Beyond the Higgs

Virtual Theory Institute of the Terascale Alliance

Heidelberg, May 17, 2010

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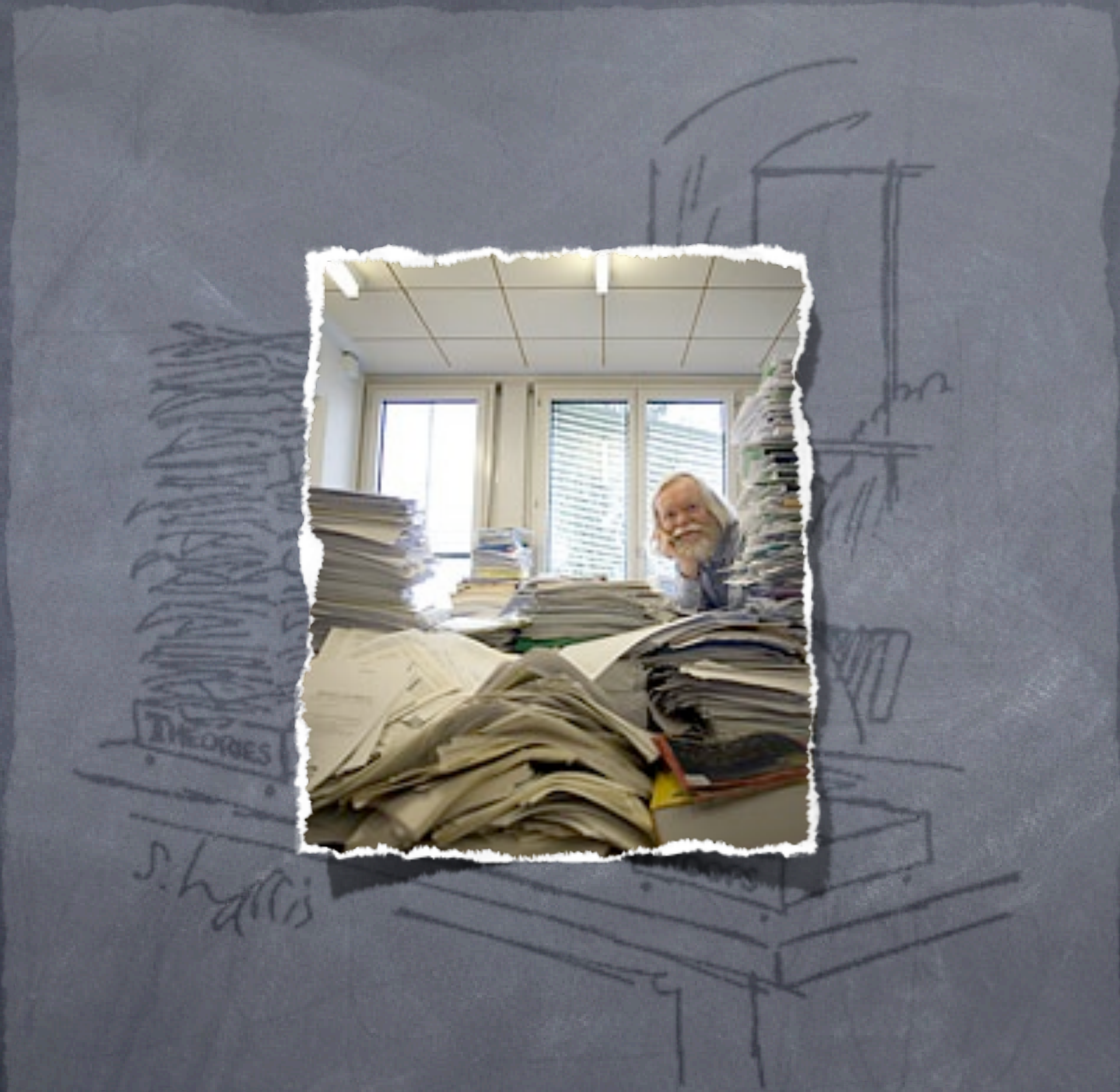
EWSB on March 29, 2010 23:59 (Geneva time)

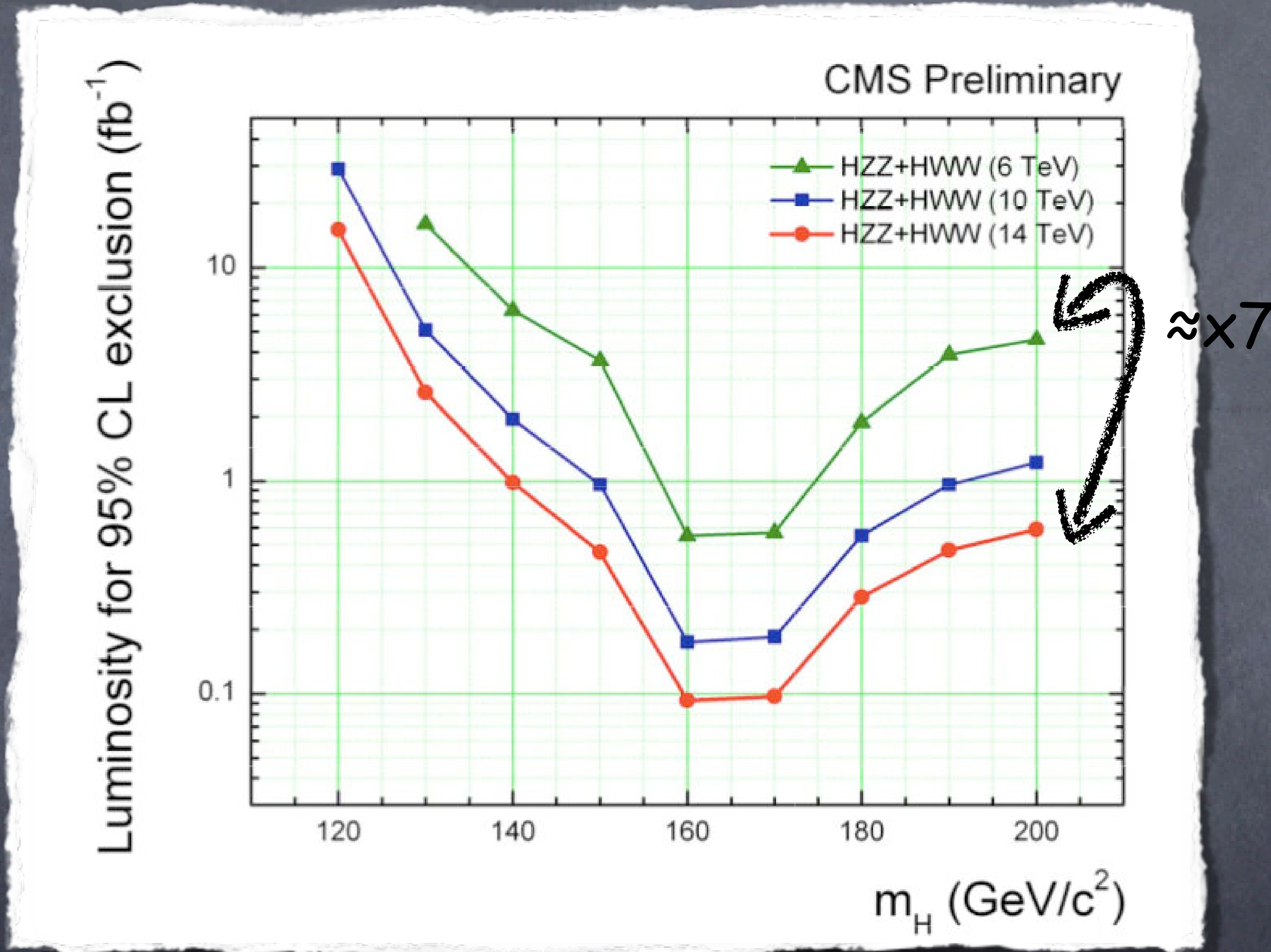
waiting for collisions... and still building models

EWSB on May 17, 2010 16:19 (Heidelberg time)



first data, but we are still facing the same questions...

EWSB on July 31, 2011 (any time)



the first LHC run is unlikely to change the picture

Higgs = "raison d'être" of LHC

- ≈500 physics papers over the last 5 years have an introduction starting like

  "The main goal of the LHC is to unveil the mechanism of electroweak symmetry breaking",

  "How the electroweak gauge symmetry is spontaneously broken is one of the most urgent and challenging questions before particle physics."

- ≈9000 papers in Spires contain "Higgs" in their title
- ≈3×10^6 references in google

Higgs = "raison d'être" of LHC

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  "The main goal of the LHC is to unveil the mechanism of electroweak symmetry breaking",

  "How the electroweak gauge symmetry is spontaneously broken is one of the most urgent and challenging questions before particle physics."

- ≈9000 papers in Spires contain "Higgs" in their title
- ≈3x10^6 references in google (≈1% of M. Jackson)
- ... no Nobel prize (so far)

Reasons of a success

- last missing piece of the SM?
- at the origin of the masses of elementary particles?
- unitarization of WW scattering amplitudes
- screening of gauge boson self-energies

The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

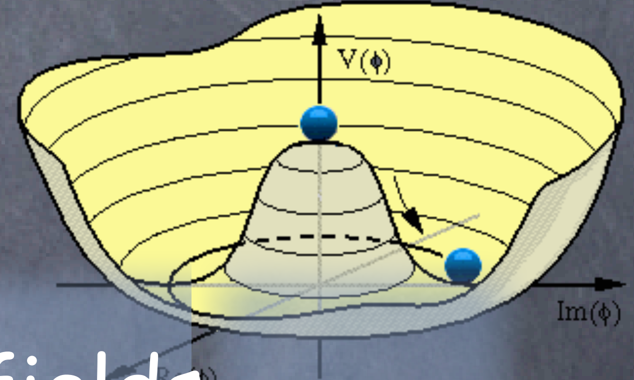
massive $W^{\pm}$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

⇛ Where are these Goldstone's coming from? ⇚

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

The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

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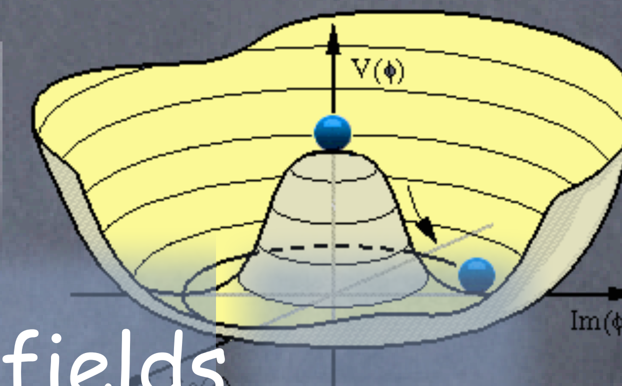


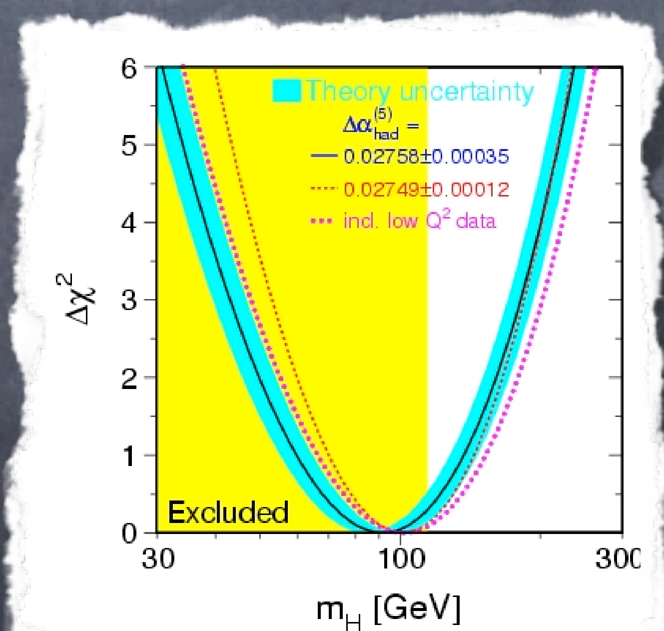
common lore: from a scalar Higgs doublet

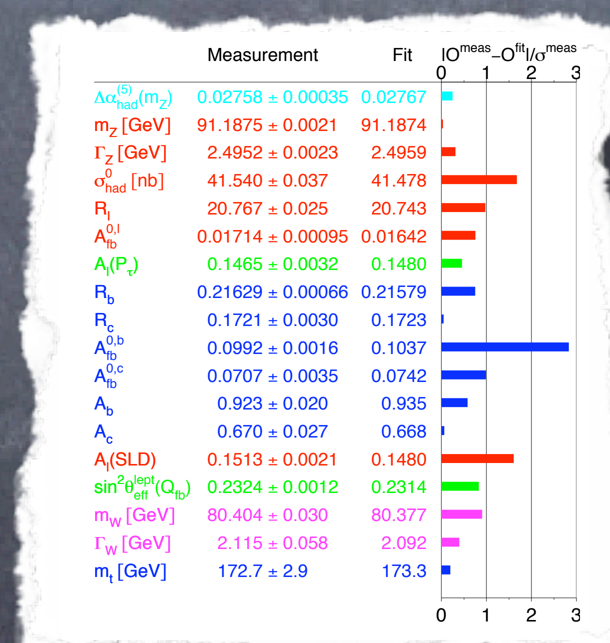
$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

Higgs doublet = 4 real scalar fields

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...

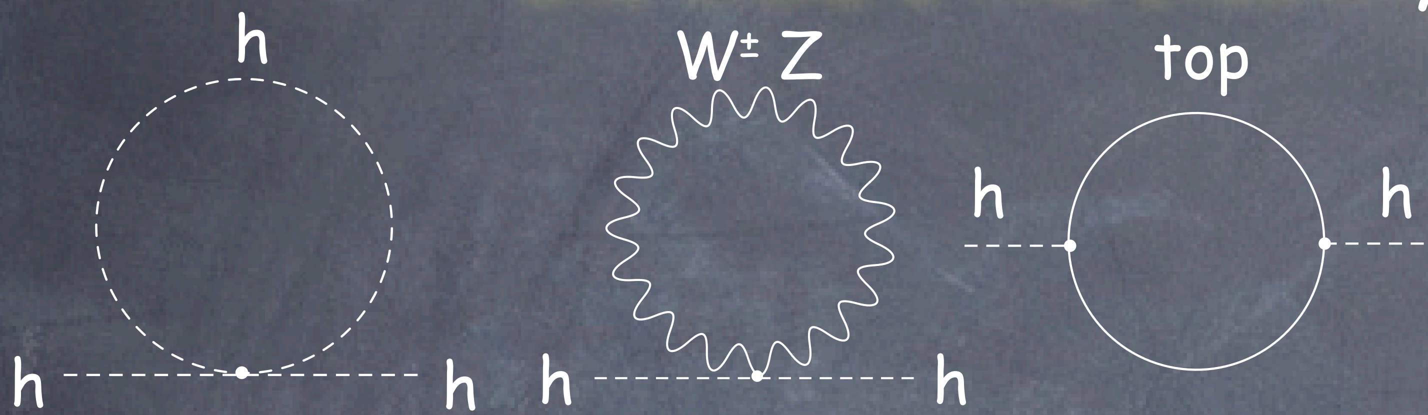
"Myth or fact?"

How close to reality is the SM Higgs boson?

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
$\Lambda <$ 3-4 TeV	?	$\Lambda > 10^{4\div5}$ 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	?	Flavor
Λ < 3-4 TeV	$\Leftrightarrow$	Λ > $10^{4\div5}$ TeV

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

Weak	Strong
SM & al.	**Technicolor**
H = elem. scalar: dim=1	H=<$q\bar{q}$>: dim=3
$\Lambda^2 \vert H\vert^2$	$\frac{1}{\Lambda^2}\vert H\vert^2$
sick when $\Lambda \to \infty$	fine when $\Lambda \to \infty$
$y_{ij}\, H q_i \bar{q}_j$ & $\frac{1}{\Lambda^2}(q_i\bar{q}_j q_k \bar{q}_l)$	$\frac{1}{\Lambda^2} H q_i \bar{q}_j$ & $\frac{1}{\Lambda^2}(q_i\bar{q}_j q_k \bar{q}_l)$
fine when $\Lambda \to \infty$	sick when $\Lambda \to \infty$

Hierarchy problem vs flavor: lesson?

Clash of Scales

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

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

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]

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
$\Lambda < 3\text{-}4$ TeV

?

Flavor
$\Lambda > 10^{4\div 5}$ 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 [Kaplan '91]

partial compositeness

mixing elem. and composite fermions

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

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

$d_{R,L} \approx 5/2$ 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 $f_{q_{L,R}}$

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

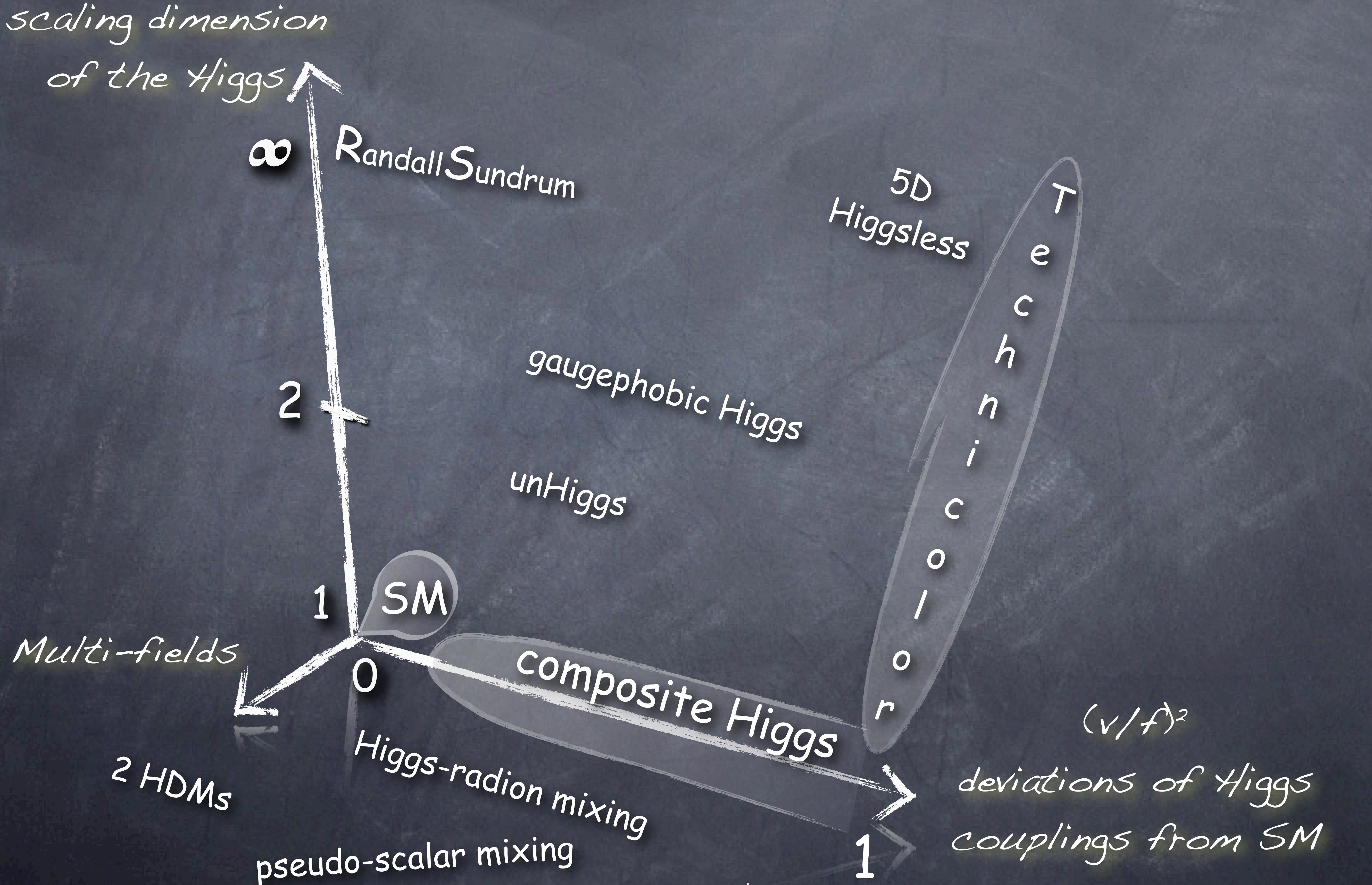
1. fermion mass hierarchy easily generated by small diff. in anomalous dims
2. alignment mixing angles/masses is also explained

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

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

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

A multi-dimensional deformation of the SM



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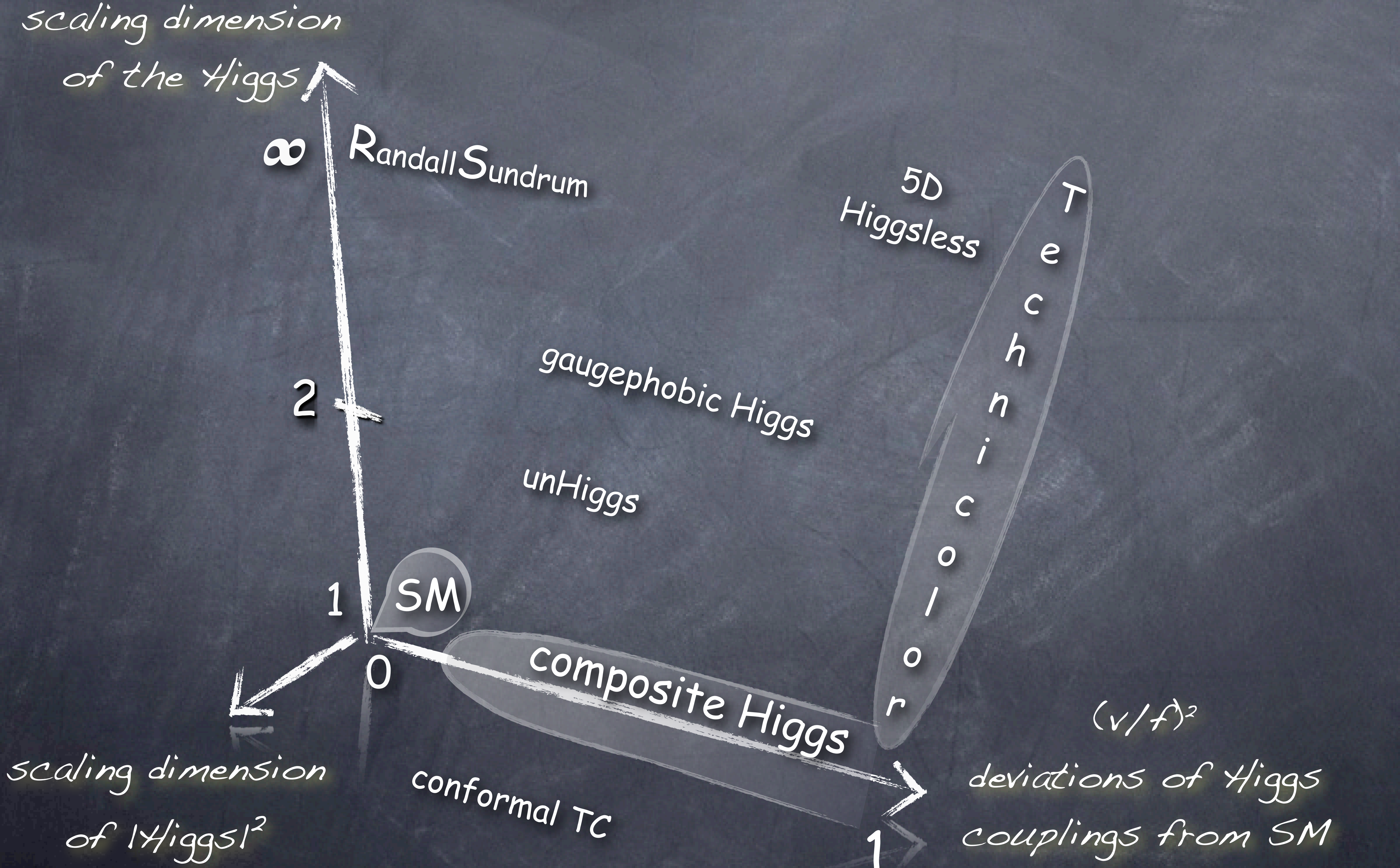


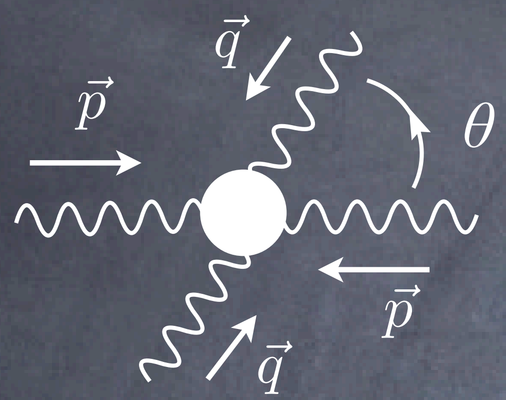
5D Higgsless Models

Unitarization of (Elastic) Scattering Amplitude

[Csaki, Grojean, Murayama, Pilo, Terning '03

Same KK mode 'in' and 'out'

$$\epsilon_\perp^\mu = \left(\frac{|\vec{p}|}{M}, \frac{E}{M}\frac{\vec{p}}{|\vec{p}|}\right)$$



$$\mathcal{A} = \mathcal{A}^{(4)}\left(\frac{E}{M}\right)^4 + \mathcal{A}^{(2)}\left(\frac{E}{M}\right)^2 + \dots$$

contact interaction   s channel exchange   t channel exchange   u channel exchange

$$\mathcal{A}^{(4)} = i\left(g^2_{nnnn} - \sum_k g^2_{nnk}\right)\left(f^{abe}f^{cde}(3+6c_\theta - c_\theta^2) + 2(3-c_\theta^2)f^{ace}f^{bde}\right)$$

= 0 KK sum rules (enforced by 5D Ward identities)

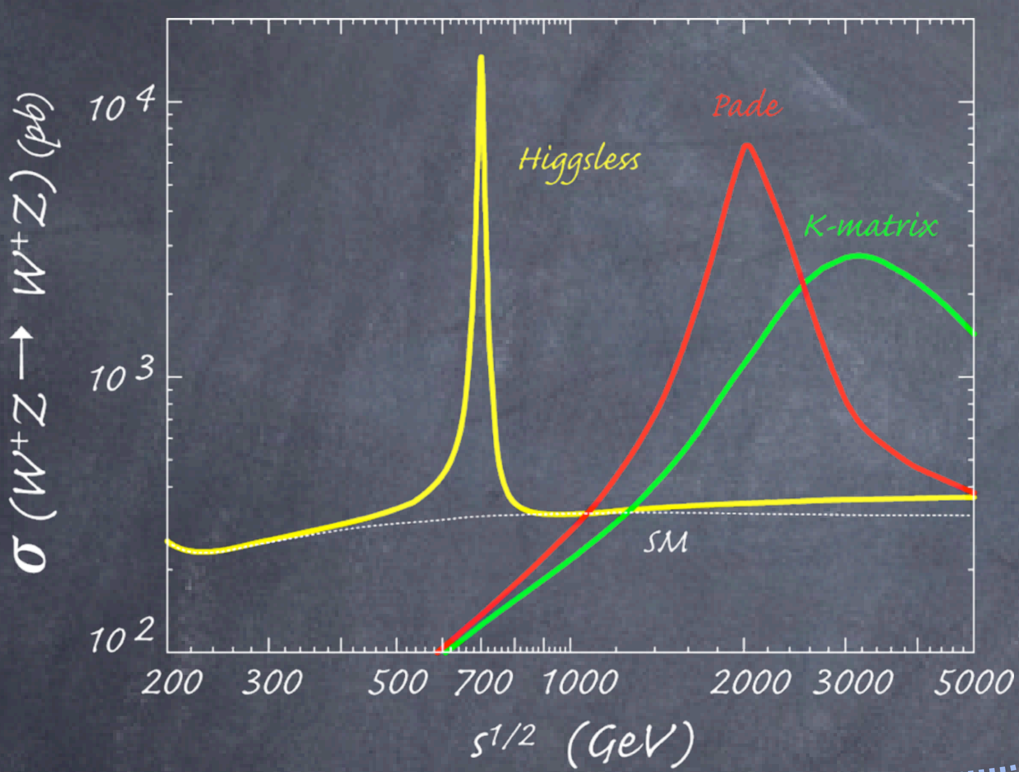
$$\mathcal{A}^{(2)} = i\left(4g^2_{nnnn} - 3\sum_k g^2_{nnk}\frac{M_k^2}{M_n^2}\right)\left(f^{ace}f^{bde} - s^2_{\theta/2}f^{abe}f^{cde}\right)$$

Collider Signatures

unitarity restored by vector resonances whose masses and couplings are constrained by the unitarity sum rules

[Birkedal, Matchev, Perelstein '05]
[He et al. '07]

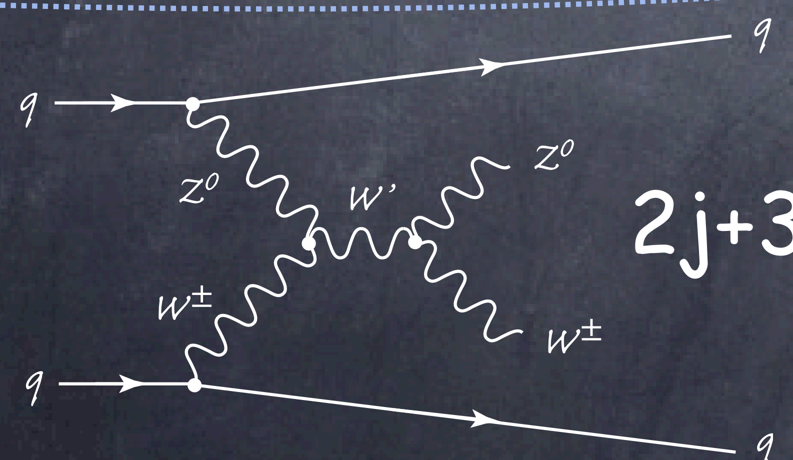
WZ elastic cross section



$$g_{WW'Z} \leq \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_{W'} M_W} \qquad \Gamma(W' \to WZ) \sim \frac{\alpha M_{W'}^3}{144 s_w^2 M_W^2}$$

a narrow and light resonance

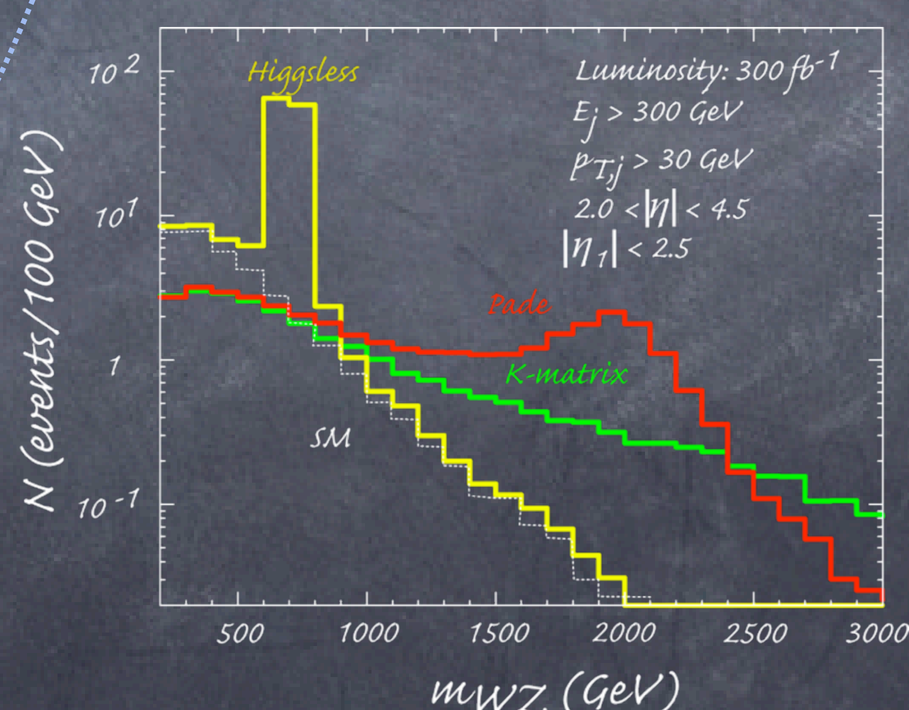
no resonance in WZ for SM/MSSM



2j+3l+$\not{E}_T$

VBF (LO) dominates over DY since couplings of q to W' are reduced

W' production



Number of events at the LHC, 300 fb^{-1}

discovery reach
@ LHC
(10 events)

550 GeV $\to$ 10 fb^{-1}
1 TeV $\to$ 60 fb^{-1}

should be seen within one/two year

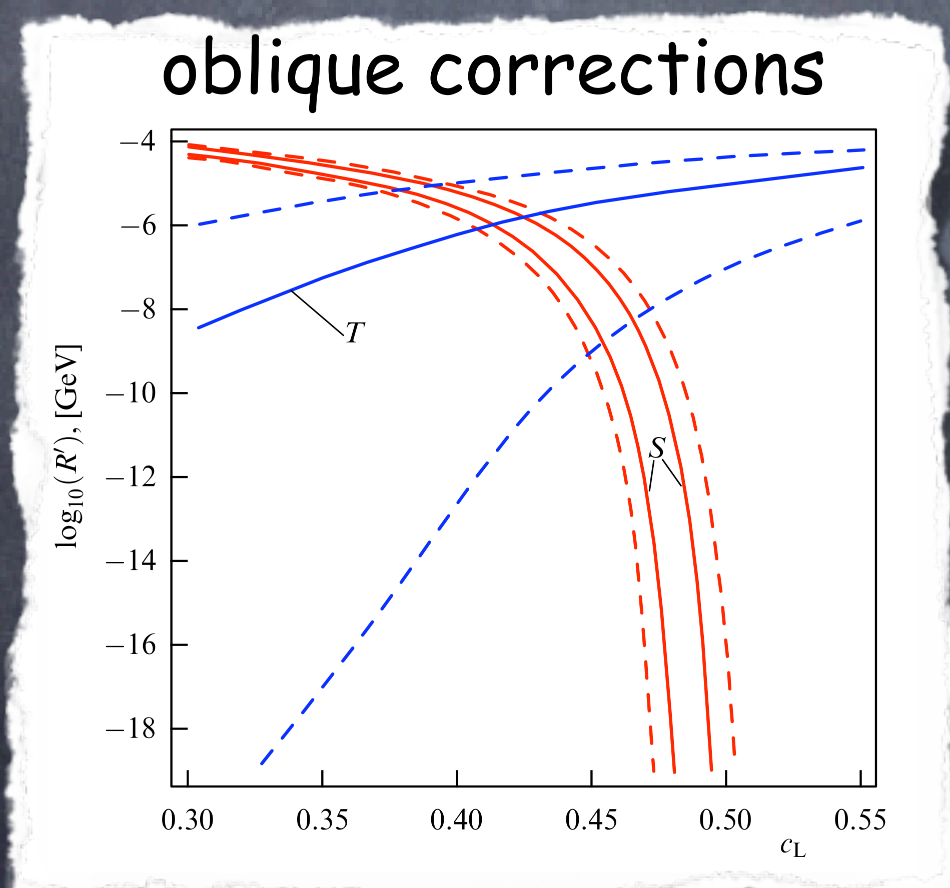
Facing EW precision data

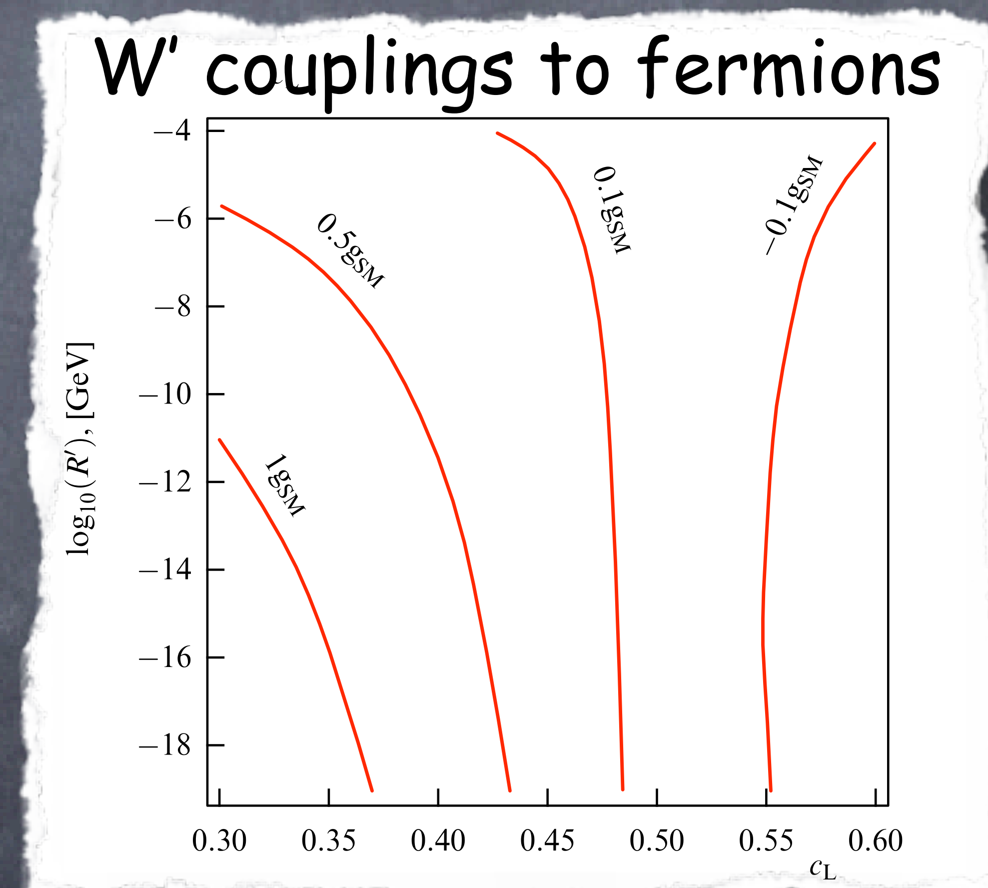
At the lowest order in the Log(R_{IR}/R_{UV}) expansion: S=T=Y=W=0

At next order $S = \frac{6\pi}{g^2 \log(R_{IR}/R_{UV})} \approx 1.15$ ...like in usual technicolor models

S can be tuned away by delocalizing the fermions in the bulk
they will decouple from W', Z' etc

[Cacciapaglia et al '04, Foadi et al '04, Casalbuoni et al '05





Setup stable under radiative corrections?

[Dawson, Jackson '08]

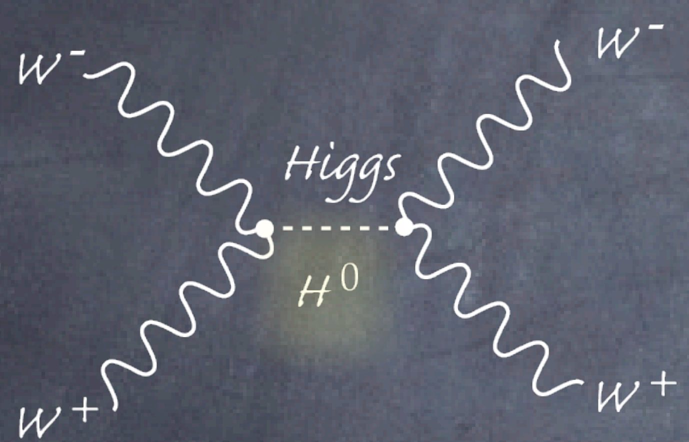
Composite Higgs Models

SM Higgs as a peculiar scalar resonance.

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

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

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

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

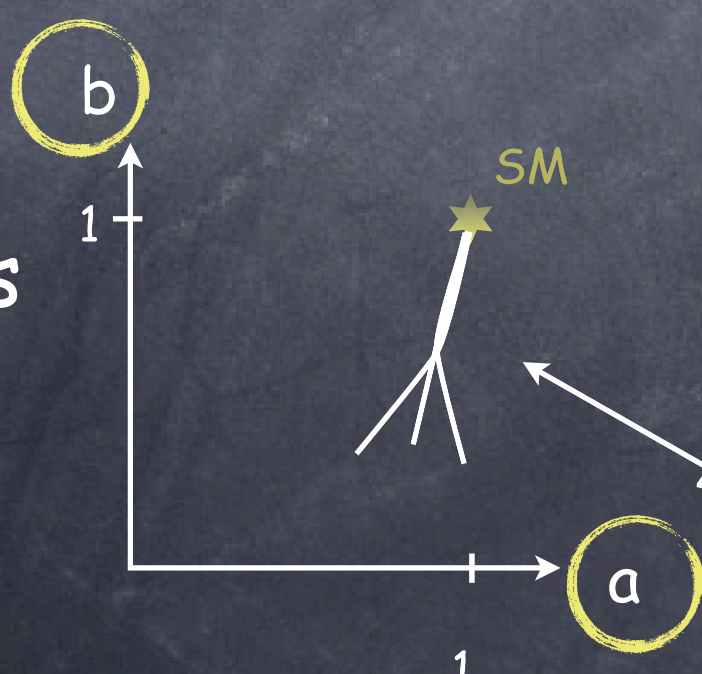
all resonances of strong sector, except the Higgs, decouple

$\xi = 1$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

Composite Higgs vs. SM Higgs



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

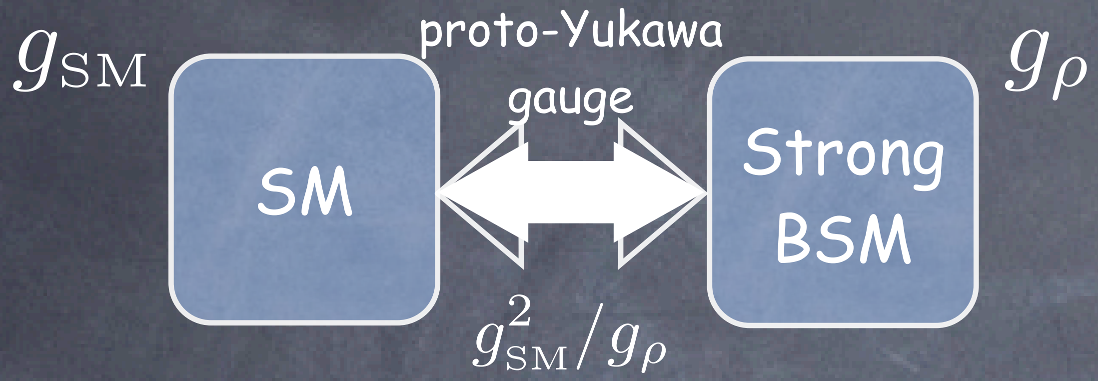
Composite Higgs

universal behavior for large f

a=1-v/2f b=1-2v/f

How to obtain a light composite Higgs?

Higgs=Pseudo-Goldstone boson of the strong sector



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

global symmetry → G/H ← residual global symmetry

3 scales:

UV completion

$4\pi f$ — 10 TeV

$m_\rho = g_\rho f$ — usual resonances of the strong sector

} not directly accessible to LC → indirect probes

v — 246 GeV Higgs = light resonance of the strong sector

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

What distinguishes a composite Higgs?

Giudice, Grojean, Pomarol, Rattazzi '07

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

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

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

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)

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

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

minimal coupling: $h\to\gamma Z$

loop-suppressed strong dynamics

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

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 $m_h \sim 115$ 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

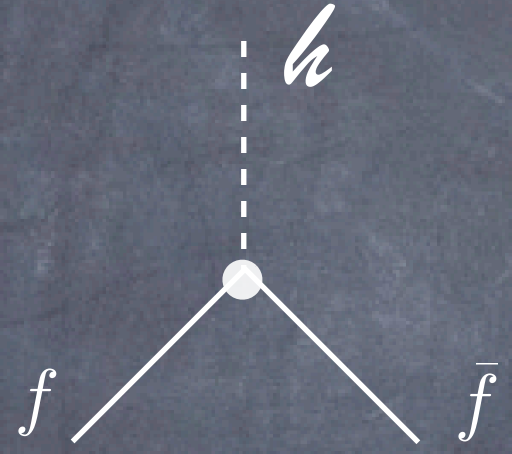
SILH: c_y is flavor universal

$\Rrightarrow$ Minimal flavor violation built in

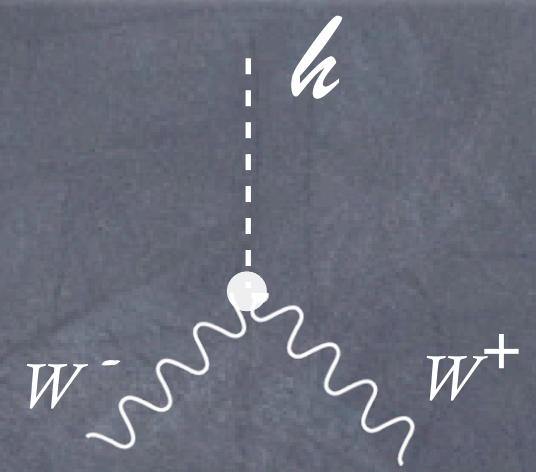
Higgs anomalous couplings

Lagrangian in unitary gauge

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



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



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

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

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

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

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

MCHM4

Fermions embedded in spinorial of SO(5)

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

$$\Downarrow$$

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

universal shift of the couplings
no modifications of BRs

MCHM5

Fermions embedded in 5+10 of SO(5)

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

$$\Downarrow$$

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

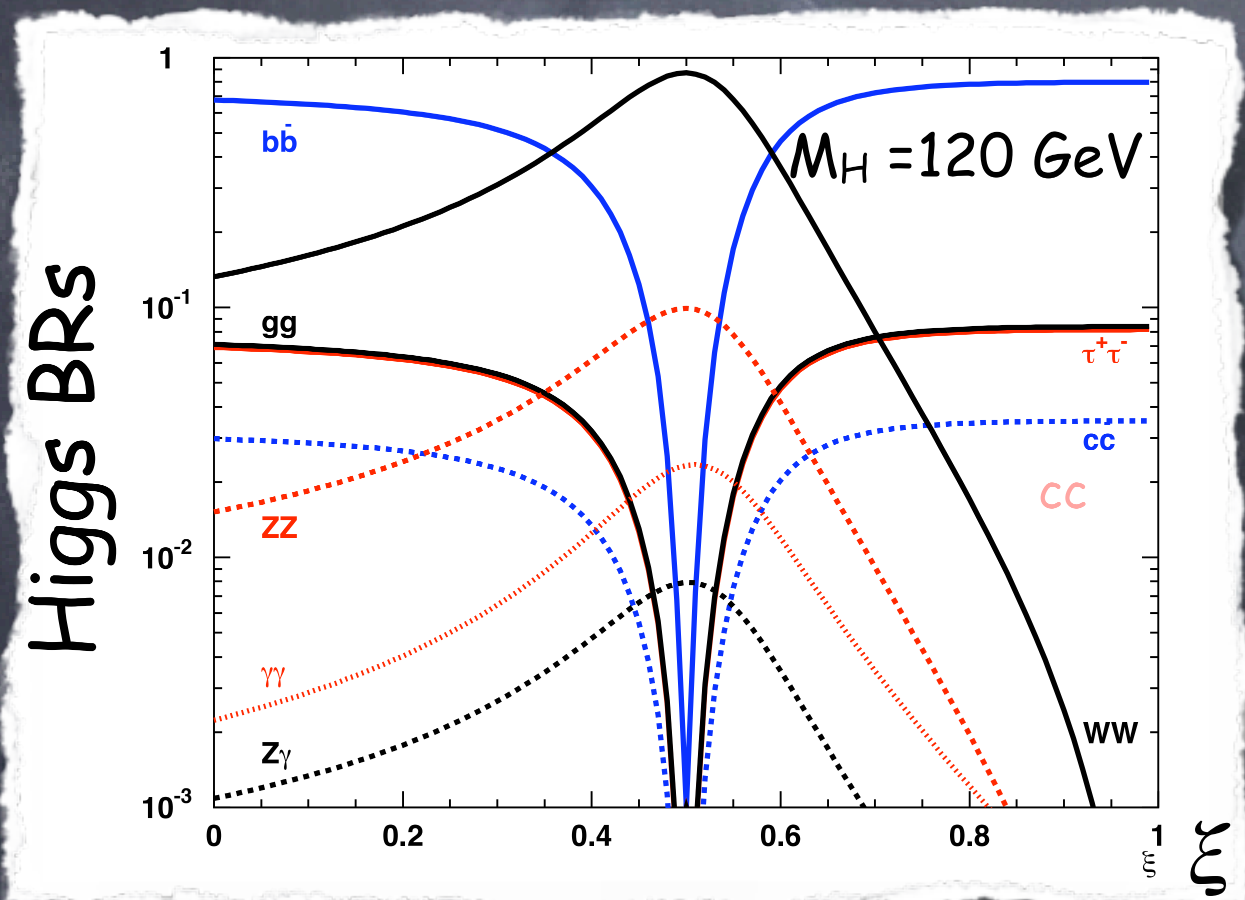
BRs now depends on v/f

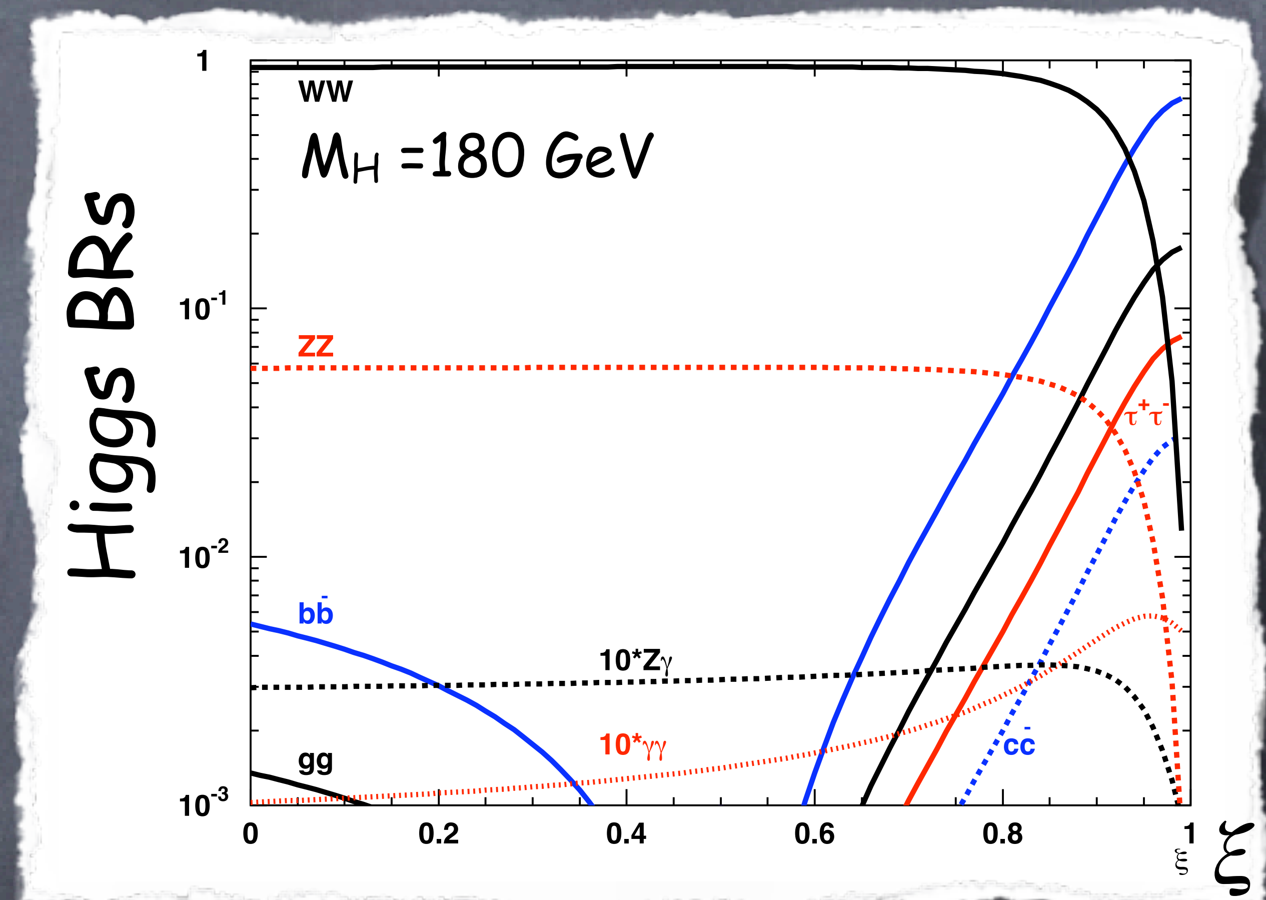
$$(\ \xi = v^2/f^2\ )$$

Higgs BRs

MCHM5

Fermions embedded in 5+10 of SO(5)





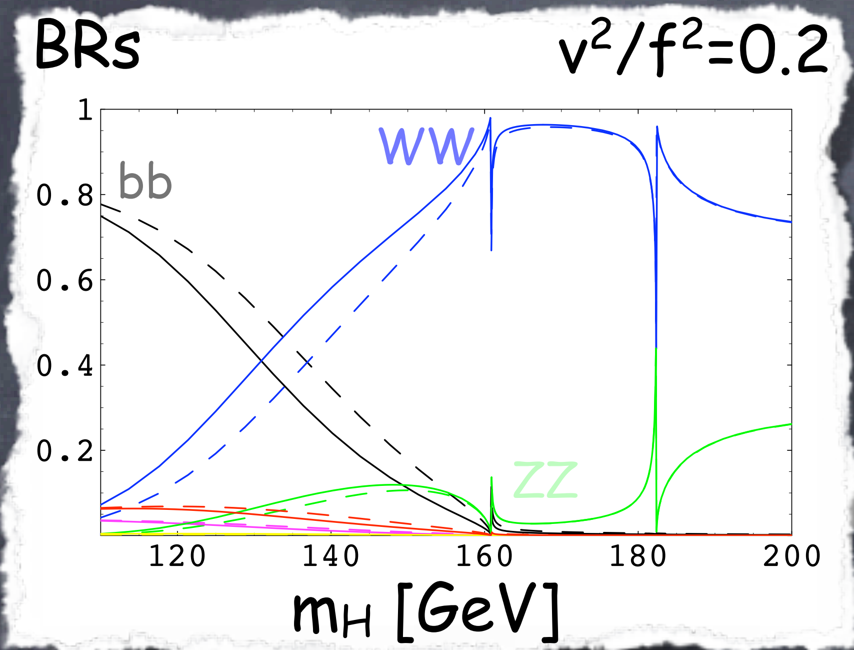
h→WW can dominate even for low Higgs mass

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

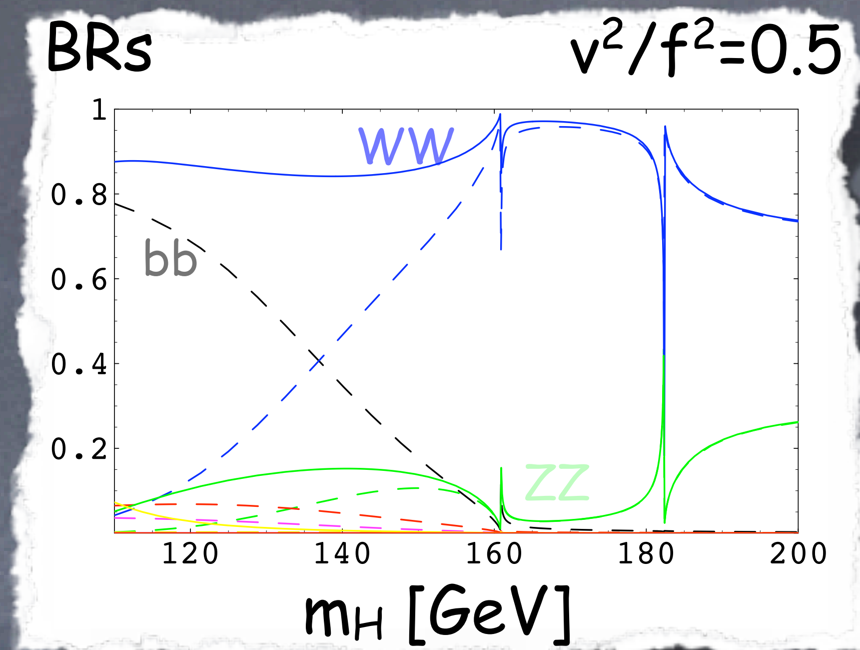
Higgs BRs and total width

MCHM5

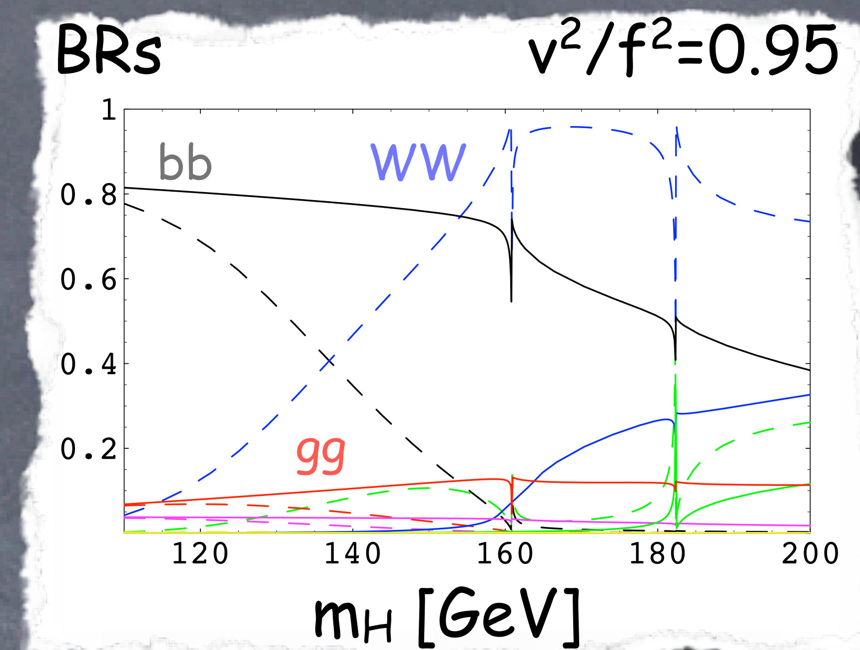
Fermions embedded in 5+10 of SO(5)



slight modifications

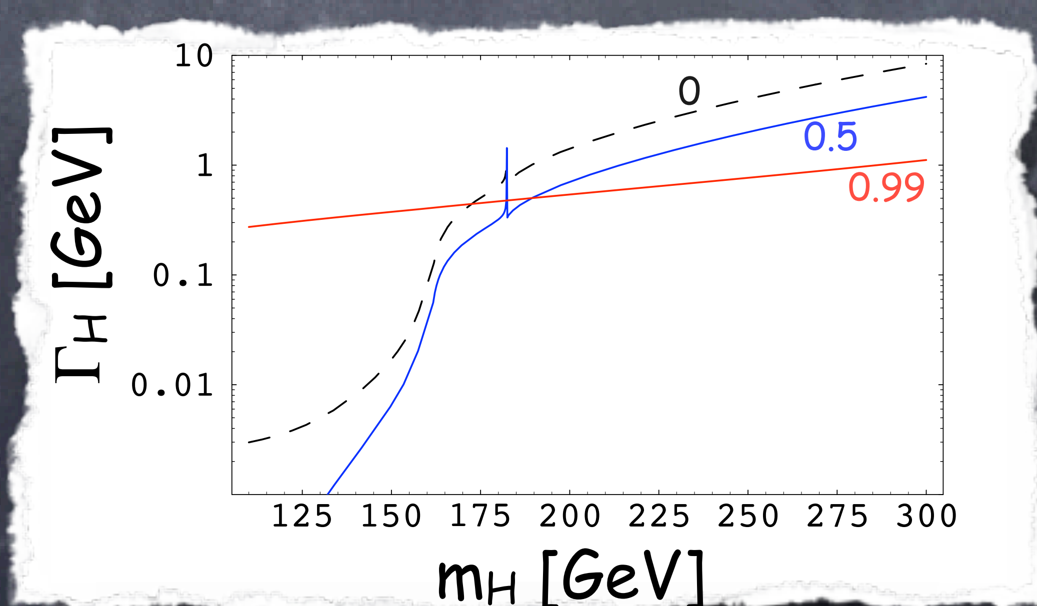


suppress bb



suppress WW

Higgs total width



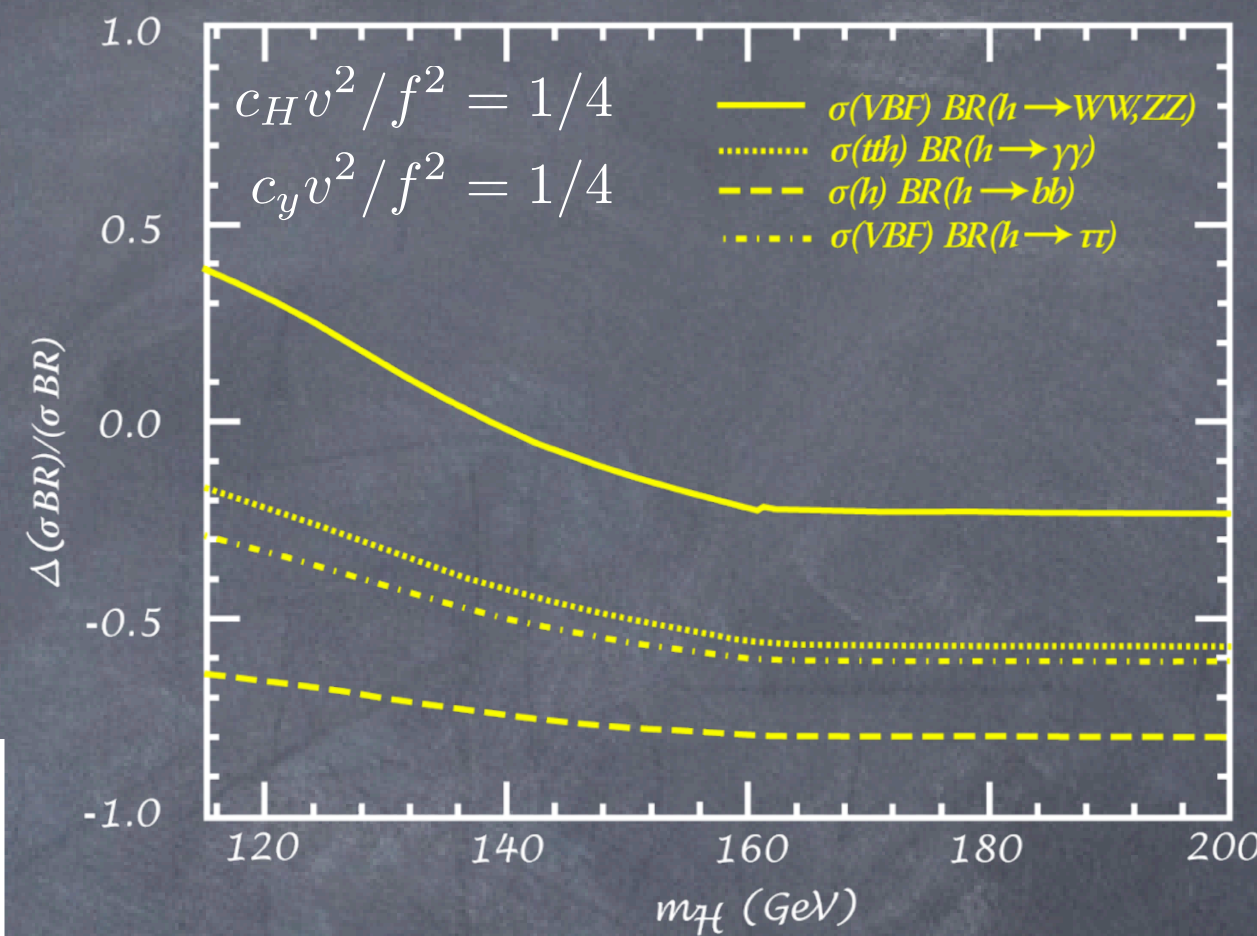
——— MCHM

------- SM

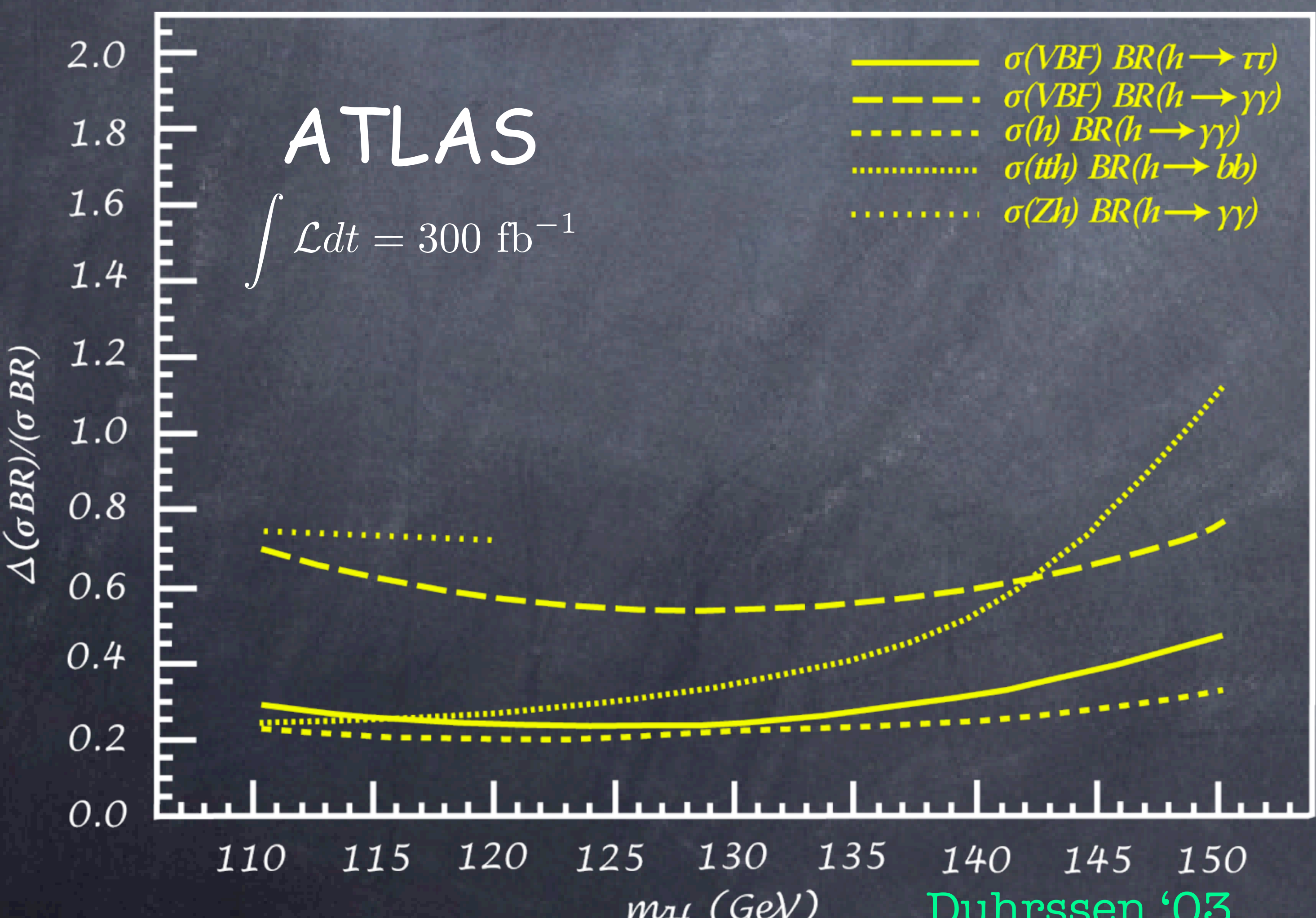
Higgs anomalous couplings @ LHC

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

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



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

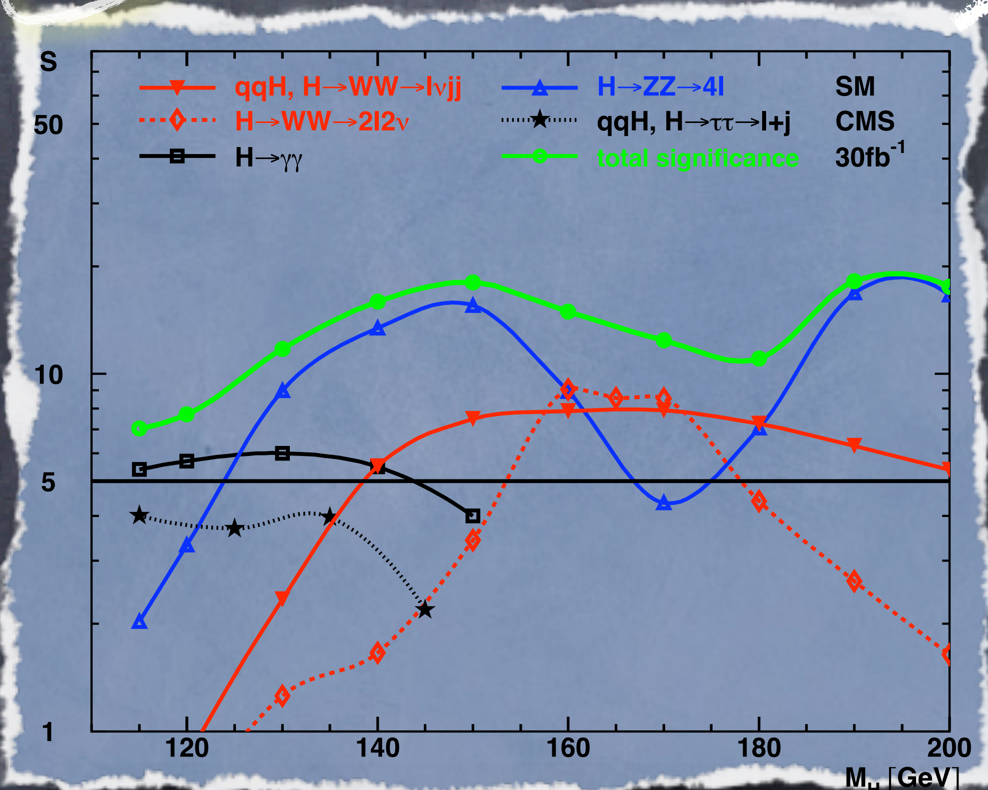
(ILC could go to few % ie test composite Higgs up to $4\pi f \sim 30\ \mathrm{TeV}$)

Composite Higgs search @ LHC

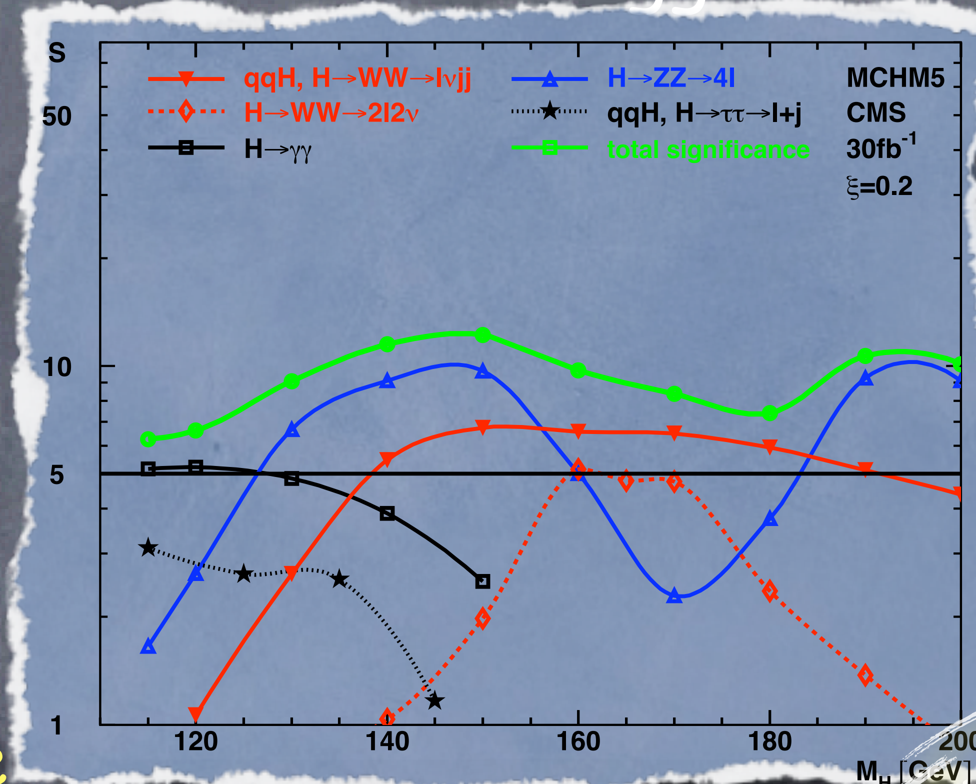
Espinosa, Grojean, Muehlleitner '10

the modification of Higgs couplings and BRs affects the Higgs search

SM

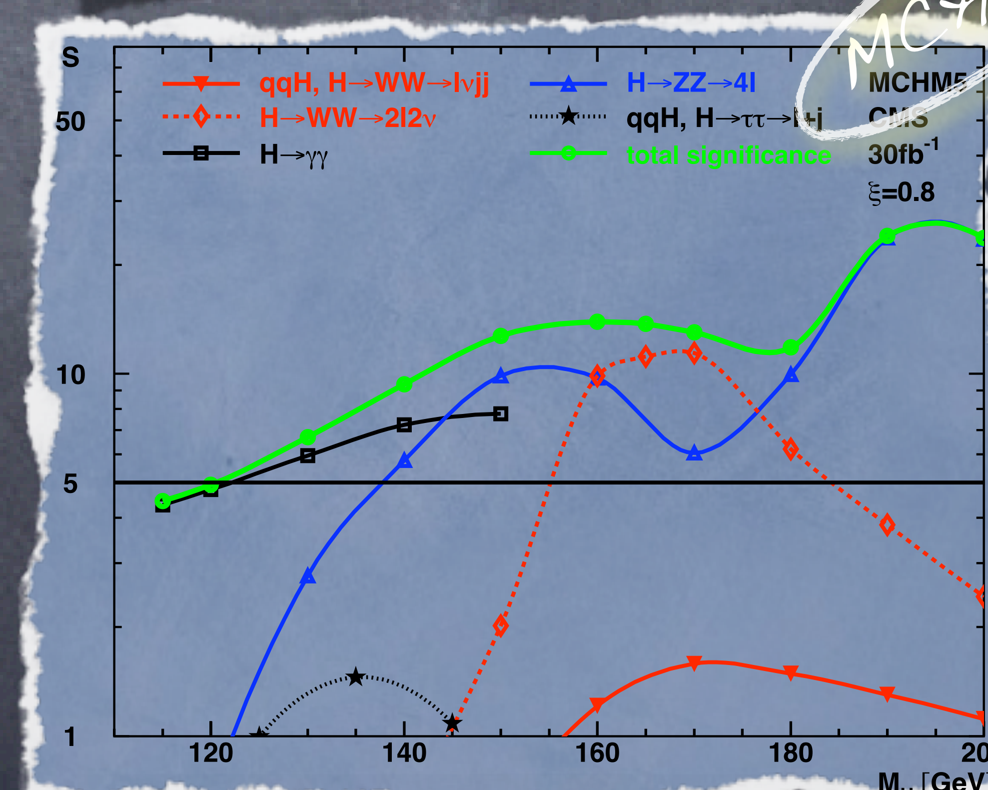


large
compositeness scale



signal significance
for L=30/fb

MCHM5

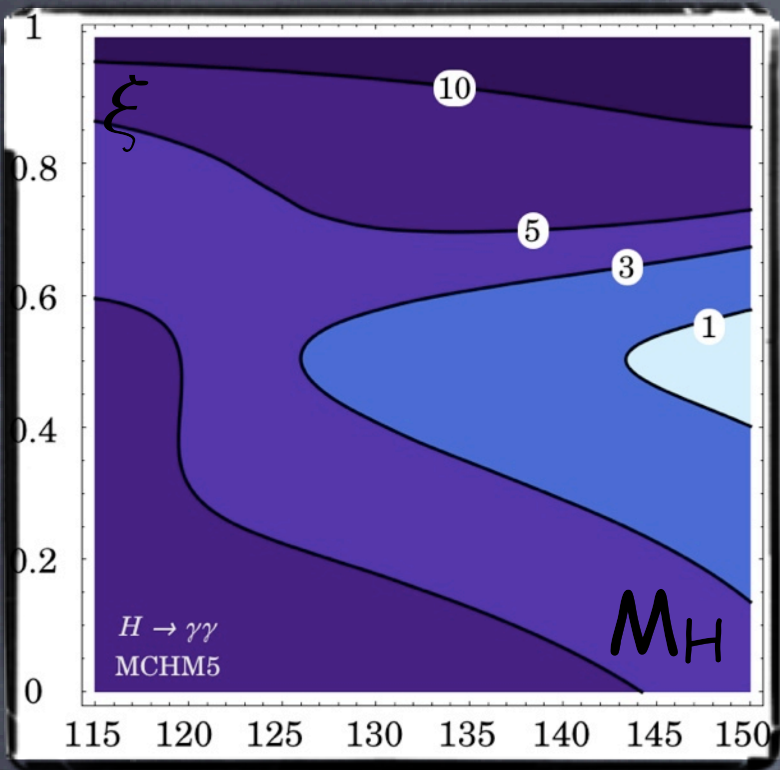


small
compositeness scale

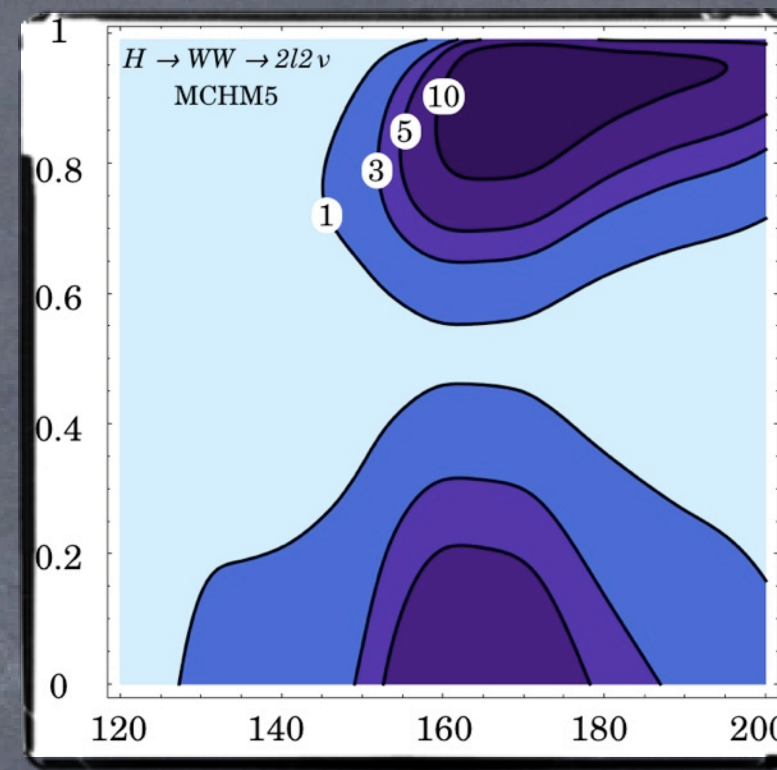
Composite Higgs search @ LHC

Espinosa, Grojean, Muehlleitner '10

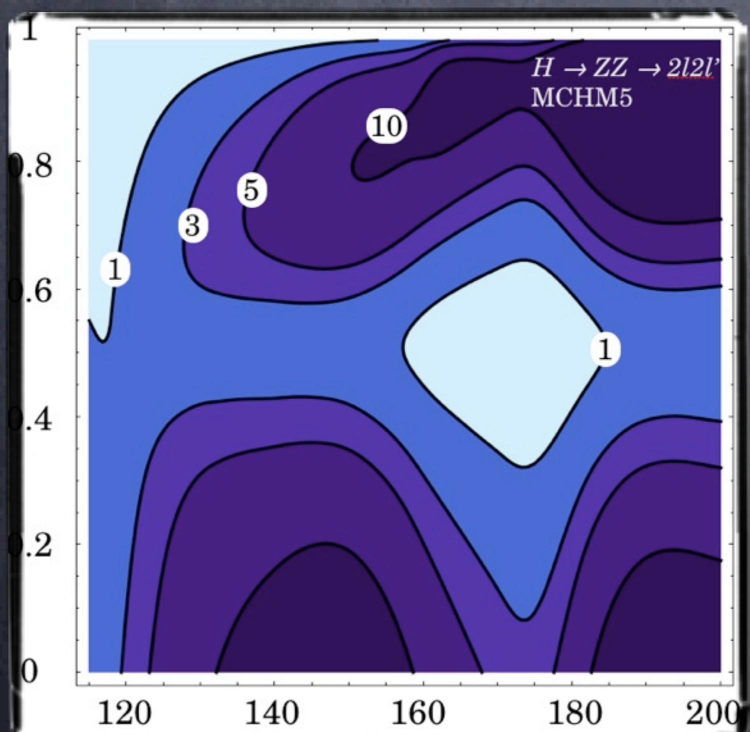
the modification of Higgs couplings and BRs affects the Higgs search

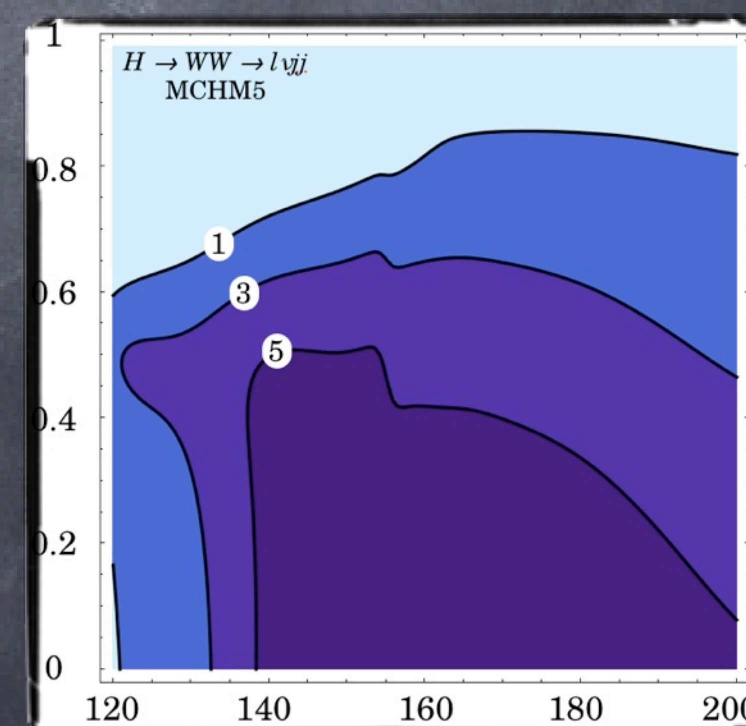


MCHM5



contour lines of
signal significance
for L=30/fb
in the (ξ,M_H) plane

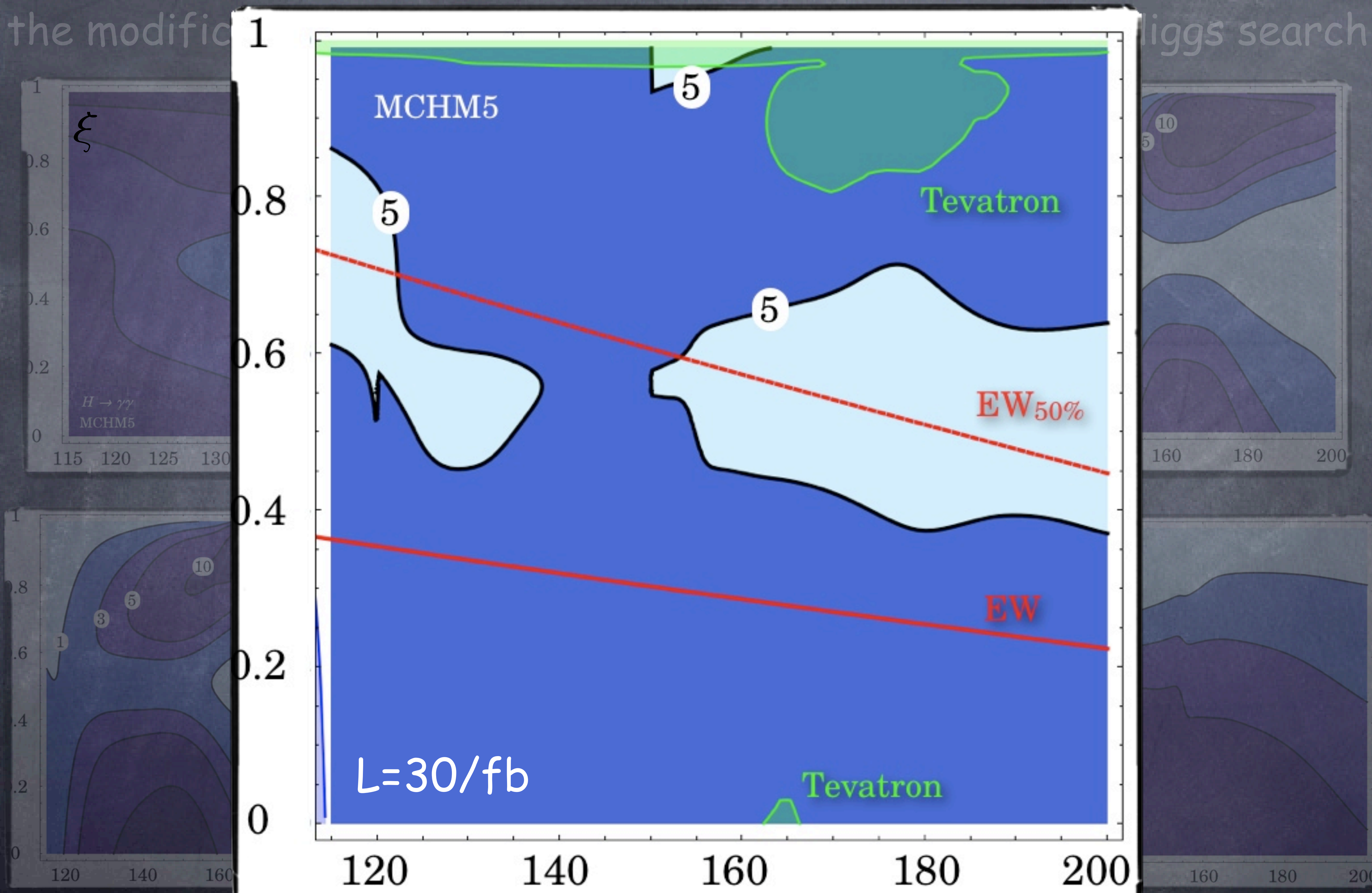




(neglect effects from heavy resonances)

Composite Higgs search @ LHC

Espinosa, Grojean, Muehlleitner '10



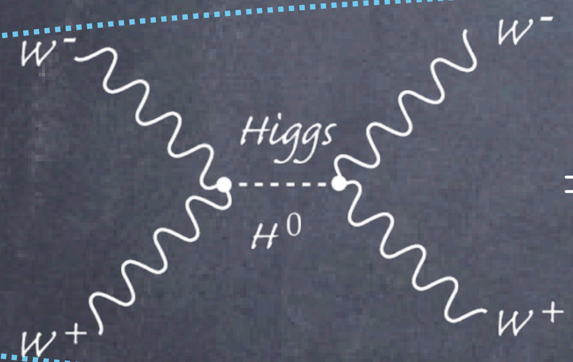
Strong WW scattering

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



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

no exact cancellation of the growing amplitudes

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

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

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

LET=SM-Higgs

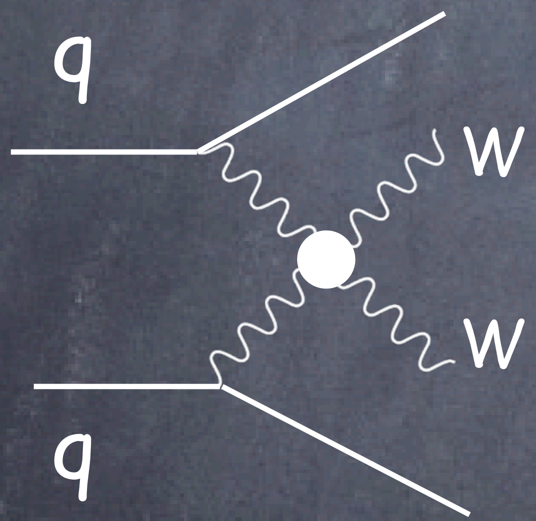
Strong WW scattering @ LHC

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

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

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

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



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

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

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

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

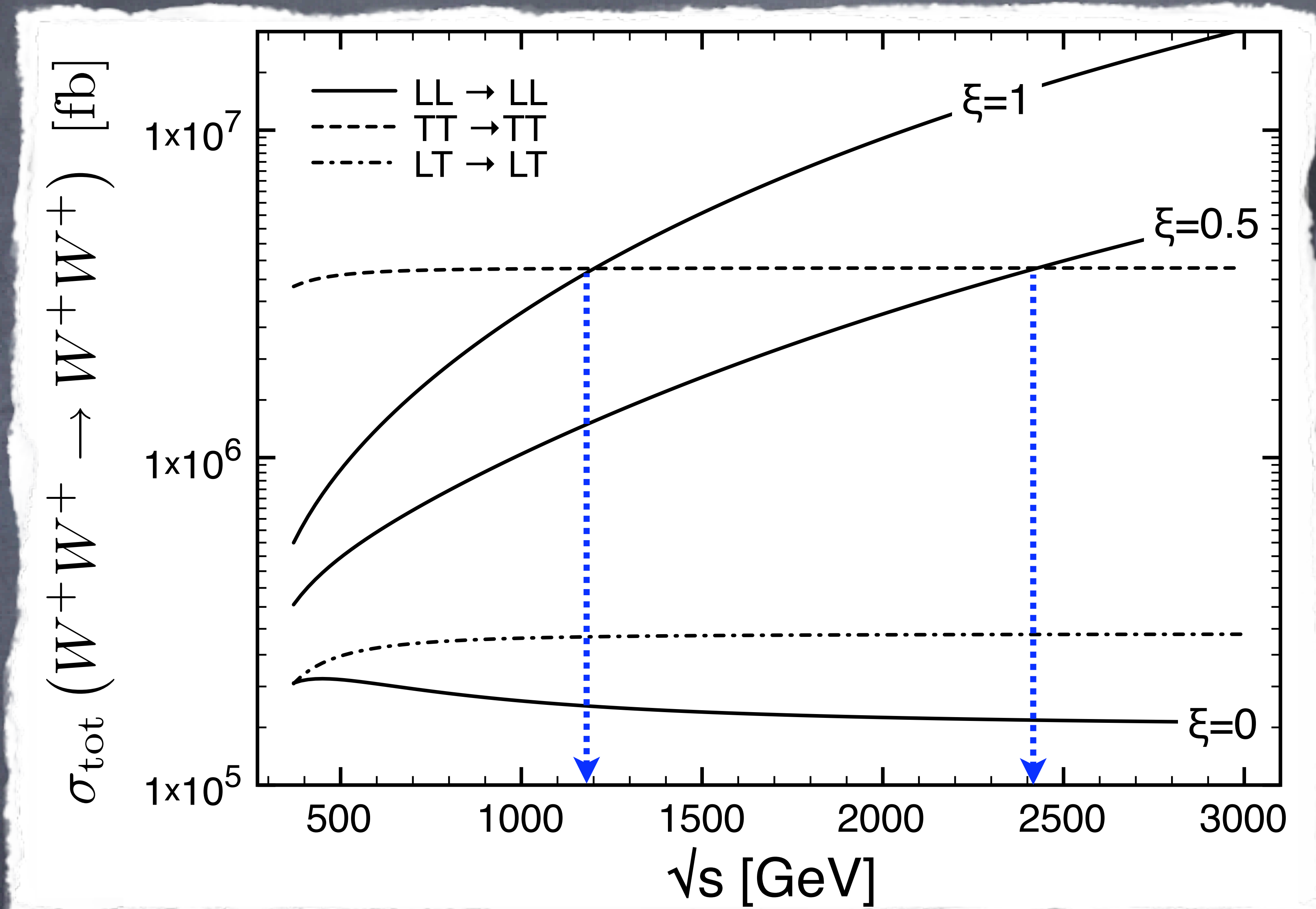
NDA estimates

$N_h \sim 1$

$N_s \sim 1$

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

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

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

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

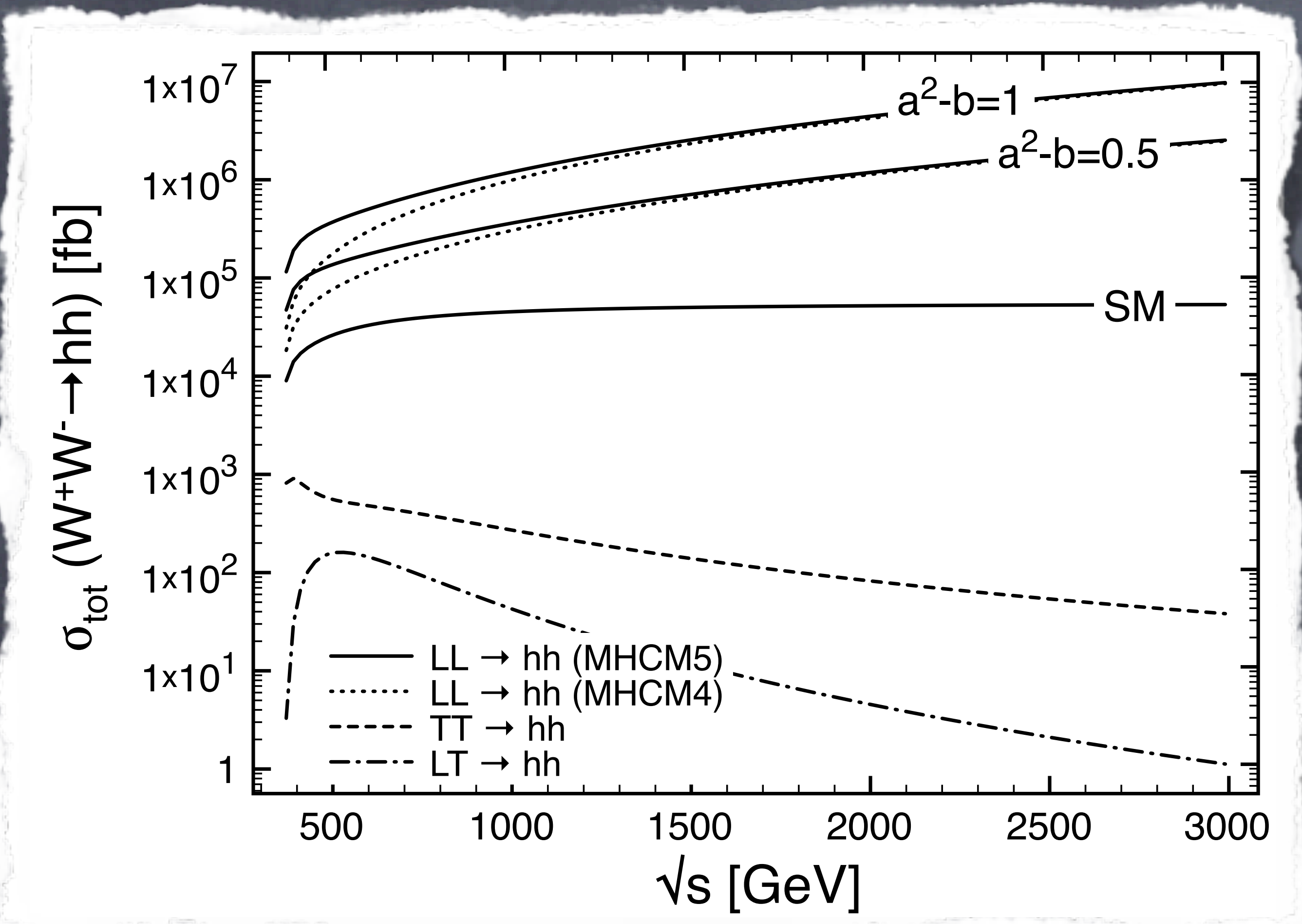
$$\frac{\sigma_{TT\to TT}}{\sigma_{LL\to LL}} \sim 20$$

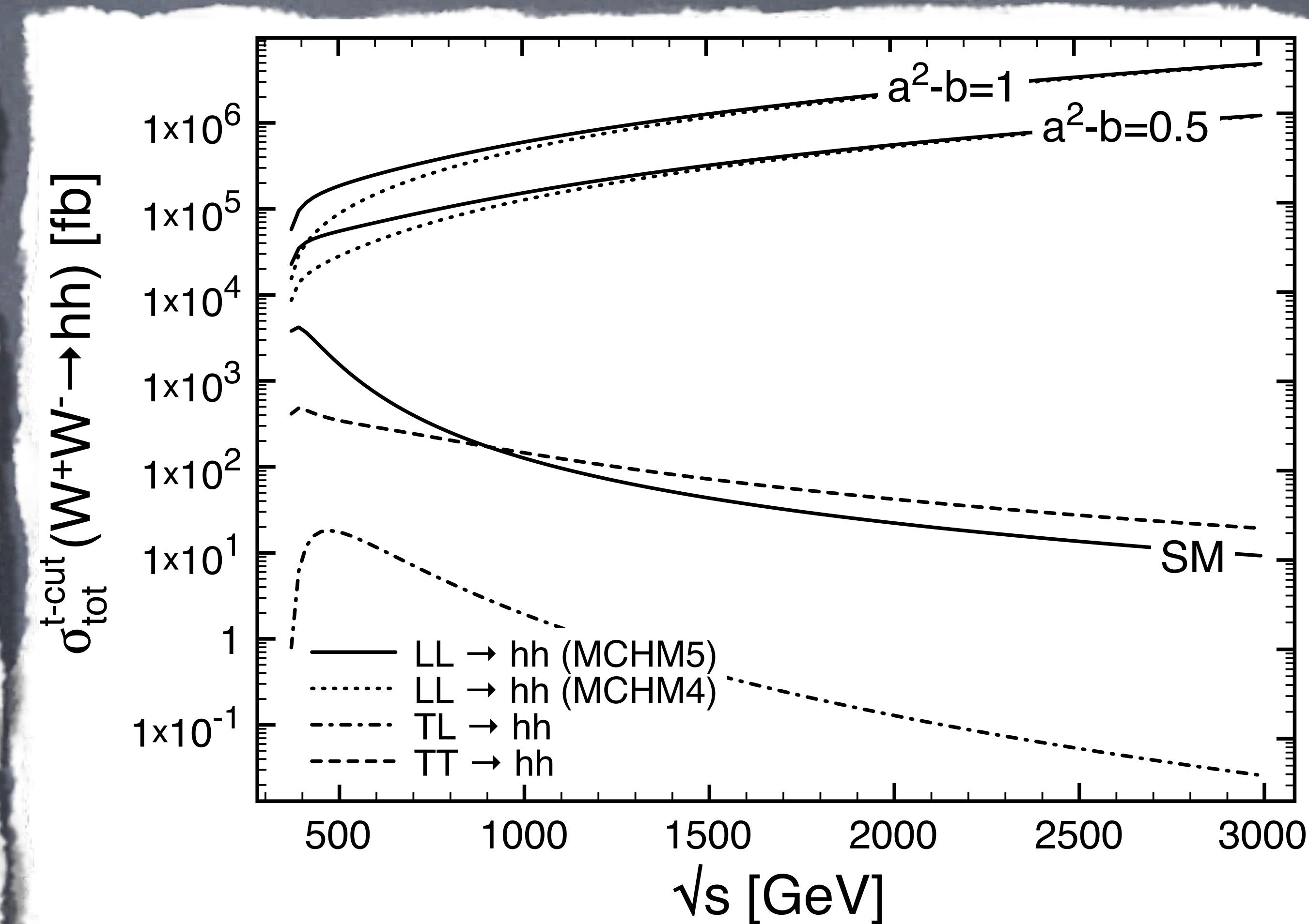
(for $M_\gamma \sim M_Z$)

$$N_s \sim 1/500$$

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

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

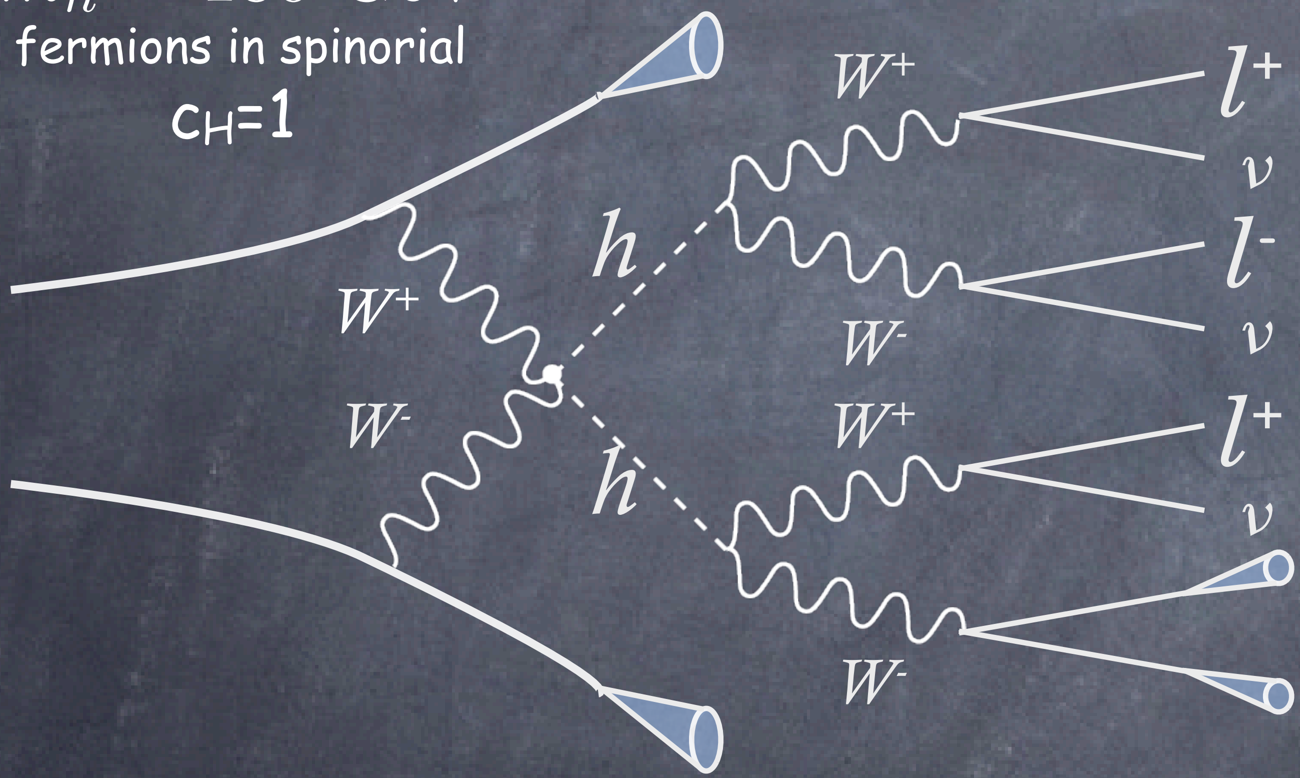
Strong Higgs production: (3L+jets) analysis

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...

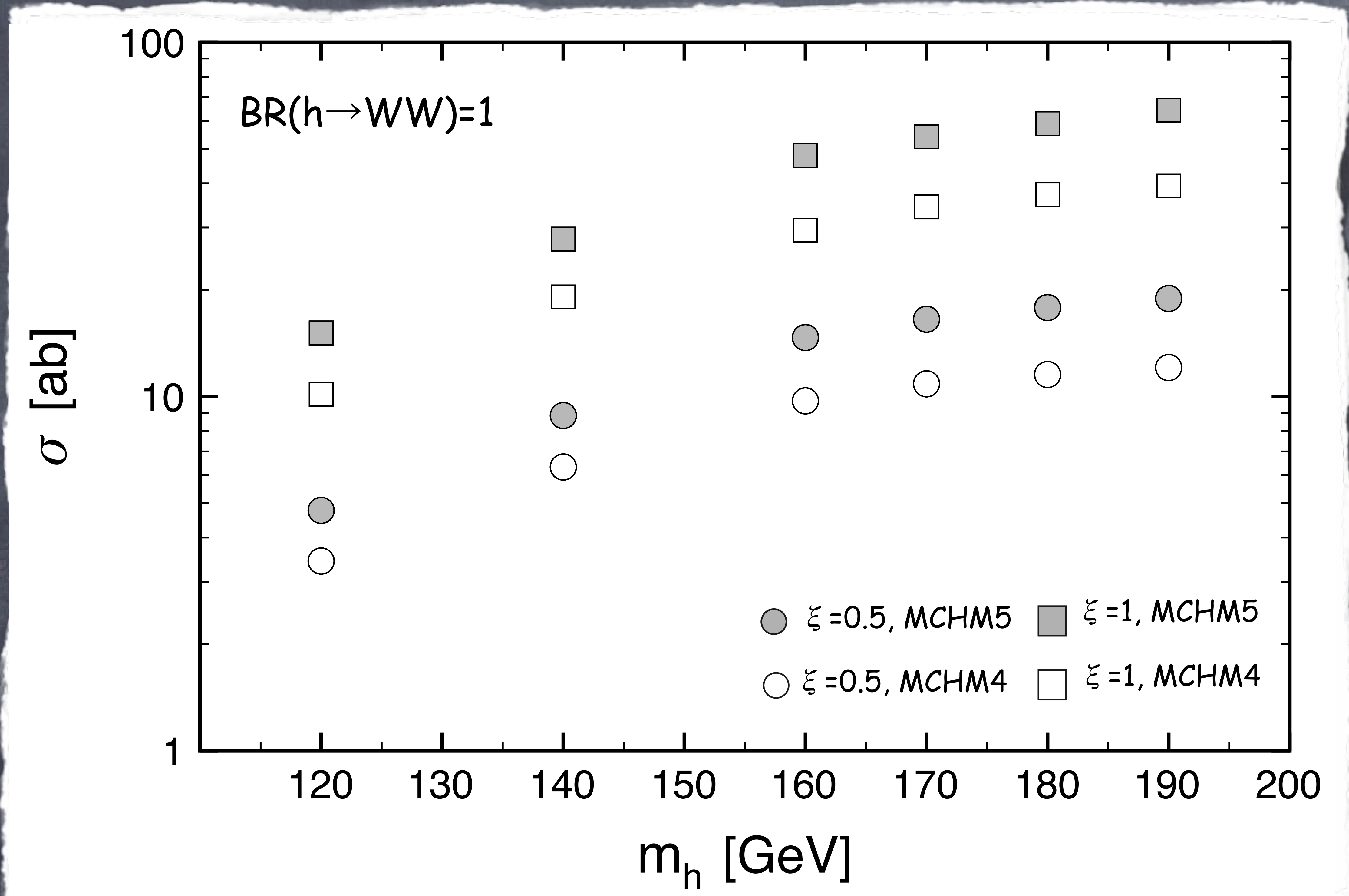
forward jet-tag, back-to-back lepton, central jet-veto

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

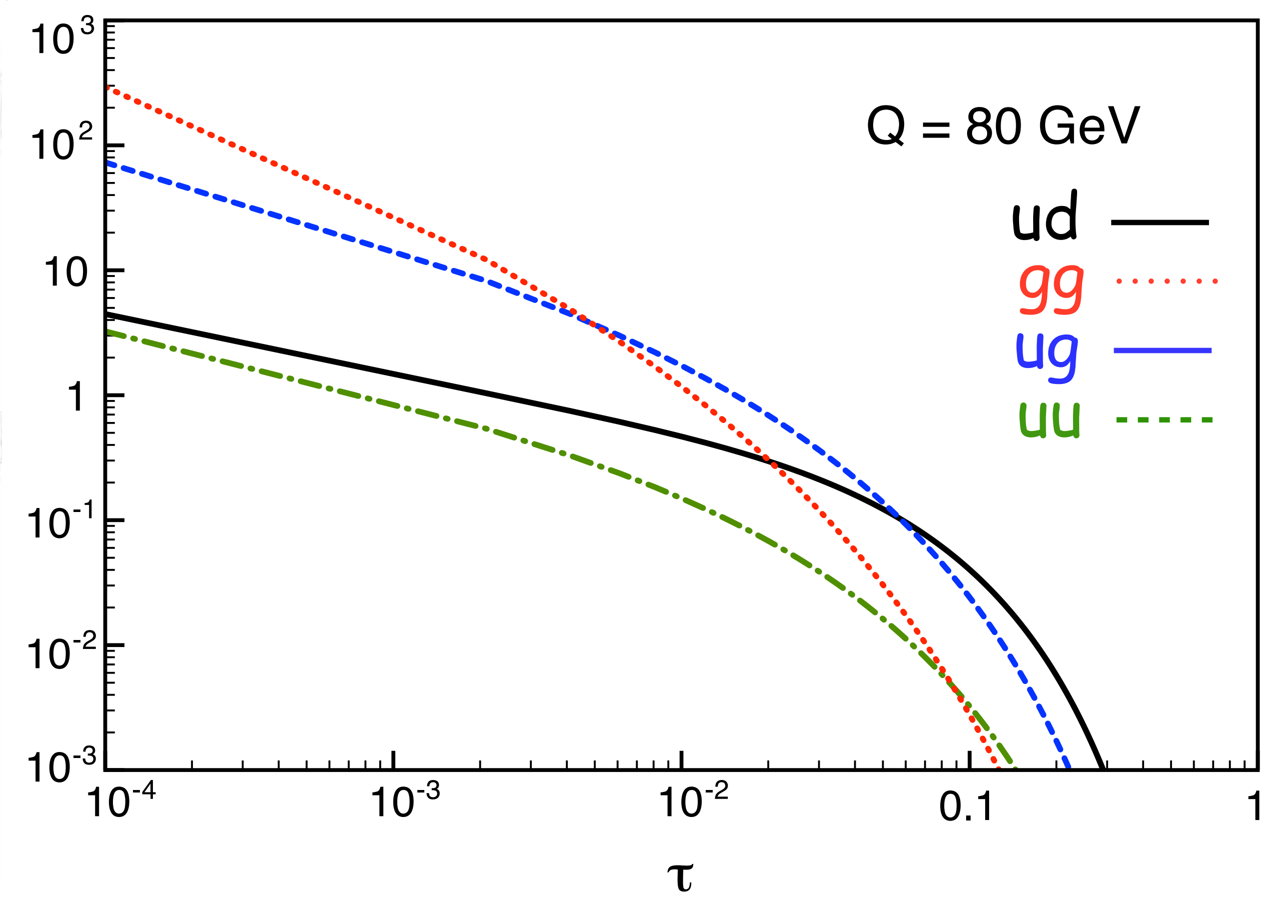
Higgs mass dependence



- production at threshold: $x_1 x_2 \sim 4m_h^2/s$ 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

⇓ ⇓ ⇓

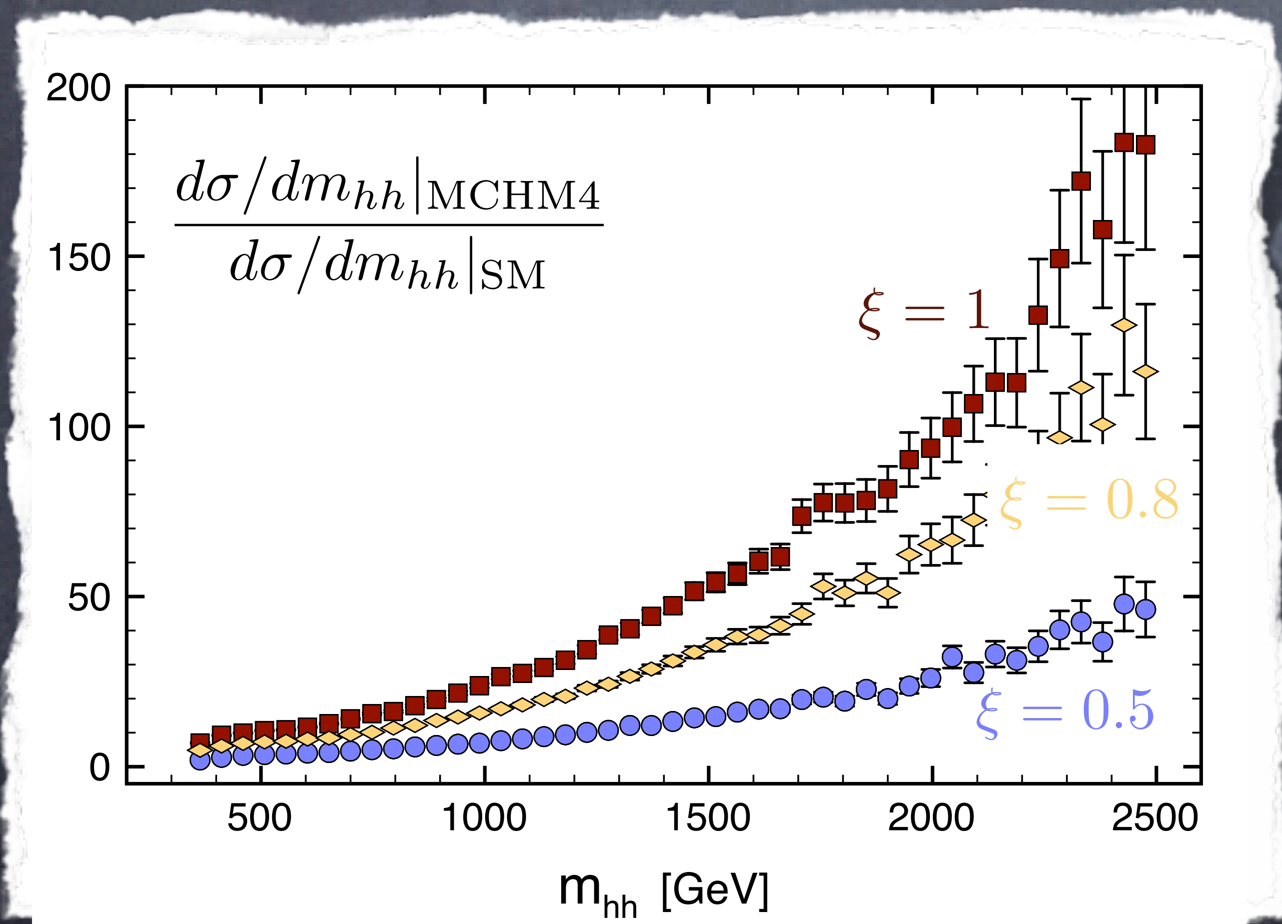
inclusive cross-section is not probing the asymptotic regime of hard scattering

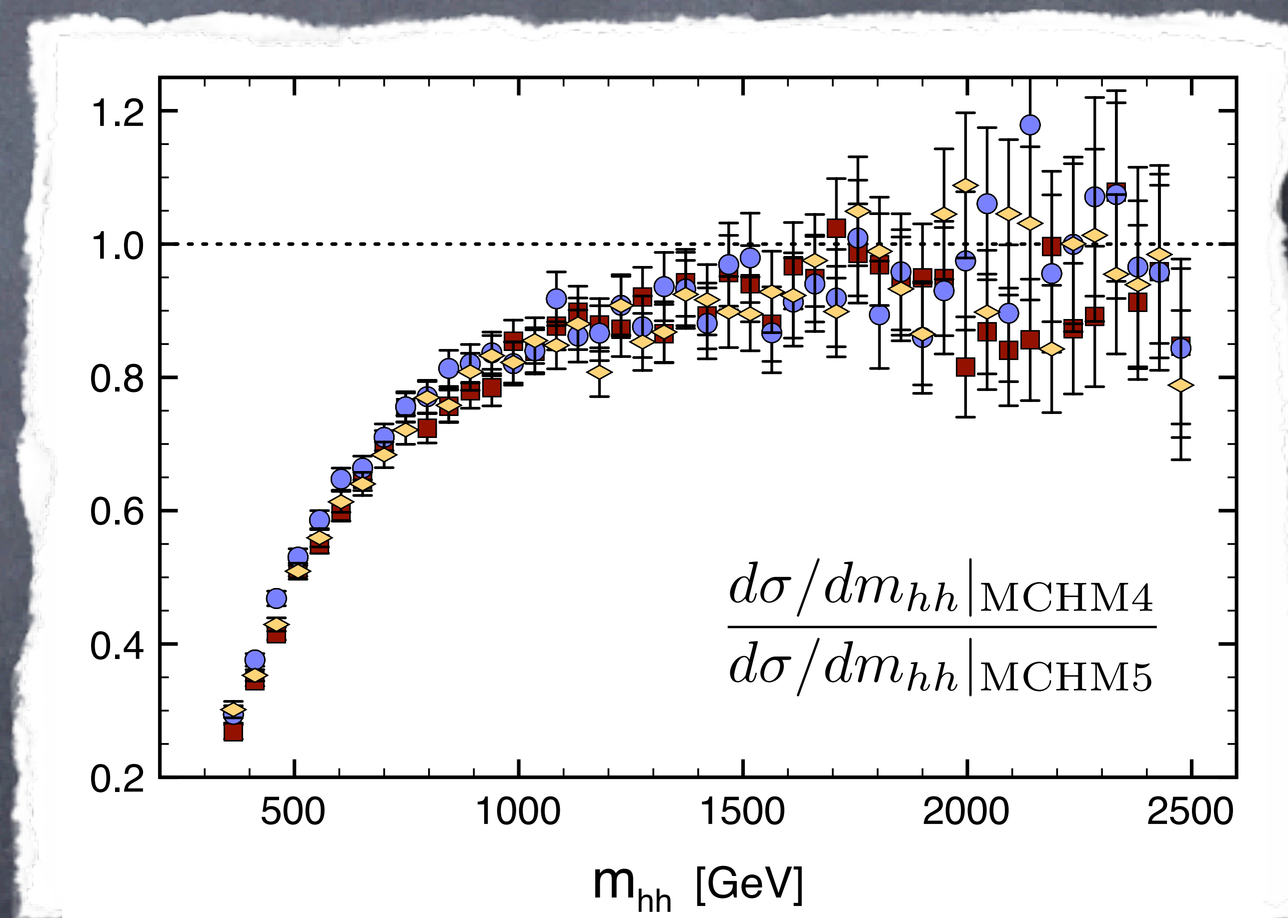
sensitivity on Higgs self-coupling and not only on strong scattering (b-a^2)

Isolating Hard Scattering

isolate events with large m_{hh}

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





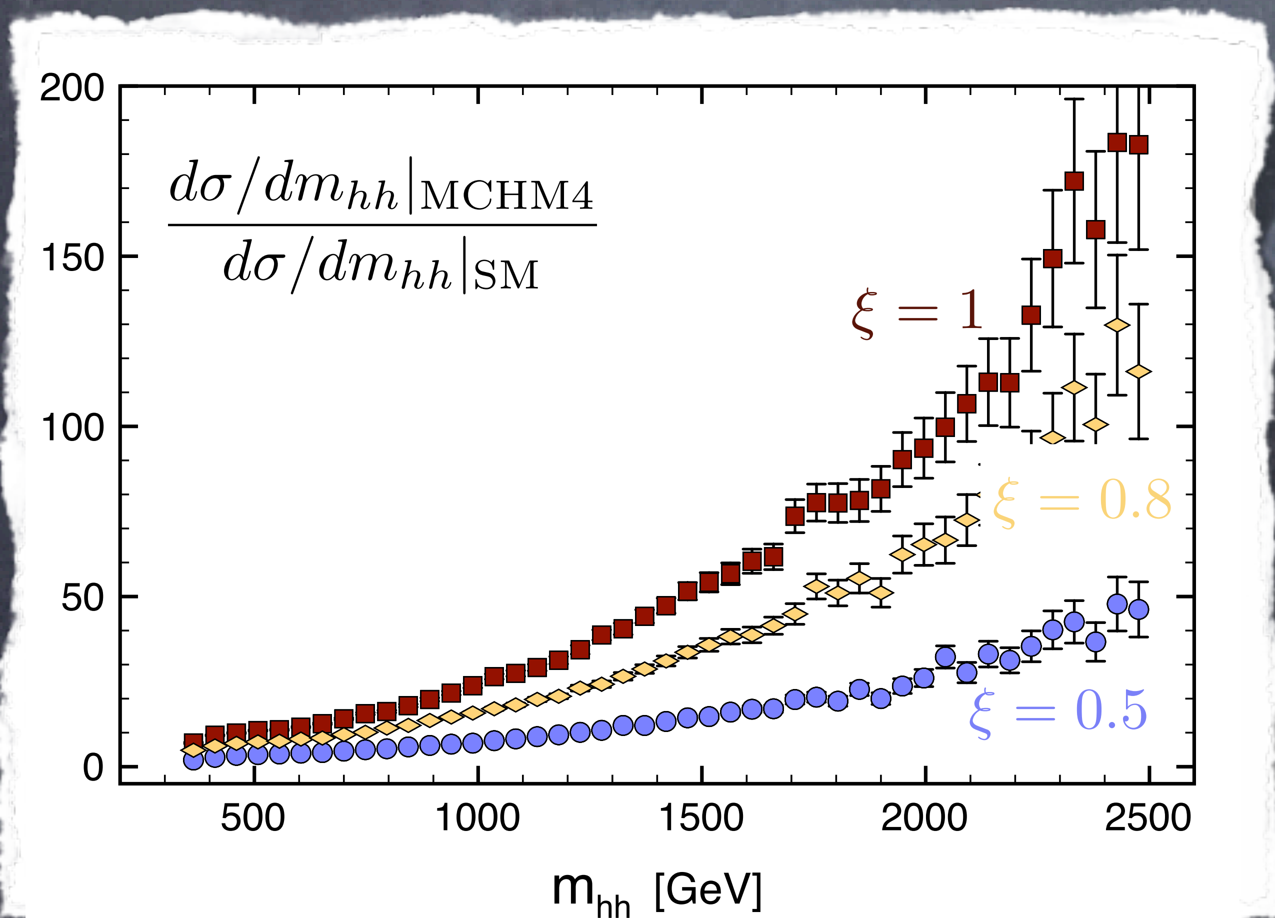
Isolating Hard Scattering

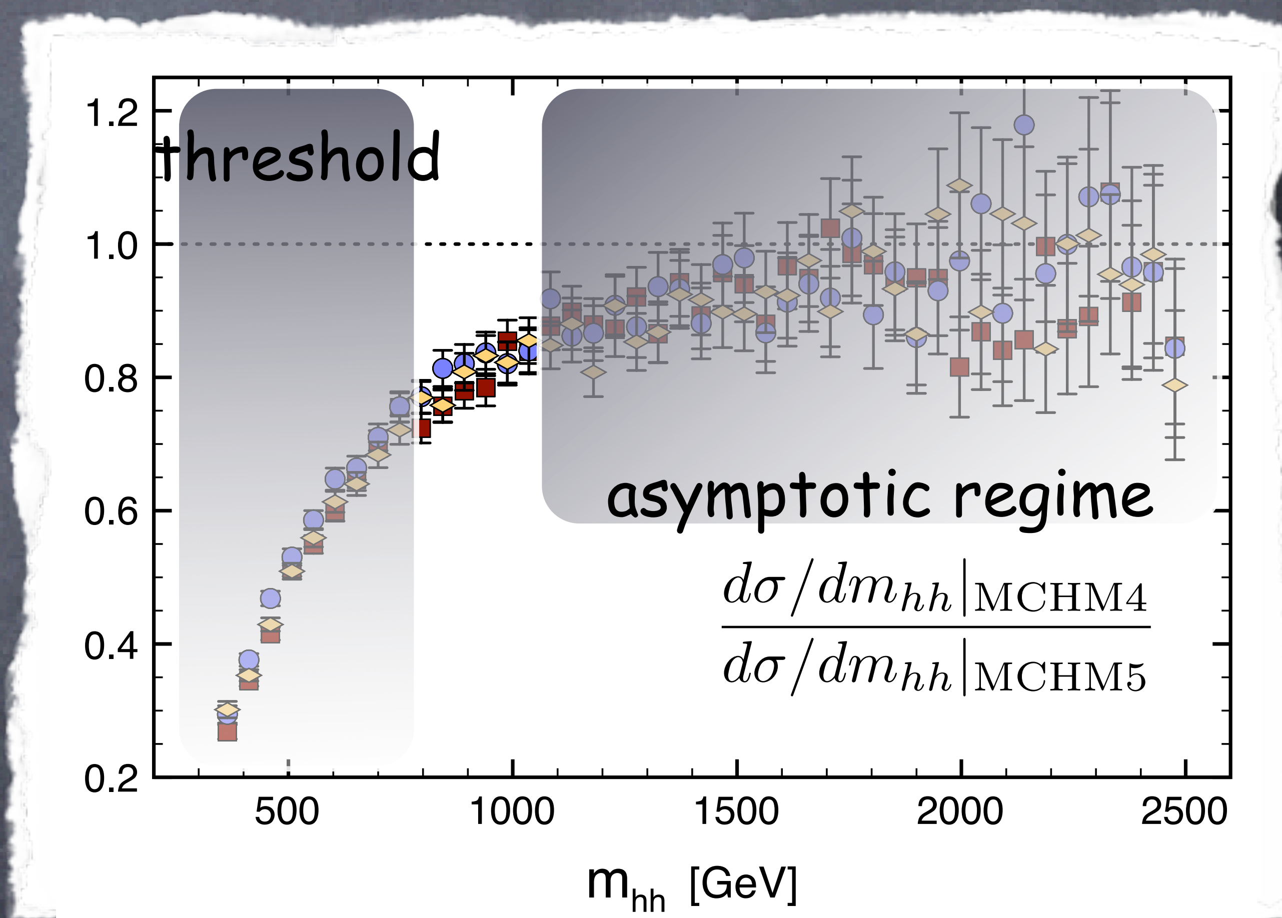
isolate events with large m_{hh}

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

measure H^3

measure $b-a^2$

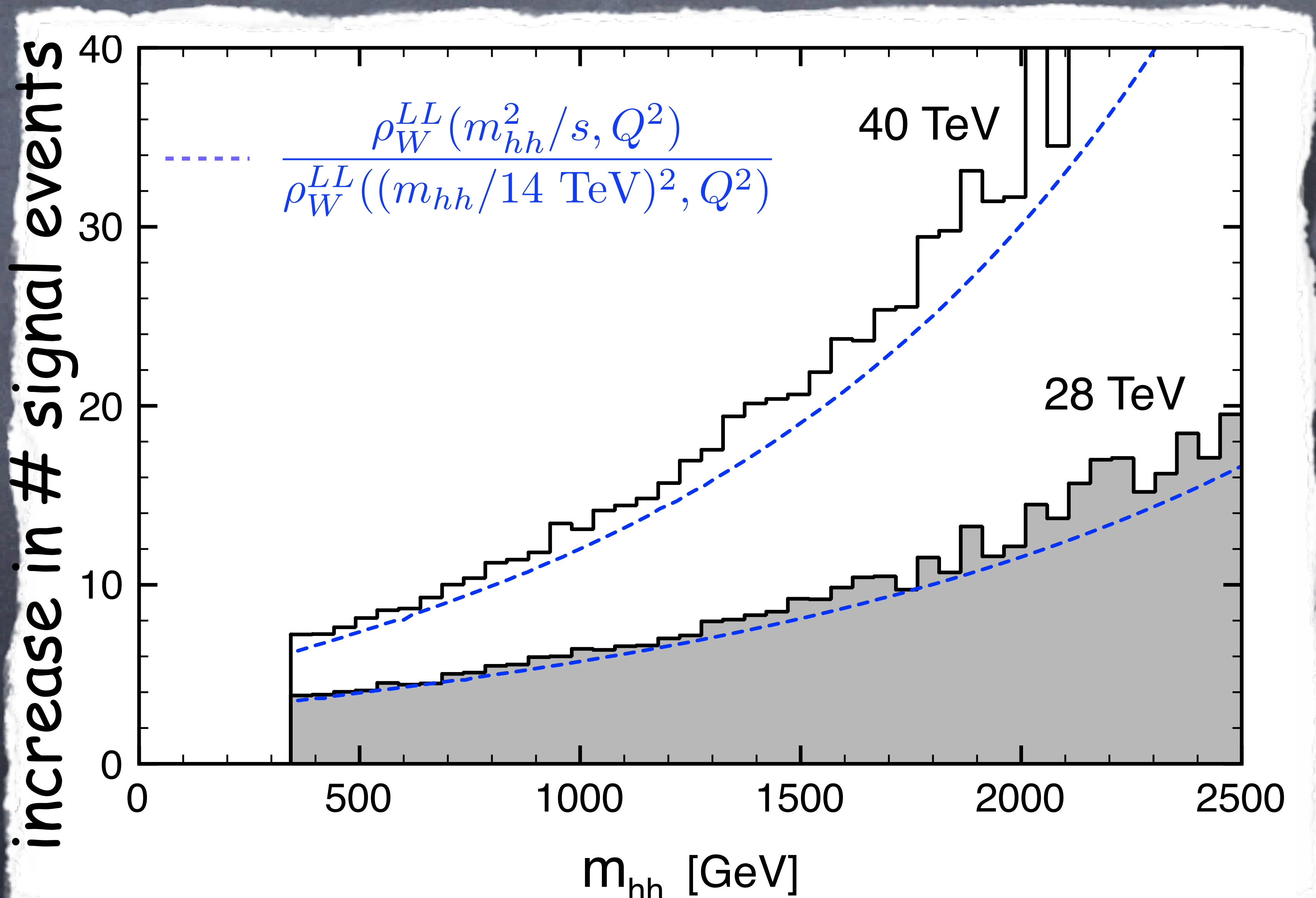




Dependence on Collider Energy

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

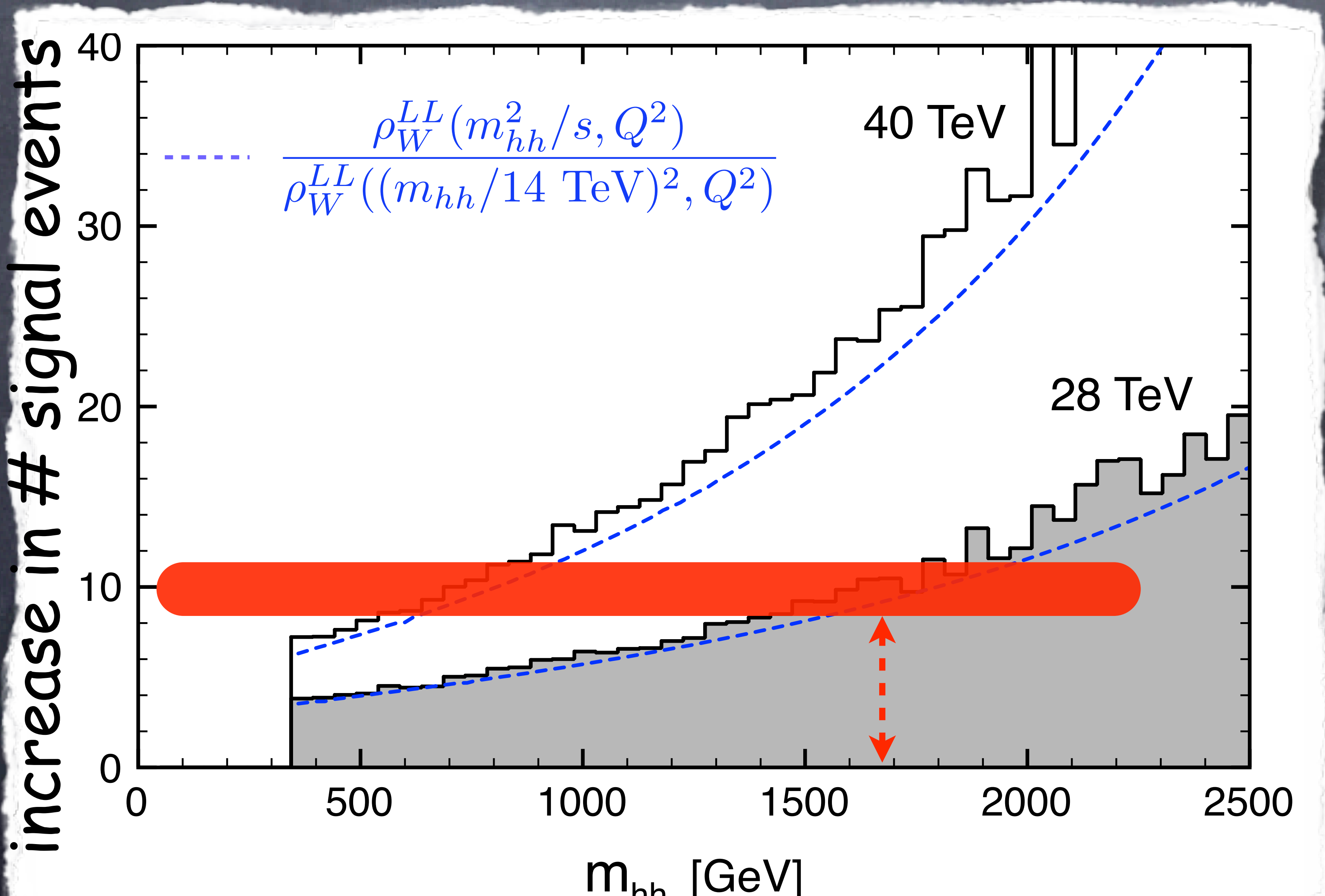
increase collider energy s = sensitive to PDFs at smaller x
bigger cross-sections



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
bigger cross-sections



sLHC vs. VLHC

10 x lum = 10 x events

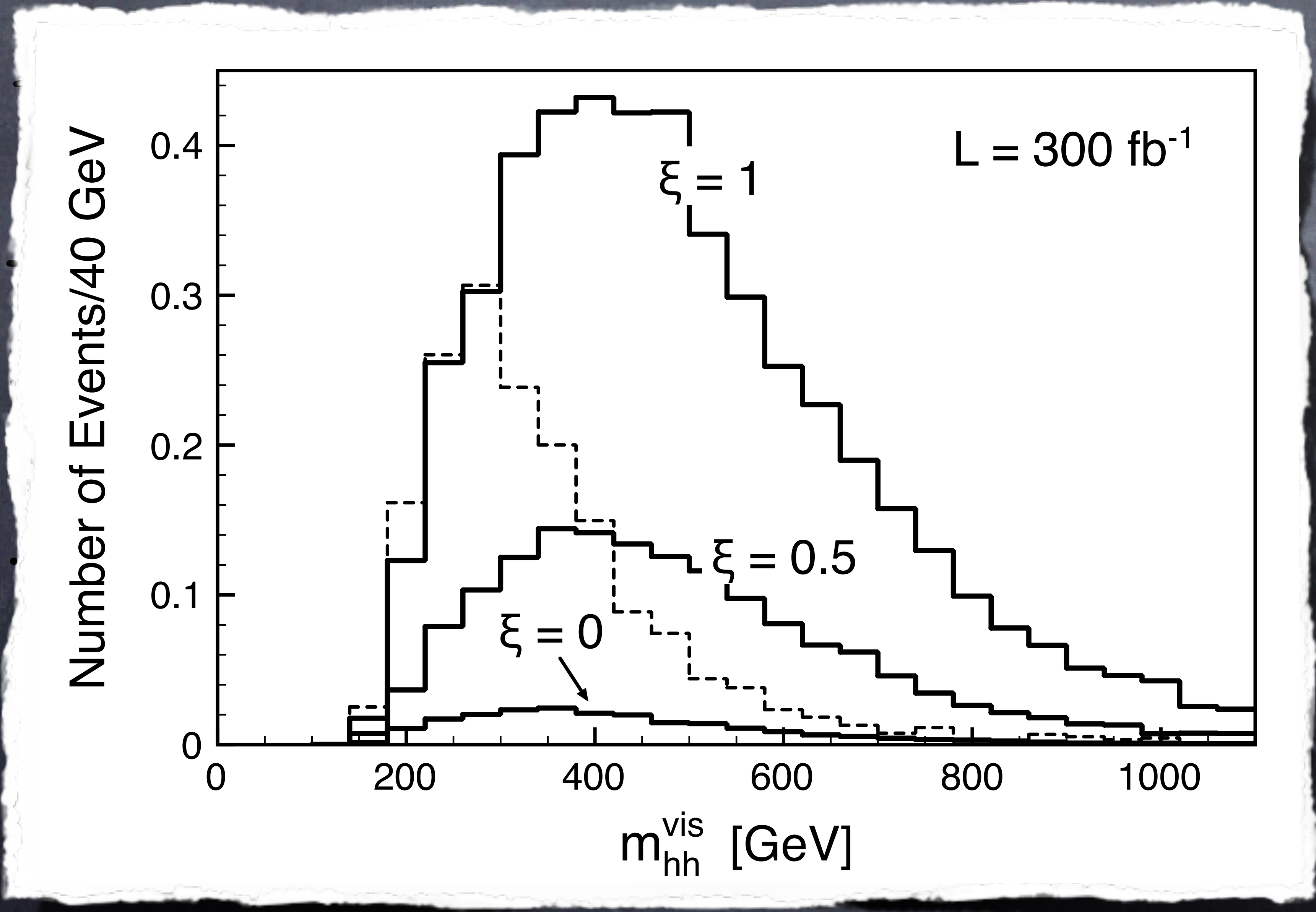
2 x √s = 10 x events
iif m_{hh}>1.6TeV

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 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