

Composite Higgs Physics

work in progress with

R. Contino, M. Moretti, F. Piccinini and R. Rattazzi

also related to

G. Giudice, C.G., A. Pomarol and R. Rattazzi

hep-ph/0703164 = JHEP06(2007)045

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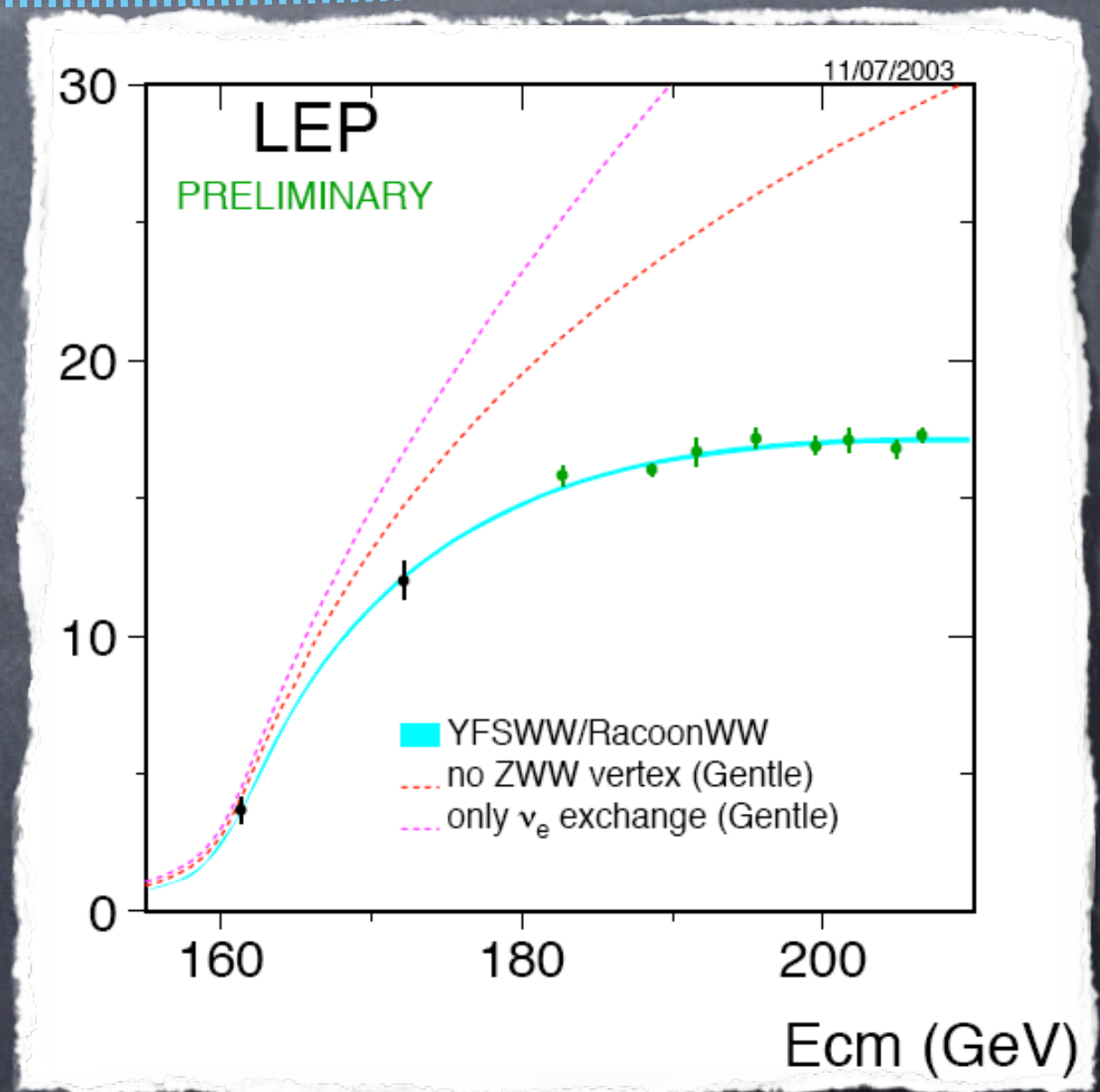
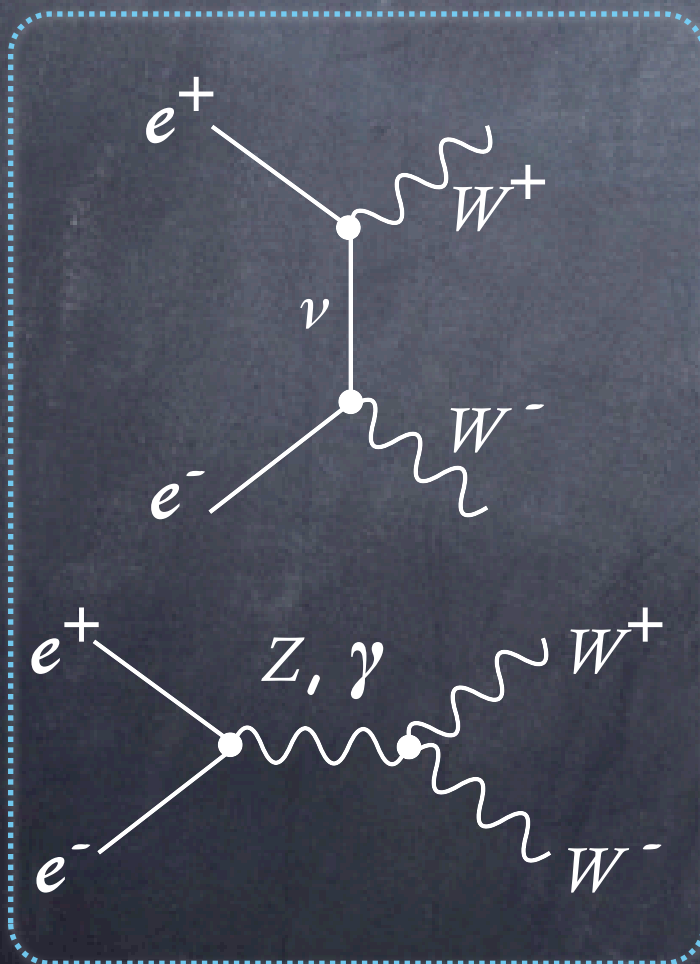
(Christophe.Grojean[at]cern.ch)

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 $\delta A_\mu^a = \partial_\mu \epsilon^a + g f^{abc} A_\mu^b \epsilon^c$

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

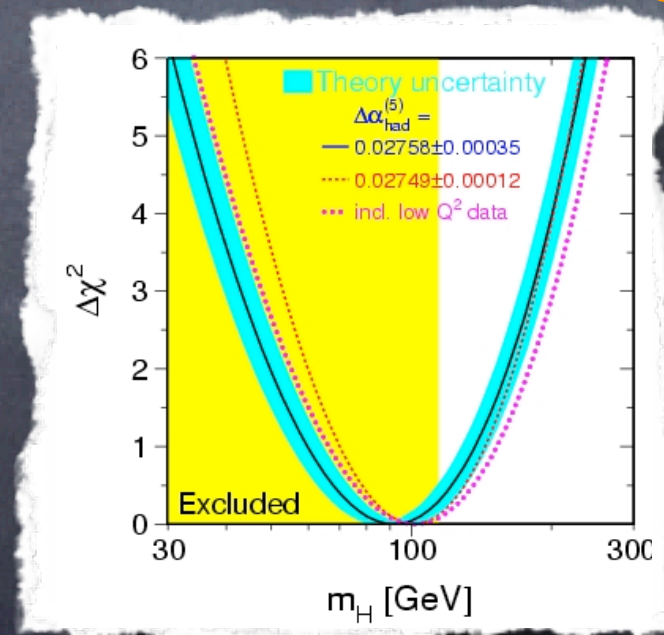
$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

Higgs doublet = 4 real scalar fields

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

Is the Higgs Really There?

Good agreement with EW data (doublet $\Leftrightarrow \rho=1$)



	Measurement	Fit	$10^{meas} - 10^{fit} / \sigma$
$\Delta\alpha_{had}^{(5)}(m_Z)$	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...

- Standard Model with a light Higgs provides a good fit to all data, indirect determination of H mass:
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$$M_H < 186 \text{ GeV} \quad (95\% \text{ c.l.})$$

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

Which Higgs?

UnHiggs?

Private Higgs?

Little Higgs?

Gaugephobic Higgs?

Littlest Higgs?

Composite Higgs?

Intermediate Higgs?

Slim Higgs?

Fat Higgs?

Higgsless?

Portal Higgs?

Peter's Higgs?

Brout-Englert's Higgs?

Gauge-Higgs?

Lone Higgs?

Twin Higgs?

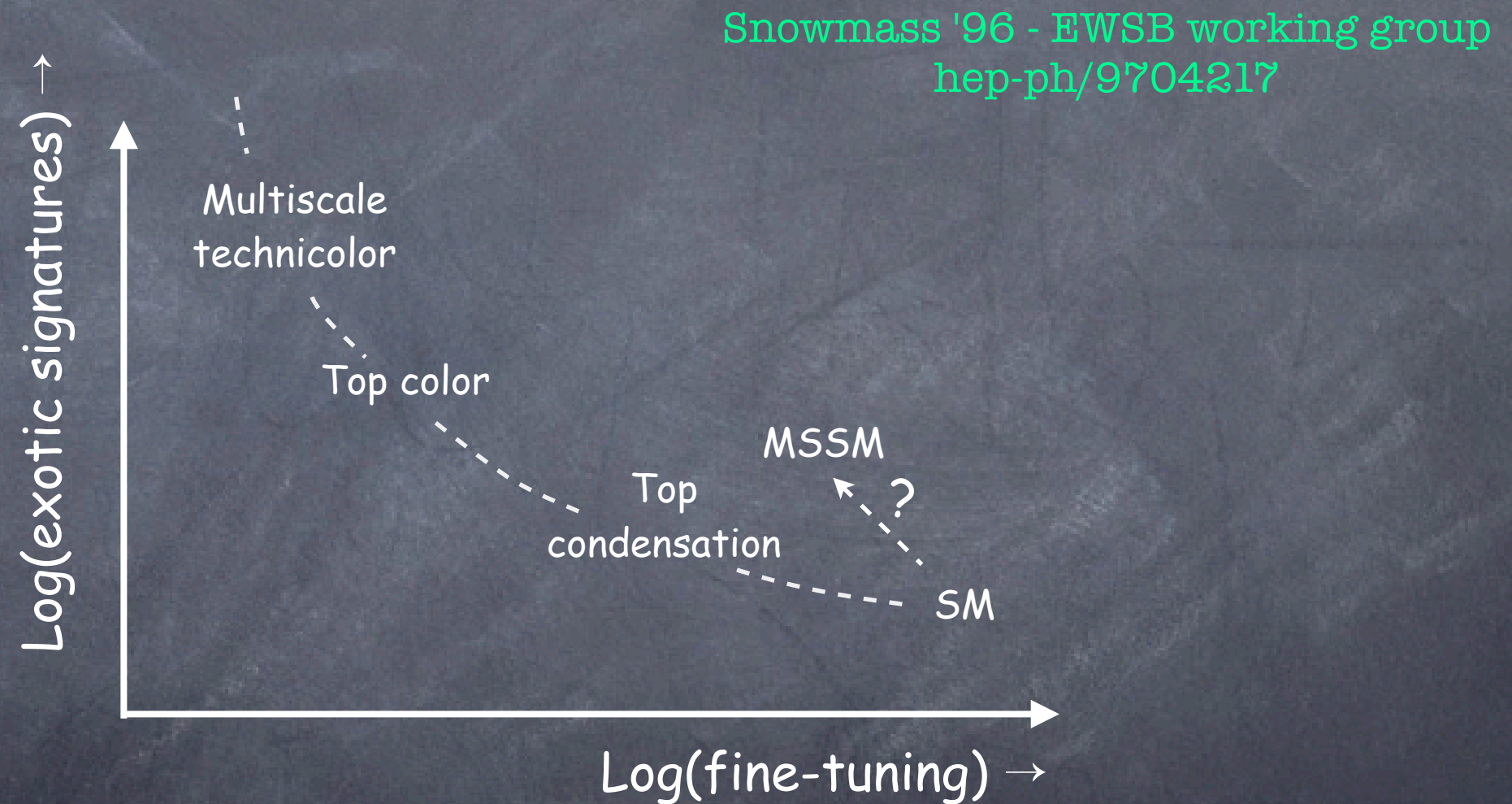
Simplest Higgs?

Phantom Higgs?



EWSB from a Strongly Coupled Sector

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



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



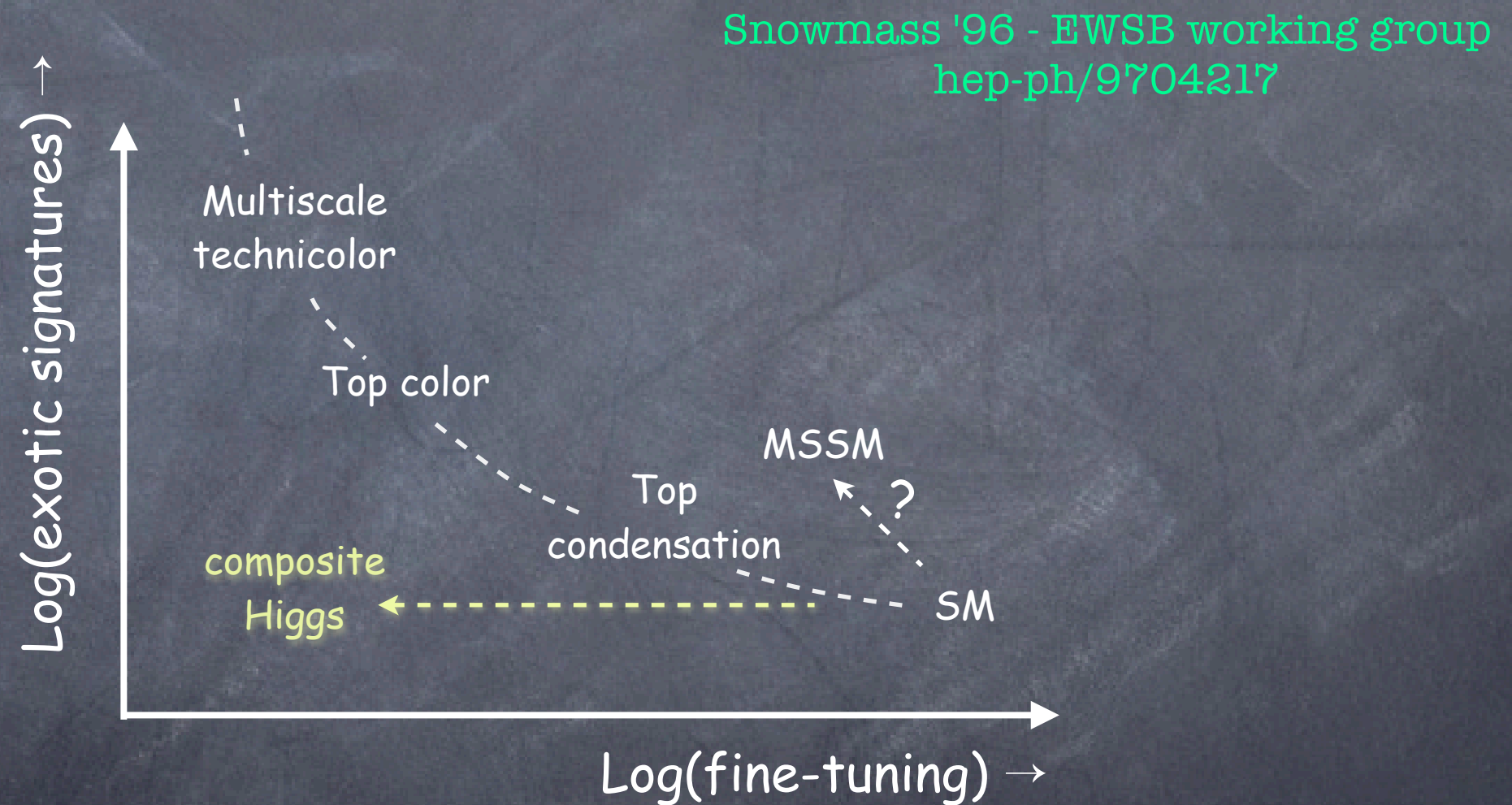
generates a tree-level effect on the SM gauge bosons self-energy

$$\hat{S} \sim \frac{m_W^2}{m_\rho^2} \quad \begin{array}{c} |\hat{S}| < 10^{-3} \\ \xrightarrow{\text{at 95\% CL}} \end{array} \quad m_\rho > 2.5 \text{ TeV}$$

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

EWSB from a Strongly Coupled Sector

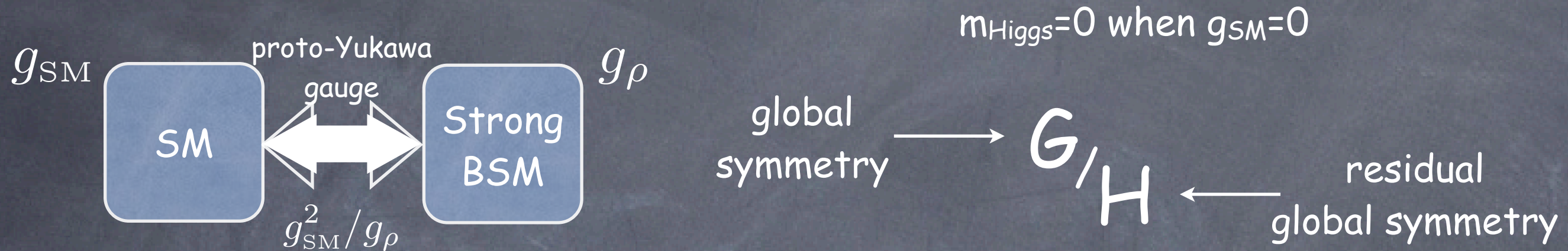
A strong sector, around few TeV, driving EW symmetry breaking is a plausible/conservative scenario



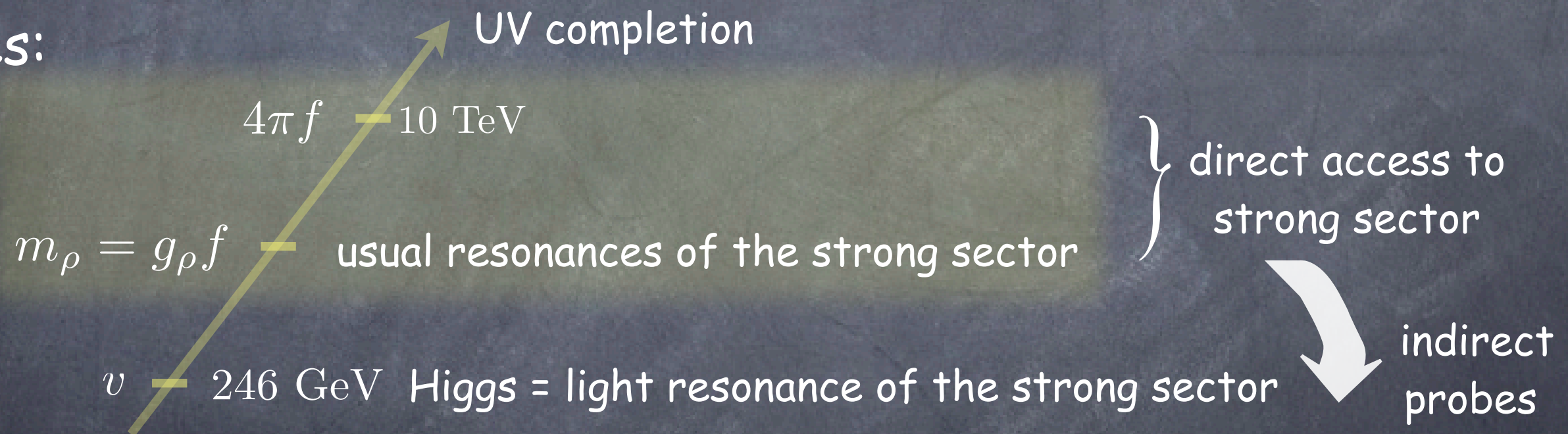
One way out: a light composite Higgs emerging from the strong sector

How to obtain a light composite Higgs?

Higgs=Pseudo-Goldstone boson of the strong sector



3 scales:

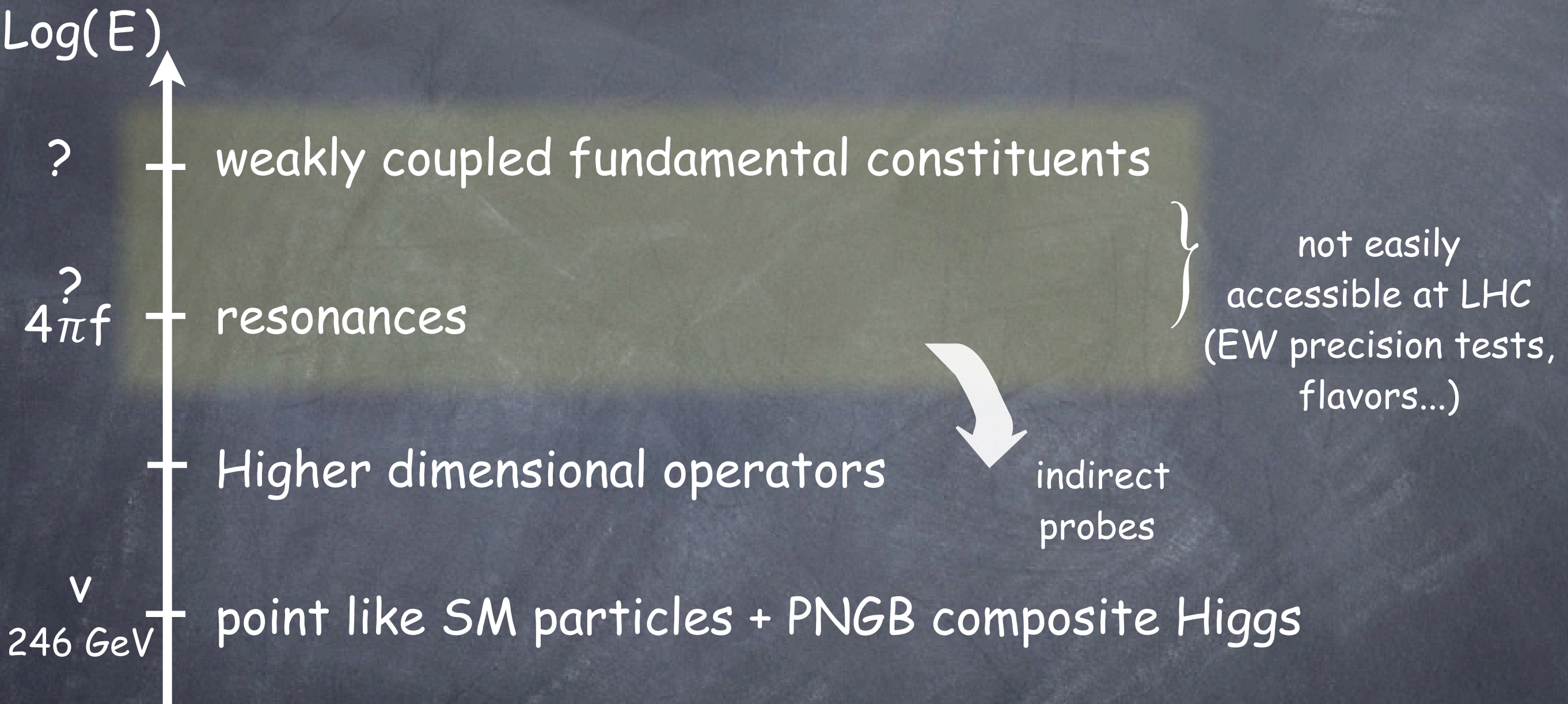


strong sector broadly characterized by 2 parameters

m_{ρ} = mass of the resonances

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

Physics of a light composite Higgs?



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

Continuous interpolation between SM and TC

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

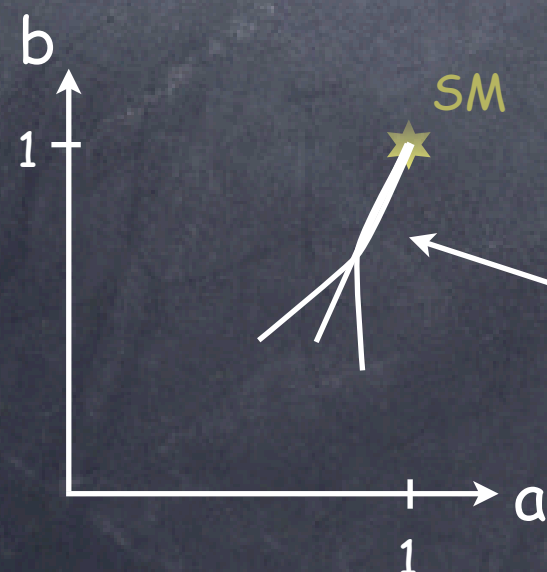
$\xi = 0$
SM limit

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



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

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

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

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

$$f^2 \text{tr} (\partial_\mu U^\dagger \partial^\mu U) = |\partial_\mu H|^2 + \frac{\#}{f^2} (\partial |H|^2)^2 + \frac{\#}{f^2} |H|^2 |\partial H|^2 + \frac{\#}{f^2} |H^\dagger \partial H|^2$$

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)

$$\frac{c_H}{2f^2} (\partial_\mu (|H|^2))^2$$

$$\frac{c_T}{2f^2} \left(H^\dagger \overleftrightarrow{D}^\mu H \right)^2$$

custodial breaking

$$\frac{c_y y_f}{f^2} |H|^2 \bar{f}_L H f_R + \text{h.c.}$$

$$\frac{c_6 \lambda}{f^2} |H|^6$$

■ Form factor operators (sensitive to the scale m_ρ)

$$\frac{i c_W}{2m_\rho^2} \left(H^\dagger \sigma^i \overleftrightarrow{D}^\mu H \right) (D^\nu W_{\mu\nu})^i$$

$$\frac{i c_B}{2m_\rho^2} \left(H^\dagger \overleftrightarrow{D}^\mu H \right) (\partial^\nu B_{\mu\nu})$$

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

$$\frac{i c_{HB}}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling: $h \rightarrow \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} \frac{g_\rho^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

$$\frac{c_g}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} \frac{y_t^2}{g_\rho^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}$$

Goldstone sym.

Anomalous Higgs Couplings

Giudice, Grojean, Pomarol, Rattazzi '07

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

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

Modified
Higgs propagator

$\sim$

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

$$\hat{T} = c_T \frac{v^2}{f^2} \implies |c_T \frac{v^2}{f^2}| < 2 \times 10^{-3} \quad \text{removed by custodial symmetry}$$

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

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



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

effective
Higgs mass

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

LEP II, for $m_h \sim 115 \text{ GeV}$: $c_H v^2 / f^2 < 1/3 \sim 1/2$

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 $\nearrow$

Higgs fermion interactions $\nearrow$

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

$\Rightarrow$ FCNC

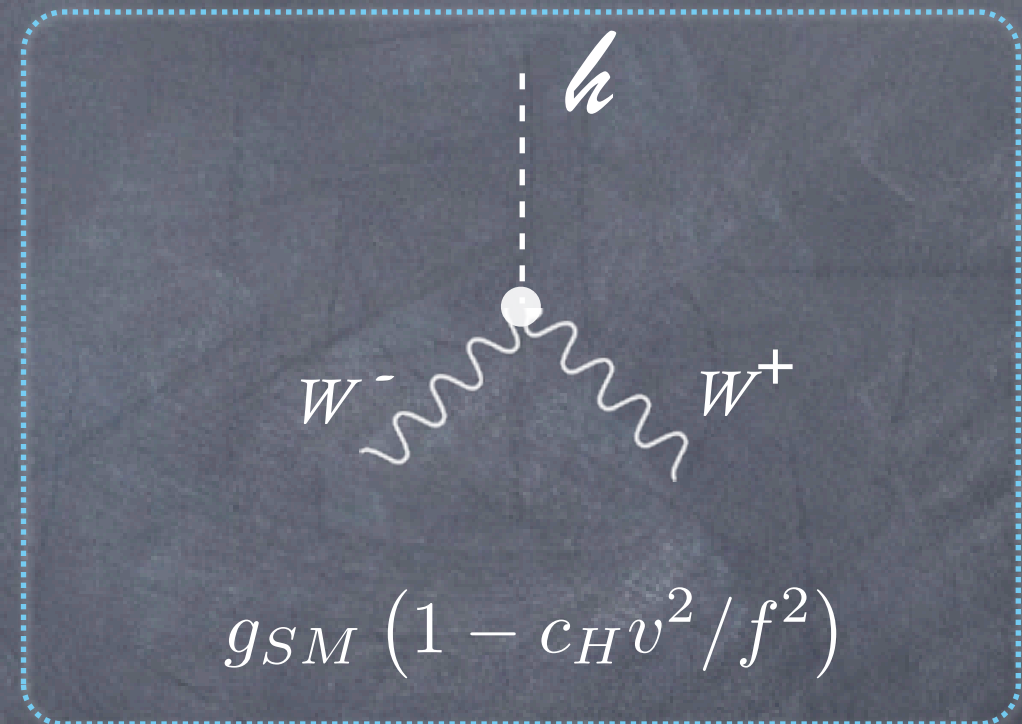
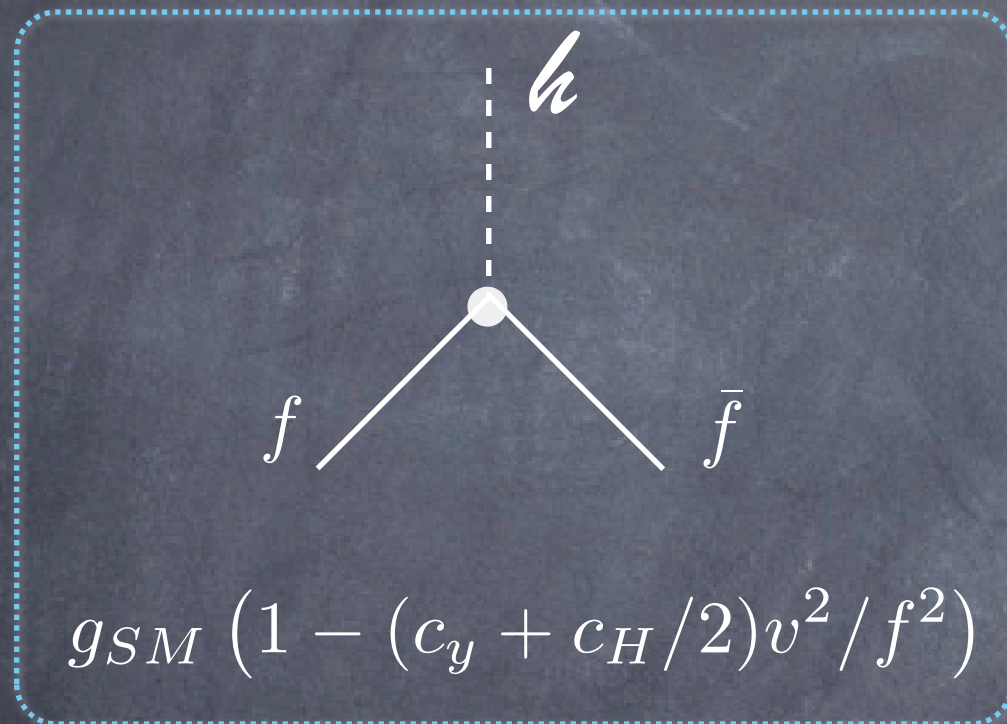
SILH: c_γ is flavor universal

$\Rightarrow$ Minimal flavor violation built in

Higgs anomalous couplings

Lagrangian in unitary gauge

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



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



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

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

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

Fermions embedded in spinorial of $SO(5)$

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



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

universal shift of the couplings
no modifications of BRs

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

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



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

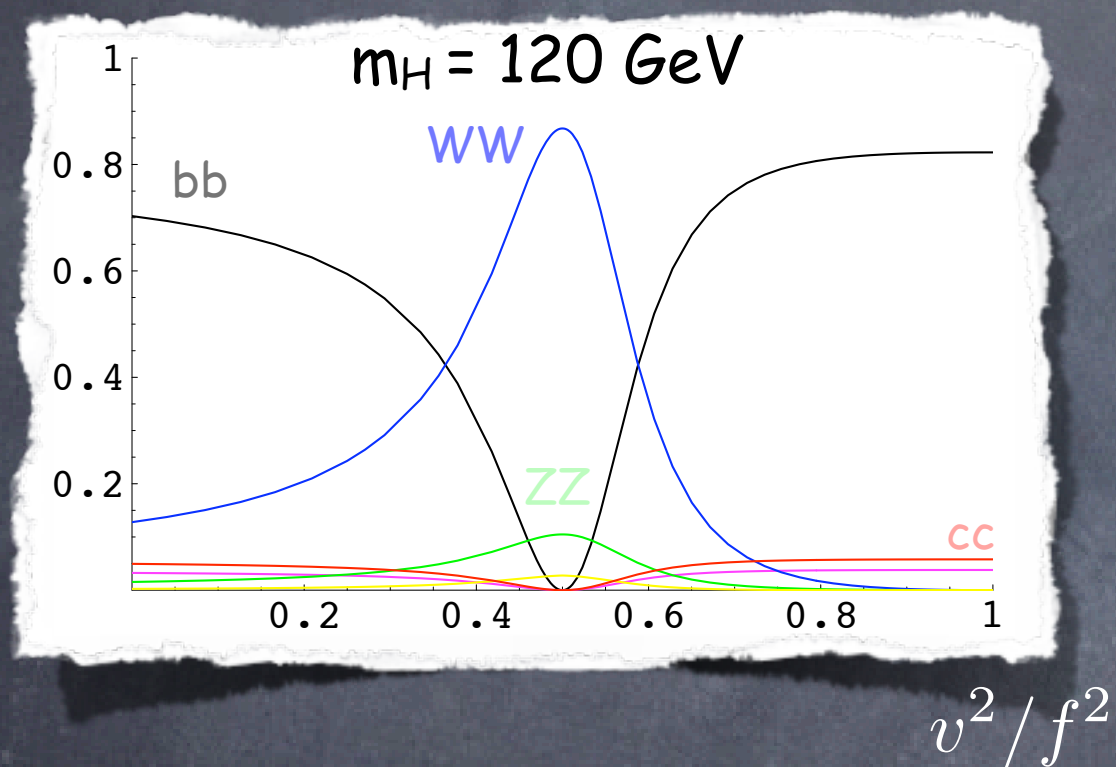
BRs now depends on v/f

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

Higgs BRs

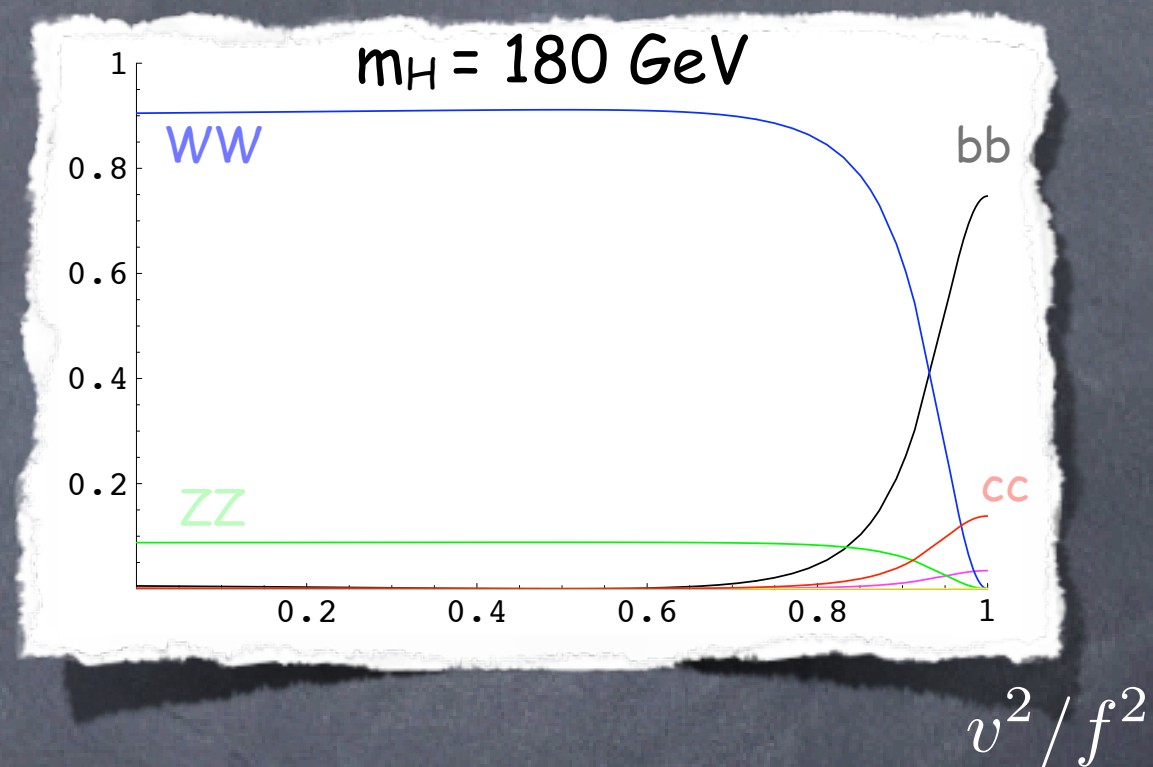
Fermions embedded in 5+10 of $SO(5)$

BRs



$h \rightarrow WW$ can dominate
even for low Higgs mass

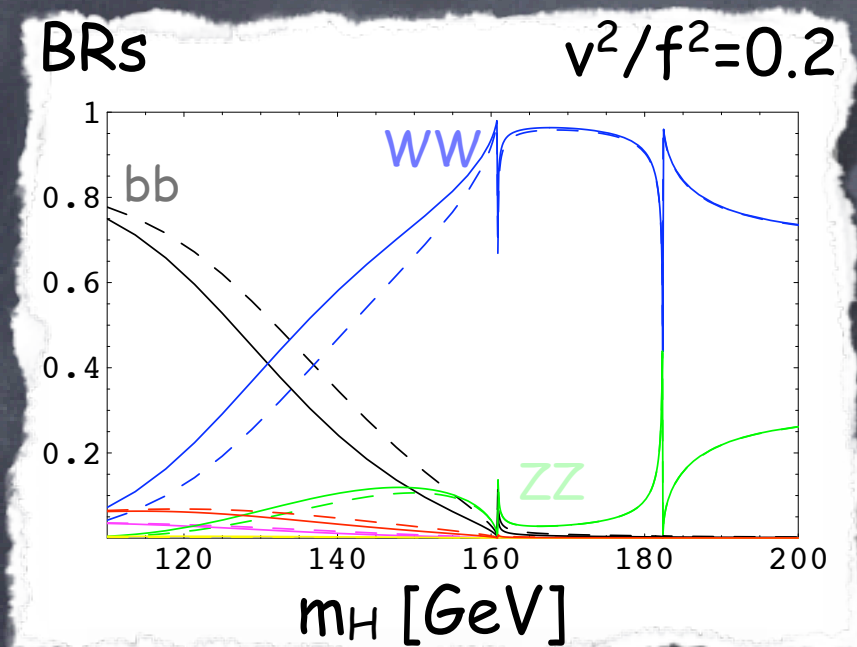
BRs



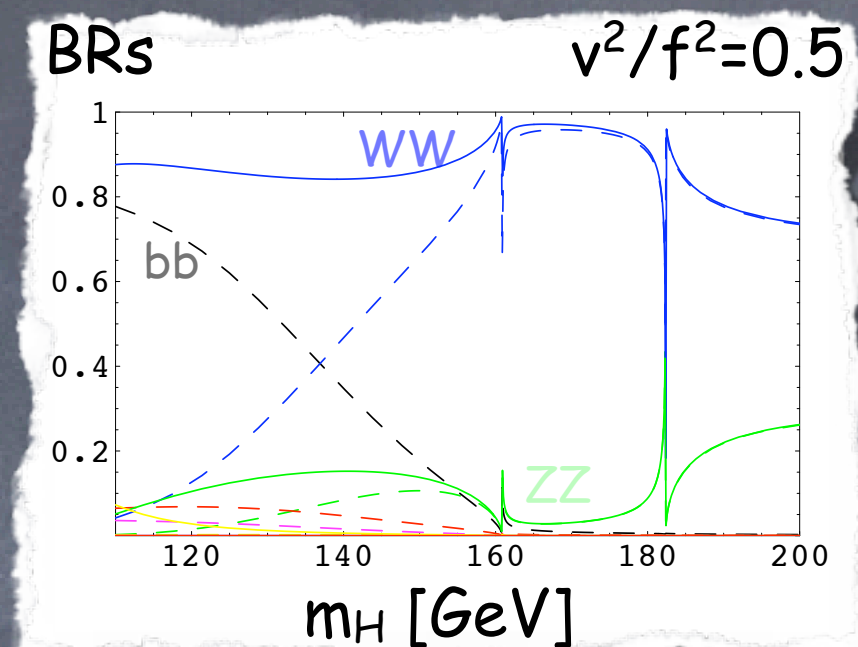
BRs remain SM like except
for very large values of v/f

Higgs BRs and total width

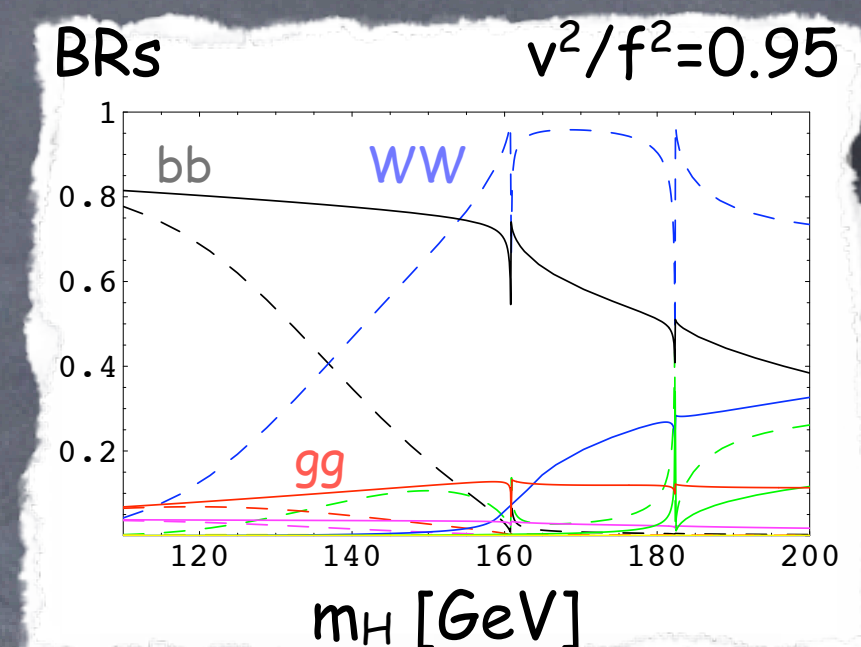
Fermions embedded in 5+10 of $SO(5)$



slight modifications

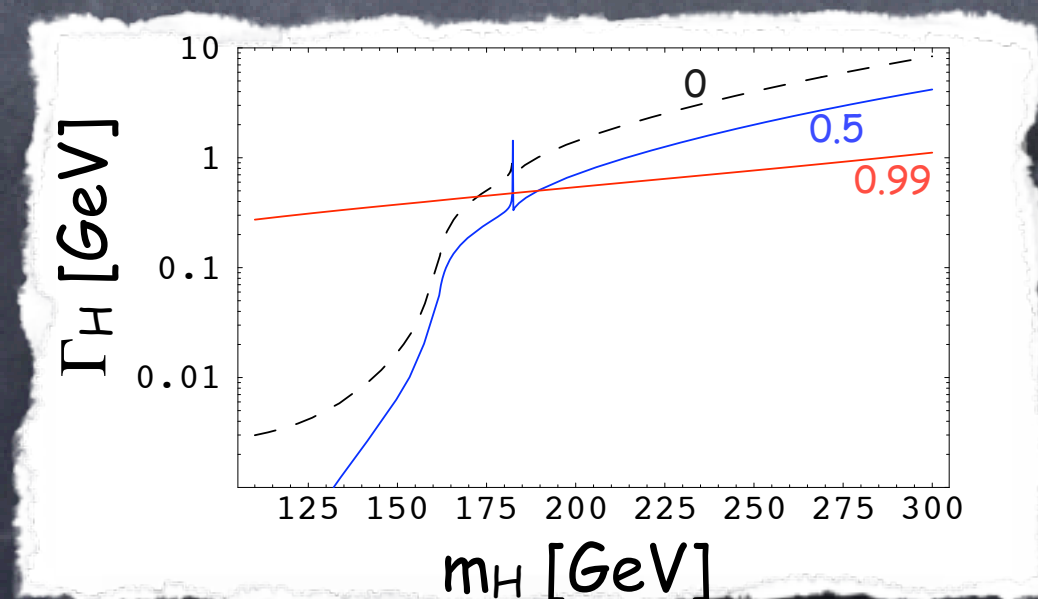


suppress bb



suppress WW

Higgs total width



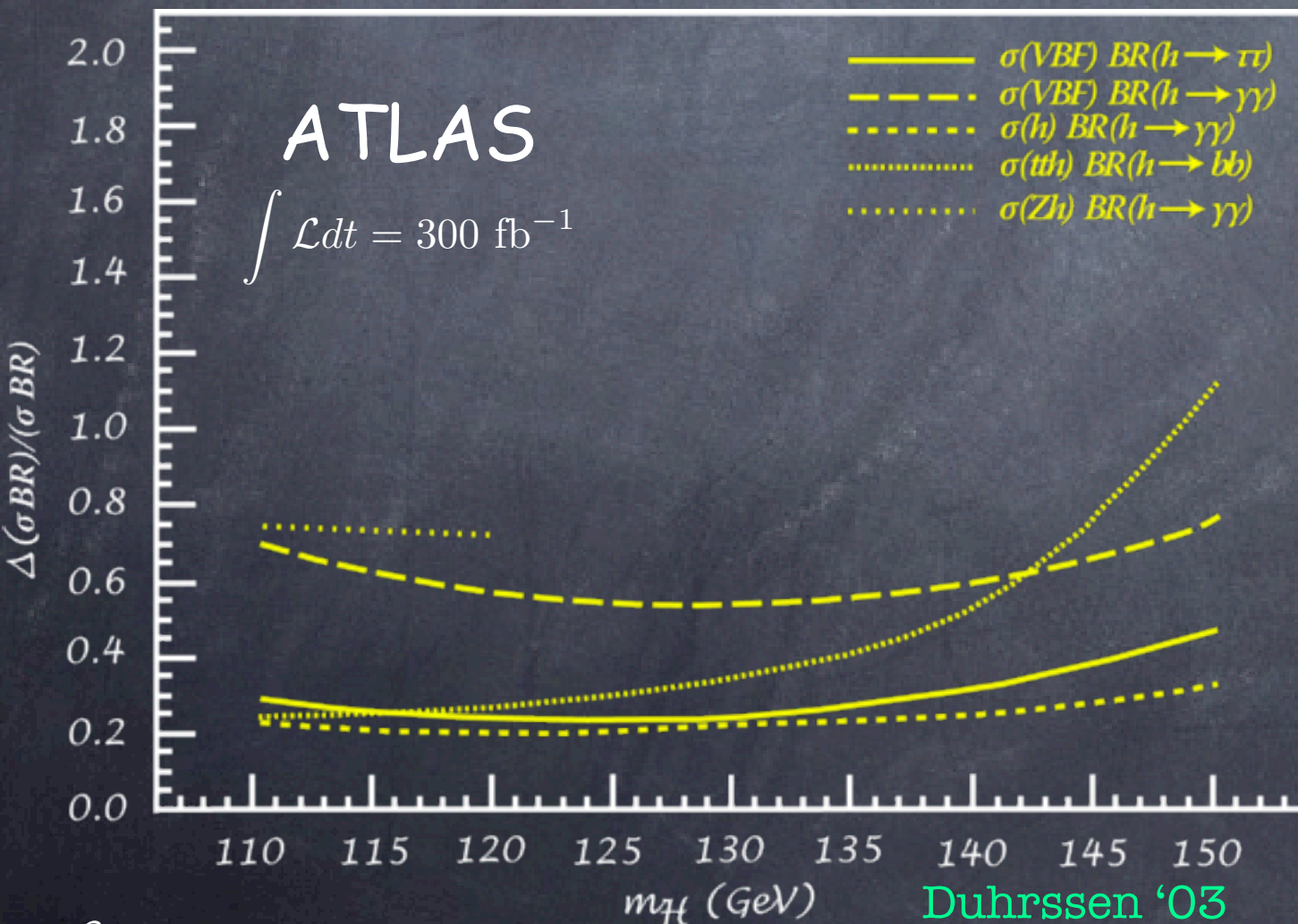
Composite Higgs

Higgs anomalous couplings @ LHC

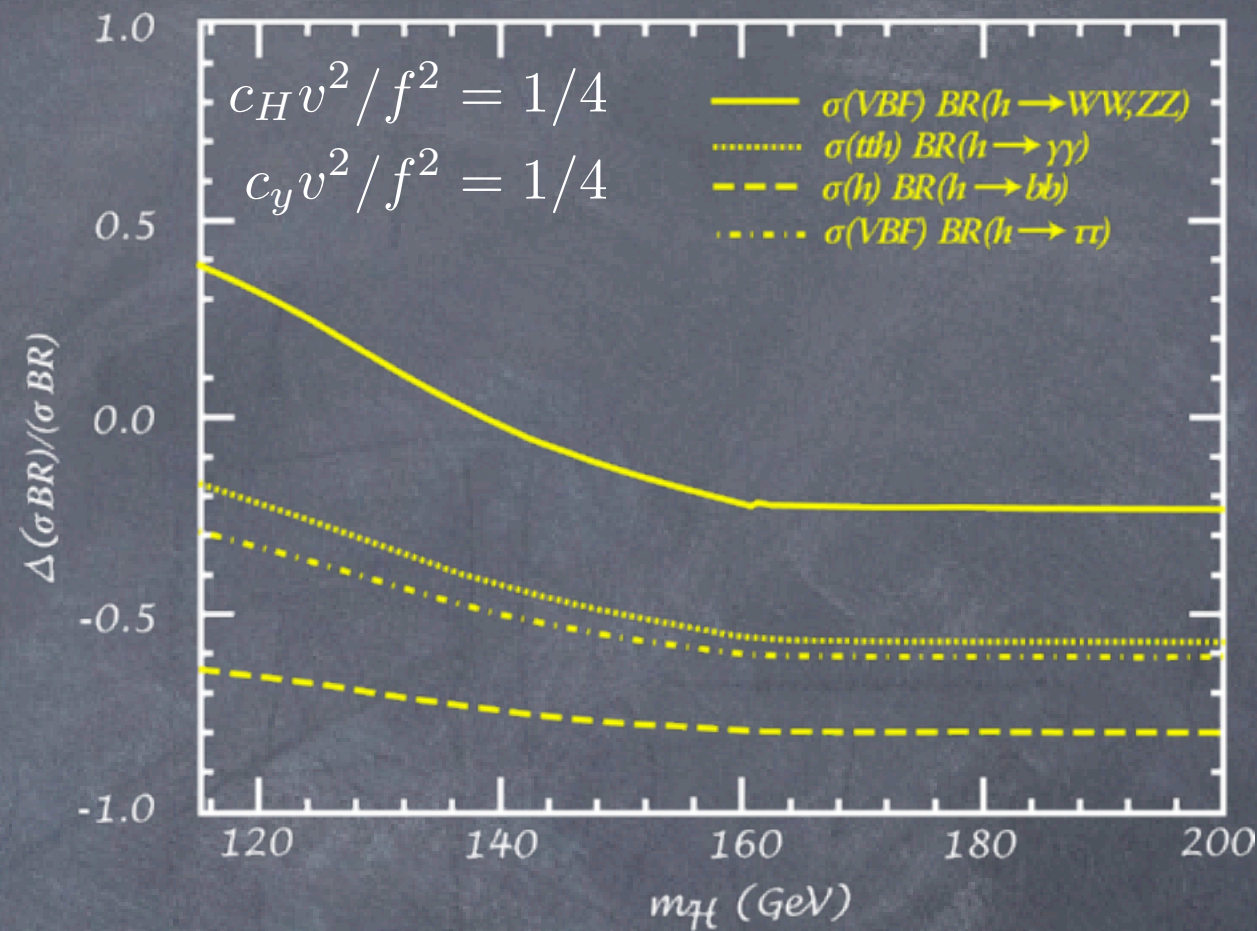
$$\Gamma(h \rightarrow f\bar{f})_{\text{SILH}} = \Gamma(h \rightarrow f\bar{f})_{\text{SM}} [1 - (2c_y + c_H) v^2 / f^2]$$

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

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

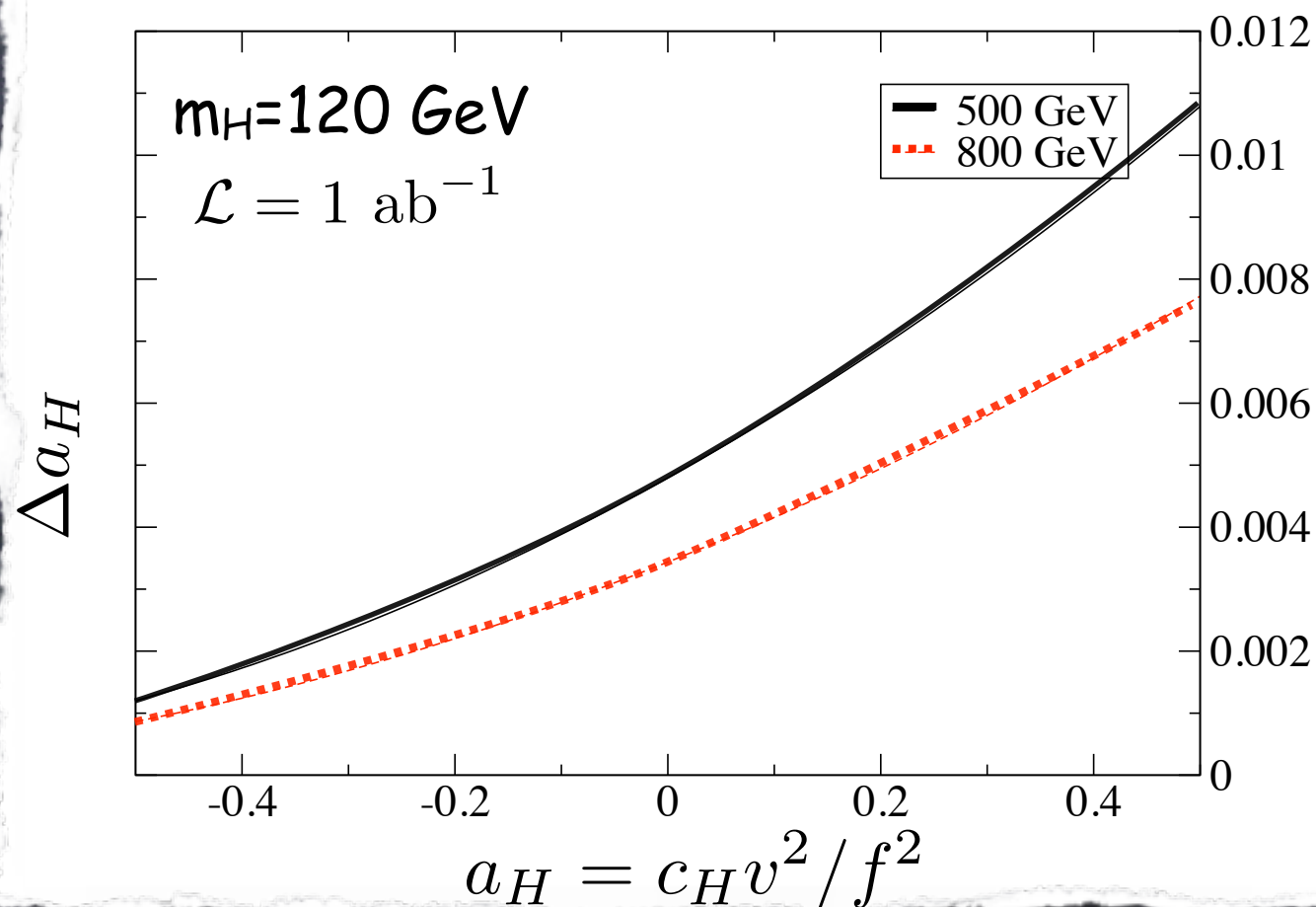
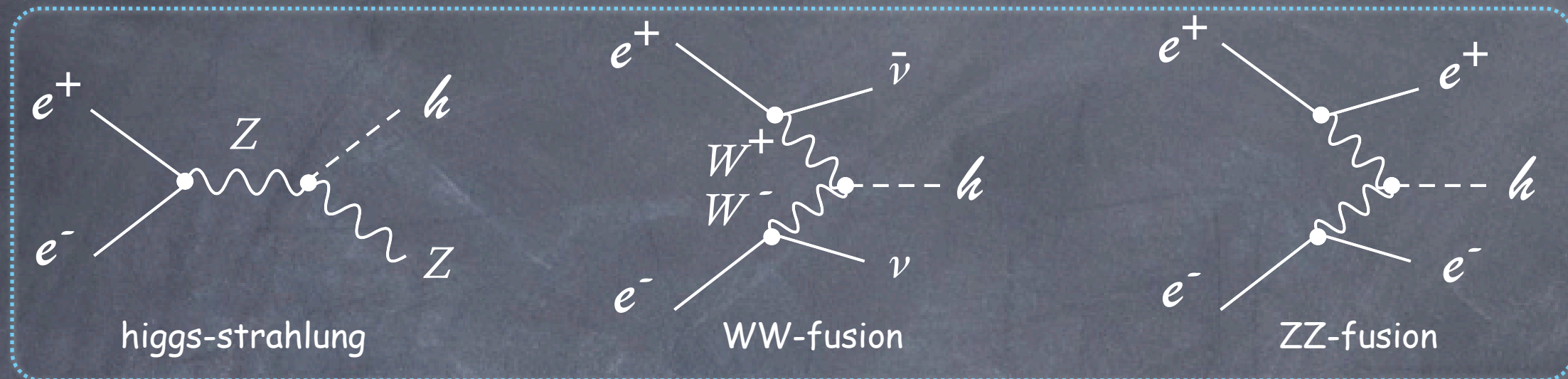
i.e. $4\pi f \sim 5 - 7 \text{ TeV}$

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

Higgs anomalous couplings @ LC

Barger et al. hep-ph/0301097

single Higgs production



$m_H = 120 \text{ GeV}$

$$\Delta a_H \sim 0.005 \Rightarrow 4\pi f \sim 44 \text{ TeV}$$

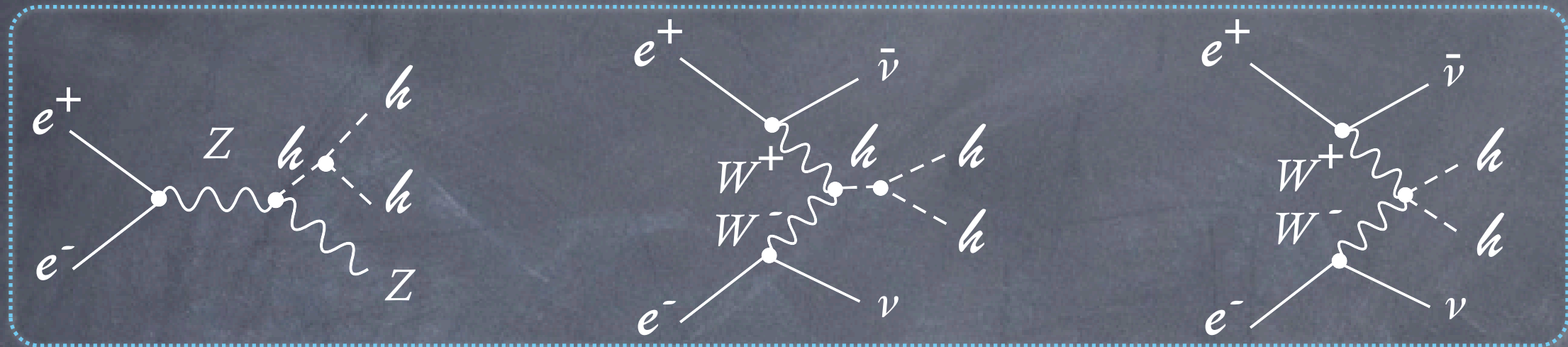
$m_H = 240 \text{ GeV}$

$$\Delta a_H \sim 0.02 \Rightarrow 4\pi f \sim 22 \text{ TeV}$$

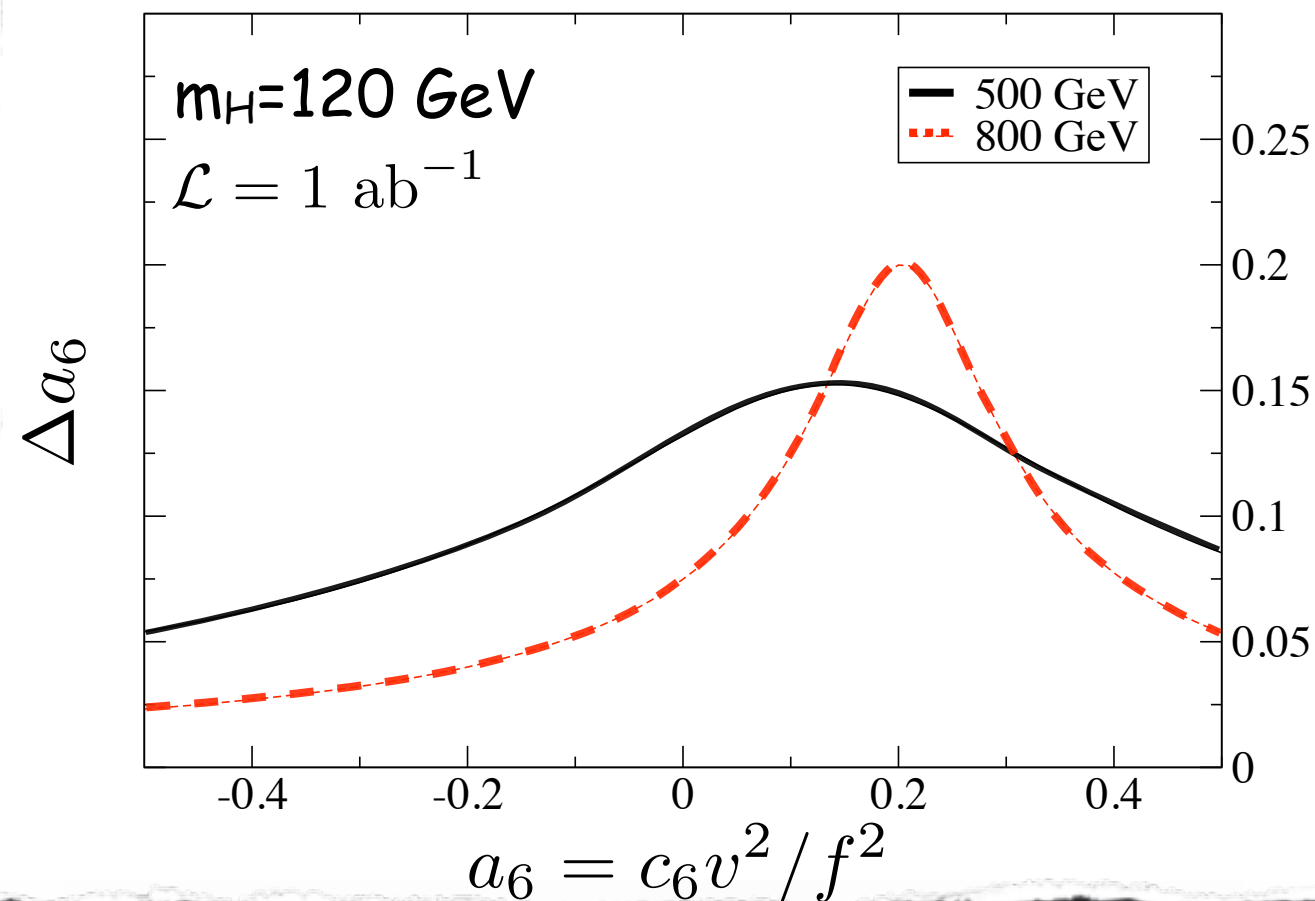
Higgs anomalous (self-)couplings @ LC

Barger et al. hep-ph/0301097

double Higgs production



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



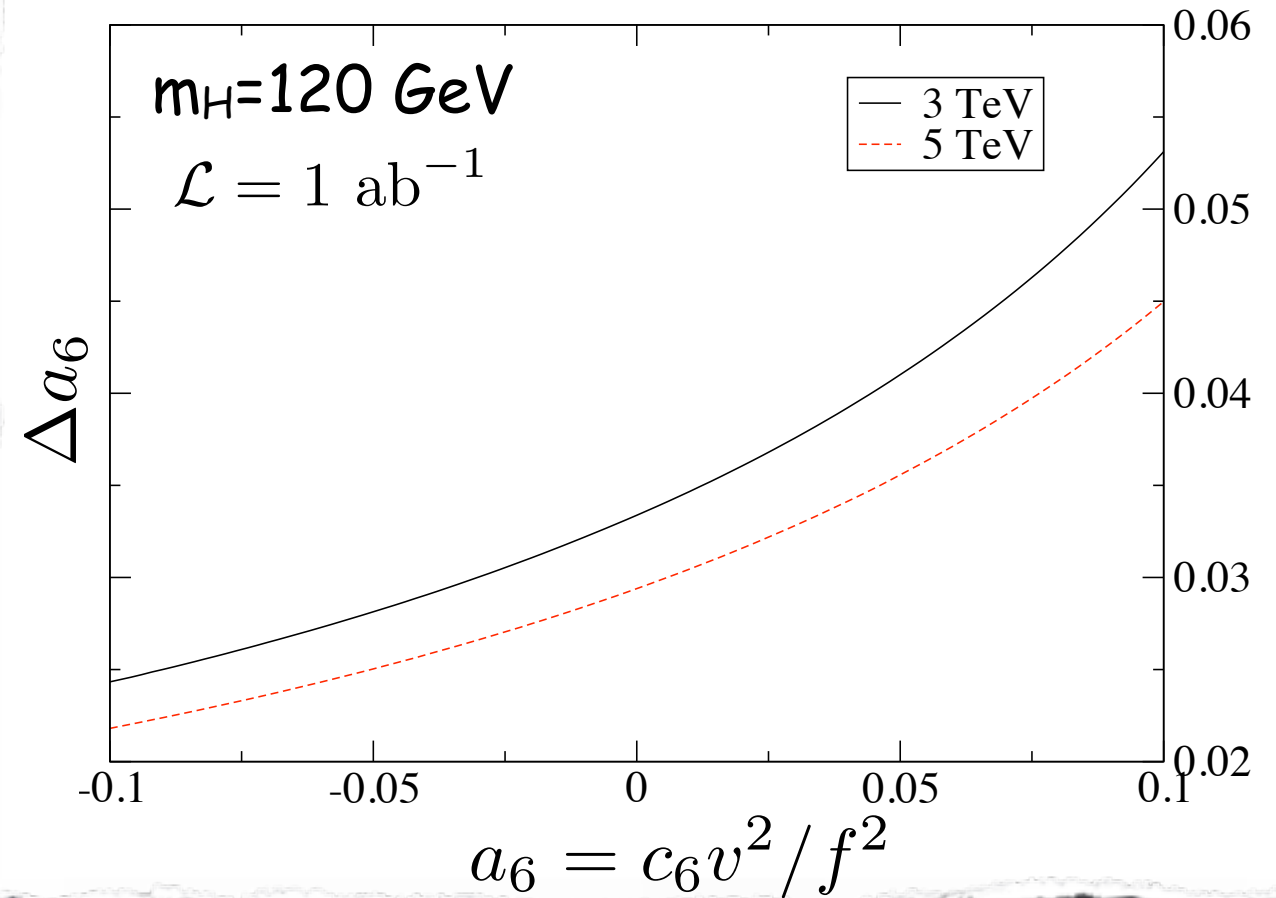
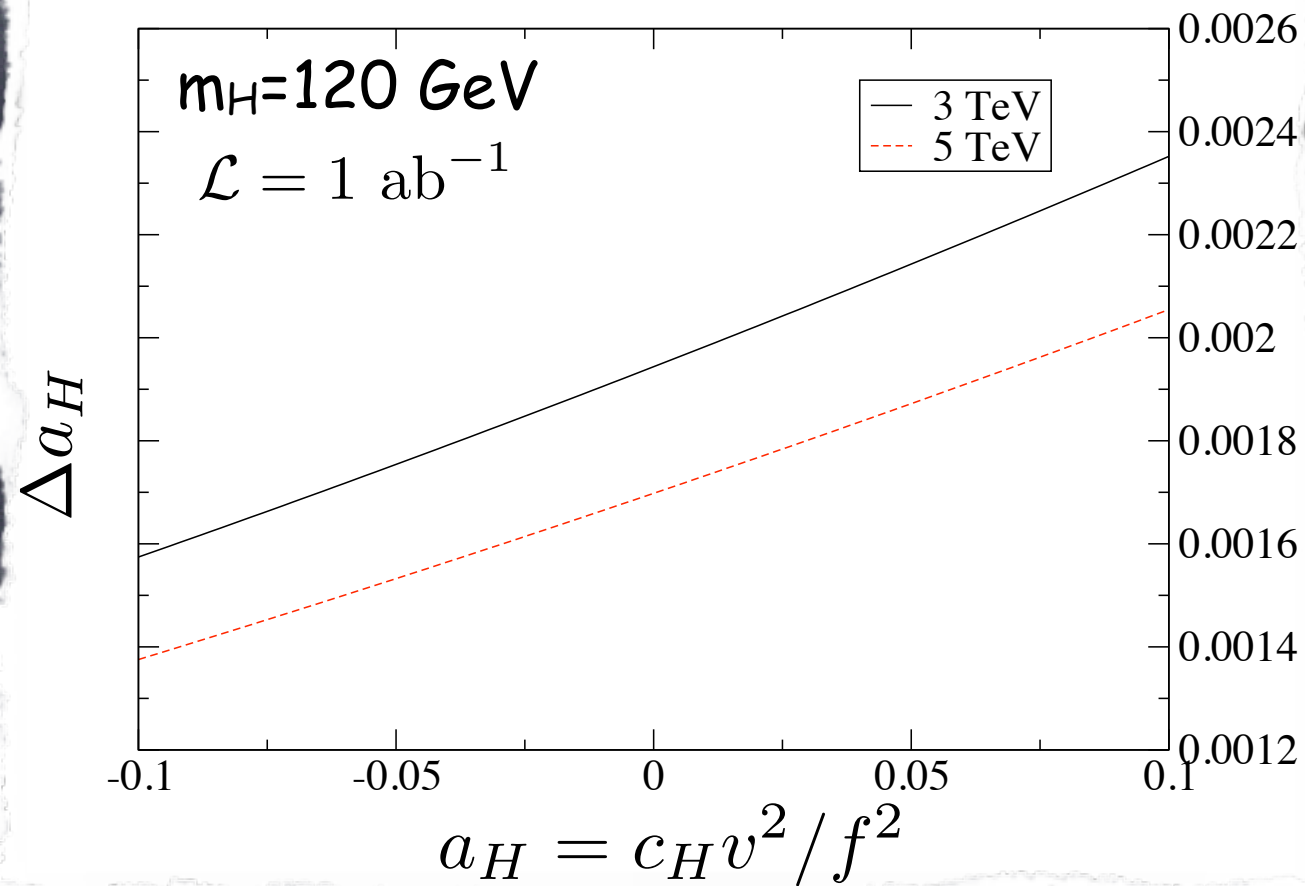
it allows to constrain a_6

$$m_H = 120 \text{ GeV}$$

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

Higgs anomalous couplings @ CLIC

Barger et al. hep-ph/0301097



$$\Delta a_H \sim 0.002 \Rightarrow 4\pi f \sim 70 \text{ TeV}$$

$$\Delta a_6 \sim 0.04 \Rightarrow 4\pi f \sim 15 \text{ TeV}$$

a factor 2 improvement from ILC

Triple gauge boson couplings (TGC) @ LC

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

TGC are generated by heavy resonances

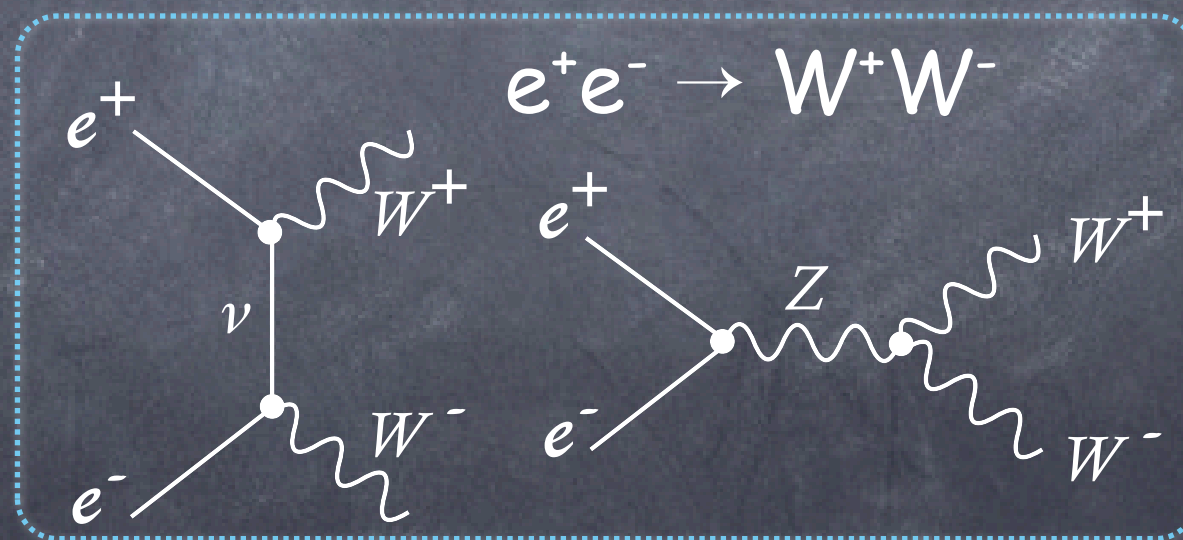
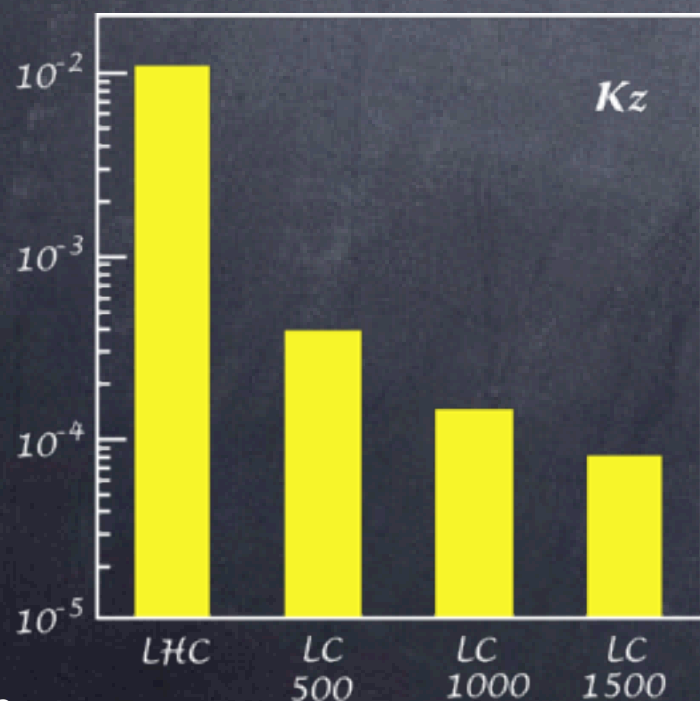
$$g_1^Z = \frac{m_Z^2}{m_\rho^2} c_W \quad \kappa_\gamma = \frac{m_W^2}{m_\rho^2} \left(\frac{g_\rho}{4\pi} \right)^2 (c_{HW} + c_{HB}) \quad \kappa_Z = g_1^Z - \tan^2 \theta_W \kappa_\gamma$$

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

sensitive to resonance
up to $m_\rho \sim 800 \text{ GeV}$

not competitive with the measure of S at LEP II

@ ILC



0.1% accuracy $\Rightarrow$

sensitive to resonance
up to $m_\rho \sim 8 \text{ TeV}$

T. Abe et al, Snowmass '01

Composite Higgs

Strong WW scattering

Giudice, Grojean, Pomarol, Rattazzi '07

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

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

Modified
Higgs propagator

$\sim$

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)

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

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

LET=SM-Higgs



$$\mathcal{A}_\xi = \xi \mathcal{A}_{\text{LET}}$$

Composite Higgs

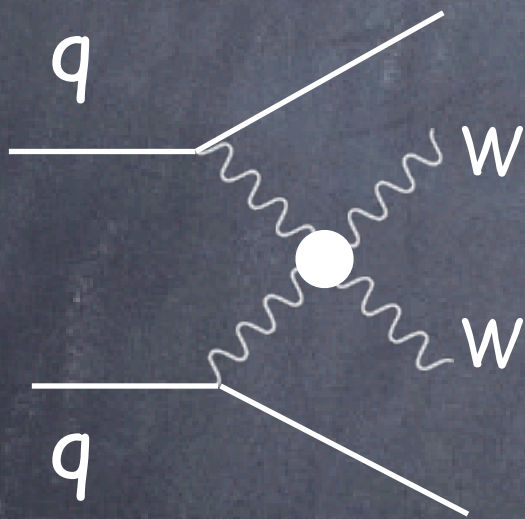
Strong WW scattering @ LHC

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

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

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

$$\mathcal{A}(Z_L^0 Z_L^0 \rightarrow Z_L^0 Z_L^0) = 0$$



$$\sigma(pp \rightarrow V_L V_L X)_\xi = \xi^2 \sigma(pp \rightarrow V_L V_L X)_{\text{LET}}$$

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

Bagger et al '95
Butterworth et al. '02

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

Scale of Strong WW scattering?

NDA estimates

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

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

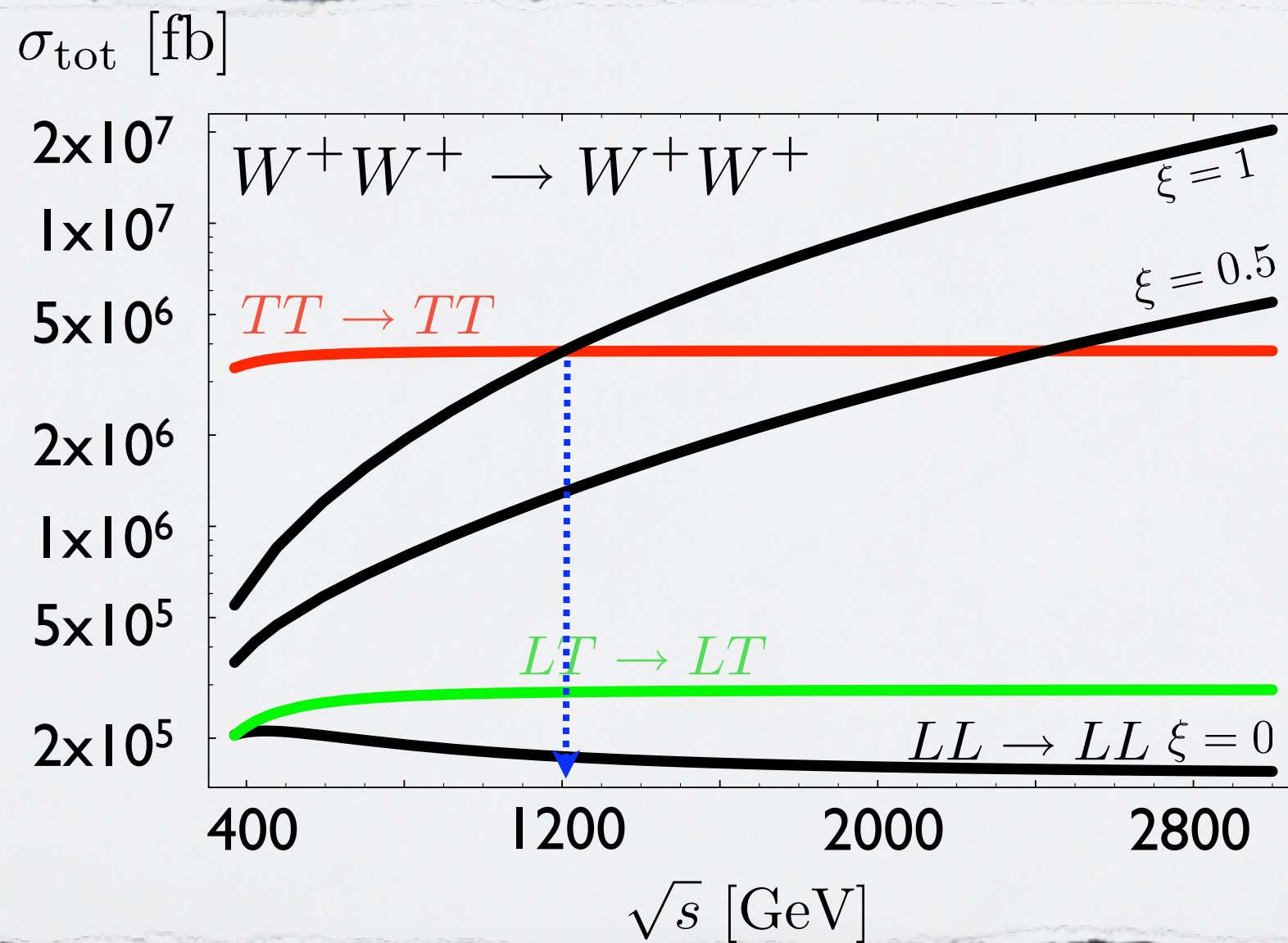
$$\mathcal{A}_{LL \rightarrow LL} \sim \mathcal{A}_{TT \rightarrow TT}$$

for

$$\sqrt{s} \sim 4M_W$$

EW background

disentangling L from T polarization is hard



The onset of strong scattering is delayed to larger energies due to the dominance of $TT \rightarrow TT$ 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 γ and Z in the t- and u-channels

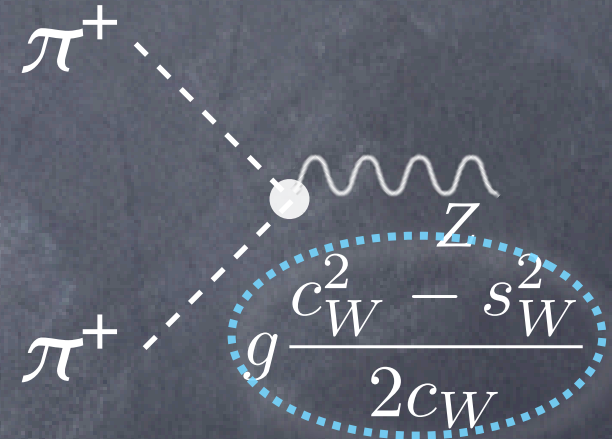
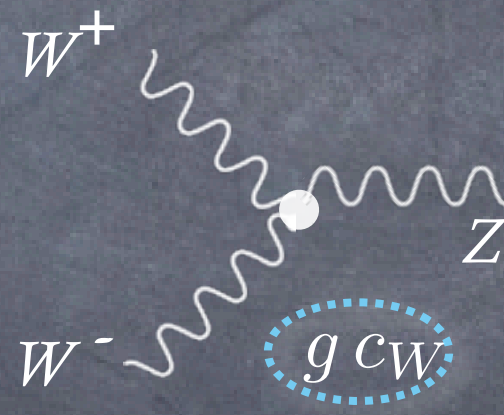
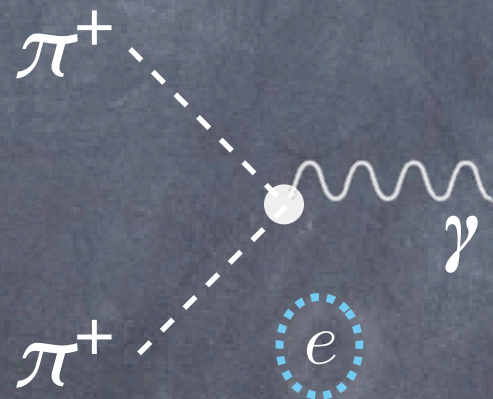
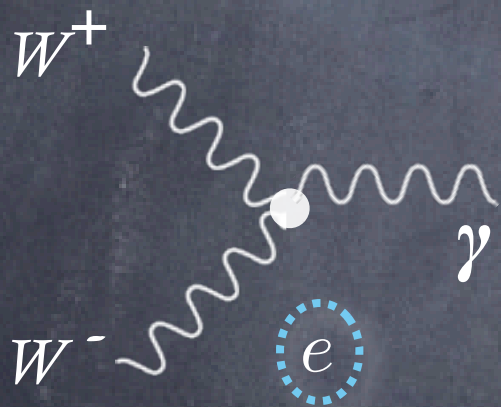
$W^+W^+ \rightarrow W^+W^+$

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

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

$a_\gamma = 2 \cdot (\text{electric charge of } W^+)^2$
universal for T and L

$a_Z = 2 \cdot (\text{"SU(2) charge" of } W^+)^2$
different for T and L



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

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

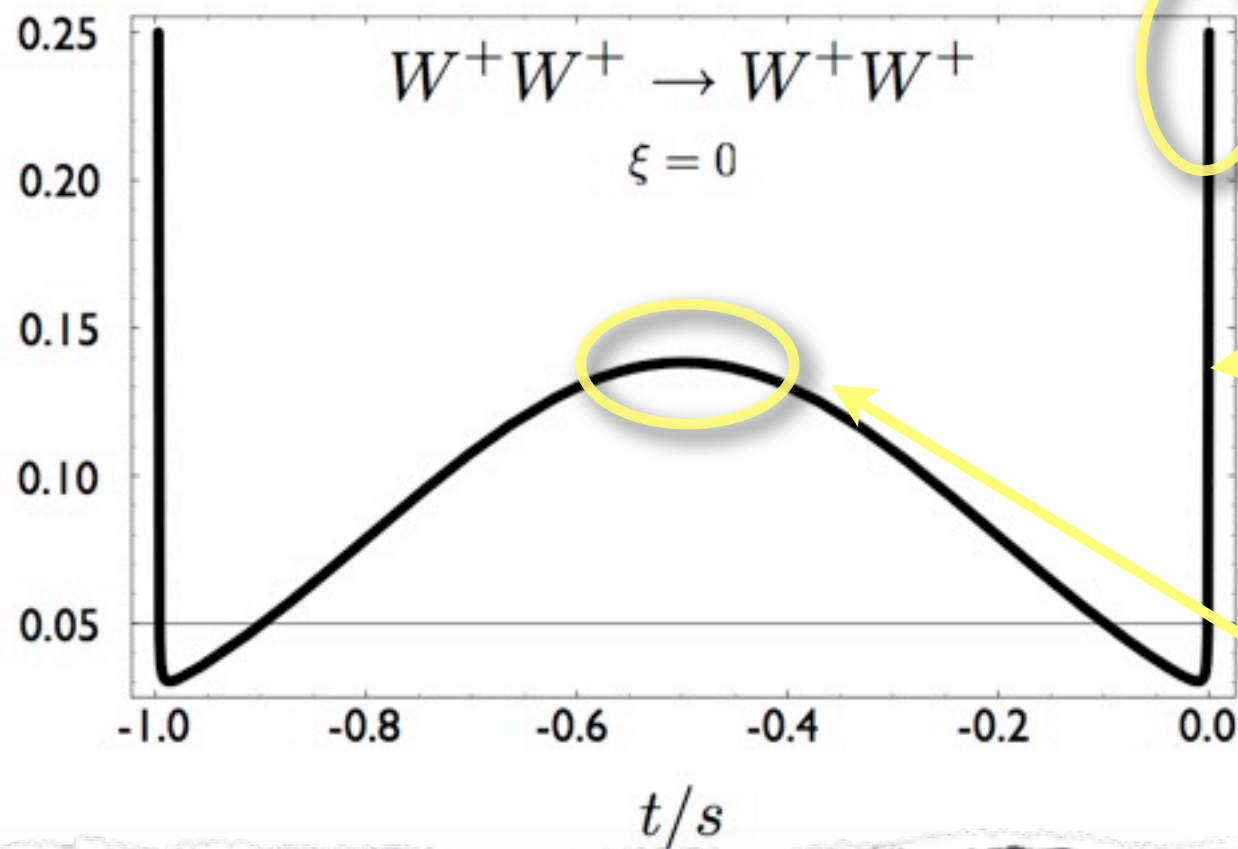
σ_{tot} is only sensitive to IR physics: not good observable to probe EWSB sector

EW bckg in the central region (SM)

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

$$\frac{d\sigma_{LL}/dt}{d\sigma_{TT}/dt}$$

$m_H=180 \text{ GeV}$



γ pole only
 $\Rightarrow$ multiplicity factor

γ and Z poles

poles + constant regular piece

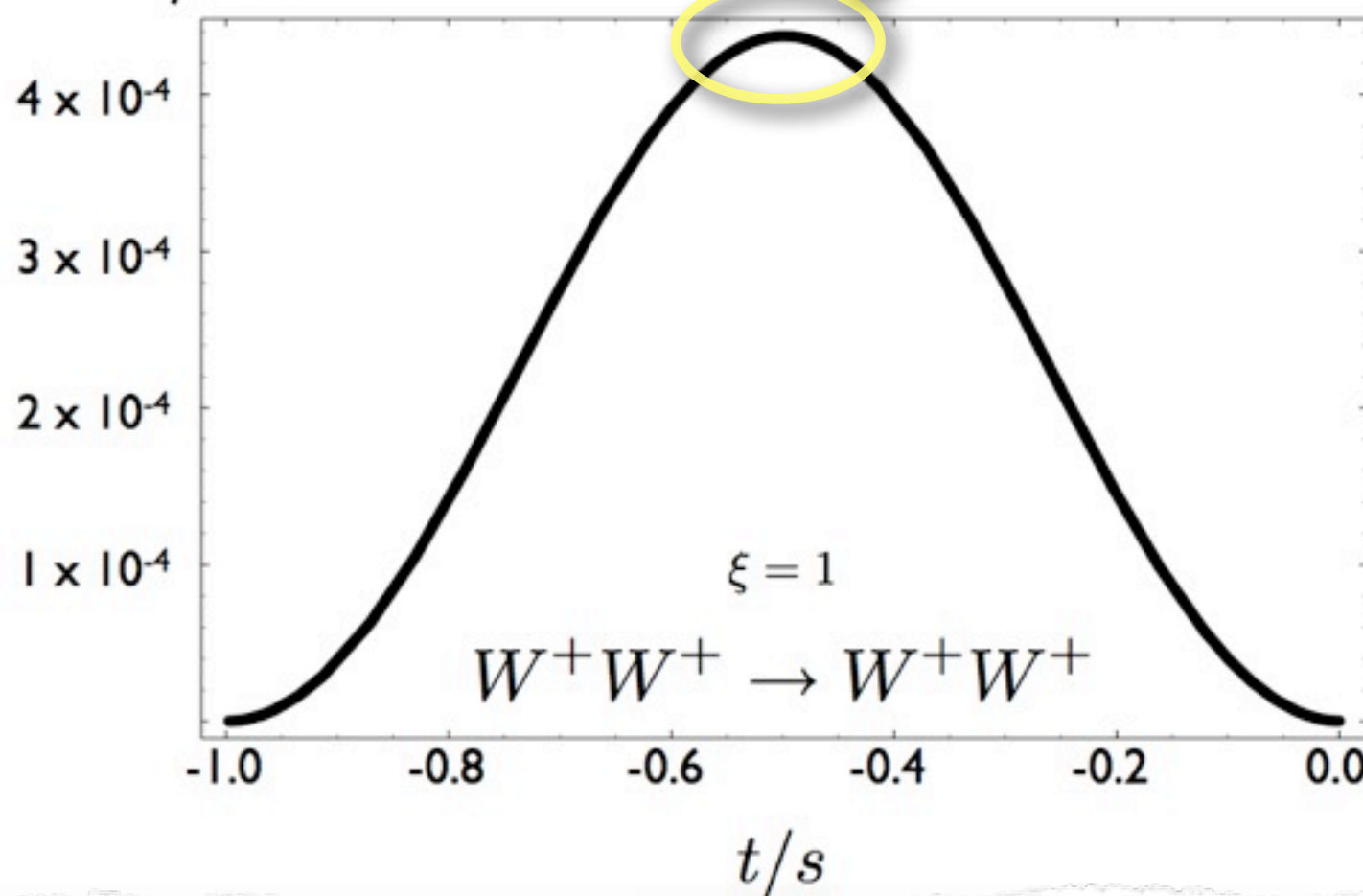
$$\frac{d\sigma_{LL}/dt}{d\sigma_{TT}/dt} = \frac{(c_W^2 M_H^2 + 3M_W^2)^2}{576 c_W^4 M_W^4} \sim 0.15$$

small number again as the result of multiplicity and larger SU(2) charges for T polarizations

EW bckg in the central region ($\xi=1$)

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

$$\frac{d\sigma_{LL}/dt}{d\sigma_{TT}/dt} \bigg/ \frac{s^2}{M_W^4}$$



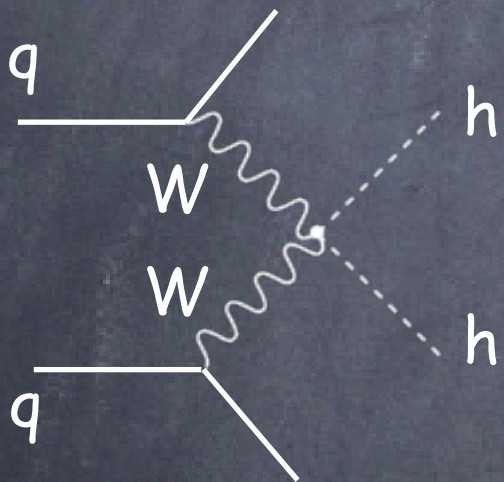
2 orders of magnitude
smaller than NDA
estimates...

Strong Higgs production

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

strong boson scattering $\Leftrightarrow$ strong Higgs production

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

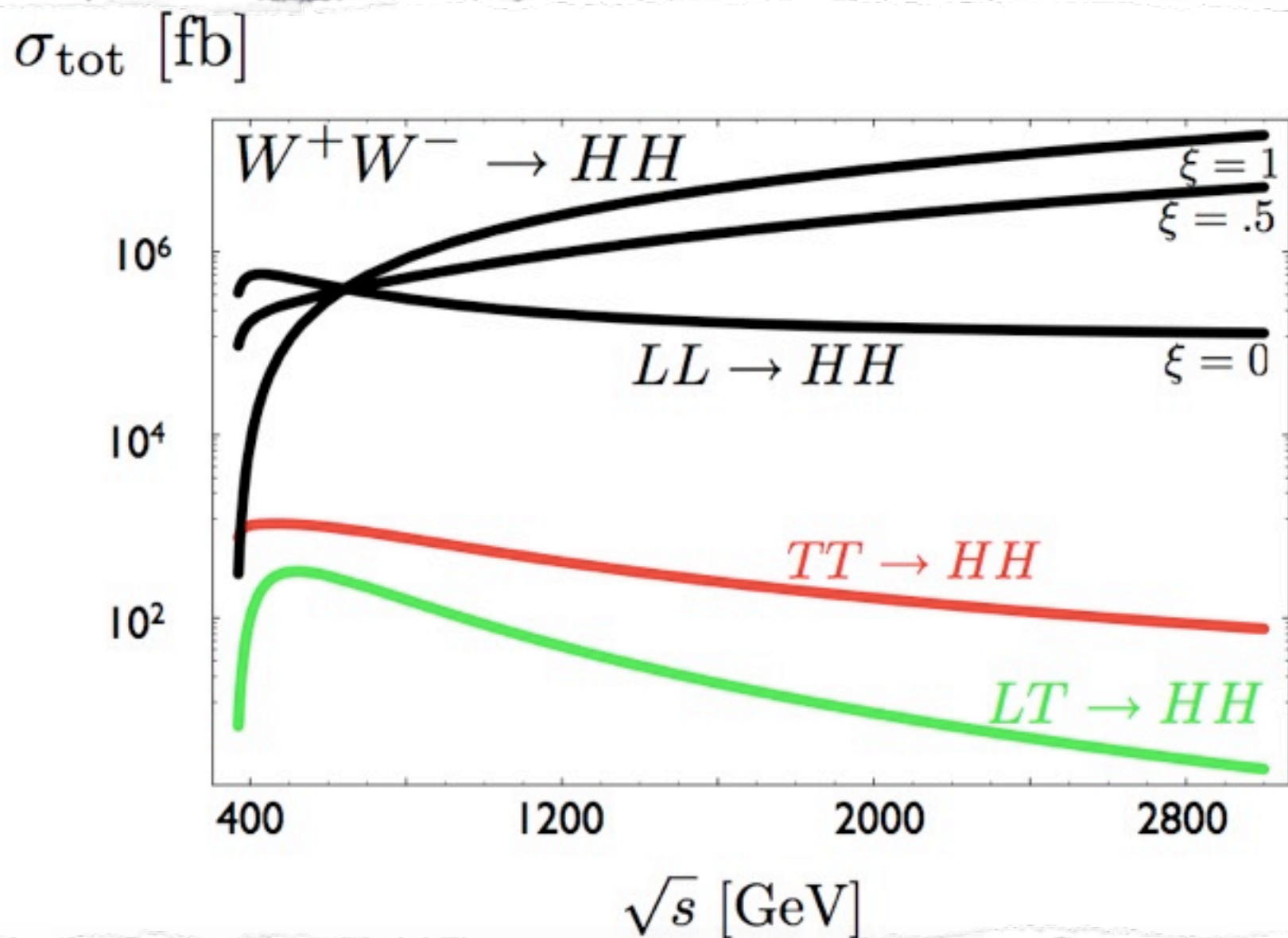


signal: $hh \rightarrow bbbb$

$hh \rightarrow 4W \rightarrow 3\ell^\pm 3\nu + \text{jets}$

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

EW bckg for $WW \rightarrow hh$



$$\sigma = \frac{g^4 s \xi^2}{16\pi M_W^4}$$

$$\sigma = \frac{g^4}{32\pi(M_\gamma^2 + M_W^2)}$$

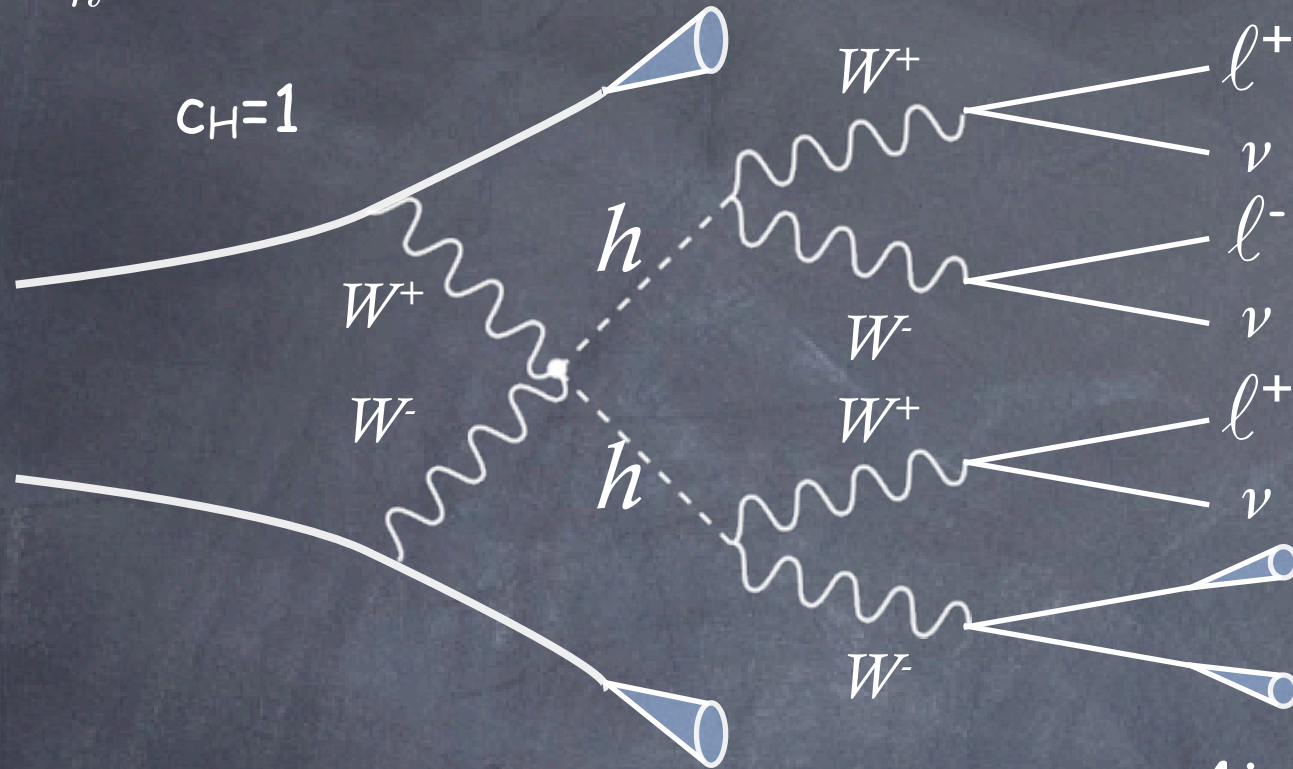
$$\frac{d\sigma^{LL \rightarrow hh}/dt}{d\sigma^{TT \rightarrow hh}/dt} = \frac{1}{8} \frac{\xi^2}{\xi^2 + (1 - \xi)^2} \left(\frac{\sqrt{s}}{M_W} \right)^4$$

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

$$m_h = 180 \text{ GeV}$$



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

events after accept. cuts (with 300 fb⁻¹)

$v/f = 1$	$v/f = \sqrt{.8}$	$v/f = \sqrt{.5}$	$v/f = 0$
14.5	9.8	4.3	0.5
19.5	13.2	5.9	0.8

4jets →

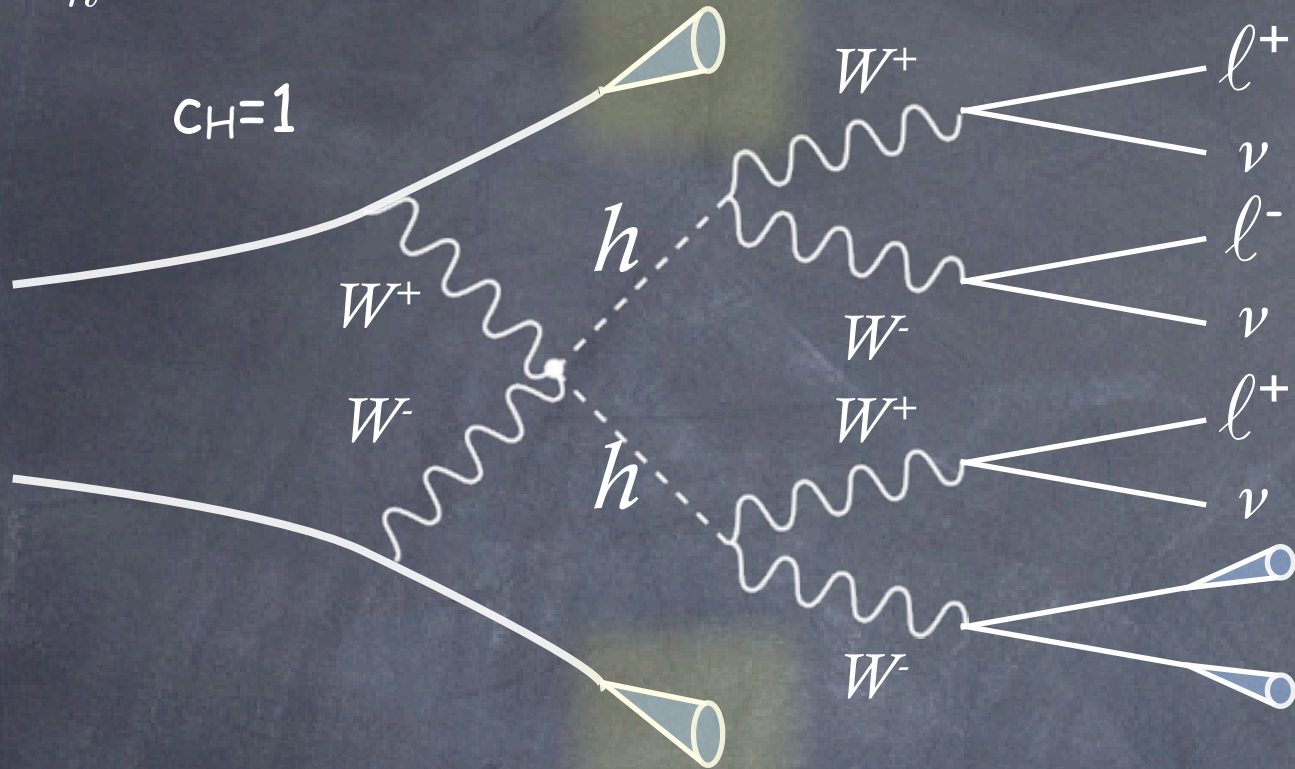
3jets →

Dominant backgrounds

	4jets	3jets
$t\bar{t}2W (\rightarrow b\bar{b}4W \rightarrow 3l3\nu2b2j)$	94 evts	223 evts
$t\bar{t}W2j (\rightarrow b\bar{b}3W2j \rightarrow 3l3\nu2b2j)$	122 evts	230 evts
$3W4j (\rightarrow 3l3\nu4j)$	26 evts	94 evts
$Wll4j (\rightarrow 3l1\nu4j)$	580 evts	1580 evts

Strong Higgs production: 3L+4jets

$$m_h = 180 \text{ GeV}$$



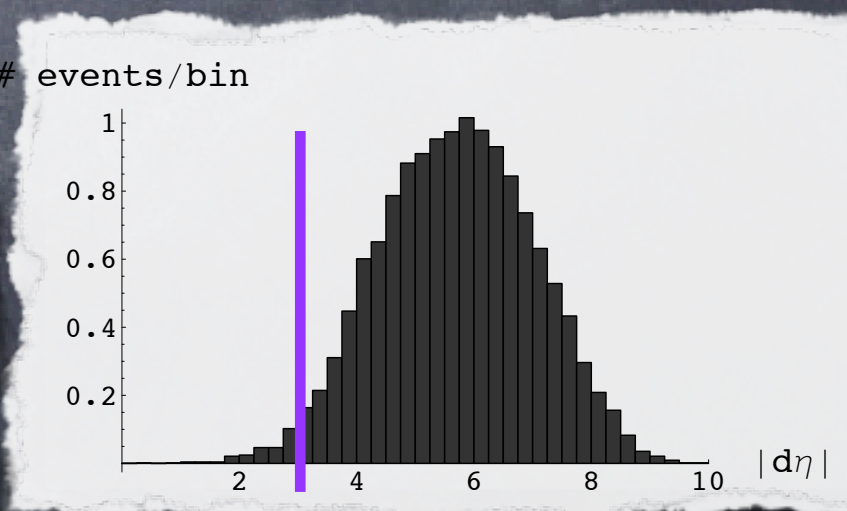
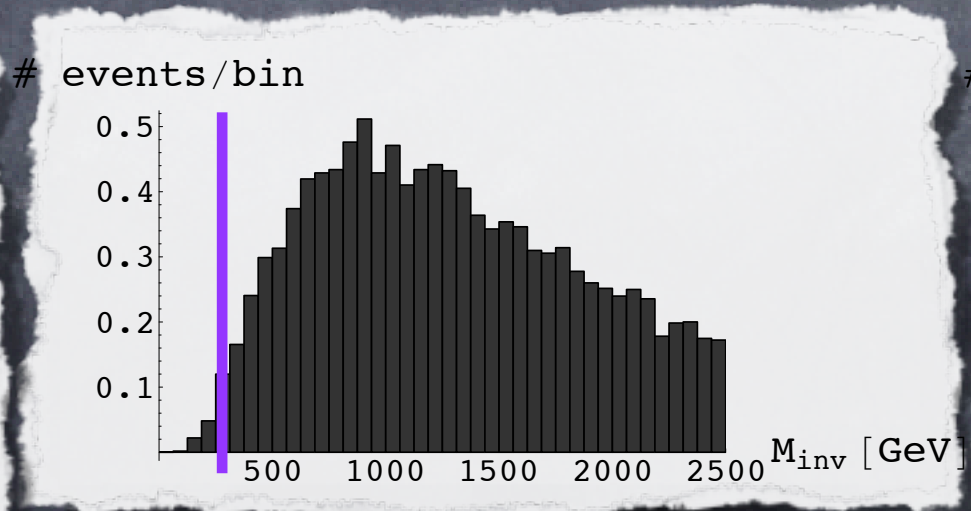
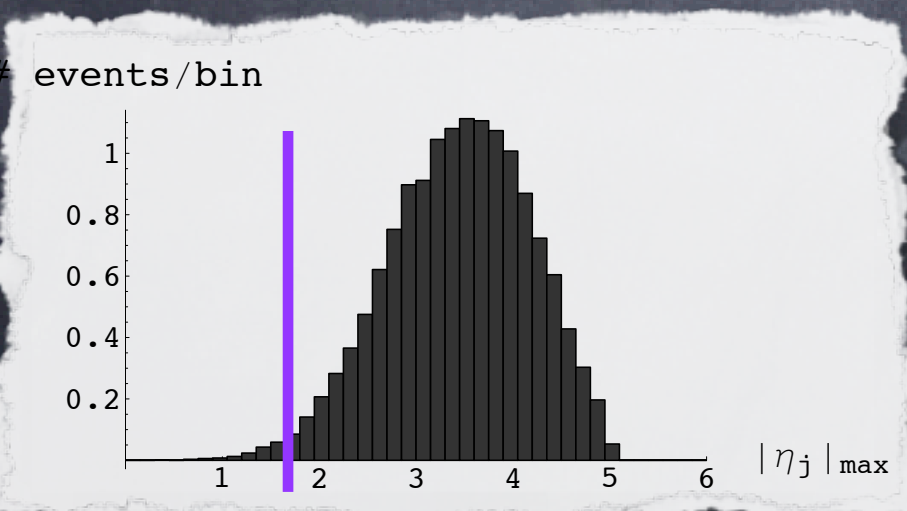
① identify the "external" jets:

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

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

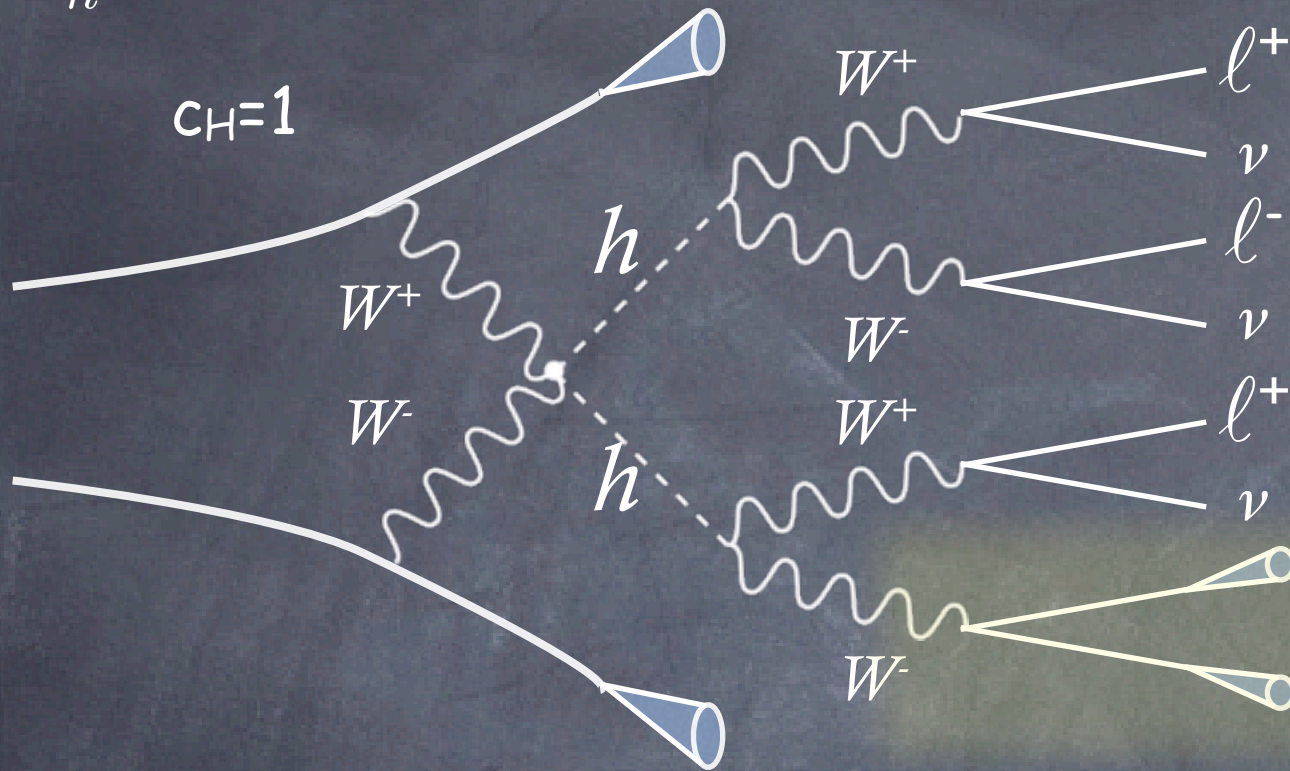
$$M_{jj} \geq 330 \text{ GeV}$$

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



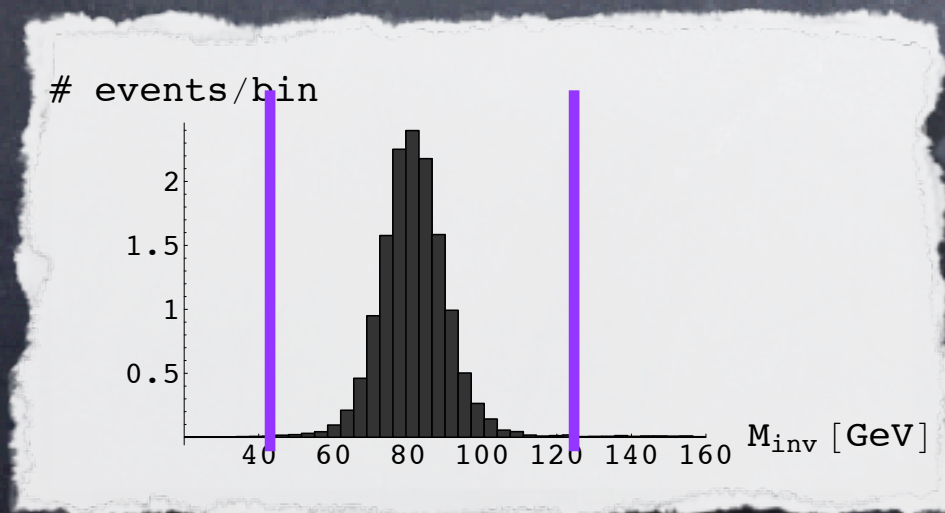
Strong Higgs production: 3L+4jets

$$m_h = 180 \text{ GeV}$$



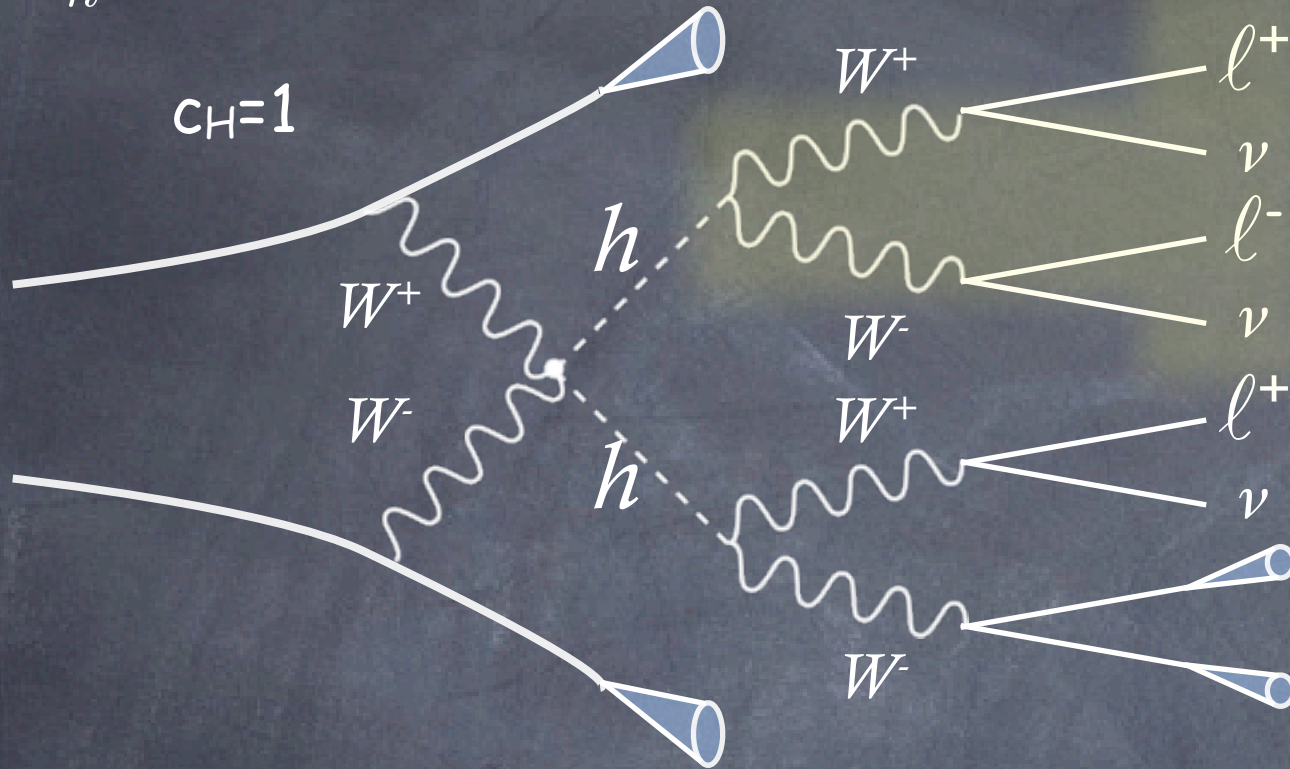
② reconstruction of hadronic W

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



Strong Higgs production: 3L+4jets

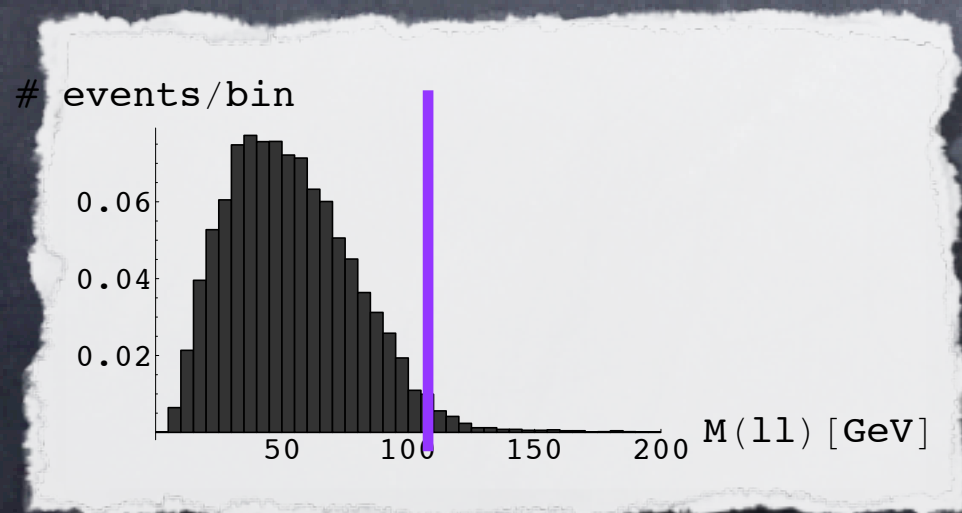
$$m_h = 180 \text{ GeV}$$



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

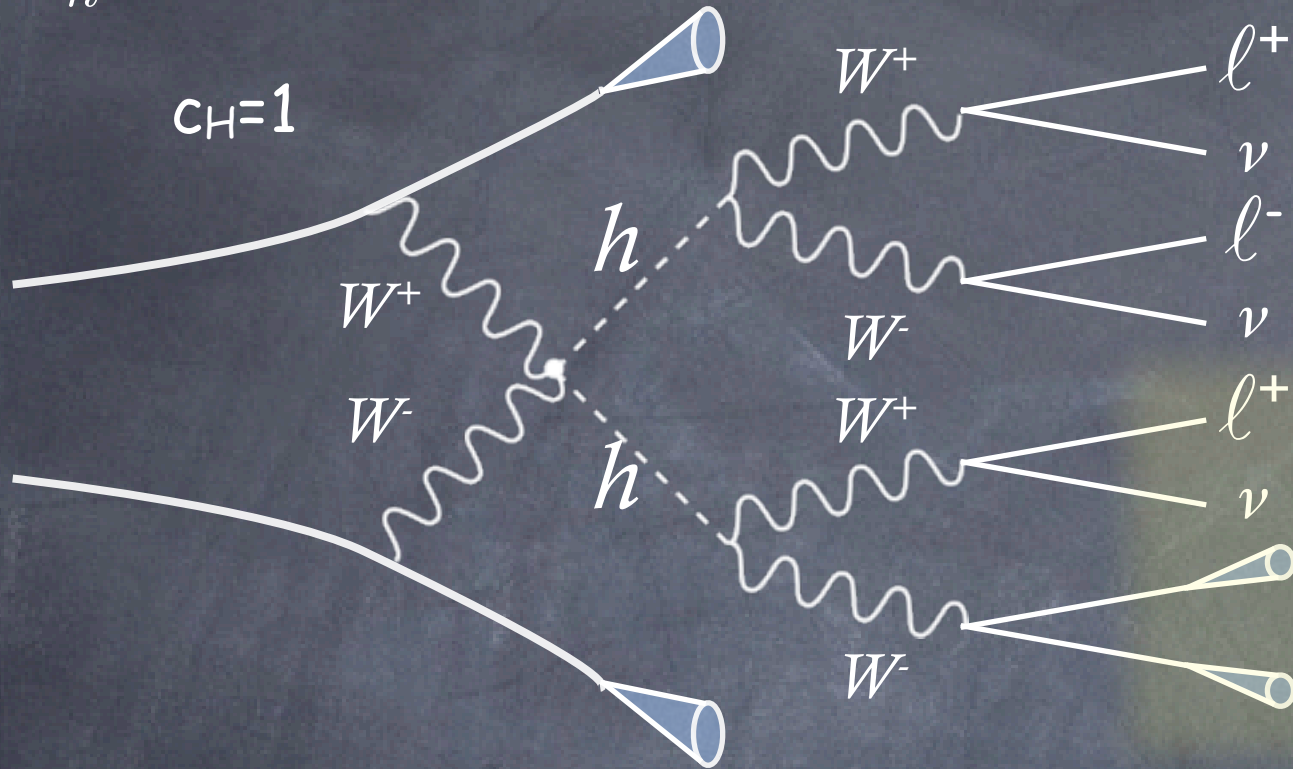
the pair with the smallest angle

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



Strong Higgs production: 3L+4jets

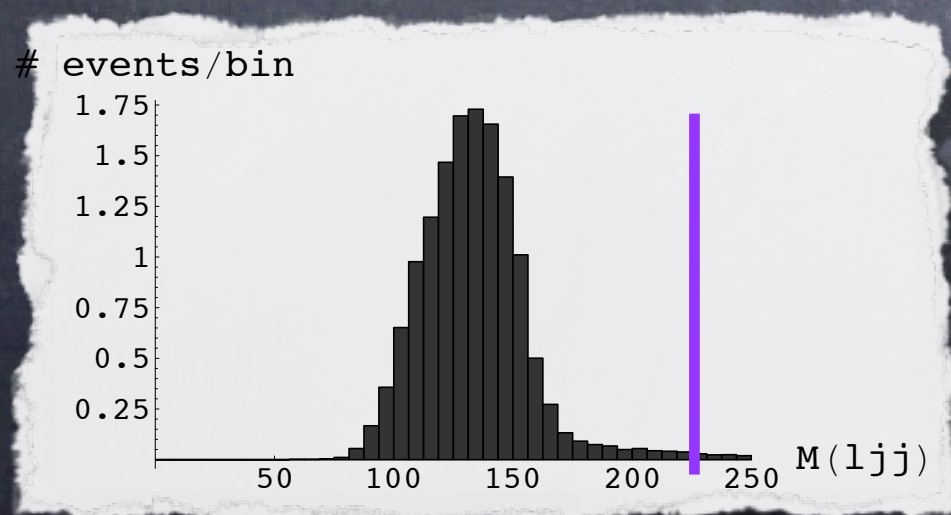
$$m_h = 180 \text{ GeV}$$



④ left with a $\ell^\pm jj$ triplet

cut on its inv. mass

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



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

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 $\Leftrightarrow$ gauge symmetries?