Beyond the Standard Model: the LHC reach

XIV Frascati Spring School "Bruno Touschek"

$E = mc^2$ $E = \hbar\nu$ $\mathcal{R}_{\mu\nu} - \frac{1}{2}\mathcal{R}g_{\mu\nu} = 16\pi G T_{\mu\nu}$

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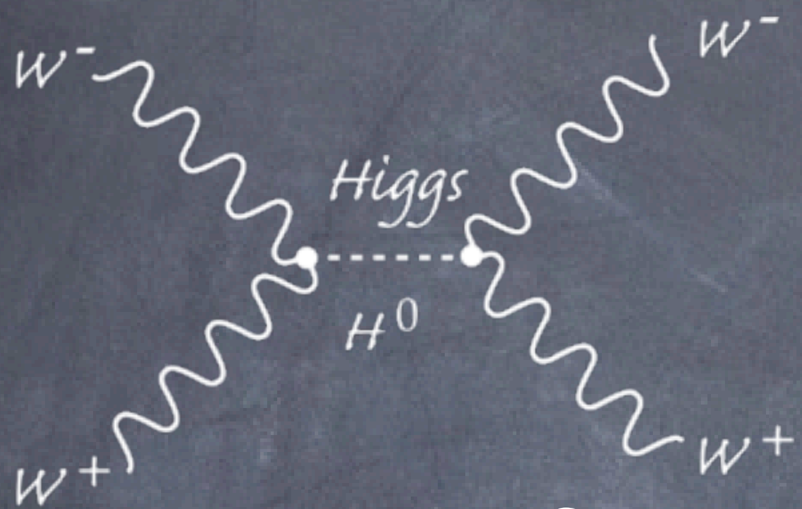
BSM: the LHC reach

- Higgs mechanism. SM Higgs.
- EW precision tests. The Higgs as a UV moderator of EW interactions. Needs for New Physics beyond the Higgs.
- Review of possible scenarios: Little Higgs, Gauge-Higgs Unification, (5D) Higgsless models, Composite Higgs.

Composite Higgs Models

Drawbacks of Usual Appraoches

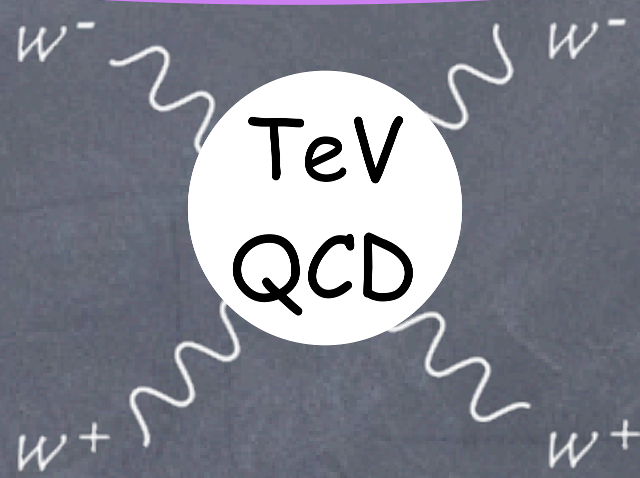
Weakly coupled models



prototype: Susy

susy partners ~ 100 GeV

Strongly coupled models



prototype: Technicolor

rho meson ~ 1 TeV

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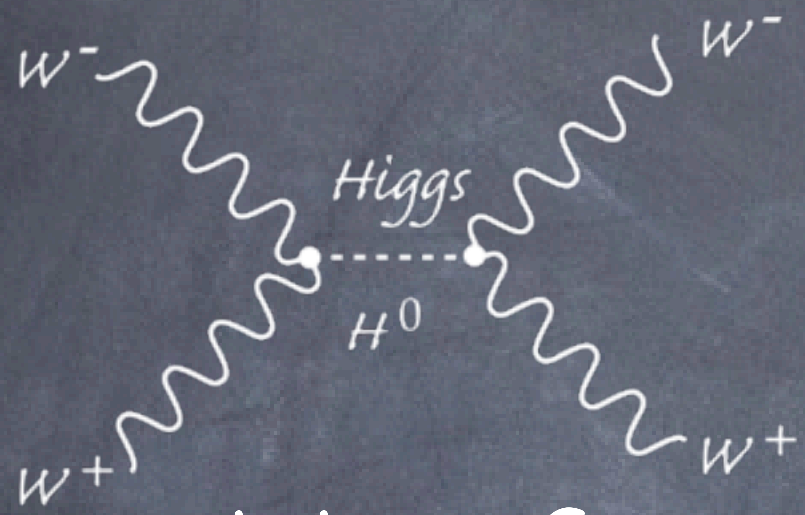

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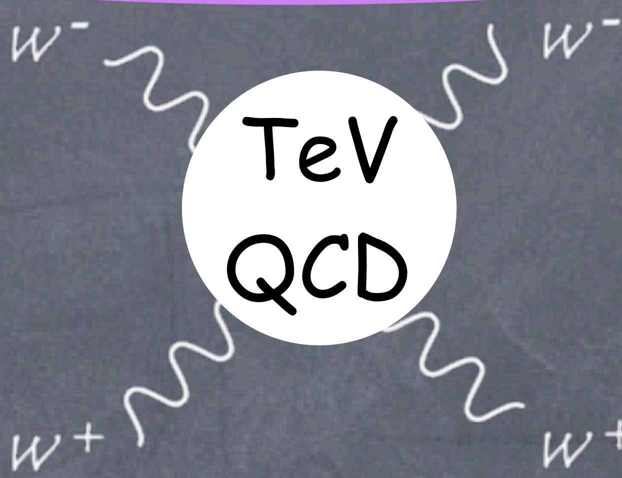
need new particles to stabilize the Higgs mass

bounds on the masses of these particles

⇓

fine-tuning O(1%)

Strongly coupled models



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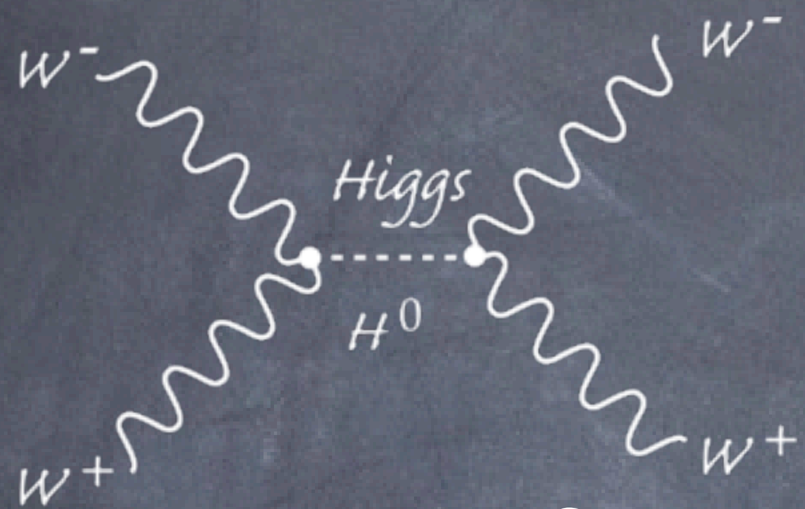

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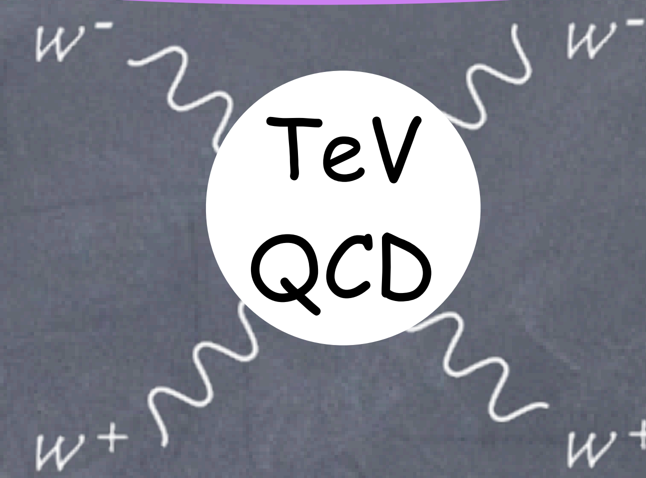

prototype: Technicolor

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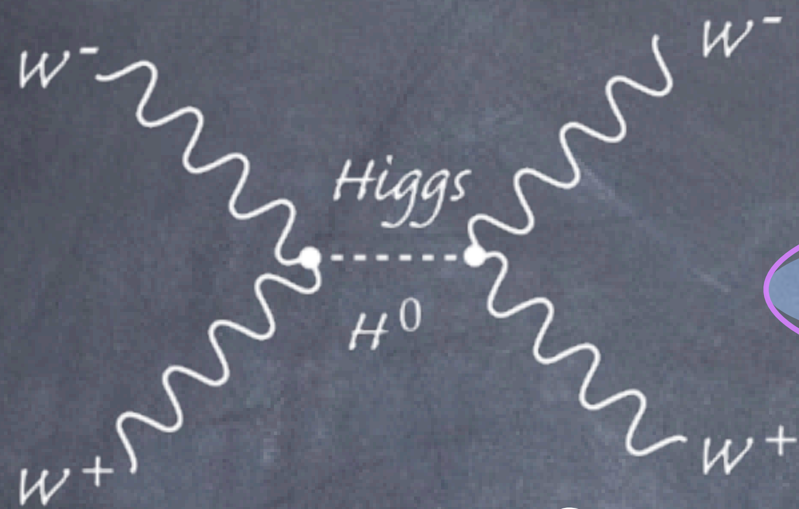
resonances needed for unitarization generate EW oblique corrections

$$\hat{S} \sim \frac{m_W^2}{m_\rho^2} \quad \xrightarrow[\text{@ 95\% CL}]{|\hat{S}| < 10^{-3}} \quad m_\rho > 2.5\ \text{TeV}$$

Drawbacks of Usual Appraoches

Weakly coupled models



prototype: Susy

susy partners ~ 100 GeV

need new particles to stabilize the Higgs mass

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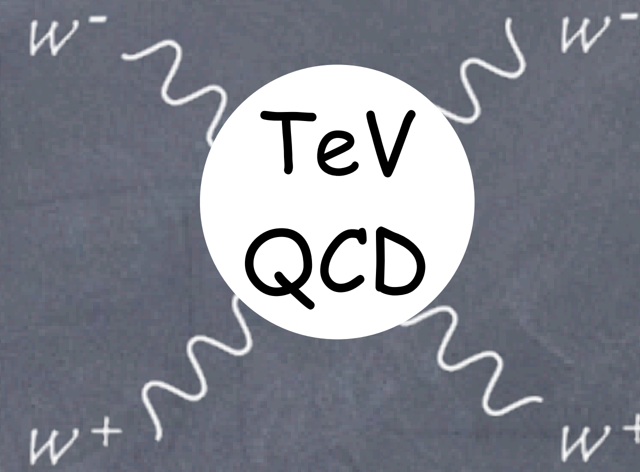
⇓

fine-tuning O(1%)

other ways?

Strongly coupled models



prototype: Technicolor

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Scattering amplitudes

non-linear realization of the gauge symmetry

W_L, Z_L are Goldstone bosons ~ pions of QCD

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

2x2 matrix: π^a ~ W_L,Z_L

$$\Sigma \to SU(2)_L \cdot \Sigma \cdot U(1)_Y$$

$$\mathcal{L}_{\rm mass} = \frac{v^2}{4} {\rm Tr} \left(D_\mu \Sigma^\dagger D_\mu \Sigma \right)$$

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bad behavior of scattering amplitudes

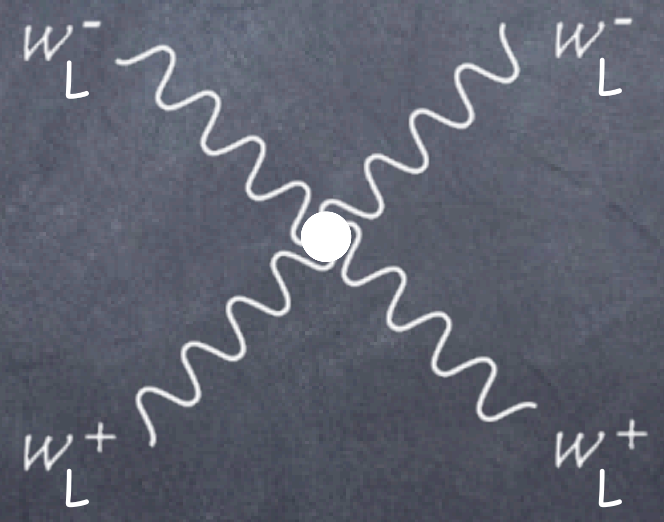
$$\epsilon_l = \left(\frac{|\vec{k}|}{M}, \frac{E}{M} \frac{\vec{k}}{|\vec{k}|} \right)$$

scattering of W_L

~

scattering of QCD pions

(Goldstone equivalence theorem)



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

loss of perturbative unitarity

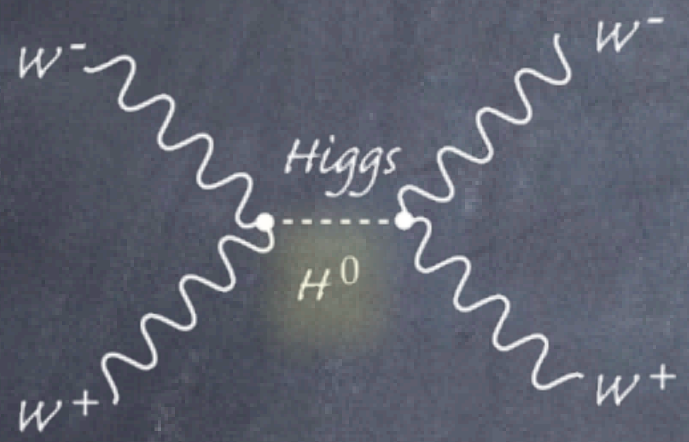
around 1.2 TeV

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

Unitarity with Composite Higgs

Technicolor: W_L and Z_L are part of the strong sector

Higgs = composite object (part of the strong sector too)
its couplings deviate from a point-like scalar

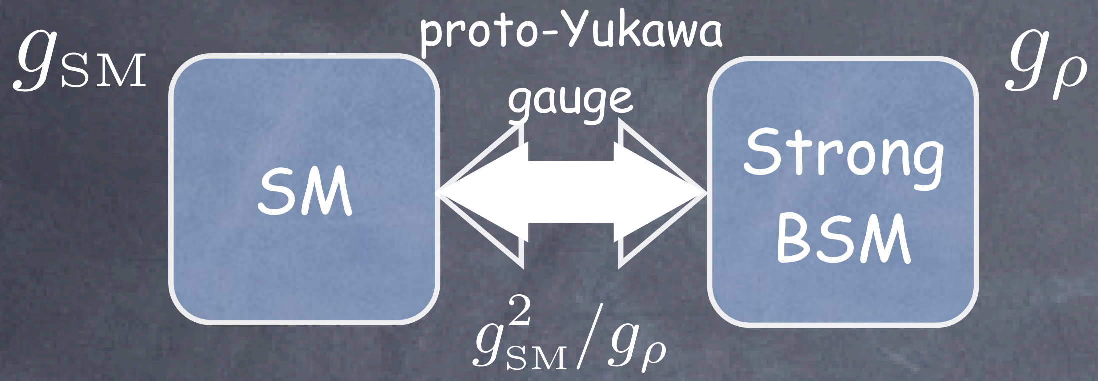
Georgi, Kaplan '84

unitarization halfway between weak and strong unitarizations!

- ≠ susy: composite particle ⊃ no naturalness pb ⊃ no need for new particles
- ≠ technicolor: amplitude partially cancelled by Higgs ⊃ allows for heavier rho ⊃ smaller oblique corrections.

How to obtain a light composite Higgs?

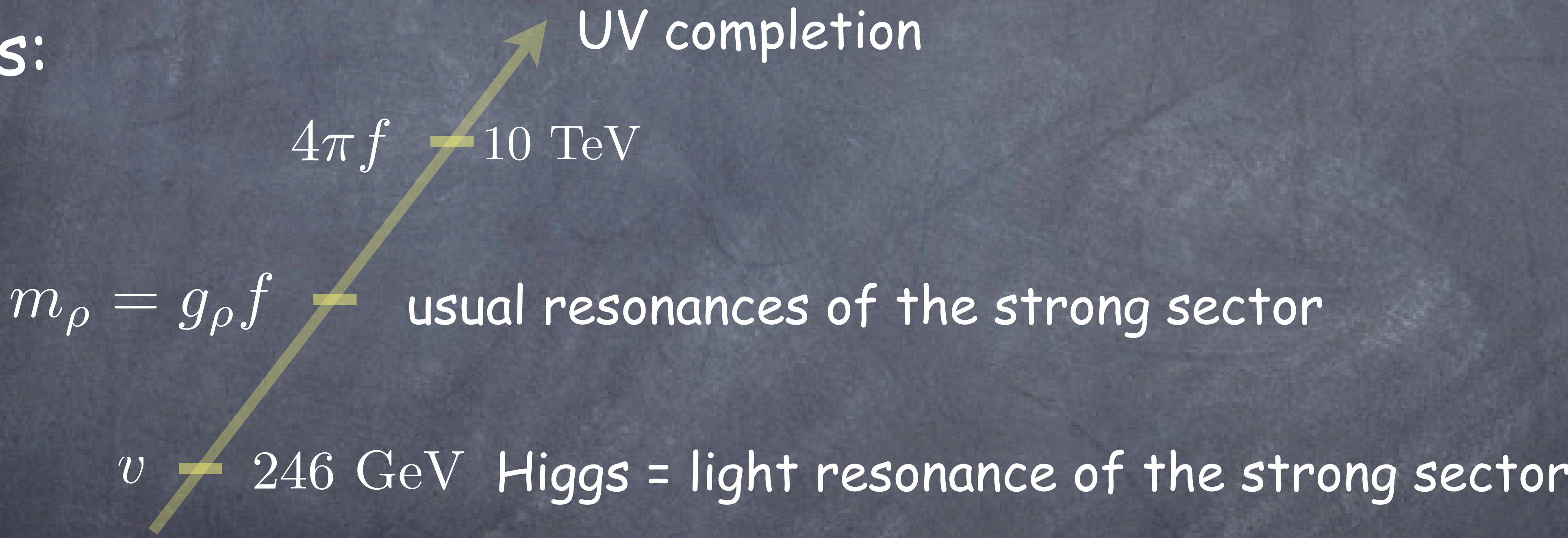
Higgs=Pseudo-Goldstone boson of the strong sector



$m_{\rm Higgs}$=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 $f = \dfrac{m_\rho}{g_\rho}$

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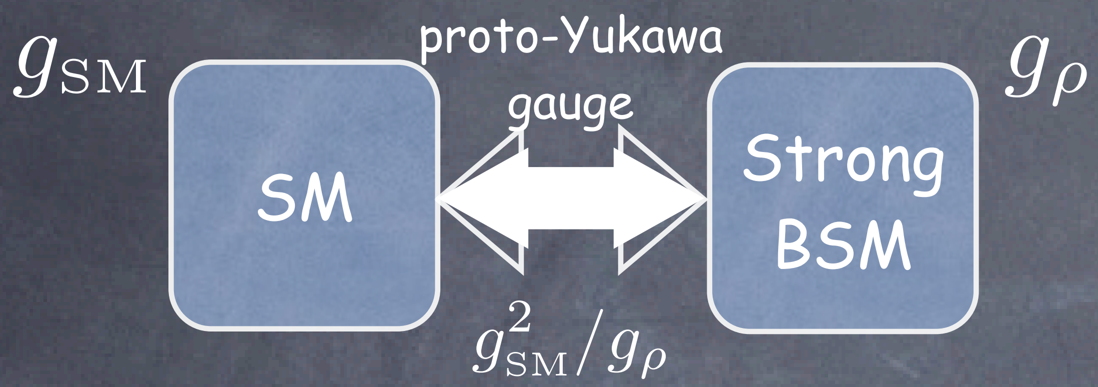

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3 scales:

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

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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

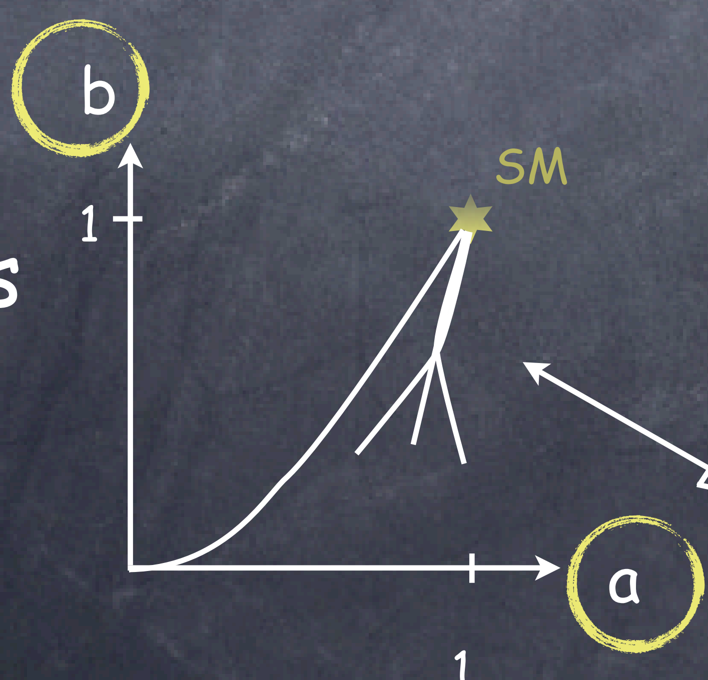
all resonances of strong sector, except the Higgs, decouple

$\xi = 1$

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

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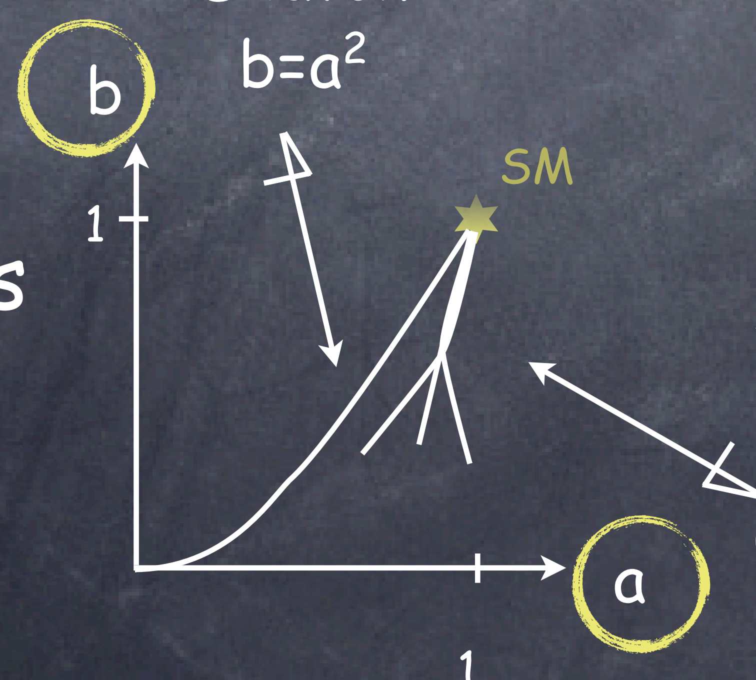
Composite Higgs vs. Dilaton

Dilaton
b=a^2



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

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

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

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

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

Anomalous Higgs Couplings

Giudice, Grojean, Pomarol, Rattazzi '07

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$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Longrightarrow \mathcal{L} = \frac{1}{2}\left(1 + c_H\frac{v^2}{f^2}\right)(\partial^\mu h)^2 + \ldots$$

Modified Higgs propagator ~ Higgs couplings rescaled by $\frac{1}{\sqrt{1+c_H\frac{v^2}{f^2}}} \sim 1 - c_H\frac{v^2}{2f^2} \equiv 1 - \xi/2$

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)

- **Form factor operators** (sensitive to the scale m_ρ)

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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)

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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

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

removed by custodial symmetry

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

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

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

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

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

mass terms

Higgs fermion interactions

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

$\Rrightarrow$ FCNC

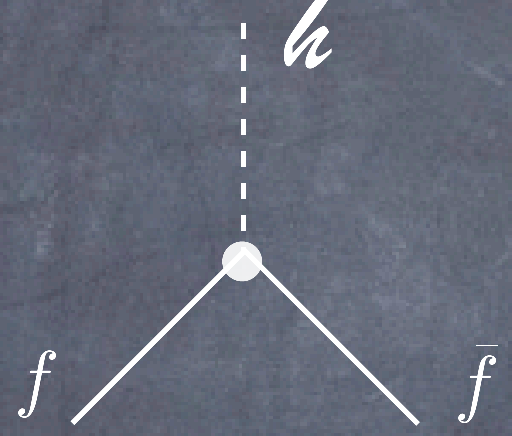
SILH: c_y is flavor universal

$\Rrightarrow$ Minimal flavor violation built in

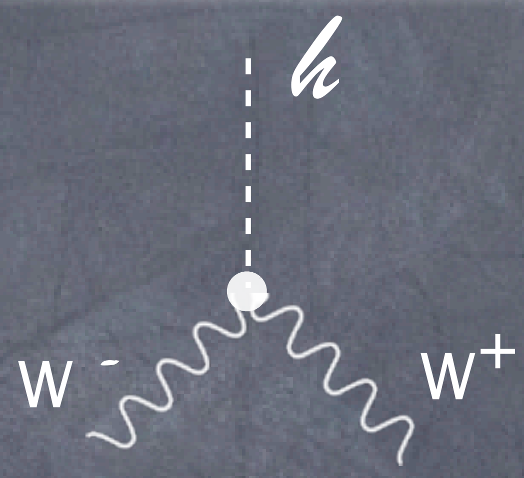
Higgs anomalous couplings

Lagrangian in unitary gauge

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



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



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

⇘ ⇙

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

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

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

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

Fermions embedded in spinorial of SO(5)

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

$$\Downarrow$$

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

universal shift of the couplings
no modifications of BRs

Fermions embedded in 5+10 of SO(5)

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

$$\Downarrow$$

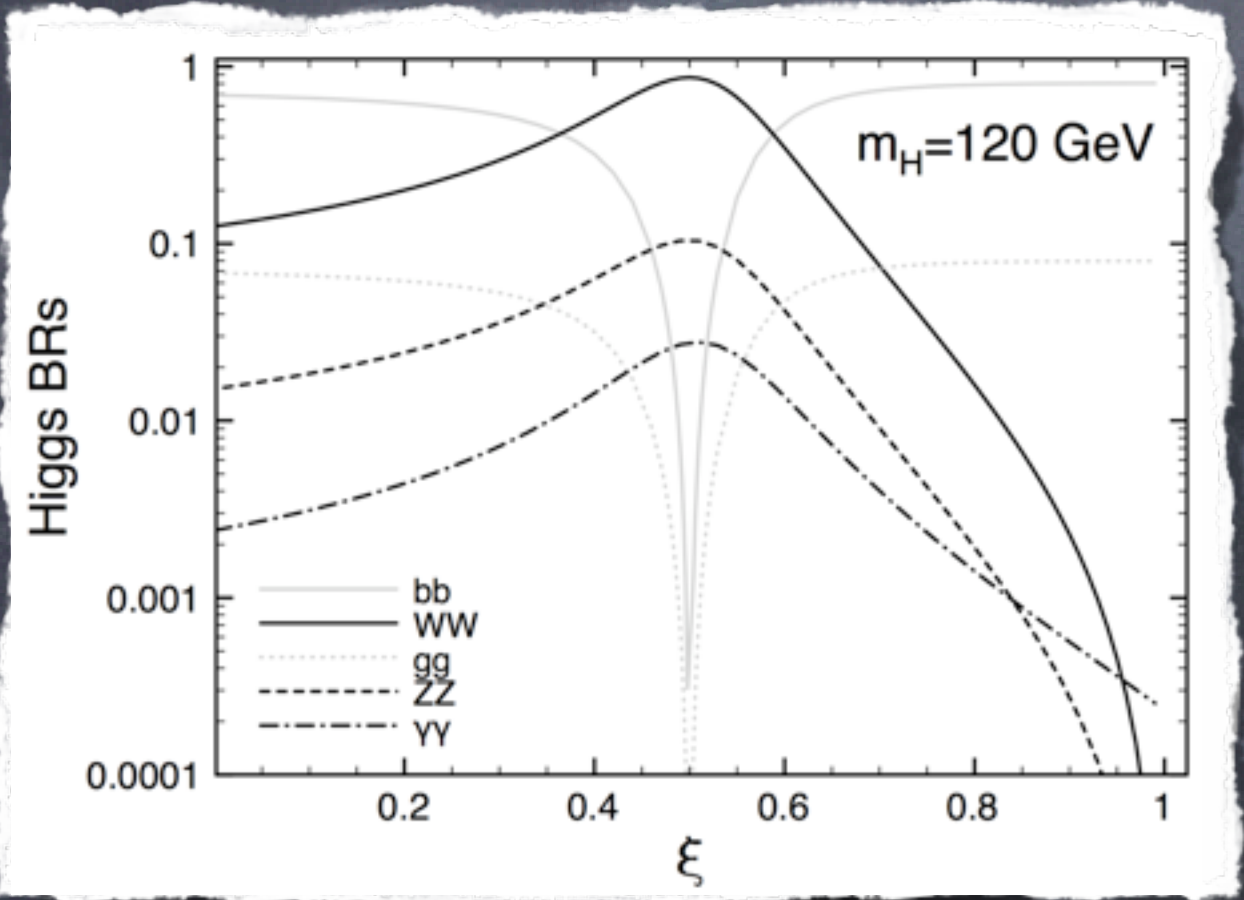
$$g_{hff} = \frac{1-2\xi}{\sqrt{1-\xi}}\, g_{hff}^{\text{SM}}$$

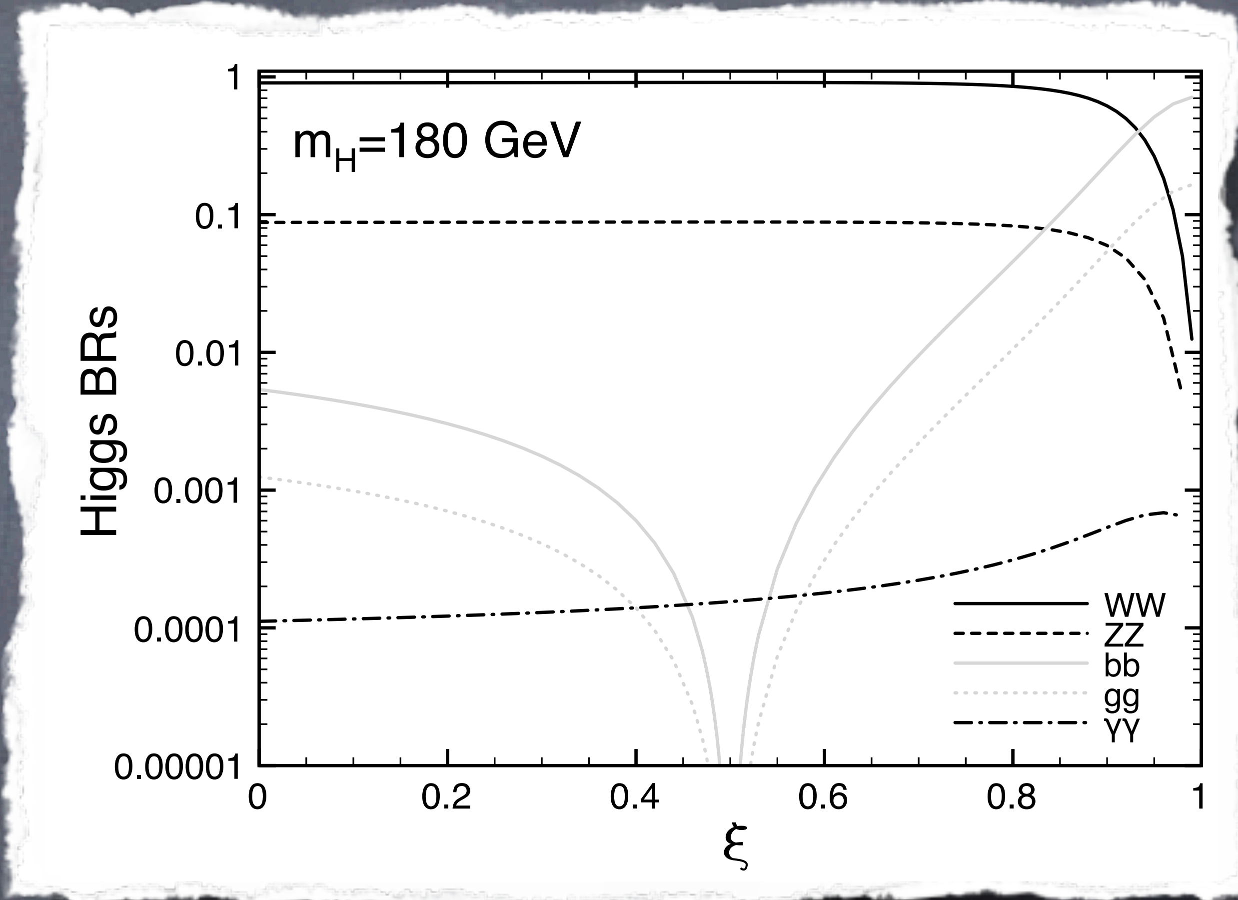
BRs now depends on v/f

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

Higgs BRs

Fermions embedded in 5+10 of SO(5)



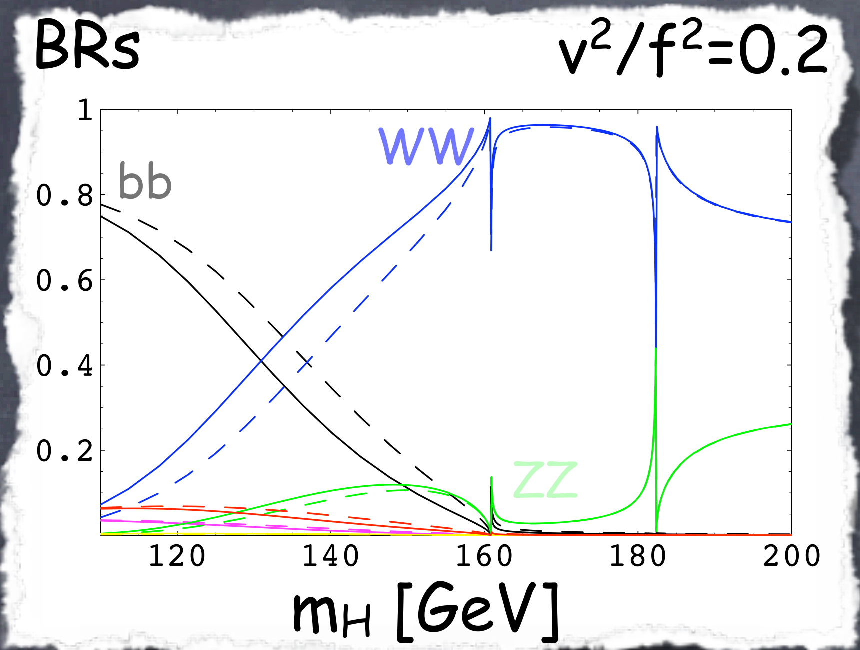


h→WW can dominate even for low Higgs mass

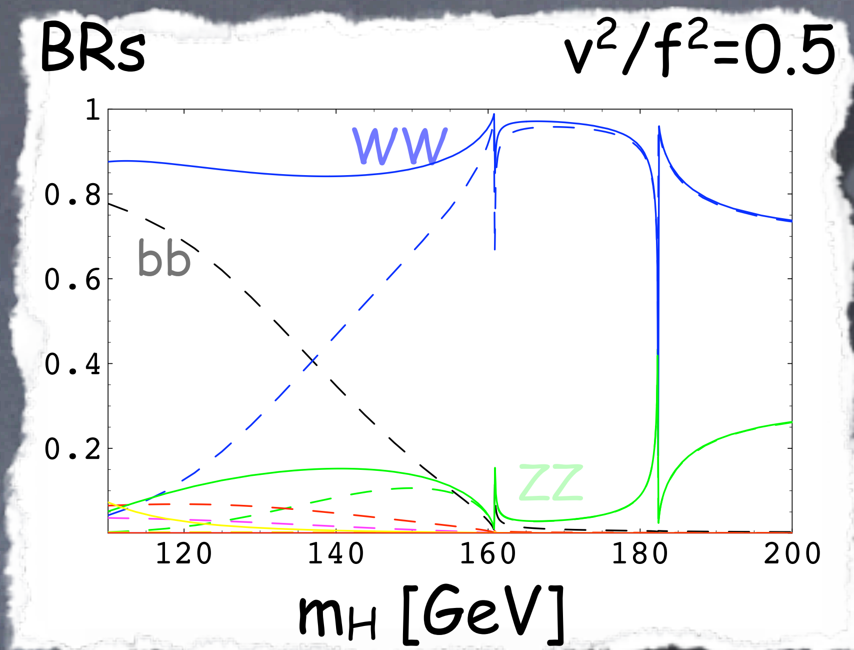
BRs remain SM like except for very large values of v/f

Higgs BRs and total width

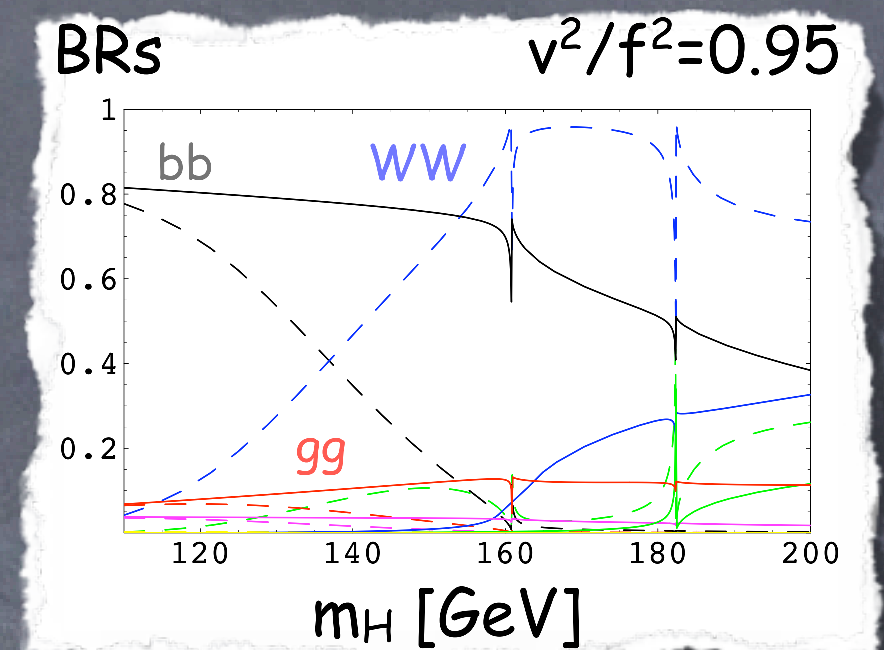
Fermions embedded in 5+10 of SO(5)



slight modifications

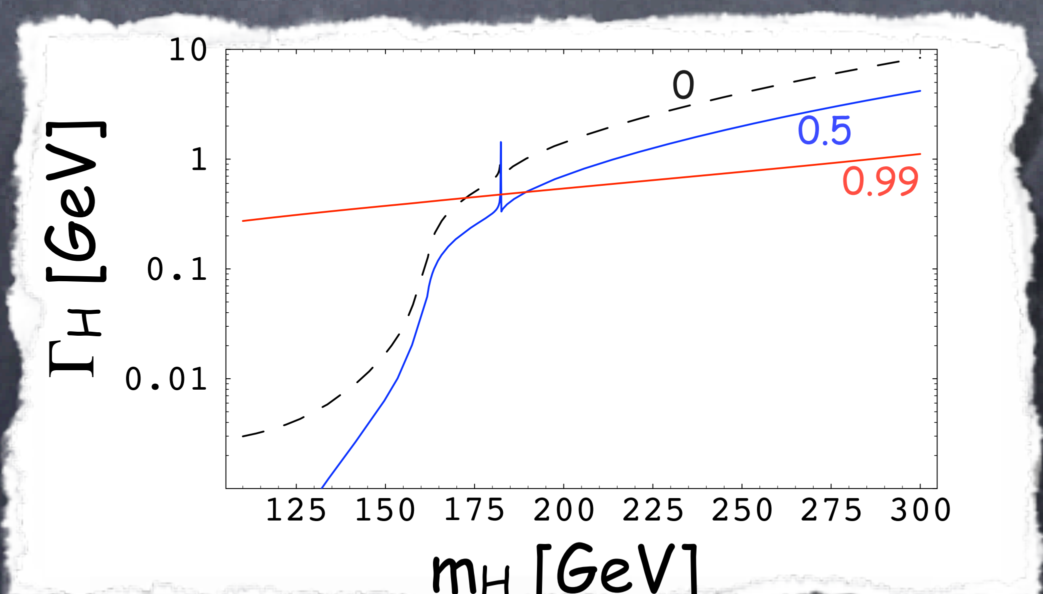


suppress bb



suppress WW

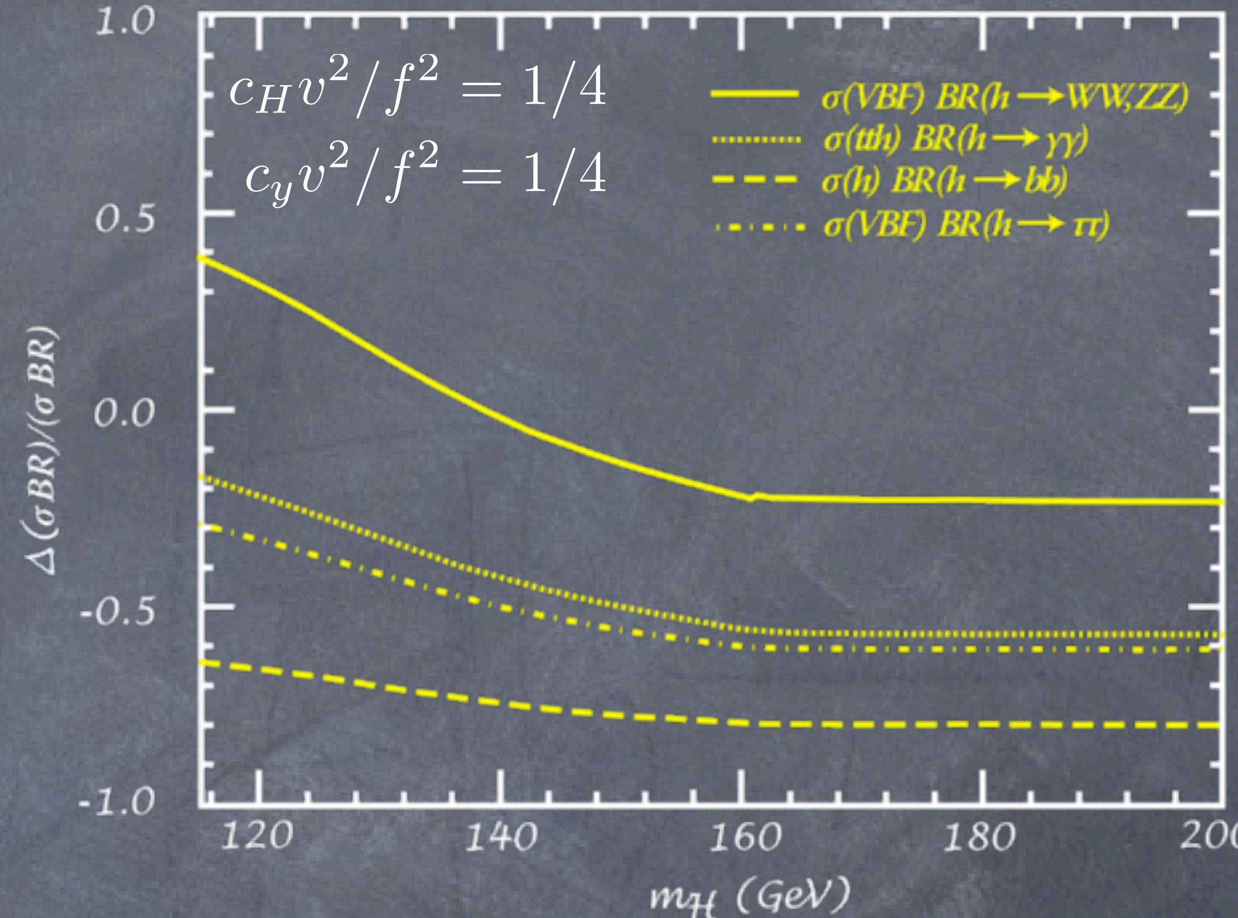
Higgs total width



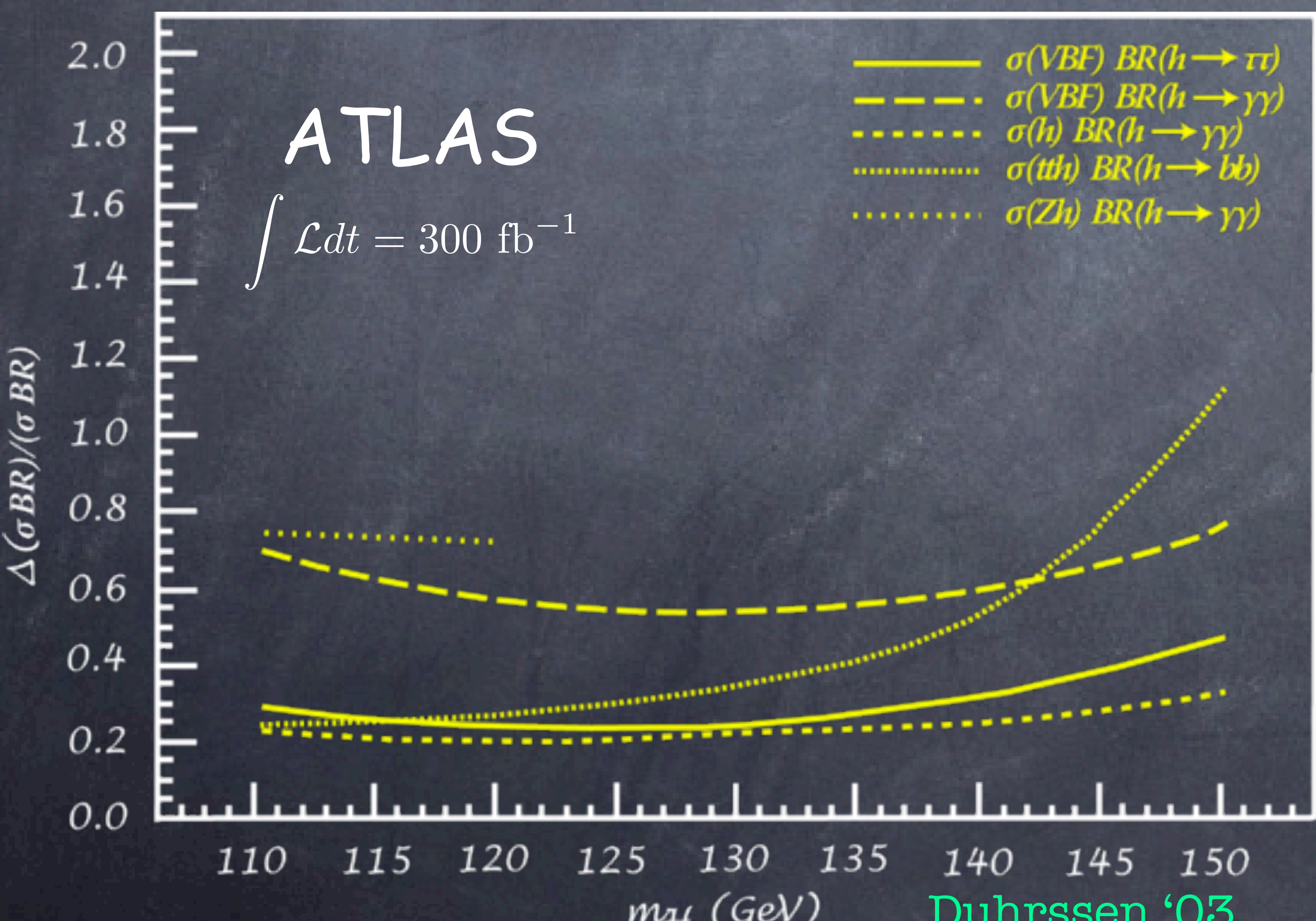
Higgs anomalous couplings @ LHC

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

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



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

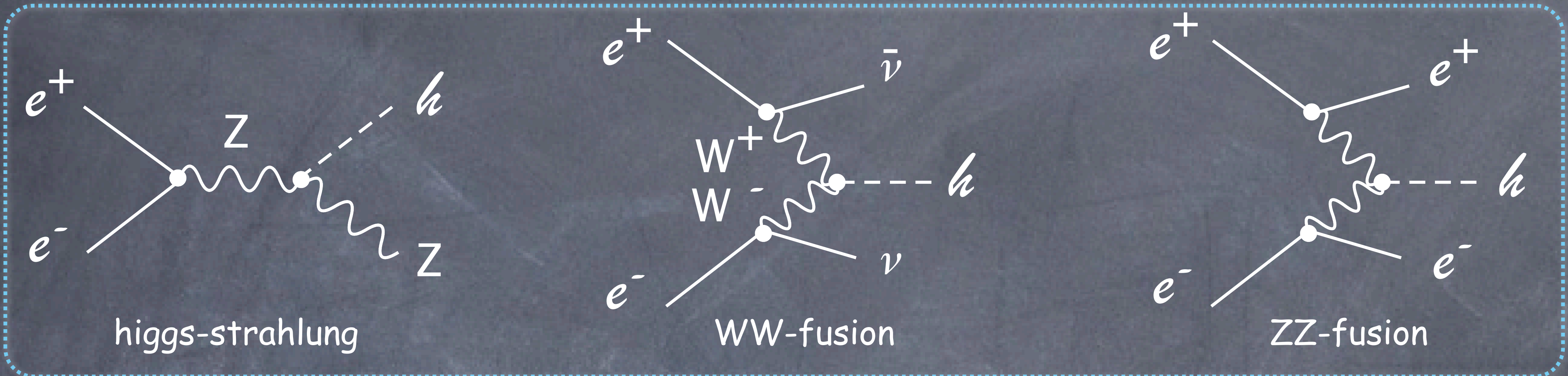
i.e. $4\pi f \sim 5-7$ TeV

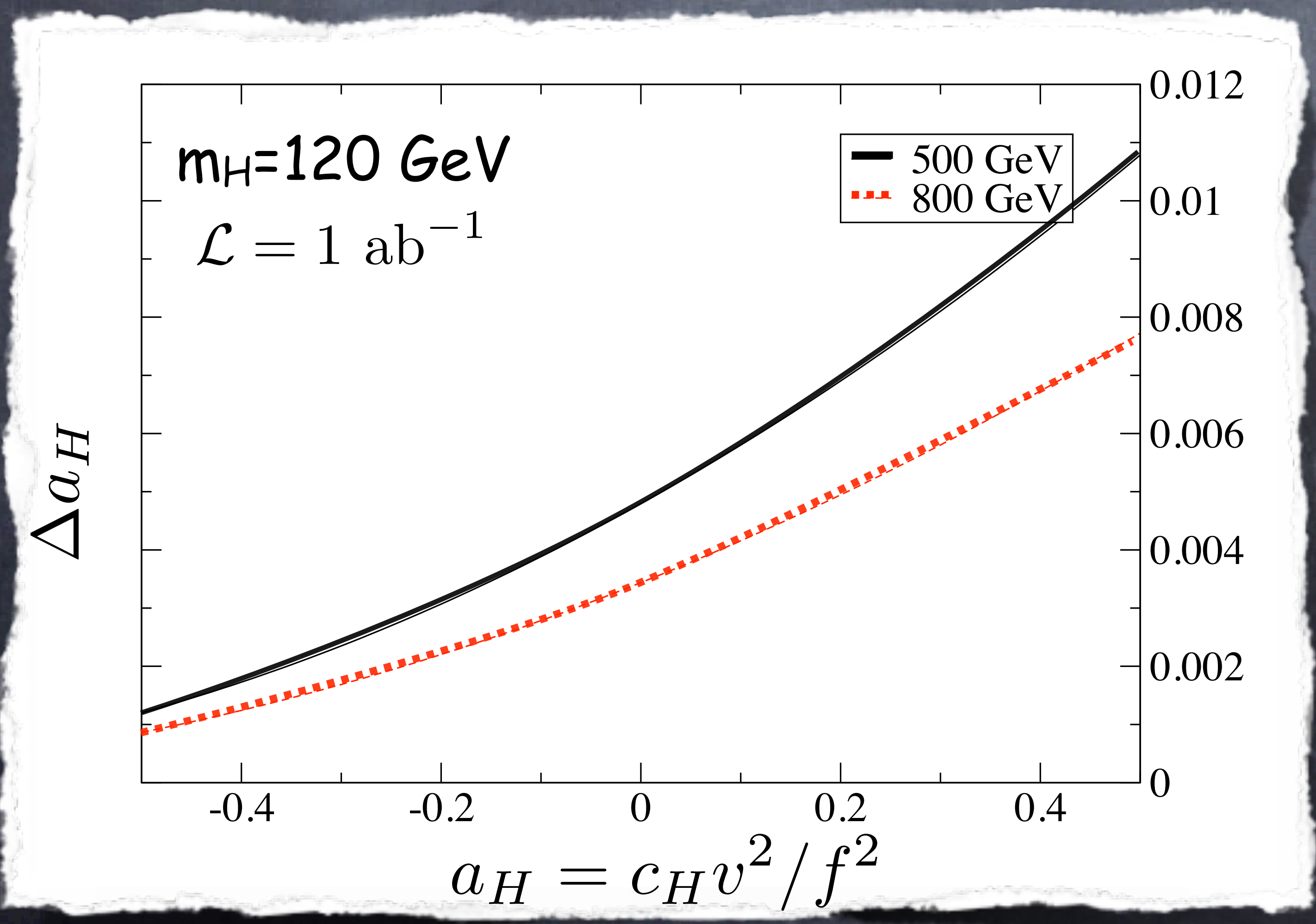
(ILC could go to few % ie
test composite Higgs up to $4\pi f \sim 30$ TeV)

Higgs anomalous couplings @ LC

Barger et al. hep-ph/0301097

single Higgs production





m_H=120 GeV

$$\Delta a_H \sim 0.005 \quad \Rrightarrow \quad 4\pi f \sim 44\ \mathrm{TeV}$$

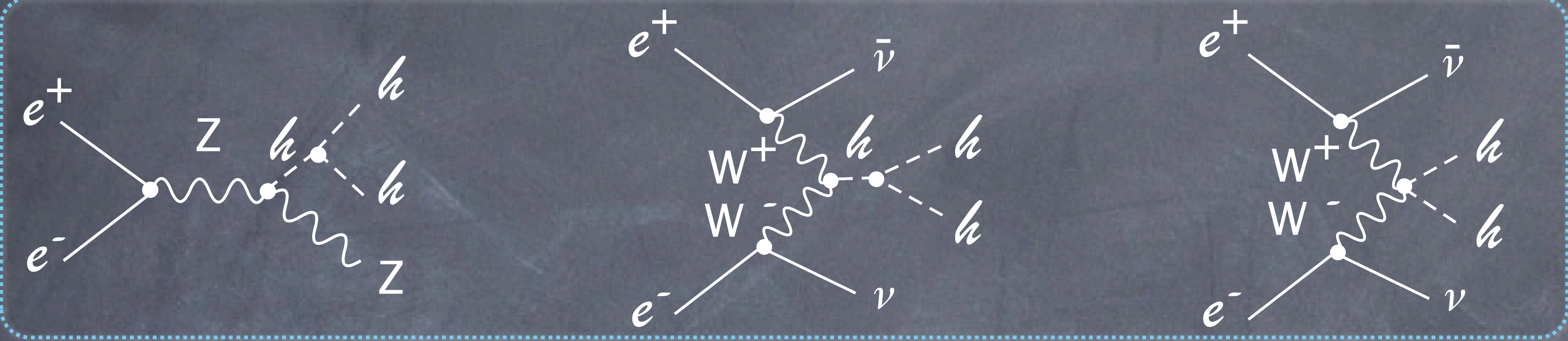
m_H=240 GeV

$$\Delta a_H \sim 0.02 \quad \Rrightarrow \quad 4\pi f \sim 22\ \mathrm{TeV}$$

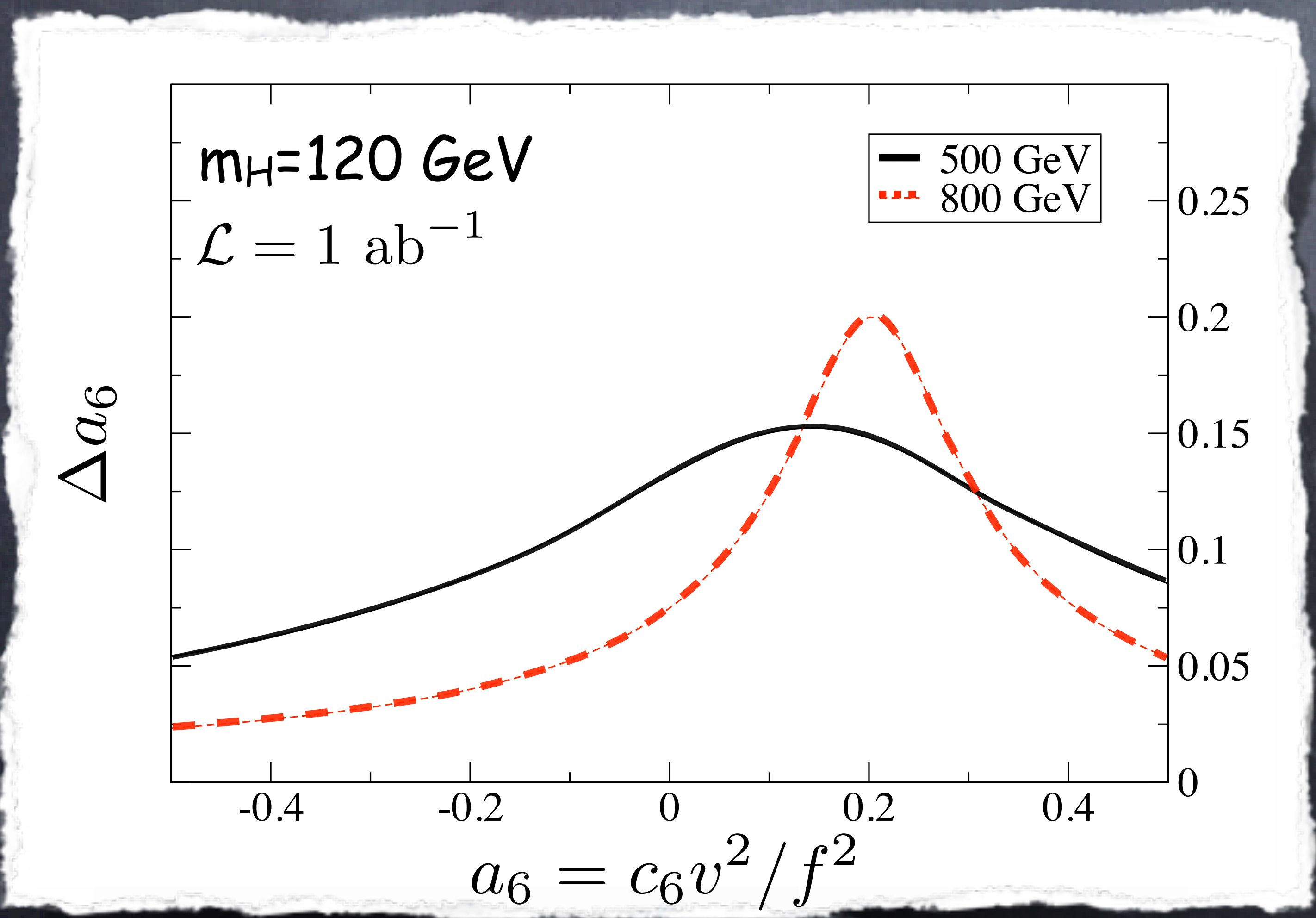
Higgs anomalous (self-)couplings @ LC

Barger et al. hep-ph/0301097

double Higgs production



the accuracy on a_H is not competitive compared to single Higgs production



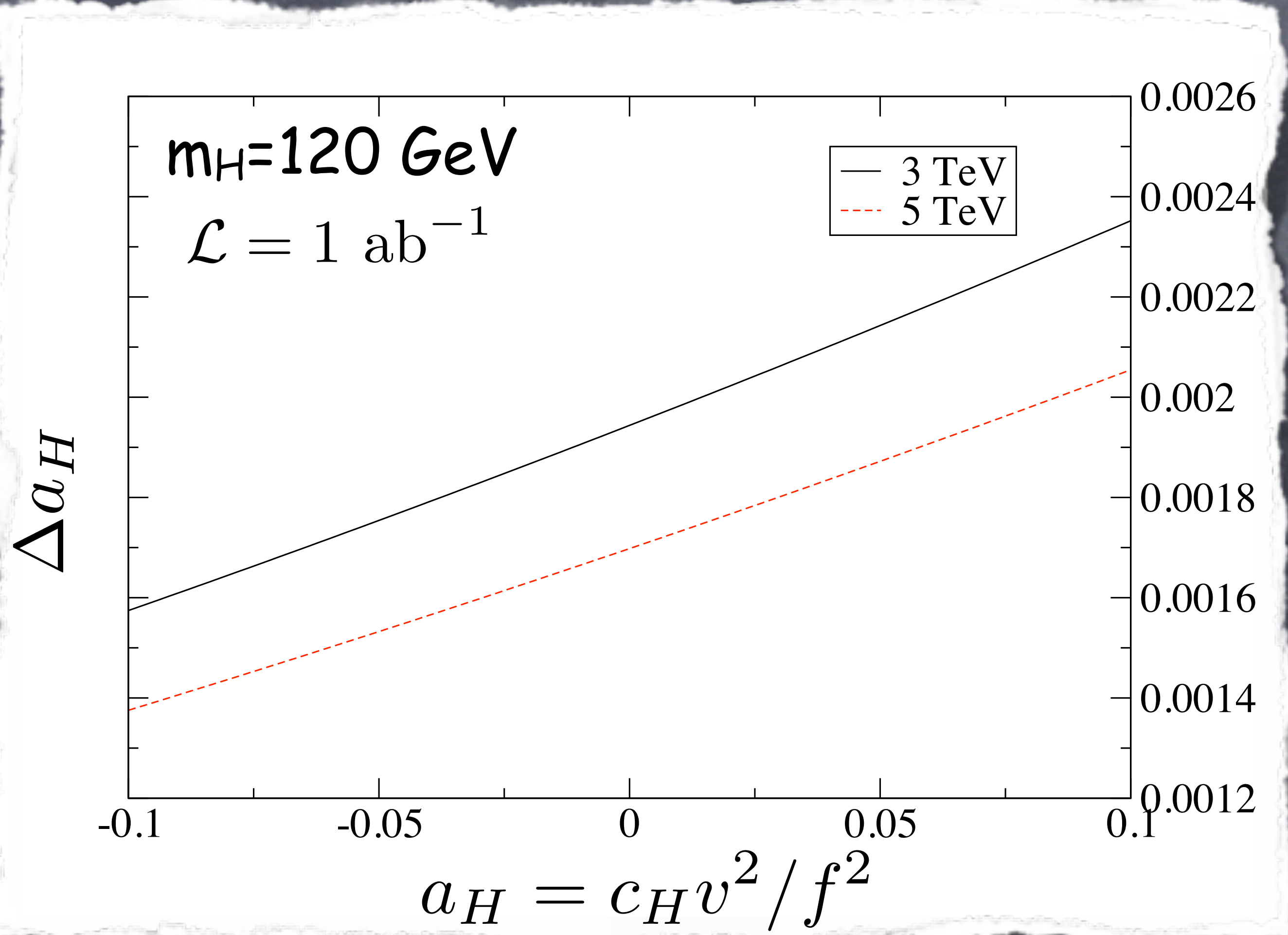
it allows to constrain a_6

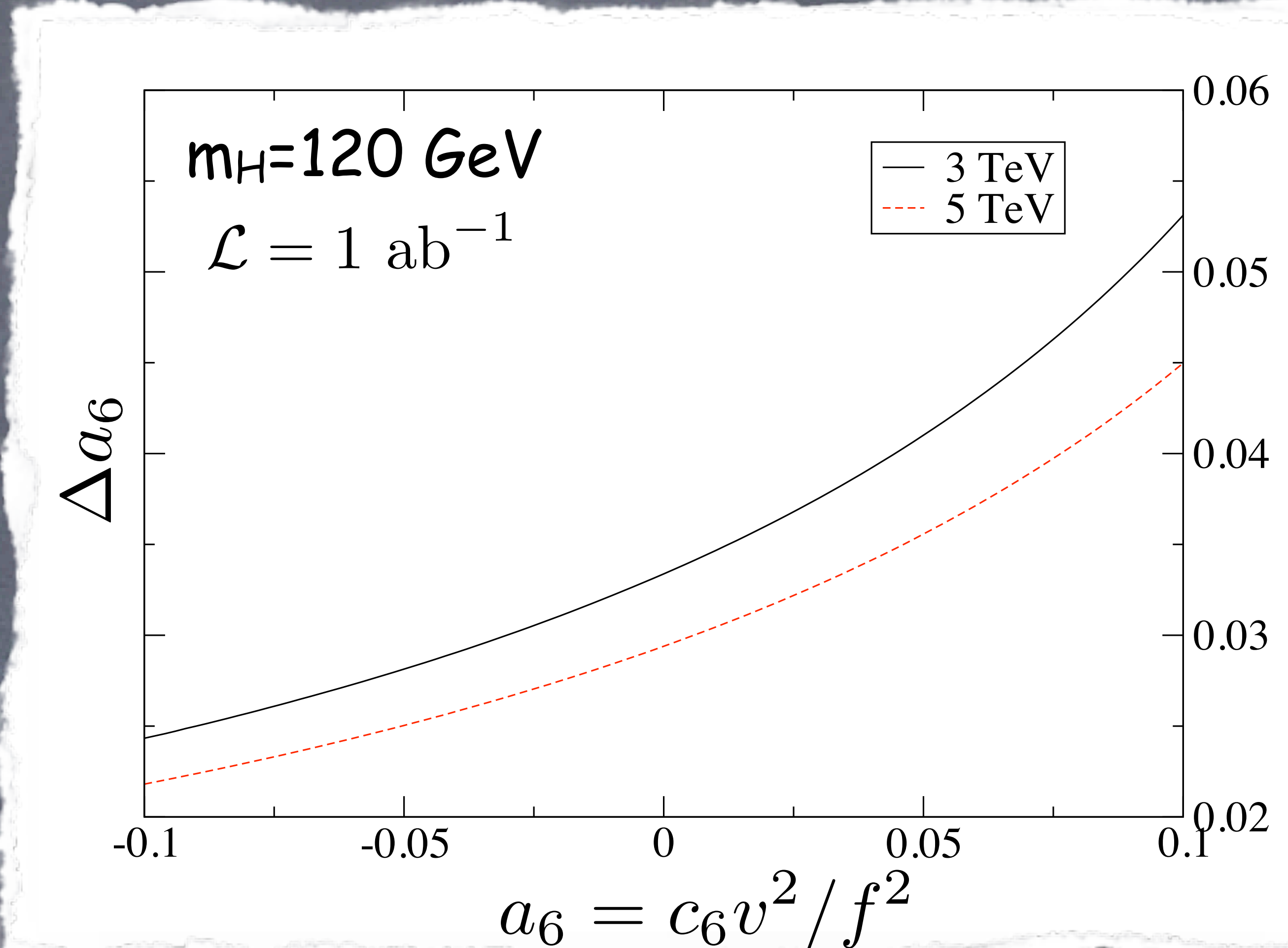
m_H=120 GeV

$$\Delta a_6 \sim 0.1 \quad \Rrightarrow \quad 4\pi f \sim 10\ \text{TeV}$$

Higgs anomalous couplings @ CLIC

Barger et al. hep-ph/0301097





$\Delta a_H \sim 0.002 \implies 4\pi f \sim 70$ TeV

$\Delta a_6 \sim 0.04 \implies 4\pi f \sim 15$ TeV

a factor 2 better than ILC

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

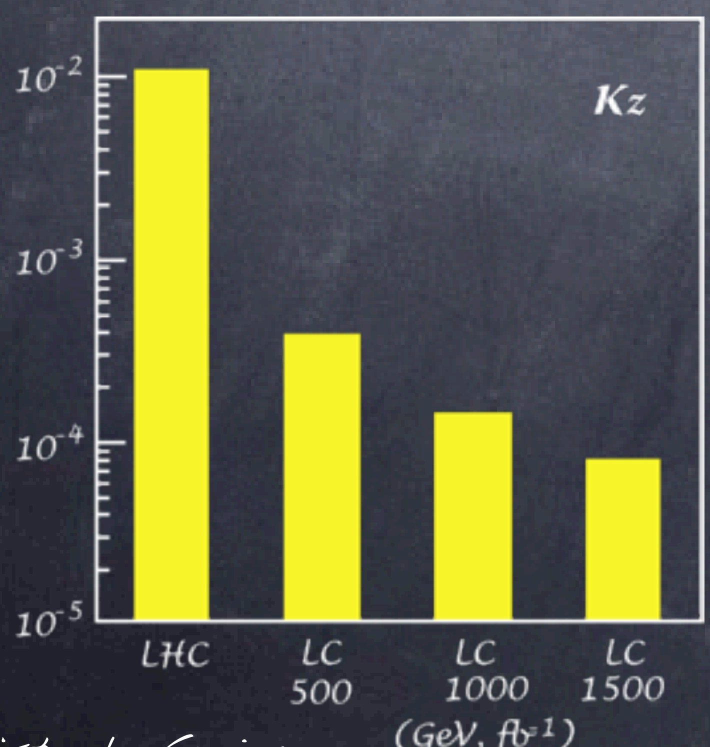
$$g_1^Z = \frac{m_Z^2}{m_\rho^2} c_W \qquad \kappa_\gamma = \frac{m_W^2}{m_\rho^2}\left(\frac{g_\rho}{4\pi}\right)^2 (c_{HW} + c_{HB}) \qquad \kappa_Z = g_1^Z - \tan^2\theta_W \kappa_\gamma$$

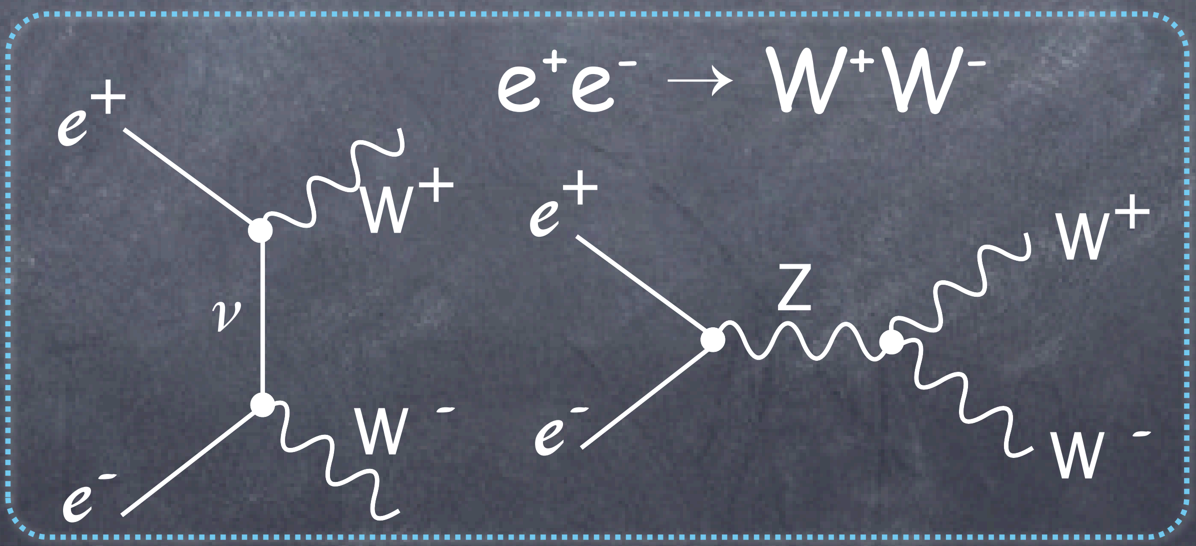
@ LHC 100fb^{-1} $\quad g_1^Z \sim 1\% \qquad \kappa_\gamma \sim \kappa_Z \sim 5\%$

sensitive to resonance up to m_ρ~800 GeV

not competitive with the measure of S at LEPII

@ ILC





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

T. Abe et al, Snowmass '01

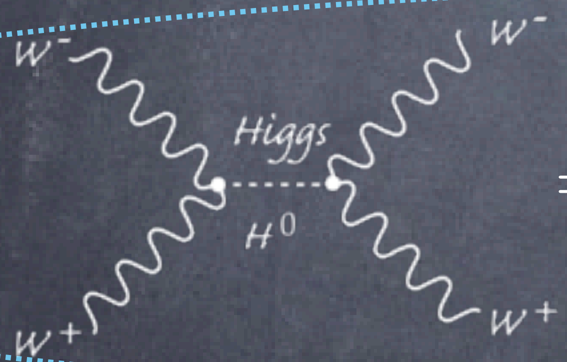
Strong WW scattering

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)

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

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

LET=SM-Higgs

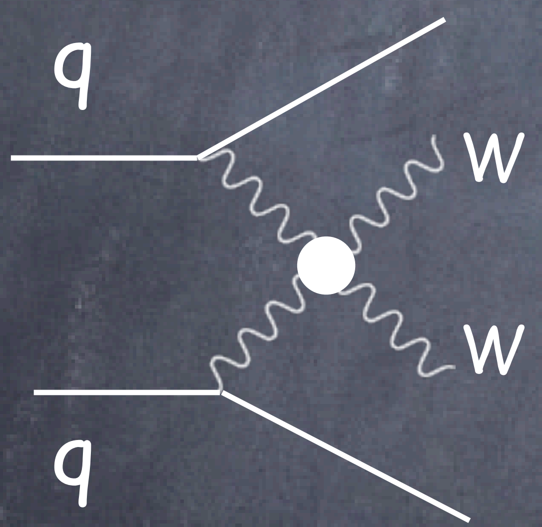
Strong WW scattering @ LHC

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

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

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

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



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

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

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

Bagger et al '95
Butterworth et al. '02

Scale of Strong WW scattering?

NDA estimates

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

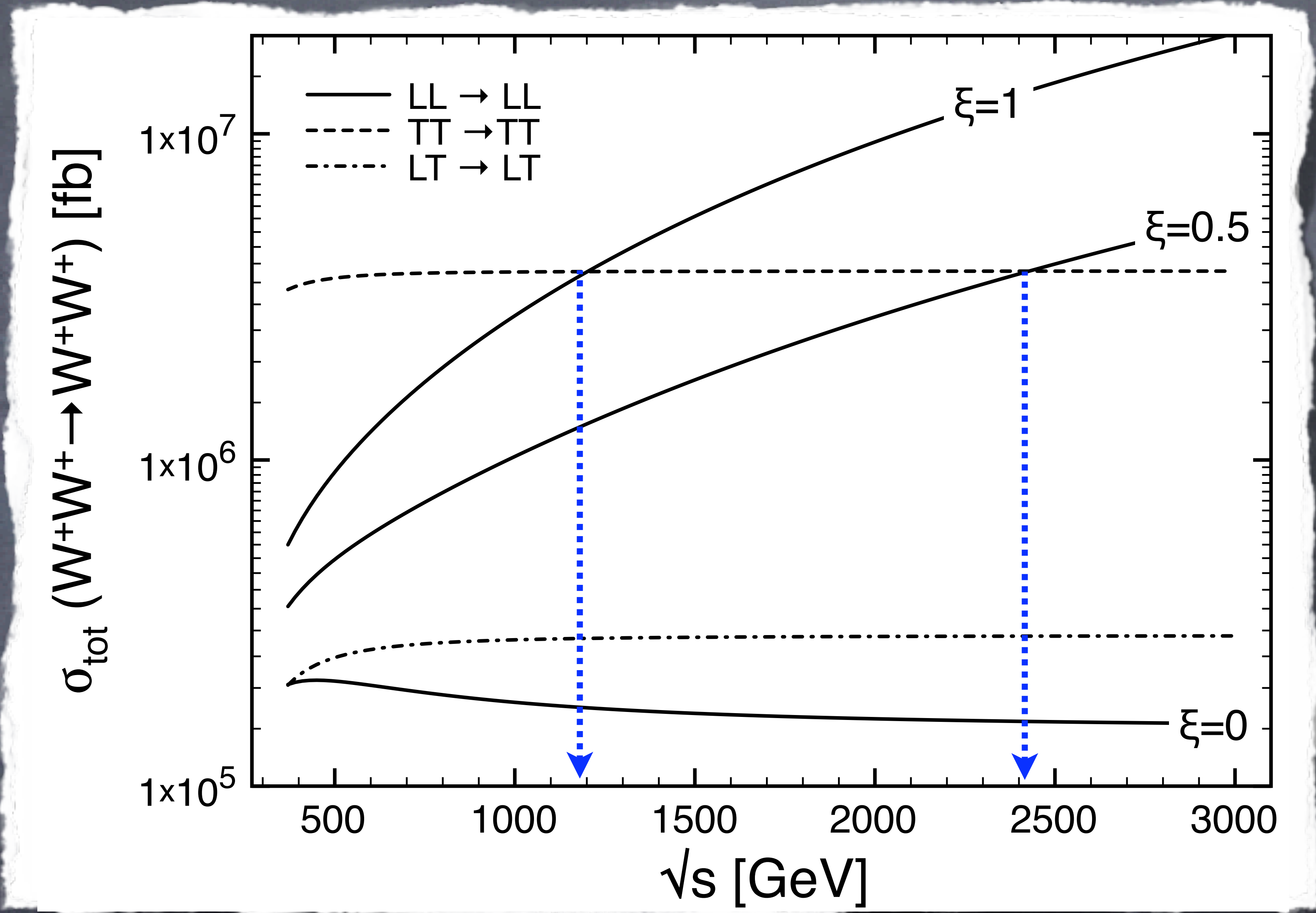
$$\mathcal{A}_{LL\to LL} \sim \mathcal{A}_{TT\to TT}$$

for

$$\sqrt{s} \sim 2\, M_W$$

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

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

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

M_γ = regulateur of Coulomb singularity=off-shellness of W $\sim M_W$

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

$$\frac{\sigma_{TT\to TT}}{\sigma_{LL\to LL}} \sim 20 \quad (\text{for } M_\gamma \sim M_Z)$$

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

Coulomb enhancement (Composite Higgs)

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

- Transverse channels are still dominated by the Coulomb singularities

$$\sigma_{TT\to TT} \sim \frac{2g^4}{\pi}\left(\frac{s_W^4}{M_\gamma^2}+\frac{c_W^4}{M_\gamma^2+M_Z^2}\right).$$

- Longitudinal channel: the contact interactions will win over the Coulomb singularities

$$\sigma_{LL\to LL} \sim \frac{\xi^2\, s}{16\pi v^4}$$

$$\frac{\sigma_{LL\to LL}}{\sigma_{TT\to TT}} \simeq \frac{\xi^2}{512}\left(\frac{s_W^4}{-t_{\min}}+\frac{c_W^4}{-t_{\min}+M_Z^2}\right)^{-1}\frac{s}{M_W^4}$$

$M_\gamma \sim M_W$: ~ 1 @ $\sqrt{s} \sim 13 M_W/\xi$

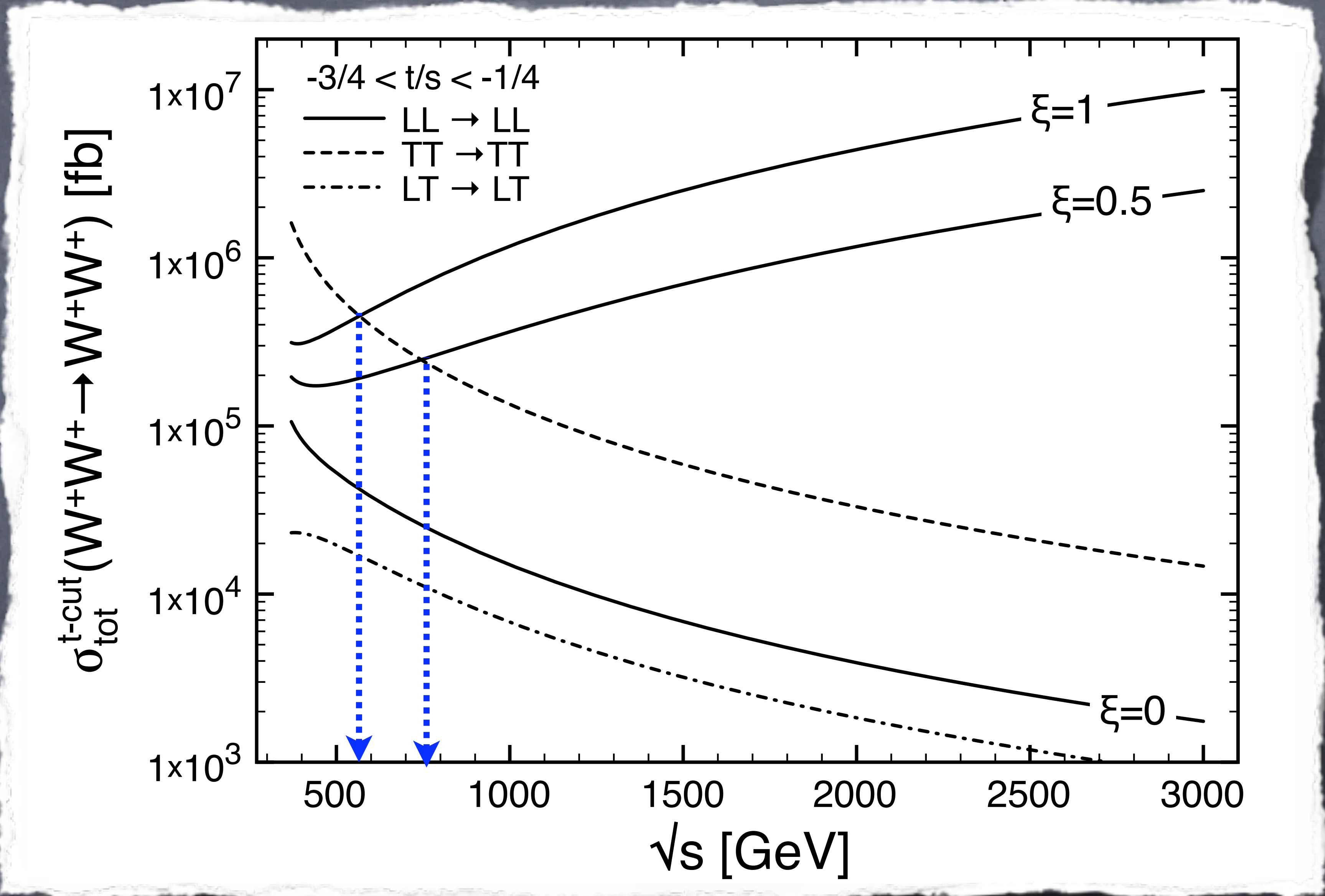
$M_\gamma \ll M_W$: ~ 1 @ $\sqrt{s} \sim 5 M_W^2/(M_\gamma \xi)$

onset of strong scattering is delayed to higher energies compared to NDA estimates

σ_{tot} is very sensitive to IR physics: not good observable to proble EWSB sector

Hard scattering (central region)

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



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

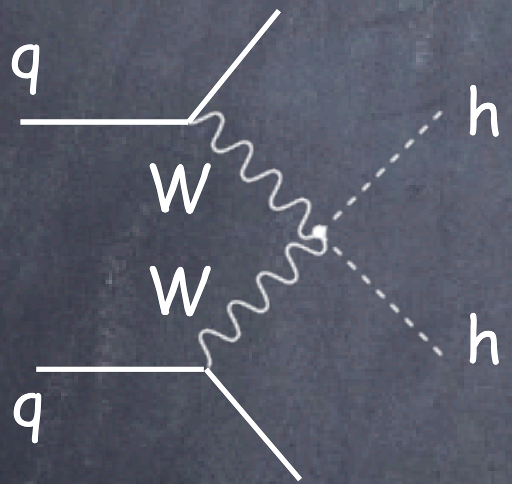
- hard cross-section = faster growth with energy
- onset of strong scattering still at high scale

Strong Higgs production

O(4) symmetry between W_L, Z_L and the physical Higgs

strong boson scattering ⇔ strong Higgs production

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

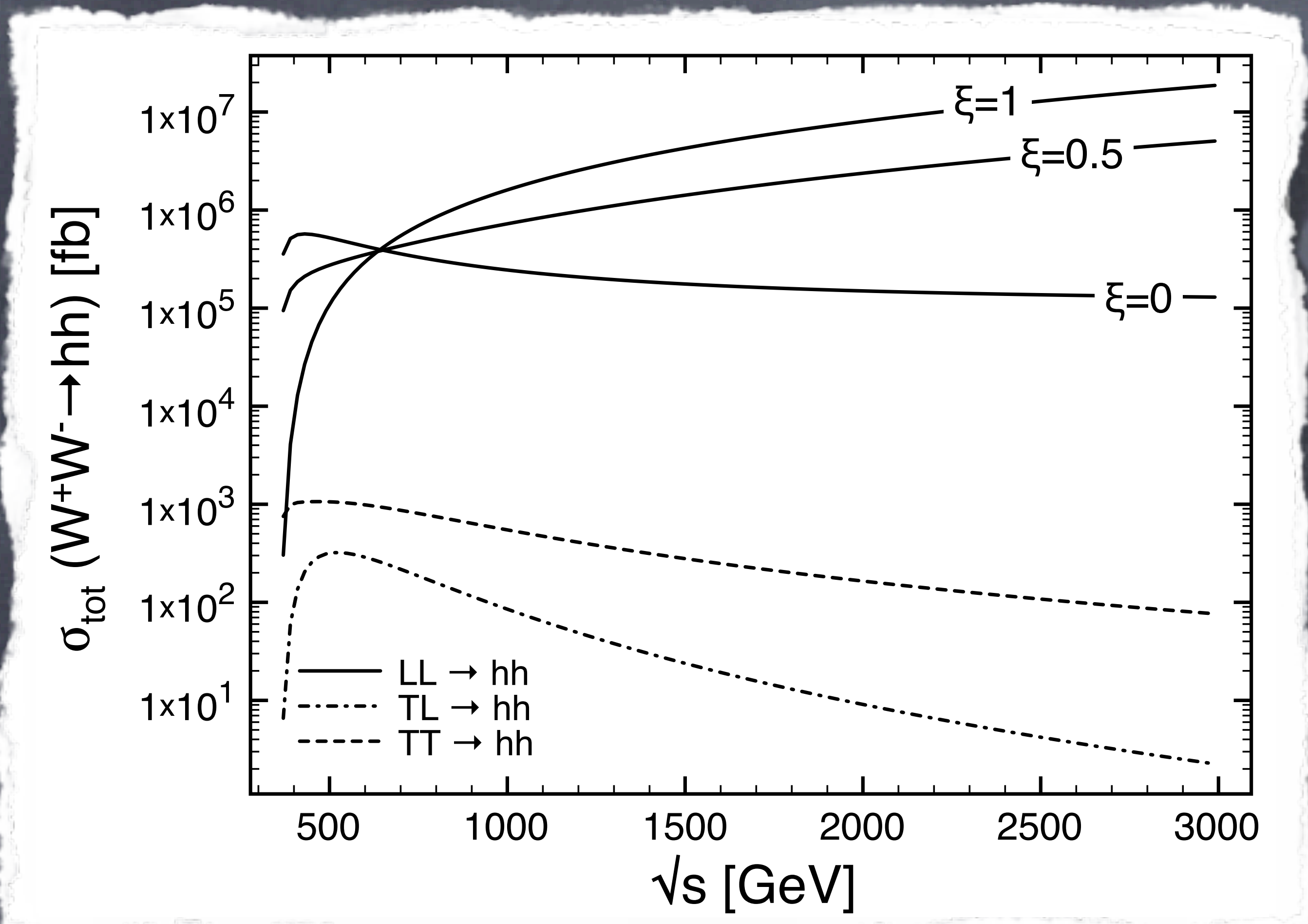


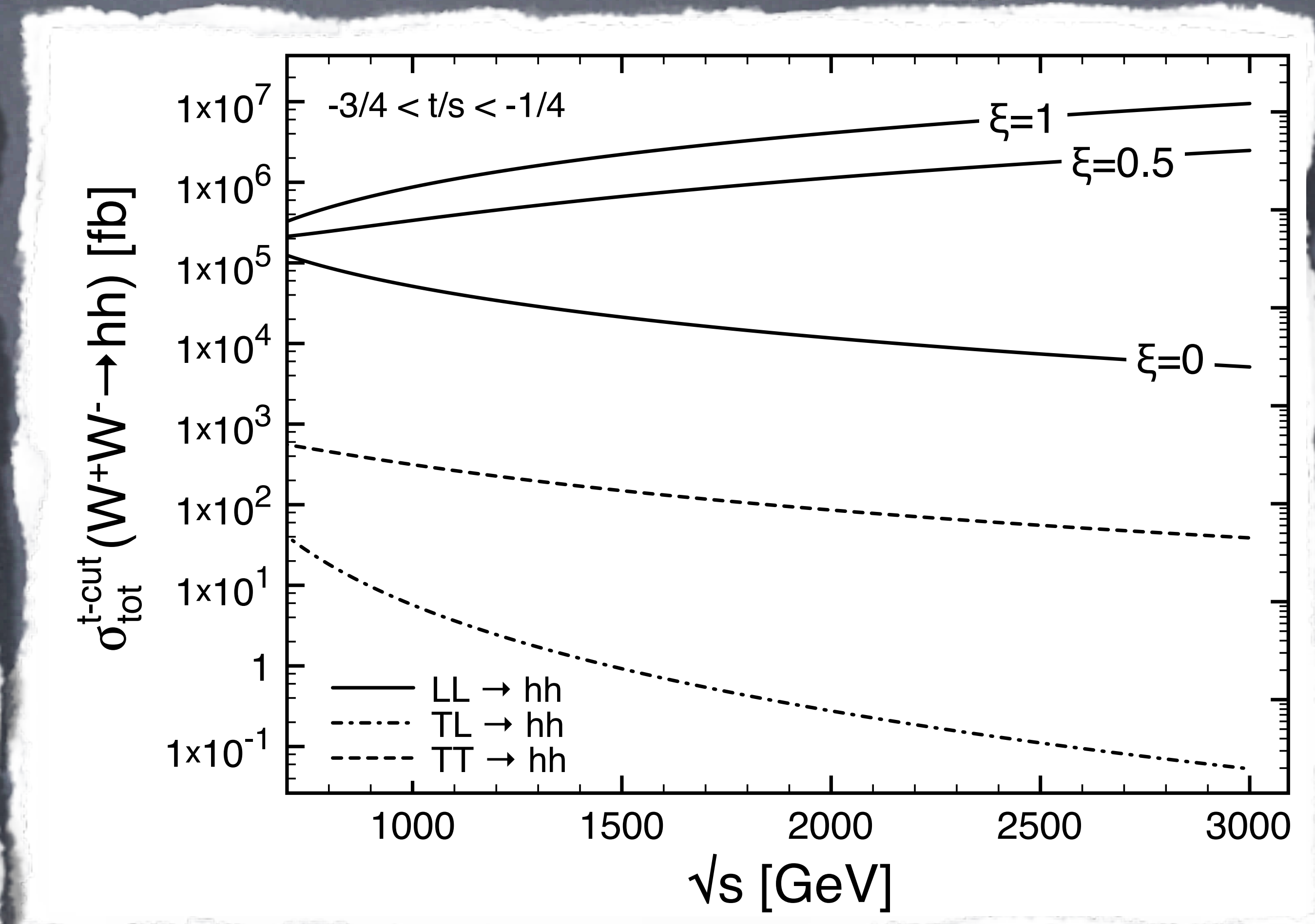
signal:

- hh → bbbb
- hh → 4W → $3l^{\pm}3\nu$ + jets

More complicated final states than for WW → WW,
smaller BRs,
but no T polarization pollution

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 'in progress

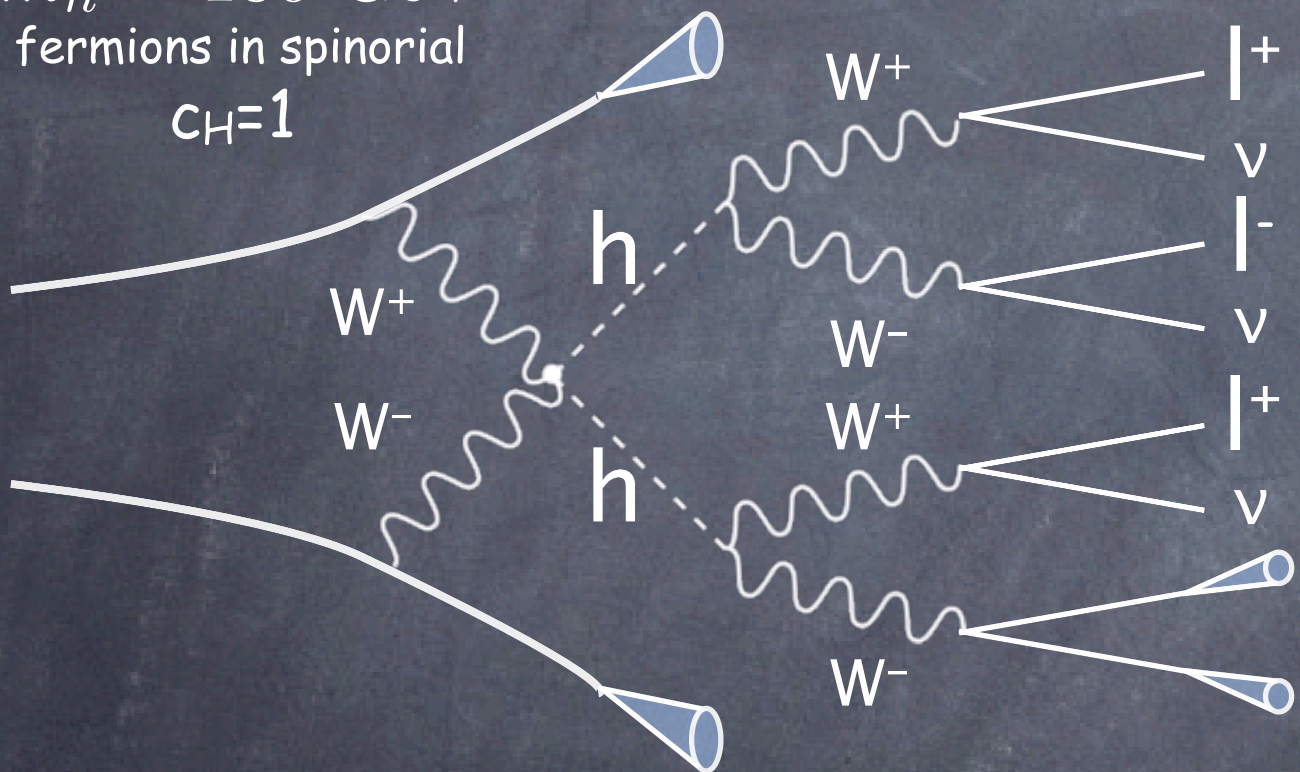
strong boson scattering ⇔ strong Higgs production

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

$m_h = 180$ GeV

fermions in spinorial

c_H=1



acceptance cuts

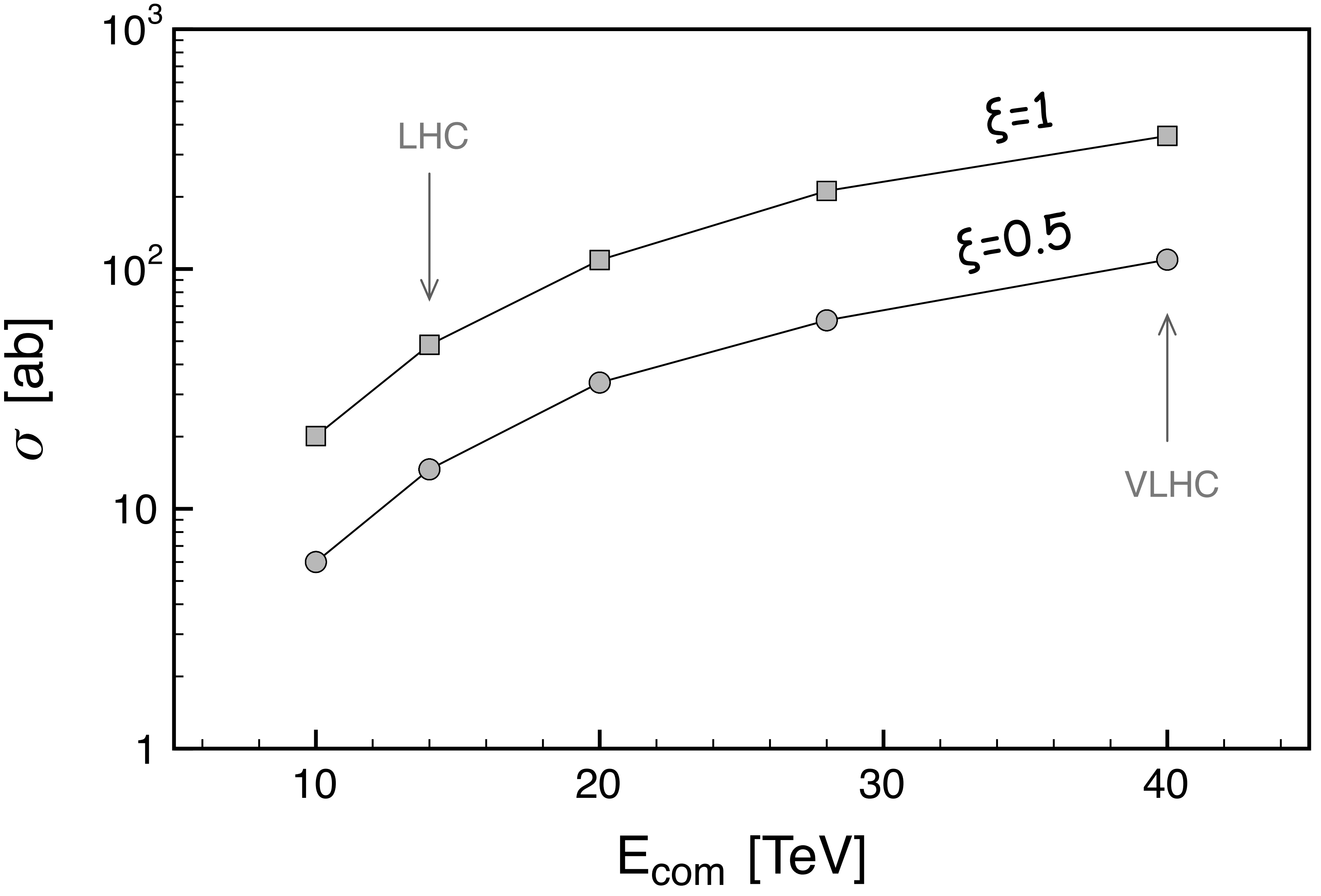
jets	leptons
$p_T \geq 30$ GeV	$p_T \geq 20$ GeV
$\delta R_{jj} > 0.7$	$\delta R_{lj(ll)} > 0.4(0.2)$
$\lvert\eta_j\rvert \leq 5$	$\lvert\eta_j\rvert \leq 2.4$

Dominant backgrounds: Wll4j, $t\bar{t}$W2j, $t\bar{t}$2W, 3W4j...

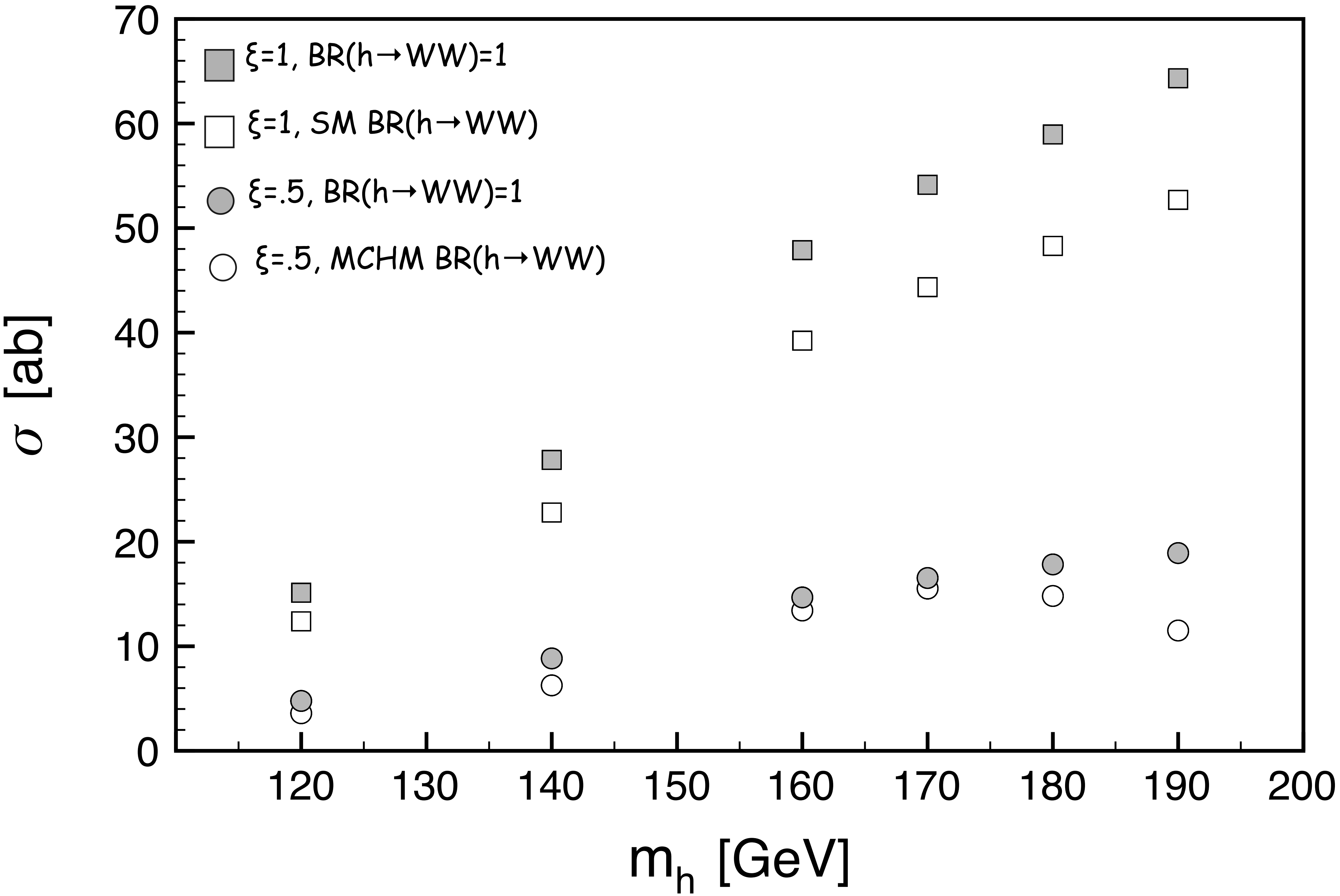
forward jet-tag, back-to-back lepton, central jet-veto

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



10^3
10^2
10
1
σ [ab]
LHC
VLHC
ξ=1
ξ=0.5
10
20
30
40
E_{com} [TeV]



ξ=1, BR(h→WW)=1
ξ=1, SM BR(h→WW)
ξ=.5, BR(h→WW)=1
ξ=.5, MCHM BR(h→WW)
σ [ab]
m_h [GeV]
0
10
20
30
40
50
60
70
120
130
140
150
160
170
180
190
200

Conclusions

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

EW interactions need a UV moderator/new physics
to unitarize WW scattering amplitude

Not just the search for the Higgs boson
(still another particle, even though the missing one?)

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EW interactions need Goldstone bosons to provide mass to W, Z
EW interactions need a UV moderator/new physics
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Not just the search for the Higgs boson
(still another particle, even though the missing one?)

	LHC	ILC	CLIC
1/ is there a Higgs?	✓	✓	✓
2/ what are the Higgs mass/couplings	✓/-	✓	✓
3/ is the Higgs a SM like weak doublet?	☁	✓	✓
4/ is the Higgs elementary or composite?	☁	✓	✓✓
5/ is EWSB natural or fine-tuned?	?	✓	✓✓
6/ are there new dimensions? new strong forces?	-	✓	✓

"theorists are getting cold feet" J. Ellis

"they have done their best to predict the possible and impossible"

G. Giudice

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I guess, during these lectures, I gave you a flavour of what the impossible could be!

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LHC is prepared to discover the "Higgs"

collaboration EXP-TH is important to make sure
e.g. that no unexpected physics is missed (triggers, cuts...)
and in this regards, approaches like "unparticle" or "hidden valleys" might be useful.

Thank you for your attention