Dissecting Multi-Higgs Boson Production in New Physics Models

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[Kennesaw State University, GA, USA]

HHH Workshop, Dubrovnik, Croatia [July 14th — 16th 2023]

Based on (previous work):

AP, Tania Robens, Gilberto Tetlalmatzi-Xolocotzi, **arXiv:2101.00037**

$$hhh \to 6b\text{--jets}$$

[SM + 2 scalar fields = "TRSM"]

&

AP, Gilberto Tetlalmatzi-Xolocotzi, Marco Zaro, **arXiv:1909.09166**

$$hhh \to 6b\text{--jets}$$

[SM + 1 scalar field = "xSM"]

[& see also:]

AP, Kazuki Sakurai, **arXiv:1508.06524**

$$hhh \to 4b\text{--jets} + \gamma\gamma$$

AP, Graham White,
arXiv:2010.00597 &
arXiv:2108.11394

[Strong EW phase transition with 1 scalar field + searches @ future colliders]

Based on (upcoming work):

Alexandra Carvalho, AP, Marko Stamenkovic, Gilberto Tetlalmatzi-Xolocotzi, Alberto Tonero […]

[**hhh** with Anomalous Couplings]

&

Osama Karkout, Carlo Pandini, AP, Marieke Postma, Tristan du Pree, Gilberto Tetlalmatzi-Xolocotzi, Jorinde van de Vis […]

[**hhh** in TRSM + Cosmology]

Did you know?

- ∃ factor of $\mathcal{O}(10^{-3})$ each time you "draw" an extra Higgs boson @ pp colliders.

$\sigma(h) \sim 50$ pb

SM, 14 TeV

(with apologies to Peter Higgs!)

Did you know?

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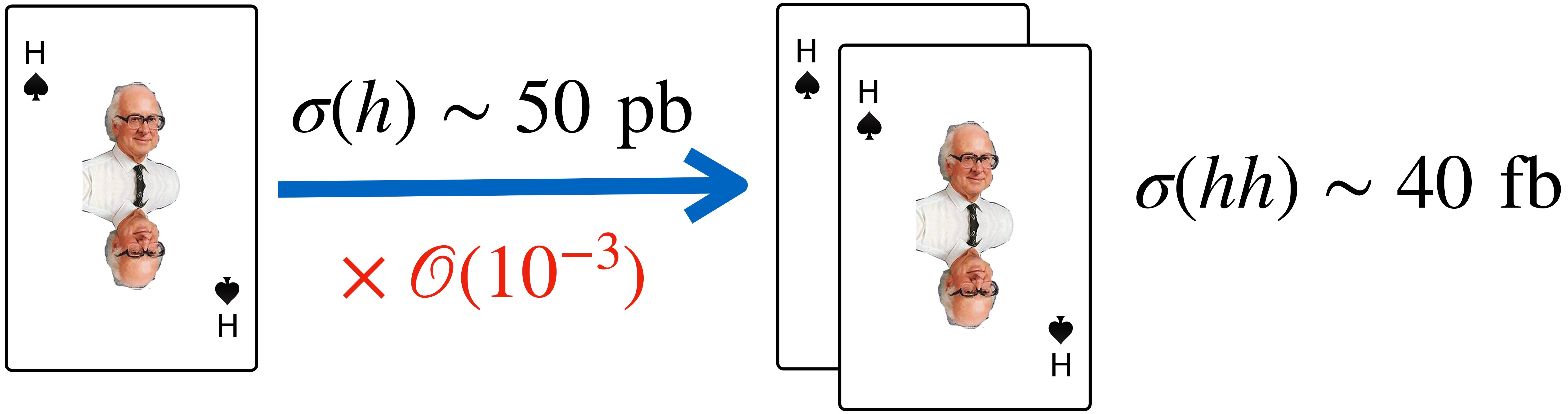


$\sigma(h) \sim 50$ pb

$\times\, \mathcal{O}(10^{-3})$

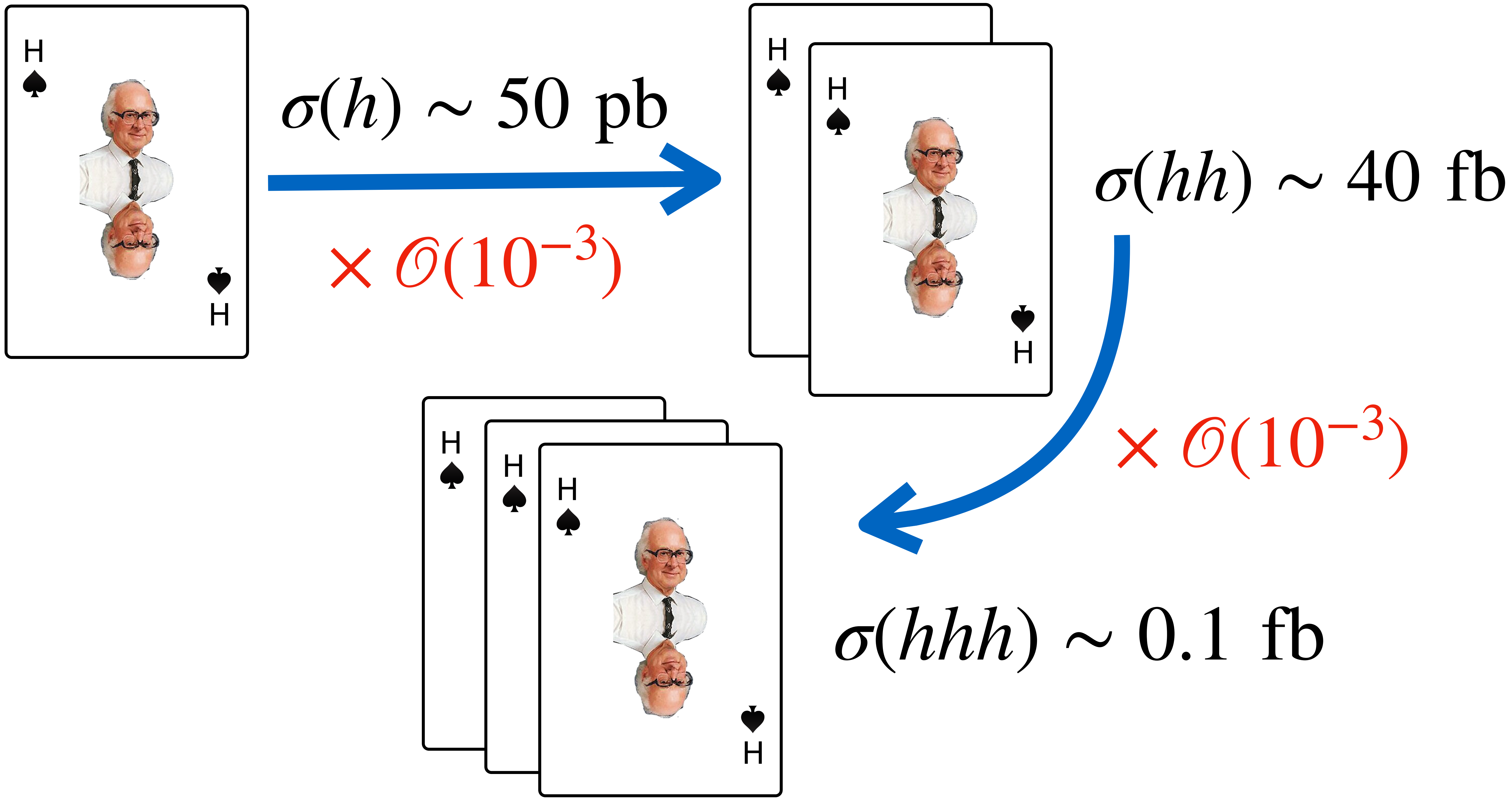
$\sigma(hh) \sim 40$ fb

SM, 14 TeV

(with apologies to Peter Higgs!)

Did you know?

- $\exists$ factor of $\mathcal{O}(10^{-3})$ each time you “draw” an extra Higgs boson @ pp colliders.



$\sigma(h) \sim 50$ pb

$\times\, \mathcal{O}(10^{-3})$

$\sigma(hh) \sim 40$ fb

$\times\, \mathcal{O}(10^{-3})$

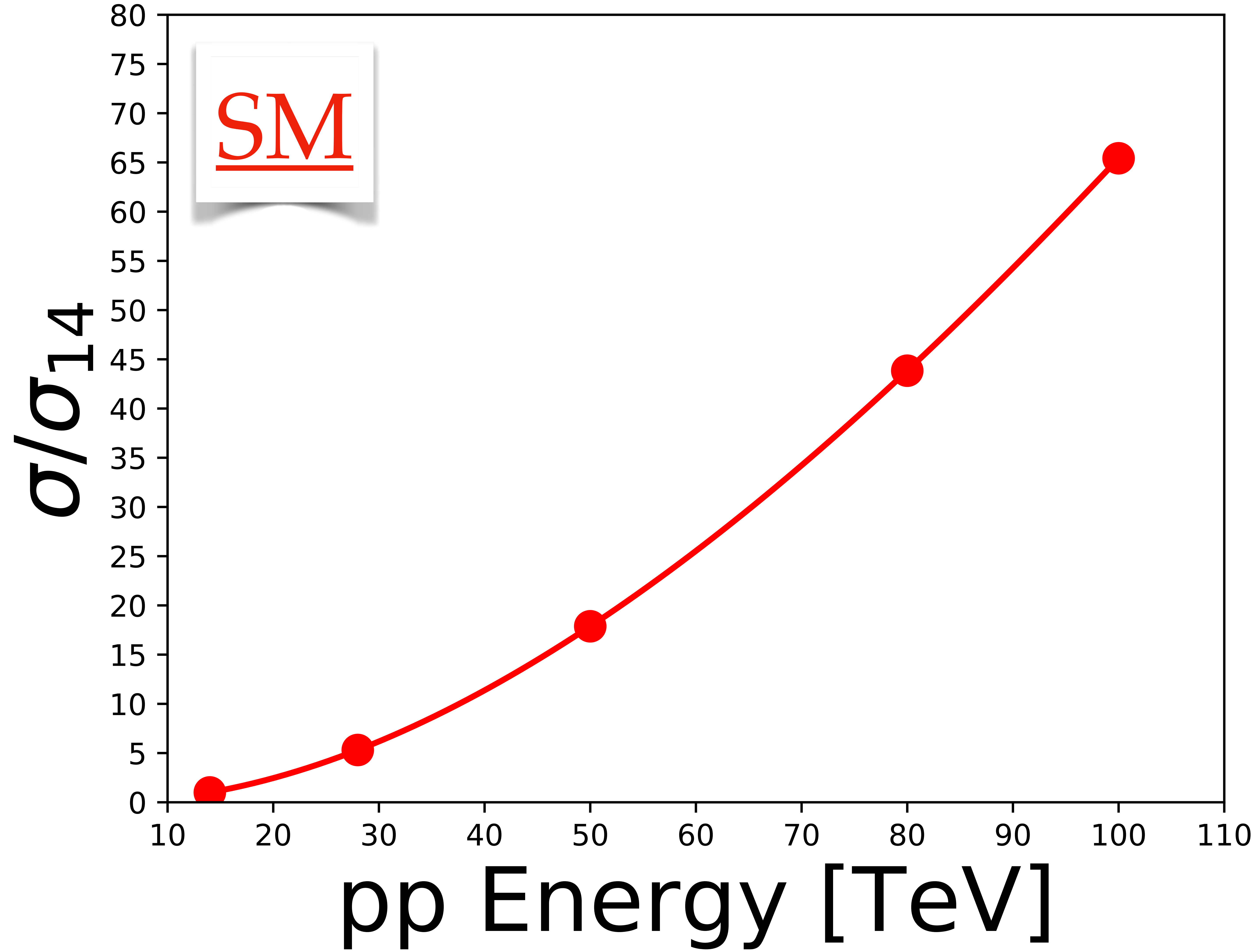
$\sigma(hhh) \sim 0.1$ fb

SM, 14 TeV

(with apologies to Peter Higgs!)

Did you know?

- Cranking up the pp energy could help!



~ ×60 increase in cross section 14 TeV → 100 TeV.

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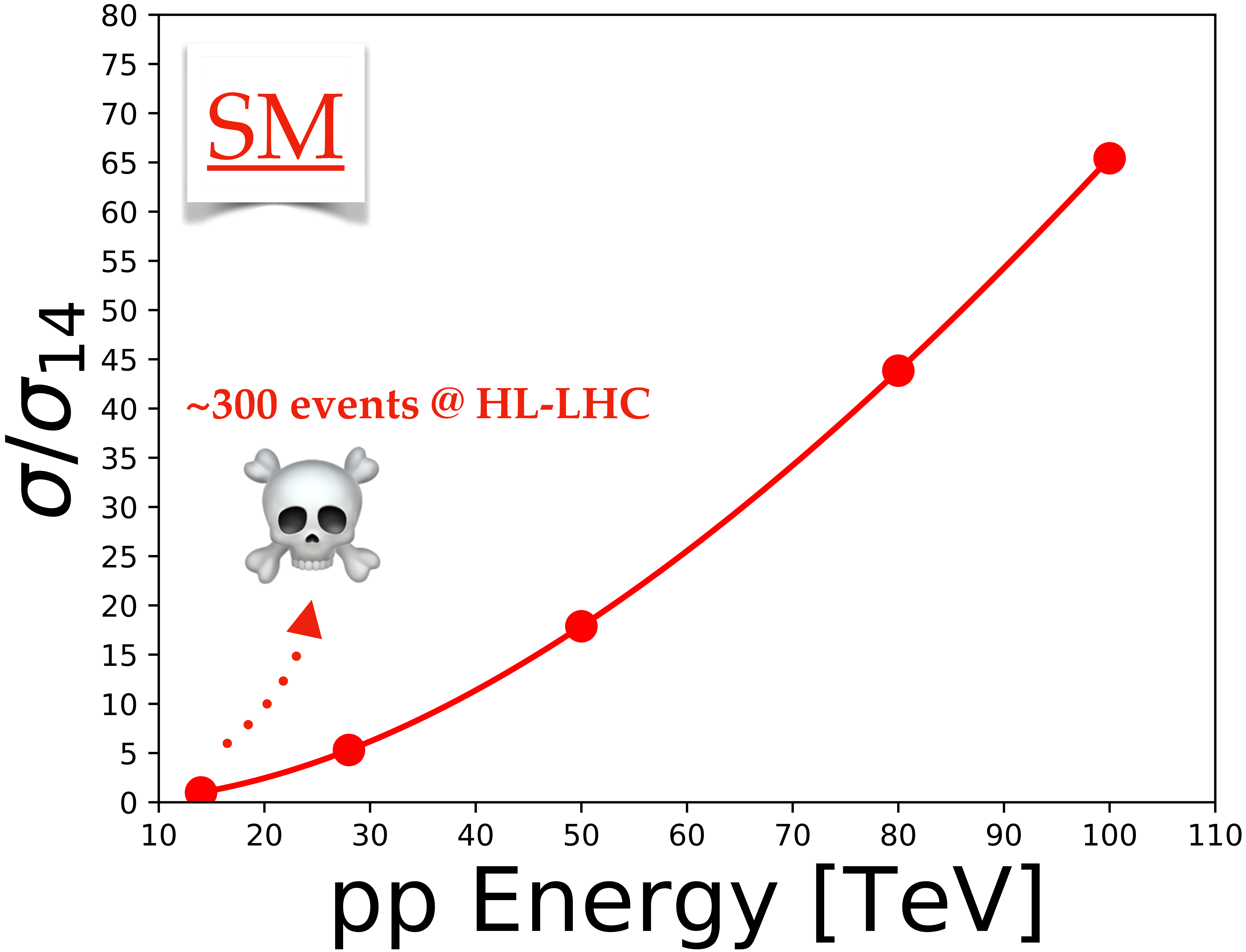

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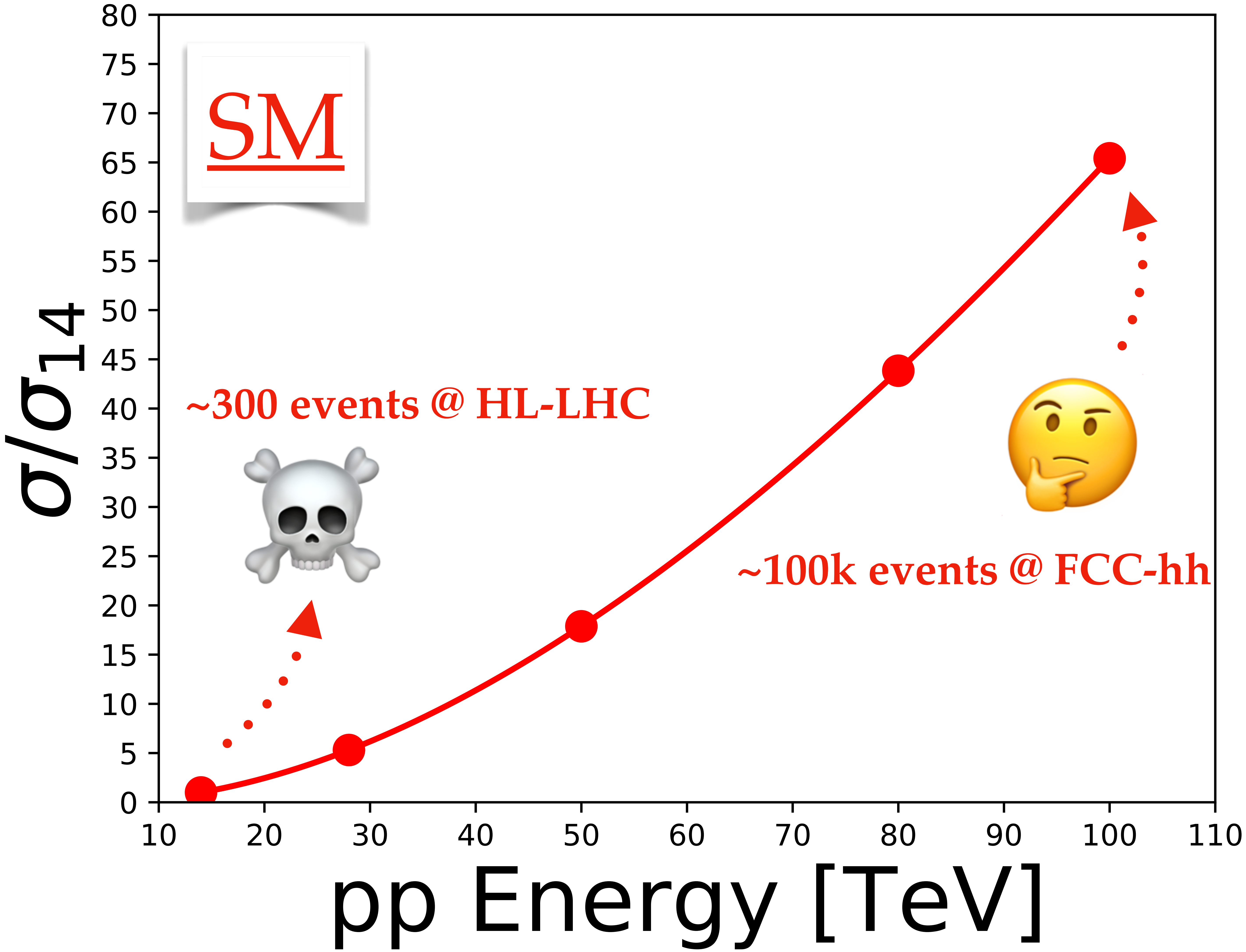

~300 events @ HL-LHC

~100k events @ FCC-hh

~ ×60 increase in cross section 14 TeV → 100 TeV.

THE SECRET
INGREDIENT
IS ALWAYS
LOVE

THE SECRET INGREDIENT IS ALWAYS ~~LOVE~~ NEW PHYSICS

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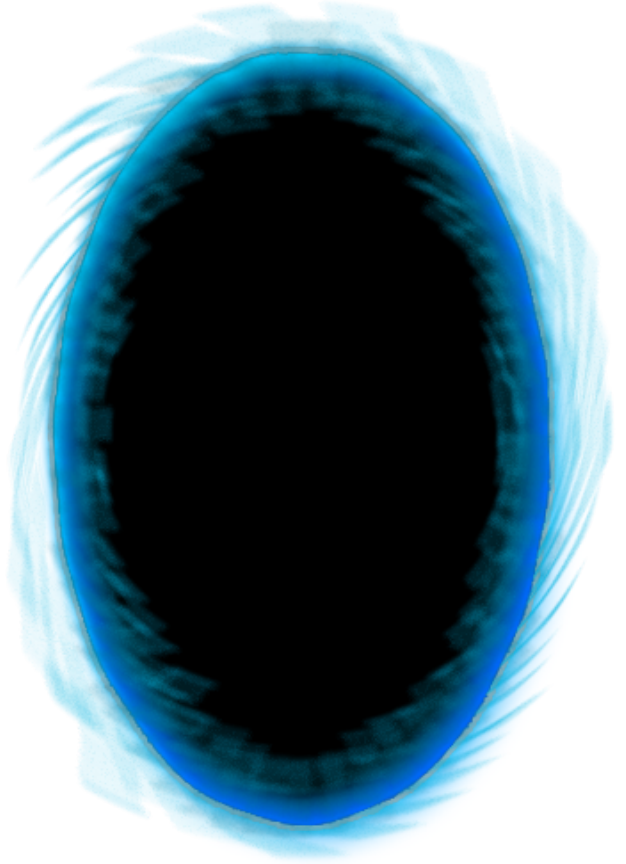
Goals of this talk:

A. **hhh** and new gauge-singlet scalar fields,

B. **hhh** with anomalous couplings.

A. **hhh** & New Gauge-Singlet Scalar Fields

Higgs Portals and Singlet Scalars



- The Higgs doublet bilinear $\phi^\dagger\phi$:

the <u>only</u> SM gauge- and Lorentz-invariant ***D*=2** operator!

- Can act as a "**portal**": you can always multiply $\phi^\dagger\phi$ by another singlet operator, *S*!

$$\text{e.g.:}\quad \mathscr{L} \supset {\color{red}\blacktriangle}\,\phi^\dagger\phi S + {\color{blue}\blacksquare}\,\phi^\dagger\phi S^2$$

- Then, following **Electro-Weak Symmetry Breaking** (**EWSB**):

$$\begin{aligned} \phi &\rightarrow \langle\phi\rangle + h \\ S &\rightarrow \langle S\rangle + \chi \end{aligned} \quad \Rightarrow \mathscr{L} \supset {\color{blue}\blacktriangle}\, h\chi^2 + {\color{red}\blacktriangle} h^2\chi + {\color{blue}\blacksquare} h^2\chi^2 + \ldots$$

$\uparrow$

Vacuum Expectation Values (**VEVs**)

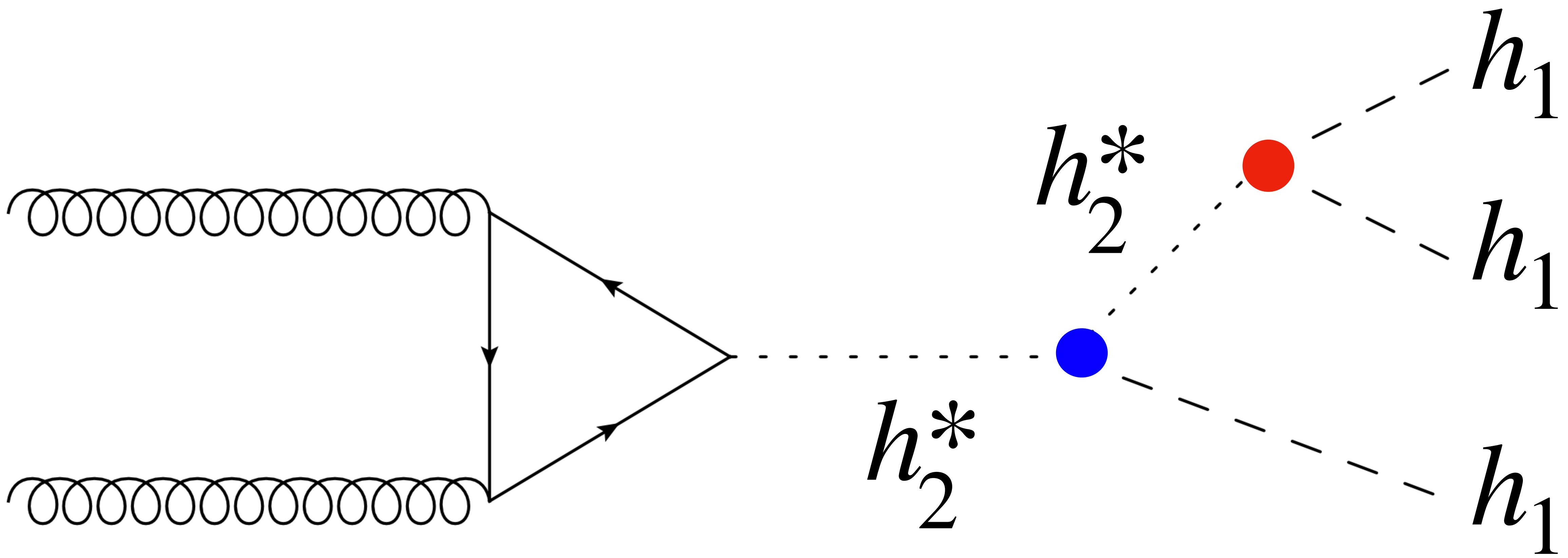
SM + New Singlet Scalars

- Diagonalize mass matrix → get eigenstates: $h_1, h_2, h_3 \ldots$ → h_1 ≈ SM-like Higgs boson!

$$\mathscr{L} \supset \blacktriangle\, h_1 h_2^2 + \blacktriangle\, h_1^2 h_2 + \blacksquare\, h_1^2 h_2^2 + \ldots$$

⇒ **Modified** & **new** triple/quartic couplings,

⇒ **Additional** contributions to **hhh**, e.g.:



SM + New Singlet Scalars

- Diagonalize mass matrix → get eigenstates: $h_1, h_2, h_3 \dots$ → $h_1 \approx$ SM-like Higgs boson!

$$\mathscr{L} \supset {\color{blue}\blacktriangle}\, h_1 h_2^2 + {\color{red}\blacktriangle}\, h_1^2 h_2 + {\color{green}\blacksquare}\, h_1^2 h_2^2 + \dots$$

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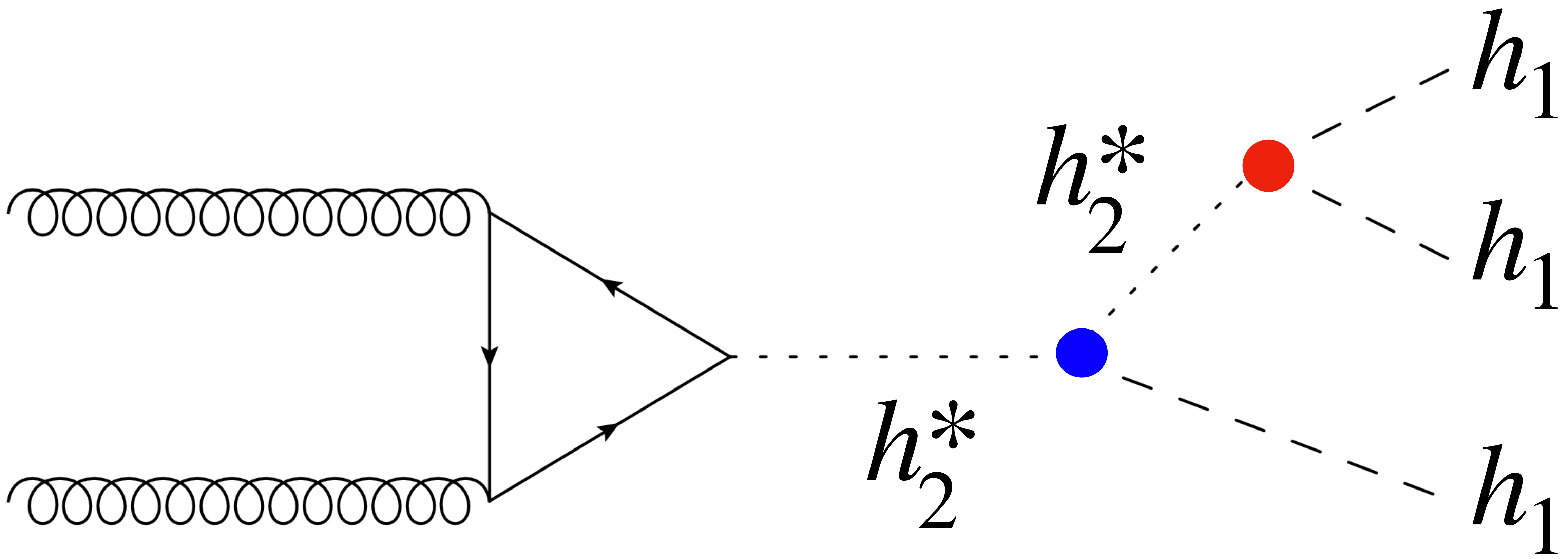

⇒ Triple Higgs boson production could be <u>enhanced</u> in models with extended scalar sectors!

& Measuring it could probe multi-scalar interactions!

SM + Two Real Singlet Scalars [= TRSM]

- Let's now consider adding **two real singlet scalar fields** $S, X \rightarrow$ the TRSM.
- And: impose **discrete $\mathcal{Z}_2$ symmetries:**

$$\mathcal{Z}_2^S : S \rightarrow -S,\;\; X \rightarrow X$$

$$\mathcal{Z}_2^X : X \rightarrow -X,\;\; S \rightarrow S$$

$\Rightarrow$ TRSM scalar potential:

$$\begin{aligned}\mathcal{V}(\phi, S, X) = {} & \text{🟢}\, |\phi|^2 + \text{🟦}|\phi|^4 + \text{🔴}S^2 + \text{🟦}S^4 + \text{🟣}X^2 + \text{🟫}X^4 \\ & + \text{🟩}S^2X^2 \\ & + \text{🟪}|\phi|^2 S^2 + \text{🟩}|\phi|^2 X^2\end{aligned}$$

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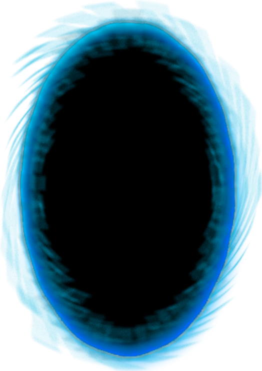
$$\mathcal{V}(\phi, S, X) = \bullet\, |\phi|^2 + \blacksquare |\phi|^4 + \bullet S^2 + \blacksquare S^4 + \bullet X^2 + \blacksquare X^4$$

$$+ \blacksquare S^2 X^2$$

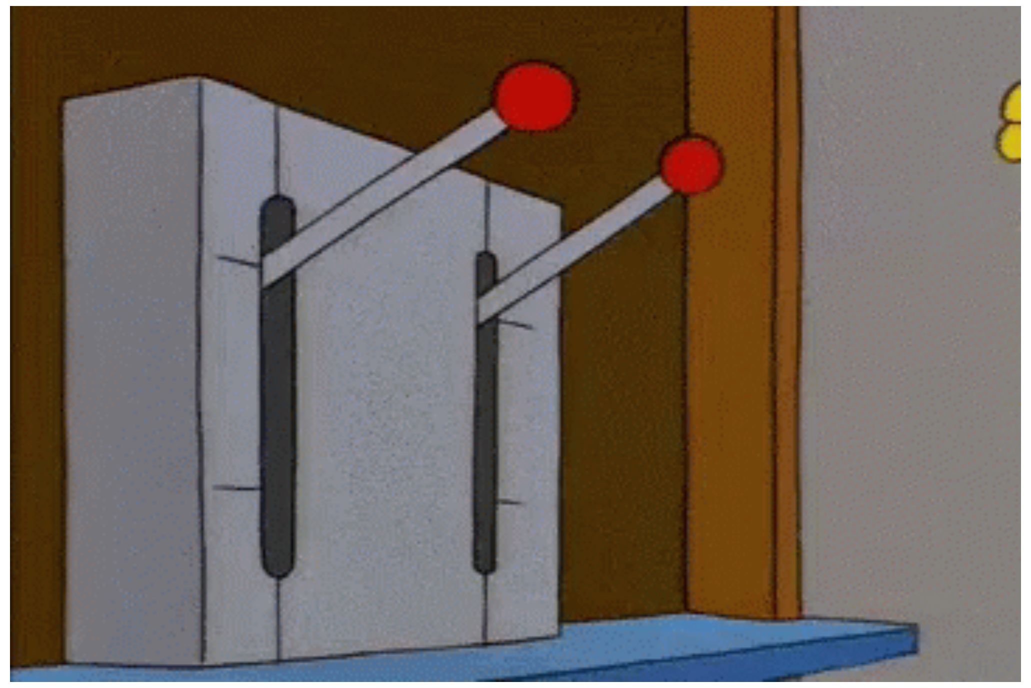


$$+ \blacksquare |\phi|^2 S^2 + \blacksquare |\phi|^2 X^2$$

← "**Portal**" interactions.

SM + Two Real Singlet Scalars [= TRSM]

- Go through EWSB…



$\Rightarrow$ Get **three** scalar bosons: $h_1, h_2, h_3 \to h_1 \approx$ SM-like Higgs boson.

$\Rightarrow$ Seven independent parameters: M_2, M_3 + three mixing angles + two VEVs.

$\Rightarrow$ Modified / Additional interactions between scalars.

$\Rightarrow$ **hhh** that may even be detectable at the LHC! [AP, Robens, Tetlalmatzi-Xolocotzi, **arXiv:2101.00037**]

$$\text{e.g.:} \quad pp \to h_3 \to h_2 h_1 \to h_1 h_1 h_1$$

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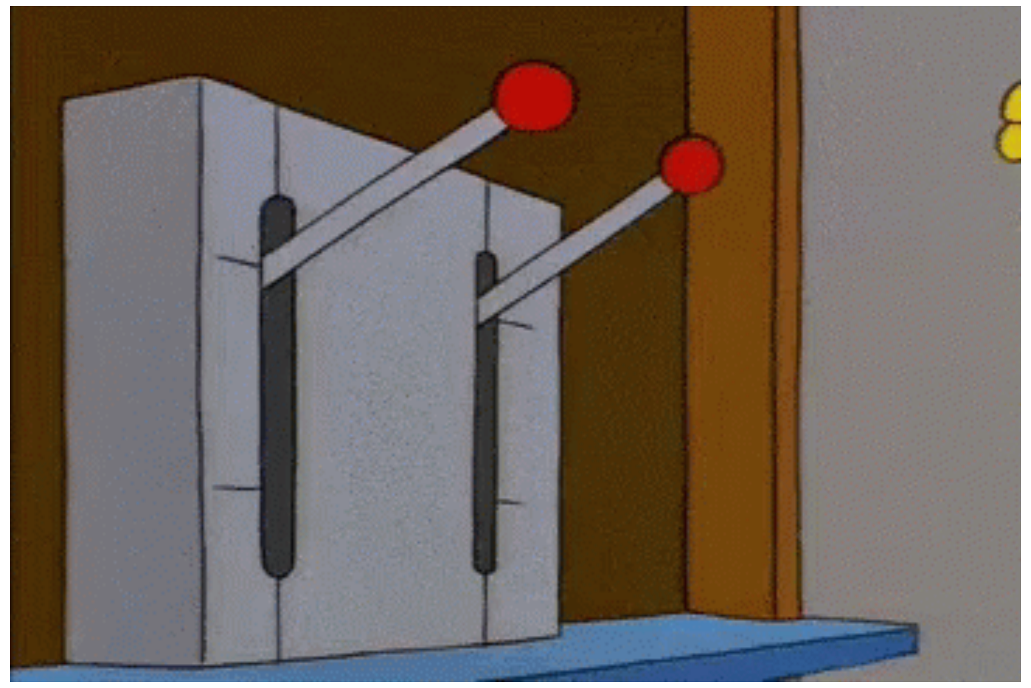

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$$\text{e.g.:} \quad pp \rightarrow h_3 \rightarrow h_2 h_1 \rightarrow h_1 h_1 h_1$$

hhh in the TRSM [14 TeV]

- Focus on a particular family of benchmark points: **"Benchmark Plane 3"** = **"BP3"** in [Robens, Stefaniak, Wittbrodt, **arXiv:908.08554**].

Label	(M_2, M_3) [GeV]	$\sigma(pp \to h_1 h_1 h_1)$ [fb]
A	$(255, 504)$	32.40
B	$(263, 455)$	50.36
C	$(287, 502)$	39.61
D	$(290, 454)$	49.00
E	$(320, 503)$	35.88
F	$(264, 504)$	37.67
G	$(280, 455)$	51.00
H	$(300, 475)$	43.92
I	$(310, 500)$	37.90
J	$(280, 500)$	40.26

Cross section can be much higher than the SM hhh! 😲

→ c.f. SM σ ~ 0.1 fb @ 14 TeV.

[AP, Tania Robens, Gilberto Tetlalmatzi-Xolocotzi, **arXiv:2101.00037**]

hhh in the TRSM "BP3" [14 TeV]

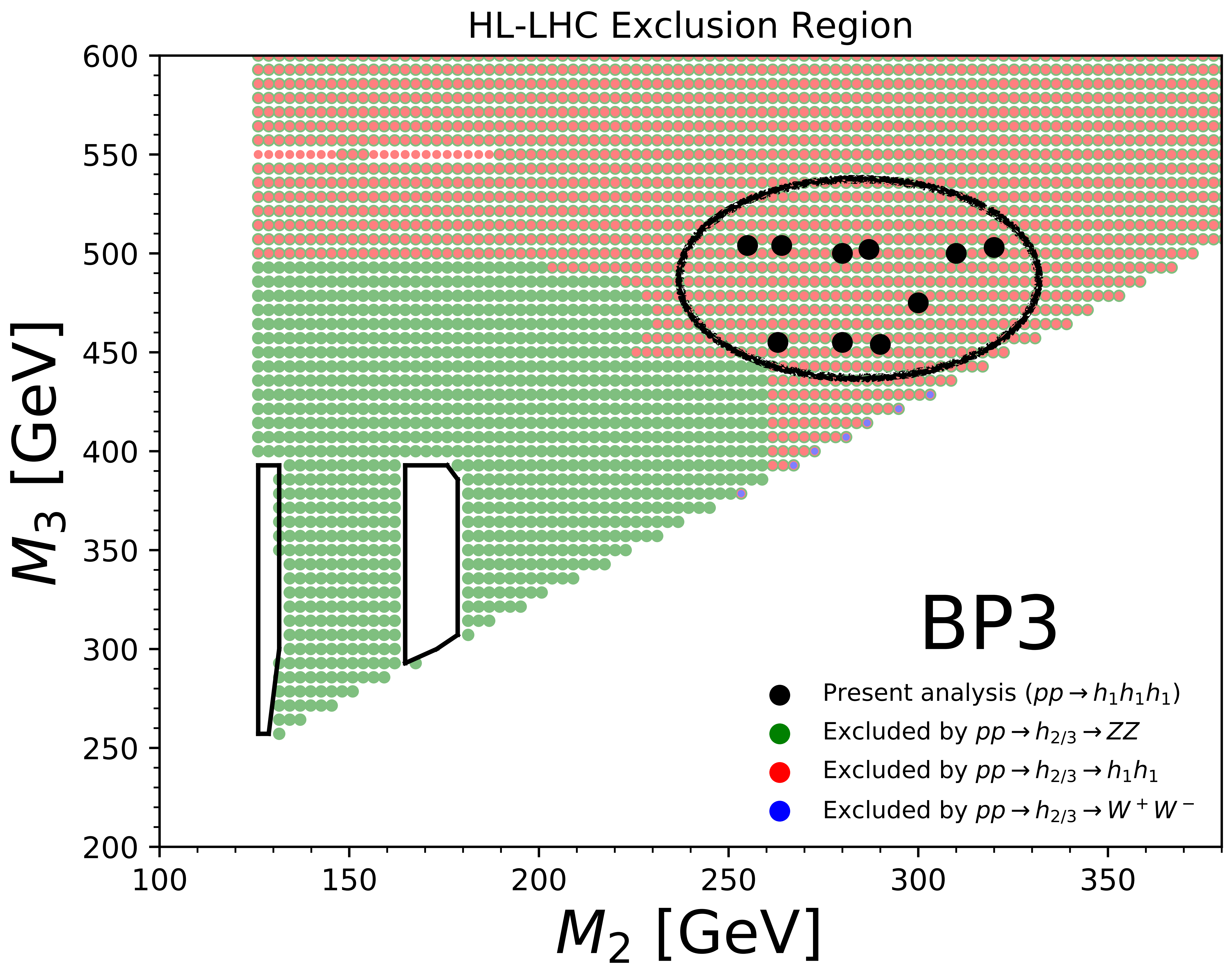
- Search for hhh via: $pp \to (b\bar{b})(b\bar{b})(b\bar{b})$.
- About **20%** of the hhh final state!
- Significances **large** even when including systematic uncert.:

[AP, Tania Robens, Gilberto Tetlalmatzi-Xolocotzi, **arXiv:2101.00037]**

Label	$\text{sig}\vert_{300\text{fb}^{-1}}$ (syst.)	$\text{sig}\vert_{3000\text{fb}^{-1}}$ (syst.)
A	2.92 (2.63)	9.23 (5.07)
B	4.78 (4.50)	15.10 (10.14)
C	4.01 (3.56)	12.68 (6.67)
D	5.02 (4.03)	15.86 (6.25)
E	3.76 (2.87)	11.88 (4.18)
F	3.56 (3.18)	11.27 (5.98)
G	5.18 (4.16)	16.39 (6.45)
H	4.64 (3.47)	14.68 (4.94)
I	4.09 (2.88)	12.94 (3.87)
J	4.00 (3.56)	12.65 (6.66)

hhh in the TRSM “BP3” [14 TeV]

- **hhh** will (**probably?**) **not be a discovery channel,**
- but could be **important in determining the parameters of the model**, if scalars are discovered!



Solve the “**inverse problem**”?

(→ see also: [**AP**, White, arXiv:2108.11394] for first steps in the xSM + SFO-EWPT.)

TRSM Monte Carlo Event Generation

- We have implemented a **MadGraph5_aMC@NLO (MG5_aMC) “loop” model for the TRSM:**
  - **MG5_aMC input parameters**: the three mixing angles, two masses/widths and **all** the scalar couplings (only 7 are independent in **TRSM**).
  - Comes with a **Python script** that:
    - allows conversion of M_2, M_3 + three mixing angles + two VEVs to the **MG5_aMC** model input,
    - calculates several single-production cross sections, branching ratios, widths,
    - and writes associated **MG5_aMC** parameter card (**param_card.dat**) automatically.
  - **Get it at:** https://gitlab.com/apapaefs/twosinglet.

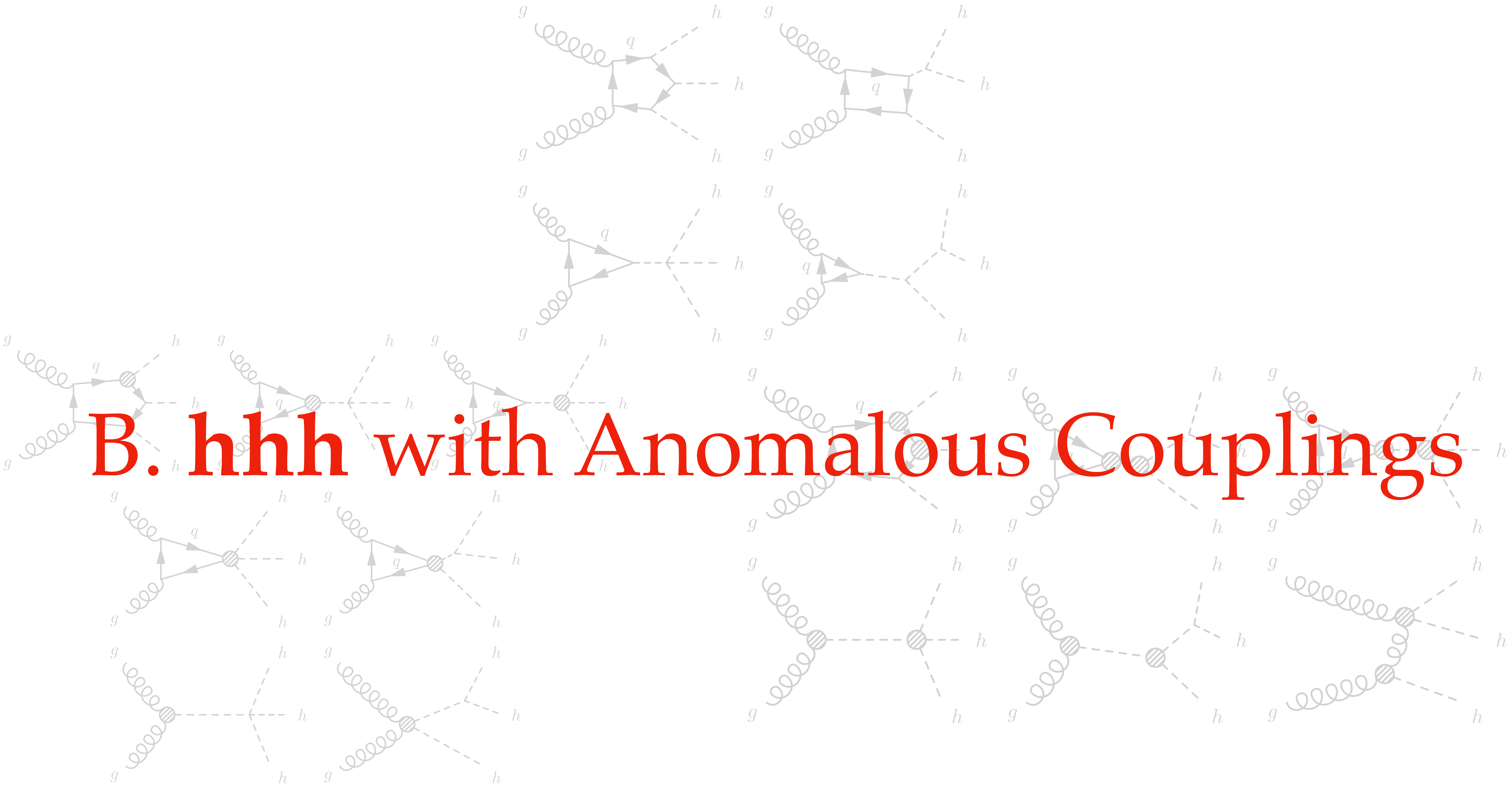
  [AP, Tania Robens, Gilberto Tetlalmatzi-Xolocotzi, arXiv:2101.00037]

More TRSM hhh Pheno In Progress!

Q: Can there be a **first-order electro-weak phase transition** in the TRSM, related to **electro-weak baryogenesis**?

And if so, will this lead to **enhanced multi-Higgs boson production?**

[Osama Karkout, Carlo Pandini, AP, Marieke Postma, Tristan du Pree, Gilberto Tetlalmatzi-Xolocotzi, Jorinde van de Vis, …]



B. **hhh** with Anomalous Couplings

D=6-Inspired Anomalous Couplings

- Add **higher-dimensional operators** to the SM Lagrangian!

→ To capture the **effects of new particles at scales ≫ collision energies**.

- e.g. Add D=6 operators **relevant to multi-Higgs boson production**, of the form $\frac{\mathcal{O}_6}{\Lambda^2}$:

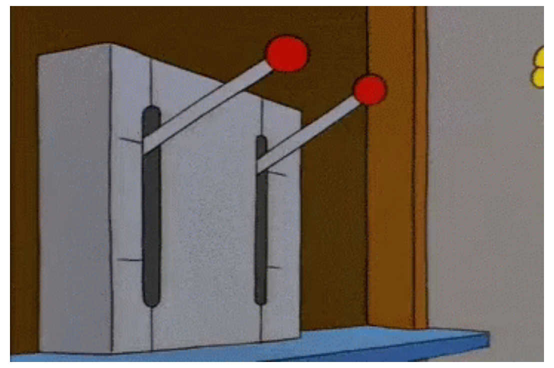
$$\mathcal{L}_{h^n} = -\mu^2 |H|^2 - \lambda |H|^4 - \left(y_t \bar{Q}_L H^c t_R + y_b \bar{Q}_L H b_R + \mathrm{h.c.} \right)$$

$$+ \frac{c_H}{2\Lambda^2} (\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2} \lambda_{\mathrm{SM}} |H|^6 + \frac{\alpha_s c_g}{4\pi\Lambda^2} |H|^2 G^a_{\mu\nu} G^{\mu\nu}_a$$

$$- \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \mathrm{h.c.} \right)$$

[see e.g. Goertz, AP, Yang, Zurita, arXiv:1410.3471 for **hh** study]

D=6-Inspired Anomalous Couplings

- Go through EWSB…  → in terms of the <u>physical scalar Higgs</u> boson h:

$$\begin{aligned}
\mathscr{L}_{\mathrm{D=6}} = & -\frac{m_h^2}{2v}\left(1+c_6\right)h^3 - \frac{m_h^2}{8v^2}\left(1+6c_6\right)h^4 \\
& +\frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^a_{\mu\nu}G^{\mu\nu}_a \\
& -\left[\frac{m_t}{v}\left(1+c_t\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1+c_b\right)\bar{b}_L b_R h + \mathrm{h.c.}\right] \\
& -\left[\frac{m_t}{v^2}\left(\frac{3c_t}{2}\right)\bar{t}_L t_R h^2 + \frac{m_b}{v^2}\left(\frac{3c_b}{2}\right)\bar{b}_L b_R h^2 + \mathrm{h.c.}\right] \\
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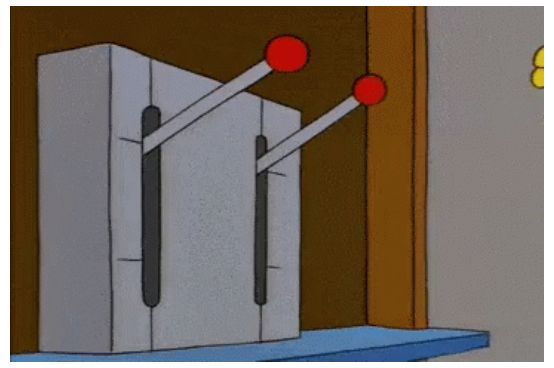

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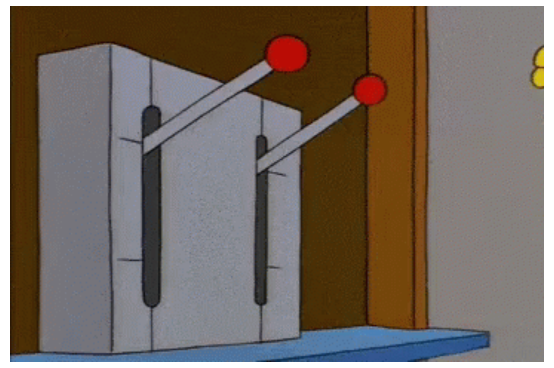

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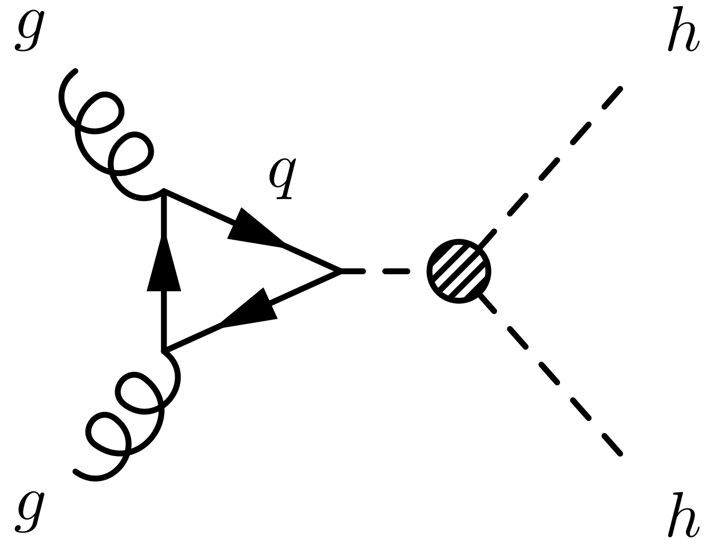

$$\mathscr{L}_{\mathrm{D=6}} = \boxed{-\frac{m_h^2}{2v}\left(1+c_6\right)h^3 - \frac{m_h^2}{8v^2}\left(1+6c_6\right)h^4}$$
$$+\frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^a_{\mu\nu}G_a^{\mu\nu}$$
$$-\left[\frac{m_t}{v}\left(1+c_t\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1+c_b\right)\bar{b}_L b_R h + \mathrm{h.c.}\right]$$
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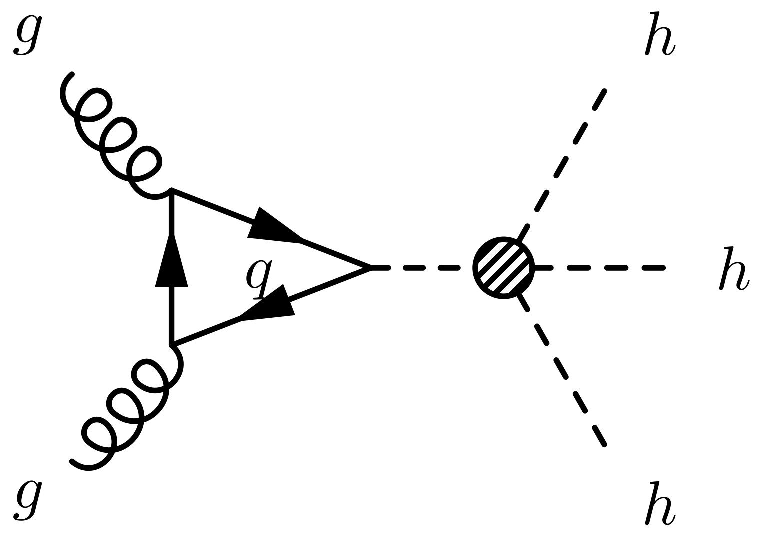
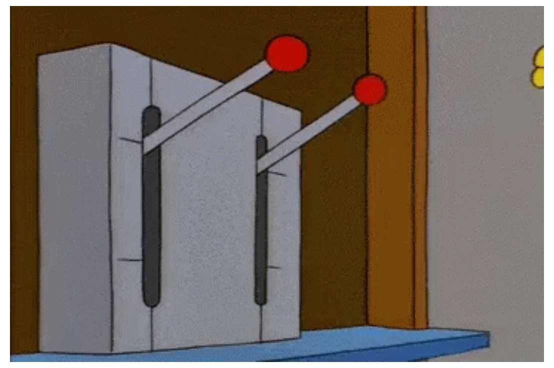
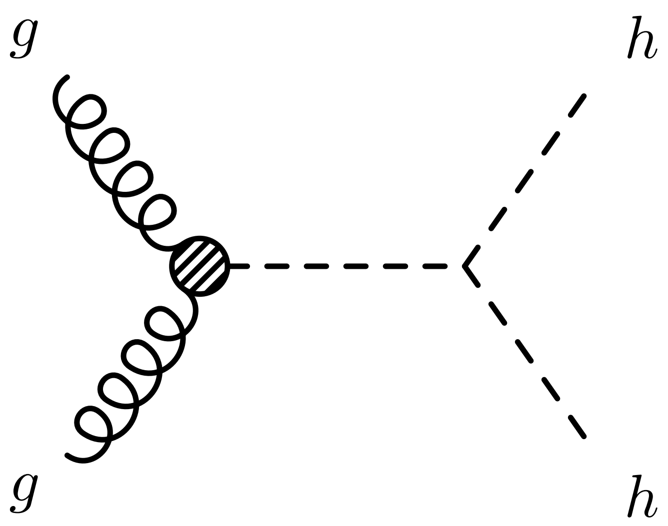


D=6-Inspired Anomalous Couplings

- Go through EWSB…  → in terms of the physical scalar Higgs boson h:



$$
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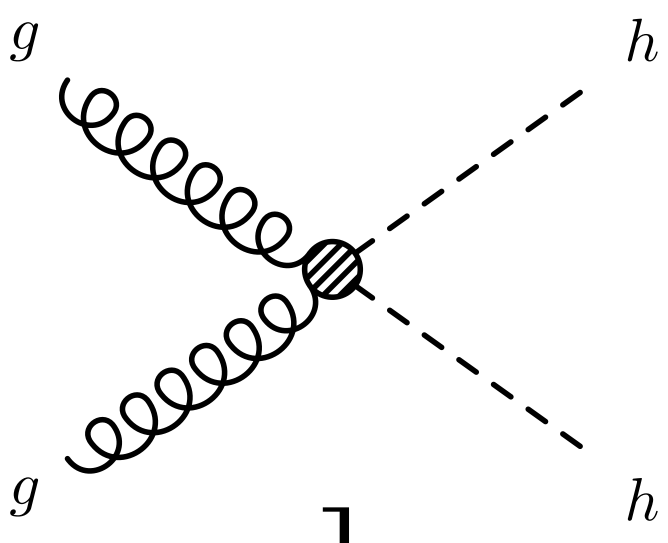
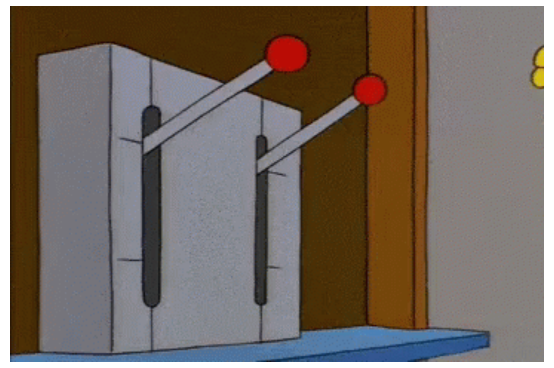


D=6-Inspired Anomalous Couplings

- Go through EWSB…  → in terms of the physical scalar Higgs boson h:

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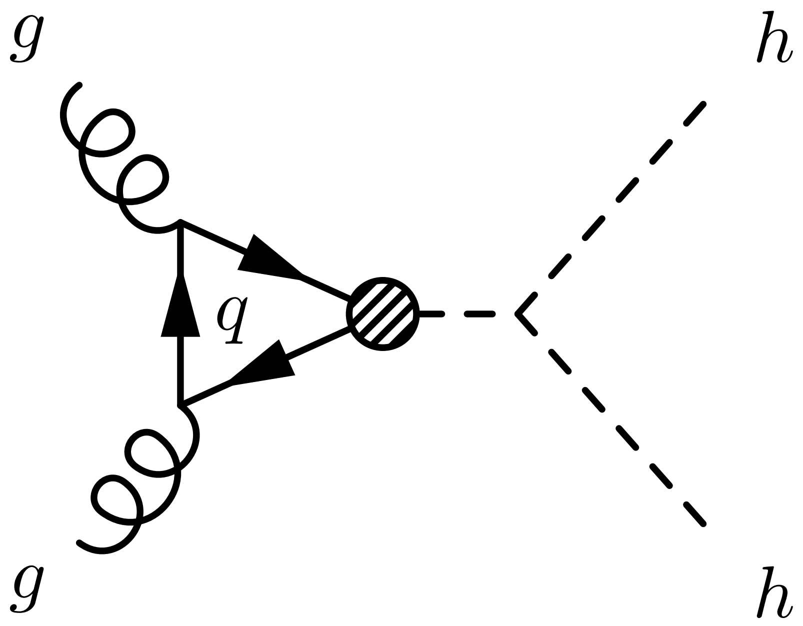
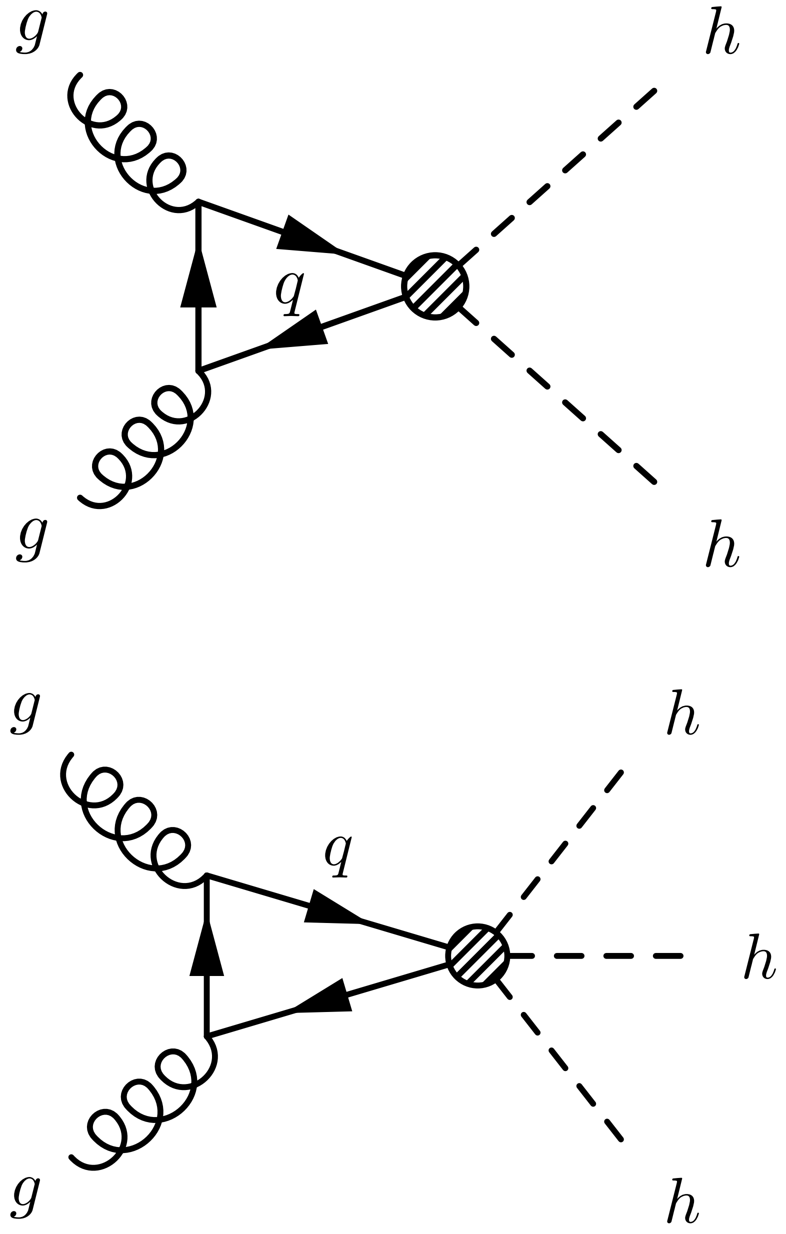
$$+\frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^a_{\mu\nu}G_a^{\mu\nu}$$



$$\boxed{\begin{aligned}&-\left[\frac{m_t}{v}\left(1+c_t\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1+c_b\right)\bar{b}_L b_R h + \text{h.c.}\right]\\&-\left[\frac{m_t}{v^2}\left(\frac{3c_t}{2}\right)\bar{t}_L t_R h^2 + \frac{m_b}{v^2}\left(\frac{3c_b}{2}\right)\bar{b}_L b_R h^2 + \text{h.c.}\right]\\&-\left[\frac{m_t}{v^3}\left(\frac{c_t}{2}\right)\bar{t}_L t_R h^3 + \frac{m_b}{v^3}\left(\frac{c_b}{2}\right)\bar{b}_L b_R h^3 + \text{h.c.}\right],\end{aligned}}$$



D=6-Inspired Anomalous Couplings

- A slightly more “general” picture is obtained by “**dissociating**” the operators as:

$$\begin{aligned}\mathscr{L}_{\text{Pheno}} = &-\frac{m_h^2}{2v}\left(1+d_3\right)h^3 - \frac{m_h^2}{8v^2}\left(1+d_4\right)h^4\\ &+\frac{\alpha_s}{4\pi}\left(c_{g1}\frac{h}{v}+c_{g2}\frac{h^2}{2v^2}\right)G^a_{\mu\nu}G^{\mu\nu}_a\\ &-\left[\frac{m_t}{v}\left(1+c_{t1}\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1+c_{b1}\right)\bar{b}_L b_R h + \text{h.c.}\right]\\ &-\left[\frac{m_t}{v^2}\left(\frac{3c_{t2}}{2}\right)\bar{t}_L t_R h^2 + \frac{m_b}{v^2}\left(\frac{3c_{b2}}{2}\right)\bar{b}_L b_R h^2 + \text{h.c.}\right]\\ &-\left[\frac{m_t}{v^3}\left(\frac{c_{t3}}{2}\right)\bar{t}_L t_R h^3 + \frac{m_b}{v^3}\left(\frac{c_{b3}}{2}\right)\bar{b}_L b_R h^3 + \text{h.c.}\right],\end{aligned}$$

Recover D=6 by setting:

$$\begin{aligned} d_3 &= c_6,\\ d_4 &= 6c_6,\\ c_{g1} = c_{g2} &= c_g,\\ c_{f1} = c_{f2} = c_{f3} &= c_f\,. \end{aligned}$$

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D=6-Inspired Anomalous Couplings

- **Further modify** to match more closely **LHC experiments' definitions**:

$$
\begin{aligned}
\mathscr{L}_{\text{PhenoExp}} = & -\lambda_{\text{SM}} v \left(1+d_3\right) h^3 - \frac{\lambda_{\text{SM}}}{4}\left(1+d_4\right) h^4 \\
& + \frac{\alpha_s}{12\pi}\left(c_{g1}\frac{h}{v} - c_{g2}\frac{h^2}{2v^2}\right) G^a_{\mu\nu}G^{\mu\nu}_a \\
& - \left[\frac{m_t}{v}\left(1+c_{t1}\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1+c_{b1}\right)\bar{b}_L b_R h + \text{h.c.}\right] \\
& - \left[\frac{m_t}{v^2} c_{t2}\bar{t}_L t_R h^2 + \frac{m_b}{v^2} c_{b2}\bar{b}_L b_R h^2 + \text{h.c.}\right] \\
& - \left[\frac{m_t}{v^3}\left(\frac{c_{t3}}{2}\right)\bar{t}_L t_R h^3 + \frac{m_b}{v^3}\left(\frac{c_{b3}}{2}\right)\bar{b}_L b_R h^3 + \text{h.c.}\right],
\end{aligned}
$$

Defined: $\lambda_{\text{SM}} = m_h^2/2v^2$.

Obtain **CMS-like** parametrization by:

$$
\begin{aligned}
\kappa_\lambda &= (1+d_3), \\
k_t &= c_{t1}, \\
c_2 &= c_{t2}, \\
c_g &= c_{g1}, \\
c_{gg} &= c_{2g}\,.
\end{aligned}
$$

And **ATLAS-like** parametrization by:

$$
\begin{aligned}
c_{hhh} &= (1+d_3), \\
c_{ggh} &= 2c_{g1}/3, \\
c_{gghh} &= -c_{g2}/3.
\end{aligned}
$$

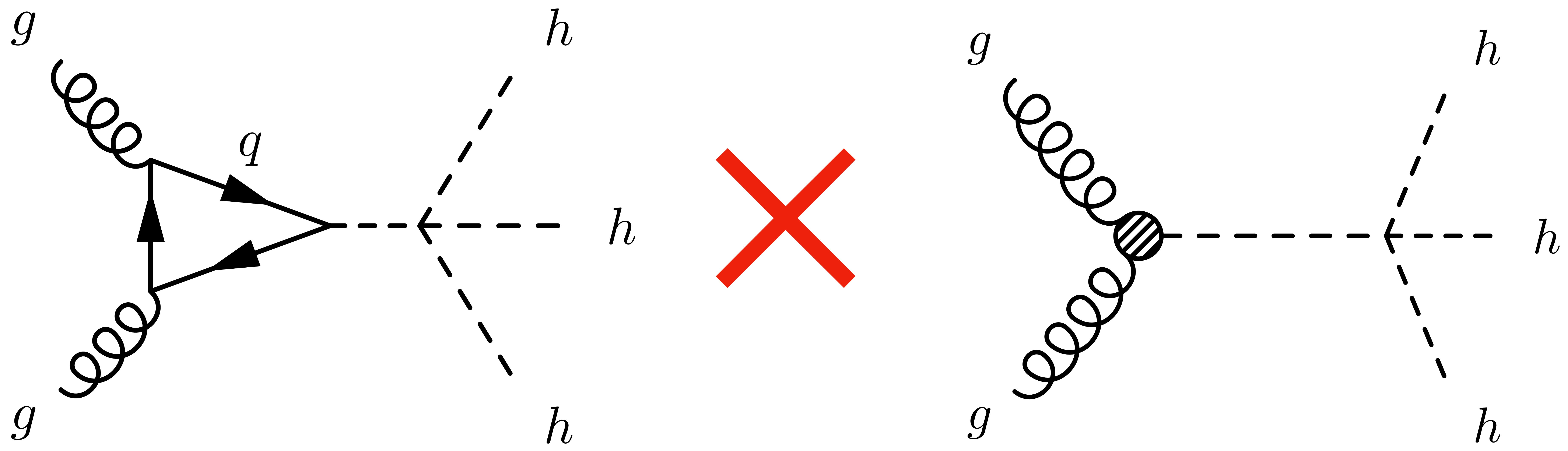
Monte Carlo Implementation of Anomalous Couplings

- We have implemented a **MadGraph5_aMC@NLO "loop" model** for $\mathscr{L}_{\text{PhenoExp}}$.

- **Includes Loop × Tree level interference between the various diagrams.**

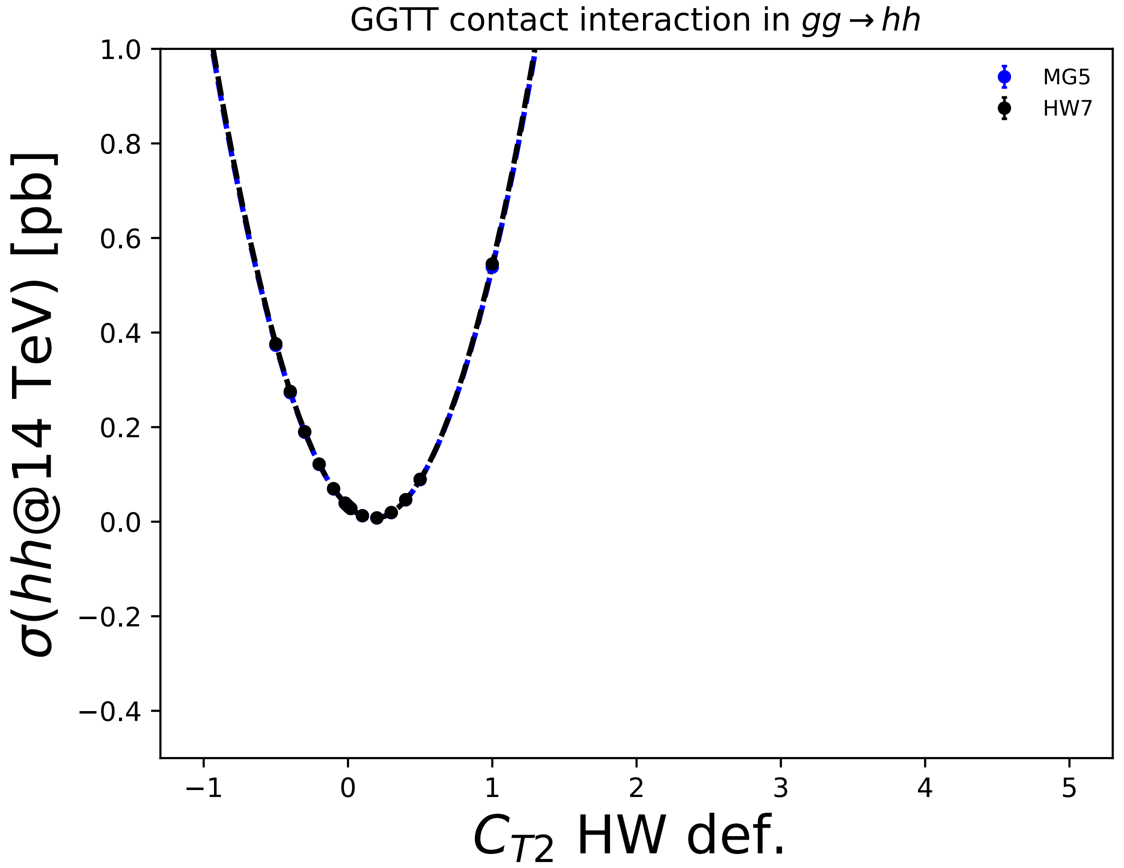
  [see V. Hirschi, https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/LoopInducedTimesTree].

- e.g.:



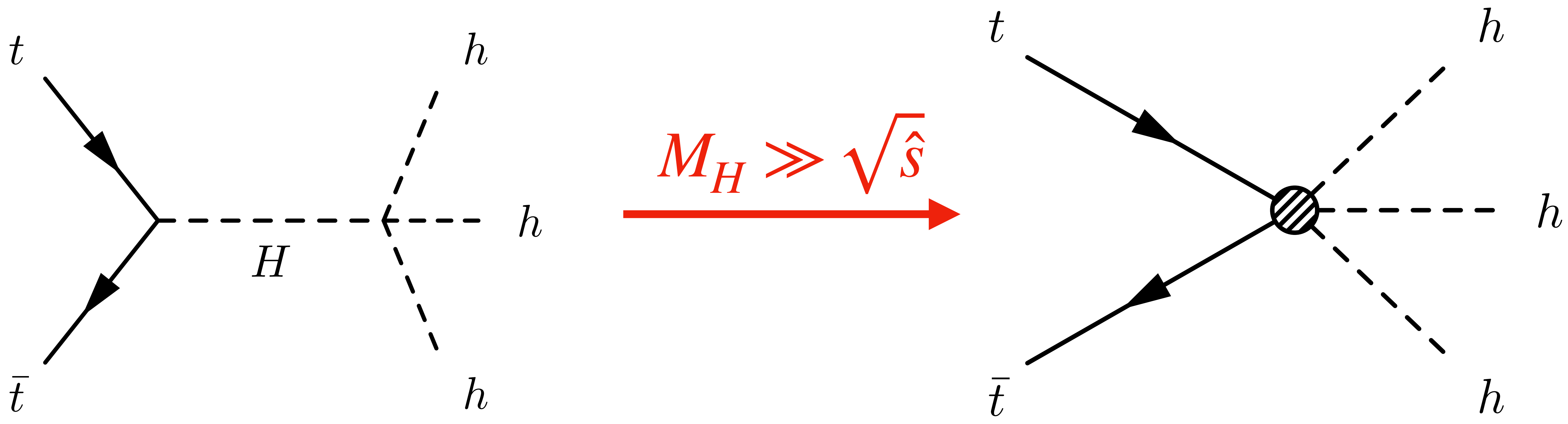
Model Validation

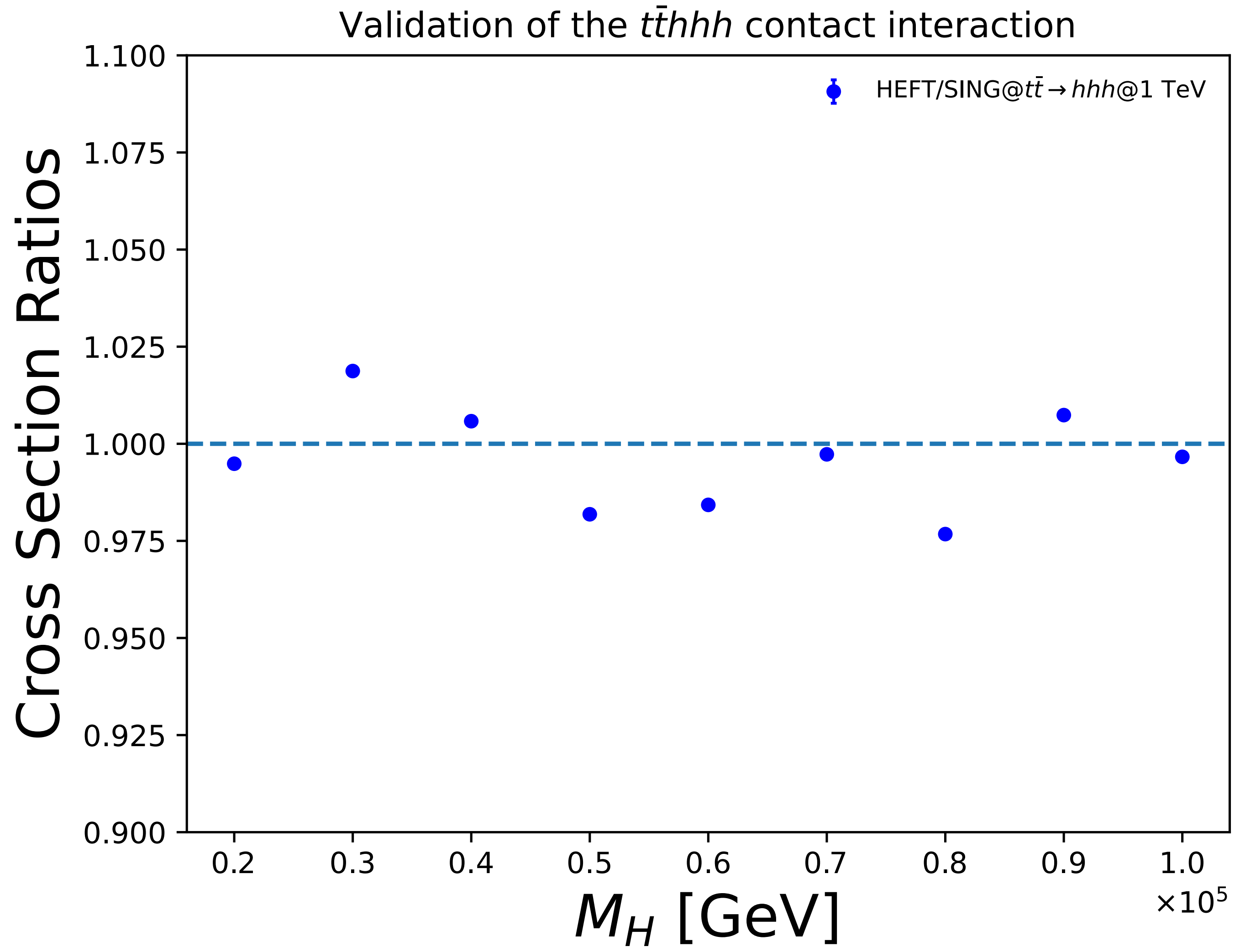
- Most couplings validated vs. a **Herwig 7** $pp \to hh$ implementation, e.g.:



✓

- The one "new" non-trivial coupling that appears, $\propto c_{t3} t\bar{t} h^3$ has been validated via an **"EFT" limit**, in the $t\bar{t} \to hhh$ process:





✓

Monte Carlo Implementation of Anomalous Couplings

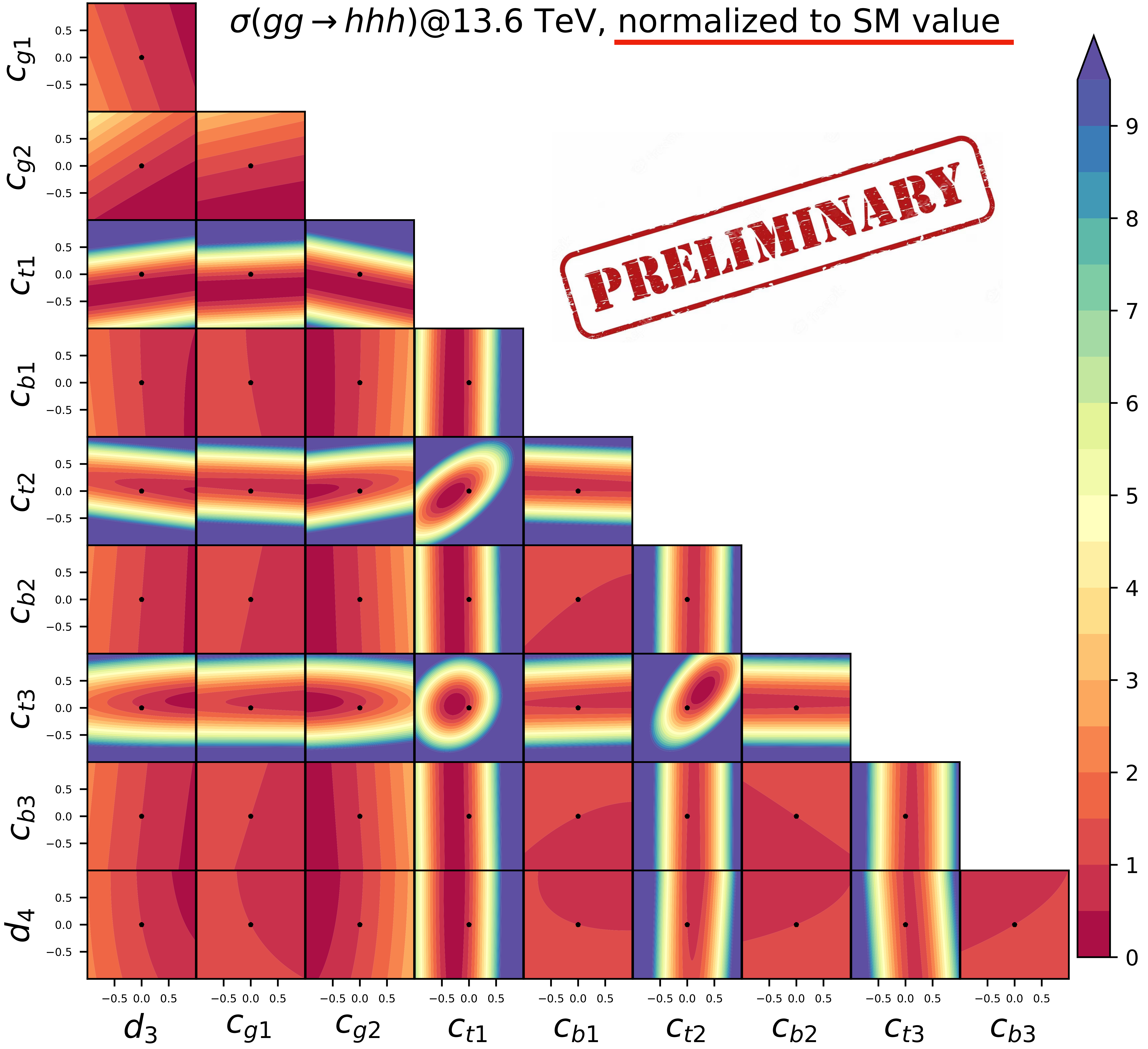
- Get the **MG5_aMC model** at: https://gitlab.com/apapaefs/multihiggs_loop_sm.
- [A patch to **MG5_aMC** to enable **Loop** × **Tree** is included].
- Can generate events either at:
  - **SM**^2 + interference of [**SM** × **One**-Insertion diagrams], i.e.:
    $|\mathscr{M}|^2 = |\mathscr{M}_{\mathrm{SM}}|^2 + 2\mathrm{Re}\{\mathscr{M}^*_{\mathrm{SM}}\mathscr{M}_{1-\mathrm{ins.}}\} \ \propto 1 + c_i$

    or

  - **SM**^2 + interference of [**SM** × **One** or **Two** insertion diagrams] + [**One** Insertion]^2, i.e.:
    $|\mathscr{M}|^2 = |\mathscr{M}_{\mathrm{SM}}|^2 + 2\mathrm{Re}\{\mathscr{M}^*_{\mathrm{SM}}\mathscr{M}_{1-\mathrm{ins.}}\} + 2\mathrm{Re}\{\mathscr{M}^*_{\mathrm{SM}}\mathscr{M}_{2-\mathrm{ins.}}\} + |\mathscr{M}_{1-\mathrm{ins.}}|^2$
    $\propto 1 + c_i + c_j c_k + c_\ell^2$

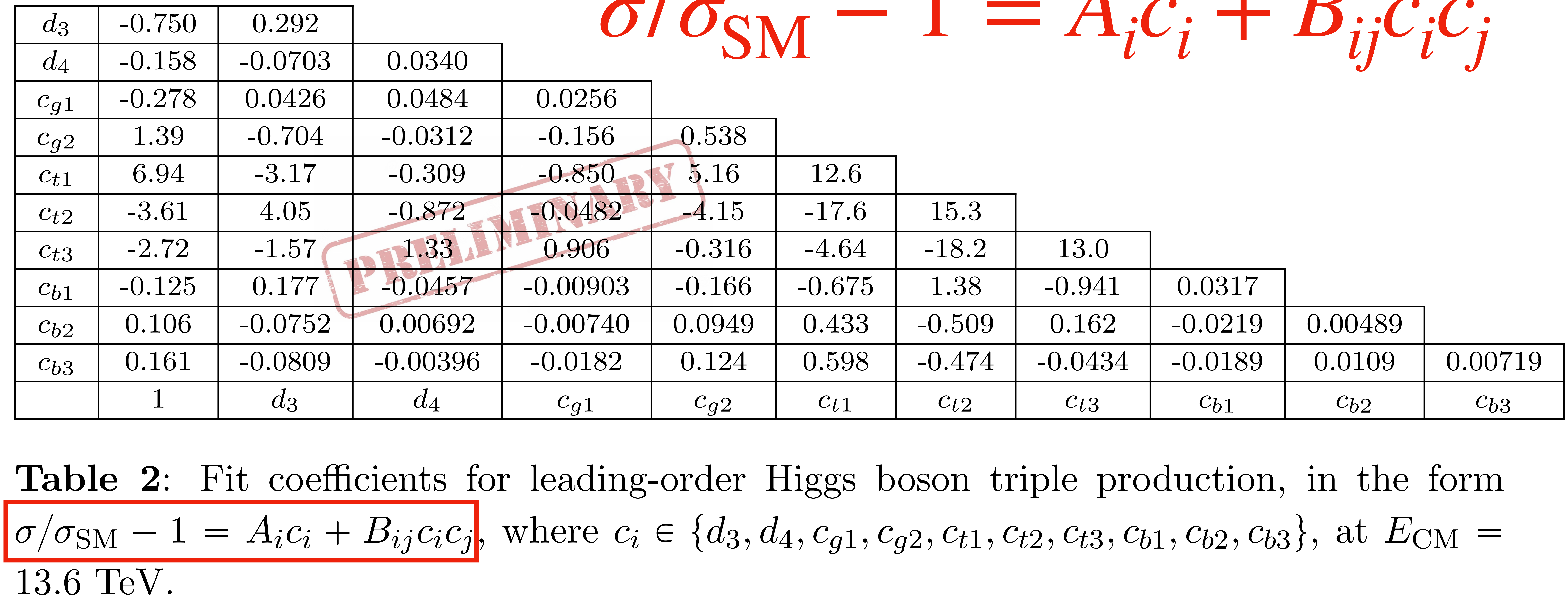
hhh Cross Sections @ 13.6 TeV

- Cross section as a multiple of the SM
- ($\sigma_{\mathrm{SM}} \sim 0.04$ fb at LO@13.6 TeV).
- In each 2D panel shown: **all other coefficients set to zero!**



Fit Coefficients for hhh Cross Sections @ 13.6 TeV

$$\sigma/\sigma_{\mathrm{SM}} - 1 = A_i c_i + B_{ij} c_i c_j$$



d_3	-0.750	0.292									
d_4	-0.158	-0.0703	0.0340								
c_{g1}	-0.278	0.0426	0.0484	0.0256							
c_{g2}	1.39	-0.704	-0.0312	-0.156	0.538						
c_{t1}	6.94	-3.17	-0.309	-0.850	5.16	12.6					
c_{t2}	-3.61	4.05	-0.872	-0.0482	-4.15	-17.6	15.3				
c_{t3}	-2.72	-1.57	1.33	0.906	-0.316	-4.64	-18.2	13.0			
c_{b1}	-0.125	0.177	-0.0457	-0.00903	-0.166	-0.675	1.38	-0.941	0.0317		
c_{b2}	0.106	-0.0752	0.00692	-0.00740	0.0949	0.433	-0.509	0.162	-0.0219	0.00489	
c_{b3}	0.161	-0.0809	-0.00396	-0.0182	0.124	0.598	-0.474	-0.0434	-0.0189	0.0109	0.00719
	1	d_3	d_4	c_{g1}	c_{g2}	c_{t1}	c_{t2}	c_{t3}	c_{b1}	c_{b2}	c_{b3}

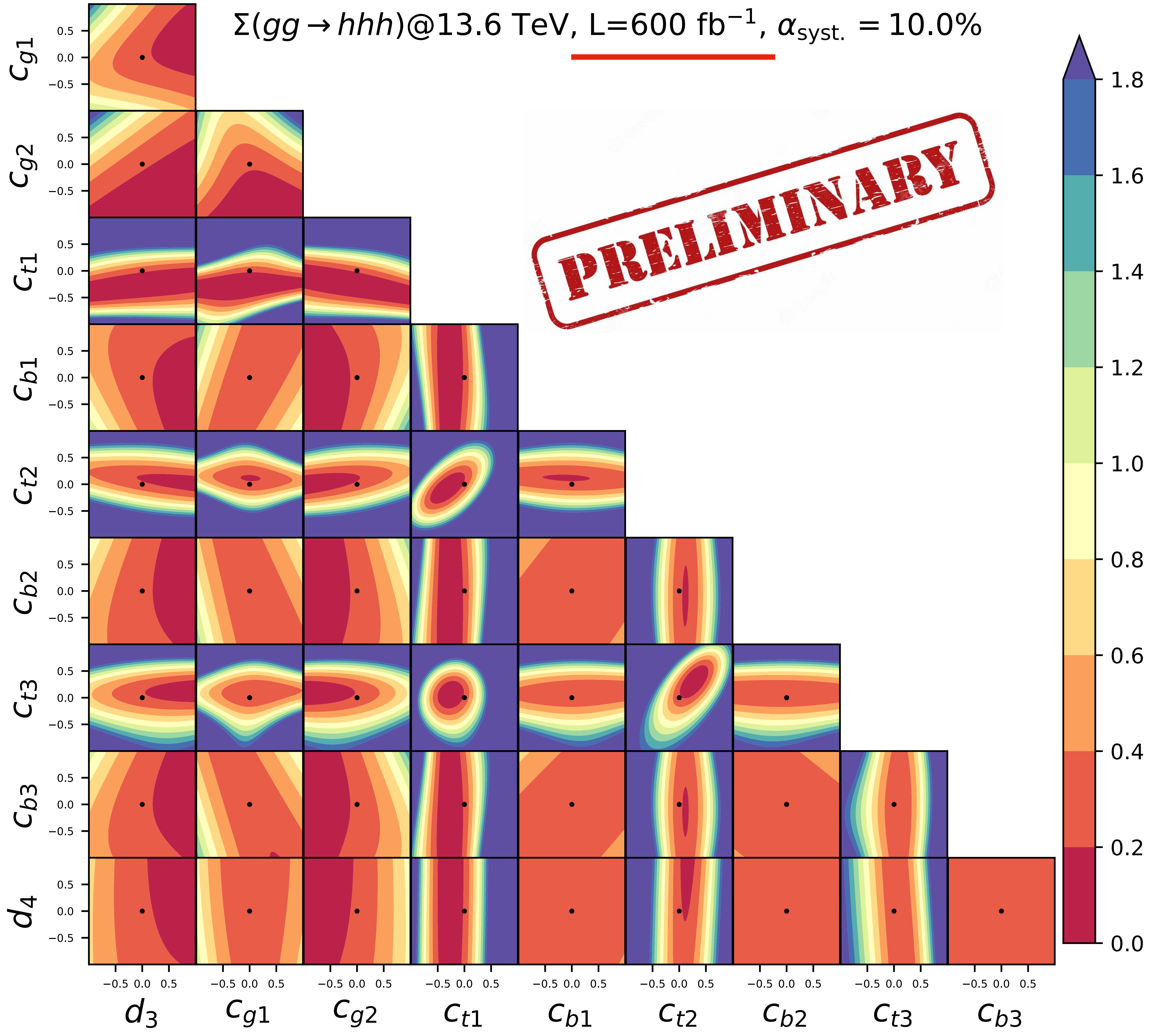
Table 2: Fit coefficients for leading-order Higgs boson triple production, in the form $\sigma/\sigma_{\mathrm{SM}} - 1 = A_i c_i + B_{ij} c_i c_j$, where $c_i \in \{d_3, d_4, c_{g1}, c_{g2}, c_{t1}, c_{t2}, c_{t3}, c_{b1}, c_{b2}, c_{b3}\}$, at $E_{\mathrm{CM}} =$ 13.6 TeV.

Anomalous Couplings @ LHC 13.6 TeV

- Again, using the **6 b-jet final state**:
  - b-jet tagging probability ~ 75% (no miss-identification),
  - $p_{T,b} > [50, 40, 30, 25, 25, 25]$ GeV, $|\eta_b| < 4.0$.
- $\mathscr{O}(1)$ events of SM $hhh \to 6b$ expected at pp@13.6 TeV in 600 fb^{-1}! [***Note***: LO, i.e. **NO** K-factors at present.]
- Versus: $\mathscr{O}(20)$ from QCD 6 b-jet backgrounds.
- **"LHC-like" smearing** applied & **10% systematic uncertainty** on background.
- Using: $|\mathscr{M}|^2 = |\mathscr{M}_{\text{SM}}|^2 + 2\text{Re}\{\mathscr{M}^*_{\text{SM}}\mathscr{M}_{1-\text{ins.}}\} + 2\text{Re}\{\mathscr{M}^*_{\text{SM}}\mathscr{M}_{2-\text{ins.}}\} + |\mathscr{M}_{1-\text{ins.}}|^2$.
- We applied the analysis on various combinations of anomalous coupling coefficients, and fitted the efficiency.

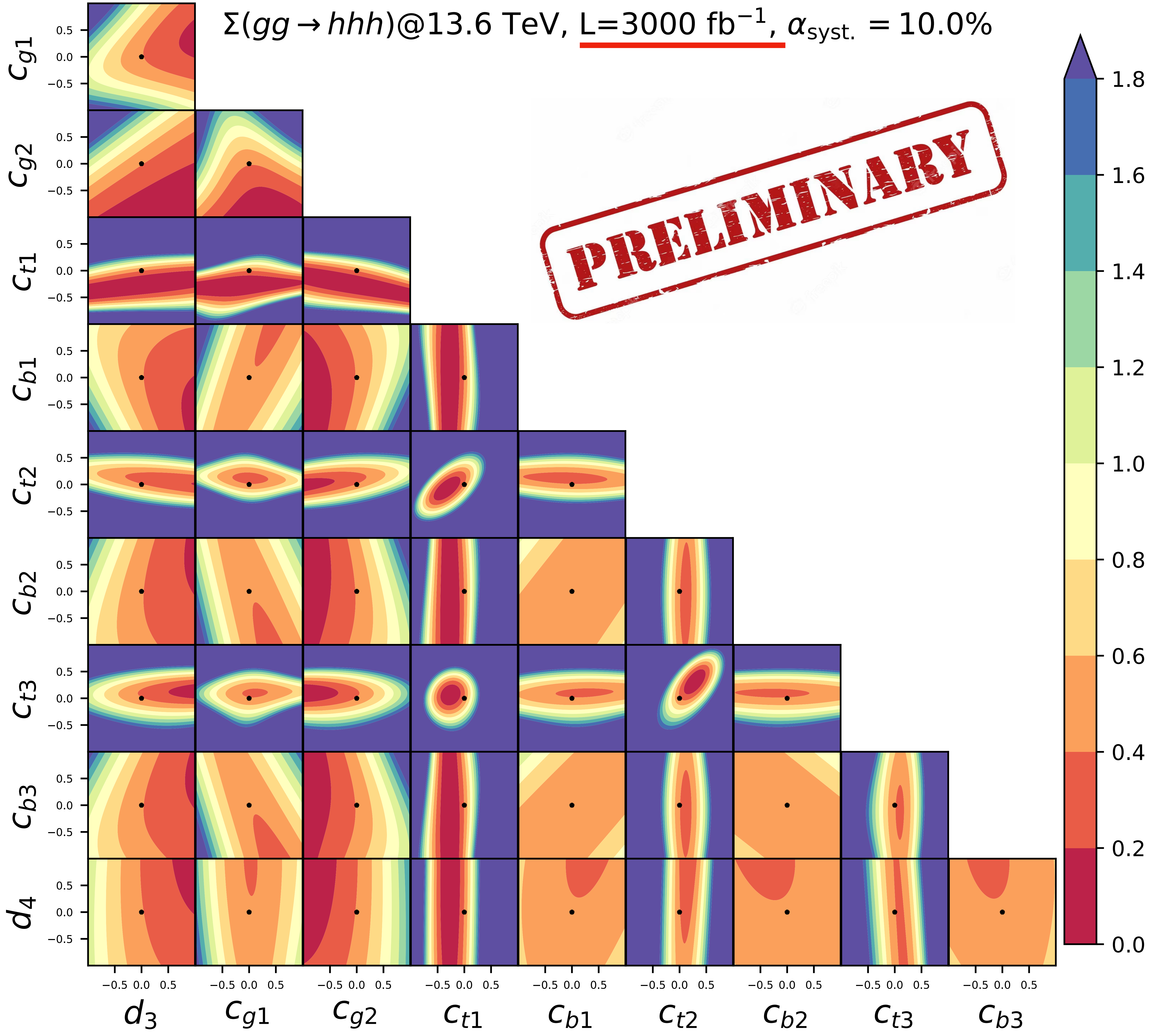
Anomalous Couplings @ LHC 13.6 TeV w/ 600 fb^{-1}

- Shown: **Significance** (Σ) for $hhh \to 6b$ for any two coefficients at 13.6 TeV with **integrated luminosity** ~ 600 fb^{-1}.
- **Dark blue regions excluded @ ≥ 2σ.**
- Obviously **no** good constraints on triple/quartic scalar coupling modifiers (close to SM).
- But *some* constraints on **fermion-Higgs contact interactions**: c_{t1}, c_{t2}, c_{t3}!



Anomalous Couplings @ LHC 13.6 TeV w/ 3000 fb^{-1}

- **Dark blue regions excluded @ ≥ 2σ.**
- Similar conclusions at 3000 fb^{-1}!
- **TO-DO:**
  - What about higher energies, e.g. 100 TeV?
  - Comparison to SMEFT? e.g. using “SMEFT@NLO” [C. Degrande, G. Durieu, Fabio Maltoni, K. Mimasu, E. Vryonidou, C. Zhang, arXiv:1607.04251]




Stay
Tuned

Summary & Outlook

- **hhh** is one of the few ways to probe the Higgs quartic coupling @pp colliders; **extremely rare** within the SM → a 100 TeV SM measurement.
- Nevertheless, **hhh may be enhanced by new phenomena.**
- Measurement of **hhh** within models with **extra scalars** possible at the LHC:
  - an avenue for **solving the inverse problem** in case of discovery
  - and perhaps understanding **electro-weak baryogenesis.**
- **Anomalous couplings can also modify hhh**: some constraints can be obtained at the LHC! What are the possibilities at **higher energies**?

Models @

TRSM: https://gitlab.com/apapaefs/twosinglet

Anomalous Couplings: https://gitlab.com/apapaefs/multihiggs_loop_sm

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Thanks!

KENNESAW STATE UNIVERSITY

Supplementary material

SM + One Real Singlet Scalar [= xSM]

- Motivation: simple model for a strong first-order electro-weak phase transition:
  - ➡ Singlet scalar field acts as a “catalyst”.
  - ➡ Can help explain **matter-anti-matter asymmetry** of the universe.

$$\mathcal{V}(\phi, S) = \bullet\,|\phi|^2 + \blacksquare\,|\phi|^4$$

$$+\bullet S^2 + \blacktriangle S^3 + \blacksquare S^4$$

$$+\blacktriangle\,|\phi|^2 S + \blacksquare\,|\phi|^2 S^2$$

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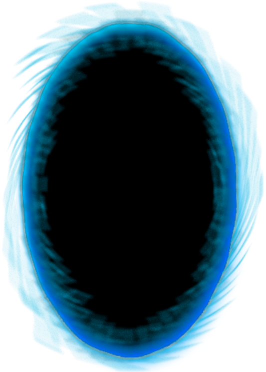

$$+ \blacktriangle\, |\phi|^2\, S + \blacksquare\, |\phi|^2\, S^2$$ ← “**Portal**” interactions.

SM + One Real Singlet Scalar [= xSM]

$$\mathcal{V}(\phi, S) = \textcolor{lime}{\bullet}\,|\phi|^2 + \textcolor{blue}{\blacksquare}\,|\phi|^4 + \textcolor{magenta}{\bullet}\,S^2 + \textcolor{cyan}{\blacktriangle}\,S^3 + \textcolor{brown}{\blacksquare}\,S^4 + \textcolor{red}{\blacktriangle}\,|\phi|^2\,S + \textcolor{purple}{\blacksquare}\,|\phi|^2\,S^2$$

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EWSB ↔ VEVs:

$$\phi \rightarrow \langle\phi\rangle + h$$

$$S \rightarrow \langle S\rangle + \chi$$

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Mass Eigenstates:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \chi \end{pmatrix}$$

θ: mixing angle

Note that we choose:
$\theta \to 0$ as the SM limit.

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$\Rightarrow$ Two scalar particles:

h_1 → The “SM-like” Higgs boson &

h_2 → a new scalar boson!

→ Prime collider targets!

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Higgs signal strength measurements

Direct searches for new heavy scalars

[**AP**, White, arXiv:2010.00597]

⇒ Future colliders could **discover** this model!

⇒ Q: Can we use hhh to find out more about xSM?

$$\phi \to \langle \phi \rangle + h$$

$$S \to \langle S \rangle + \chi$$

$$\Longrightarrow \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \chi \end{pmatrix}$$

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Direct searches for new heavy scalars

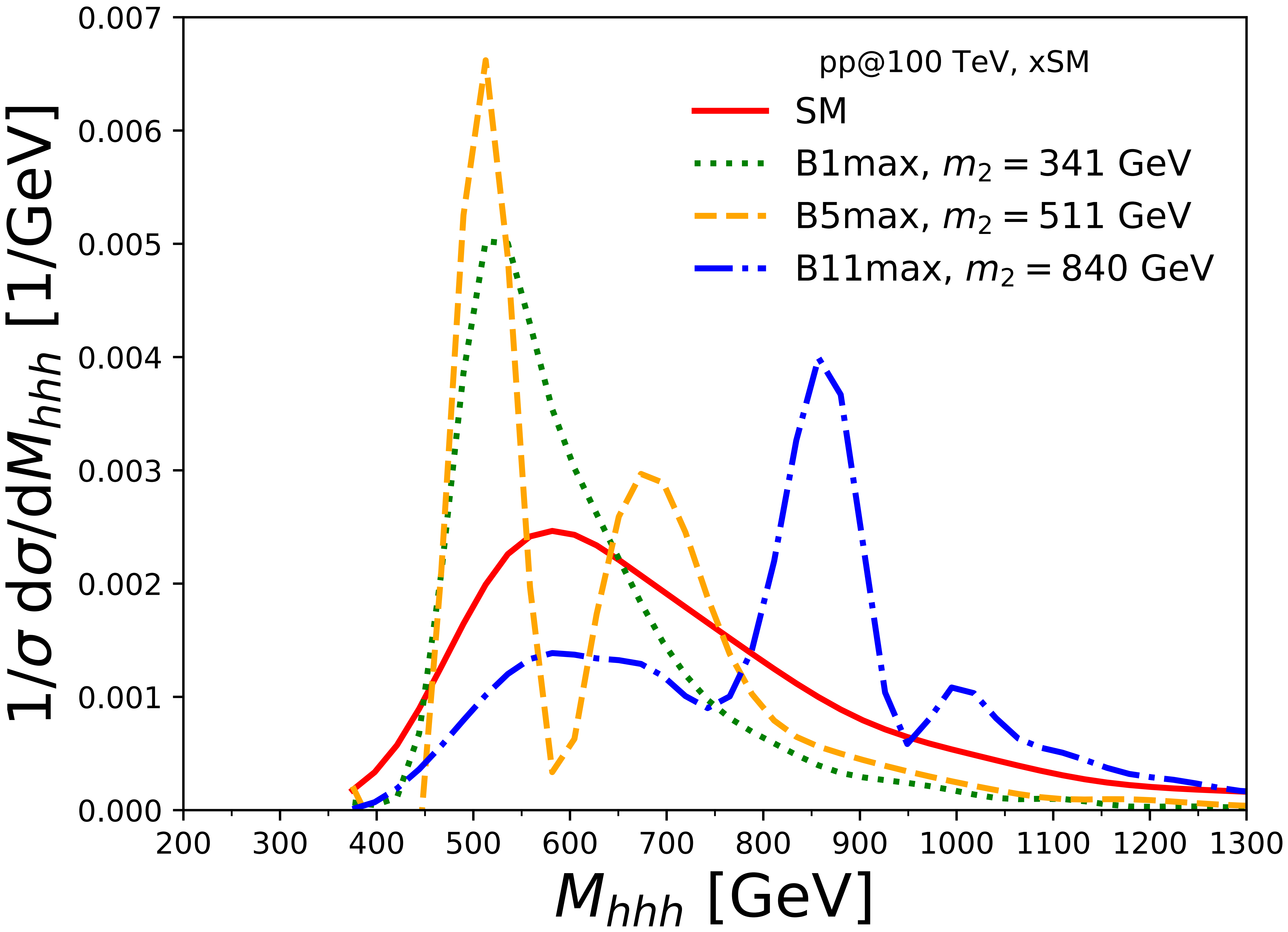
hhh in the xSM [pp@100 TeV]

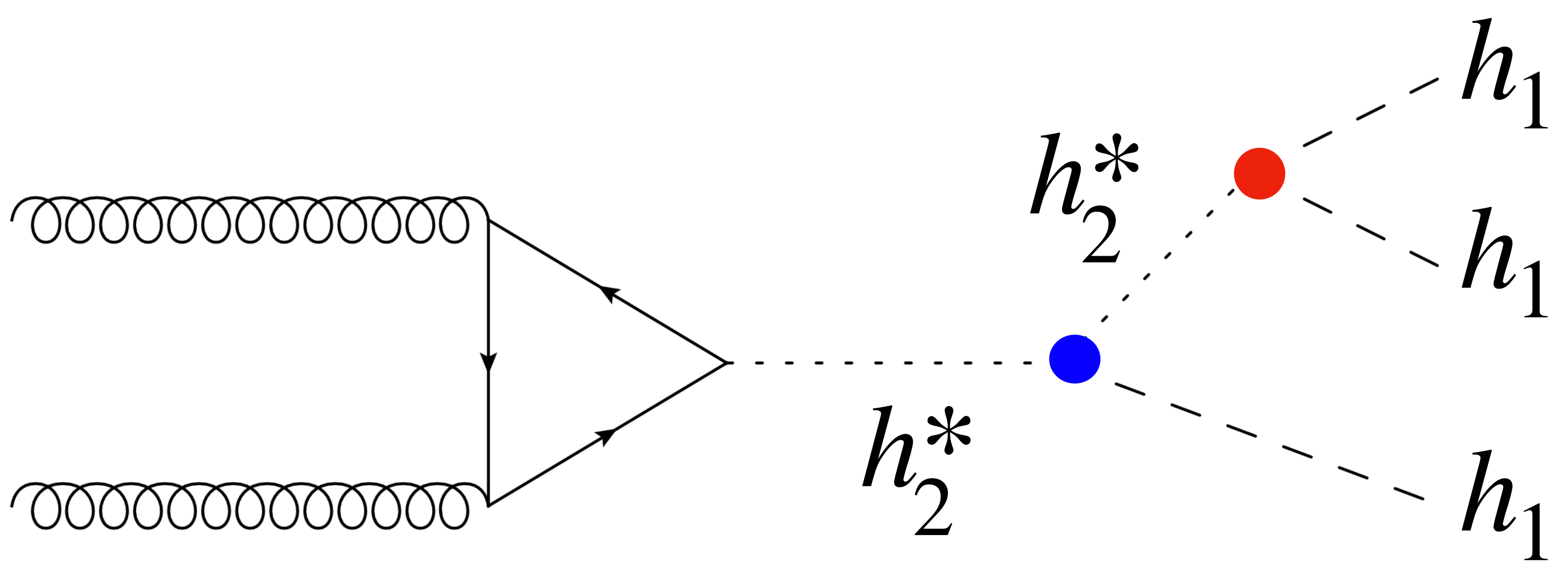
- Search for hhh via: $pp \to (b\bar{b})(b\bar{b})(b\bar{b})$ [AP, Tetlalmatzi-Xolocotzi, Zaro, **arXiv:1909.09166**]
- About **20%** of the hhh final state!
- Parton-level events for signal/backgrounds via **MadGraph5_aMC@NLO**.
- Parton shower/non-perturbative effects with **HERWIG 7**.
- Analysis with specialised **HERWIG 7** package → **"HwSim"**. [**AP**, https://gitlab.com/apapaefs/hwsim]
- **QCD 6 b-jet <u>by far</u> the largest background.**

hhh in the xSM and Strong First-Order Phase Transitions

- Strong First-Order Phase Transition (SFO-EWPT) benchmark points (**B***) of [Kotwal, Ramsey-Musolf, No, Winslow, **arXiv:1605.06123**].

[AP, Tetlalmatzi-Xolocotzi, Zaro, **arXiv:1909.09166**]





$h_1h_1h_1$ system invariant mass for selected benchmark points, “B1max”, “B5max”, “B11max”.

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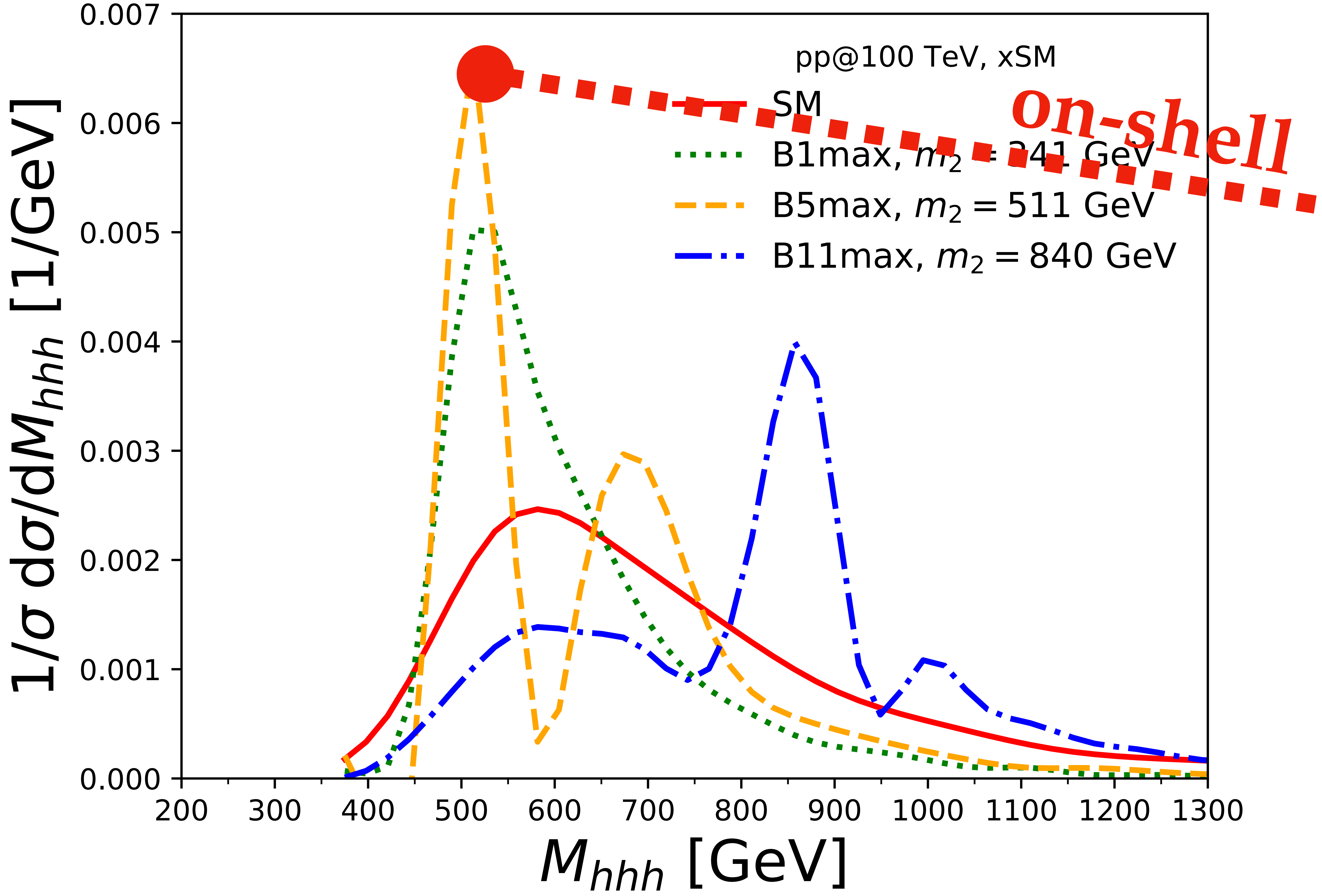

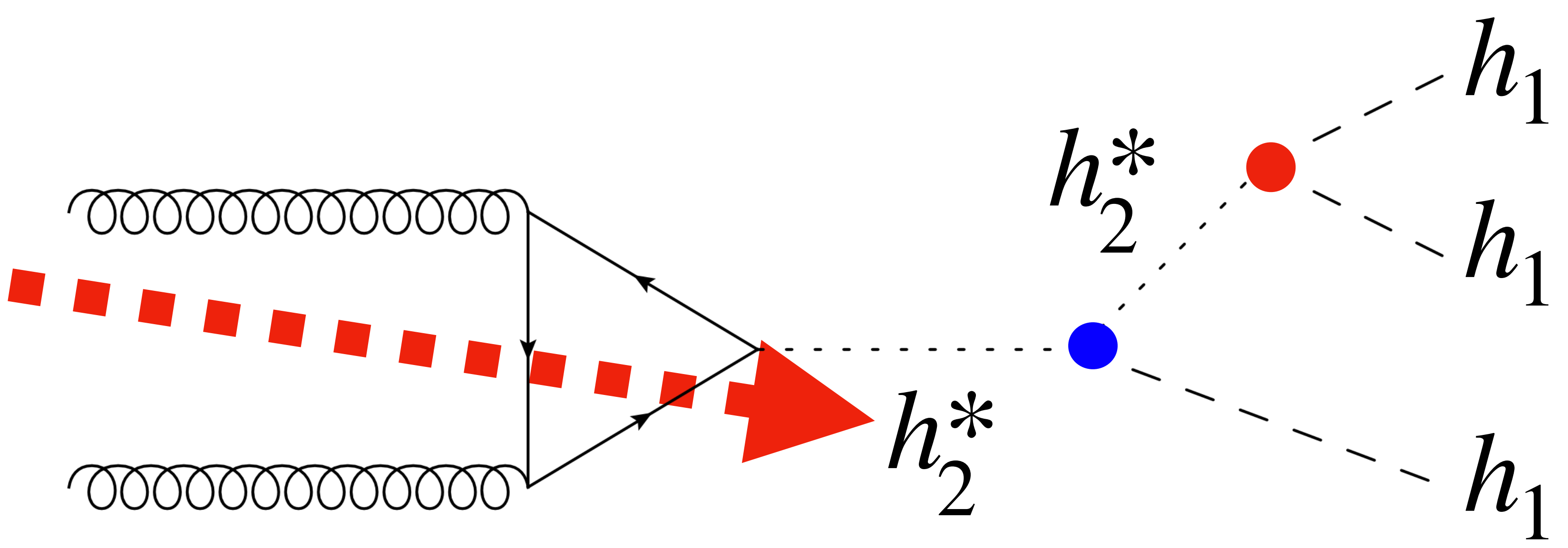

$h_1h_1h_1$ system invariant mass for selected benchmark points, "B1max", "B5max", "B11max".

hhh in the xSM and Strong First-Order Phase Transitions

- Strong First-Order Phase Transition (SFO-EWPT) benchmark points (**B***) of [Kotwal, Ramsey-Musolf, No, Winslow, **arXiv:1605.06123**].

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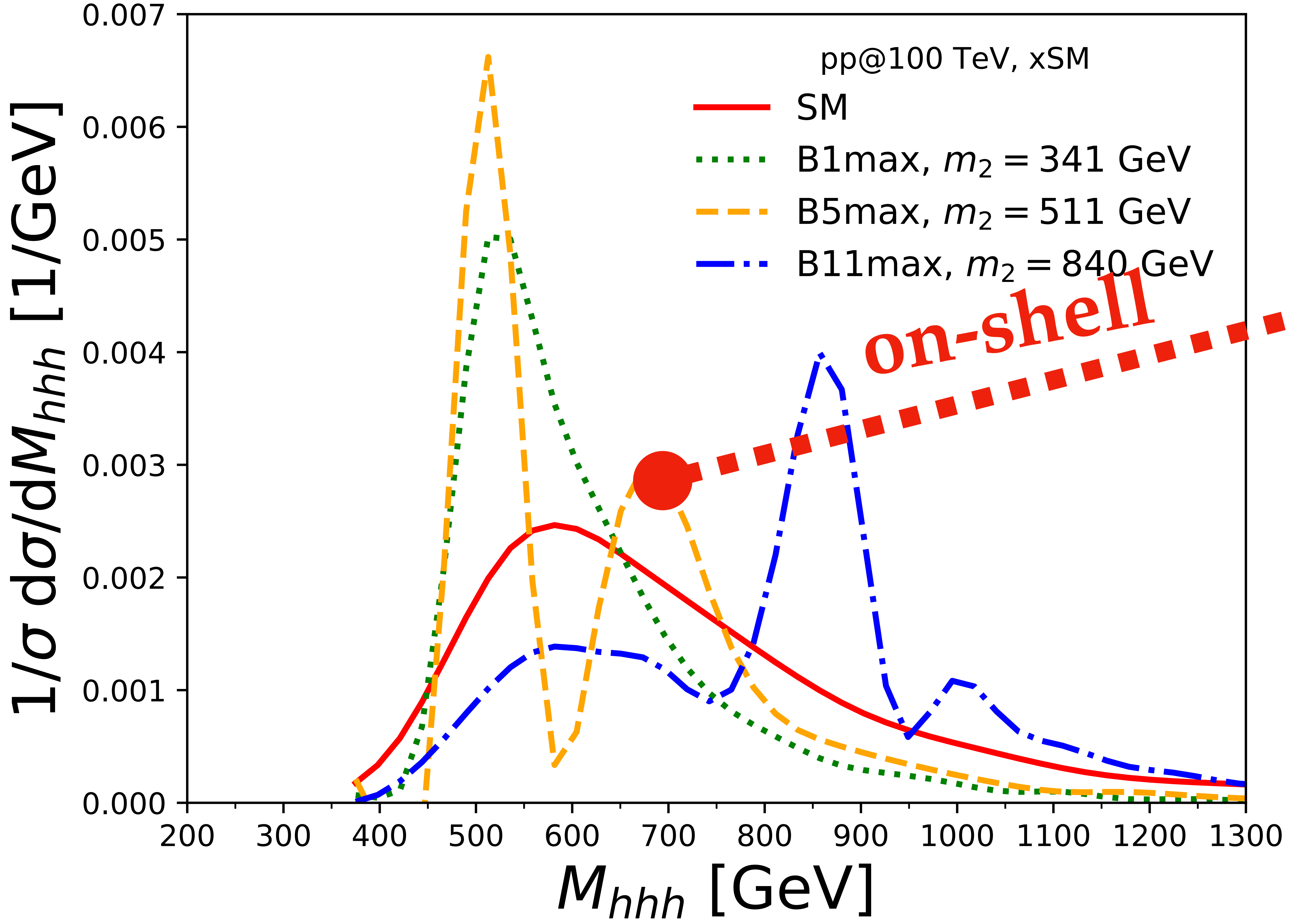

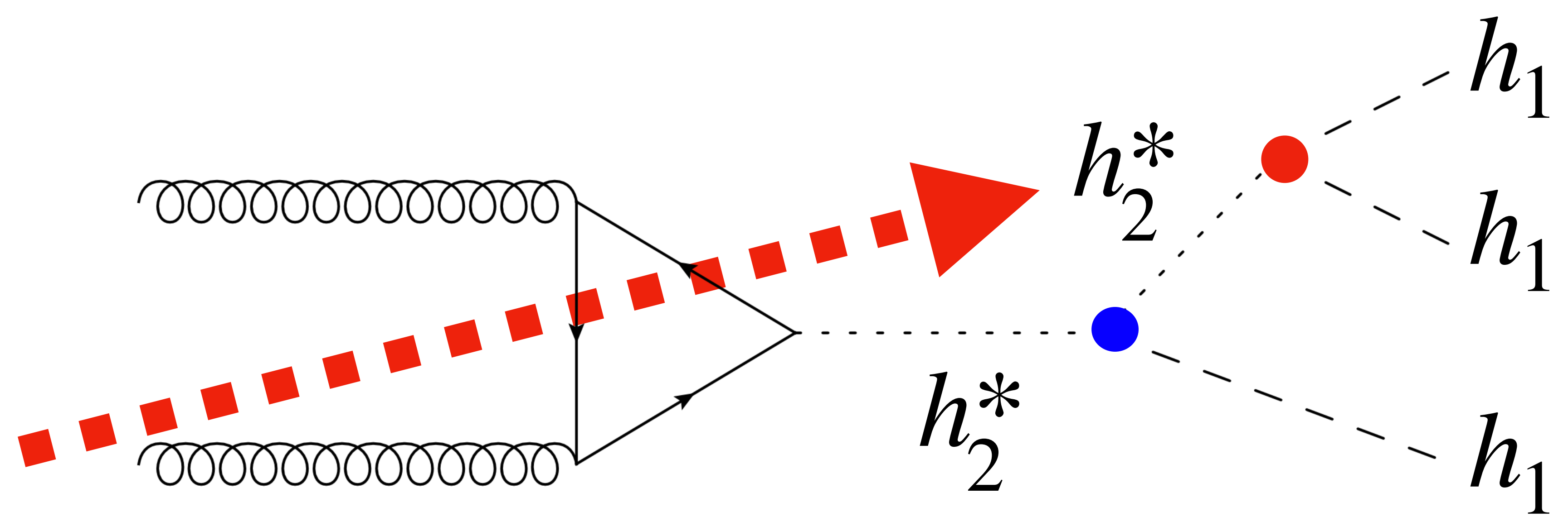

$h_1h_1h_1$ system invariant mass for selected benchmark points, "B1max", "B5max", "B11max".

hhh in the xSM and SFO-EWPT

Benchmark	$\frac{\sigma(h_1 h_1 h_1)}{\sigma(hhh)_{\mathrm{SM}}}$
B1max	60.55
B2max	56.69
B3max	3.01
B4max	3.37
B5max	2.94
B6max	3.60
B7max	4.70
B8max	4.91
B9max	2.68
B10max	2.35
B11max	1.03

Cross section can be much higher than the SM hhh! 😲

pp@100 TeV

hhh in the xSM and SFO-EWPT

Benchmark	Significance **(stdevs)**
B1max	46.6
B2max	42.9
B3max	2.9
B4max	3.7
B5max	3.0
B6max	3.8
B7max	5.3
B8max	7.8
B9max	5.9
B10max	4.9
B11max	2.3

Significance can be much higher than the SM! (c.f. ~1.7σ)

pp@100 TeV

⇒ use $h_1h_1h_1$ to determine model parameters, if a new scalar is discovered?

***Note: analysis applied as for SM.**

hhh: Final states

Assume: K-factor = 2.

[Maltoni, Vryonidou, Zaro, 1408.6542]

$hhh \to$ final state	BR (%)	$N_{20\mathrm{ab}^{-1}}$
$(b\bar{b})(b\bar{b})(b\bar{b})$	19.21	22207
$(b\bar{b})(b\bar{b})(WW_{1\ell})$	7.20	8328
$(b\bar{b})(b\bar{b})(\tau\bar{\tau})$	6.31	7297
$(b\bar{b})(\tau\bar{\tau})(WW_{1\ell})$	1.58	1824
$(b\bar{b})(b\bar{b})(WW_{2\ell})$	0.98	1128
$(b\bar{b})(WW_{1\ell})(WW_{1\ell})$	0.90	1041
$(b\bar{b})(\tau\bar{\tau})(\tau\bar{\tau})$	0.69	799
$(b\bar{b})(b\bar{b})(\gamma\gamma)$	0.23	263

→ Fuks, Kim, Lee, 1510.07697, Fuks, Kim, Lee, 1704.04298.

→Kilian, Sun, Yan, Zhao, Zhao, 1702.03554.

→ AP, Sakurai, 1508.06524, Chen, Yan, Zhao, Zhao, Zhong, 1510.04013, Fuks, Kim, Lee, 1510.07697.

[AP, Sakurai, 1508.06524]

Singlet model details

$$m_h^2 \equiv \frac{d^2V}{dh^2} = 2\lambda v_0^2$$

$$m_s^2 \equiv \frac{d^2V}{ds^2} = b_3 x_0 + 2b_4 x_0^2 - \frac{a_1 v_0^2}{4x_0}$$

$$m_{hs}^2 \equiv \frac{d^2V}{dhds} = (a_1 + 2a_2 x_0)\frac{v_0}{2}.$$

$$h_1 = h\cos\theta + s\sin\theta$$

$$h_2 = -h\sin\theta + s\cos\theta$$

$$m_{2,1}^2 = \frac{m_h^2 + m_s^2 \pm |m_h^2 - m_s^2| \sqrt{1 + \left(\frac{m_{hs}^2}{m_h^2 - m_s^2}\right)^2}}{2},$$

$$\sin 2\theta = \frac{(a_1 + 2a_2 x_0)v_0}{m_1^2 - m_2^2}$$

KENNESAW STATE UNIVERSITY

The 6b final state, analysis [AP, Gilberto Tetlalmatzi-Xolocotzi, Marco Zaro, arXiv:1909.09166]

- What can we learn about the anomalous couplings via **hhh** at 13.6 TeV?

- Begin by using the **6 b-jet final state!**

1. Require 6 tagged b-jets.

1
2
3
4
5
6

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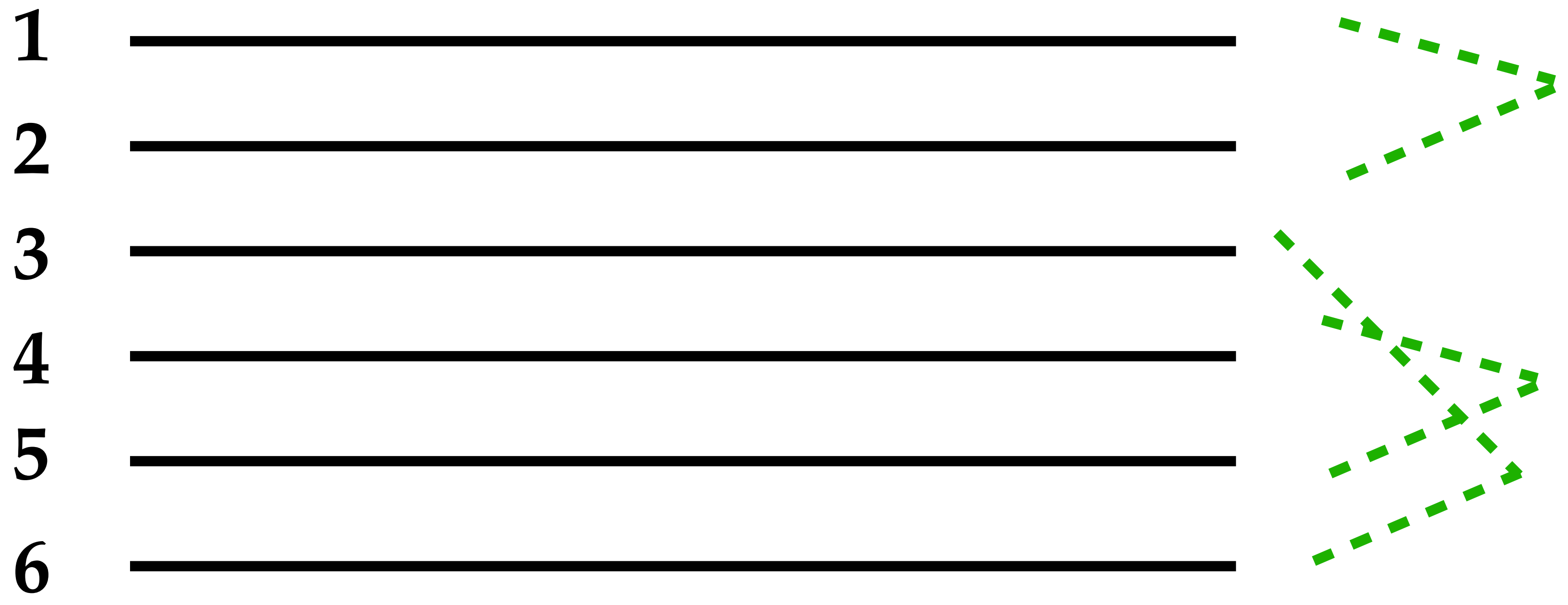

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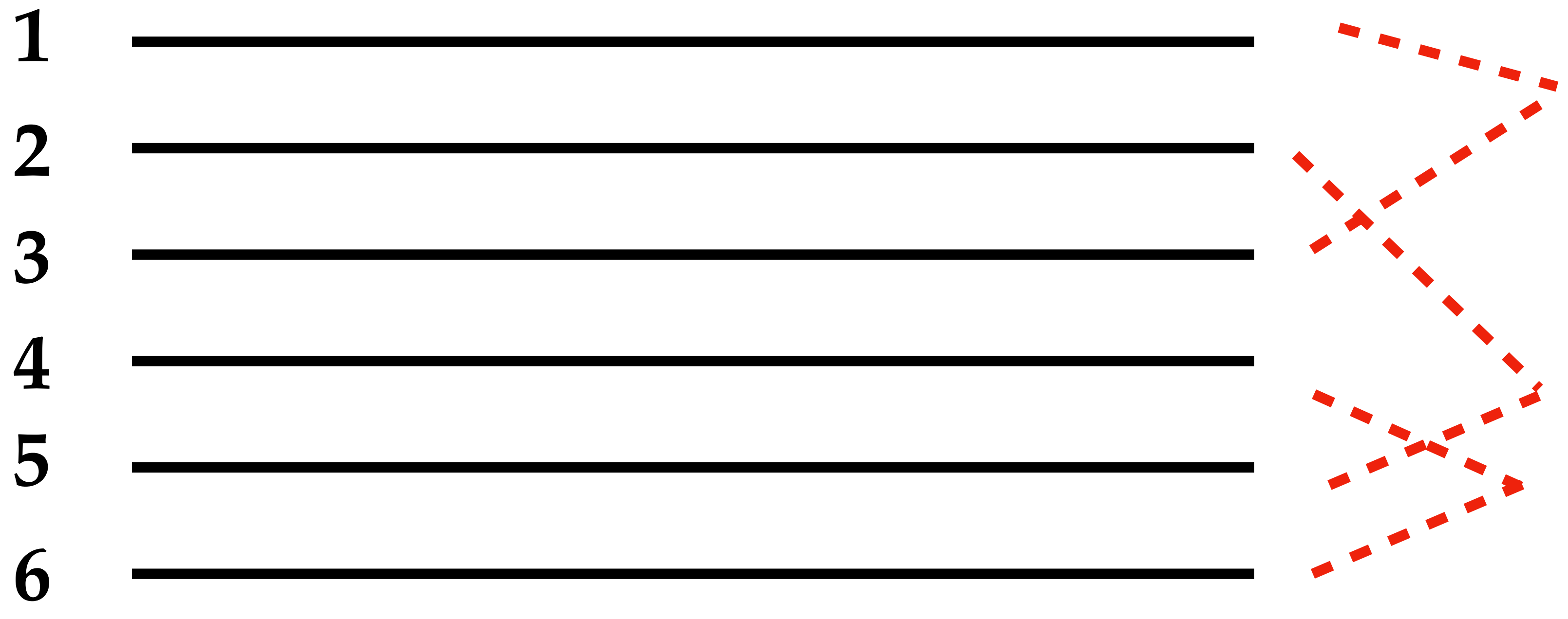

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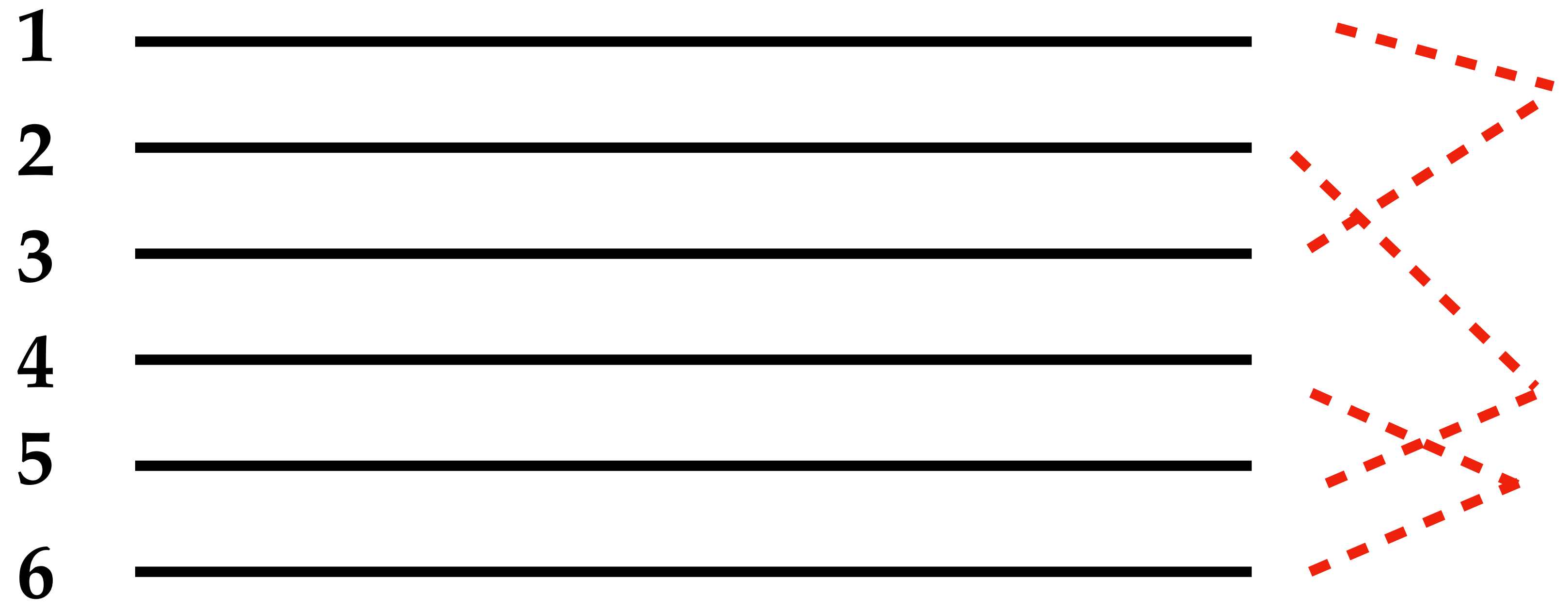

3. For each pairing construct:

$$\chi^2 = \sum_{qr\in\text{pairings } I} (M_{qr} - m_h^2)^2$$

≡ sum of squared differences from Higgs mass (~125 GeV)

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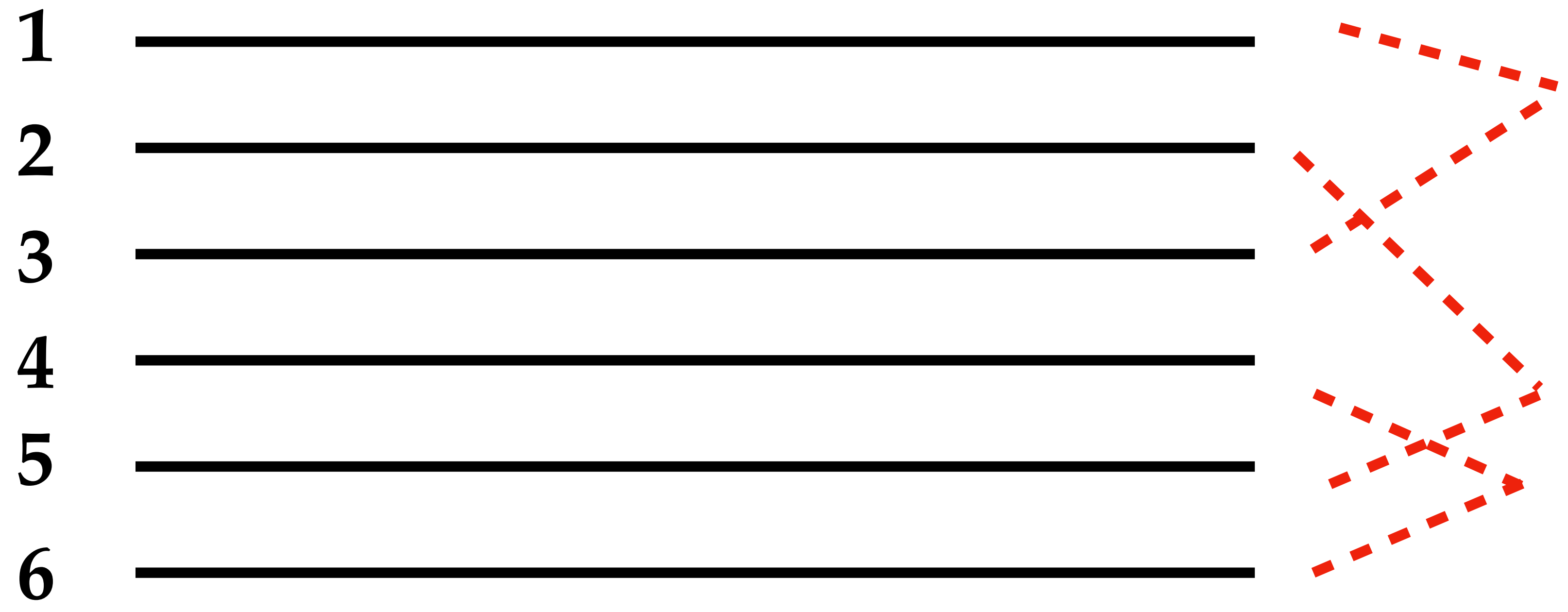

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$\Rightarrow$ **4. Pairing that gives $\underbrace{\text{minimum } \chi^2}_{\chi^2_{\text{min}}}$ determines “reconstructed Higgs boson”.**

The 6b final state, analysis

h_r^i →**Higgs boson candidates**

observable	cut
$p_{T,b}$	> 45 GeV
$\|\eta_b\|$	< 3.2
$\Delta R_{b,b}$	> 0.3
$p_T(h_r^i)$	$> [170, 120, 0]$ GeV, $i = 1, 2, 3$
χ^2_{min}	< 17 GeV
$\Delta m_{\text{min, mid, max}}$	$< 8, 8, 11$ GeV
$\Delta R(h_r^i, h_r^j)$	$< [3.5, 3.5, 3.5]$, $(i, j) = [(1,2), (1,3), (2,3)]$
$\Delta R_{bb}(h_r^i)$	$< [3.5, 3.5, 3.5]$, $i = 1, 2, 3$

← **the three terms in χ^2_{min}.**

signal/backgrounds after analysis

Process	σ_{GEN} (pb)	$\sigma_{\text{NLO}} \times \text{BR}$ (pb)	$\varepsilon_{\text{analysis}}$	$N^{\text{cuts}}_{20\ \text{ab}^{-1}}$
hhh (SM)	2.88×10^{-3}	1.06×10^{-3}	0.0131	278
QCD $(b\bar{b})(b\bar{b})(b\bar{b})$	26.15	52.30	2.6×10^{-5}	27116
$q\bar{q} \to hZZ \to h(b\bar{b})(b\bar{b})$	8.77×10^{-4}	4.99×10^{-4}	1.8×10^{-4}	~ 2
$q\bar{q} \to ZZZ \to (b\bar{b})(b\bar{b})$	7.95×10^{-4}	7.95×10^{-4}	1.2×10^{-5}	< 1
ggF $hZZ \to h(b\bar{b})(b\bar{b})$	1.08×10^{-4}	1.23×10^{-4}	$\mathcal{O}(10^{-3})$	~ 2
ggF $ZZZ \to (b\bar{b})(b\bar{b})$	1.36×10^{-5}	2.73×10^{-5}	2×10^{-5}	$\ll 1$
$h(b\bar{b})(b\bar{b})$	1.46×10^{-2}	1.66×10^{-2}	5.4×10^{-4}	179
$hh(b\bar{b})$	1.40×10^{-4}	9.11×10^{-5}	2.8×10^{-4}	~ 1
$hhZ \to hh(b\bar{b})$	4.99×10^{-3}	1.61×10^{-3}	7.2×10^{-4}	23
$hZ(b\bar{b}) \to h(b\bar{b})(b\bar{b})$	9.08×10^{-3}	1.03×10^{-2}	1.4×10^{-4}	29
$ZZ(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	2.87×10^{-2}	5.74×10^{-2}	1×10^{-5}	11
$Z(b\bar{b})(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	0.93	1.87	3×10^{-5}	1121
$\sum$ backgrounds				2.8×10^{4}

Reducible backgrounds

process	$\sigma_{\rm GEN}$ (pb)	$\sigma_{\rm GEN} \times \mathscr{P}(6\,b-\text{jets})$ (pb)
$(b\bar{b})(b\bar{b})(c\bar{c})$	76.8	0.768
$(b\bar{b})(c\bar{c})(c\bar{c})$	75.6	0.00756
$(c\bar{c})(c\bar{c})(c\bar{c})$	22.5	22.5×10^{-5}
$(b\bar{b})(b\bar{b})(jj)$	1.32×10^4	1.32
$(b\bar{b})(jj)(jj)$	9.79×19^5	0.00979
$(jj)(jj)(jj)$	1.37×10^6	1.37×10^{-6}

c.f. $\sigma_{\rm GEN}$(6b)= 26.15 pb

applied:

$$\mathcal{P}_{c\to b} = 0.1$$
$$\mathcal{P}_{j\to b} = 0.01$$

⇒ Assuming perfect b-tagging + identical analysis efficiency to QCD 6b:

→~10% contribution from reducible backgrounds.

for P(b-tagging) = 0.8:

→~30% contribution.

Scalar singlet model self-couplings

triple:

$$
\begin{aligned}
\lambda_{111} &= \lambda v_0 c_\theta^3 + \frac{1}{4}(a_1 + 2a_2 x_0) c_\theta^2 s_\theta \ , \\
&+ \frac{1}{2} a_2 v_0 s_\theta^2 c_\theta + \left(\frac{b_3}{3} + b_4 x_0\right) s_\theta^3 \ , \\
\lambda_{112} &= v_0(a_2 - 3\lambda) c_\theta^2 s_\theta - \frac{1}{2} a_2 v_0 s_\theta^3 \\
&+ \frac{1}{2}(-a_1 - 2a_2 x_0 + 2b_3 + 6b_4 x_0) c_\theta s_\theta^2 + \frac{1}{4}(a_1 + 2a_2 x_0) c_\theta^3 \\
\lambda_{122} &= v_0(3\lambda - a_2) s_\theta^2 c_\theta + \frac{1}{2} a_2 v_0 c_\theta^3 \\
&+ (b_3 + 3b_4 x_0 - \frac{1}{2} a_1 - a_2 x_0) s_\theta c_\theta^2 + \frac{1}{4}(a_1 + 2a_2 x_0) s_\theta^3 \ , \\
\lambda_{222} &= \frac{1}{12} \left[4(b_3 + 3b_4 x_0) c_\theta^3 - 6a_2 v_0 c_\theta^2 s_\theta \right. \\
&+ \left. 3(a_1 + 2a_2 x_0) c_\theta s_\theta^2 - 12\lambda v_0 s_\theta^3\right] \ ,
\end{aligned}
$$

quartic:

$$
\begin{aligned}
\lambda_{1111} &= \frac{1}{4}(\lambda c_\theta^4 + a_2 c_\theta^2 s_\theta^2 + b_4 s_\theta^4) \ , \\
\lambda_{1112} &= -\frac{1}{2}[-b_4 + \lambda + (-a_2 + b_4 + \lambda)(2c_\theta^2 - 1)] c_\theta s_\theta \ , \\
\lambda_{1122} &= \frac{1}{16}\{a_2 + 3(b_4 + \lambda) \\
&+ 3(a_2 - b_4 - \lambda)[(c_\theta^2 - s_\theta^2)^2 - (s_\theta c_\theta)^2]\} \ , \\
\lambda_{1222} &= \frac{1}{4}[b_4 - \lambda + (-a_2 + b_4 + \lambda)(c_\theta^2 - s_\theta^2)] s_\theta c_\theta \ , \\
\lambda_{2222} &= \frac{1}{4}(b_4 c_\theta^4 + a_2 c_\theta^2 s_\theta^2 + \lambda s_\theta^4) \ .
\end{aligned}
$$

TRSM hhh → 6b analysis details

Introduce two observables: $\chi^{2,(4)} = \sum_{qr \in I} \left(M_{qr} - M_1 \right)^2$

$$\chi^{2,(6)} = \sum_{qr \in J} \left(M_{qr} - M_1 \right)^2$$

→ constructed from different pairings of 4 and 6 b-tagged jets, M_{qr} is the invariant mass of the pairing qr.

TRSM hhh → 6b analysis details

Label	(M_2, M_3) [GeV]	$< P_{T,b}$ [GeV]	$\chi^{2,(4)} <$ [GeV^2]	$\chi^{2,(6)} <$ [GeV^2]	$m_{4b}^{\text{inv}} <$ [GeV]	$m_{6b}^{\text{inv}} <$ [GeV]
A	$(255, 504)$	34.0	10	20	-	525
B	$(263, 455)$	34.0	10	20	450	470
C	$(287, 502)$	34.0	10	50	454	525
D	$(290, 454)$	27.25	25	20	369	475
E	$(320, 503)$	27.25	10	20	403	525
F	$(264, 504)$	34.0	10	40	454	525
G	$(280, 455)$	26.5	25	20	335	475
H	$(300, 475)$	26.5	15	20	352	500
I	$(310, 500)$	26.5	15	20	386	525
J	$(280, 500)$	34.0	10	40	454	525

Table 3. The optimised selection cuts for each of the benchmark points within **BP3** shown in table 2. The cuts not shown above are common for all points, as follows: $|\eta|_b < 2.35$, $\Delta m_{\text{min, med, max}} < [15, 14, 20]$ GeV, $p_T(h_1^i) > [50, 50, 0]$ GeV, $\Delta R(h_1^i, h_1^j) < 3.5$ and $\Delta R_{bb}(h_1) < 3.5$. For some of the points a m_{4b}^{inv} cut is not given, as this was found to not have an impact when combined with the m_{6b}^{inv} cut.

TRSM hhh → 6b analysis details (Signal vs Bkg)

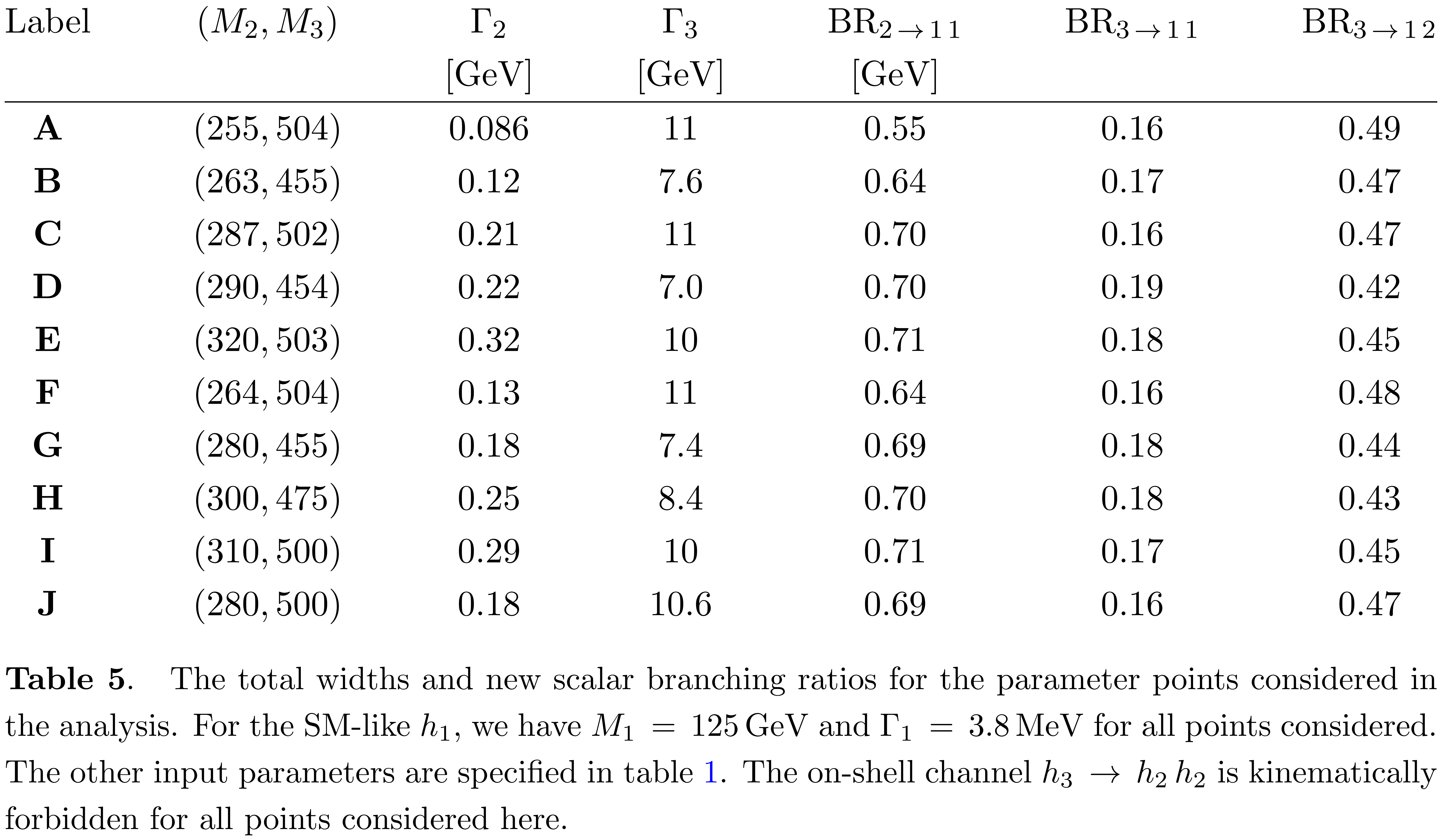
Label	(M_2, M_3) [GeV]	$\varepsilon_{\text{Sig.}}$	$\text{S}\vert_{300\text{fb}^{-1}}$	$\varepsilon_{\text{Bkg.}}$	$\text{B}\vert_{300\text{fb}^{-1}}$	$\text{sig}\vert_{300\text{fb}^{-1}}$ (syst.)	$\text{sig}\vert_{3000\text{fb}^{-1}}$ (syst.)
A	$(255, 504)$	0.025	14.12	8.50×10^{-4}	19.16	2.92 (2.63)	9.23 (5.07)
B	$(263, 455)$	0.019	17.03	3.60×10^{-5}	8.12	4.78 (4.50)	15.10 (10.14)
C	$(287, 502)$	0.030	20.71	9.13×10^{-5}	20.60	4.01 (3.56)	12.68 (6.67)
D	$(290, 454)$	0.044	37.32	1.96×10^{-4}	44.19	5.02 (4.03)	15.86 (6.25)
E	$(320, 503)$	0.051	31.74	2.73×10^{-4}	61.55	3.76 (2.87)	11.88 (4.18)
F	$(264, 504)$	0.028	18.18	9.13×10^{-5}	20.60	3.56 (3.18)	11.27 (5.98)
G	$(280, 455)$	0.044	38.70	1.96×10^{-4}	44.19	5.18 (4.16)	16.39 (6.45)
H	$(300, 475)$	0.054	41.27	2.95×10^{-4}	66.46	4.64 (3.47)	14.68 (4.94)
I	$(310, 500)$	0.063	41.43	3.97×10^{-4}	89.59	4.09 (2.88)	12.94 (3.87)
J	$(280, 500)$	0.029	20.67	9.14×10^{-5}	20.60	4.00 (3.56)	12.65 (6.66)

Table 4. The resulting selection efficiencies, $\varepsilon_{\text{Sig.}}$ and $\varepsilon_{\text{Bkg.}}$, number of events, S and B for the signal and background, respectively, and statistical significances for the sets of cuts presented in table 3. A b-tagging efficiency of 0.7 has been assumed. The number of signal and background events are provided at an integrated luminosity of 300 fb^{-1}. Results for 3000 fb^{-1} are obtained via simple extrapolation. The significance is given at both values of the integrated luminosity excluding (including) systematic errors in the background according to Eq. (5.1) (or Eq. (5.2) with $\sigma_b = 0.1 \times \text{B}$).

TRSM BP3 Definition

Parameter	Value
M_1	125.09 GeV
M_2	$[125,\ 500]$ GeV
M_3	$[255,\ 650]$ GeV
θ_{hS}	-0.129
θ_{hX}	0.226
θ_{SX}	-0.899
v_S	140 GeV
v_X	100 GeV
κ_1	0.966
κ_2	0.094
κ_3	0.239

TRSM BP3 Benchmark Point Info



Label	(M_2, M_3)	Γ_2 [GeV]	Γ_3 [GeV]	$\mathrm{BR}_{2\to 1\,1}$ [GeV]	$\mathrm{BR}_{3\to 1\,1}$	$\mathrm{BR}_{3\to 1\,2}$
A	$(255, 504)$	0.086	11	0.55	0.16	0.49
B	$(263, 455)$	0.12	7.6	0.64	0.17	0.47
C	$(287, 502)$	0.21	11	0.70	0.16	0.47
D	$(290, 454)$	0.22	7.0	0.70	0.19	0.42
E	$(320, 503)$	0.32	10	0.71	0.18	0.45
F	$(264, 504)$	0.13	11	0.64	0.16	0.48
G	$(280, 455)$	0.18	7.4	0.69	0.18	0.44
H	$(300, 475)$	0.25	8.4	0.70	0.18	0.43
I	$(310, 500)$	0.29	10	0.71	0.17	0.45
J	$(280, 500)$	0.18	10.6	0.69	0.16	0.47

Table 5. The total widths and new scalar branching ratios for the parameter points considered in the analysis. For the SM-like h_1, we have $M_1 = 125\,\mathrm{GeV}$ and $\Gamma_1 = 3.8\,\mathrm{MeV}$ for all points considered. The other input parameters are specified in table 1. The on-shell channel $h_3 \to h_2\,h_2$ is kinematically forbidden for all points considered here.

hhh with Anomalous Couplings