Beyond the Higgs

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Why do we need to go beyond the SM Higgs?

1. unsuccessful searches for a Higgs boson

2. EW precision data:

   - consistency with a light Higgs
   - strong constraints on anything else

'legacy of last 20 years of expts.'

we have to live with either
fine-tuning in parameter space
or
larger theory space

The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

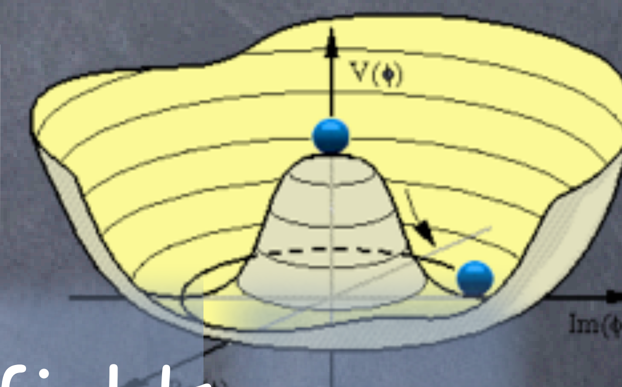
massive $W^{\pm}$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

$\Rightarrow$ Where are these Goldstone's coming from? $\Leftarrow$

what is the sector responsible for the breaking $SU(2)_L \times SU(2)_R$ to $SU(2)_V$?

with which dynamics? with which interactions to the SM particles?

common lore: from a scalar Higgs doublet



$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

Higgs doublet = 4 real scalar fields

3 eaten Goldstone bosons ← → One physical degree of freedom the Higgs boson

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⇛ Where are these Goldstone's coming from? ⇚

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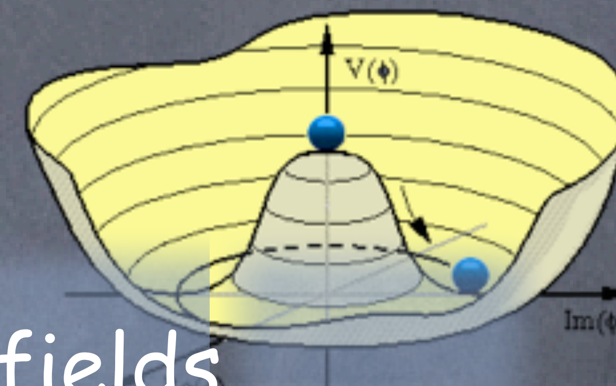

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

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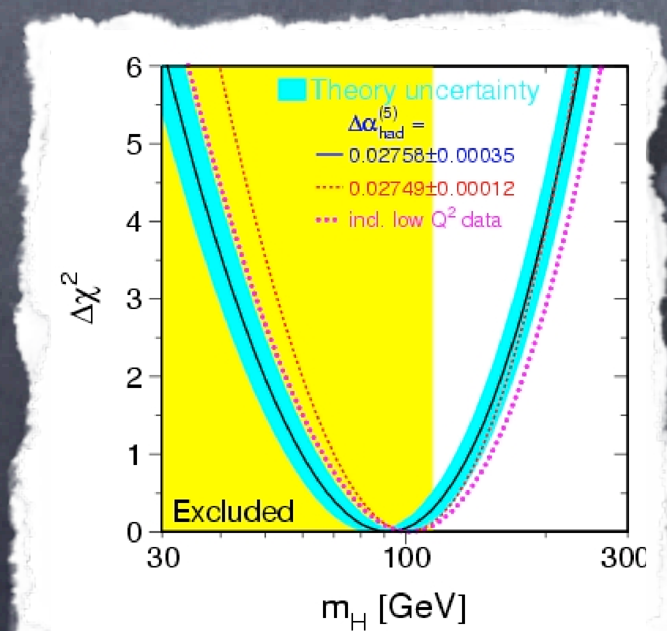
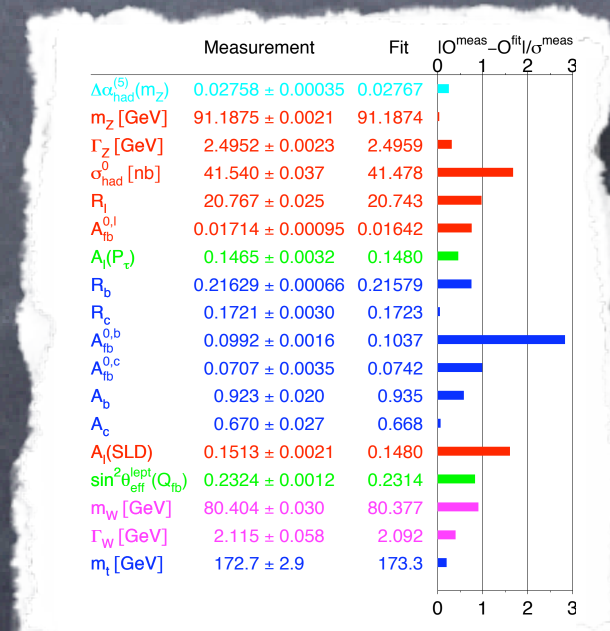
Good agreement with EW data

(doublet ⇔ ρ=1)





	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ_{had}^0 [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.743	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037	
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1480	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.404 ± 0.030	80.377	
Γ_W [GeV]	2.115 ± 0.058	2.092	
m_t [GeV]	172.7 ± 2.9	173.3	

But the Higgs hasn't been seen yet...

other origins of the Goldstone's: condensate of techniquarks, A_5...

Which Higgs?

UnHiggs?

Private Higgs?

Guralnik's Higgs?

Little Higgs?

Gaugephobic Higgs?

Kibble's Higgs?

Littlest Higgs?

Buried Higgs?

Intermediate Higgs?

Slim Higgs?

Composite Higgs?

Fat Higgs?

Higgsless?

Portal Higgs?

Peter's Higgs?

Brout-Englert's Higgs?

Gauge-Higgs?

Lone Higgs?

Twin Higgs?

Simplest Higgs?

Phantom Higgs?

$$H = \left(\begin{array}{c} h^+ \\ h^0 \end{array} \right)$$

Higgs doublet = 4 real scalar fields

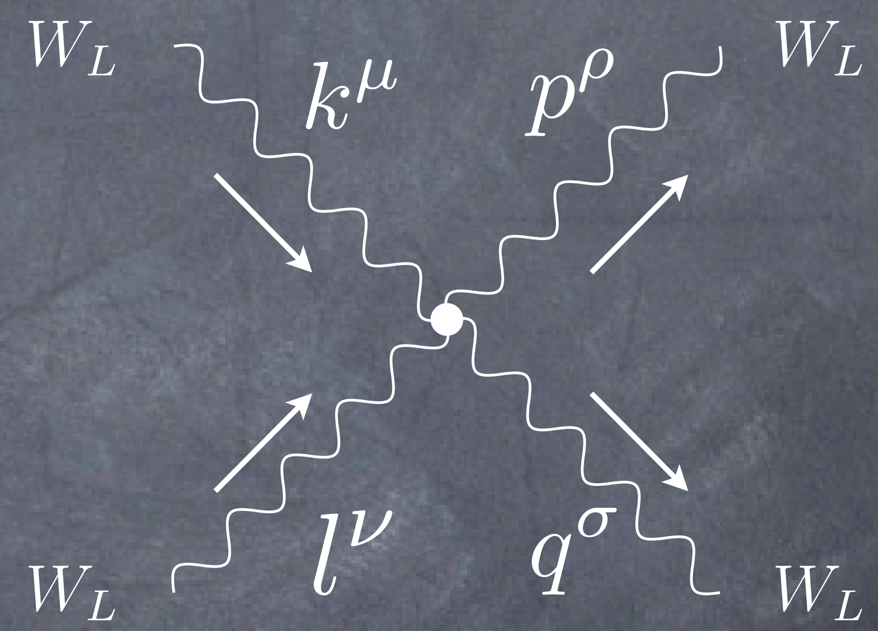
3 eaten Goldstone bosons ← → One physical degree of freedom the Higgs boson

Higgs as a UV moderator

Why do we need a Higgs ?

The W and Z masses are inconsistent with the known particle content! Need more particles to soften the UV behavior of massive gauge bosons.

Bad UV behavior for the scattering of the longitudinal polarizations



$$\mathcal{A} \propto g^2 \frac{E^4}{M^4}$$

violations of perturbative unitarity around E ~ M

A QCD antecedent

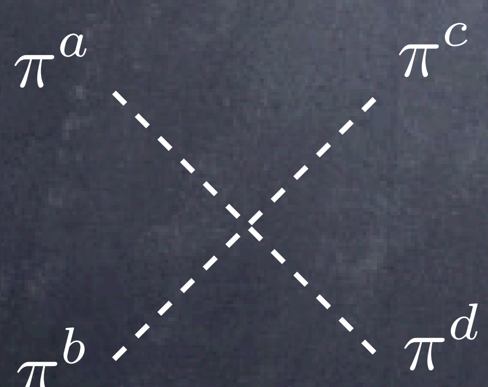
QCD pions are Goldstone bosons associated to $SU(2)_L \times SU(2)_R / SU(2)_V$

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

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

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

contact interaction growing with energy



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

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

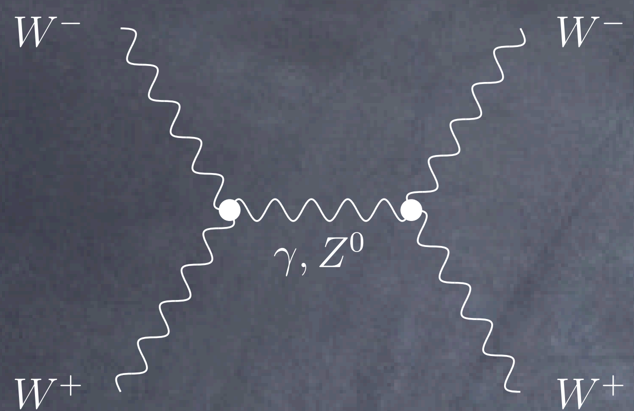
$$f_\pi = 93 \text{ MeV}$$

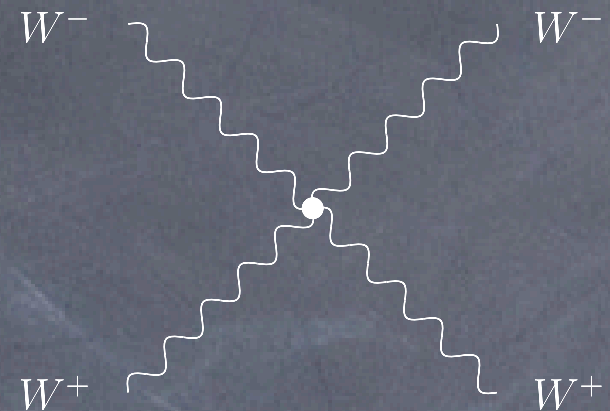
$\Rightarrow$ unitarity bound

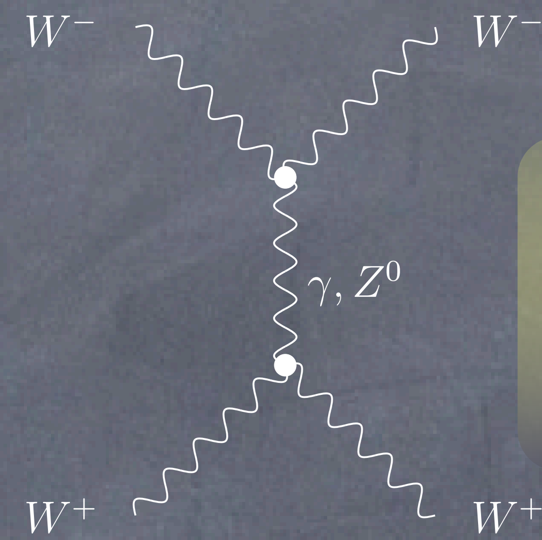
$$\sqrt{s} \sim 4\sqrt{\pi} f_\pi = 660 \text{ MeV}$$

rho meson (m=770 MeV) is restoring unitarity

Why do we need a Higgs ?

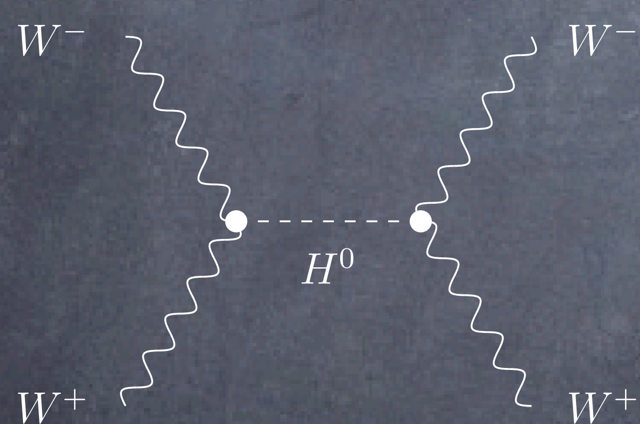


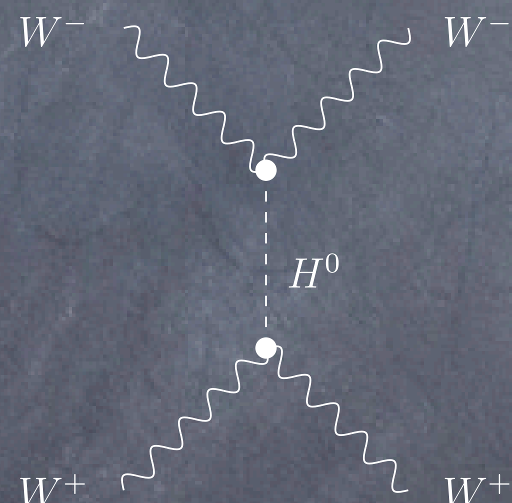




$$\mathcal{A} = g^2 \left(\frac{E}{M_W} \right)^2$$

+





$$\mathcal{A} = -g^2 \left(\frac{E}{M_W} \right)^2$$

$$\mathcal{A} = g^2 \left(\frac{M_H}{2M_W} \right)^2$$

Lewellyn Smith '73
Dicus, Mathur '73
Cornwall, Levin, Tiktopoulos '73

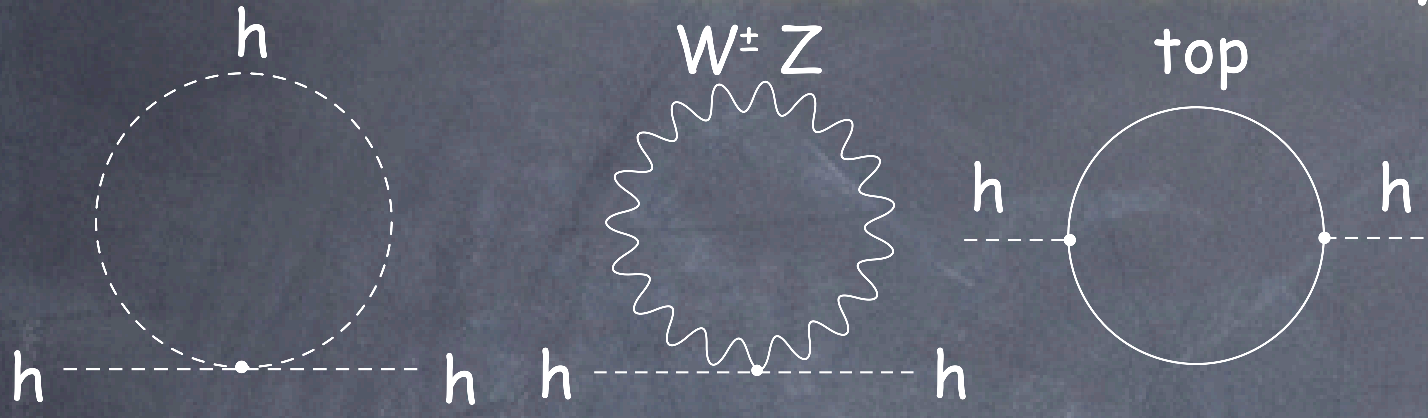
The Higgs boson unitarize the W scattering
(if its mass is below ~ 700 GeV)

W_L scattering = pion scattering
Goldstone equivalence theorem

New physics: hierarchy pb @ flavor

The hierarchy problem

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



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

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

3 remove the Higgs

- technicolor [Weinberg '79, Susskind '79]

Hierarchy problem vs flavor: tension

Clash of Scales

?

Higgs sector		Flavor
Λ < 3-4 TeV	⟺	Λ > $10^{4\div5}$ TeV

the higher the scale of new physics, the more fine-tuned the Higgs, the less likely a discovery at LHC

Weak

SM & al.

H = elem. scalar: dim=1

$$\Lambda^2\,|H|^2$$

sick when $\Lambda \to \infty$

$$y_{ij}\,H q_i \bar{q}_j \;\; \& \;\; \frac{1}{\Lambda^2}(q_i\bar{q}_j q_k \bar{q}_l)$$

fine when $\Lambda \to \infty$

Strong

Technicolor

H=<q$\bar{q}$>: dim=3

$$\frac{1}{\Lambda^2}|H|^2$$

fine when $\Lambda \to \infty$

$$\frac{1}{\Lambda^2} H q_i \bar{q}_j \;\; \& \;\; \frac{1}{\Lambda^2}(q_i\bar{q}_j q_k \bar{q}_l)$$

sick when $\Lambda \to \infty$

Hierarchy problem vs flavor: lesson?

Clash of Scales

Higgs sector

Λ < 3-4 TeV

?

Flavor

Λ > $10^{4\div5}$ TeV

Is flavor telling us anything about the solution to the hierarchy problem?

Weak

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H = elem. scalar: dim=1

$\Lambda^2 |H|^2$

sick when $\Lambda \to \infty$

$y_{ij}\, H q_i \bar{q}_j$ & $\frac{1}{\Lambda^2}(q_i \bar{q}_j q_k \bar{q}_l)$

fine when $\Lambda \to \infty$

conformal TC

dim $_H$ = 1 but dim $_{|H|^2}$ = 4

would solve both pbs

but it seems impossible to realize

[Luty-Okui '04, Rattazzi et al '08]

Strong

Technicolor

H=<$q\bar{q}$>: dim=3

$\frac{1}{\Lambda^2}|H|^2$

fine when $\Lambda \to \infty$

$\frac{1}{\Lambda^2} H q_i \bar{q}_j$ & $\frac{1}{\Lambda^2}(q_i \bar{q}_j q_k \bar{q}_l)$

sick when $\Lambda \to \infty$

Hierarchy problem vs flavor: lesson?

Clash of Scales

Higgs sector	Flavor
$\Lambda < 3\text{-}4$ TeV	$\Lambda > 10^{4\div 5}$ TeV

Is flavor telling us anything about the solution to the hierarchy problem?

Weak

SM & al.

H = elem. scalar: dim=1

$$\Lambda^2 |H|^2$$

sick when $\Lambda \to \infty$

$$y_{ij} H q_i \bar{q}_j \ \ \& \ \ \frac{1}{\Lambda^2}(q_i \bar{q}_j q_k \bar{q}_l)$$

fine when $\Lambda \to \infty$

1

conformal TC

2

partial compositeness [Kaplan '91]

mixing elem. and composite fermions

dim $q_{R,L}$=3/2, dim $\mathcal{O}_{R,L}$=$d_{R,L}$

$$\frac{q_L \mathcal{O}_R}{\Lambda_R^{d_R-5/2}} + \frac{q_R \mathcal{O}_L}{\Lambda_L^{d_R-5/2}} + \frac{\mathcal{O}_L \mathcal{O}_R}{\Lambda^{d_L+d_R-4}}$$

$d_{R,L} \approx 5/2$ solves the flavor pb

Strong

Technicolor

H=<$q\bar{q}$>: dim=3

$$\frac{1}{\Lambda^2}|H|^2$$

fine when $\Lambda \to \infty$

$$\frac{1}{\Lambda^2} H q_i \bar{q}_j \ \ \& \ \ \frac{1}{\Lambda^2}(q_i \bar{q}_j q_k \bar{q}_l)$$

sick when $\Lambda \to \infty$

Partial compositeness: fermion masses

partial compositeness

mixing elem. and composite fermions

dim $q_{R,L}$=3/2, dim $\mathcal{O}_{R,L}$=$d_{R,L}$

$$\frac{q_L \mathcal{O}_R}{\Lambda_R^{d_R-5/2}} + \frac{q_R \mathcal{O}_L}{\Lambda_L^{d_R-5/2}} + \frac{\mathcal{O}_L \mathcal{O}_R}{\Lambda^{d_L+d_R-4}}$$

integrating out heavy fields

amount of compositeness $f_{q_{L,R}}$

$$\frac{\Lambda_R \Lambda_L}{\Lambda} \left(\frac{\Lambda}{\Lambda_R}\right)^{d_R} \left(\frac{\Lambda}{\Lambda_L}\right)^{d_L} q_L q_R$$

1. fermion mass hierarchy easily generated by small diff. in anomalous dims
2. alignment mixing angles/masses is also explained

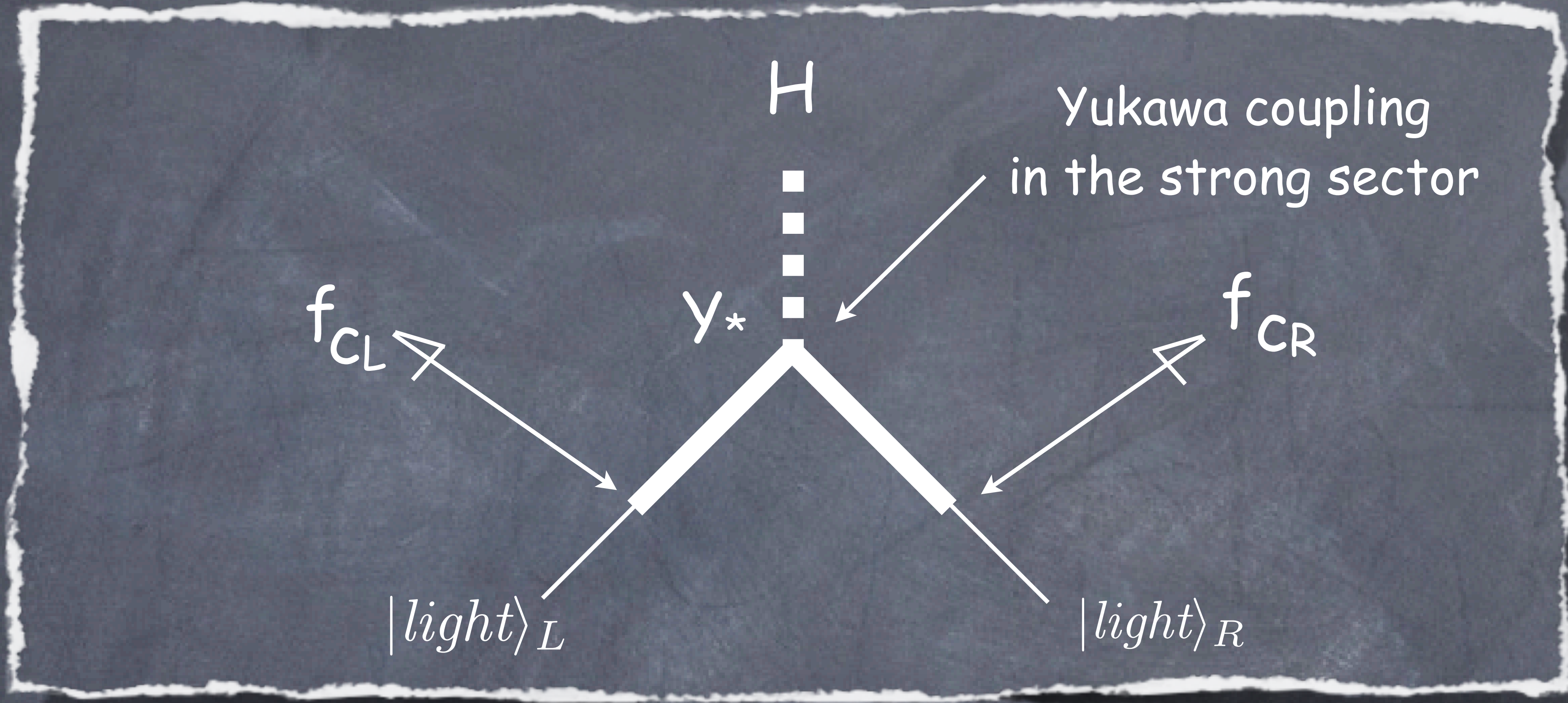
$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$m_{u_i} \propto f_{q_i} f_{u_i} \qquad m_{d_i} \propto f_{q_i} f_{d_i}$$

$$V_{CKM}^{ij} \sim f_{q_i}/f_{q_j}$$

Partial Compositeness: fermion masses

Higgs part of the strong sector: it couples only to composite fermions

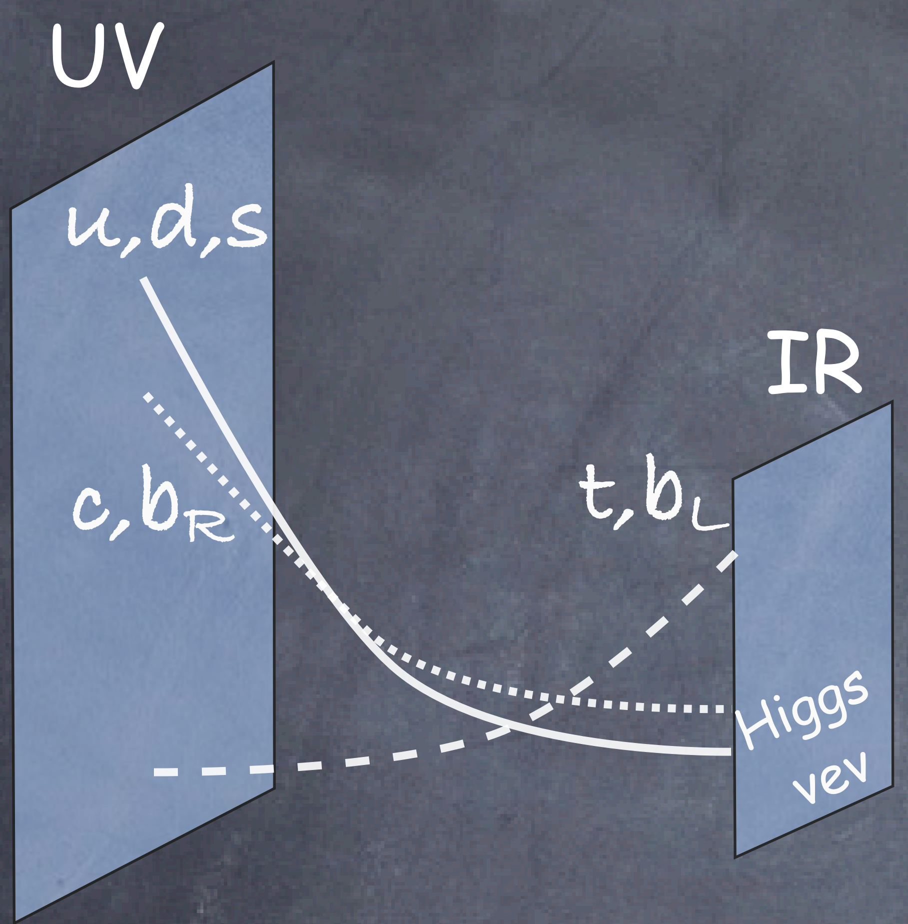


when the Higgs gets a vev, the light dof will acquire a mass prop. to

$$Y^{eff} = Y_\star f_{c_L} f_{c_R}$$

Yukawa hierarchy comes from the hierarchy of compositeness
the lighter the fermion, the less coupled to the strong sector

Partial compositeness: xdim realization



[Grossman and Neubert, '00]
[Gherghetta and Pomarol, '00]
[Huber, '03]

fermion zero-mode has
an exponential profile
in the bulk

$$\chi(z) = \frac{f_c}{\sqrt{R'}} \left(\frac{z}{R}\right)^2 \left(\frac{z}{R'}\right)^{-c}$$

f_c is the "value" of wavefct. on the IR:

$$f_c = \sqrt{\frac{1-2c}{1-(R/R')^{1-2c}}}$$

c < 1/2: heavy fermion
$f_c \sim \mathcal{O}(1)$

c > 1/2: light fermion
$f_c \sim (R/R')^{c-1/2} \ll 1$

light fermion exponentially localized on the UV brane

➲ overlap with Higgs vev on the IR tiny

➲ exponentially small 4D mass

UV localized fermion=elementary

IR localized fermion=composite

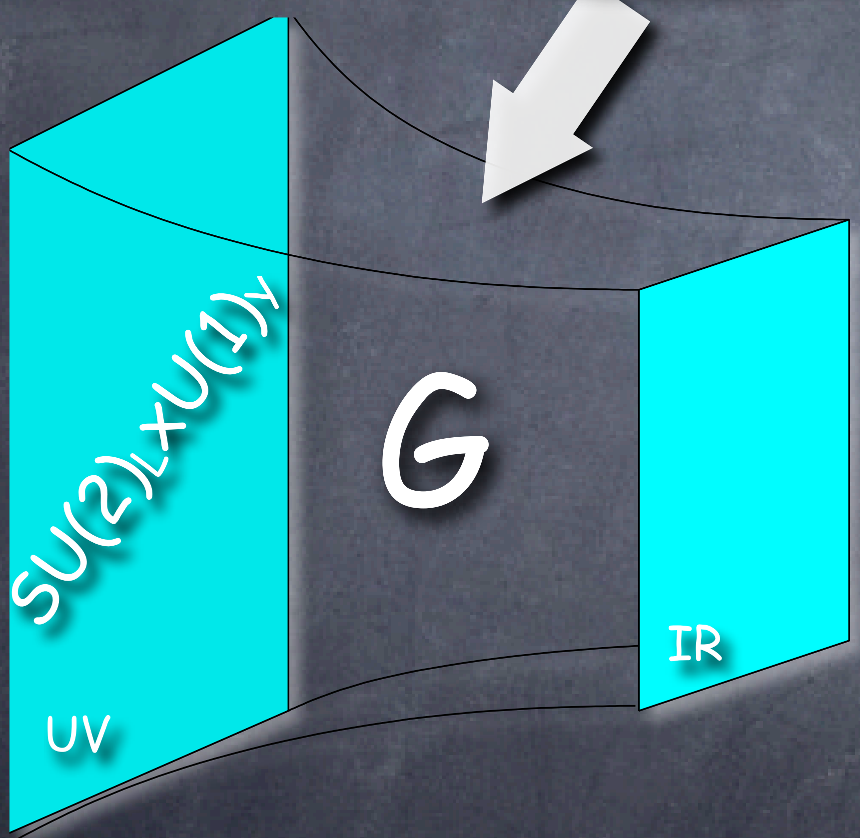
5D models=weakly coupled dual of 4D strongly models

Holographic Models of EWSB

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

Gauge fields + fermions in the bulk

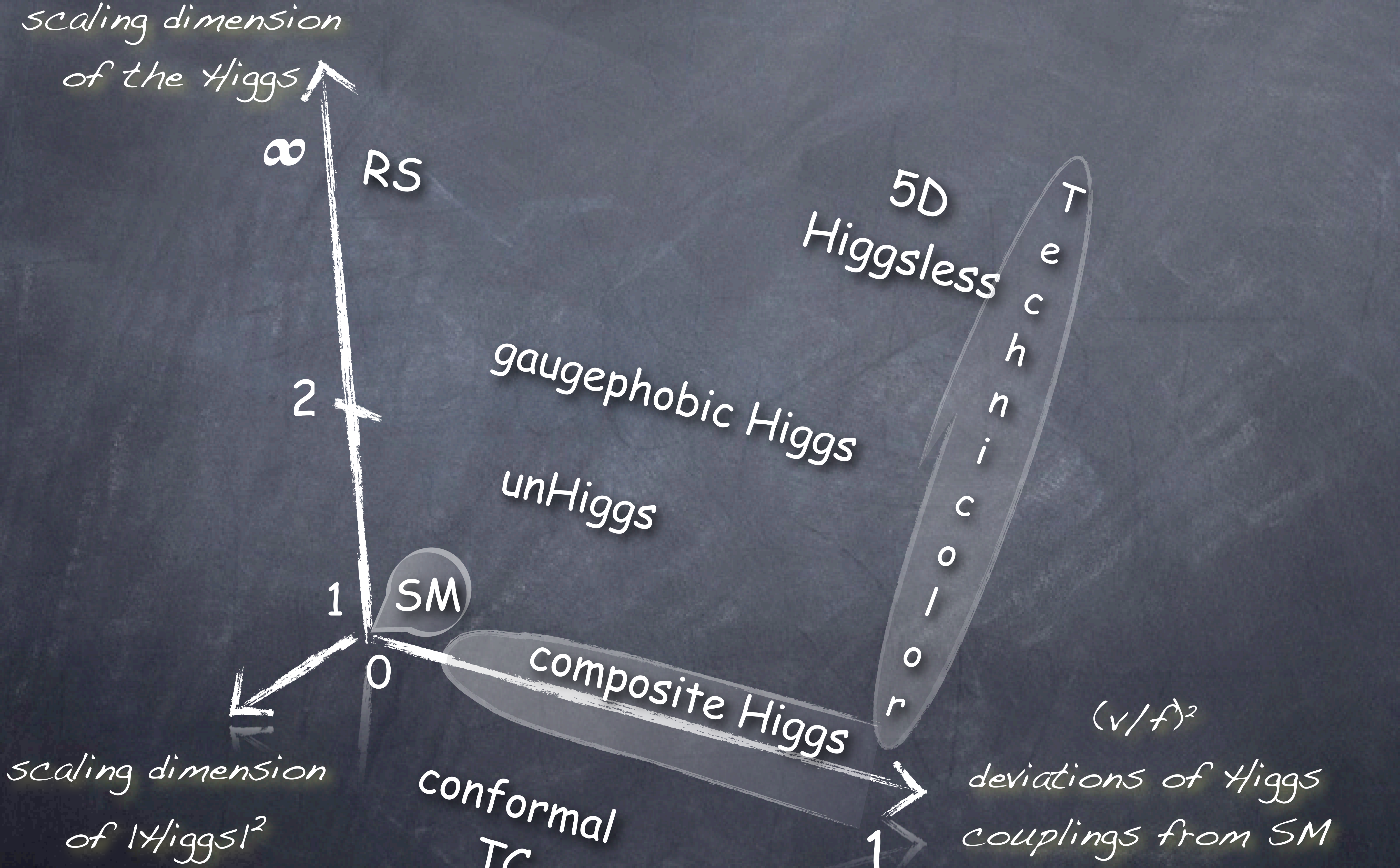
Higgs on the IR brane
or
Gauge breaking by boundary conditions



$G=SU(2)_L x SU(2)_R x U(1)_{B-L}$
$G=SO(5) x U(1)_X$
$G=SO(6) x U(1)_X$

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

A multi-dimensional deformation of the SM

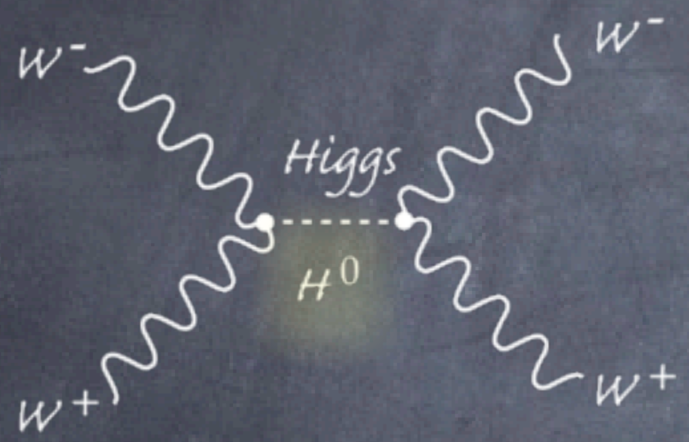


SM Higgs as a peculiar scalar resonance

A single scalar degree of freedom with no charge under $SU(2)_L x U(1)_Y$

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

'a' and 'b' 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

For b = a^2: perturbative unitarity also maintained in inelastic channels

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

$\mathcal{L}_{\rm mass} + \mathcal{L}_{\rm EWSB}$ 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 $SU(2)_L x U(1)_Y$

Higgs properties depend on a single unknown parameter (m_H)

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

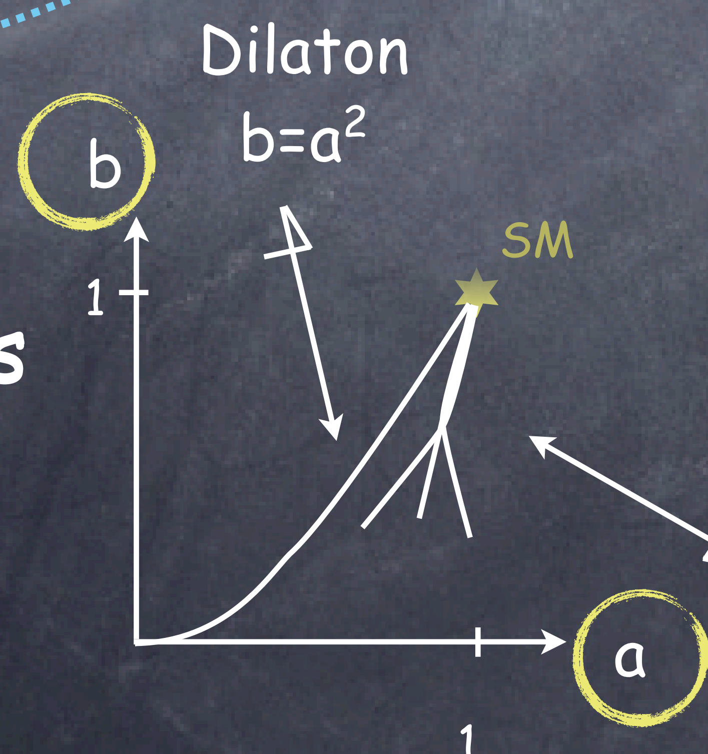
Higgs decouple from SM; vector resonances like in TC

Composite Higgs

vs.

SM Higgs

Dilaton

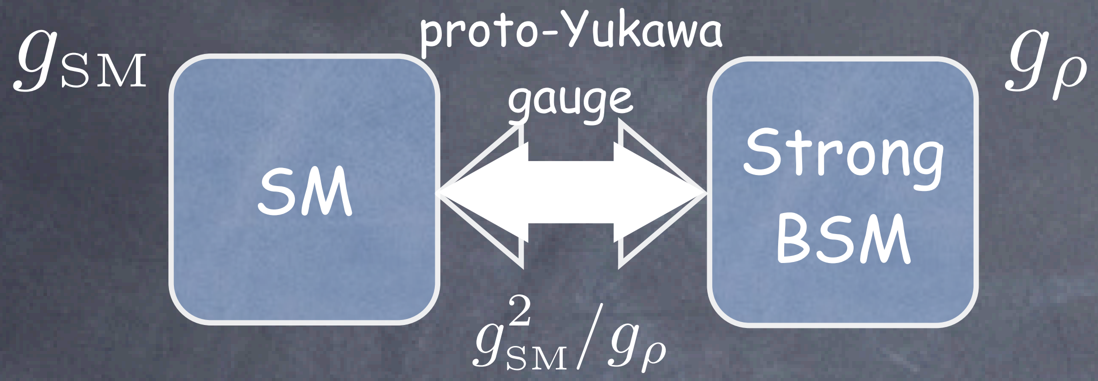


$$\mathcal{L}_{\rm EWSB} = \left(a\, \frac{v}{2}\, h \; + b\, \frac{1}{4}\, h^2 \right) {\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma \right)$$

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

How to obtain a light composite Higgs?

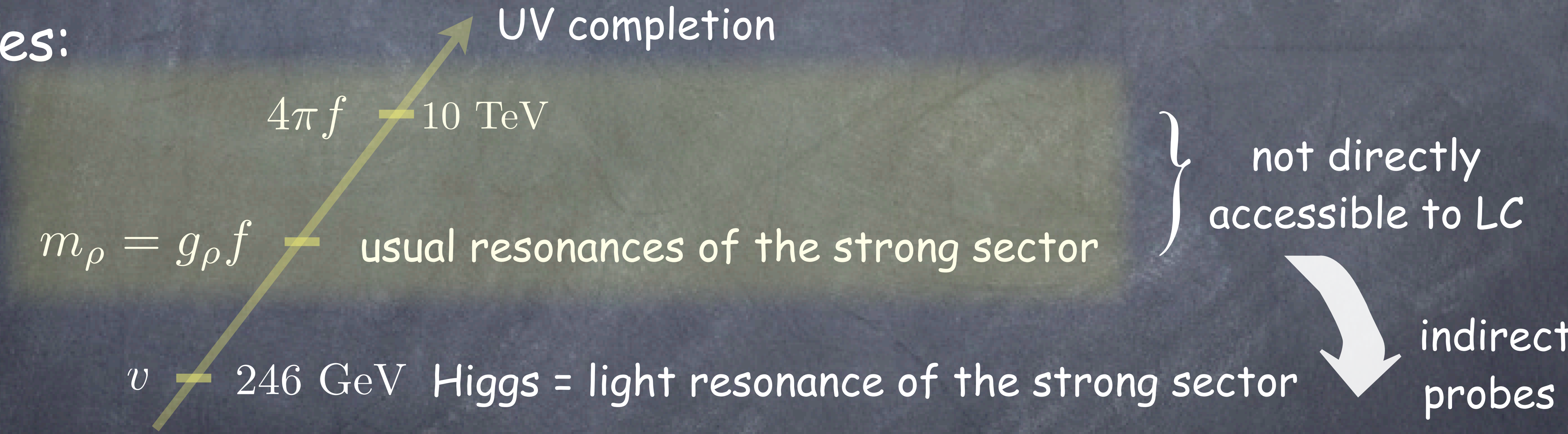
Higgs=Pseudo-Goldstone boson of the strong sector



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

global symmetry → G/H ← residual global symmetry

3 scales:



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 $f = \frac{m_\rho}{g_\rho}$

Testing the composite nature of the Higgs?

if LHC sees a Higgs and nothing else*:
is it elementary or composite?

¿¿¿ evidence for fine-tuning & string landscape ???

¿¿¿ Higgs forces have a secret hidden gauge origin ???

- Model-dependent: production of resonances at m_ρ
- Model-independent: study of Higgs properties & W scattering
  - strong WW scattering
  - strong HH production
  - Higgs anomalous coupling
  - anomalous gauge bosons self-couplings

* a likely possibility that precision data seems to point to,
at least in strongly coupled models

What distinguishes a composite Higgs?

Giudice, Grojean, Pomarol, Rattazzi '07

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

$$U = e^{i\begin{pmatrix} & H/f \\ H^\dagger/f & \end{pmatrix}} U_0$$

$$f^2 \operatorname{tr}\left(\partial_\mu U^\dagger \partial^\mu U\right) = |\partial_\mu H|^2 + \frac{\sharp}{f^2}\left(\partial|H|^2\right)^2 + \frac{\sharp}{f^2}|H|^2 \left|\partial H\right|^2 + \frac{\sharp}{f^2}\left|H^\dagger \partial H\right|^2$$

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

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)

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

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

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

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

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

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: $c_H v^2 / f^2 < 1/3 \sim 1/2$

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

Flavor Constraints

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

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

mass terms

Higgs fermion interactions

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

$\Rrightarrow$ FCNC

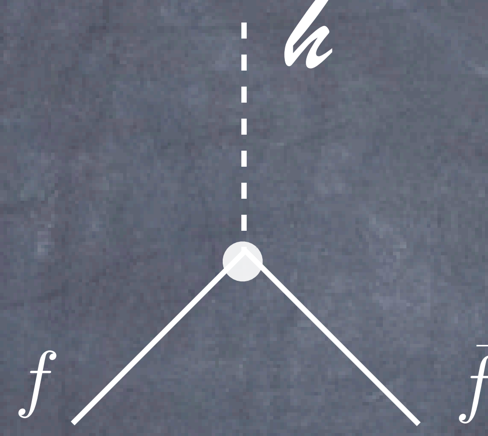
SILH: c_y is flavor universal

$\Rrightarrow$ Minimal flavor violation built in

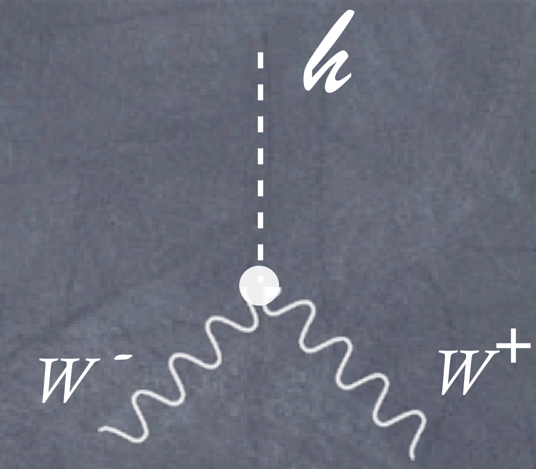
Higgs anomalous couplings

Lagrangian in unitary gauge

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \left(-\frac{m_H^2}{2v}(c_6 - 3c_H/2)h^3 + \frac{m_f}{v}\bar{f}f(c_y + c_H/2)h - c_H \frac{m_W^2}{v} h W_\mu^+ W^{-\mu} - c_H \frac{m_Z^2}{v} h Z_\mu Z^\mu \right) \frac{v^2}{f^2} + \ldots$$



$$g_{SM}\left(1 - (c_y + c_H/2) v^2/f^2\right)$$



$$g_{SM}\left(1 - c_H v^2/f^2\right)$$

⇘ ⇙

$$\Gamma\left(h \to f\bar{f}\right)_{\rm SILH} = \Gamma\left(h \to f\bar{f}\right)_{\rm SM}\left[1 - \left(2c_y + c_H\right)v^2/f^2\right]$$

$$\Gamma\left(h \to gg\right)_{\rm SILH} = \Gamma\left(h \to gg\right)_{\rm SM}\left[1 - \left(2c_y + c_H\right)v^2/f^2\right]$$

Note: same Lorentz structure as in SM. Not true anymore if form factor ops. are included

Higgs anomalous couplings for large v/f

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

$$m_W^2 = \frac{1}{4} g^2 f^2 \sin^2 v/f \quad \Rrightarrow \quad g_{hWW} = \sqrt{1-\xi}\, g_{hWW}^{\mathrm{SM}}$$

Fermions embedded in spinorial of SO(5)

MCHM4

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

$$\Downarrow$$

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

universal shift of the couplings
no modifications of BRs

Fermions embedded in 5+10 of SO(5)

MCHM5

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

$$\Downarrow$$

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

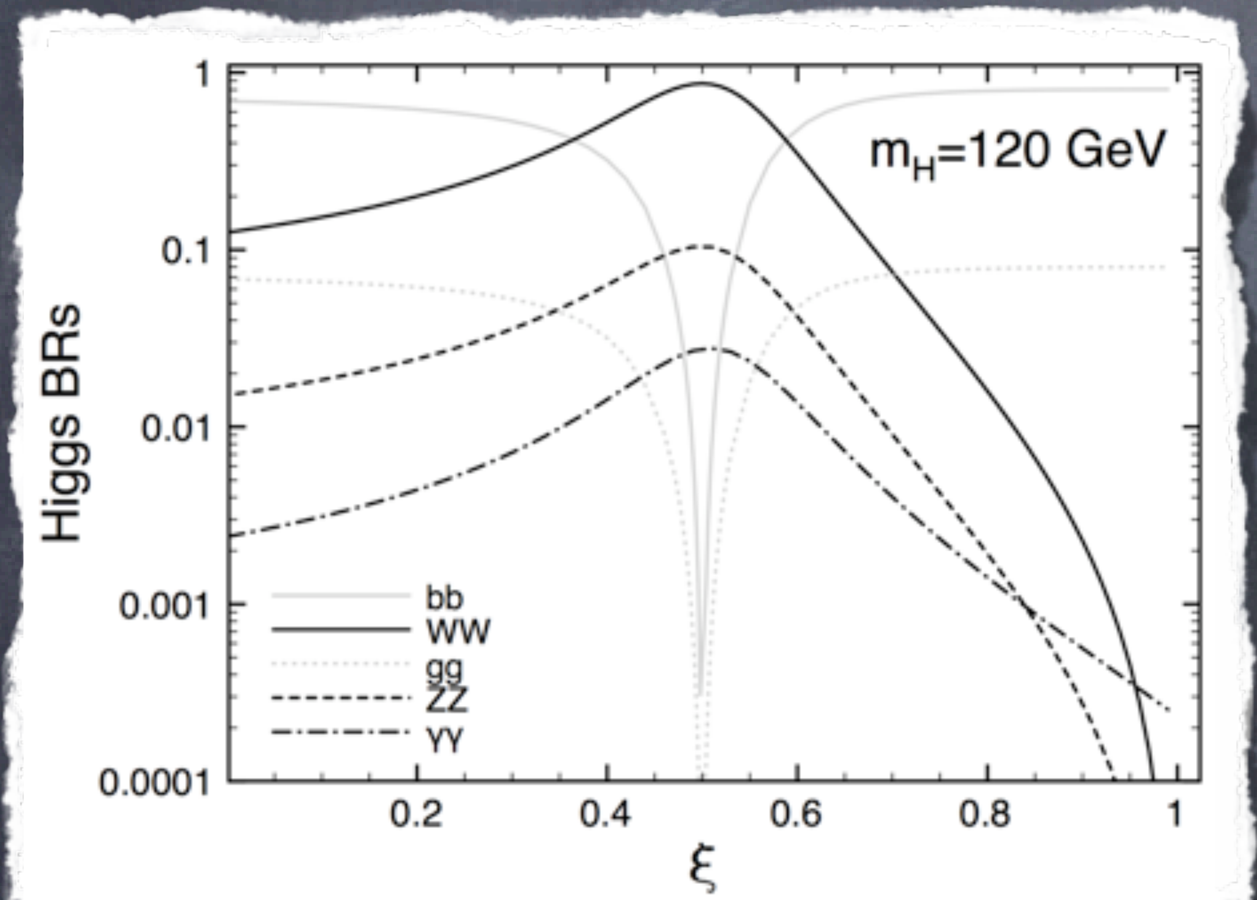
BRs now depends on v/f

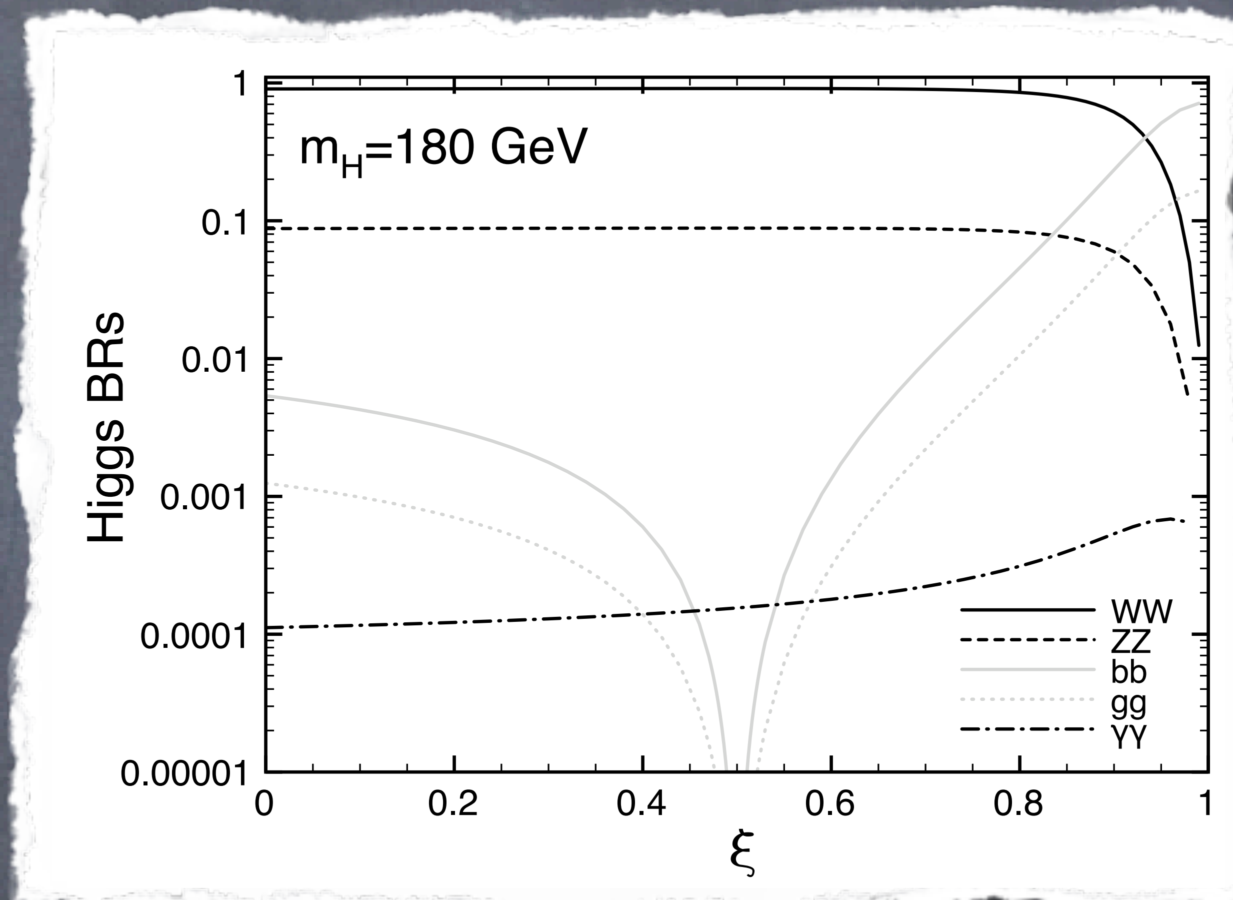
$$(\ \xi = v^2/f^2\ )$$

Higgs BRs

MCHM5

Fermions embedded in 5+10 of SO(5)





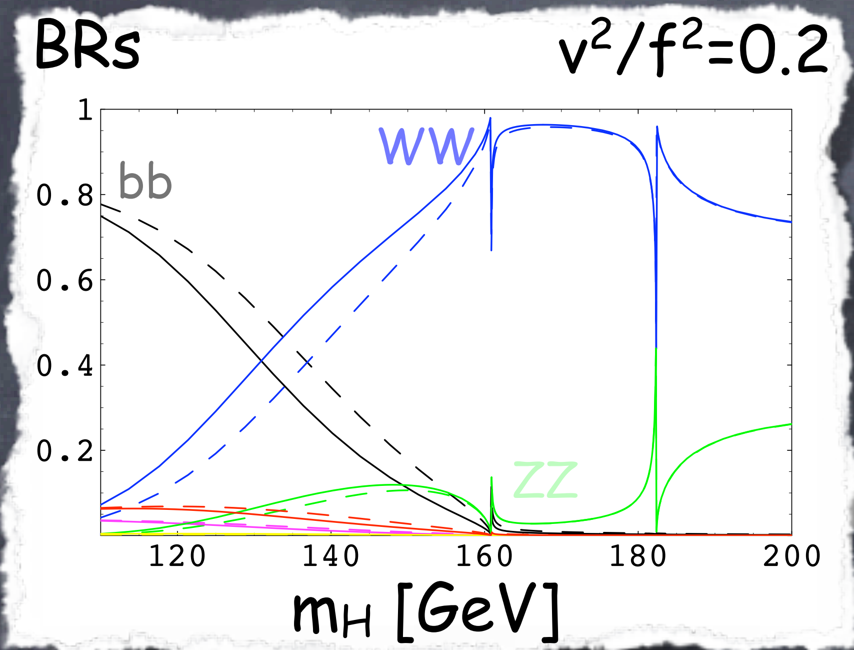
h→WW can dominate even for low Higgs mass

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

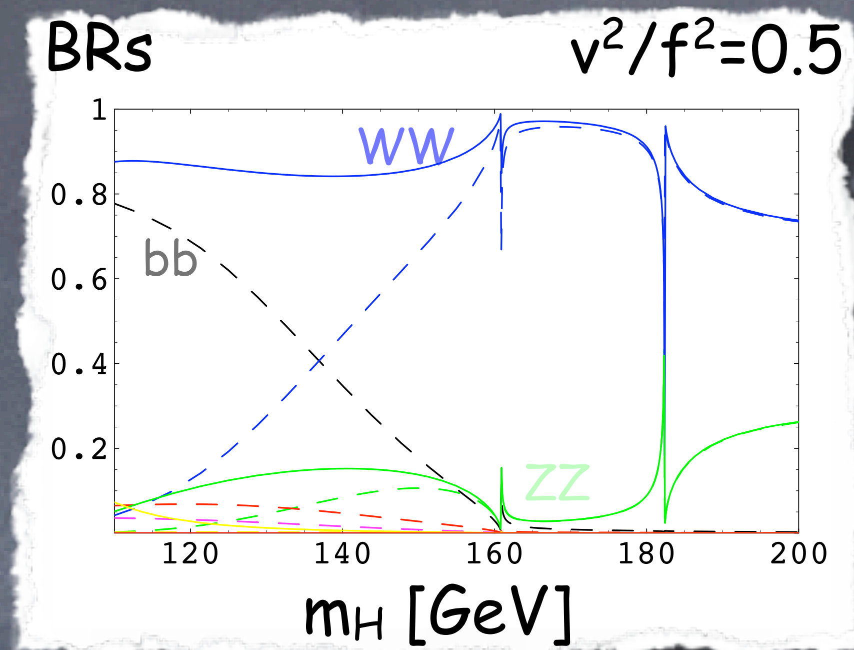
Higgs BRs and total width

MCHM5

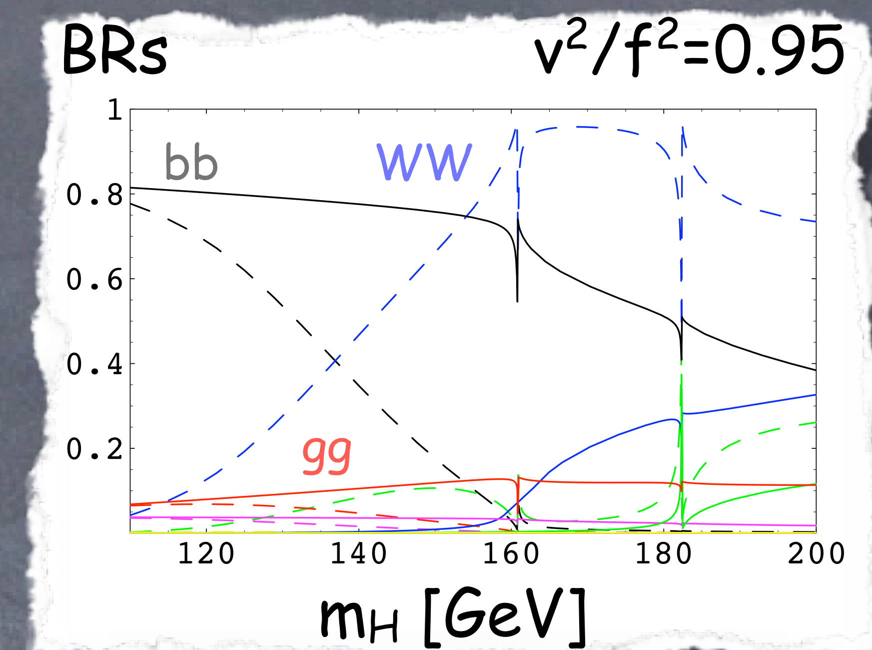
Fermions embedded in 5+10 of SO(5)



slight modifications

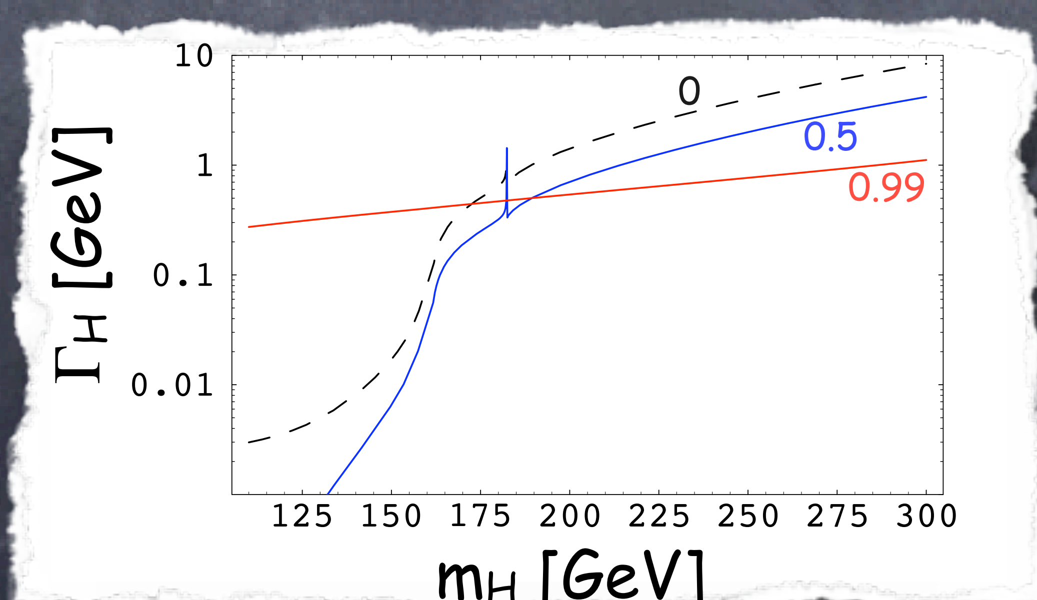


suppress bb



suppress WW

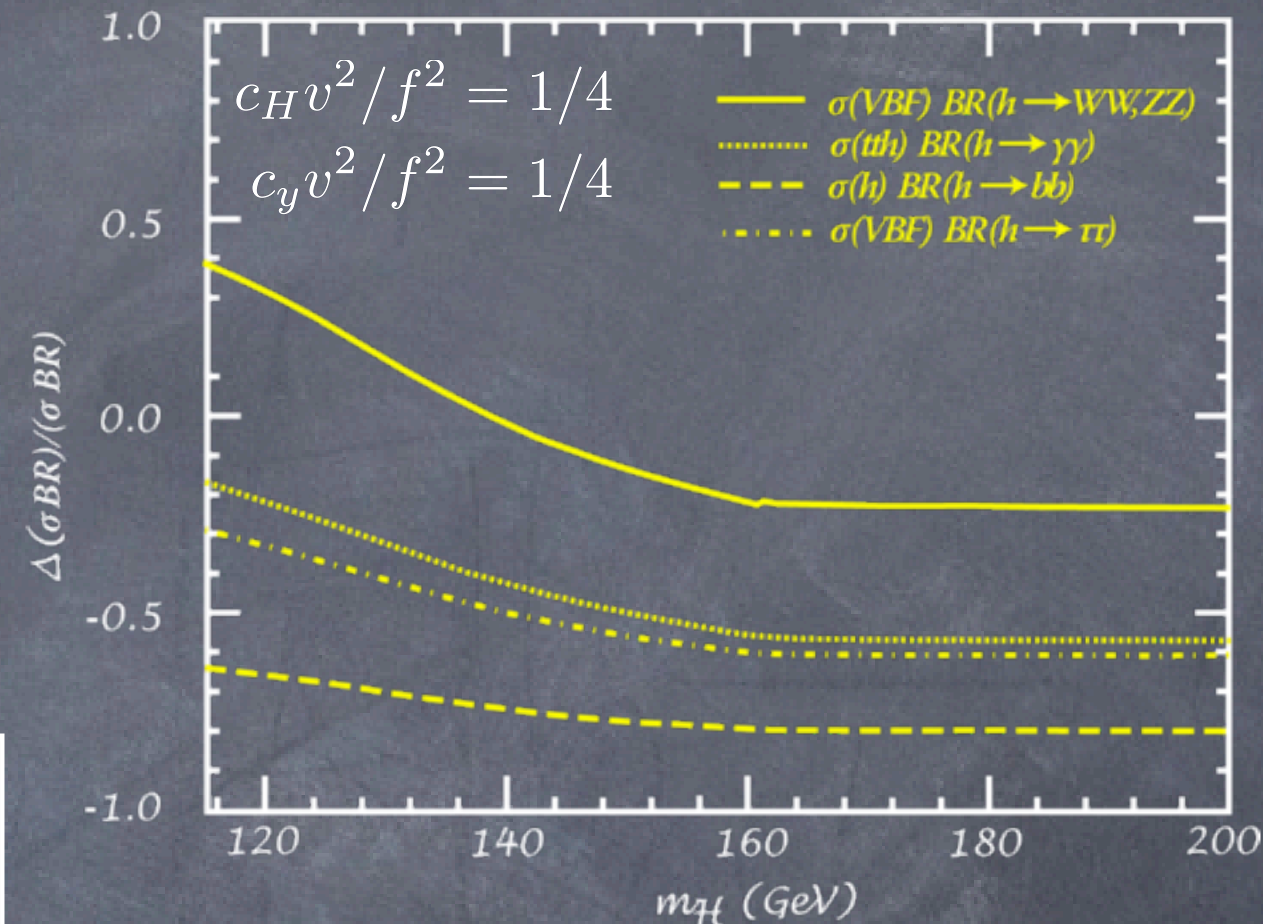
Higgs total width



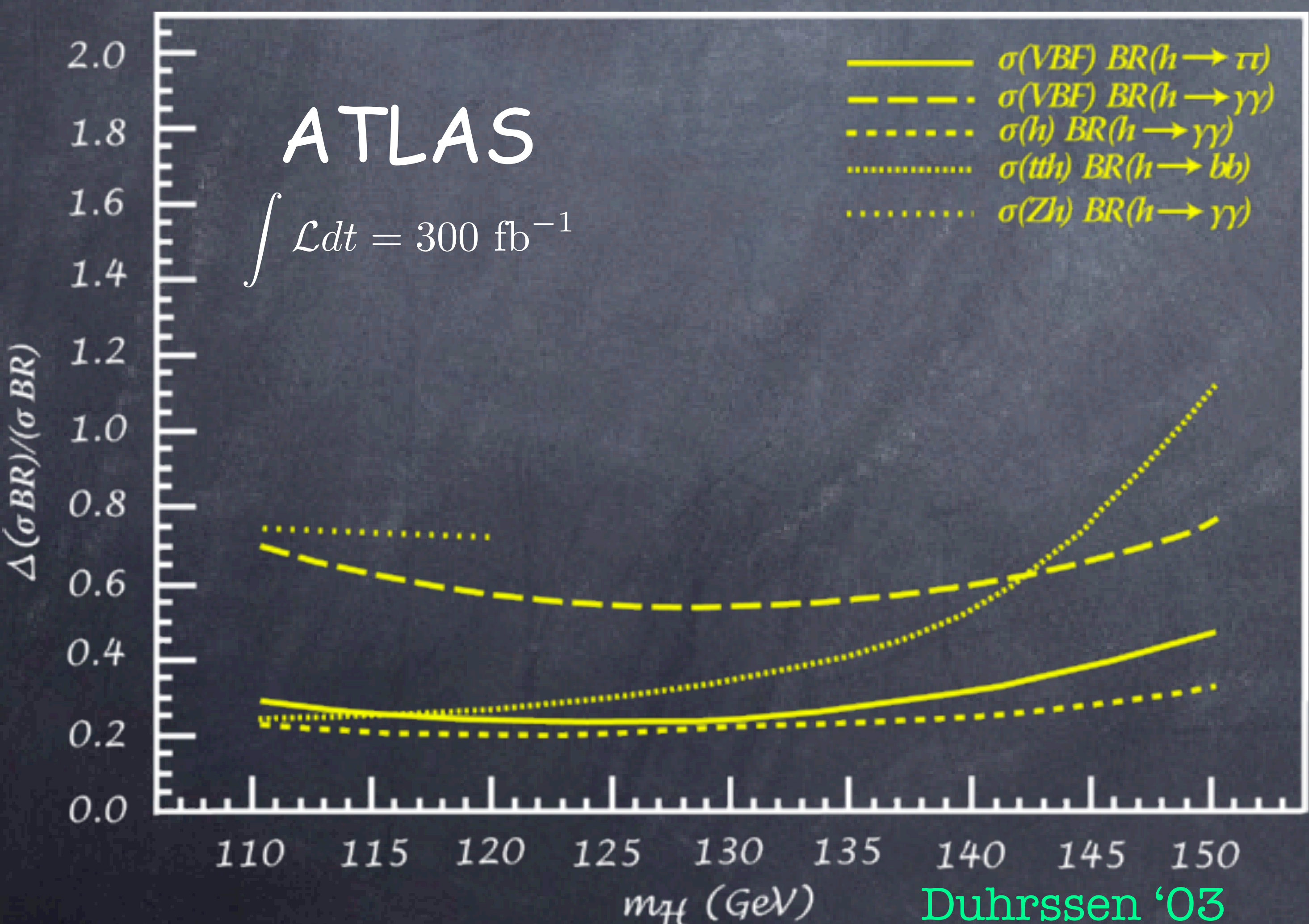
Higgs anomalous couplings @ LHC

$$\Gamma\left(h\to f\bar f\right)_{\rm SILH} = \Gamma\left(h\to f\bar f\right)_{\rm SM}\left[1-\left(2c_y+c_H\right)v^2/f^2\right]$$

$$\Gamma\left(h\to gg\right)_{\rm SILH} = \Gamma\left(h\to gg\right)_{\rm SM}\left[1-\left(2c_y+c_H\right)v^2/f^2\right]$$



observable @ LHC?



Duhrssen '03

LHC can measure

$$c_H\frac{v^2}{f^2},\quad c_y\frac{v^2}{f^2}$$

up to 0.2-0.4

i.e. $4\pi f\sim 5-7\ \mathrm{TeV}$

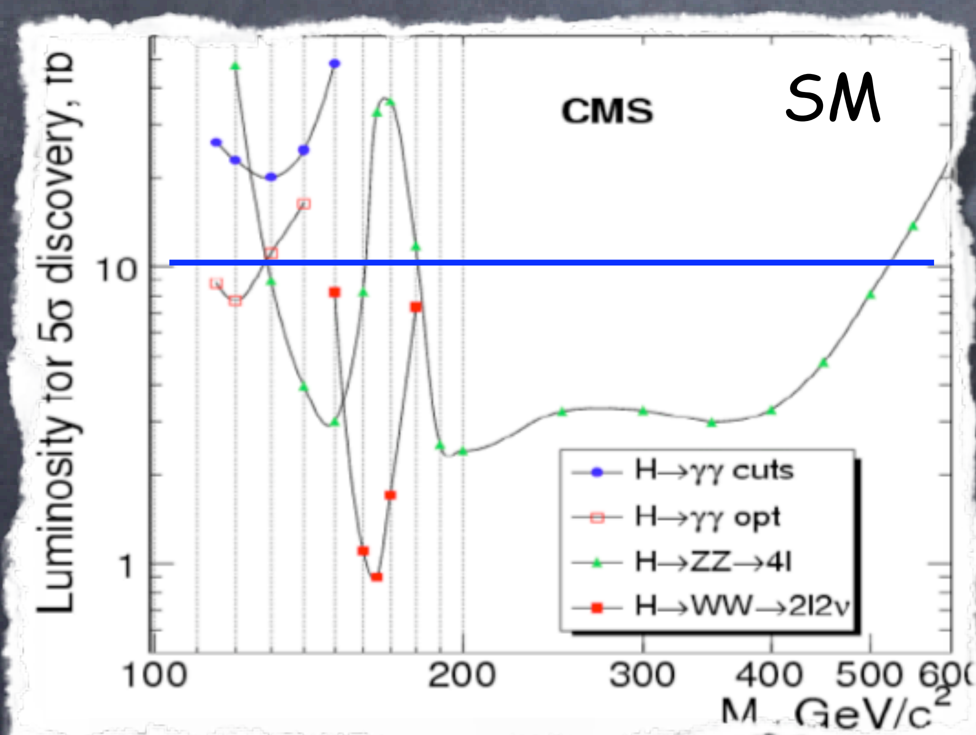
(ILC could go to few % ie
test composite Higgs up to $4\pi f\sim 30\ \mathrm{TeV}$)

Composite Higgs search @ LHC

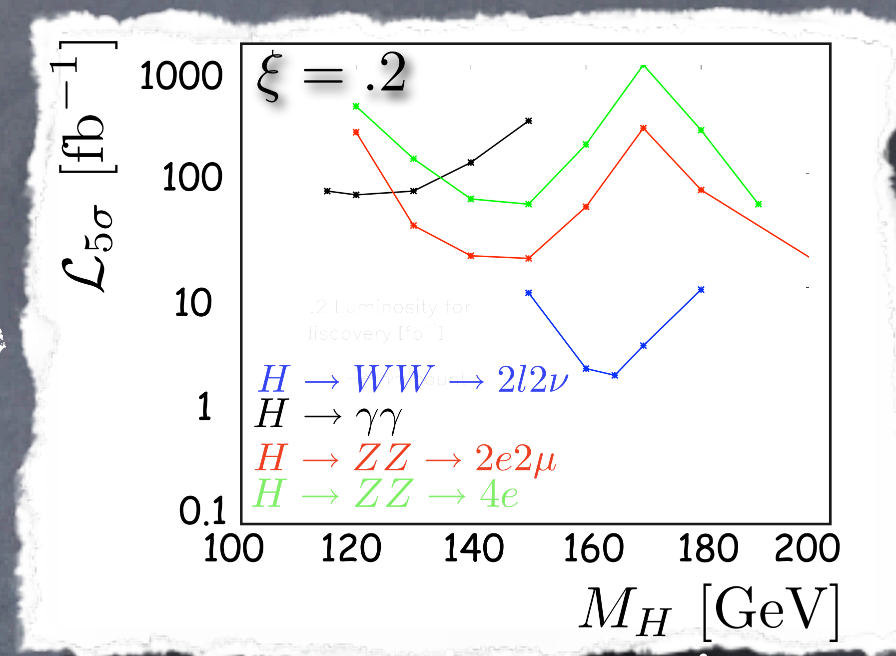
[Espinosa, Grojean, Muehlleitner 'to appear]

the modification of Higgs couplings and BRs affects the Higgs search

MCHMs



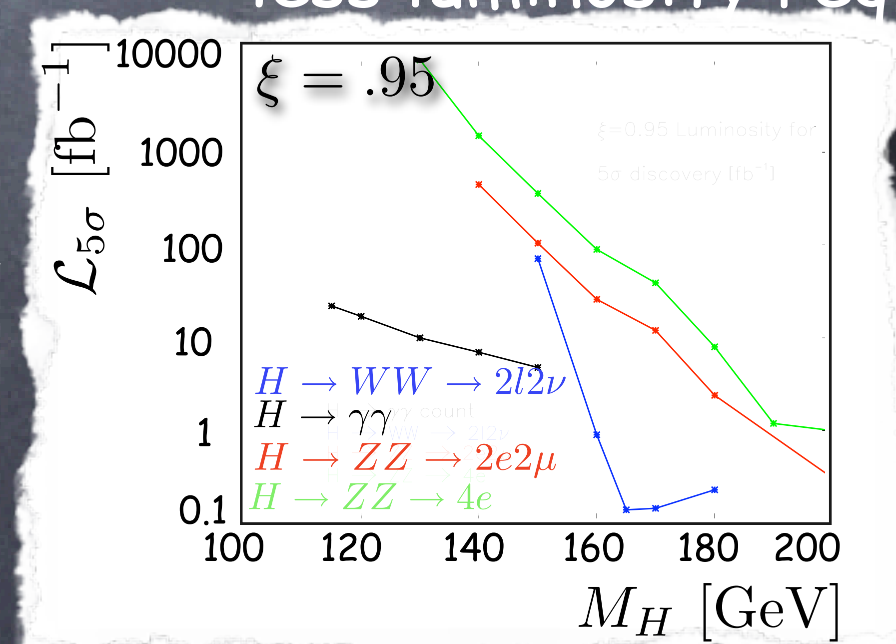
large
compositeness scale



more luminosity required

less luminosity required

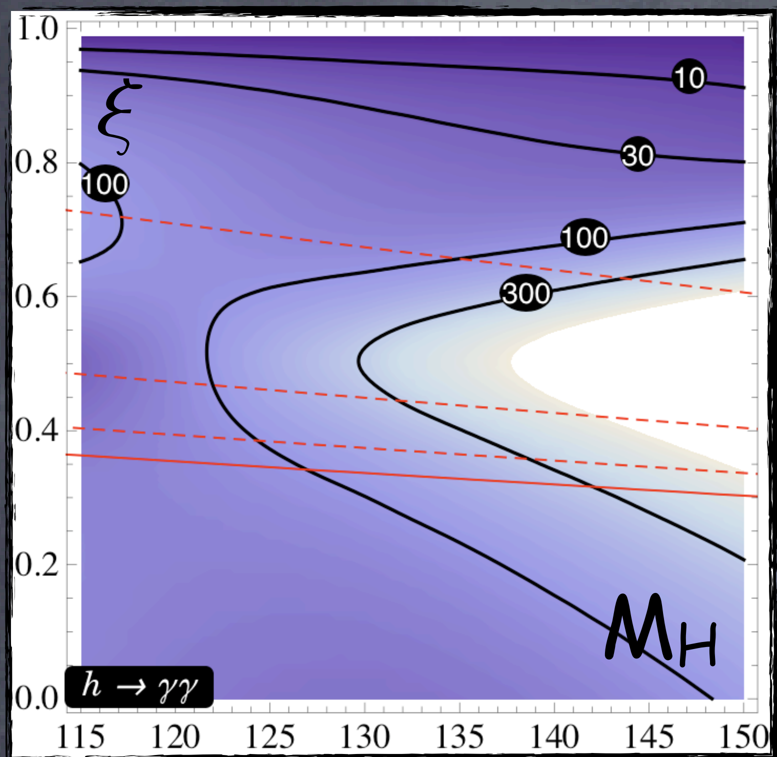
small
compositeness scale



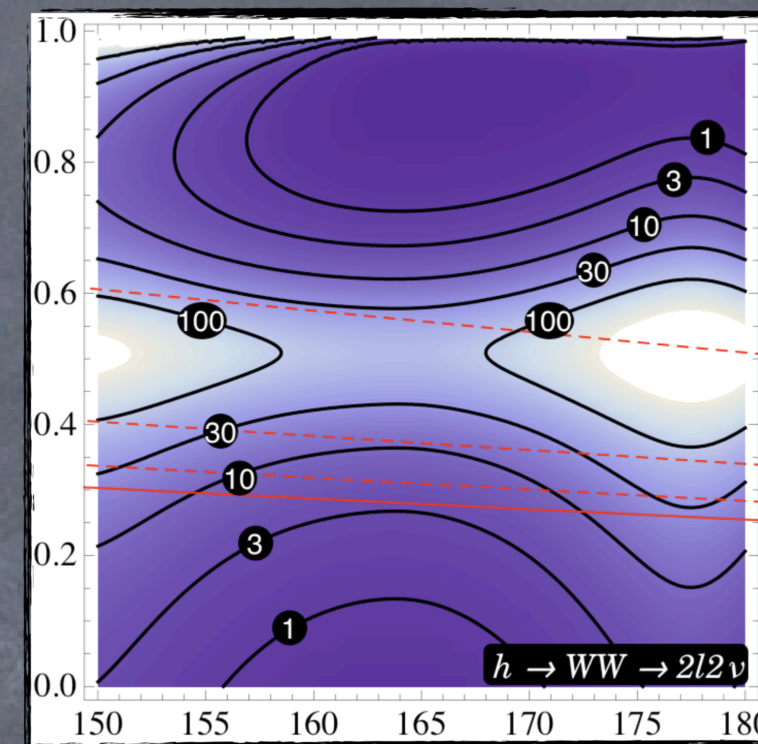
Composite Higgs search @ LHC

[Espinosa, Grojean, Muehlleitner 'to appear]

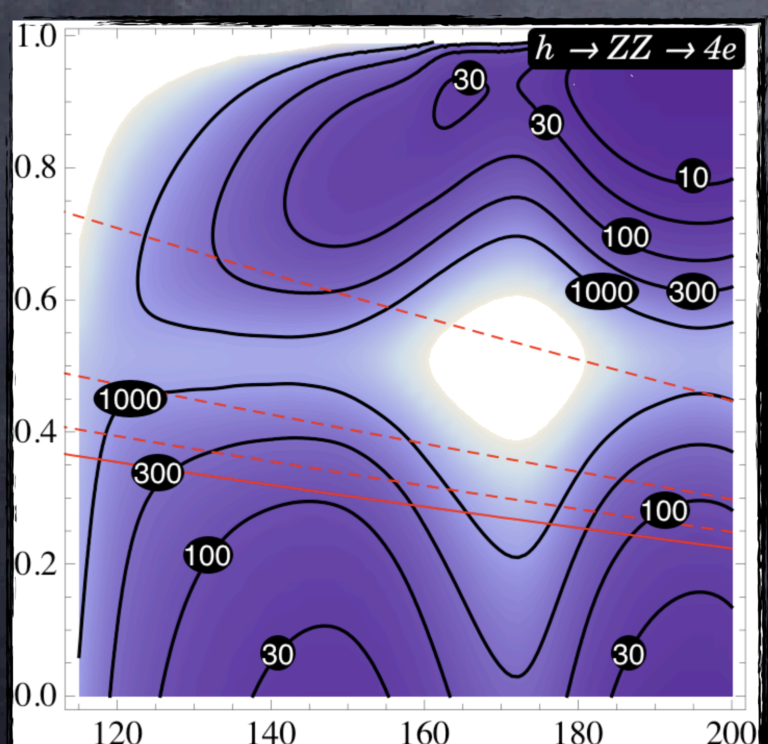
the modification of Higgs couplings and BRs affects the Higgs search

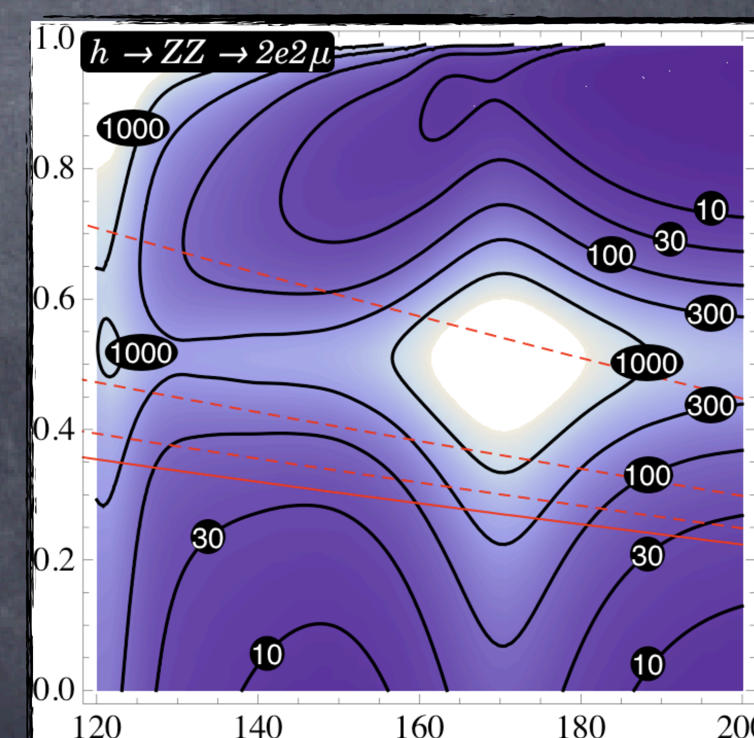


MCHM5



contour lines of luminosity needed for 5σ discovery in the (ξ,M_H) plane





(neglect effects from heavy resonances)

Triple gauge boson couplings (TGC) @ LC

$$\mathcal{L}_V = -ig\cos\theta_W g_1^Z Z^\mu \left(W^{+\nu}W^-_{\mu\nu} - W^{-\nu}W^+_{\mu\nu}\right) - ig\left(\cos\theta_W \kappa_Z Z^{\mu\nu} + \sin\theta_W \kappa_\gamma A^{\mu\nu}\right) W^+_\mu W^-_\nu$$

TGC are generated by heavy resonances

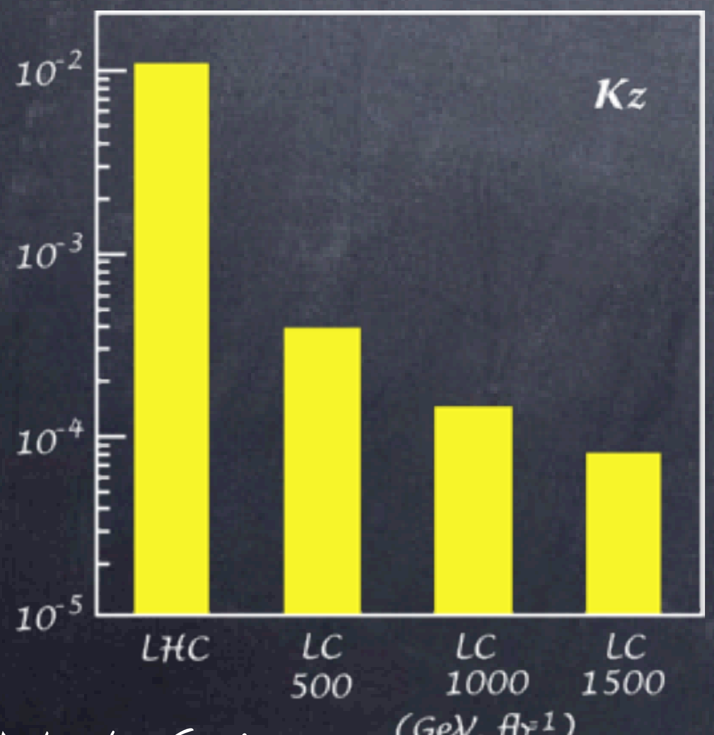
$$g_1^Z = \frac{m_Z^2}{m_\rho^2} c_W \qquad \kappa_\gamma = \frac{m_W^2}{m_\rho^2}\left(\frac{g_\rho}{4\pi}\right)^2 (c_{HW} + c_{HB}) \qquad \kappa_Z = g_1^Z - \tan^2\theta_W \kappa_\gamma$$

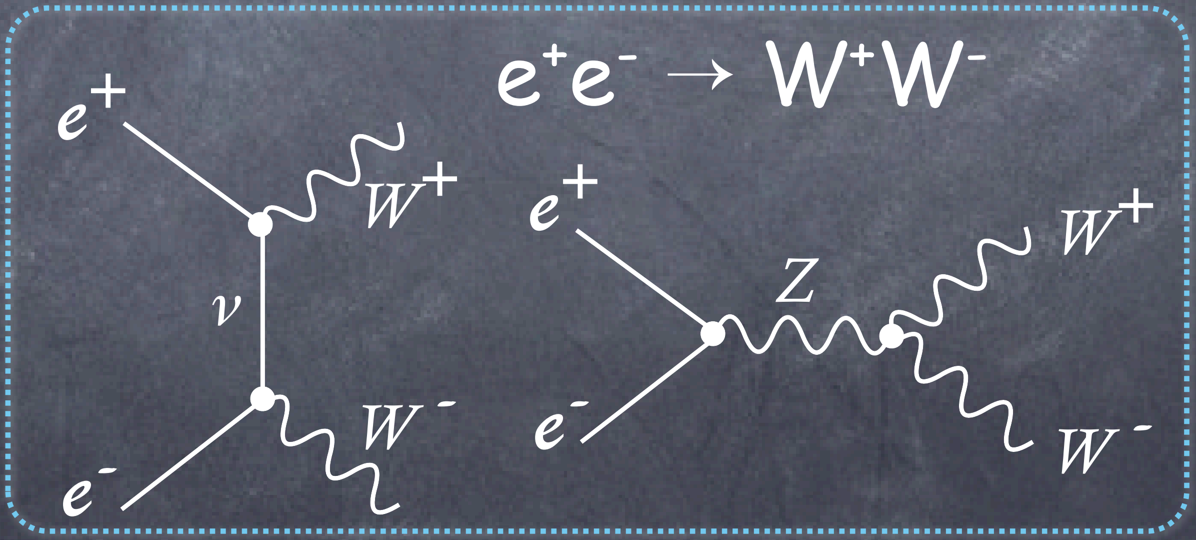
@ LHC 100fb^{-1} $g_1^Z \sim 1\%$ $\kappa_\gamma \sim \kappa_Z \sim 5\%$

sensitive to resonance up to m_ρ~800 GeV

not competitive with the measure of S at LEPII

@ ILC





T. Abe et al, Snowmass '01

0.1% accuracy $\Rightarrow$ sensitive to resonance up to m_ρ~8TeV

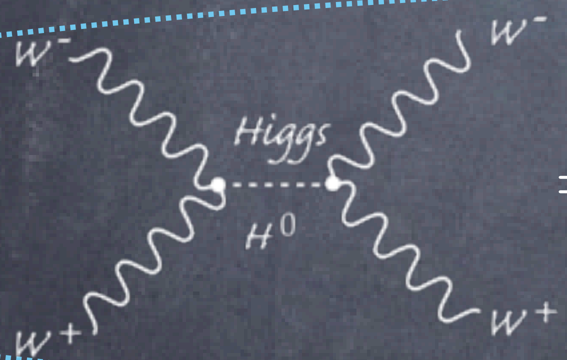
Strong WW scattering

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



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

no exact cancellation of the growing amplitudes

Even with a light Higgs, growing amplitudes (at least up to m_ρ)

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

$$\mathcal{A}_{\rm LET}(s,t,u) = \frac{s}{v^2} \Longrightarrow \mathcal{A}_\xi = \xi\,\mathcal{A}_{\rm LET}$$

LET=SM-Higgs

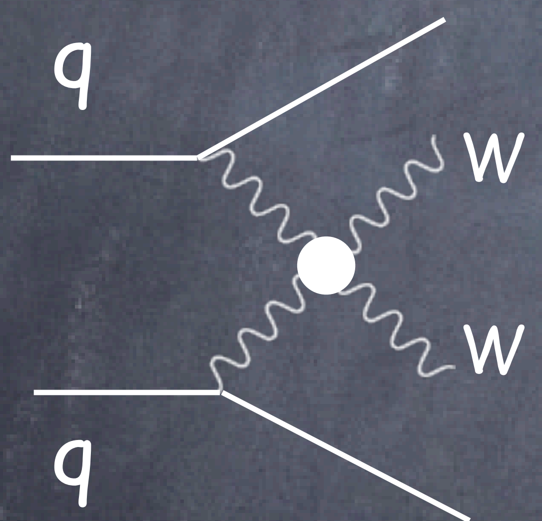
Strong WW scattering @ LHC

Even with a light Higgs, growing amplitudes (at least up to m_ρ)

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

$$\mathcal{A}\left(W^\pm Z_L^0 \to W^\pm Z_L^0\right) = \frac{c_H t}{f^2}, \quad \mathcal{A}\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = \frac{c_H (s+t)}{f^2}$$

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to Z_L^0 Z_L^0\right) = 0$$



$$\sigma\left(pp \to V_L V_L X\right)_\xi = \xi^2\, \sigma\left(pp \to V_L V_L X\right)_{\rm LET}$$

leptonic vector decay channels

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

	LET($\xi = 1$)	SM bckg
ZZ	4.5	2.1
W^+W^-	15.0	36
$W^\pm Z$	9.6	14.7
$W^\pm W^\pm$	39	11.1

$\mathcal{L} = 300\,\text{fb}^{-1}$

Bagger et al '95
Butterworth et al. '02

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

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

'inclusive' cross-section

$(-s+Q^2_{\rm min} < t < -Q^2_{\rm min})$

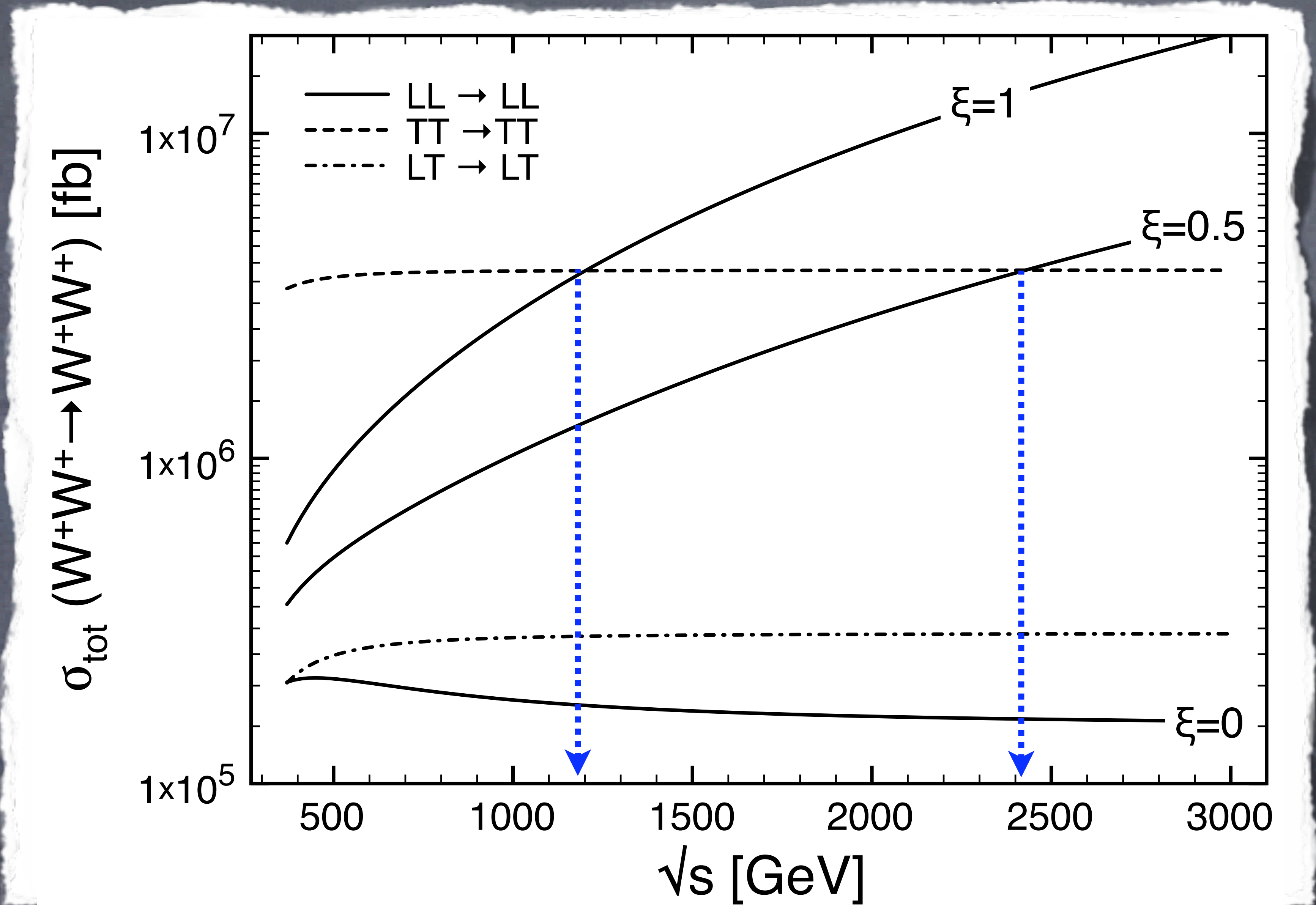
$$\frac{\sigma_{LL\to LL}(Q_{\rm min})}{\sigma_{TT\to TT}(Q_{\rm min})} = N_s \frac{s\, Q^2_{\rm min}}{M_W^4}$$

NDA estimates

$N_h \sim 1$ $\quad$ $N_s \sim 1$

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)

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

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

$$\mathcal{A} = \frac{a_\gamma^t\, s}{t} + \frac{a_Z^t\, s}{t - M_Z^2} + \frac{a_\gamma^u\, s}{u} + \frac{a_Z^u\, s}{u - M_Z^2} + \ldots \Longrightarrow \sigma \sim \frac{1}{16\pi}\left(\frac{{a_\gamma^t}^2 + {a_\gamma^u}^2}{M_\gamma^2} + \frac{{a_Z^t}^2 + {a_Z^u}^2}{M_\gamma^2 + M_Z^2}\right)$$

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

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

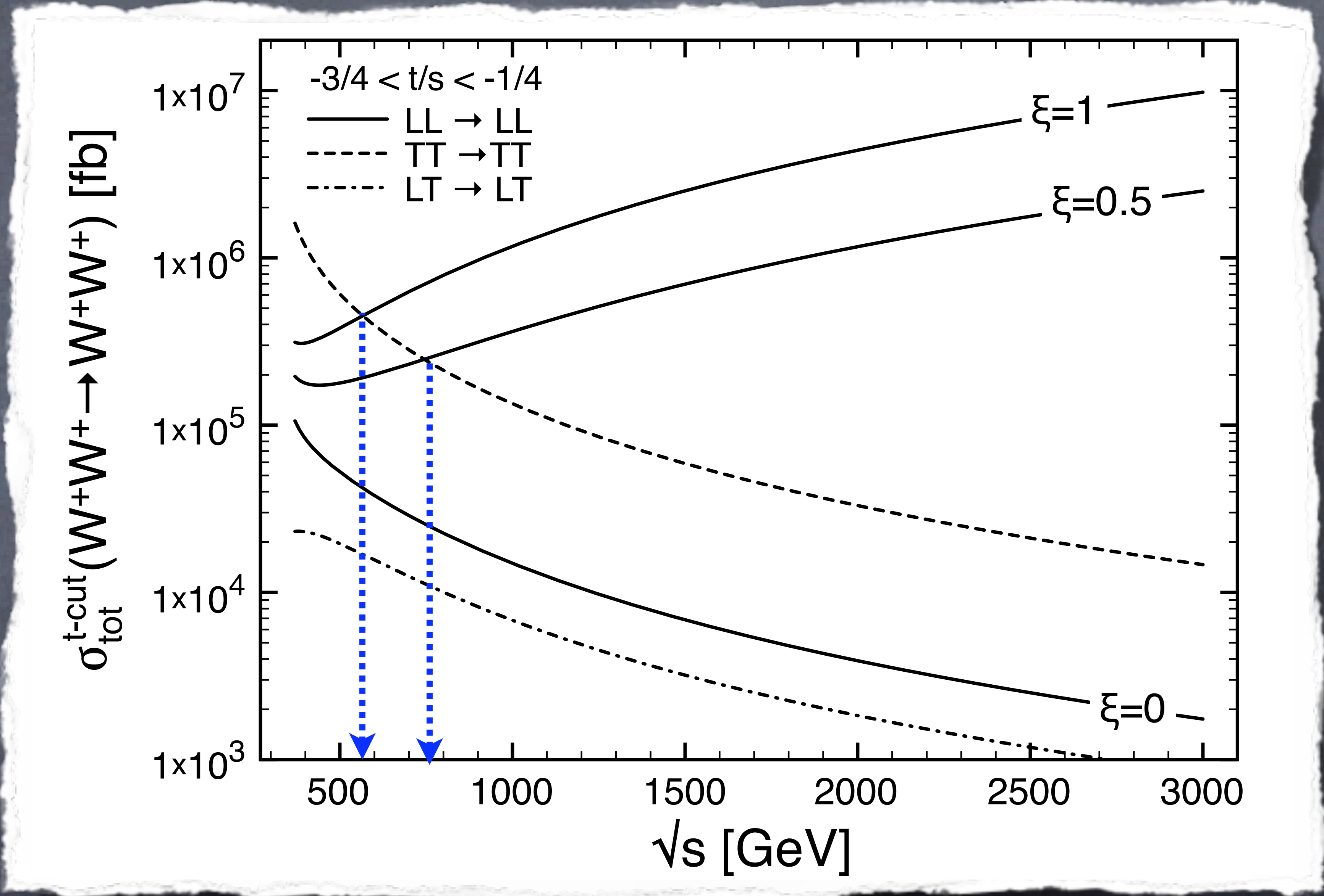
(for $M_\gamma \sim M_Z$)

$$N_s \sim 1/500$$

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

Hard scattering (central region)

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

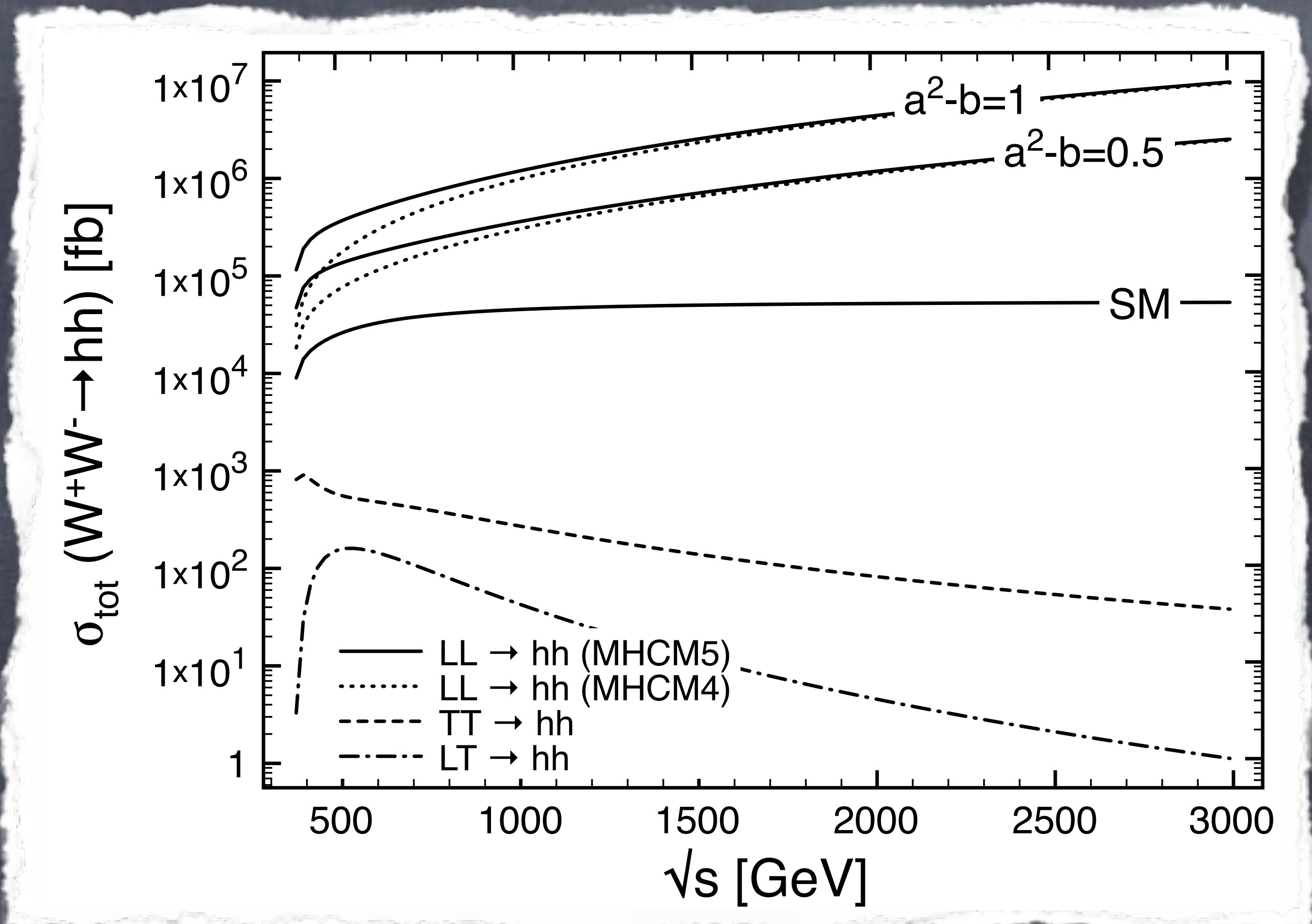


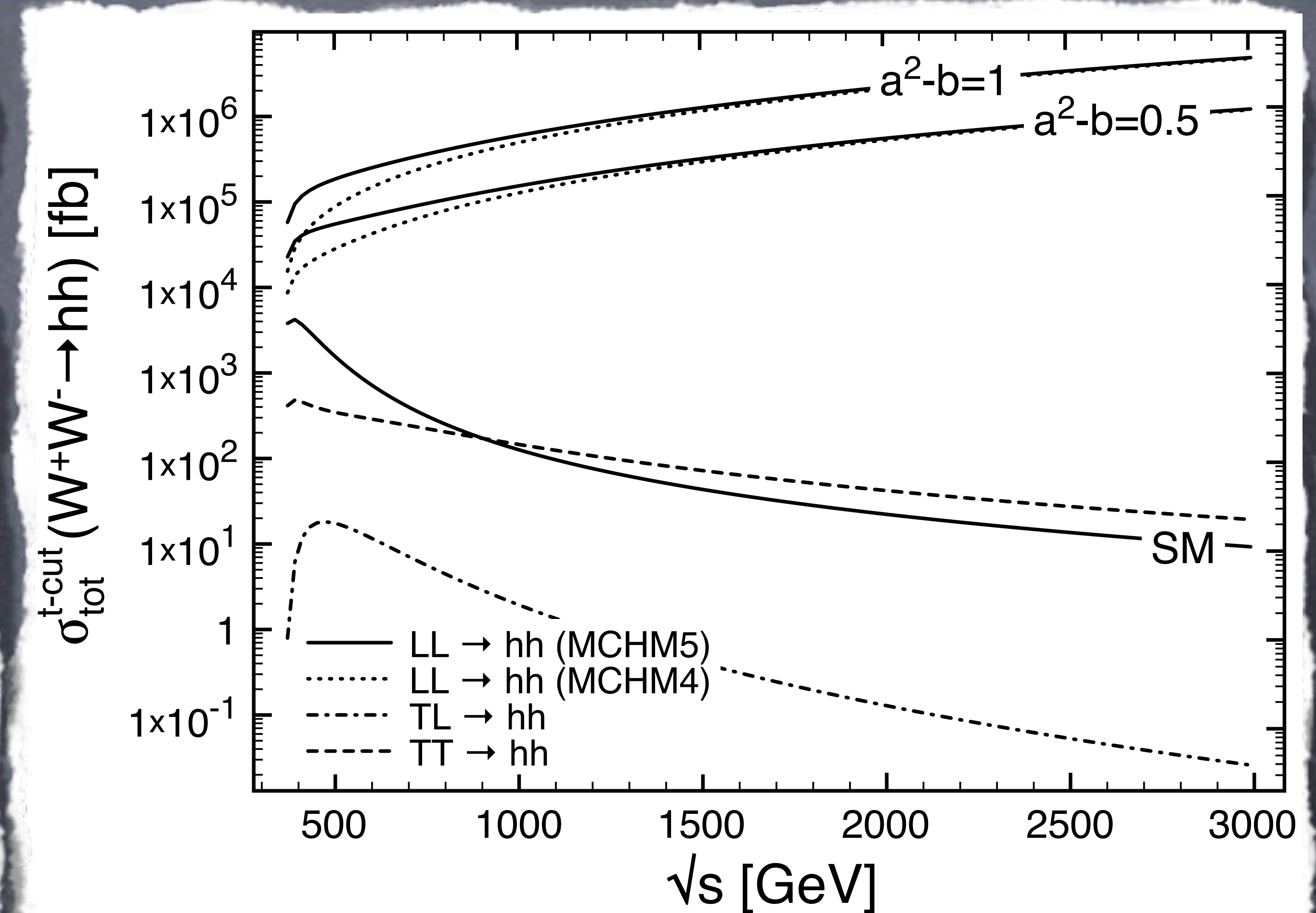
$$\frac{\sigma^{\rm hard}_{LL\to LL}}{\sigma^{\rm hard}_{TT\to TT}} \simeq \left(\frac{\sqrt{s}}{7.4\, M_W}\right)^4 \xi^2$$

$$N_h = 1/2304$$

- 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

Strong Higgs production: (3L+jets) analysis

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

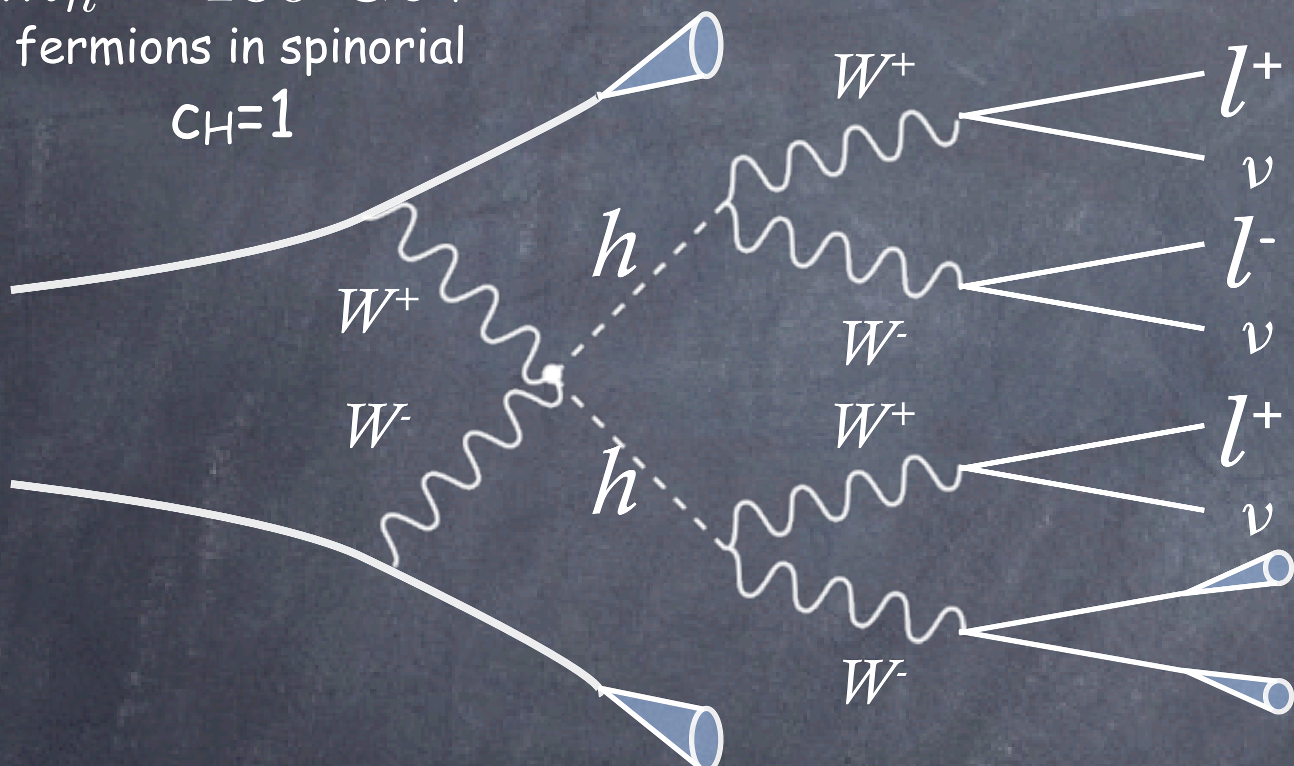
strong boson scattering ⇔ strong Higgs production

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

$m_h = 180$ 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...

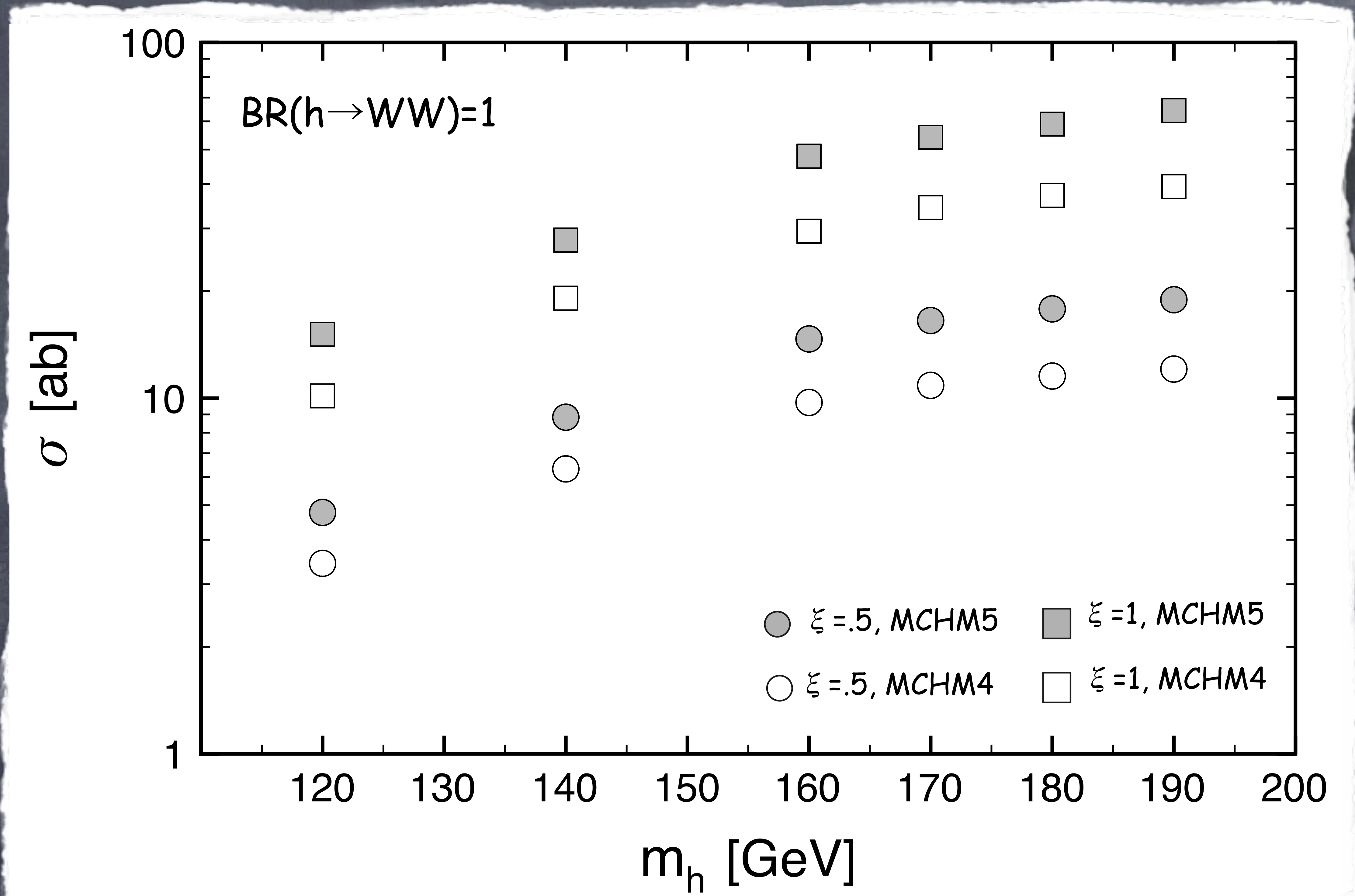
forward jet-tag, back-to-back lepton, central jet-veto

v/f	1	$\sqrt{.8}$	$\sqrt{.5}$
significance (300 fb^{-1})	4.0	2.9	1.3
luminosity for 5σ	450	850	3500

.

⇚ good motivation to SLHC

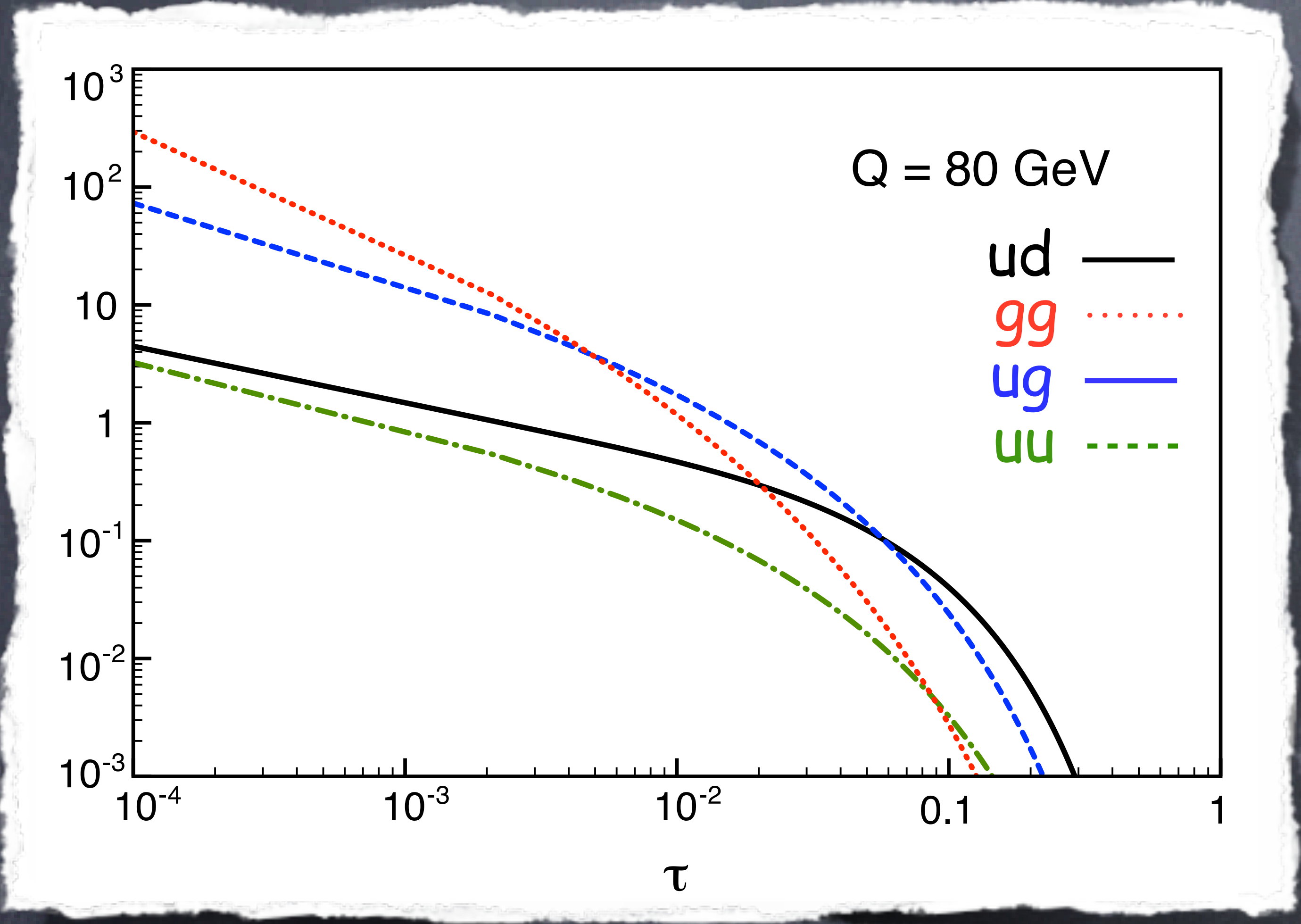
Higgs mass dependence



- production at threshold: $x_1 x_2 \sim 4 m_h^2/s$ σ↘ w/. m_h
- lighter Higgs, softer decay products, less effective cuts σ↗ w/. m_h

Threshold production

$$\frac{d\sigma}{d\hat{s}} = \frac{1}{\hat{s}}\hat{\sigma}(q_A q_B \to hh)\rho_{AB}(\hat{s}/s, Q^2)$$



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

integral is saturated at threshold

⇓ ⇓ ⇓

inclusive cross-section is not probing the asymptotic regime of hard scattering

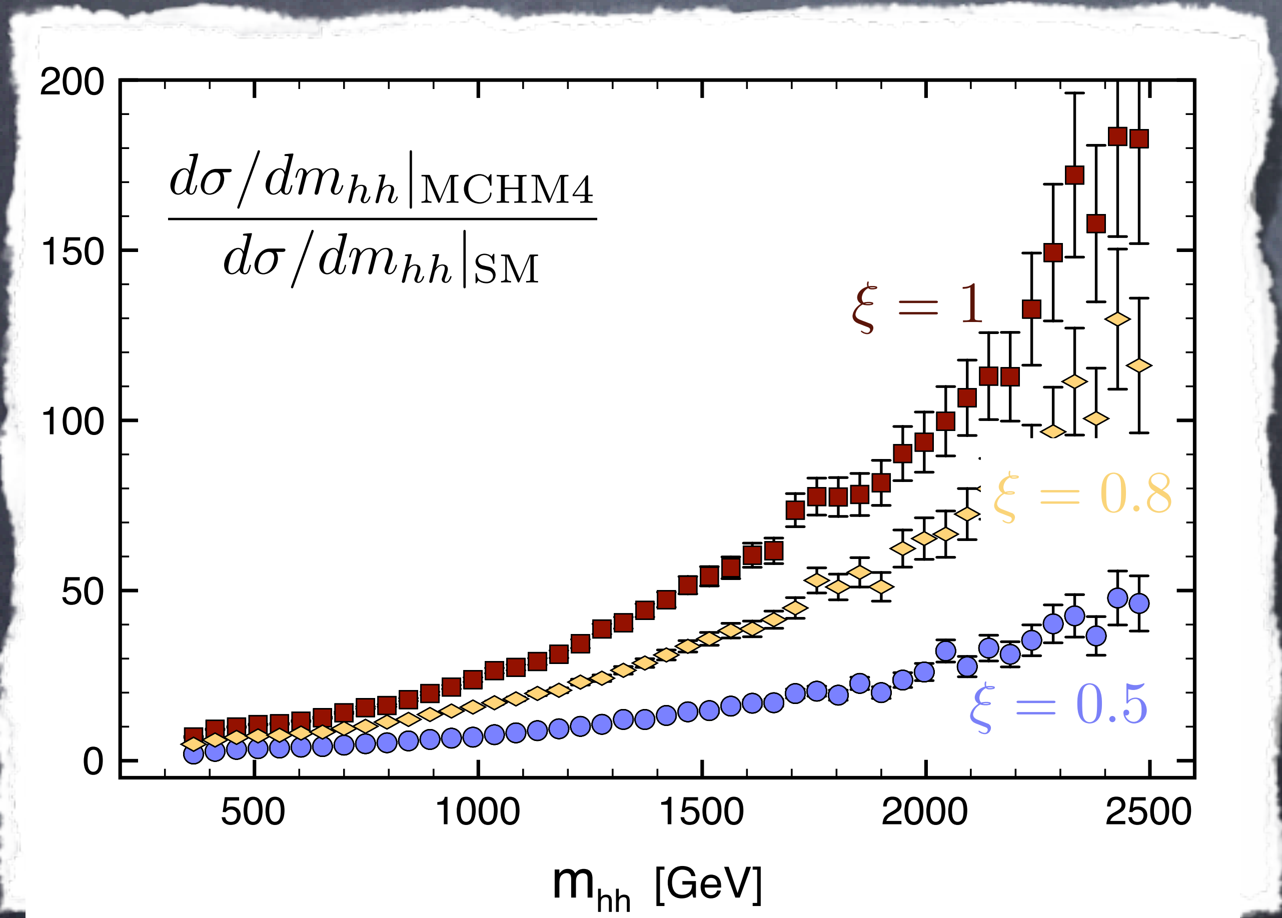
sensitivity on Higgs self-coupling and not only on strong scattering ($b-a^2$)

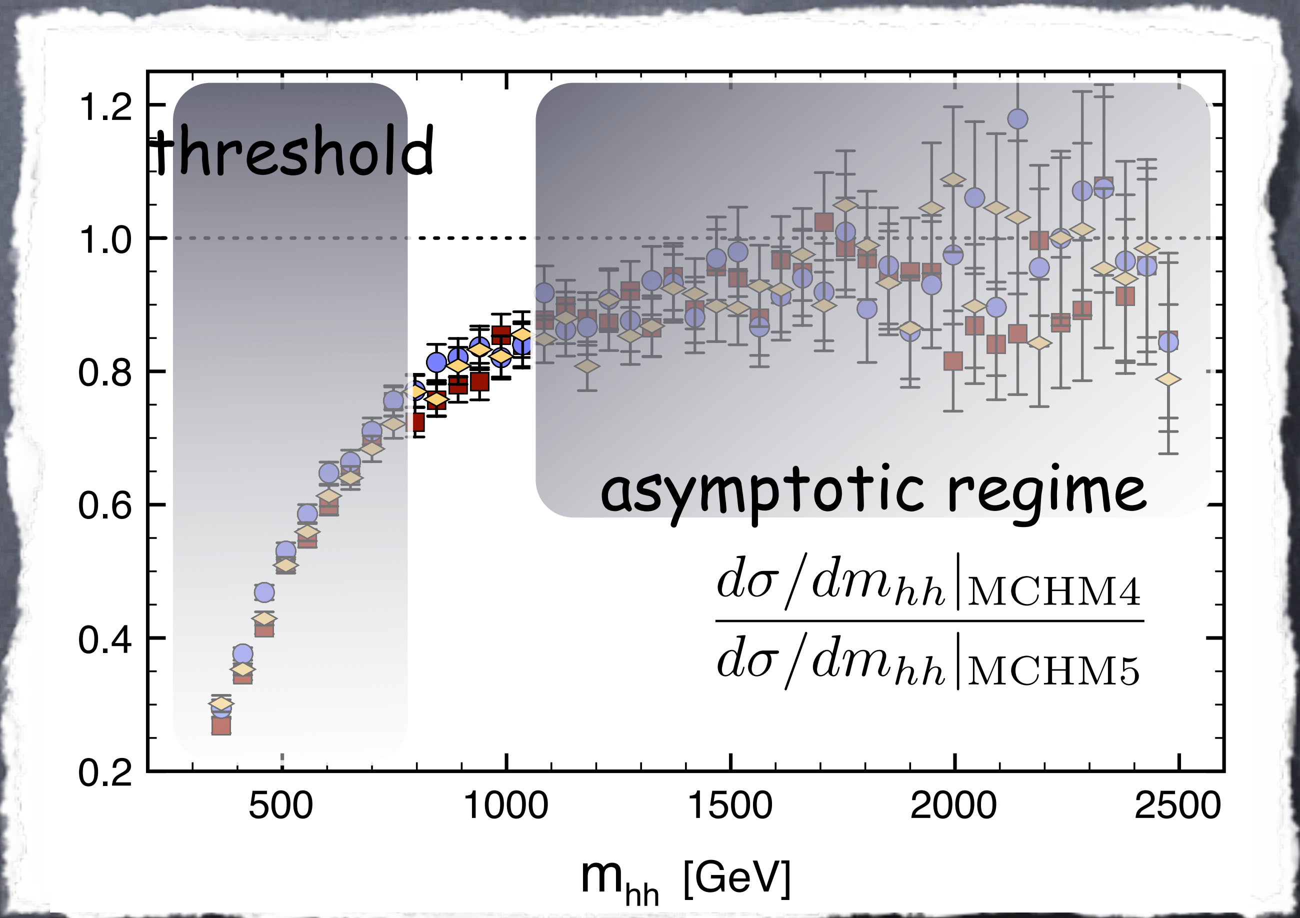
Isolating Hard Scattering

isolate events with large m_{hh}

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

measure H^3 | measure $b-a^2$

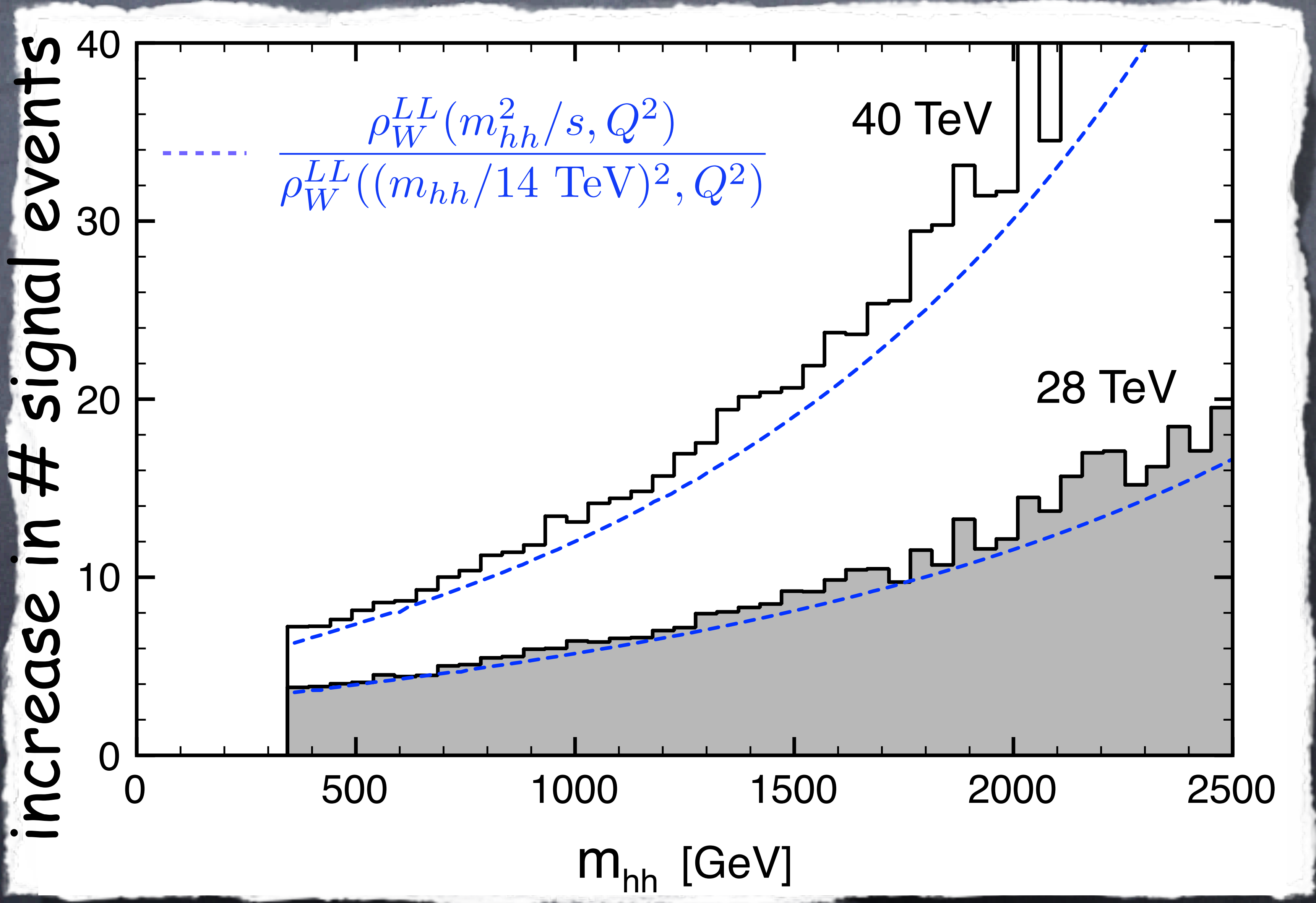




Dependence on Collider Energy

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

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



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
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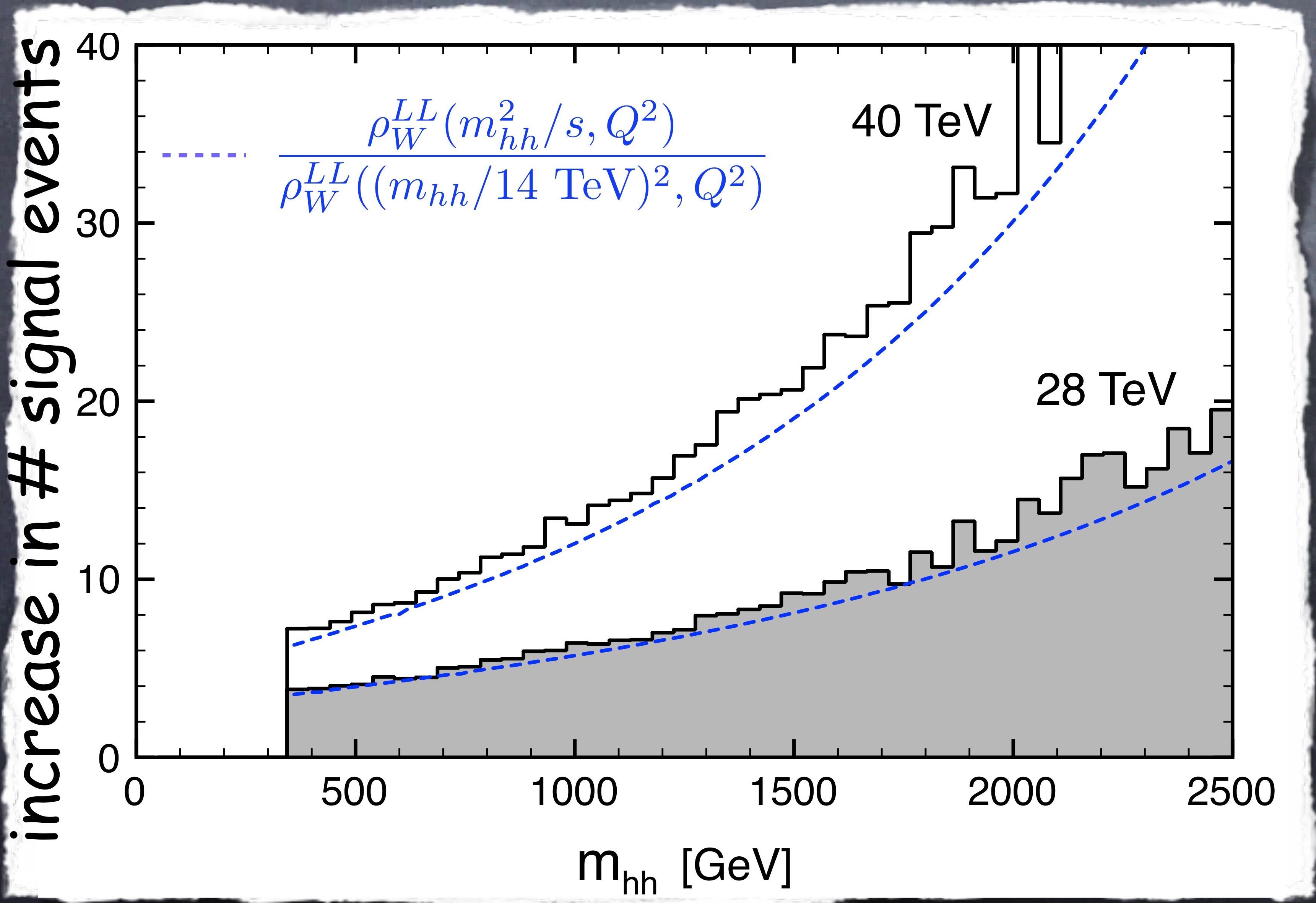
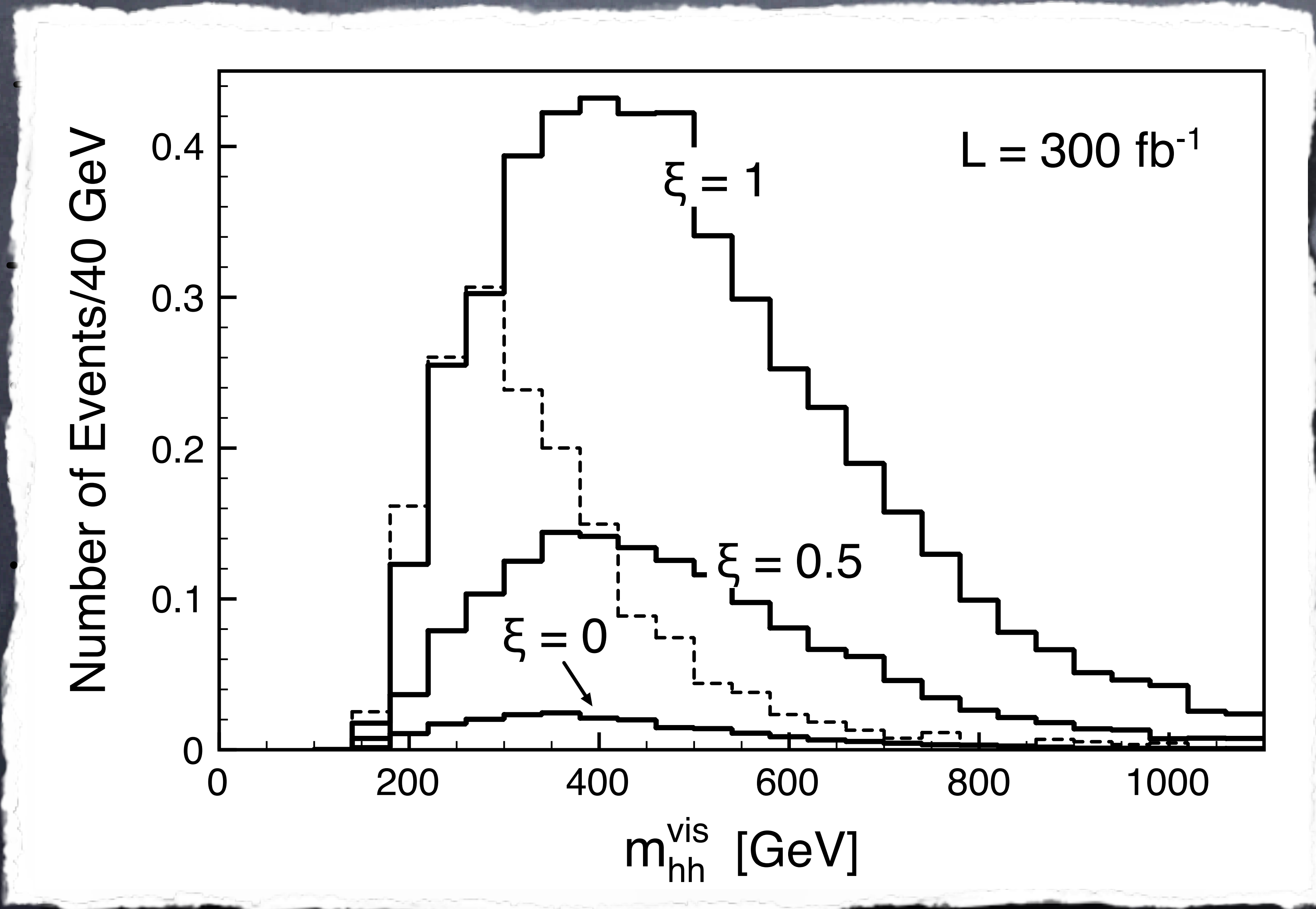


sLHC vs. VLHC

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

sLHC might be better

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 ⇔ ?

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