Sum rules for extended electroweak symmetry breaking sectors

Ryo Nagai (Tohoku U.)

[1] **RN**, M. Tanabashi, and K. Tsumura PRD 91 034030
[2] **RN** and T. Abe PRD 95 075022

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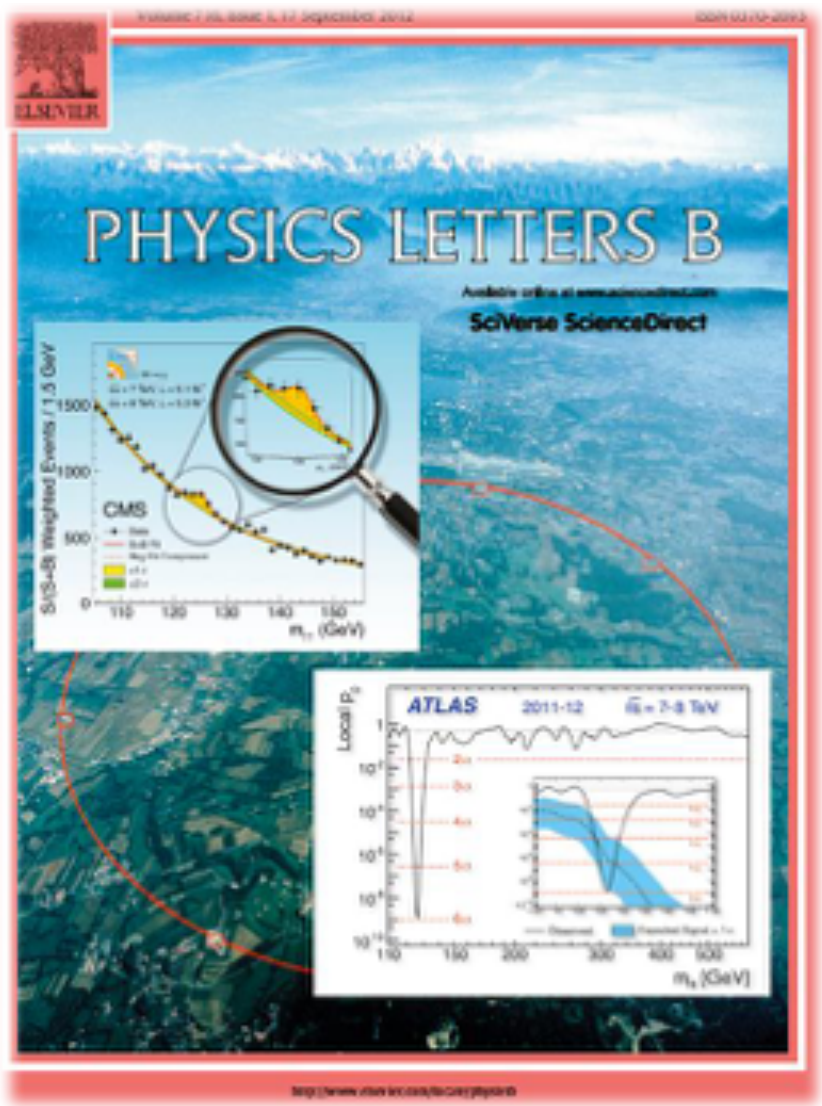
We found the h(125) !

- The 125GeV Higgs boson was discovered at the LHC.



Beyond the SM ?

- We now confirm the existence of all particles predicted from the standard model (SM).

- However, we believe the SM is NOT complete yet.

Why is the EM scale around 100GeV ??

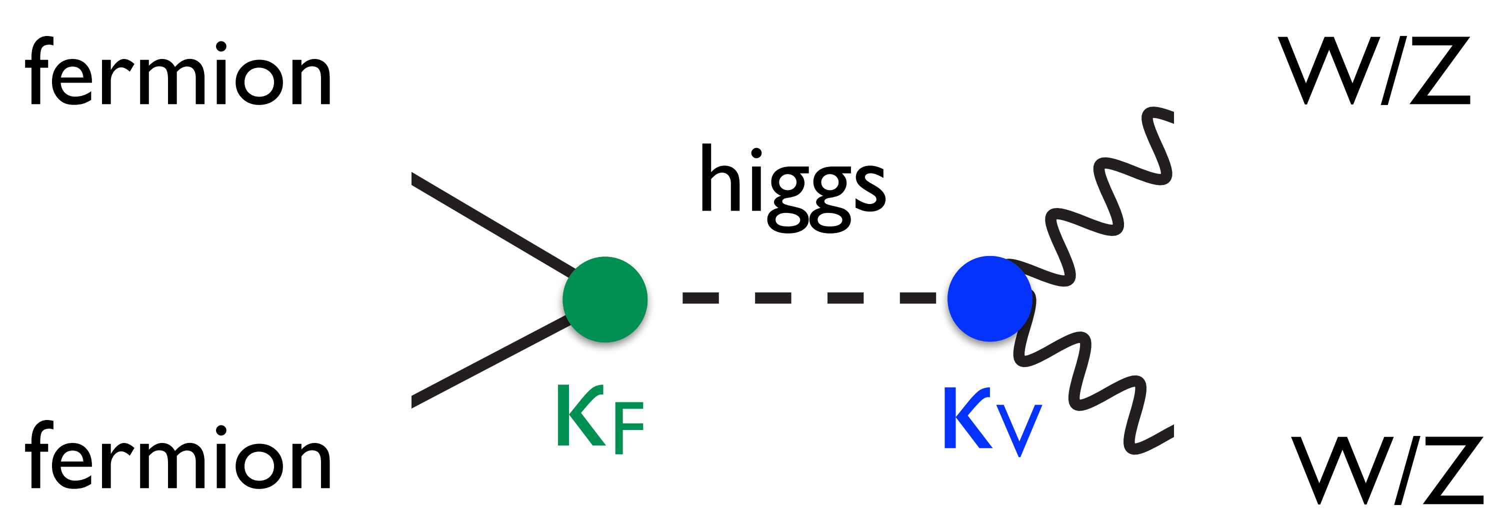
What is an origin of dark matter ??

….

- We expect the SM should be embedded in a larger theory.

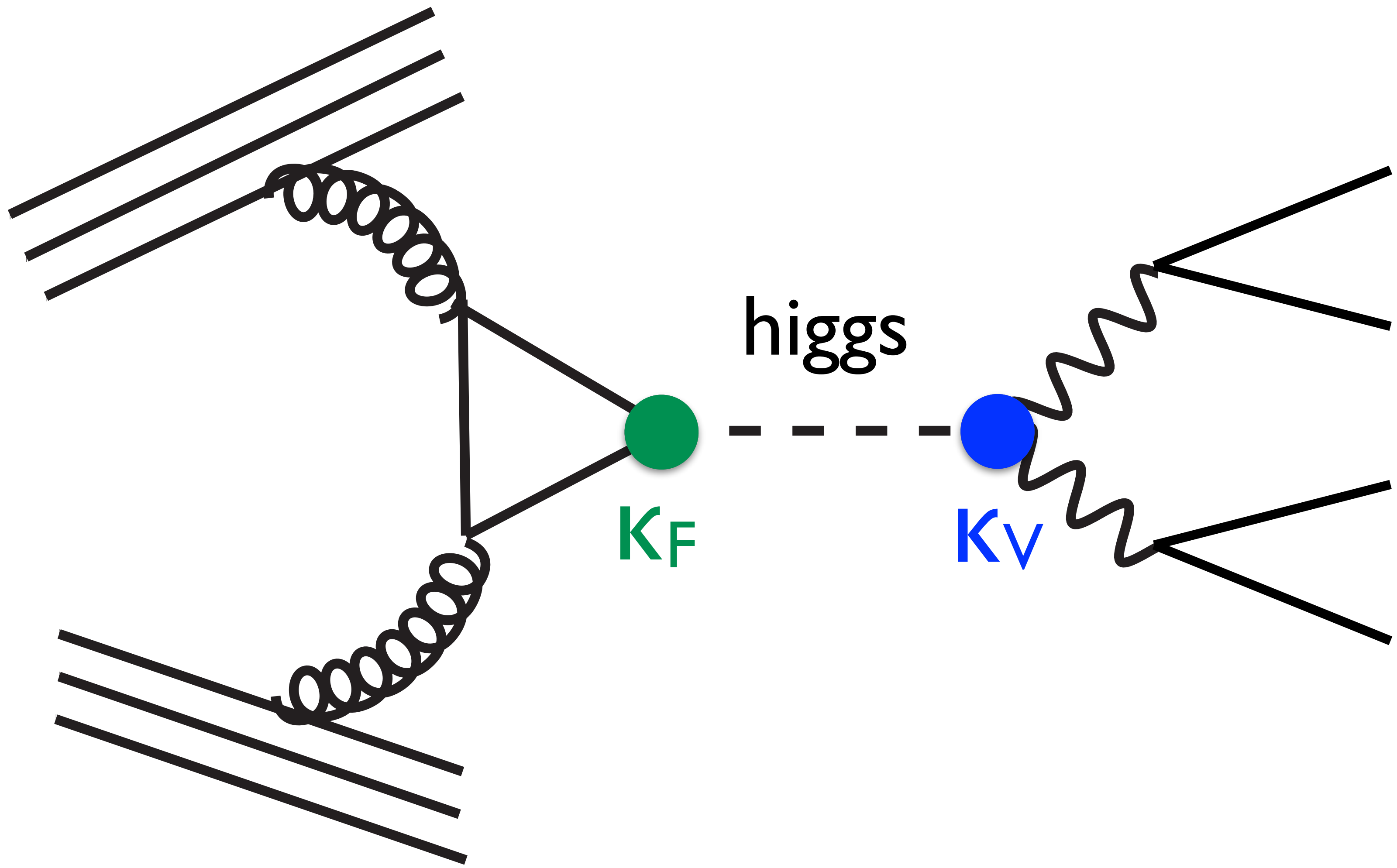
Beyond the SM ?

- What happens if the EWSB sector is extended ?



Beyond the SM ?

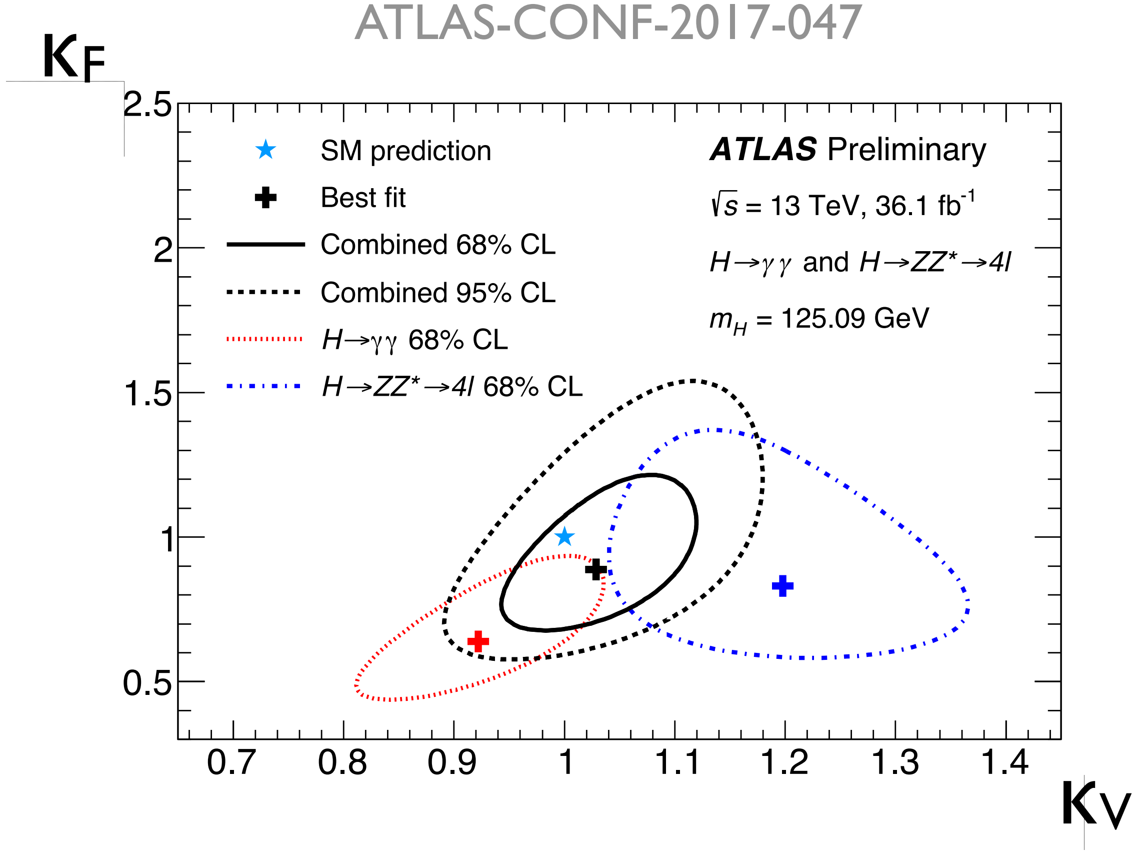
- Higgs coupling measurements



Beyond the SM ?

- Higgs coupling measurements

ATLAS-CONF-2017-047



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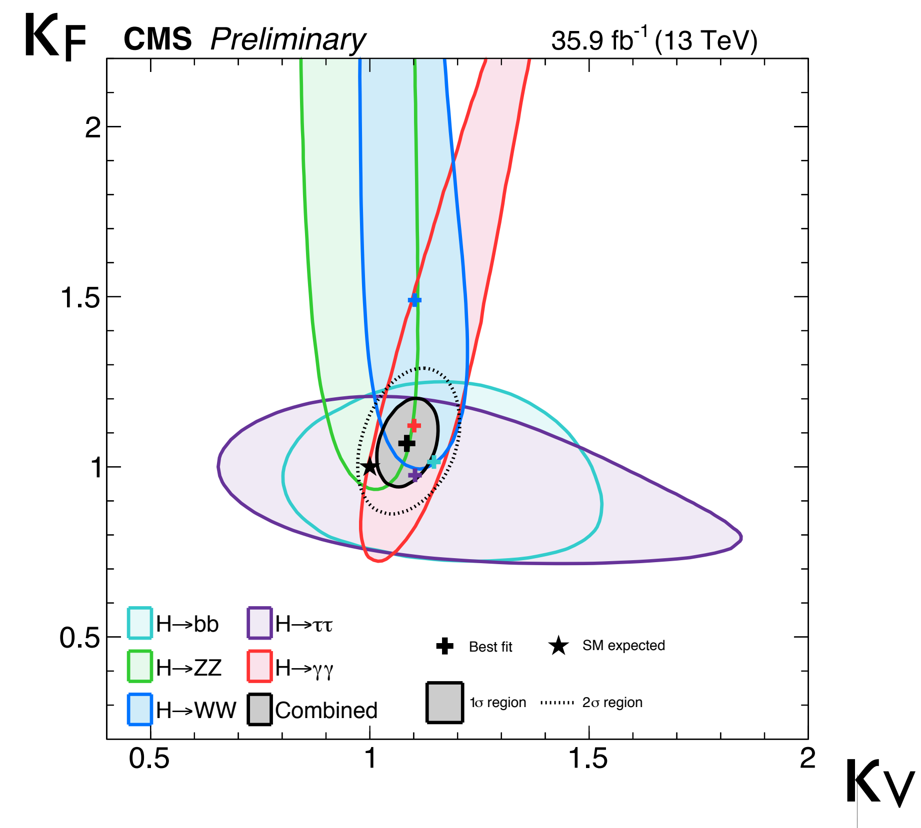
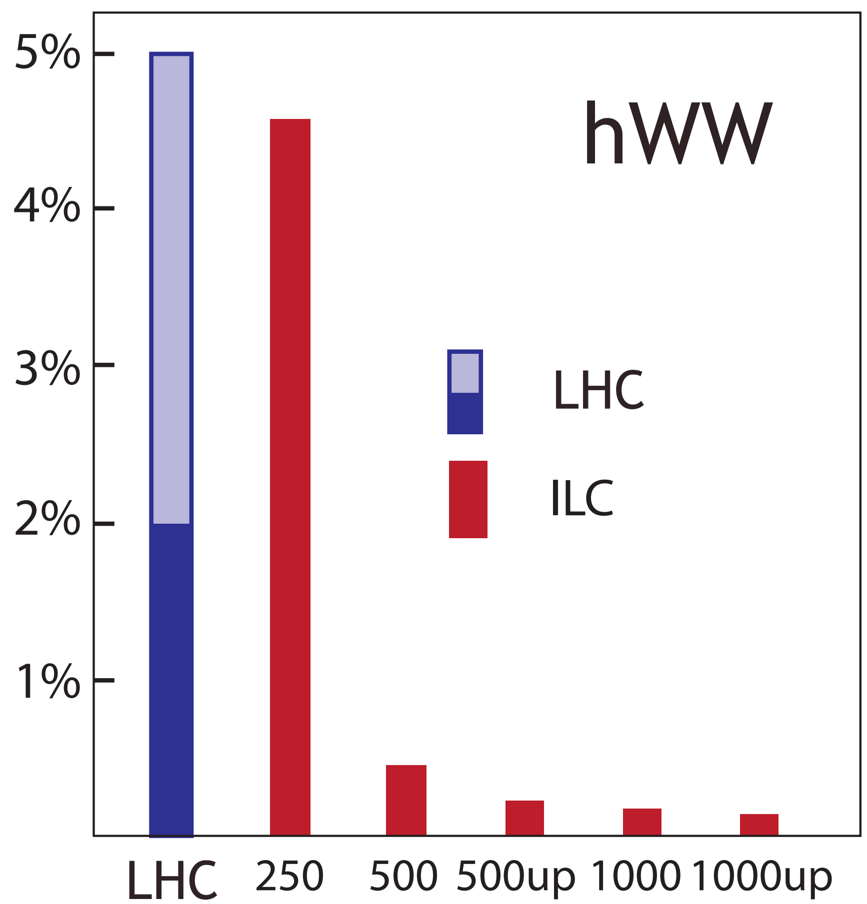


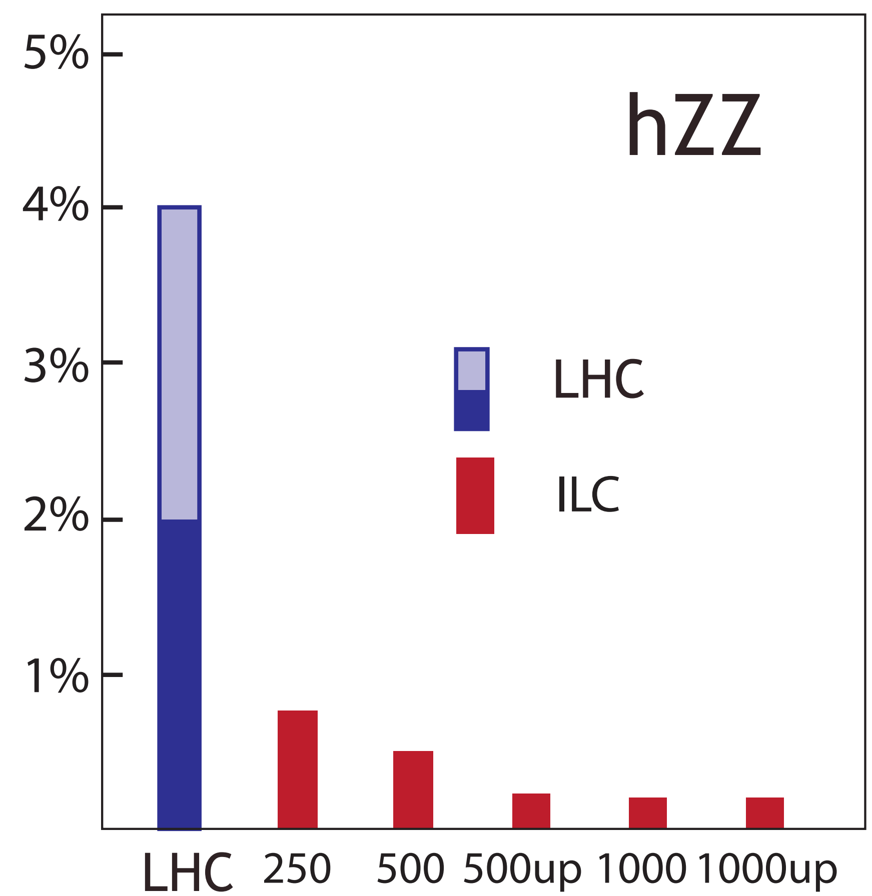
~10% deviation from $\kappa_{V,F}$ = 1 is still allowed.

Beyond the SM ?

- Higgs coupling measurements

M.Peskin (2014)





~1% precise measurement is expected to be realize

Beyond the SM ?

- Higgs coupling measurements

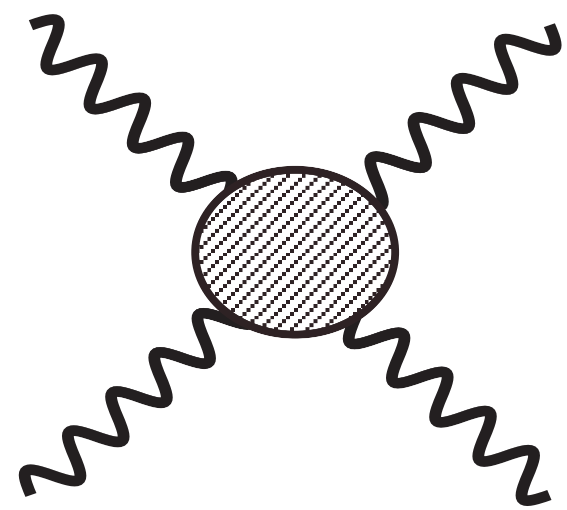
Can we make definite predictions for BSM, if the Higgs coupling strengths turn out to deviate from the SM predictions?

~1% precise measurement is expected to be realize

What if $\kappa_V \neq 1$?

<u>$W_L W_L \to W_L W_L$</u>

Longitudinal Longitudinal



Longitudinal Longitudinal

What if $\kappa_V \neq 1$?

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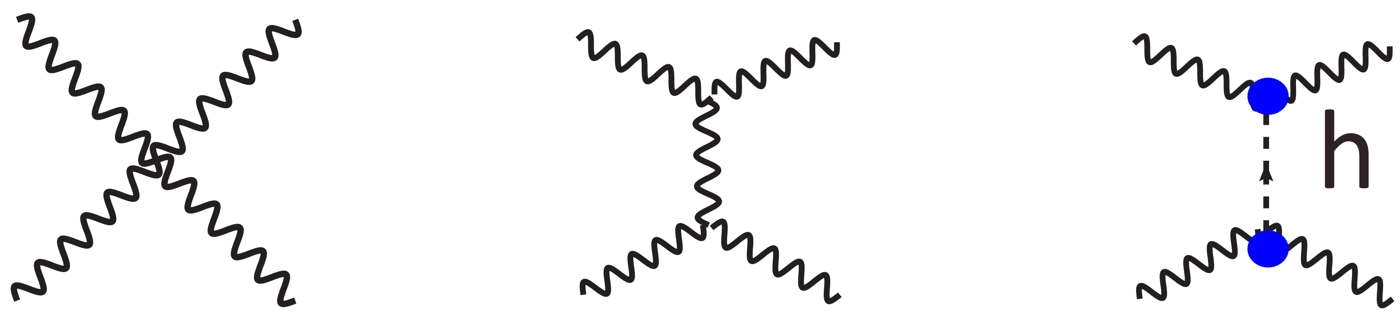


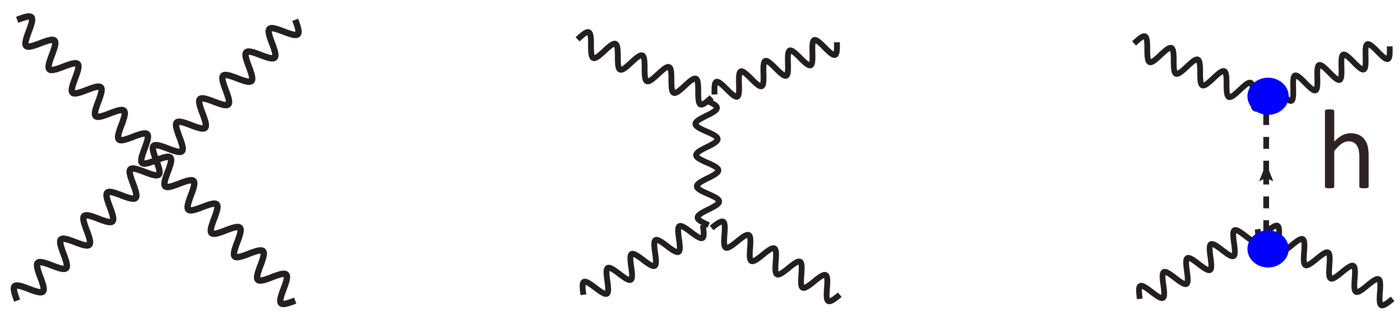
$$\mathcal{M}_{W_L W_L \to W_L W_L} \sim \frac{E^2}{M^2}(1 - \kappa_V^2)$$

Gauge boson

Higgs boson

What if $\kappa_V \neq 1$?

$W_L W_L \to W_L W_L$

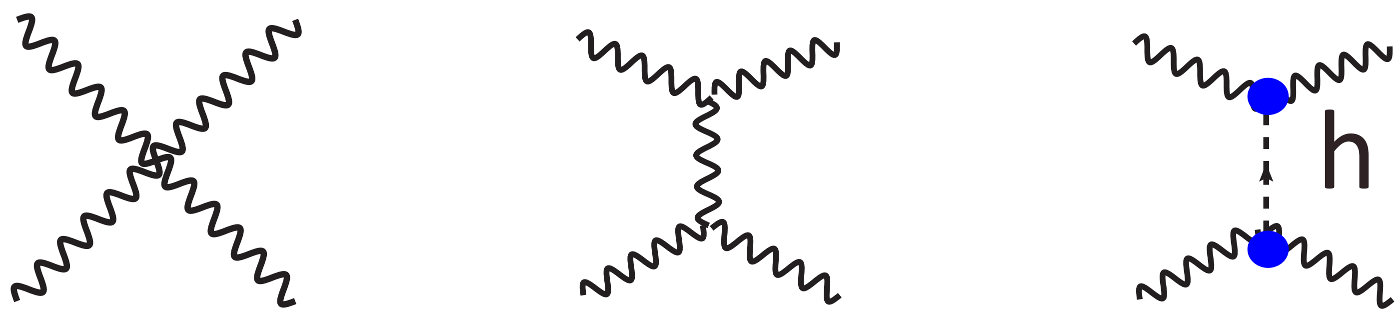


$$\mathcal{M}_{W_L W_L \to W_L W_L} \sim \frac{E^2}{M^2}(1 - \kappa_V^2)$$

- The SM higgs boson ($\kappa_V = 1$) keeps the theory perturbatively unitary.

What if $\kappa_V \neq 1$?

<u>$W_L W_L \to W_L W_L$</u>

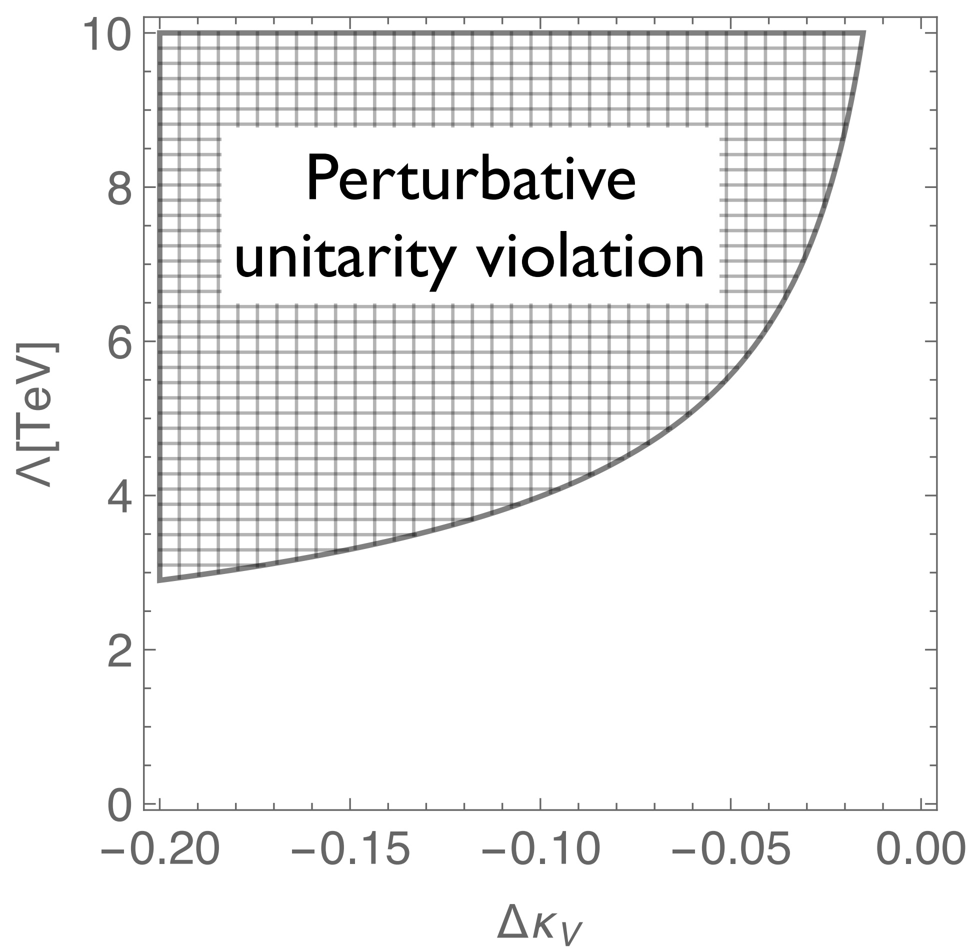


$$\mathcal{M}_{W_L W_L \to W_L W_L} \sim \frac{E^2}{M^2}(1 - \kappa_V^2)$$

- If $\kappa_V \neq 1$, perturbative **unitarity** in $W_L W_L$ scattering seems to be **violated** at certain energy scale.

What if $\kappa_V \neq 1$?

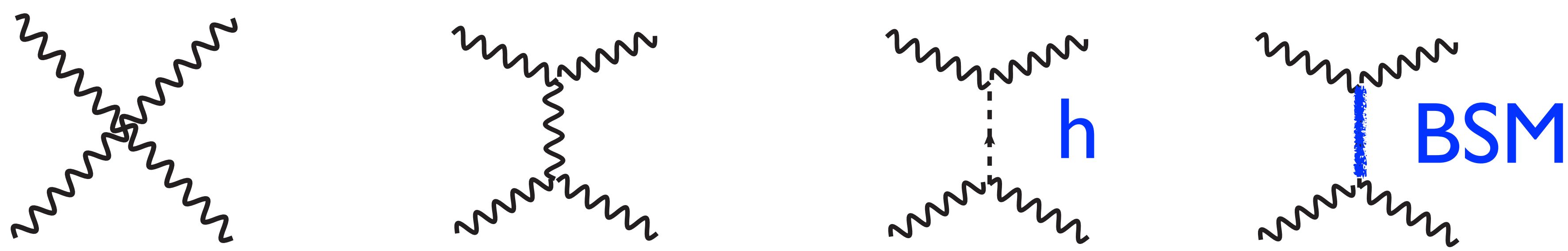
<u>$W_L W_L \to W_L W_L$</u>



- If $\kappa_V \neq 1$, perturbative **unitarity** in $W_L W_L$ scattering seems to be **violated** at certain energy scale.

What if $\kappa_V \neq 1$?

- In order to keep perturbative unitarity at high energy scale, new particles are needed.



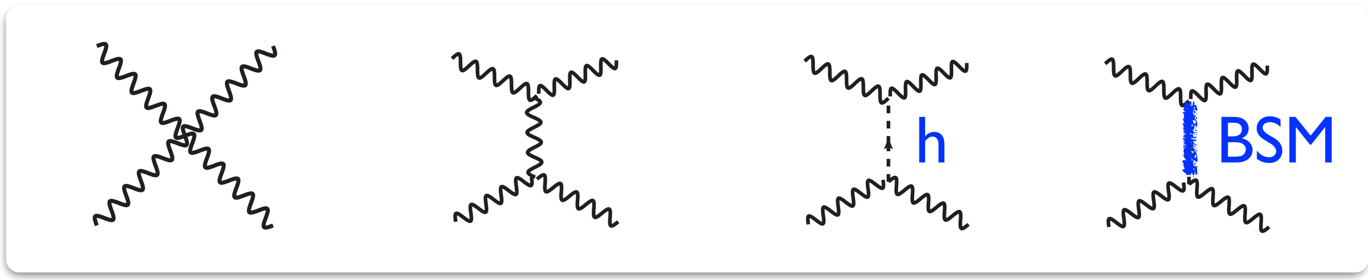
$$\mathcal{M}_{W_L W_L \to W_L W_L} \sim \frac{E^2}{M^2}\underbrace{(1 - \kappa_V^2 + \text{BSM})}_{= 0}$$

"Unitarity sum rule"

- Perturbative BSM should satisfy the "unitarity sum rule(s)"

Strategy

- Guide for studying perturbative BSM : **"Unitarity sum rule(s)"**



$$\boxed{\mathrm{BSM} = \kappa_V^2 - 1}$$

- We expect the sum rule(s) tell us
    - Importance of the SM coupling measurements
    - Non-trivial property of new particles
    - Possibility of non-perturbative EWSB
    - …..

Outline

- Introduction
- Extended Higgs sector

  RN, M.Tanabashi, and K.Tsumura
- Extended EW gauge sector

  RN and T.Abe
- Summary

~ 30 pages

~ 10 pages

Outline

- Extended Higgs sector

  RN, M.Tanabashi, and K.Tsumura

  - Unitarity sum rules

The model

- Let us first discuss a extended EWSB model with extra neutral scalars (h’,h”, …) :

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}[D_\mu U^\dagger D^\mu U]\left(1 + 2\sum_h \kappa_{WW}^h \frac{h}{v} + \sum_{h,h'} \kappa_{WW}^{hh'} \frac{hh'}{v^2}\right)$$

- NGB fields : $U = e^{\frac{i}{v} w^a \tau^a}$
- Gauge bosons : $D_\mu U = \partial_\mu U - igU\mathbf{W}_\mu + ig_Y \mathbf{B}_\mu U$

- $SU(2)_L \times U(1)_Y$ gauge invariant

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Reminder: The SM

$$\mathcal{L}_{\mathrm{SM}} = \frac{v^2}{4}\mathrm{Tr}[D_\mu U^\dagger D^\mu U]\left(1 + 2\frac{h}{v} + \frac{h^2}{v^2}\right) + \cdots$$

- $SU(2)_L \times U(1)_Y$ gauge invariant

The model

- Let us first discuss a extended EWSB model with extra neutral scalars (h',h'', …) :

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- $SU(2)_L \times U(1)_Y$ gauge invariant
- Custodial (Global SU(2)) symmetry

The model

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$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}[D_\mu U^\dagger D^\mu U]\left(1 + 2\sum_h \kappa^h_{WW}\frac{h}{v} + \sum_{h,h'}\kappa^{hh'}_{WW}\frac{hh'}{v^2}\right)$$

- Custodial symmetry breaking can be easily added:

$$\mathcal{L}_{\cancel{\mathrm{cust}}} = -\frac{i}{4}\mathrm{Tr}[U^\dagger D_\mu U\tau_3]\sum_{h,h'}\kappa^{hh'}_Z(h\overleftrightarrow{\partial}_\mu h')$$
$$+\frac{v^2}{8}\mathrm{Tr}[U^\dagger D_\mu U\tau_3]\mathrm{Tr}[U^\dagger D^\mu U\tau_3]\left(\beta + 2\sum_h \tilde{\kappa}^h_{WW}\frac{h}{v} + \sum_{h,h'}\tilde{\kappa}^{hh'}_{WW}\frac{hh'}{v^2}\right)$$

- More general parameterization than SM + N-singlet scalars

$V_L V_L$ scattering

$\underline{W_L W_L \rightarrow W_L W_L}$

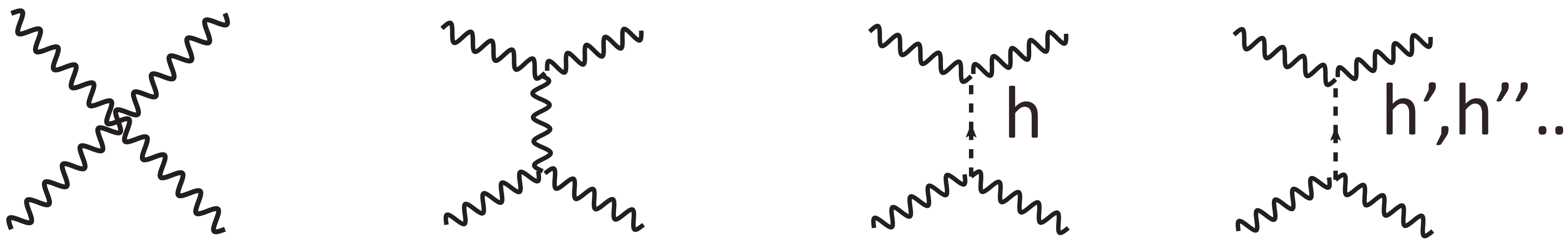
- Tree-level scattering amplitude:

$$\mathcal{M}_{W_L W_L \to W_L W_L} \sim \frac{s}{v^2}\left[1 + \beta - \sum_h (\kappa^h_{WW})^2\right]$$

Gauge boson Higgs boson(s)

$V_L V_L$ scattering

$W_L W_L \to W_L W_L$



- Tree-level scattering amplitude:

$$\mathcal{M}_{W_L W_L \to W_L W_L} \sim \frac{s}{v^2}\left[1+\beta-\sum_h (\kappa_{WW}^h)^2\right]$$

- Unitarity sum rule:

$$\sum_h (\kappa_{WW}^h)^2 = 1+\beta$$

$V_L V_L$ scattering

$W_L W_L \to W_L W_L$

$$\mathcal{M}_{W_L W_L \to W_L W_L} \sim \frac{s}{v^2}\left[1 + \beta - \sum_h (\kappa^h_{WW})^2\right]$$

$W_L W_L \to Z_L Z_L$

$$\mathcal{M}_{W_L W_L \to Z_L Z_L} \sim \frac{s}{v^2}\left[(1+\beta)^2 - \sum_h \kappa^h_{WW}(\kappa^h_{WW} - \tilde{\kappa}^h_{WW})\right]$$

$W_L W_L \to hZ_L$

$$\mathcal{M}_{W_L W_L \to hZ_L} \sim \frac{s}{v^2}\left[\sum_h \kappa^{hh'}_Z \kappa^{h'}_{WW}\right] + \frac{i(t-u)}{v^2}\left[\tilde{\kappa}^h_{WW} - \beta\kappa^h_{WW}\right]$$

$W_L W_L \to hh'$

$$\mathcal{M}_{W_L W_L \to hh'} \sim \frac{s}{v^2}\left[\kappa^h_{WW}\kappa^{h'}_{WW} - \kappa^{hh'}_{WW}\right] + \frac{i(t-u)}{v^2}\kappa^{hh'}_Z$$

$Z_L Z_L \to hh'$

$$\mathcal{M}_{Z_L Z_L \to hh'} \sim \frac{s}{v^2}\Big[(\kappa^h_{WW} - \tilde{\kappa}^h_{WW})(\kappa^{h'}_{WW} - \tilde{\kappa}^{h'}_{WW}) - (1+\beta)(\kappa^{hh'}_{WW} - \tilde{\kappa}^{hh'}_{WW}) + \sum_{h''} \kappa^{hh''}_Z \kappa^{h'h''}_Z\Big]$$

Implication of unitarity

Unitarity sum rules

Gunion-Haber-Wudka (1991)
Falkowski-Rychkov-Urbano (2012)

$$\sum_h (\kappa^h_{WW})^2 = 1 \qquad \kappa^h_{WW}\kappa^{h'}_{WW} = \kappa^{hh'}_{WW}$$

$$\tilde{\kappa}^h_{WW} = 0 \qquad \tilde{\kappa}^{hh'}_{WW} = 0$$

$$\kappa^{hh'}_Z = 0 \qquad \beta = 0$$

- We find if Higgs couplings satisfy the above conditions, the E^2 terms in $V_L V_L$ scattering amplitudes are canceled at tree-level.

Implication of unitarity

<u>Observation (i)</u>

Gunion-Haber-Wudka (1991)
Falkowski-Rychkov-Urbano (2012)

$$\sum_h (\kappa^h_{WW})^2 = 1 \qquad \kappa^h_{WW}\kappa^{h'}_{WW} = \kappa^{hh'}_{WW}$$

$$\tilde{\kappa}^h_{WW} = 0 \qquad \tilde{\kappa}^{hh'}_{WW} = 0$$

$$\kappa^{hh'}_Z = 0 \qquad \beta = 0$$

- $\kappa_V \leqq 1$ to keep perturbative unitarity in the setup.
- $\kappa_V > 1$ is possible if we introduce doubly-charged scalar(s)

Implication of unitarity

Observation (iii)

$$\sum_h (\kappa_{WW}^h)^2 = 1 \qquad \kappa_{WW}^h \kappa_{WW}^{h'} = \kappa_{WW}^{hh'}$$

$$\tilde{\kappa}_{WW}^h = 0 \qquad \tilde{\kappa}_{WW}^{hh'} = 0$$

$$\kappa_Z^{hh'} = 0 \qquad \beta = 0$$

- Custodial symmetric relations are derived solely from unitarity arguments

Implication of unitarity

Unitarity sum rules

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Outline

- Extended Higgs sector

  RN, M.Tanabashi, and K.Tsumura

  - Unitarity sum rules
  - Unitarity vs. Predictability

Unitarity vs. Predictability

- A violation of the perturbative unitarity often causes a UV div. in fermion-scattering amps through EW corrections.

In the SM

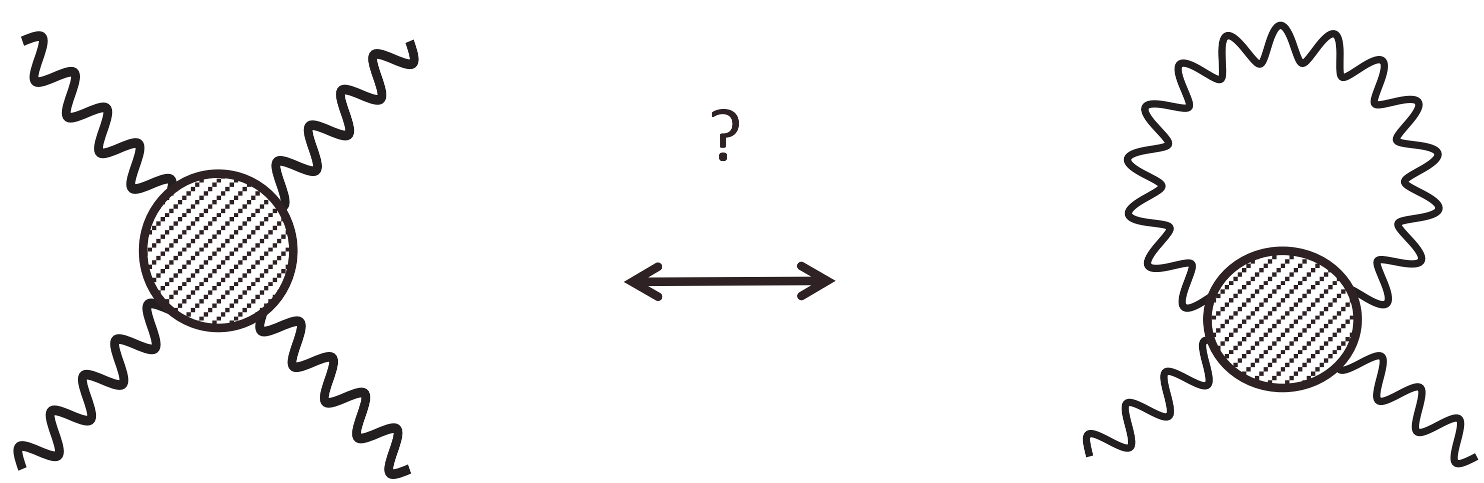
WW scattering: $$\mathcal{M}_{W_L W_L \to W_L W_L} \simeq \frac{s}{v^2}\left(1-\kappa_V^2\right)$$

ff scattering: $$S \simeq \frac{1}{12}\left(1-\kappa_V^2\right)\ln\frac{\Lambda^2}{M_h^2}$$

Unitarity vs. Predictability

- A violation of the perturbative unitarity often causes a UV div. in fermion-scattering amps through EW corrections.

- Does perturbative unitarity ensures predictability for EW corrections?



Unitarity sum rules

UV finiteness condition

EW corrections

- In order to make the fermion scattering amps UV finite, the following combinations are required to be UV finite.

$$S \sim \quad \Pi'_{33}(0) - \Pi'_{3Q}(0)$$

$$T \sim \quad \Pi_{11}(0) - \rho_0 \Pi_{33}(0)$$

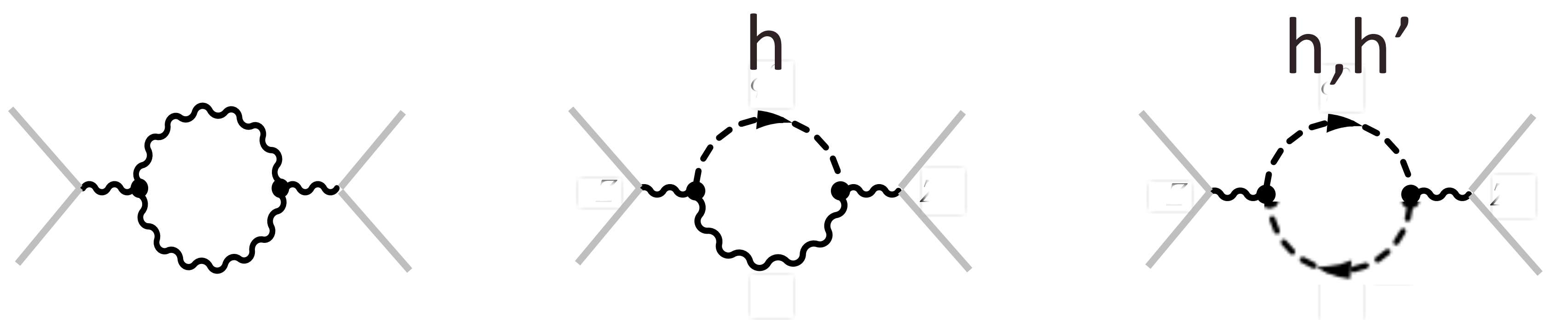
$$U \sim \quad \Pi'_{11}(0) - \Pi'_{33}(0)$$

Kennedy-Lynn (1989)
Peskin-Takeuchi (1992)

- Can we obtain new "sum rules" by requiring the UV finiteness of above functions ?

Predictability

<u>S-parameter at one-loop</u>



- UV divergence:

$$(\kappa^h_{ZZ} = \kappa^h_{WW} - \tilde{\kappa}^h_{WW})$$

$$S_{\log} = \frac{1}{12}\left[1 - \sum_h (\kappa^h_{ZZ})^2 - \frac{1}{2}\sum_{h,h'}(\kappa^{hh'}_Z)^2\right] \ln\frac{\Lambda^2}{M_h^2}$$

- Finiteness condition:

$$1 - \sum_h (\kappa^h_{ZZ})^2 - \frac{1}{2}\sum_{h,h'}(\kappa^{hh'}_Z)^2 = 0$$

Predictability

$$(\kappa^h_{ZZ} = \kappa^h_{WW} - \tilde{\kappa}^h_{WW})$$

S (LogΛ)

$$1 - \sum_h (\kappa^h_{ZZ})^2 - \frac{1}{2}\sum_{h,h'} (\kappa^{hh'}_Z)^2 = 0$$

T (Λ²)

$$\sum_h \left[\tilde{\kappa}^{hh}_{WW} - 2\tilde{\kappa}^h_{WW}(2\kappa^h_{WW} - \tilde{\kappa}^h_{WW}) + \sum_{h'} (\tilde{\kappa}^{hh'}_Z)^2 \right] = 0$$

T (LogΛ)

$$\sum_h \left[\tilde{\kappa}^h_{WW}(2\kappa^h_{WW} - \tilde{\kappa}^h_{WW}) - \tilde{\kappa}^{hh}_{WW} - \sum_{h'} (\tilde{\kappa}^{hh'}_Z)^2 \right] \frac{M_h^2}{v^2}$$

$$-\frac{3}{4}g^2 \left[\sum_h (\kappa^h_{WW})^2 - 1 \right] + \frac{3}{4}g_Z^2 \left[\sum_h (\kappa^h_{ZZ})^2 - 1 \right] = 0$$

U (LogΛ)

$$\sum_h \left[\tilde{\kappa}^h_{WW}(2\kappa^h_{WW} - \tilde{\kappa}^h_{WW}) - \frac{1}{2}\sum_{h'} (\tilde{\kappa}^{hh'}_Z)^2 \right] = 0$$

Predictability

$(\kappa^h_{ZZ} = \kappa^h_{WW} - \tilde{\kappa}^h_{WW})$

<u>UV finiteness condition</u>

$$\sum_h (\kappa^h_{WW})^2 = \sum_h (\kappa^h_{ZZ})^2 = 1$$

$$\tilde{\kappa}^{hh}_{WW} = (\kappa^h_{WW})^2 - (\kappa^h_{ZZ})^2$$

$$\kappa^{hh'}_Z = 0 \qquad \beta = 0$$

- We find if Higgs couplings satisfy the above conditions, the UV finiteness of EW corrections are ensured at one-loop level.

Unitarity vs. Predictability

$(\kappa^h_{ZZ} = \kappa^h_{WW} - \tilde{\kappa}^h_{WW})$

Unitarity sum rules

* $\sum_h (\kappa^h_{WW})^2 = 1$
* $\kappa^h_{WW} = \kappa^h_{ZZ}$
* $\kappa^h_{WW}\kappa^{h'}_{WW} = \kappa^{hh'}_{WW}$
* $\tilde{\kappa}^{hh'}_{WW} = 0$
* $\kappa^{hh'}_{Z} = 0$
* $\beta = 0$

UV finiteness condition

* $\sum_h (\kappa^h_{WW})^2 = 1$
* $\sum_h (\kappa^h_{WW})^2 = \sum_h (\kappa^h_{ZZ})^2$
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UV finiteness condition

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* $\sum_h (\kappa^h_{WW})^2 = \sum_h (\kappa^h_{ZZ})^2$
* $\tilde{\kappa}^{hh}_{WW} = (\kappa^h_{WW})^2 - (\kappa^h_{ZZ})^2$
* $\kappa^{hh'}_{Z} = 0$
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Unitarity vs. Predictability

$(\kappa^h_{ZZ} = \kappa^h_{WW} - \tilde{\kappa}^h_{WW})$

Unitarity sum rules

* $\sum_h (\kappa^h_{WW})^2 = 1$
* $\kappa^h_{WW} = \kappa^h_{ZZ}$
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UV finiteness condition

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* $\sum_h (\kappa^h_{WW})^2 = \sum_h (\kappa^h_{ZZ})^2$
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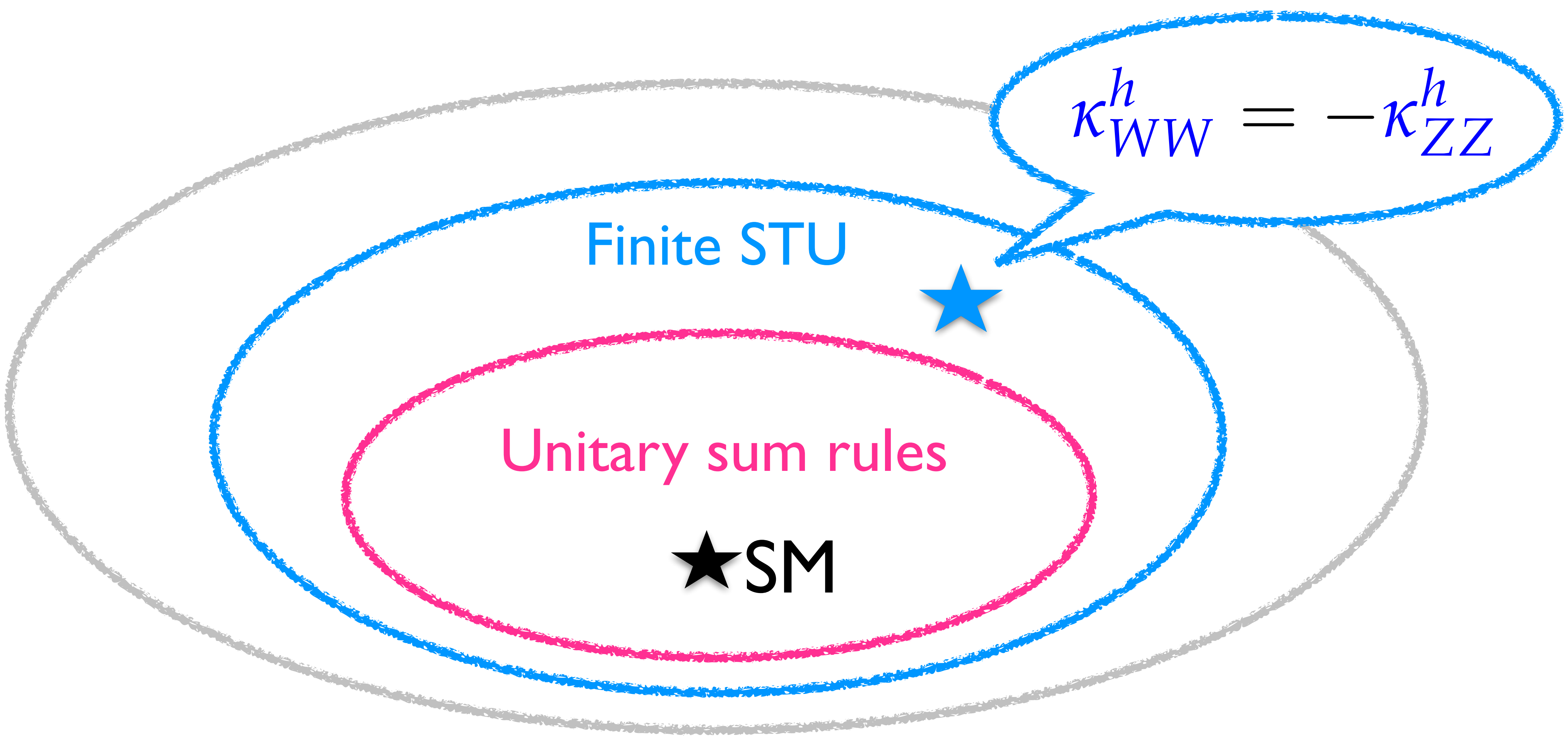
* $\kappa^{hh'}_{Z} = 0$
* $\beta = 0$

Unitarity vs. Predictability

- The finiteness of EW corrections does not imply the perturbative unitarity.
- For example, wrong sign hWW/hZZ coupling.



Unitarity vs. Predictability

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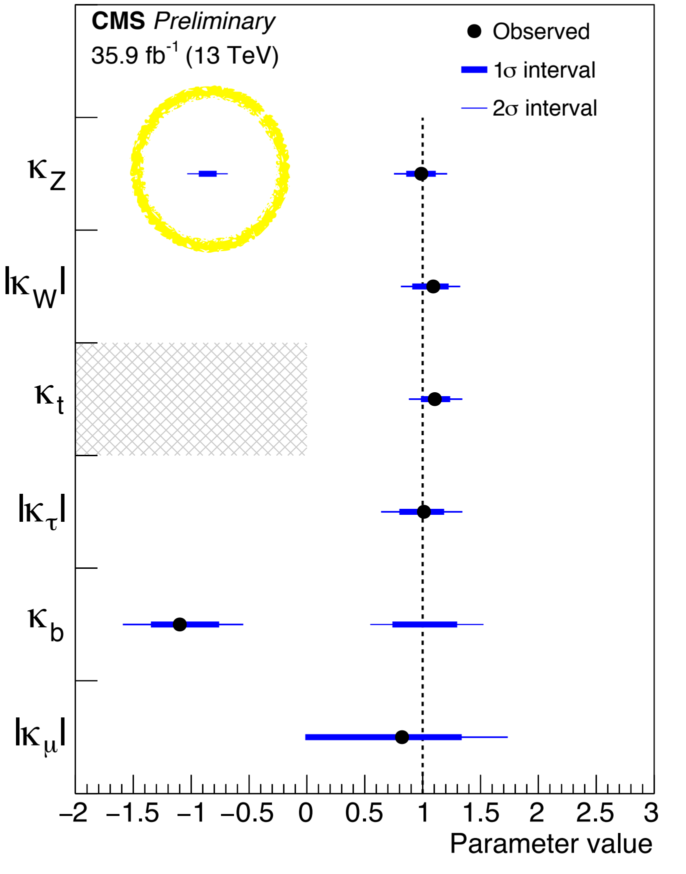
- For example, wrong sign hWW/hZZ coupling.
- Wrong sign hWW/hZZ coupling

$$\kappa^h_{WW} = -\kappa^h_{ZZ}$$

may cause strong WW→ZZ/Zh scattering keeping the consistency with EWPTs and higgs data. (?)

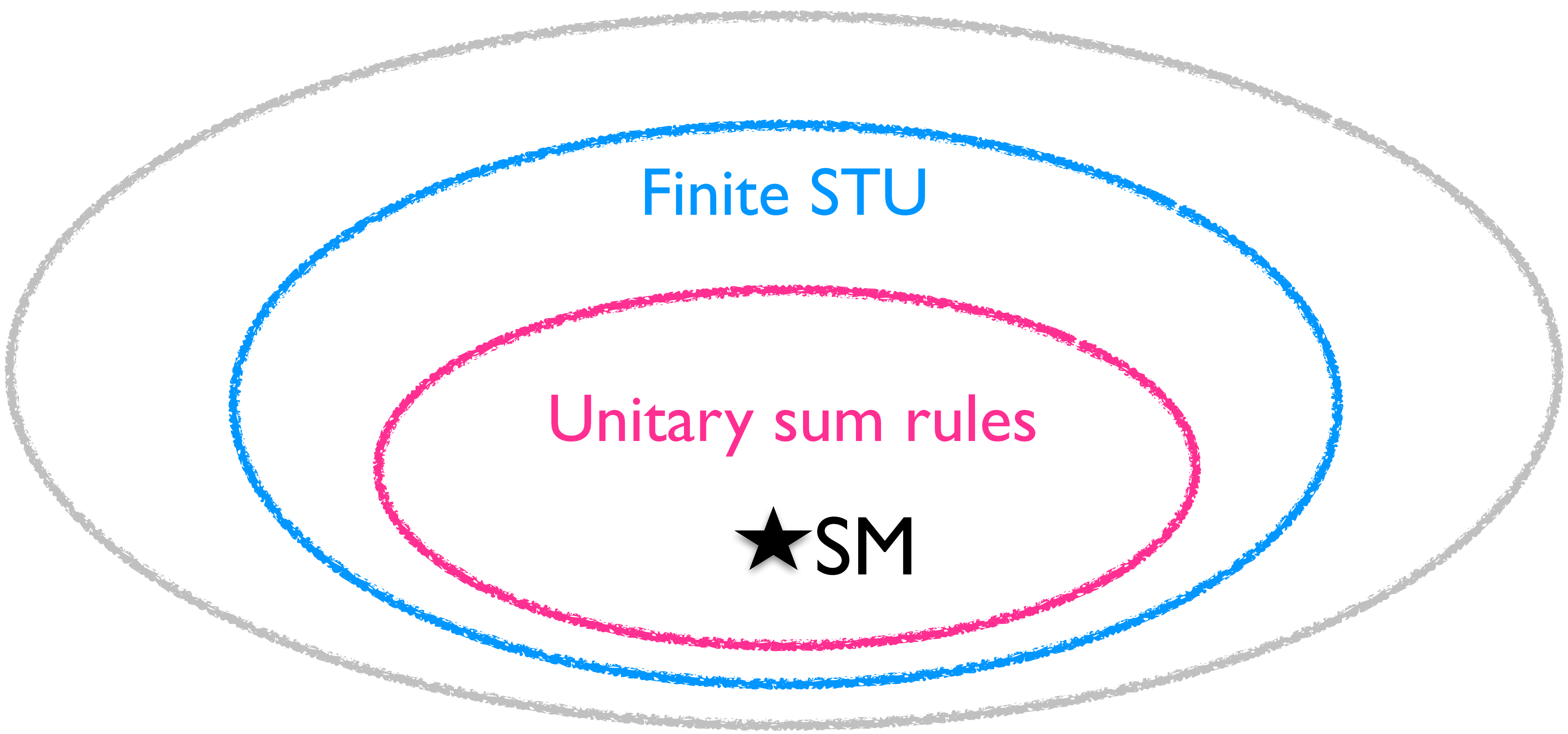


CMS-PAS-HIG-17-031

Unitarity vs. Predictability

- If the Higgs couplings satisfy the unitarity sum rules, the one-loop finiteness of EW corrections is automatically ensured.

Perturbative Unitary → Testable by EWPTs !



Outline

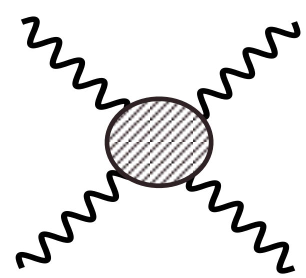
- Extended Higgs sector

  RN, M.Tanabashi, and K.Tsumura

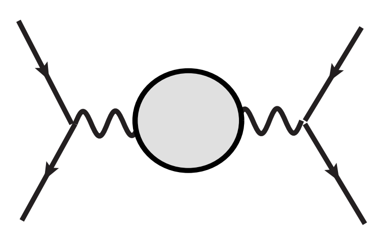
  - Unitarity sum rules
  - Unitarity vs. Predictability
  - Phenomenological application

Constraints on heavy Higgses

- If ($h_1, h_2, h_3, \ldots$) satisfy the unitarity sum rules,



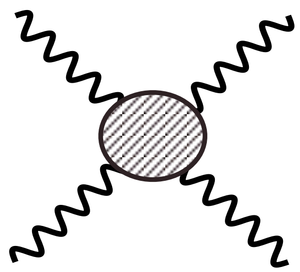
$$\sim A \cancel{\frac{E^2}{v^2}} + B$$



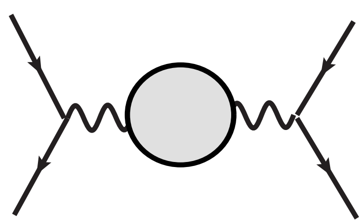
$$\sim C \cancel{\ln\frac{\Lambda^2}{v^2}} + D$$

Constraints on heavy Higgses

- Even if (h_1,h_2,h_3,…) satisfy the unitarity sum rules, extremely heavy extra higgs bosons causes PU violation / inconsistency with EWPTs.



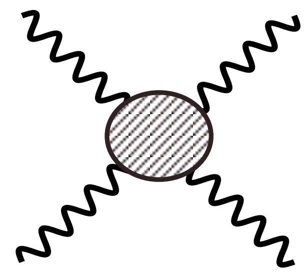
$$\sim \sum_n (\kappa_{WW}^{h_n})^2 \frac{m_{h_n}^2}{v^2}$$



$$\sim \sum_n (\kappa_{WW}^{h_n})^2 \ln \frac{m_{h_n}^2}{m_{h_1}^2}$$

Constraints on heavy Higgses

- Even if (h_1,h_2,h_3,…) satisfy the unitarity sum rules, extremely heavy extra higgs bosons causes PU violation / inconsistency with EWPTs.



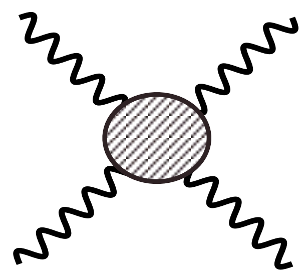
$$\sim \sum_n (\kappa_{WW}^{h_n})^2 \frac{m_{h_n}^2}{v^2} \qquad (\kappa_V = \kappa_{WW}^{h_1})$$

$$\geq \kappa_V^2 \frac{m_h^2}{v^2} + \sum_{n=2} (\kappa_{WW}^{h_n})^2 \frac{m_{h_2}^2}{v^2}$$

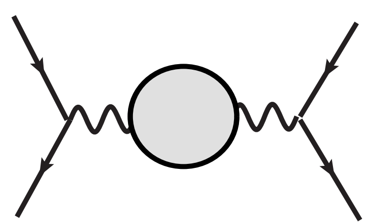
$$= \kappa_V^2 \frac{m_h^2}{v^2} + (1-\kappa_V^2) \frac{m_{h_2}^2}{v^2}$$

Constraints on heavy Higgses

- If $(h, h_2, h_3, \ldots)$ satisfy the unitarity sum rules,



$$\geq \kappa_V^2 \frac{m_h^2}{v^2} + (1-\kappa_V^2)\frac{m_{h_2}^2}{v^2}$$

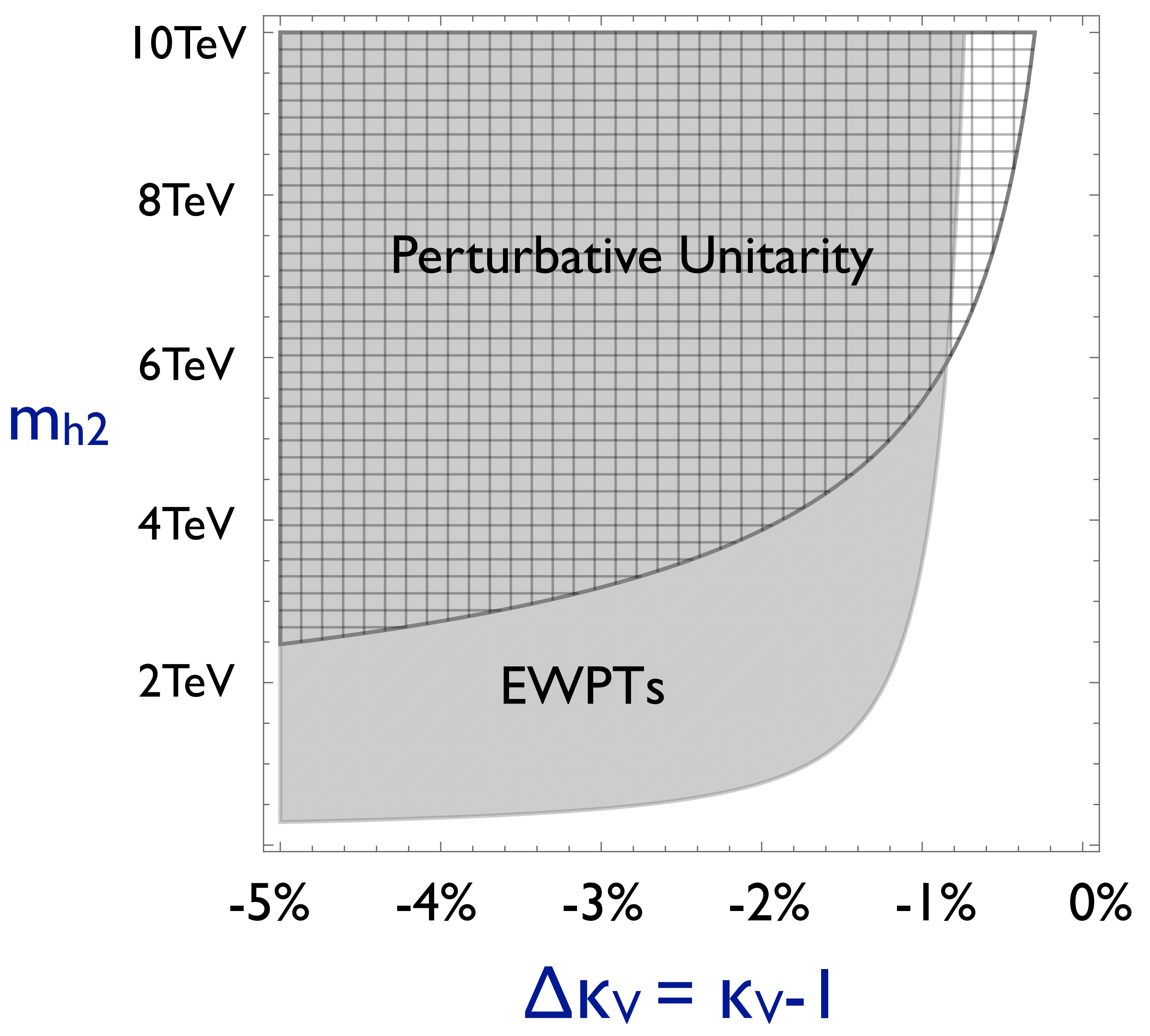


$$\geq (1-\kappa_V^2)\ln\frac{m_{h_2}^2}{m_h^2}$$

- PU constraint : | s-wave amplitude | < 1/2 Lee-Quigg-Thacker (1977)
- EWPTs : $S = 0.06 \pm 0.09$, $T = 0.10 \pm 0.07$ Gfitter group (2014)

Constraints on heavy Higgses

SM + (h_2, h_3, …)



- Only from the unitarity sum rules, we derive upper mass bound on extra scalars as a functions of the deviation of hVV coupling ($\Delta\kappa_V$).

Constraints on heavy Higgses

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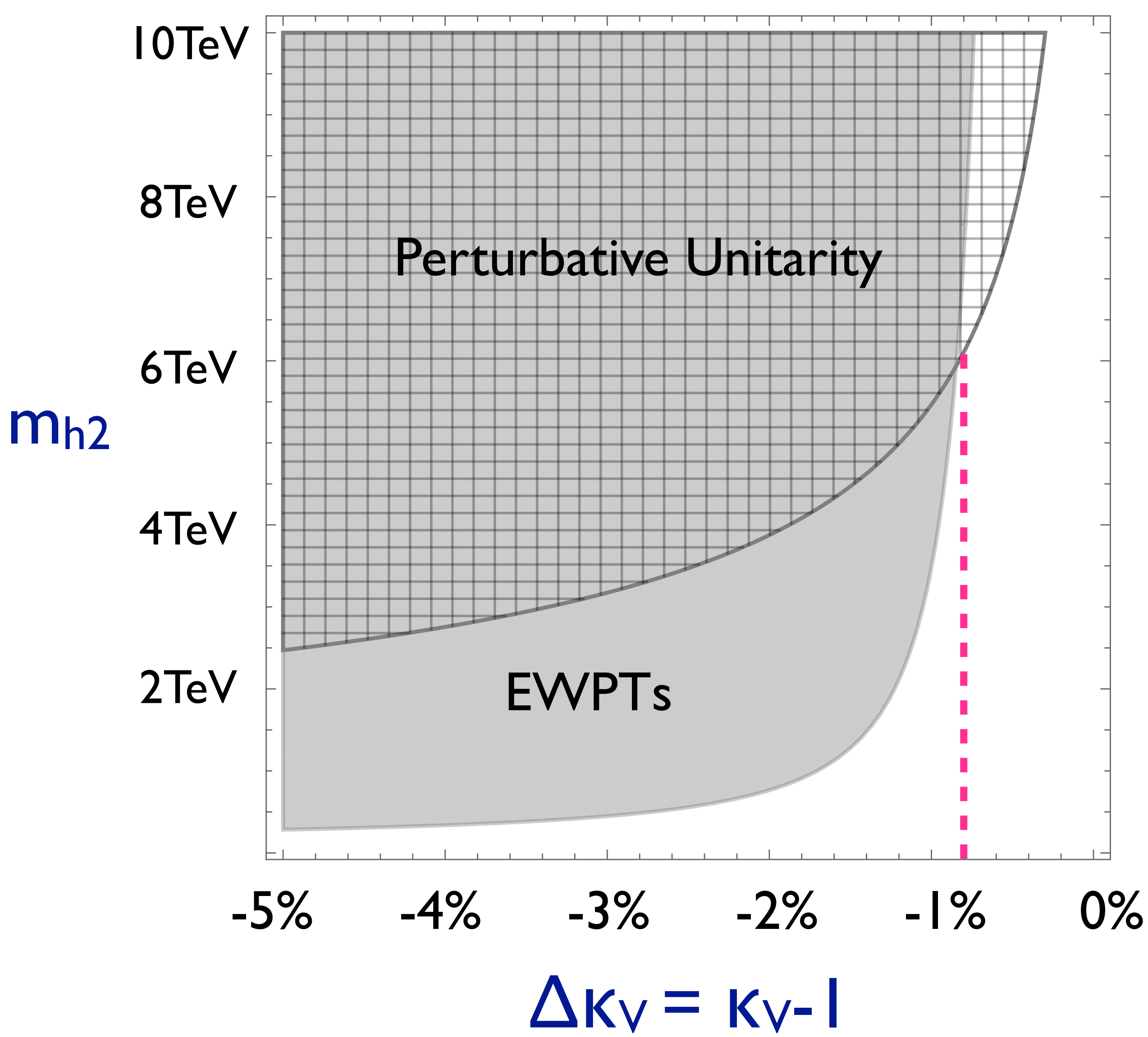

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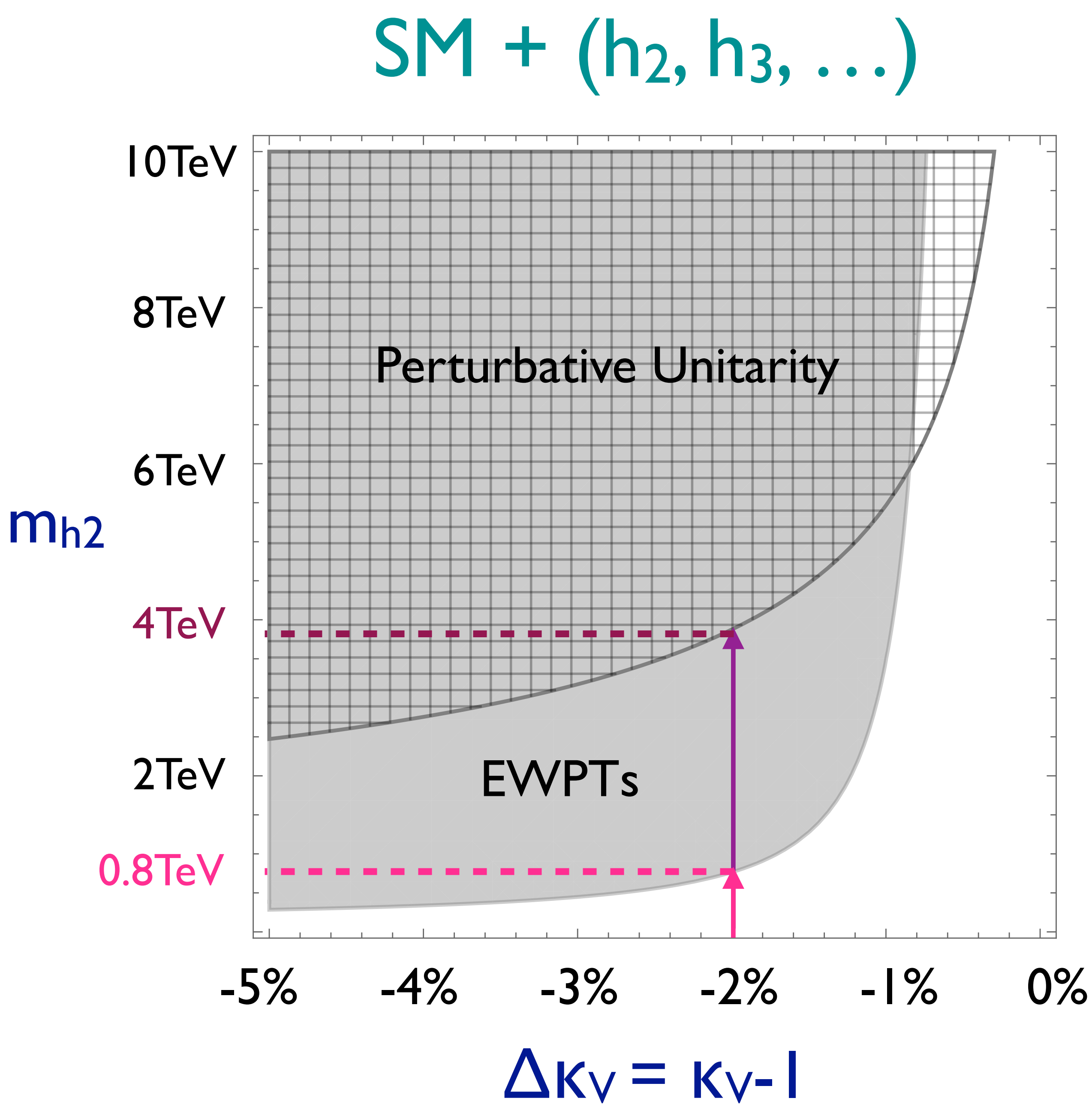
- If $|\Delta\kappa_V| > 0.008$, the constraints from EWPTs are stronger than perturbative unitarity (PU) limit.

Constraints on heavy Higgses



- Only from the unitarity sum rules, we derive upper mass bound on extra scalars as a functions of the deviation of hVV coupling ($\Delta\kappa_V$).
- If $|\Delta\kappa_V| > 0.008$, the constraints from EWPTs are stronger than perturbative unitarity (PU) limit.

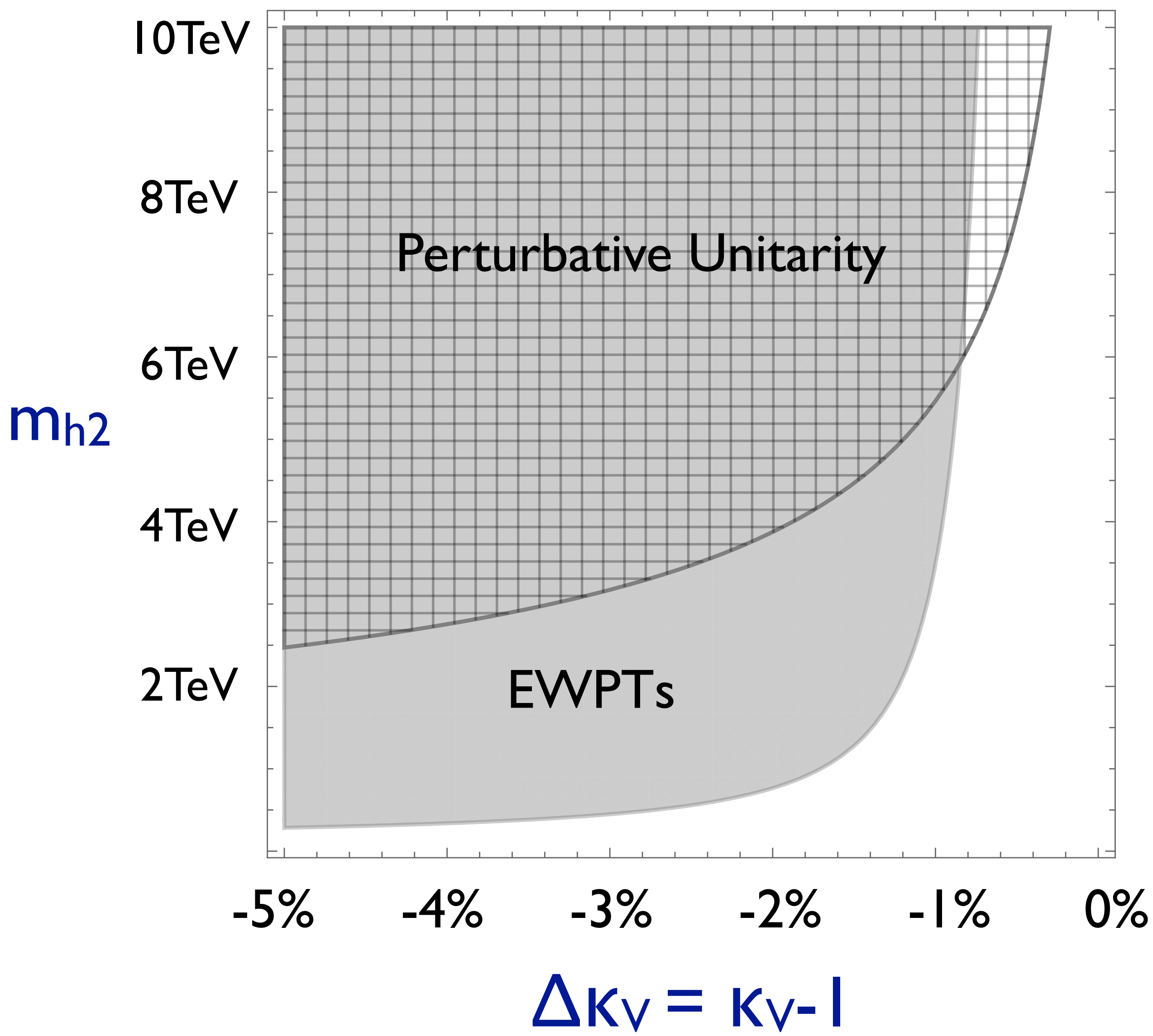
$\Delta\kappa_V \sim -0.02$

➡ $m_{h2} < 800\text{GeV}$ (EWPTs)

$< 4\text{TeV}$ (PU)

Constraints on heavy Higgses

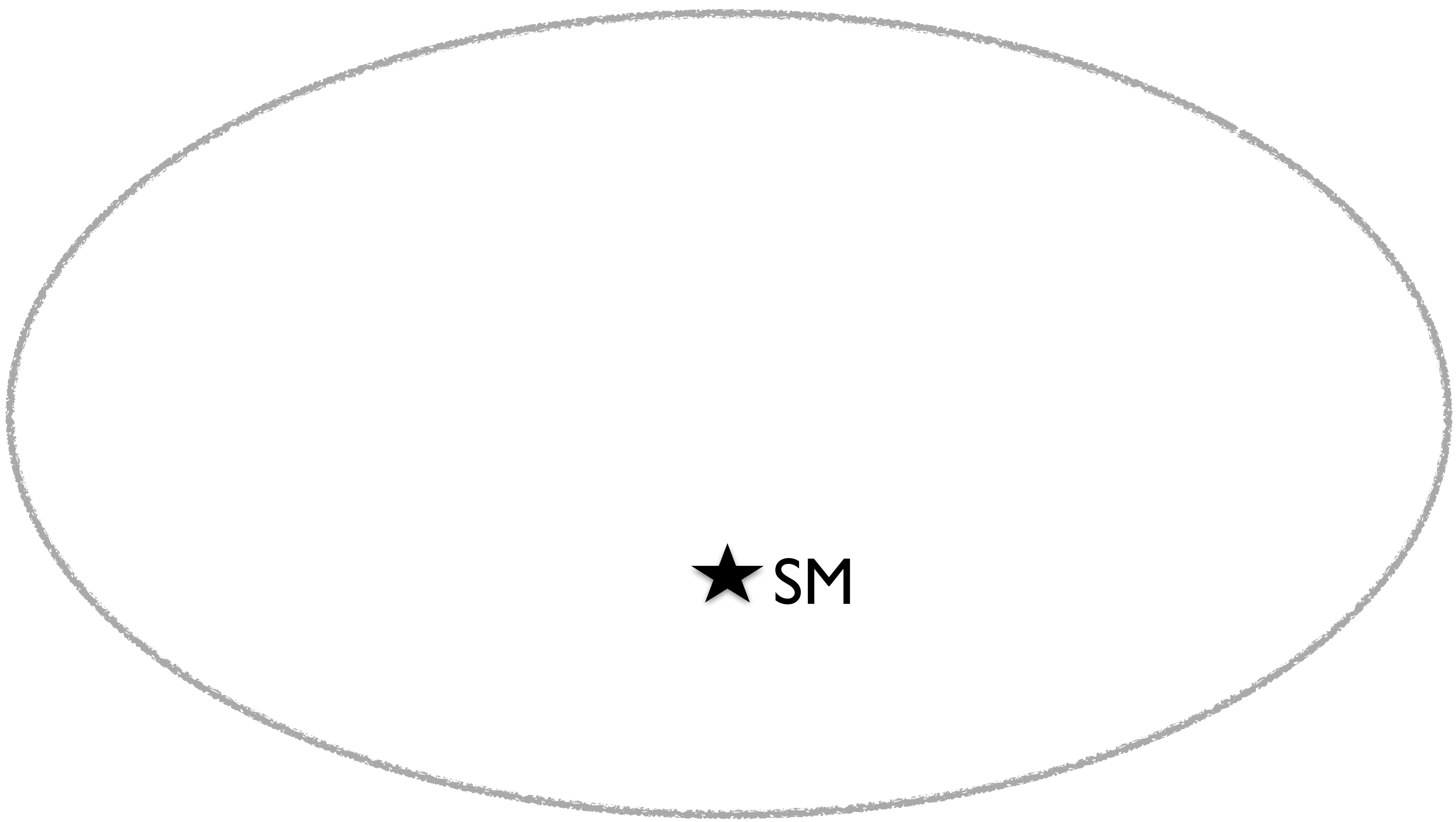
SM + (h_2, h_3, …)



- Only from the unitarity sum rules, we derive upper mass bound on extra scalars as a functions of the deviation of hVV coupling ($\Delta\kappa_V$).
- If $|\Delta\kappa_V| > 0.008$, the constraints from EWPTs are stronger than perturbative unitarity (PU) limit.
- Precise measurements of κ_V is important for investigating BSM.

Summary so far

EWSB with extra neutral scalars (h’,h”, …)



Summary so far

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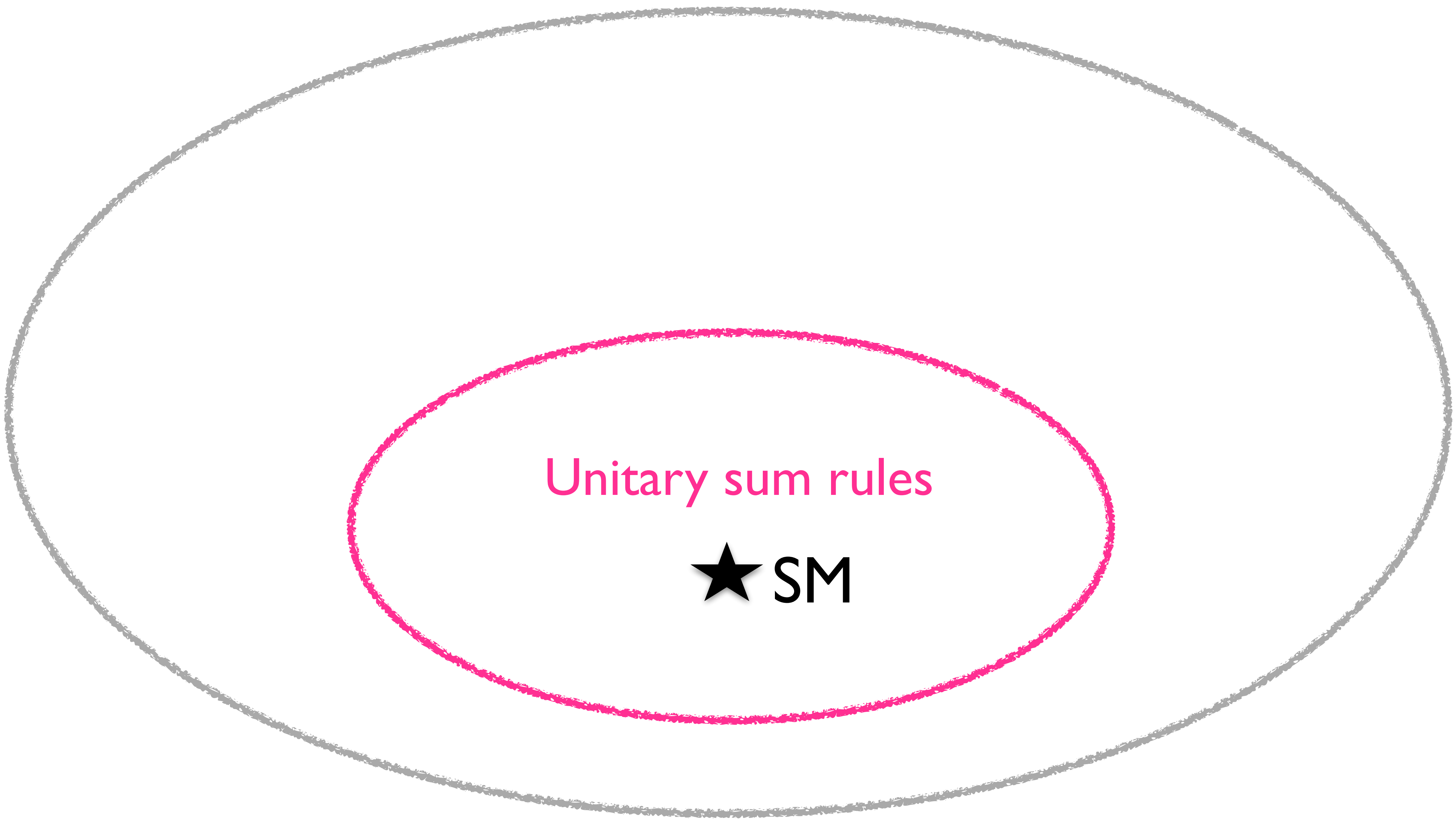


Summary so far

EWSB with extra neutral scalars (h',h'', ...)

$$\sum_h (\kappa_{WW}^h)^2 = 1 \qquad \kappa_{WW}^h \kappa_{WW}^{h'} = \kappa_{WW}^{hh'}$$

$$\tilde{\kappa}_{WW}^h = 0 \qquad \tilde{\kappa}_{WW}^{hh'} = 0$$

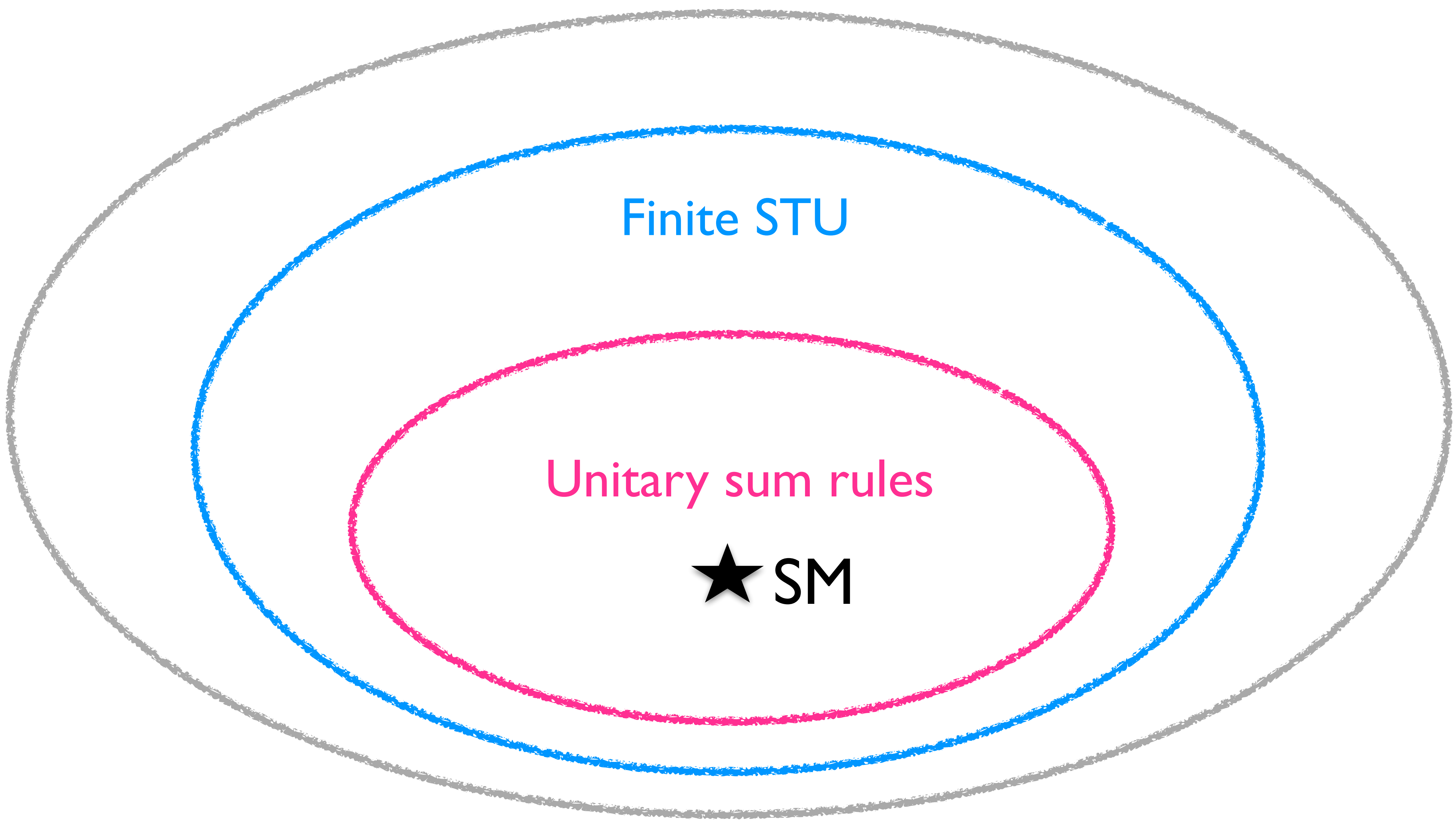
$$\kappa_Z^{hh'} = 0 \qquad \beta = 0$$

Unitary sum rules

★ SM

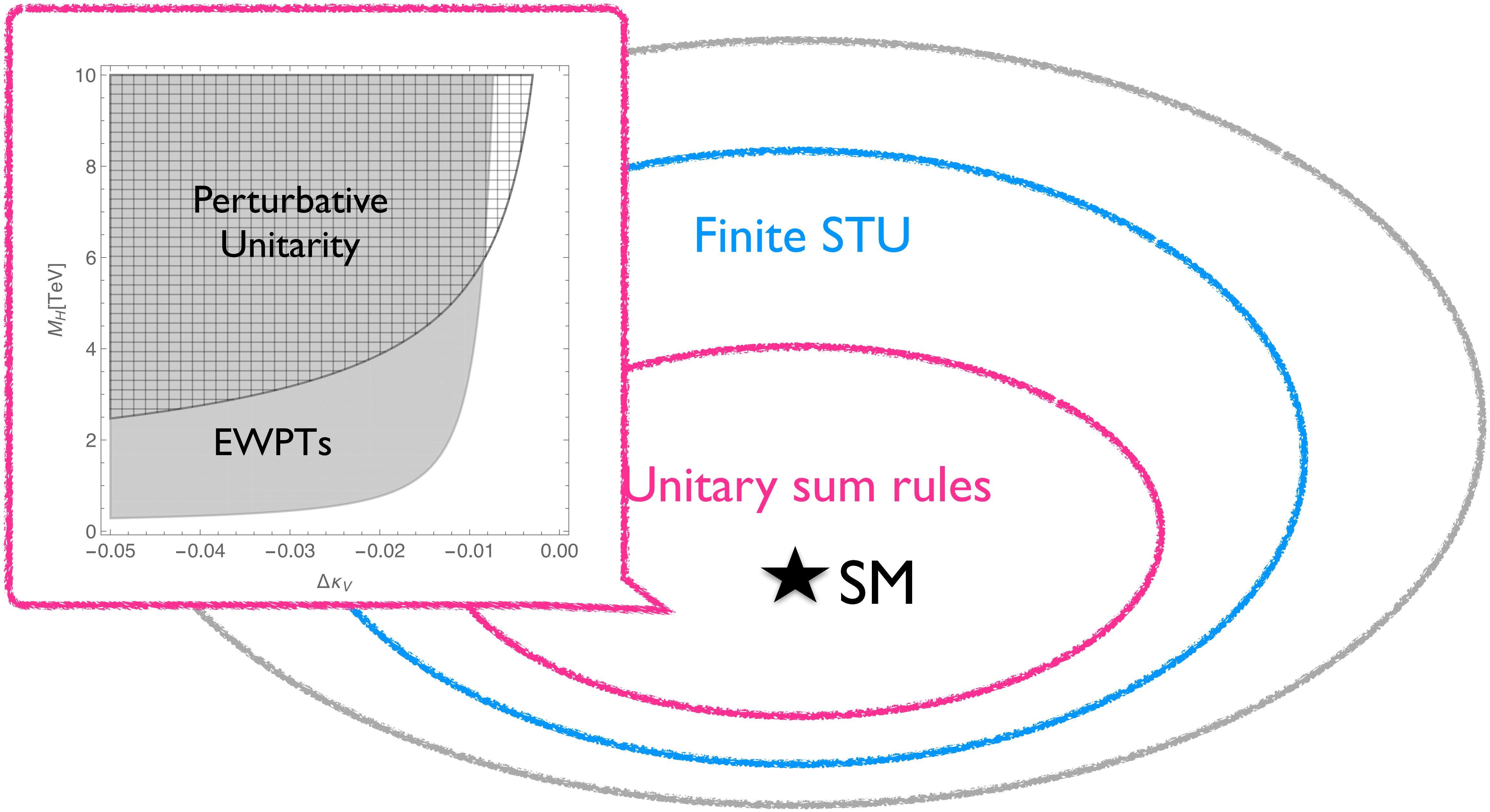
Summary so far

EWSB with extra neutral scalars (h’,h”, …)



Summary so far

EWSB with extra neutral scalars (h’,h”, …)



Outline

- Introduction
- Extended Higgs sector

  RN, M.Tanabashi, and K.Tsumura
- Extended EW gauge sector

  RN and T.Abe
- Summary

The model

- Let us next discuss the following class of extended EWSB models:

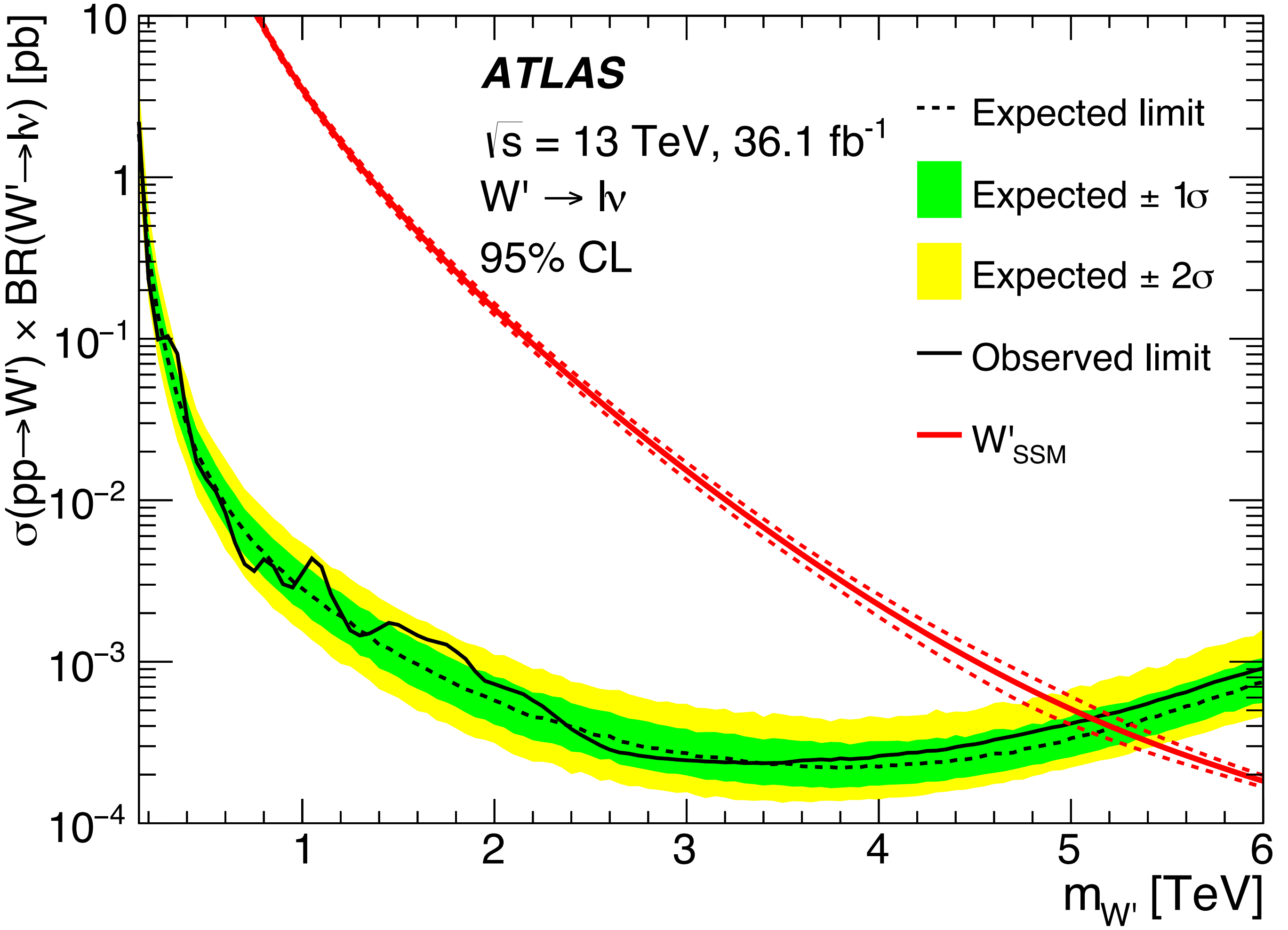
SM + h', h'',… + **W'/Z'**

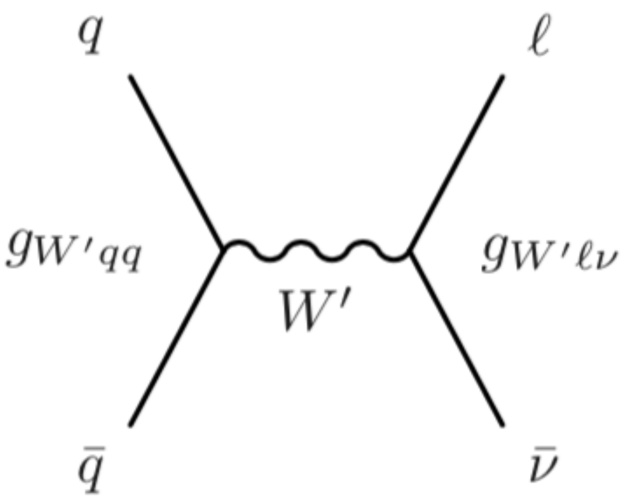
- W'/Z' ??

Motivated by various models beyond the SM

- Dynamical EWSB scenarios (ρ' meson)
- Extra dimension models (KK gauge boson)
- Unification models (W_R, ….)
- …….

Current bound on V'





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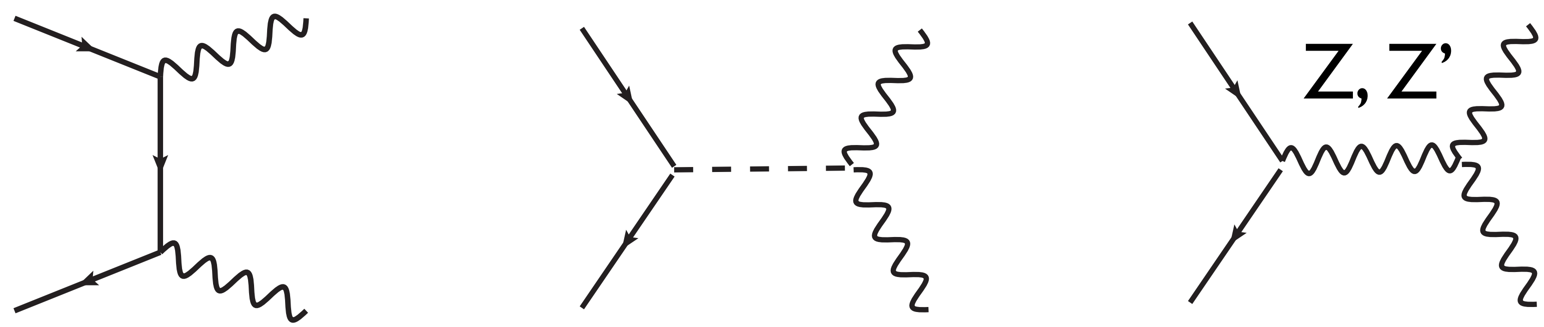
- $m_{W'}$ > 5TeV with the assumption, $g_{W'ff} = g_{Wff}$ (SM).
- This bound depends on W' couplings.

PU and W'couplings

- Unitarity sum rules tell us general relations among W' couplings.

ff $\rightarrow W_L W'_L$ scattering



Unitarity sum rules

E²-term: $$\sum_{V=Z,Z'} g_{WW'V}\, g_{Vff} = g_{Wff}\, g_{W'ff}$$

E-term: $$m_f \sum_{V=Z,Z'} g_{WW'V}\, g_{Vff} \frac{m_W^2 - m_{W'}^2}{m_V^2} = 0$$

PU and W'couplings

- To ensure perturbative unitarity of ff → $W_L W'_L$ scattering,

$$g_{W'ff}^2 = g_{W'WZ}^2 \frac{m_Z^4}{m_{Z'}^4}\left(1 - \frac{m_Z^2}{m_{Z'}^2}\right)^2$$

W'ff coupling

W'WZ coupling

- Let us focus on

$$R = \frac{\Gamma(W' \to WZ)}{\sum_f \Gamma(W' \to ff)} \simeq \frac{1}{48}\frac{m_{W'}^4}{m_W^2 m_Z^2}\frac{g_{WW'Z}^2}{g_{W'ff}^2}$$

PU and W'couplings

- To ensure perturbative unitarity of ff → $W_L W'_L$ scattering,

$$R = \frac{\Gamma(W' \to WZ)}{\sum_f \Gamma(W' \to ff)} \simeq \frac{1}{48} \times \underbrace{\frac{m_{W'}^4}{m_{Z'}^4}}_{\sim 1} \times \underbrace{\frac{g_{Wff}^2 m_Z^2}{g_{Zff}^2 m_W^2}}_{\sim 1}$$

- This means Br(W'→WZ) should be smaller than 2%

$$\mathrm{Br}(W' \to WZ) = \frac{\Gamma(W' \to WZ)}{\Gamma(W' \to WZ) + \sum_f \Gamma(W' \to ff) + \sum_X \Gamma(W' \to X)}$$

$$\leq \frac{\Gamma(W' \to WZ)}{\Gamma(W' \to WZ) + \sum_f \Gamma(W' \to ff)} \simeq 0.02$$

PU and W'couplings

- Our setup: SM + h', h'',… + **W'/Z'**

- Perturbative unitarity of ff → WW' scattering requires

$$\mathrm{Br}(W' \to WZ) \leqq 2\%$$

- If W' is discovered in WZ decay channel in future, it implies

[1] The existence of other new particles

[2] Non-perturbative ff → WW' scattering

PU and W' couplings

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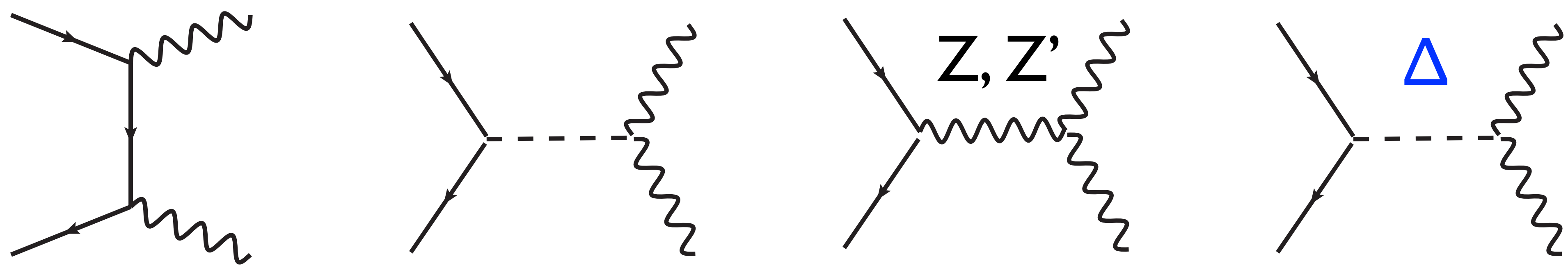
CP-odd scalar and W'

- CP-odd scalar can make Br(W'→WZ) >> 2%.

<u>ff → $W_L W'_L$ scattering</u>



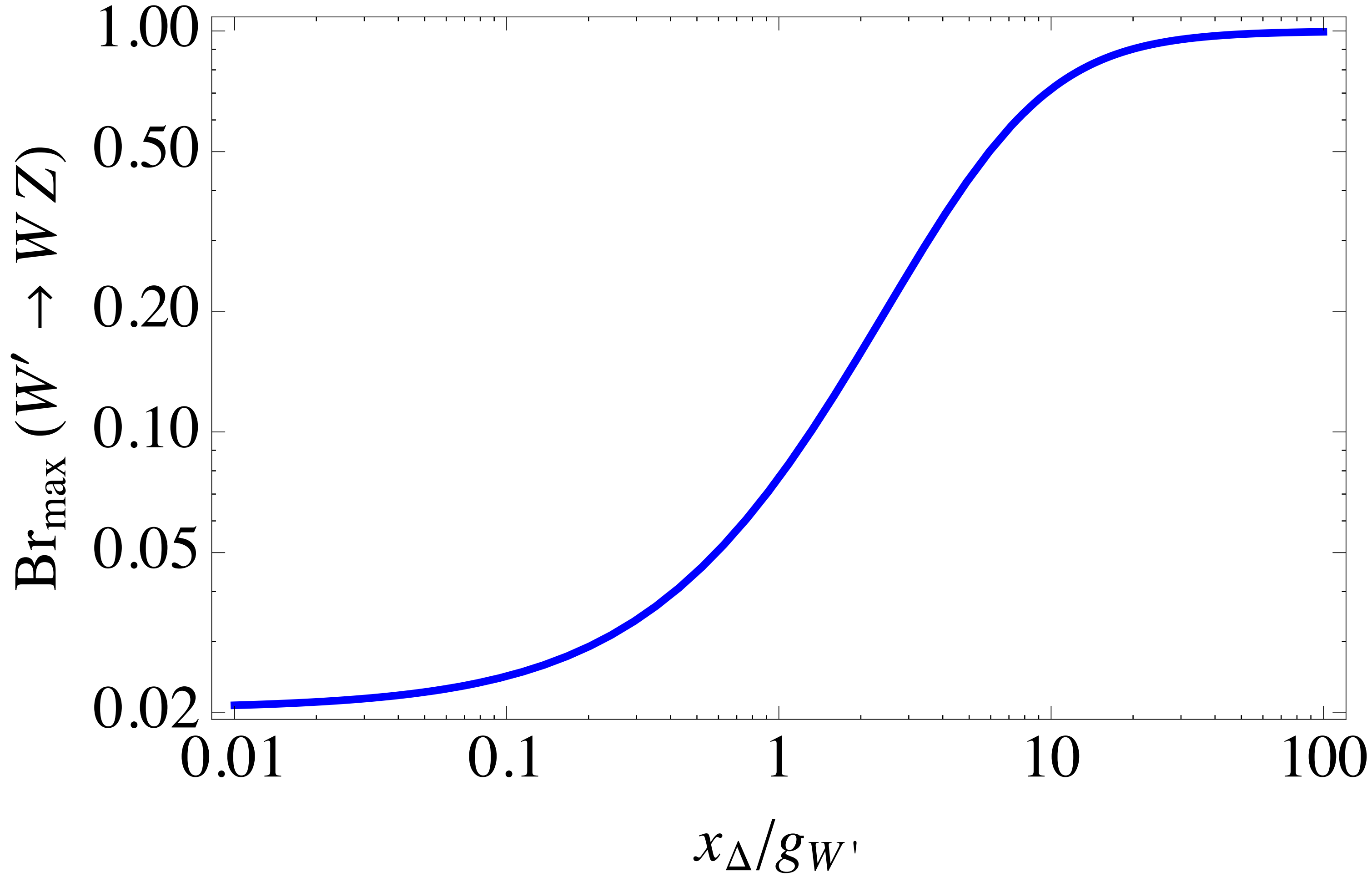
Unitarity sum rules

E²-term: $$\sum_{V=Z,Z'} g_{WW'V}\, g_{Vff} = g_{Wff}\, g_{W'ff}$$

E-term: $$m_f \sum_{V=Z,Z'} g_{WW'V}\, g_{Vff} \frac{m_W^2 - m_{W'}^2}{m_V^2} = \frac{1}{2}\sum_{\Delta} g_{ff\Delta}\, g_{W'W\Delta}$$

CP-odd scalar and W'

- CP-odd scalar can make Br(W'→WZ) >> 2%.



$$x_\Delta = \sum_\Delta \frac{g_{ff\Delta}}{m_f} \frac{g_{WW'\Delta}}{g_{Wff}}$$

- Concrete example: T. Abe and R. Kitano (2013)

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Summary

Unitarity sum rules are good guiding principle for investigating extended EWSB scenarios

EWSB with h',h'', …

- The one-loop finiteness of EW corrections is automatically ensured by the unitarity sum rules.

- Applying the unitarity sum rules, we derive upper mass bound on 2nd Higgs as functions of the deviation of the 125GeV Higgs coupling.

Summary

Unitarity sum rules are good guiding principle for investigating extended EWSB scenarios

EWSB with h’,h”, … + W’/Z’

- From the unitarity sum rules for ff → WW’ scattering, we show Br(W’→WZ) < 2%.
- CP-odd scalar can make Br(W’→WZ) >> 2% with keeping perturbative unitarity