Composite Higgses

Brando Bellazzini

IPhT - CEA/Saclay & Universite' Paris-Saclay

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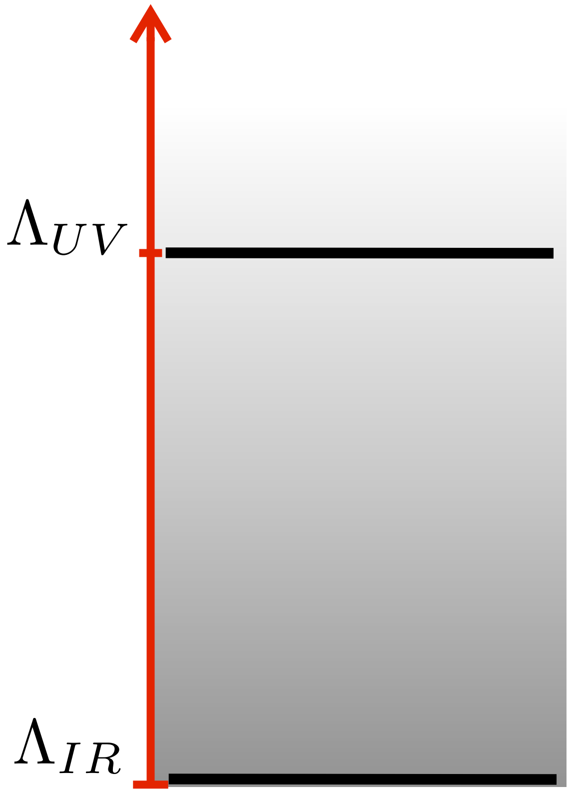
A new strong force, the origin of masses, and the LHC

OUTLINE

- *Compositeness and the Hierarchy Problem*
- *Composite Higgs*
    - *Higgs couplings*
    - *EWPTs*
    - *Higgs potential*
    - *Light resonances*
- *Conclusions*

Hierarchy of scales

a blessing…



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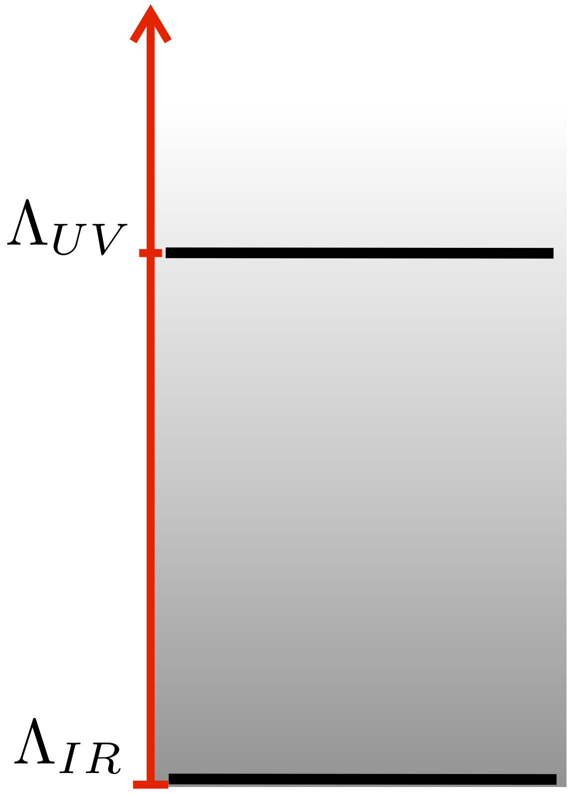
- perturbative expansion in E/Λ_{UV}
- few parameters, emerging patterns
- suppress dangerous operators
- …



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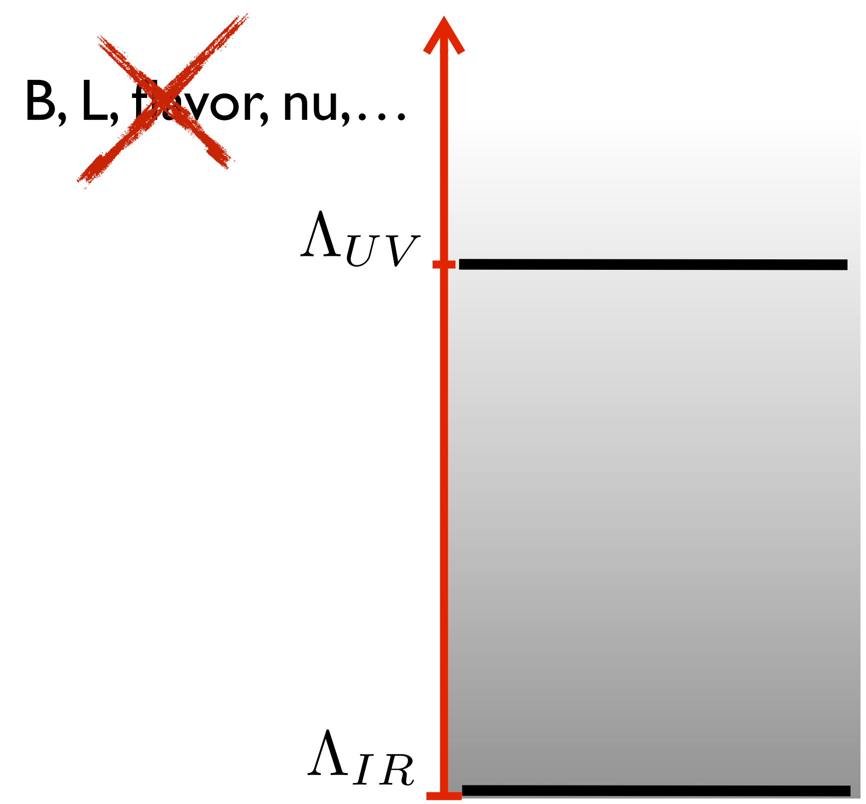

$$\mathcal{L}_{\mathcal{IR}} = \mathcal{L}^{\Delta \leq 4} + \sum_{\mathcal{O}} \frac{\mathcal{O}(x)}{\Lambda_{UV}^{\Delta - 4}}$$

Hierarchy of scales

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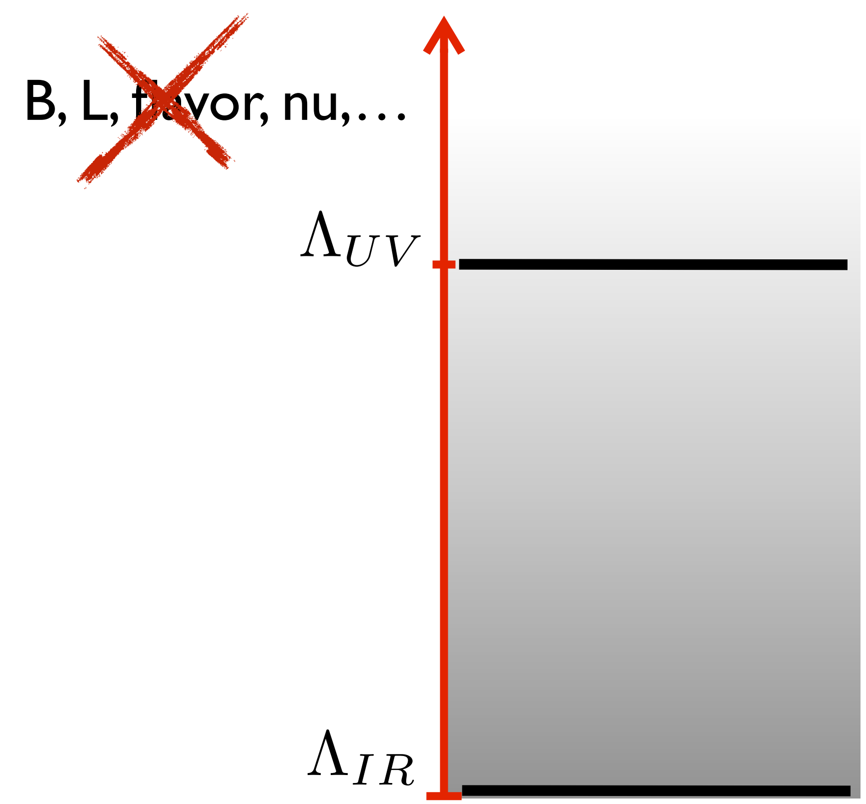

$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + g A_\mu \bar{\psi} \gamma^\mu \psi + y_{ij} \bar{\psi}_i H \psi_j + \lambda (H^\dagger H)^2 \qquad \textbf{D=4}$$

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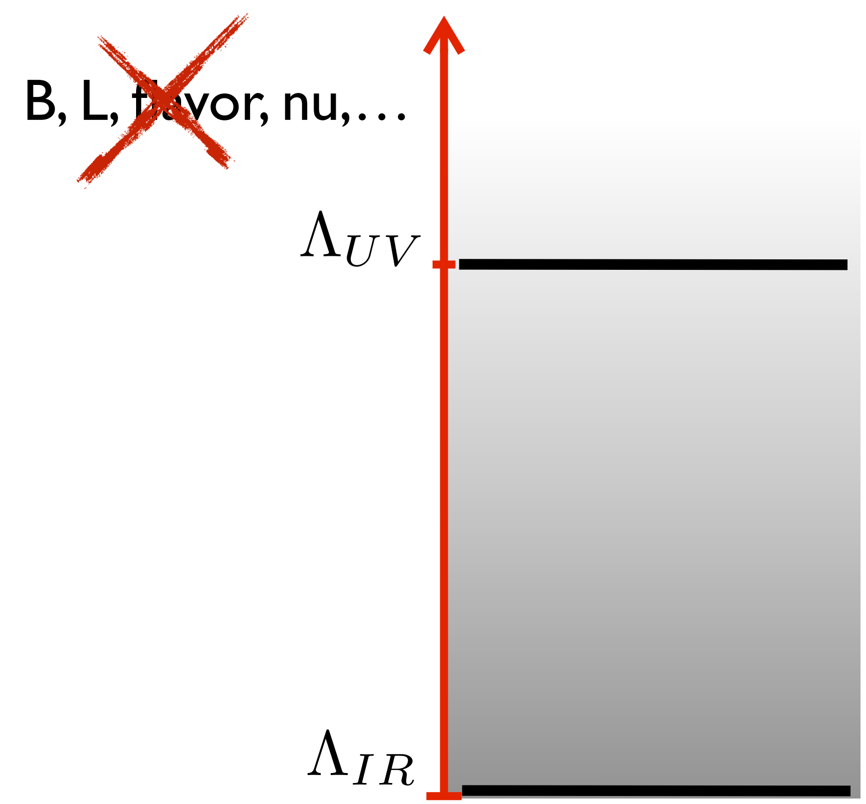

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$$+\frac{c_{ij}}{\Lambda_{UV}} L_i L_j H H$$ **D=5**

$$+\frac{c_{ijkl}}{\Lambda_{UV}^2}\bar{\psi}_i\psi_j\bar{\psi}_k\psi_l + \ldots$$ **D=6**

$$+\ldots$$ ⋮

$$\mathcal{L}_{\mathcal{IR}} = \mathcal{L}^{\Delta\leq 4} + \sum_{\mathcal{O}} \frac{\mathcal{O}(x)}{\Lambda_{UV}^{\Delta-4}}$$

Hierarchy of scales

a blessing…or a curse

$$+a\,\Lambda_{UV}^2 H^\dagger H \;\; +c\,\Lambda_{UV}^4\,\mathbf{1}$$ **D<4**

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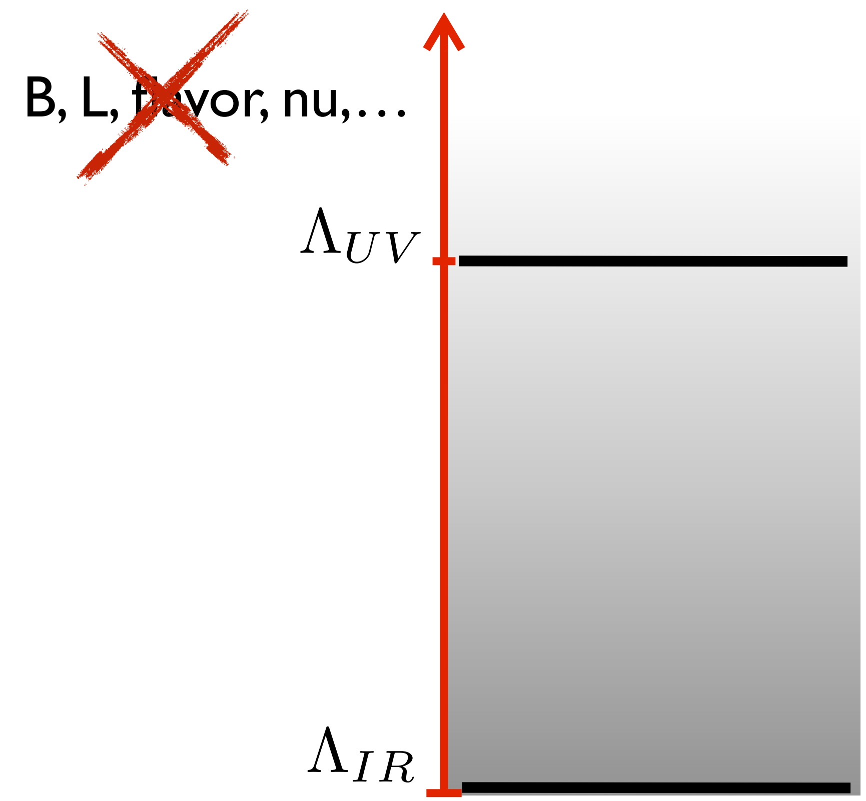

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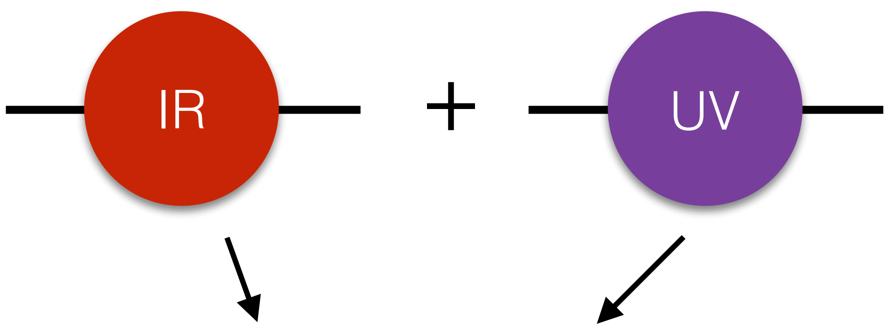
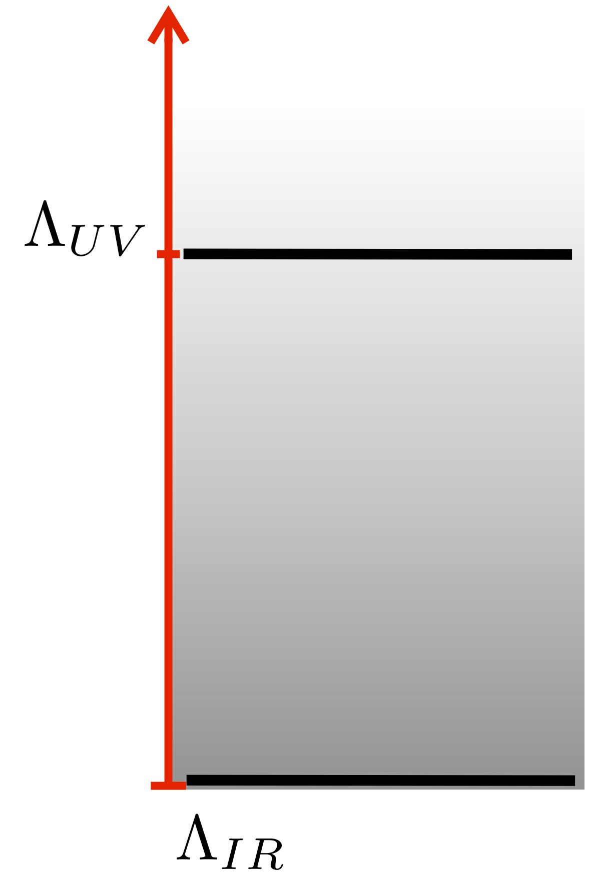
Hierarchy of scales

fine-tuning $\mathcal{L}^{\Delta<4} = c_h \Lambda_{UV}^2 |H|^2 + \ldots$



$$(1.0000 - 1.0001)\, \Lambda_{UV}^2$$



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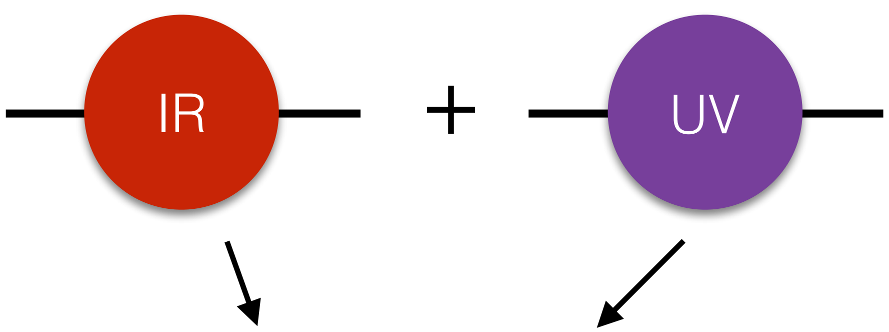

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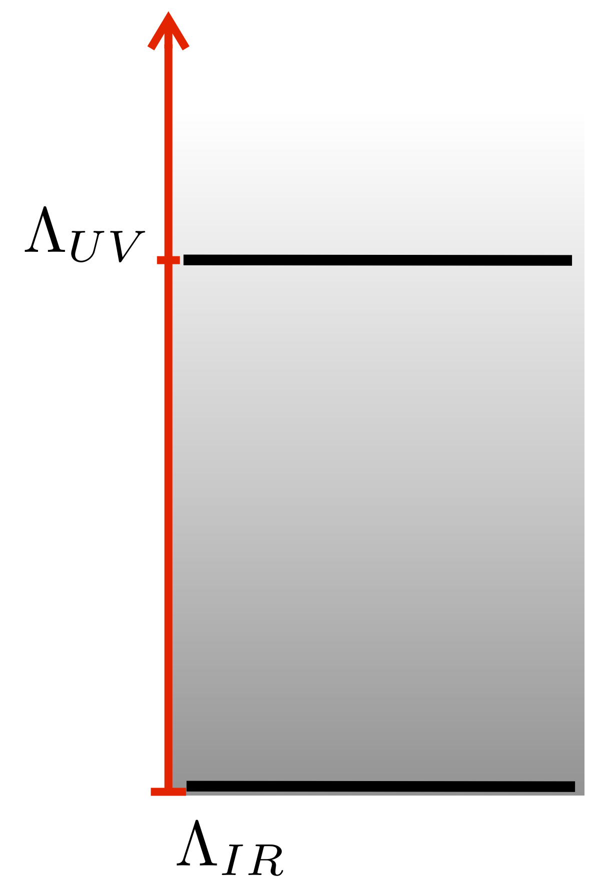
$$\underbrace{\int_{\Lambda_{IR}}^{\Lambda_{UV}} f(k^2)}_{\text{IR-calculable}} + \underbrace{\int_{\Lambda_{UV}}^{\infty} f(k^2)}_{\text{UV-unknown}}$$



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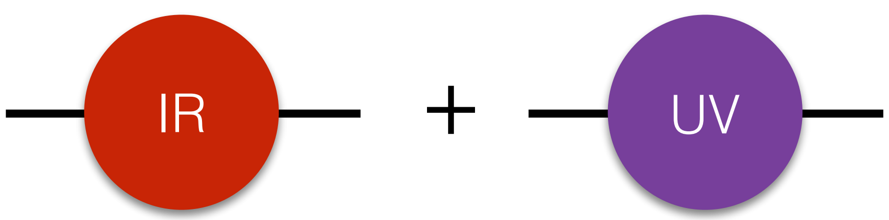
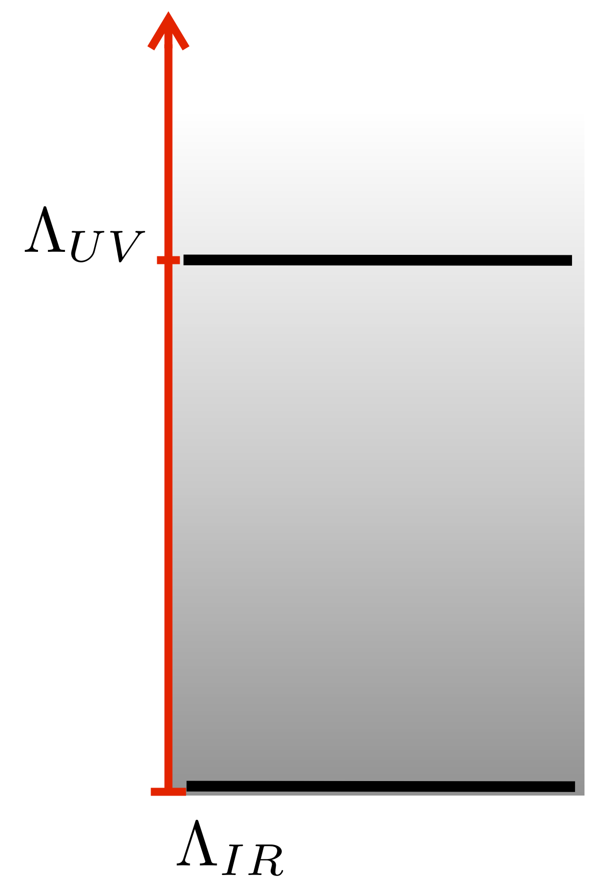
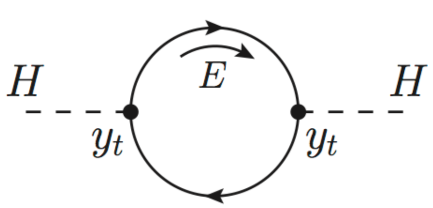


$$\int_{\Lambda_{IR}}^{\Lambda_{UV}} f(k^2) + \int_{\Lambda_{UV}}^{\infty} f(k^2)$$

IR-calculable UV-unknown

$(1.0000 - 1.0001)\, \Lambda_{UV}^2$





IR-top-contribution

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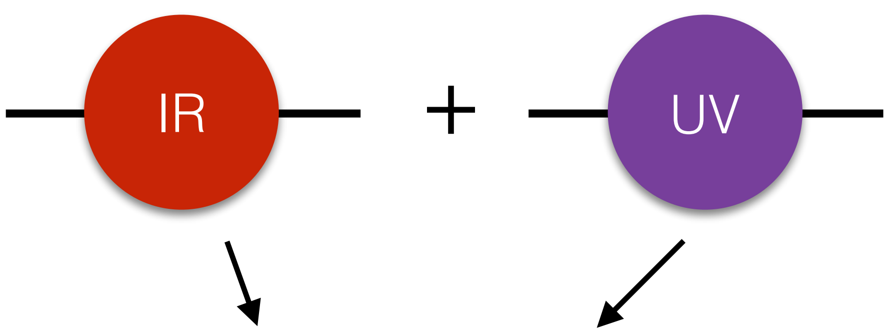

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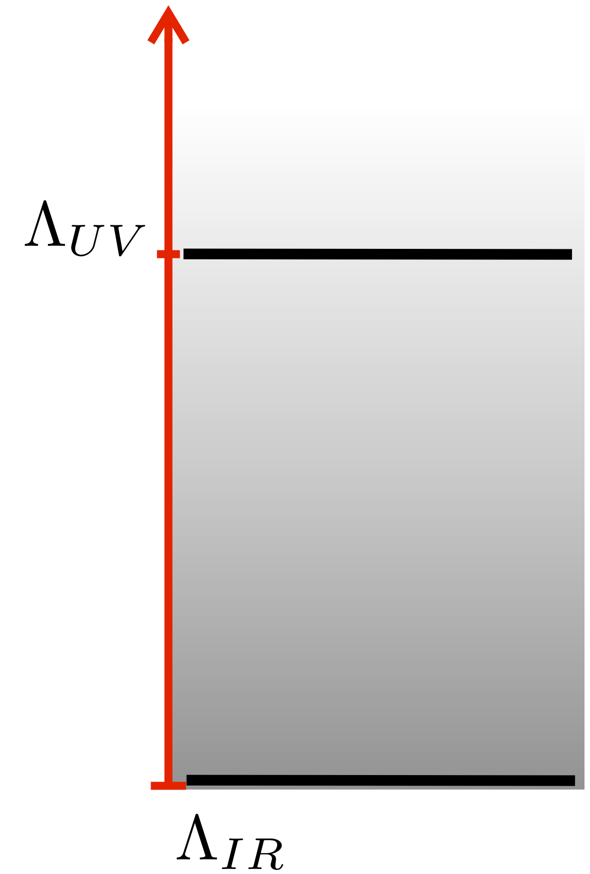

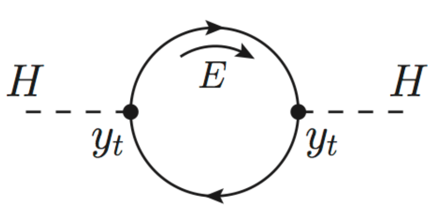

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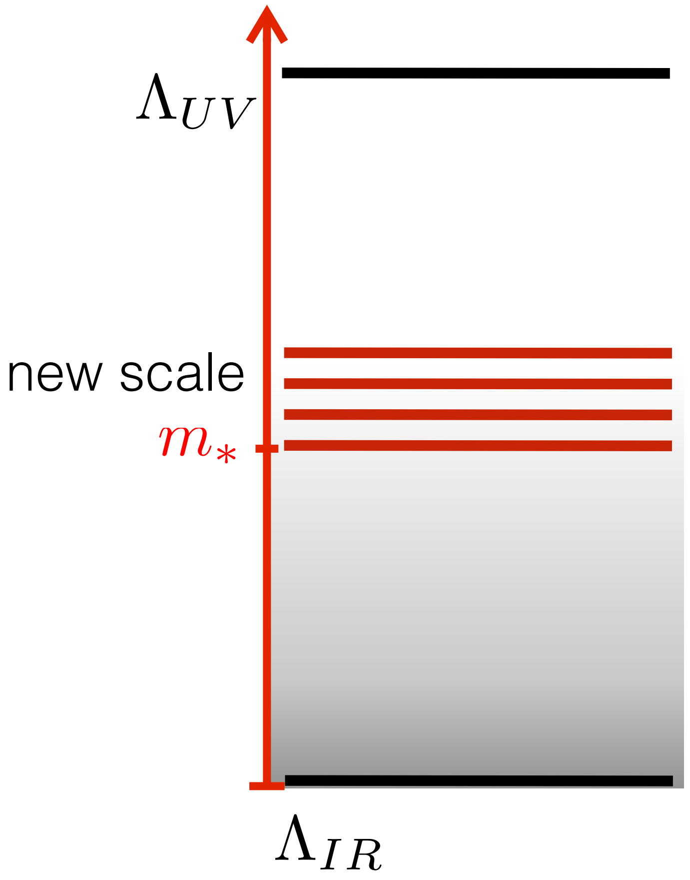
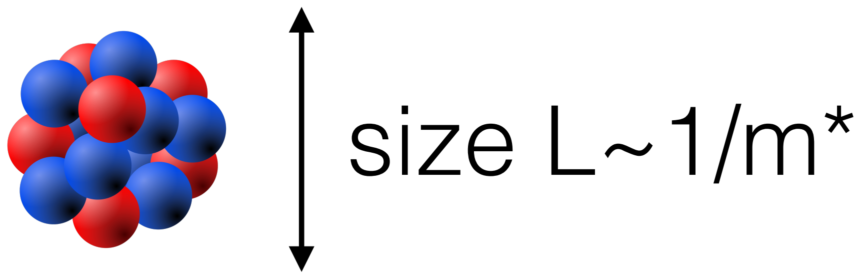
$$c_h = \frac{3y_t^2}{8\pi^2} + (\text{unknown})_{UV}$$

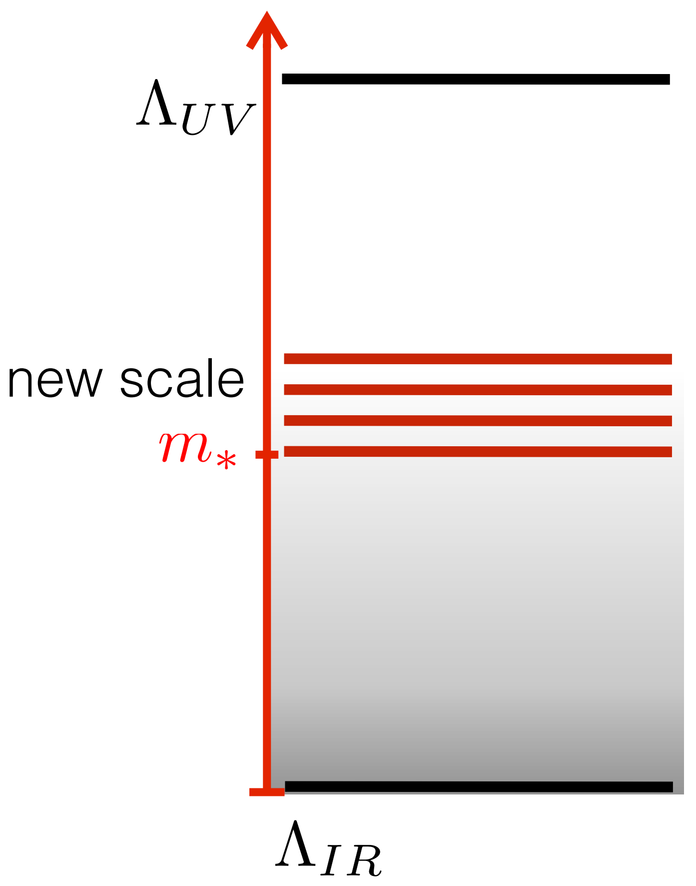
minimal tuning $\Delta_H = \dfrac{\delta m_H^2}{m_H^2} \sim \left(\dfrac{100\text{GeV}}{m_H}\right)^2 \left(\dfrac{\Lambda_{UV}}{\text{few} \times 100\text{GeV}}\right)^2$

Higgs-Compositeness



Higgs-Compositeness

The Higgs isn't pointlike, it's composite 



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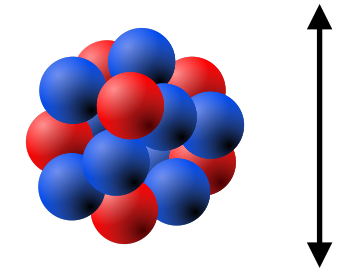
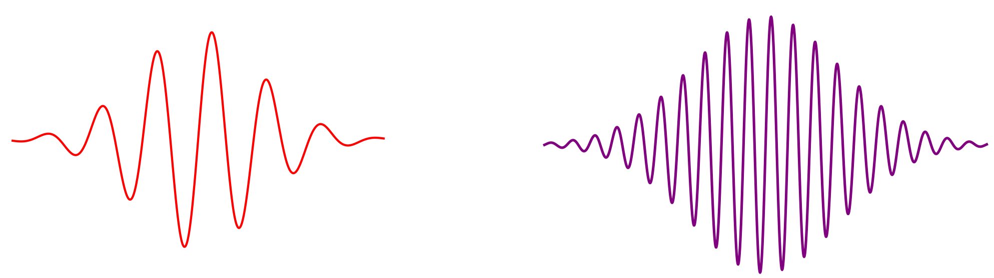
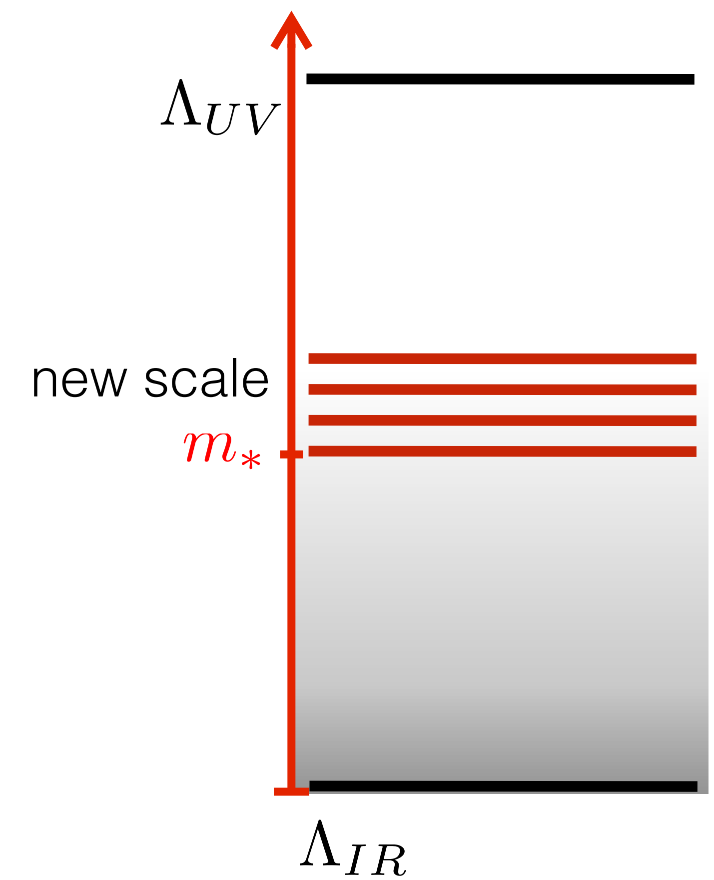
The Higgs isn't pointlike, it's composite  size L~1/m*

$$m_H^2 = \int_{\Lambda_{IR}}^{m_*} dE\, \frac{dm_H}{dE} + \int_{m_*}^{\infty} dE\, \frac{dm_H}{dE}$$



low-virtuality high-virtuality



for E<< m* the Higgs is essentially point-like

for E~ m* finite size becomes important

for E>>1/m* there Higgs is transparent

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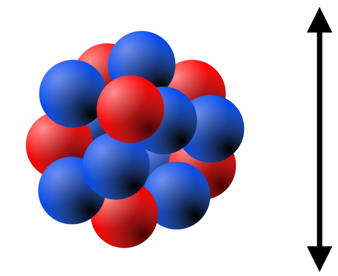

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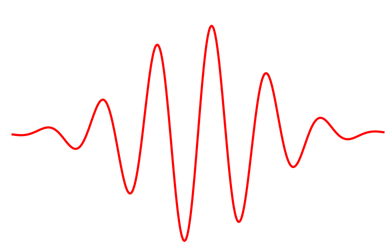

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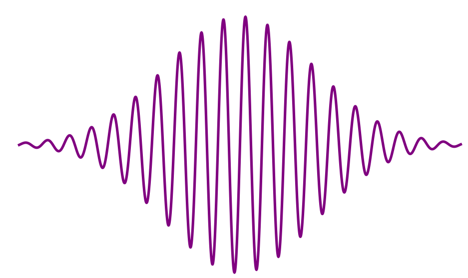
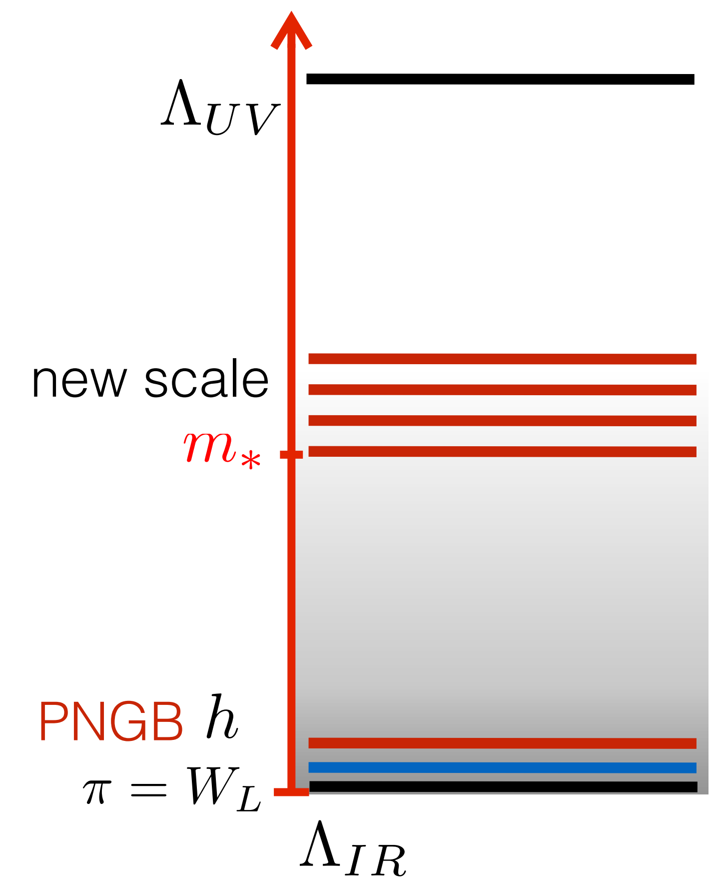


high-virtuality



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Vacuum (mis)alignment

strong sector

$$\mathcal{G} \to \mathcal{H} \supset \mathcal{G}_{EW}$$

$$\phi = \begin{cases} W_L^{\pm} \quad Z_L \quad h \; \} \; \pi & \text{spin-0} \\ \rho_\mu & \text{spin-1} \\ \Psi & \text{spin-1/2} \end{cases}$$

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weak sector

$$A_\mu = W_\mu \quad B_\mu$$

$$\psi = \psi_L \quad \psi_R$$

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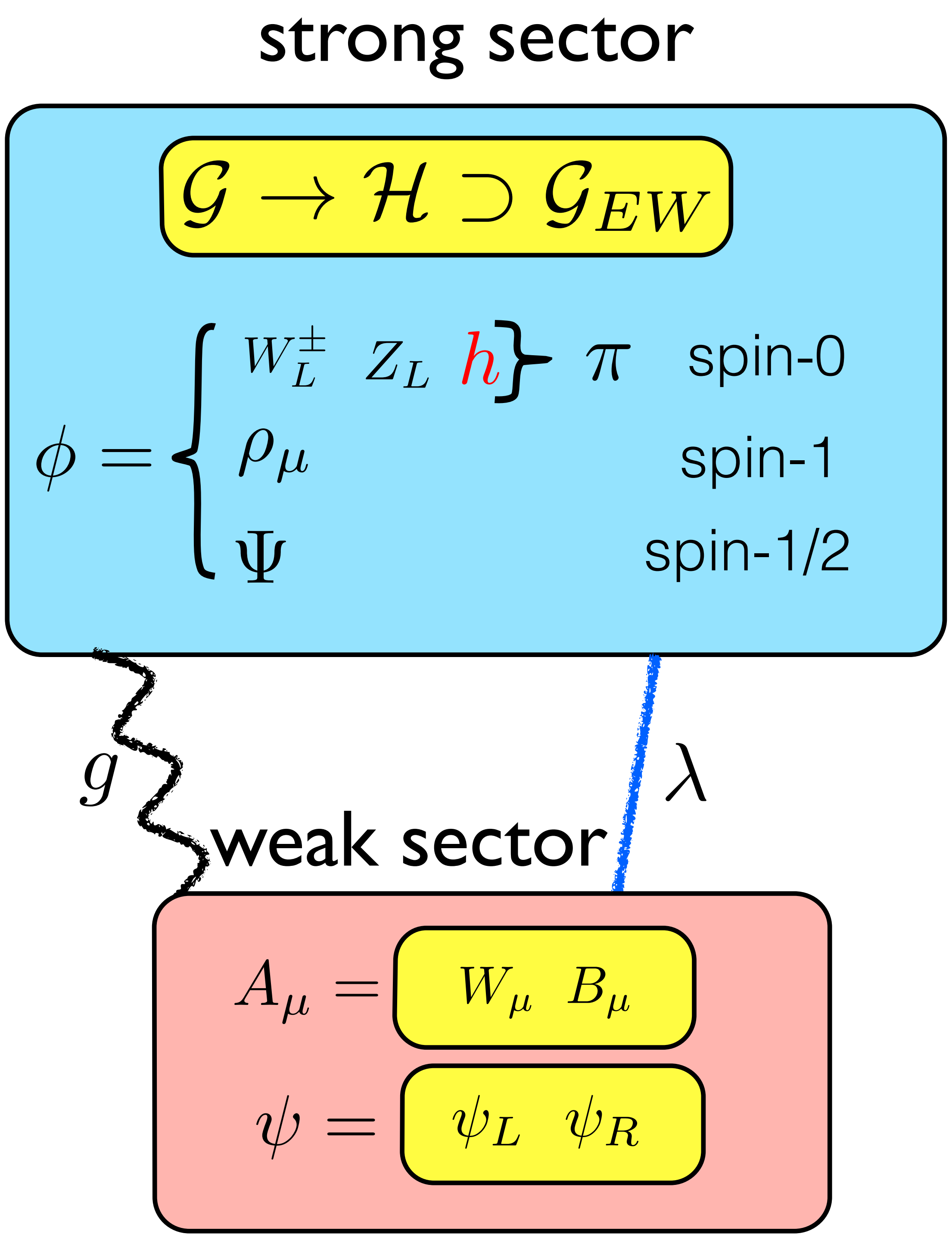

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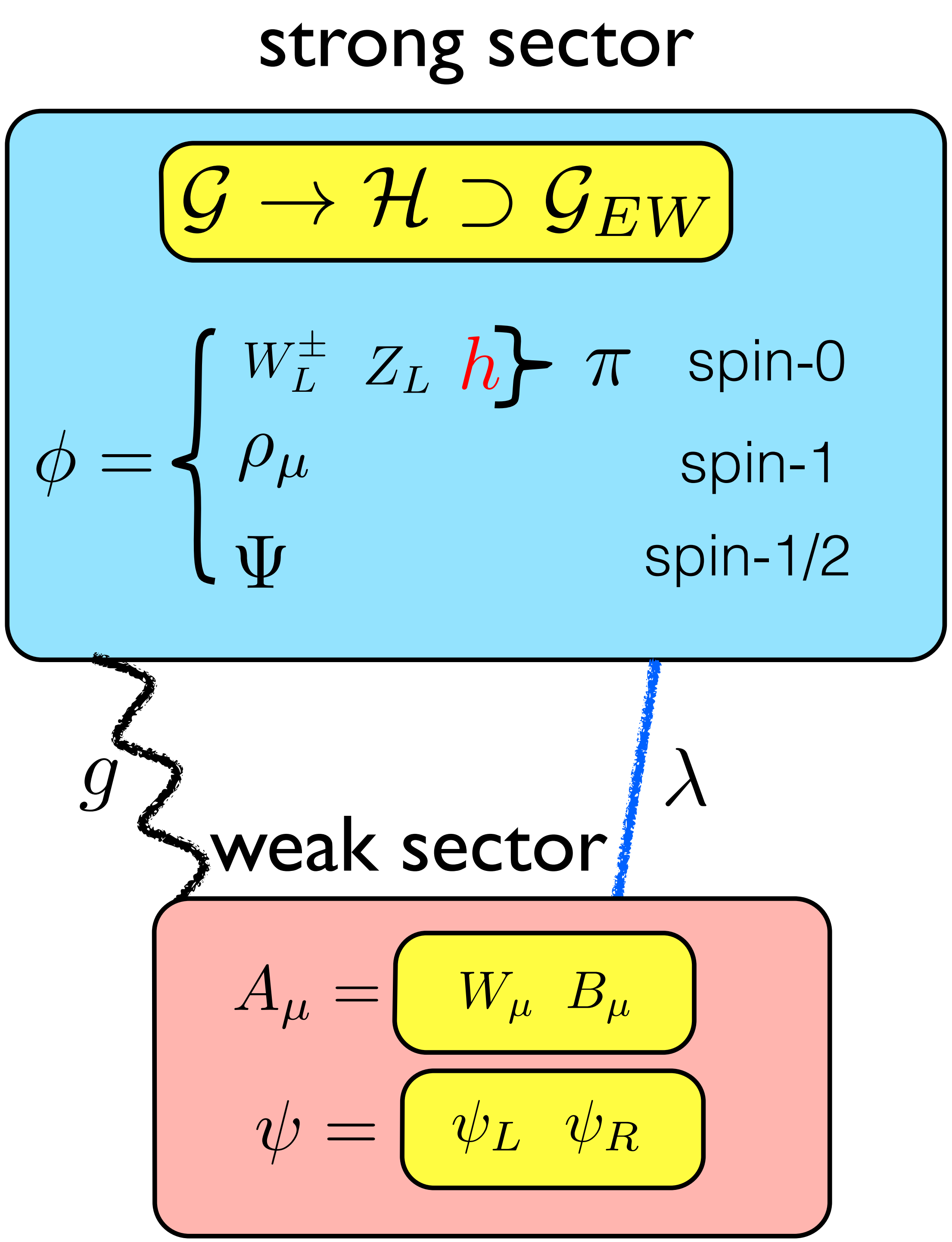

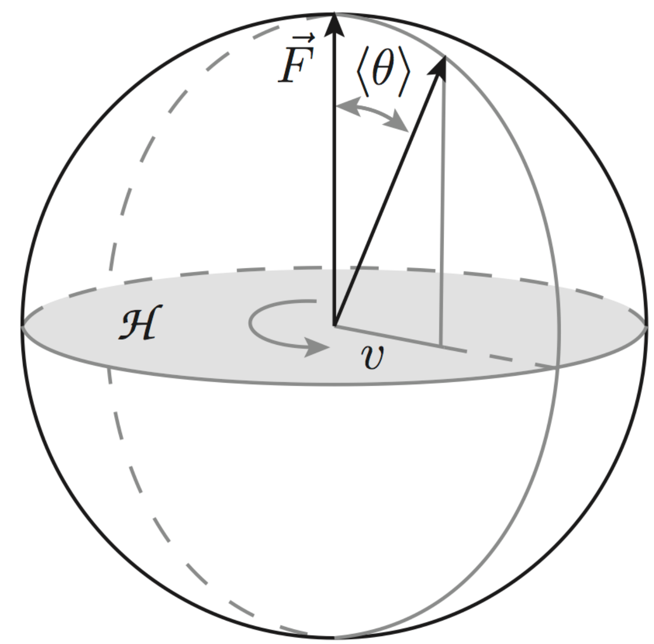

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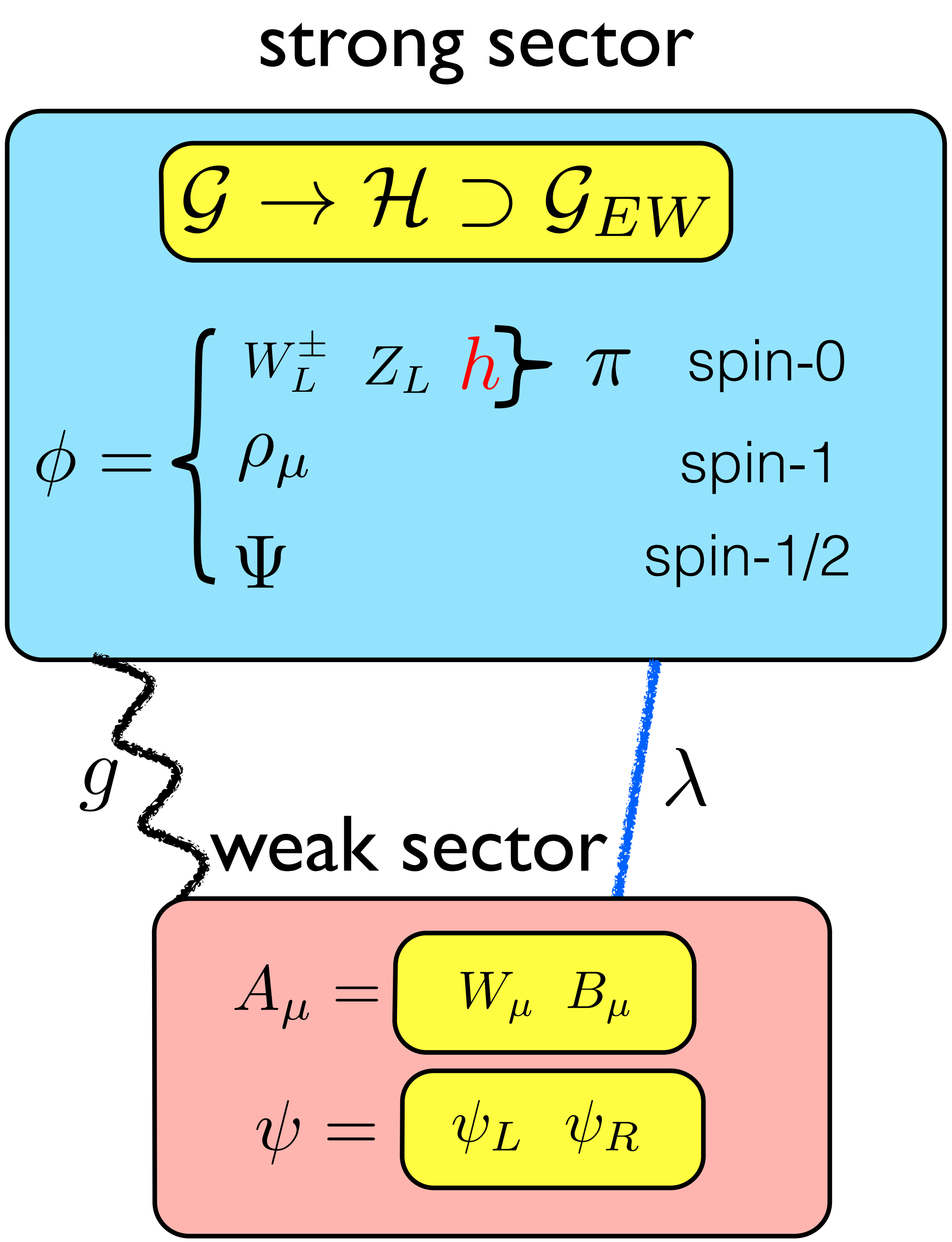
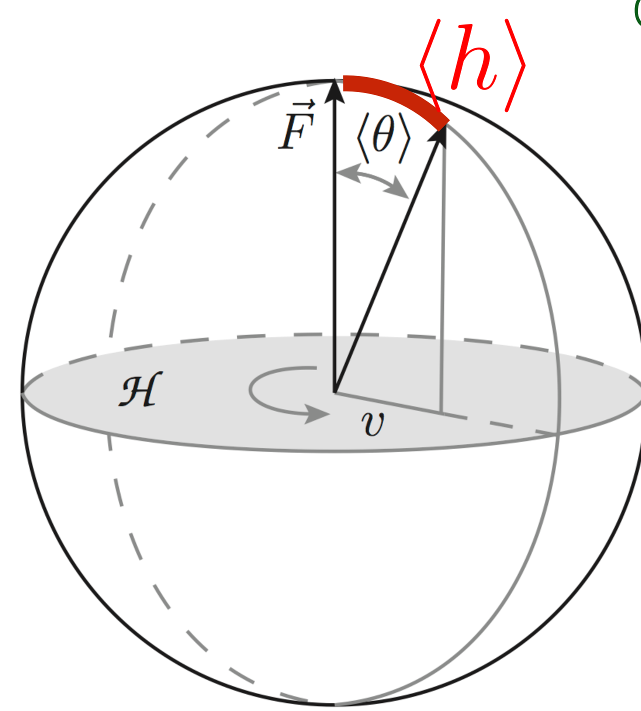


EWSB triggered by vacuum misalignment

Georgi, Kaplan in the 80s



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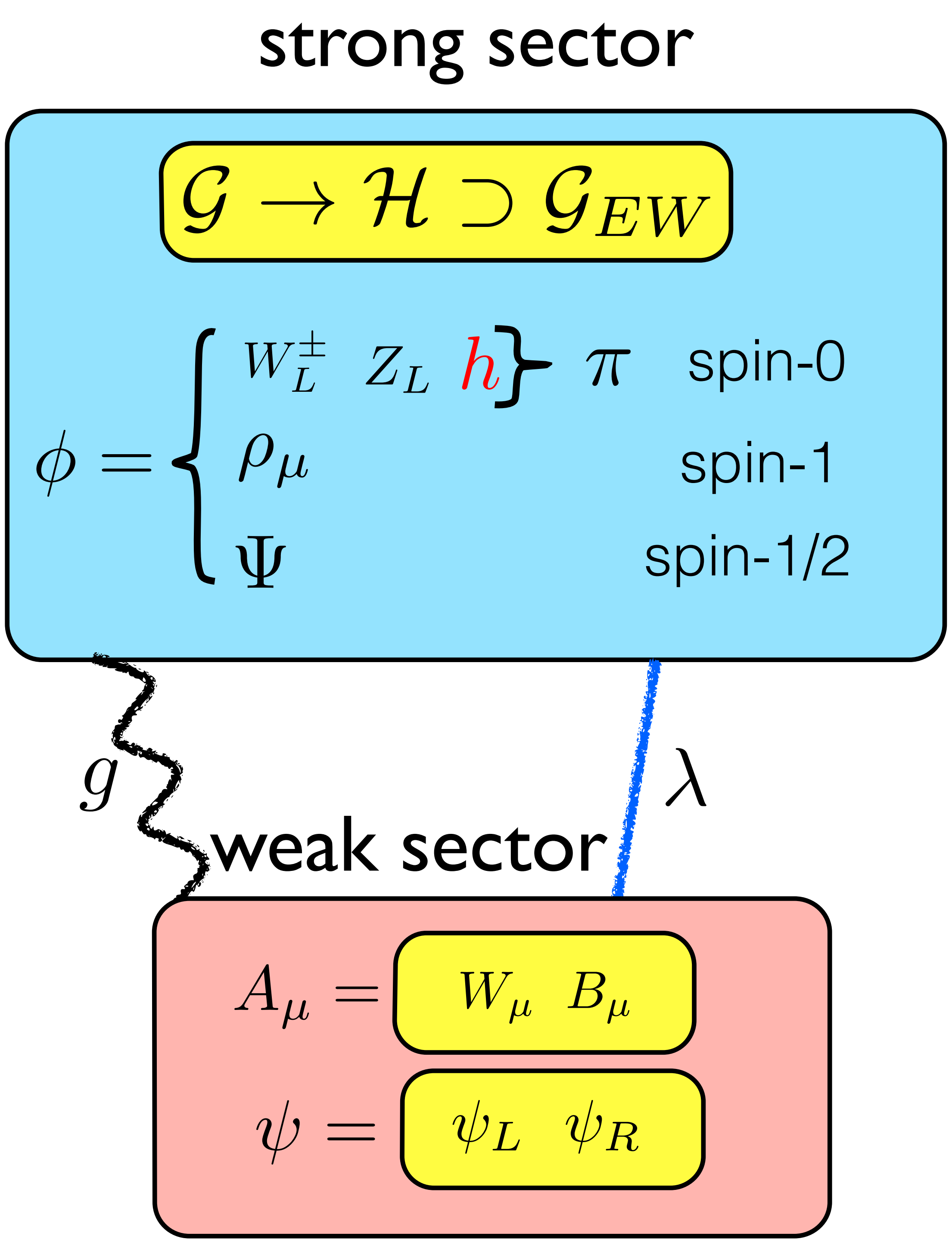

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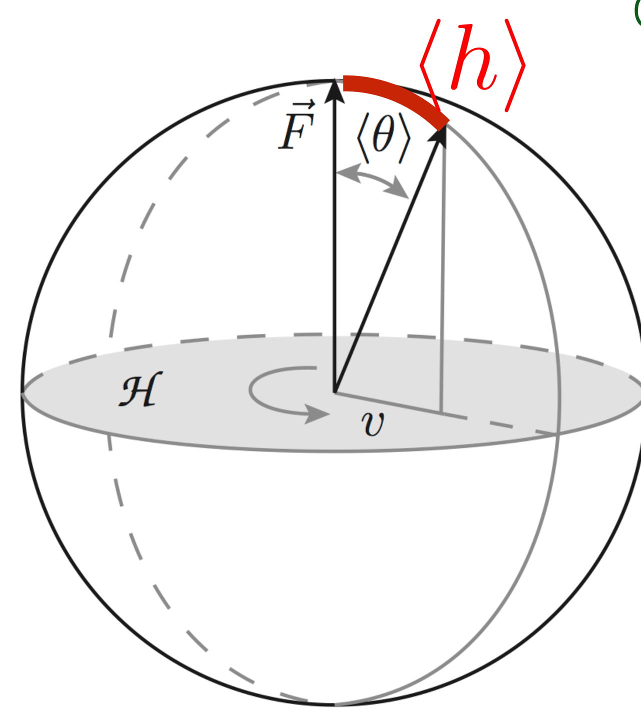

beyond SM effects controlled by v/f=sin<h>

decoupling limit f—>infty

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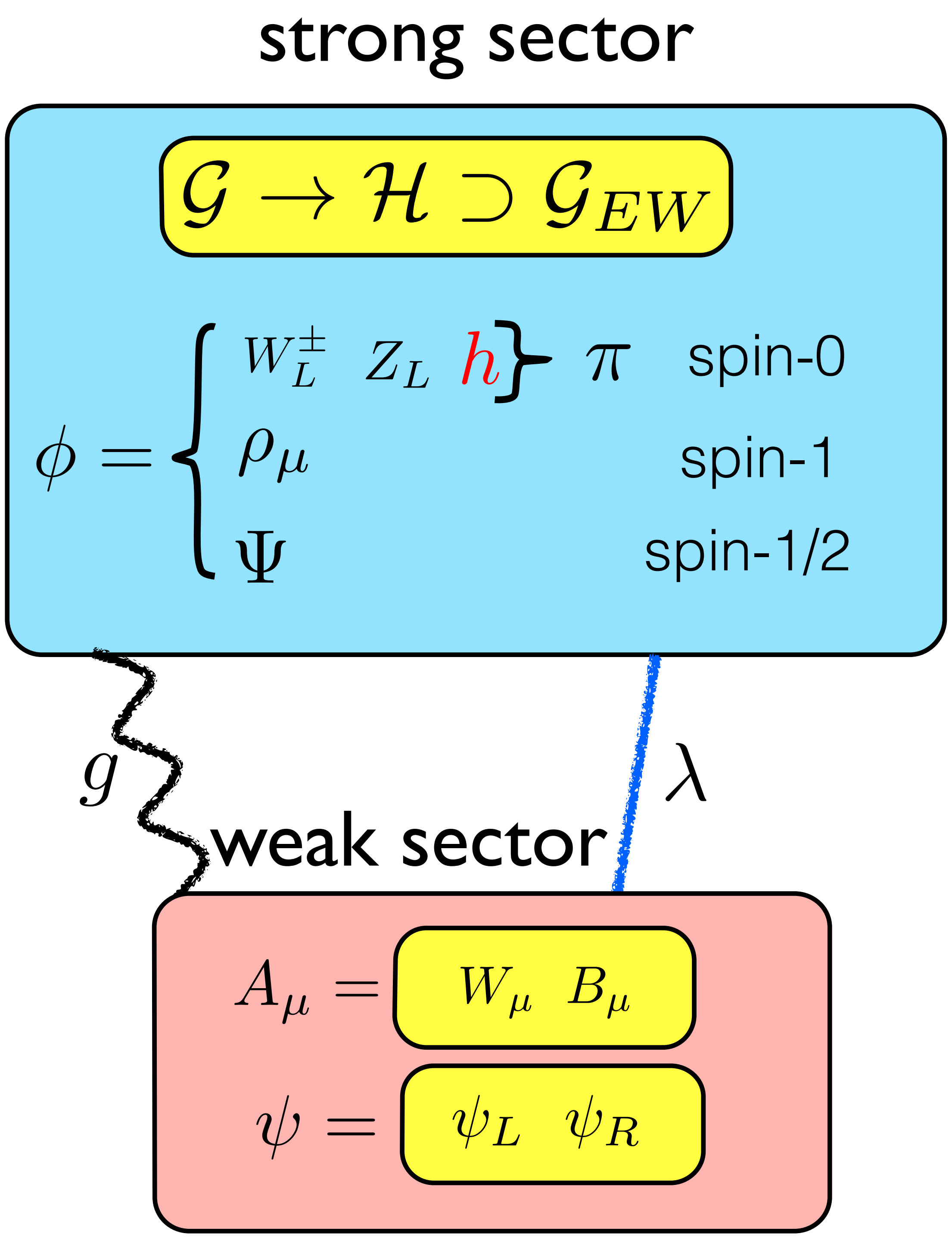

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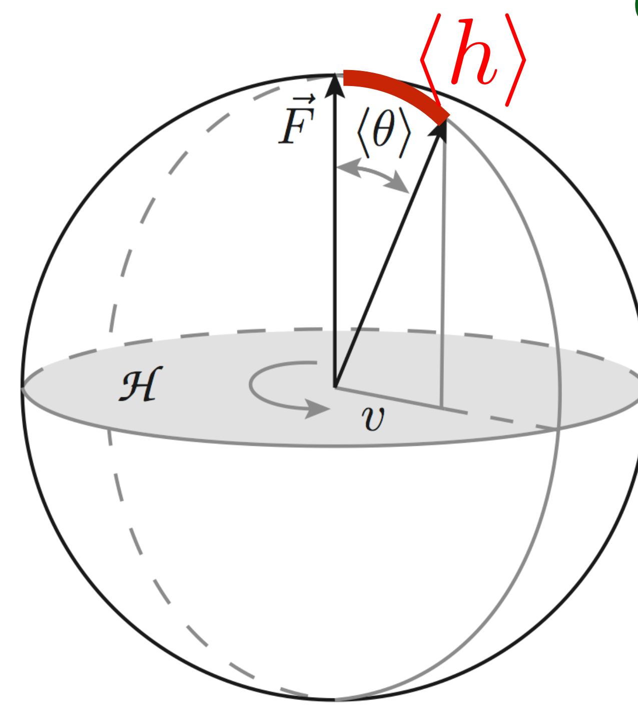

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minimal composite Higgs:

$SO(5)/SO(4)$ Agashe, Contino, Pomarol 0412089

$SU(3)/SU(2) \times U(1)$ Contino, Nomura, Pomarol 0306259

Higgs Couplings: tree

non-linear realisation of G: $f^2|\partial e^{i\pi/f}|^2 = (\partial\pi)^2 + \frac{(\pi\partial\pi)^2}{f^2} + \frac{\pi^2(\pi\partial\pi)^2}{f^4} + \ldots$

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$$\to |D_\mu H|^2 + \frac{c_H}{2f^2}\left(\partial_\mu |H|^2\right)^2 + \frac{c'_H}{2f^4}|H|^2\left(\partial_\mu |H|^2\right)^2 + \ldots$$

SILH-lagrangian

Giudice, Grojean, Pomarol, Rattazzi 0703164

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2. Higgs-scattering grows with energy

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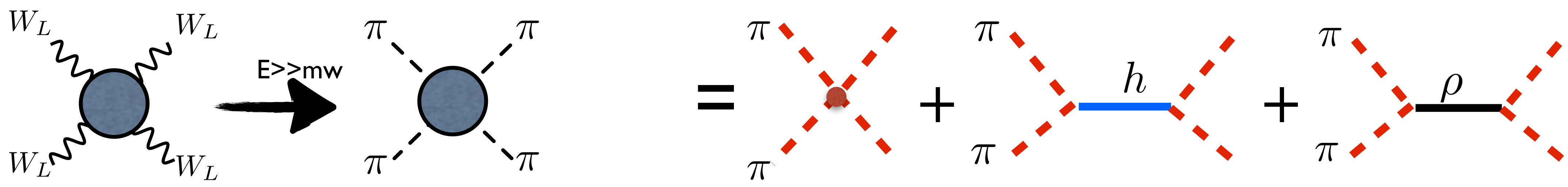

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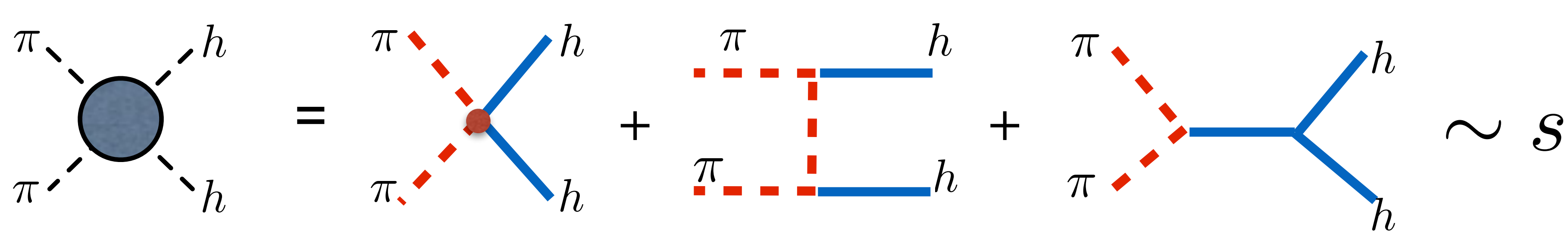

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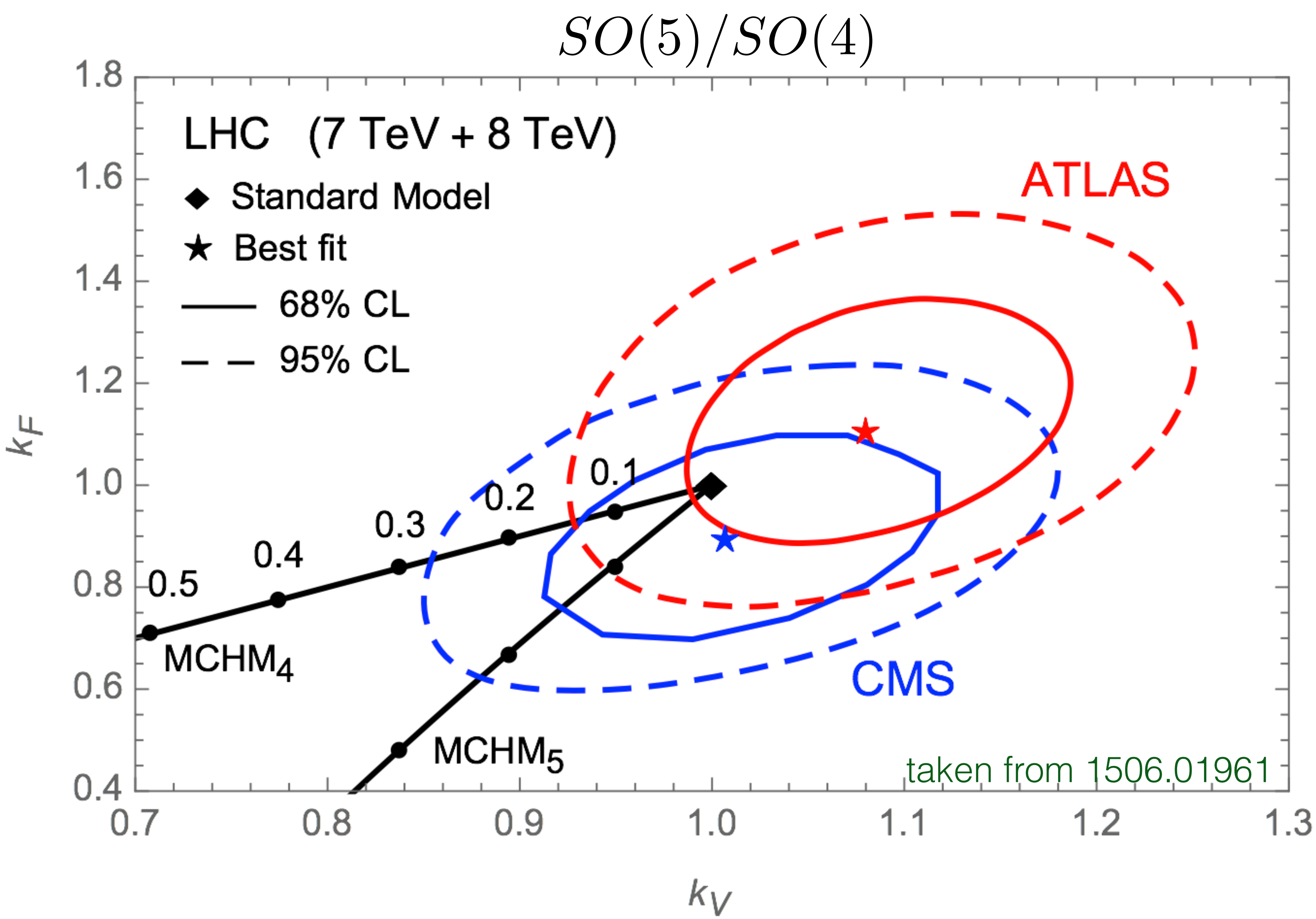
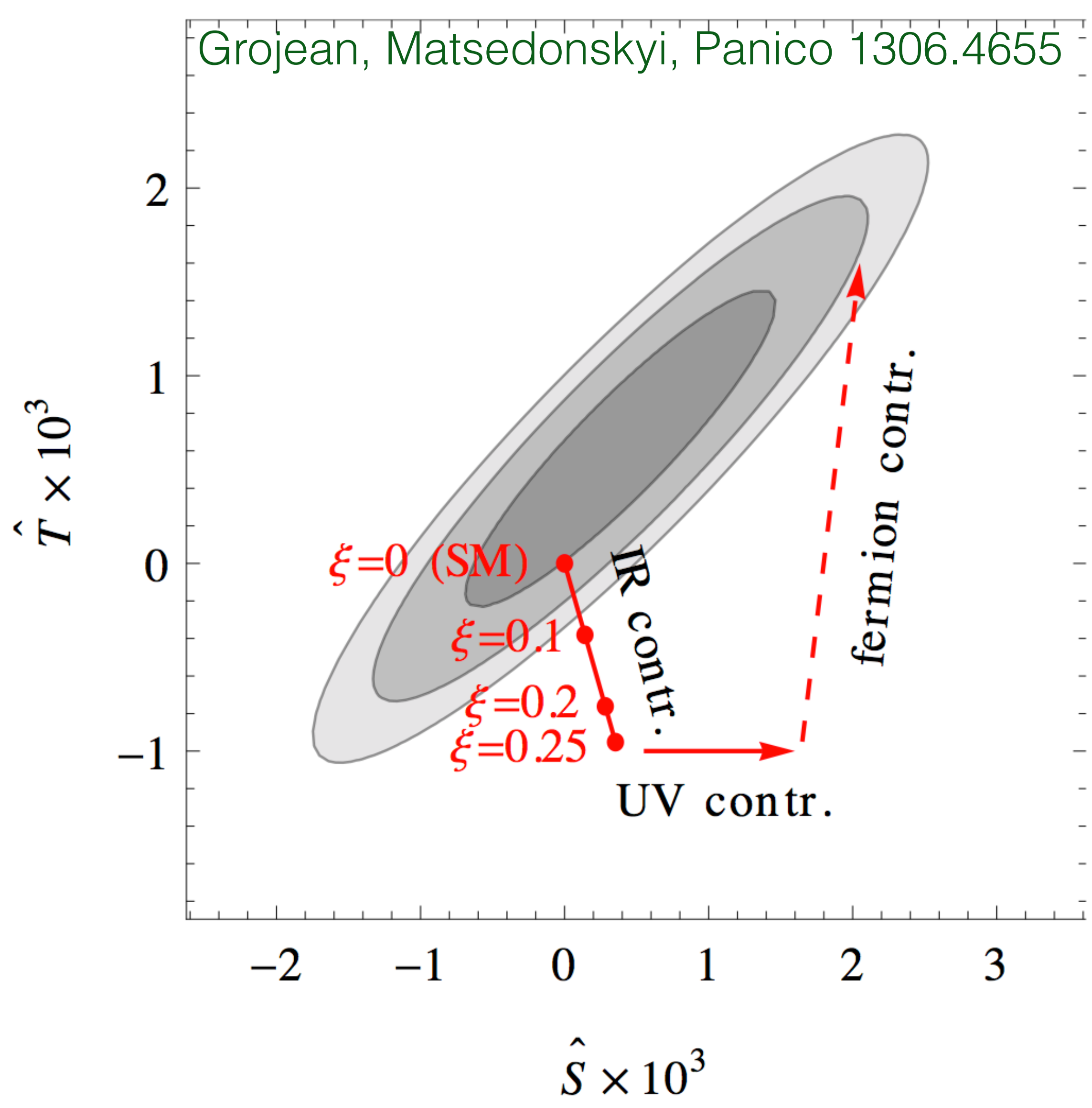


$$\xi \equiv \frac{v^2}{f^2} \lesssim 0.2$$

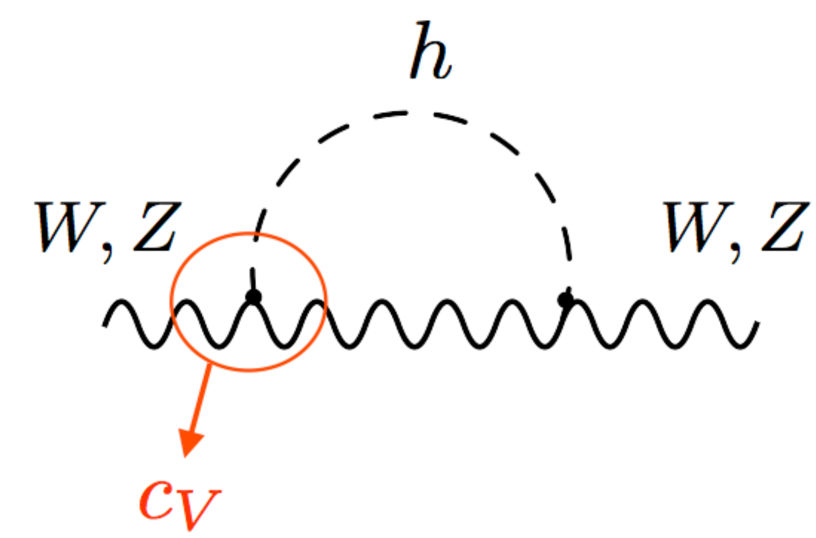
some tuning in the model

EWPTs



$$\frac{v^2}{f^2} \lesssim 0.1 - 0.2 \qquad f > 600 - 800\,\text{GeV}$$

Barbieri, B.B., Rychkov Varagnolo 0706.0432



$$\hat{T}_{IR} \simeq -\frac{3g'}{32\pi^2} \log\left[\frac{m_h}{m_Z}\left(\frac{\Lambda}{m_h}\right)^{1-c_V^2}\right]$$

$$\hat{S}_{IR} \simeq -\frac{g^2}{96\pi^2} \log\left[\frac{m_h}{m_Z}\left(\frac{\Lambda}{m_h}\right)^{1-c_V^2}\right]$$

$$\hat{S}_{UV} \approx \frac{m_W^2}{m_\rho^2} \qquad \Lambda \approx m_\rho$$

Higgs Couplings: loop

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power-counting:
1mass-1coupling

$$\mathcal{L}_{EFT} = \frac{m_*^4}{g_*^2} \times \widehat{\mathcal{L}}\left(\frac{g_*\phi}{m_*}, \frac{g_*\Psi}{m_*^{3/2}}, \frac{\partial}{m_*}, \frac{gA_\mu}{m_*}, \frac{\lambda\psi}{m_*^{3/2}}\right)$$

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partial compositeness $\quad g\, J_\mu A^\mu + \lambda\bar{\psi}\mathcal{O}$

e.g. Yukawas: $\left(\frac{\lambda_L\lambda_R}{g_*}\right)\bar{\psi}_L\psi_R H$

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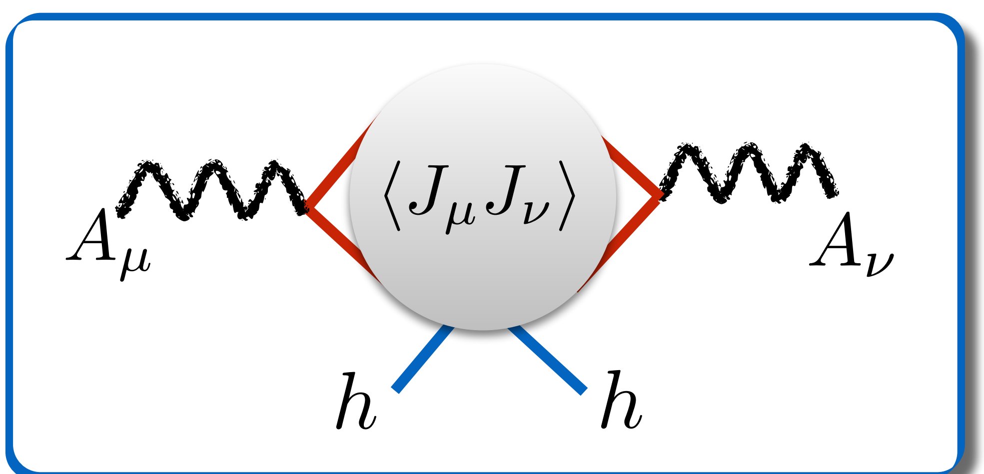
e.g. Yukawas: $\left(\frac{\lambda_L\lambda_R}{g_*}\right)\bar{\psi}_L\psi_R H$

top-partners are charged under SM



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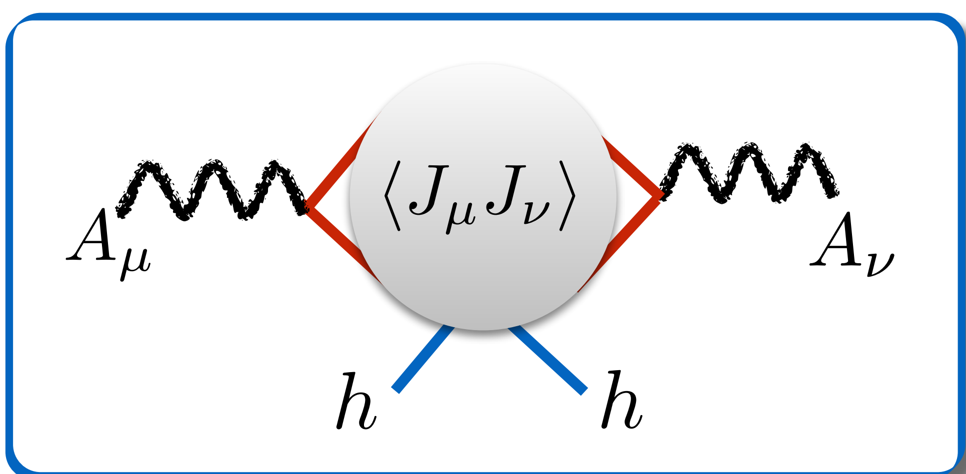

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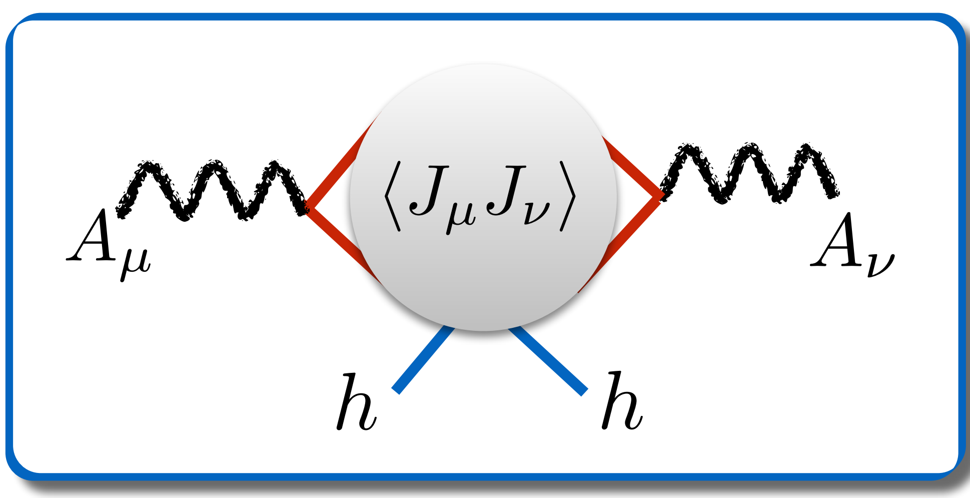

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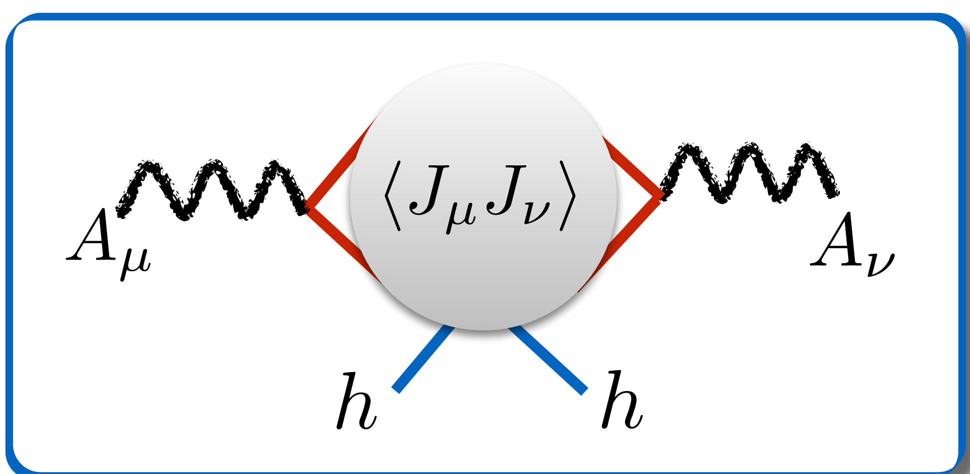

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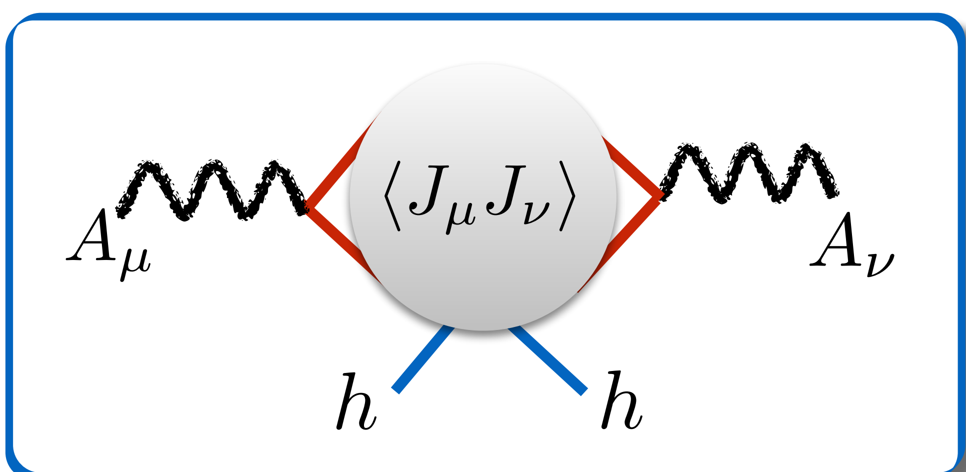

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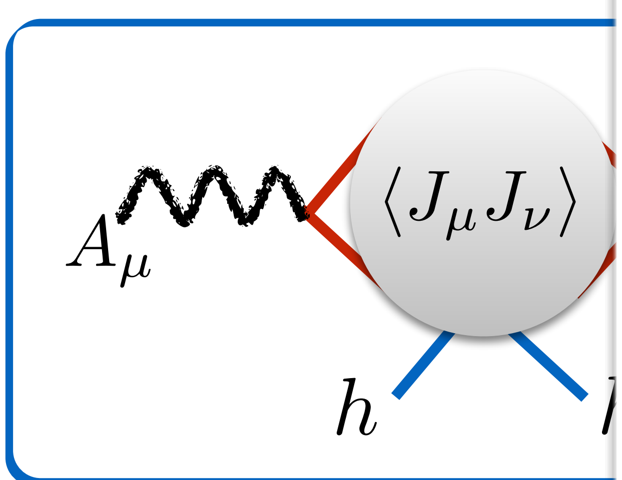

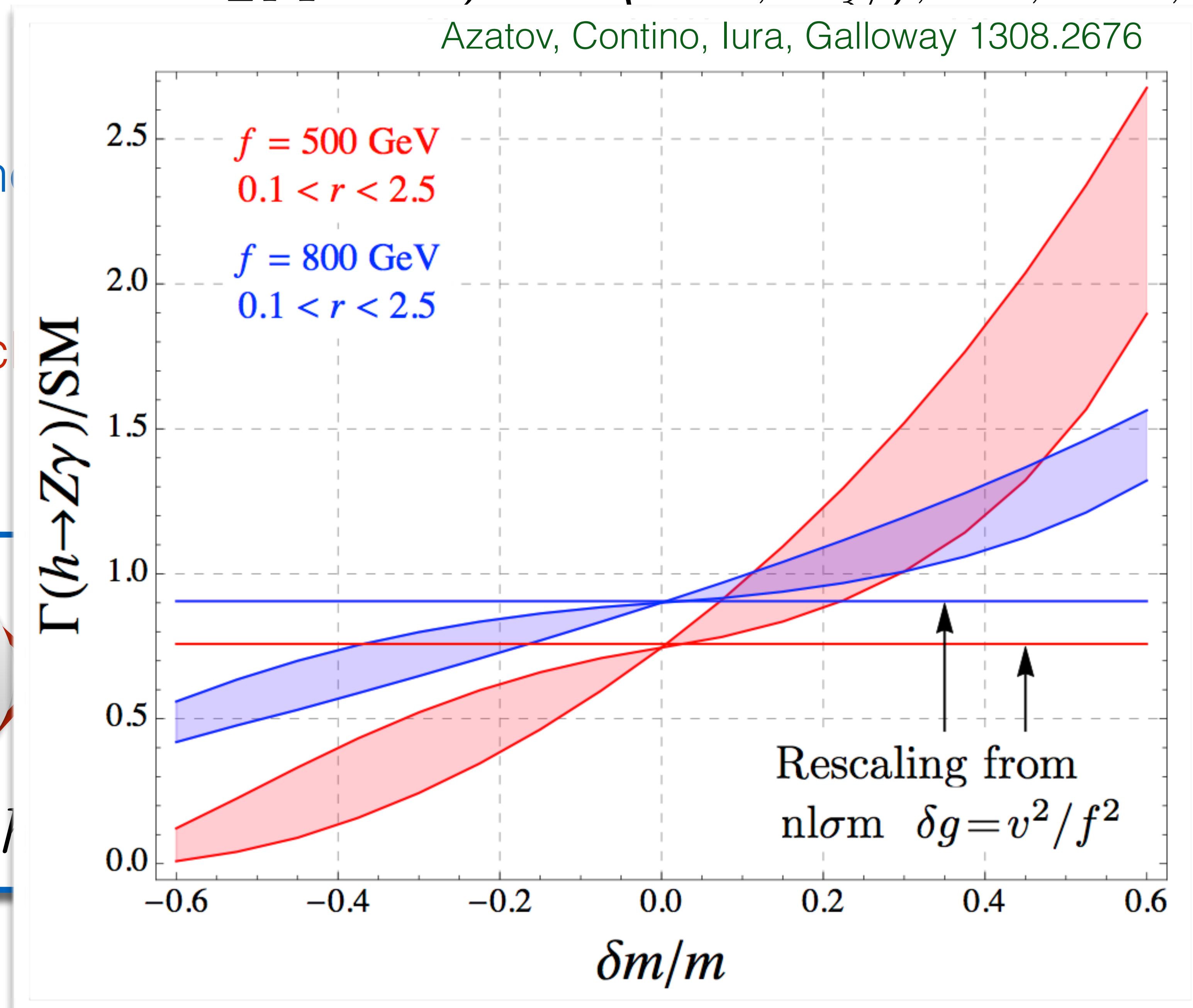

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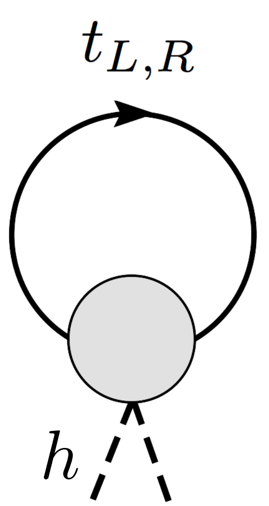

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Light Higgs= Light top partners

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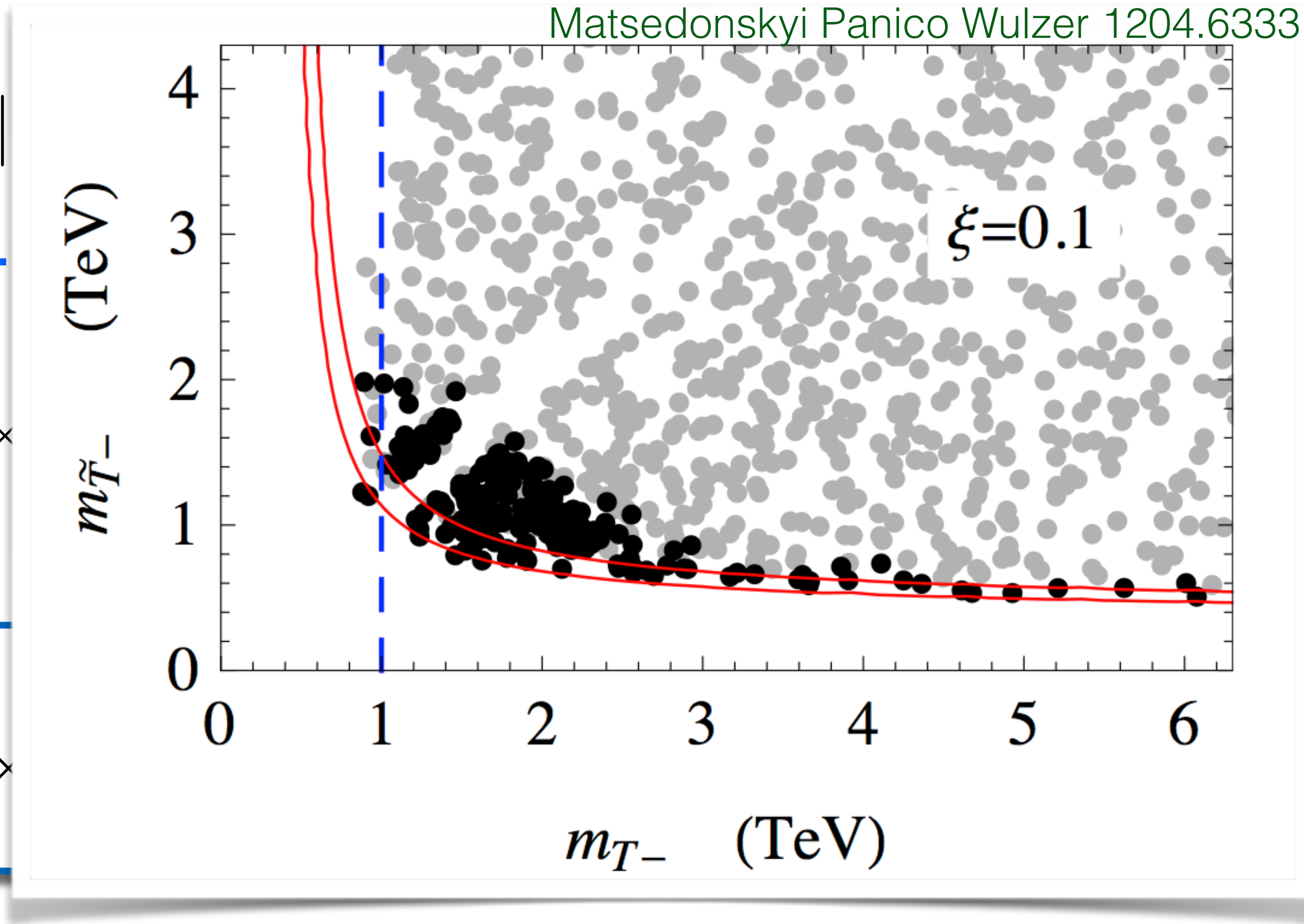

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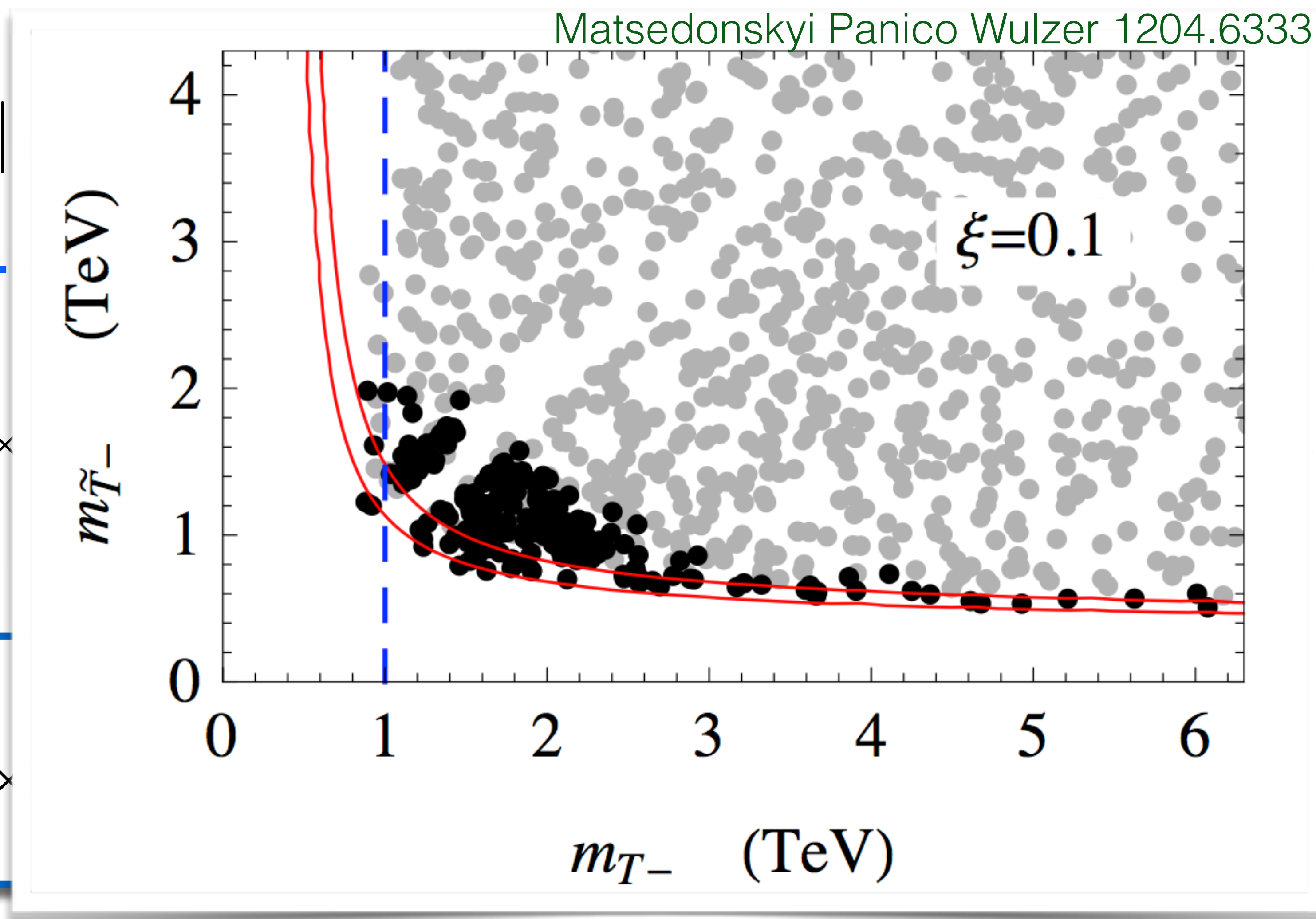

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irreducible fine-tuning

$$\Delta_{v^2} = \frac{\delta v^2}{v_{\text{exp}}^2} = \frac{f^2}{v^2} \times \left(\frac{a}{b}\right) \gtrsim (10\%)^{-1} \qquad \Delta_{m_H^2} = \frac{g_{SM}^2}{8\pi^2}\left(\frac{m_*}{m_h}\right)^2 = \left(\frac{m_*}{500}\right)^2$$

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$$g_{SM}^2 = N_c\, y_{top}^2$$

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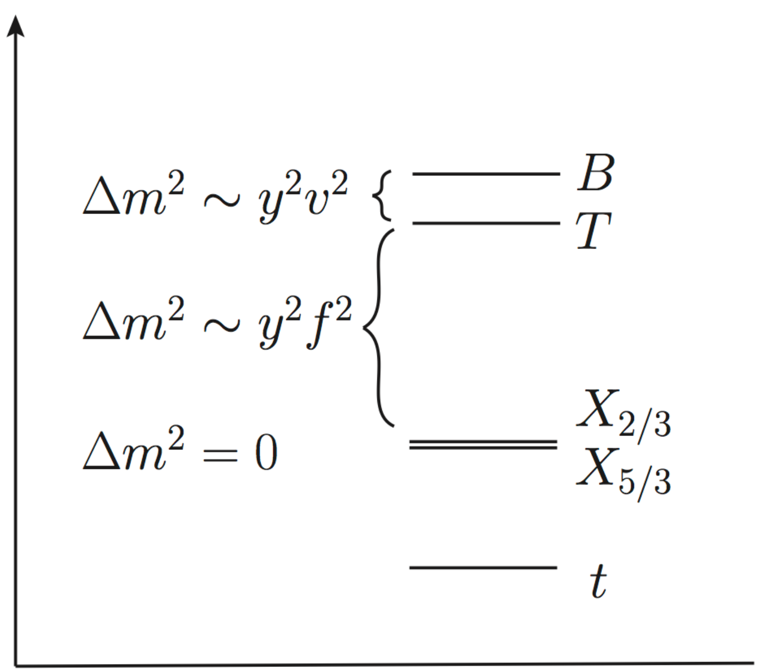
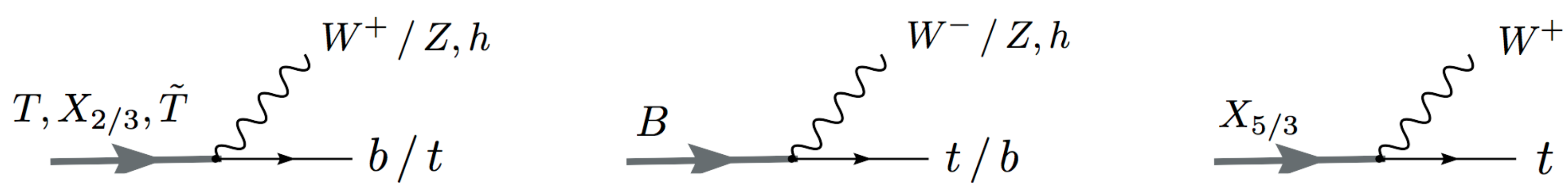
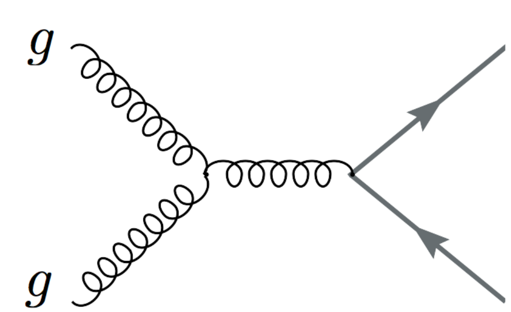
extra spurion of Z2-breaking: $\delta m_H^2 = \frac{g_{SM}^2}{g_*^2} \times \frac{g_{SM}^2}{16\pi^2} m_*^2 \sim \frac{g_{SM}^4 f^2}{16\pi^2}$ tuning unrelated to colored resonances!

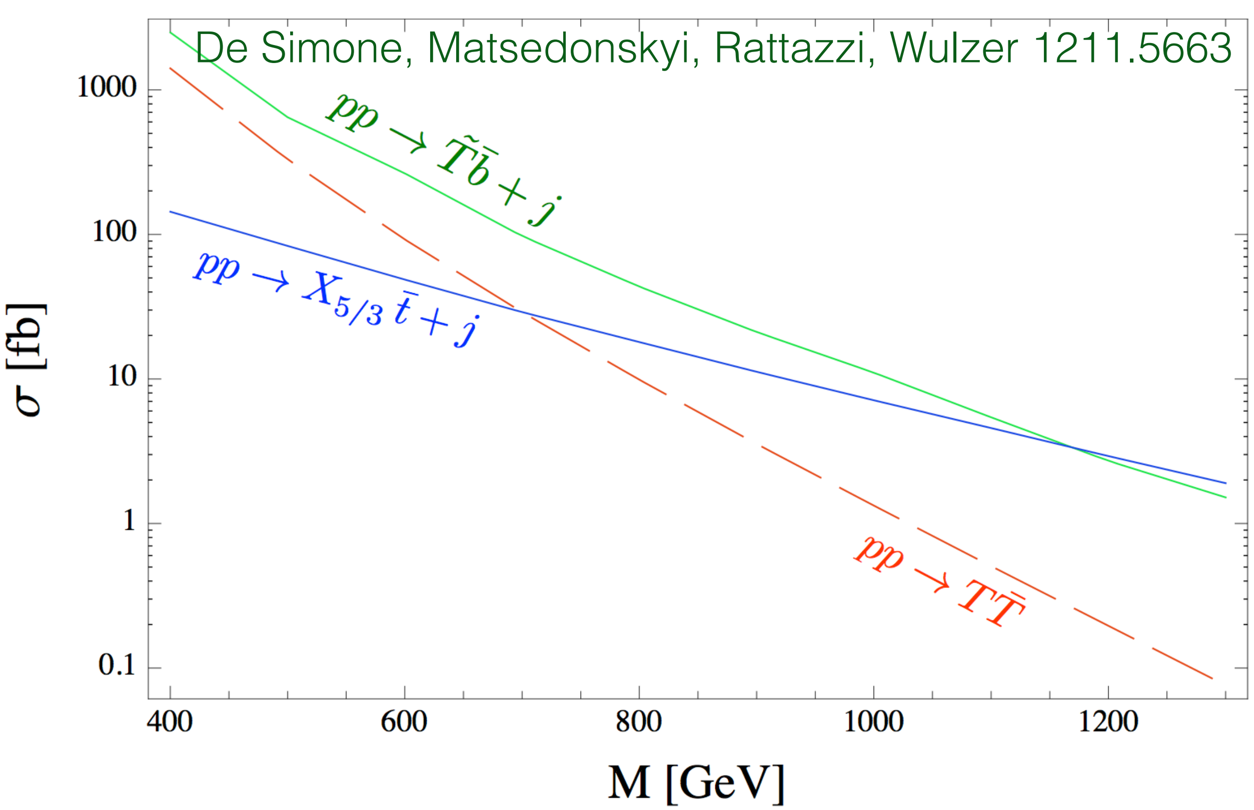
SPIN-1/2 RESONANCES

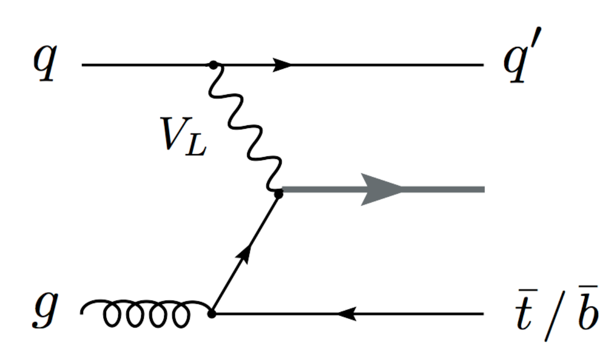






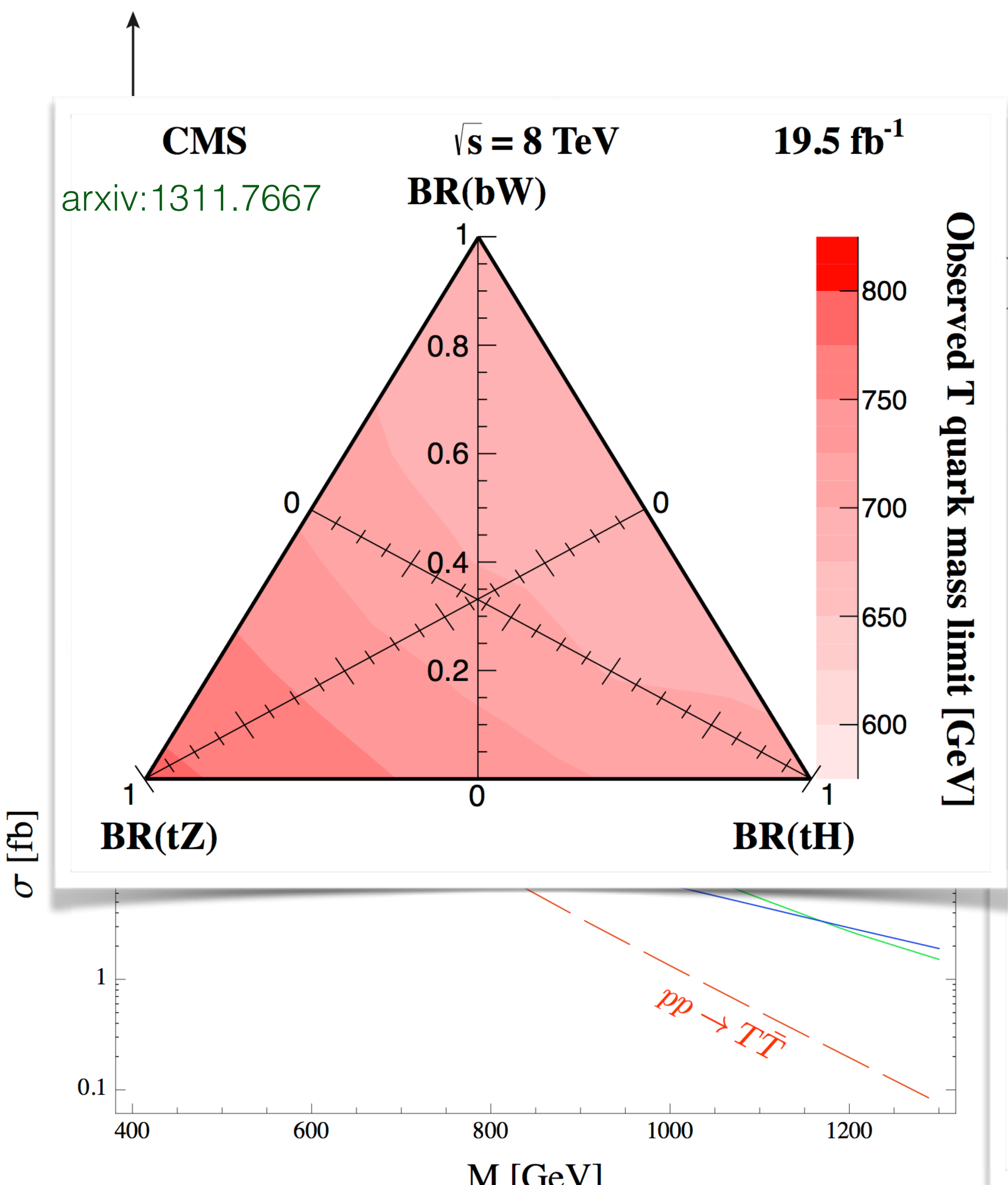
pair production

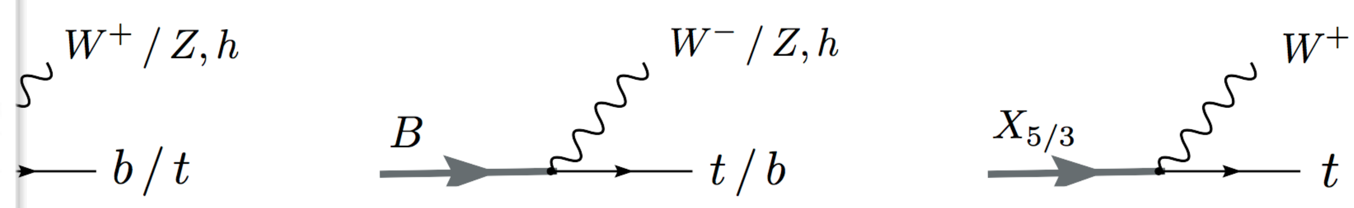


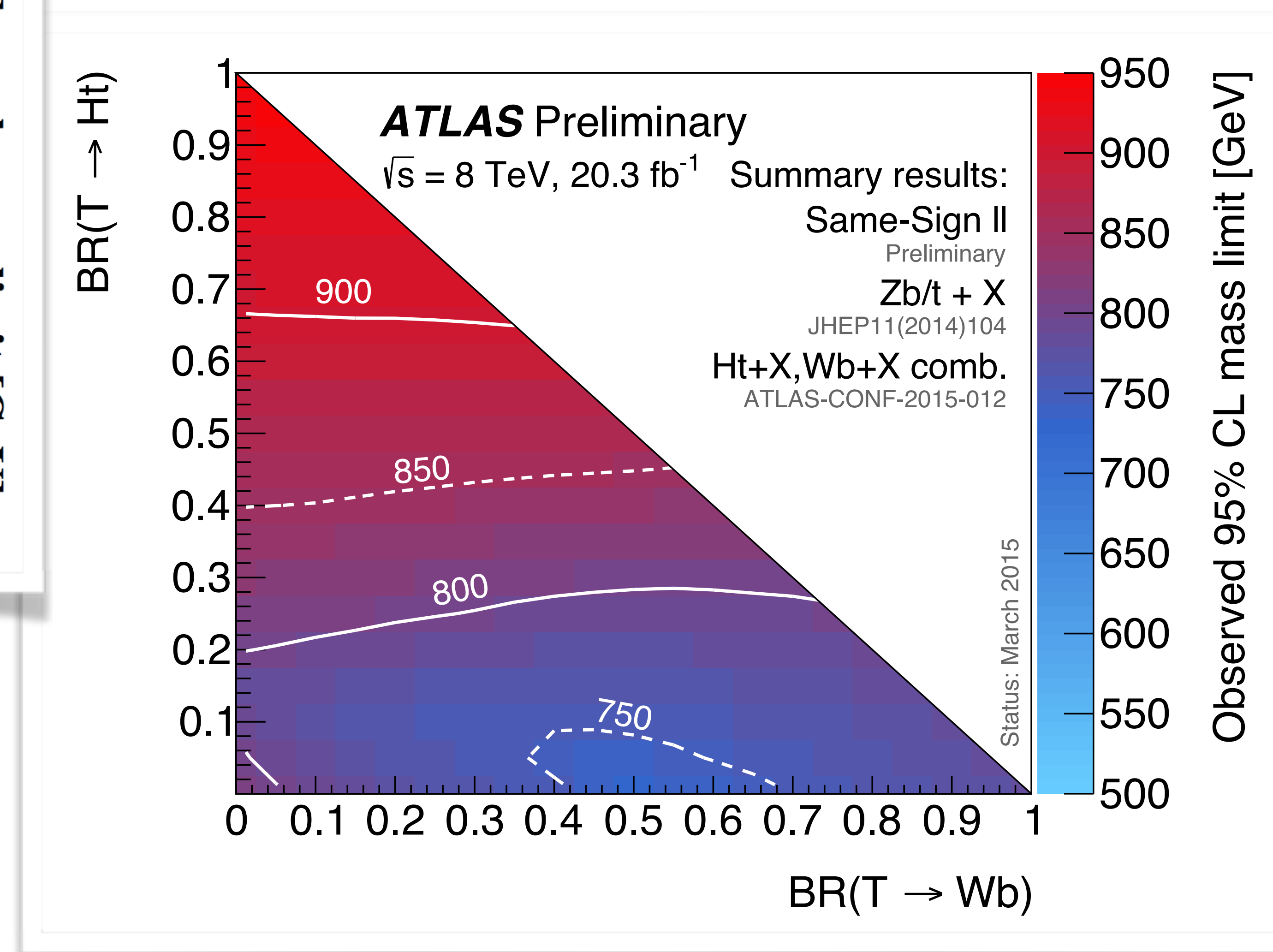


EW single production

SPIN-1/2 RESONANCES

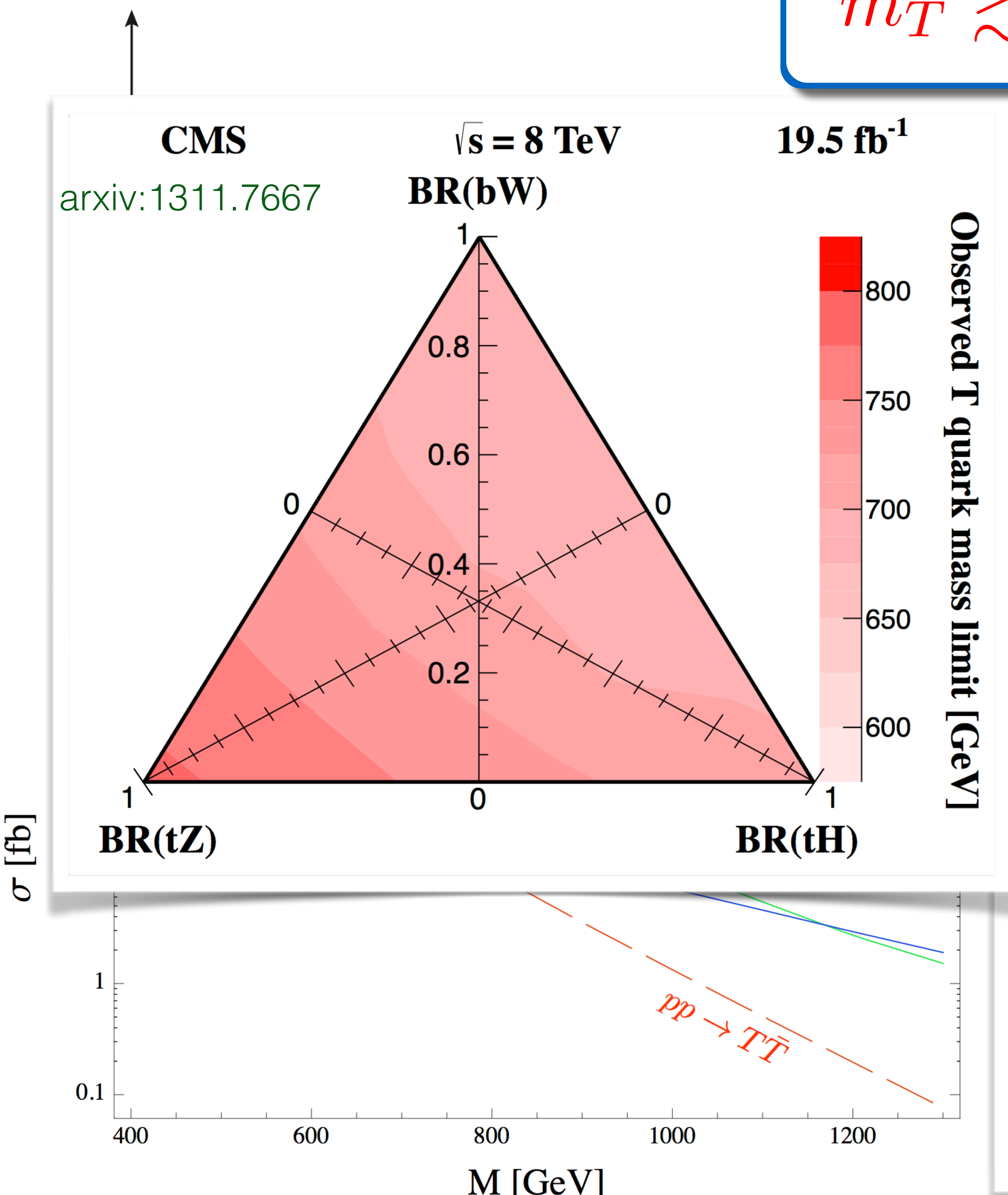


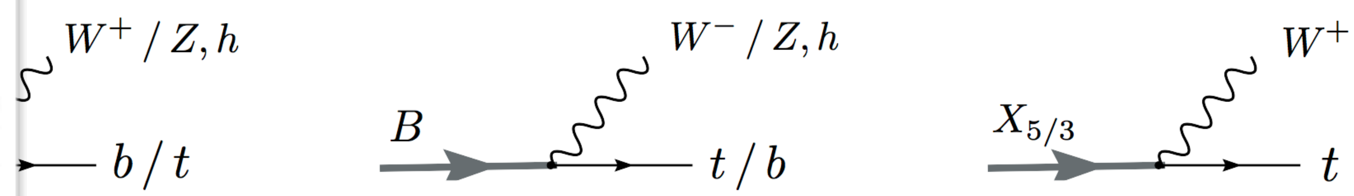


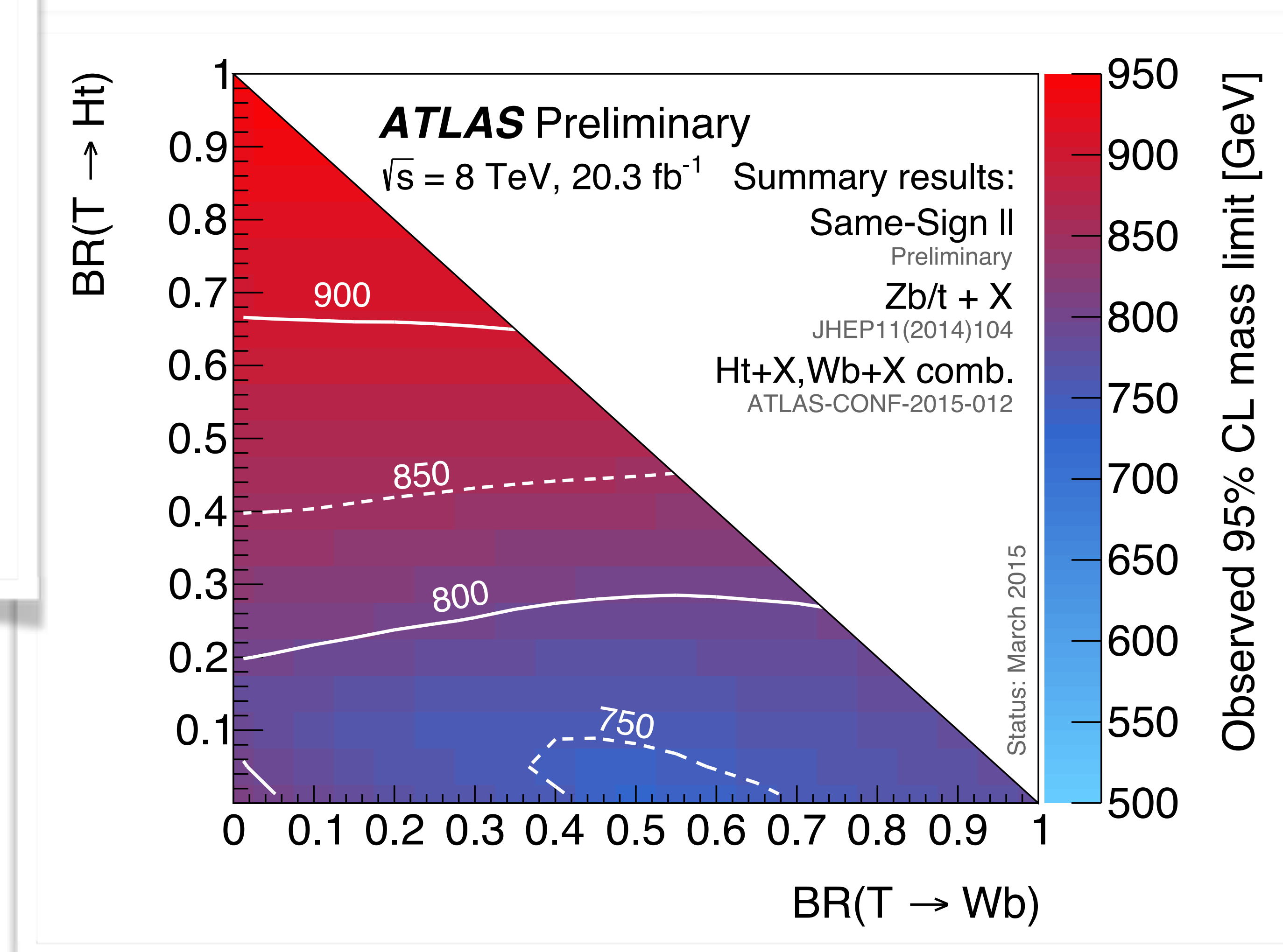


SPIN-1/2 RESONANCES

$$m_T \gtrsim 800\,\mathrm{GeV}$$







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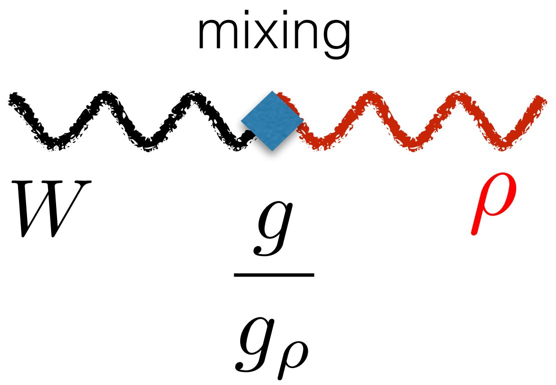
$$g\, J_\mu A^\mu + \lambda \bar{\psi} \mathcal{O} \longrightarrow \langle 0 | J_\mu | \rho \rangle = \epsilon_\mu f_\rho \longrightarrow$$



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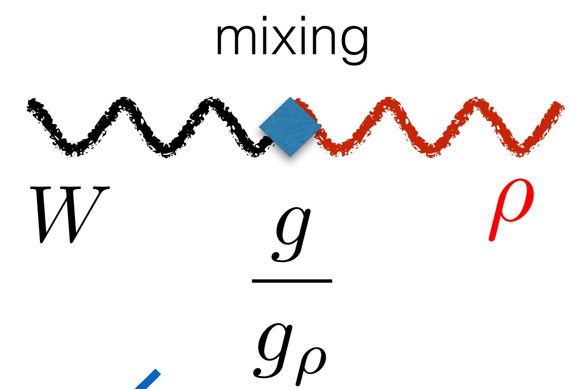

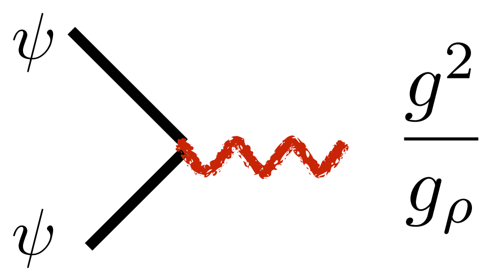

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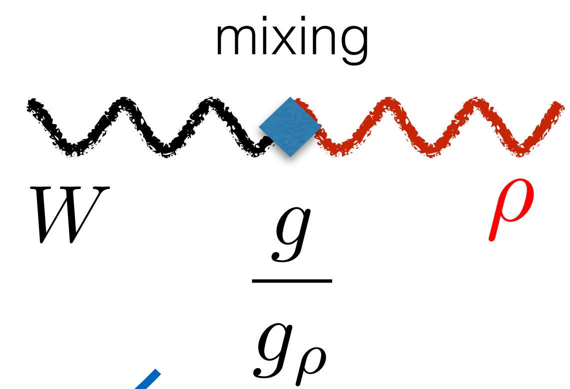
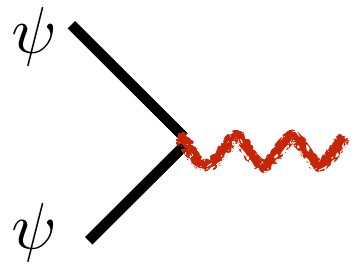
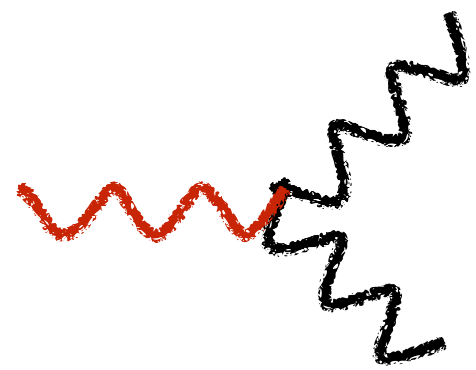




$$\frac{g^2}{g_\rho}$$



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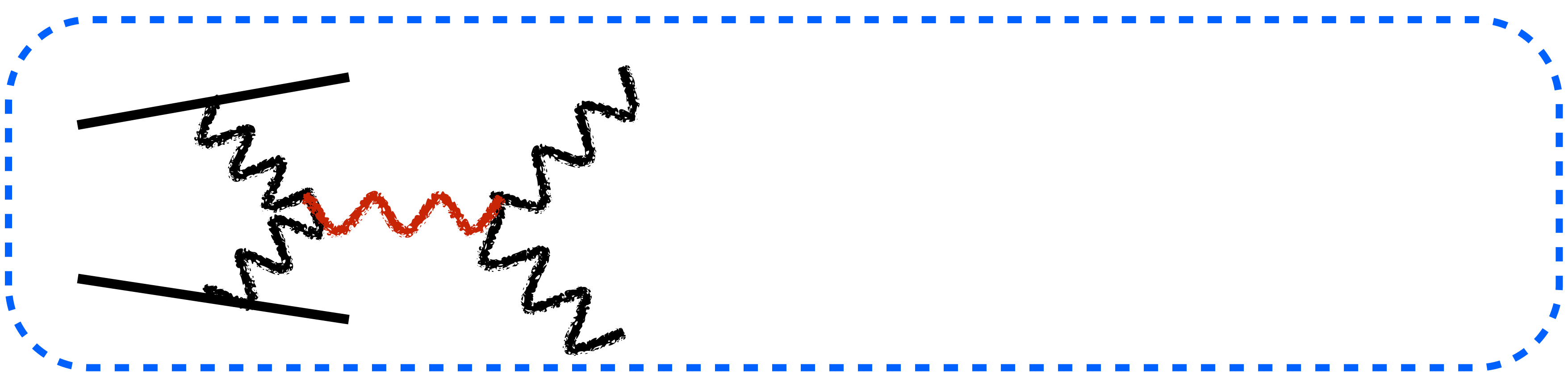
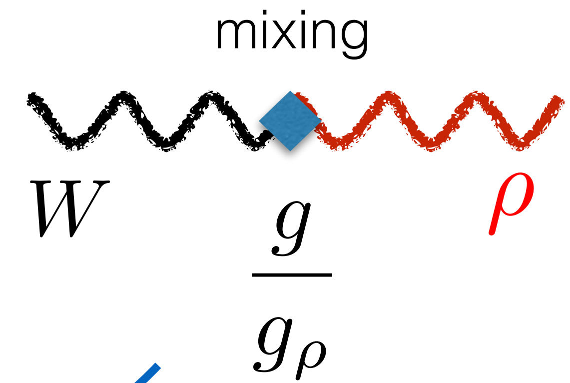
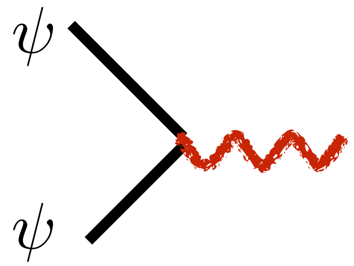


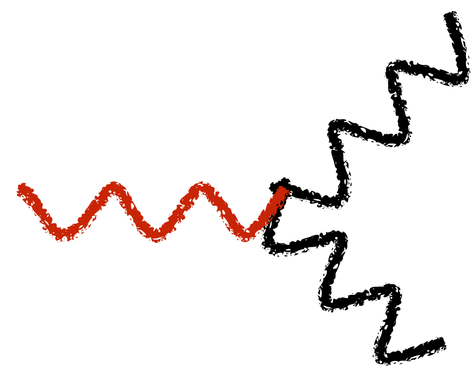
SPIN-1 RESONANCES

$$g\,J_\mu A^\mu + \lambda\bar{\psi}\mathcal{O} \;\rightarrow\; \langle 0|J_\mu|\rho\rangle = \epsilon_\mu f_\rho \;\rightarrow$$

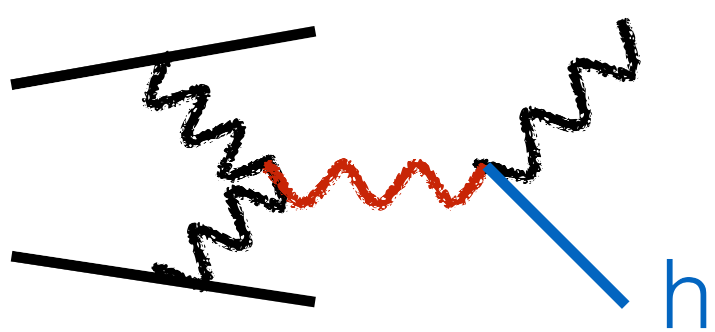




$$\frac{g^2}{g_\rho}$$

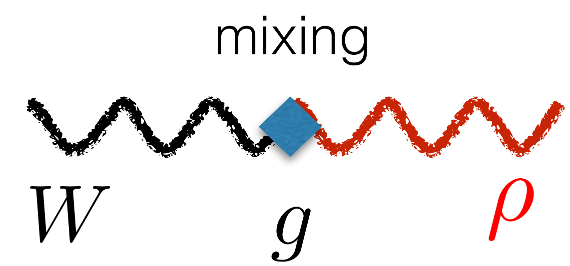


$$\frac{g^2}{g_\rho}$$

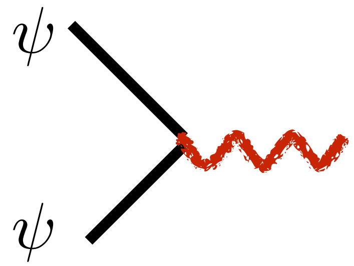


SPIN-1 RESONANCES

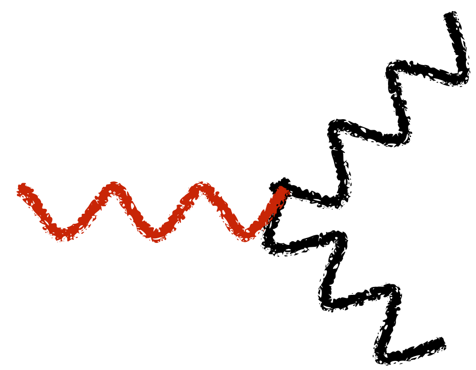
$$g\, J_\mu A^\mu + \lambda \bar{\psi} \mathcal{O} \longrightarrow \langle 0 | J_\mu | \rho \rangle = \epsilon_\mu f_\rho \longrightarrow$$



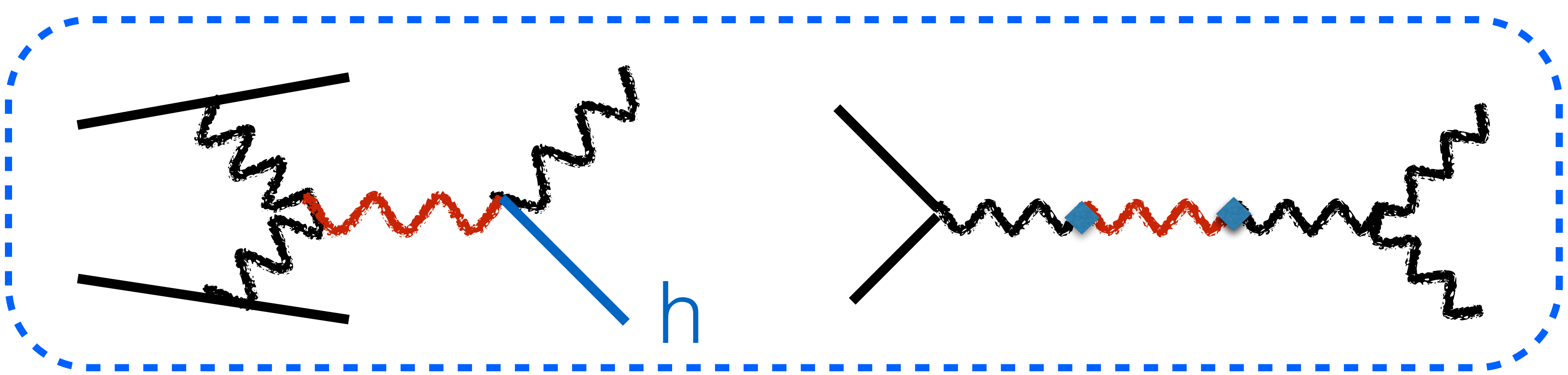
$$\frac{g}{g_\rho}$$



$$\frac{g^2}{g_\rho}$$

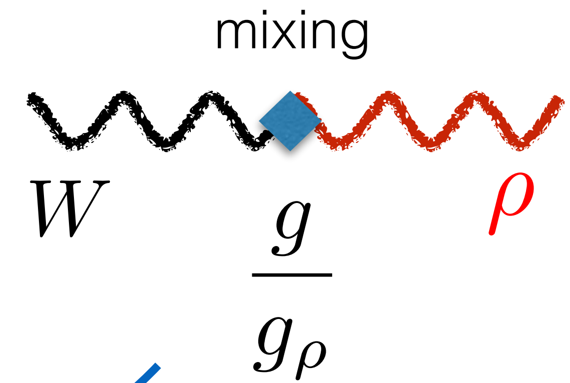


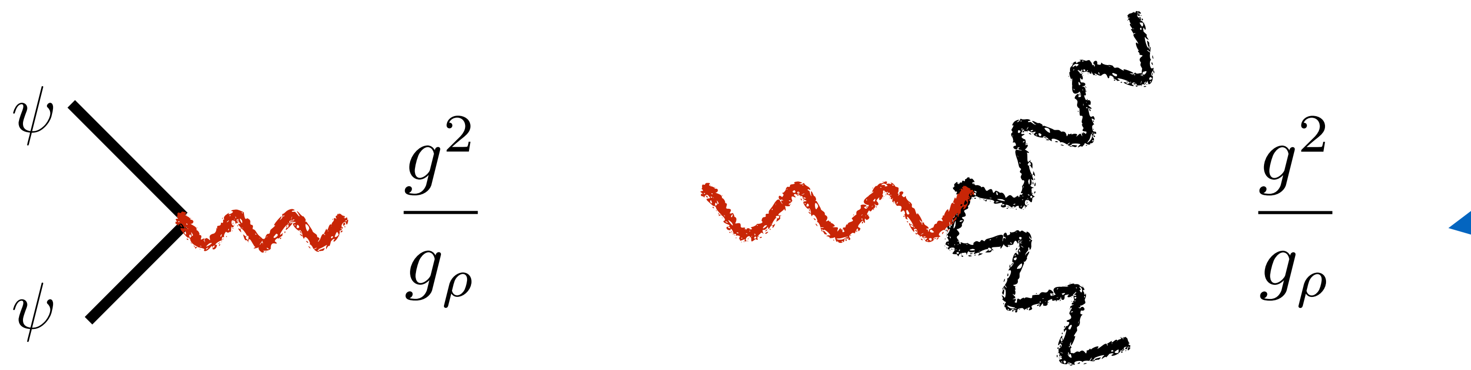
$$\frac{g^2}{g_\rho}$$

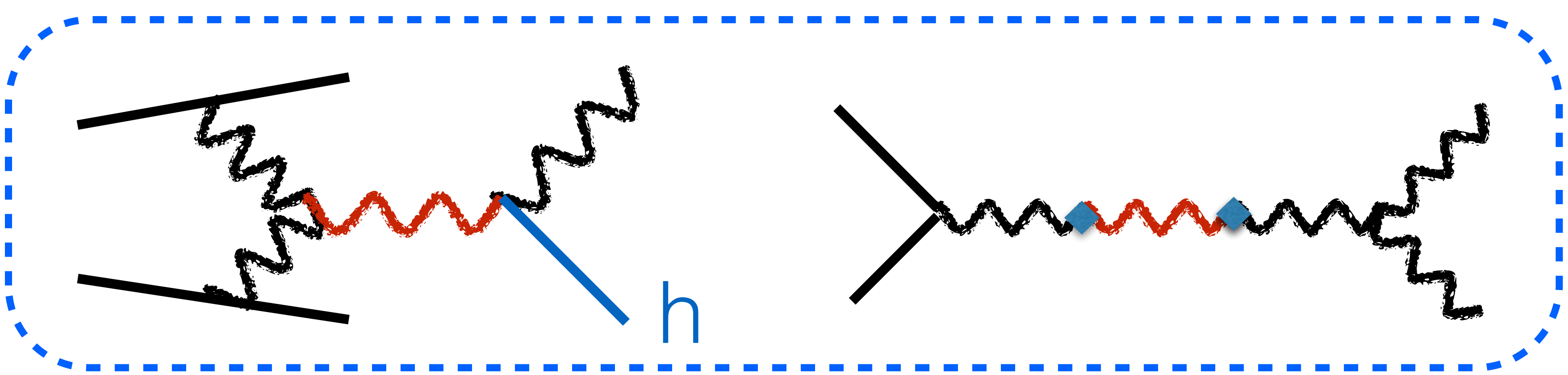


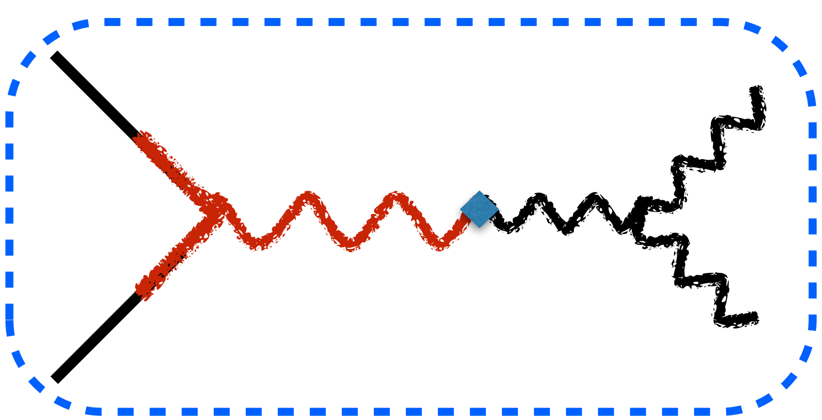
SPIN-1 RESONANCES

$$g\, J_\mu A^\mu + \lambda \bar{\psi}\mathcal{O} \longrightarrow \langle 0|J_\mu|\rho\rangle = \epsilon_\mu f_\rho \longrightarrow$$



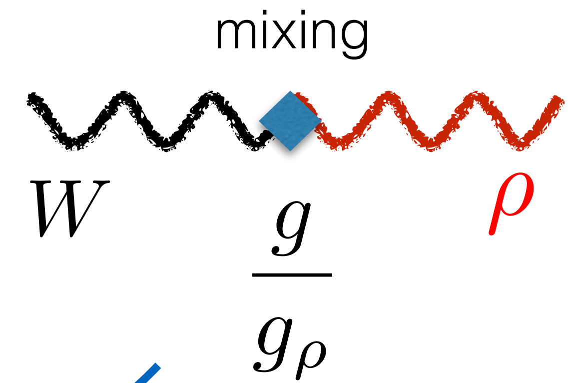


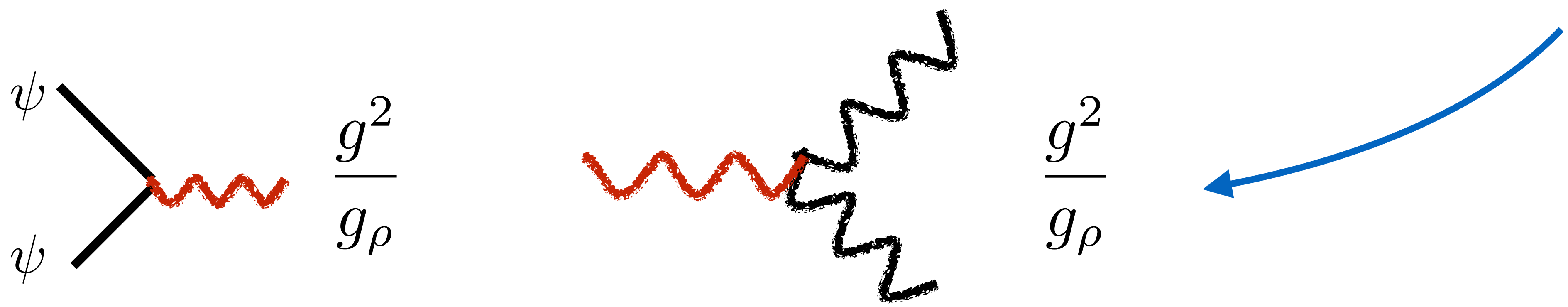


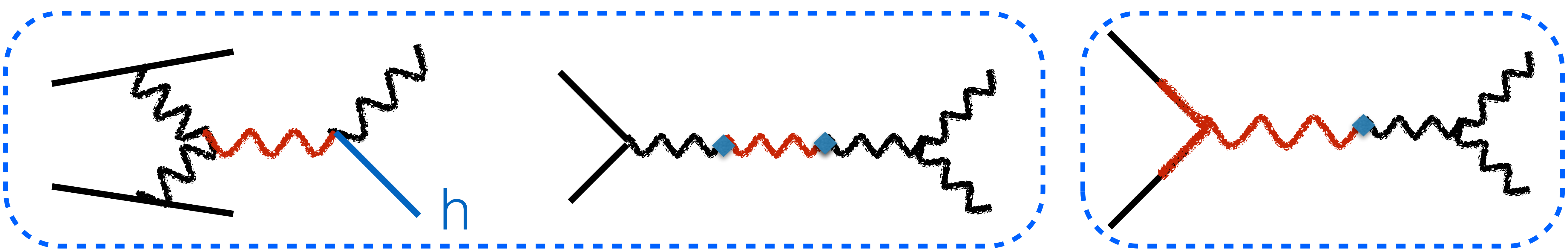


SPIN-1 RESONANCES

$$g\,J_\mu A^\mu + \lambda\bar{\psi}\mathcal{O} \;\longrightarrow\; \langle 0|J_\mu|\rho\rangle = \epsilon_\mu f_\rho \;\longrightarrow$$







$g_\rho \approx 3$ can fit ATLAS excess at $m_\rho \approx 2\,\mathrm{TeV}$

see e.g.Thamm, Torre, Wulzer, 1506.08688

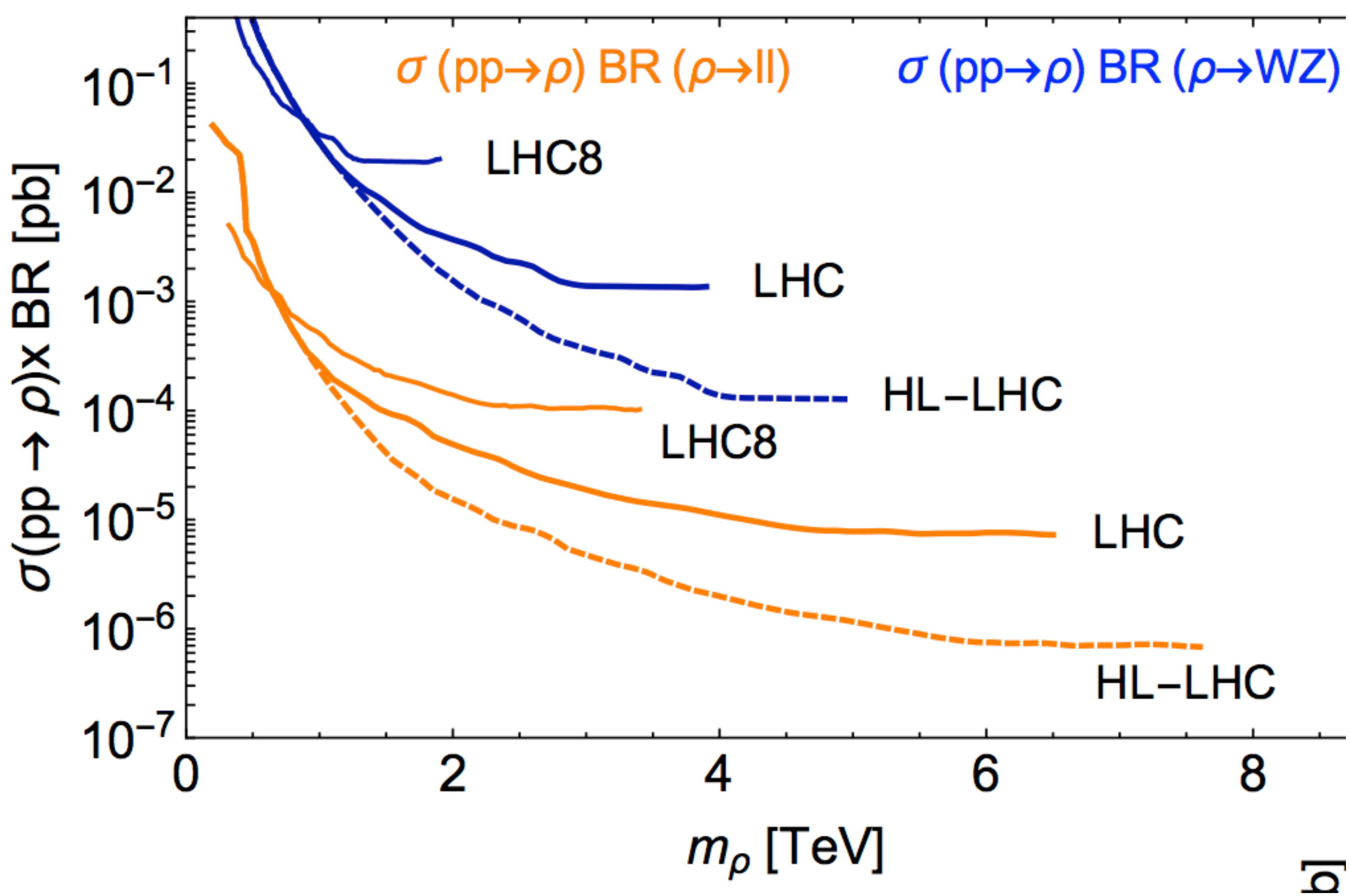
CONCLUSIONS

- PNGB-Higgs can naturally be light and narrow
- Decoupling limit v/f —> infty where SM is recovered
- Fine-tuning worsens with larger f and g*
- Predictions and largest effects:
    - strong double H production
    - 10% corrections to tree-level Higgs couplings
    - small h—> gluons and photons but (possibly large) h—> Z gamma
    - light vector-like coloured partners expected below 1.5 TeV

Thank you!

back-up slides

taken from Thamm, Torre, Wulzer arXiv:1502.01701



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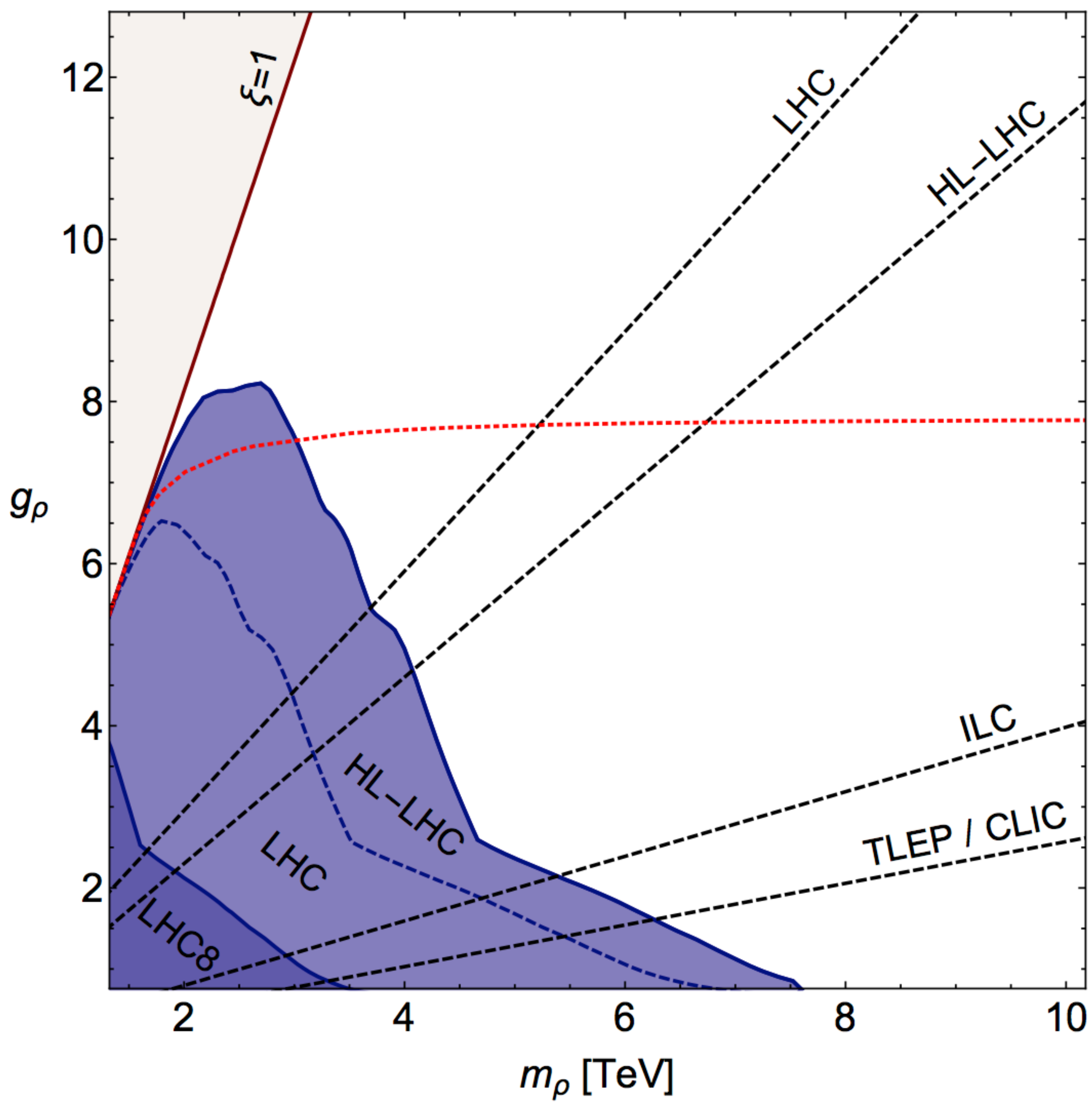
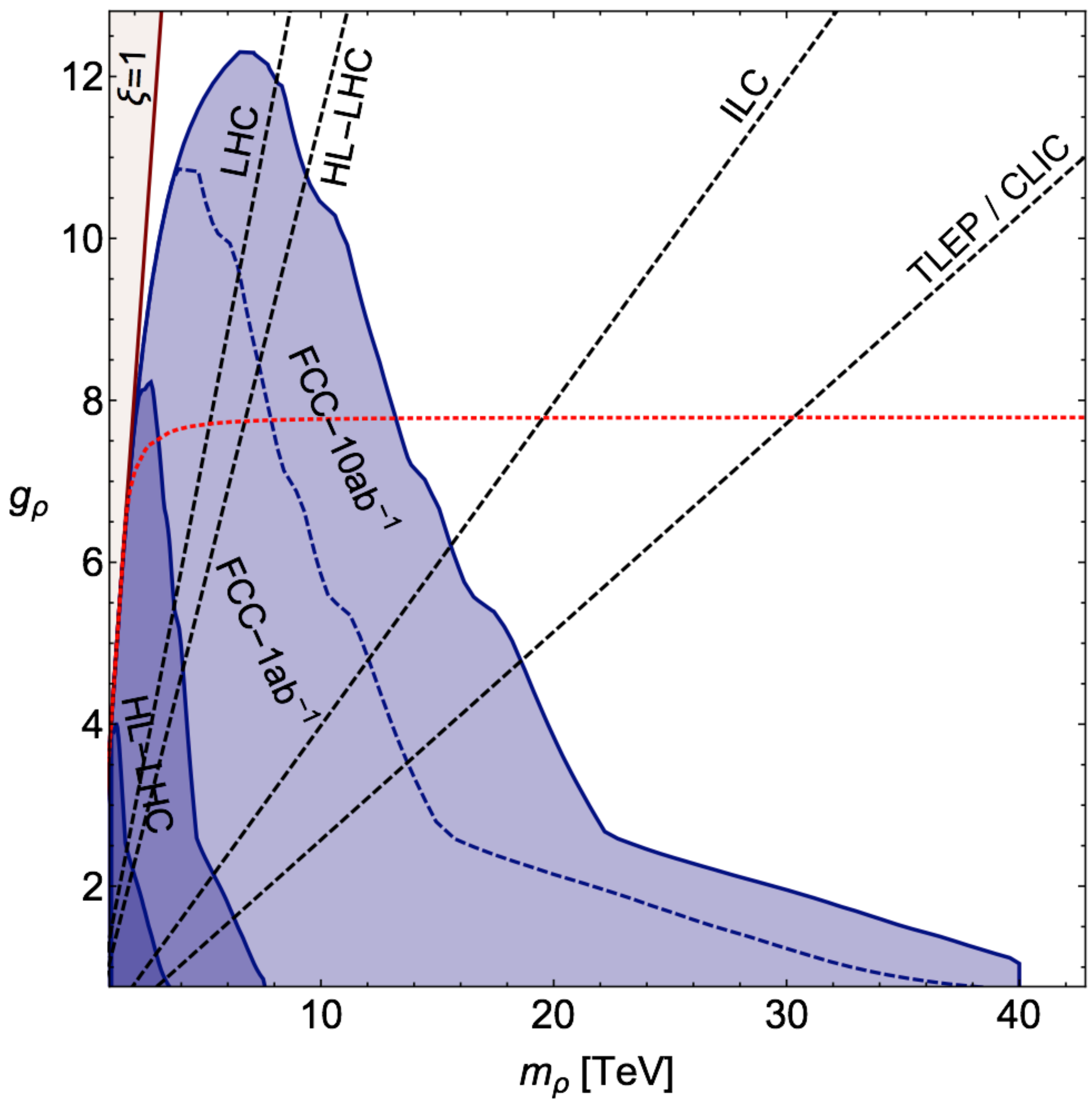


- theoretically excluded $\xi \leq 1$
- LHC8 at 8 TeV with 20 fb^{-1}

  LHC at 14 TeV with 300 fb^{-1}

  HL-LHC at 14 TeV with 3 ab^{-1}
- di-leptons more sensitive for small g_ρ
- di-boson more sensitive for large g_ρ
- increase in $\sqrt{s}$: improves mass reach
- increase in L: improves g_ρ reach
- resonances too broad for large g_ρ

taken from Thamm, Torre, Wulzer arXiv:1502.01701



theoretically excluded $\xi \leq 1$

LHC8 at 8 TeV with 20 fb^{-1}

LHC at 14 TeV with 300 fb^{-1}

HL-LHC at 14 TeV with 3 ab^{-1}

di-leptons more sensitive for small g_ρ

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increase in $\sqrt{s}$: improves mass reach

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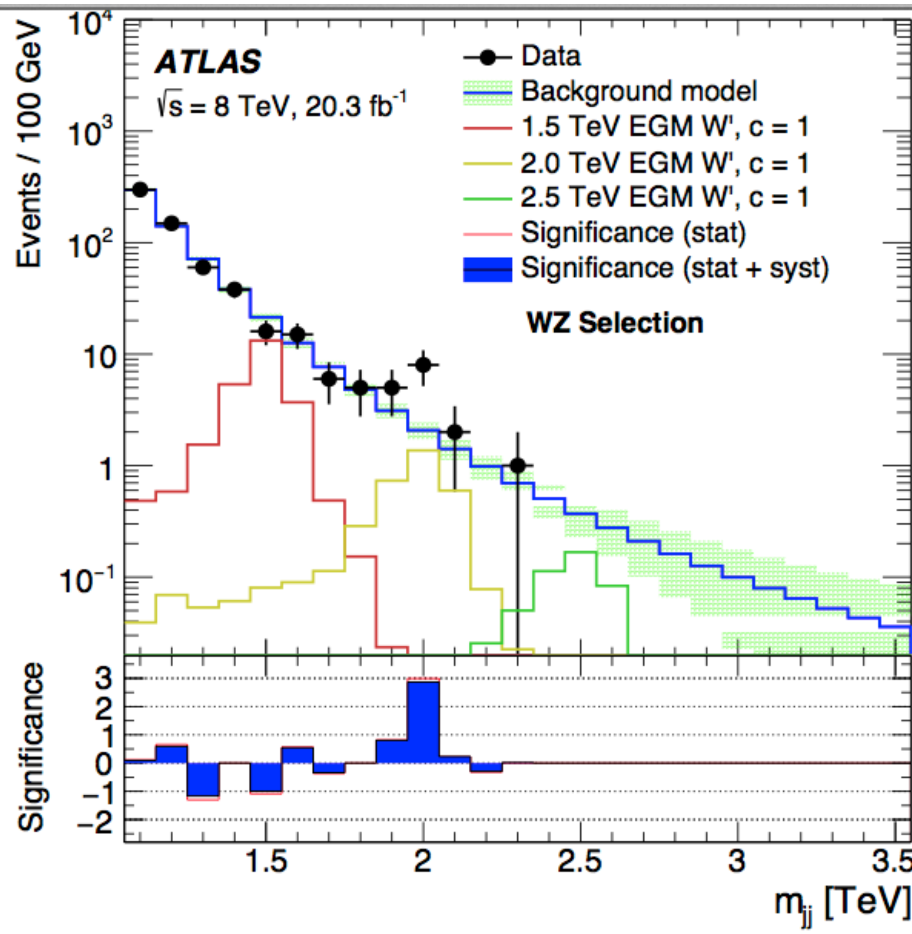
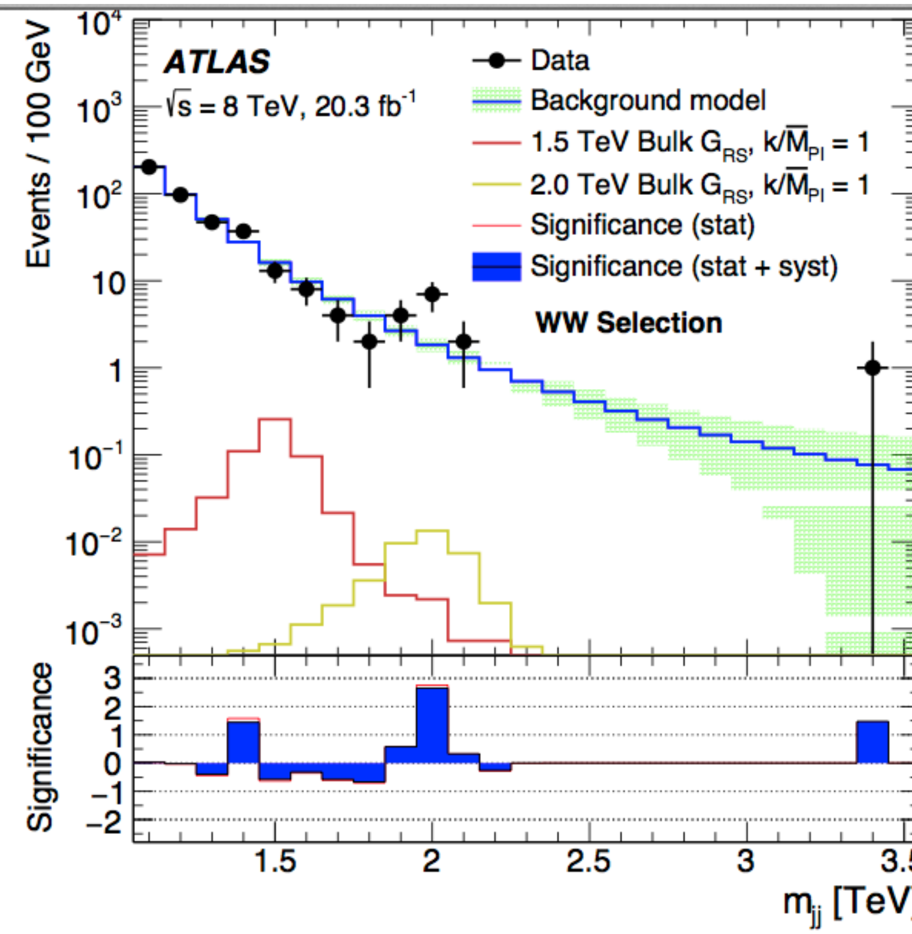
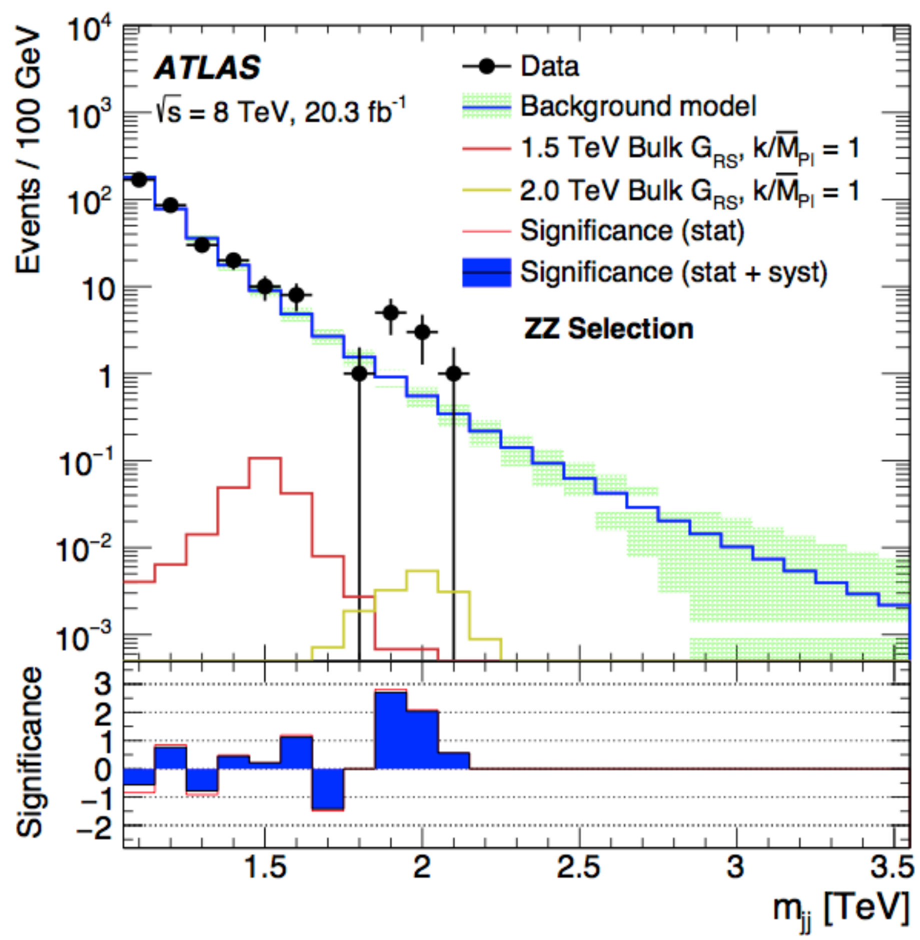
resonances too broad for large g_ρ

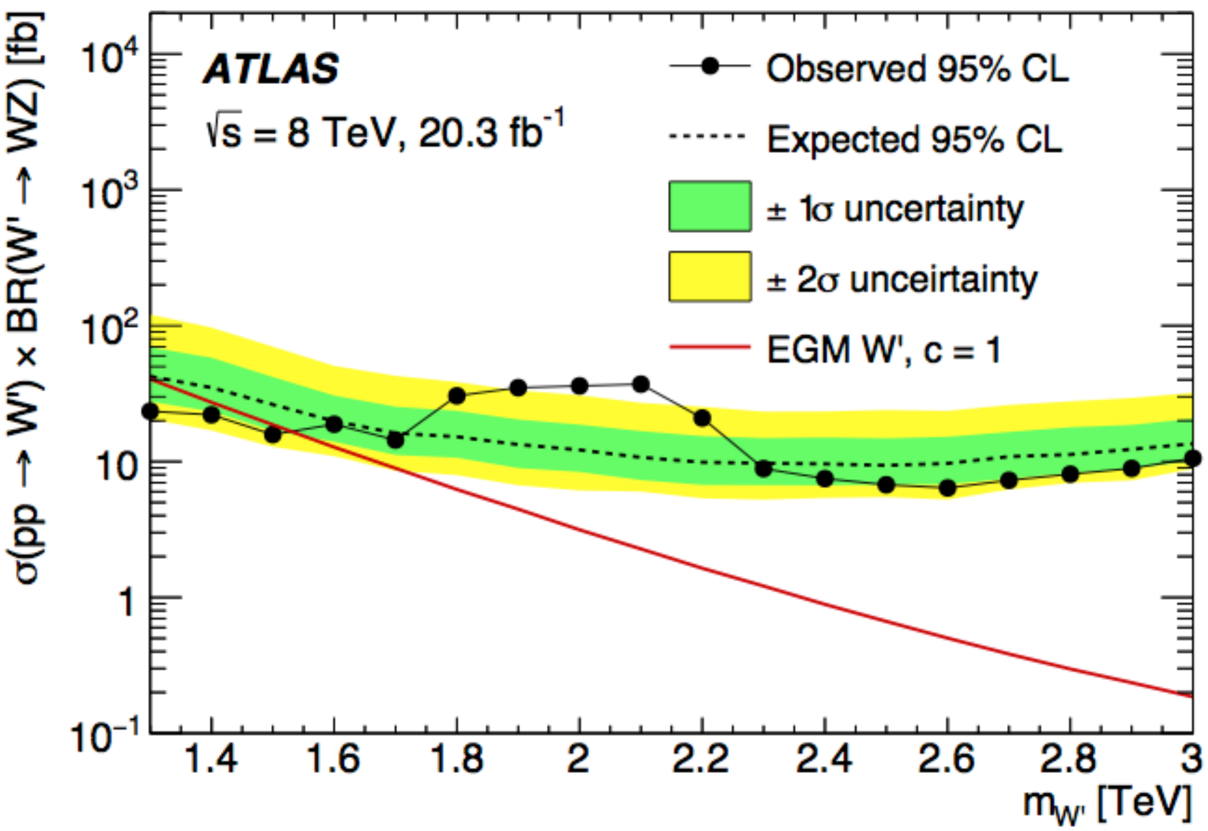

ATLAS
√s = 8 TeV, 20.3 fb-1
Data
Background model
1.5 TeV EGM W', c = 1
2.0 TeV EGM W', c = 1
2.5 TeV EGM W', c = 1
Significance (stat)
Significance (stat + syst)
WZ Selection
Events / 100 GeV
Significance
m_jj [TeV]

(a)

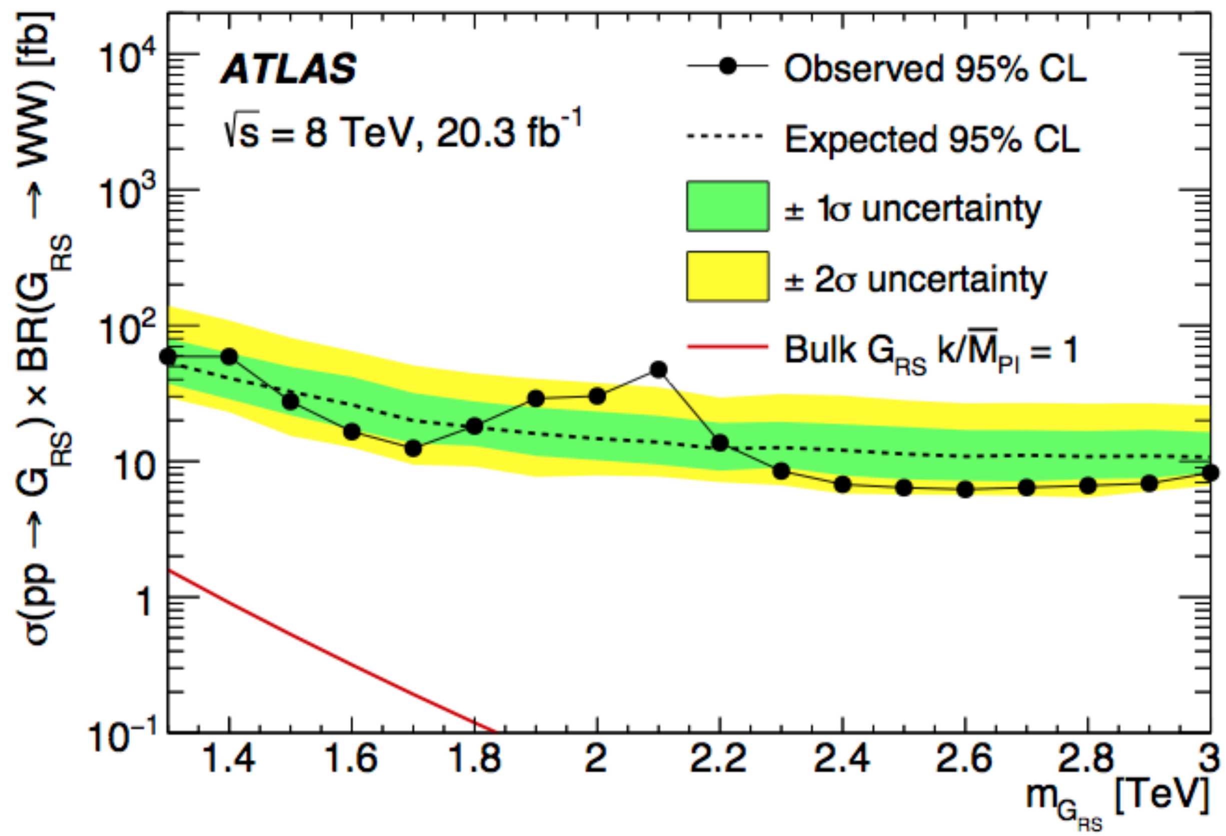

ATLAS
√s = 8 TeV, 20.3 fb-1
Data
Background model
1.5 TeV Bulk G_RS, k/M̄_Pl = 1
2.0 TeV Bulk G_RS, k/M̄_Pl = 1
Significance (stat)
Significance (stat + syst)
WW Selection
Events / 100 GeV
Significance
m_jj [TeV]

(b)

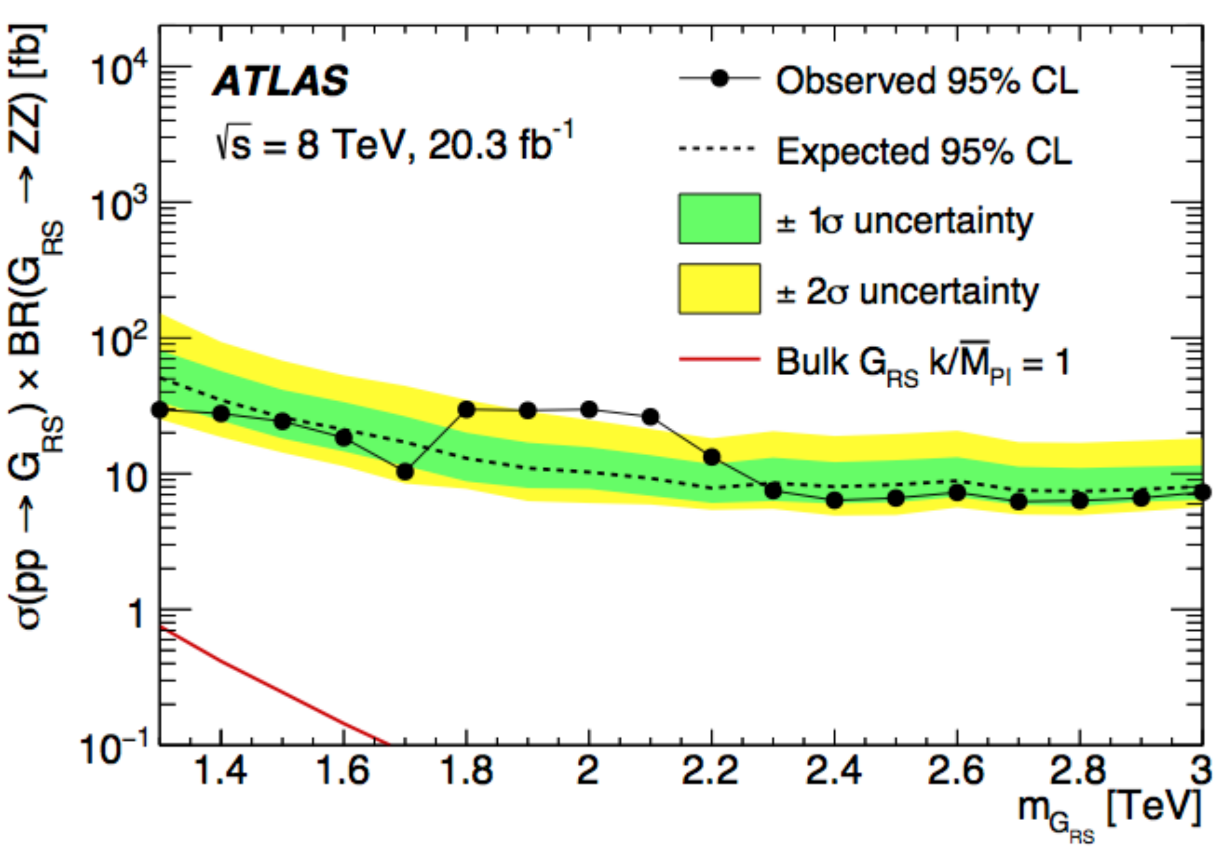

ATLAS
√s = 8 TeV, 20.3 fb-1
Data
Background model
1.5 TeV Bulk G_RS, k/M̄_Pl = 1
2.0 TeV Bulk G_RS, k/M̄_Pl = 1
Significance (stat)
Significance (stat + syst)
ZZ Selection
Events / 100 GeV
Significance
m_jj [TeV]


ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Observed 95% CL
Expected 95% CL
± 1σ uncertainty
± 2σ unceirtainty
EGM W', c = 1
σ(pp → W') × BR(W' → WZ) [fb]
$m_{W'}$ [TeV]

(a)


ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Observed 95% CL
Expected 95% CL
± 1σ uncertainty
± 2σ uncertainty
Bulk G_{RS} $k/\overline{M}_{Pl}$ = 1
σ(pp → G_{RS}) × BR(G_{RS} → WW) [fb]
$m_{G_{RS}}$ [TeV]

(b)


ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Observed 95% CL
Expected 95% CL
± 1σ uncertainty
± 2σ uncertainty
Bulk G_{RS} $k/\overline{M}_{Pl}$ = 1
σ(pp → G_{RS}) × BR(G_{RS} → ZZ) [fb]
$m_{G_{RS}}$ [TeV]