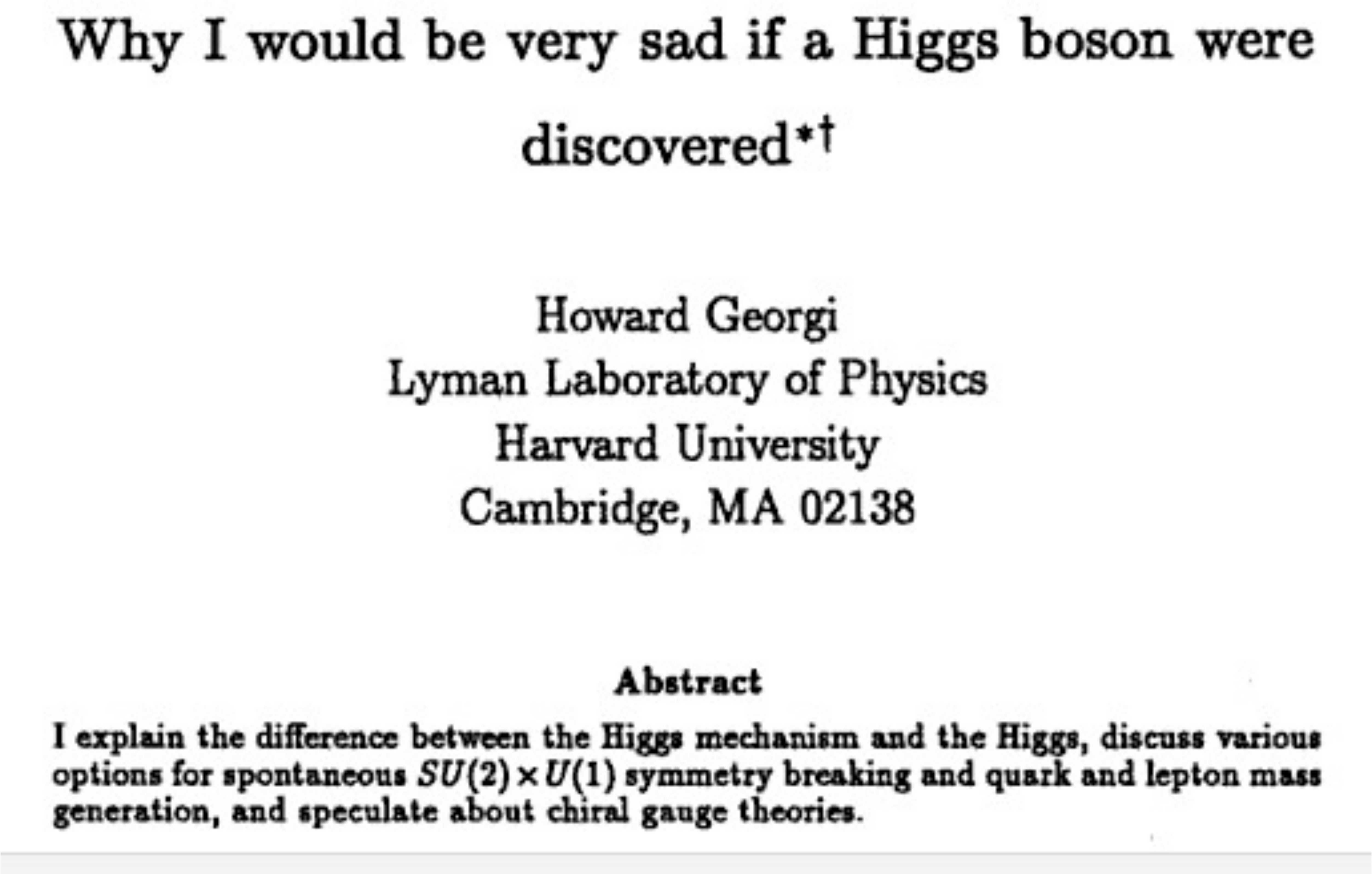
An Effective Theory for Higgs Compositeness

Jay Hubisz
Syracuse University
2/27/2011

WIP - Bellazzini, Csáki, JH, Serra, Terning

Perspectives on Higgs physics

By G. L. Kane



Why I would be very sad if a Higgs boson were discovered*†

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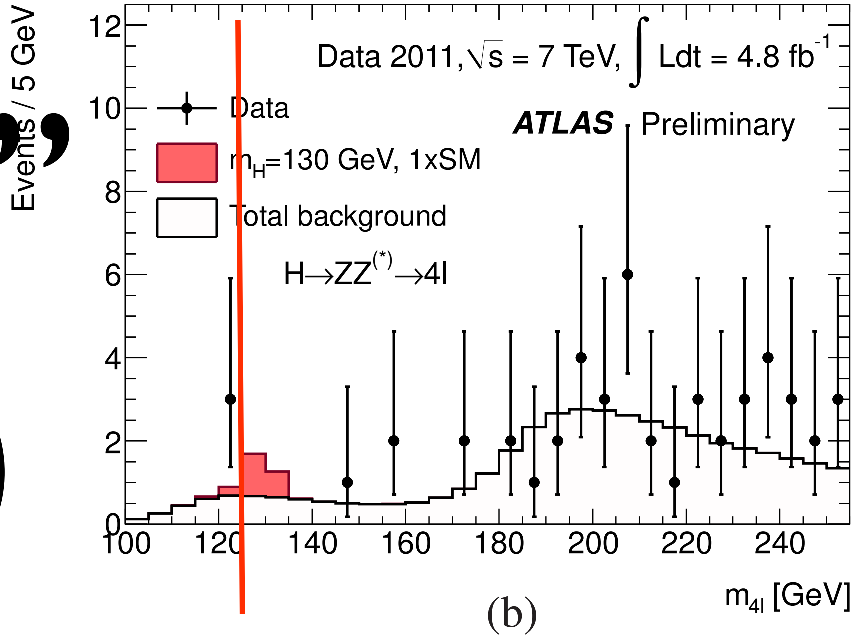
Abstract

I explain the difference between the Higgs mechanism and the Higgs, discuss various options for spontaneous $SU(2) \times U(1)$ symmetry breaking and quark and lepton mass generation, and speculate about chiral gauge theories.

The “Higgs” at 125(ish)



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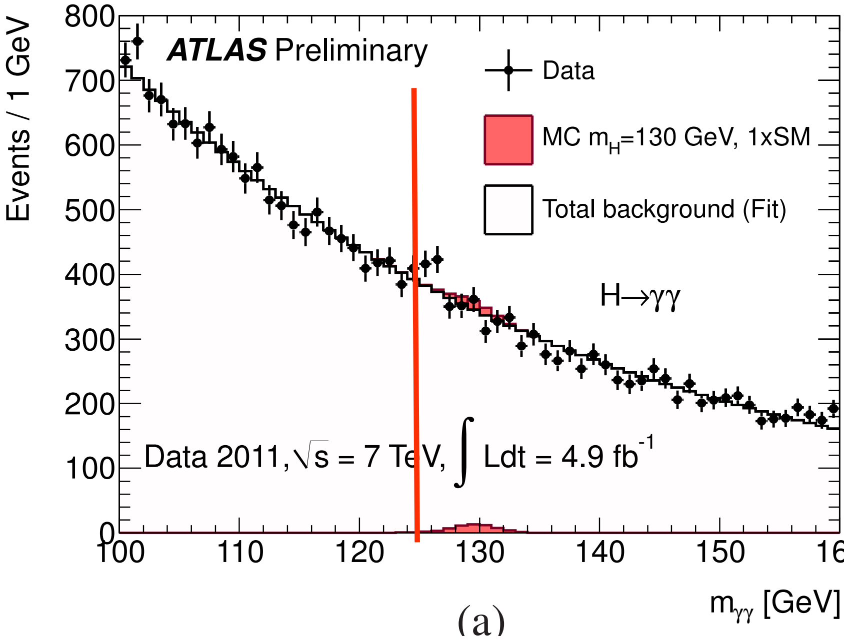
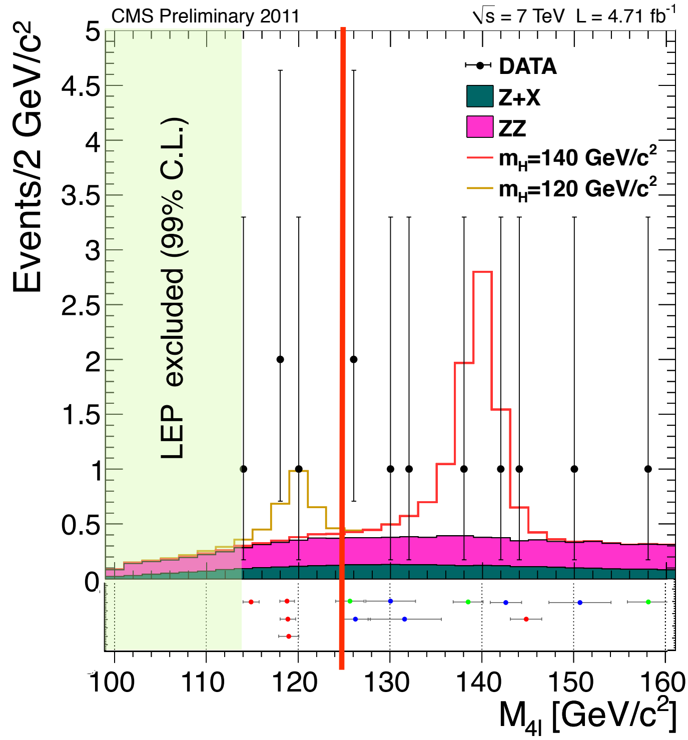
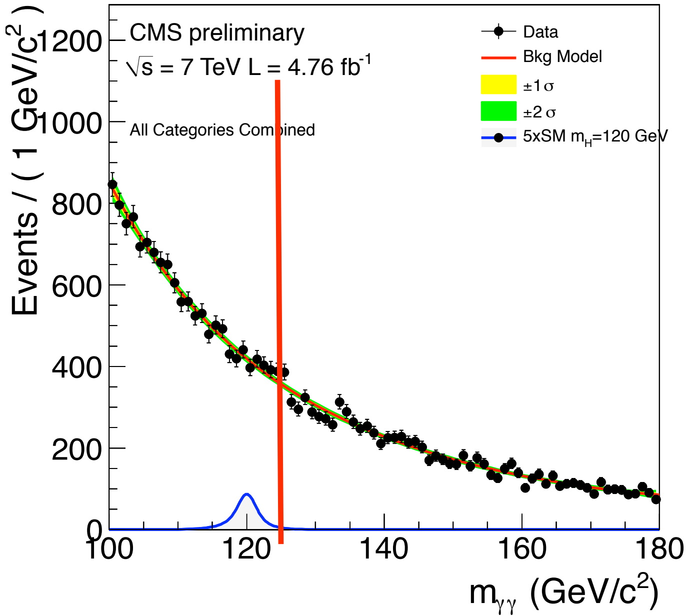


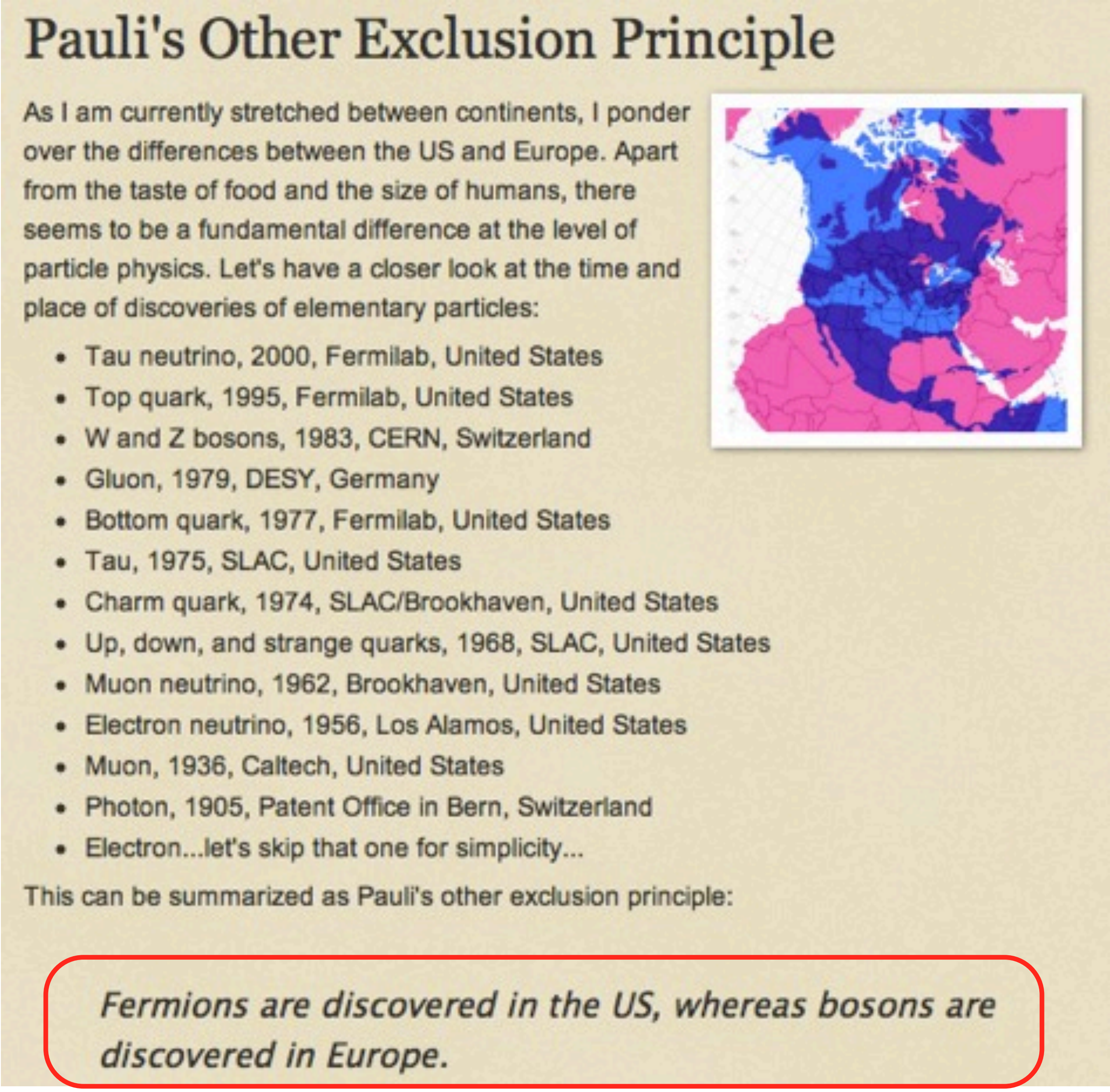
(a)

- ATLAS + CMS have excesses in γγ
- Backed up by collections of 4l events
- Slight excesses in CMS low res. channels
- “Smells” right





Consistent with other fundamental laws:



Pauli's Other Exclusion Principle

As I am currently stretched between continents, I ponder over the differences between the US and Europe. Apart from the taste of food and the size of humans, there seems to be a fundamental difference at the level of particle physics. Let's have a closer look at the time and place of discoveries of elementary particles:

- Tau neutrino, 2000, Fermilab, United States
- Top quark, 1995, Fermilab, United States
- W and Z bosons, 1983, CERN, Switzerland
- Gluon, 1979, DESY, Germany
- Bottom quark, 1977, Fermilab, United States
- Tau, 1975, SLAC, United States
- Charm quark, 1974, SLAC/Brookhaven, United States
- Up, down, and strange quarks, 1968, SLAC, United States
- Muon neutrino, 1962, Brookhaven, United States
- Electron neutrino, 1956, Los Alamos, United States
- Muon, 1936, Caltech, United States
- Photon, 1905, Patent Office in Bern, Switzerland
- Electron...let's skip that one for simplicity...

This can be summarized as Pauli's other exclusion principle:

Fermions are discovered in the US, whereas bosons are discovered in Europe.

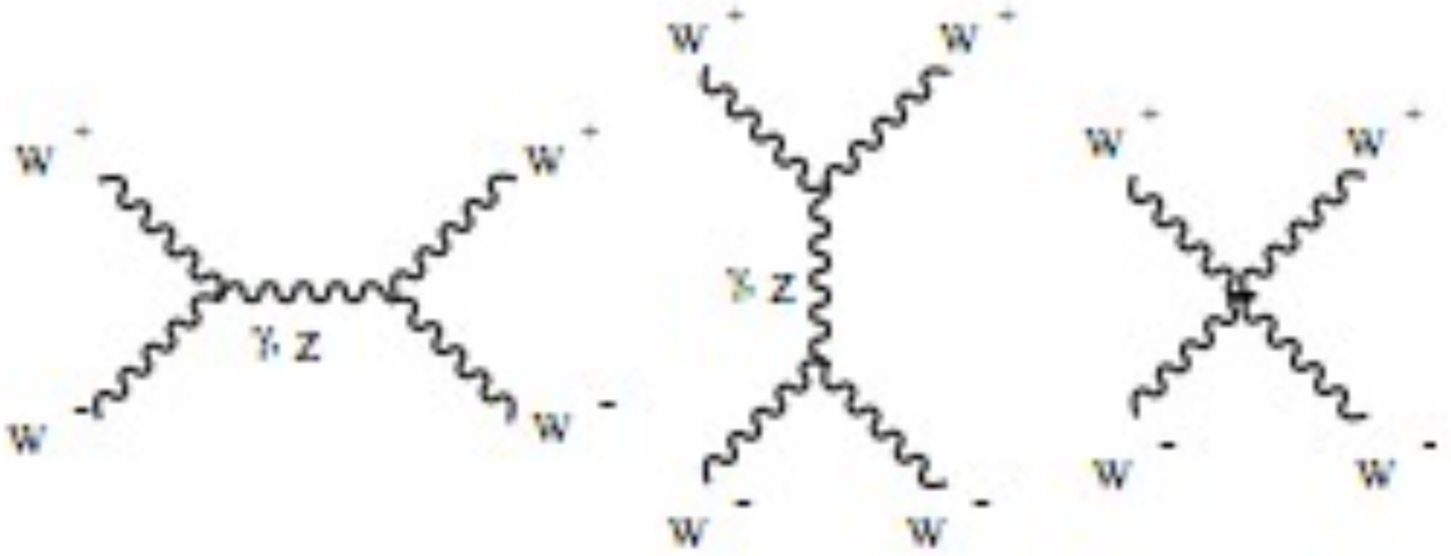
Resonaances - Falkowski

Naturalness and a Composite Higgs

- Higgs not necessarily a fundamental scalar
  - composite at the TeV/few-TeV scale
- Composite models 'natural' in sense that the loops that correct the higgs mass are cut off at a much lower scale (little hierarchy often remains)
- models which combine these ideas address LH prob
  - Little Higgs, composite SUSY, ...
- motivates a simplified model approach to CH
  - what are generic signatures/constraints?

Unitarity

- The principle of unitarity in EWSB provides the strongest justification for the LHC program
- The Higgs (or cousins) had to be there



$$\sim \left(\frac{gE}{M}\right)^2$$

Amplitude grows with energy - non-perturbative for E>>M

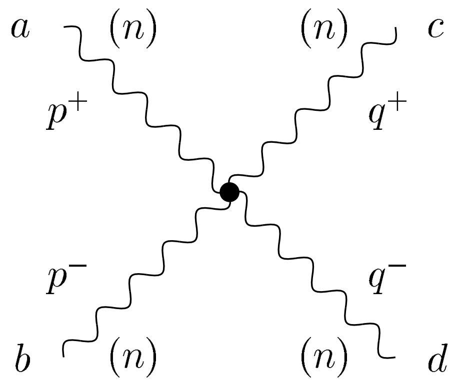
SM: Fixed by including higgs contributions
(gauge invariance forces a ‘sum-rule’)

Gaugephobic Higgs

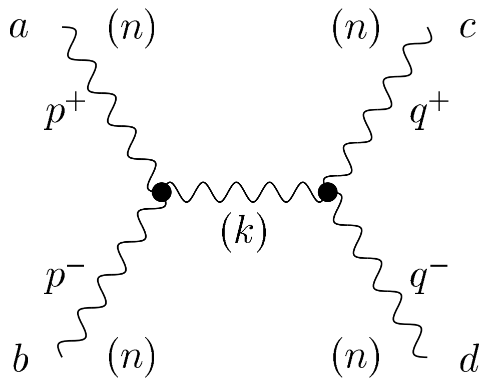
Limit of decoupled Higgs

Unitarity with only vectors:

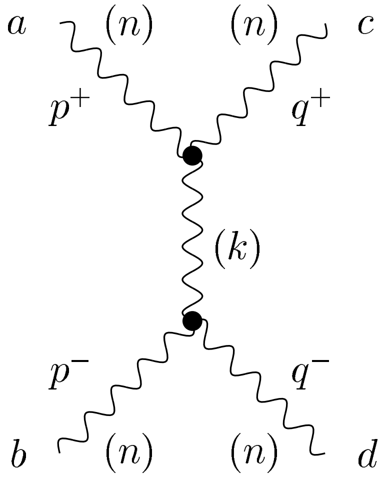
gauge resonances terminate growth of amplitudes via KK-mode sum rule



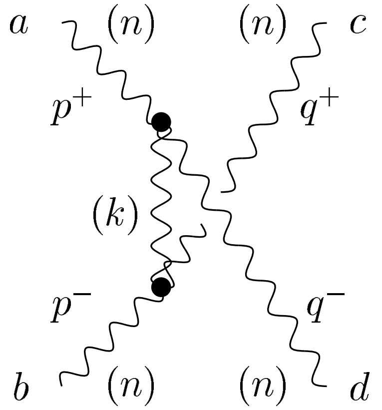
contact interaction



s channel exchange



t channel exchange



u channel exchange

$$\mathcal{A} = A^{(4)}\frac{E^4}{M_n^4} + A^{(2)}\frac{E^2}{M_n^2} + A^{(0)} + \mathcal{O}\left(\frac{M_n^2}{E^2}\right)$$

$$A^{(2)} = \frac{i}{M_n^2}\left(4g_{nnnn}M_n^2 - 3\sum_k g_{nnk}^2 M_k^2\right)\left(f^{ace}f^{bde} - \sin^2\tfrac{\theta}{2}\ f^{abe}f^{cde}\right)$$

$$g_{nnnn}M_n^2 = \frac{3}{4}\sum_k g_{nnk}^2 M_k^2$$

sum rule automatic (5D gauge invariance)

review: Csaki, JH, Meade

Simplified model for LHC unitarity

WIP: Bellazzini, Csáki, JH, Serra, Terning

- Unitarity sum-rule only partially saturated by Higgs exchange diagrams - suppressed couplings
- one set of vector resonances (ρ's) - completes saturation of the electroweak GB sum-rules
  - non-linear realization of custodial coset:
    - $SU(2)_L \times SU(2)_R/SU(2)_C$ a-la hidden local symmetry

      Cassalbuoni, Curtis, Dominici, Gatto '87
      Falkowski, Grojean, Kaminska, Pokorski, Weiler '11
    - ρ's come as triplet of $SU(2)_C$

The Goldstones

Symmetry spontaneously broken at f = v_{ew}

Element of coset G/H: $U(\Pi) = e^{i\Pi^{\hat{a}}T^{\hat{a}}}$

$$-iU^{-1}\partial_\mu U = \Pi_\mu^{\hat{a}}T^{\hat{a}} + E_\mu^a T^a \equiv \Pi_\mu + E_\mu$$

Under transformation g_0 in G:

$$\begin{aligned}\Pi_\mu \to & h(\Pi, g_0)\Pi_\mu h^{-1}(\Pi, g_0) \\ E_\mu \to & h(\Pi, g_0)E_\mu h^{-1}(\Pi, g_0) - ih(\Pi, g_0)\partial h^{-1}(\Pi, g_0)\end{aligned}$$

Π_μ transforms linearly

E_μ transforms like gauge field

The Goldstones

Build action that is invariant under G:

$$\boxed{\mathcal{L}_{\Pi}^{(2)} = \frac{f^2}{2}\mathrm{Tr}[\Pi_\mu \Pi^\mu]}$$

Goldstone kinetic terms

Add Higgs interactions (singlet couplings):

$$\boxed{\mathcal{L}^{(h)} = \frac{1}{2}(\partial h)^2 + V(h) + \frac{f^2}{2}(2\underset{\uparrow}{a_h}\frac{h}{f} + \underset{\uparrow}{b_h}\frac{h^2}{f^2})\mathrm{Tr}[\Pi_\mu \Pi^\mu]}$$

free parameters

a_h sets $h\pi\pi$ coupling - unitarity saturated for a_h=1

The ρ's

With E_μ, can write down invariant action that includes additional gauge fields transforming under $SU(2)_C$

free parameter

$$\boxed{\mathcal{L}_\rho^{(2)} = -\frac{1}{4g_\rho^2}\rho^a_{\mu\nu}\rho^a_{\mu\nu} + \frac{a_\rho^2 f^2}{2}(\rho^a_\mu - E^a_\mu(\Pi))^2}$$

Generates a ρ mass: $m_\rho = a_\rho g_\rho f$

g_ρ sets self-interactions of ρ's

a_ρ sets mass, interactions with goldstones, and adds goldstone self-interactions

---

Higgs couplings to ρ's: $\boxed{\mathcal{L}_{\mathrm{h}\rho} = \frac{f^2}{2}(2c_h\frac{h}{f} + d_h\frac{h^2}{f^2})(\rho^a_\mu - E^a_\mu)^2}$

SM Gauge Bosons

Gauging SU(2)$_L$xU(1)$_Y$: gauge fields in Π_μ and E_μ.

ρ's mix with SM gauge bosons:

$$W^\pm \longrightarrow W^\pm - \frac{g_2}{2g_\rho}\rho^\pm$$

$$Z \longrightarrow Z + \frac{g_1^2 - g_2^2}{2g_\rho\sqrt{g_1^2+g_2^2}}\rho^0$$

$$A \longrightarrow A - \frac{e}{g_\rho}\rho^0$$

$$\rho^3 \longrightarrow \rho^0 + \frac{e}{g_\rho}A - \frac{g_1^2 - g_2^2}{2g_\rho\sqrt{g_1^2+g_2^2}}Z$$

SU(2)$_C$ insures against large T-parameter

after diagonalization, have explicit ρVV couplings:

$$g_{WW\rho^0} = -\frac{g_2^2}{4g_\rho} = -\left(\frac{\sqrt{g_1^2+g_2^2}}{4g_\rho}\right) g^{SM}_{WWZ}$$

$$g_{\rho WZ} = -\left(\frac{g_2}{4g_\rho}\right)\sqrt{g_1^2+g_2^2} = -\left(\frac{g_1^2+g_2^2}{4g_2 g_\rho}\right) g^{SM}_{WWZ}$$

participates in unitarization of VBS

Couplings to light fermions

mixing also generates couplings to non-composite fermions:

$$\mathcal{L}^{(elment.)}_{\rho-currents} = -\frac{g_2^2}{2\sqrt{2}g_\rho}\rho^{\pm}_{\mu}\bar{\psi}\gamma^{\mu}T^{\mp}\psi + \rho^0_\mu\bar{\psi}\left[\frac{(g_1^2-g_2^2)}{2g_\rho}T^3 - \frac{g_1^2}{2g_\rho}Q\right]\gamma^\mu\psi$$

light quark coupling - Drell Yan production

Couple with strength $g_{\rho\bar{f}f} = g_{\rm SM}\left(a_\rho\frac{m_W}{m_\rho}\right)$

Heavy fermions may be composite

carry charge under SU(2)$_C$

couple strongly

The Model - Summary

We gauge unbroken global SU(2)$_C$

g_ρ is ρ 'gauge coupling' a_ρ fixes ρ mass

a_h controls suppression of higgs couplings

$$\begin{aligned}\mathcal{L} &= \frac{v^2}{2}(\Pi_\mu^{\hat{a}})^2 - \frac{1}{4}(\rho_{\mu\nu}^a)^2 + a_\rho^2 \frac{v^2}{2}\left(g_\rho \rho_\mu^a - E_\mu^a\right)^2 \\ &+ \frac{1}{2}(\partial_\mu h)^2 + V(h) + \frac{v^2}{2}\left(2a_h \frac{h}{v} + b_h \frac{h^2}{v^2}\right)(\Pi_\mu^{\hat{a}})^2 + \frac{v^2}{2}\left(2c_h \frac{h}{v} + d_h \frac{h^2}{v^2}\right)\left(g_\rho \rho_\mu^a - E_\mu^a\right)^2 \\ &+ O(p^4)\end{aligned}$$

Sufficient to consider π scattering for unitarity (goldstones eaten by W, Z)

Electroweak bosons mix with ρ's couple to SM gauge fields/fermions

Specific models predict values for some/all parameters

Unitarization

Couplings and masses must satisfy sum rules
to ensure perturbative W/Z scattering

$$\mathcal{M}(\pi^+\pi^- \to \pi^+\pi^-) = \frac{1}{32\pi}\frac{s}{f^2}\left(1 - a_h^2 - \hat{a}_\rho^2\right) - \frac{1}{48\pi f^2}\left[m_\rho^2 \hat{a}_\rho^2 (1 - 2\log[s/m_\rho^2]) + 3 m_h a_h^2 (2 m_h - i\Gamma_h)\right]$$

$$\hat{a}_\rho^2 \equiv \frac{3}{4} a_\rho^2$$

Sum Rule: $a_h^2 + \frac{3}{4} a_\rho^2 = 1$

Log growth remains

We limit m_ρ by requiring perturbative scattering up to a few TeV (LHC unitarity)

include inelastic channels

Parameters

Unitarity sum-rule fixes a_ρ in terms of a_h

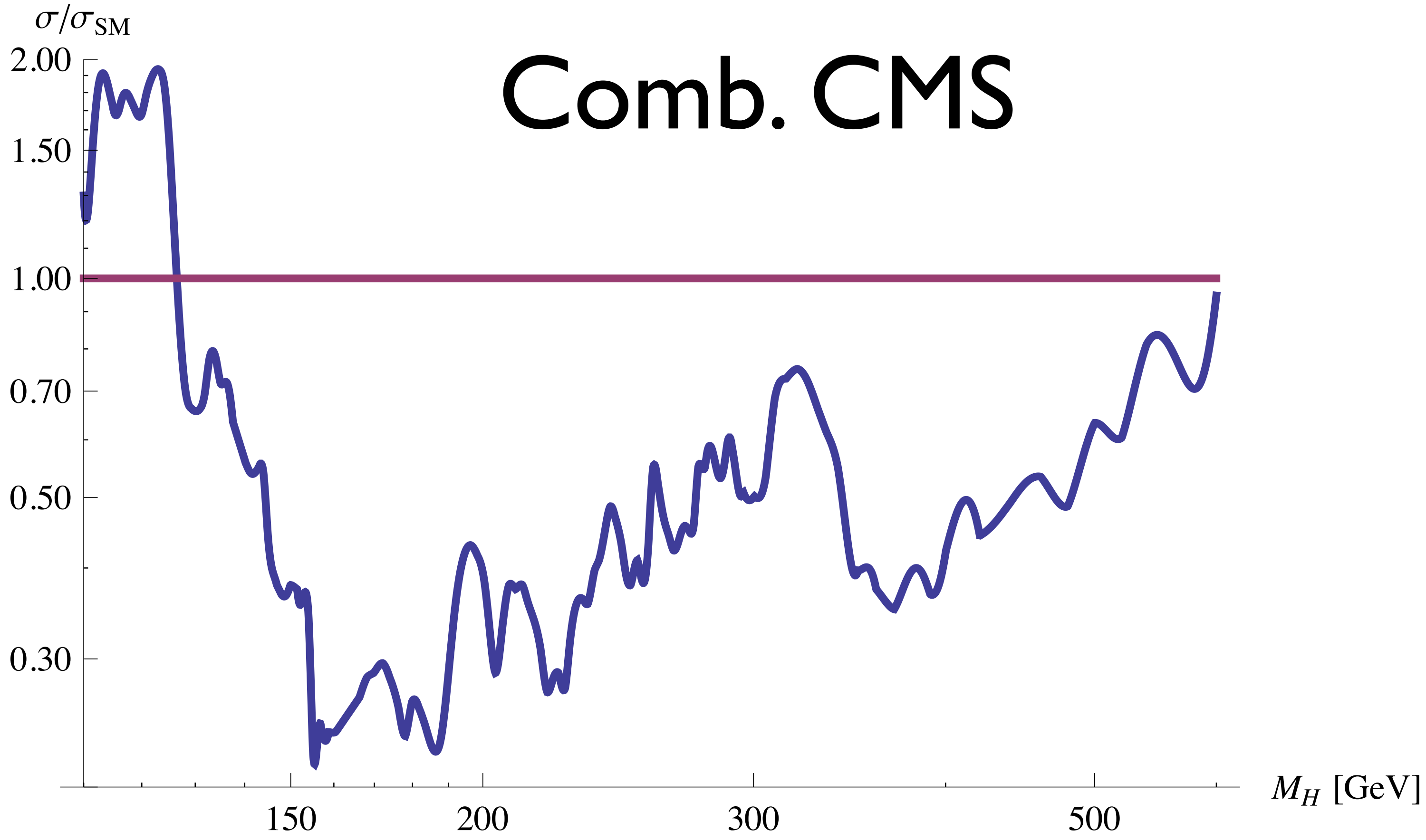
VB Mass matrix set by g_ρ, a_ρ, and f=246 GeV

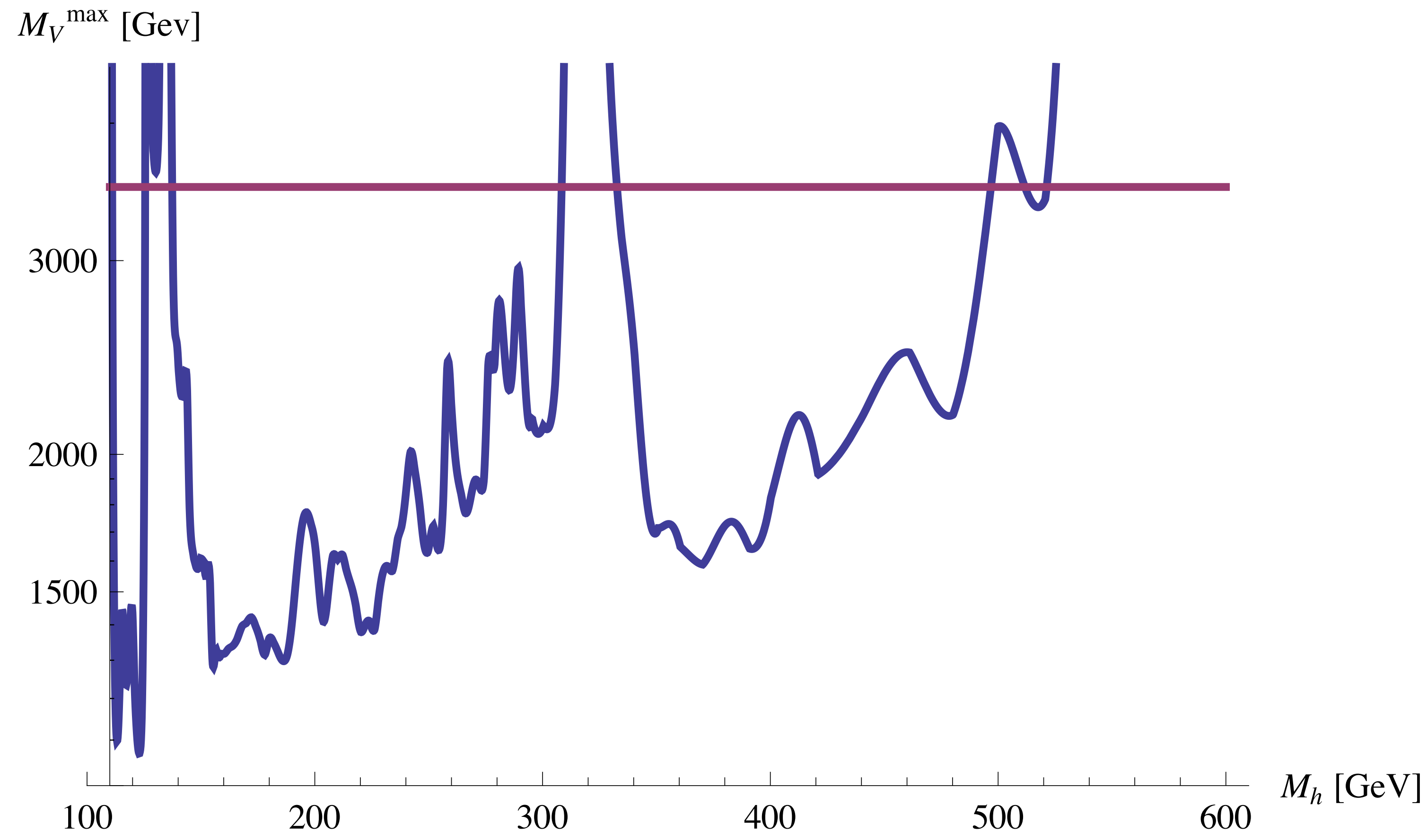
Mixing with SM gauge fields determines most interesting phenomenology

effectively have a 2-parameter model

We parameterize in terms of a_h and m_ρ

Turn that Higgs bound up-side down!





Exercise:
Higgs is at mass m_H, but with suppressed overall couplings

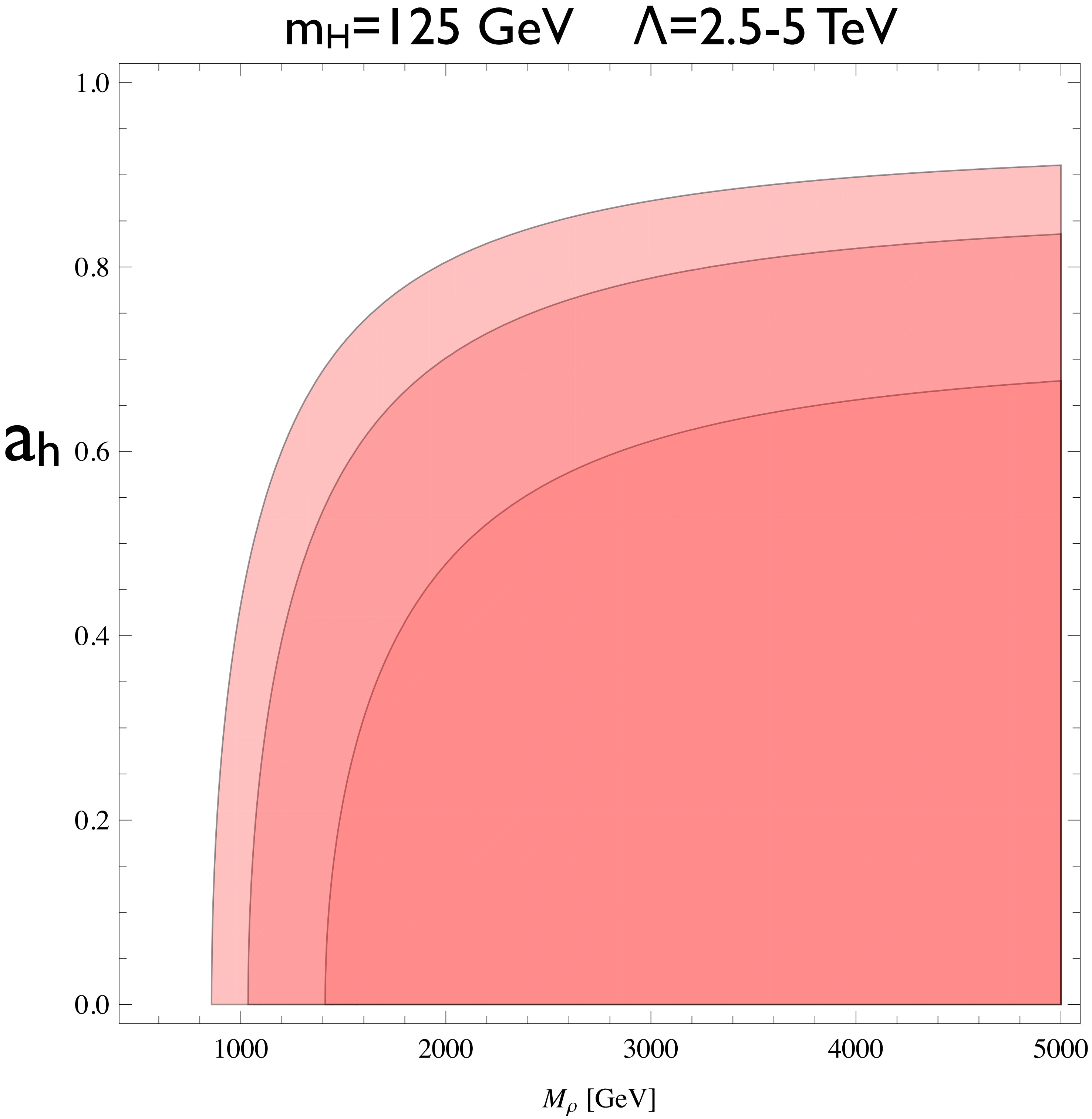
Saturate s-growth sum-rule

What is max allowed ρ mass?

The unitarity constraint

Pink regions forbidden for different values of effective cutoff

As Higgs couplings reduced, ρ's must come in earlier to unitarize scattering



Vector Production

- Vector Boson Fusion
  - Pro: model independent (unitarity)
  - Con: cross section small, signal challenging
- Drell-Yan
  - most models have mixing with SM W's, Z
  - coupling to light quarks (but small)
  - Pro: potentially large (enough) σ
  - Con: model dependent production

Vector decays

- The ρ’s are composite strongly interacting states
  - prefer to decay to other composites
  - massive degrees of freedom typically have larger degrees of compositeness

$$
\begin{array}{lll}
\rho^0 & \rightarrow & W^+W^- \\
 & \rightarrow & \bar{t}t \\
 & \rightarrow & \bar{b}b
\end{array}
\qquad\qquad
\begin{array}{lll}
\rho^\pm & \rightarrow & W^\pm Z \\
 & \rightarrow & \bar{b}t(\bar{t}b) \\
 & &
\end{array}
$$

decays to light fermions typically suppressed

decays to 3rd gen fermions present challenging final states

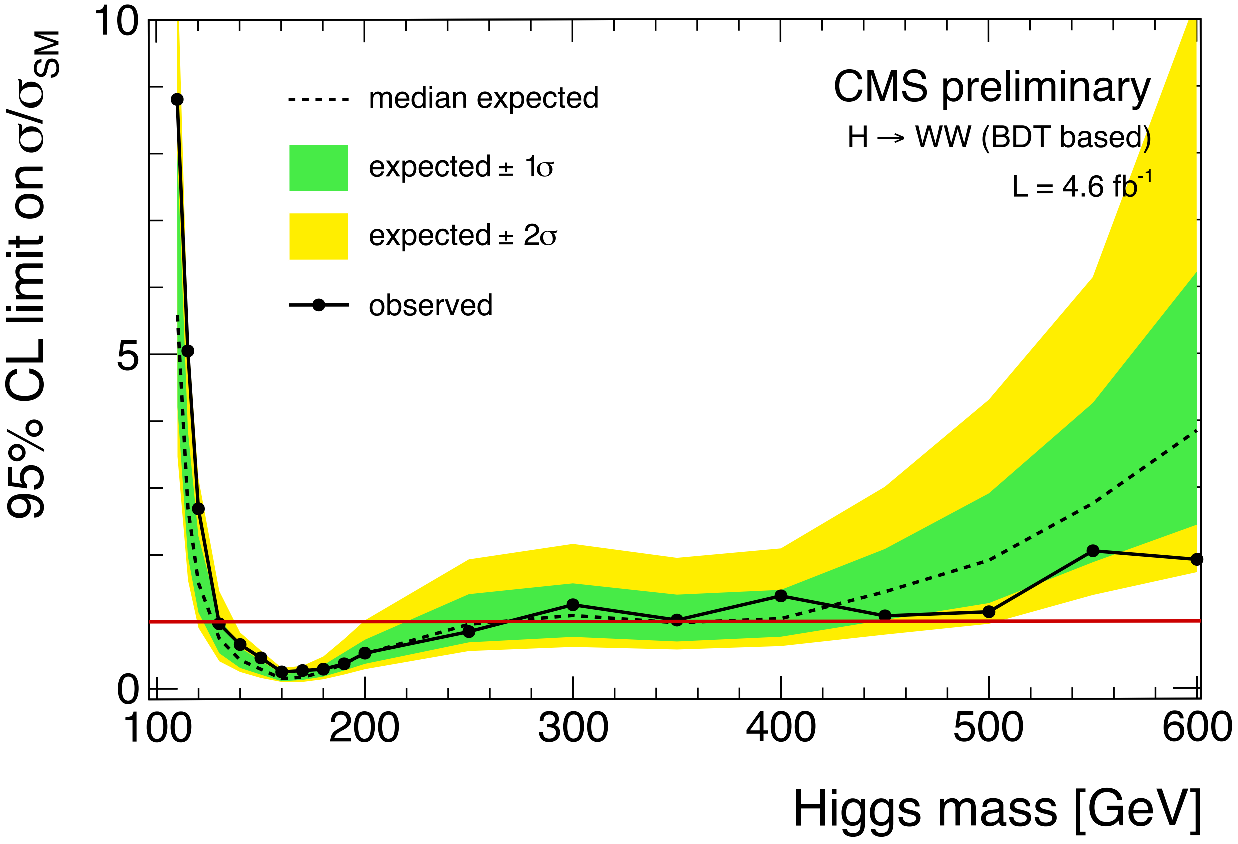
resonances in di-boson spectrum (leptonic) best bet

Direct Bounds on new resonances

Higgs search

$\rho^0 \to W^+W^-$

lνlν



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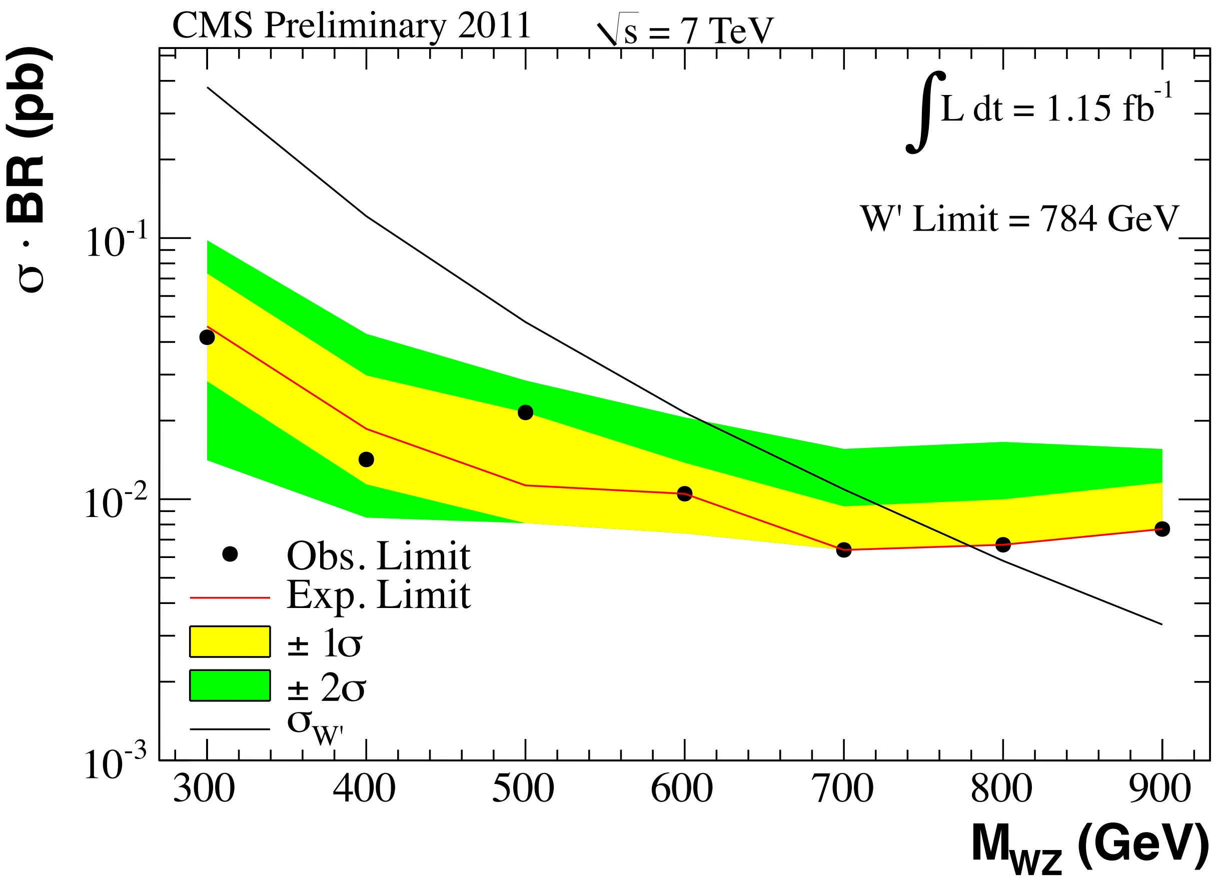
Dedicated di-boson

$\rho^\pm \to W^\pm Z$

3l+ν



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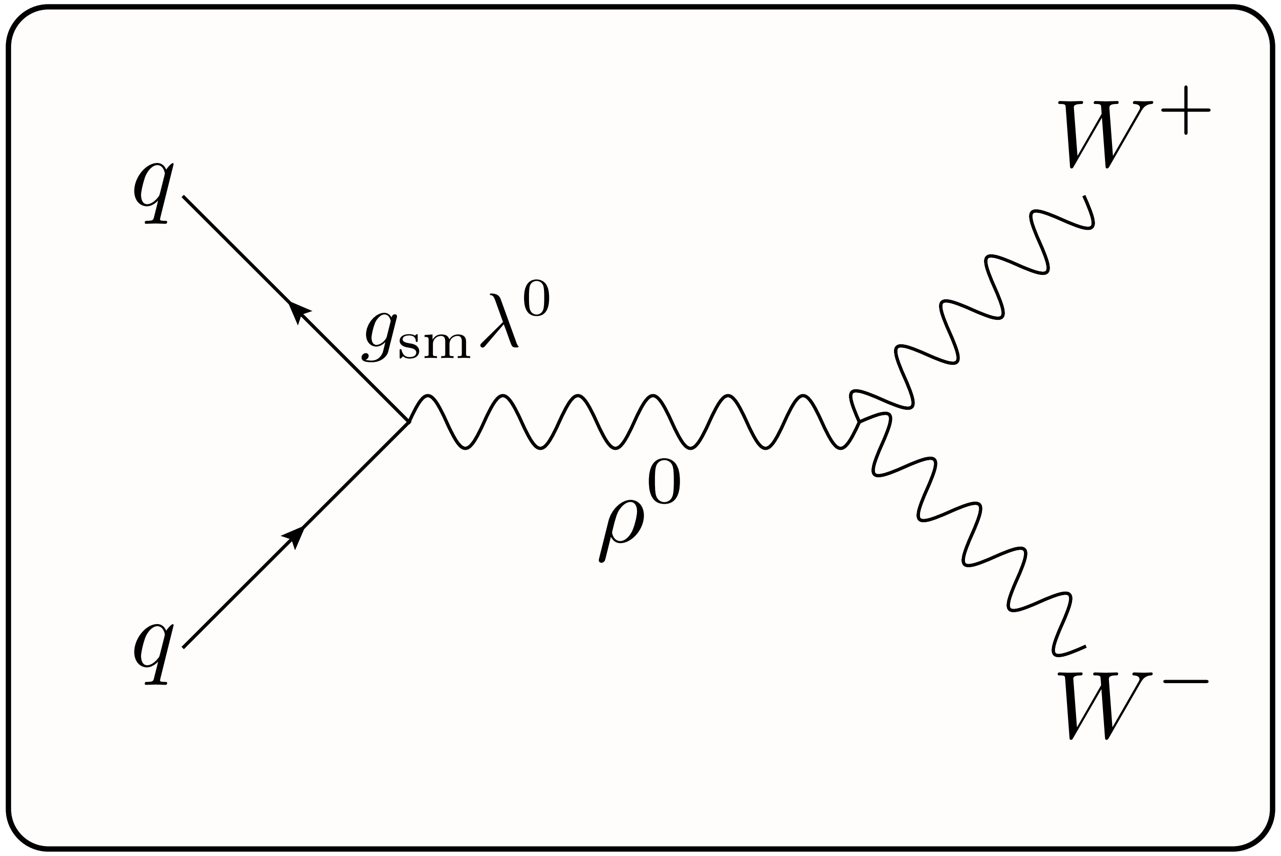
Modeling the ρ^0

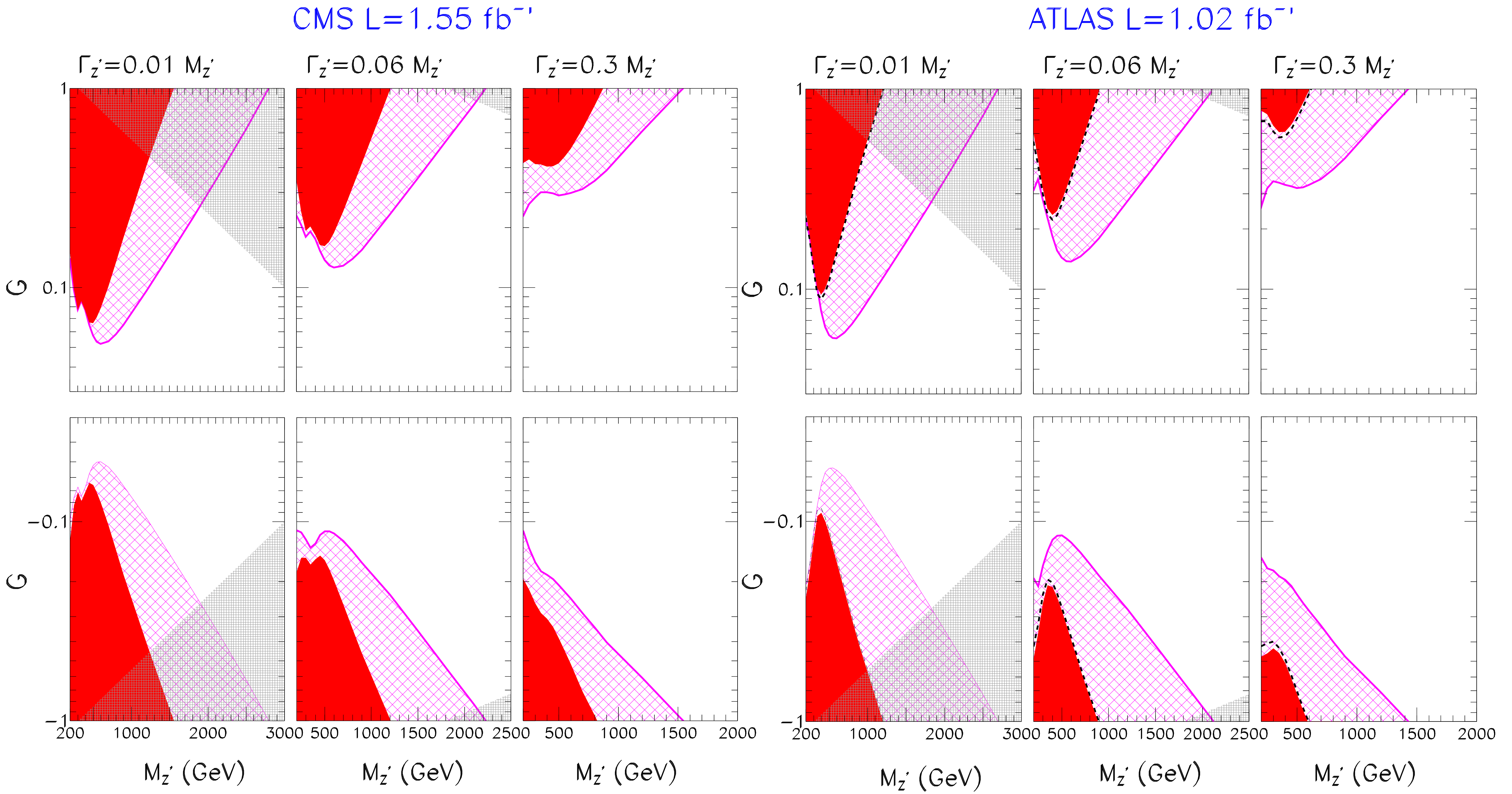


Z' with suppressed coupling to light quarks

High mass Higgs search restricts values of λ^2 Br($\rho^0 \rightarrow WW$)

Seems hard - Higgs search is very optimized for SM

Recent Bounds on Z' bosons

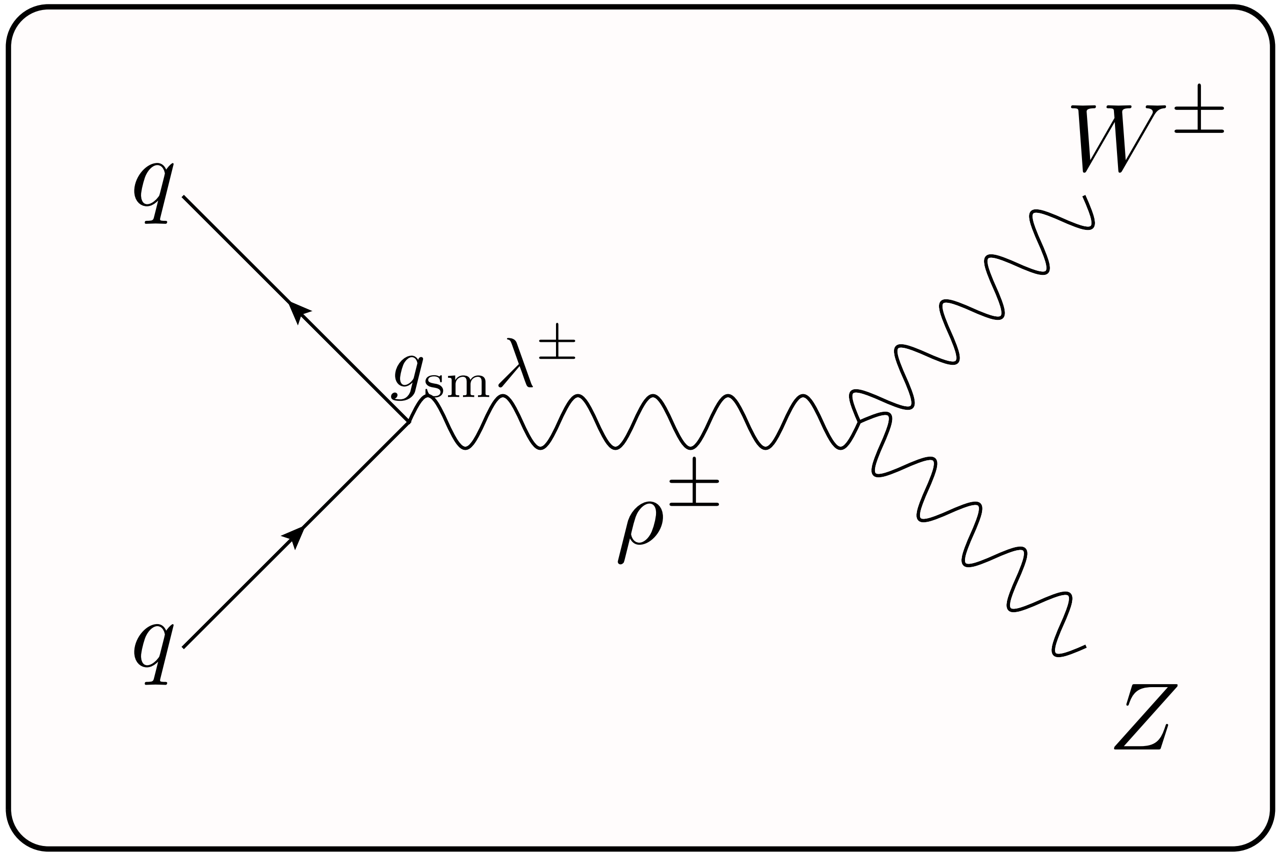


$$G = \left(\frac{g_{Z'q\bar{q}}}{g_{Zq\bar{q}}}\right)\left(\frac{g_{Z'WW}}{g_{Z'WW\,max}}\right)$$

O.J.P. Eboli, J. Gonzalez-Fraile, M.C. Gonzalez-Garcia.

Really requires dedicated di-boson resonance search

Modeling charged ρ’s

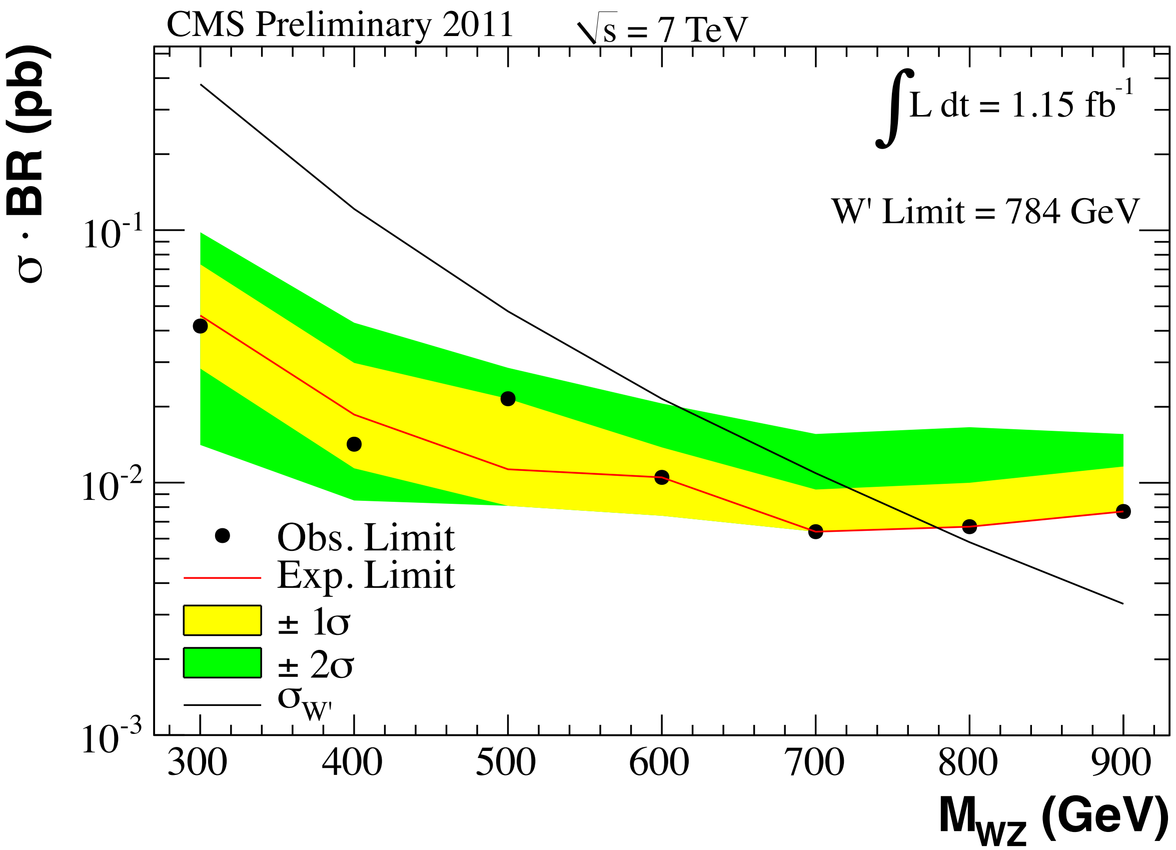


W’ with suppressed coupling to fermions

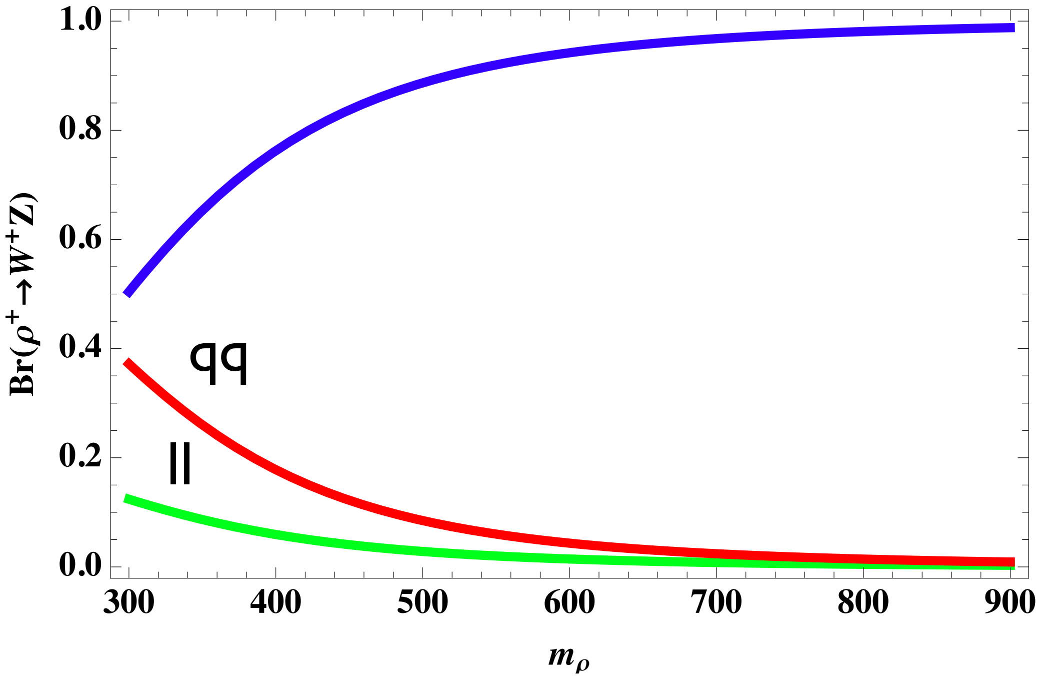
Search for W’/techni-rho limits λ^2 Br($\rho^0 \rightarrow WW$)

Limits on charged ρ's

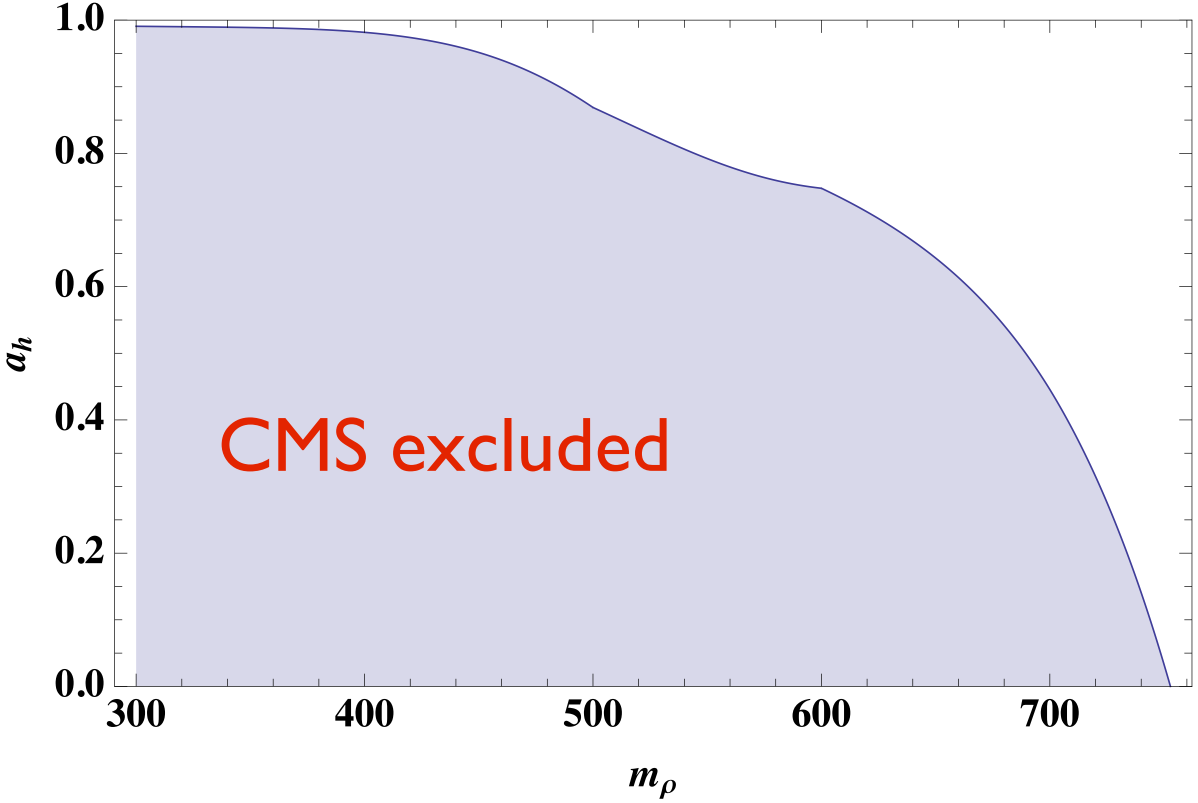
Implemented model in Madgraph



Calculate σ*Br in terms of a_h and m_ρ



mixing (coupling to quarks) increases with a_ρ

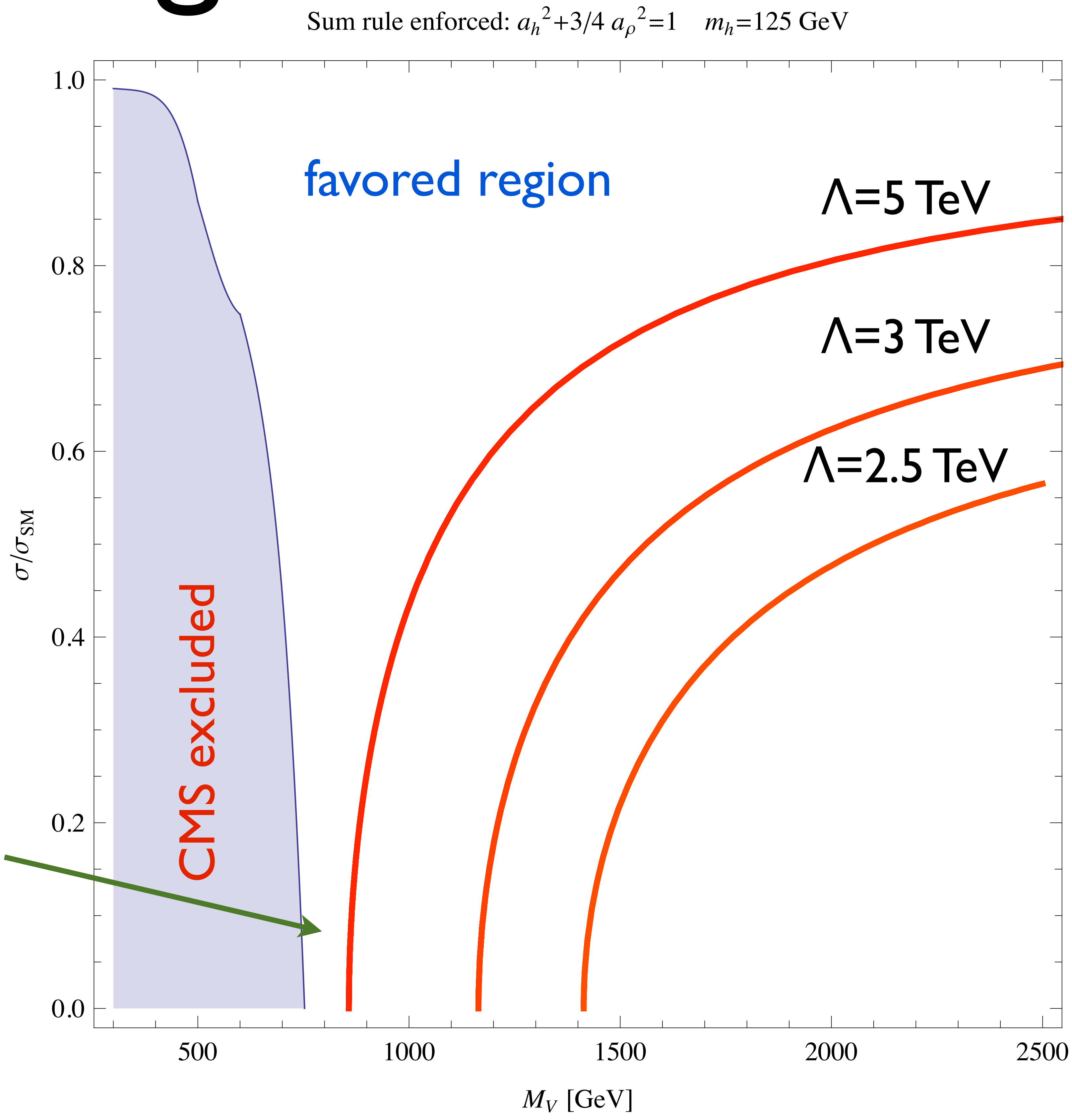


Combining limits

Direct limits from below

Theory limits from above

Rather tight for gaugephobic scenarios



Higgs to γγ in composite models

- Higgs couplings in composite models are modified

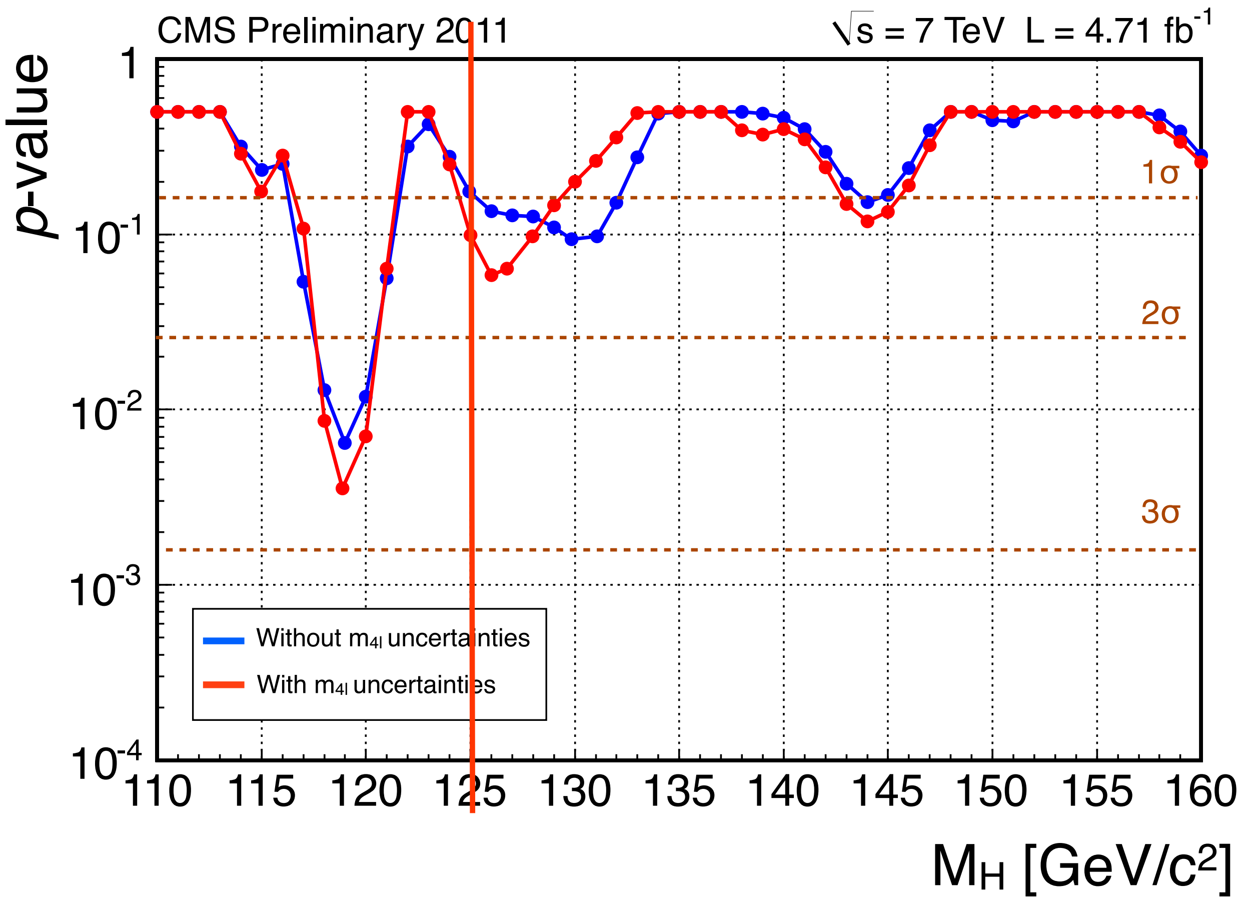
$$\lambda_i = \lambda_i^{\mathrm{SM}} \left(1 + c \left(\frac{v}{f} \right)^2 \right)$$

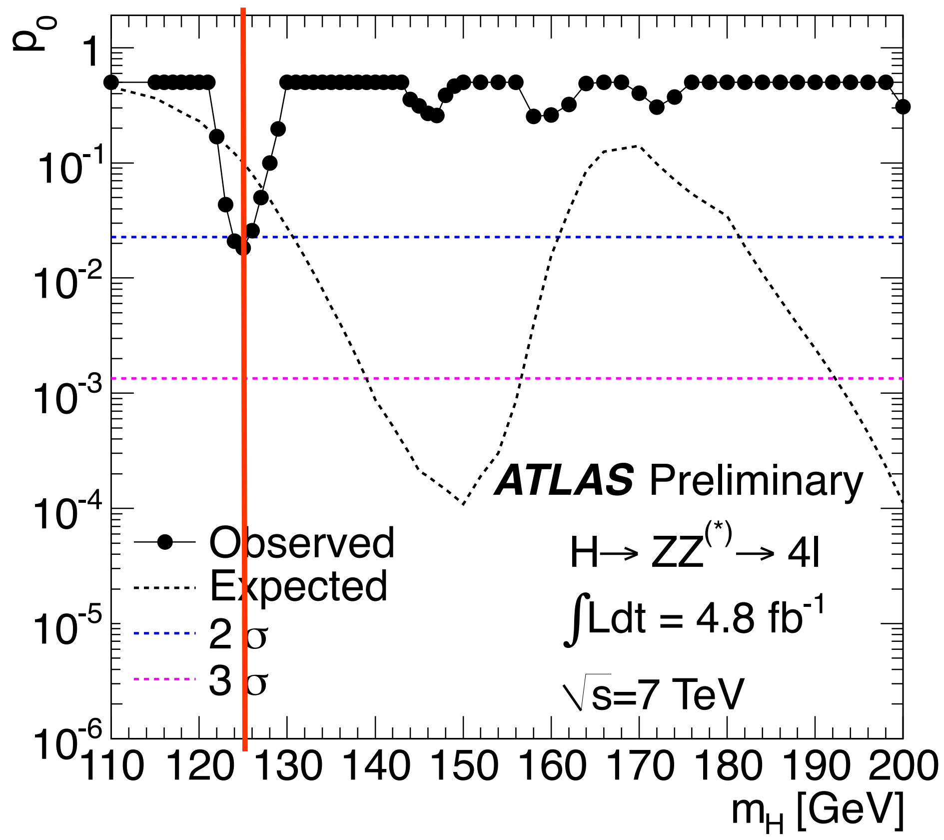
- f is related to scale of compositeness
  - decay constant in higgs as PGB
- Of primary interest are hWW, htt, hbb couplings

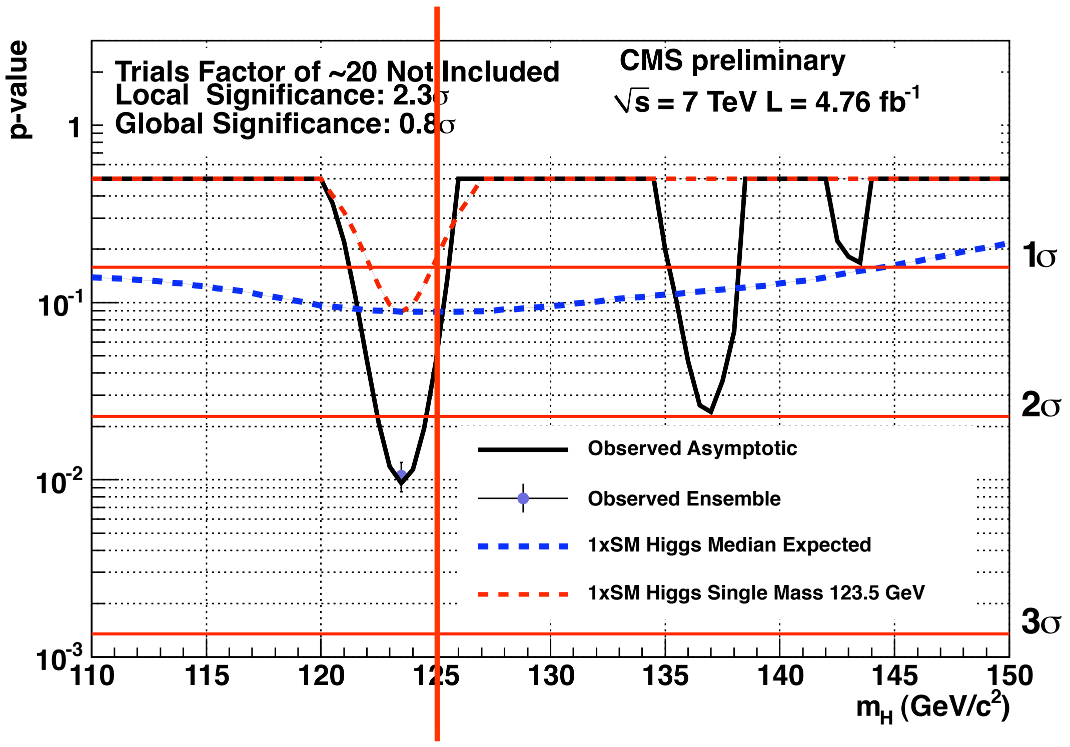
Unitarity arguments

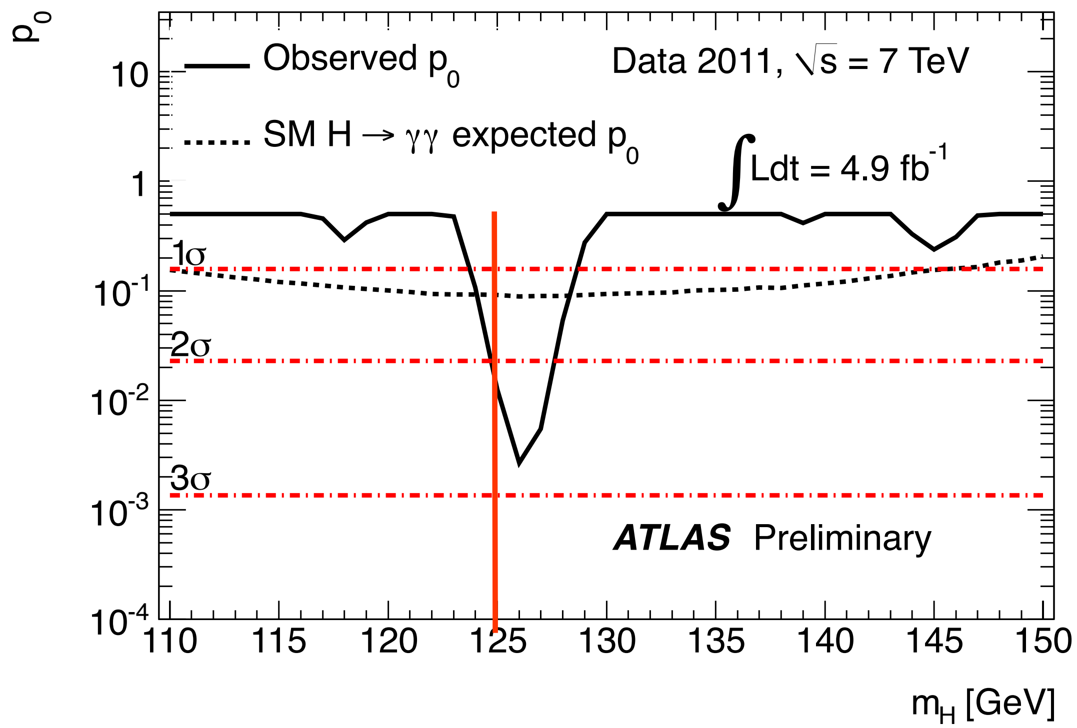
- in composite models, higgs couplings are generally <u>suppressed</u>
  - otherwise sum rules supersaturated
  - hard to get negative contribution
    - exception: Falkowski, Rychkov, Urbano (2012)
  - best bet for increase in signal is decrease in hbb coupling, or new charged fields

Big Higgs









getting lucky, or σ x Br is about 2 x SM

Enhancement in γγ

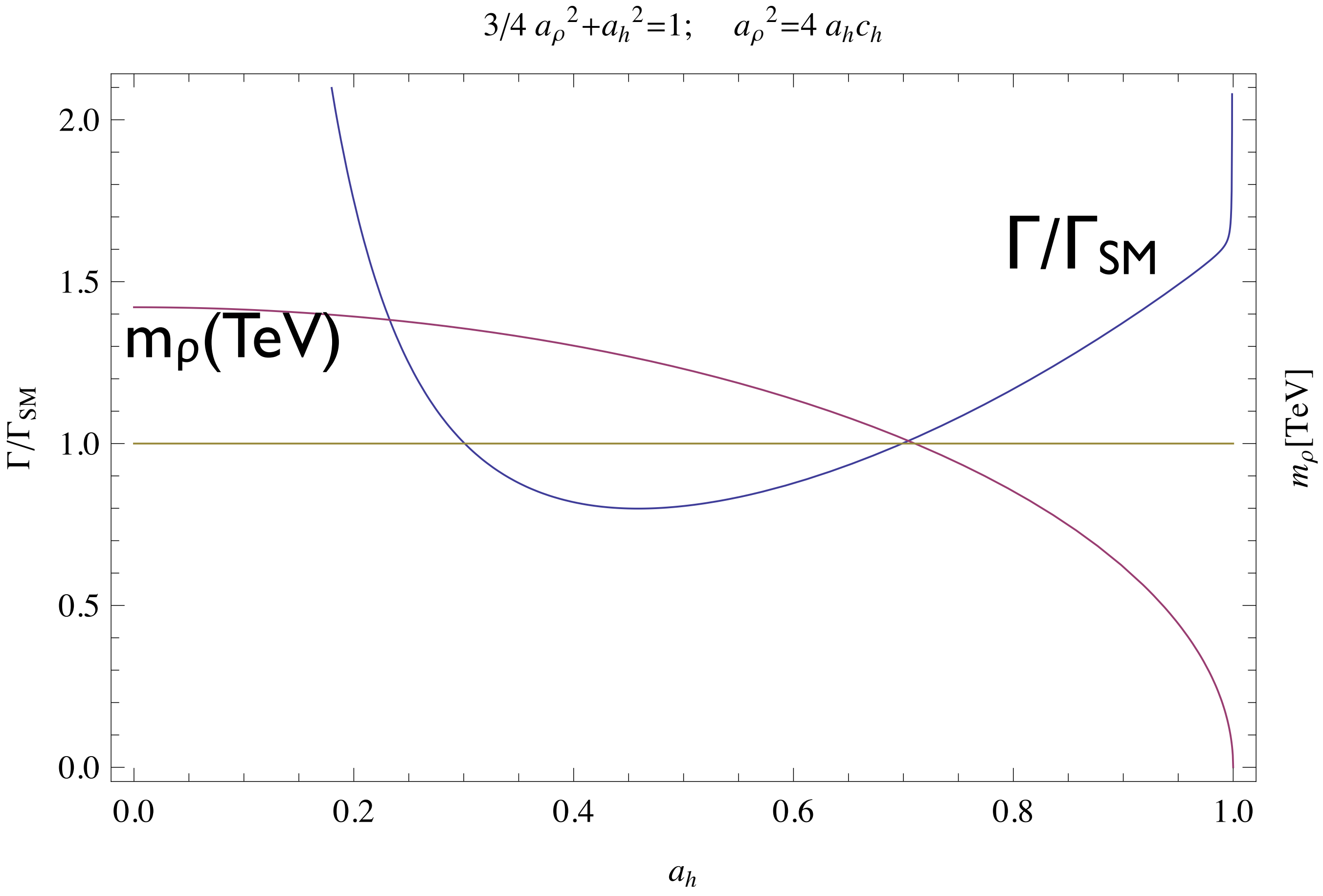
- Charged ρ’s may contribute in hγγ triangle

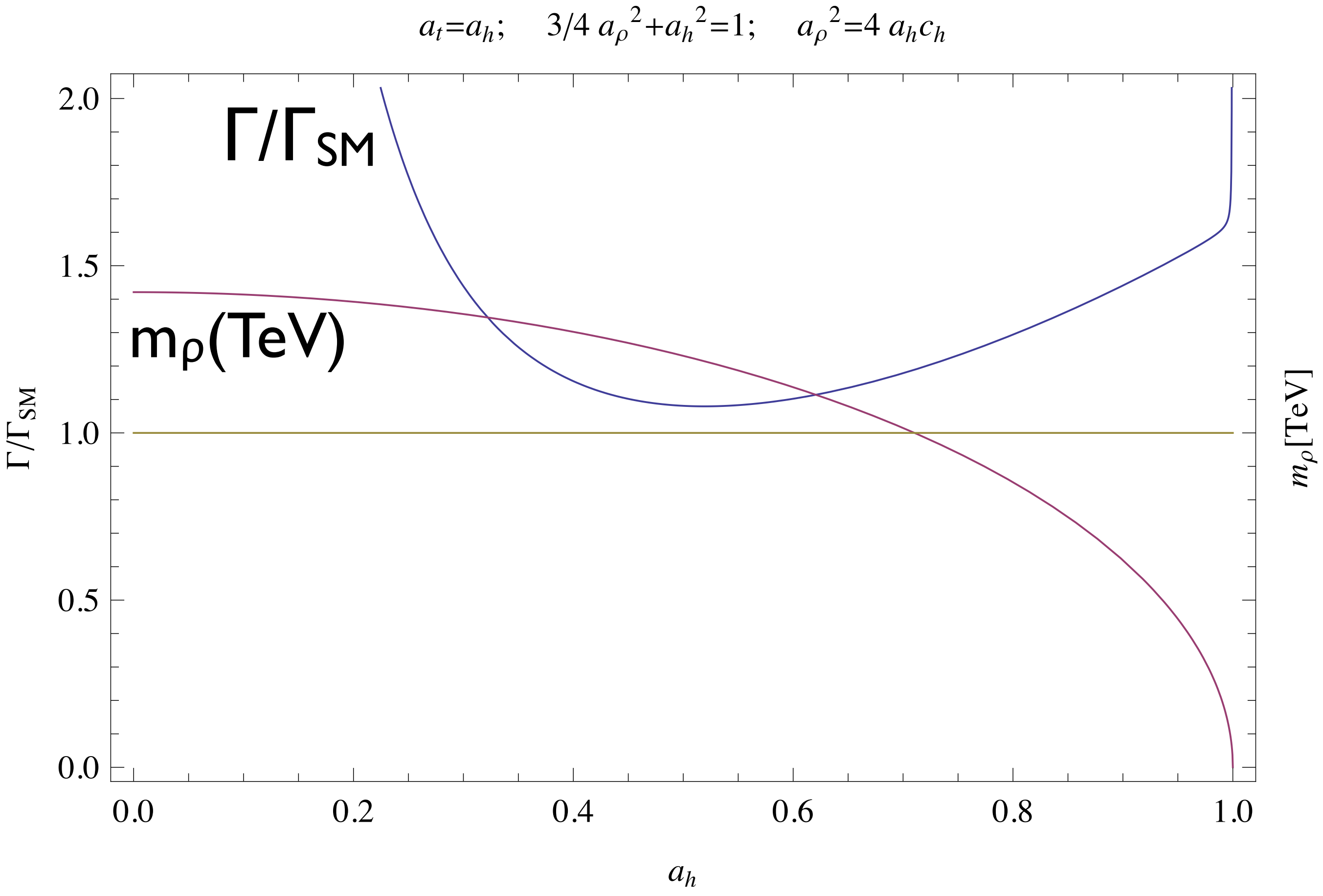
$$\begin{aligned}\mathcal{L} &= \frac{v^2}{2}(\Pi^{\hat{a}}_\mu)^2 - \frac{1}{4}(\rho^a_{\mu\nu})^2 + a_\rho^2\frac{v^2}{2}\left(g_\rho\rho^a_\mu - E^a_\mu\right)^2 \\ &+ \frac{1}{2}(\partial_\mu h)^2 + V(h) + \frac{v^2}{2}\left(2a_h\frac{h}{v} + b_h\frac{h^2}{v^2}\right)(\Pi^{\hat{a}}_\mu)^2 + \frac{v^2}{2}\left(\boxed{2c_h\frac{h}{v}} + d_h\frac{h^2}{v^2}\right)\left(g_\rho\rho^a_\mu - E^a_\mu\right)^2 \\ &+ O(p^4)\end{aligned}$$

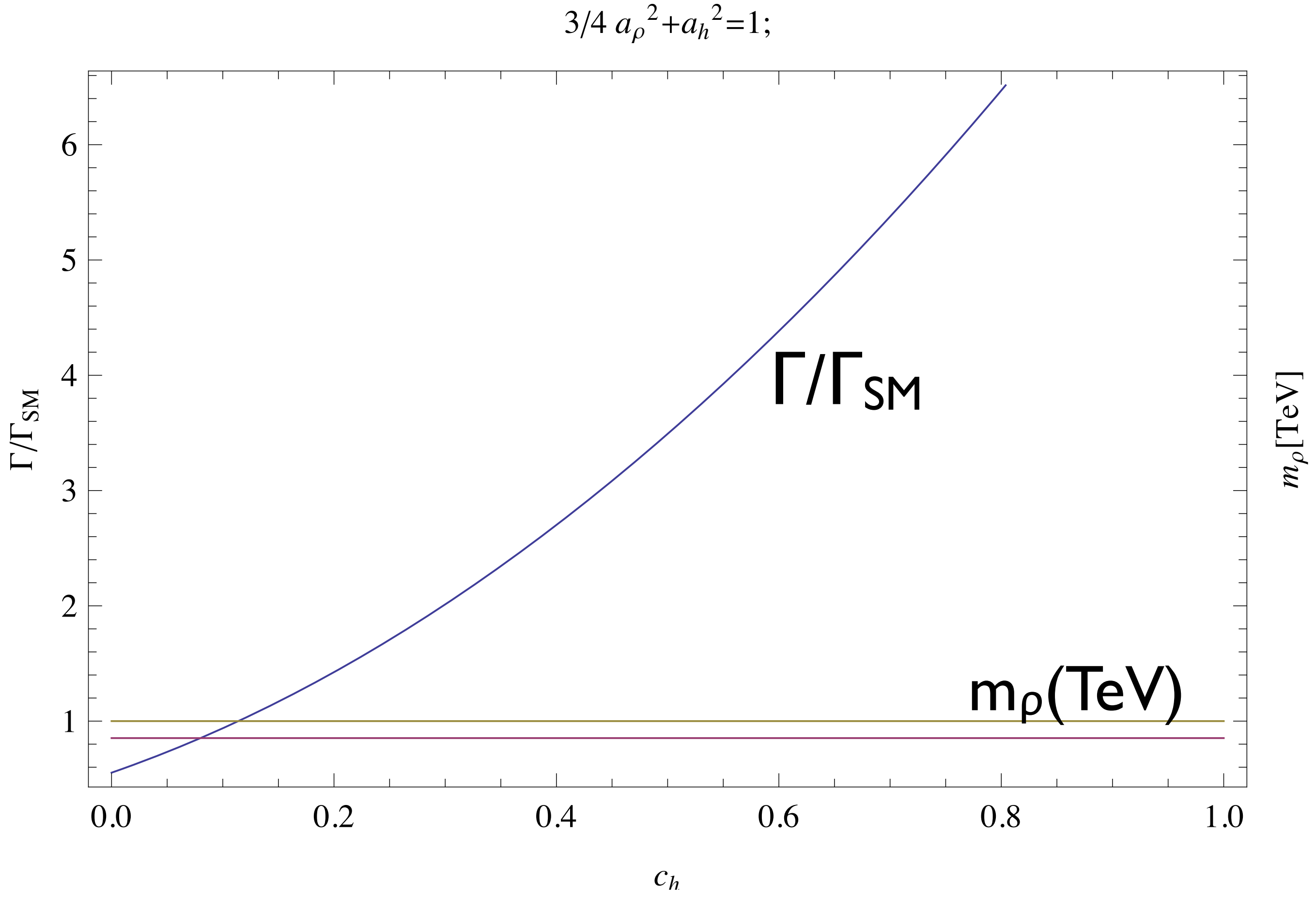
This coupling is arb. from perspective of low energy EFT

Vanishes in Higgs as PGB

Can compensate for reduction in gg coupling common in composite models







Can obtain enhancements in the h→γγ signal

Conclusions

- A simplified model approach to Higgs compositeness - new VB's in representation of SU(2)$_C$
- new vector masses bounded from above (unitarity) and below (LHC)
- Can manage increase in h signal, even with suppressed couplings (new triangle diagrams)
- Upcoming experimental searches for di-boson resonances will be extremely valuable