Composite Higgs Physics

based on works in collaboration with

G. Giudice, A. Pomarol and R. Rattazzi

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work in progress

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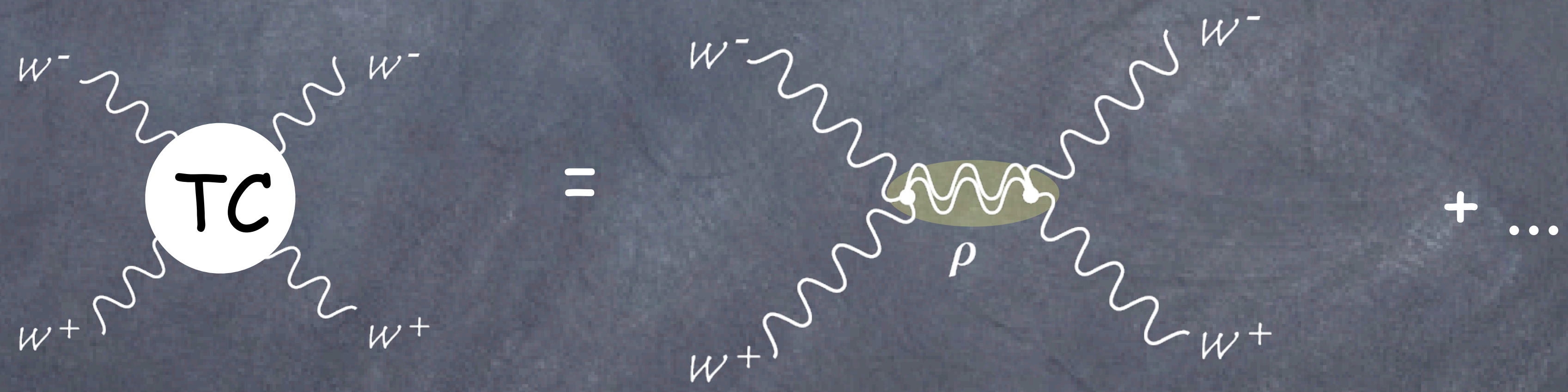
EWSB from a Strongly Coupled Sector

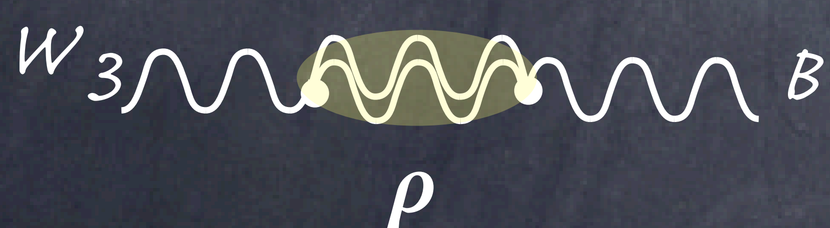
A strong sector, around few TeV, driving EW symmetry breaking
is a plausible/conservative scenario

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



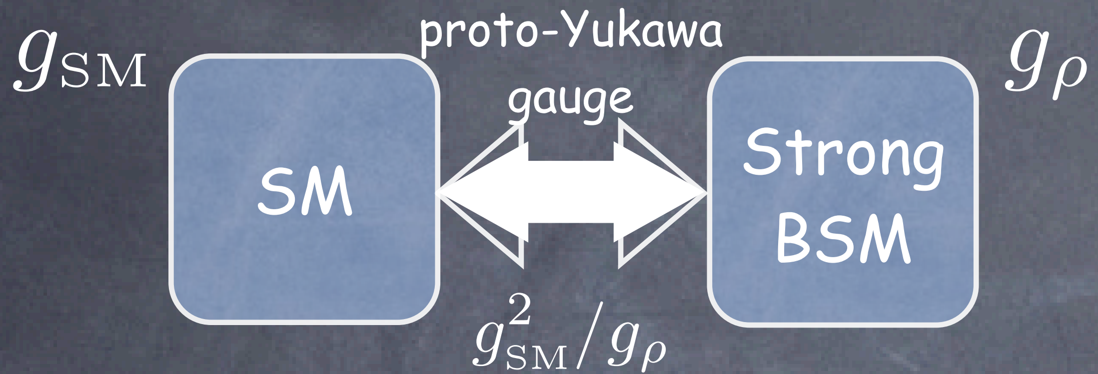
S parameter of order 1.
Not seen at LEP

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

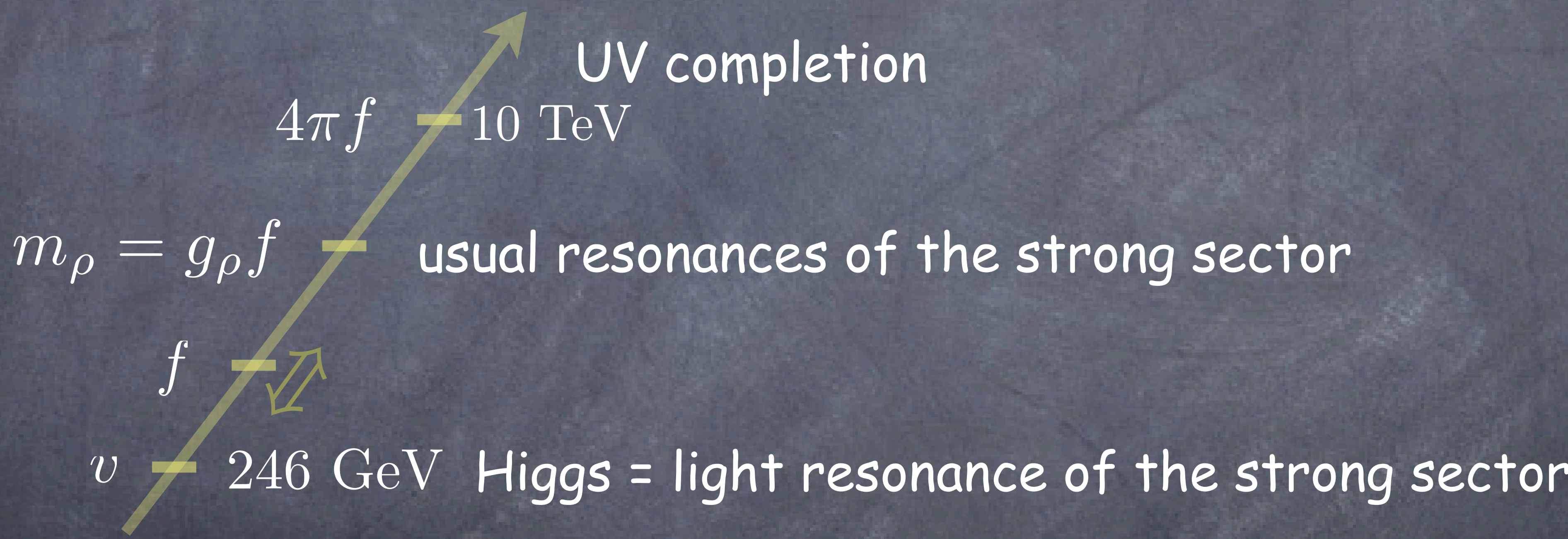
How to obtain a light composite Higgs?

Higgs=Pseudo-Goldstone boson of the strong sector

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



global symmetry → G/H ← residual global symmetry



strong sector broadly characterized by 2 parameters

m_ρ = mass of the resonances

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

Testing the composite nature of the Higgs?

if LHC sees a Higgs and nothing else*:

- evidence for string landscape?
- it will be more important then ever to figure out whether the Higgs is a fundamental or a composite scalar!

- Model-dependent: production of resonances at m_ρ
- Model-independent: study of Higgs properties & W scattering
  - strong WW scattering
  - Higgs anomalous coupling
  - strong HH production
  - (gauge bosons self-couplings) ⟵ not covered in this talk

* 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

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

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

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

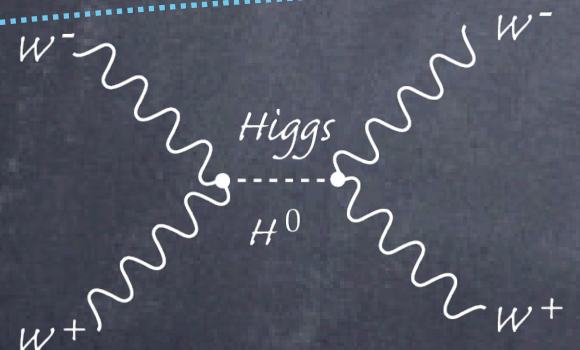
What distinguishes a composite Higgs?

Giudice, Grojean, Pomarol, Rattazzi '07

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

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

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



$$= -\left(1 - c_H \frac{v^2}{f^2}\right) g^2 \frac{E^2}{M_W^2}$$

no exact cancellation of the growing amplitudes

unitarization restored by heavy resonances

Falkowski, Pokorski, Roberts '07

Strong W scattering below m_ρ ?

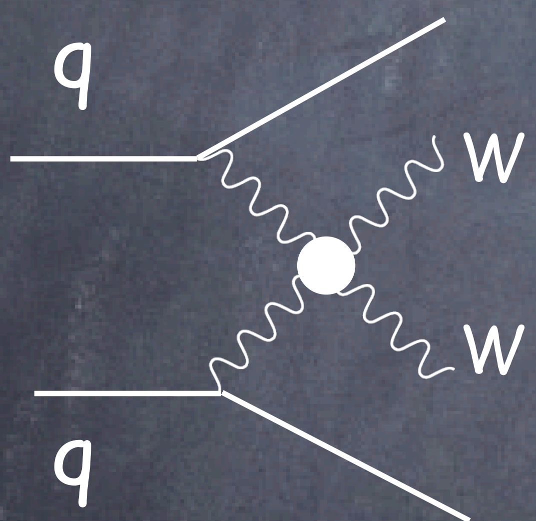
Strong W scattering

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

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

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

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



$$\sigma\left(pp \to V_L V_L' X\right)_{c_H} = \left(c_H \frac{v^2}{f^2}\right)^2 \sigma\left(pp \to V_L V_L' X\right)_{\not H}$$

leptonic vector decay channels

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

with 300 fb^{-1}

30 signal-events and 10 background-events

Bagger et al '95
Butterworth et al. '02

LHC is sensitive to

$$c_H \frac{v^2}{f^2}$$

bigger than

0.5 ~ 0.7

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)

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

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

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

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

Goldstone sym.

EWPT constraints

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

removed by custodial symmetry

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

There are also some 1-loop IR effects

Barbieri, Bellazzini, Rychkov, Varagnolo '07

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

modified Higgs couplings to matter

$$\Downarrow$$

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

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

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

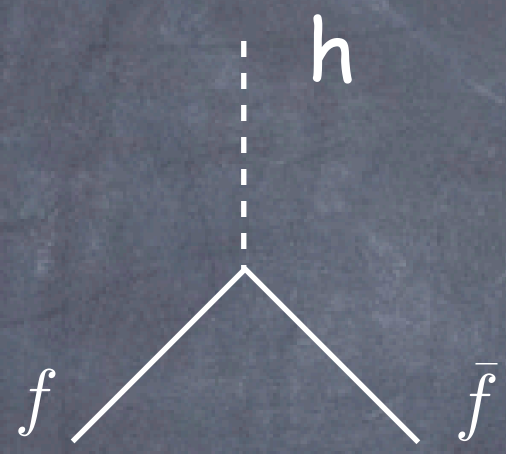
SILH: c_y is flavor universal

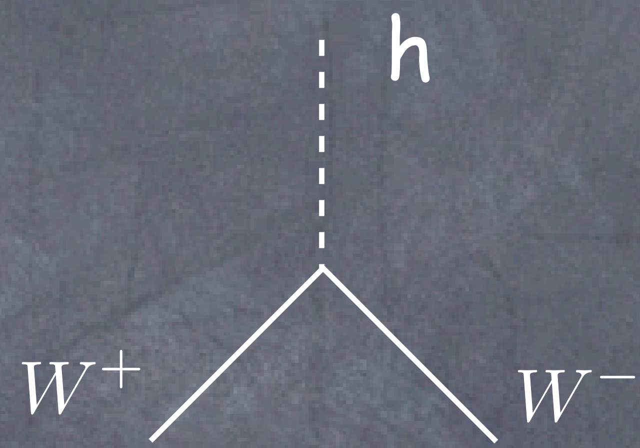
$\Rrightarrow$ Minimal flavor violation built in

Higgs anomalous couplings

Lagrangian in unitary gauge

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





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

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

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

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

Higgs anomalous couplings

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

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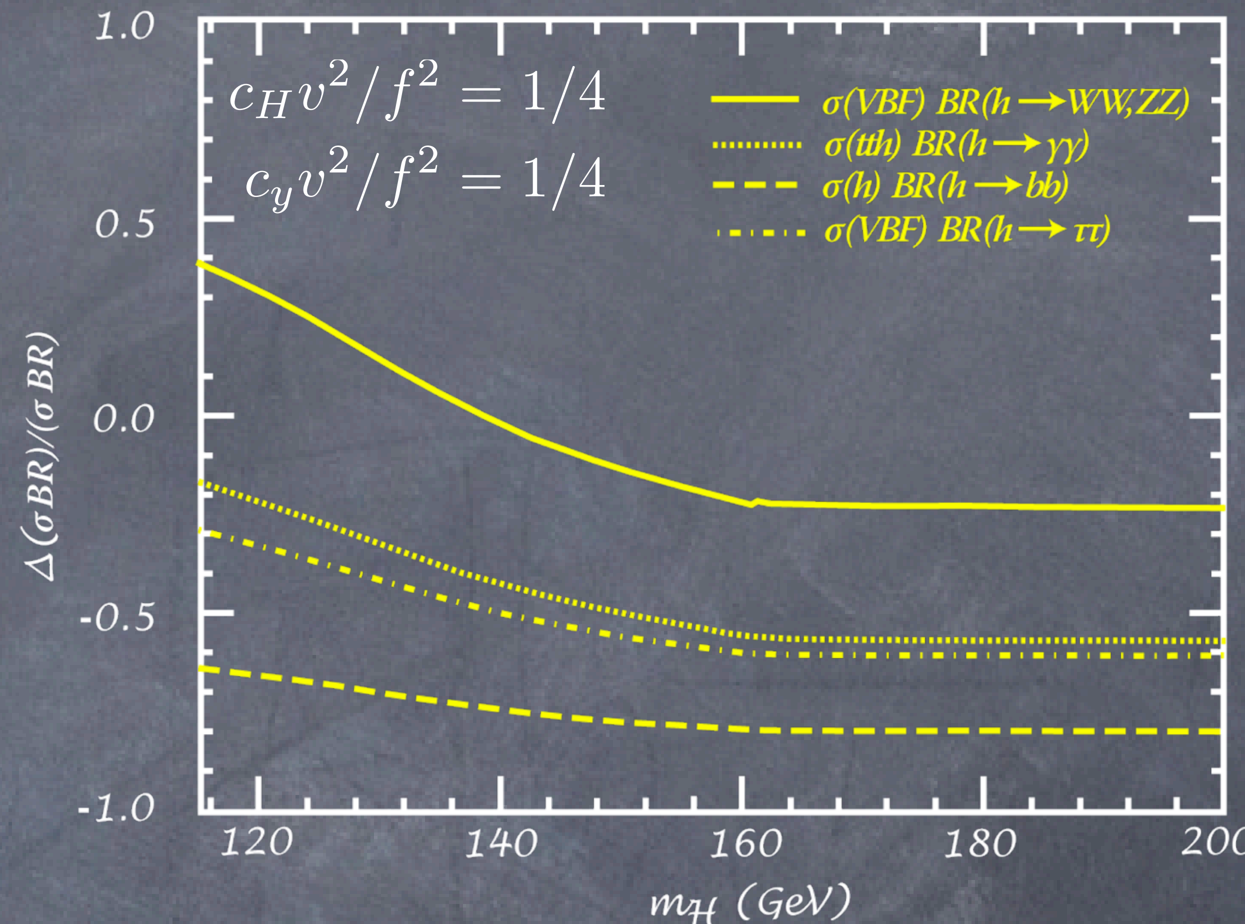
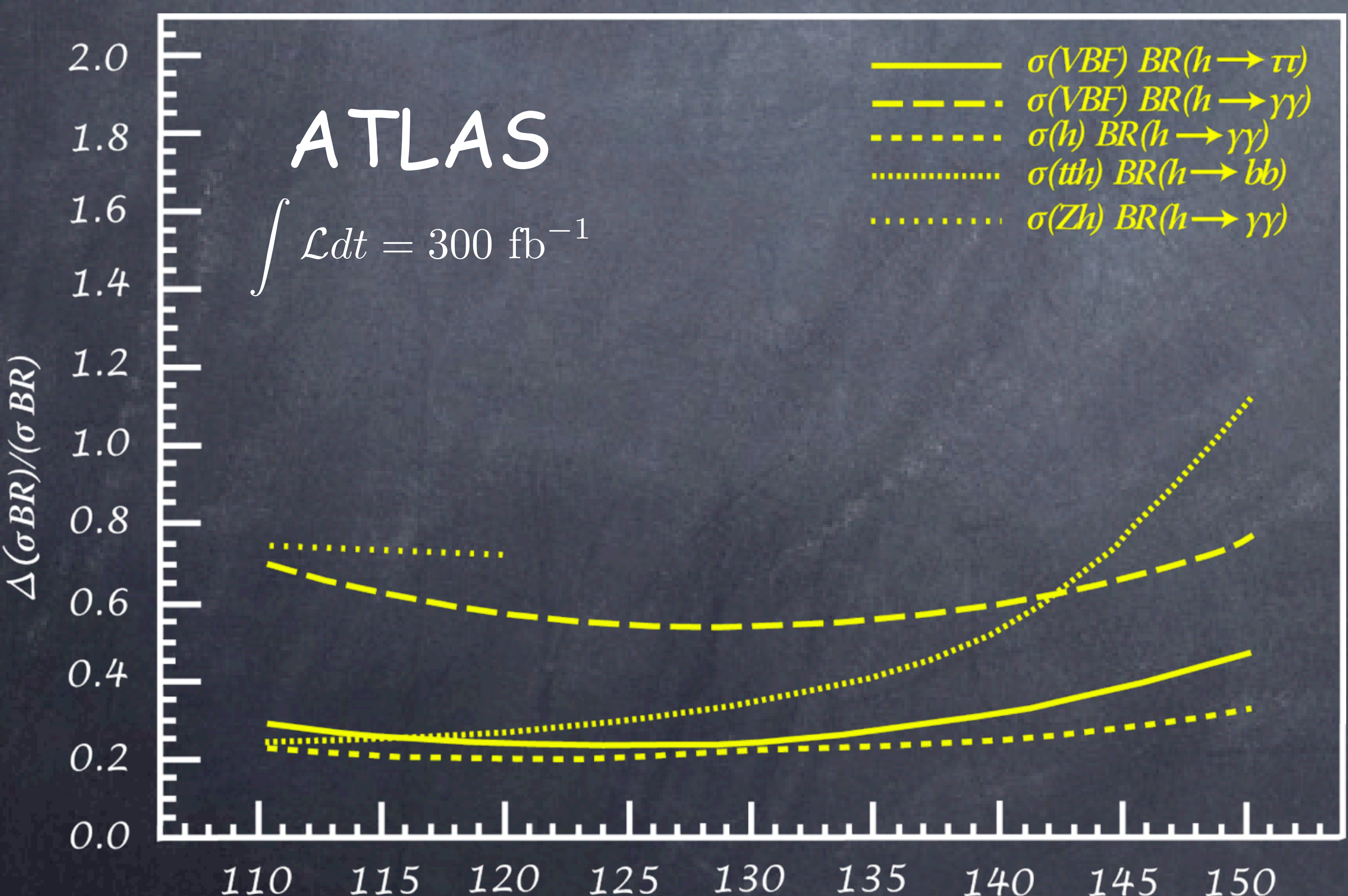


observable @ LHC?



Duhrssen '03

LHC can measure

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

up to 20-40%

(composite scale 5-7 TeV)

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

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)

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

$$\Downarrow$$

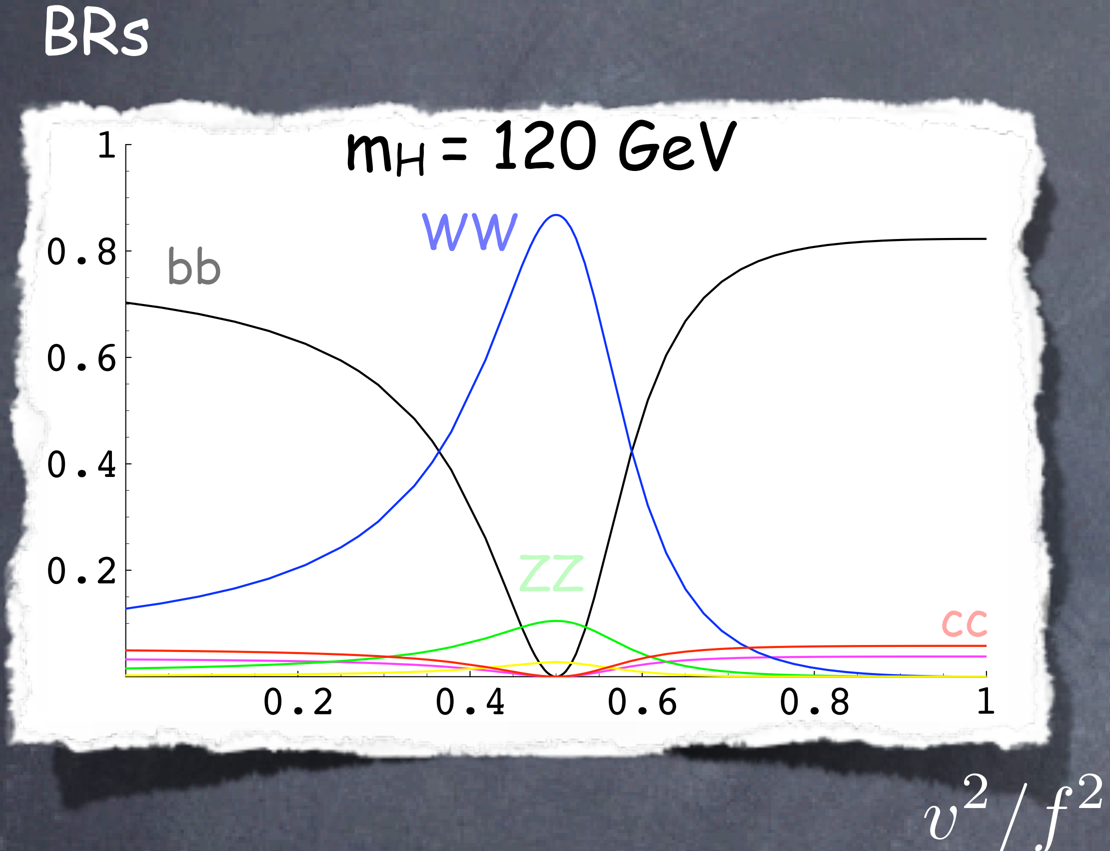
$$g_{hff} = \frac{1-2\xi}{\sqrt{1-\xi}}\, g_{hff}^{\mathrm{SM}}$$

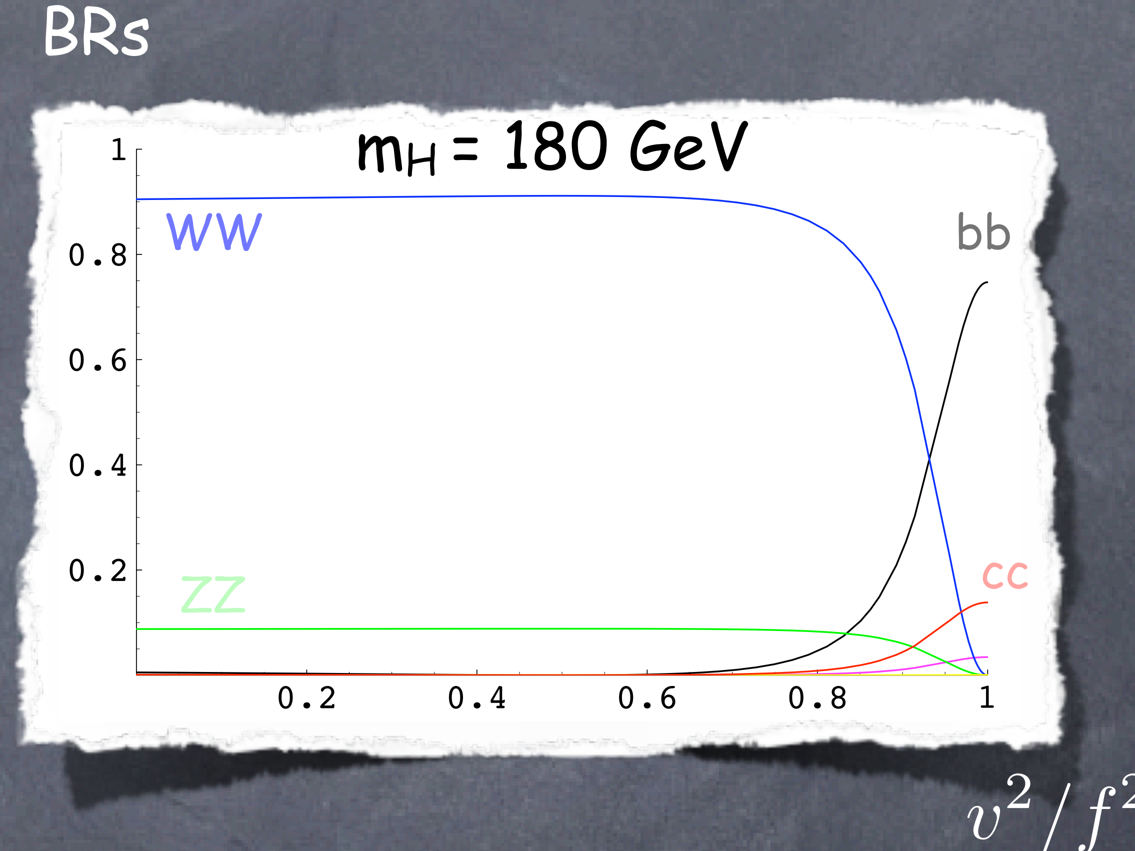
BRs now depends on v/f

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

Higgs BRs

Fermions embedded in 5+10 of SO(5)





h→WW can dominate
even for low Higgs mass

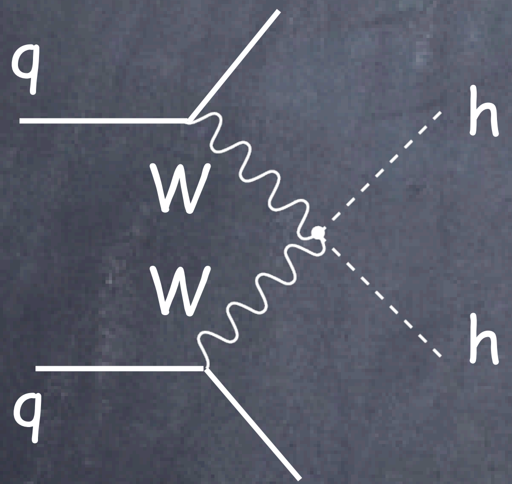
BRs remain SM like
even for large values of v/f

Strong Higgs production

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

strong boson scattering ⇔ strong Higgs production

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



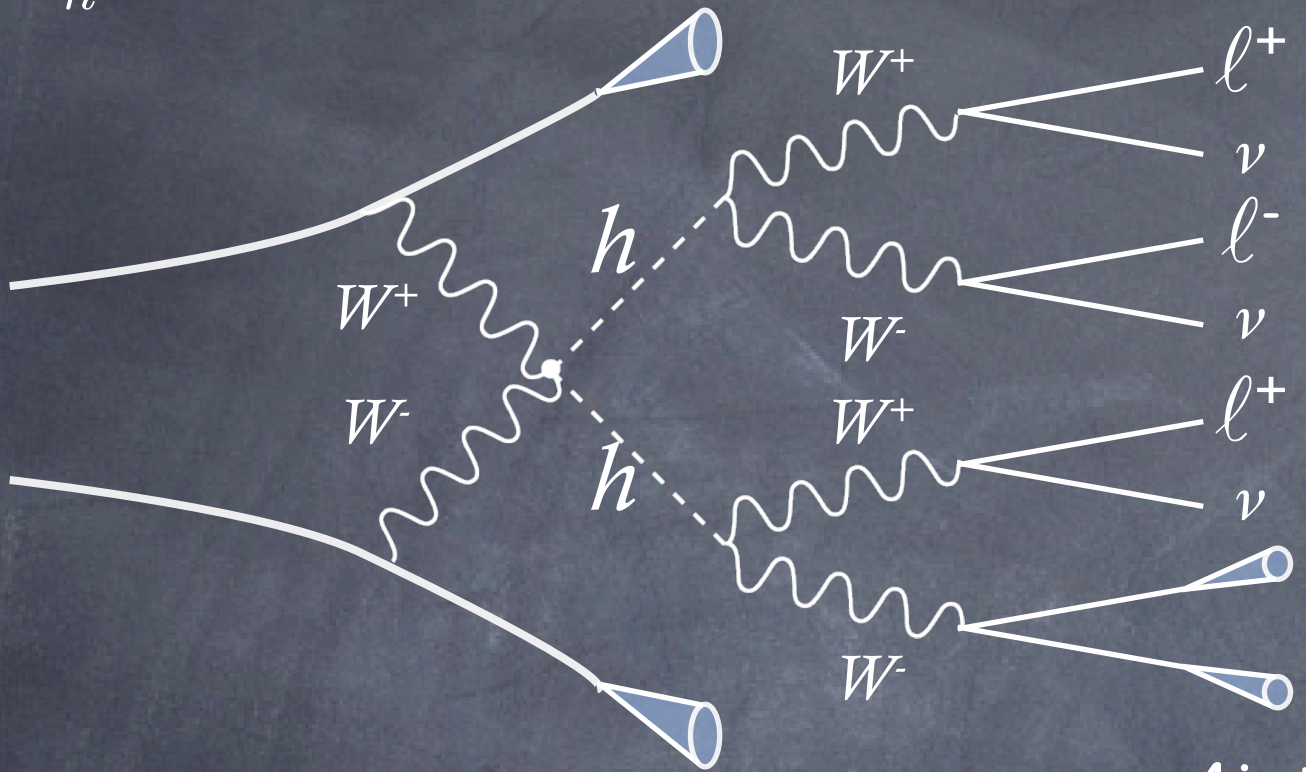
signal:
- $hh \to bbbb$
- $hh \to 4W \to 3\ell^\pm 3\nu$+jets

Sum rule (with cuts $|\Delta\eta| < \delta$ and $s < M^2$)

$$2\sigma_{\delta,M}\left(pp \to hhX\right)_{c_H} = \sigma_{\delta,M}\left(pp \to W_L^+ W_L^- X\right)_{c_H} + \frac{1}{6}\left(9 - \tanh^2\frac{\delta}{2}\right)\sigma_{\delta,M}\left(pp \to Z_L^0 Z_L^0 X\right)_{c_H}$$

Strong Higgs production: (3L+jets) analysis

$m_h = 180$ GeV



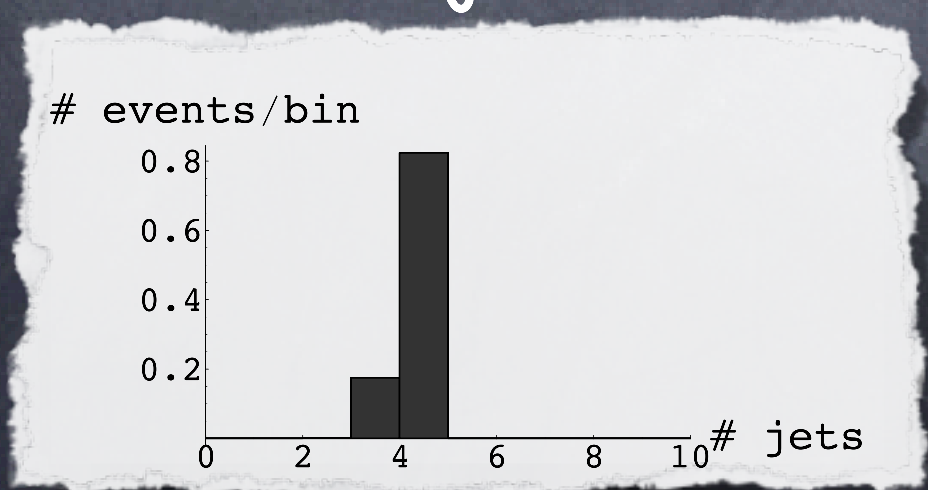
acceptance cuts

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})

	$v/f = 1$	$v/f = .8$	$v/f = .5$	$v/f = 0$
4jets →	14.5	9.8	4.3	0.5
3jets →	19.5	13.2	5.9	0.8

jets

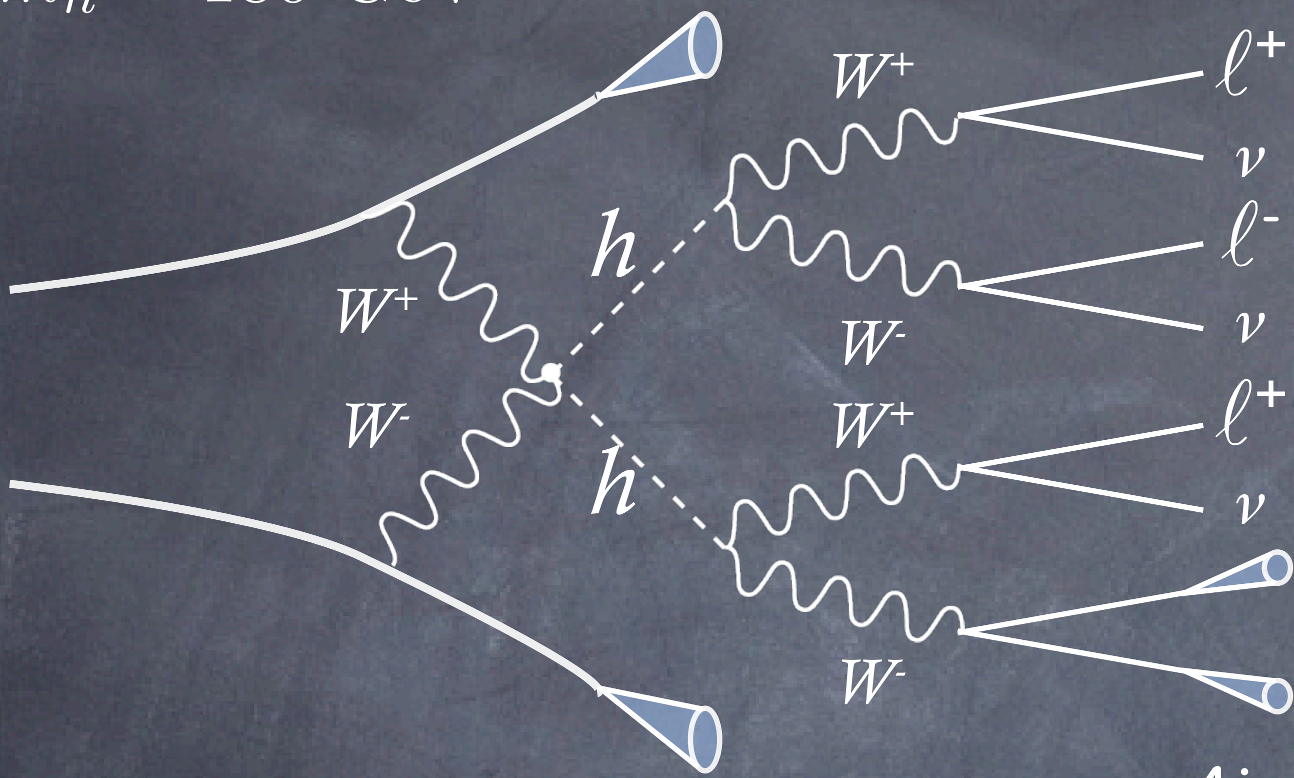


jets with p_T>30 GeV

most of the time, a W jet is lost

Strong Higgs production: (3L+jets) analysis

$m_h = 180$ GeV



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$\lvert\eta_j\rvert \leq 5$	$\lvert\eta_j\rvert \leq 2.4$

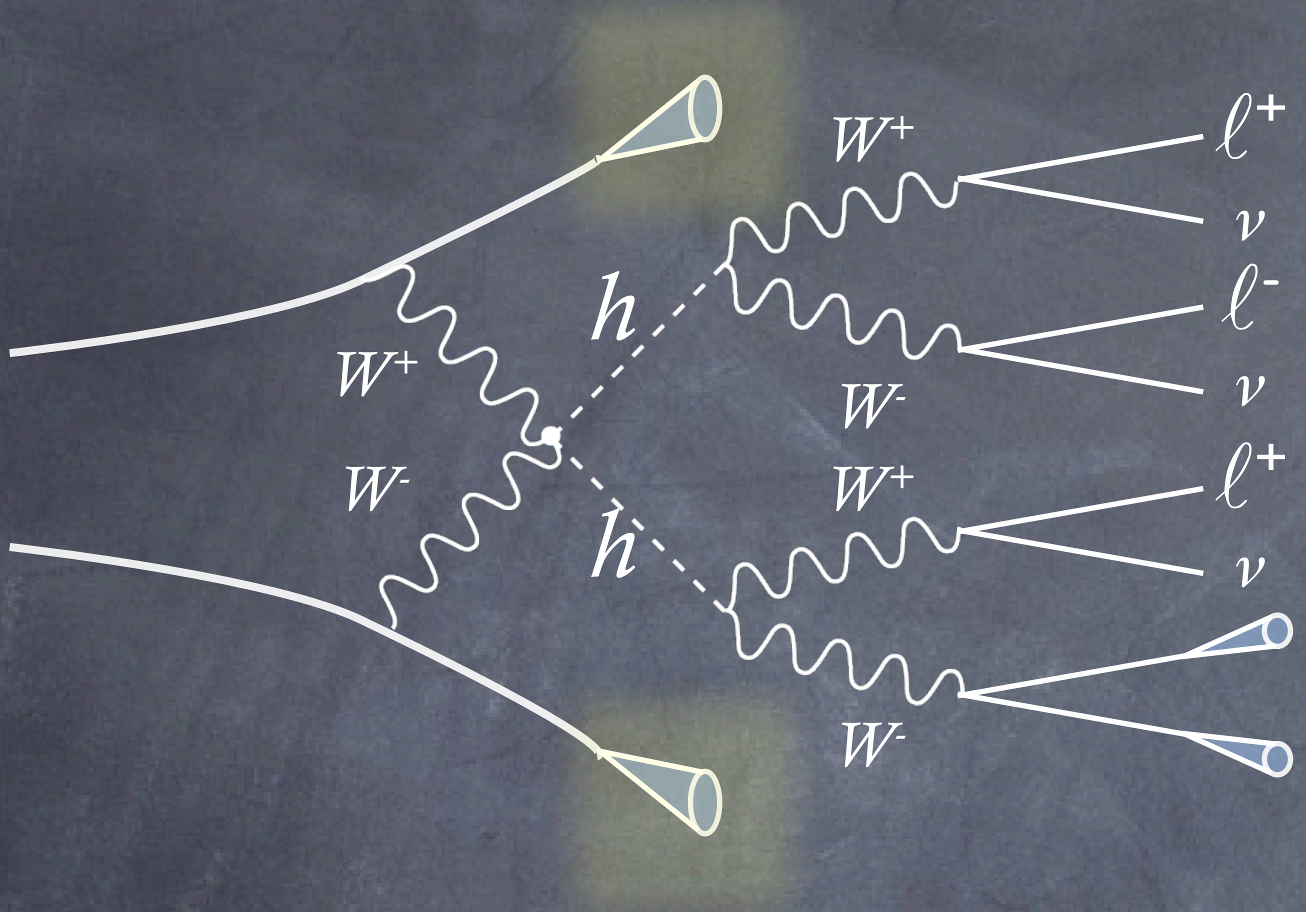
events after accept. cuts (with 300 fb^{-1})

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

Dominant backgrounds

	4jets	3jets
$t\bar{t}2W \to b\bar{b}4W \to 3l3\nu 2b2j$	104 evts	223 evts
$t\bar{t}W2j \to b\bar{b}3W2j \to 3l3\nu 2b2j$	121 evts	230 evts
$3W4j \to 3l3\nu 4j$	26 evts	94 evts
$WZ4j \to 3l1\nu 4j$	580 evts	1580 evts

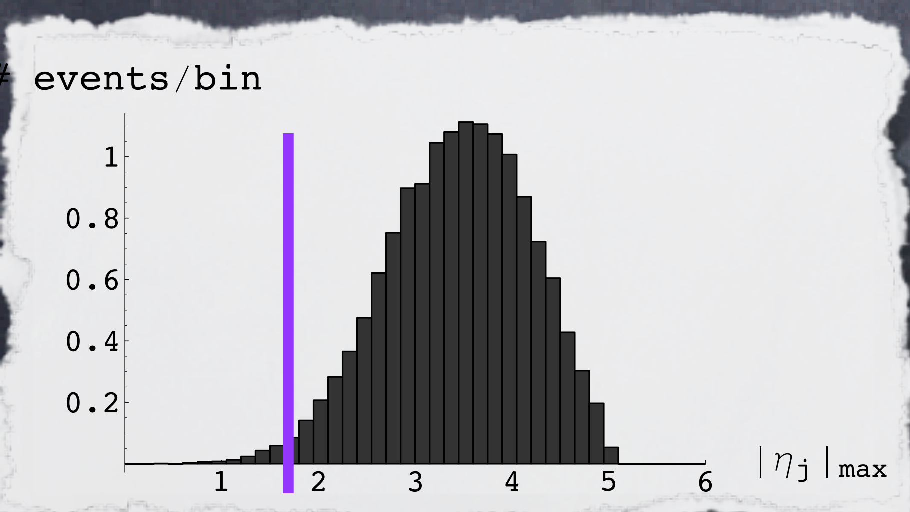
Strong Higgs production: 3L+4jets



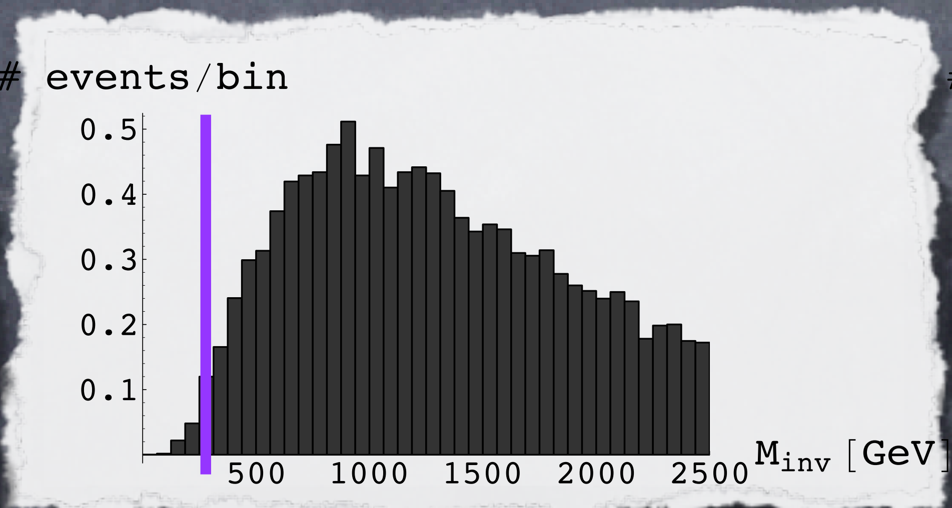
1 identify the "external" jets:

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

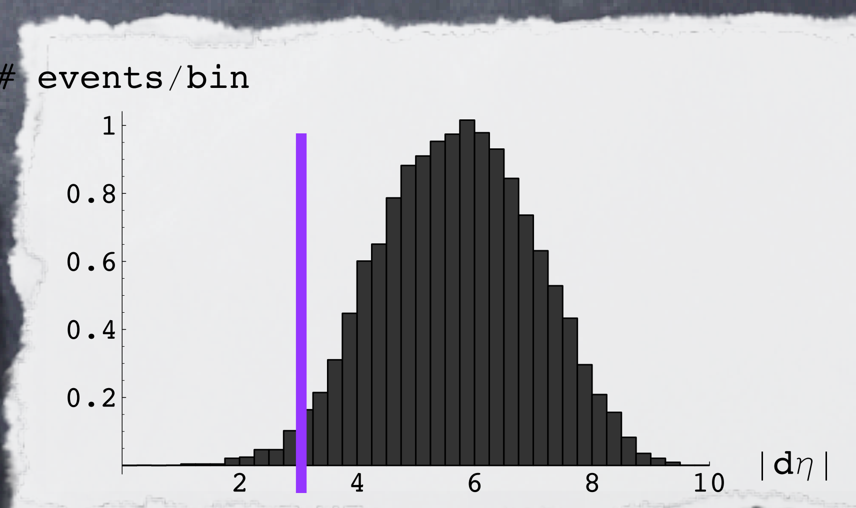
$|\eta|_{\max} \geq 1.8$



$M_{jj} \geq 330$ GeV



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



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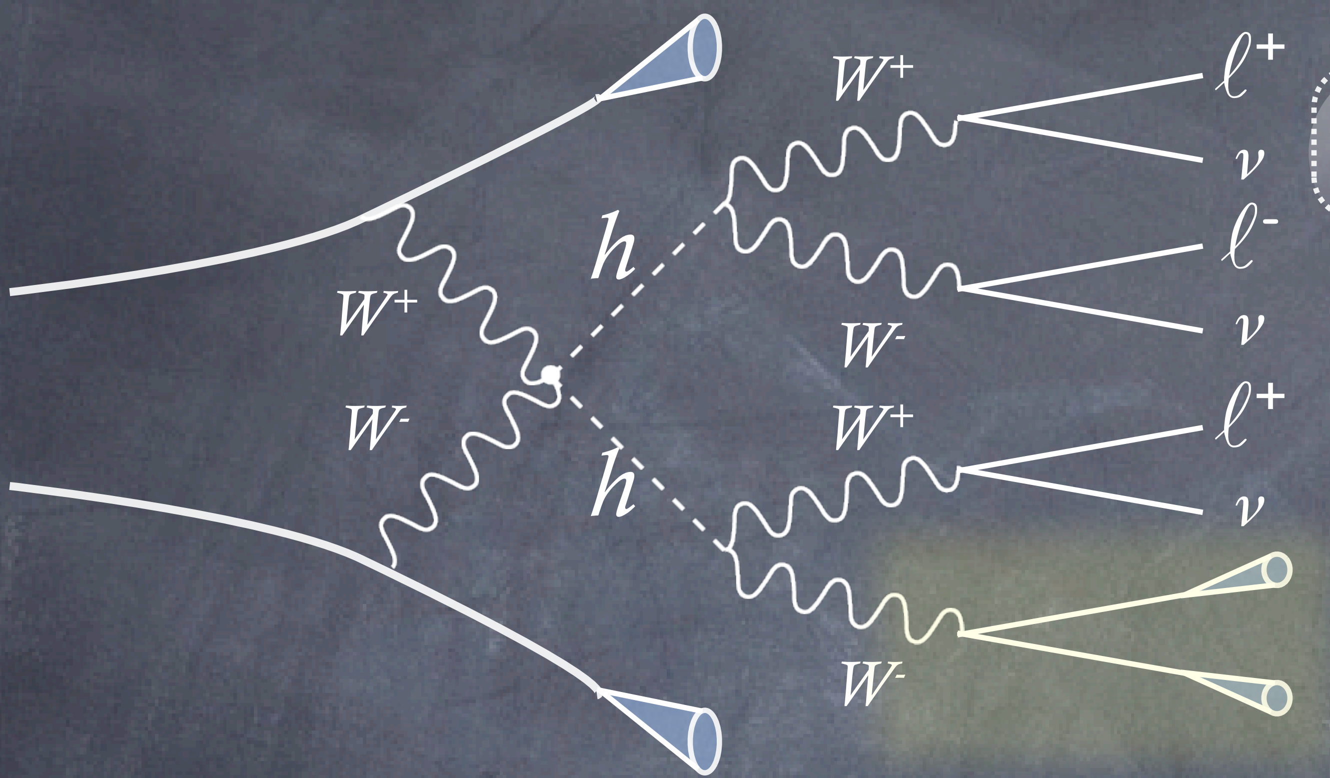
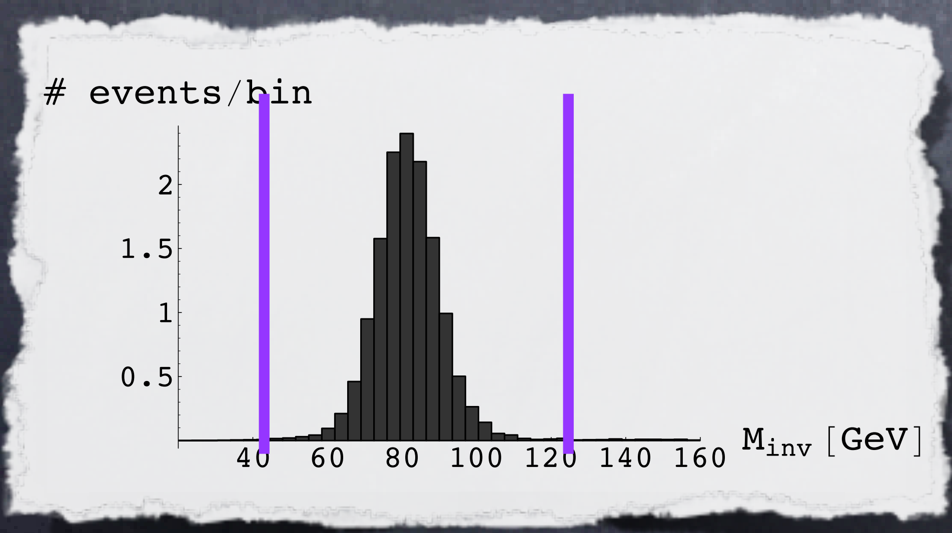
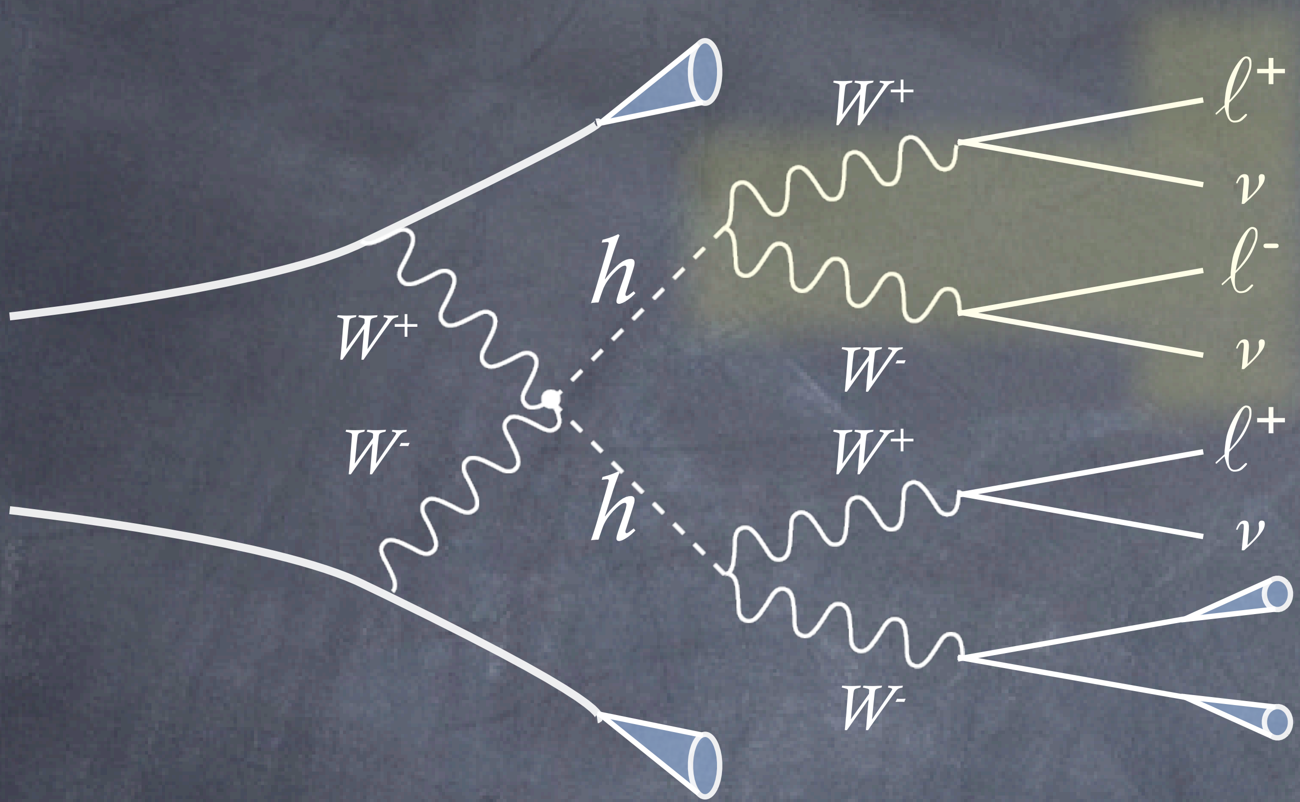


2 reconstruction of hadronic W

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



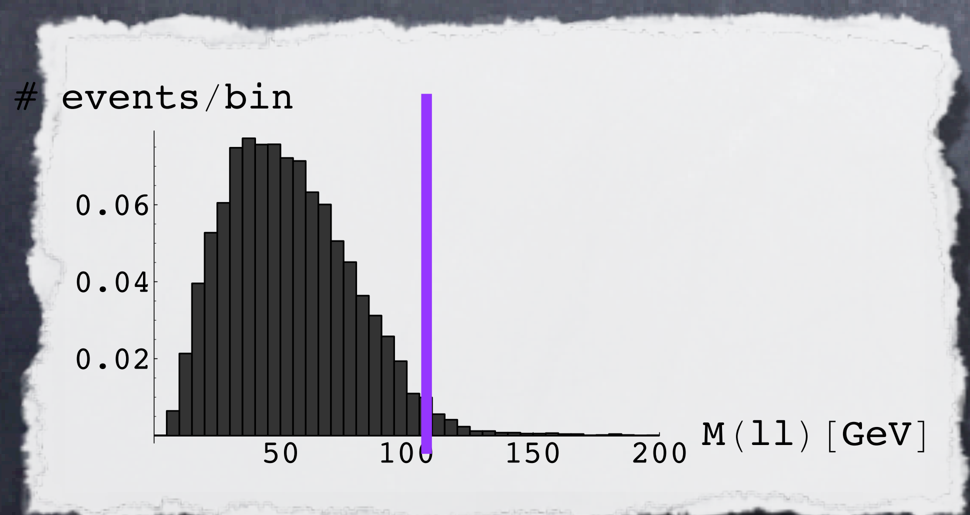
Strong Higgs production: 3L+4jets



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

the pair with the smallest angle

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



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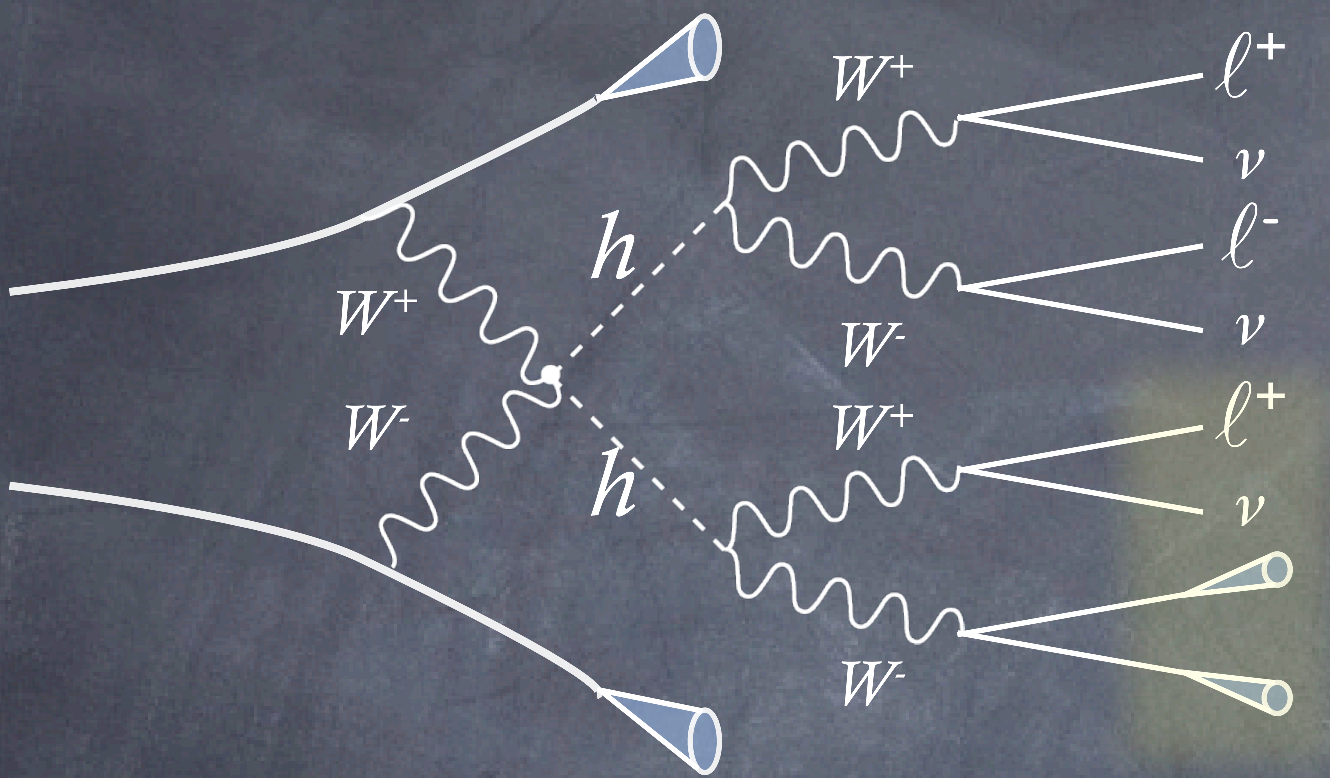
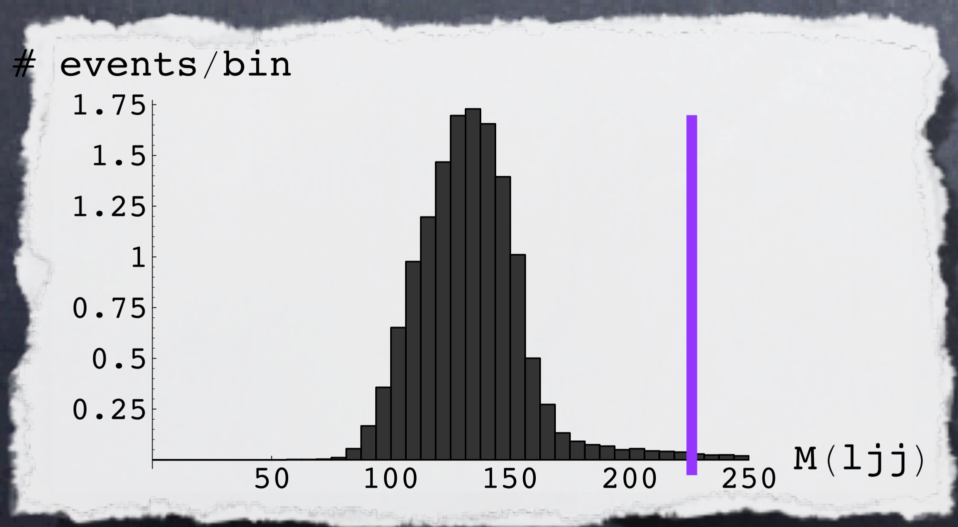


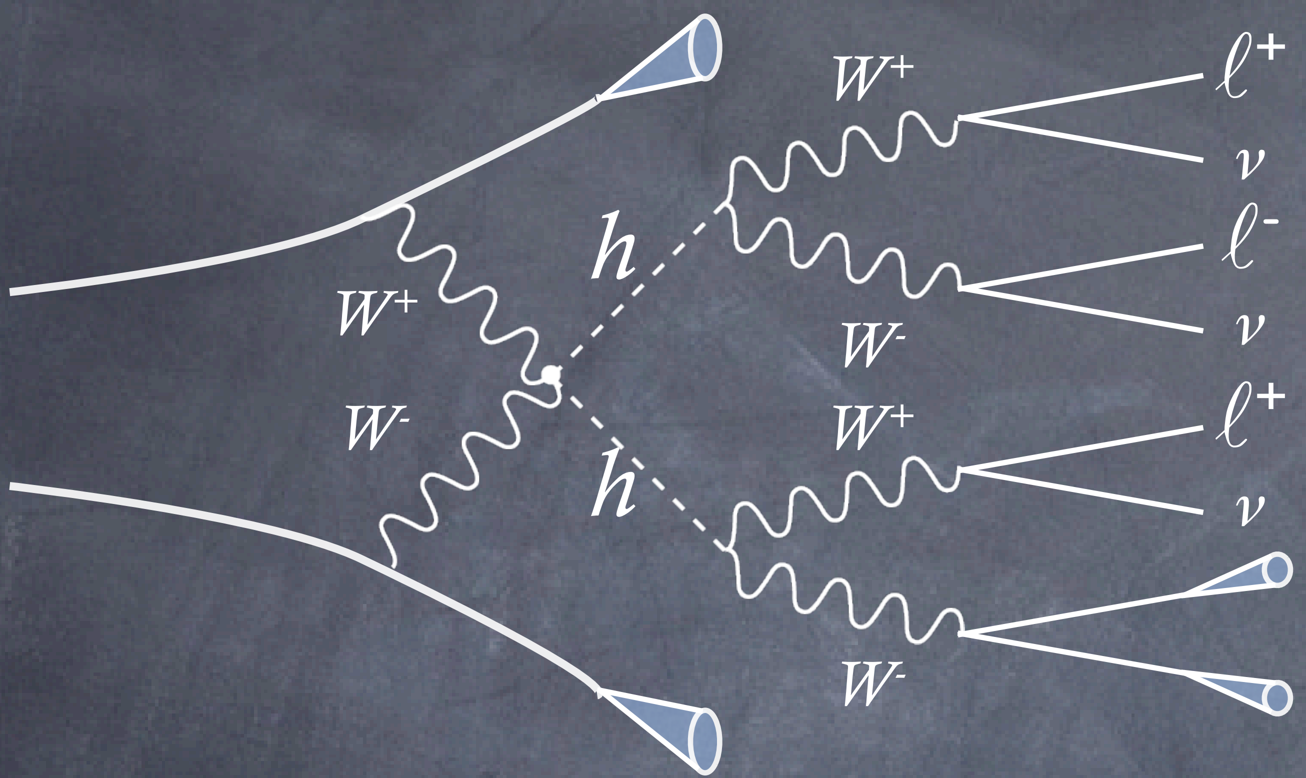
4 left with a $\ell^{\pm}$jj triplet

cut on its inv. mass

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



Strong Higgs production: 3L+4jets



After optimized cuts (with 300 fb^{-1})

events in signal

$v/f=1$	$v/f=\sqrt{.8}$	$v/f=\sqrt{.5}$	$v/f=0$
7.4	4.9	2.2	0.2

events in background

ttWW	ttWjj	3W4j	WZ4j
.01	.14	.10	1.20

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

Conclusions

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

Oblique corrections provide a guide to the scale of new physics

We need observables to distinguish whether
the EWSB sector is strongly or weakly coupled:
WW scattering, WW HH, Higgs anomalous couplings

If the LHC sees a Higgs and nothing else, it will be a challenging
time to deciphering the true nature of the Higgs

LHC and ILC are complementary in the exploration
of the TeV scale population