Higgs & SUSY Phenomenology

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Plan

- Motivation & Introduction to SUSY
  - Further reading: S.P.Martin, hep-ph/9709356
- SUSY Higgs
  - Further reading: Spira & Zerwas, hep-ph/9803257
- Higgs & SUSY Higgs phenomenology at hadron colliders (esp. LHC)
  - Further reading: ATLAS Physics TDR

Reminder: EW interactions…

Are based on invariance under local $SU(2) \times U(1)_Y$ transformations. Note: left– and right–handed fields transform differently, e.g.

$$L_e \equiv \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} : \text{ doublet under } SU(2)\,;$$

$$e_R : \text{ singlet under } SU(2)\,.$$

Invariance under local $SU(2) \times U(1)_Y$ transformations fixes the form of the electroweak interactions completely.
$SU(2) \times U(1)_Y$ invariance cannot be an exact symmetry of Nature: it must be broken!

Exact SU(2)xU(1)$_Y$ invariance would imply

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How to break SU(2)xU(1)$_Y$

Introduce scalar $SU(2)$ doublet "Higgs field" $\phi = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix}$

Introduce scalar potential $V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2$

Higgs field likes to sit at minimum of potential: acquires vacuum expectation value (vev)

$$\langle \phi \rangle = \begin{pmatrix} v \\ 0 \end{pmatrix} \quad \text{with } v = \sqrt{2\mu^2/\lambda}$$

Vacuum is not $SU(2) \times U(1)_Y$ invariant (even though $\mathcal{L}$ is): symmetry is broken *spontaneously*!

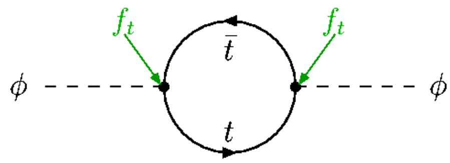
Breaking SU(2)xU(1)$_Y$

Solves all three problems:

- Allows electron mass:
  $\mathcal{L}_{\text{Yuk}} = -f_e \overline{e_R} \phi L_e + h.c. \underset{\phi \to \langle \phi \rangle}{\longrightarrow} - f_e v \overline{e_R} e_L$ is invariant;
  $m_e = f_e v$.
- Allows mass of W boson:
  $\mathcal{L}_{W-\text{mass}} = \frac{g^2}{2} W_\mu^+ W^{\mu -} \phi^\dagger \phi \underset{\phi \to \langle \phi \rangle}{\longrightarrow} \frac{g^2}{2} v^2 W_\mu^+ W^{\mu -}$ is invariant; $M_W = \frac{g}{\sqrt{2}} v$.
- Distinguishes electron and neutrino: $\mathcal{L}_{\text{Yuk}}$ does *not* produce a neutrino mass.

The hierarchy problem

So far: discussion ignored quantum corrections. Problem: corrections to Higgs boson mass diverge quadratically:



$$\delta m^2_{\phi,t} = \frac{3f_t^2}{8\pi^2}\Lambda^2 + \mathcal{O}(\Lambda/m_\phi)$$

Λ: cut–off for momentum in loop.

m_ϕ Likes to be at *highest* relevant mass scale, e.g. $M_{\mathrm{GUT}} \sim 10^{16}$ GeV, $M_{\mathrm{Planck}} \sim 10^{18}$ GeV!

If $m^2_{\phi,\mathrm{phys.}} = m^2_{\phi,0} + \delta m^2_\phi = \stackrel{!}{\simeq} (100\ \mathrm{GeV})^2$: Need to finetune $m^2_{\phi,0}$ to 1 part in 10^{30}!

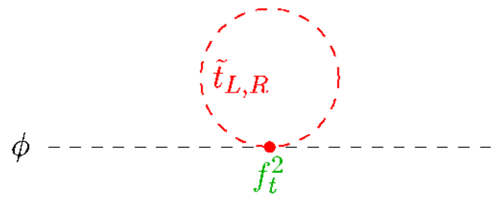
SUSY solves fine-tuning problem

- Postulate symmetry between fermions-bosons

  fermions ↔ bosons

- SUSY: "To every fermionic degree of freedom corresponds one bosonic degree of freedom".
- So, a SM fermion acquires two super-partners
  - e.g. t-quark → s-tops: t_R & t_L
- What about the partners of the SM bosons?
  - Gauginos, Higgsinos, gluinos…
  - (Exercise)

Diagrammatically: each chirality state of t quark has scalar superpartner $\tilde{t}_L,\ \tilde{t}_R$: get new corrections:



$$\delta m^2_{\phi,\tilde{t}} = -\frac{3f_t^2}{8\pi^2}\Lambda^2 + \cdots = -\delta m^2_{\phi,t} + \mathcal{O}\left([m_t^2 - m_{\tilde{t}}^2]\ln\frac{\Lambda}{m_t}\right)$$

Quadratic divergencies cancel exactly!

SUSY is broken

- …or else SUSY particles should have been observed (with same mass as SM-partners)
- How? (beyond the scope of these lectures…)
  - Gauge/Gravity mediated SUSY breaking
- What happens to the cancellation of quadratic divergences?
  - SUSY partners must be not heavier than ~TeV

Other arguments for SUSY

- Biggest possible symmetry of interacting QFTs
  - (Lorentz sym.) ⊕ (gauge sym.) ⊕ (SUSY)
- New particles automatically lead to unification of gauge couplings at $M_{GUT} \sim 10^{16}$ GeV
- Provides a good candidate for Dark Matter (the lightest SUSY particle – LSP)
- …

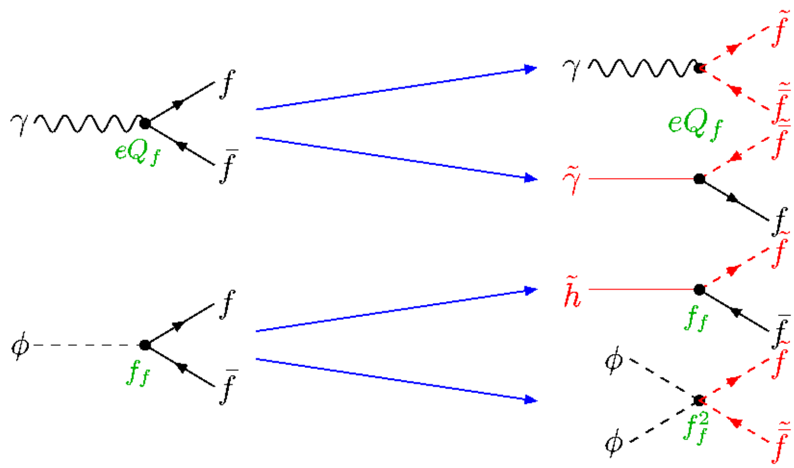
R-parity and the LSP

- A totally unconstrained SUSY would lead to the proton decaying with lifetime of ~hours!!!
- Introduce R-parity

$$R = (-1)^{3(B-L)+2s}$$

- All SM particles have R=+1, all sparticles R=-1
- R-parity conservation implies that there are always two sparticles in a vertex
- The minimal SUSY extension to the SM (MSSM) is R-parity conserving

Interactions of SUSY particles



SUSY simplifications

- Unconstrained SUSY would bring in 105 parameter (on top of the ____ of the SM)
- mSUGRA: simple boundary conditions at GUT scale reduce the number of parameters to ~5!
  - Common scalar mass m_0
  - Common gaugino mass $m_{1/2}$
  - Common trilinear scalar interaction A
  - Ratio of vevs of two Higgs fields $\tan\beta$
  - Sign of Higgs mass parameter μ

Can predict SUSY spectrum at our energies

SUSY Higgs

- The SM Higgs mechanism is very economical
- In SUSY, two Higgs doublets are needed. Quoting S&Z:

  "…the Higgsino fields associated with a single Higgs field would generate triangle anomalies; they cancel if the two conjugate doublets are added up…"

- This means:
  - 8 DoF, 3 eaten up by the $W^{\pm}$ and Z => 5 Higgs fields: h^0,A^0,H^0,$H^{\pm}$

Higgs mass spectrum

- Connection between Higgs masses and gauge boson masses:

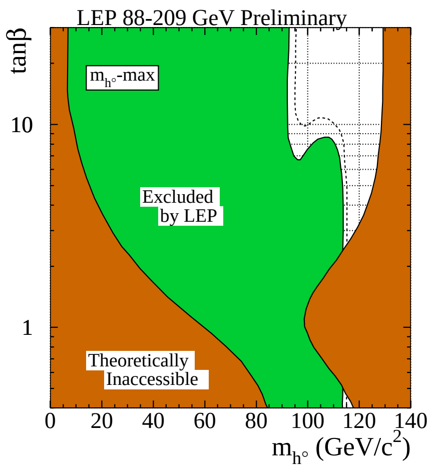
  $M^2_{H^{\pm}} = M^2_A + M^2_W$ => $M_{H^{\pm}} > M_W$

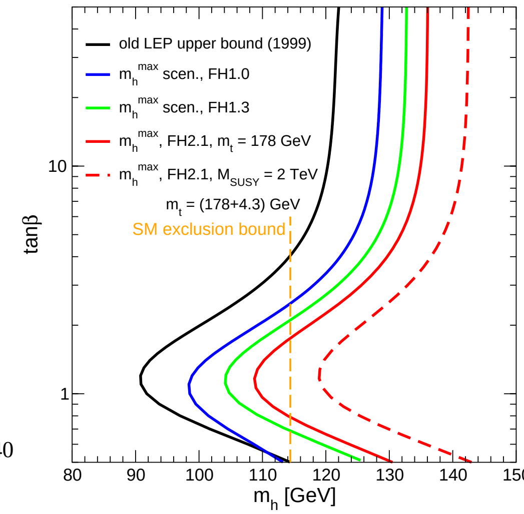
  … $M_h < M_Z$

- Unfortunately, only true at tree level. When including higher order contributions:

  $M_h <$ ~140GeV (or so…)

Upper bound on the mass of h





Higgs Search @ LHC

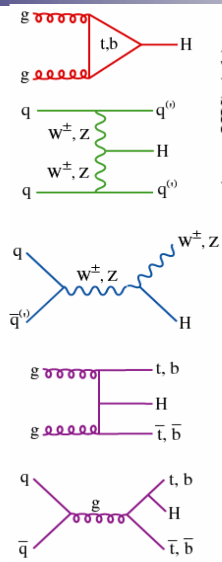
SM Higgs production at the LHC

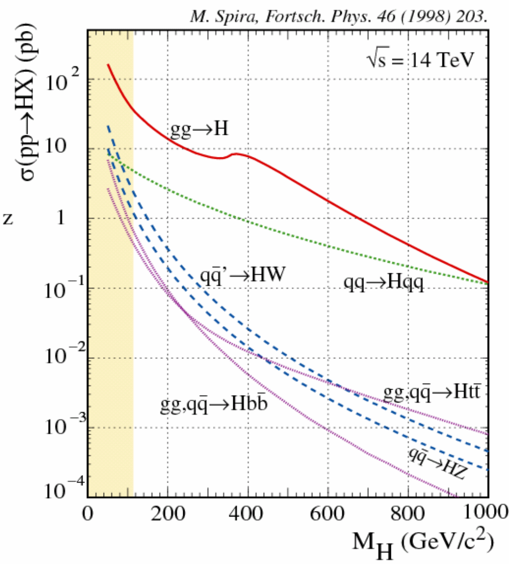
Direct Production (gg fusion)

Vector Boson Fusion

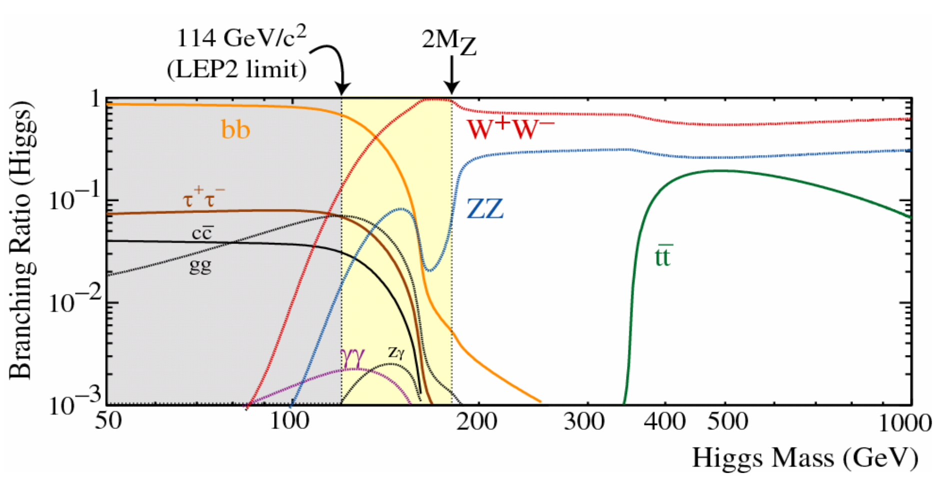
Associated production (with W/Z)

Associated Production (with tt/bb)





SM Higgs decays



LHC – Tevatron: Differences

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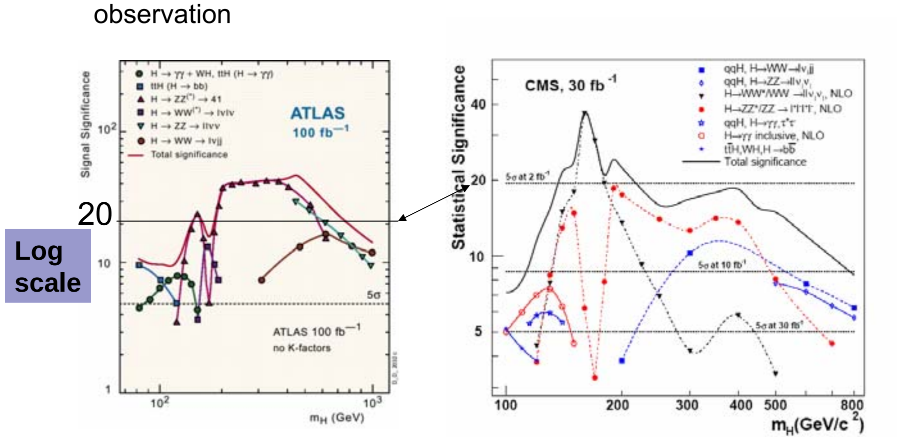
LHC running

- Planned to start in 2007. After commissioning
  - Initially at $2x10^{33}$ $cm^{-2}sec^{-1}$, giving ~$10fb^{-1}$/year
  - Ramping up to $10^{34}cm^{-2}sec^{-1}$, giving ~$100fb^{-1}$/year (Tevatron will ultimately collect <~$10fb^{-1}$)

Higgs discovery prospects @ LHC

- The LHC can probe the entire set of "allowed" Higgs mass values;
  - in most cases a few months at $2\times10^{33}cm^{-2}s^{-1}$ are adequate for a 5σ observation

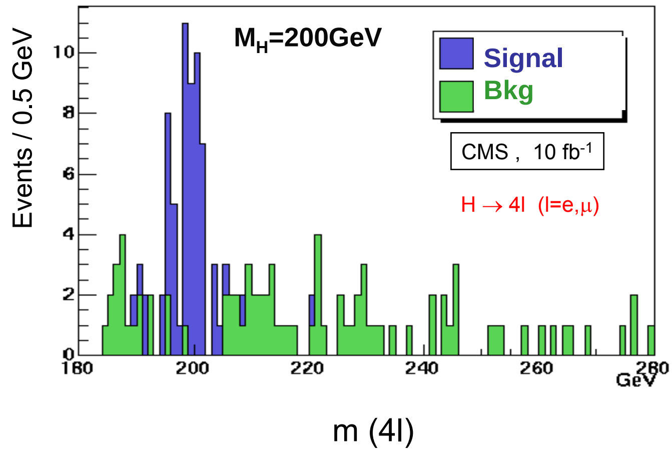


Search regions

Three distinct mass ranges:

- High masses: m_H > 180GeV
  - The easiest region: $H \rightarrow ZZ$
- Intermediate masses: 130-180 GeV
  - Golden channel useful, but not enough
- low masses: m_H < ~130GeV
  - The hardest region (and most interesting!)

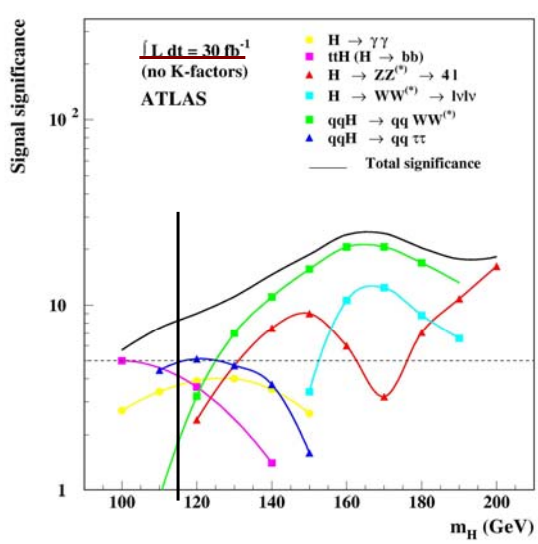
High mass Higgs



Easy to see but requires:
-- ~ 90% e, μ efficiency even at low pT (analysis cuts : pT 1,2,3,4 > 20, 20, 7, 7, GeV)
-- σ /m ~ 1%, tails < 10% → good quality of E, p measurements in ECAL and tracker

Intermediate masses

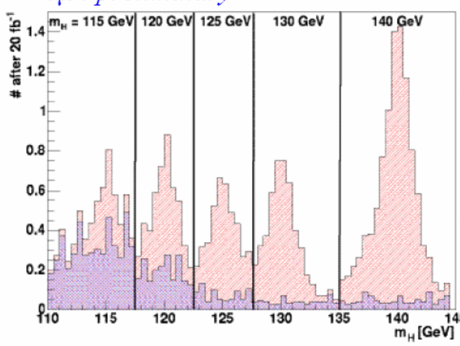
- Deep of H → ZZ covered by
  - VBF qqH (H→ WW)
  - Direct H → WW

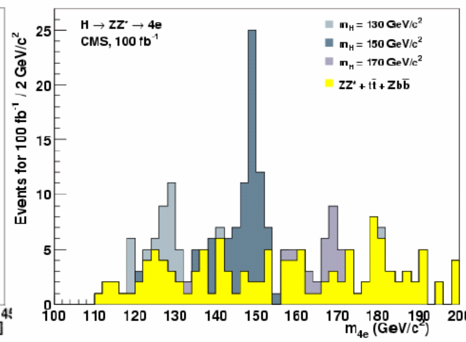


The golden channel (II)

Background : tt, ZZ*, Zbb. Selections : lepton isolation, cut on lepton p_T, M_Z, M_{Z*}

4μ : preliminary





Higgs Mass, GeV	*120*	*130*	*140*
4e; L for 5 σ discovery, fb^{-1}	351	106	31
4μ; L for 5 σ discovery, fb^{-1}	152	35	15

Significance is calculated with Poisson probability .

Low masses

- Arguably the most interesting region:

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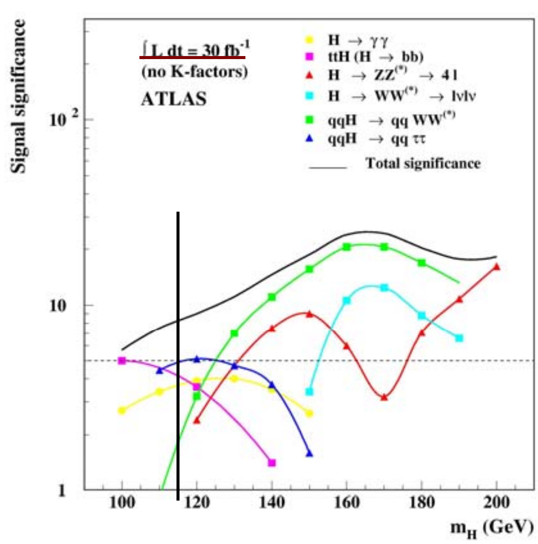
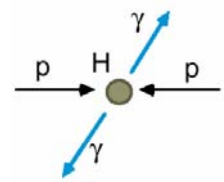
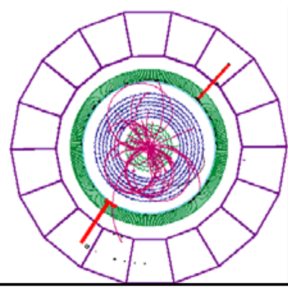
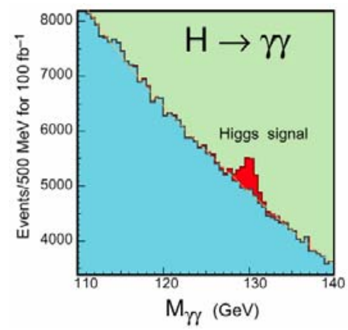


Low mass Higgs (M_H<130 GeV)

- $H \to \gamma\gamma$: decay is rare ($B \sim 10^{-3}$)
  - But with good resolution, one gets a mass peak
  - Motivation for LAr/$PbWO_4$ calorimeters
  - CMS example: at 100 GeV, $\sigma \approx$1GeV -> S/B ≈ 1:20

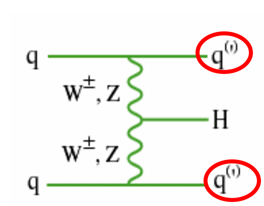


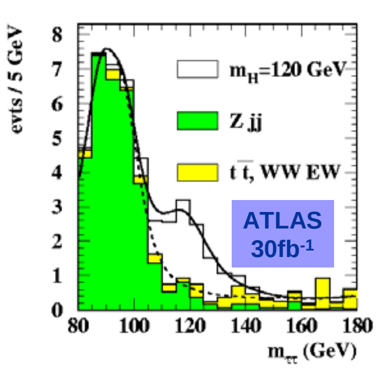


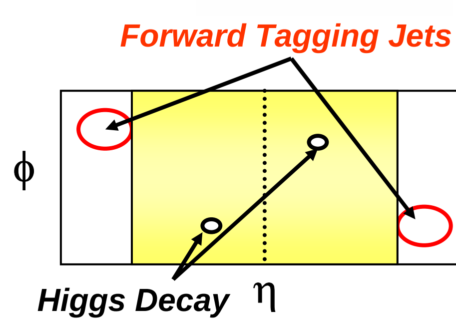


VBF with $H \to \tau\tau$

- VBF 2nd largest x-section
  - Needs efficient jet reco to high eta
  - Main bkg: Zjj
  - Bkg shape easy to estimate

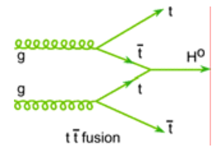


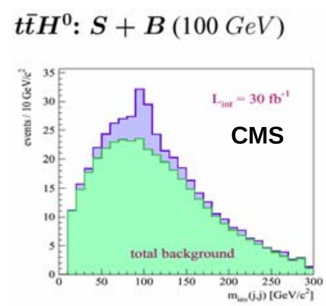




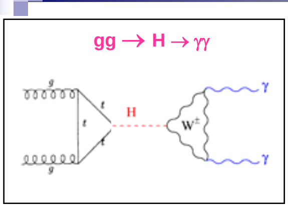
ttH (H–>bb)

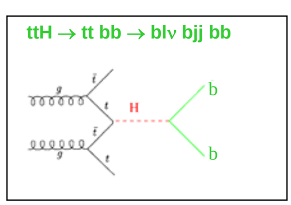
- σxBR ~0.3pb
  - Main bkg: ttbb/jj
- Relies on
  - b-tagging (4 jets)
  - Complete reconstruction of tops
- Bkg shape critical
  - Can be measured in the data (with ttjj events)
- Efficiencies ~1%
  - A factor 10 from b-tagging
  - A factor 10 from kinematical cuts

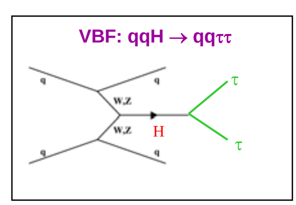




Channels for M_H~115GeV







Different production/decay modes
Different backgrounds
➡ complementary!

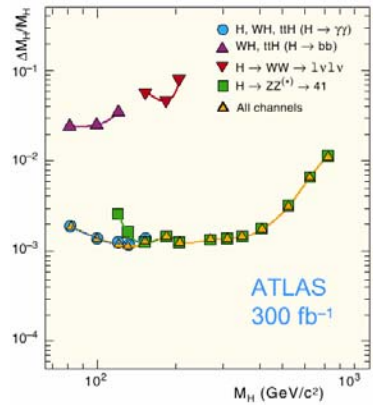
ATLAS	S	B	S/√B
H→γγ*	130	4300	2.0
ttH	15	35	2.2
qqττ	10	10	2.7

*(K-factors ≡ σ(NLO)/σ(LO) ≈ 2 not included)

($10fb^{-1}$) total $S/\sqrt{B} \approx 4^{+2.2}_{-1.3}$

SM Higgs properties – mass

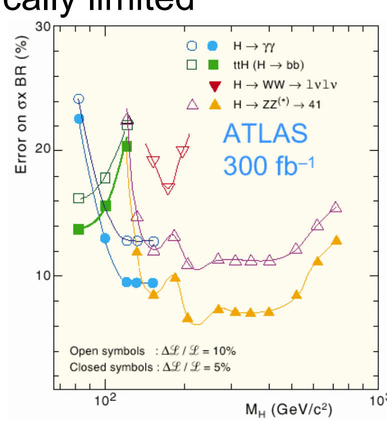
- Mass measurement
  - Limited by absolute energy scale
    - leptons & photons: 0.1% (with Z calibration)
    - Jets: 1%
  - Resolutions:
    - For $\gamma\gamma$ & $4\ell \approx 1.5$ GeV/c²
    - For bb ≈ 15 GeV/c²
  - At large masses: decreasing precision due to large Γ_H
  - CMS ≈ ATLAS



SM Higgs properties – BRs

- Biggest uncertainty (5-10%): Luminosity
  - Relative couplings statistically limited
    - Small overlap regions

Measure	Error	M_H range
$\frac{B(H\to\gamma\gamma)}{B(H\to b\bar{b})}$	30%	80–120
$\frac{B(H\to\gamma\gamma)}{B(H\to ZZ^*)}$	15%	125–155
$\frac{\sigma(t\bar{t}H)}{\sigma(WH)}$	25%	80–130
$\frac{B(H\to WW^{(*)})}{B(H\to ZZ^{(*)})}$	30%	160–180



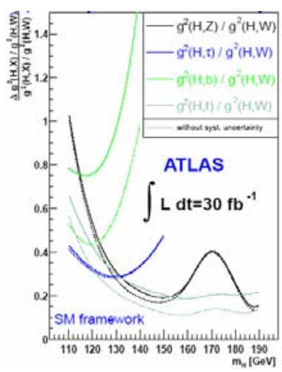
Higgs properties – couplings

$$\frac{\sigma(gg \to H)\cdot \mathrm{B}(H \to WW)}{\sigma(gg \to H)\cdot \mathrm{B}(H \to ZZ)} = \frac{\Gamma_W}{\Gamma_Z}$$

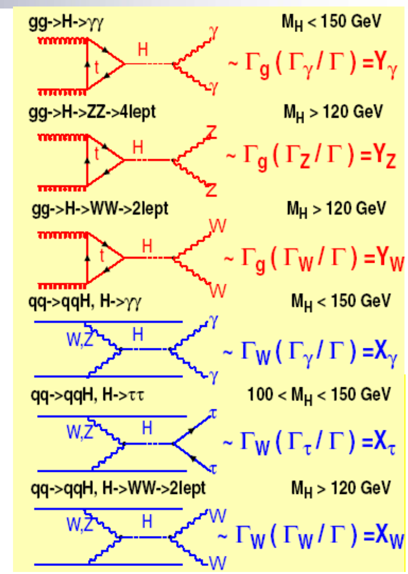
Th-err: ~4%

$$\frac{\sigma(gg \to H)\cdot \mathrm{B}(H \to \gamma\gamma)}{\sigma(gg \to H)\cdot \mathrm{B}(H \to ZZ)} = \frac{\Gamma_\gamma}{\Gamma_Z} \propto \frac{\Gamma_W}{\Gamma_Z}$$

$$\frac{\sigma(qq \to qqH)\cdot \mathrm{B}(H \to WW^*)}{\sigma(gg \to H)\cdot \mathrm{B}(H \to ZZ^*)} = \mathrm{F}_{QCD}\frac{\Gamma_W}{\Gamma_Z}$$

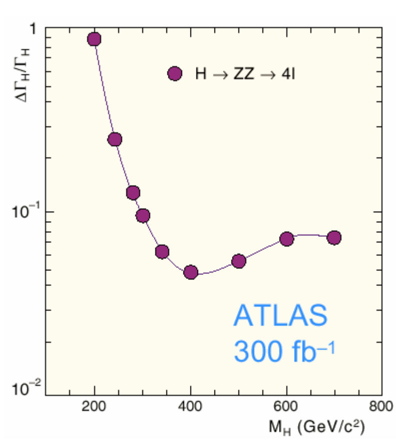


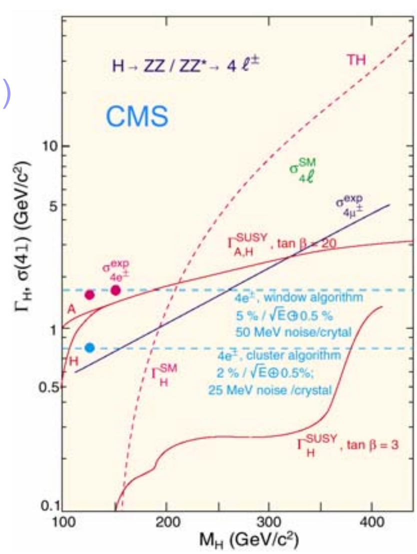
Th-err: ~20%



SM Higgs properties – width

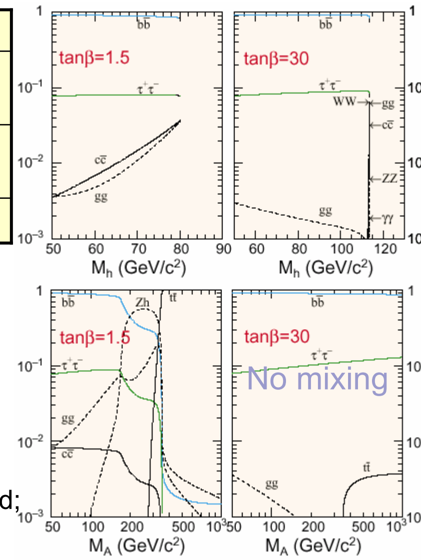
- Direct measurement:
  - Possible for M_H>200
    - Using golden mode (4ℓ)





MSSM Higgs: decays

Φ	g(Φuu)	g(Φdd)	g(ΦVV)
h	cosα/sinβ →1	-sinα/cosβ →1	sin(β–α) →1
H	sinα/sinβ →1/tanβ	cosα/cosβ →tanβ	cos(β–α) →0
A	1/tanβ	tanβ	0

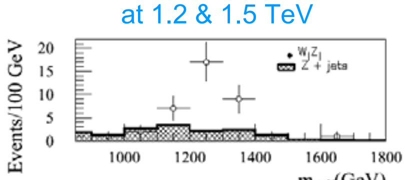


- h is light
  - Decays to bb (90%) & ττ (8%)
    - cc, gg decays suppressed
- H/A "heavy"
  - Decays to top open (low tanβ)
  - Otherwise still to bb & ττ
  - But: WW/ZZ channels suppressed; lose golden modes for H

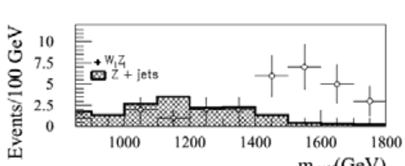
If no Higgs: $V_L V_L$ scattering

- Biggest background is Standard Model VV scattering
  - Analyses are difficult and limited by statistics – this is really the limit of the LHC

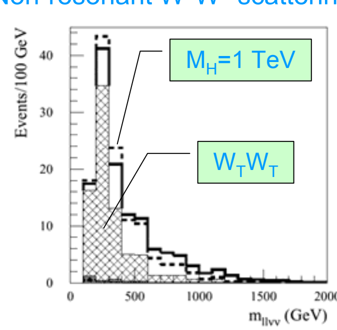
Resonant WZ scattering at 1.2 & 1.5 TeV



L=300 fb^{-1}



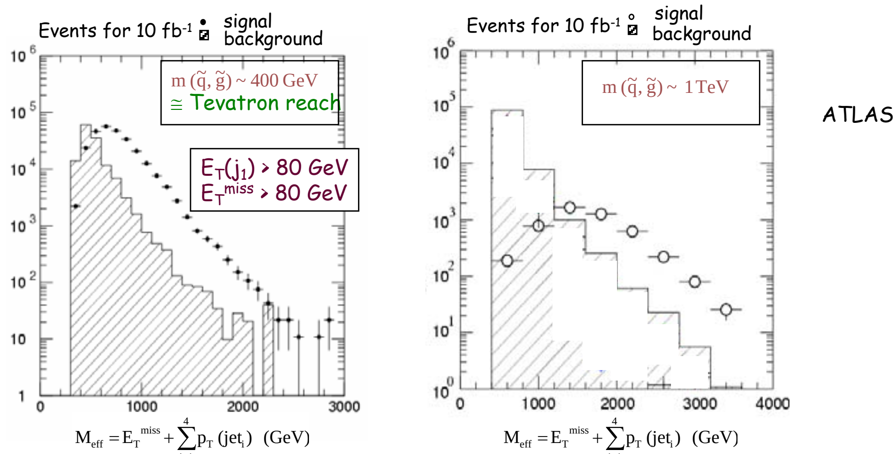
Non-resonant W^+W^+ scattering



First estimate of SUSY scale

Cascades of heavy SUSY particles to decaying to lighter ones
LSP stable (with R-parity conserved), hence escapes

} Final states with lots of jets, leptons and E_T^{mis}



From M_{eff} peak → first/fast measurement of SUSY mass scale to ≈ 20% (10 fb^{-1}, mSUGRA)