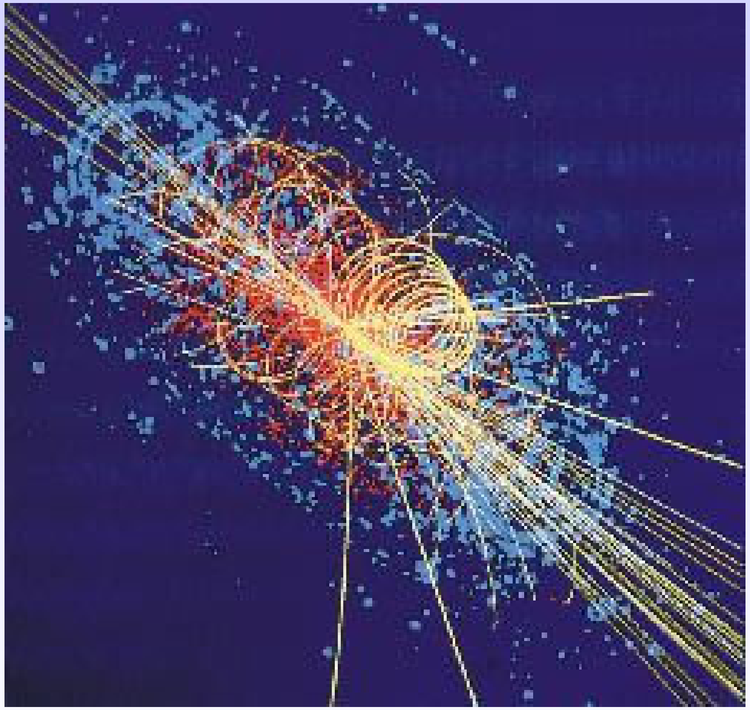
The Physics Program at the LHC

- What can be done during the first years ? -



- **Introduction**

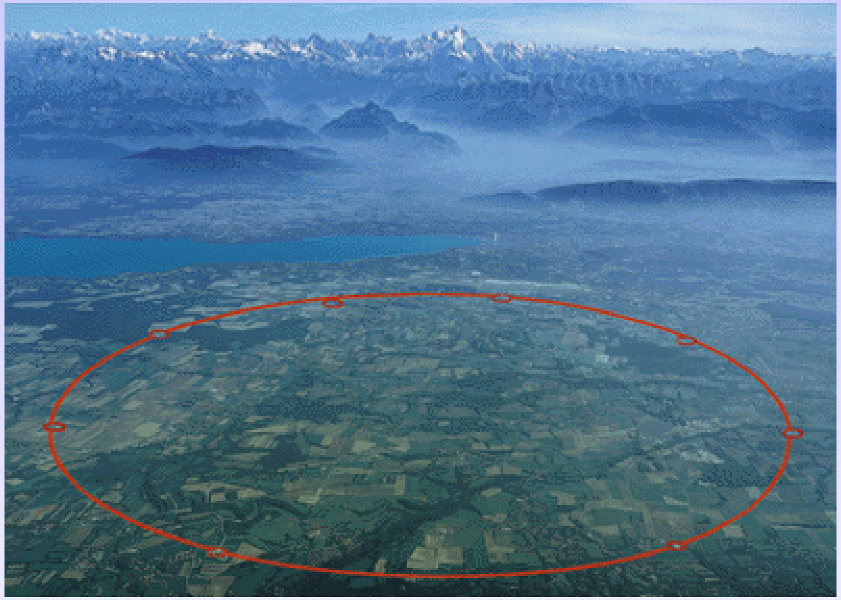
- **Search for Higgs Bosons**
  - Standard Model Higgs Boson
  - How reliable are the signals at low mass?
  - MSSM Sector

- **Supersymmetry**

- **Other Physics beyond the Standard Model**

Karl Jakobs
Physikalisches Institut
Universität Freiburg / Germany

The Large Hadron Collider (LHC)



- **Revised Time Schedule:**

Dec. 2006 Ring closed and cold

Jan. - Mar. 2007 Machine commissioning

Spring 2007 First collisions , pilot run.
$L = 5 \times 10^{32}$ to 2×10^{33} cm^{-2} sec^{-1},
≤ 1 fb^{-1}
Start detector commissioning,
~ 10^5 $Z \to \ell\ell$, $W \to \ell\nu$, tt events

June - Dec. 2007 Complete detector commissioning,
Physics run

→ 2009 $L = 1\text{-}2 \times 10^{34}$, 100 fb^{-1} per year
(high luminosity LHC)

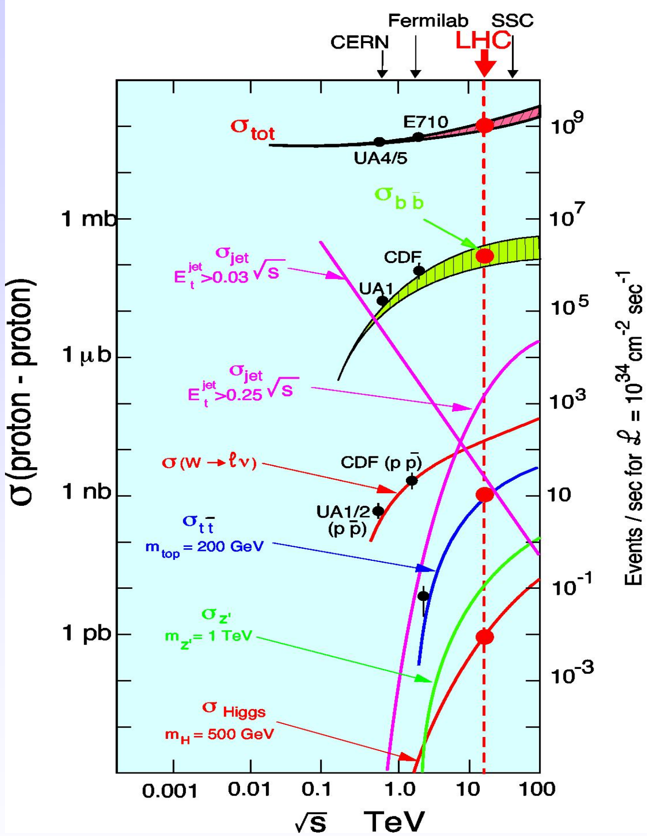
low luminosity: **$L = 1 \times 10^{33}$ cm^{-2} sec^{-1}**
10 fb^{-1} / year

high luminosity: **$L = 1 \times 10^{34}$ cm^{-2} sec^{-1}**
100 fb^{-1} / year

Which physics the first year(s) ?

Expected event rates at production in ATLAS and CMS at $L = 10^{33}$ cm^{-2} s^{-1}

Process	Events / sec	Events for 10 fb^{-1}	Total stat. collected at previous machines by 2007
$W \rightarrow e\nu$ $Z \rightarrow ee$	15 1.5	10^8 10^7	10^4 (LEP) 10^7 TeV 10^7 (LEP)
tt bb	1 10^6	10^7 10^{12}-10^{13}	10^4 (Tevatron) 10^9 (BaBar/Belle)
Higgs M_H = 130 GeV	0.02	10^5	?
Squarks, Gluinos M ~ 1 TeV	0.001	10^4	--



Already in first year, large statistics expected from:

-- known SM processes → understand detector and physics at $\sqrt{s}$ = 14 TeV

-- several New Physics scenarios

First goals ….

- Understand and calibrate detector and trigger in situ using well-known physics samples

e.g. - $Z \to ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
- $tt \to b\ell\nu\ bjj$ 10^4 evts/day after cuts → jet scale from W→jj, b-tag performance, etc.

- Understand basic SM physics at $\sqrt{s}$ = 14 TeV → first checks of Monte Carlos (hopefully well understood at Tevatron)

e.g. - measure cross-sections for W, Z, tt, QCD jets, events features (P_T spectra etc.)

…. and in parallel…

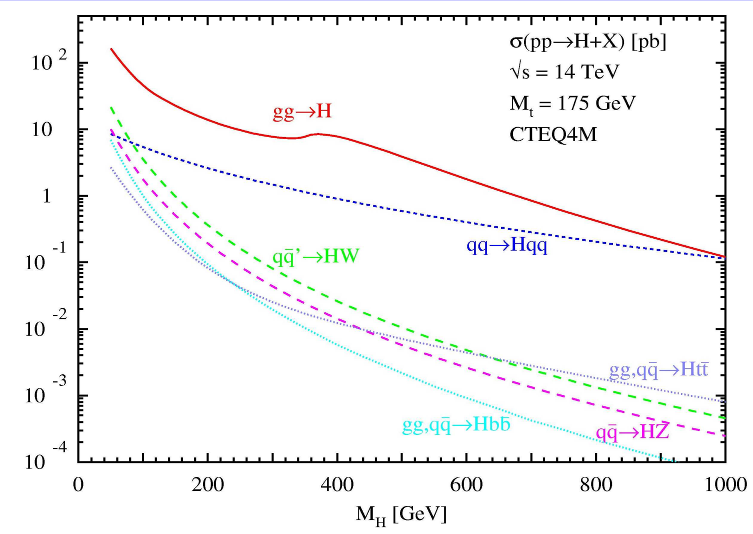
- Prepare the road to discovery:
  - -- measure backgrounds to New Physics : e.g. tt and W/Z+ jets (omnipresent …)
  - -- look at specific "control samples" for the individual channels:
    e.g. ttjj with j ≠ b "calibrates" ttbb irreducible background to ttH → ttbb

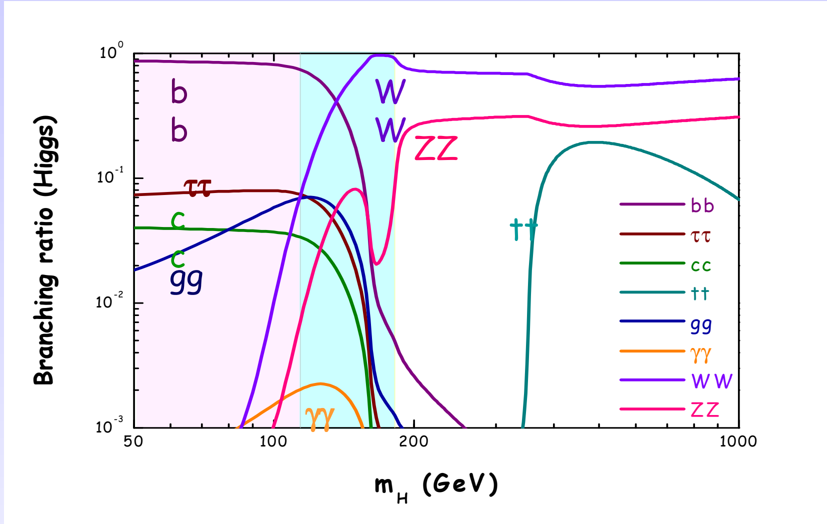
- Look for New Physics potentially accessible in first year (SUSY, Higgs, …)

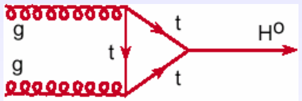
Note: if m_H < 120 GeV : fast Higgs discovery may be crucial in case of competition with Tevatron
This may be the most difficult physics goal for the first year …

Higgs Boson Production at Hadron Colliders

M. Spira

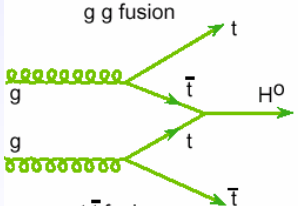






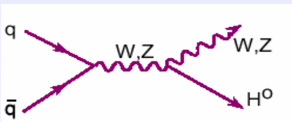
g g fusion

K [1] ~ 1.8
K [2] ~ 2.1



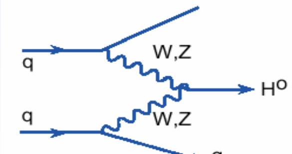
t t̄ fusion

K ~ 1.2



W, Z bremsstrahlung

K ~1.3



WW, ZZ fusion

K ~1.1

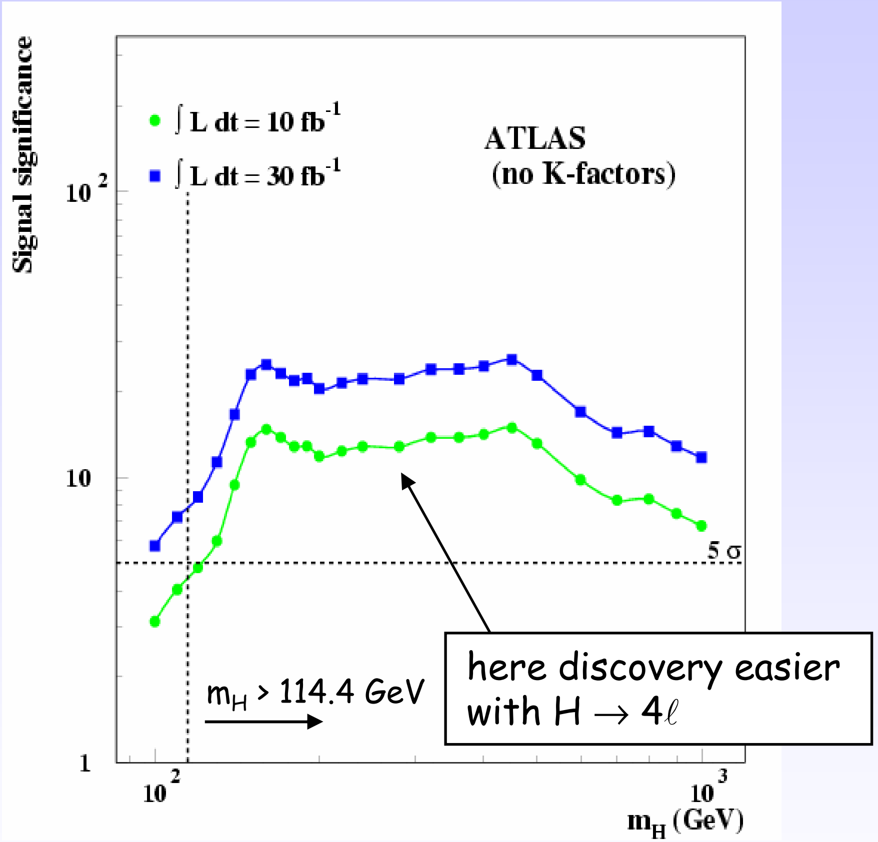
Lepton and Photon final states are essential (**via H → WW , ZZ, (ττ), γγ**)

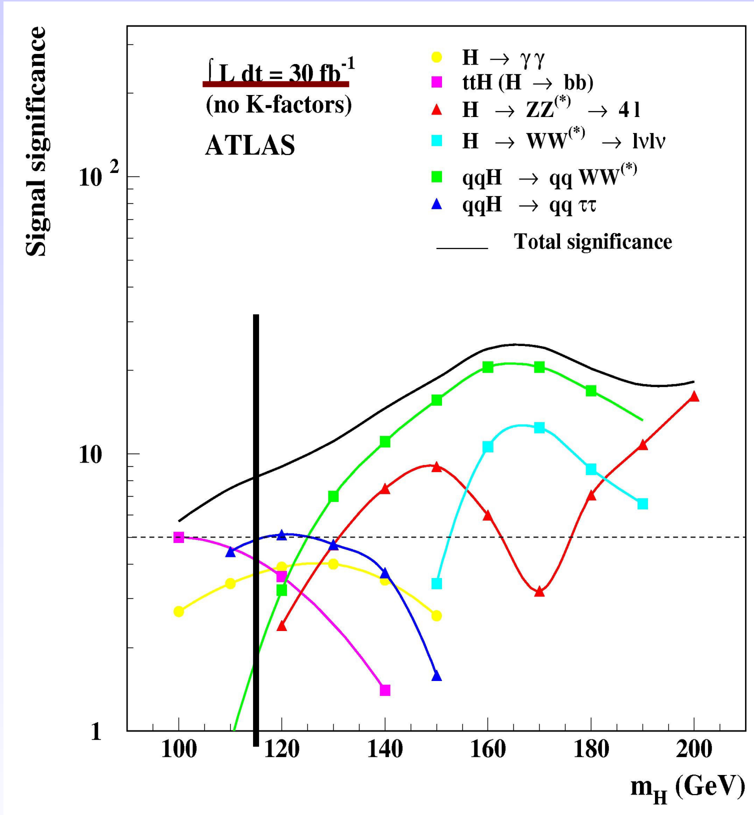
bb decay mode only possible in associated production (W/Z, tt)

(QCD jet background)

Large higher order QCD corrections for the gluon fusion process

Summary of the LHC Higgs boson discovery potential (one experiment)





- Higgs boson discovery possible over the full mass range with ~10 fb^{-1}
- Low mass region may be difficult (calibration, backgrounds, ….)
- How reliable is the signal in the low mass region ? VBF is important

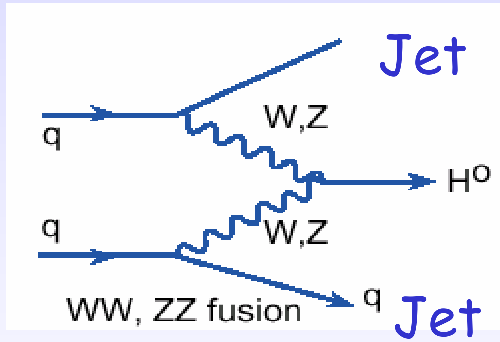
Higgs Boson Search using vector boson fusion at low mass

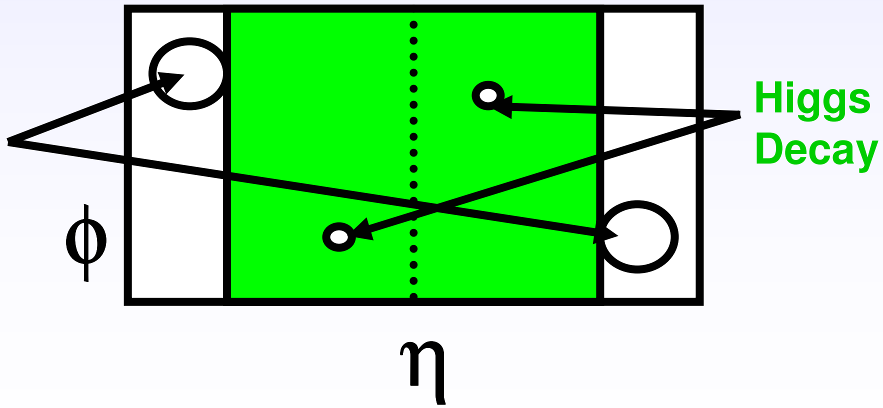
Motivation: Increase discovery potential at low mass
Improve measurement of Higgs boson parameter
(couplings to bosons, fermions (taus))
Search for non-standard decays (invisible Higgs)

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

Distinctive Signature of:

- **two high P_T forward tag jets**
- **little jet activity in the central region**
  $\Rightarrow$ **central jet Veto**



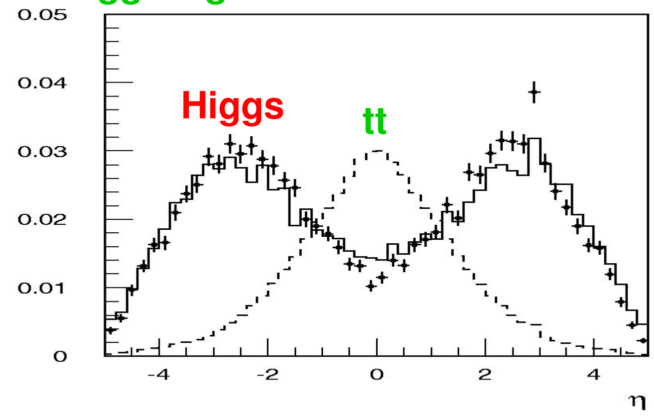


⇒ **Experimental Issues:**

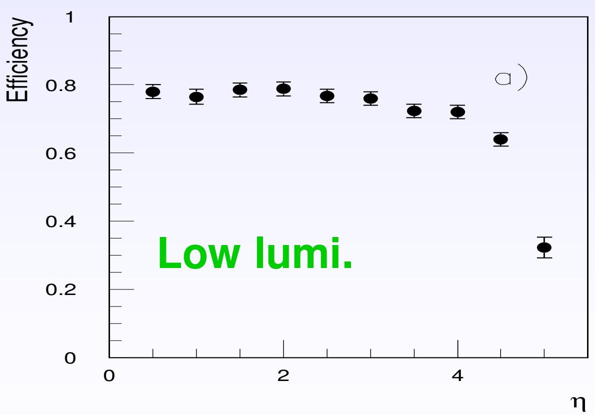
- Forward jet reconstruction
- Jets from pile-up in the central / forward region

Studied in full simulation by ATLAS and CMS

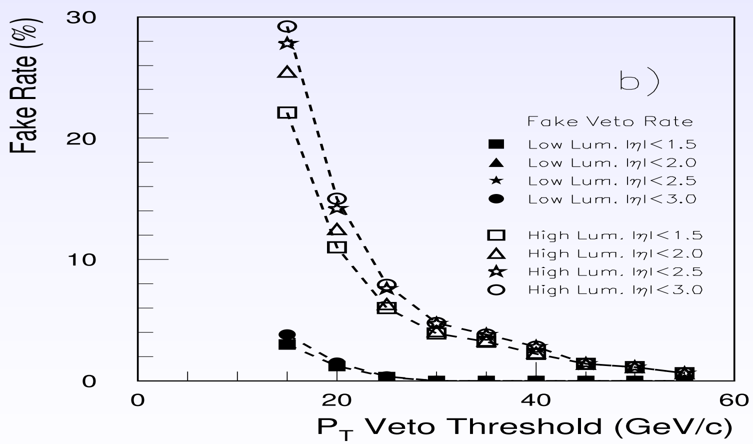
Rapidity distribution of jets in tt and Higgs signal events:



Efficiency of forward jet reconstruction



Fraction of events with jet in central region



Looks feasible at low lumi, higher tag jet P_T- thresholds needed at high lumi

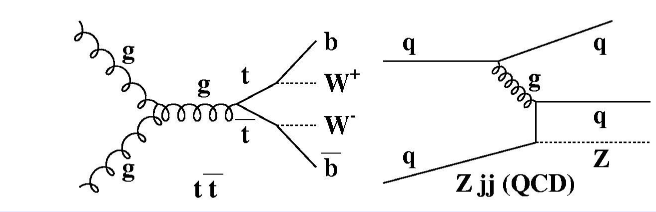
Background for channel: $qqH \rightarrow qqWW^* \rightarrow qq\,l\,\nu\,l\,\nu$

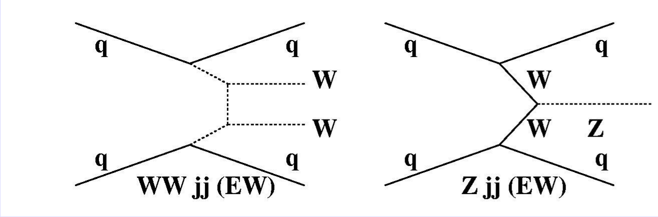
QCD backgrounds:

tt production Z + 2 jets

el.weak background:

WW jj production Z + 2 jets

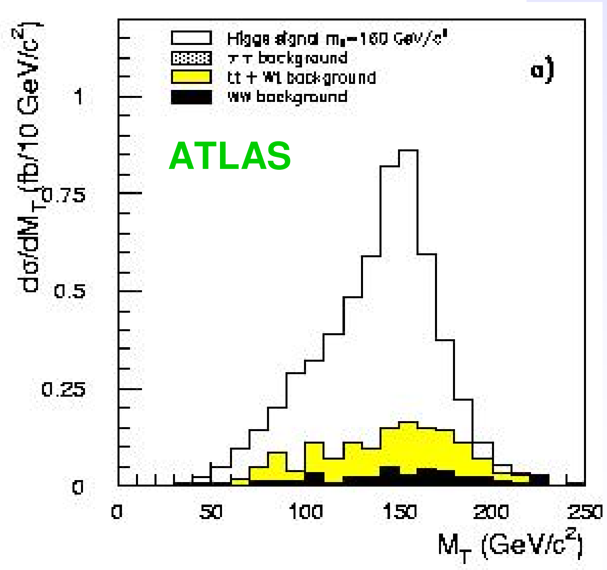




Background rejection: $qqH \rightarrow qqWW^* \rightarrow qq\,l\,\nu\,l\,\nu$

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

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



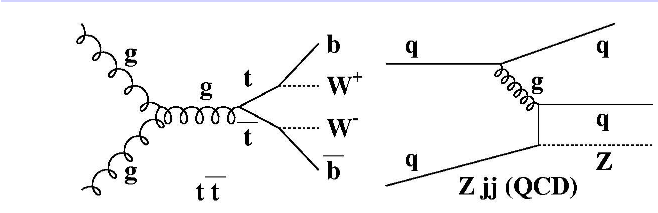
Background for channel: qqH $\rightarrow$ qqWW* $\rightarrow$ qq l ν l ν

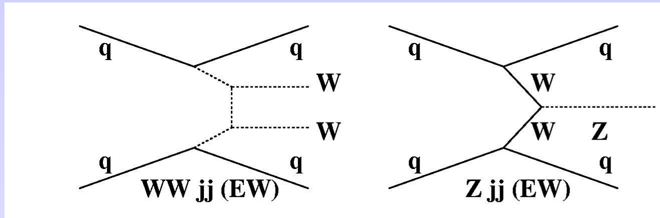
QCD backgrounds:

tt production Z + 2 jets

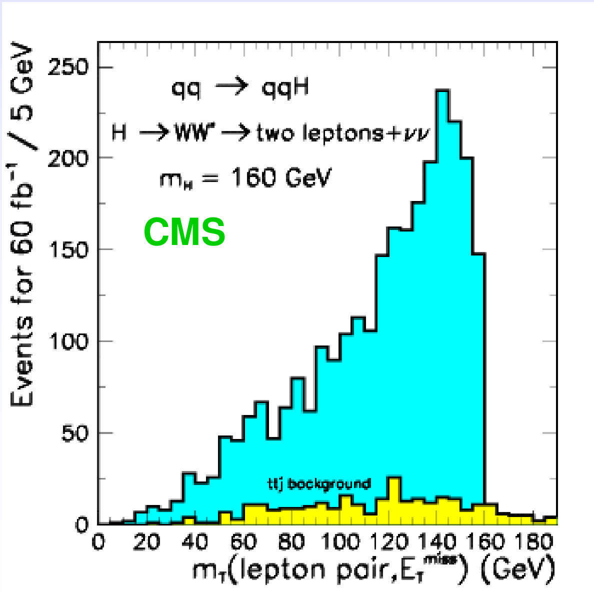
el.weak background:

WW jj production Z + 2 jets

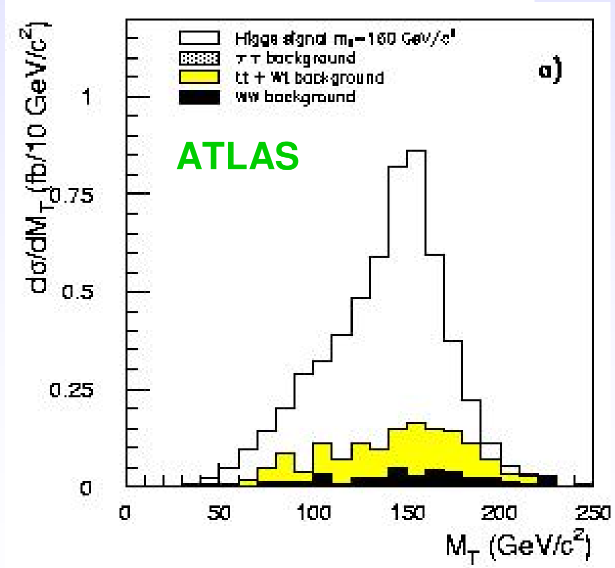




Background rejection: qqH $\rightarrow$ qqWW* $\rightarrow$ qq l ν l ν



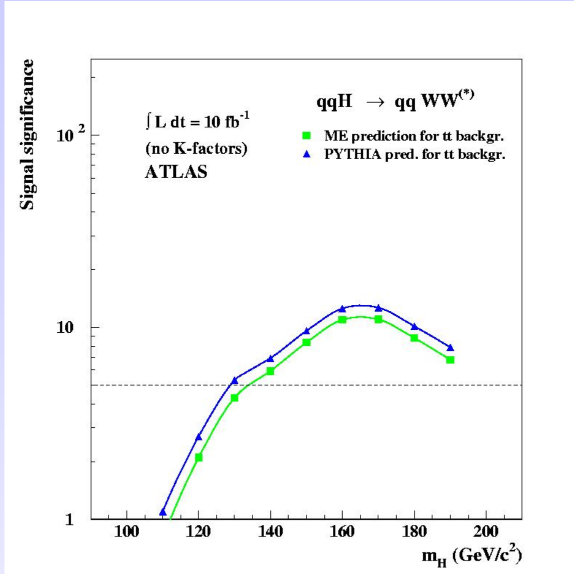
$$M_T = \sqrt{(E_T^{ll} + E_T^{\nu\nu})^2 - (\vec{p}_T^{\,e\mu} + \vec{p}_T^{\,miss})^2}$$



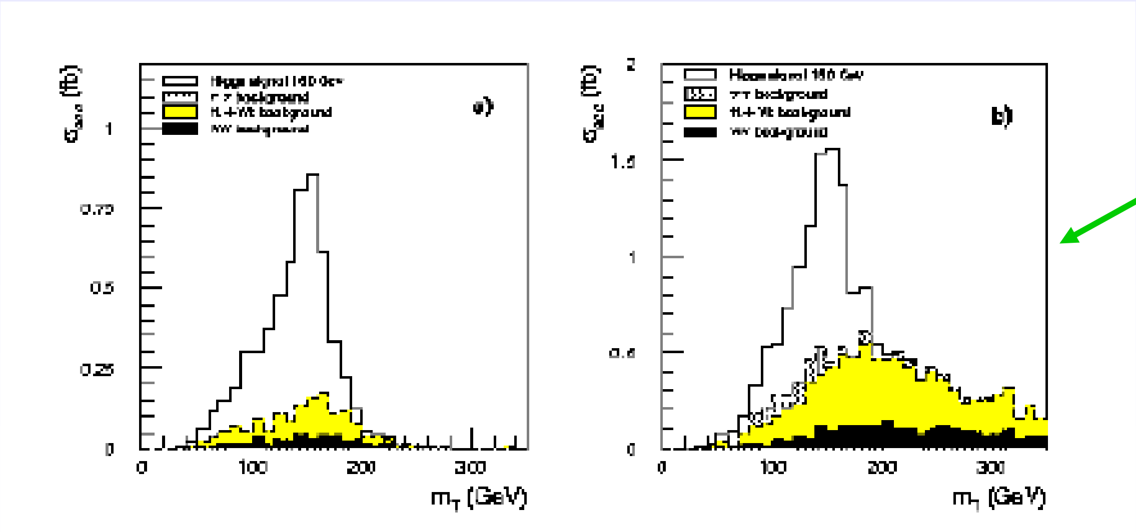
How reliable is this signal ?

- Factor of two uncertainty found on the tt background calculation
  (PYTHIA vs. ttj + ttjj matrix element calculation, issue of parton shower matching)
  ATLAS-SN-2003-024, Les Houches (2003)

  However: large (S : B) ratio,
  discovery significance is stable

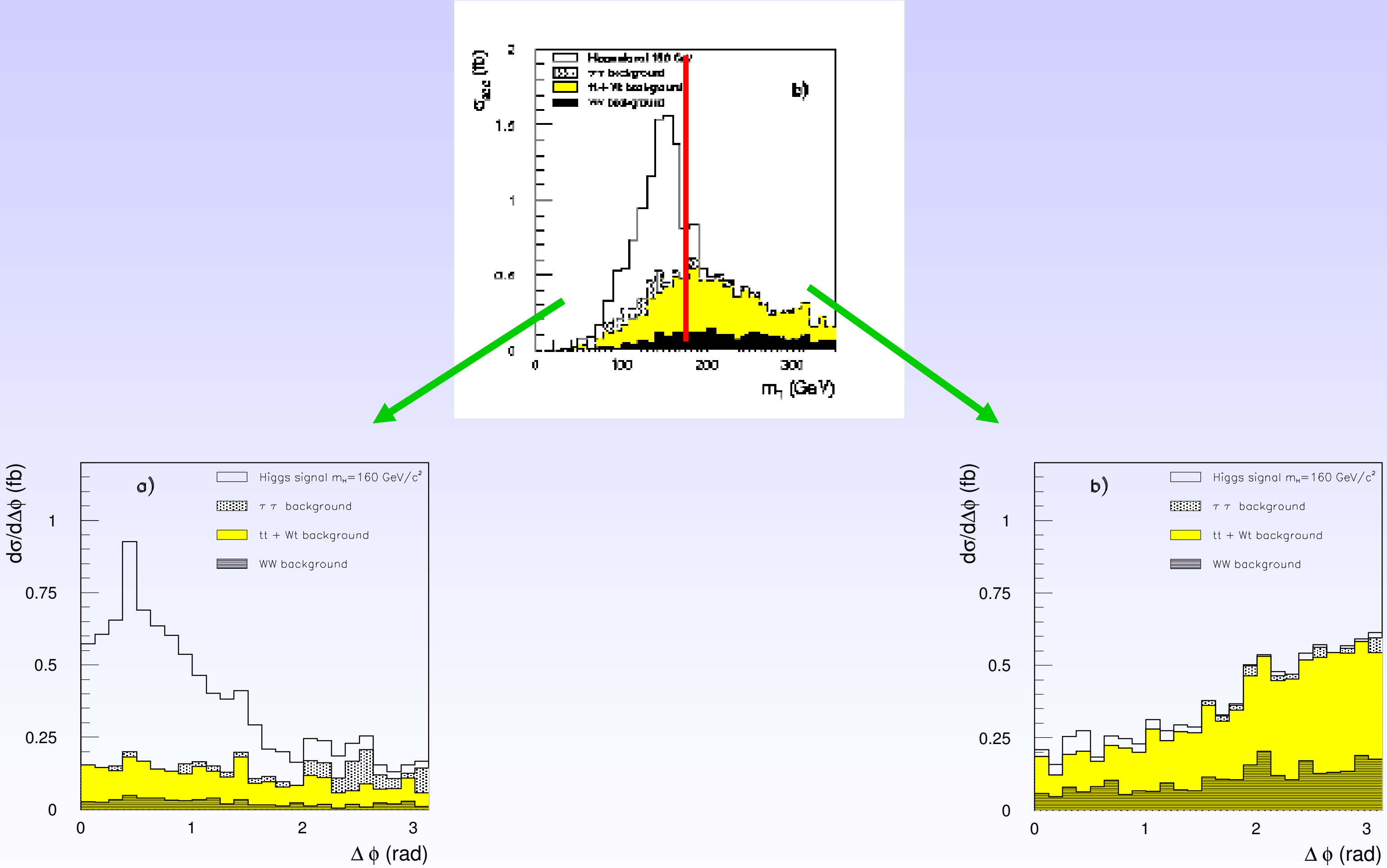


- Cuts can be relaxed, to get background shape from the data:



No kinematical cuts on leptons applied: (ATLAS study)

- Presence of a signal can also be demonstrated in the $\Delta\phi$ distribution (i.e. azimuthal difference between the two leptons)

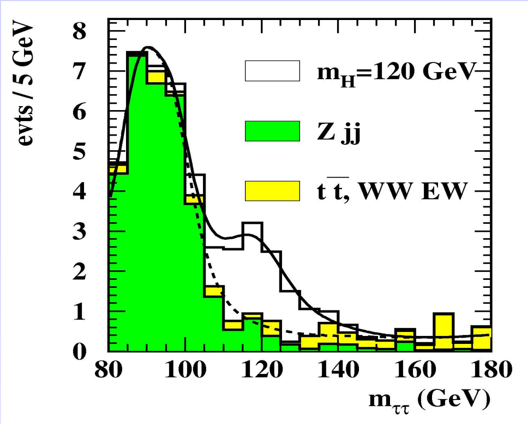


signal region

background region

$qq\,H \rightarrow qq\,\tau\,\tau$

$\rightarrow qq\;l\,\nu\,\nu\;\;l\,\nu\,\nu$

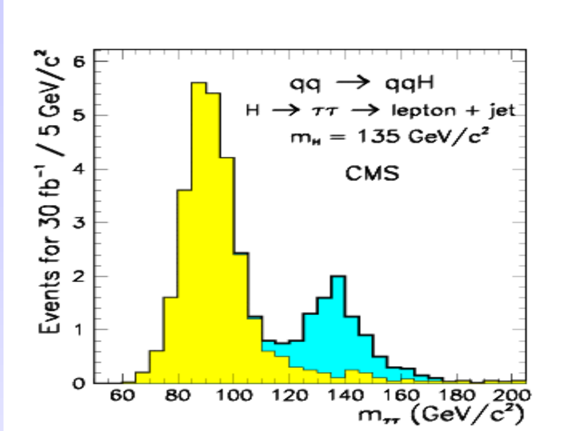


ATLAS

m_H = 120 GeV

$qq\,H \rightarrow qq\,\tau\,\tau$

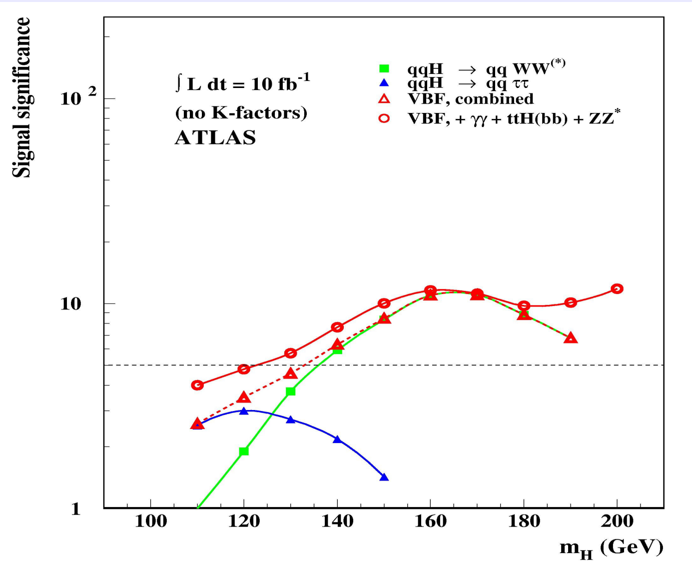
$\rightarrow qq\;l\,\nu\,\nu\;\;had\;\nu$



CMS

m_H = 135 GeV

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

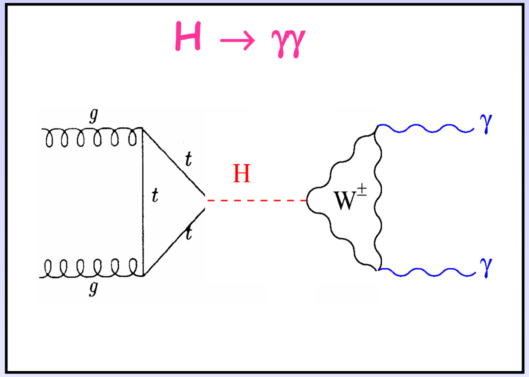


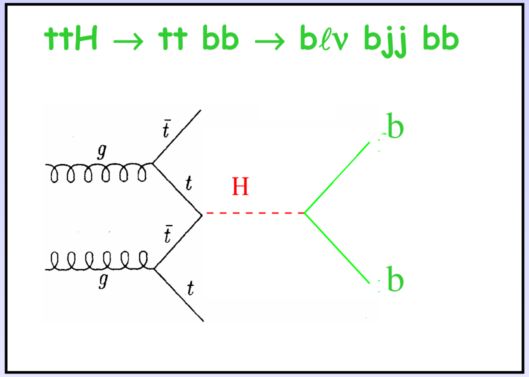
- VBF channels (in particular WW*) are discovery channels at low luminosity
- **For 10 fb^{-1} in ATLAS:**
  5 σ significance for
  $120 \leq m_H \leq 190$ GeV
- **low mass: combination with**
  $H \rightarrow \gamma\gamma$ and ttH, H→bb

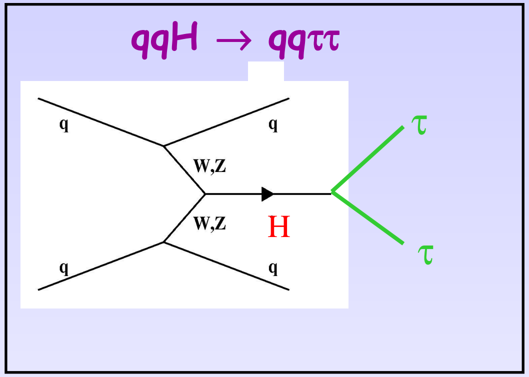
Remarks for a light Higgs with m_H < 120 GeV and 10 fb^{-1}:

Three channels with ~ 2-3 σ each → observation of all channels important to extract convincing signal in first year(s)

The 3 channels are complementary → robustness:







- different production and decay modes
- different backgrounds
- different detector/performance requirements:
  - -- ECAL crucial for H → γγ (σ/m ~ 1% needed)
  - -- b-tagging is crucial for ttH : (4 b-tagged jets needed to reduce combinatorics)
  - -- efficient jet reconstruction over |η| < 5 crucial for qq H → qq ττ

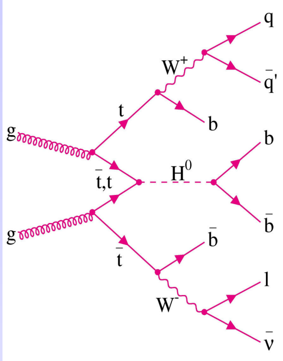
Note : -- all require "low" trigger thresholds

e.g. ttH analysis cuts : p_T (ℓ) > 20 GeV, p_T (jets) > 15-30 GeV

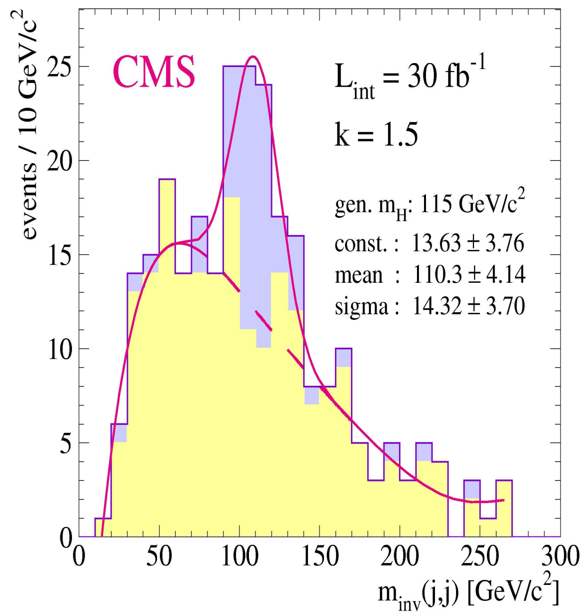
-- ttH requires very good understanding (5 -10%) of the backgrounds

$t\bar{t}H \rightarrow t\bar{t}b\bar{b}$

σ x BR ≈ 300 fb
Complex final state: $H \rightarrow bb$, $t \rightarrow bjj$, $t \rightarrow b\ell\nu$



- Main backgrounds:
  - -- combinatorial from signal (4b in final state)
  - -- Wjjjjjj, WWbbjj, etc.
  - -- ttjj (dominant, non-resonant)



- b-tagging performance is crucial
  ATLAS results for 2D-b-tag from full simulation
  (ε_b =60% R_j (uds)~ 100 at low L)

S = 38 events
B = 52 events
S/B ~ 0.73

$S/\sqrt{B} = 3.5$
for K = 1.0

- Shape of background must be known;
  60% (from ttbb) can be measured from ttjj using anti-b tag
- LHC experiments need a better understanding of the signal and the backgrounds (K-factors for backgrounds)

Measurement of Higgs-Boson Coupling Ratios

assumptions: only SM particles couple to Higgs boson,

no large couplings of light fermions

Global fit (ATLAS study)

(all channels at a given mass point)

Fit parameters:

$$\frac{g_Z^2}{g_W^2} \quad \frac{g_\tau^2}{g_W^2} \quad \frac{g_b^2}{g_W^2} \quad \frac{g_t^2}{g_W^2} \quad \frac{g_W^2}{\sqrt{\Gamma_H}}$$

Production cross sections

$$\sigma_{ggH} = \alpha_{ggH} \bullet g_t^2$$

$$\sigma_{VBF} = \alpha_{WF} \bullet g_W^2 + \alpha_{ZF} \bullet g_Z^2$$

$$\sigma_{ttH} = \alpha_{ttH} \bullet g_t^2$$

$$\sigma_{WH} = \alpha_{WH} \bullet g_W^2$$

$$\sigma_{ZH} = \alpha_{ZH} \bullet g_Z^2$$

b loop neglected for now in ggH

α from theory with assumed uncertainty $\Delta\alpha$

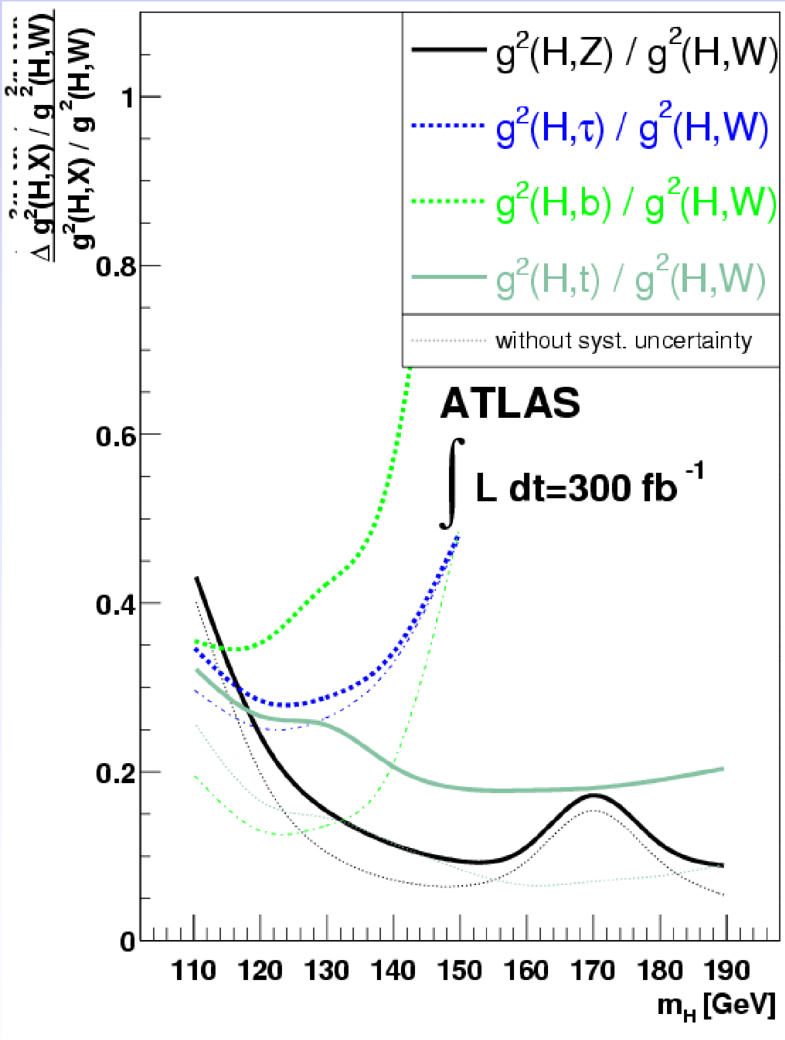
$$\Delta\alpha_{ggH} = 20\%$$

$$\Delta\alpha_{WF} = \alpha_{ZF} = 4\%$$

$$\Delta\alpha_{ttH} = 15\%$$

$$\Delta\alpha_{WH} = \Delta\alpha_{ZH} = 7\%$$

Ratio of Higgs-Boson Couplings



Branching ratios

$$BR(H \to WW) = \beta_W \frac{g_W^2}{\Gamma_H}$$

$$BR(H \to ZZ) = \beta_Z \frac{g_Z^2}{\Gamma_H}$$

$$BR(H \to \gamma\gamma) = \frac{\left(\beta_{\gamma(W)} g_W - \beta_{\gamma(t)} g_t\right)^2}{\Gamma_H}$$

$$BR(H \to \tau\tau) = \beta_\tau \frac{g_\tau^2}{\Gamma_H}$$

$$BR(H \to bb) = \beta_b \frac{g_b^2}{\Gamma_H}$$

$\Delta\beta = 1\%$

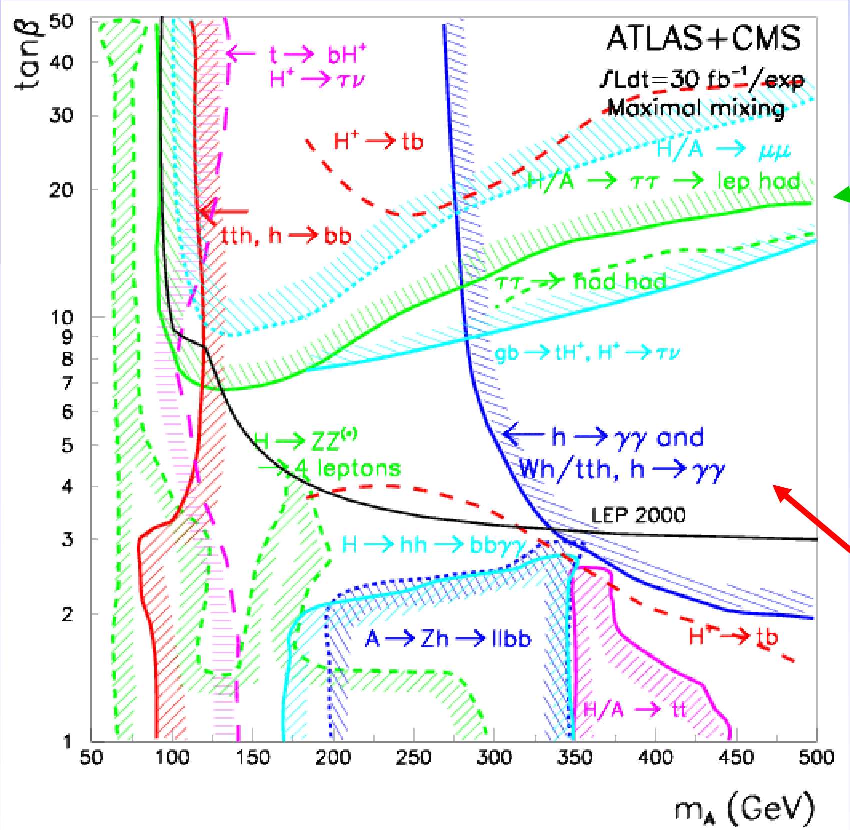
Rate as function of x_i, e.g.

$$(\sigma \bullet BR)_{ggH, H \to ZZ} =$$

$$\alpha_{ggH} \frac{g_t^2}{g_W^2} \frac{g_W^2}{\sqrt{\Gamma_H}} \beta_Z \frac{g_Z^2}{g_W^2} \frac{g_W^2}{\sqrt{\Gamma_H}}$$

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

m_h < 135 GeV
$m_A \approx m_H \approx m_{H\pm}$ at large m_A



A, H, H± cross-section ~ tan2β

-- best sensitivity from A/H → ττ, H± → τν
(not easy the first year ..)

-- A/H → μμ experimentally easier
(esp. at the beginning)

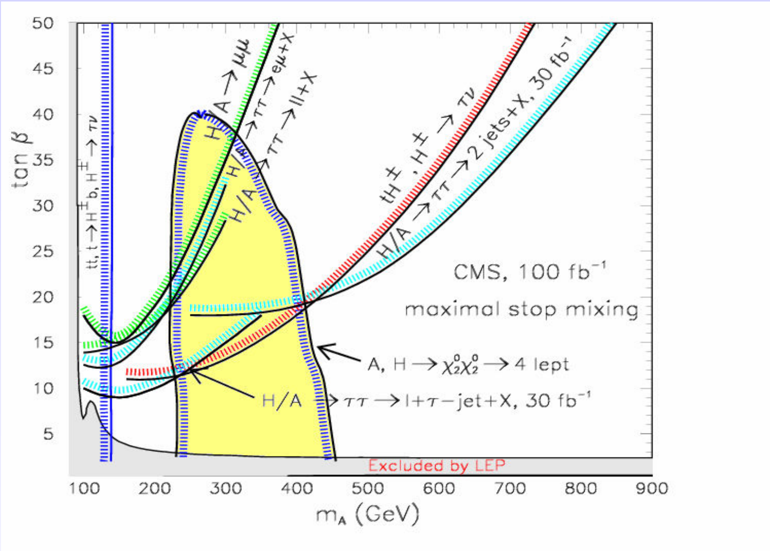
Here only SM-like h observable if SUSY particles neglected.

Higgs decays via SUSY particles

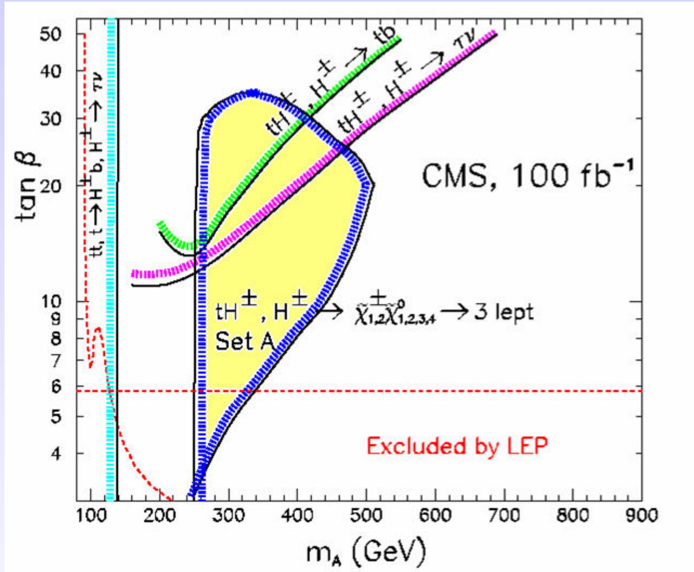
If SUSY exists : search for

$H/A \rightarrow \chi^0_2 \chi^0_2 \rightarrow \ell\ell\chi^0_1 \; \ell\ell\chi^0_1$

$gb \rightarrow tH^+, H^\pm \rightarrow \chi^0_{2,3} \, \chi^\pm_{1,2} \rightarrow 3l + E_T^{miss}$



s



CMS: special choice in MSSM (no scan)

M_1 = 60 GeV

M_2 = 110 GeV

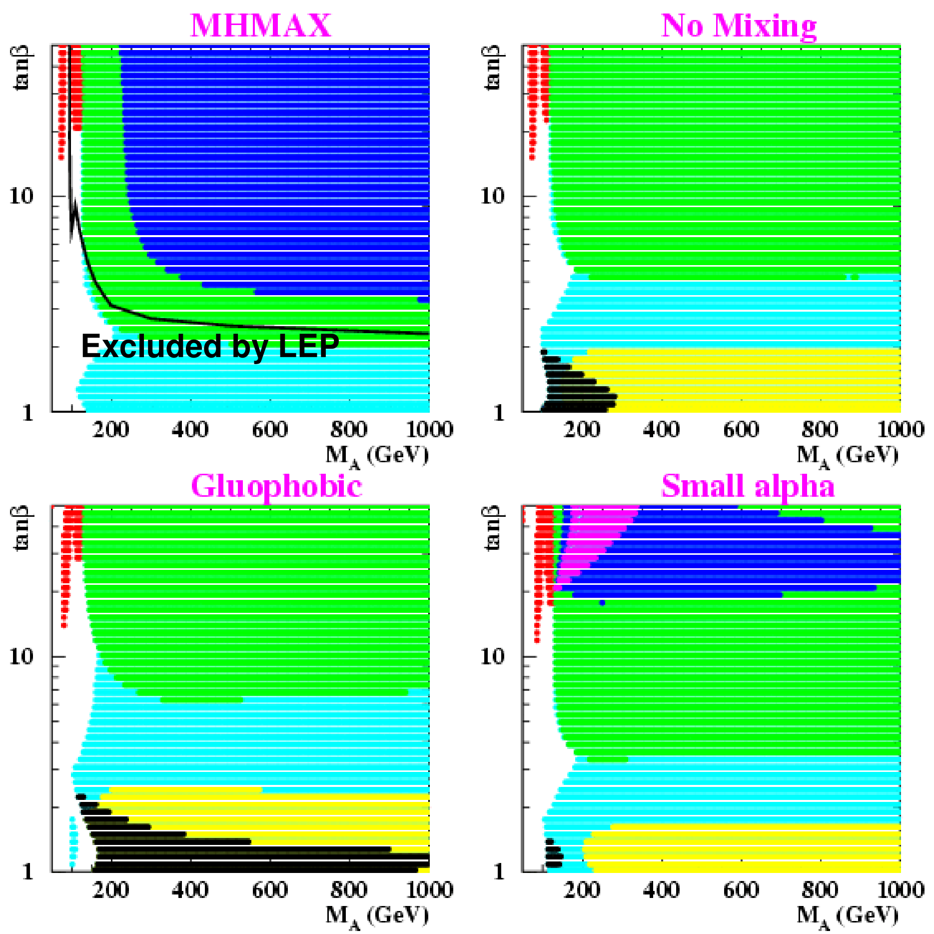
μ = -500 GeV

Exclusions depend on MSSM parameters
(slepton masses, μ)

Updated MSSM scan for different benchmark sceanarios

- Vector boson channels included
- Benchmark scenarios as defined by M.Carena et al. (h mainly affected)

ATLAS,   30 fb^{-1},   5σ coverage for h



MHMAX scenario   (M_{SUSY}=1 TeV)
maximal theoretically allowed region for m_h

Nomixing scenario   (M_{SUSY}= 2TeV)
(1TeV almost excl. by LEP)
small m_h → difficult for LHC

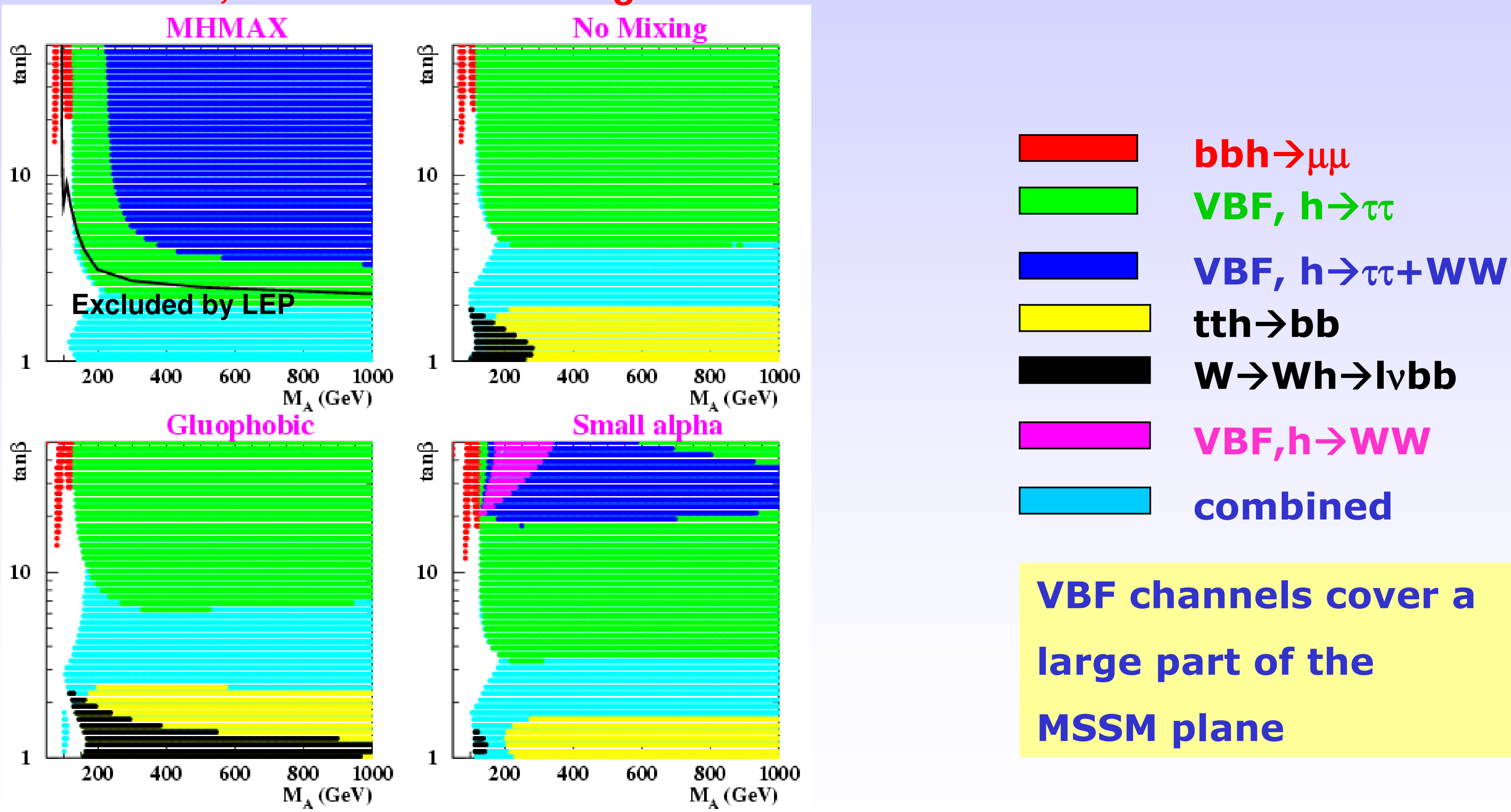
Gluophobic scenario   (M_{SUSY} = 350 GeV)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for g g → H, H→γγ and Z→4 ℓ

Small α scenario   (M_{SUSY} = 800 GeV)
coupling to b (and **t**) suppressed
(cancellation of sbottom, gluino loops) for
large tan β and M_A 100 to 500 GeV

Updated MSSM scan for different benchmark sceanarios

- Vector boson channels included
- Benchmark scenarios as defined by M.Carena et al. (h mainly affected)

ATLAS,   30 fb^{-1},   5σ coverage for h



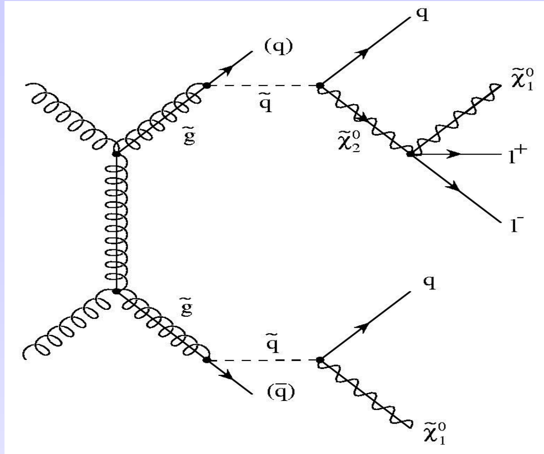
VBF channels cover a large part of the MSSM plane

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)



⇒ combination of Jets, Leptons, E_T^{miss}

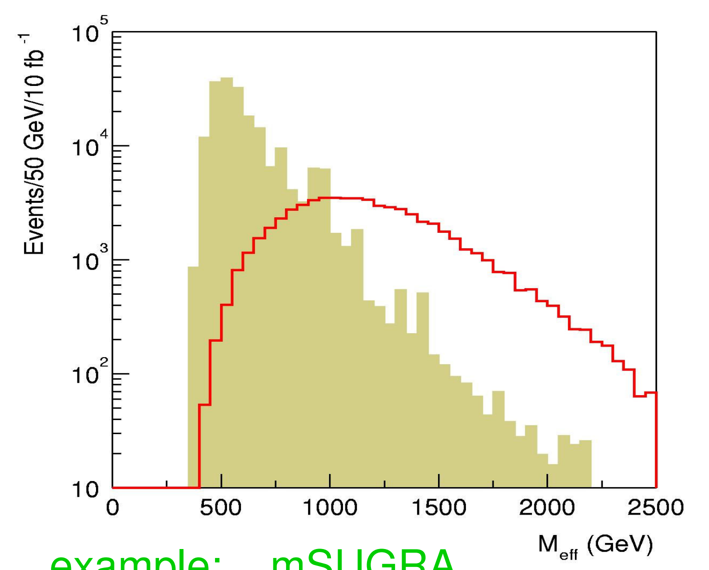
1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

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
$\tan\beta$ = 10, $A_0 = 0$, $\mu > 0$

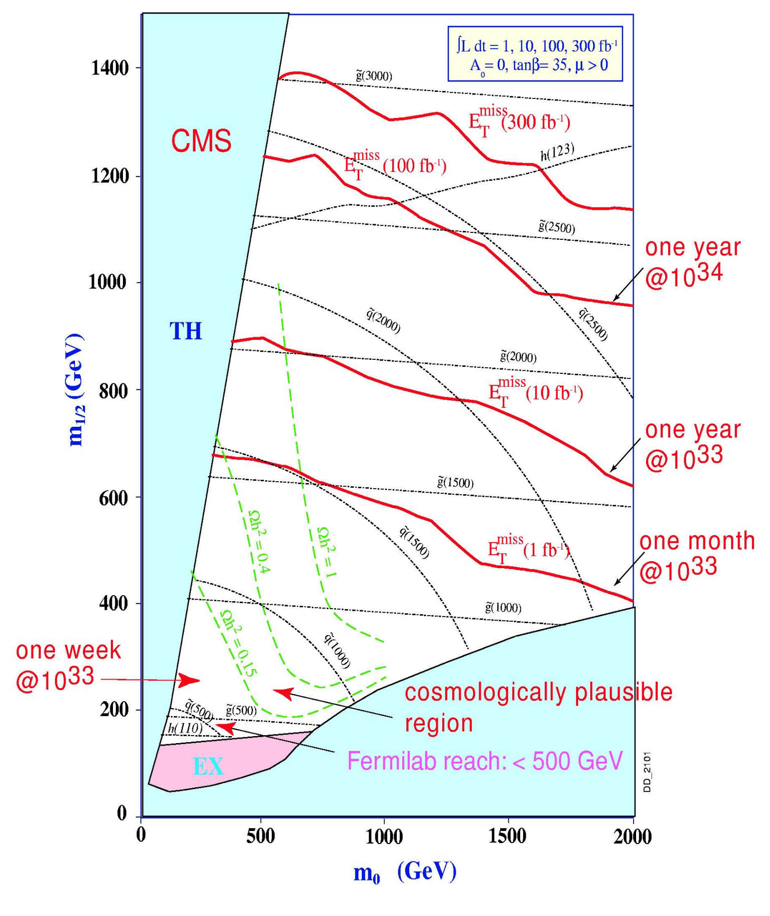
LHC reach for Squark- and Gluino masses:

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

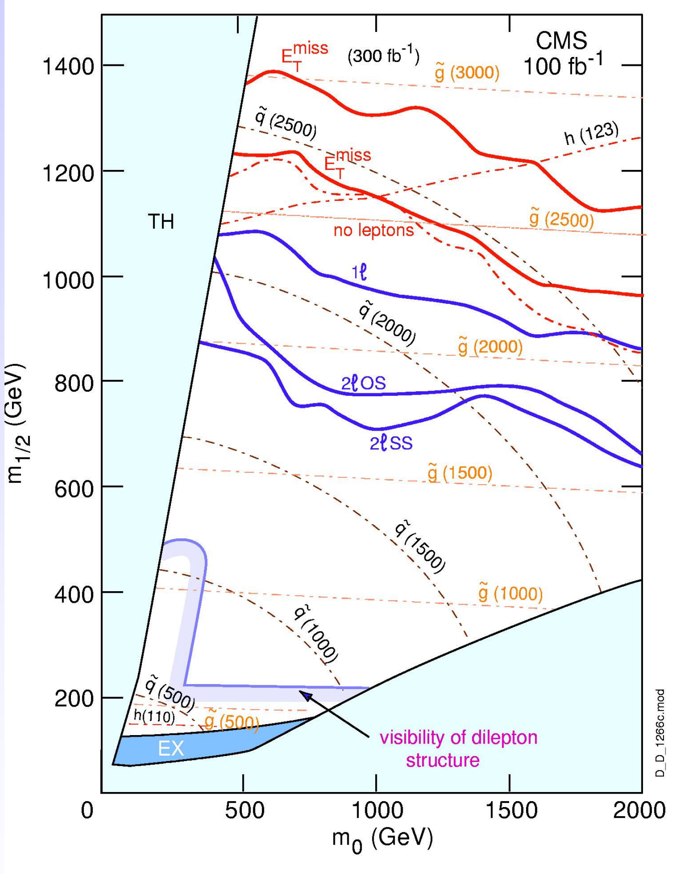
TeV-scale SUSY can be found quickly !

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

Multijet + E_T^{miss} signature



SUSY cascade decays give also rise to many other inclusive signatures: **leptons, b-jets, τ's**



Expect multiple signatures for TeV-scale SUSY

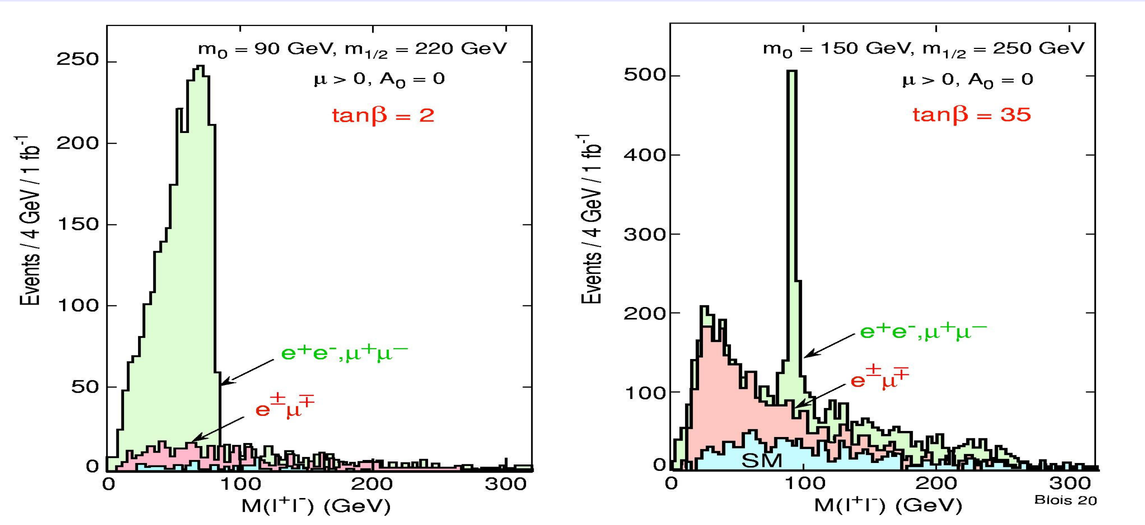
Determination of model parameters

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

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

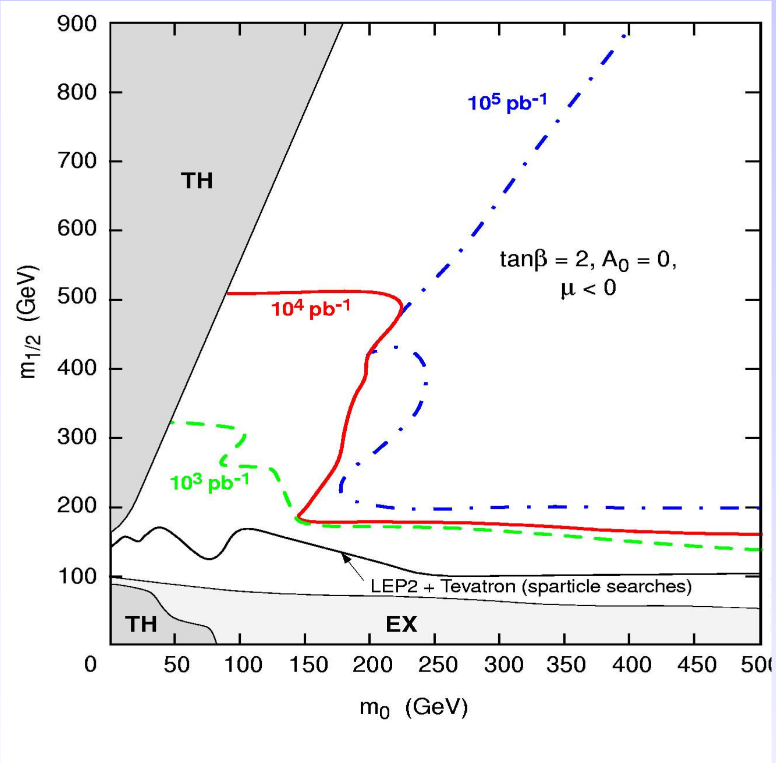
(significant mode if no $\chi^0_2 \rightarrow \chi^0_1 Z$, $\chi^0_1 h$, $\tilde{\ell}\,\ell$ decays)

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



Modes can be distinguished

using shape of $\ell\ell$-spectrum

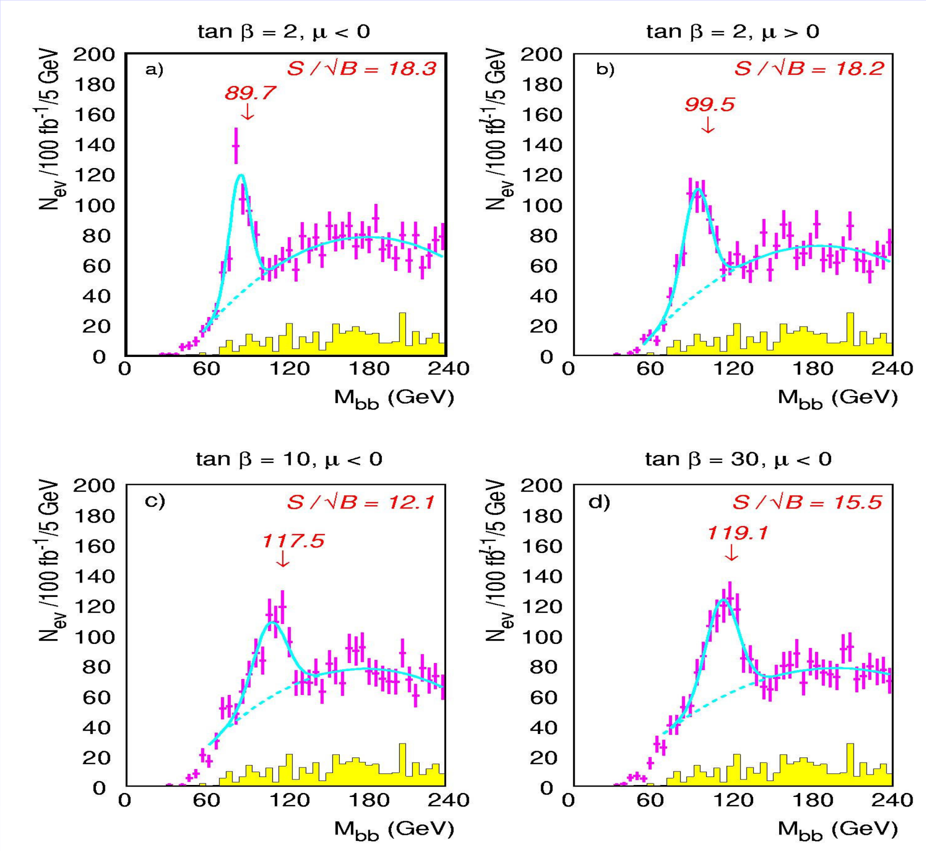


$\ell\ell$ - endpoint can be observed over a significant fraction of the parameter space

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

$h \rightarrow bb$:

CMS



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 !

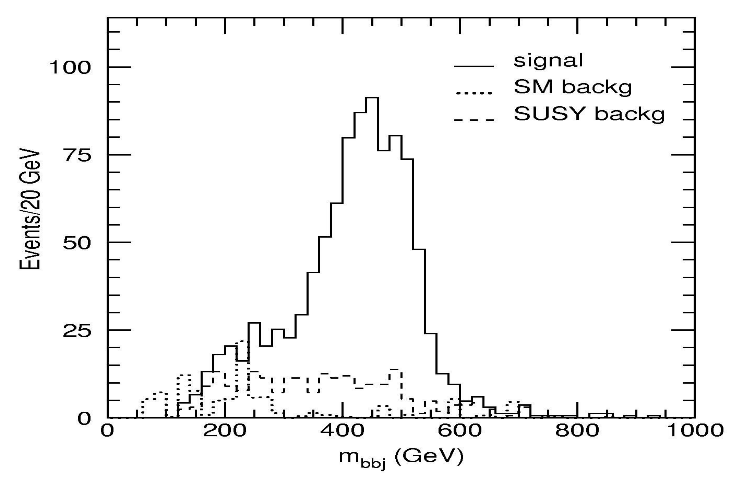
SM background can be reduced by applying a cut on E_T^{miss}

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

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

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

combine h → bb with jets to
determine other masses



$\tilde{q} \longrightarrow \tilde{\chi}_1^0 h q$ 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. $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \tilde{\chi}_1^0 \ell^+\ell^- \rightarrow \tilde{G}\gamma\ell^+\ell^-$

- ⇒ models with prompt NLSP decays give add handles and hence are easier than SUGRA

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

RPV :

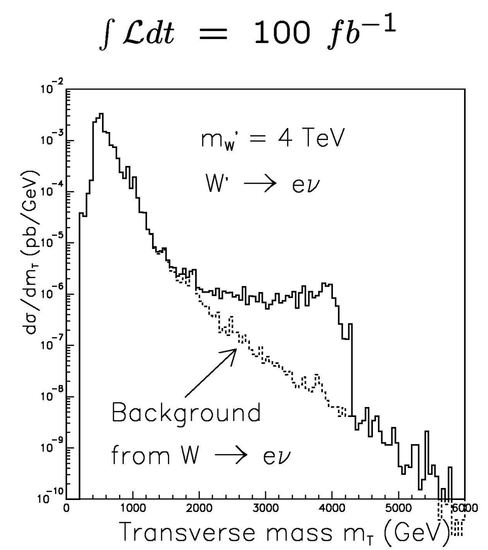
- R-violation via $\chi^0{}_1 \rightarrow \ell\ell\nu$ or $qq\ell$, $qq\nu$ gives additional leptons and/or E_T^{miss}

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

LHC reach for other BSM Physics

(a few examples for 30 and 100 fb^{-1})

	30 fb^{-1}	100 fb^{-1}
Excited Quarks $Q^* \rightarrow q\,\gamma$	M (q*) ~ 3.5 TeV	M (q*) ~ 6 TeV
Leptoquarks	M (LQ) ~ 1 TeV	M (LQ) ~ 1.5 TeV
Z' → ℓℓ, jj W'→ ℓ ν	M (Z') ~ 3 TeV M (W') ~ 4 TeV	M (Z') ~ 5 TeV M (W') ~ 6 TeV
Compositeness (from Di-jet)	Λ ~ 25 TeV	Λ ~ 40 TeV



Conclusions

1. Experiments at the LHC have a huge discovery potential

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

   - MSSM Higgs: parameter space covered; also for new proposed
     benchmark scenarios

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

   - Exotics: experiments seem robust enough to cope with new scenarios,
     incl extra dimensions

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 ....