Channels and Challenges:
Higgs Search at the LHC

Tilman Plehn
CERN

The Puzzle of Mass & the Higgs Boson

Standard Model Higgs Boson at the LHC

Supersymmetric Higgs Bosons at the LHC

ELEMENTARY PARTICLES

Standard Model: particles & interactions

- leptons (essentially means 'like electron')

  1897 Thomson: electron$^{(1)}$ $m_e = 0.5$ MeV

  1937 Anderson: muon$^{(2)}$ $m_\mu = 106$ MeV

  1975 Perl: tau lepton$^{(3)}$ $m_\tau = 1800$ MeV

  definition of 'mass': inertia in TV tube, dropping in LEP ring

- plus three neutrinos and anti-neutrinos ν

  1990s CERN: no more than 3 light neutrinos

- quarks (essentially means 'not like electron at all')

  neutron (uud) and proton (udd): up$^{(1)}$ and down$^{(1)}$

  in bound states: strange$^{(2)}$, charm$^{(2)}$ and bottom$^{(3)}$

  1995 Fermilab: top$^{(3)}$ $m_t = 175$ GeV

⇒ Fermions in three generations, different only by mass

Mixing of generations

- quarks mix a little (Cabbibo–Kobayashi–Maskawa matrix)

  → one complex phase in 3 × 3 mixing matrix

  → 'CP violating effect' observed

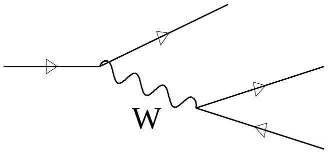
- leptons mix a lot (Maki–Nakagawa–Sakata matrix)

  → CP violation not yet observed

THE PUZZLE OF MASS

Another take on particle masses

- Rutherford 1911: electrons and protons/neutrons compose matter
  → proton mass multiparticle effect
  → electron mass essentially zero
- electromagnetic and gravitational interactions
  → all forces with infinite range (Coulomb potential $V \propto 1/r$)
  → equivalent to massless (virtual) photon exchange
- Fermi 1934: theory of weak interactions ($n \to p e^- \bar{\nu}_e$ and $\mu \to e^- \bar{\nu}_e \nu_\mu$)
  → divergent four fermion reaction amplitude: $\mathcal{A} \propto G_F E^2$
  → unitarity violation (transition probability $\propto |\mathcal{A}|^2$)
  → 'effective theory' valid for $E < 600$ GeV



- Yukawa 1935: massive virtual particle exchange
  → Fermi's theory for $E \ll M$
  → unitary for large energies: $\mathcal{A} \propto g^2 E^2/(E^2 - M^2)$
  → mass of Yukawa particles means??
- CERN 1983: W, Z bosons discovered
  → $m_W \sim 80$ GeV and $m_Z \sim 91$ GeV ($m_{W,Z} \sim (m_t + m_b)/2$)
  → mass: inertia when pushed, dropping to the ground in flight

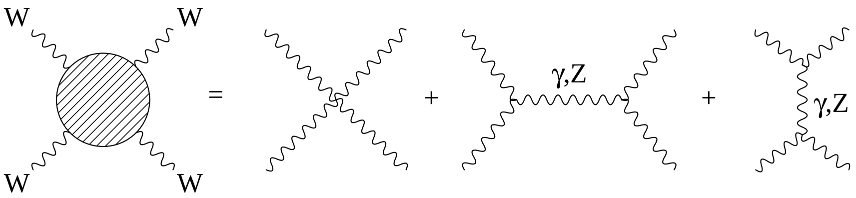
⇒ boson and fermion masses the same thing

UNITARITY AND HIGGS BOSON

Theory of W, Z bosons

- start with $SU(2)$ gauge theory (massless W, Z)
- measured masses $\mathcal{L} \sim -m_{W,Z} A_\mu A^\mu$
  - → not gauge invariant (except in small $m_{W,Z}$ limit)
  - → not renormalizable (means not predictive to all scales)
  - → but valid effective theory of massive W, Z bosons

Unitarity tests



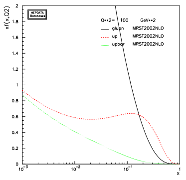
- probe theory in $WW \to WW$ scattering
  - → $\mathcal{A} \propto G_F E^2$ just like Fermi's theory, not unitary above 1.2 TeV
  - → postulate additional scalar particle: Higgs boson
  - → unitarity conserved
  - → fixed coupling $g_{WWH} \propto m_W$
- add fermions: $WW \to f\bar{f}$ scattering
  - → fixed coupling $g_{ffH} \propto m_f$
- test new theory with $WW \to HH$ scattering
  - → fixed coupling $g_{HHH} \propto m_H^2/m_W$
- final test: $HH \to HH$ scattering
  - → fixed coupling $g_{HHHH} \propto m_H^2/m_W^2$

- Standard Model: complete unitary theory of massive W, Z bosons
- Higgs mass a free parameter, all Higgs couplings fixed

HADRON COLLIDERS: TEVATRON & LHC

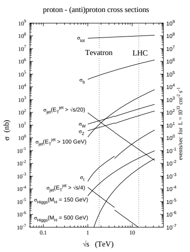
Conversion of energy into mass ($E = mc^2$ with c=1)

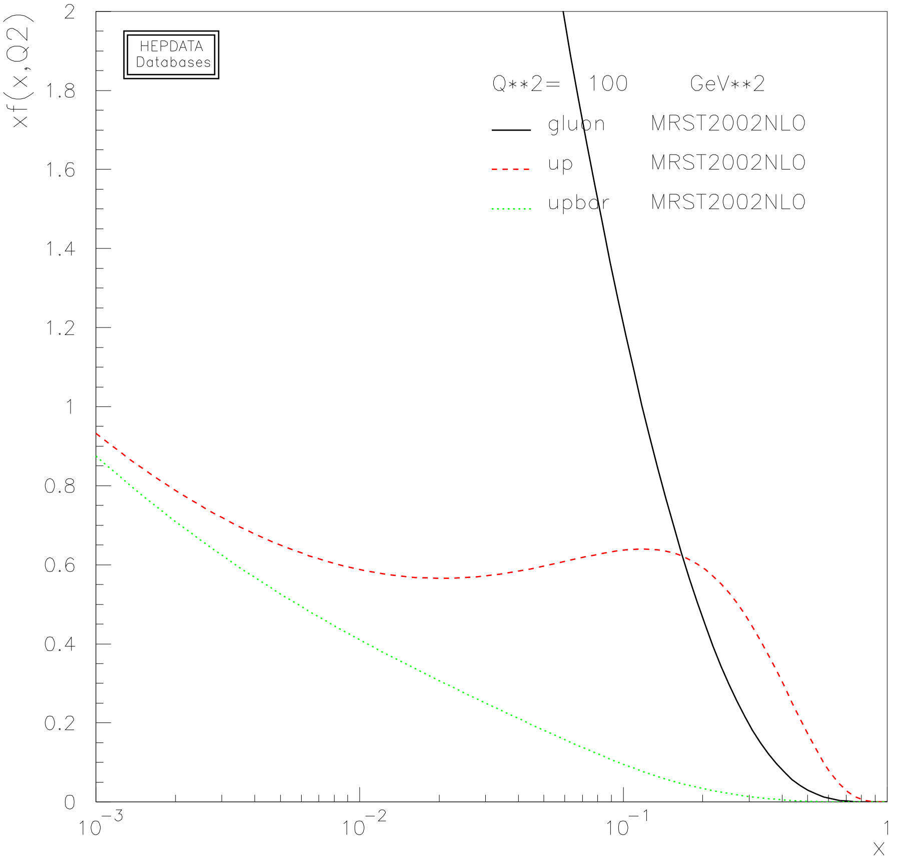
- search for new physics/particles (conclusive only if real particle produced)
  → highest possible energies required
- electron colliders: collide two highly relativistic e^+e^-
  LEP: 46 GeV each to produce one Z
  LEP2: 103 GeV each to produce pairs of new particles
  TESLA/CLIC: 1...3 TeV?
- hadron colliders: collide protons
  Tevatron: $p\bar{p}$ collision with 2 TeV (mostly valence quarks)
  LHC: pp collisions with 14 TeV (mostly gluons)
  → LHC mass reach roughly 3 TeV
- special feature: trade luminosity for energy

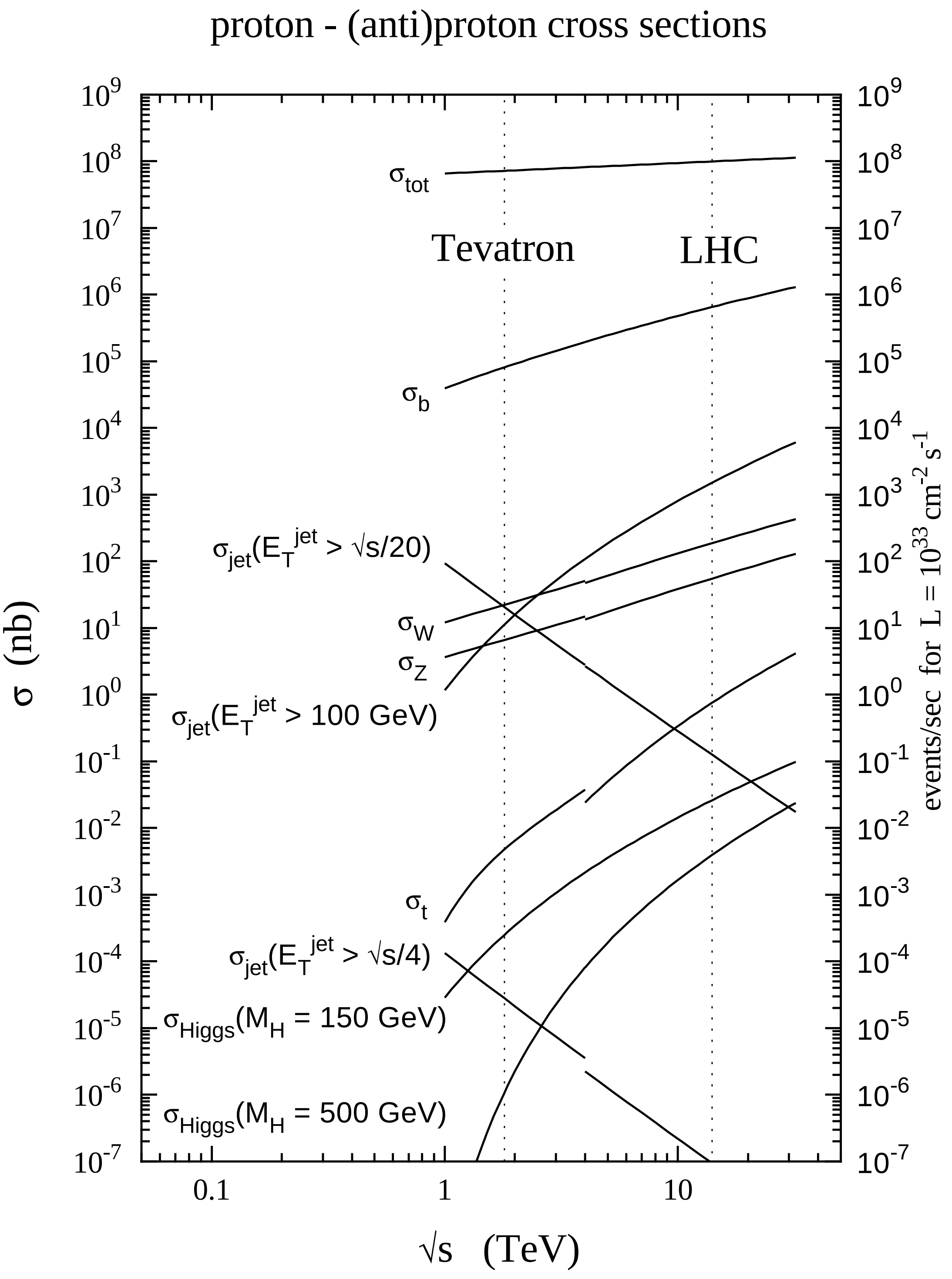


New physics with hadron colliders

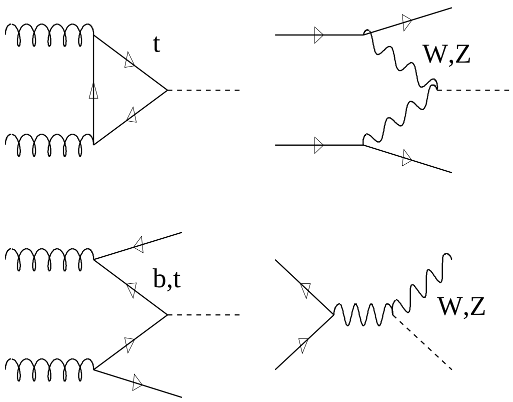
- what is a jet and what isn't??? (b tag, τ tag)
- trigger: 'no leptons — no data' (e.g. $pp \to t\bar{t} \to W^+bW^-\bar{b} \to b\bar{b} + 4$jets)
- huge and uncertain backgrounds rates $pp \to jj$ or $pp \to WZ$+jets
- statistical significance: $S/\sqrt{B} > 5$ is discovery




xf(x,Q2)
HEPDATA
Databases
Q**2= 100 GeV**2
gluon MRST2002NLO
up MRST2002NLO
upbar MRST2002NLO
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^-3
10^-2
10^-1
1
x


proton - (anti)proton cross sections
σ (nb)
events/sec for L = 10^33 cm^-2 s^-1
√s (TeV)
0.1
1
10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
Tevatron
LHC
σtot
σb
σjet(ET jet > √s/20)
σW
σZ
σjet(ET jet > 100 GeV)
σt
σjet(ET jet > √s/4)
σHiggs(MH = 150 GeV)
σHiggs(MH = 500 GeV)

CHALLENGE 1: FIND SM HIGGS



Designing Higgs searches for the LHC

- (a) unitarity limit: $m_H < 1$ TeV
  (b) electroweak precision tests: $m_H < 220$ GeV
- production and decay combos for light Higgs

$gg \rightarrow H$
$qq \rightarrow qqH$
$gg \rightarrow t\bar{t}H$
$q\bar{q}' \rightarrow WH\ldots$

$\Longleftrightarrow$

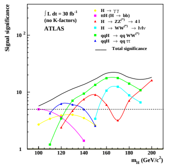
signal × trigger
backgrounds
systematics
$S/\sqrt{B}$ vs. S/B
mass resolution...

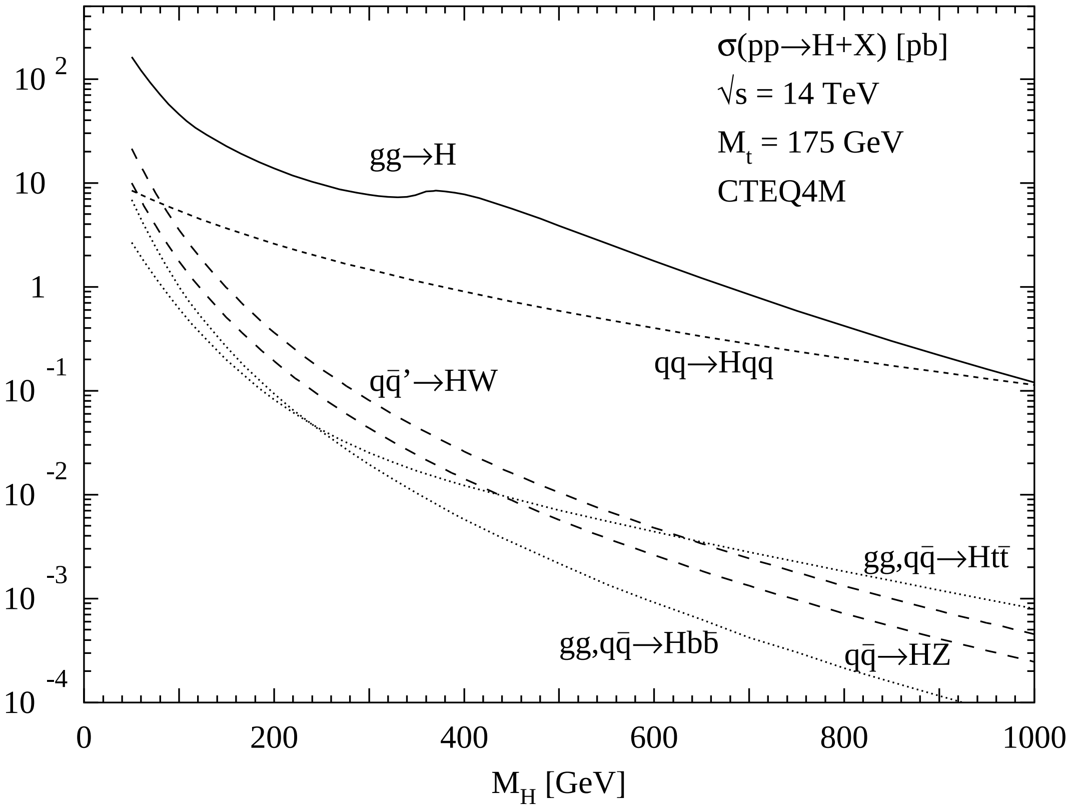
$\Longleftrightarrow$

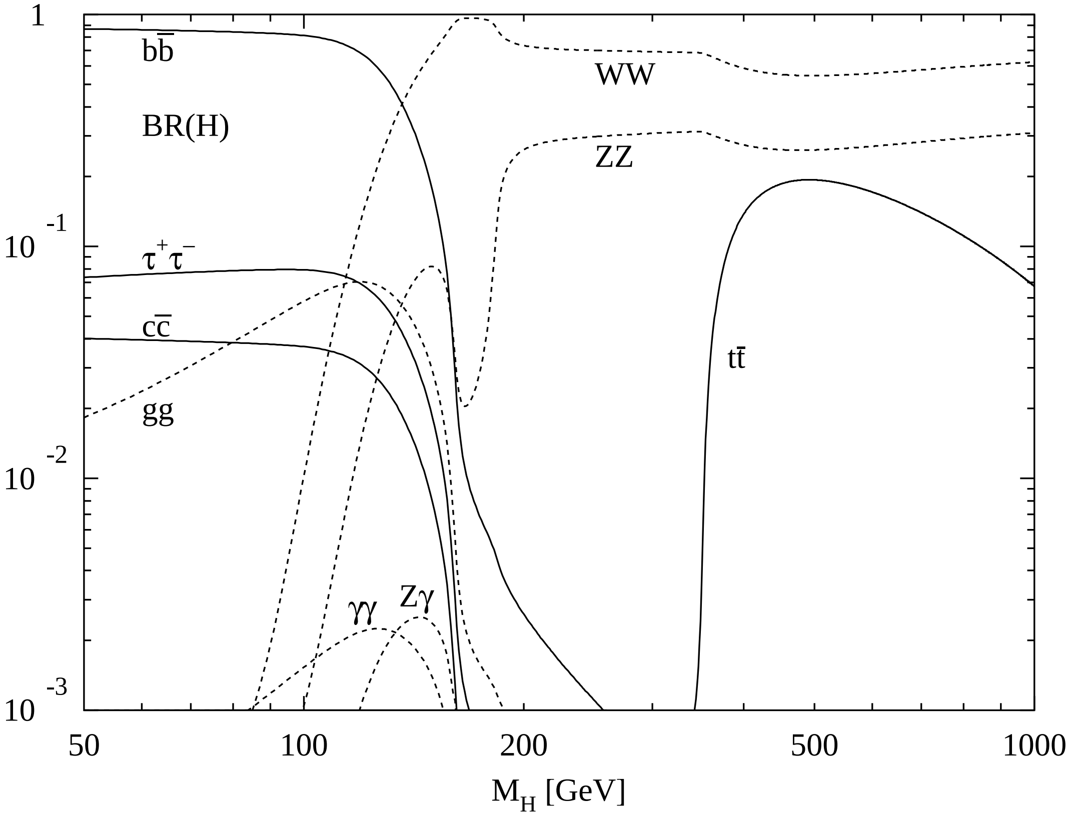
$H \rightarrow b\bar{b}$
$H \rightarrow WW$
$H \rightarrow \tau^+_{\ell h}\tau^-_{\ell}$
$H \rightarrow \gamma\gamma$
$H \rightarrow \mu\mu\ldots$

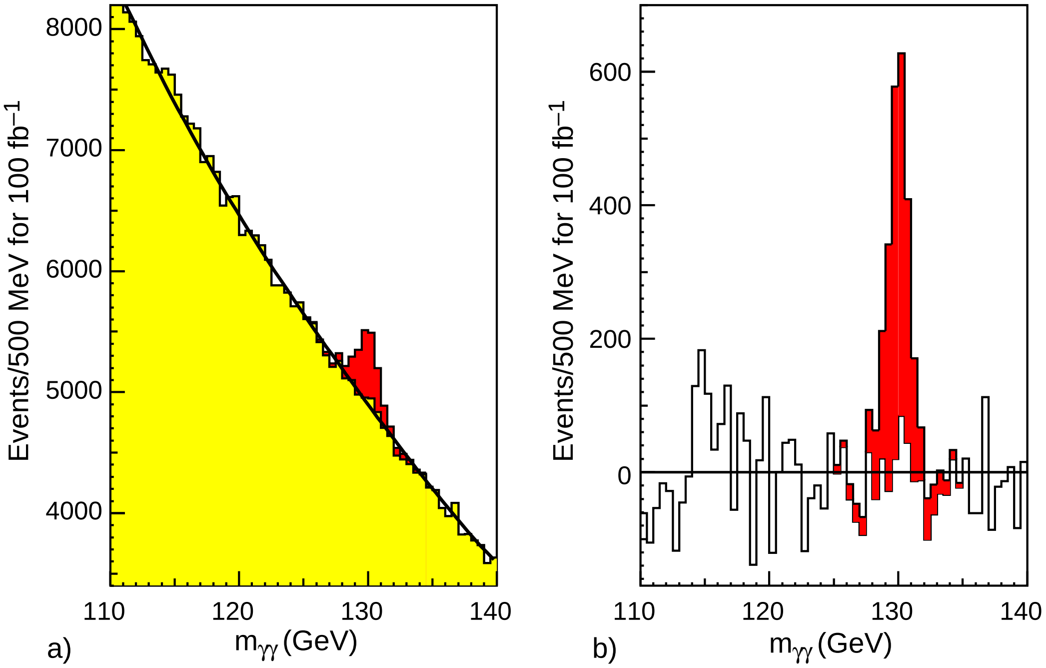
State of the art

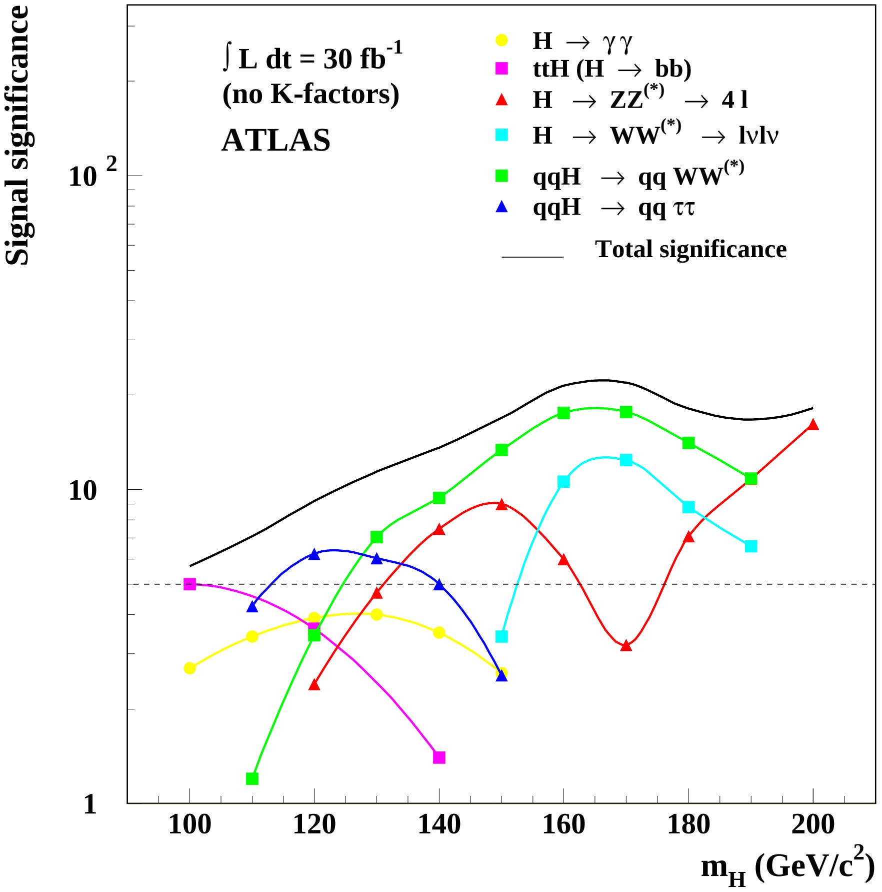
- 6 million Higgses in gluon fusion: $gg \rightarrow H \rightarrow \gamma\gamma$
  (mass resulution $\Delta m_H/m_H \sim \Gamma/\sqrt{S} < 0.5\%$)
- backgrounds smaller in WW fusion: $qq \rightarrow qqH \rightarrow qq\tau\tau$
  (reconstruct $m_{\tau\tau}$ in collinear approximation, $S/B = \mathcal{O}(1)$)
- off-shell Higgs decays: $qq \rightarrow qqH \rightarrow qqWW$
  (works down to $m_H < 120$ GeV)
- few examples of ‘marginally successful’ strategies:
  $gg \rightarrow t\bar{t}H \rightarrow t\bar{t}b\bar{b}$ (complexity of signal)
  $gg \rightarrow t\bar{t}H \rightarrow t\bar{t}\tau\tau$ (never openly admitted)
  $q\bar{q}' \rightarrow WH \rightarrow Wb\bar{b}$ (NLO background estimate)
  $qq \rightarrow qqH \rightarrow qqb\bar{b}$ (no ATLAS trigger) ....




σ(pp→H+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4M
gg→H
qq→Hqq
$q\bar{q}'$→HW
gg,$q\bar{q}$→$Ht\bar{t}$
gg,$q\bar{q}$→$Hb\bar{b}$
$q\bar{q}$→HZ
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
200
400
600
800
1000
M_H [GeV]


$b\bar{b}$
BR(H)
$\tau^+\tau^-$
$c\bar{c}$
gg
WW
ZZ
$t\bar{t}$
γγ
Zγ
1
10^{-1}
10^{-2}
10^{-3}
50
100
200
500
1000
M_H [GeV]


Events/500 MeV for 100 fb^{-1}
8000
7000
6000
5000
4000
110
120
130
140
a)
m$_{\gamma\gamma}$ (GeV)
Events/500 MeV for 100 fb^{-1}
600
400
200
0
110
120
130
140
b)
m$_{\gamma\gamma}$ (GeV)


∫ L dt = 30 fb^{-1}
(no K-factors)
ATLAS
● H → γγ
■ ttH (H → bb)
▲ H → ZZ$^{(*)}$ → 4 l
■ H → WW$^{(*)}$ → lνlν
■ qqH → qq WW$^{(*)}$
▲ qqH → qq ττ
Total significance
Signal significance
10^2
10
1
100
120
140
160
180
200
m$_H$ (GeV/c^2)

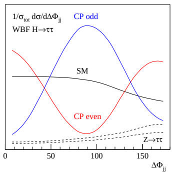
CHALLENGE 2: HIGGS PROPERTIES

Find the Higgs — what are you talking about???

$+$ mass measurement $(H \to \gamma\gamma)$

$+$ coupling to W $(qq \to qqH \text{ and } gg \to H \to \gamma\gamma)$
coupling to Z $(gg \to H \to ZZ)$
coupling to top $(gg \to H)$
coupling to tau $(qq \to qqH \to qq\tau\tau)$

$+$ WWH coupling $g_{\mu\nu}$ and CP $(qq \to qqH \to qq\tau\tau \text{ jet correlations})$



$+$ ZZH coupling $g_{\mu\nu}$ and CP $(gg \to H \to ZZ \text{ decay correlations})$

$+$ invisible Higgs decay $(qq \to qqH$ for 10% invisible decays)

? trilinear Higgs self coupling λ_{HHH} (really tough, next transparency)

? spin 0 scalar (spin 1 ruled out by $H \to \gamma\gamma$)

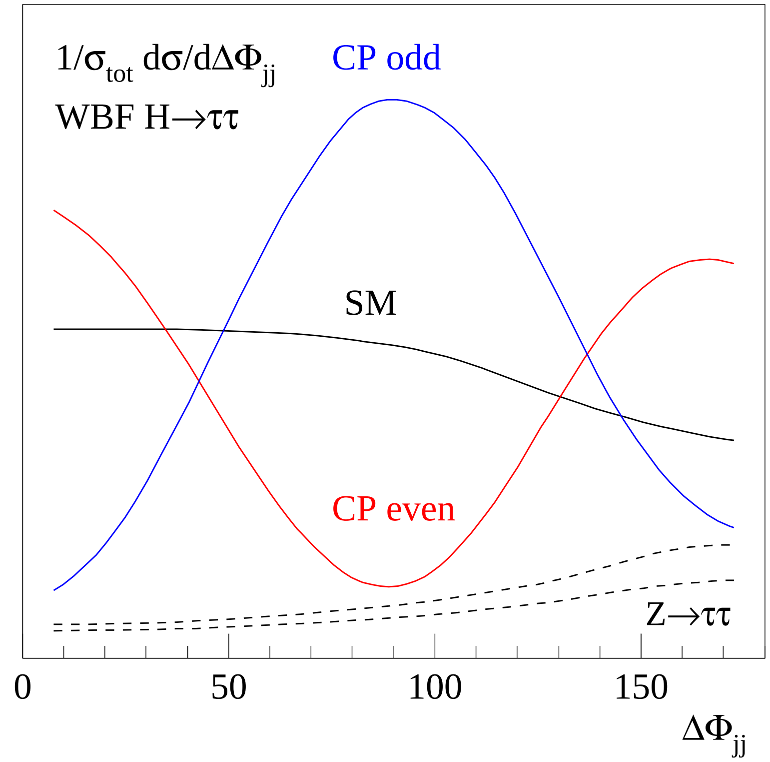
$-$ coupling to bottom and to light generations? (maybe $qq \to qqH \to qq\mu\mu$)
→ Yukawa couplings to fermions not established

$-$ total width? (to compare with sum of observed decays)

$-$ four Higgs self coupling λ_{4H}? (not in my life time)

⇒ LHC luminosity upgrade for precision studies

⇒ linear collider TESLA mandatory (rule of thumb: factor 10 better)


$1/\sigma_{tot}\, d\sigma/d\Delta\Phi_{jj}$
WBF $H\rightarrow\tau\tau$
CP odd
SM
CP even
$Z\rightarrow\tau\tau$
0
50
100
150
$\Delta\Phi_{jj}$

CHALLENGE 2B: HIGGS SELF COUPLING

Higgs Self Coupling

- scalar with Yukawa couplings to fermions, so what?
- back to Higgs potential $(\lambda = m_H^2/(2v^2))$

$$V(H) = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v} H^3 + \frac{m_H^2}{8v^2} H^4$$

$\Rightarrow$ self couplings the holy grail of Higgs physics

Higgs pair production

- $HH \to 4W$: serious detector simulation needed, not hopeless

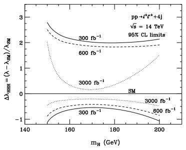
  (use observable m_{vis} to determine λ_{HHH})
- $HH \to b\bar{b}\tau\tau$: miracle required
- $HH \to 4b$: several major miracles mandatory

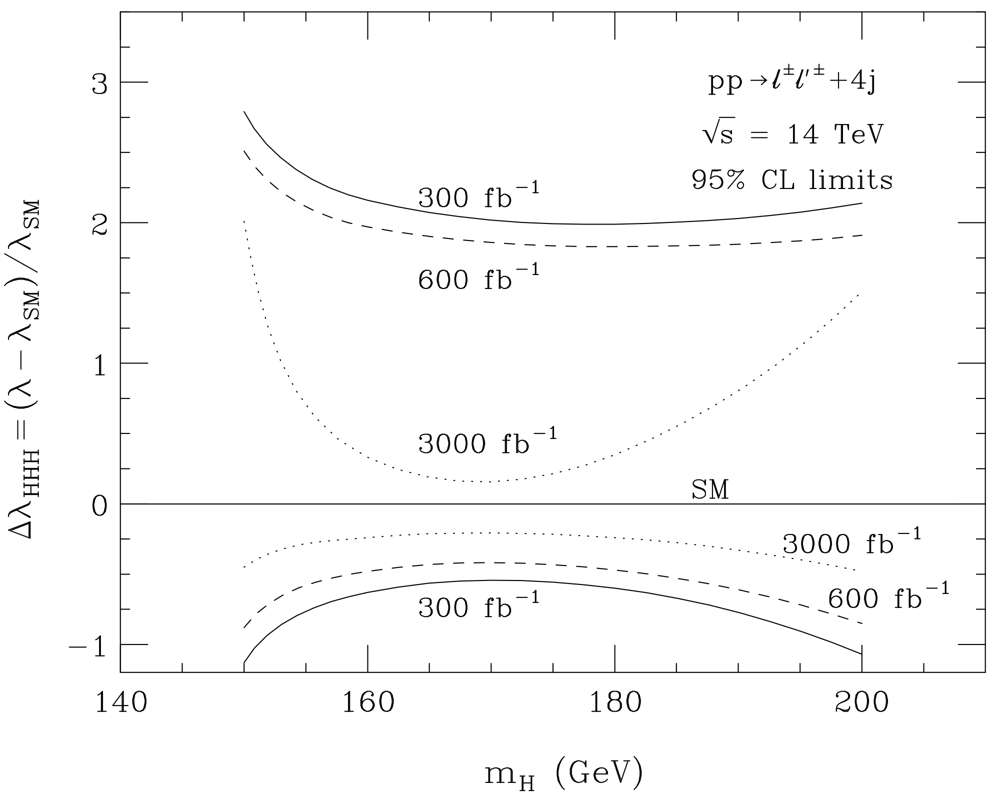
  (TESLA in better shape)
- $HH \to b\bar{b}\mu\mu$: at least small miracle would be helpful

  (might come out of $\mu\mu$ mass resolution)
- $HH \to b\bar{b}\gamma\gamma$: some enhancement needed

$\Rightarrow$ serious challenge to detectors and machine

(my personal favorite for luminosity upgrade)




$pp \to \ell^\pm \ell'^\pm + 4j$
$\sqrt{s} = 14$ TeV
95% CL limits
300 fb^{-1}
600 fb^{-1}
3000 fb^{-1}
SM
3000 fb^{-1}
600 fb^{-1}
300 fb^{-1}
$\Delta\lambda_{HHH} = (\lambda - \lambda_{SM})/\lambda_{SM}$
m_H (GeV)
3
2
1
0
−1
140
160
180
200

CHALLENGE 3: VARIANTS

Many attempts to modify the Higgs sector

- idea usually to hide it at some unwanted collider

  (always easier to hide things than to find them)
- example: many Higgs doublets (thought to hide at LHC)

  (a) precision data: $m_H^2 \to \sum C_i^2 m_{h_i}^2 = \langle M^2 \rangle \lesssim (200\text{GeV})^2$

  (b) W, Z masses: $v^2 \to \sum v_i^2 = v^2 \sum C_i^2$

  (c) fermion masses: $m_t = vY_t \to \sum v_i Y_t^i = v \sum C_i Y_t^i$
- assume $v_i = v/N$ and $Y_i = Y$ (also $\sum C_i^2 = NC^2 = 1$ and $\sum C_i = NC = \sqrt{N}$)

  → fermion widths $\Gamma_f = \Gamma_f^{\text{SM}} C_i^2 / (\sum_i C_i)^{-2} = \Gamma_f^{\text{SM}}/N^2$

  → gauge boson widths $\Gamma_{W,Z} = \Gamma_{W,Z}^{\text{SM}}/N^2$

⇒ all decays same as SM Higgs with mass m_{h_i}

LHC strategy

- production process for $\langle M^2 \rangle \sim (200\text{GeV})^2$

  → integrated $qq \to qqH$ production rate roughly matches SM rate
- decay channel without mass reconstruction: $H \to WW \to \ell^- \ell^+ \nu \bar{\nu}$

⇒ no problem to find continuum Higgs at all

- We will find the Higgs at the LHC
- We will measure some Higgs parameters
- Funny variants will not prevent that

MSSM HIGGS SECTOR

Why Minimal Supersymmetric Standard Model?

- quadratically divergent one-loop corrections to m_H:

$$\delta m_H^2 = \Lambda^2 \frac{3}{8\pi^2 v^2} \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)$$

  → Higgs mass always driven to cutoff scale (except Veltman's condition)
  → invent theory with mirror particles which enter with (-1)
  → remember spin–statistics: change spin by $1/2$
  → call it supersymmetry → stabilize proton → explain dark matter ...

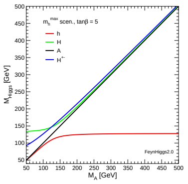
- Higgs sector: two Higgs doublets for top and bottom mass

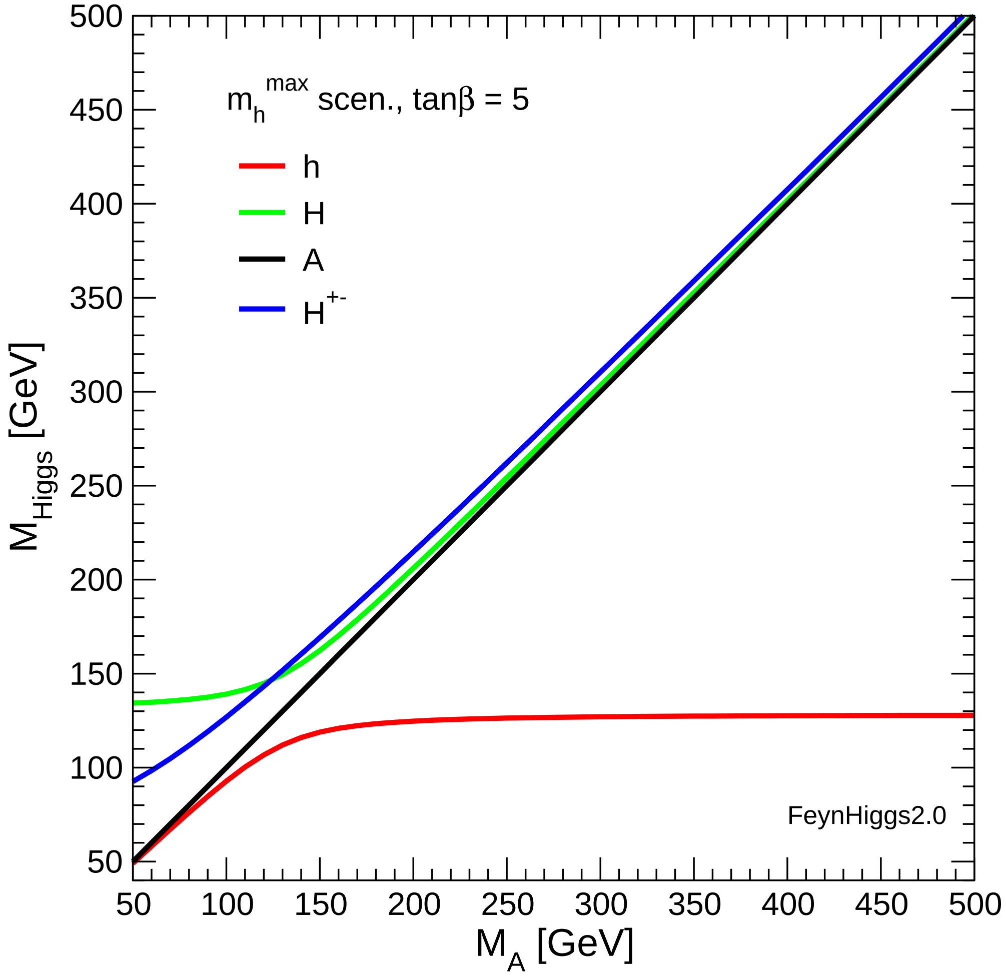
Two Higgs doublet model

- one (complex) Higgs doublet: 4 degrees of freedom
  → three for longitudinal gauge bosons, one for (neutral) scalar Higgs

- two (complex) Higgs doublet: 8 degrees of freedom
  → three for longitudinal gauge bosons, five for physical Higgs particles
  → two scalars h^0, H^0, one pseudoscalar A^0, one charged $H^\pm$

- free parameters
  (1) still only one free mass scale: m_A (usually heavy)
  (2) two vacuum expectation values: $\tan\beta = v_t/v_b$
  → surprising prediction: $m_h < 135$ GeV



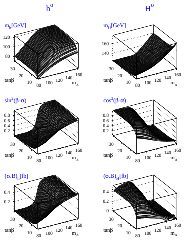


m_h^{max} scen., tanβ = 5
h
H
A
H^{+-}
FeynHiggs2.0
M_{Higgs} [GeV]
M_A [GeV]
50
100
150
200
250
300
350
400
450
500

CHALLENGE 4: FIND ONE MSSM HIGGS BOSON

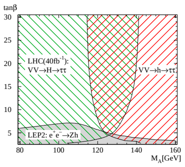
MSSM Higgs bosons and $qq \to qqH \to qq\tau\tau$

- allowed MSSM Higgs masses: $m_Z \ll m_h < 135$ GeV
- decoupling regime $m_A \gtrsim 160$ GeV
  → pseudoscalar, scalar H^0, and charged Higgs heavy
  → light scalar h^0 looks like SM Higgs (of the corresponding mass)
  → production rate: $g_{WWh} \sim 1$
  → branching fraction: $BR(h^0 \to \tau\tau) > BR(H_{\rm SM} \to \tau\tau)$



M_{SUSY}=1 TeV, maximal mixing

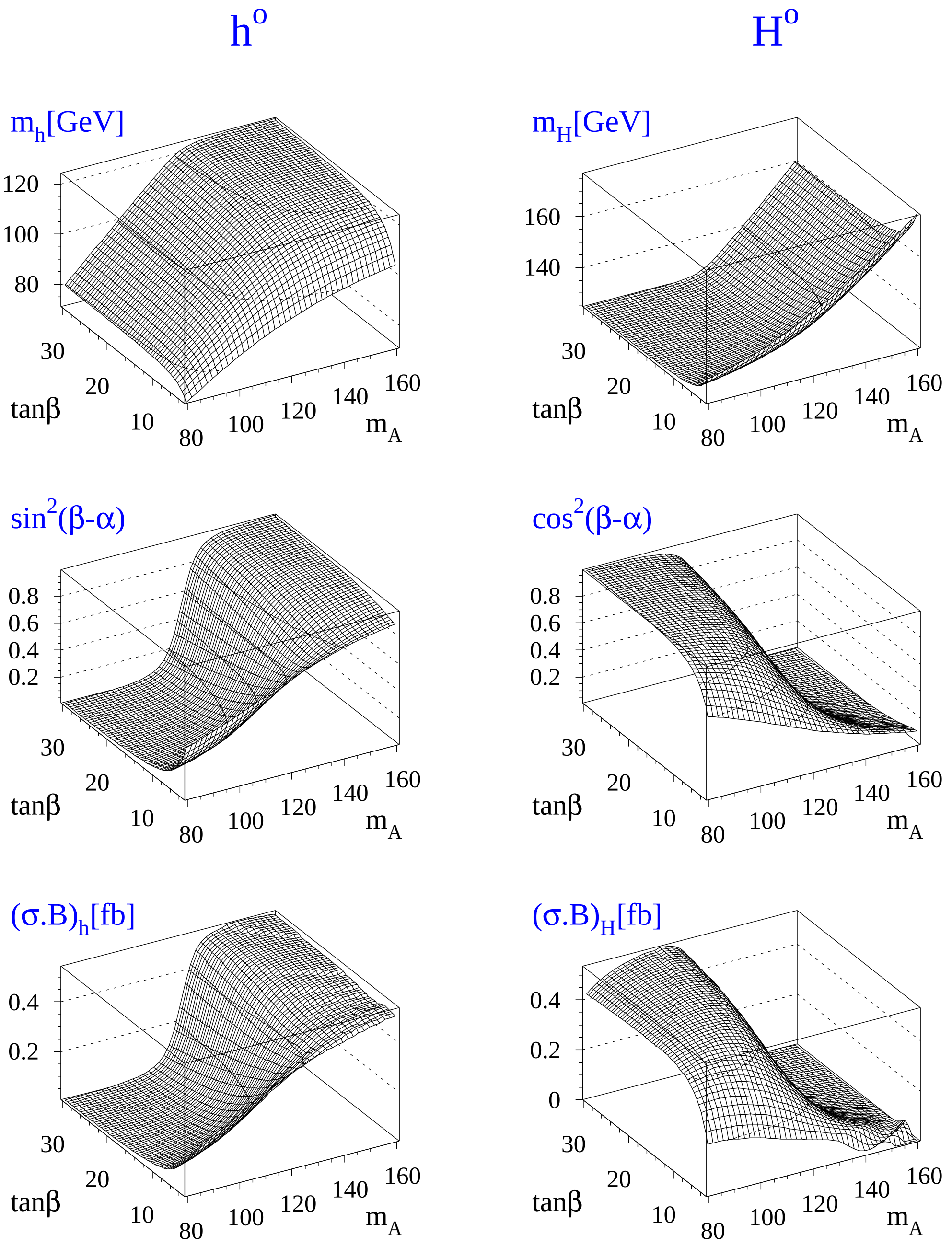
- opposite case $m_A \lesssim 120$ GeV
  → heavy scalar H^0 around 135 GeV
  → $qq \to qqH^0 \to qq\tau\tau$ SM-like
- intermediate case $m_A \sim 120$ GeV
  → usually regarded as toughest
  → $h^0, H^0 \to \tau\tau$ just add up



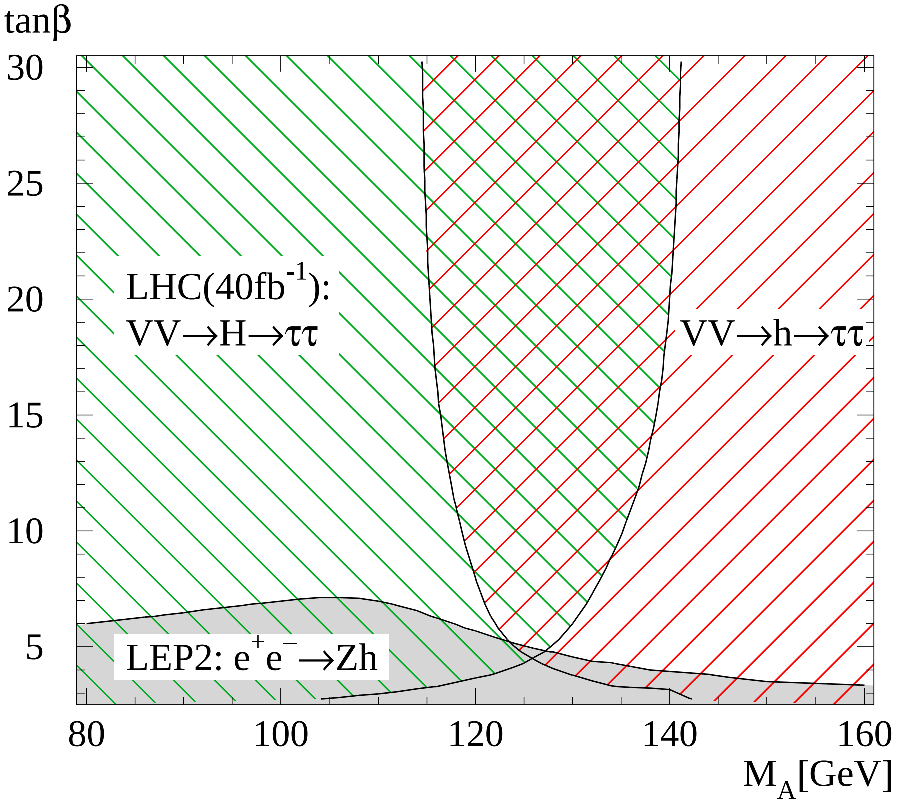
⇒ perfect channel $qq \to qqh^0 \to qq\tau\tau$: MSSM no–lose theorem

Futile attempts to escape this channel

- low $\tan\beta$: forbidden by LEP2
- super–large mixing $A_t > 6$ TeV: enhanced WBF WW and $\gamma\gamma$ rate
- CP phases in A_t: coverage solid
- funny couplings of all kind: still standing



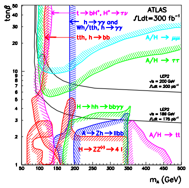
M_{SUSY}=1 TeV, maximal mixing


tanβ
30
25
20
15
10
5
80
100
120
140
160
M_A[GeV]
LHC(40fb^-1):
VV→H→ττ
VV→h→ττ
LEP2: e^+e^-→Zh

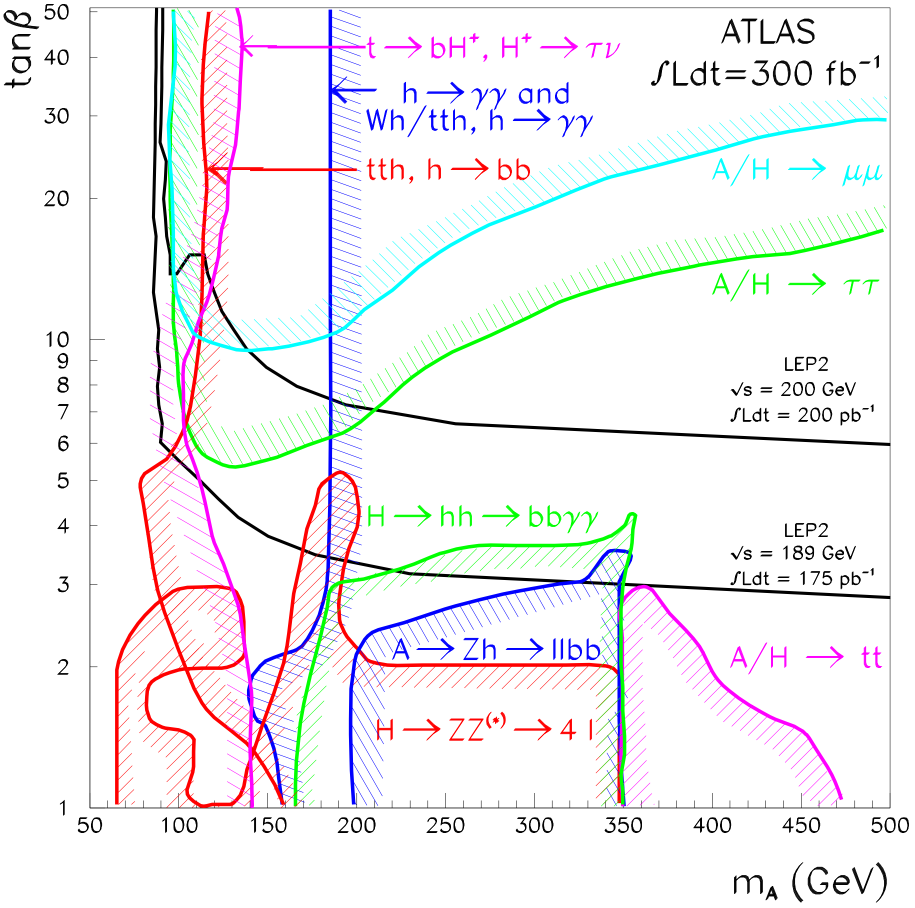
CHALLENGE 5: FIND ALL MSSM HIGGS BOSONS

How to tell it is two Higgs doublets (not even talking about MSSM)

- intermediate $m_A \sim 120$ GeV:
  $\longrightarrow$ lots of Higgs bosons observable
  $\longrightarrow$ problem distinguishing them: $H^0 \to \mu\mu$
  $\longrightarrow$ top quark decays $t \to bH^+$? (Tevatron RunI top sample still small)
- decoupling regime $m_A \gtrsim 160$ GeV
  $\longrightarrow$ light SM like h^0 guaranteed (indirect evidence tough)
  $\longrightarrow$ Yukawa coupling for heavy states: $m_b \tan\beta$ and $m_t / \tan\beta$
  $\longrightarrow$ $\tan\beta < 20$ hopeless? (possibly $gg \to H^0 \to h^0h^0$ or SUSY cascades?)
- decoupling regime $m_A \gtrsim 160$ GeV and large $\tan\beta$
  $\longrightarrow$ bottom Yukawa coupling $m_b \tan\beta \gtrsim 100$ GeV desirable
  $\longrightarrow$ production processes $b\bar{b} \to H^0$ or $b\bar{b} \to A^0$ or $gb \to tH^-$
  $\longrightarrow$ decays $H^0, A^0 \to \tau\tau, \mu\mu$ or $H^- \to \bar{t}b, \tau\bar{\nu}$
  $\longrightarrow$ SUSY correction $m_b/(1-\Delta_b)$ with $\Delta_b \propto \mu m_{\tilde{g}}/M^2_{\text{SUSY}}$



- We will find one MSSM Higgs at the LHC
- We might find all of them
- Some more progress would not hurt


tanβ
50
40
30
20
10
9
8
7
6
5
4
3
2
1
50
100
150
200
250
300
350
400
450
500
m_A (GeV)
ATLAS
∫Ldt=300 fb⁻¹
t → bH⁺, H⁺ → τν
h → γγ and
Wh/tth, h → γγ
tth, h → bb
A/H → μμ
A/H → ττ
LEP2
√s = 200 GeV
∫Ldt = 200 pb⁻¹
H → hh → bbγγ
LEP2
√s = 189 GeV
∫Ldt = 175 pb⁻¹
A → Zh → llbb
A/H → tt
H → ZZ(*) → 4 l