Composite Higgs Physics at Colliders

Bethe Forum

Bonn, Nov. 14, 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 behavior of these Goldstone's? $\Lleftarrow$

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

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

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

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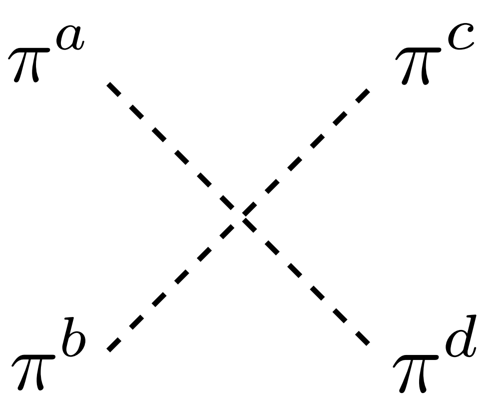
$$\boxed{\mathcal{L}_{\text{mass}} = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6v^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2 (\partial_\mu \pi^a)^2\right) + \ldots}$$

contact interaction growing with energy



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

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

Lee, Quigg & Thacker '77

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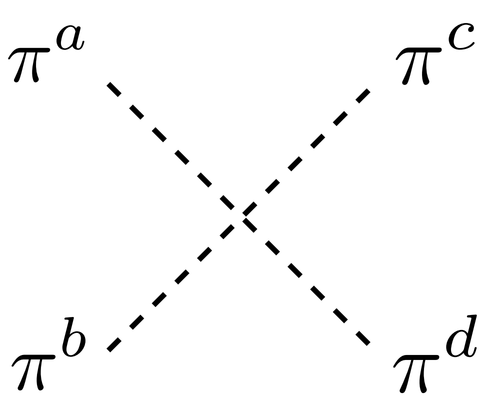

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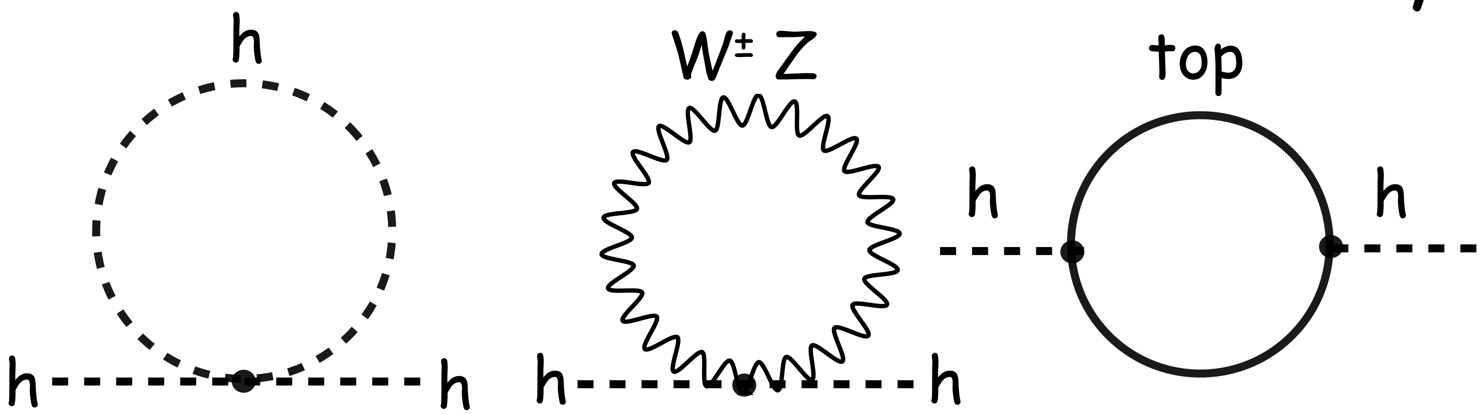
the behavior of this amplitude is not consistent above $4\pi v$ (≈1÷3TeV)

Lee, Quigg & Thacker '77

Beyond the Higgs: The hierarchy problem

need new degrees of freedom to cancel Λ^2 divergences
and ensure the stability of the weak scale



$$m_H^2 \sim m_0^2 - (115\ \mathrm{GeV})^2 \left(\frac{\Lambda}{400\ \mathrm{GeV}}\right)^2$$

1 add a sym. such that a Higgs mass is forbidden until this sym. is broken

- supersymmetry [Witten, '81]
- gauge-Higgs unification [Manton, '79, Hosotani '83]
- Higgs as a pseudo Nambu-Goldstone boson [Georgi-Kaplan, '84]

2 lower the UV scale

- large extra-dimensions [Arkani-Hamed-Dimopoulos-Dvali, '98]
- 10^{32} species [Dvali '07]

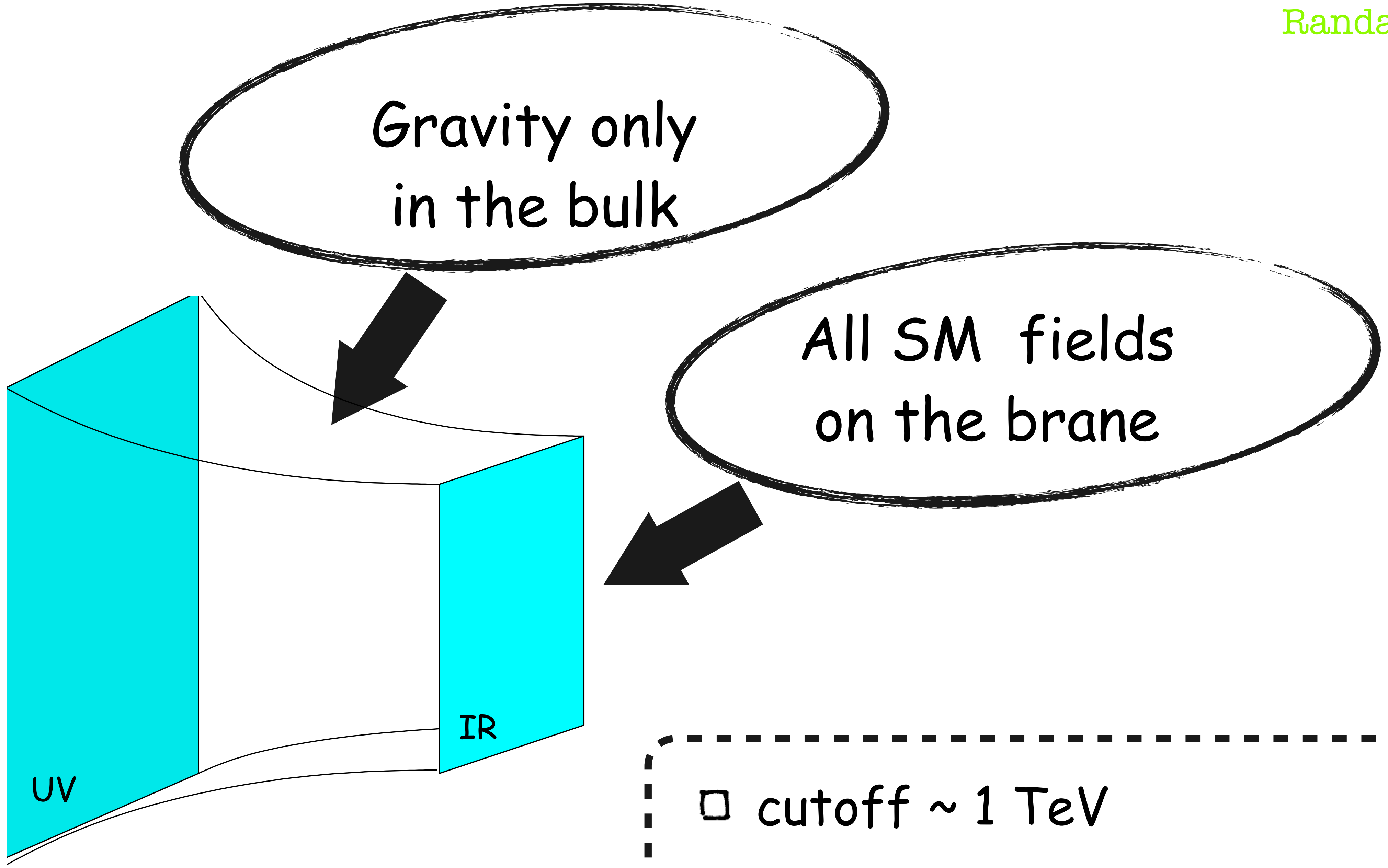
3 remove the Higgs

- technicolor [Weinberg '76, Weinberg '79, Susskind '79]

Holographic Models of EWSB

Original Randall-Sundrum proposal

Randall, Sundrum, '99



- cutoff ~ 1 TeV
- conflict with EW precision data
- problems with flavor

Holographic Models of EWSB

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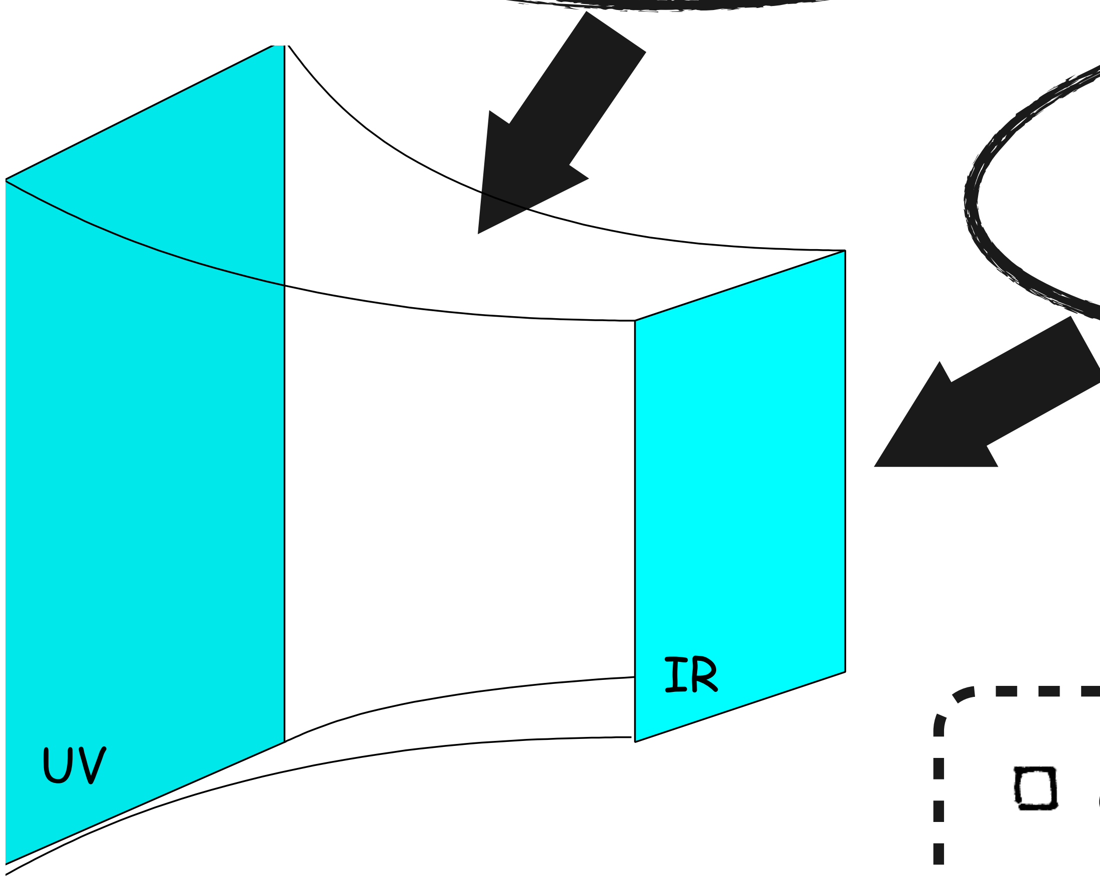
Gravity only
in the bulk

All SM fields
on the brane



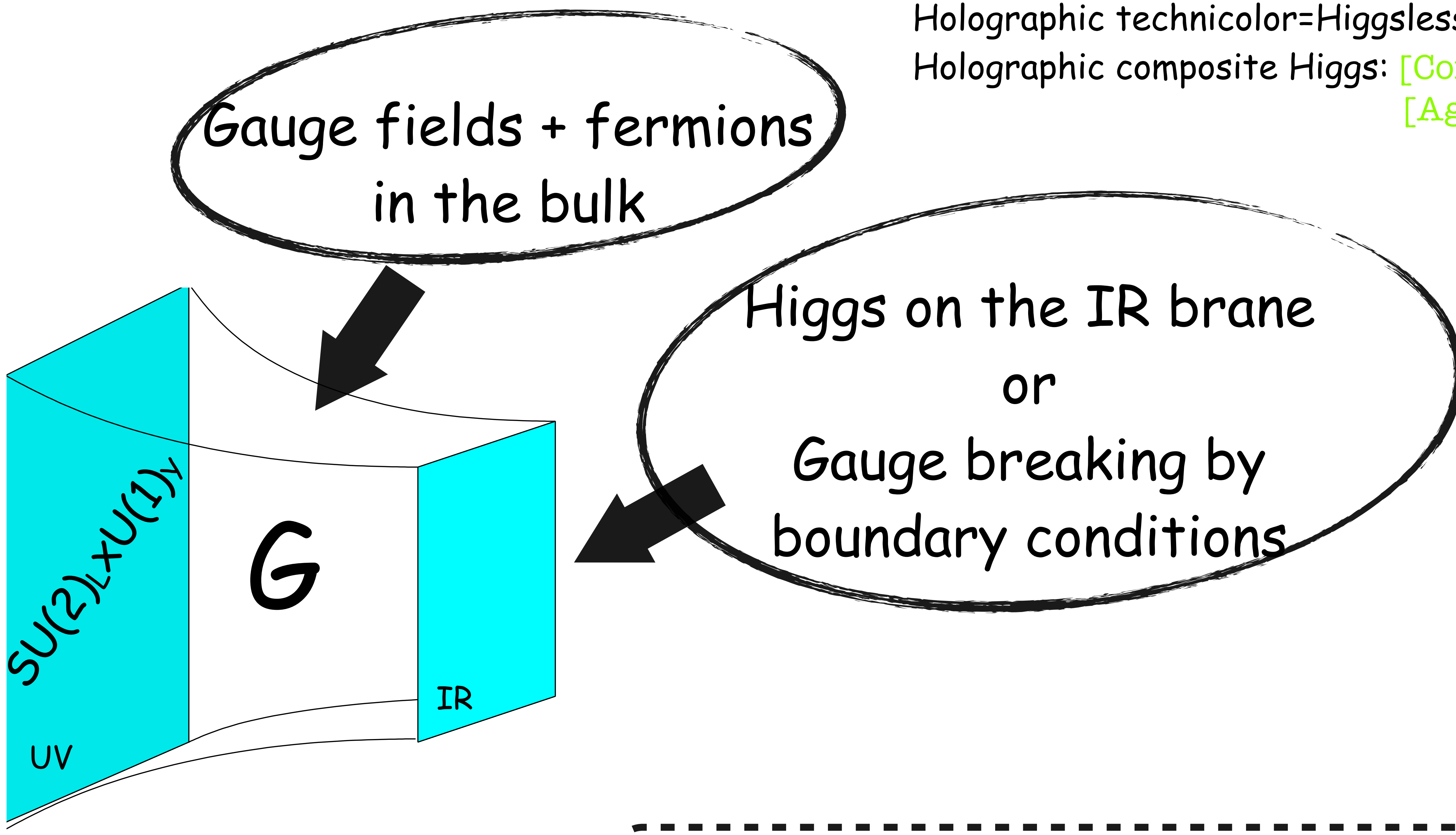
Little Hierachy pb

2 solutions: 1) higgsless breaking 2) higgs as A_5

- cutoff ~ 1 TeV
- conflict with EW precision data
- problems with flavor

Holographic Models of EWSB

Bulk gauge fields: [Pomarol, ’00]
Holographic technicolor=Higgsless: [Csaki et al., ‘03
Holographic composite Higgs: [Contino et al., ’03]
[Agashe et al., ’04]



G=SU(2)LxSU(2)RxU(1)B-L
G=SO(5)xU(1)X
G=SO(6)xU(1)X

- UV completion: log running of gauge couplings
- Custodial symmetry from bulk SU(2)R

Composite Higgs Models

what is the SM Higgs? ➲ what is a composite Higgs? ➲,

Higgs anomalous couplings ➲ strong scatterings ➲

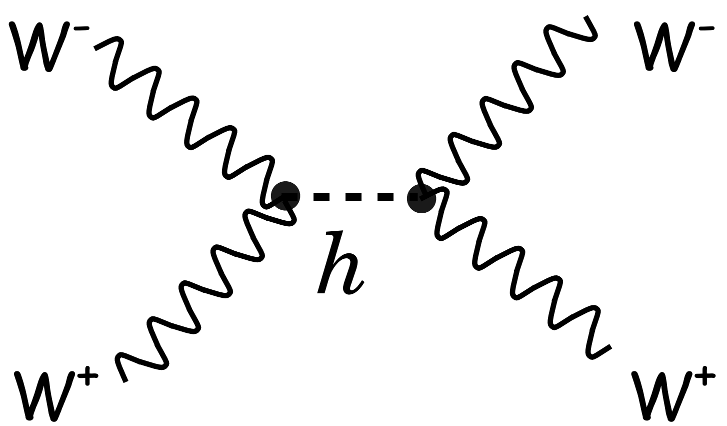
triple Higgs production ➲ resonances production ➲

What is the SM Higgs?

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

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

'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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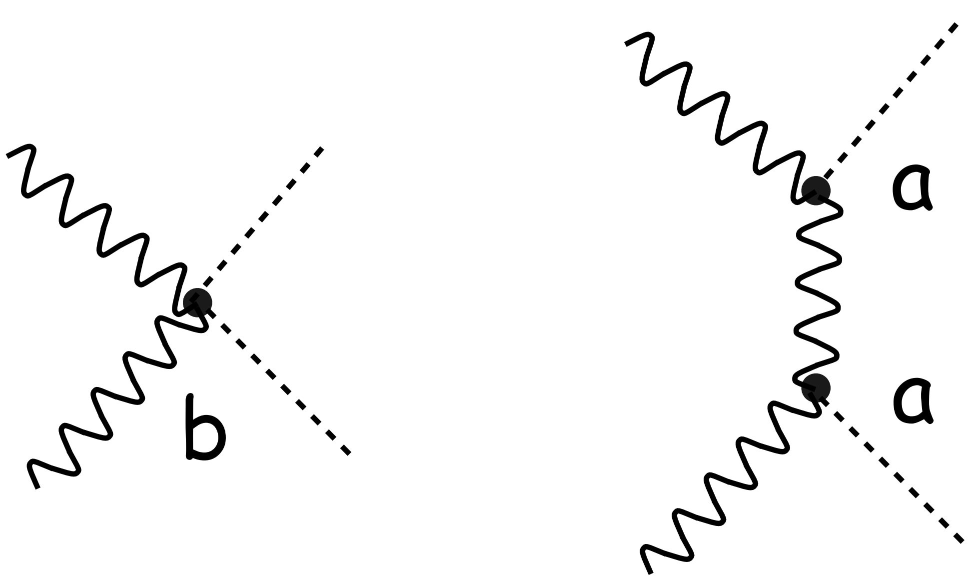

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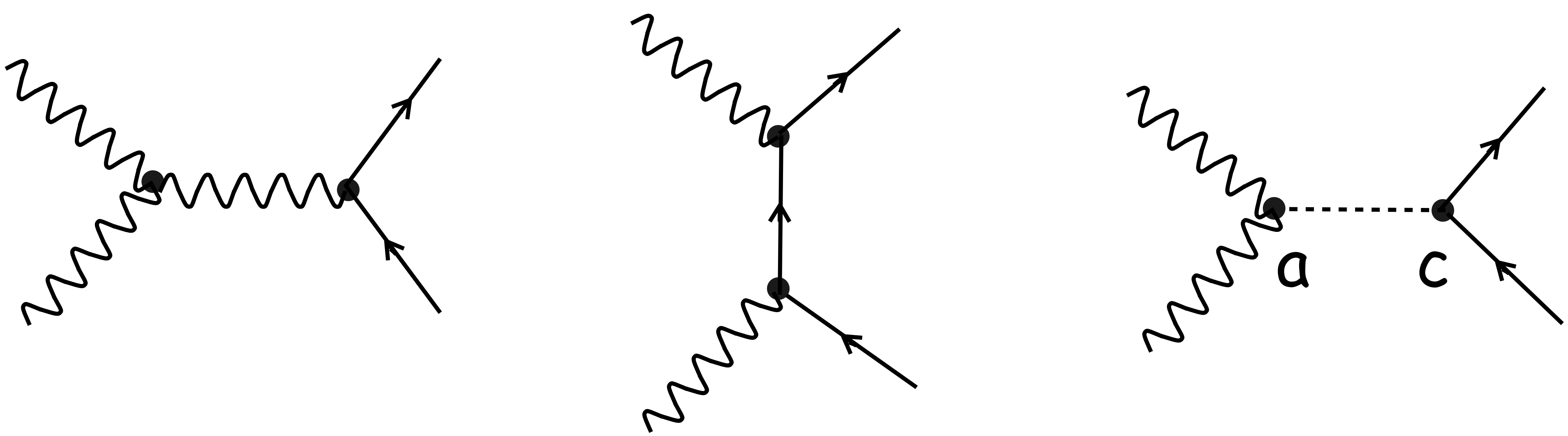

What is the SM Higgs?

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

For ac=1: perturbative unitarity in inelastic $WW \to \psi\,\psi$

'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 $SU(2)_L \times U(1)_Y$

What is a composite Higgs?

A σ particle that combines with W_L and Z_L to form a SU(2) doublet

renormalizable level = uniqueness

$SU(2)_L \times U(1)_Y$ linearly realized $\Leftrightarrow$ Standard Model $\Leftrightarrow$ a=b=c=1

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non-renormalizable level

$SU(2)_L \times U(1)_Y$ linearly realized & a, b, c ≠ 1 $\Leftrightarrow$ Composite Higgs

deviations of Higgs couplings originate from higher dimensional operators

$$\left(\partial_\mu |H|^2\right)^2 \quad |H|^2 \bar{\psi} H \psi \quad |H|^2 B_{\mu\nu} B^{\mu\nu} \quad |H|^2 G_{\mu\nu} G^{\mu\nu}$$

Anomalous 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 $\frac{1}{\sqrt{1 + c_H \frac{v^2}{f^2}}} \sim 1 - c_H \frac{v^2}{2f^2} \equiv 1 - \xi/2$

$$\boxed{\begin{array}{c} \xi = v^2/f^2 \\ a = 1-\xi/2 \qquad b = 1-2\xi \qquad c = 1-\xi/2 \end{array}}$$

Deformation of the SM Higgs: current constraints

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

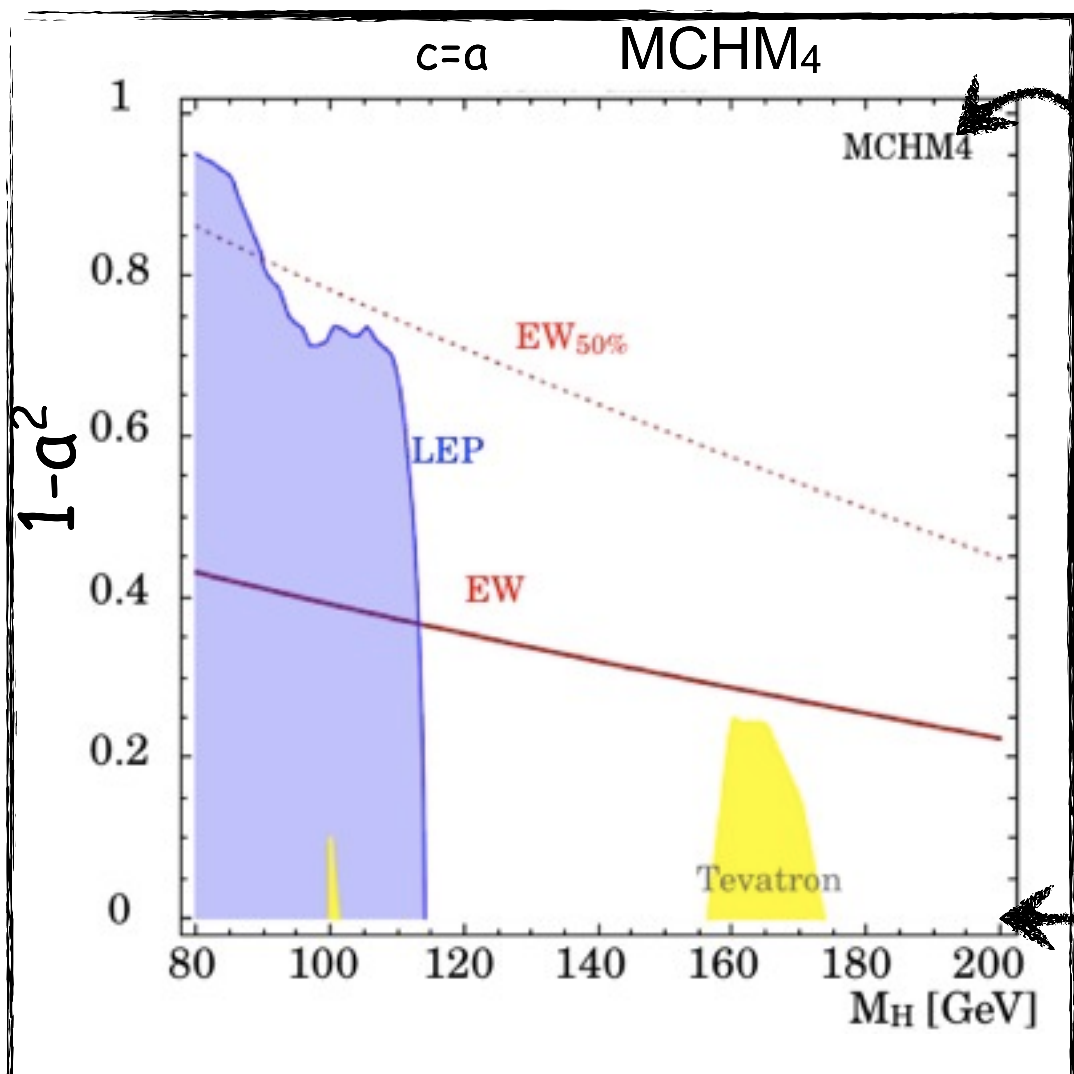
$\Sigma = e^{i\sigma^a\pi^a/v}$ Goldstone of $SU(2)_L\times SU(2)_R/SU(2)_V$ $D_\mu\Sigma \approx W_\mu$

SM 'a=1', 'b=1' & 'c=1'

Current EW data constrain only 'a' (and marginally 'c')

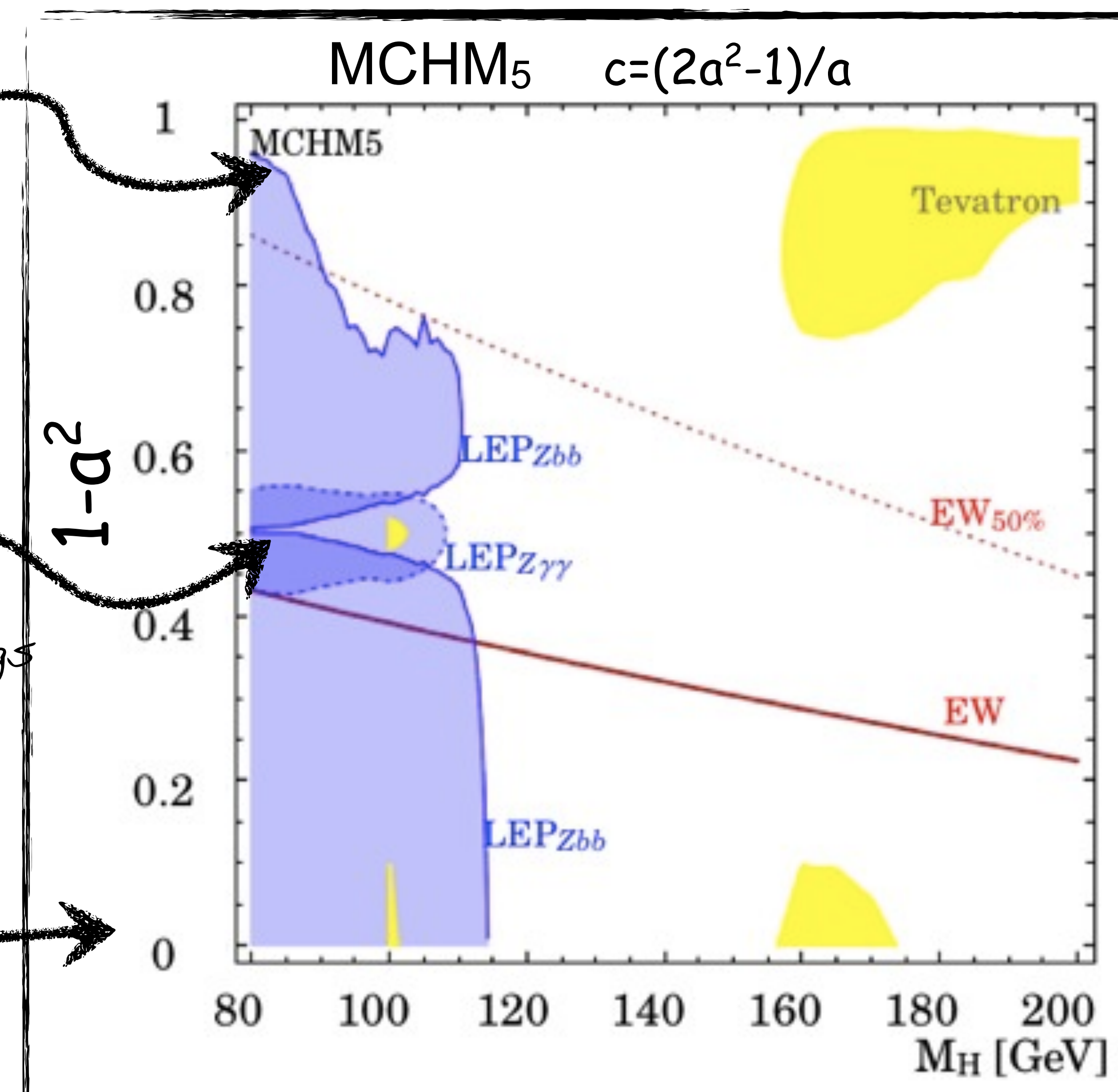
Espinosa, Grojean, Muehlleitner '10

gaugephobic Higgs

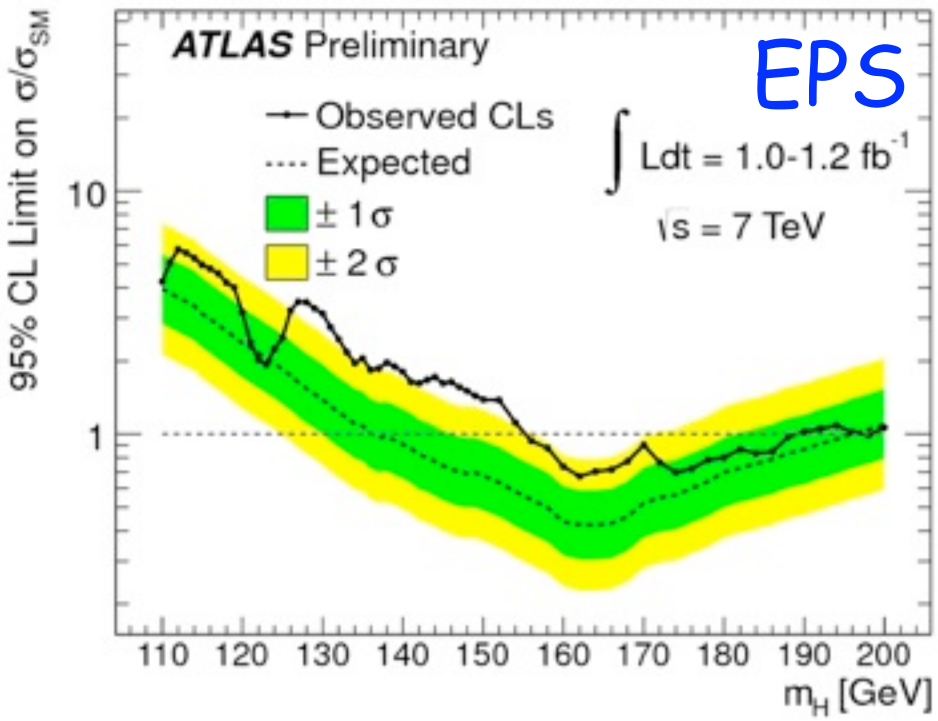


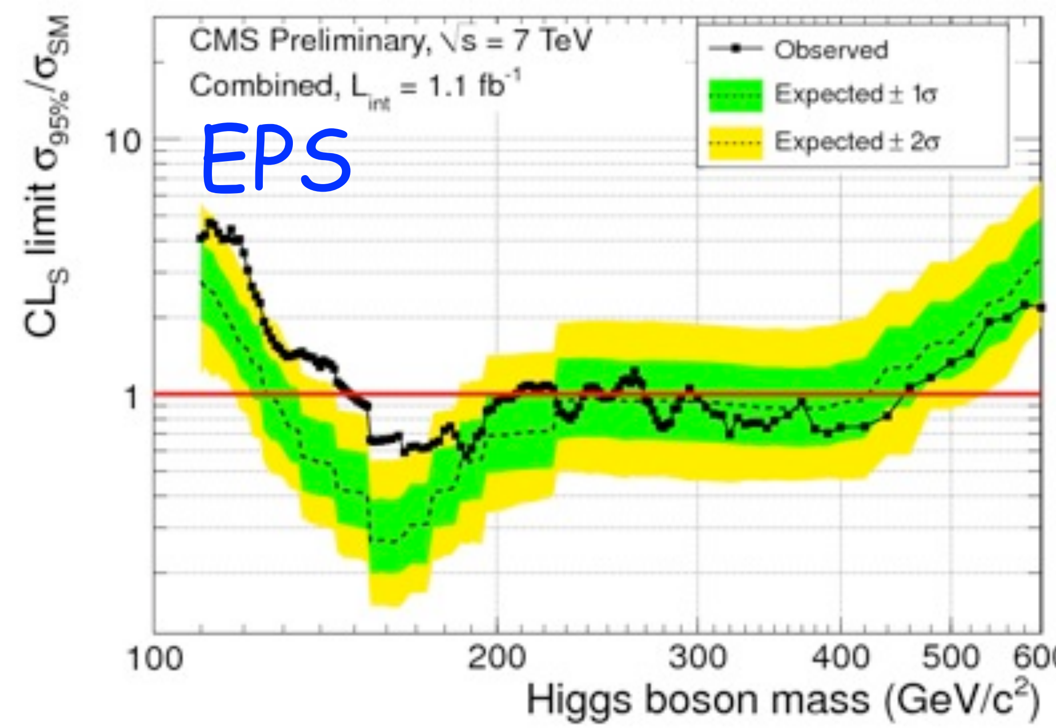
fermiophobic Higgs

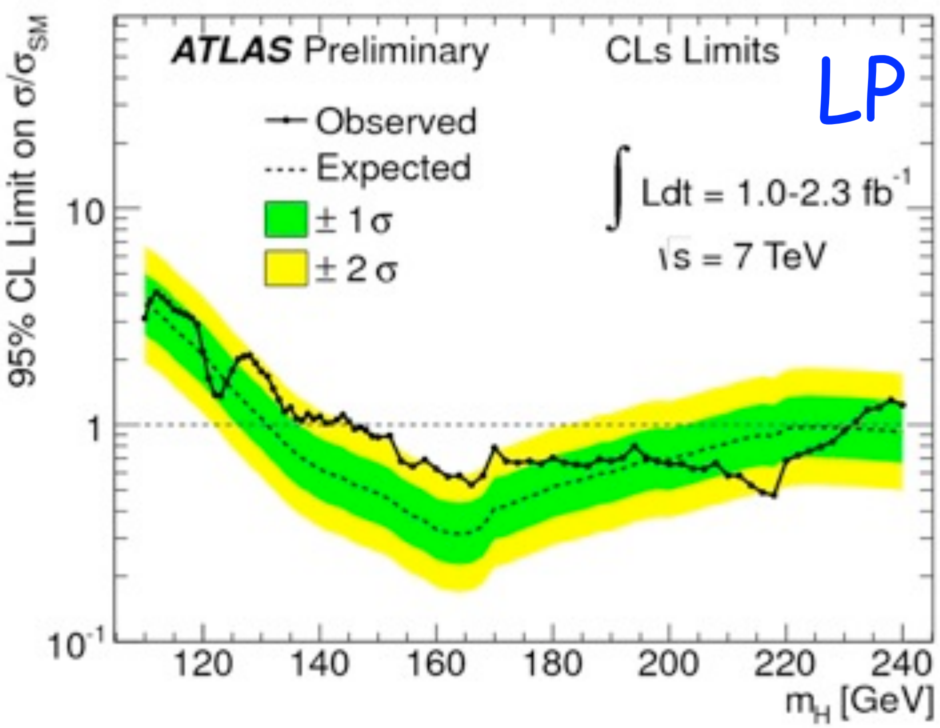
SM limit

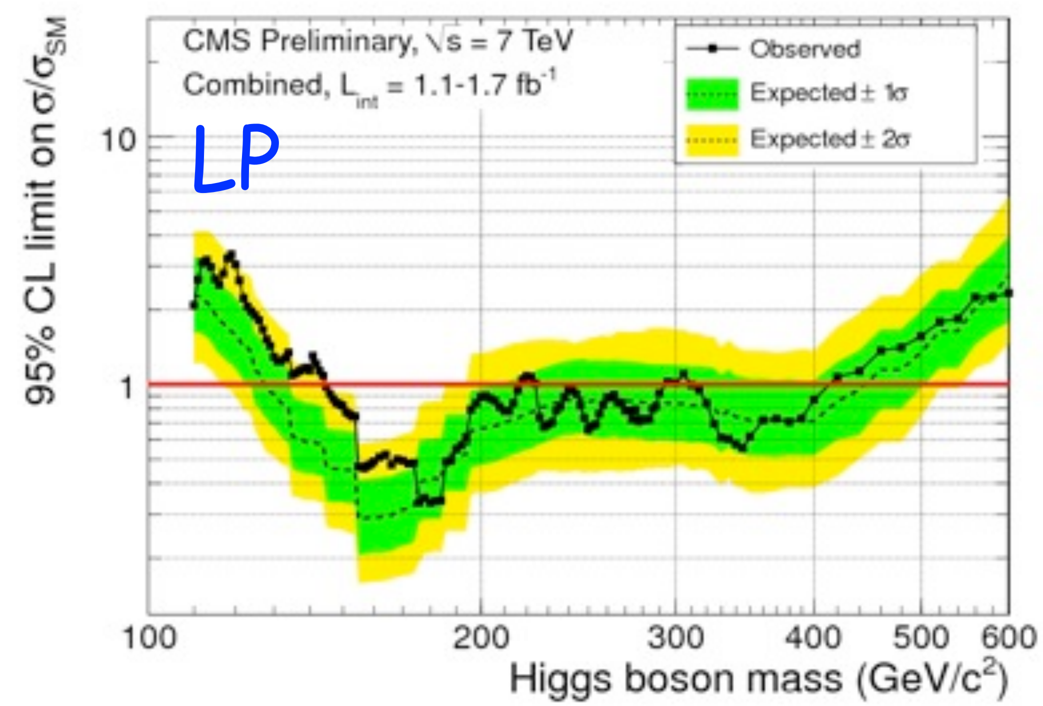


Deformation of the SM Higgs: LHC constraints









LHC is now a Higgs exploring machine

(and it has quickly surpassed Tevatron)

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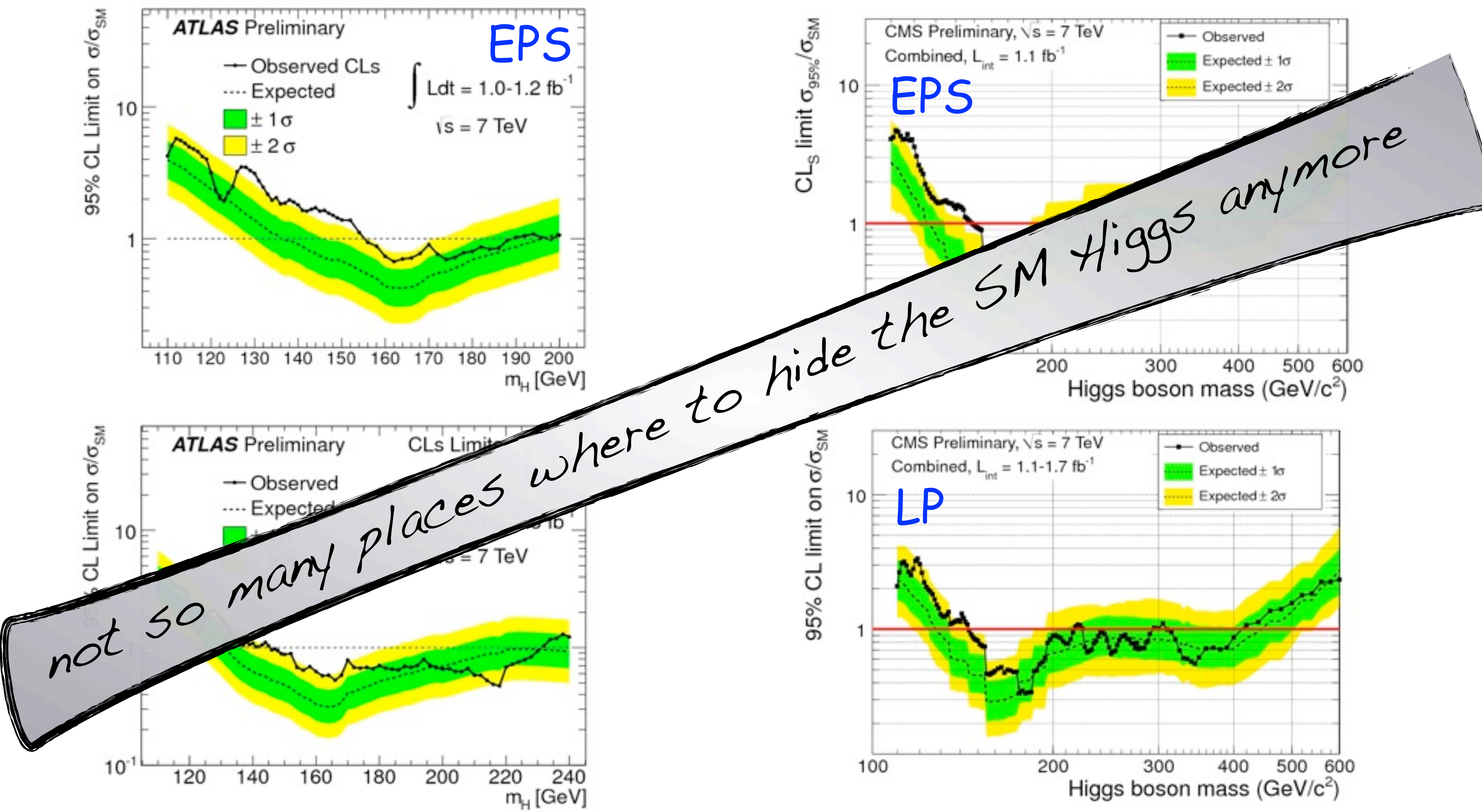

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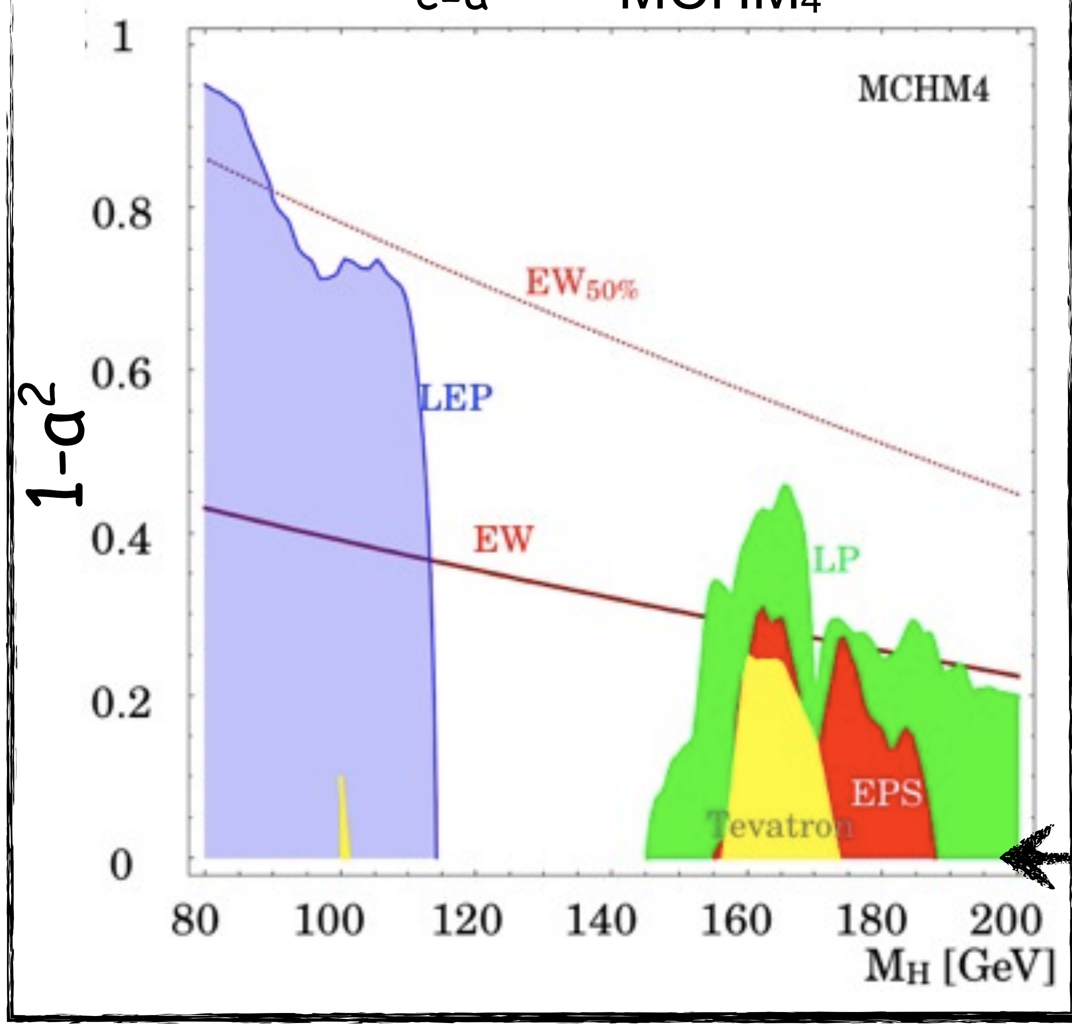
(LightCompositeHiggs) LCH@LHC

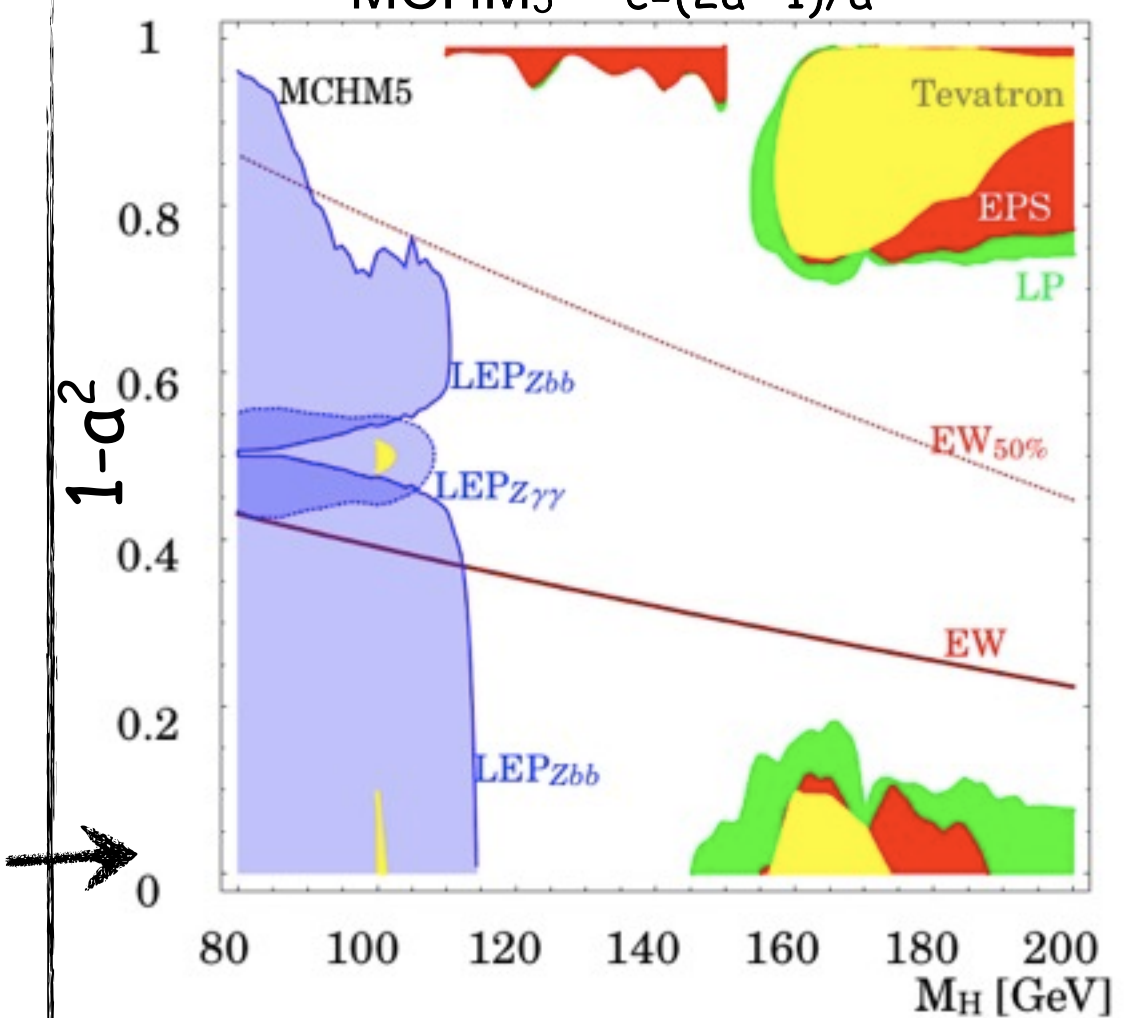
the SM exclusion bounds are easily rescaled in the (m_H,a) plane

Espinosa, Grojean, Muehlleitner '11

c=a MCHM4



MCHM5 c=(2a²-1)/a



SM limits

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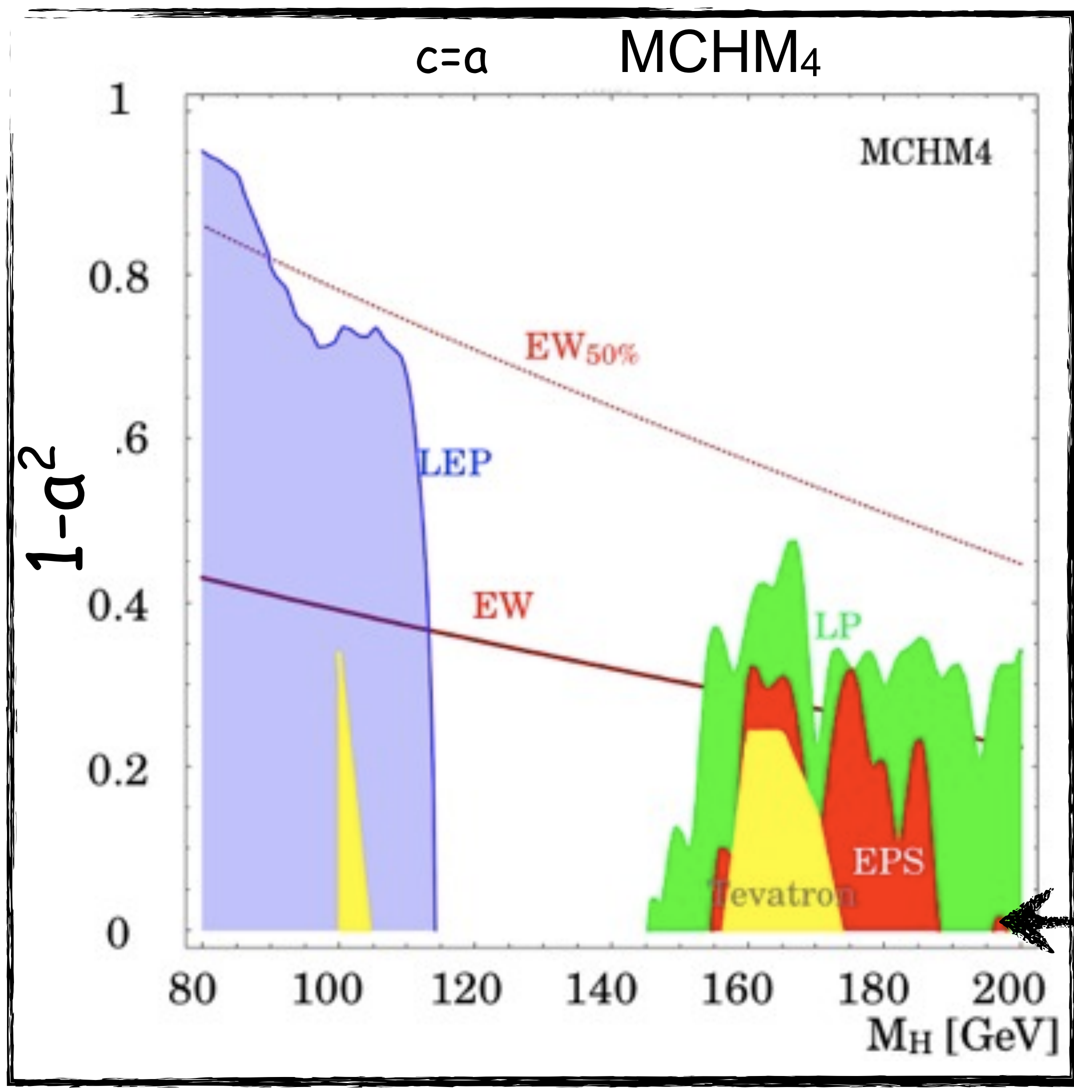
Espinosa, Grojean, Muehlleitner '11



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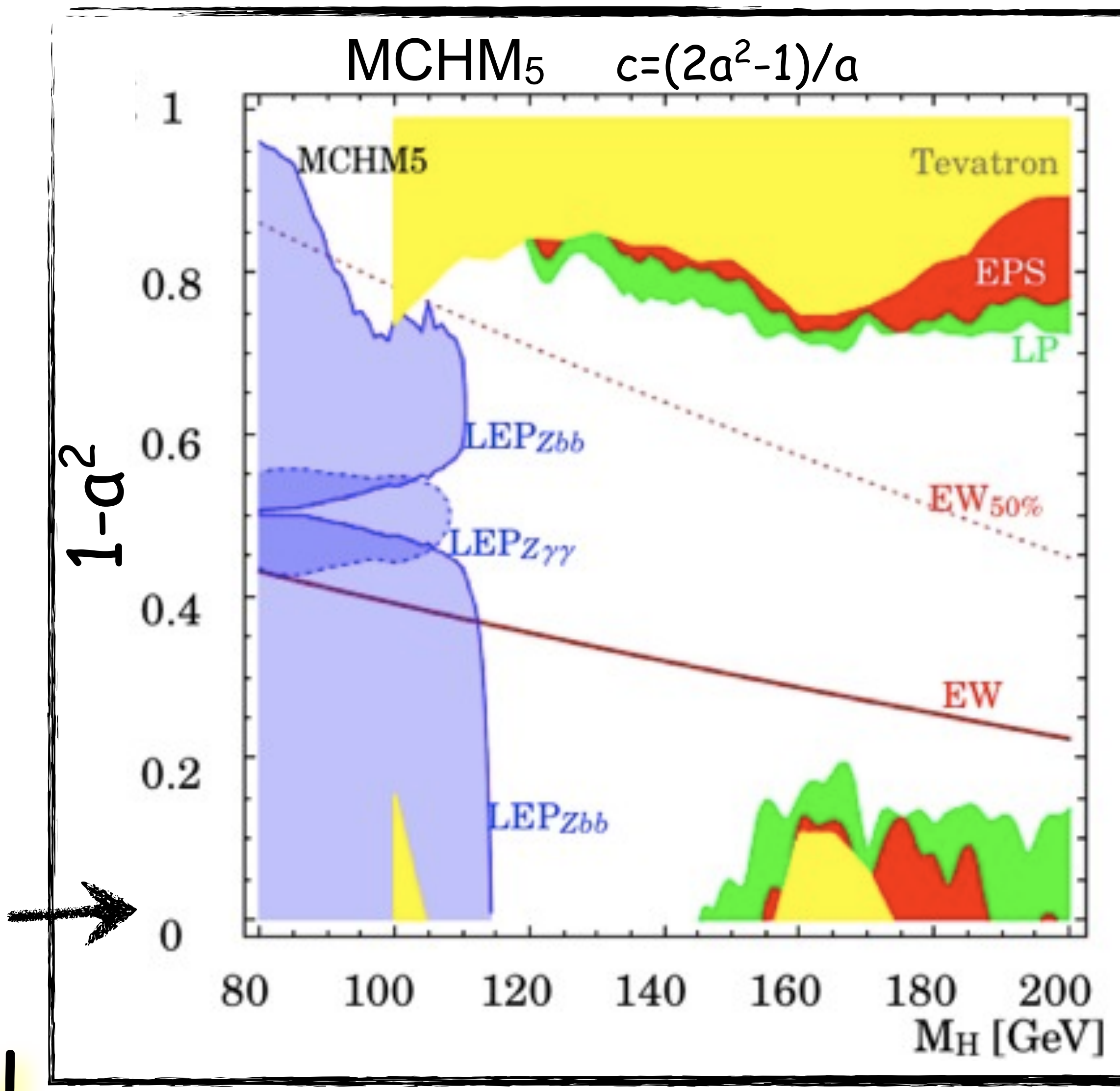
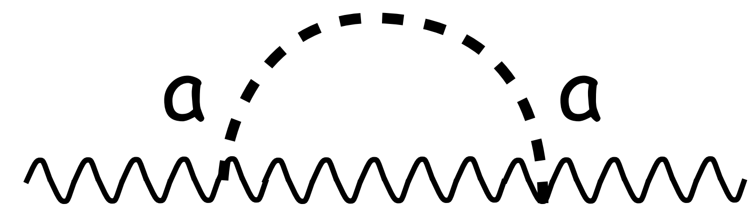


Be careful

- rescaling combination ≠ combination of the rescaled channels
  (can be particularly important far away from SM)
- effeciency of the cuts may also depends on ξ

Deformation of the SM Higgs: EW constraints

The parameter 'a' controls the size of the one-loop IR contribution to the LEP precision observables



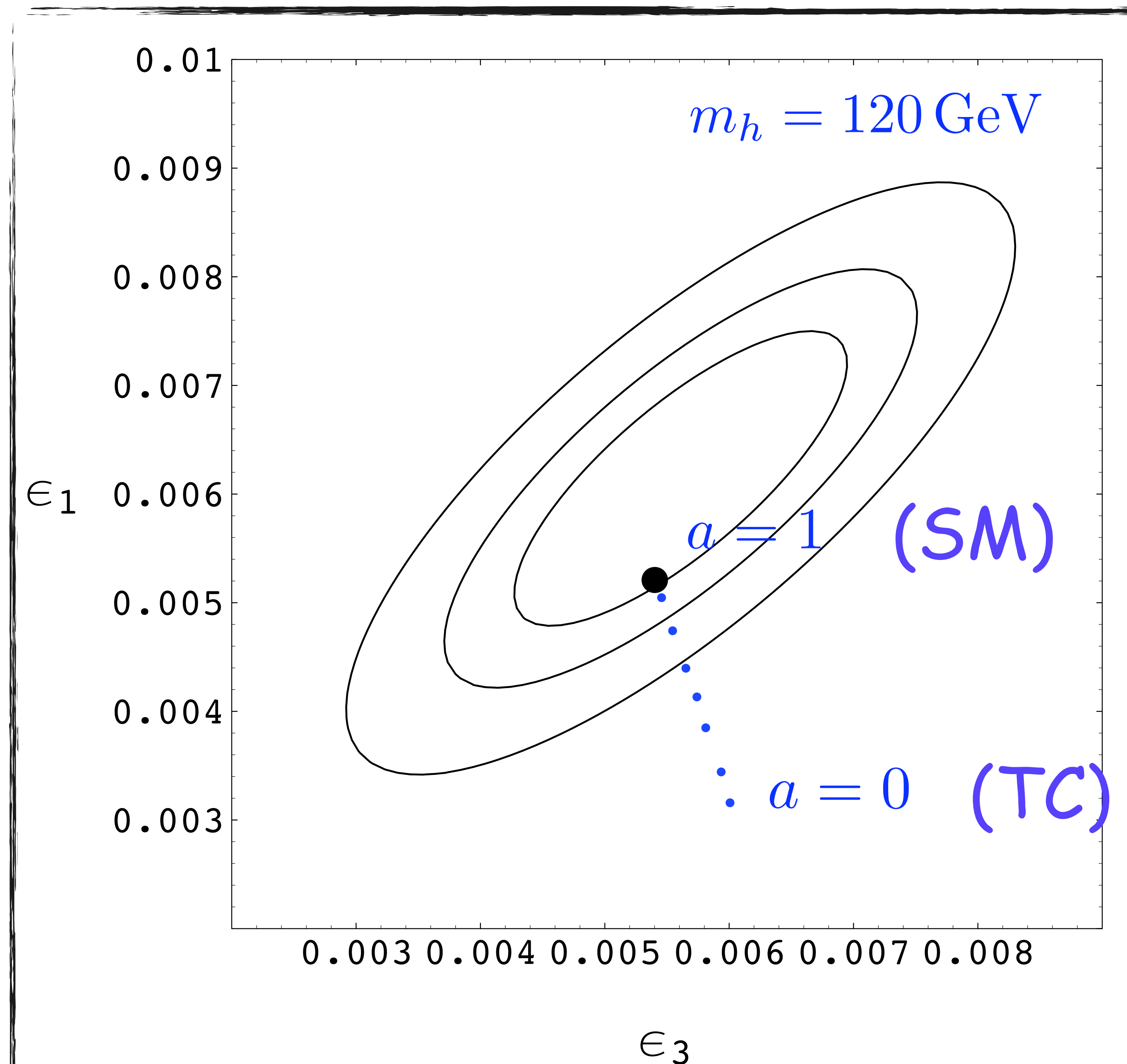
$$\epsilon_{1,3} = c_{1,3}\log(m_Z^2/\mu^2) - c_{1,3}\, a^2 \log(m_h^2/\mu^2) - c_{1,3}\,\left(1-a^2\right)\log(m_\rho^2/\mu^2) + \text{finite terms}$$

$$c_1 = +\frac{3}{16\pi^2}\frac{\alpha(m_Z)}{\cos^2\theta_W}$$

$$c_3 = -\frac{1}{12\pi}\frac{\alpha(m_Z)}{4\sin^2\theta_W}$$

$$\Delta\epsilon_{1,3} = -c_{1,3}\,\left(1-a^2\right)\log(m_\rho^2/m_h^2)$$

Barbieri, Bellazzini, Rychkov, Varagnolo '07

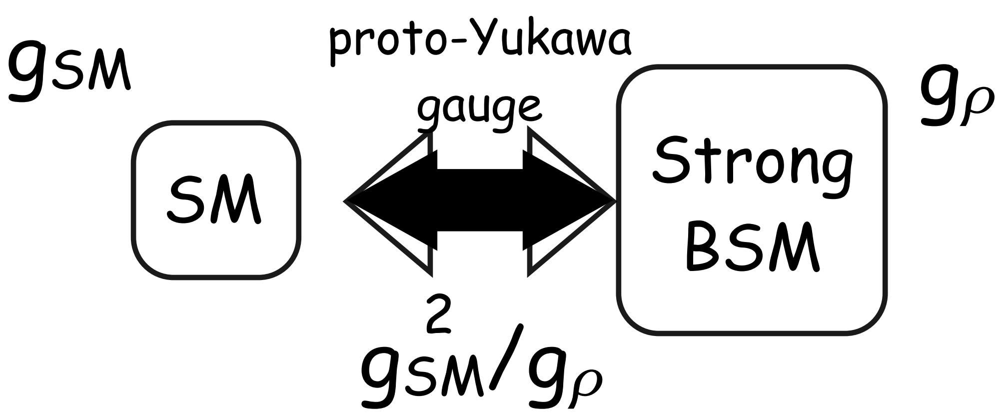


How to obtain a light composite Higgs?

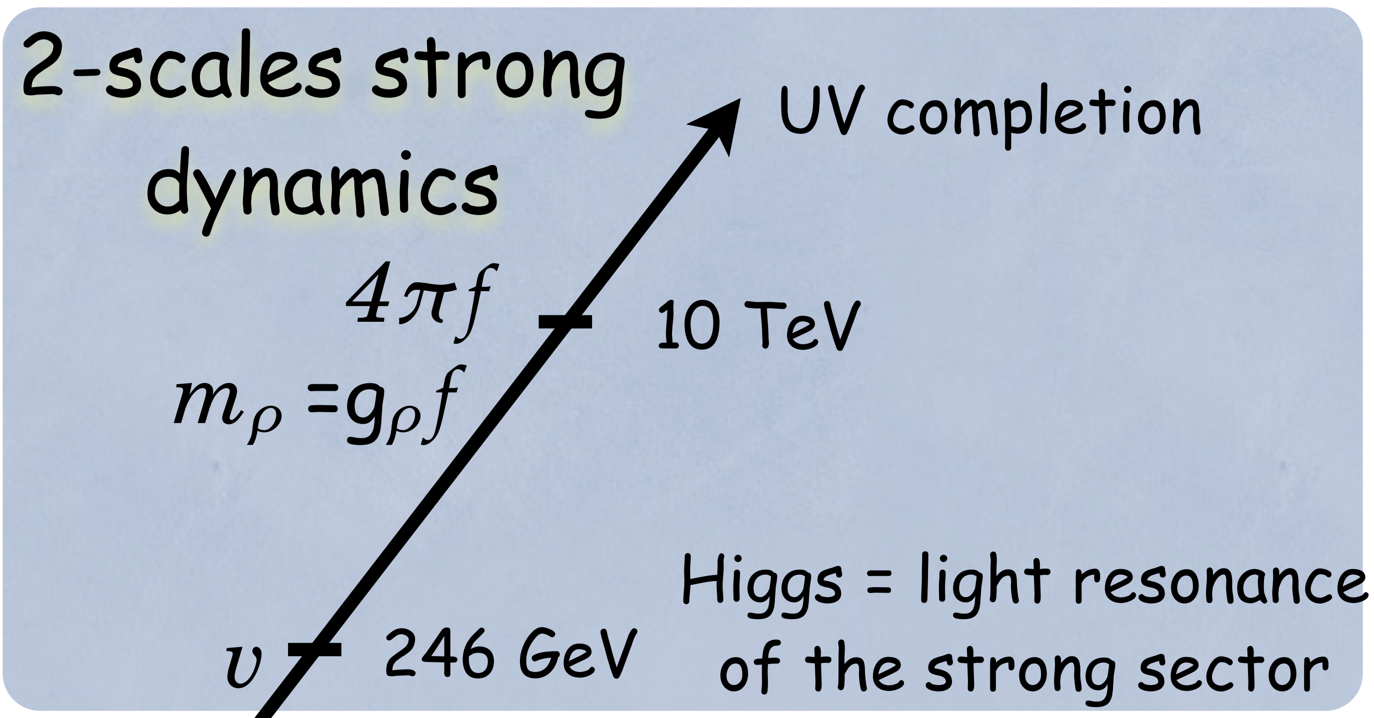
Georgi, Kaplan '84 Giudice, Grojean, Pomarol, Rattazzi '07

Higgs=Pseudo-Goldstone boson of the strong sector

$m_{Higgs}=0$ when $g_{SM}=0$



global symmetry $\longrightarrow$ G/H $\longleftarrow$ residual global symmetry



Coset broken by SM couplings
$\Rightarrow$ Higgs potential

v/f≈0.2÷0.3 generated dynamically
(might require mild-tuning in explicit models)

strong sector broadly characterized by 2 parameters

m_ρ = mass of the resonances

g_ρ = coupling of the strong sector or decay cst of strong sector $f = m_\rho / g_\rho$

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 ⇒ G/H $W^{\pm}_L$ & Z_L & h *BSM*

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

$SO(6)/SO(4)\times SO(2)$: 8 PGBs=H_1+H_2 — Minimal Composite Two Higgs Doublets

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

Continuous interpolation between SM and TC

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

$$\xi = 0$$

SM limit

all resonances of strong sector, except the Higgs, decouple

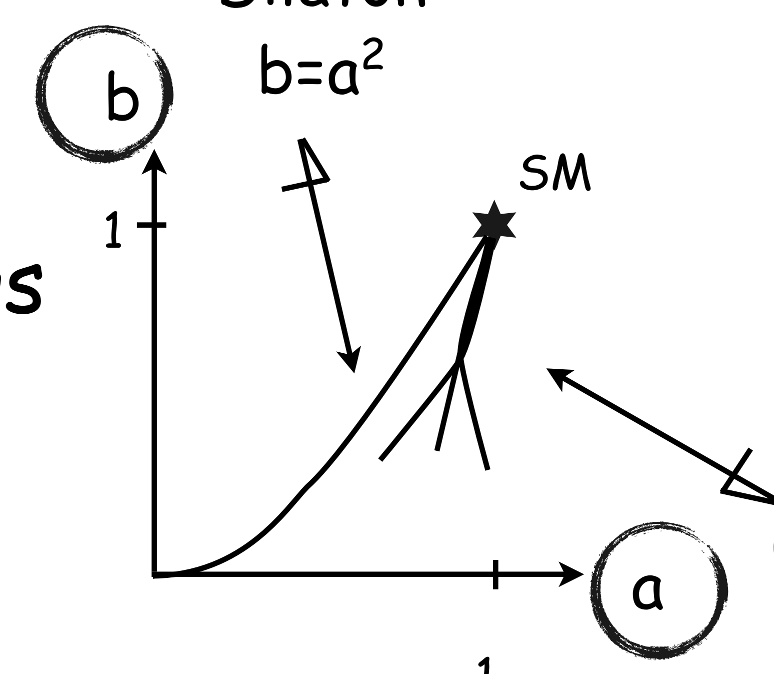
$$\xi = 1$$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

Composite Higgs vs. SM Higgs

Dilaton
b=a^2



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

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

SILH Effective Lagrangian

(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi '07

- extra Higgs leg: H/f
- extra derivative: ∂/m_ρ

Genuine strong operators (sensitive to the scale f)

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

custodial breaking

Form factor operators (sensitive to the scale m_ρ)

$$\frac{ic_W}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i \qquad \frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$\frac{ic_{HW}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} \qquad \frac{ic_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} \qquad \frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

Goldstone sym.

EWPT constraints

$$\hat{T} = c_T \frac{v^2}{f^2} \Longrightarrow |c_T \frac{v^2}{f^2}| < 2 \times 10^{-3}$$

removed
by custodial symmetry

$$\hat{S} = (c_W + c_B) \frac{m_W^2}{m_\rho^2} \Longrightarrow$$

$$m_\rho \geq (c_W + c_B)^{1/2}\, 2.5\,\mathrm{TeV}$$

EWPT constraints

$$\hat{T} = c_T \frac{v^2}{f^2} \Rightarrow \left| c_T \frac{v^2}{f^2} \right| < 2 \times 10^{-3}$$

removed by custodial symmetry

$$\hat{S} = (c_W + c_B) \frac{m_W^2}{m_\rho^2} \Rightarrow m_\rho \geq (c_W + c_B)^{1/2}\, 2.5\,\text{TeV}$$

There are also some 1-loop IR effects

Barbieri, Bellazzini, Rychkov, Varagnolo '07

$$\hat{S}, \hat{T} = a \log m_h + b$$

modified Higgs couplings to matter

$$\Downarrow$$

$$\hat{S}, \hat{T} = a \left((1 - c_H \xi) \log m_h + c_H \xi \log \Lambda \right) + b$$

effective Higgs mass

$$m_h^{eff} = m_h \left(\frac{\Lambda}{m_h} \right)^{c_H v^2/f^2} > m_h$$

LEPII, for m_h~115 GeV: $c_H v^2/f^2 < 1/3 \div 1/2$

IR effects can be cancelled by heavy fermions (model dependent)

Flavor Constraints

$$\left(1+\frac{c_{ij}|H|^2}{f^2}\right)y_{ij}\bar{f}_{Li}Hf_{Rj}=\left(1+\frac{c_{ij}v^2}{2f^2}\right)\frac{y_{ij}v}{\sqrt{2}}\bar{f}_{Li}f_{Rj}$$

$$\left(1+\frac{3c_{ij}v^2}{2f^2}\right)\frac{y_{ij}v}{\sqrt{2}}h\bar{f}_{Li}f_{Rj}$$

mass terms

Higgs fermion interactions

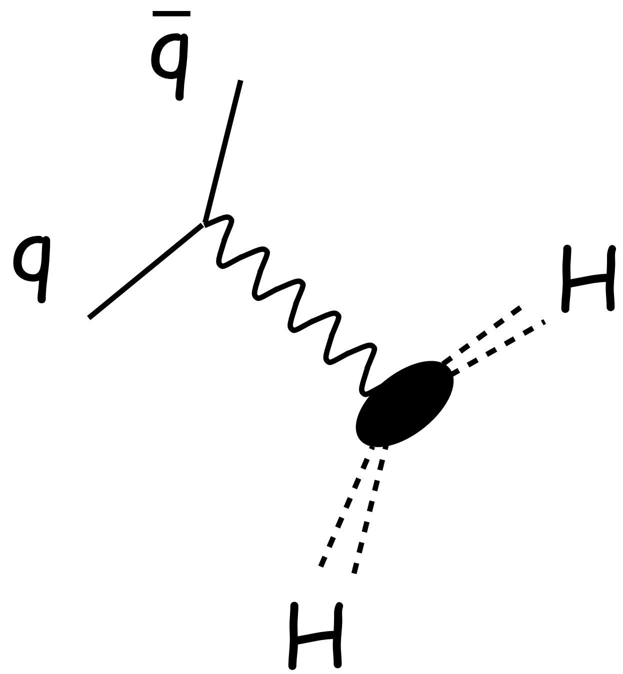
mass and interaction matrices are not diagonalizable simultaneously if c_{ij} are arbitrary

$\Rrightarrow$ FCNC

SILH: c_y is flavor universal

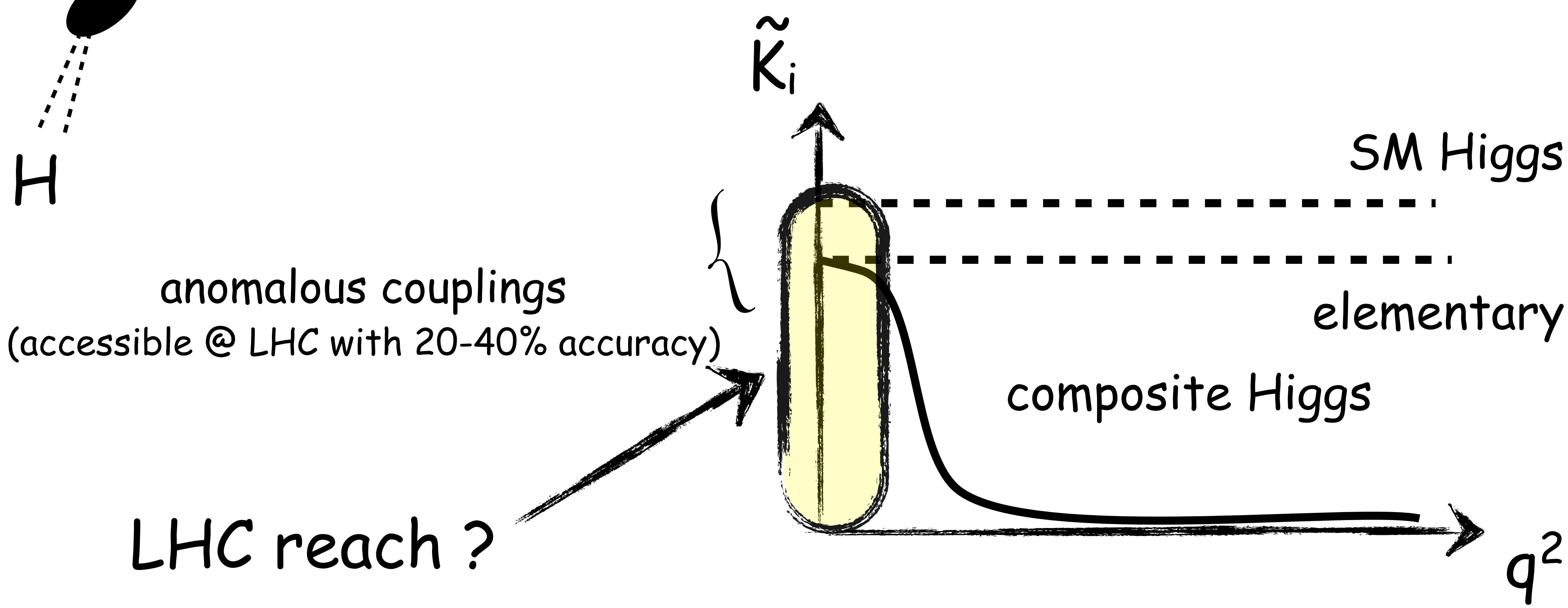
$\Rrightarrow$ Minimal flavor violation built in

How to probe the compositeness of the Higgs?



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16 m_H^2 \sin^4\theta/2}\frac{E'}{E^3}\left(2\tilde{K}_1 q^2 \sin^2\theta/2 + \tilde{K}_2\cos^2\theta/2\right)$$

Rosenbluth-type cross-section



Need to develop tools to understand the physics of a composite Higgs

- use effective theory approach
- rely on symmetries of the problem

} identify interesting processes

How to probe the composite nature of the Higgs?

1. Anomalous Higgs couplings

Higgs anomalous couplings for large v/f

The SILH Lagrangian is an expansion for small v/f
5D MCHM give a completion for large v/f

$$m_W^2 = \frac{1}{4} g^2 f^2 \sin^2 v/f \;\Rrightarrow\; g_{hWW} = \sqrt{1-\xi}\, g_{hWW}^{\rm SM} \;\Rrightarrow\; \begin{cases} a = \sqrt{1-\xi} \\ b = 1 - 2\xi \end{cases}$$

Fermions embedded in spinorial of SO(5)

MCHM4

$$m_f = M \sin v/f$$

$$\Downarrow$$

$$g_{hff} = \sqrt{1-\xi}\, g_{hff}^{\rm SM}$$

$$\Downarrow$$

$$c = \sqrt{1-\xi}$$

universal shift of the couplings
no modifications of BRs

Fermions embedded in 5+10 of SO(5)

MCHM5

$$m_f = M \sin 2v/f$$

$$\Downarrow$$

$$g_{hff} = \frac{1-2\xi}{\sqrt{1-\xi}}\, g_{hff}^{\rm SM}$$

$$\Downarrow$$

$$c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

BRs now depends on v/f

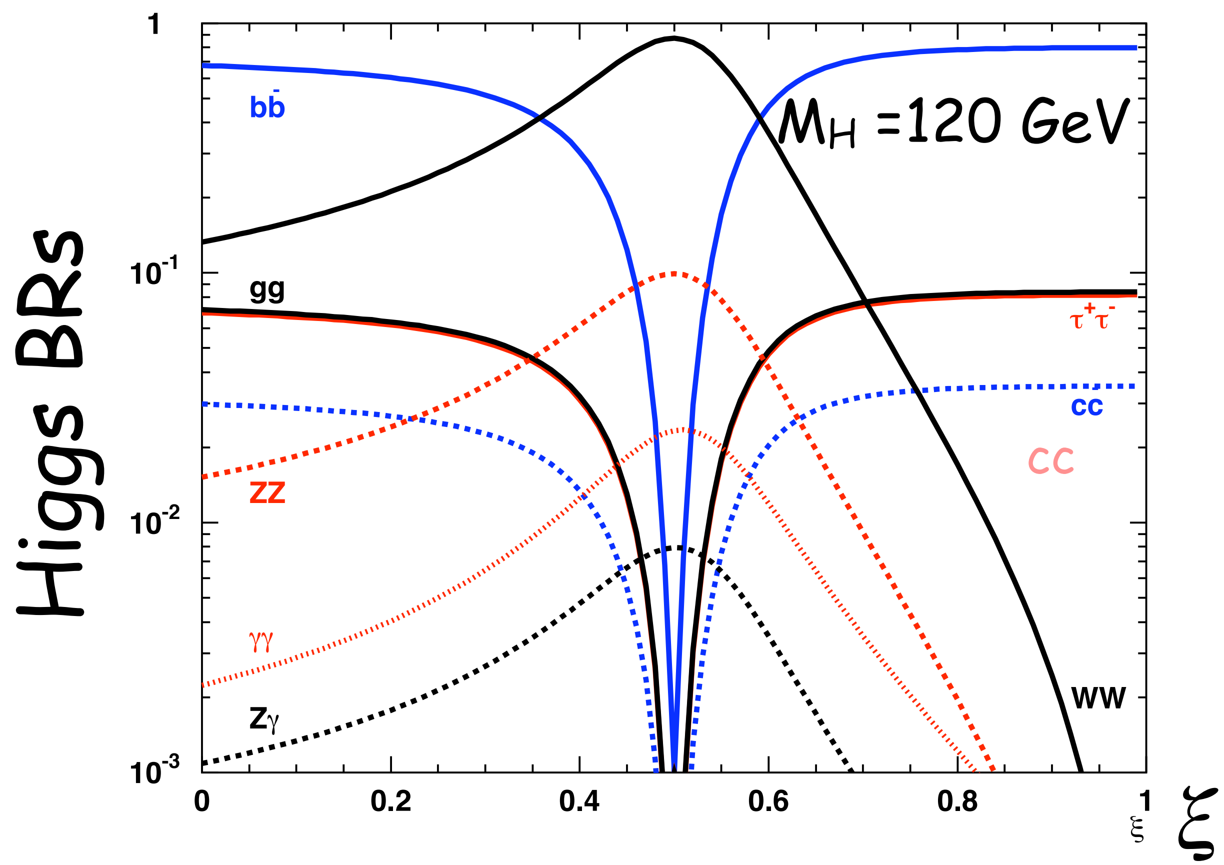
$$\left(\xi = v^2/f^2\right)$$

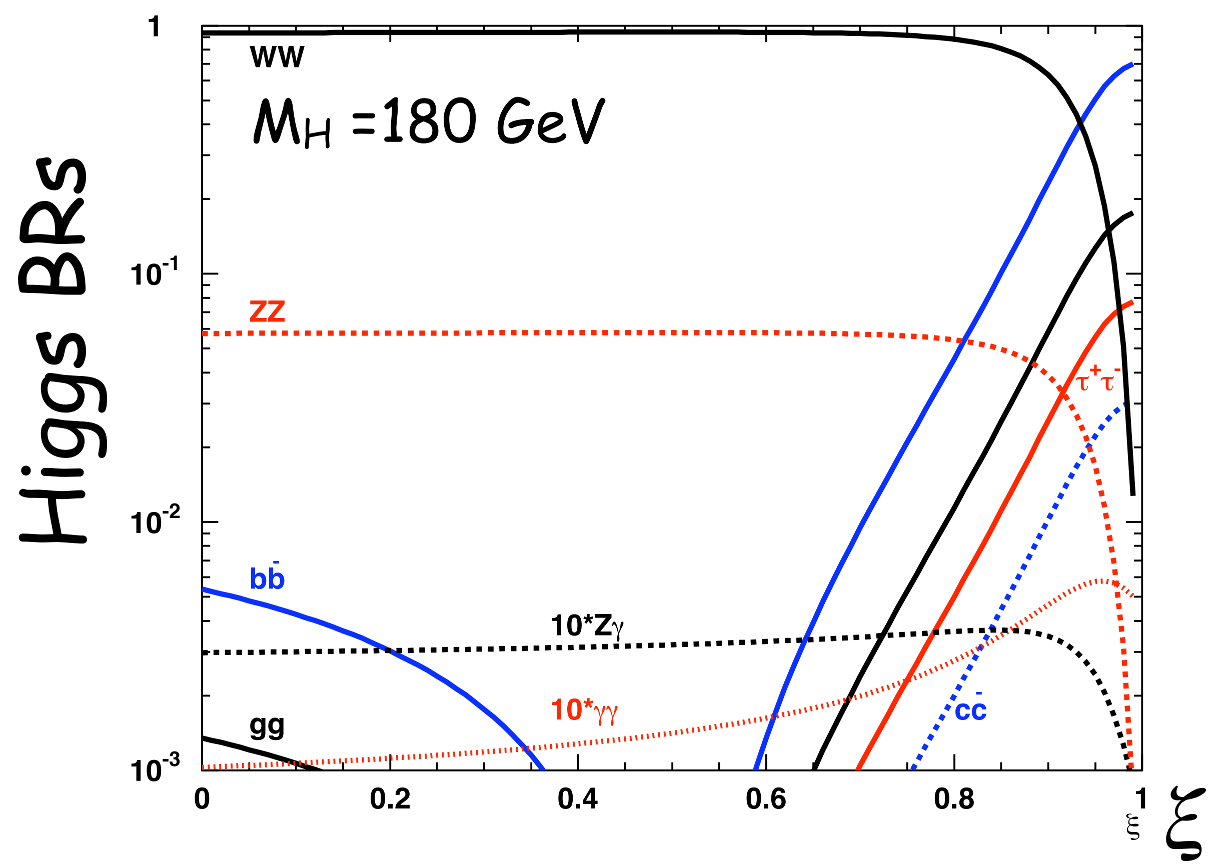
Higgs BRs

MCHM5

Fermions embedded in 5+10 of SO(5)

$$a = \sqrt{1-\xi} \quad b = 1 - 2\xi \quad c = \frac{1-2\xi}{\sqrt{1-\xi}}$$





h→WW can dominate
even for low Higgs mass

BRs remain SM like except
for very large values of v/f

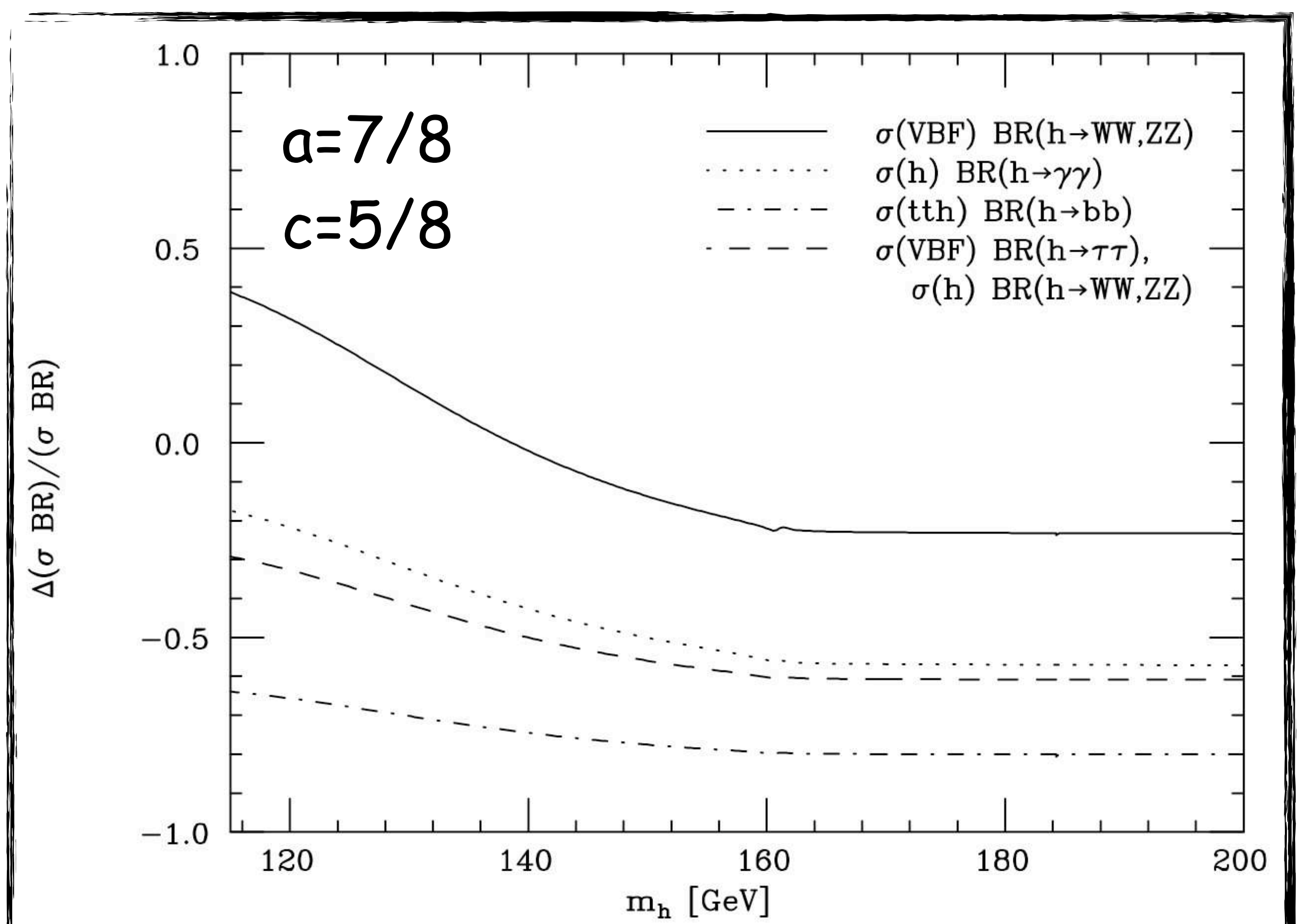
Higgs anomalous couplings @ LHC

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

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

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

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



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?

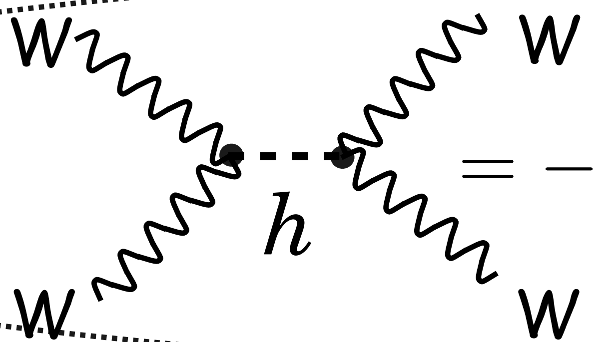
2. Processes probing the strong interactions

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

$$\mathcal{A}\left(W_L^a W_L^b \to W_L^c W_L^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc} \qquad \mathcal{A} = \left(1-a^2\right)\frac{s}{v^2}$$

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

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

How to probe the strong dynamics?

Look at pair production of strong states

Giudice, Grojean, Pomarol, Rattazzi '07

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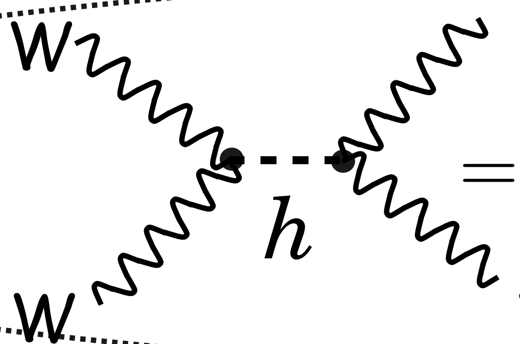

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large $\mathcal{L}_{int}$ needed

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

- 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'

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

Scale of Strong WW scattering?

$$\mathcal{A}_{TT\to TT} \sim g^2 f(t/s)$$

f is a rational fct
expected O(1) for t~-s/2

$$\mathcal{A}_{LL\to LL} \sim \frac{s}{v^2}$$

onset of strong scattering at the weak scale

hard cross-section
(t~-s/2)

$$\left.\frac{d\sigma_{LL\to LL}/dt}{d\sigma_{TT\to TT}/dt}\right|_{t\sim -s/2} = N_h \frac{s^2}{M_W^4}$$

'inclusive' cross-section
$(-s+Q^2_{\min} < t < -Q^2_{\min})$

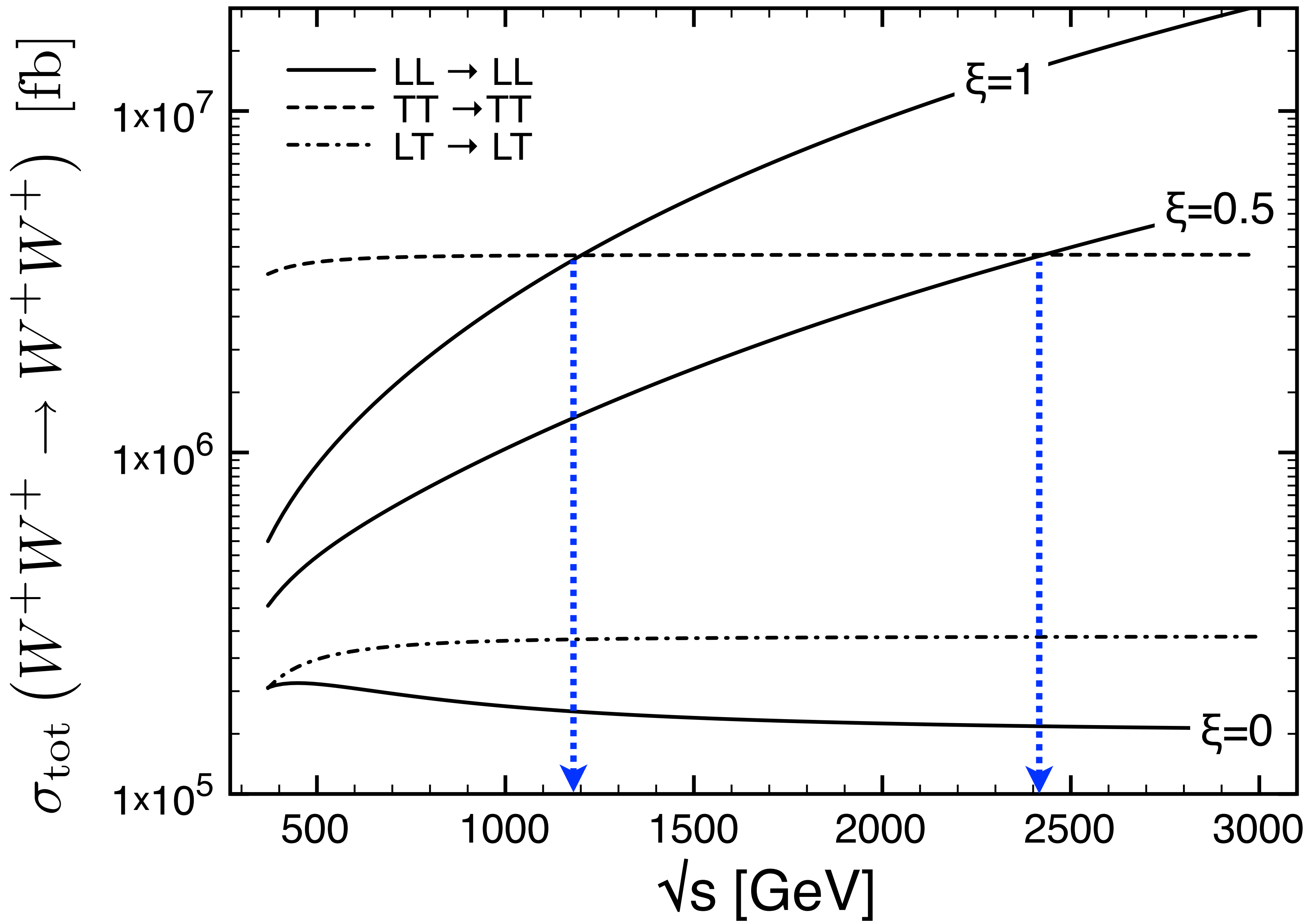
$$\frac{\sigma_{LL\to LL}(Q_{\min})}{\sigma_{TT\to TT}(Q_{\min})} = N_s \frac{s\, Q^2_{\min}}{M_W^4}$$

NDA estimates

$$N_h \sim 1 \qquad\qquad N_s \sim 1$$

Total cross sections

disentangling L from T polarization is hard



The onset of strong scattering is delayed to larger energies due to the dominance of TT → TT background

The dominance of T background will be further enhanced by the pdfs since the luminosity of W_T inside the proton is $\log(E/M_W)$ enhanced

Coulomb enhancement (SM)

$W^+W^+ \to W^+W^+$

the total cross section is dominated by the poles
in the exchange of γ and Z in the t- and u-channels

$$\mathcal{A} = \frac{a^t_\gamma\, s}{t} + \frac{a^t_Z\, s}{t - M_Z^2} + \frac{a^u_\gamma\, s}{u} + \frac{a^u_Z\, s}{u - M_Z^2} + \ldots \qquad \sigma \sim \frac{1}{16\pi}\left(\frac{{a^t_\gamma}^2 + {a^u_\gamma}^2}{M_\gamma^2} + \frac{{a^t_Z}^2 + {a^u_Z}^2}{M_\gamma^2 + M_Z^2}\right)$$

M_γ = regulateur of Coulomb singularity=off-shellness of W ~ M_W

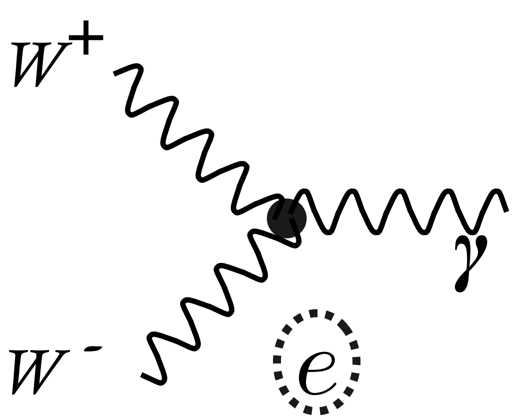
eïkonal limit

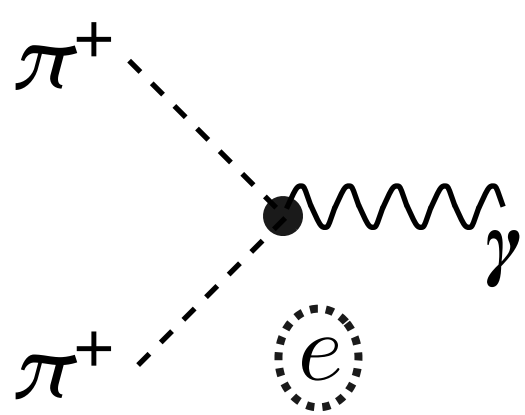
$a_\gamma = 2 \cdot (\text{electric charge of } W^+)^2$

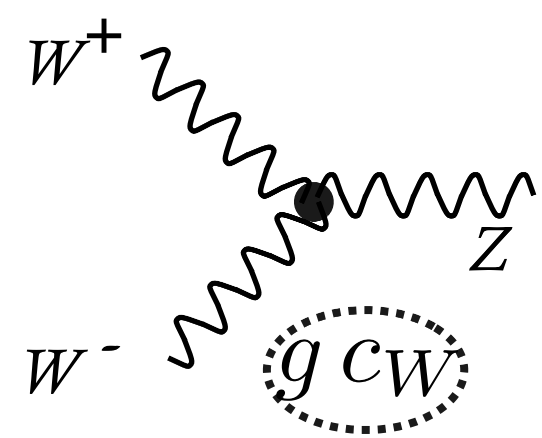
universal for T and L

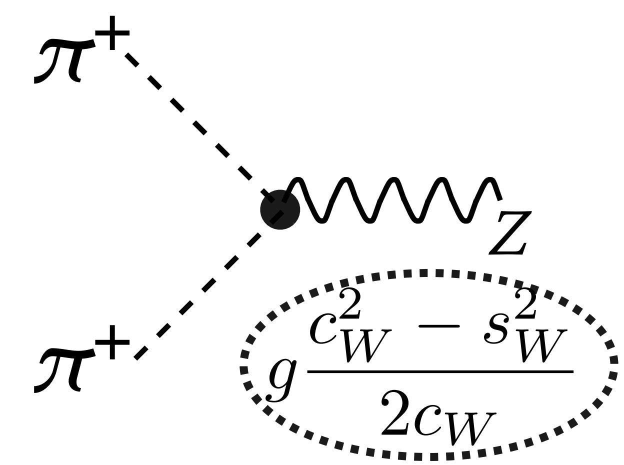
$a_Z = 2 \cdot (\text{“SU(2) charge” of } W^+)^2$

different for T and L









SM

$$\frac{\sigma_{TT\to TT}}{\sigma_{LL\to LL}} \sim 20$$

(for $M_\gamma \sim M_Z$)

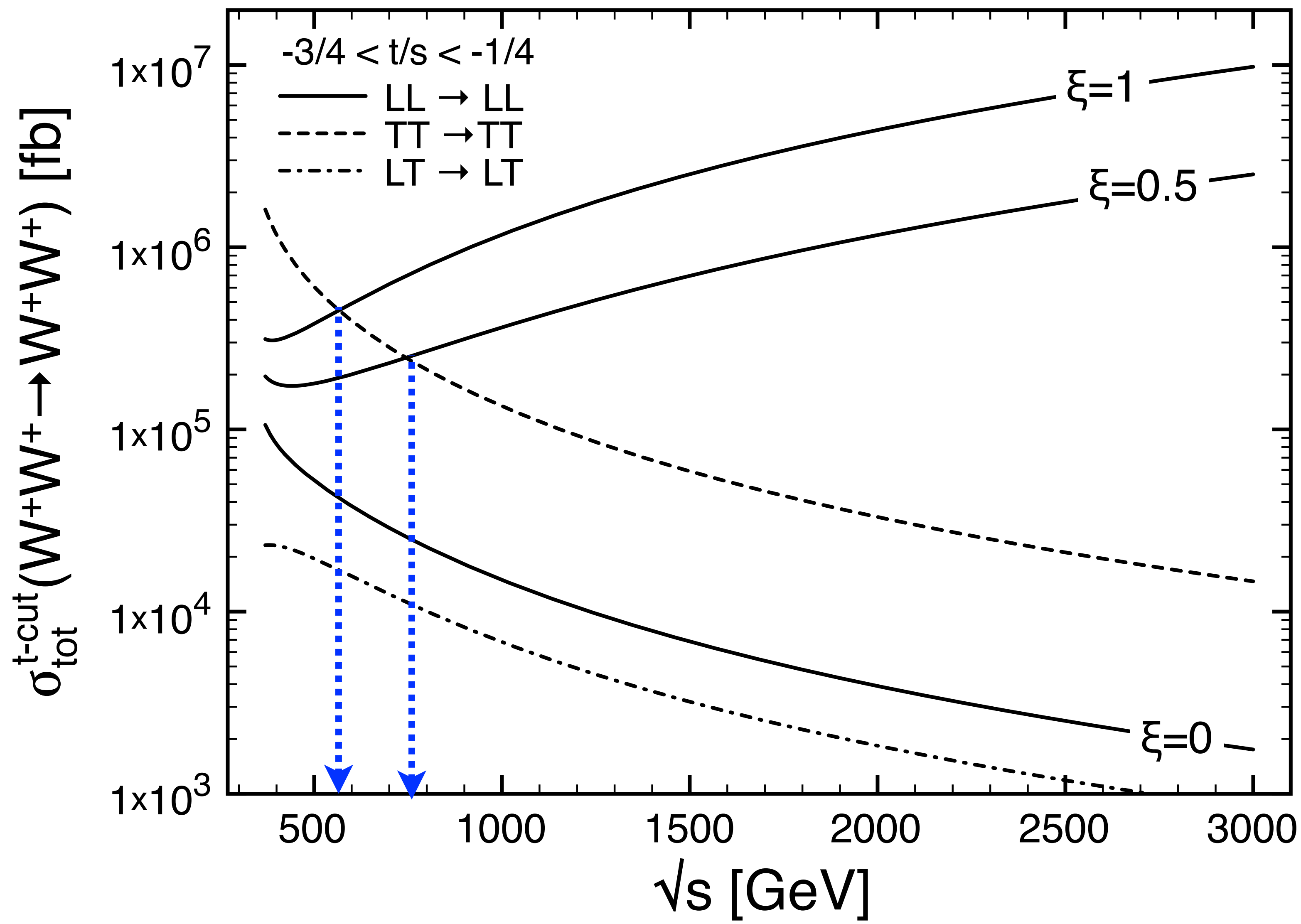
$$N_s \sim 1/500$$

$\Rrightarrow$ T-dominance is the result of multiplicity and larger SU(2) charges $\Lleftarrow$

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

Hard scattering (central region)

we need to look at the central region, i.e. large scattering angle, to be sensitive to strong EWSB

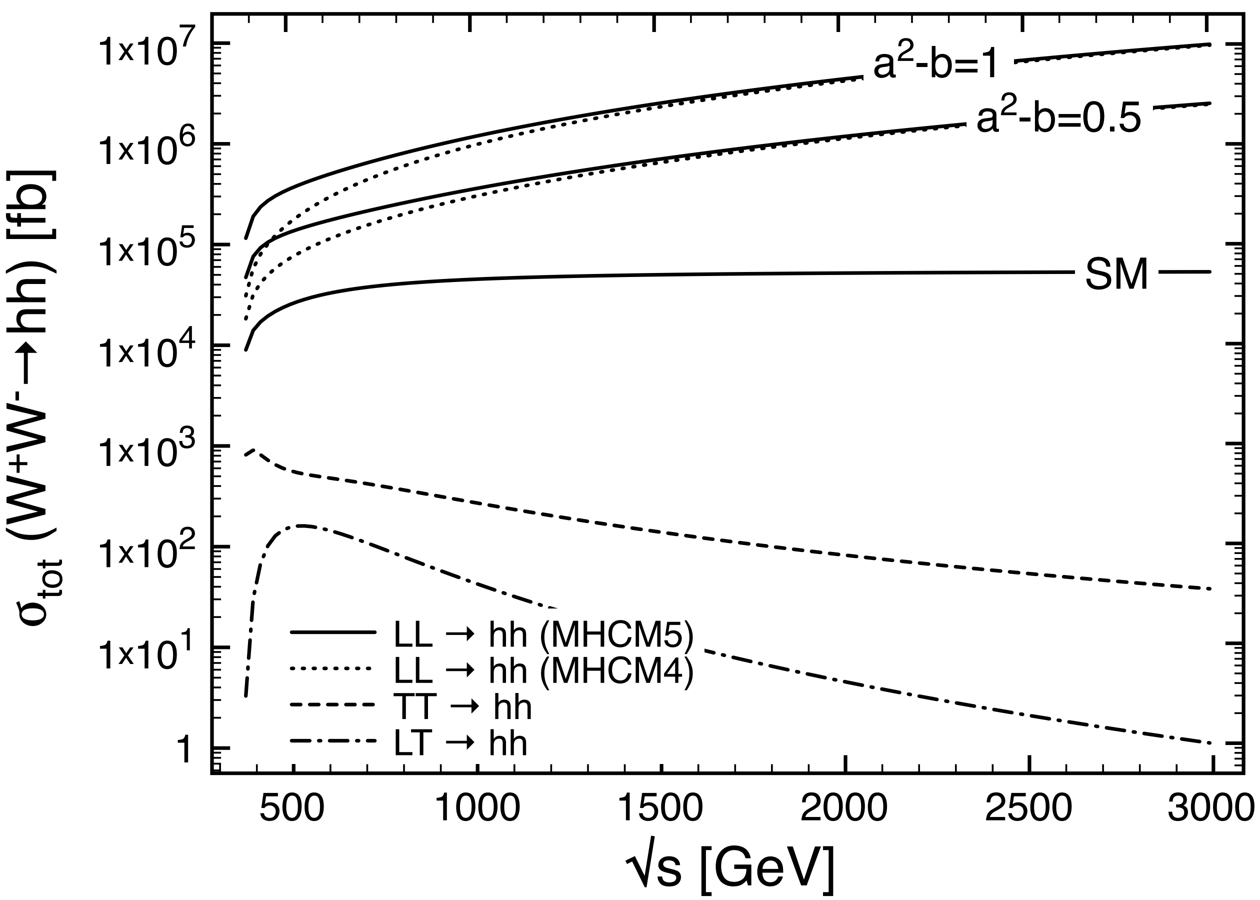


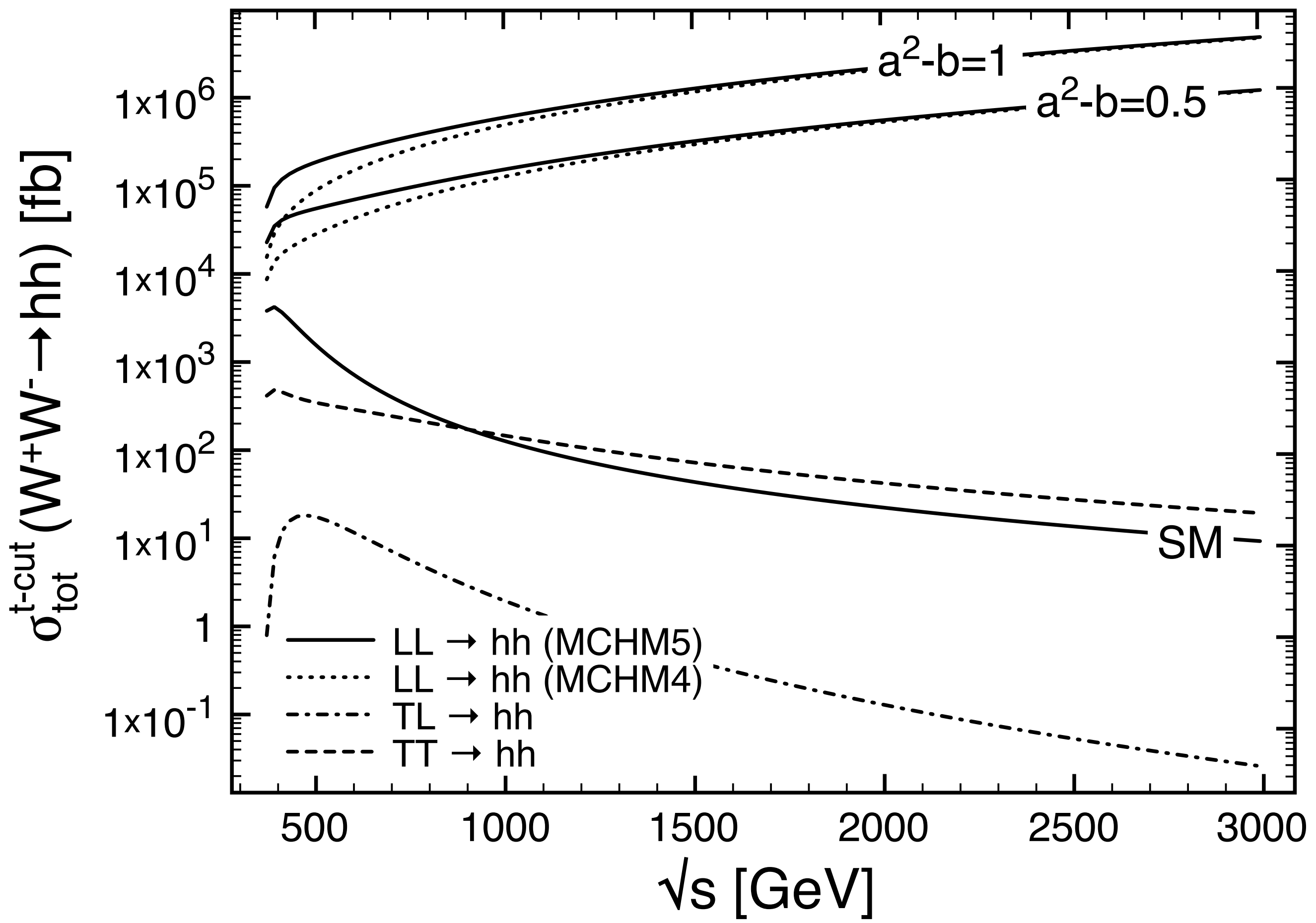
$$\frac{\sigma^{\text{hard}}_{LL\to LL}}{\sigma^{\text{hard}}_{TT\to TT}} \simeq \left(\frac{\sqrt{s}}{7.4 M_W}\right)^4 \xi^2$$

$$N_h = 1/2304$$

- hard cross-section = faster growth with energy
- onset of strong scattering still at high scale

EW bckg for WW → hh

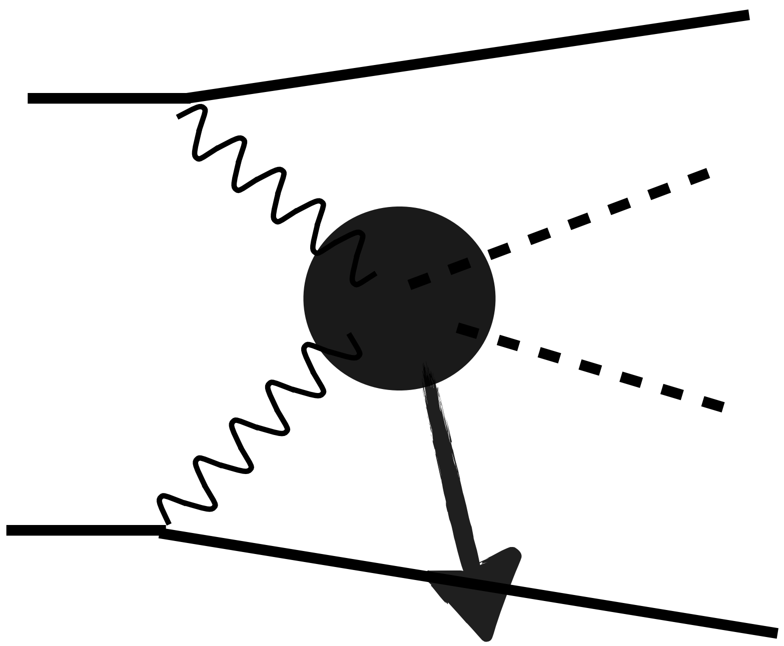




$$\frac{d\sigma^{LL\to hh}/dt}{d\sigma^{TT\to hh}/dt} = \frac{1}{8}\frac{\xi^2}{\xi^2+(1-\xi)^2}\left(\frac{\sqrt{s}}{M_W}\right)^4$$

no T polarization pollution,
neither in the total cross section,
nor in the central region

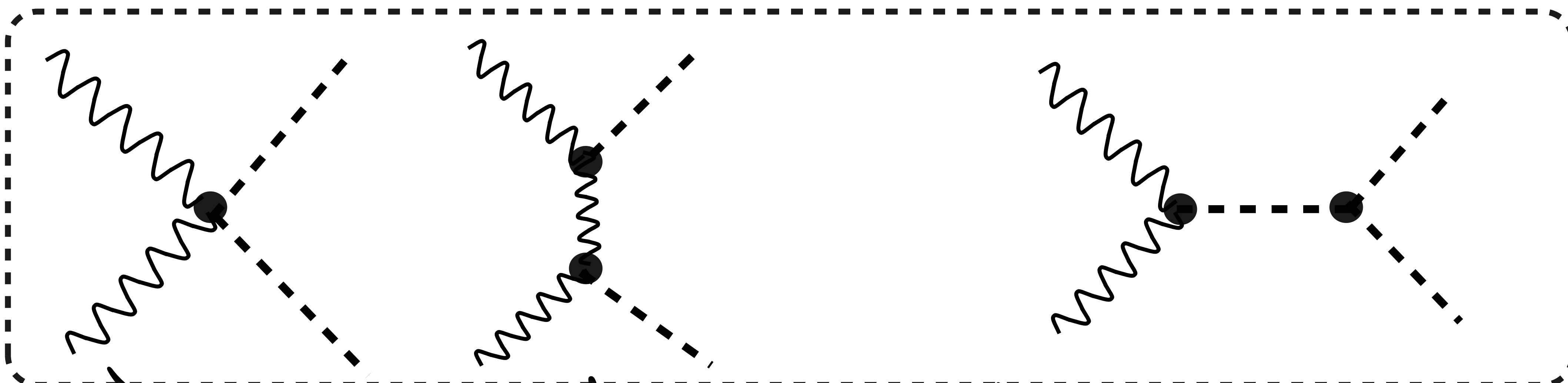
Double Higgs production



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

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

SM: a=b=d_3=d_4=1



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

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

asymptotic behavior
sensitive to strong interaction

threshold effect
anomalous coupling'

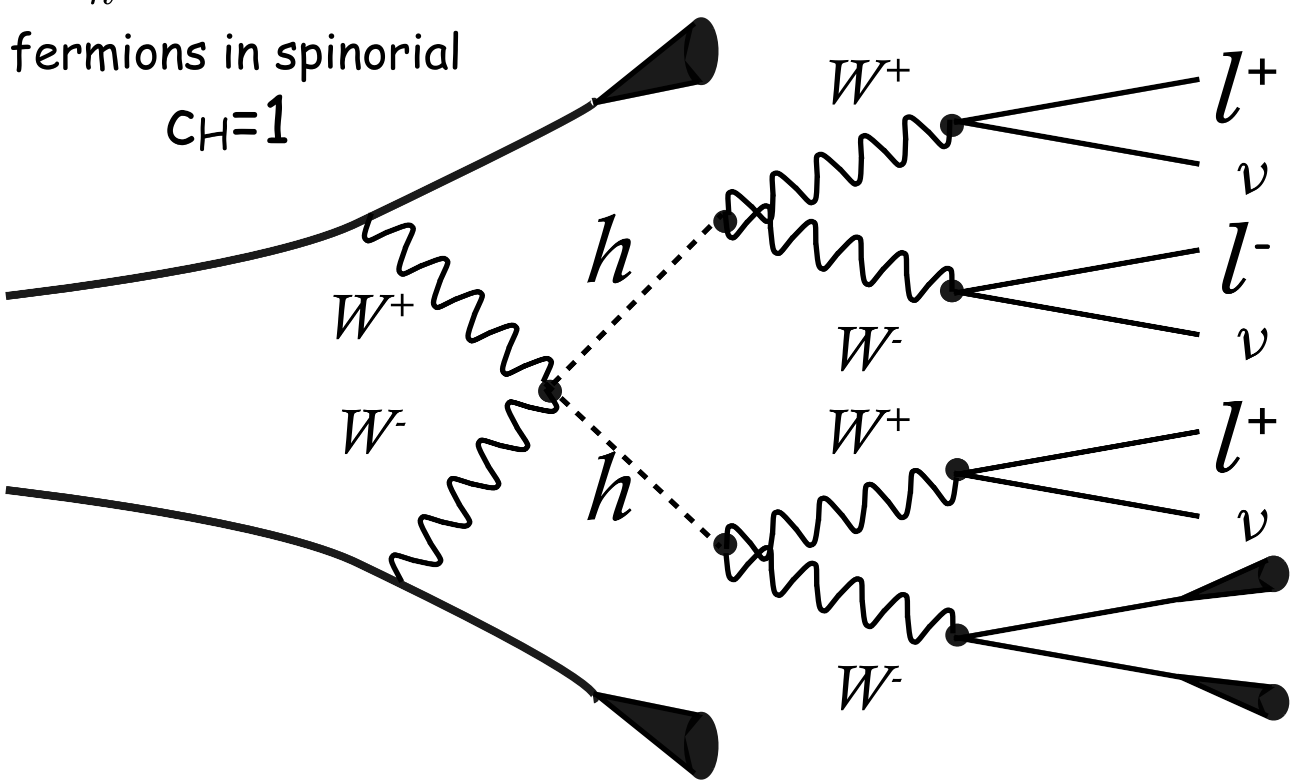
Strong Higgs production: (3L+jets) analysis

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

⋘ good motivation to SLHC

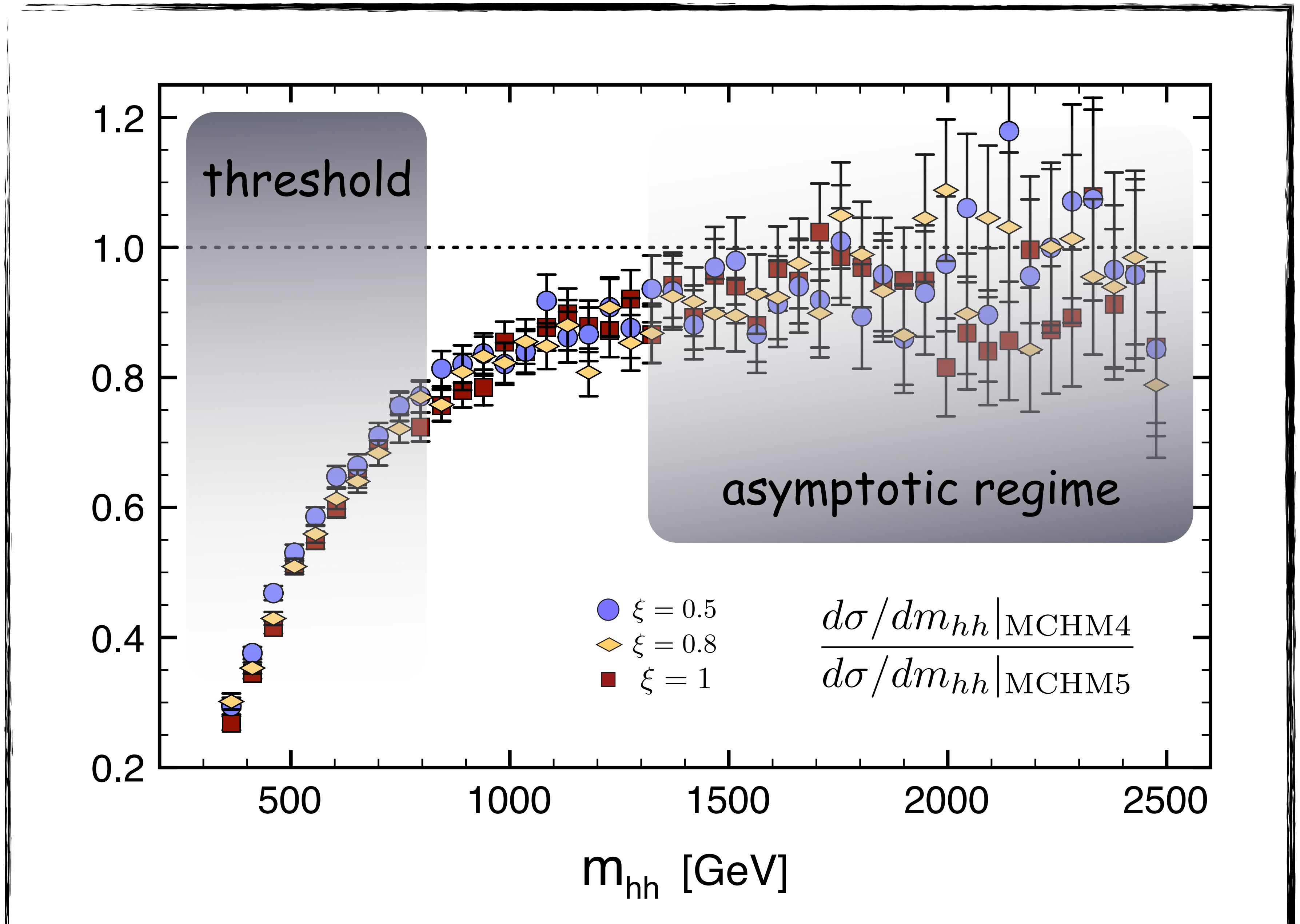
Isolating Hard Scattering

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

isolate events with large m_{hh}

luminosity factor drops out in ratios: extract the growth with m_{hh}

measure H^3 measure $(b-a^2)$

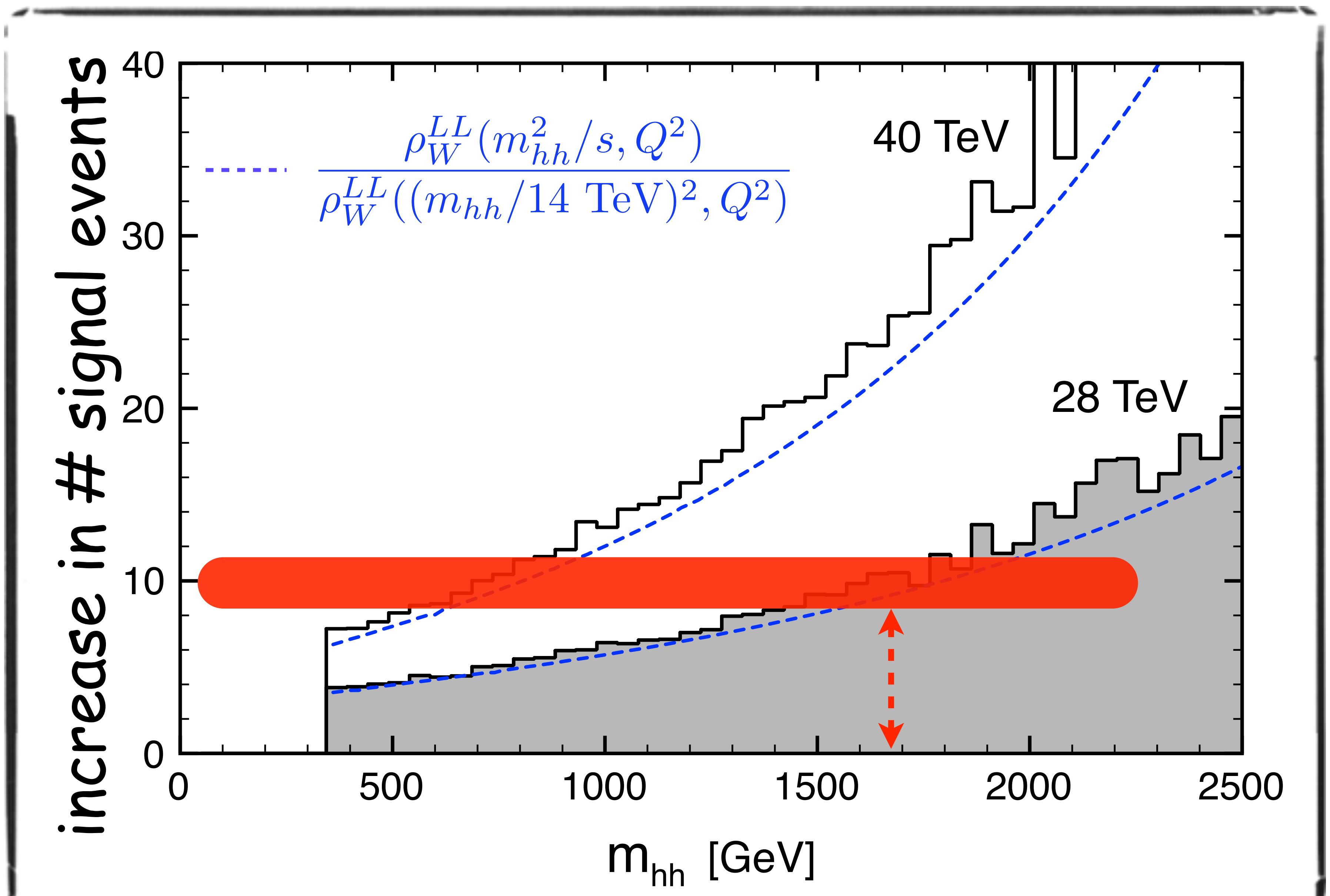


two models with
same asymptotic regime but
different higgs-self-coupling

Dependence on Collider Energy

$$\sigma = \hat{\sigma}(s_0) \times \int_{s_0} \frac{d\hat{s}}{\hat{s}} \frac{\hat{\sigma}(\hat{s})}{\hat{\sigma}(s_0)} \rho(\hat{s}/s)$$

increase collider energy √s = sensitive to PDFs at smaller x
bigger cross-sections



sLHC vs. VLHC

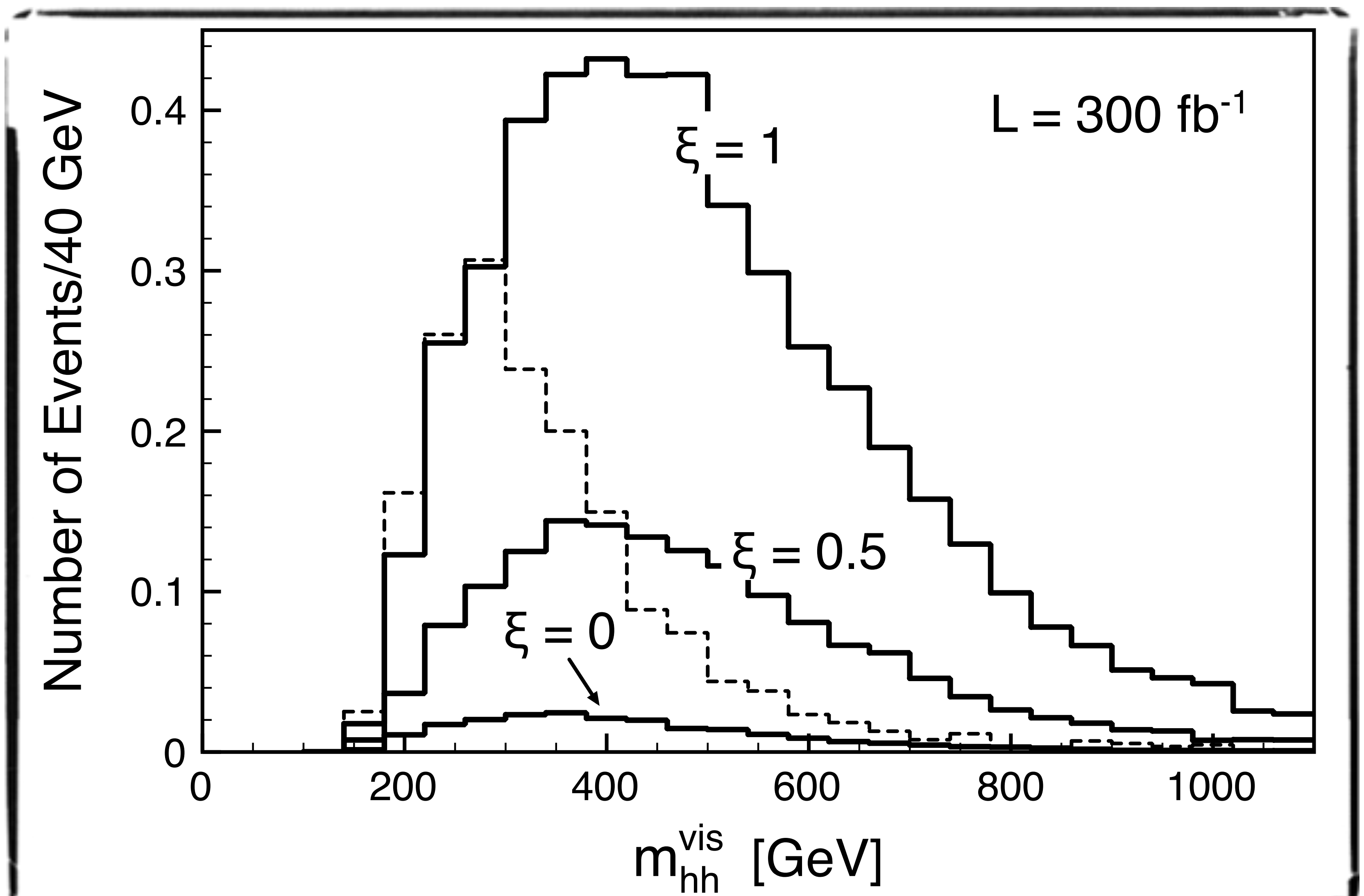
10 x lum ≈ 10 x events

2 x √s = 10 x events
iif m_{hh}>1.6TeV

Dependence on Collider Energy

$$\sigma = \hat{\sigma}(s_0) \times \int_{s_0} \frac{d\hat{s}}{\hat{s}} \frac{\hat{\sigma}(\hat{s})}{\hat{\sigma}(s_0)} \rho(\hat{s}/s)$$

increase collider energy $\sqrt{s}$ = sensitive to PDFs at smaller x
bigger cross-sections



sLHC vs. VLHC

10 x lum ≈ 10 x events

2 x $\sqrt{s}$ = 10 x events
iif m_{hh}>1.6TeV

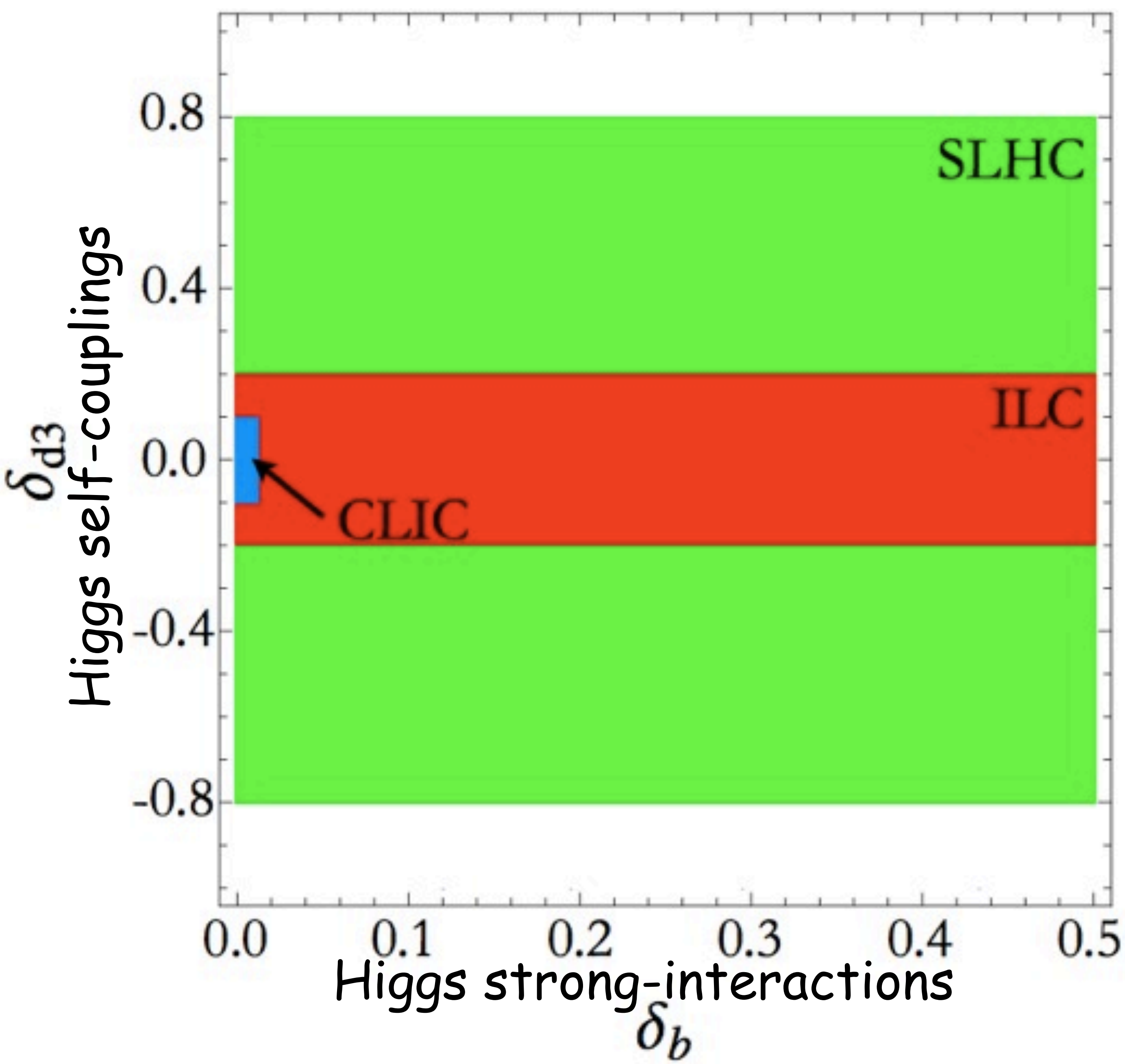
... very few events

sLHC might be better

Measuring Higgs Non-Linearities

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

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



- (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 coupling should we measure?

- 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 the composite nature of the Higgs?

3. Probing discrete symmetries of the strong sector

Geometry of Coset from $W^+W^- \to 3h$

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

Strong EWSB

$$\sigma_{2\pi\to 3\pi} \sim \frac{1}{8\pi}\frac{E^2}{f^4}\frac{E^2}{(4\pi f)^2}$$

$$E/f \leftrightarrow g$$

SM

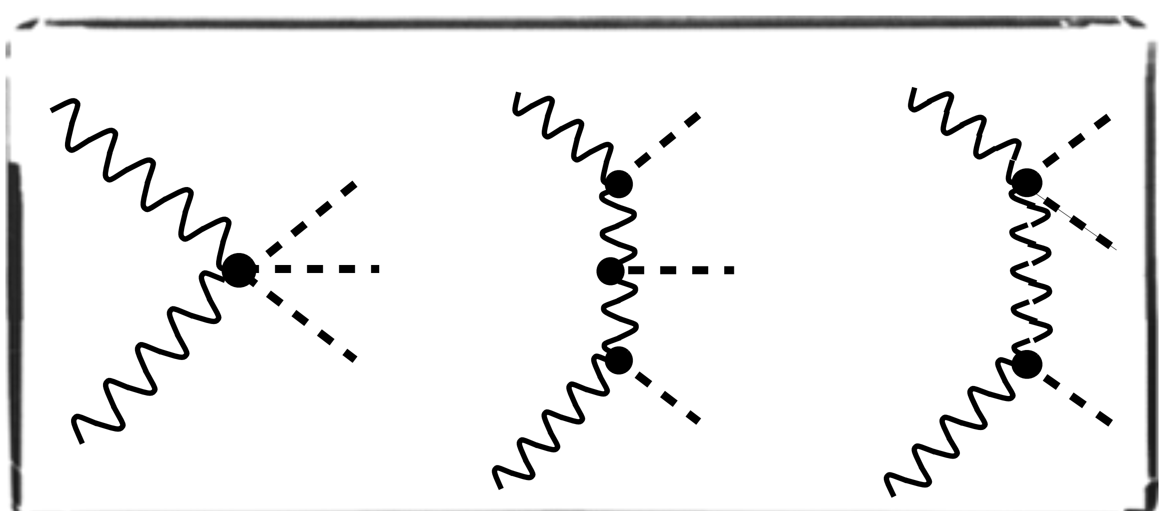
$$\sigma_{2\pi\to 3\pi} \sim \frac{1}{8\pi}\frac{g^2}{v^2}\frac{g^2}{16\pi^2}$$

Probe of possible discrete symmetries in the strong dynamics

G/H symmetric space ⇒ invariance under $\pi \to -\pi$

selection rule

a process with an odd # of PGBs
requires a coupling breaking the coset structure
ie cannot be mediated by strong interactions alone

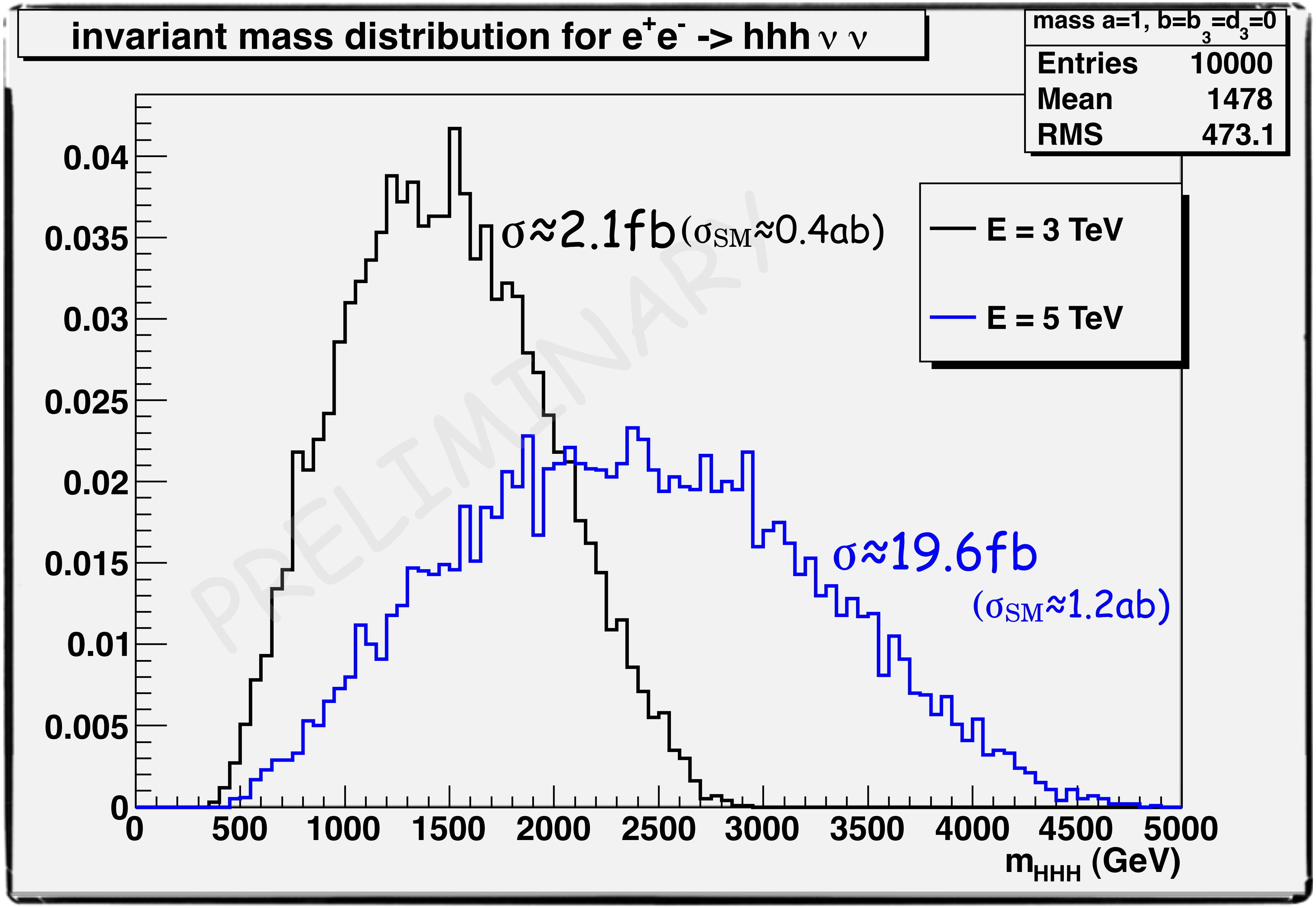


$$\mathcal{A}_{WW\to 3h} \sim 4i\frac{s}{v^3}\underbrace{\left(a(b-a^2) - \frac{3}{4}b_3\right)}_{\text{=0 for symmetric coset}} + \underbrace{\sharp\, s \times \left(\frac{m_W}{\sqrt{s}}\right)^2}_{\text{mediated by SM gauge interactions (breaking of coset structure)}}$$

$W^+W^- \to 3h$ @ CLIC

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

non-symmetric coset

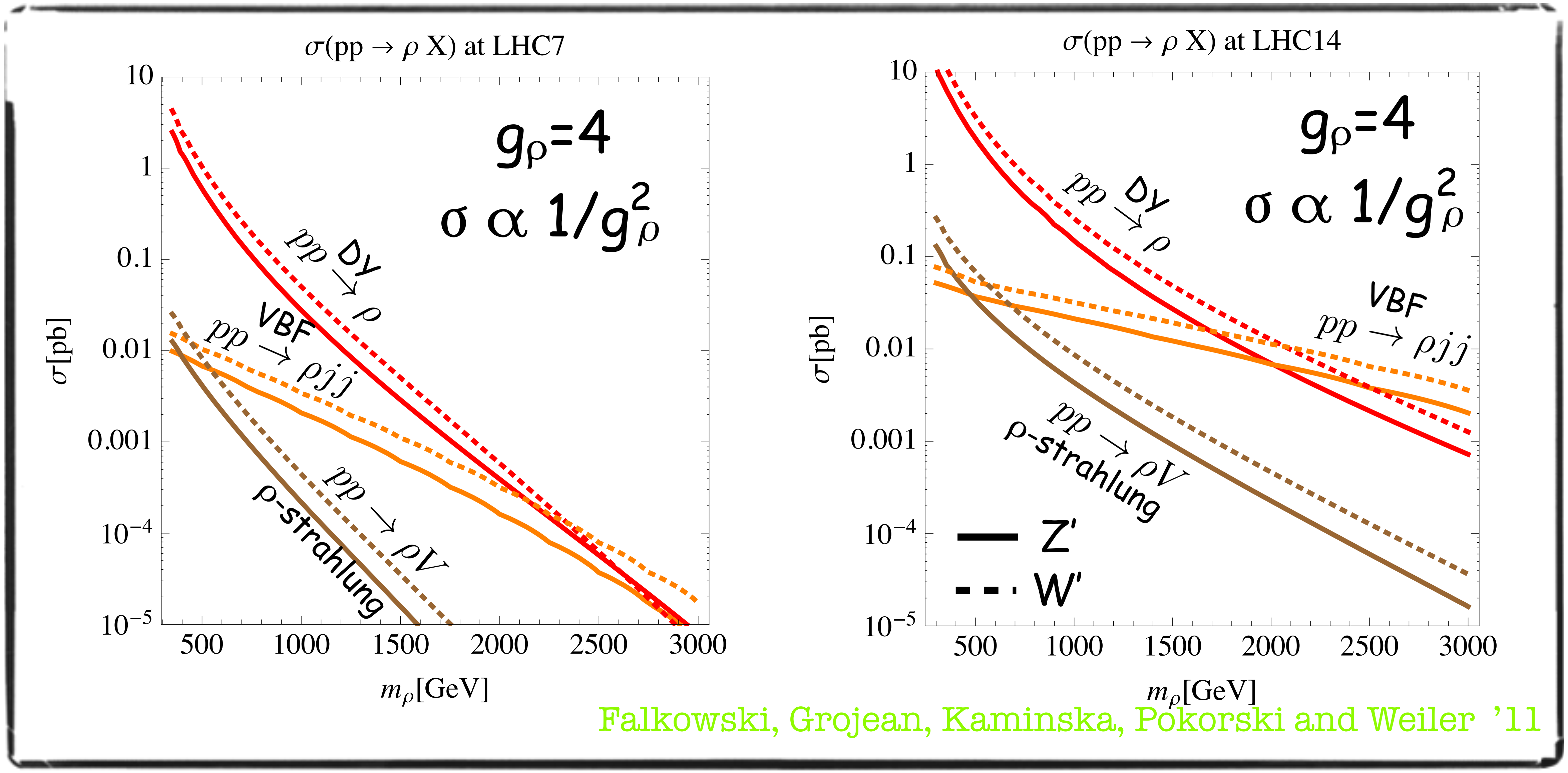


How to probe the composite nature of the Higgs?

4. Detecting resonances

Resonance Searches

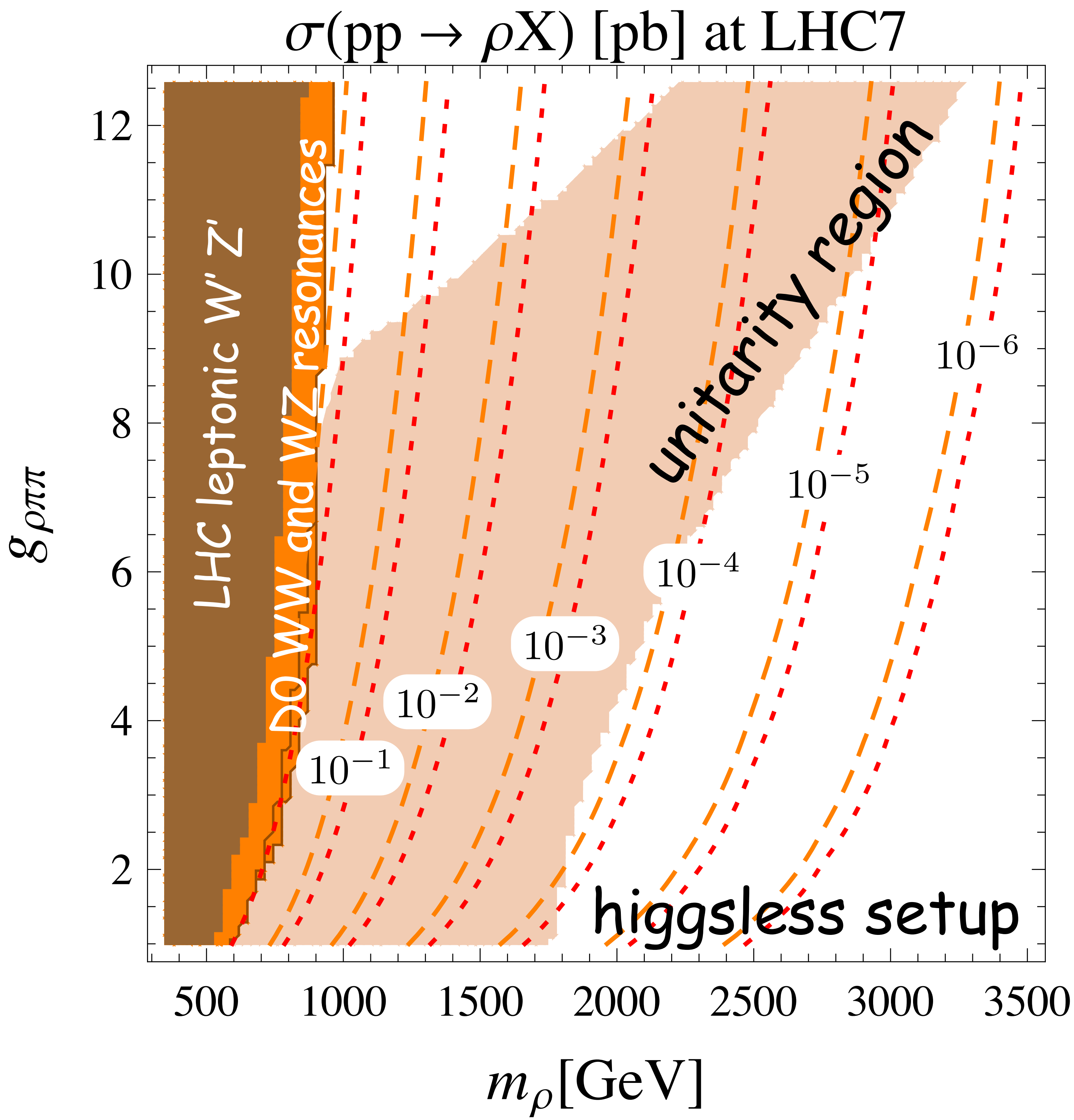
Observing a tower of resonances would a direct evidence of the strong interactions
However, in the best configuration, LHC will have access to a few ones only

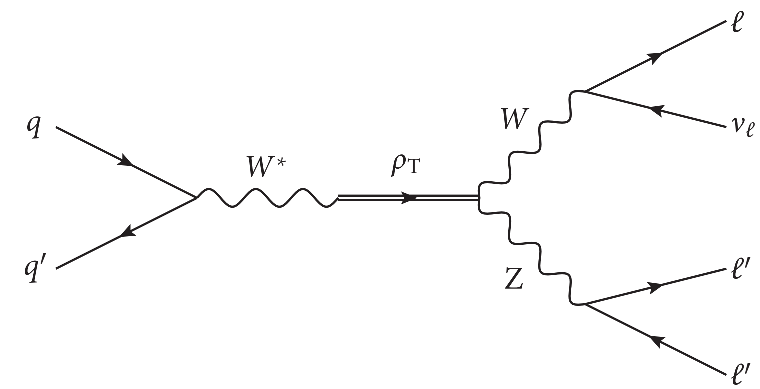


VBF vs. DY:
- 3-body final state
- qq initiated process ⇨ PDFs become more dominant at large x

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

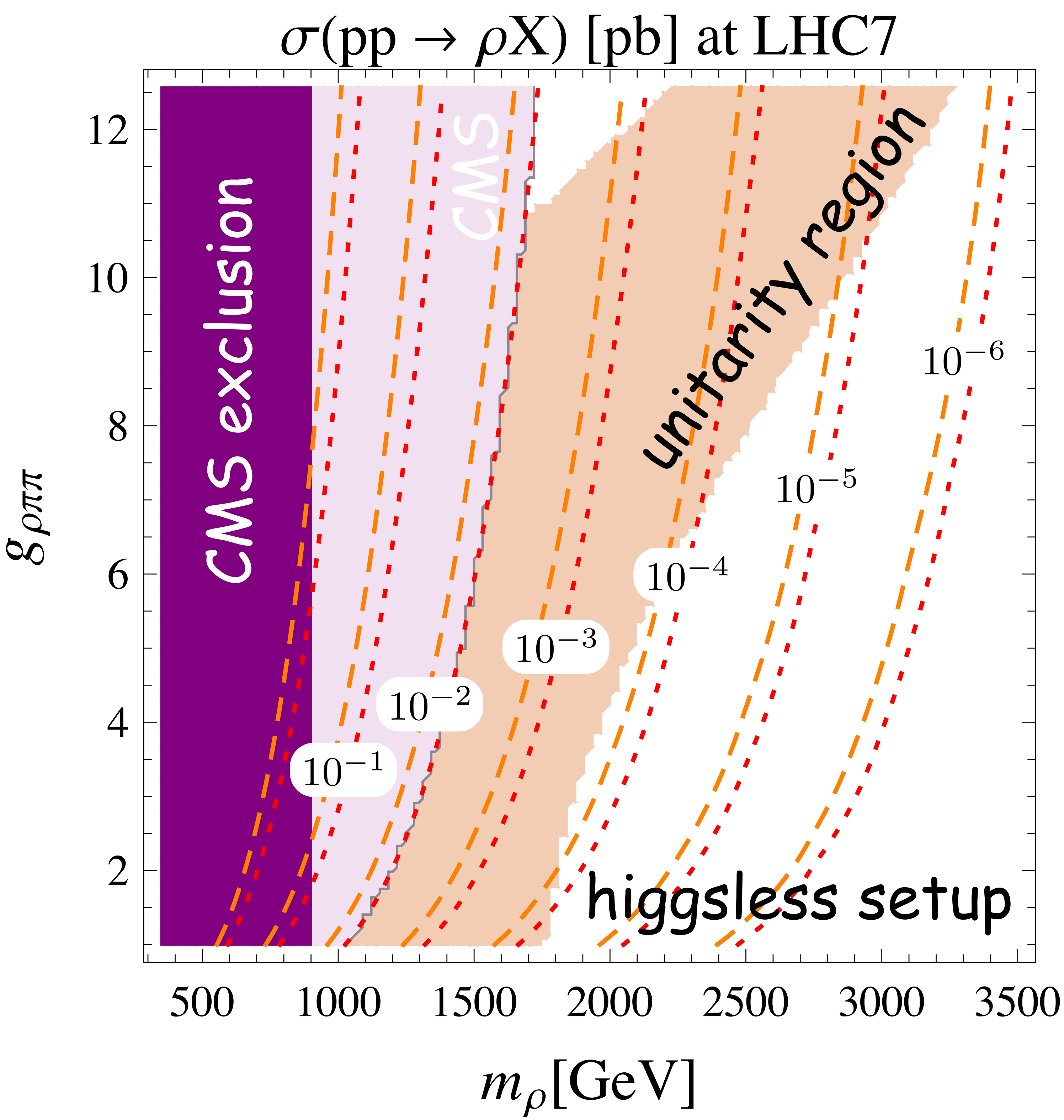
- D0 search for WW and WZ resonances gives weaker bounds

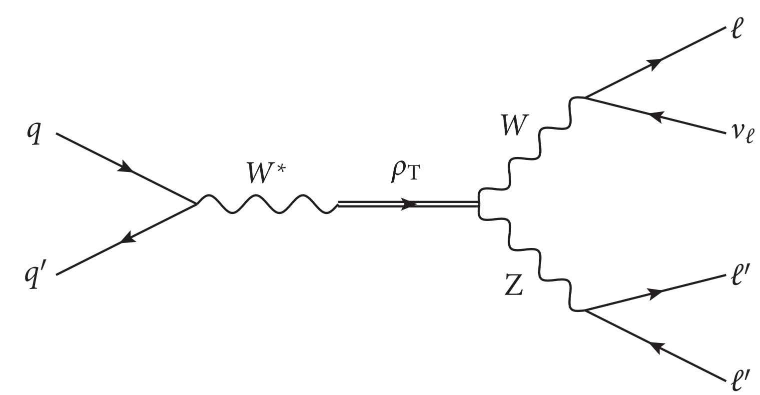
Abazov et al, '10

- 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

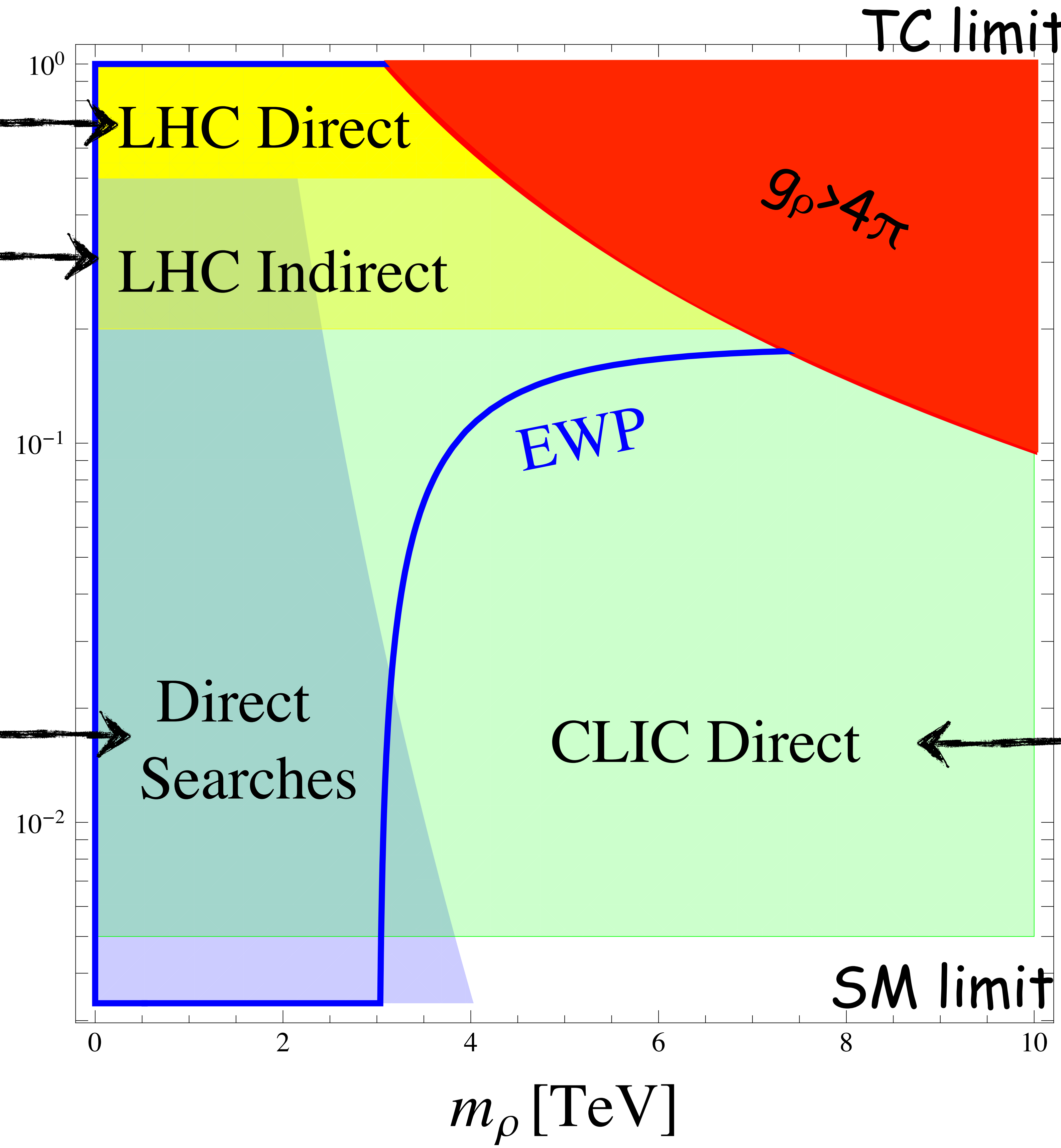
Strong WW scattering

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?

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 ⇔ Λ >> M/e ⇔ 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

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Ferrara, Porrati, Telegdi '92

composite spin-1

g≠2 & Λ > 5÷10 M ⇔ 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

Conclusions

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

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

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 $\Leftrightarrow$ gauge principle

Higgs NC $\Leftrightarrow$?

LHC is prepared to discover the "Higgs"

collaboration EXP-TH is important to make sure
e.g. that no unexpected physics (unparticle, hidden valleys) is missed (triggers, cuts...)

Should not forget that the LHC will be a (quark) top machine

and there are many reasons to believe that the top is an important agent of the Fermi scale