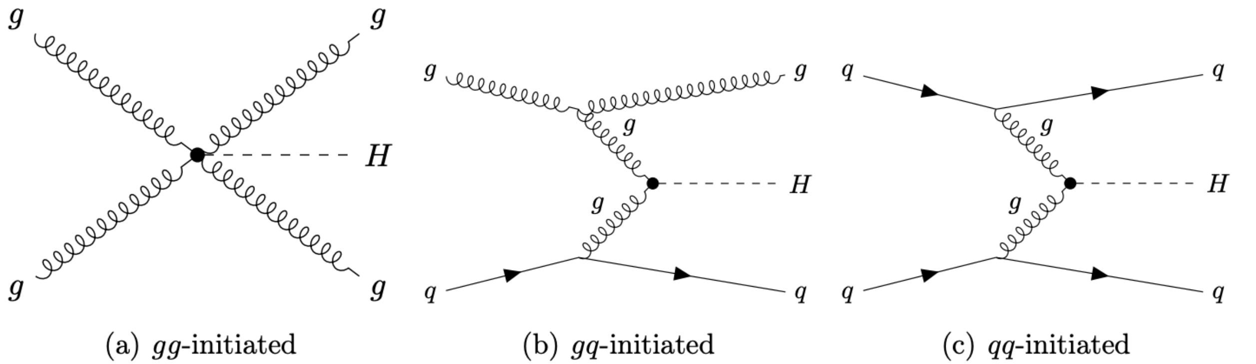
- Gluon fusion is the largest Higgs production channel → wealth of data.
- Two additional jets in the final state allow to construct CP-odd observables → direct CP test.
- Allows for indirect constraint of CP character of top-Yukawa interaction.

ggF2j— amplitude structure



(a) *gg*-initiated (b) *gq*-initiated (c) *qq*-initiated

ggF2j— amplitude structure



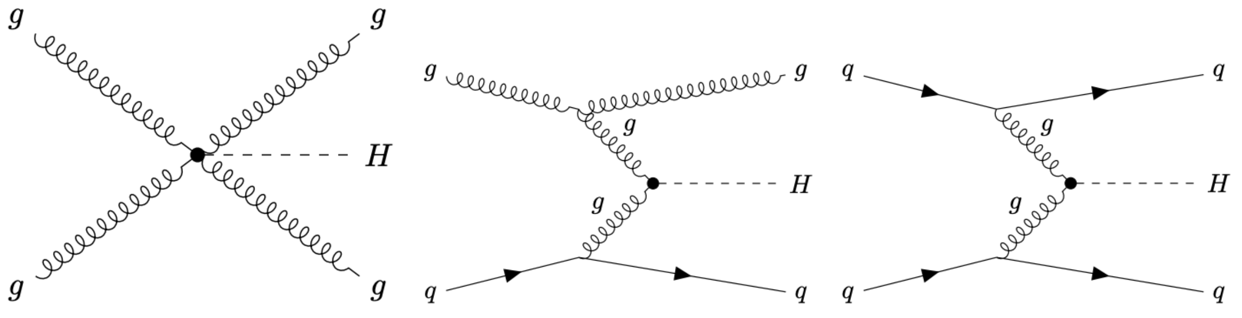
(a) gg-initiated (b) gq-initiated (c) qq-initiated

- Effective Lagrangian (after integrating out the top quark, SM: $c_g = 1$, $\tilde{c}_g = 0$):

$$\mathcal{L}_{Hgg} = -\frac{1}{4v} H \left(-\frac{\alpha_s}{3\pi} c_g G^a_{\mu\nu} G^{a,\mu\nu} + \frac{\alpha_s}{2\pi} \tilde{c}_g G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \right)$$

(heavy top limit enforced by p_T cut)

ggF2j— amplitude structure



(a) *gg*-initiated (b) *gq*-initiated (c) *qq*-initiated

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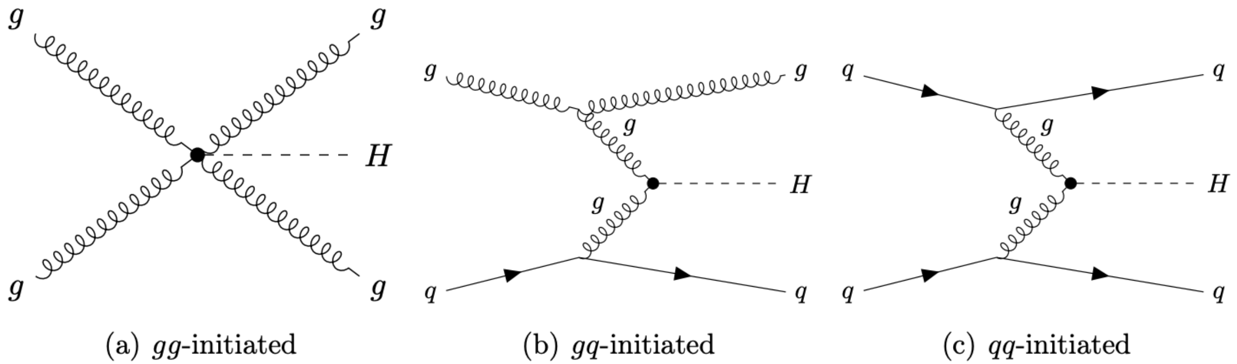
(heavy top limit enforced by p_T cut)

- Amplitude splits up into three pieces:

$$\left|\mathcal{M}_{\mathrm{ggF2j}}\right|^2 = c_g^2 |\mathcal{M}_{\mathrm{even}}|^2 + \underbrace{2 c_g \tilde{c}_g Re[\mathcal{M}_{\mathrm{even}} \mathcal{M}_{\mathrm{odd}}{}^*]}_{\text{interference}} + \tilde{c}_g^2 |\mathcal{M}_{\mathrm{odd}}|^2$$

ggF2j— amplitude structure



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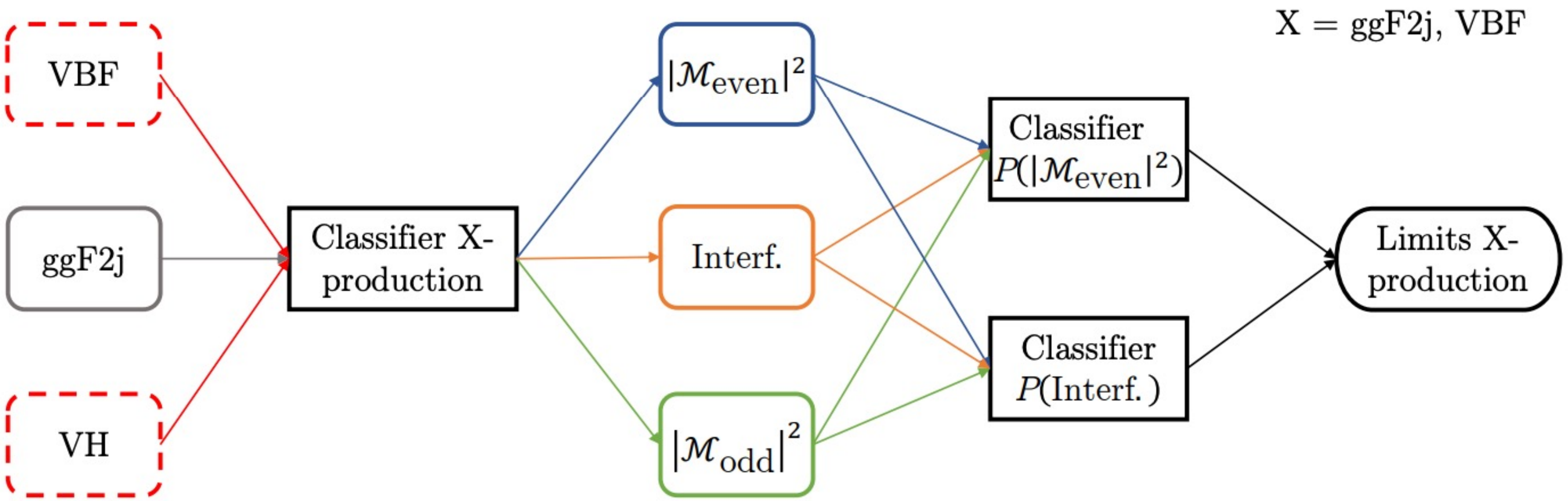
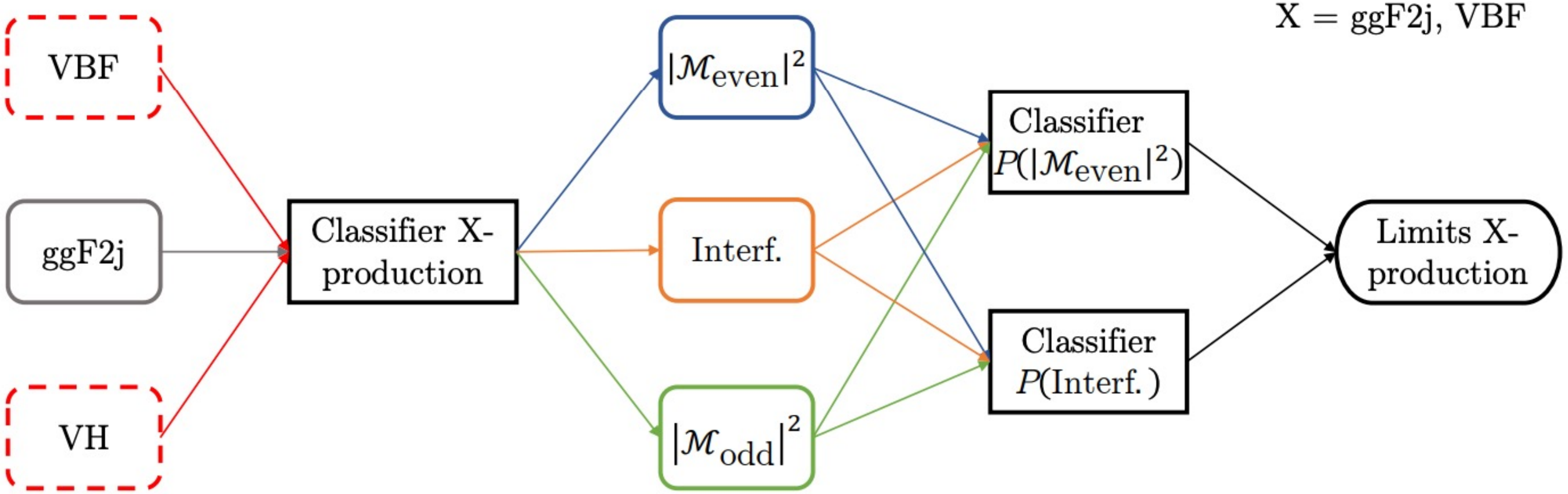
- Existing measurements focus on CP-odd $\Delta\phi_{jj}$ observable to constrain interference term.

Analysis flow



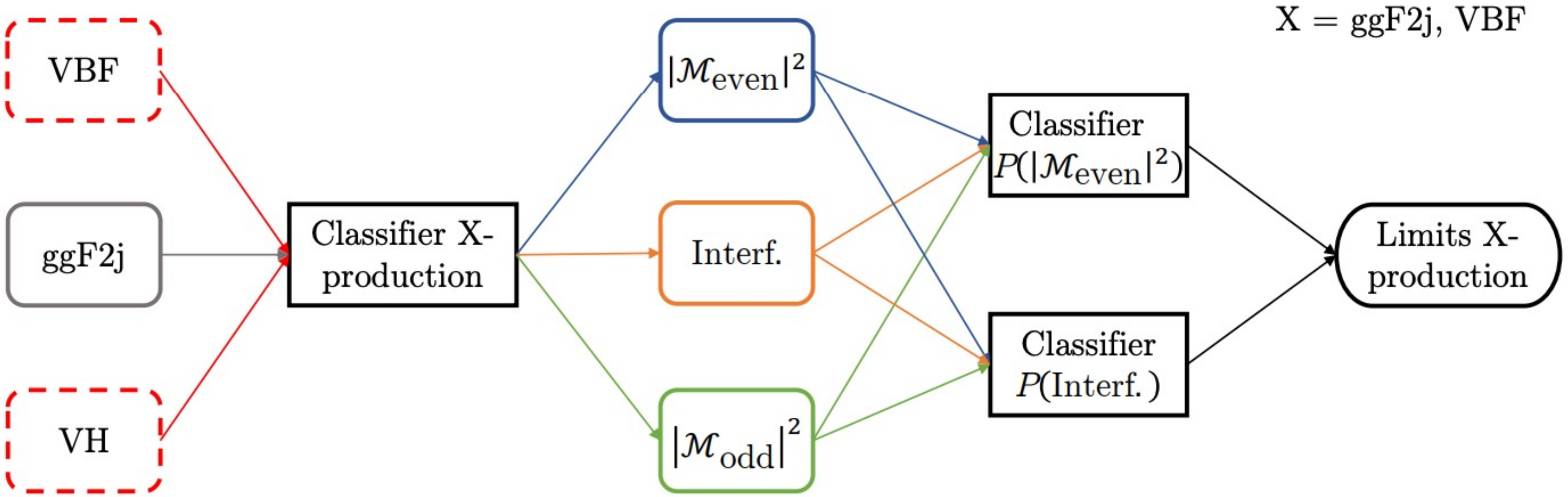
- Focus on $H \to \gamma\gamma$ decay channel.

Analysis flow



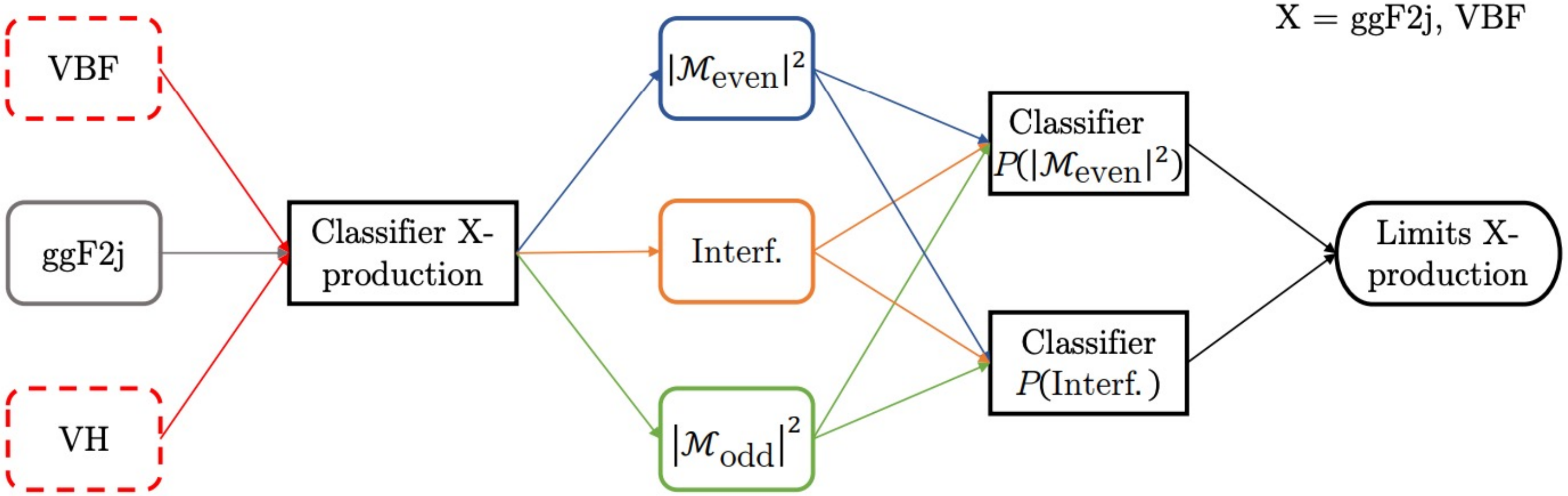
- Focus on $H \to \gamma\gamma$ decay channel.
- Two signal regions: **ggF2j-SR**, VBF-SR

Analysis flow



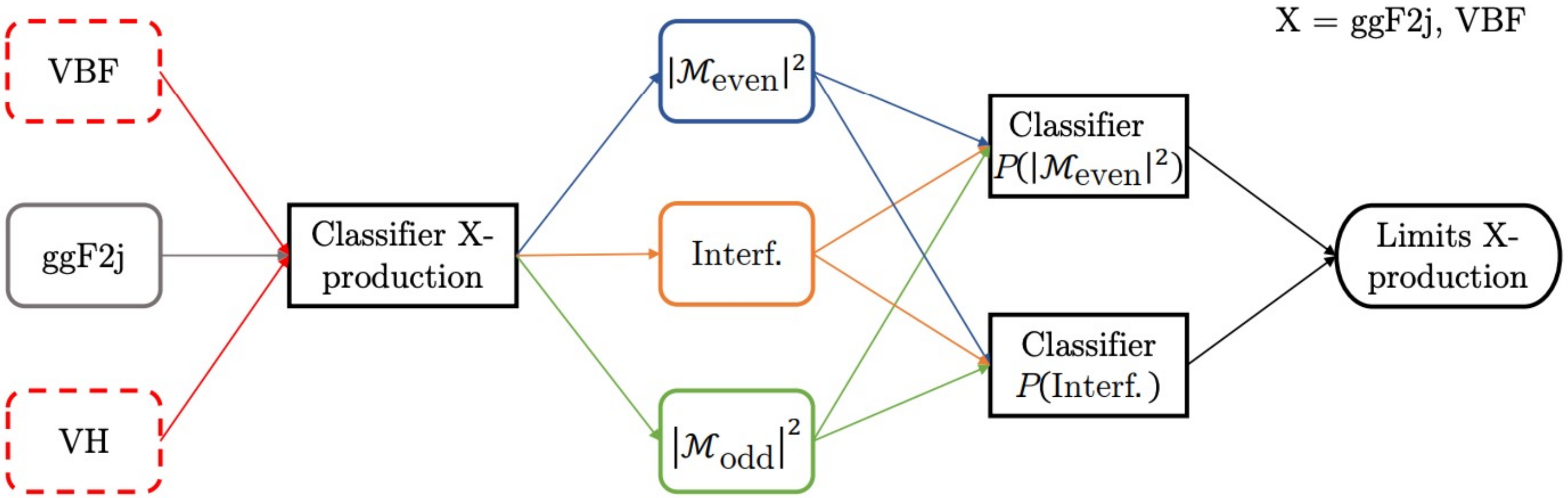
- Focus on $H \to \gamma\gamma$ decay channel.
- Two signal regions: **ggF2j-SR**, VBF-SR
- For each signal region: train classifier to distinguish signal (ggF2j) from Higgs background (VBF, VH).

Analysis flow



- Focus on $H \to \gamma\gamma$ decay channel.
- Two signal regions: **ggF2j-SR**, VBF-SR
- For each signal region: train classifier to distinguish signal (ggF2j) from Higgs background (VBF, VH).
- Then, train two classifiers to distinguish
  - $|\mathcal{M}_{\text{even}}|^2$ vs. $|\mathcal{M}_{\text{odd}}|^2 \to P(|\mathcal{M}_{\text{even}}^2|)$, and
  - (positive intf.) vs (negative intf) $\to P(\text{Interf.})$.

Analysis flow



- Focus on $H \to \gamma\gamma$ decay channel.
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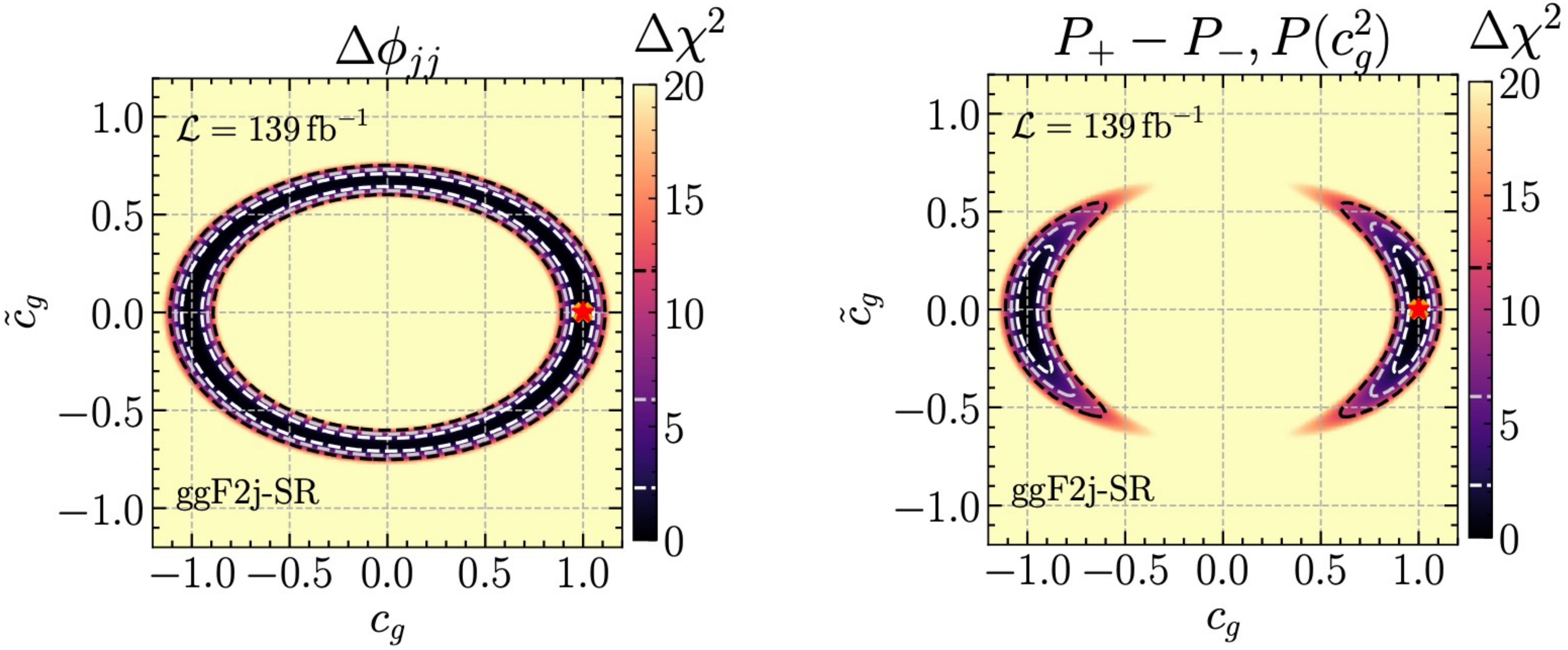
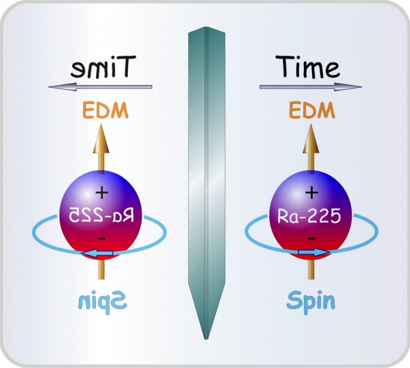
- For each signal region: train classifier to distinguish signal (ggF2j) from Higgs background (VBF, VH).
- Then, train two classifiers to distinguish
  - $|\mathcal{M}_{\text{even}}|^2$ vs. $|\mathcal{M}_{\text{odd}}|^2 \to P(|\mathcal{M}_{\text{even}}^2|)$, and
  - (positive intf.) vs (negative intf) $\to P(\text{Interf.})$.
- Build two observables: CP-even $P(c_g^2)$ and CP-odd $P_+ - P_-$.

ggF2j signal region



- ggF2j signal region outperforms VBF signal region (not shown),
- $\Delta\phi_{jj}$ limit is significantly worse.

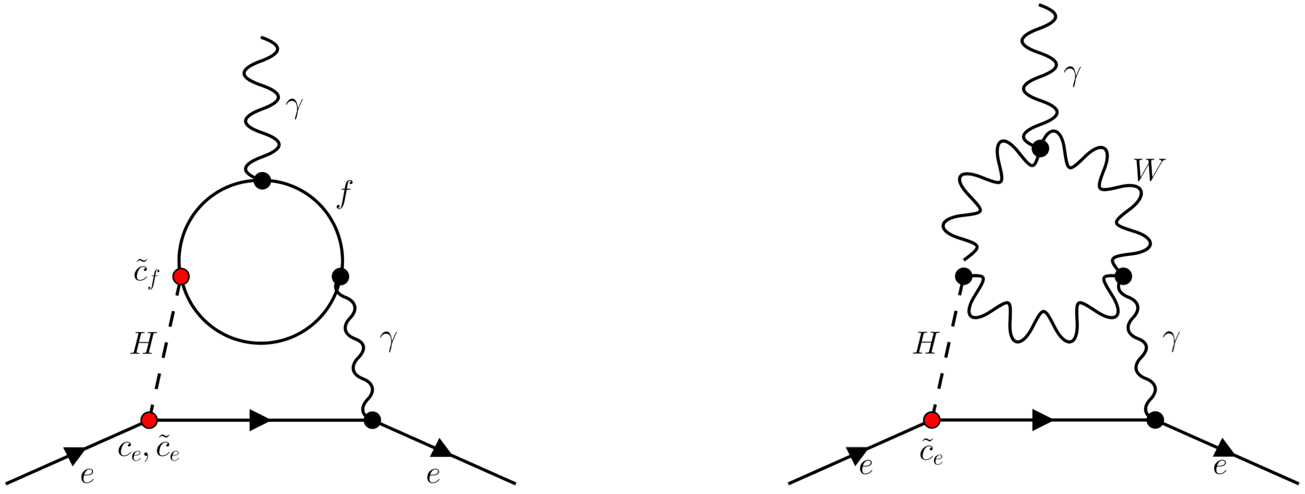


Complementarity with EDM measurements

What do EDM measurements tell us about the Higgs CP nature?

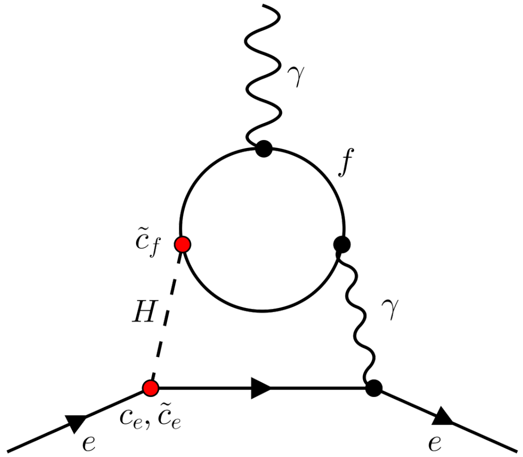
[HB et al., 2202.11753; see also Brod et al., 2203.03736]

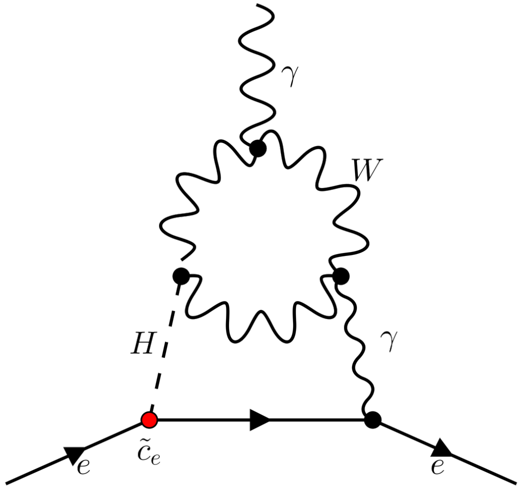
Complementarity with EDM constraints



- Several EDMs are sensitive to CP violation in the Higgs sector.
- Consider here only constraints from theoretically cleanest EDM: the electron EDM.
  [Brod et al.,1310.1385,1503.04830, 1810.12303, 2203.03736;Panico et al.,1810.09413;Altmannshofer et al.,2009.01258]
- Limit by ACME collaboration: $d_e^{\mathrm{ACME}} = 1.1 \cdot 10^{-29} e\ \mathrm{cm}$ at 90% CL. [ACME, *Nature* 562 (2018) 7727, 355-360]

Complementarity with EDM constraints





- Several EDMs are sensitive to CP violation in the Higgs sector.
- Consider here only constraints from theoretically cleanest EDM: the electron EDM.
  [Brod et al.,1310.1385,1503.04830, 1810.12303, 2203.03736;Panico et al.,1810.09413;Altmannshofer et al.,2009.01258]
- Limit by ACME collaboration: $d_e^{\mathrm{ACME}} = 1.1 \cdot 10^{-29} e$ cm at 90% CL. [ACME, *Nature* 562 (2018) 7727, 355-360]
- $\frac{d_e}{d_e^{\mathrm{ACME}}} \simeq c_e(870.0\tilde{c}_t + 3.9\tilde{c}_b + 3.4\tilde{c}_\tau + \cdots) + \tilde{c}_e(610.1c_t + 3.1c_b + 2.8c_\tau - 1082.6c_V + \cdots)$

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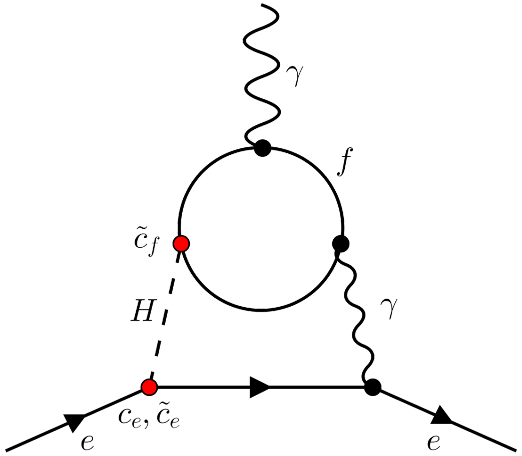

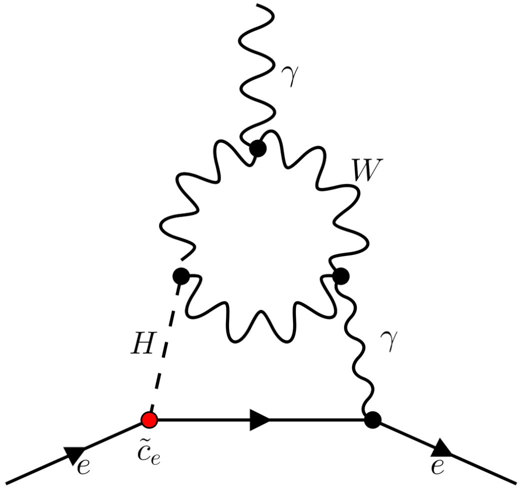

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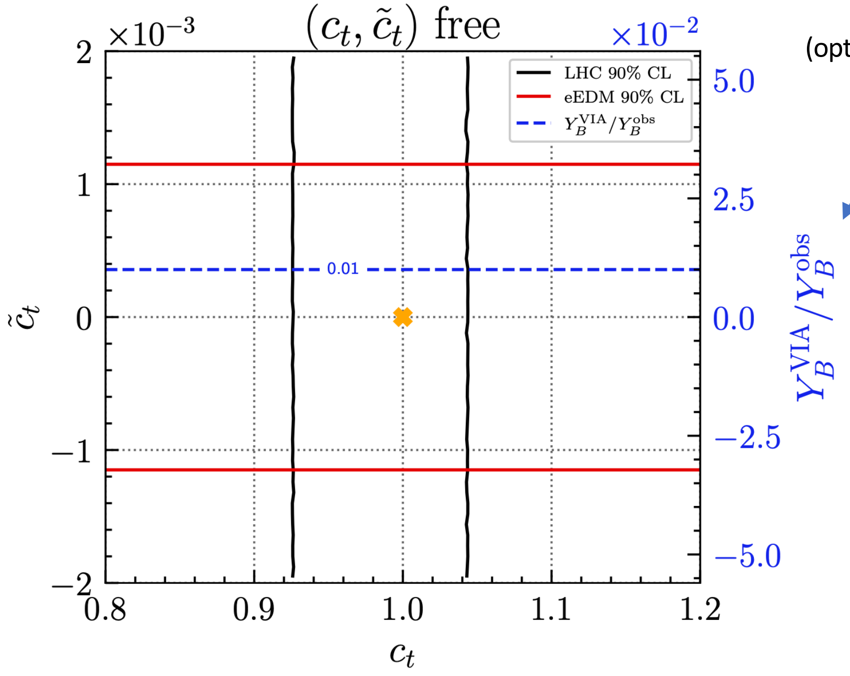
- Bounds strongly depend on assumptions about electron-Yukawa coupling.

Complementarity with EDM constraints: t and τ



Ratio of baryon asymmetry to observation
(optimistic upper bound)

Very strong constraints on CP-odd top-Yukawa coupling.

Complementarity with EDM constraints: t and τ

Ratio of baryon asymmetry to observation
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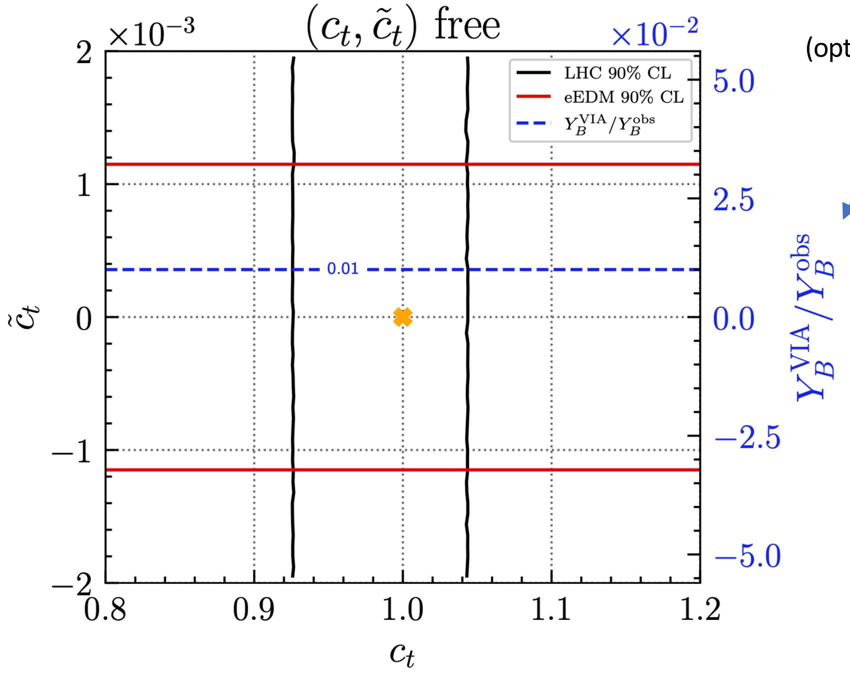
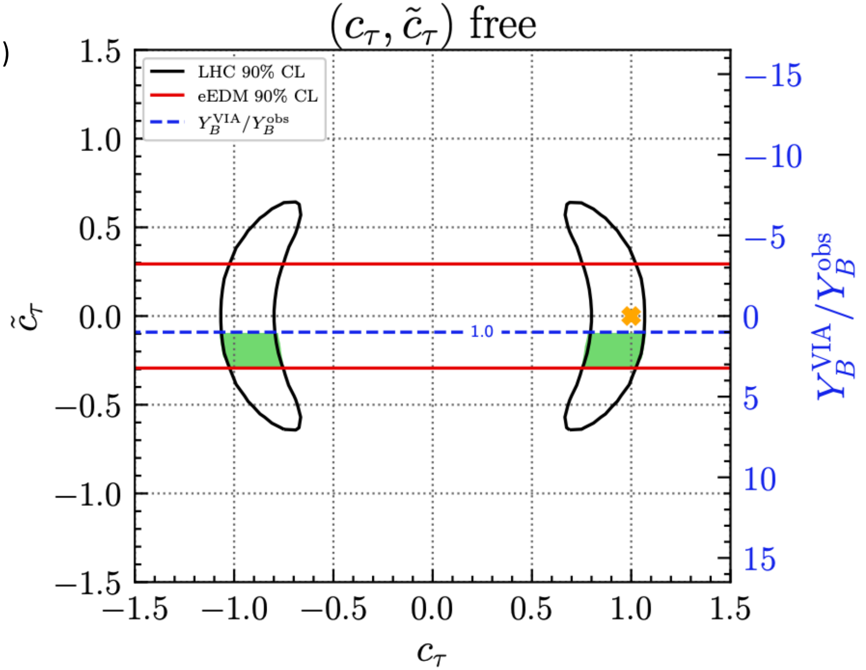
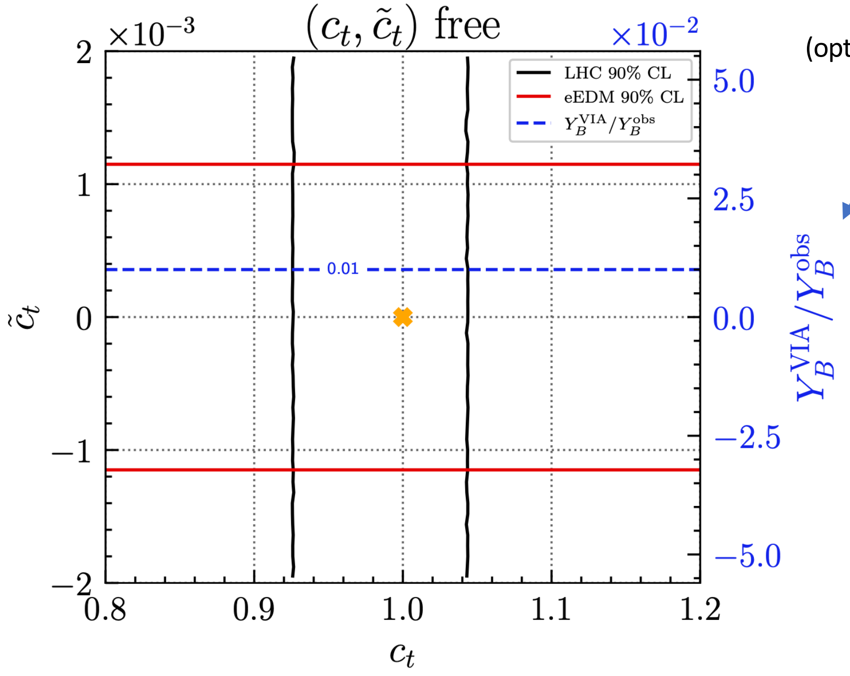




Very strong constraints on CP-odd top-Yukawa coupling.

CP-odd τ coupling can contribute significantly to baryon asymmetry.

Complementarity with EDM constraints: t and τ



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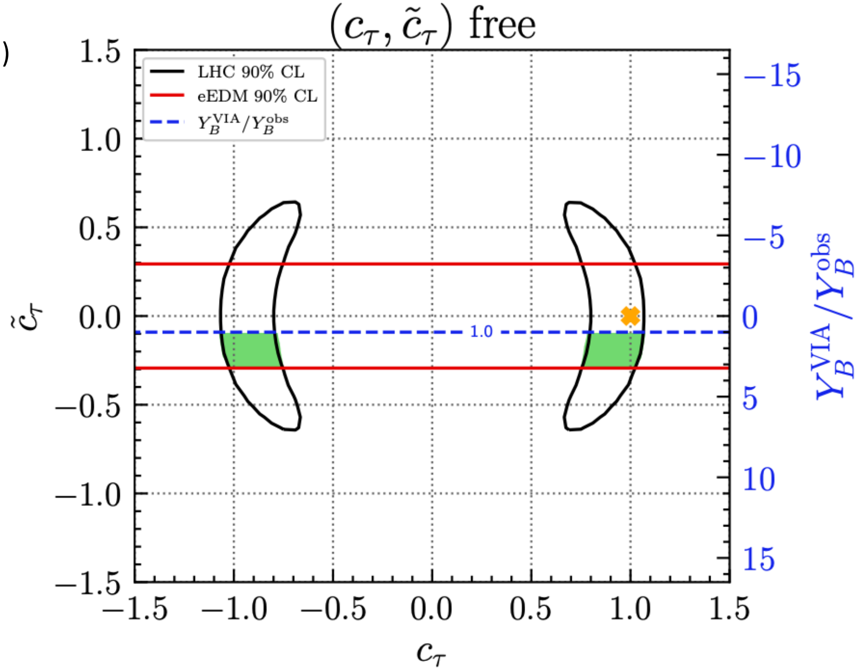

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CP-odd τ coupling can contribute significantly to baryon asymmetry.

→ updated EDM measurement almost completely excludes green area

[Roussy et al., 2212.11841]

EDM > LHC?

[see also Fuchs et al.,1911.08495]

EDM > LHC? **No.**

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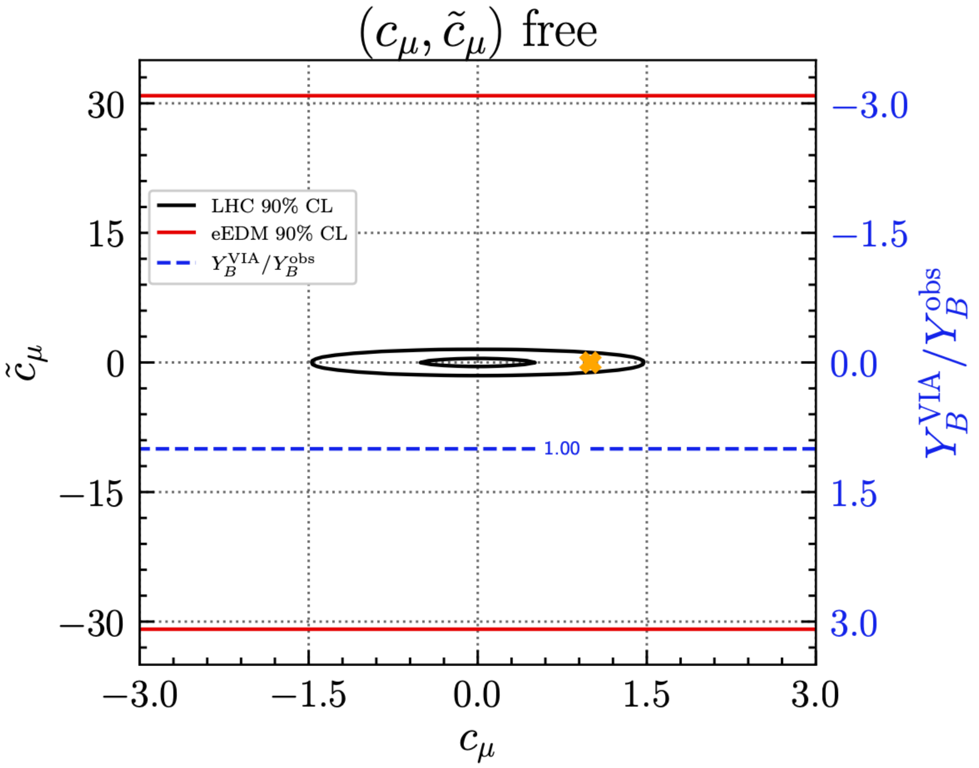
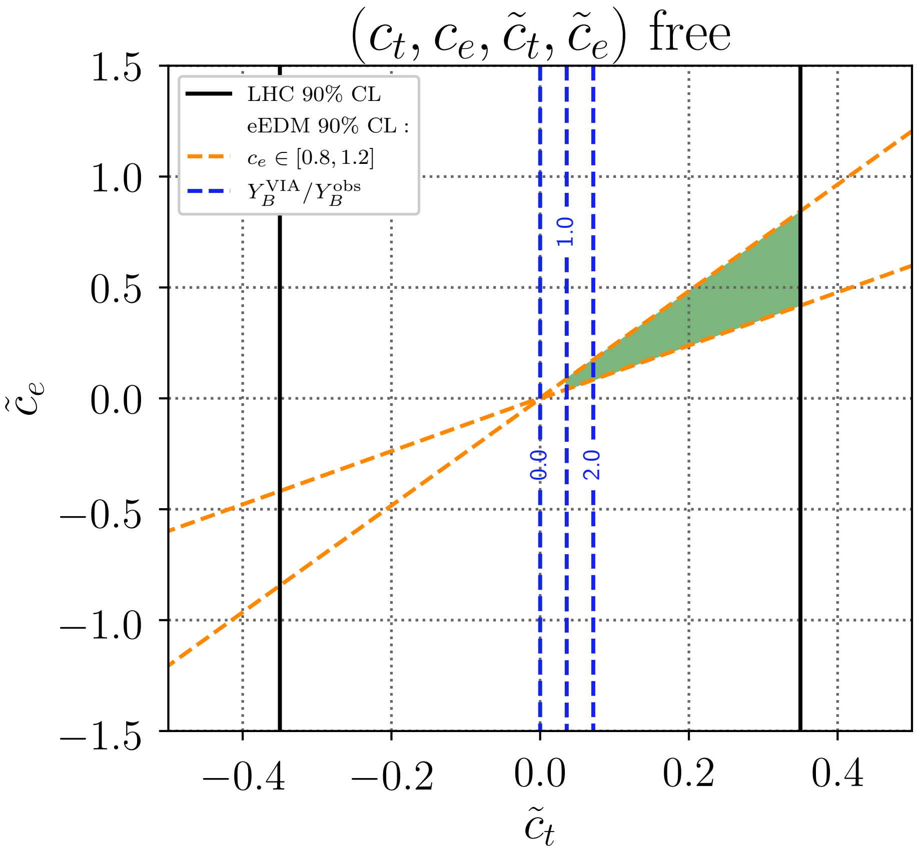


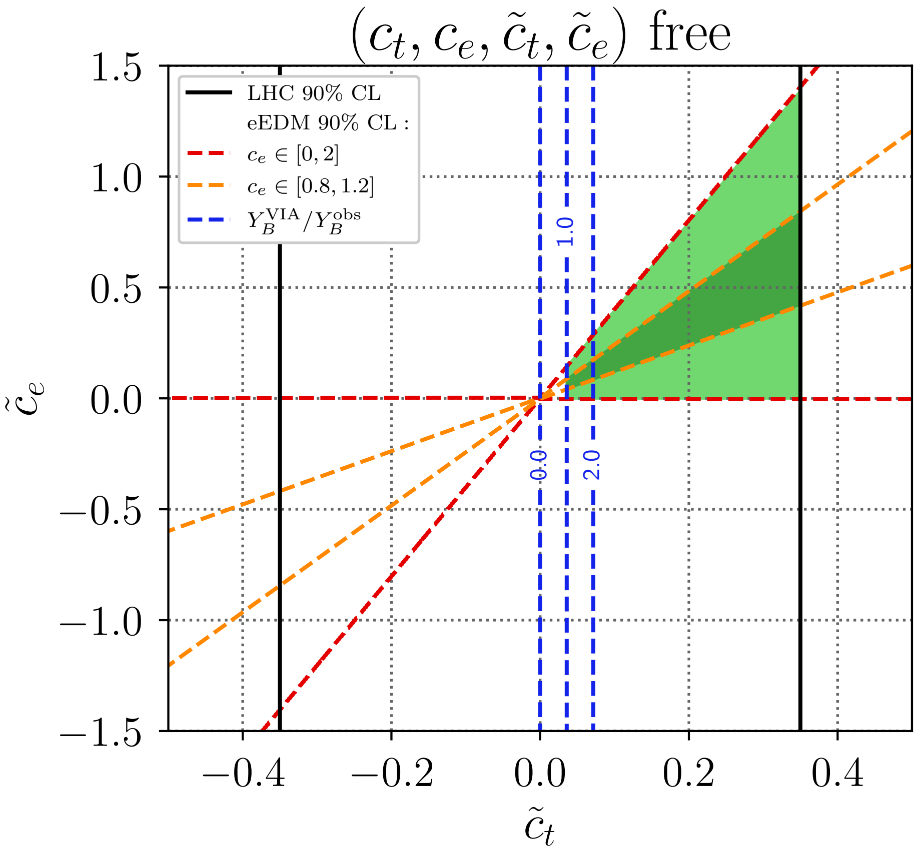
CP-insensitive $H \rightarrow \mu^+\mu^-$ rate measurement outperforms EDM constraint.

Dependence on electron-Yukawa coupling



- Electron Yukawa-coupling only very weakly constrained ($g_e \leq 268$ at 95% CL).
- If c_e smaller, eEDM significantly weakened.
- Moreover, we can fine-tune CP-odd electron-Yukawa coupling such that $d_e < d_e^{\rm ACME}$.
- Neutron EDM has similar dependence on first-generation quark-Yukawa couplings.

Dependence on electron-Yukawa coupling



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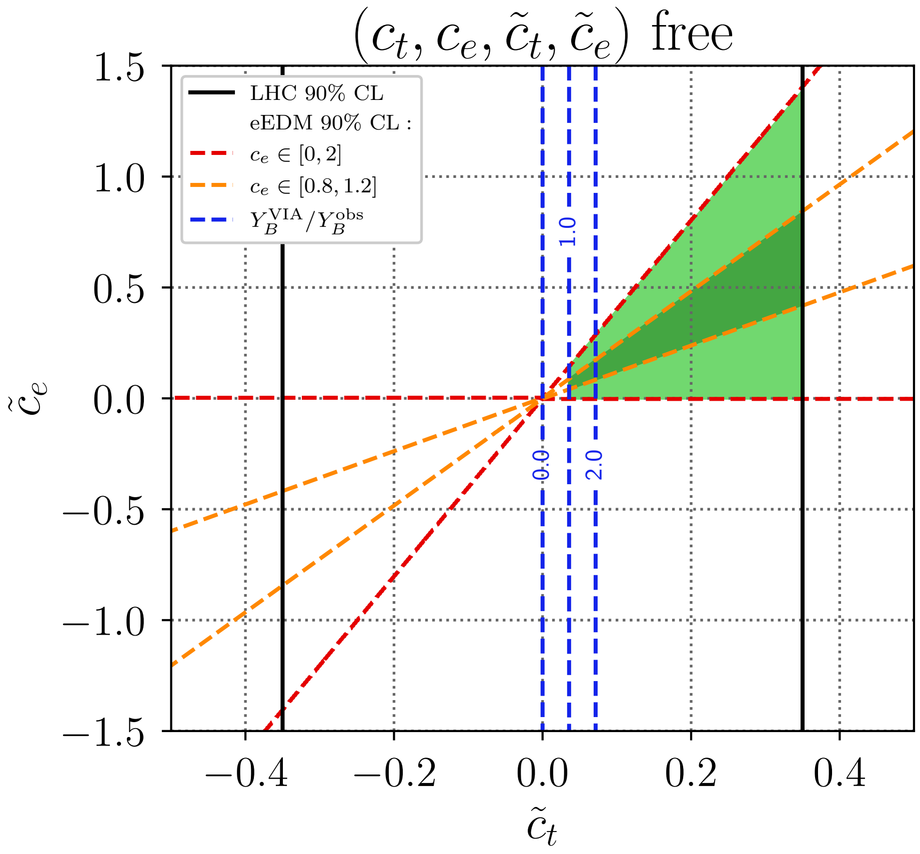
Dependence on electron-Yukawa coupling



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LHC bounds important since they do not depend on 1st gen. Yukawa couplings.

Conclusions

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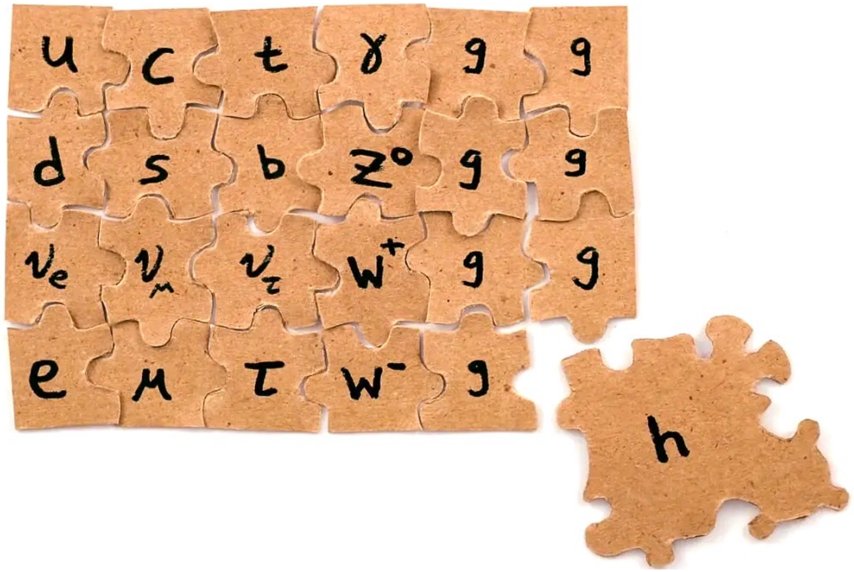
- The Higgs is not the last missing puzzle piece of the SM but could be the link to many BSM scenarios.



Conclusions

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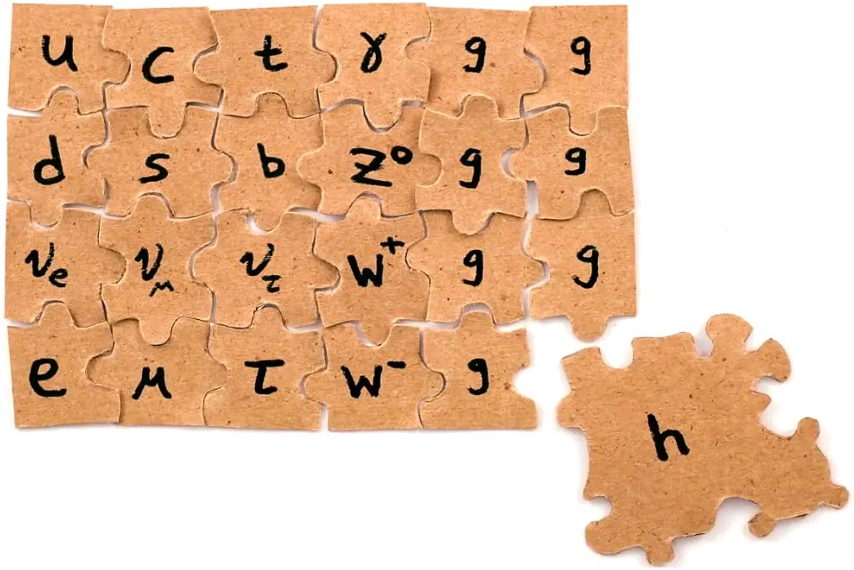
- Many Higgs properties still need to be determined:
  - Light Yukawas,
  - **Higgs CP structure**,
  - Higgs potential,
  - Higgs width,
  - …



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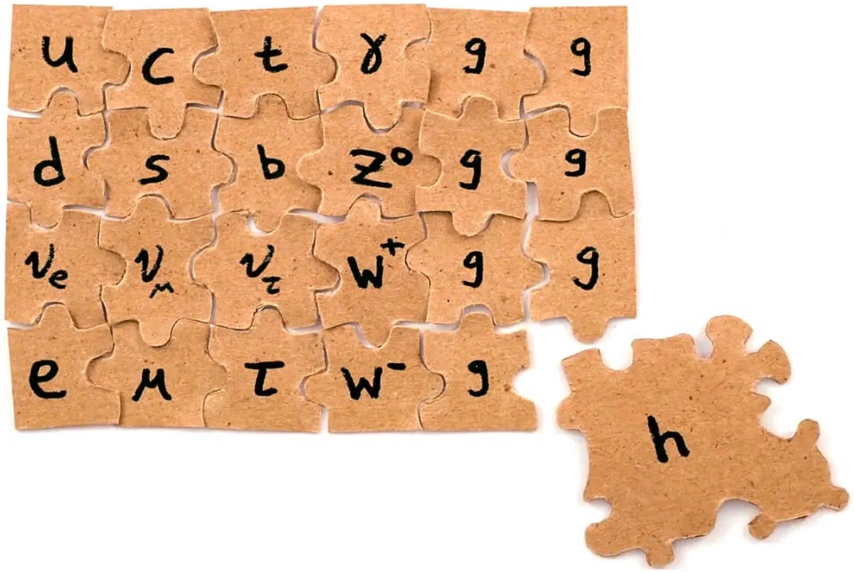
    - The Higgs boson could be a CP-admixed state.
    - Exploit multi-dimensional kinematic information to improve existing bounds.
    - Important interplay between LHC and EDM measurements.



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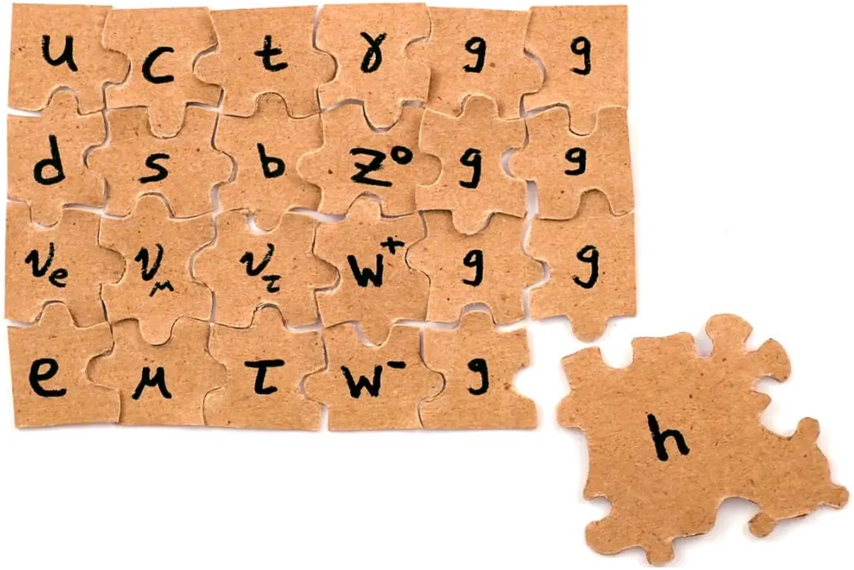


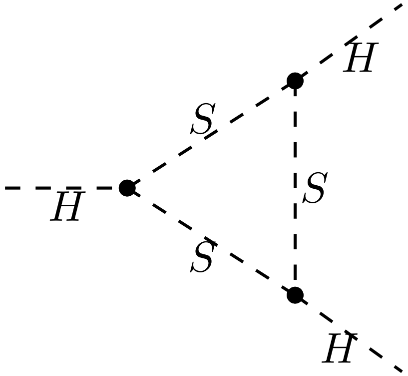
→ **The Higgs will keep us busy for many decades to come!**

Appendix

Case study: real singlet extension of the SM

$$V(\Phi, S) = V_{\text{SM}}(\Phi) + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \lambda_{S\Phi} S^2 \Phi^\dagger \Phi$$

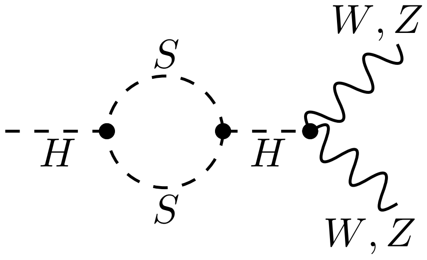
If S does not get a vev, $\lambda_{HHH} = \lambda_{HHH}^{\text{SM}}$ at the tree-level ($m_S^2 = \mu_S^2 + \lambda_{S\Phi} v^2$).



The 1L correction to λ_{HHH} scales like ($\lambda_\Phi^{\text{SM}} \sim 0.25$)

$$\kappa_\lambda \equiv \frac{\lambda_{HHH}}{\lambda_{HHH}^{\text{SM}}} = 1 + \frac{1}{(4\pi)^2}\frac{m_S^4}{v^4 \lambda_\Phi^{\text{SM}}}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3$$

whereas the dominant correction to other Higgs couplings scale like

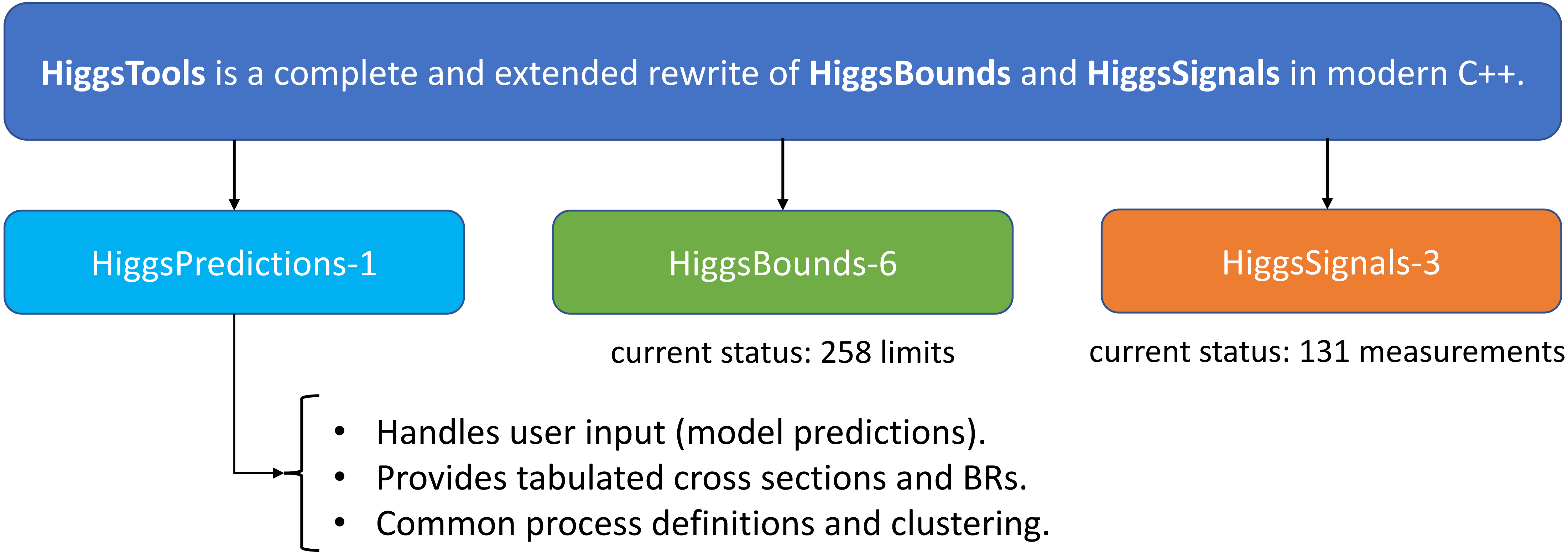


$$\kappa_g \equiv \frac{g}{g^{\text{SM}}} = 1 + \frac{1}{(4\pi)^2}\frac{m_S^2}{v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2$$

➡ Deviation in λ_{HHH} enhanced by a factor $\frac{m_S^2}{v^2 \lambda_\Phi^{\text{SM}}}\left(1 - \frac{\mu_S^2}{m_S^2}\right)$ w.r.t. to other Higgs couplings!

Interlude: HiggsTools

[HB et al., 2210.09332]



HiggsTools is a complete and extended rewrite of **HiggsBounds** and **HiggsSignals** in modern C++.

HiggsPredictions-1

HiggsBounds-6

current status: 258 limits

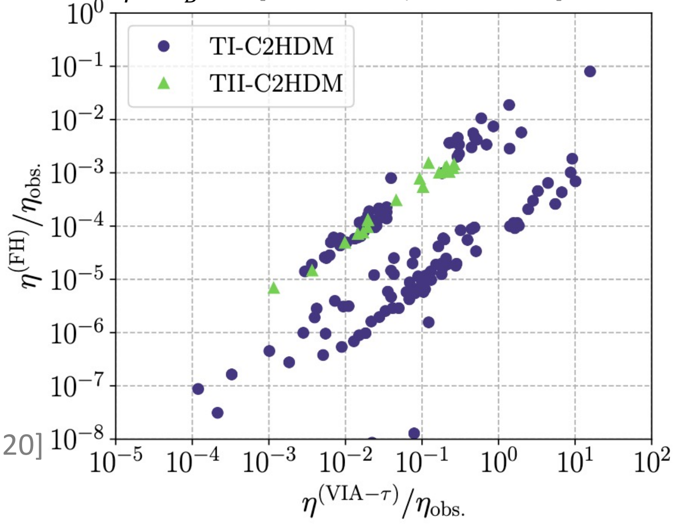
HiggsSignals-3

current status: 131 measurements

- Handles user input (model predictions).
- Provides tabulated cross sections and BRs.
- Common process definitions and clustering.

→ C++ interface for high performance; Python and Mathematica interfaces for ease of use.

Baryon asymmetry of the Universe


$\eta \equiv Y_B$ [Basler et al.,2108.03580]

- Different techniques used in the literature to calculate BAU Y_B:
  - Vev-insertion approach (VIA),

    [Huet&Nelson,9504427,9506477;Carena et al., 9603420;Riotto, 9712221;Lee et al.,0412354;Postma et al.,2206.01120]
  - WKB (or FH) approximation.

    [Joecy et al.,9410282;Kainulainen et al.,0105295, 0202177;Prokopec et al., 0312110, 0406140;Konstandin et al.,1302.6713, 1407.3132]
- VIA approach yields consistently higher results by orders of magnitude.
- We use VIA approach with bubble wall parameters close to optimal values for Y_B:

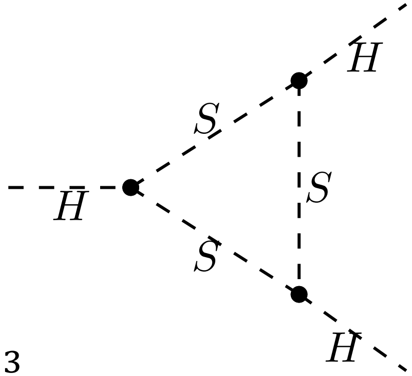
  [de Vries,1811.11104;Fuchs et al.,2003.00099,2007.06940;Shapira,2106.05338]

$$\frac{Y_B}{Y_B^{\mathrm{obs}}} \simeq 28\tilde{c}_t - 0.2\tilde{c}_b - 11\tilde{c}_\tau + \cdots$$

Y_B values should be regarded as **upper bound** on what is theoretically achievable.

Case study: real singlet extension of the SM

$$V(\Phi, S) = V_{\text{SM}}(\Phi) + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \lambda_{S\Phi} S^2 \Phi^\dagger \Phi$$



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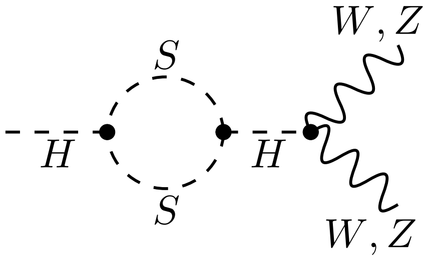
The 1L correction to λ_{HHH} scales like

$$\lambda_{HHH}^{1L} \propto \frac{g_{HSS}^3}{(4\pi)^2} C_0(\dots) \propto \frac{g_{HSS}^3}{(4\pi)^2}\frac{1}{m_S^2} \propto \frac{1}{(4\pi)^2}\frac{m_S^4}{v^3}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3 \Rightarrow \kappa_\lambda \equiv \frac{\lambda_{HHH}}{\lambda_{HHH}^{\text{SM}}} = 1 + \frac{1}{(4\pi)^2}\frac{m_S^4}{v^4 \lambda_\Phi^{\text{SM}}}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3$$

whereas the dominant correction to other Higgs couplings scale like

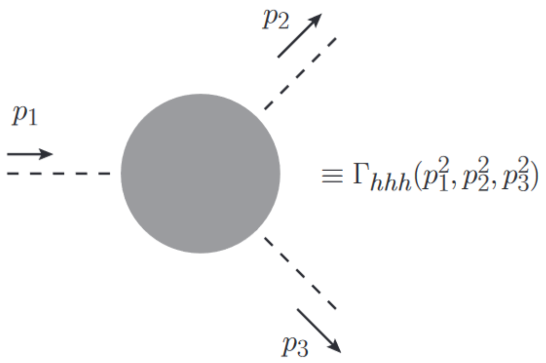


$$g^{1L} \propto \frac{g_{HSS}^2}{(4\pi)^2} B_0'(\dots) \cdot g_{\text{tree}} \propto \frac{1}{(4\pi)^2}\frac{m_S^2}{v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2 \Rightarrow \kappa_g \equiv \frac{g}{g^{\text{SM}}} = 1 + \frac{1}{(4\pi)^2}\frac{m_S^2}{v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2$$

➡ Deviation in λ_{HHH} enhanced by a factor $\frac{m_S^2}{v^2\lambda_\Phi^{\text{SM}}}\left(1 - \frac{\mu_S^2}{m_S^2}\right)$ w.r.t. to other Higgs couplings!

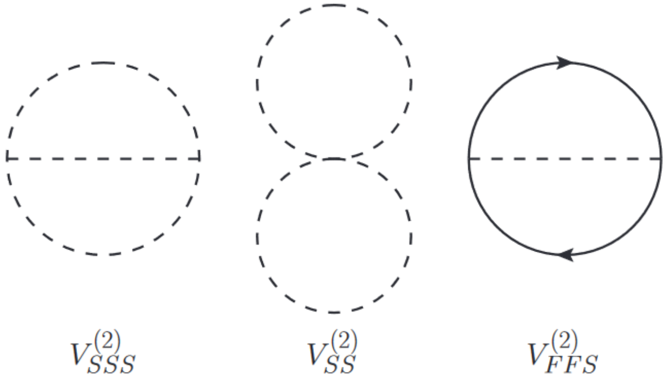
Calculating BSM corrections to κ_λ

- Need to calculate Higgs three-point function:



- Alternatively, employ zero momentum approximation and then use effective potential:

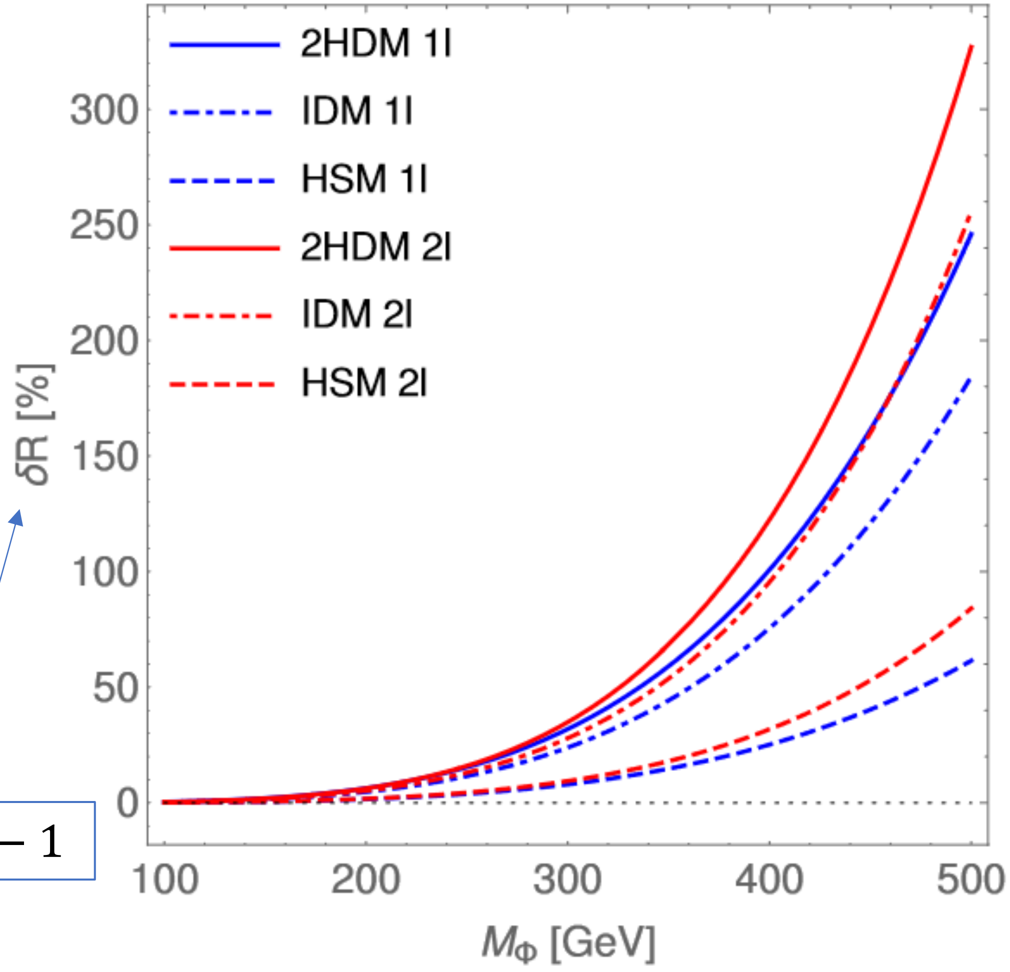
$$\lambda_{hhh} \equiv \left.\frac{\partial^3 V_{\text{eff}}}{\partial h^3}\right|_{\text{min}} \equiv \lambda^{(0)}_{hhh} + \kappa\delta^{(1)}\lambda_{hhh} + \kappa^2\delta^{(2)}\lambda_{hhh}$$



- Using V_{eff}, 1L and 2L corrections have been calculated in various BSM Higgs models (see e.g. [Braathen,Kanemura,1911.11507]).

Calculating BSM corrections to κ_λ

[Braathen,Kanemura,1911.11507]



$\delta R = \kappa_\lambda - 1$

- Large non-decoupling corrections found in several BSM models.
- Analysis assumed that all BSM masses are equal M_Φ.
- No phenomenological analysis has been performed.

Idea of this work:

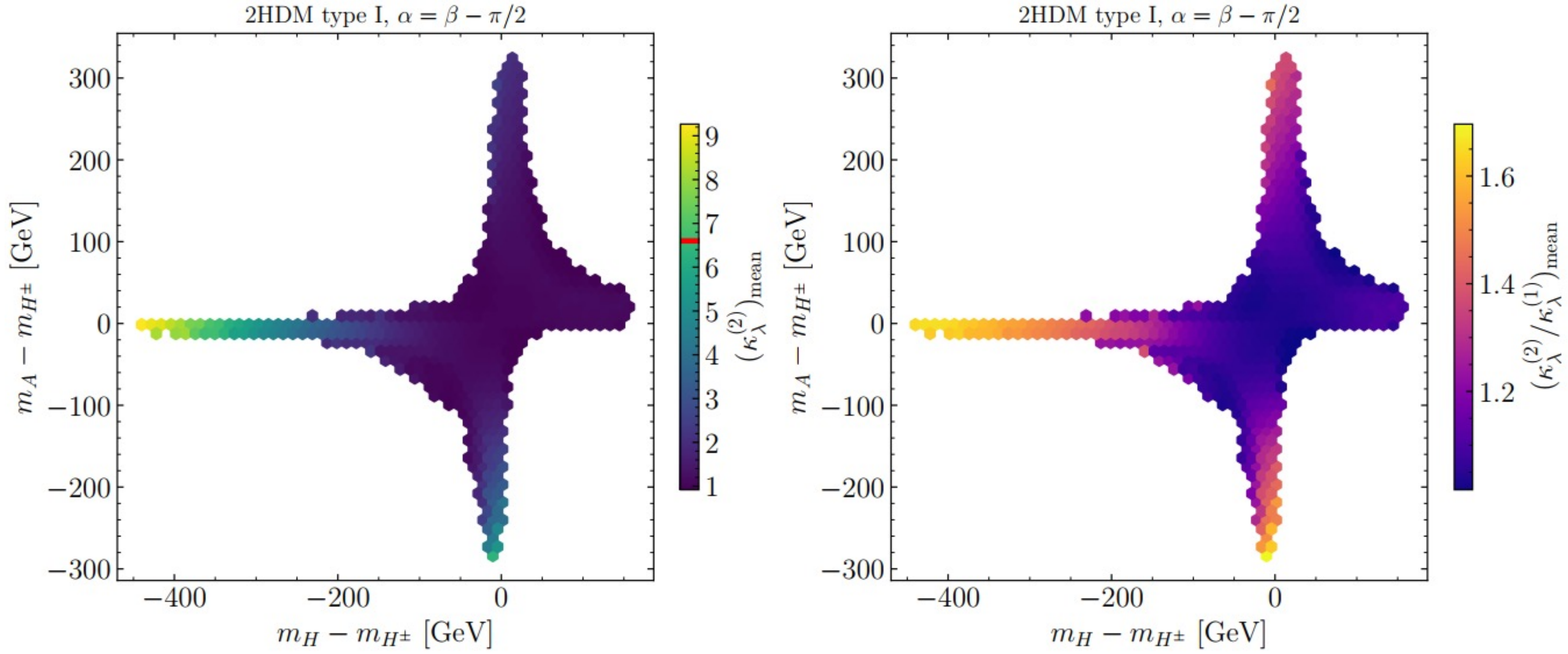
Can we constrain these models based on the large corrections to κ_λ?

2HDM parameter scan

- We checked for
  - vacuum stability and boundedness-from-below,
  - NLO perturbative unitarity, [Grinstein et al., 1512.04567; Cacchio et al., 1609.01290]
  - electroweak precision observables (calculated at the 2L level using THDM_EWPOS), [Hessenberger & Hollik,1607.04610,2207.03845]
  - SM-like Higgs measurements via HiggsSignals, [Bechtle et al., 2012.09197]
  - direct searches for BSM scalars via HiggsBounds, [Bechtle et al., 2006.06007]
  - b-physics constraints.
- Most constraints checked using ScannerS. [Mühlleitner et al., 2007.02985]
- For each point passing the constraints, we calculate κ_λ at the 1L and 2L level ($\kappa_\lambda^{(1)}$ and $\kappa_\lambda^{(2)}$). [Braathen,Kanemura,1911.11507]

2HDM parameter scan — results

(showing only points passing all constraints mentioned on previous slide)



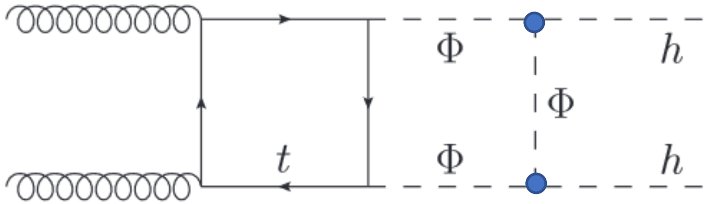
➡

- Largest corrections for $m_A \simeq m_{H^\pm}, m_H < m_{H^\pm}$ and $m_H \simeq m_{H^\pm}, m_A < m_{H^\pm}$ (κ_λ of up to 9).
- 2L corrections have sizeable impact (up to 70%).

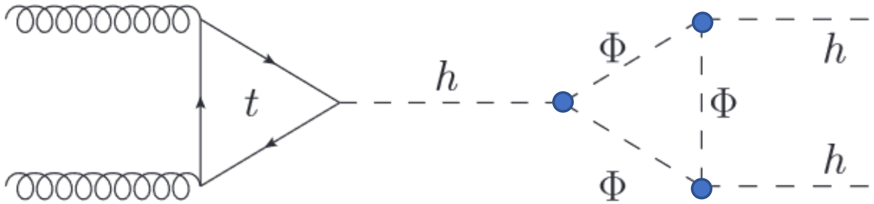
Can we apply the experimental constraints on κ_λ?

Assumptions of experimental bound:

- All other Higgs couplings are SM-like.
  - 2HDM in the alignment limit with heavy BSM masses. ✓
- Higgs-boson pair production only deviates from the SM via a modified trilinear Higgs coupling.
  - No resonant contribution because Hhh coupling is zero in alignment limit. ✓
  - Other BSM contributions to hh production?



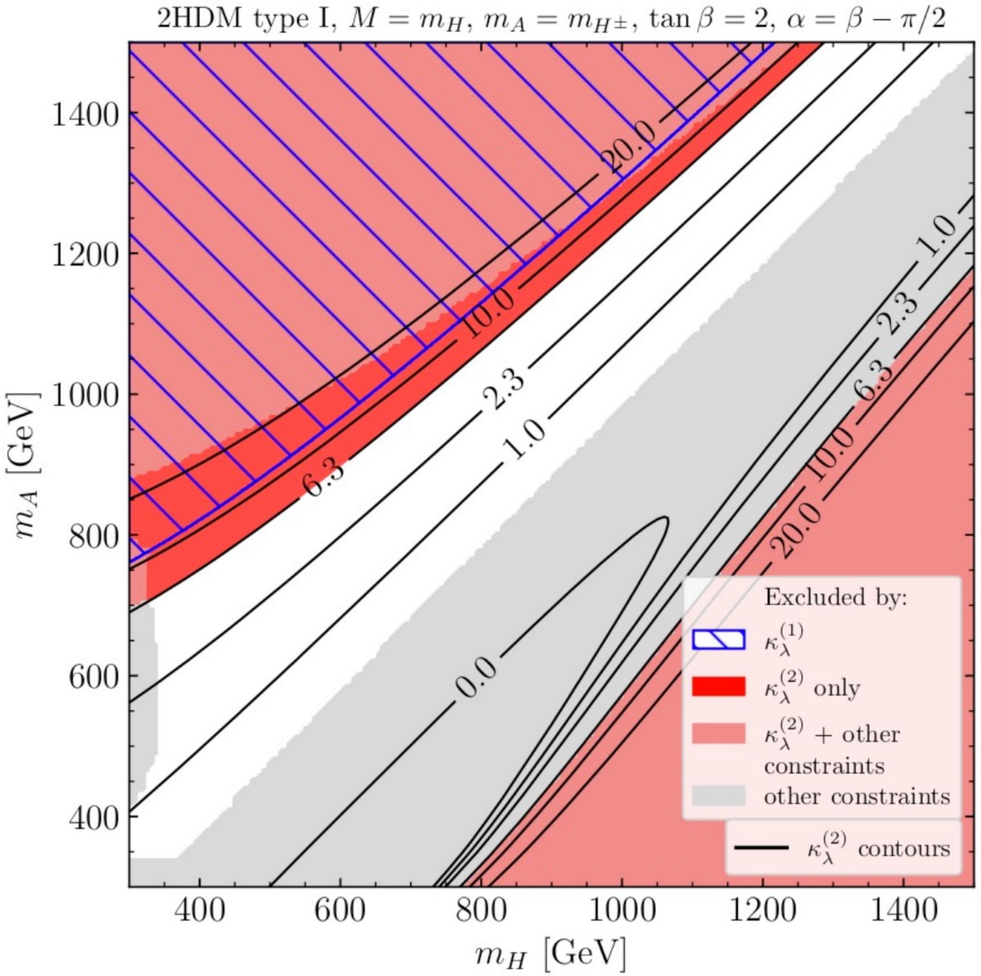
$\propto \mathcal{O}(y_t^2 g_{hh\Phi\Phi}^2)$ (not included)



$\propto \mathcal{O}(y_t g_{hh\Phi\Phi}^3)$ (included)

  - We include the all corrections leading in the large coupling $g_{hh\Phi\Phi}$ at the NLO and NNLO level. ✓

Constraints on κ_λ — benchmark scenario



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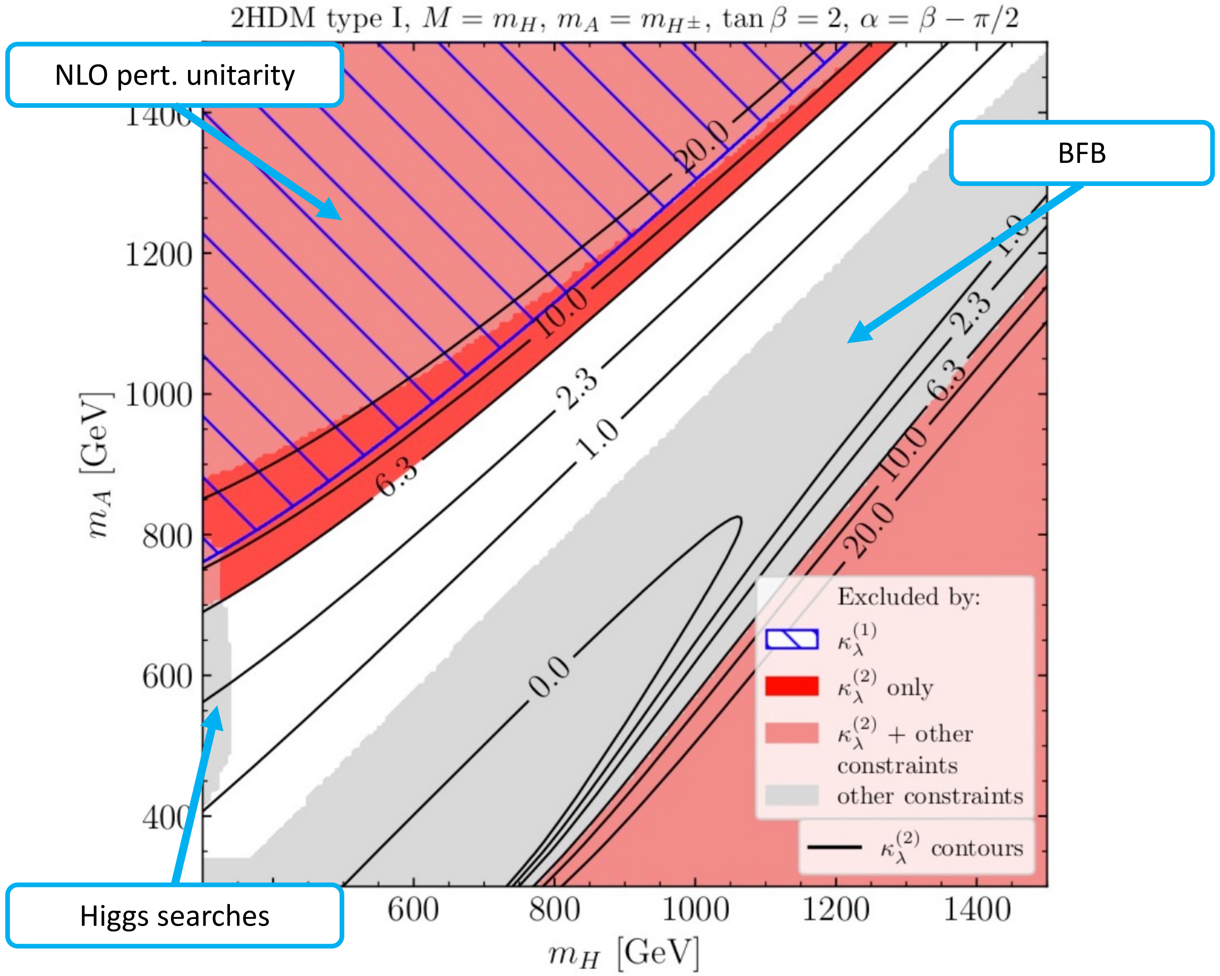
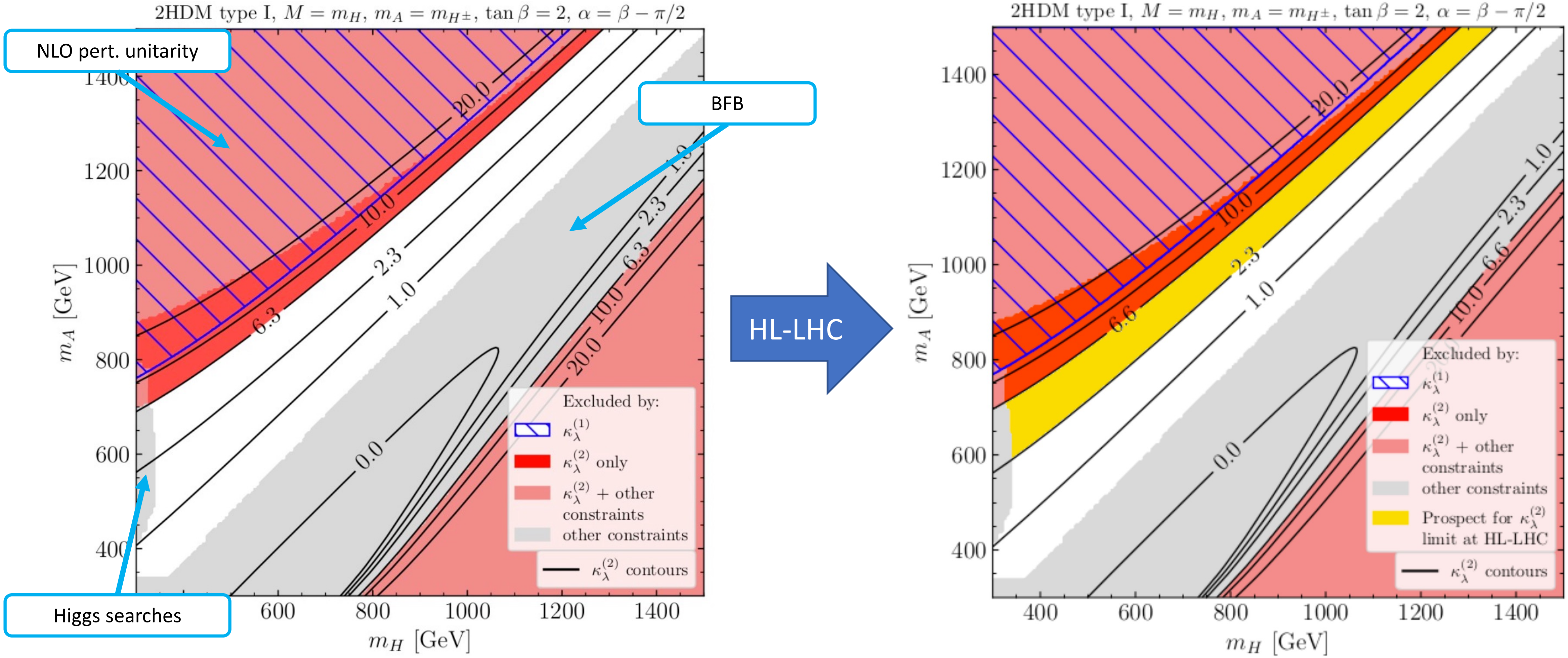


NLO pert. unitarity

BFB

Higgs searches

Constraints on κ_λ — benchmark scenario


2HDM type I, $M = m_H$, $m_A = m_{H^\pm}$, $\tan\beta = 2$, $\alpha = \beta - \pi/2$

NLO pert. unitarity

BFB

Higgs searches

HL-LHC

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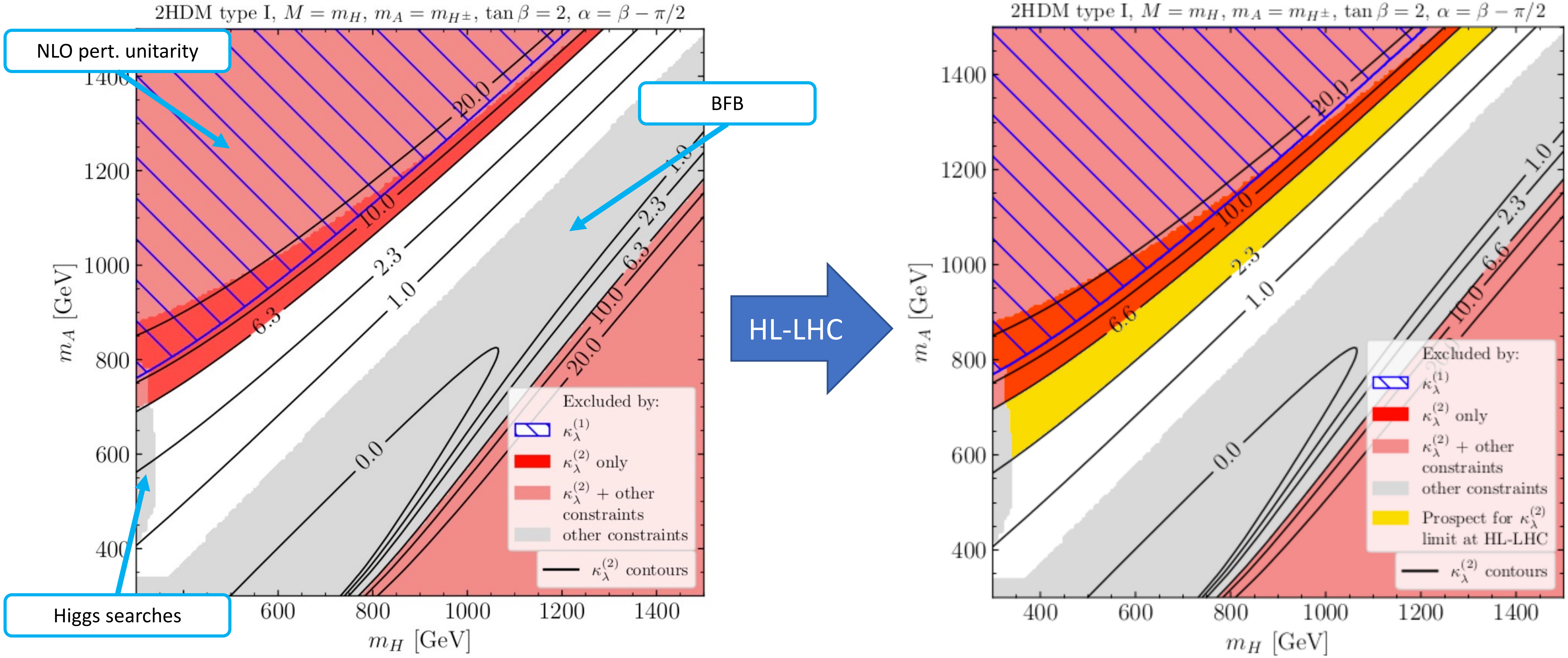
NLO pert. unitarity

BFB

Higgs searches

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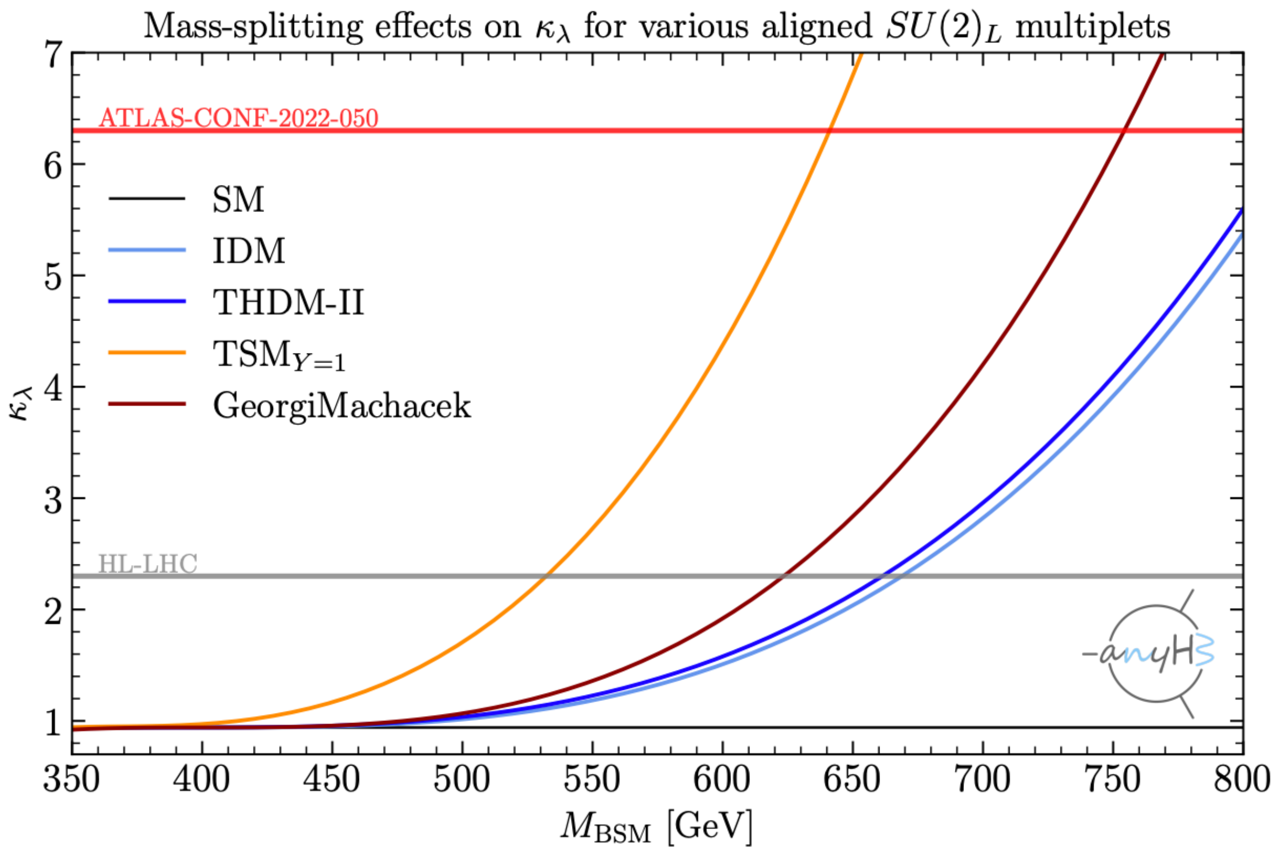
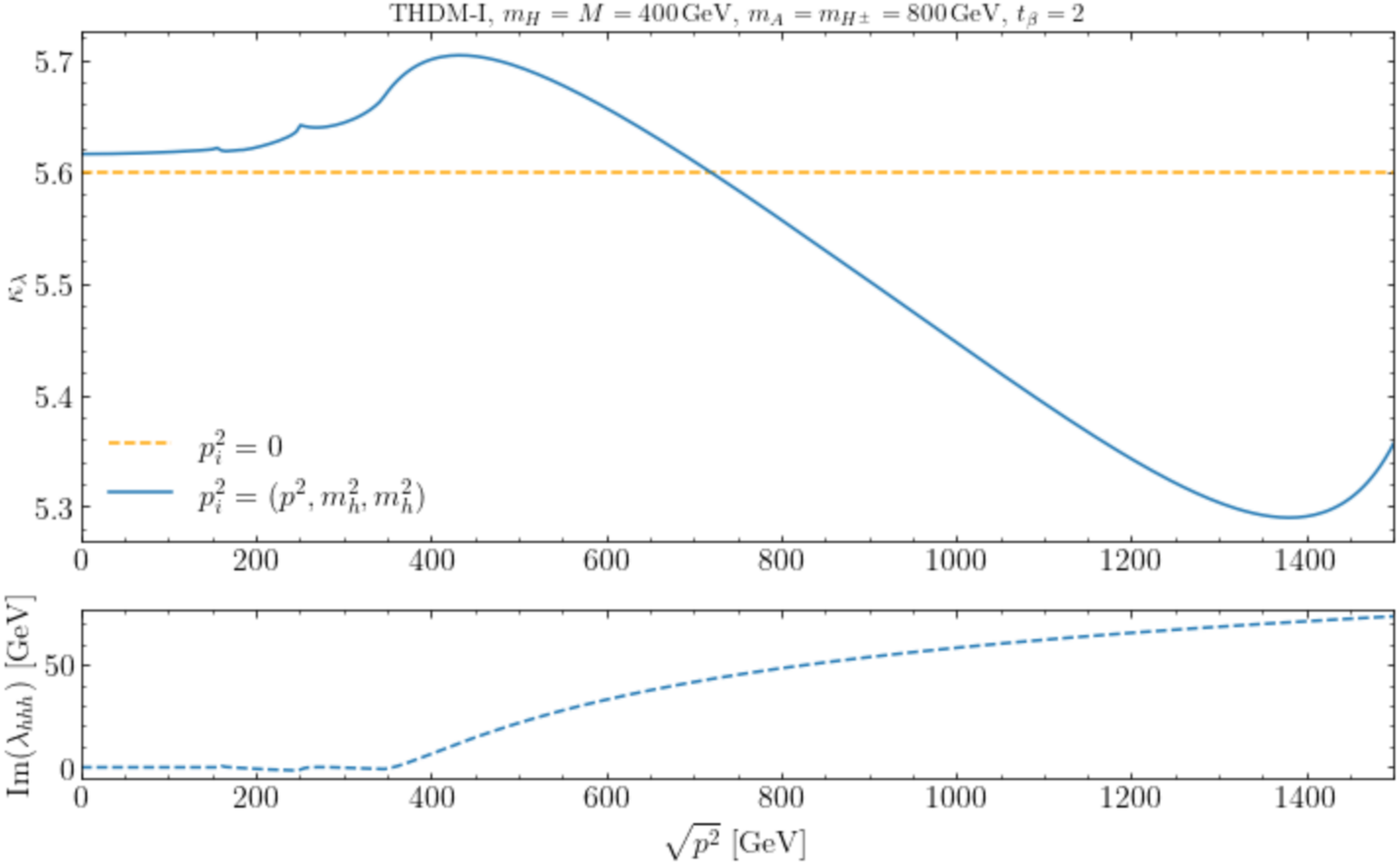
Other extension of SM Higgs sector



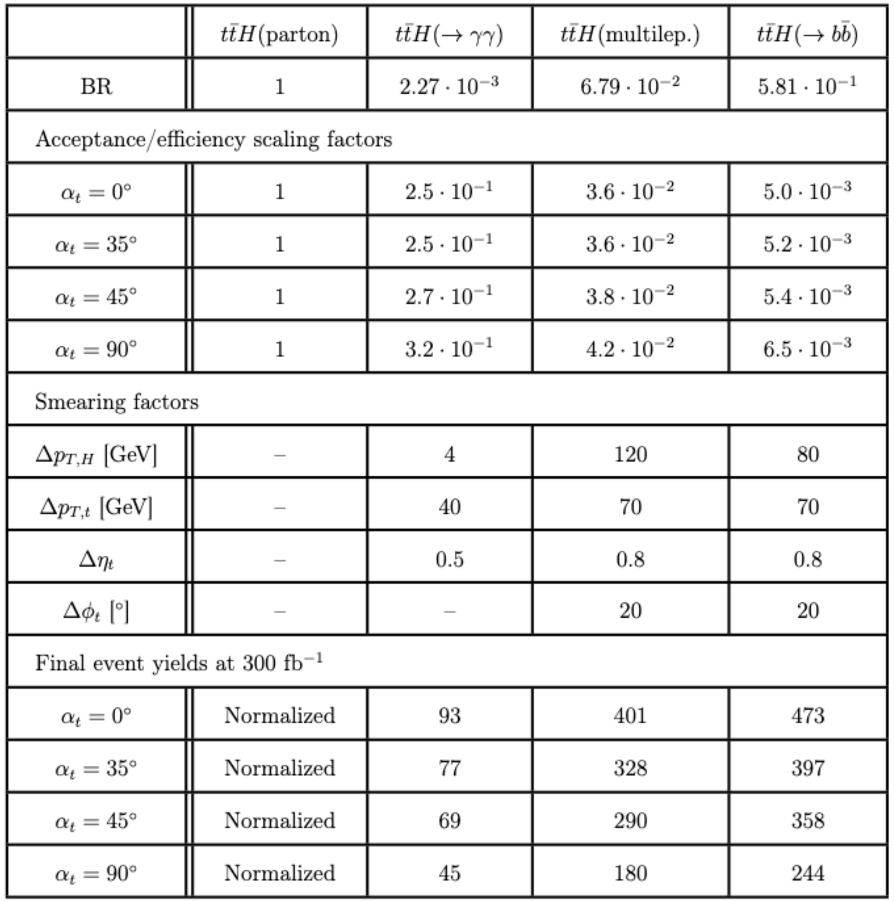
- Large loop corrections to κ_λ possible in various models.
- κ_λ very sensitive to BSM scalar couplings.
- Automatized calculation of κ_λ available in Python package `anyH3`.
- See also [1704.01953,1902.05936,2209.00666] for other models/more discussion.

Strong motivation for the experimental di-Higgs program!

Momentum dependence



Smearing and reconstruction efficiencies



	$t\bar{t}H$(parton)	$t\bar{t}H(\to \gamma\gamma)$	$t\bar{t}H$(multilep.)	$t\bar{t}H(\to b\bar{b})$
BR	1	$2.27 \cdot 10^{-3}$	$6.79 \cdot 10^{-2}$	$5.81 \cdot 10^{-1}$
Acceptance/efficiency scaling factors				
$\alpha_t = 0°$	1	$2.5 \cdot 10^{-1}$	$3.6 \cdot 10^{-2}$	$5.0 \cdot 10^{-3}$
$\alpha_t = 35°$	1	$2.5 \cdot 10^{-1}$	$3.6 \cdot 10^{-2}$	$5.2 \cdot 10^{-3}$
$\alpha_t = 45°$	1	$2.7 \cdot 10^{-1}$	$3.8 \cdot 10^{-2}$	$5.4 \cdot 10^{-3}$
$\alpha_t = 90°$	1	$3.2 \cdot 10^{-1}$	$4.2 \cdot 10^{-2}$	$6.5 \cdot 10^{-3}$
Smearing factors				
$\Delta p_{T,H}$ [GeV]	–	4	120	80
$\Delta p_{T,t}$ [GeV]	–	40	70	70
$\Delta \eta_t$	–	0.5	0.8	0.8
$\Delta \phi_t$ [°]	–	–	20	20
Final event yields at 300 fb^{-1}				
$\alpha_t = 0°$	Normalized	93	401	473
$\alpha_t = 35°$	Normalized	77	328	397
$\alpha_t = 45°$	Normalized	69	290	358
$\alpha_t = 90°$	Normalized	45	180	244

Interpretation in terms of top-Yukawa coupling

- Effective Lagrangian (SM: $c_t = 1, \tilde{c}_t = 0$)

$$\mathcal{L}_{\text{yuk}} = -\frac{y_t^{\text{SM}}}{\sqrt{2}} \bar{t}\,(c_t + i\gamma_5 \tilde{c}_t)\,tH$$

- If no colored BSM particles at low energies: $c_g \simeq c_t, \tilde{c}_g \simeq \tilde{c}_t$