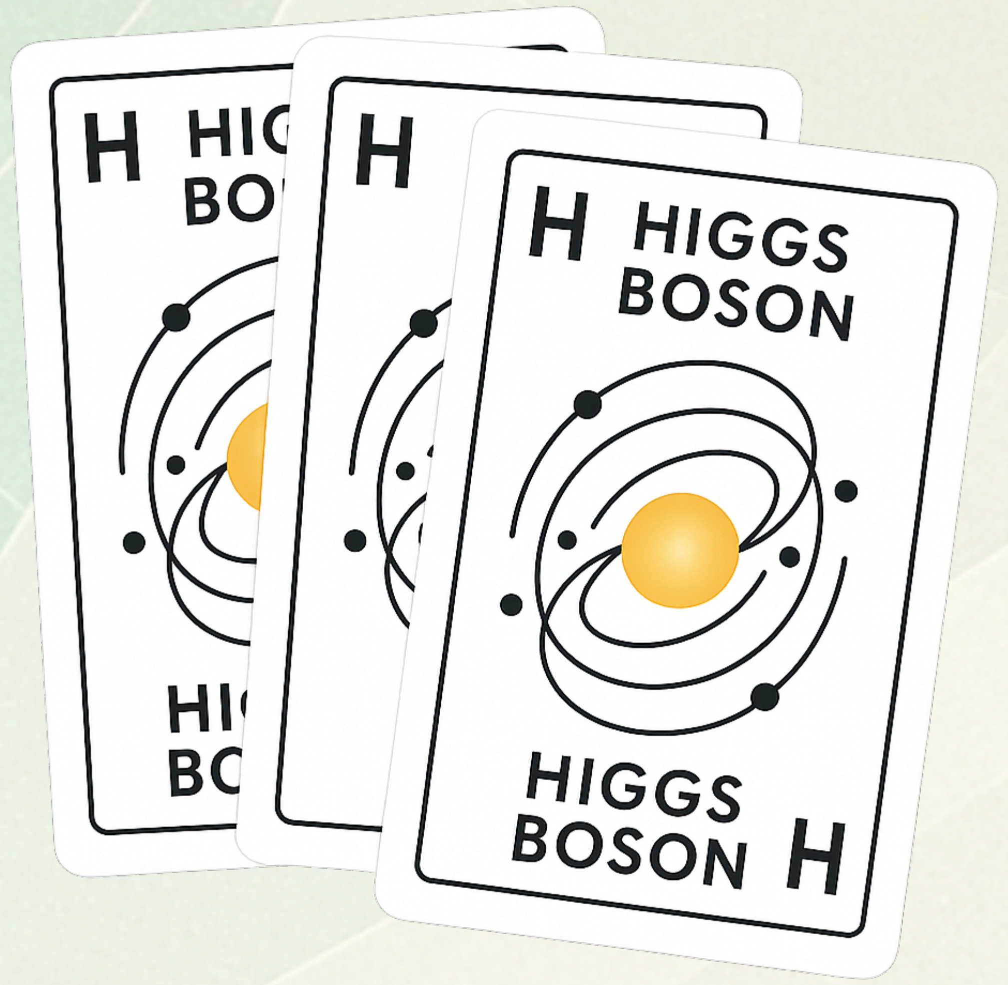
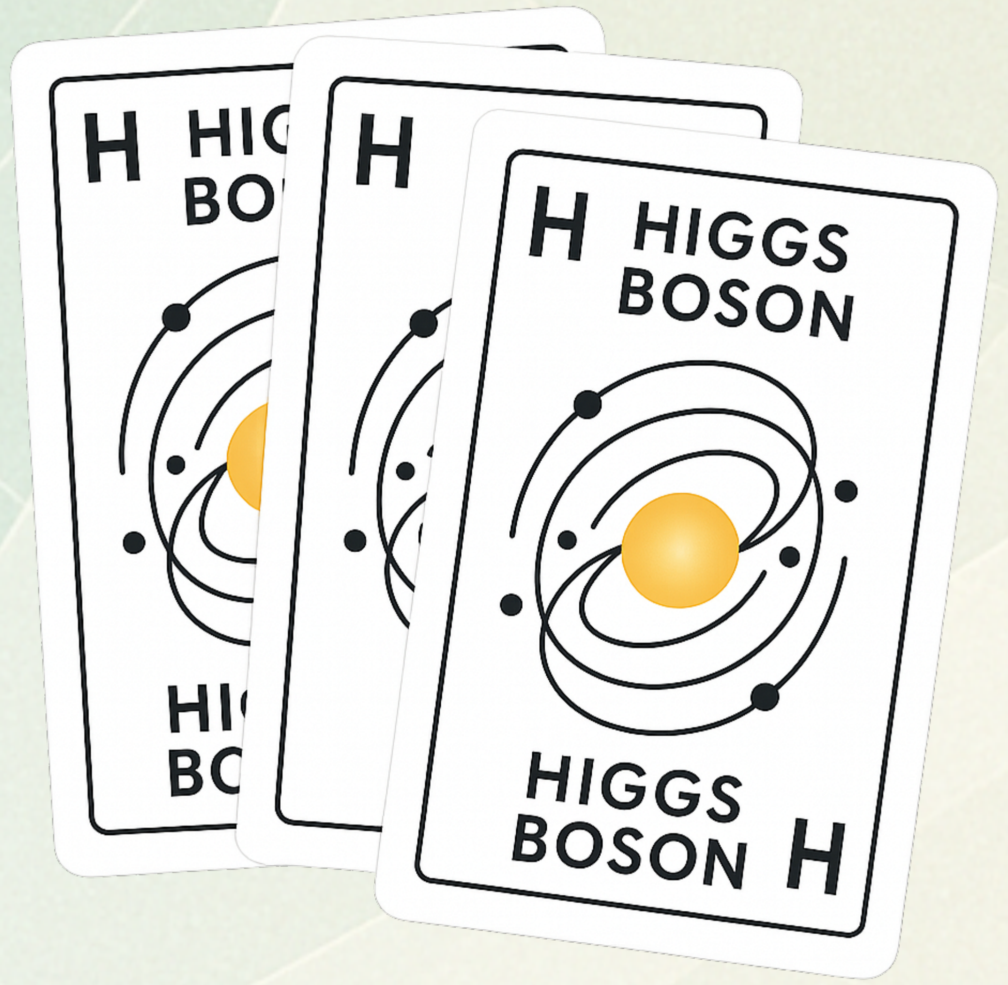
Triple Higgs Boson Production at the LHC in Extended Scalar Sectors



Andreas Papaefstathiou
Kennesaw State University, GA, USA

@ QCD@LHC 2025 [Sept. 8-12, 2025]

hhh at the LHC in Extended Scalar Sectors*



*Plus a digression into non-resonant *hhh*!

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Motivation: Measuring the Higgs Potential

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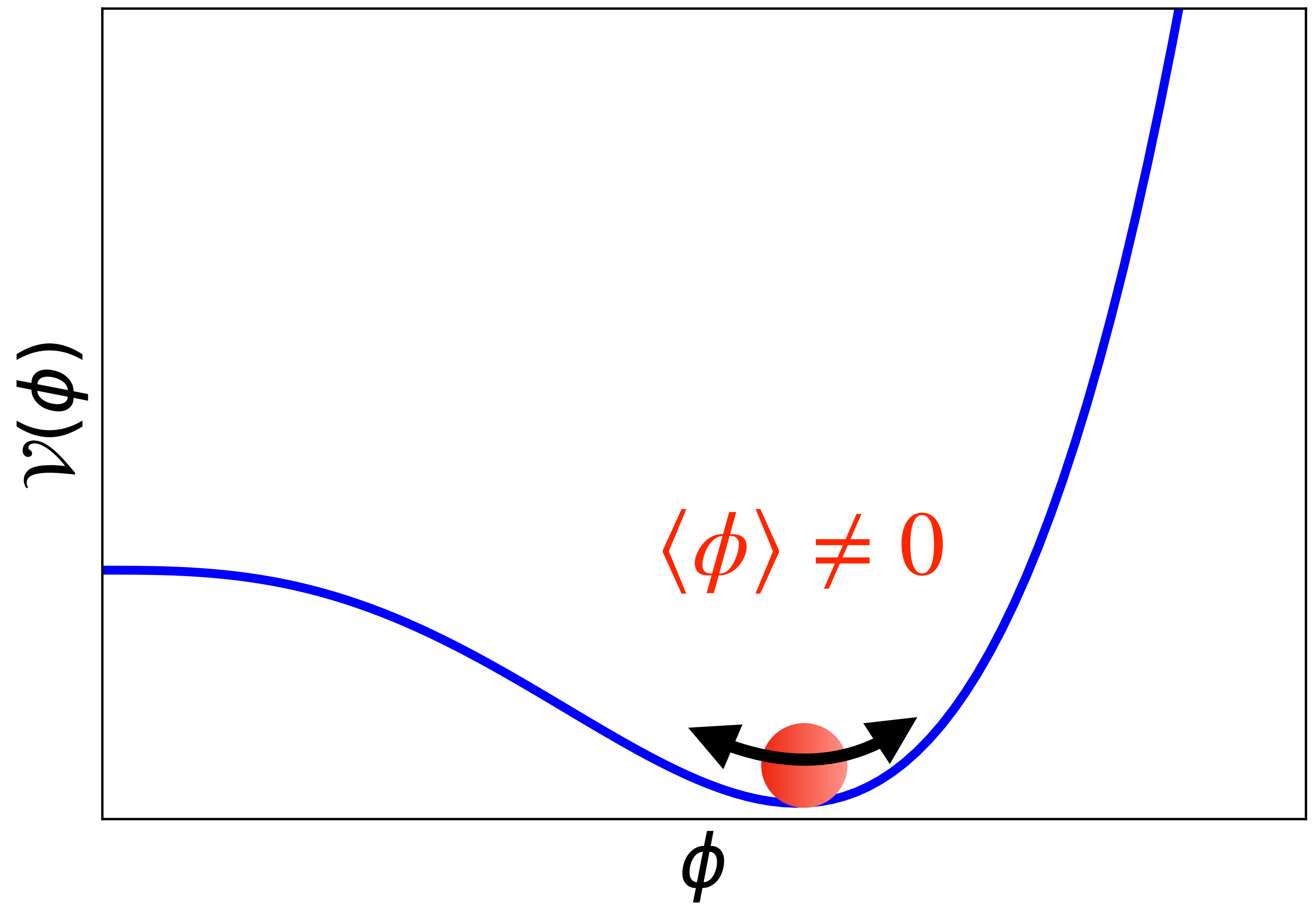
Motivation: Measuring the Higgs Potential

- In the SM, the Higgs field ϕ "sits" in a potential $\mathcal{V}(\phi) = \bullet\, |\phi|^2 + \blacksquare\, |\phi|^4$.



- **Electroweak Symmetry Breaking**:

$$\mathcal{V}(\langle\phi\rangle + h) = \bullet h^2 + \blacktriangle h^3 + \blacksquare h^4$$

where ***h*** is the Higgs boson.

➡ $\{\bullet, \blacktriangle, \blacksquare\}$ → **the Higgs boson's self-interactions**

- Predicted in the SM via the Higgs boson's mass and the VEV:

$$\bullet_{\mathrm{SM}} = \frac{1}{2} m_h^2 \,; \qquad \blacktriangle_{\mathrm{SM}} = \frac{m_h^2}{2v} \,; \qquad \blacksquare_{\mathrm{SM}} = \frac{m_h^2}{8v^2}$$

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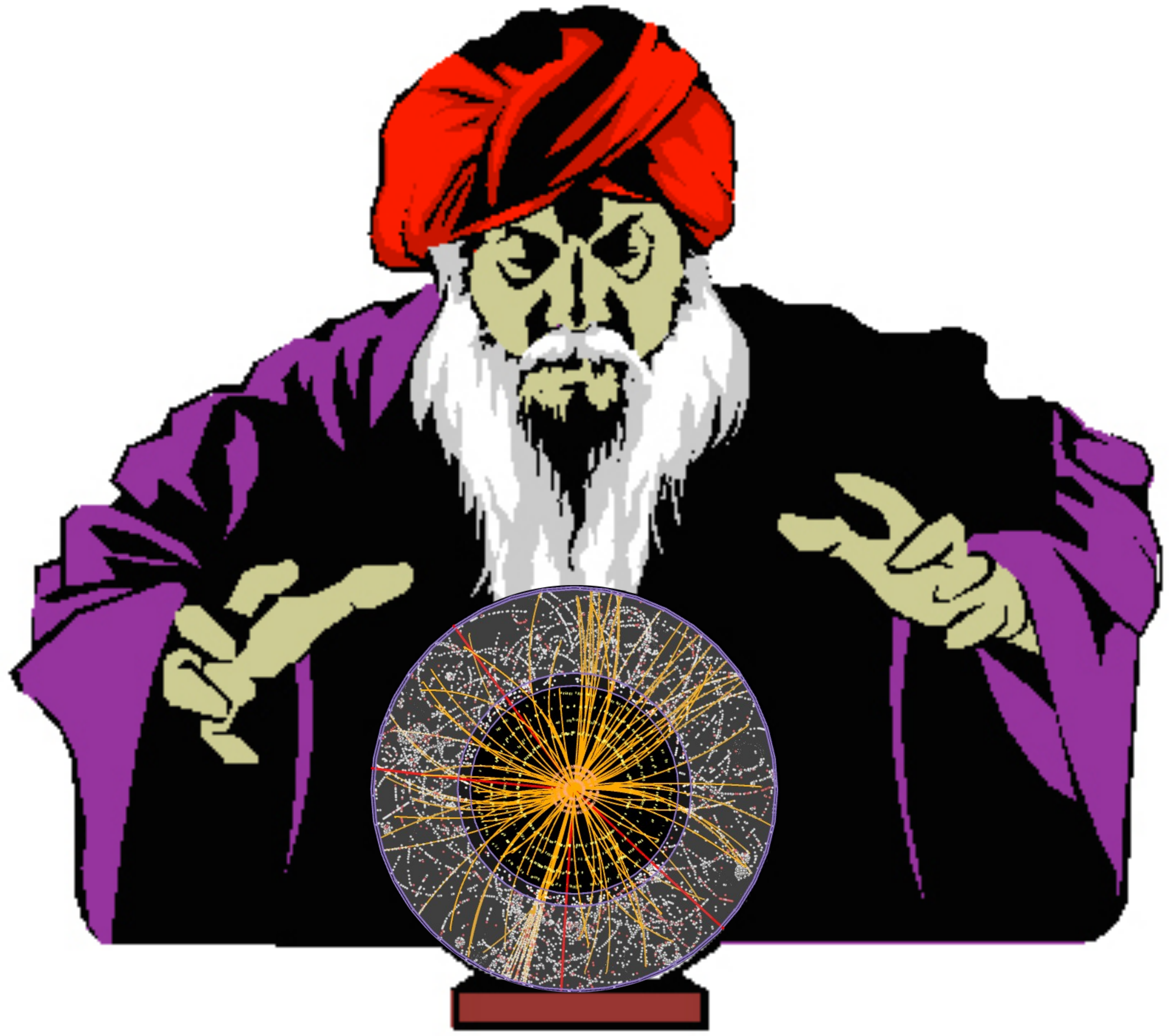

Q: Can we probe *hhh* at the LHC?

And if so, what can we learn?

Motivation: Measuring the Higgs Self-Couplings

- **Q:** Can we verify that $\{\bullet, \blacktriangle, \blacksquare\} \approx \{\bullet, \blacktriangle, \blacksquare\}_{\rm SM}$ at the LHC?
- We can certainly try! Most "direct" way is to produce on-shell Higgs bosons:

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Higgs boson discovery @ LHC, 2012 ✅

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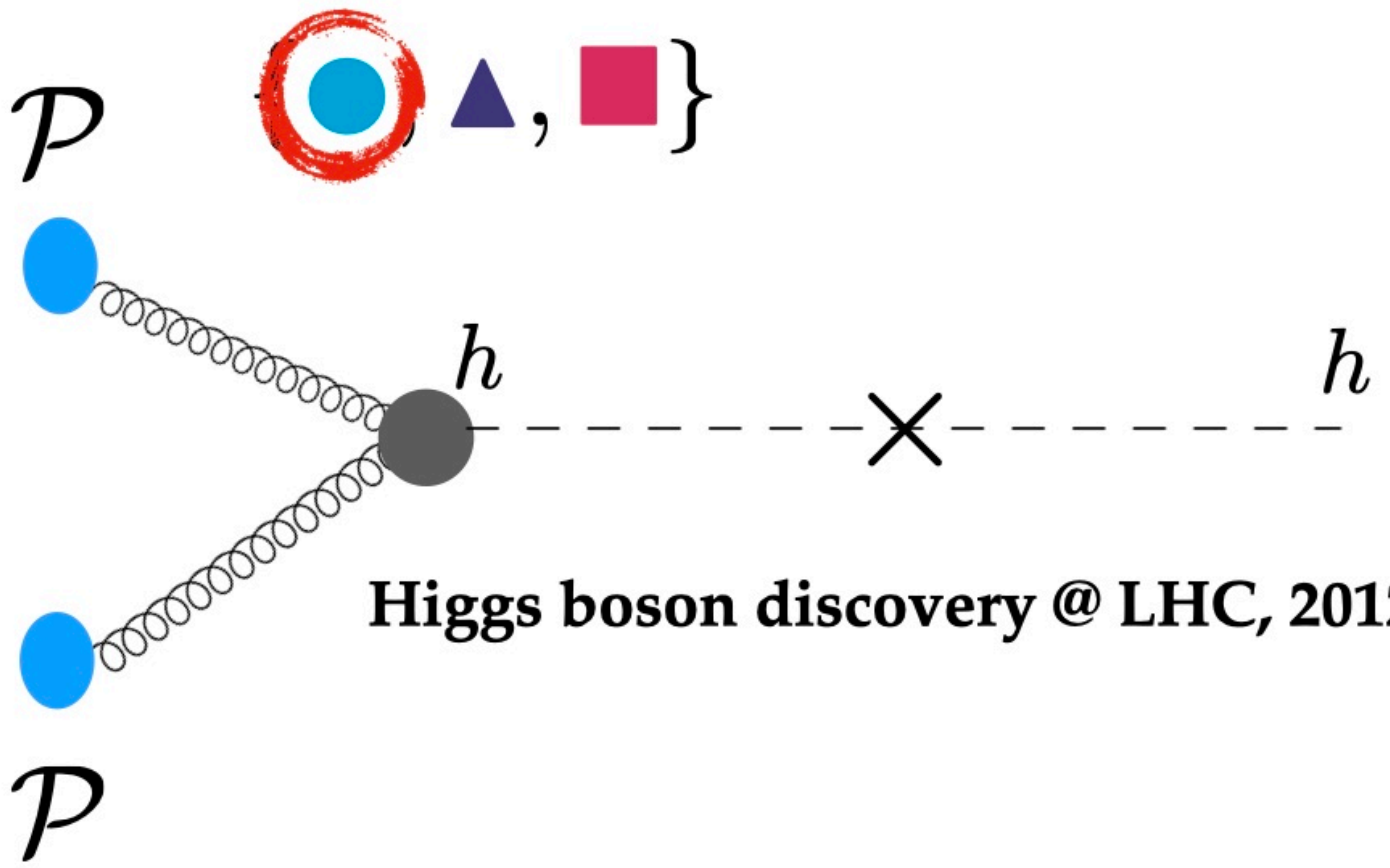

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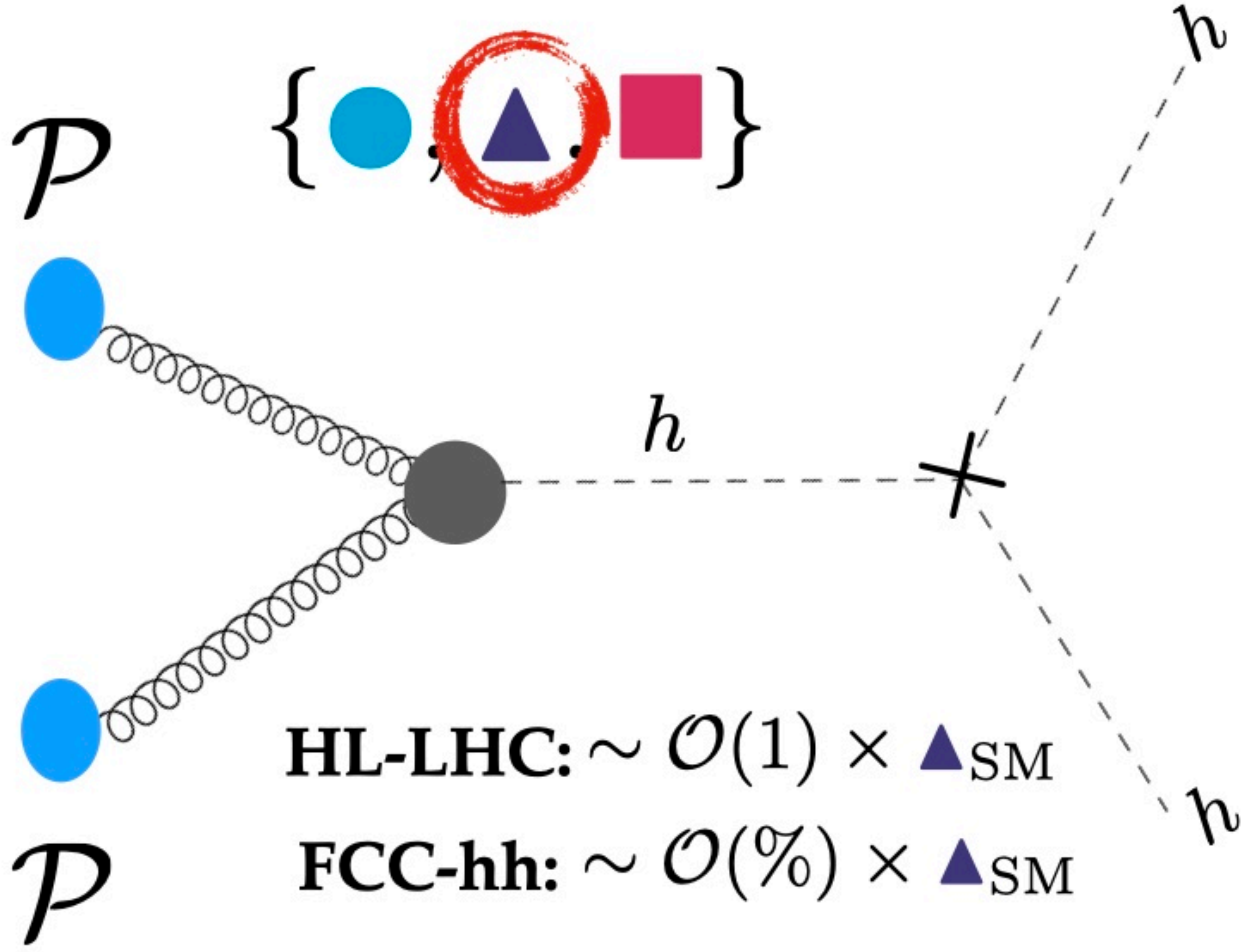

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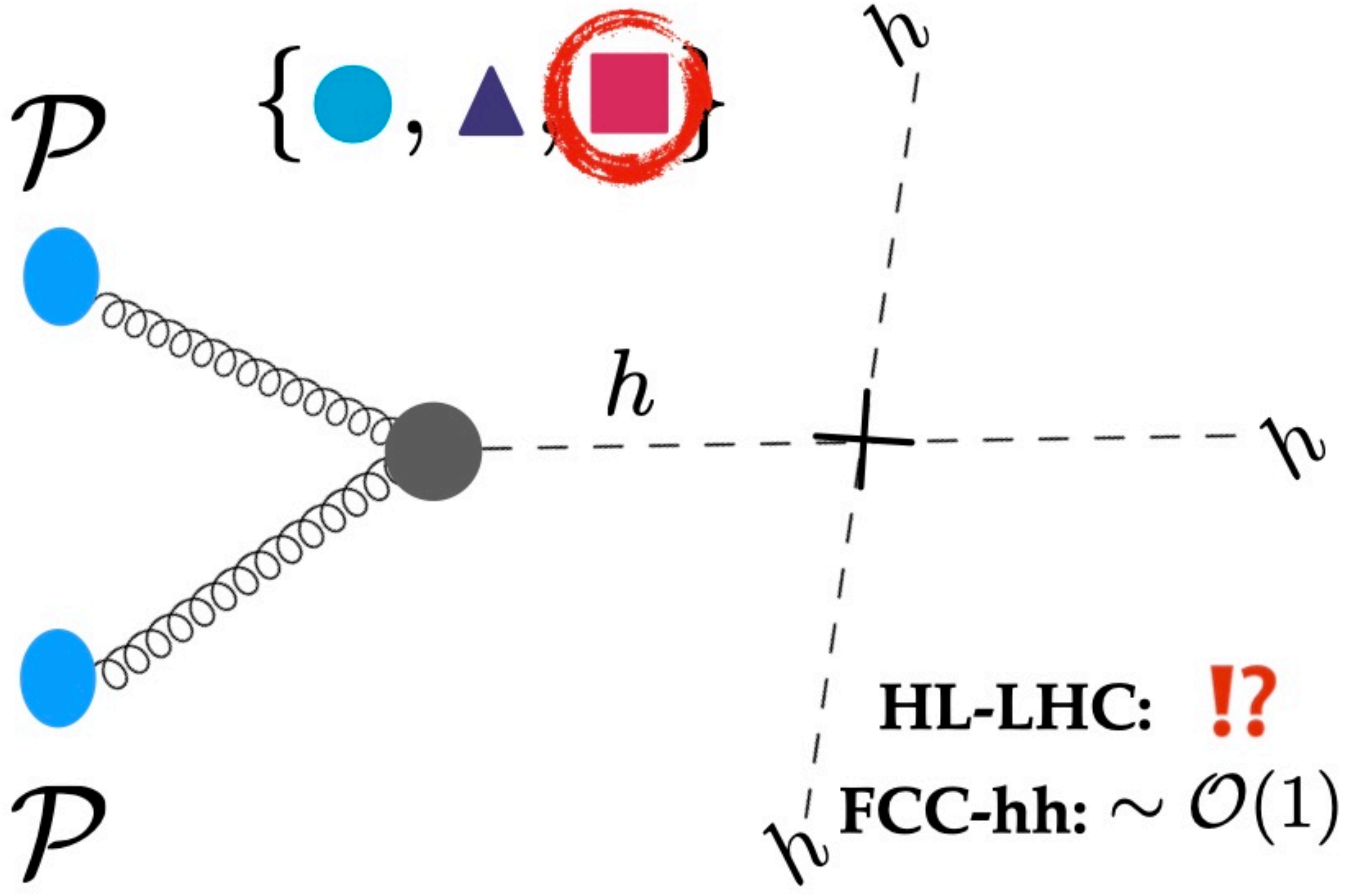

HL-LHC: **!?**

FCC-hh: $\sim \mathcal{O}(1) \times \blacksquare_{\mathrm{SM}}$

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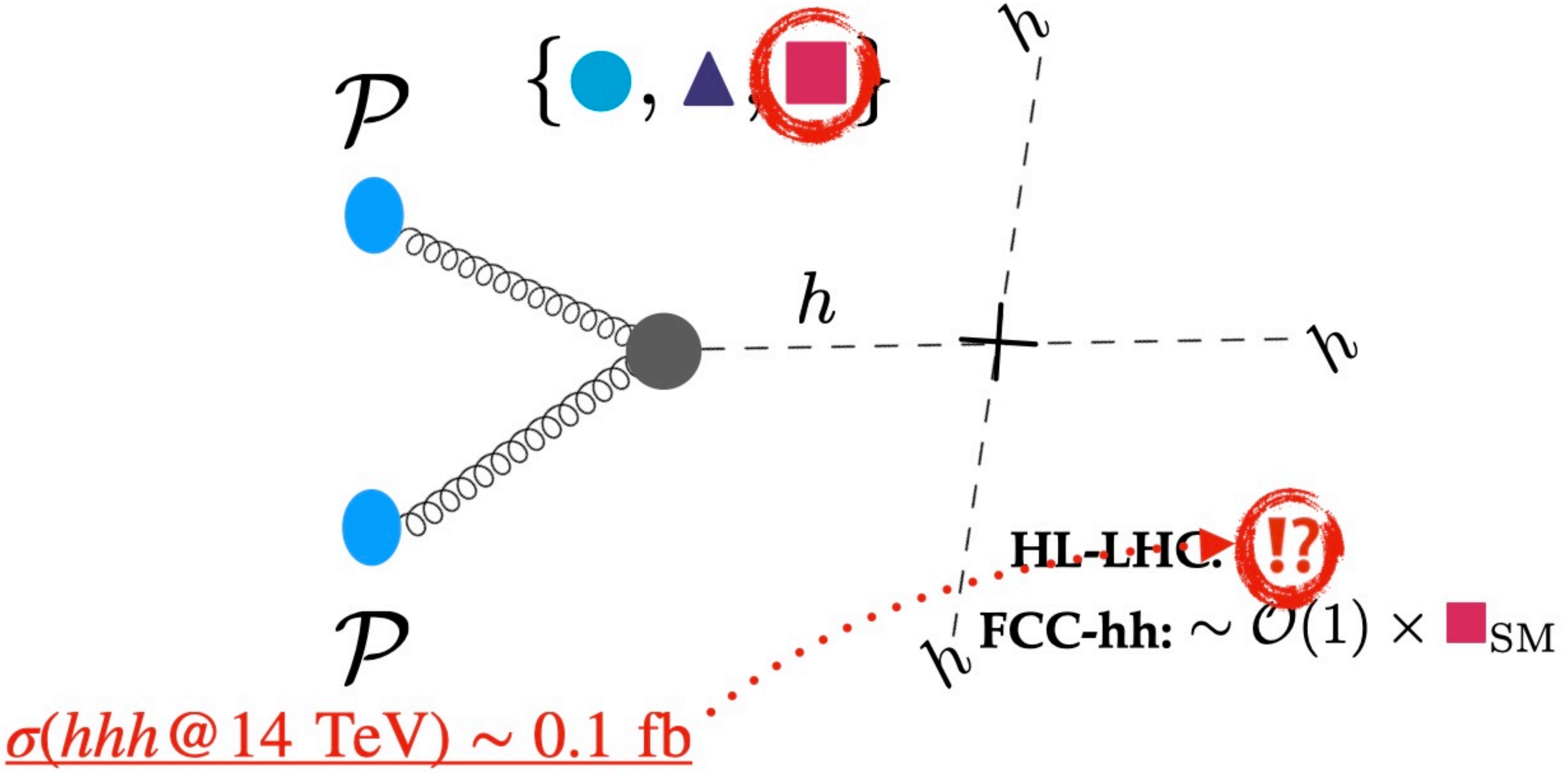
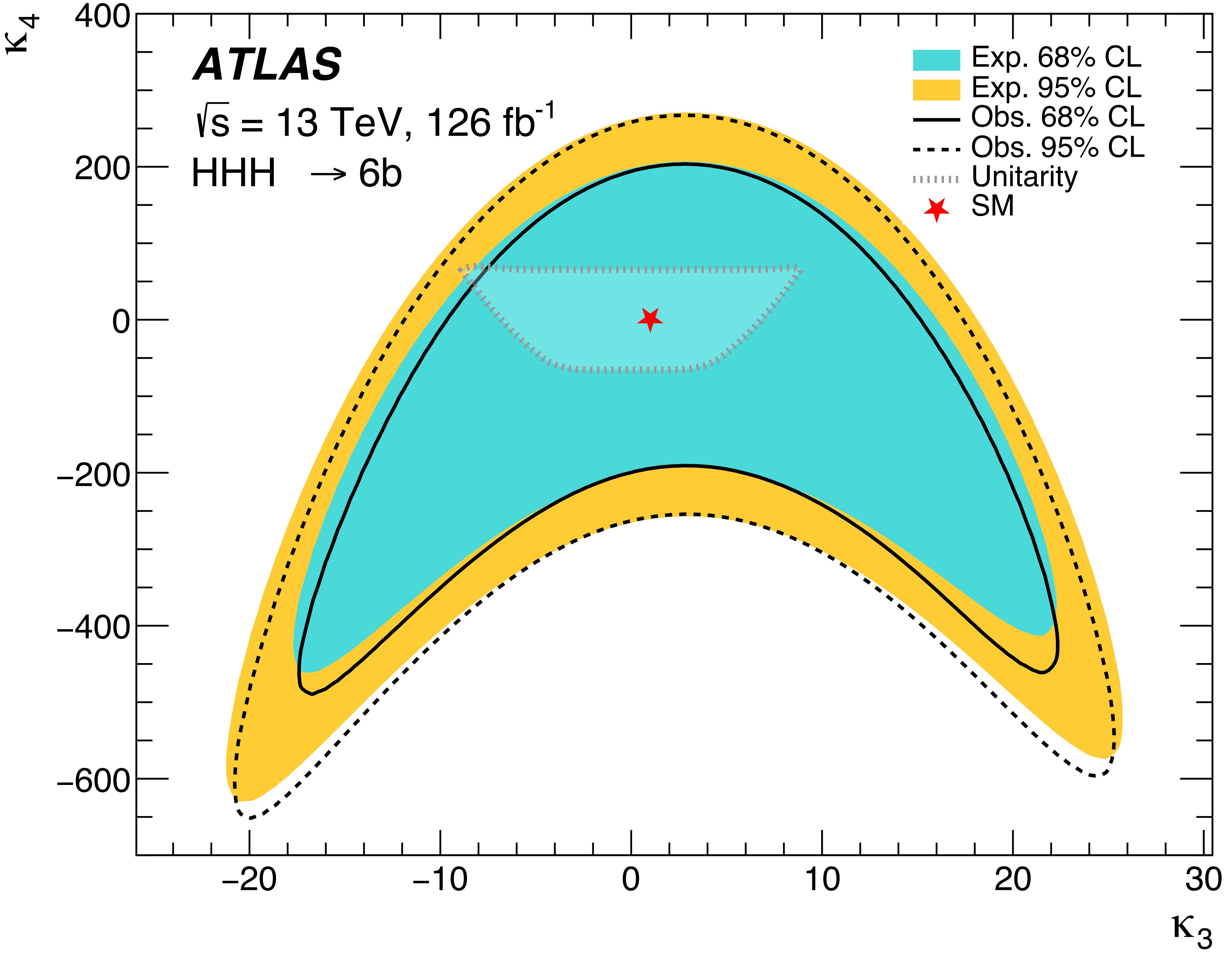


Digression: Non-Resonant Anomalous *hhh* @ LHC

- Anomalous couplings can enhance *hhh*! **e.g. inspired by an Effective Field Theory.**

[e.g. Stylianou, Weiglein, **arXiv:2312.04646**, ATLAS, **arXiv:2411.02040, CMS-PAS-HIG-24-015**]



$$\mathscr{L} \supset -\lambda_{\rm SM} v \underbrace{(1+c_3)}_{\kappa_3} h^3 - \frac{\lambda_{\rm SM}}{4} \underbrace{(1+d_4)}_{\kappa_4} h^4$$

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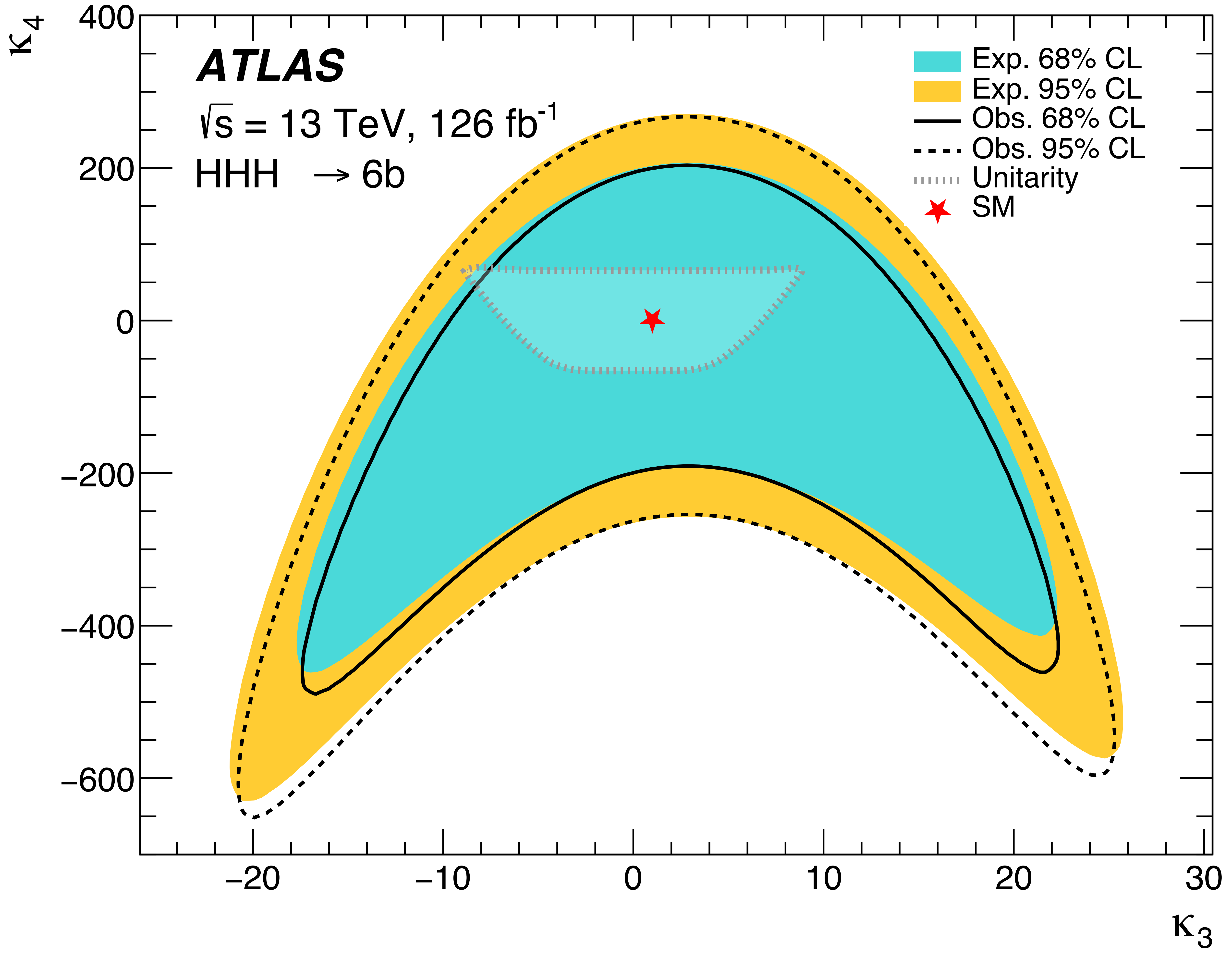

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⇒ **Cross section** modifications (ratio to SM):

$$\sigma/\sigma_{SM}(13.6\text{ TeV}) - 1 \approx 0.88c_3^2 - 0.82c_3 - 0.32c_3^3$$
$$-0.17c_3d_4 - 0.09d_4 + 0.05c_3^2d_4$$
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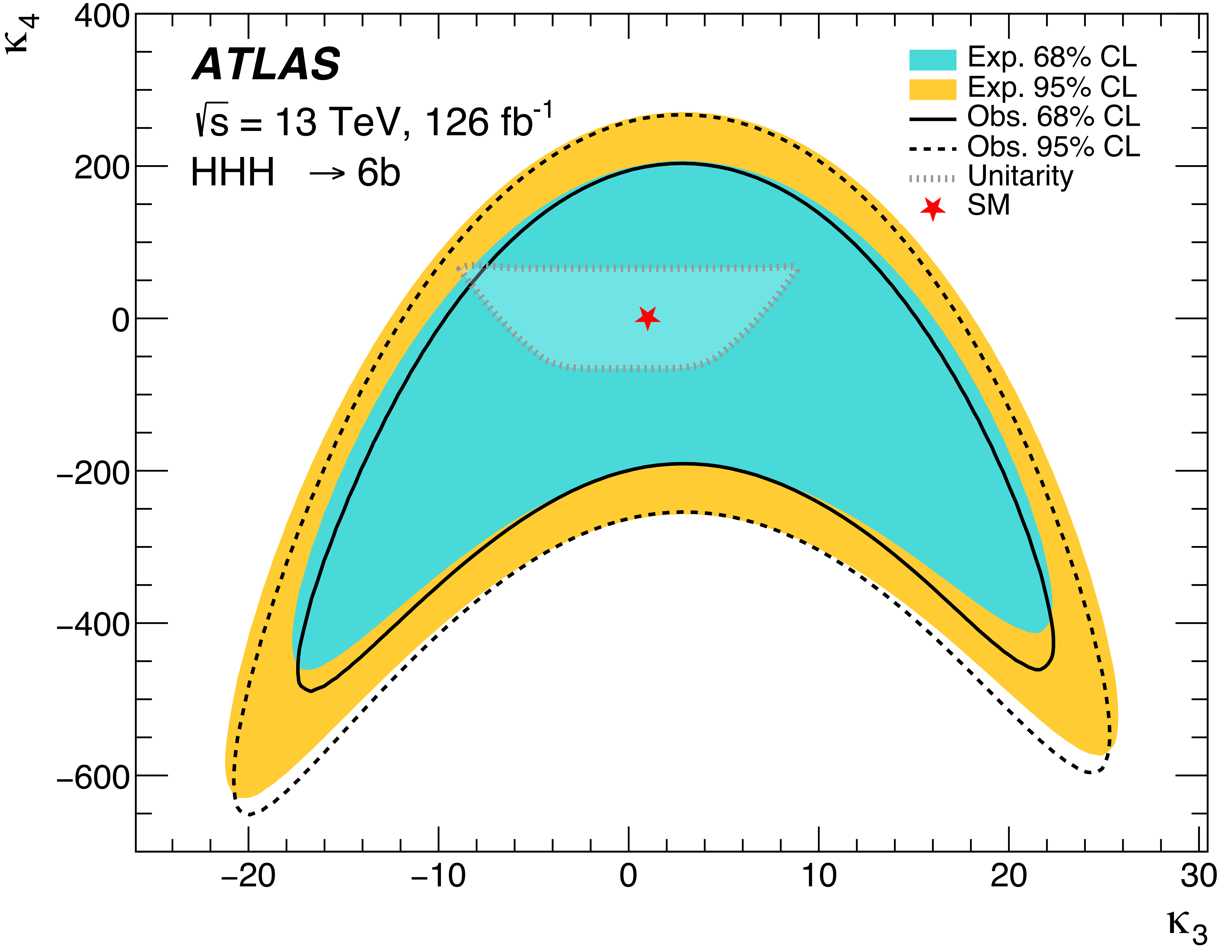

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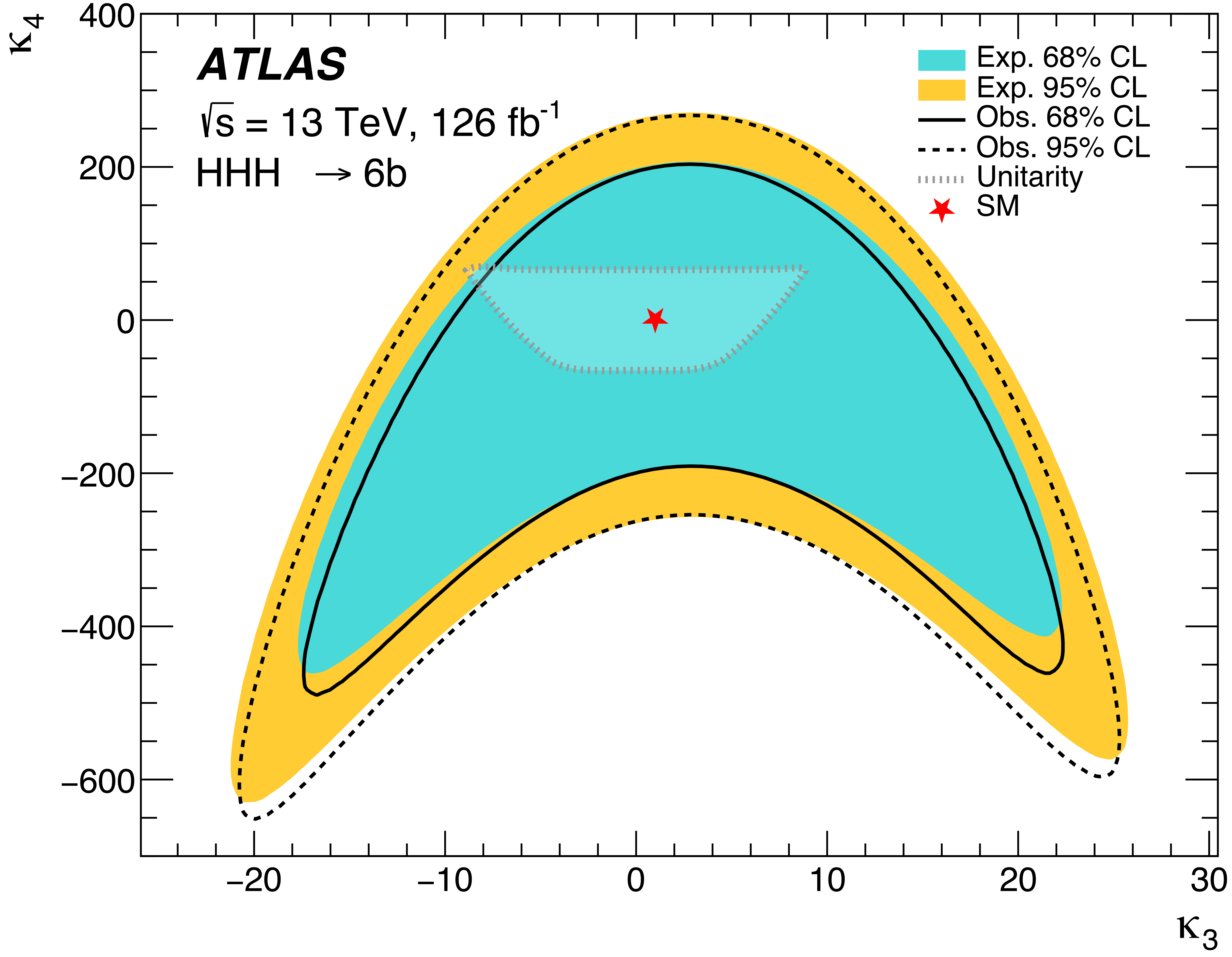

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Note: For **additional** anomalous couplings, e.g. $t\bar{t}h^3$, see: [AP, Tetlalmatzi-Xolocotzi, arXiv:2312.13562]

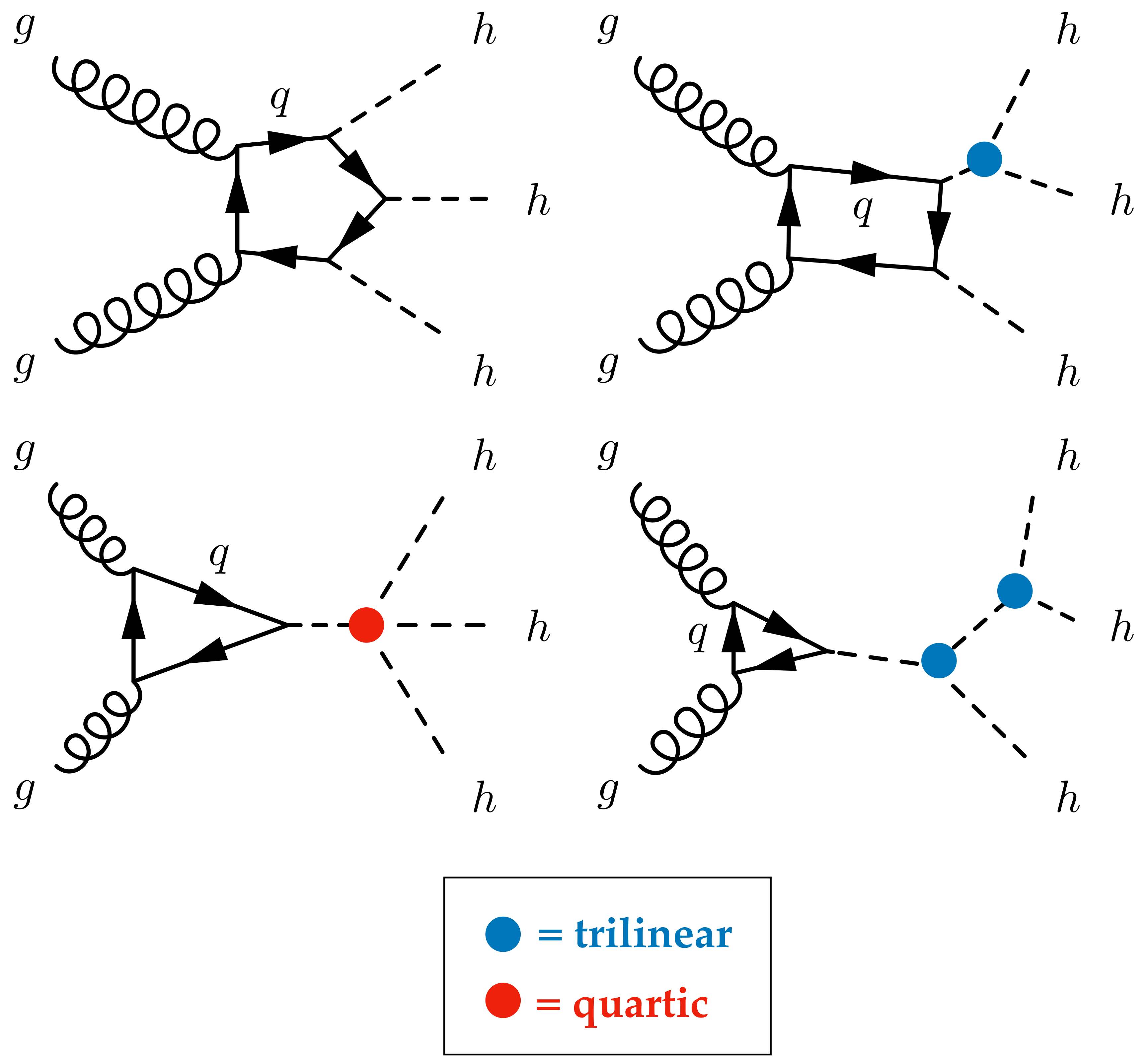
and: `MadGraph5_aMC` model at: https://gitlab.com/apapaefs/multihiggs_loop_sm

Digression: Truncated Non-Resonant *hhh*

- **Q:** Which anomalous contributions to keep @ the **matrix element-squared level**?

- Effective Field Theory considerations: **not settled yet!** [→ see, e.g. discussions of **arXiv:2201.04974, 2304.01968]**.

- Consider **linear**, **quadratic** or **cubic** truncations?



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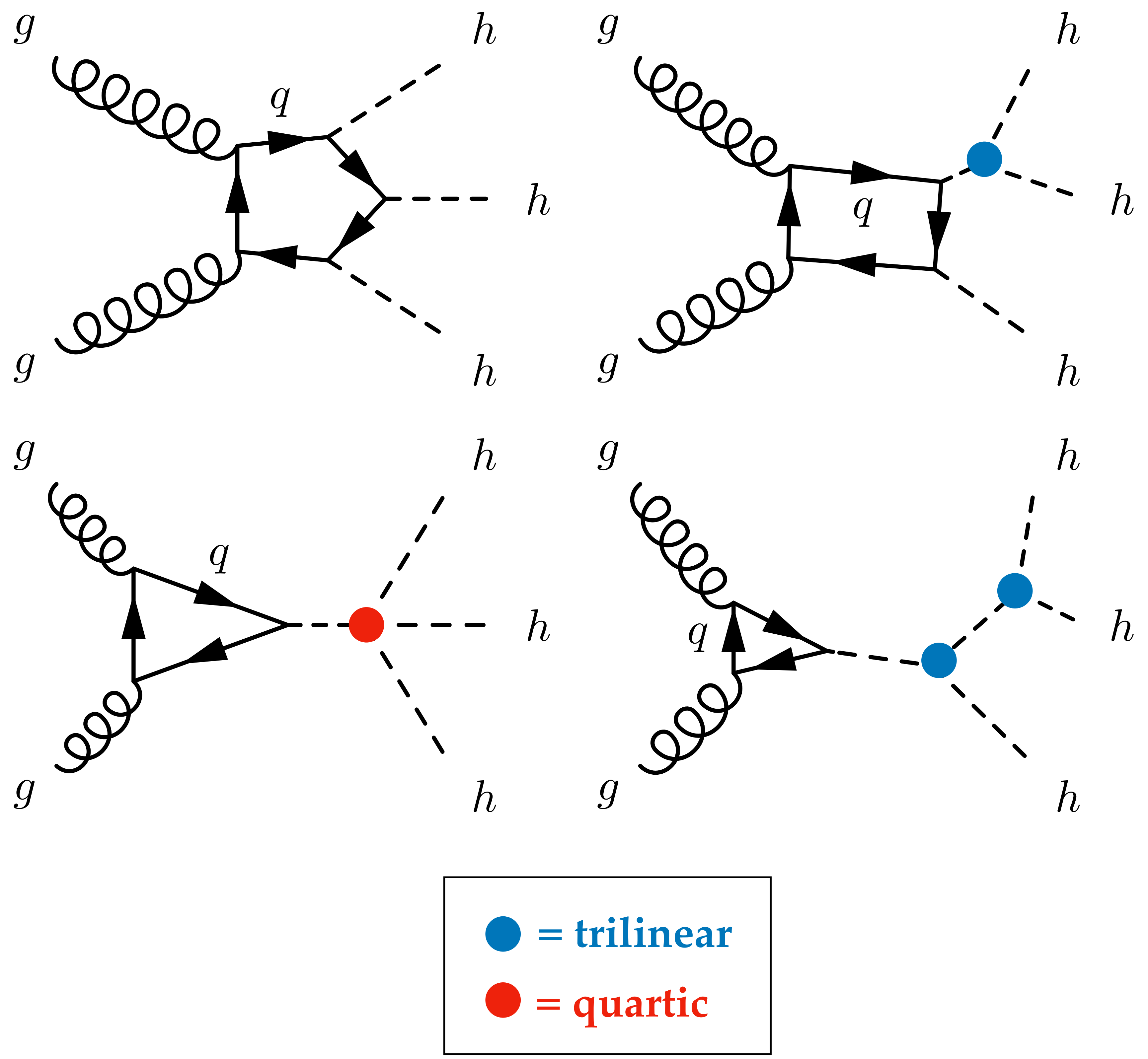

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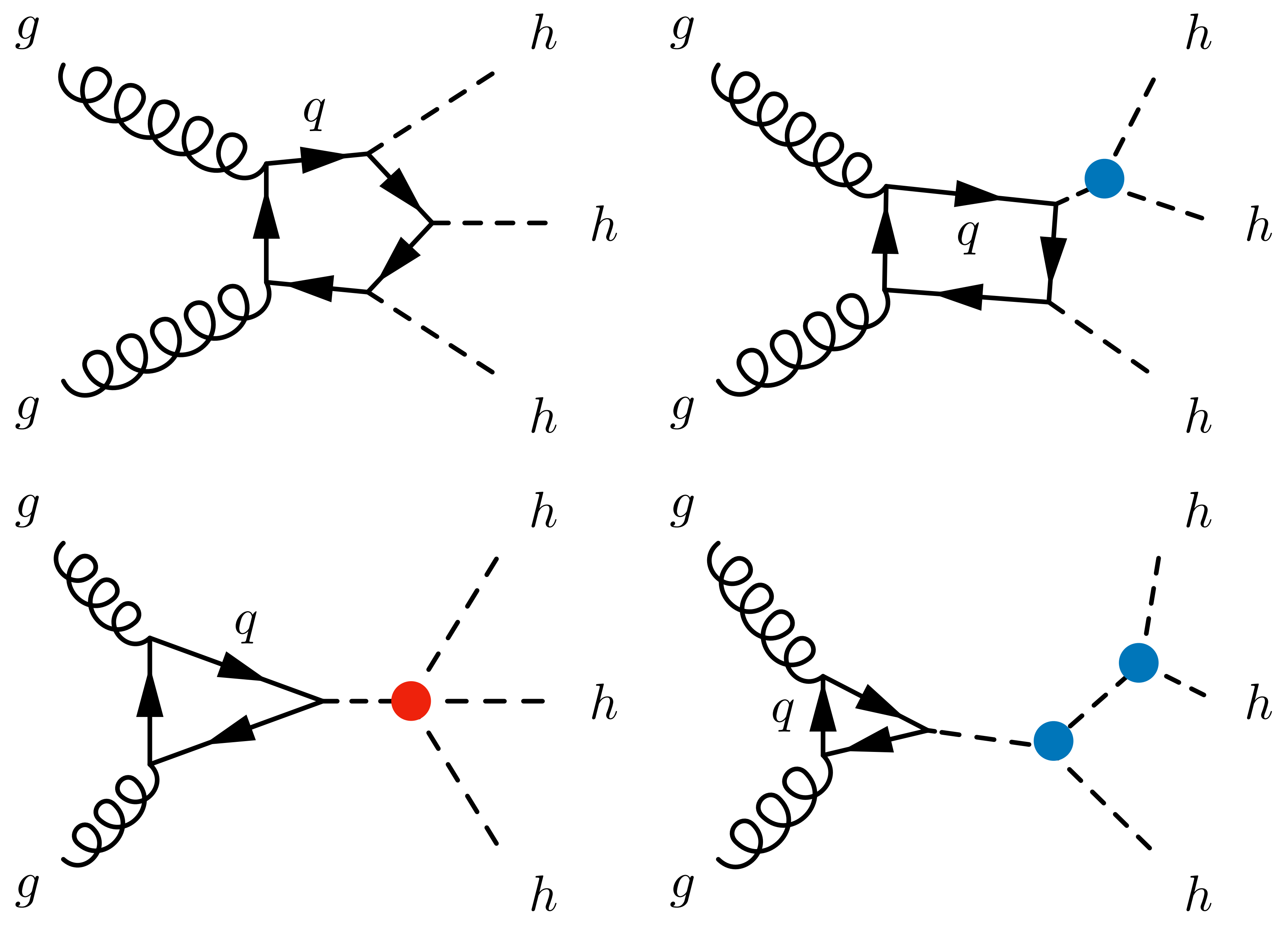

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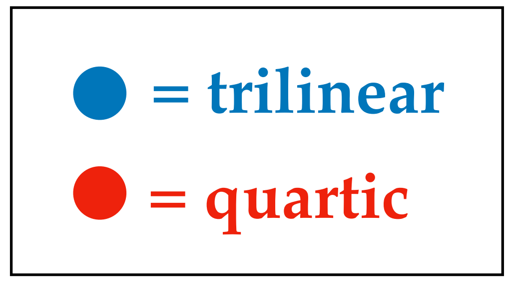

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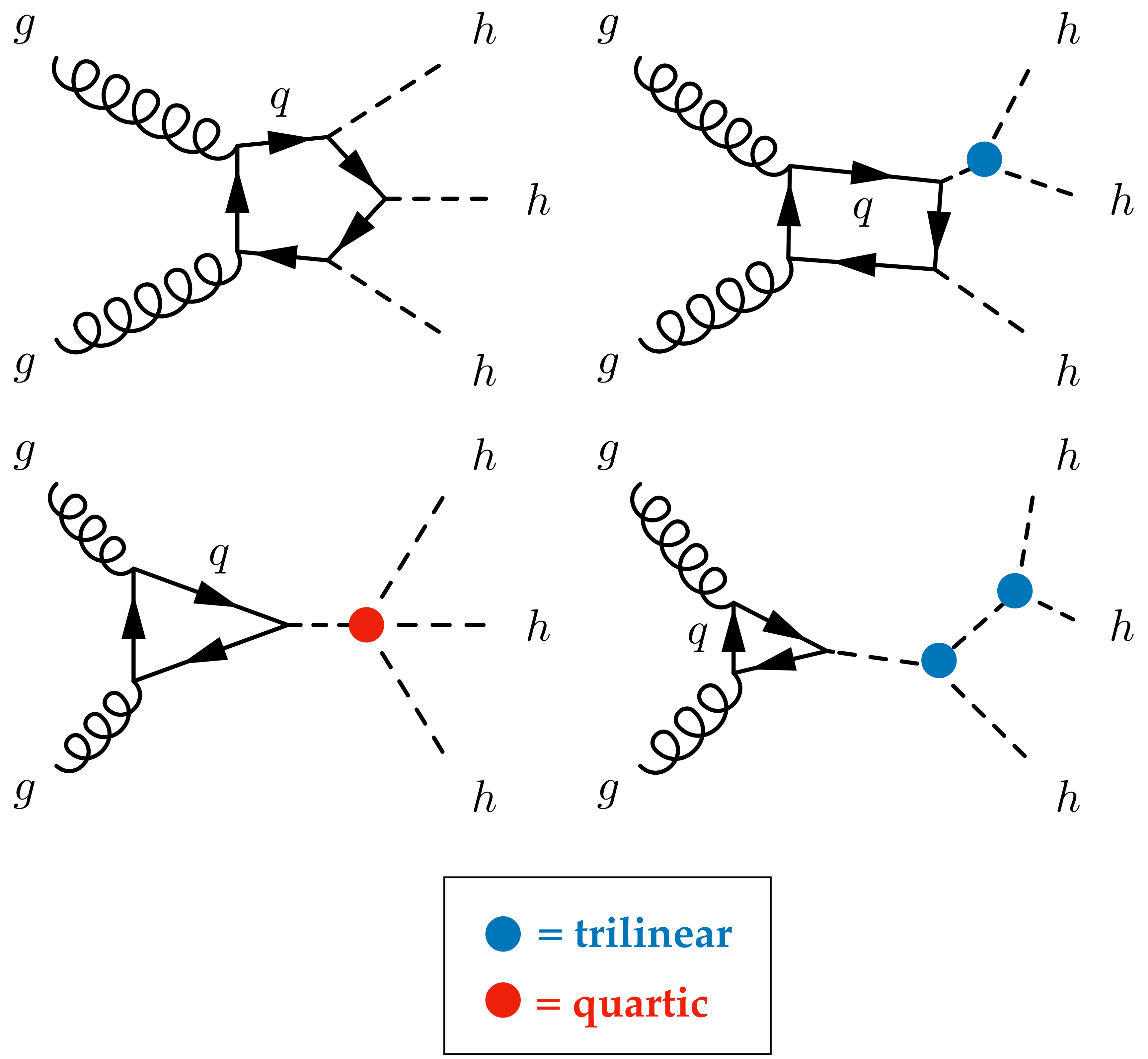

$$
\begin{aligned}
|\mathcal{M}|^2 \sim 1 &+ A c_3 + B d_4 && \text{(linear)}\\
&+ C d_4^2 + D c_3 d_4 + E c_3^2 && \text{(quadratic)}\\
&+ F c_3^2 d_4 + G c_3^3 && \text{(cubic)}\\
&+ c_3^4 && \text{(no trunc.)}
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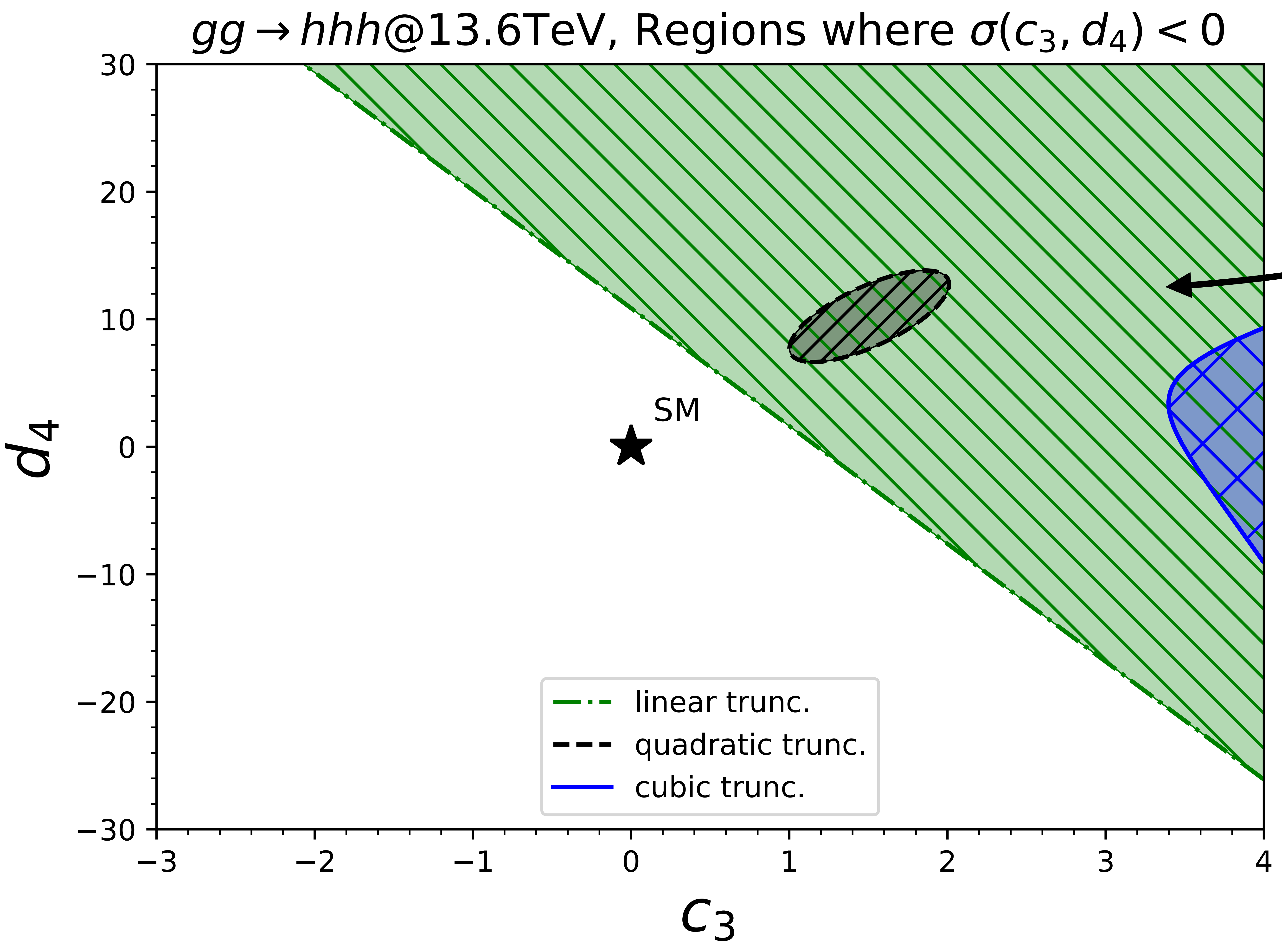

<u>Shaded regions</u>: Negative *hhh* cross section @ 13.6 TeV!
(⇒ unphysical!)

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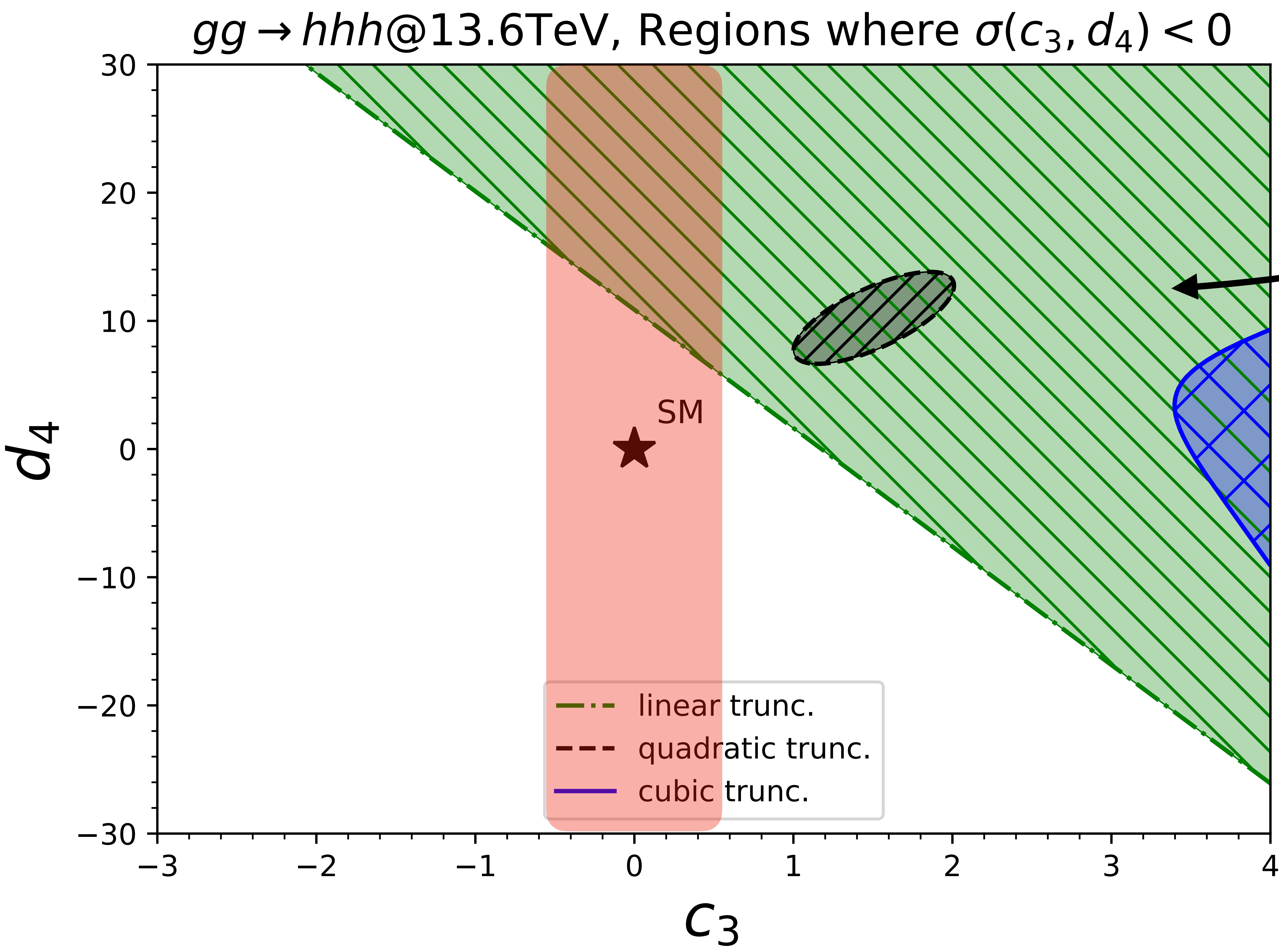

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= **50%** uncertainty on Higgs trilinear (c_3), achievable at High-Luminosity LHC

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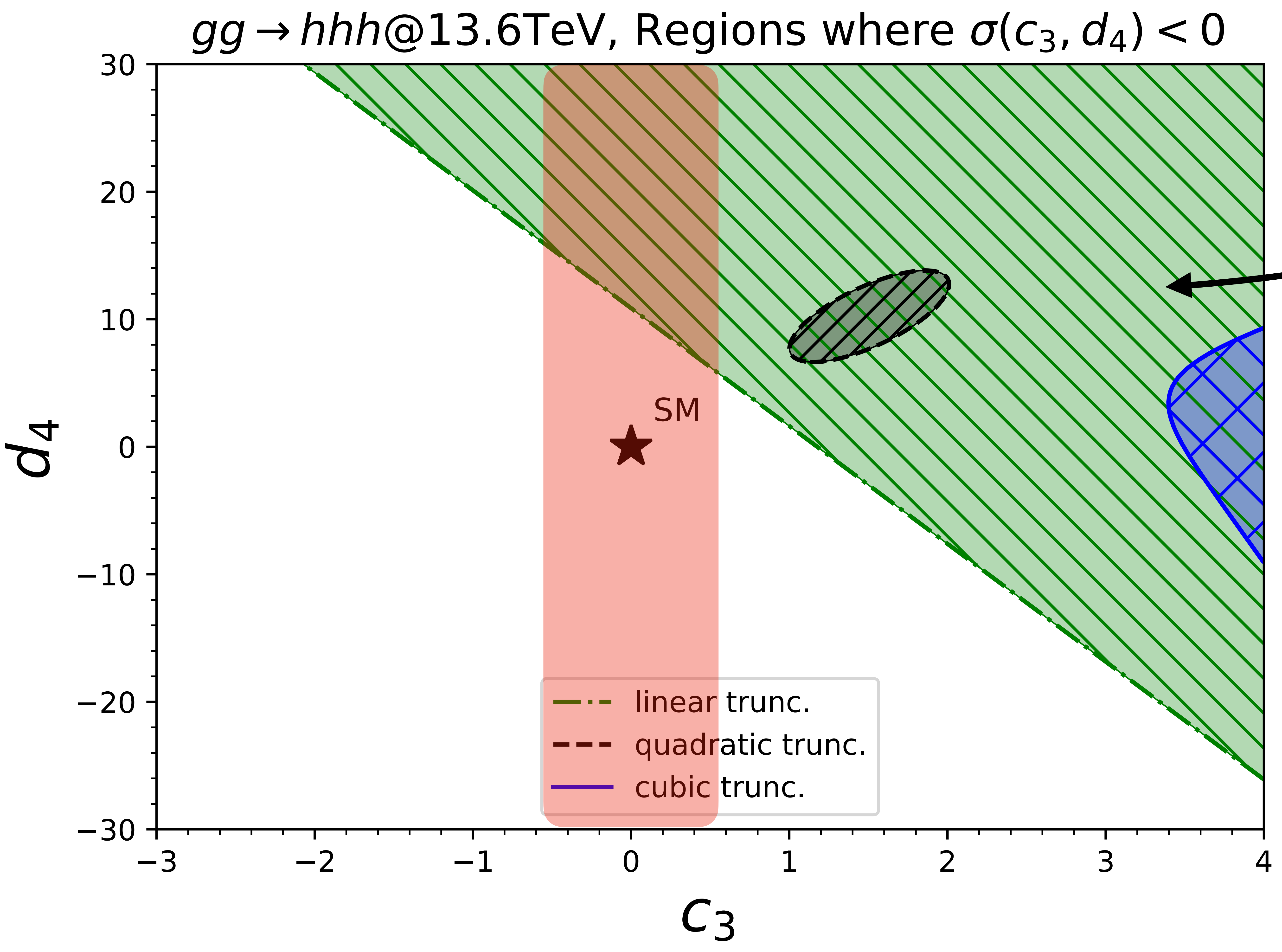

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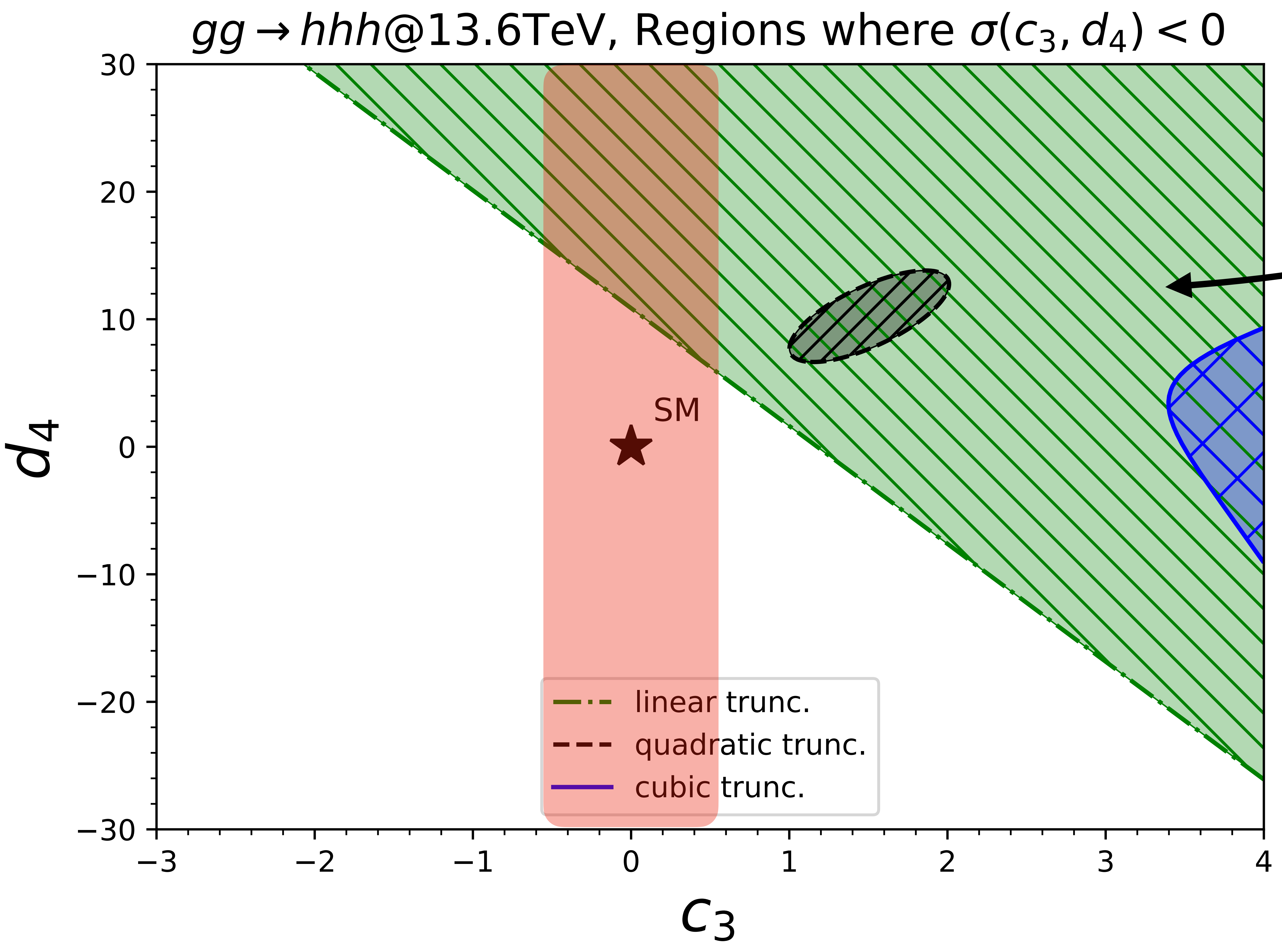

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⇒ When combining with HL-LHC Higgs trilinear constraints, quadratic or cubic truncations could also make sense!

⇒ Should experiments consider these?

[Fuks, AP, Tetlalmatzi-Xolocotzi, arXiv:25xx.xxxx]

Extended Scalar Sectors and *hhh*

Andreas Papaefstathiou

Extended Scalar Sectors: Why?

- Dark Matter (the scalar themselves, or portals to hidden sectors),
- First-order EW phase transitions ($\Rightarrow$ EW baryogenesis $\Rightarrow$ matter-antimatter asymmetry), [e.g. **AP**, White, **arXiv:2010.0059 & arXiv:2108.11394**]
- & Model the scalar sector of more complicated models, e.g. SUSY.

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- & Model the scalar sector of more complicated models, e.g. SUSY.

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

Singlet ≡ NO SM "charges"

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

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

← "**Portal**" interactions.

[$|\phi|^2$ is also an SM singlet!]

$$+ S \times (\text{Hidden Sector}) + \ldots$$

← **Dark Matter**?

Simplest extension to the SM: add ONE real singlet scalar field.

SM+One Real Singlet [=xSM]

[e.g. **AP**, White, arXiv:2010.00597]

$$\mathcal{V}(\phi, S) = \bullet\, |\phi|^2 + \blacksquare\, |\phi|^4 + \bullet\, S^2 + \blacktriangle\, S^3 + \blacksquare\, S^4 + \blacktriangle\, |\phi|^2 S + \blacksquare\, |\phi|^2 S^2$$

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

$h_1 \rightarrow$ "SM-like" Higgs boson.

$h_2 \rightarrow$ new scalar resonance.

i.e. choose: $|\theta| \gtrsim 0$, and:

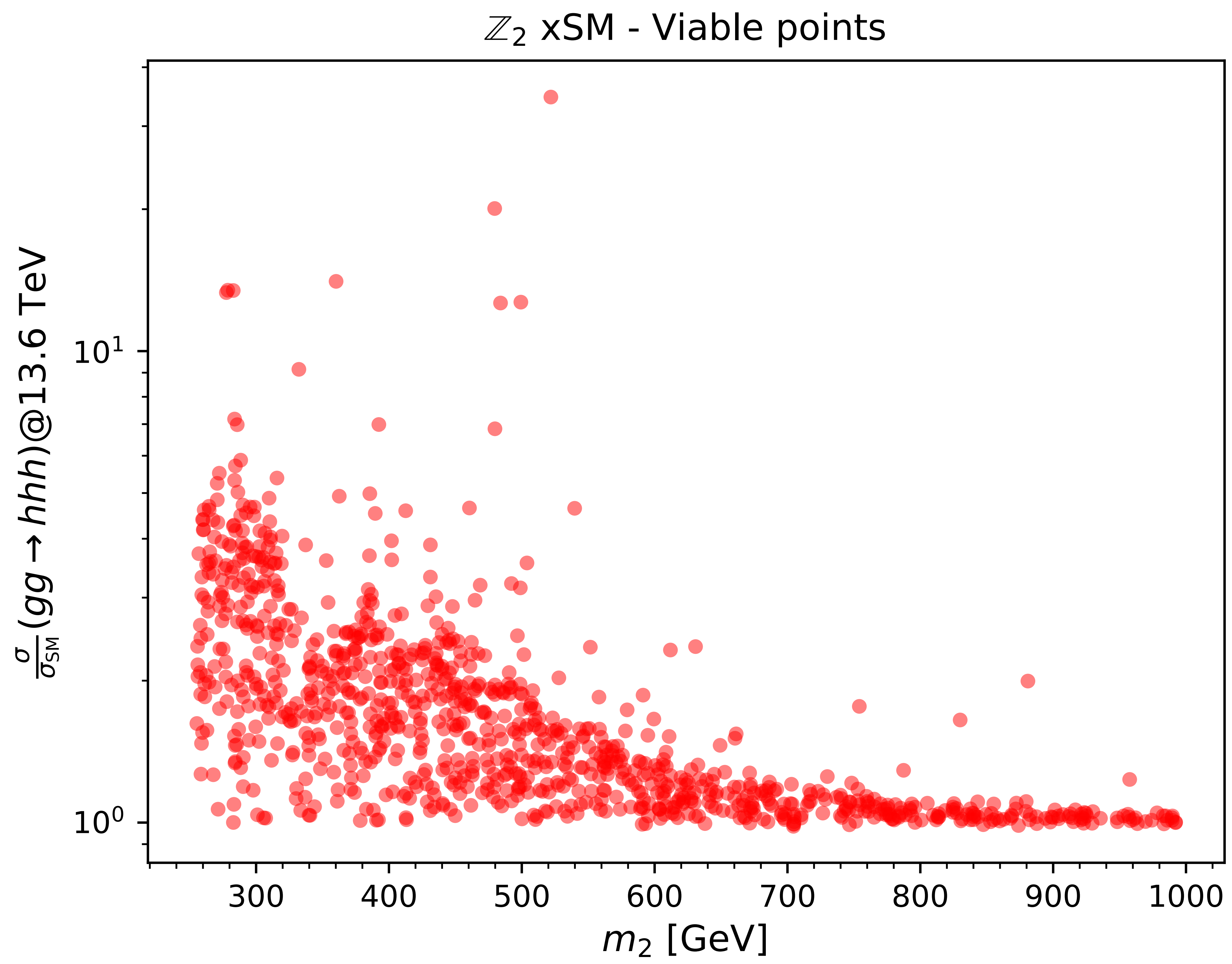
$$h_1 = h\cos\theta + \chi\sin\theta$$

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

Resonant *hhh* in the SM+One Real Singlet [=xSM]

- What about ***hhh*** in the **xSM**? An example **with $\mathbb{Z}_2$ symmetry: $\mathbb{Z}_2 : S \to -S$.**

- **Including:** boundedness of potential + perturbativity + `HiggsTools` (i.e. experimental) constraints [Bahl, Biekötter, Heinemeyer, Li, Paasch, Weiglein, Wittbrodt, **arXiv:2210.09332**].



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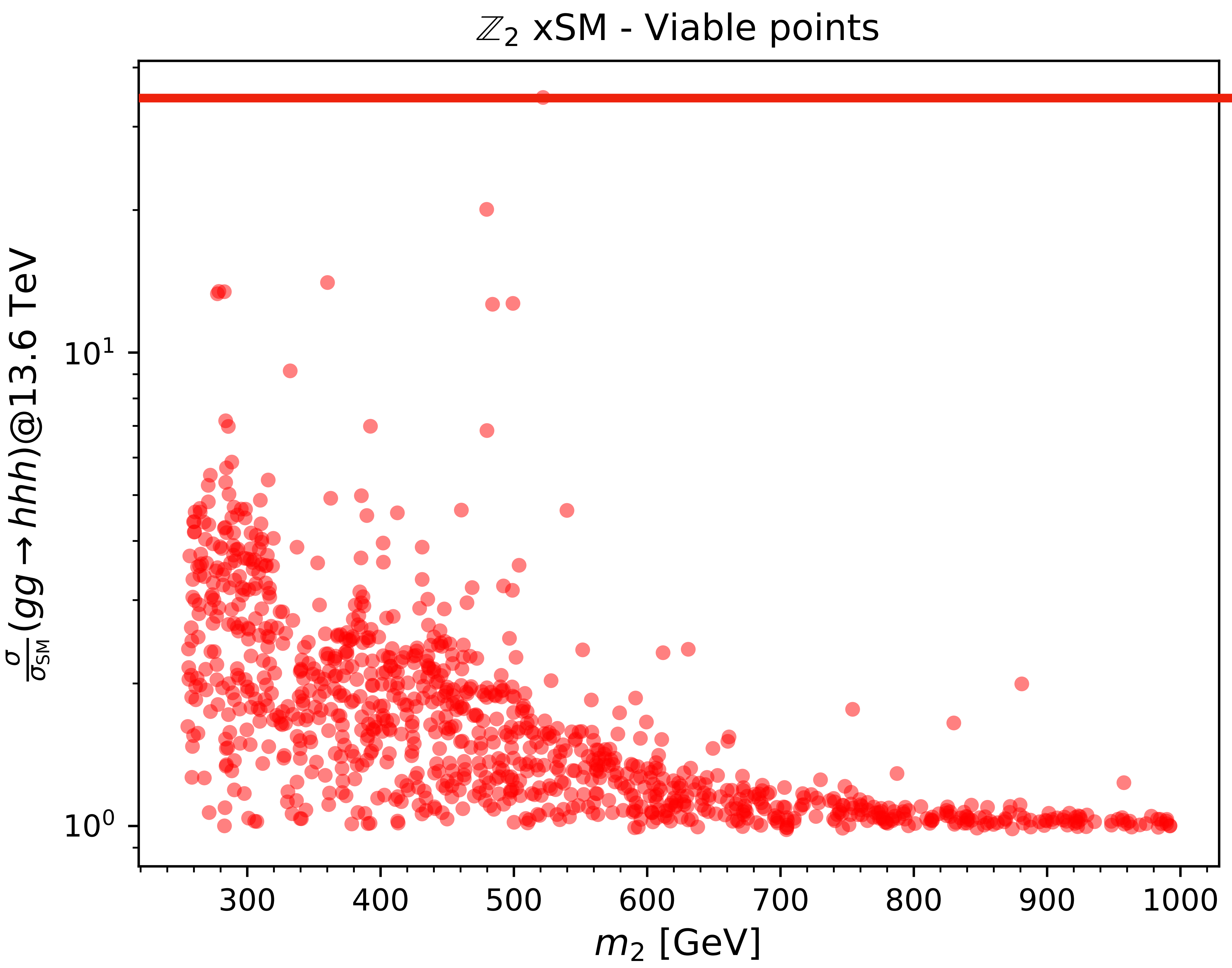
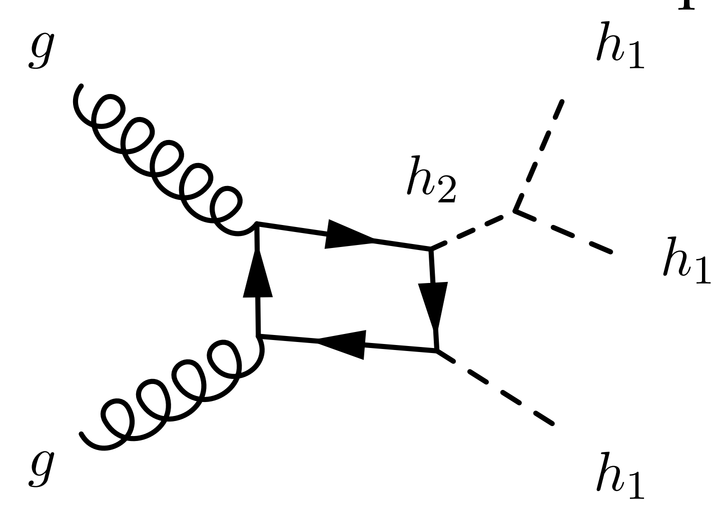


Maximum enhancement ~ $\mathcal{O}(30)$!

[**But**: I suspect these will be excluded quickly by resonant *hh*! Due to:



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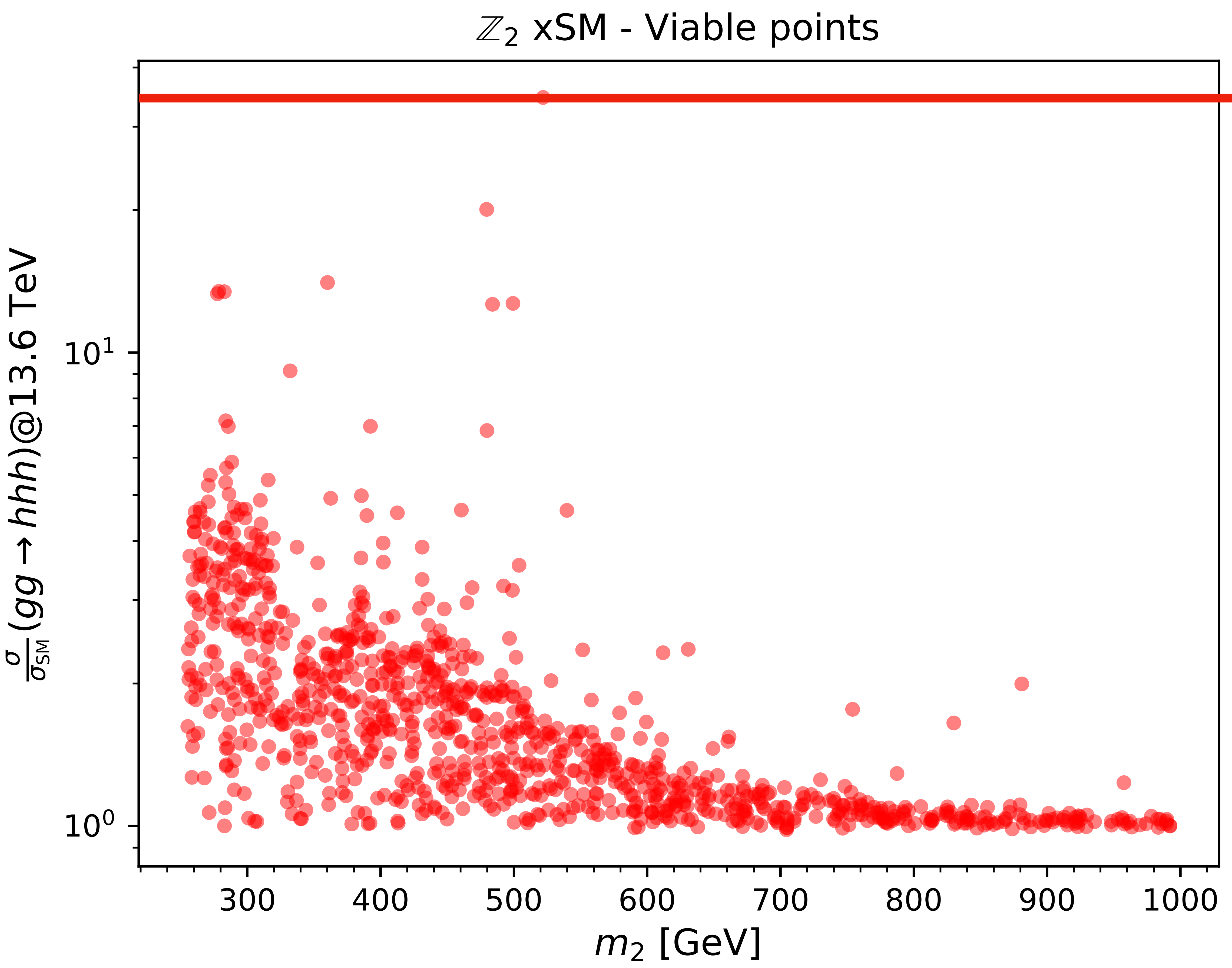

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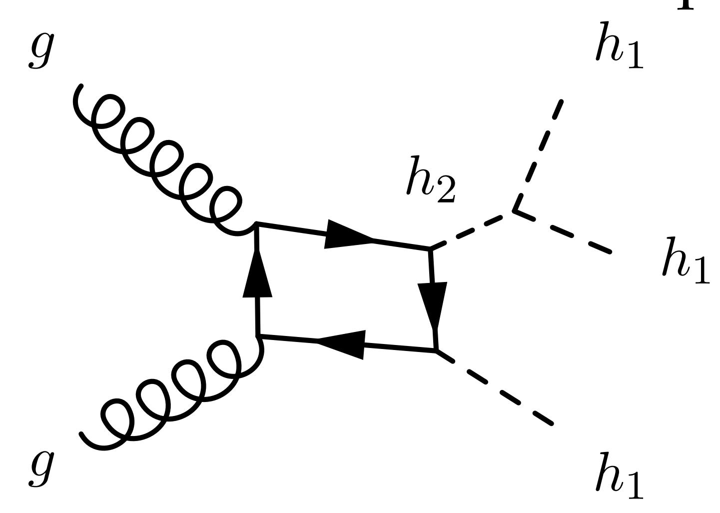

]

⇒ Look at further extended scalar sectors!

SM + Two Real Singlet Scalars [= TRSM]

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

$$\mathbb{Z}_2^S : S \to -S, \;\; X \to X$$

$$\mathbb{Z}_2^X : X \to -X, \;\; S \to S$$

$\Rightarrow$ TRSM Scalar Potential:

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

SM + Two Real Singlet Scalars [= TRSM]

- Electroweak Symmetry Breaking in the TRSM:

  ⇒ **Three** scalar bosons: $h_1, h_2, h_3 \to h_1 \approx$ SM-like “Higgs boson”.

  ⇒ ***hhh*** that may even be detectable at the LHC!

through: $pp \to h_3 \to h_2 h_1 \to h_1 h_1 h_1$ [Robens, Stefaniak, Wittbrodt, **arXiv:1908.08554**, AP, Robens, Tetlalmatzi-Xolocotzi, **arXiv:2101.00037**]

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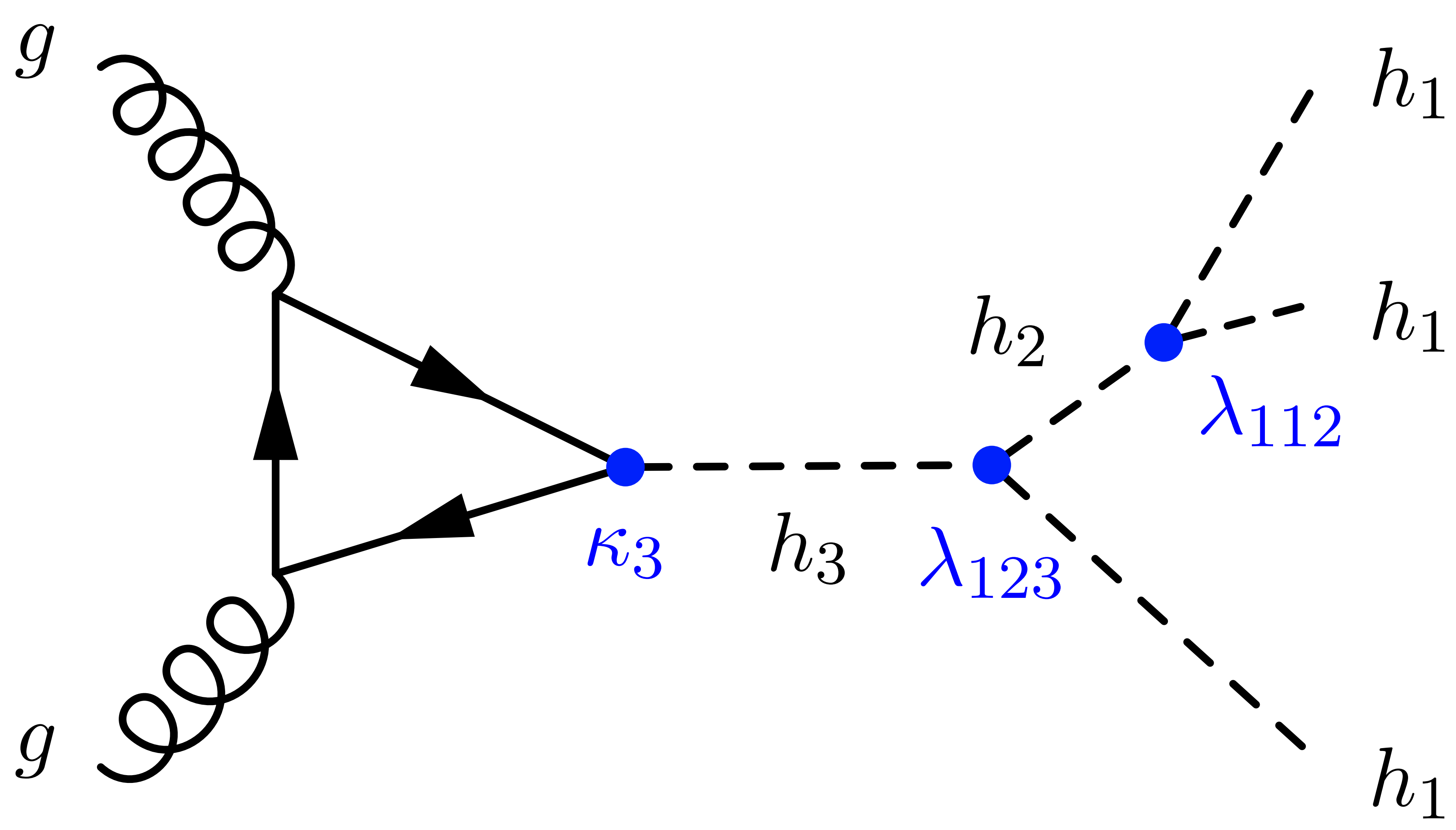
→ **Double-Resonant enhancement!**



Requires:

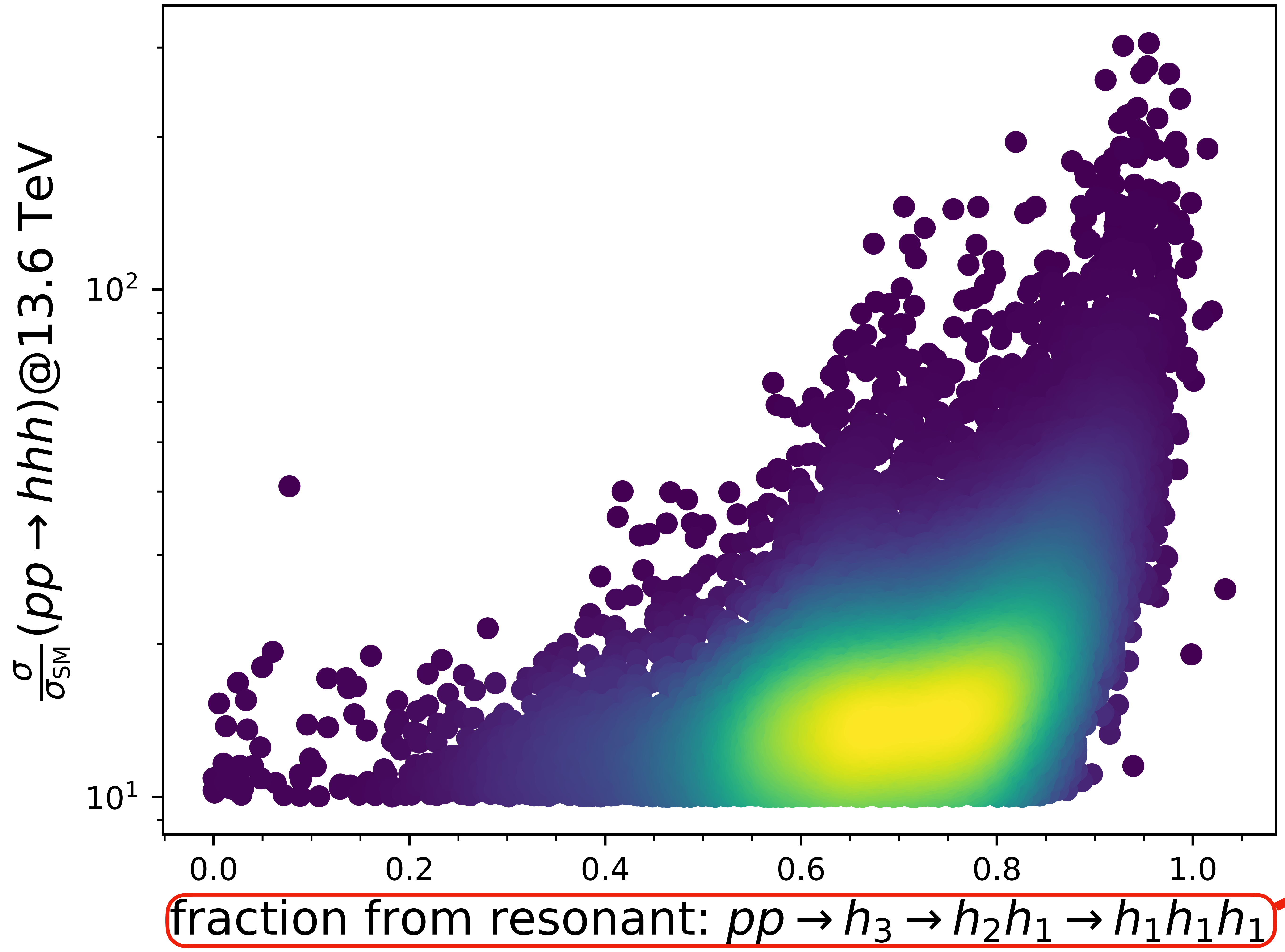
$m_3 > m_2 + m_1,\ m_2 > 2m_1$

Double-Resonant *hhh* in the TRSM

- Enhancement of ***hhh*** ⇔ Large "fraction" of double-resonant process!

Viable points with $\sigma > 10 \times \sigma_{SM}(pp \to hhh)$@13.6 TeV

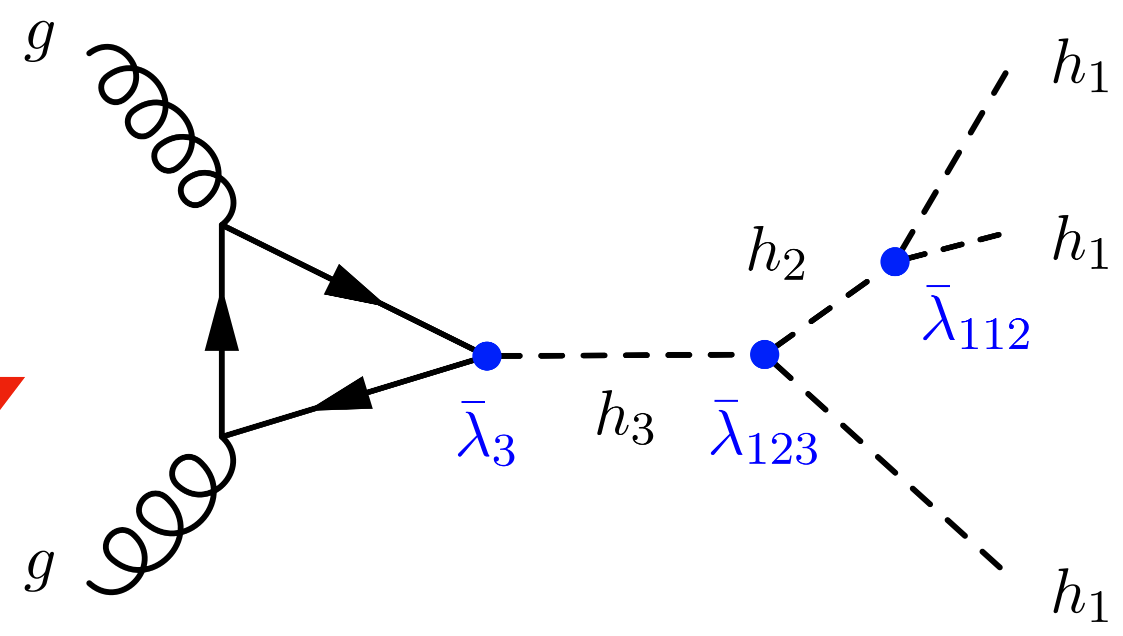
Enhancement over SM



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

[including boundedness of potential + perturbativity + `HiggsTools` constraints.]

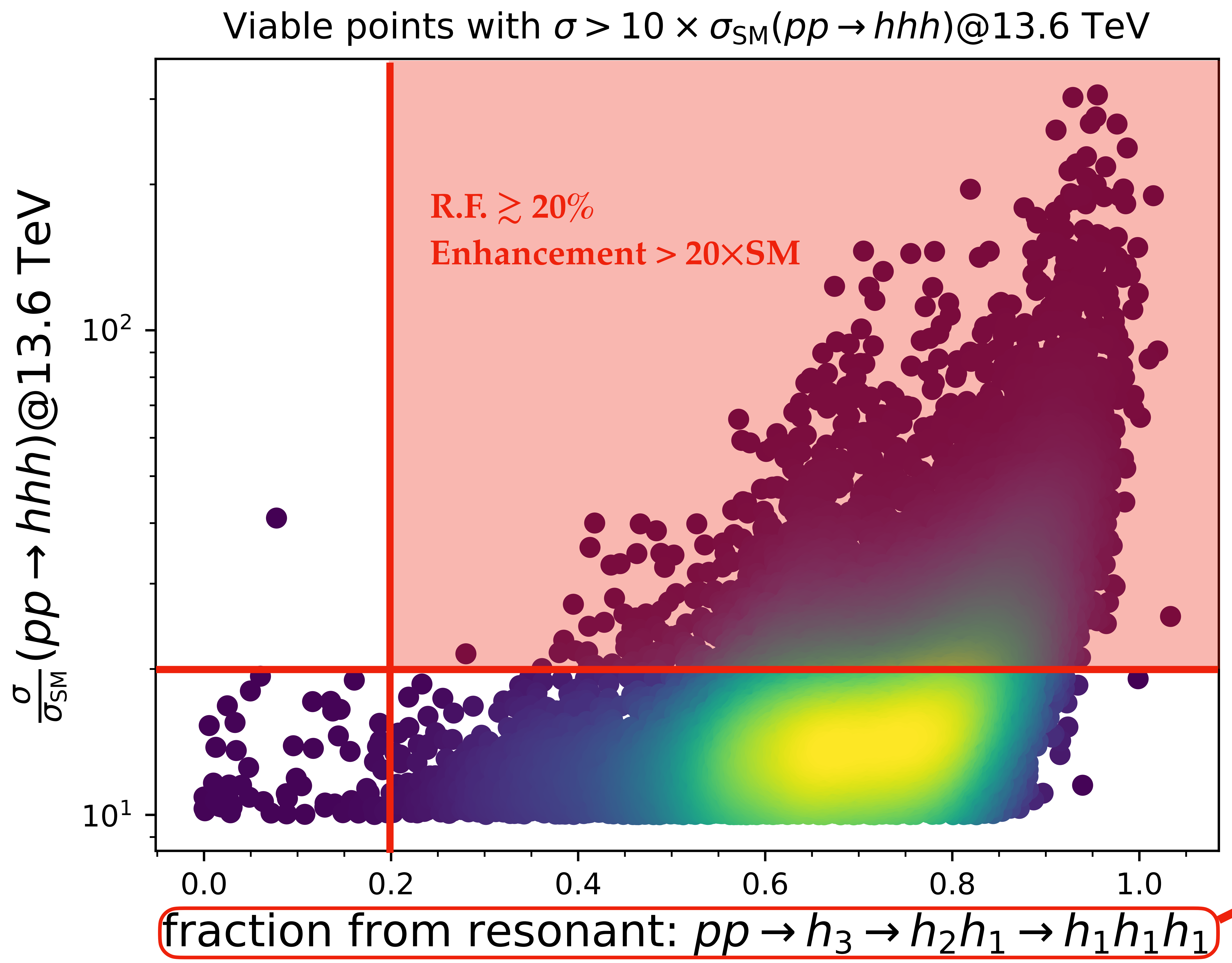
Resonant Fraction (R.F.) =
How much of the total cross section comes from… ?



Andreas Papaefstathiou

Double-Resonant *hhh* in the TRSM

- Enhancement of ***hhh*** ⇔ Large "fraction" of double-resonant process!



Enhancement over SM

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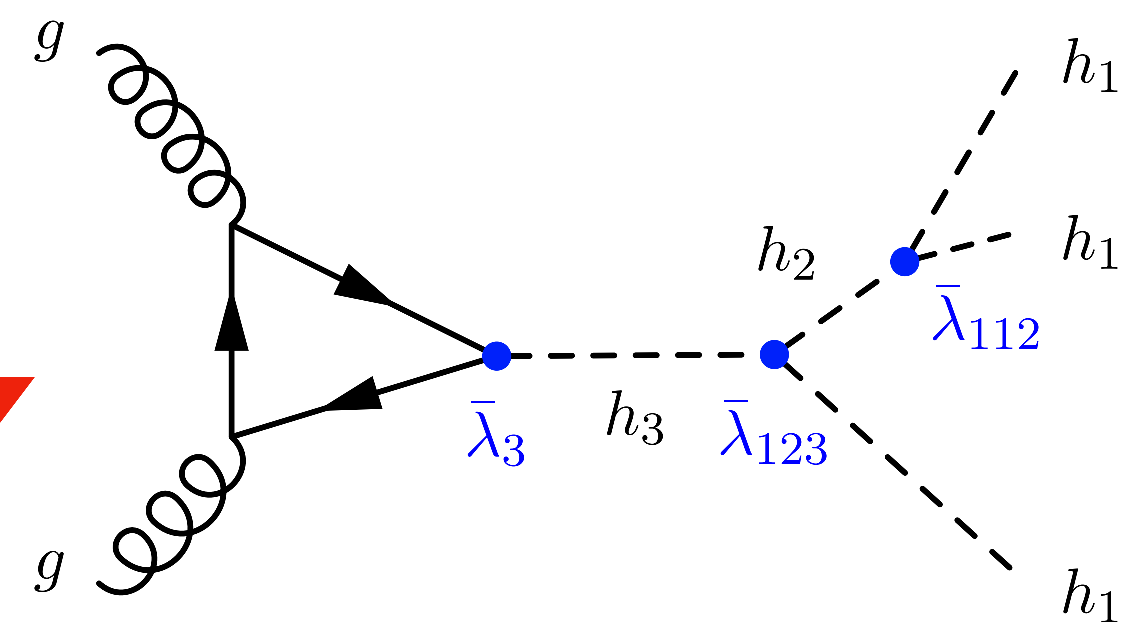

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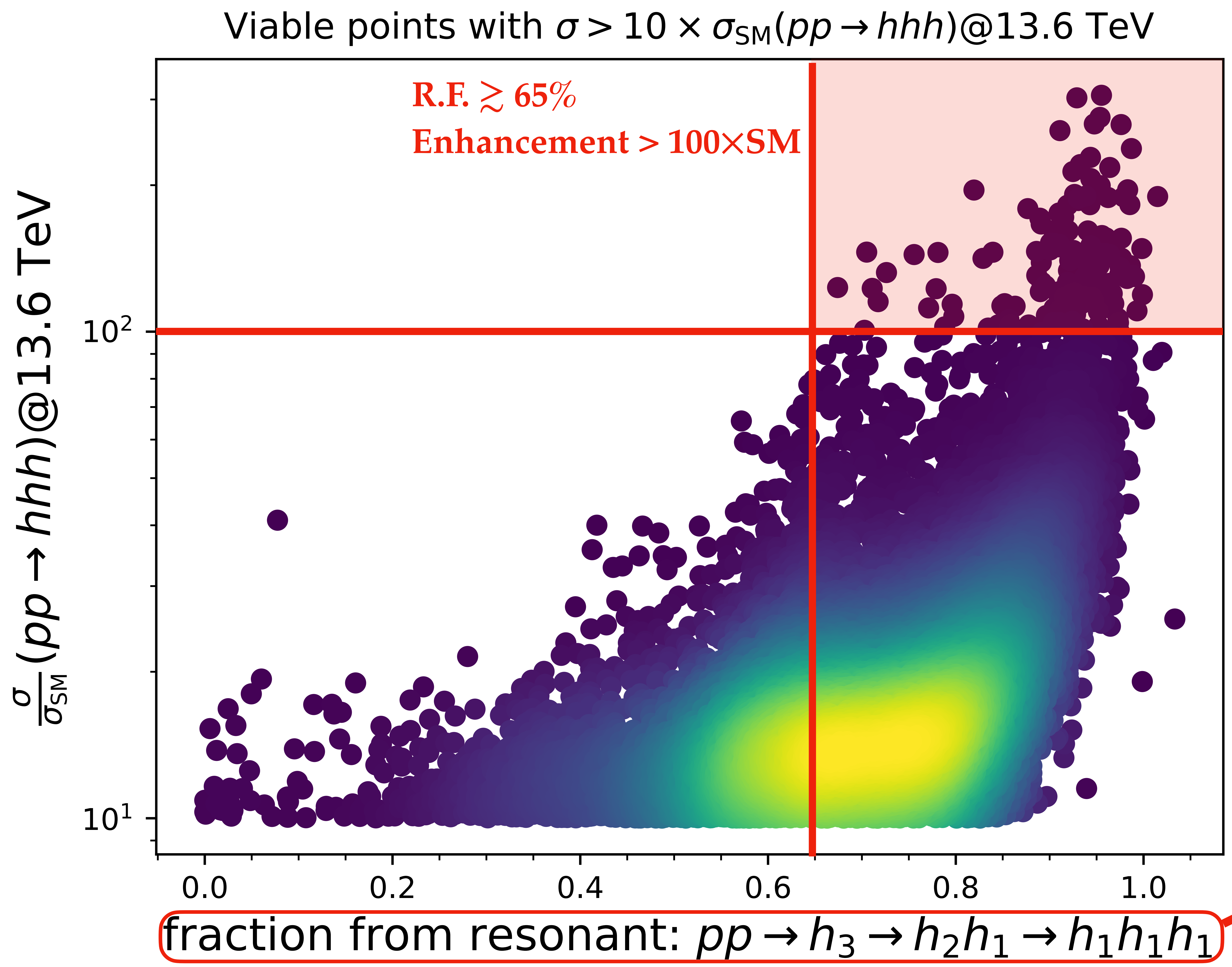

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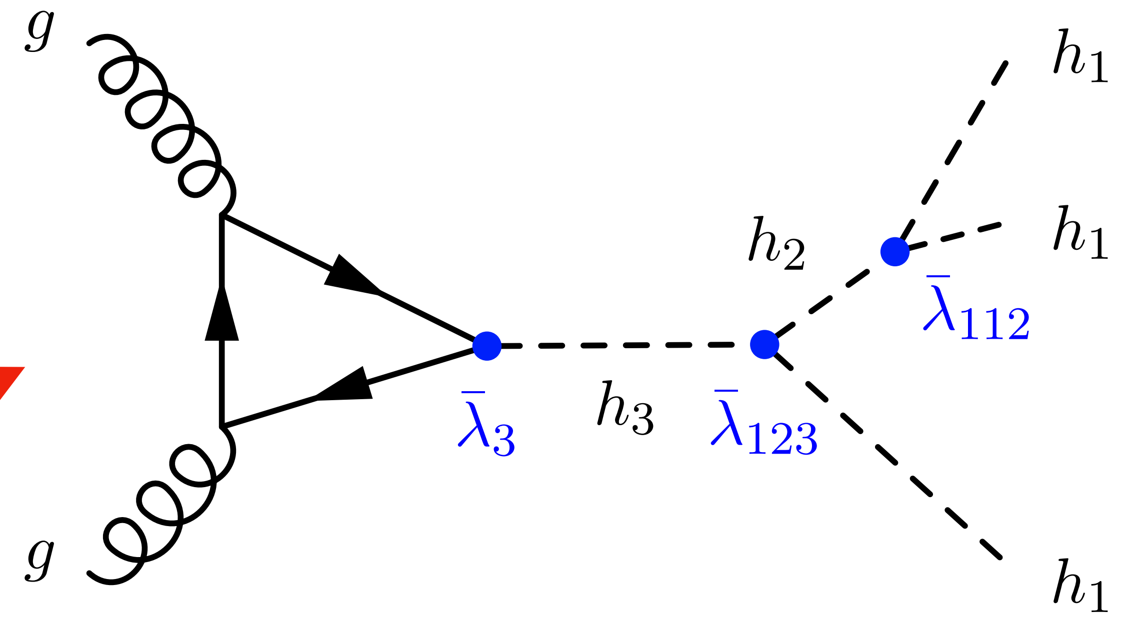

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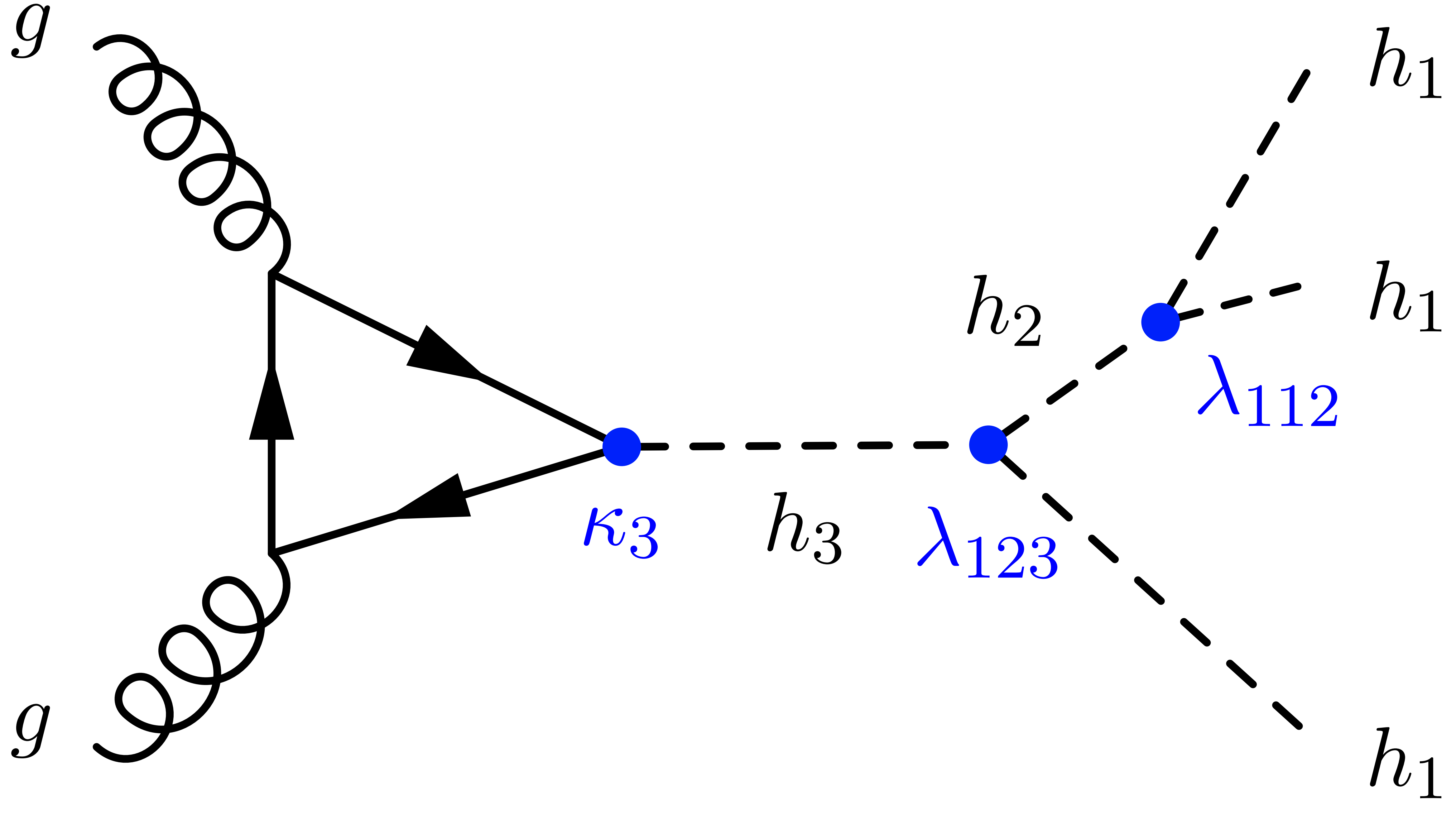
Anatomy of Double-Resonant *hhh*



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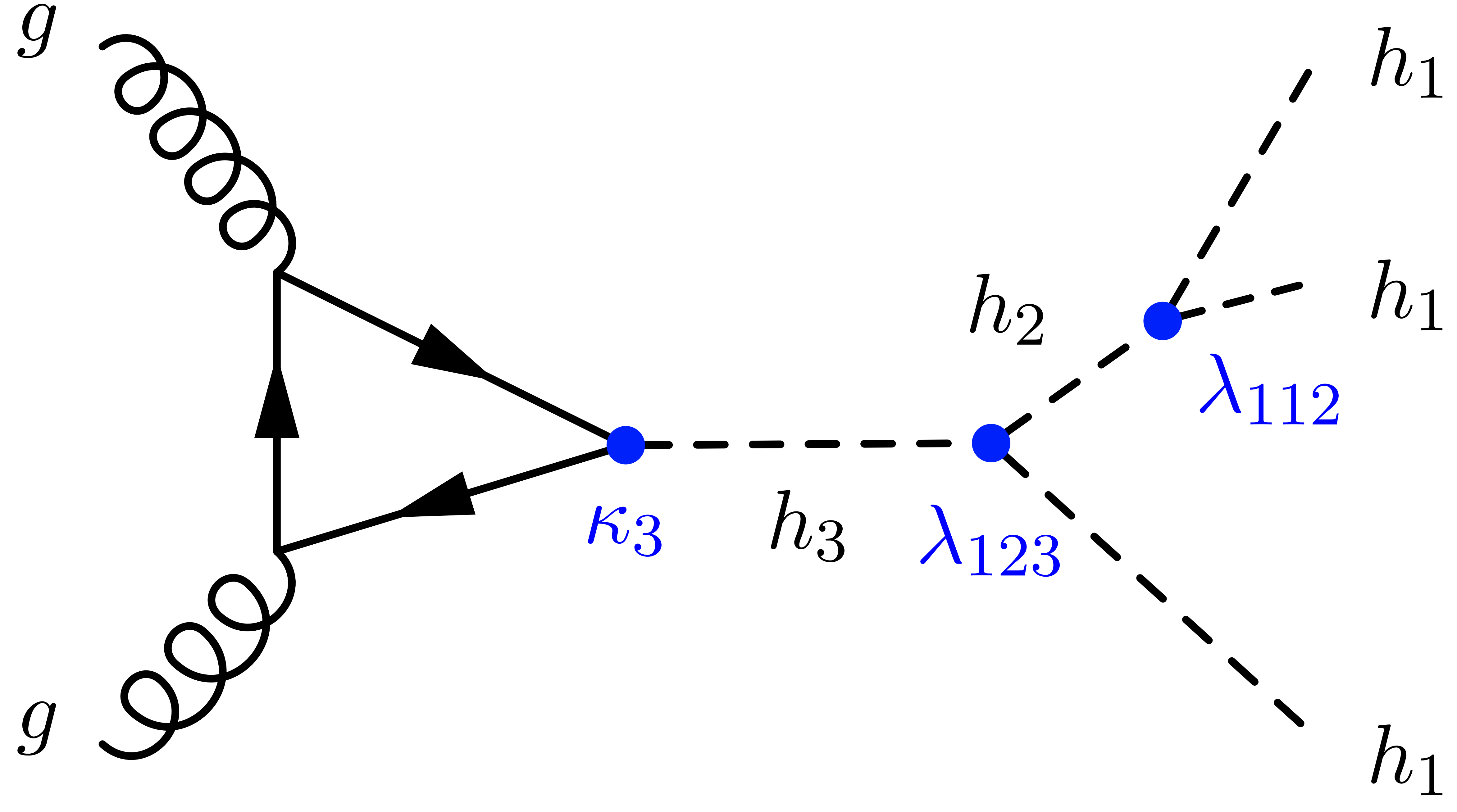

$$\sigma(m_2, m_3) = \sigma_u(m_2, m_3) \times \kappa_3^2 \lambda_{123}^2 \lambda_{112}^2$$

① Factor out couplings

*Narrow width: See appendix!

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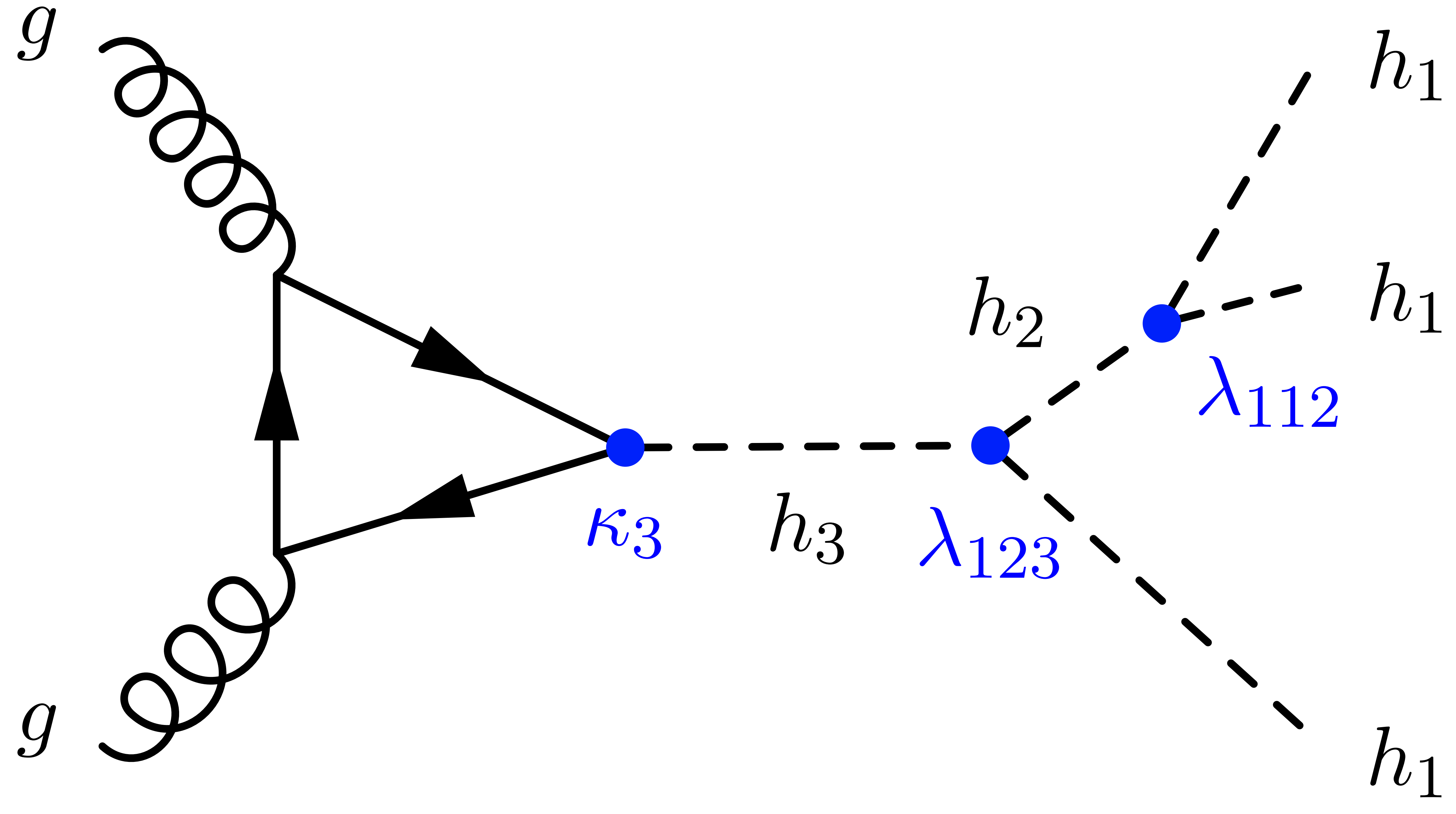

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② Apply the **narrow-width approximation*** for h_2 and h_3:

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

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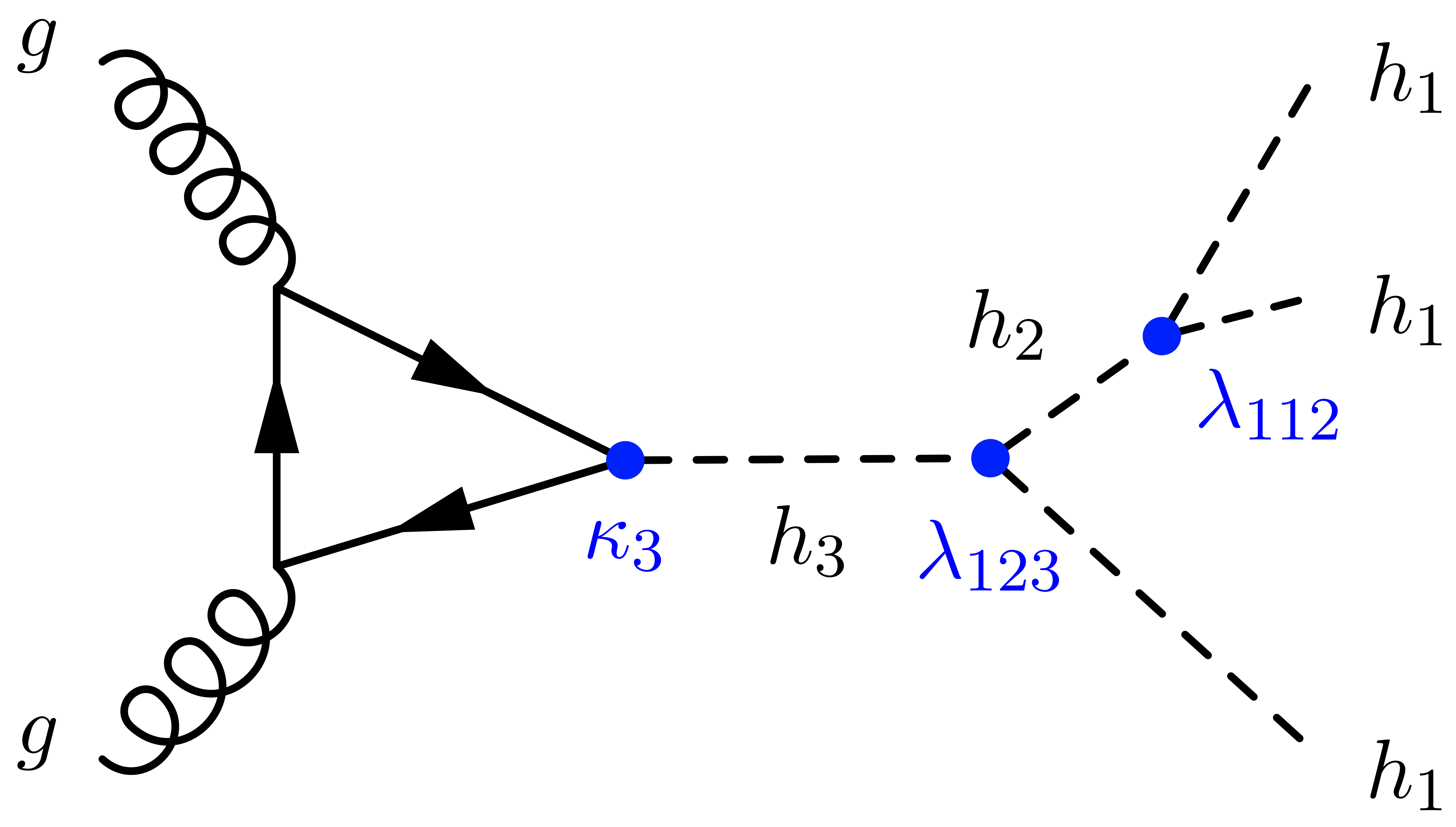

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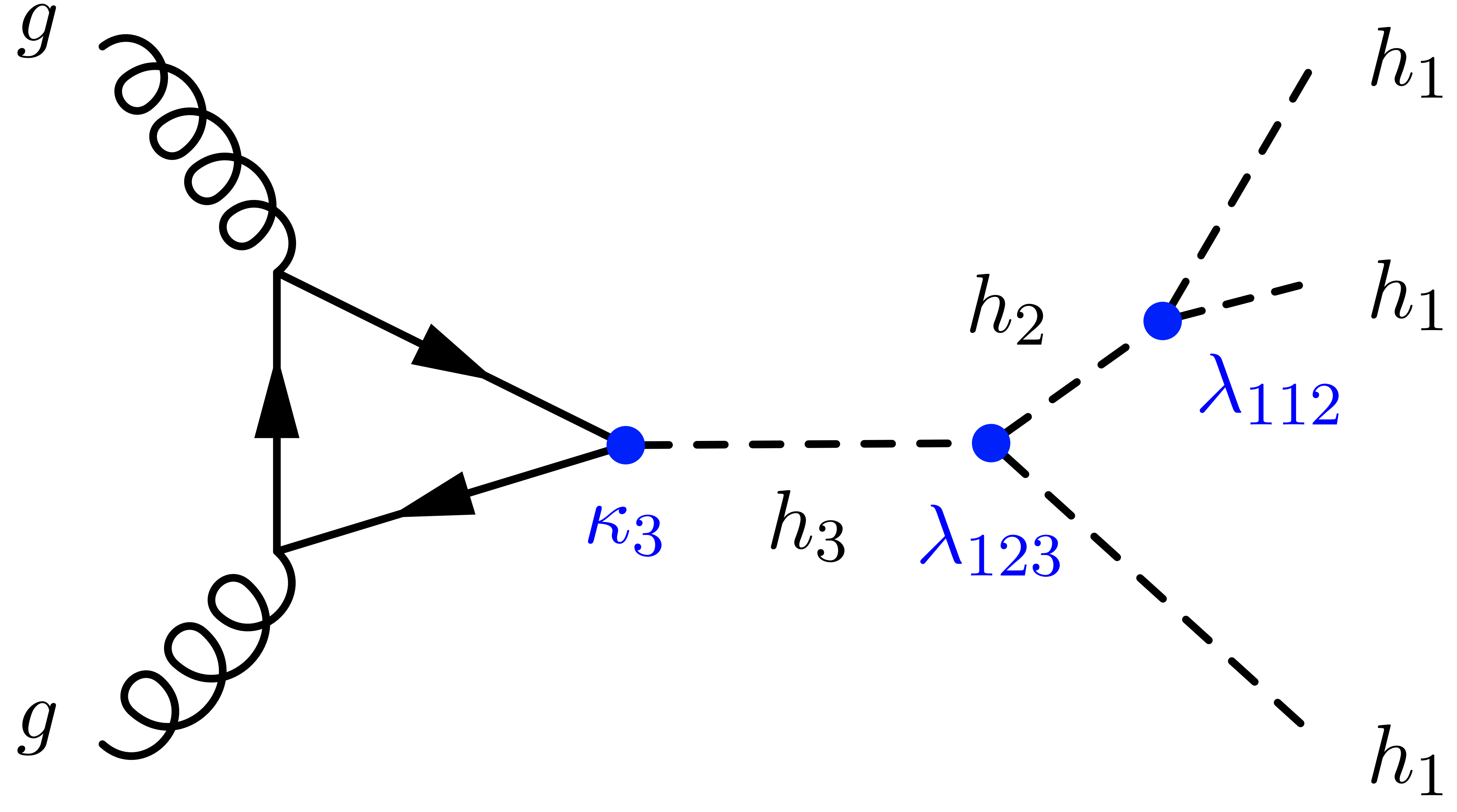
Andreas Papaefstathiou

Anatomy of Double-Resonant *hhh*



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④ Define: $\rho^2 \equiv \kappa_3^2 \lambda_{123}^2 \lambda_{112}^2 / (\Gamma_2 \Gamma_3)$

"rescaling factor"

*Narrow width: See appendix!

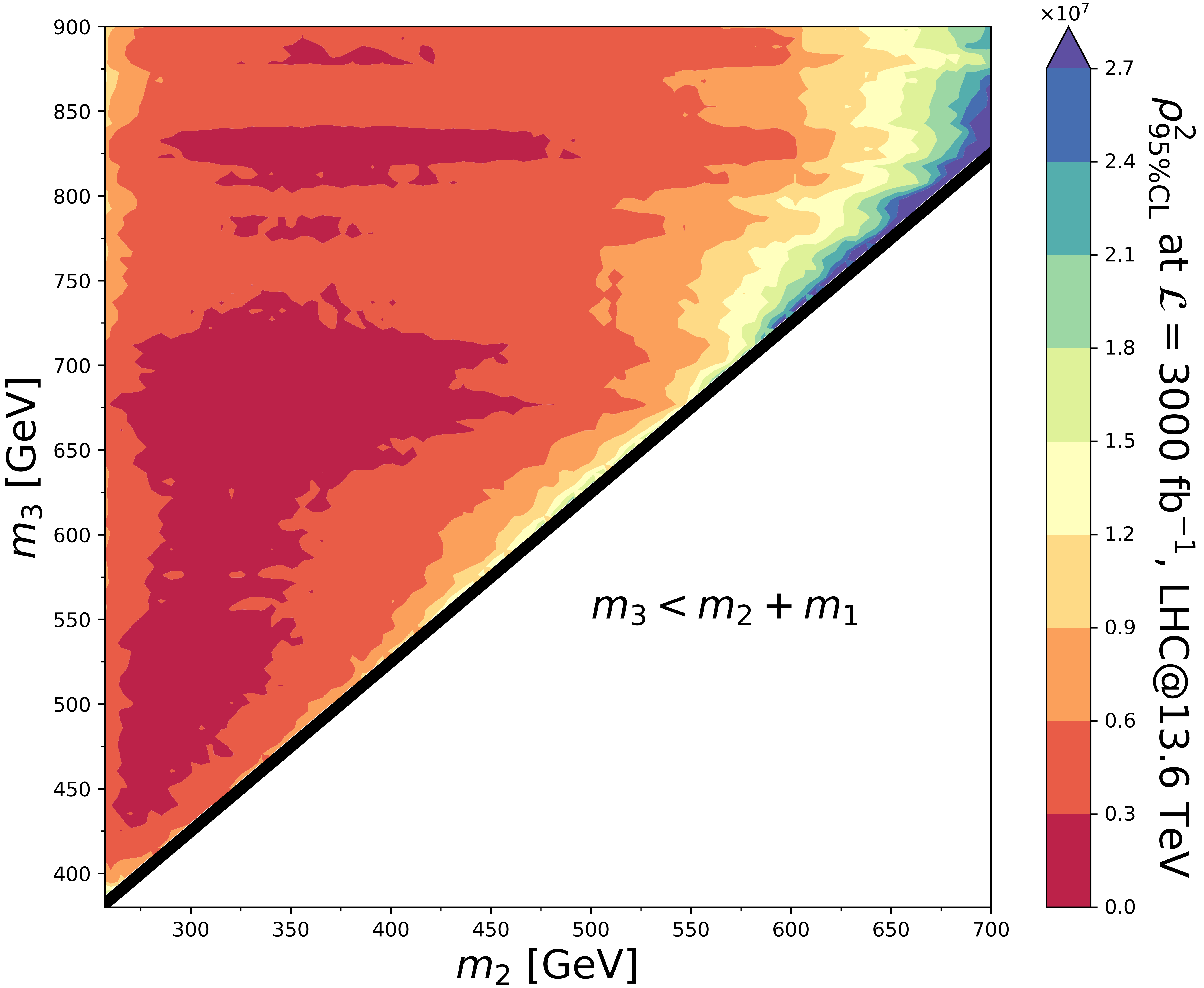
What if…?

- **Let's suppose two new scalars h_2 and h_3 are discovered (🍾🍾):**
  ➡ m_2, m_3 [and possibly] the widths Γ_2, Γ_3 would be known.
- ***hhh*** can provide relevant **information** on the theoretical parameter space.
  ➡ An important contribution to solving the **inverse problem**!
  ➡ through rescaling factor $\rho^2 = \kappa_3^2 \lambda_{123}^2 \lambda_{112}^2 / (\Gamma_2 \Gamma_3)$ (**if narrow width!***)
- We derived **constraints on** ρ^2 via: $pp \rightarrow (b\bar{b})(b\bar{b})(b\bar{b}) \rightarrow$ **6 b-jets.**
  ➡ [~20% of the ***hhh*** final state.]

[AP, Tetlalmatzi-Xolocotzi, Zaro, **arXiv:1909.09166**, AP, Robens, Tetlalmatzi-Xolocotzi, **arXiv:2101.00037**, AP, Tetlalmatzi-Xolocotzi, **arXiv:2501.14866**]

*Narrow width: See appendix!

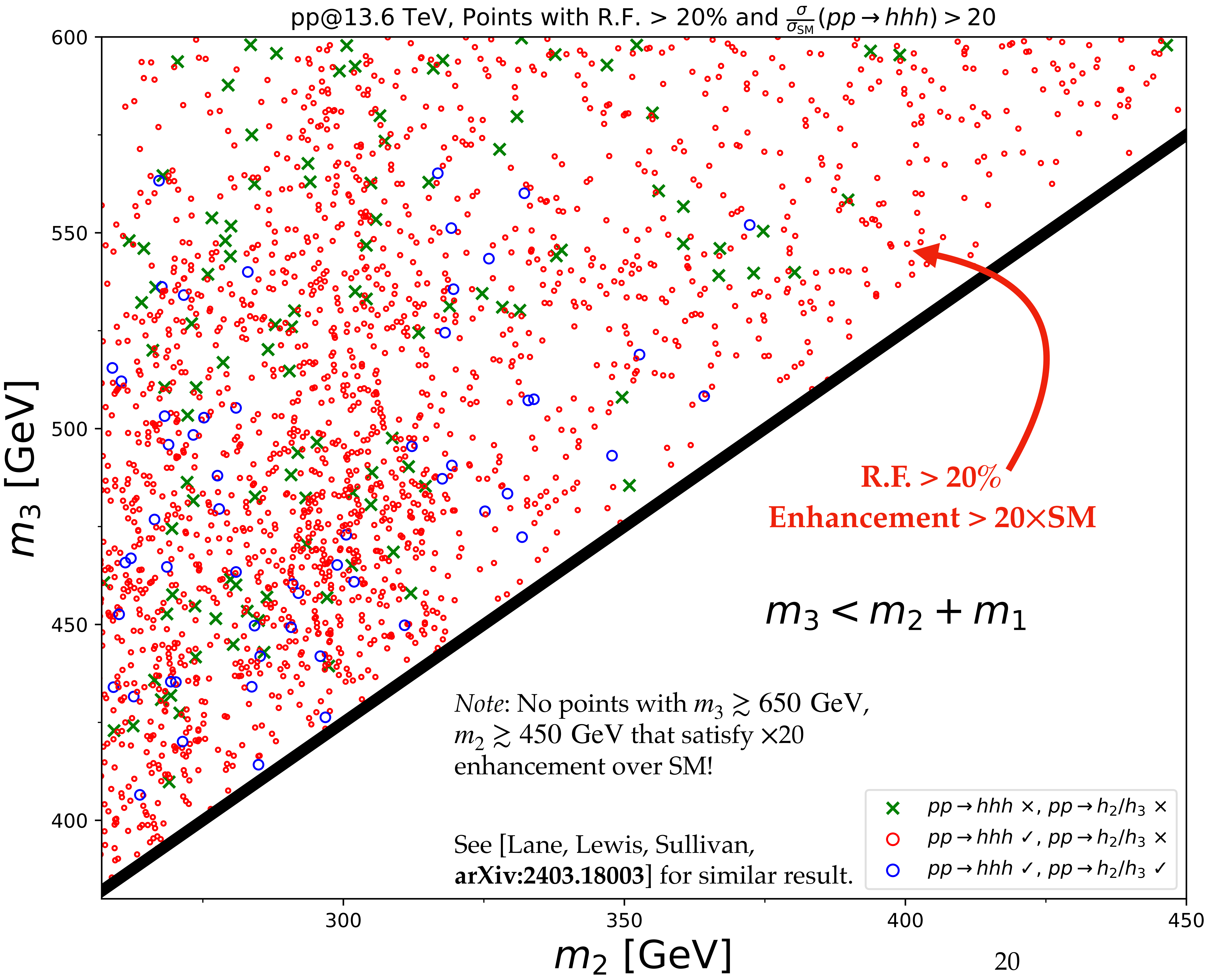
Constraints on $\rho^2 = \kappa_3^2 \lambda_{123}^2 \lambda_{112}^2 / (\Gamma_2 \Gamma_3)$ on the (m_2, m_3)-plane



95% C.L. Constraint on ρ^2 at HL-LHC.

[AP, Tetlalmatzi-Xolocotzi, **arXiv:2501.14866**]

Applied to TRSM Benchmark Points [R.F. > 20%, 20×SM enhancement]



HL-LHC results:

×: Excluded **BOTH** by *hhh* & single h_2 and h_3 production,

∘: Excluded **ONLY** by single h_2 and h_3 production, **NOT** by ***hhh*.**

∘: **NOT** excluded @ HL-LHC

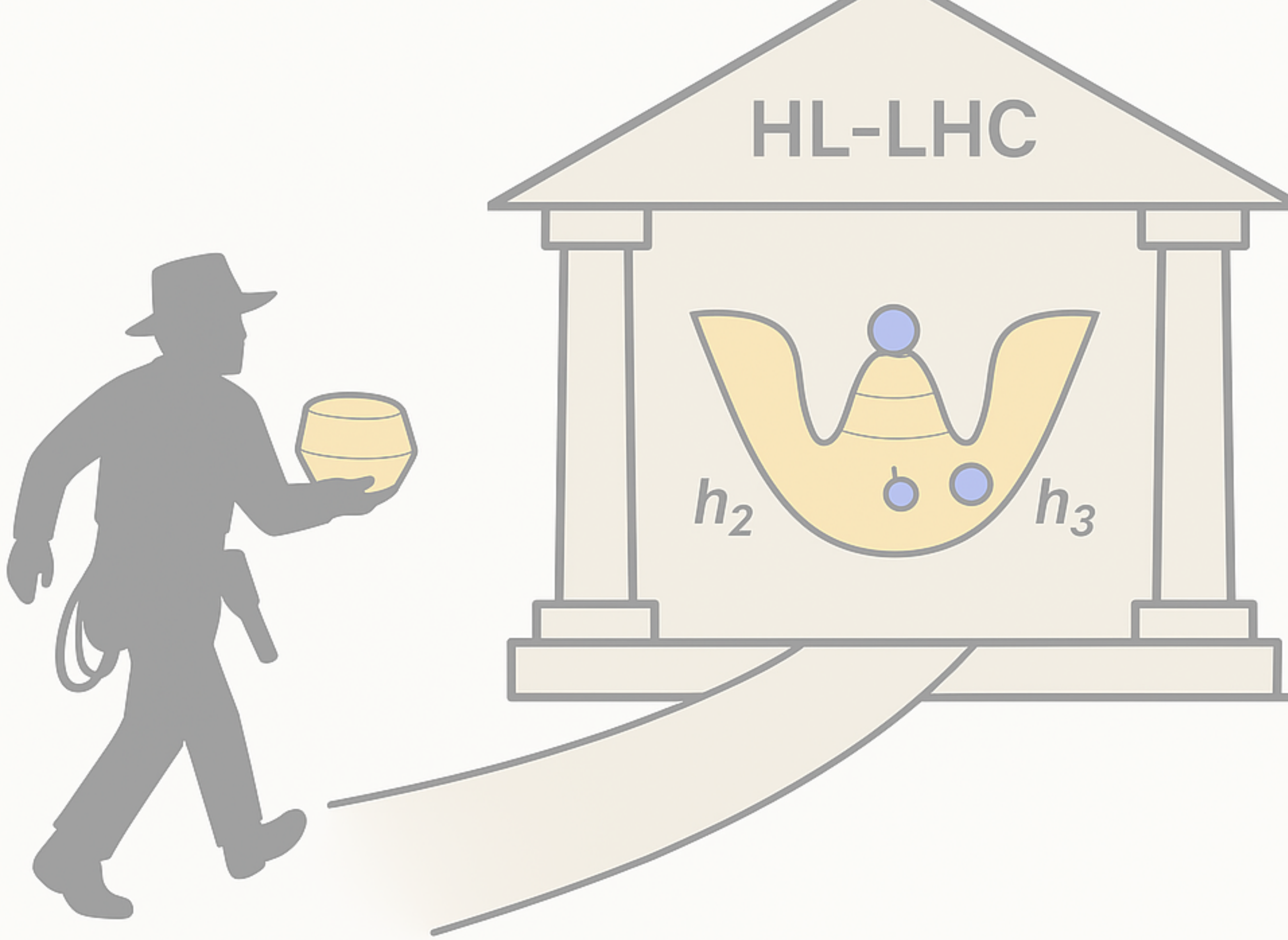
(⇒ Future Colliders?)

Notice: **NO** *hhh* exclusion **without** single h_2 and h_3 exclusion!

⇒ in TRSM, *hhh* is ***unlikely*** to be a "discovery" channel.

[AP, Tetlalmatzi-Xolocotzi, **arXiv:2501.14866**]

Conclusions & Outlook



- ***hhh*: a direct probe of the Higgs quartic self-couping!**
- **But:** @LHC: **Non-resonant *hhh***: extremely challenging,

  → *even* with large anomalous couplings (c_3, d_4)!

  & digging out the quartic self-coupling will be *hard*!

  → **Truncation** of the cross section to be considered within the context of EFTs (**?**)

- **Extended scalar sectors** can enhance ***hhh*** ⇝ **observable at the LHC!**

  e.g.: **<u>TRSM</u>** → **Two <u>new</u> scalars** → **double-resonant enhancement:** $pp \to h_3 \to h_2 h_1 \to h_1 h_1 h_1$

  → **Information about the nature of extended scalar sectors (⇝ Inverse problem)**.

- Future directions: **non-$\mathbb{Z}_2$ symmetric TRSM, examine the Electroweak Phase Transition, Dark Matter, investigate further-extended scalar sectors […].**

Conclusions & Outlook

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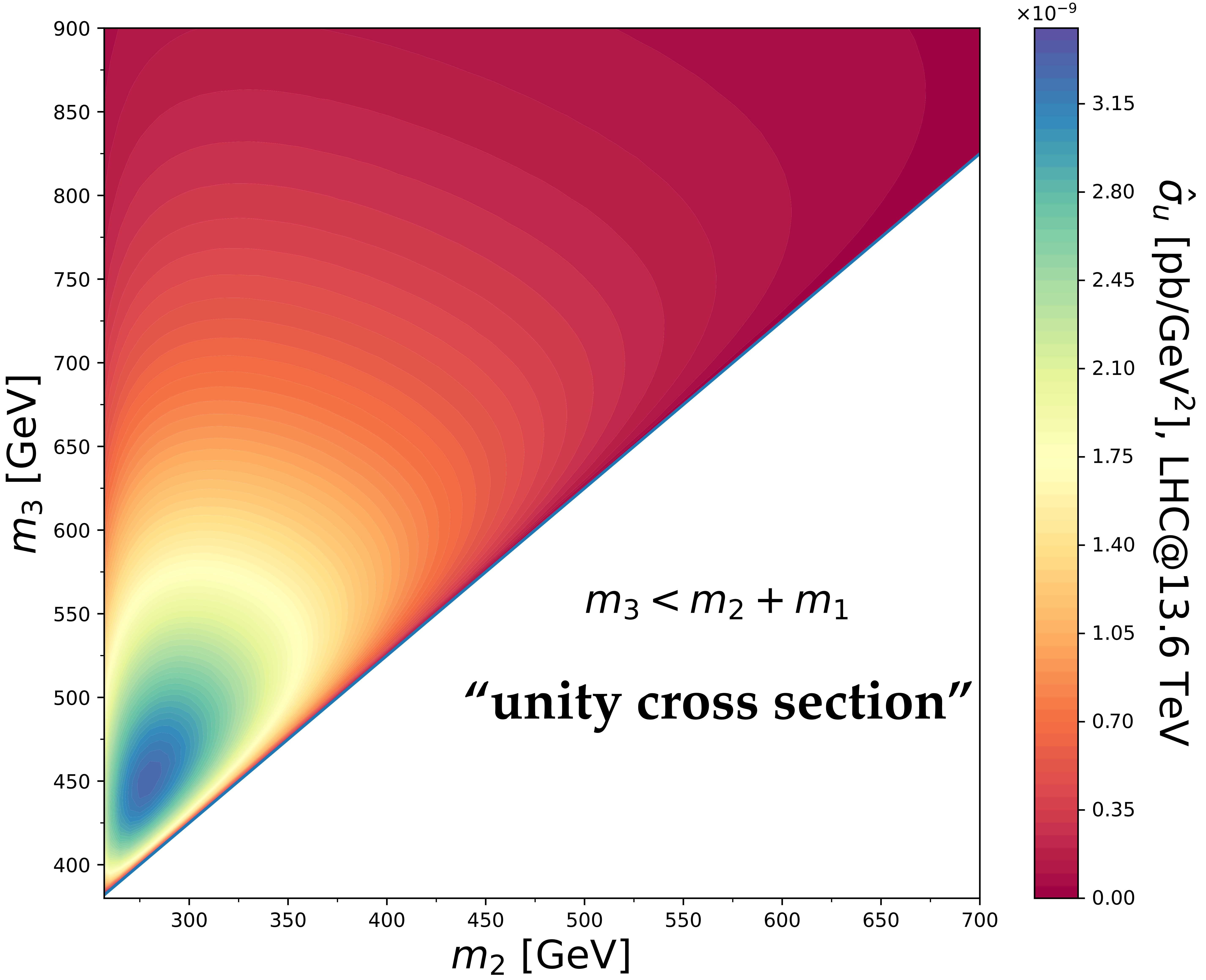
APPENDICES

Anatomy of Double-Resonant *hhh*

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

"unity cross section":
depends only on m_2, m_3.
Derived once and for all!
(at fixed collider energy)



with: $\rho^2 \equiv \kappa_3^2 \lambda_{123}^2 \lambda_{112}^2 / (\Gamma_2 \Gamma_3)$

"rescaling factor":
couplings and widths

[AP, Tetlalmatzi-Xolocotzi, **arXiv:2501.14866**]

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

Benchmark quantities relevant for double-resonant triple Higgs boson production

Name	m_2	m_3	Γ_2	Γ_3	κ_3	λ_{123}	λ_{112}	[GeV^2] ρ^2 [$\times 10^6$]	[pb/GeV^2] $\hat{\sigma}_u$ [$\times 10^{-9}$]
BM0	259.0	495.0	0.003514	3.927	0.1854	-191.8	8.167	6.11	2.018
BM1	270.6	444.7	0.5078	2.586	0.1571	-204.3	67.52	3.574	3.408
BM2	268.6	452.7	0.3805	3.142	0.1741	-203.6	57.78	3.509	3.165
BM3	272.6	480.7	0.2009	4.758	0.2024	-224.6	41.39	3.703	2.908
BM4	269.0	409.8	0.2836	1.995	0.1713	-180.3	48.89	4.031	2.663
BM5	269.1	486.9	0.0003346	2.017	0.1527	103.3	-2.477	2.264	2.805
BM6	259.2	577.0	0.0006274	5.79	0.1908	196.3	-3.701	5.289	1.108
BM7	283.7	575.0	0.001056	5.587	0.1884	193.5	-3.578	2.885	1.711
BM8	264.3	469.3	0.3916	2.941	0.1746	-144.3	55.88	1.721	2.789
BM9	266.5	461.9	0.3092	2.042	0.1635	142.8	39.98	1.381	3.29
BM10	259.2	399.7	0.2188	0.9312	0.1463	121.2	35.41	1.936	2.159

Including:

- **EXP constraints** through HiggsTools.
- **TH constraints:** perturbativity & boundedness from below.

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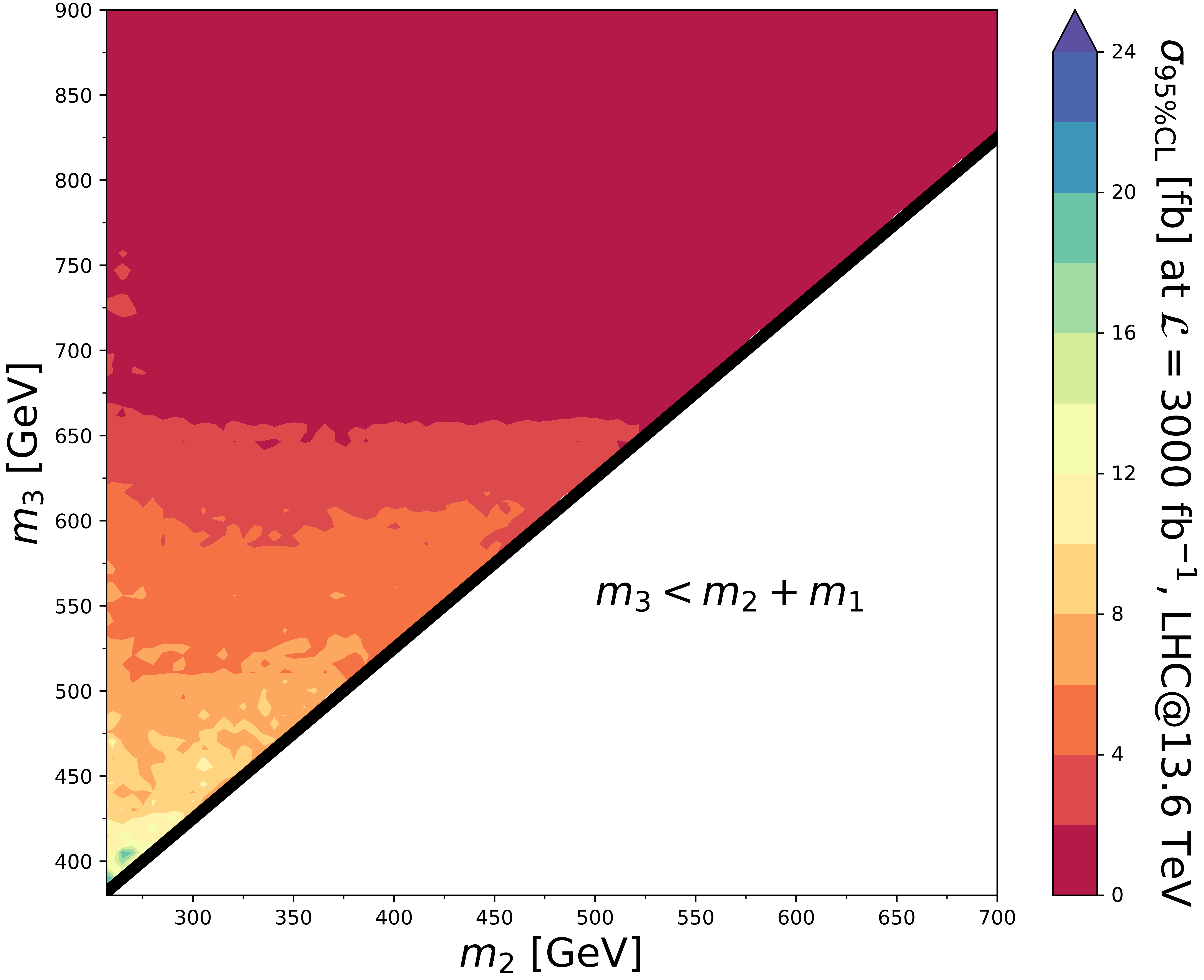
$\sigma(13.6\text{ TeV}) \gtrsim \mathcal{O}(10)$ fb

[AP, Tetlalmatzi-Xolocotzi, **arXiv:2501.14866**]

Constraints on the Cross Section



95% C.L. Constraint on the cross section at HL-LHC.

[AP, Tetlalmatzi-Xolocotzi, **arXiv:2501.14866**]

Comment: Validity of the Narrow-Width Approximation

- **<u>In the TRSM</u>**: h_2 and h_3 are **constrained** to possess small mixing angles.

  (e.g. we know this from h_1 signal strength)

  $\Rightarrow$ Contributions to width from $h_{2,3} \to f\bar{f}, VV$ are small!

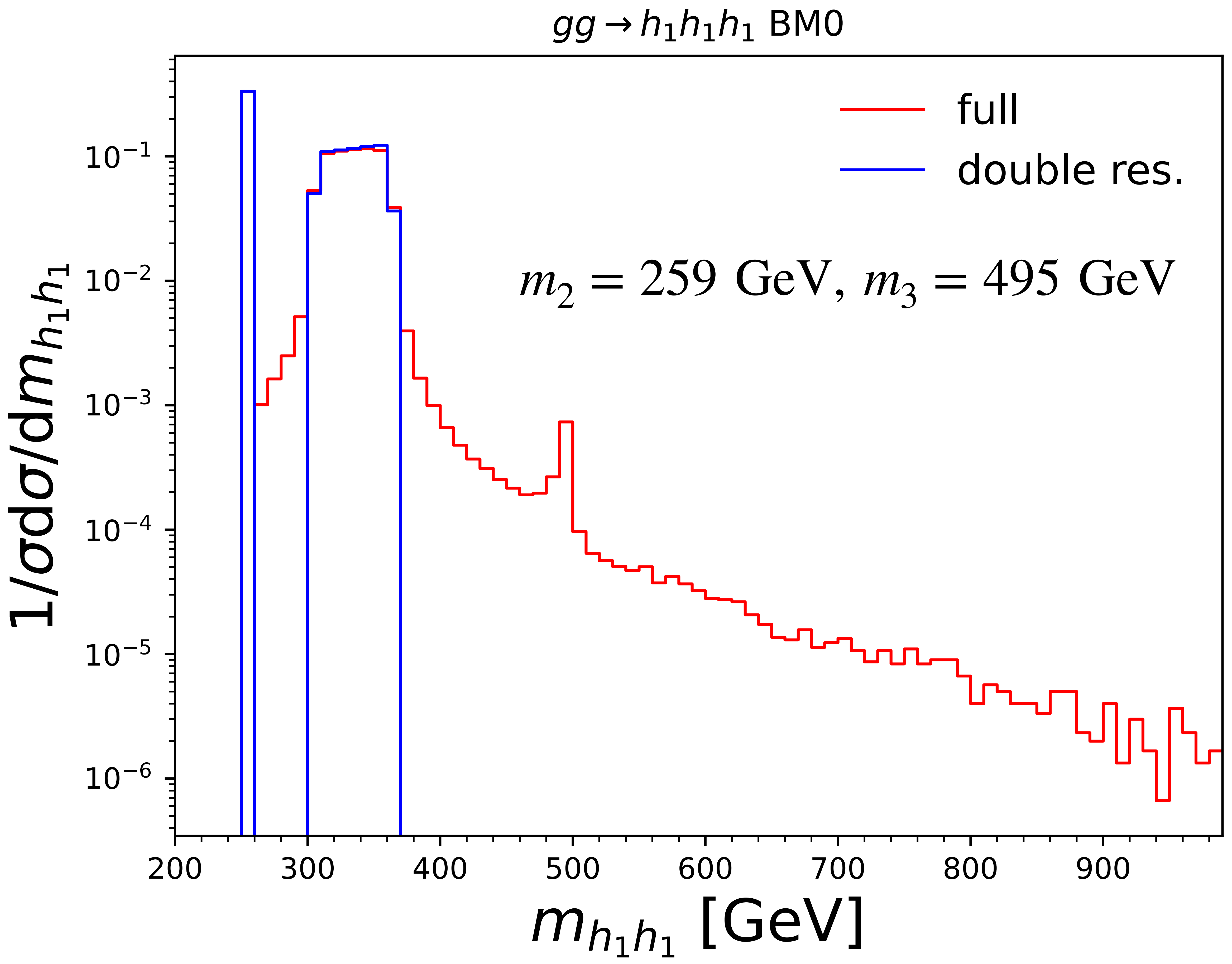
- **<u>In general</u>**: Can increase width of h_2 and h_3 through **scalar-to-scalar decays** $\Rightarrow$ **<u>no guarantee</u> in generic models for the narrow width.**

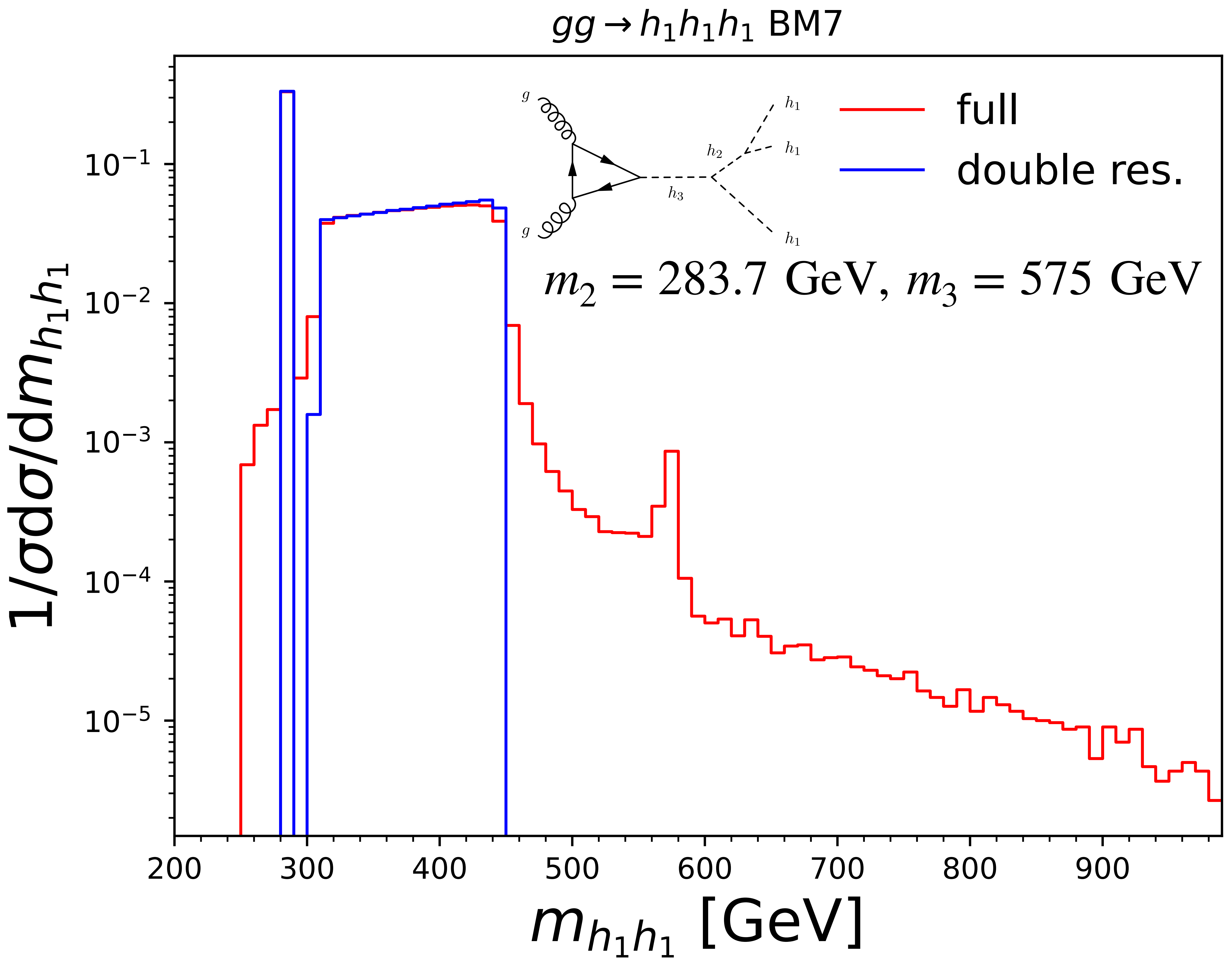
- If h_2 and h_3 are already discovered, Γ_2, Γ_3 would be known (or limited) $\Rightarrow$ the **narrow-width approximation validity <u>should be checked</u>**!

- **TL;DR**: The narrow width approximation is OK due to mixing constraints <u>in the TRSM</u>, but this statement is somewhat <u>model dependent</u>! **[***see appendix for a case study!]**

Non-Resonant Effects in *hhh* in the TRSM

(any) two Higgs invariant mass distributions in *hhh* ("parton level", all combinations)





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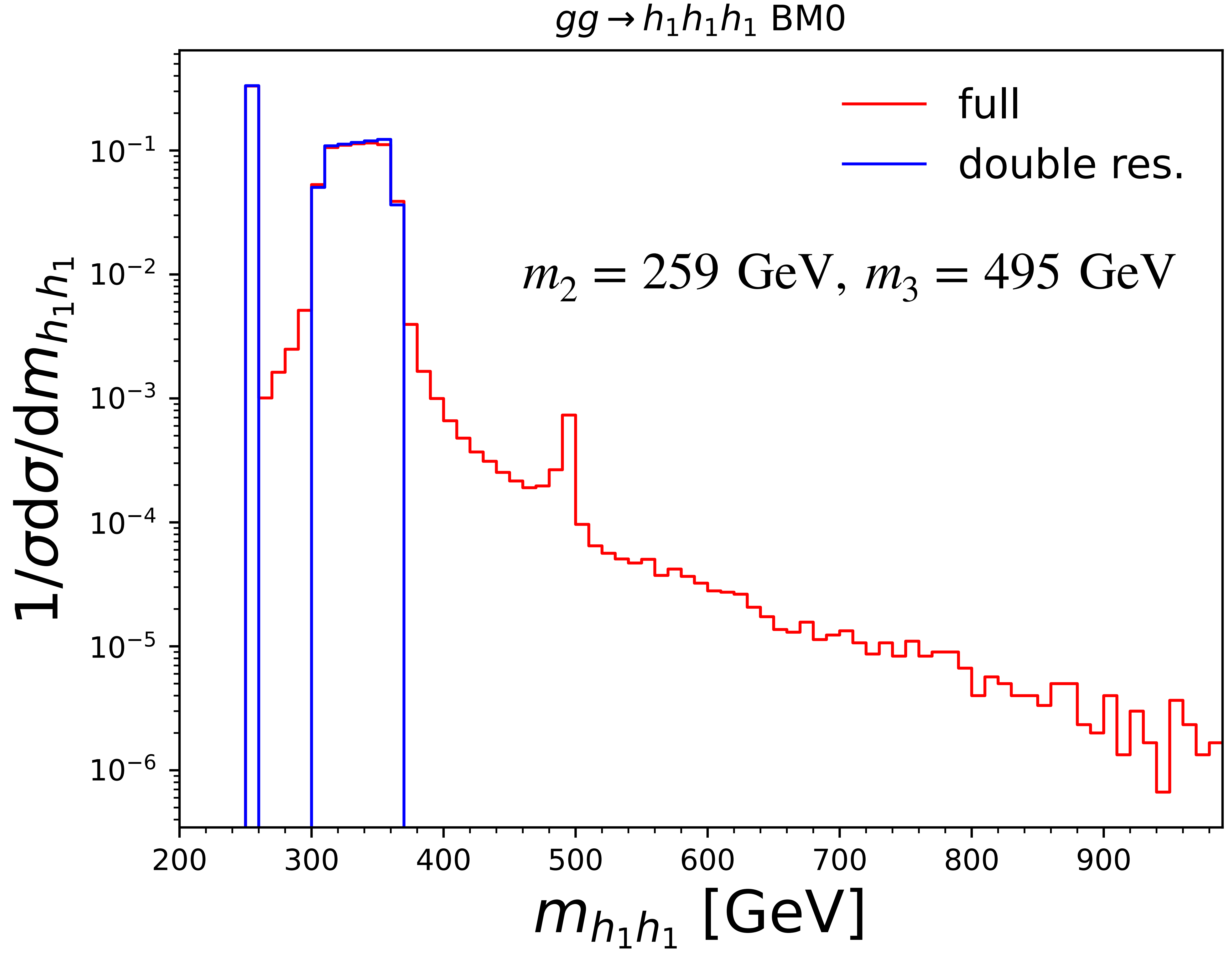

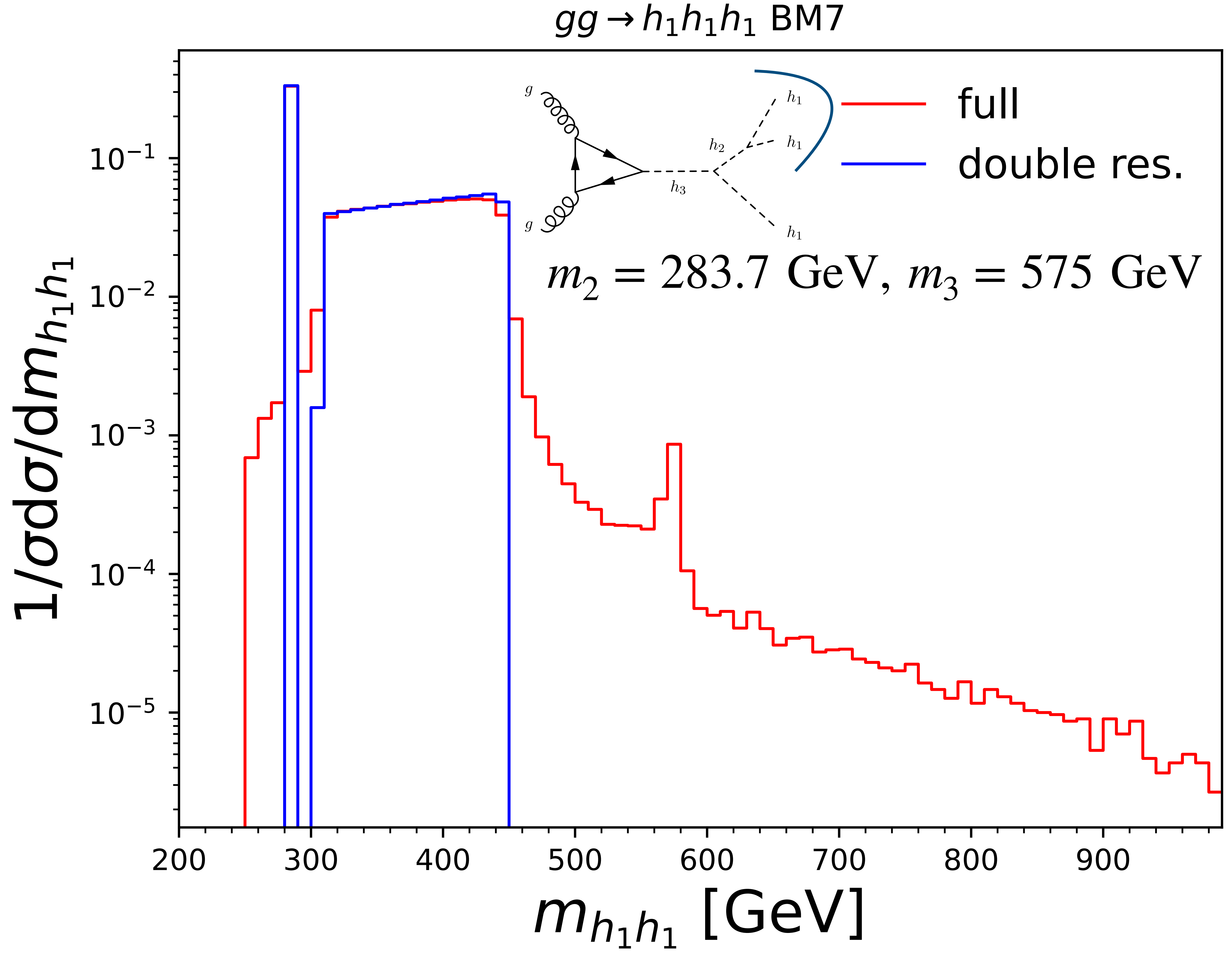

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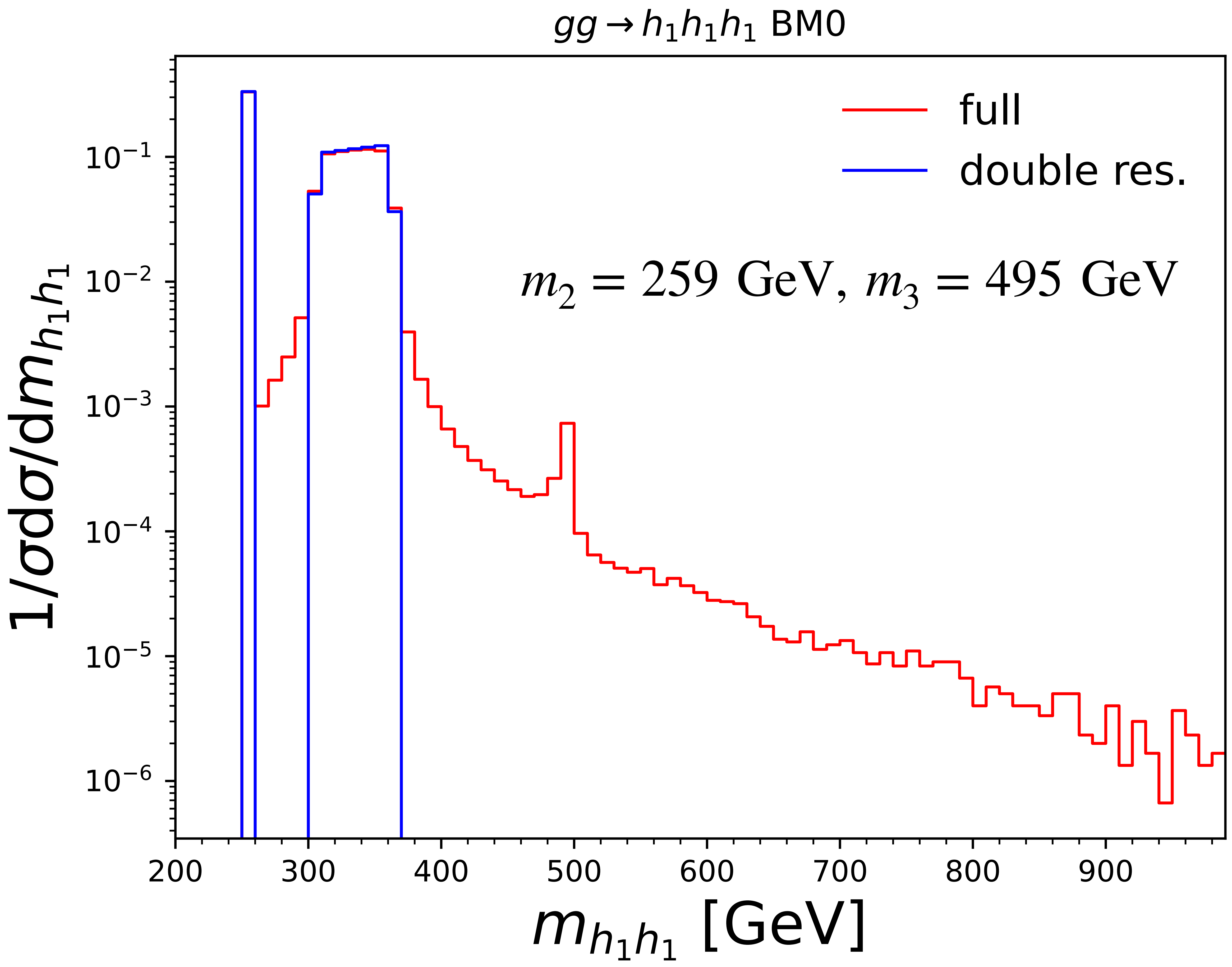

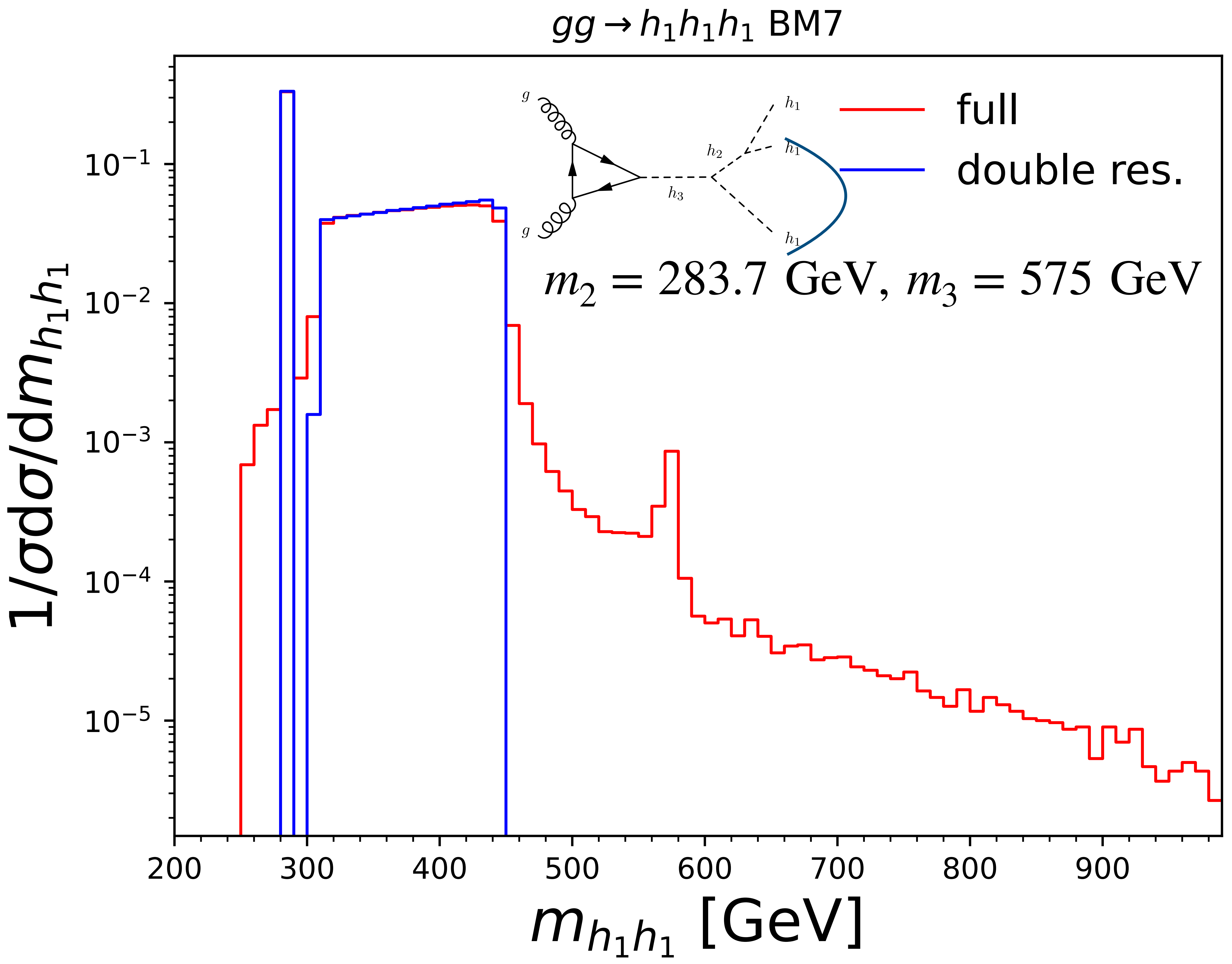

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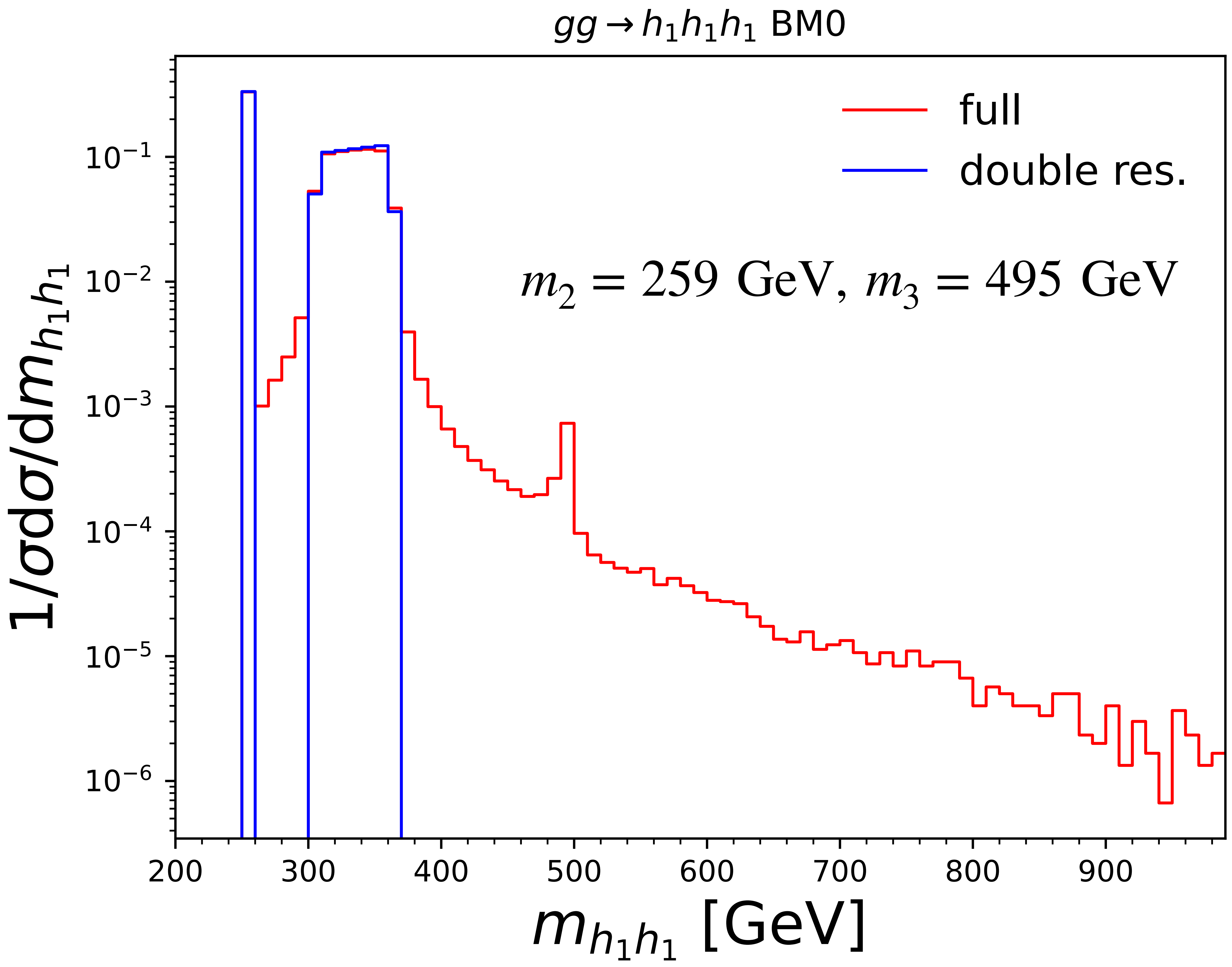

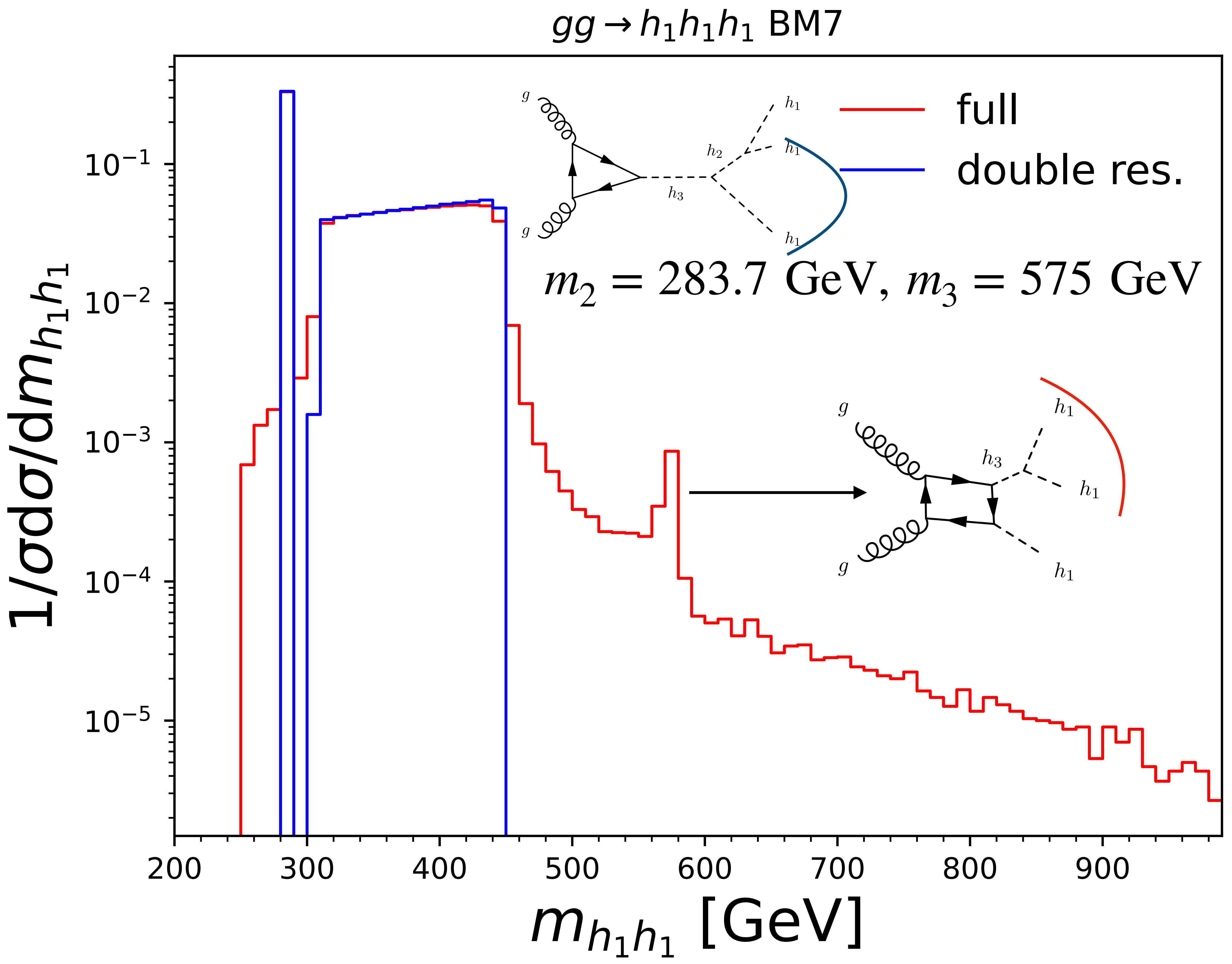

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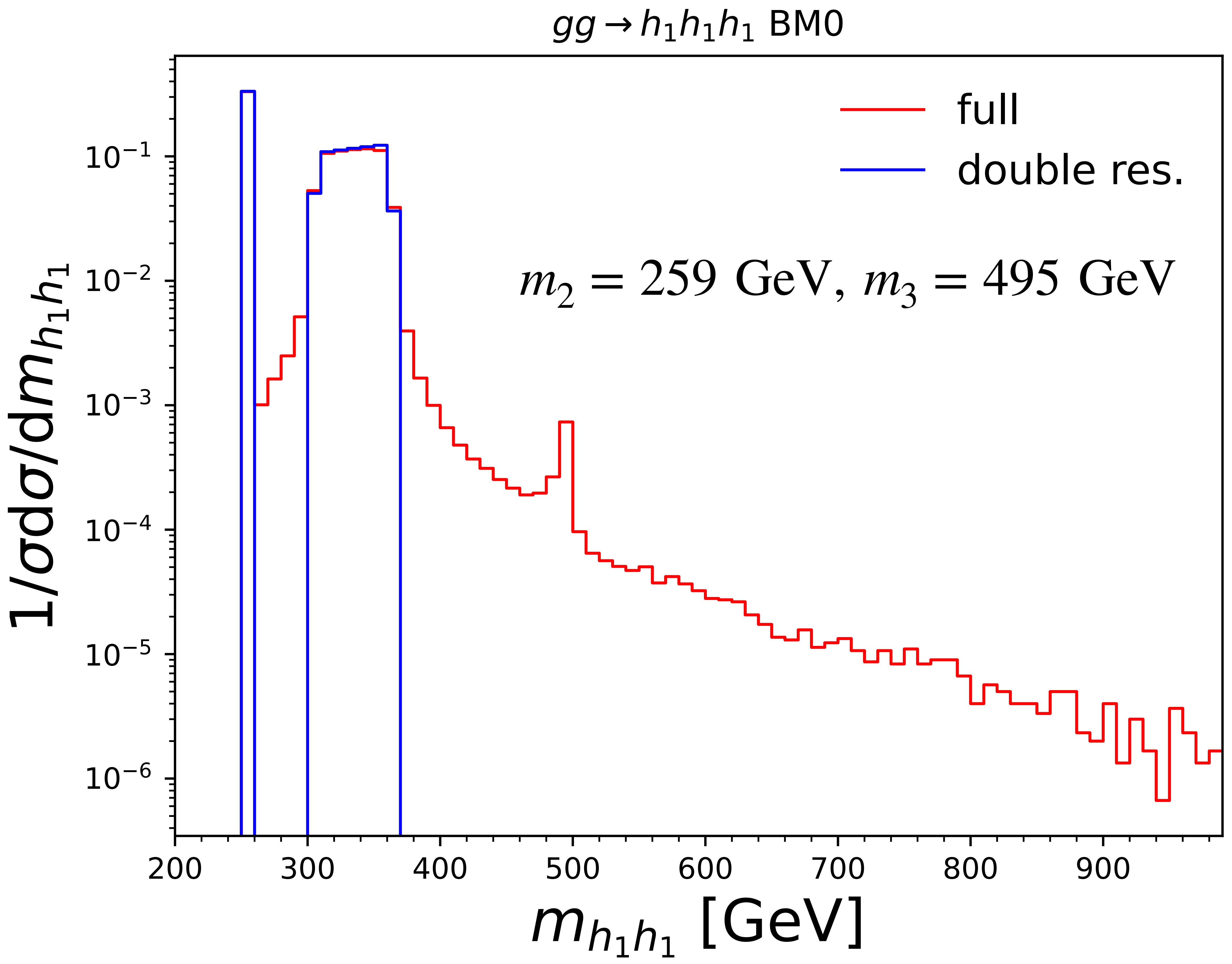
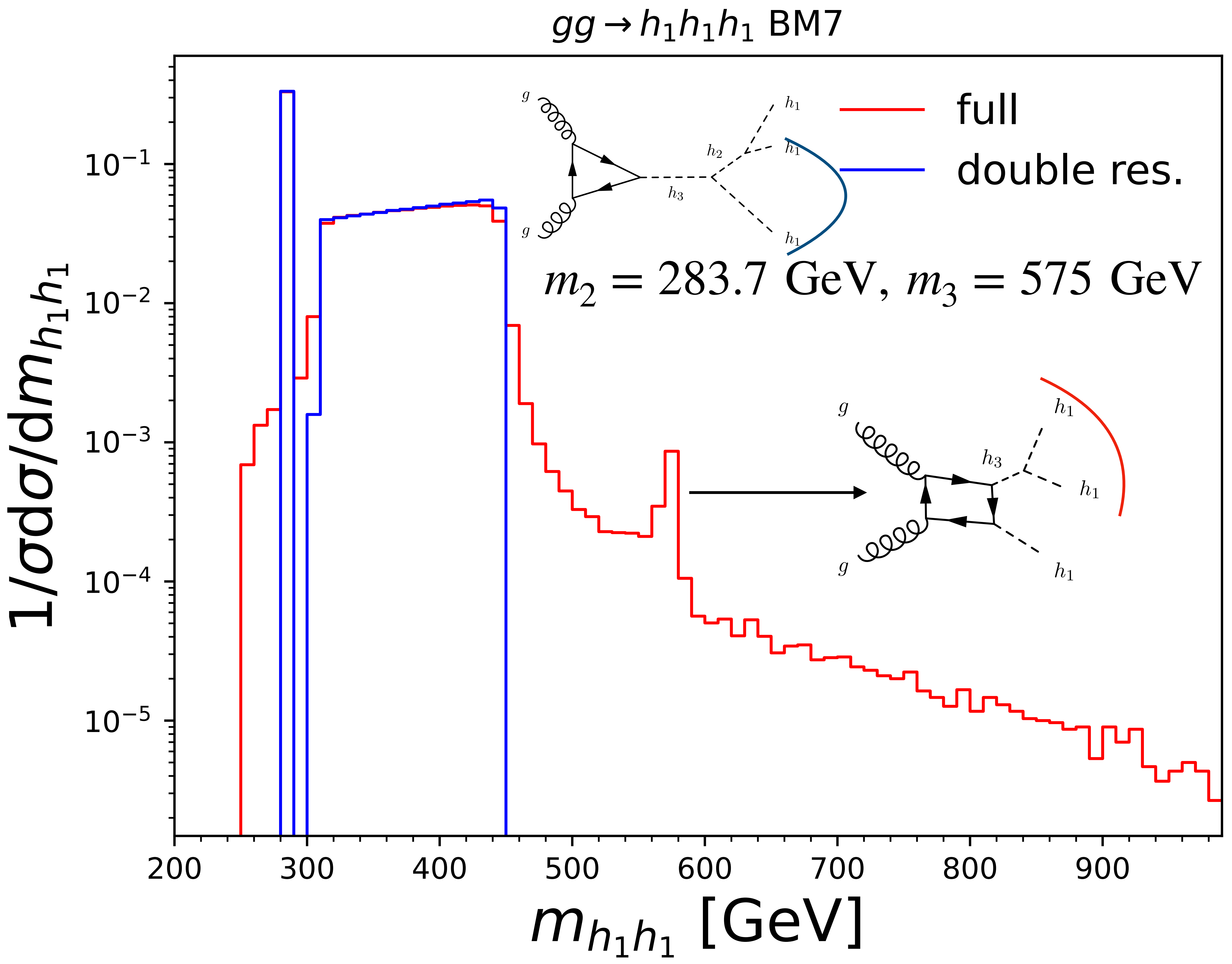
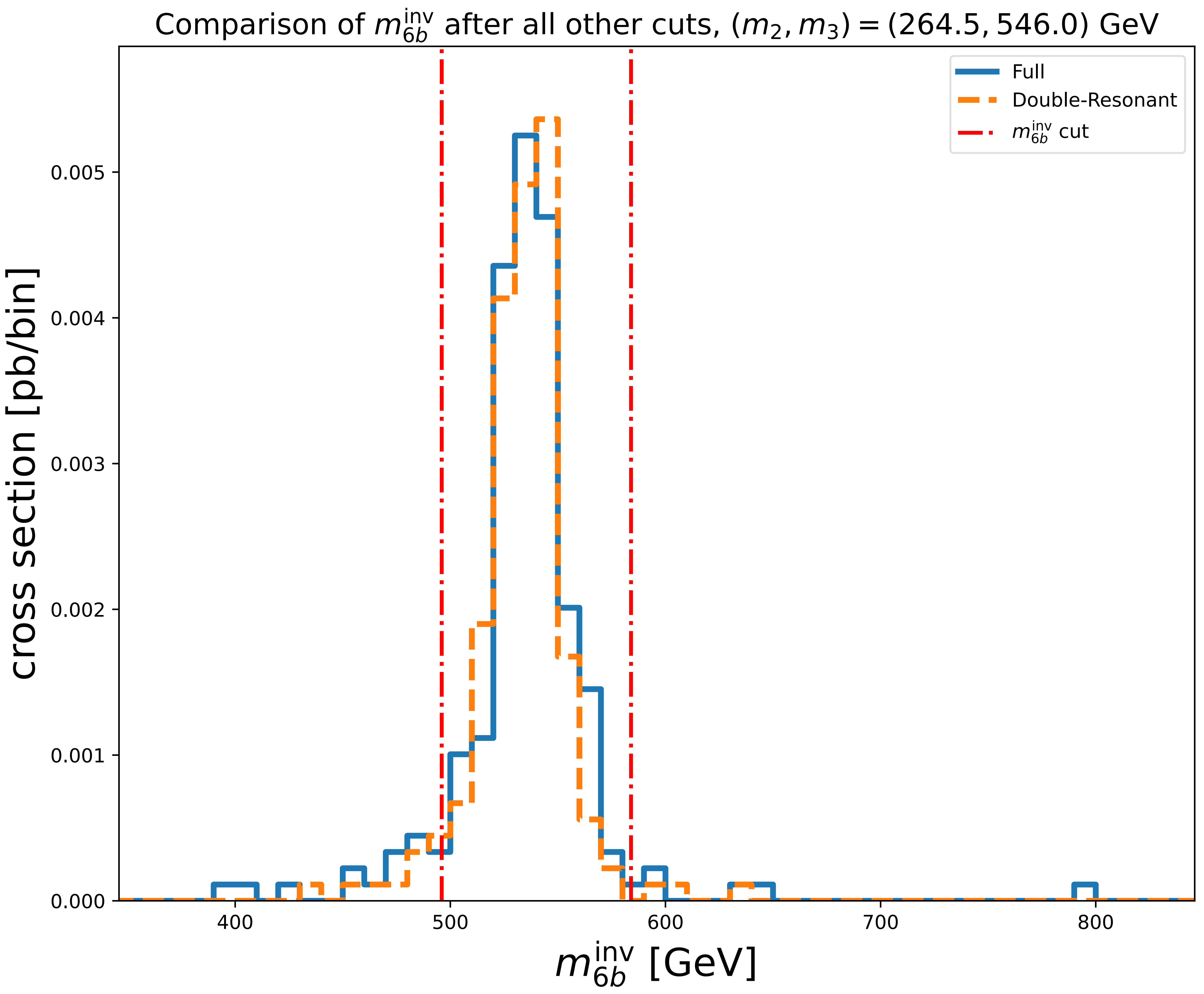


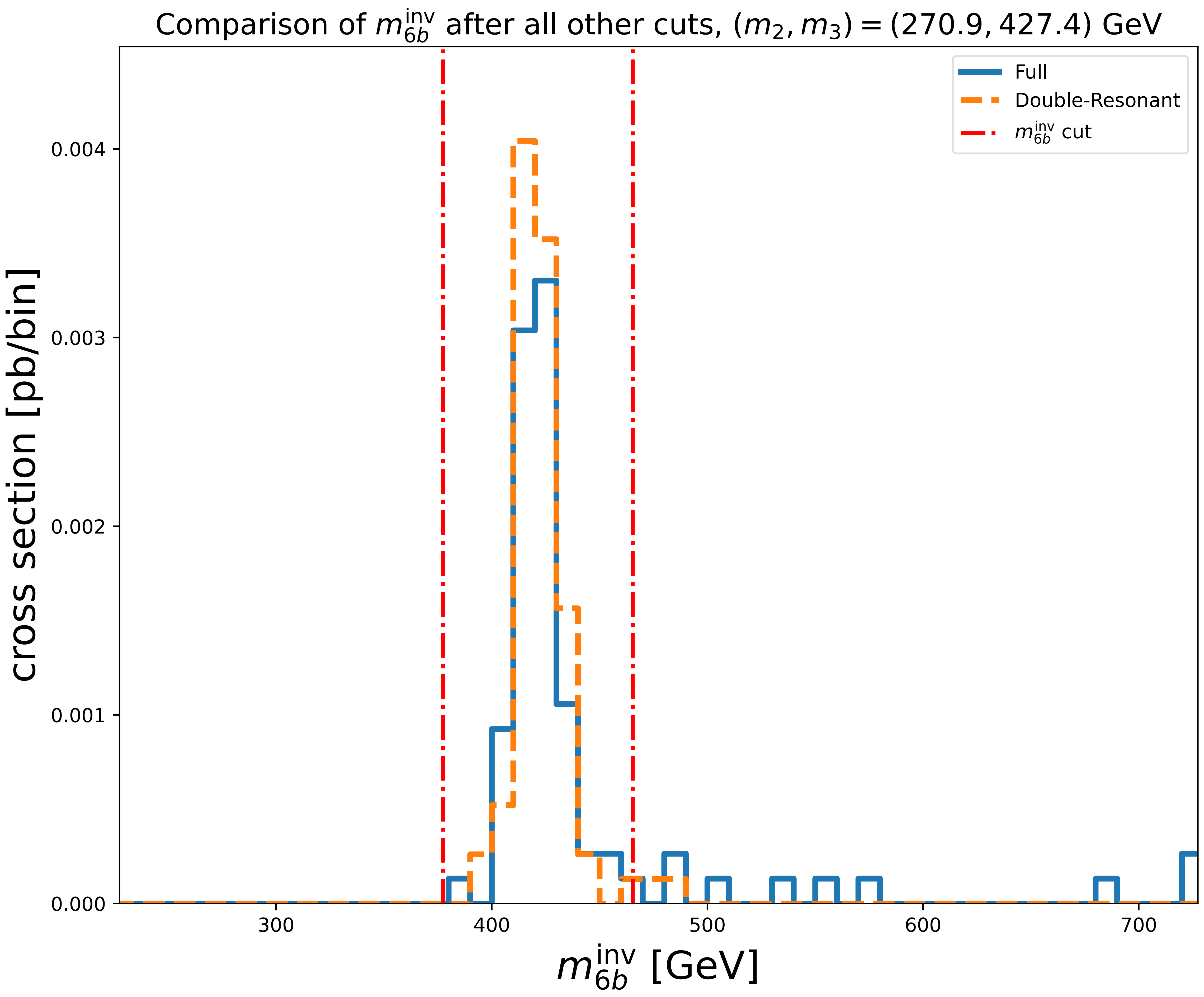


➡ **Bulk of cross section from double-resonant process.**

Non-Resonant Effects in *hhh* in the TRSM

Sample 6 b-jet invariant mass distributions in our analysis (**all other cuts applied**):





m_{6b} [GeV] m_{6b} [GeV]

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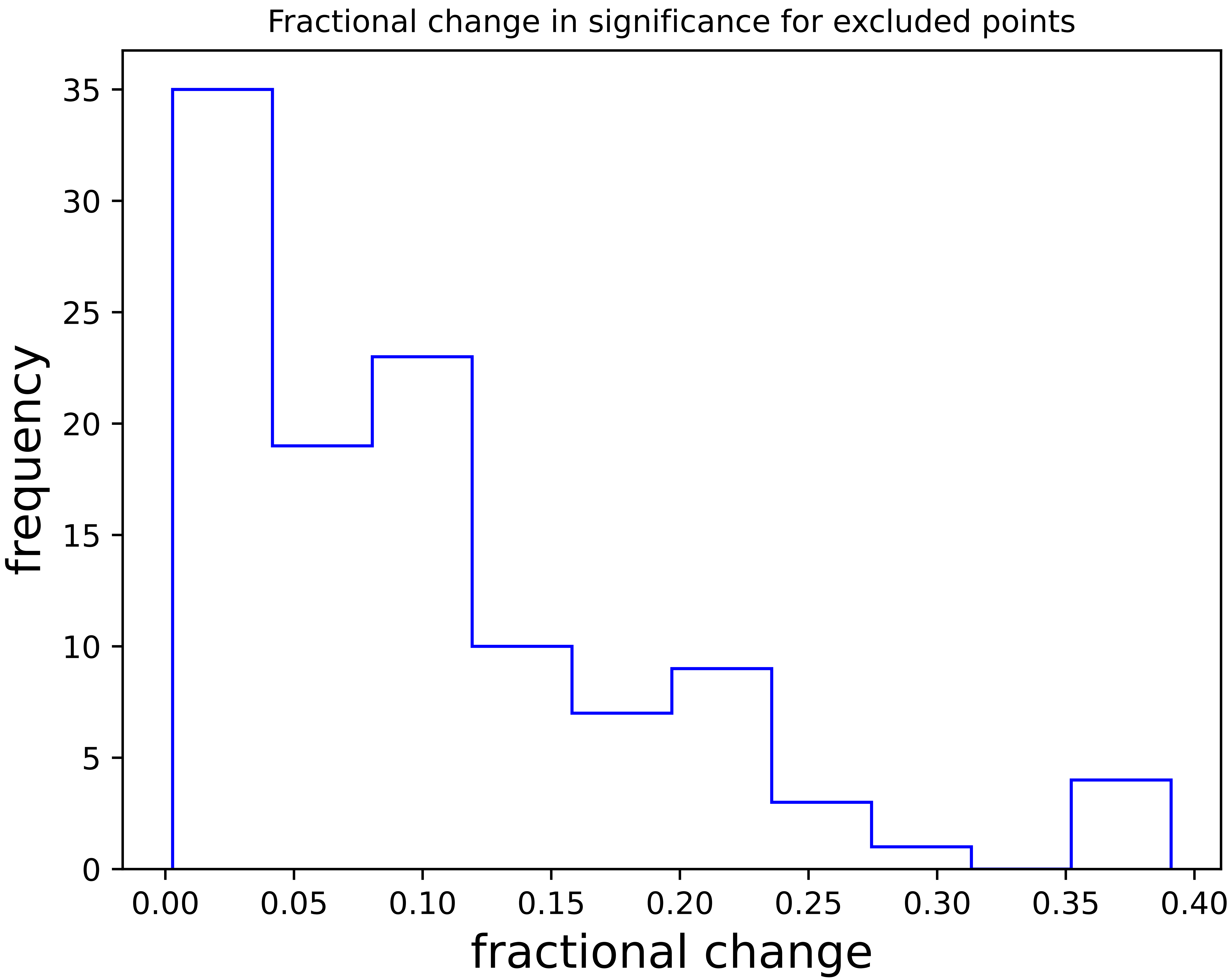
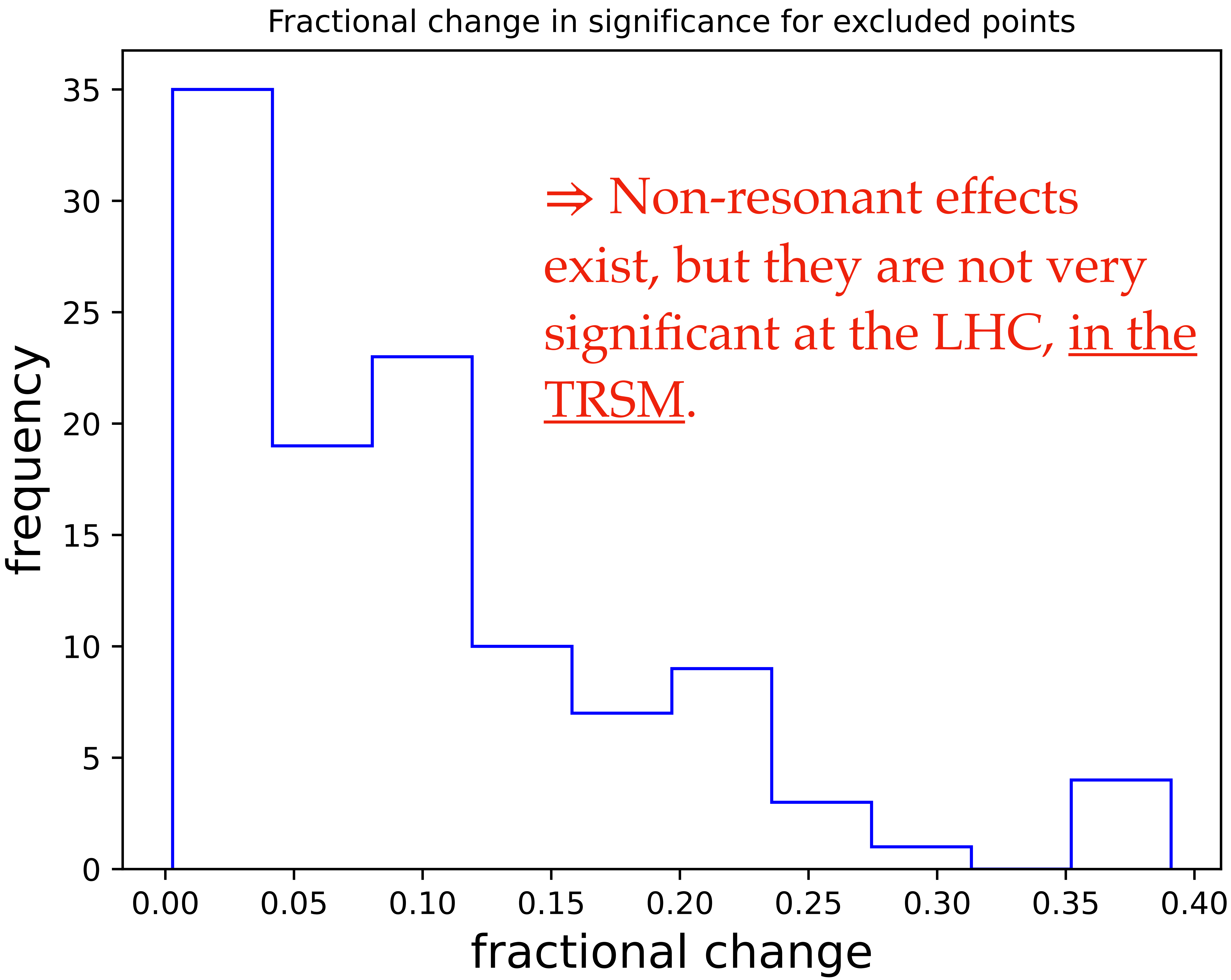
Non-Resonant Effects in *hhh* in the TRSM

= Number of Parameter Space Points in our Scan
that can be excluded at 95% C.L.



Non-Resonant Effects in *hhh* in the TRSM

= **Number of Parameter Space Points in our Scan that can be excluded at 95% C.L.**



⇒ Non-resonant effects exist, but they are not very significant at the LHC, <u>in the TRSM</u>.

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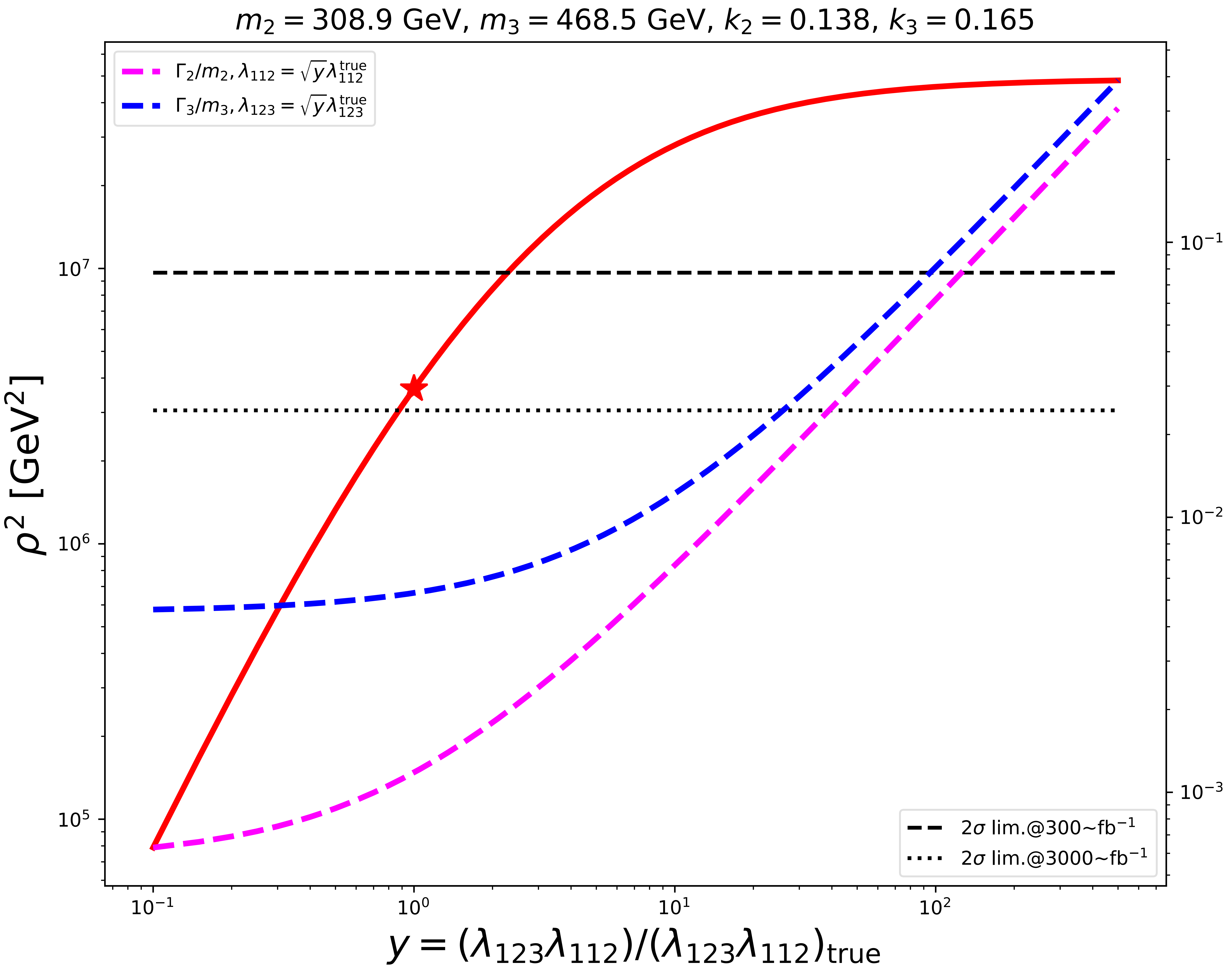
The Narrow Width Approximation: An Example



- Pick a parameter space point, **fix**: m_2, m_3 and scalar coupling λ_{113}.
- **Rescale:** $\lambda_{112} = \sqrt{y}\lambda_{112}^{\rm true}$ and $\lambda_{123} = \sqrt{y}\lambda_{123}^{\rm true}$.
- **Plot**: ρ^2, Γ_2/m_2 and Γ_3/m_3 versus y.
- Red star = **true** parameter point value.
- Plot pheno analysis limits (dashed: 300 fb^{-1}, dotted: 3000 fb^{-1}).
- **For both limits, NWA approximation is valid!**

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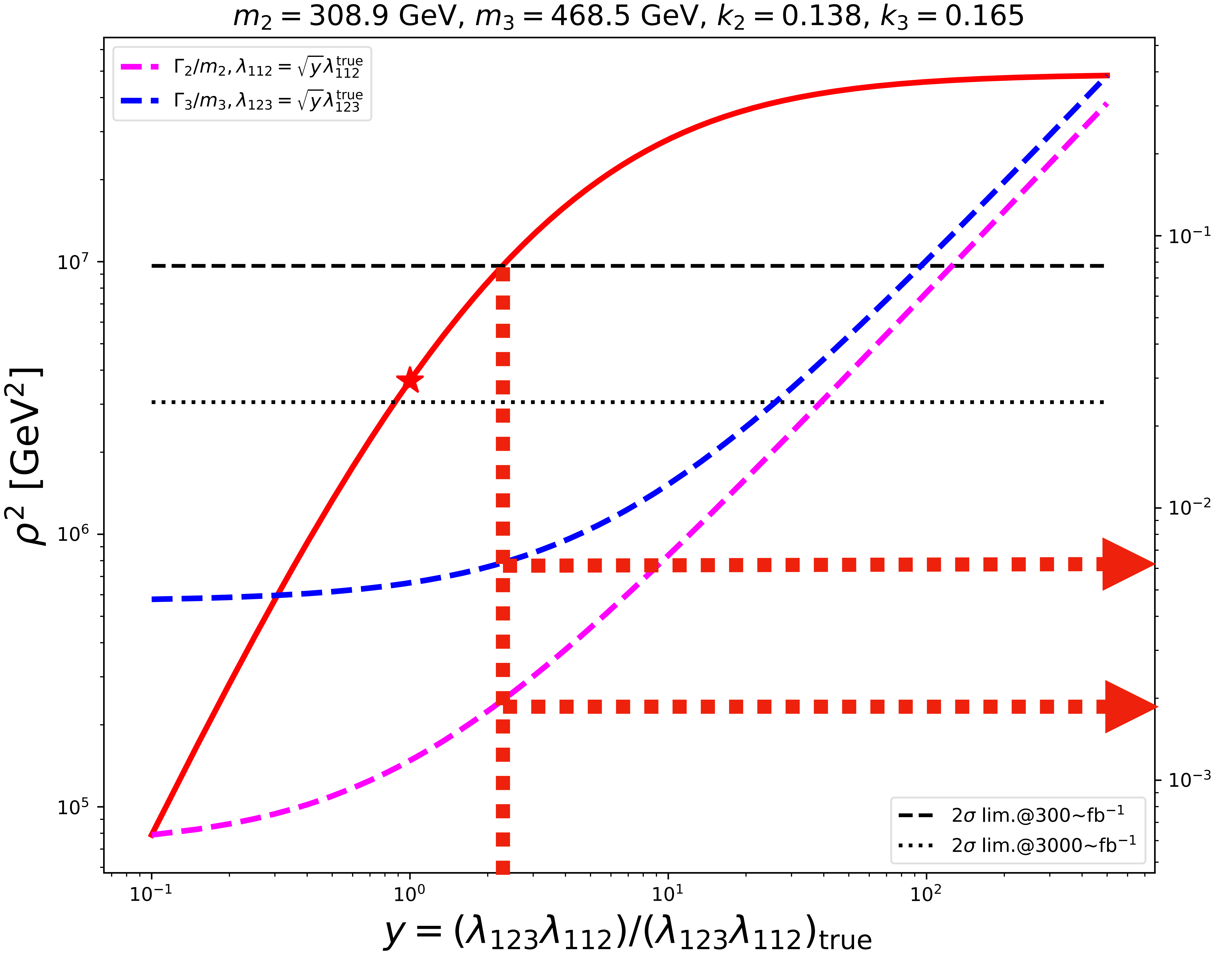

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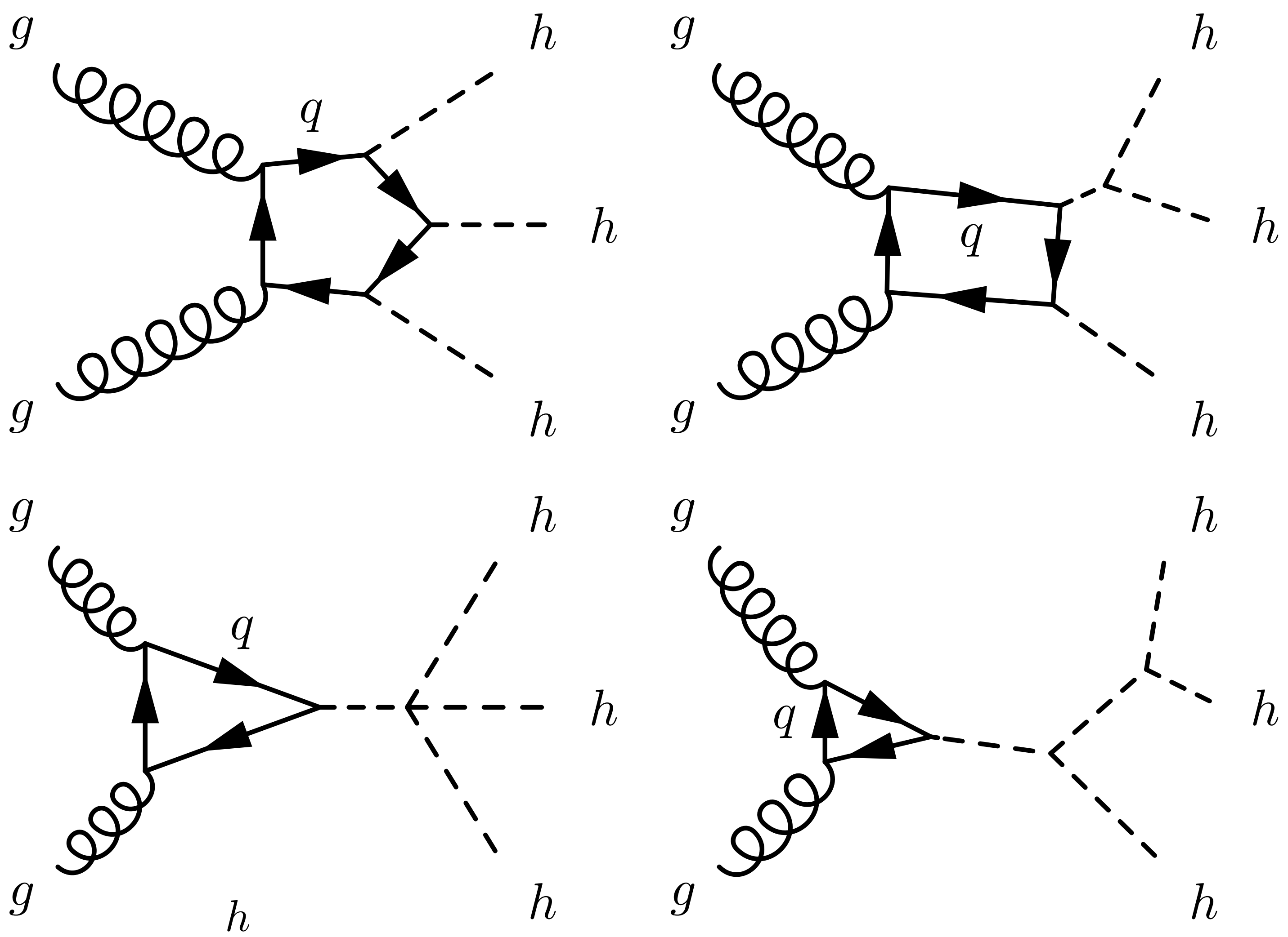
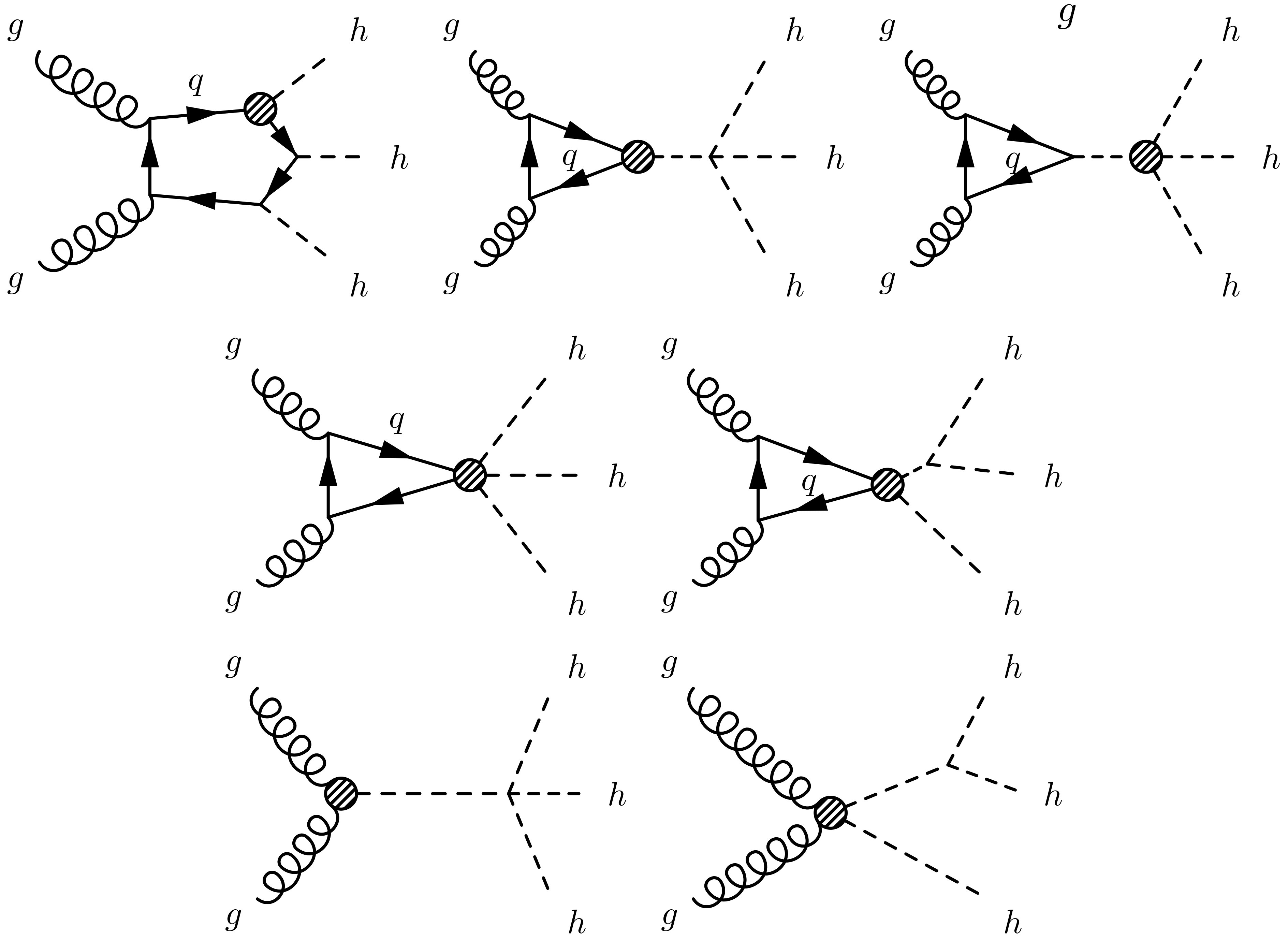
TRSM Monte Carlo Event Generation

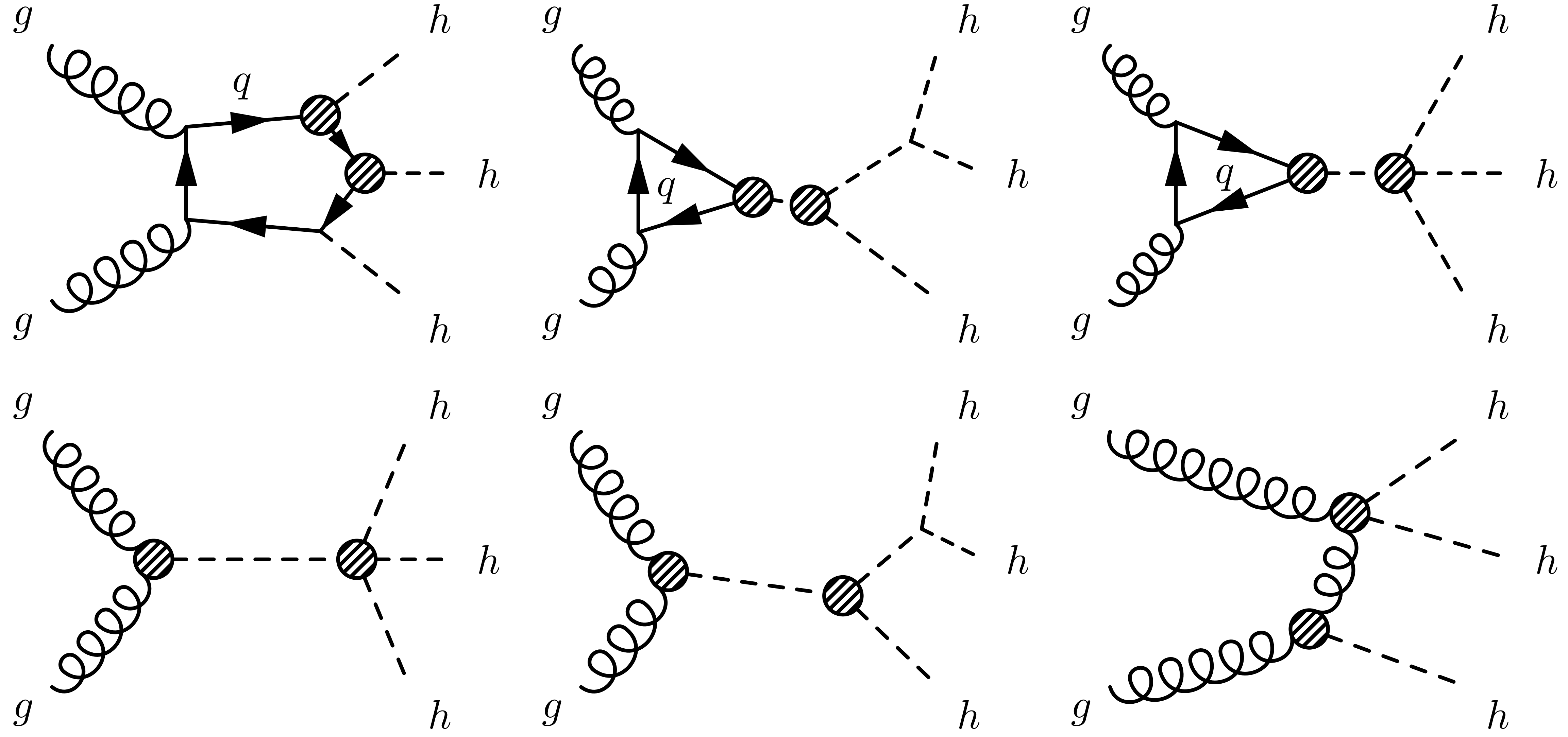
- We have implemented a **MadGraph5_aMC@NLO (MG5_aMC) "loop" model for the TRSM:**
  - **MG5_aMC input parameters**: the three mixing angles, two masses/widths and **all** the scalar couplings (only 7 are independent in **TRSM**).
  - Comes with a **Python script** that:
    - allows conversion of M_2, 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]

hhh with Anomalous Couplings







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hhh: Final states

Assume: K-factor = 2.

[Maltoni, Vryonidou, Zaro, 1408.6542]

$hhh \to$ final state	BR (%)	$N_{20\text{ab}^{-1}}$
$(b\bar{b})(b\bar{b})(b\bar{b})$	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]

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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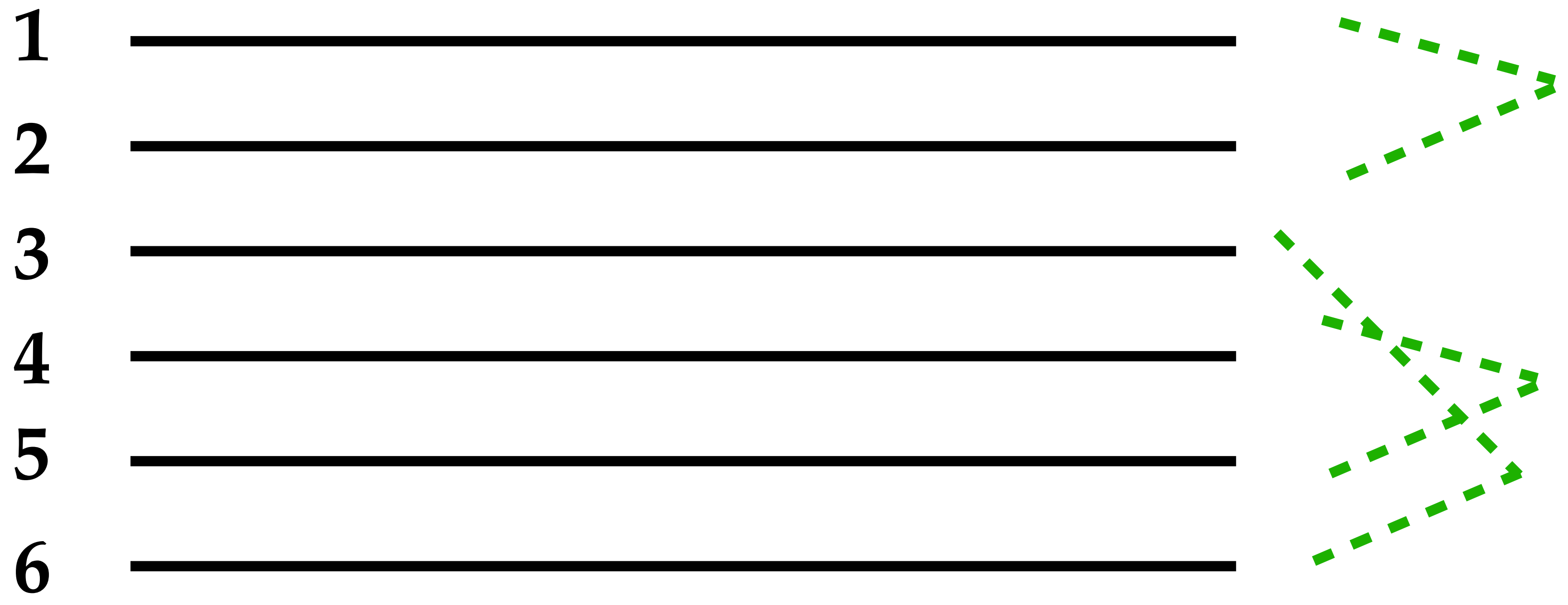

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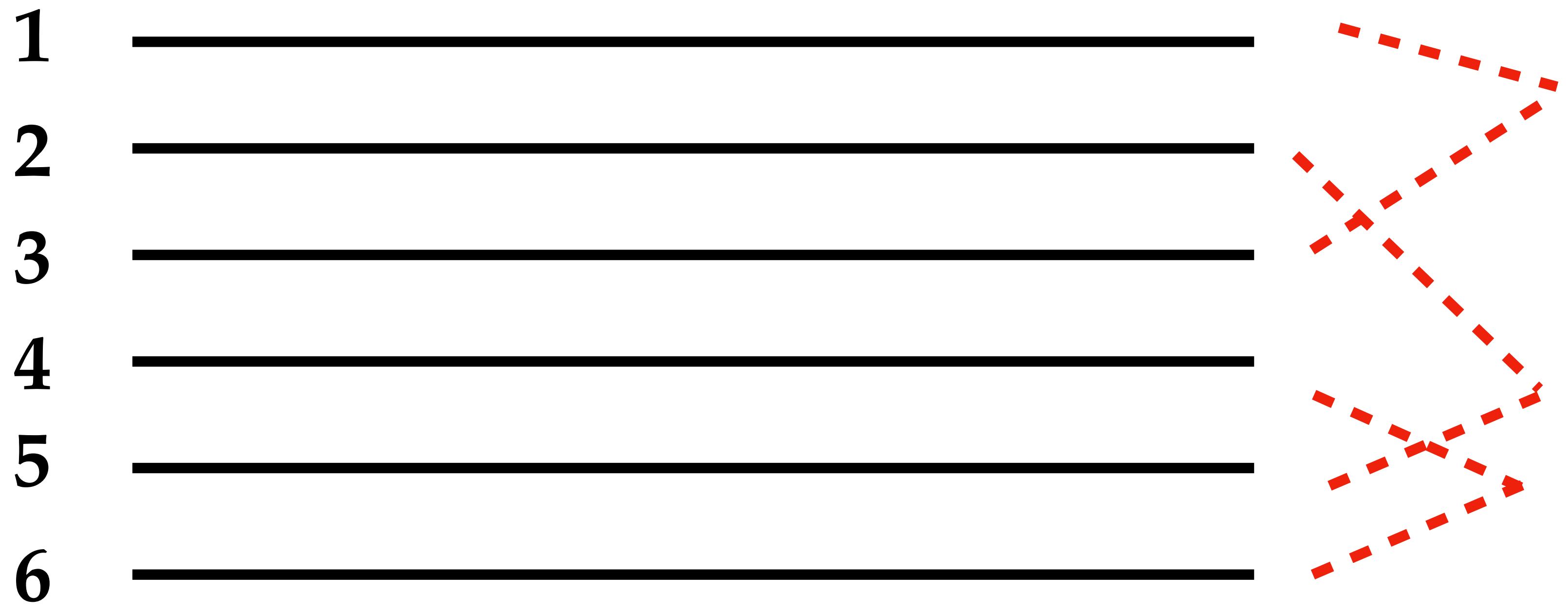

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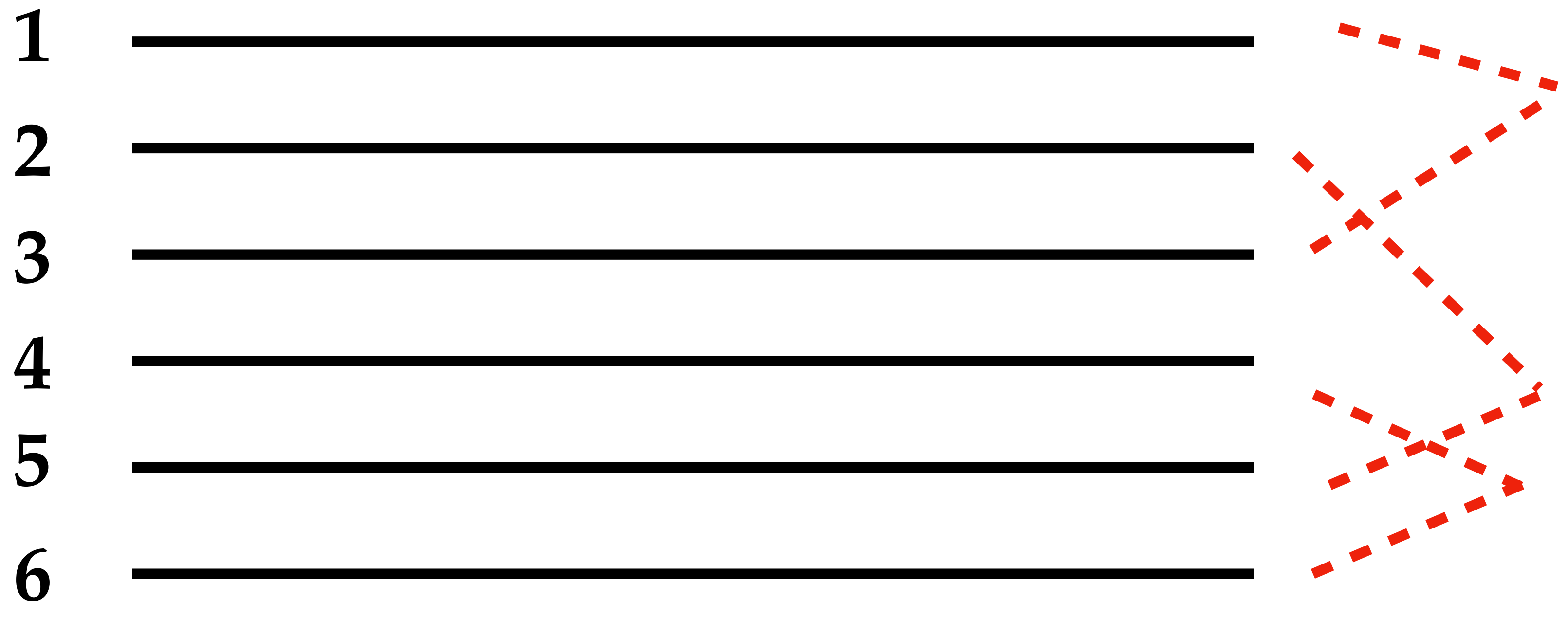

3. For each pairing construct:

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

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

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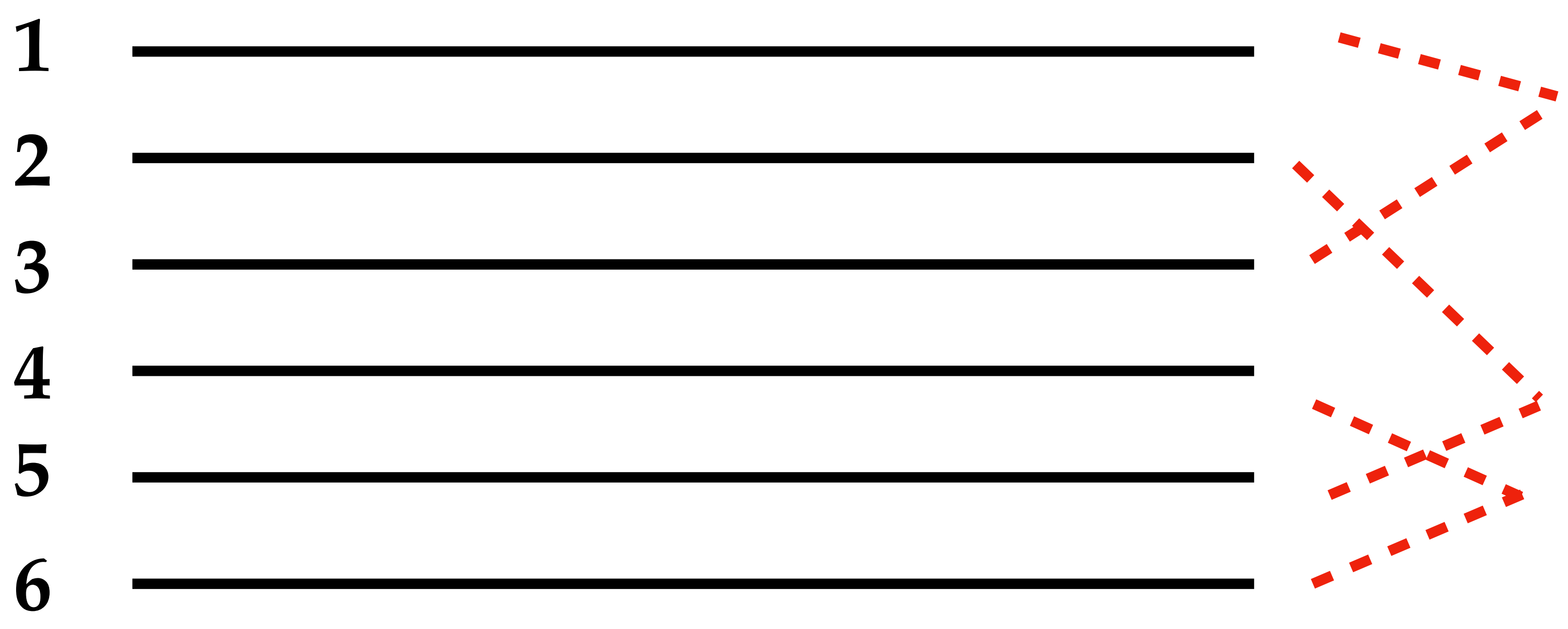

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⇒ **4. Pairing that gives $\underbrace{\text{minimum } \chi^2}_{\chi^2_{\text{min}}}$ determines "reconstructed Higgs boson".**

The 6b final state, analysis

h_r^i →**Higgs boson candidates**

observable	cut
$p_{T,b}$	> 45 GeV
$\lvert\eta_b\rvert$	< 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 ← **the three terms in χ^2_{min}.**
$\Delta R(h_r^i, h_r^j)$	$< [3.5, 3.5, 3.5]$, $(i, j) = [(1,2),(1,3),(2,3)]$
$\Delta R_{bb}(h_r^i)$	$< [3.5, 3.5, 3.5]$, $i = 1,2,3$

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signal/backgrounds after analysis

Process	σ_{GEN} (pb)	$\sigma_{\text{NLO}} \times$ 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}

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Reducible backgrounds

process	σ_{GEN} (pb)	$\sigma_{\mathrm{GEN}} \times \mathscr{P}(6\ b-\mathrm{jets})$ (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}

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

→~10% contribution from reducible backgrounds.

for P(b-tagging) = 0.8:

→~30% contribution.

c.f. σ_{GEN}(6b)= 26.15 pb

applied:

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

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.

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

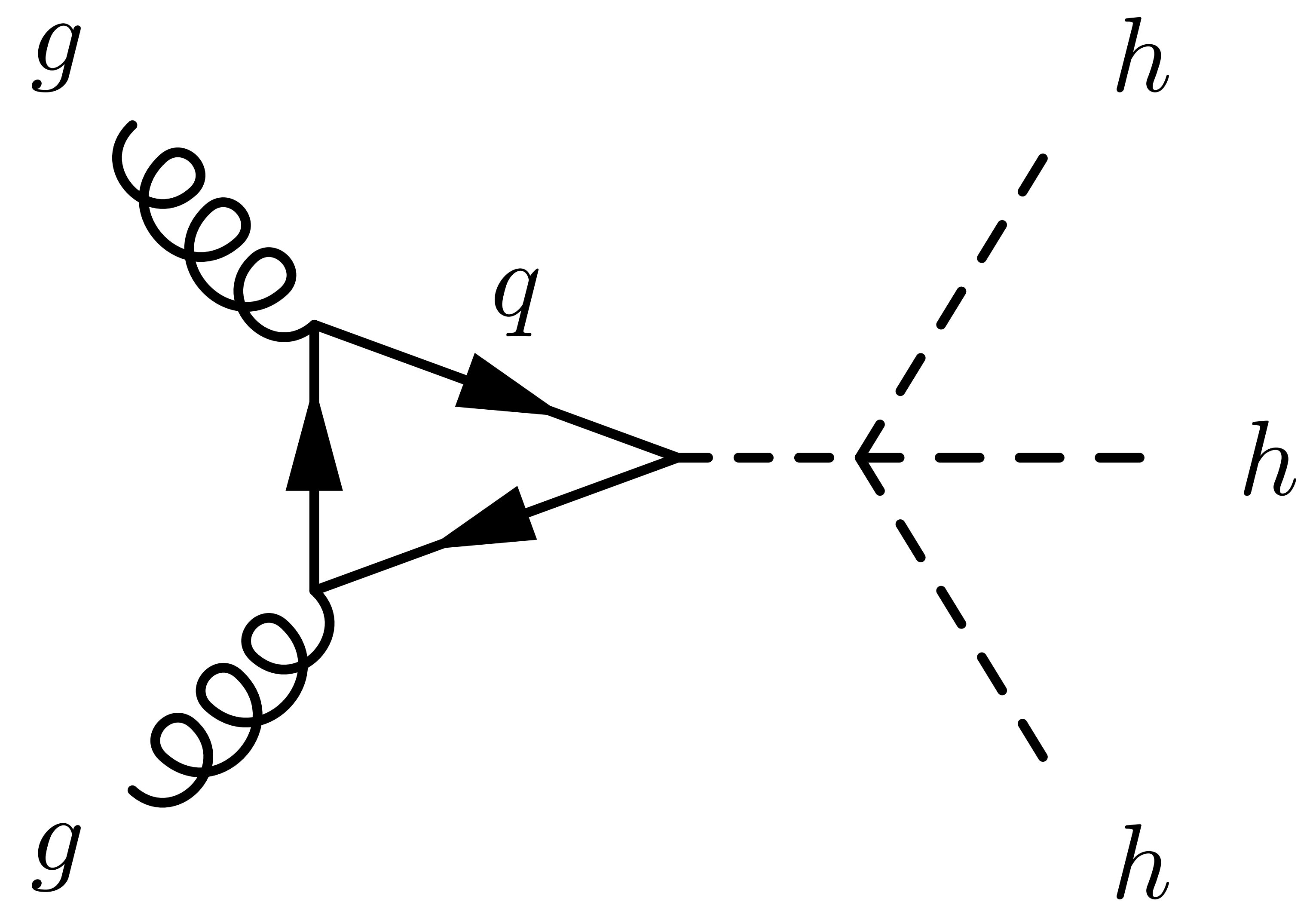
  - **SM^2** + interference of [**SM** × **One** or **Two** insertion diagrams] + [**One** Insertion]^2, i.e.:
    $|\mathscr{M}|^2 = |\mathscr{M}_{\mathrm{SM}}|^2 + 2\mathrm{Re}\{\mathscr{M}^*_{\mathrm{SM}}\mathscr{M}_{1-\mathrm{ins.}}\} + 2\mathrm{Re}\{\mathscr{M}^*_{\mathrm{SM}}\mathscr{M}_{2-\mathrm{ins.}}\}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

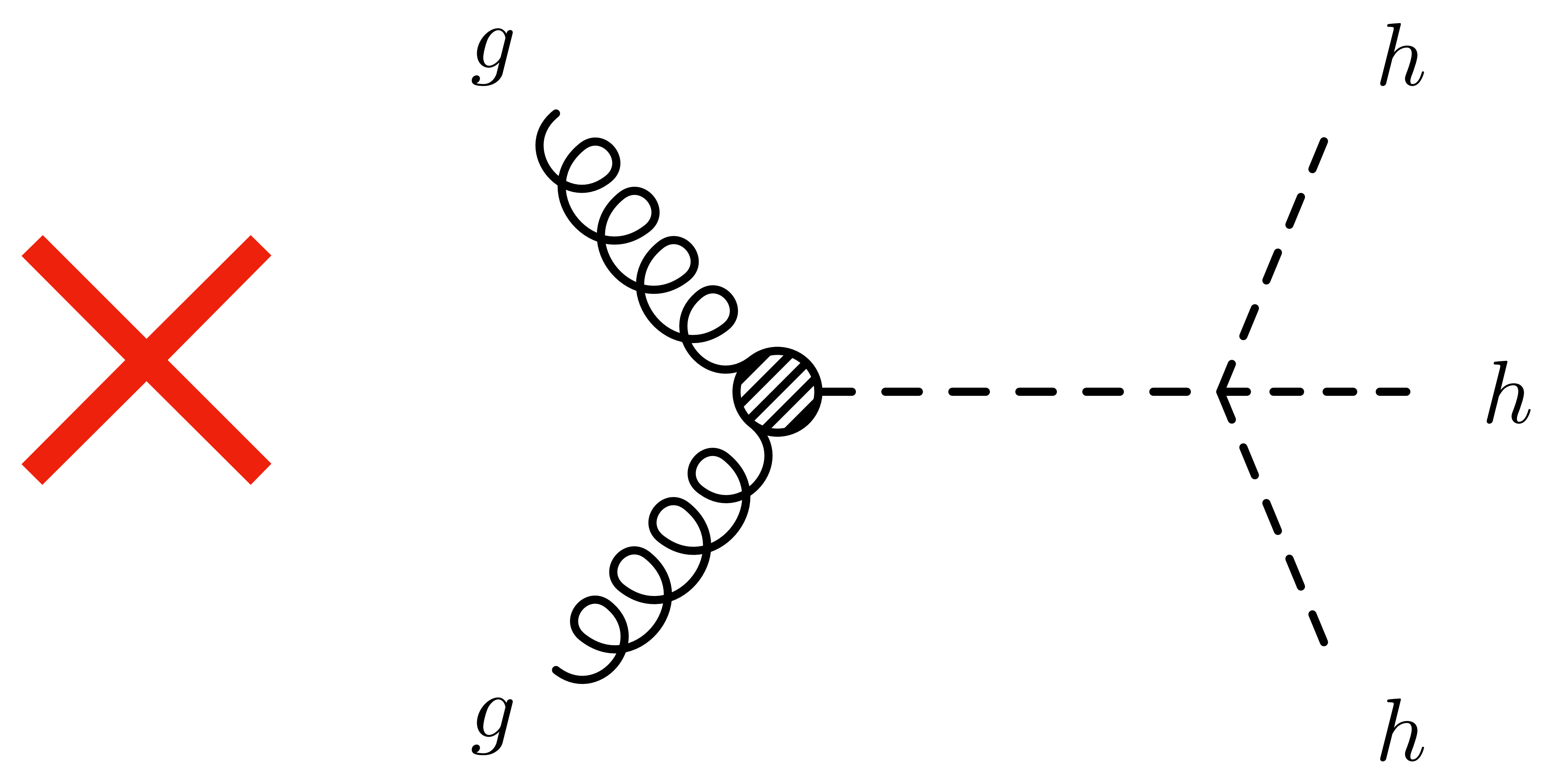
Monte Carlo Implementation of Anomalous Couplings

- We have implemented a **MadGraph5_aMC@NLO "loop" model** for $\mathscr{L}_{\text{PhenoExp}}$.
- **Includes <u>Loop × Tree level interference</u> between the various diagrams.**

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

- e.g.:





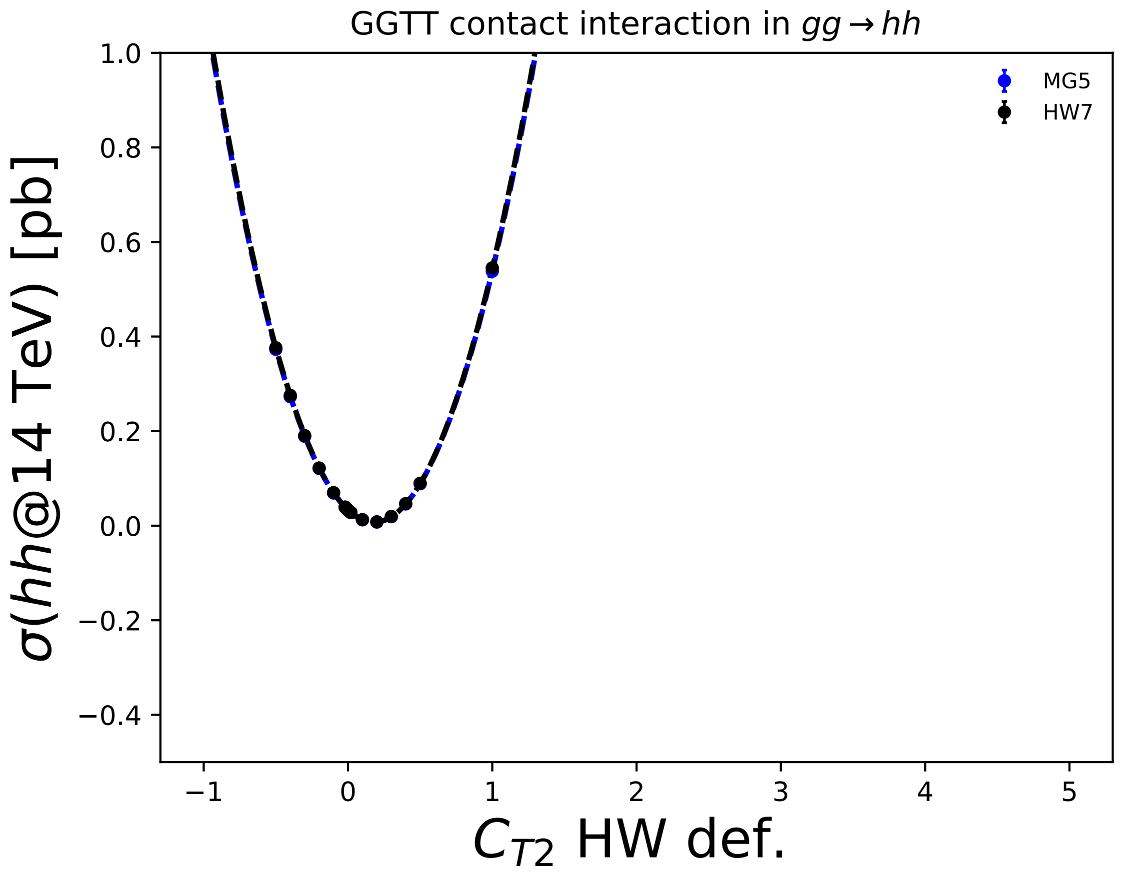
[**AP**, Tetlalmatzi-Xolocotzi, arXiv:2312.13562]

[Get model at: https://gitlab.com/apapaefs/multihiggs_loop_sm]

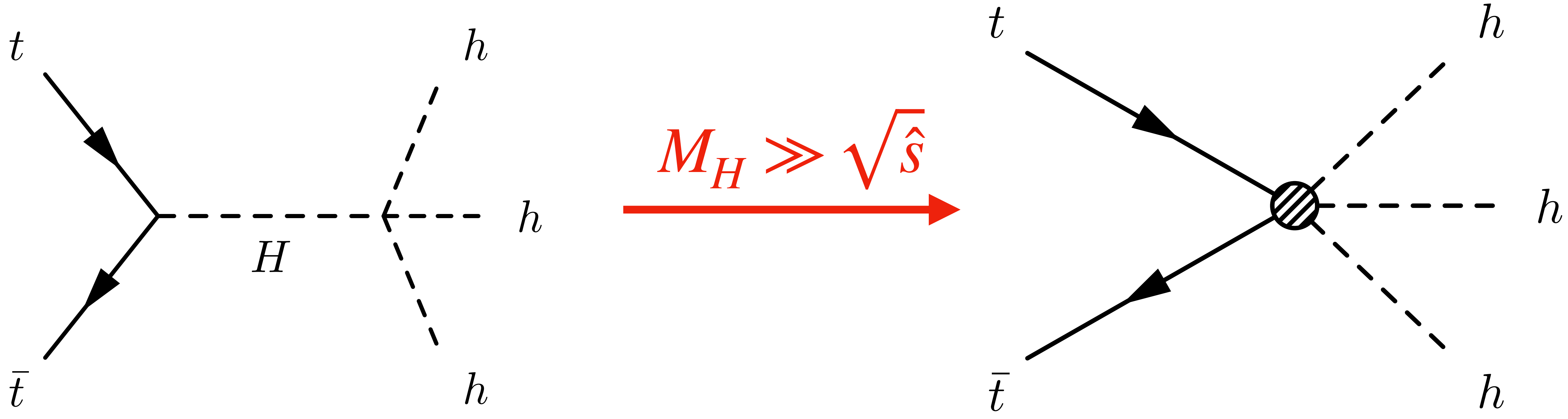
Model Validation

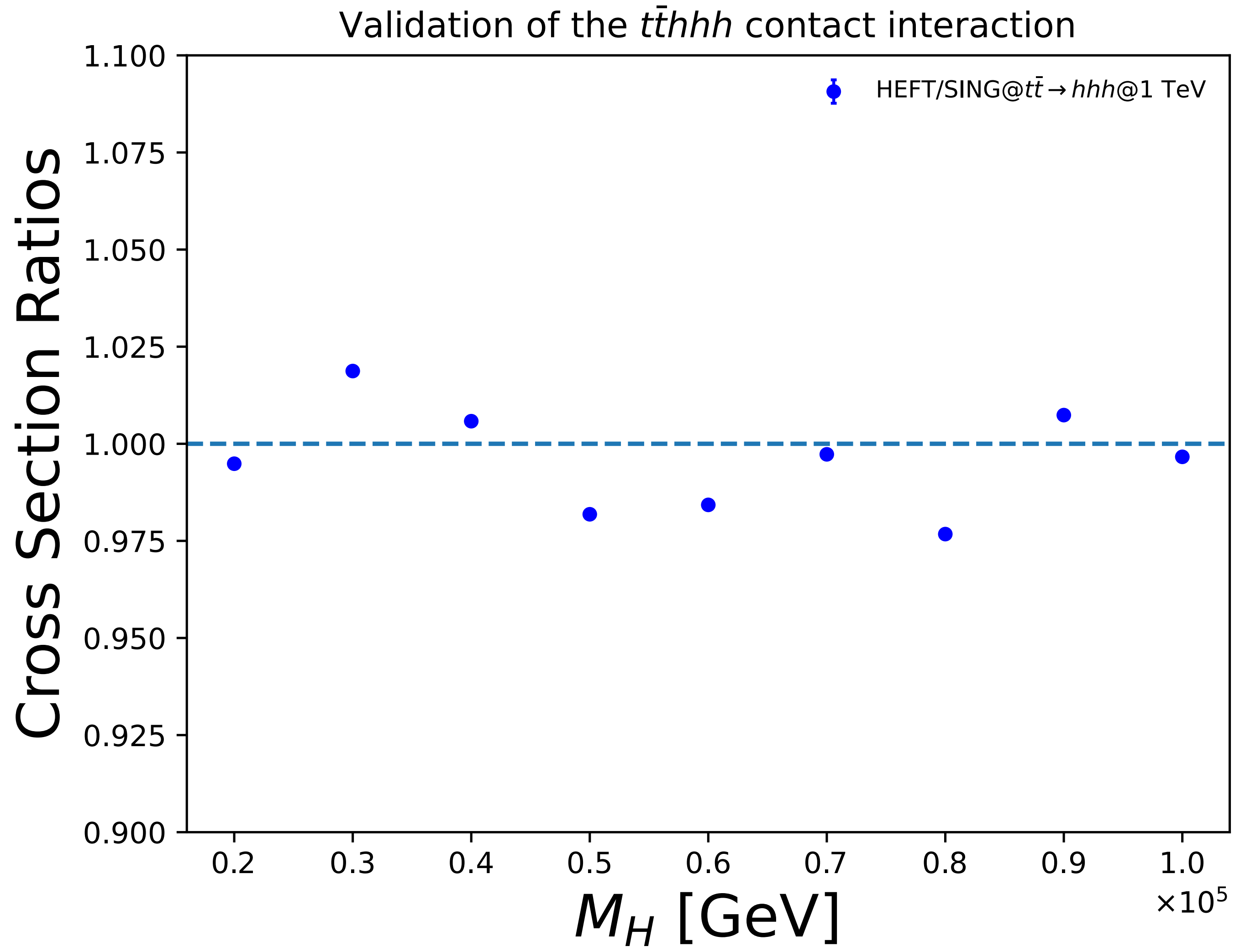
[**AP**, Tetlalmatzi-Xolocotzi, arXiv:2312.13562]

- 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:

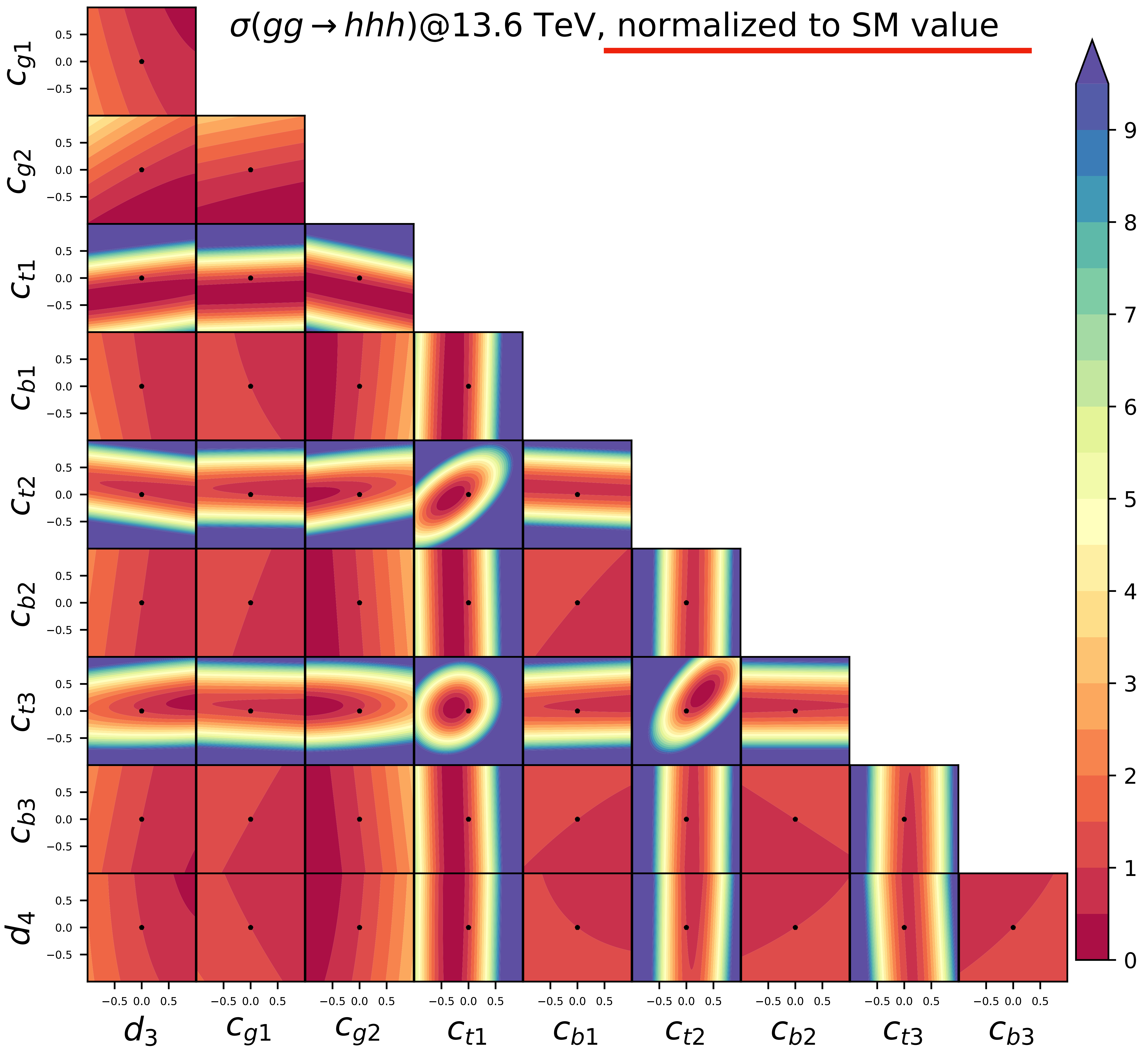




hhh Cross Sections @ 13.6 TeV

[**AP**, Tetlalmatzi-Xolocotzi, arXiv:2312.13562]

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



Anomalous Couplings Constraints

- Other processes constrain (at LO) all coefficients except $\{c_{t3}, d_4\}$ **(only in hhh)**.
- **Projected constraints:**

Percentage uncertainties			
	HL-LHC	FCC-hh	Ref.
$\delta(d_3)$	50	5	[145] (table 12)
$\delta(c_{g1})$	2.3	0.49	[145] (table 3)
$\delta(c_{g2})$	5	1	[140] (Figure 12, right)
$\delta(c_{t1})$	3.3	1.0	[145] (table 3)
$\delta(c_{t2})$	30	10	[140] (Figure 12, right)
$\delta(c_{b1})$	3.6	0.43	[145] (table 3)
$\delta(c_{b2})$	30	10	assumed same as c_{t2}

[See **AP**, Tetlalmatzi-Xolocotzi, arXiv:2312.13562 for the references]

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Digression: Non-Resonant *hhh* @ LHC

- Anomalous couplings can enhance ***hhh*! e.g.** $\kappa_3 \neq 1, \kappa_4 \neq 1$**, but also others!**

$$\mathcal{L}_{\rm PhenoExp} \supset -\lambda_{\rm SM} v \left(1+c_3\right) h^3 - \frac{\lambda_{\rm SM}}{4}\left(1+d_4\right) h^4$$
$$+\frac{\alpha_s}{12\pi}\left(c_{g1}\frac{h}{v} - c_{g2}\frac{h^2}{2v^2}\right) G^a_{\mu\nu} G^{\mu\nu}_a$$
$$-\left[\frac{m_t}{v}\left(1+c_{t1}\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1+c_{b1}\right)\bar{b}_L b_R h + \text{h.c.}\right]$$
$$-\left[\frac{m_t}{v^2} c_{t2} \bar{t}_L t_R h^2 + \frac{m_b}{v^2} c_{b2} \bar{b}_L b_R h^2 + \text{h.c.}\right]$$
$$-\left[\frac{m_t}{v^3}\left(\frac{c_{t3}}{2}\right)\bar{t}_L t_R h^3 + \frac{m_b}{v^3}\left(\frac{c_{b3}}{2}\right)\bar{b}_L b_R h^3 + \text{h.c.}\right]$$

[AP, Tetlalmatzi-Xolocotzi, **arXiv:2312.13562**]

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➡ **Here: Examine models with new scalar resonances!**

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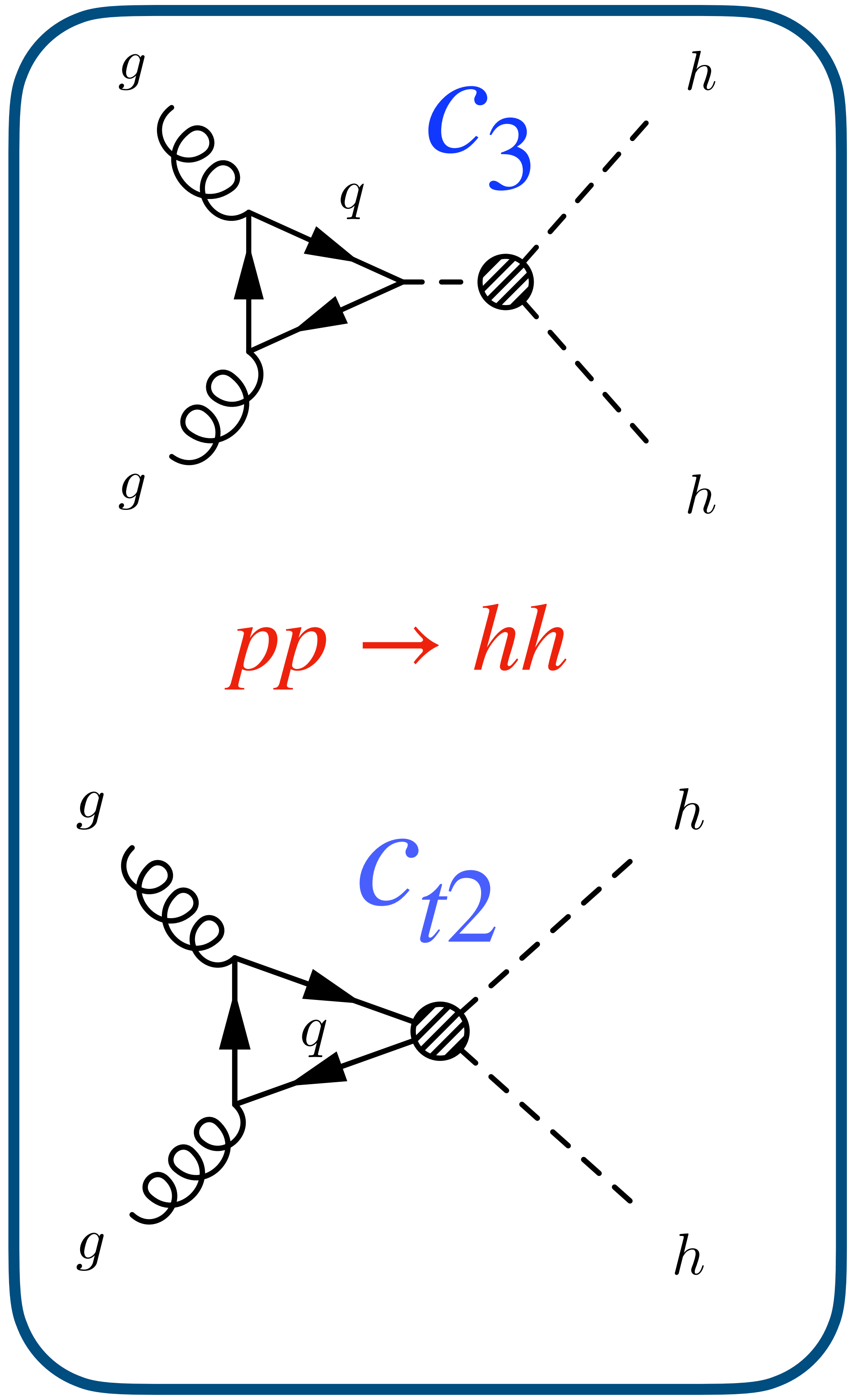

$$
\begin{aligned}
\mathcal{L}_{\text{PhenoExp}} \supset & -\lambda_{\text{SM}} v\,(1+c_3)\,h^3 - \frac{\lambda_{\text{SM}}}{4}(1+d_4)\,h^4 \\
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& - \left[\frac{m_t}{v}(1+c_{t1})\,\bar{t}_L t_R h + \frac{m_b}{v}(1+c_{b1})\,\bar{b}_L b_R h + \text{h.c.}\right] \\
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& - \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}
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[AP, Tetlalmatzi-Xolocotzi, **arXiv:2312.13562**]

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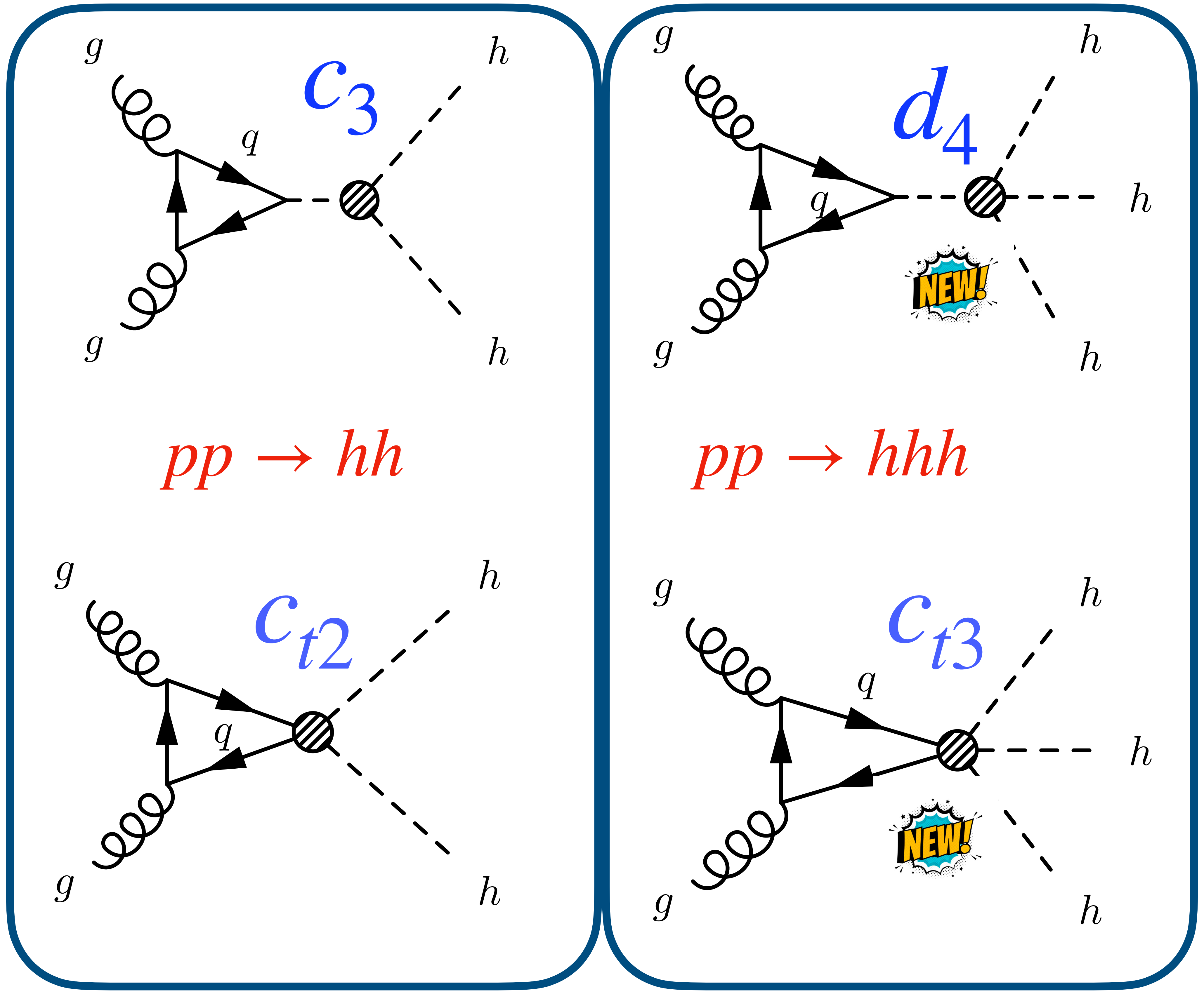

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Anomalous Couplings Constraints

[**AP**, Tetlalmatzi-Xolocotzi, arXiv:2312.13562]

- Focusing on a model with non-zero $\{c_{t2}, d_3, c_{t3}, d_4\}$:

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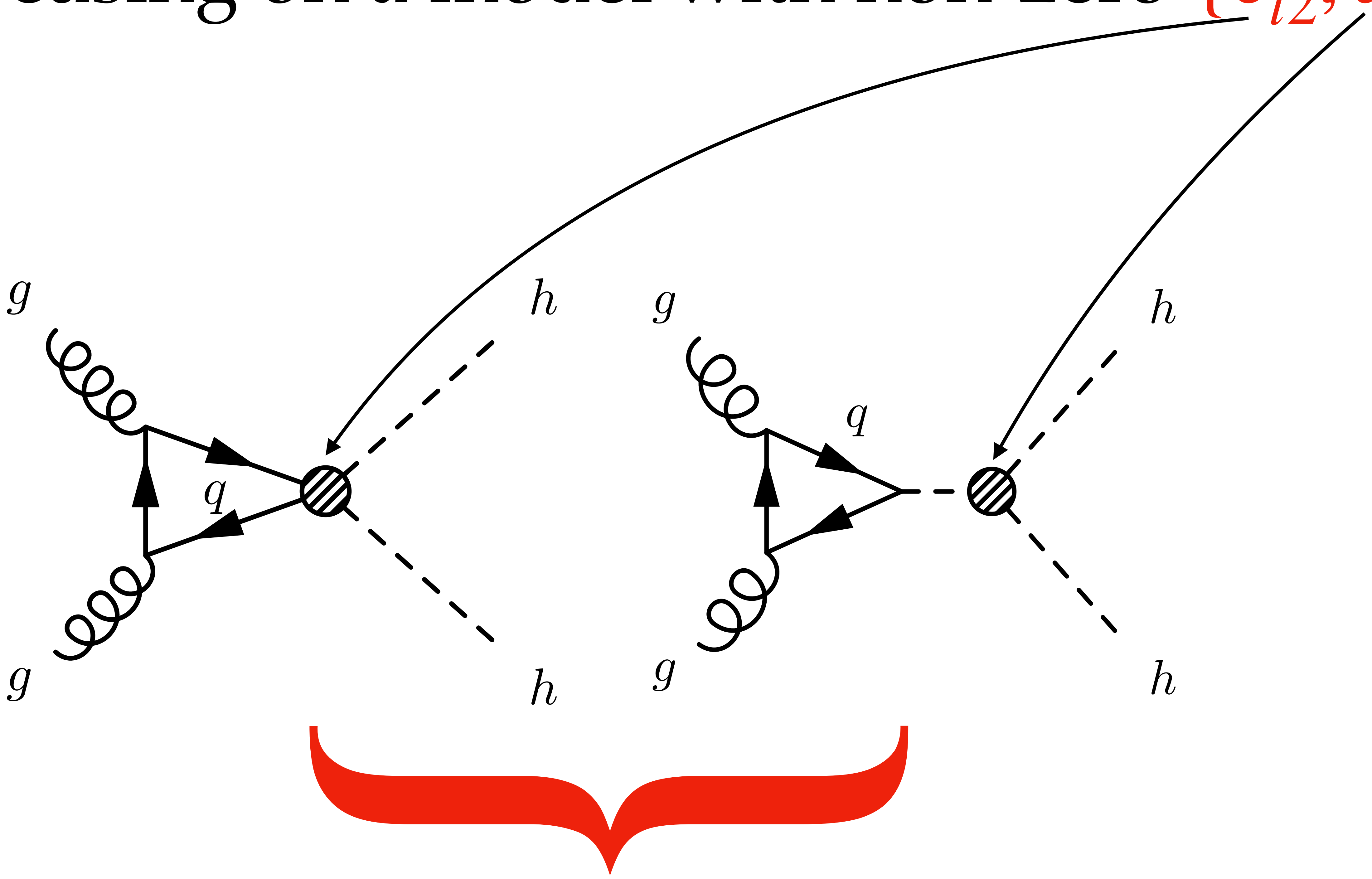

constrained by $pp \to hh$

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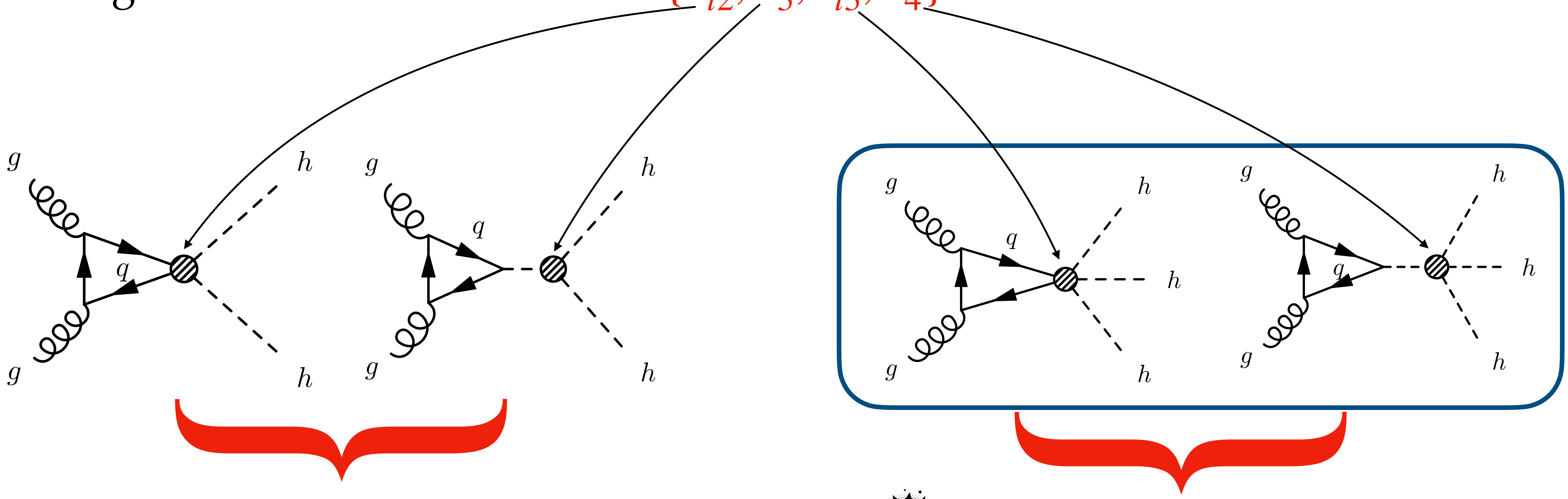


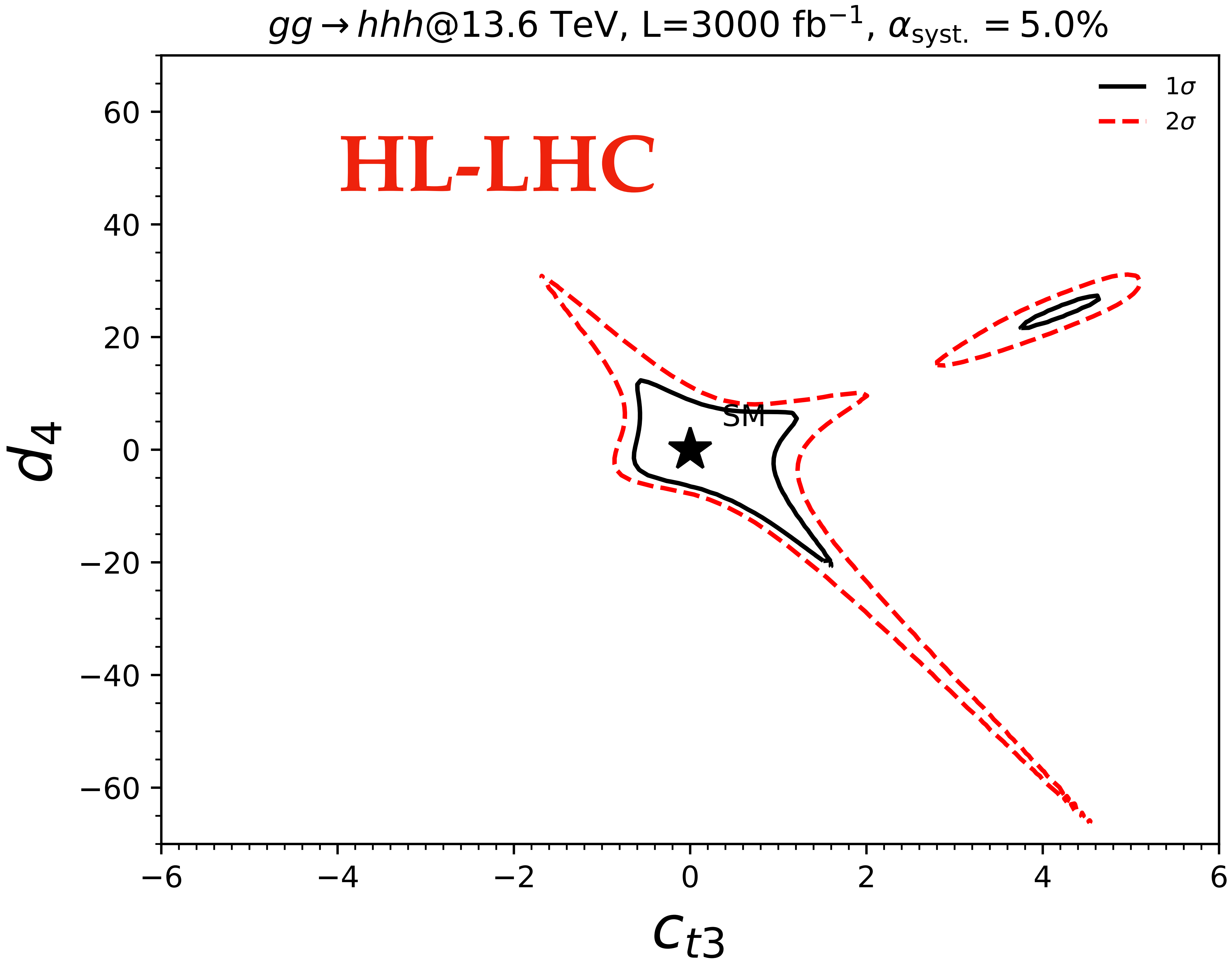
constrained by $pp \to hh$

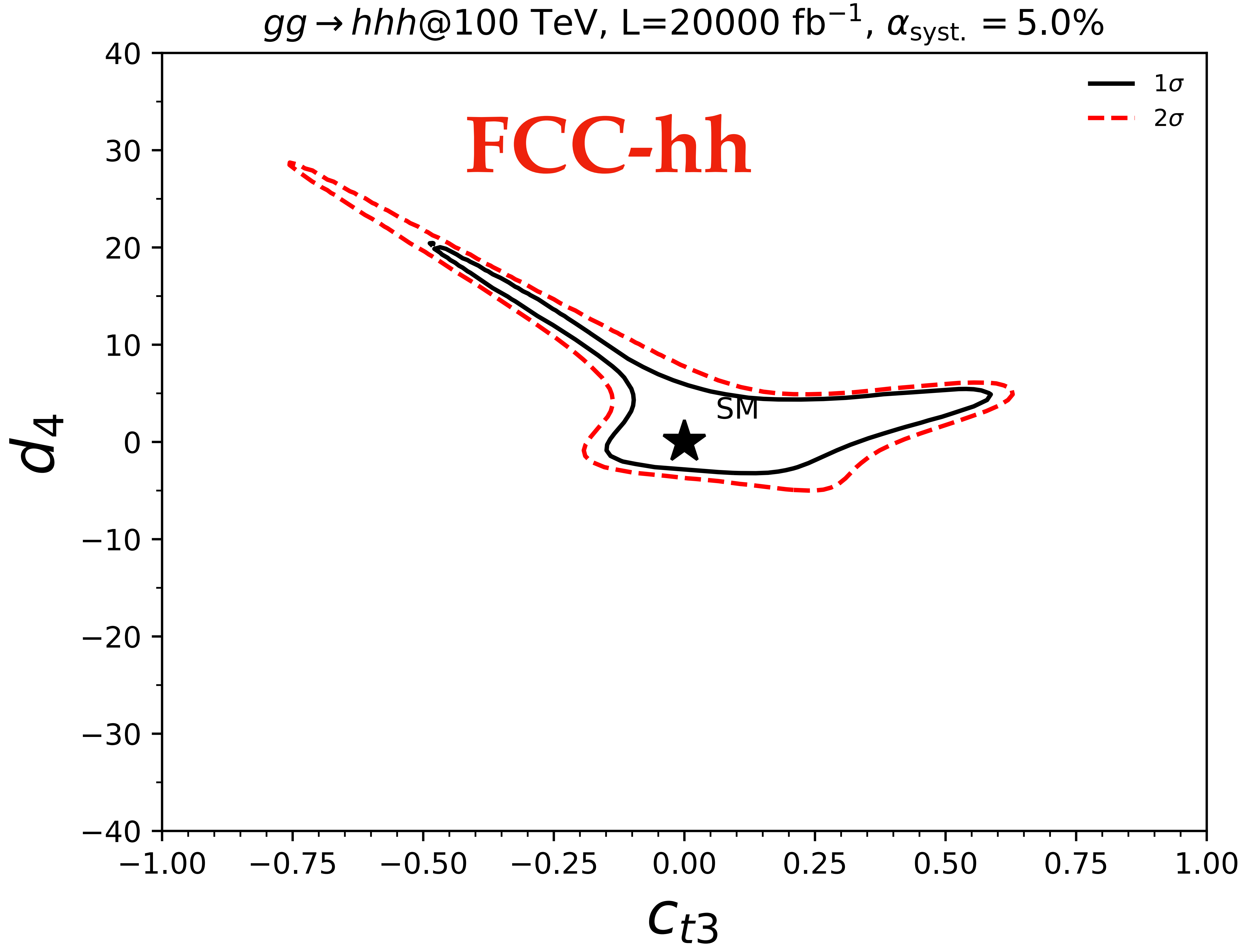
constrained by $pp \to hhh$

Anomalous Couplings Constraints

[**AP**, Tetlalmatzi-Xolocotzi, arXiv:2312.13562]

- Focusing on a model with only $\{c_{t2}, d_3, c_{t3}, d_4\}$,
- Using the **6 b-jet final state,** and marginalizing over $\{c_{t2}, d_3\}$ within projected constraints:





Anomalous Couplings Constraints

[**AP**, Tetlalmatzi-Xolocotzi, arXiv:2312.13562]

- Focusing on a model with only $\{c_{t2}, d_3, c_{t3}, d_4\}$,

- Using the **6 b-jet final state,** and marginalizing over $\{c_{t2}, d_3\}$ within projected constraints:

	HL-LHC 68%	HL-LHC 95%	FCC-hh 68%	FCC-hh 95%
d_4	$[-6.6, 12.4]$	$[-10.0, 21.3]$	$[-3.9, 10.5]$	$[-10.6, 18.8]$
c_{t3}	$[-0.6, 1.1]$	$[-0.9, 3.6]$	$[-0.1, 0.3]$	$[-0.4, 0.6]$

$$\Rightarrow \quad c_{t3} \sim \mathcal{O}(0.1 - 1)$$

$$d_4 \sim \mathcal{O}(10)$$

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