The LHC Physics Program

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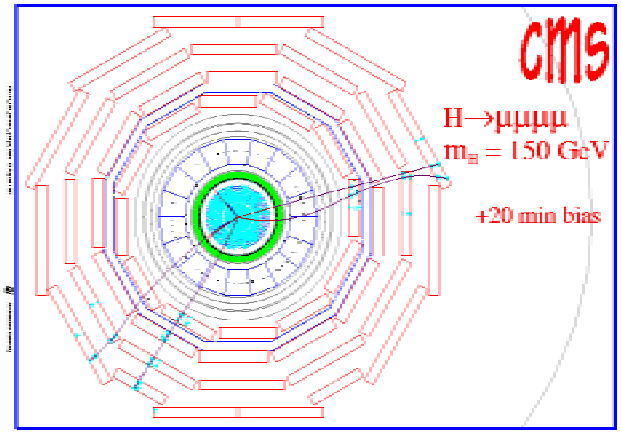
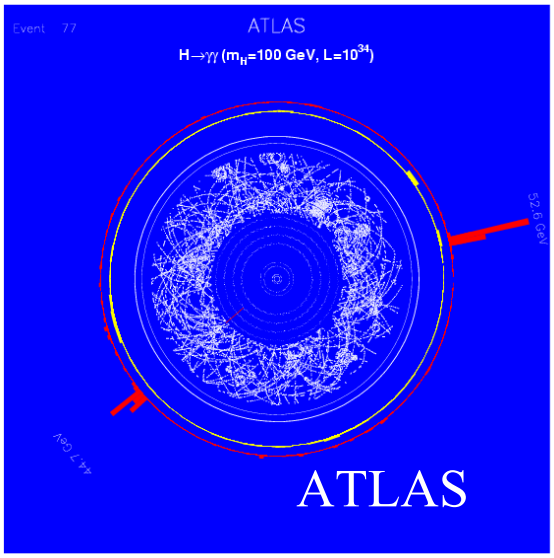
- Introduction
- SM Higgs boson
- SUSY Higgs
- SUSY
- New strong dynamics
- Extra dimensions
- LHC Upgrades
- Summary/Conclusions

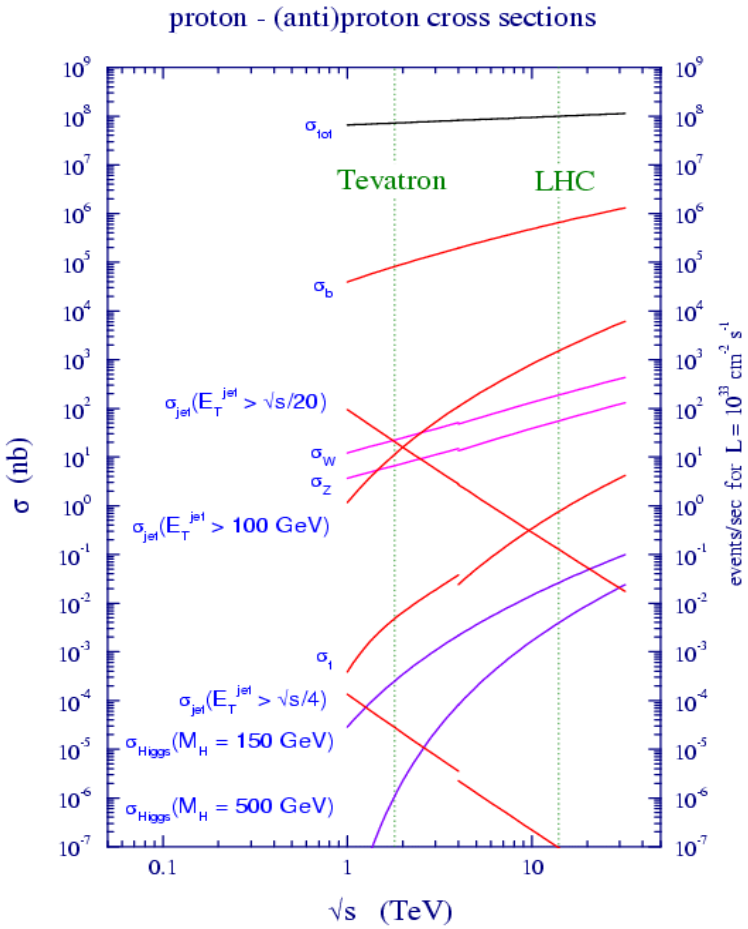




LHC Machine

- 7+7 TeV pp collider
- Luminosity:
  - 10^{33} "low"
  - 10^{34} "high"
- 25ns bunch spacing
- ≈ 20 int./crossing

at high luminosity



Example data sets

- 10 fb^{-1} (one yr. at low lumi.)
  - 6×10^{12} b-bbar
  - 2×10^{9} W
  - 5×10^{8} Z
  - 8×10^{6} ttbar
  - 2×10^{5} H (m_H=150)

LHC Schedule

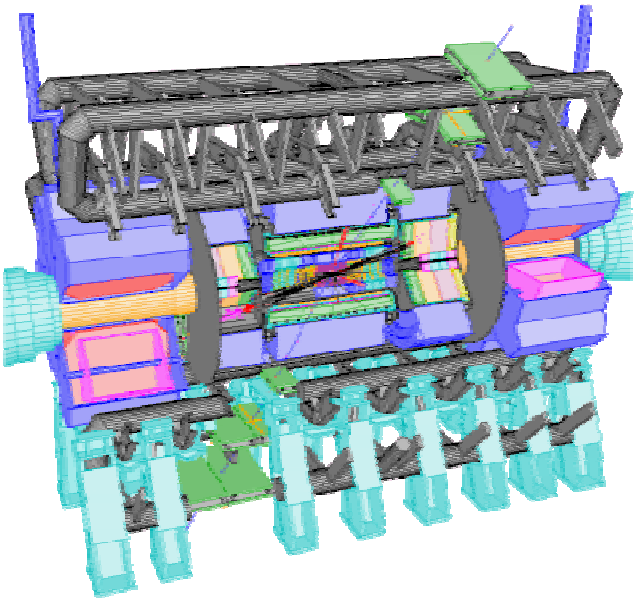
Dec. 31, 2005	Ring closed and cold
Jan. - Mar. 2006	Machine commissioning (1 beam)
April 2006	First collisions, pilot run $L=5\times10^{32}$ to 2×10^{33}, ≤ 1 fb^{-1} Start detector commissioning $\sim 10^5$ $Z \rightarrow \ell\ell$, $W \rightarrow \ell\nu$, tt events
May - July 2006	Shutdown: continue det. installation
Aug. 2006	Physics run : $L=2\times10^{33}$, 10 fb^{-1}
- Feb. 2007	Complete detector commissioning, start of physics
$\rightarrow$ 2008	$L=10^{34}$, 100 fb^{-1} /year (high lumi. LHC)

LHC Detectors

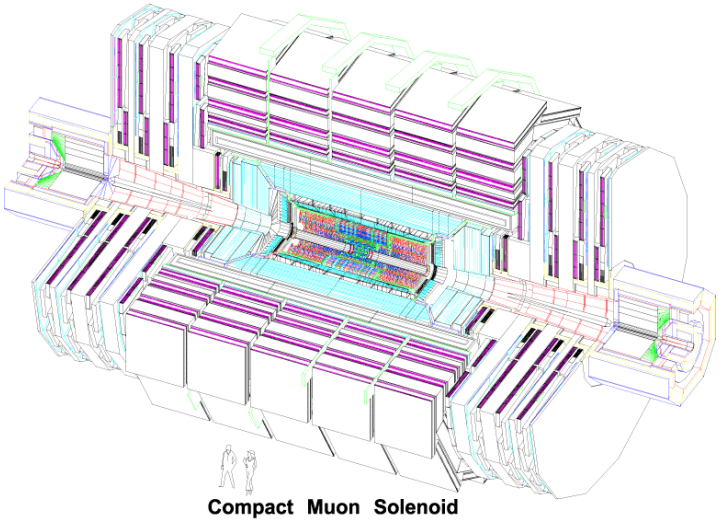
- **LHC-B** - dedicated b-physics experiment
- **ALICE** - dedicated heavy ion experiment

- for this talk, consider only the two general purpose, high pT detectors

ATLAS

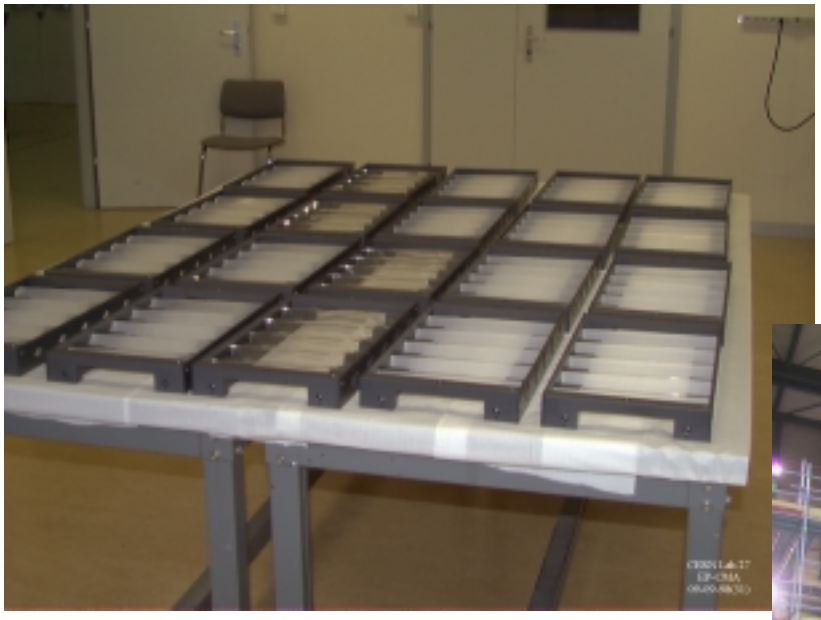


CMS



- General ATLAS/CMS detector features
  - precision EM calorimetry
  - large magnet configurations for muon meas.
  - multi-layer Si trackers for b-tagging
  - hermetic calorimetry to $|\eta| < 5$ for E_T^{miss} res'n.

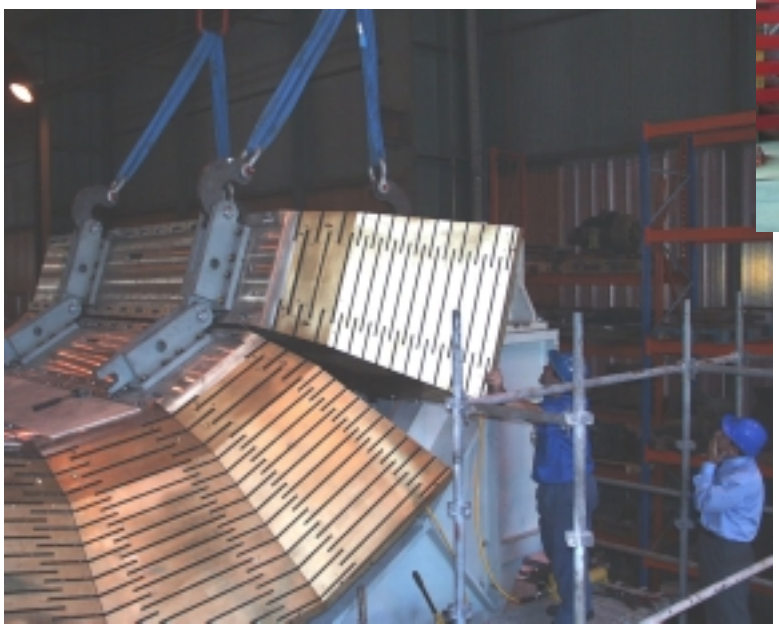
CMS Construction



Crystals for

EM calorimeter

Magnet yoke

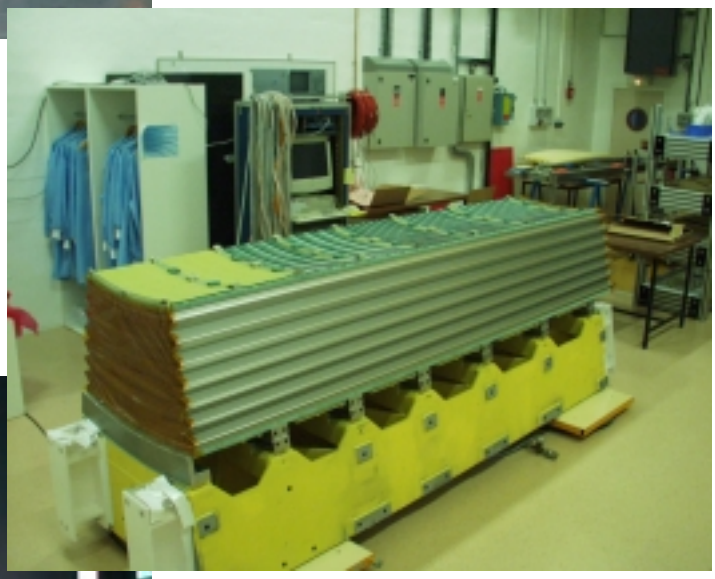


Hadronic calorimeter

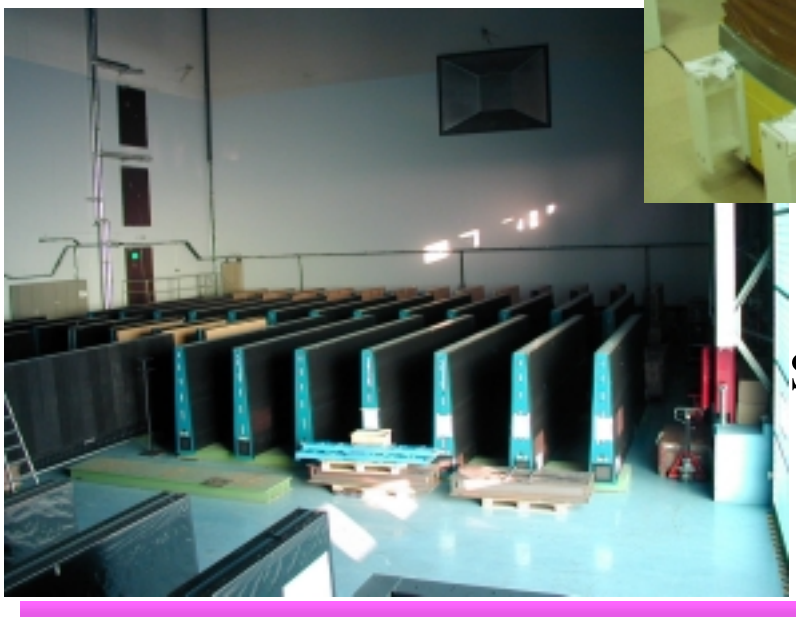
modules

ATLAS Construction

Superconducting solenoid



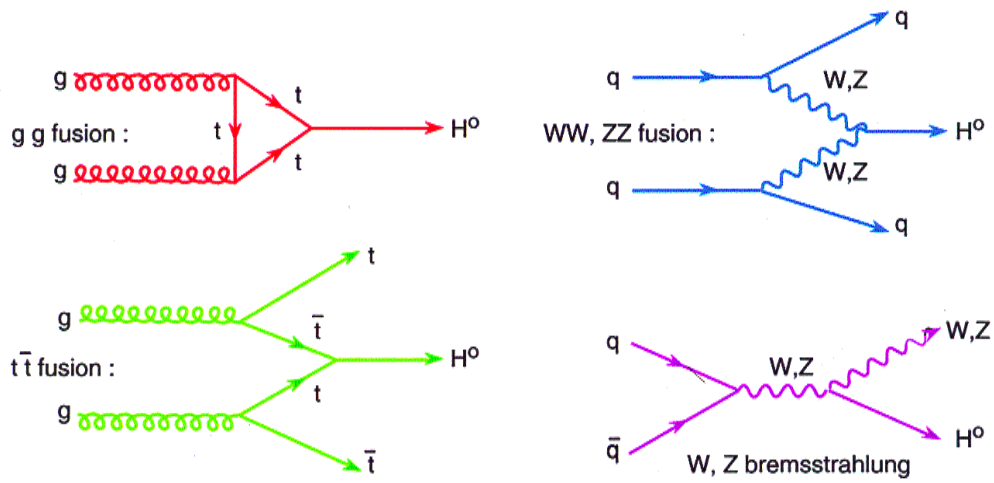
Liquid Argon EM calorimeter

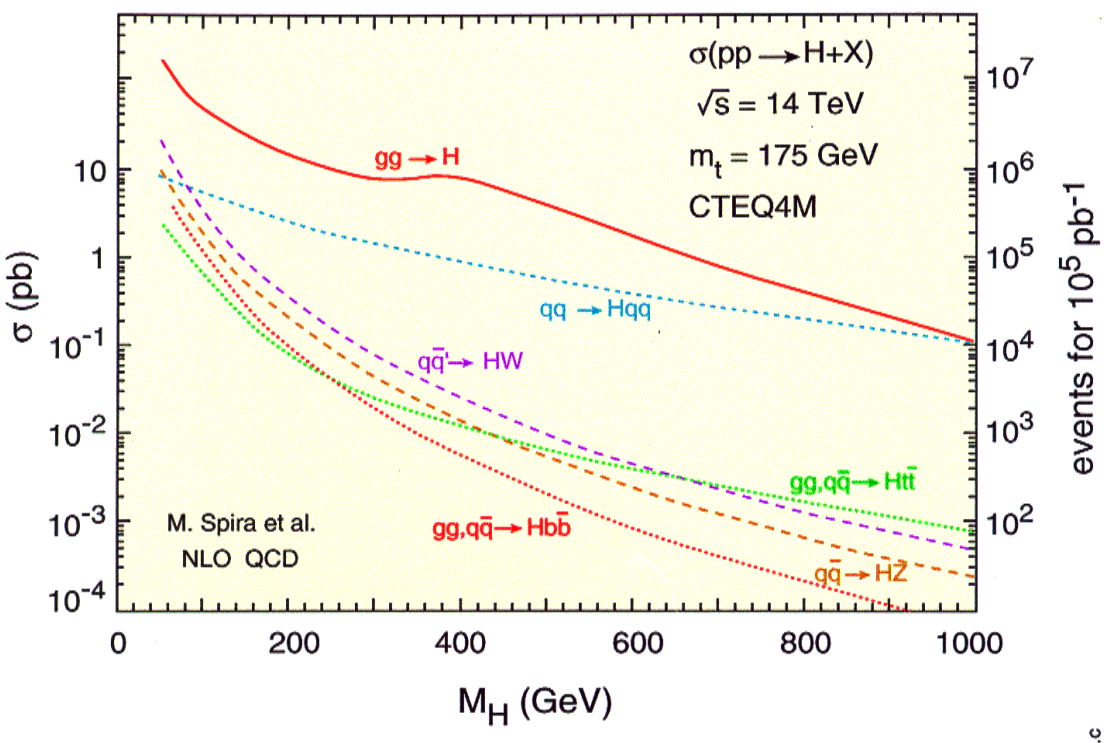


Storage of SciTile hadronic calorimeter modules

SM Higgs Production at LHC

H^o production at hadron colliders:

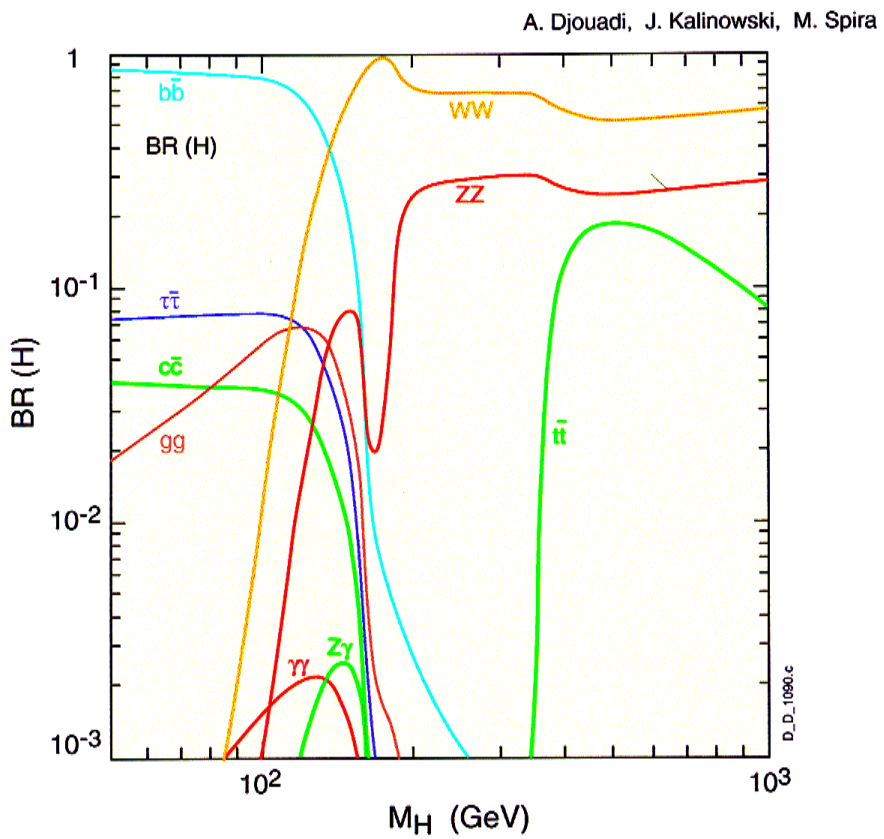




But : BR ($H \to Z^oZ^o \to 4l^{\pm}$) = $1.4 \cdot 10^{-3}$
BR ($H \to Z^oZ^o \to 4\mu^{\pm}$) = $3 \cdot 10^{-4}$

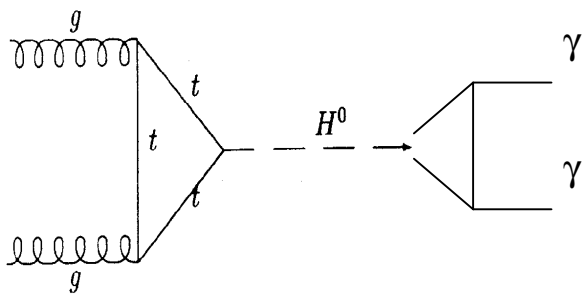
- K-factors (≡ higher-order corrections) = 1.6 – 1.9 gg → H
- Residual uncertainties on NLO cross-sections (PDF, NNLO, etc.) ≤ 20% (except ttH)

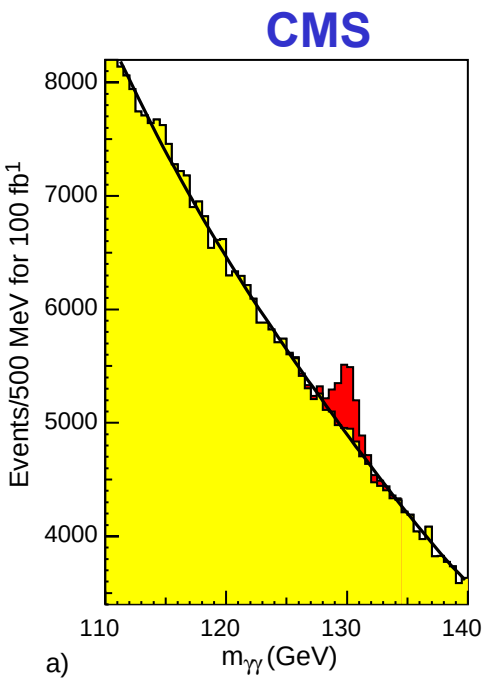
Higgs Branching Ratios



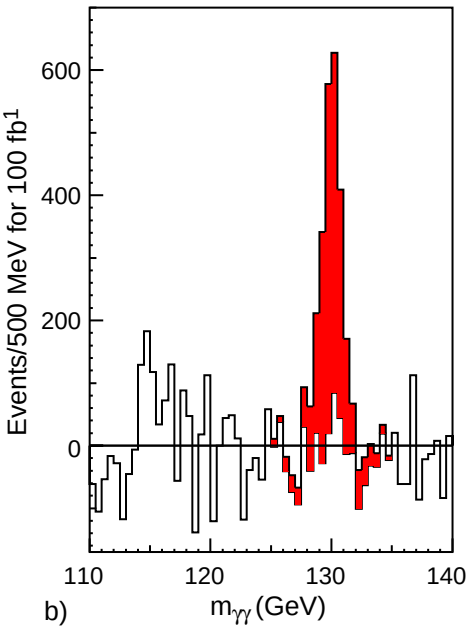
WH → WWW → 3ℓν ℓν	150-190 GeV	ass. prod.
WH → WWW → ℓℓνν jj	150-190 GeV	ass. prod.
H → ZZ → 4ℓ	180-800 GeV	gg-fusion
qqH → ZZ → ℓℓνν	400-1000 GeV	WW-fusion
qqH → WW → ℓνjj	400-1000 GeV	WW-fusion

$H \rightarrow \gamma\gamma$





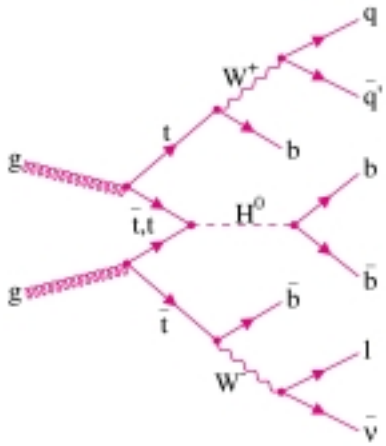
- **works for $100 < m_H < 150$**
- **$\sigma \times BR \approx 50$ fb**
- **<u>Backgrounds</u>**
  - **$\gamma j + jj$ (reducible)**
    - ▲ **for γ-eff. = 80%, need jet-rej. > 10^3, incl. π^0-rej. > 3 in order to be << $\gamma\gamma$ bkgnd.**
  - **$\gamma\gamma$ (irreducible)**
    - ▲ **$\sigma(\gamma\gamma) \approx 2$ pb/GeV $\Rightarrow$ need excellent mass resolution to find narrow peak on large bkgnd**



- **most demanding channel for EMCAL performance (E-res'n, pointing res'n, γ/jet and γ/π^0 separation, …)**

t-tbar H → t-tbar b-bbar

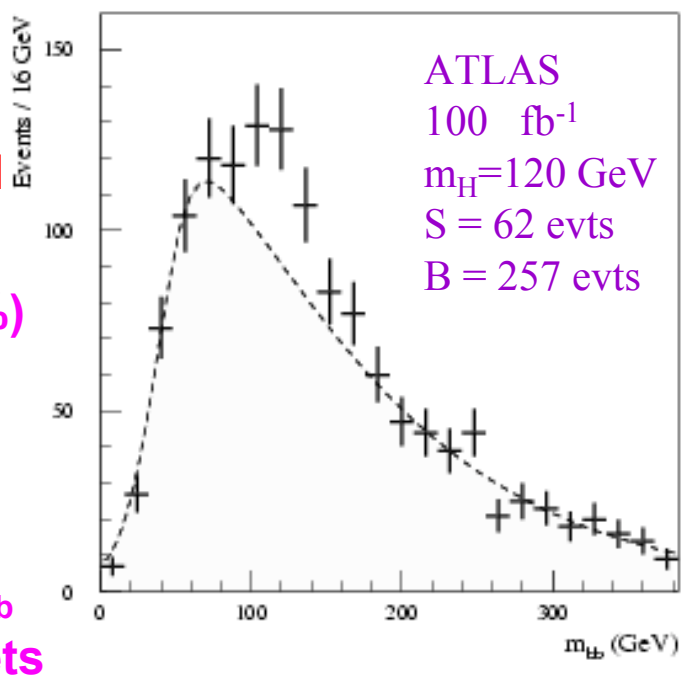
- works for $100 < m_H < 130$
- $\sigma \times BR \approx 300$ fb
- complicated final state, with 4 b-jets



Backgrounds

- combinatorics from signal
- Wjjjjjj, WWbbjj, etc.
- non-res. t-tbar jj

⇒ b-tagging is critical (ATLAS/CMS expect $R_{uds} \approx 100$ for $\varepsilon_b = 60\%$)



Signal reconstruction

- reconst. t and tbar
- look for peak in m_{bb} among remaining b-jets

- can use channel to determine Yukawa coupling of top quark to ≈ 10 - 20%
- channel very important for MSSM (see later)

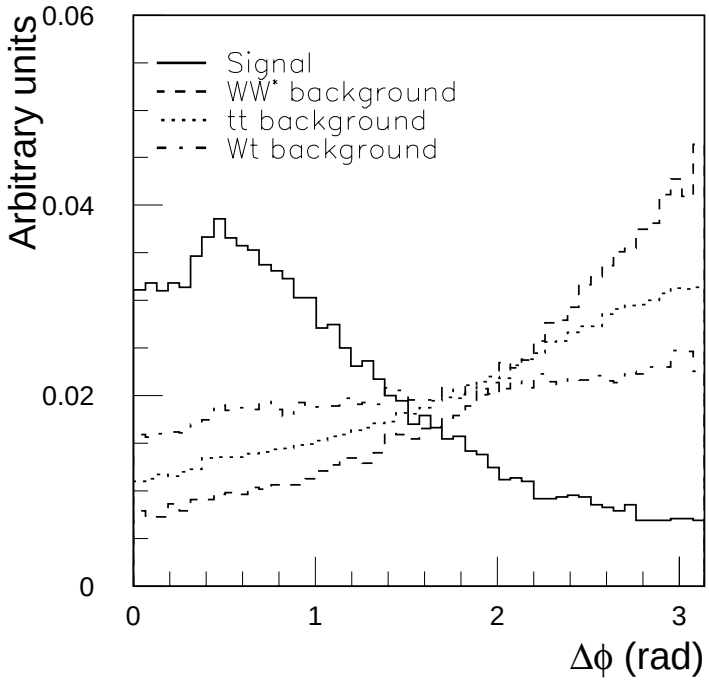
$H \rightarrow 4$ leptons

$H \rightarrow ZZ^{(*)} \rightarrow 4$ charged leptons

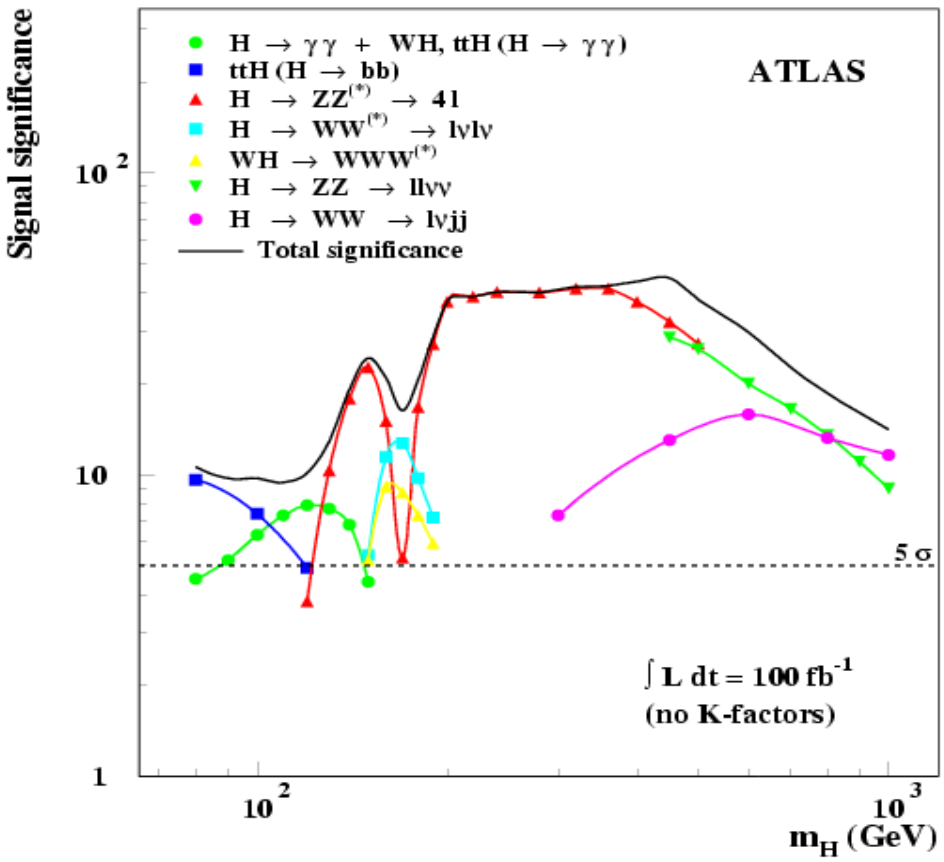
- "gold-plated" discovery mode
- works for $130 < m_H < 800$ GeV

$H \rightarrow WW^{(*)} \rightarrow \ell\nu\ \ell\nu$

- important for m_H near 160 GeV
- dominant bkgnd is WW production
- can use azimuthal angle between two charged leptons to separate signal from bkgnd

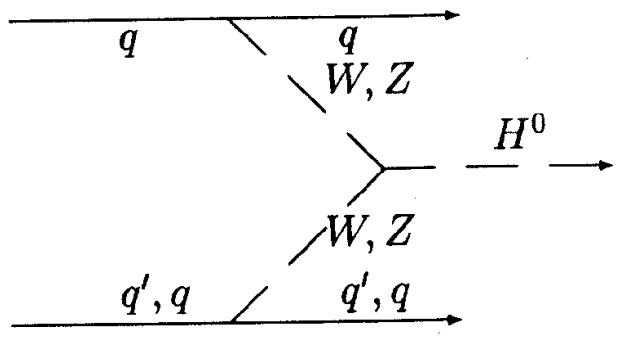


SM Higgs Discovery Potential



- SM Higgs will be observed or excluded over entire mass range from LEP2 limit (113.5 GeV) to mH = 1 TeV
  - over most of range, > 1 channel is accessible
- results are conservative:
  - no K-factors are used (K ≈ 1.6 - 1.9 for gg → H)
  - cut-based analyses used (no neural nets, etc.)
  - other interesting modes (eg. Higgs production via weak boson fusion) not yet included

Higgs from Weak Boson Fusion



- Xsect smaller than gg fusion (eg. 20% @ m_H = 120)
- <u>BUT</u> has a distinctive signature
  - two high p_T forward jets
  - little jet activity in central region
- study first proposed by Zeppenfeld et al.
  - new (prelim.) studies by ATLAS/CMS of

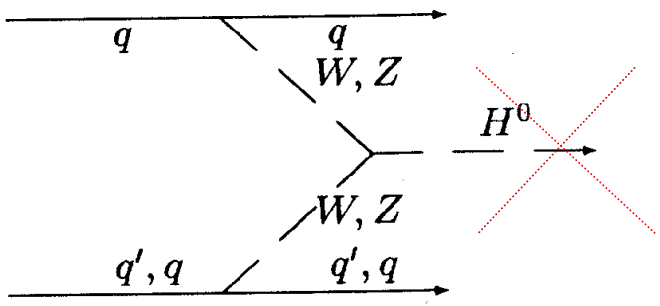
    $qqH \rightarrow qq\ WW \rightarrow qq\ (e\nu)(\mu\nu)$

    $qqH \rightarrow qq\ \tau\tau$

  support claim that signals can be extracted
- WBF signals would be important for
  - additional Higgs discovery potential
  - measurement of Higgs couplings
  - detection of an invisible Higgs!!??

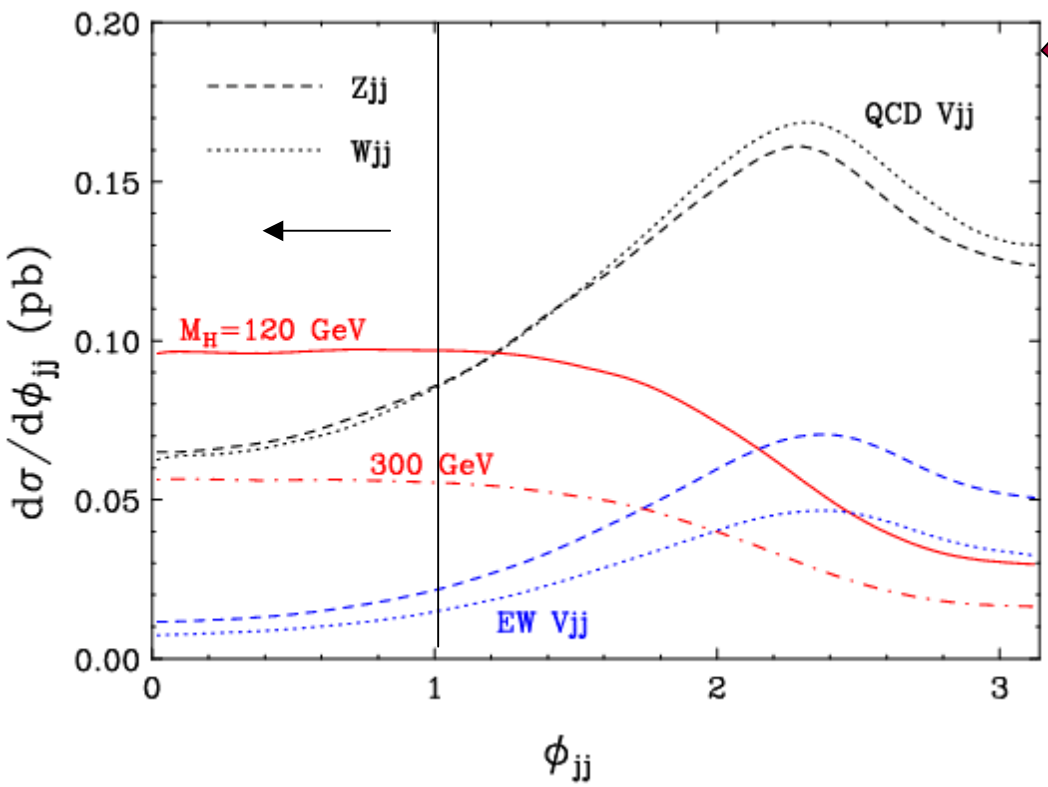
Invisible Higgs Search at LHC?

- **assume non-SM Higgs decay to neutralinos, gravitinos, gravitons, …**



2 forward jets $p_T > 40$ GeV
large $E_T^{miss} > 100$ GeV
no additional jet $p_T > 20$ GeV
$M_{jj} > 1200$ GeV

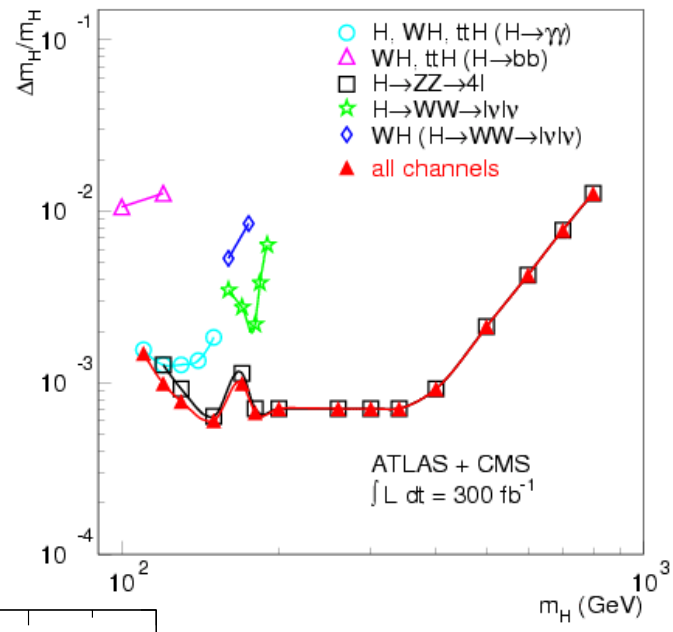
Eboli and Zeppenfeld, hep-ph 0009158

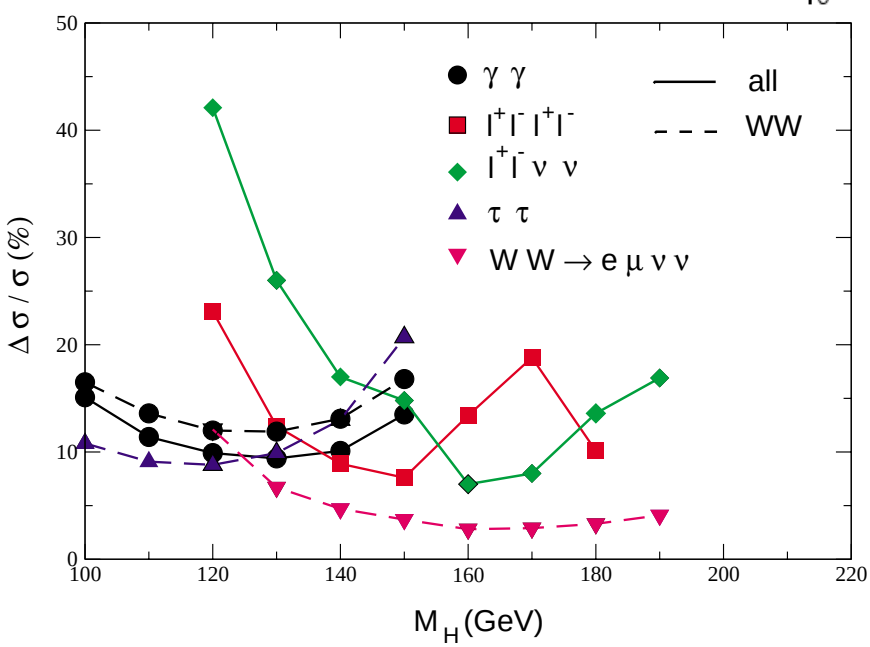


- **intriguing, but <u>very difficult</u>**
  - **ATLAS/CMS have verified trigger rate/efficiency would be acceptable (forward jet + E_T^{miss})**

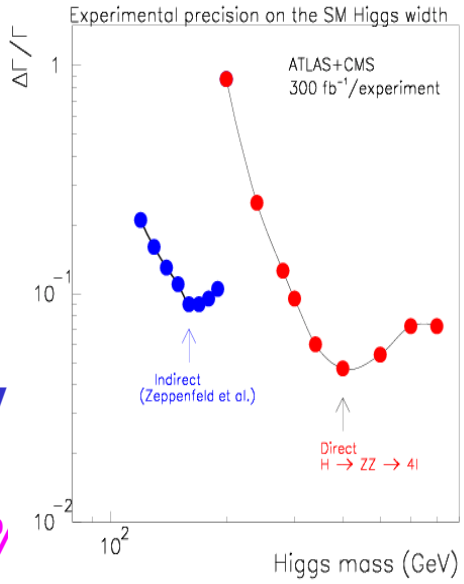
SM Higgs Parameters

- up to 400 GeV, measure mH to < 0.1%





- for mH < 200, measure several $\sigma \times$ BR to ≈ 5 - 25% (mostly stats limited)



- use with theory to indirectly determine Higgs width (can directly measure Γ(H) for mH > 200)
  - determine couplings to ≈ 15%

MSSM Higgs ($h,A,H,H^{\pm}$)

- at tree level, MSSM Higgs sector depends on only two parameters (choose to be mA and tanβ)
  - masses, decays modified thru loop corrections
- many discovery channels available, including SM Higgs discovery channels

$h \to \gamma\gamma$,

t-tbar h → t-tbar b-bbar

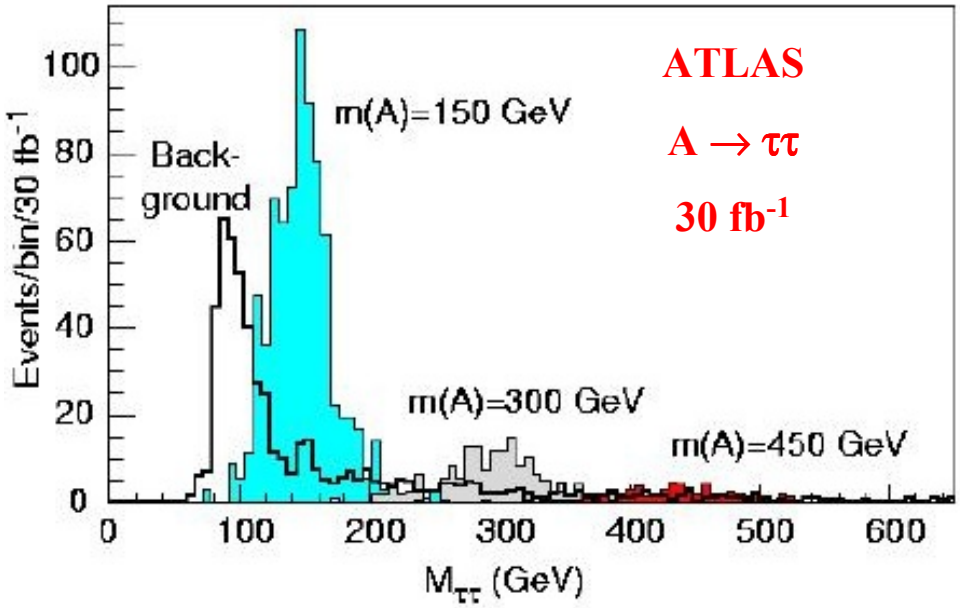
$H \to ZZ^{(*)} \to$ 4 leptons

and MSSM-specific channels

$A/H \to \mu\mu, \tau\tau$, t-tbar

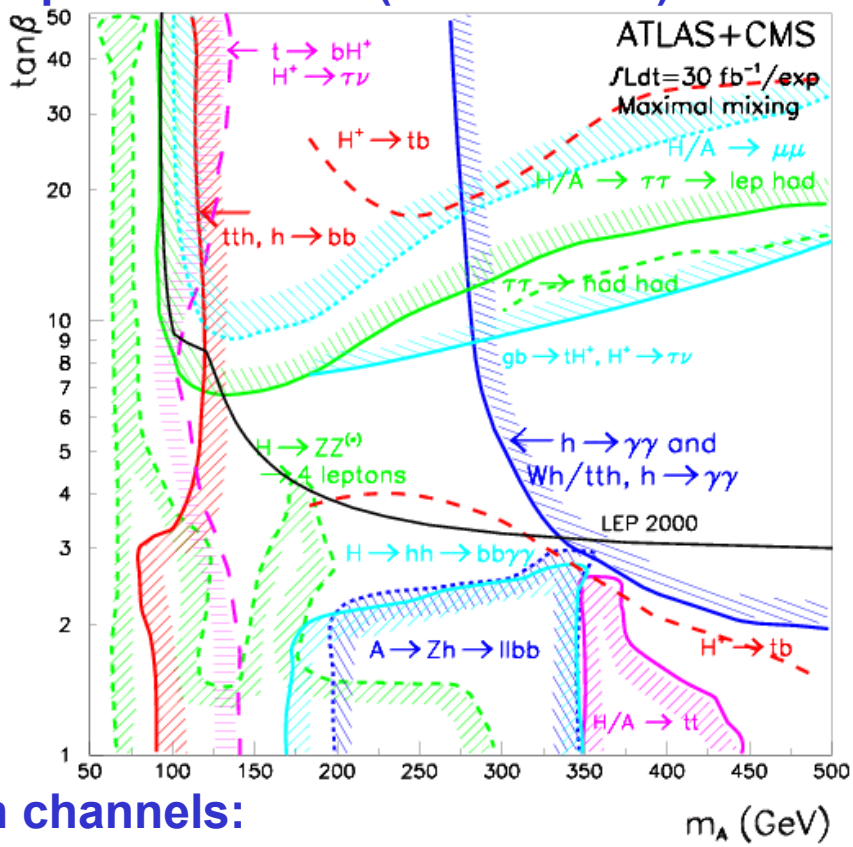
$H \to hh$, $A \to Zh$

$H^{\pm} \to \tau\nu$, cs, tb



MSSM Higgs Discovery

- assume sparticles are heavy (Higgs → SM particles)
- entire plane covered (ie. no holes) with 30 fb^{-1}



- main channels:

  $h \to \gamma\gamma$, $tt\,h \to tt\,bb$ (mA>100, any tanβ)

  $A/H \to \mu\mu, \tau\tau$ (large tanβ)

  $H^{\pm} \to \tau\nu$ (mA<130, any tanβ)

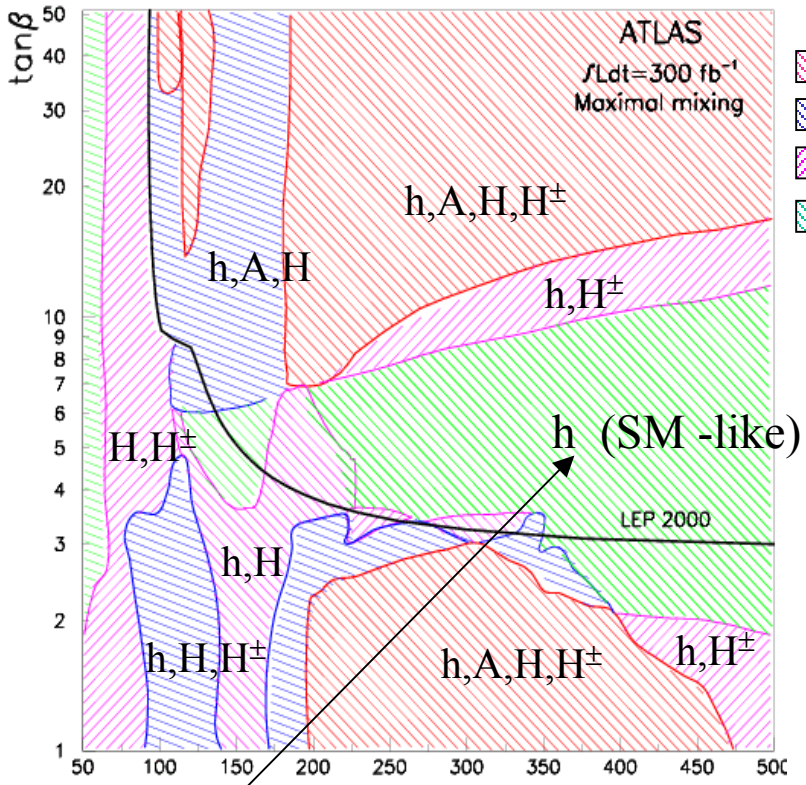
  $H^{\pm} \to tb$ (mA>150, large/small tanβ)

- if LEP excess due to hZ prod. (mA>115, tanβ>2), LHC would observe

  h any mA, any tanβ

  $A,H,H^{\pm}$ large tanβ, moderate mA

MSSM Higgs Discovery

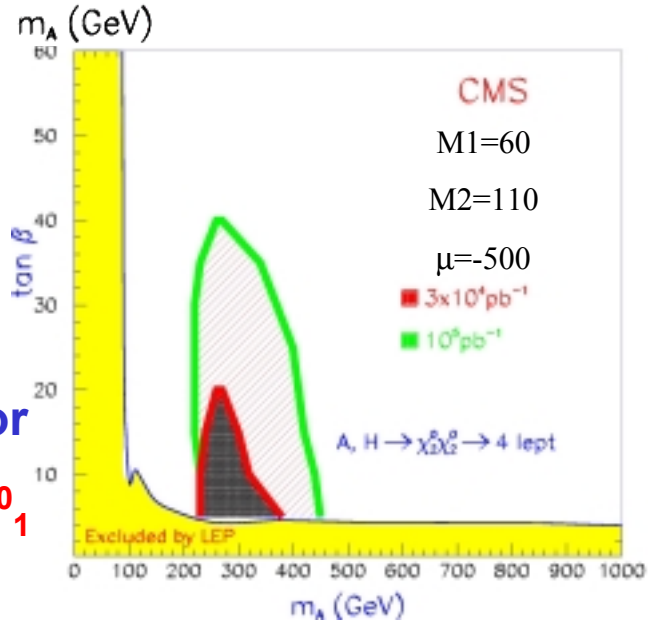


4 Higgs observable
3 Higgs observable
2 Higgs observable
1 Higgs observable

5σ contours

Assuming decays to SM particles only

Here only SM-like h observable if SUSY particles neglected.



- **for light SUSY, search for**

eg. H/A→$\chi^0_2\chi^0_2 \rightarrow \ell\ell\chi^0_1\ell\ell\chi^0_1$

- **principle quite general; detailed exclusions depend on MSSM parameters**

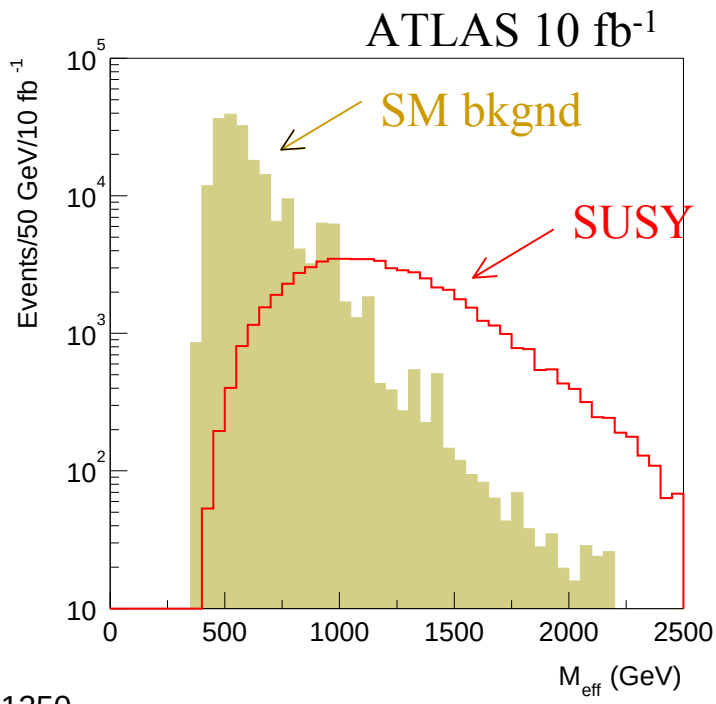
SUSY Particle Production

- if weak-scale SUSY exists, LHC is a SUSY factory
- production dominated by strong pair-production of squarks/gluinos
  - typical Xsect ≈ 10 pb for masses ≈ 1 TeV
- sel. of SUSY-dominated sample is possible using simple kinematic variables

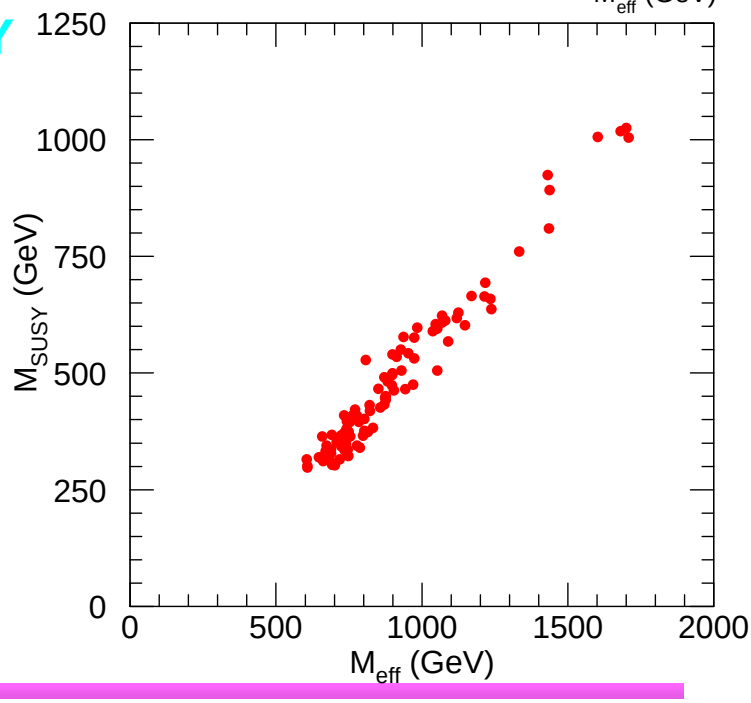
  eg. Meff in multi-jet events where

$$\mathbf{M_{eff}} = E_T^{miss} + \sum_{i=1}^{4} p_{T,i}$$

⇒background to SUSY is SUSY!!

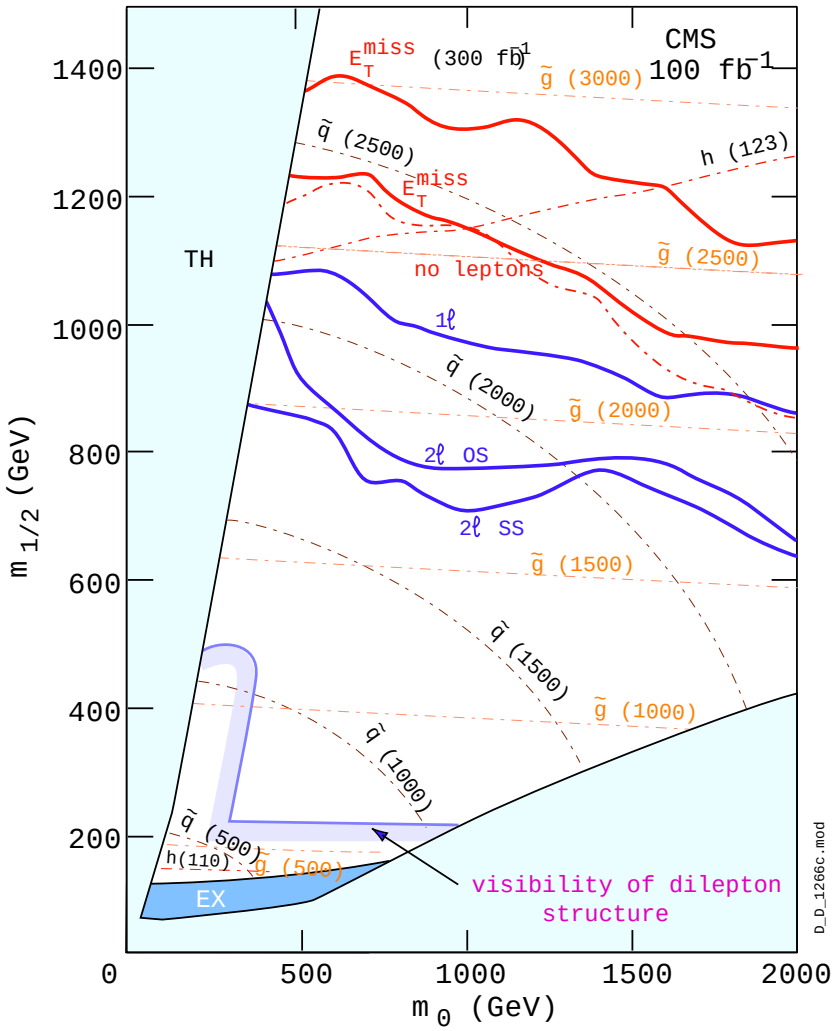


- Meff correlates with SUSY mass scale



SUGRA Potential

- for R-parity conservation, E_T^{miss} (with/without jets, leptons) provides clear signature

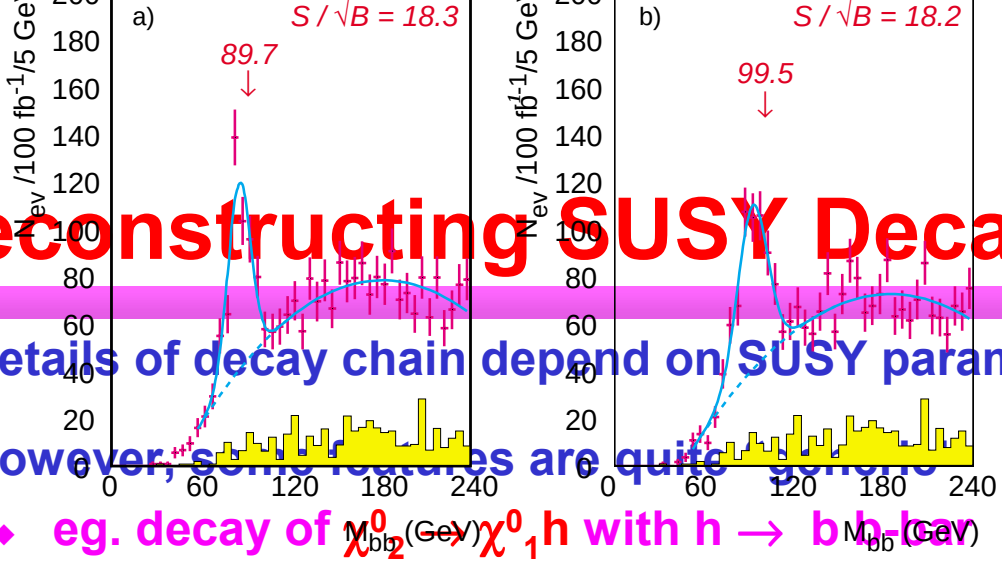


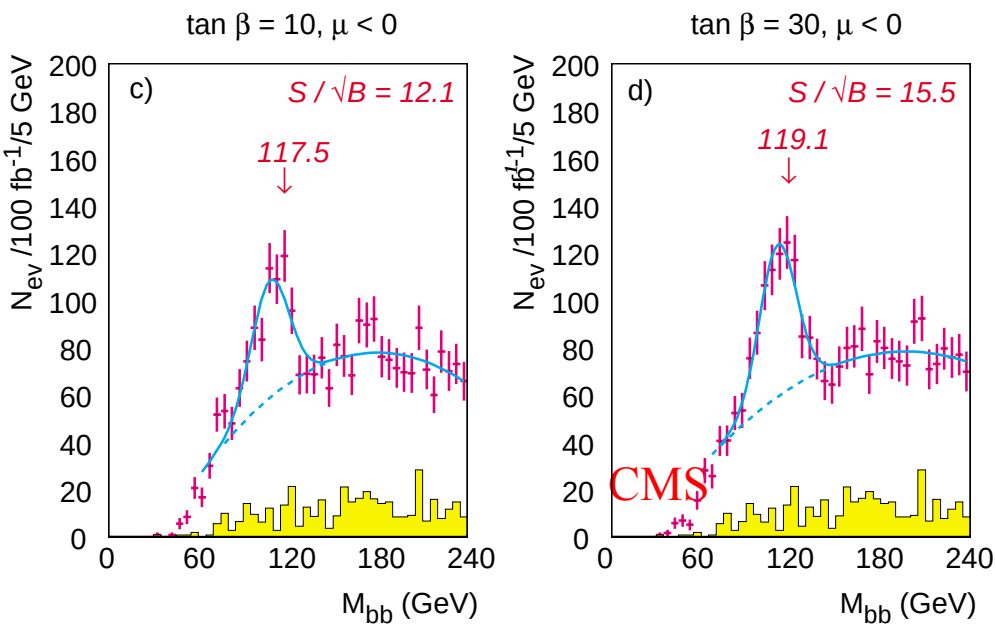
  - squark/gluino mass reach ≈ 2.5 TeV (100 fb^{-1})

- with RPV, signature depends on decay mode of LSP
  - leptonic ⇒ multi-lepton final states - EASY!
  - hadronic ⇒ high jet multiplicities - more difficult
    - possibilities studied include using leptons from cascade decays

Reconstructing SUSY Decays

- details of decay chain depend on SUSY parameters
- however, some features are quite generic
  - eg. decay of $\chi^0_2 \to \chi^0_1 h$ with $h \to b\bar{b}$-bar



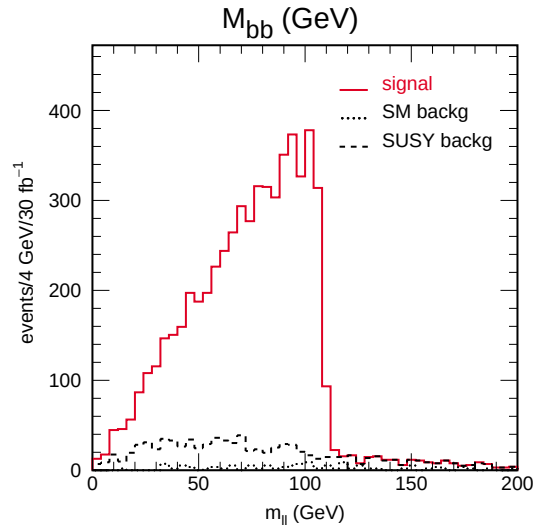


CMS

100 fb^{-1}

or $\chi^0_2 \to \chi^0_1 l^+ l^-$, possibly via $\chi^0_2 \to \tilde{l}^+ l^-$

$$M_{endpt} = M(\chi^0_2)\sqrt{1-\left(\frac{M(\tilde{l}_R)}{M(\chi^0_2)}\right)^2}\sqrt{1-\left(\frac{M(\chi^0_1)}{M(\tilde{l}_R)}\right)^2}$$



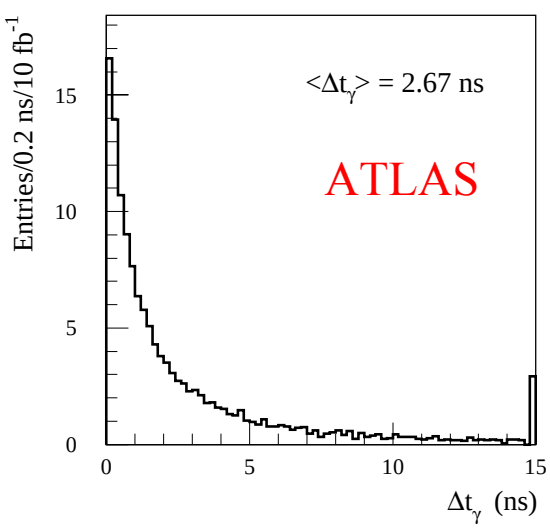
- use this as starting pt. to move up decay chain to identify several SUSY particles

Gauge Mediated SUSY

- GMSB naturally accounts for observed lack of FCNC
- Gravitino is LSP (mass ≈ keV) and escapes detector
- GMSB phenomenology dominated by NLSP decay and lifetime
  - NLSP lifetime probes scale of SUSY-breaking
- two cases for NLSP:

$$\chi_1^0 \rightarrow \gamma + \tilde{G}$$

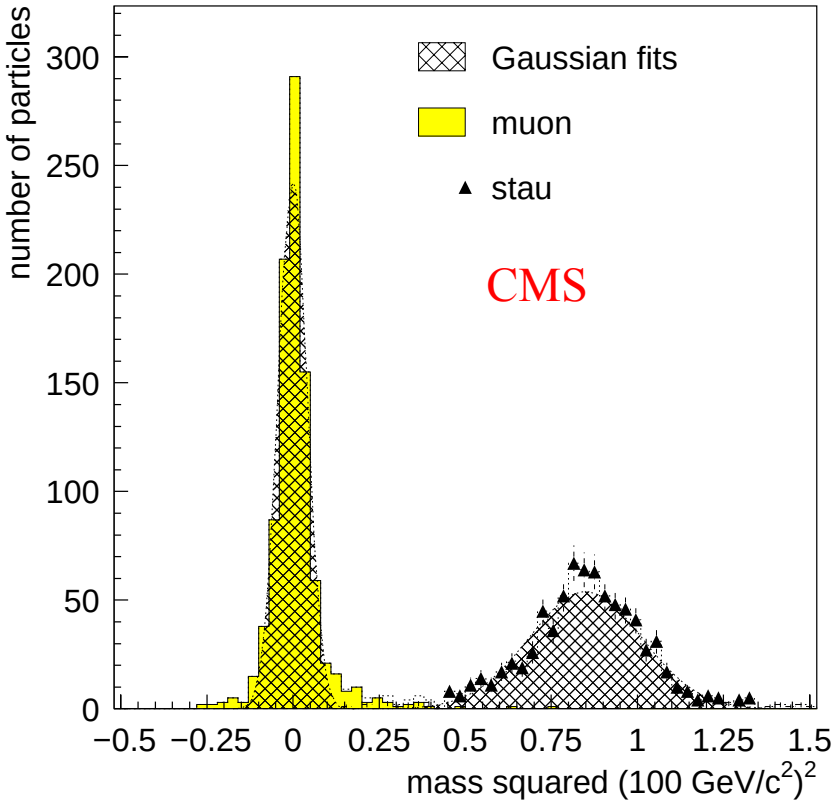
  - short-lived ⇒ multi-γ final states - EASY! (use Dalitz decay to measure lifetime)
  - long-lived ⇒ SUGRA-like signatures (eg. E_T^{miss})
  - intermediate ⇒ count non-pointing photons
    - can also use gamma delay for confirmation



GMSB

$$\tilde{\tau}_1 \rightarrow \tau + \tilde{G}$$

- short-lived ⇒ multi-τ final states - EASY!
- long-lived ⇒ heavy quasi-stable charged slepton!
  - use muon system as large ToF detector

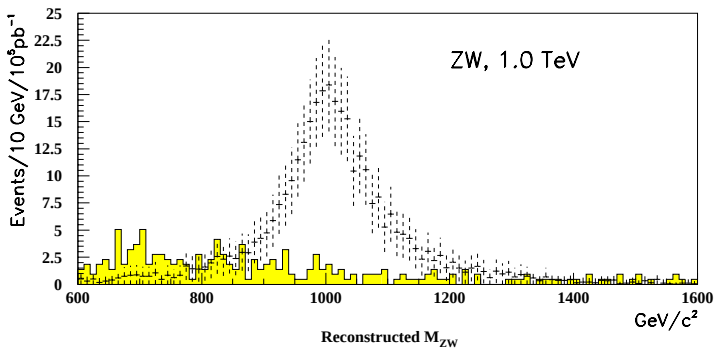


New Strong Dynamics

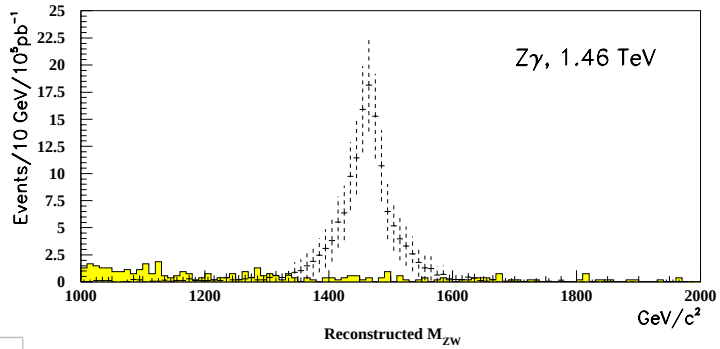
- if no light Higgs found, expect strong $V_L V_L$ scattering (either resonant or non-resonant)
- some examples:

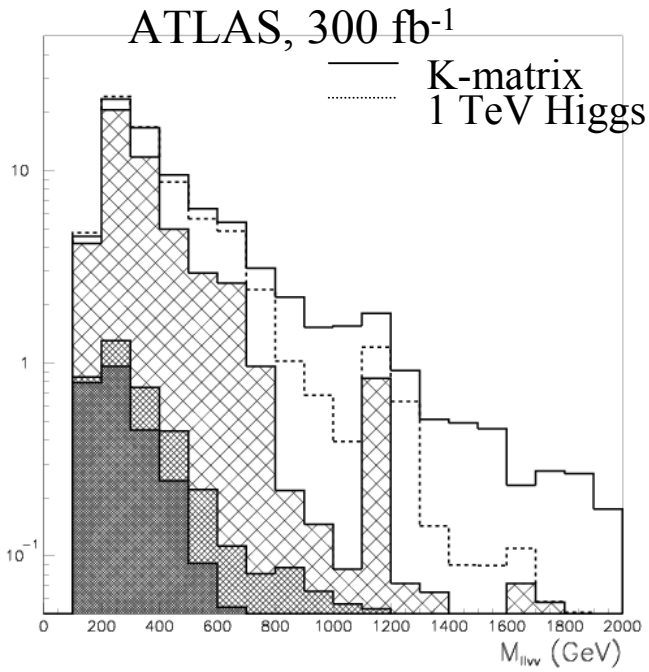
ATLAS

$\rho_T \rightarrow ZW$



$\omega_T \rightarrow Z\gamma$





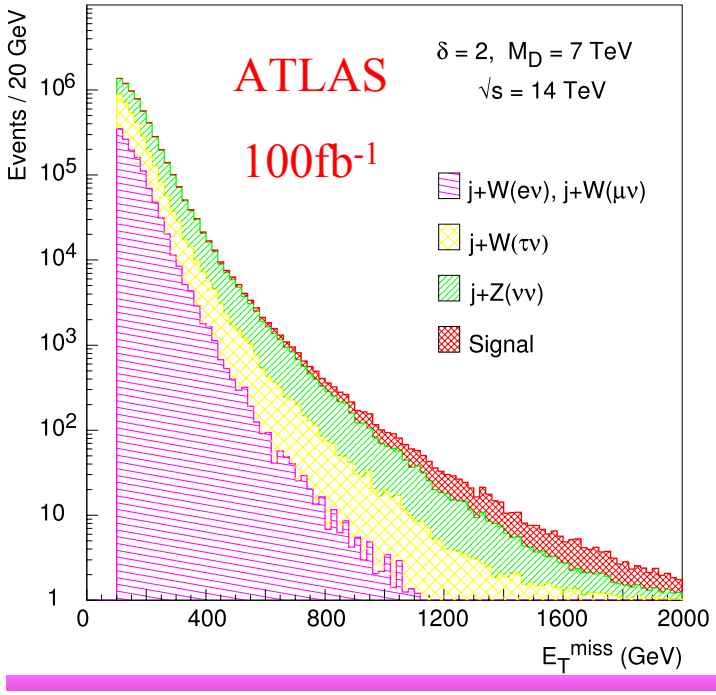
Non – resonant WW scattering

Extra Dimensions

- a lot of recent interest in models with extra dimensions, as alternative approach to Hierarchy Problem
- two general types of models considered:

Large extra dimensions

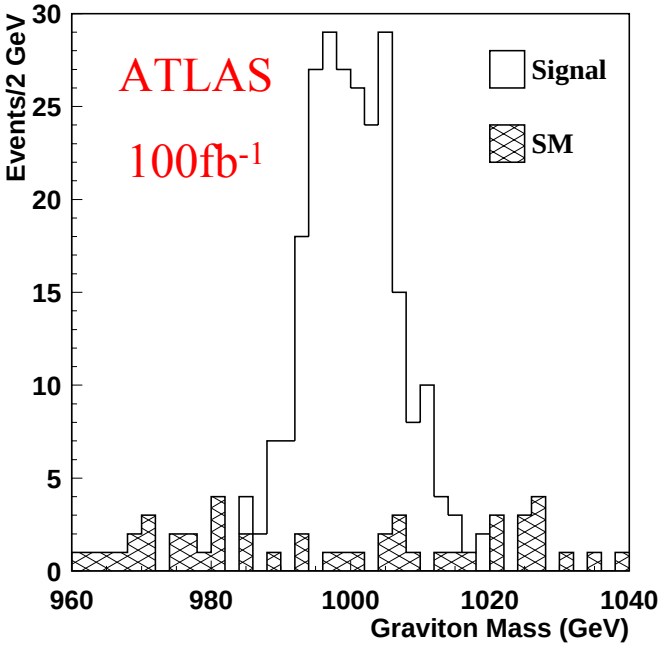
- apparent weakness of gravity due to spreading of grav. field lines into extra dim's
  - model parametrized by δ (no. of large extra dim's) and M_D (fundamental scale)
- KK tower of MANY graviton excitations, each coupling with gravitational strength
- $gg \rightarrow gG$, $gq \rightarrow qG$ and $q\ qbar \rightarrow Gg$, $G\gamma$ lead to signature of large E_T^{miss} plus jet/gamma

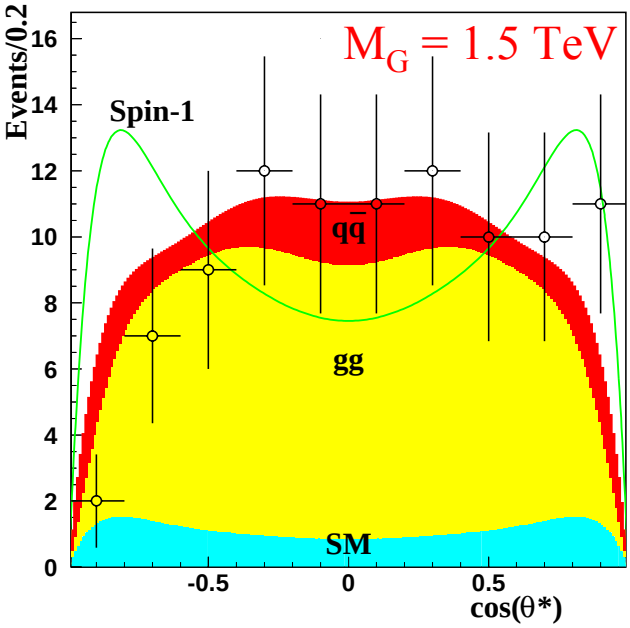


δ	M_D
2	9 TeV
3	7 TeV
4	6 TeV

"Warped" Extra Dimensions

- **Randall-Sundrum model**
  - apparent weakness of gravity due to fact that SM lives on one brane, gravity on another
  - production/decay of massive spin-2 Graviton states could lead to resonance in $gg \rightarrow e^+e^-$, $q\ qbar \rightarrow e^+e^-$
  - decay angular analysis can verify spin = 2





  - for a particular theoretical model, could:
    - discover Graviton (5σ) for masses up to $\approx$ 2.1 TeV
    - verify spin = 2 for Graviton masses up to $\approx$ 1.7 TeV

(assuming 100 fb^{-1})

Possible LHC Upgrades

- CERN has initiated investigation of possible lumi. and energy upgrades to the LHC
- Possible luminosity upgrade:
  - increase bunch intensity to beam-beam limit
  - new focusing quads at IP to reduce β^*
  - reduce bunch spacing to 12.5 ns

  $\Rightarrow$ could reach lumi. = $5 \times 10^{34} - 10^{35}$

  (in as little as $\approx$ 5 years after LHC turn-on!)

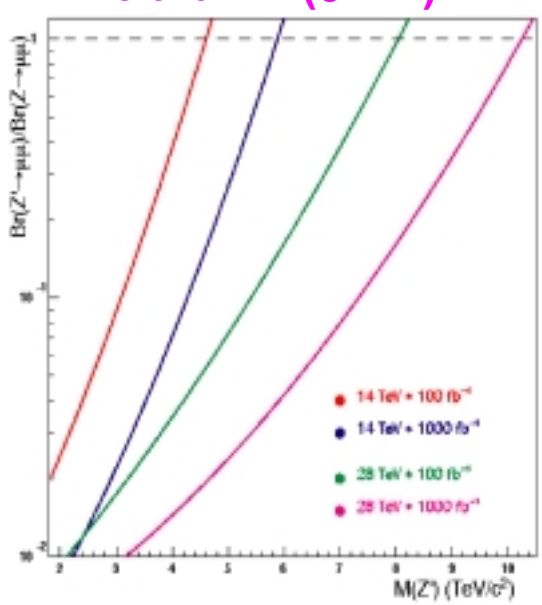
  - high lumi. working group formed to look at physics, and also detector upgrade issues
- Possible energy upgrade:
  - LHC dipoles could reach $\sqrt{s} \approx$ 15 TeV (9 T)
  - today's technology could reach $\approx$ 18 TeV (10.5 T) (synch. rad'n limit for current beam screen is also $\approx$ 18 TeV)
- to evaluate, CERN requested experiments to examine the following benchmark scenarios:
  - $\sqrt{s}$ = 14 TeV, L = 10^{35}
  - $\sqrt{s}$ = 28 TeV, L = 10^{34}
  - $\sqrt{s}$ = 28 TeV, L = 10^{35}

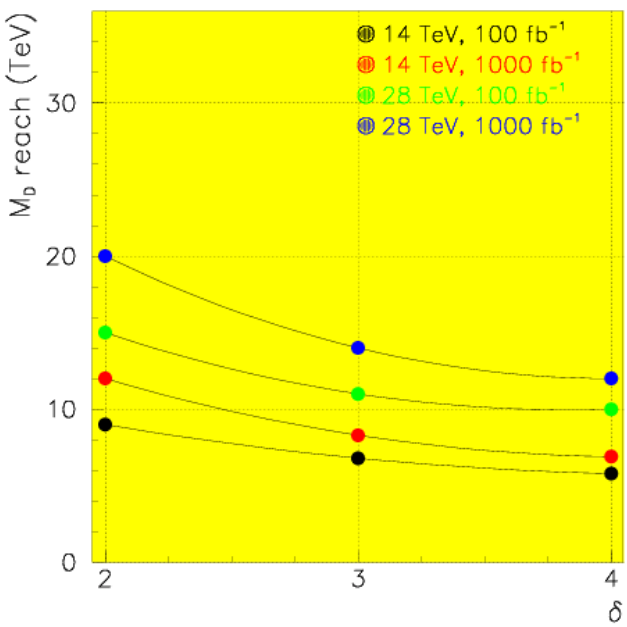
"SuperLHC" (14 TeV, 10^{35})

- current ATLAS/CMS detectors would suffer degraded performance
  - studies concentrated on physics reach with high pT muons and jets

- a few examples:

	100 fb^{-1}	1000 fb^{-1}
Inclusive jets	3.6 TeV	4.2 TeV
Z'	4.5 TeV	5.4 TeV
SUSY	2.5 TeV	3 TeV
Extra dim. (δ = 2)	9 TeV	12 TeV





General conclusions:

- energy/mass reach extended by typ. 20 - 30%
- for precision studies, need detector upgrades to preserve b-tagging, electron id, ...

Summary

- the LHC and ATLAS/CMS will explore the TeV energy scale, where we expect the source of EWSB
- SM Higgs
  - observation (> 5σ) over full allowed mass range
  - mass measurement to 0.1%
  - some BR's to < 25%, couplings ≈ 15%
- SUSY Higgs
  - discovery of at least one Higgs over full plane
    - > 1 Higgs visible over much of plane
    - for moderate tanβ, see only h
- SUSY
  - squarks/gluinos visible to ≈ 2.5 TeV
  - gauginos, sleptons only in cascade decays
  - reconstruction of decays provides indication of SUSY breaking mechanism, and (model-dep.) precision measurement of SUSY parameters
- Strong VV scattering
  - eg. resonances up to ≈ 2 TeV
- Extra dimensions
  - large extra dim. to 9 TeV with $\delta = 2$
  - warped extra dim. to $M_G \approx 2$ TeV

Summary (cont'd)

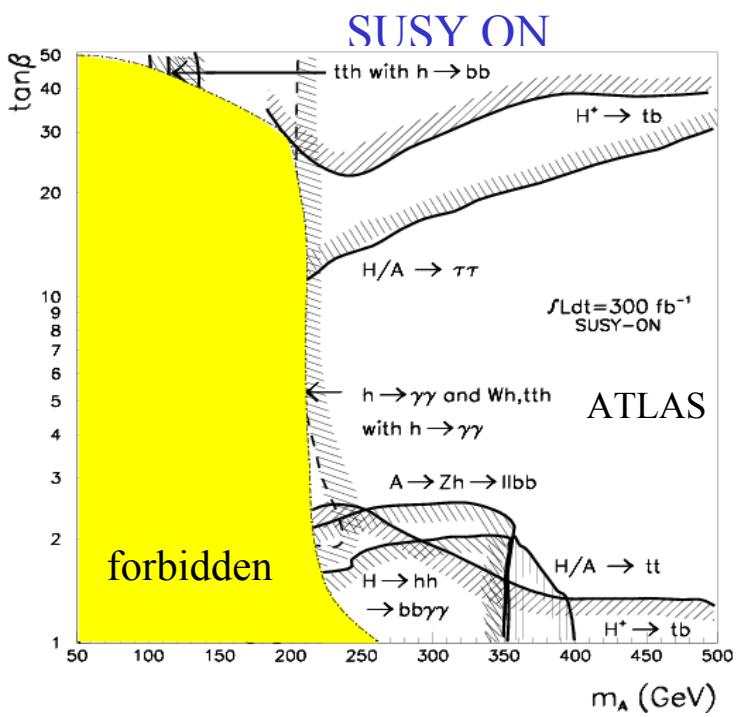
- Some other things the LHC can do:
  - W', Z' up to masses of 5 - 6 TeV
  - leptoquarks up to masses ≈ 2 TeV
  - substructure probed to scale of 40 TeV
  - top quark physics:
    - mass measurement to 1 - 2 GeV
    - Yukawa coupling measurement to < 20%
    - rare decays to BR ≈ 10^{-5}
  - b-physics
    - CP violation
    - rare decays (eg. $B \to \mu\mu$) to BR ≈ 10^{-9}
- lumi. upgrade (very likely) extends energy reach by ≈20-30% (even without significant detector upgrade)
- Some things the LHC (probably) can't do:
  - J^{PC} of Higgs
  - precision Higgs couplings, width
  - measurement of all heavy SUSY Higgs'
  - measurement of entire SUSY particle spectrum
    - weakly coupled sparticles
    - very heavy sparticles
  - probe energy scales (eg. GMSB messenger sector) > few TeV

How robust is SUSY Higgs potential?

- SUSY loops can enhance/suppress Higgs production (e.g. $gg \rightarrow h$) and decay (e.g. $h \rightarrow \gamma\gamma$)
- $A/H/H^{\pm} \rightarrow$ sparticles can compete with SM decays

Preliminary study : mSUGRA impact of SUSY on Higgs decays to SM particles is small :

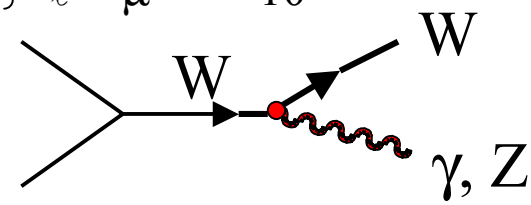
-- $gg \rightarrow h \rightarrow \gamma\gamma$ 10% smaller
-- $tth/Wh \rightarrow \gamma\gamma$ 30% smaller
-- $ttH \rightarrow tt\ bb$ not affected
-- BR ($A/H/H^{\pm} \rightarrow$ SM particles) reduced by at most 40%

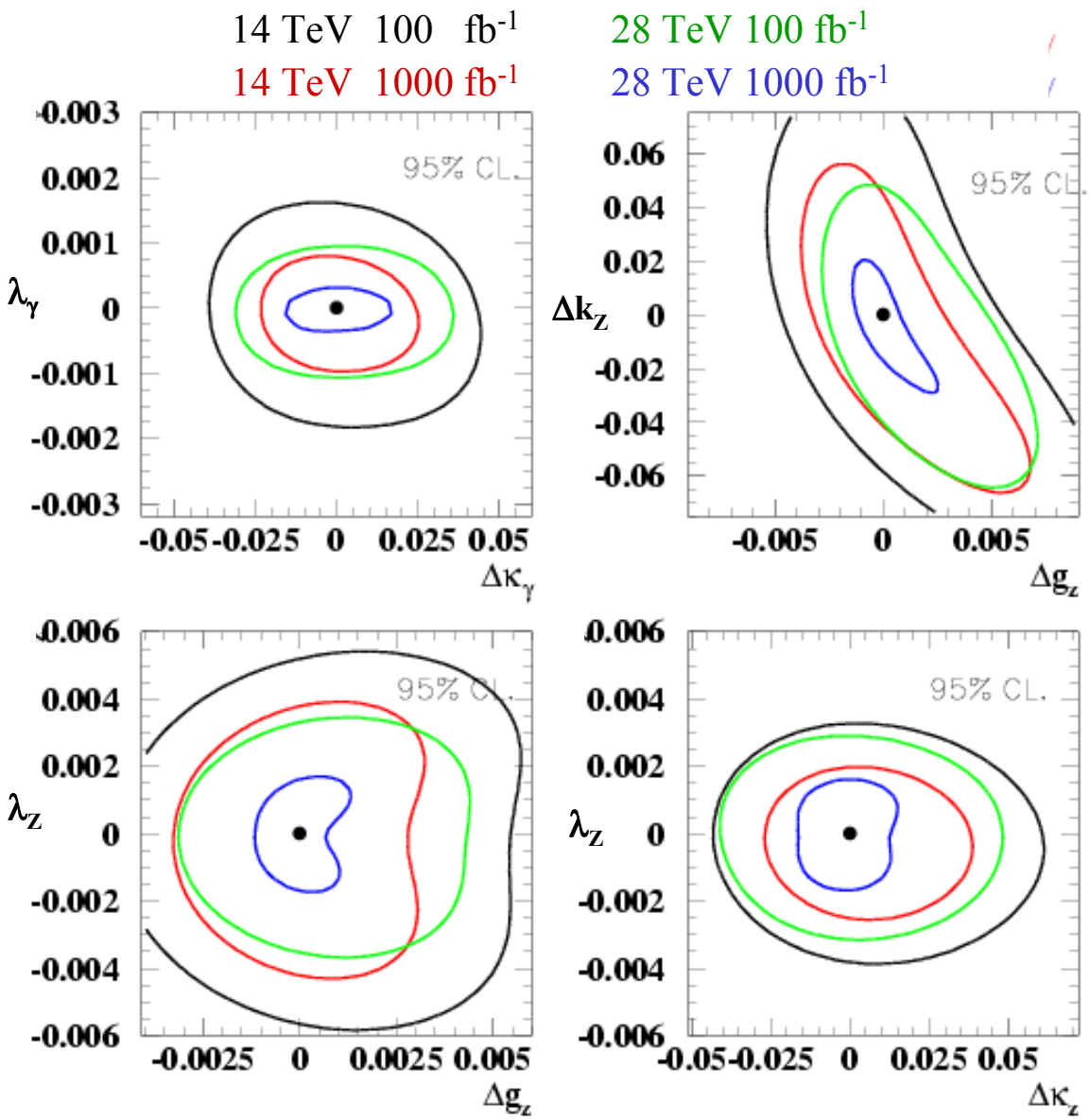


However : impact of mixing on couplings not studied for all possible mixing scenarios $\rightarrow$ more work needed

Triple Gauge Couplings

λ_γ, Δk_γ	from	$W\gamma \rightarrow \ell\nu\gamma$	ℓ =e, μ	10^{34}
λ_Z, Δk_Z, $g^1{}_Z$	from	$WZ \rightarrow \ell\nu\,\ell\ell$	$\ell = \mu$	10^{35}





Triple Gauge Couplings

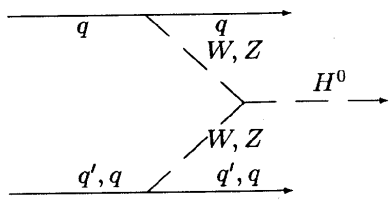
95% C.L. constraints
for 1 experiment

	NLC 500 GeV 500 fb^{-1}	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	28 TeV 1000 fb^{-1}
λ_γ	0.0014	0.0014	0.0006	0.0002
λ_Z	0.0013	0.0028	0.0018	0.0009
Δk_γ	0.0010	0.034	0.020	0.013
Δk_Z	0.0016	0.040	0.034	0.013
g^1_Z	0.0050	0.0038	0.0024	0.0007

-- Angular distributions not used → pessimistic for Δk_γ, Δk_Z
-- Precision for λ_γ, λ_Z (≈ SM radiative corrections) similar to 500 GeV NLC
-- Only muon channels included at 10^{35} (50% of $W\gamma$ and 25% of WZ) → conservative

→ LHC luminosity upgrade has significant impact

Higgs production via Weak Boson Fusion



- $\sigma \approx 4$ pb is ~20 % of total Higgs cross-section for $m_H \sim 120$ GeV
- however: distinctive signature of two very forward jets + little additional jet activity (tools against background)

First proposed by Zeppenfeld et al.
Parton-level analysis + "reasonable" detection efficiencies :

LHC 30 fb^{-1} (Phys. Rev. D62 (2000)): S/√B, S, B

m_H (GeV)	110	120	130	150	160	190
qqH → γγ	6 30, 27	7 40, 30	7 40, 28	4.5 25, 25	---	----
qqH → ττ	9.5 65, 40	13 55, 17	12.5 40, 10	4 13, 8		
qqH → WW → μν eν	----	6.3 46, 45	14 110,50	34 300,70	51 480,80	25 270,110

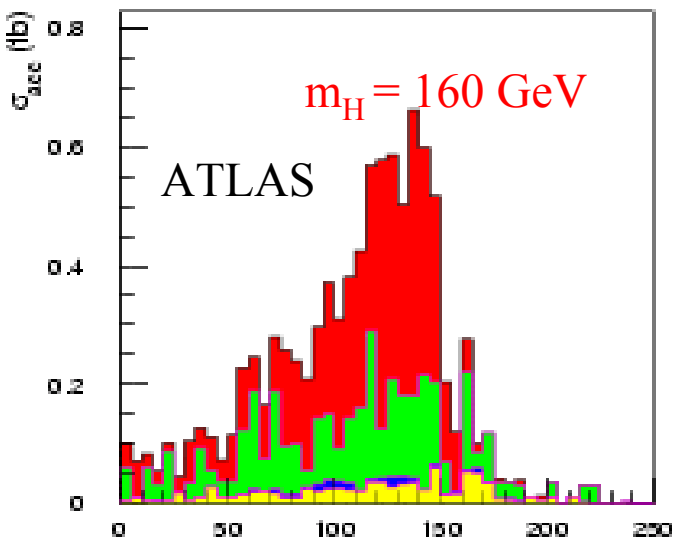
Interesting for :
-- discovery
-- measurements of couplings (e.g. Hττ) and Γ_H
(indirect measurement, cross-section uncertainty ~ 5%)

First studies by ATLAS and CMS (including detector simulation) performed:

New, preliminary, promising

-- qqH → WW → μν eν, qqH → ττ → eμ E_T^{miss} studied
(qqH → ττ → ℓ h E_T^{miss} being finalised)
-- worse results than Zeppenfeld (e.g. signal is ~ 2 smaller)
-- however: confirmed that WBF gives discovery channels

qqH → WW → μν eν



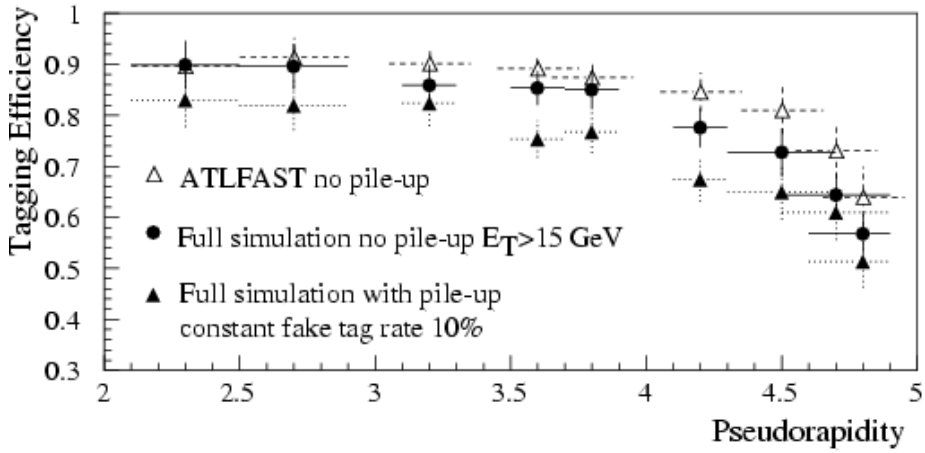
$$m_T = \sqrt{2\, p_T^{\ell\ell}\, E_T^{miss}\, (1 - \cos\Delta\varphi)}$$

ATLAS , 10 fb^{-1}

m_H (GeV)	130	150	170	190
S	10	30	55	40
S/B	0.3	0.9	1.5	1.1
S/√B	1.4	5.0	8.8	6.3

Counting experiment
→ 5% systematics on B included in S/√B

Double tag efficiency ~ 50% from full simulation (fake tags < 1% at 10^{34})



Higgs rates

ATLAS + CMS
300 fb $^{-1}$

From gg-fusion :

$$\frac{R\,(H \to \gamma\gamma)}{R\,(H \to ZZ \to 4\ell)} \Rightarrow \frac{g_{H\gamma\gamma}}{g_{HZZ}}$$

$120 \le m_H \le 150$ GeV
precision **< 15%**

$$\frac{R\,(H \to WW \to \ell\nu\ell\nu)}{R\,(H \to ZZ \to 4\ell)} \Rightarrow \frac{g_{HWW}}{g_{HZZ}}$$

$150 \le m_H \le 190$ GeV
precision **< 15%**

From WB-fusion: (Zeppenfeld)

$$\frac{R\,(qqH \to \gamma\gamma)}{R\,(qqH \to \tau\tau)} \Rightarrow \frac{g_{H\gamma\gamma}}{g_{H\tau\tau}}$$

$100 \le m_H \le 150$ GeV
precision **< 15%**

$$\frac{R\,(qqH \to WW)}{R\,(qqH \to \tau\tau)} \Rightarrow \frac{g_{HWW}}{g_{H\tau\tau}}$$

$120 \le m_H \le 150$ GeV
precision **~10%**

$$\frac{R\,(qqH \to \gamma\gamma)}{R\,(qqH \to WW)} \Rightarrow \frac{g_{H\gamma\gamma}}{g_{HWW}}$$

$120 \le m_H \le 150$ GeV
precision **~15%**

From associated ttH, WH :

$$\frac{R\,(ttH + WH \to \gamma\gamma)}{R\,(ttH + WH \to bb)} \Rightarrow \frac{g_{H\gamma\gamma}}{g_{Hbb}}$$

$80 \le m_H \le 120$ GeV
precision **~15%**

Different production mechanism:

$$\frac{R\,(WH \to \gamma\gamma, WW)}{R\,(H \to \gamma\gamma,\ WW)} \Rightarrow \frac{g_{HWW}}{g_{Htt}}$$

$100 \le m_H \le 190$ GeV
precision **< 30%**

$$\frac{R\,(qqH \to WW)}{R\,(H \to WW)} \Rightarrow \frac{g_{HWW}}{g_{Htt}}$$

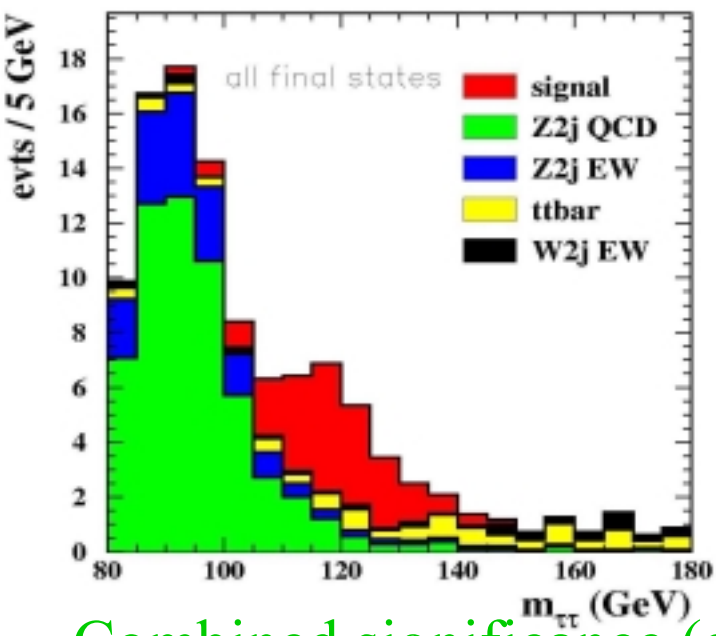
$150 \le m_H \le 190$ GeV
precision **~ 25%**

Error dominated by statistics in most cases

$qqH \rightarrow qq\,\tau\,\tau \rightarrow qq\,l\,\nu\,\nu\,l\,\nu\,\nu$

ATLAS:

- Similar basic cuts as in WW analysis
- Tau mass reconstruction using collinear approximation
- Optimized cuts for eμ, ee and μμ channels



$m_H = 115$ GeV

30 fb^{-1}

all channels
(eμ best channel)

S = 17.3 events

B = 11.4 events

S/B > 1

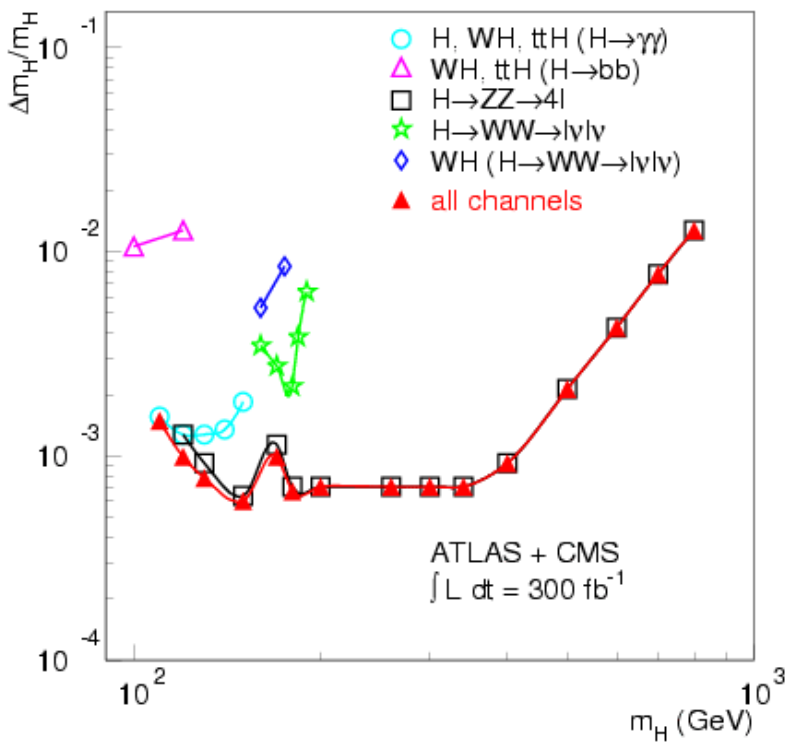
Combined significance (ee, μμ, eμ):

m_H (GeV)	110	115	120	125	130	140	150
10 fb^{-1}	2.2	2.6	2.6	2.4	2.3	1.3	0.6 σ
30 fb^{-1}	3.8	4.3	4.3	4.1	3.8	2.7	1.4 σ

Preliminary, no systematics yet, l-had channel to be added

Measurement of Higgs boson masses

Mass of Standard Model Higgs boson



No theoretical error e.g. mass shift for large Γ_H (interference resonant/non-resonant production)

Dominant systematic uncertainty: γ/ℓ E scale.
Assumed 1‰
Goal 0.2‰
Scale from $Z \to \ell\ell$ (close to light Higgs)

Mass of MSSM Higgs bosons

MSSM Higgs	$\Delta m/m$ (%)
$h, A, H \to \gamma\gamma$	0.1–0.4
$H \to 4\,\ell$	0.1–0.4
$H/A \to \mu\mu$	0.1-1.5
$h \to bb$	1–2
$H \to hh \to bb\,\gamma\gamma$	1-2
$A \to Zh \to bb\,\ell\ell$	1–2
$H/A \to \tau\tau$	1-10

300 fb^{-1}