EWSB beyond SUSY

LHC Physics Discussions

~~5/9/2011~~ 19/9/2011

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Main Goal of the LHC

Understanding the theory of the weak scale.

Finding the mechanism that unitarizes $W_L W_L$ scattering.

This often (but not always!) means finding a Higgs-like particle.

SM predictive f(m_H), but naturalness requires new physics and new (heavy?) particles.

⇒ Impact Higgs on phenomenology!

EWSB

- o Weak interactions are gauge interactions ⇒ symmetry
- o Weak interactions are short range ⇒ symmetry broken
- o What's the symmetry? At least $SU(2)_L \times U(1)_Y \to U(1)_{em}$
- o Precise features $m_Z/m_W \cos\theta_W \simeq 1 \Rightarrow T \sim 0$

$$\frac{v^2}{\Lambda^2} Z_{\mu\nu} F^{\mu\nu} \Rightarrow S \sim 0$$

The Physics discovered so far

$$\mathcal{L}_{SM} = \mathcal{L}_0 + \mathcal{L}_{mass}$$

$$\mathcal{L}_0 = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\,\mu\nu} - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \sum_{j=1}^{3}\left(\bar{\Psi}_L^{(j)} i \not{D} \Psi_L^{(j)} + \bar{\Psi}_R^{(j)} i \not{D} \Psi_R^{(j)}\right)$$

$$\begin{aligned}\mathcal{L}_{mass} =& M_W^2\, W_\mu^+ W^{-\,\mu} + \frac{1}{2}M_Z^2\, Z^\mu Z_\mu \\ & - \sum_{i,j}\left\{\bar{u}_L^{(i)} M_{ij}^u u_R^{(j)} + \bar{d}_L^{(i)} M_{ij}^d d_R^{(j)} + \bar{e}_L^{(i)} M_{ij}^e e_R^{(j)} + \bar{\nu}_L^{(i)} M_{ij}^\nu \nu_R^{(j)} + h.c.\right\}\end{aligned}$$

The Physics discovered so far

$$\mathcal{L}_{SM} = \mathcal{L}_0 + \mathcal{L}_{mass}$$

$SU(2)_L x U(1)_Y$ gauge invariant

$$\mathcal{L}_0 = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\,\mu\nu} - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \sum_{j=1}^{3}\left(\bar{\Psi}_L^{(j)} i \not{D} \Psi_L^{(j)} + \bar{\Psi}_R^{(j)} i \not{D} \Psi_R^{(j)}\right)$$

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$$\mathcal{L}_{mass} = M_W^2\, W_\mu^+ W^{-\,\mu} + \frac{1}{2}M_Z^2\, Z^\mu Z_\mu$$

$$- \sum_{i,j}\left\{\bar{u}_L^{(i)} M_{ij}^u u_R^{(j)} + \bar{d}_L^{(i)} M_{ij}^d d_R^{(j)} + \bar{e}_L^{(i)} M_{ij}^e e_R^{(j)} + \bar{\nu}_L^{(i)} M_{ij}^\nu \nu_R^{(j)} + h.c.\right\}$$

only $U(1)_{em}$ gauge invariant

Hidden symmetry

Introduce goldstone bosons Σ of SSB:

$$\Sigma = \exp\left(i\sigma^a \chi^a / v\right)$$

$$D_\mu \Sigma = \partial_\mu \Sigma - i g_2 \frac{\sigma^a}{2} W_\mu^a \Sigma + i g_1 \Sigma \frac{\sigma_3}{2} B_\mu$$

$$\mathcal{L}_{mass} = \frac{v^2}{4} \mathrm{Tr}\left[\left(D_\mu \Sigma\right)^\dagger \left(D^\mu \Sigma\right)\right] - \frac{v}{\sqrt{2}} \sum_{i,j} \left(\bar{u}_L^{(i)}\ \bar{d}_L^{(i)}\right) \Sigma \begin{pmatrix} \lambda_{ij}^u u_R^{(j)} \\ \lambda_{ij}^d d_R^{(j)} \end{pmatrix} + h.c.$$

- The $SU(2)_L x U(1)_Y$ symmetry is now manifest (and non-linearly realized)

$$\Sigma \to U_L\, \Sigma\, U_Y^\dagger \qquad U_L(x) = \exp(i\, \alpha_L^a(x) \sigma^a / 2) \quad U_Y(x) = \exp(i\, \alpha_Y(x) \sigma^3 / 2)$$

- In the unitary gauge $\langle \Sigma \rangle = 1$, $\mathcal{L}_{mass}$ is equal to the original mass Lagrangian with

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1$$

General Lagrangian with spontaneous symmetry breaking and a scalar

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}m_h^2 h^2 + d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + \ldots$$

$$+ \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \cdots\right)$$

$$- \frac{v}{\sqrt{2}}\sum_{i,j}\left(u_L^{(i)}\ d_L^{(i)}\right)\Sigma\left(1 + c\,\frac{h}{v} + c_2\,\frac{h^2}{v^2} + \cdots\right)\begin{pmatrix}\lambda_{ij}^u\, u_R^{(j)} \\ \lambda_{ij}^d\, d_R^{(j)}\end{pmatrix} + h.c.$$

Goldstone bosons giving mass to *W,Z*

General Lagrangian with spontaneous symmetry breaking and a scalar

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}m_h^2 h^2 + d_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 + \ldots$$

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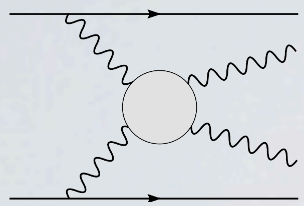
$$- \frac{v}{\sqrt{2}}\sum_{i,j}\left(u_L^{(i)}\ d_L^{(i)}\right)\Sigma\left(1 + c\frac{h}{v} + c_2\frac{h^2}{v^2} + \cdots\right)\begin{pmatrix}\lambda_{ij}^u\, u_R^{(j)} \\ \lambda_{ij}^d\, d_R^{(j)}\end{pmatrix} + h.c.$$

a, b, c, c_2, d_3 free parameters

[for a SM Higgs: a=b=c=d_3=1 ; c_2=0]

The value of a, b, c, c_2 sets the scale of strong interactions:



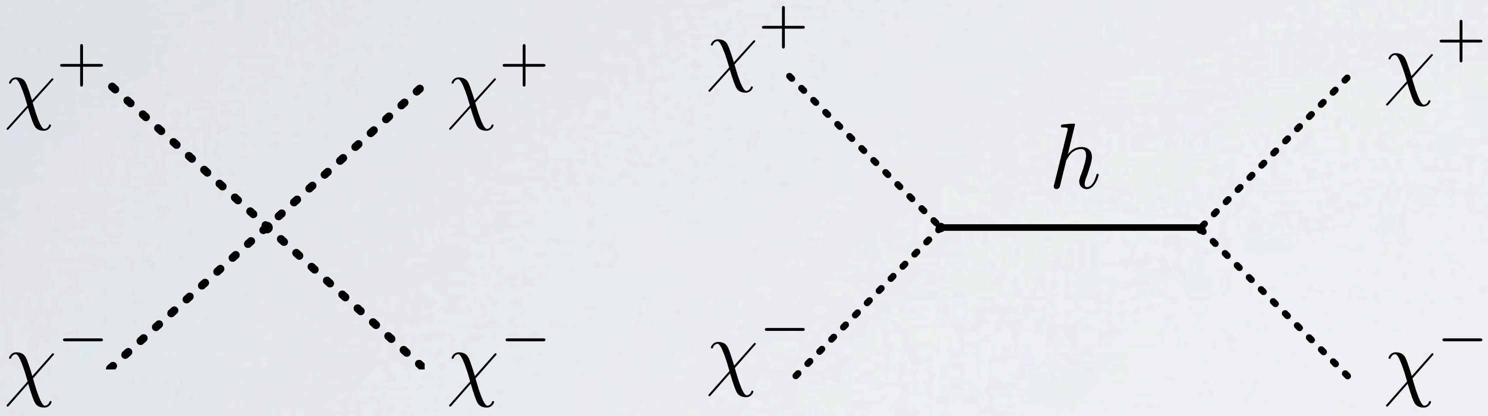
$W_L W_L \to W_L W_L$ scattering

Theory is weakly coupled to all scales only if

$a = b = c = 1,\ c_2 = 0$

= elementary SM Higgs

Elementary Higgs as UV moderator !



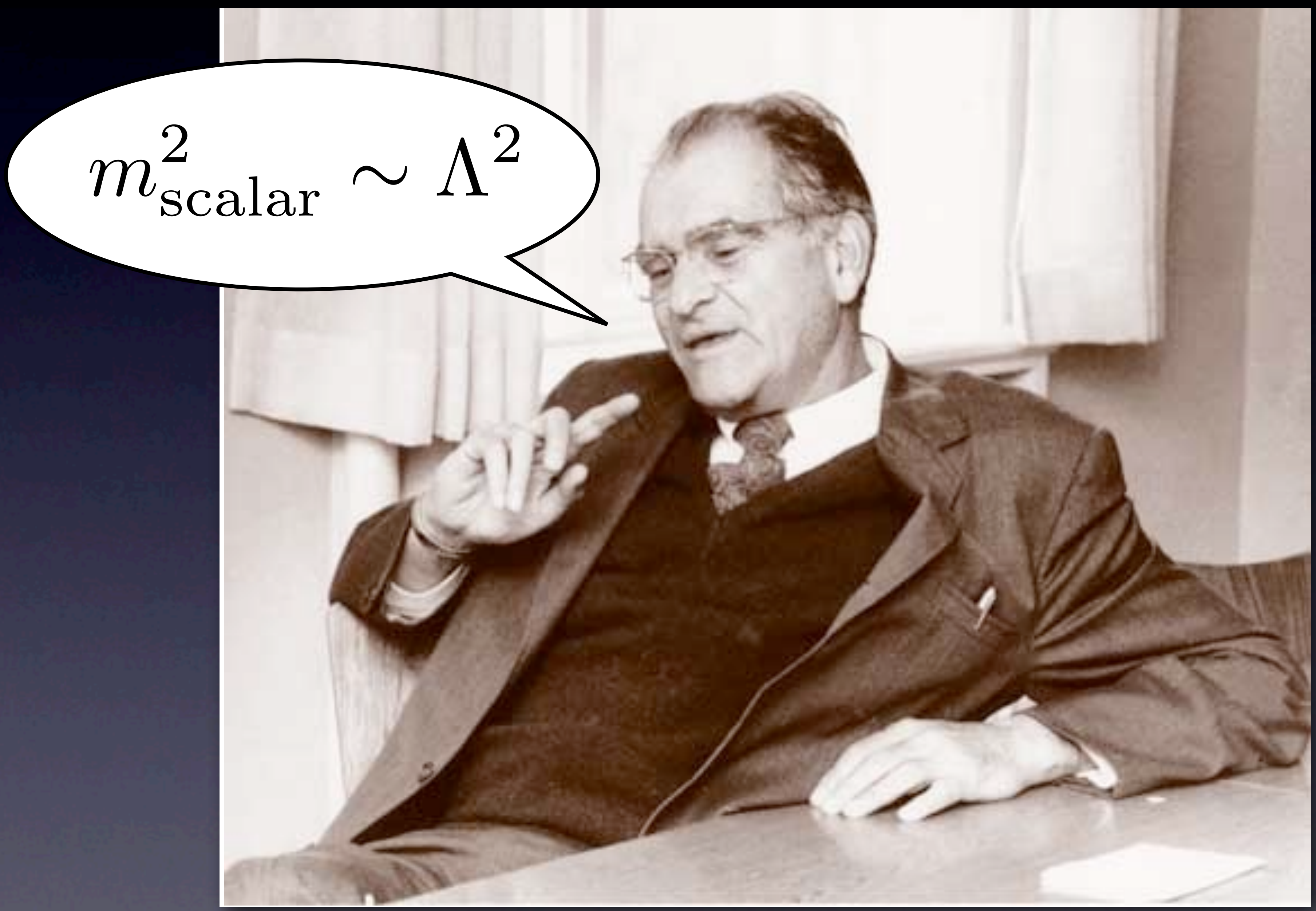
$$\mathcal{A} \simeq \frac{1}{v^2}\left[s - \frac{a^2 s^2}{s - m_h^2} + (s \leftrightarrow t)\right]$$

strong coupling scale

$$\Lambda_S \approx \frac{4\pi v}{\sqrt{1-a^2}}$$

"What's the problem?"

with an elementary Higgs

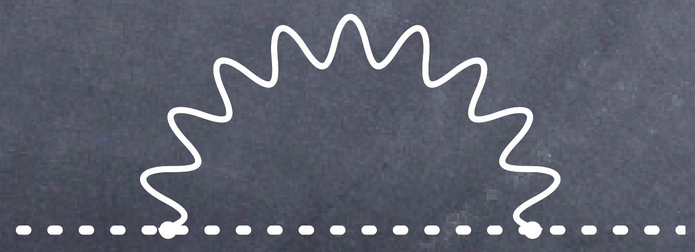


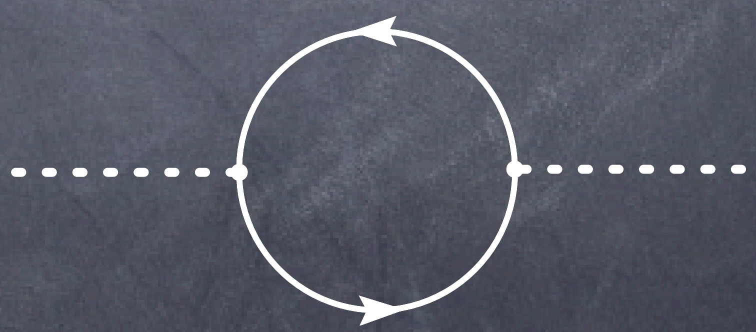
Weisskopf Phys. Rev.56 (1939) 72

Q: what is the nature of the Higgs boson ?

is it a fundamental (= elementary) scalar field ?

naively, if the Higgs boson is a fundamental scalar, the natural value of its mass is of the order of the largest scale in the theory : UV instability





$$\delta m_H^2 = \frac{3}{64\pi^2}(3g_2^2 + g_1^2)\Lambda^2$$

$$\delta m_H^2 = -\frac{3}{4\pi^2}\frac{m_t^2}{v^2}\Lambda^2$$

possibility #1: all the couplings of the theory remain weak up to the Planck scale and the Higgs is an elementary scalar (perturbative case)

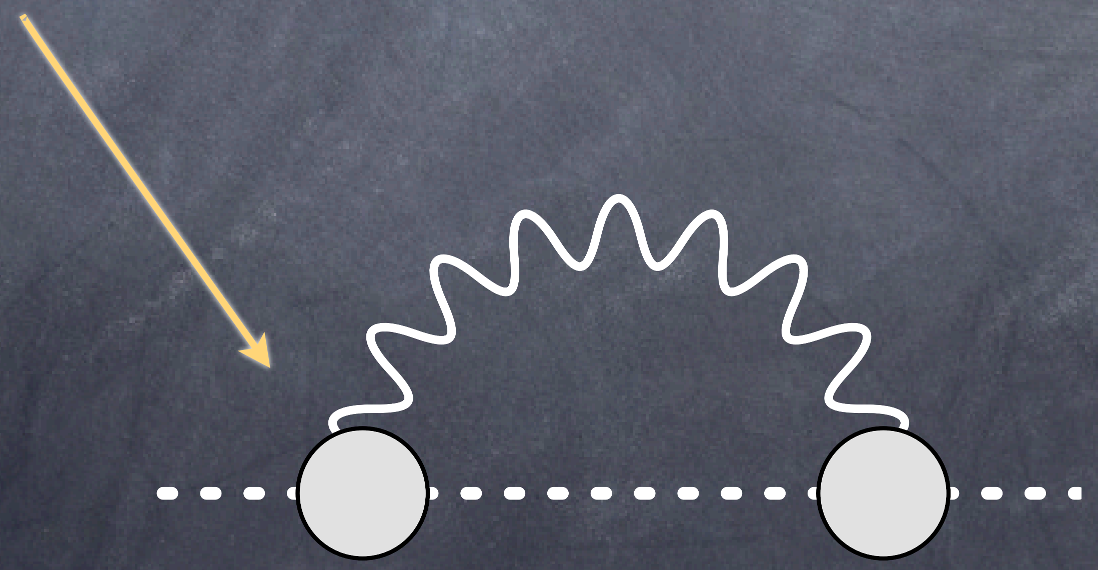
then there must be a symmetry protection (and new particles) which ensures a light Higgs

example: → SuperSymmetry

SM + sSM = no UV instability !

possibility #2: (a subsector of) the theory becomes strongly interacting at a scale Λ and the Higgs is a composite bound state (strongly-interacting case)

for virtual momenta larger than the compositeness scale the Higgs couplings switch off (form factors)



= finite

★ **Problem:** the other resonances of the strongly-interacting sector cannot be too light in order not to spoil the success of EW precision tests:

$$m \sim \Lambda \gtrsim \text{a few TeV}$$

Q: can be the composite Higgs be naturally lighter than the other resonances ?

☞ yes, if it is a (pseudo) Goldstone boson

An example from QCD: the Pion

- strongly interacting sector = QCD

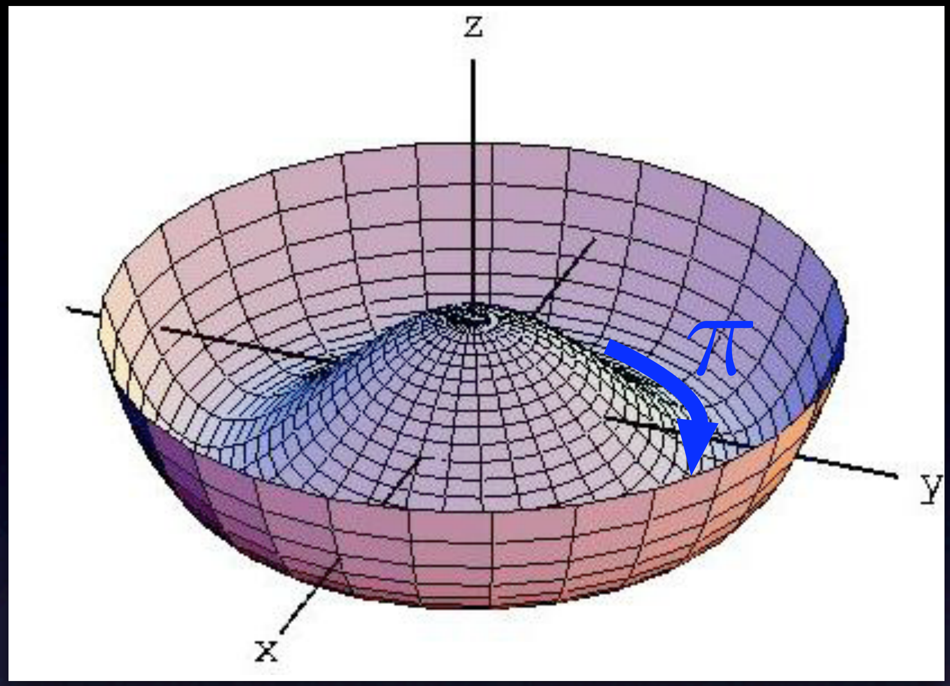
- the pion is a quark-antiquark bound state

- QCD has other resonances, with m~1 GeV

  ex: the ρ, $m_\rho = 770$ MeV

- the pion is lighter ($m_\pi = 135$ MeV): it is the Goldstone boson of chiral symmetry breaking

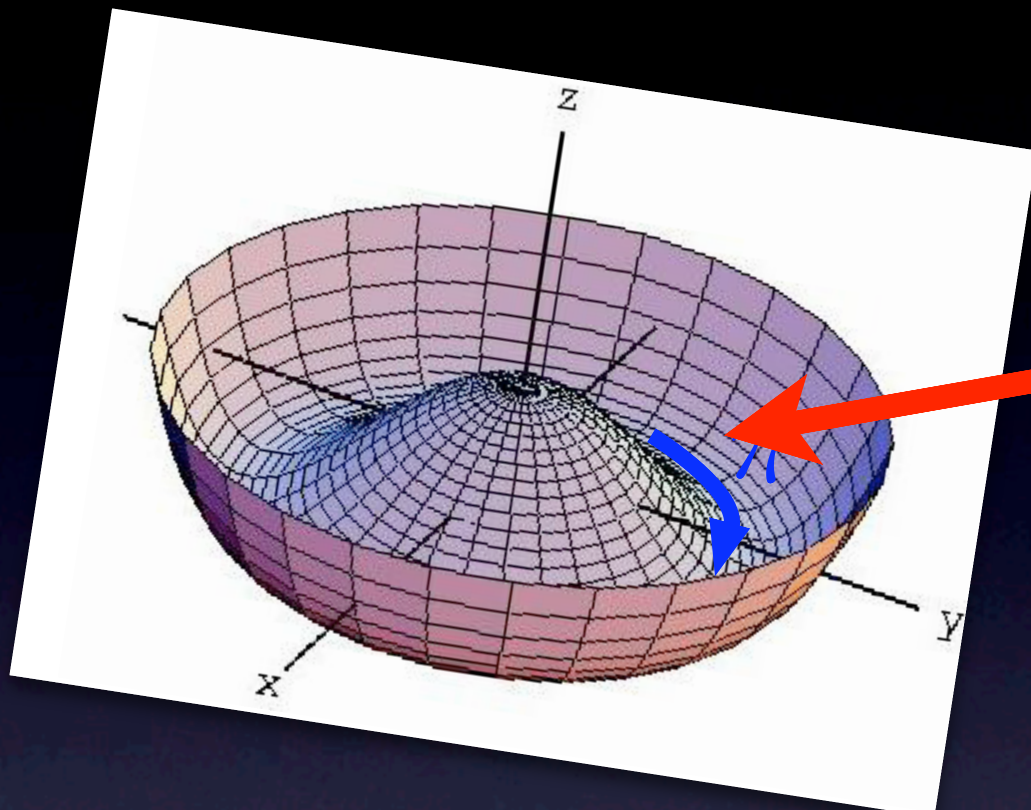
Inspired by QCD



mass protected by global symmetry

$$\pi \to \pi + \alpha$$

Inspired by QCD



Potential tilted:
due to quark masses
and gauging of EM

GB → *pGB*

$$m_{\pi^\pm}^2 \approx \frac{\alpha_{em}}{4\pi}\Lambda_{QCD}^2$$

Minimal Composite Higgs

Agashe, Contino, Pomarol

- $m_Z/m_W \cos\theta_W \simeq 1 \Rightarrow T \sim 0$
- Need custodial symmetry: replace $U(1)_Y$ by $SU(2)_R$
- $SU(2)_L \times SU(2)_R \rightarrow SU(2)_C$
- Need 'symmetry' for S-parameter: $SO(5) \rightarrow SO(4)$
- GBs: **4** $SO(4) = (2,2)$ of $SU(2)_L \times SU(2)_R$ like the Higgs !

Higgs potential finite & calculable eg. in holographic picture,

e.g. Oda, AW

$$v_{\rm eff}(\hat v) = I_{\rm IR} + \frac{I_{\rm UV}}{a^{4-\varepsilon}} + 2\int_0^\infty dx\, x^{3-\varepsilon} \log\Bigg[1 - \frac{1}{2}\left(\frac{K_0(x)I_0(ax)}{I_0(x)K_0(ax)} + \frac{K_1(x)I_1(ax)}{I_1(x)K_1(ax)} - \frac{K_0(x)I_1(ax)}{I_0(x)K_1(ax)} - \frac{K_1(x)I_0(ax)}{I_1(x)K_0(ax)}\right) + \frac{K_0(x)K_1(x)I_0(ax)I_1(ax)}{I_0(x)I_1(x)K_0(ax)K_1(ax)} - \frac{\cos\left(\frac{\hat v}{a^2}(1-a^2)\right)}{2ax^2 I_0(x)I_1(x)K_0(ax)K_1(ax)}\Bigg],$$

$$\simeq I_{\rm IR} + \frac{I_{\rm UV}}{a^{4-\varepsilon}} + 2\int_0^\infty dx\, x^{3-\varepsilon} \log\left[1 - \frac{I_0(x)K_1(x) - K_0(x)I_1(x) - \frac{1}{x}\cos\frac{\hat v}{a^2}}{2I_0(x)I_1(x)\left(\gamma + \log\frac{ax}{2}\right)}\right]$$

Flavor is almost ok

Csaki, Falkowski, AW

$$C_K^4 = -3\, C_K^5 \sim \frac{1}{M_G^2}\frac{g_{s*}^2}{g_*^2}\frac{8m_d m_s}{v^2}\frac{1+\tilde m^2}{\tilde m_d^2}$$

Some tension with CPV (see e.g. Redi, AW)

Minimal composite Higgs at the LHC

MCH @ LHC

(slides from Jose Ramon Espinosa's talk at CERN:
Implications of LHC results for TeV-scale physics)

EFFECTIVE LAGRANGIAN DESCRIPTION

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L}_{SILH} = \frac{c_H}{2f^2}\left(\partial_\mu |H|^2\right)^2 + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2 + \left(\frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + h.c.\right)$$
$$+ \frac{i c_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}^\mu H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i c_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(\partial^\nu B_{\mu\nu}\right) + \ldots$$

H of Goldstone origin:

$\mathcal{L}_{SILH}$ Non generic! ➔ More predictive

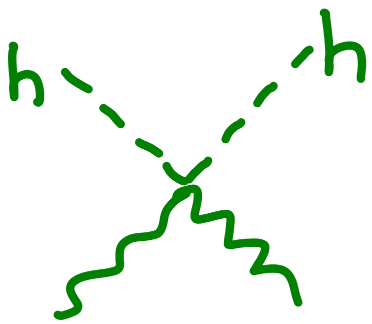
Relic effects from heavy strong sector, controlled by

$\xi \equiv \frac{v^2}{f^2}$ $\quad$ $\xi = 0 \Rightarrow$ SM $\quad$ $\xi = 1 \Rightarrow$ Technicolor limit

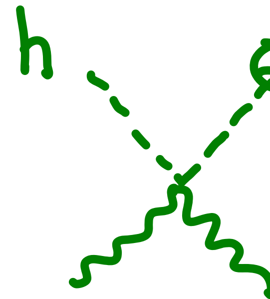
Electroweak precision tests prefer smaller ξ

ANOMALOUS HIGGS PROPERTIES

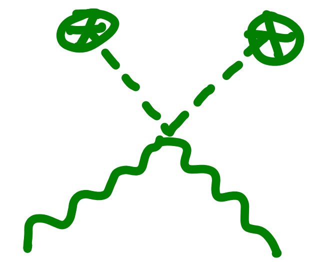
SM connection between masses and Higgs couplings:



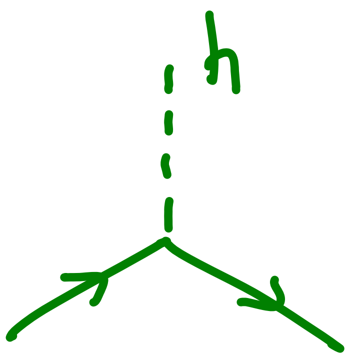
$\sim g^2$ $\Rightarrow$



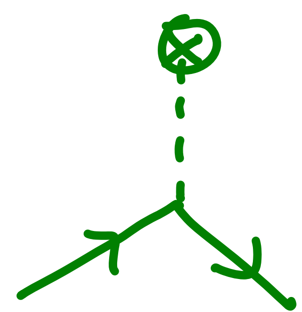
$\sim 2g^2 v$



$m_V^2 \sim g^2 v^2$



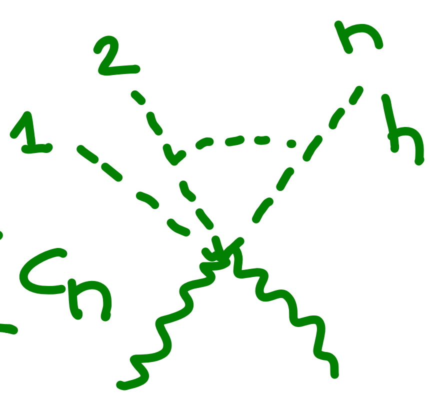
$\sim y$ $\Rightarrow$



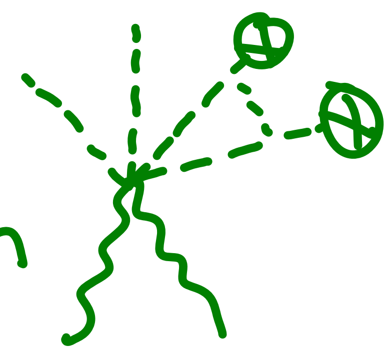
$m_f \sim y v$

is **LOST** in the presence of nonrenormalizable h interactions

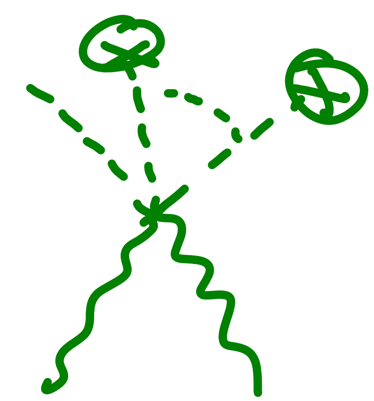
$\sum_n c_n$



$\Rightarrow \sum_n n(n-1)c_n$



$\sum_n n c_n$



$\dots$

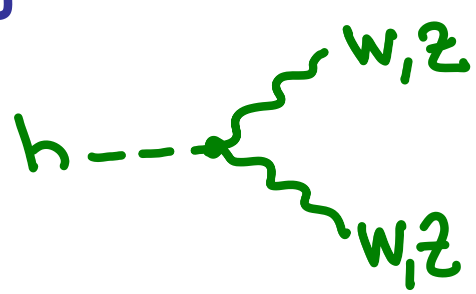
TWO CONCRETE MODELS

Based on holographic 5D AdS models with $SO(5)/SO(4)$ coset space

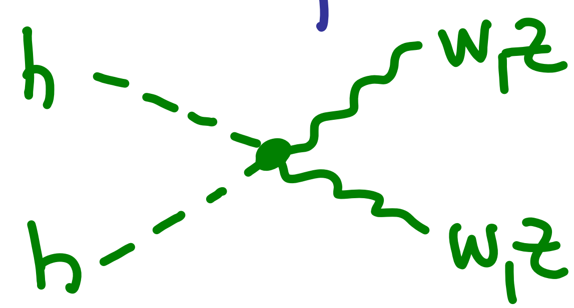
Contino, Nomura, Pomarol, Agashe, Da Rold '03 '05 '07

Minimal ⇒ just 4 Goldstones : $\{\underbrace{G^0, G^\pm}_{Z_L^0,\, W_L^\pm}, h\}$ ← LCH

Gauge interactions of h fixed by coset structure :

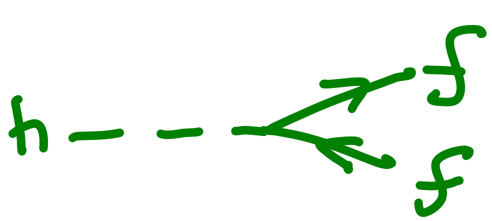


$\sqrt{1-\xi} \times (SM)$



$(1-2\xi) \times (SM)$

Interaction with fermions depend on the fermionic reps. under $SO(5)$

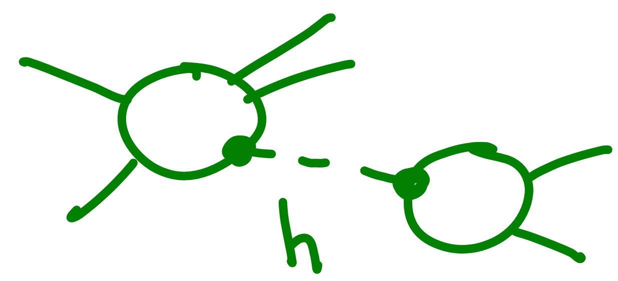


- Spinorials : $\sqrt{1-\xi} \times (SM)$ MCHM4
- Fundamentals: $\frac{1-2\xi}{\sqrt{1-\xi}} \times (SM)$ MCHM5

SEARCH OF LIGHT COMPOSITE HIGGS

★ Only h couplings modified w.r.t. SM
(only composite state)

Signal process
modified



but same kinematics.

★ Background processes unaffected.

➡ Can use SM analyses!

MODEL SPACE

$$\mathcal{L}_{EWSB} = \frac{v^2}{4} \mathrm{Tr}\left[D_\mu \Sigma^\dagger D^\mu \Sigma\right]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - y_f \bar{f}_L \Sigma f_R \left(1 + c\frac{h}{v}\right)$$

Unknown parameters a, b, c.

	a	b	c
SM	1	1	1
MCHM4	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$
MCHM5	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
Dilaton	$\sqrt{b}$	b	$\sqrt{b}$

MCHM4

Universal reduction: 

$\sqrt{1-\xi} \times (SM)$

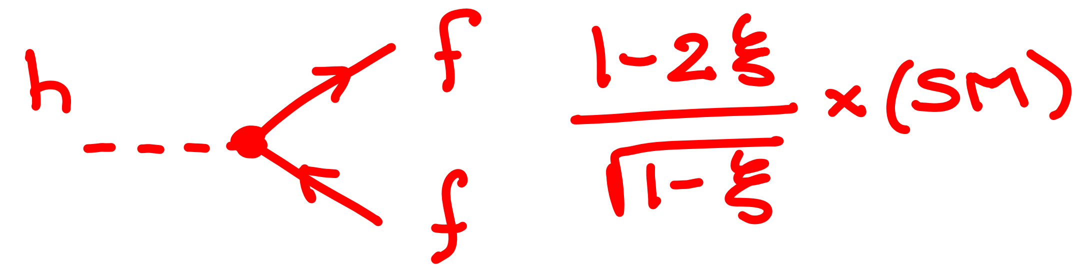
Production Xsections $\quad \sigma_{LCH} = (1-\xi)\,\sigma_{SM}$

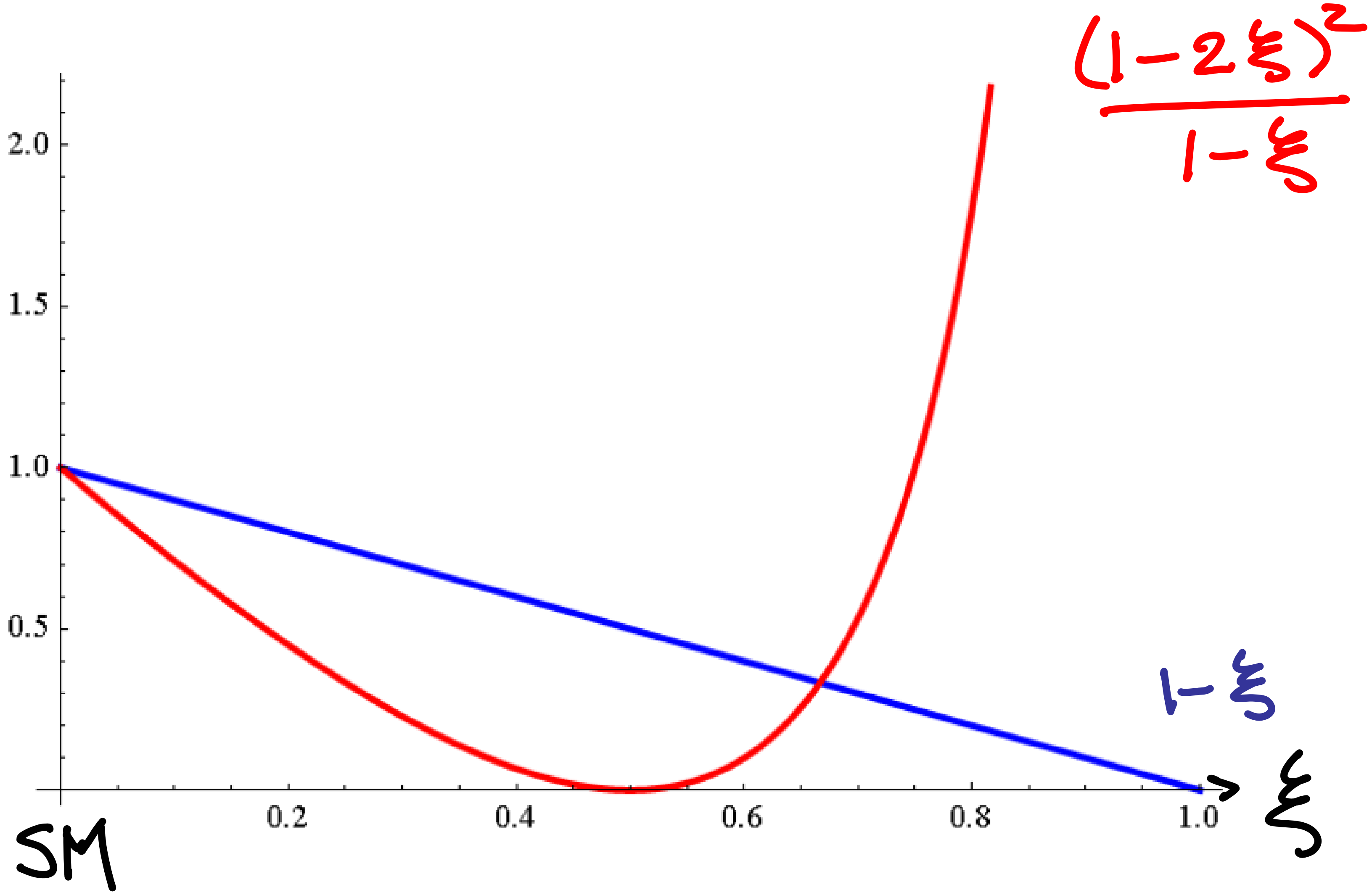
BRs unaffected

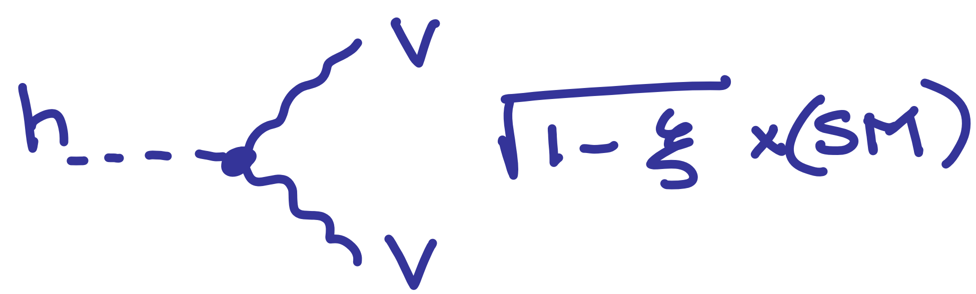
Higgs width $\quad \Gamma_h = (1-\xi)\,\Gamma_{SM}$

MCHM5

(Rescaling factors)^2

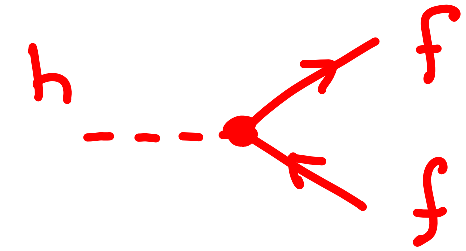




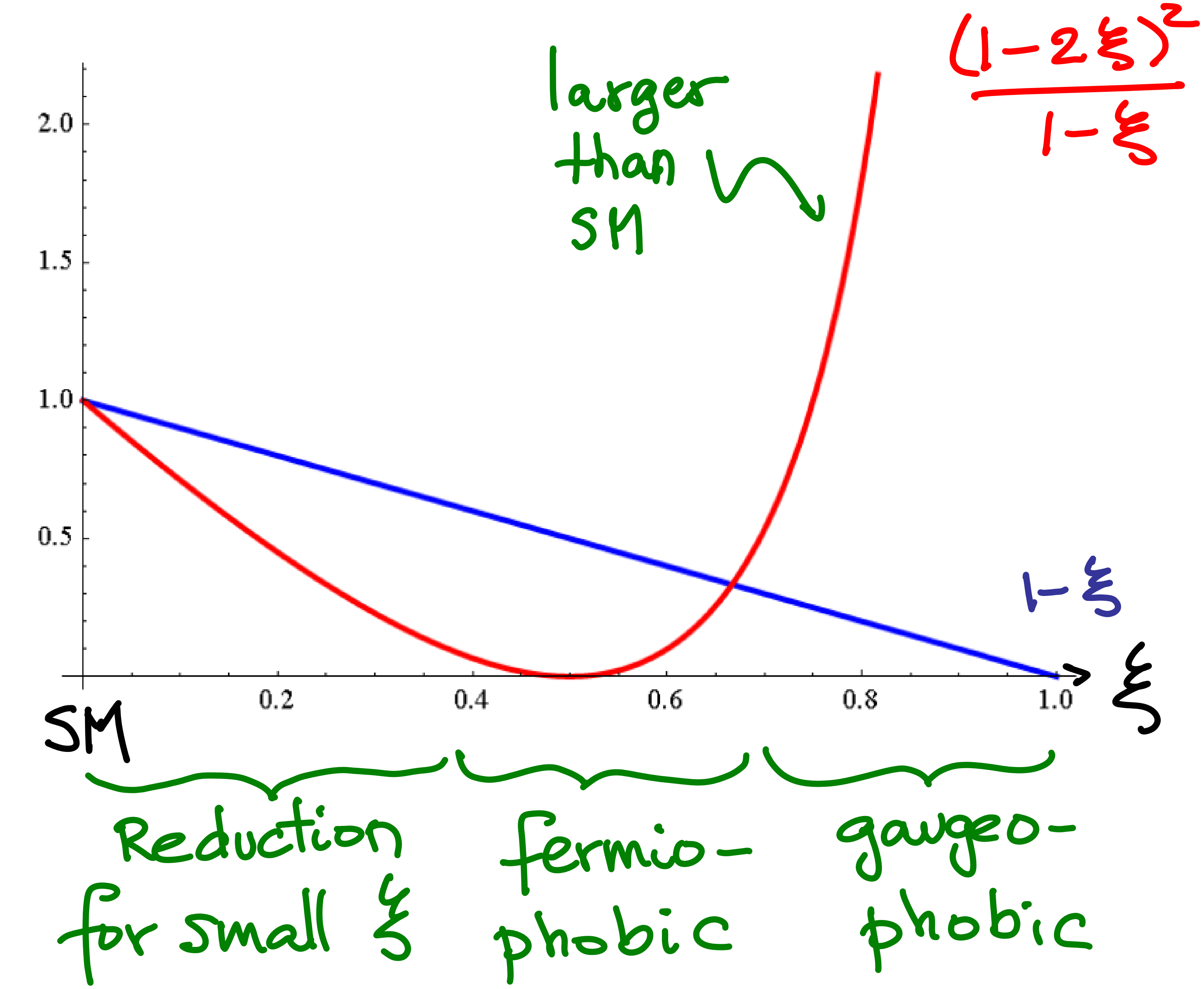


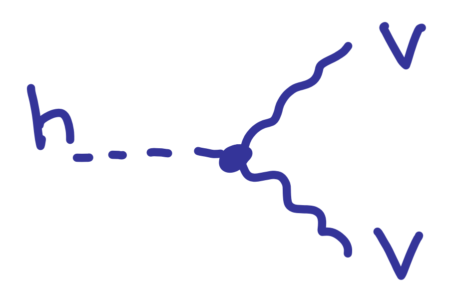
MCHM5

(Rescaling factors)^2



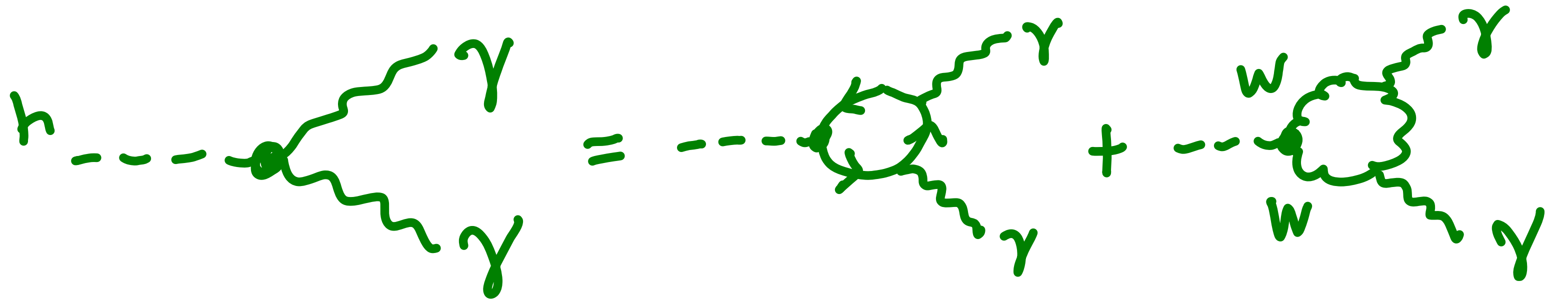
$\frac{1-2\xi}{\sqrt{1-\xi}} \times (SM)$



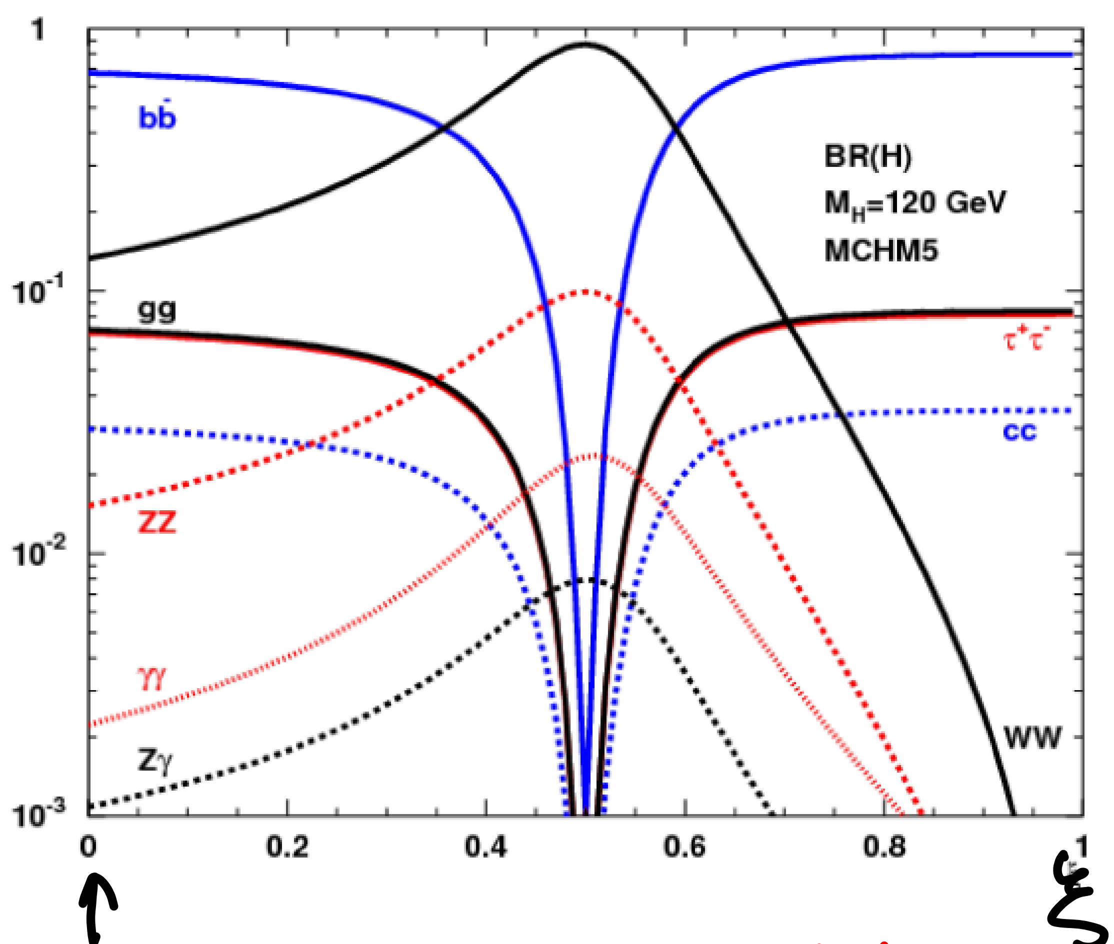


$\sqrt{1-\xi} \times (SM)$

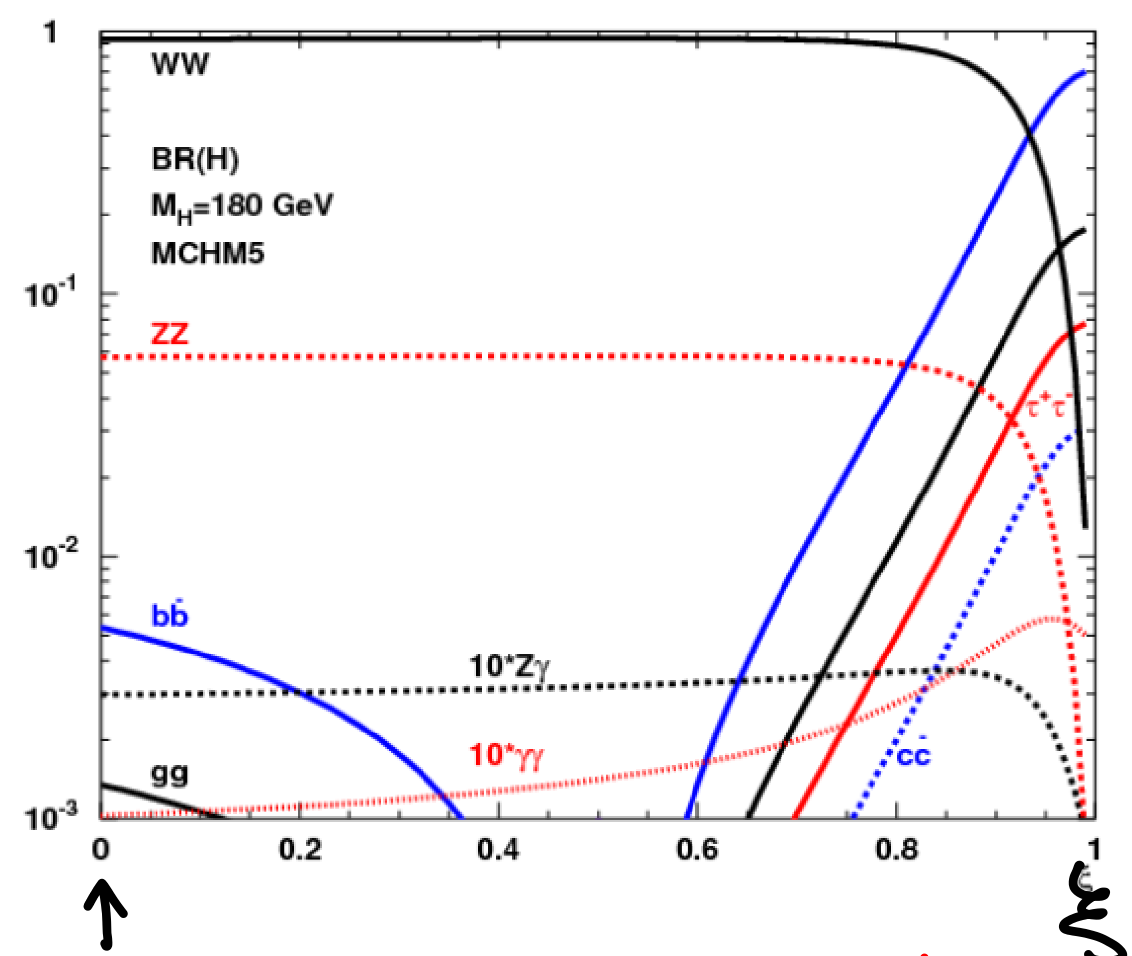
BRs (MCHM5)



$$\frac{1-2\xi}{\sqrt{1-\xi}} \times (SM)_f + \sqrt{1-\xi} \times (SM)_W$$

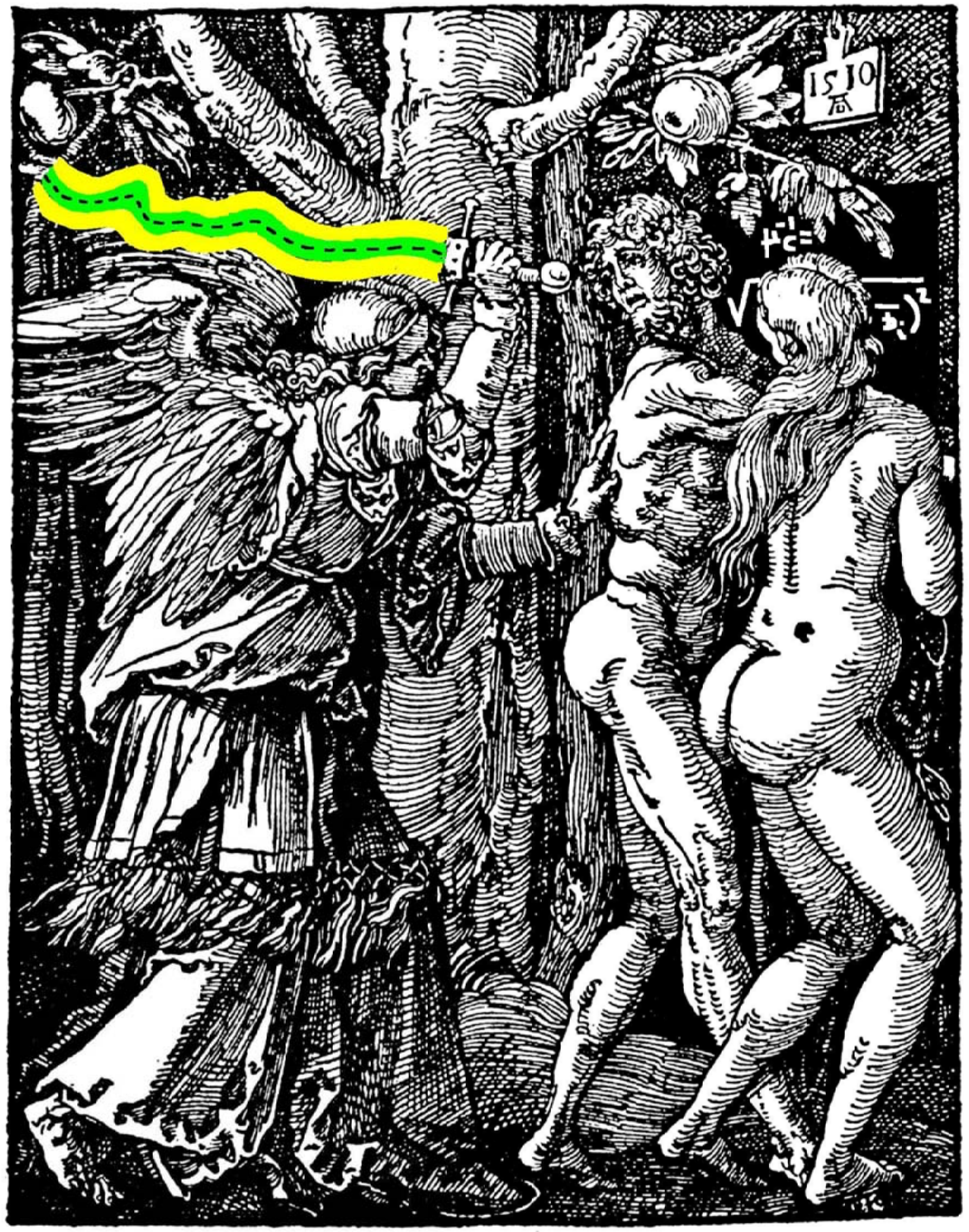


SM $m_h = 120$ GeV

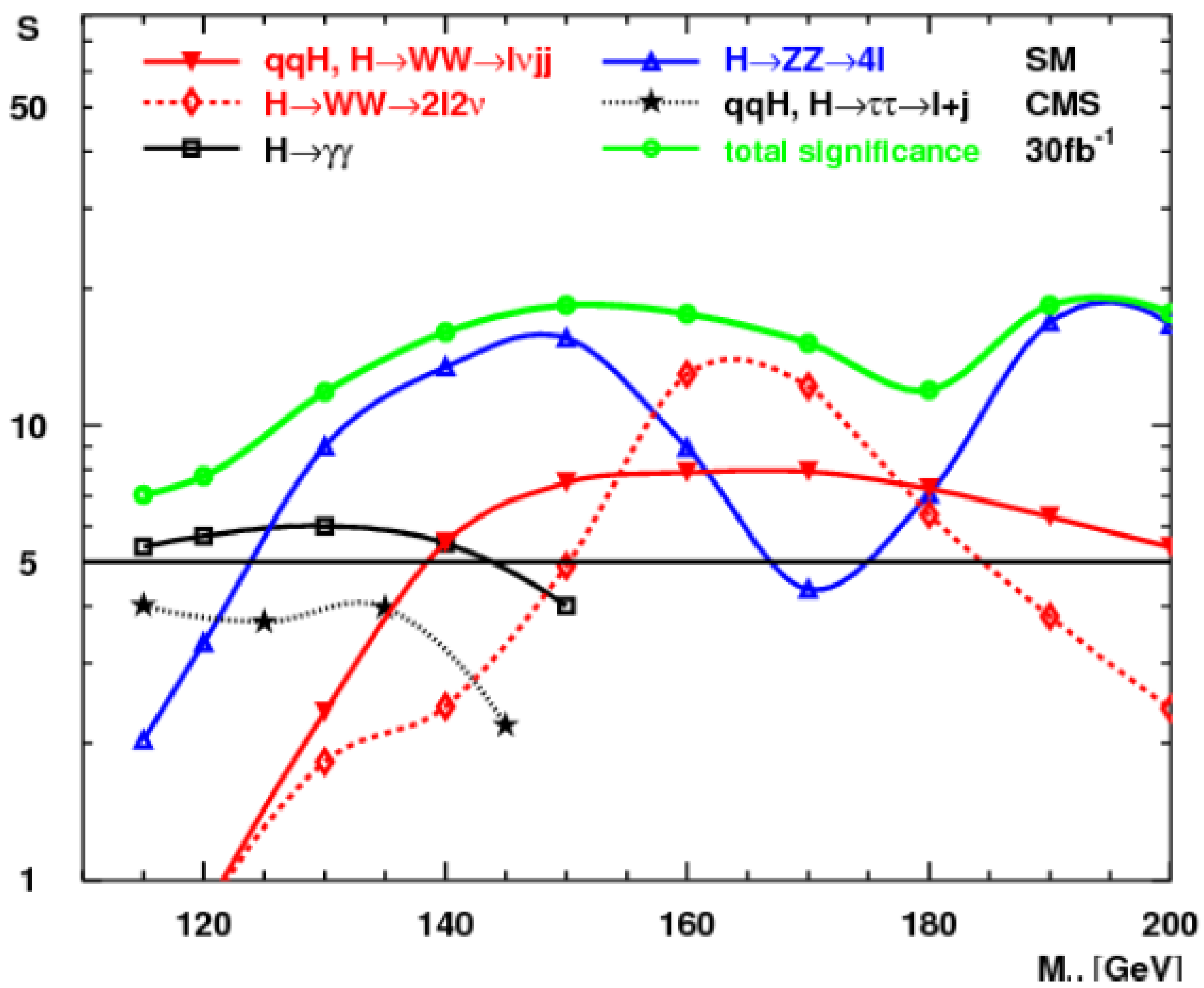


SM $m_h = 180$ GeV

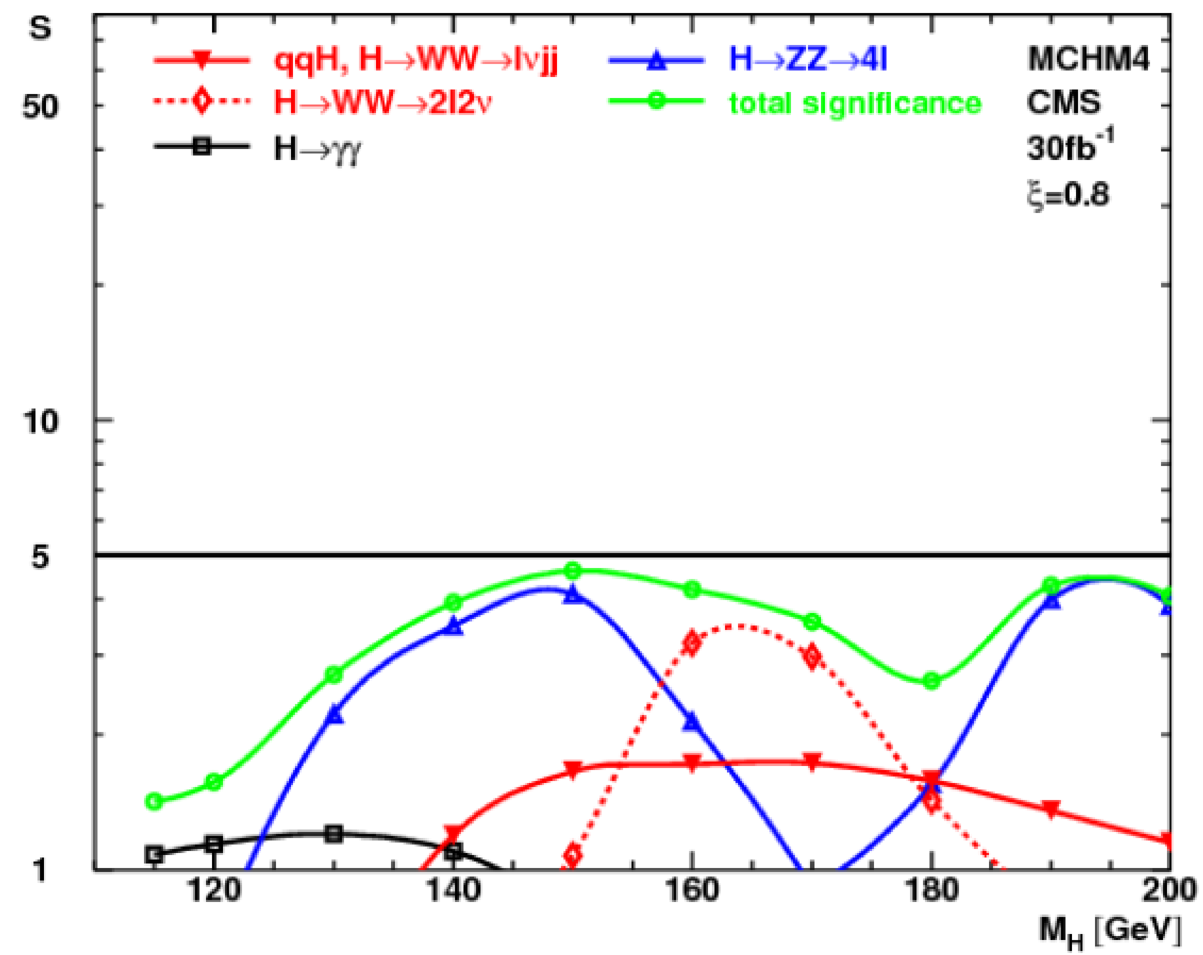
YE SHALL NOT COMBINE!



EXPECTATIONS ($30 fb^{-1}$)



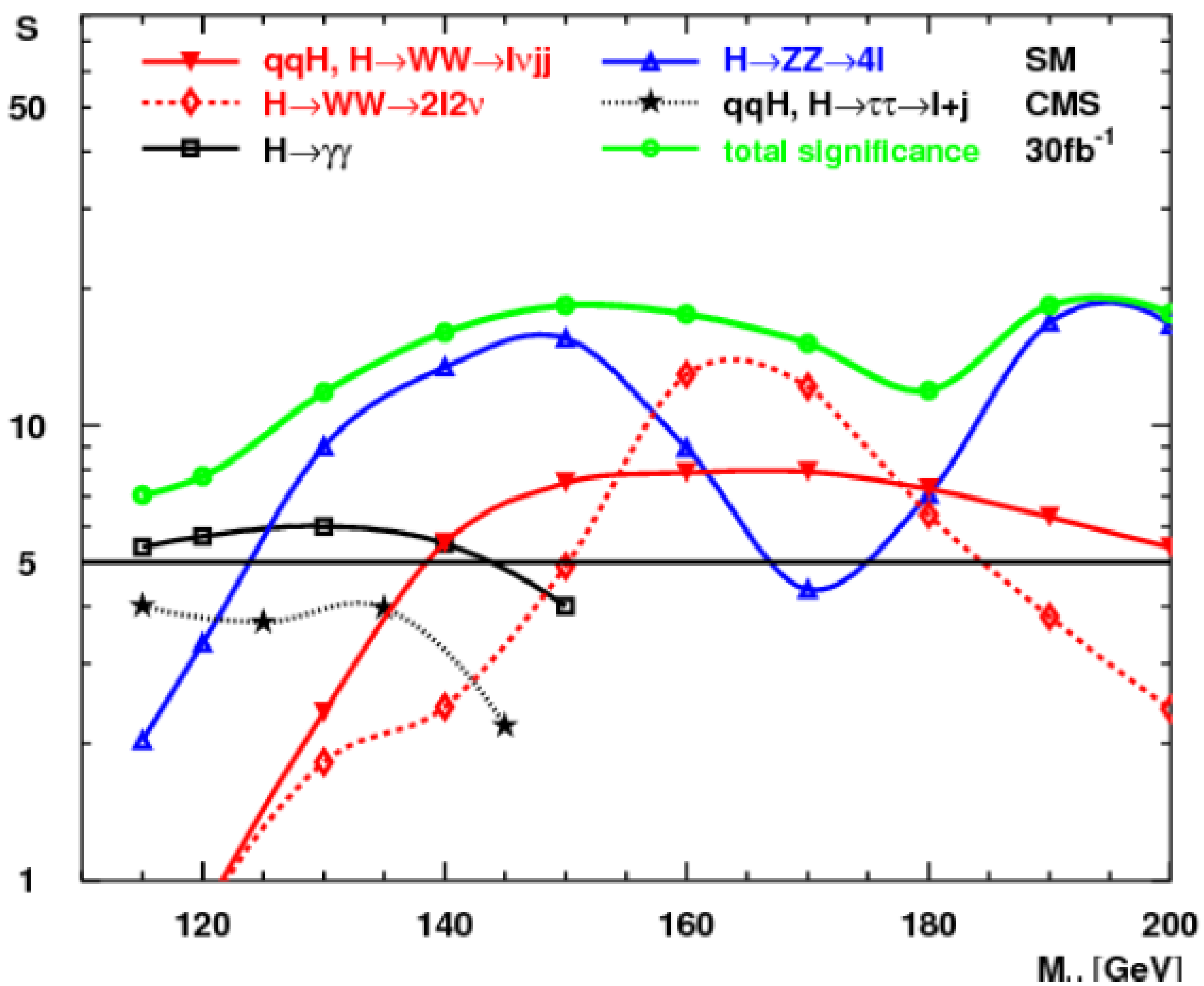
SM



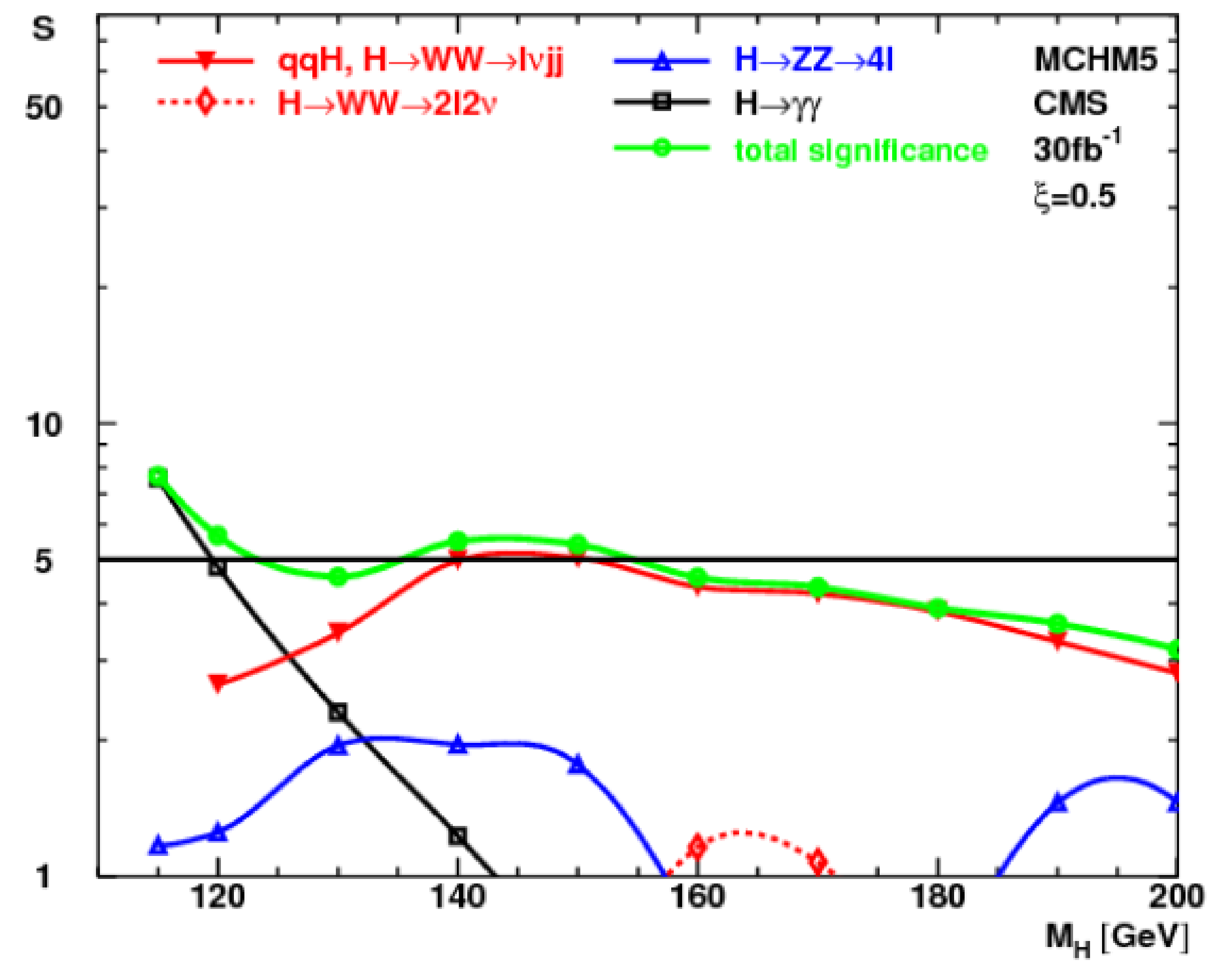
MCHM4

($\xi = 0.8$)

EXPECTATIONS ($30 fb^{-1}$)



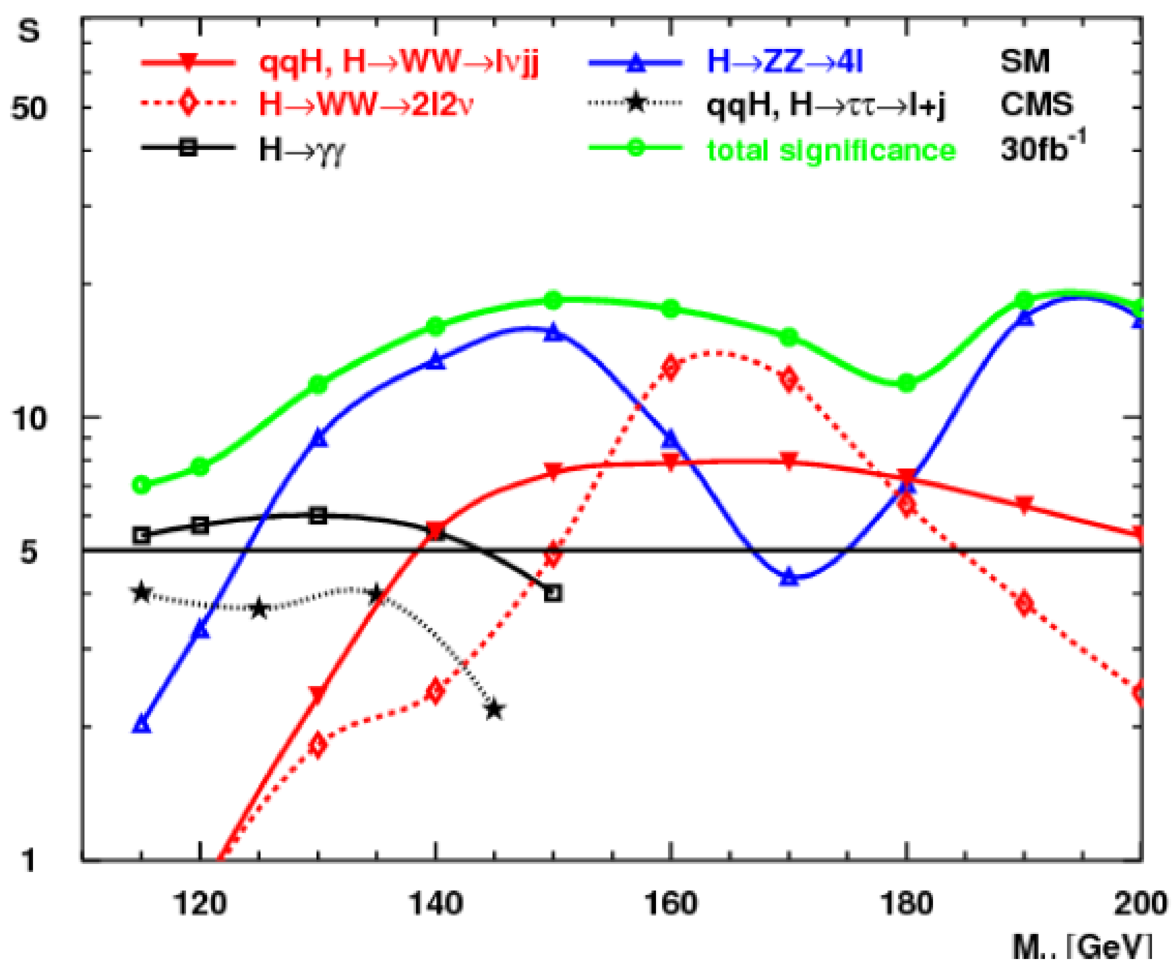
SM



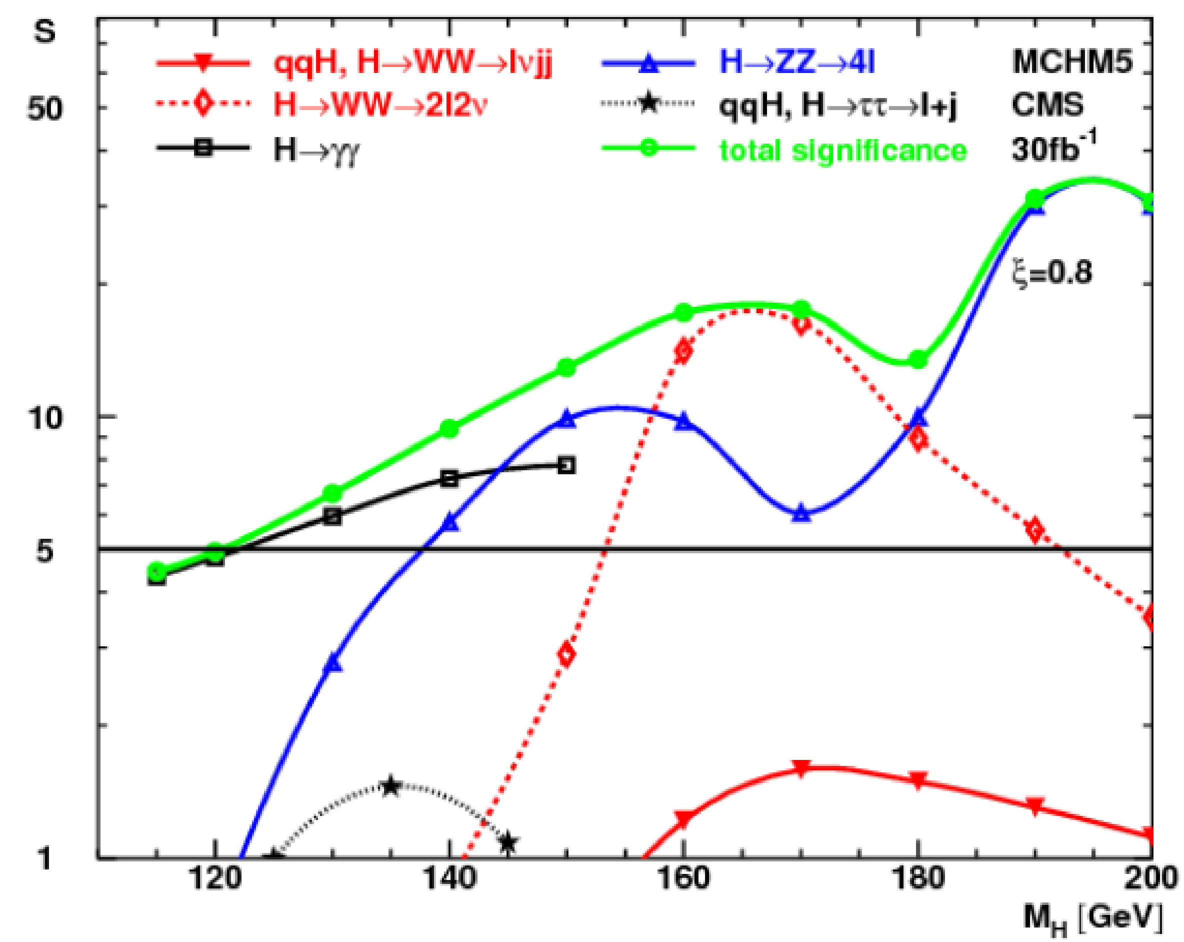
MCHM5

($\xi = 0.5$)

EXPECTATIONS ($30 fb^{-1}$)



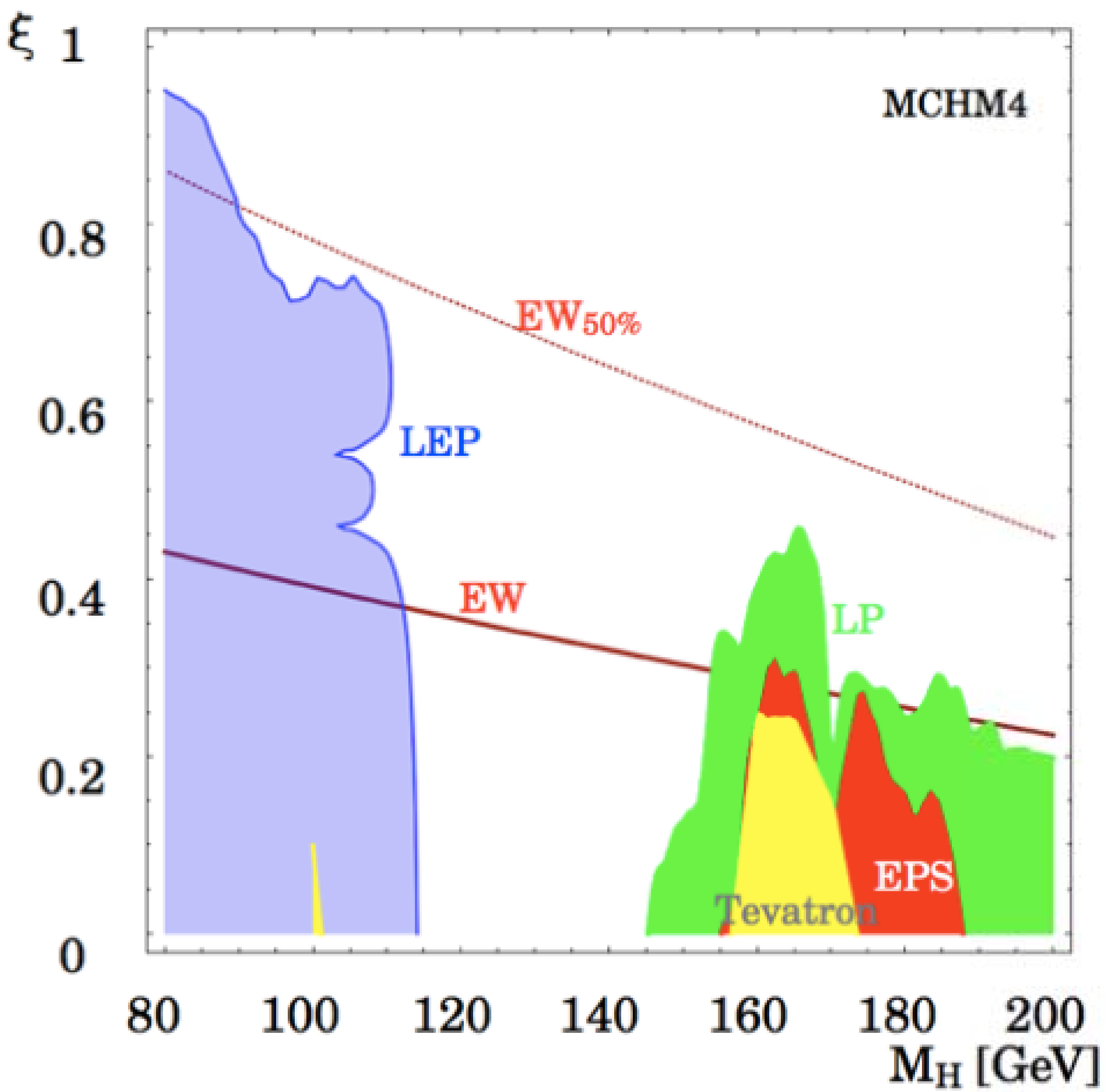
SM



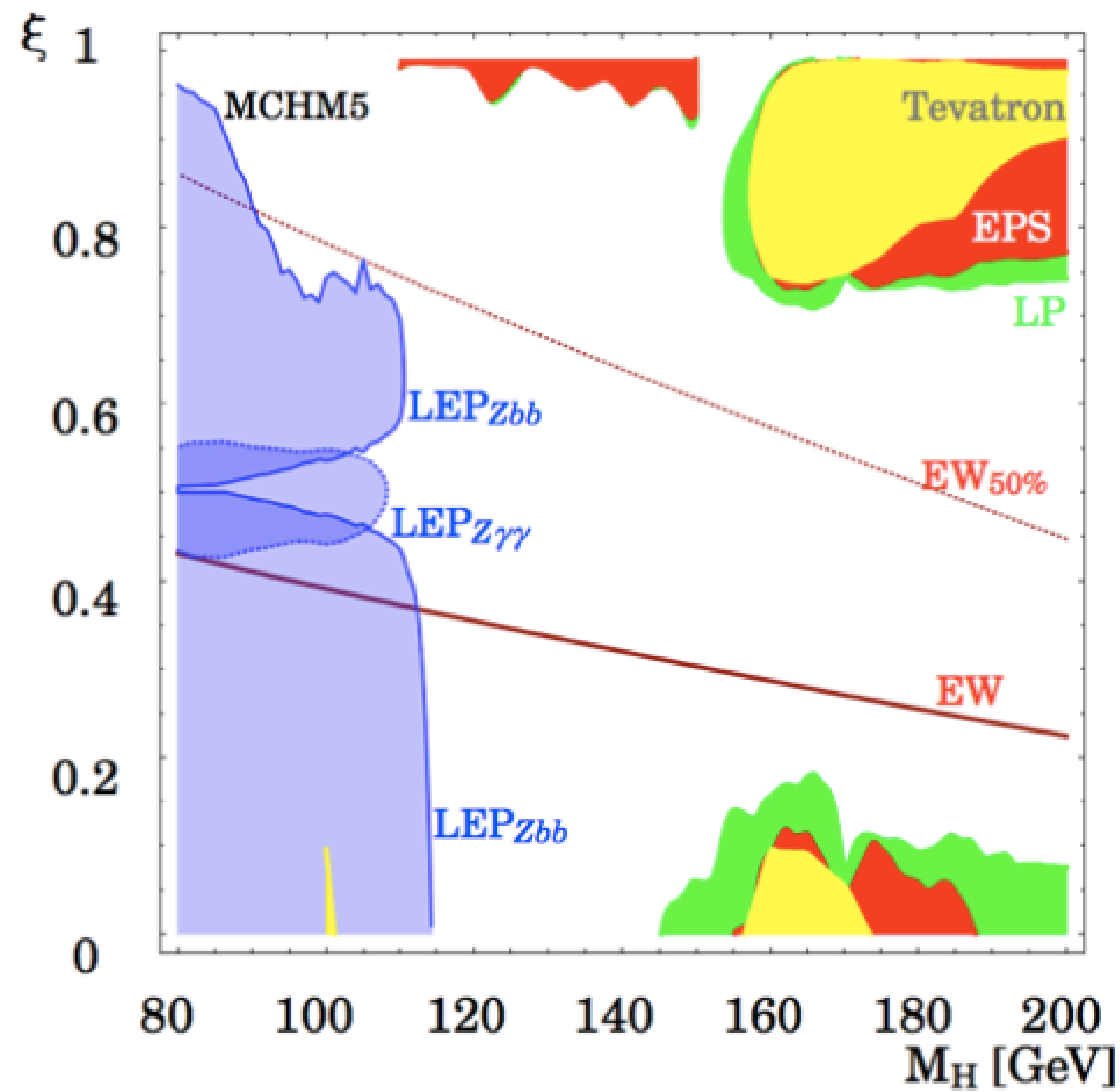
MCHM5

($\xi = 0.8$)

EXCLUSIONS

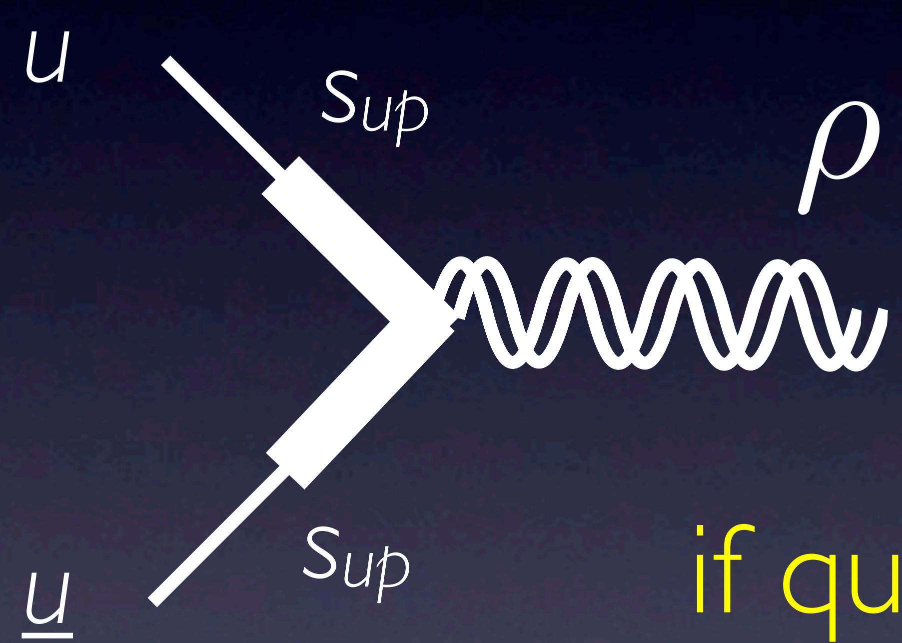


MCHM4



MCHM5

Additional expectation:
Resonance production (like in QCD)



$$\sim g_*^2 \sin^2 \theta_{u_R}$$

if quarks are partially composite, can be very large => flavor trivial prediction!!

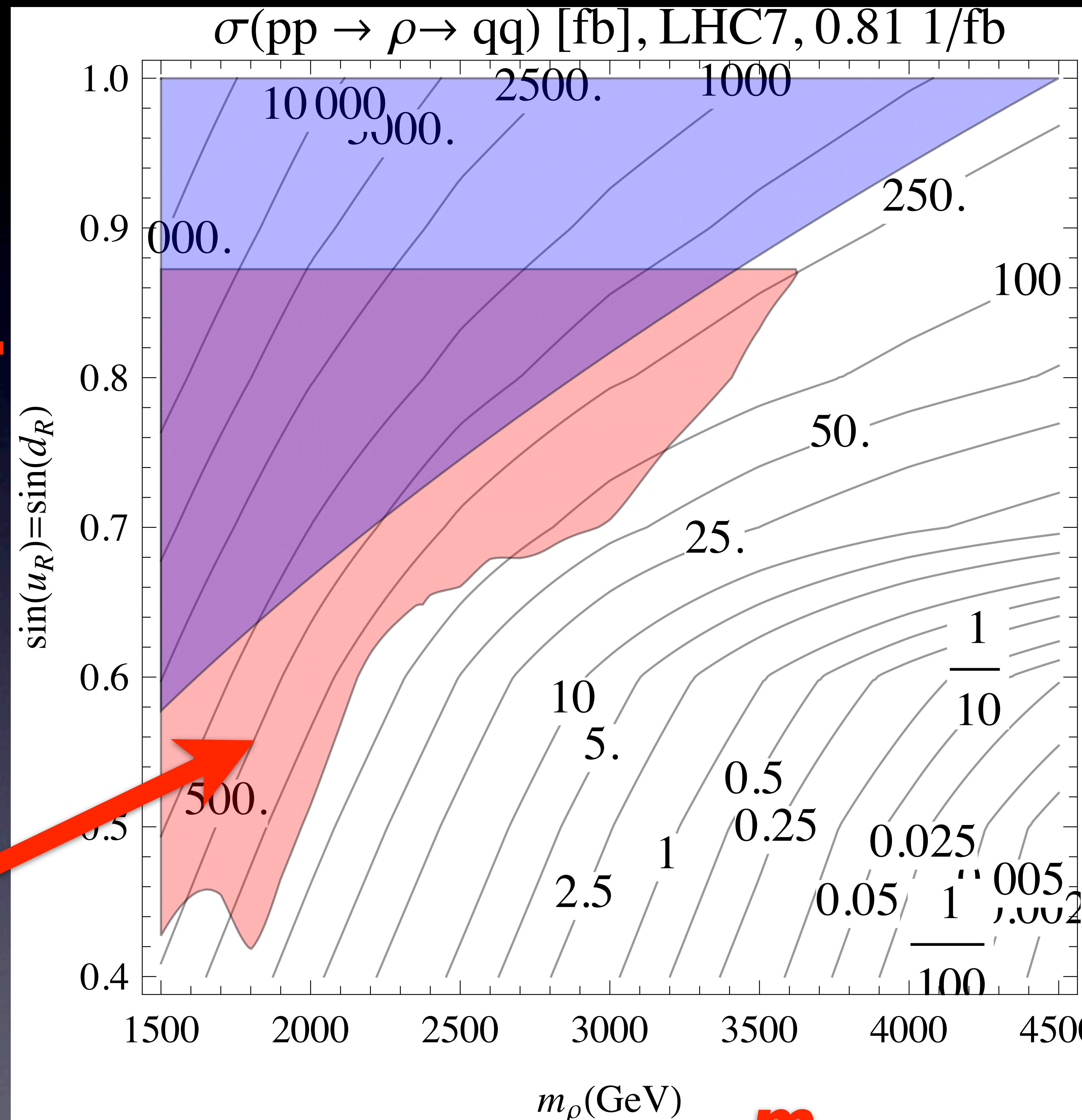
Cacciapaglia, Csaki, Galloway, Marandella, Terning, A.W.

LHC dijets (compositeness & bump search)

Redi, AW

x

compositeness



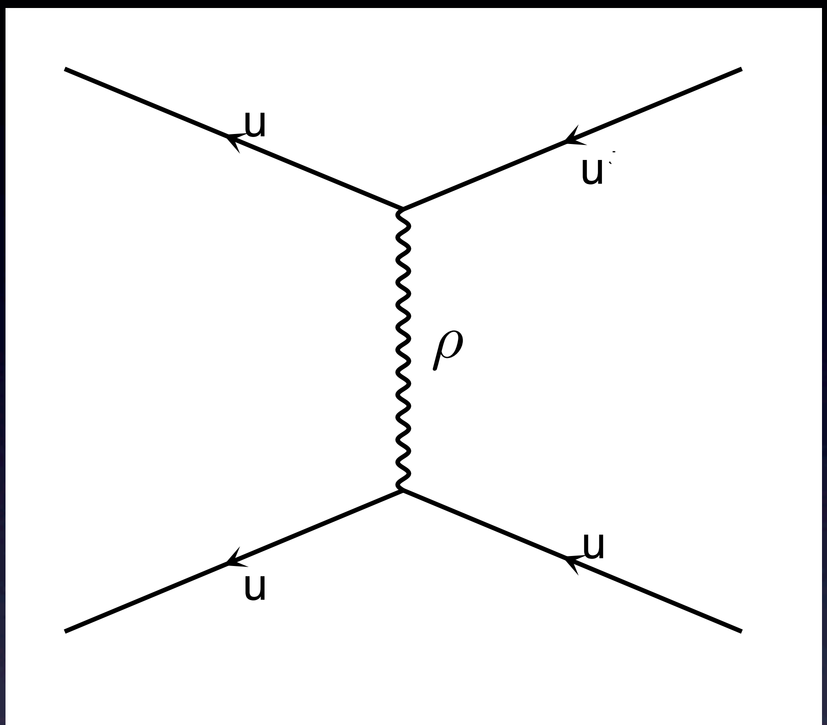
m_resonance

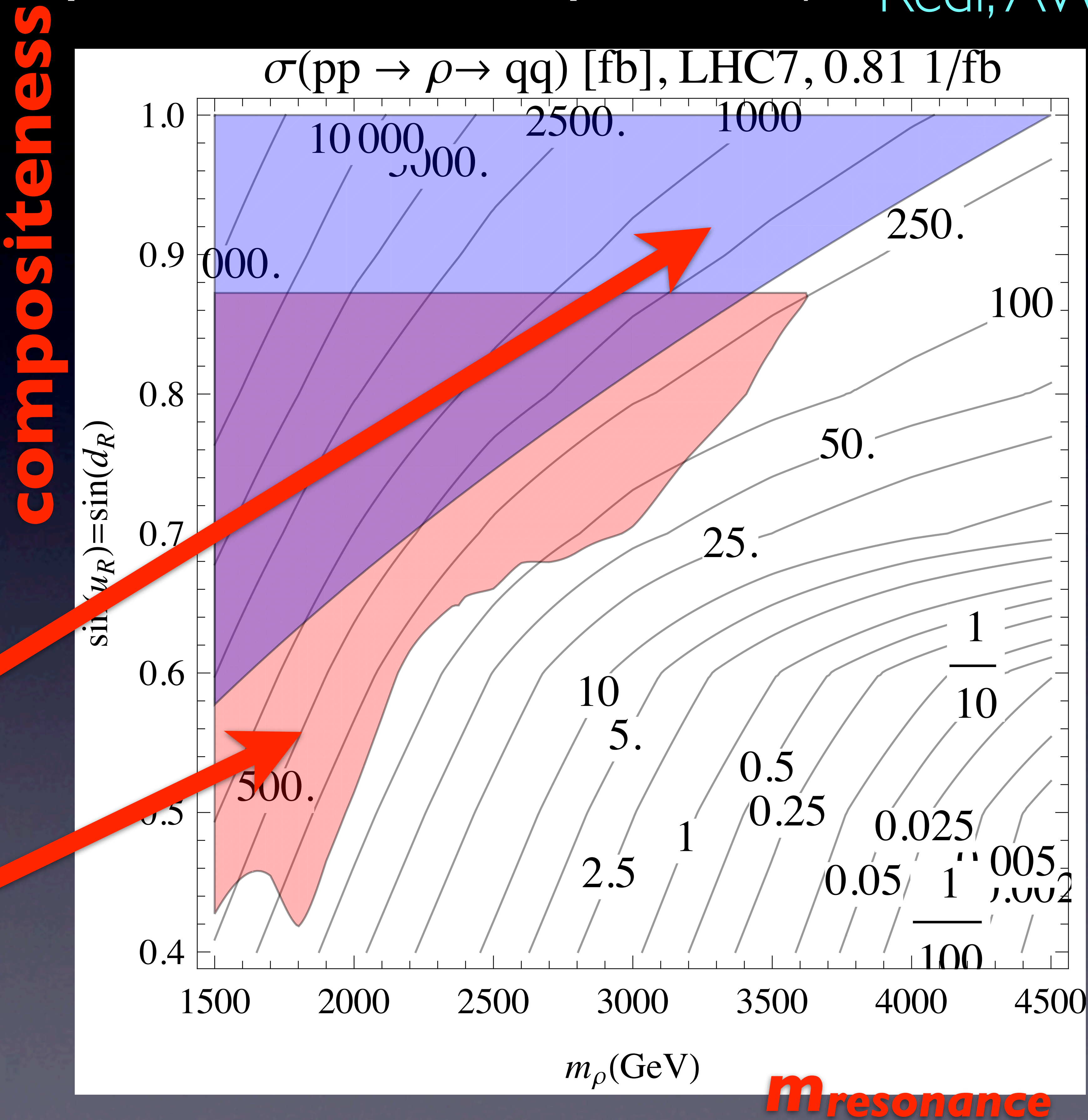
bump hunt

using *810 1/pb* (ATLAS NOTE)

LHC dijets (compositeness & bump search)

Redi, AW





compositeness

bump hunt

using *810 1/pb* (ATLAS NOTE)

possibility #0:

there is no Higgs!

Possibility #0:

There is no Higgs!

Higgs-less spontaneous symmetry breaking is already realized in nature: **low energy QCD**

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$$

by a quark-quark condensate. Recycle this: techni-color.

Consequences: No Higgs, but resonances in $W_L W_L$ scattering (VBF and maybe DY)

A QCD antecedent

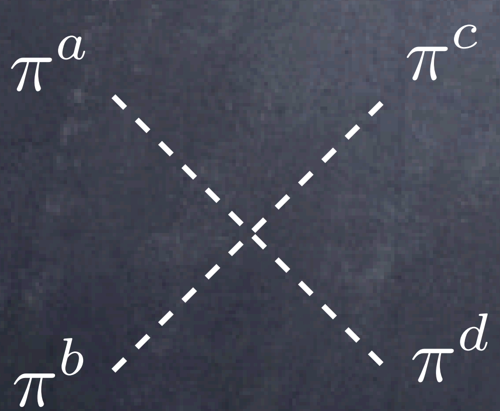
QCD pions are Goldstone bosons associated to $SU(2)_L \times SU(2)_R / SU(2)_V$

$$U = e^{i\pi^a \sigma^a / f_\pi} \begin{pmatrix} 0 \\ \frac{f_\pi}{\sqrt{2}} \end{pmatrix}$$

kinetic terms for U $\Leftrightarrow$ interaction terms for π^a

$$\mathcal{L} = |\partial_\mu U|^2 = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6f_\pi^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2(\partial_\mu \pi^a)^2\right) + \ldots$$

contact interaction growing with energy



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

$$\mathcal{A}(s,t,u) = \frac{s}{f_\pi^2}$$

$$f_\pi = 93 \text{ MeV}$$

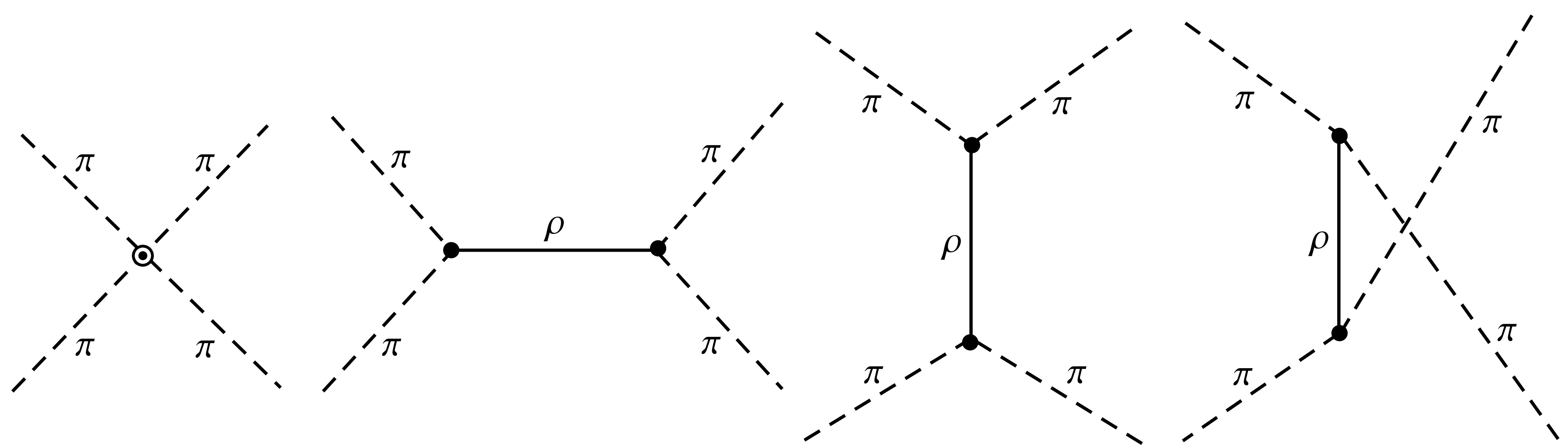
$\Rightarrow$ unitarity bound

$$\sqrt{s} \sim 4\sqrt{\pi} f_\pi = 660 \text{ MeV}$$

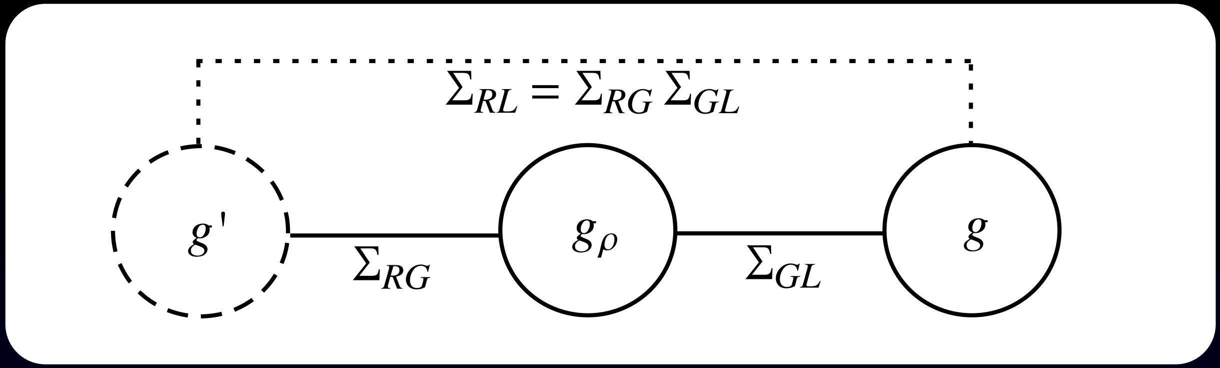
rho meson (m=770 MeV) is restoring unitarity

Consequences: No Higgs, but resonances in $W_L W_L$ scattering (VBF and maybe DY)

Translating QCD: first resonance at 2 TeV (rho-meson)!
($f_{pi} \rightarrow v_{EW}$)



Effective description in terms of a 3-site model



see e.g. Grojean,Falkowski, Pokorski, AW '11

Minimal set-up describing the SM gauge sector includes (fermions later)

- Standard Model gauge bosons L^a_μ, B_μ
- 3 Goldstone bosons π who become the longitudinal polarizations of the W and Z bosons
- Approximate $SU(2)_C$ custodial symmetry
- A triplet of massive vector bosons called the ρ_μ mesons

Unitarity of the S-matrix implies the relation for the scattering amplitudes

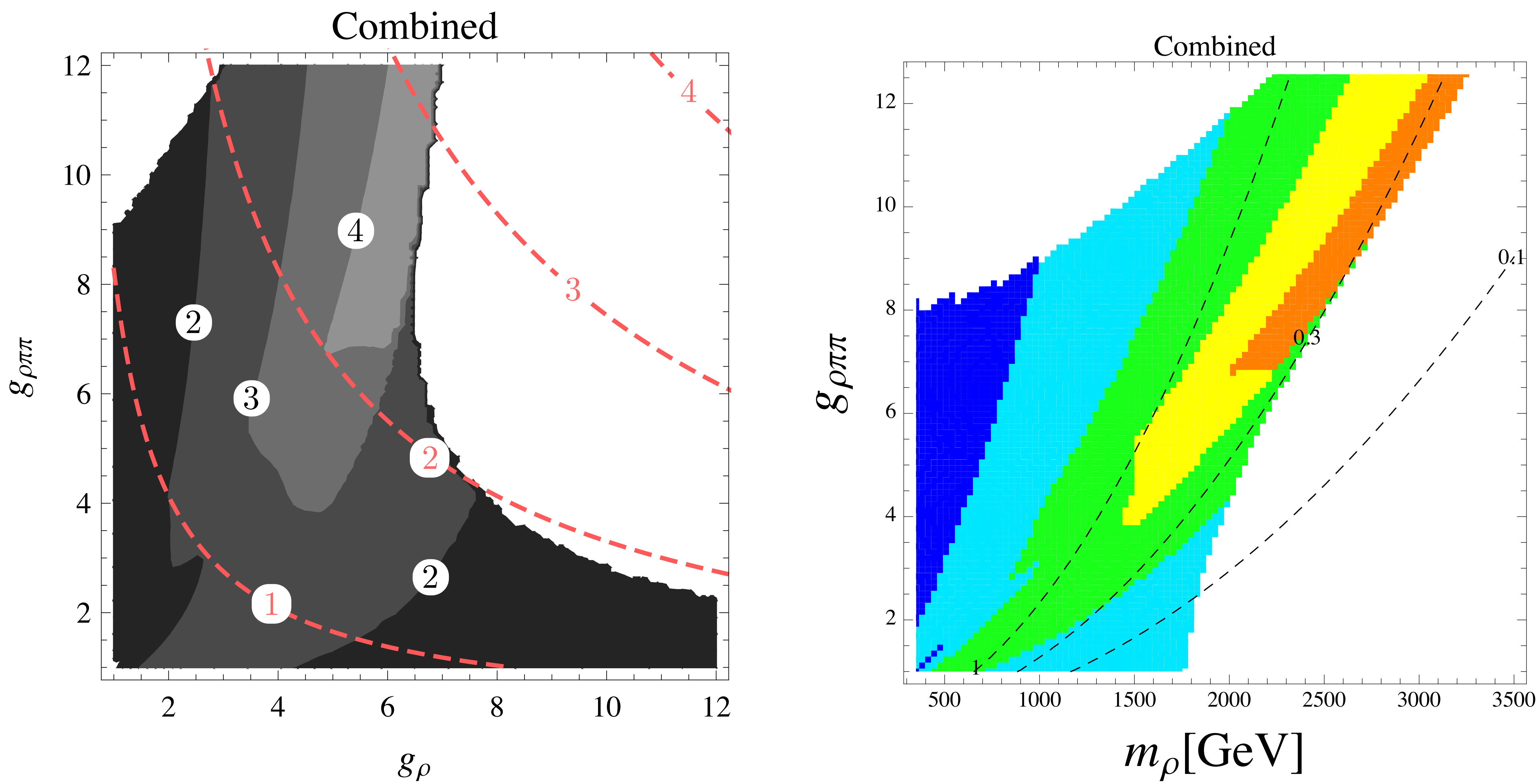
$$\mathrm{Im}\,\mathcal{M}_{\alpha\beta} = \sum_{\gamma} \mathcal{M}_{\alpha\gamma}\sigma_{\gamma}\mathcal{M}^{*}_{\beta\gamma}$$

where $\sigma_{\alpha}^2 = (1 - m_1^2/s - m_2^2/s)^2 - 4m_1^2 m_2^2/s^2$ for $s > (m_1 + m_2)^2$, and $\sigma_{\alpha} = 0$ otherwise. For one initial and one final state available it implies

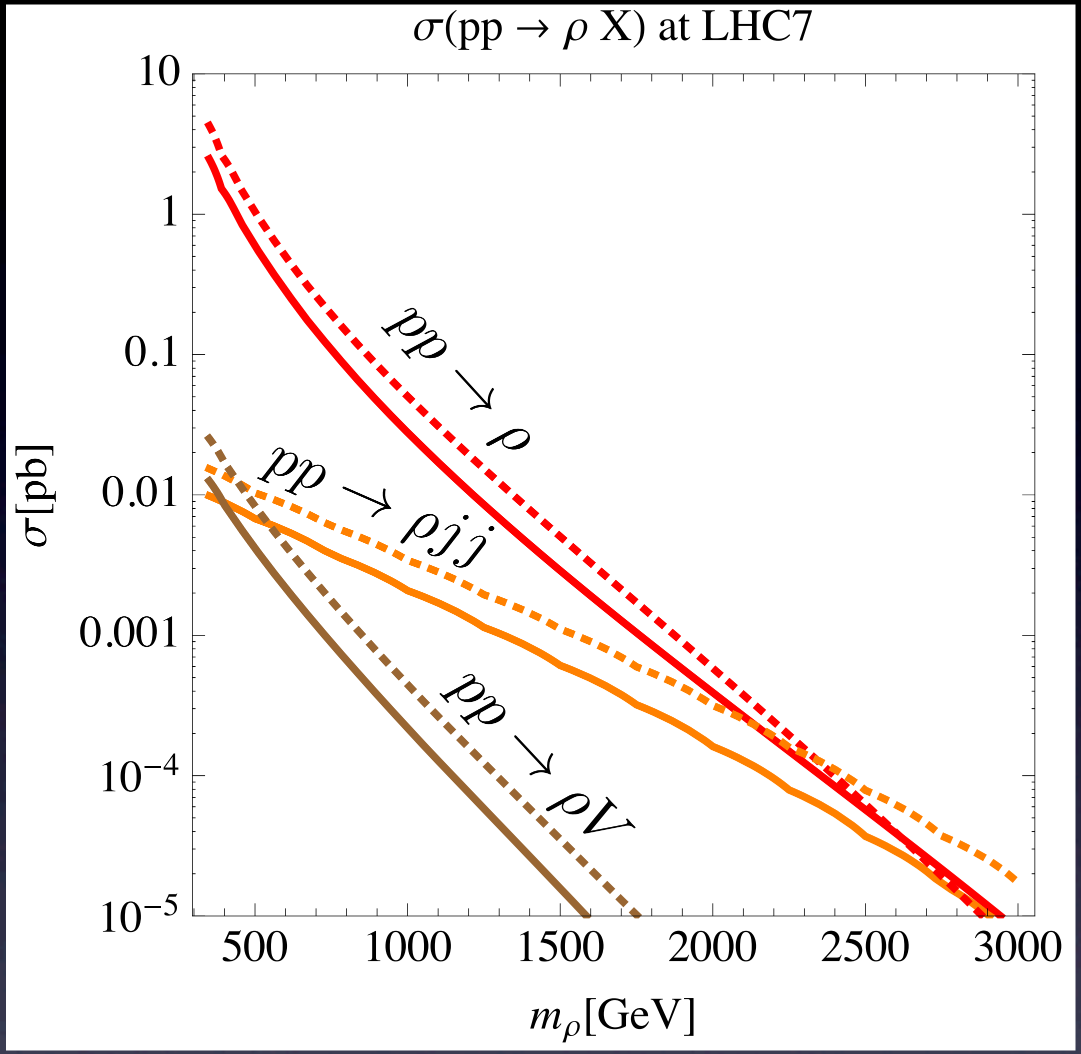
$$|\mathcal{M}_{\alpha\alpha}| \leq \sigma_{\alpha} \qquad \text{or} \qquad |\mathrm{Re}\,\mathcal{M}_{\alpha\alpha}| \leq 1/2\sigma_{\alpha}$$

Projecting into partial waves, the same condition for each partial wave. Typically, s-wave gives the strongest bound. We take into account

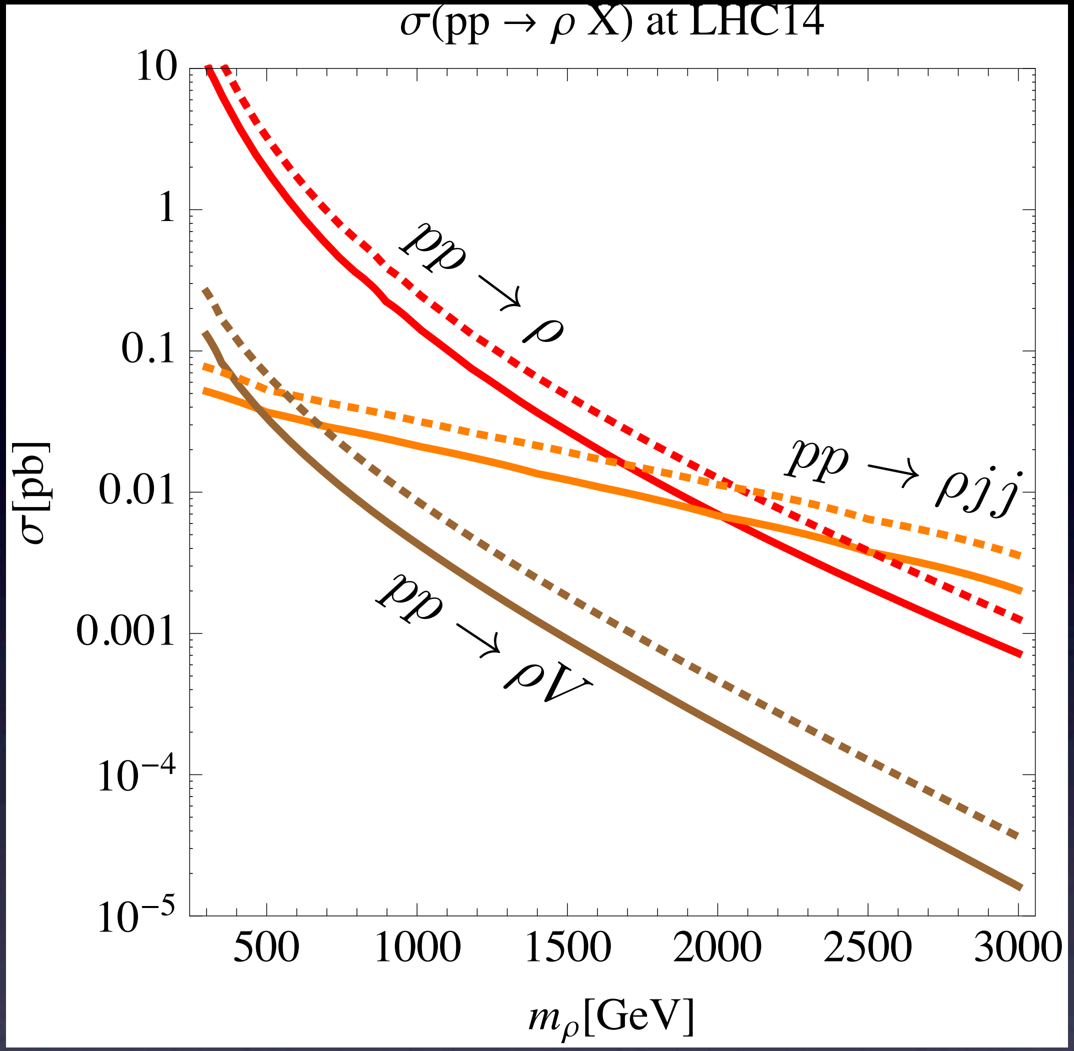
- "Elastic" channels $\pi\pi \to \pi\pi$, Bagger et al [hep-ph/9306256]
- Inelastic channels $\pi\pi \to \rho\rho$,
- "Semielastic" channels $\pi\rho \to \pi\rho$



Contour plots of the maximum cut-off scale Λ overlaid it with contours of constant m_ρ (left,dashed red) or S-parameter (right,dashed).

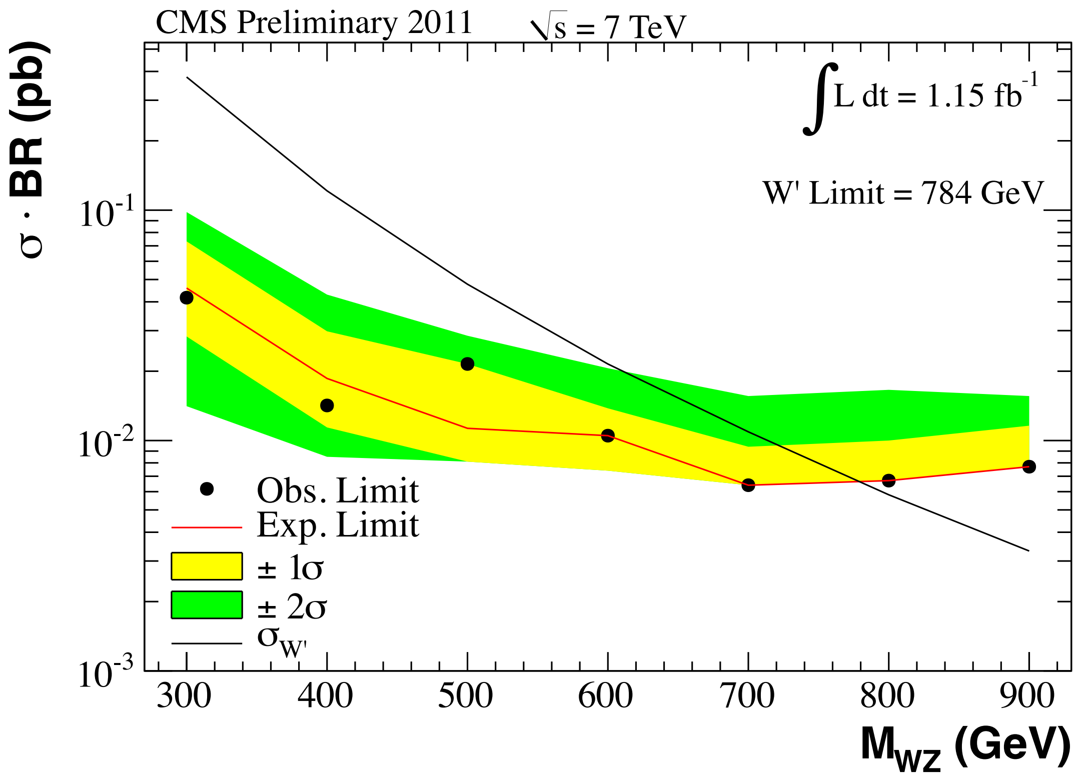


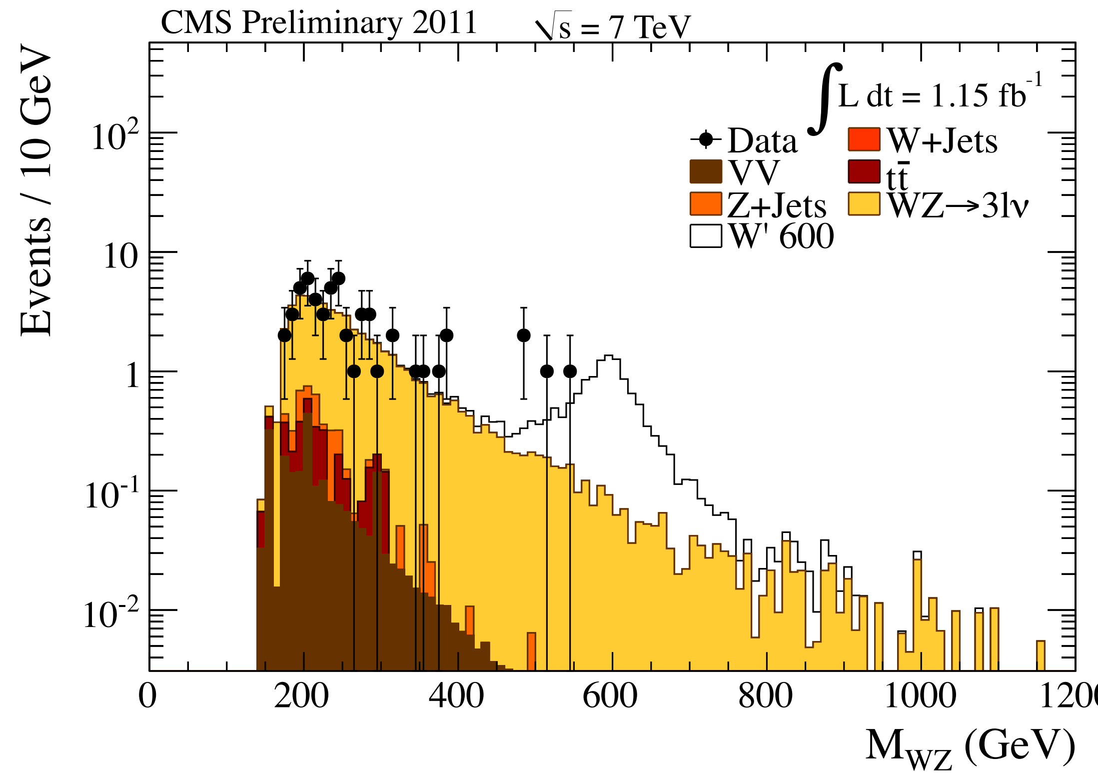
σ(pp → ρ X) at LHC7
σ[pb]
10
1
0.1
0.01
0.001
10^−4
10^−5
500
1000
1500
2000
2500
3000
m_ρ[GeV]
pp → ρ
pp → ρjj
pp → ρV



σ(pp → ρ X) at LHC14
σ[pb]
10
1
0.1
0.01
0.001
10^−4
10^−5
500
1000
1500
2000
2500
3000
m_ρ[GeV]
pp → ρ
pp → ρjj
pp → ρV

- Previous best limits on WW and WZ resonances currently from D0 [1011.6278]
- Current best limits from the 1fb-1 CMS search for WZ resonances, EXO-11-041
- LHC limits on leptonic Z' and W' resonances are not competitive because of the small leptonic branching fraction





Conclusions

LHC's main task: Unraveling the mechanism of EWSB →

Is it EWSB weak or strong? An Elementary or a composite Higgs? Higgs-less?

Precise Higgs properties will tell us. Higher lumi/energy goal: $W_L W_L \rightarrow W_L W_L$ scattering

Soon we will know if a Higgs exists - determining if it is composite will take more time. †

† ILC would be the perfect machine… can rule out compositeness scales up to ~ 30 TeV.