$H \rightarrow \gamma\gamma$ beyond the standard model

J.Llodra-Perez
IPN Lyon
LC09 Perugia

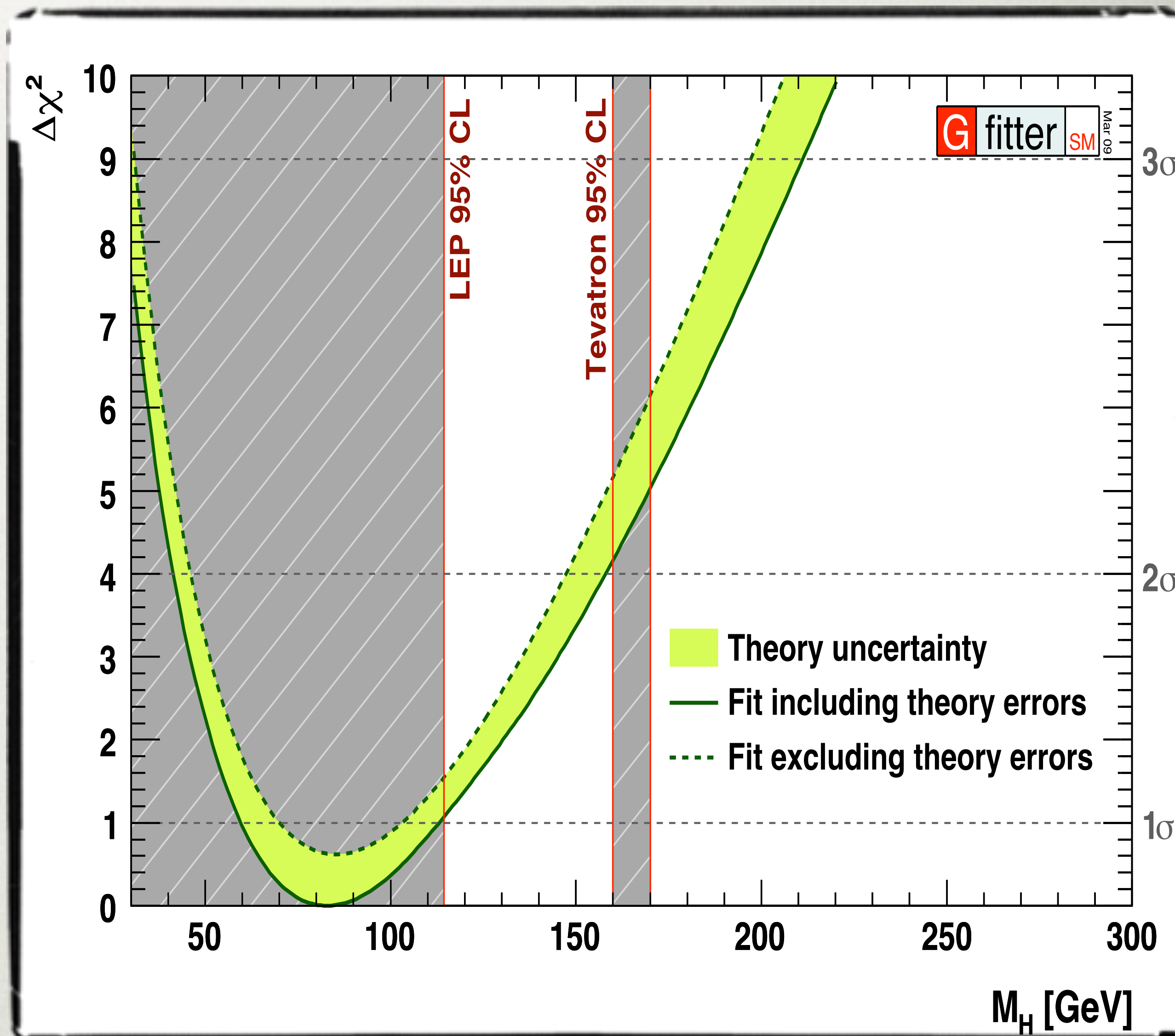
G.Cacciapaglia, A.Deandrea & J.L.P, arXiv: 0901.0927
JHEP: 0906:054, 2009

Outline

- Introduction of SM Higgs Physics
- Observables and New Physics
- Model-independent parametrization
- Use for data analysis and models survey

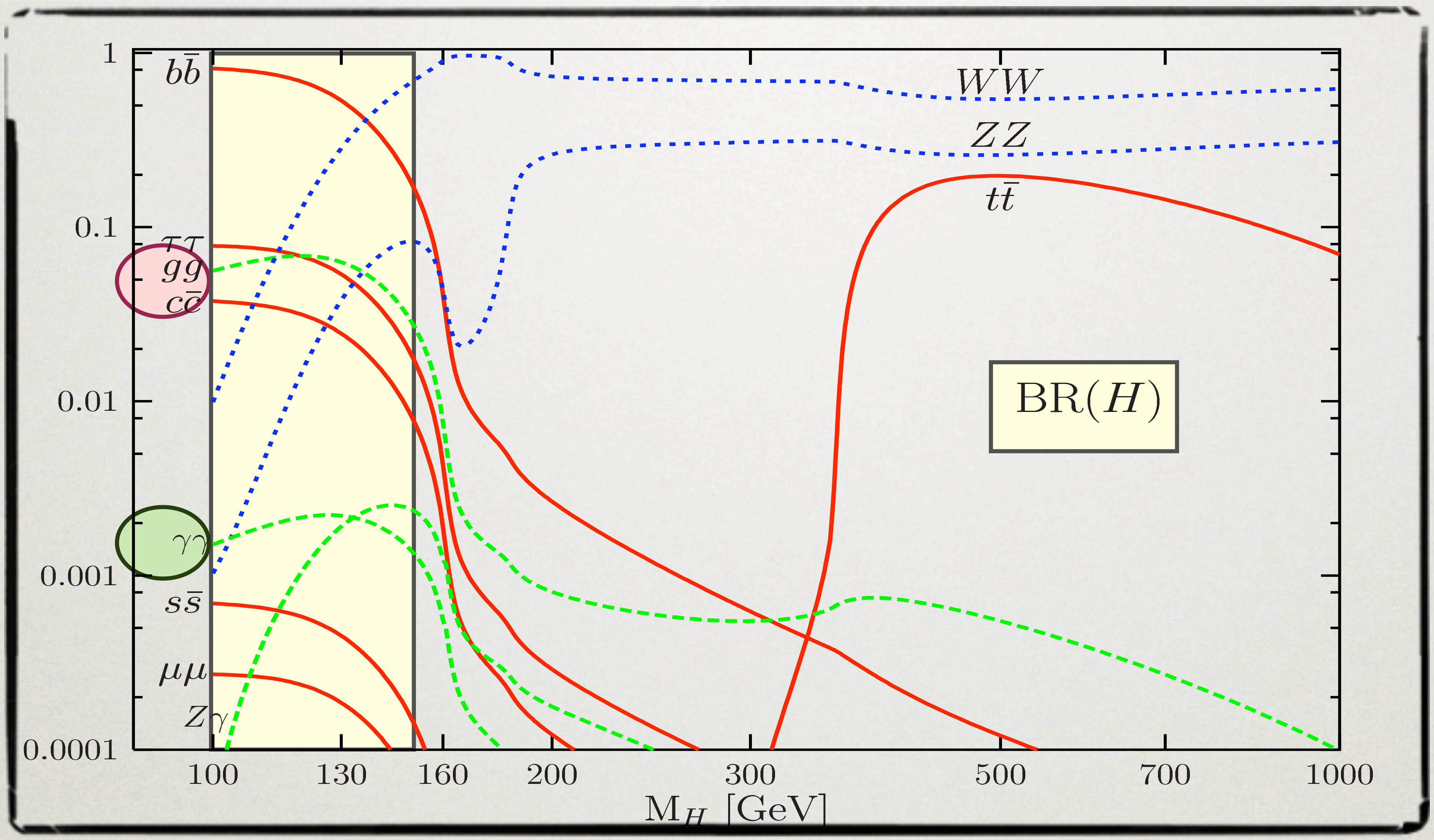
Where Is The Higgs Boson?

- LEP and Tevatron results
  → Higgs at low mass ?
- 115 GeV < M_H < 150 GeV
- SM Higgs
  Radiative instability of Higgs mass
- New Physics ????
  → Link with EWSB



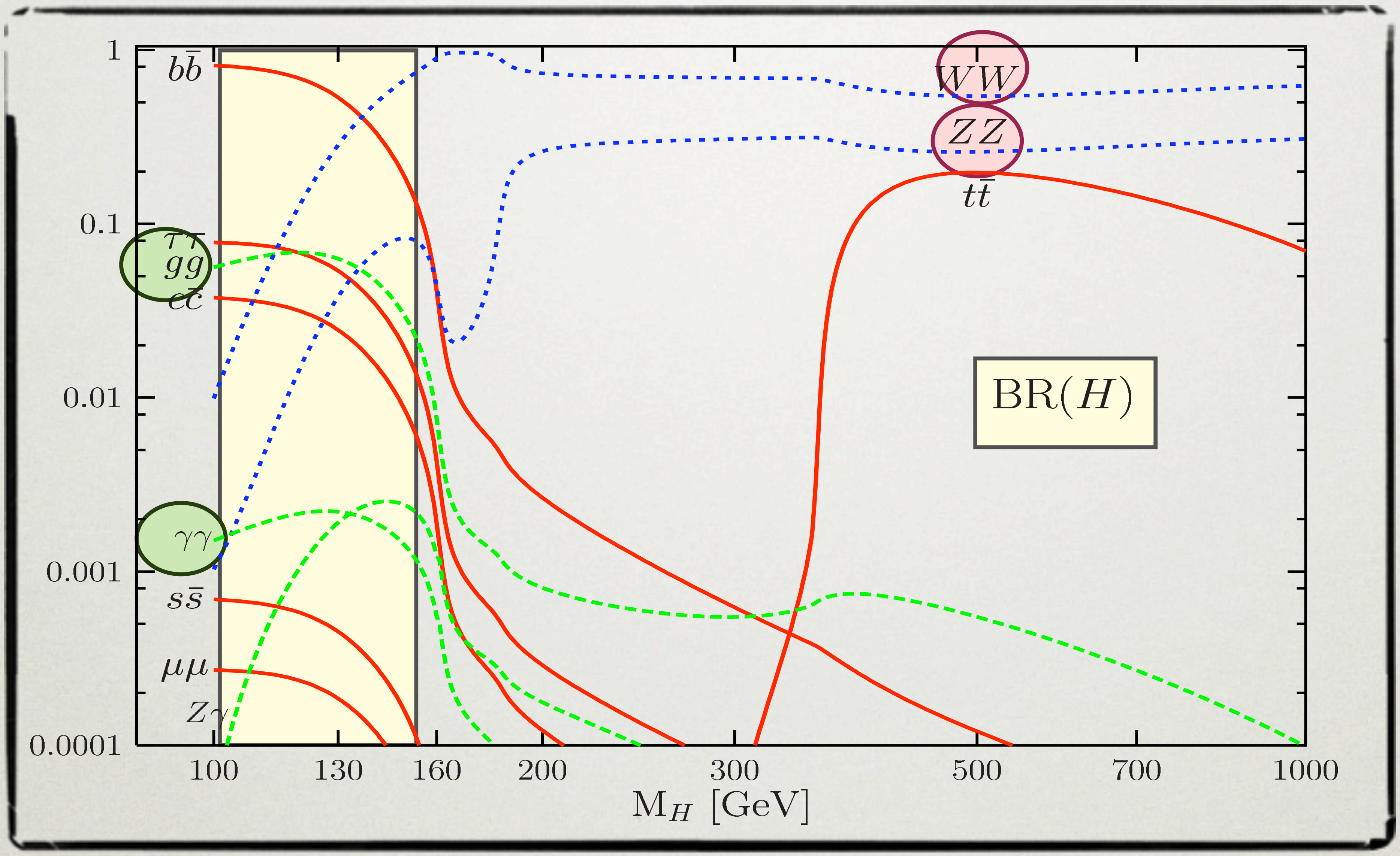
J. Ellis, J.R. Espinosa , G.F. Giudice, A. Hoecker, A. Riotto, e-Print: arXiv:0906.0954 [hep-ph]

Light Higgs At Lhc



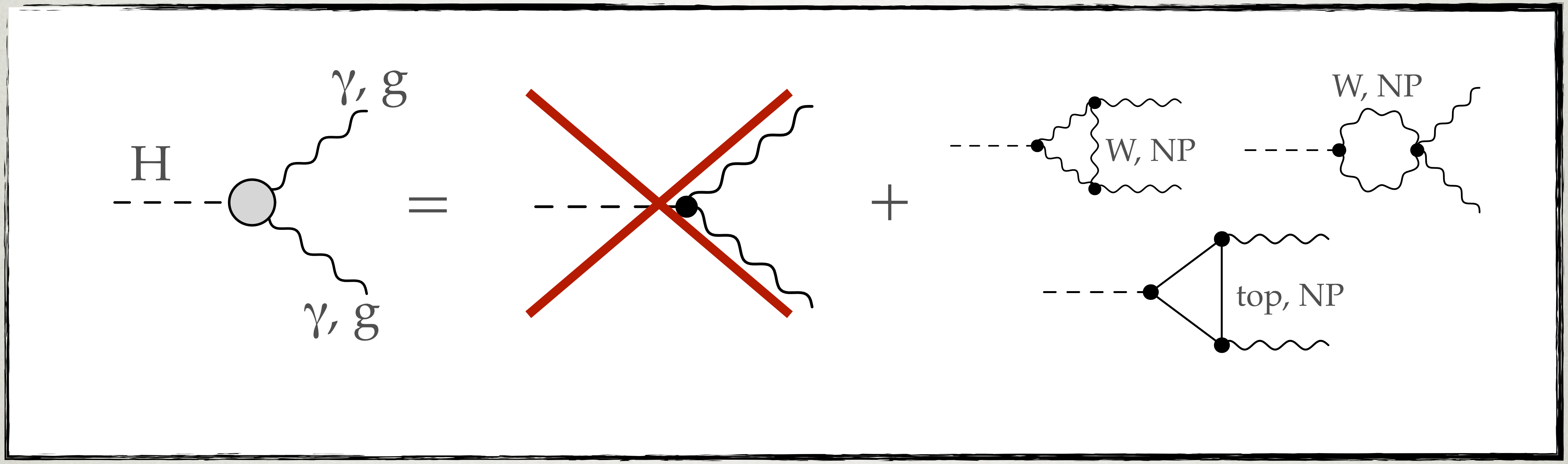
- Production → Gluons Fusion
- Detection Channel → Decay into two photons

Light Higgs At Ilc



- Production → Vector Bosons Fusion, Higgsstrahlung
- Detection Channel → Decay into photons & gluons

Loop Induced Processes And New Physics



- Loop induced → Small effects
- Couplings sensitive to NP running into the loops
- Links between New Physics and EWSB
  (even beyond direct detection threshold)

New Physics Effects On The Decay Widths

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| A_W(\tau_W) + \sum_{\text{fermions}} N_{c,f} Q_f^2 A_F(\tau_f) + \sum_{NP} N_{c,NP} Q_{NP}^2 A_{NP}(\tau_{NP}) \right|^2$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^3}{16\sqrt{2}\pi^3} \left| \frac{1}{2} \sum_{\text{quarks}} A_F(\tau_f) + \sum_{NP} C(r_{NP}) A_{NP}(\tau_{NP}) \right|^2 \quad \text{where} \quad \tau_x = \frac{m_H^2}{4m_x^2}$$

- SM ⟶ Masses proportional to Higgs VEV: v_{SM}
  ⟶ No decoupling

$$A_F(0) = \frac{4}{3}, \quad A_W(0) = -7, \quad A_S(0) = \frac{1}{3}, \quad A_{F,W,S}(\infty) \longrightarrow 0$$

New Physics Effects On The Decay Widths

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- New Physics ⟶ Charged and Colored Particles
  ⟶ Couplings not necessarily proportional to Higgs VEV

$$A_{NP} = \frac{v_{SM}}{m_{NP}} \frac{\partial m_{NP}}{\partial v} \, A_{F,W,S} \, .$$

New Physics Effects On The Decay Widths

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$$A_{NP} = \frac{v_{SM}}{m_{NP}} \frac{\partial m_{NP}}{\partial v} A_{F,W,S} \, .$$

Coupling normalized by the SM one

New Physics Effects On The Decay Widths

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- New Physics → Charged and Colored Particles
  → Couplings not necessarily proportional to Higgs VEV

$$A_{NP} = \frac{v_{SM}}{m_{NP}} \frac{\partial m_{NP}}{\partial v} A_{F,W,S}.$$

→ Only depends on spin and mass of NP

A Model Independent Parametrization

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| A_W(\tau_W) + 3\left(\frac{2}{3}\right)^2 A_t(\tau_t)\,[1+\kappa_{\gamma\gamma}] + \dots \right|^2 ,$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^3}{16\sqrt{2}\pi^3} \left| \frac{1}{2} A_t(\tau_t)\,[1+\kappa_{gg}] + \dots \right|^2 ,$$

where
$$\kappa_{\gamma\gamma} = \sum_{NP} \frac{3}{4} N_{c,NP} Q_{NP}^2 \,\frac{v_{SM}}{m_{NP}} \frac{\partial m_{NP}}{\partial v}\, \frac{A_{F,W,S}(m_{NP})}{A_t} ,$$

$$\kappa_{gg} = \sum_{NP} 2C(r_{NP})\, \frac{v_{SM}}{m_{NP}} \frac{\partial m_{NP}}{\partial v}\, \frac{A_{F,W,S}(m_{NP})}{A_t}$$

- Normalization with the top contribution
- Introduction of 2 new parameters
- Only loop effects & no tree level modifications

A Model Independent Parametrization

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$$\kappa_{gg} = \sum_{NP} 2C(r_{NP}) \, \frac{v_{SM}}{m_{NP}} \frac{\partial m_{NP}}{\partial v} \frac{A_{F,W,S}(m_{NP})}{A_t}$$

- If $2\,M_{NP} >> M_H$, only spin dependent ratios

$$\frac{A_{NP}}{A_t} = \begin{cases} 1 & \text{for fermions} \\ -\frac{21}{4} & \text{for vectors} \\ \frac{1}{4} & \text{for scalars} \end{cases}$$

A Model Independent Parametrization

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| A_W(\tau_W) + 3\left(\frac{2}{3}\right)^2 A_t(\tau_t)\,[1+\kappa_{\gamma\gamma}] + \ldots \right|^2 ,$$

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$$\kappa_{gg} = \sum_{NP} 2C(r_{NP}) \boxed{\frac{v_{SM}}{m_{NP}} \frac{\partial m_{NP}}{\partial v}} \frac{A_{F,W,S}(m_{NP})}{A_t}$$

- If there is decoupling

$$\frac{v_{SM}}{m_{NP}} \frac{\partial m_{NP}}{\partial v} \sim \frac{v_{SM}^2}{m_{NP}^2}$$

Corrections to Standard Model

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| A_W(\tau_W) + 3\left(\frac{2}{3}\right)^2 A_t(\tau_t)\,[1+\kappa_{\gamma\gamma}] + \ldots \right|^2 ,$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^3}{16\sqrt{2}\pi^3} \left| \frac{1}{2} A_t(\tau_t)\,[1+\kappa_{gg}] + \ldots \right|^2 ,$$

- New Physics can modified Standard Model W and top couplings:

$$\kappa_{\gamma\gamma}(top) = \kappa_{gg}(top) = \frac{v_{SM}}{m_t}\frac{\partial m_t}{\partial v} - 1\,.$$

$$\kappa_{\gamma\gamma}(W) = \frac{3}{4}\left(\frac{v_{SM}}{m_W}\frac{\partial m_W}{\partial v} - 1\right)\frac{A_W(\tau_W)}{A_F(\tau_{top})}\,,$$

$$\kappa_{gg}(W) = 0\,.$$

Principal Interests of this Parametrization

- Top is charged and colored
- New Physics probably linked to the top physics
- For a top partner: $\kappa_{\gamma\gamma} = \kappa_{gg}$
- Same sign for one new particle
- Positive kappas enhance gluon and decrease photon widths.
- Easy to extend to non minimal Higgs sector (Multiple Higgs, mixing with other scalars,...)

New Parametrization and Lhc/Ilc Observables

$$\bar{\sigma}(H) = \left(\frac{\sigma_{gg}^{NP} + \sigma_{VBF}^{SM} + \sigma_{VH,\bar{t}tH}^{SM}}{\sigma_{gg}^{SM} + \sigma_{VBF}^{SM} + \sigma_{VH,\bar{t}tH}^{SM}} \right) \simeq \left(\frac{(1+\kappa_{gg})^2 \sigma_{gg}^{SM} + \sigma_{VBF}^{SM} + \sigma_{VH,\bar{t}tH}^{SM}}{\sigma_{gg}^{SM} + \sigma_{VBF}^{SM} + \sigma_{VH,\bar{t}tH}^{SM}} \right) .$$

Inclusive cross section normalized to SM

- Corrections to Hbb and HWW couplings neglected
- If correction to Hbb too important
  → Parametrization non valid (SUSY in general)
- But an extended parametrization is possible using new parameters

Other interesting Observables

$$\overline{BR}(H \to \gamma\gamma) = \frac{\Gamma^{NP}_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} \frac{\Gamma^{SM}_{\text{tot}}}{\Gamma^{NP}_{gg} + \Gamma^{NP}_{\gamma\gamma} + \Gamma^{SM}_{\text{others}}}$$

$$\simeq \left(1 + \frac{\kappa_{\gamma\gamma}}{\frac{9}{16} A_W(\tau_W) + 1}\right)^2 \frac{\Gamma^{SM}_{\text{tot}}}{(1+\kappa_{gg})^2 \Gamma^{SM}_{gg} + (\Gamma^{SM}_{\text{tot}} - \Gamma^{SM}_{gg})}$$

Photon Branching Ratio normalized to SM

$$\overline{BR}(H \to gg) = \frac{\Gamma^{NP}_{gg}}{\Gamma^{SM}_{gg}} \frac{\Gamma^{SM}_{\text{tot}}}{\Gamma^{NP}_{gg} + \Gamma^{NP}_{\gamma\gamma} + \Gamma^{SM}_{\text{others}}}$$

$$\simeq \frac{(1+\kappa_{gg})^2 \Gamma^{SM}_{\text{tot}}}{(1+\kappa_{gg})^2 \Gamma^{SM}_{gg} + (\Gamma^{SM}_{\text{tot}} - \Gamma^{SM}_{gg})} .$$

Gluon Branching Ration normalized to SM

From Spectra of Given Models to NP Parameters

- Easy to compute these contributions
- For instance: 4th chiral generation

190 GeV < m_Q < 2 TeV

100 GeV < m_L < 2 TeV

arXiv:0706.3718 [hep-ph]

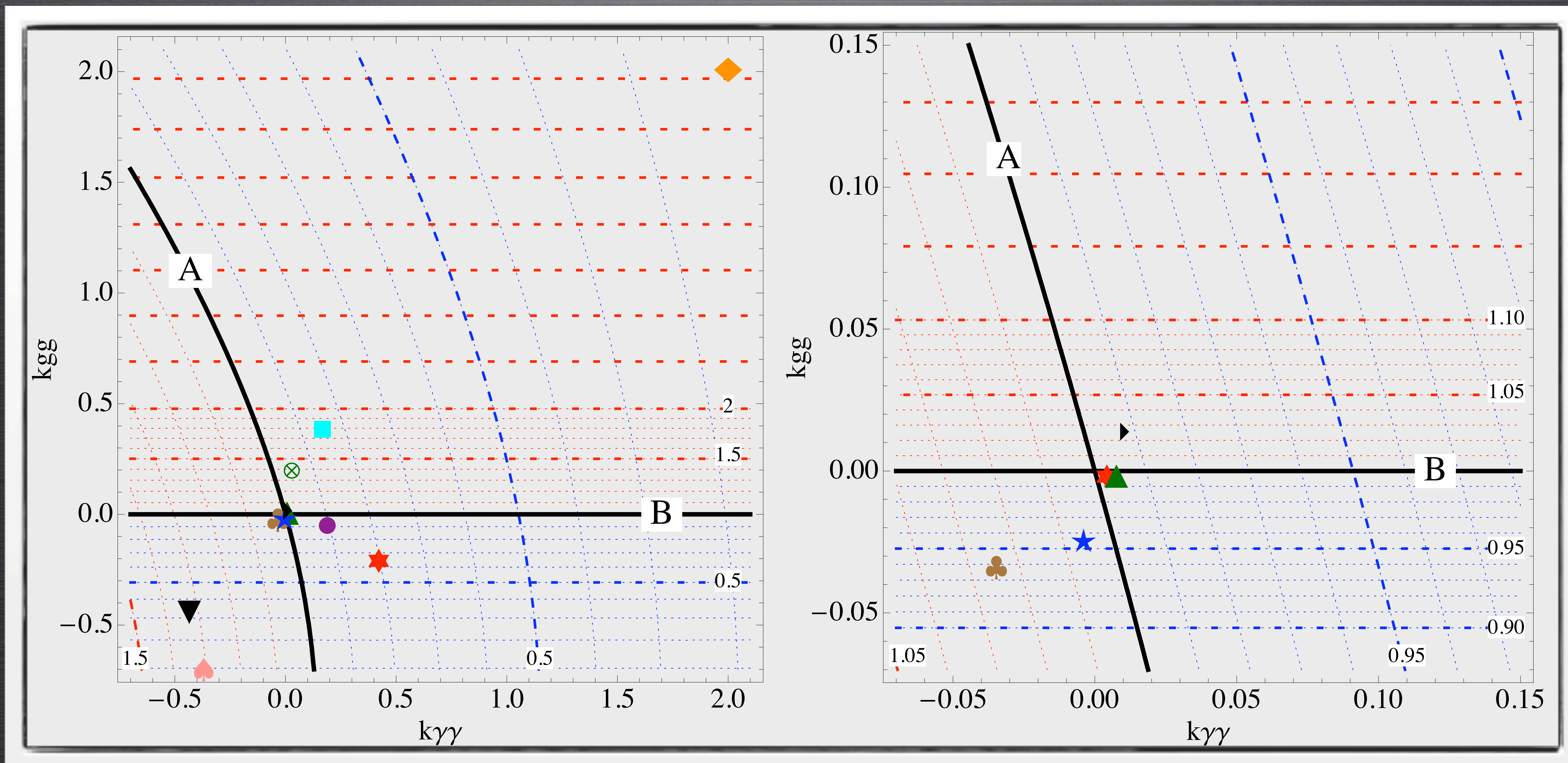
$$
\begin{aligned}
\kappa_{gg} &= 2 \\
\kappa_{\gamma\gamma} &= \frac{3}{4}\left[3\left(\frac{2}{3}\right)^2 + 3\left(-\frac{1}{3}\right)^2 + 1\right] = 2
\end{aligned}
$$

→ Equivalent to 2 extra tops!

Survey of Models

♦	Fourth Generation
♣	SuperSymmetry in MSSM Golden Region
▲	Simplest Little Higgs *(W′ @ 2TeV)*
✻	Littlest Higgs *(T-Parity: f=500 GeV, without T-parity: f=5 TeV)*
■	Color Octet Model
►	Lee Wick Standard Model *(LW Higgs mass @ 1 TeV)*
⊗	Universal Extra Dimension Model *(M_{KK} @ 500 GeV)*
★	Model of Gauge Higgs Unification in Flat Space *($W^{(1)}$ @ 2 TeV)*
•	Minimal Composite Higgs (GHU in Warped Space) *($W^{(1)}$ @ 2.4 TeV)*
▼	Brane Higgs Model with Flavour in Flat Space *($W^{(1)}$ @ 2 TeV)*
♠	Brane Higgs Model with Flavour in Warped Space *($W^{(1)}$ @ 2 TeV)*

MH=120 GeV @ ILC



A-BR(H⟶γγ) B-BR(H⟶gg)

♦	4^{th}	✻	Littlest Higgs	•	Warped GHU Space	★	Flat GHU
♣	SUSY	■	Color Octet	▼	Flat BH with Flavour	⊗	UED Model
▲	SLH	▶	Lee Wick SM	♠	Warped BH with Flavour		

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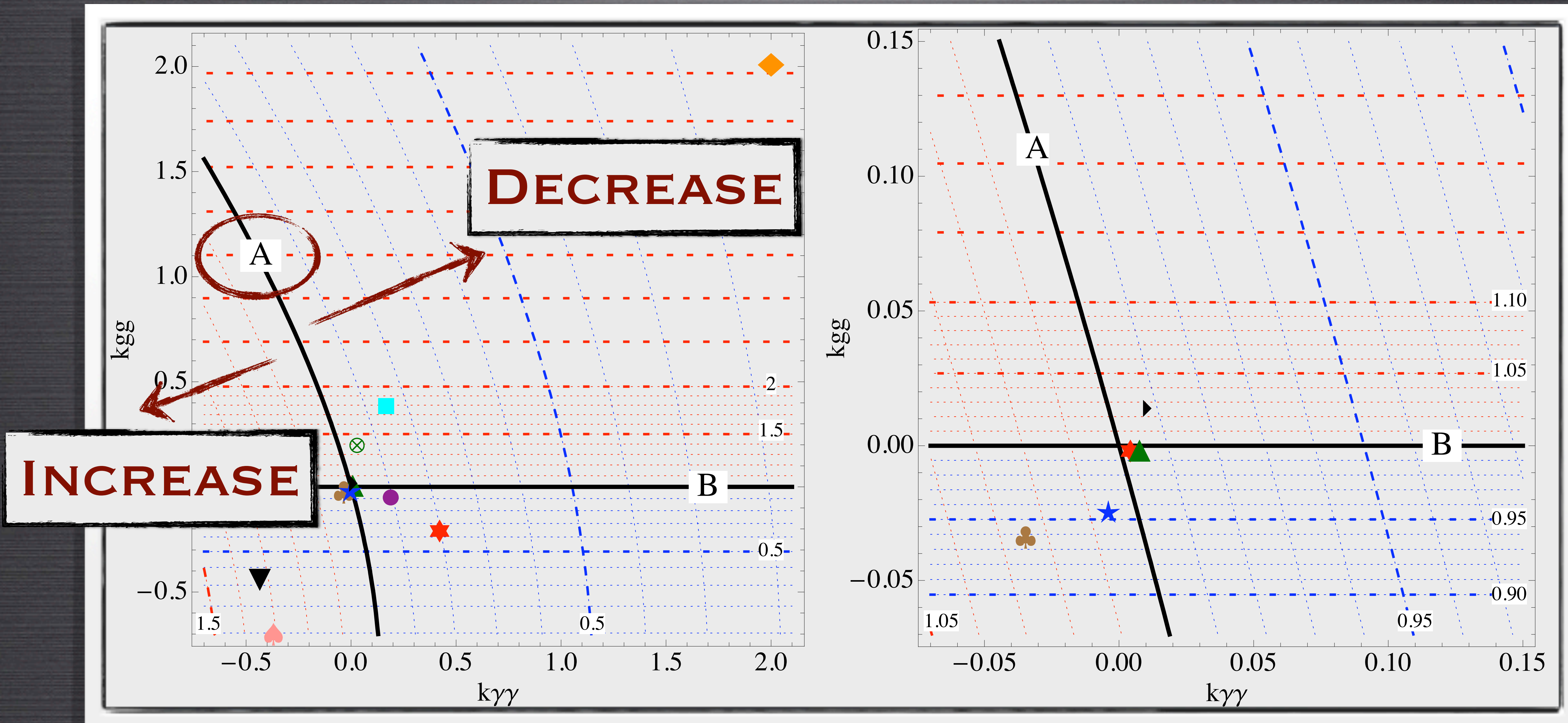

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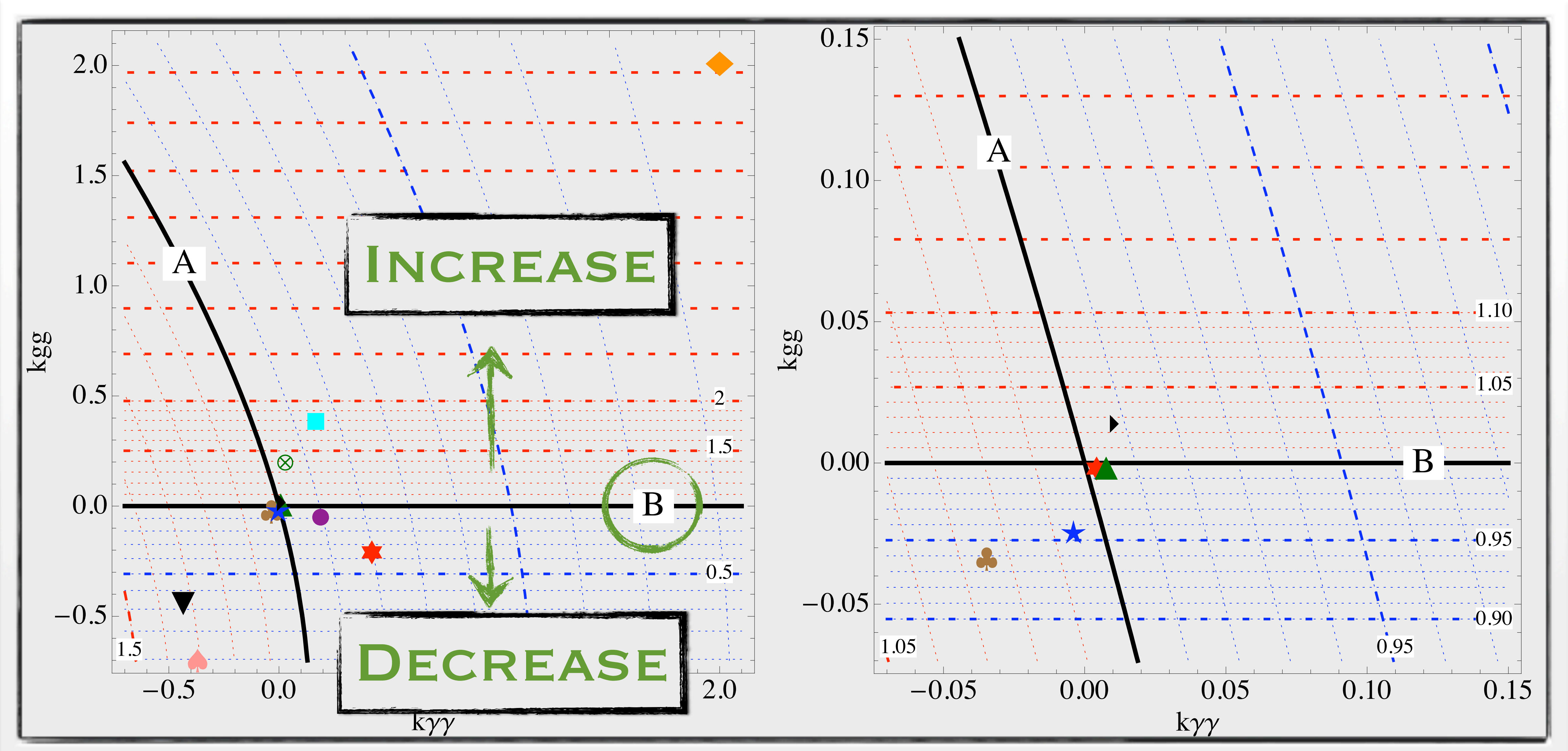

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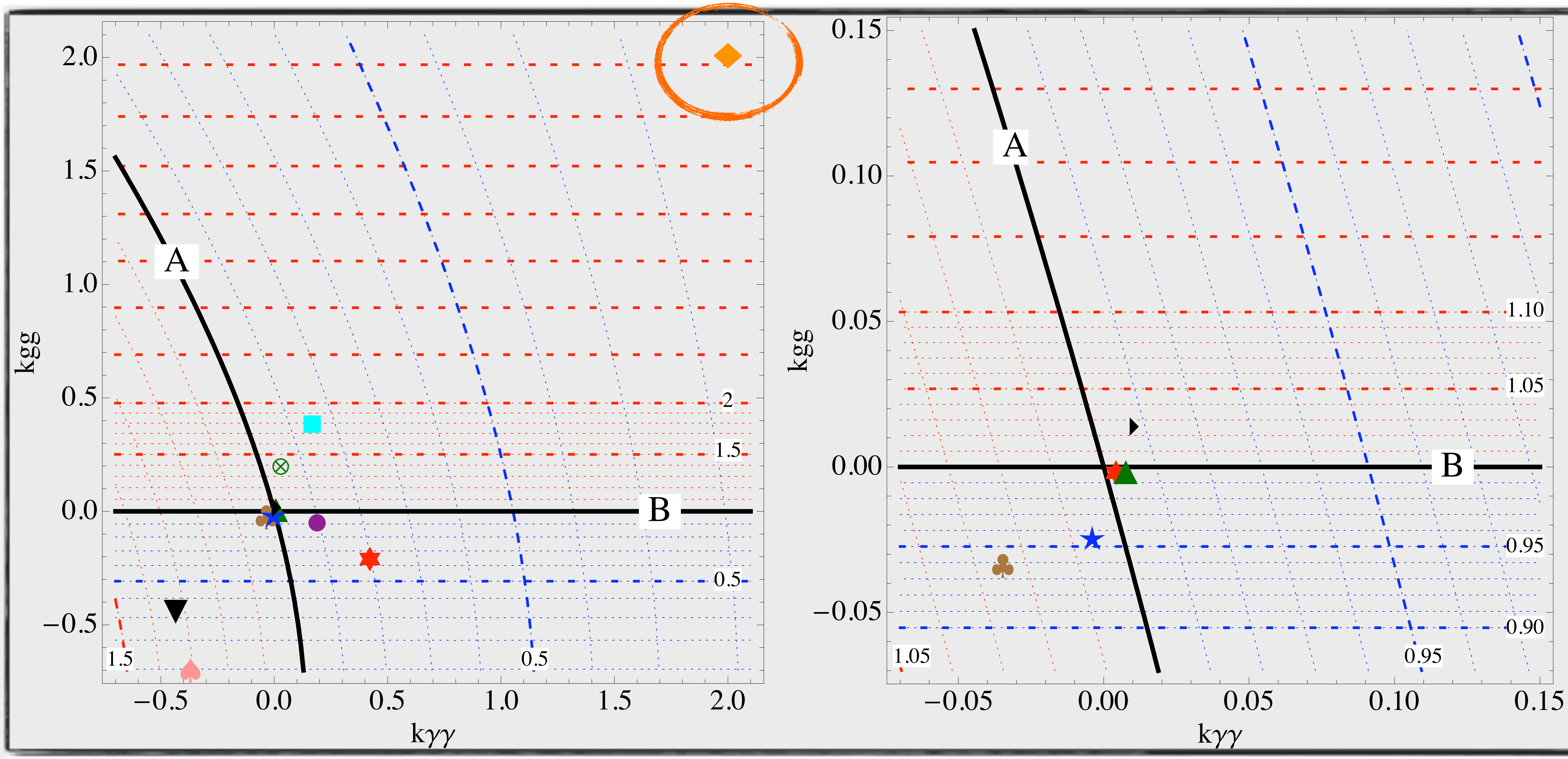
General Features



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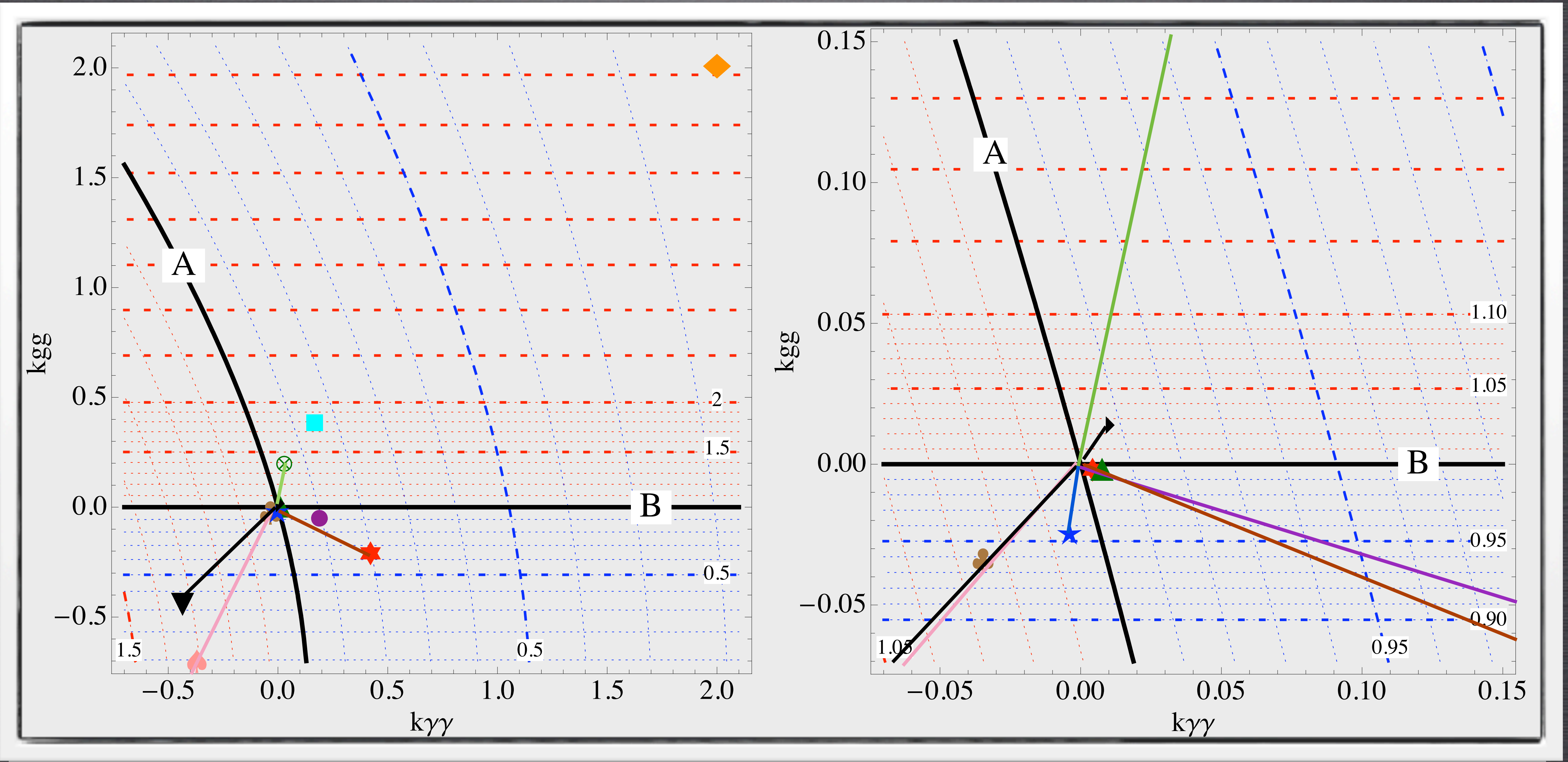

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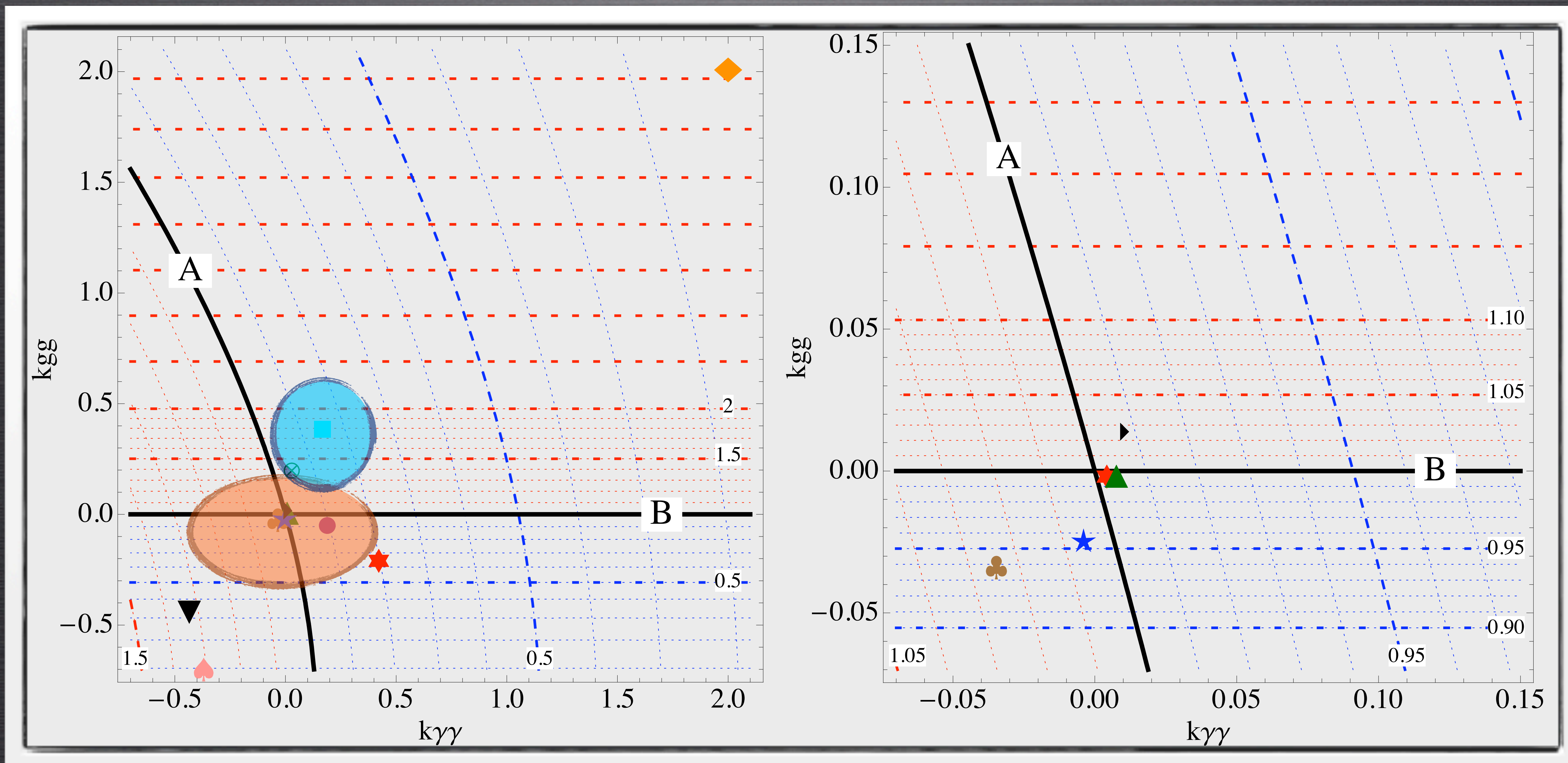

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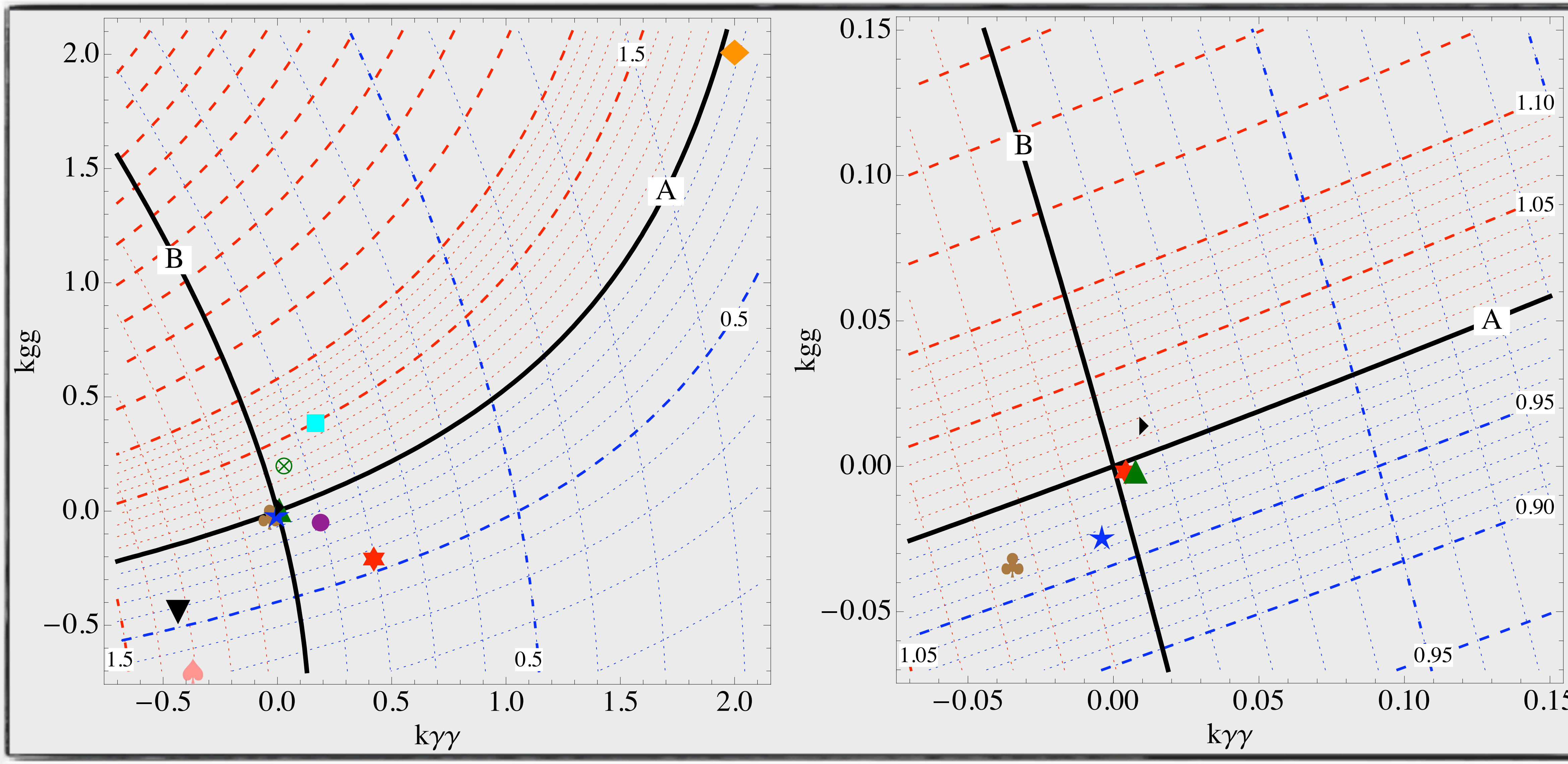
$M_H = 120$ GeV @ LHC



A-Inclusive H⟶γγ B- VBF⟶H⟶γγ

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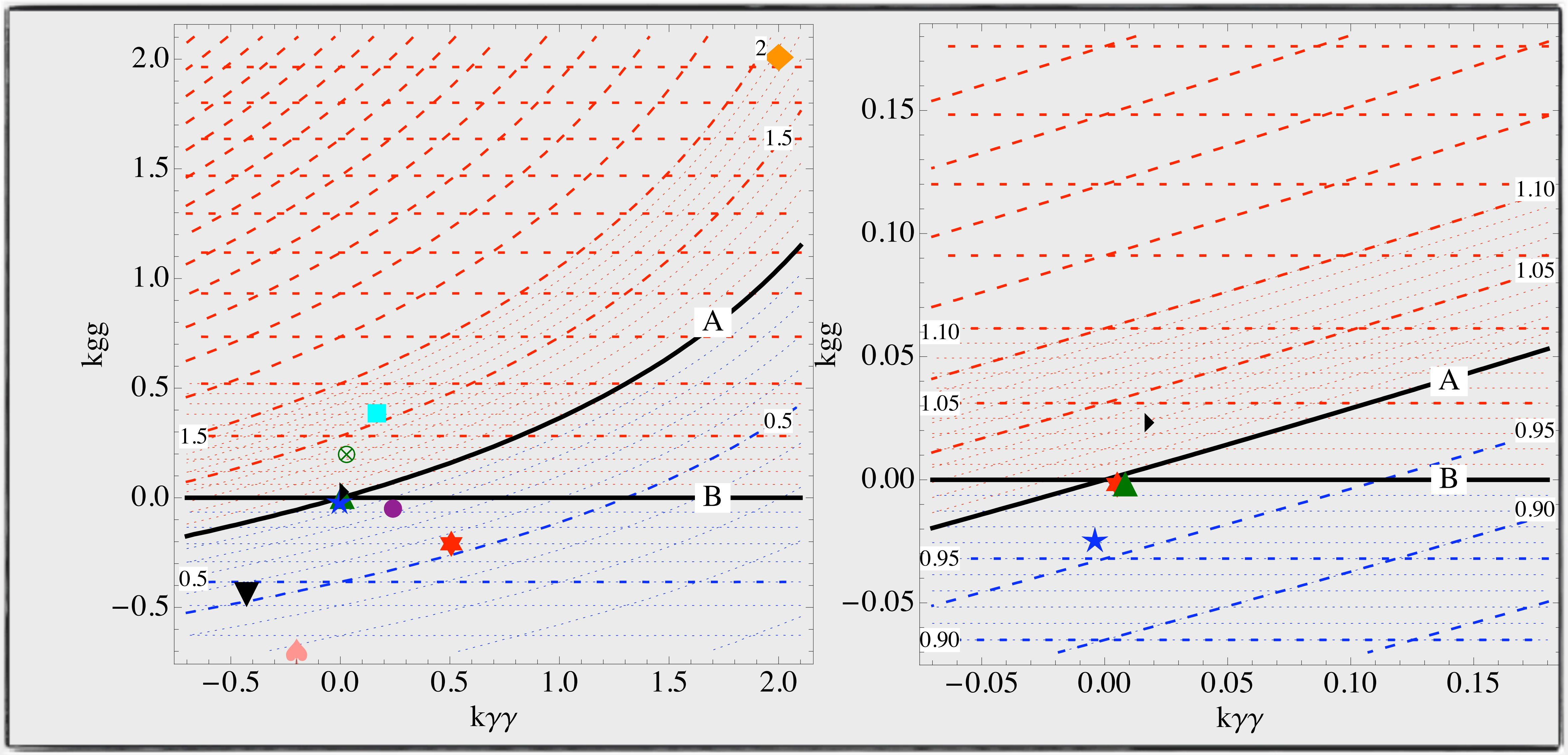
Mh=150 GeV @ LHC



A-Inclusive H⟶γγ B- VBF⟶H⟶VV

♦	4^{th}	✻	Littlest Higgs	●	Warped GHU Space	★	Flat GHU
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▲	SLH	▶	Lee Wick SM	♠	Warped BH with Flavour		

Conclusion

- ✓ **Usefull tool** to study EWSB complementary to direct detection
- ✓ **Sizeable effects** and possible detection of new particles even beyond direct detection threshold $\longrightarrow$ **Good for LC**
- ✓ **Model independent parametrization** with few parameters
- ✓ Models pointing in well-defined directions in parameter space $\longrightarrow$ **Good discrimination power !**
- ❖ Now, need to be implemented in MC for more detailed analysis.
- ❖ Possible analysis with different observables (BR($H \to VV$),...)
- ❖ Possible extension for non minimal Higgs sector

The End

Easy Implementation of this Parametrization

- If $m_H << m_{NP}$ ==> NP only modifies Higgs loops
  ==> Same kinematics
- For instance, in Madgraph with HEFT model: Higgs loops described with effective vertices
  ==> Just tunable coefficients

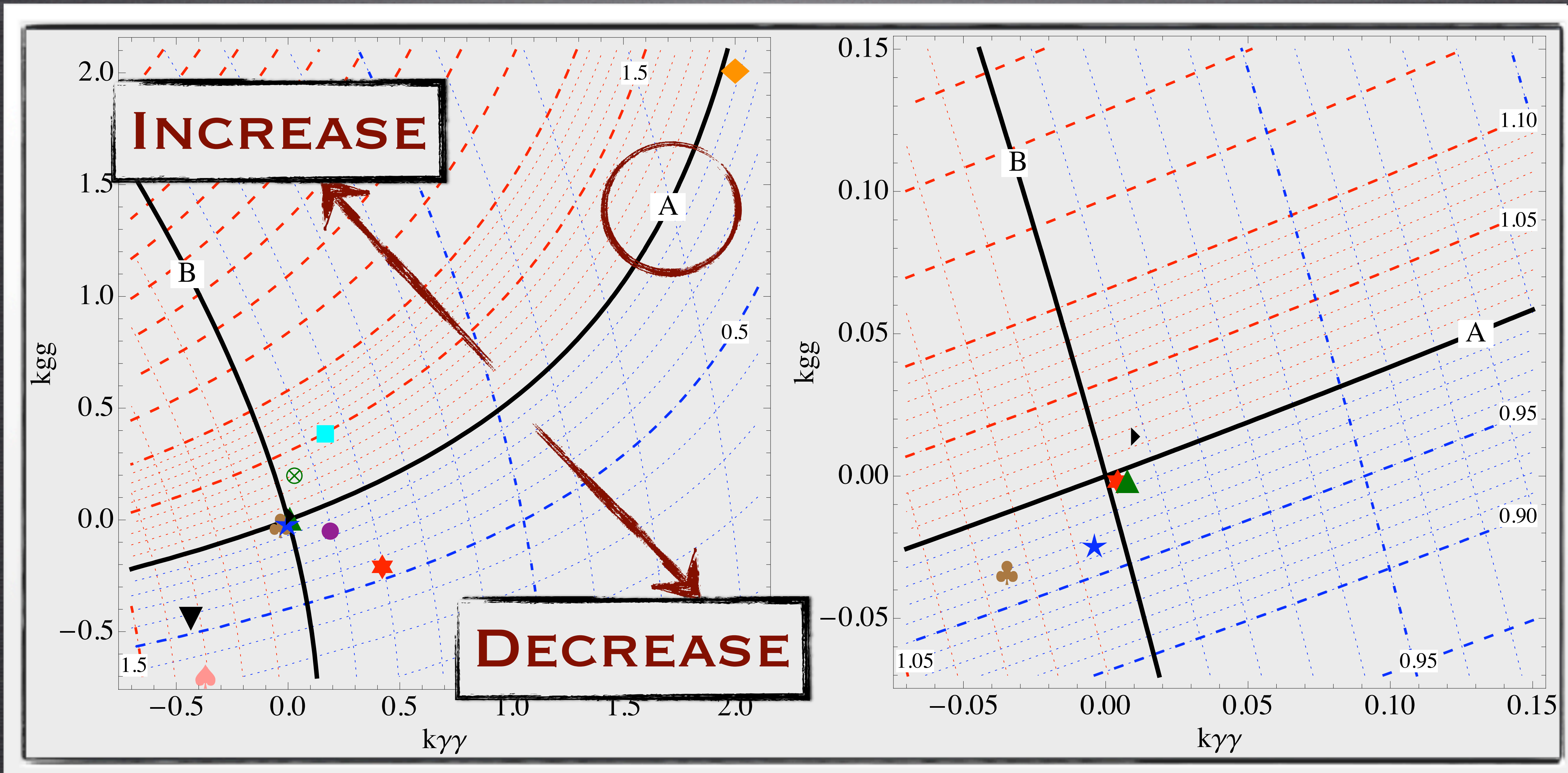
```
c Higgs effective couplings (couplings of
   Higgs's directly to gluons)
   c--------------------------------
   c Coupling to gluons
   c Higgs coupling:

   tau = hmass**2/(4d0*tmass**2)
   series_t = 1d0 + tau*7d0/30d0 +
   tau**2*2d0/21d0 + tau**3*26d0/525d0
   series_p = 1d0 + tau/3d0      +
   tau**2*8d0/45d0 + tau**3*4d0/35d0

   c kglu is the effective coupling
   modification to H-> gluon gluon
   c such that (1+kglu) multiplies the top
   triangle contribution

kglu = 0d0
   scalarf = 1d0+kglu
   axialf  = 0d0
   gh(1) = dcmplx( scalarf*g**2/4d0/PI/
   (3d0*PI*V)*series_t, Zero)
   gh(2) = dcmplx( axialf *g**2/4d0/PI/
   (2d0*PI*V)*series_p, Zero)
   c Pseudo-scalar Higgs coupling (set to
   zero):
         ga(1) = dcmplx( Zero, Zero)
         ga(2) = dcmplx( Zero, Zero)
```

MH=120 GeV @ LHC



A-Inclusive H⟶γγ **B- VBF⟶H⟶γγ**

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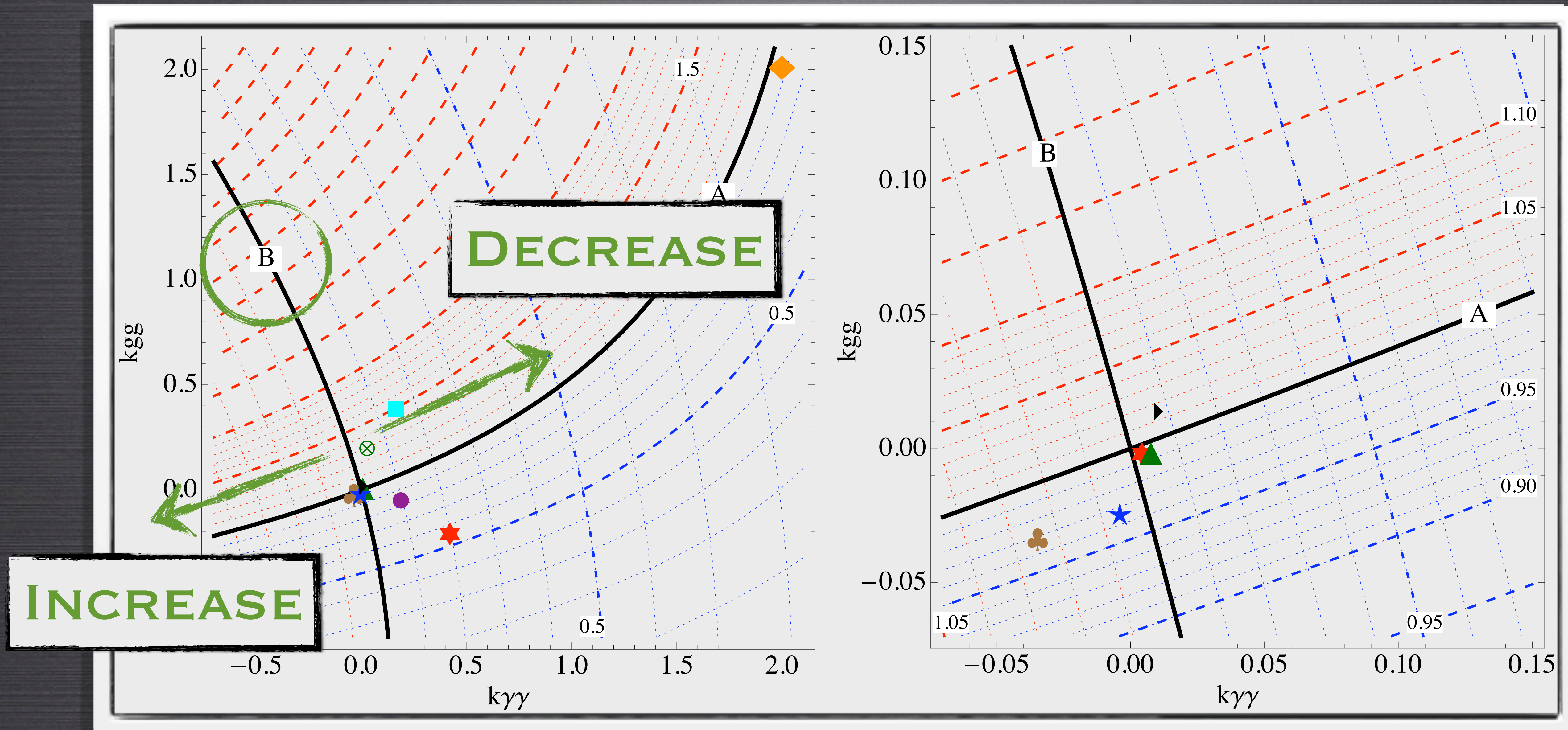
M_H=120 GeV @ LHC



A-Inclusive H⟶γγ   B- VBF⟶H⟶γγ

4th	Littlest Higgs	Warped GHU Space	Flat GHU
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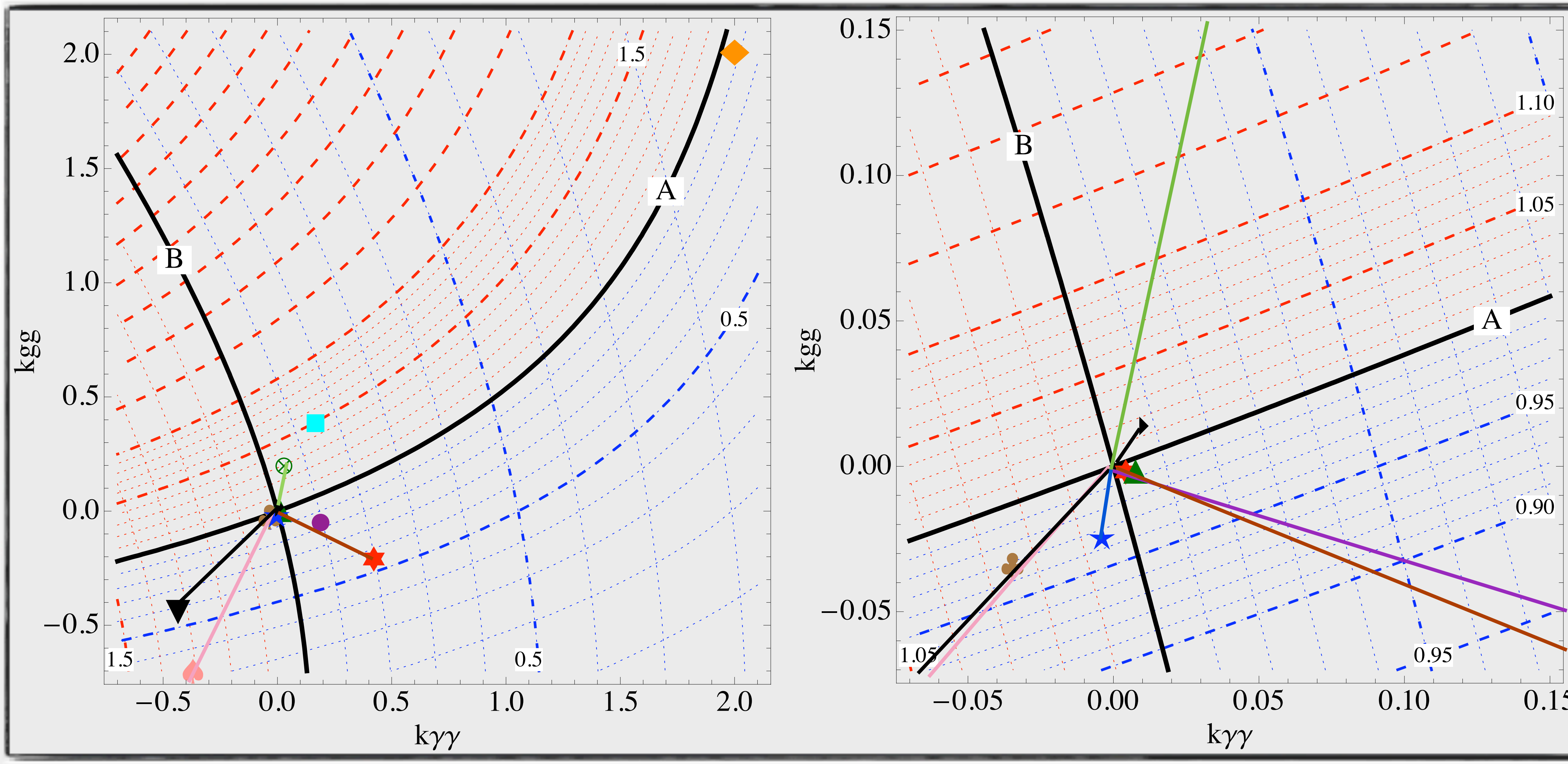
SLH	Lee Wick SM	Warped BH with Flavour	

General Features



A-Inclusive $H \longrightarrow \gamma\gamma$ B- VBF $\longrightarrow H \longrightarrow \gamma\gamma$

♦	4th	✻	Littlest Higgs	•	Warped GHU Space	★	Flat GHU
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Generalization

- Previous parametrization for a SM-like Higgs sector
- Extension for a non minimal scalar sector
  - Multiple higgses:

$$\phi_i = \frac{1}{\sqrt{2}}(v_i + c_i h + ...)$$

$$\frac{v_{SM}}{m}\frac{\partial m(v)}{\partial v} \rightarrow \frac{v_{SM}}{m}\sum_i \frac{\partial m}{\partial v_i} c_i$$

  - Mixing with no vev scalars:

$$S_j = s_j h + ...$$

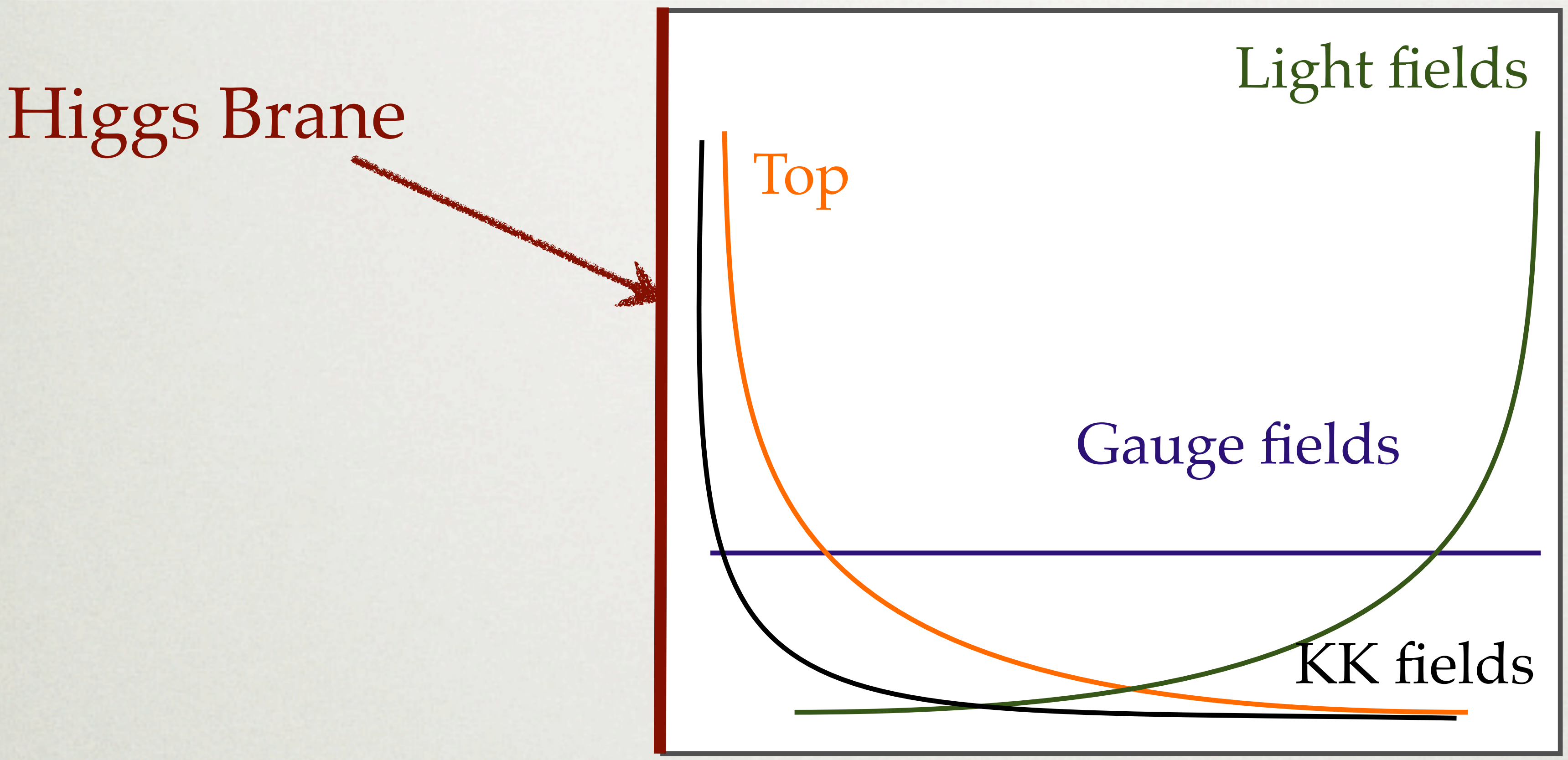
$$\frac{v_{SM}}{m}\frac{\partial m(v)}{\partial v} \rightarrow \frac{v_{SM}}{m}\left(\sum_i \frac{\partial m}{\partial v_i} c_i + \sum_j g_{S_j} s_j\right)$$

SUSY: MSSM in the Golden Region (arXiv: hep-ph 0702038)

- Motivated by naturalness, minimal fine tuning, precision tests, ...
- Large tan β compensated by small mixing angle α in Higgs sector:
  - Sparticles: large mixing in the stop sector
  - Charginos: mostly higgsinos
  - Heavy Higgses masses above 1TeV

$$\frac{g_{W^+W^-h}}{g_{SM}} = \sin(\beta - \alpha)\,, \qquad \frac{g_{\bar{t}th}}{g_{SM}} = \frac{\cos\alpha}{\sin\beta}\,, \qquad \frac{g_{\bar{b}bh}}{g_{SM}} = -\frac{\sin\alpha}{\cos\beta}$$

Models with Flavor in Extra dimensions



- Fermion mass hierarchy ⟶ Exponential localization
- O(1) Yukawa on the brane and O(1) mass in the bulk

Flavor in Extra-dim Gauge Bosons

$$\begin{cases} \partial_5 W_\mu^+(y_1) - \frac{g_5^2 v^2}{4}\, W_\mu^+(y_1) = 0 \\ \partial_5 W_\mu^+(y_2) = 0 \end{cases}$$

$$W^+(y,x) = \sum_n f_n(m_n y)\, W_n(x)^+ \,,$$

$$\longrightarrow \qquad m_n \frac{f'(m_n y_1)}{f(m_n y_1)} - \frac{g_5^2 v^2}{4} = 0$$

$$\longrightarrow \qquad \sum_n \frac{v}{m_n} \frac{\partial m_n}{\partial v} = 1$$

$$\longrightarrow \qquad \kappa_{\gamma\gamma} \quad \alpha \quad \left(1 - \frac{v}{m_W} \frac{\partial m_W}{v}\right) (A_W(0) - A_W(\tau_W))$$

$$\kappa_{\gamma\gamma} \quad \simeq \quad 0$$

Negligible contribution of W gauge boson

Flavor in Extra-dim Fermions

- In general, different bulk masses of right handed and left handed fermions $M_L \neq M_R$

$$\sum_n \frac{\beta}{m_n} \frac{\partial m_n}{\partial \beta} \simeq -\pi^2 \beta^2$$

β is linked to the VEV and the Yukawa of the field

⟶ All fermions contribute to the kappas

$$\kappa_{\gamma\gamma} = \kappa_{gg} \simeq 6(-\pi^2\beta^2) - \frac{\pi^2\alpha^2}{6} \sim -0.45 \left(\frac{2\text{TeV}}{m_{KK}}\right)^2 ,$$