What if the Higgs coupling ($\kappa_X \neq 1$) deviates from the SM one

PRESENTATION

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R. Nagai, M. Tanabashi, K. Tsumura, work in progress

The Higgs boson

"the" = Higgs boson (h) in the SM

❖ Minima for the Higgs boson

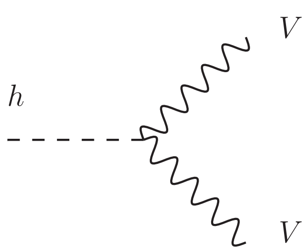
- ✧ The vacuum expectation value [VEV] ($v/\sqrt{2} = \langle \Phi^0 \rangle$) of the Higgs boson triggers electroweak symmetry breaking [EWSB]
  - → generate weak gauge boson masses

$$m_V^2 = \frac{1}{4} g_V^2 v^2$$

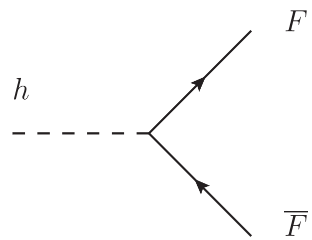
- ✧ Fermion masses are generated via Yukawa interaction

$$m_F = \frac{Y_F}{\sqrt{2}} v$$

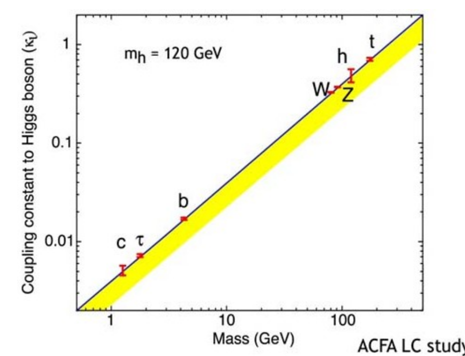
- ✧ "Mass" and "Coupling" relation



$$\lambda_{hVV} = 2m_V^2/v$$



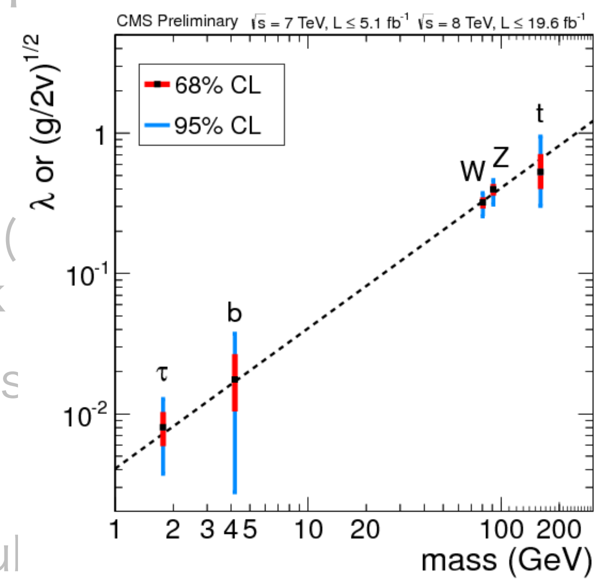
$$\lambda_{hF\overline{F}} = m_F/v$$



The Higgs boson

"the" = Higgs boson (h) in the SM

- **Minima for the Higgs boson**
  - The vacuum expectation value [VEV] (
    the Higgs boson triggers electroweak
    → generate weak gauge boson mass

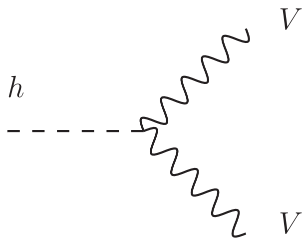


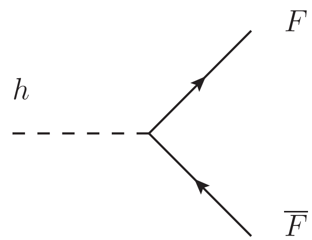
B]

  - Fermion masses are generated via Yul

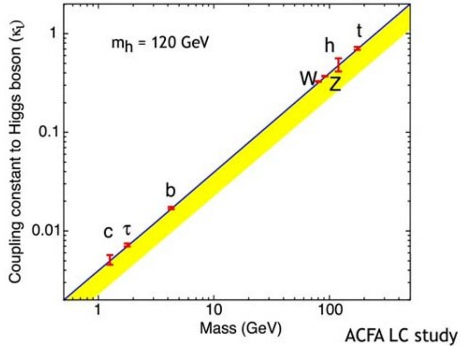
$$m_F = \frac{Y_F}{\sqrt{2}} v$$

  - "Mass" and "Coupling" relation





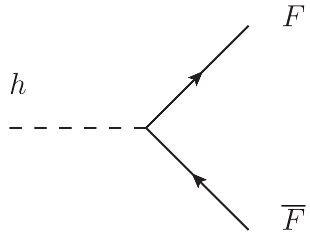
$$\lambda_{hVV} = 2m_V^2/v \qquad \lambda_{hF\overline{F}} = m_F/v$$

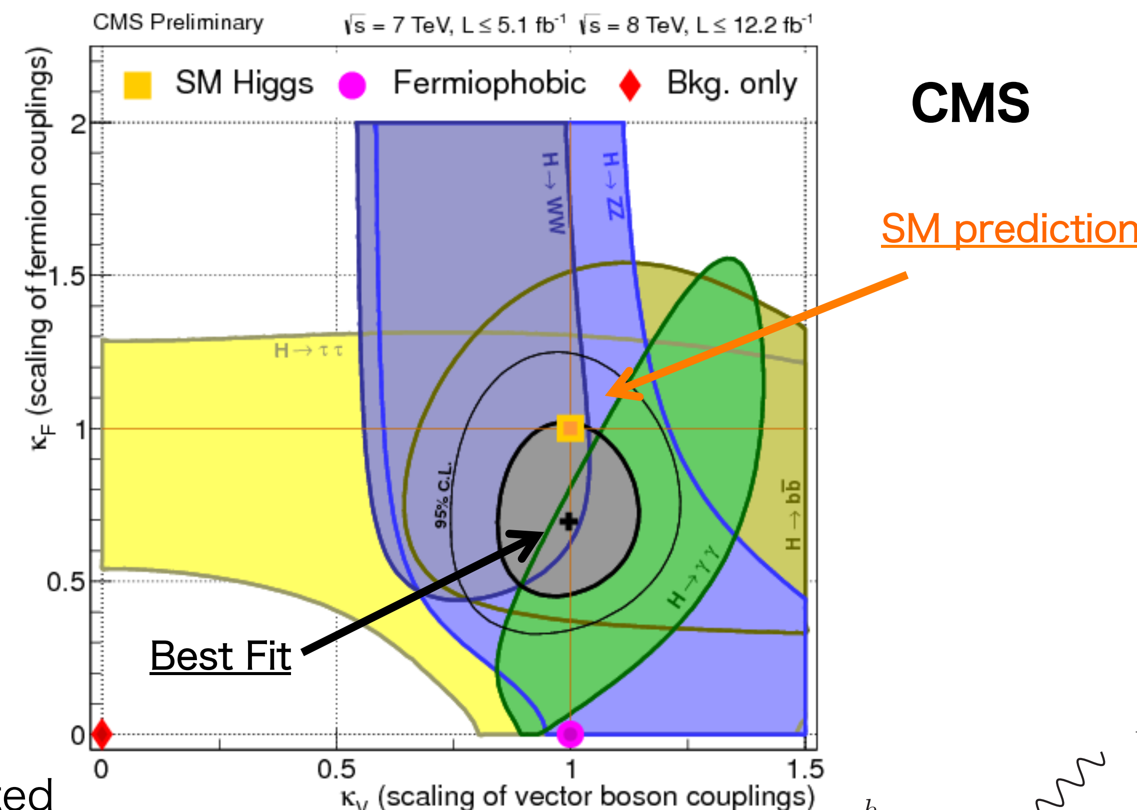


Scaling factors

Higgs couplings can be deviated from the SM one

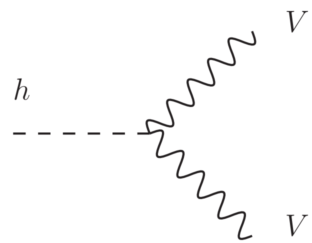
$$\kappa_F = \lambda_{hF\overline{F}} / \lambda_{hF\overline{F}}^{\rm SM}$$





Shaded regions are indicated by each Higgs decay channel.

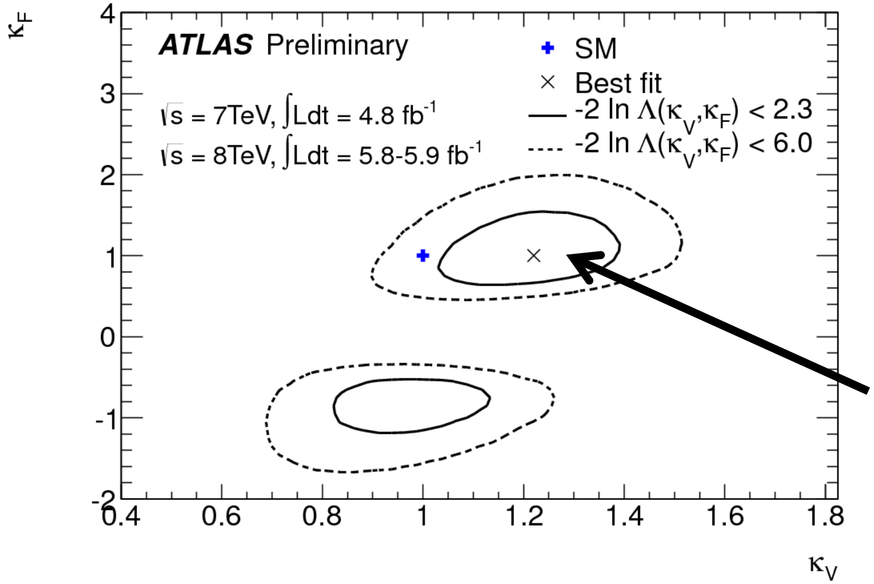
$$\kappa_V = \lambda_{hVV} / \lambda_{hVV}^{\rm SM}$$



The deviations

can be regarded as a consequence of

the Beyond the Standard Model



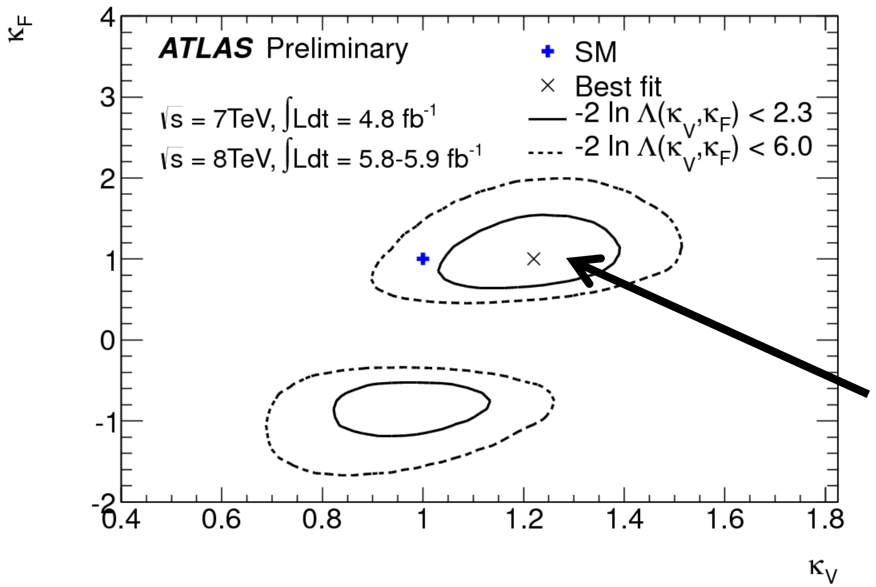
ATLAS

$\kappa_V > 1$ is favored

The deviations

=

Today's Goal: the sign of the 2nd Higgs boson



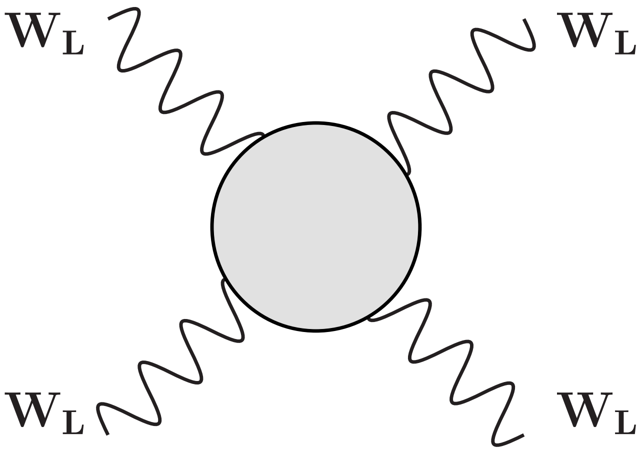
ATLAS

$\kappa_V > 1$ is favored

$W_L W_L$ scattering

(Lessons from the SM)

$W_L W_L \to W_L W_L$ scattering



ε_L (Longitudinal polarizations) diverges for higher energy

$$\epsilon^{\mu}_{(L)} = \frac{E}{m_W}\begin{pmatrix} \frac{|\vec{p}|}{E} \\ \frac{\vec{p}}{|\vec{p}|} \end{pmatrix}$$

$$E^2 = |\vec{p}|^2 + m_W^2$$
$$\epsilon_{(L)\mu}\epsilon^{\mu}_{(L)} = -1$$

Scattering amplitudes also diverge

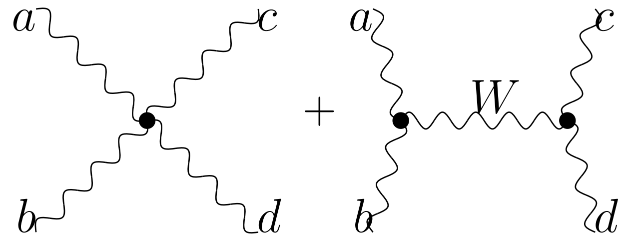
$$\mathcal{M}(W_L^a W_L^b \to W_L^c W_L^d) \propto |\epsilon_{(L)\mu}|^4 \sim \frac{E^4}{m_W^4}$$

→ perturbation theory may be broken !?

$W_L W_L \to W_L W_L$ scattering

More precisely

$$i\mathcal{M}_{\rm gauge}(ab \to cd) =$$



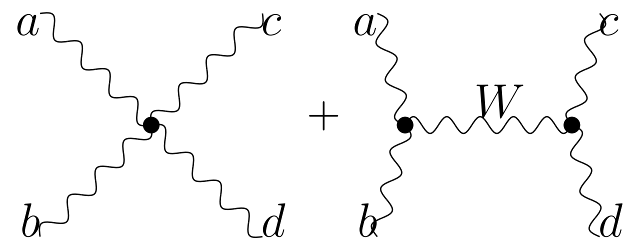
$+$ crossed.

Quartic gauge interaction, contact int.

$$\mathcal{M}_\times = g_{WWWW}\left\{+\frac{E^4}{m_W^2}({\color{red}A}+{\color{blue}B})+\frac{E^2}{m_W^2}({\color{red}a}+{\color{blue}b})\right\}$$

$W_L W_L \rightarrow W_L W_L$ scattering

More precisely

$i\mathcal{M}_{\text{gauge}}(ab \to cd) =$  + crossed.

Quartic gauge interaction, contact int.

$$\mathcal{M}_\times = g_{WWWW}\left\{+\frac{E^4}{m_W^2}(A+B)+\frac{E^2}{m_W^2}(a+b)\right\}$$

Gauge boson exchange, t (u) channel

$$\mathcal{M}_t = g_{WWW}^2\left\{-\frac{E^4}{m_W^2}\left(A+\frac{m_W^2}{E^2}a\right)+\frac{E^2}{m_W^2}C+(\cdots)\right\}$$

$$\mathcal{M}_u = g_{WWW}^2\left\{-\frac{E^4}{m_W^2}\left(B+\frac{m_W^2}{E^2}b\right)+\frac{E^2}{m_W^2}C+(\cdots)\right\}$$

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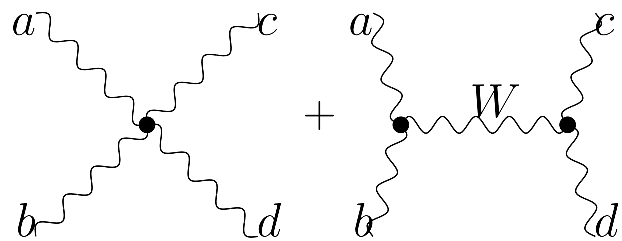
$i\mathcal{M}_{\rm gauge}(ab \to cd) =$  + crossed.

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Gauge sym.:

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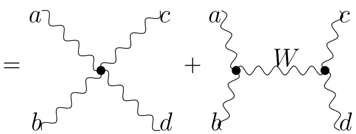
$$g_{WWWW} = g_{WWW}^2 = g^2$$

$\frac{E^2}{m_W^2}$ divergence

$W_L W_L \to W_L W_L$ scattering

$i\mathcal{M}_{\rm gauge}(ab \to cd) =$



$+$ crossed.

$$\mathcal{M}_{\rm gauge} = +8g^2\left\{+\frac{s}{m_W^2}\,C + (\cdots)\right\}$$

where $E^2 = \frac{s}{4}$, $m_W^2 = \frac{g^2v^2}{4}$

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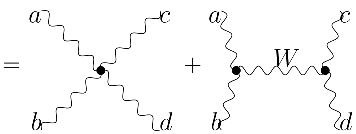
$i\mathcal{M}_{\text{gauge}}(ab \to cd) =$  + crossed.

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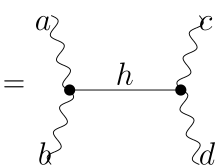
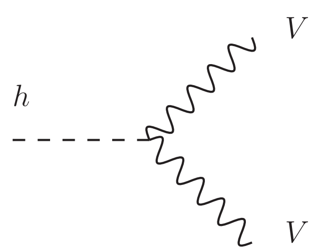
Moreover, Higgs exchange diagram

$i\mathcal{M}_{\text{Higgs}}(ab \to cd) =$  + crossed.

$$\mathcal{M}_{\text{Higgs}} = 8g^2 \kappa_W^2 \left\{ +\frac{s}{m_W^2} \frac{-s}{s - m_h^2} C + (\cdots) \right\}$$

$$\kappa_V = \lambda_{hVV} / \lambda_{hVV}^{\text{SM}}$$



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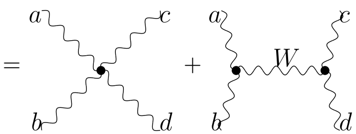
$i\mathcal{M}_{\mathrm{gauge}}(ab \to cd) =$  $+$ crossed.

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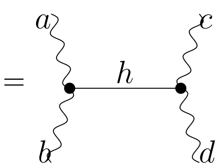
$i\mathcal{M}_{\mathrm{Higgs}}(ab \to cd) =$  $+$ crossed.

$$\mathcal{M}_{\mathrm{Higgs}} = 8g^2\kappa_W^2\left\{+\frac{s}{m_W^2}\,\frac{-s}{s-m_h^2}\,C + (\cdots)\right\}$$

SM : $\mathcal{M}_{\mathrm{tot}} = \frac{m_h^2}{v^2}\frac{s}{s-m_h^2} + \cdots \quad (\kappa_W = 1)$

$W_L W_L$ scattering amplitude is unitarized (cancel E^2/m_W^2 divergence)

Unitarity bound on m_h

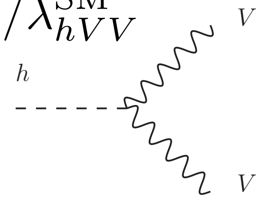
$\mathcal{M} \propto \frac{m_h^2}{v^2}$ for high energy

Too large m_h (again) leads divergence of amp.

Mass bound: $$\frac{m_h^2}{v^2} \leq 4\pi$$

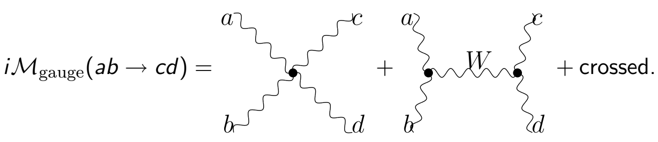
Lee, Quigg, Thacker (1977)

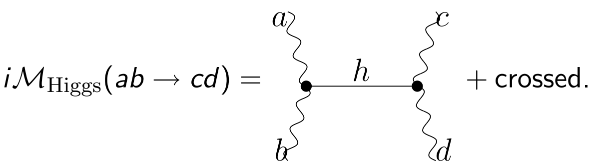
$\kappa_V = \lambda_{hVV}/\lambda_{hVV}^{\rm SM}$



If $\kappa_{\mathbf{W}} \neq \mathbf{1}$

cancellation mech. doesn't work





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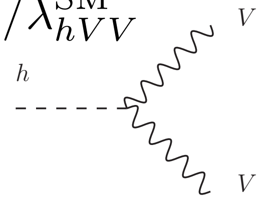
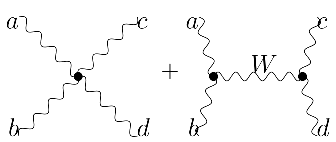


Sum-rule (with one more neutral Higgs)

$$(\kappa_W^h)^2 + (\kappa_W^H)^2 = 1$$

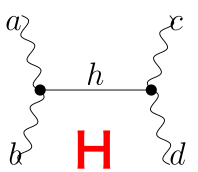
J.F.Gunion et al (1991)

$i\mathcal{M}_{\rm gauge}(ab \to cd) =$



$+$ crossed.

$i\mathcal{M}_{\rm Higgs}(ab \to cd) =$



$+$ crossed.

-Singlet mixing: $\sin^2\alpha + \cos^2\alpha = 1$

-2HDM: $\sin(\beta-\alpha)^2 + \cos(\beta-\alpha)^2 = 1$

Kang, Park (2013) [case for additional singlet]
Nagai, Tanabashi, KT (2013)

Unitarity bound on m_H

$$\mathcal{M} \propto \kappa_W^2 \frac{m_h^2}{v^2} + (1-\kappa_W^2)\frac{m_H^2}{v^2}$$ for high energy

Too large m_H (again) leads divergence of amp.

$\kappa \equiv 1 + \Delta\kappa$

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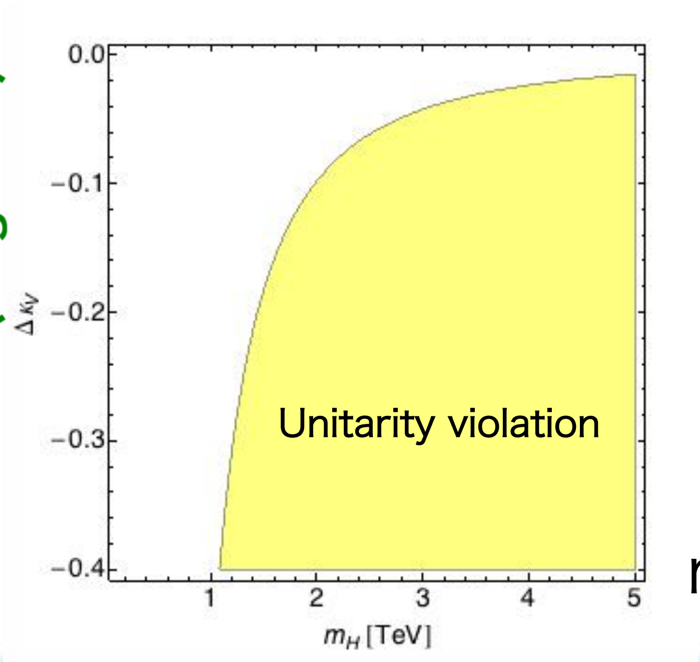
Mass bound:

$\Delta\kappa<0$ (Negative)



m_H[TeV]

$\kappa \equiv 1 + \Delta\kappa$

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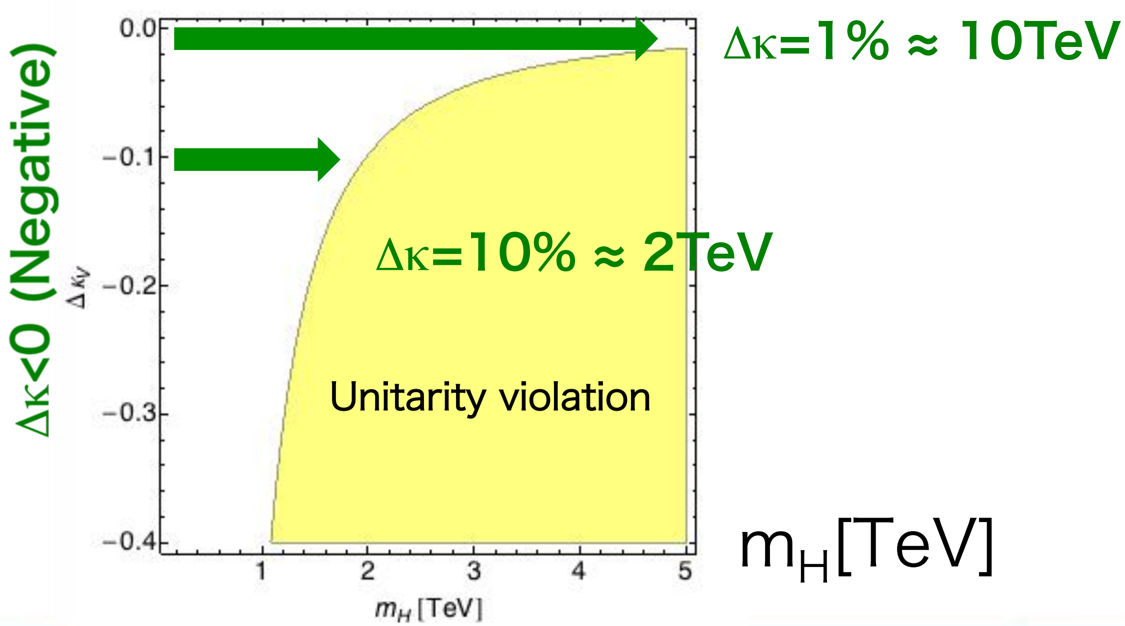

$\kappa \equiv 1 + \Delta\kappa$

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"Δκ < 0" = Additional neutral Higgs

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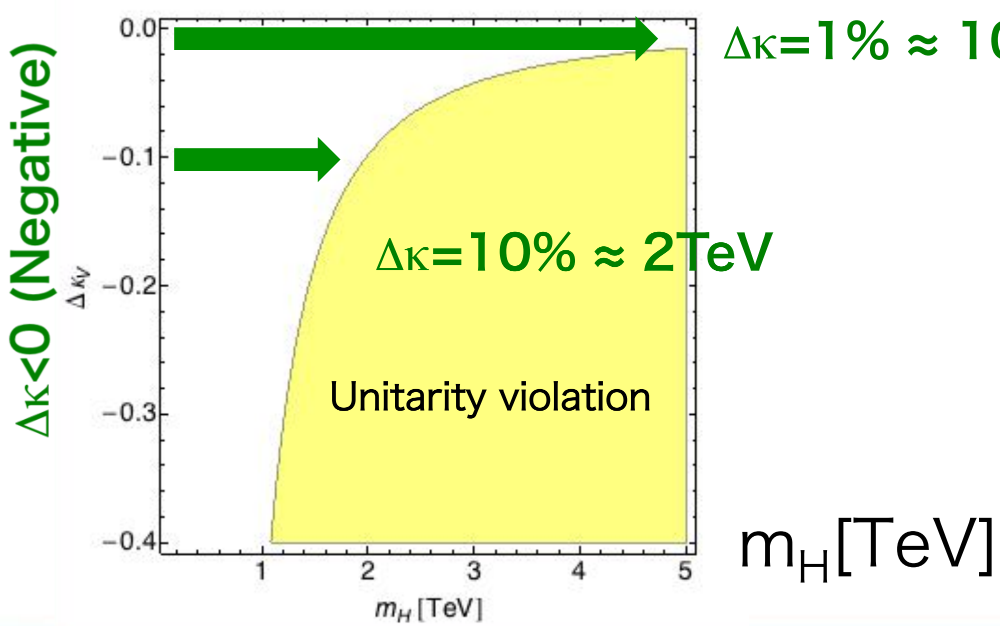


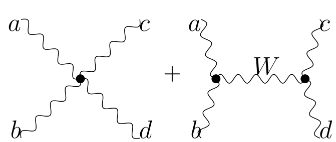
$\kappa \equiv 1 + \Delta\kappa$

If $\kappa_{\mathbf{W}} > \mathbf{1}$

Does the sum-rule break?

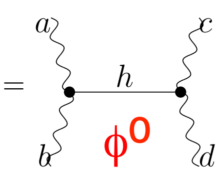
$$\sum_{\phi^0} (\kappa_W^{\phi^0})^2 = 1$$

$i\mathcal{M}_{\rm gauge}(ab \to cd) =$



$+$ crossed.

$i\mathcal{M}_{\rm Higgs}(ab \to cd) =$

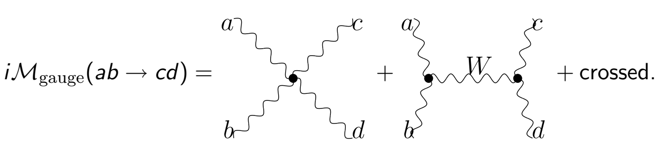


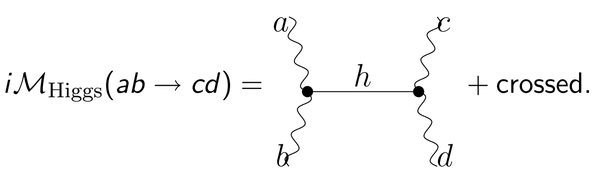
$+$ crossed.

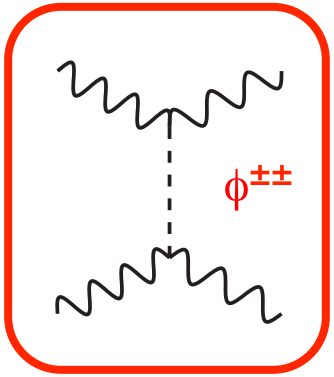
Modified Sum-rule (with H^{++})

$$\sum_{\phi^0}(\kappa_W^{\phi^0})^2 - 4\sum_{\phi^{\pm\pm}}(\kappa_W^{\phi^{\pm\pm}})^2 = 1$$

J.F.Gunion et al (1991)







Unitarity bound on $m_{H^{\pm\pm}}$

$$\mathcal{M} \propto 2\kappa_W^2 \frac{m_h^2}{v^2} - (1-\kappa_W^2)\frac{m_{H^{\pm\pm}}^2}{v^2}$$ for high energy

Too large $m_{H^{\pm\pm}}$ (again) leads divergence of amp.

$\kappa \equiv 1 + \Delta\kappa$

Nagai, Tanabashi, KT (2013)

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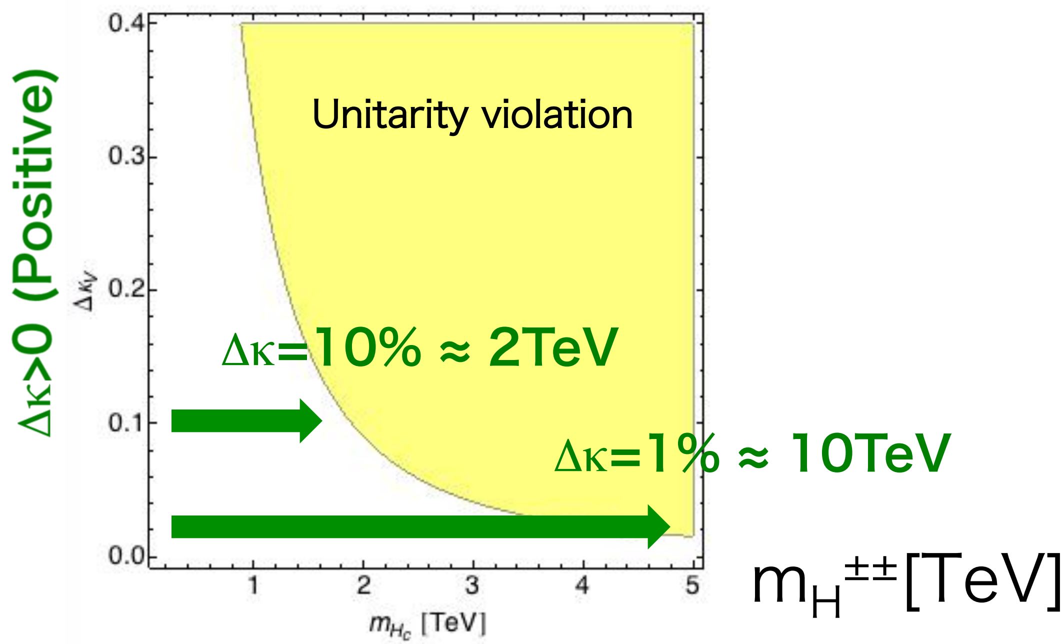
Mass bound:



$\kappa \equiv 1 + \Delta\kappa$

Nagai, Tanabashi, KT (2013)

"Δκ > 0" = Additional charged Higgs

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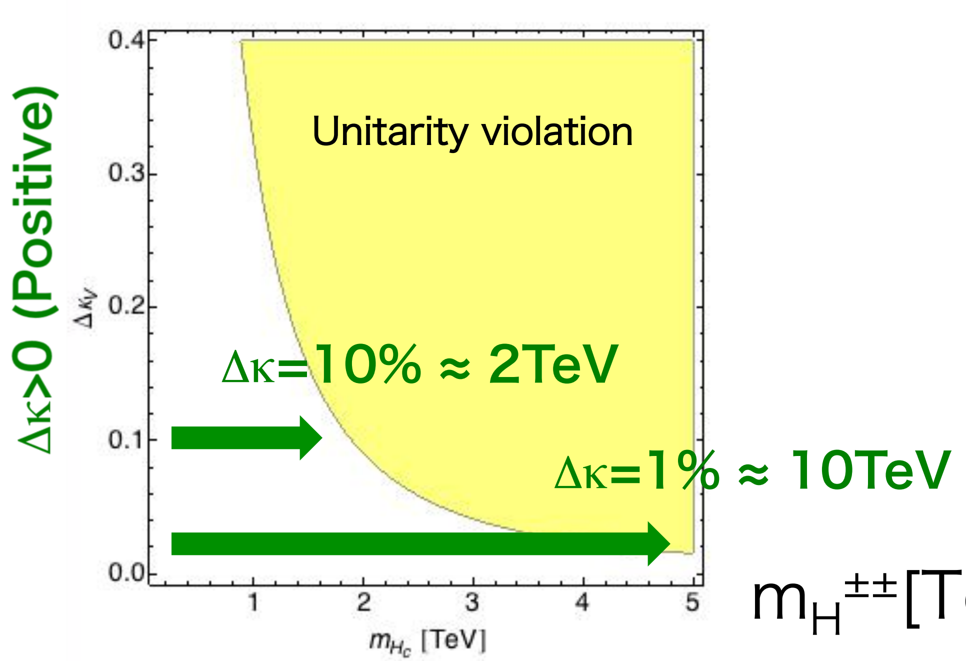

$m_H^{\pm\pm}$[TeV]

$\kappa \equiv 1 + \Delta\kappa$

Beyond the tree level

Beyond the tree level

J.F.Gunion et al (1991)

$$\sum_{\phi^0}(\kappa_W^{\phi^0})^2 - 4\sum_{\phi^{\pm\pm}}(\kappa^{\phi^{\pm\pm}_W})^2 = 1$$

Assumption: Massive vector boson + Arbitrary Higgs bosons

Beyond the tree level

J.F.Gunion et al (1991) $$\sum_{\phi^0}(\kappa_W^{\phi^0})^2-4\sum_{\phi^{\pm\pm}}(\kappa^{\phi_W^{\pm\pm}})^2=1$$

Assumption: Massive vector boson + Arbitrary Higgs bosons

Gauge inv. is NOT manifest (key point for loop calc.)

Gauge covariant extension

Assumption: massive vector boson + arbitrary Higgs bosons

J.F.Gunion et al (1991)

$$\mathbf{W}^{\pm}_{\mu}, \mathbf{Z}_{\mu} \qquad \mathbf{h}, \mathbf{H}, \mathbf{H}^{\pm}, \mathbf{H}^{\pm\pm}, \cdots$$

Gauge covariant extension

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To make EWCh Lagrangian

Nagai, Tanabashi, KT (2013)

$$\mathrm{tr}[\mathbf{U}^{\dagger}\mathbf{D}_{\mu}\mathbf{U}\tau_{\pm}], \mathrm{tr}[\mathbf{U}^{\dagger}\mathbf{D}_{\mu}\mathbf{U}\tau_{\mathbf{3}}]$$

Manifestly gauge cov. Ext.

Covariant derivative

NG bosons

$$\mathbf{U} = \exp(\mathbf{i}\,\omega^{\mathbf{a}}\tau^{\mathbf{a}})$$

Unitary gauge

$$\mathrm{tr}[U^{\dagger}D_{\mu}U\tau_{\pm}] = \frac{ig}{\sqrt{2}}W^{\pm}_{\mu} \qquad \mathrm{tr}[U^{\dagger}D_{\mu}U\tau_{3}] = ig_{Z}Z_{\mu}$$

Gauge covariant extension

Assumption: massive vector boson + arbitrary Higgs bosons

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Nagai, Tanabashi, KT (2013)

$$\mathrm{tr}[\mathbf{U}^\dagger \mathbf{D}_\mu \mathbf{U} \tau_\pm], \mathrm{tr}[\mathbf{U}^\dagger \mathbf{D}_\mu \mathbf{U} \tau_\mathbf{3}]$$

$$\mathcal{L}_\phi = -v \sum_{n=1}^{N_0} \kappa_W^{\phi_n^0} \phi_n^0 \mathrm{tr}[U^\dagger D_\mu U \tau_+] \mathrm{tr}[U^\dagger D^\mu U \tau_-]$$

$$-v \sum_{n=1}^{N_0} \frac{1}{4} \kappa_Z^{\phi_n^0} \phi_n^0 \mathrm{tr}[U^\dagger D_\mu U \tau_3] \mathrm{tr}[U^\dagger D^\mu U \tau_3]$$

$$-v \left(\sum_{n=1}^{N_+} \frac{1}{\sqrt{2}} \kappa_{WZ}^{\phi_n^+} \phi_n^+ \mathrm{tr}[U^\dagger D_\mu U \tau_-] \mathrm{tr}[U^\dagger D^\mu U \tau_3] - \sum_{n=1}^{N_{++}} \frac{1}{2} \kappa_W^{\phi_n^{++}} \phi_n^{++} \mathrm{tr}[U^\dagger D_\mu U \tau_-] \mathrm{tr}[U^\dagger D^\mu U \tau_-] + h.c. \right)$$

Thanks to Gauge covariance

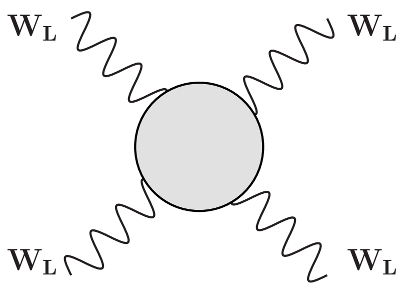
Nagai, Tanabashi, KT (2013)

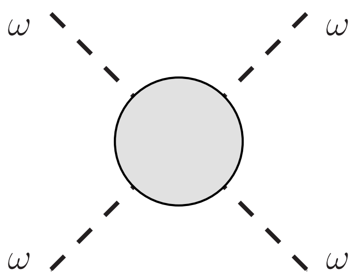
Equivalence theorem

$$\mathcal{M}(V_L V_L \to V_L V_L) \simeq \mathcal{M}(\omega\omega \to \omega\omega) + \mathcal{O}(m_V^2/s)$$

V_L V_L scattering amp.

NGB scattering amp.



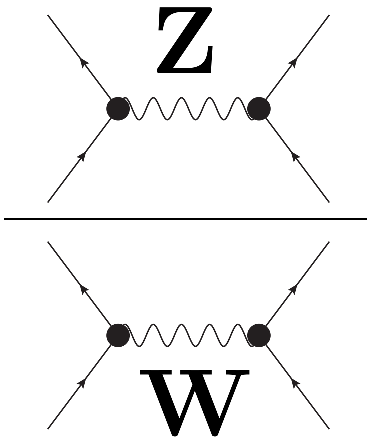


$$\sum_{\phi^0} (\kappa_W^{\phi^0})^2 - 4 \sum_{\phi^{\pm\pm}} (\kappa^{\phi_W^{\pm\pm}})^2 = 1$$

We successfully reproduce all unitarity sum-rules by much simpler calc. with NGBs

(We extend these sum-rules without $\rho \neq 1$)

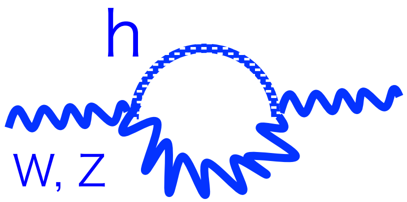
ρ parameter (tree)

$\rho =$  $= \dfrac{v_W^2}{v_Z^2}$

$$g_V \times \frac{1}{m_V^2} \times g_V \approx \frac{1}{4\,v_V^2}$$

The ratio between the charged and neutral current int.

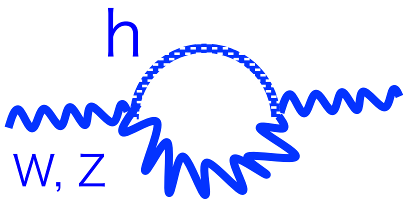
ρ parameter (1-loop)



$$\rho = 1 + \Delta\rho$$

$$\Delta\rho = \frac{\Pi_{WW}(p^2=0)}{m_W^2} - \frac{\Pi_{ZZ}(p^2=0)}{m_Z^2}$$

ρ parameter (1-loop)



$$\rho = 1 + \Delta\rho$$

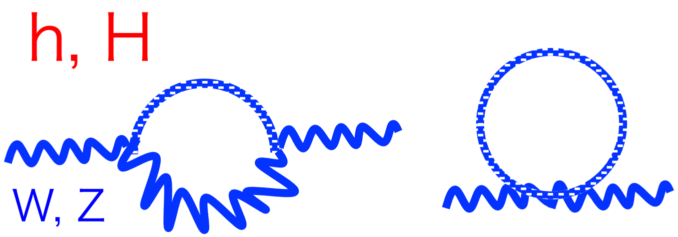
ρ is measured very precisely!!

$$\rho_0 = (\rho/\rho_{\rm SM}) = 1.0004^{+0.0003}_{-0.0004}$$

Nagai, Tanabashi, KT (2013)

Ex. 2 neutral Higgs bosons (h,H)

$$\Delta\rho = G_F\left\{ A m^2_{\phi_n^Q}\ln\Lambda^2 + B\Lambda^2 + C m_W^2 \ln\Lambda^2 + D m_Z^2 \ln\Lambda^2 + E \right\}$$



Nagai, Tanabashi, KT (2013)

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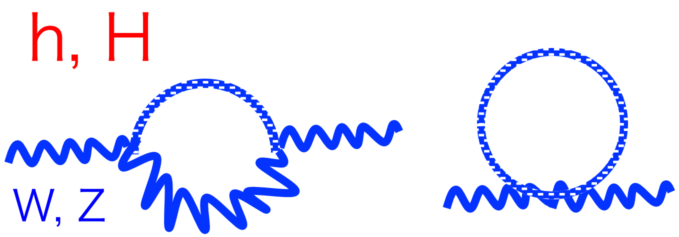


Unitariry sum-rules for ($V_L V_L \rightarrow \phi\phi$)

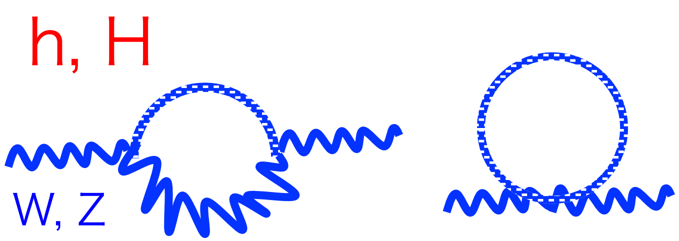
$$A = 0 \text{ and } B - (C + D) = 0$$

Nagai, Tanabashi, KT (2013)

Ex. 2 neutral Higgs bosons (h,H)

[Unitariry sum-rules (VV→ϕϕ) are also assumed]

$$\Delta\rho = G_F\left\{(C+D)\Lambda^2 + Cm_W^2\ln\Lambda^2 + Dm_Z^2\ln\Lambda^2 + E\right\}$$



Nagai, Tanabashi, KT (2013)

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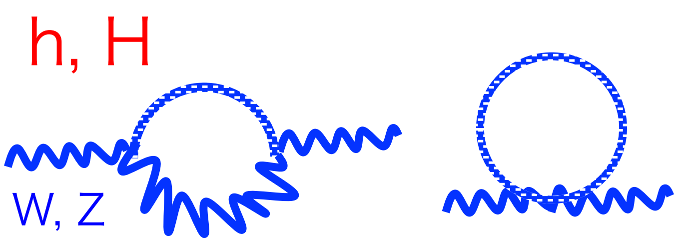

Divergences appear unless C=0 and D=0

[New sum-rules]

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$$\kappa_W^n = \rho_{\rm tree} \kappa_Z^n$$

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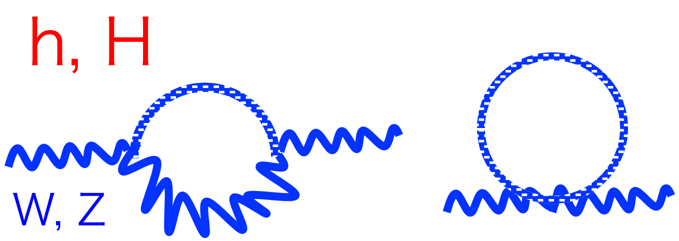
Ex. 2 neutral Higgs bosons (h,H)

[Unitariry sum-rules (VV→ϕϕ) are also assumed]

$$\Delta\rho = G_F \left\{ (C + D)\Lambda^2 + C m_W^2 \ln \Lambda^2 + D m_Z^2 \ln \Lambda^2 + E \right\}$$



Let's evaluate exp. constraint on finite term E

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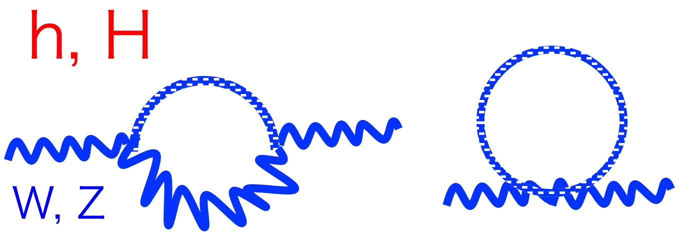
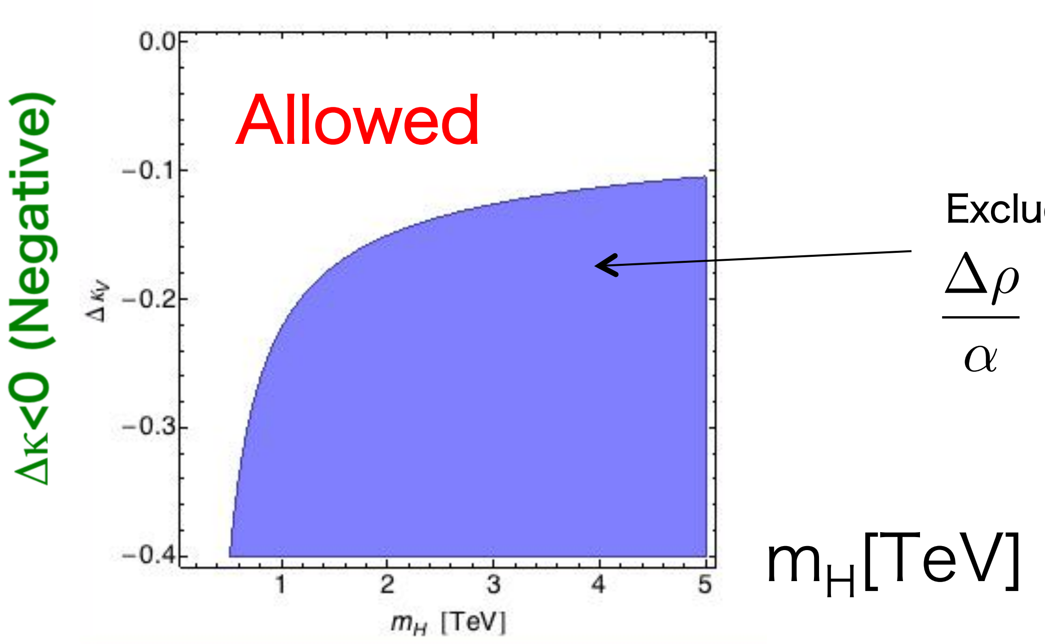
Ex. 2 neutral Higgs bosons (h,H)



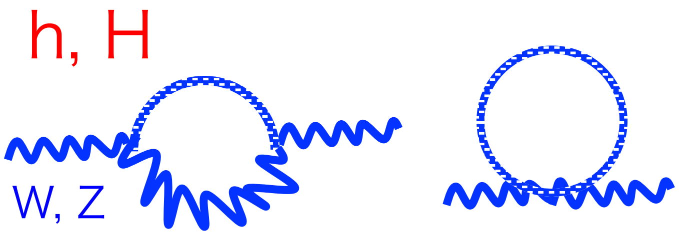
$$\Delta\rho \simeq (1-\kappa_V^2)\ln\frac{m_h^2}{m_H^2}$$



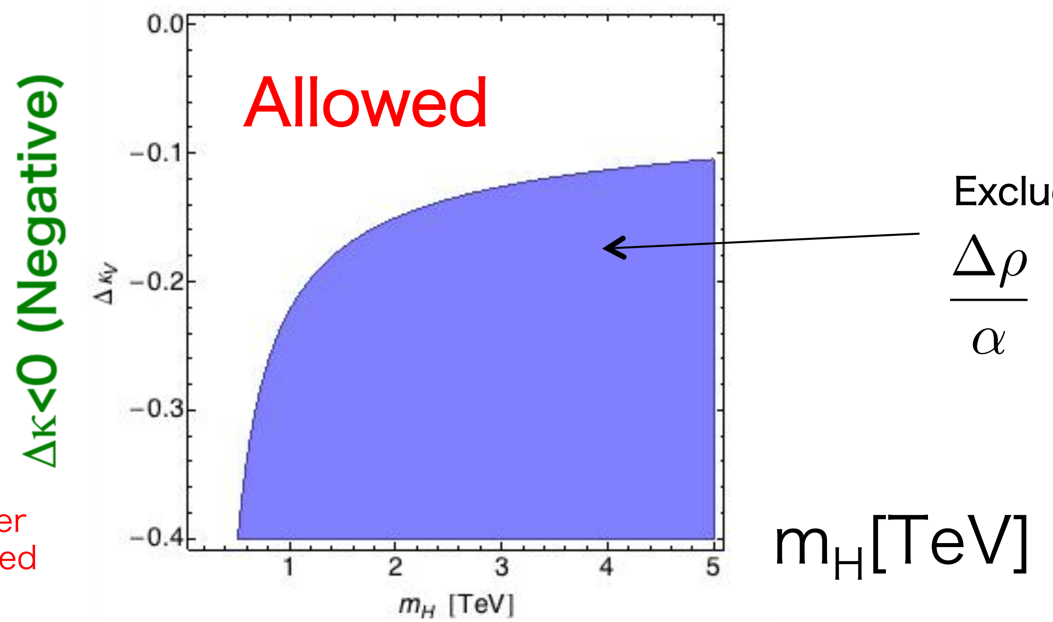
$$\frac{\Delta\rho}{\alpha} = 0.02^{+0.11}_{-0.12}$$

Nagai, Tanabashi, KT (2013)

Ex. 2 neutral Higgs bosons (h,H)



$$\Delta\rho \simeq (1-\kappa_V^2)\ln\frac{m_h^2}{m_H^2}$$



$$\frac{\Delta\rho}{\alpha} = 0.02^{+0.11}_{-0.12}$$

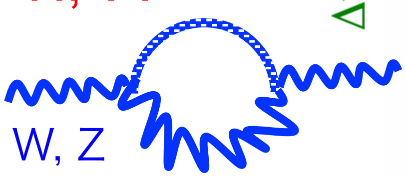
Caution: absence of other new particles are assumed

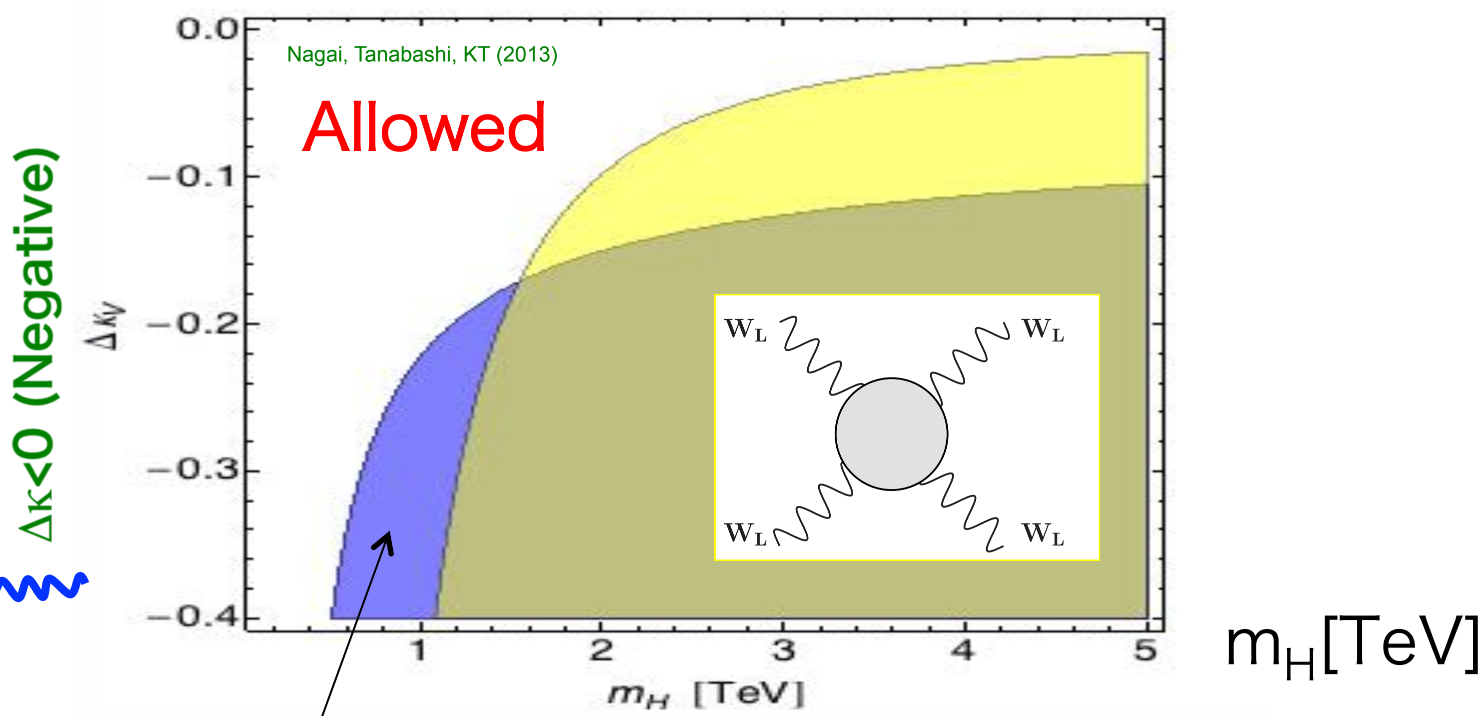
Stronger bound would be obtained if we combine S, T, U constraints simultaneously.

Summary

Summary

- ✓ $W_L W_L$ scattering Unitarity and $\Delta\rho$ are evaluated using EWCh Lagrangian
- ✓ Deviation(s) of Higgs coupling = the sign of the 2nd Higgs boson





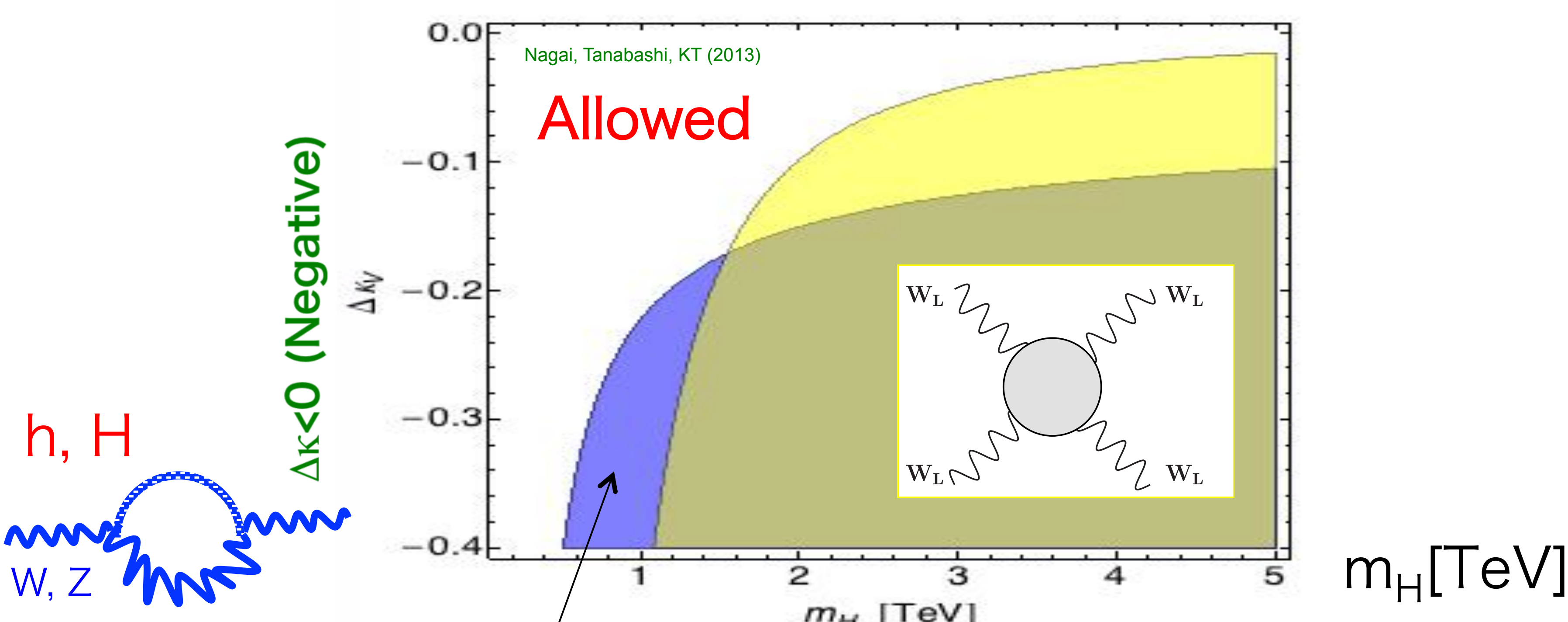
$$\Delta\rho \simeq (1-\kappa_V^2)\ln\frac{m_h^2}{m_H^2}$$

$$\left|\kappa_V^2\frac{m_h^2}{v^2}+(1-\kappa_V^2)\frac{m_H^2}{v^2}\right|\leq 8\pi$$

Fin.

Summary

- ✓ $W_L W_L$ scattering Unitarity and Dr are evaluated using EWCh Lagrangian
- ✓ Deviation(s) of Higgs coupling = the sign of the 2^{nd} Higgs boson



Precision measurement of $\Delta\kappa \neq 0$

= Determine New Higgs scales