# Composite Higgs Physics

*work in progress with*

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*also related to*

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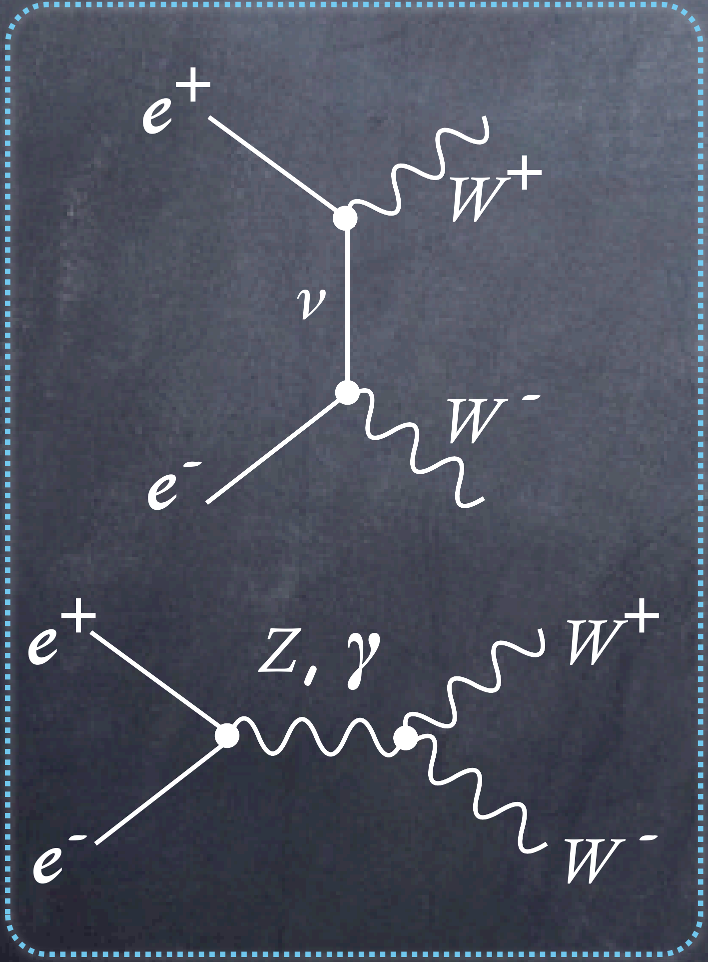
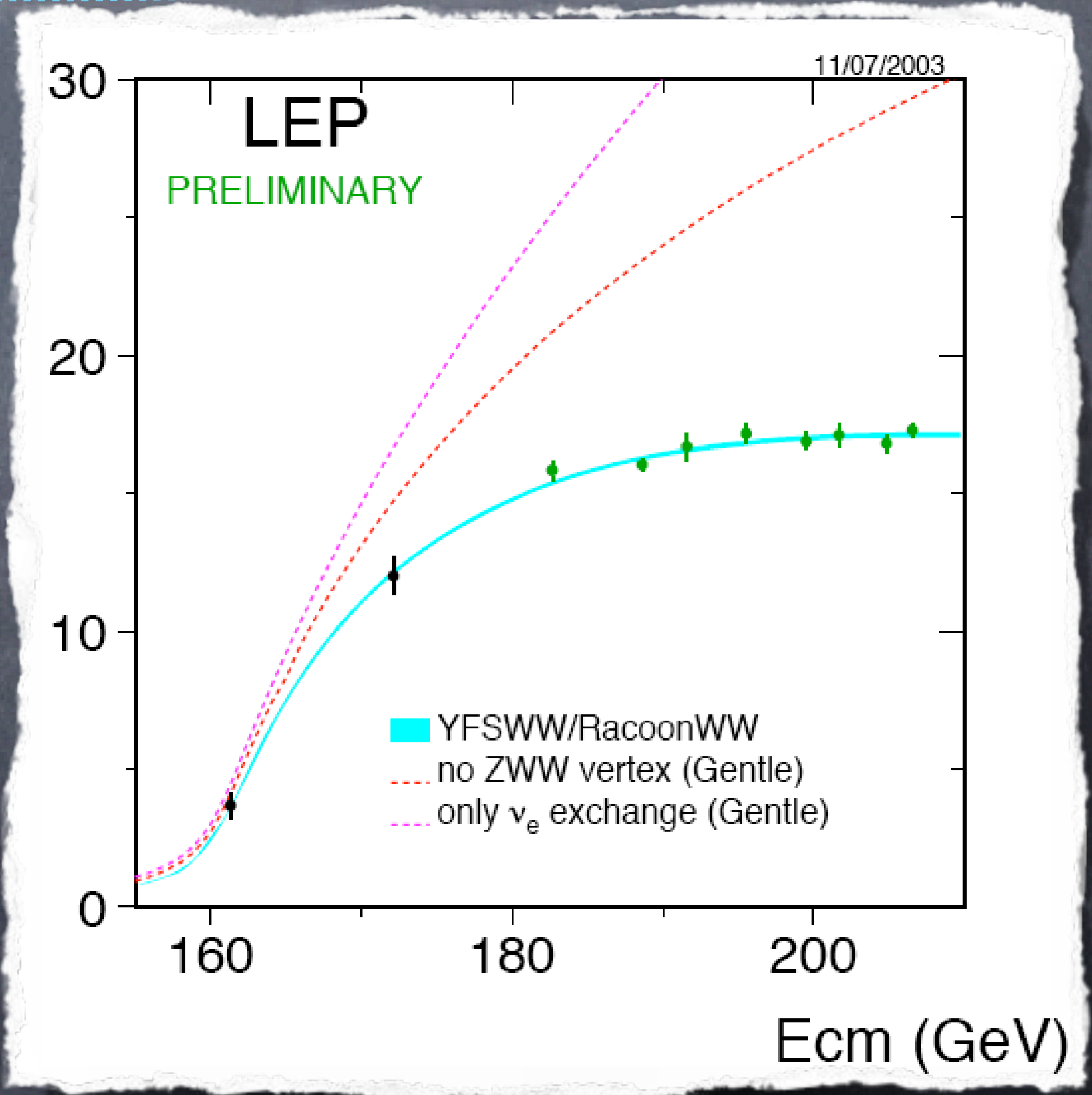
# The Standard Model

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$

$e^+e^- \rightarrow W^+W^-$





# The Standard Model and the Mass Problem

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$

the masses of the quarks, leptons and gauge bosons don't obey the full gauge invariance

- $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ is a doublet of $SU(2)_L$ but $m_{\nu_e} \ll m_e$
- a mass term for the gauge field isn't invariant under gauge transformation $\delta A^a_\mu = \partial_\mu \epsilon^a + g f^{abc} A^b_\mu \epsilon^c$

⇒ spontaneous breaking of gauge symmetry ⇐

# The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

massive W, Z: 3 physical polarizations=eaten Goldstone bosons

⇛ Where are these Goldstone's coming from? ⇚

common lore: from a scalar Higgs doublet

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

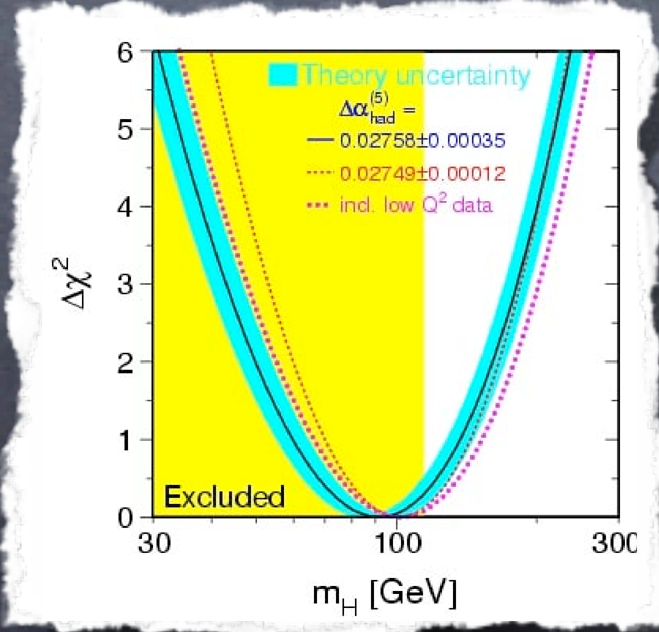
Higgs doublet = 4 real scalar fields

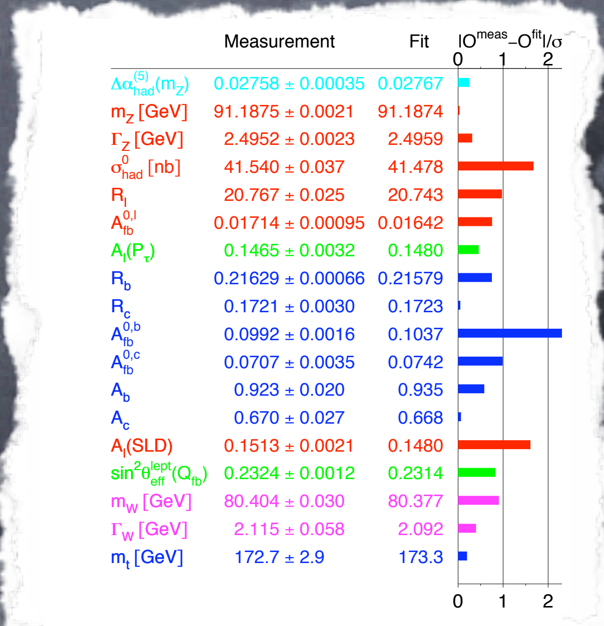
3 eaten
Goldstone bosons

One physical degree of freedom
the Higgs boson

Good
agreement
with EW data

(doublet ⇔ $\rho$=1)



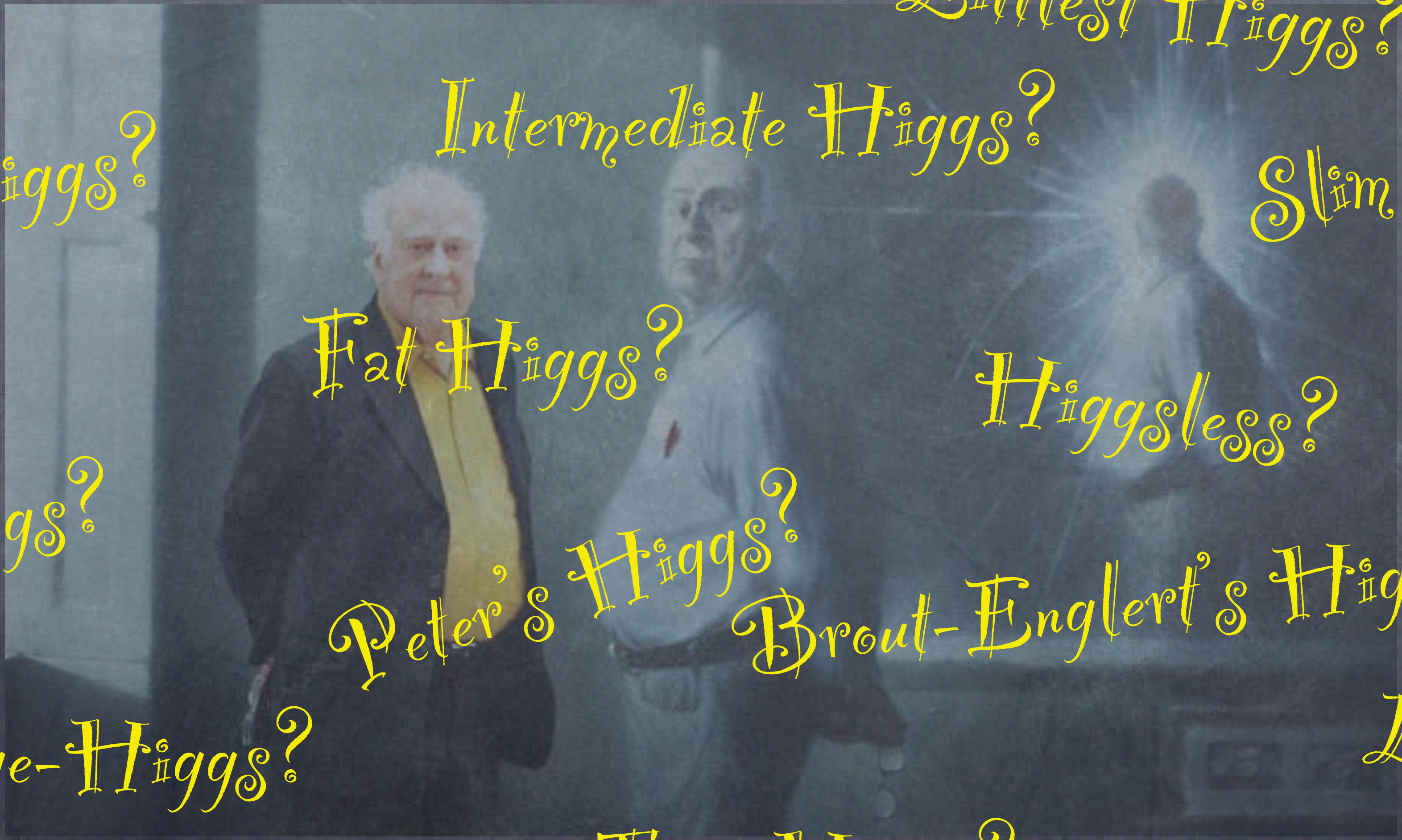


| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha^{(5)}_{had}(m_Z)$ | 0.02758 ± 0.00035 | 0.02767 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 |
| $\sigma^0_{had}$ [nb] | 41.540 ± 0.037 | 41.478 |
| $R_l$ | 20.767 ± 0.025 | 20.743 |
| $A^{0,l}_{fb}$ | 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 |
| $A^{0,b}_{fb}$ | 0.0992 ± 0.0016 | 0.1037 |
| $A^{0,c}_{fb}$ | 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 |
| $\sin^2\theta^{lept}_{eff}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 |
| $m_W$ [GeV] | 80.404 ± 0.030 | 80.377 |
| $\Gamma_W$ [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?

Intermediate Higgs?

Composite Higgs?

Slim Higgs?

Fat Higgs?

Higgsless?

Portal Higgs?

Peter's Higgs?

Brout-Englert's Higgs?

Gauge-Higgs?

Lone Higgs?

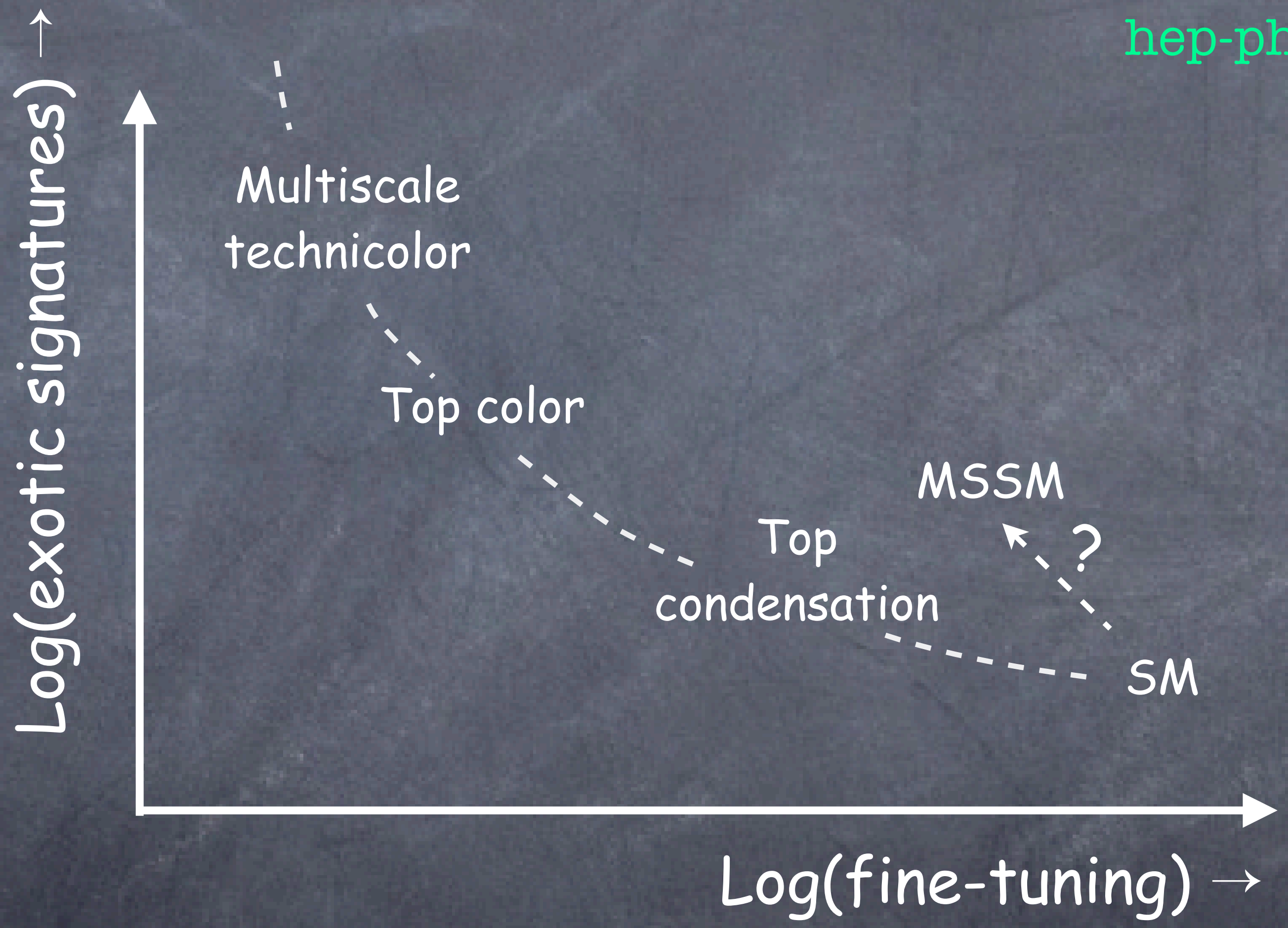
Twin Higgs?

Simplest Higgs?

Phantom Higgs?

# EWSB from a Strongly Coupled Sector

A strong sector, around few TeV, driving EW symmetry breaking is a plausible/conservative scenario



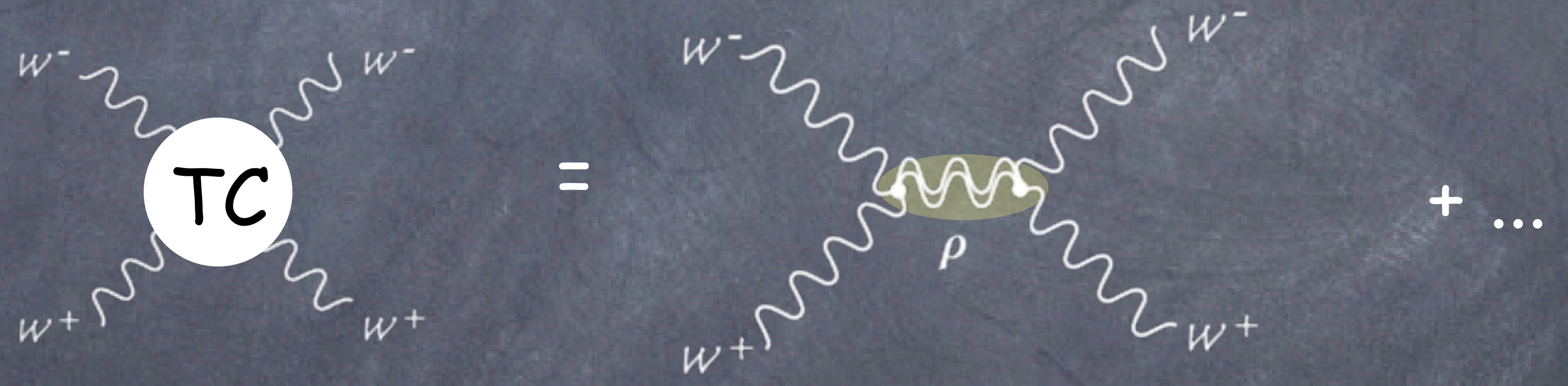
Snowmass '96 - EWSB working group
hep-ph/9704217

# EWSB from a Strongly Coupled Sector

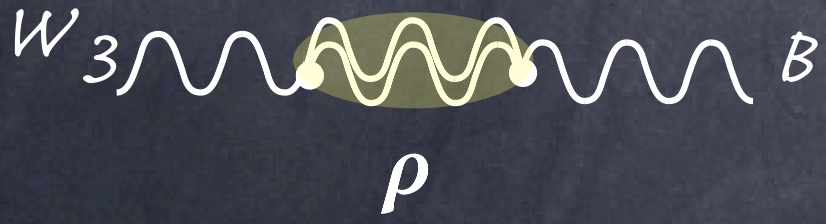
A strong sector, around few TeV, driving EW symmetry breaking is a plausible/conservative scenario

a technical challenge: how to evade EW precision data

The resonance that unitarizes the WW scattering amplitudes



generates a tree-level effect on the SM gauge bosons self-energy

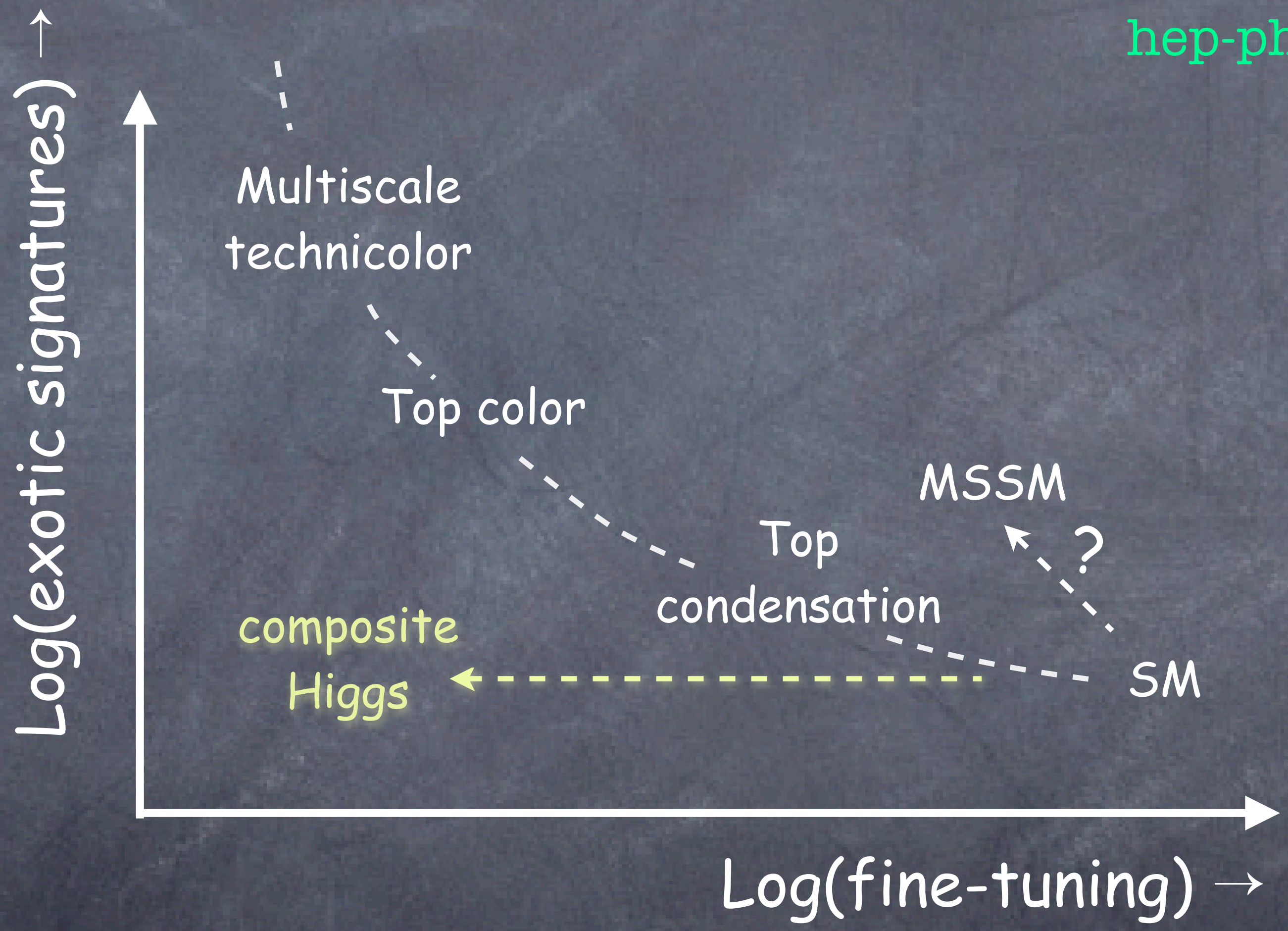


$$\hat{S} \sim \frac{m_W^2}{m_\rho^2} \quad \xrightarrow[\text{@ 95\% CL}]{|\hat{S}| < 10^{-3}} \quad m_\rho > 2.5\ \text{TeV}$$

One way out: a light composite Higgs emerging from the strong sector

# EWSB from a Strongly Coupled Sector

A strong sector, around few TeV, driving EW symmetry breaking is a plausible/conservative scenario



Snowmass '96 - EWSB working group
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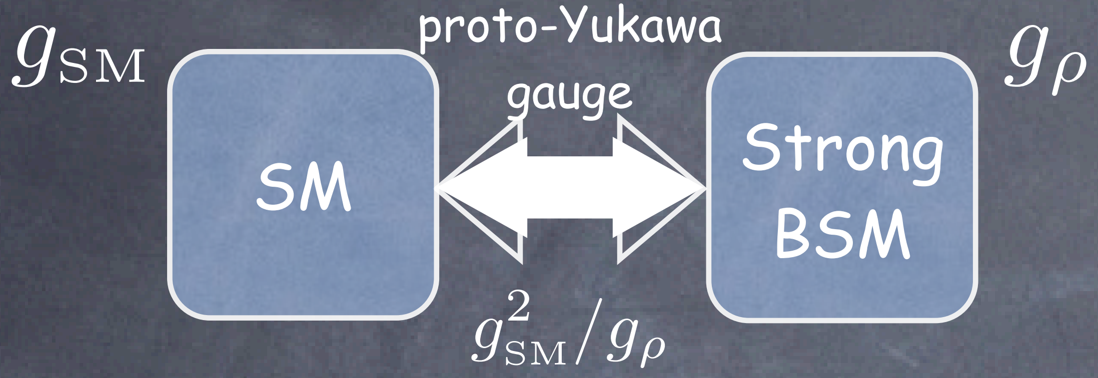
One way out: a light composite Higgs emerging from the strong sector

# How to obtain a light composite Higgs?

## Higgs=Pseudo-Goldstone boson of the strong sector



$g_{\rm SM}$

SM

proto-Yukawa

gauge

$g_{\rm SM}^2/g_\rho$

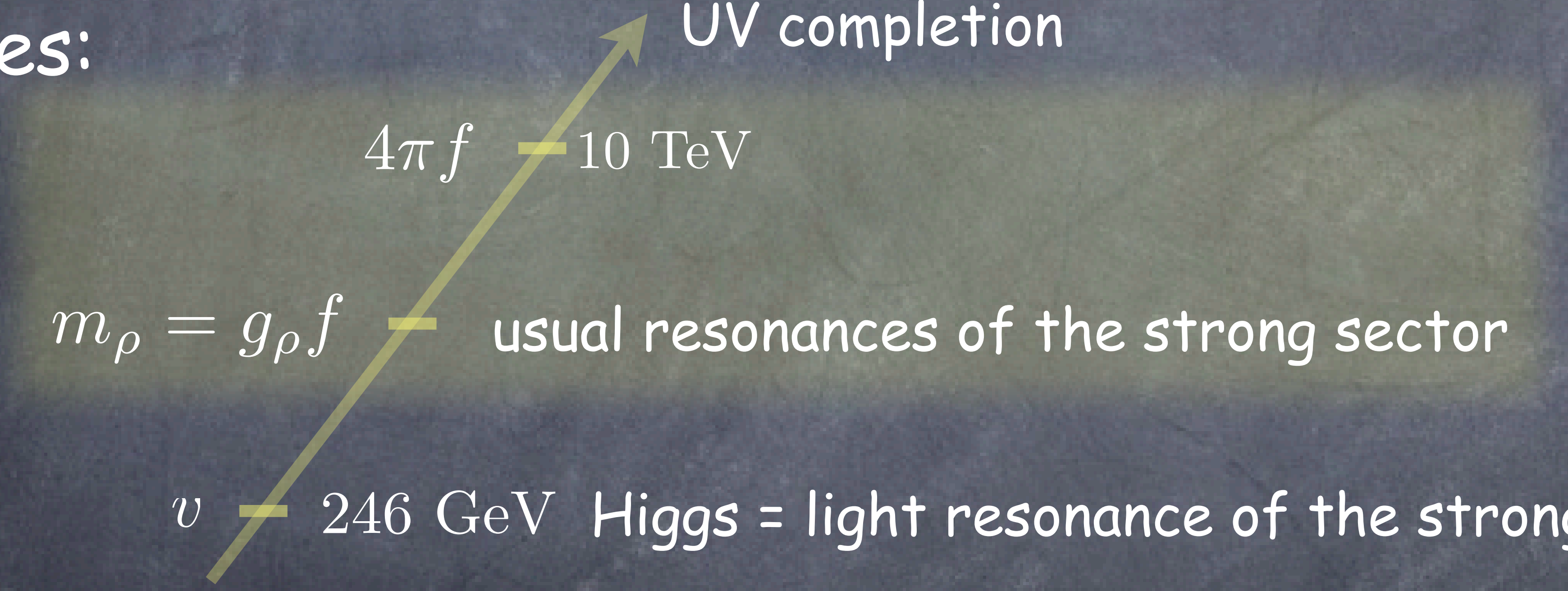
Strong BSM

$g_\rho$

$m_{\rm Higgs}$=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

} direct access to strong sector

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

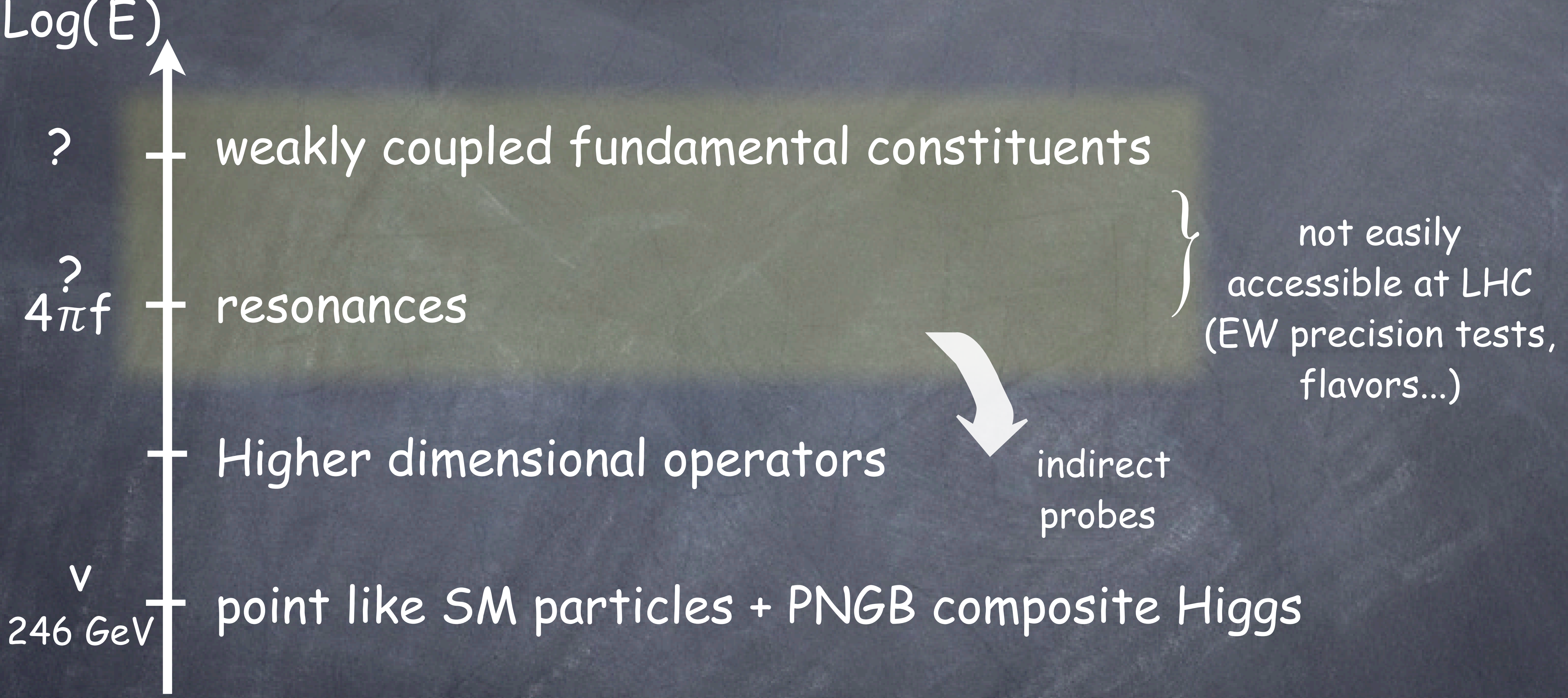
indirect probes

strong sector broadly characterized by 2 parameters

$m_\rho$ = mass of the resonances

$g_\rho$ = coupling of the strong sector or decay cst of strong sector $f = \dfrac{m_\rho}{g_\rho}$

# Physics of a light composite Higgs?



Log(E)

? weakly coupled fundamental constituents

$\overset{?}{4\pi f}$ resonances

not easily accessible at LHC (EW precision tests, flavors...)

Higher dimensional operators

indirect probes

$\overset{v}{246\ \text{GeV}}$ point like SM particles + PNGB composite Higgs

Higgs=resonance emerging from strong sector but it is light because it is a 4th Goldstone

# Continuous interpolation between SM and TC

$$\xi = \frac{v}{f} = \frac{\text{weak scale}}{\text{strong coupling scale}}$$

$$\xi = 0$$

**SM limit**

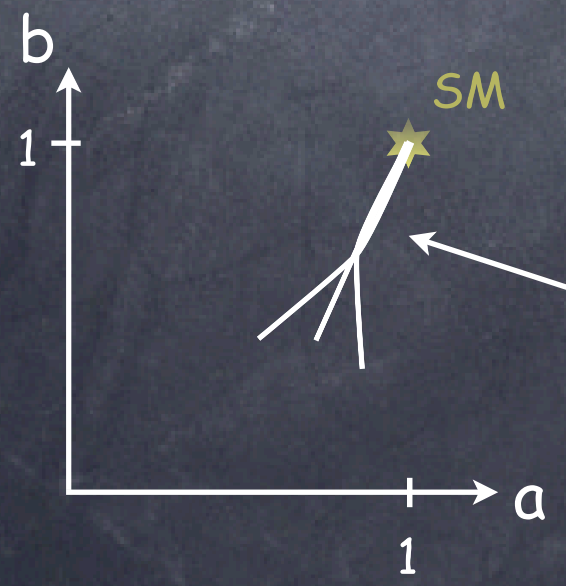
all resonances of strong sector, except the Higgs, decouple

$$\xi = 1$$

**Technicolor limit**

Higgs decouple from SM; vector resonances like in TC

Composite
vs.
SM Higgs



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

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 $m_\rho$
- **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

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

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

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

# SILH Effective Lagrangian

(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi '07

- extra Higgs leg: $H/f$
- extra derivative: $\partial/m_\rho$

## 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$_\rho$)

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

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

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.

# Anomalous Higgs Couplings

Giudice, Grojean, Pomarol, Rattazzi ‘07

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

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

Modified
Higgs propagator

~

Higgs couplings
rescaled by

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

# 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

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

There are also some 1-loop IR effects

Barbieri, Bellazzini, Rychkov, Varagnolo '07

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

modified Higgs couplings to matter

$$\Downarrow$$

$$\hat{S}, \hat{T} = a \left( (1 - c_H v^2/f^2) \log m_h + c_H v^2/f^2\ \log \Lambda \right) + b$$

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

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

# Flavor Constraints

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

mass terms

Higgs fermion interactions

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

$\Rrightarrow$ FCNC

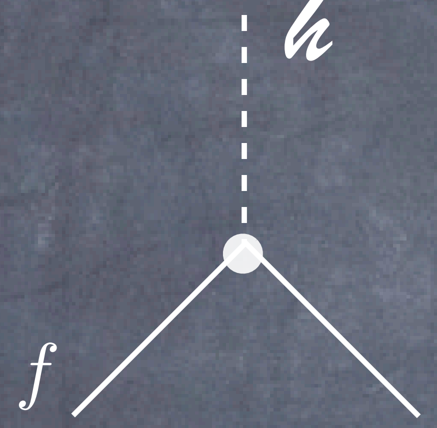
SILH: $c_y$ is flavor universal

$\Rrightarrow$ Minimal flavor violation built in

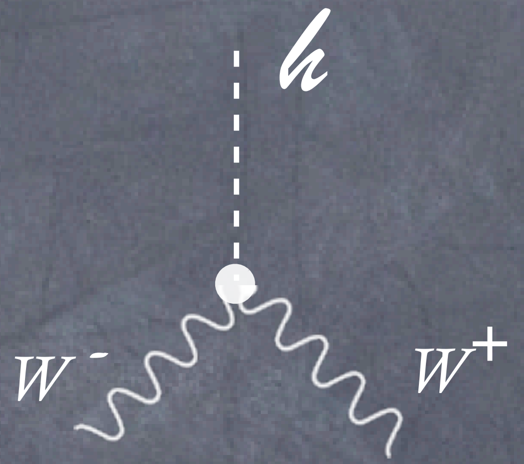
# Higgs anomalous couplings

## Lagrangian in unitary gauge

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



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



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

⇘ ⇙

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

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

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

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

Fermions embedded in spinorial of SO(5)

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

$$\Downarrow$$

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

universal shift of the couplings
no modifications of BRs

Fermions embedded in 5+10 of SO(5)

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

$$\Downarrow$$

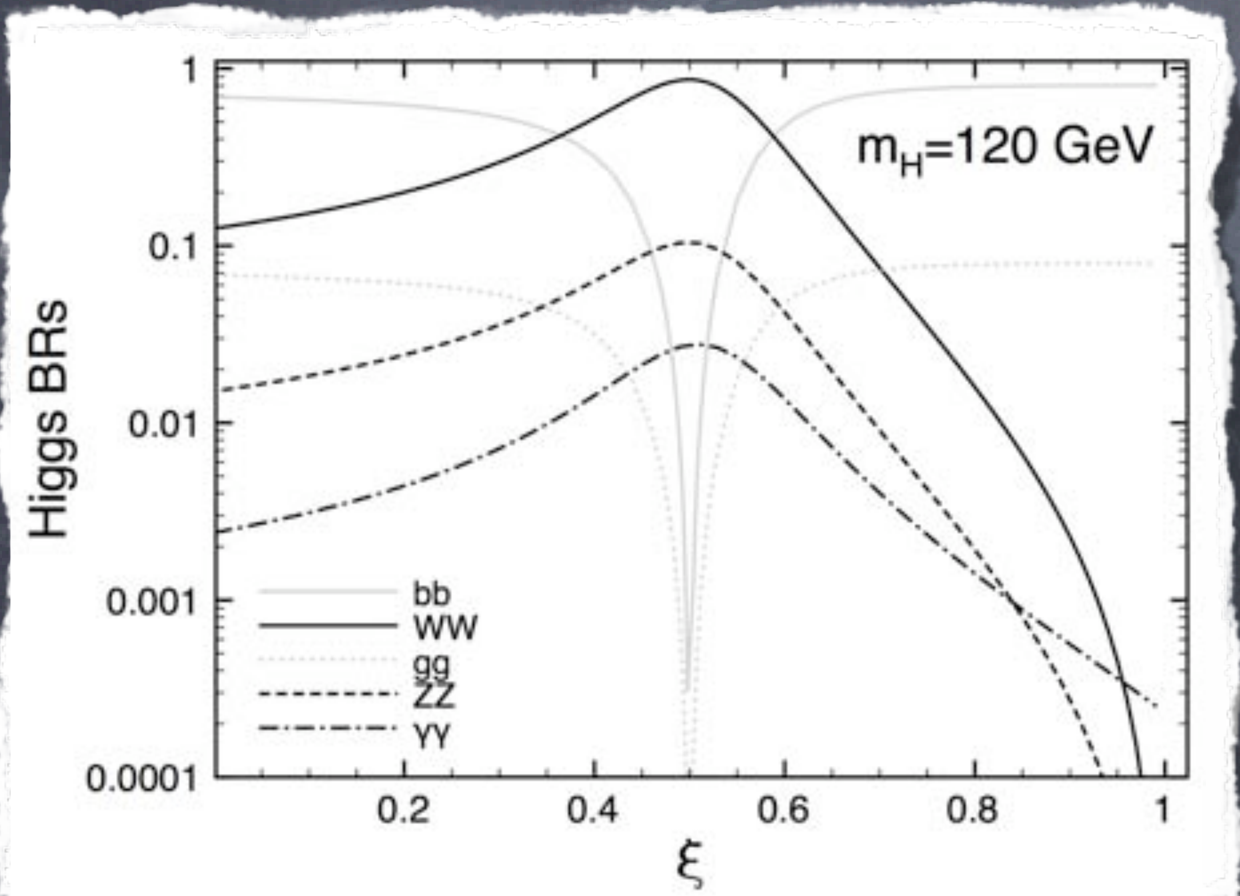
$$g_{hff} = \frac{1-2\xi}{\sqrt{1-\xi}}\, g_{hff}^{\mathrm{SM}}$$

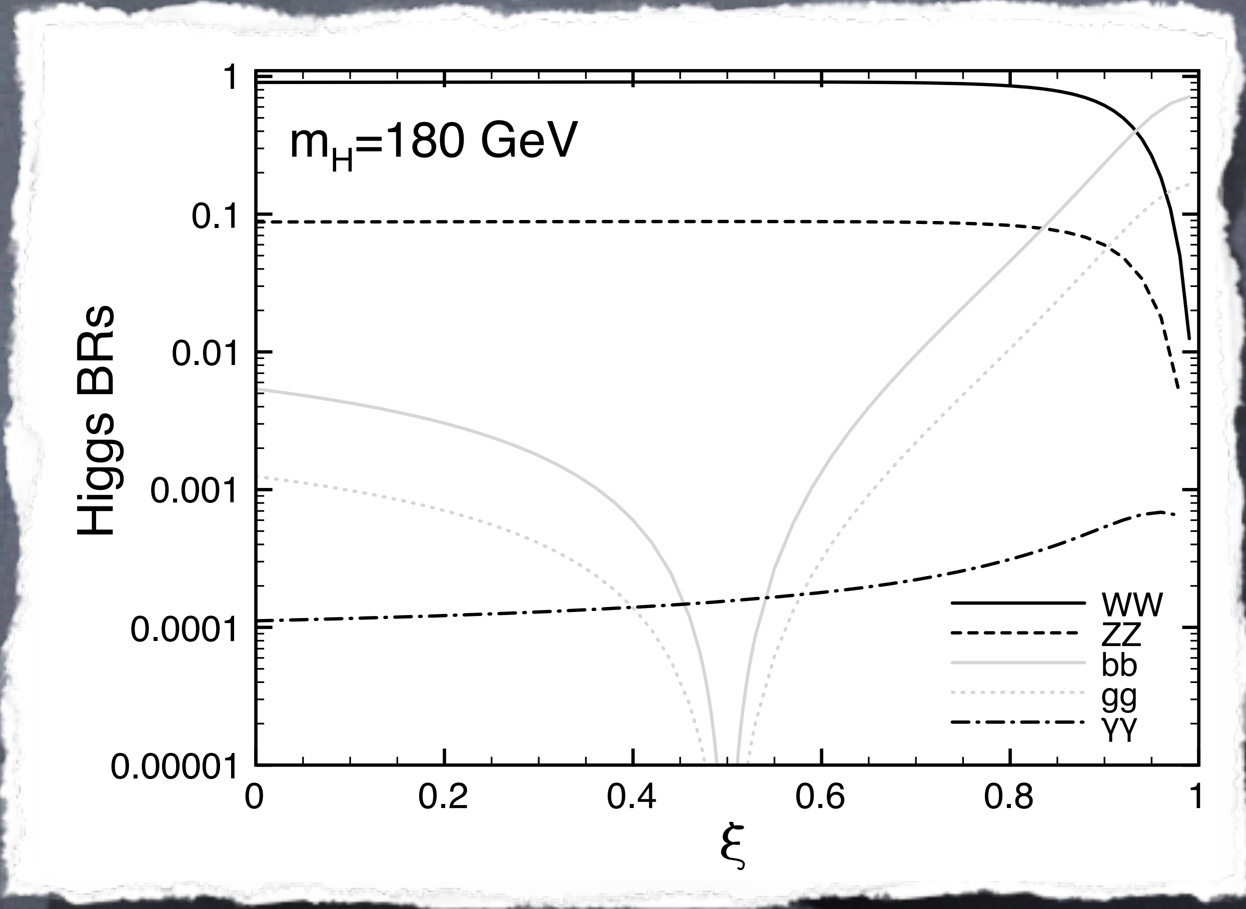
BRs now depends on v/f

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

# Higgs BRs

Fermions embedded in 5+10 of SO(5)



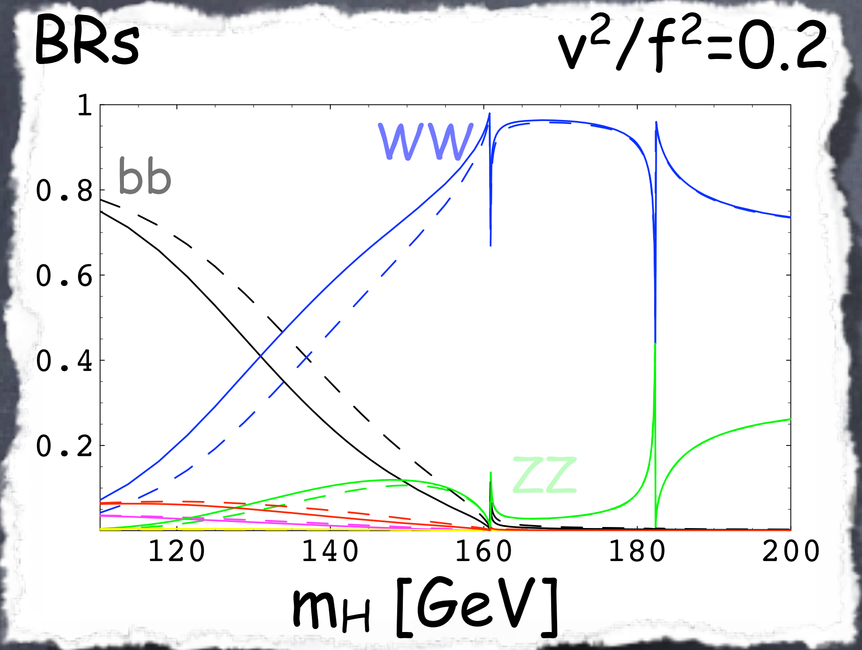


h→WW can dominate
even for low Higgs mass

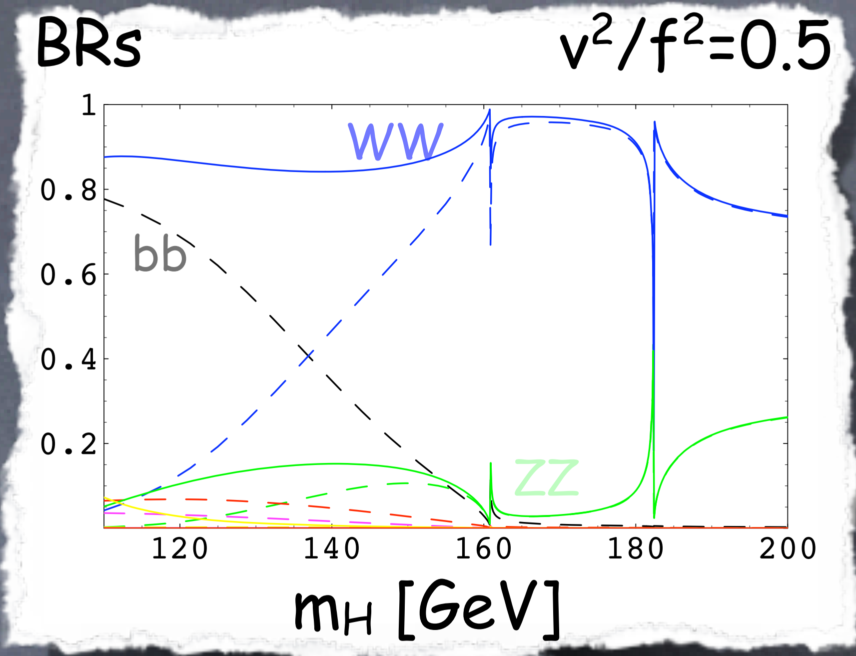
BRs remain SM like except
for very large values of v/f

# Higgs BRs and total width

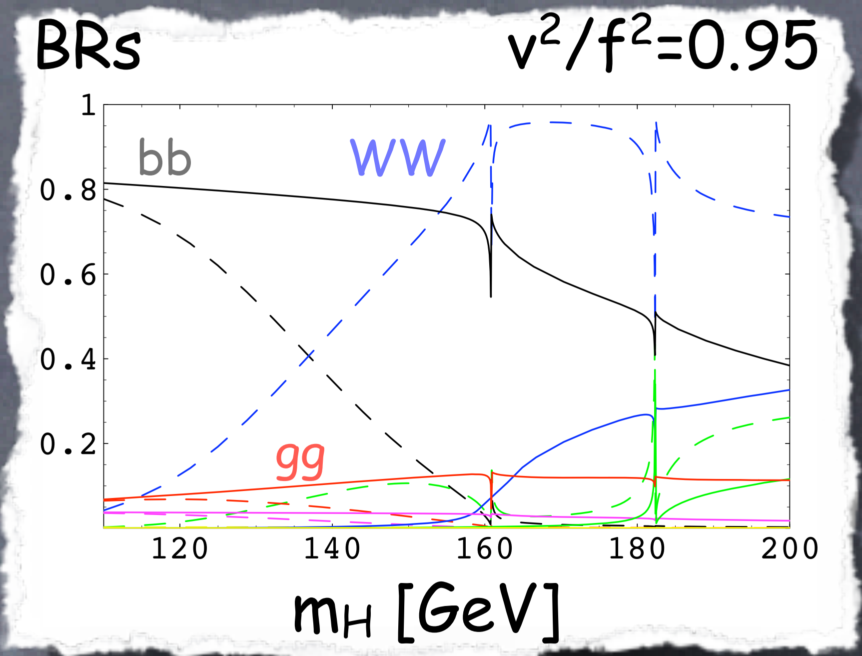
## Fermions embedded in 5+10 of SO(5)



slight modifications

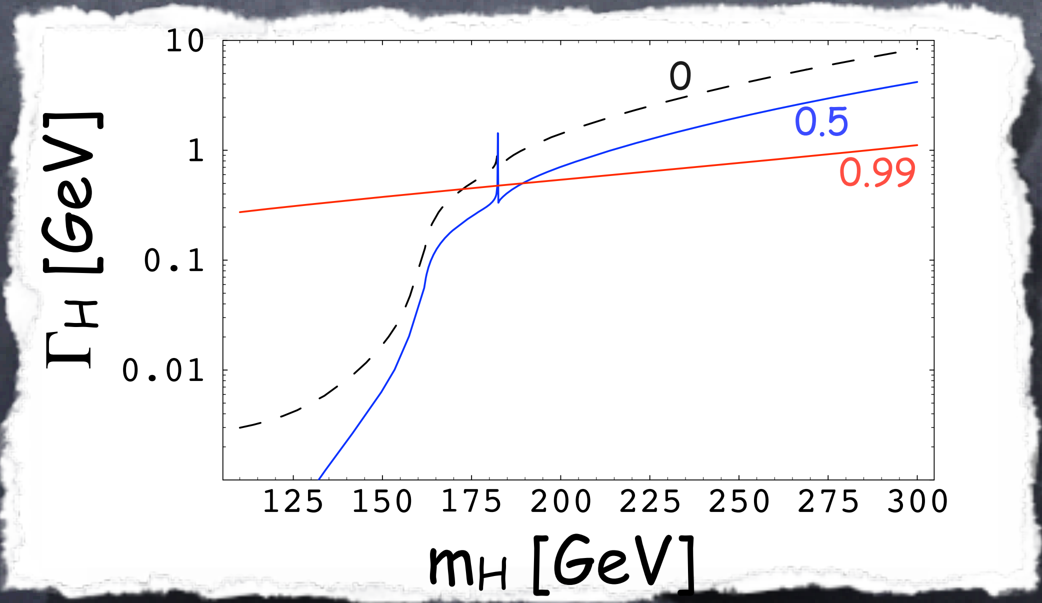


suppress bb



suppress WW

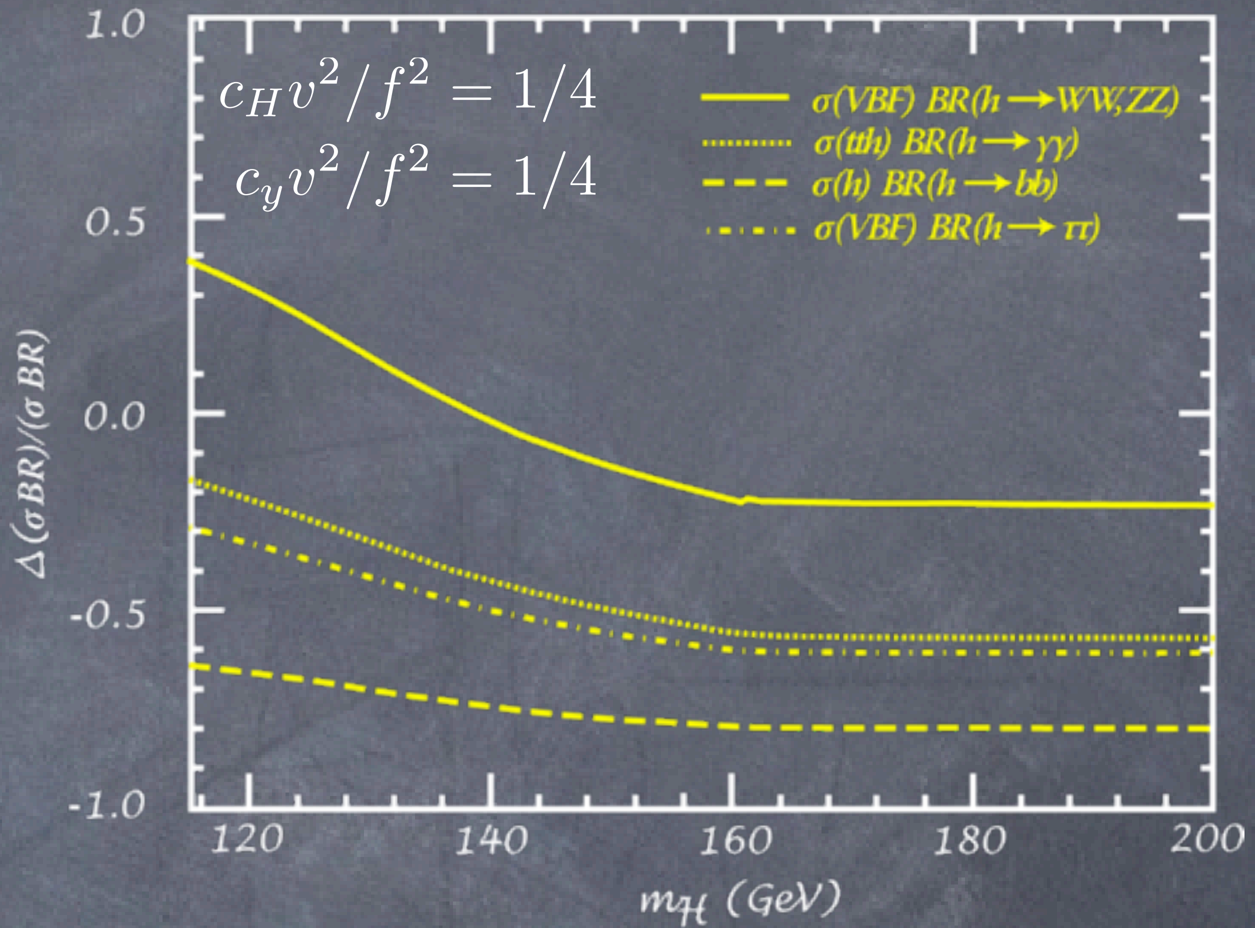
## Higgs total width



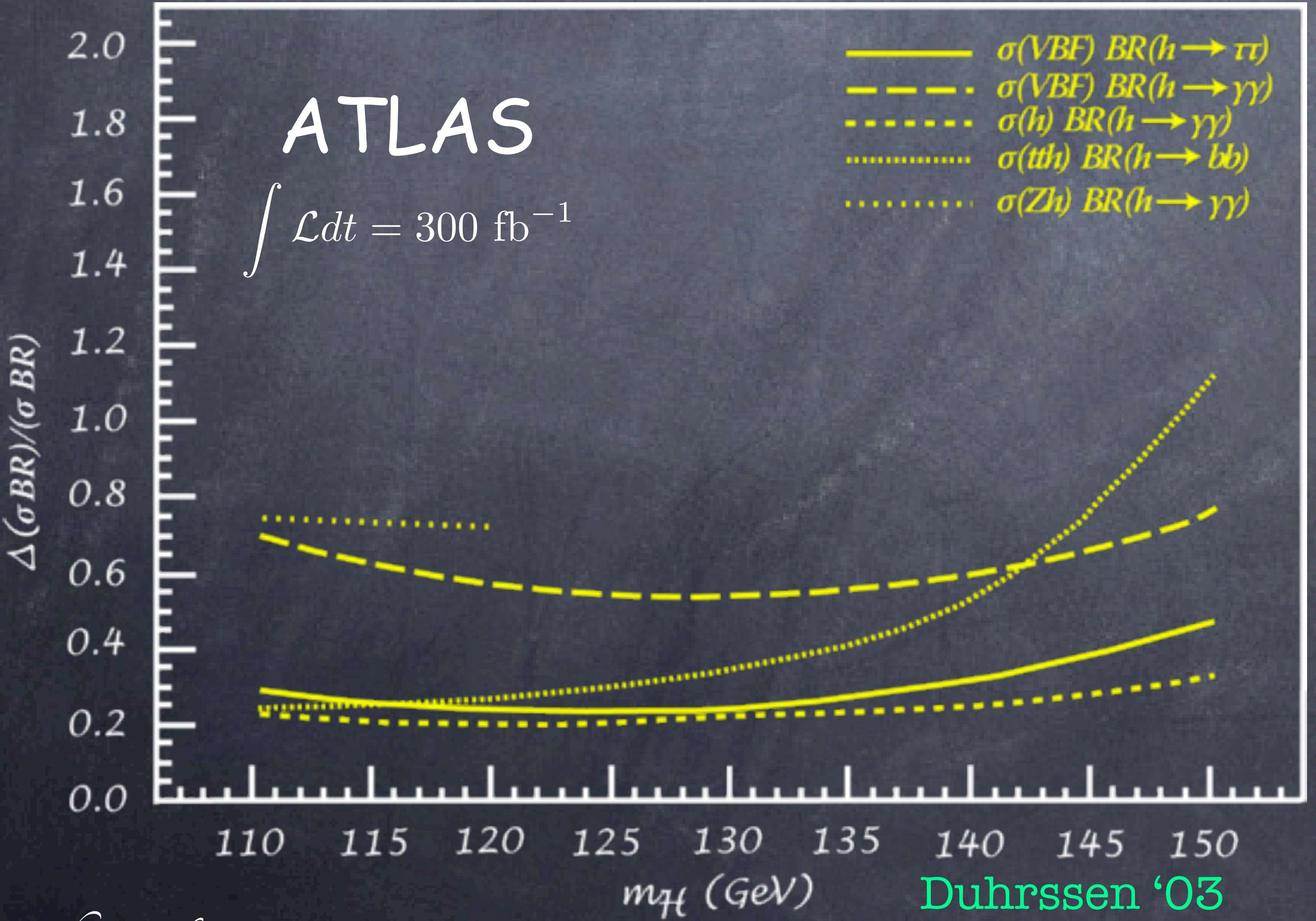
# Higgs anomalous couplings @ LHC

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

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



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

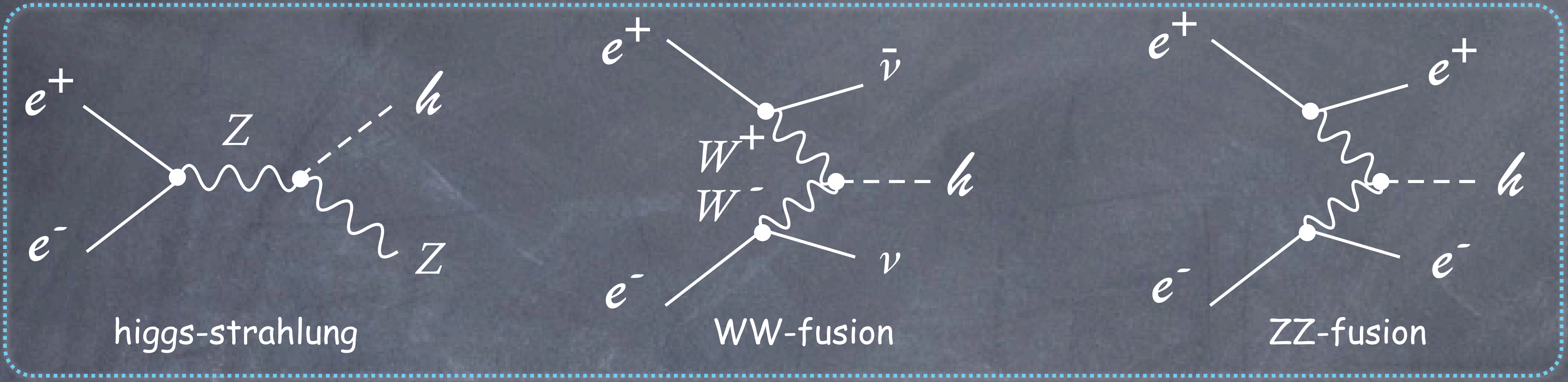
i.e. $4\pi f \sim 5-7\ \mathrm{TeV}$

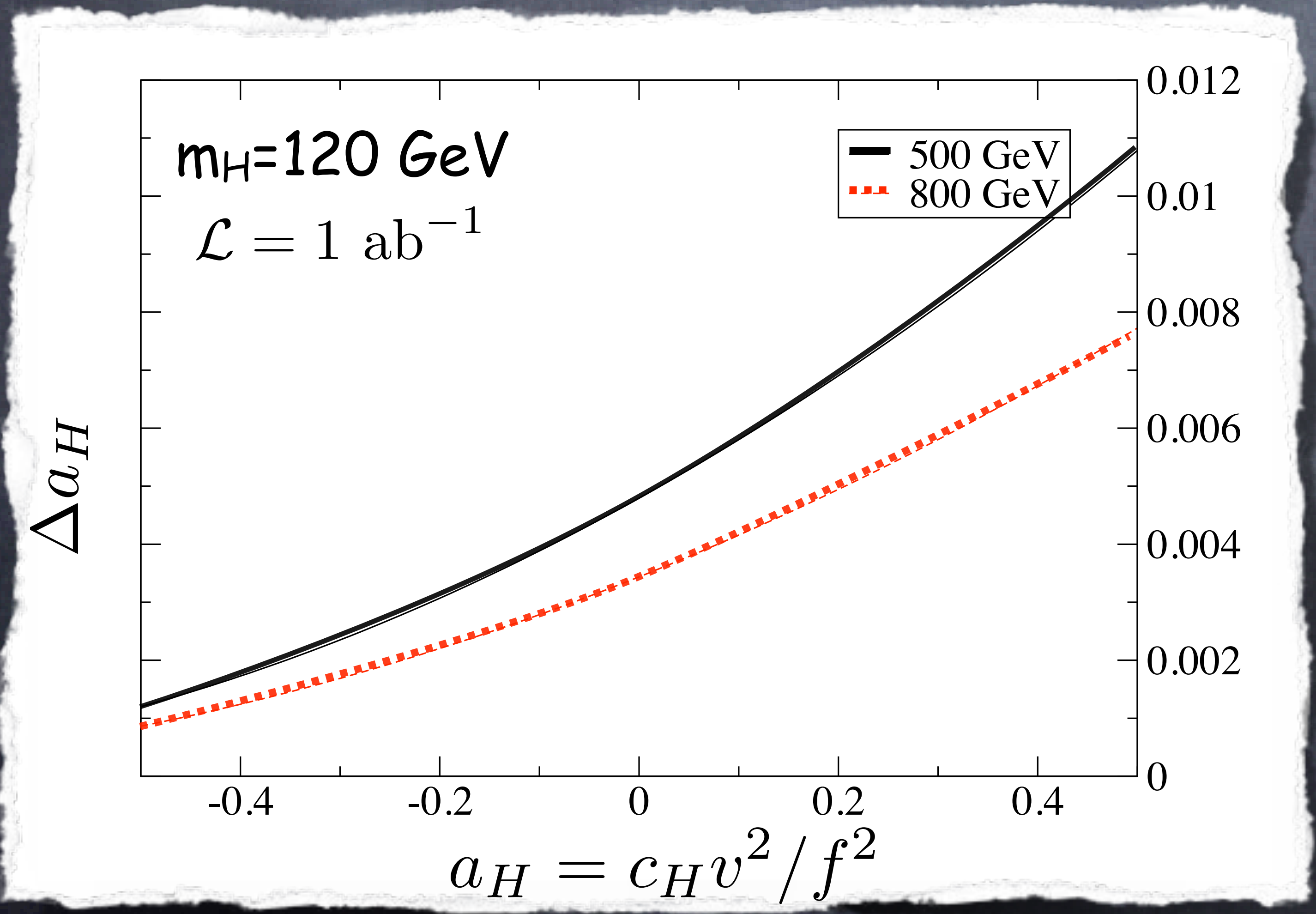
(ILC could go to few % ie
test composite Higgs up to $4\pi f \sim 30\ \mathrm{TeV}$)

# Higgs anomalous couplings @ LC

Barger et al. hep-ph/0301097

## single Higgs production





$m_H$=120 GeV

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

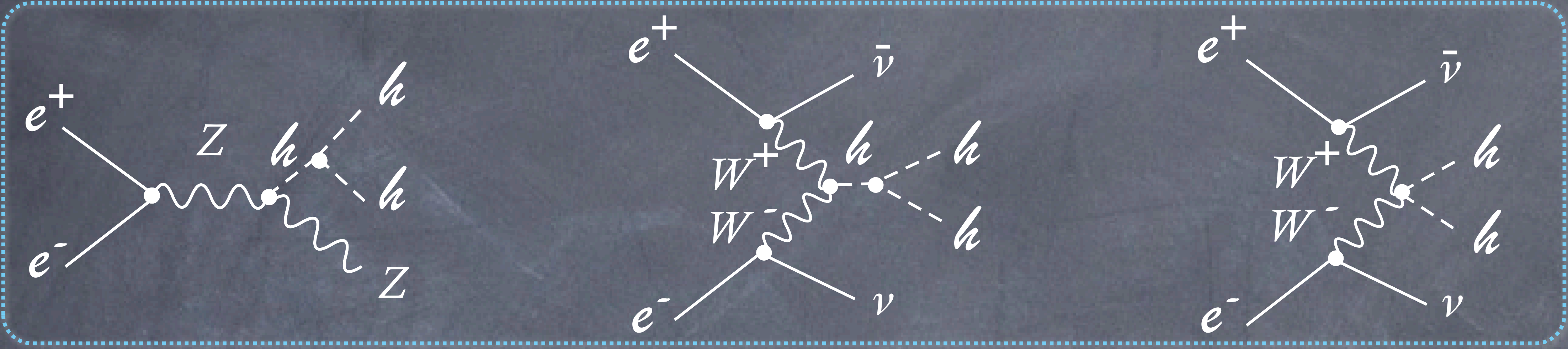
$m_H$=240 GeV

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

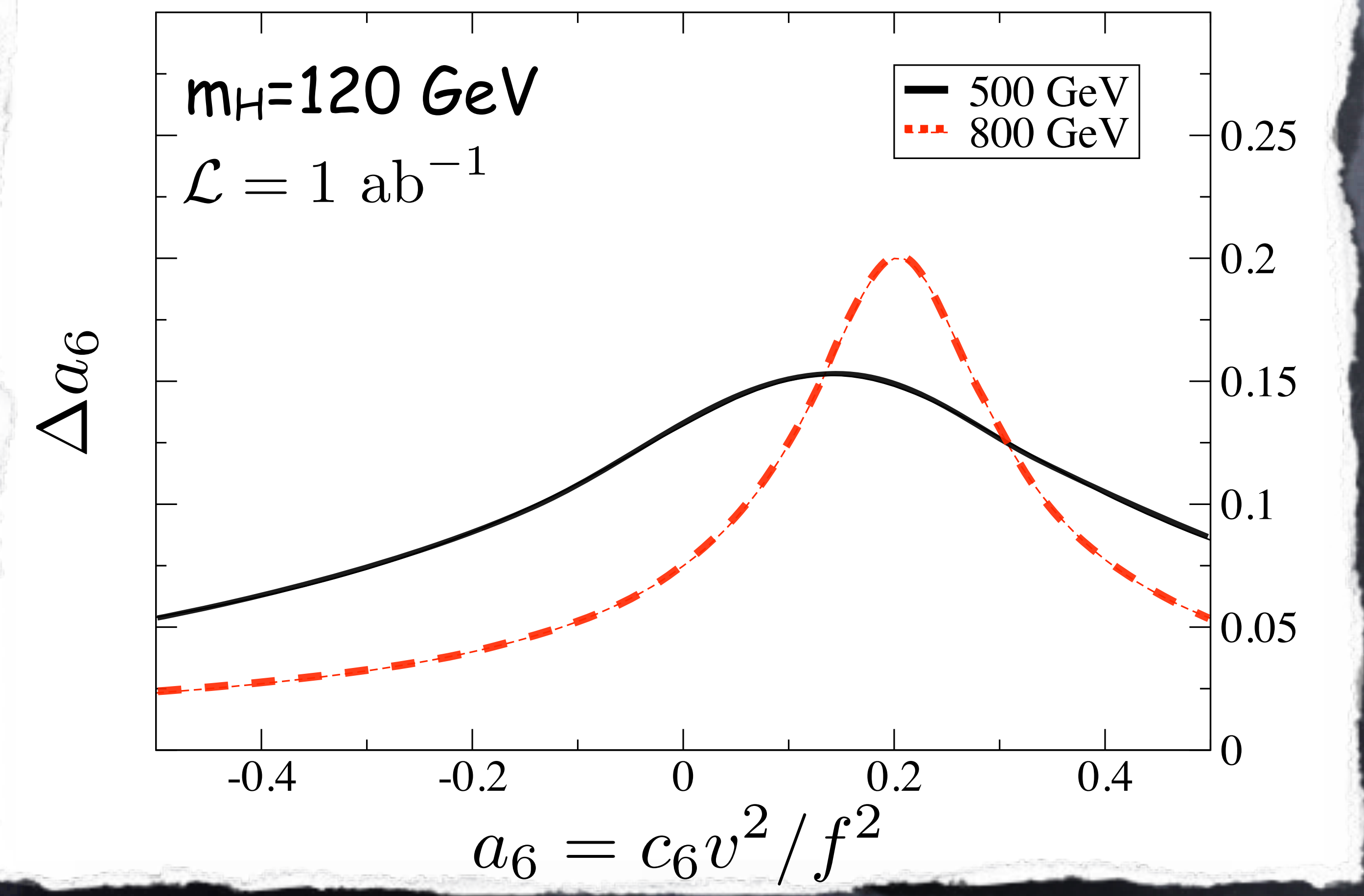
# Higgs anomalous (self-)couplings @ LC

Barger et al. hep-ph/0301097

## double Higgs production



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



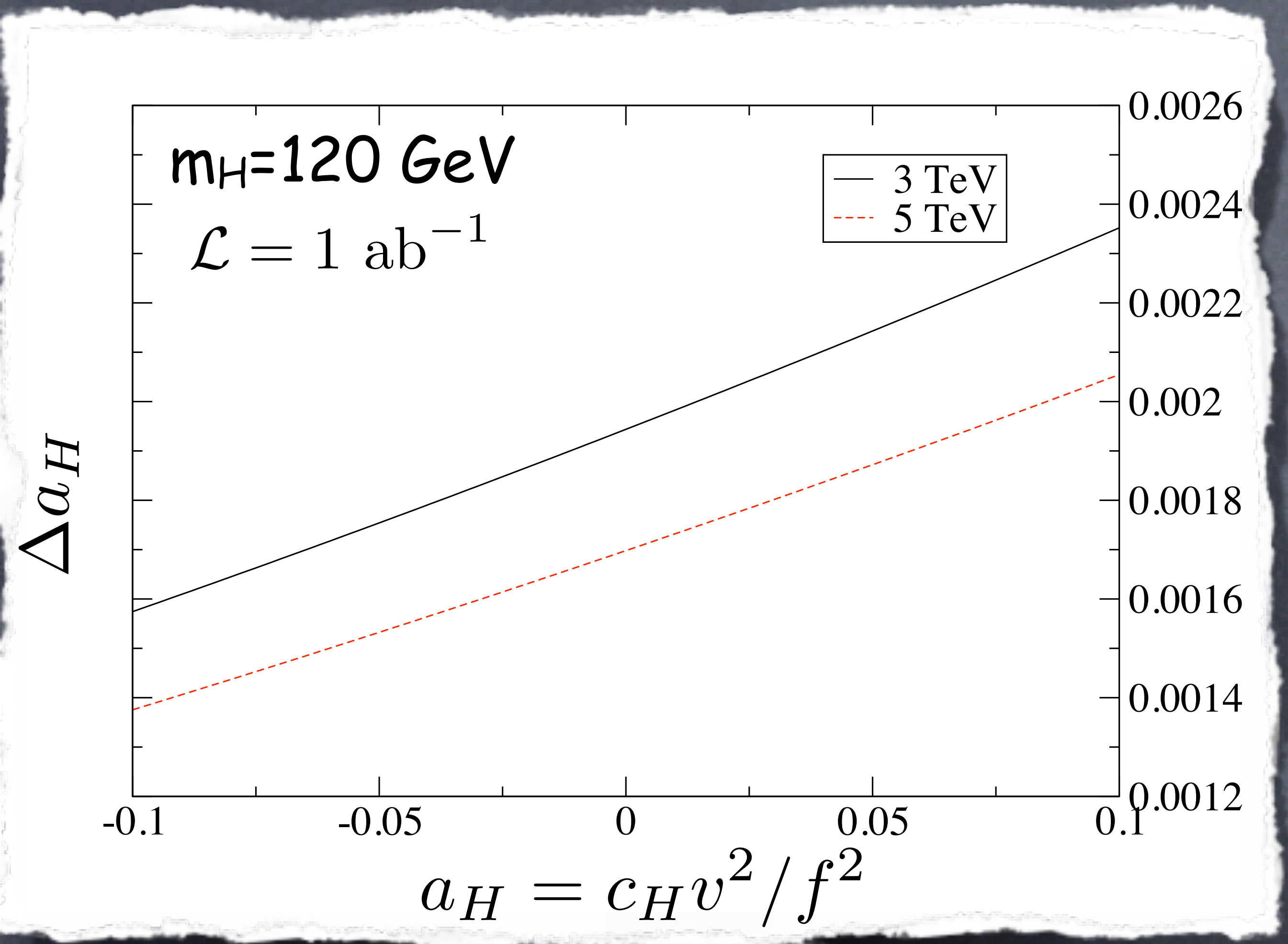
it allows to constrain $a_6$

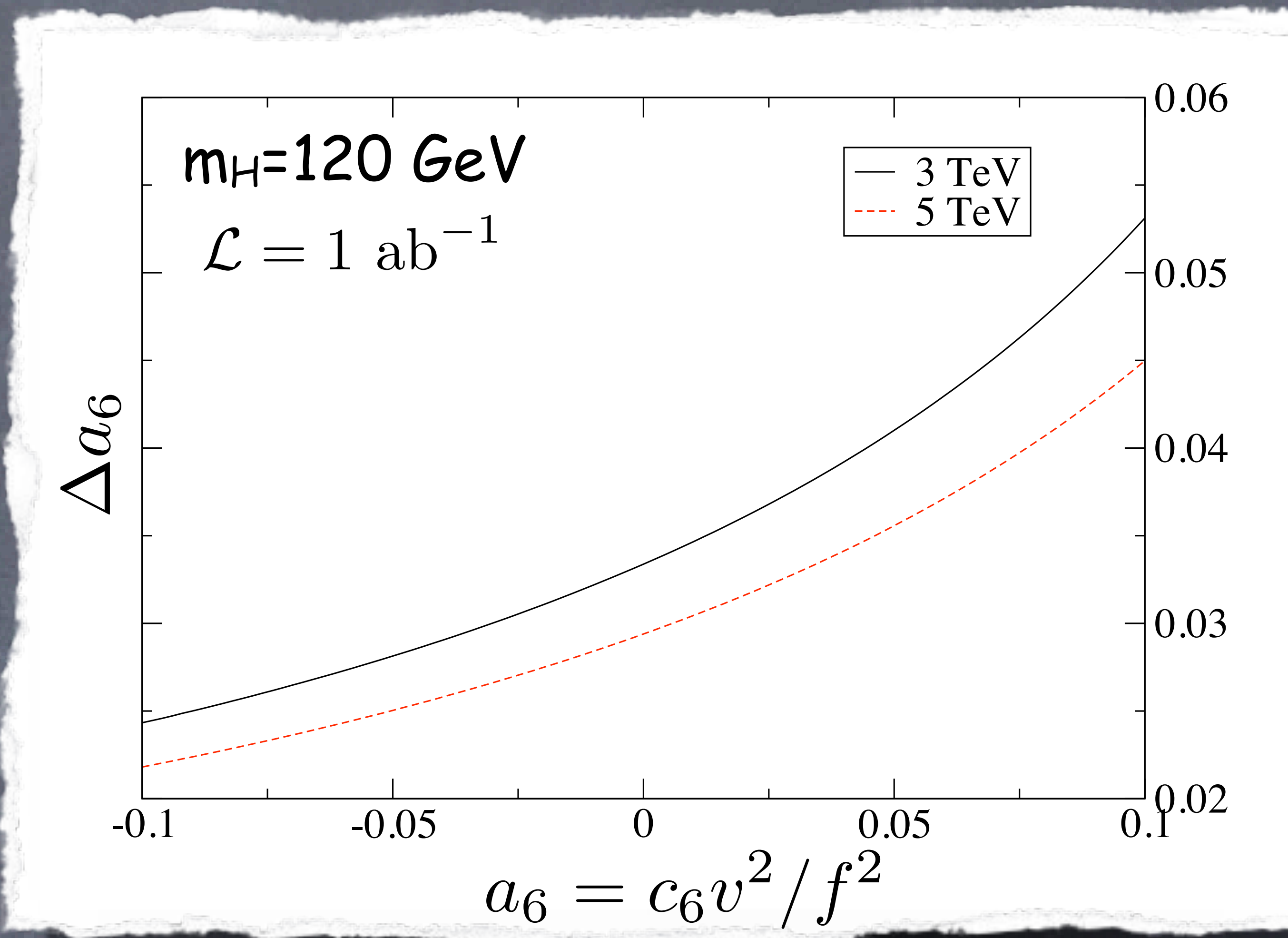
$m_H$=120 GeV

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

# Higgs anomalous couplings @ CLIC

Barger et al. hep-ph/0301097





$\Delta a_H \sim 0.002 \quad \Rrightarrow \quad 4\pi f \sim 70$ TeV

$\Delta a_6 \sim 0.04 \quad \Rrightarrow \quad 4\pi f \sim 15$ TeV

a factor 2 improvement from 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

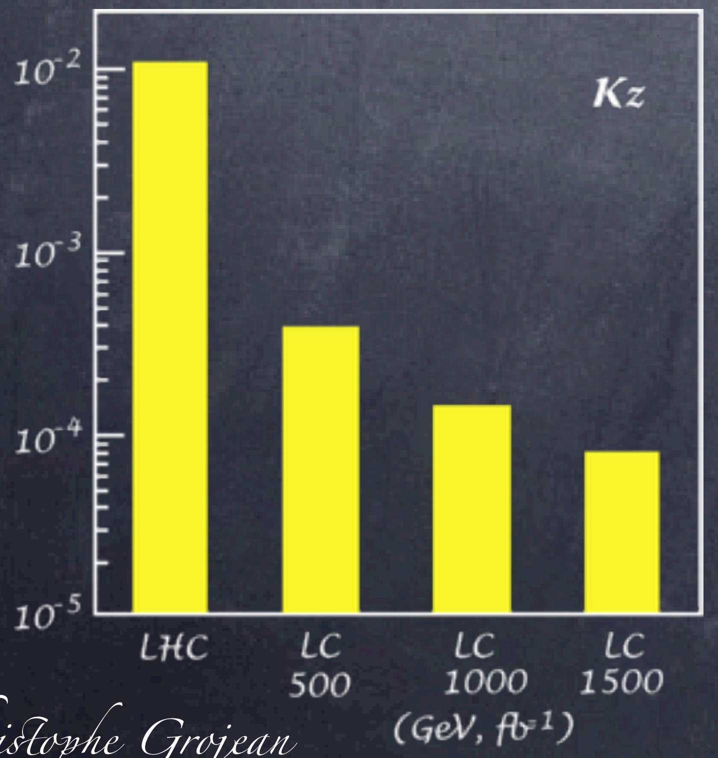
$$g_1^Z = \frac{m_Z^2}{m_\rho^2} c_W \qquad \kappa_\gamma = \frac{m_W^2}{m_\rho^2}\left(\frac{g_\rho}{4\pi}\right)^2 (c_{HW} + c_{HB}) \qquad \kappa_Z = g_1^Z - \tan^2\theta_W \kappa_\gamma$$

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

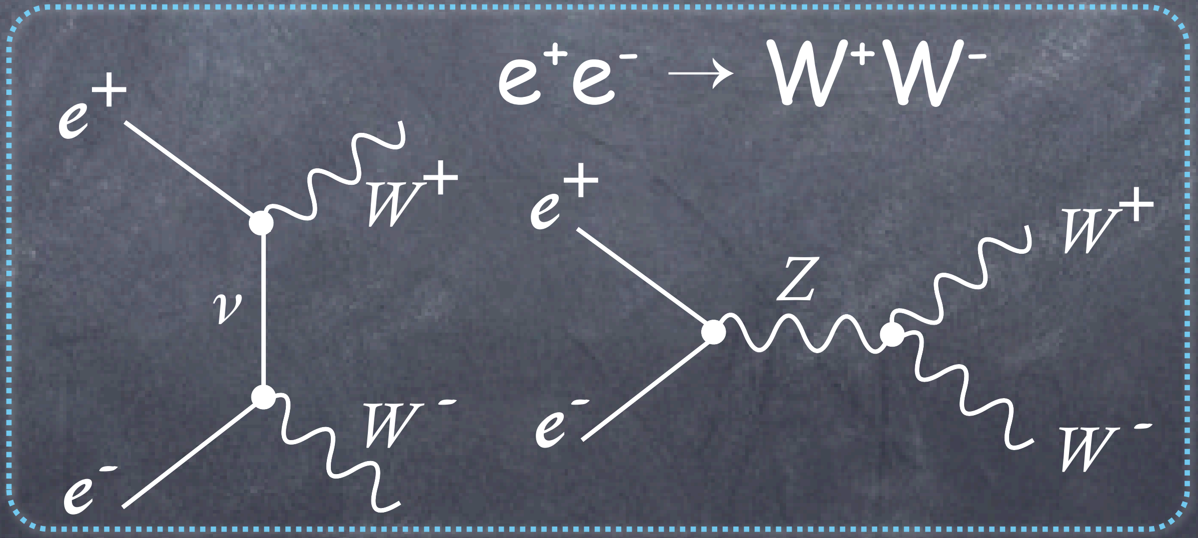
sensitive to resonance up to m$_\rho$~800 GeV

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$_\rho$~8TeV

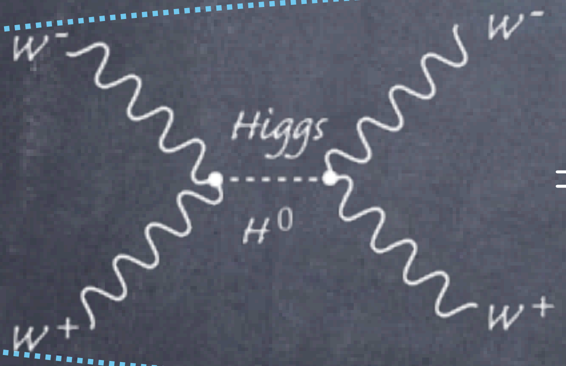
# Strong WW scattering

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



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

no exact cancellation of the growing amplitudes

Even with a light Higgs, growing amplitudes (at least up to $m_\rho$)

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

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

LET=SM-Higgs

Composite Higgs

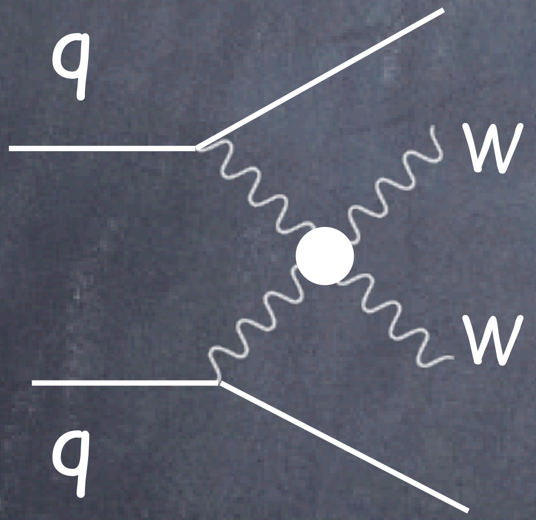
# Strong WW scattering @ LHC

Even with a light Higgs, growing amplitudes (at least up to $m_\rho$)

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

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

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



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

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

$$\mathcal{A}_{TT\to TT} \sim g^2$$

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

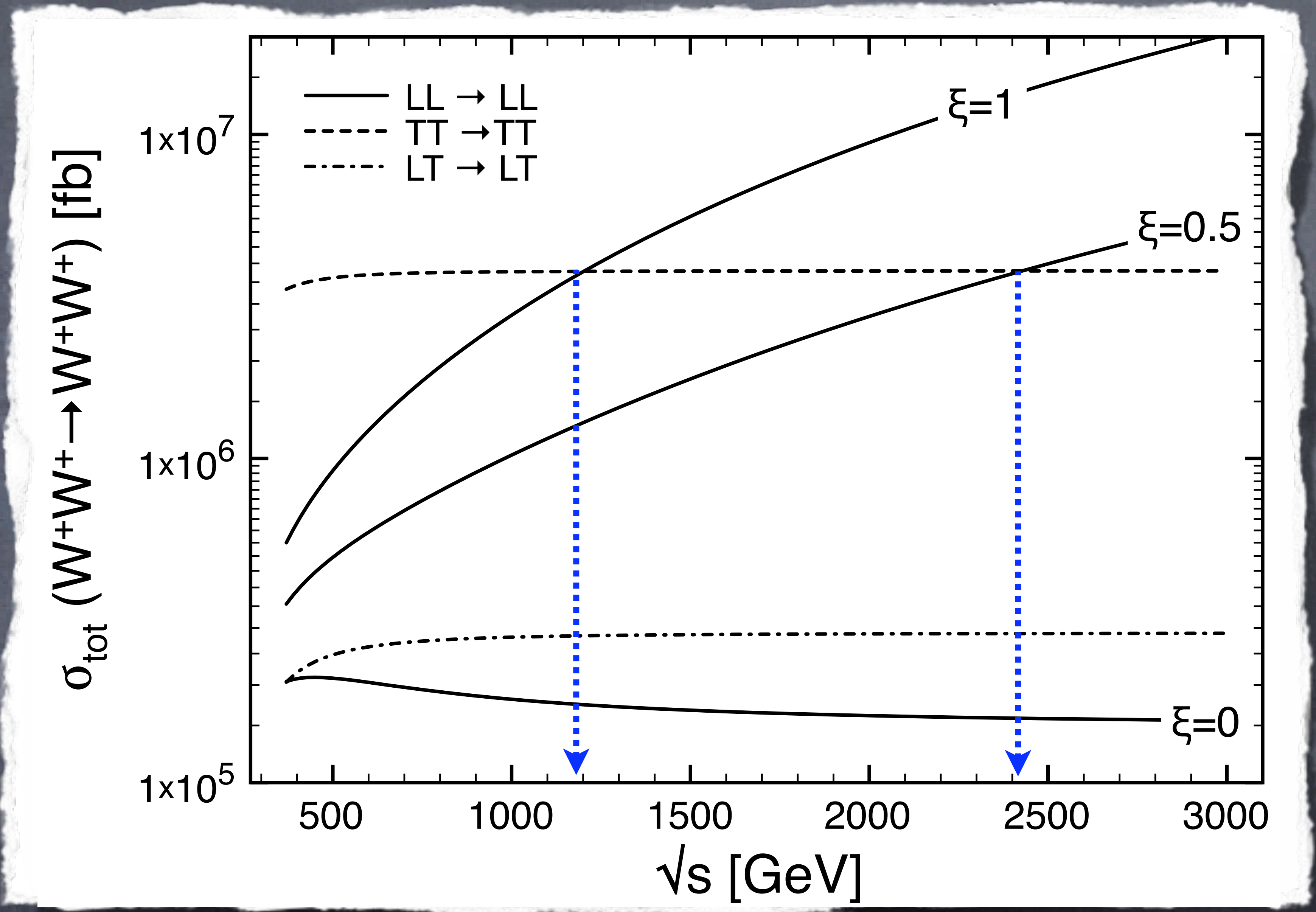
$$\mathcal{A}_{LL\to LL} \sim \mathcal{A}_{TT\to TT}$$

for

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

# EW background

## 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

# Dominance of T polarization

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

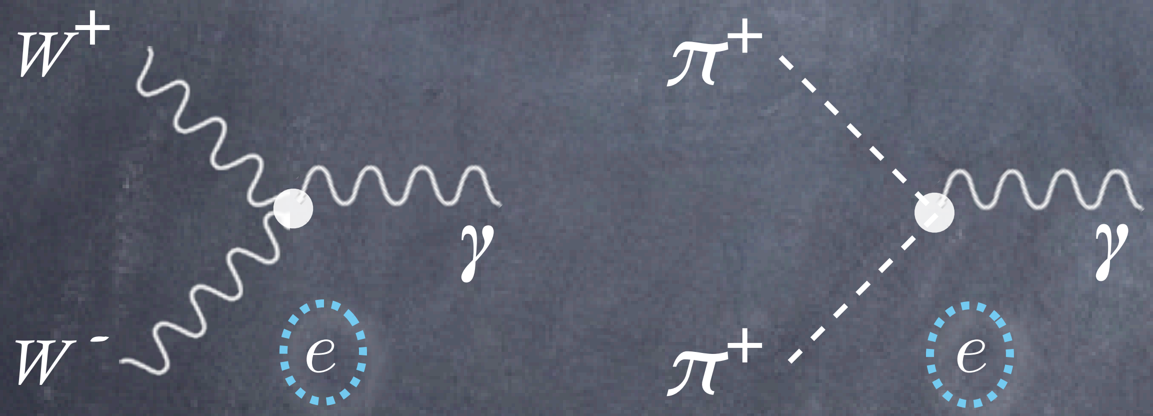
$W^+W^+ \to W^+W^+$

$$\mathcal{A} = \frac{a_\gamma^t\, s}{t} + \frac{a_Z^t\, s}{t - M_Z^2} + \frac{a_\gamma^u\, s}{u} + \frac{a_Z^u\, s}{u - M_Z^2} + \ldots \Longrightarrow \sigma \sim \frac{1}{16\pi}\left(\frac{{a_\gamma^t}^2 + a_\gamma^{u2}}{M_\gamma^2} + \frac{{a_Z^t}^2 + {a_Z^u}^2}{M_\gamma^2 + M_Z^2}\right)$$

$M_\gamma$ = regulateur of Coulomb singularity=off-shellness of W ~$M_W$

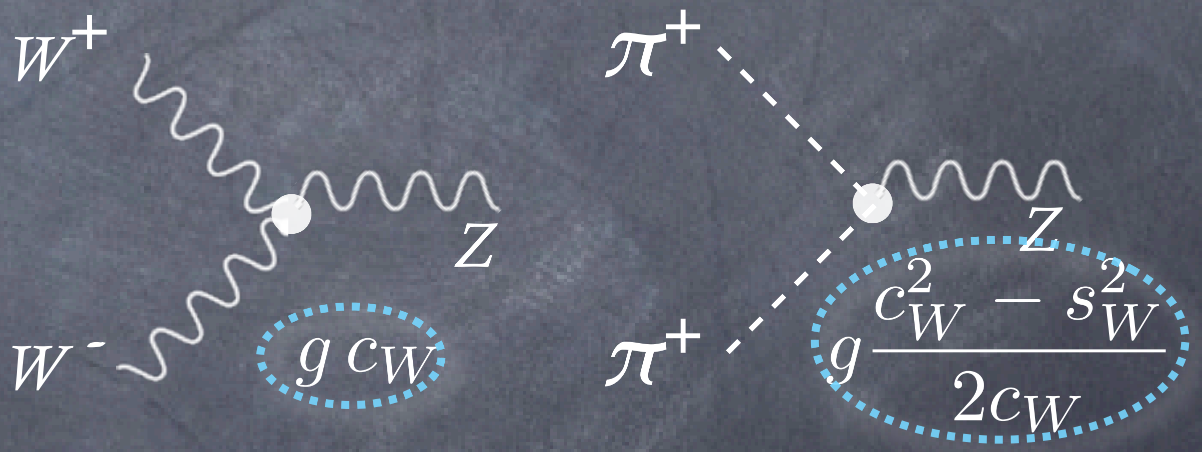
$a_\gamma = 2 \cdot (\text{electric charge of } W^+)^2$

universal for T and L



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

different for T and L



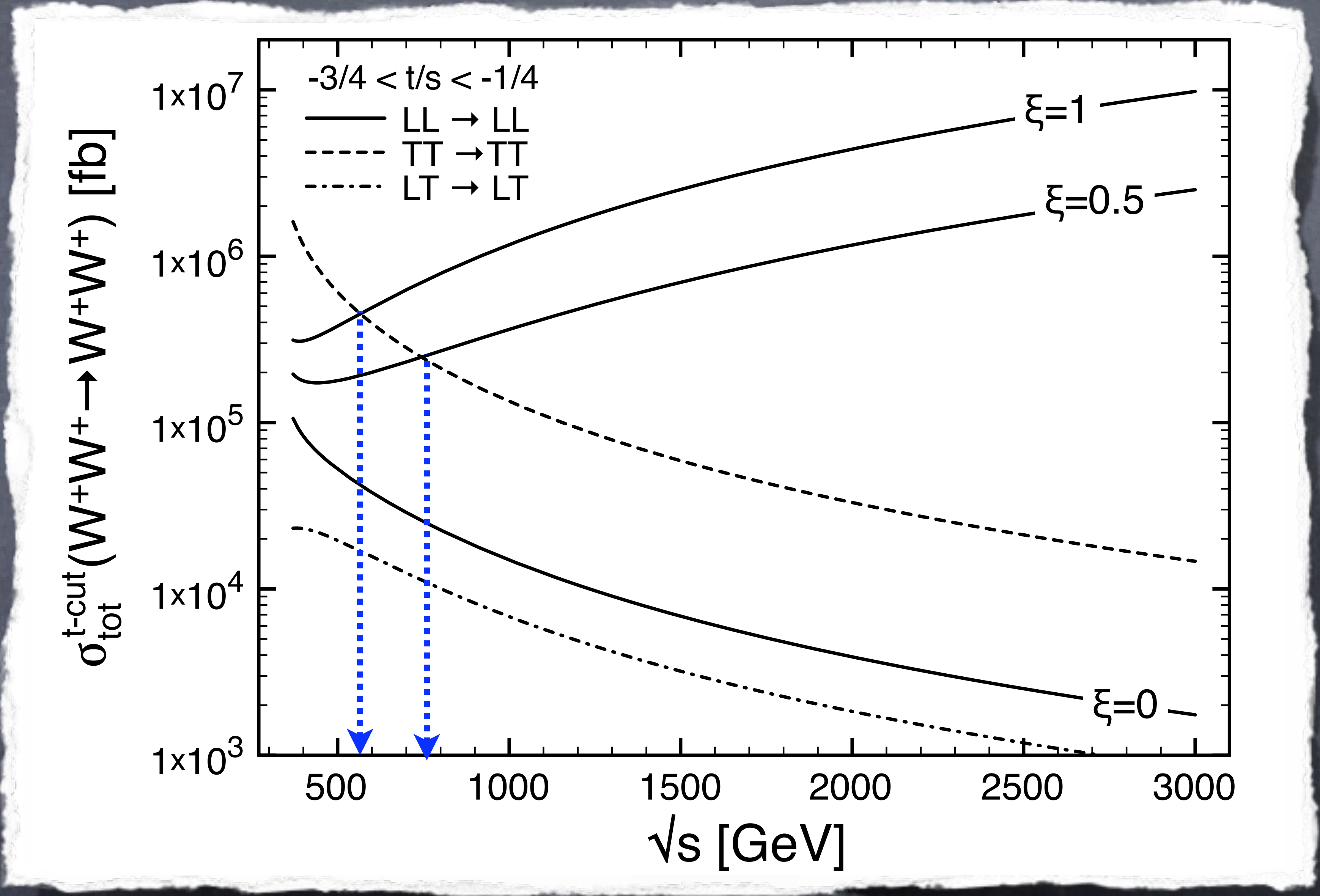
$$\frac{\sigma_{TT\to TT}}{\sigma_{LL\to LL}} \sim 20 \quad (\text{for } M_\gamma \sim M_Z)$$

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

$\sigma_{\text{tot}}$ is only sensitive to IR physics: not good observable to proble EWSB sector

# EW bckg in the central region

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



$$\frac{d\sigma^{LL}/dt}{d\sigma^{TT}/dt}_{|t=-s/2} = \frac{1}{2304}\left(\frac{\sqrt{s}}{M_W}\right)^4 \xi^2$$

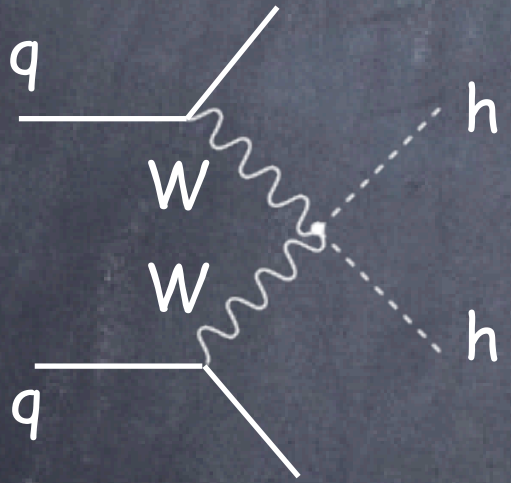
← 2 orders of magnitude smaller than NDA estimates...

# Strong Higgs production

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

strong boson scattering ⇔ strong Higgs production

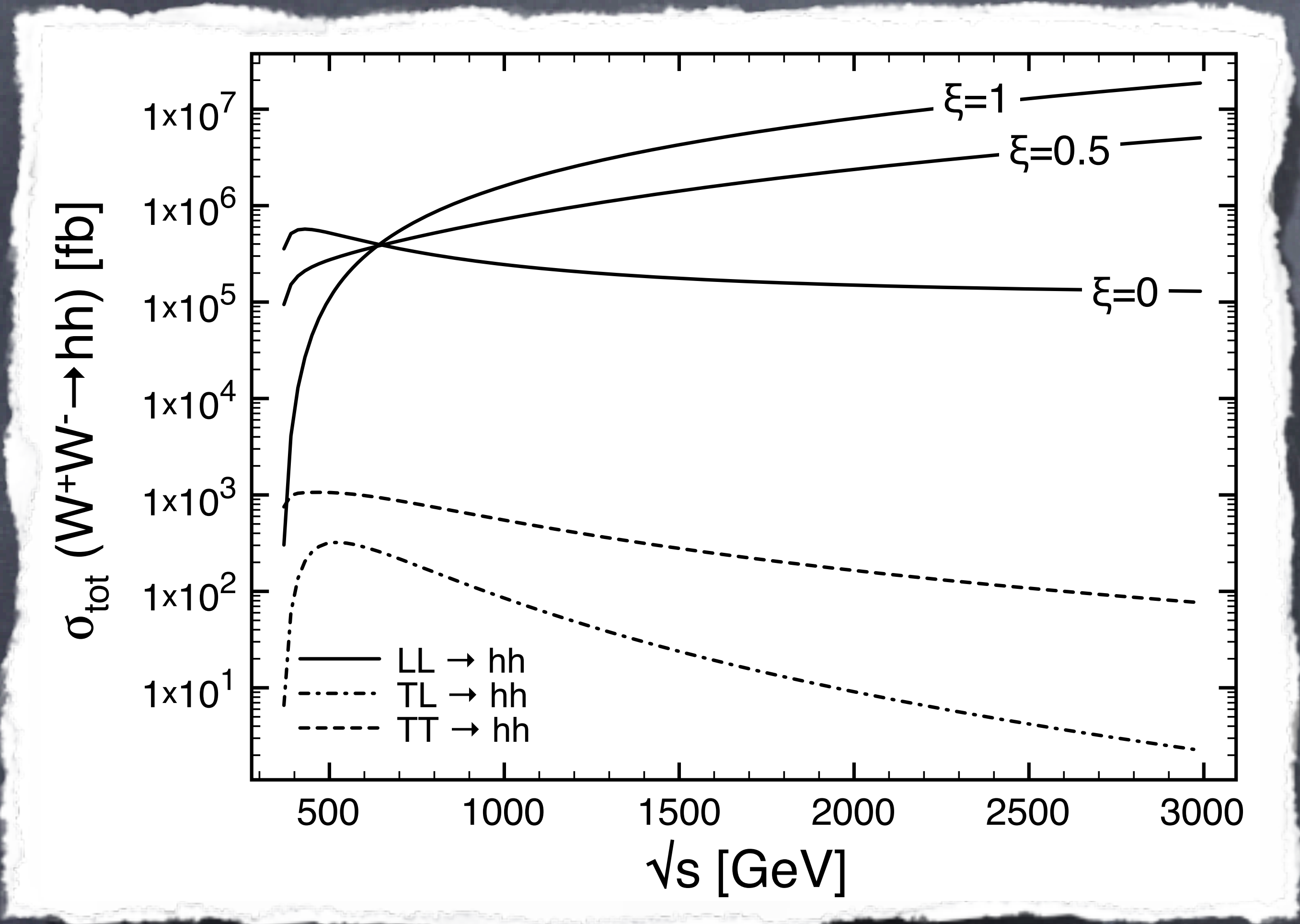
$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \mathcal{A}\left(W_L^+ W_L^- \to hh\right) = \frac{c_H\, s}{f^2}$$

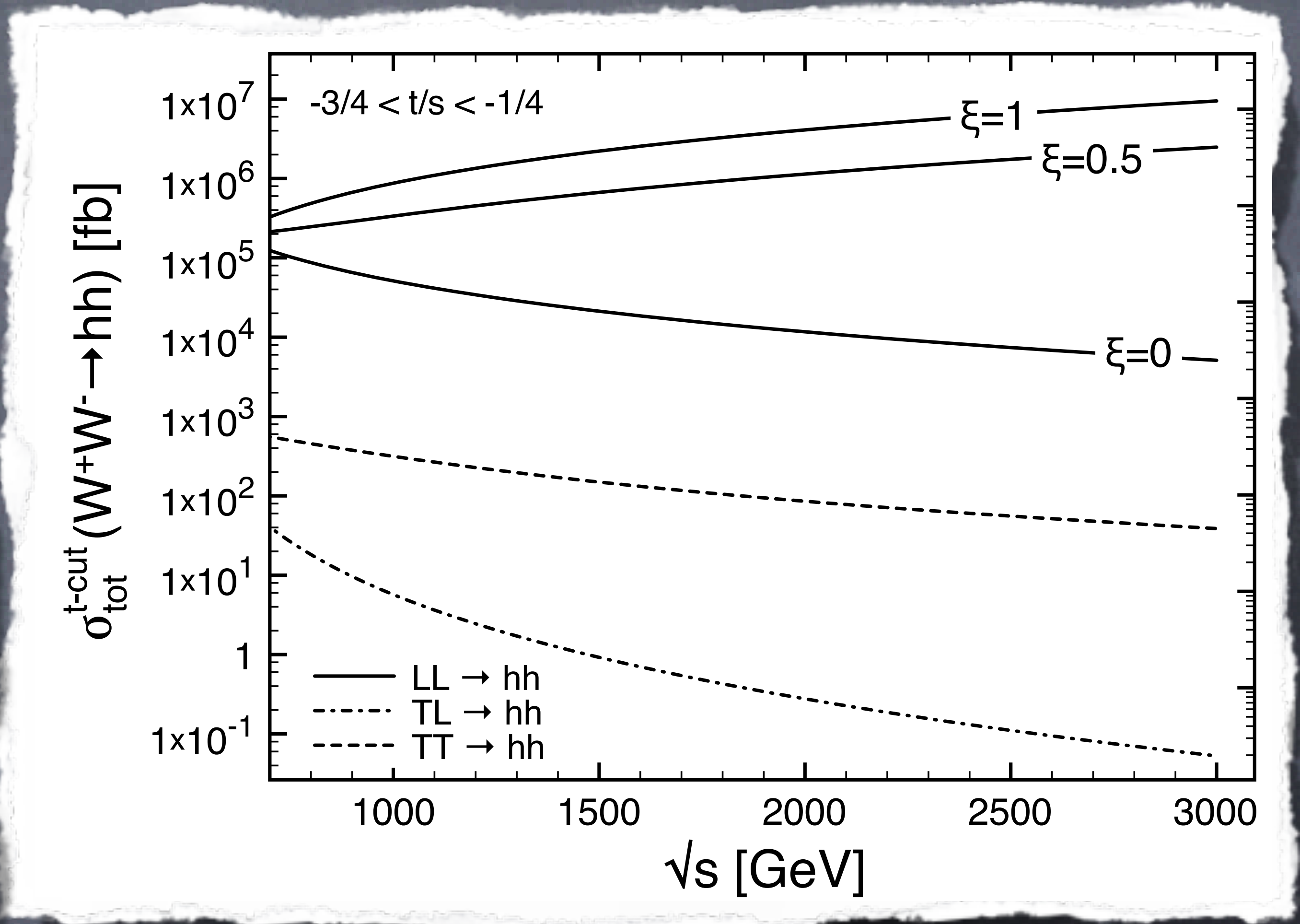


signal:
- $hh \to bbbb$
- $hh \to 4W \to 3\ell^{\pm}3\nu$ +jets

More complicated final states than for $WW \to WW$,
smaller BRs,
but no T polarization pollution

# EW bckg for WW → hh





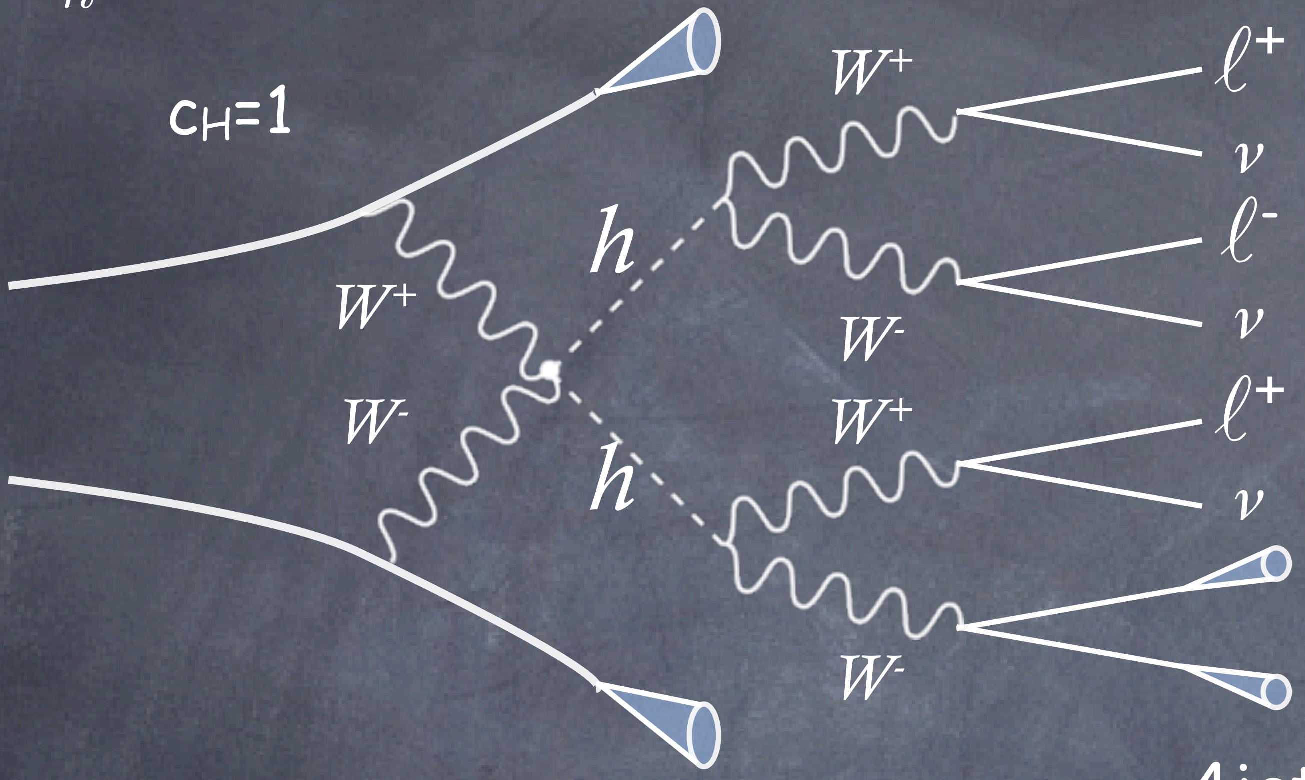
$$\frac{d\sigma^{LL\to hh}/dt}{d\sigma^{TT\to hh}/dt} = \frac{1}{8}\frac{\xi^2}{\xi^2+(1-\xi)^2}\left(\frac{\sqrt{s}}{M_W}\right)^4$$

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

$m_h = 180$ GeV



acceptance cuts

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

# events after accept. cuts (with 300 fb$^{-1}$)

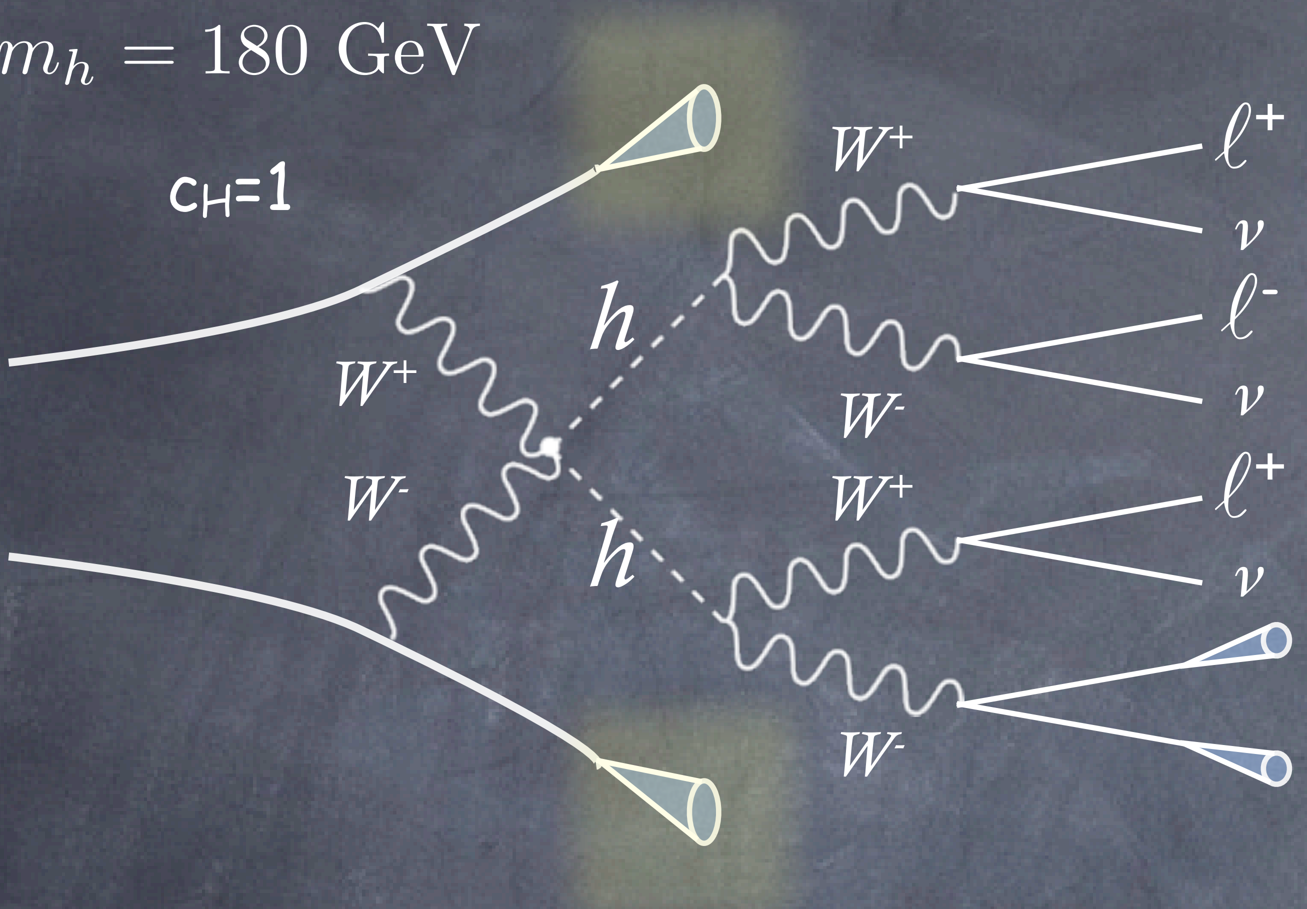
| | $v/f = 1$ | $v/f = \sqrt{.8}$ | $v/f = \sqrt{.5}$ | $v/f = 0$ |
|---|---|---|---|---|
| 4jets → | 14.5 | 9.8 | 4.3 | 0.5 |
| 3jets → | 19.5 | 13.2 | 5.9 | 0.8 |

## Dominant backgrounds

| | 4jets | 3jets |
|---|---|---|
| $t\bar{t}2W$ ($\hookrightarrow b\bar{b}4W \to 3l3\nu 2b2j$) | 94 evts | 223 evts |
| $t\bar{t}W2j$ ($\hookrightarrow b\bar{b}3W2j \to 3l3\nu 2b2j$) | 122 evts | 230 evts |
| $3W4j$ ($\hookrightarrow 3l3\nu 4j$) | 26 evts | 94 evts |
| $Wll4j$ ($\hookrightarrow 3l1\nu 4j$) | 580 evts | 1580 evts |

# Strong Higgs production: 3L+4jets

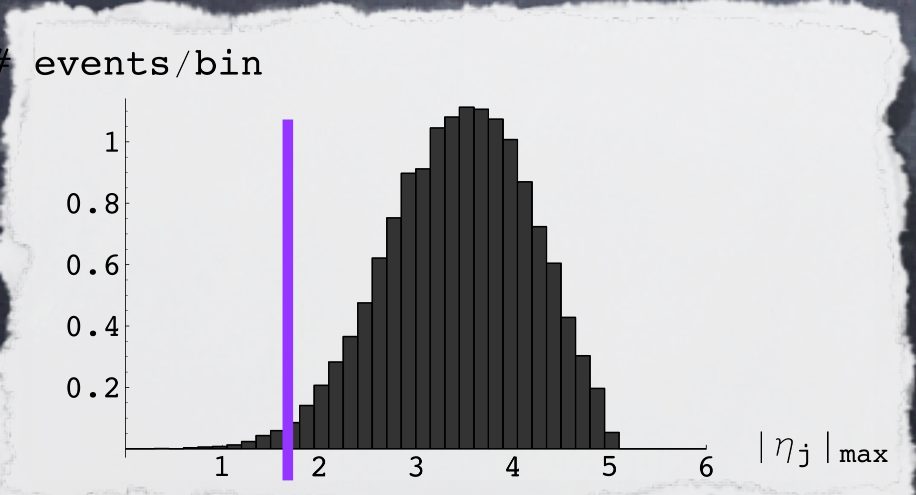
$m_h = 180$ GeV



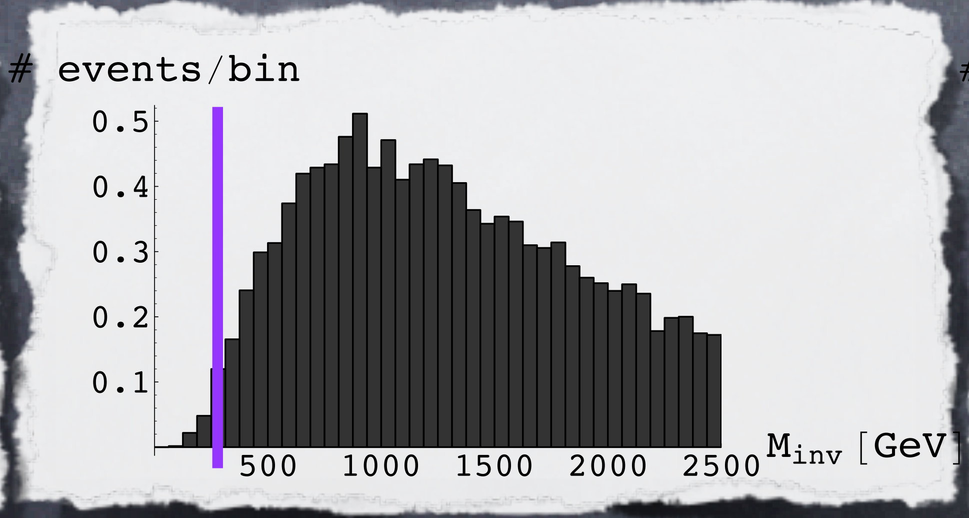
1 identify the “external” jets:

- get the most forward jet
- construct the pair with the largest $M_{inv}$ or $\delta\eta$

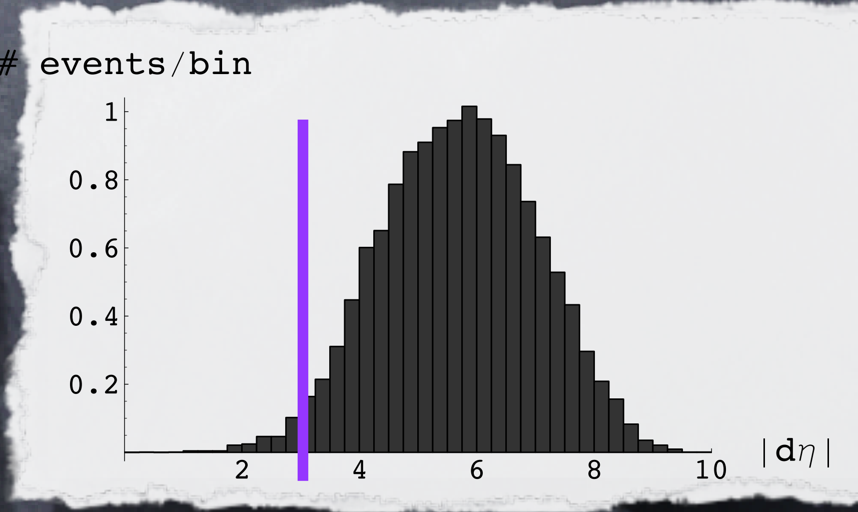
$|\eta|_{\max} \geq 1.8$



$M_{jj} \geq 330$ GeV



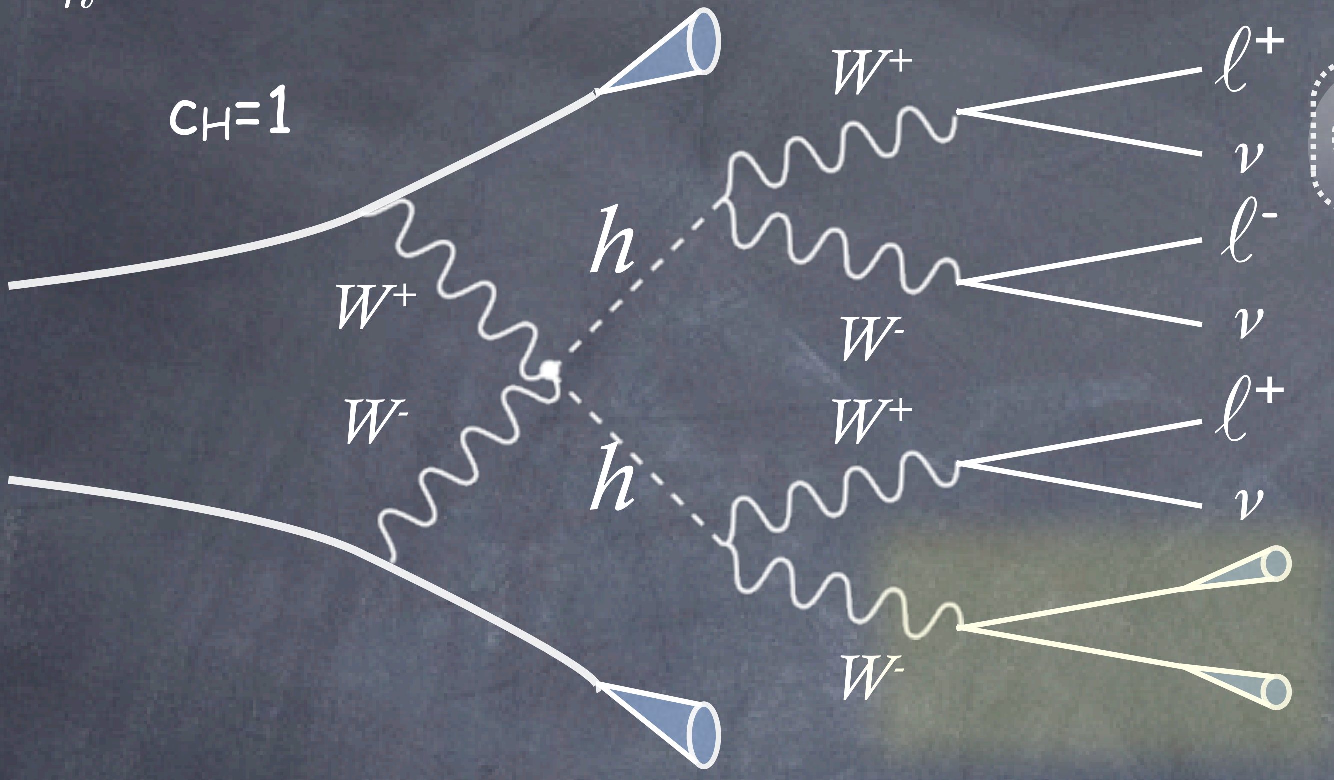
$|\delta\eta_{jj}| \geq 3.0$



# Strong Higgs production: 3L+4jets

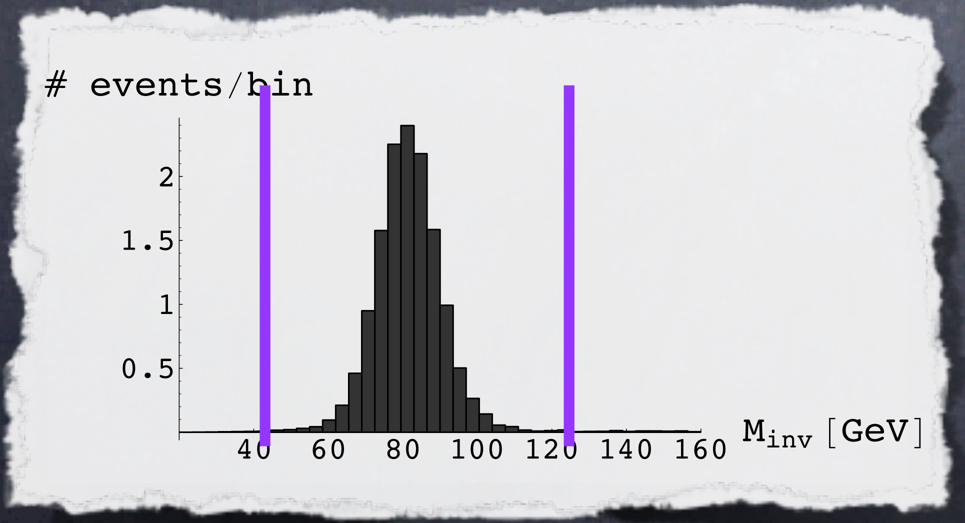
$m_h = 180\ \text{GeV}$

$c_H$=1



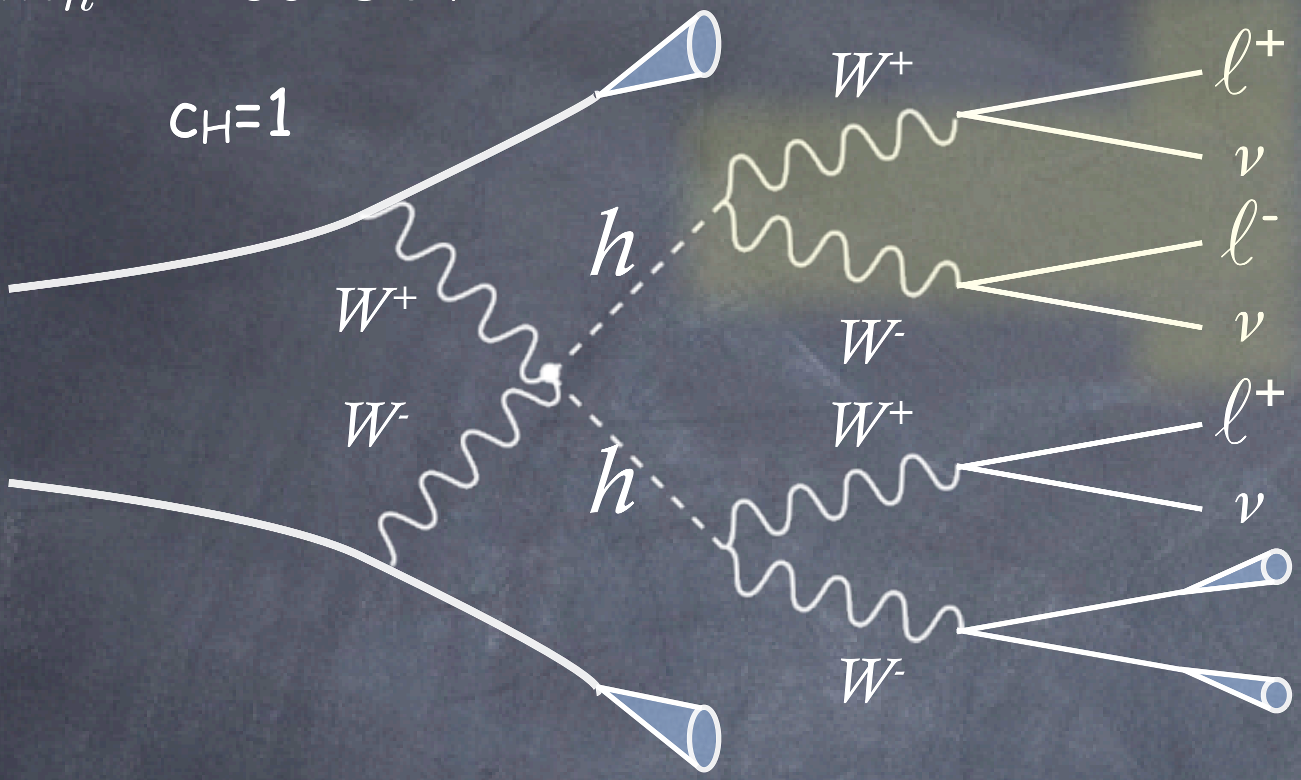
② reconstruction of hadronic W

$$|M_{jj} - M_W| < 40\ \text{GeV}$$



# Strong Higgs production: 3L+4jets

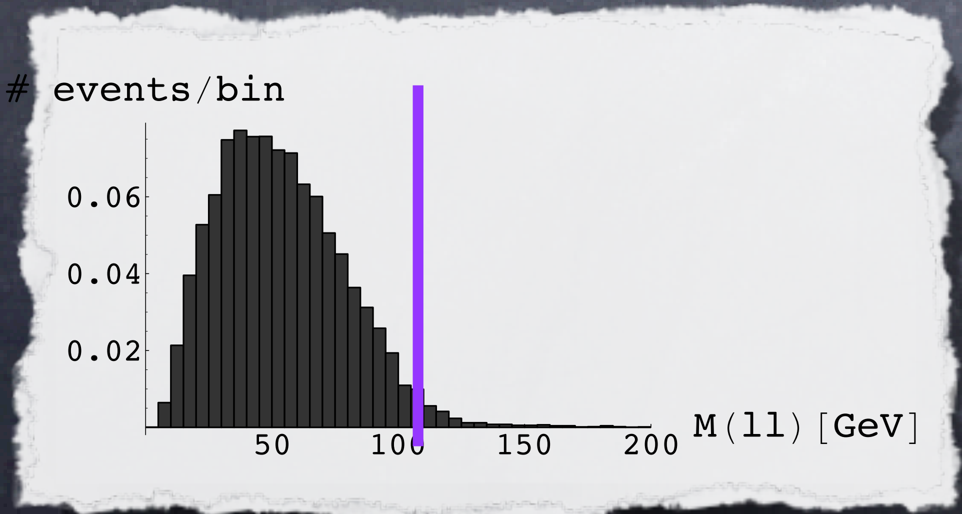
$m_h = 180$ GeV



③ identify the $\ell^+\ell^-$ pair coming from the same Higgs

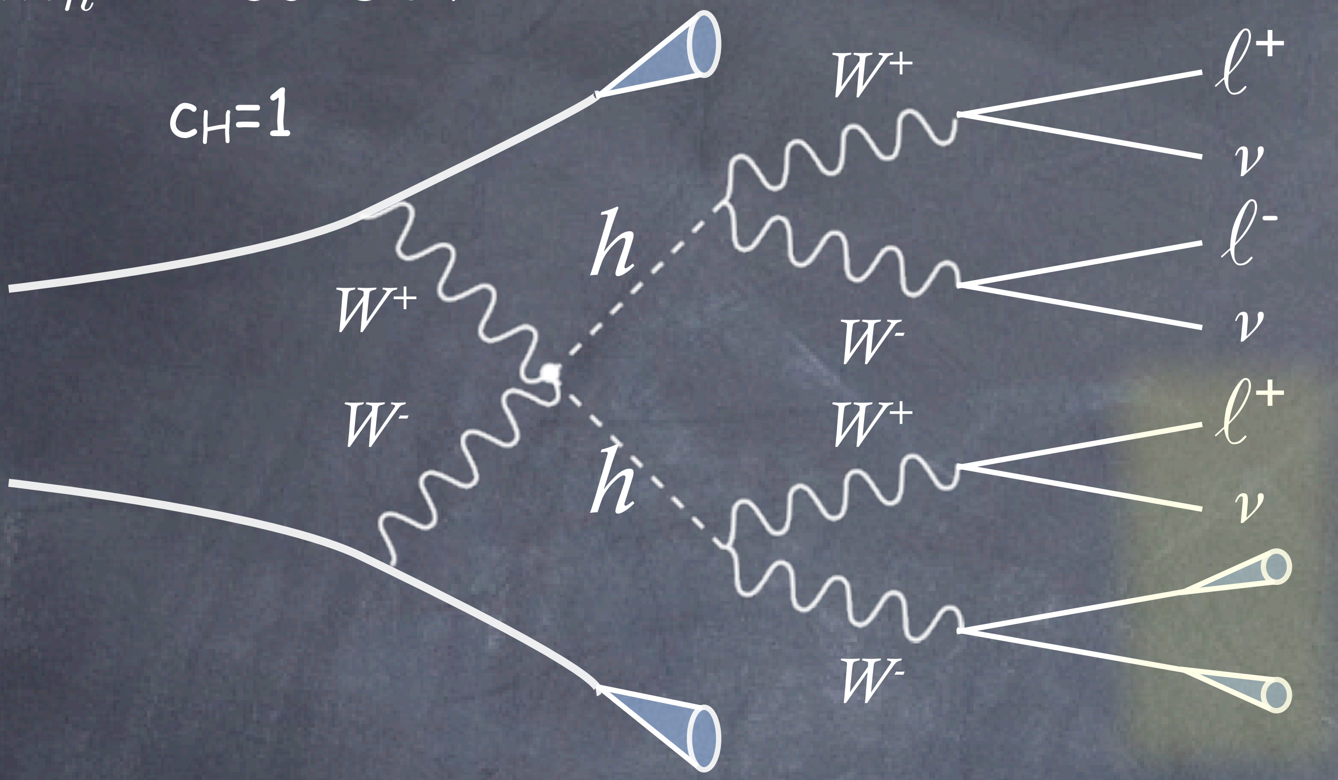
the pair with the smallest angle

$$M_{l+l-(\phi \text{ min})} \leq 110 \text{ GeV}$$



# Strong Higgs production: 3L+4jets

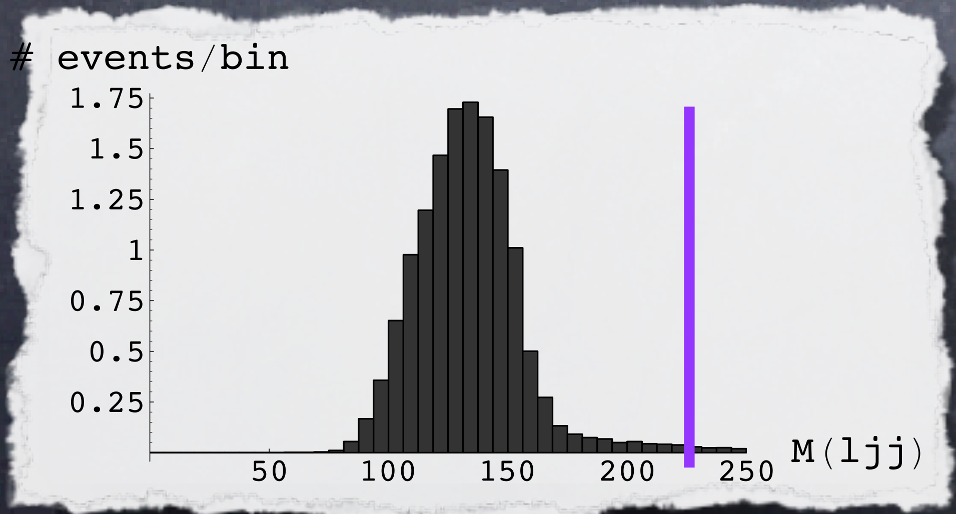
$m_h = 180\ \text{GeV}$



④ left with a $\ell^{\pm}jj$ triplet

cut on its inv. mass

$M_{jjl^{\pm}} \le 230\ \text{GeV}$



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

.

⇑

good motivation to SLHC

# 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

⇛ Direct access to a strong sector is not easy ⇚

BSM-no lose theorem doesn't really apply to LHC:
we might just see a Higgs but telling for sure that it is elementary or
composite will require a lot of luminosity/time

Not just the search for the Higgs boson
(its discovery has already been announced to journalists and politics, so it has to be there)
We are after the organizing principles of nature at high energies

is SM natural or fine-tuned in a stringy landscape?

fundamental interactions ⇔ gauge symmetries?