Physics at the LHC

- Introduction, Detector Aspects

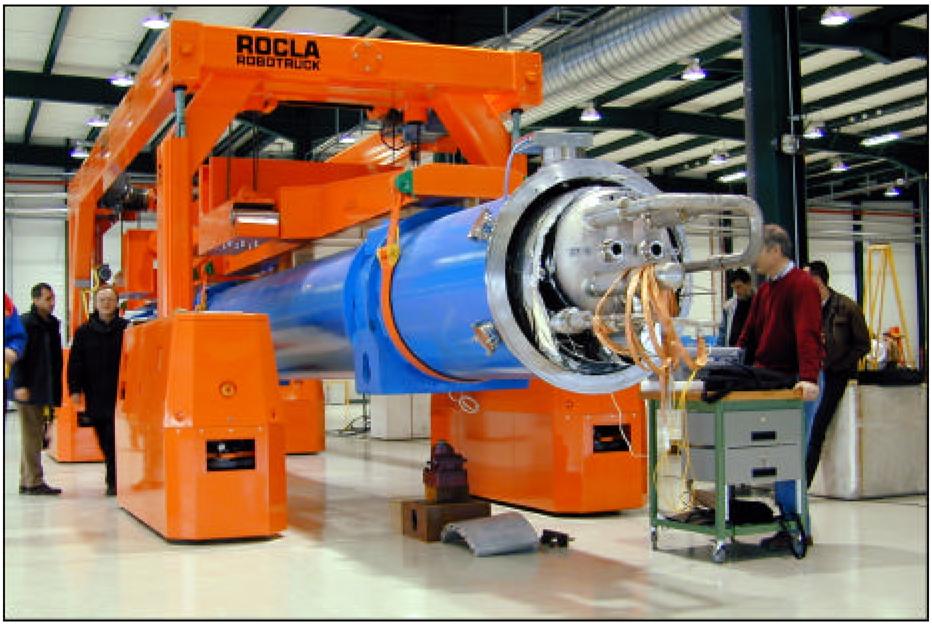
- Search for the Higgs Boson
  - Vector boson fusion mode
  - Measurement of Higgs boson parameters

- Standard Model Physics
  - W-mass measurement
  - Top Quark Physics

- Physics Beyond the Standard Model
  - SUSY Signatures
  - Search for Signals from Extra Dimensions

Karl Jakobs
Institut für Physik
Universität Mainz
55099 Mainz

Revised LHC Schedule



Dec. 2006	Ring closed and cold
Jan. - Mar. 2007	Machine commissioning
Spring 2007	First collisions , pilot run L=5x10^{32} to 2x10^{33} , £ 1 fb^{-1} Start detector commissioning ~ 10^5 Z ® ℓℓ, W ® ℓn, tt events
June - Dec. 2007	Complete detector commissioning, Physics run
® 2009	L=1-2 x10^{34}, 100 fb^{-1} per year (high luminosity LHC)

---

low luminosity: L = 1x10^{33} 10 fb^{-1} / year
high luminosity: L = 1x10^{34} 100 fb^{-1} / year

Cross sections and production rates

$\mathcal{L} = 1.0 \cdot 10^{33}$ cm^{-2} sec^{-1}

Process	σ	Events/s	Events/year
$W \to e\nu$	15 nb	15	10^8
$Z \to ee$	1.5 nb	1.5	10^7
$t\bar{t}$	800 pb	0.8	10^7
$b\bar{b}$	500 μb	10^5	10^{12}
QCD jets ($P_T > 200$ GeV)	100 nb	10^2	10^9
$\tilde{g}\tilde{g}$ ($m_{\tilde{g}} = 1$ TeV)	1 pb	0.001	10^4
Higgs ($m_H = 0.2$ TeV)	10 pb	0.01	10^5
($m_H = 0.8$ TeV)	1 pb	0.001	10^4

Large production rates

Þ

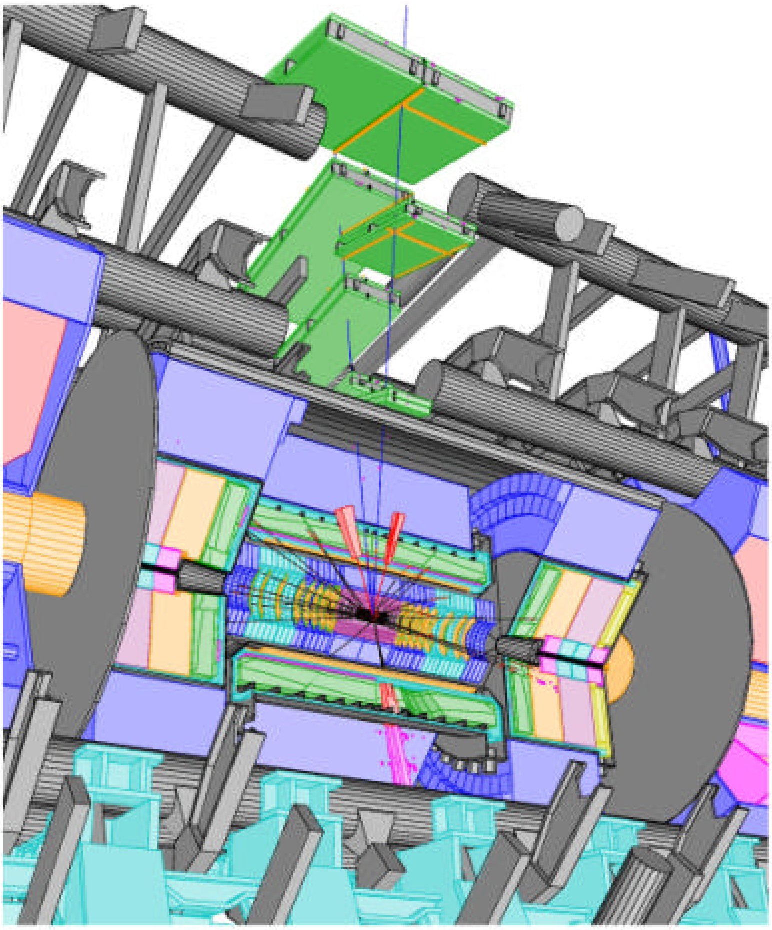
- **Precision measurements**
  at initial low luminosity
  (W physics, top physics)
  precision will be limited by systematic uncertainties.

- **Discoveries** (at low and high luminosity)
  Mass reach for new particles up to ~ 2 TeV

- Disadvantages:
  $\sigma_{inelastic} \sim 70$ mb $\Rightarrow$ 700 Mio events / sec at high L

  Pile-up: 23 minimum bias events/bunch crossing at high L
  2.3 mimimum bias events/bunch crossing at low L

Detector Requirements



- Good measurement of leptons and photons

  momentum range:
  ~ GeV ($b \rightarrow l \nu c$)
  ~ TeV ($W \rightarrow l \nu$)

  lepton energy / momentum scale: 0.1 % $\rightarrow$ 0.02%

  (large statistics for calibration,
  $Z \rightarrow \ell\ell$,
  m_Z is close to m_W and m_H (?)

- Good measurement of missing transverse energy (E_T^{miss})
  and
  Jet energy measurements and jet-tagging in forward region
  $\Rightarrow$ calorimeter coverage down to $\eta \sim 5$

  Jet energy scale: 1% (relevant for m_{top}, SUSY)

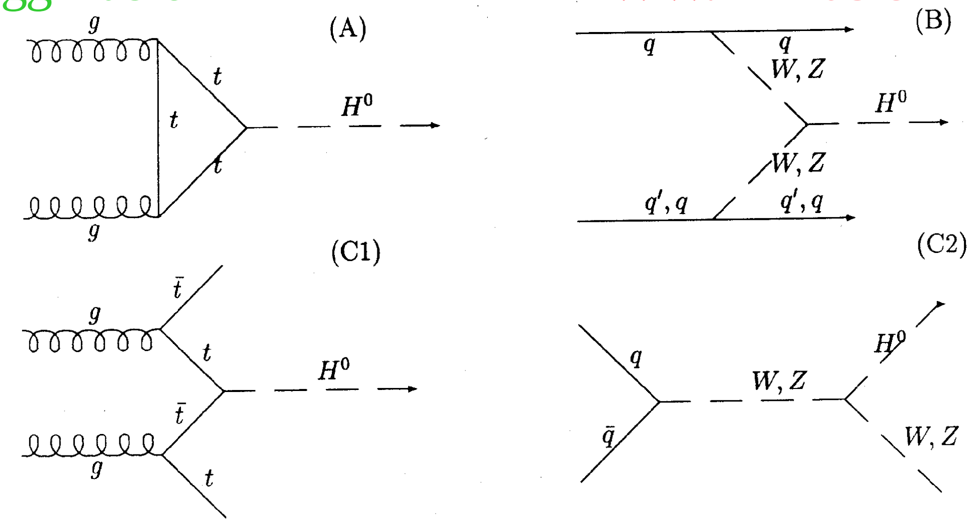
- Efficient b-tagging and τ identification
  (silicon strip and pixel detectors)

- Fast (25 ns bunch crossing) and rad. hard detectors and electronics

Search for the Higgs boson

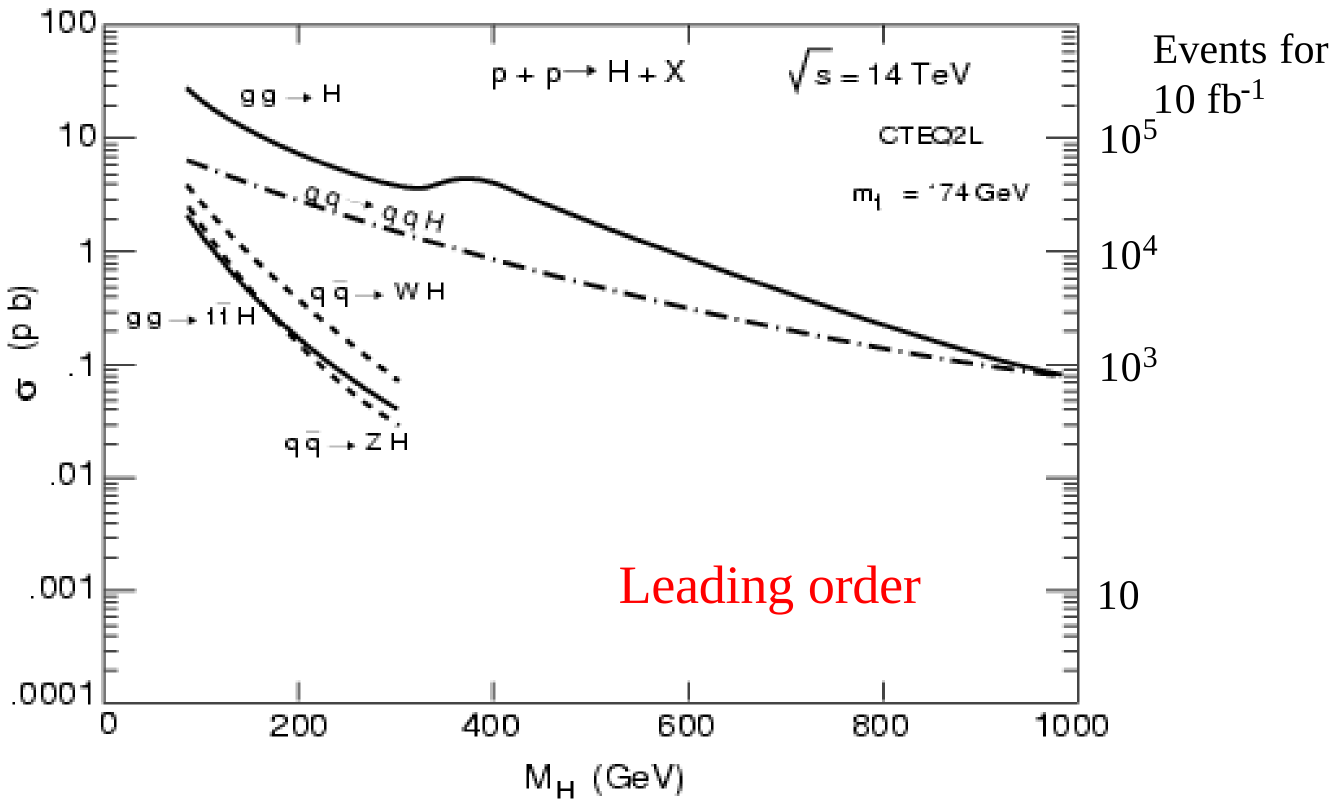
gg fusion

WW/ZZ fusion



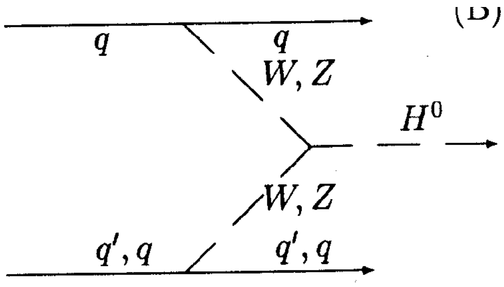
associated $t\bar{t}H$

associated WH, ZH



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

Higgs production via Vector Boson Fusion



Motivation:

•Additional potential for Higgs boson discovery at low mass

•Important for the measurement of Higgs boson parameters
(couplings to bosons, fermions (taus), total width)

proposed by D.Rainwater and D.Zeppenfeld et al.:
(hep-ph/9712271, hep-ph/9808468 and hep-ph/9906218)

Destinctive Signature of:

- **two high P_T forward jets**
- **little jet activity in the central region**

  Þ **Jet Veto**

Þ **Experimental Issues:**

- **Forward jet reconstruction**
- **Jets from pile-up in the central/forward region**

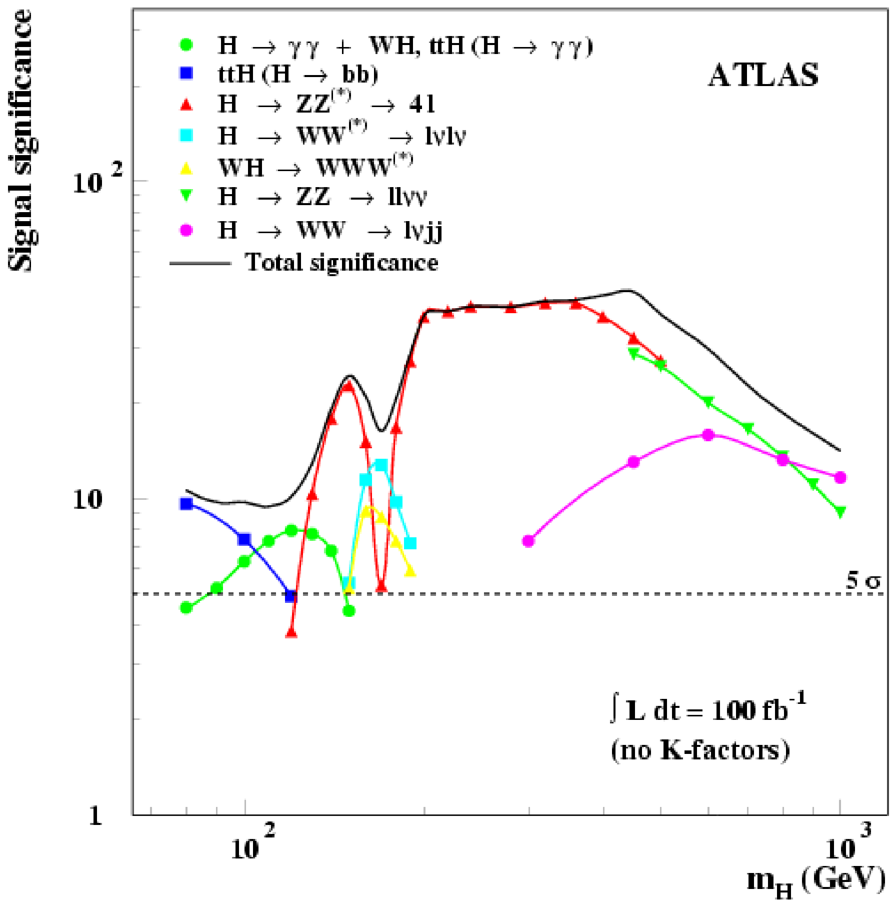
Channels studied: **qqH** ® **WW*** ® **l** n **l** n

qqH ® t t ® **l** n n **l** n n

® **l** n n **had** n

Main search channels at the LHC

$$\frac{S}{\sqrt{B}}$$



$m_H < 2\, m_Z$: $\quad t\bar{t}H \rightarrow \ell b\bar{b} + X,\ \ H \rightarrow gg,$

$H \rightarrow ZZ^* \rightarrow 4\ell,\ \ H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$

$m_H > 2\, m_Z$: $\quad H \rightarrow ZZ \rightarrow 4\ell$

$qqH \rightarrow ZZ \rightarrow \ell\ell\ \nu\nu$
$qqH \rightarrow ZZ \rightarrow \ell\ell\ jj$
$qqH \rightarrow WW \rightarrow \ell\nu jj$
} $m_H > 300$ GeV, forward jet tag

10 fb^{-1}: Discovery possible over the full mass range, however, needs combination of ATLAS + CMS

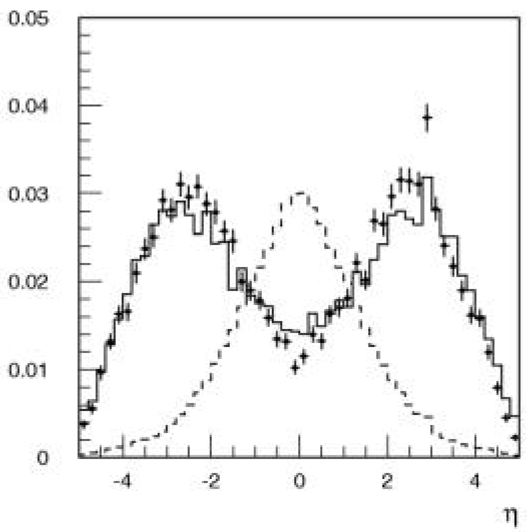
M_H = 115 GeV: **S/ ÖB = 4.7**

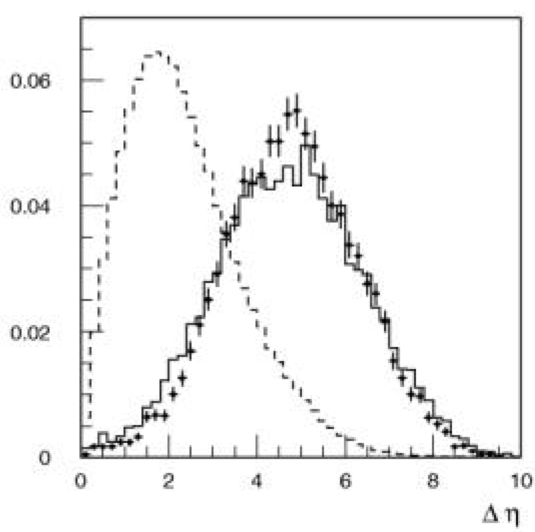
Forward tag Jets

Rapidity distribution of tag jets

VBF Higgs events vs. tt-background

Rapidity separation



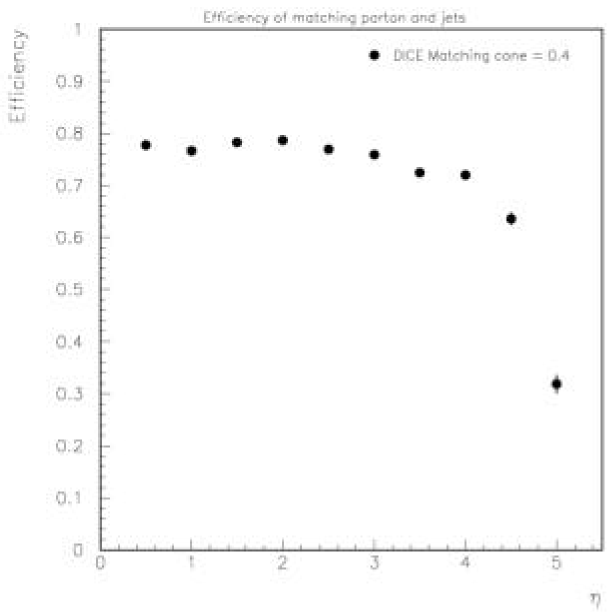


Forward tag jet reconstruction has been studied in full simulation in ATLAS

Results are consistent with TDR-results

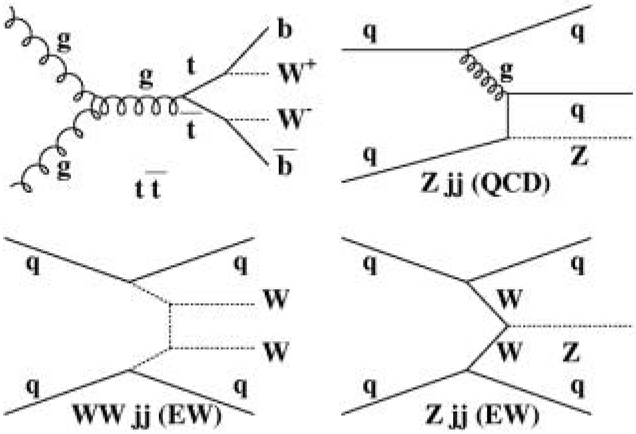
kin. eff. for tag jets ($P_{T,}$ Δ η) = 51.9%

tag eff. per jet: around 75%



Physics studies based on a fast simulation have been corrected for efficiency losses

Background:



QCD backgrounds:
tt production
Z + 2 jets
(PYTHIA MC)

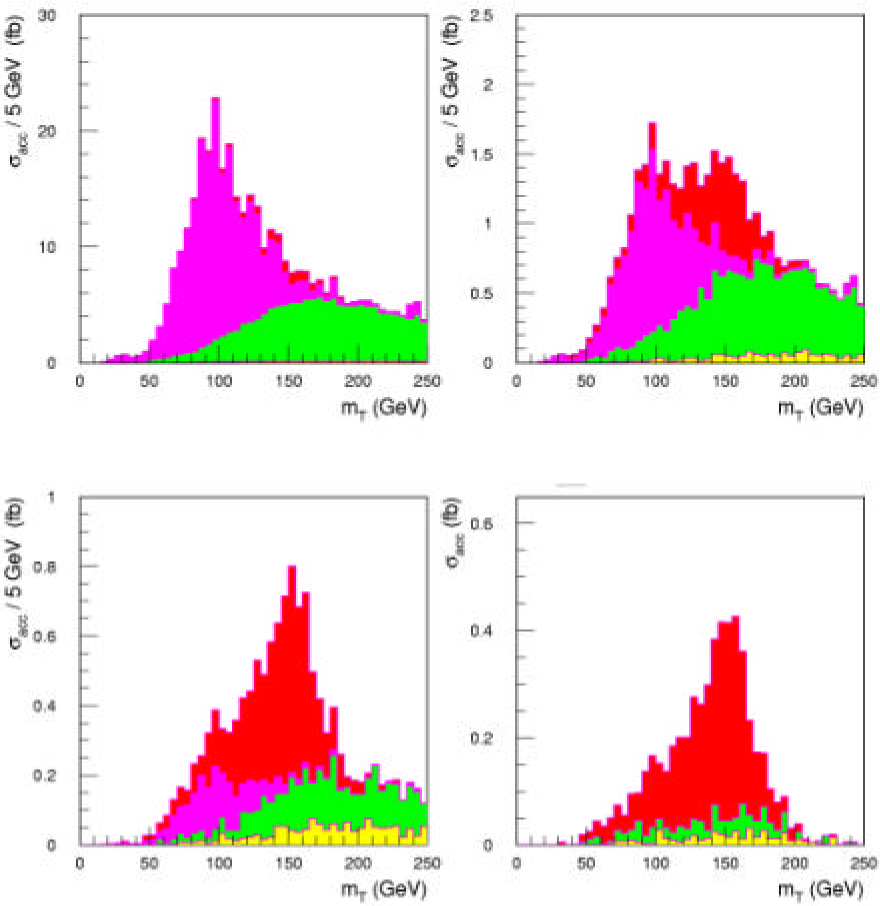
el.weak background:
WW jj production
Z + 2 jets
(matrix elements interfaced to PYTHIA)

Background rejection: qqH ® WW* ® l n l n

- Lepton P_T cuts and tag jet requirements ($\Delta\eta$, P_T)
- Require large mass of tag jet system, tau rejection
- Jet veto
- Lepton angular and mass cuts

$$M_T = \sqrt{(E_T^{ll} + E_T^{\nu\nu})^2 - (\vec{p}_T^{\,e\mu} + \vec{p}_T^{\,miss})^2}$$

qqH ® WW* ® l n l n



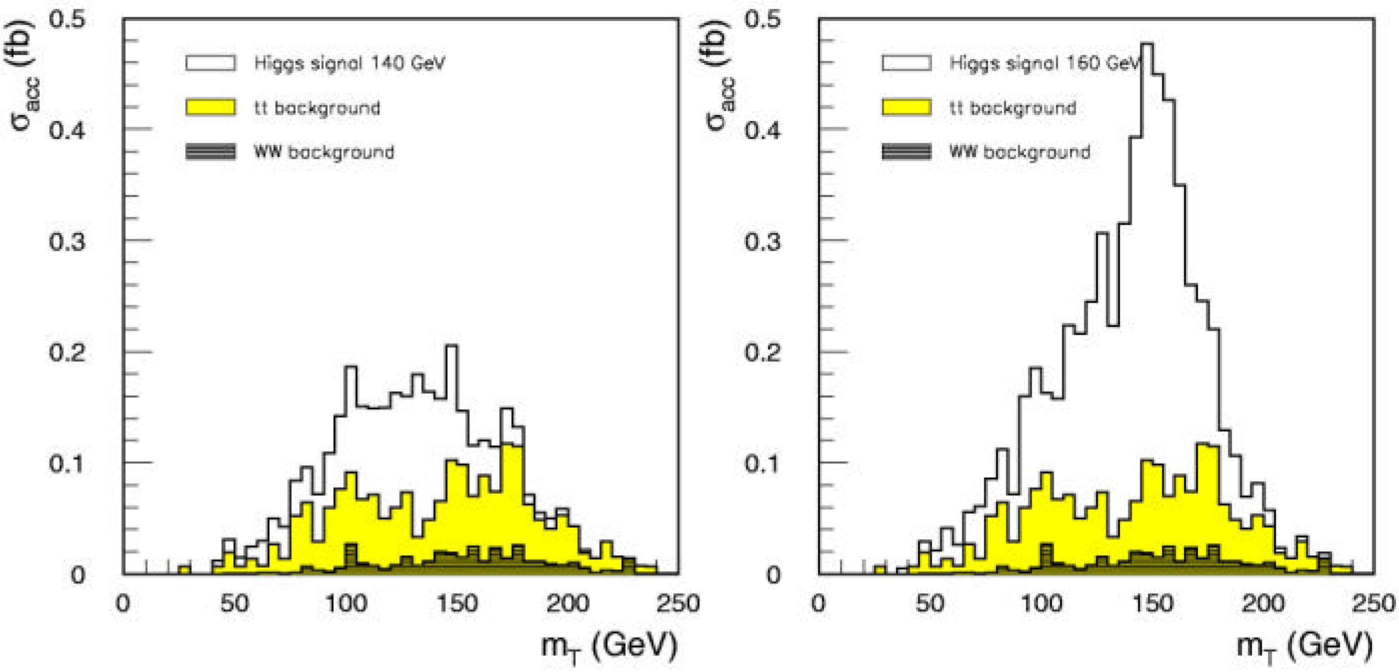
tt background

g* / Z + jets

el.weak WW jj

Higgs boson
m_H = 160 GeV

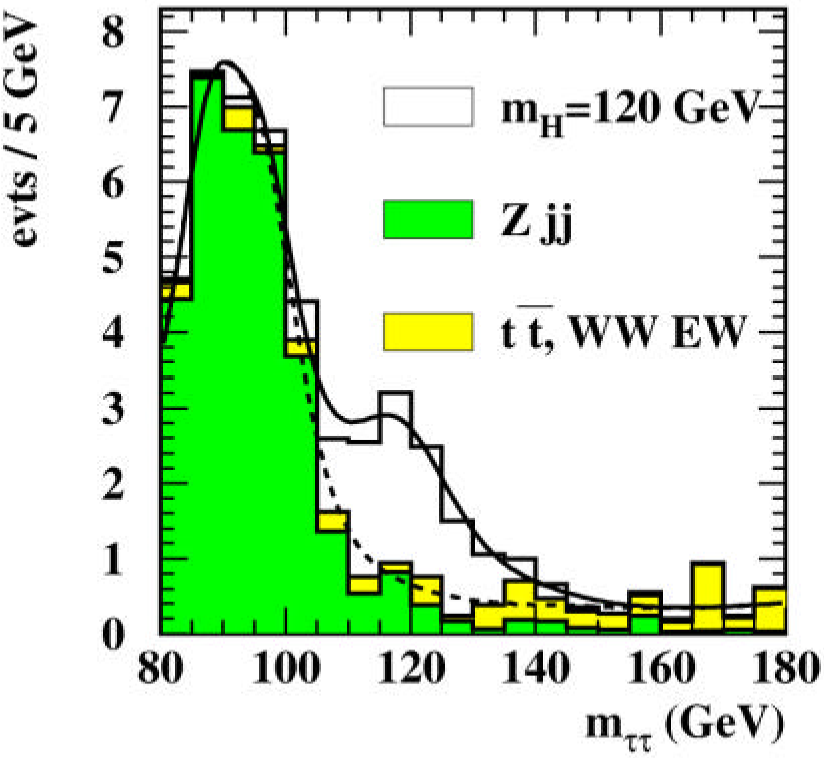
qq H ® qq WW* ® qq l n l n



Number of expected events and signal significance for 5 fb^{-1}

m_H (GeV)		130	140	150	160	170	180
$H \rightarrow WW^{(*)} \rightarrow e\mu + X$							
Signal	(5 fb^{-1})	4.7	8.3	13.3	21.6	21.7	18.1
Background	(5 fb^{-1})	3.1	3.8	4.3	5.5	6.2	6.9
Stat. significance	(5 fb^{-1})	2.1	3.3	4.7	6.5	6.3	5.2
$H \rightarrow WW^{(*)} \rightarrow ee/\mu\mu + X$							
Signal	(5 fb^{-1})	4.4	8.3	14.1	20.4	22.8	18.3
Background	(5 fb^{-1})	4.2	4.7	5.5	6.4	7.3	7.9
Stat. significance	(5 fb^{-1})	1.8	3.0	4.6	6.0	6.2	5.1

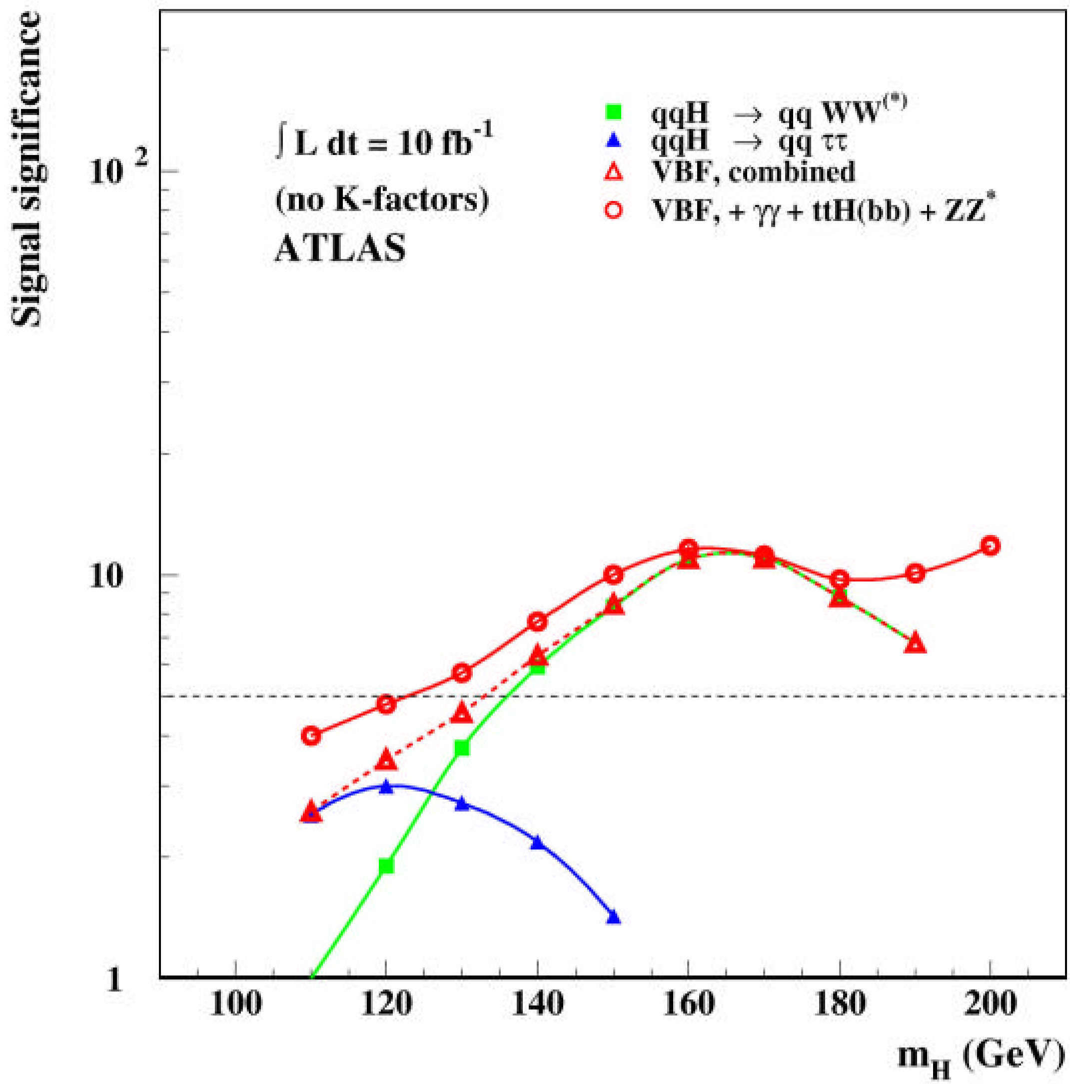
qq H ® qq t t



Number of expected events and signal significance for 30 fb^{-1} :

m_H (GeV)	110	120	130	140	150
$H \to \tau\tau \to e\mu P_T^{miss}$					
Signal	7.7	7.0	5.1	3.3	1.5
Background	10.1	3.7	3.3	2.7	2.2
Stat. significance	2.1	2.8	2.2	1.6	-
$H \to \tau\tau \to ee/\mu\mu P_T^{miss}$					
Signal	9.2	7.2	5.7	3.1	1.5
Background	15.4	7.6	5.6	4.6	3.4
Stat. significance	2.1	2.2	2.0	1.2	-
$H \to \tau\tau \to l\ had\ P_T^{miss}$					
Signal	19	15.6	13	10	5
Background	27.0	11.7	10.6	7.4	6.7
Stat. significance	3.3	3.8	3.4	3.0	1.6
combined					
Stat. significance	4.3	5.1	4.4	3.6	2.1

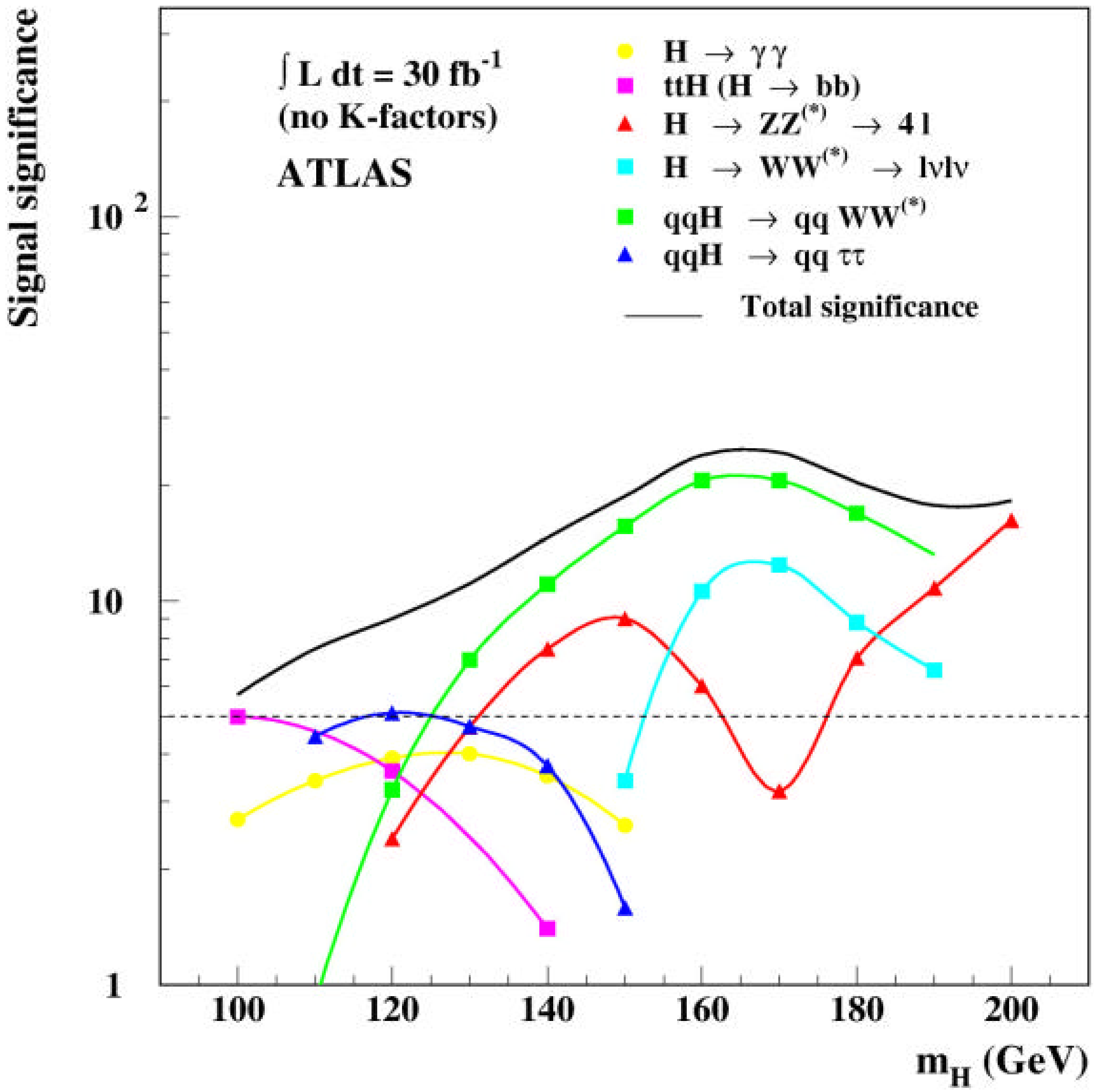
Combined significance of VBF channels for 10 fb^{-1}



- Vector boson fusion channels (in particular WW*) are discovery channels at low luminosity

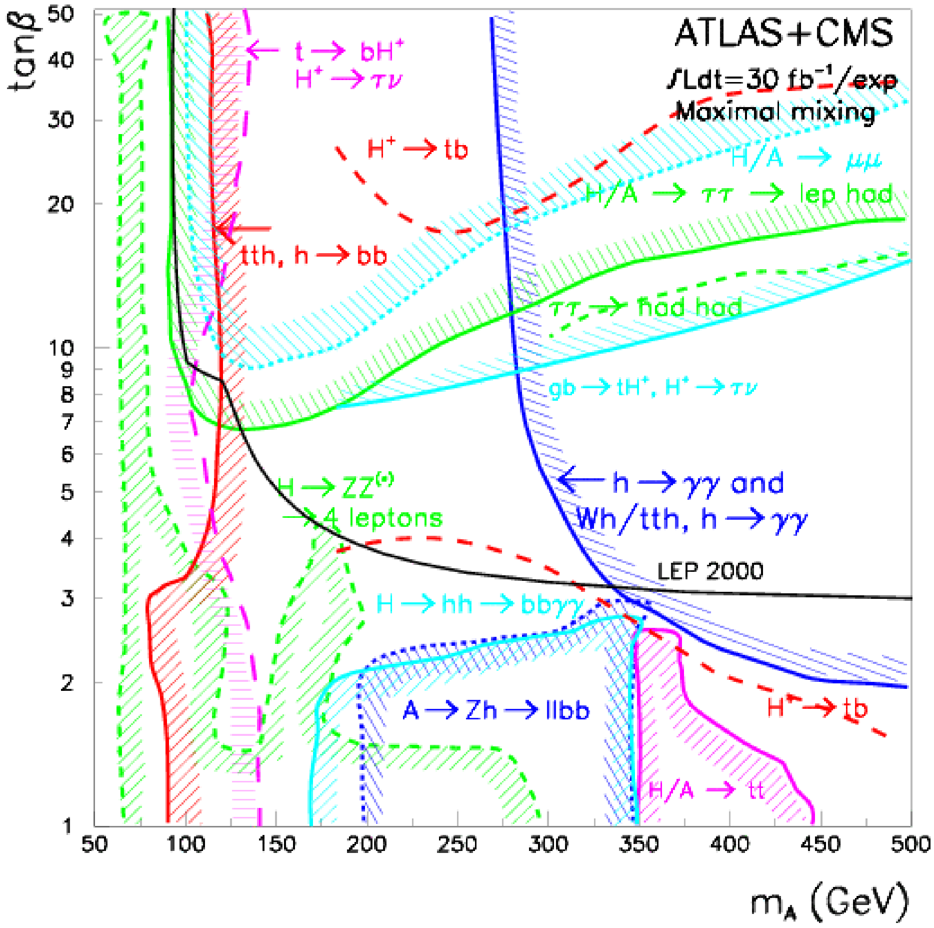
- For 10 fb^{-1} in ATLAS: 5 s significance for 120 £ m_H £ 190 GeV (after combination with the standard channels)

ATLAS Higgs discovery potential for 30 fb^{-1}



- Vector boson fusion channels improve the sensitivity significantly in the low mass region
- Several channels available over the full mass range

LHC discovery potential for MSSM Higgs bosons



Assuming SUSY particles are heavy

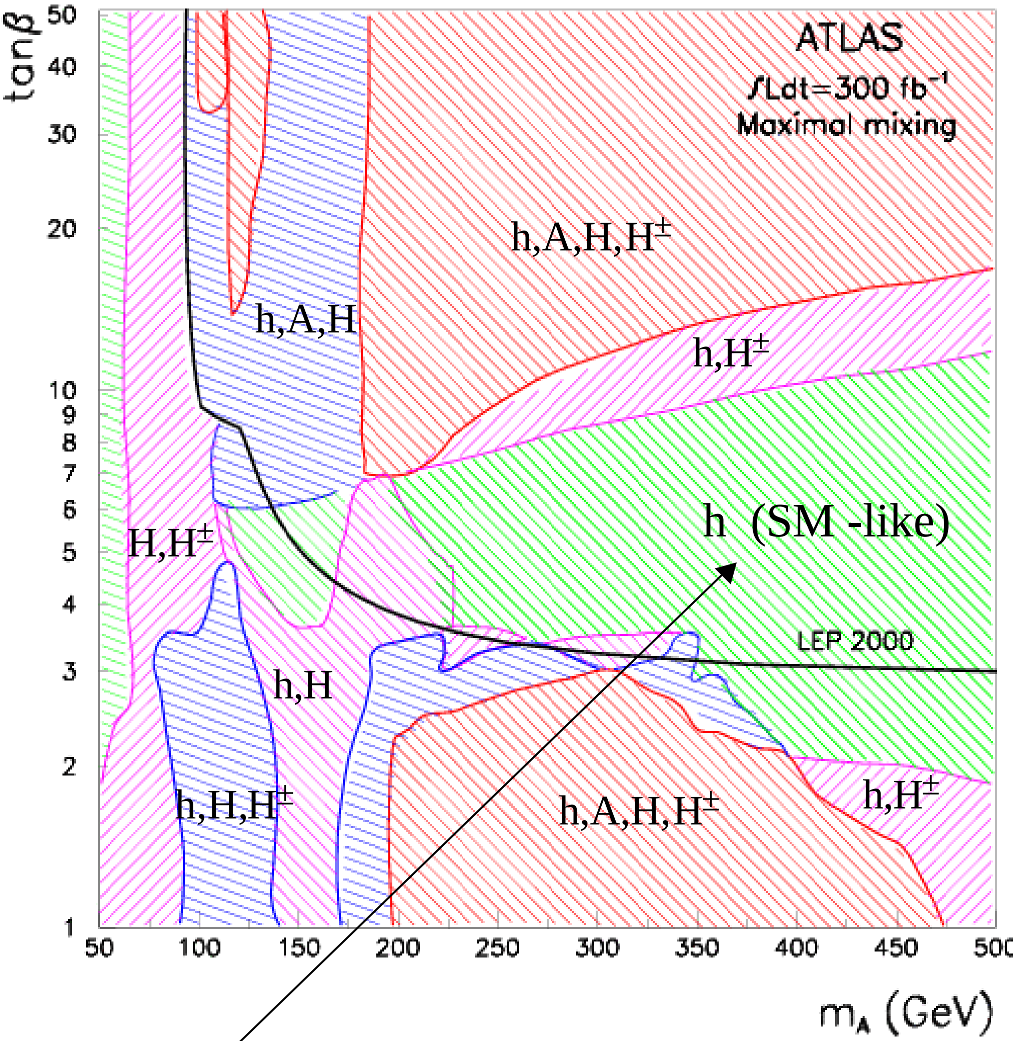
Not all channels shown

- Plane fully covered (no holes) at low L (30 fb^{-1})
- Main channels : $h \rightarrow gg$, $b\bar{b}$, A/H $\rightarrow mm$, tt , $H^{\pm} \rightarrow tn$
- Two or more Higgs can be observed over most of the parameter space $\rightarrow$ disentangle SM / MSSM

- If LEP excess due to hZ production (tanβ > 2, m_A>115GeV), LHC will observe:

h for any tan β and m_A

A,H,H$^{\pm}$ for large tan β and moderate m_A



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

5σ contours

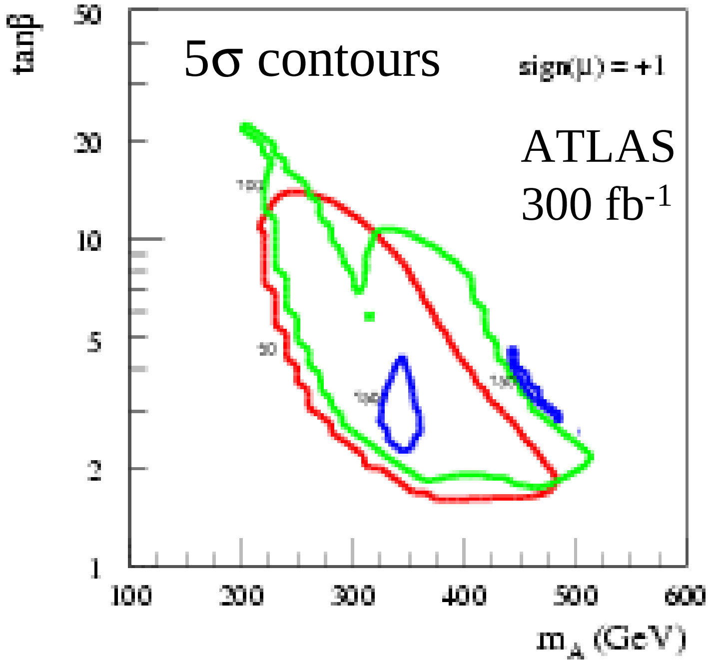
Assuming decays to SM particles only

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

Higgs decays via SUSY particles

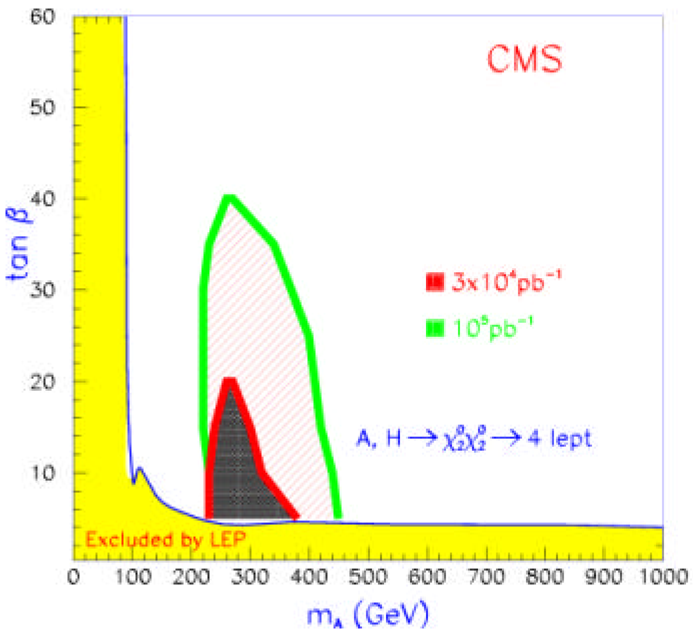
If SUSY exists : search for

$H/A \to \chi^0_2\chi^0_2 \to \ell\ell\chi^0_1\ \ell\ell\chi^0_1$



ATLAS:
SUGRA scan

m_0 = 50 - 250 GeV
$m_{1/2}$ = 100 - 300 GeV
$\tan\beta$ = 1.5 - 50
A_0 = 0

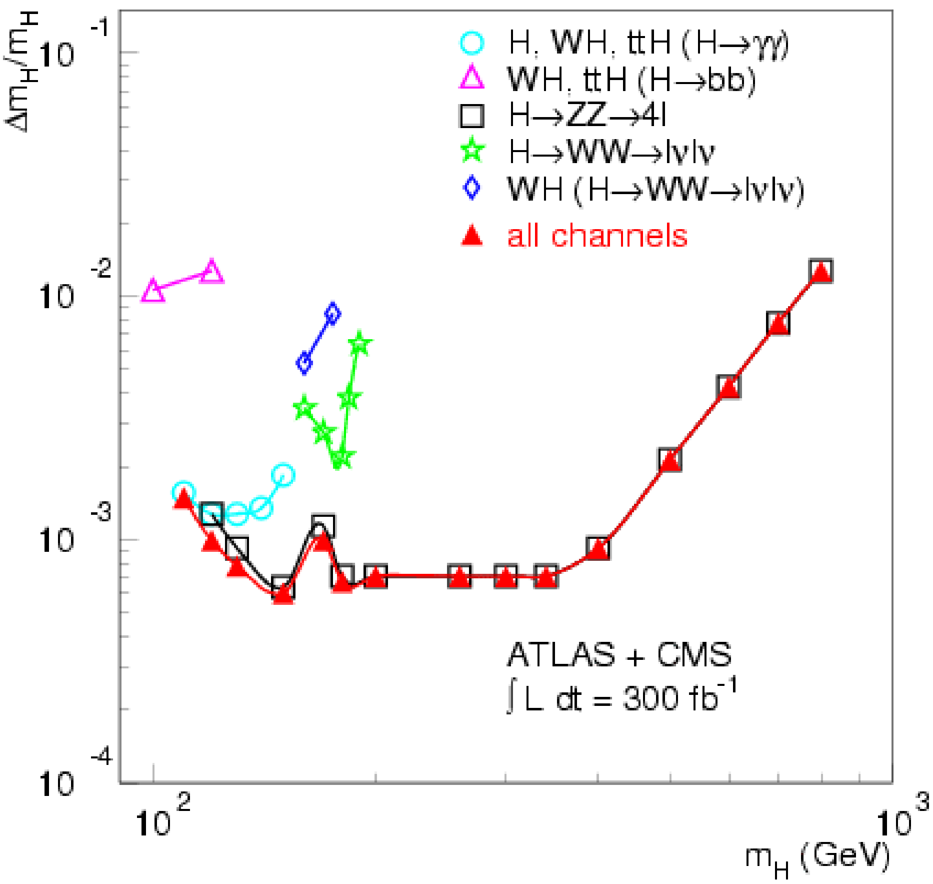


CMS:
special choice in MSSM (no scan)

M_1 = 60 GeV
M_2 = 110 GeV
μ = -500 GeV

Exclusions depend on MSSM parameters (slepton masses, μ)

Measurement of the Higgs boson mass



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 $Z \rightarrow \ell\ell$ (close to light Higgs)

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

300 fb^{-1}

Note: present theoretical error $\Delta m_h \sim 3$ GeV

Measurements of Higgs boson couplings

i) Ratio between W and Z partial widths

- **Direct measurements**

$$-\ \frac{\sigma \times \mathrm{BR}(H \to WW^*)}{\sigma \times \mathrm{BR}(H \to ZZ^*)} = \frac{\Gamma_g \Gamma_W}{\Gamma_g \Gamma_Z} = \frac{\Gamma_W}{\Gamma_Z}$$

  - QCD corrections cancel

- **Indirect measurements (via H ® gg)**

ii) Ratio of boson to fermion couplings

- Direct measurement

VBF: $$-\ \frac{\sigma \times \mathrm{BR}(qq \to qqH(H \to WW))}{\sigma \times \mathrm{BR}(qq \to qqH(H \to \tau\tau))} = \frac{\Gamma_W \Gamma_W}{\Gamma_W \Gamma_\tau} = \frac{\Gamma_W}{\Gamma_\tau}$$

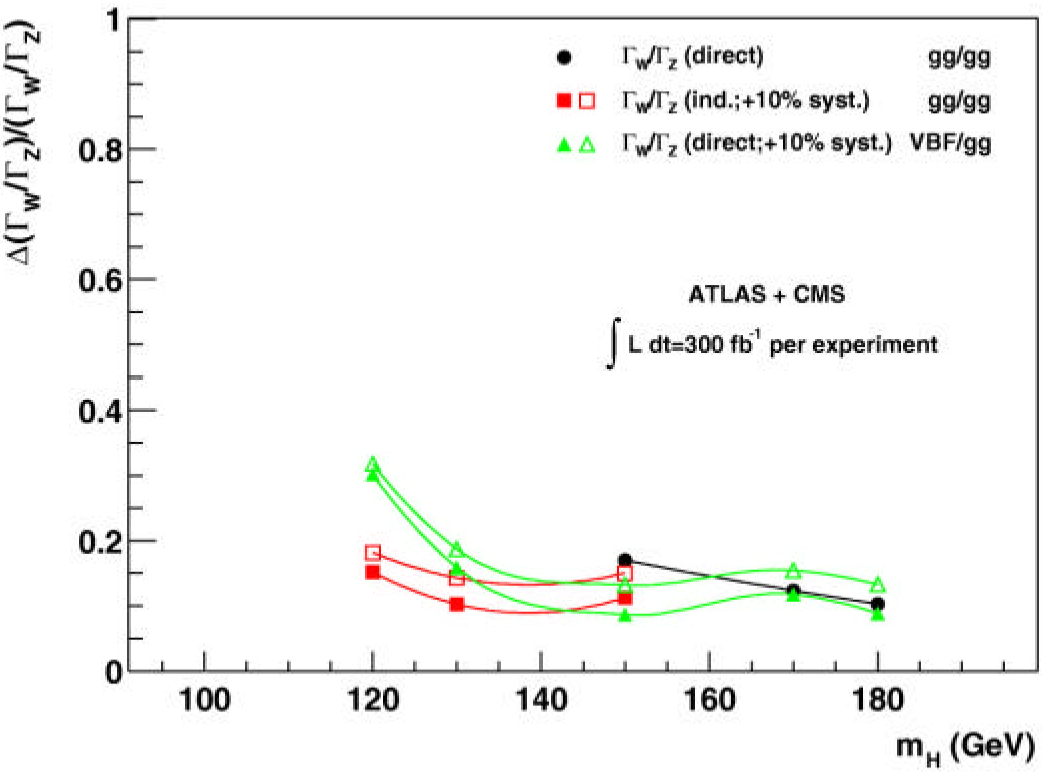
- Indirect measurement

$$-\ \frac{\sigma \times \mathrm{BR}(WH(H \to \gamma\gamma))}{\sigma \times \mathrm{BR}(H \to \gamma\gamma)} = \frac{\Gamma_W \Gamma_\gamma}{\Gamma_g \Gamma_\gamma} \sim \frac{\Gamma_W}{\Gamma_t} * C_{QCD}$$

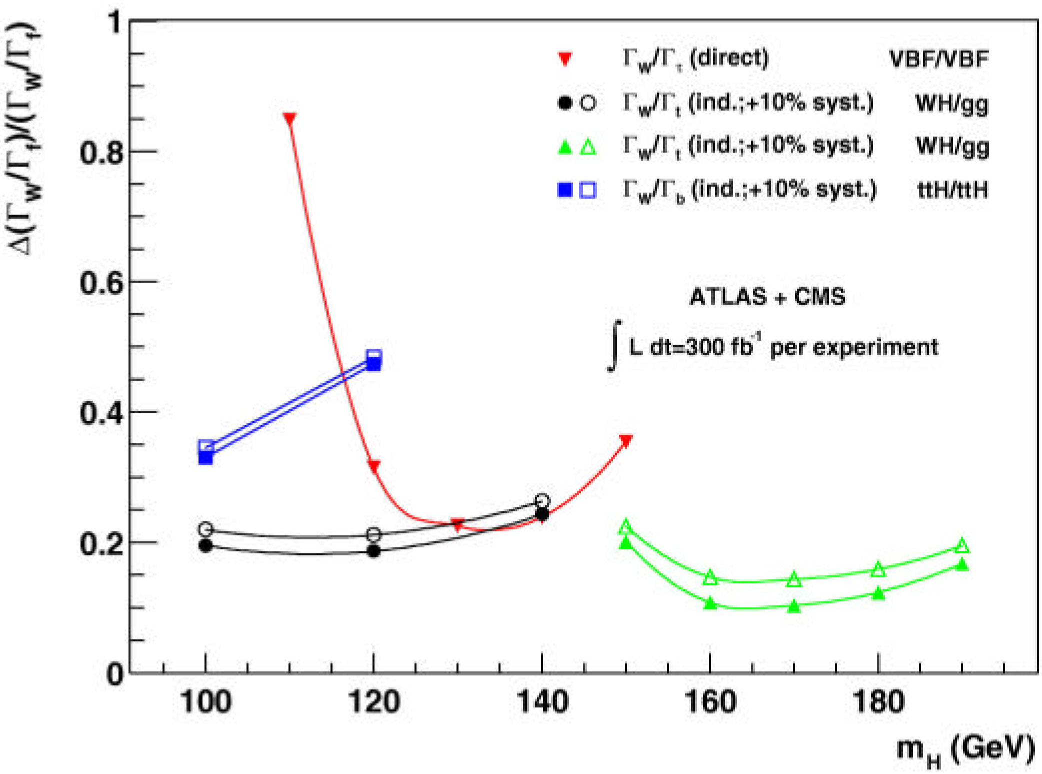
$$-\ \frac{\sigma \times \mathrm{BR}(WH(H \to WW))}{\sigma \times \mathrm{BR}(H \to WW^*)} = \frac{\Gamma_W \Gamma_W}{\Gamma_g \Gamma_W} \sim \frac{\Gamma_W}{\Gamma_t} * C_{QCD}$$

$$-\ \frac{\sigma \times \mathrm{BR}(ttH(H \to bb))}{\sigma \times \mathrm{BR}(ttH(H \to \gamma\gamma))} = \frac{\Gamma_t \Gamma_b}{\Gamma_t \Gamma_\gamma} \sim \frac{\Gamma_b}{\Gamma_W}$$

* Uncertainties on the ratio arising through different production processes are not included



$\Delta(\Gamma_W/\Gamma_Z)/(\Gamma_W/\Gamma_Z)$
Γ_W/Γ_Z (direct) gg/gg
Γ_W/Γ_Z (ind.;+10% syst.) gg/gg
Γ_W/Γ_Z (direct;+10% syst.) VBF/gg
ATLAS + CMS
$\int$ L dt=300 fb^{-1} per experiment
m_H (GeV)



$\Delta(\Gamma_W/\Gamma_f)/(\Gamma_W/\Gamma_f)$
Γ_W/Γ_τ (direct) VBF/VBF
Γ_W/Γ_t (ind.;+10% syst.) WH/gg
Γ_W/Γ_t (ind.;+10% syst.) WH/gg
Γ_W/Γ_b (ind.;+10% syst.) ttH/ttH
ATLAS + CMS
$\int$ L dt=300 fb^{-1} per experiment
m_H (GeV)

W-mass measurement

Physics motivation:

Test of the Standard Model: m_Z, m_W, m_{top} $\Rightarrow$ m_H

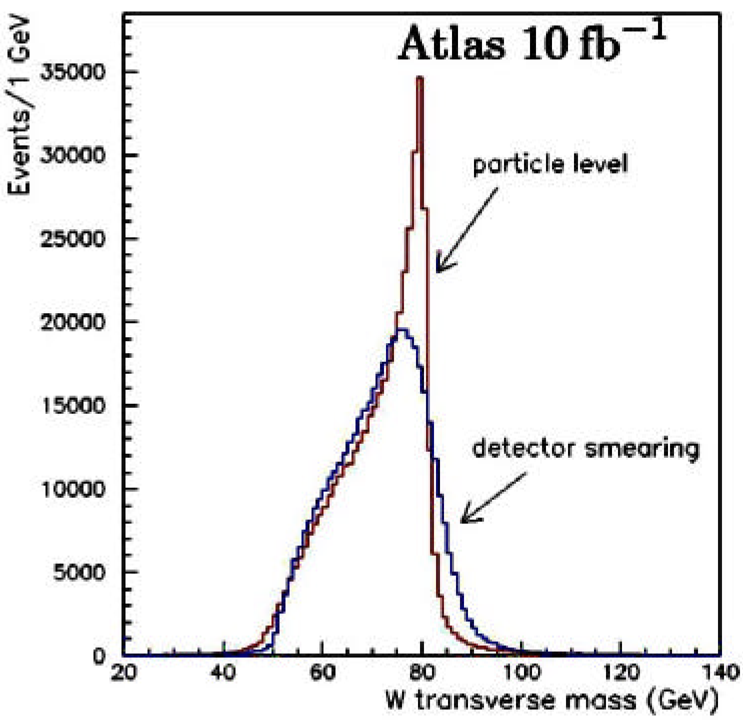
Year 2007: Δm_W < 30 MeV (LEP2 + Tevatron)

LHC goal: Δm_W ~15 MeV to match the precision on the top quark mass measurement

Experimental numbers:

- L dt = 10 fb-1: 60 Mio. well measured W $\rightarrow \ell \nu$ decays
- Background conditions from pile-up events at low luminosity (2 events / bunch crossing) similar to Tevatron today
- Standard transverse mass technique can be used:

$$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^n \cdot \left(1 - \cos \Delta f^{l,n}\right)}$$



Estimate of D m_W

Source of syst.	CDF Run 1b	ATLAS	Comments
Lepton scale	75 MeV	15 MeV	<40MeV at Run II
Lepton resolution	25 MeV	5 MeV	Known to <1.5%
$P_T(W)$	15 MeV	5 MeV	Constrain with $P_T(Z)$
Recoil model	37 MeV	5 MeV	Constrain with Z data
W width	10 MeV	7 MeV	
PDFs	15 MeV	< 10 MeV	Constraints from the LHC
Radiative decays	20 MeV	< 10 MeV	Theor. calculations
Total	92 MeV	< 25 MeV	per lepton species

- Total error per lepton species and per experiment is estimated to be ± 25 MeV
- Main uncertainty: lepton energy scale (goal is an uncertainty of ± 0.02 %)
- Many systematic uncertaincies can be controlled in situ, using the $Z \rightarrow \ell\ell$ sample ($P_T(W)$, recoil model, resolution)

Combining both experiments (ATLAS + CMS), both lepton species and assuming a scale uncertainty of ± 0.02%

Þ D m_W ~ ± 15 MeV

Measurement of the Top Quark Mass

Year 2007: Δm_{top} ~ 2-3 GeV (Tevatron)

Best channel for mass measurement:

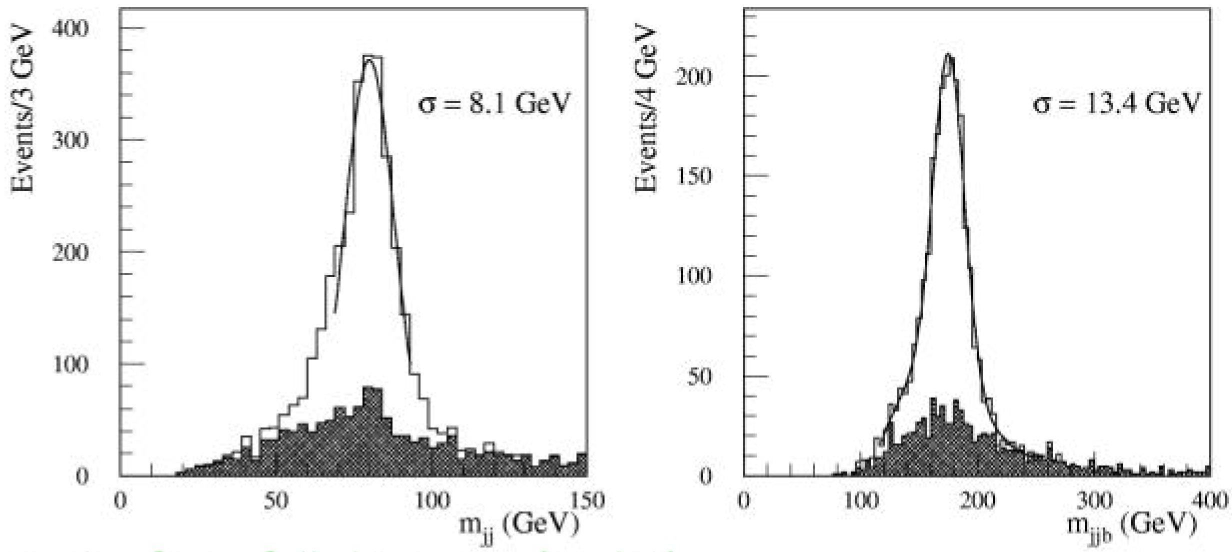
$tt \rightarrow Wb \quad Wb \rightarrow \ell \nu b \quad$ jet jet b

(trigger) (mass measurement)

Experimental numbers:

• Production cross section: 590 pb

• After exp. cuts: 130.000 tt events in 10 fb^{-1} S/B ~ 65



results from full detector simulation

Contribution	Δm_{top} (GeV)
statistics	< 0.07
u,d,s jet scale	0.3
b-jet scale	0.7
b-fragmentation	0.3
initial state rad.	0.3
final state rad.	1.2
background	0.2
Total	~ 1.5 GeV

Syst. uncertainties dominated by final state radiation

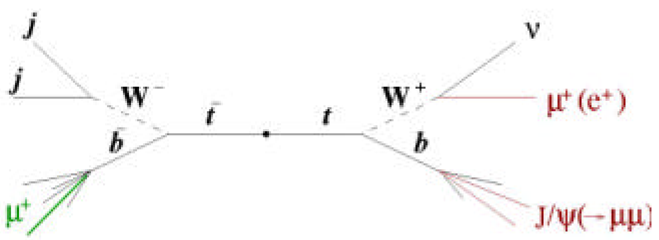
Additional Methods

- Full reconstruction applying kinematical constraints

$m_{jj} = m_{\ell\nu} = m_W$ and $m_{jjb} = m_{\ell\nu b}$

Precision of **$\sim \pm$ 1 GeV** can be reached

- Using ℓ-J/ψ final states:



Reconstruct $m_{\ell\text{-}J/\Psi}$

- BR = 10^{-5}: low rate, but clean signature
- Statistical error: ±0.9 GeV (for 500 fb^{-1})
- Different systematic uncertainties (dominated by b-fragmentation: ~ 0.4 GeV)

combination of various methods:

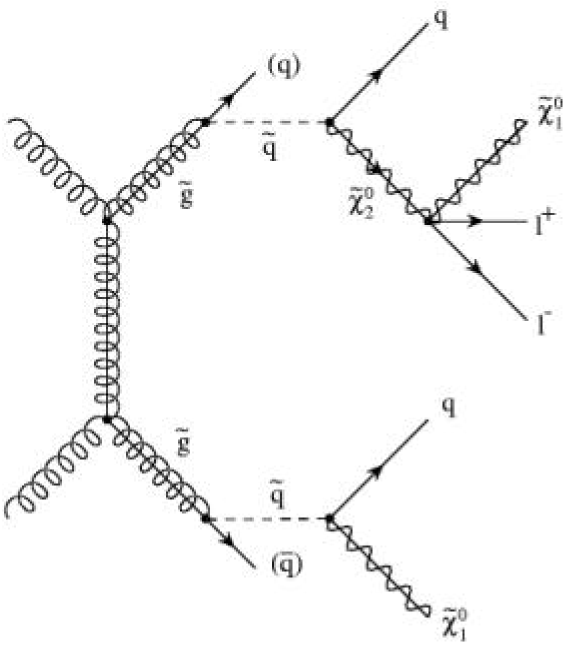
D $\mathbf{m_{top}}$ < **$\sim \pm$ 1 GeV**

Search for Supersymmetry

- If SUSY exists at the electroweak scale, a discovery at the LHC should be easy

- Squarks and Gluinos are strongly produced

  They decay through cascades to the lightest SUSY particle (LSP)



$\Rightarrow$ combination of

Jets, Leptons, E_T^{miss}

1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

2. Step: Establish the SUSY mass scale
   use inclusive variables, e.g. effective mass distribution

3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use
   kinematics to determine mass combinations

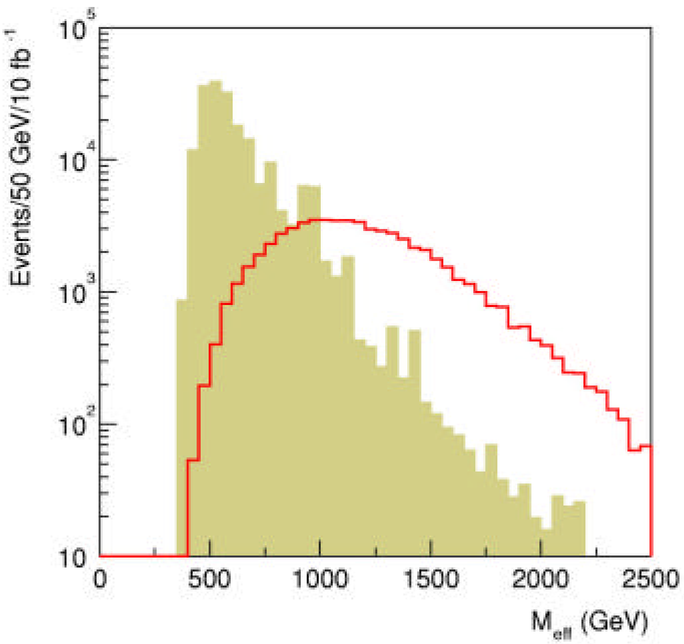
Squarks and Gluinos

• strongly produced, cross sections comparable to QCD cross sections at same Q^2

• If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and E_T^{miss}

• Typical selection: $N_{jet} > 4$, $E_T > 100, 50, 50, 50$ GeV
$E_T^{miss} > 100$ GeV

• Define: $$M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$$
(effective mass)



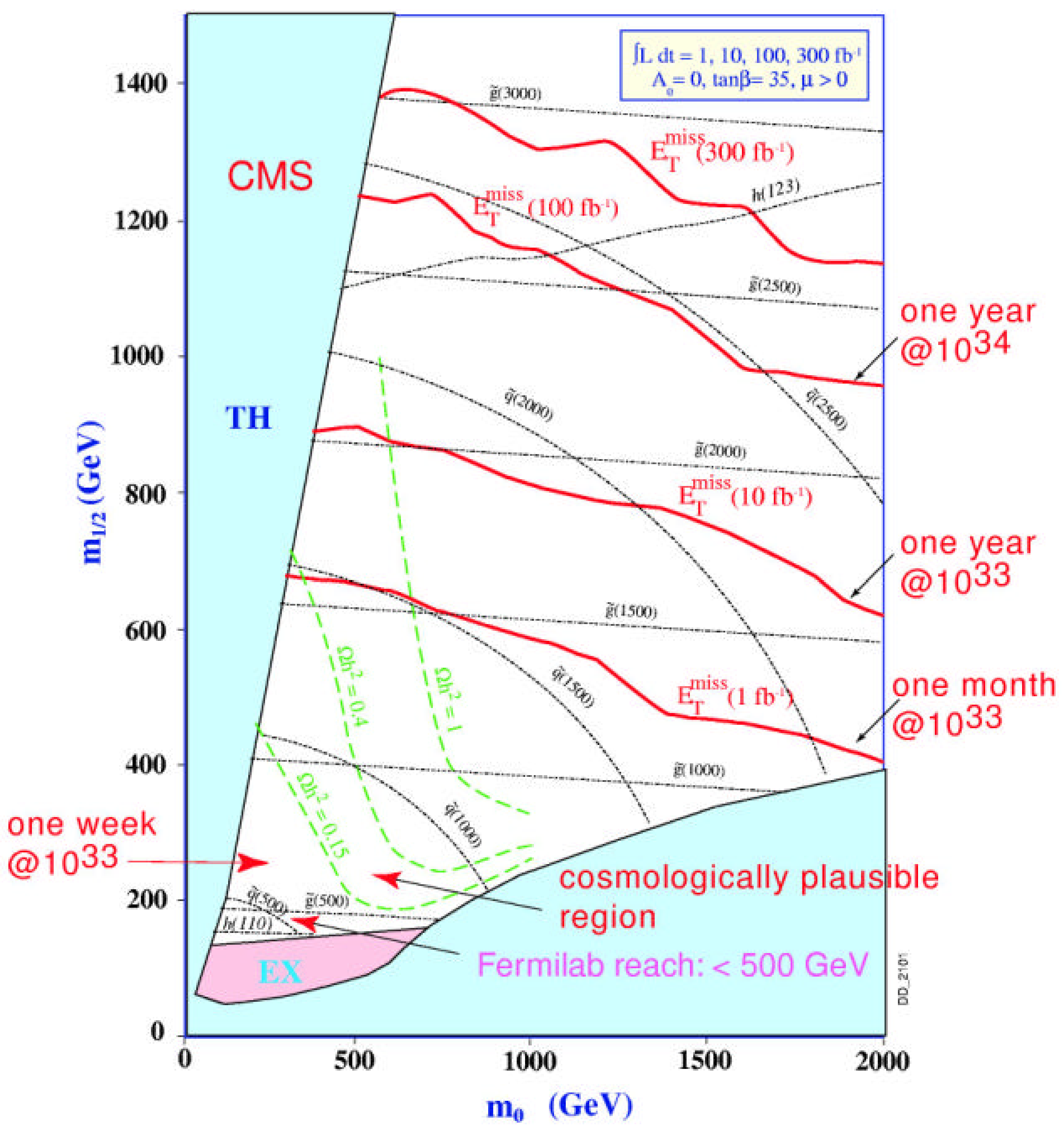
example: mSUGRA
m_0 = 100 GeV
$m_{1/2}$ = 300 GeV
tan β = 10
$A_0 = 0$, $\mu > 0$

• LHC reach for Squark- and Gluino masses:

1 fb^{-1}	$\Rightarrow$	M ~ 1500 GeV
10 fb^{-1}	$\Rightarrow$	M ~ 1900 GeV
100 fb^{-1}	$\Rightarrow$	M ~ 2500 GeV

TeV-scale SUSY can be found quickly !

LHC reach in m_0 - $m_{1/2}$ mSUGRA plane:

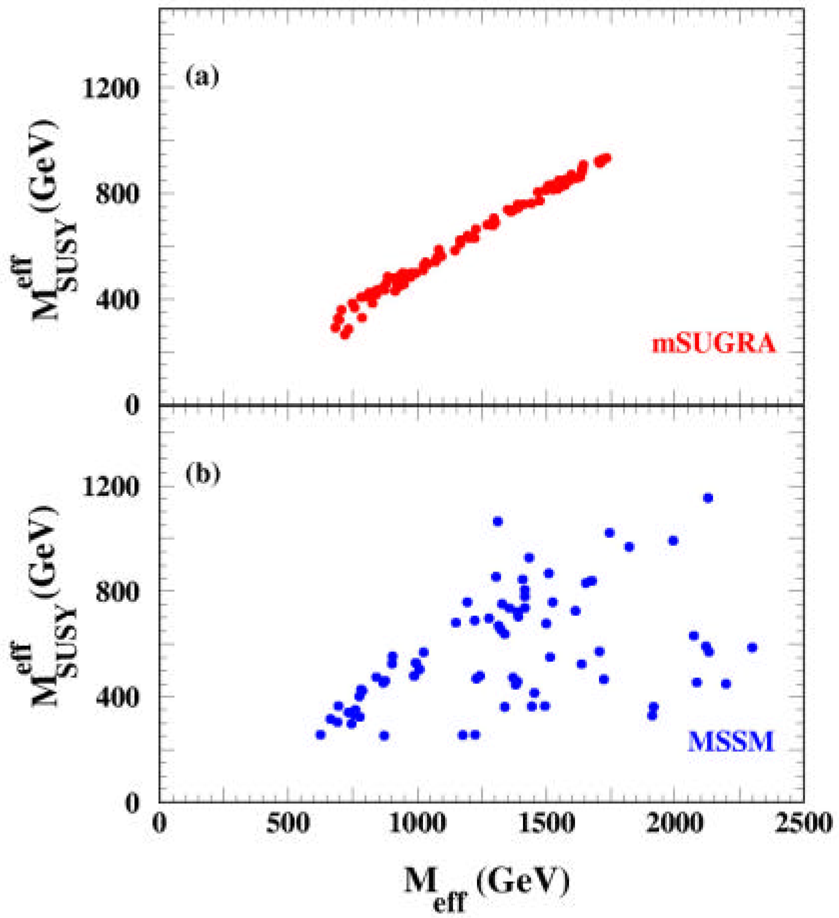


SUSY mass scale

• define average produced SUSY mass

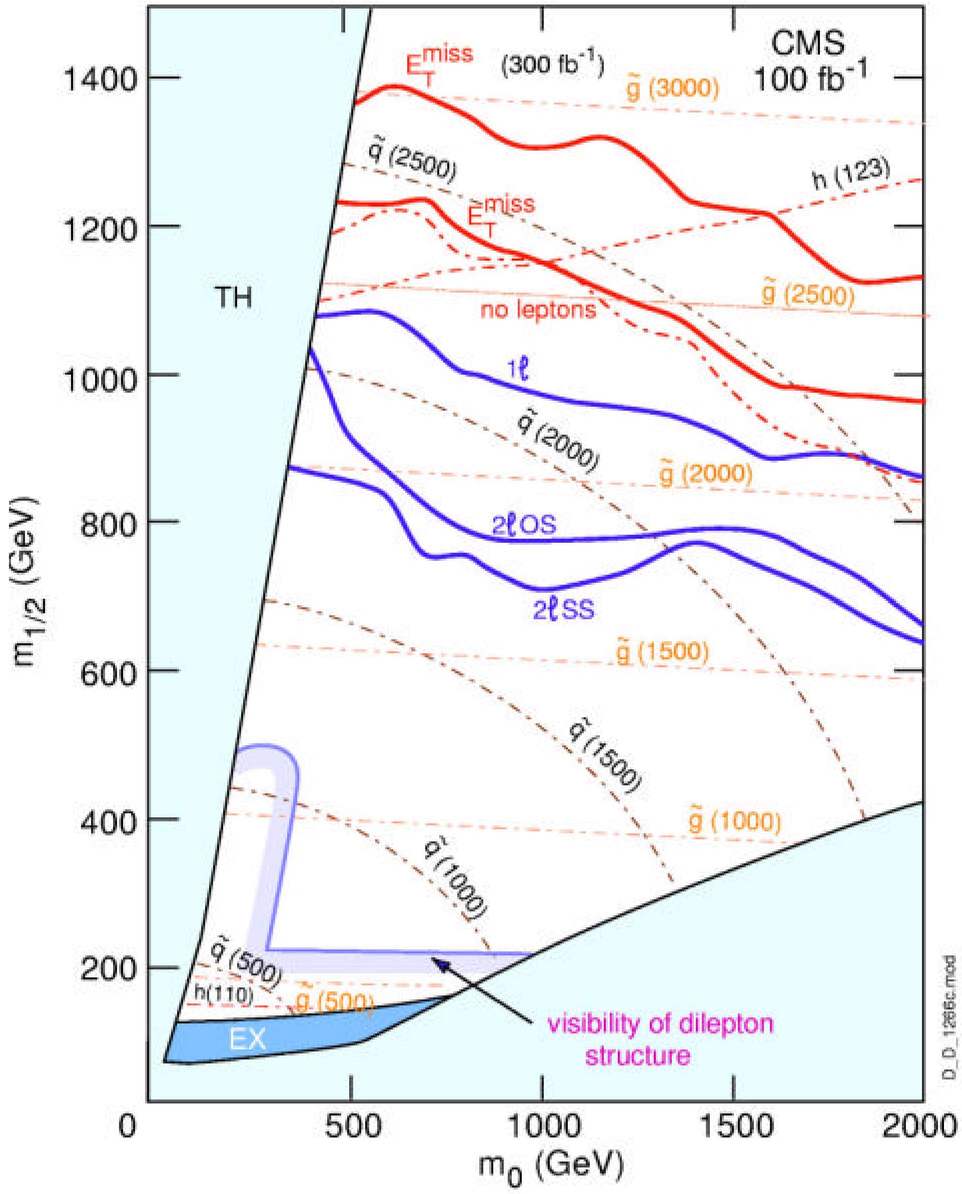
$$M_{\rm SUSY} \equiv \frac{\sum_i M_i \sigma_i}{\sum_i \sigma_i}$$

$$M_{\rm SUSY}^{\rm eff} \equiv M_{\rm SUSY} - \frac{M^2(\tilde{\chi}_1^0)}{M_{\rm SUSY}}$$



• Good correlation with $M_{\rm eff}$ for mSUGRA
• Not bad even for MSSM (Tovey, ATLAS)

SUSY cascade decays give rise to many inclusive signatures: leptons, b-jets, τ ‘s



Expect multiple signatures for TeV-scale SUSY

Determination of model parameters

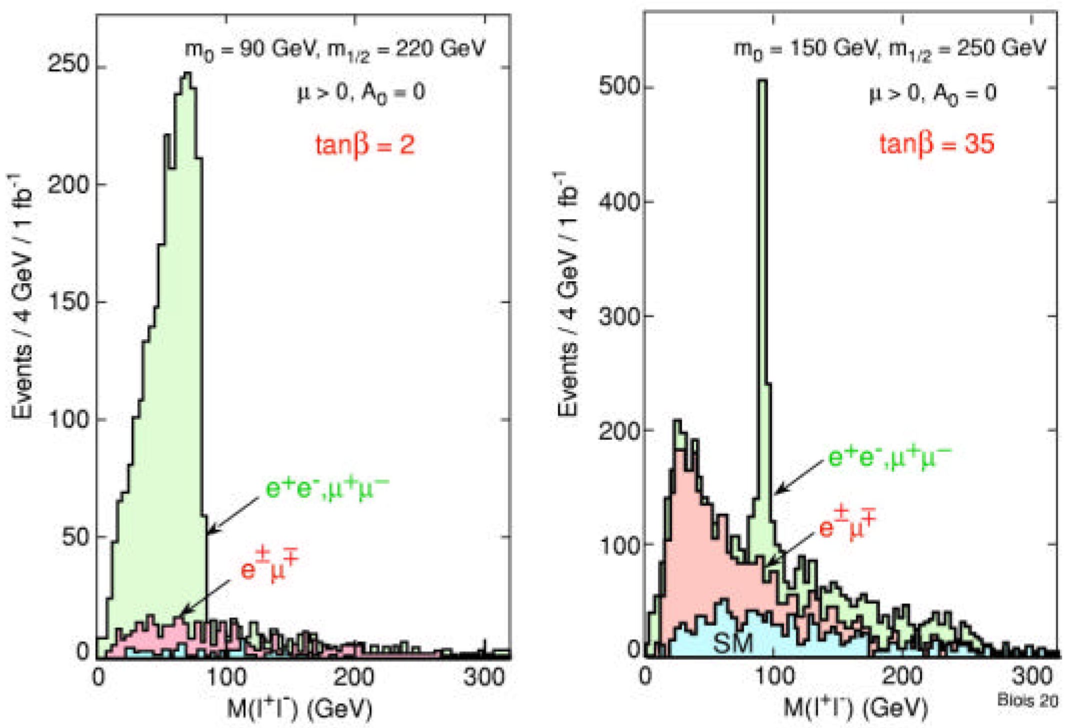
- Invisible LSP $\Rightarrow$ no mass peaks,
  but kinematic endpoints
  $\Rightarrow$ mass combinations

- Simplest case: $\chi^0_2 \rightarrow \chi^0_1\ \ell^+\ \ell^-$

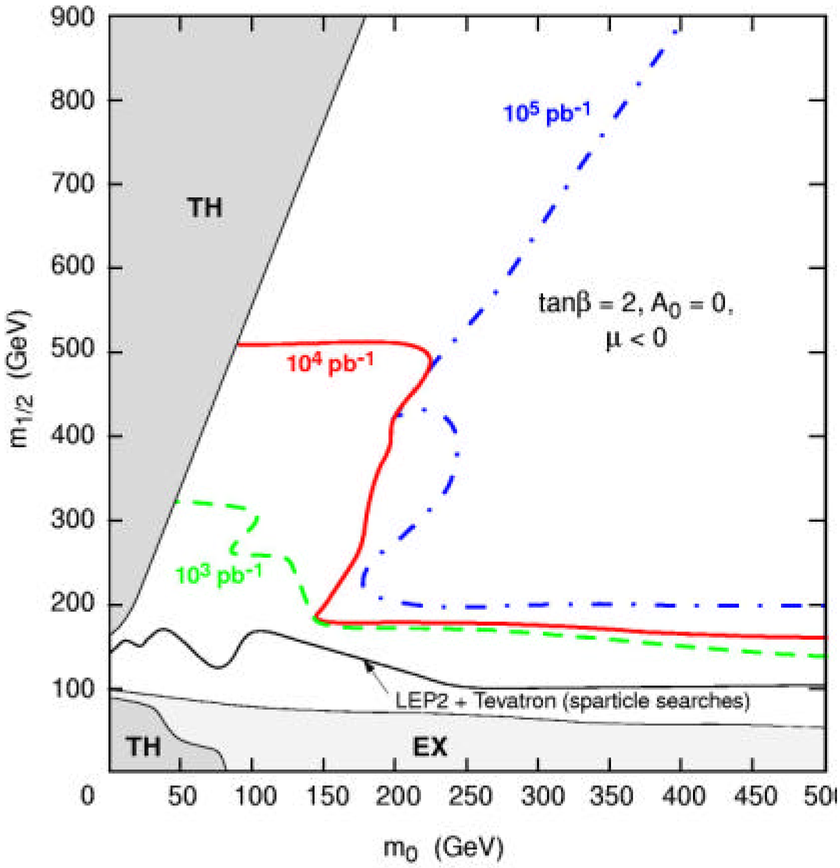
  endpoint: $M_{\ell\ell} = M(\chi^0_2) - M(\chi^0_1)$

- Significant mode if no $\chi^0_2 \rightarrow \chi^0_1 Z$, $\chi^0_1 h$, $\tilde{\ell}\ \ell$ decays

- Require: 2 isolated leptons, multiple jets, and large E_T^{miss}



- Modes can be distinguished using shape of $\ell\ell$-spectrum

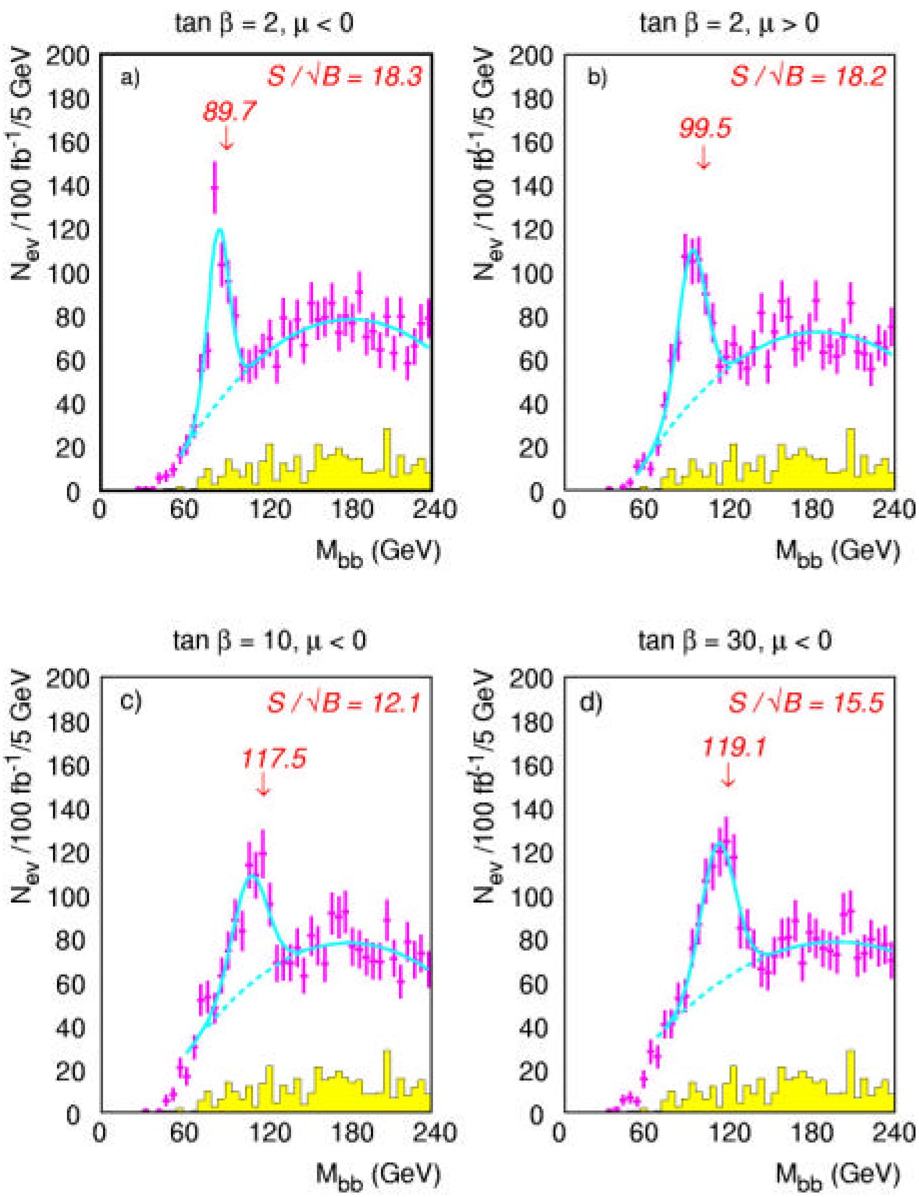


$\ell\ell$ - endpoint can be observed over a significant fraction of the parameter space

(covers part of the SUGRA region favoured by cold dark matter (Ellis et al.))

h ® bb: important if $\chi^0_2 \rightarrow \chi^0_1 h$ is open;

bb peak can be reconstructed in many cases



Could be a Higgs discovery mode !

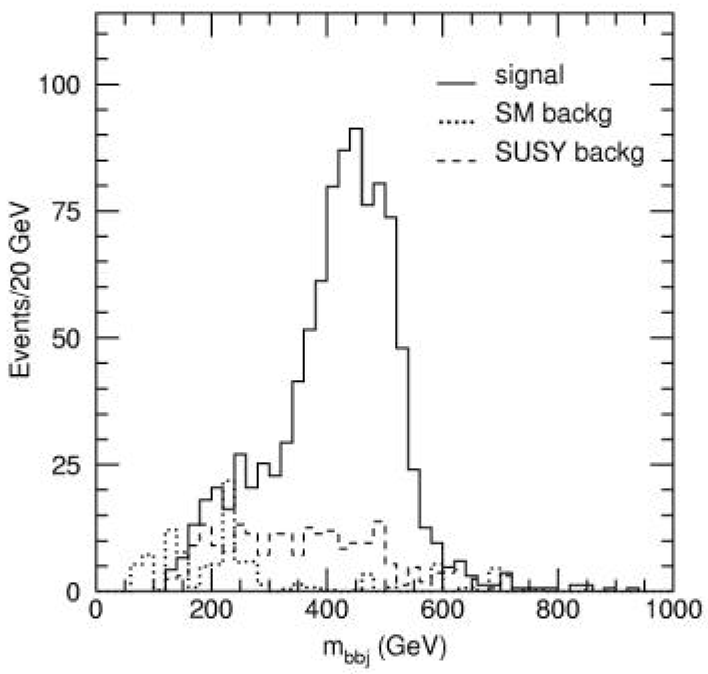
SM background can be reduced by applying a cut on E_t^{miss}

work backwards the decay chain:
example: SUGRA study point 5

$pp \to \tilde{q}_L \tilde{q}_R$: $\tilde{q}_R \to \tilde{\chi}_1^0 q$

$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\chi}_1^0 h q \to \tilde{\chi}_1^0 b\bar{b} q$

combine h → bb with jets to determine other masses



$\tilde{q} \to \tilde{\chi}_1^0 h q$ endpoint

Strategy in SUSY Searches at the LHC:

- Search for multijet + E_T^{miss} excess
- If found, select SUSY sample (simple cuts)
- Look for special features (γ's , long lived sleptons)
- Look for $\ell^\pm$, $\ell^+ \ell^-$, $\ell^\pm \ell^\pm$, b-jets, τ's
- End point analyses, global fit

Models other than SUGRA

GMSB:

- LSP is light gravitino
- Phenomenology depends on nature and lifetime of the NLSP
- Generally longer decay chains, e.g.

$$\tilde{\chi}_2^0 \to \tilde{\ell}^\pm \ell^\mp \to \tilde{\chi}_1^0 \ell^+ \ell^- \to \tilde{G} \gamma \ell^+ \ell^-$$

- $\Rightarrow$ models with prompt NLSP decays give add. handles and hence are easier than SUGRA

- NLSP lifetime can be measured:

  - For $\tilde{\chi}_1^0 \to \tilde{G}\gamma$, use Dalitz decays (short lifetime) or search for non-pointing photons
  - Quasi stable sleptons: muon system provides excellent „Time of Flight“ system

RPV :

- R-violation via $\chi^0{}_1 \to \ell\ell\nu$ or $qq\ell$, $qq\nu$ gives additional leptons and/or E_T^{miss}

- R-violation via $\chi^0{}_1 \to$ cds is probably the hardest case; (c-tagging, uncertaities on QCD N-jet background)

Beyond SUSY, a few examples

Excited quarks: $q^* \to q\gamma$, up to: $m \sim$6 TeV

Leptoquarks, up to: $m \sim$1.5 TeV

Monopoles: $pp \to \gamma\gamma pp$, up to: $m \sim$20 TeV

Lepton flavour viol. $\tau \to \mu\gamma$: $10^{-6} - 10^{-7}$

Compositeness, up to: $\Lambda \sim$ 40 TeV

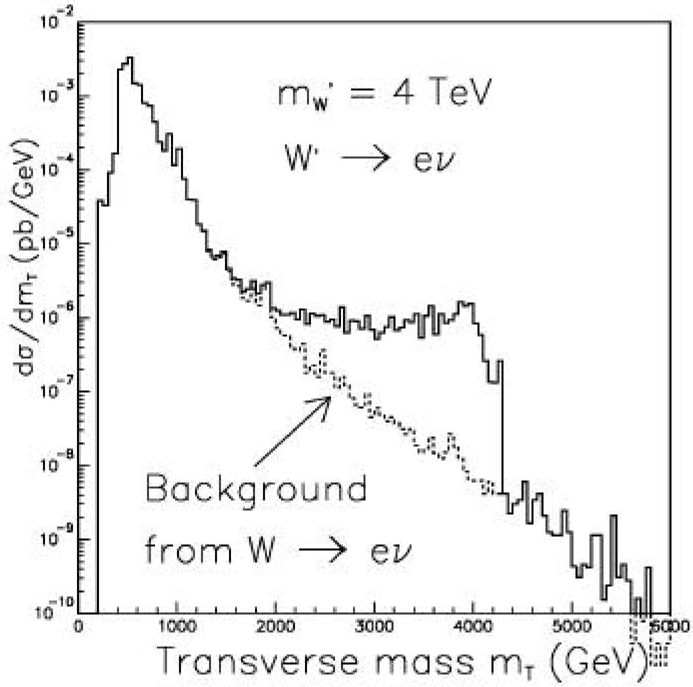
from di-jet and Drell-Yan,

needs calorimeter linearity better than 2%

$Z' \to ll, jj$, up to: $m \sim$5 TeV

$W' \to l\nu$, up to: $m \sim$6 TeV

$$\int \mathcal{L}dt = 100\ fb^{-1}$$



Search for Signals from Extra Dimensions

- Much recent theoretical interest in models with extra dimensions
- New physics can appear at the TeV-mass scale, i.e. accessible at the LHC
- Gravitons propagating in the extra dimensions will appear as massive states

Examples of searches:

(1) Search for direct graviton production

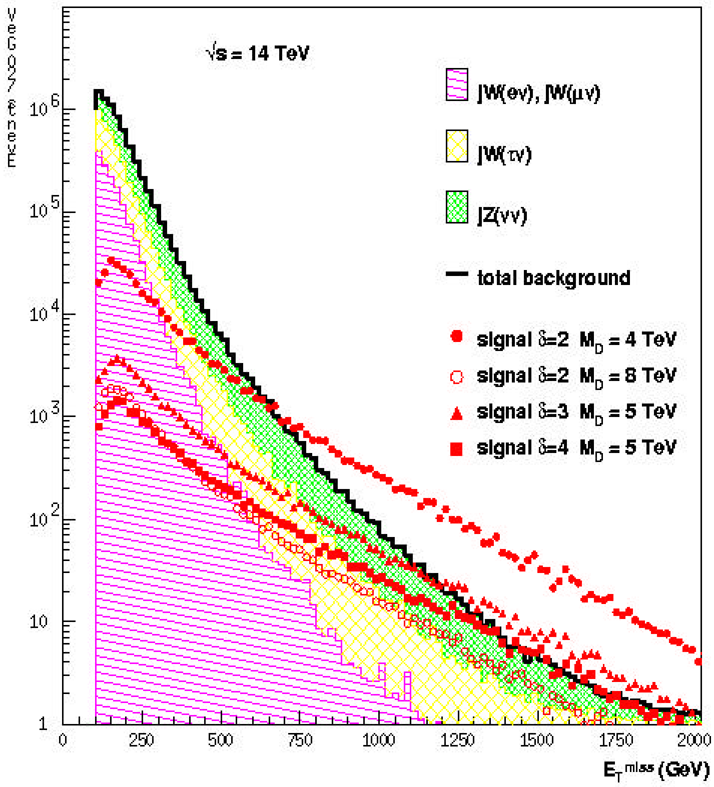
gg ® gG, qg ® qG, $q\bar{q}$ ® Gg

$q\bar{q}$ ® Gg

⇒ Jets or Photons with E_T^{miss}

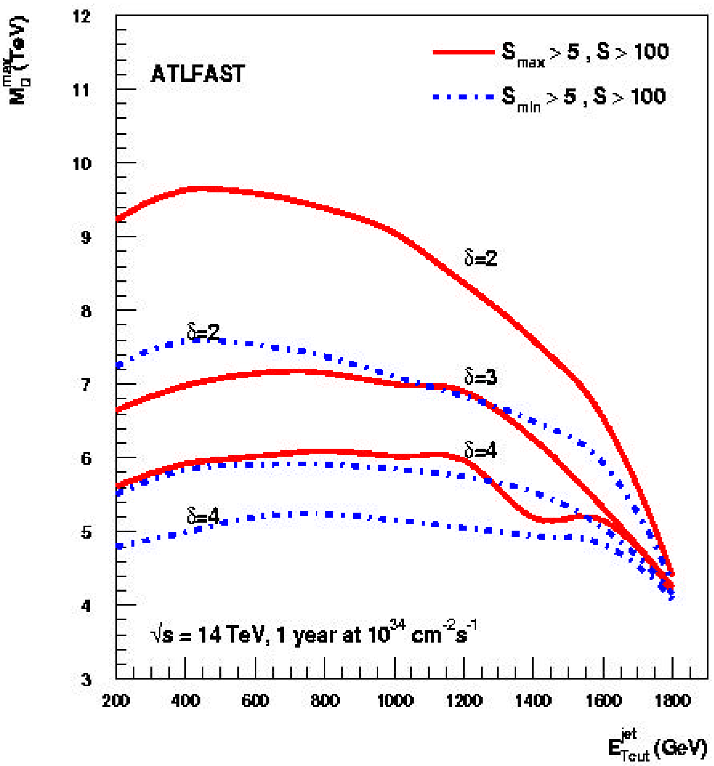
(2) Search for graviton resonances
(Randall Sundrum models)

Search for Graviton Production



Jet + E_T^{miss} search:

Main backgrounds:
jet+Z(→νν), jet+W→jet+(e,μ,τ)ν



$$G_N^{-1} = 8\pi R^{\delta} M_D^{2+\delta}$$

δ : # extra dimensions
M_D = scale of gravity

for 100 fb^{-1}:

M_D^{max} = 9.1, 7.0, 6.0 for
δ = 2 3 4

(γ + E_T^{miss} search is less sensitive)

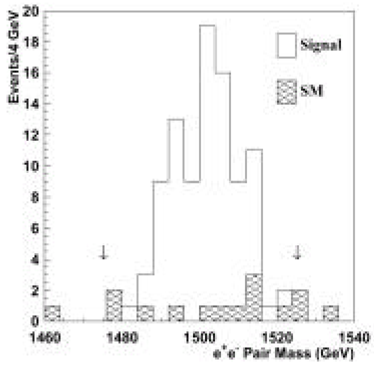
Search for Narrow Graviton Resonances

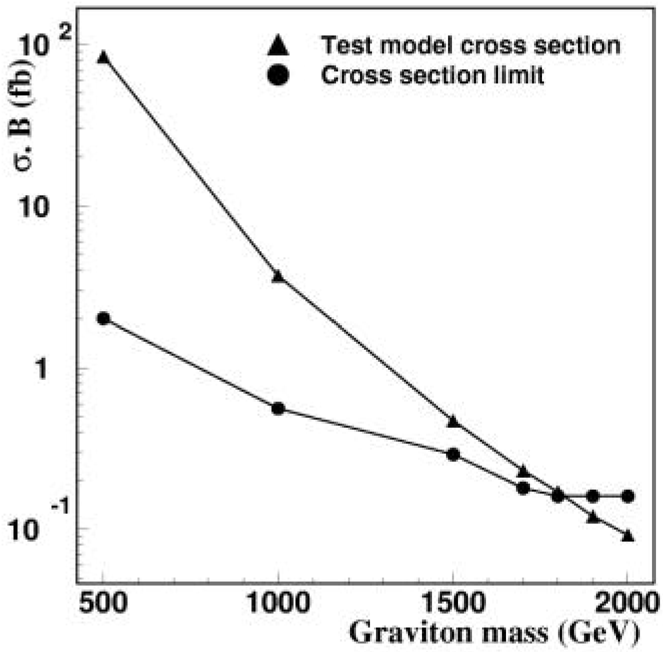
- use Randall Sundrum model as reference model:
- Kaluza-Klein graviton spectrum with a scale

  $\Lambda_\pi = M_{Planck} \exp(-k\pi r_c)$
- Properties of the model are determined by the ratio k/M_{Planck}

Atlas and CMS studies on sensitivity to narrow resonance states decaying into lepton pairs:

$gg\ (qq) \rightarrow G \rightarrow e^+e^-$



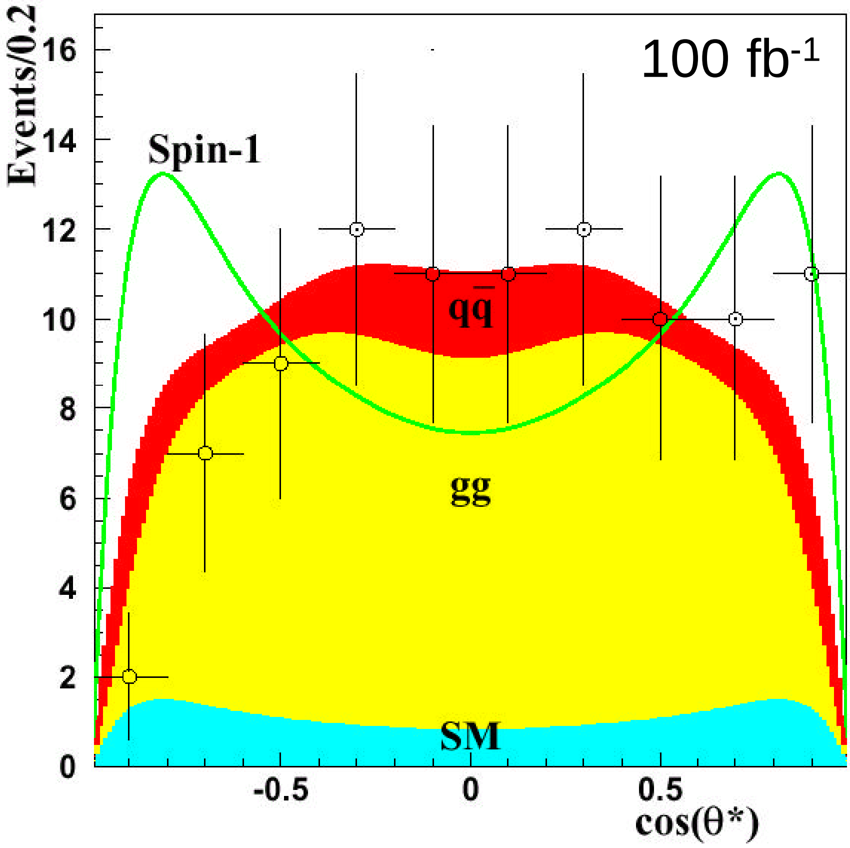


For $k / M_{Planck} = 0.01$ (conservative choice)

With 100 fb^{-1}, signal can be seen in the mass range

$0.5 < M < 2.08$ TeV

Spin determination:
from di-lepton angular distribution



acceptance effects included;
use likelihood method to discriminate between spin-1 and spin-2 hypotheses

Spin determination possible up to M ~ 1.7 TeV ($100\ fb^{-1}$, 90%CL)

Conclusions

1. The pp experiments at the LHC have a huge discovery potential

   - SM Higgs: full mass range, already at low lumi; Vector boson fusion channels improve the sensitivity significantly

   - MSSM Higgs: parameter space covered; new benchmark scenarios investigated at present

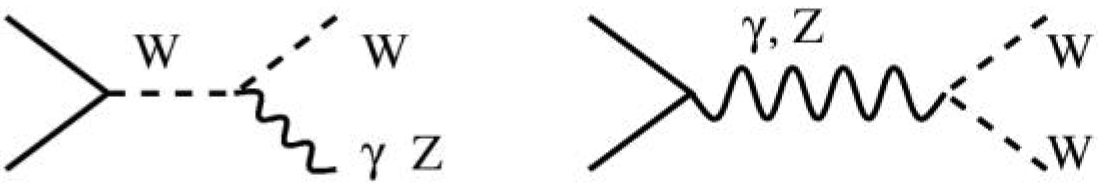
   - SUSY: discovery of TeV-scale SUSY should be easy, determination of model param. is more difficult

   - Exotics: experiments seem robust enough to cope with new scenarios

2. Experiments have also a great potential for precision measurements
   - m_W to ~15 MeV
   - m_{top} to ~ 1 GeV
   - $\Delta m_H / m_H$ to 0.1% (100 - 600 GeV)

   + gauge couplings and measurements in the top sector ....

Triple Gauge Boson Couplings



- Probe non-Abelian structure of $SU(2) \times U(1)$ and sensitive to New Physics

- general assumptions (Lorentz invariance, P,C inv.):
  $\Rightarrow$ $WW\gamma$ and WWZ couplings specified by five parameters: $g_1^Z, \lambda_\gamma, \lambda_Z, \kappa_\gamma, \kappa_Z$

  $WW\gamma$-vertex: related to

  – magnetic moment $\mu_W = \frac{e}{2M_W} \; (g_1^Z + \kappa_\gamma + \lambda_\gamma)$

  – quadrupole moment $Q_W = -\frac{e}{M_W^2} \; (\kappa_\gamma - \lambda_\gamma)$

  Standard Model: $g_1^Z = \kappa_V = 1$
  $\lambda_V = 0$

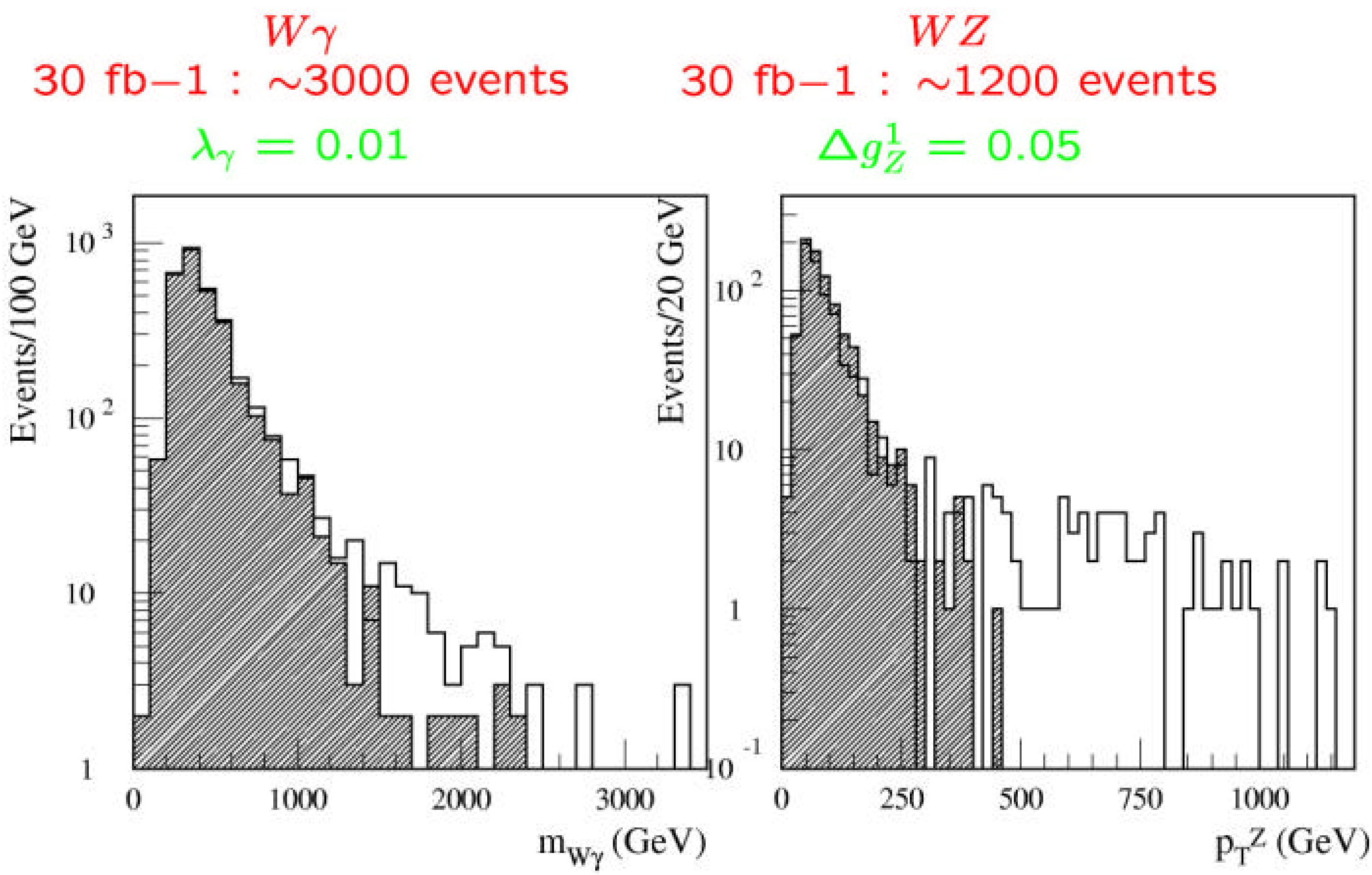
  year 2005: known to better than 10^{-2} from LEP2+TeVatron

- $W\gamma \rightarrow l\nu\gamma$ studied
  $WZ \rightarrow l\nu ll$ studied
  $WW \rightarrow l\nu l\nu$ large $t\bar{t}$ background

- Sensitivity from:

  – cross section measurements: λ-type, increase with s

  – P_T and angular distributions: constrain κ-type



$\int \mathcal{L} dt = 30\ fb^{-1}$

Coupling	95% C.L.
Δg_Z^1	0.008
λ_γ	0.0025
λ_Z	0.0060
$\Delta\kappa_\gamma$	0.035
$\Delta\kappa_Z$	0.070

Systematics under study

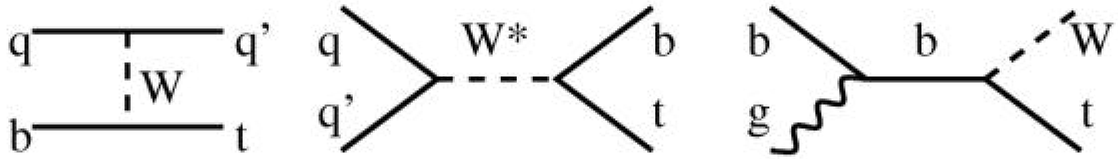
Other measurements in top physics

- Cross section measurement, $\sigma_{t\bar{t}} < 10\%$
  (limited by uncertainty on luminosity)

- Sensitivity to FCNC top couplings:

			$\int \mathcal{L}dt = 100\ fb^{-1}$
$BR(t \to Zq)$	$<$	10^{-4}	5σ discovery limit
$BR(t \to \gamma q)$	$<$	10^{-4}	5σ discovery limit
$BR(t \to gq)$	$<$	$7 \cdot 10^{-3}$	95% C.L.

- Single Top production: $\sigma \sim 300$ pb (40% of $t\bar{t}$)



  - probe $W - tb$ vertex,
    $\to$ sensitive to new physics
  - measure V_{tb} to $\sim 10\%$ (syst. limited)
  - measure W, top polarisation
    $\to$ anomalous couplings, ...