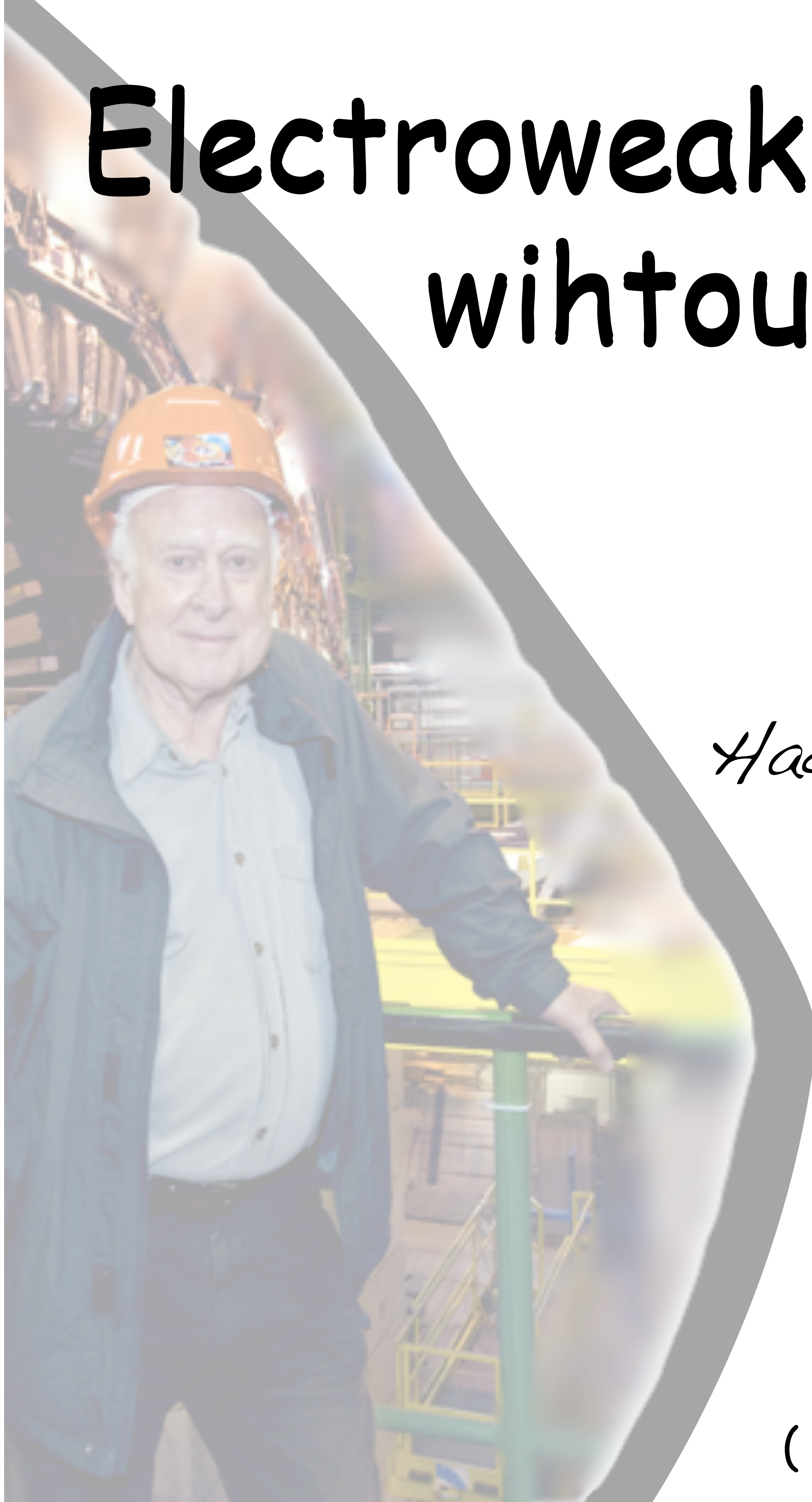
Electroweak Symmetry Breaking wihtout a SM (or susy) Higgs



Hadron Collider Physics Symposium

Paris, Nov. 14-18 2011

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Why have we built the LHC?

symmetry breaking: new phase with more degrees of freedom

massive $W^{\pm}$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

$\Rrightarrow$ UV physics of these Goldstone's? $\Lleftarrow$

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  - $\Rrightarrow$ require at least one additional degree of freedom (the Higgs boson!)

... but the Higgs boson is only one possible UV completion

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At which scale should we expect to see something?

The UV behavior of the weak Goldstone

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Lee, Quigg & Thacker '77

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$$\Sigma = e^{i\sigma^a \pi^a / v}$$

Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\mathcal{L}_{\rm mass} = m_W^2 W_\mu^+ W^{\mu\,-} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu = \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)$$

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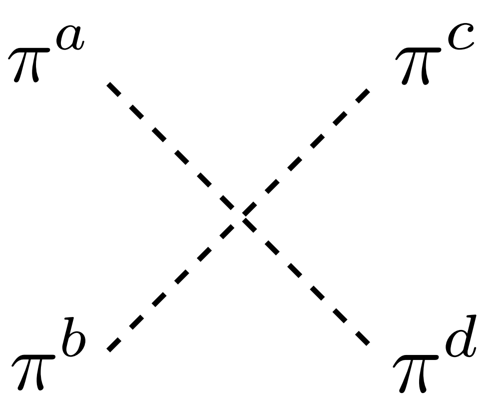
$$\mathcal{L}_{\rm mass} = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6v^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2 (\partial_\mu \pi^a)^2\right) + \dots$$

contact interaction growing with energy



$$\mathcal{A}\left(\pi^a \pi^b \to \pi^c \pi^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc}$$

$$\mathcal{A}(s,t,u) = \frac{s}{v^2}$$ Weinberg's LET

Lee, Quigg & Thacker '77

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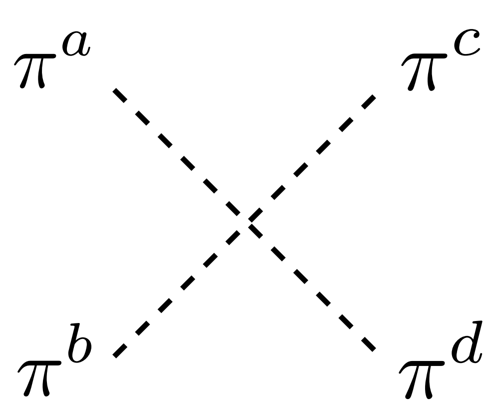

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the behavior of this amplitude is not consistent above $4\pi v$ (≈1÷3TeV)

Lee, Quigg & Thacker '77

Higgs as a PGB: a natural extension of SM

One solution to the hierarchy pb:
Higgs transforms non-linearly under some global symmetry

Higgs=Pseudo-Goldstone boson (PGB)

SM

$SO(4)/SO(3)$

$W^{\pm}_L$ & Z_L

3 Goldstone's

Chacko, Batra '08

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SM $\quad SO(4)/SO(3) \quad \Rightarrow \quad G/H \quad$ BSM

$W^{\pm}_L$ & Z_L $\qquad$ $W^{\pm}_L$ & Z_L & h

3 Goldstone's $\qquad$ at least a 4th Goldstone

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3 Goldstone's at least a 4th Goldstone

Examples:

$SO(5)/SO(4)$: 4 PGBs=$W^{\pm}_L$, Z_L, h ← Minimal Composite Higgs Model
Agashe, Contino, Pomarol '04

$SO(6)/SO(5)$: 5 PGBs=H, a ← Next MCHM
Gripaios, Pomarol, Riva, Serra '09

$SU(4)/Sp(4,\mathbb{C})$: 5 PGBs=H, s
Chacko, Batra '08

$SO(6)/SO(4)\times SO(2)$: 8 PGBs=H_1+H_2 ← Minimal Composite Two Higgs Doublets
Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

How to probe the composite nature of the Higgs?

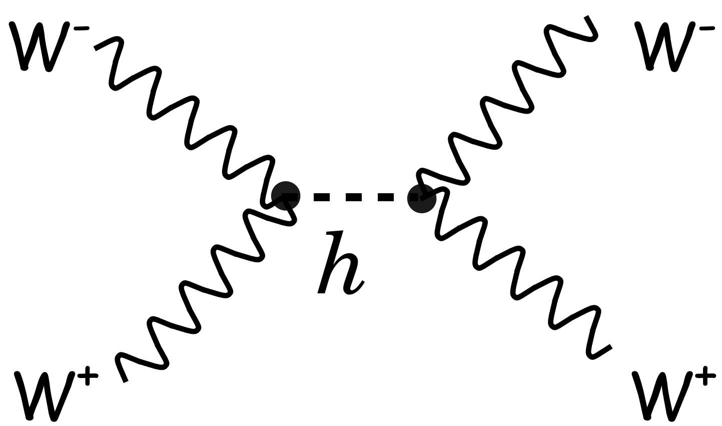
1. Anomalous couplings

What is the SM Higgs?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R / SU(2)_L$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4} {\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right) \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s - m_h^2}\right)$$

growth cancelled for
a = 1
restoration of
perturbative unitarity

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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For a=1: perturbative unitarity in elastic channels $WW \to WW$

For $b = a^2$: perturbative unitarity in inelastic channels $WW \to hh$

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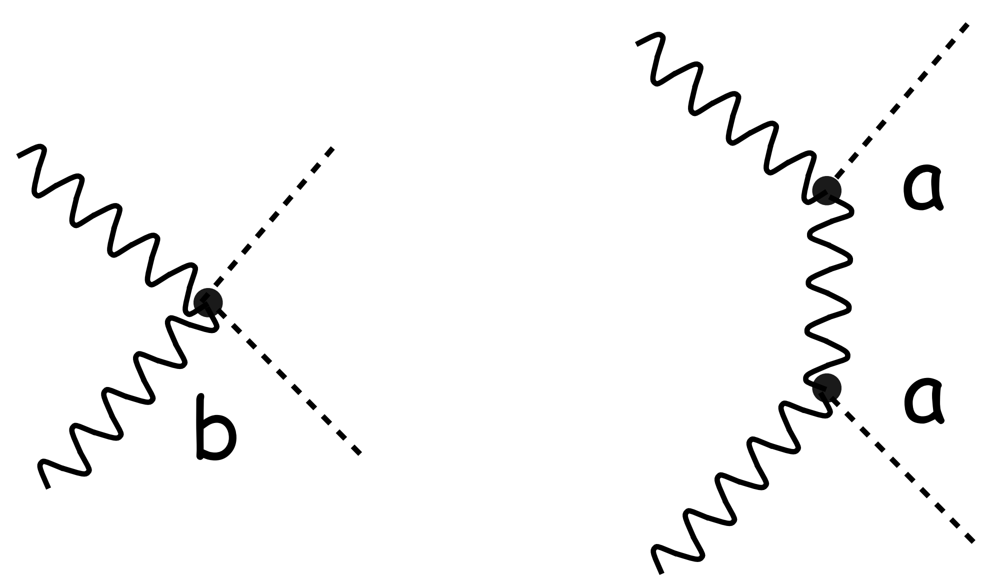

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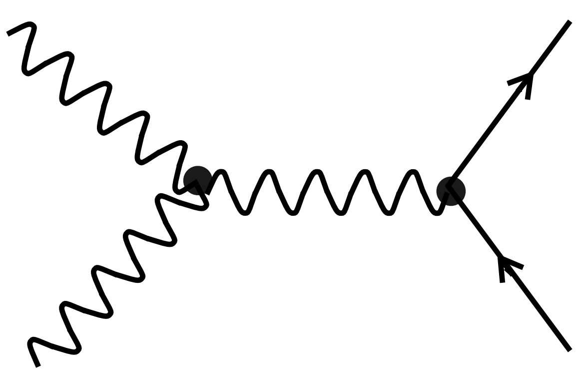

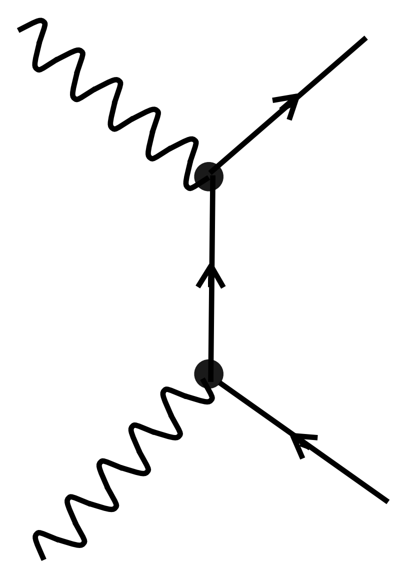

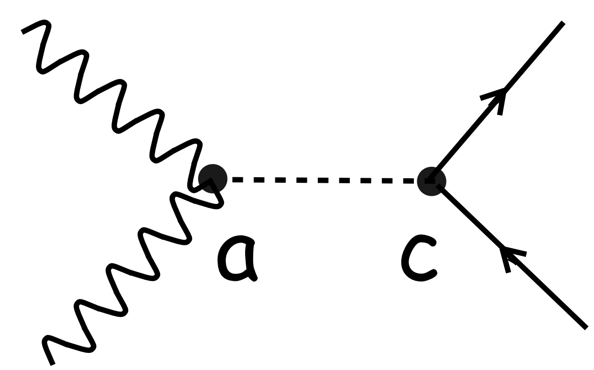

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'a=1', 'b=1' & 'c=1' define the SM Higgs

Higgs properties depend on a single unknown parameter (m_H)

$\mathcal{L}_{\mathrm{EWSB}}$ can be rewritten as $D_\mu H^\dagger D_\mu H$

$$H = \frac{1}{\sqrt{2}} e^{i\sigma^a \pi^a / v} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

h and π^a (ie W_L and Z_L) combine to form a linear representation of $SU(2)_L \times U(1)_Y$

Anomalous composite-Higgs couplings

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L} \supset \frac{c_H}{2f^2}\partial^\mu\left(|H|^2\right)\partial_\mu\left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Longrightarrow \mathcal{L} = \frac{1}{2}\left(1 + c_H \frac{v^2}{f^2}\right)(\partial^\mu h)^2 + \ldots$$

Modified Higgs propagator ~ Higgs couplings rescaled by $\frac{1}{\sqrt{1+c_H\frac{v^2}{f^2}}} \sim 1 - c_H \frac{v^2}{2f^2} \equiv 1 - \xi/2$

$\xi = v^2/f^2$

a = 1-ξ/2 b = 1-2ξ c = 1-ξ/2

PGB Higgs: Strong EWSB with 2 Scales

$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

$$\xi = 0$$

SM limit

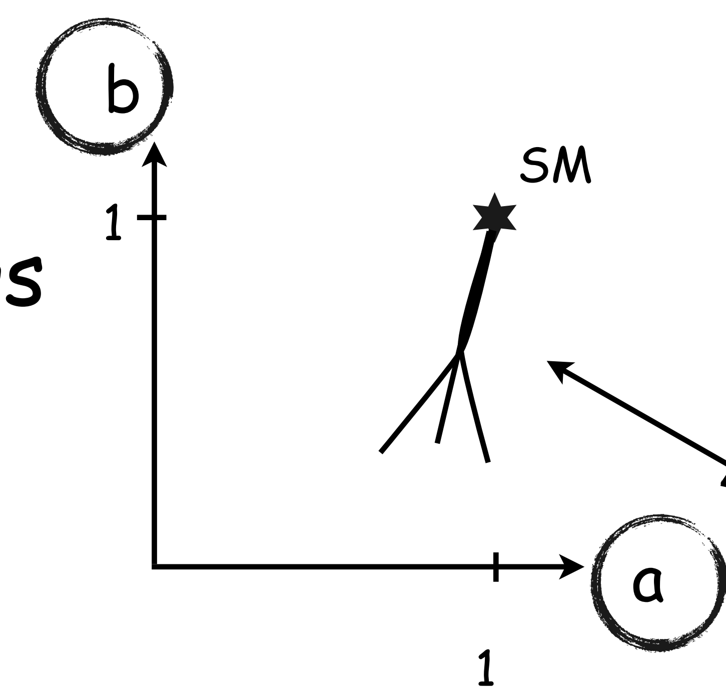
all resonances of strong sector, except the Higgs, decouple

$$\xi = 1$$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

Composite Higgs
vs.
SM Higgs



$$\mathcal{L}_{\text{EWSB}} = \left(a\, \frac{v}{2}\, h \ + b\, \frac{1}{4}\, h^2 \right) \mathrm{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma \right)$$

Composite Higgs
universal behavior for large f
$a=1-v^2/2f^2$ $b=1-2v^2/f^2$

Composite Higgs vs generic anomalous couplings

generic anomalous couplings can be quite complicated, e.g.

$$\mathcal{L}_{h-Z} = m_Z h \left(c_1 Z_\mu Z^\mu + \frac{c_2}{m^2} Z_{\mu\nu} Z^{\mu\nu} + \frac{c_3}{m^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

...many coefficients, various possible origins

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...many coefficients, various possible origins

if Higgs emerges as a bound state of strongly interacting theory

a few coefficients only and related to symmetries of the coset space

$$\boxed{\frac{c_H}{2f^2} \left(\partial^\mu |H|^2 \right)^2} \quad \boxed{\frac{c_T}{2f^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right)^2} \quad \boxed{\frac{c_y y_f}{f^2} |H|^2 \bar{f}_L H f_R + \text{h.c.}} \quad \boxed{\frac{c_6 \lambda}{f^2} |H|^6}$$

custodial breaking

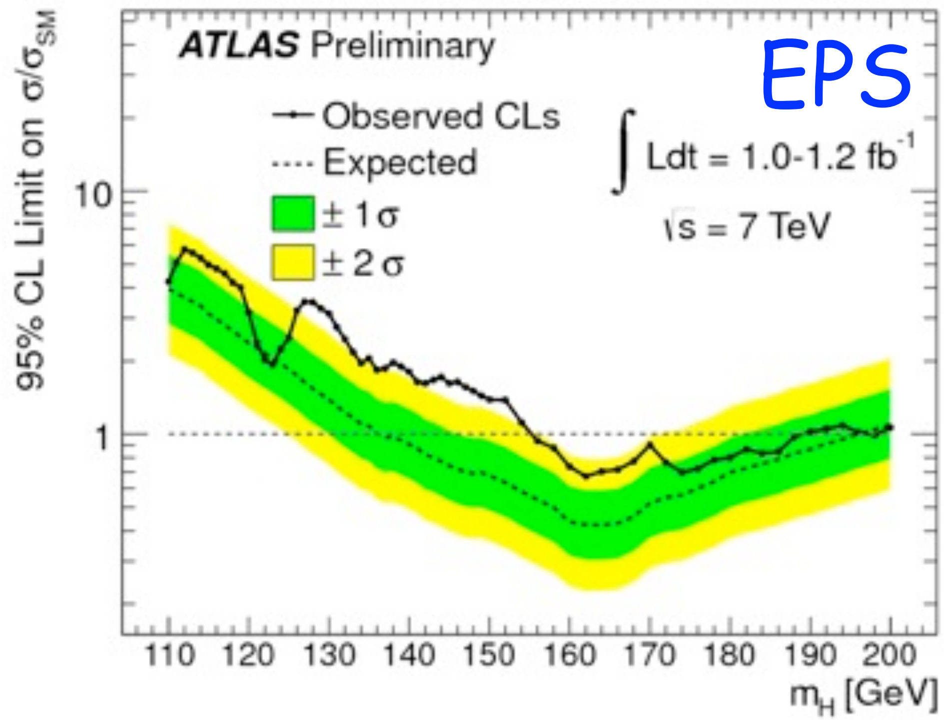
(other resonances etc give subleading contributions)

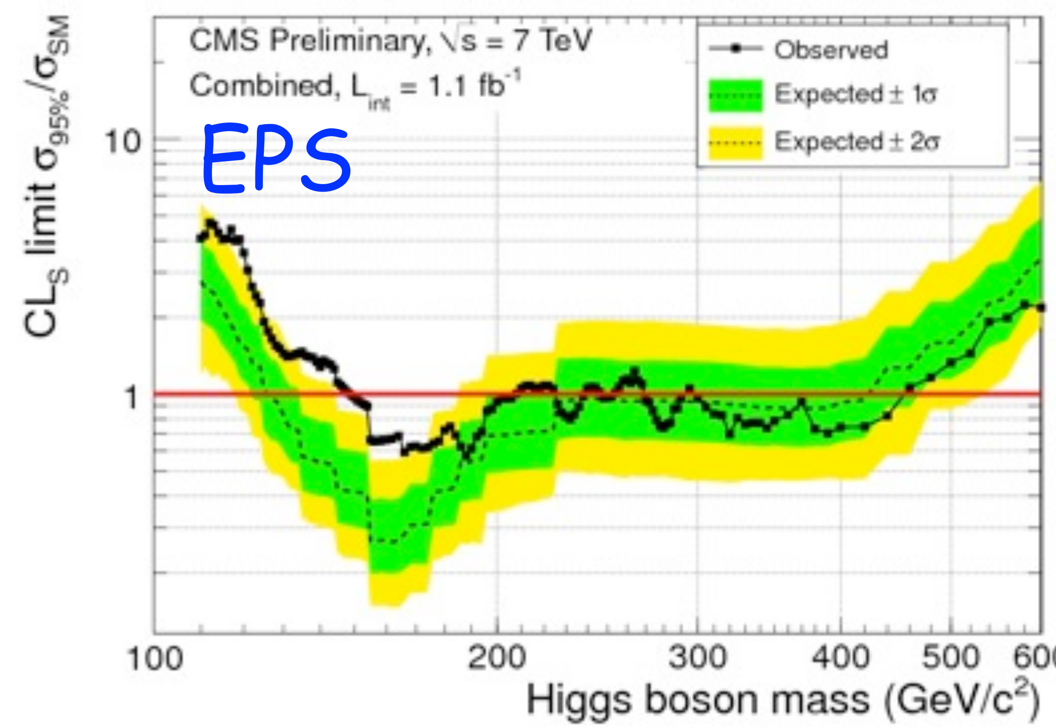
very predictive models:

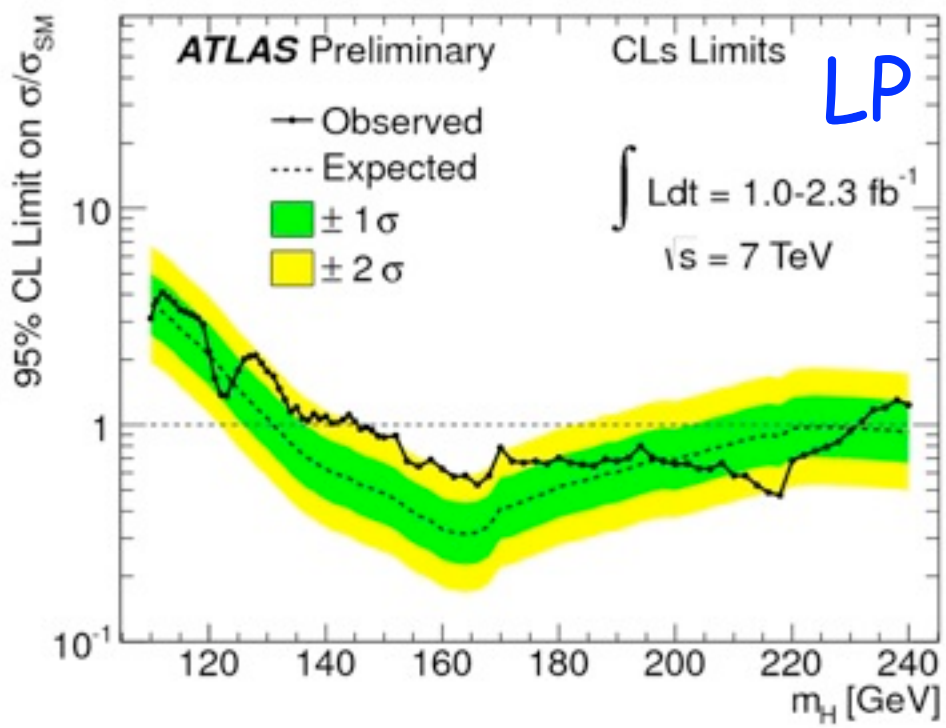
given the coset space, the Higgs couplings depend only on ξ

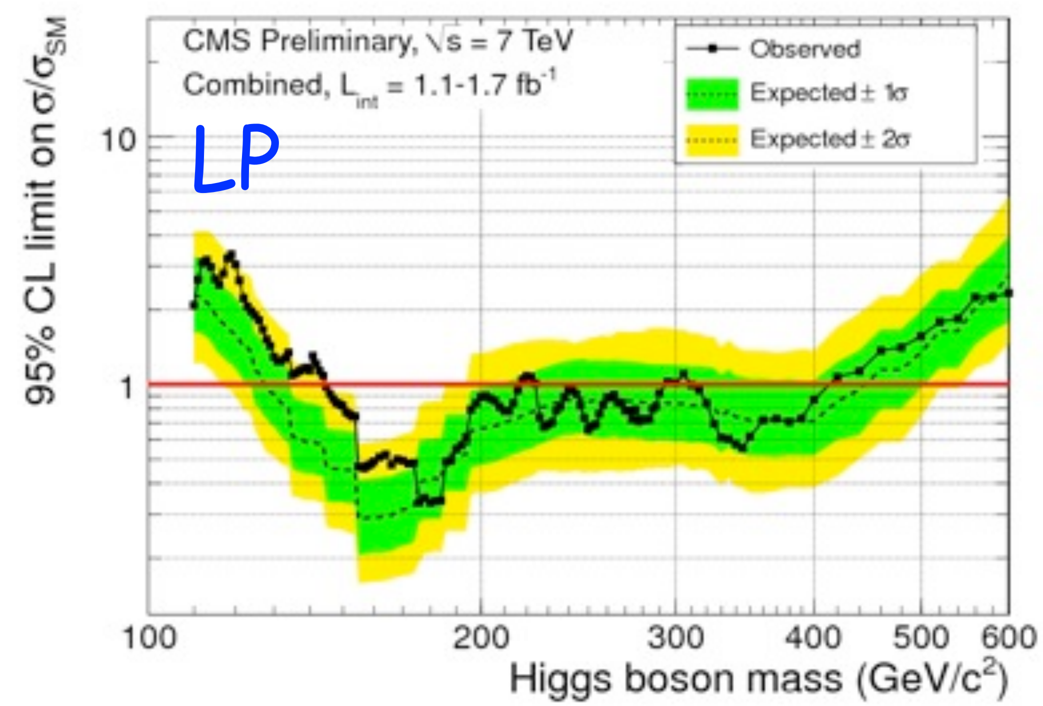
(plus a few subdominant corrections)

Higgs searches at the LHC









LHC is now a Higgs exploring machine

(and it has quickly surpassed Tevatron)

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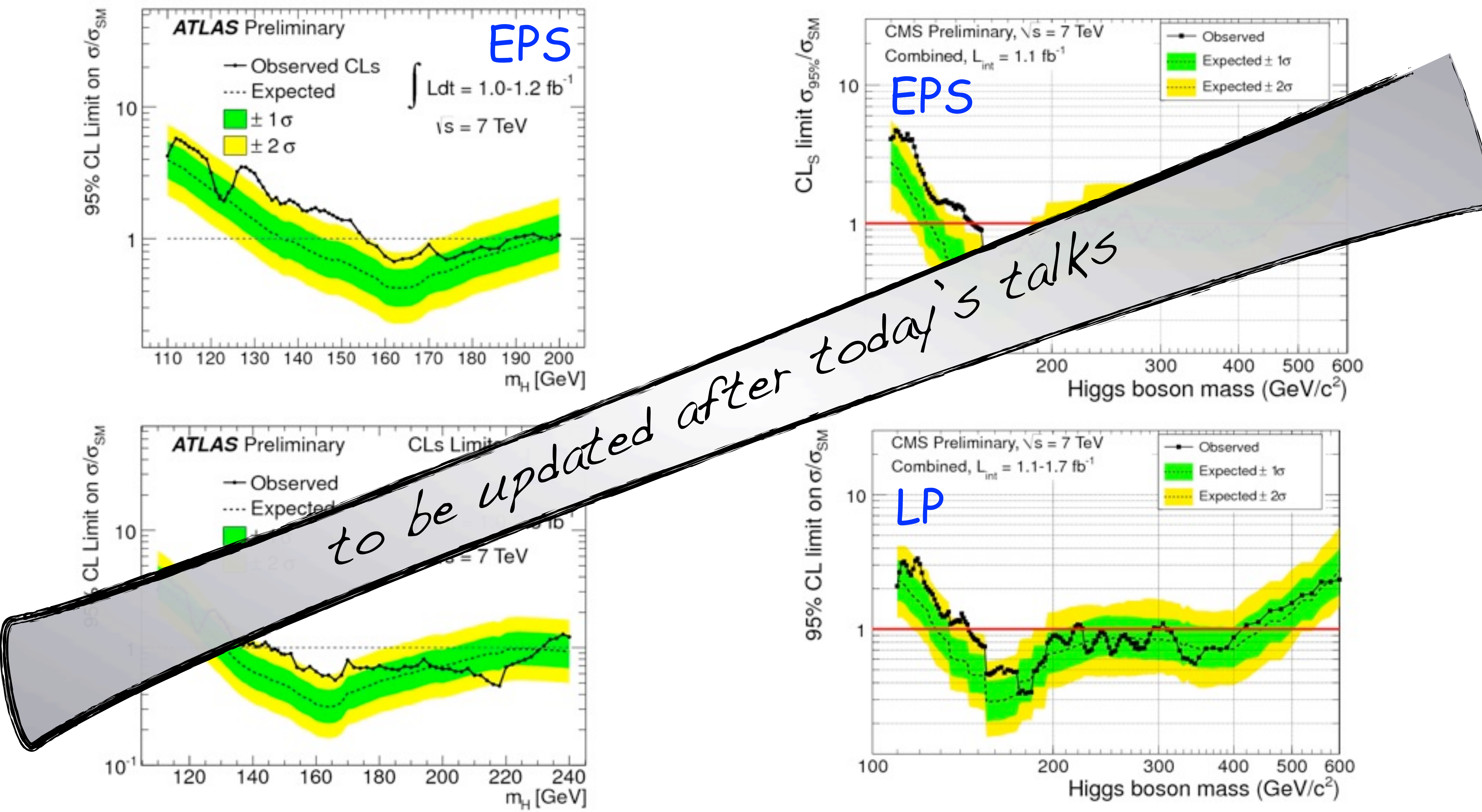

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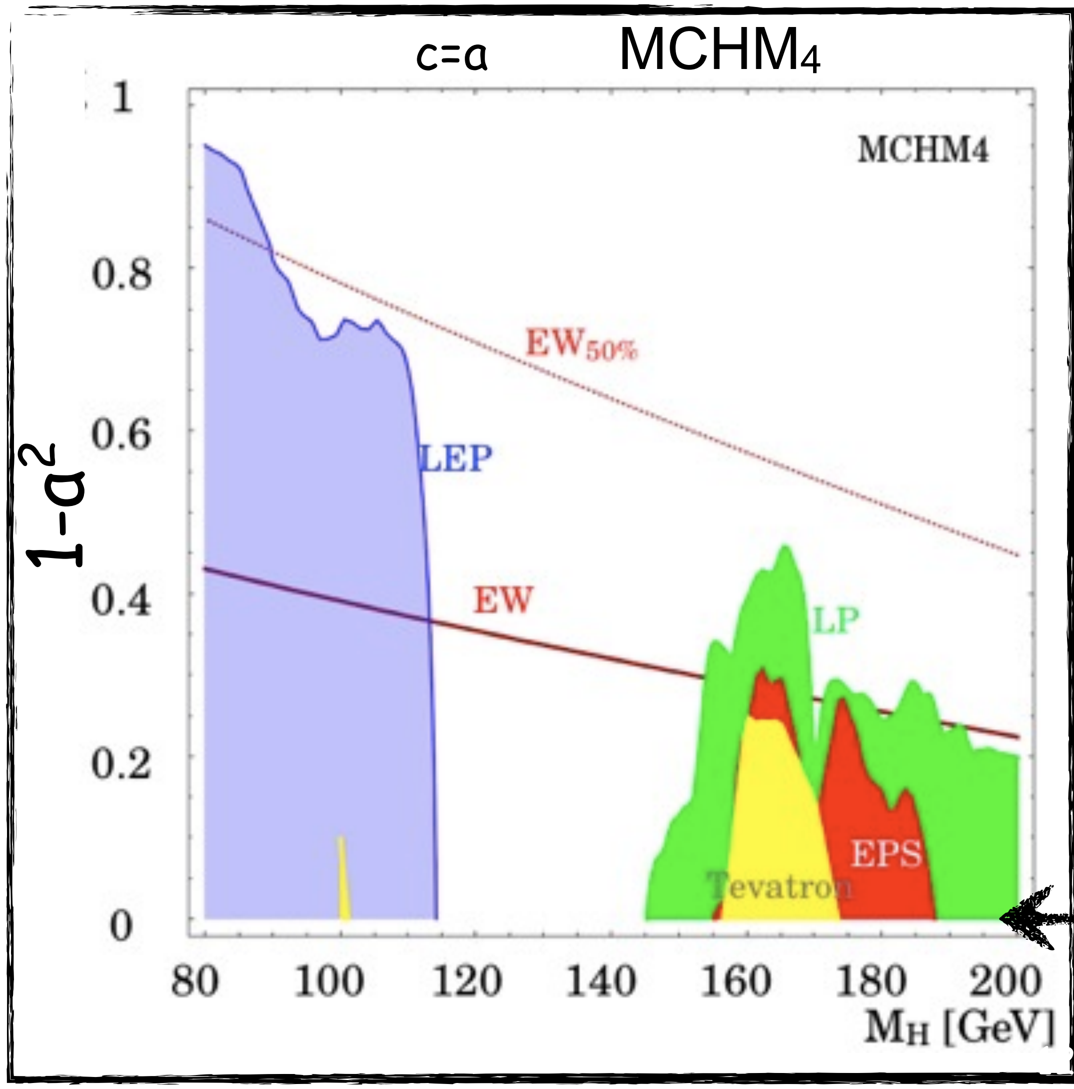
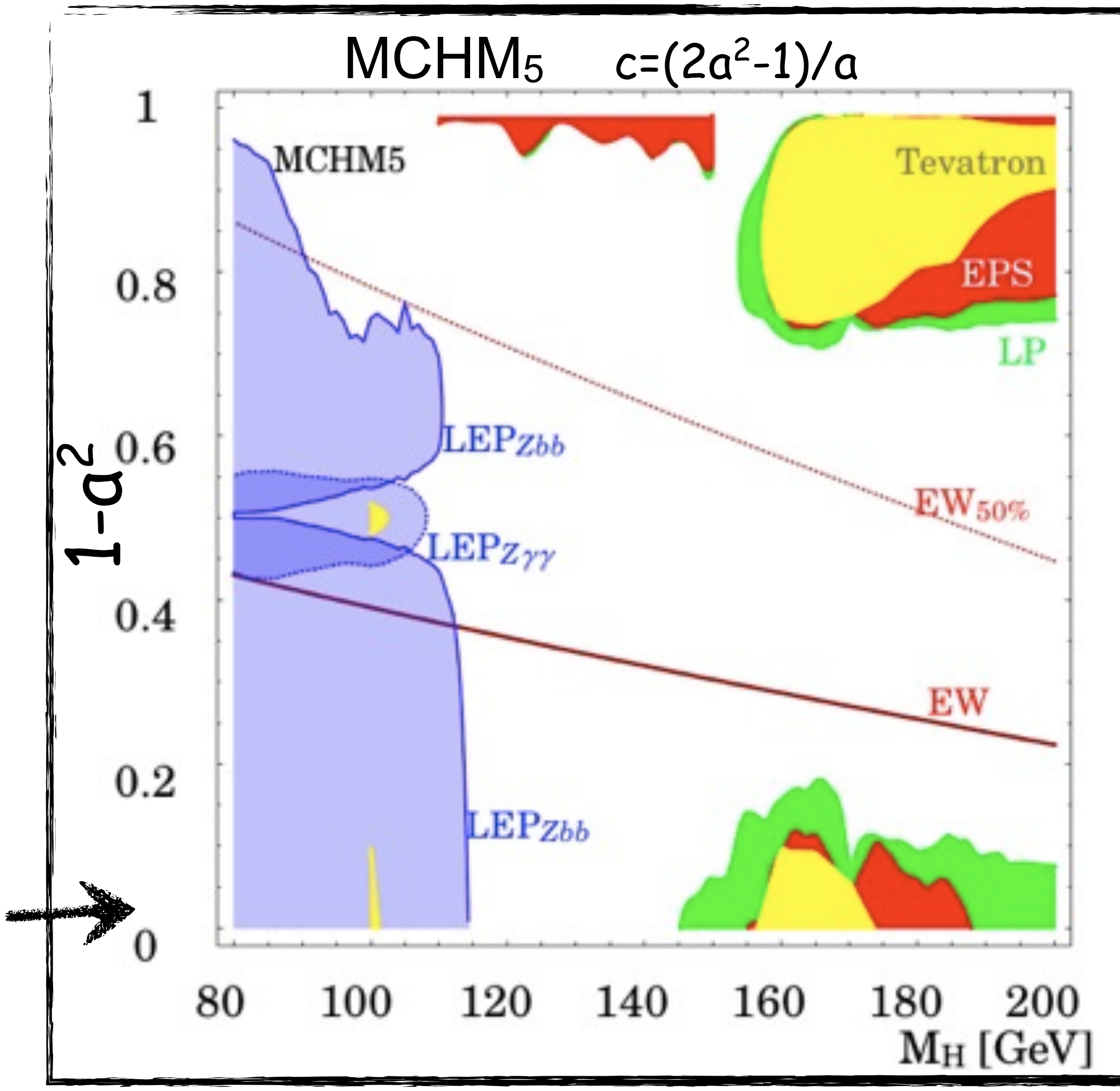
Deformation of the SM Higgs

the SM exclusion bounds are easily rescaled in the (m_H,a) plane

Espinosa, Grojean, Muehlleitner '11



SM limits



the LHC can do much more than simply excluding the SM Higgs

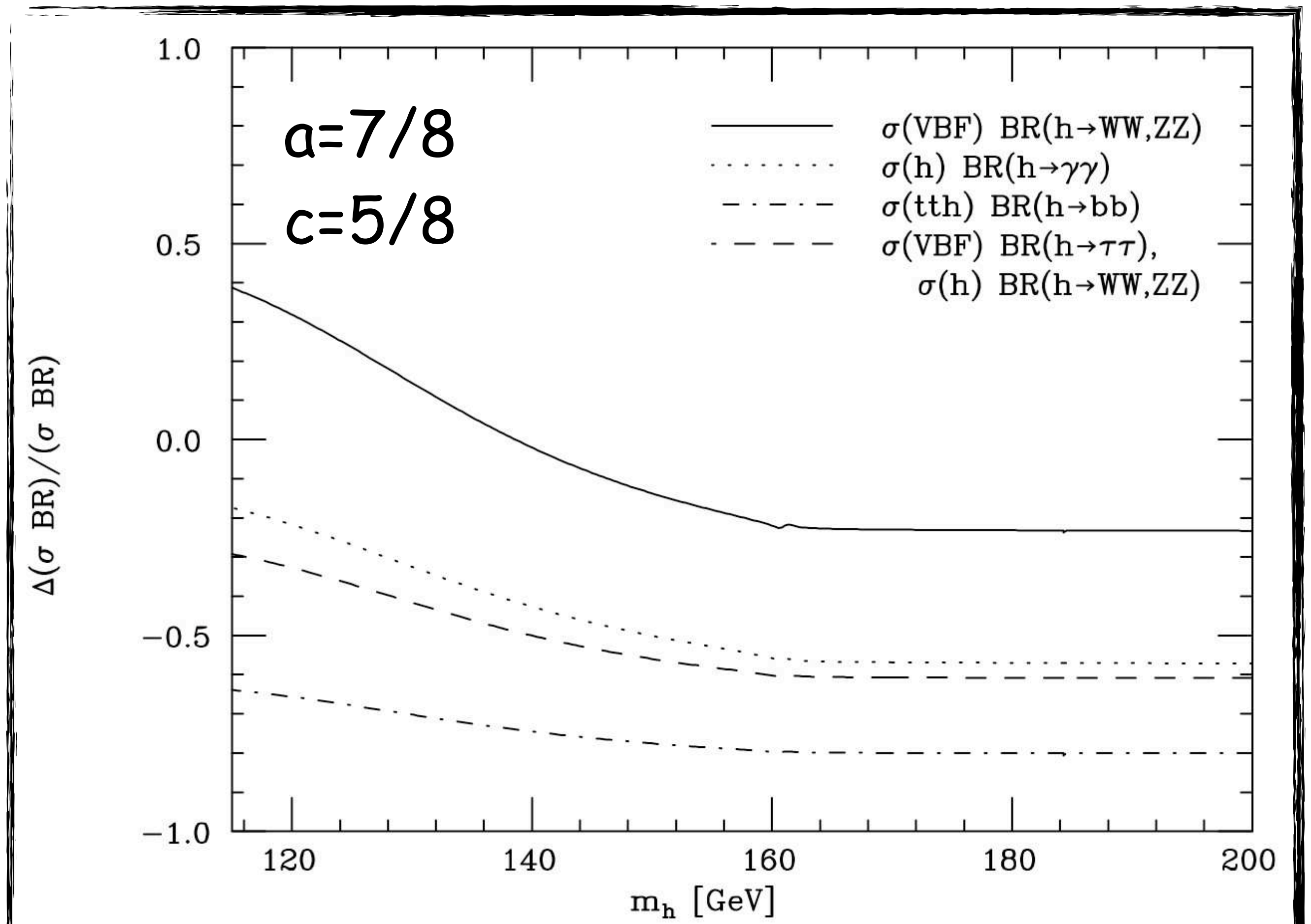
Higgs anomalous couplings @ LHC

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}+b_3\frac{h^3}{v^3}+\ldots\right) - \lambda\bar\psi_L\Sigma\psi_R\left(1+c\frac{h}{v}+c_2\frac{h^2}{v^2}+\ldots\right)$$

$$a=\sqrt{1-\xi} \qquad b=1-2\xi \qquad b_3=-\frac{4}{3}\xi\sqrt{1-\xi} \qquad c=\left(\sqrt{1-\xi},\frac{1-2\xi}{\sqrt{1-\xi}}\right) \qquad c_2=-(\xi,4\xi)$$

Minimal composite Higgs model (MCHM): SO(5)/SO(4)

$$\Gamma(h\to f\bar f) = (2c-1)\,\Gamma(h\to f\bar f)_{\rm SM} \quad \Gamma(h\to ZZ) = (2a-1)\,\Gamma(h\to ZZ)_{\rm SM}$$



Giudice, Grojean, Pomarol, Rattazzi '07

LHC can probe

Δa & Δc
up to ~ 0.1÷0.2
i.e. 4πf ~ 5÷7 TeV

compositeness scale of the Higgs

(ILC/CLIC could go to few %, ie, test composite Higgs up to 4πf ~ 30/60 TeV)

How to probe the composite nature of the Higgs?

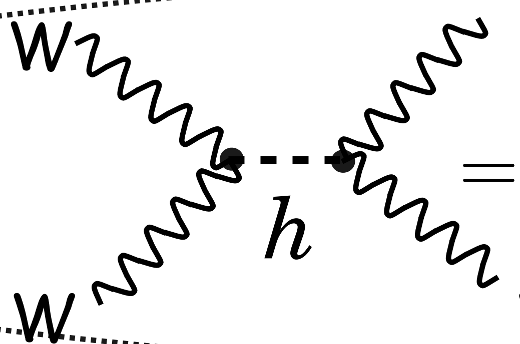
2. Strong scattering

How to probe the strong dynamics?

Look at pair production of strong states

Giudice, Grojean, Pomarol, Rattazzi '07

- strong WW scattering



$$= -(1-\xi)g^2\frac{E^2}{M_W^2}$$

no exact cancellation of the growing amplitudes

$$\mathcal{A}\left(W_L^a W_L^b \to W_L^c W_L^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc}$$

$$\mathcal{A} = \underbrace{\left(1-a^2\right)\frac{s}{v^2}}_{\frac{s}{f^2}}$$

large $\mathcal{L}_{int}$ needed

not competitive with the measurement of 'a' via anomalous couplings

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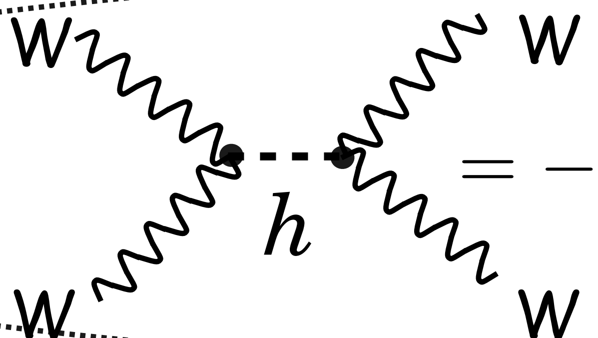

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large $\mathcal{L}_{int}$ needed

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- strong double Higgs production

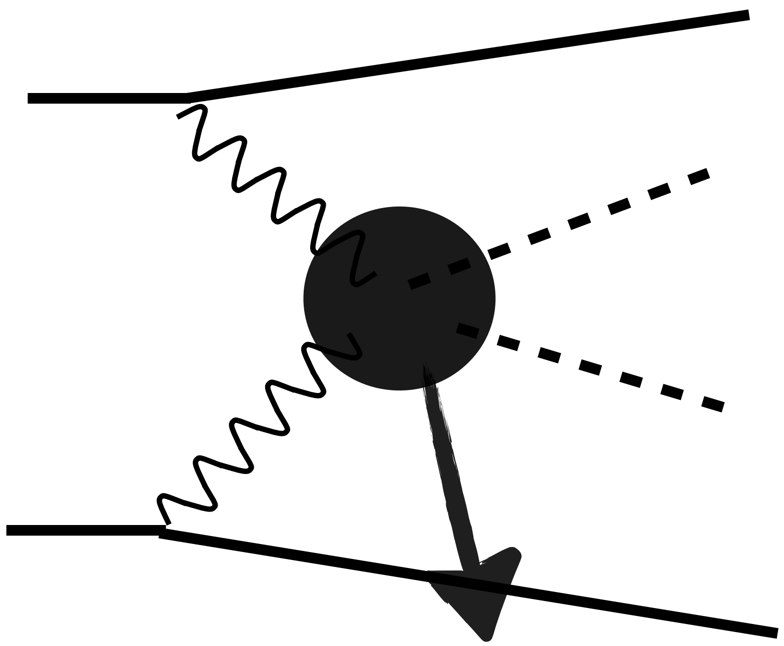
Contino, Grojean, Moretti, Piccinini, Rattazzi '10

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \left(W_L^+ W_L^- \to hh\right) = \left(b - a^2\right)\frac{s}{v^2}$$

access to a new interaction, 'b', which measures Higgs non-linearities

distinction between 'active' (higgs) and 'passive' (dilaton) scalar in EWSB dynamics

Double Higgs production: 'b' and 'd_3' couplings



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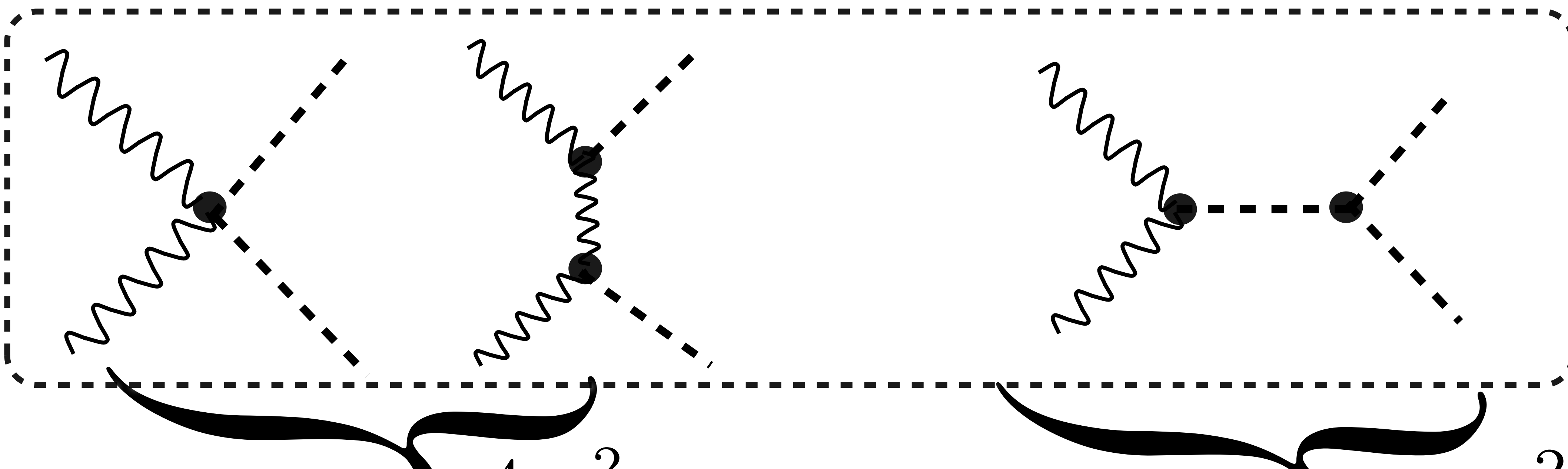
$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \dots$$

SM: $a=b=d_3=d_4=1$



$$\mathcal{A} \underset{m_{hh}^2 \gg m_W^2}{\sim} \left(b - a^2\right)\frac{4m_{hh}^2}{v^2}$$

asymptotic behavior
sensitive to strong interaction

$$\mathcal{A} \underset{m_{hh}^2 \sim 4m_h^2}{\sim} \text{cst.} + 3ad_3\frac{m_h^2}{v^2}$$

threshold effect
anomalous coupling'

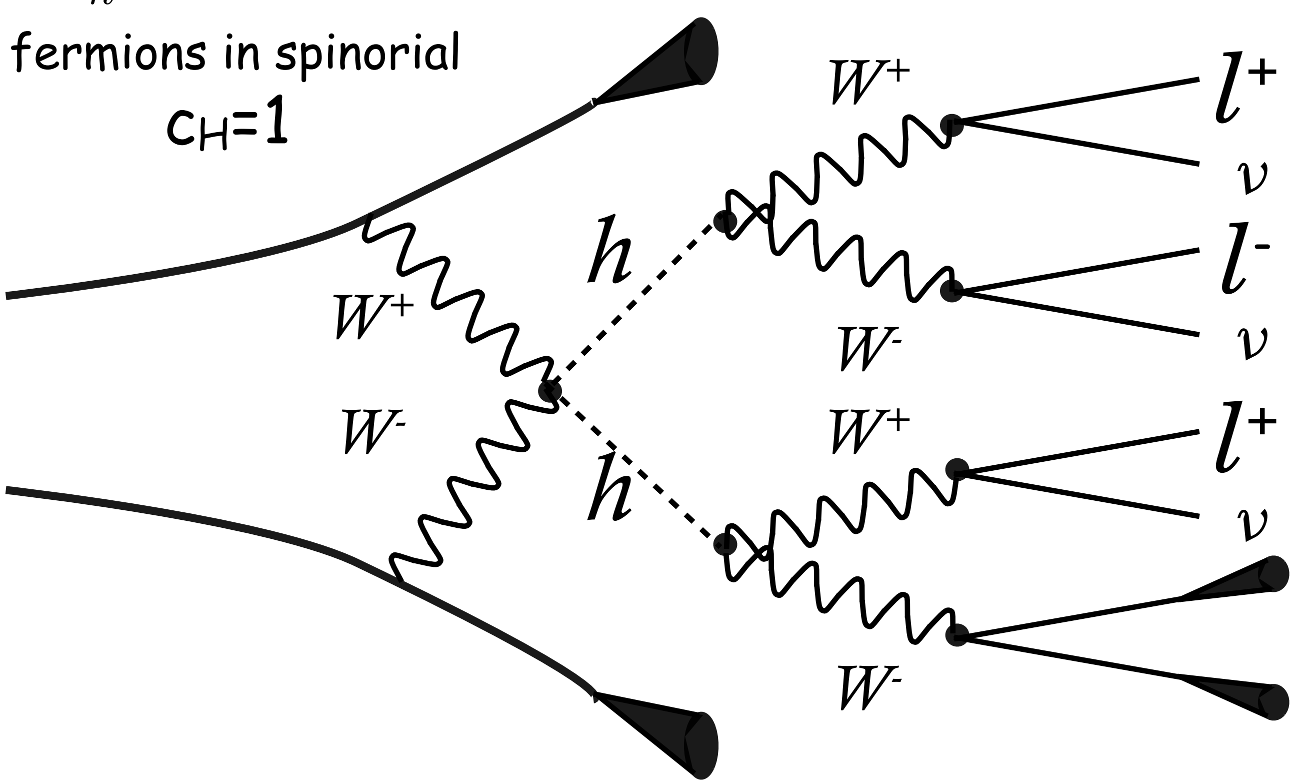
Strong Higgs production: (3L+jets) analysis

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

strong boson scattering ⇔ strong Higgs production

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \mathcal{A}\left(W_L^+ W_L^- \to hh\right) = \frac{c_H s}{f^2}$$

$m_h = 180$ GeV
fermions in spinorial
$c_H=1$



acceptance cuts

jets	leptons
$p_T \geq 30$ GeV	$p_T \geq 20$ GeV
$\delta R_{jj} > 0.7$	$\delta R_{lj(ll)} > 0.4(0.2)$
$\lvert\eta_j\rvert \leq 5$	$\lvert\eta_j\rvert \leq 2.4$

Dominant backgrounds: Wll4j, $t\bar{t}$W2j, $t\bar{t}$2W(j), 3W4j...

forward jet-tag, back-to-back lepton, central jet-veto

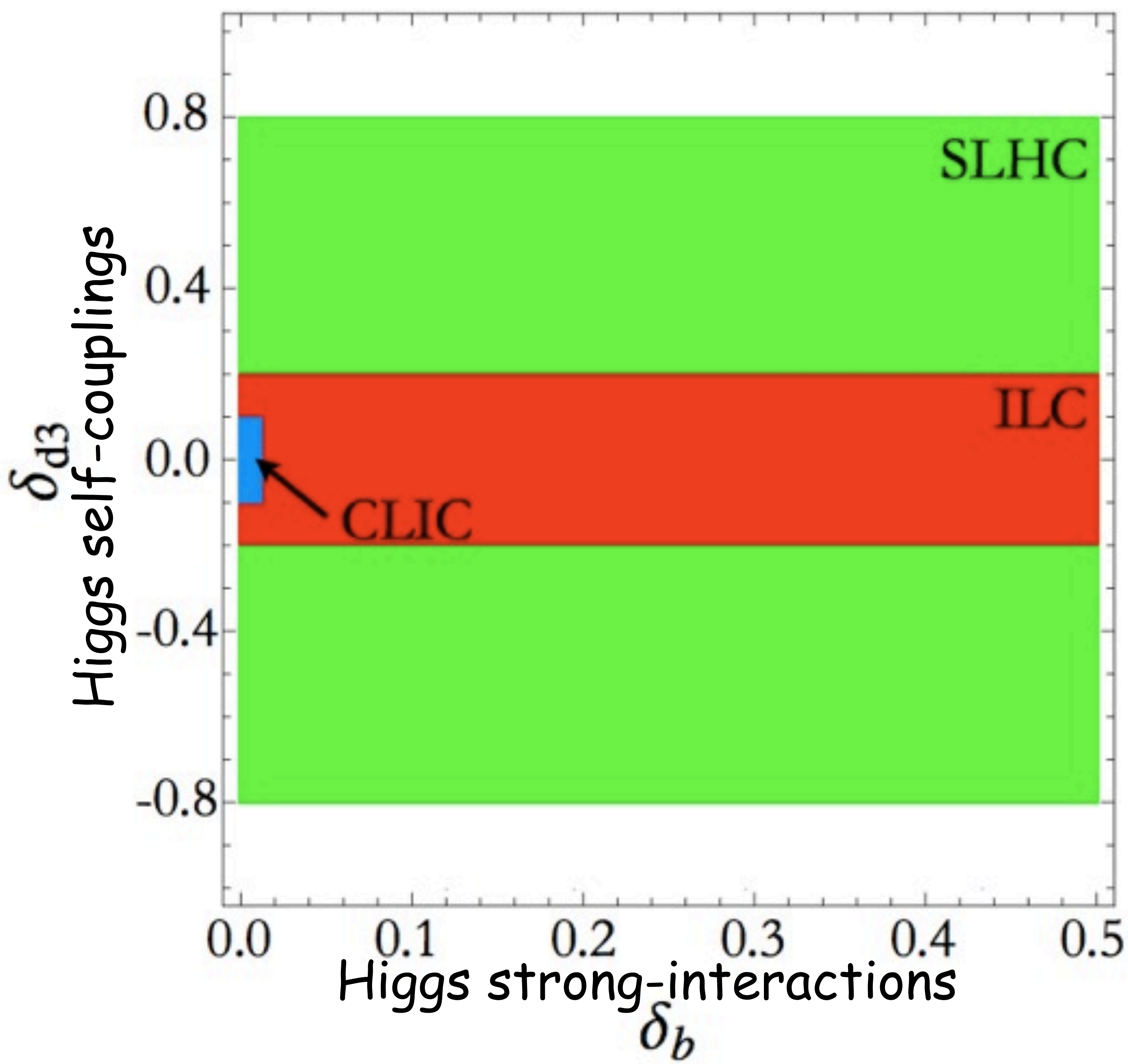
v/f	1	$\sqrt{0.8}$	$\sqrt{0.5}$
significance @ 300 fb^{-1}	4.0	2.9	1.3
luminisity for 5σ (fb^{-1})	450	850	3500

$\Lleftarrow$ good motivation to SLHC or CLIC

Measuring Higgs Non-Linearities

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4}\text{Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) \qquad V(h)=\frac{1}{2}m_h^2h^2+d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3$$



- (S)LHC is barely sensitive to d_3 and b
- ILC has a sensitivity on d_3 but not on b
- CLIC can probe both d_3 and b

Which probe of strong dynamics?

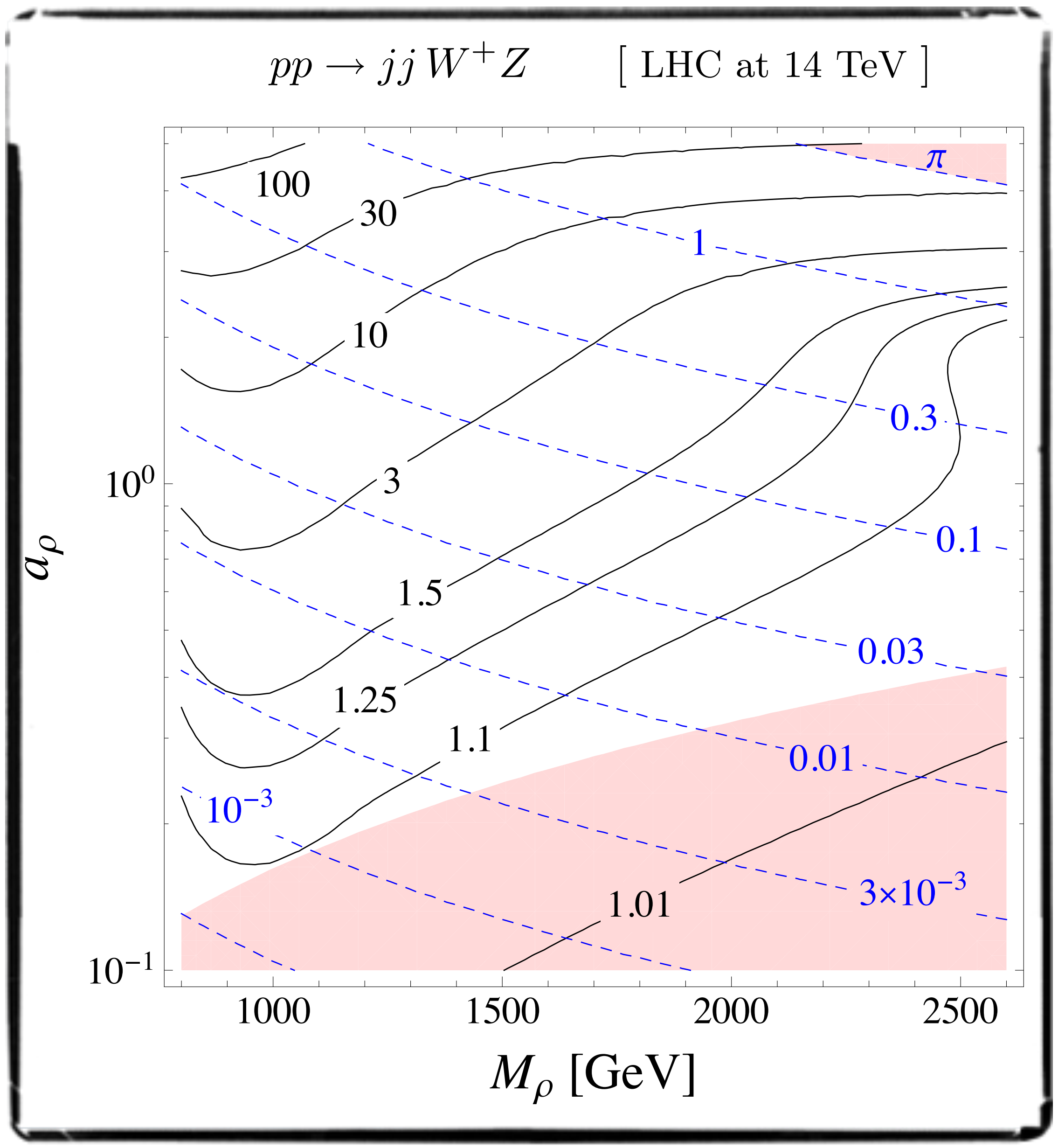
- Higgs self-couplings controls the dynamics of EWSB ⇨ red herring (various weak states can modify h^3)
- to learn about strong interactions triggering EWSB ⇨ need to measure quadratic coupling b to Goldstones!

How to probe strong EW symmetry breaking?

3. Detecting heavy resonances

Resonances Effects in WW Scatterings

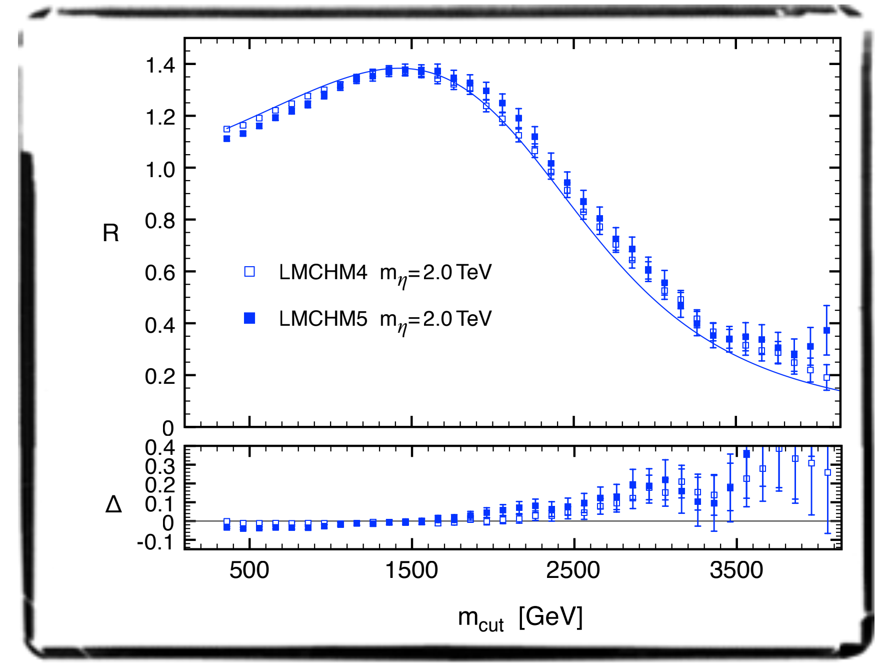
Contino, Marzocca, Pappadopulo, Rattazzi '11



$\xi = 0.5$

$m_{\rm cut} = 800\,\text{GeV}$

$R = \dfrac{\sigma(\rho_L)}{\sigma(\text{LET})}$ $\qquad \dfrac{\Gamma_{\rho_L}}{m_{\rho_L}}$

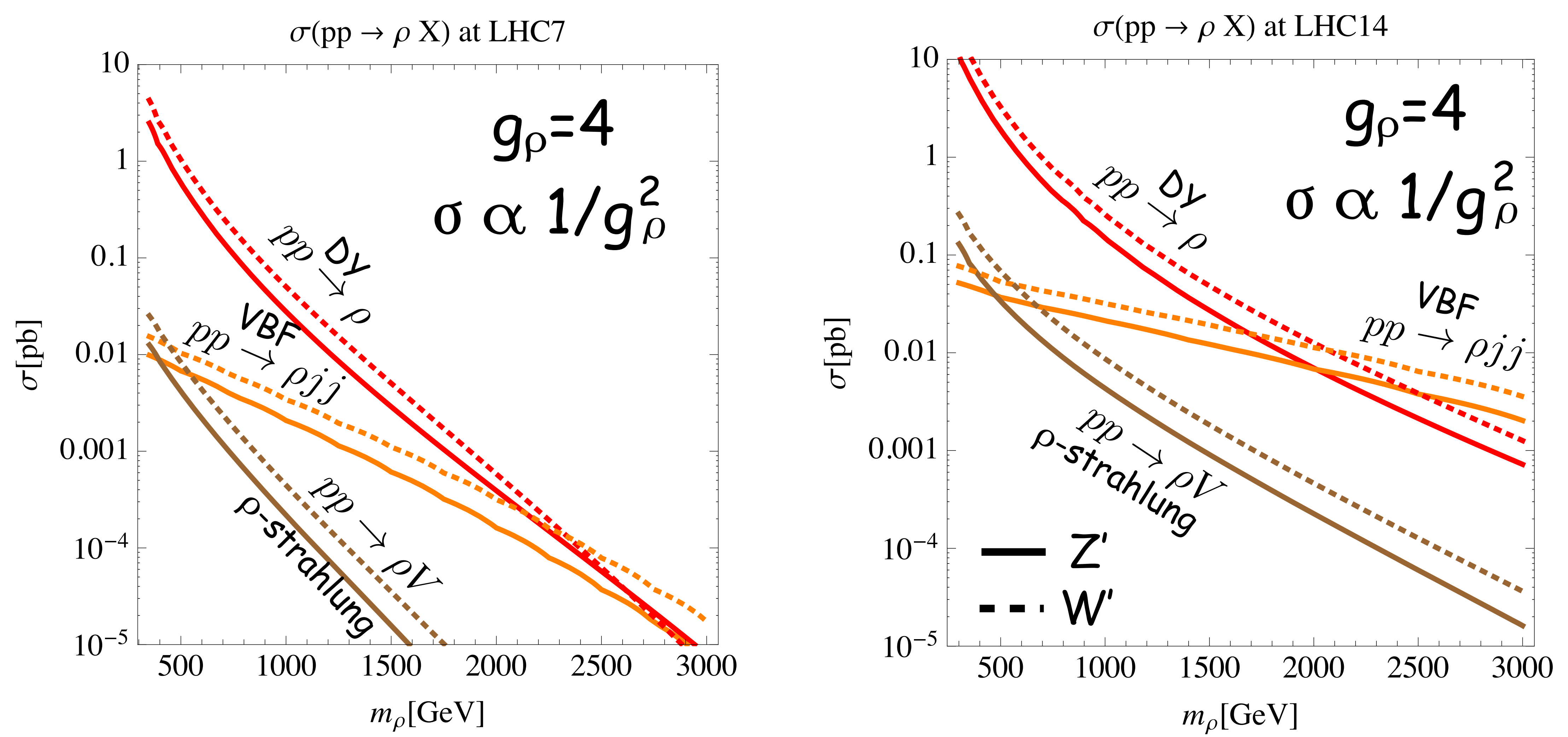


channel complementary
to pin down the nature of the resonance

		W^+W^-	W^+Z	W^+W^+	hh
ρ	(1,3)	↑	↑	↓	↓
η	(1,1)	↑	↓	↓	↑
Δ	(3,3)	↑	↑	↑	↑

Resonance Production

Observing a tower of resonances would a direct evidence of the strong interactions
However, in the best configuration, LHC will have access to a few ones only



Falkowski, Grojean, Kaminska, Pokorski and Weiler '11

VBF vs. DY:

- 3-body vs 2-body final state
- qq (more important at large x) vs qq initiated process

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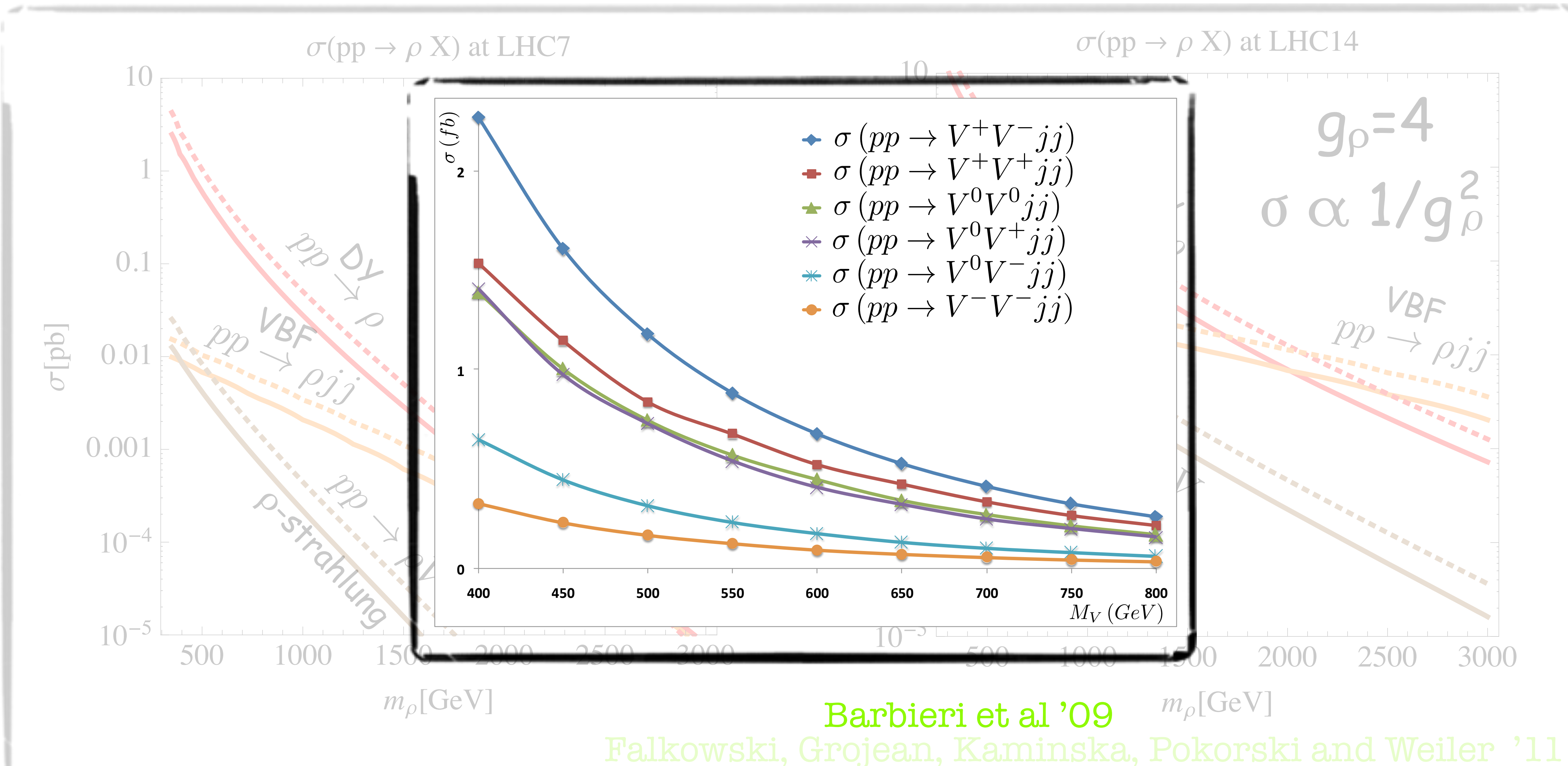


Barbieri et al '09

Falkowski, Grojean, Kaminska, Pokorski and Weiler '11

VBF vs. DY:
- 3-body vs 2-body final state
- qq (more important at large x) vs qq initiated process

Resonance Decays

Dominant decays into longitudinal SM gauge bosons

$$\Gamma(\rho^0 \to W^+W^-) \approx \Gamma(\rho^\pm \to ZW^\pm) \approx \frac{m_\rho g_{\rho\pi\pi}^2}{48\pi} = \frac{m_\rho^5}{192\pi g_\rho^2 v^4}$$

corrections 30%-10% from transverse SM gauge bosons

Suppressed decays to SM quarks and leptons

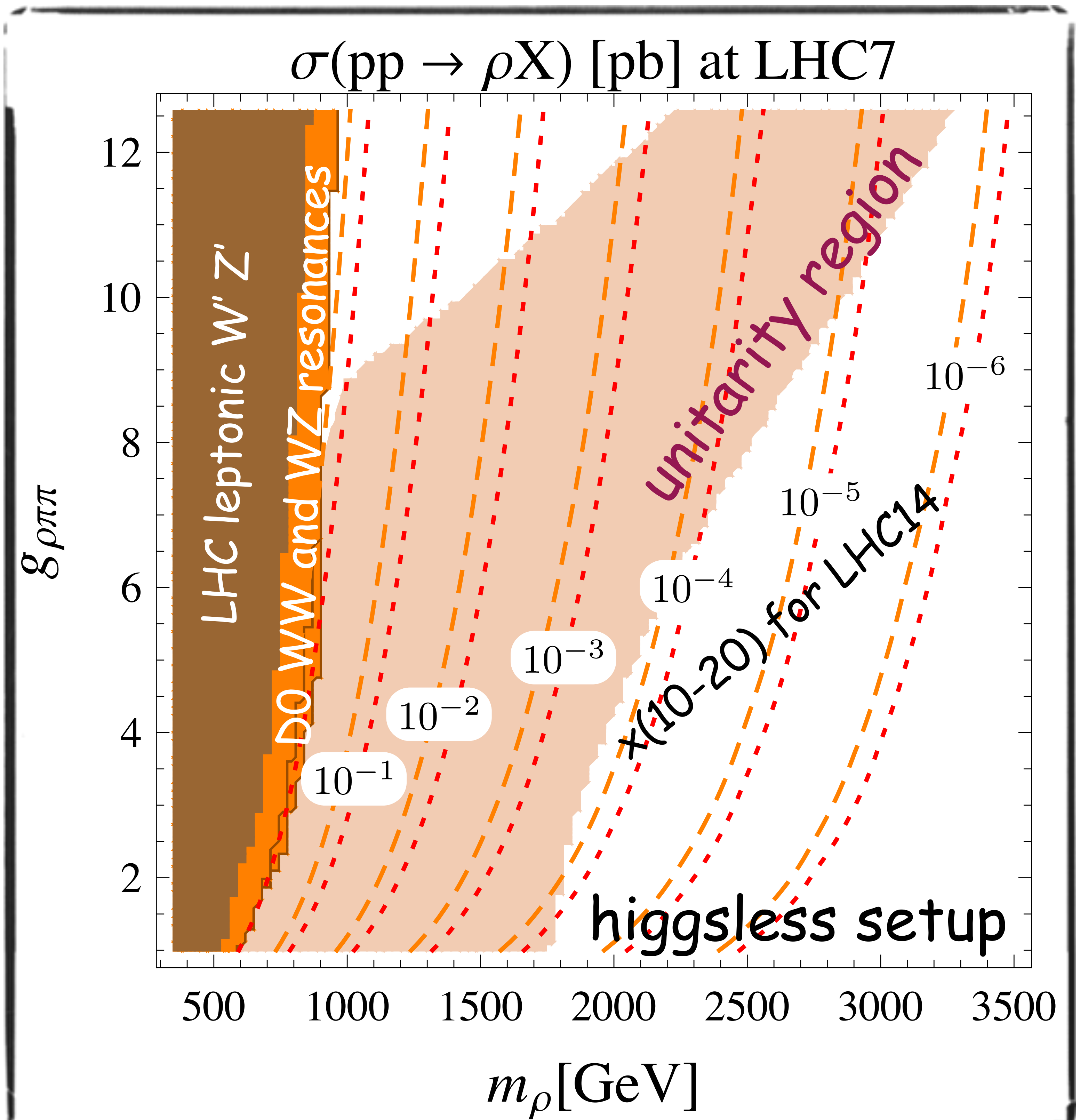
$$\mathrm{Br}(\rho^\pm \to e^\pm \nu) \approx 2\mathrm{Br}(\rho^0 \to e^+e^-) \approx \frac{16 m_W^4}{m_\rho^4}$$

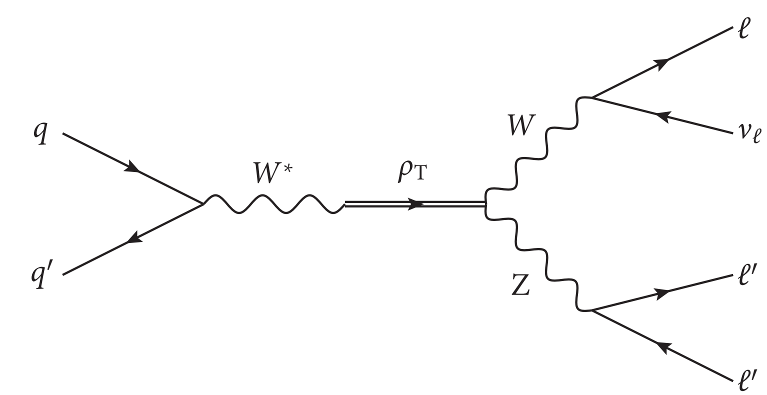
$\Downarrow$ $\Downarrow$ $\Downarrow$

searches in WW, WZ channels in DY processes

Resonance Searches

Falkowski, Grojean, Kaminska, Pokorski and Weiler '11





- Current best limits from the $1fb^{-1}$ CMS search for WZ resonances

  CSM-PAS-EXO-11-041

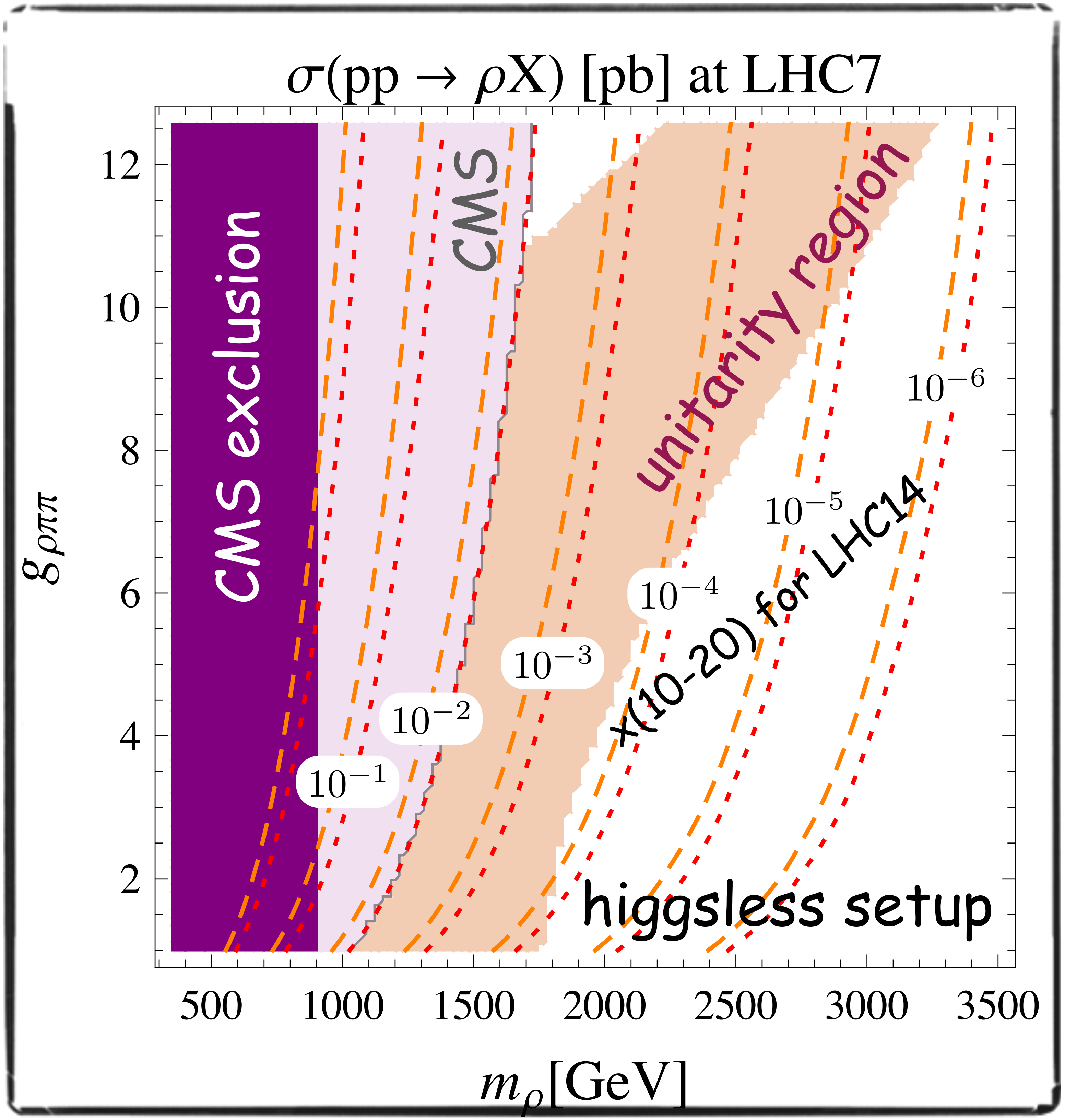
- D0 search for WW and WZ resonances gives weaker bounds

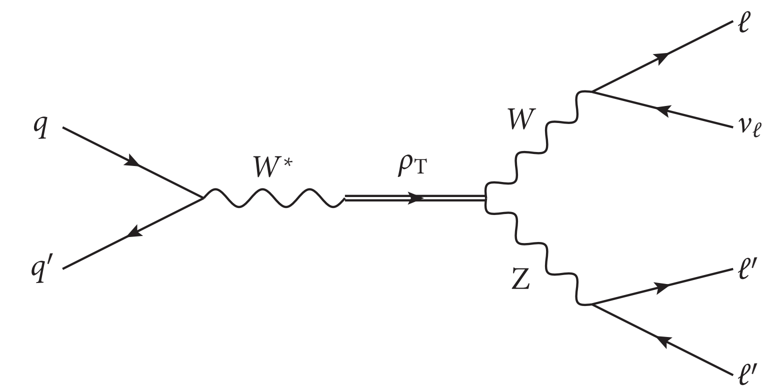
  Abazov et al, '10

- LHC limits on leptonic Z' and W' resonances are not competitive because of the small leptonic branching fraction

Resonance Searches

Falkowski, Grojean, Kaminska, Pokorski and Weiler '11





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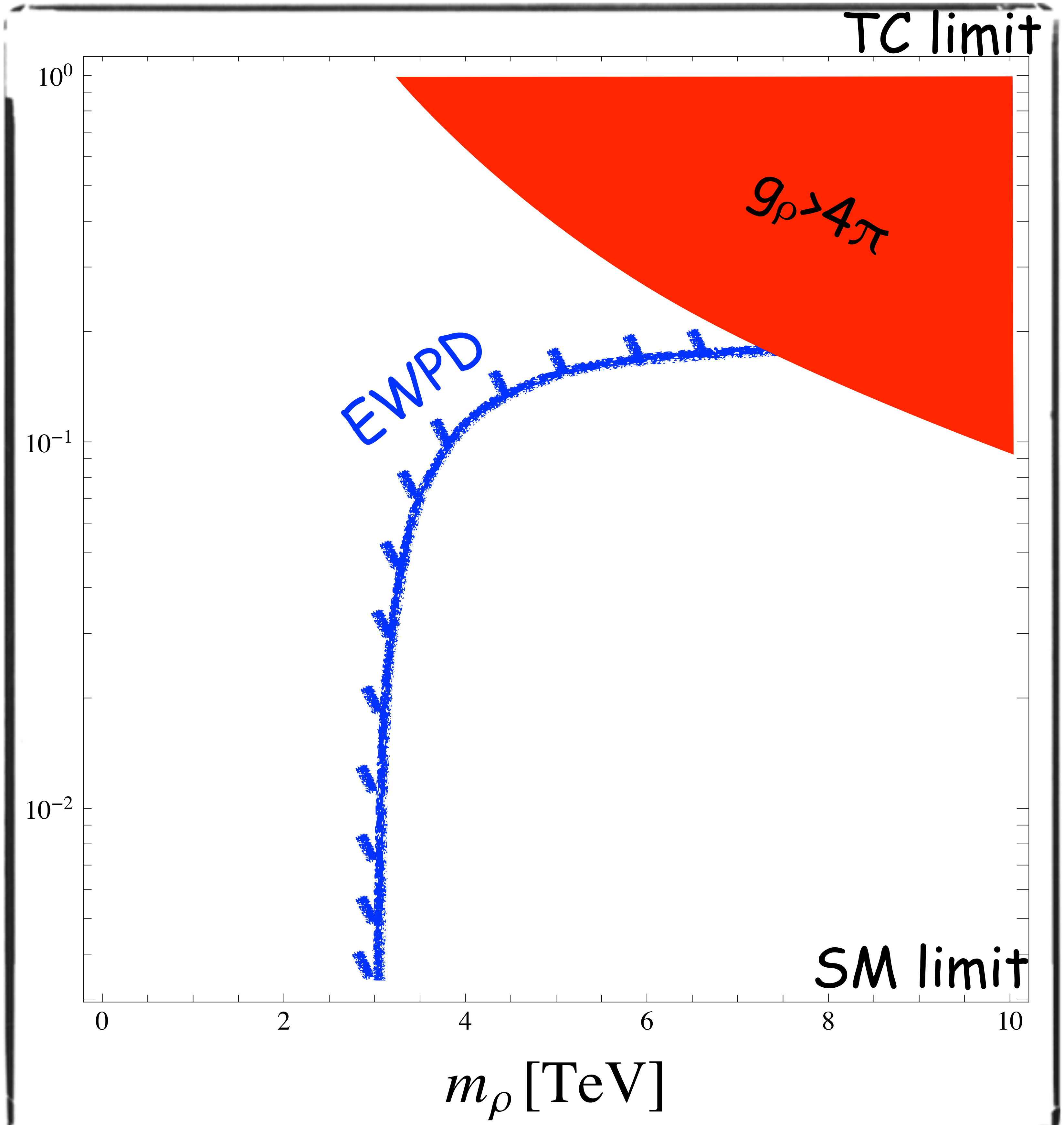
Resonance Searches vs Indirect Probes

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

$$\left(\frac{\text{weak scale}}{\text{strong scale}}\right)^2 = \xi$$



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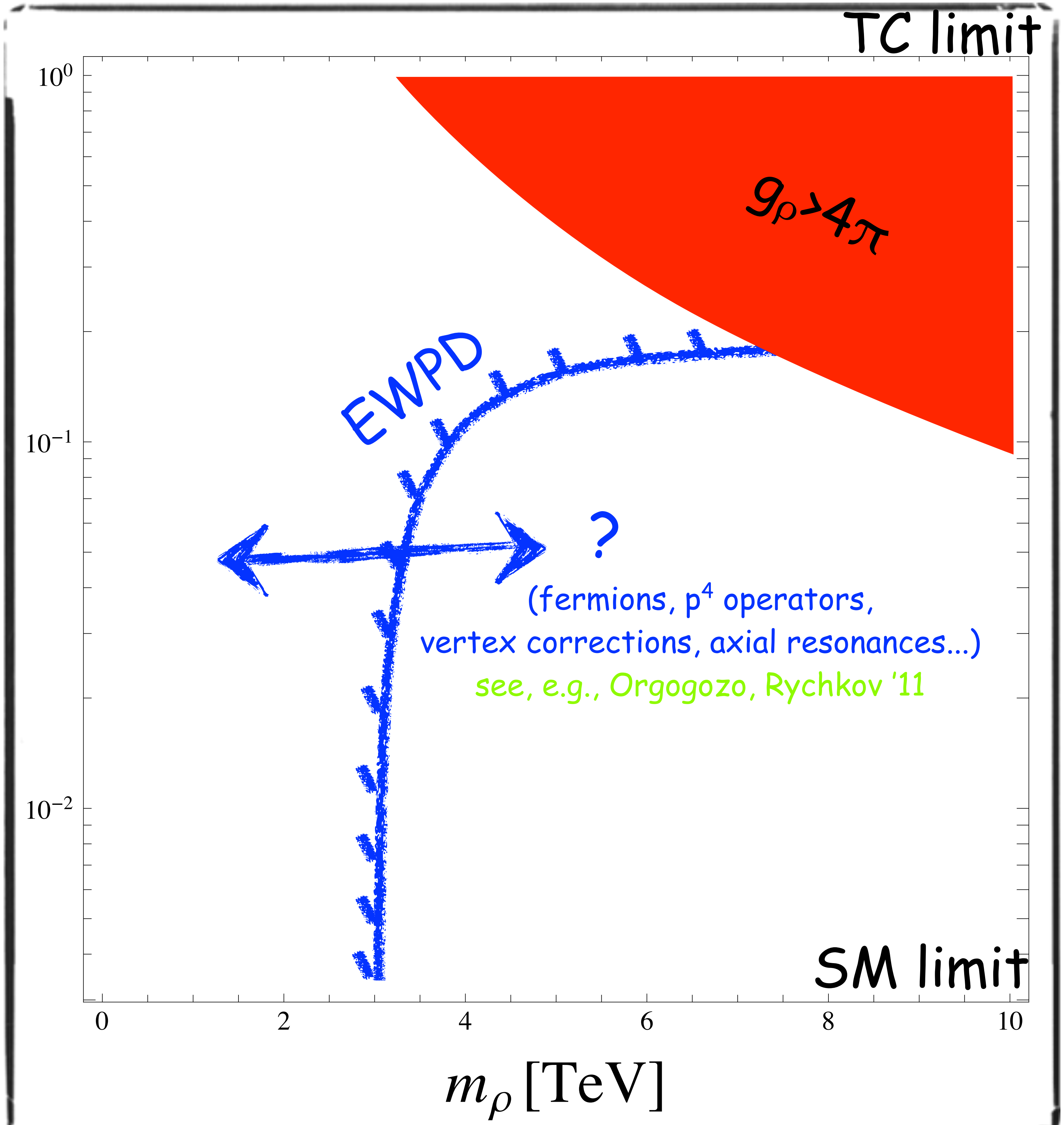
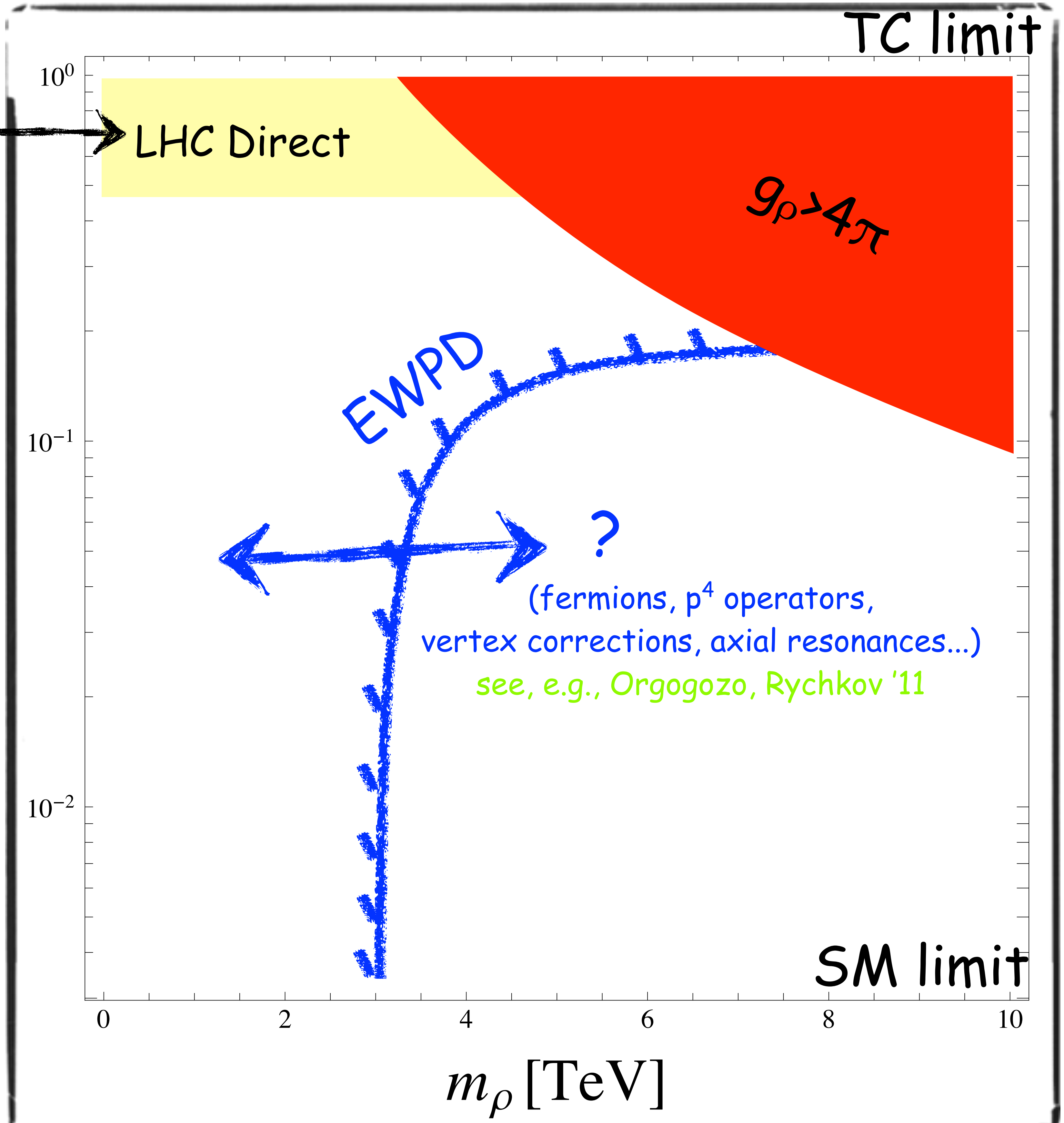


Resonance Searches vs Indirect Probes

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

Strong WW scattering

$$\left(\frac{\text{weak scale}}{\text{strong scale}}\right)^2 = \xi$$



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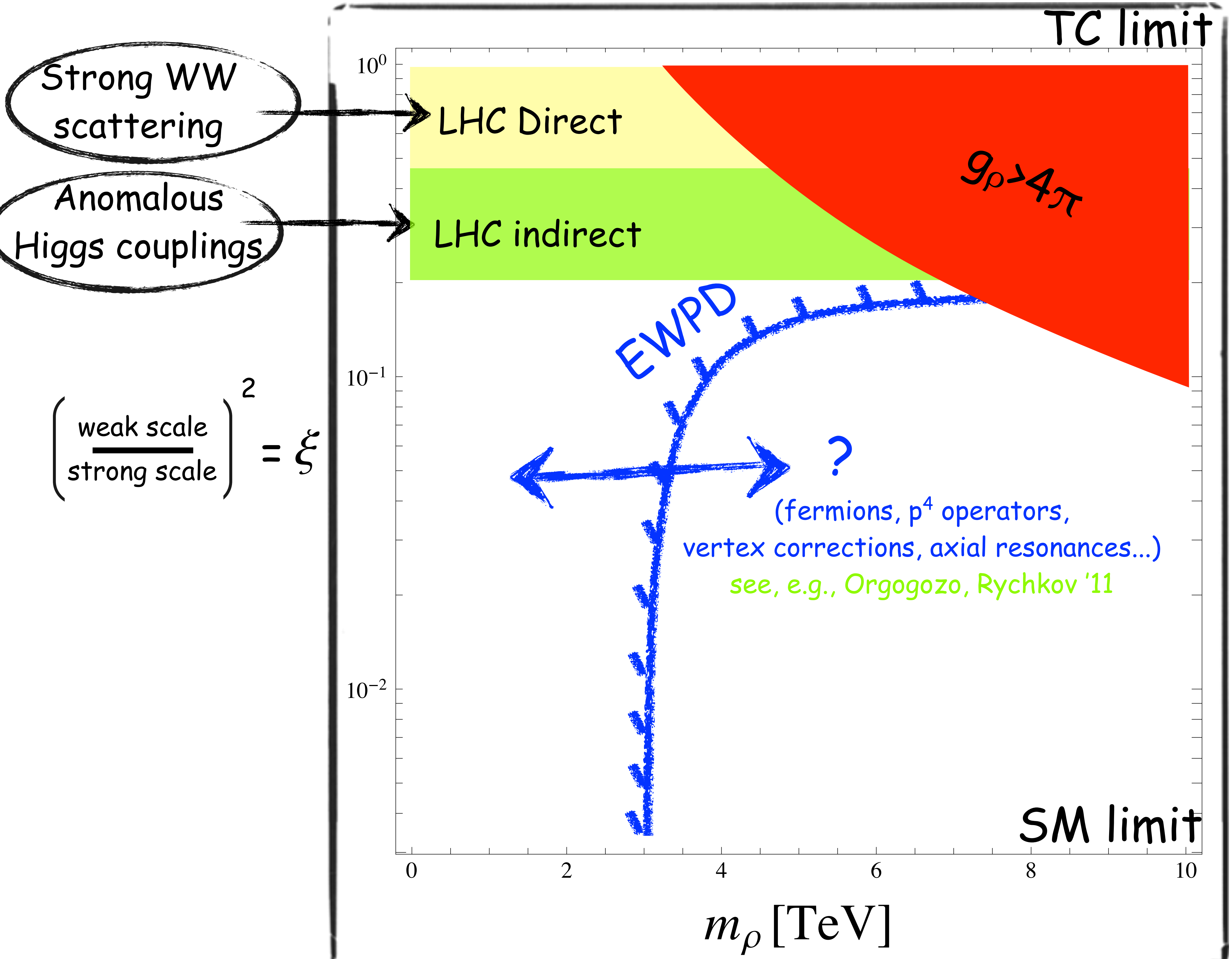

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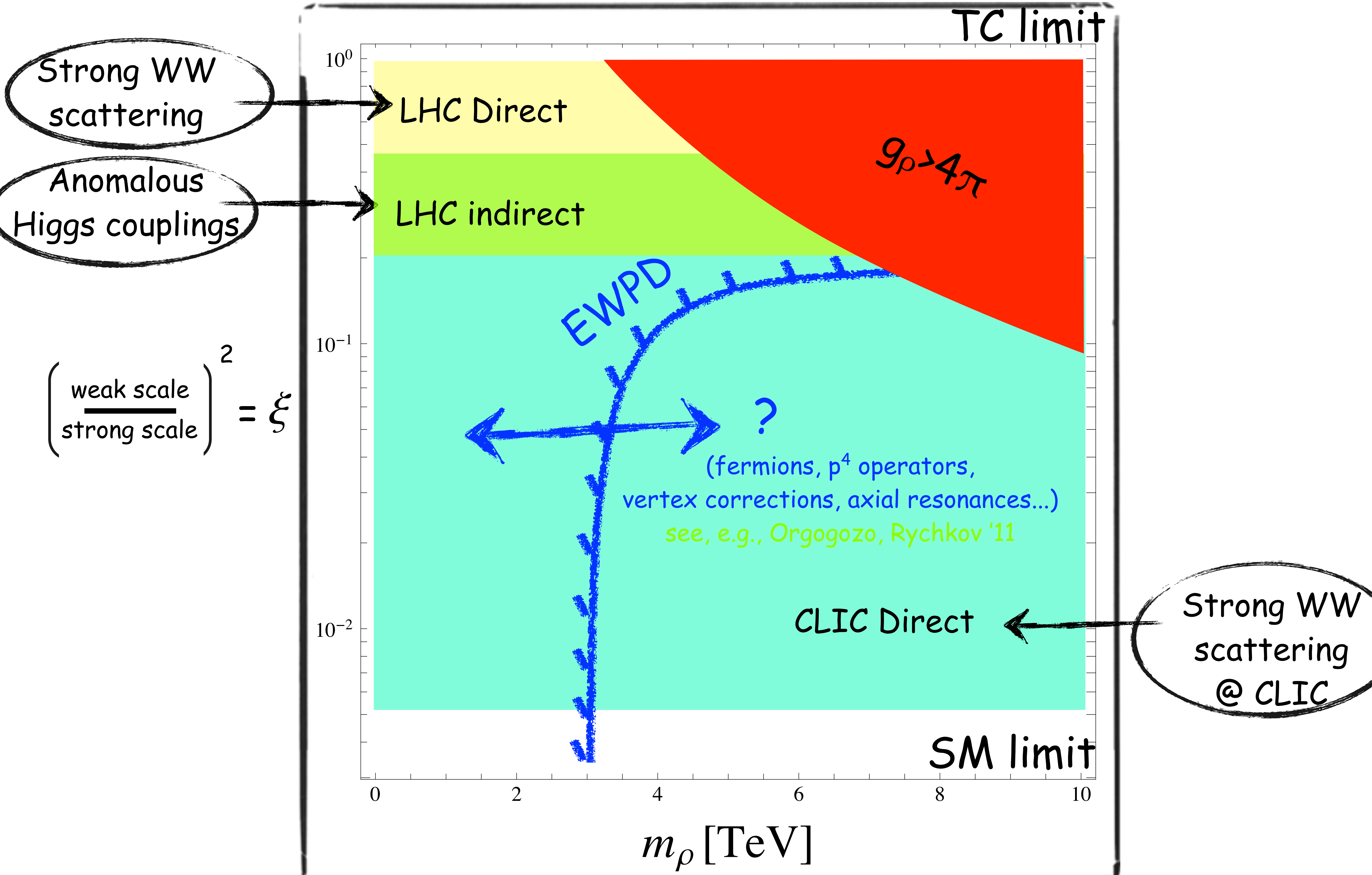


Resonance Searches vs Indirect Probes

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

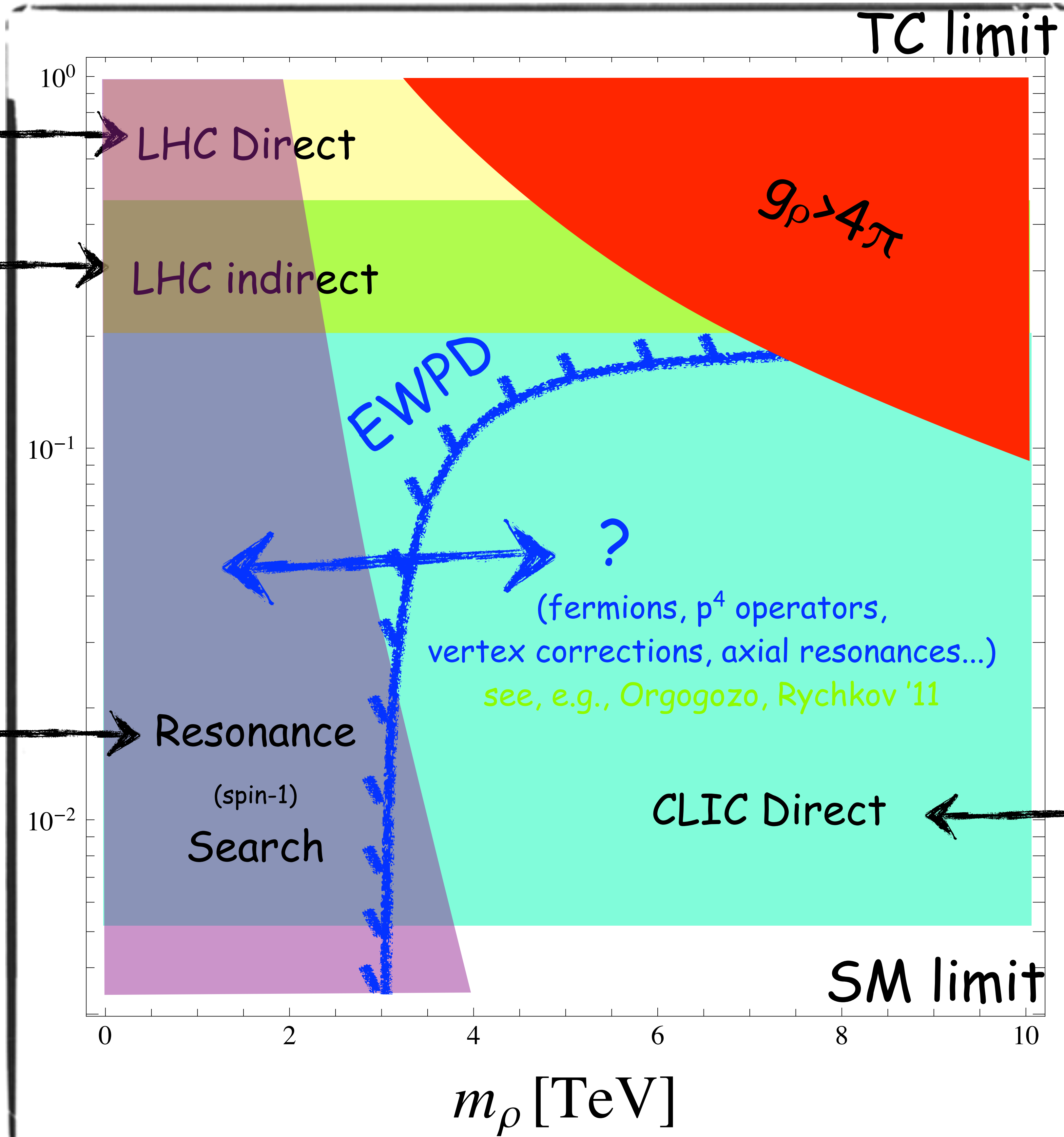
Strong WW scattering

Anomalous Higgs couplings

$$\left(\frac{\text{weak scale}}{\text{strong scale}}\right)^2 = \xi$$

Resonance searches

NB:
the lower the scale of strong interaction, the more difficult to see resonances
(broader resonances & weaker couplings to light SM quarks)



Strong WW scattering @ CLIC

Resonance vs Heavy Gauge Boson

Grojean, Salvioni, Torre '11

How can we tell the difference between a massive gauge field and a resonance from a strong sector?

elementary spin-1

g=2 $\Leftrightarrow$ Λ >> M/e $\Leftrightarrow$ W'→Wγ highly suppressed

gyromagnetic ratio of any elementary particle of mass M coupled to photon must be g=2 at tree-level to maintain perturbative unitarity up to energy Λ >> M/e

Ferrara, Porrati, Telegdi '92

composite spin-1

g≠2 & Λ > 5÷10 M $\Leftrightarrow$ W'→Wγ allowed and potentially large

$(g-1)B^{\mu\nu}W'^{+}_{\mu}W'^{-}_{\nu}$ dimension-4 operator mediating W' →Wγ after W-W' mixing

Fermionic Resonances

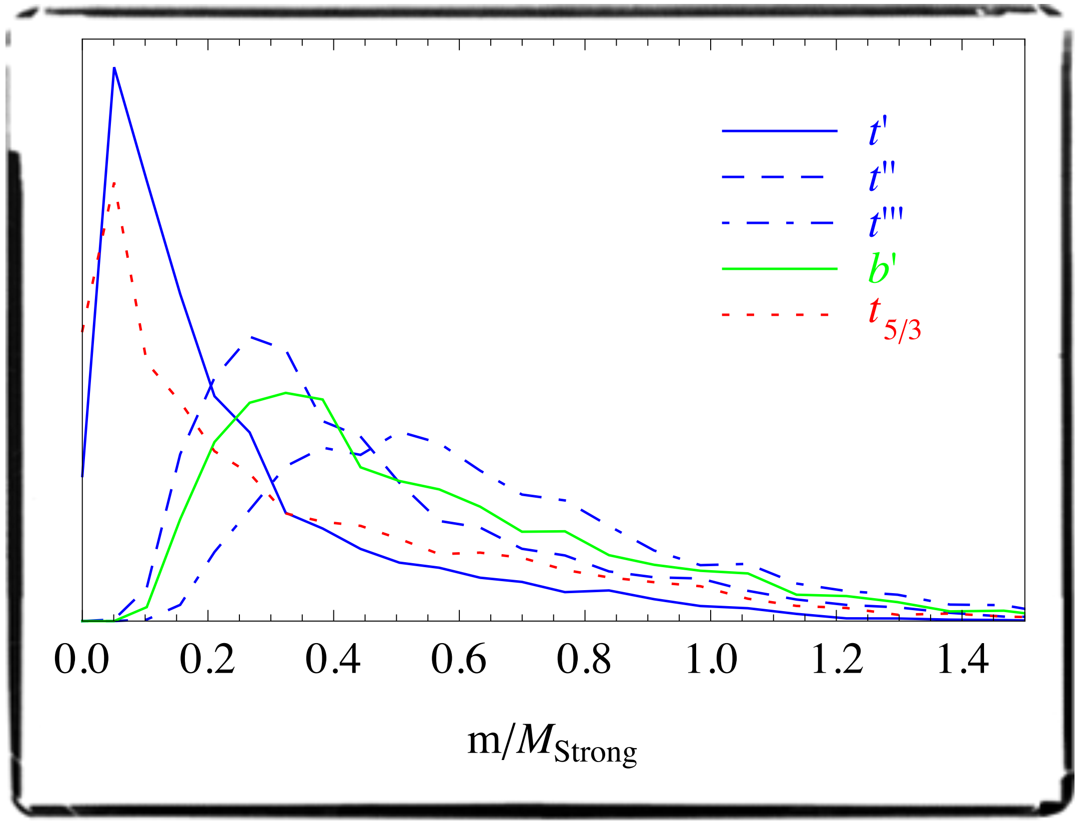
[Agashe, Contino, Da Rold, Pomarol '06]

- Custodial symmetry: exotic top partners

SU(2)$_L$xSU(2)$_R$ embedding

$$Q_L = \begin{pmatrix} t_L^{2/3} & t_L^{5/3} \\ b_L^{-1/3} & b_L^{2/3} \end{pmatrix} \equiv (2, \bar{2})_{2/3} \qquad t_R \equiv (1,1)_{2/3} \qquad b_R \equiv (1,1)_{-1/3}$$

$\Rightarrow \delta_{Z b_L \bar{b}_L} = 0$



Panico, Wulzer '11

partial compositness

⇓ ⇓

the heavier the SM quark,
the lighter its resonances and partners

the top sector is
a promizing place to look
for strong dynamics

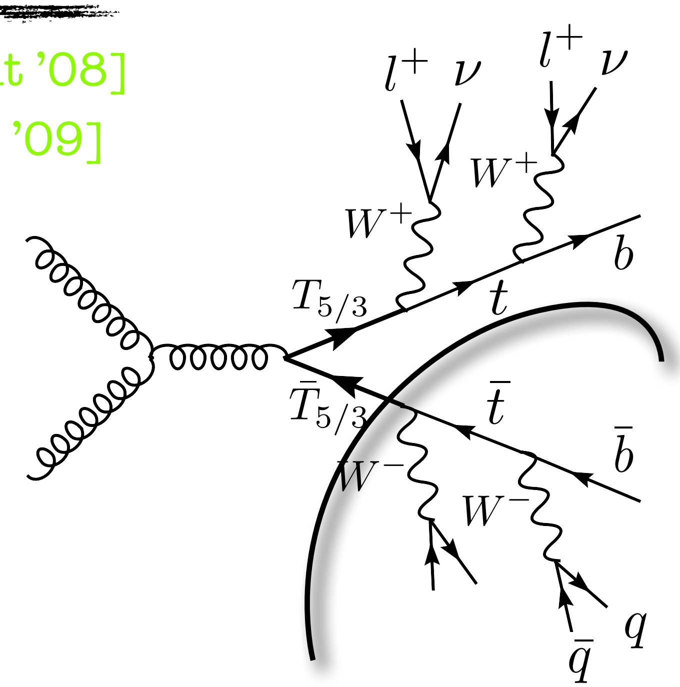
Searching for Exotic Top Partners

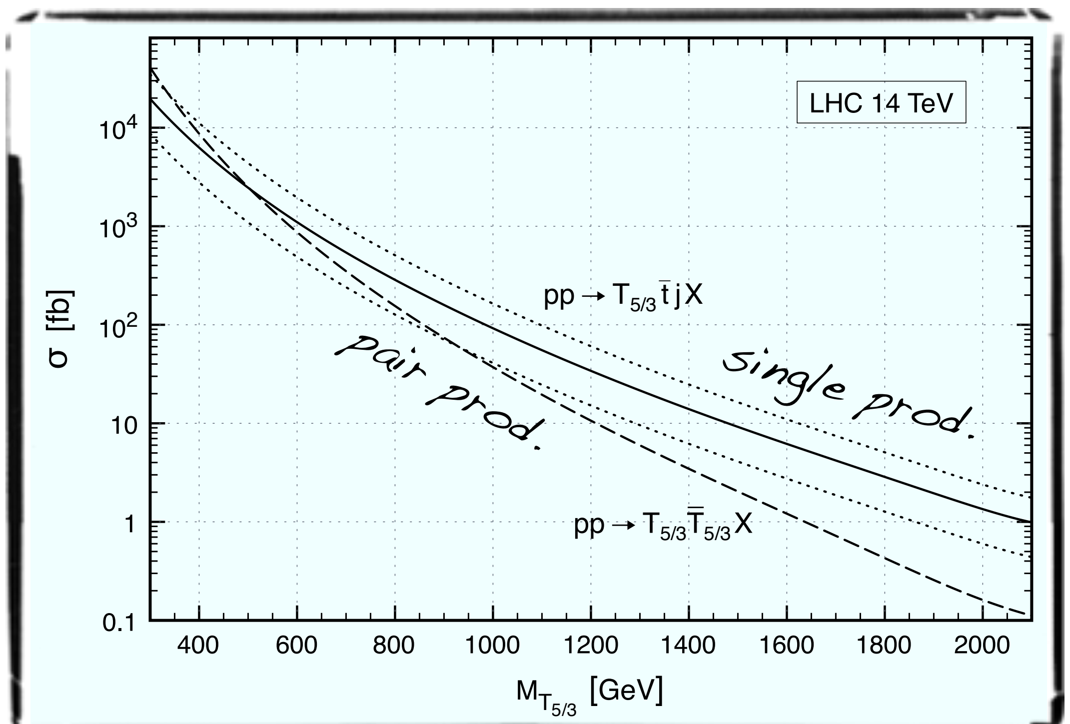
Search in same-sign di-lepton events

[Contino, Servant '08]
[Mrazek, Wulzer '09]

- $t\bar{t}$+jets is not a background [except for charge mis-ID and fake e^-]
- the resonant (tW) invariant mass can be reconstructed

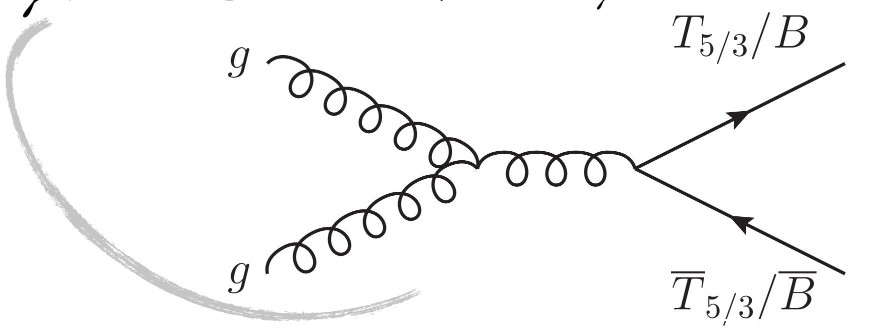
discovery potential (LHC$_{14TeV}$)
$M_{5/3}$=500 GeV (σxBR≈100/fb) → 56 pb^{-1}
$M_{5/3}$=1 TeV (σxBR≈2/fb) → 15 fb^{-1}

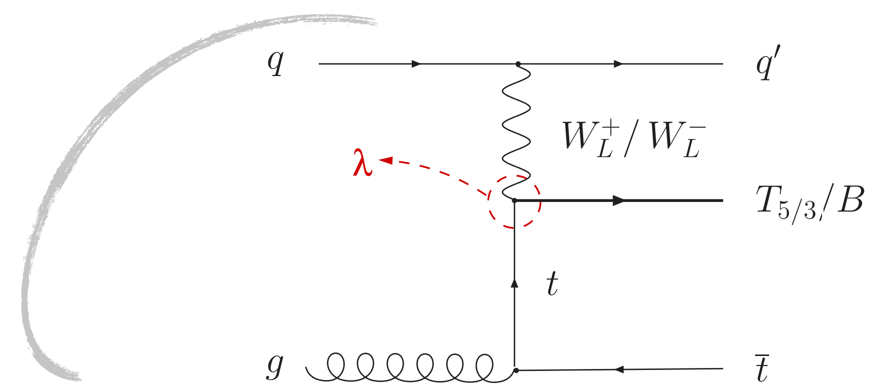




[Contino, Servant '08]

Pair production (model independent)





Single production (model dependent)

Conclusions

EW interactions need Goldstone bosons to provide mass to W, Z

⇓ ⇓ ⇓ ⇓ ⇓ ⇓

EW interactions also need a UV moderator/new physics
to unitarize WW scattering amplitude

We'll need another Gargamelle experiment
to discover the still missing neutral current of the SM: the Higgs

weak NC ⇔ gauge principle

Higgs NC ⇔ ?

Strong EWSB w/o an elementary Higgs can be very similar to SM
it might take some time to decipher the true dynamics of EWSB!