Physics Perspectives with the high luminosity LHC

SLHC-PP Annual Meeting
Saclay, Feb. 7th 2011

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Why high luminosity?

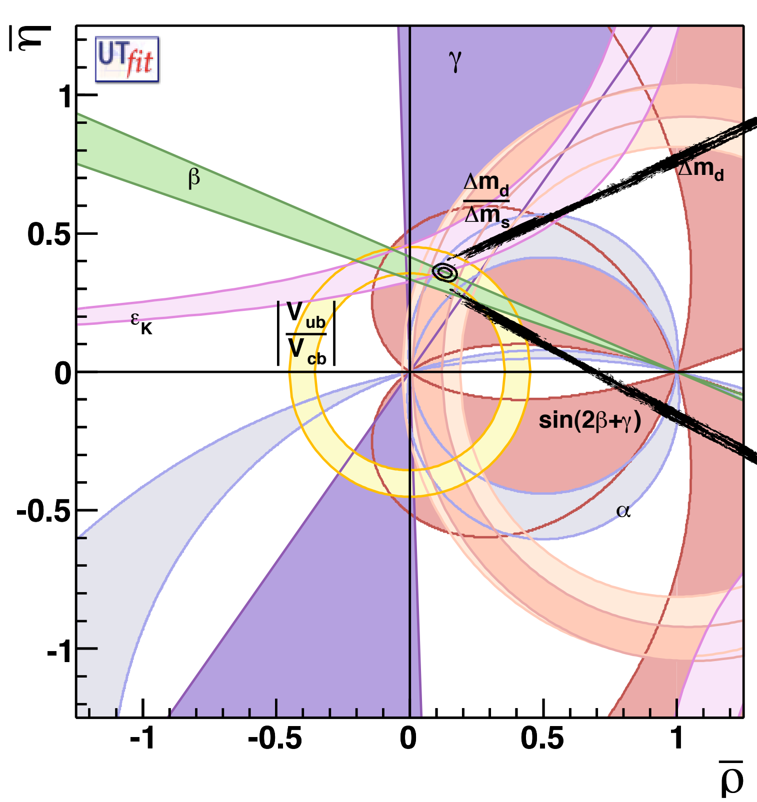
better precision?

All that remains to do in physics is to fill in the sixth decimal place.

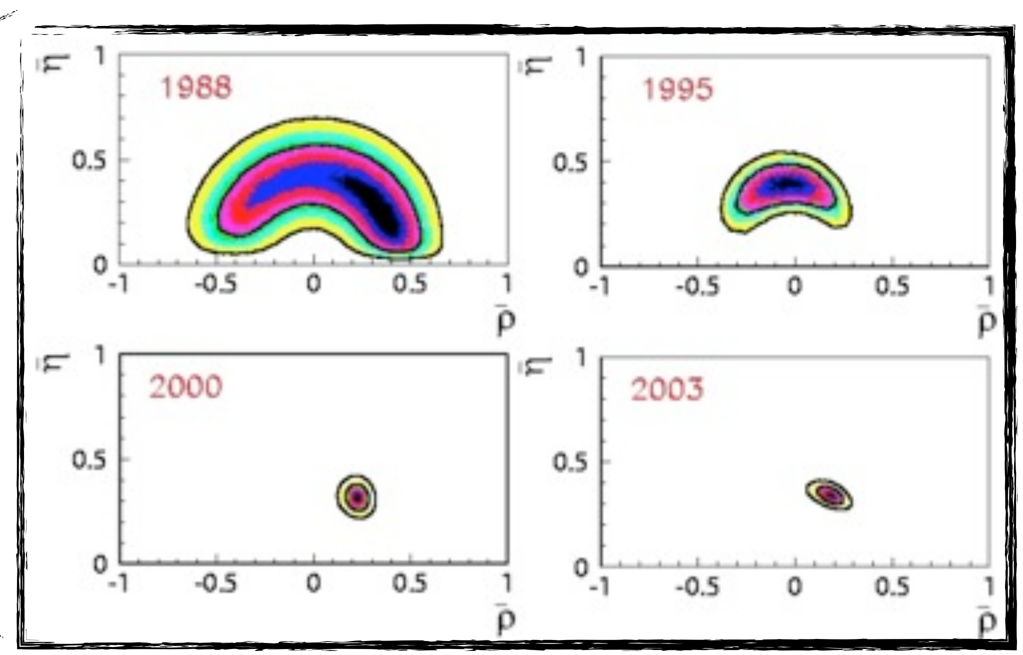
(Albert Michelson, 1894)

There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

(W. Thomson, Lord Kelvin, 1900)



UTfit, ICHEP'10

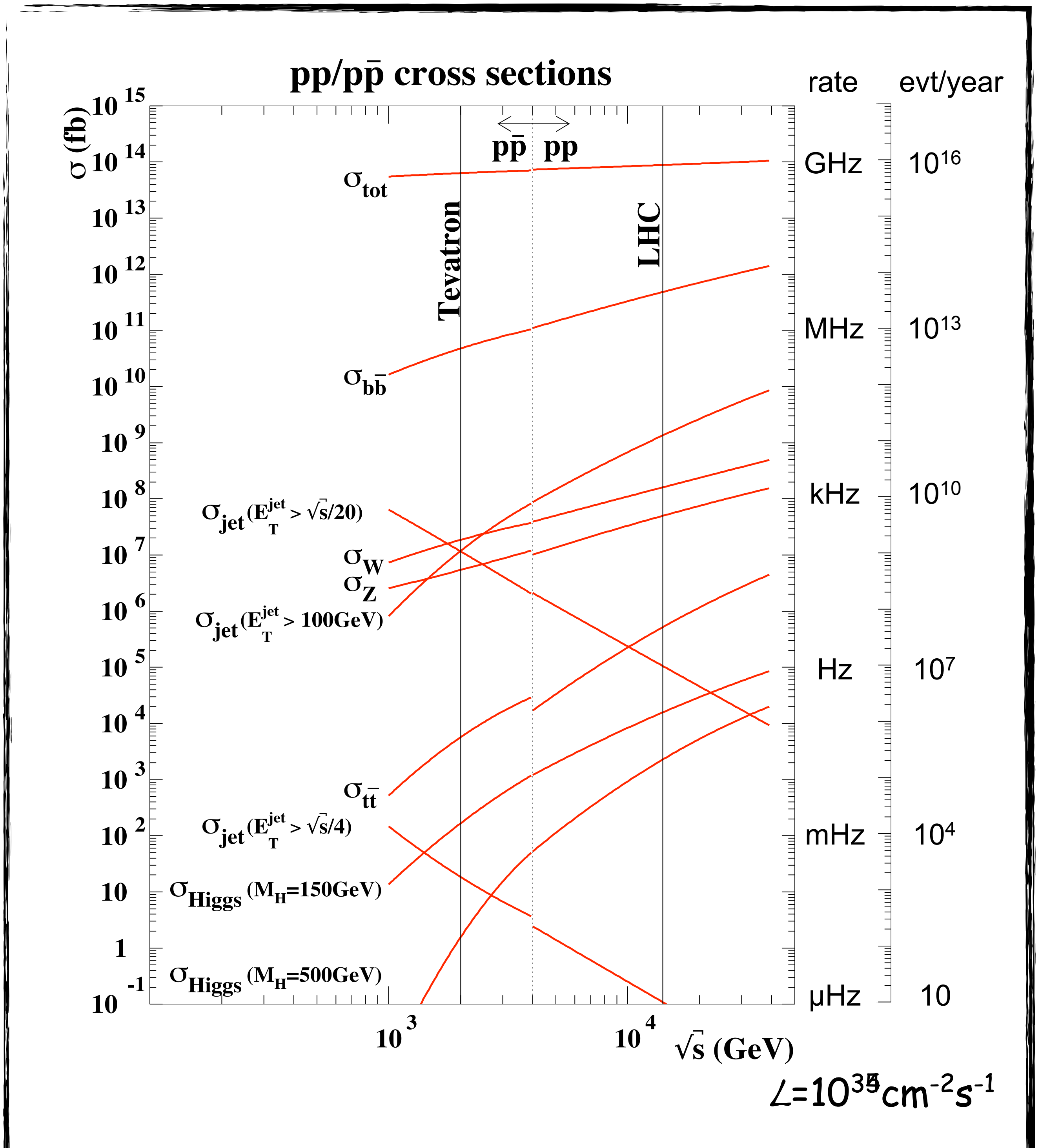


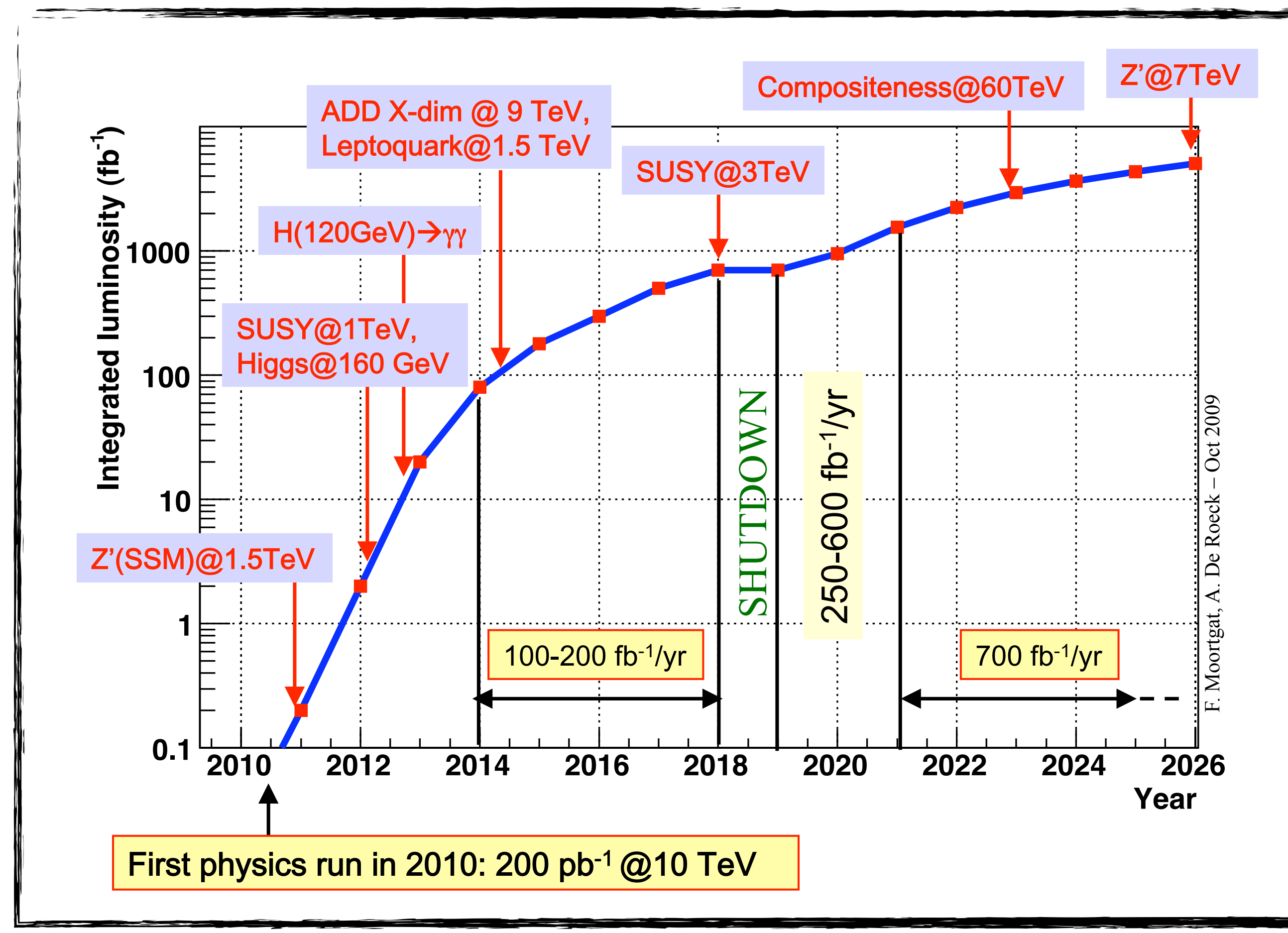
➲ establish CKM as the source of flavour violation & CP

➲ No new physics?

Why high luminosity?

access to rare events?





$\mathcal{L}_{int} \nearrow$ makes new & exciting discoveries possible

$$\frac{S}{\sqrt{B}} \propto \sqrt{\mathcal{L}_{\rm int}}$$

SLHC Physics Potential

A. De Roeck '09

- Higgs physics
  - Higgs anomalous couplings to SM fermions and bosons
  - Higgs self-couplings
  - rare Higgs decays; multi-Higgs (MSSM or not)
  - Dynamics of EW symmetry breaking

The LHC key topic!

- Electroweak physics
  - anomalous gauge boson self-couplings
  - top quark rare/flavour violating decays
- Supersymmetry
  - measurement mass spectrum
  - extend the mass gluino/squarks reach to 3 TeV.
- Extra dimensions
  - KK production
  - Black hole production
- New forces
  - W', Z' etc
  - technicolour

I won't have time to cover these topics. See refs next page

To learn more...

Reports

- "Physics potential and experimental challenges of the LHC luminosity upgrade", F. Gianotti et al, EPJC39(2005)293, hep-ph/0204087
- "From the LHC to a Future Collider", A. De Roeck et al., EPJC66(2010)525, arXiv:0909.3240

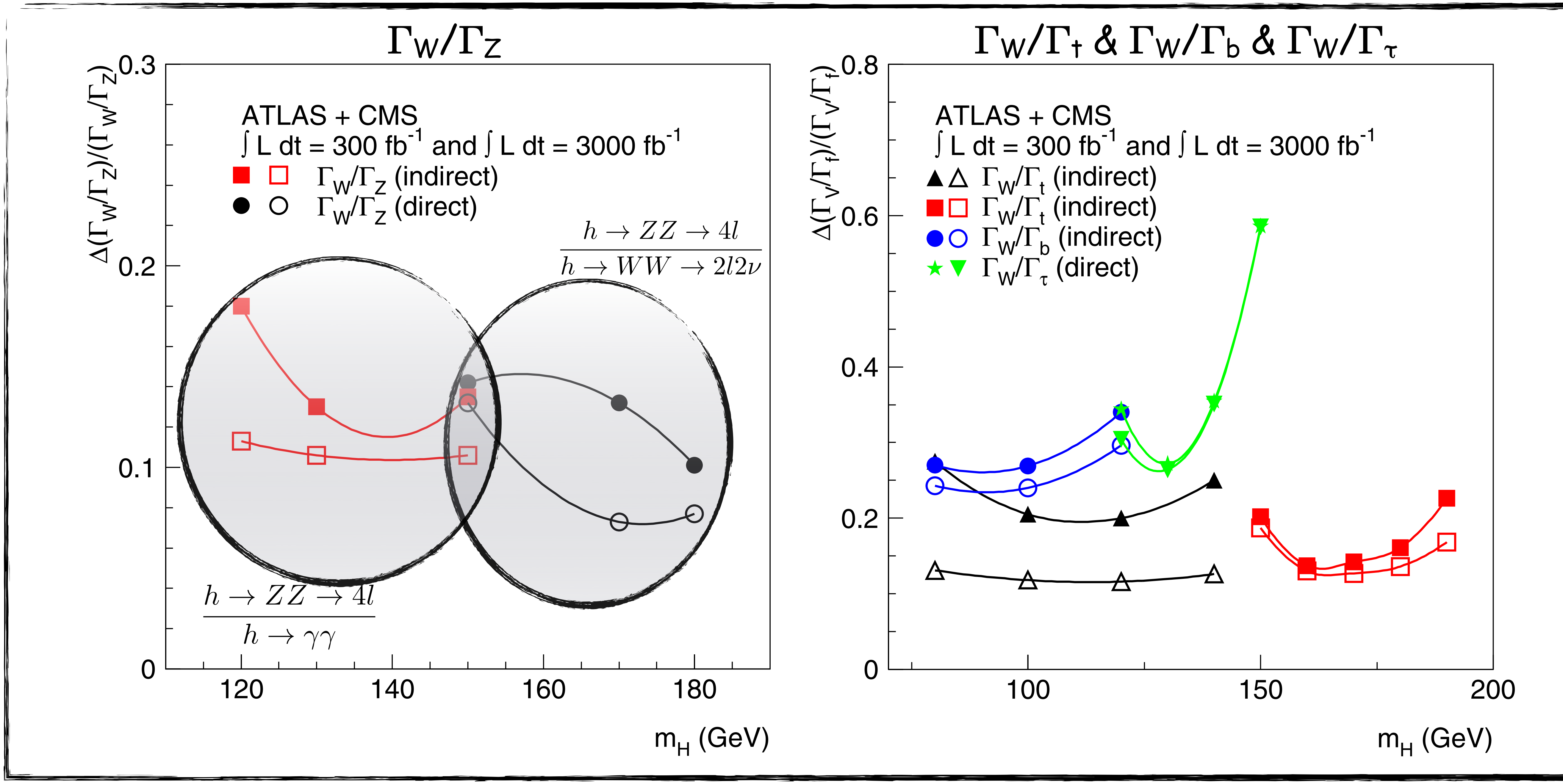
Talks

- D. Denegri, Care-HHH workshop, November '04
- M. Mangano, SLHC kickoff meeting, April '08
- G. Giudice, PLHC conference, October '08
- A. De Roeck, XXXVii SLAC Summer Institute, August '09

Precision physics in the Higgs sector

Anomalous Higgs couplings

F. Gianotti et al. '02



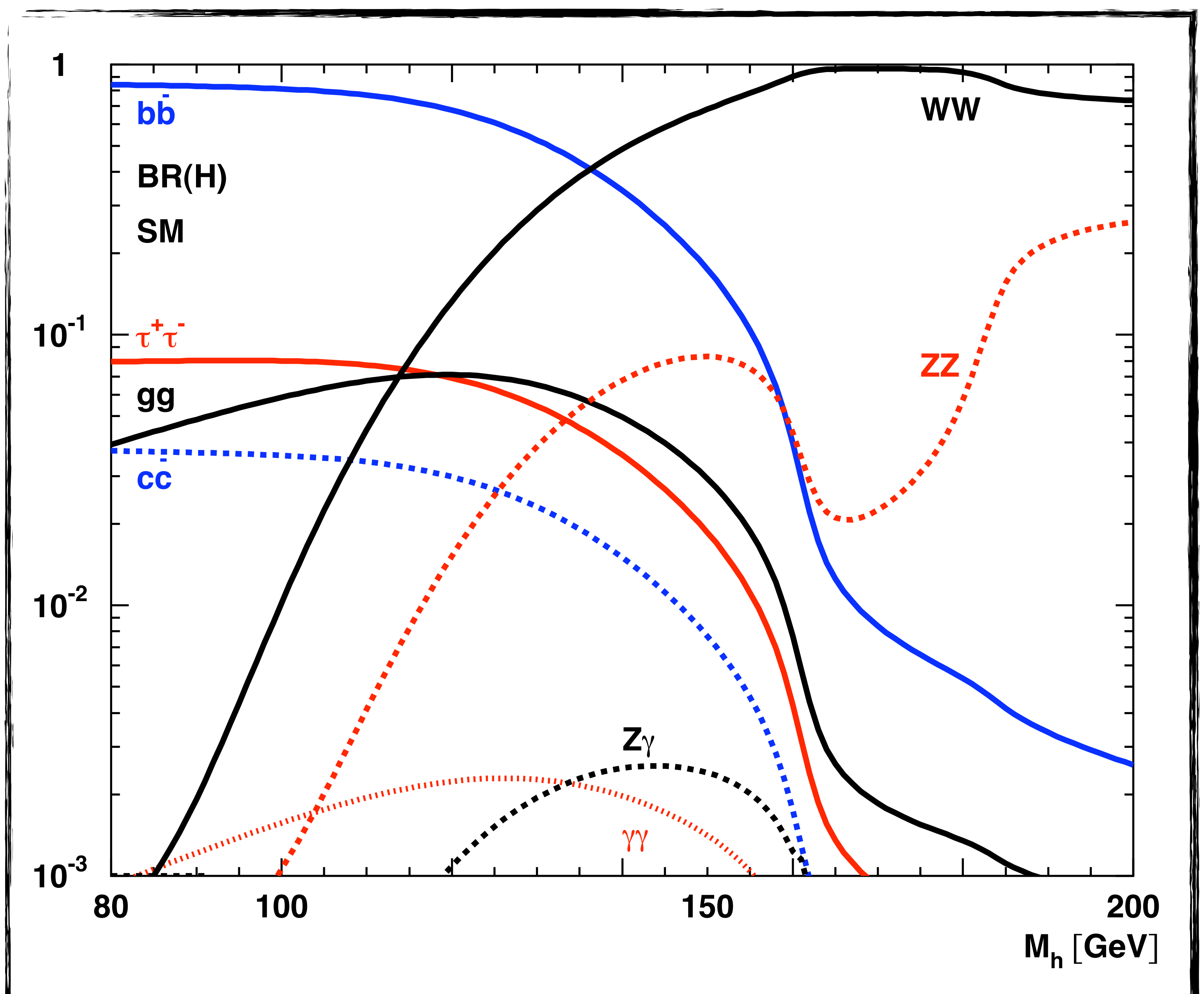
closed symbol=$LHC_{300/fb}$ open symbol=$SLHC_{3/ab}$

ratio Γ_i/Γ_j because total Higgs production cross-section, width and luminosity cancel

SLHC can reach a sensitivity of O(10%)

Higgs rare decays

Higgs couplings ≈ mass
light particle ➔ small coupling



- $BR(h \to \mu\mu) \approx 10^{-4}$
- $BR(h \to Z\gamma) \approx 10^{-3}$
  but $BR(Z \to \ell\ell) \approx 6\%$
  $\sigma \times BR \approx 2.5$fb

	$LHC_{600/fb}$	$SLHC_{6/ab}$
$h \to \mu\mu$	3.5σ	11σ
$h \to Z\gamma$	3.5σ	9.5σ

sensitivity on BR @ (S)LHC_{14TeV}

Higgs agenda

LHC

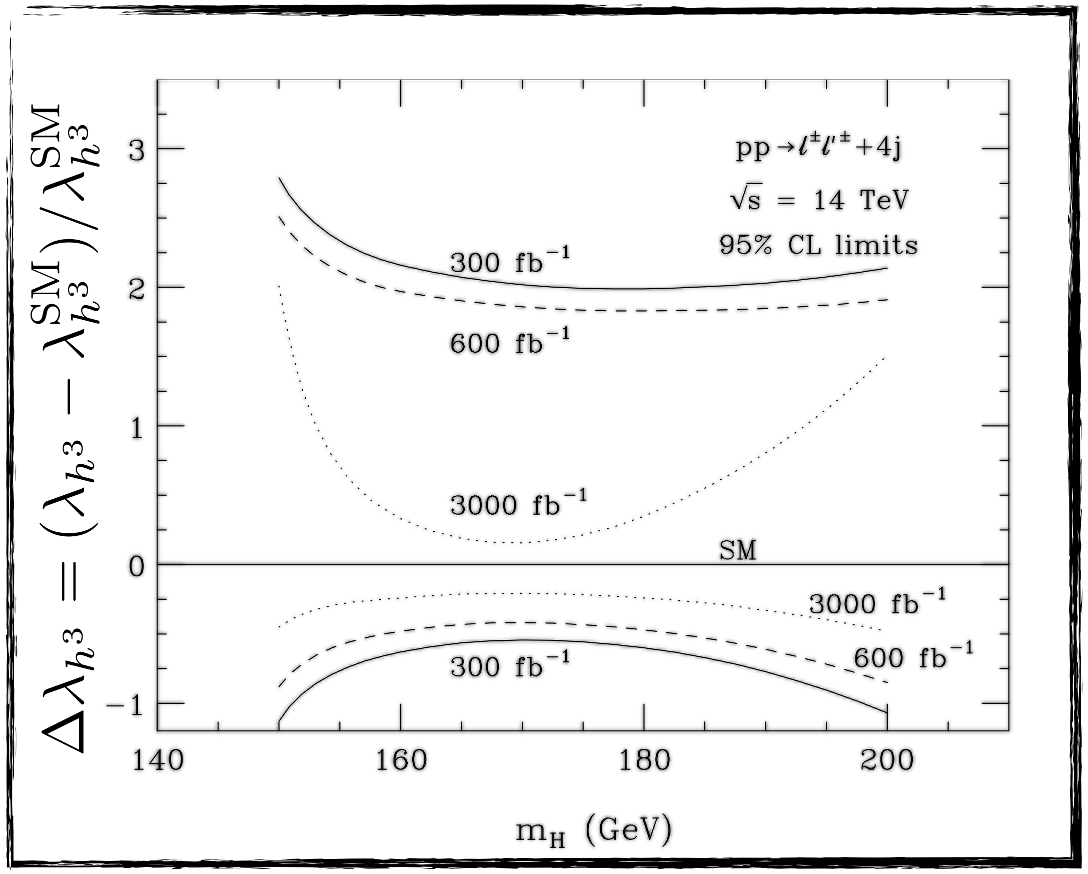
- Higgs discovery
  - measure its mass
    - measure its width

SLHC

- measure cross sections x BR
  - ratios of couplings to particle
    - measure CP and spin
      - measure Higgs self-couplings
        - measure Higgs dynamics ~ dynamics of EWSB

EW phase transition in the early Universe

Higgs self-coupling sensitivity



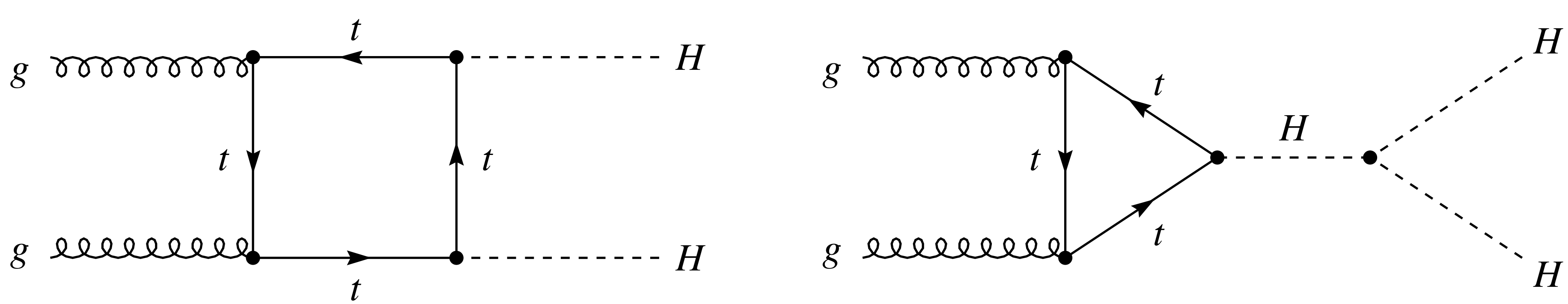
Baur, Plehn, Rainwater '02

$$V_{\rm SM} = \frac{1}{2} m_h^2 h^2 + \frac{1}{6}\left(\frac{3m_h^2}{v_0}\right) h^3 + \frac{1}{24}\left(\frac{3m_h^2}{v_0^2}\right) h^4$$

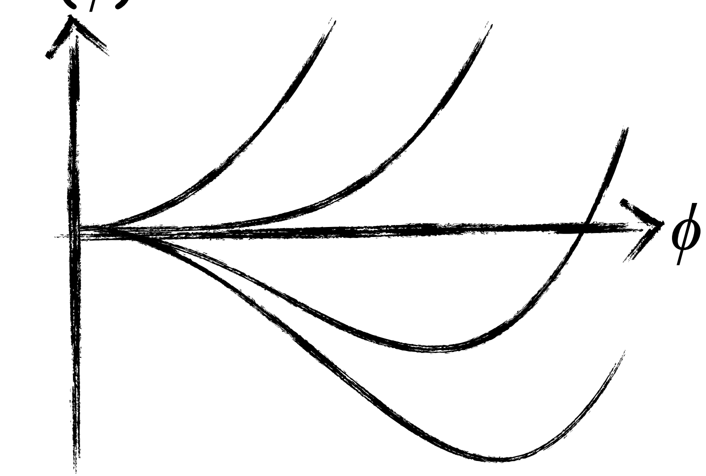
LHC: λ_{h3}=0 can be excluded at 95% CL

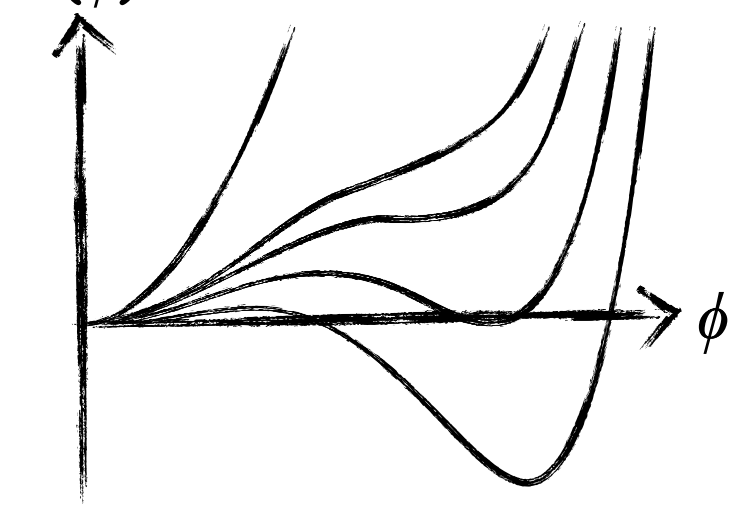
SLHC: λ_{h3} can be determined to 20÷30%

$gg \to hh \to WW \to \ell\nu\ell'\nu'$ 4j



EW phase transition





In the SM, a 1st order phase transition could occur due to thermally generated cubic Higgs interactions:

$$V(\phi,T) \approx \frac{1}{2}(-\mu_h^2 + cT^2)\phi^2 + \frac{\lambda}{4}\phi^4 - E\,T\phi^3$$

$$-\frac{T}{12\pi}\sum_{\text{bosons}} m^3(\phi)$$

In the SM: $\sum_{\text{bosons}} \approx \sum_{W,Z}$ ➡ not enough $\quad E = \frac{4m_W^3 + 2m_Z^3}{12\pi v_0^3} \sim 6\cdot 10^{-3}$

$$\frac{\langle\phi(T_c)\rangle}{T_c} = \frac{2E\,v_0^2}{\lambda v_0^2} = \frac{4\,E\,v_0^2}{m_h^2}$$

$$\frac{\langle\phi(T_c)\rangle}{T_c} \geq 1 \quad \Longleftrightarrow \quad m_h \leq 47\ \text{GeV}$$

Higgs self-coupling and EW phase transition

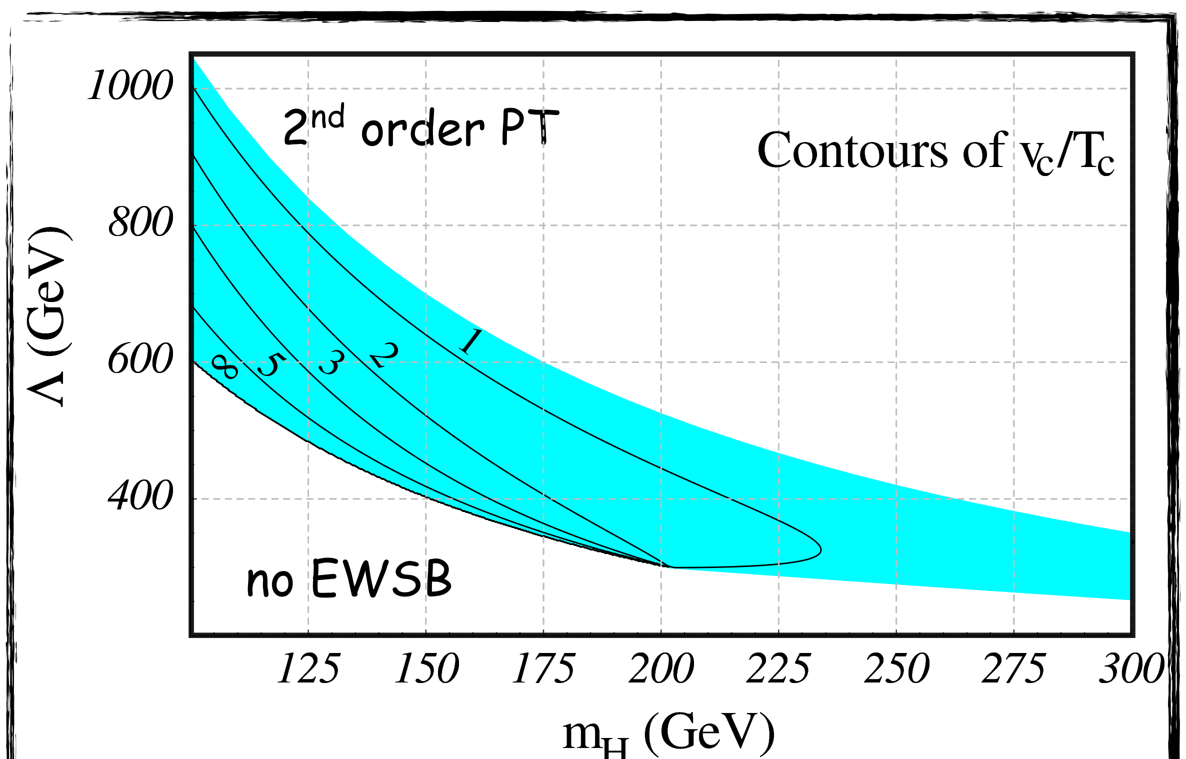
Grojean, Servant, Wells '04

- does not rely on a thermally generated negative Higgs cubic interaction

- instead, we add a non-renormalizable Φ^6 interaction in the Higgs potential

$$V(\Phi) = \mu_h^2 |\Phi|^2 - \lambda |\Phi|^4 + \frac{|\Phi|^6}{\Lambda^2}$$

Can induce a strong 1st order phase transition if $\Lambda \sim 1$ TeV

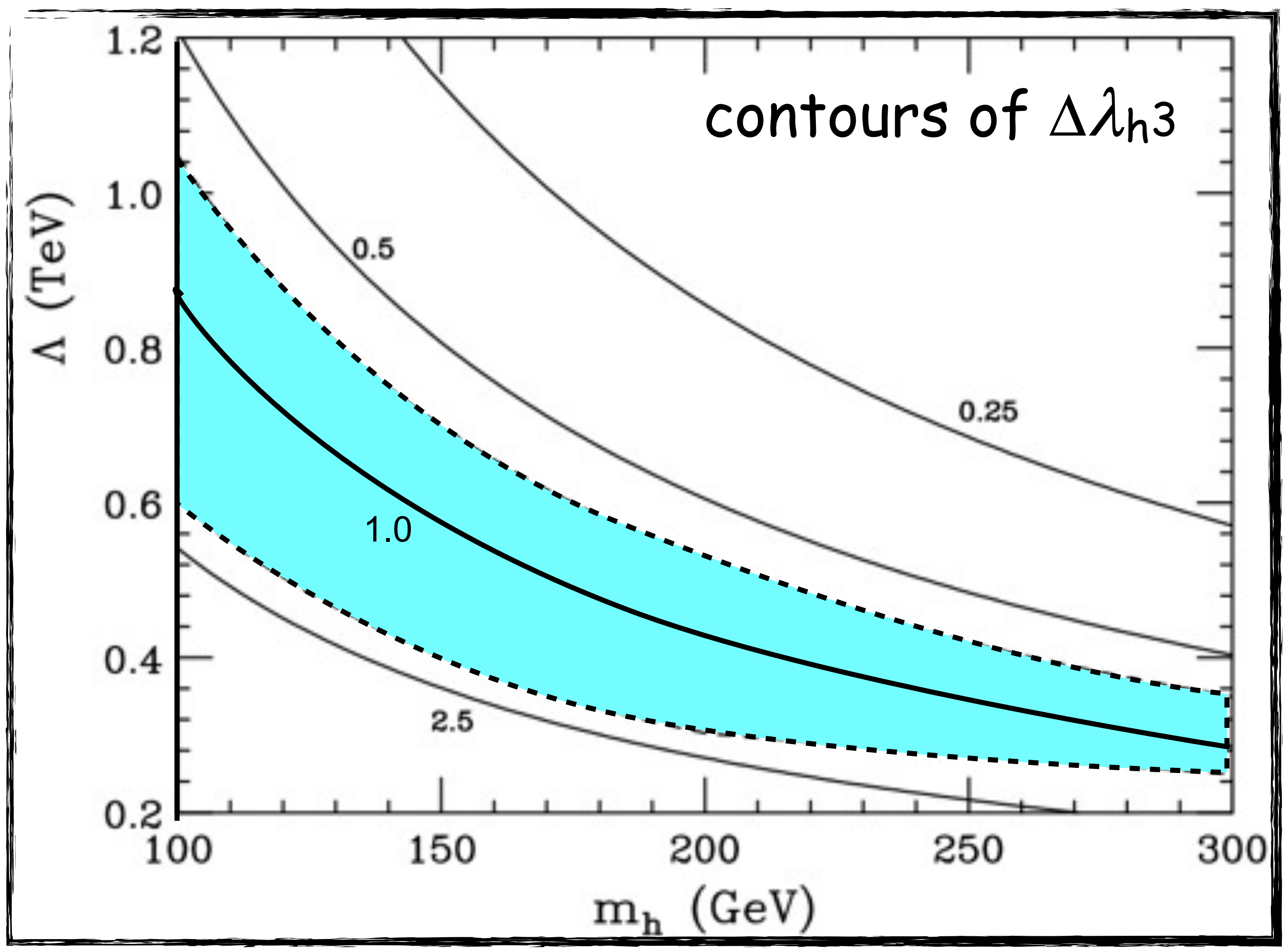


Testing the H^6 interaction @ SLHC

Grojean, Servant, Wells '04

The H^6 interaction generates large deviations of the Higgs self-couplings

$$V_{\rm SM} = \frac{1}{2} m_h^2 h^2 + \frac{1}{6}\left(\frac{3m_h^2}{v_0} + \frac{6v_0^3}{\Lambda^2}\right) h^3 + \frac{1}{24}\left(\frac{3m_h^2}{v_0^2} + \frac{36 v_0^2}{\Lambda^2}\right) h^4$$



$$\Delta\lambda_{h^3} = (\lambda_{h^3} - \lambda_{h^3}^{\rm SM})/\lambda_{h^3}^{\rm SM}$$

LHC: $\lambda_{h3}=0$ can be excluded at 95% CL

SLHC: λ_{h3} can be determined to 20÷30%

SLHC can teach us something about
the cosmological EW phase transition in the (very) early Universe

See also Noble, Perelstein '07

Dynamics of EW symmetry breaking

A Higgs-like

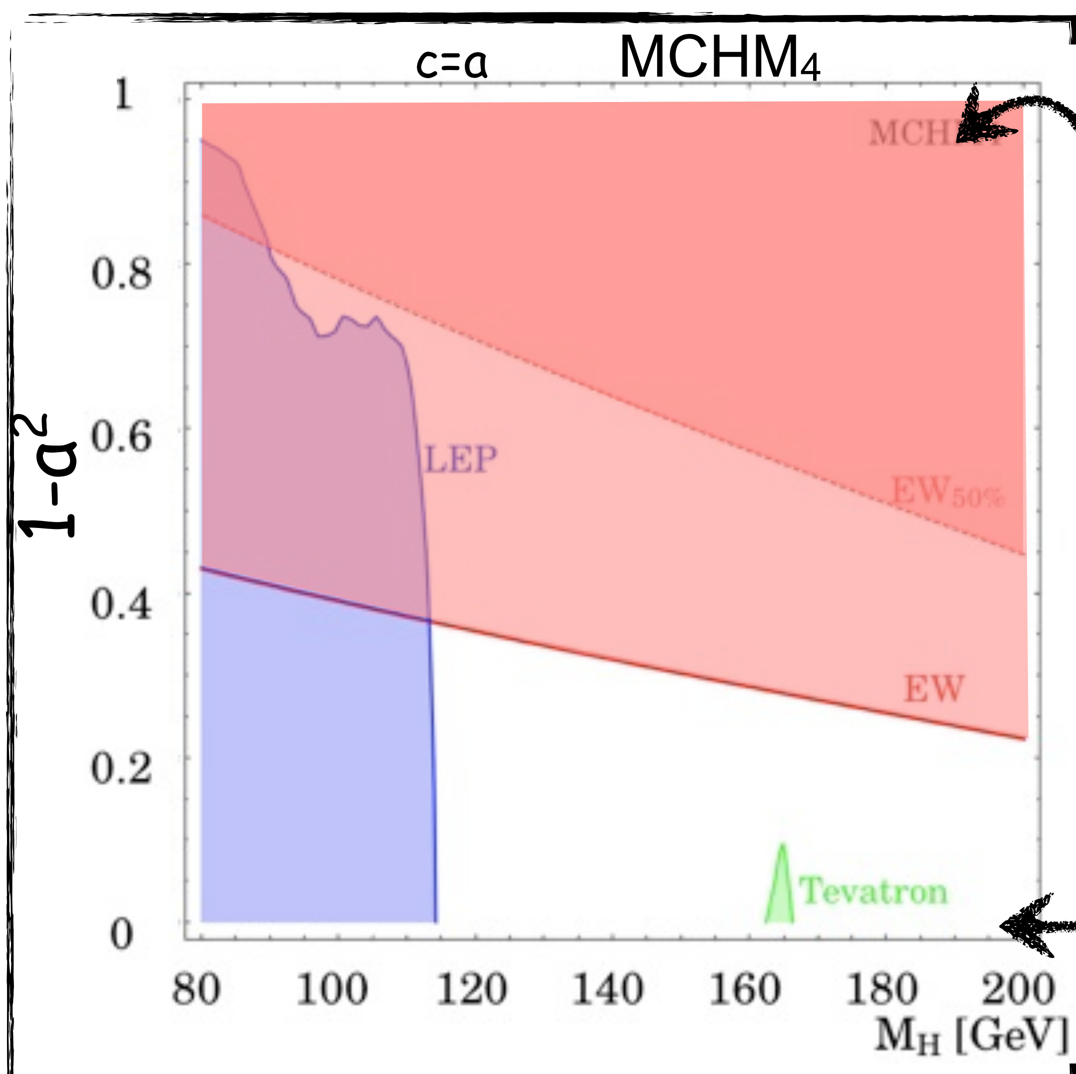
$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4}\text{Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) - \lambda\bar{\psi}_L\Sigma\psi_R\left(1+c\frac{h}{v}\right)$$

$\Sigma = e^{i\sigma^a\pi^a/v}$ Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$ $D_\mu\Sigma \approx W_\mu$

SM 'a=1', 'b=1' & 'c=1'

Current EW data constrain only 'a' (and marginally 'c')

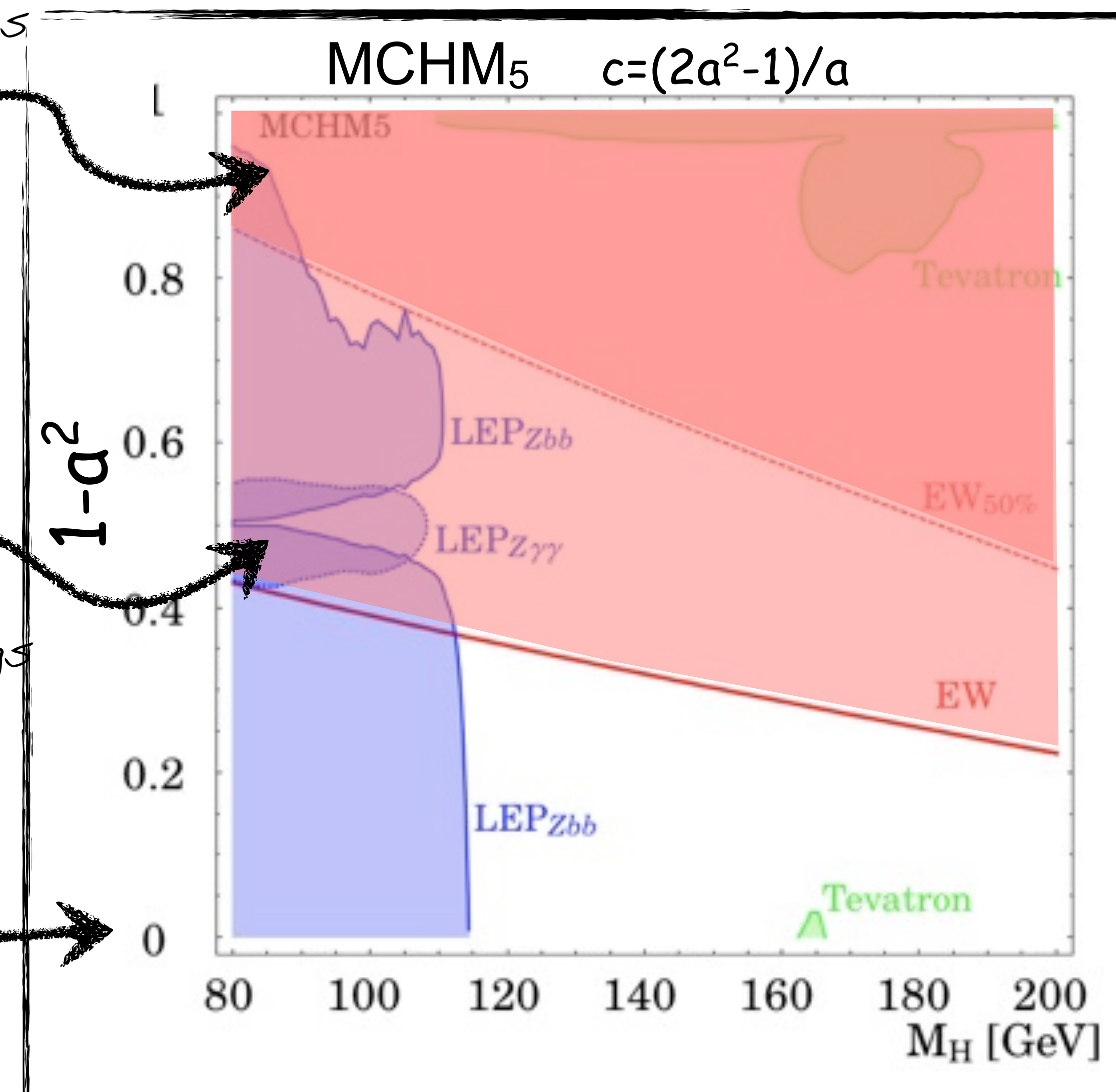
Espinosa, Grojean, Muehlleitner '10



gaugephobic Higgs

fermiophobic Higgs

SM limit



Strong EWSB: Composite Higgs

Higgs=Pseudo-Goldstone boson (PGB)

SM: $SO(4)/SO(3)$ — $W^\pm_L$ & Z_L ⇒ BSM: G/H — $W^\pm_L$ & Z_L & h

Continuous interpolation between SM and TC

$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

$\xi = 0$

SM limit

all resonances of strong sector, except the Higgs, decouple

$\xi = 1$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

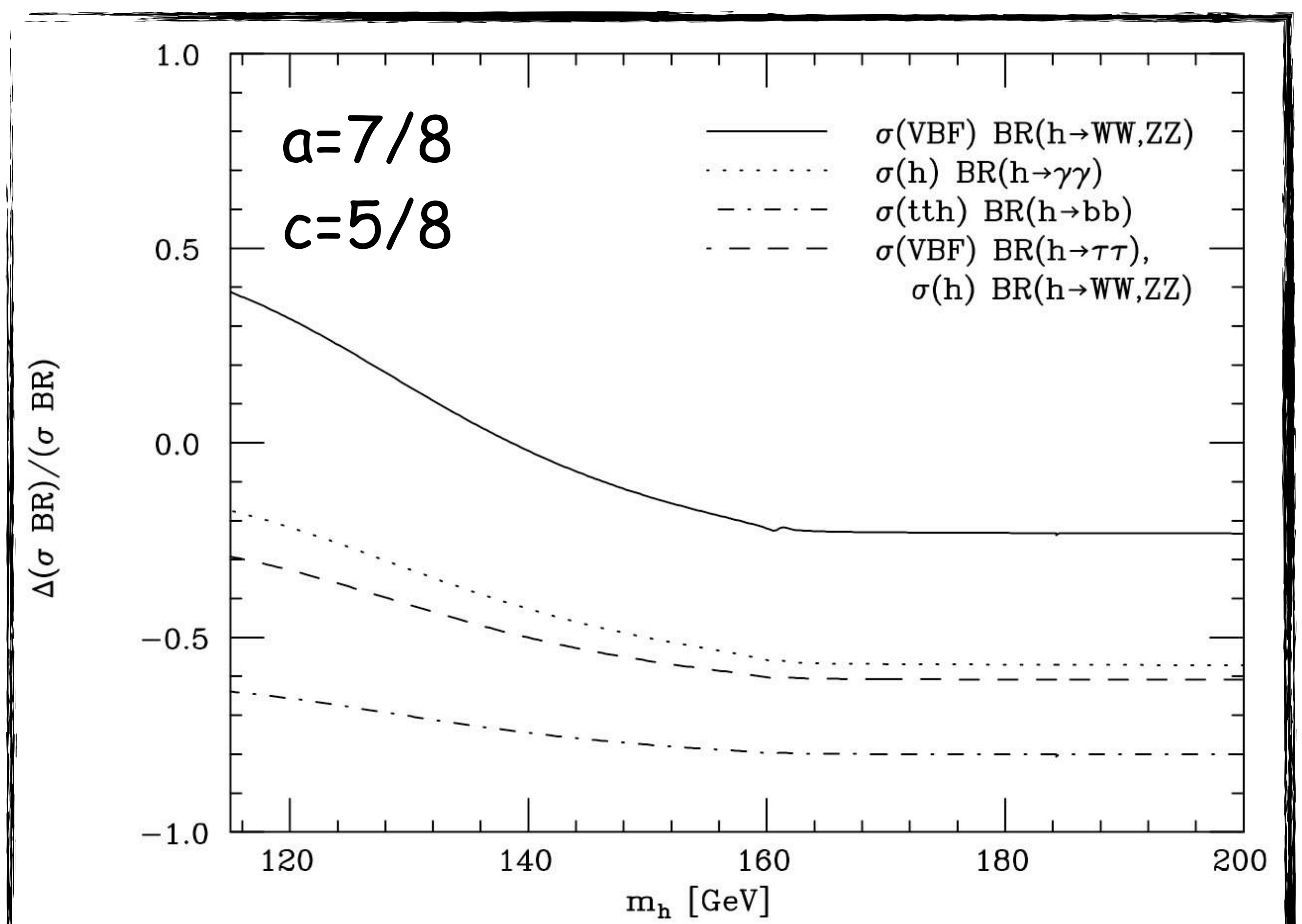
Composite Higgs couplings

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}+b_3\frac{h^3}{v^3}+\ldots\right) - \lambda\bar\psi_L\Sigma\psi_R\left(1+c\frac{h}{v}+c_2\frac{h^2}{v^2}+\ldots\right)$$

$$a=\sqrt{1-\xi} \qquad b=1-2\xi \qquad b_3=-\frac{4}{3}\xi\sqrt{1-\xi} \qquad c=\left(\sqrt{1-\xi},\frac{1-2\xi}{\sqrt{1-\xi}}\right) \qquad c_2=-(\xi,4\xi)$$

Minimal composite Higgs model (MCHM): SO(5)/SO(4)

$$\Gamma(h\to f\bar f) = (2c-1)\,\Gamma(h\to f\bar f)_{\rm SM} \quad \Gamma(h\to ZZ) = (2a-1)\,\Gamma(h\to ZZ)_{\rm SM}$$



SLHC can probe

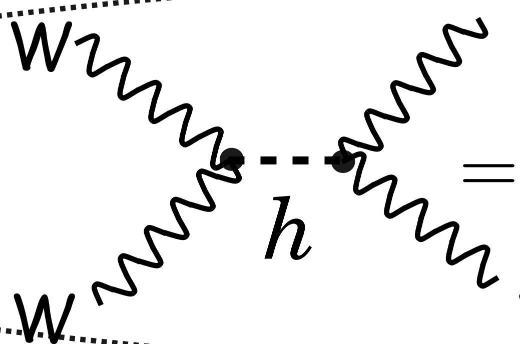
Δa & Δc
up to ~ 0.1÷0.2
i.e. 4πf ~ 5÷7 TeV

compositeness scale of the Higgs

Strong EW symmetry breaking

Giudice, Grojean, Pomarol, Rattazzi '07

strong WW scattering



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

no exact cancellation of the growing amplitudes

$$\mathcal{A}\left(W_L^a W_L^b \to W_L^c W_L^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc} \qquad \mathcal{A} = \left(1-a^2\right)\frac{s}{v^2}$$

large $\mathcal{L}_{int}$ needed

not competitive with the measurement of 'a' via anomalous couplings

strong double Higgs production

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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

access to a new interaction, 'b'

distinction between 'active' (higgs) and 'passive' (dilaton) scalar in EWSB dynamics

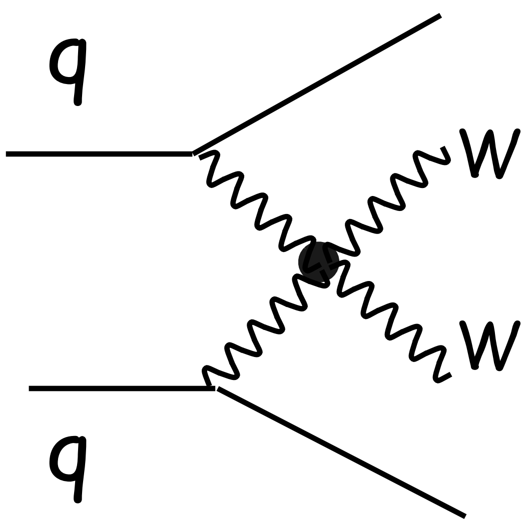
Strong WW scattering @ LHC

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

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to W_L^+ W_L^-\right) = \mathcal{A}\left(W_L^+ W_L^- \to Z_L^0 Z_L^0\right) = -\mathcal{A}\left(W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm\right) = (1-a^2)\frac{s}{v^2}$$

$$\mathcal{A}\left(W_L^\pm Z_L^0 \to W_L^\pm Z_L^0\right) = (1-a^2)\frac{t}{v^2} \qquad \mathcal{A}\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = (1-a^2)\frac{s+t}{v^2}$$

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



$$\sigma\left(pp \to V_L V_L X\right)_a = (1-a^2)\,\sigma\left(pp \to V_L V_L X\right)_{\text{LET}}$$

leptonic vector decay channels

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

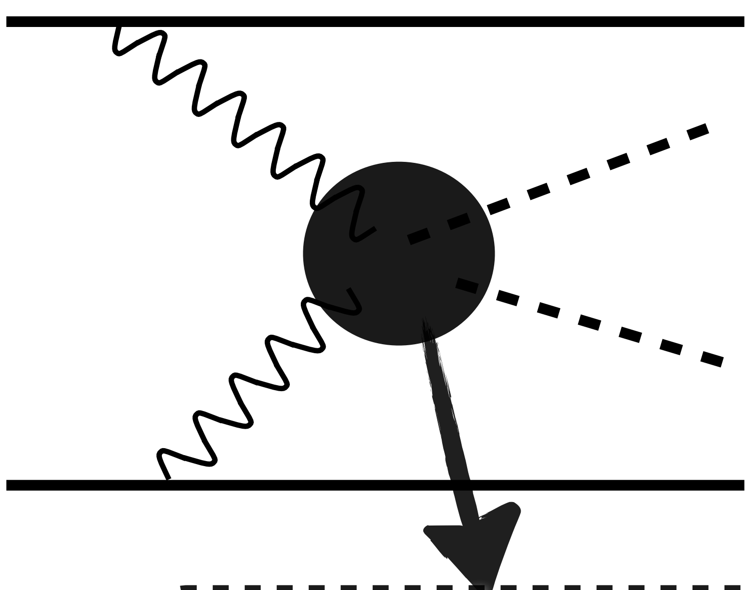
	LET$(a=0)$	SM bckg
ZZ	4.5	2.1
W^+W^-	15.0	36
$W^\pm Z$	9.6	14.7
$W^\pm W^\pm$	39	11.1

Bagger et al '95
Butterworth et al. '02

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

New technics being developed : boosted jets, jet substructures...

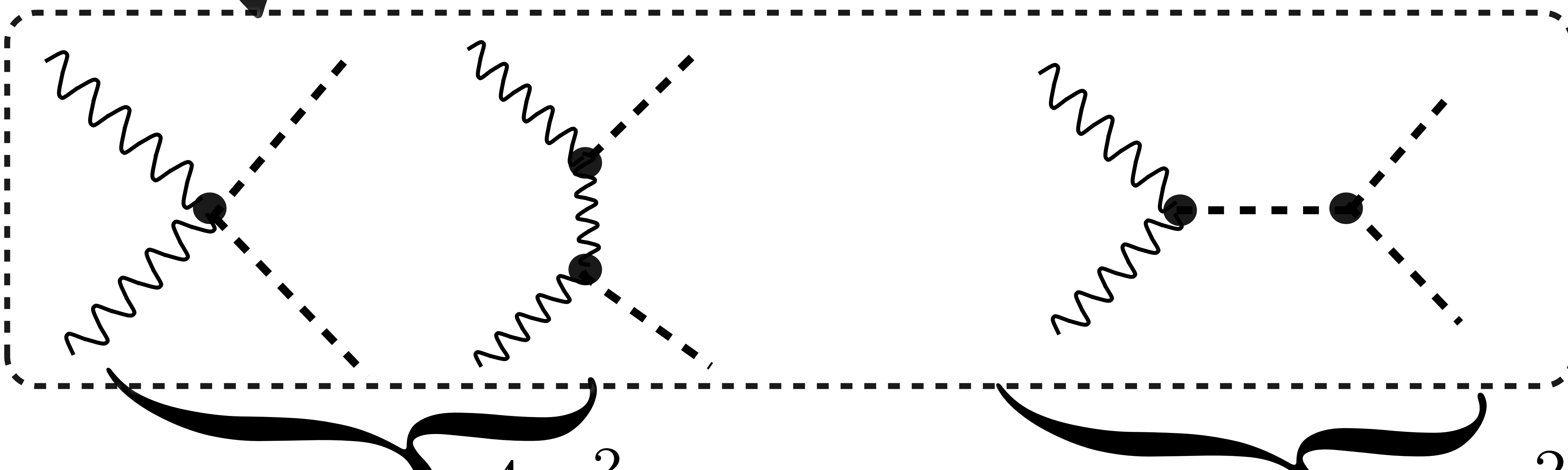
Strong hh production @ LHC



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

$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4 \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots$$

SM: $a=b=d_3=d_4=1$



$$\mathcal{A} \underset{m_{hh}^2 \gg m_W^2}{\sim} \left(b - a^2\right)\frac{4m_{hh}^2}{v^2}$$

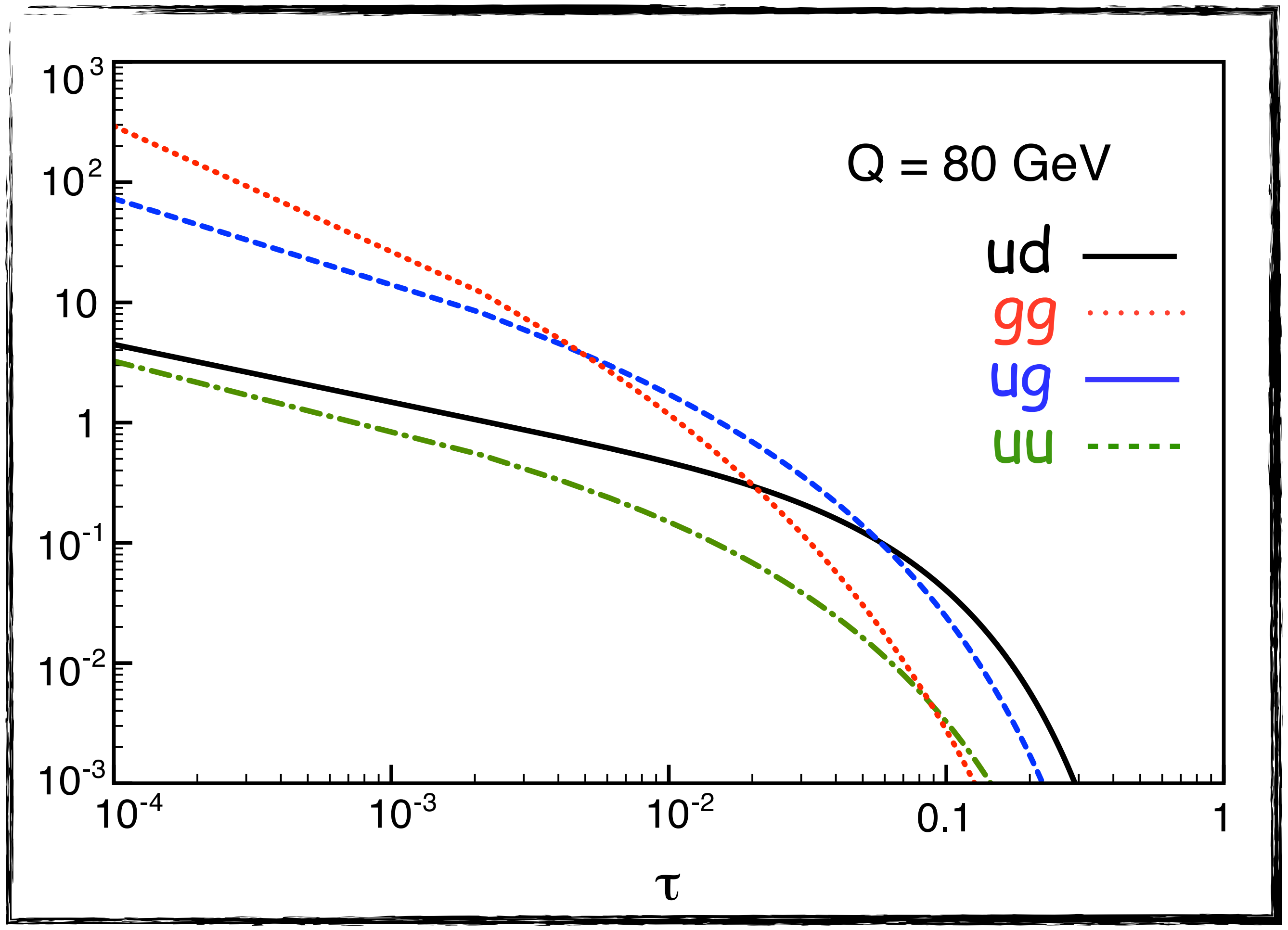
asymptotic behavior
sensitive to strong interaction

$$\mathcal{A} \underset{m_{hh}^2 \sim 4m_h^2}{\sim} \mathrm{cst.} + 3ad_3\frac{m_h^2}{v^2}$$

threshold effect

Threshold production

$$\frac{d\sigma}{d\hat{s}} = \frac{1}{\hat{s}}\hat{\sigma}(q_A q_B \to hh)\rho_{AB}(\hat{s}/s, Q^2)$$



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

integral is saturated at threshold

$\Downarrow \quad \Downarrow \quad \Downarrow$

inclusive cross-section is dominated by threshold production, it is not probing the asymptotic regime of hard scattering

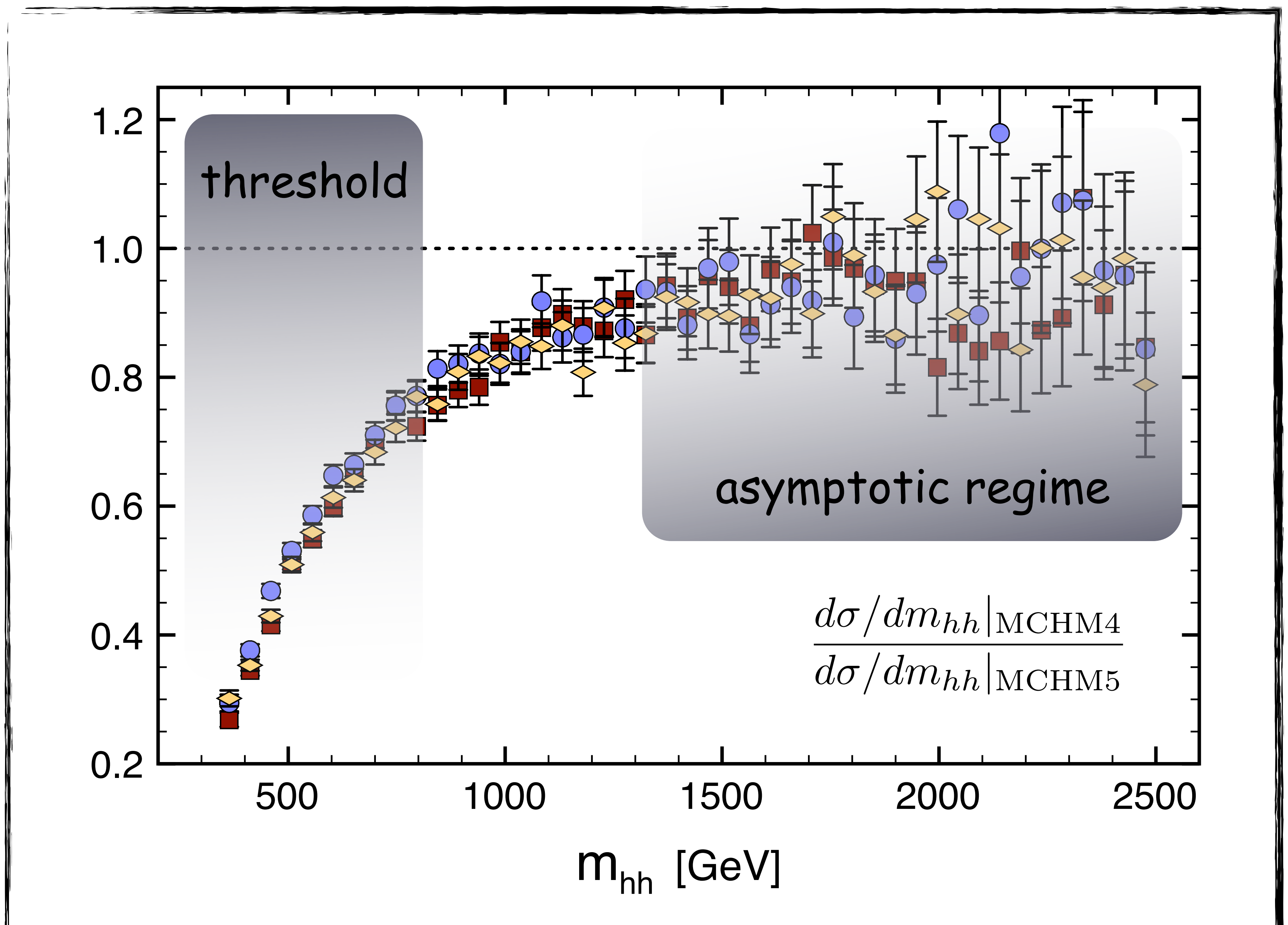
Isolating Hard Scattering

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

isolate events with large m_{hh}

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

measure H^3 measure $(b-a^2)$



two models with same asymptotic regime but different higgs-self-coupling

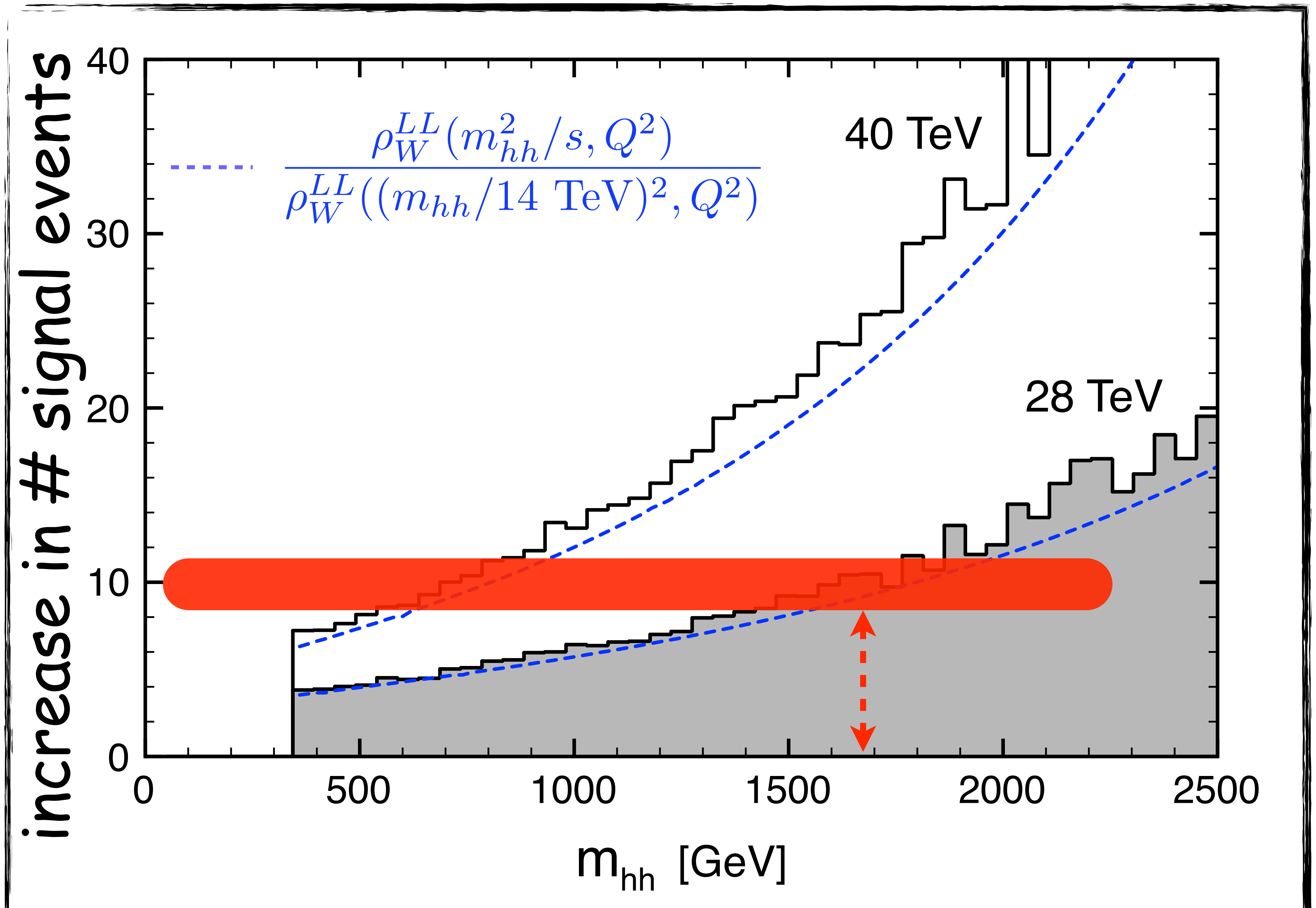
Dependence on Collider Energy

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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

increase collider energy s = sensitive to PDFs at smaller x

bigger cross-sections



SLHC vs. VLHC

10 x lum ≈ 10 x events

2 x √s ≈ 10 x events

iif m_{hh}>1.6TeV

Dependence on Collider Energy

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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

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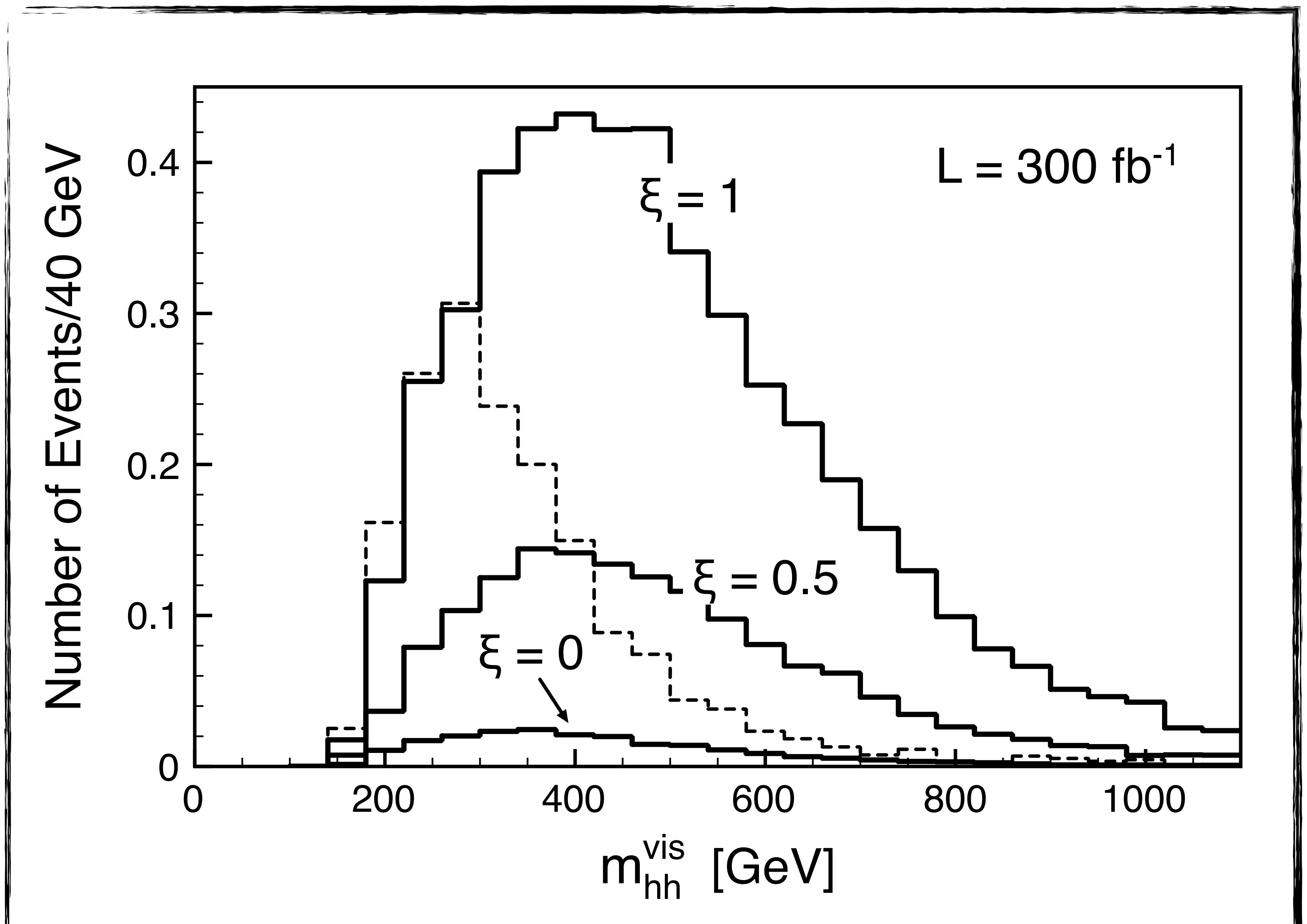


SLHC vs. VLHC

10 x lum ≈ 10 x events

2 x √s ≈ 10 x events

iif m_{hh}>1.6TeV

very few events only!

SLHC seems better

$W^+W^- \to$ 3h, Zhh, WWh, WWZ

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

Strong EWSB

$$\sigma_{2\pi\to 3\pi} \sim \frac{1}{8\pi}\frac{E^2}{f^4}\frac{E^2}{(4\pi f)^2}$$

$$E/f \leftrightarrow g$$

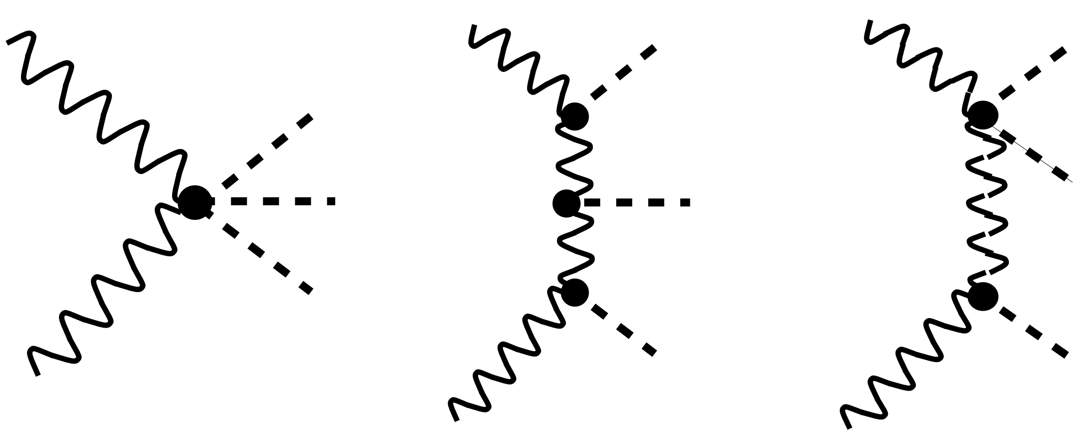
SM

$$\sigma_{2\pi\to 3\pi} \sim \frac{1}{8\pi}\frac{g^2}{v^2}\frac{g^2}{16\pi^2}$$

Probe of possible discrete symmetries in the strong dynamics

G/H symmetric space ⇒ invariance under $\pi \to -\pi$

a process with an odd # of PGBs
requires a coupling breaking the coset structure
ie cannot be mediated by strong interactions alone



$$\mathcal{A}_{WW\to 3h} \sim 4i\frac{s}{v^3}\left(a(b-a^2) - \frac{3}{4}b_3\right) + \sharp\, s \times \left(\frac{m_W}{\sqrt{s}}\right)^2$$

=0 for symmetric coset

mediated by SM gauge interactions (breaking of coset structure)

Conclusions

a lot

There is ~~nothing~~ new to be discovered in physics now. All that remains is more and more precise measurement.

(W. Thomson, Lord Kelvin, 1900)