[made with unstability.ai]

In Pursuit of Multiple Scalars @ Colliders

Andreas Papaefstathiou
Kennesaw State University, GA, USA

@ Nikhef, NL [May 23rd 2024]

Disambiguation: “Multiple Scalars”

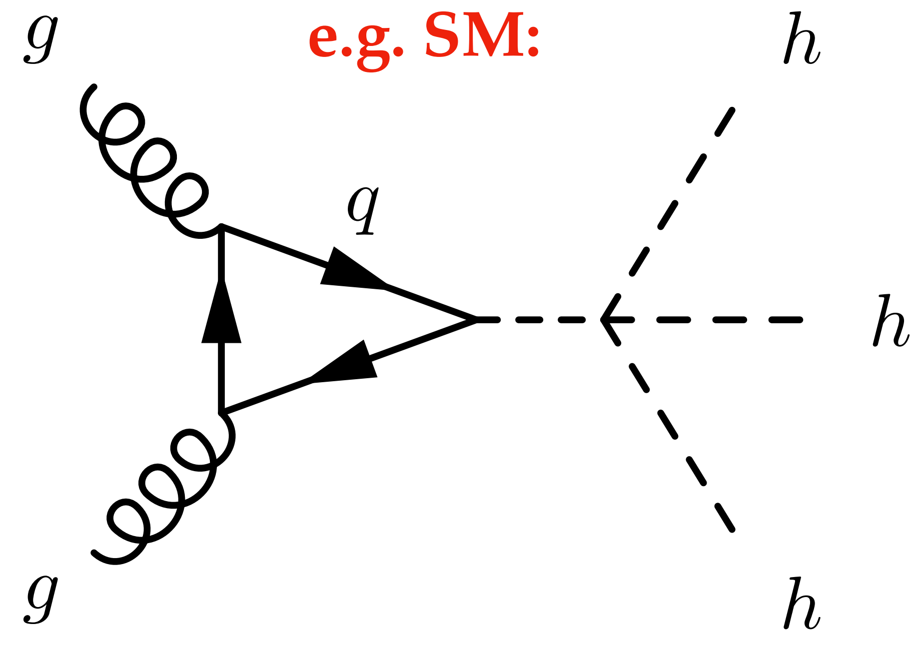
= New scalar fields added to the Standard Model,

e.g. SM + one singlet scalar field: $\mathcal{V}(\phi, S) = \bullet\, |\phi|^2 + \blacksquare\, |\phi|^4 + \bullet S^2 + \blacktriangle S^3 + \blacksquare S^4 + \blacktriangle\, |\phi|^2 S + \blacksquare\, |\phi|^2 S^2$

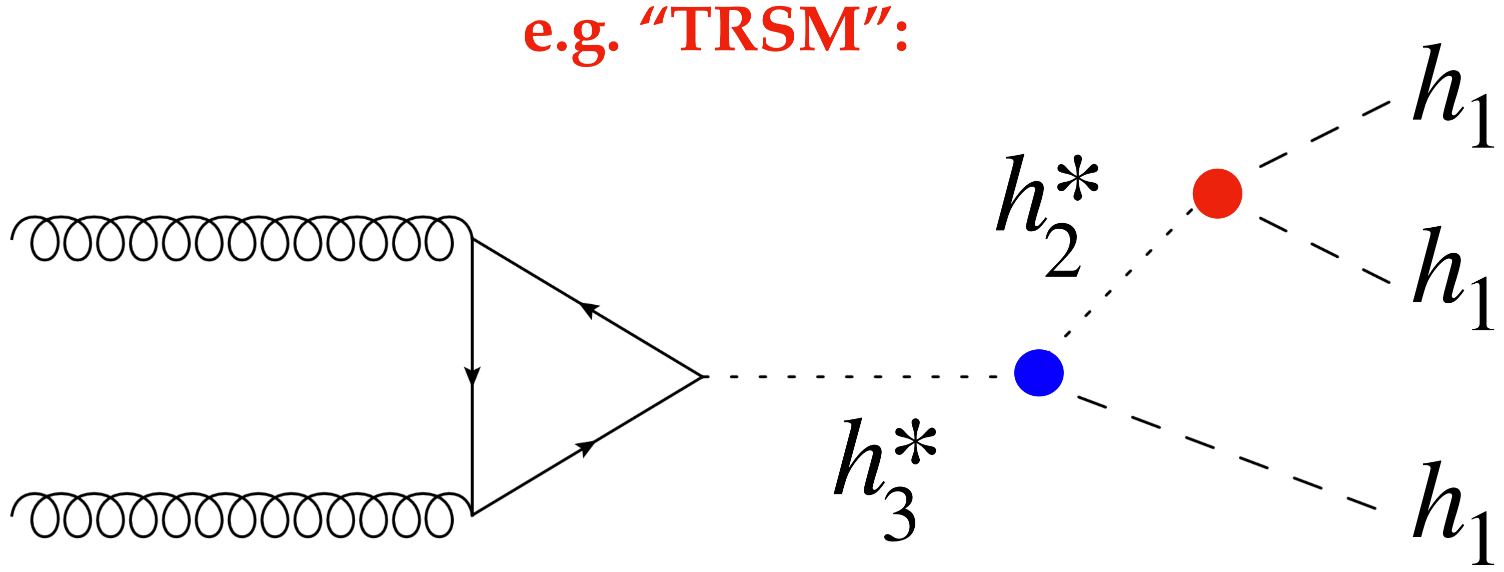
and/or

= The production of multiple physical scalar states at colliders.

e.g. SM:



e.g. “TRSM”:



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The Plan:

The Plan:

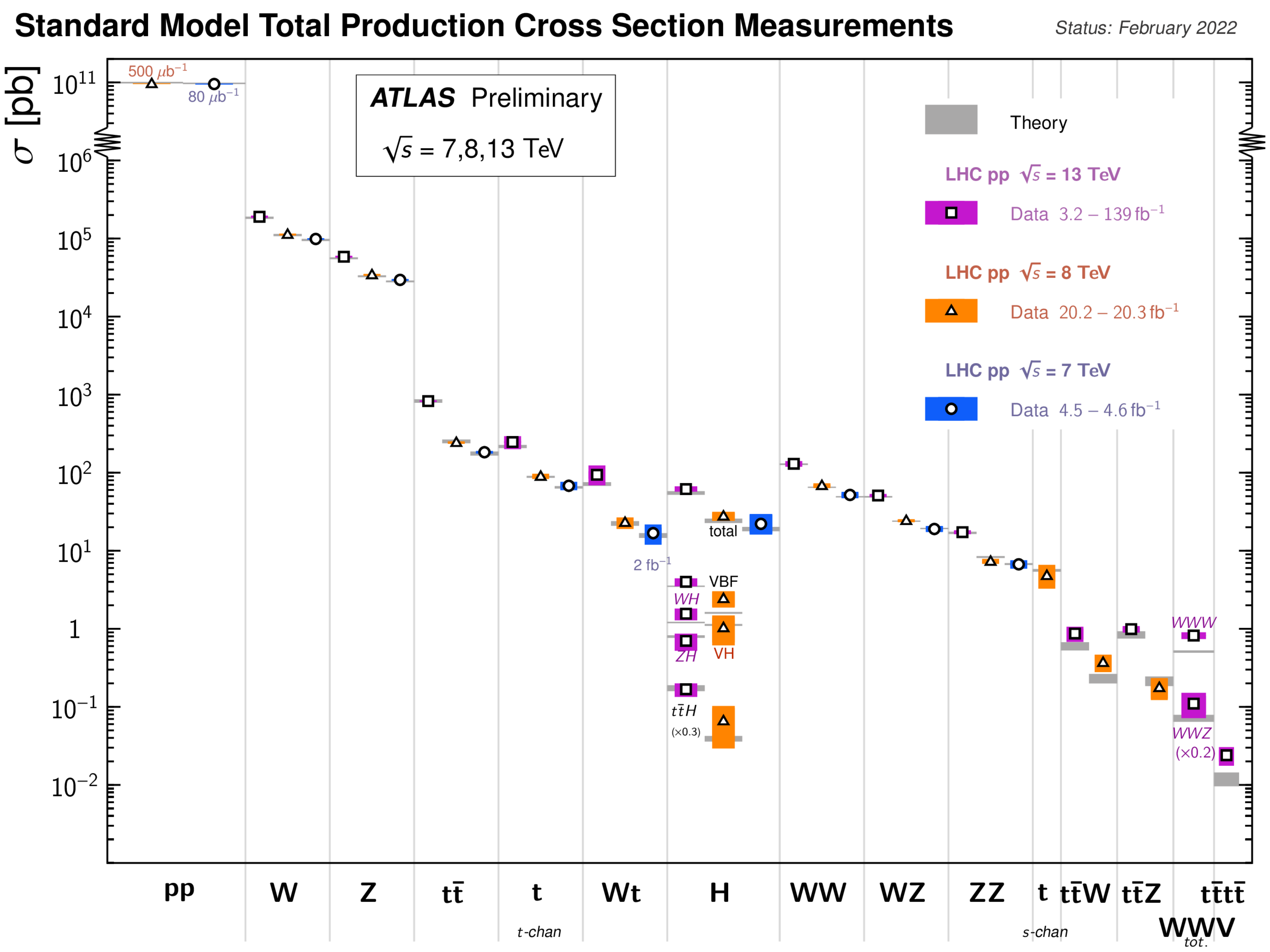
1 High Energy Physics Today

2 ➜ The Breaking of Symmetry,

3 ➜ Multi-scalar production.

Experiment VS Theory

Cross Sections [pb]



Process Type

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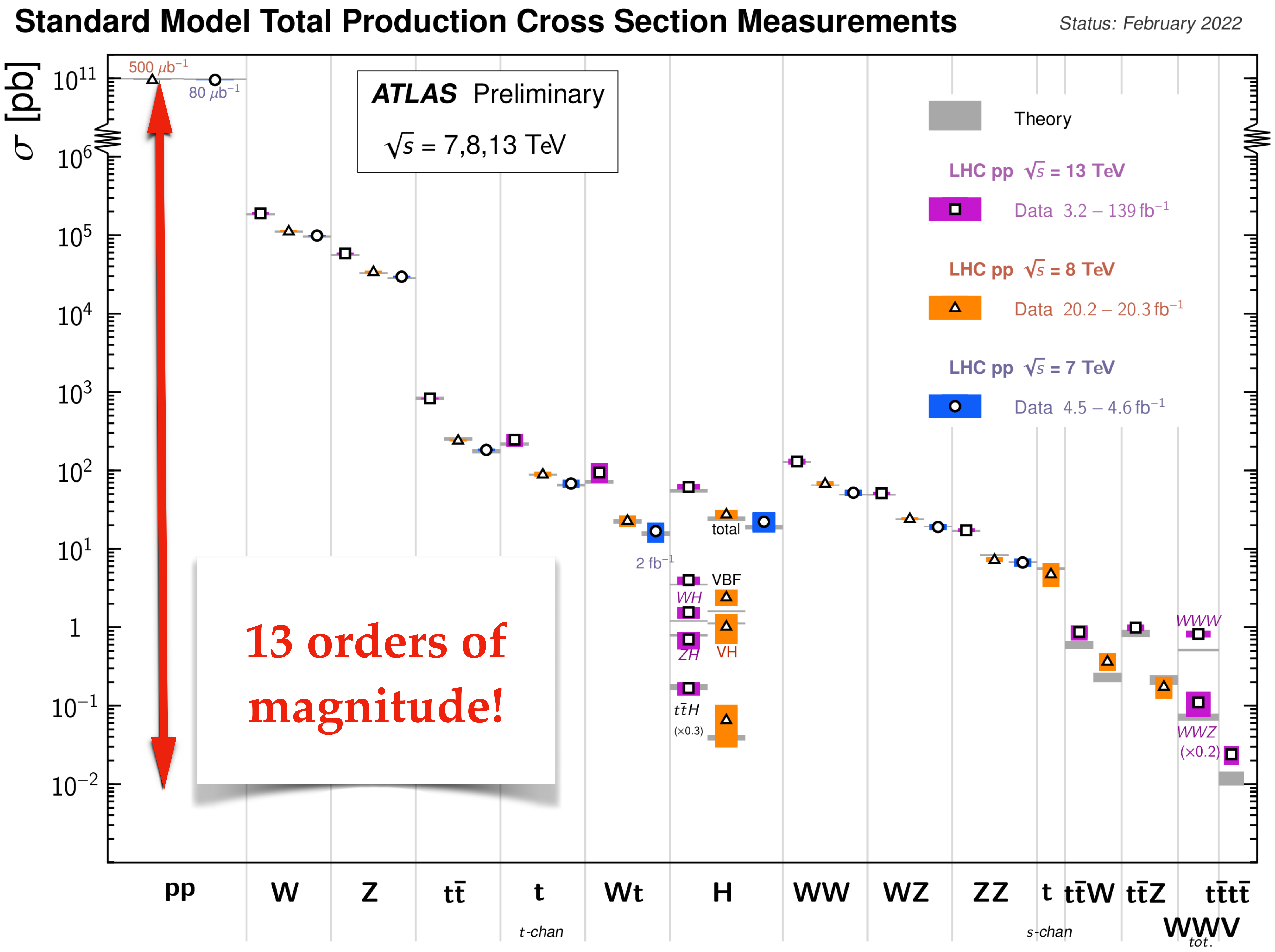
Experiment VS Theory

Cross Sections [pb]



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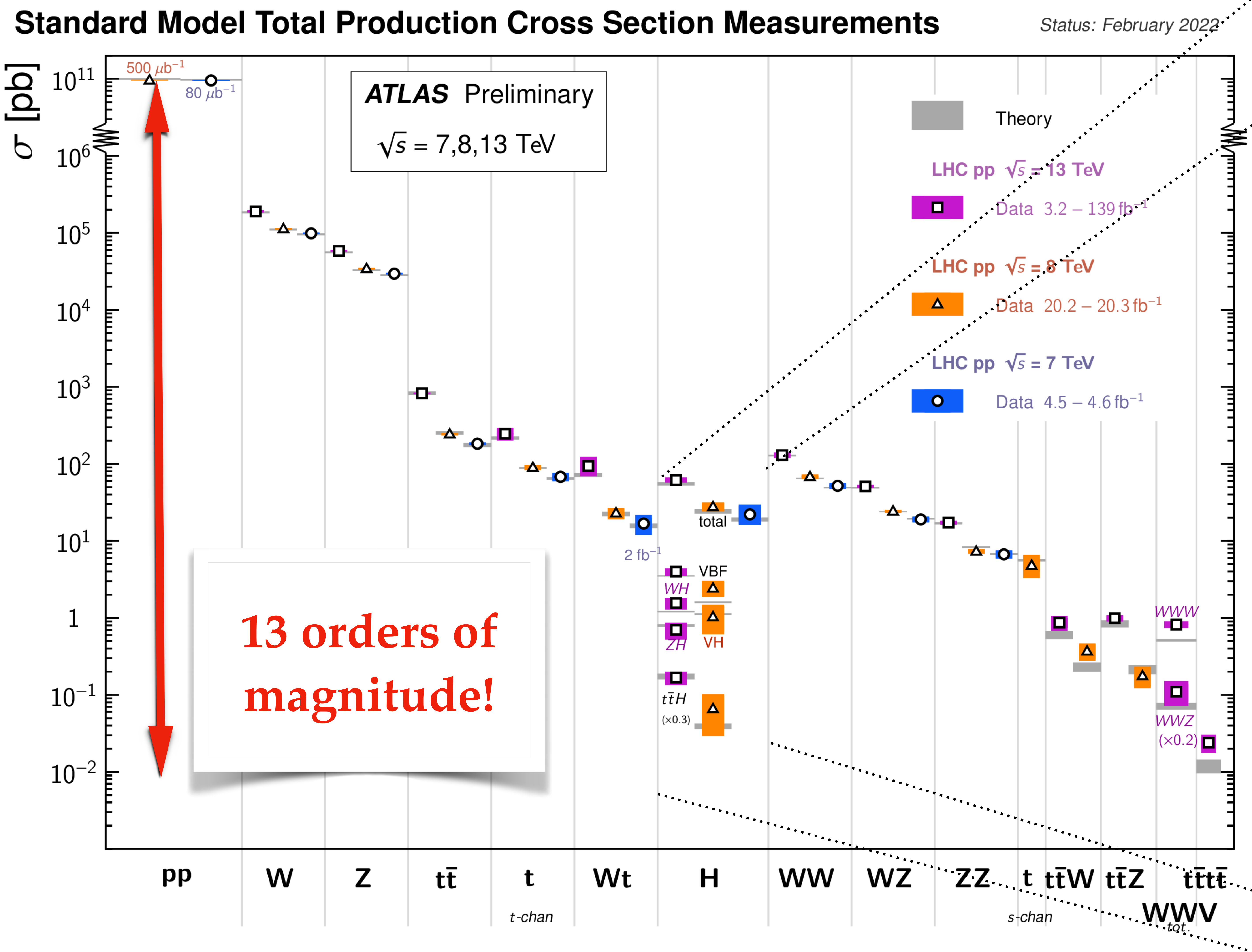
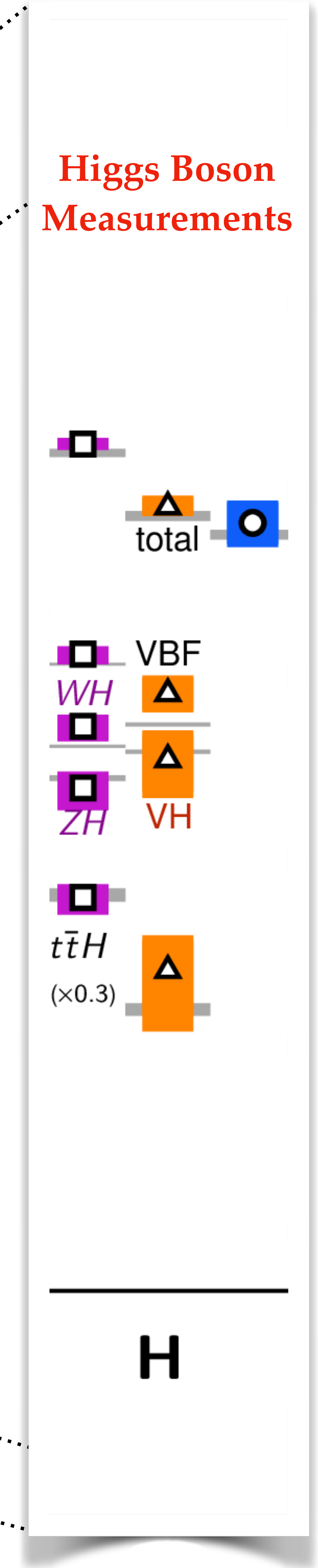
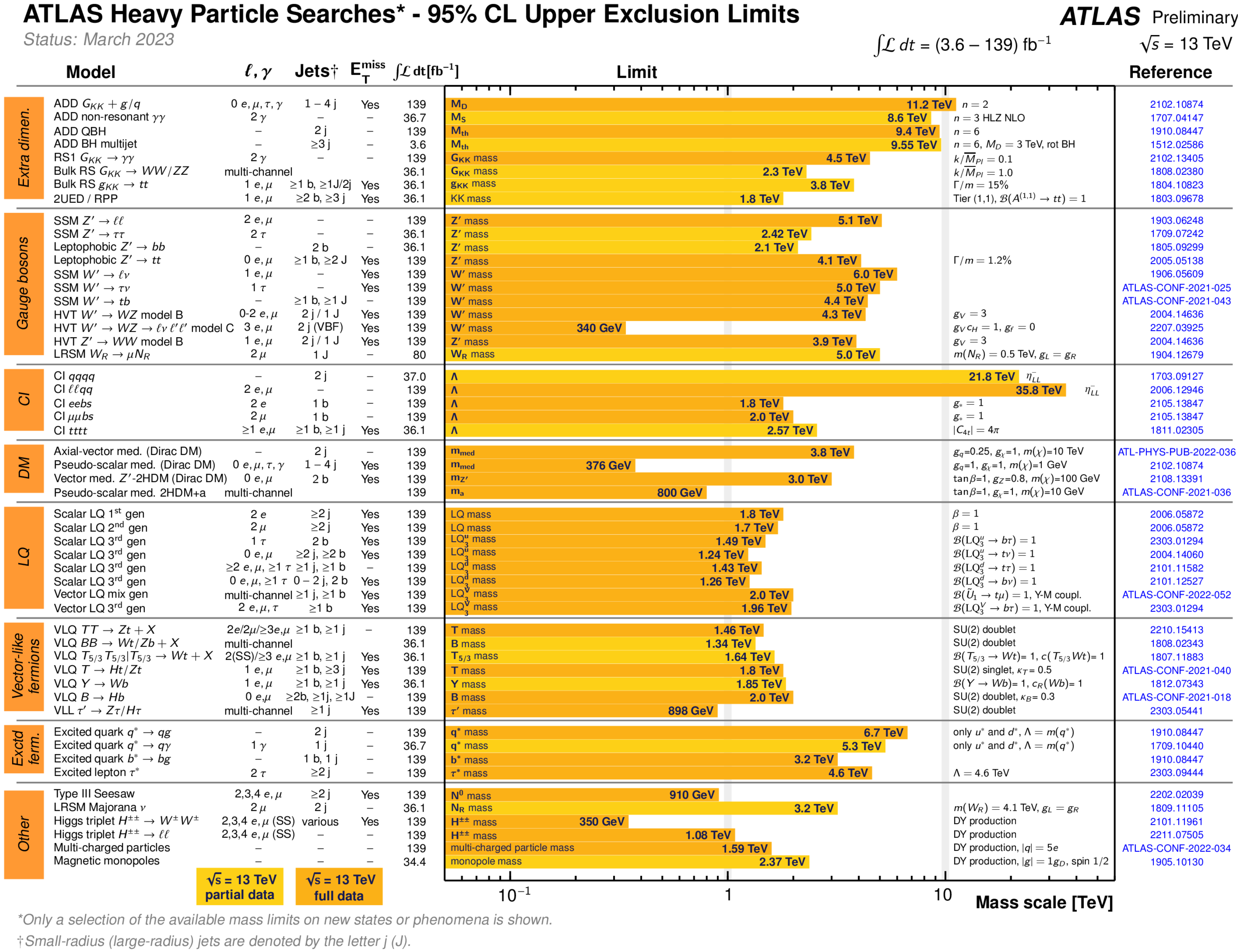




Process Type

Experiment VS Exotic New Phenomena

Kinds of New Physics



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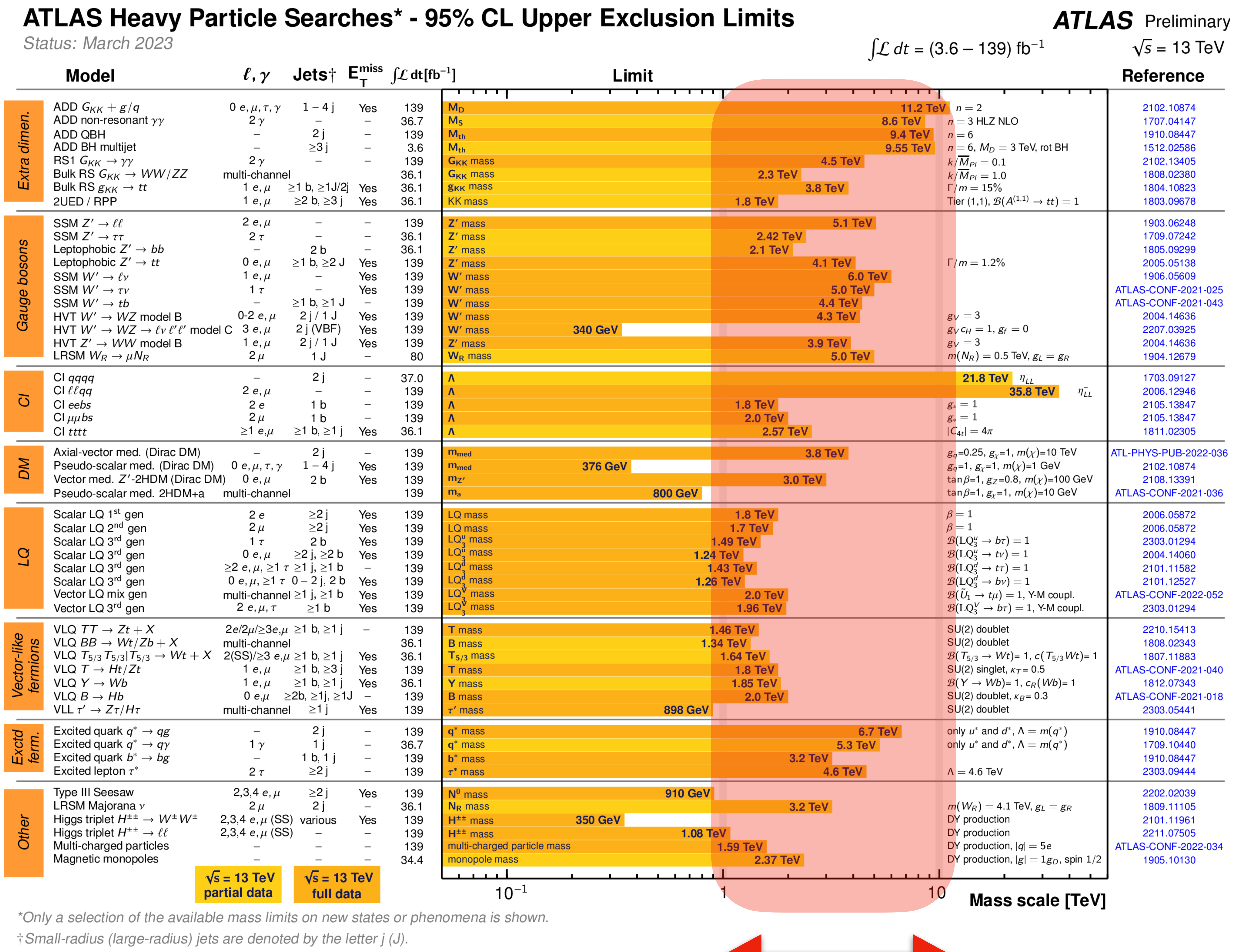
Experiment VS Exotic New Phenomena



Kinds of New Physics

Mass Scale limits: $\mathcal{O}(1 - 10$ TeV$)$

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STANDARD MODEL WINS!

$\Rightarrow$ NO NEW PHENOMENA?

STANDARD MODEL WINS!

$\Rightarrow$ NO NEW PHENOMENA?

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Questions

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Provence

Questions

Answers

Questions

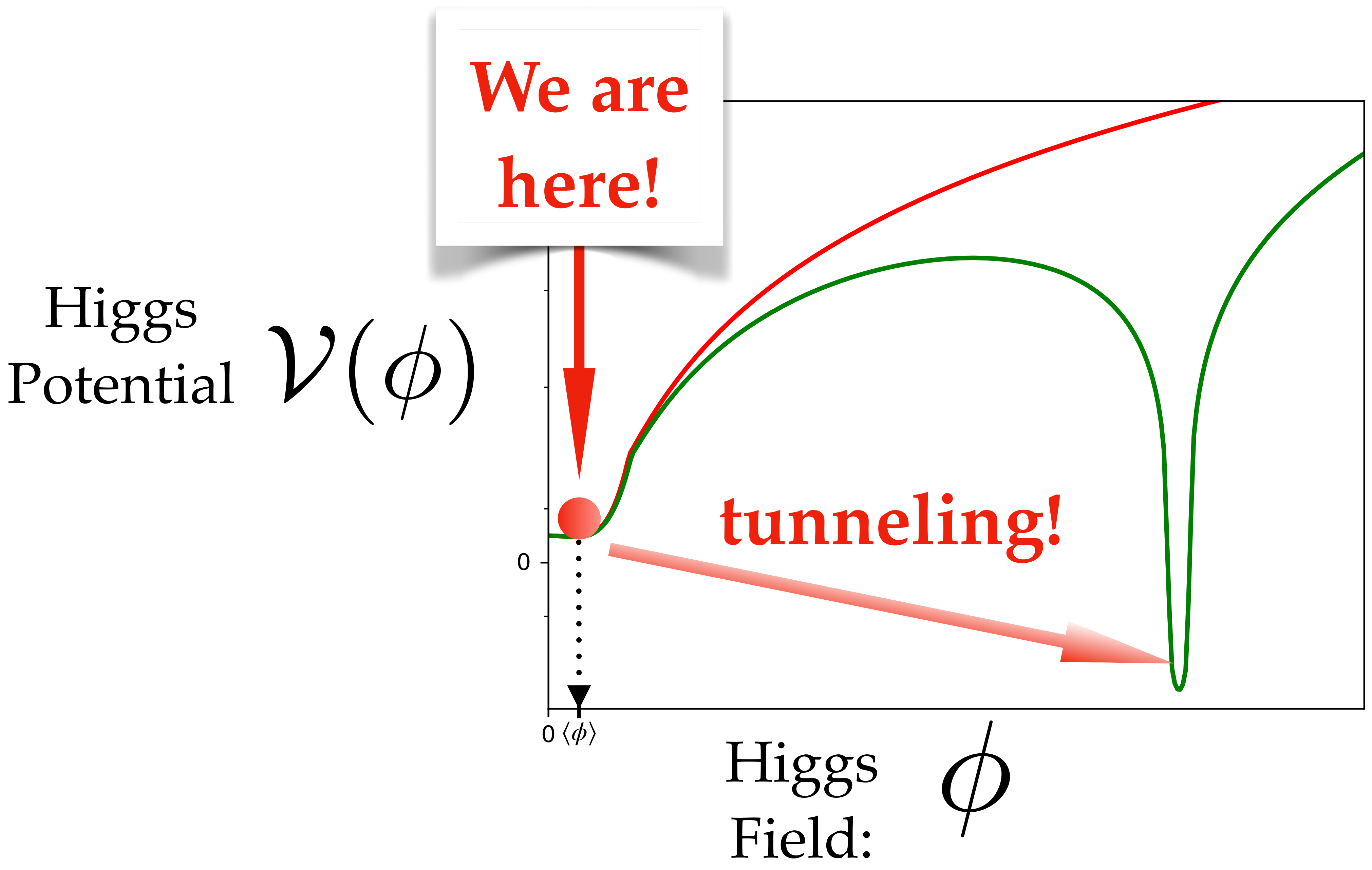
Answers

Questions

Answers

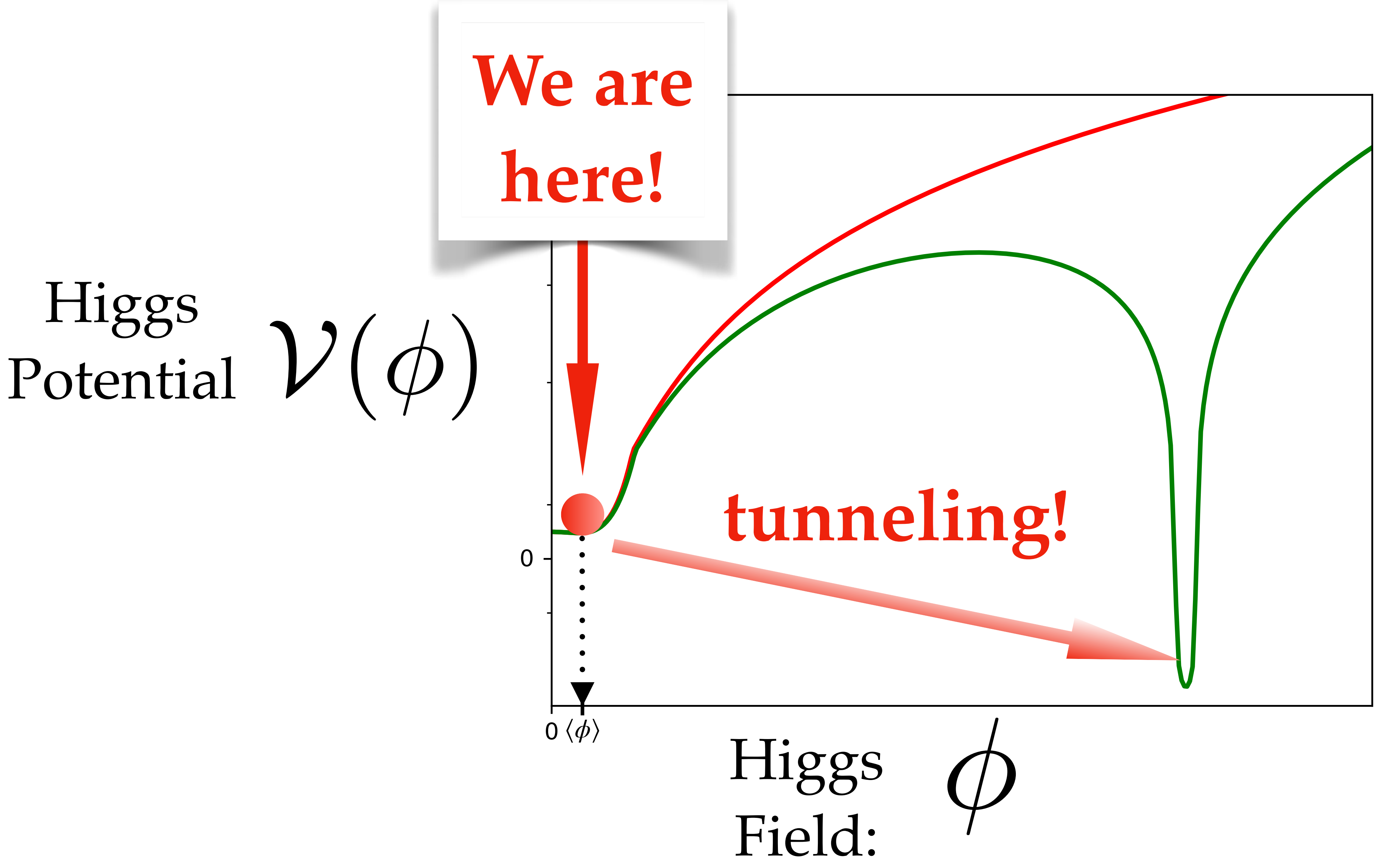
Questions

Questions



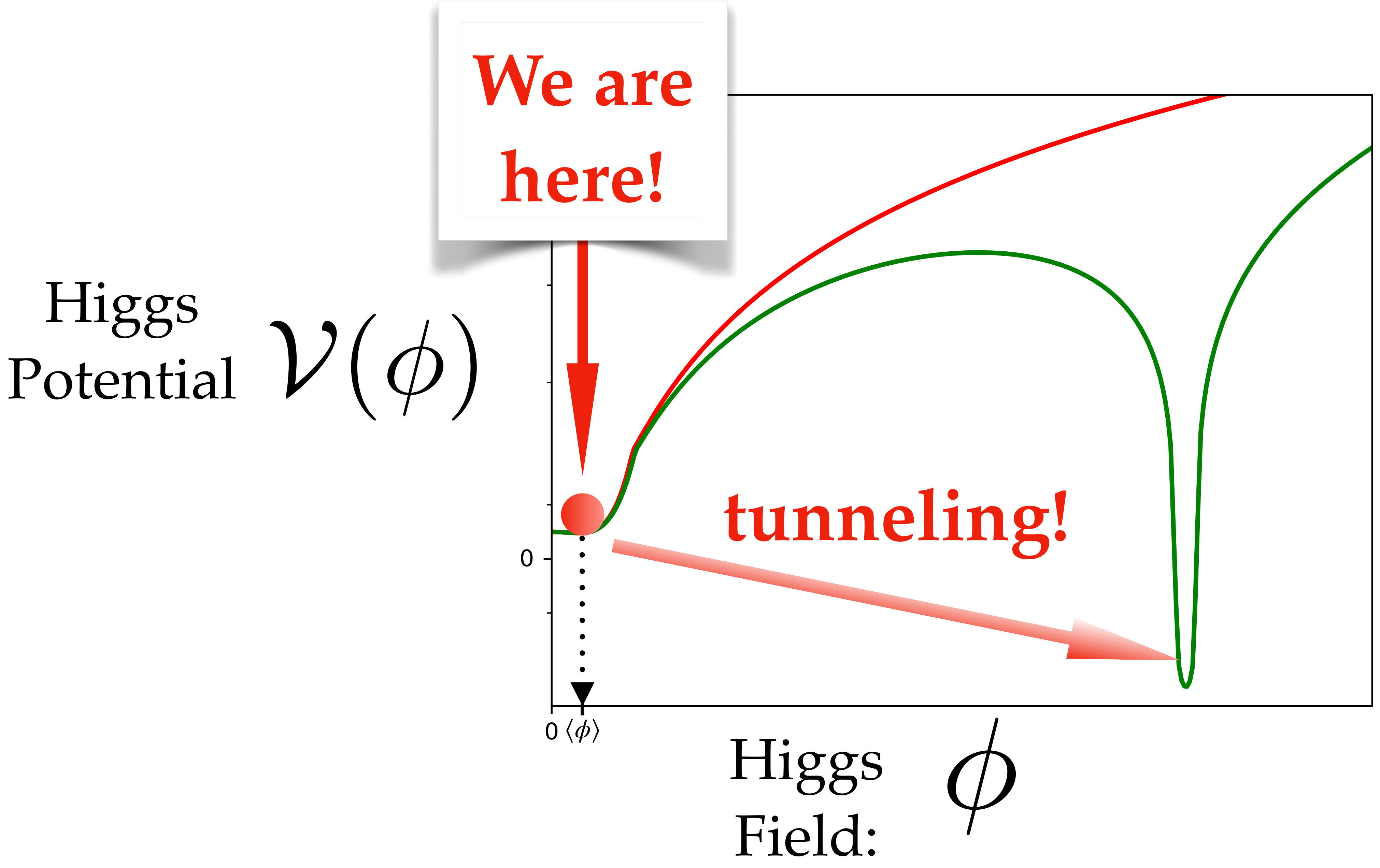
We are here!
Higgs Potential $\mathcal{V}(\phi)$
0
tunneling!
0 $\langle\phi\rangle$
Higgs Field: ϕ

Questions



Vacuum Stability

Questions



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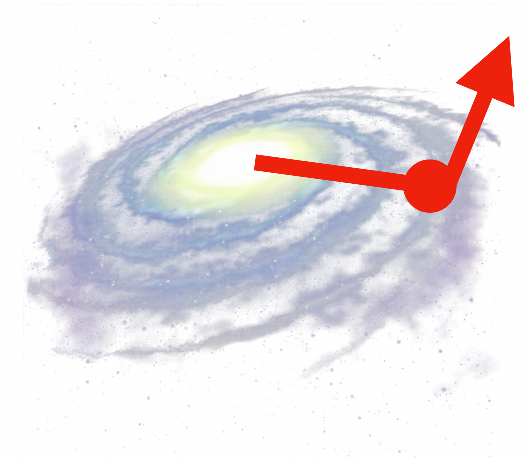
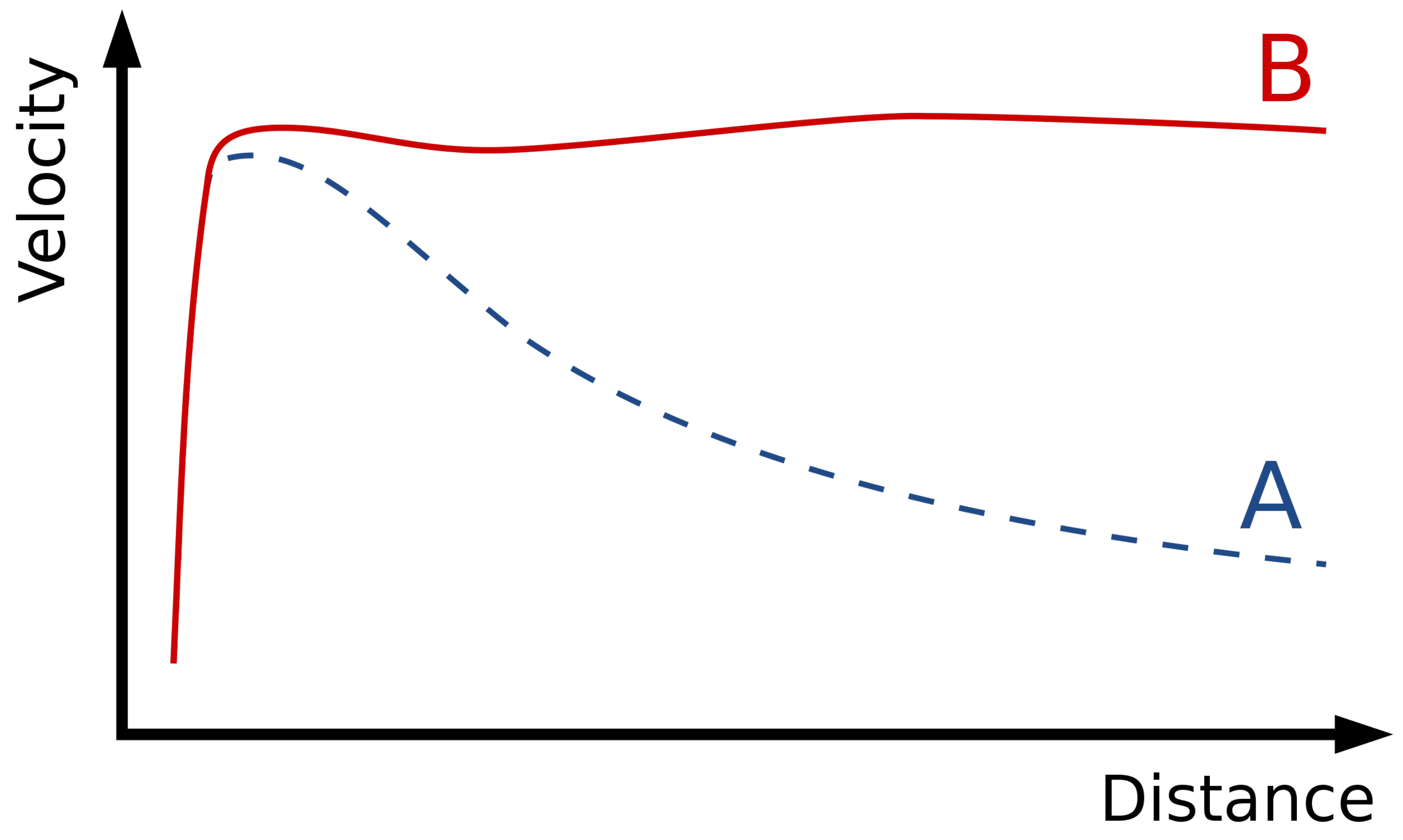


Rotation curve of a typical spiral galaxy: predicted (A) and observed (B).



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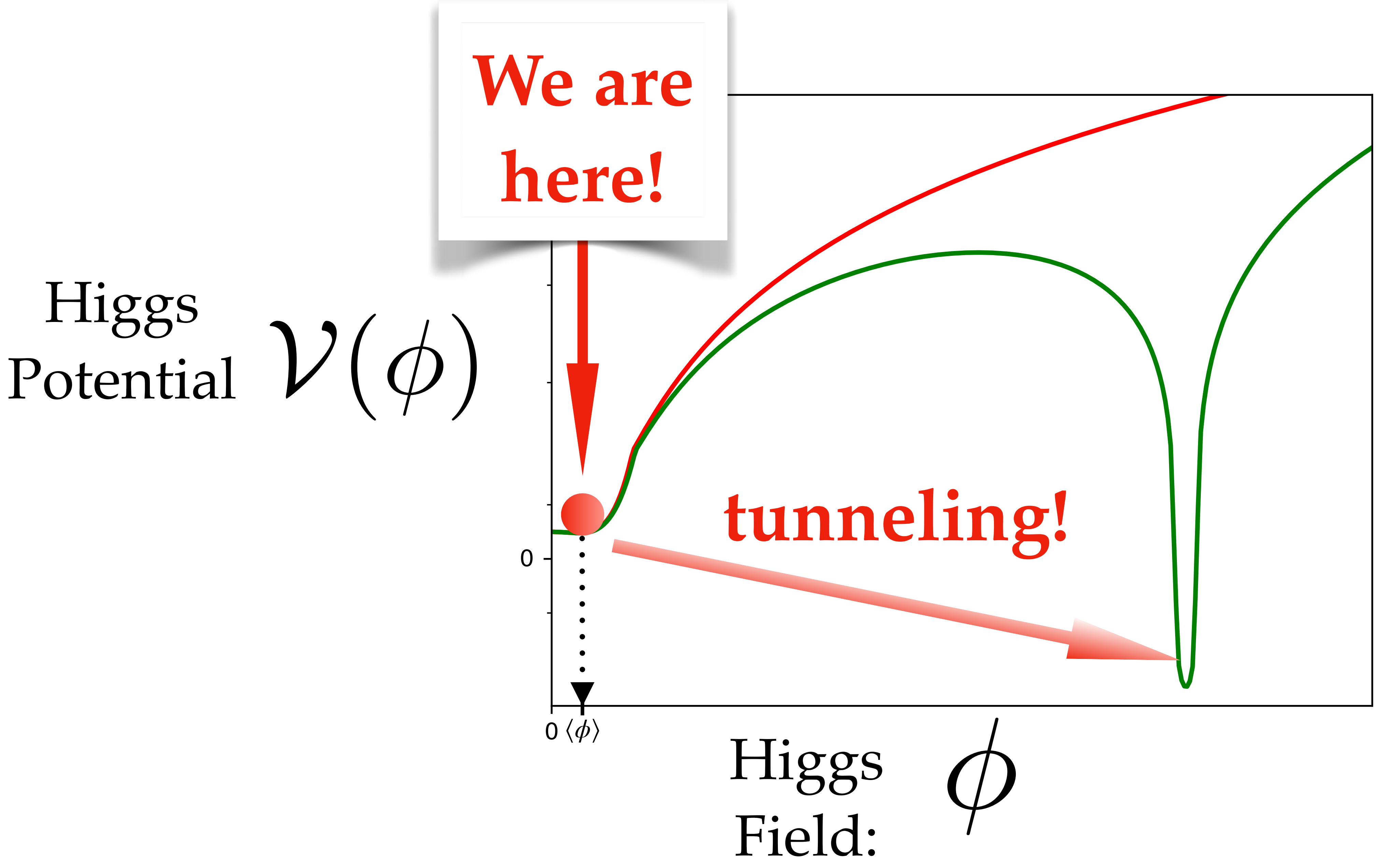
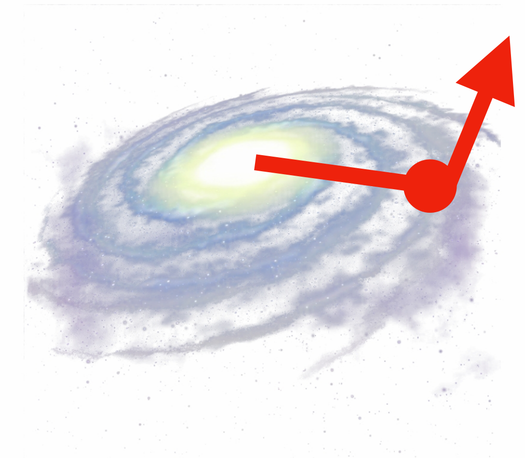


Vacuum Stability

Dark Matter



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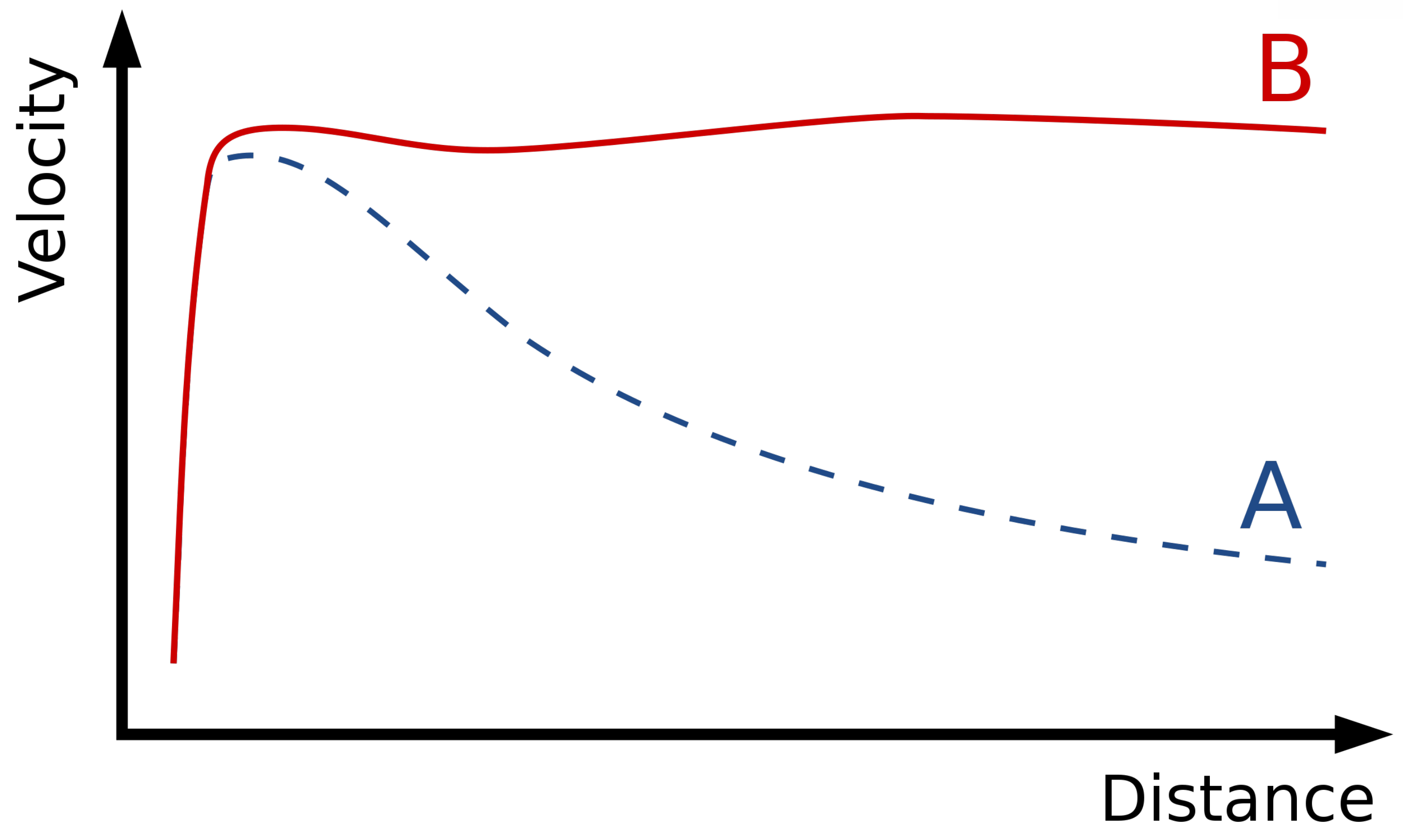

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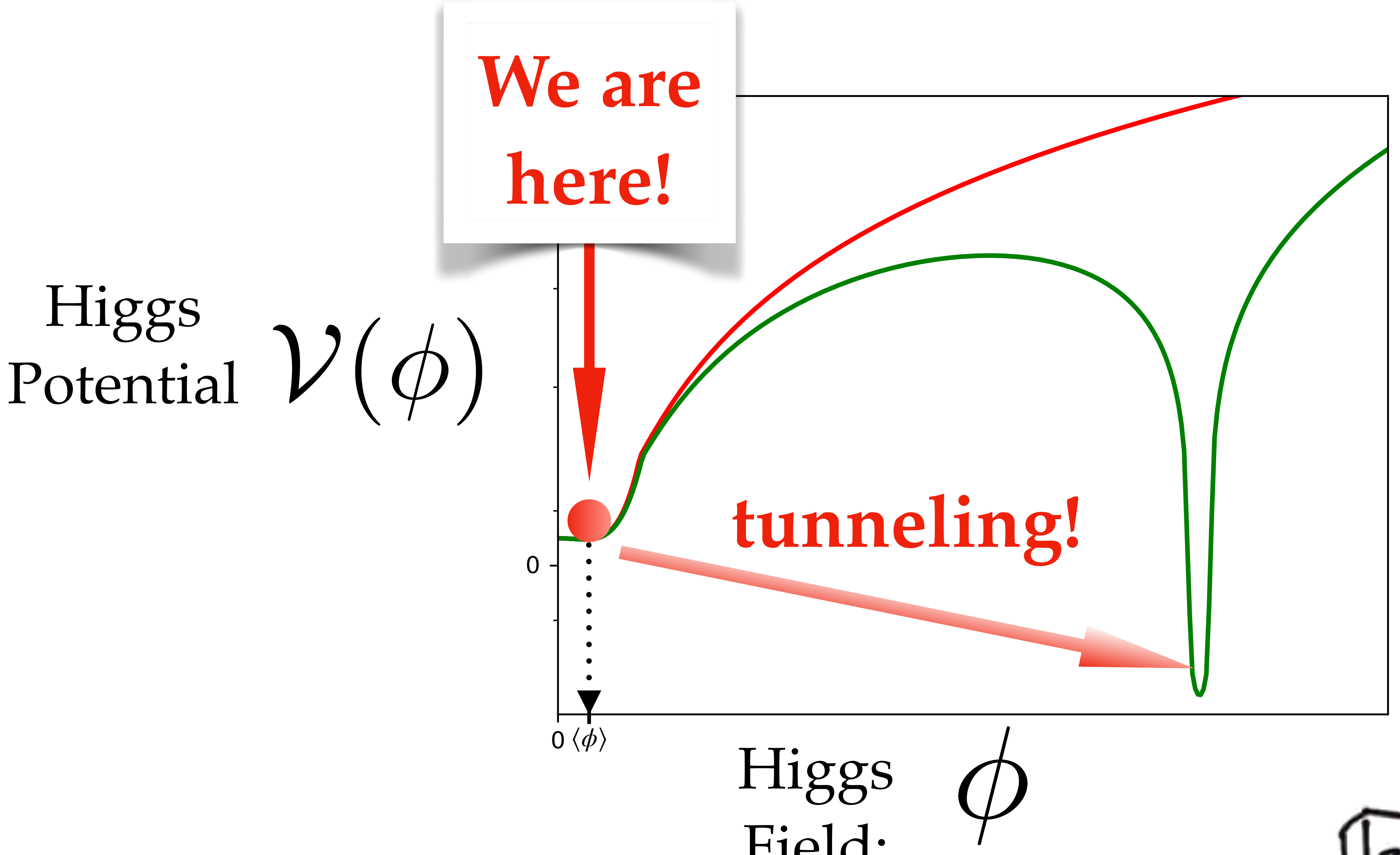

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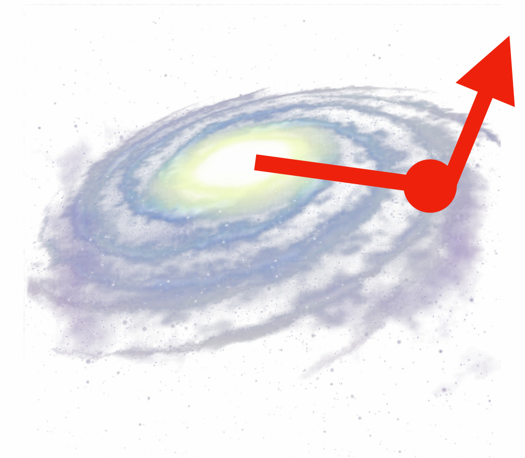

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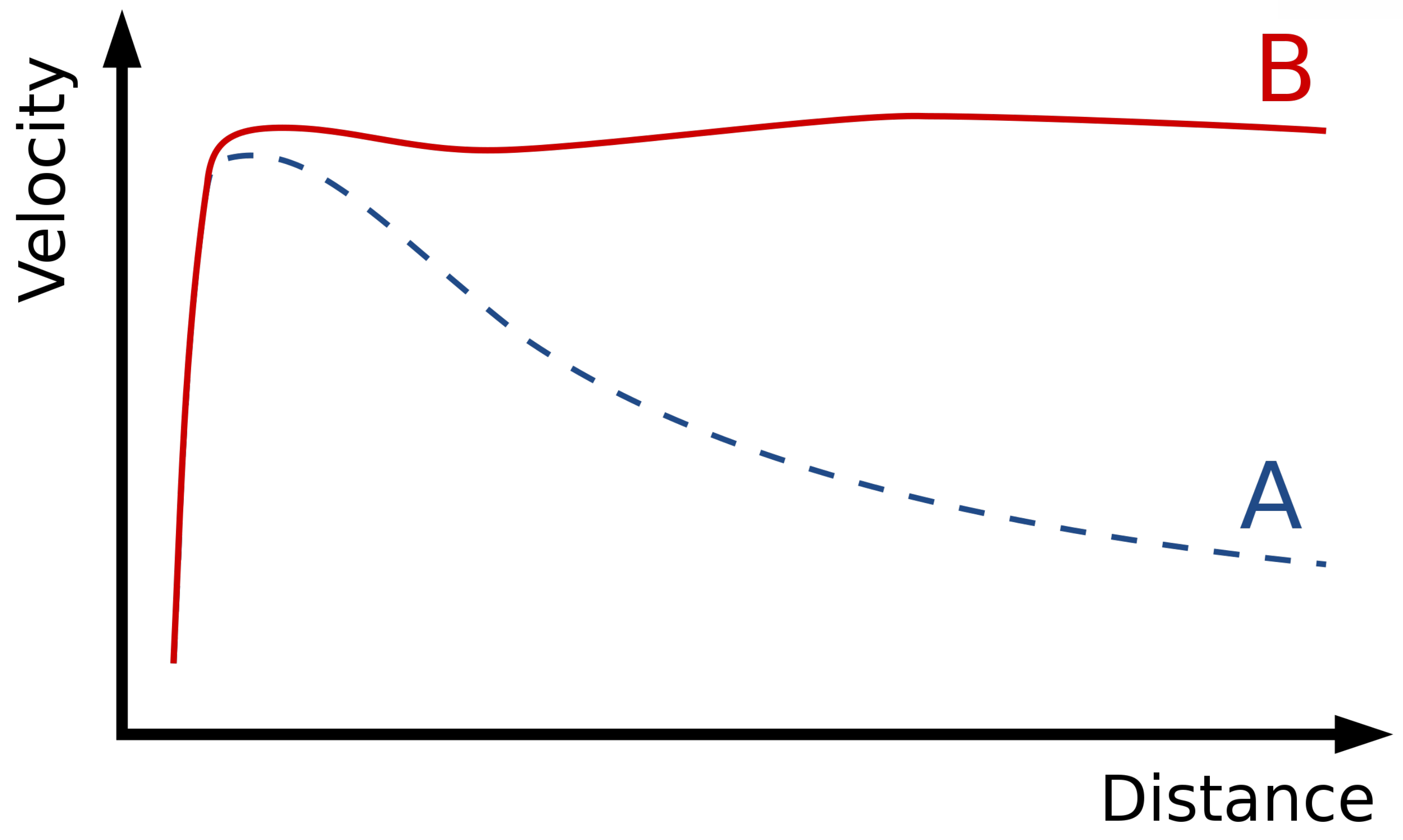

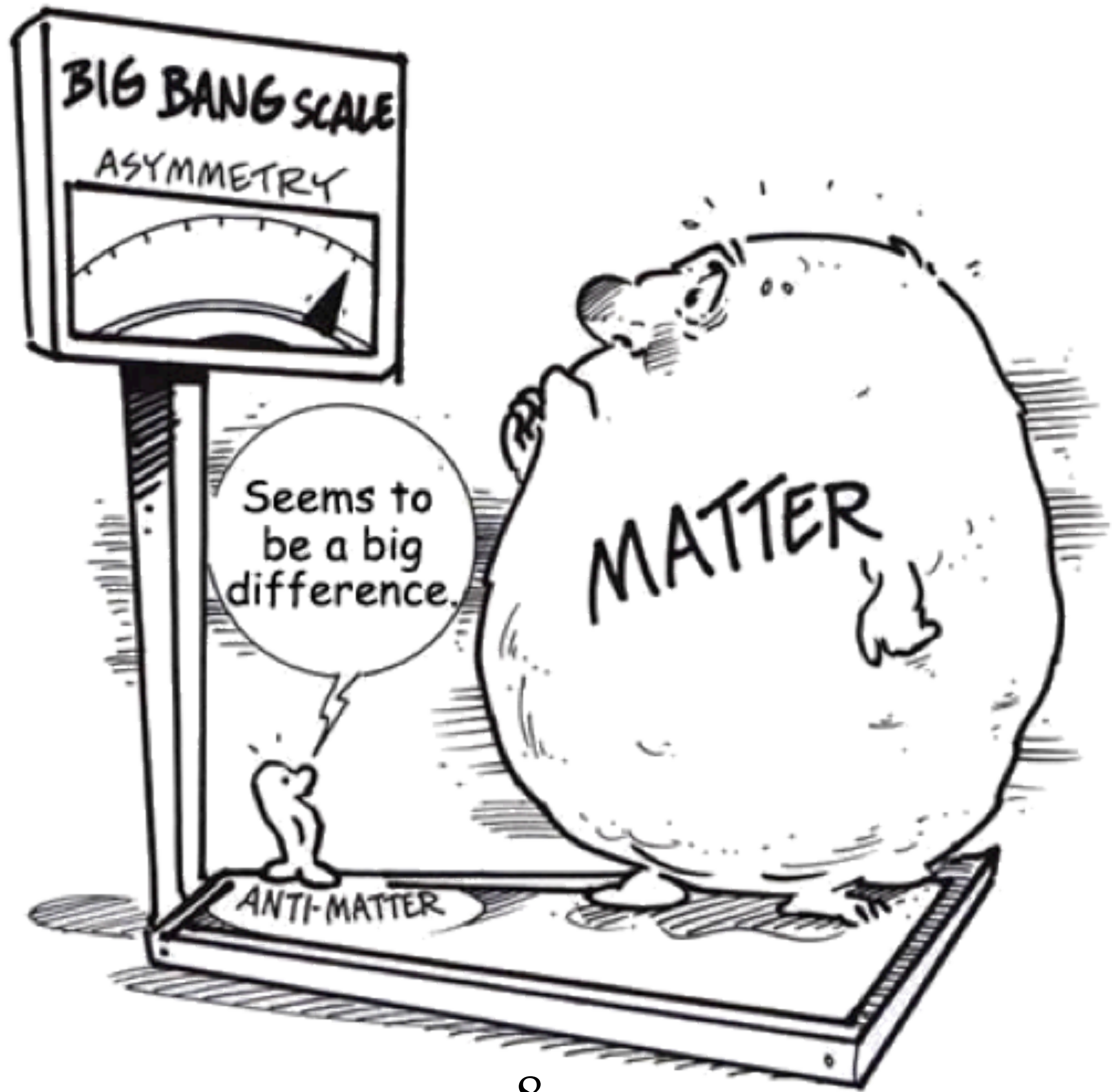

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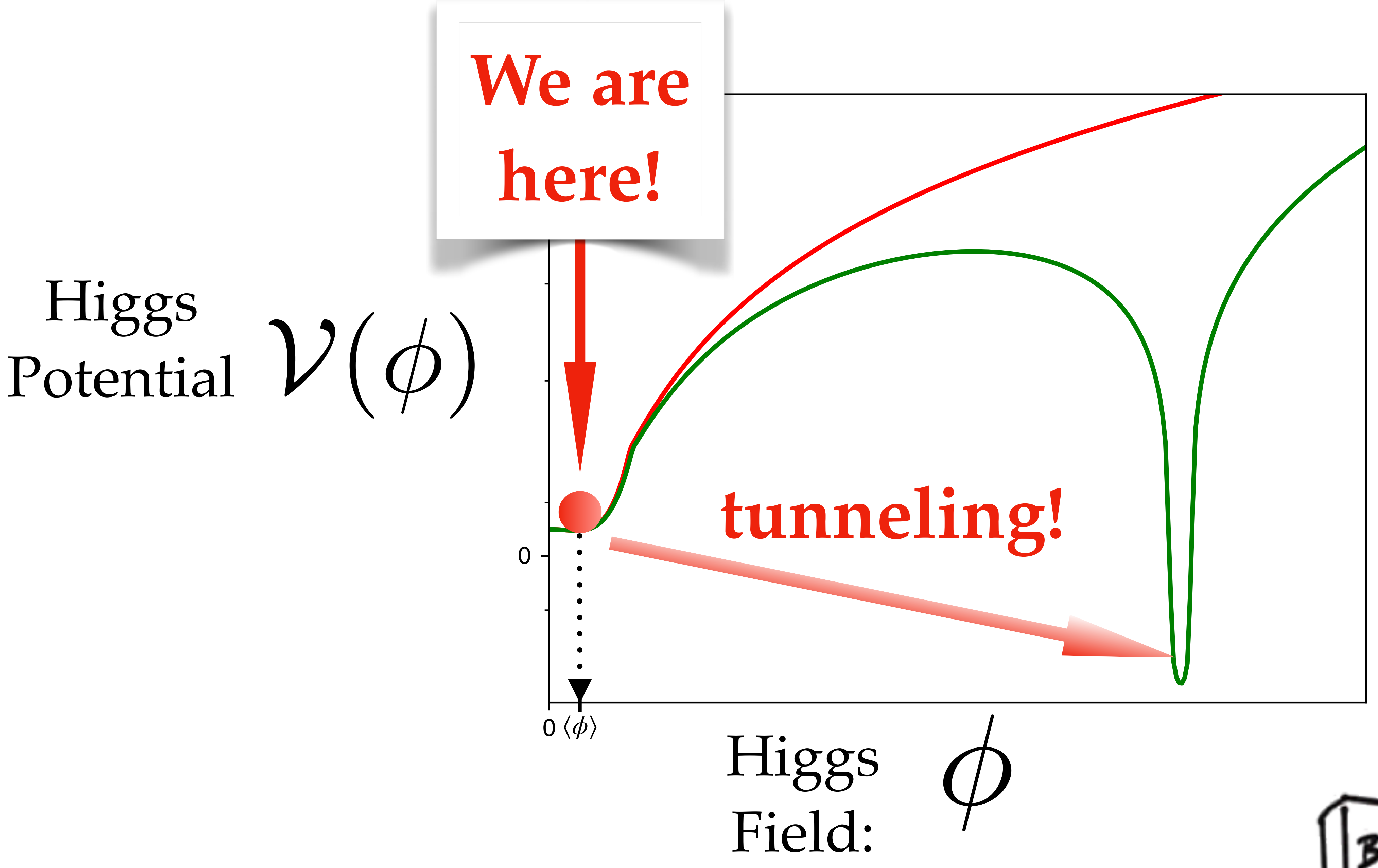

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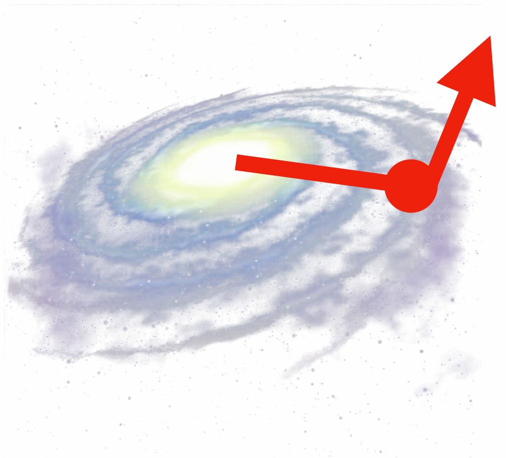

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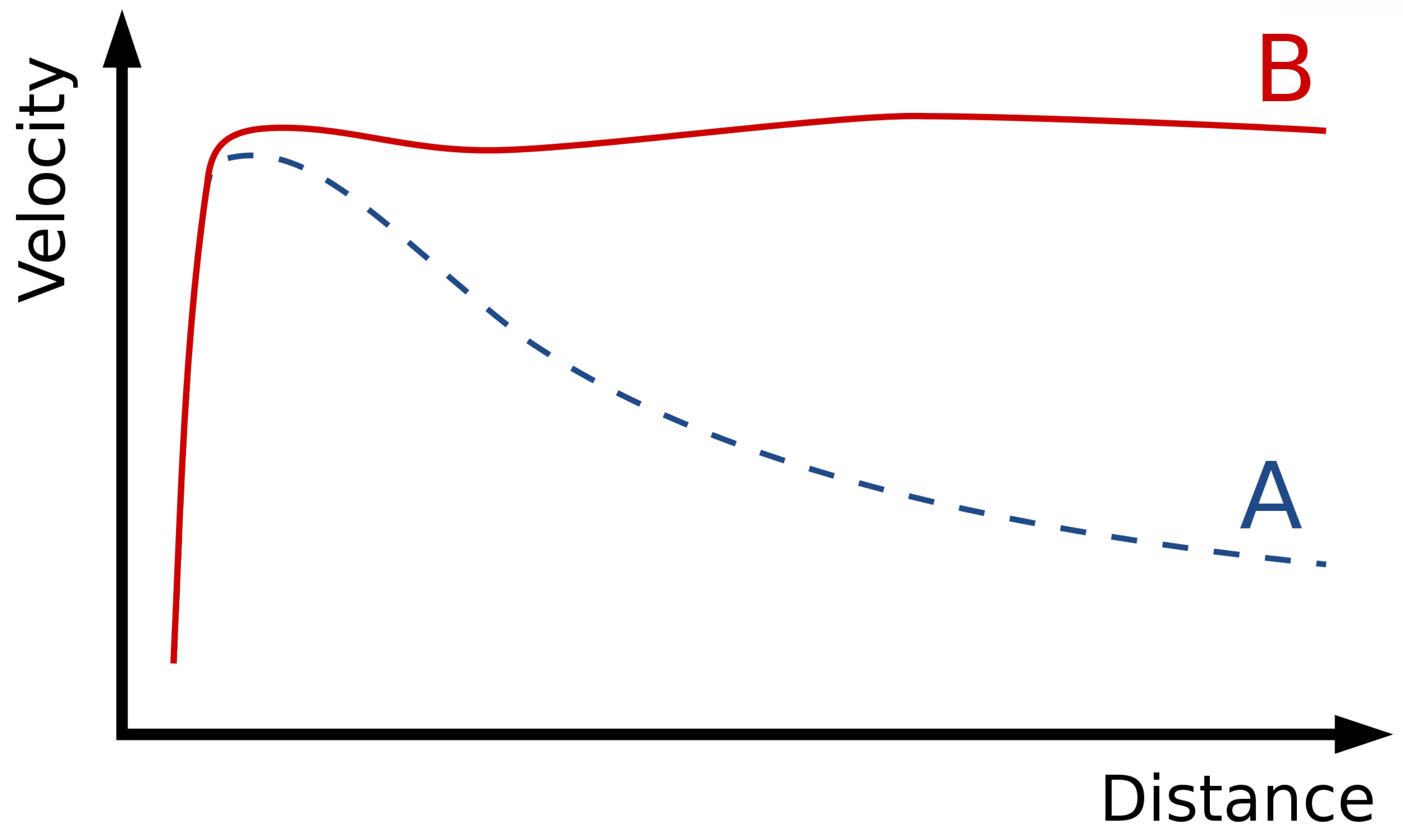

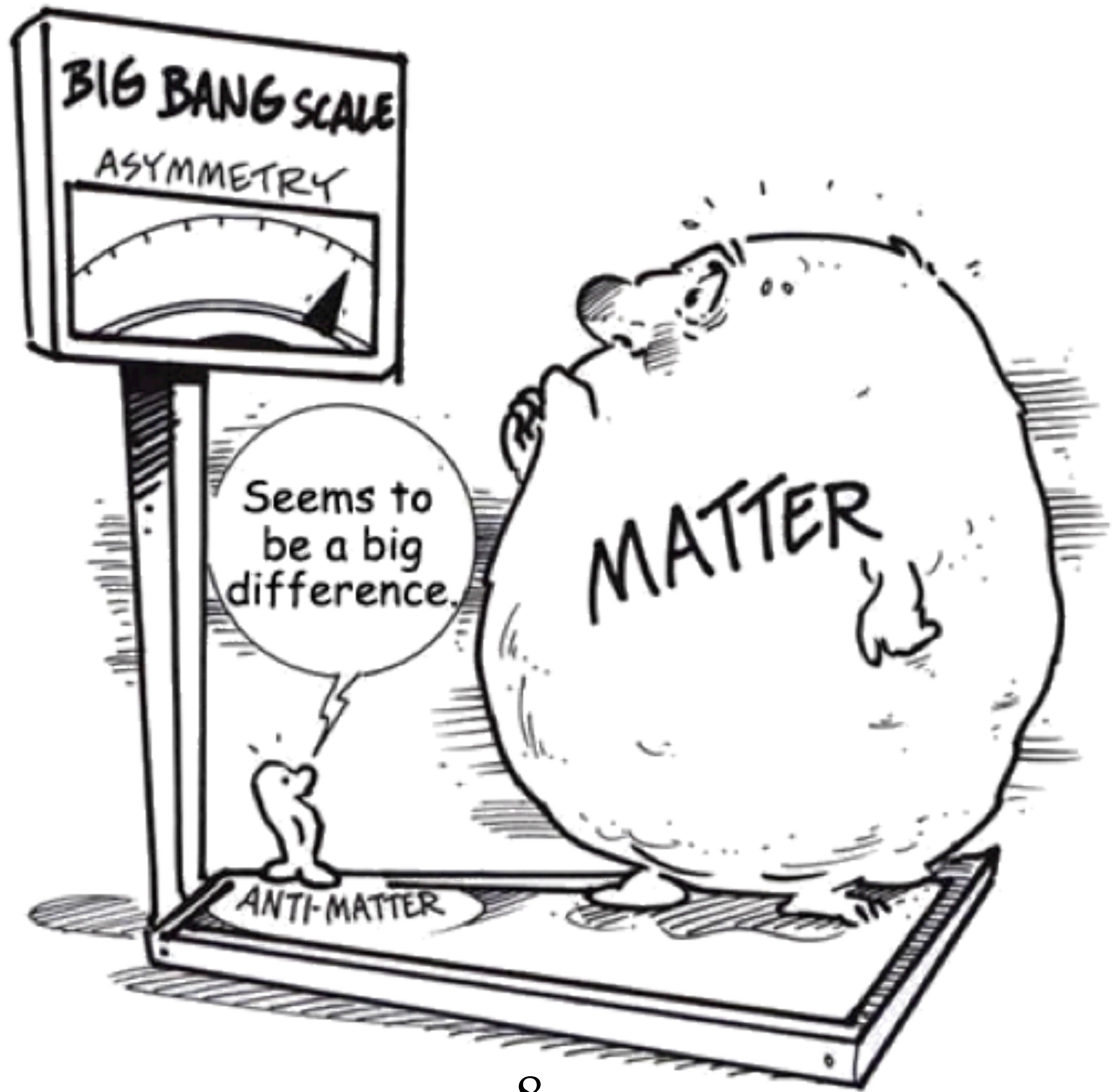

Matter-anti-matter Asymmetry

Dark Matter

Vacuum Stability

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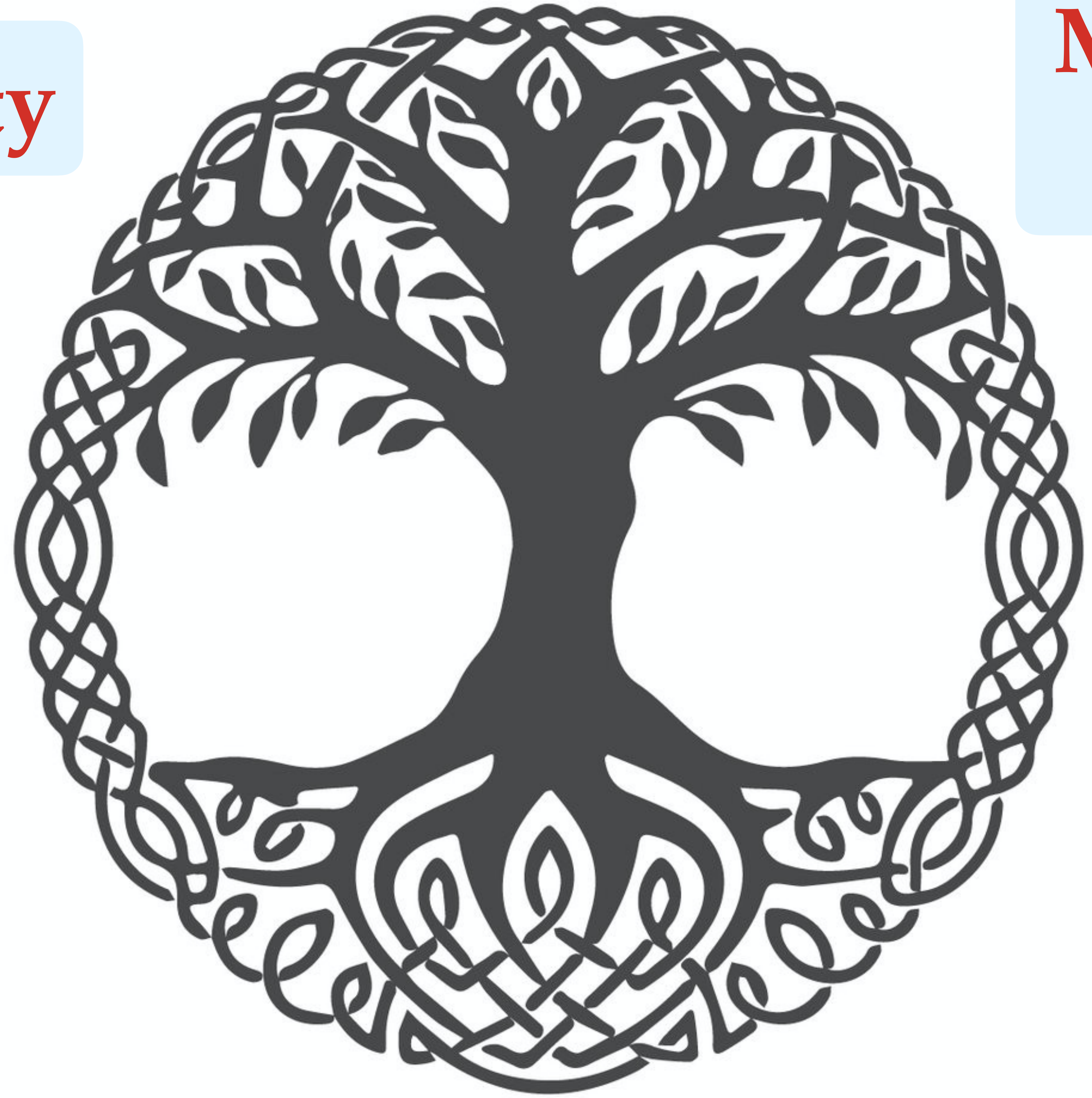

The Higgs Field & Symmetry Breaking

Dark Matter

Vacuum Stability

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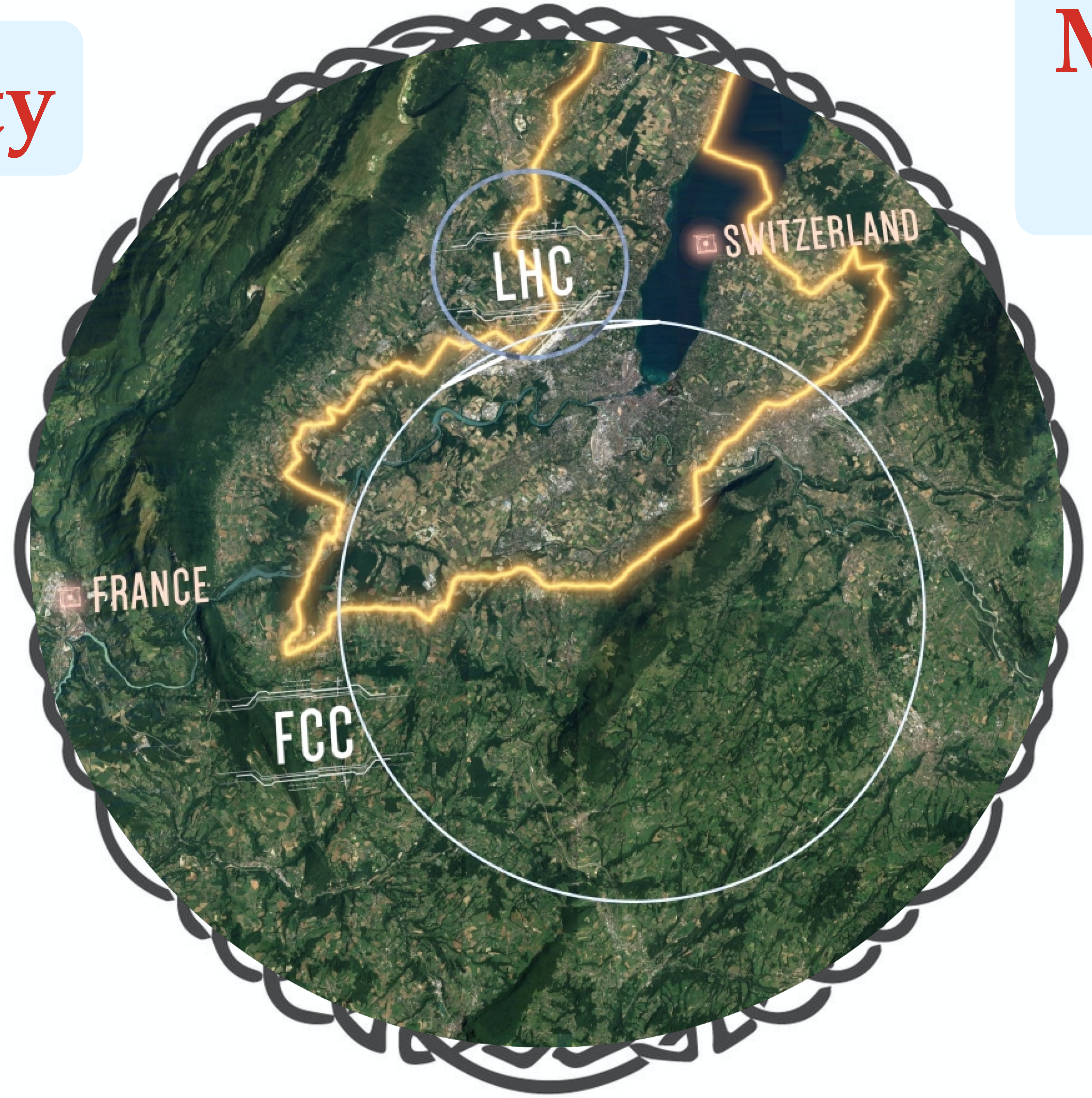

e.g. Future Circular Collider: pp@100 TeV, e^+e^-.

e.g. "High-Energy" LHC: pp@27 TeV.

e.g. Muon Collider.

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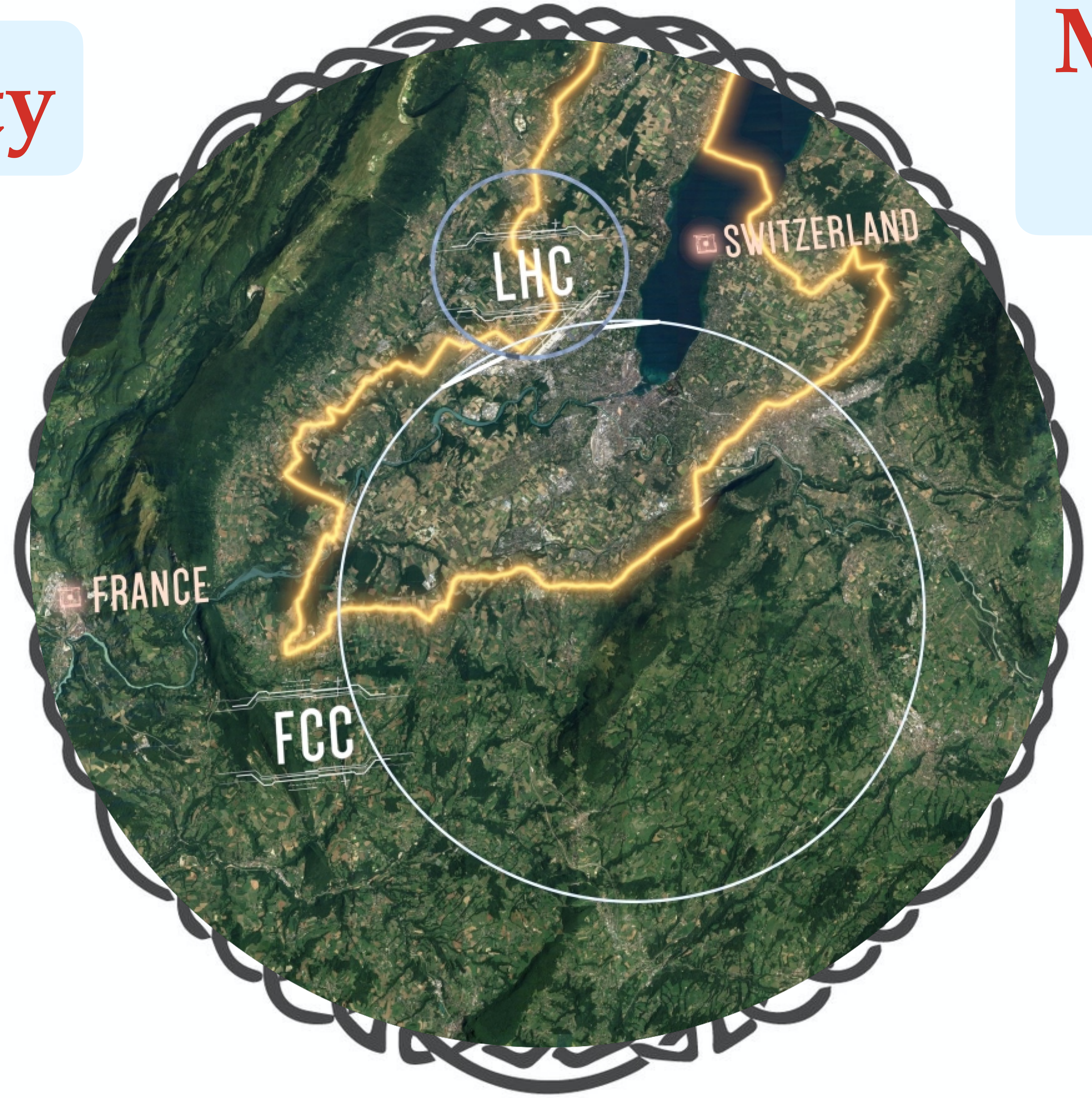

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The Higgs Field & Symmetry Breaking

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Breaking the Symmetry

Andreas Papaefstathiou

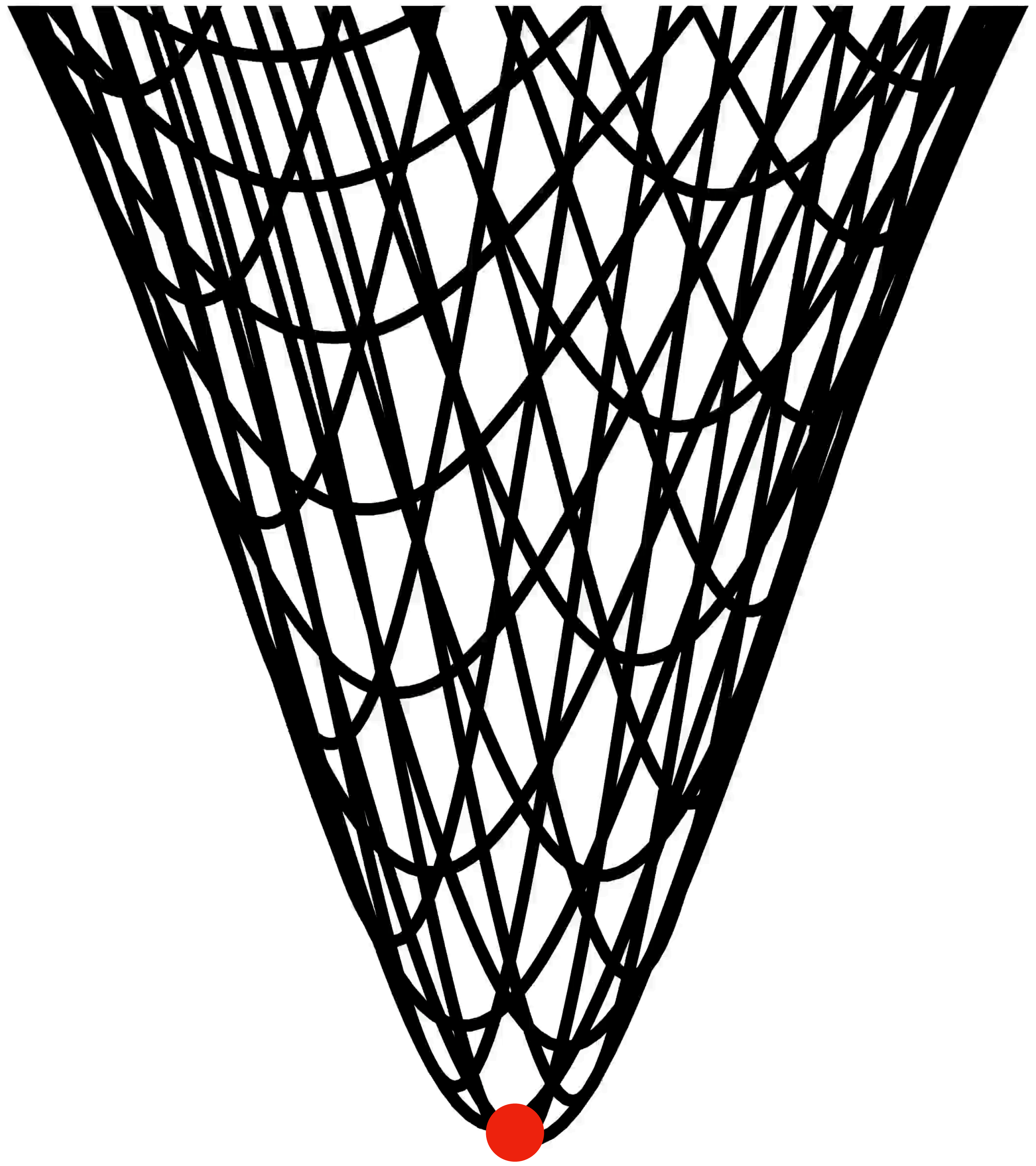
Breaking the Symmetry in the Standard Model

The potential of the Higgs field (ϕ), a complex doublet:

$$\phi = \begin{pmatrix} \phi_1 + i\phi_3 \\ \phi_2 + i\phi_4 \end{pmatrix}$$

(Arbitrarily) Set $\phi_3 = \phi_4 = 0$ to illustrate potential in (ϕ_1, ϕ_2) plane.

An example of the evolution of $\mathscr{V}(\phi)$,
Early universe → Today:



$\mathscr{V}(\phi)$

Higgs Field Potential

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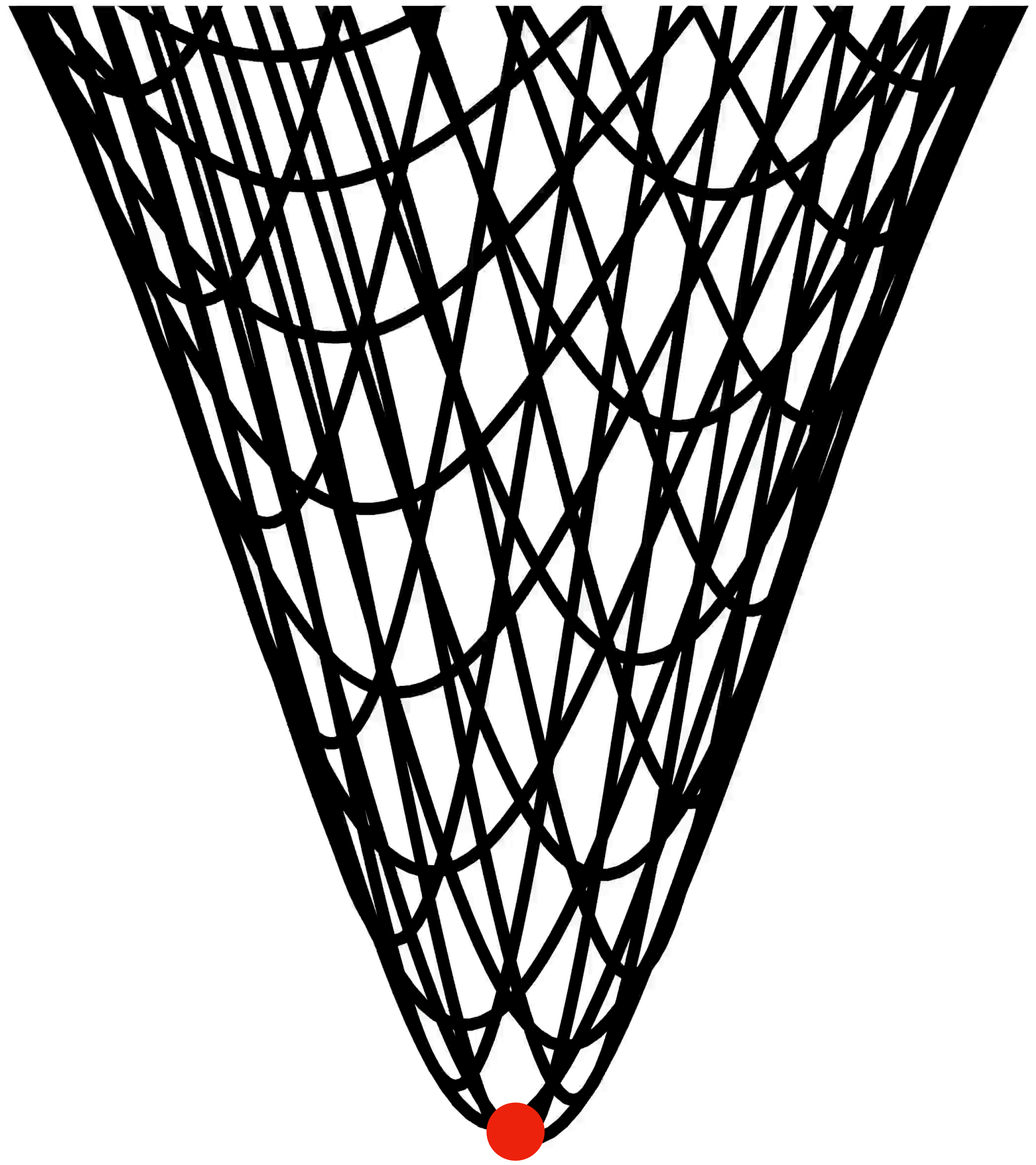

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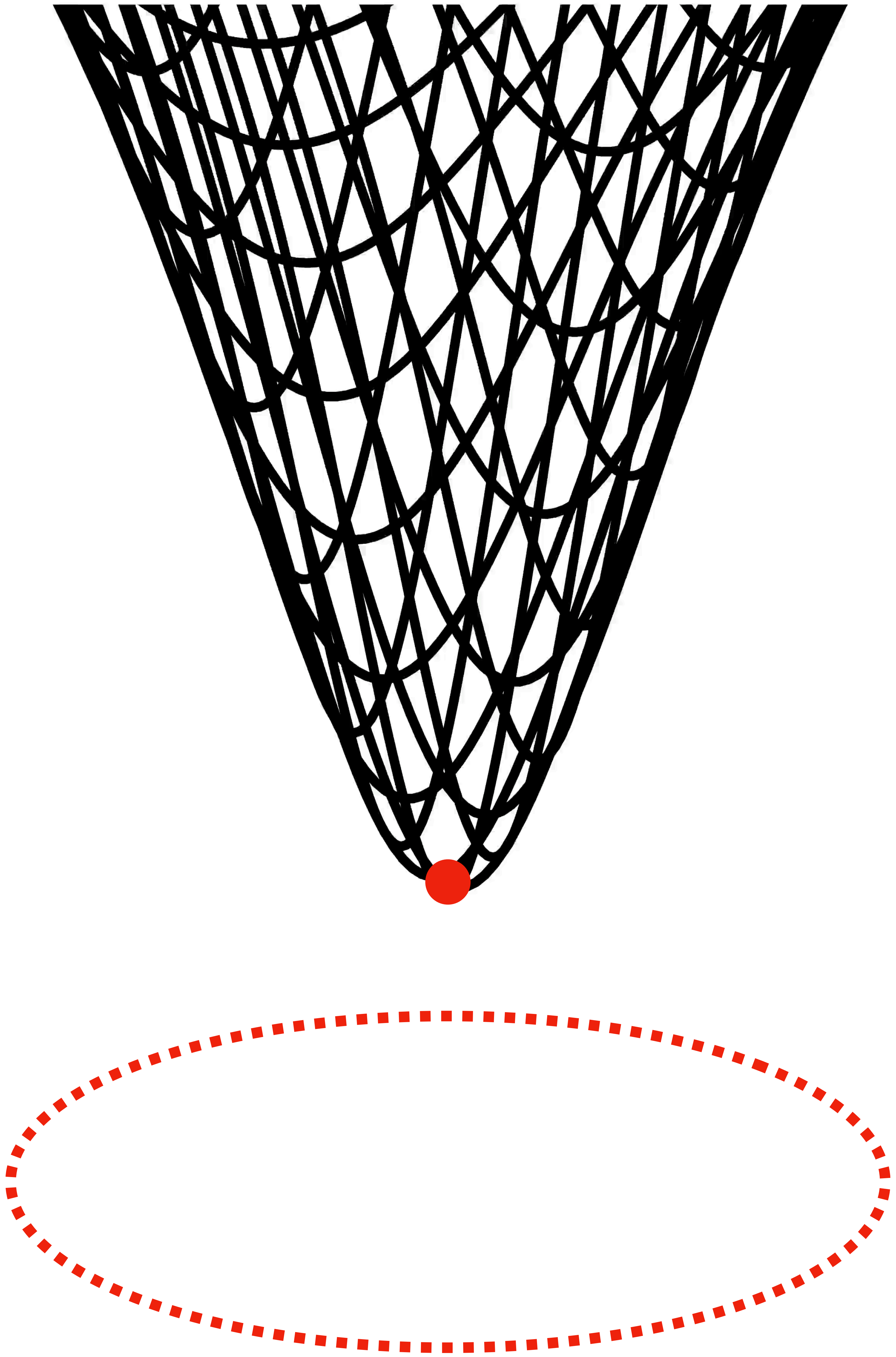

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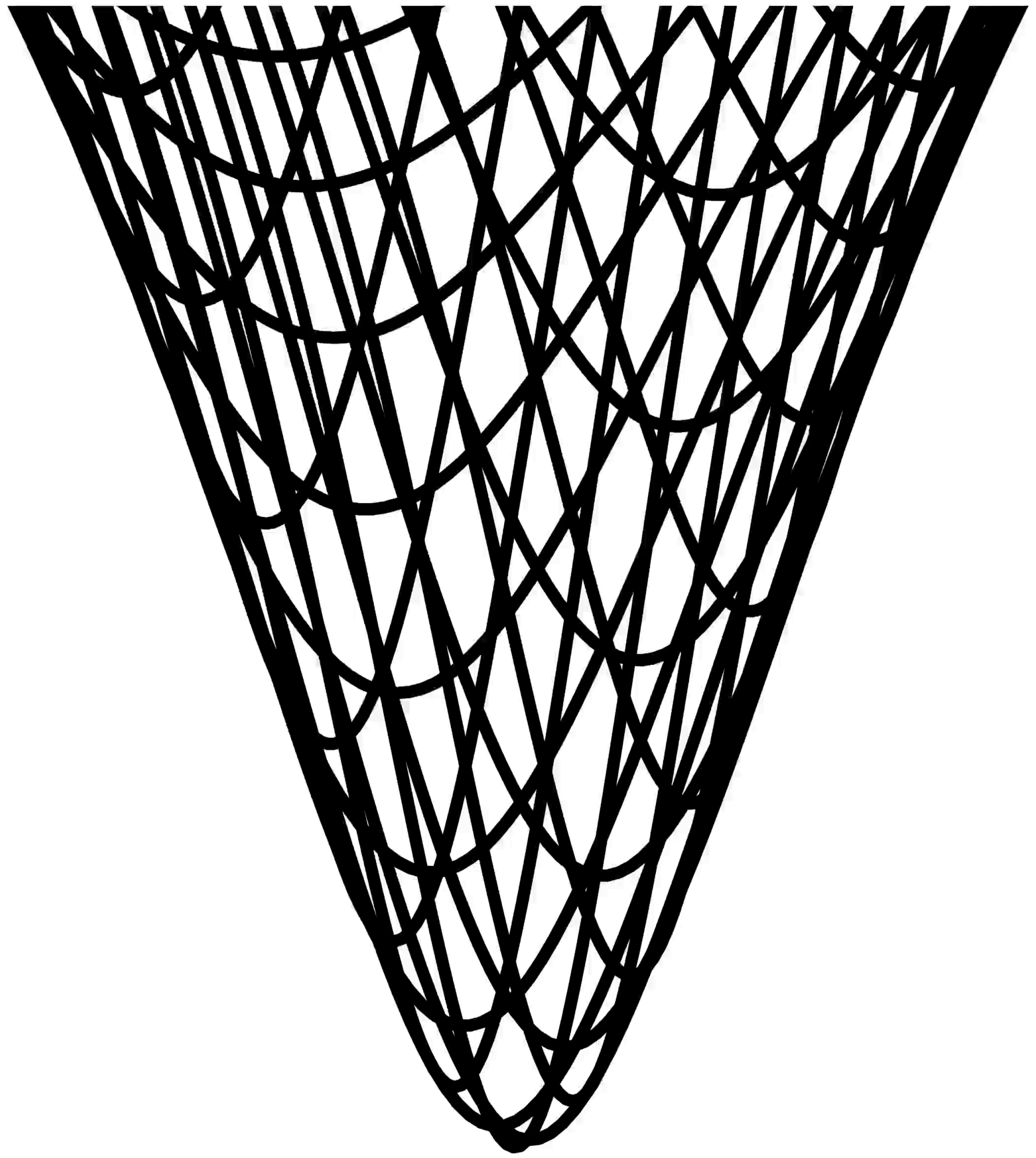

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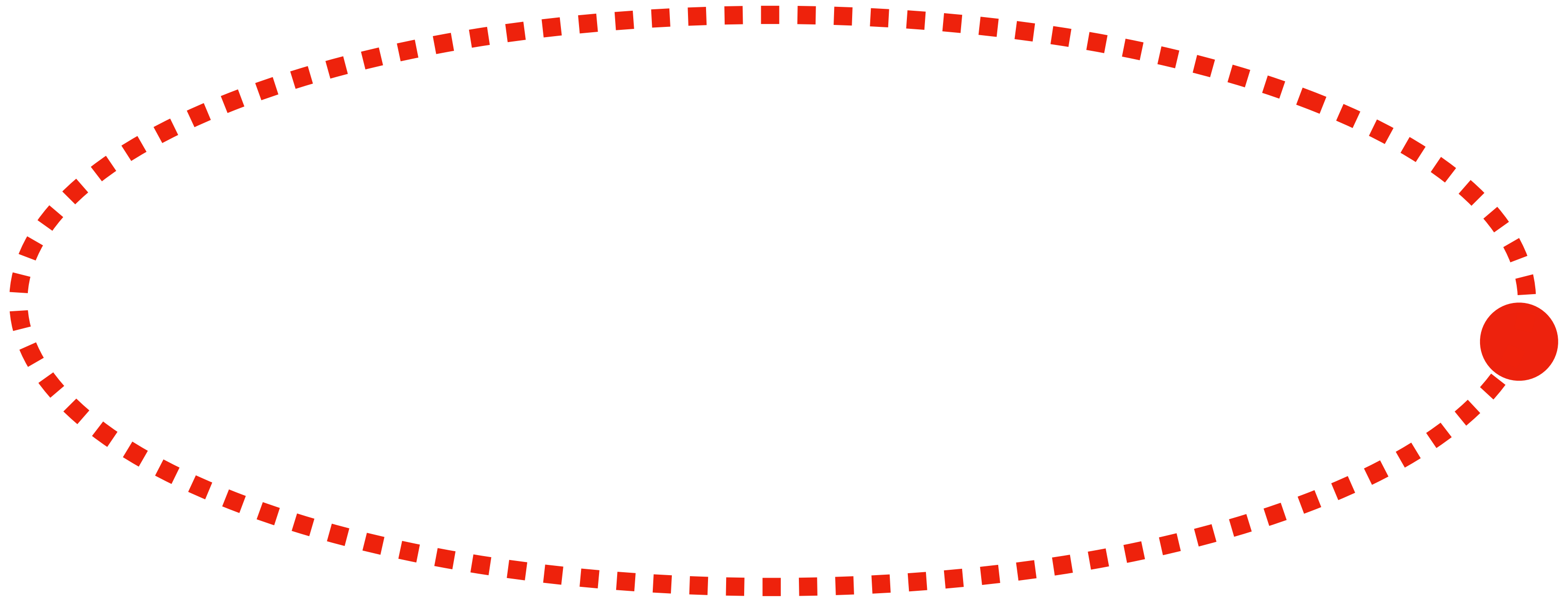
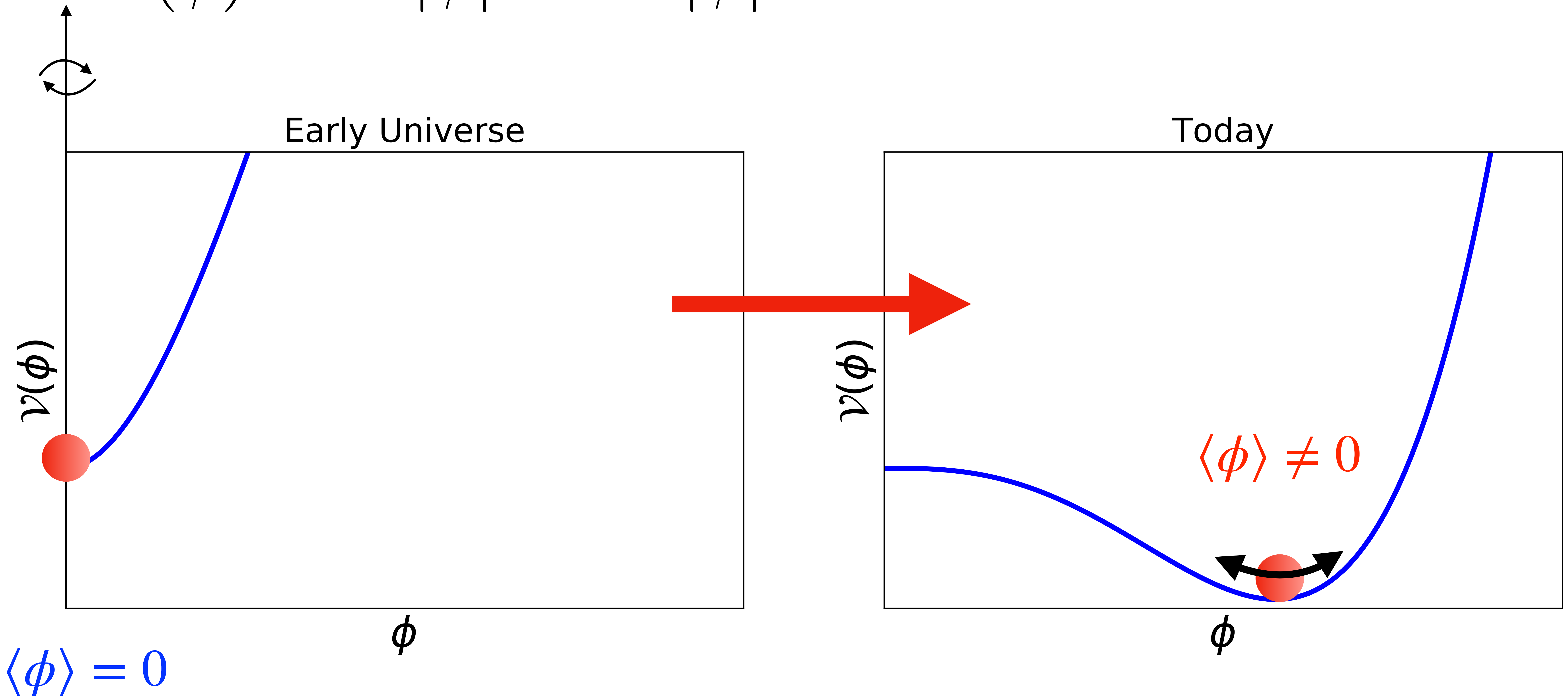


Breaking the Symmetry in the Standard Model

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

Higgs field (ϕ) potential

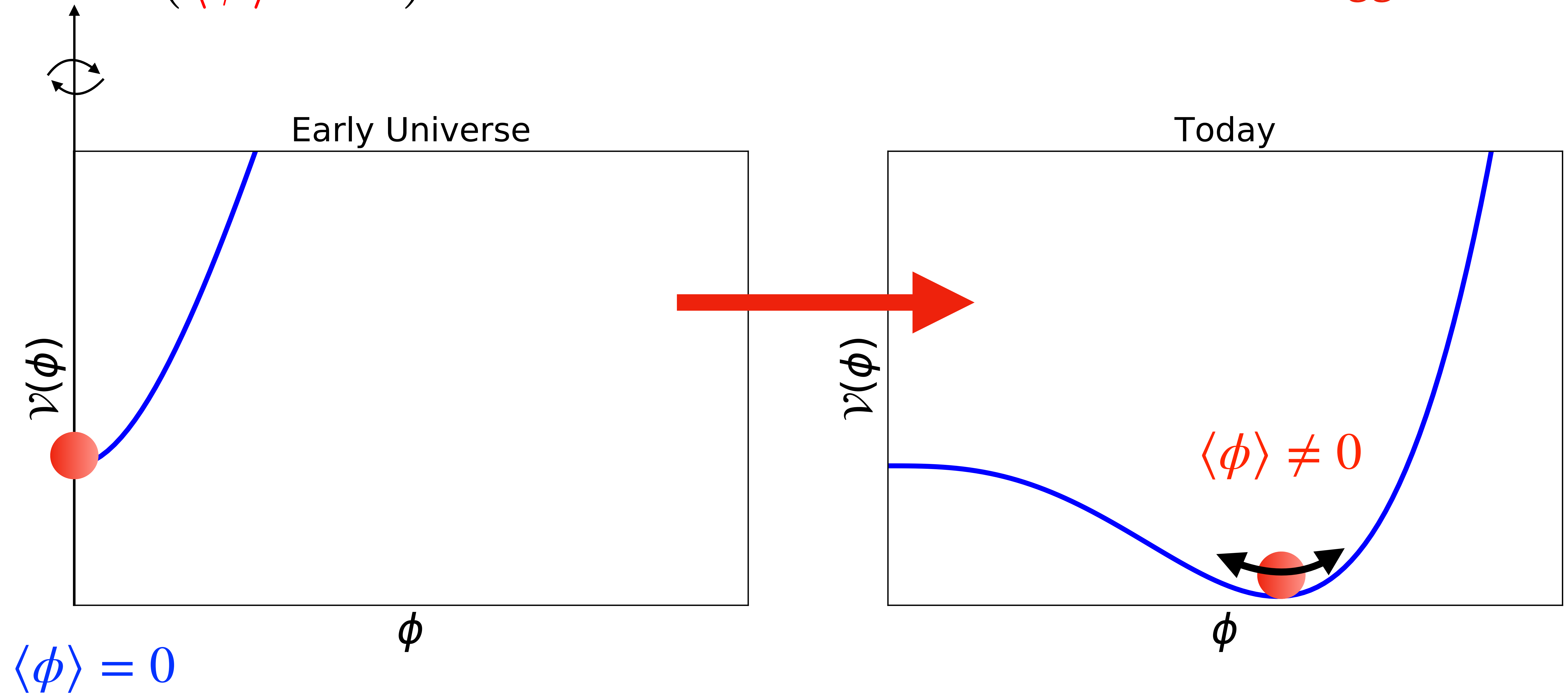


More Symmetry → Less (obvious) Symmetry

Breaking the Symmetry in the Standard Model

$$\mathcal{V}(\langle\phi\rangle + h) = \bullet h^2 + \blacktriangle h^3 + \blacksquare h^4$$ → h **is the Higgs boson! (LHC, 2012)**

Higgs field (ϕ) potential



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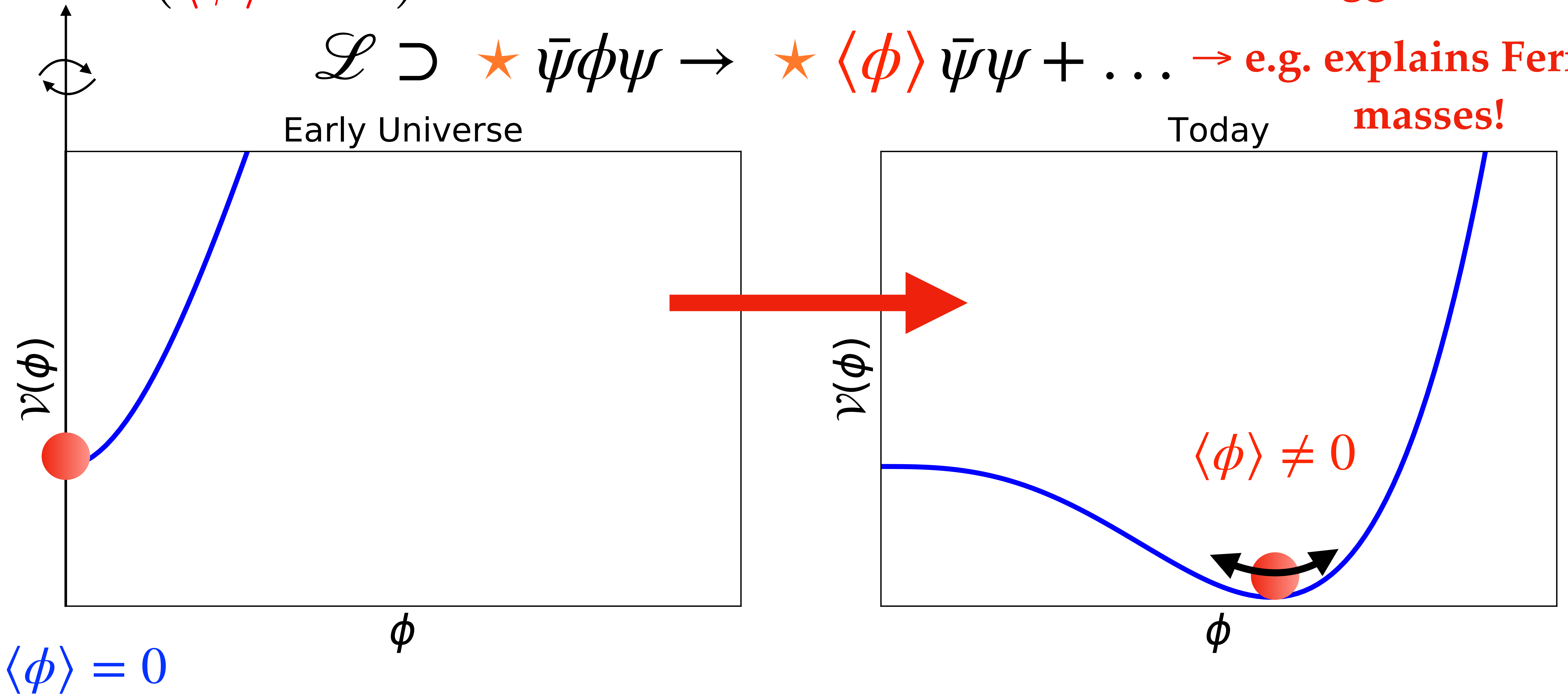
$$\mathscr{L} \supset \star\, \bar{\psi}\phi\psi \rightarrow \star\, \langle\phi\rangle\, \bar{\psi}\psi + \ldots$$ → **e.g. explains Fermion masses!**

Higgs field (ϕ) potential



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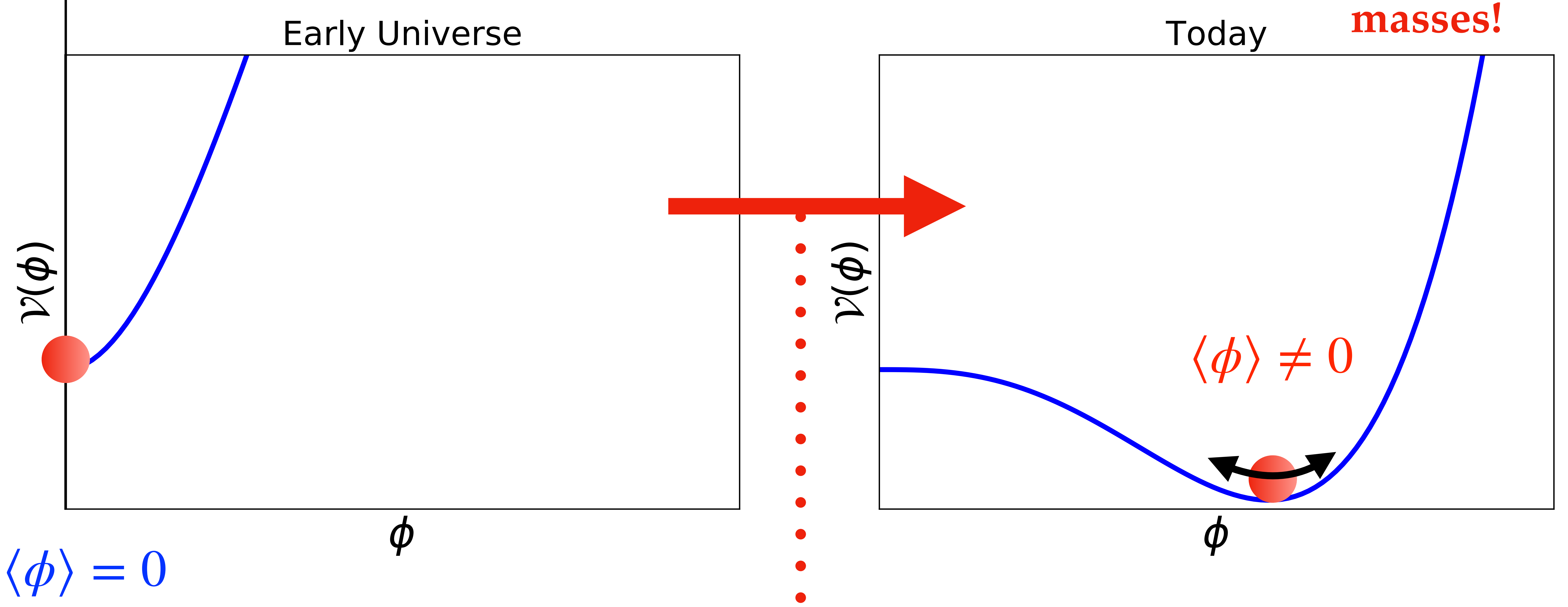

More Symmetry → Less (obvious) Symmetry

≡ Electro-Weak Phase Transition (EWPT)

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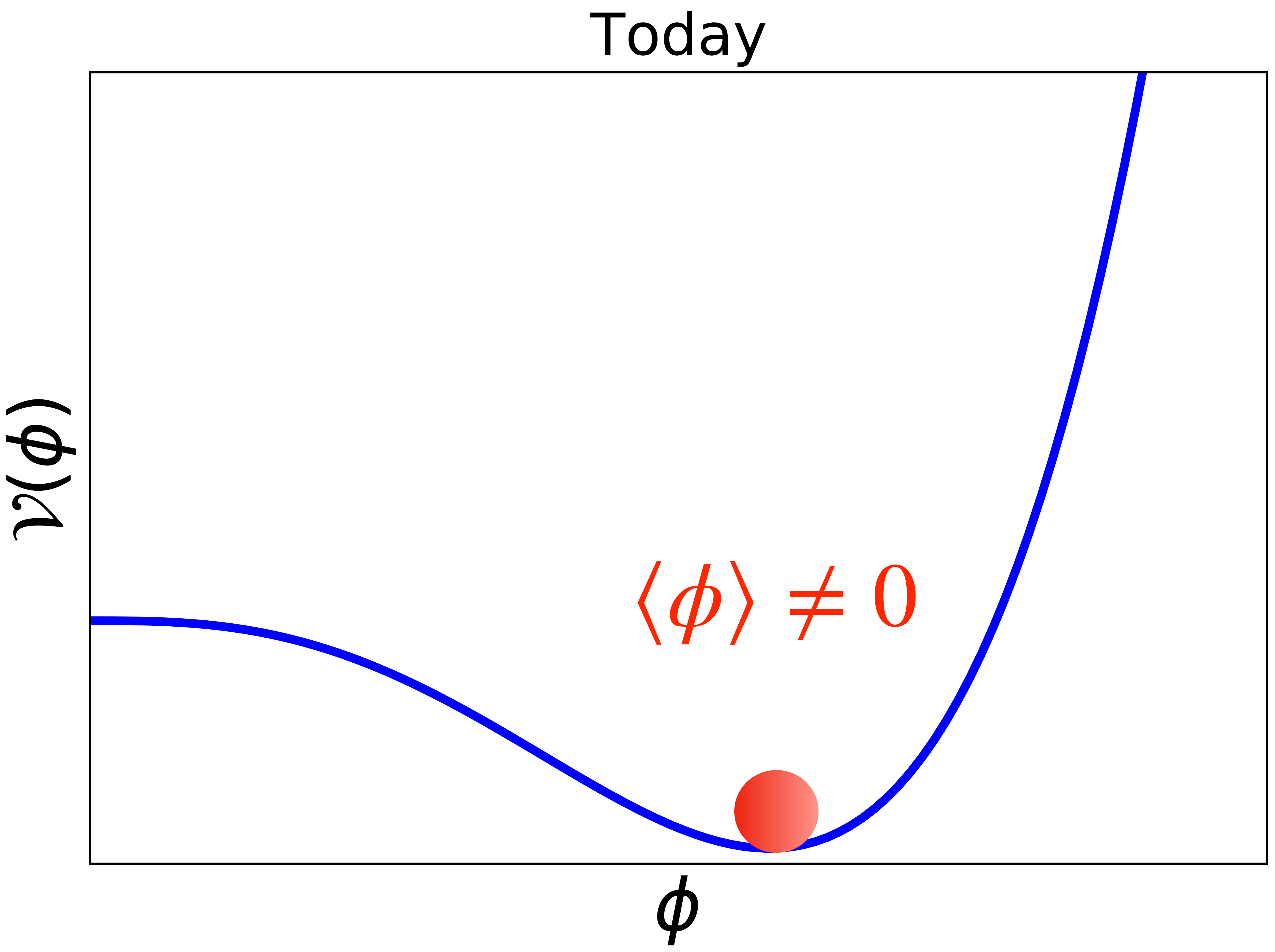
The Higgs Boson's Potential

$$\mathcal{V}(\langle\phi\rangle + h) = \bullet h^2 + \blacktriangle h^3 + \blacksquare h^4$$ → **the Higgs boson's self-interactions.**



→ **Determine shape of potential by measuring:**

$$\{\bullet, \blacktriangle, \blacksquare\}$$

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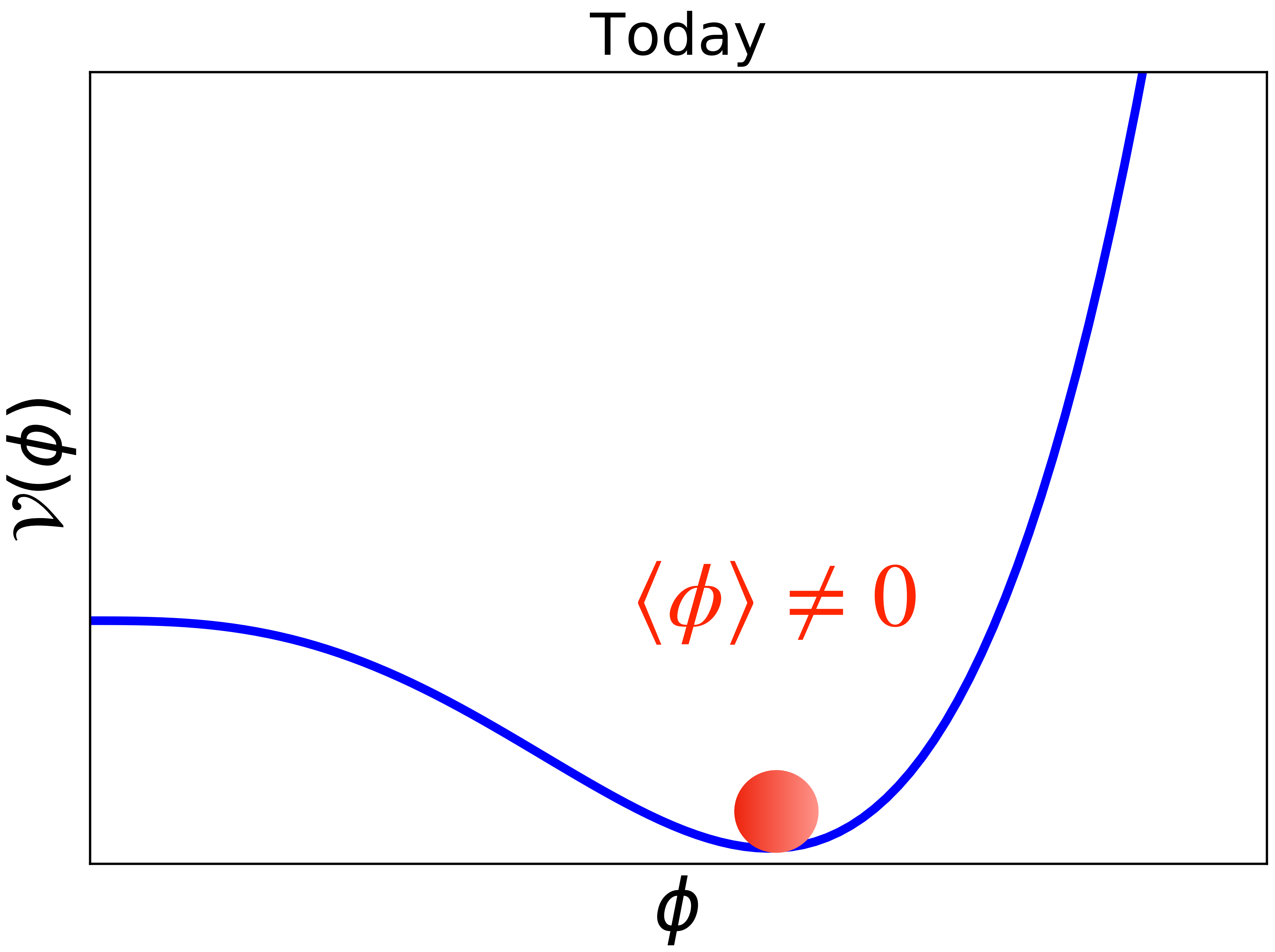

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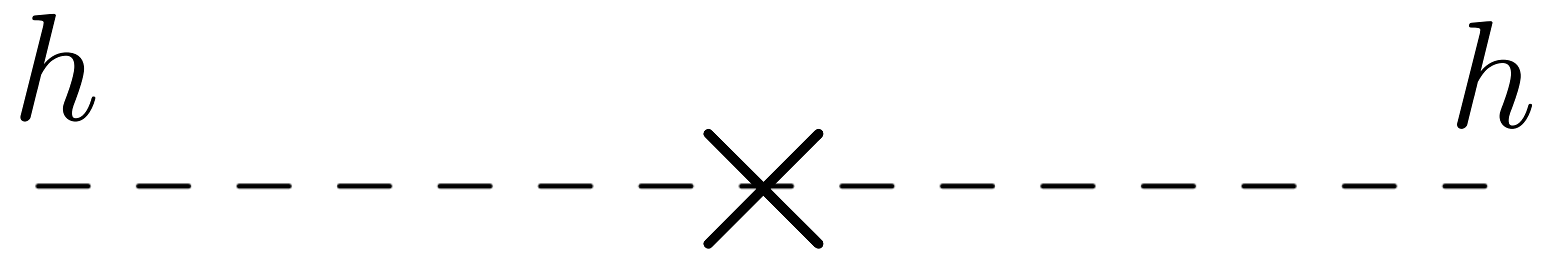

Higgs boson discovery @ LHC, 2012 ✅

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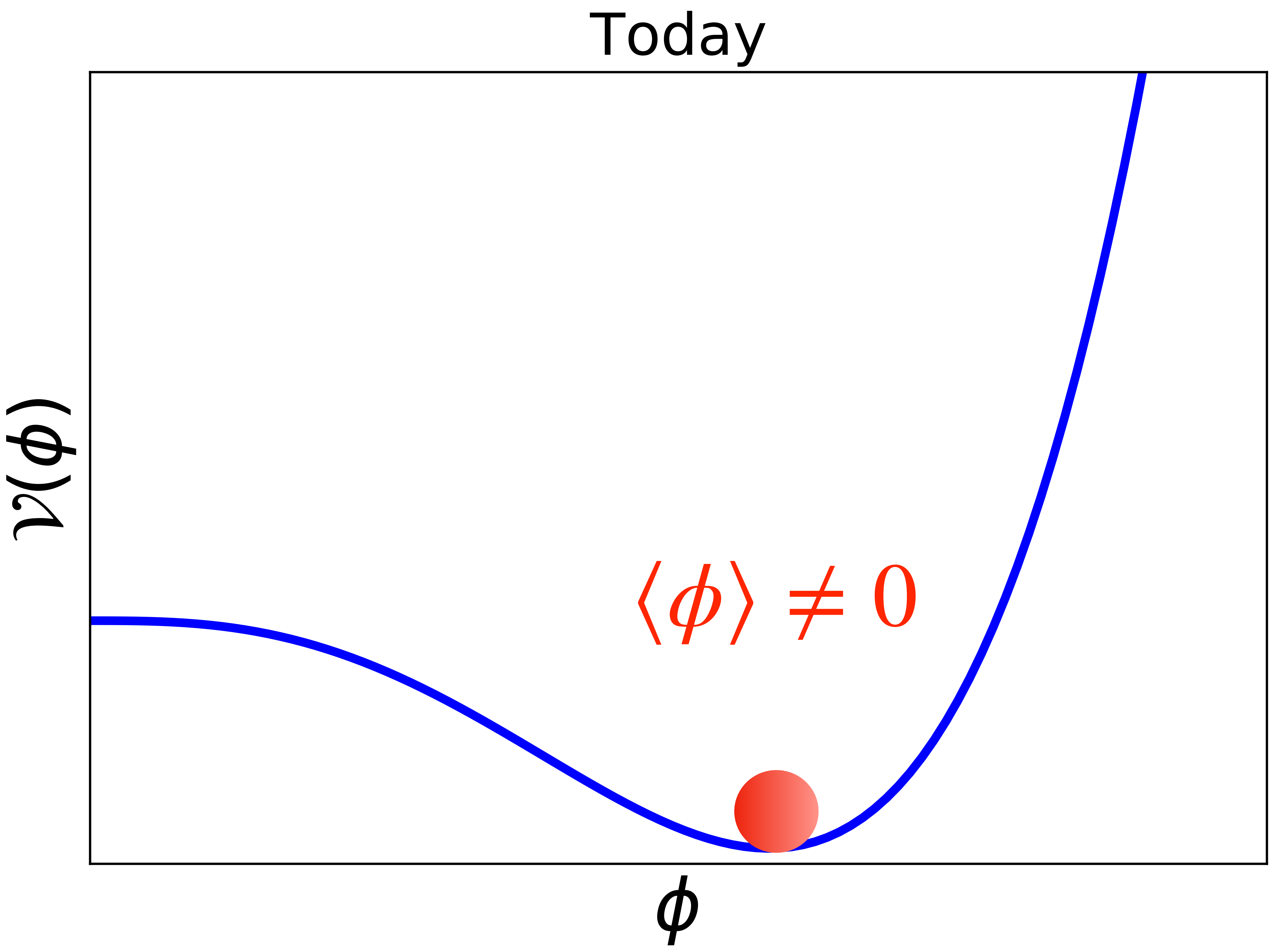

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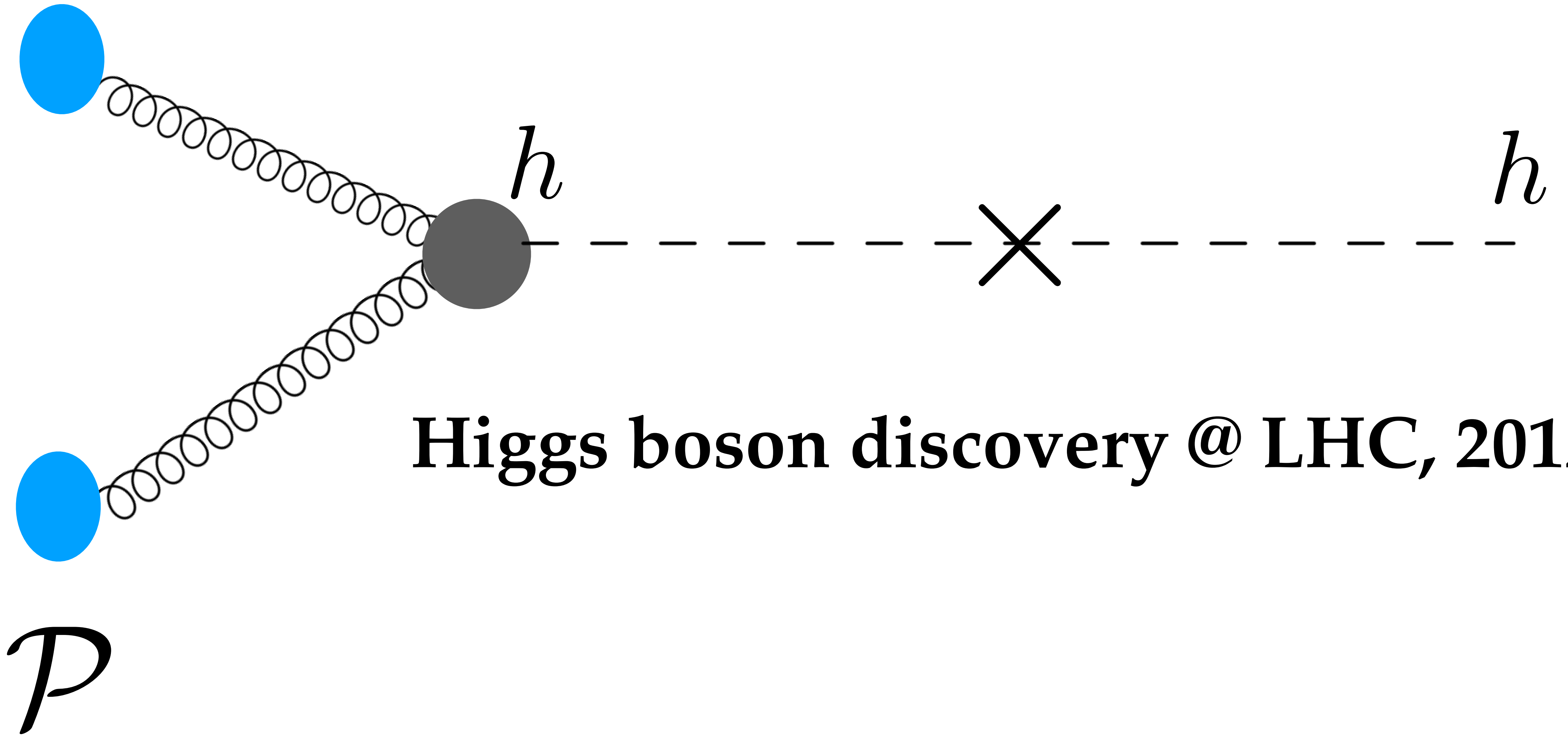

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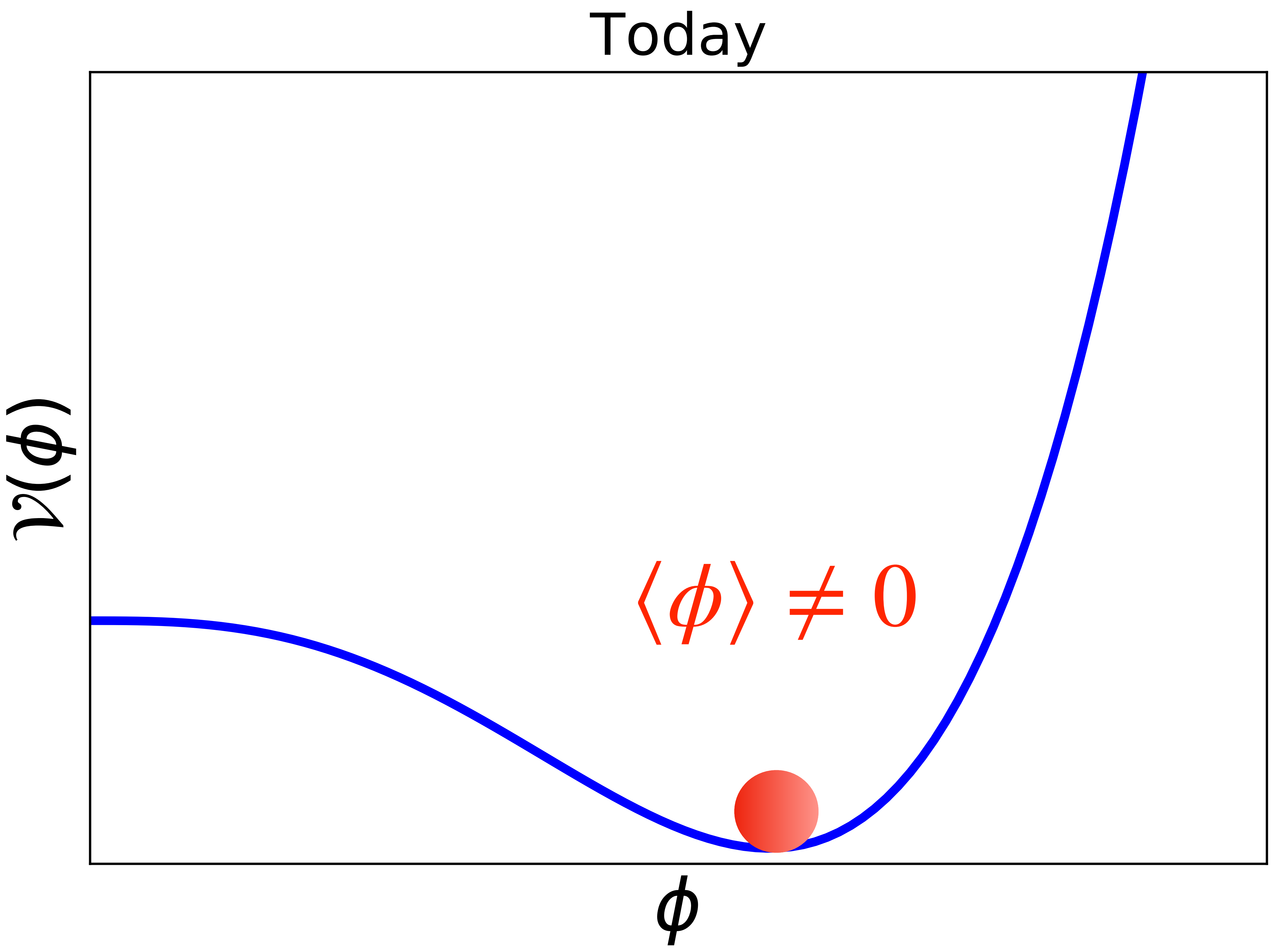

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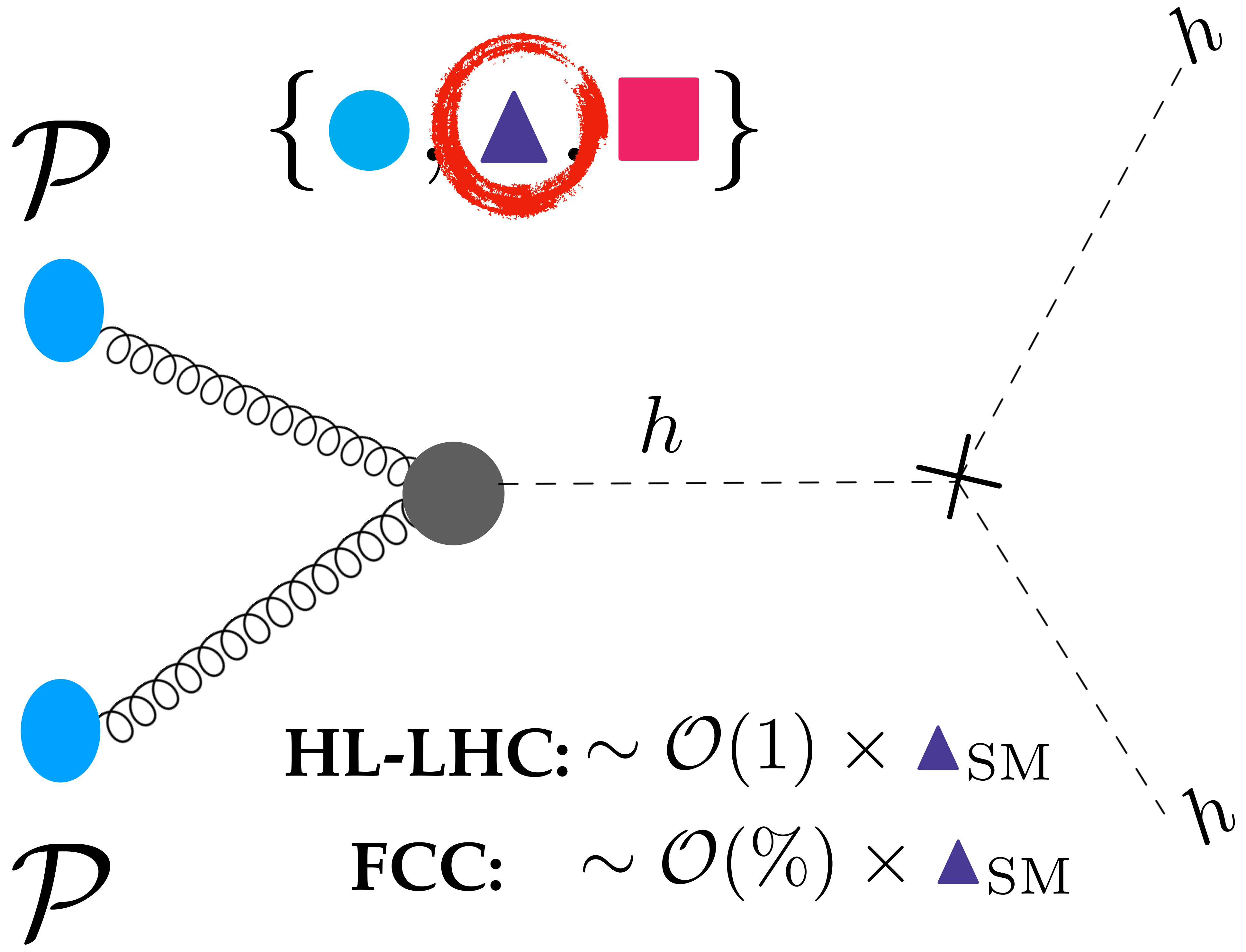

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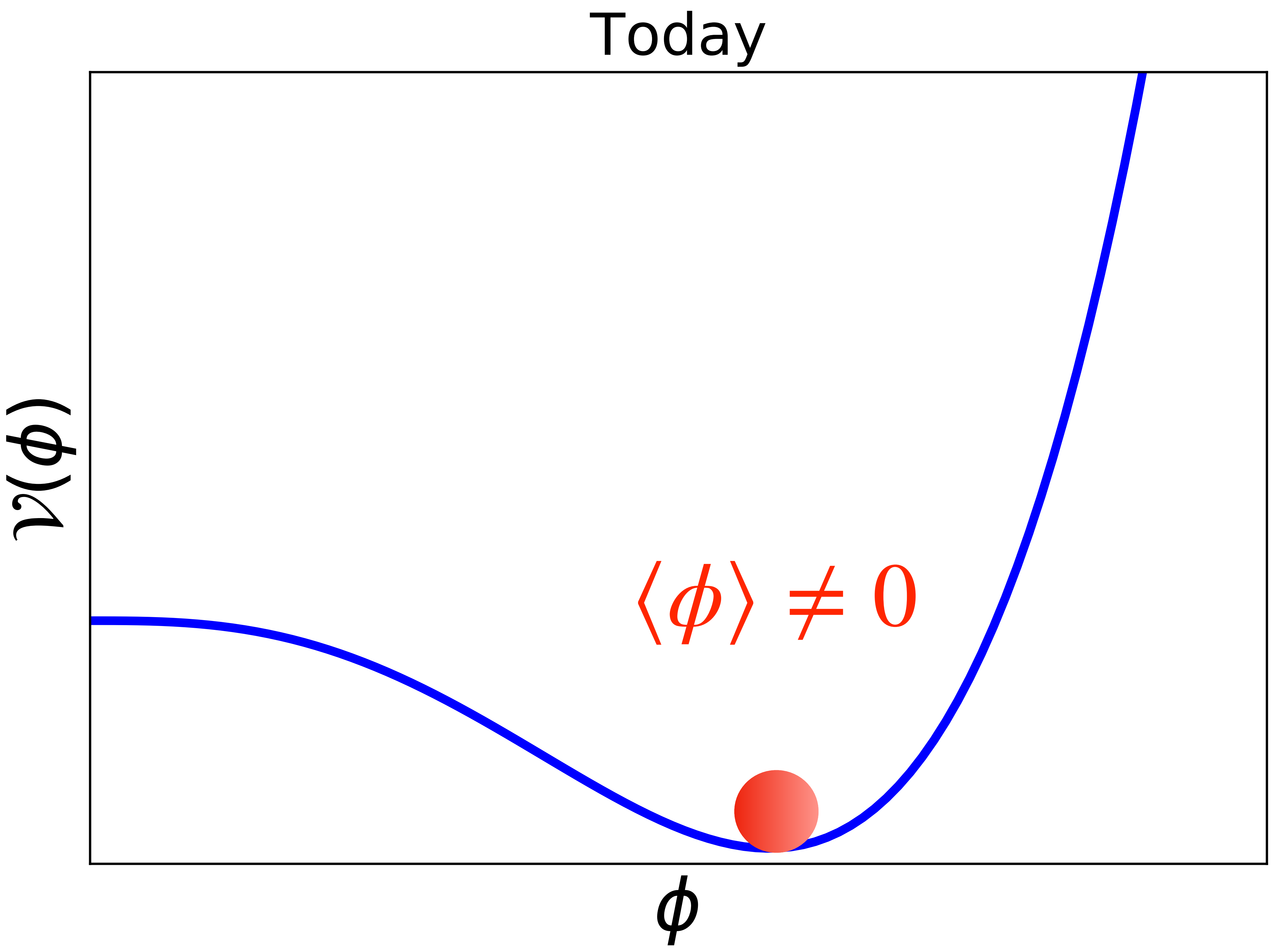

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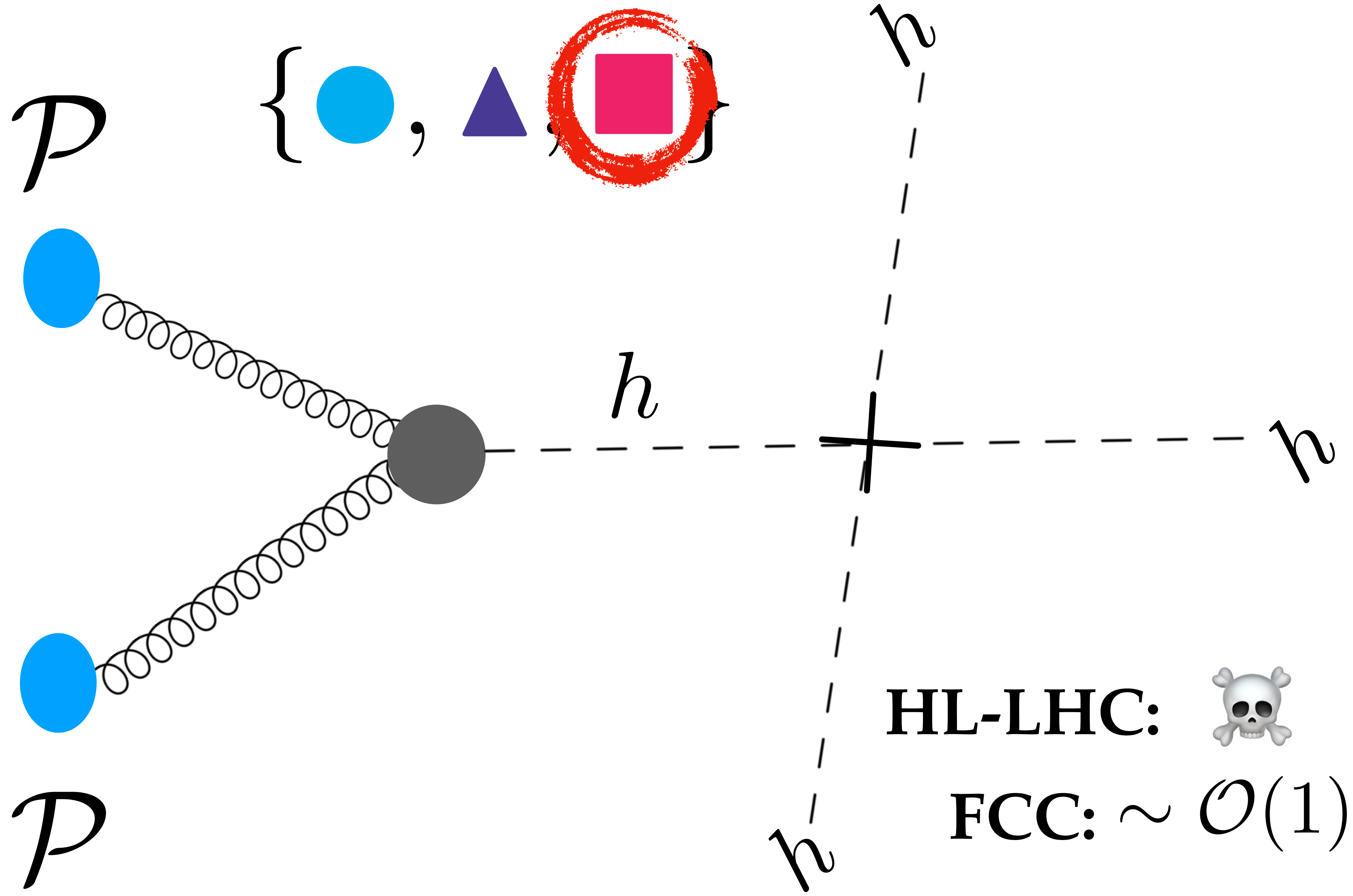

HL-LHC: ☠️

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

[e.g. **AP**, Sakurai, arXiv:1508.06524, **AP**, Tetlalmatzi-Xolocotzi, Zaro, arXiv:1909.09166]

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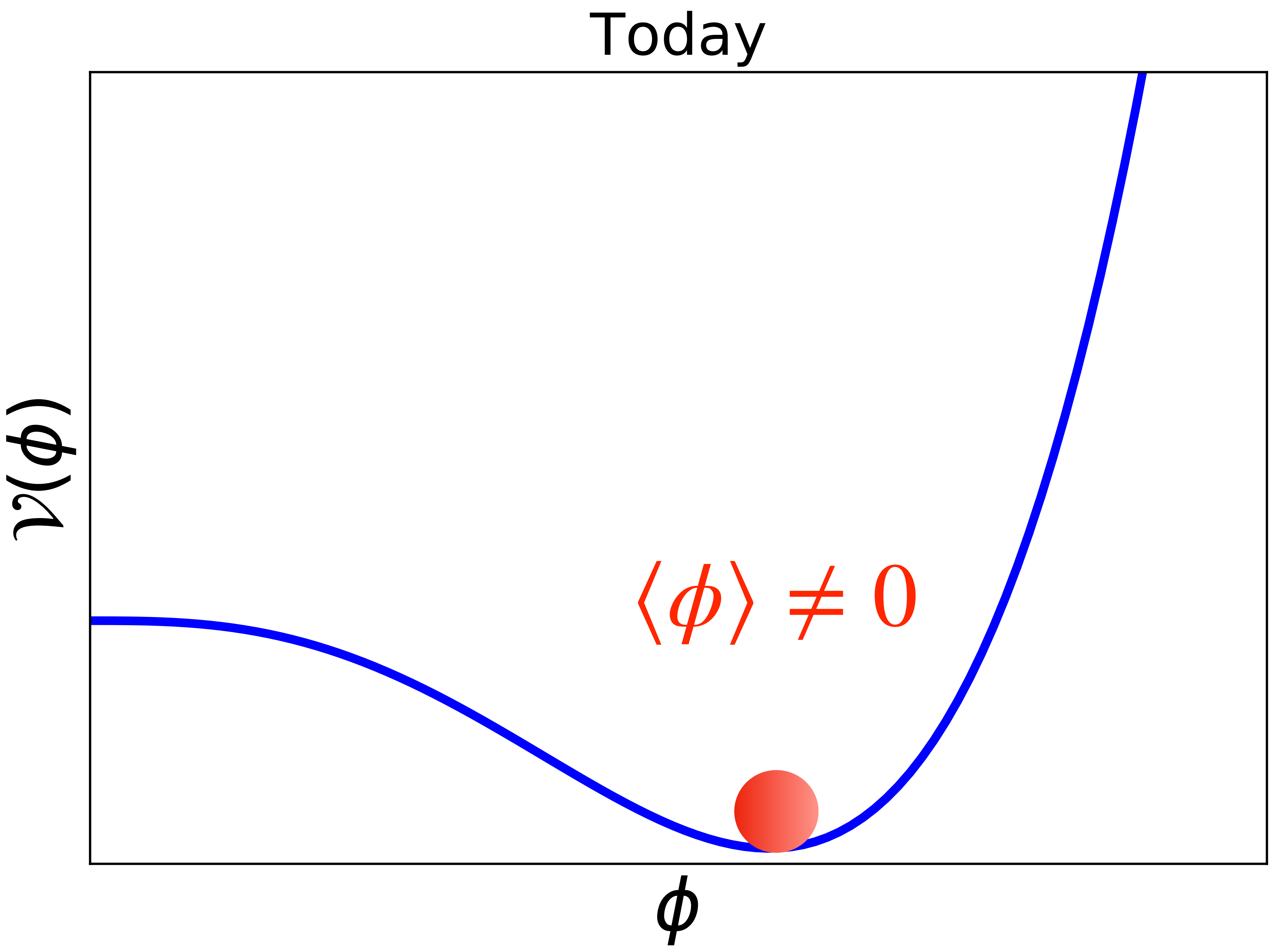

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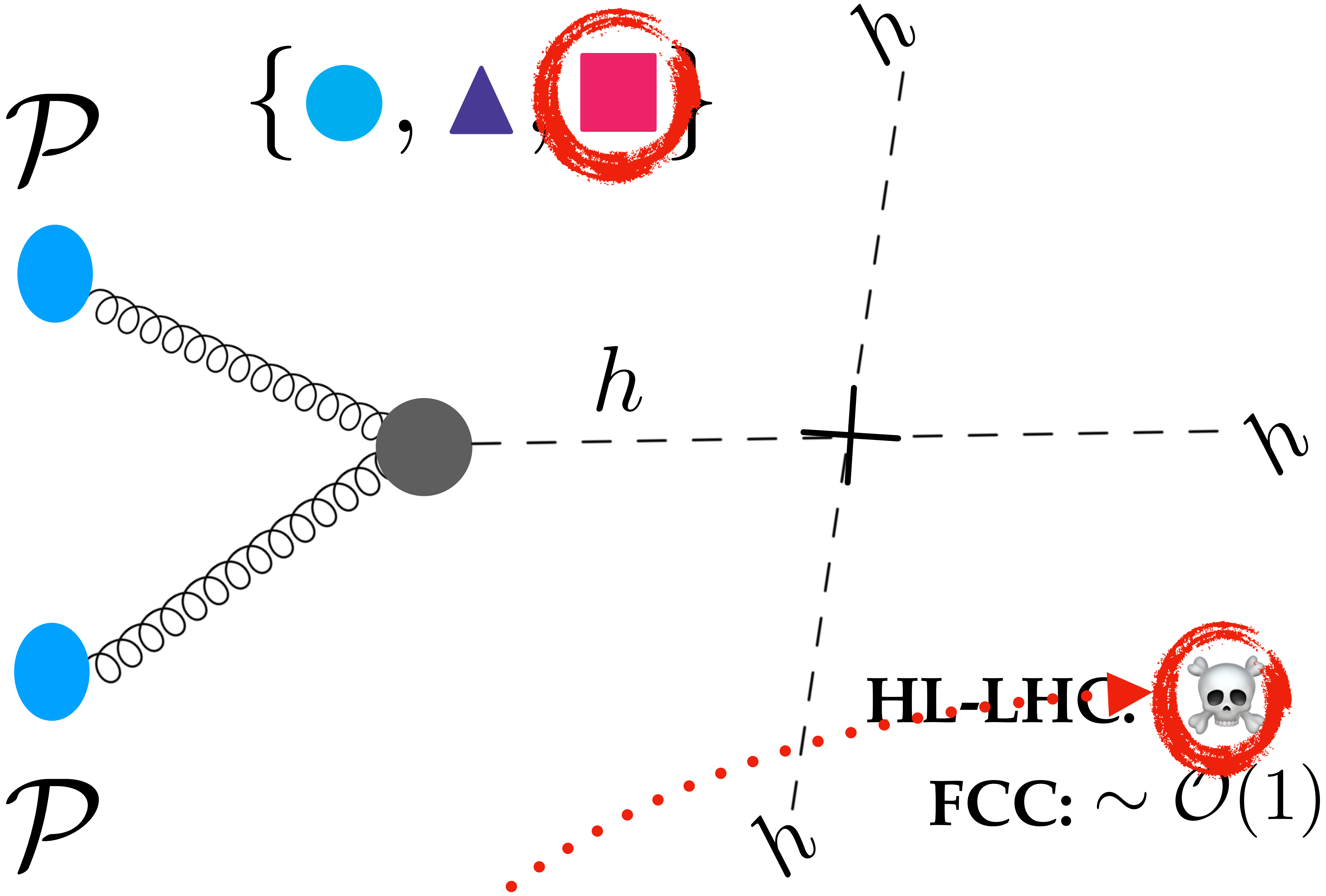

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[**AP**, Robens, Tetlalmatzi-Xolocotzi, arXiv:2101.00037 + Karkout, **AP**, Postma, Tetlalmatzi-Xolocotzi, van de Vis, du Pree, arXiv:2404.12425, **AP**, Tetlalmatzi-Xolocotzi, aXiv:2312.13562]

SEE LATER!

[e.g. **AP**, Sakurai, arXiv:1508.06524, **AP**, Tetlalmatzi-Xolocotzi, Zaro, arXiv:1909.09166]

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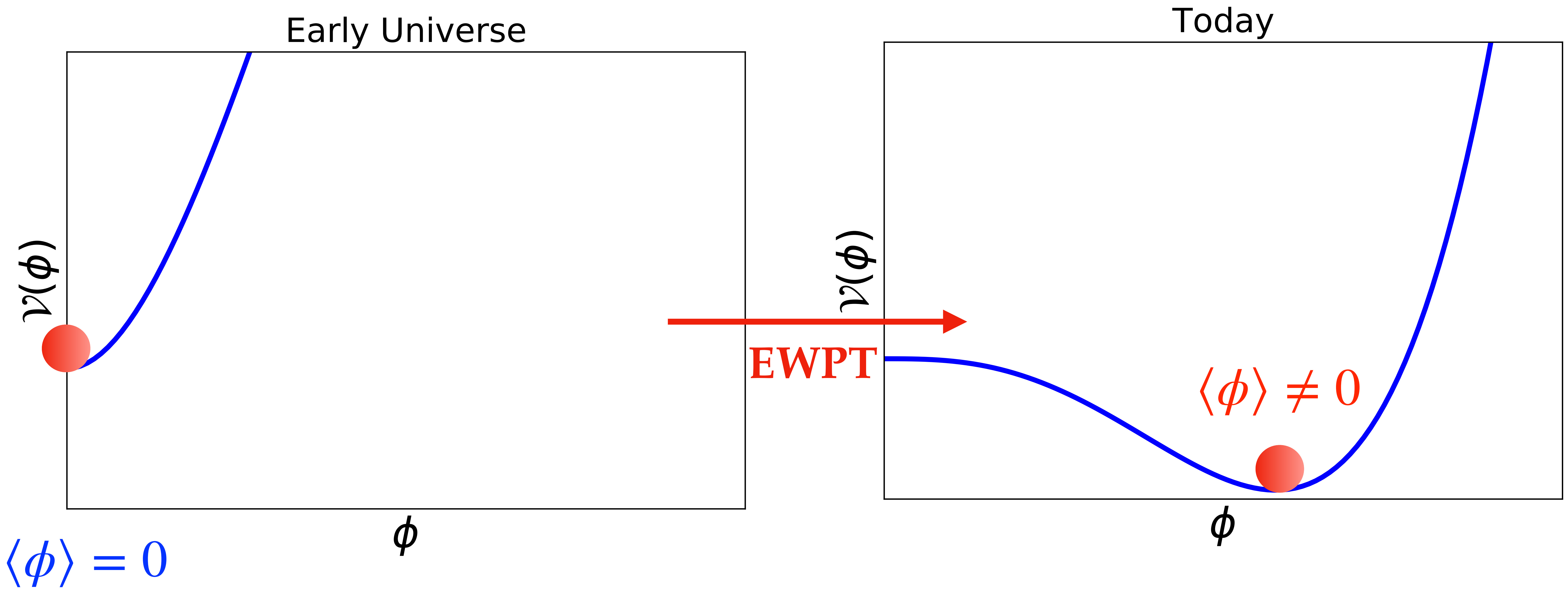
Breaking the Symmetry in the SM

Higs field (ϕ) potential



- **Nature** of **EWPT** $\rightarrow$ Important open question, e.g. **its order**:
  - A **First-Order transition** (e.g. the boiling of water)?
  - or a **Second-Order transition** (e.g. the superfluid transition) or **cross-over**?

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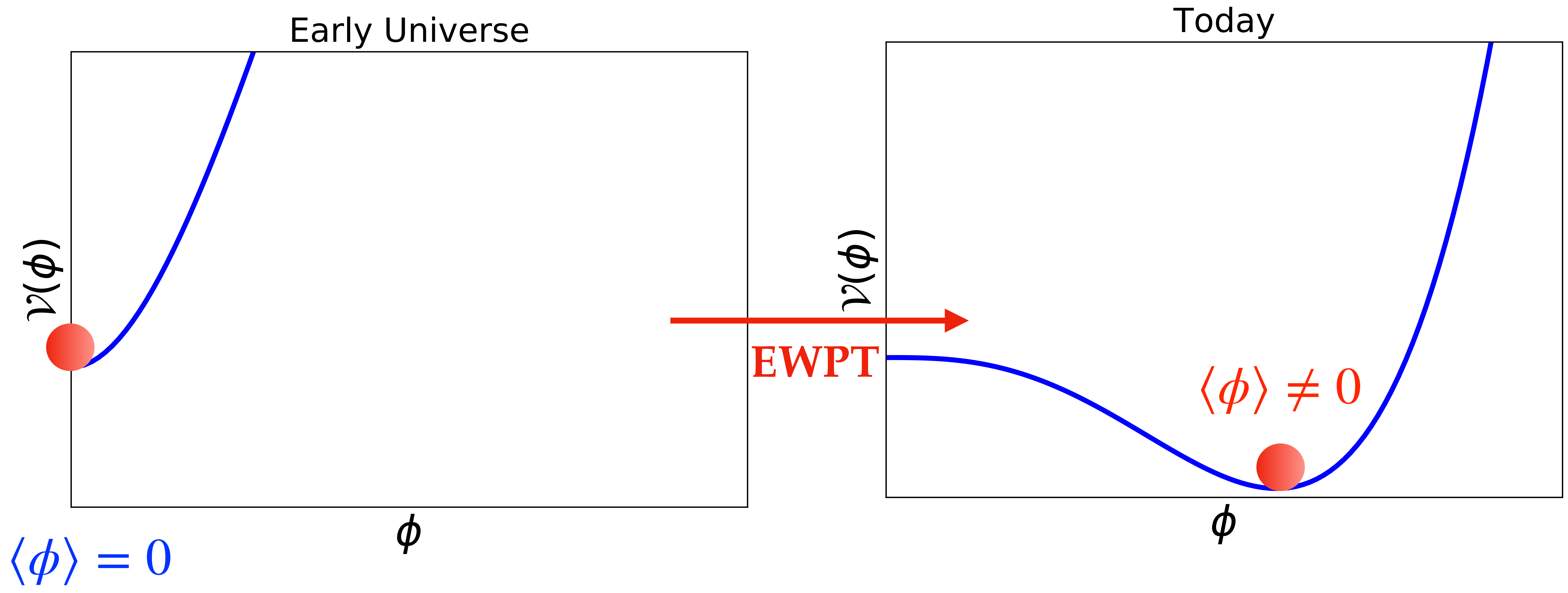

- **Nature** of **EWPT** → Important open question, e.g. **its order**:
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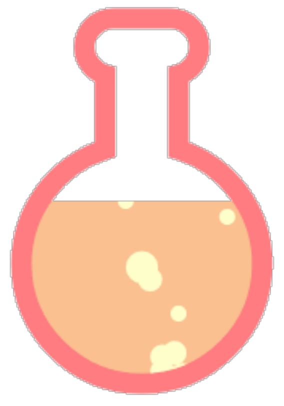


  - or a **Second-Order transition** (e.g. the superfluid transition) or **cross-over**?

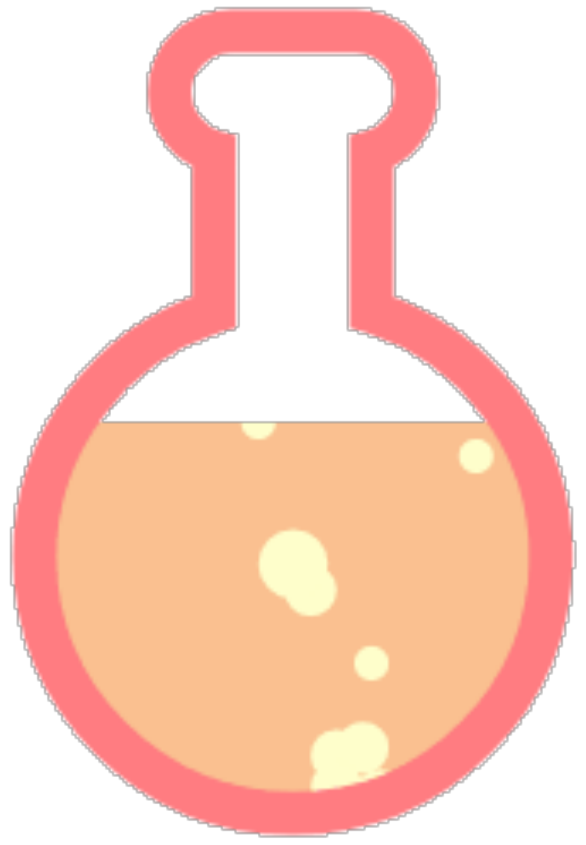
The Nature of the Phase Transition

→ **Clues** to the origin of **matter-anti-matter asymmetry**.

- Was the asymmetry created **during** the **EWPT**?

  → "Electro-Weak Baryogenesis" (EWBG).

- **Pre-requisite**: **a First-Order transition**. ⟶



- *Note*: This **does not** occur in the SM!

[Kajantie, Laine, Rummukainen, Shaposhnikov hep-ph/9605288]

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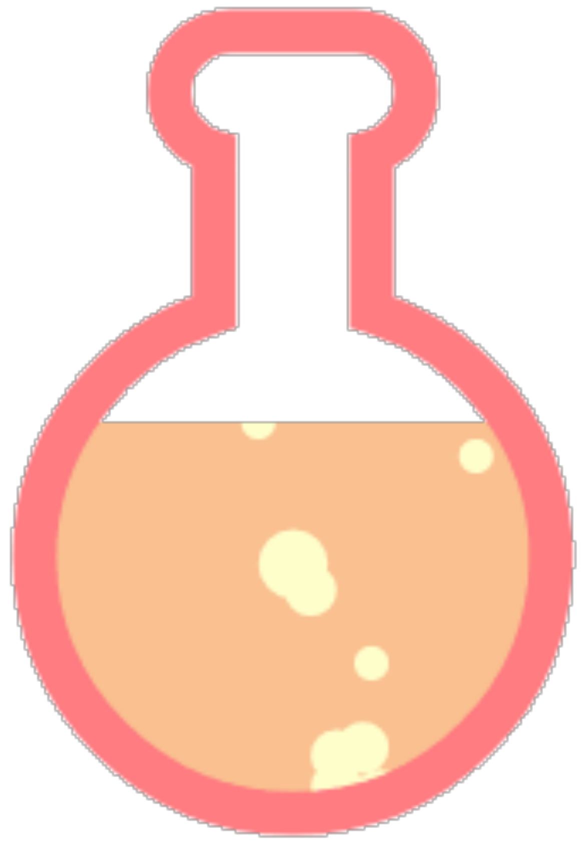

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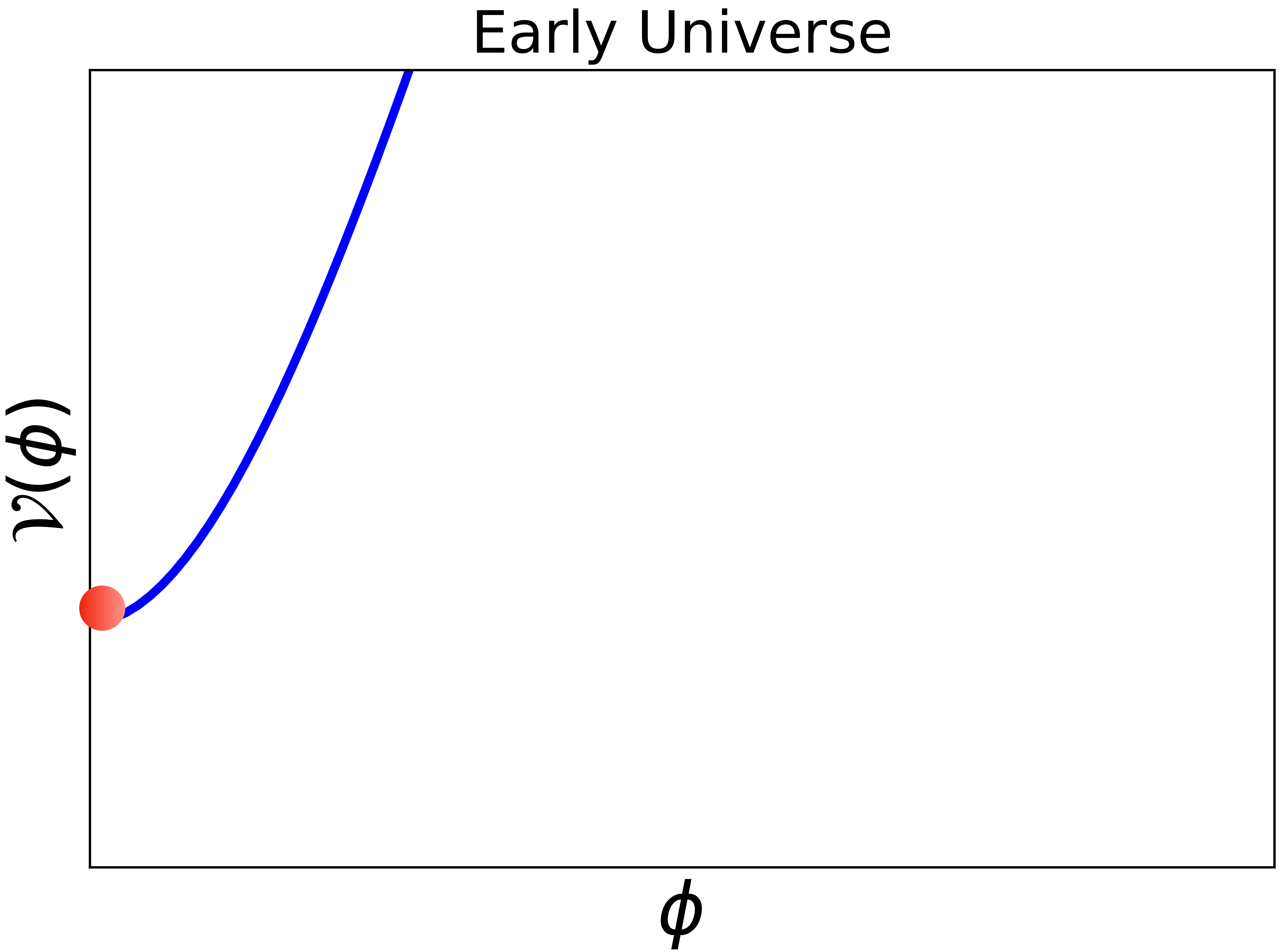
A **First-Order Electro-Weak Phase Transition**: As the Universe Cools Down!

Higgs field (ϕ) potential



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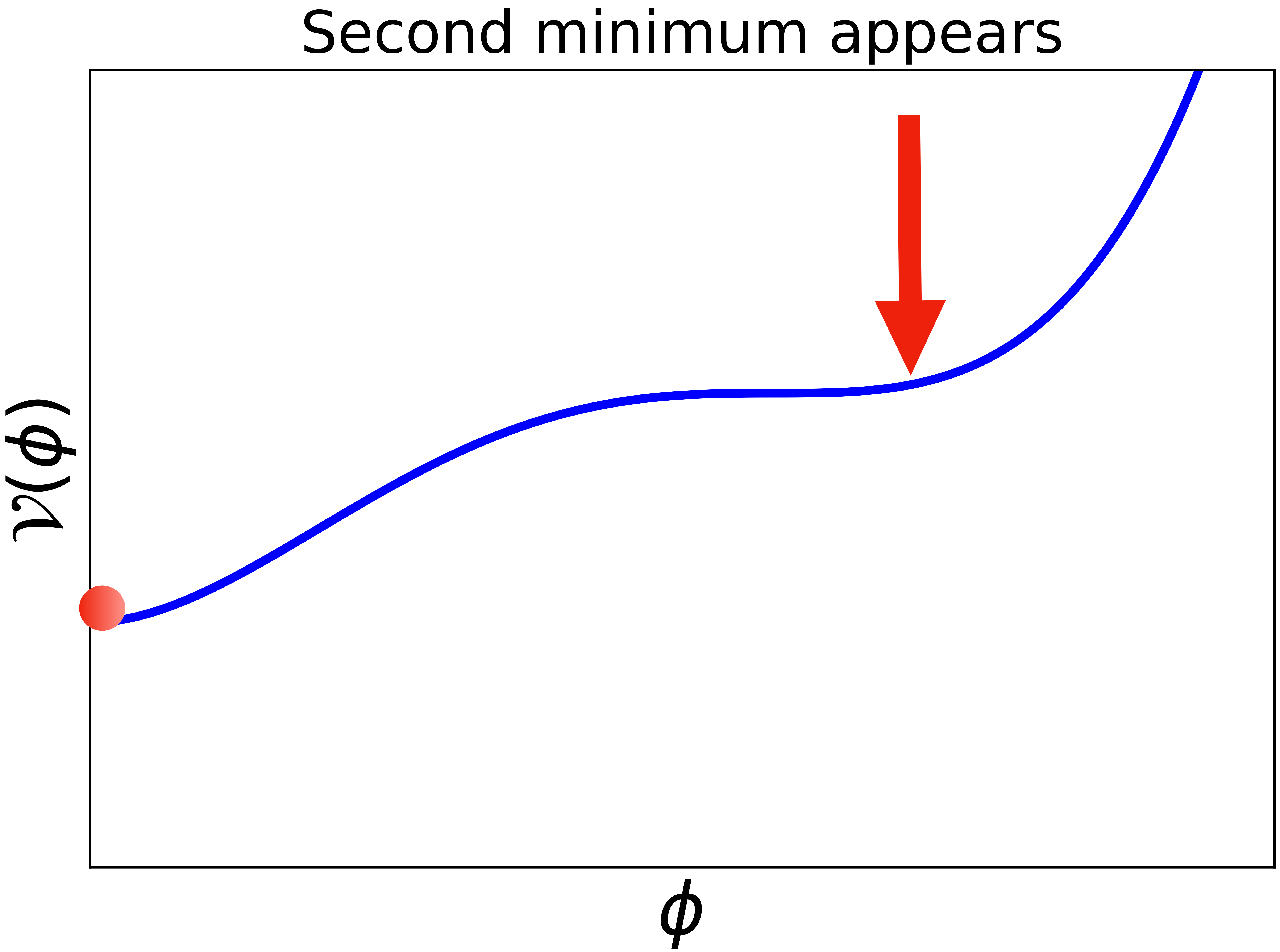

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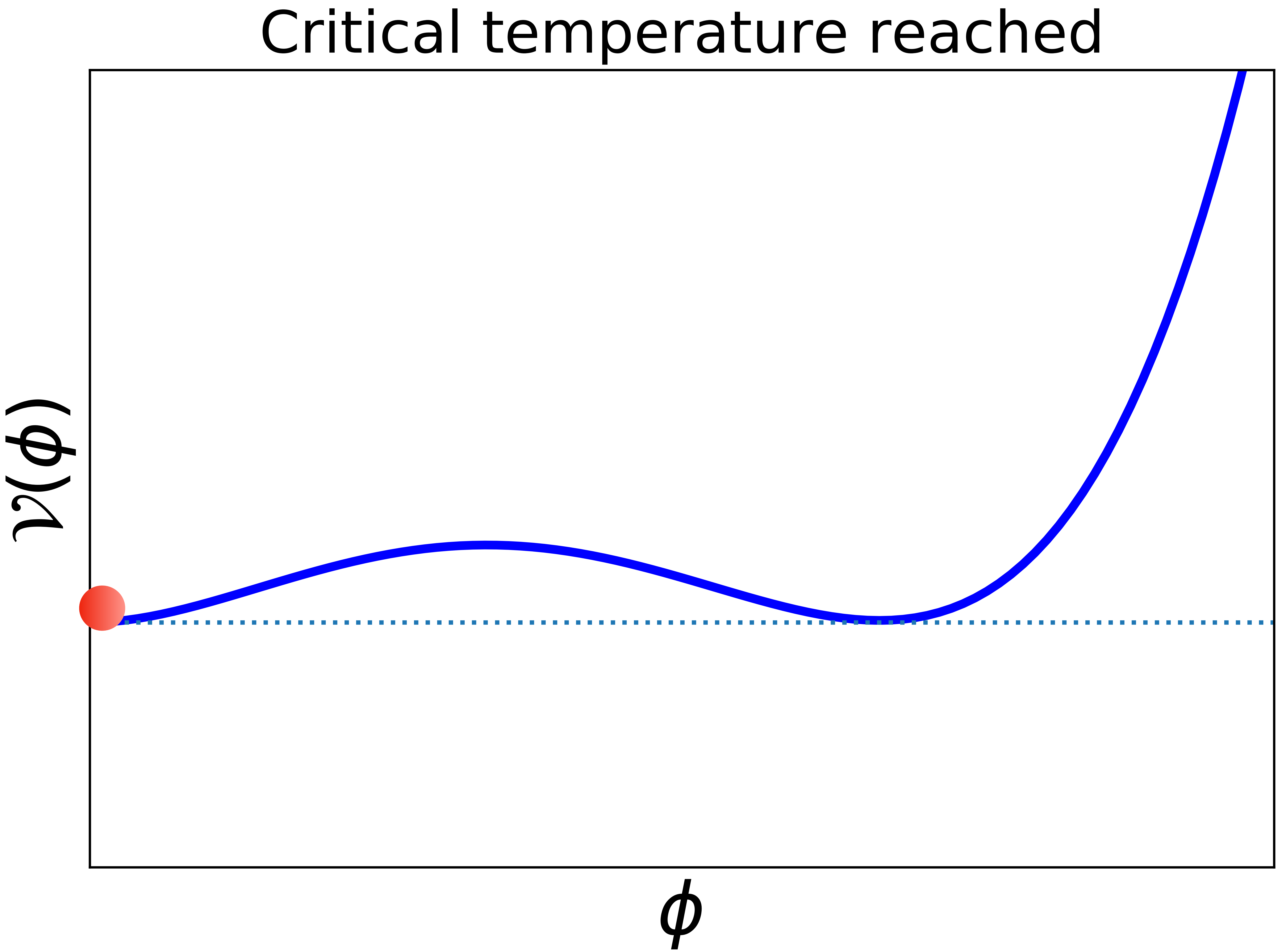

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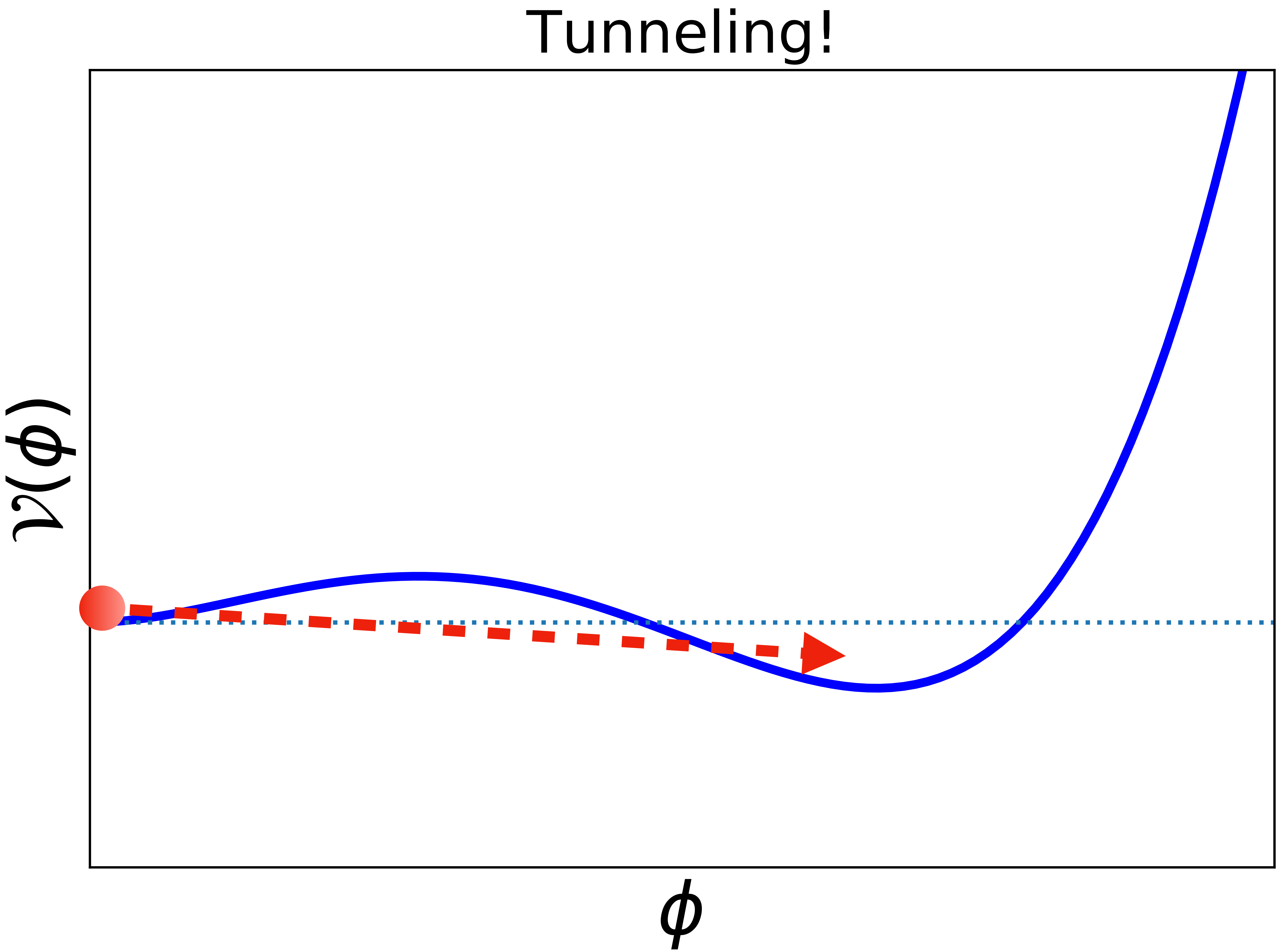

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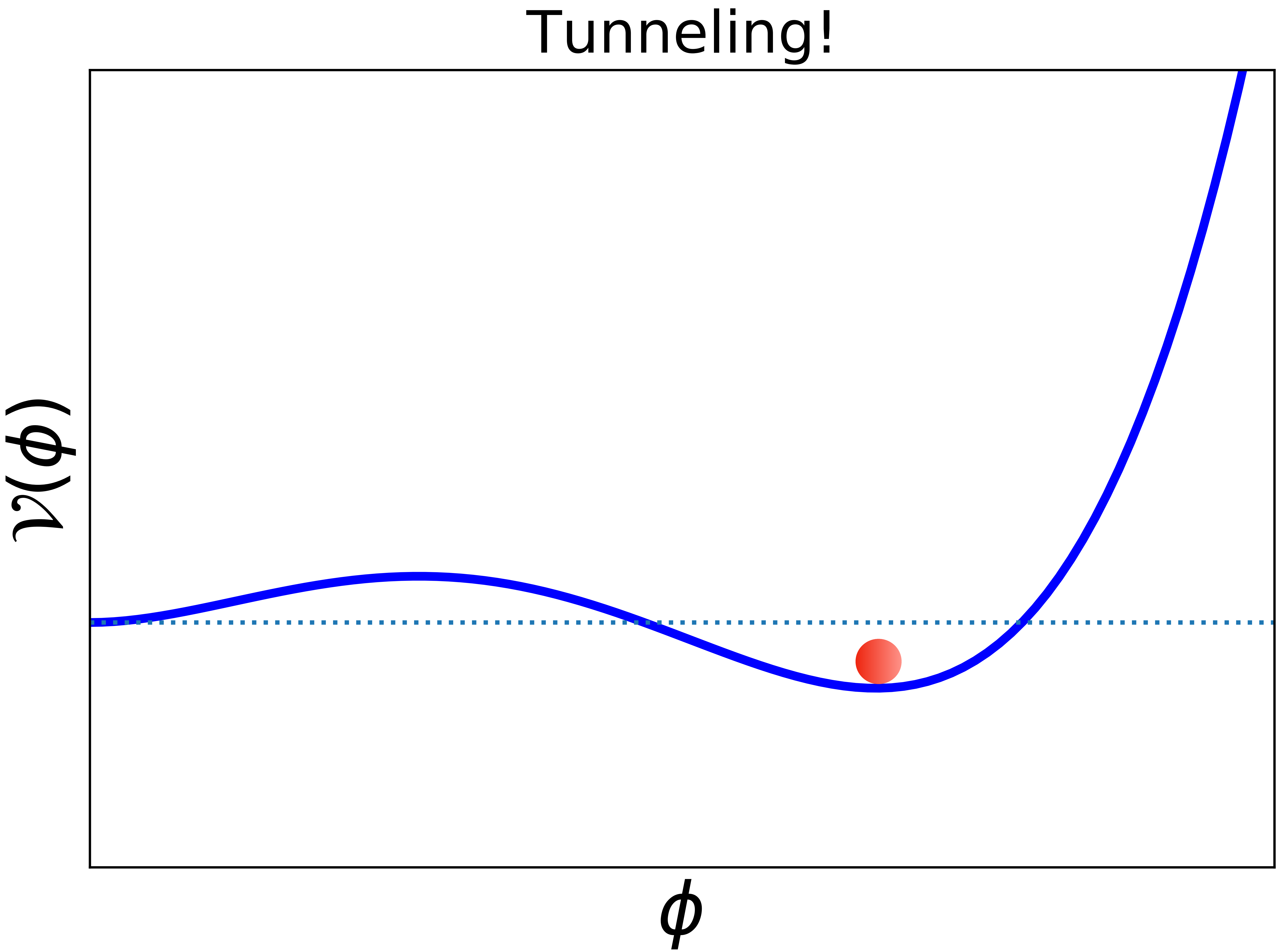

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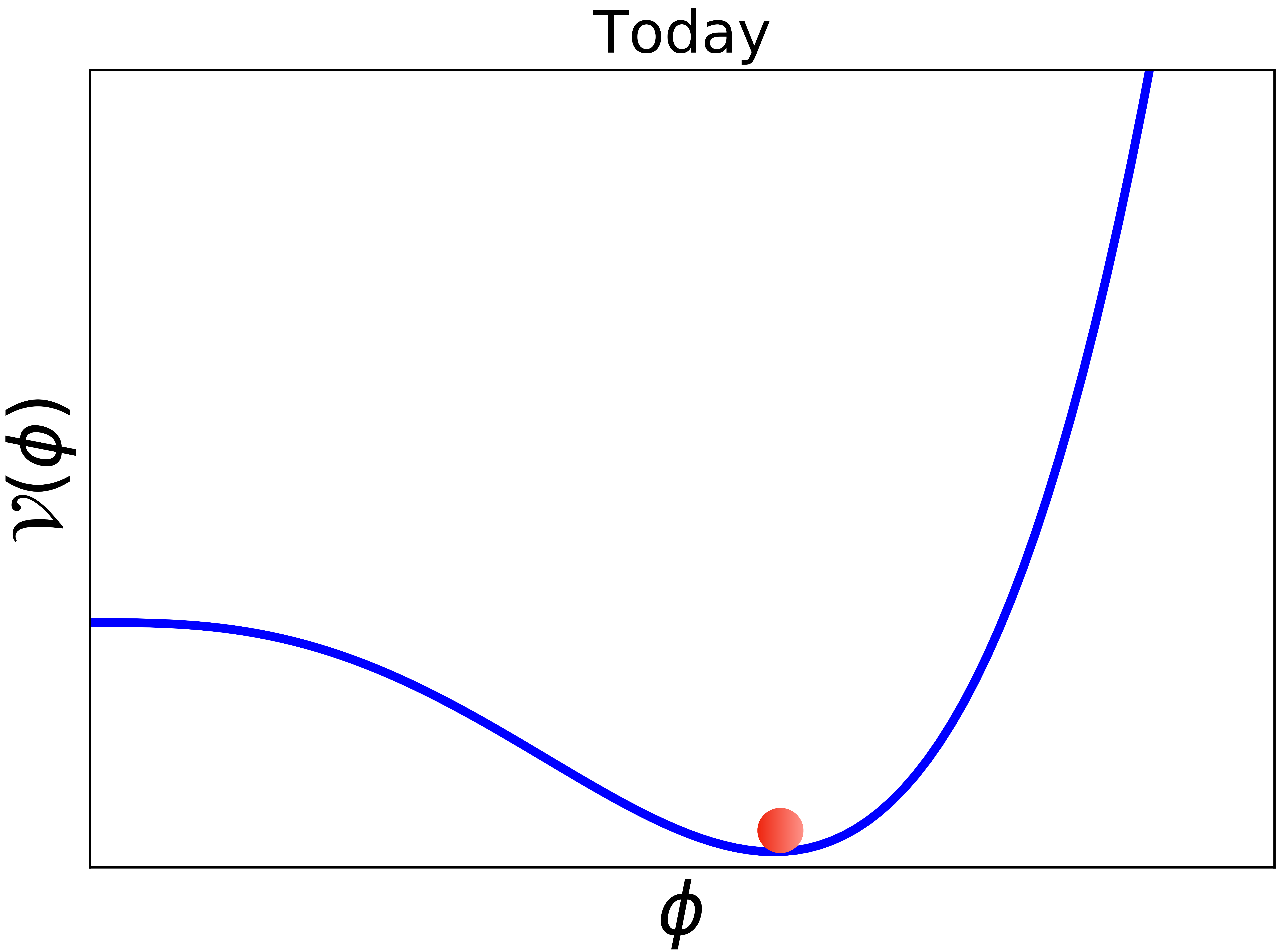

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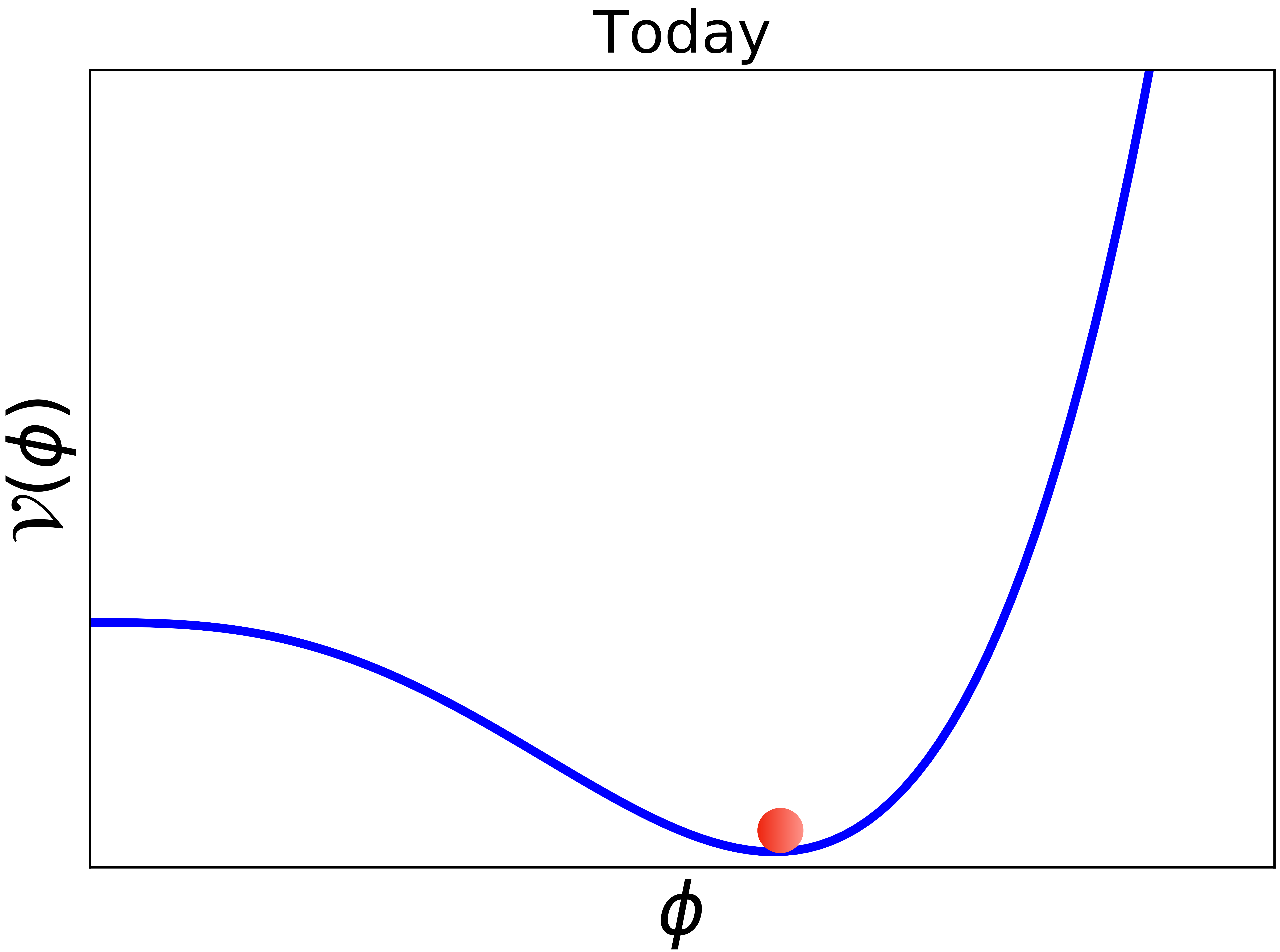

$\langle \phi \rangle \neq 0$

VEV

$\Rightarrow$

Symmetry Breaking.

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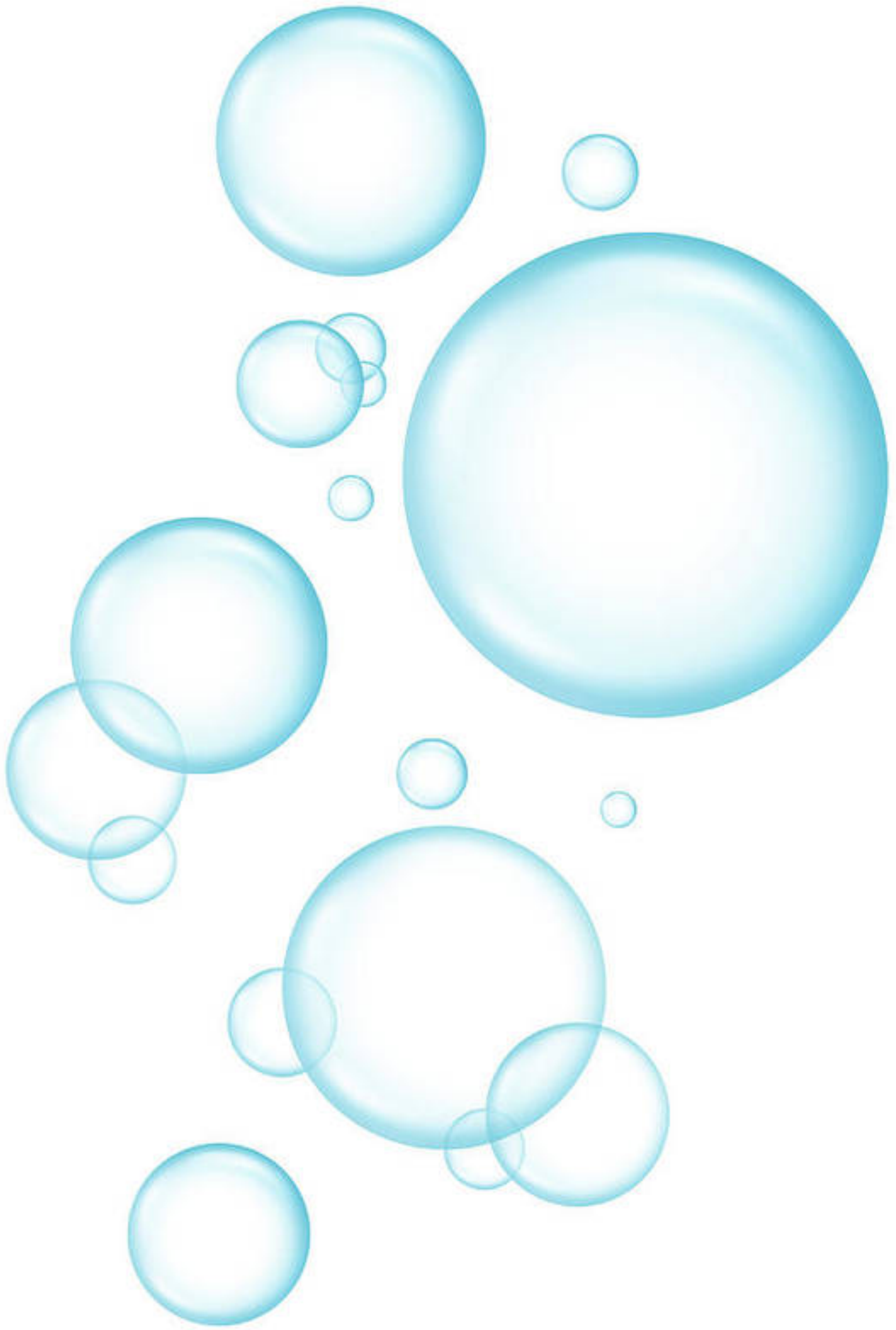
A First-Order EWPT

Some time after critical temperature is reached:

→ **Bubbles** of the broken phase nucleate and expand.



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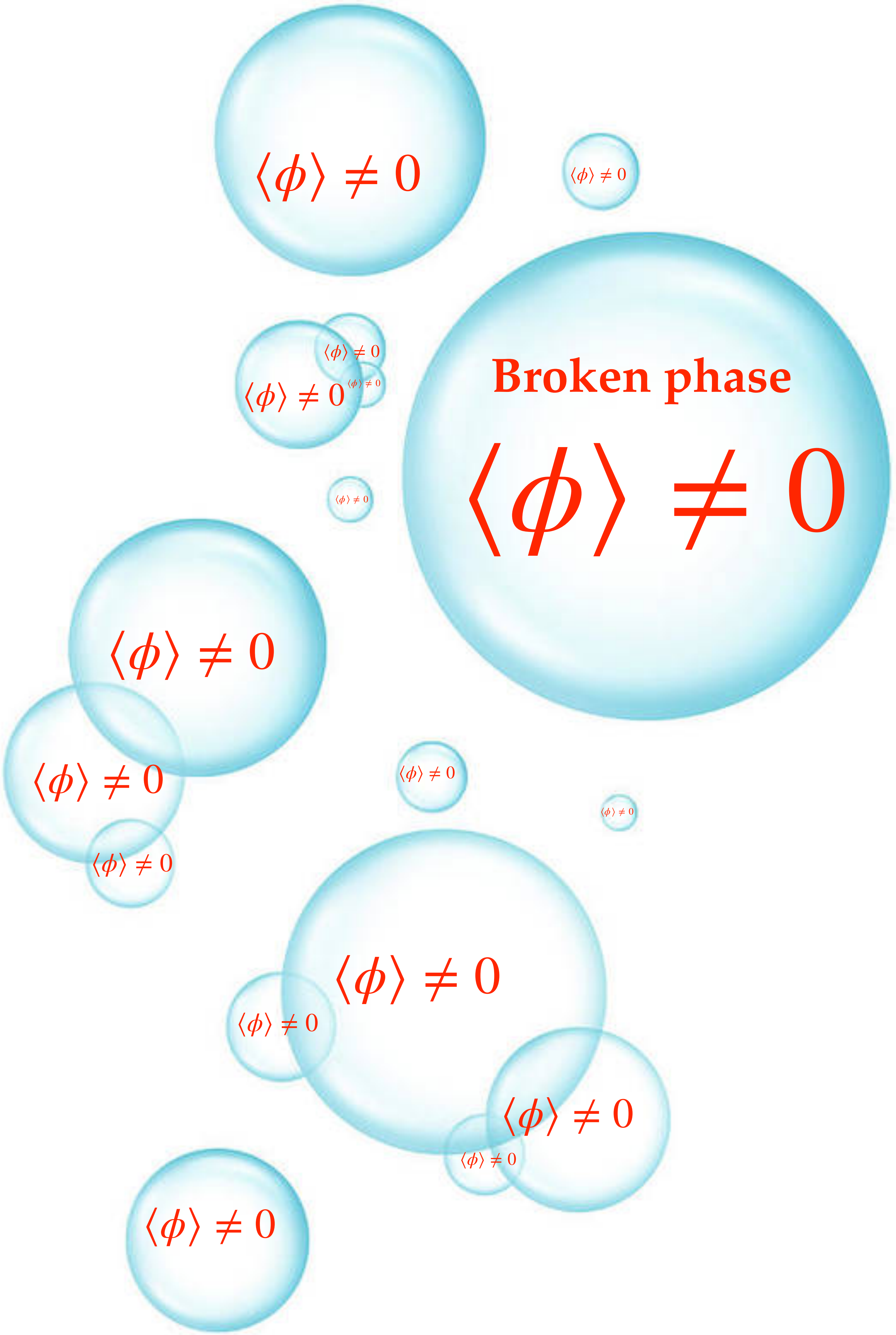

$$\langle\phi\rangle = 0$$

Symmetric phase

A First-Order EWPT

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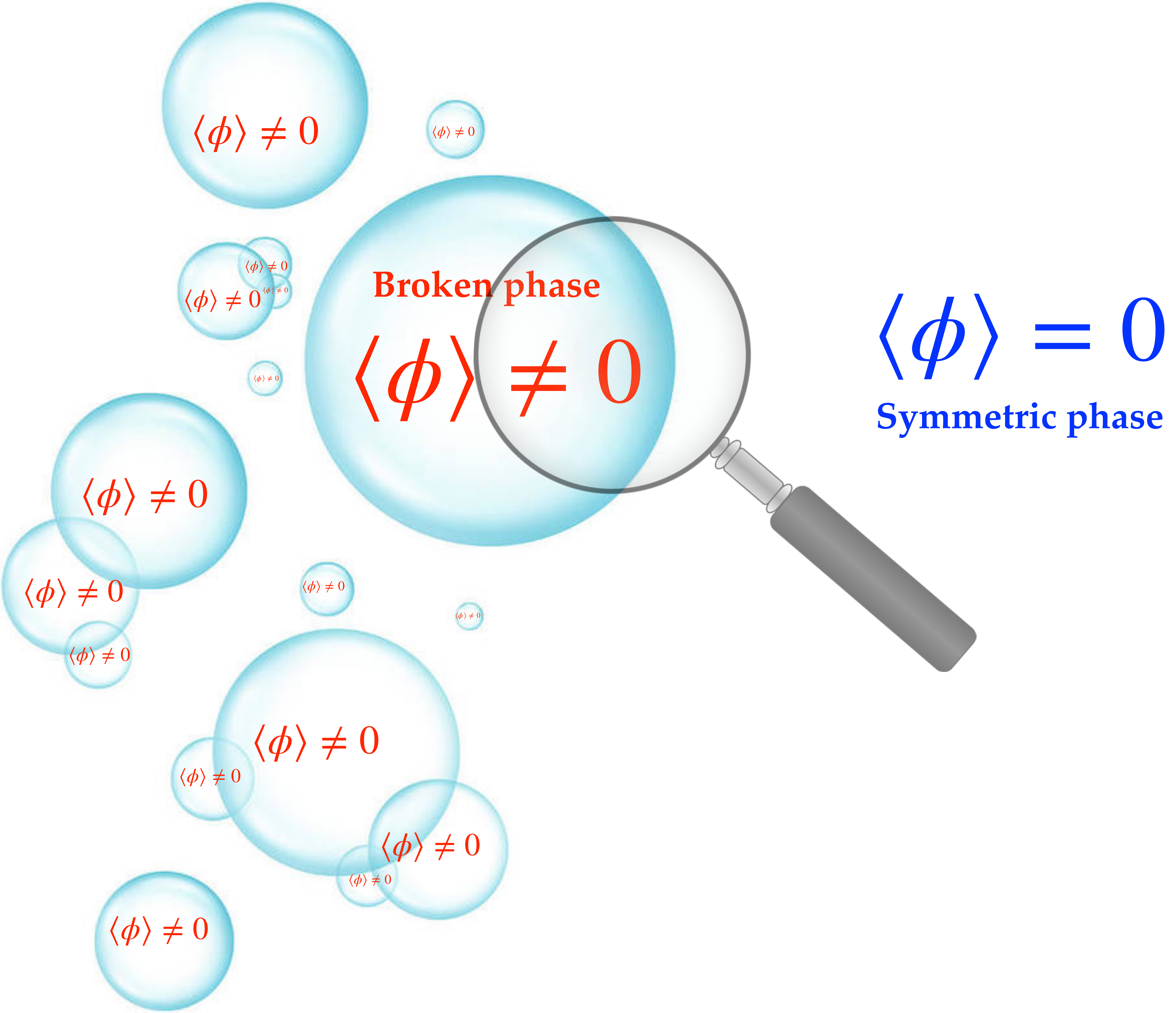

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Electro-Weak Baryogenesis

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[AP, Sakurai, Plätzer, arXiv:1910.4761,
+ Grefsurd, Buanes, Koutroulis, Lipniacka, AP,
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Electro-Weak Baryogenesis

A First-Order Transition requires New Phenomena beyond the SM!

[AP, Sakurai, Plätzer, arXiv:1910.4761,
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A Note on Sphaleron Suppression

- **Suppression** of sphaleron rate **inside bubble**,

  $\Rightarrow$ Baryon Asymmetry "swept in" broken phase and "frozen in".

- **Rate** $\sim \exp[-\langle \phi(T_C) \rangle / T_C \times \ldots]$,

  [T_C: the critical temperature.]

  $\Rightarrow$ Require: $\langle \phi(T_C) \rangle / T_C \geq 1$,

  $\Rightarrow$ a "Strong" First-Order EWPT $\equiv$ SFO-EWPT.

Electro-Weak Archaeology

We live here!

~~Sphaleron~~

$$\langle \phi \rangle \neq 0$$

Broken phase

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Electro-Weak Archaeology

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→ What are the imprints of Electro-Weak Baryogenesis at Colliders?

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Electro-Weak Archaeology

We live here!

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→ What are the imprints of Electro-Weak Baryogenesis at Colliders?

→ Let's explore this in explicit New Physics models!

Extending the Scalar Sector [**AP**, White, arXiv:2010.00597]

- A First-Order EWPT **dictates** new phenomena. [Kajantie, Laine, Rummukainen, Shaposhnikov hep-ph/9605288]

- Consider first the **simplest possible extension to the SM**!

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

Add: S, a new scalar field,
No SM "charges" ≡ Singlet.

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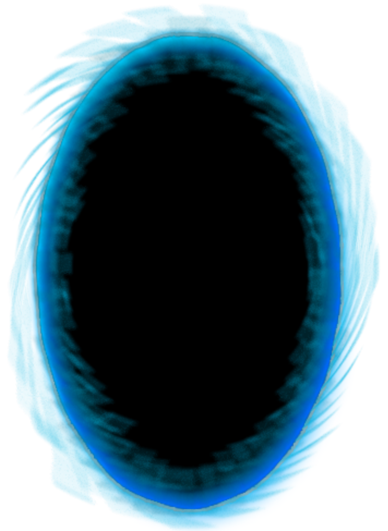

$$+ \blacktriangle\, |\phi|^2\, S + \blacksquare\, |\phi|^2\, S^2$$

← "**Portal**" interactions.
[$|\phi|^2$ is also an SM singlet!]

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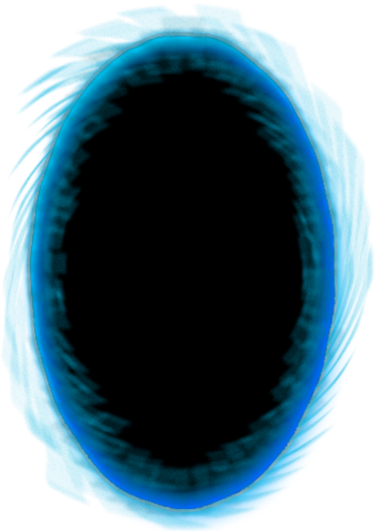

$$+\blacktriangle\,|\phi|^2 S + \blacksquare\,|\phi|^2 S^2$$

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

← **Dark Matter**?

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EWSB ↔ VEVs:

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

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

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⇒ Mass (squared) matrix:

$$M^2 = \begin{pmatrix} \frac{\partial^2 \mathscr{V}}{\partial h^2} & \frac{\partial^2 \mathscr{V}}{\partial h \partial \chi} \\ \frac{\partial^2 \mathscr{V}}{\partial h \partial \chi} & \frac{\partial^2 \mathscr{V}}{\partial \chi^2} \end{pmatrix}$$

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Diagonalize!

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

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$h_2 \to$ new scalar resonance.

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

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Primary targets for collider studies!

$h_1 \Rightarrow$ **Reductions** in Higgs boson rates.

$h_2 \Rightarrow$ **New resonance searches.**

SM+Singlet: Current Collider Constraints

(i) LHC searches for **scalar resonances** in $h_2 \to h_1 h_1, ZZ, W^+W^-, \ldots$, since:

$$g_{h_2XX} \sim g_{hXX}^{\mathrm{SM}} \times \sin\theta \text{ and } h_2 \to h_1 h_1 \text{ (if allowed)},$$

(ii) **Reductions in Higgs boson signal strengths** (LHC), since:

$$g_{h_1XX} \sim g_{hXX}^{\mathrm{SM}} \times \cos\theta,$$

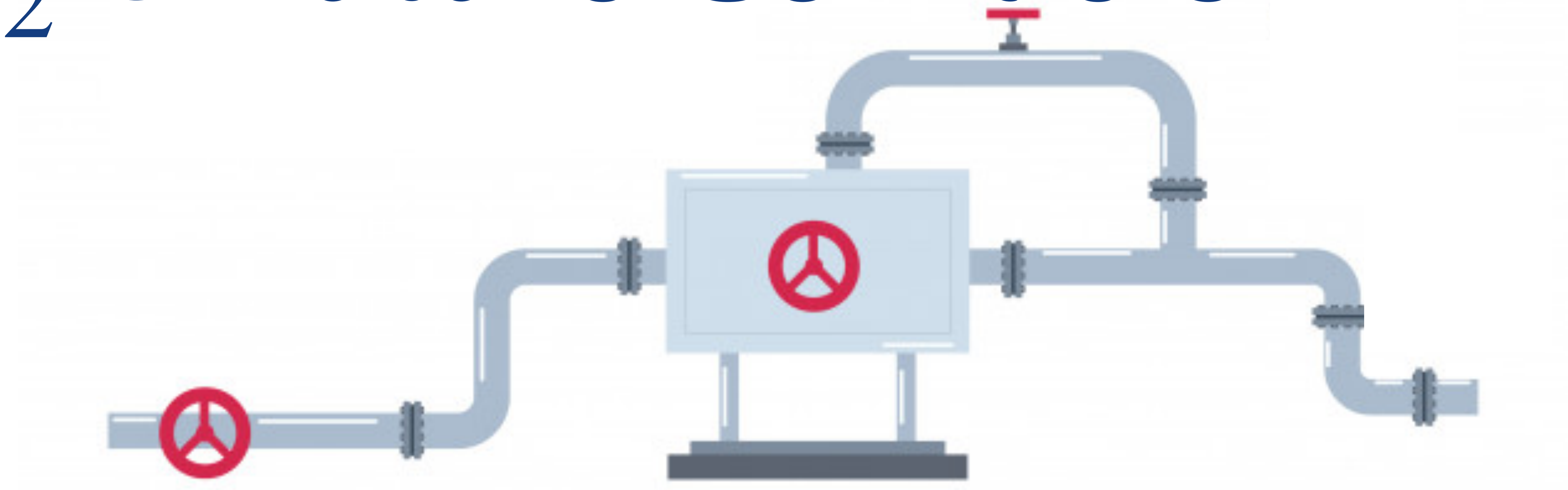
[(i)+(ii)→ e.g. through `HiggsBounds/HiggsSignals`]

(iii) **Electro-Weak Precision Observables** (LEP). [e.g. Profumo, Ramsey-Musolf, Wainwright, Winslow, arXiv:1407.5342]

[+ **W mass constraints**. [e.g. López-Val, Robens arXiv:1406.1043, **AP**, Robens, White, arXiv:2205.14379]

$pp \to h_2$ @ Future Colliders

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



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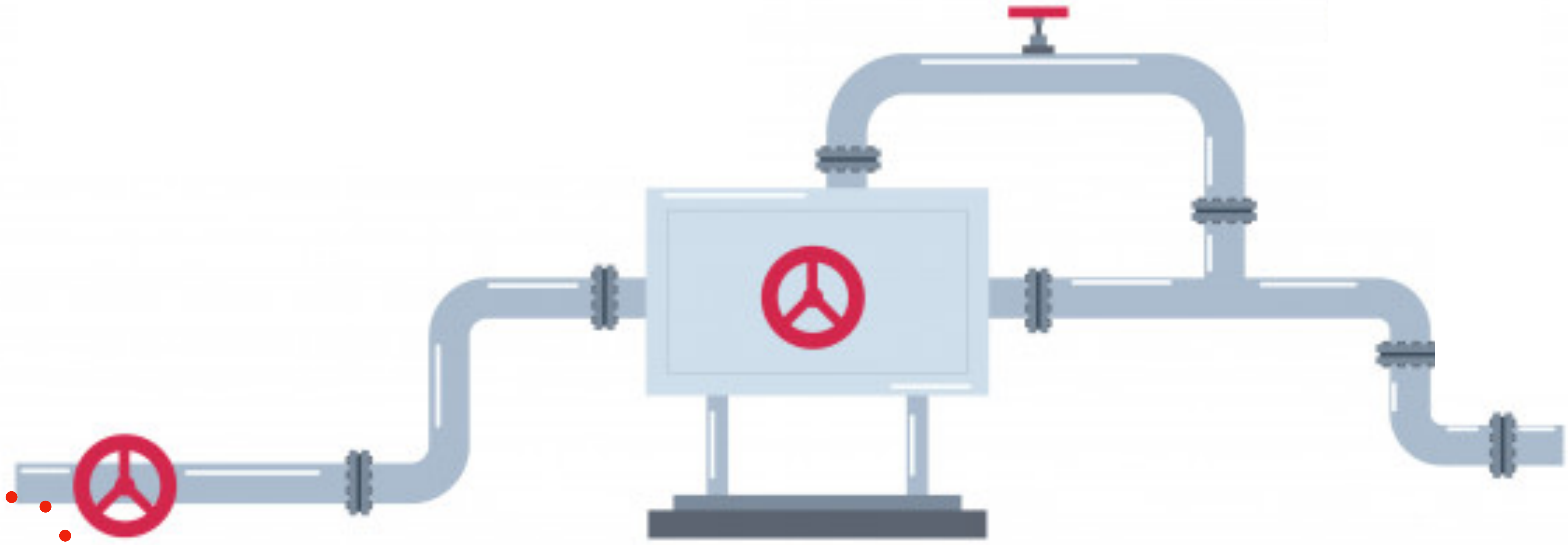

$$\mathcal{V}(\phi, S)$$

One-loop Effective Potential

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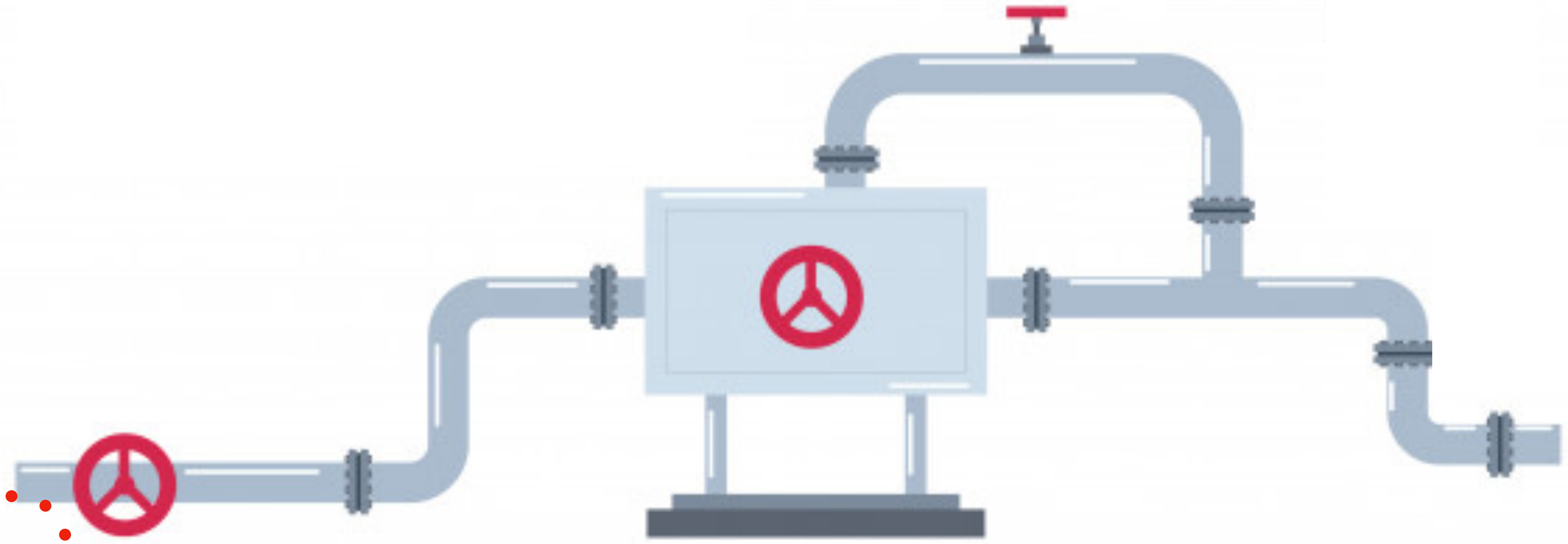

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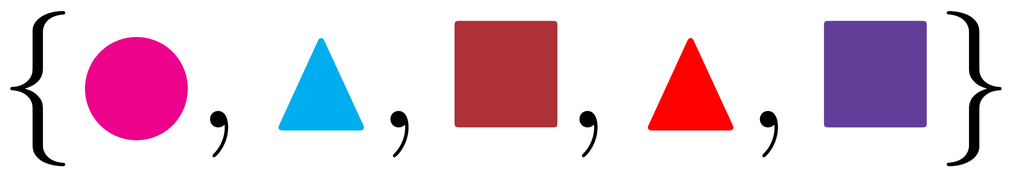
SFO-EWPT



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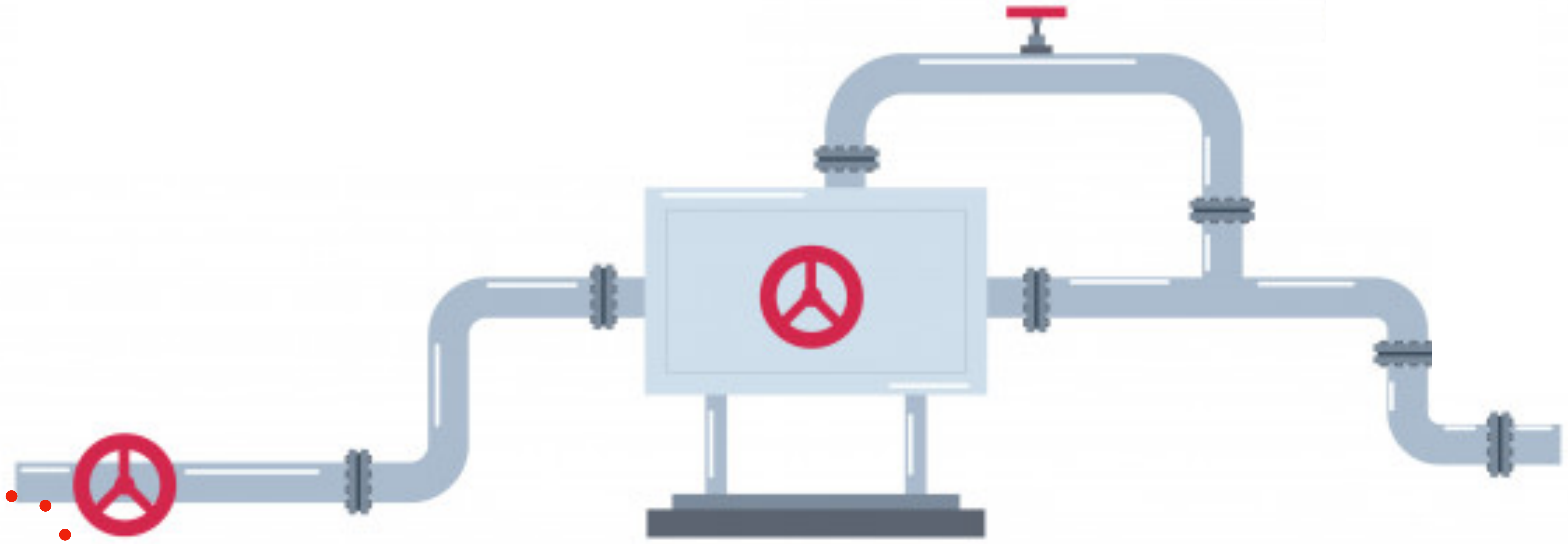

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SFO-EWPT

{●, ▲, ■, ▲, ■}

→

`MadGraph5_aMC@NLO`

[Loop model]

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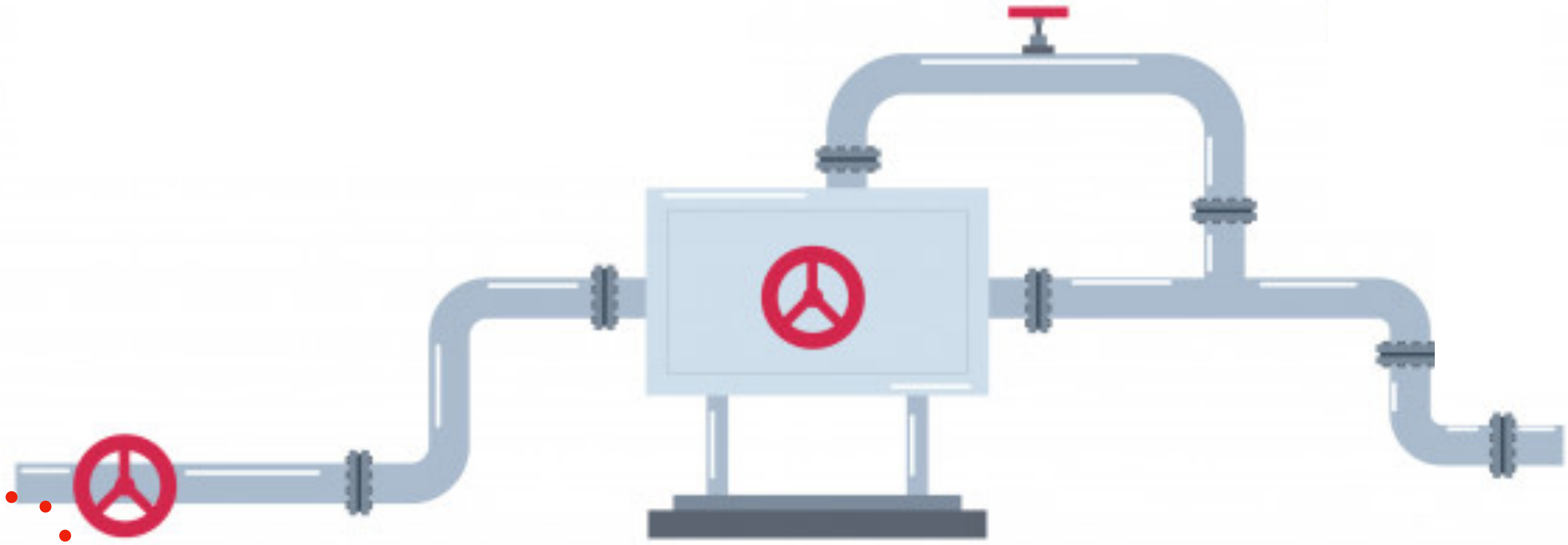

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`HERWIG 7`

→ MC Events@LO, NLO, FxFx multi-jets@NLO

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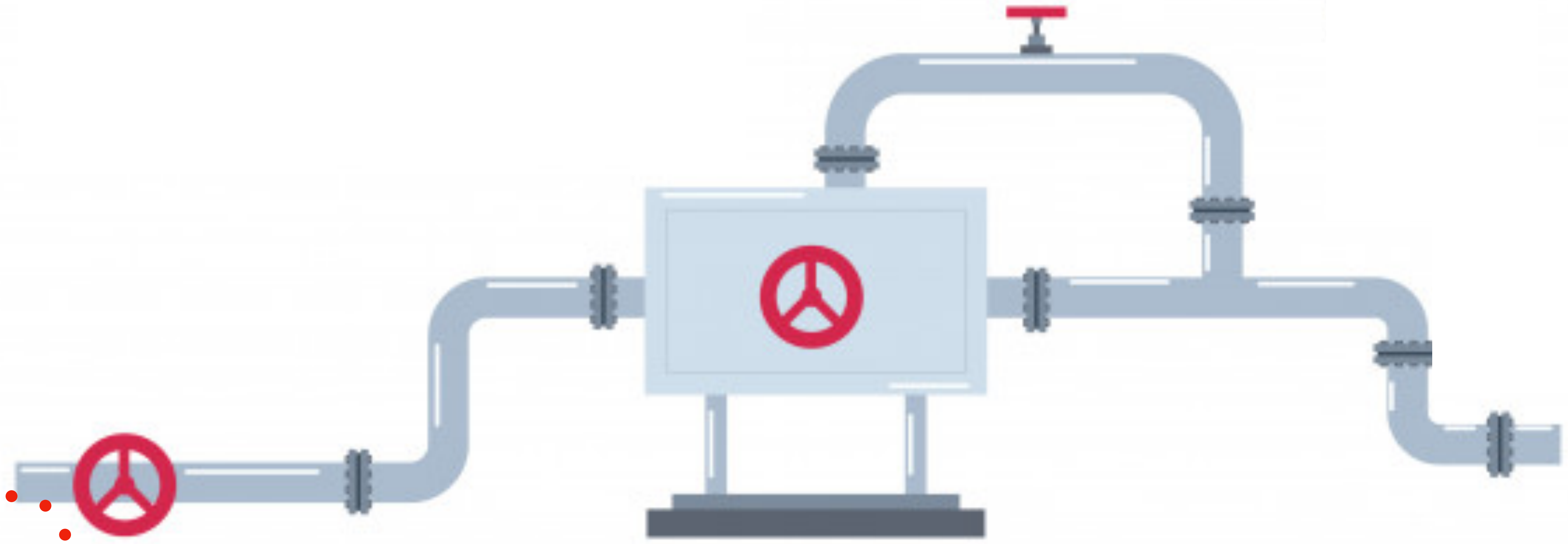

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$\{$ ●, ▲, ■, ▲, ■ $\}$

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HERWIG 7

$\to$ MC Events@LO, NLO, FxFx multi-jets@NLO

→ [HwSim, AP, 2020]

Analysis

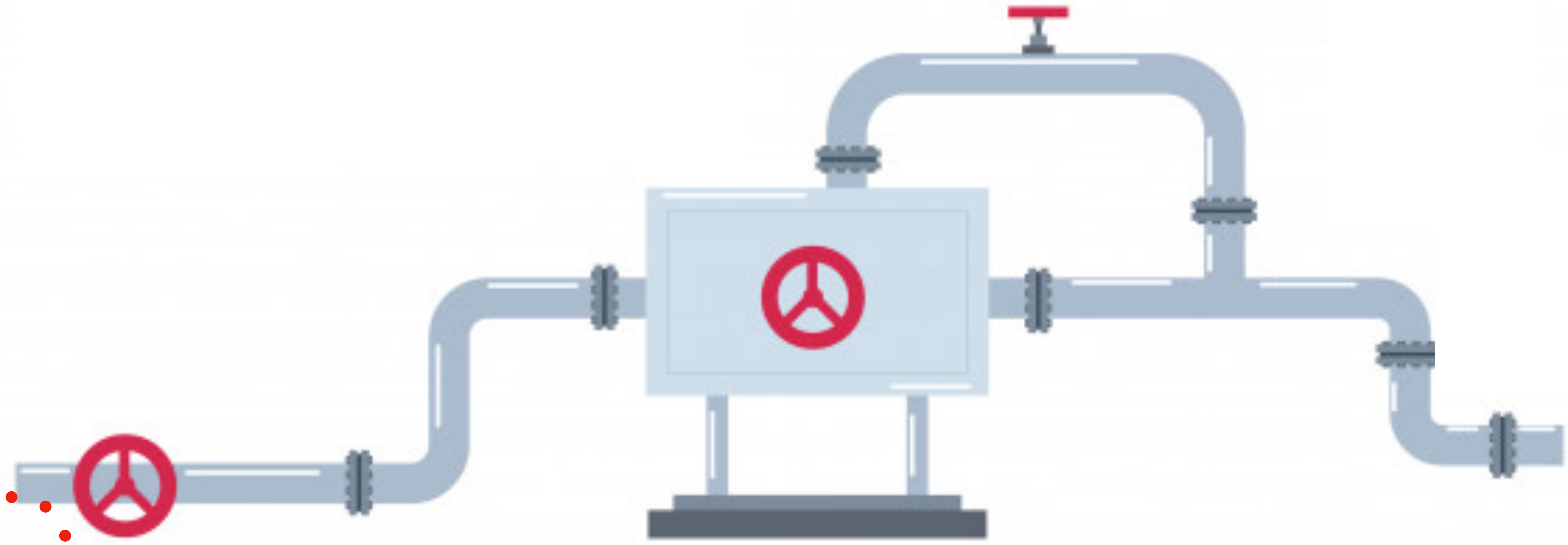
ROOT TMVA

↓

Statistical Significance for $pp \to h_2$

$pp \to h_2$ @ Future Colliders

[AP, White, arXiv:2010.00597]



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Statistical Significance for $pp \to h_2$

Degrees of Theoretical Uncertainty

[AP, White, arXiv:2010.00597]

Lower uncertainty
⇒
SFO-EWPT
more certain to
have occurred.

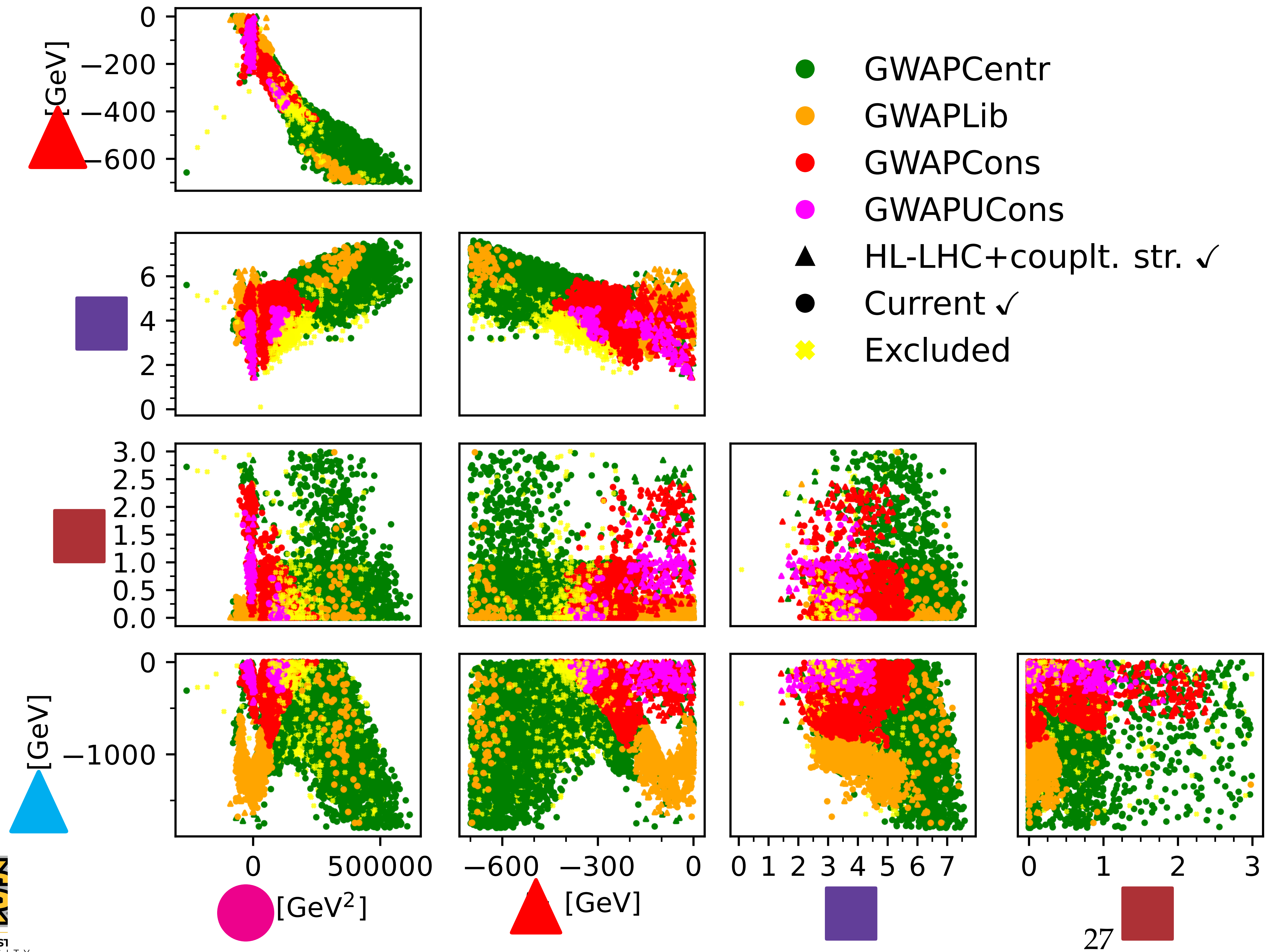
- Liberal
- Centrist
- Conservative
- Ultra-Conservative

⇒ Colour-coded parameter-space points, denoting theoretical uncertainty.

& if: × = Point is excluded today.

SFO-EWPT Parameter Space

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



5 free parameters.

Liberal

Centrist

Conservative

Ultra-Conservative

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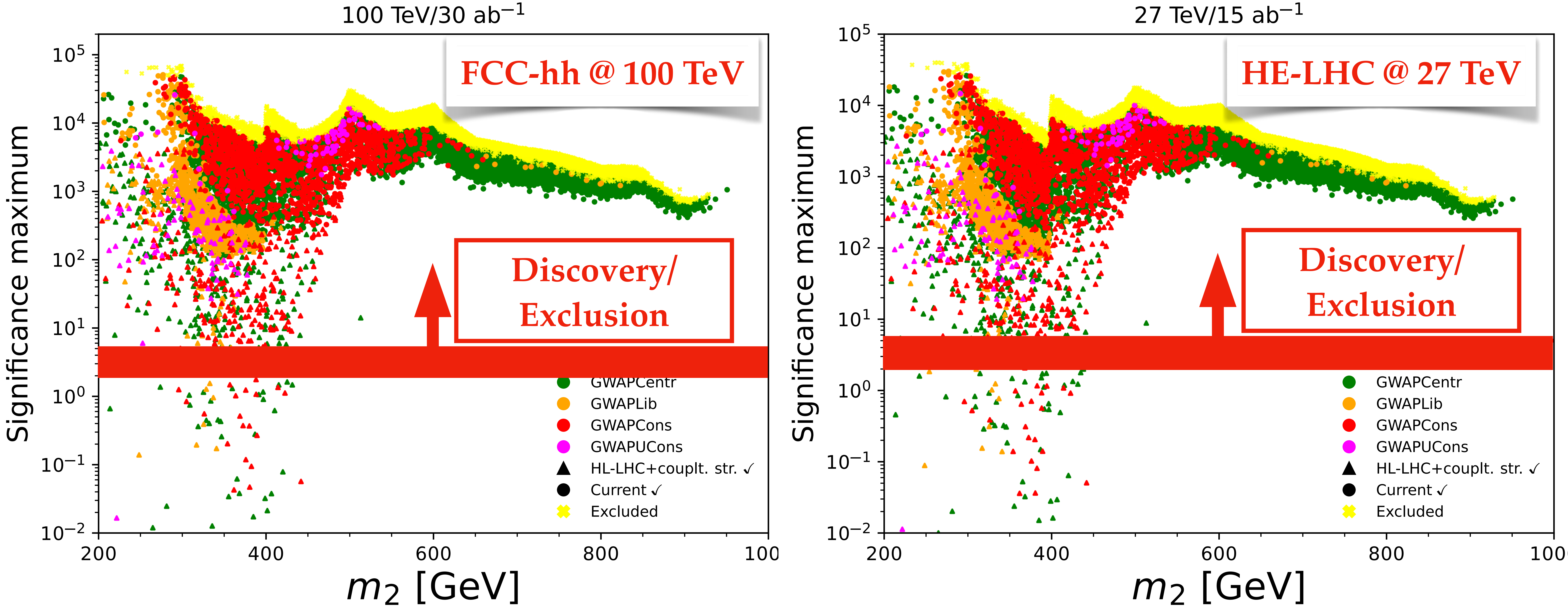
$pp \to h_2$ Significance @ Future Colliders

Color-coding of parameter-space points denotes theoretical uncertainty.



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Discovery Post-Mortem

"With 4 parameters I can fit an elephant and with 5 I can make him wiggle his trunk."
— John Von Neumann

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***Can we* indeed fit the shape of an elephant with 4 parameters?**

Discovery Post-Mortem

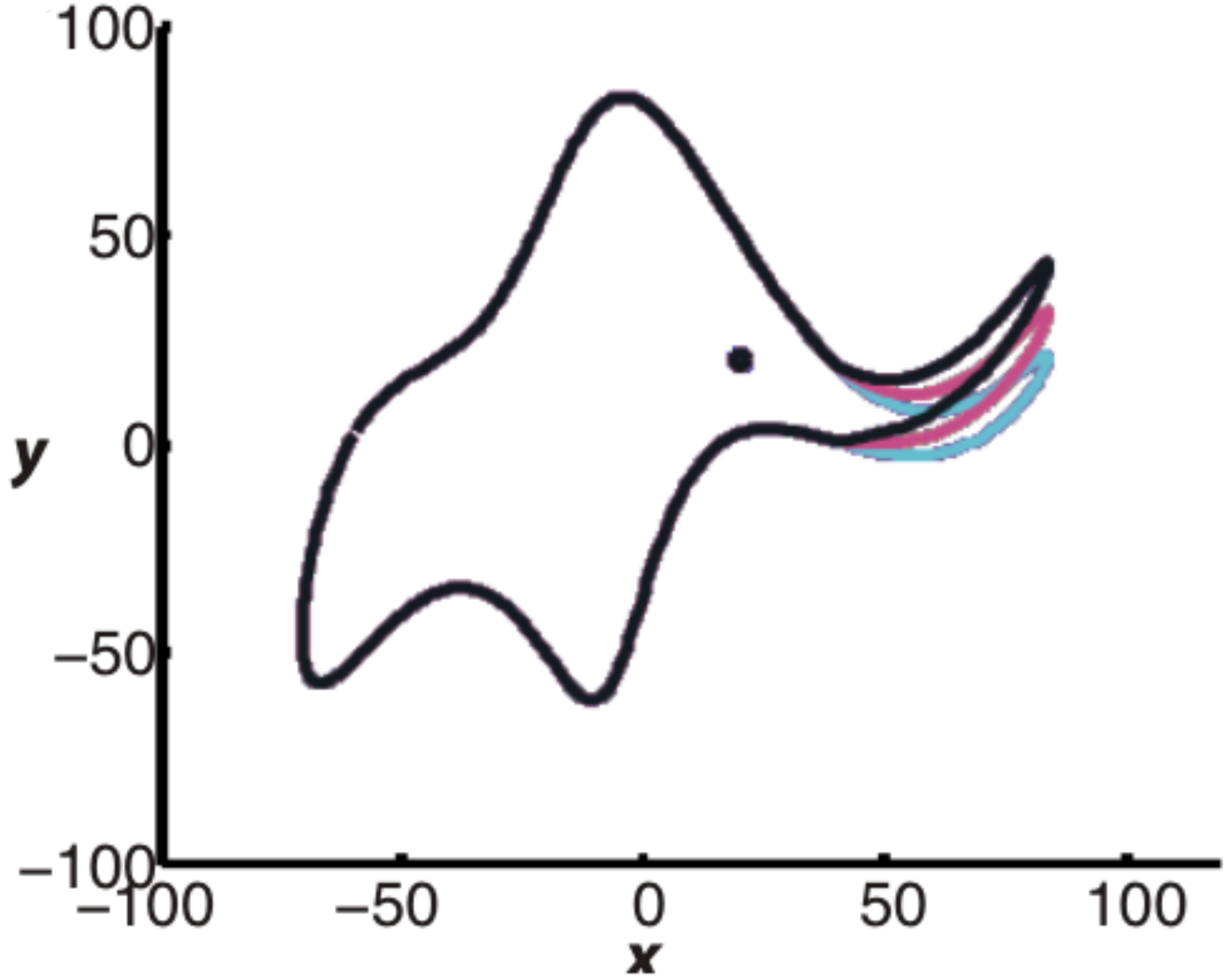
"With 4 parameters I can fit an elephant and with 5 I can make him wiggle his trunk."
— John Von Neumann

***Can we* indeed fit the shape of an elephant with 4 parameters?**

→ **Yes!** With **four** complex parameters,

[and with **five** we can make it wiggle its trunk.]

[Mayer, Khairy, Howard, Am. J. Phys., Vol. 78, No. 6, June 2010]



Discovery Post-Mortem

"With 4 parameters I can fit an elephant and with 5 I can make him wiggle his trunk."
— John Von Neumann

If we discover e.g. a new scalar particle at colliders,

→ Can we verify that it is indeed the remnant of a singlet field that generates a SFO-EWPT?

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⇒ The "**Inverse Problem**".

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

⇒ The "**Inverse Problem**". ⟶ **Experimental observations** → $\{\bullet, \blacktriangle, \blacksquare, \blacktriangle, \blacksquare\}$

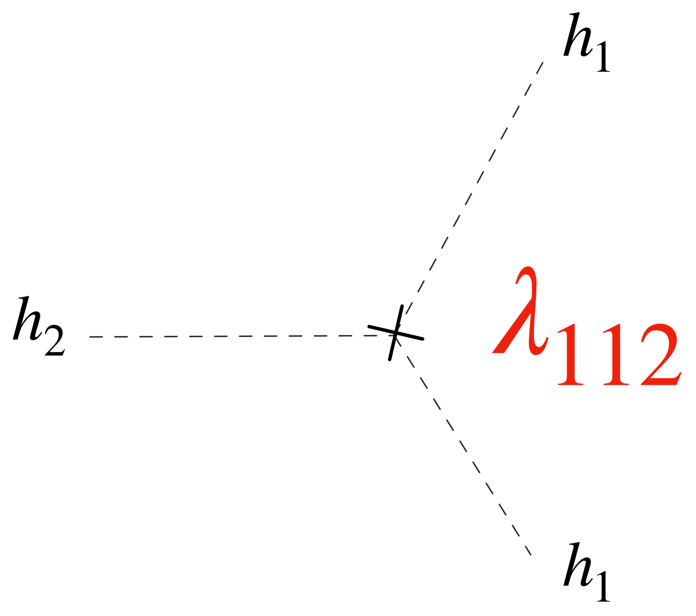
Andreas Papaefstathiou
KENNESAW STATE UNIVERSITY

Discovery Post-Mortem Example [**AP**, White, arXiv:2108.11394]

Combine possible measurements:

$pp \to h_2 \to ZZ$

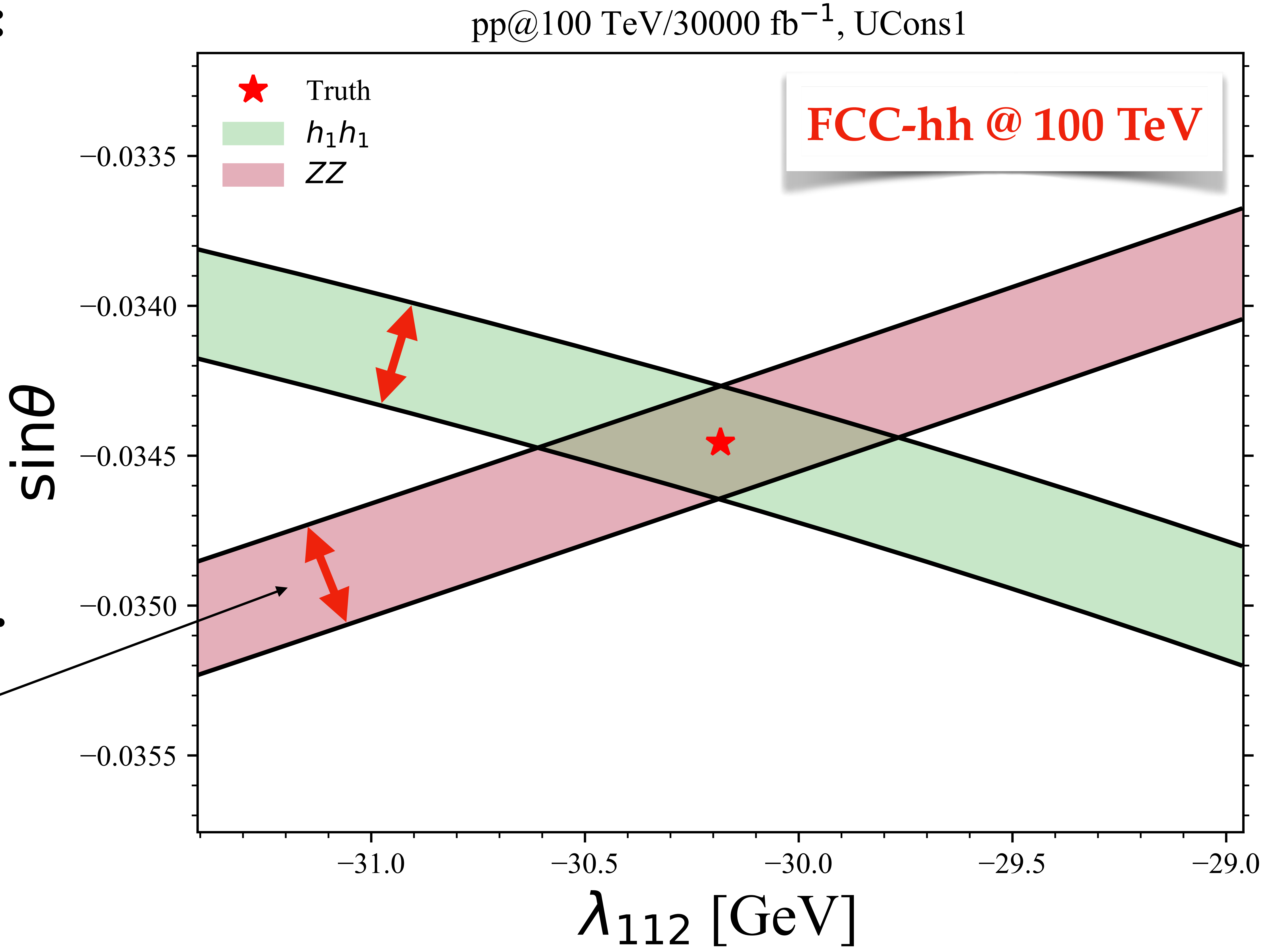
$pp \to h_2 \to h_1 h_1$



→ **both functions of** $\sin\theta$ **&** λ_{112}**!**

→ **in turn f^ns^ of** {●, ▲, ■, ▲, ■}.

[Width of bands represents expected measurement uncertainty].



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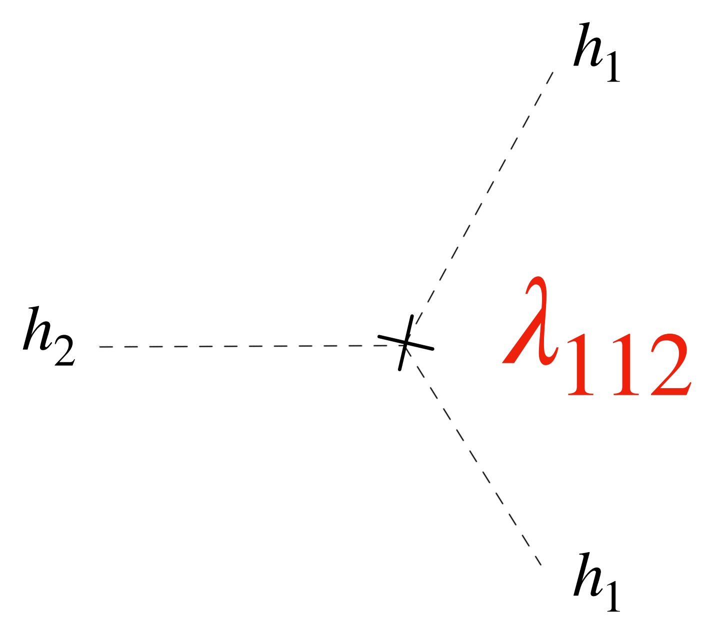

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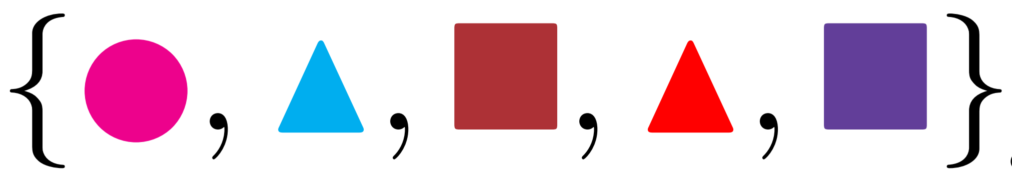
→ **in turn f^ns^ of** **.**

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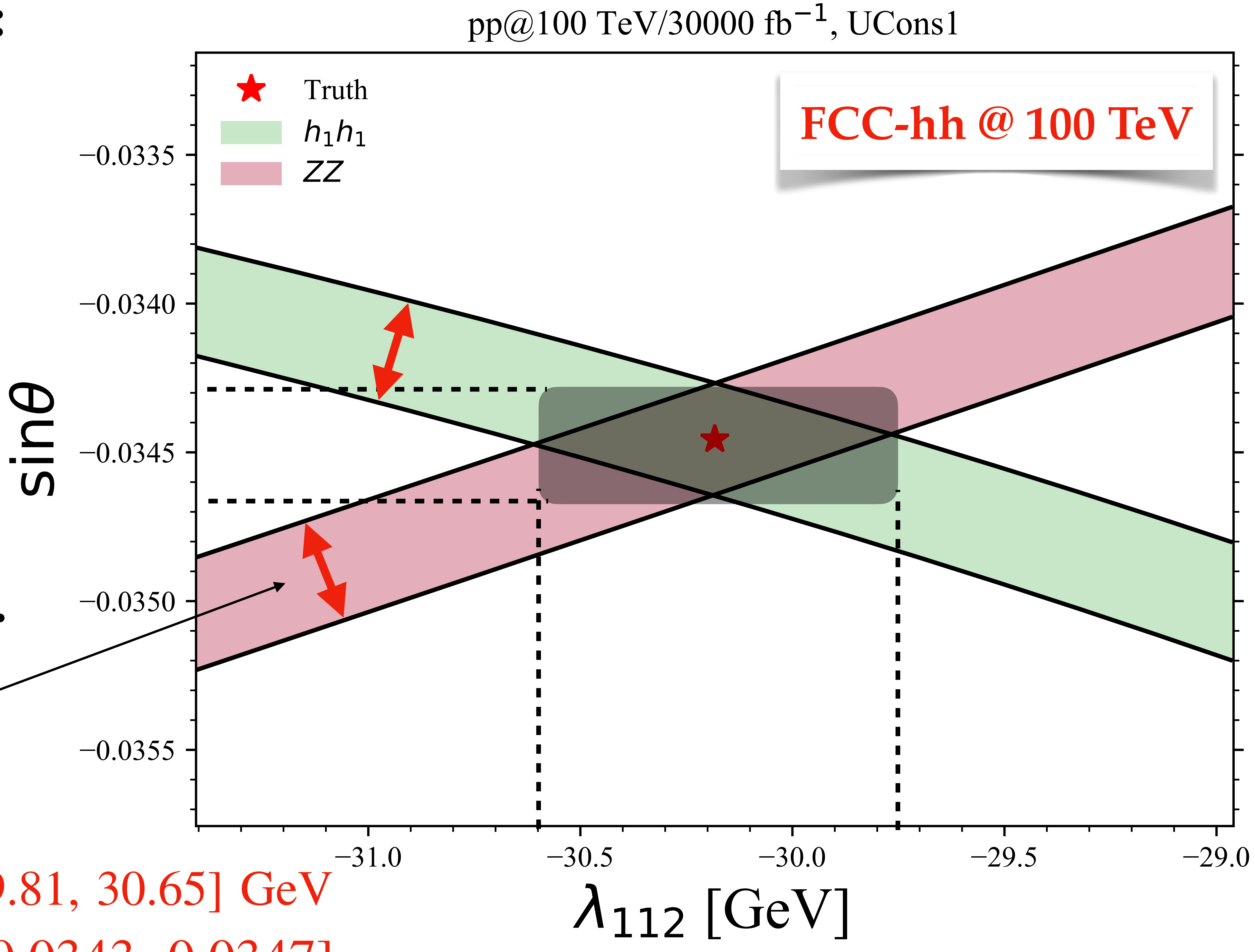

$\lambda_{112} \in [29.81,\ 30.65]$ GeV

$\sin\theta \in [0.0343,\ 0.0347]$

The Inverse Problem in Extended Scalar Sectors:

Multi-scalar processes should play a **crucial rôle**:

$pp \to h_1 h_2$ $\quad |\mathcal{M}|^2 \sim \lambda_{122}^2, \lambda_{112}^2 + \ldots$

$pp \to h_2 h_2$ $\quad |\mathcal{M}|^2 \sim \lambda_{222}^2, \lambda_{122}^2 + \ldots$

$pp \to h_1 h_1 h_1$ $\quad |\mathcal{M}|^2 \sim f[\lambda_{1111}, \lambda_{1112}, \lambda_{111}, \lambda_{112}]$

[…]

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[…]


$pp \to hhh$

SM Multi-Higgs Boson Production "Fun" Facts

- ∃ 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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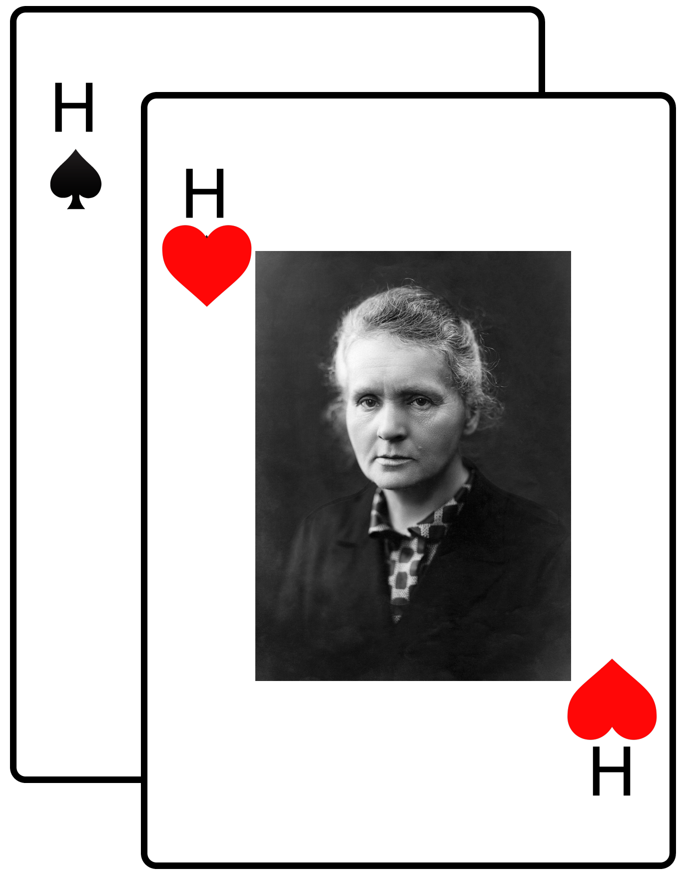
$\times\, \mathcal{O}(10^{-3})$



$\sigma(hh) \sim 40$ fb

SM, 14 TeV

Andreas Papaefstathiou

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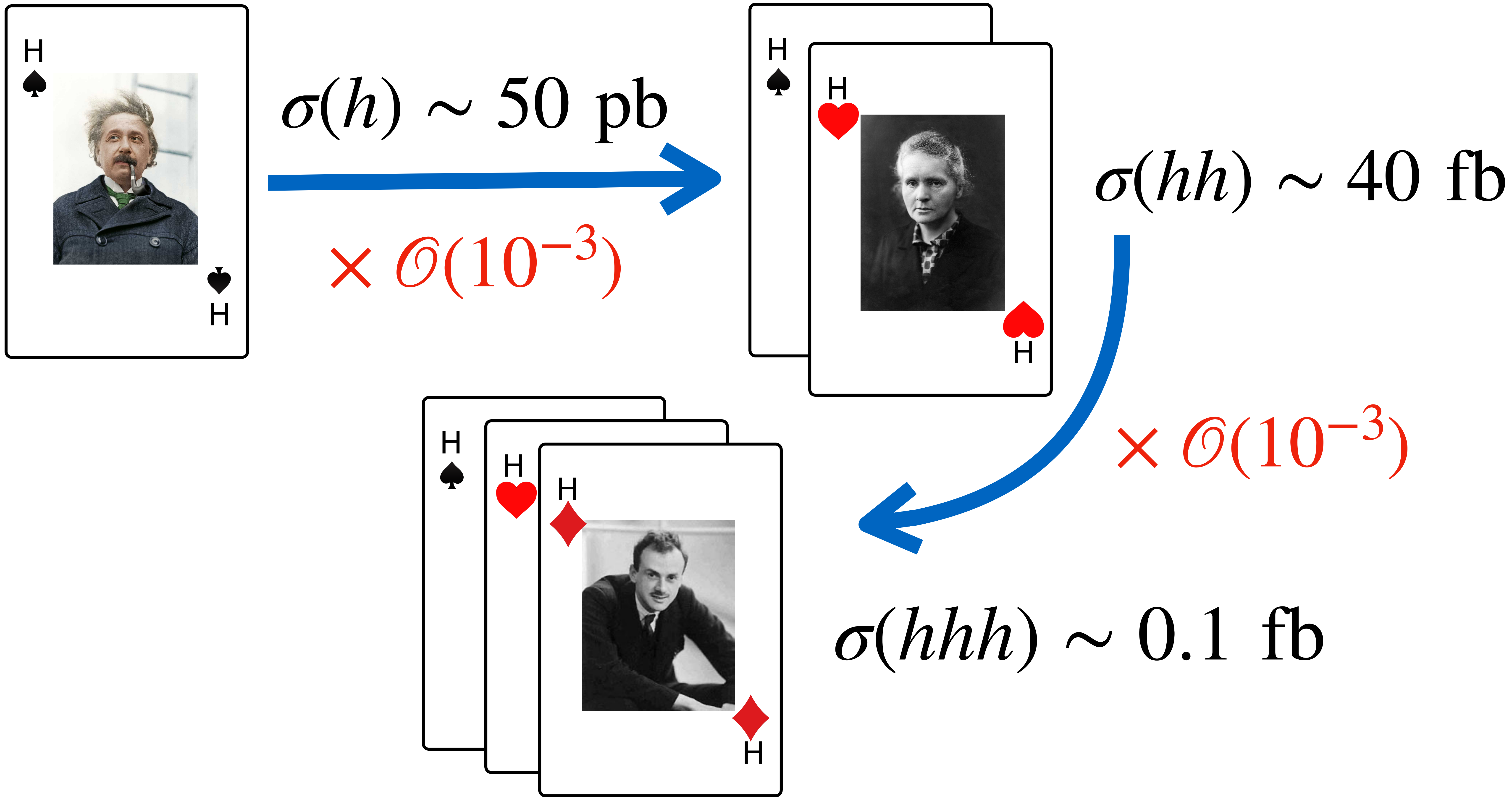

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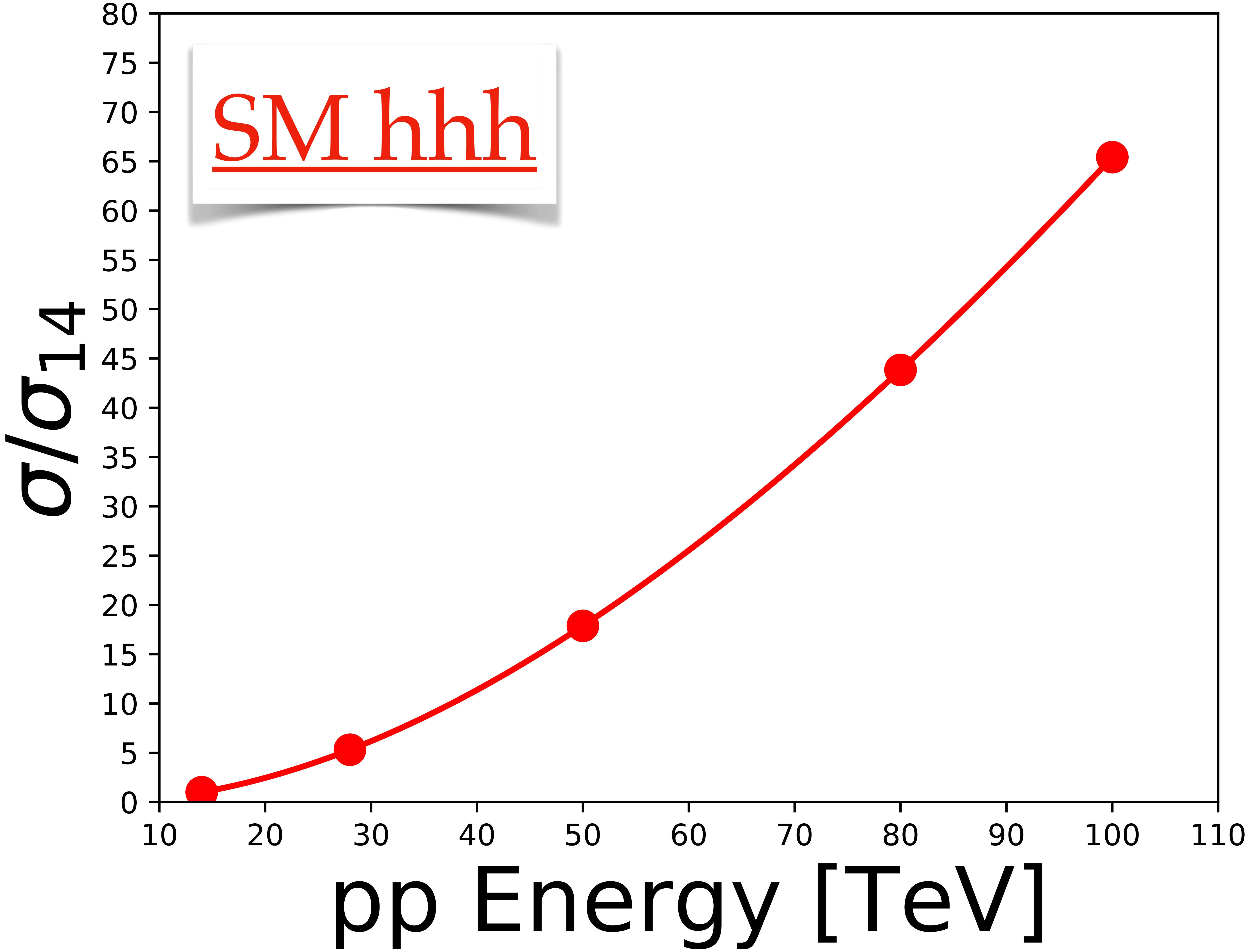
SM Multi-Higgs Boson Production "Fun" Facts

- Cranking up the pp energy could help!



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

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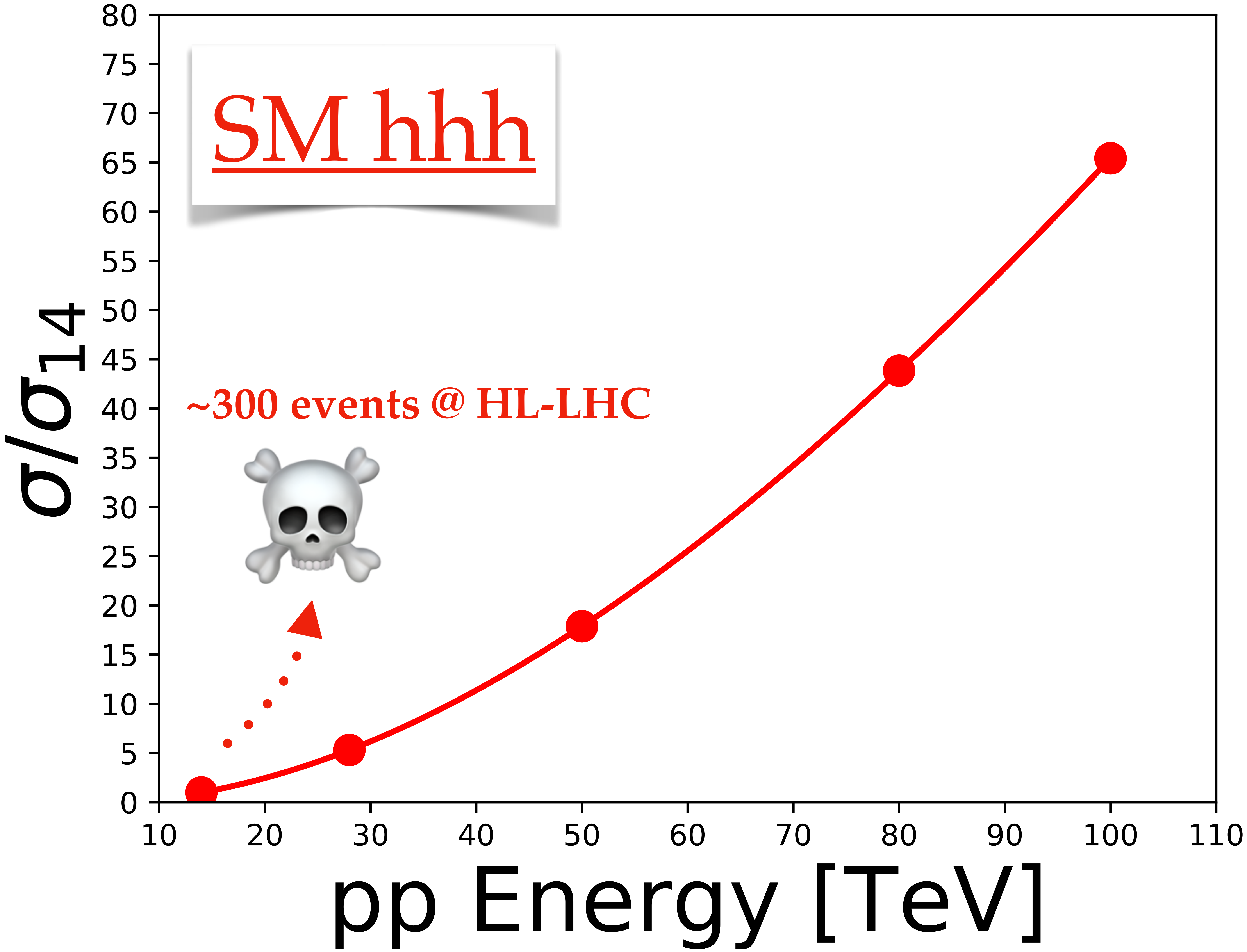

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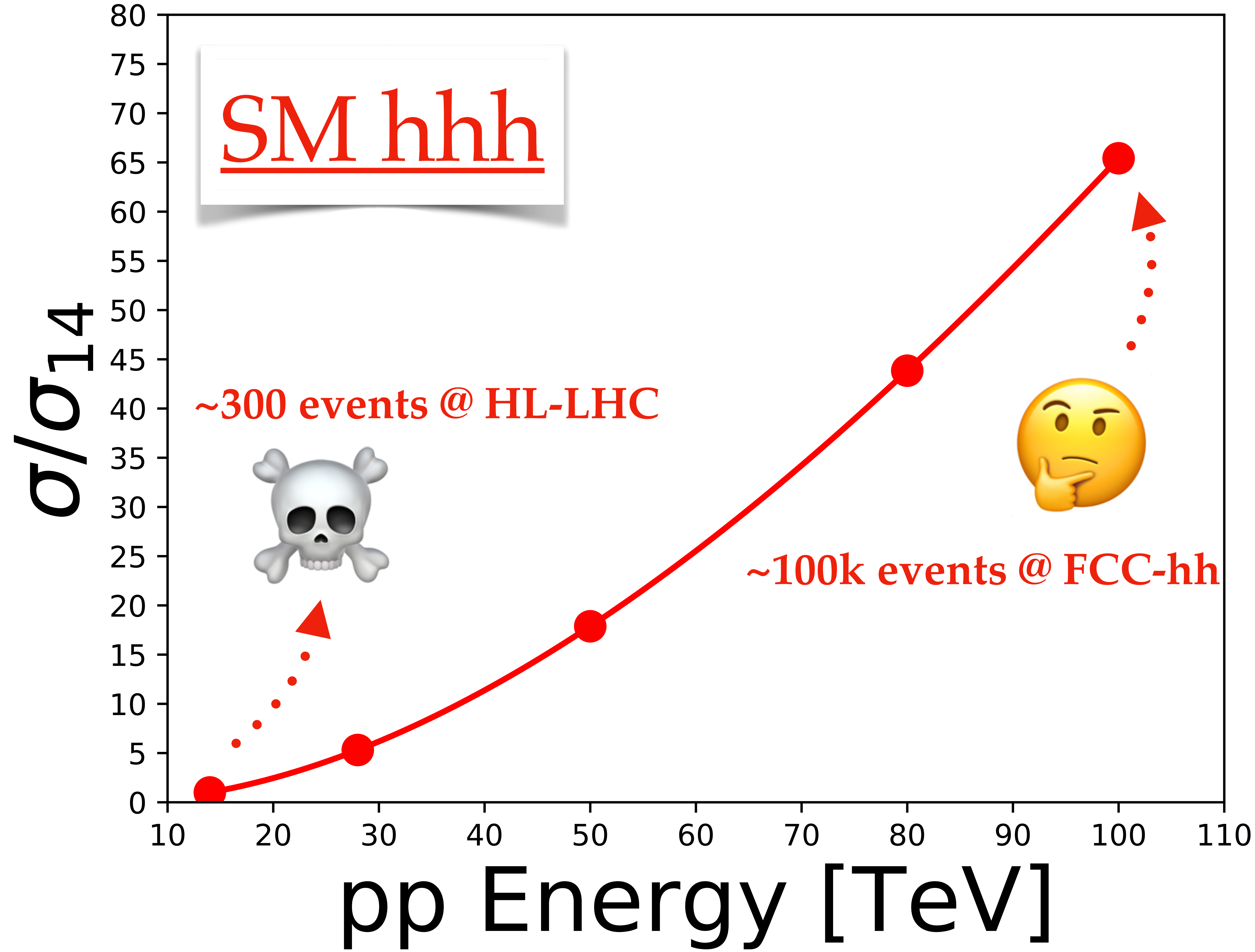

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THE SECRET INGREDIENT IS ALWAYS LOVE

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

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Here:

A. **hhh** in SM+2 singlet scalar fields,

B. **hhh** with anomalous couplings.

A. **hhh** in SM+2 singlet scalar fields,

SM + Two Real Singlet Scalars [= TRSM]

- 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:

$$\mathcal{V}(\phi, S, X) = \bullet\, |\phi|^2 + \blacksquare |\phi|^4 + \bullet S^2 + \blacksquare S^4 + \bullet X^2 + \blacksquare X^4$$
$$+ \blacksquare S^2 X^2$$
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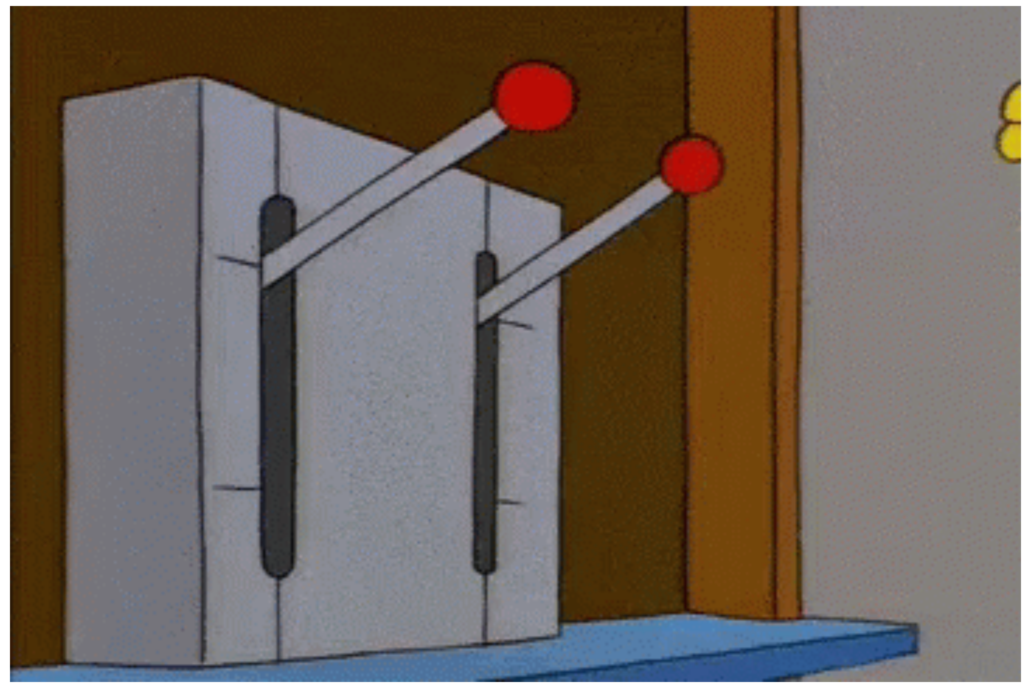
SM + Two Real Singlet Scalars [= TRSM]

- Go through EWSB…



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

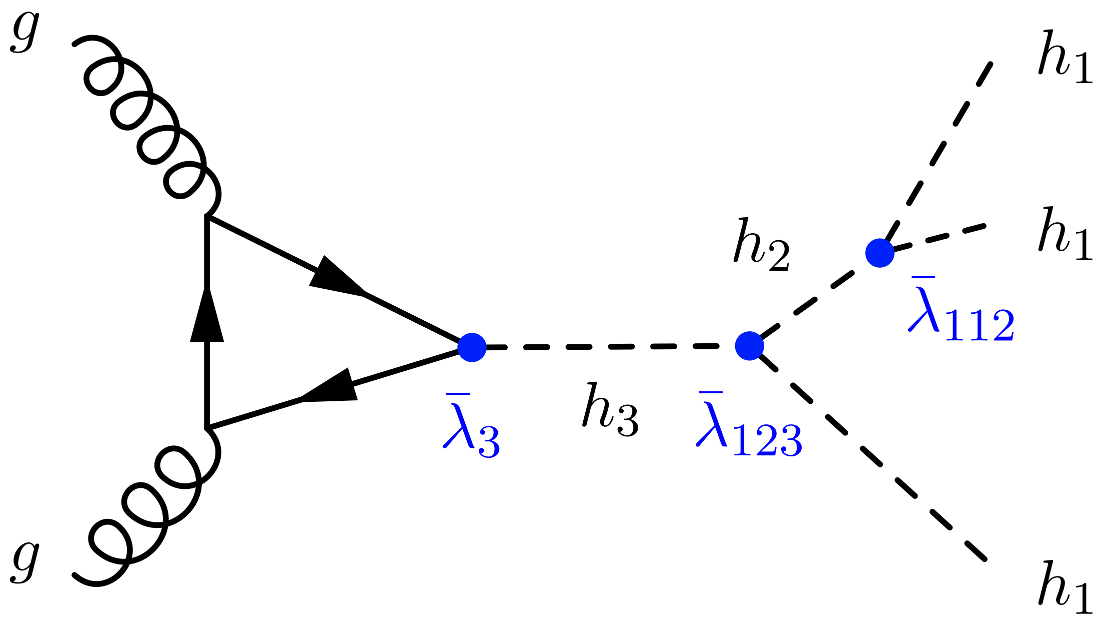
⇒ Seven independent parameters: M_2, M_3 + three mixing angles + two VEVs.

⇒ Modified / Additional interactions between scalars.

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

e.g.: $pp \to h_3 \to h_2 h_1 \to h_1 h_1 h_1$

→ **Double-resonant enhancement!**



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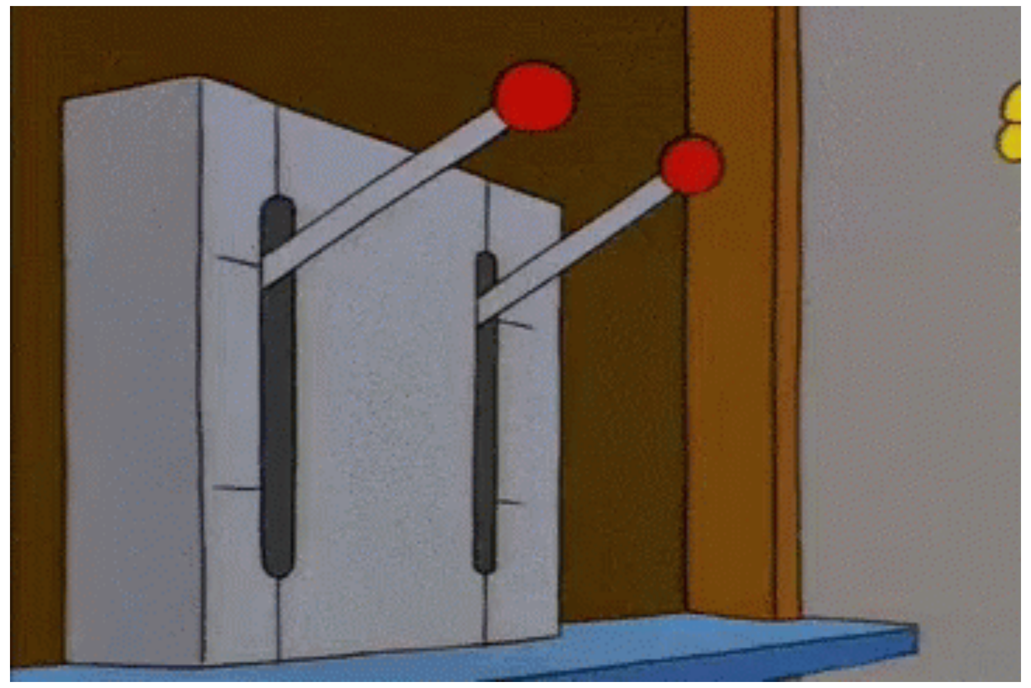

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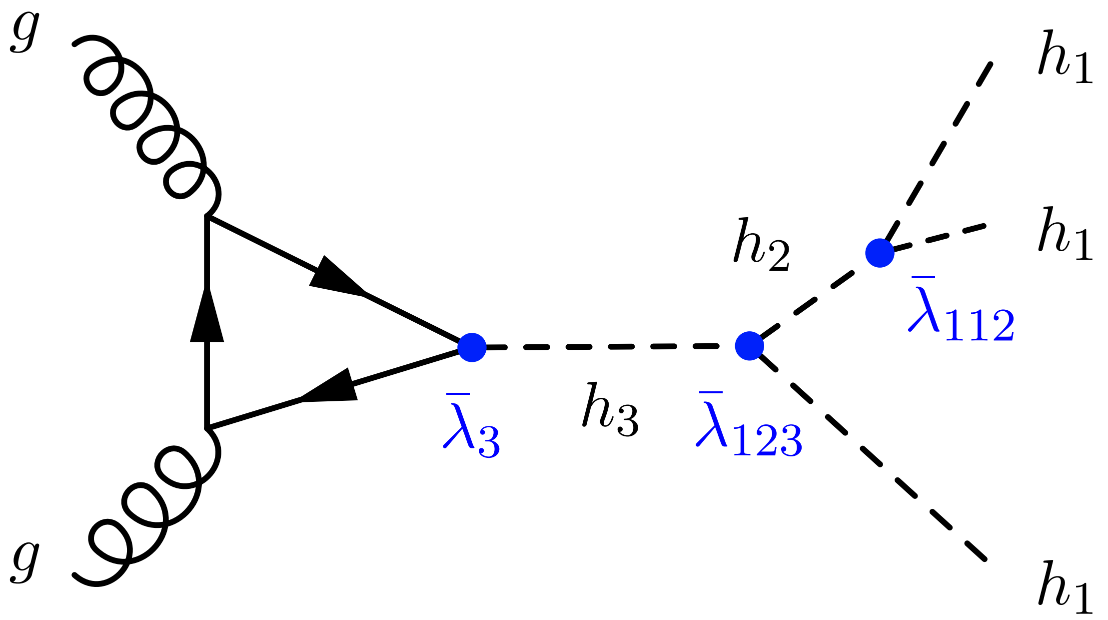


hhh in the TRSM [14 TeV]

- Focus on a particular family of benchmark points: **"Benchmark Plane 3"** = **"BP3"** in [Robens, Stefaniak, Wittbrodt, arXiv:1908.08554].

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

- In BP3: All params fixed except M_2, M_3!

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

→ c.f. SM: σ ~ 0.1 fb @ 14 TeV.

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

hhh in the TRSM "BP3" [14 TeV]

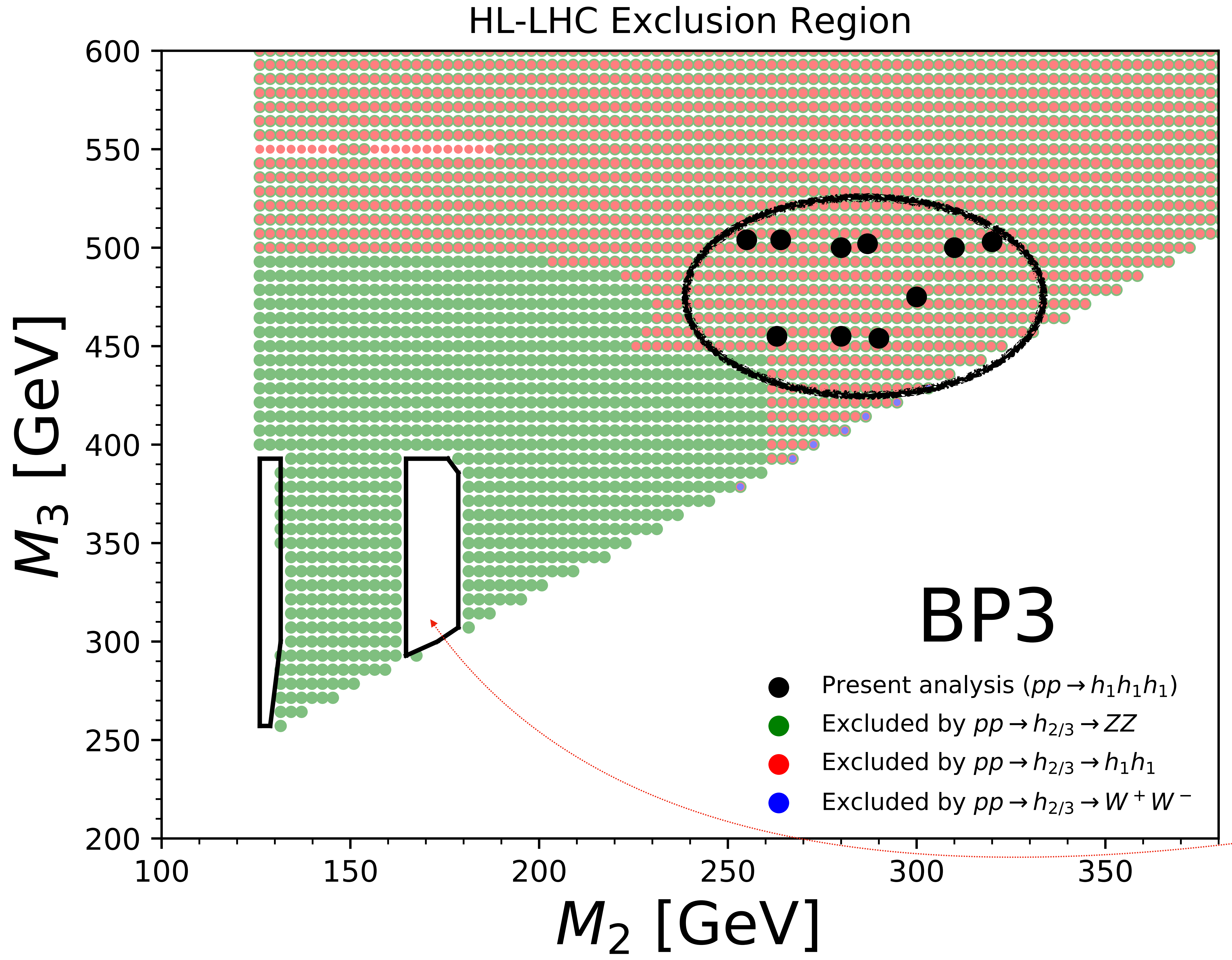
- Search for **hhh** via: $pp \to (b\bar{b})(b\bar{b})(b\bar{b}) \to$ **6 b-jets**.
- About **20%** of the **hhh** final state!
- Significances **large**, even when including systematic uncert.:

Label	$\text{sig}\|_{300\text{fb}^{-1}}$ (syst.)	$\text{sig}\|_{3000\text{fb}^{-1}}$ (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)

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

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!



Could help solve the "**inverse problem**" in the **TRSM**?

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

Note: regions near $M_2 \sim 130$ GeV and $M_2 \sim 170$ GeV will remain viable at the end of the HL-LHC.

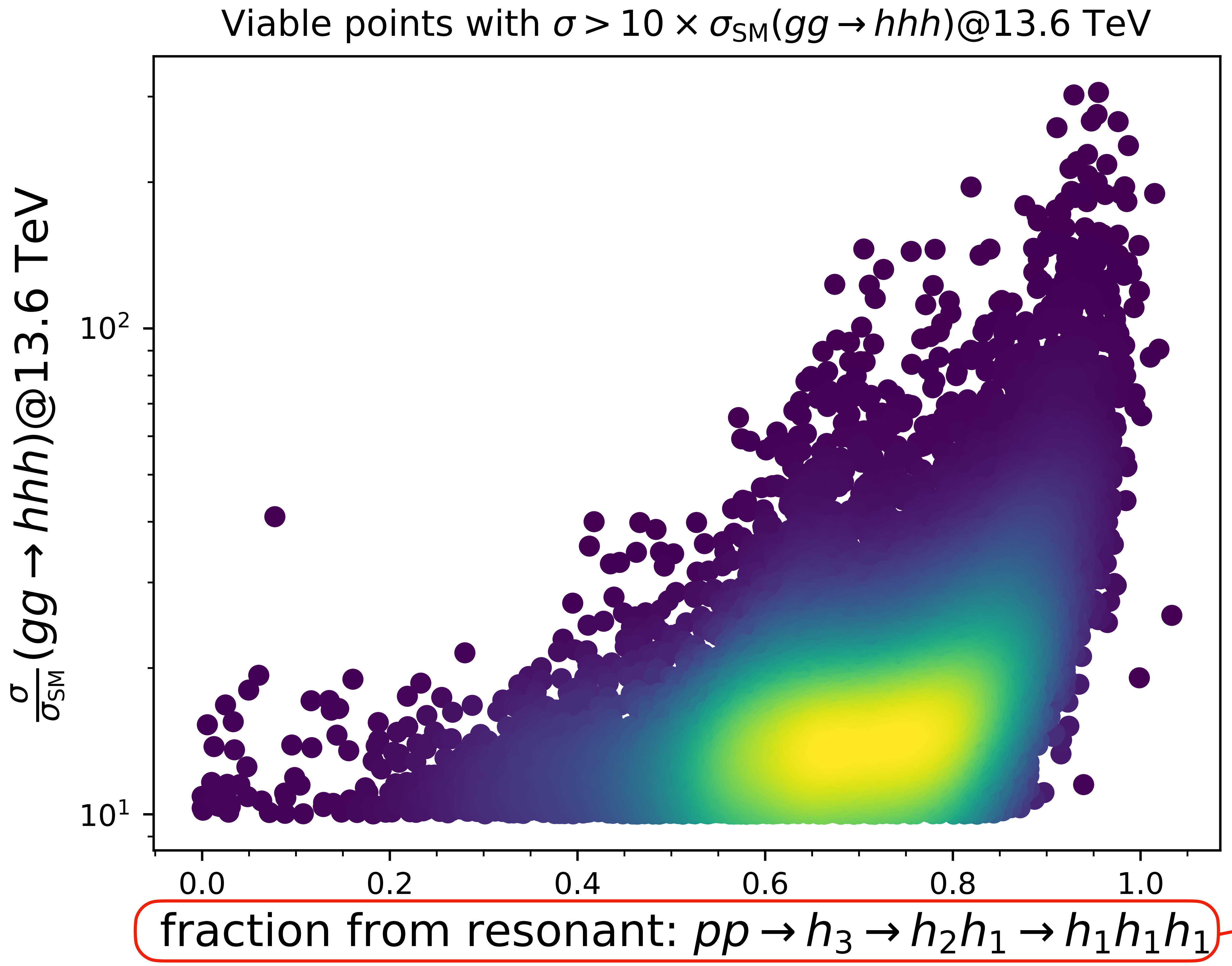
SFO-EWPT and hhh in the TRSM

- ***Q***: Can there be a **SFO-EWPT** in the **TRSM**, related to **electro-weak baryogenesis**?

- and if so, will this lead to **enhanced hhh at the LHC?**

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

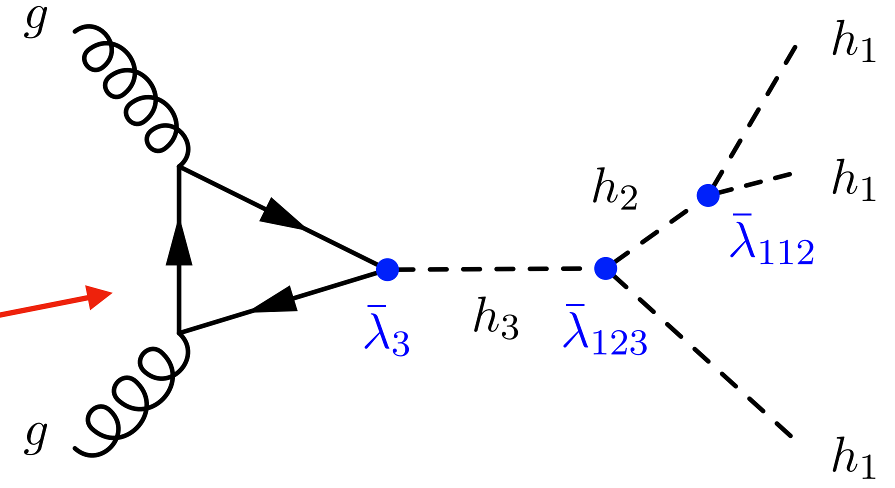
Enhancement over SM



- Updated TRSM scan with **additional TH+EXP constraints.**

- Enhancements $\mathcal{O}(100) \times \mathrm{SM}$!

How much of the total cross section comes from… ?



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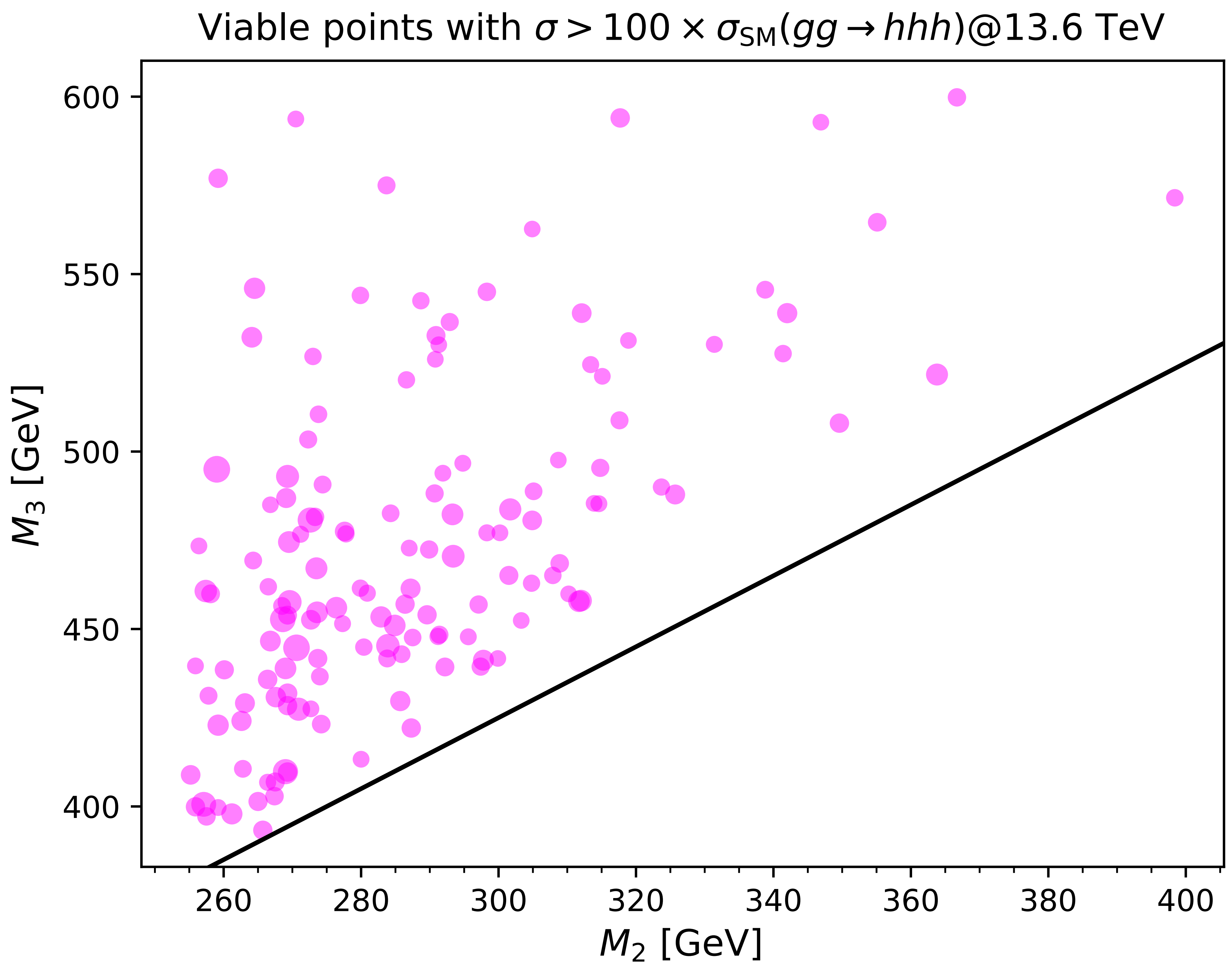

Mass of h_3

Mass of h_2

- An updated set of benchmark points,
- they go *beyond* BP3: all params. **varied**!
- Enhancements $\mathcal{O}(100) \times$ SM @ 13.6 TeV!

SFO-EWPT and hhh in the TRSM

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- **Unfortunately…**
  - **SFO-EWPT** & **enhanced hhh** are **mutually exclusive**!
  - barrier **not** generated **if both new scalars attain a non-zero VEV**,
  - and **non-zero VEVs are necessary** for sufficient mixing!

➡ **Removing the $\mathcal{Z}_2$ restrictions might help!**

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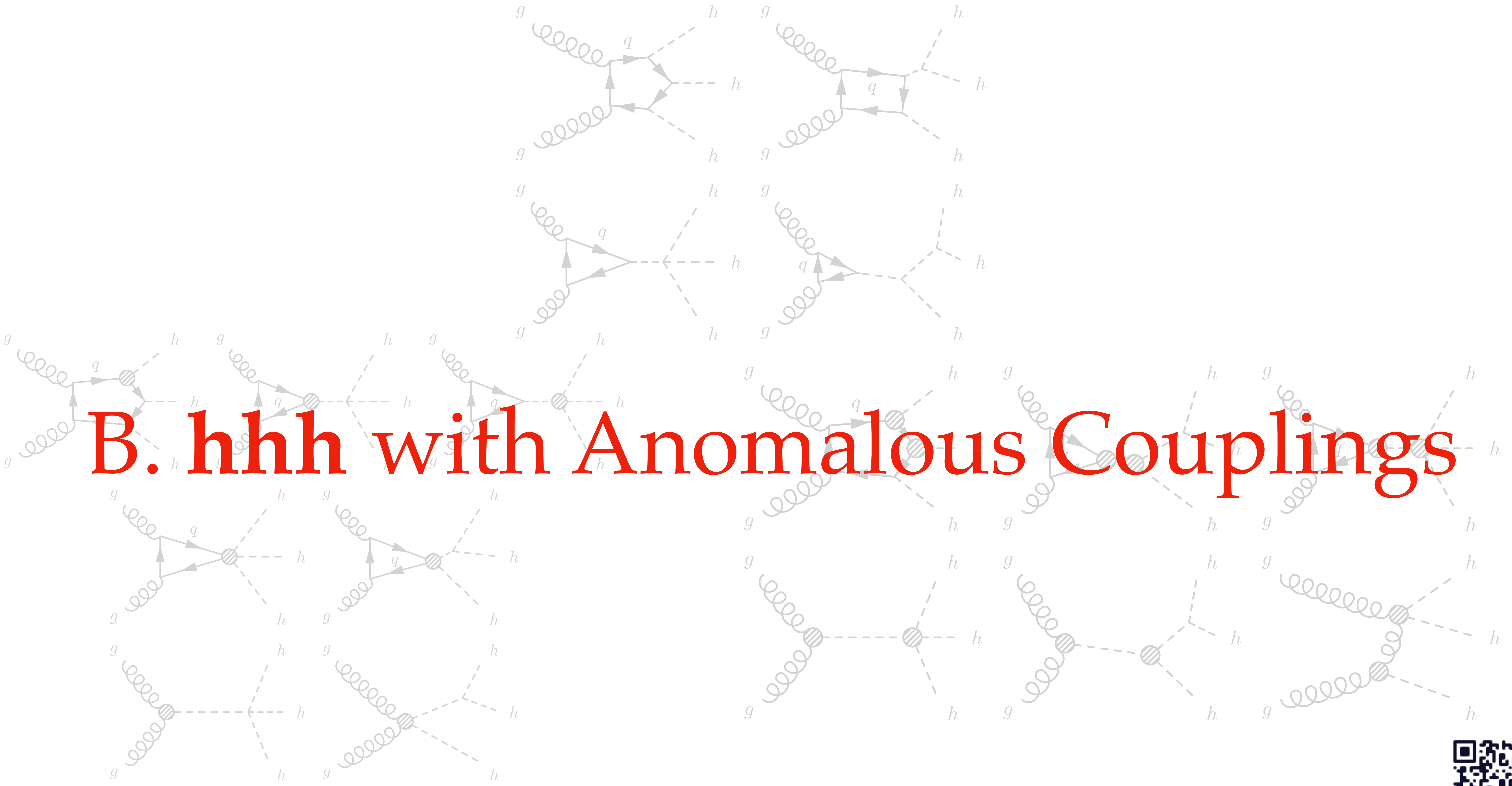
B. **hhh** with Anomalous Couplings



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D=6-Inspired Anomalous Couplings

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

  → 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 $\frac{\mathcal{O}_6}{\Lambda^2}$:

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

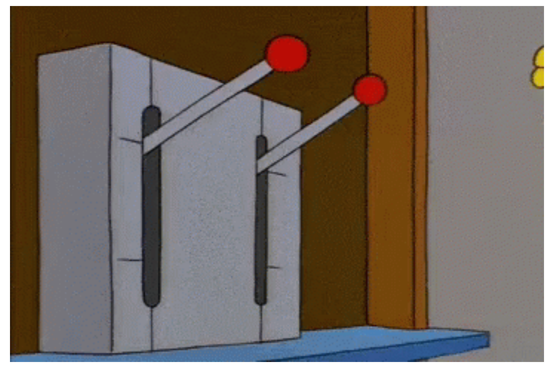
$$+ \frac{c_H}{2\Lambda^2} (\partial^\mu |\phi|^2)^2 - \frac{c_6}{\Lambda^2} \lambda_{\mathrm{SM}} |\phi|^6 + \frac{\alpha_s c_g}{4\pi\Lambda^2} |\phi|^2 G^a_{\mu\nu} G^{\mu\nu}_a$$

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

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

D=6-Inspired Anomalous Couplings

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

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

$$
\begin{aligned}
\mathcal{L}_{\mathrm{D}=6} \supset & -\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] \\
& - \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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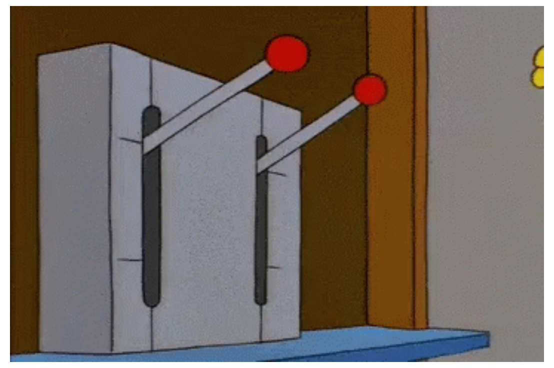
- Go through EWSB…  ⇒ in terms of the <u>physical scalar Higgs</u> boson h:

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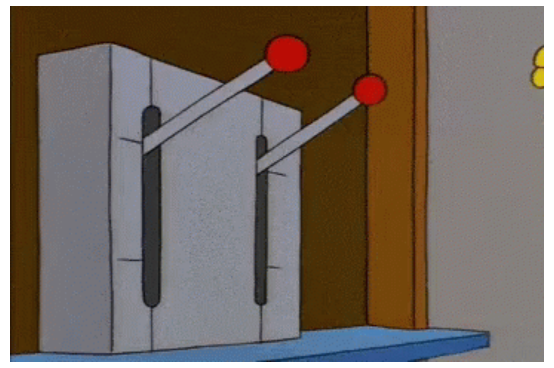
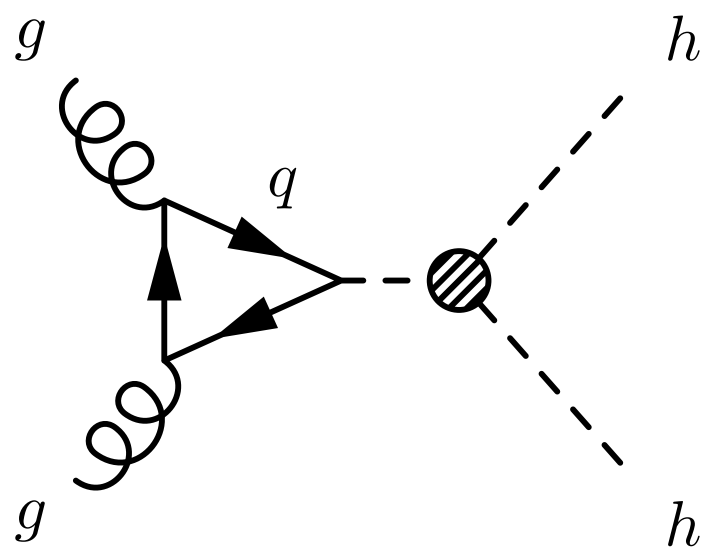
- Go through EWSB…  ⇒ in terms of the physical scalar Higgs boson h:



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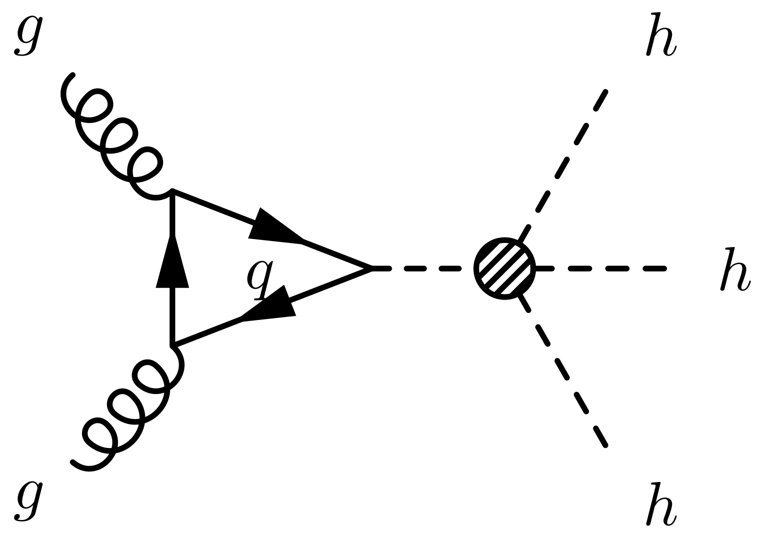
$$-\left[\frac{m_t}{v^3}\left(\frac{c_t}{2}\right)\bar{t}_L t_R h^3 + \frac{m_b}{v^3}\left(\frac{c_b}{2}\right)\bar{b}_L b_R h^3 + \mathrm{h.c.}\right],$$



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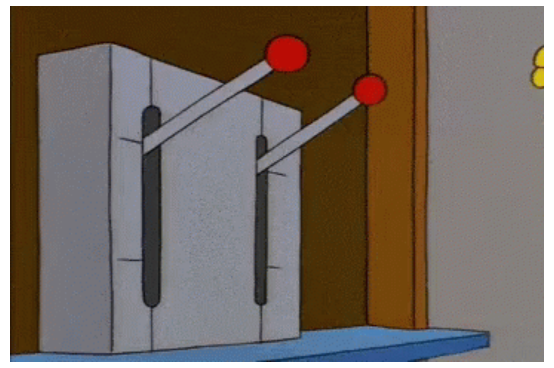
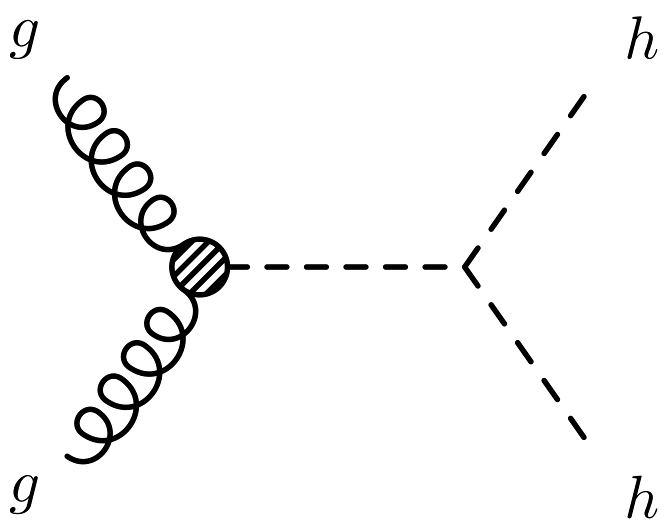
- Go through EWSB…  ⇒ in terms of the physical scalar Higgs boson h:



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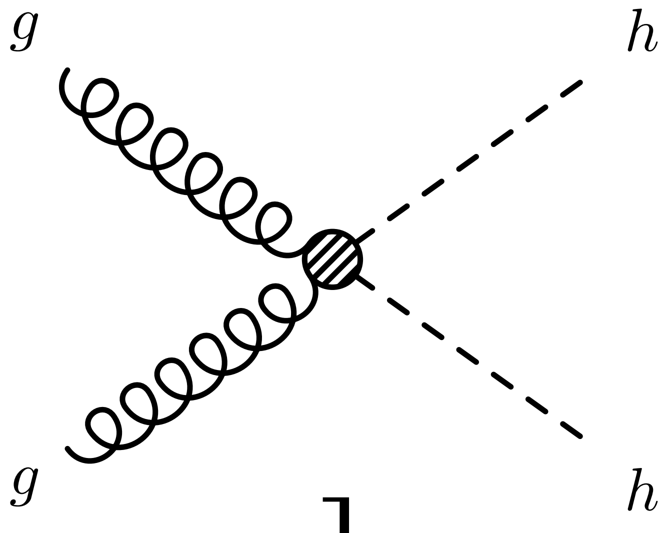
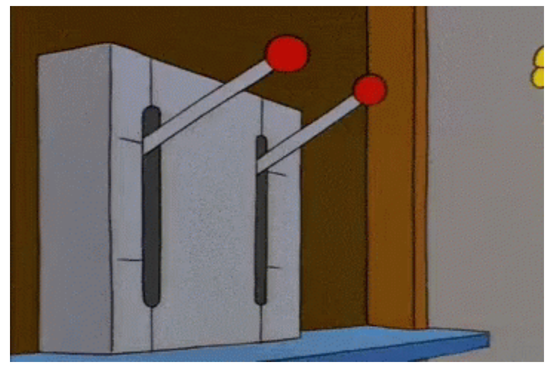


D=6-Inspired Anomalous Couplings

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

- Go through EWSB…



$\Rightarrow$ in terms of the <u>physical scalar Higgs</u> boson h:

$$\mathscr{L}_{\mathrm{D=6}} \supset -\frac{m_h^2}{2v}\left(1+c_6\right)h^3 - \frac{m_h^2}{8v^2}\left(1+6c_6\right)h^4$$

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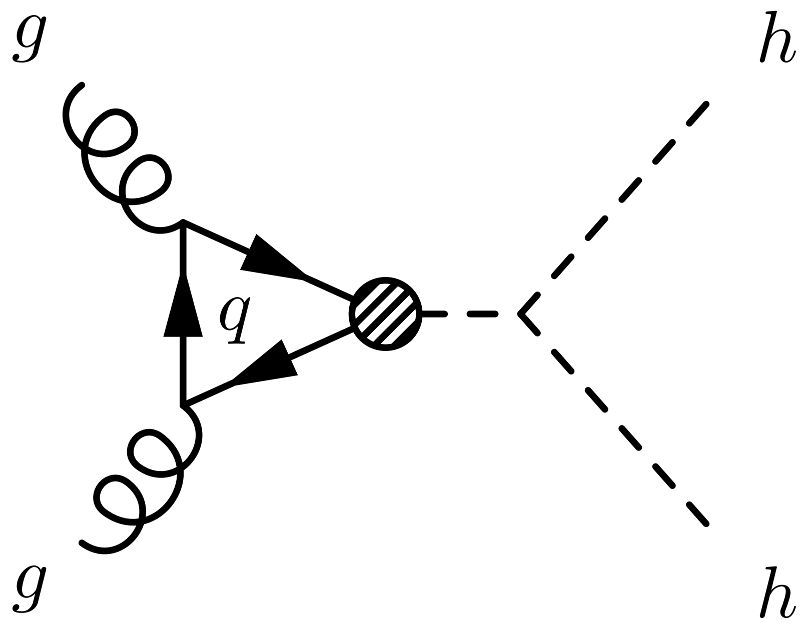

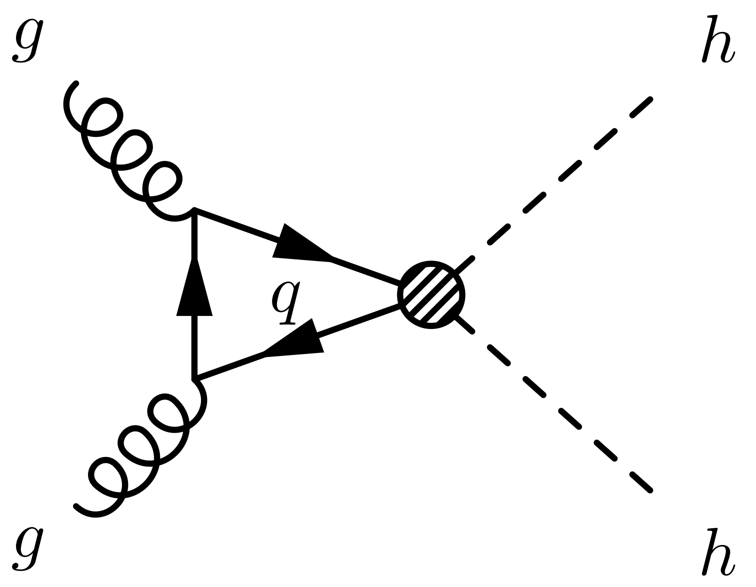

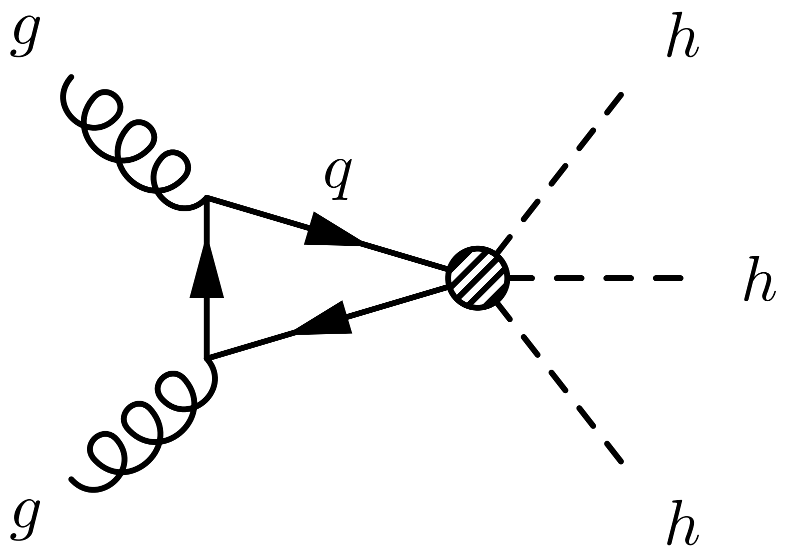

D=6-Inspired Anomalous Couplings

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

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

$$\mathscr{L}_{\rm Pheno} \supset -\frac{m_h^2}{2v}\left(1+d_3\right)h^3 - \frac{m_h^2}{8v^2}\left(1+d_4\right)h^4$$
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Recover D=6 by setting:

$$d_3 = c_6,$$
$$d_4 = 6c_6,$$
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Note: This can be also be motivated via the Electro-weak Chiral Lagrangian,
[see e.g. Buchalla, Catá, Krause arXiv:1307.5017]

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instead of c_g

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[see e.g. Buchalla, Catá, Krause arXiv:1307.5017]

D=6-Inspired Anomalous Couplings

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

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

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

Obtain **CMS-like** parametrization by:

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

And **ATLAS-like** parametrization by:

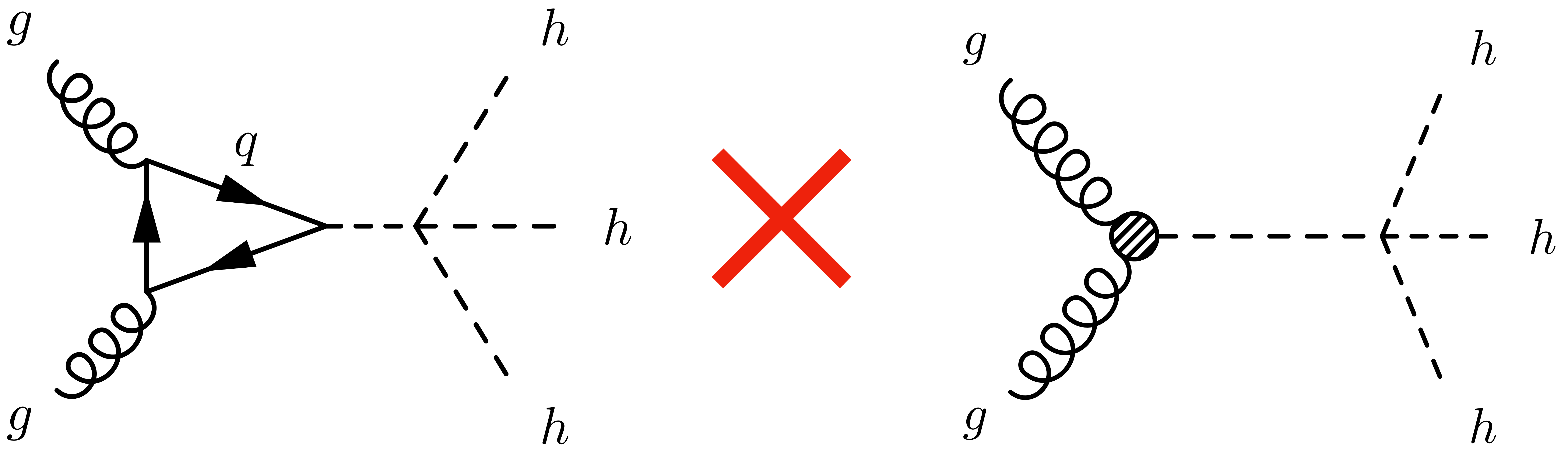
$$c_{hhh} = (1+d_3),$$
$$c_{ggh} = 2c_{g1}/3,$$
$$c_{gghh} = -c_{g2}/3.$$

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.:



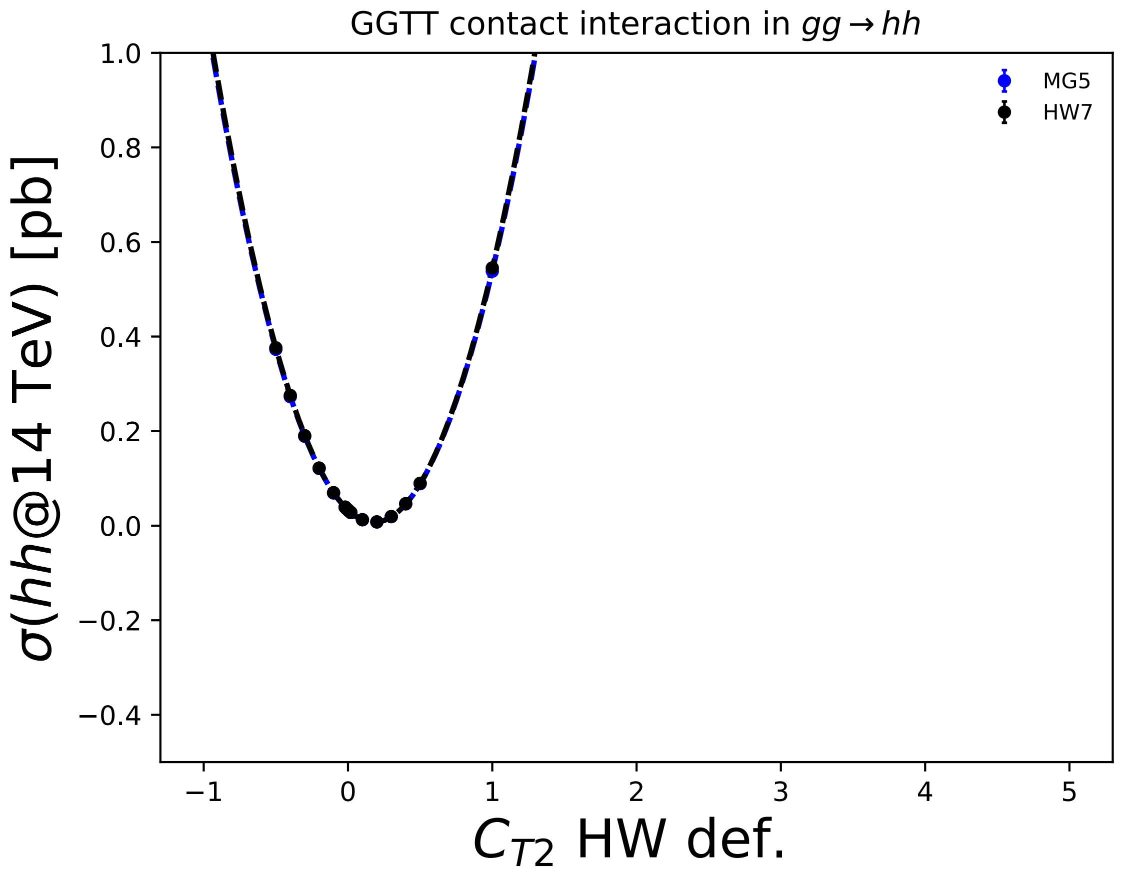
[**AP**, Tetlalmatzi-Xolocotzi, arXiv:2312.13562]

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

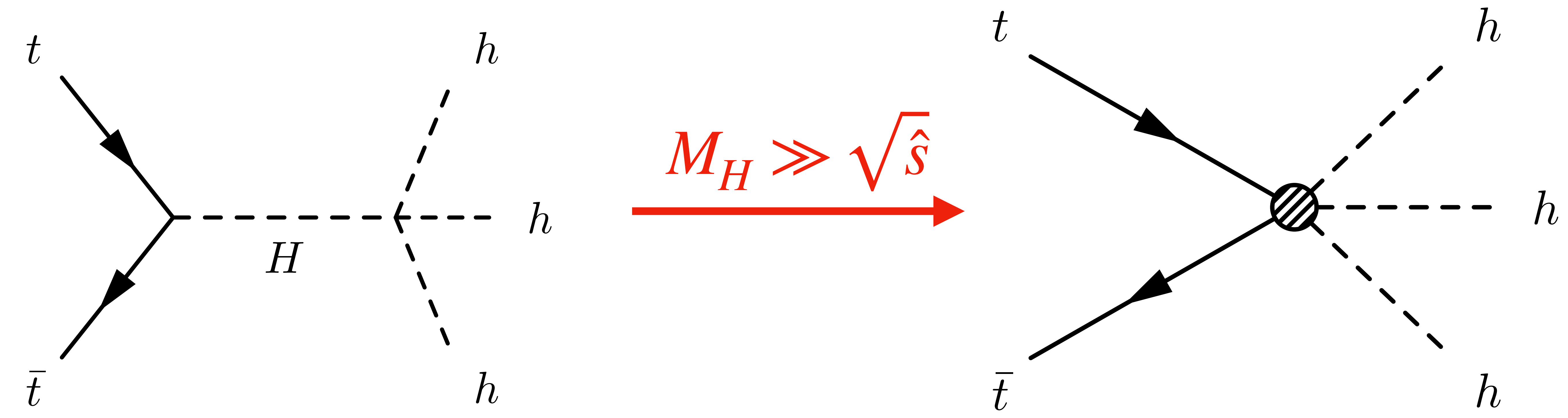
Model Validation

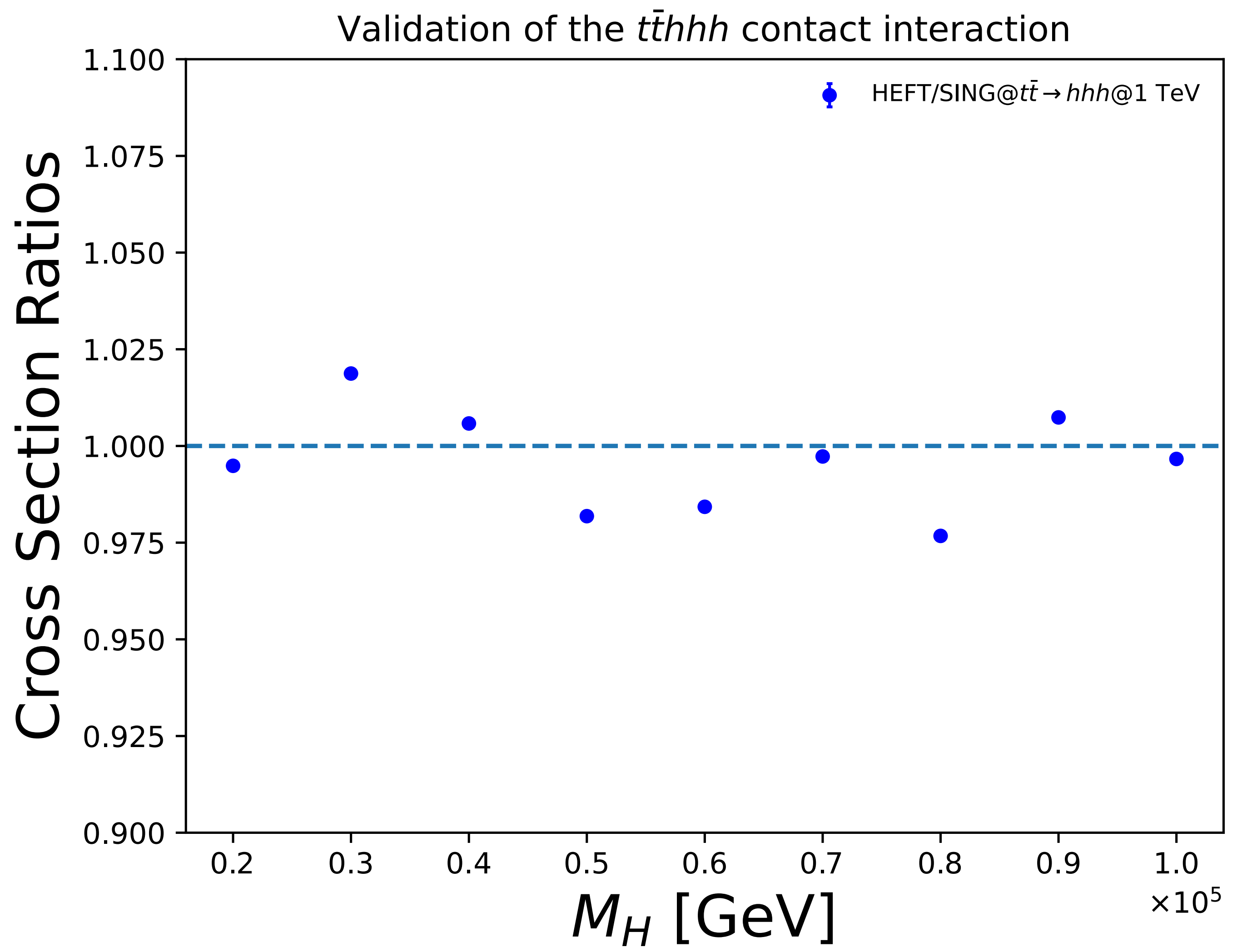
[**AP**, Tetlalmatzi-Xolocotzi, arXiv:2312.13562]

- 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:





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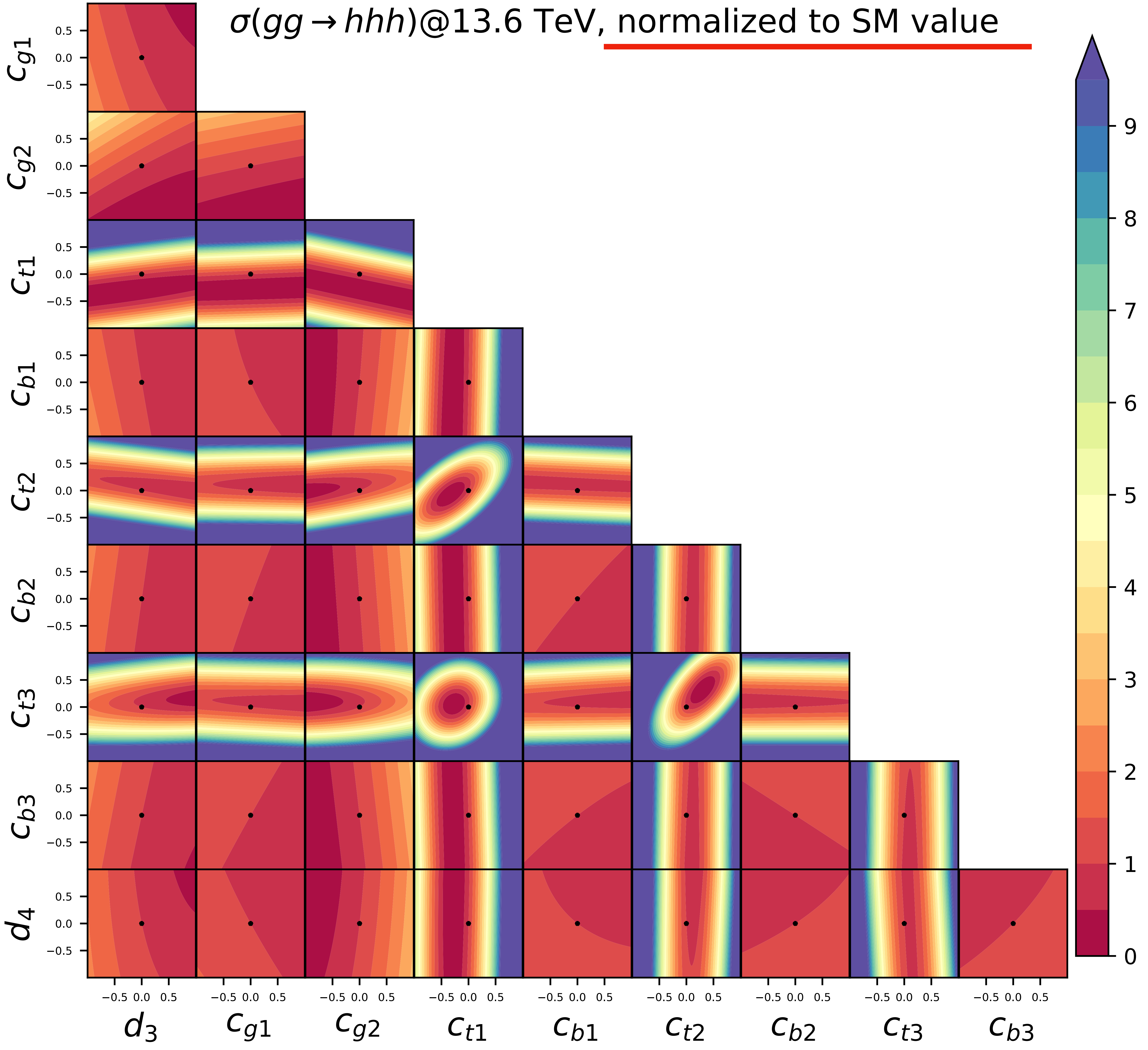
hhh Cross Sections @ 13.6 TeV

[**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]

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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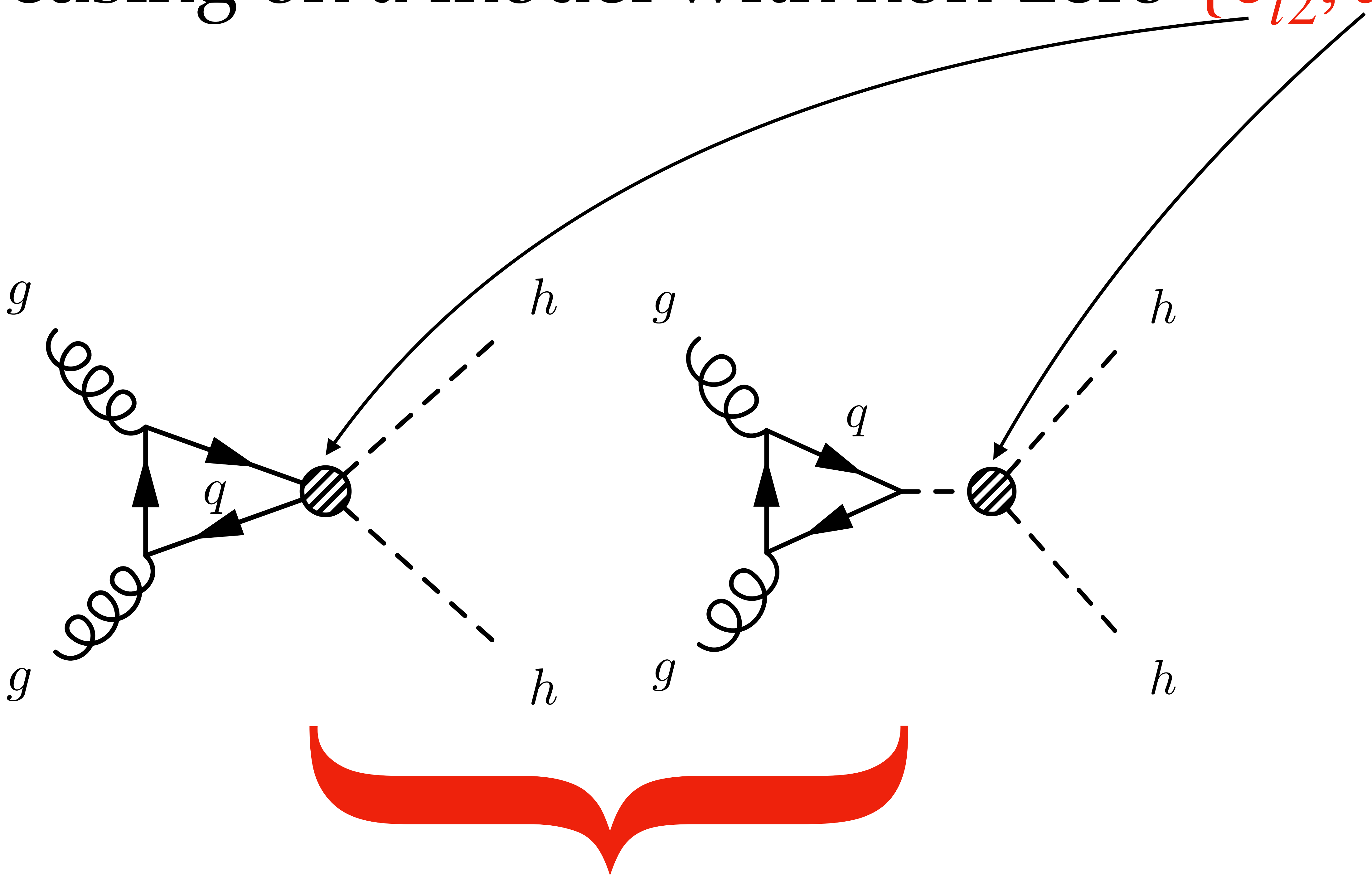

constrained by $pp \to hh$

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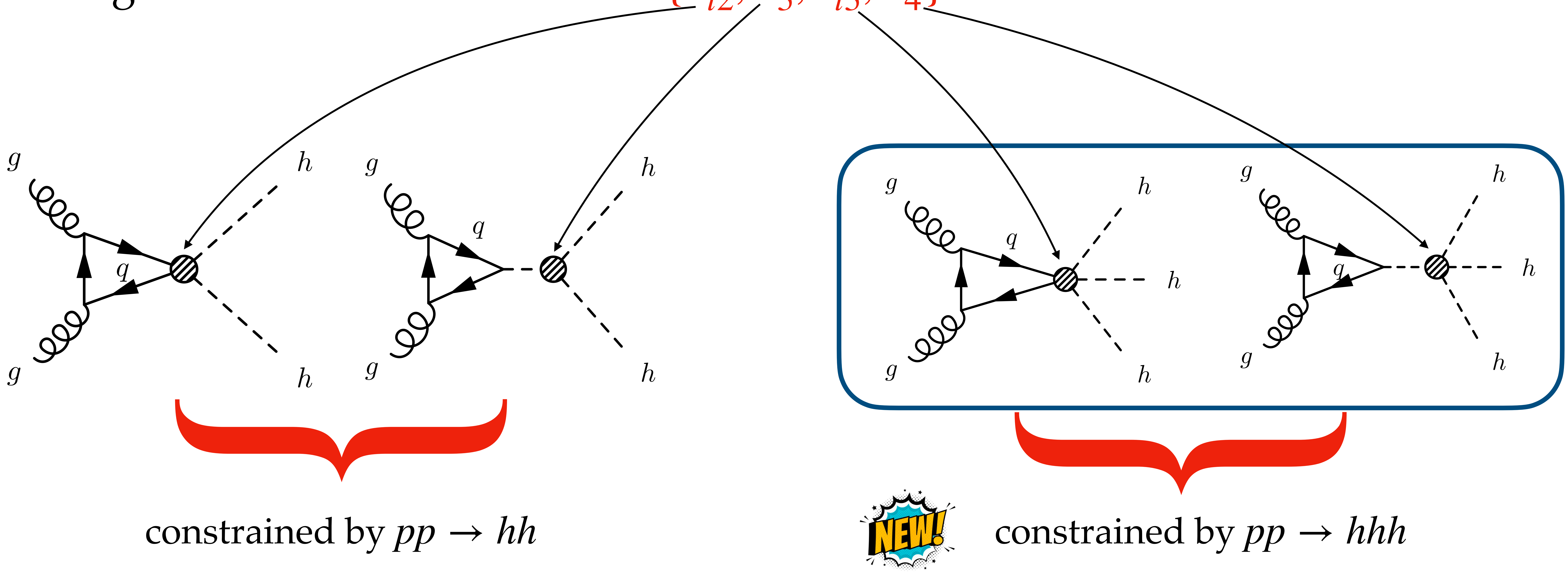
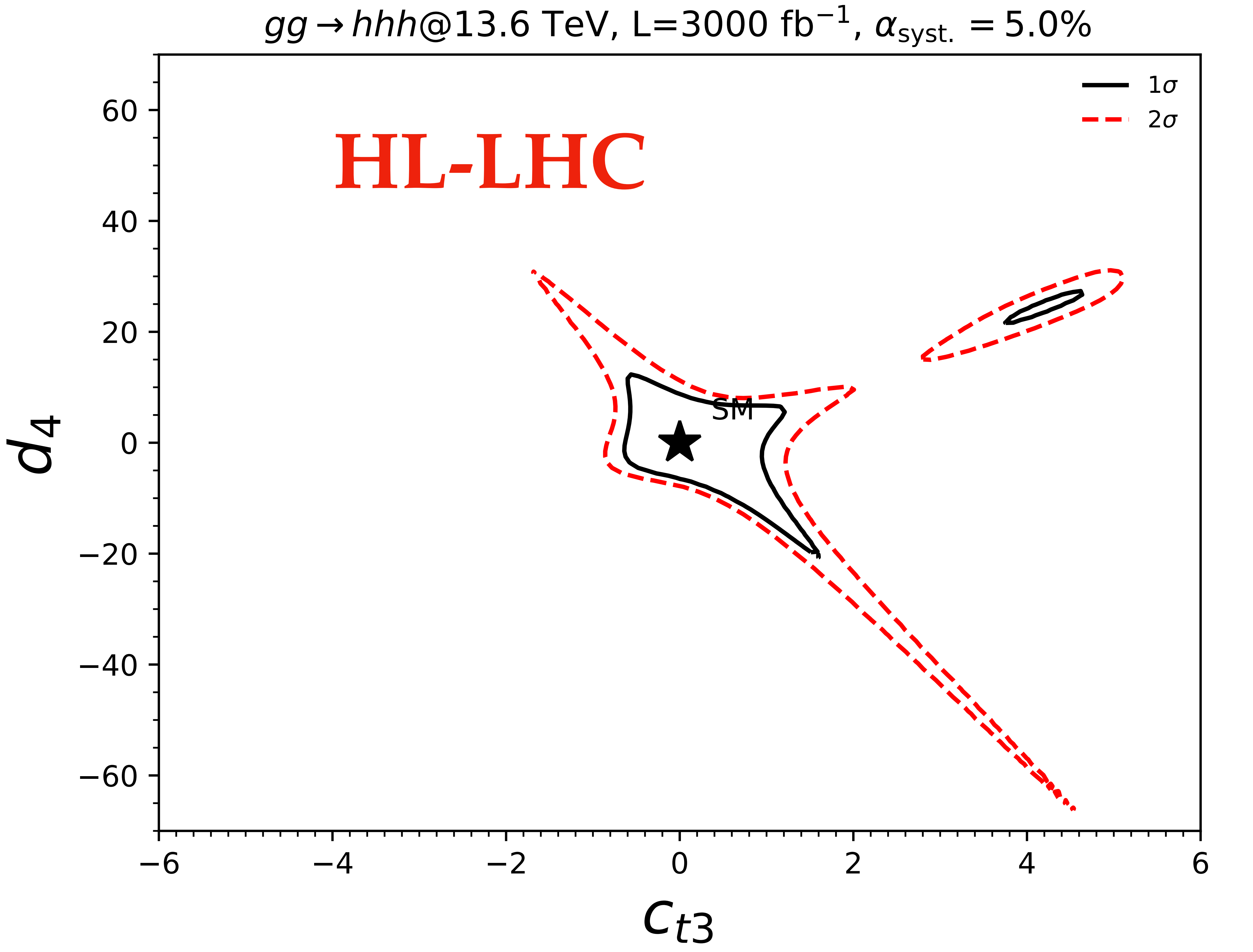
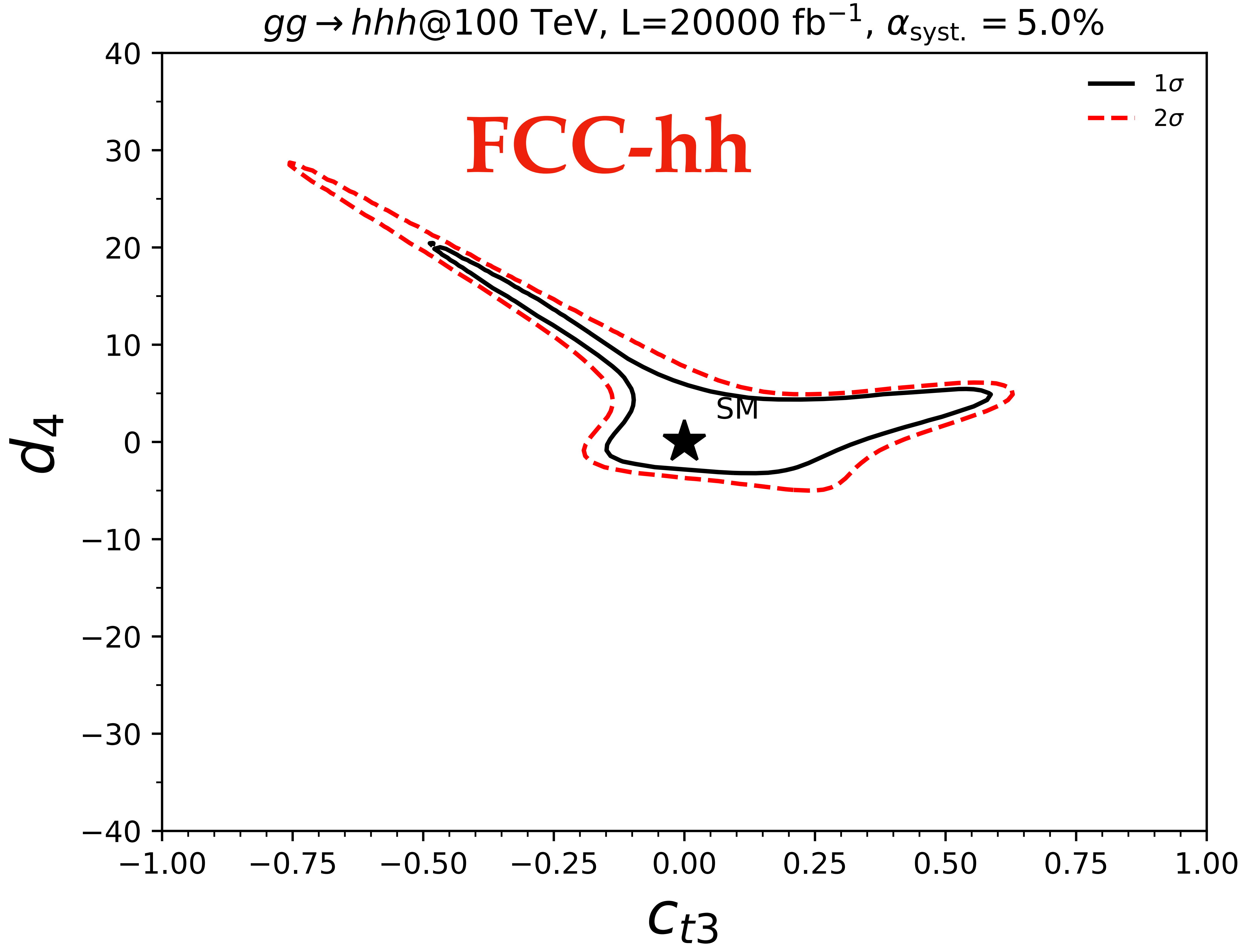


Anomalous Couplings Constraints

[**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:





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	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}	$[-0.6, 1.1]$	$[-0.9, 3.6]$	$[-0.1, 0.3]$	$[-0.4, 0.6]$

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

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

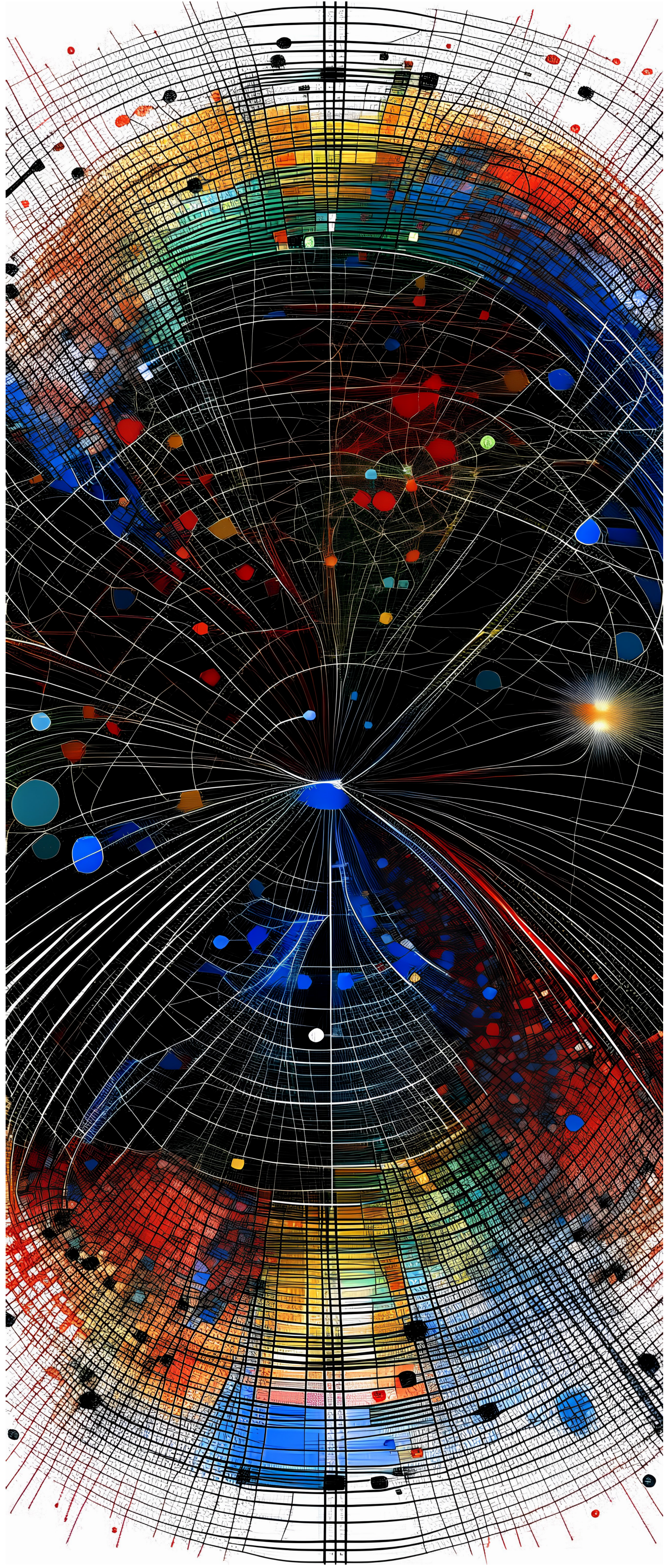
Summary & Outlook (I)

- Despite the successes of the SM, there remains a multitude of **open questions**,

  ➡ Some may be linked via the **Electro-Weak Phase Transition.**

- The **Nature of the Electro-Weak Phase Transition** is an important scientific enquiry.

  - **(Strong) First-Order EWPT [not in SM!] → Matter-Anti-Matter asymmetry.**
  - Extending the **scalar sector of the SM could be the necessary catalyst.**
  - Future particle colliders have the **potential to probe this mechanism**.



[made with stablecog]

Summary & Outlook (II)

- Following *any* discovery, **solving the inverse problem** would be the **crucial** next step.

- **Multi-scalar production processes** (e.g. **hhh** production) may play a crucial role in models with extended scalar sectors.

- **hhh** may be enhanced in models with extended scalar sectors. **Could we see hints at the LHC?**

- **hhh** production will probe modifications to the **Higgs quartic self-coupling, within the anomalous coupling picture**.

- **Questions merit investigation both at the LHC and other future colliders (e.g. FCC, Muon Collider, …).**

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Dank je wel!

Thanks!

Questions?

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Appendices

Theoretical Uncertainties

- **Uncertainties** → Can affect e.g. the **strength of the transition,** $\langle \phi(T) \rangle / T$.
- Due to:
  - **gauge dependence**, [Patel, Ramsey-Musolf, arXiv:1101.4665]
  - **scale dependence** → Linde's IR problem: expansion parameter is $g n_B \sim gT/m$, (n_B mode occupation), diverges as $m \to 0 \Rightarrow$ perturbativity breaks down.

    [Linde, Phys. Lett. 96B (1980) 289.]
- ⇒ **To make reliable and sensible statements on colliders prospects:**

  → **Crucial to take uncertainties into account.**

Theoretical Uncertainty Bands

- **Define "uncertainty band"** by:

1. Deriving 1-loop effective potential in the covariant gauge,

   [Arnold, Espinosa, hep-ph/9212235], [Andreassen, MSc, Norwegian U. Sci. Tech., 2013]

2. Run couplings $\lambda \to \lambda(\mu)$, μ is RGE scale, [`SARAH`, Staub, arXiv:0806.0538]

3. Scan parameter space of Lagrangian,

4. Vary $\mu \in [\frac{1}{2} \times m_Z,\, 5 \times m_Z]$ & gauge params. $\xi_i \in [0,3] \to$ band of 8 pts.

5. Use **`PhaseTracer`** for each point in band $\to$ Get phase transitions, $\langle \phi(T_c) \rangle / T_c$.

   [Athron, Balázs, Fowlie, Zhang, arXiv:2003.02859]

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Parameter-space Categories

1. Define two conditions:

   i. VEV at 1-loop: $\langle \phi(T=0) \rangle = 246 \pm 30$ GeV **&** deepest minimum.

   ii. $\left\langle \phi(T_c) \right\rangle / T_c > 1$ **&** no other transition with higher T_c.

2. Define four mutually-exclusive categories*:

SFO-EWPT more certain →

Liberal | **Centrist** | **Conservative** | **Ultra-Conservative**

*An alternative classification appears in our article: see Appendix.

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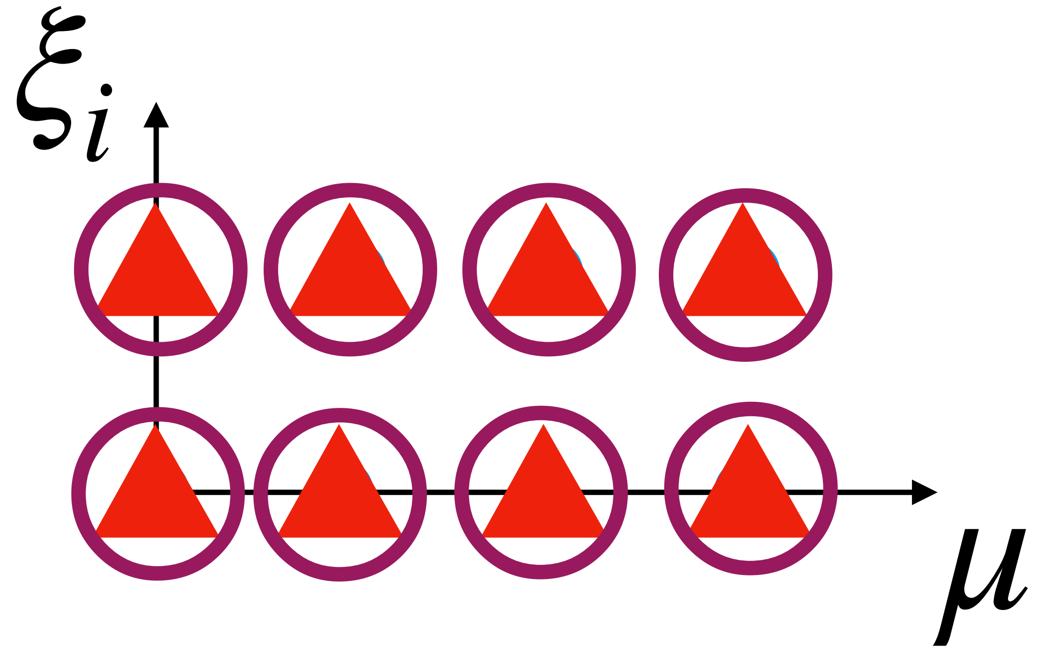

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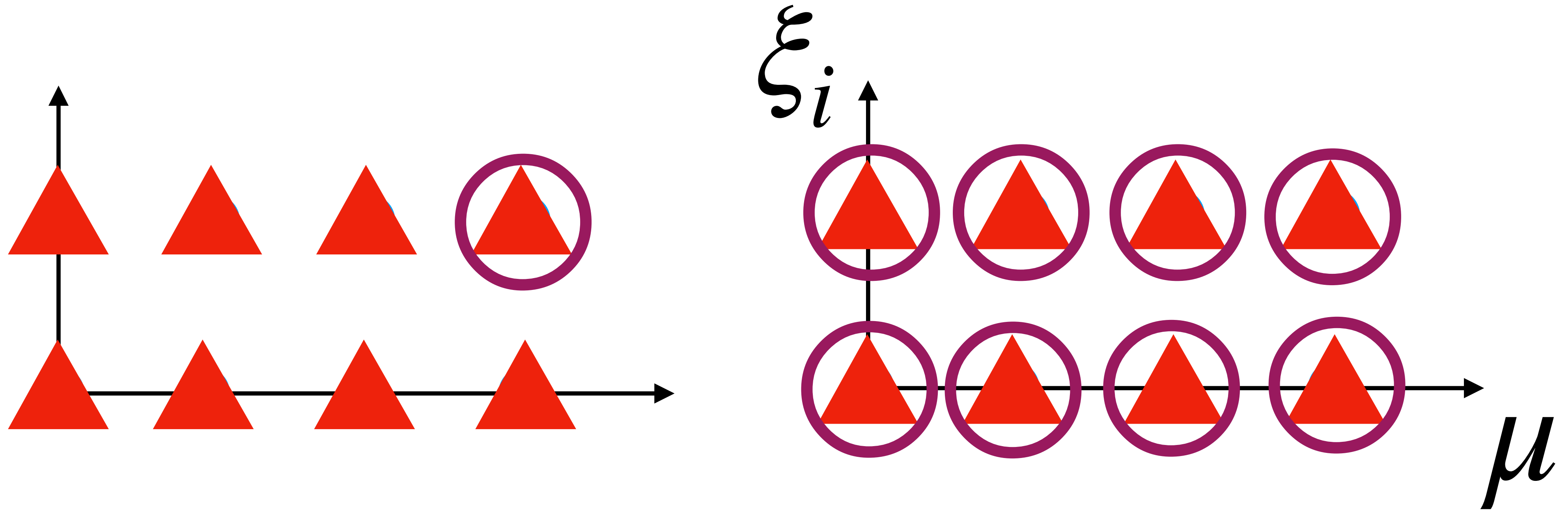

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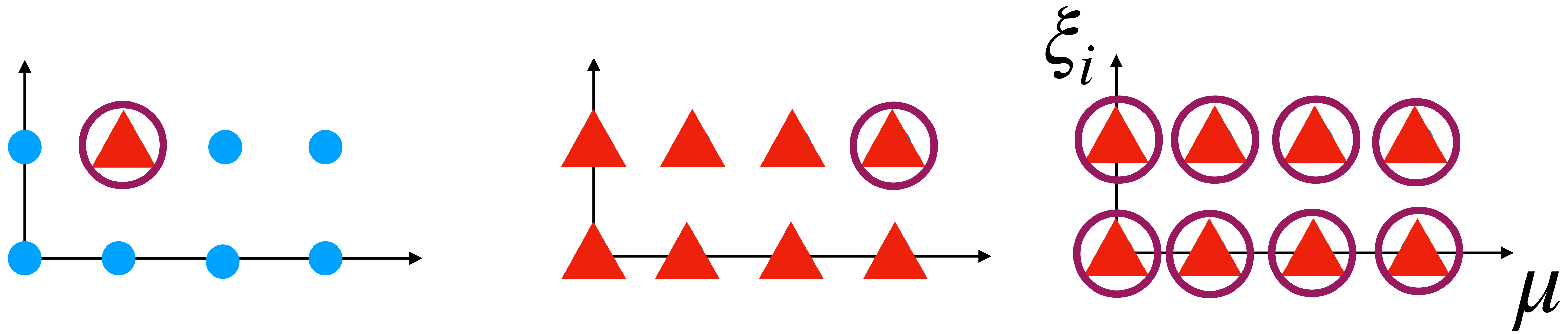

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   ii. $\langle \phi(T_c) \rangle / T_c > 1$ & no other transition with higher T_c.

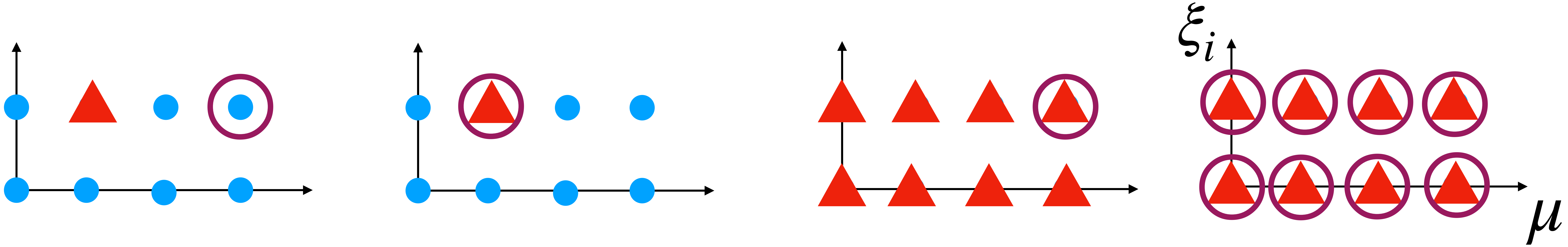
2. Define four mutually-exclusive categories*:

*An alternative classification appears in our article: see Appendix.

SFO-EWPT more certain →

Liberal	Centrist	Conservative	Ultra-Conservative

e.g.:



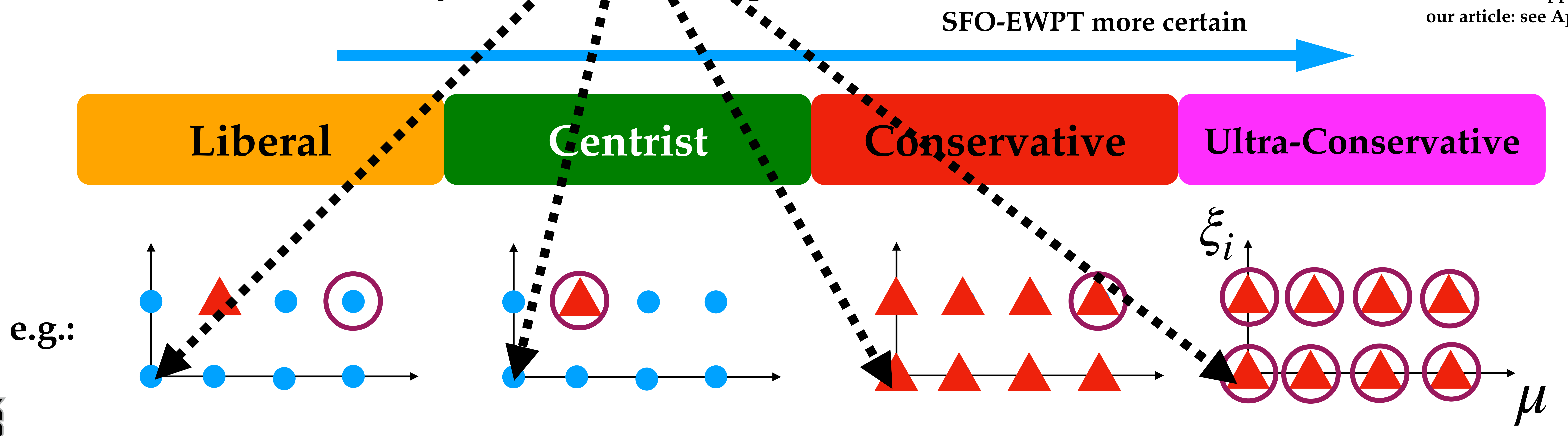
Parameter-space Categories

1. Define two conditions:

Note: For phenomenological analyses, take "central" μ and ξ_i.

2. Define four mutually-exclusive categories*:

*An alternative classification appears in our article: see Appendix.



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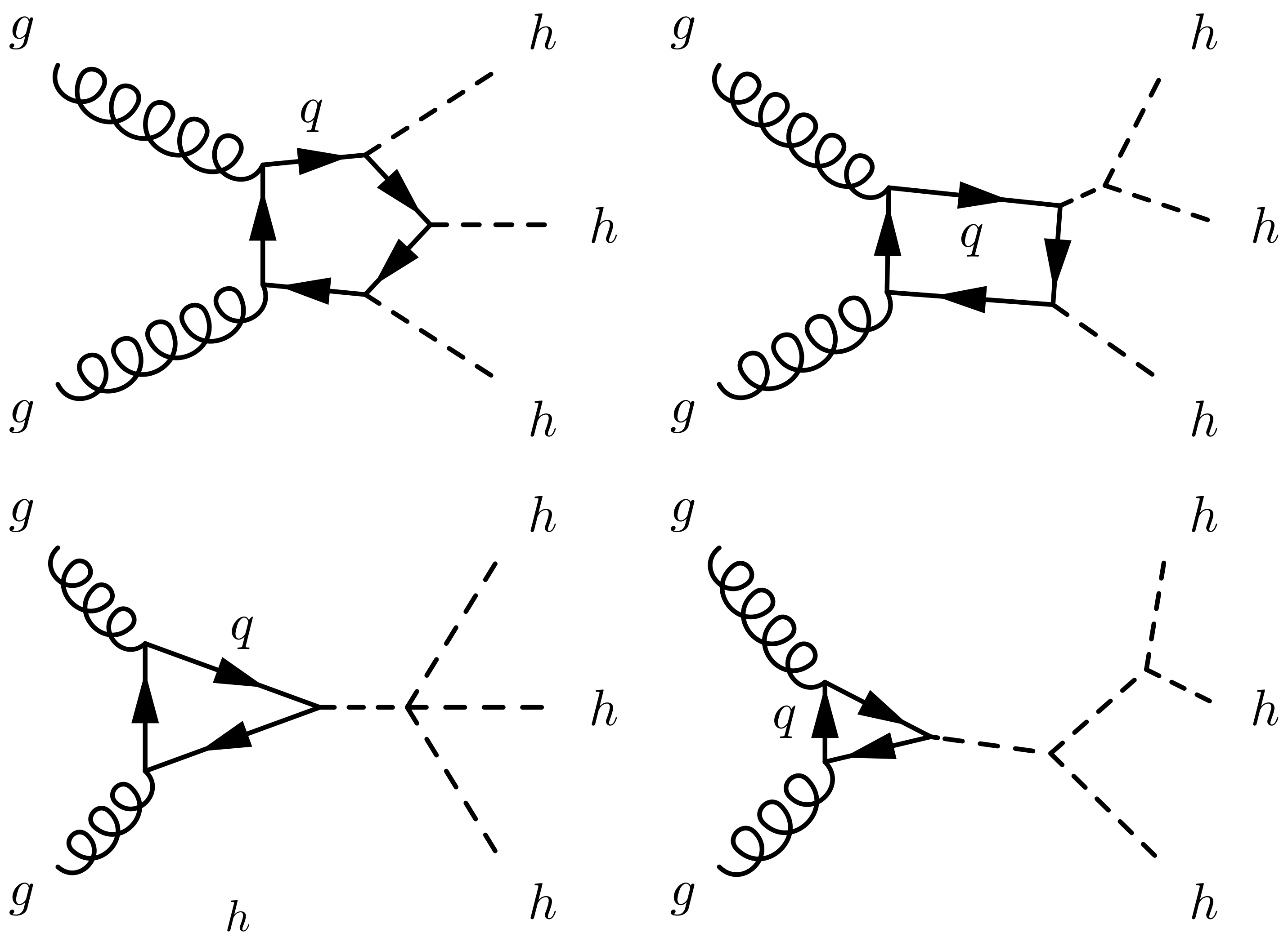
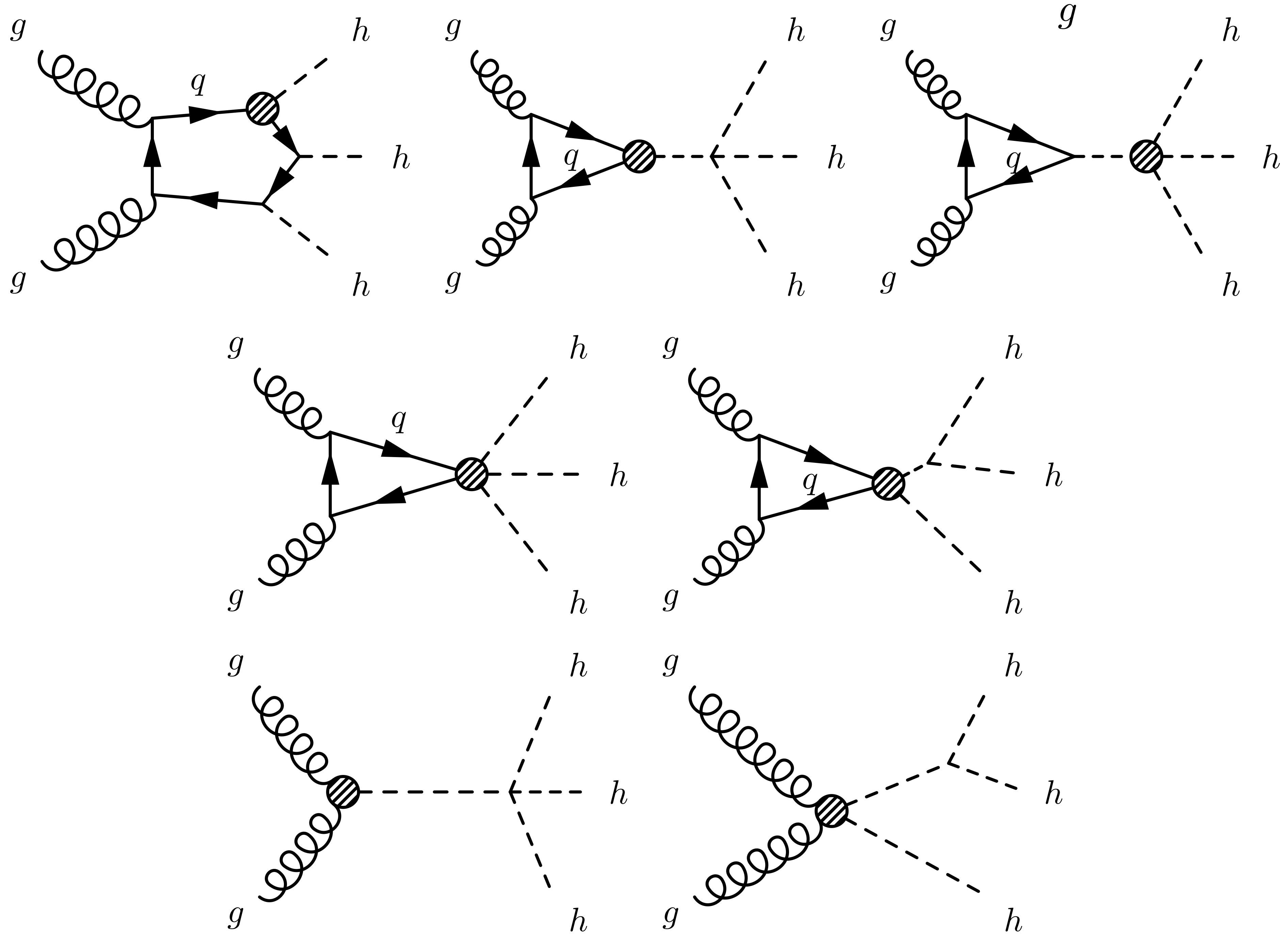
TRSM Monte Carlo Event Generation

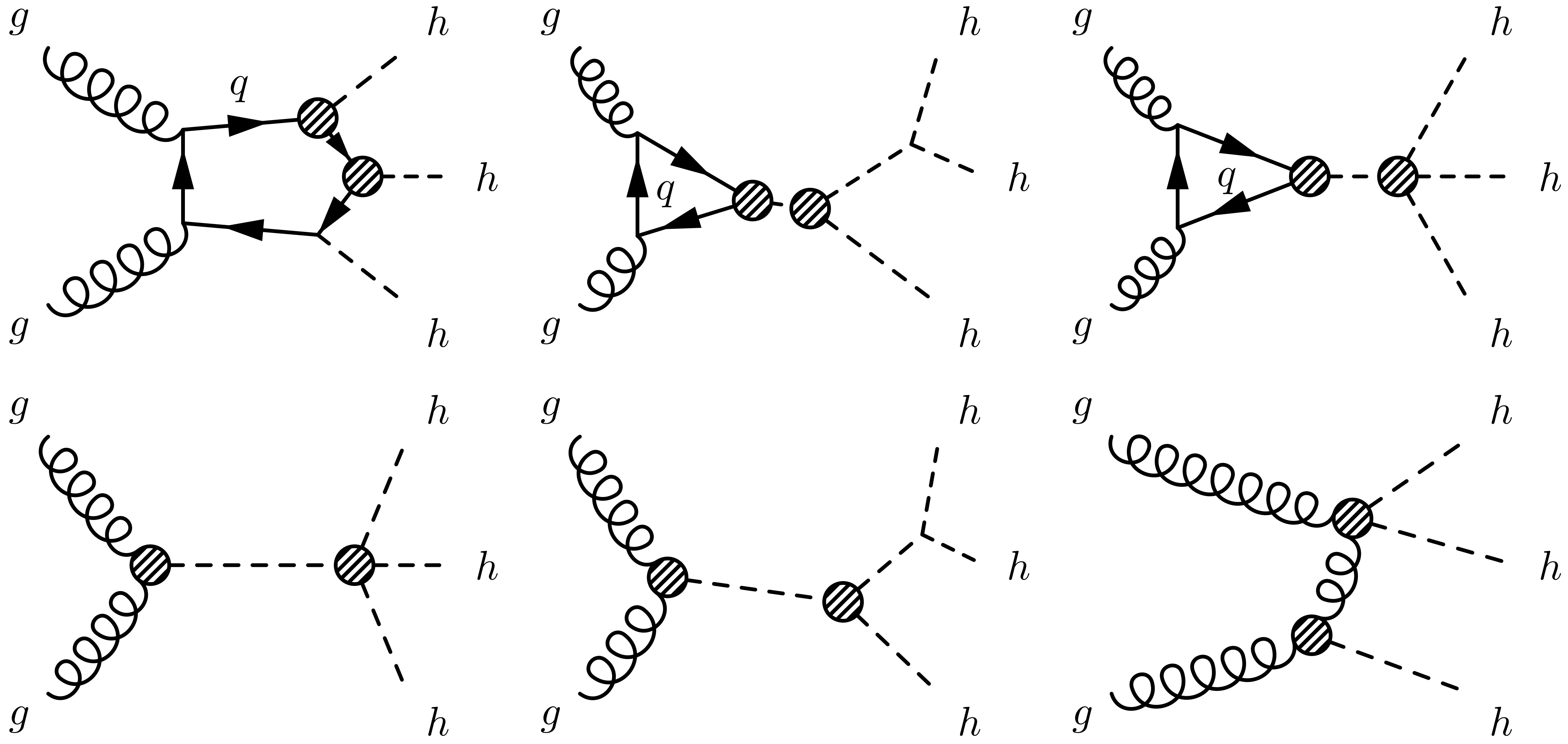
- We have implemented a **MadGraph5_aMC@NLO (MG5_aMC) "loop" model for the TRSM:**
  - **MG5_aMC input parameters**: the three mixing angles, two masses/widths and **all** the scalar couplings (only 7 are independent in **TRSM**).
  - Comes with a **Python script** that:
    - allows conversion of M_2,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







Electro-Weak Precision Observables

- Real singlet scalar field
  - $\rightarrow$ modifies Higgs contributions to diagonal weak gauge boson vacuum polarisation diagrams,
  - & introduces additional contributions.
- Quantify via S, T, U parameters. **[Hagiwara, Matsumoto, Haidt, Kim, hep-ph/9409380]**
- Change in EWPO $\mathcal{O}$ $(= S, T, U)$:

$$\Delta\mathcal{O} = (\mathcal{O}(m_2^2) - \mathcal{O}(m_1^2)) \times \sin^2\theta$$

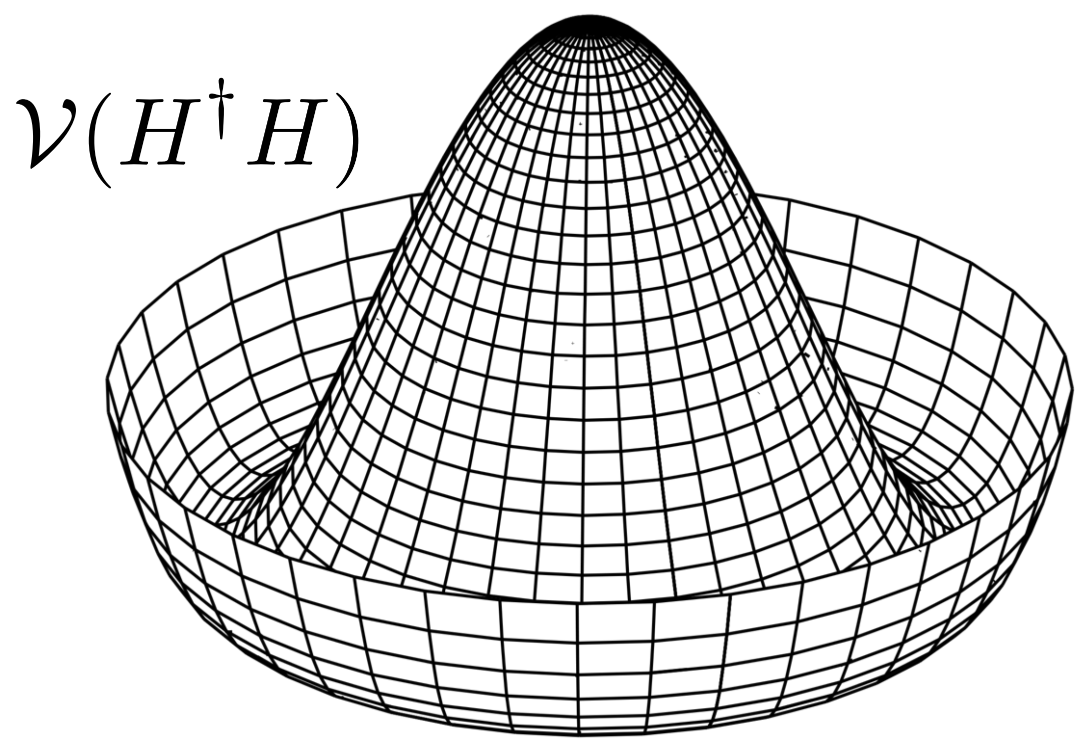
$\Rightarrow$ calculate compatibility with experimental measurement $\Delta\mathcal{O}^{\rm EXP}$.

The Higgs Potential & Vacuum Stability

The Importance of the Higgs sector

- the Higgs boson: the central protagonist of EWSB:

H: Higgs doublet



- an important characteristic of the Higgs boson is the way it couples to itself:

The Importance of the Higgs sector

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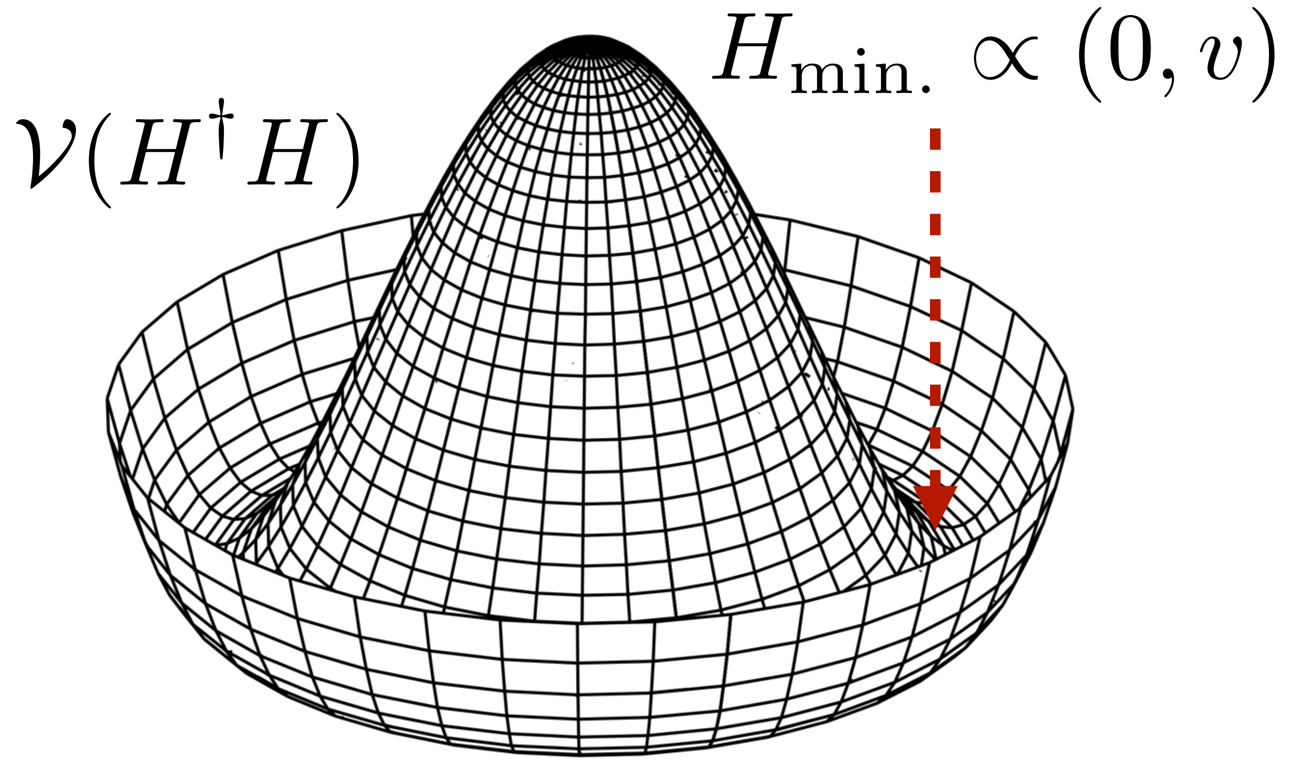

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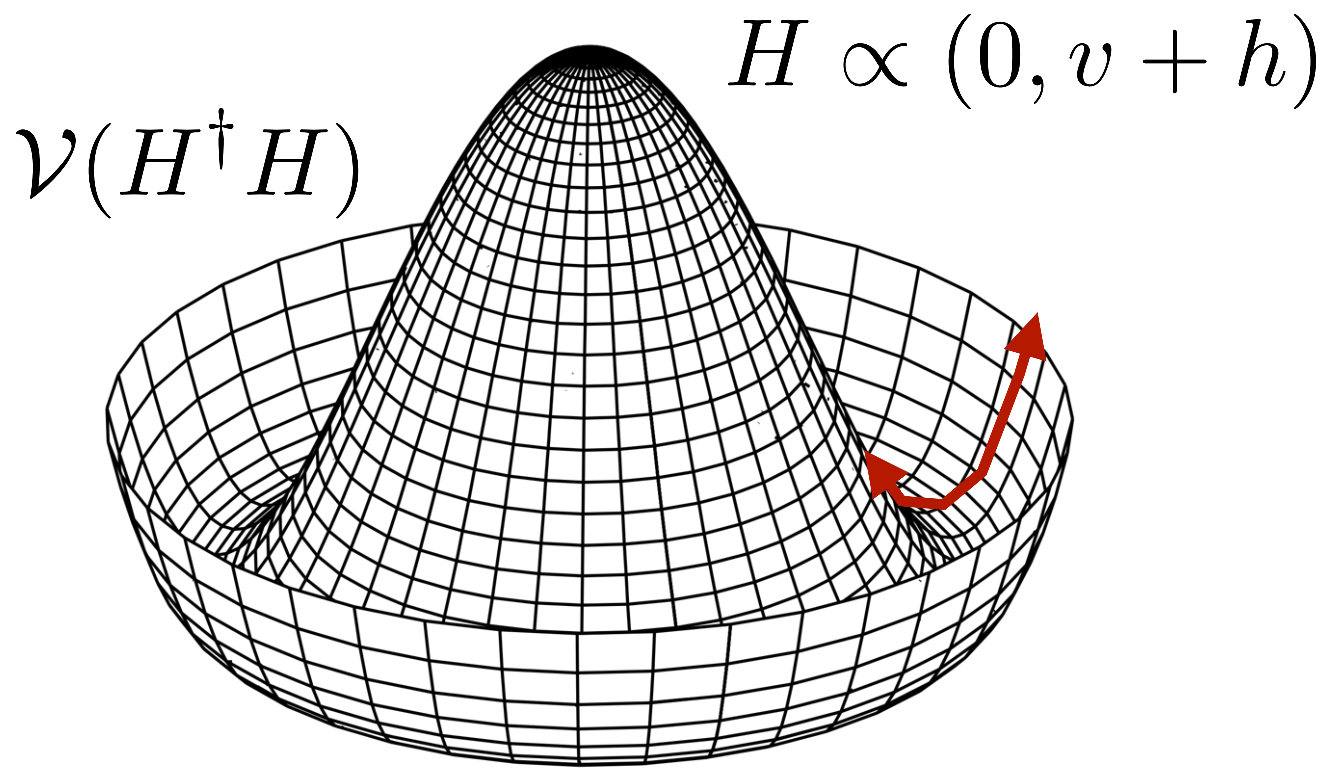

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The Importance of the Higgs sector

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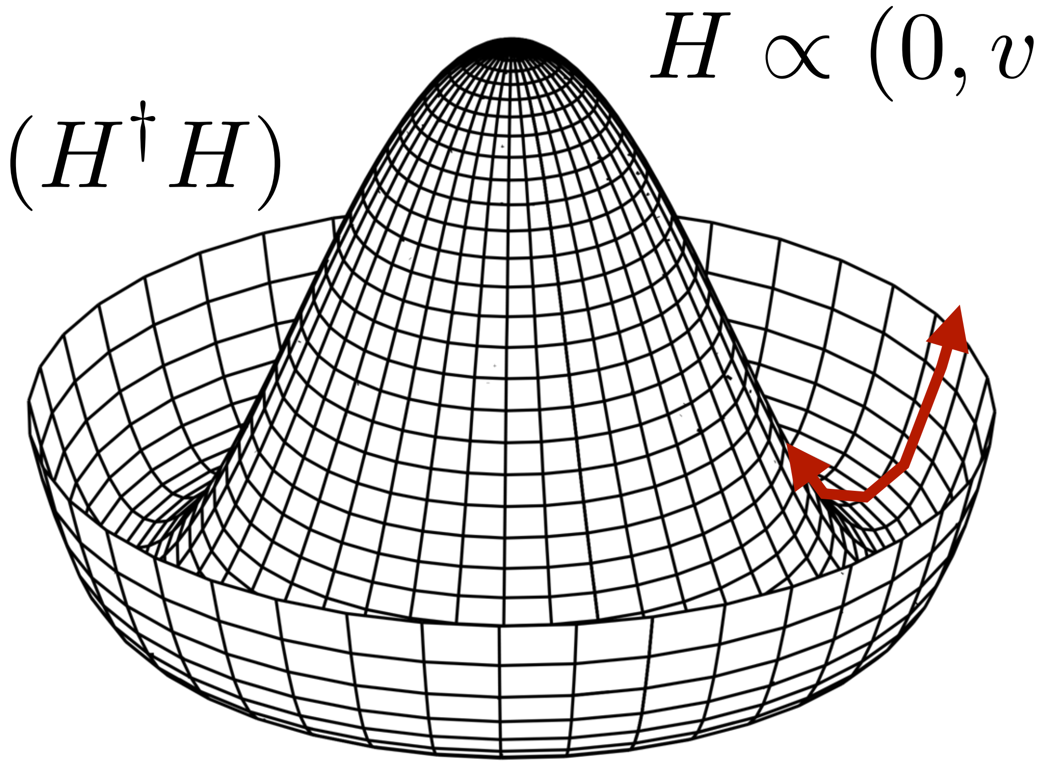
H: Higgs doublet

$\mathcal{V}(H^\dagger H)$ $\quad H \propto (0, v+h)$



$\Rightarrow$

e.g. fermion masses & interactions:

$$\mathcal{L} \supset -\, m_f \bar{f}_L f_R - \frac{m_f}{v} h \bar{f}_L f_R + \text{h.c.}$$

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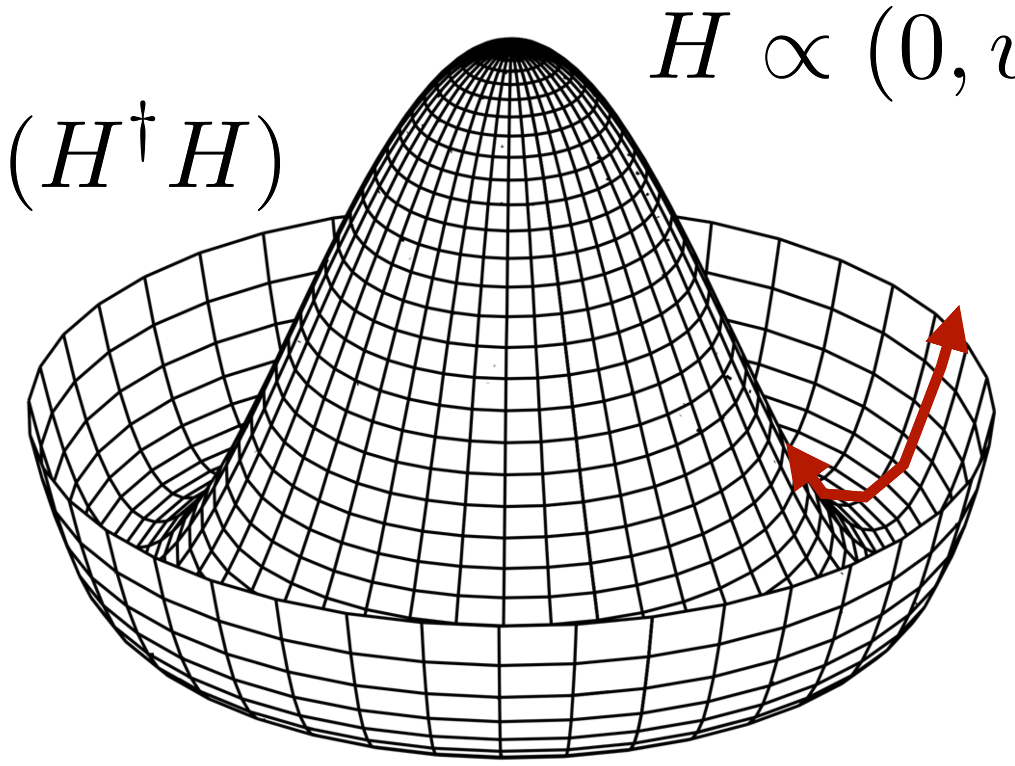

$\Rightarrow$

e.g. gauge boson masses
& interactions:

$$\mathcal{L} \supset [m_W^2 W^{\mu +} W_\mu^- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu] \times \left(1 + \frac{h}{v}\right)^2$$

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The Importance of the Higgs sector

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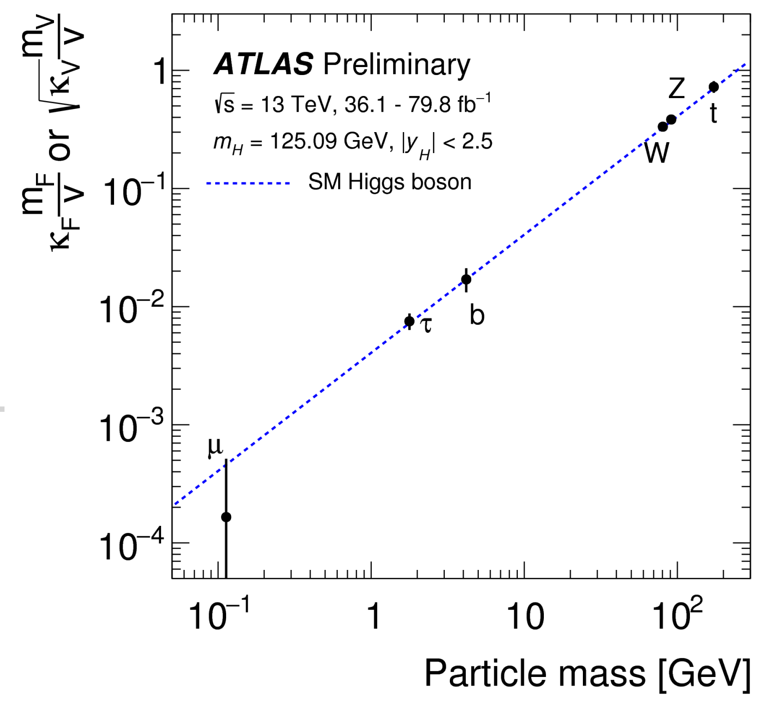
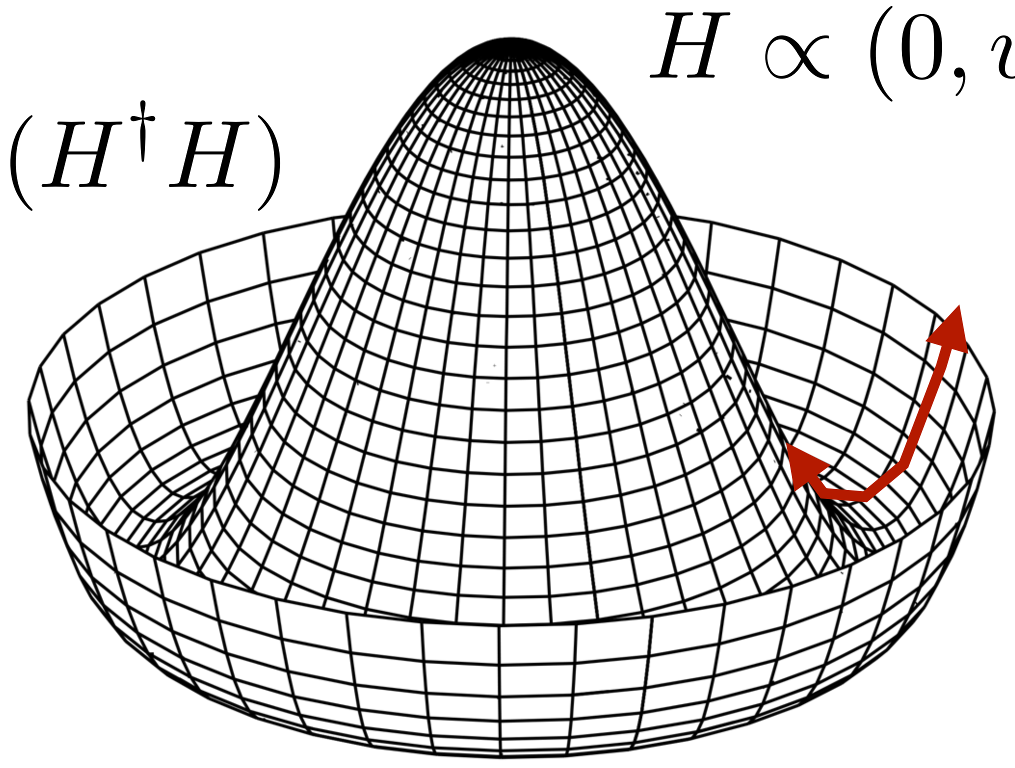


***H*: Higgs doublet**

$\mathcal{V}(H^\dagger H)$



$H \propto (0, v+h)$

$\Longrightarrow$

e.g. gauge boson masses & interactions:

$$\mathcal{L} \supset [m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu] \times \left(1 + \frac{h}{v}\right)^2$$

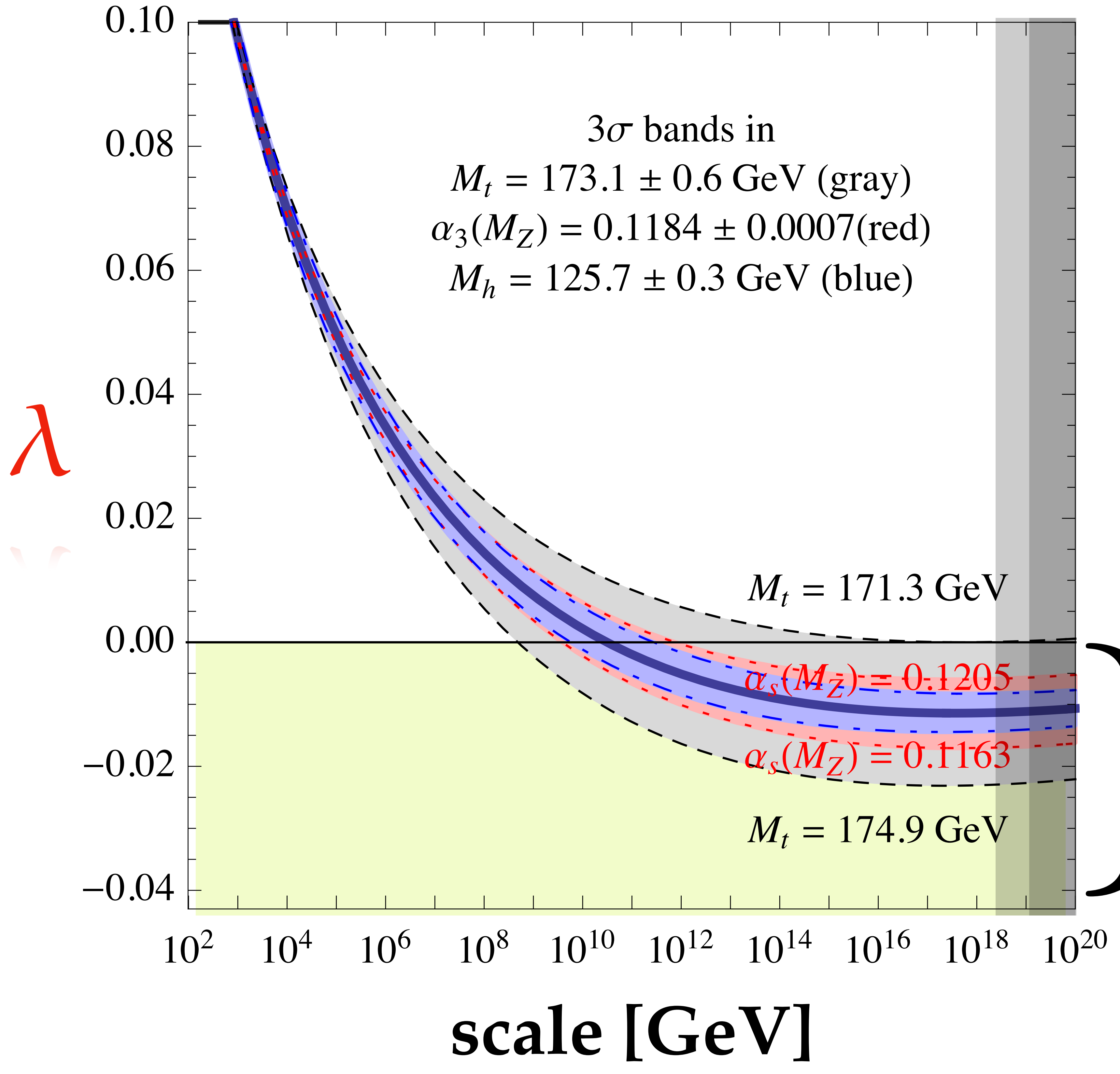
- an important characteristic of the Higgs boson is the way it couples to itself:

Vacuum Stability

- SM potential for the Higgs doublet:

$$\mathcal{V}(H^\dagger H) = -m^2(H^\dagger H) + \lambda(H^\dagger H)^2$$

- renormalisation group evolution of the coupling λ:

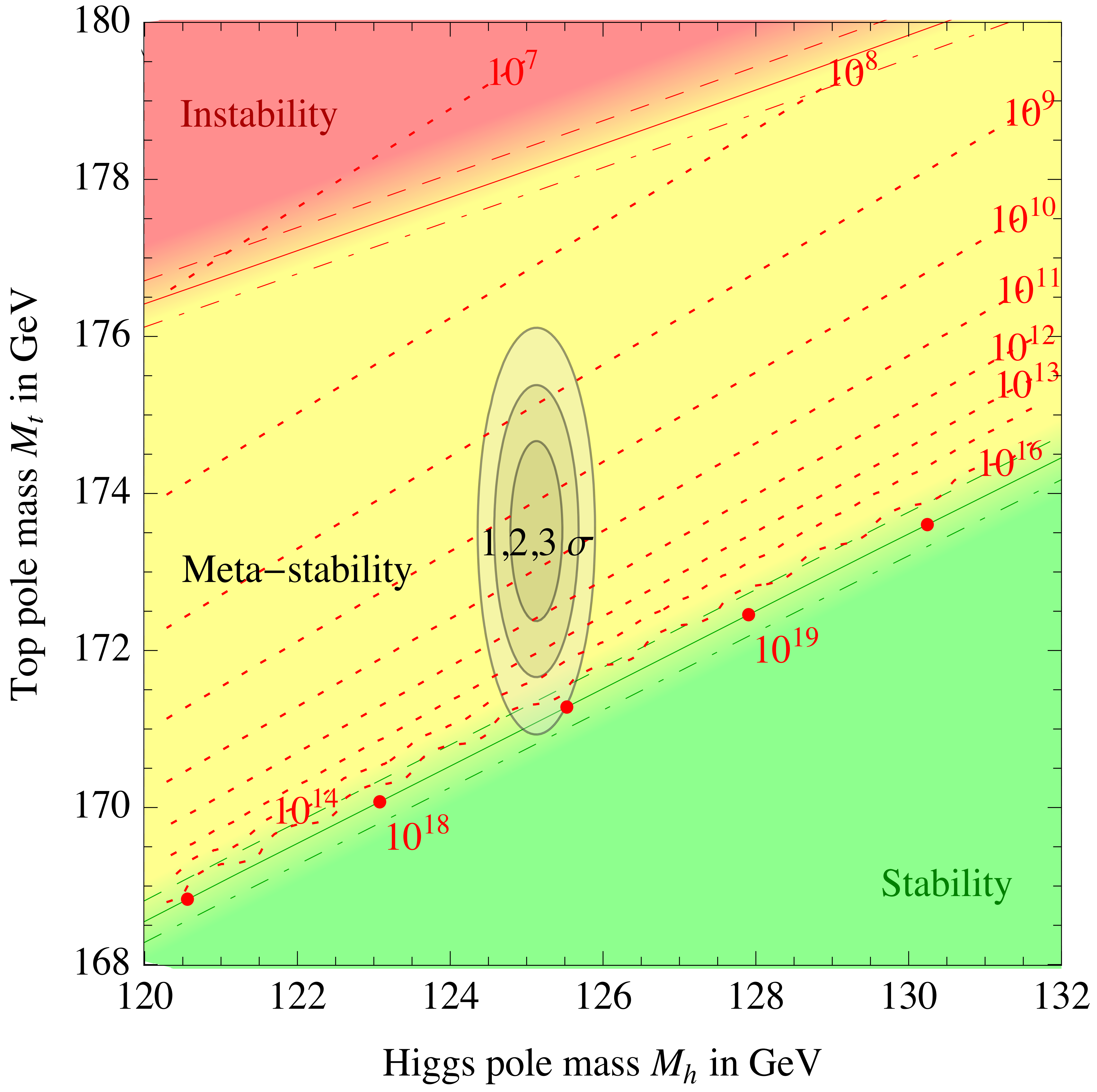


$\lambda < 0\,! \Longrightarrow$ **potentially unstable or meta-stable vacuum!**

[Cabibbo, Maiani, Parisi, Petronzio, 1979, Hung, 1979, …, Degrassi, Di Vita, Elias-Miró, Giudice, Isidori, Strumia, 1205.6497, Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, 1307.3536 …, Espinosa, 1512.01222]

vacuum stability

[Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, 1307.3536, Espinosa, 1512.01222]



in deriving this: **assumed Standard Model.**

➡ a hint for a non-standard Higgs sector?

➡ further investigation necessary.

Sphaleron/Instanton Processes

Instantons and Baryon-# Violation

- toy model:

  (1+1)-dimensions, Abelian gauge field A^μ, complex scalar Φ^μ, Dirac fermion of unit charge Ψ.

- Euclidean space action:

$$S = \int \mathrm{d}^2 x \left[\frac{1}{4} F_{\mu\nu}^2 + |(\partial_\mu - ieA_\mu)\Phi|^2 + V(\Phi) + i\bar{\Psi}(\partial_\mu - ieA_\mu)\gamma^\mu \Psi \right]$$

"Higgs potential": $V(\Phi) = \lambda(\Phi^* \Phi - v^2)^2 \Longrightarrow$ **"EWSB"** $\Longrightarrow M_A, \; M_h$

Instantons and Baryon-# Violation

- consider the current:

$$K_\mu = \frac{e}{2\pi}\epsilon_{\mu\nu}A_\nu$$

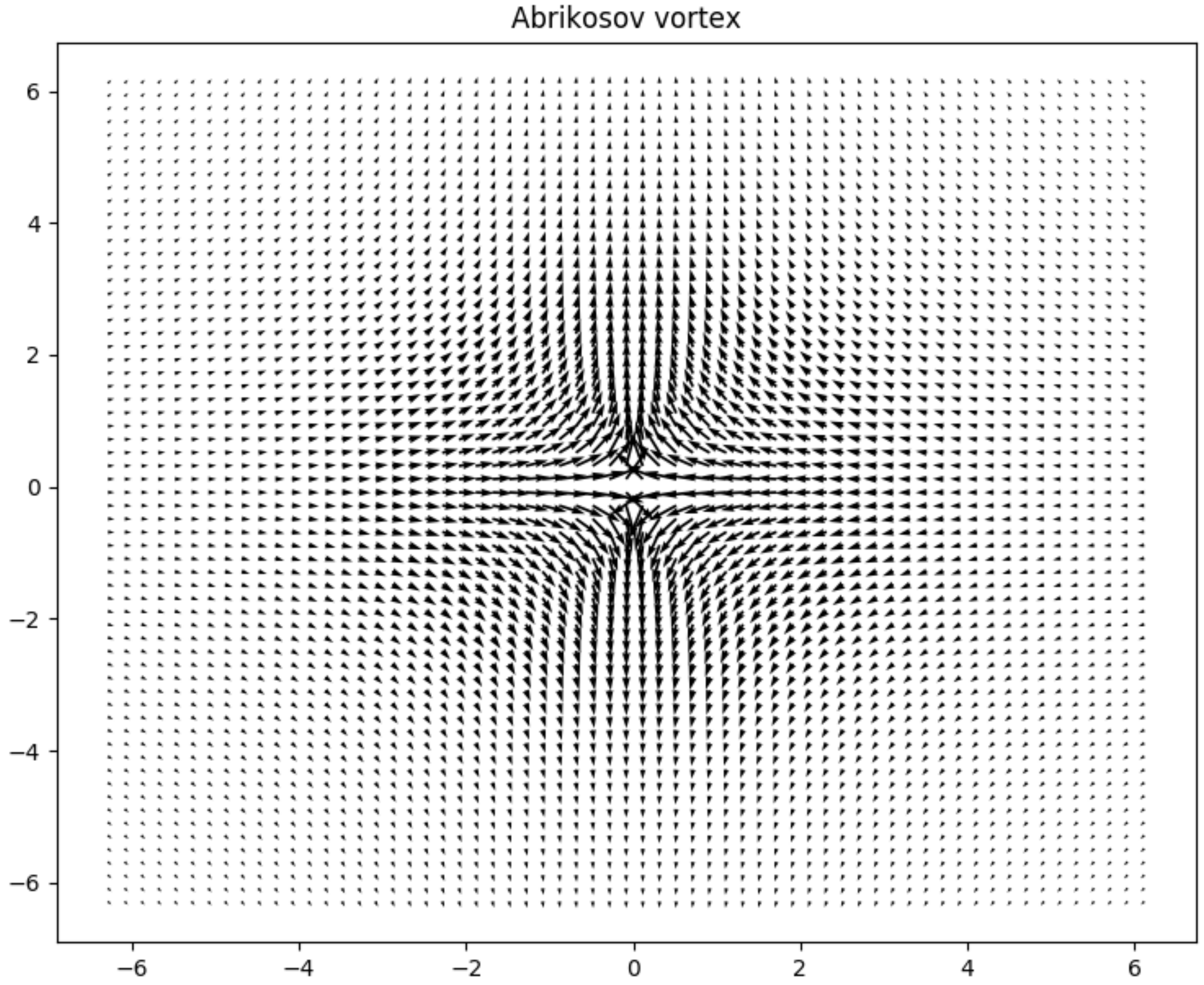
- corresponds to "charge density":

$$N_{\rm CS} = \int {\rm d}x\; K_0 = \frac{e}{2\pi}\int {\rm d}x\; A_1$$

- known as the "winding" or "Chern-Simons" number.

Instantons and Baryon-# Violation

- a classical solution to equations of motion is the "Abrikosov vortex":



$$A_r = 0,\ A_\theta = \frac{1}{er} f(r),$$
$$f(0) = 0,\ 1 - f(r) \sim e^{-M_A r}$$

$\Rightarrow$ changes the Chern-Simons number by one unit:

$$\Delta N_{\rm CS} = \int \mathrm{d}^2x\ \partial_\mu K^\mu = \boxed{\frac{e}{4\pi}\int \mathrm{d}^2x\ \epsilon_{\mu\nu}F^{\mu\nu}} = 1$$

Instantons and Baryon-# Violation

- "instanton" transition necessarily accompanied by change of chirality of fermions by two units:

$$j^5_\mu = \bar{\Psi}\gamma_\mu\gamma_5\Psi$$

$$\frac{1}{2}\partial_\mu j^{5\mu} = \frac{e}{4\pi}\epsilon_{\mu\nu}F^{\mu\nu}$$

anomalous divergence of the axial-vector current.

$$\Delta N_{\rm CS} = \int \mathrm{d}^2x\ \partial_\mu K^\mu = \boxed{\frac{e}{4\pi}\int \mathrm{d}^2x\ \epsilon_{\mu\nu}F^{\mu\nu}} = 1$$

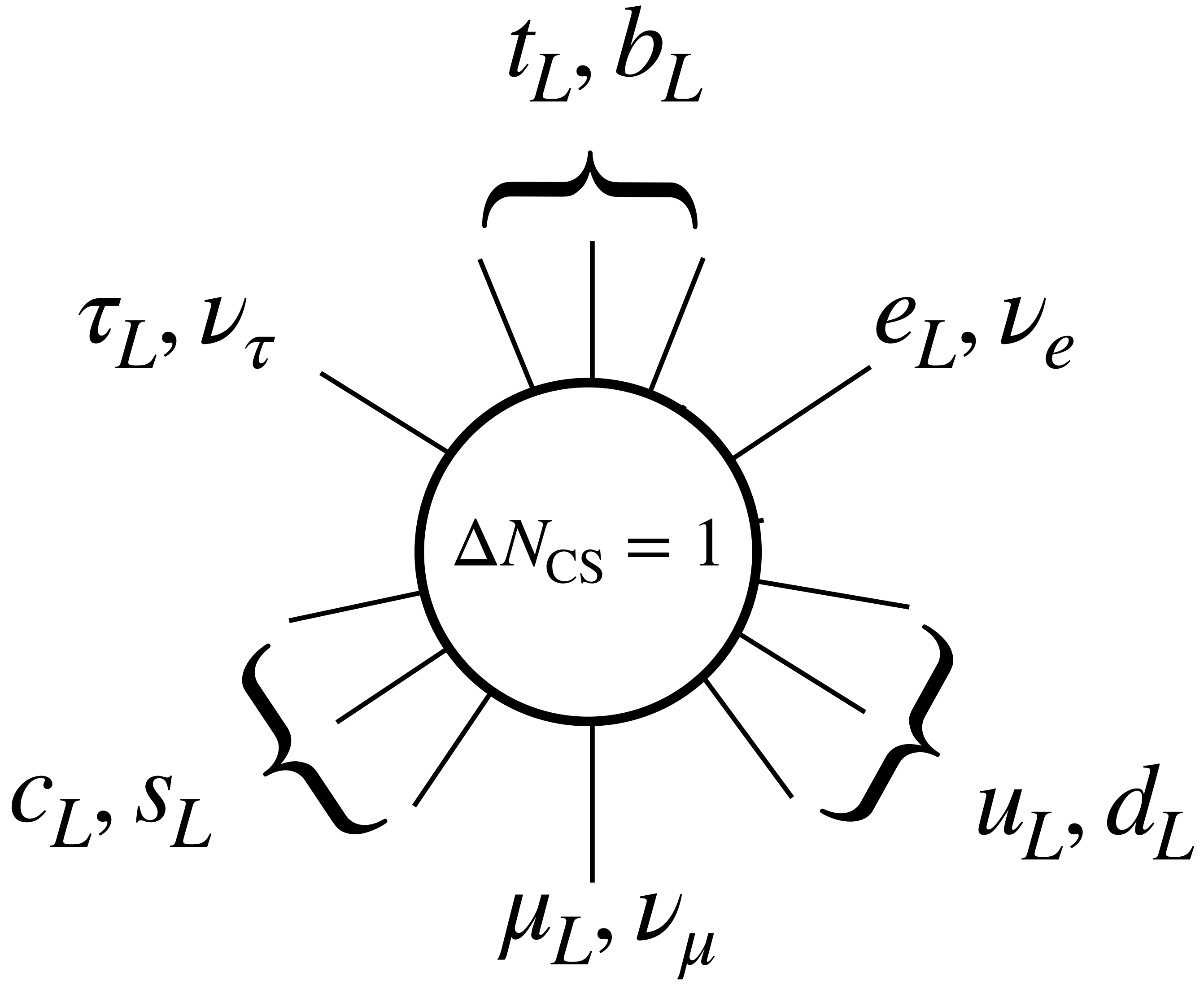
$$\Longrightarrow \quad \Delta Q_5 = \Delta \int \mathrm{d}x j^5_0 = 2$$

EW Sphalerons at colliders?

- Rate and observability of sphaleron processes at colliders debated.

e.g. [Bezrukov, Levkov, Rebbi, Rybakov, Tinyakov, hep-ph/0304180] VS. [Tye, Wong, 1505.0360, 1710.07223].

- Ponder: **Sphaleron-induced interactions at hadron colliders**:



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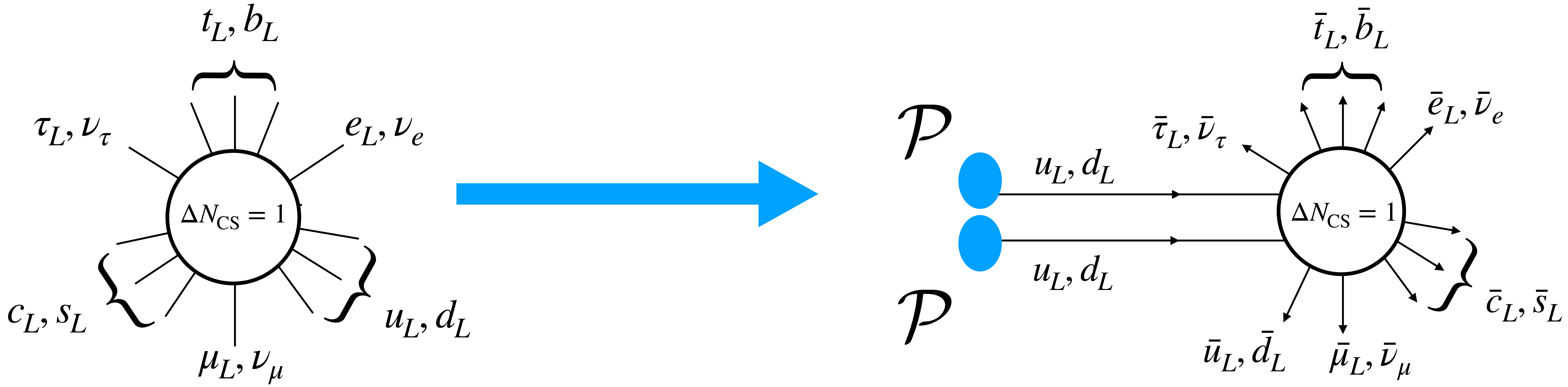
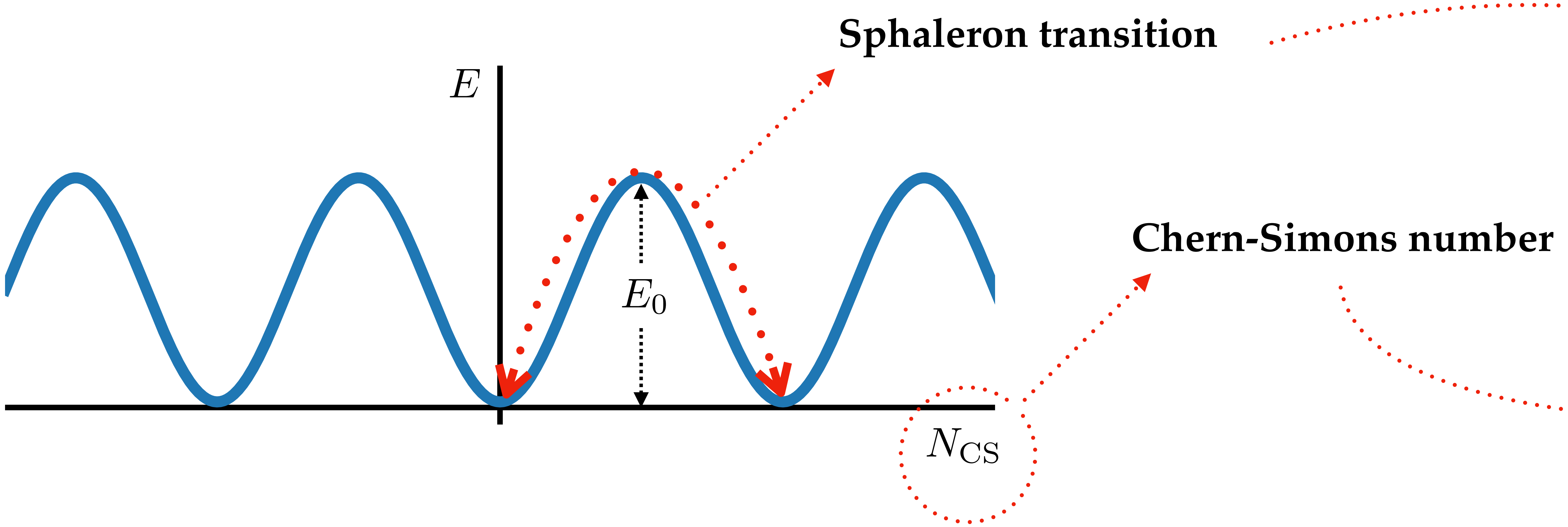
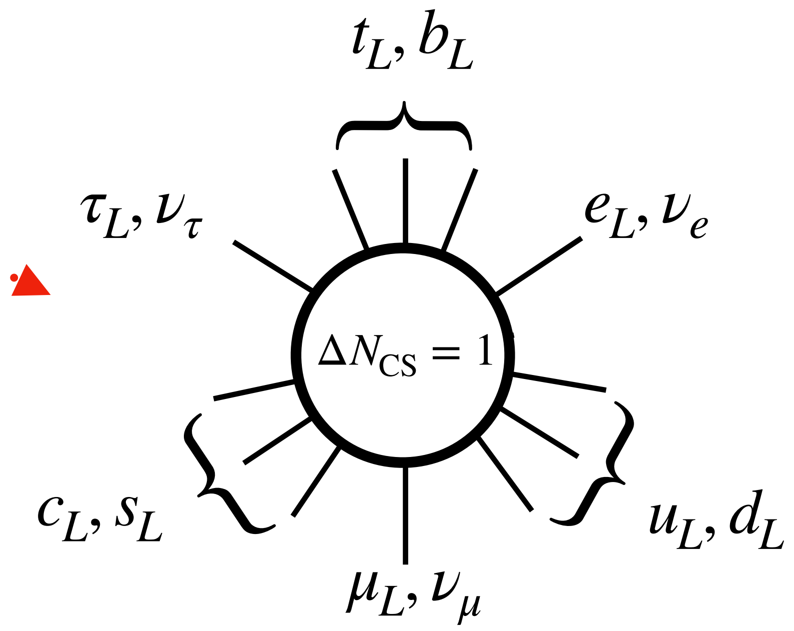


What is the Sphaleron?

- $E_0 \sim \mathcal{O}(10)$ TeV, separates **degenerate** Electro-Weak vacua.





$$\Delta N_{CS} = \frac{1}{3}\Delta B = \Delta L_i$$

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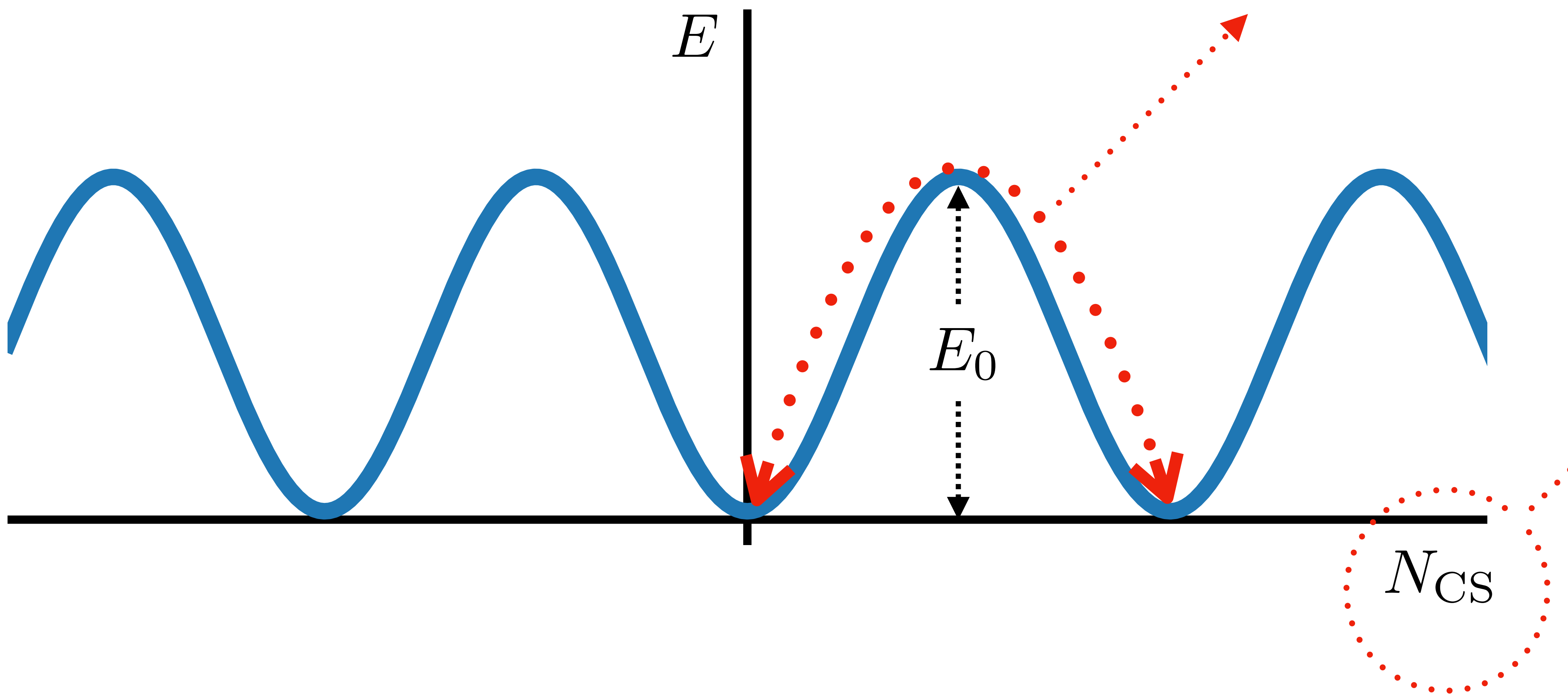
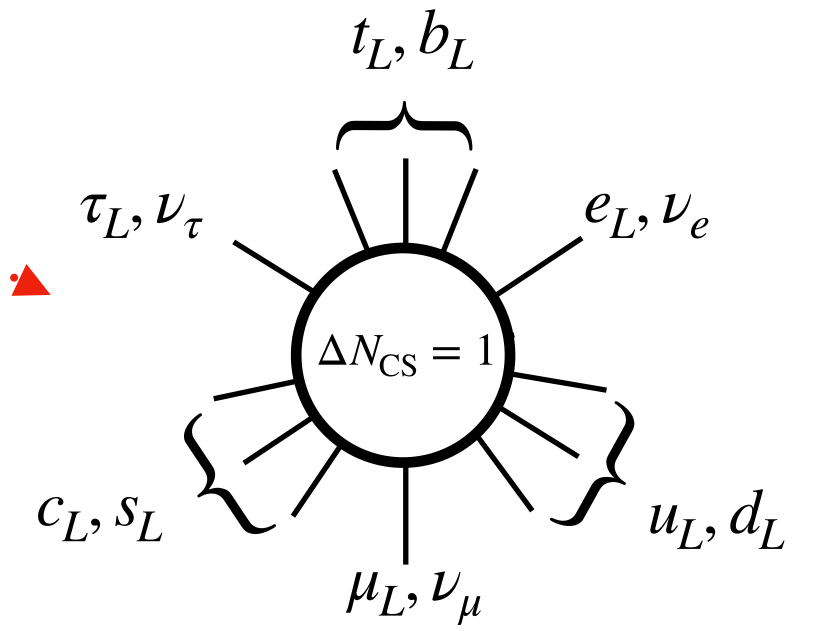


Sphaleron transition



Chern-Simons number

$$\Delta N_{\rm CS} = \frac{1}{3}\Delta B = \Delta L_i$$

The Sphaleron energy depends <u>crucially</u> on the Higgs sector!

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A Note on Sphaleron Suppression

- **Suppression** of sphaleron rate **inside bubble**

  $\Rightarrow$ Baryon Asymmetry "swept in" broken phase and "frozen in".

- **Rate** $\sim \exp[-\langle \phi(T_C) \rangle / T_C \times \ldots]$,

  [T_C: the critical temperature.]

- $\Rightarrow$ Require: $\langle \phi(T_C) \rangle / T_C \geq 1 \Rightarrow$ a "Strong" First-Order EWPT (SFO-EWPT).

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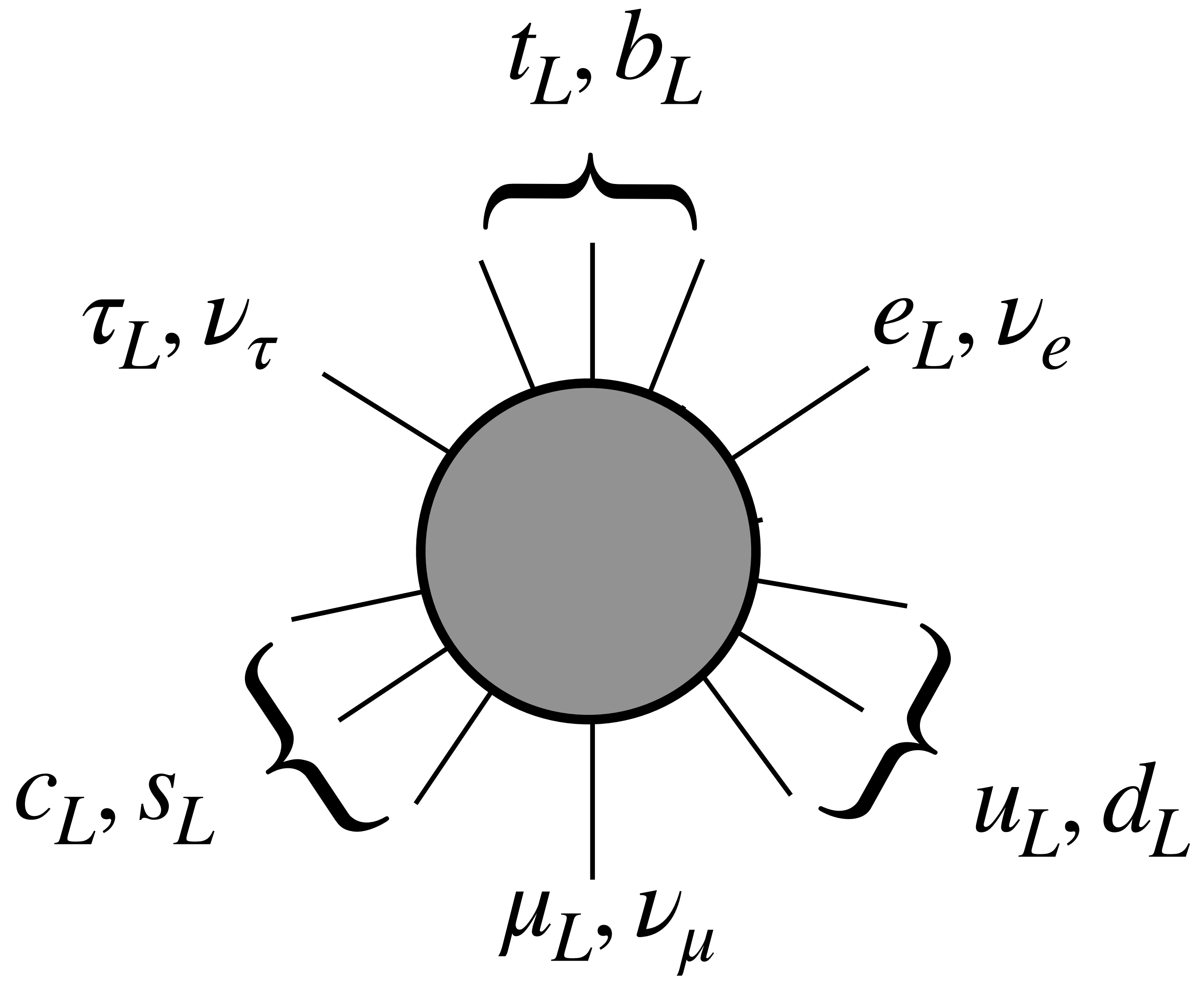
Sphaleron Suppression

- Inside the bubble: 

- Suppression requires "**Strong**" First-Order EWPT (SFO-EWPT).

- **Despite suppression**: Sphalerons @ colliders?



Sphaleron Suppression

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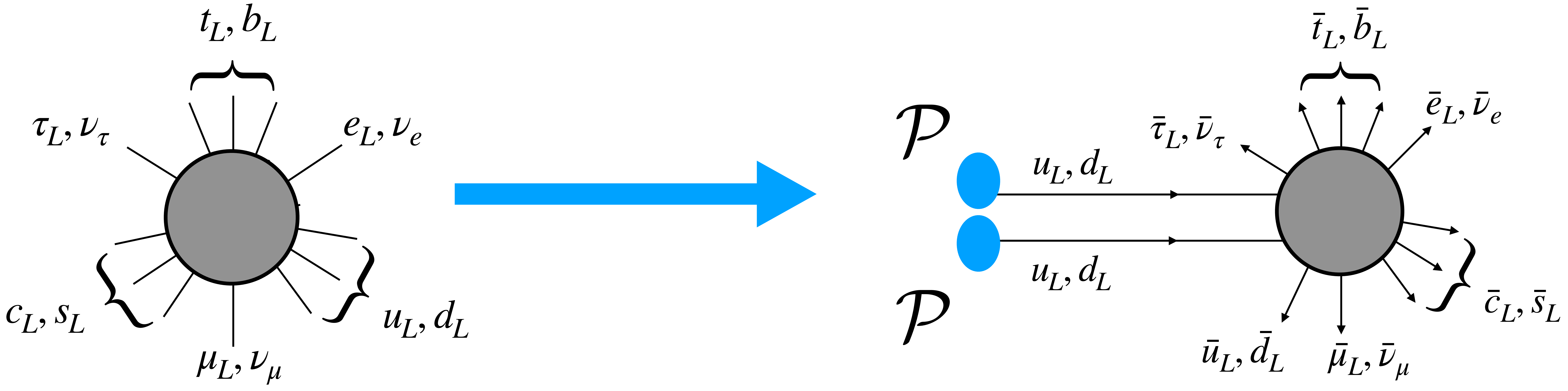

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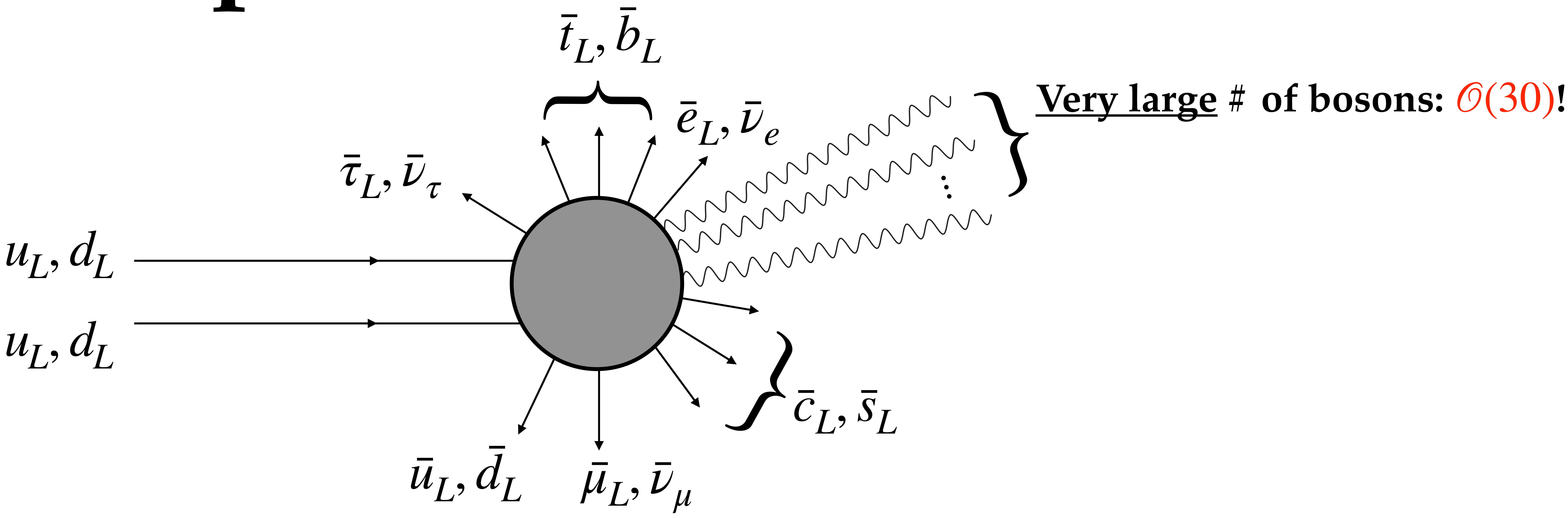
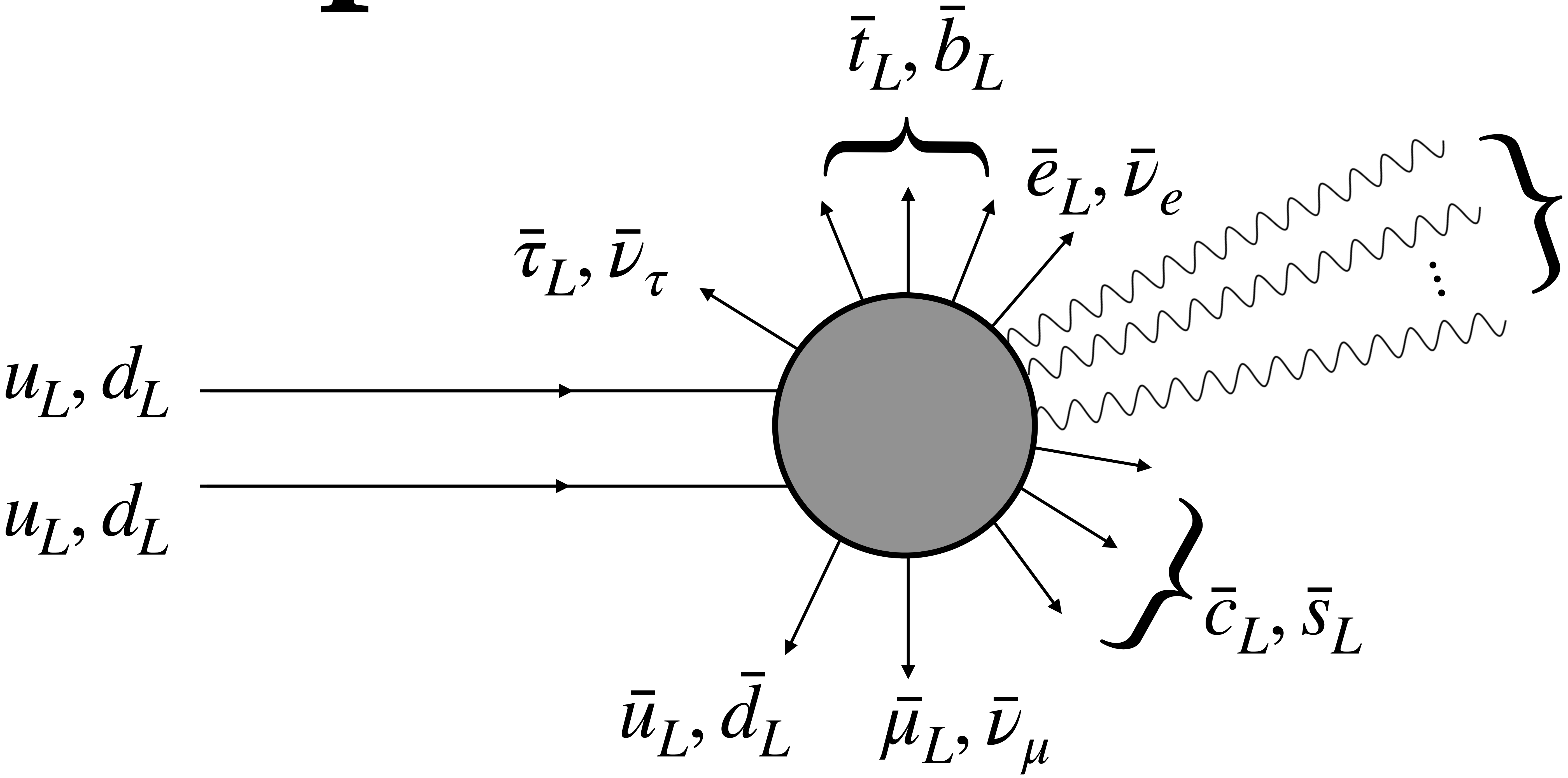
EW Sphalerons at Colliders?



- Possible enhancement if large number of bosons,

$\Rightarrow$ Events would **spectacularly light up detectors** at experiments!

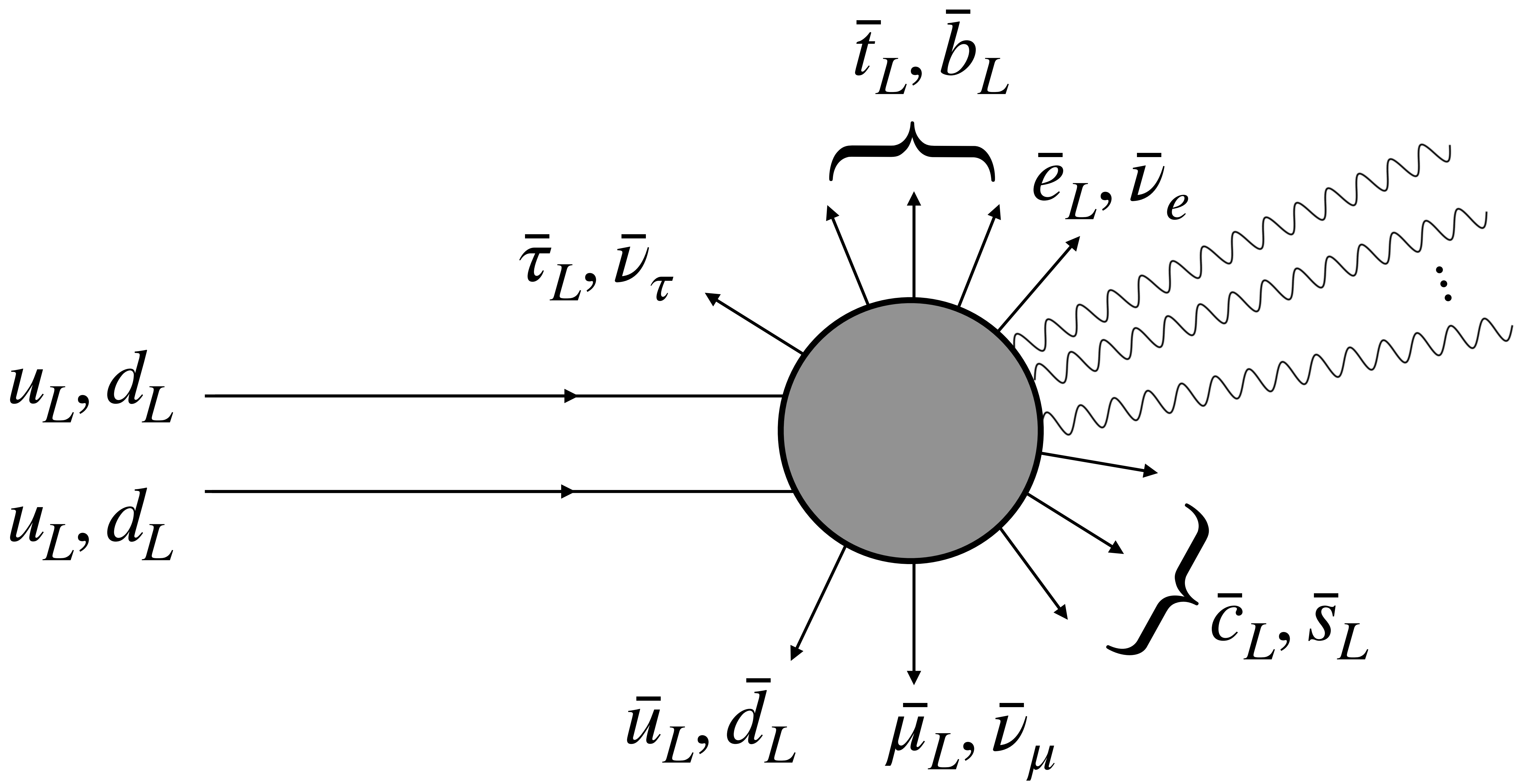
EW Sphalerons at Colliders?



Very large # of bosons: $\mathcal{O}(30)$!

- Possible enhancement if large number of bosons,

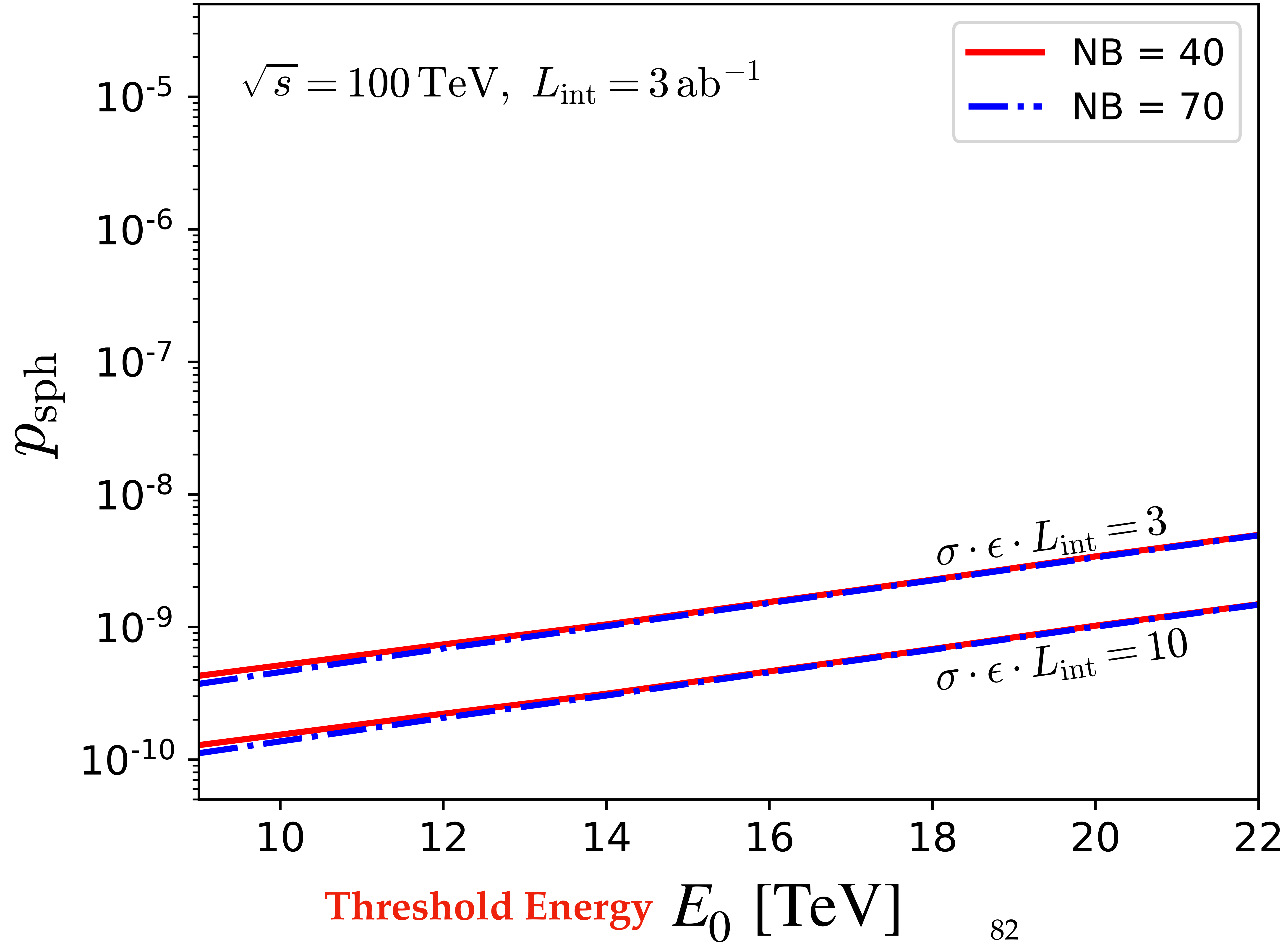
$\Rightarrow$ Events would **spectacularly light up detectors** at experiments!


$\bar{t}_L, \bar{b}_L$
$\bar{e}_L, \bar{\nu}_e$
$\bar{\tau}_L, \bar{\nu}_\tau$
u_L, d_L
u_L, d_L
$\bar{c}_L, \bar{s}_L$
$\bar{u}_L, \bar{d}_L$
$\bar{\mu}_L, \bar{\nu}_\mu$

Sphalerons at the FCC

- Parametrise parton-parton cross section by $p_{\rm sph}$:

$$\hat{\sigma}(E) = \frac{p_{\rm sph}}{m_W^2}\Theta(E - E_0)$$



→ **Event Generator within `HERWIG 7`.**

[AP, Sakurai, Plätzer, arXiv:1910.4761]

EW Sphalerons at Colliders?

[**AP**, Sakurai, Plätzer, arXiv:1910.4761]

EW Sphalerons at Colliders?

[AP, Sakurai, Plätzer, arXiv:1910.4761]

Homework:

(i) What can we learn about the Higgs sector and EWBG?

(ii) New theoretical features in Sphaleron MC.

(iii) Model discrimination, e.g. VS micro-black holes.

(iv) Collaboration with experimentalists for measurements.

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]

Singlet model details

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

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

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

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

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

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

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

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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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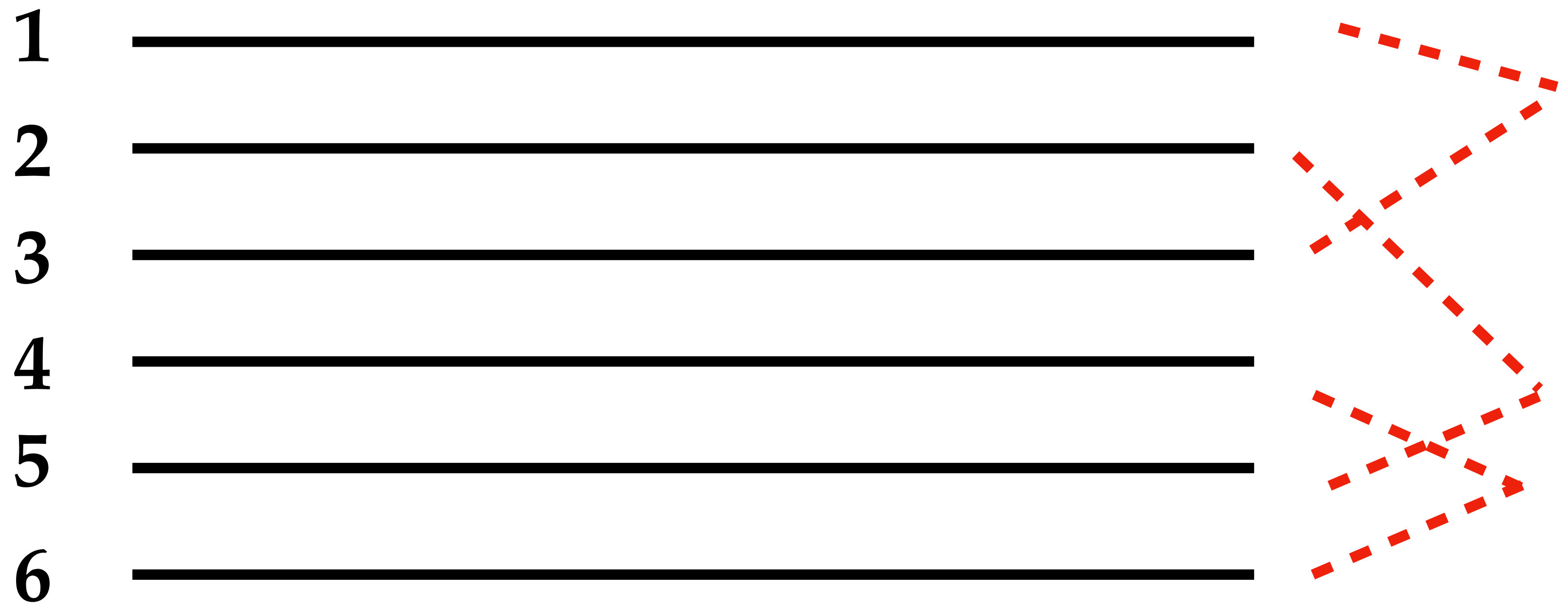

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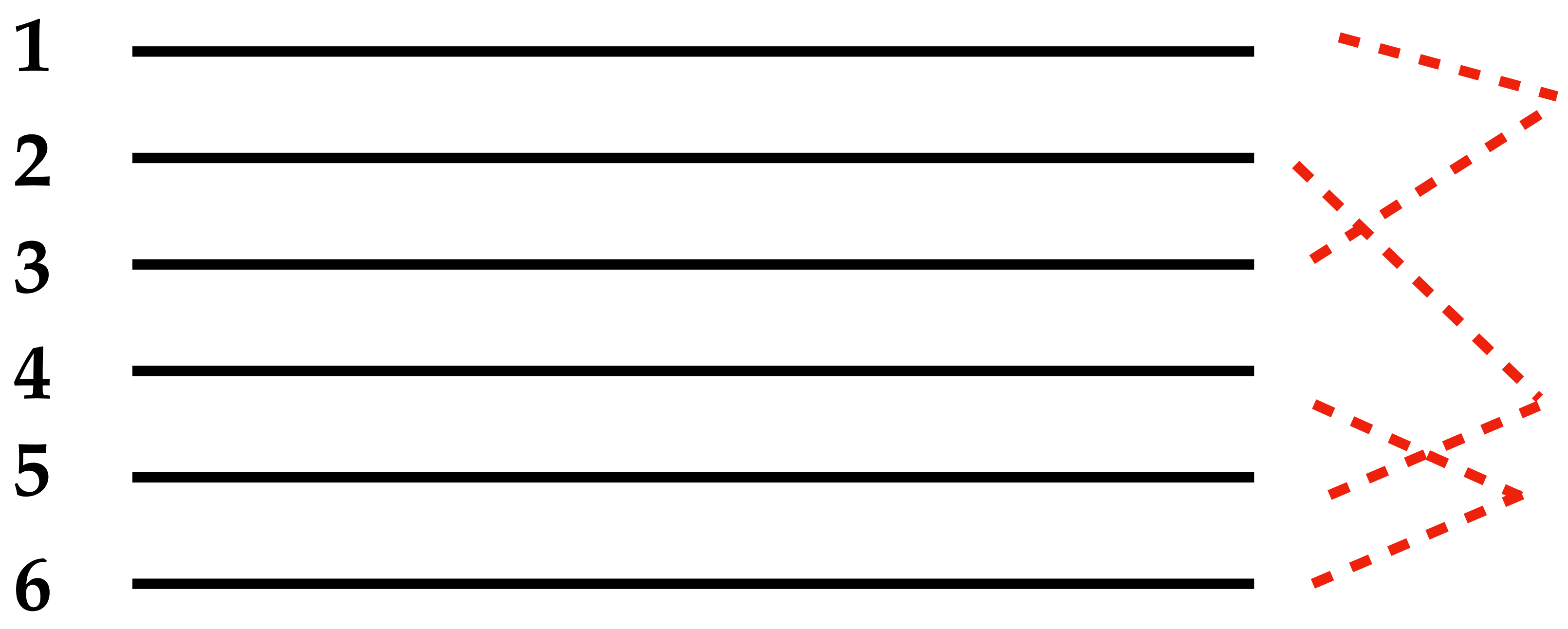

3. For each pairing construct:

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

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

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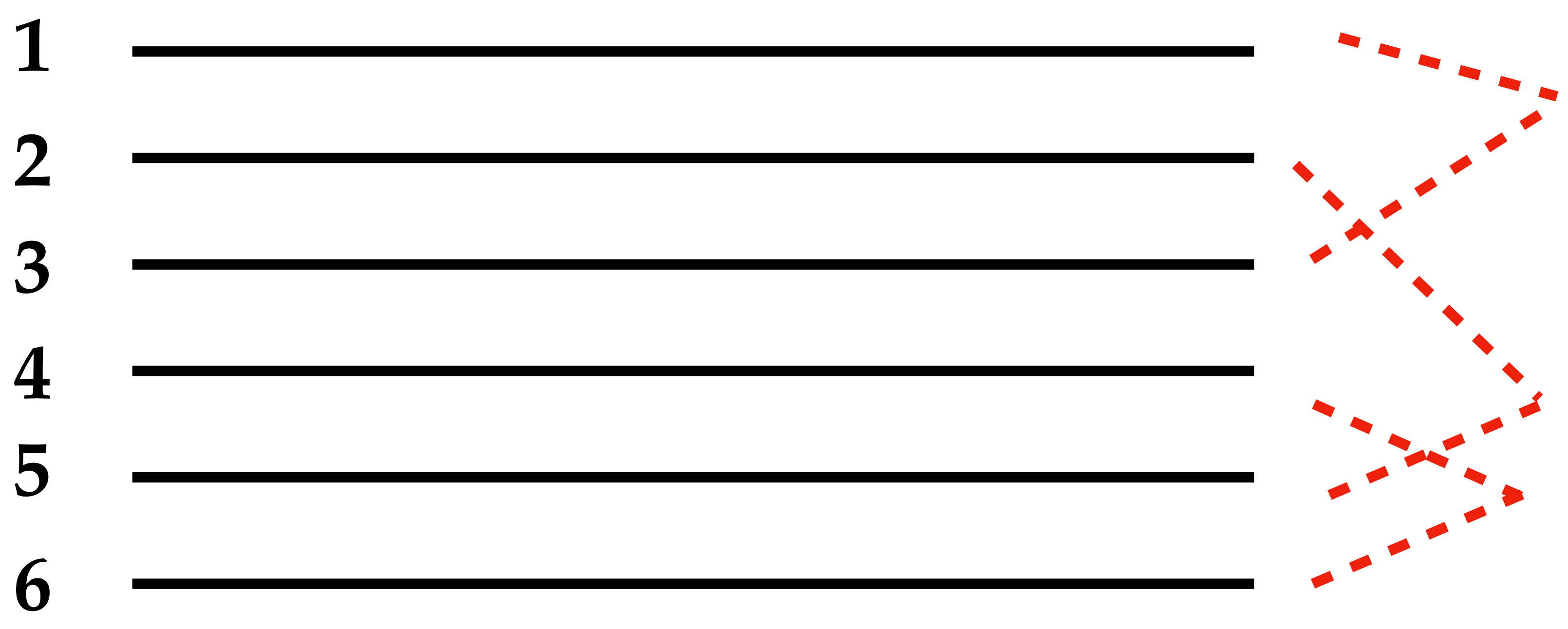

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≡ sum of squared differences from Higgs mass (~125 GeV)

$\Rightarrow$ **4. Pairing that gives minimum χ^2 determines "reconstructed Higgs boson".**

$\underbrace{\text{minimum } \chi^2}_{\chi^2_{\min}}$

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 ← **the three terms in χ^2_{min}.**
$\Delta R(h_r^i, h_r^j)$	$< [3.5, 3.5, 3.5]$, $(i, j) = [(1,2), (1,3), (2,3)]$
$\Delta R_{bb}(h_r^i)$	$< [3.5, 3.5, 3.5]$, $i = 1, 2, 3$

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.

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Scalar singlet model self-couplings

triple:

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

quartic:

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

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.

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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]	$m_{4b}^{\rm inv} <$ [GeV]	$m_{6b}^{\rm inv} <$ [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: $|\eta|_b < 2.35$, $\Delta m_{\rm min,\ med,\ max} < [15, 14, 20]$ 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 $m_{4b}^{\rm inv}$ cut is not given, as this was found to not have an impact when combined with the $m_{6b}^{\rm inv}$ 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 $\sigma_b = 0.1 \times \text{B}$).

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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

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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.

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.:
    $|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\mathrm{Re}\{\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{1-\mathrm{ins.}}\} \propto 1 + c_i$

    or

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