

Imprints of Electroweak Symmetry Breaking at the LHC

Andreas Papaefstathiou



@ CMS Higgs Workshop, Sept 2nd, 2026

The Plan

01

The Higgs Potential: A Brief Introduction

02

The Higgs Potential: Electroweak Baryogenesis

03

Probing the Scalar Sector: Multi-Scalar Production

04

Conclusions

SECTION 01

The Higgs Potential: A Brief Introduction

The Higgs Field's Potential

SM assumption: ϕ complex doublet scalar field $\longrightarrow \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$

Potential: $\mathcal{V}(\phi) = \frac{1}{2}\mu^2 |\phi|^2 + \frac{1}{4}\lambda |\phi|^4$

For $\lambda > 0$ and $\mu^2 > 0 \Rightarrow$ Minimum at origin,

or: $\mu^2 < 0 \Rightarrow$ Minimum **away** from origin

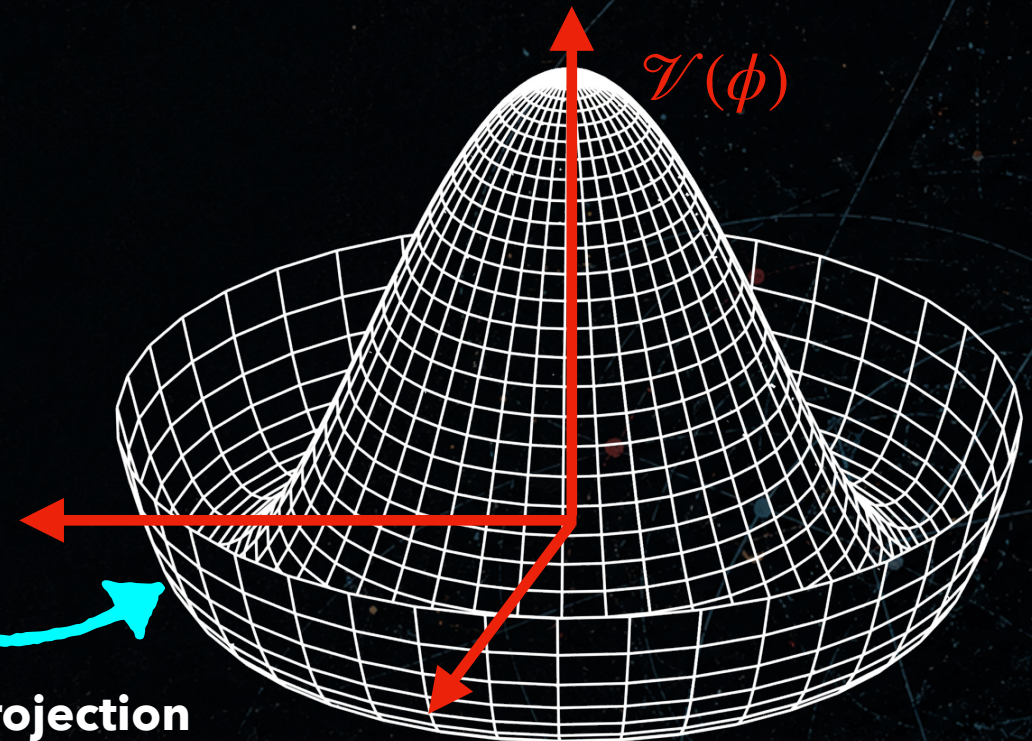
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The Higgs Boson's Potential

Higgs doublet ϕ acquires **VEV**: $\phi \sim \langle \phi \rangle + \frac{1}{2} \begin{pmatrix} 0 \\ h \end{pmatrix} \longrightarrow h$ is the Higgs **boson**!

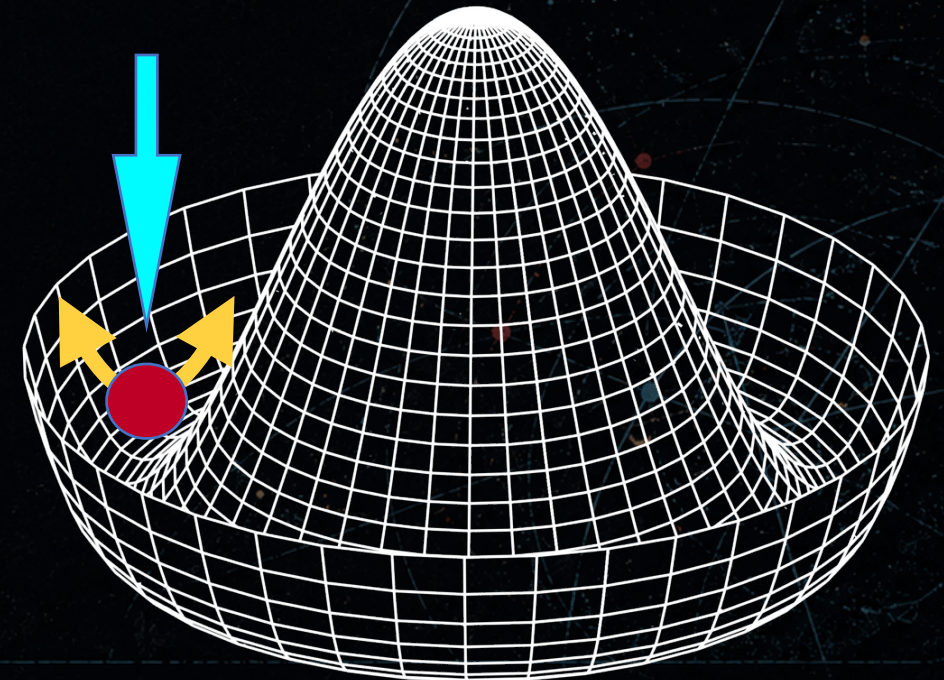
$$\Rightarrow \mathcal{V} \left(\langle \phi \rangle + \frac{1}{2} \begin{pmatrix} 0 \\ h \end{pmatrix} \right) = \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4$$

[where: $\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$ and $v^2 = -\mu^2/\lambda$]

& Gauge boson & Fermion masses!

Electroweak Symmetry Breaking

Life takes place about one of the degenerate minima:



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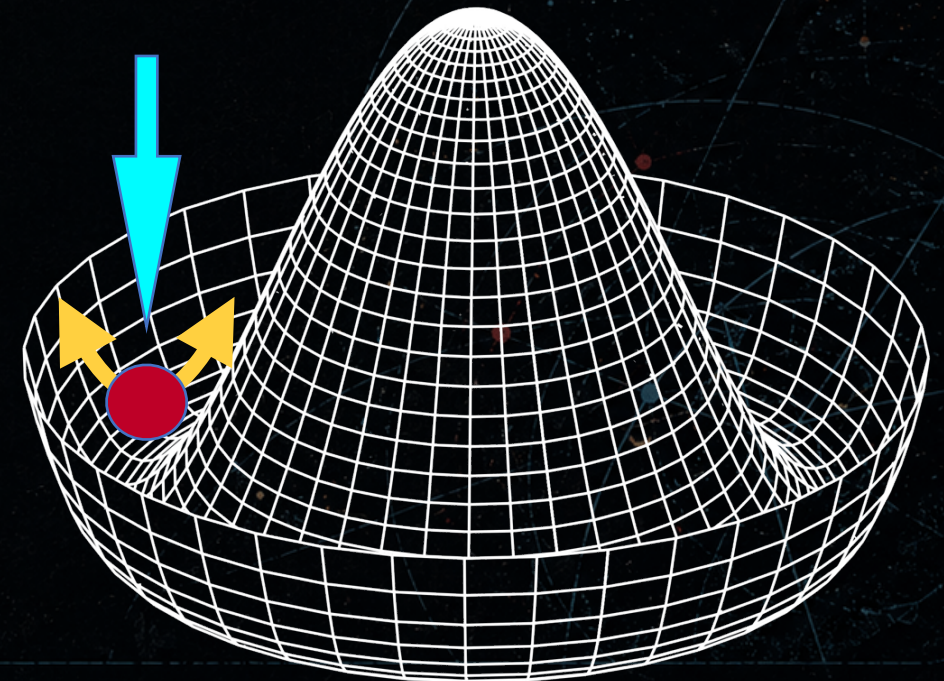
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[where: $\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$ and $v^2 = -\mu^2/\lambda$] **SM predictions!**

& Gauge boson & Fermion masses!

Electroweak Symmetry Breaking

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SECTION 02

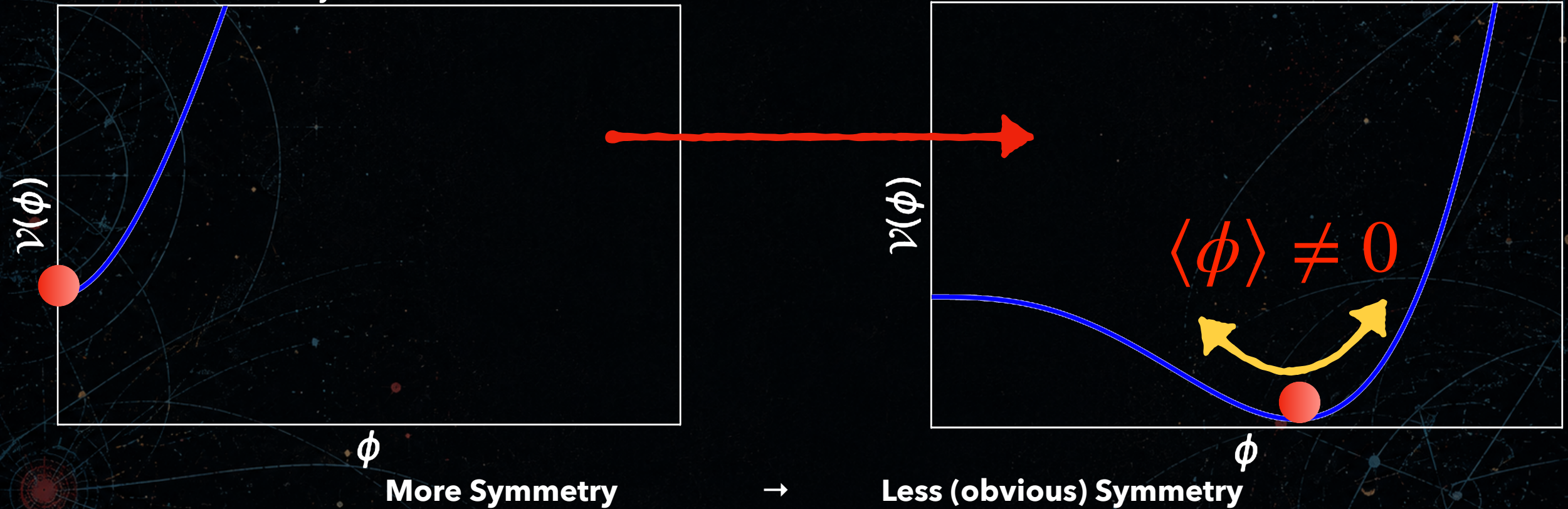
The Higgs Potential: Electroweak Baryogenesis

The Electroweak Phase Transition

1D projection of the Higgs field's potential

Early Universe

Today

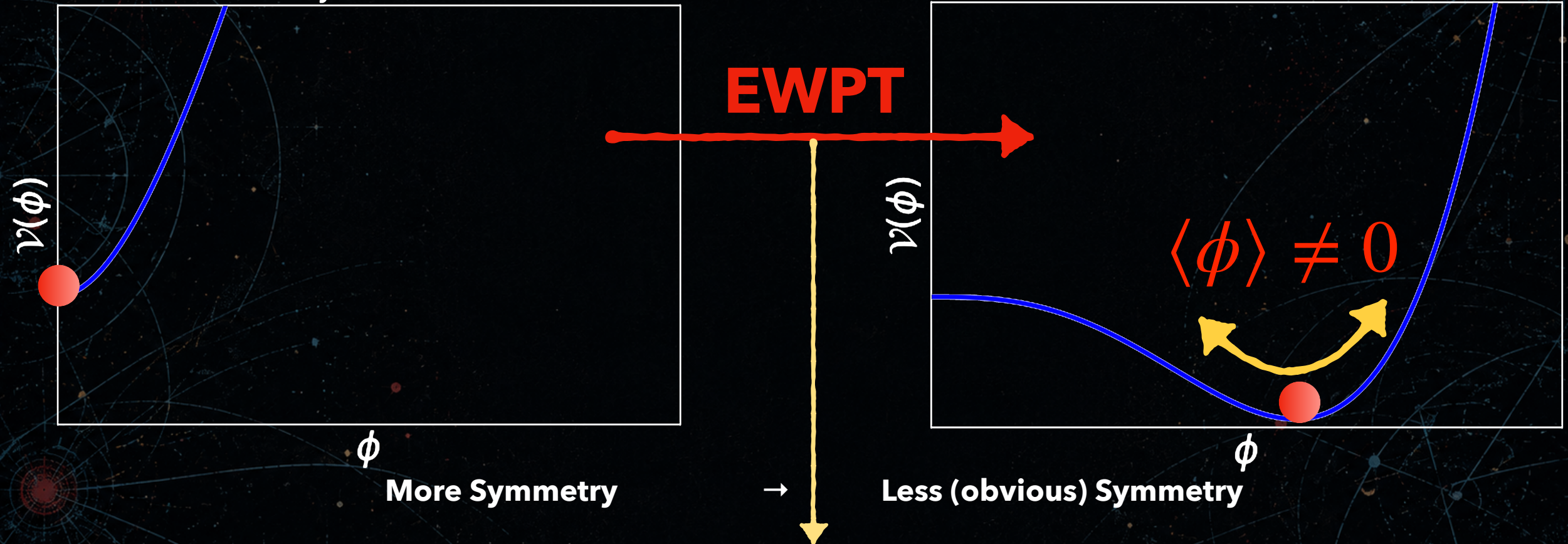


The Electroweak Phase Transition

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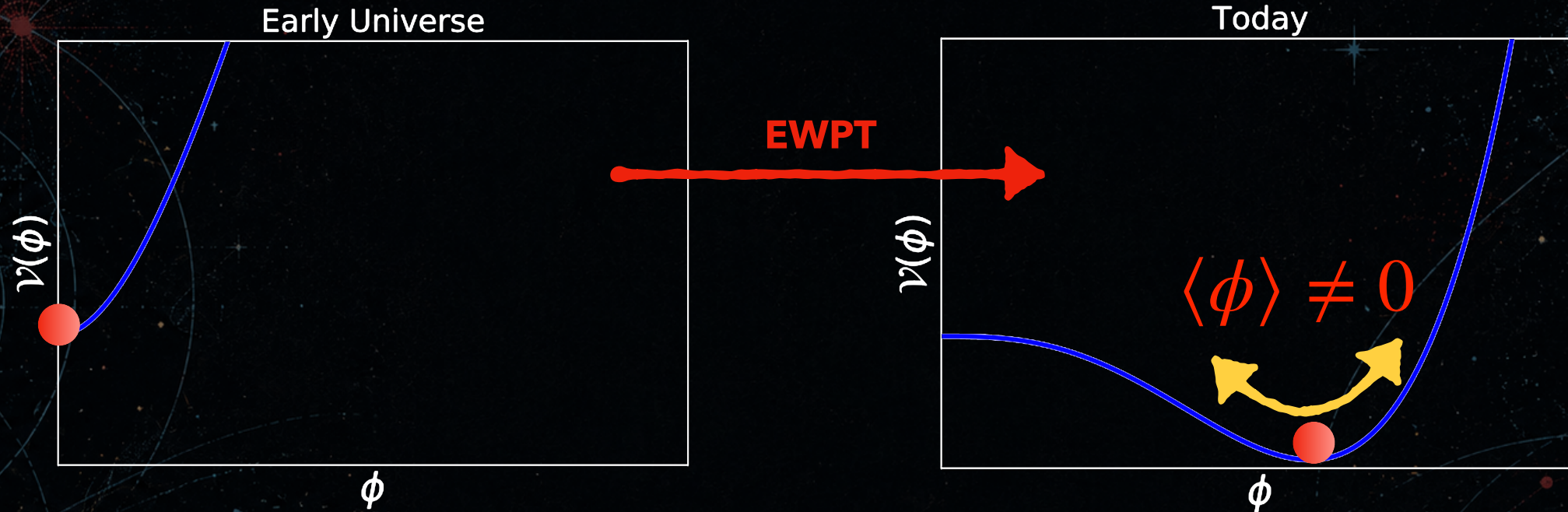
Early Universe

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≡ The Electroweak Phase Transition (**EWPT**)

The Nature of the Electroweak Phase Transition



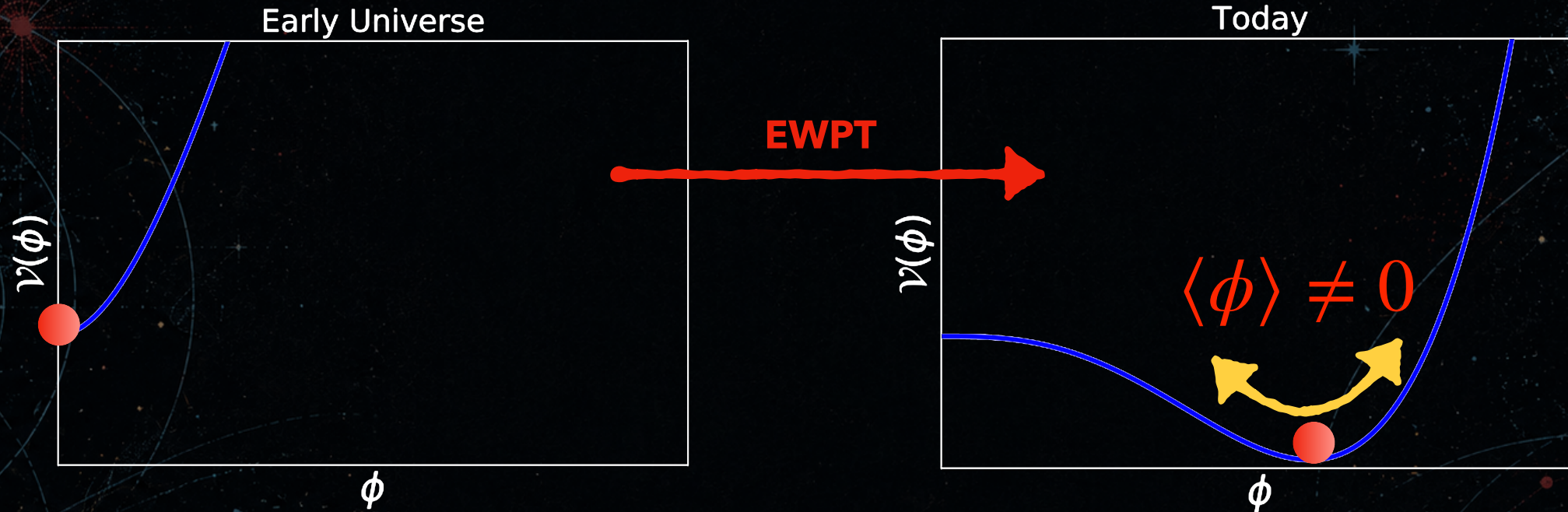
The **nature** of the EWPT is an important open question: i.e. its **order**:

Is it a **first-order transition**? (e.g. the boiling of water)



or a **second-order transition**? (e.g. the superfluid transition) or **cross-over**?

The Nature of the Electroweak Phase Transition



The **nature** of the EWPT is an important open question: i.e. its **order**:

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Electroweak Baryogenesis



Electroweak Baryogenesis

May provide clues to the origin of the **matter-antimatter asymmetry**:

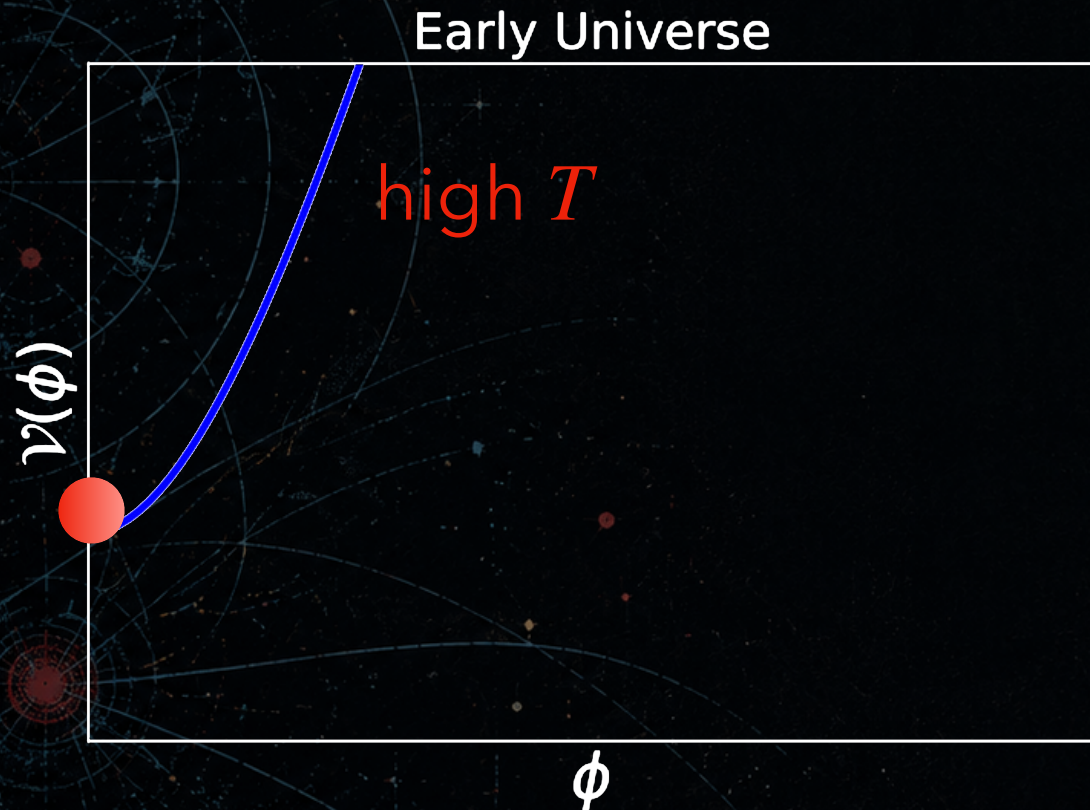
Was the asymmetry created **during** the EWPT? → **Electroweak Baryogenesis.**

A **pre-requisite: A first-order EWPT!** → 

But: this **does not** occur in the SM [Kajantie, Laine, Rummukainen, Shaposhnikov hep-ph/9605288].

A First-Order Electroweak Phase Transition

Schematically:



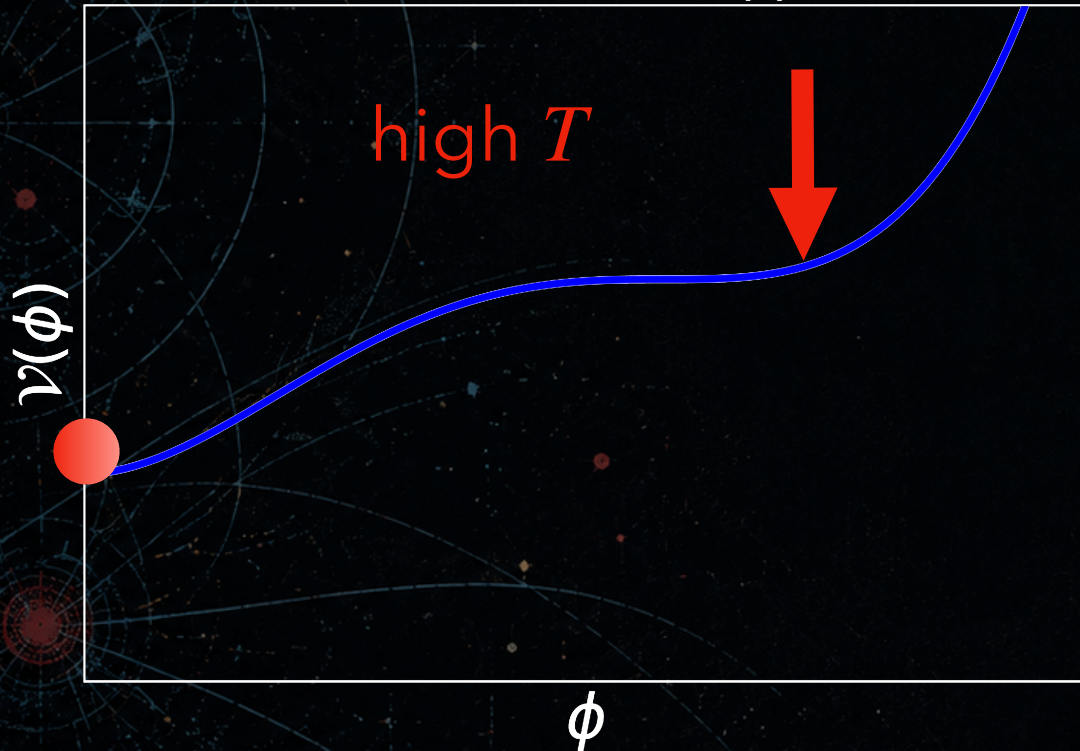
Higgs Potential evolution,
as the universe cools down.

A First-Order Electroweak Phase Transition

Schematically:

Second minimum appears

high T

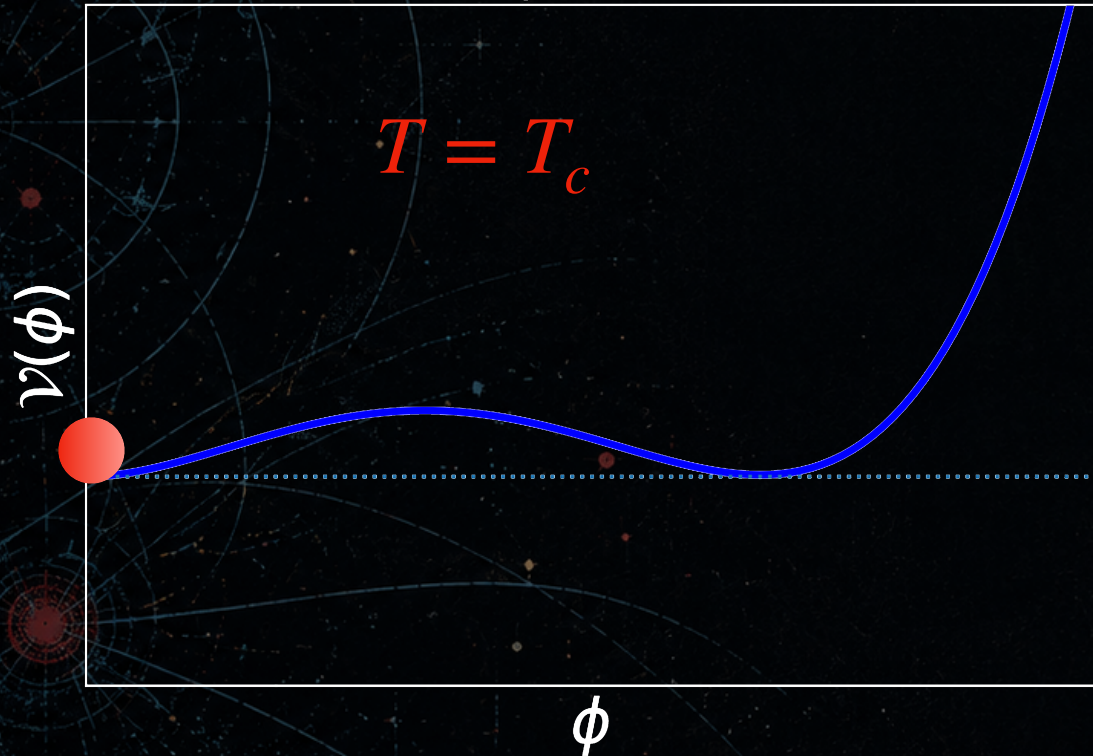


Higgs Potential evolution,
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A First-Order Electroweak Phase Transition

Schematically:

Critical temperature reached

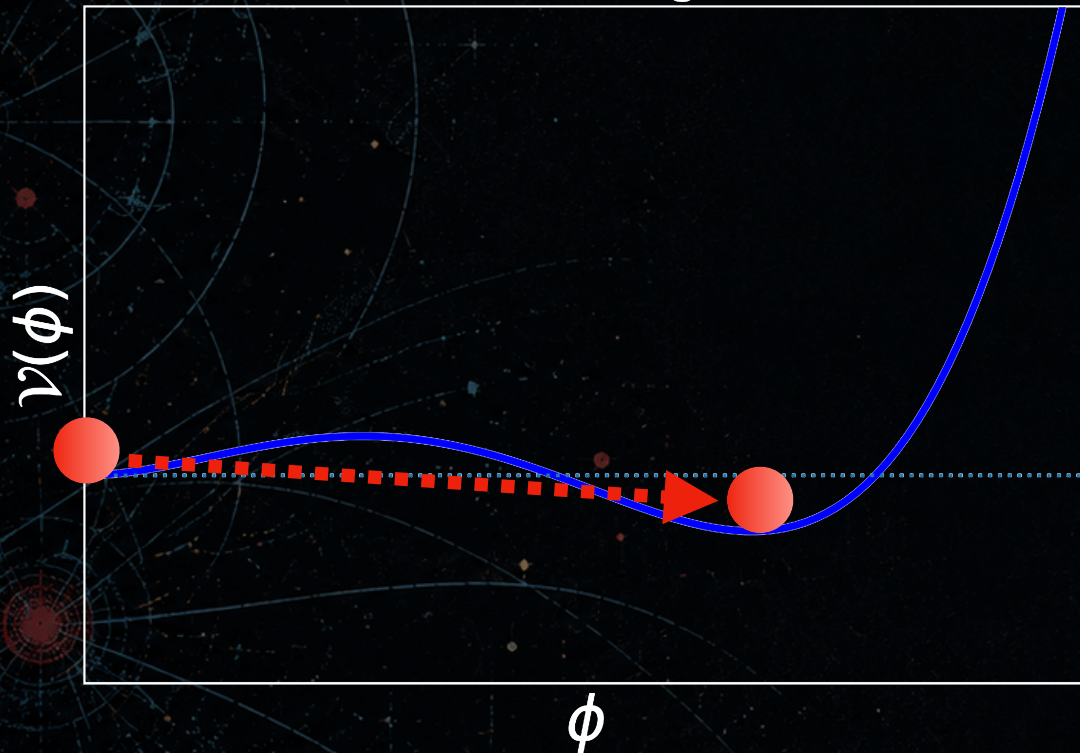


Higgs Potential evolution,
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A First-Order Electroweak Phase Transition

Schematically:

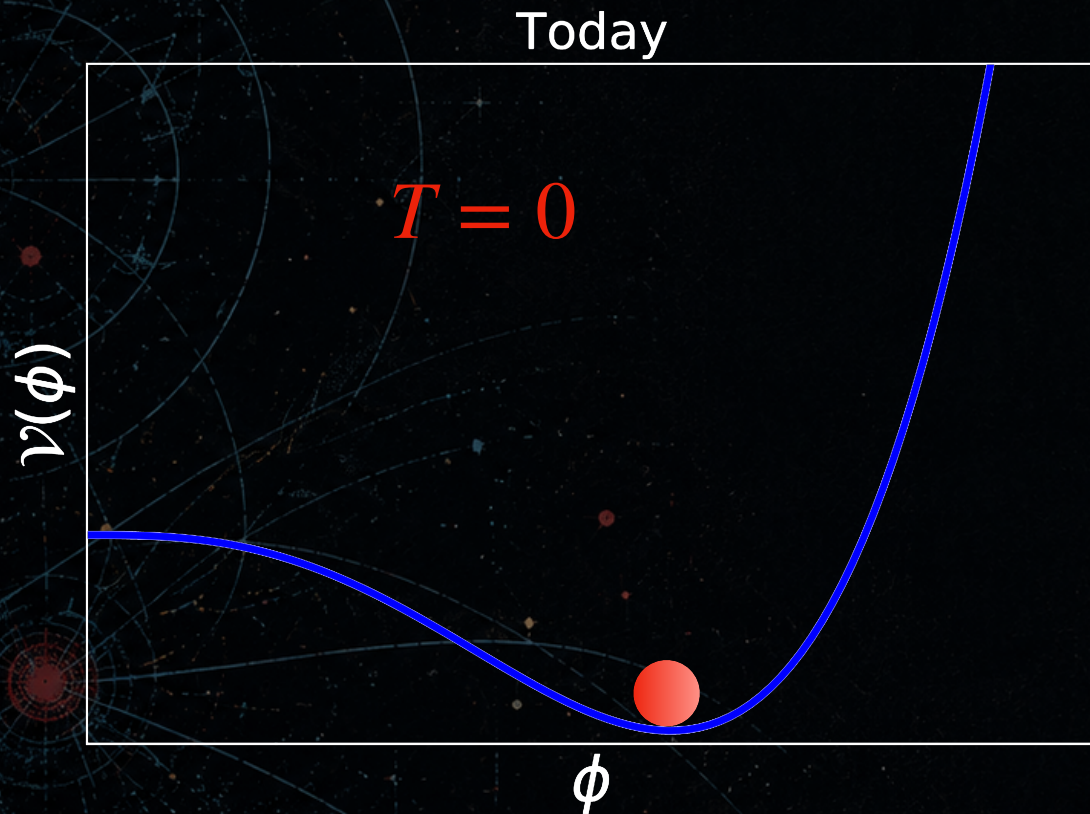
Tunneling!



Higgs Potential evolution,
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A First-Order Electroweak Phase Transition

Schematically:



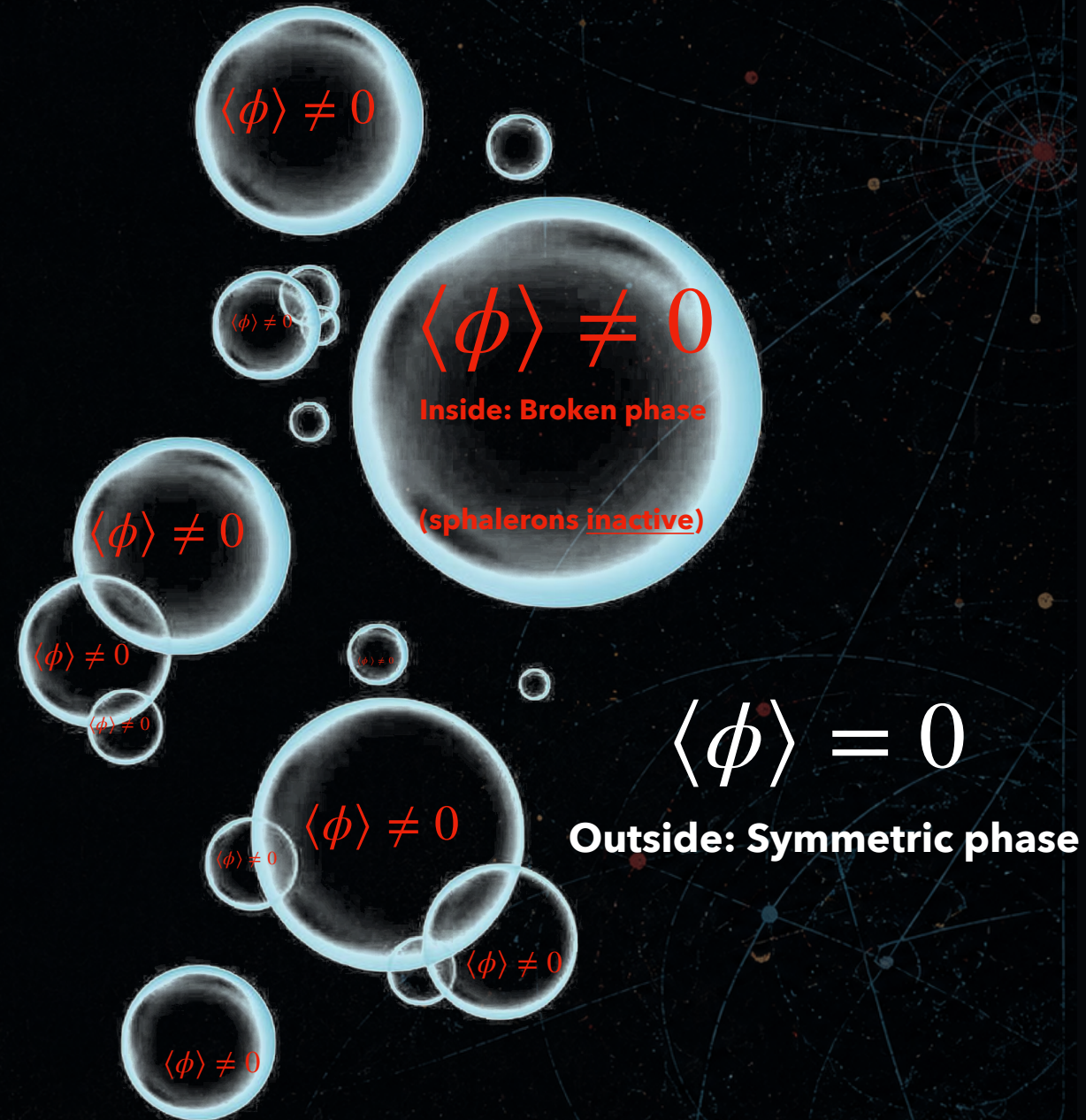
Higgs Potential evolution,
as the universe cools down.

$\langle \phi \rangle \neq 0 \Rightarrow$ **Symmetry breaking**

Some time *after* the critical temperature T_c :

Broken-phase Bubbles nucleate and expand:*

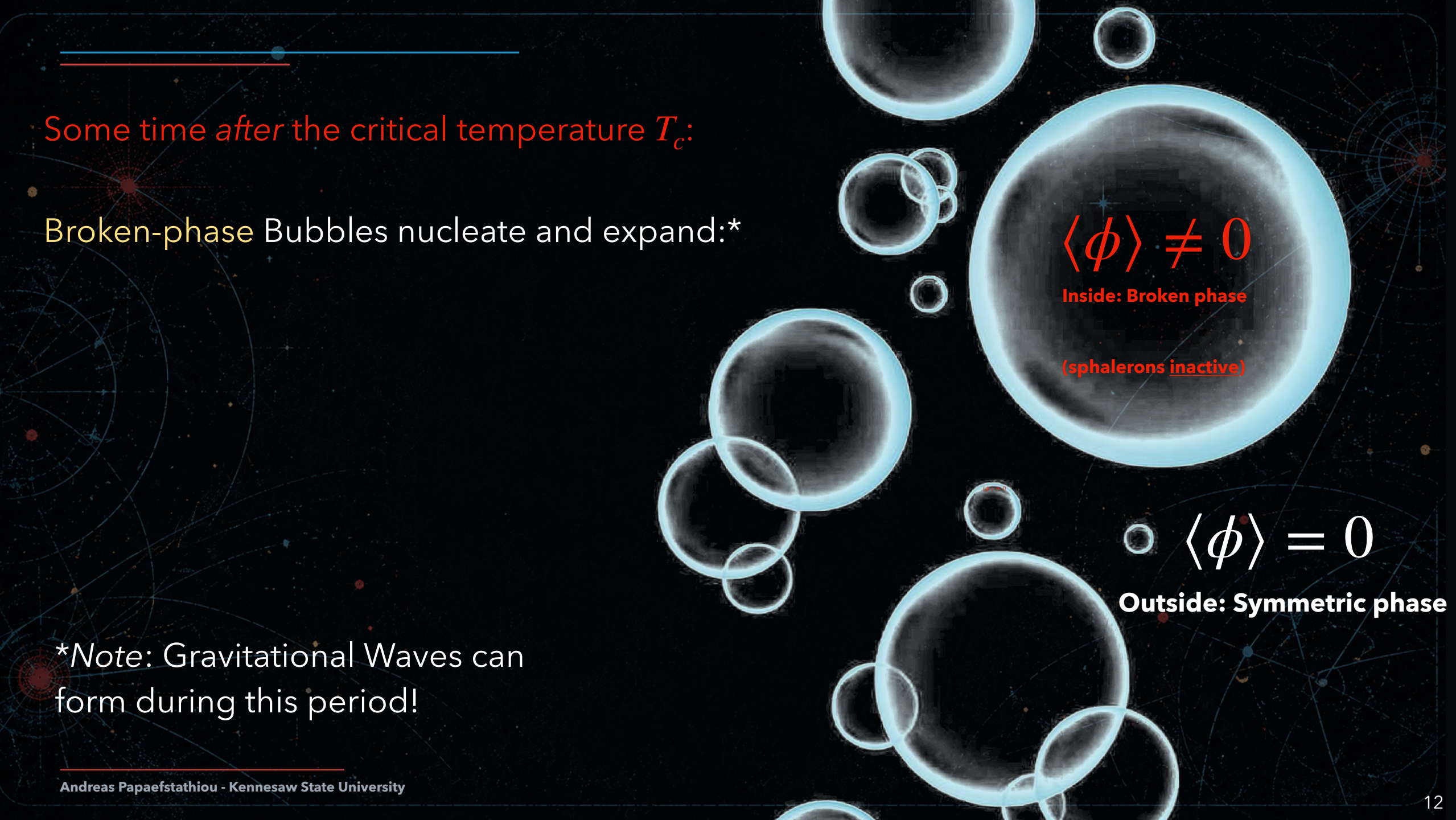
*Note: Gravitational Waves can form during this period!



Some time *after* the critical temperature T_c :

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The background of the slide is a dark blue space filled with numerous translucent, glowing blue spheres of various sizes, representing bubbles of a broken phase. Some bubbles are overlapping. Faint, light blue concentric circles and radial lines are visible in the background, resembling a celestial map or a coordinate system. The text is overlaid on this background.
$$\langle \phi \rangle \neq 0$$

Inside: Broken phase

(sphalerons inactive)

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

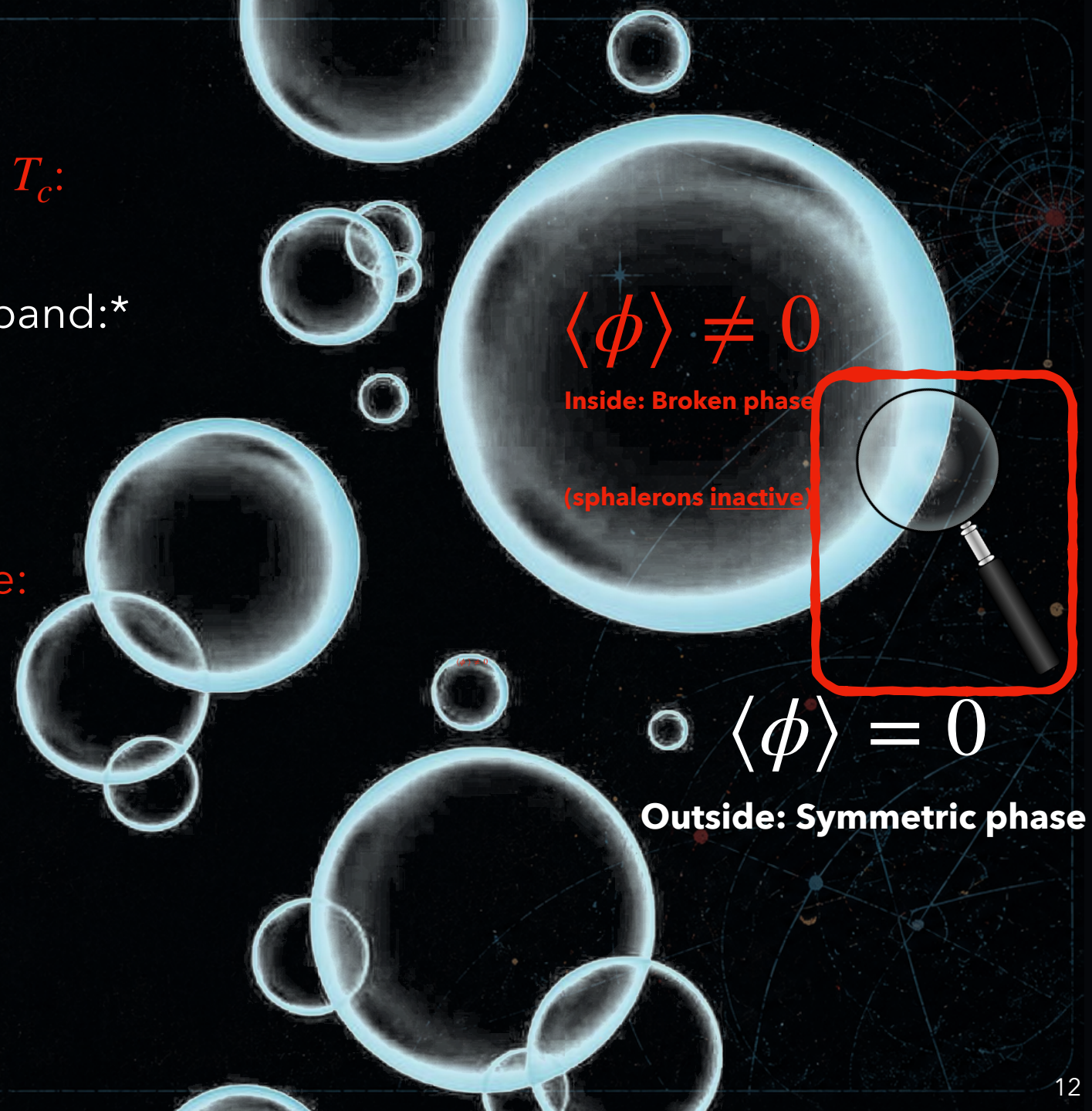
Outside: Symmetric phase

Some time *after* the critical temperature T_c :

Broken-phase Bubbles nucleate and expand:*

Zoom in at surface of expanding bubble:

*Note: Gravitational Waves can form during this period!



Electroweak Baryogenesis

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

Inside: Broken phase

(sphalerons inactive)



Left- and right-handed fermions

$$\psi_L + \psi_R$$

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

Outside: Symmetric phase



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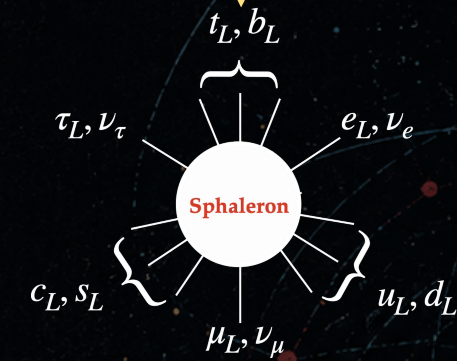
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[AP, Sakurai, Plätzer, arXiv:1910.4761]

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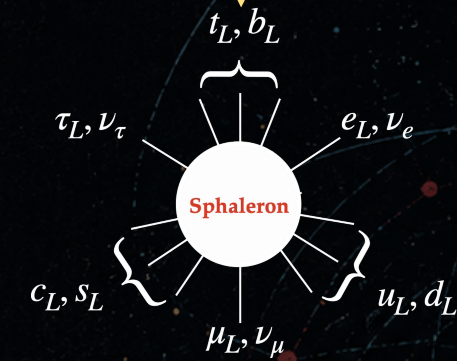
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M

Electroweak Baryogenesis

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Important Reminder:
A first-order EWPT *requires* BSM phenomena!

e.g. Extended scalar sectors!

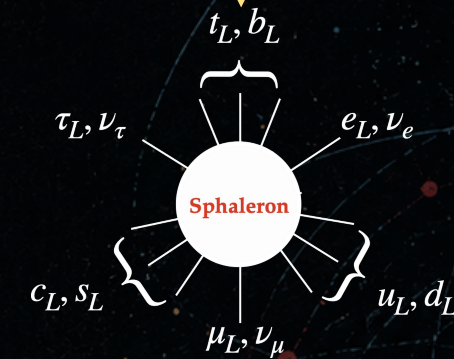
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Outside: Symmetric phase



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M

A Note on a “Strong” Transition

Suppression of sphaleron rate inside the bubble,

⇒ Matter-antimatter asymmetry swept in broken phase & “**frozen in**”.

$$\text{Rate} \sim \exp[-\langle \phi(T_C) \rangle / T_C \times \dots]$$

[T_C is the critical temperature]

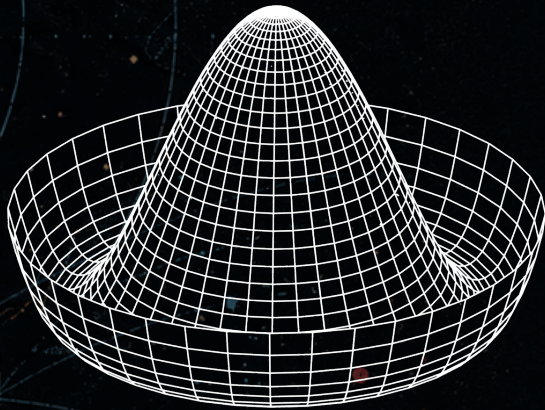
⇒ Require $\langle \phi(T_C) \rangle / T_C \geq 1 \longrightarrow$ a “**Strong**” first-order EWPT (**SFO-EWPT**).

SECTION 03

Probing the Scalar Sector: **Multi-Scalar Production**

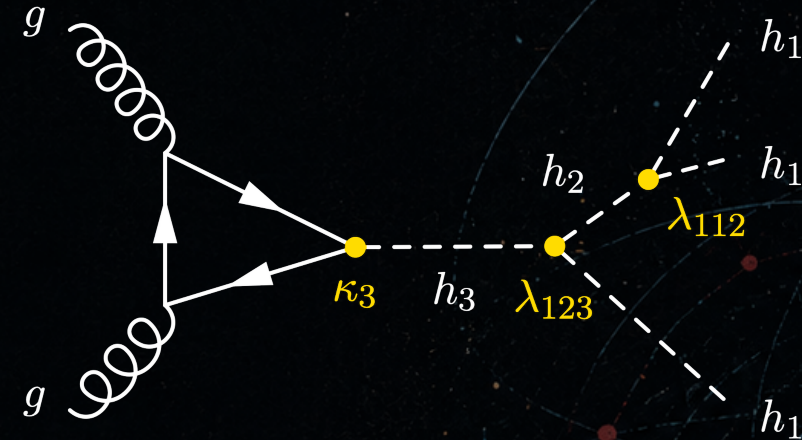
Multi-Scalar Production:

A. Can probe the Higgs Potential:



Does it indeed have the expected shape?

B. Search for extended Scalar Sectors:



⇒ and test electroweak baryogenesis!

SECTION 03

A. Measuring the Higgs Potential

Measuring The Higgs **Boson's** Potential: **Mass**

$$\mathcal{V}(\langle\phi\rangle + h) = \frac{1}{2}m_h^2 h^2 + \kappa_3 \frac{m_h^2}{2v} h^3 + \kappa_4 \frac{m_h^2}{8v^2} h^4$$



Verify SM predictions:

$$\kappa_{3,4} \stackrel{?}{=} 1$$

Measuring The Higgs **Boson's** Potential: **Mass**

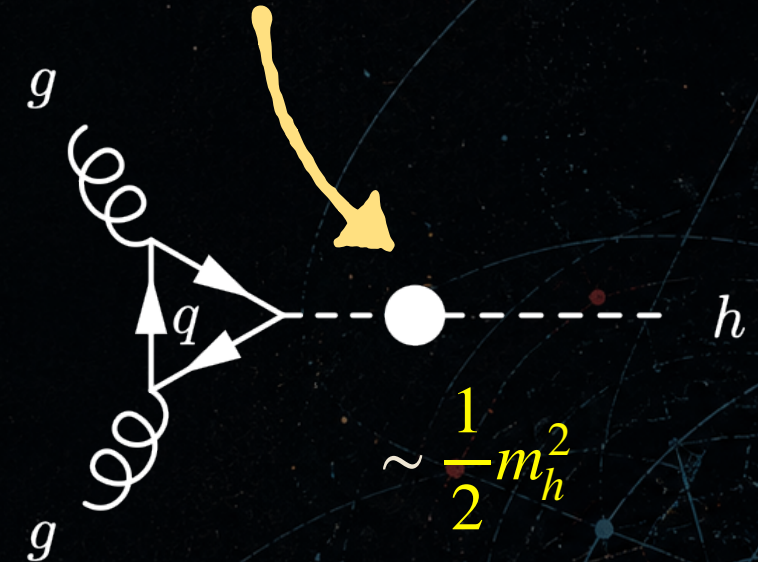
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Step 1: Single Higgs boson production:

Mass measurement:



Measuring The Higgs **Boson's** Potential: **Mass**

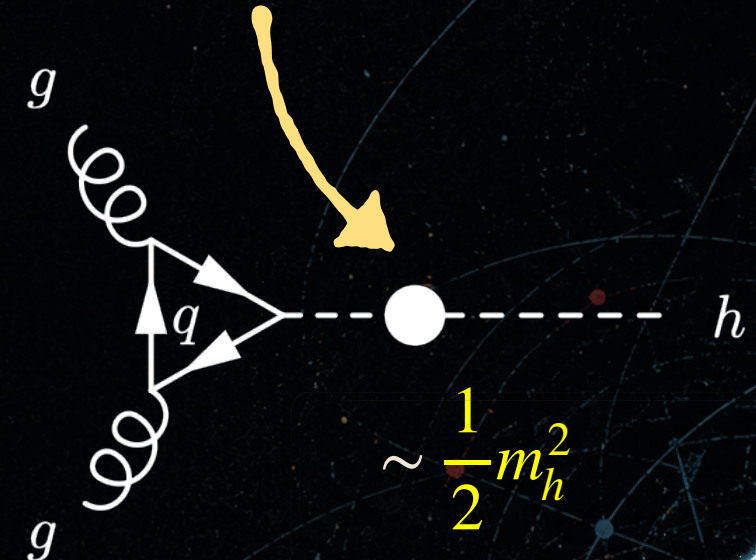
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Step 1: Single Higgs boson production:

Mass measurement:



$$m_h \simeq 125.1 \pm 0.1 \text{ GeV}$$



Measuring The Higgs **Boson's** Potential: **Trilinear**

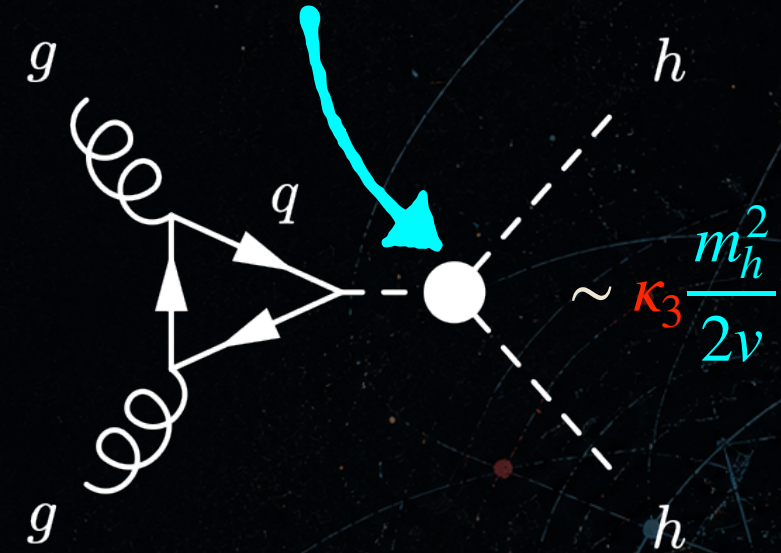
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Verify SM predictions:

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Step 2: Double Higgs boson production:

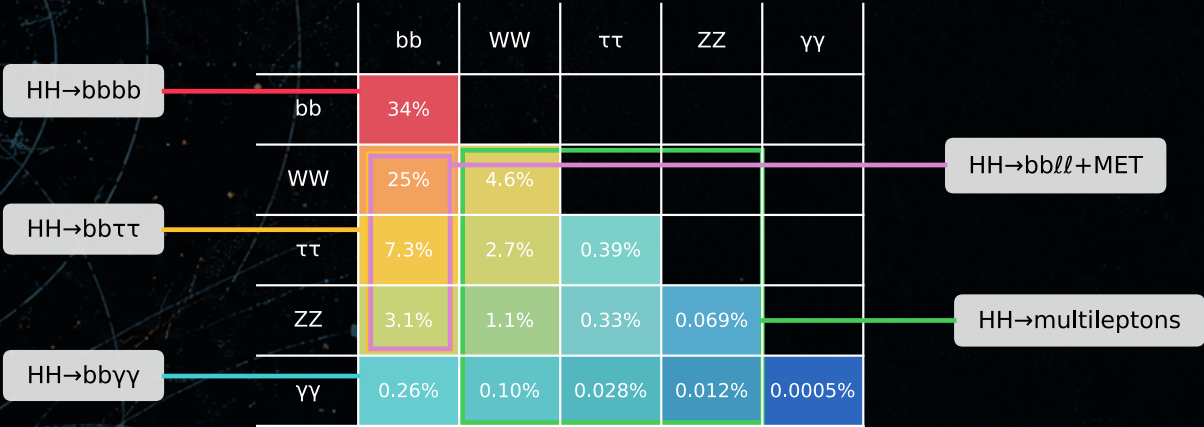
Trilinear coupling measurement:



Measuring The Higgs Boson's Potential: Trilinear

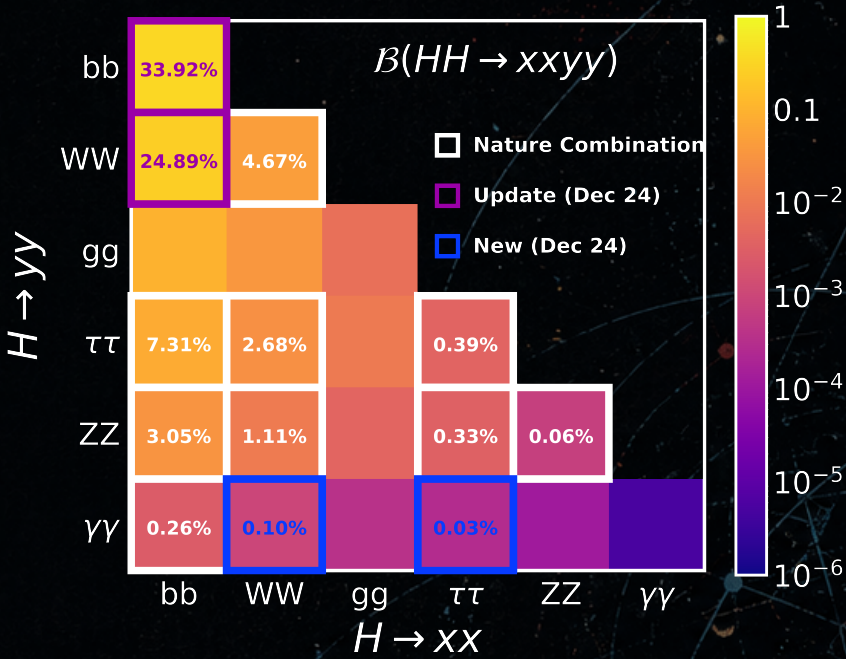
$pp \rightarrow hh \rightarrow (xx)(yy)$ final states @ LHC, Branching Ratios:

ATLAS:



[A. Sidley, HIGGS 2025]

CMS:

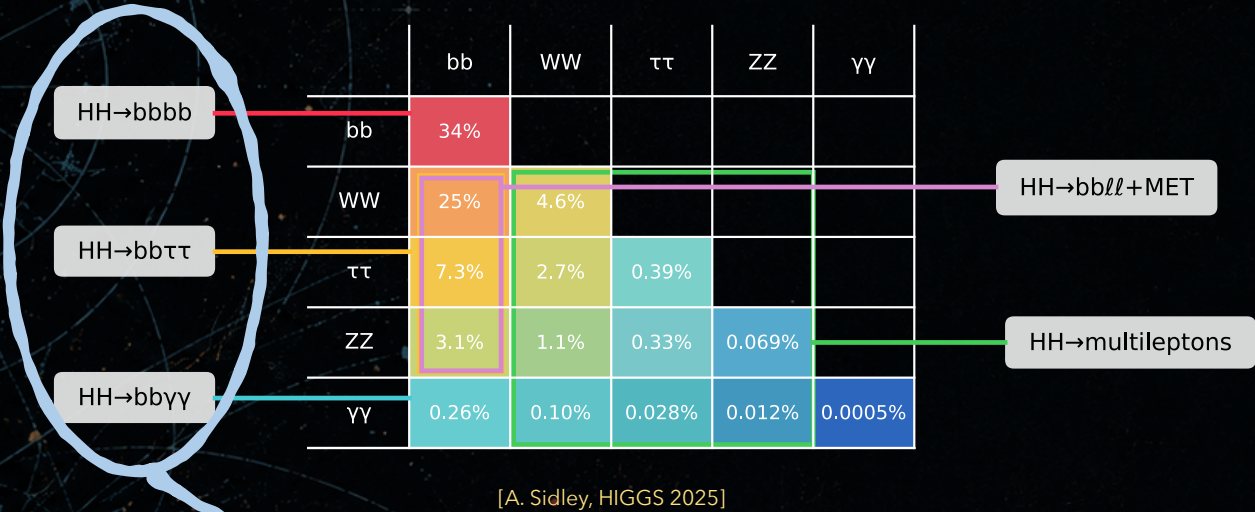


[N. De Filippis, HIGGS 2025]

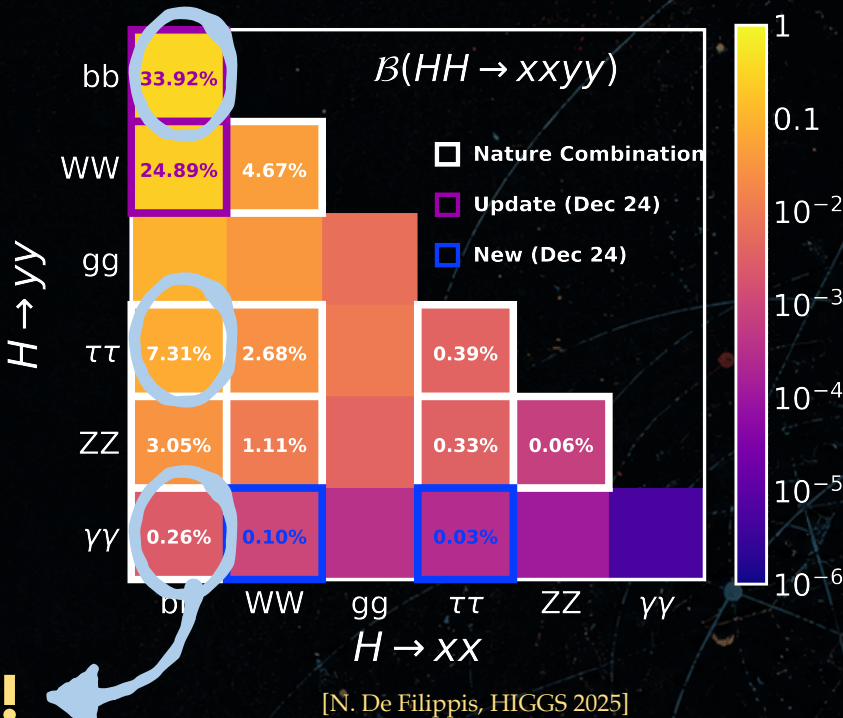
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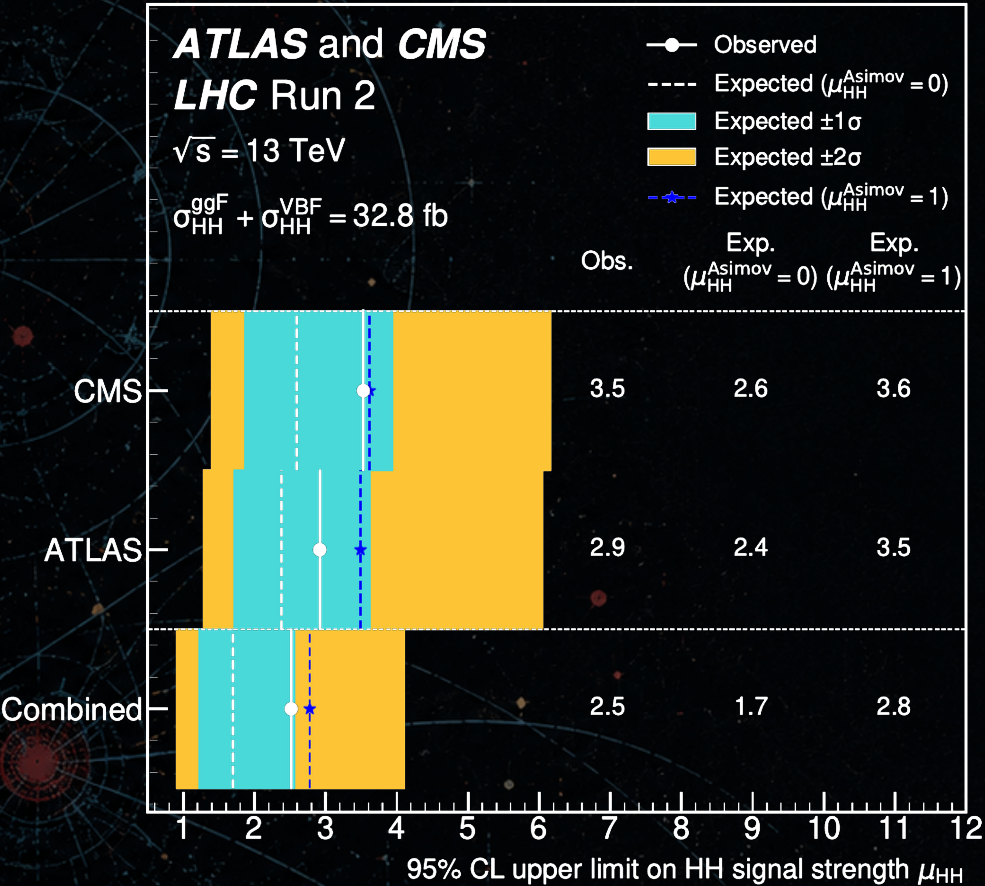


Best channels!

Trilinear @ LHC (Today!)

ATLAS + CMS Combo (13 TeV): [arXiv:2602.23991]

$$\mu_{HH} = \sigma_{\text{obs}}/\sigma_{\text{SM}}$$

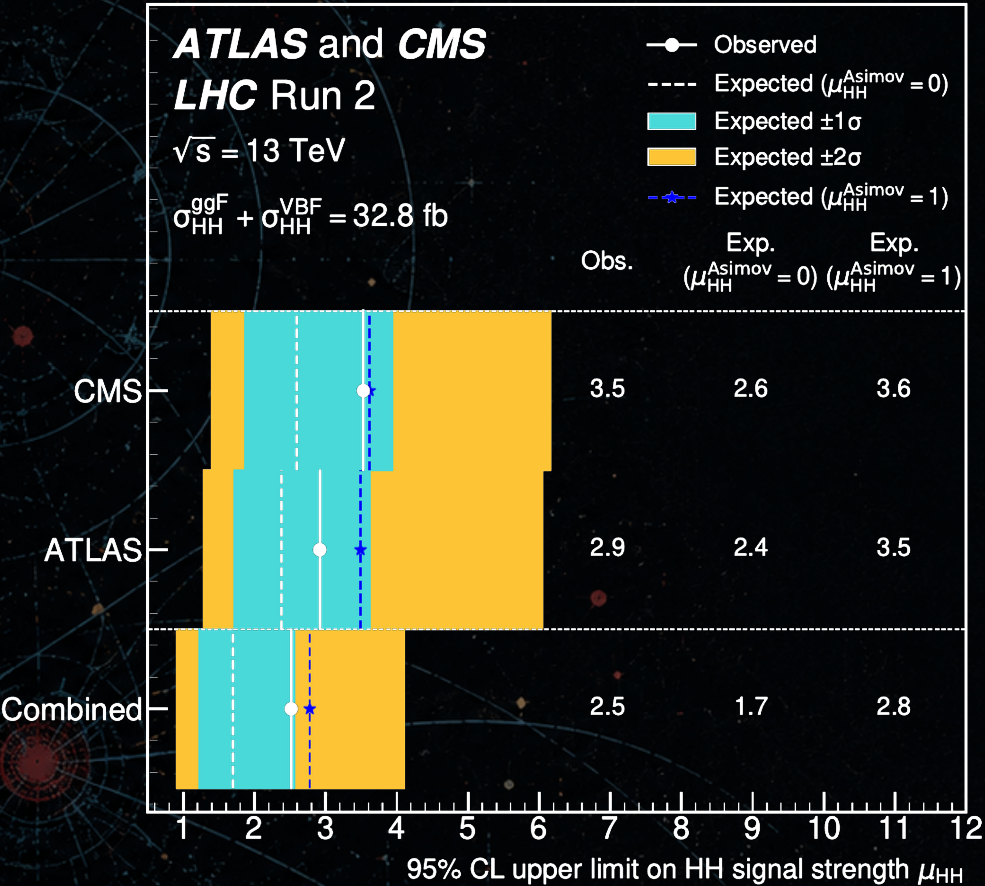


	Channel	Observed	
		signal strength μ_{HH}	κ_3 95% CL interval
ATLAS	$bbbb$	< 5.4	$[-3.4, 11]$
	$bb\tau\tau$	< 5.8	$[-3.3, 9.1]$
	$bb\gamma\gamma$	< 4.1	$[-1.6, 7.0]$
	$bb\ell\ell + E_T^{\text{miss}}$	< 9.6	$[-6.5, 13]$
	Multilepton	< 17	$[-6.4, 12]$
	Combined	< 2.9	$[-1.3, 7.2]$
CMS	$bbbb$	< 7.0	$[-5.0, 12]$
	$bb\tau\tau$	< 3.5	$[-1.9, 8.9]$
	$bb\gamma\gamma$	< 8.7	$[-3.5, 8.0]$
	$bbWW$	< 15	$[-6.1, 13]$
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ATLAS + CMS combined		< 2.5	$[-0.71, 6.1]$

Trilinear @ LHC (Today!)

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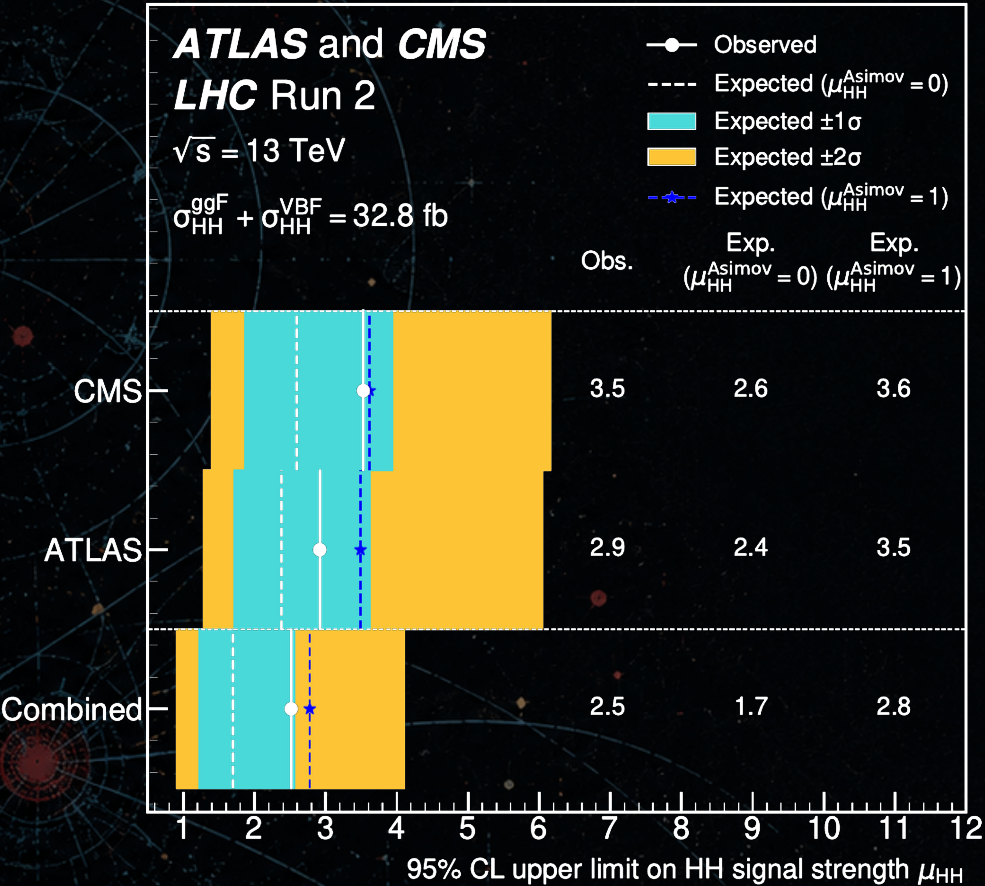


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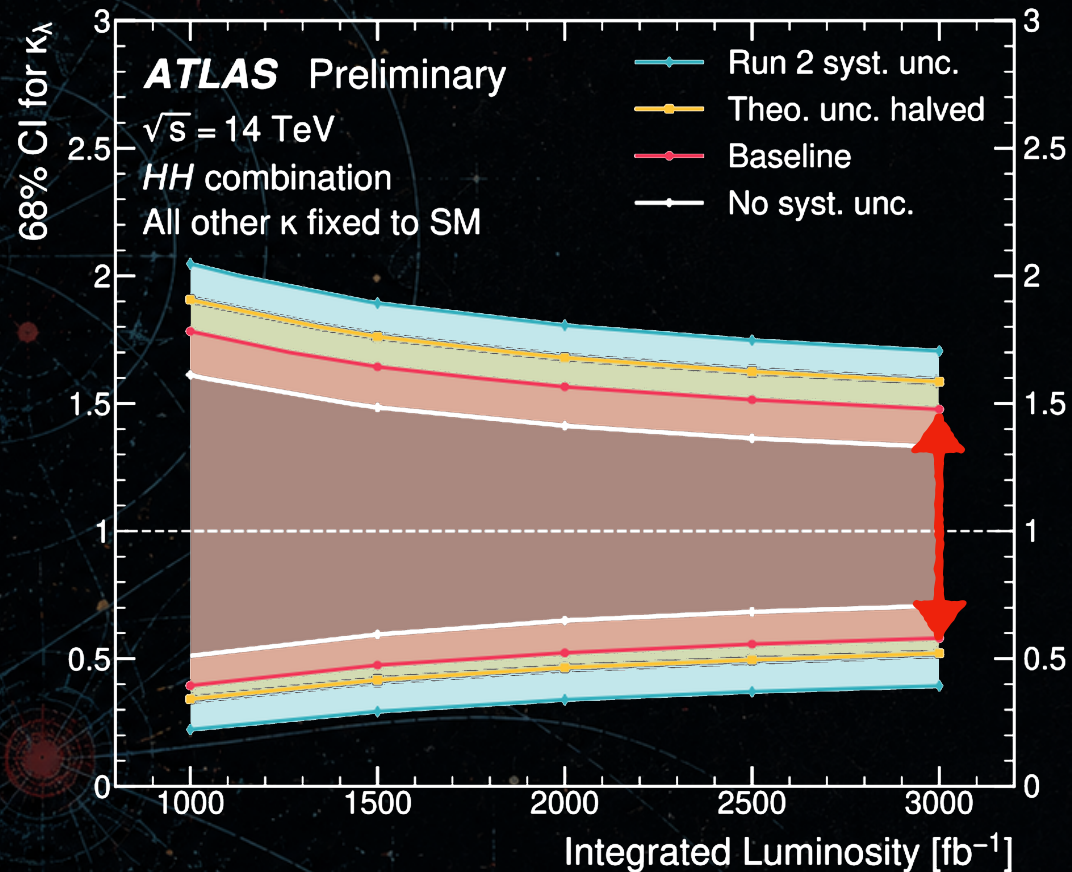
$$\Rightarrow -0.71 < \kappa_3 < 6.1$$



Trilinear @ HL-LHC

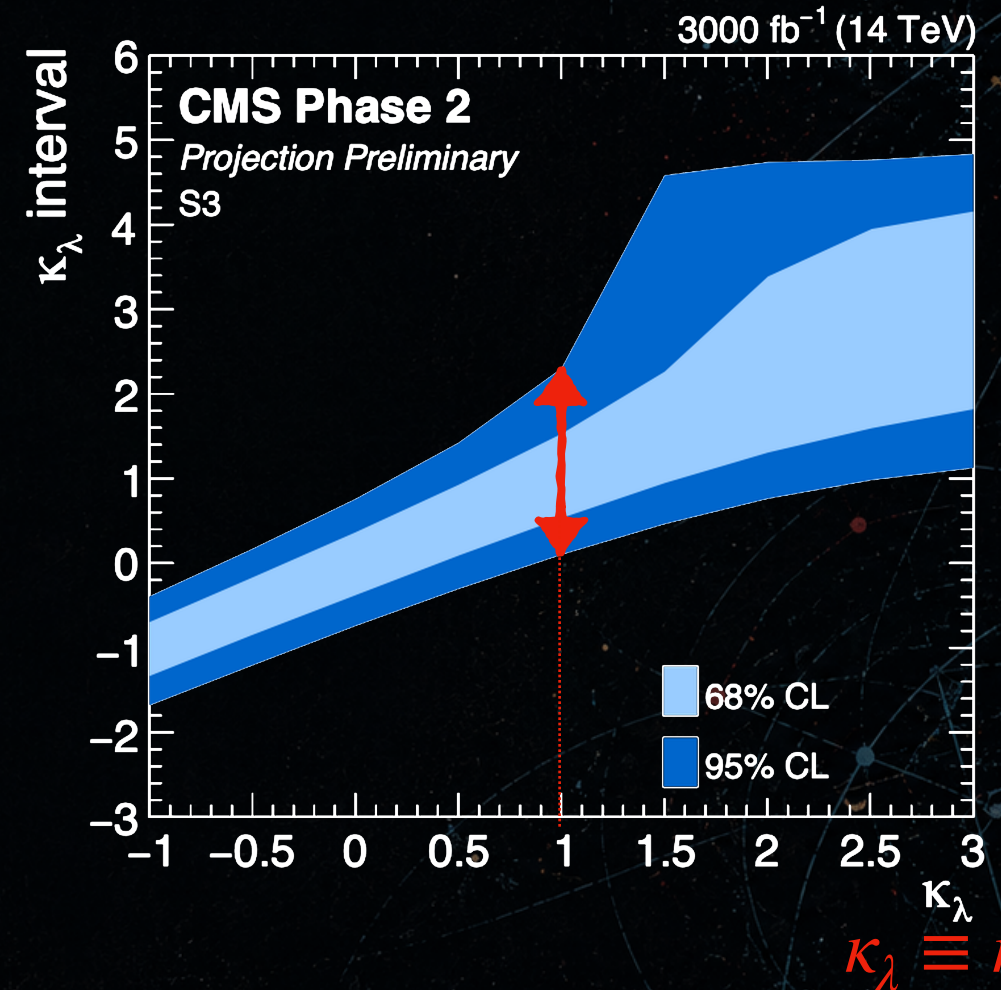
ATLAS: $\kappa_3 = 1^{+0.48}_{-0.42}$

[ATL-PHYS-PUB-2025-006]



CMS: $\kappa_3 = 1^{+0.50}_{-0.47}$

[CMS NOTE -2025/006]



WG4 Notice: $gg \rightarrow hh$ @ HL-LHC $\longrightarrow$ Report 5 on Higher-Order Corrections Out!

Major CERN Report 5 contribution out, LHCHWG-INT-2026-001:

- NLO corrections with top quark mass effects,
- Approximate NNLO/N³LO corrections,
- Electroweak corrections,
- Top mass scheme uncertainty investigations (inclusive),
- Inclusive $gg \rightarrow hh$ cross section recommendations.

$$\sigma_{\text{rec.}}(\sqrt{s}) = \sigma_{\text{NNLO}_{\text{FTapprox}}}(\sqrt{s}) \times K_3(\sqrt{s}) \times K_{\text{EW}}(\sqrt{s})$$

$\sqrt{s}$ [TeV]	13	13.6	14
$\sigma_{\text{rec.}}$ [fb]	30.40	33.62	35.81
$\pm$ PDF unc. [%]	1.96	1.92	1.89
$\pm \alpha_s$ unc. [%]	1.51	1.49	1.47
$\pm$ PDF + α_s unc. [%]	2.47	2.43	2.39
QCD scale unc. [%]	+2.11 -4.98	+2.07 -4.85	+2.01 -4.78
m_t scheme unc. [%]	+5 -16	+5 -16	+5 -16
$\pm$ TH _{num} [%]	0.14	0.19	0.21
Scale + TH _{num} + m_t scheme unc. [%]	+7.25 -21.12	+7.26 -21.04	+7.22 -20.99

Measuring The Higgs **Boson's** Potential: **Quartic**

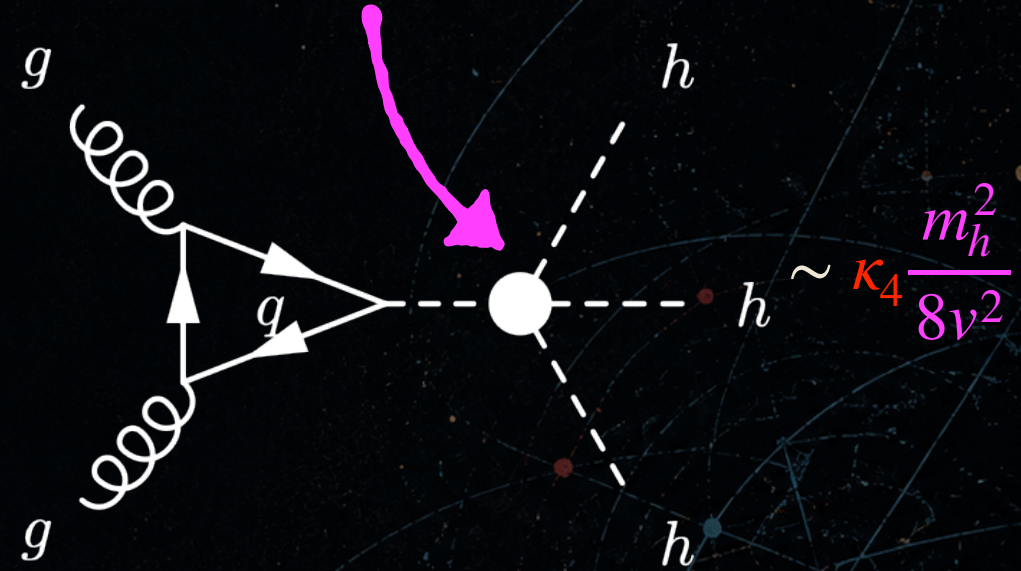
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Verify SM predictions:

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Step 3: Triple Higgs boson production:

Quartic coupling measurement:



Measuring The Higgs **Boson's** Potential: **Quartic**

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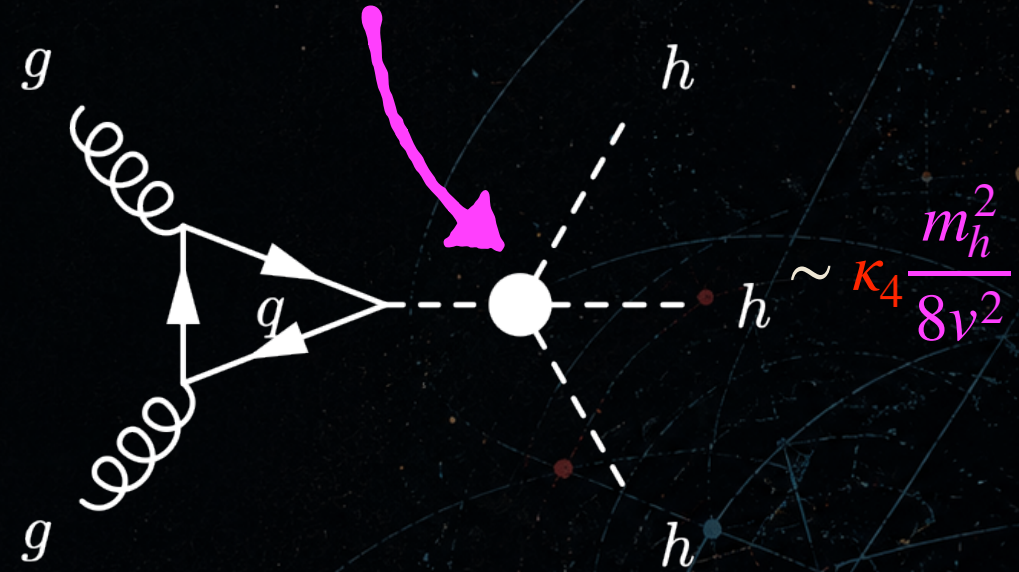
Tiny cross section @ LHC:

SM $\sigma(hhh @ 14 \text{ TeV}) \sim 0.1 \text{ fb!}$



Step 3: Triple Higgs boson production:

Quartic coupling measurement:



Measuring The Higgs **Boson's** Potential: **Quartic**

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Verify SM predictions:

$$\kappa_{3,4} \stackrel{?}{=} 1$$

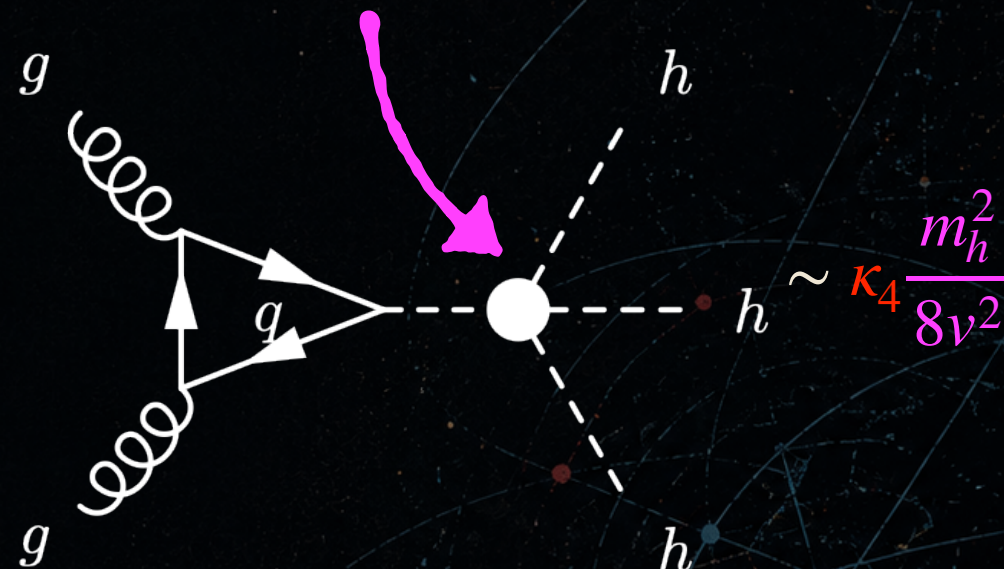
Tiny cross section @ LHC:

SM $\sigma(hhh @ 14 \text{ TeV}) \sim 0.1 \text{ fb!}$



Step 3: Triple Higgs boson production:

Quartic coupling measurement:



$$\kappa_4 \in [-533, 541] \text{ [CMS, 4b2}\gamma\text{]}$$

$$\kappa_4 \in [-190, 190] \text{ [CMS, 6b]}$$

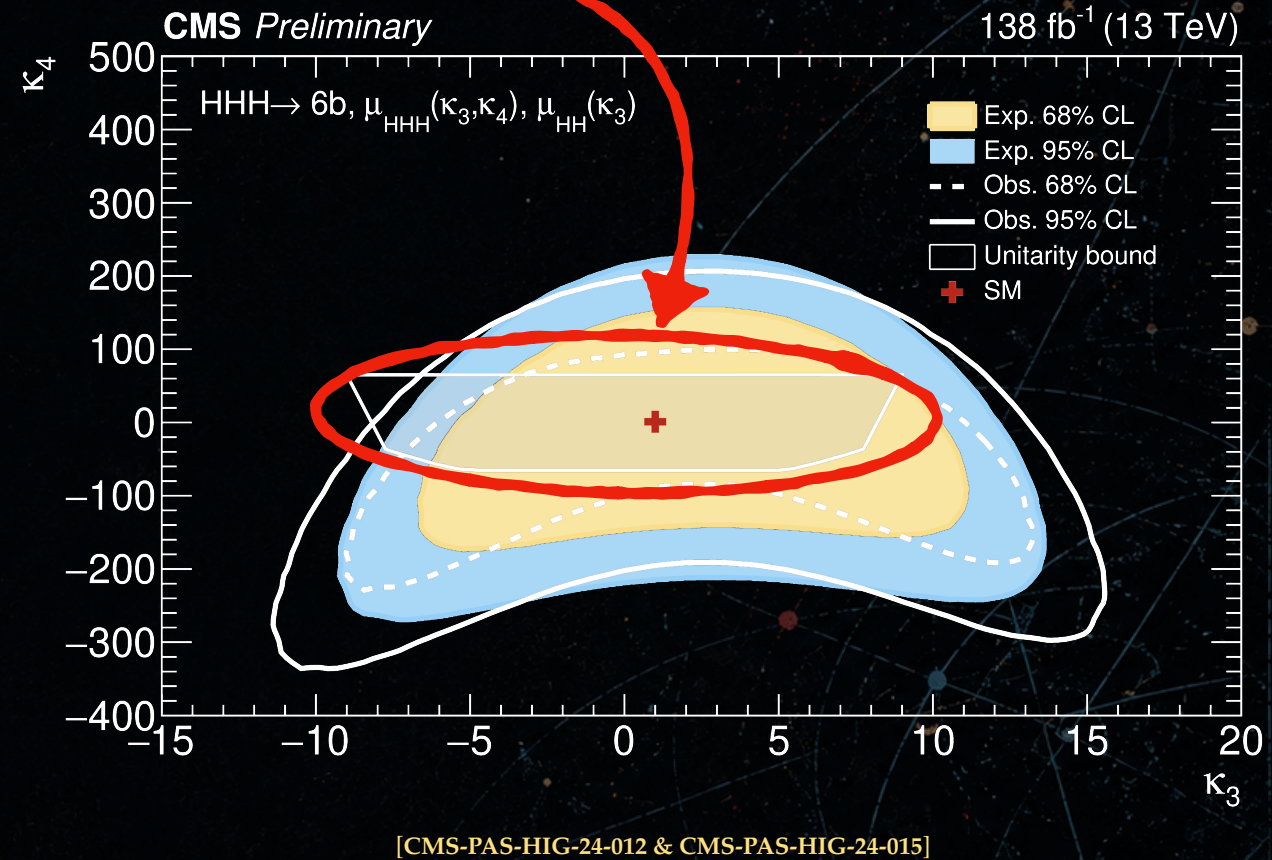
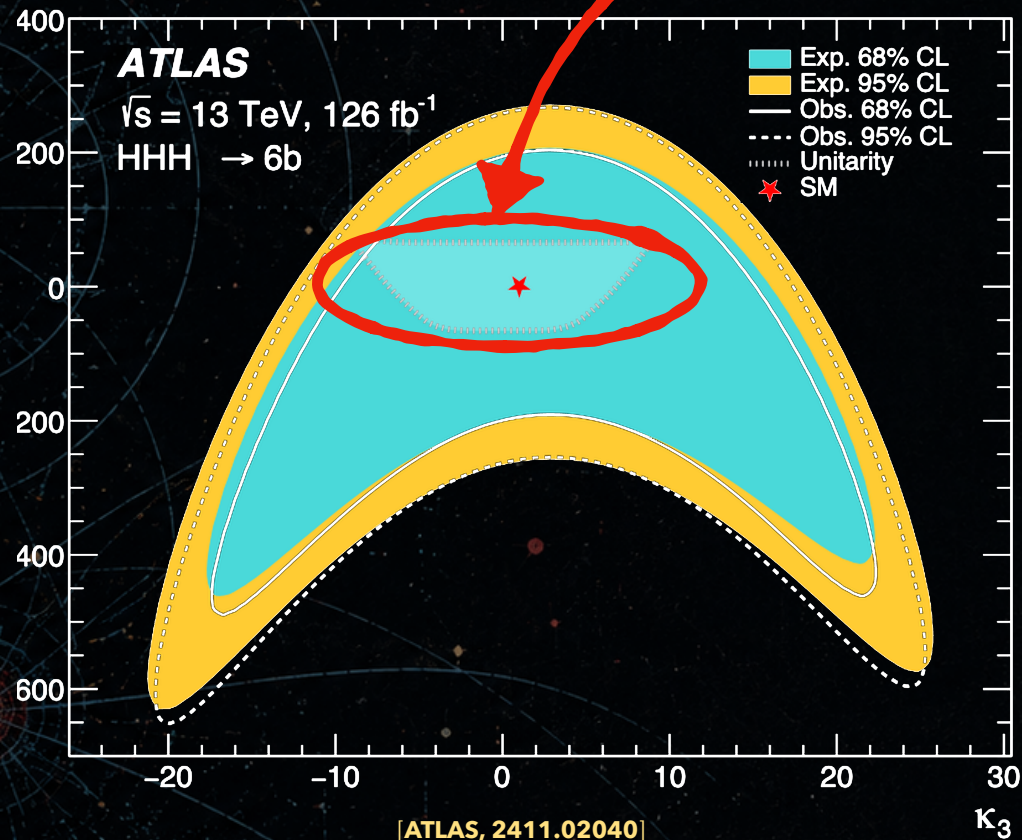
$$\kappa_4 \in [-190, 190]$$

[ATLAS, 6b]

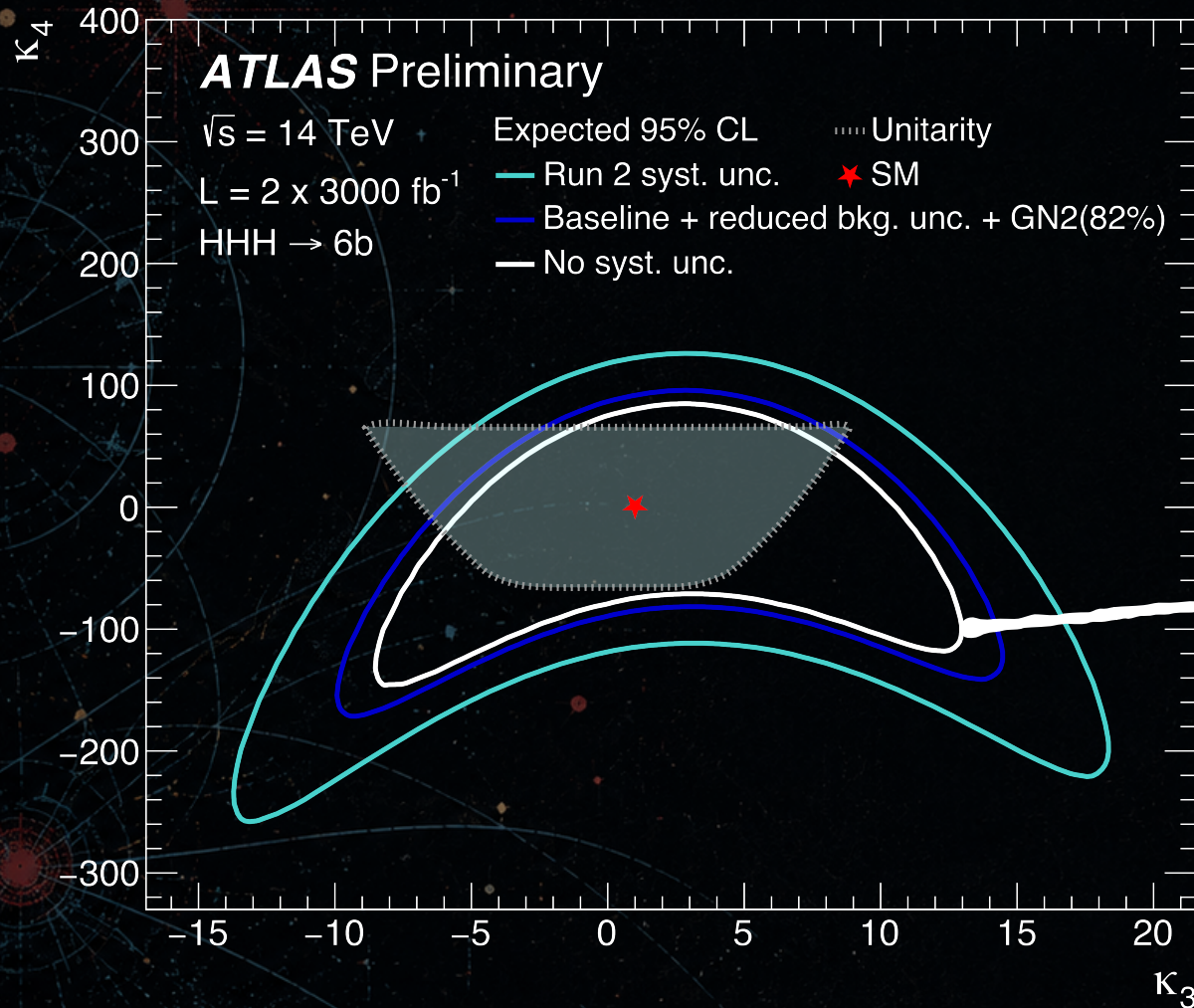
Quartic @ LHC (Present)

Final state: $pp \rightarrow (b\bar{b})(b\bar{b})(b\bar{b}) \rightarrow 6 \text{ b-jets!}$

perturbative unitarity*



Quartic @ HL-LHC



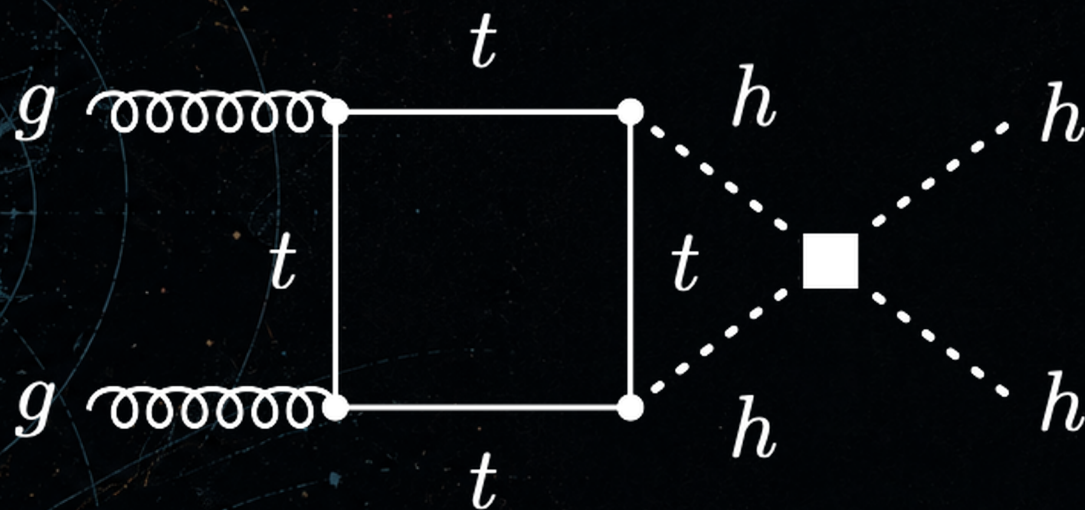
ATLAS HL-LHC
extrapolation of **6 b-jet**
final state (**6000 fb⁻¹**)
with reduced *or* no
systematics. [ATL-PHYS-PUB-2025-003]

Best-case scenario:
 $\kappa_4 \in [-65, 76]$

[Shaded region: $hh \rightarrow hh$ perturbative unitarity]

Quartic Indirect Constraints through hh

- Through electroweak corrections:



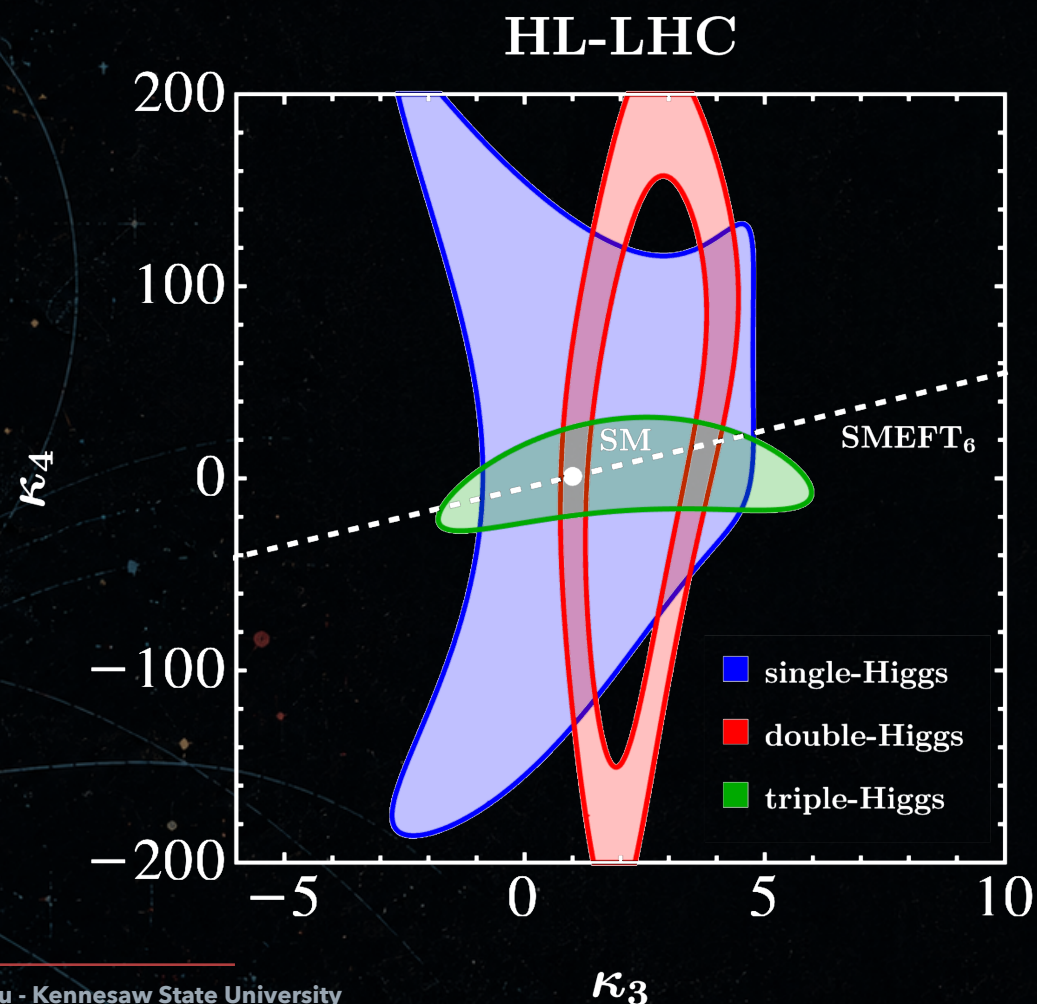
[Bizoń, Haisch, Rottoli, **1810.04665**, Li Si, Wang, Zhang, Zhao, **2407.14716**, Heinrich, Jones, Kerner, Stone, Vesten, **2407.04653**]

But: **Full** EW corrections to hh are only available for the SM!

Quartic Indirect Constraints: Single h

- Through **corrections to Higgs wave-function renormalization** from κ_3, κ_4 up to 2 **loops**.

[Haisch, Sankar, Zanderighi, 2505.20463]



@HL-LHC: $\kappa_4 \in [-21, 28]$

But: Indirect constraints somewhat more **model-dependent** than direct probes!

Quadruple Higgs Boson Production (!?)

[AP, Tetlalmatzi-Xolocotzi, 2608.16998]

- Quartic constraints are likely to remain weak at HL-LHC.

Quadruple Higgs boson production includes more diagrams involving κ_4 at LO.

At **14 TeV, LO SM**: $\sigma(hhh)/\sigma(4h) \sim 350$ ($\rightarrow \mathcal{O}(10^{-4} \text{ fb})$). **But**: can be enhanced substantially at **large κ_4** !

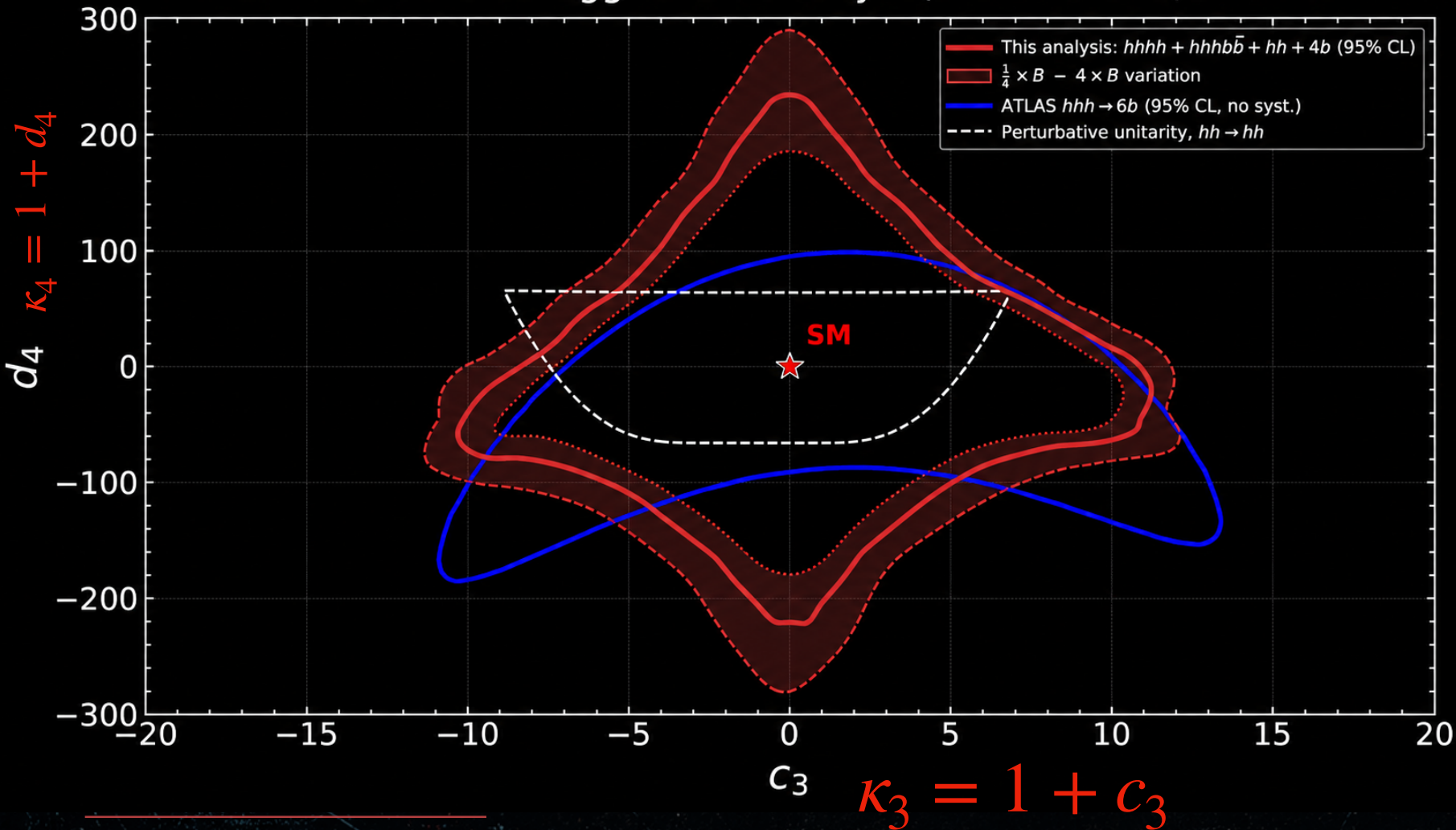
Also: Rate for **4h** can be large in **extended scalar sectors** [see e.g.: Cheng, Chiang, Low, **2202.02954**, Lane, Lewis, Sullivan, **2403.18003**, Li, Liu, Wang, **2604.14284**, Roy, Wagner, **2605.29345**, ...]. e.g. **4h > 3h** or **4h > hh**!

QCD 8 b-jet backgrounds are also likely to be much **smaller**! $\rightarrow \mathcal{O}(1 \text{ fb})$ with $p_{T,b} > 20 \text{ GeV}$!

Is it worth investigating?

Quadruple Higgs Boson Production @ HL-LHC

Resolved $8b$ multi-Higgs boson analysis, $\sqrt{s} = 14 \text{ TeV}$, $\mathcal{L} = 3 \text{ ab}^{-1}$



→ **Potentially complementary to**
 $hhh \rightarrow 6b$ jets on (k_3, k_4) plane!

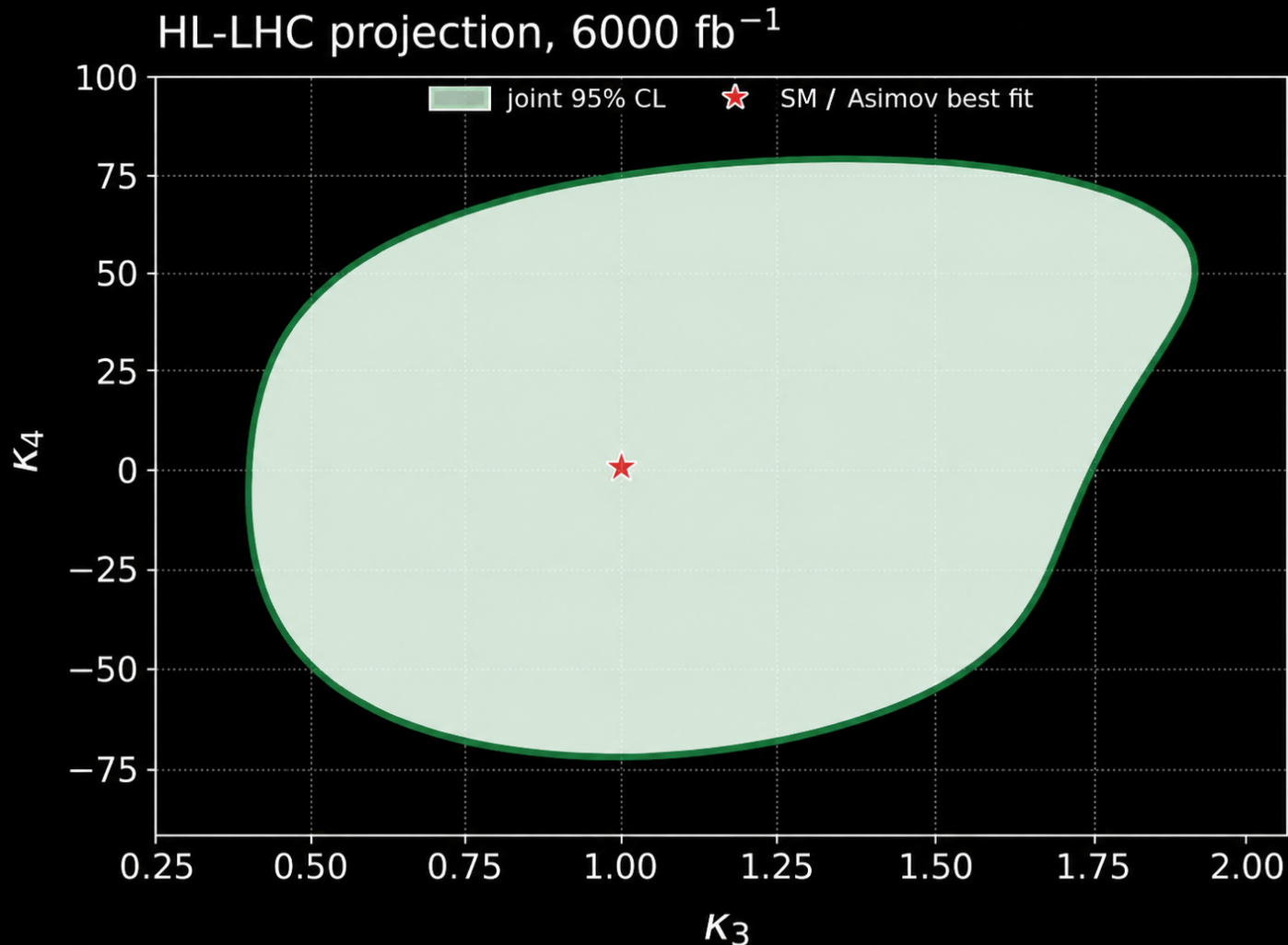
Also: $4h \rightarrow 8b$ could enter the $3h \rightarrow 6b$ signal region.

Definitive HL-LHC Self-Coupling Constraints (A Theorist's Dark Fantasy)

Ingredients:

- $gg \rightarrow hh$ ATLAS+CMS HL-LHC projection [2504.00672, Fig. 2 left]
 - with κ_4 dependence in $gg \rightarrow hh$ (rescaled for $k_4 \neq 1$) [Bizoń, Haisch, Rottoli, Gillis, Moser, Windischhofer, 2402.03463],
- $gg \rightarrow hhh$ ATLAS+CMS HL-LHC signal strength projection [ATL-PHYS-PUB-2025-003, Fig. 4 right],
- Signal strengths + κ_3, κ_4 self-coupling dependence in single Higgs:
 $pp \rightarrow h, Vh, VBF, t\bar{t}h$ [Haisch, Sankar, Zanderighi, 2505.20463],
- $gg \rightarrow hhhh$ full Poisson likelihood over κ_3, κ_4 [AP, Tetlalmatzi-Xolocotzi, 2608.16998].

Definitive HL-LHC Self-Coupling Constraints (A Theorist's Dark Fantasy)



@ 95% C.L.:

joint two-param. fit:

$$\kappa_3 \in [0.4, 1.9]$$

$$\kappa_4 \in [-71, 79]$$

one-param., the other fixed to SM:

$$\kappa_3 \in [0.5, 1.6]$$

$$\kappa_4 \in [-63, 67]$$

A challenge:

Can we beat these?

[ASIDE]

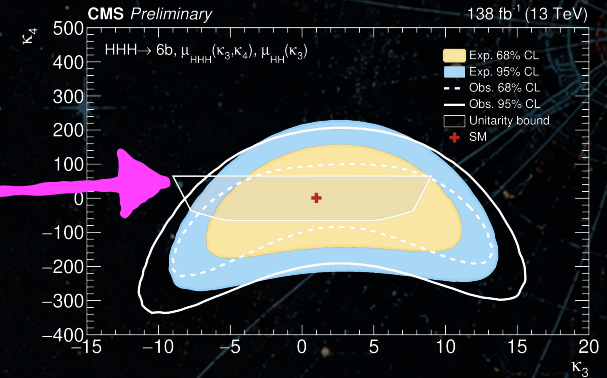
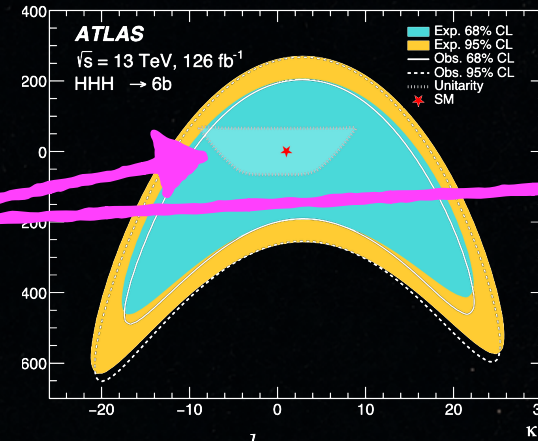
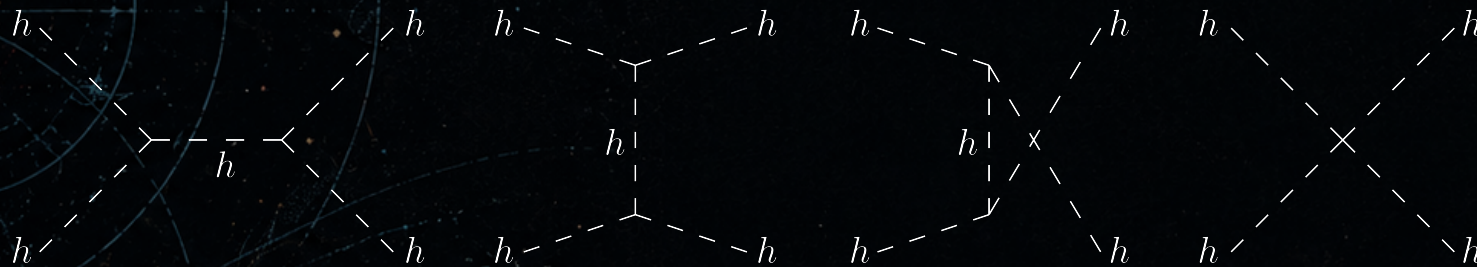
Comments on Perturbative Unitarity

Perturbative Unitarity Constraints

Experiments show limits on (κ_3, κ_4) like:

Including **perturbative unitarity** constraints

From tree-level $hh \rightarrow hh$:



$$\mathcal{M} = -\lambda_3^2 \left(\frac{1}{s - m_h^2} + \frac{1}{t - m_h^2} + \frac{1}{u - m_h^2} \right) - \lambda_4$$

Via matrix element $\mathcal{M} \sim \langle f | T | i \rangle \rightarrow T$, interacting part the **S**-matrix: $S = 1 + iT$, requiring $S^\dagger S = 1$, i.e. unitarity.

All theories must satisfy this: If violated $\Rightarrow$ tree level is **not** a good approximation for $\mathcal{M}$!

$\Rightarrow$ Higher-order contributions to $\mathcal{M}$ can't be neglected $\Rightarrow$ perturbation theory has broken down!

More Perturbative Unitarity Constraints

- What about constraints from **other** scattering processes? e.g. longitudinal gauge boson scattering at high energy:

$$W_L W_L \rightarrow W_L W_L h h, \quad W_L W_L \rightarrow W_L^4, \quad W_L W_L \rightarrow h^4, \dots$$

For these, $\exists$ breakdown energy scale Λ , e.g.:

[Mahmud, Tobioka, 2406.03522, 2501.16439]

$$\left| c_3 - \frac{1}{5} d_4 \right| < \left(\frac{12.3 \text{ TeV}}{\Lambda} \right)^2, \quad |c_3| < \left(\frac{18.9 \text{ TeV}}{\Lambda} \right)^2, \quad \left| c_3 - \frac{1}{3} d_4 \right| < \left(\frac{20.9 \text{ TeV}}{\Lambda} \right)^2, \dots$$

[quintic interaction set to zero]

[In order of most constraining processes.]

[Note: The $\Lambda \rightarrow \infty$ line is a **leading-power** null direction: sub-leading terms become important.]

Note that: for $hh \rightarrow hh$ the result is valid at **all** energy scales.

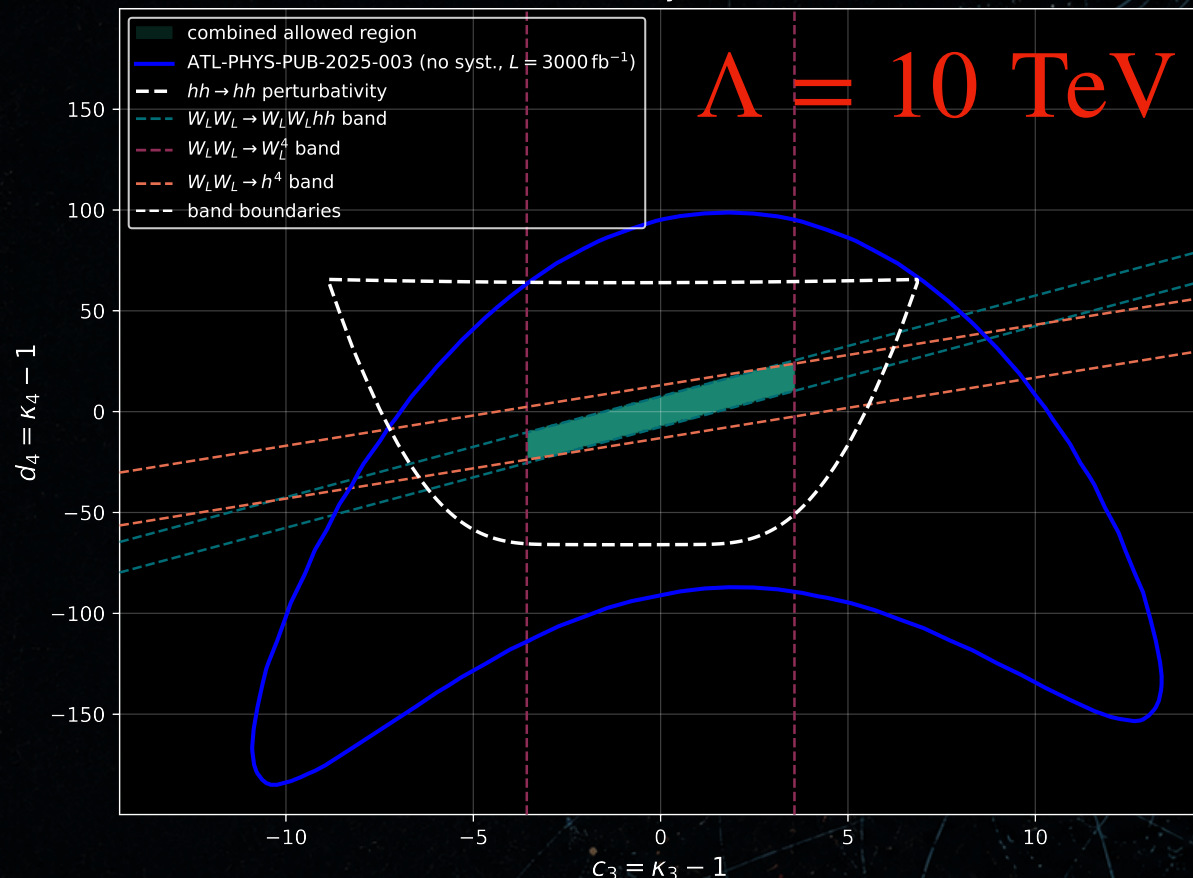
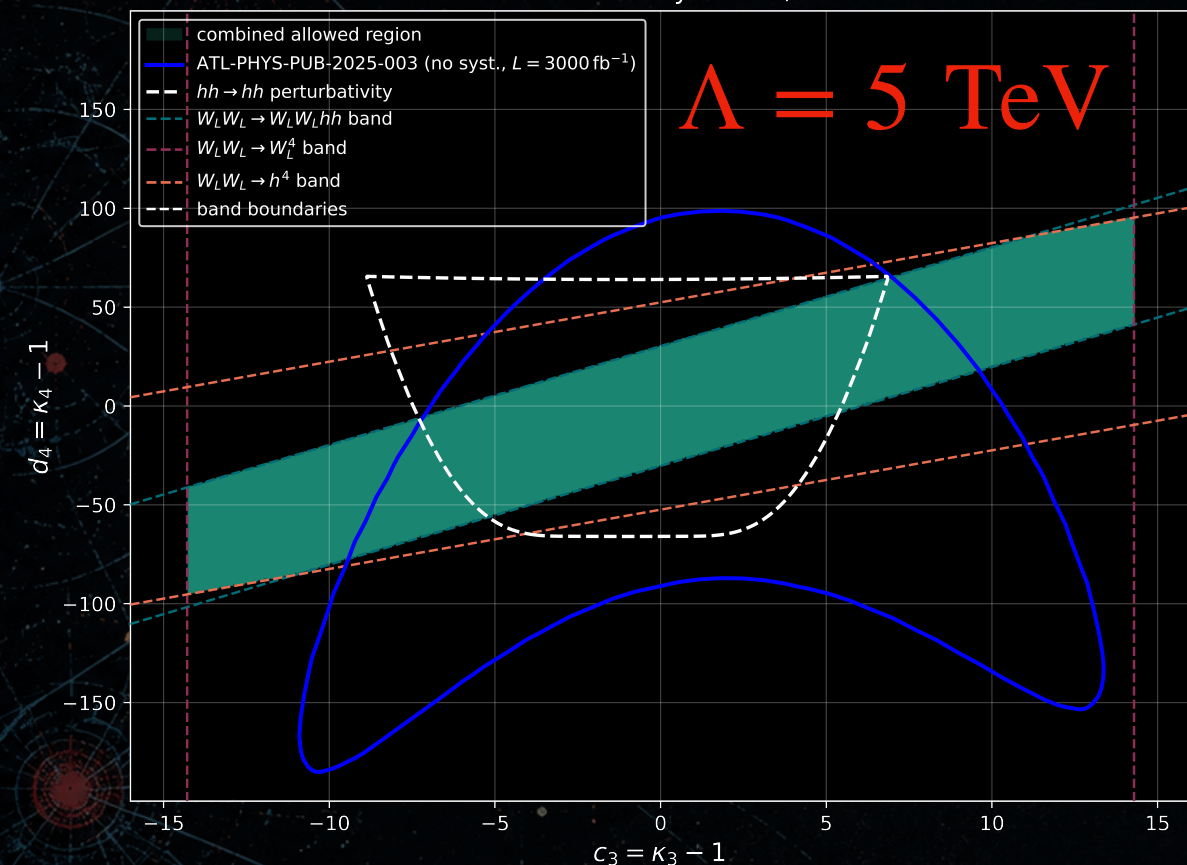
More Perturbative Unitarity Constraints

Using: $W_L W_L \rightarrow W_L W_L h h$, $W_L W_L \rightarrow W_L^4$, $W_L W_L \rightarrow h^4$

[Mahmud, Tobioka, 2406.03522, 2501.16439]

Perturbative-unitarity bands, $\Lambda = 5$ TeV

Perturbative-unitarity bands, $\Lambda = 10$ TeV



Statements on perturbative unitarity should be associated with a breakdown scale Λ !

SECTION 03

B. Searching for Extended Scalar Sectors

Extended Scalar Sectors: **One Singlet Scalar**

A simple extension to SM: add **one** singlet scalar field:

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

Singlet = No SM charges,
 $\Rightarrow$ **No direct $f\bar{f}S$, VVS , ... couplings!**

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



$$+ \blacktriangle |\phi|^2 S + \blacksquare |\phi|^2 S^2 \leftarrow \text{"Portal" interactions.}$$

$$+ S \times (\text{Hidden Sector}) + \dots \leftarrow \text{Dark Matter?}$$

Extended Scalar Sectors: **One Singlet Scalar**

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

(the "xSM")

EWSB $\leftrightarrow$ VEVs:

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

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

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EWSB $\leftrightarrow$ VEVs:

$$\begin{aligned} \phi &\rightarrow \langle \phi \rangle + h \\ S &\rightarrow \langle S \rangle + \chi \end{aligned} \quad \Rightarrow \quad \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} h \\ \chi \end{pmatrix}$$

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θ small:
 h_1 : "SM-like" Higgs boson,
 h_2 : **New** scalar resonance!

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Primary targets for collider studies:

$$h_1 = h \cos \theta + \chi \sin \theta \Rightarrow \text{Reductions in Higgs boson rates.}$$

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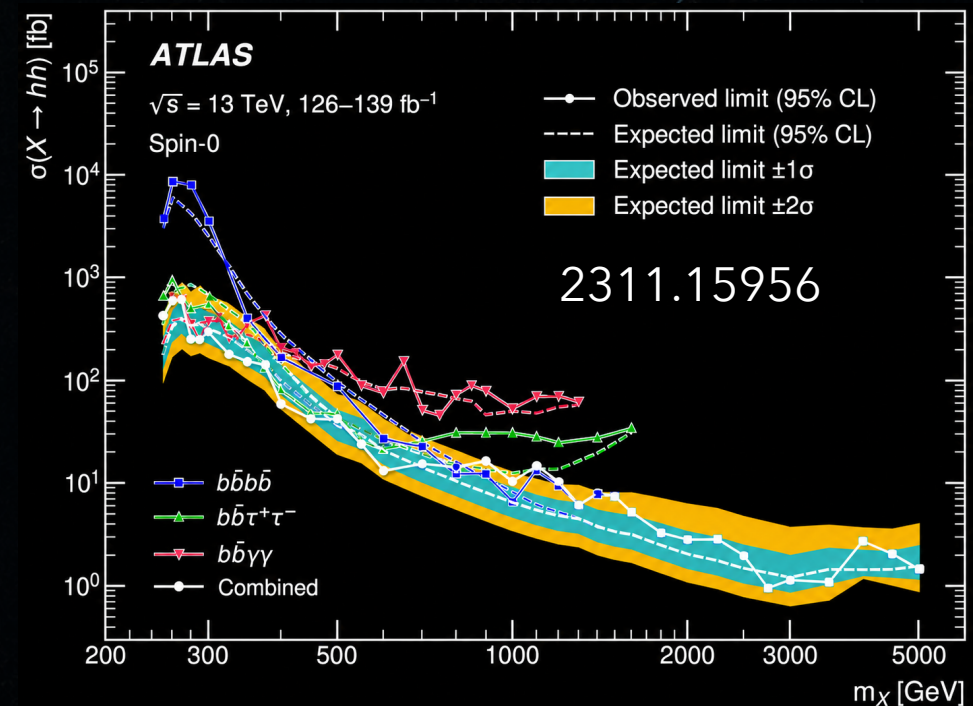
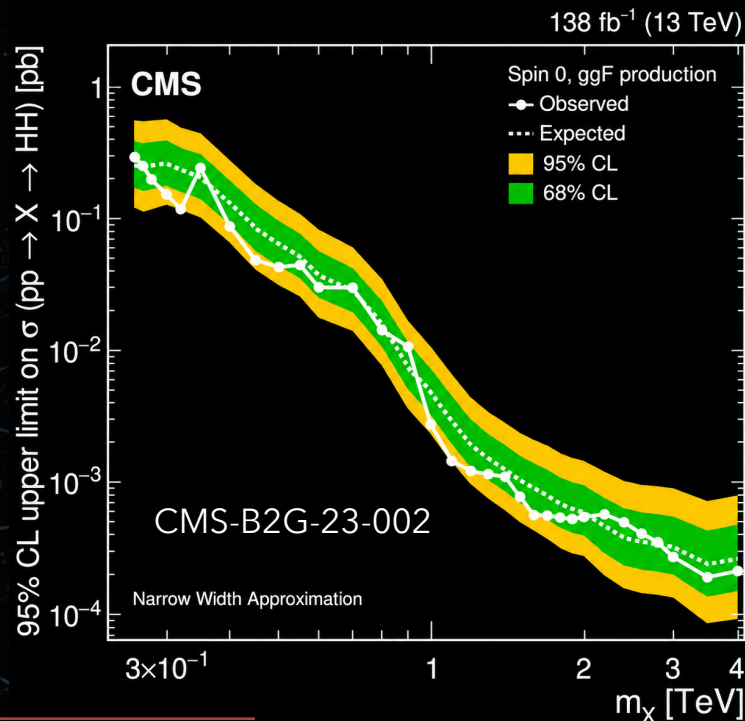
$$h_2 = -h \sin \theta + \chi \cos \theta \Rightarrow \text{New resonances searches, e.g.: } pp \rightarrow h_2 \rightarrow f\bar{f}, VV, h_1 h_1$$

Extended Scalar Sectors: One Singlet Scalar

- Pheno studies, including with **SFO-EWPT** $\rightarrow h_2 \rightarrow ZZ, WW$ and $h_2 \rightarrow h_1 h_1$ **complementary!**

[Kotwal, Ramsey-Musolf, No, Winslow, 1605.06123, **AP**, White, 2010.00597, 2108.11394, ... Many more!]

- Sample of experimental results from $h_2 \rightarrow h_1 h_1$:



Extended Scalar Sectors: **Two Singlet Scalars**

Another extension: add **two** singlet scalar fields + $\mathbb{Z}_2$ symmetries = TRSM:

$$\begin{aligned}\mathcal{V}(\phi, S, X) = & \text{green circle } |\phi|^2 + \text{blue square } |\phi|^4 + \text{red circle } S^2 + \text{cyan square } S^4 + \text{magenta circle } X^2 + \text{brown square } X^4 \\ & + \text{yellow square } S^2 X^2 \\ & + \text{purple square } |\phi|^2 S^2 + \text{teal square } |\phi|^2 X^2\end{aligned}$$

If **no vacuum expectation value** in X direction $\Rightarrow X = \mathbf{Dark Matter?}$

[Karkout, **AP**, Robens, Tetlalmatzi-Xolocotzi, in preparation]

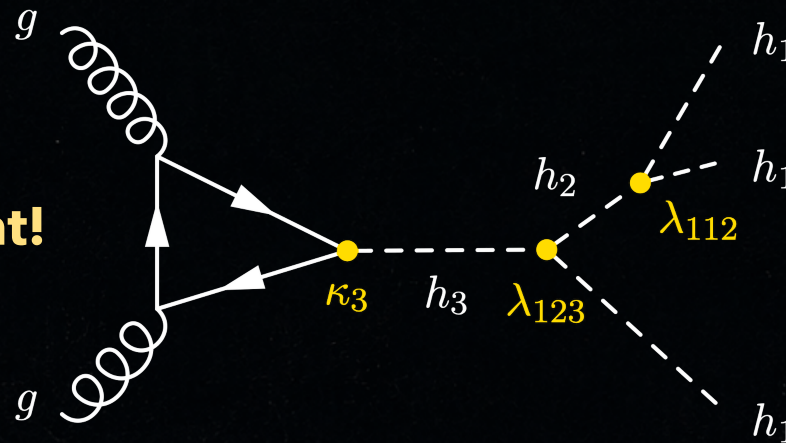
Extended Scalar Sectors: Multi-Scalar Pheno

TRSM $\Rightarrow$ scalar resonances $h_1, h_2, h_3 \Rightarrow$ richer pheno:

$pp \rightarrow h_{2,3} \rightarrow f\bar{f}, VV, h_1 h_1$, **plus** $pp \rightarrow h_1 h_1 h_1$:

double-resonant enhancement!

[Robens, Stefaniak, Wittbrodt, 1908.08554,
AP, Robens, Tetlalmatzi-Xolocotzi, 2101.00037,
Karkout, AP, Postma, Tetlalmatzi-Xolocotzi, van de Vis, du Pree, 2404.12425
AP, Tetlalmatzi-Xolocotzi, 2501.14866]



[ATLAS, 2411.02040]

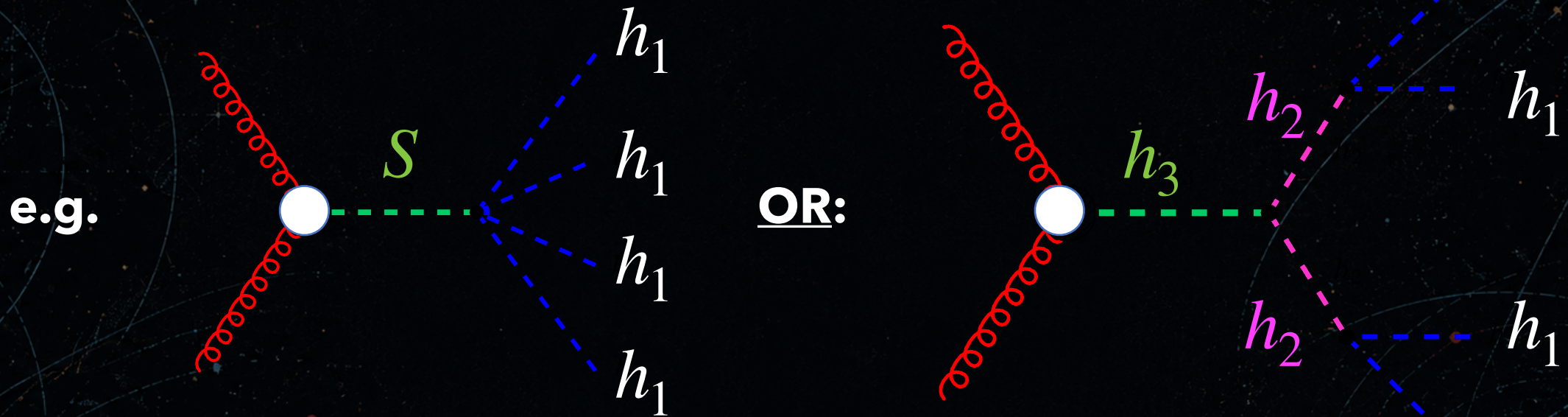
Requires:

$m_3 > m_2 + m_1, m_2 > 2m_1$
and
VEVs for X & S nonzero!

Quadruple Higgs Boson Production in Extended Scalar Sectors

[AP, Tetlalmatzi-Xolocotzi, 2608.16998]

- Rate for **4h** can be large in **extended scalar sectors**:



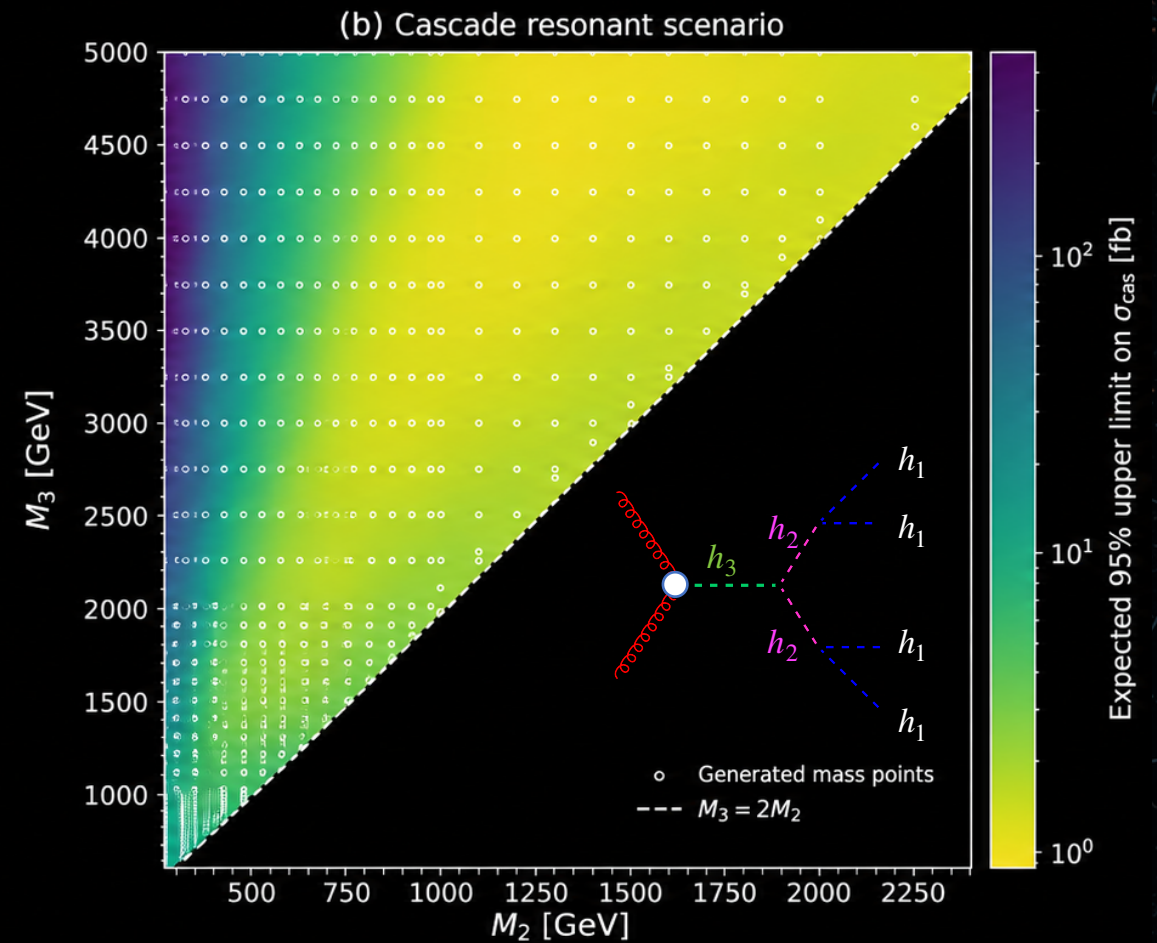
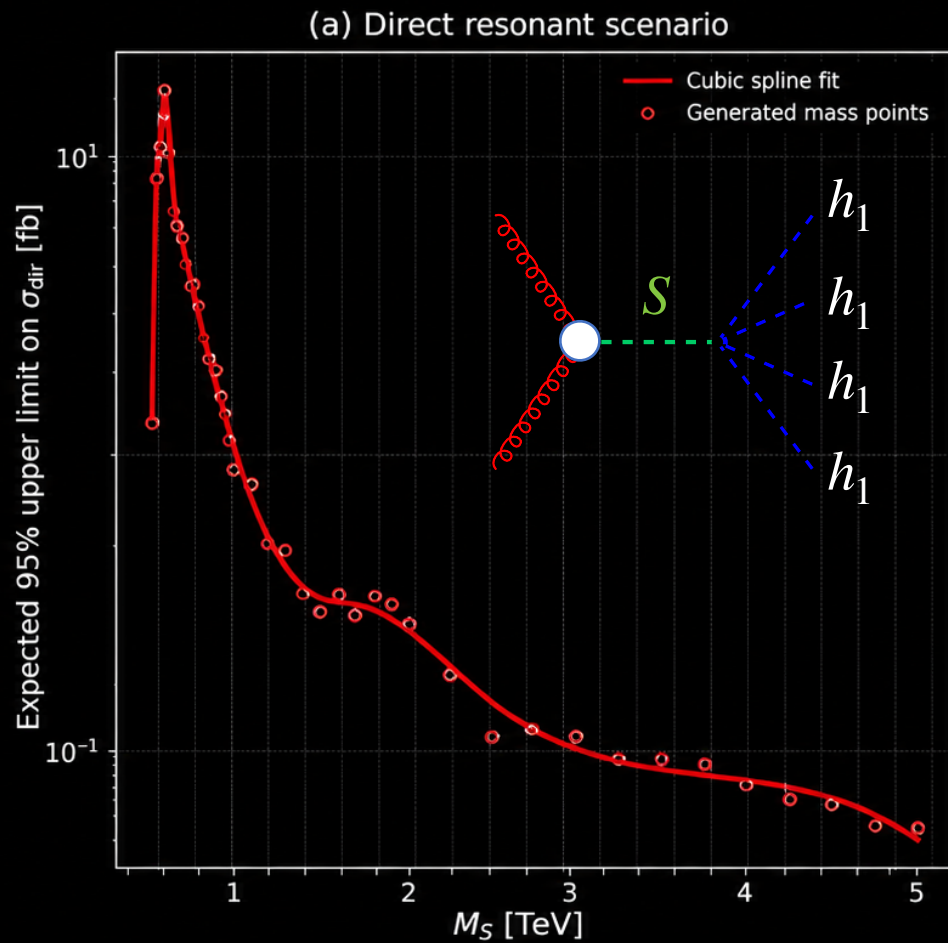
[e.g. Roy, Wagner, 2605.29345]: Through **effective** $ggh_{2,3}$ interactions,

& “**alignment limit**” ($\theta \rightarrow 0$): suppresses gauge boson decays + maintains large scalar couplings.

Quadruple Higgs Boson Production in Extended Scalar Sectors

[AP, Tetlalmatzi-Xolocotzi, 2608.16998]

- Expected constraints at **HL-LHC** through the **8 b-jet** final state:



SECTION 04

Conclusions

Conclusions & Outlook

The Higgs potential (i.e. the self-couplings) is one of the *least* understood SM ingredients.

Observed matter-antimatter asymmetry may be generated during electroweak phase transition $\rightarrow$ if SFO-EWPT $\Rightarrow$ **electroweak baryogenesis!**

$\rightarrow$ Requires **BSM!** This could be an **extended scalar sector**.

Multi-Higgs boson production $\rightarrow$ **Directly** probe self-couplings & extended scalar sectors (that *could* catalyze a SFO-EWPT).

Extremely rare & challenging (fun!) pheno.

HL-LHC: $\sim 50\%$ for κ_3 and $\sim \mathcal{O}(10)$ for κ_4 .

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Thanks!

Questions?

Appendices

(Modern) History of Triple Higgs Boson Pheno

“Interesting” final states + at least 100 events @ 100 TeV @ 30 ab⁻¹

First studies (mostly) at 100 TeV pp!

$hhh \rightarrow$ final state	BR (%)	σ (ab)	$N_{30\text{ab}^{-1}}$
$(b\bar{b})(b\bar{b})(b\bar{b})$	19.21	1110.338	33310
$(b\bar{b})(b\bar{b})(WW_{1\ell})$	7.204	416.41	12492
$(b\bar{b})(b\bar{b})(\tau\bar{\tau})$	6.312	364.853	10945
$(b\bar{b})(\tau\bar{\tau})(WW_{1\ell})$	1.578	91.22	2736
$(b\bar{b})(b\bar{b})(WW_{2\ell})$	0.976	56.417	1692
$(b\bar{b})(WW_{1\ell})(WW_{1\ell})$	0.901	52.055	1561
$(b\bar{b})(\tau\bar{\tau})(\tau\bar{\tau})$	0.691	39.963	1198
$(b\bar{b})(b\bar{b})(ZZ_{2\ell})$	0.331	19.131	573
$(b\bar{b})(WW_{2\ell})(WW_{1\ell})$	0.244	14.105	423
$(b\bar{b})(b\bar{b})(\gamma\gamma)$	0.228	13.162	394
$(b\bar{b})(\tau\bar{\tau})(WW_{2\ell})$	0.214	12.359	370
$(\tau\bar{\tau})(WW_{1\ell})(WW_{1\ell})$	0.099	5.702	171
$(\tau\bar{\tau})(\tau\bar{\tau})(WW_{1\ell})$	0.086	4.996	149
$(b\bar{b})(ZZ_{2\ell})(WW_{1\ell})$	0.083	4.783	143
$(b\bar{b})(\tau\bar{\tau})(ZZ_{2\ell})$	0.073	4.191	125

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[AP, Sakurai, **1508.06524**, Chen, Yan, Zhao, Zhao, Zhong, **1510.04013**, Fuks, Kim, Lee, **1510.07697**, ...]

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[Fuks, Kim, Lee, **1510.07697**, Fuks, Kim, Lee, **1704.04298**]

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$(bb)(bb)(\gamma\gamma)$	0.228	13.162	394
$(bb)(\tau\bar{\tau})(WW_{2\ell})$	0.214	12.359	370
$(\tau\bar{\tau})(WW_{1\ell})(WW_{1\ell})$	0.099	5.702	171
$(\tau\bar{\tau})(\tau\bar{\tau})(WW_{1\ell})$	0.086	4.996	149
$(bb)(ZZ_{2\ell})(WW_{1\ell})$	0.083	4.783	143
$(bb)(\tau\bar{\tau})(ZZ_{2\ell})$	0.073	4.191	125

First studies (mostly) at 100 TeV pp!

[AP, Tetlalmatzi-Xolocotzi, Zaro, **1909.09166**, AP, Robens, Tetlalmatzi-Xolocotzi, **2101.0037**, Stylianou, Weiglein, **2312.04646**, AP, Tetlalmatzi-Xolocotzi, **2312.13562**, Fuks, AP, Tetlalmatzi-Xolocotzi, **2509.16364**]

[Fuks, Kim, Lee, **1510.07697**, Fuks, Kim, Lee, **1704.04298**]

[AP, Sakurai, **1508.06524**, Chen, Yan, Zhao, Zhao, Zhong, **1510.04013**, Fuks, Kim, Lee, **1510.07697**, ...]

(Modern) History of Triple Higgs Boson Pheno

"Interesting" final states + at least 100 events @ 100 TeV @ 30 ab⁻¹

$hhh \rightarrow$ final state	BR (%)	σ (ab)	$N_{30\text{ab}^{-1}}$
$(bb)(bb)(bb)$	19.21	1110.338	33310
$(bb)(bb)(WW_{1\ell})$	7.204	416.41	12492
$(bb)(bb)(\tau\bar{\tau})$	6.312	364.853	10945
$(bb)(\tau\bar{\tau})(WW_{1\ell})$	1.578	91.22	2736
$(b\bar{b})(b\bar{b})(WW_{2\ell})$	0.976	56.417	1692
$(bb)(WW_{1\ell})(WW_{1\ell})$	0.901	52.055	1561
$(bb)(\tau\bar{\tau})(\tau\bar{\tau})$	0.691	39.963	1198
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[Kilian, Sun, Yan, Zhao, Zhao, **1702.03554**]

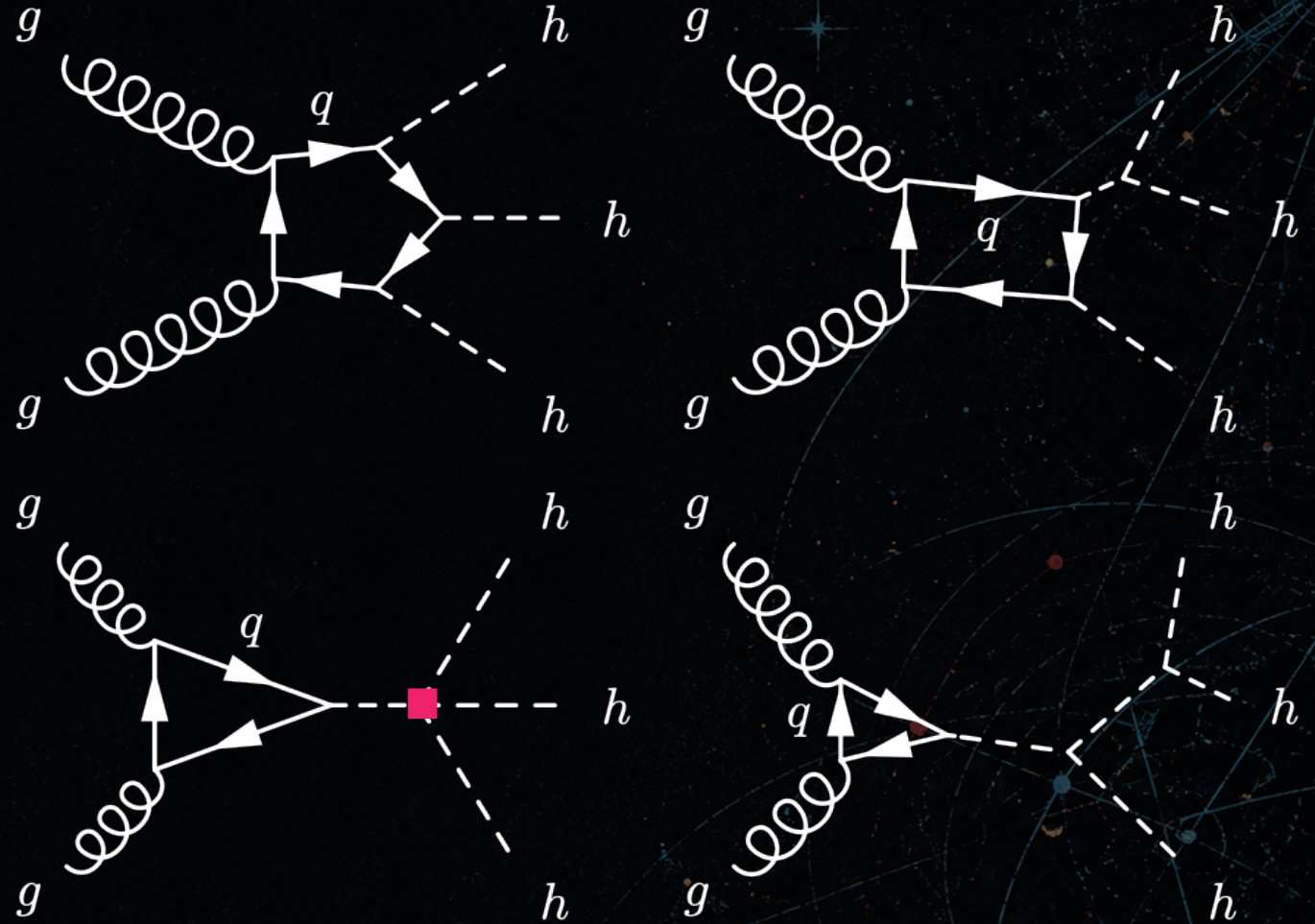
[Stylianou, Weiglein, **2312.04646**, Dong, Sun, Goo, Zhang, Li, Wang, **2504.04037**]

[**AP**, Sakurai, **1508.06524**, Chen, Yan, Zhao, Zhao, Zhong, **1510.04013**, Fuks, Kim, Lee, **1510.07697**, ...]

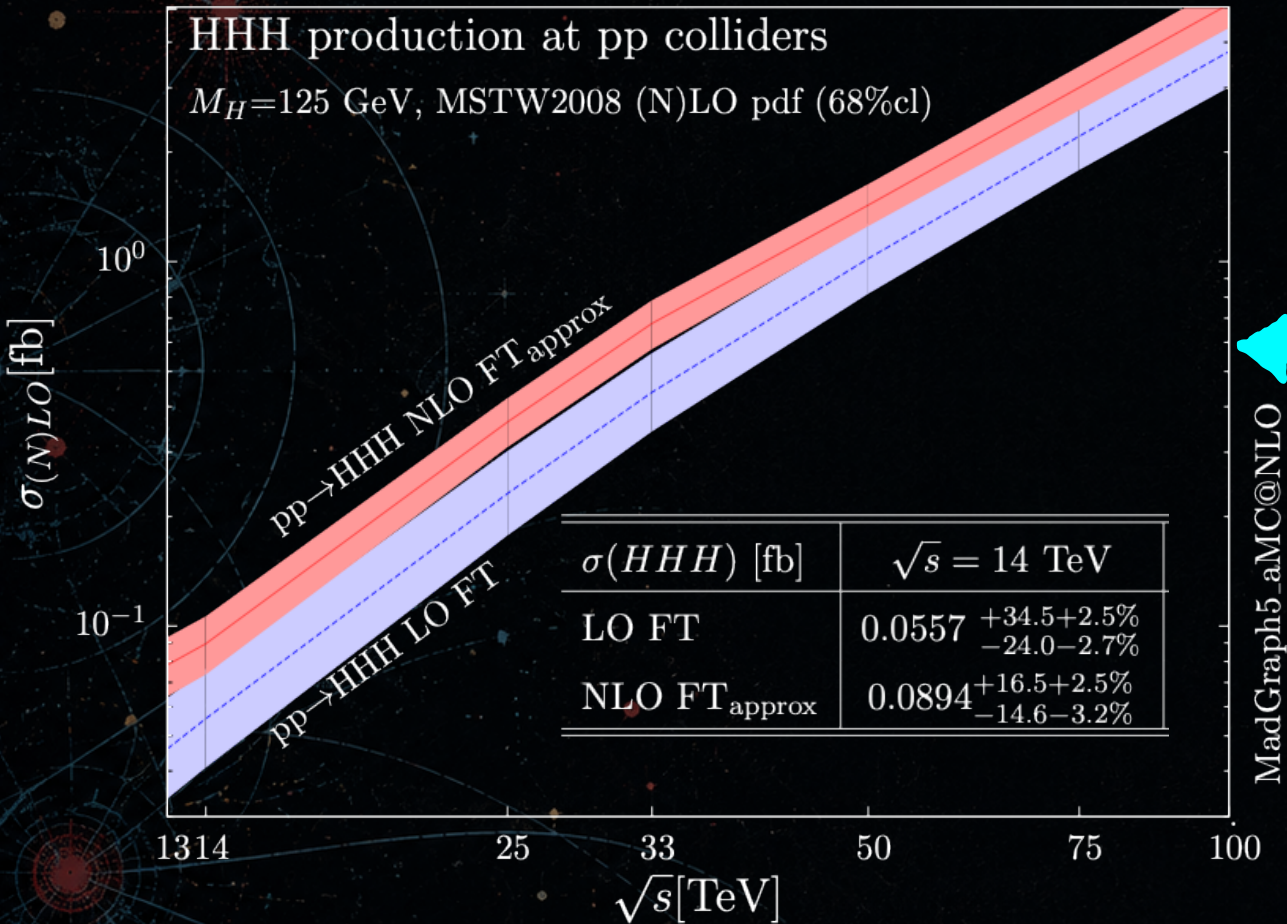
The $pp \rightarrow hhh$ Cross Section

At **LO** in SM: Loop-induced!

$$\sigma_{\text{SM}}^{\text{LO}}(14 \text{ TeV}) \sim 0.05 \text{ fb}$$

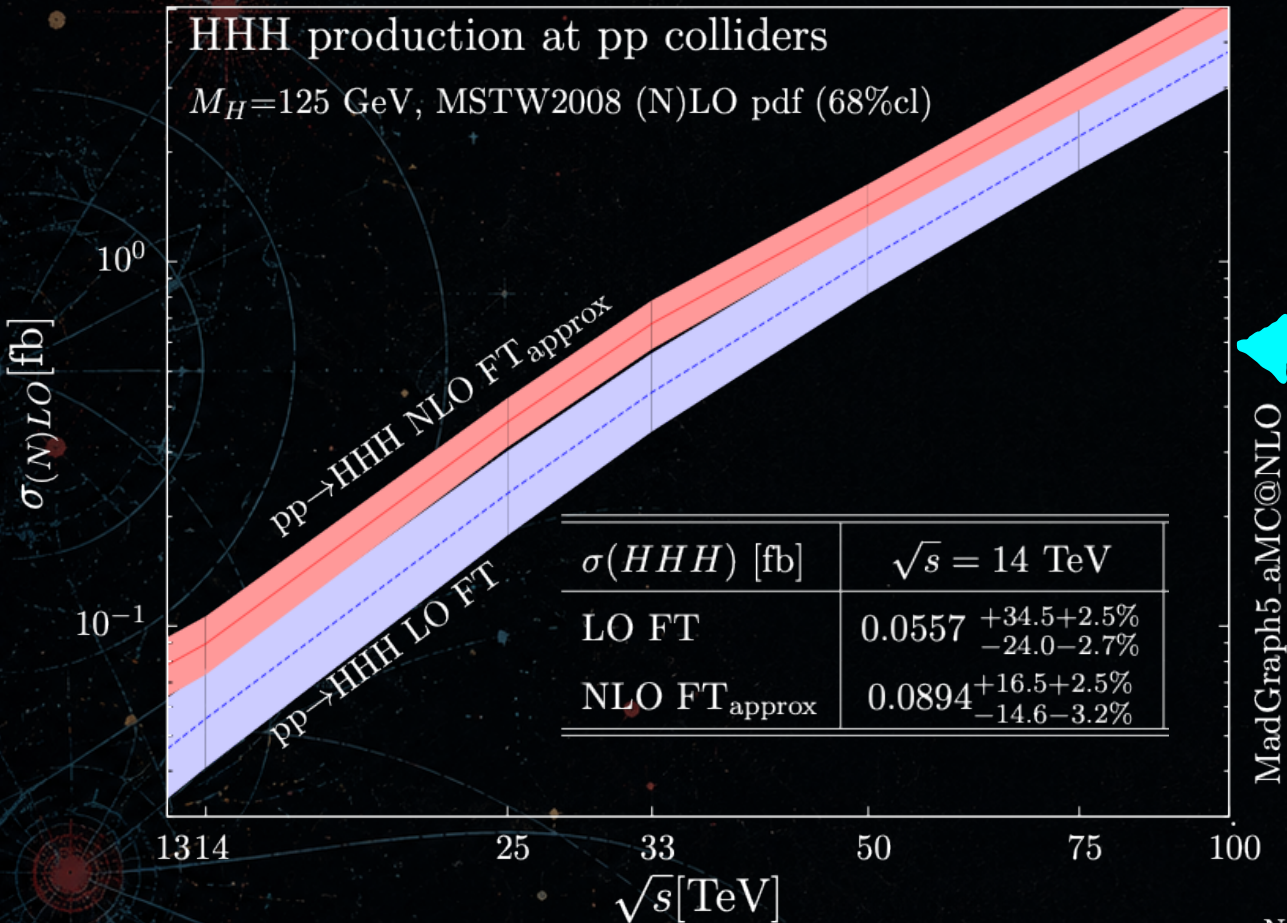


$pp \rightarrow hhh$ @ Higher Orders



NLO: [Maltoni, Vryonidou, Zaro, **1408.6542**] $\rightarrow m_t \rightarrow \infty$ plus full real emission (= **FT_{approx}**).

$pp \rightarrow hhh$ @ Higher Orders

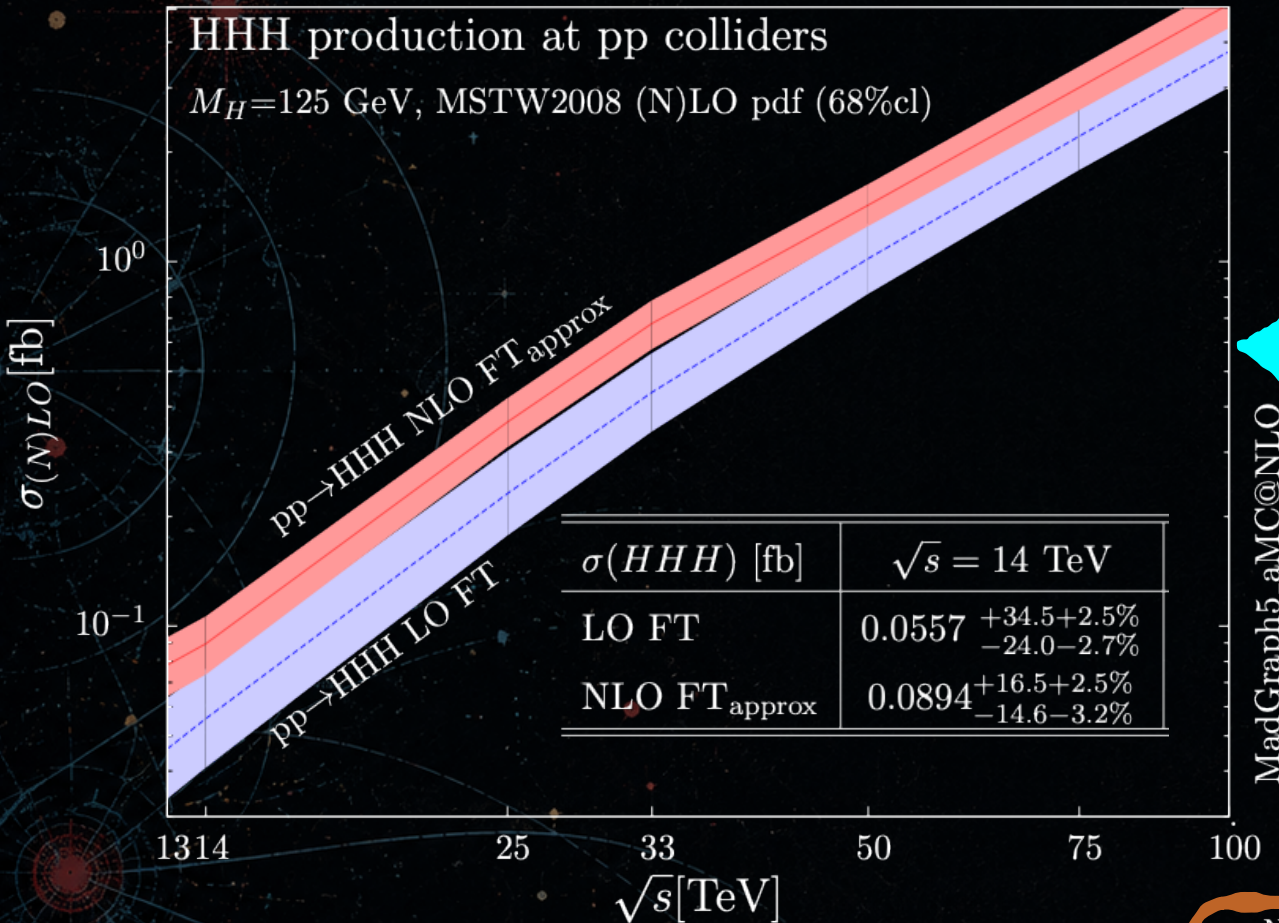


NLO: [Maltoni, Vryonidou, Zaro, **1408.6542**] $\rightarrow m_t \rightarrow \infty$ plus full real emission (= FT_{approx}).

NNLO: [De Florian, Fabre, Mazzitelli, **1912.02760**] $\rightarrow$ Full NNLO in $m_t \rightarrow \infty$, "Born-Improved" $\Rightarrow \sim 10\%$ increase wrt. NLO.

$$\sigma_{\text{Best}}^{\text{NNLO}} = 0.103^{+5\%}_{-8\%} \pm 15\% \text{ fb}, \quad K_{\text{Best}}^{\text{NNLO}} = 1.70, \quad (14 \text{ TeV})$$

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Attack of the Anomalous Couplings

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

$$\mathcal{V}(h) \supset \underbrace{(1+c_3)}_{\kappa_3} \frac{m_h^2}{2v} h^3 + \underbrace{(1+d_4)}_{\kappa_4} \frac{m_h^2}{8v^2} h^4$$

⇒ **hhh** cross section as ratio to SM (highest-to-lowest coefficient):

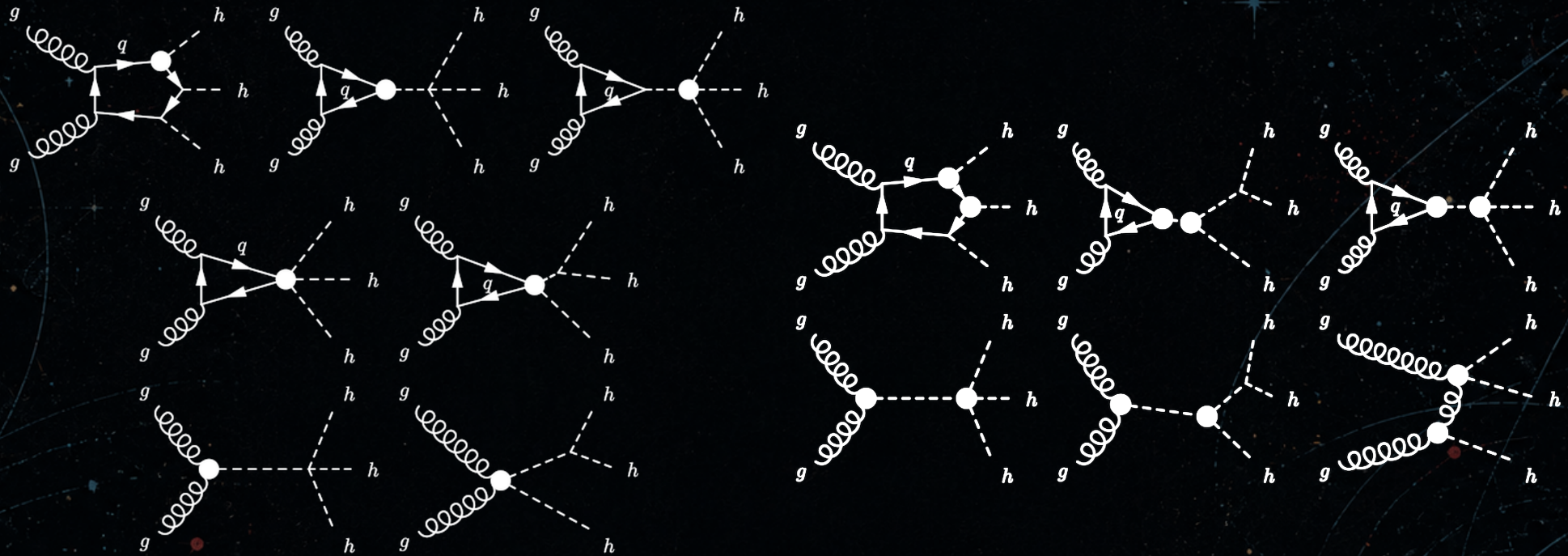
$$\begin{aligned} \sigma/\sigma_{\text{SM}}(13.6 \text{ TeV}) - 1 \approx & 0.922c_3^2 - 0.828c_3 - 0.277c_3^3 \\ & - 0.178c_3d_4 - 0.0993d_4 + 0.0510c_3^2d_4 \\ & - 0.0393c_3^4 + 0.0174d_4^2 \end{aligned}$$

⇒ Not very sensitive to the quartic!

Return of the Anomalous Couplings

Additional anomalous interactions can also be considered, e.g. $t\bar{t}h^2$, $t\bar{t}h^3$, ggh^2 ...:

SM +



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

Includes description of interference effects.

[AP, Tetlalmatzi-Xolocotzi, 2312.13562]

Future Self-Coupling Constraints

Collider:	HL-LHC	FCC-ee	FCC-hh	Muon Coll.
k_3	$\sim 50 \%$	$\sim 20 - 30 \%$	$\sim 5\%$	$5 - 30 \%$
k_4	$\mathcal{O}(10 - 100)$ [ATL-PHYS-PUB-2025-003, ATL-PHYS-PUB-2025-018 CMS-HIG-25-002]	???	$\mathcal{O}(1 - 10)$ [Fuks, AP , Tetlalmatzi- Xolocotzi, 2509.16364]	$50 - 100 \%$ [Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao, 2003.13628]

Quadruple Higgs Boson Production (!?)

- **Main background:** $gg \rightarrow 8b$ jets $\Rightarrow$ **Extremely** challenging to generate events $\Rightarrow$ Sherpa LHE + Herwig 7.

Simple **smearing** for jets applied (see e.g. [Fuks, AP, Tetalmatzi-Xolocotzi, 2509.16364]).

Pair 8 b-jets into four Higgs candidates and minimize:

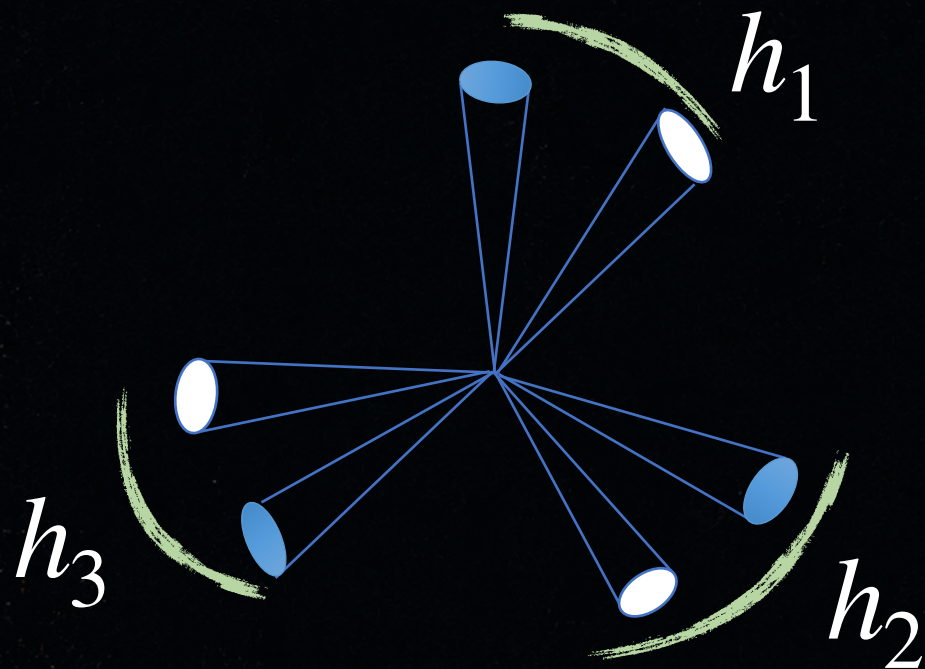
$$\chi_8^2(P) = \sum_{k=1}^4 \left(m_{h,k}(P) - m_{h,k}^{\text{target}} \right)^2 \quad \text{with:} \quad (m_{h,1}^{\text{target}}, m_{h,2}^{\text{target}}, m_{h,3}^{\text{target}}, m_{h,4}^{\text{target}}) = (120, 115, 110, 105) \text{ GeV}.$$

XGBoost analysis on a complete set of observables.

Poisson limited, with very low numbers of events! $\Rightarrow B \sim \mathcal{O}(0.1)$ expected events for $gg \rightarrow 8b$ jets!

Charging Up Multi-Higgs Boson Production

6 b-jets: if charge is unknown $\rightarrow$ **15** combinations of 6 b-jets into pairs.



$hh \rightarrow 4b$ jets: **3** combos

$hhhh \rightarrow 8b$ jets: **105 (!)**

Jet-charge tagging reduces the amount of combinations: e.g. CMS DP-2025/07
 $\rightarrow$ **70%** accuracy on b-jets (= **30%** mis-id).

[see e.g. talk by M. Stamenkovic @ HIGGS 2025]

Perturbative Unitarity Constraints @ NLO?

- Calculate perturbative unitarity at **one loop**, in Higgs Effective Field Theory:

Already available for: $W_L W_L \rightarrow W_L W_L$, $W_L W_L \rightarrow hh$, $hh \rightarrow hh$. [Asáin, Espriu, Mescia, 2109.02673], 2301.13030]

More **model dependent** than tree-level:

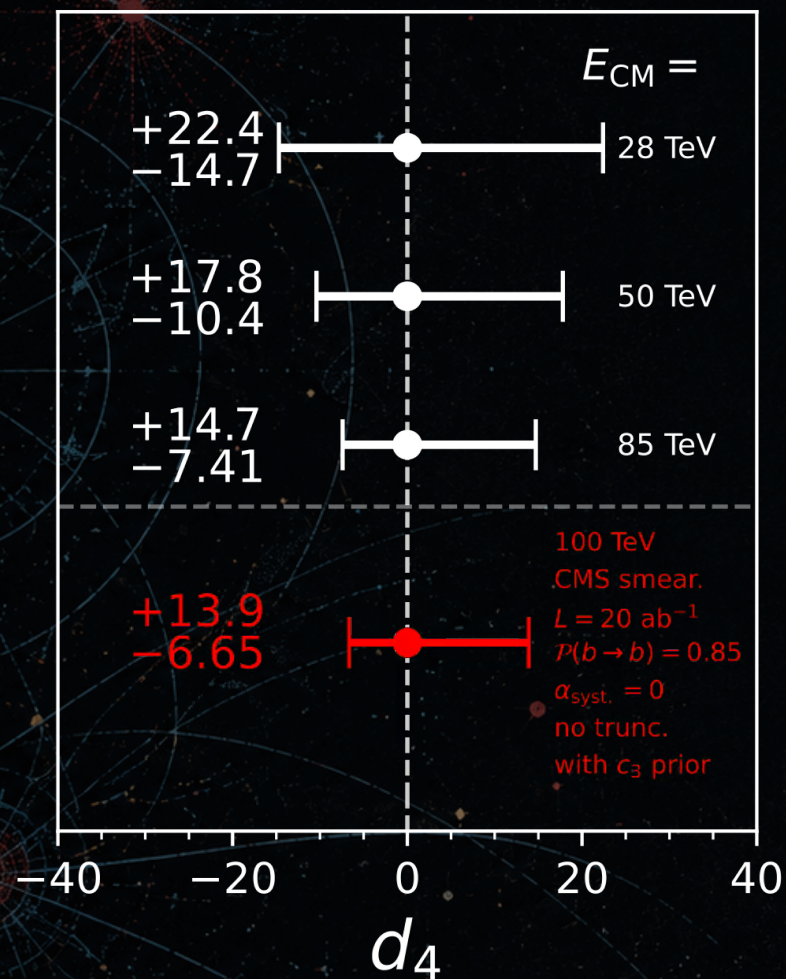
e.g. @ one loop $hh \rightarrow hh$: κ_3, κ_4 **not** sufficient: e.g. need derivative operator $\frac{\gamma}{v^4}(\partial_\mu h \partial^\mu h)^2$!

Also:

- **Massless** formulas for $hh \rightarrow hh$ are insufficient (no κ_3, κ_4 dependence).
- They set $g' = 0$ (neglect e/m) & assume exact custodial symmetry.
- Calculation is in bosonic HEFT (no top quarks).

Quartic @ Hadron Colliders @ Higher Energies

Results Summary : CM Energy



Analysis of **6 b-jet** final state

[Fuks, **AP**, Tetalmatzi-Xolocotzi, **2509.16364**]

pp collider **energy** variation
(85 $\rightarrow$ 50 $\rightarrow$ 28 TeV)

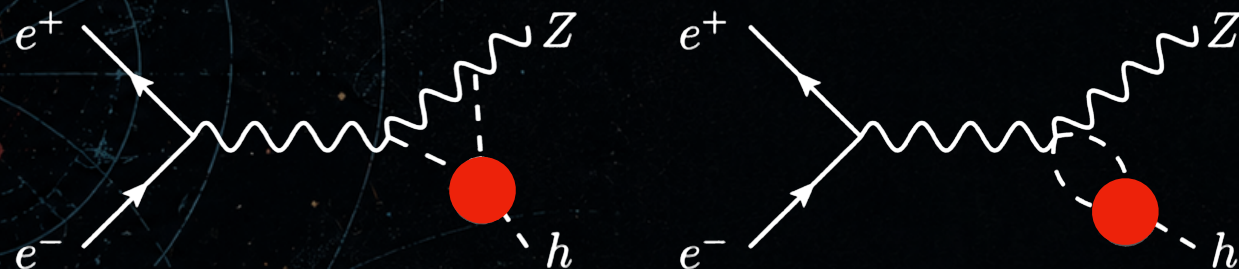
hhh 100 TeV/20 ab^{-1} +
combination with future trilinear
constraint,
assuming: $\delta c_3 = 5\%$

Note: $1 + d_4 = \kappa_4$

Trilinear @ Other Colliders

FCC-ee @ 240 GeV/365 GeV:

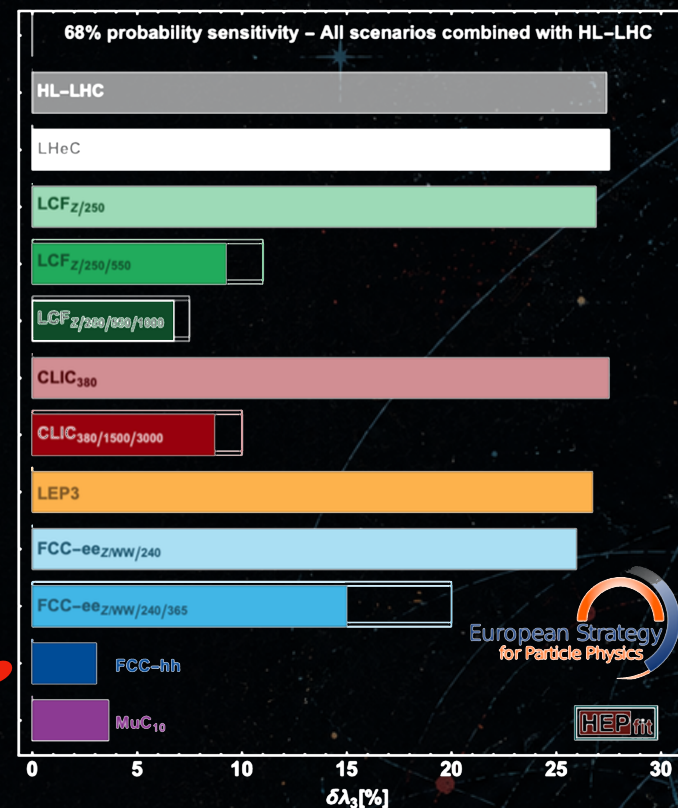
⇒ not enough for hhZ → use loop diagrams:



$$\delta(\kappa_3) \sim 28 \%$$

$$\delta(\kappa_3) \sim 18 \% \text{ (HL-LHC combo)}$$

FCC-hh (compared to others):



$$\delta(\kappa_3) = 3.2\% - 5.4 \% @ 84 \text{ TeV}$$

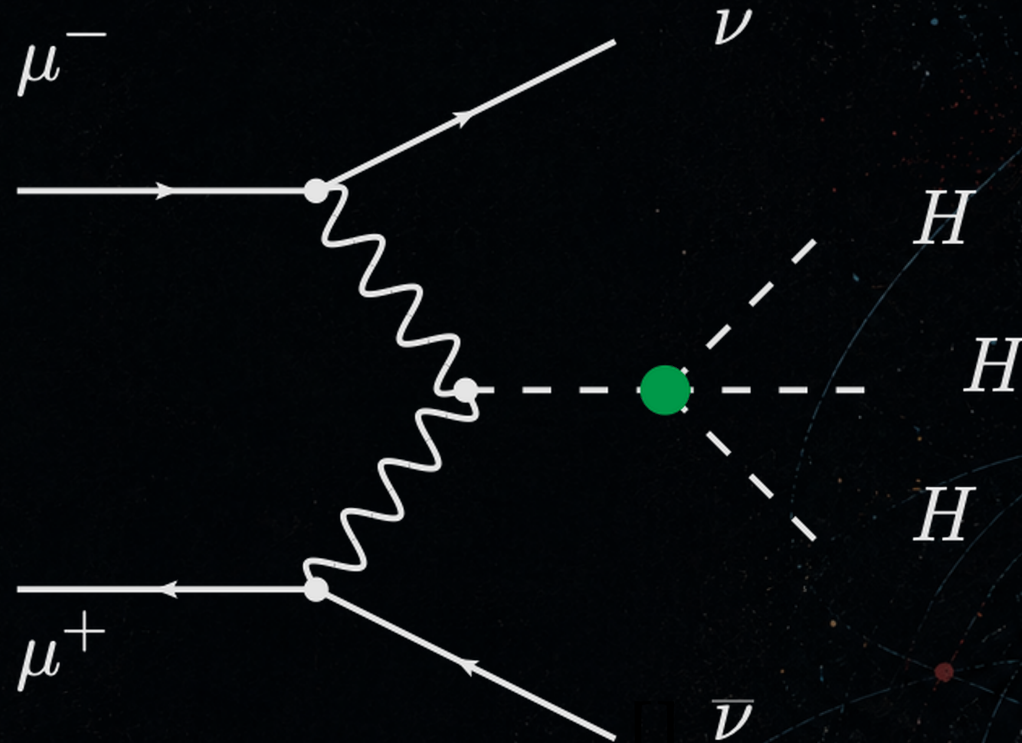
$$\delta(\kappa_3) = 2.8\% - 4.8 \% @ 100 \text{ TeV}$$

Quartic @ Lepton Colliders

FCC-ee: insufficient energy for **Zhh or $Zhhh$** production & constraints for k_4 very weak in **Zh** .

Muon Collider, through VBF:

[Haisch, Sankar, Zanderighi, **2505.20463**]



e.g. for $\sqrt{s} = 14$ TeV, 33 ab^{-1} : $\kappa_4 \sim [0.65, 1.55]$

[Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao, **2003.13628**]

Quadruple Higgs Boson Production (!?)

[AP, Tetlalmatzi-Xolocotzi, 2608.16998]

Cross-section fits (14 TeV):

$$\begin{aligned}\sigma(gg \rightarrow hhh)/\sigma_{\text{SM}}(14 \text{ TeV}) - 1 \approx & 0.881c_3^2 - 0.872c_3 - 0.261c_3^3 \\ & - 0.168c_3d_4 - 0.0934d_4 + 0.0490c_3^2d_4 \\ & + 0.0397c_3^4 + 0.0170d_4^2\end{aligned}$$

$$\begin{aligned}\sigma(gg \rightarrow hhhh)/\sigma_{\text{SM}}(14 \text{ TeV}) - 1 \approx & 0.549c_3^2 + 0.0992c_3^4 + 0.0799c_3^3 \\ & + 0.0327c_3 - 0.0184c_3^5 + 0.00329c_3^6 \\ & - 0.360d_4 - 0.107c_3d_4 - 0.104c_3^2d_4 \\ & - 0.0368c_3^3d_4 + 0.0130c_3^4d_4 \\ & + 0.0412d_4^2 + 0.00294c_3d_4^2 + 0.0141c_3^2d_4^2\end{aligned}$$

For $d_4 \sim 70$,
enhancement is ~ 200
(=100-200 events @
3000 fb⁻¹)

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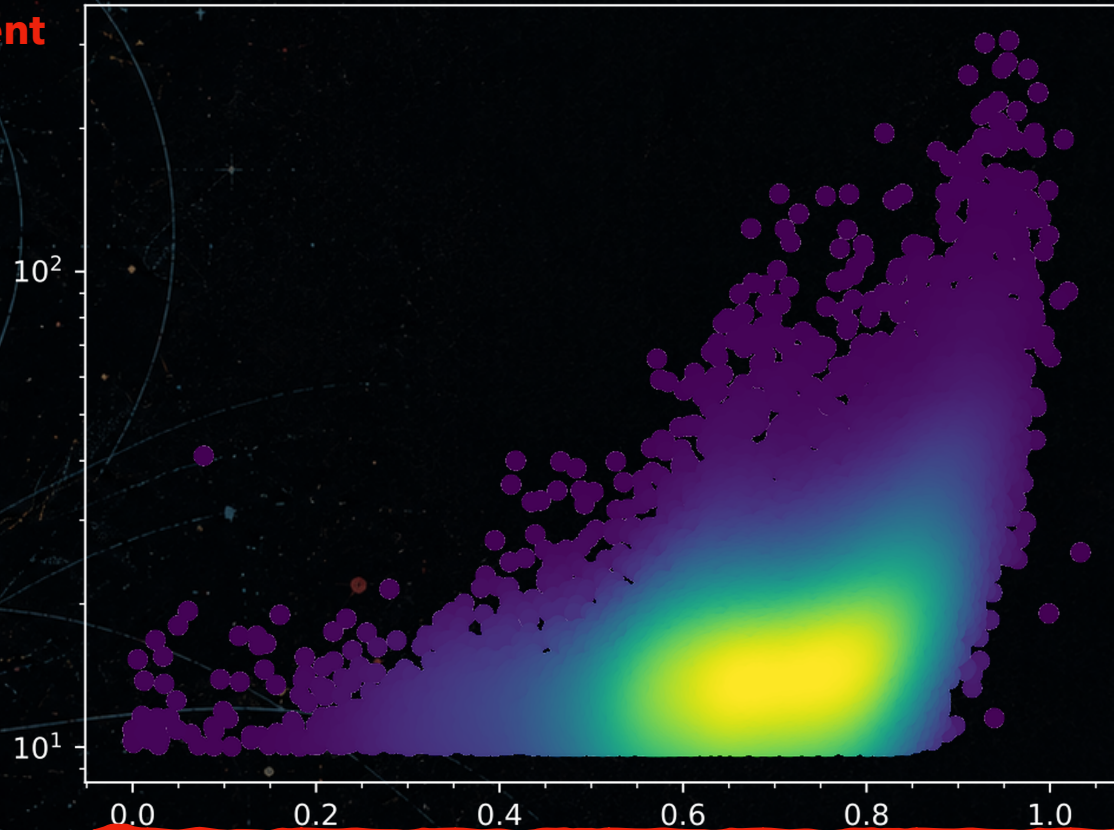
Extended Scalar Sectors: Multi-scalar Pheno

Enhancement of hhh $\Leftrightarrow$ Large "fraction" of double-resonant process!

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

Enhancement
over SM

$\frac{\sigma}{\sigma_{\text{SM}}}(pp \rightarrow hhh)$ @13.6 TeV



fraction from resonant: $pp \rightarrow h_3 \rightarrow h_2 h_1 \rightarrow h_1 h_1 h_1$

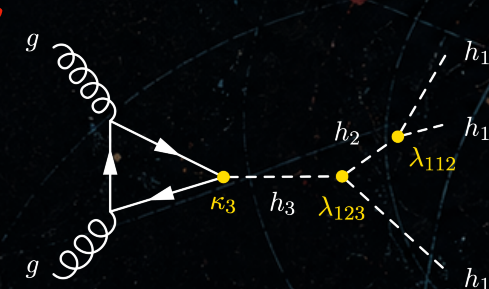
[Karkout, AP, Postma, Tetlalmatzi-Xolocotzi, van de Vis, du Pree, 2404.12425]

TRSM parameter-space scan:

Including boundedness of potential +
perturbativity + **HiggsTools** constraints.

Resonant Fraction (R.F.) =

How much of the total cross section comes from... ?



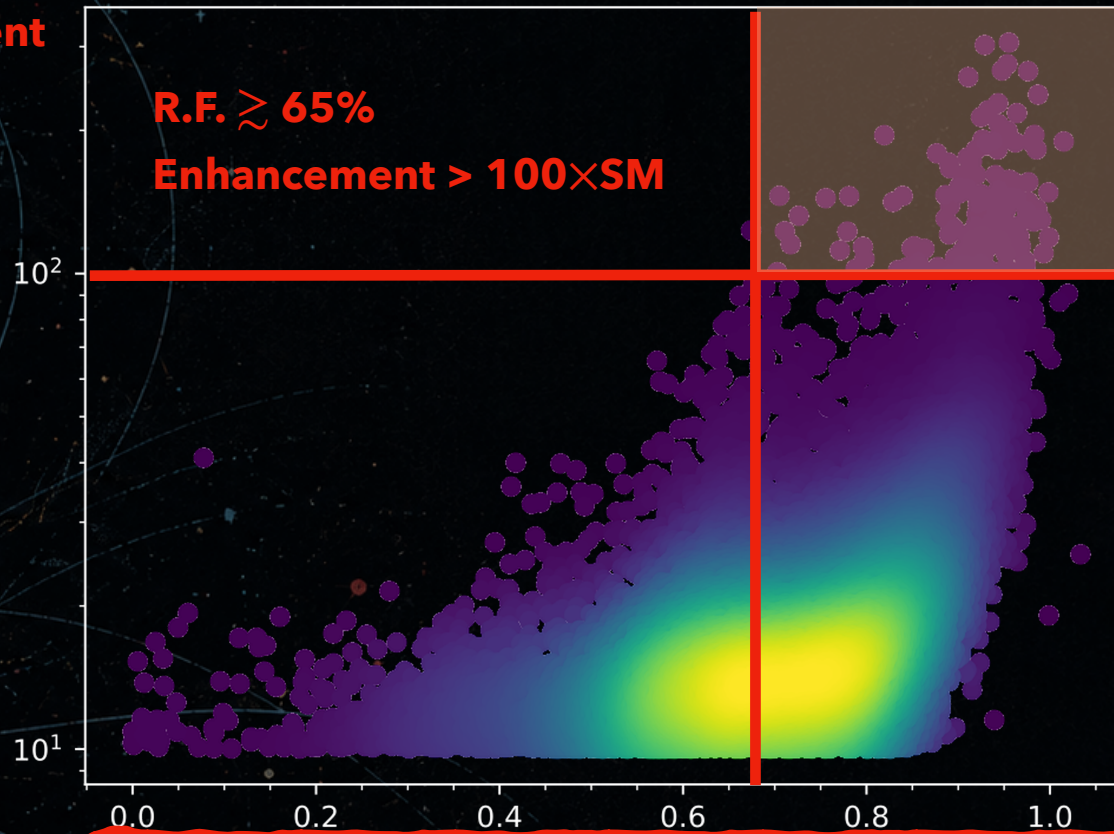
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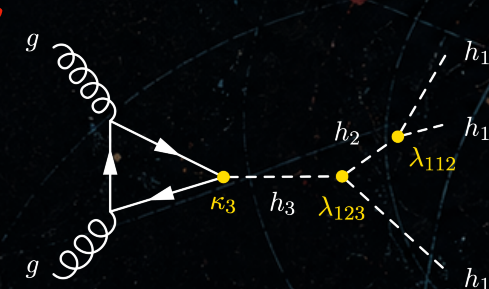
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Extended Scalar Sectors: Double-Resonant hhh

Already being searched for in ATLAS $pp \rightarrow hhh \rightarrow 6b$ jets:

