Dissecting Triple Higgs Boson Production in New Physics Models

[with Gilberto Tetlalmatzi-Xolocotzi]

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Triple Higgs Boson Production ⟶ "hhh"

Warning: Work in progress!

The Plan:

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1 SM **hhh** Production

2 ➜ Enhanced (Double-Res.) **hhh**

3 ➜ A “Simplified” Approach

1 SM **hhh** Production

SM Multi-Higgs Boson Production "Fun" Facts

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

$\sigma(h) \sim 50$ pb

SM, 14 TeV

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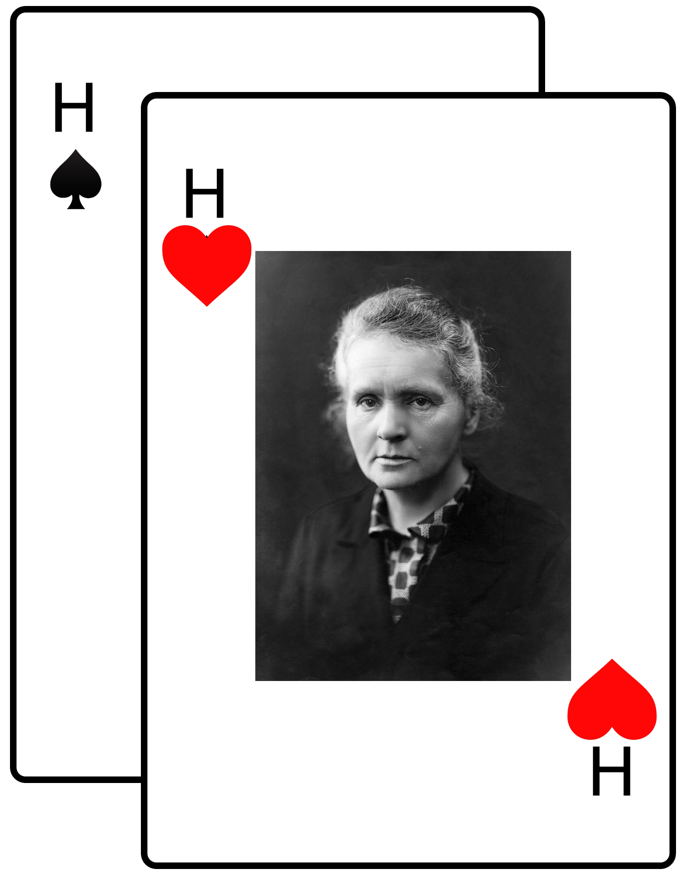

$\sigma(hh) \sim 40$ fb

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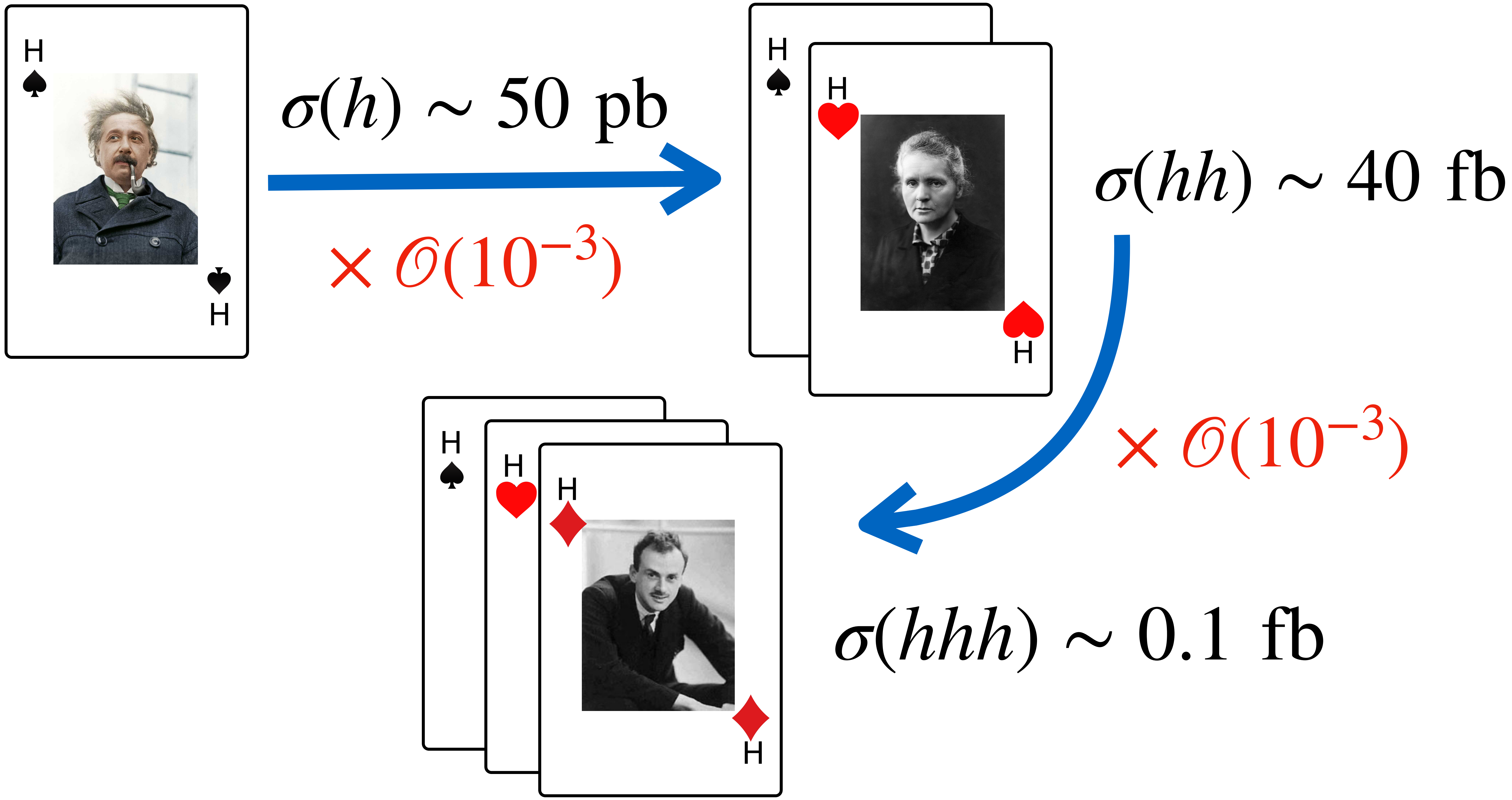

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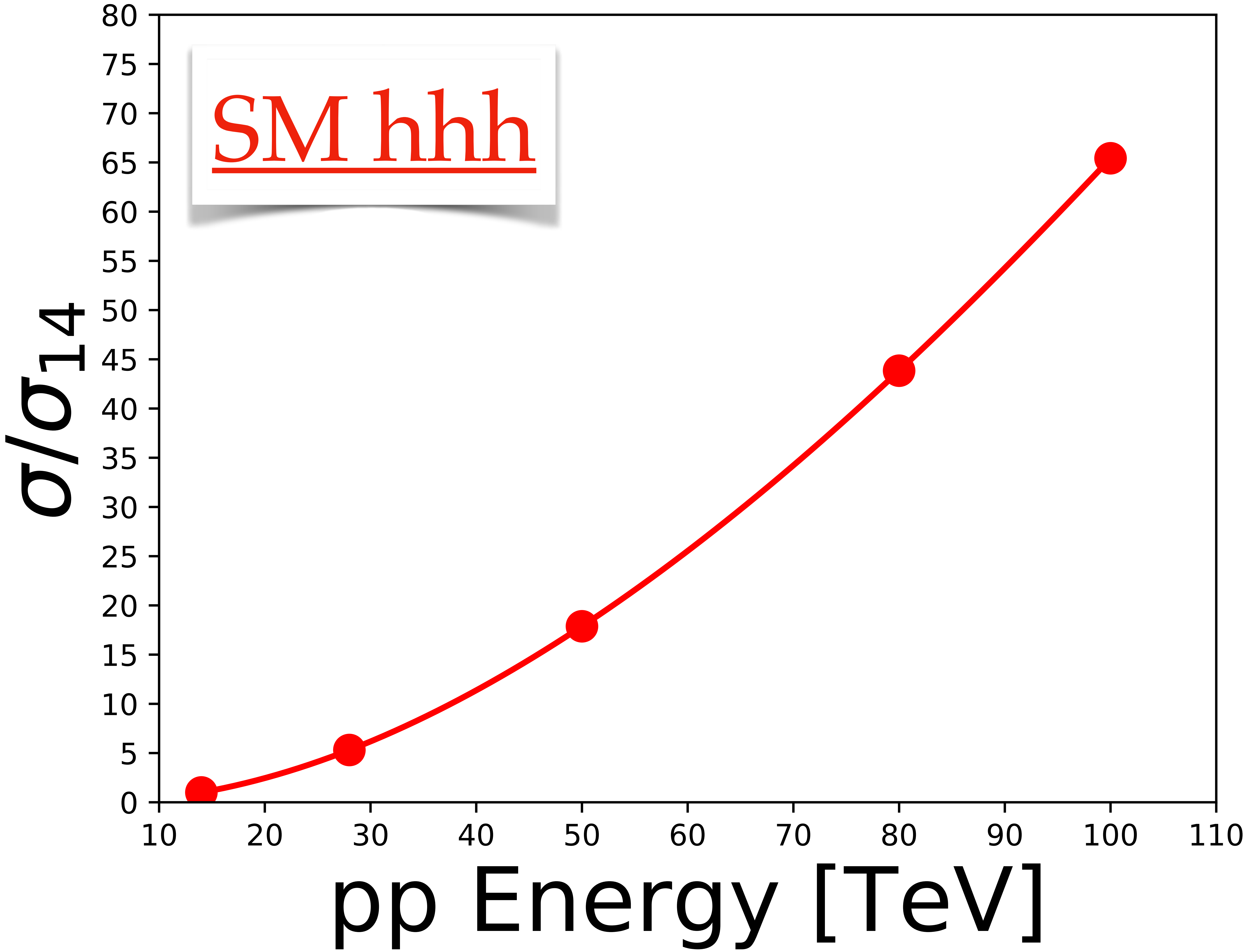
SM Multi-Higgs Boson Production "Fun" Facts

- Cranking up the pp energy could help!



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

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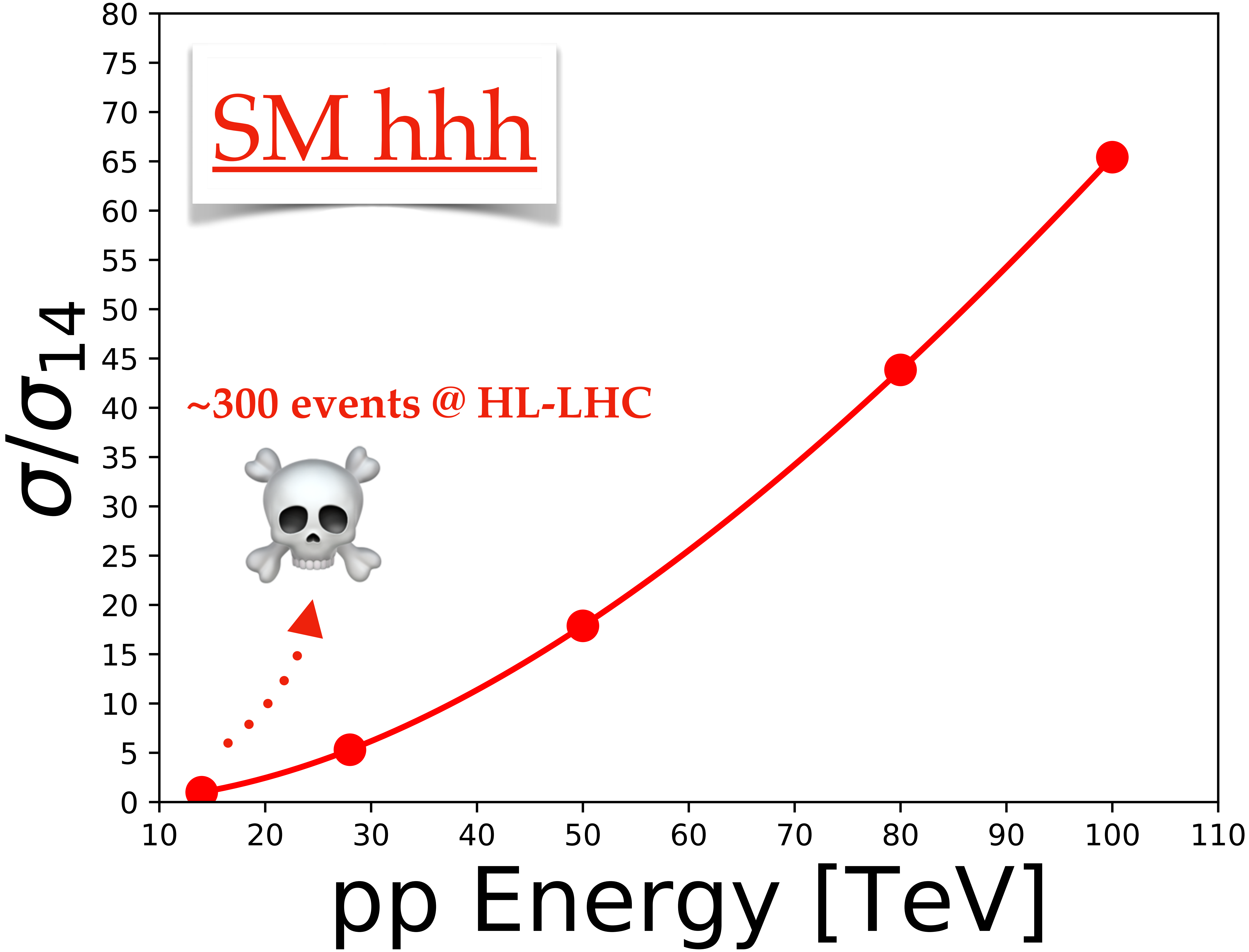

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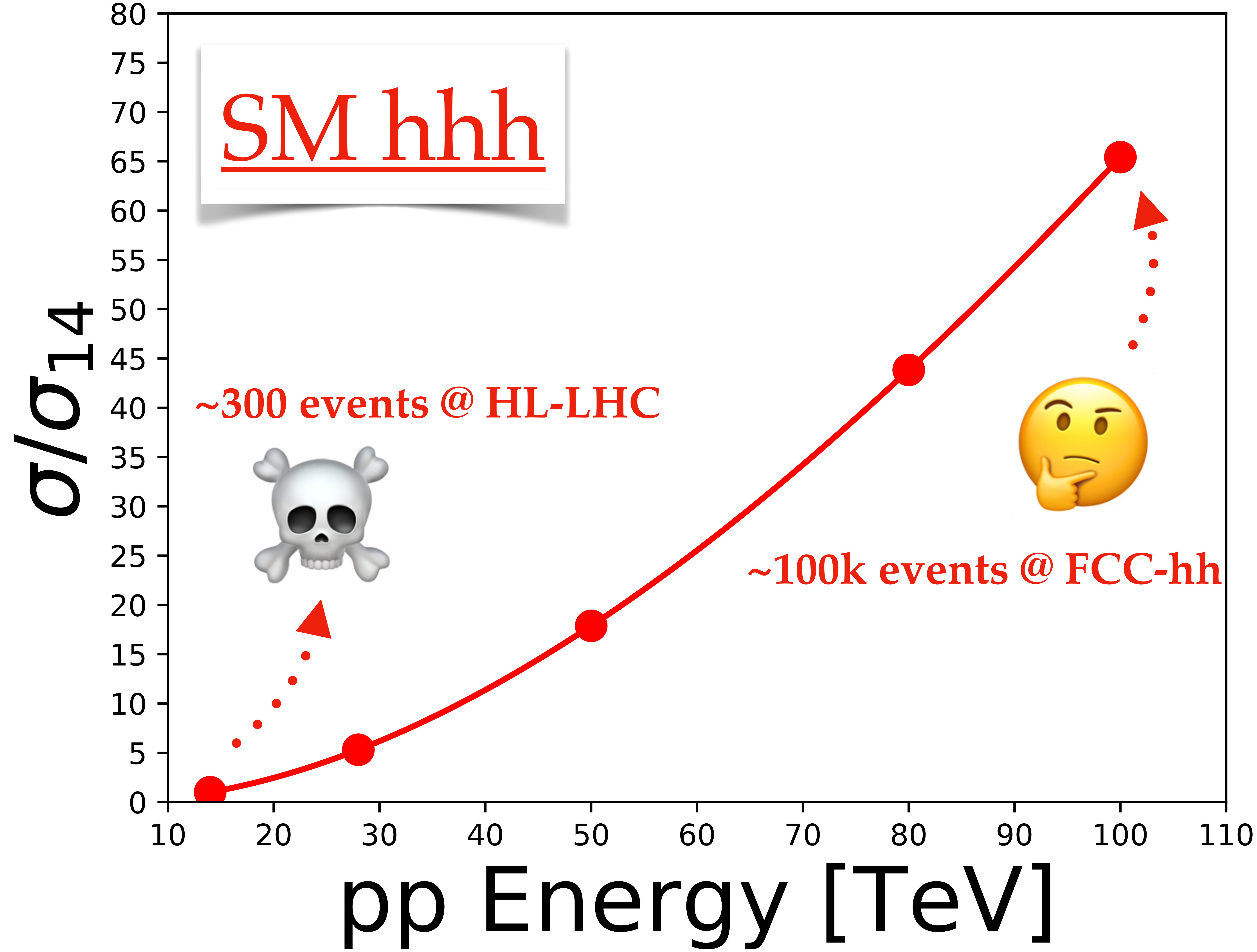

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Effective Field Theories

Explicit, UV-Complete models,

Anomalous Couplings

[e.g. **AP**, Tetlalmatzi-Xolocotzi, arXiv:2312.13562]

Simplified models

NEW PHYSICS

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NEW PHYSICS

Explicit, UV-Complete models,

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Significant enhancement in **hhh** possible through **double-resonant scalar processes!**

First proposed in:
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NEW PHYSICS

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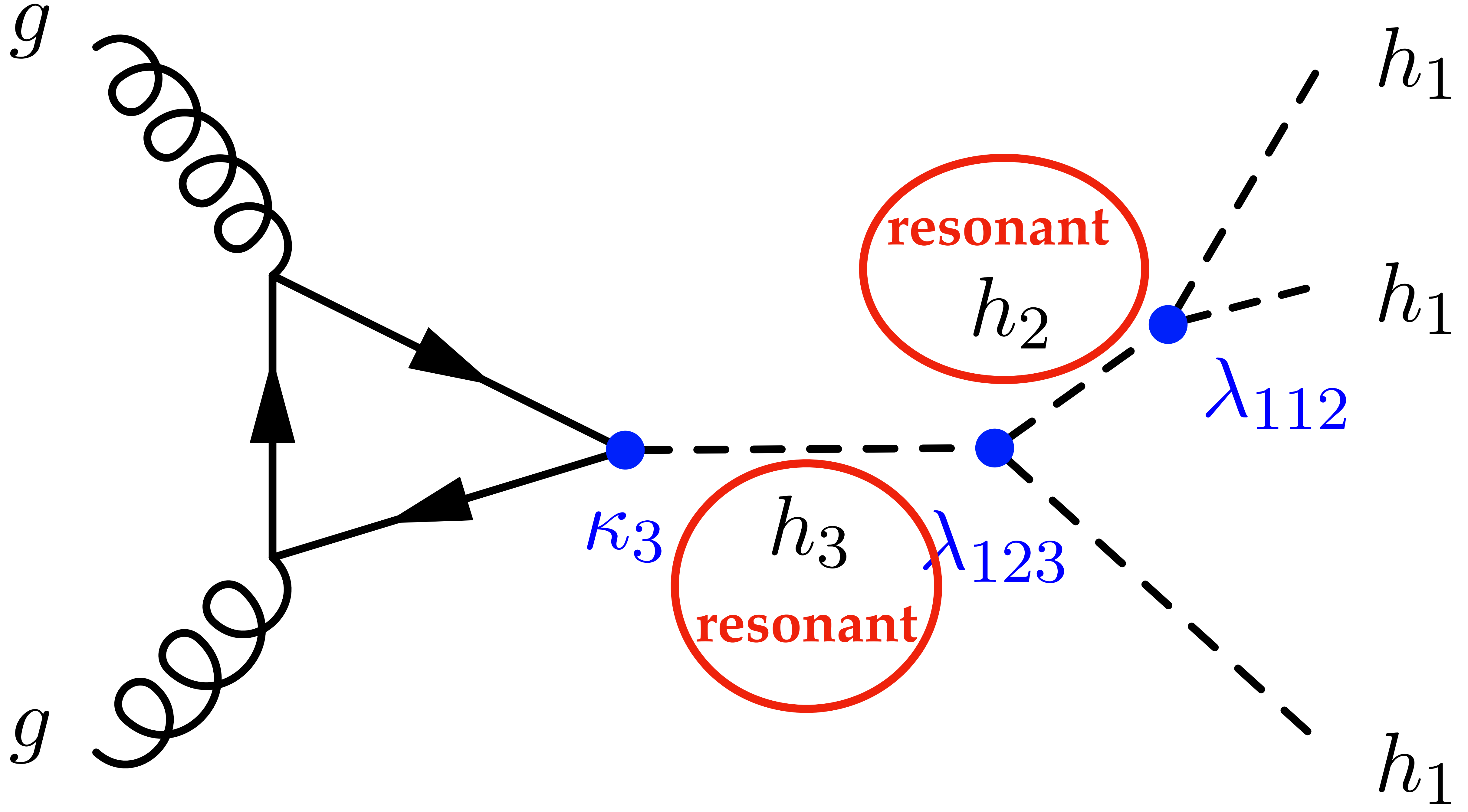
2 ➜ Enhanced (Double-Res.) hhh

Double-Resonant Triple Higgs Boson Production

- Significant enhancement possible in models with **at least two additional scalars h_2 and h_3**, with h_1 the **SM-like Higgs** boson.

- that satisfy: $m_2 > 2m_1$ and $m_3 > m_2 + m_1$.

- This occurs through a **double-resonant process** $gg \to h_3 \to h_2 h_1 \to h_1 h_1 h_1$**:**



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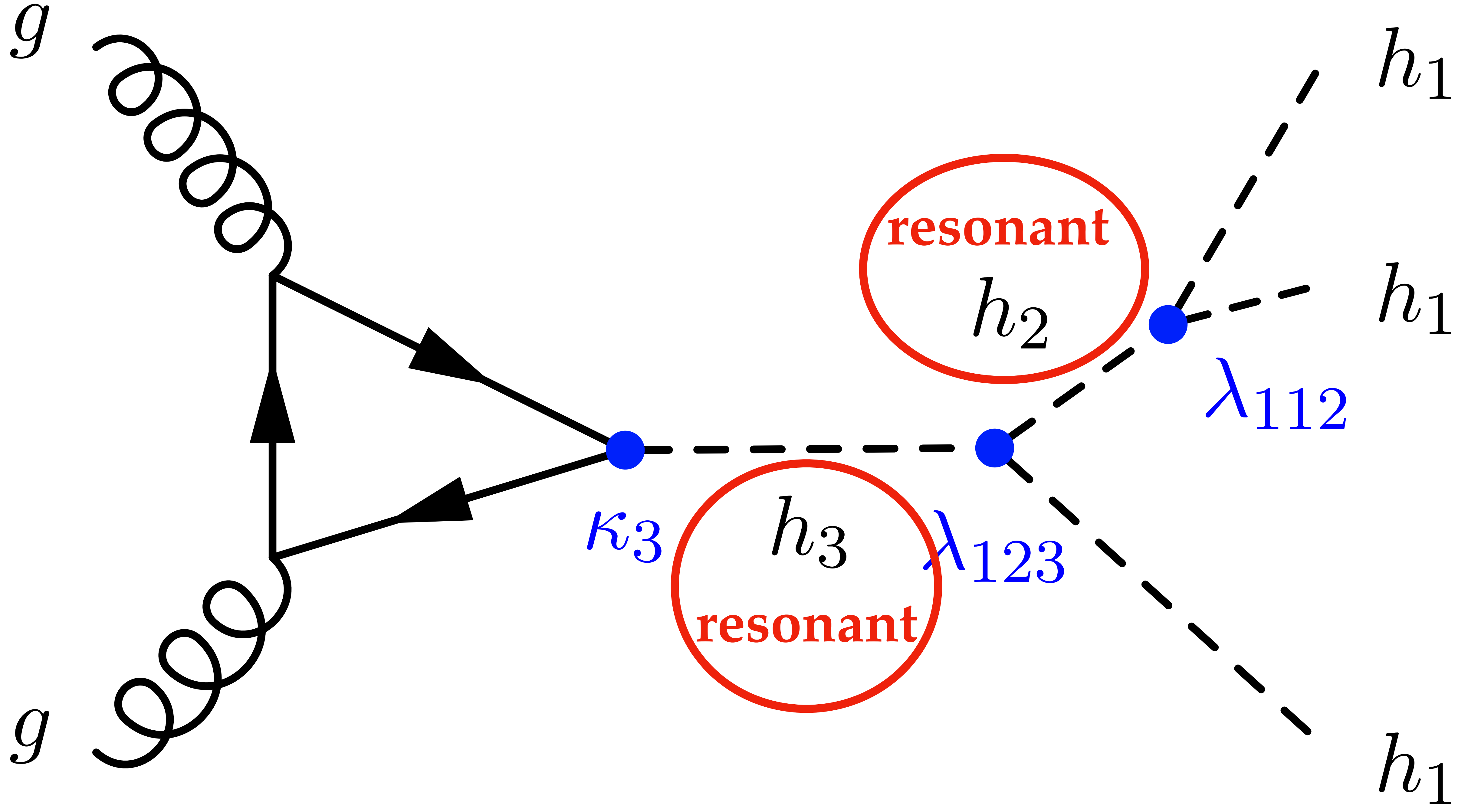
Double-Resonant Triple Higgs Boson Production

- First proposed in [Robens, Stefaniak, Wittbrodt, arXiv:1908.08554].
- And shown to be **observable at the LHC** in $h_1 h_1 h_1 \to (b\bar{b})(b\bar{b})(b\bar{b})$ in [**AP**, Robens, Tetlalmatzi-Xolocotzi, arXiv:2101.00037] for the case of the TRSM (= SM + Two Real Singlets).
- I will discuss the TRSM again later.



General Features of Double-Resonant hhh

- For now let's just assume we have a model which satisfies the condition for the existence of the double-resonant process:
  - **at least two additional scalars** h_2 **and** h_3, with h_1 the **SM-like Higgs** boson.
  - that satisfy: $m_2 > 2m_1$ and $m_3 > m_2 + m_1$,
- Generally speaking, we also require non-zero couplings:
  - h_3-h_2-h_1: $\longrightarrow \lambda_{123}$
  - h_2-h_1-h_1: $\longrightarrow \lambda_{112}$

Narrow Widths through Constraints

- For the analysis presented here to work, we also need **narrow widths**:
  - $\Gamma_2 \ll m_2$ and $\Gamma_3 \ll m_3$.
  - Should be satisfied if couplings of new scalars are inherited from Higgs couplings through mixing: e.g. as in the TRSM, since:

$$\Gamma_i = \kappa_i^2 \, \Gamma^{\rm SM}(m_i) + \sum_{j,k \neq i} \Gamma_{h_i \to h_j h_k},$$

  - Since the κ_i are constrained by experiment to be small (through Higgs boson signal strength measurements), this limits how large the widths can be **[TBC!]**.

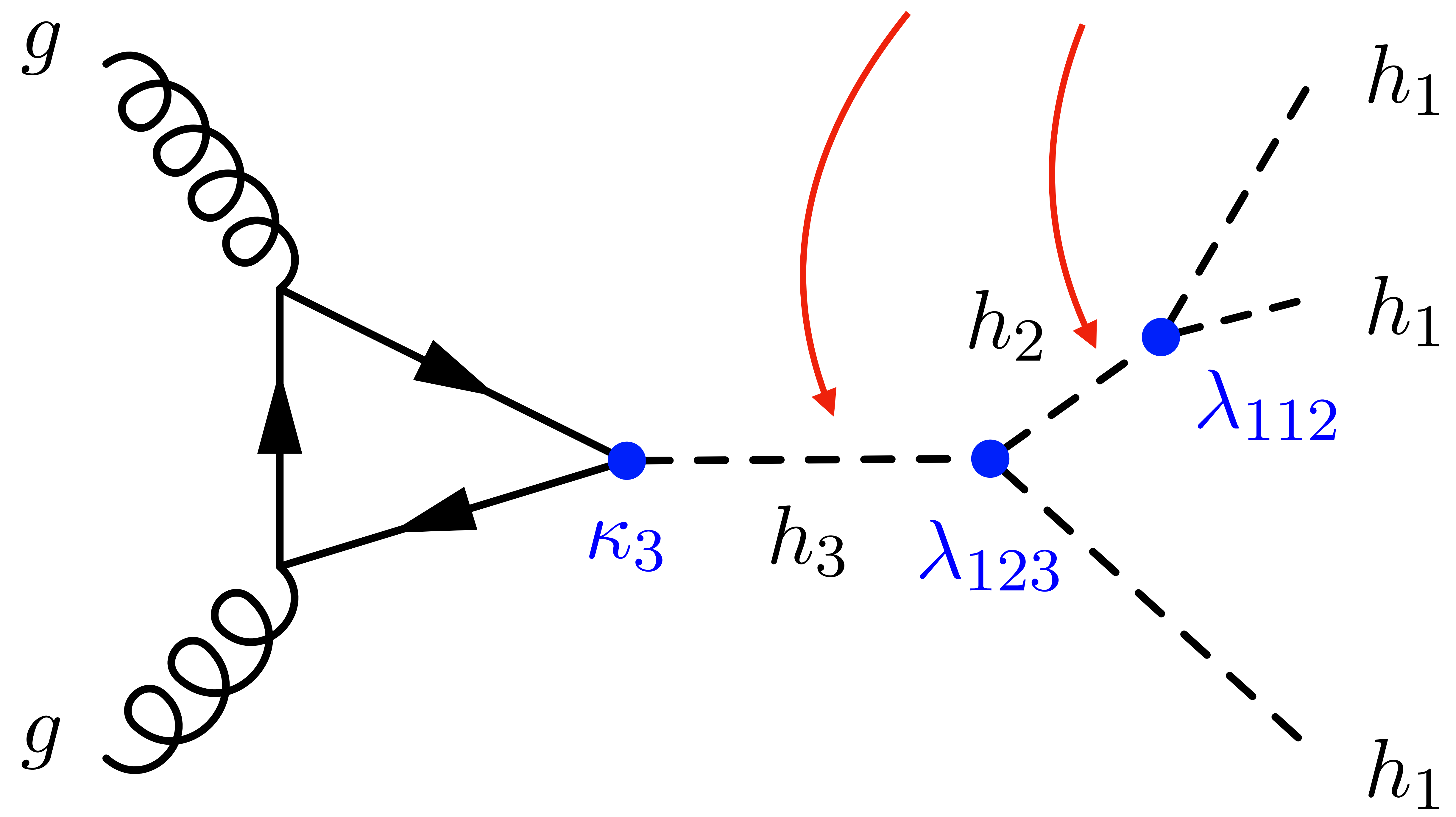
3 ➜ A "Simplified" Approach

Simplifying Double-Resonant hhh

- Let's make the preceding assumptions for double-resonant **hhh**. Keep in mind: these are satisfied by parts of TRSM parameter space!

- Narrow-width approximation (at cross section level):

$$\frac{\mathrm{d}q_i^2}{(q_i^2 - m_i^2)^2 + m_i^2\Gamma_i^2} \rightarrow \frac{\pi}{m_i\Gamma_i}\delta(q_i^2 - m_i^2)$$



Simplifying Double-Resonant hhh

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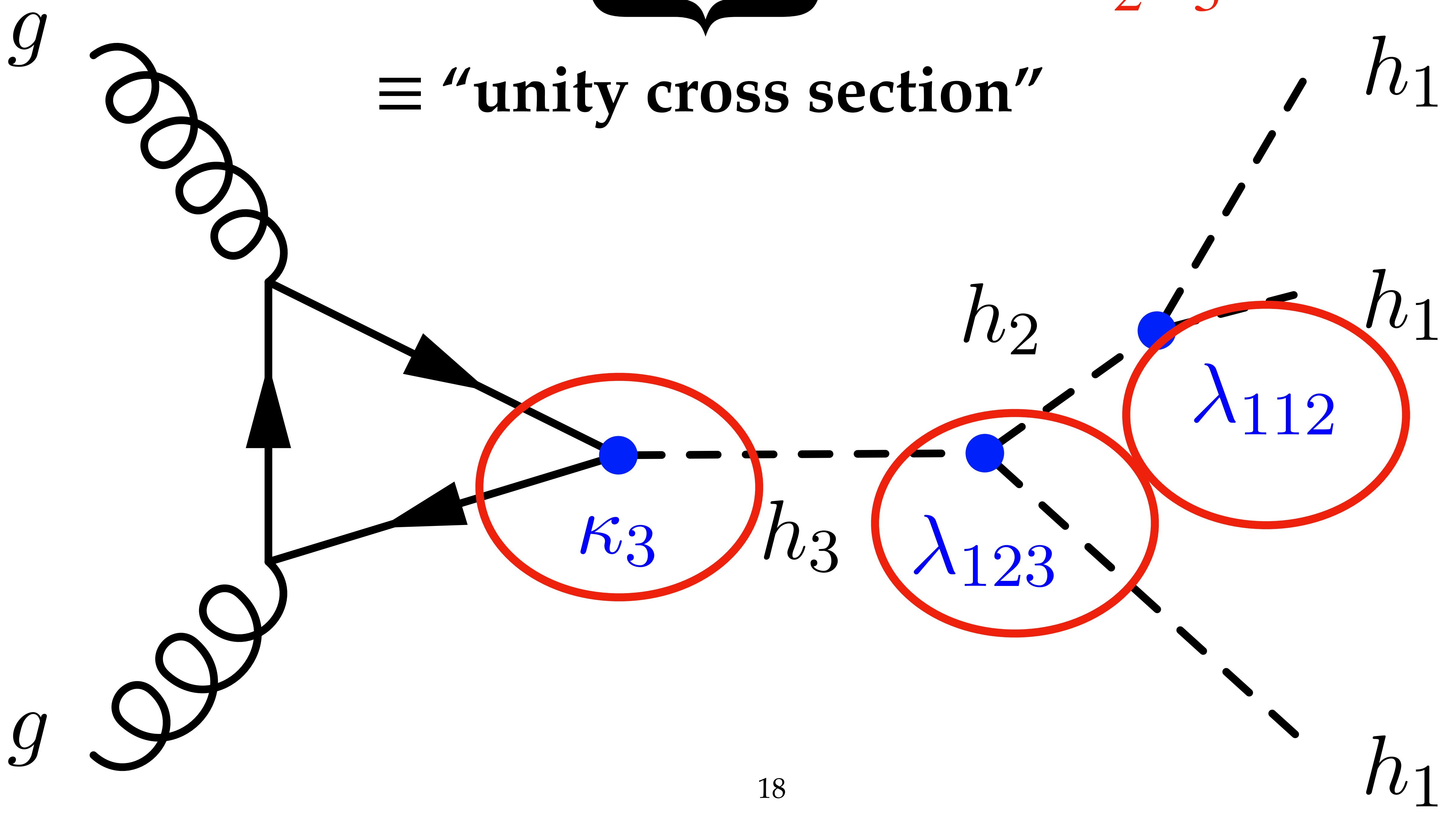
- **Factorize** cross section as:

$$\sigma(m_2, m_3, \Gamma_2, \Gamma_3, \kappa_3, \lambda_{123}, \lambda_{112}) = \underbrace{\hat{\sigma}_u(m_2, m_3)}_{\equiv \text{"unity cross section"}} \times \frac{\kappa_3^2\lambda_{123}^2\lambda_{112}^2}{\Gamma_2\Gamma_3}$$



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- **Generally**: κ_3, λ_{123}, λ_{112}, Γ_2, Γ_3 and m_2 and m_3 will be correlated,
- but: they can be calculated given the Lagrangian parameters. The factorization above would remain valid in the narrow-width approximation.

Fitting the "Unity" Cross Section $\hat{\sigma}_u(m_1, m_2)$

- For "typical" values:

  $\Gamma_{2,3} \simeq 1$ GeV

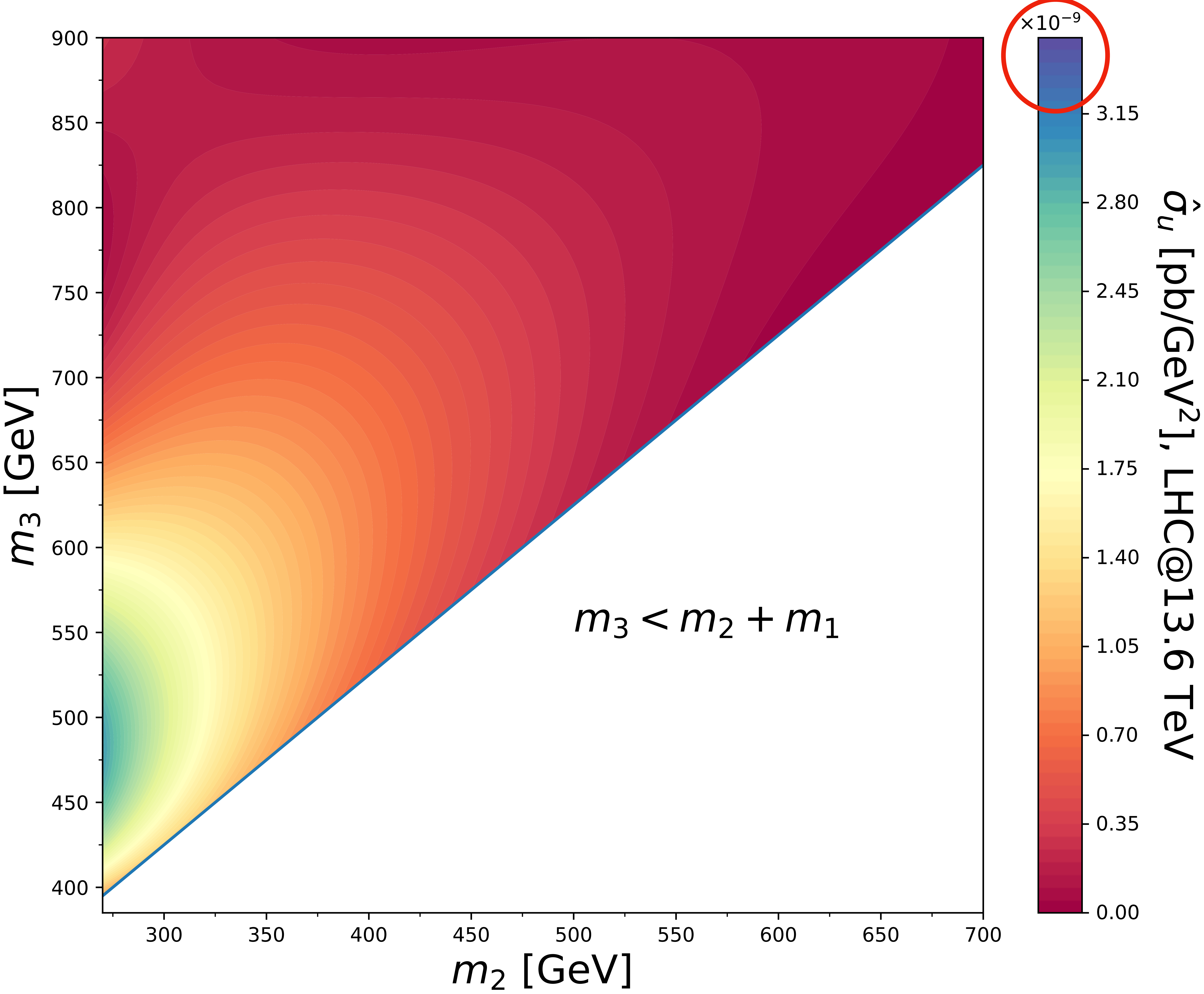
  $\kappa_3 \sim \mathcal{O}(1)$

  $\lambda_{123} \sim \lambda_{112} \sim \lambda_{111,SM} \sim 30$ GeV

- we get $\sigma/\sigma_{\rm SM} \sim \mathcal{O}(20)$ for $\hat{\sigma}_u \sim 10^{-9}$ pb,

- which corresponds to:

  $m_2 \lesssim 400$ GeV,
  $m_3 \lesssim 750$ GeV,



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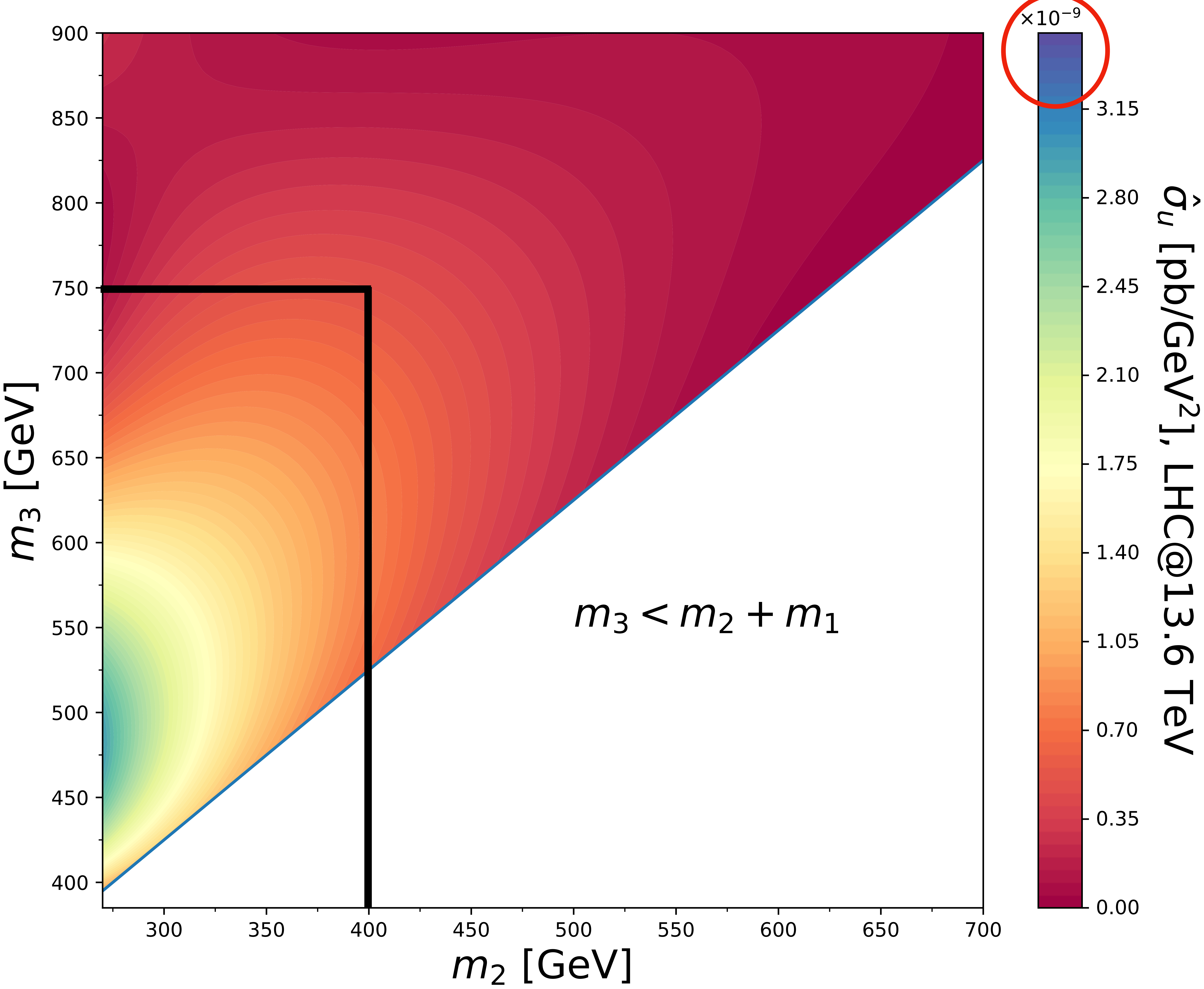
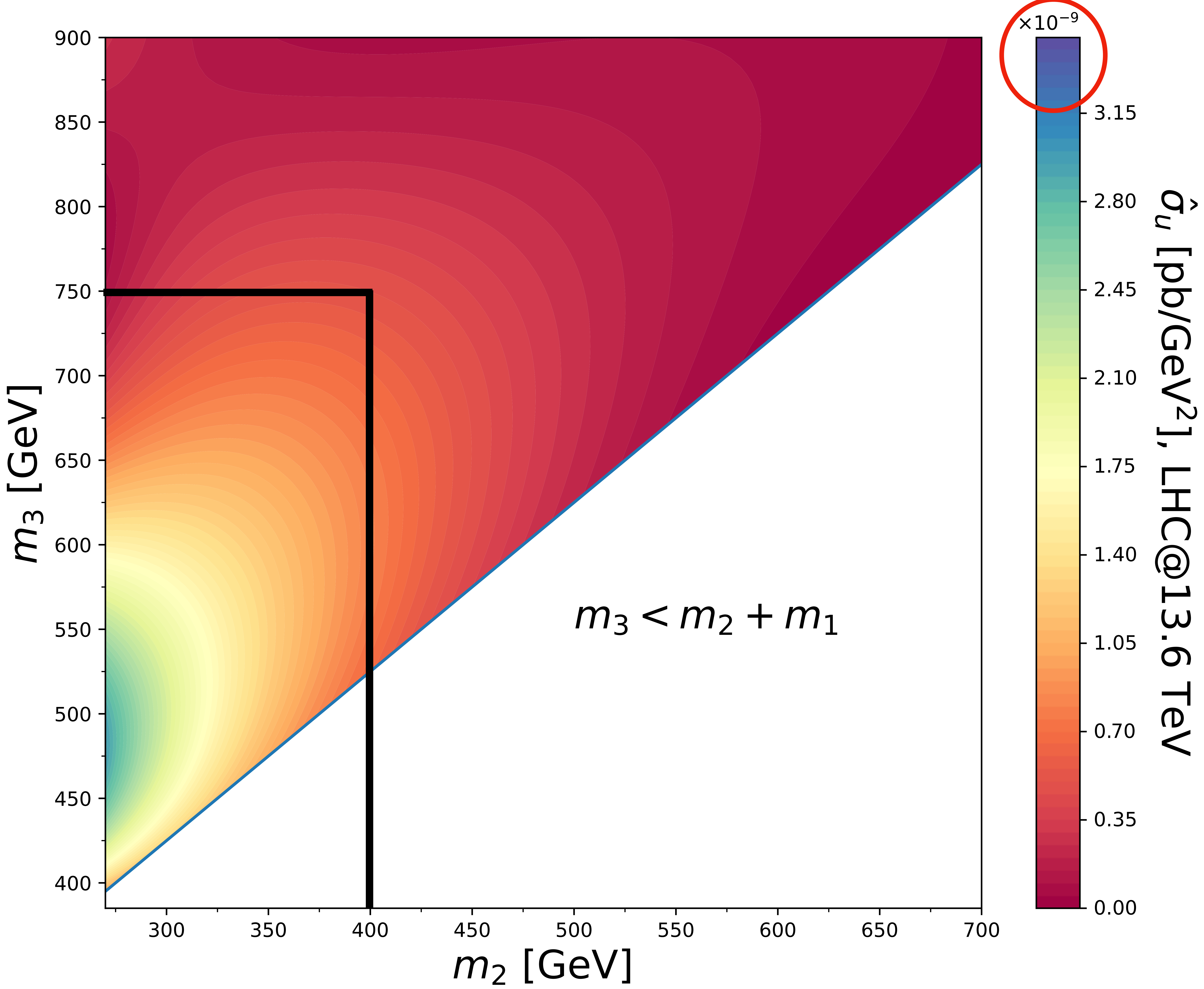


Fitting the "Unity" Cross Section $\hat{\sigma}_u(m_1, m_2)$

➡ At the LHC, we can only ever hope to observe:

$m_2 \lesssim 400$ GeV,
$m_3 \lesssim 750$ GeV.

within ***any*** model that can generate the double-resonant process!



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SM + Two Real Singlet Scalars [= TRSM]

- Consider adding **two real singlet scalar fields** $S, X \rightarrow$ the **TRSM**.
- And: impose **discrete** $\mathscr{Z}_2$ **symmetries:**

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

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

$\Rightarrow$ TRSM scalar potential:

$$\mathcal{V}(\phi, S, X) = {\color{green}\bullet}\, |\phi|^2 + {\color{blue}\blacksquare}|\phi|^4 + {\color{red}\bullet} S^2 + {\color{cyan}\blacksquare} S^4 + {\color{magenta}\bullet} X^2 + {\color{brown}\blacksquare} X^4$$

$$+ {\color{lime}\blacksquare} S^2 X^2$$

$$+ {\color{purple}\blacksquare} |\phi|^2 S^2 + {\color{teal}\blacksquare} |\phi|^2 X^2$$

SM + Two Real Singlet Scalars [= TRSM]

- Go through **EWSB**: expand fields about VEVs,
- rotate to mass eigenstates:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \phi_h \\ \phi_S \\ \phi_X \end{pmatrix} ,$$

⇒ Get three scalar bosons: h_1, h_2, h_3,

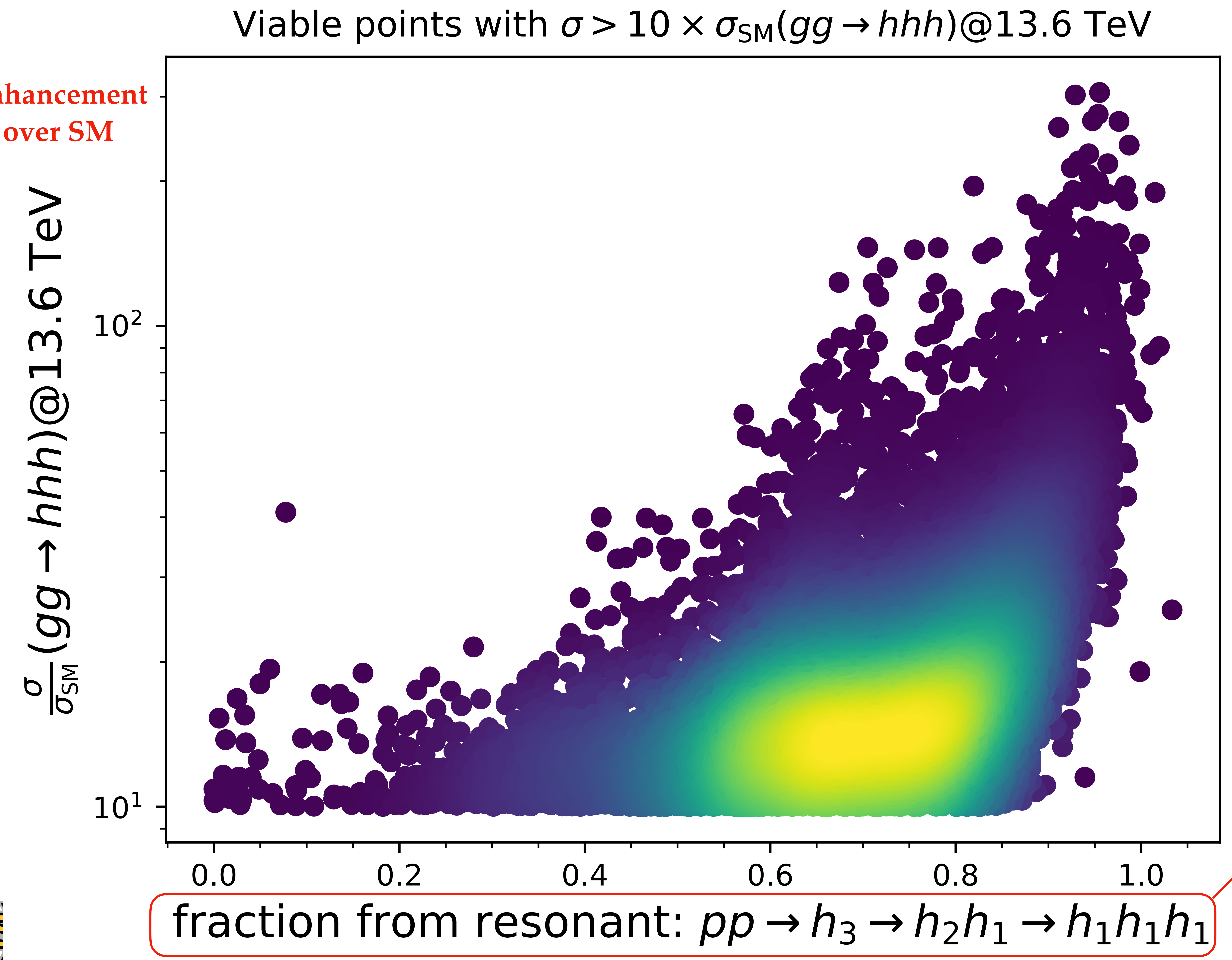
⇒ **Seven** independent parameters: $m_2 \,, m_3 \,, \theta_{12} \,, \theta_{13} \,, \theta_{23} \,, v_2, v_3$

+ Due to constraints, widths of physical scalars are generically small [**TBC!**].

⇒ Model satisfies conditions for **double-resonant hhh**!

Double-Resonant Contribution to total hhh in TRSM

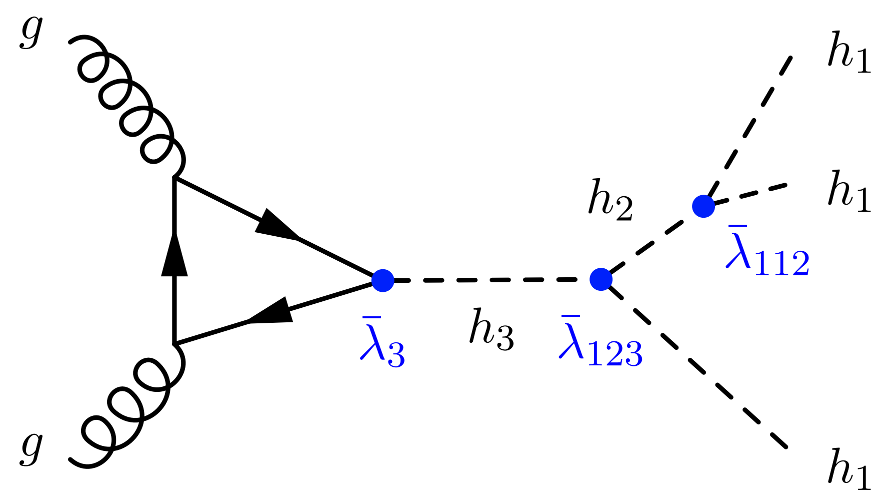
Enhancement over SM



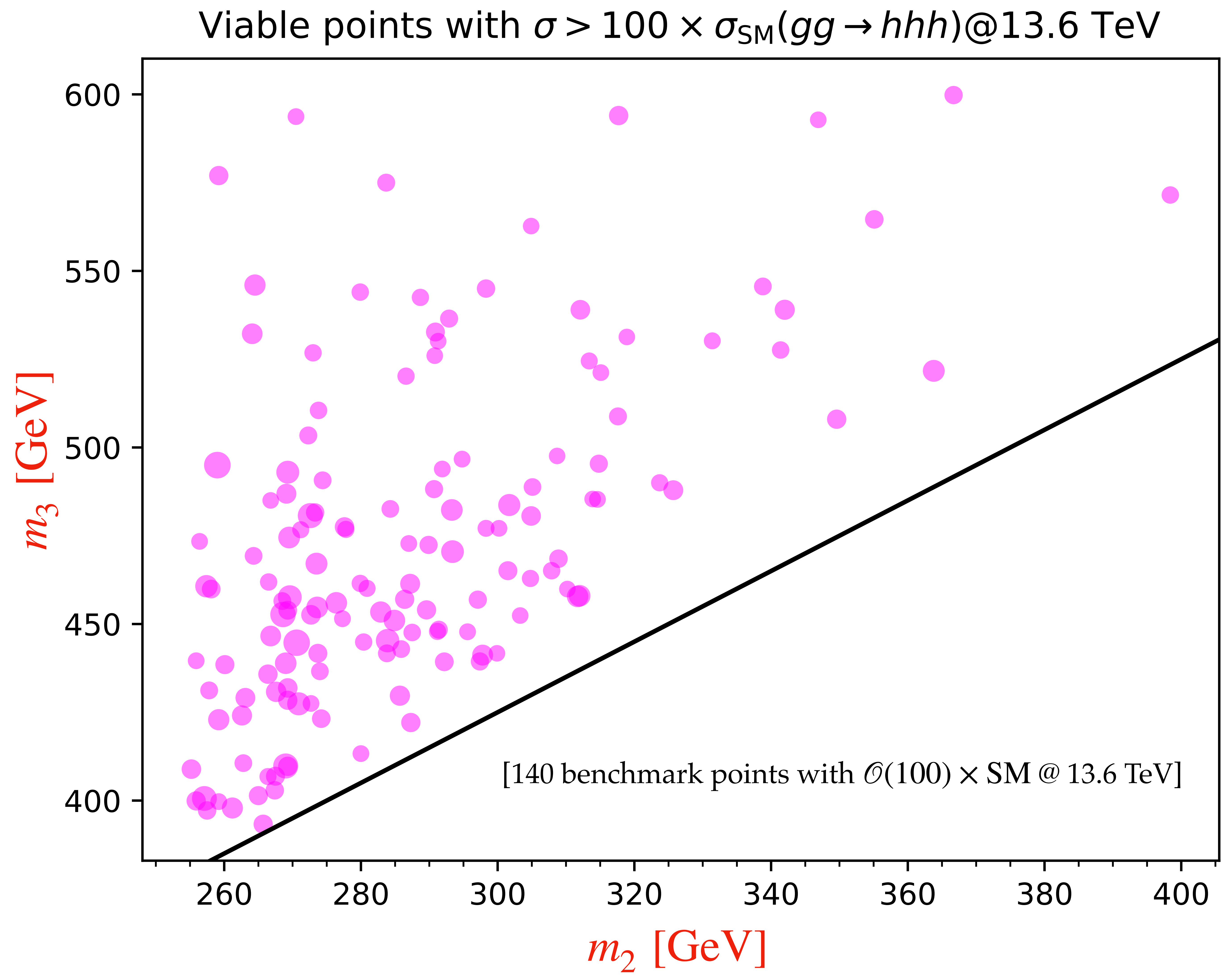
[Karkout, **AP**, Postma, Tetlalmatzi-Xolocotzi, van de Vis, du Pree, arXiv:2404.12425]

- Updated TRSM scan with **additional TH+EXP** constraints.
- Enhancements $\mathcal{O}(100) \times$ SM!

How much of the total cross section comes from… ?



Points with Enhanced hhh in the TRSM



[Karkout, **AP**, Postma, Tetlalmatzi-Xolocotzi, van de Vis, du Pree, arXiv:2404.12425]

➡

- Derived a set of benchmark points,
- All model params. **varied**!
- Enhancements $\mathcal{O}(100) \times$ SM @ 13.6 TeV!

Sample Benchmark Points

Benchmark points for enhanced triple Higgs production from ref. [111]

Name	M_2	M_3	v_2	v_3	θ_{12}	θ_{13}	θ_{23}	$\frac{\sigma}{\sigma_{SM}}$	R.F.	ρ^2 [$\times 10^6$]
BM0	259.0	495.0	215.8	180.8	6.191	0.163	5.691	306.025	0.955	0.025
BM1	270.6	444.7	122.4	847.2	0.268	0.030	0.522	302.361	0.929	3.574
BM2	268.6	452.7	137.8	784.8	0.263	0.023	0.645	275.616	0.954	3.509
BM3	272.6	480.7	928.3	143.7	3.098	2.9	2.375	267.245	0.948	3.703
BM4	269.0	409.8	138.0	599.4	0.244	0.004	0.773	266.439	0.976	4.031
BM5	269.1	486.9	227.5	307.9	0.074	6.149	2.631	157.583	0.956	2.264
BM6	259.2	577.0	289.0	275.6	0.137	6.148	2.324	145.470	0.781	5.289
BM7	283.7	575.0	259.4	330.4	0.137	6.152	2.299	122.546	0.779	2.885
BM8	264.3	469.3	207.3	359.5	0.285	6.277	0.692	119.121	0.999	1.721
BM9	266.5	461.9	653.1	229.0	2.889	3.046	1.015	112.794	0.863	1.381
BM10	259.2	399.7	444.5	217.0	2.917	3.046	1.047	103.717	0.973	1.936

Selected for large cross sections

+

Satisfying EXP+TH constraints

[Karkout, **AP**, Postma, Tetlalmatzi-Xolocotzi, van de Vis, du Pree, arXiv:2404.12425]

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Seven free parameters

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Enhancement over SM @ 13.6 TeV

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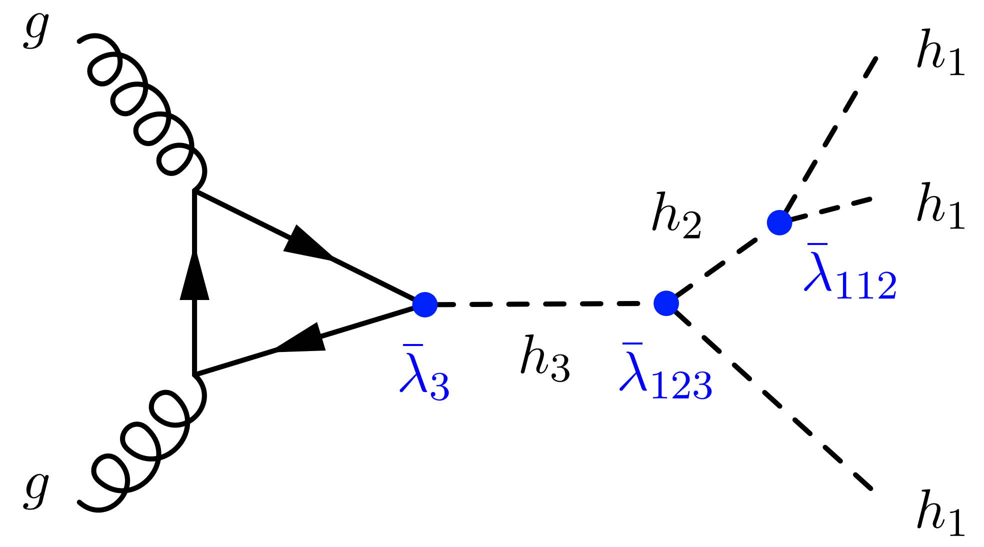
Resonant Fraction:

How much of the total cross section comes from… ?



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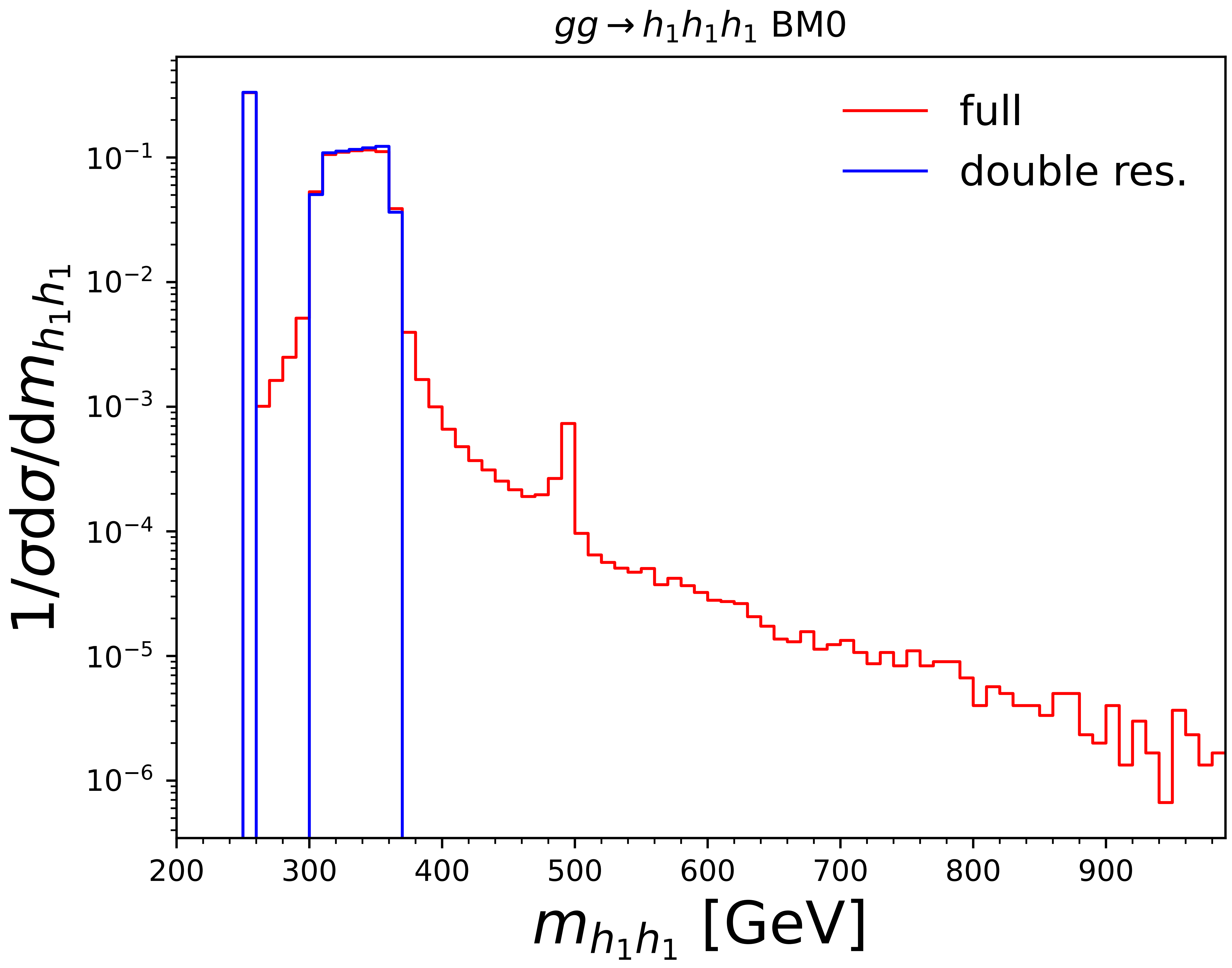
Rescaling Parameter,

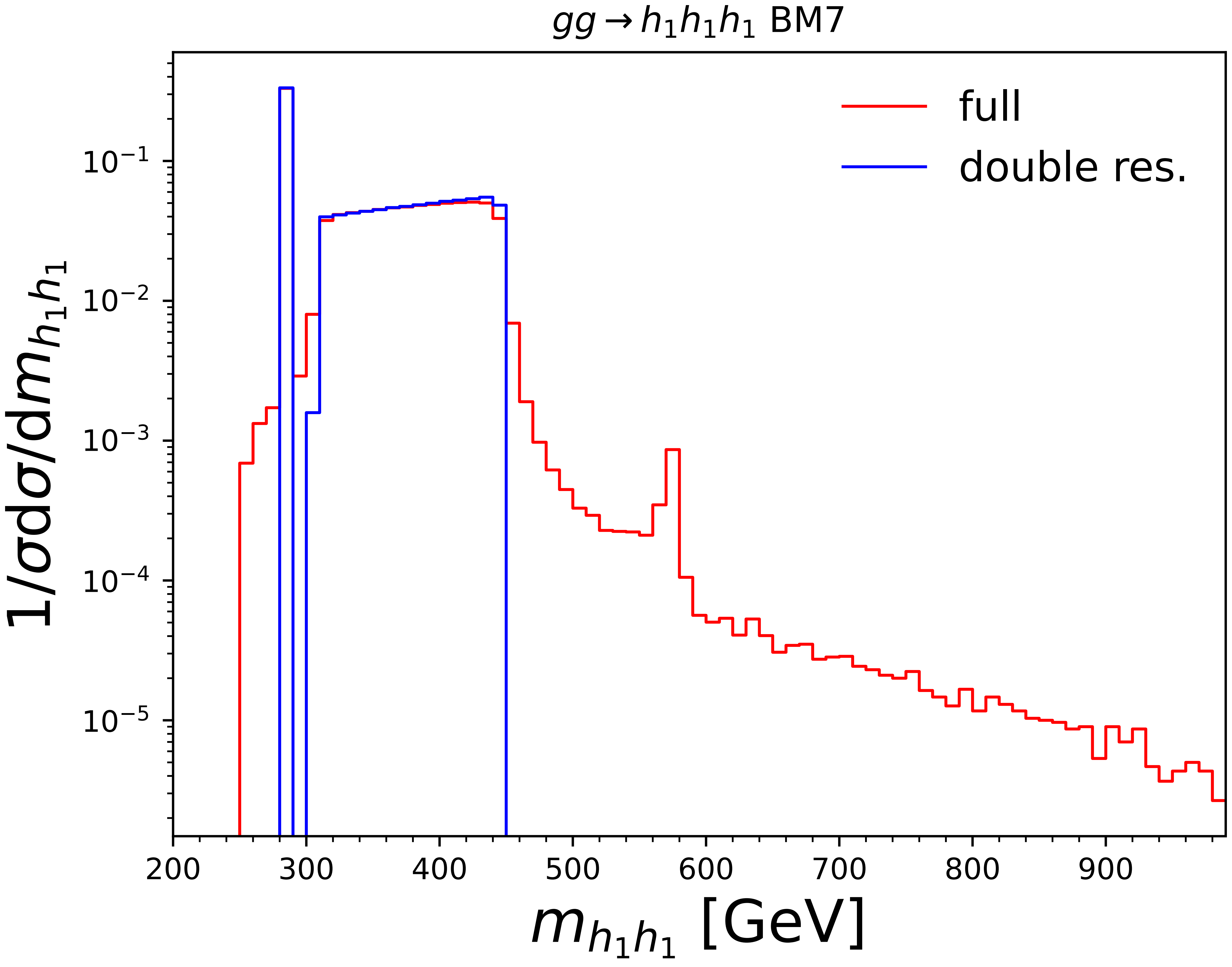
Calculate cross section@13.6 TeV using:

$$\sigma = \hat{\sigma}_u(m_2, m_3) \times \rho^2$$

How good is the narrow-width approximation?

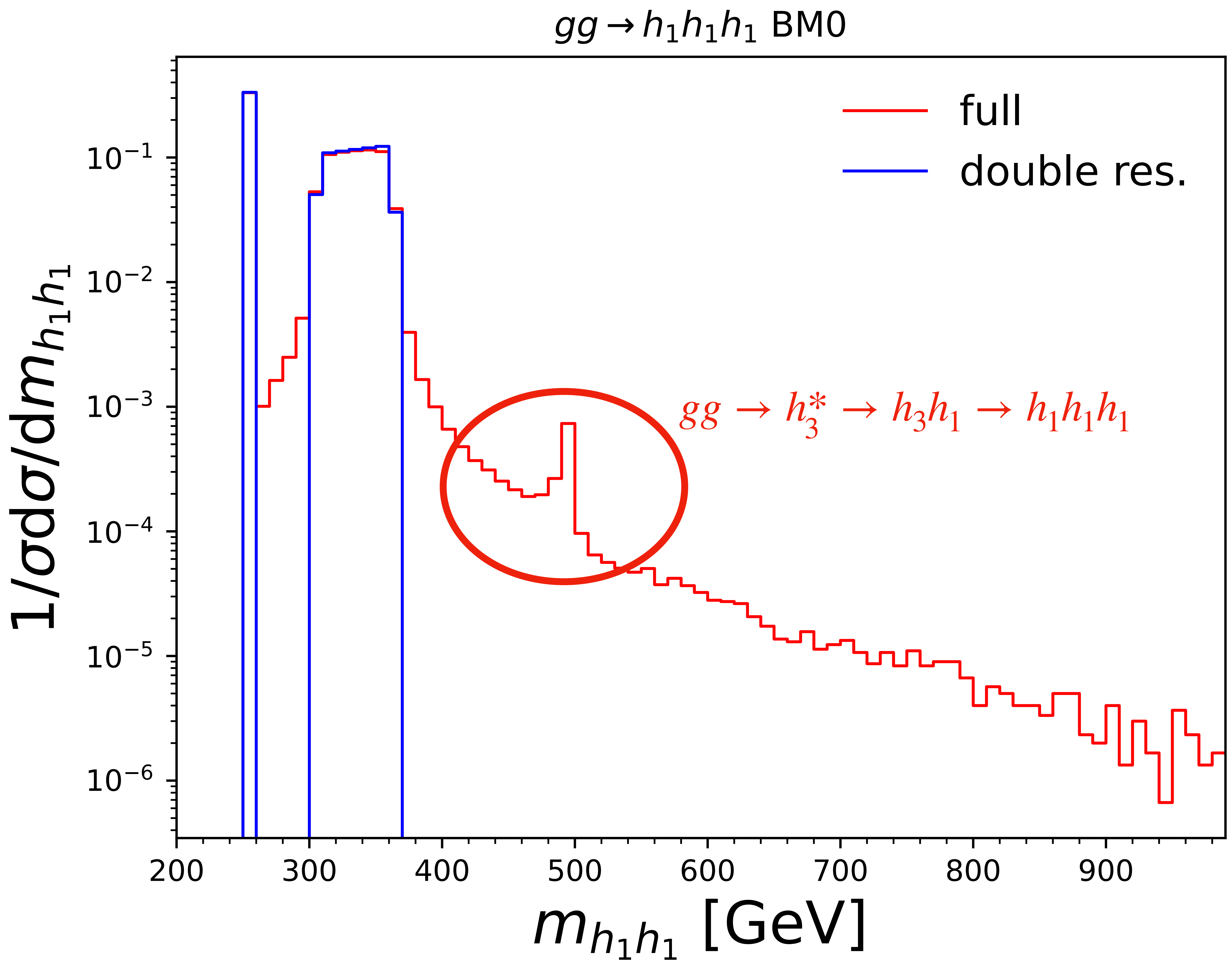
$gg \to h_3 \to h_2 h_1 \to h_1 h_1 h_1$ **versus** $gg \to h_1 h_1 h_1$ **[using MG5_aMC@NLO]**

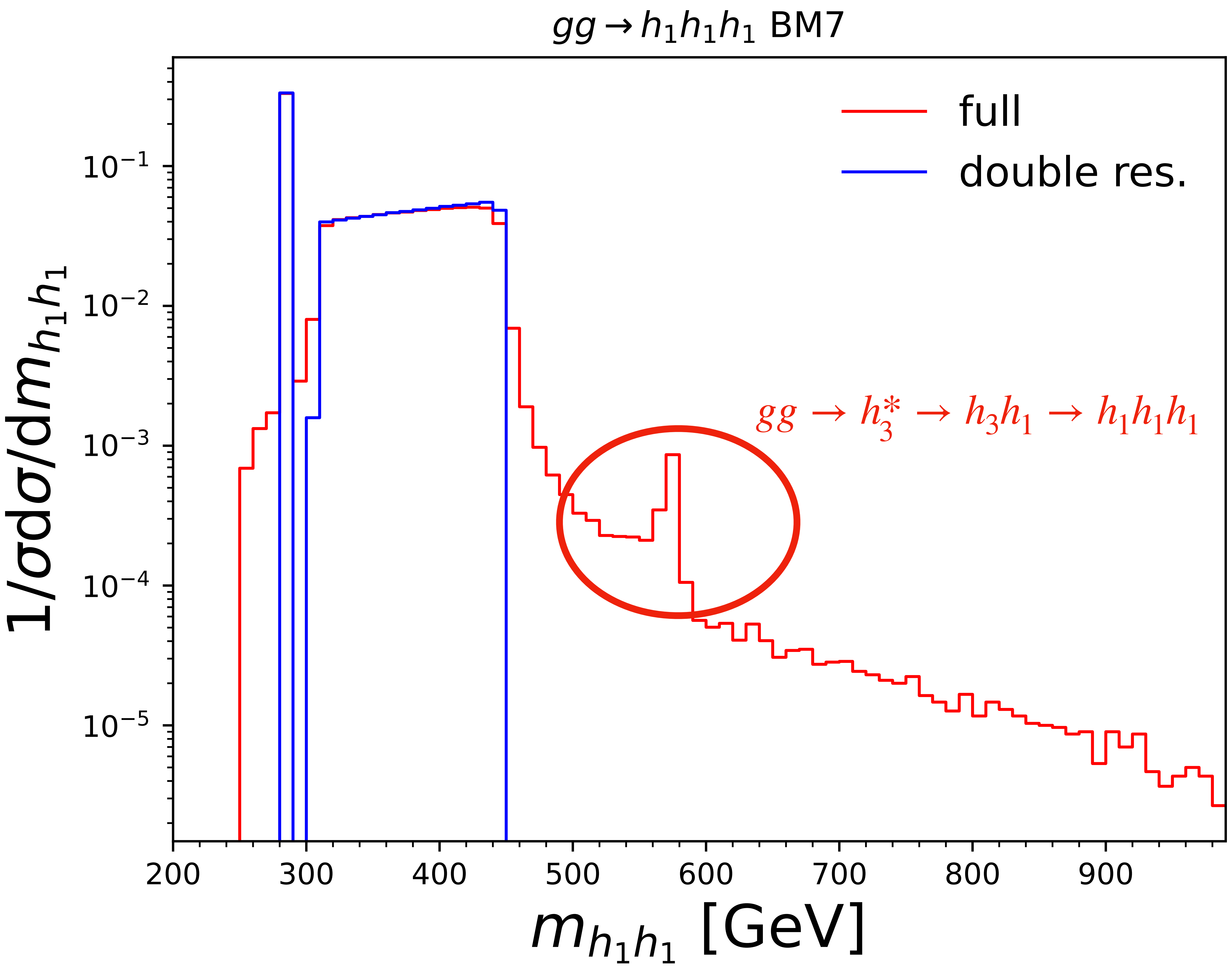




How good is the narrow-width approximation?

$gg \to h_3 \to h_2 h_1 \to h_1 h_1 h_1$ **versus** $gg \to h_1 h_1 h_1$ **[using MG5_aMC@NLO]**





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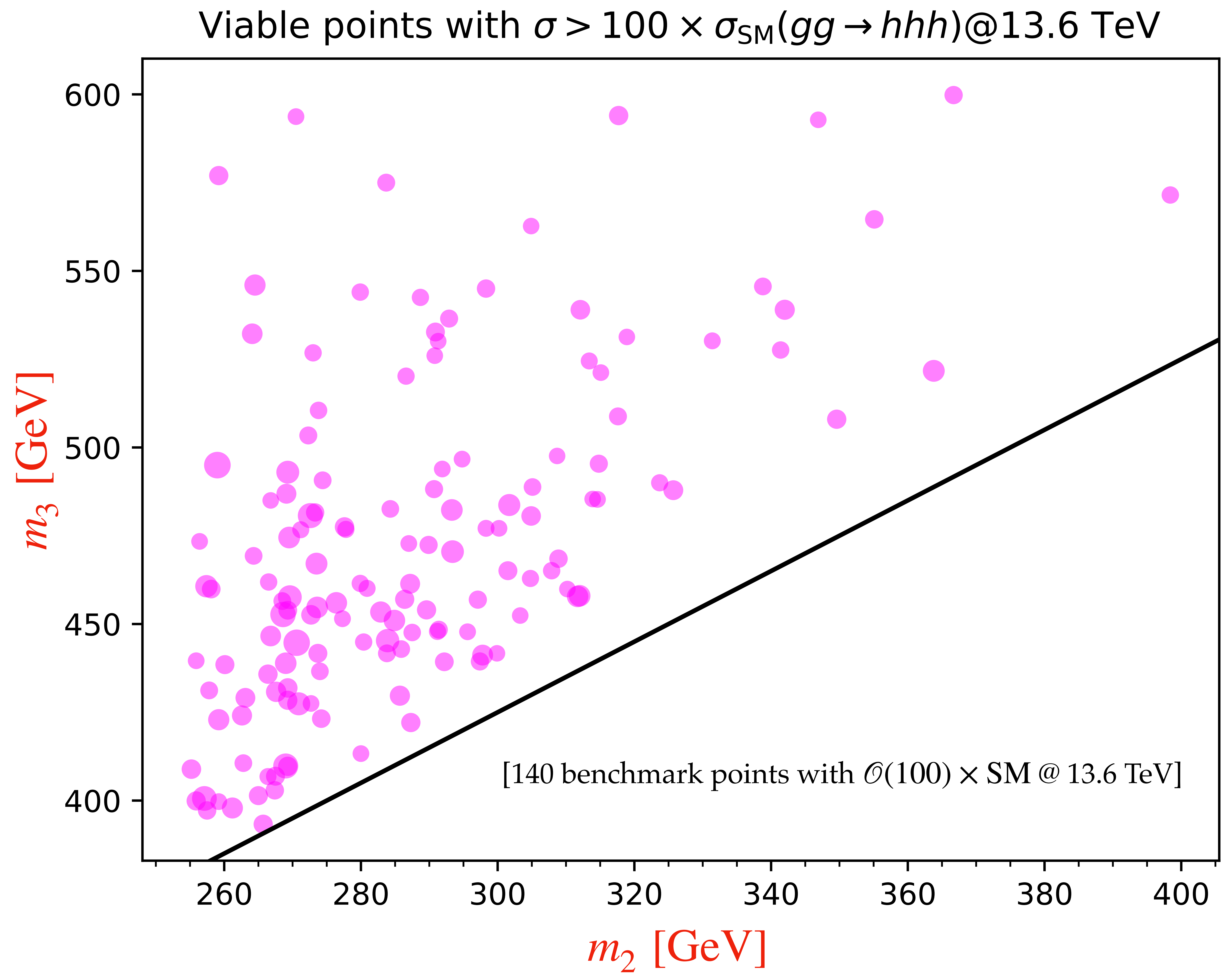
Next Steps!



Perform analysis on (m_2, m_3)-plane to find optimal set of cuts over whole plane.

➡

Find limits on rescaling parameters on ρ^2 over (m_2, m_3)-plane.

➡

These should be model-independent for the double-resonant process discussed here.

TO BE CONTINUED...

Summary & Outlook

- Triple Higgs boson production can be enhanced in models with additional scalars!

- Particularly in models with two scalars with masses that can generate a double-resonant contribution to hhh.

- If the width is narrow enough, a factorized cross section approach can be used to impose limits on a rescaling parameter in a model-independent way.

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Summary & Outlook

- Triple Higgs boson production can be enhanced in models with additional scalars!
- Particularly in models with two scalars with masses that can generate a double-resonant contribution to hhh.
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Coming: 21st century

Thanks!

Questions?

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Appendices

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.

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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]	$\text{BR}_{2\to 1\,1}$ [GeV]	$\text{BR}_{3\to 1\,1}$	$\text{BR}_{3\to 1\,2}$
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 $M_1 = 125\,\text{GeV}$ and $\Gamma_1 = 3.8\,\text{MeV}$ 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.