Physics at hadron collider with Atlas

4th lecture

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on behalf of Atlas Collaboration

Outline

- Introduction to Hadron Collider Physics

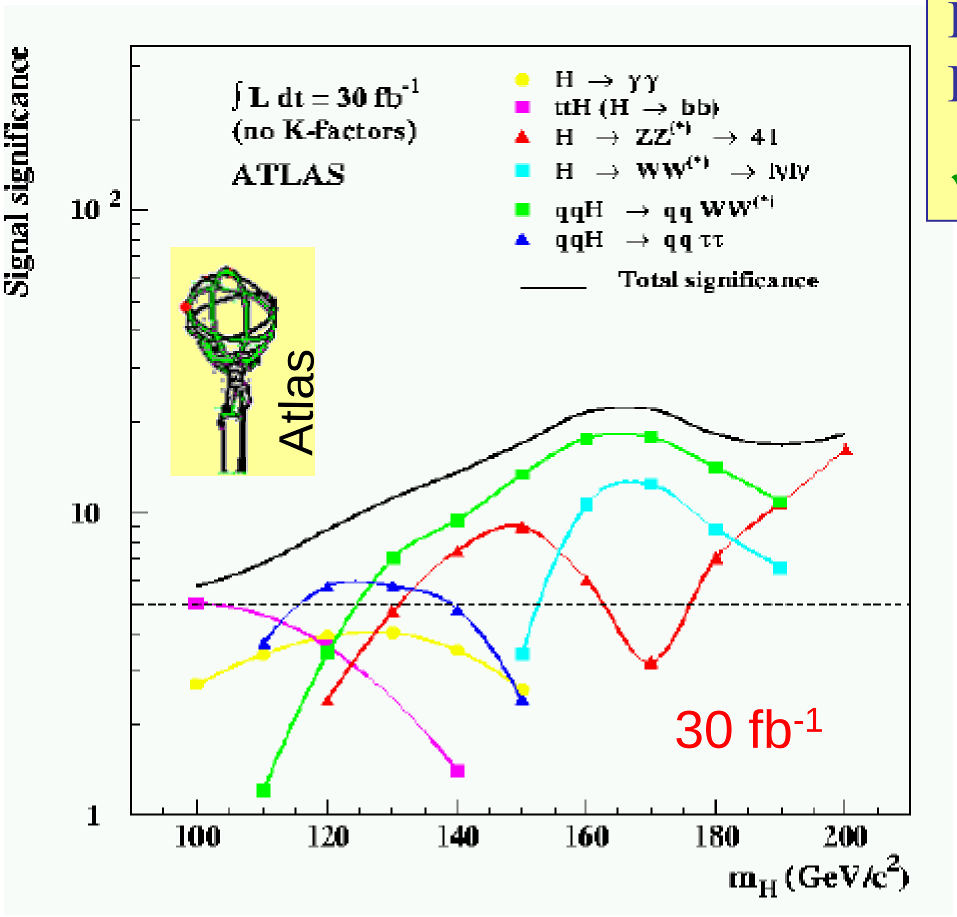
1st
- LHC and ATLAS detector
- Test of Standard Model at LHC
  - Parton distribution function
  - QCD + jet physics

2nd
  - **Electroweak physics (Z/W –bosons)**
  - **Top physics**

3rd
- **Search for Higgs boson**

4th
- Supersymmetry
- Conclusions

Higgs signal in ATLAS



LHC can probe entire set of "allowed" Higgs mass values (100 GeV – 1 TeV)

✓at least 2 channels for most of range

Full mass range can be covered After few years at low

MSSM Higgs

Minimal Supersymmetric Standard Model extention:

Two Higgs doublets: 5 Higgs particles

H, h, A

H^+, H^-

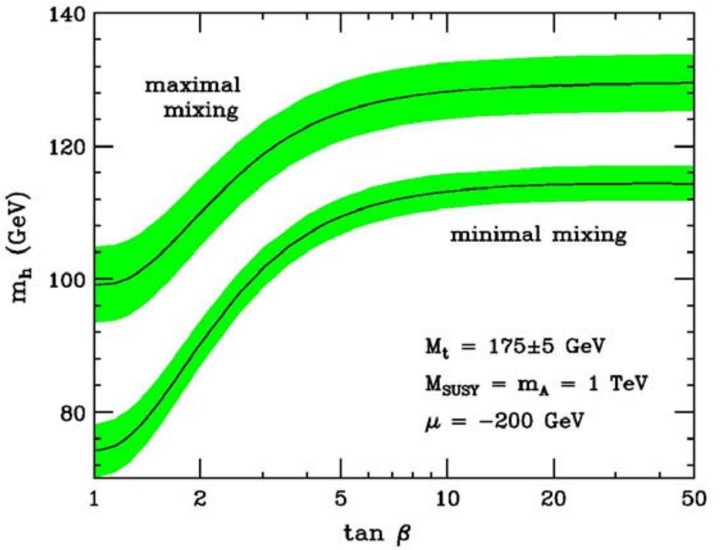
Theory prediction $m_h < 135$ GeV

- **Fixed mass relations at tree level,**
- **Important loop corrections**

(tree level relations are significantly modified) mainly dependent from **top/stop**

- two parameters: **m_A, $\tan\beta$**
- **For large m_A the h boson is SM like**

upper limit for the light Higgs mass



MSSM parameters constrains

- M_{susy},sfermion mass at EW scale
- M_2, $SU(2)_L$ gaugino mass at EW scale
- μ, supersymmetric Higgs boson mass parameter.
- **tan β**, the ratio of the two Higgs fields doublets
- A_0, a universal trilinear higgs-squarks coupling at EW scale. It is assumed to be the same for up-type squarks and for down types quarks.
- **m_A**, mass of CP-odd Higgs boson.
- M_{gluino}, it affects loop corrections for stop and bottom

Phenomenology decribed at Born level by tan β ,m_A

➢ **couplings: gMSSM = ξ · gSM**
no coupling of A to W/Z
large tanβ: large BR(h,H,A→ττ,bb)

ξ	t	b/τ	W/Z
h	cosα/sinβ	-sinα/cosβ	sin(α-β)
H	sinα/sinβ	cosα/cosβ	cos(α-β)
A	cotβ	tanβ	-----

α: mixing angle between CP even Higgs bosons (calculable from tanβ and M_A)

Decays

Large variety of observation modes

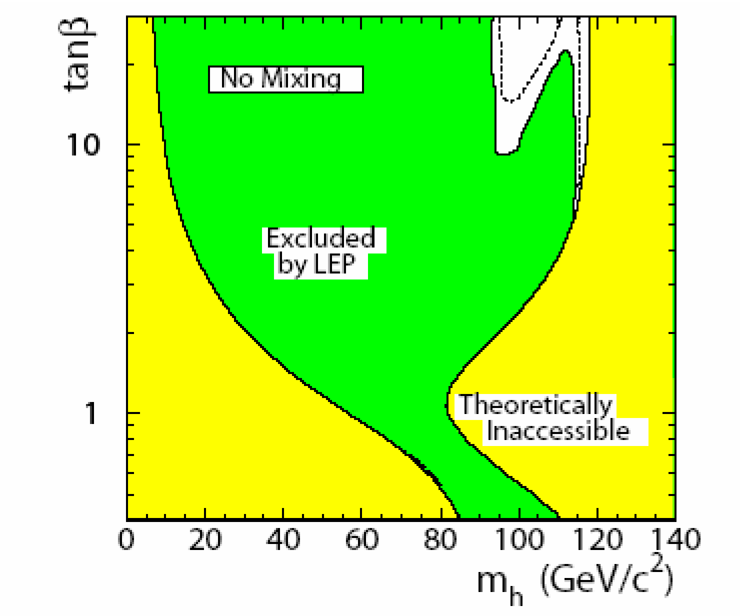
- **if SUSY particles heavy**
  - **SM-like:** **h** $\rightarrow \gamma\gamma$, **bb**
    H $\rightarrow$ **4lept**
  - **MSSM-specific: A/H** $\rightarrow \mu\mu$, $\tau\tau$, **tt**
    H $\rightarrow$ **hh**
    A $\rightarrow$ **Zh**
    $H^{\pm} \rightarrow \tau\nu$
- **if SUSY particles accessible: (not discussed)**
  - **H/A** $\rightarrow \chi^2{}_0 \chi^2{}_0 \rightarrow \chi^1{}_0 \chi^1{}_0 \rightarrow 4\ell$ **+ missing Energy**
  - **h produced in cascade decays (e.g.** $\chi^2{}_0 \rightarrow h\, \chi^1{}_0$**)**

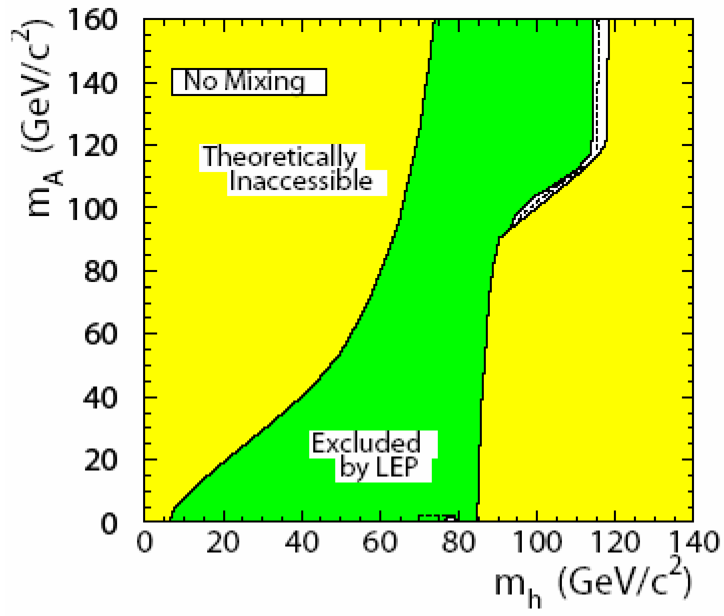
Past & future

Excluded:

$m_{h0} < 92.9$ GeV²/c $m_A < 93.4$ GeV²/c

tanβ 0.9 – 1.5





LHWG-Note 2004

Past & future

Excluded (max m_h)

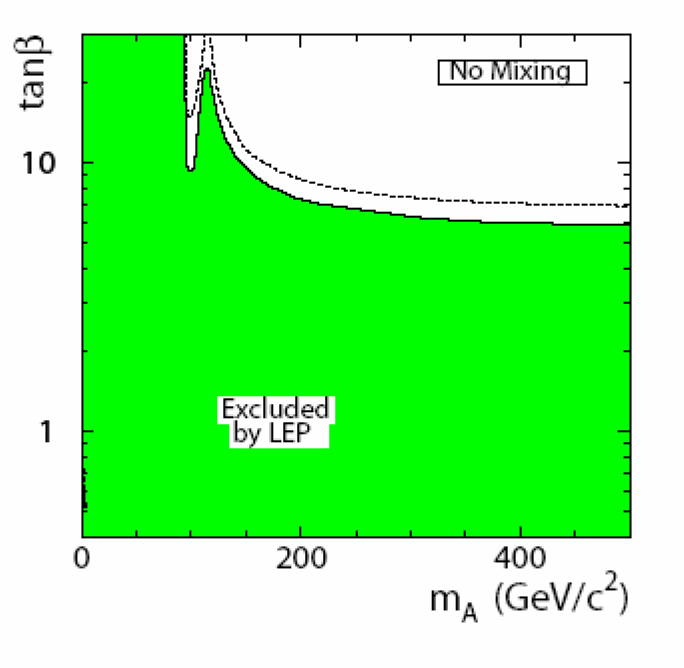
$m_{h0} < 92.9$ GeV²/c $m_A < 93.4$ GeV²/c

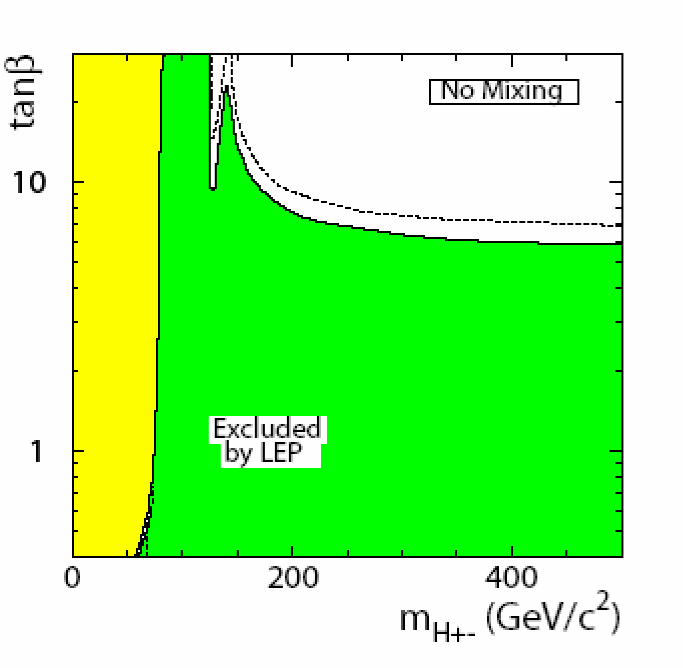
tanβ 0.9 – 1.5

Excluded (no mixing)

$m_{h0} < 93.3$ GeV²/c $m_A < 93.3$ GeV²/c

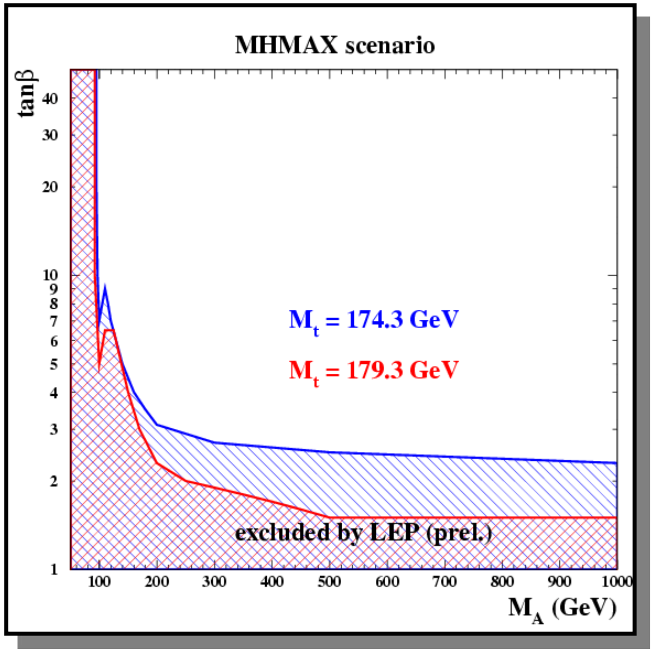
tanβ 0.4 – 5.6





LHWG-Note 2004

Benchmark Scenarios



suggested by Carena et al.,
EPJ C26, 601(2003)

Name	M_{SUSY} (GeV)	μ (GeV)	M_2 (GeV)	X_t (GeV)	M_{gluino} (GeV)
m_h-max	1000	200	200	2000	800
no mixing	2000	200	200	0	800

- **2 CP conserving scenarios considered**

(other two gluopphobic and small α not discusses)

- **to examplify the discovery potential**
- **mainly influence on phenomenology of h**

1) **MHMAX scenario** maximal M_h < 133 GeV

2) **Nomixing scenario** small M_h < 116 GeV

1) **MHMAX scenario** maximal M_h < 133 GeV

2) **Nomixing scenario** small M_h < 116 GeV

3) **Gluophobic scenario** M_h < 119 GeV
- coupling of h to gluons suppressed
- designed to affect discovery via
  gg→ h, h→γγ and h→ZZ →4l

4) **Small α scenario** M_h < 123 GeV
- coupling of h to b (τ) suppressed
  (for large tanβ and M_A 150→500GeV)
- designed to affect discovery via
  VBF, h→ττ and tth, h→bb

MSSM Higgs Accesible channels at LHC

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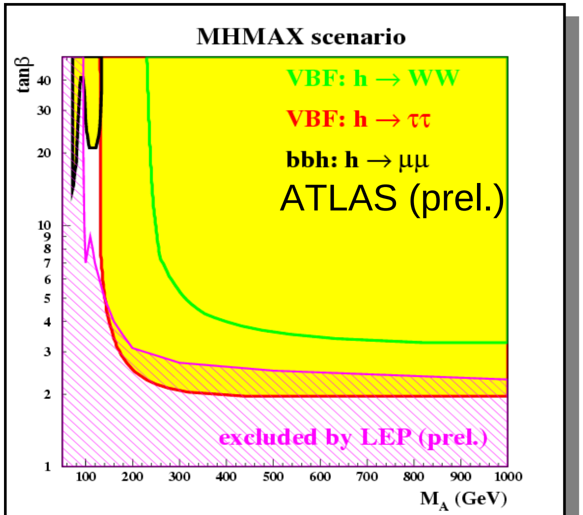
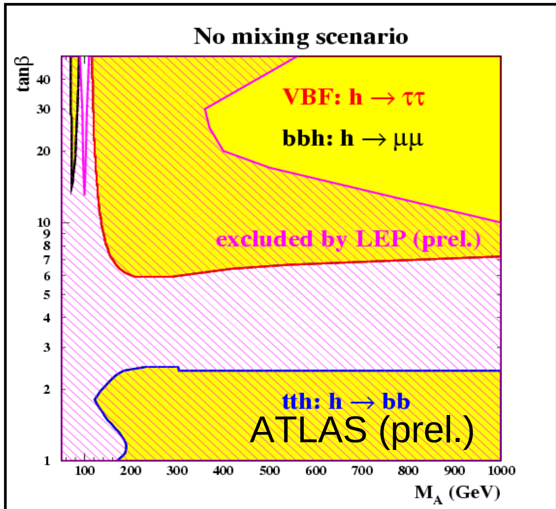
- **$h \to \gamma\gamma$, $tth \to bb$, $H \to ZZ^{(*)} \to 4\ell$** as in Standard Model
- **HWW, HZZ** strongly suppressed with $\tan\beta$,
- **A/Hbb, A/H$\tau\tau$, A/H$\mu\mu$** enhanced with $\tan\beta$
- typical of MSSM: **A/H $\to \tau\tau$, $\mu\mu$; $H^+ \to \tau\nu$, τb**

if SUSY accessible Higgs $\to$ SUSY particles or SUSY cascade $\to$ Higgs (not discussed)

Light Higgs Boson (30 fb^{-1})

h observable in entire parameter space and for all benchmark scenarios?

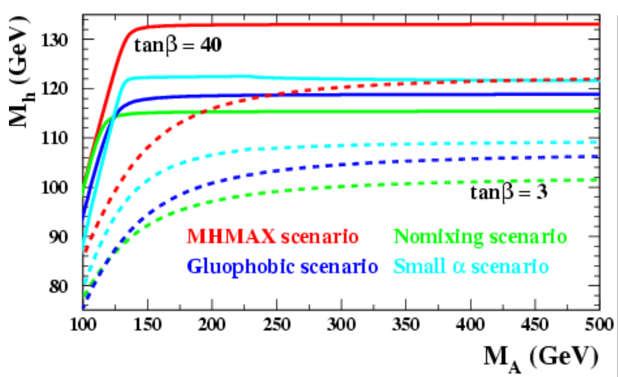




Value of M_h and M_a close at high tan β

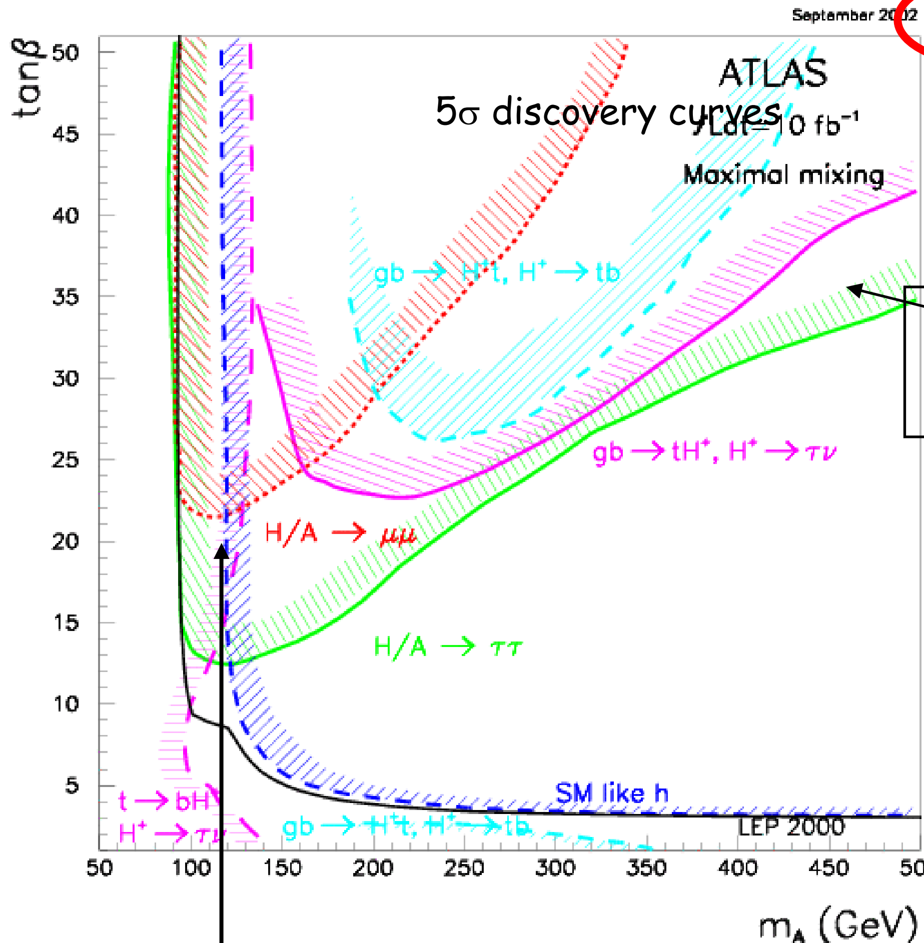
- most important channels: VBF
- differences mainly due to M_h

→ **almost entire (tanb, M_A)-plane covered**



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

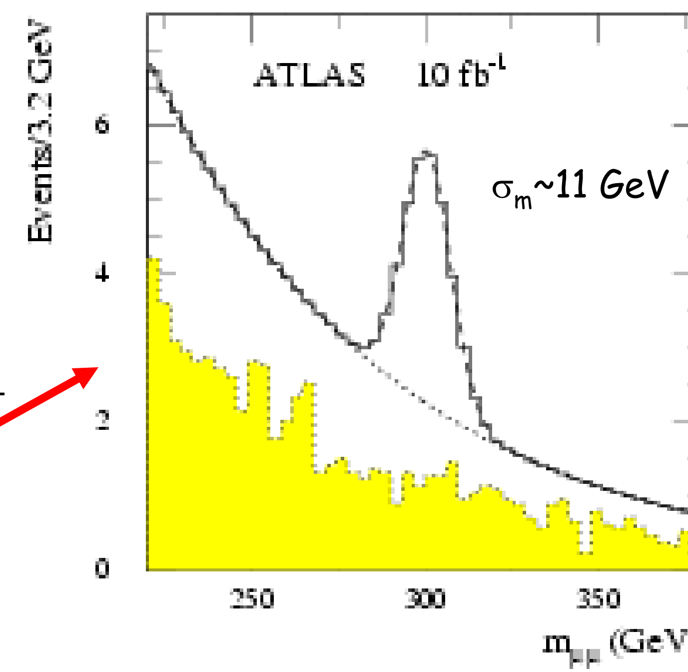
2002



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

A, H, $H^{\pm}$ cross-section ~ $tg^2\beta$
Best sensitivity from $A/H \rightarrow \tau\tau$, $H^{\pm} \rightarrow \tau\nu$

$A/H \rightarrow \mu\mu$, tg β = 38



$A/H \rightarrow \mu\mu$:

-- covers good part of region not excl. LEP
-- experimentally easier than $A/H \rightarrow \tau\tau$
-- crucial detector : Muon Spectrometer
(high-p_T muons from narrow resonance)

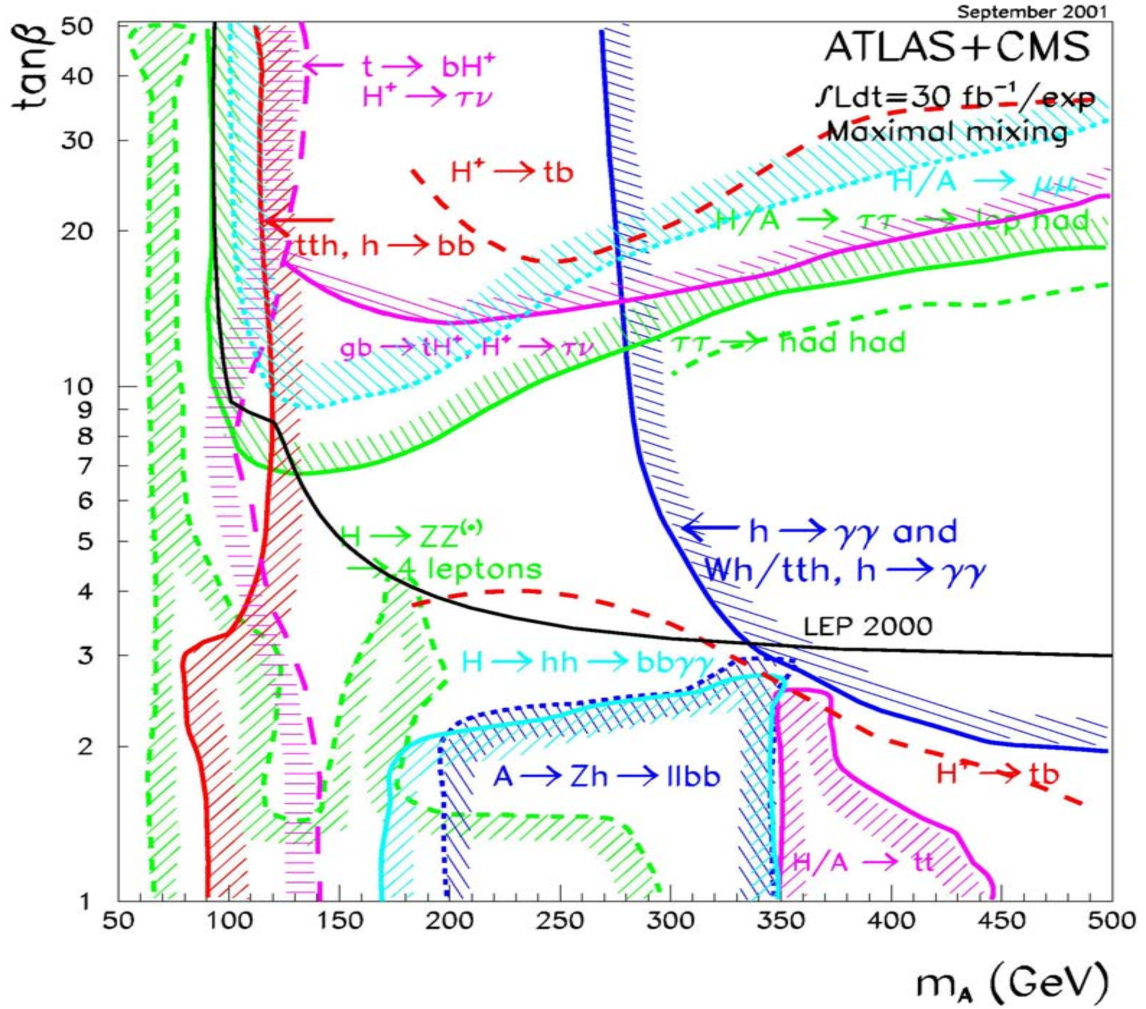
Overall discovery potential for MSSM Higgs bosons

SUSY particles heavy

5 σ contours

2001

- **Plane fully covered (no holes) at low L (30 fb^{-1})**
- **Two or more Higgs can be observed over most of the parameter space → disentangle SM / MSSM**



Tau's as final state signature in MSSM scenario

- **bbH, bbA with H/A $\rightarrow\tau\tau$ (lep-had and had-had)**
- **tt$\rightarrow H^{+}$bWb with H$\rightarrow \tau\nu$ (lep, had)**
- **gb$\rightarrow H^{+}$t with H$\rightarrow \tau\nu$ (had)**

In MSSM at large tanβ couplings
H$\tau\tau$, A$\tau\tau$, Hbb, Abb, $H^{+}\tau$b
strongly enhanced.

- **Extential a good τ identification**

Neutral Heavy Higgs Bosons (H/A)

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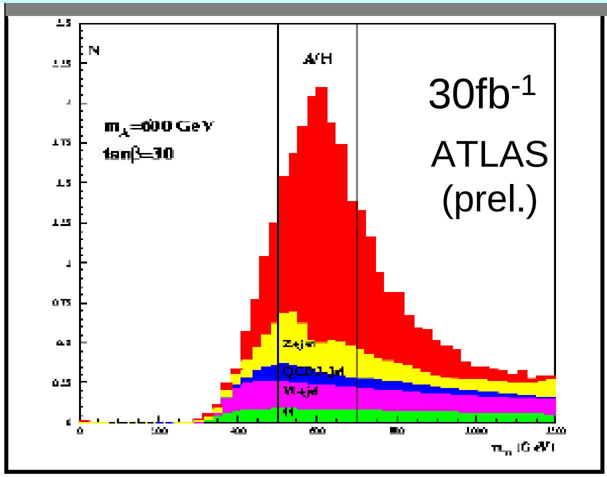
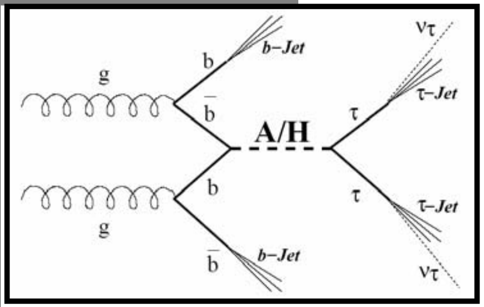
➢ **example: bbH/A, H/A → tt**

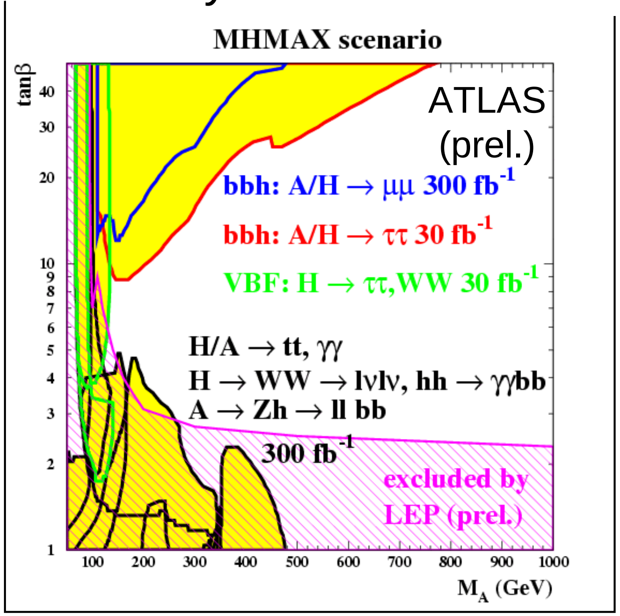
- σ_{prod} ~ $(\tan\beta)^2$; important at large $\tan\beta$
- new analysis: ττ→ had. had.
- BR(H/A→ττ) ~ 10 % , rest is bb





New: take running b-quark mass for σ_{prod}

discovery reach for H/A:



- ➢ only very few events remain after cuts (acceptance ~10^{-3})
- ➢ LVL1 trigger performance crucial
- ➢ detailed study: >90% LVL1 efficiency for M_A>450GeV via “jet+$E_{T,miss}$” and “t+ $E_{T,miss}$” triggers with a rate of ~1.4 kHz (within rate limit)

- ➢ bb H/A →bb ττ covers large tanβ region
- ➢ other scenarios similar
- ➢ intermediate tanβ region not covered

Example: bb $h_0 \rightarrow$ bb μμ

- Signal
  Pythia 6.226

  $h_0 \rightarrow \mu^+ \mu^-$ and bb
  $A_0 \rightarrow \mu^+ \mu^-$ and bb

  $\sigma \sim$ 0.2 - 0.01 pb

- **$Z/\gamma^* \rightarrow \mu^+ \mu^-$ and bb**
  σ*br(Z $\rightarrow \mu^+ \mu^-$ and bb) (Pythia 6.226)
  AcerMC (v.2.3) interfaced with Pythia 6.2 (hep/ph0405247).

  $\sigma \sim$ 22.8 pb

- **ZZ $\rightarrow \mu^+ \mu^-$ and bb :**
  σ*br(Z $\rightarrow \mu^+ \mu^-$) σ*br(Z$\rightarrow$ bb)
  Same order of magnitude of signal.
  Reduced by kinematical cuts.

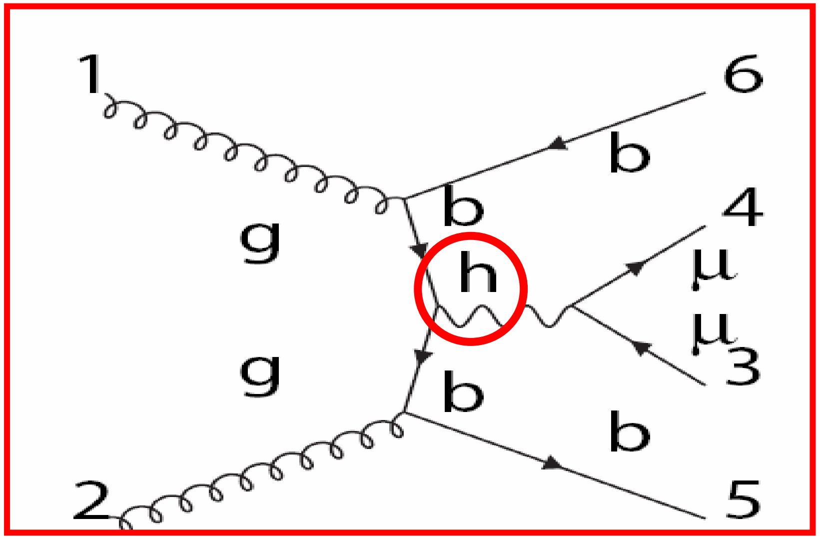
  $\sigma \sim$ 0.15 pb

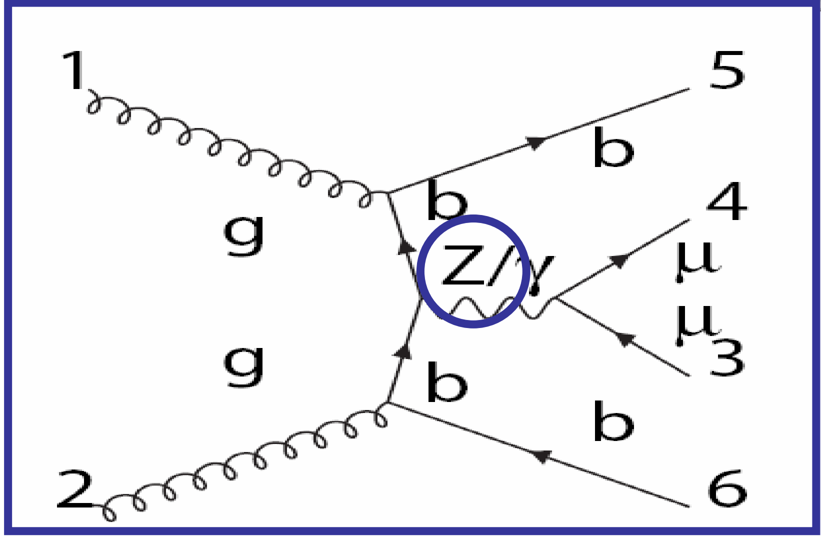
- **tt $\rightarrow W^+ W^-$ bb $\rightarrow$ bb μν μν**
  σ(tt) *br(t$\rightarrow$ bW)*br(W $\rightarrow$ μν)*br(t $\rightarrow$ bW)* br(W $\rightarrow$ μν)
  Missing energy in the event

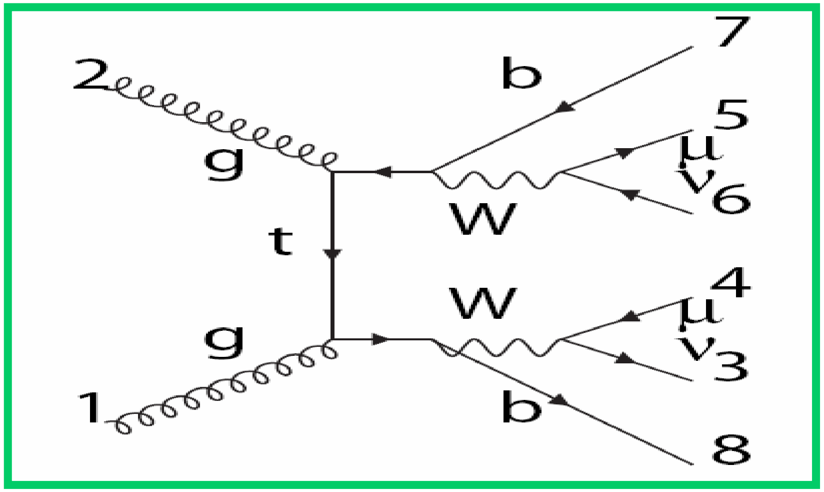
  $\sigma \sim$ 5.84 pb

M_{h0} 95 -130, GeV tan $\beta \sim$ 20 -50

Signal & background



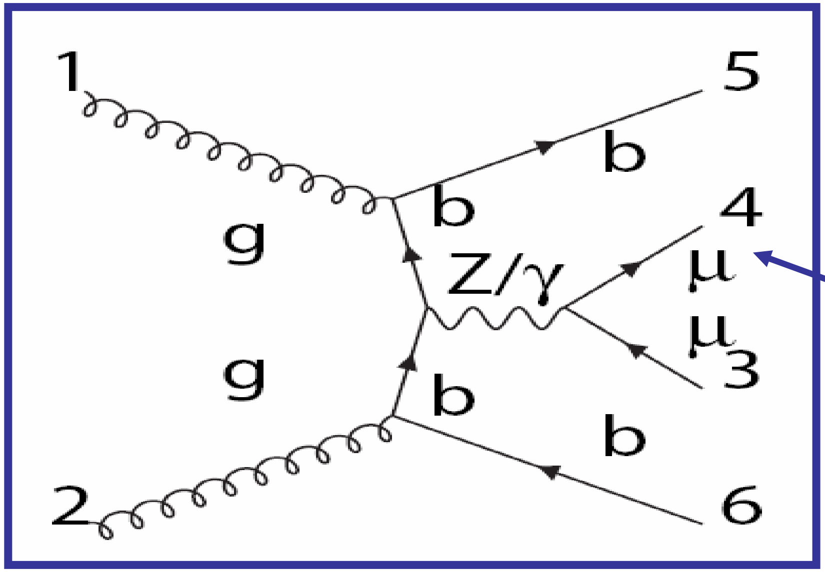


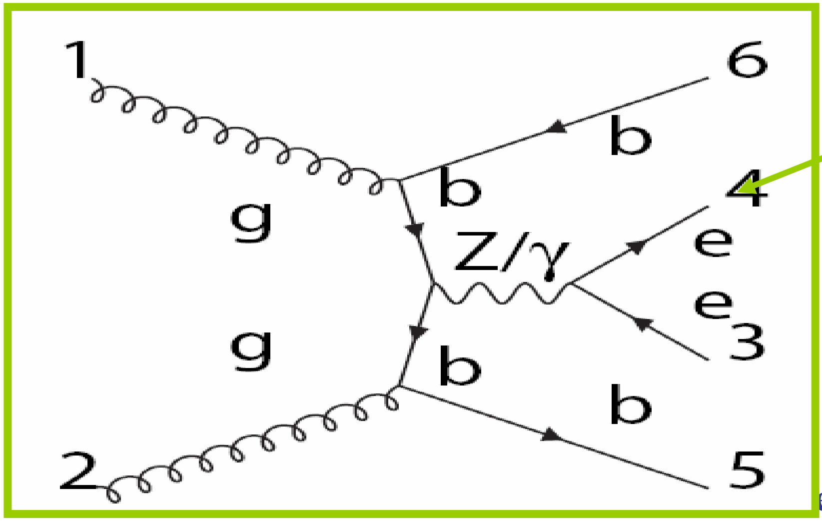


- **h_0 bb→ μ⁻ μ⁺bb**
- **Zbb → μ⁻μ⁺ bb**
- **tt missing energy**

Final state
2 b-jets and
2 μ (or 3-4)

Background Subtraction Method





Precise Knowledge of background crucial

- Experimental method

Proposed based on

$Z \rightarrow \mu^+ \mu^-$ and $Z \rightarrow e^+ e^-$

- Relying on experimental data
- Br($h_0 \rightarrow e^+ e^-$) neglegible

$$\propto \left(\frac{m_\mu}{m_e} \right)^2$$

- **Different Inner Bremhstrahlung**

Selection

➢Basic cuts:

- A pair of opposite **muons** with $\mathbf{p_t}$ **> 10 GeV |η| < 2.5**
- A pair of **jets** with $\mathbf{E_t}$ **> 10 GeV and |η| < 2.5**

➢**Selection**

- **At least 1 b-jets (p_T > 15 GeV & b-tag weight>1)**
- **25 GeV < $P_T^{\mu 1}$ < 100 GeV**
- **25 GeV < $P_T^{\mu 2}$ < 60 GeV**

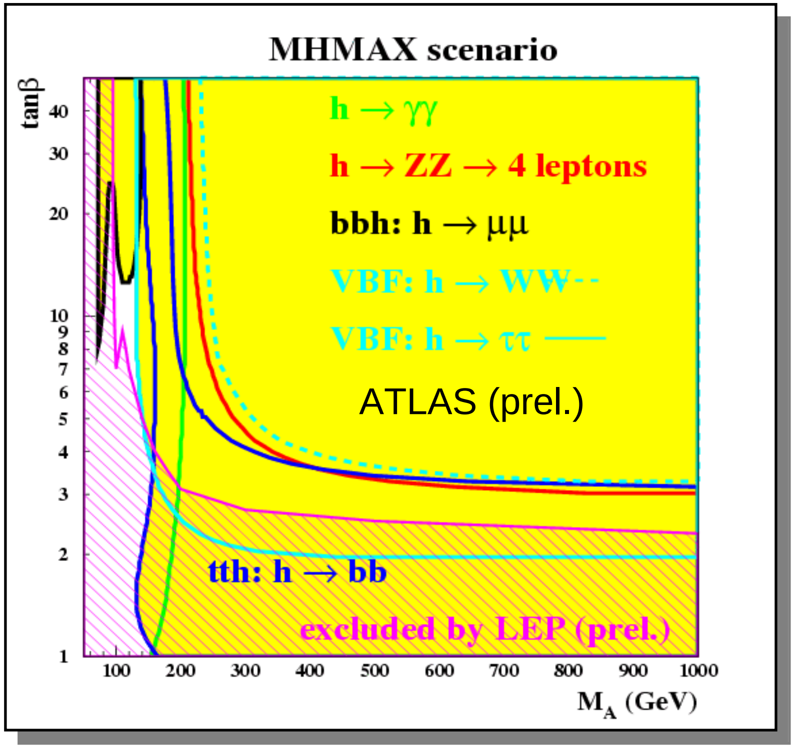
} for tt background **ATLAS-PHYS-2003-015**

- **Minv($\mu^+\mu^-$) +/- ΔM (Γ_{A0}, Γ_{h0}, ΔRes_{exp})**
- **P_T^{b1} < 60 GeV**
- **P_T^{b2} < 55 GeV**
- **P_T missing < 80 GeV**

} **for tt background**

N.B. all value of cuts for tt are Indicative not at all tuned!

Light Higgs Boson (300 fb^{-1})



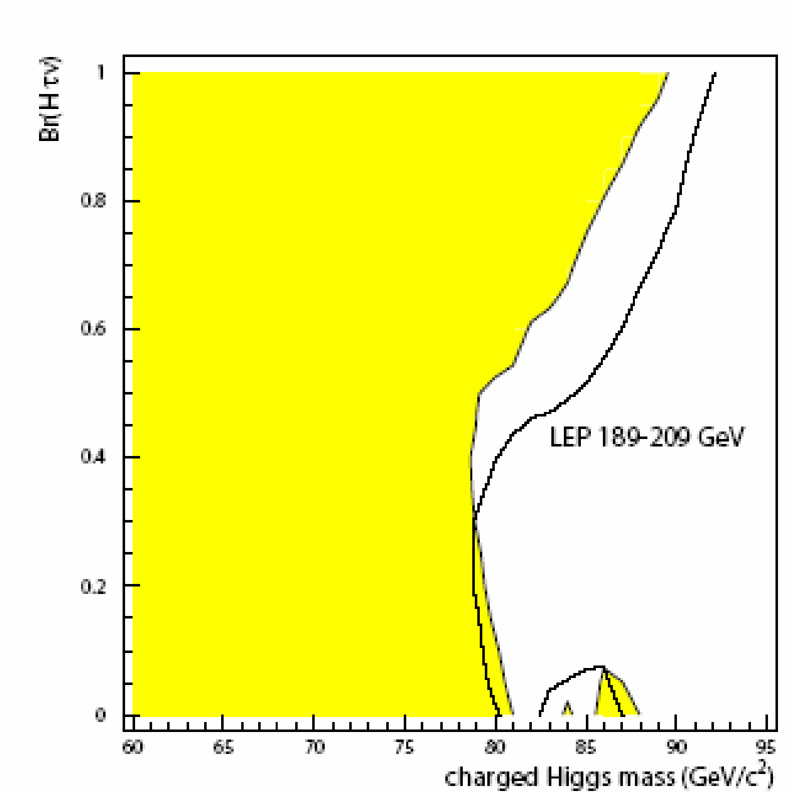
VBF: only 30 fb^{-1}

- also $h \rightarrow \gamma\gamma$, $h \rightarrow ZZ \rightarrow 4$ leptons, $tth \rightarrow bb$ contribute
- large area covered by several channels
  → stable discovery and parameter determination possible
- small area uncovered (M_h = 90 to 100 GeV)

Charged Higgs at LEP

$MH^{+} > 78.6$ GeV

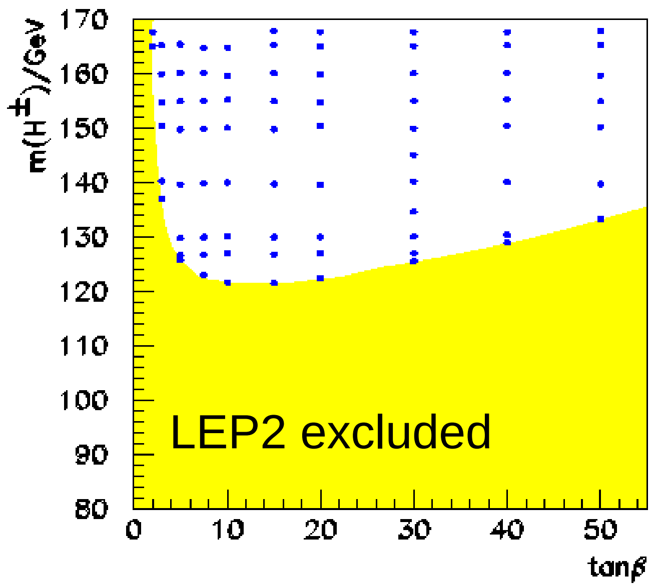
@95% C.L.



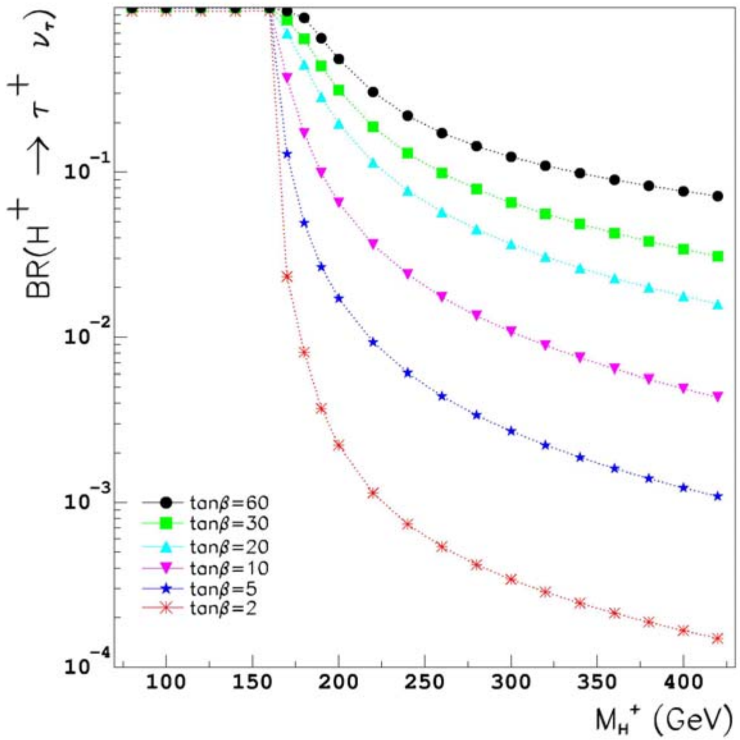
Charged Higgs

Production mechanisms:

- below top-quark mass: $gg,qq \to tt \to WbH^+b$
- above top-quark mass: $gb \to tH^+ \to t\,\tau\nu$



BR ($H^+ \to \tau\nu$)

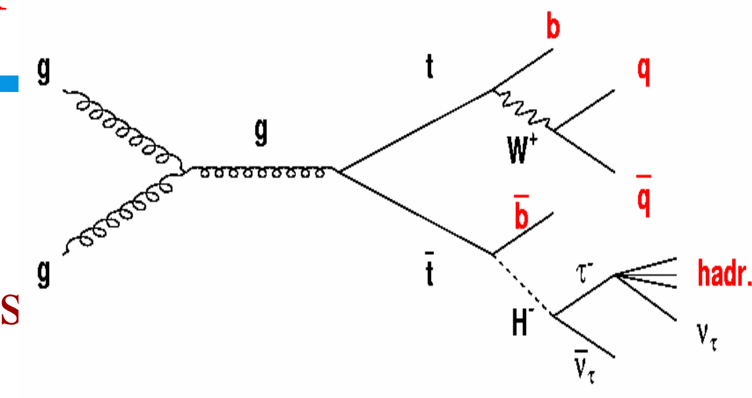


Charged Higgs below top-quark mass

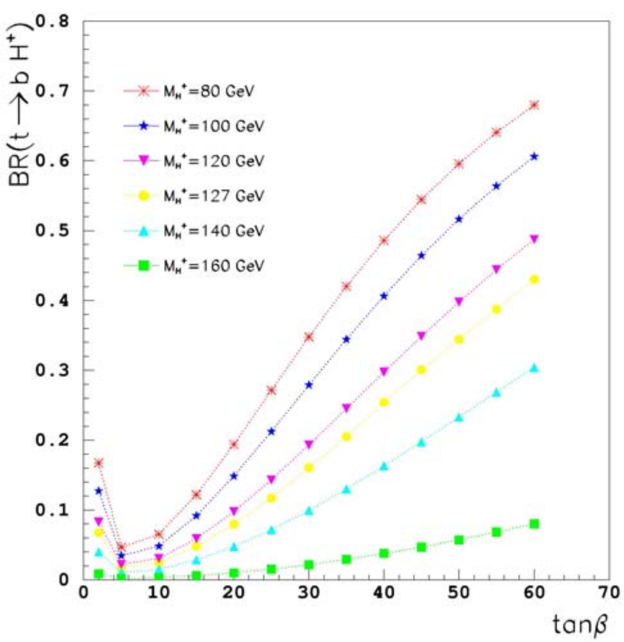
Production mechanism:

below top-quark mass:

$gg,qq \rightarrow tt \rightarrow WbH^{+}b$ large N_{exp}(tt pairs



$BR(t \rightarrow H^{+}b)$

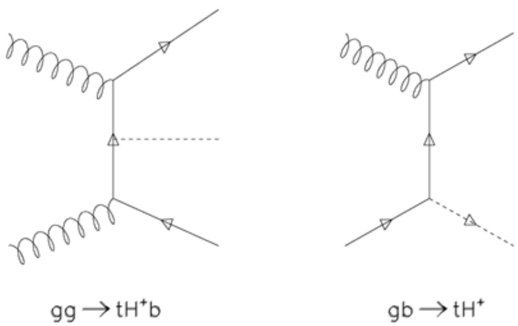


signal:

large BR $(H \rightarrow \tau\nu) \rightarrow 100\%$

bgd. : BR$(W \rightarrow \tau\nu) \rightarrow 10\%$

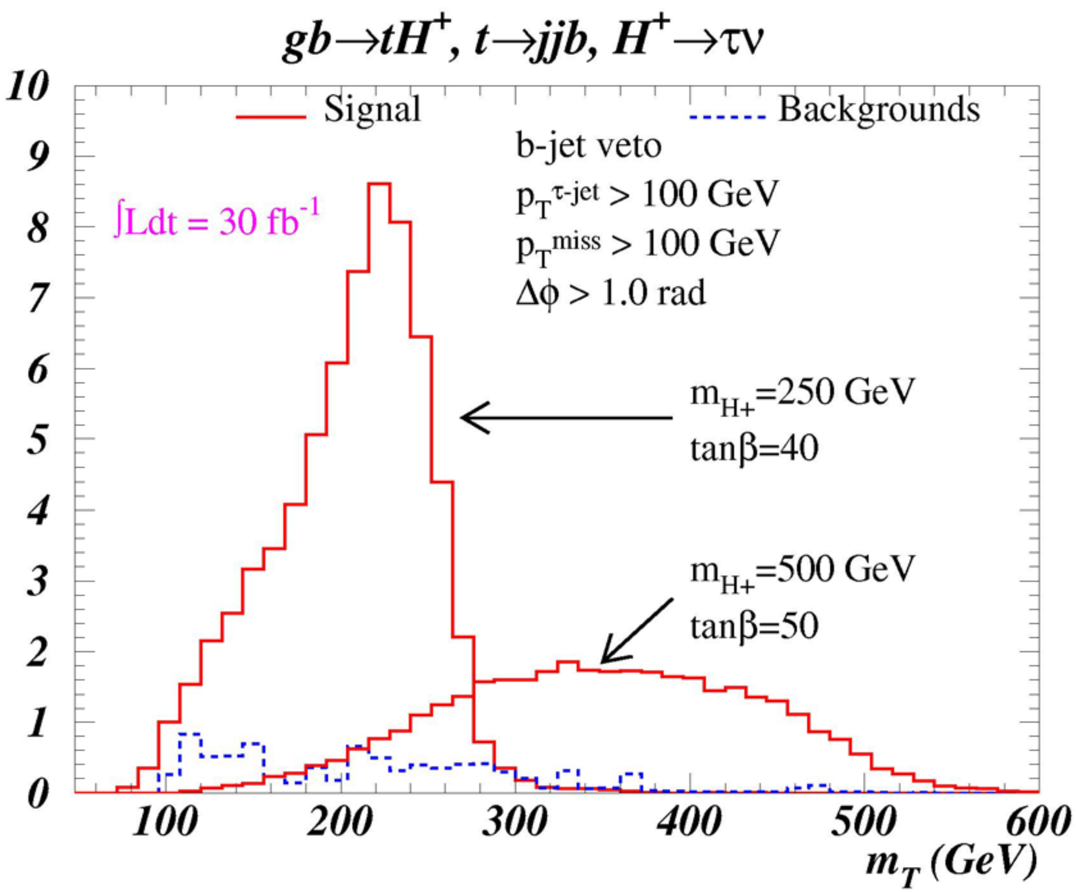
BR$(\tau \rightarrow \text{had } \nu) \rightarrow 65\%$



Charged Higgs at large masses

σ= 5 - 0.1 pb

<u>Bgds:</u> almost bgd free
W+jets, tt, Wbt



- t $\longrightarrow$ jjb reconstructed
- trigger on tau+E_T^{miss}
- tau-id crucial
- profit from 100% tau polarisation to enhance rejection against W $\longrightarrow$ $\tau\nu$
- transverse mass can be reconstructed
- good sensitivity to mass and tanβ measurement:

at 300fb^{-1}:

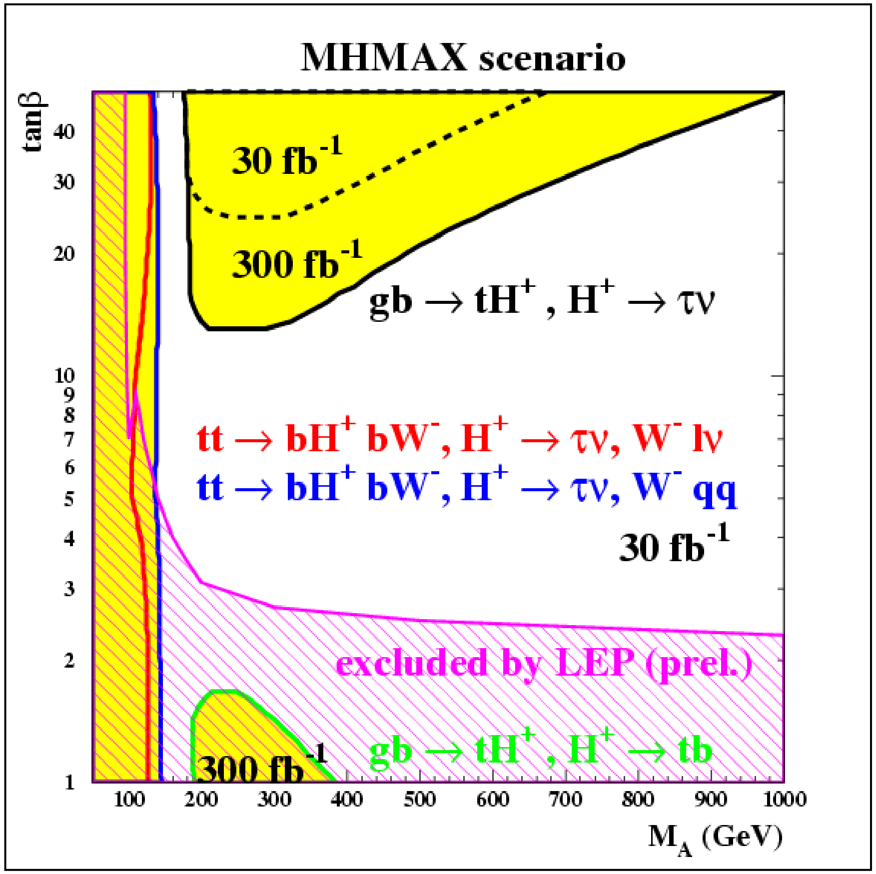
$\Delta m/m \sim$ 1-2 %

$\Delta \tan\beta/\tan\beta \sim$ 5-7 %

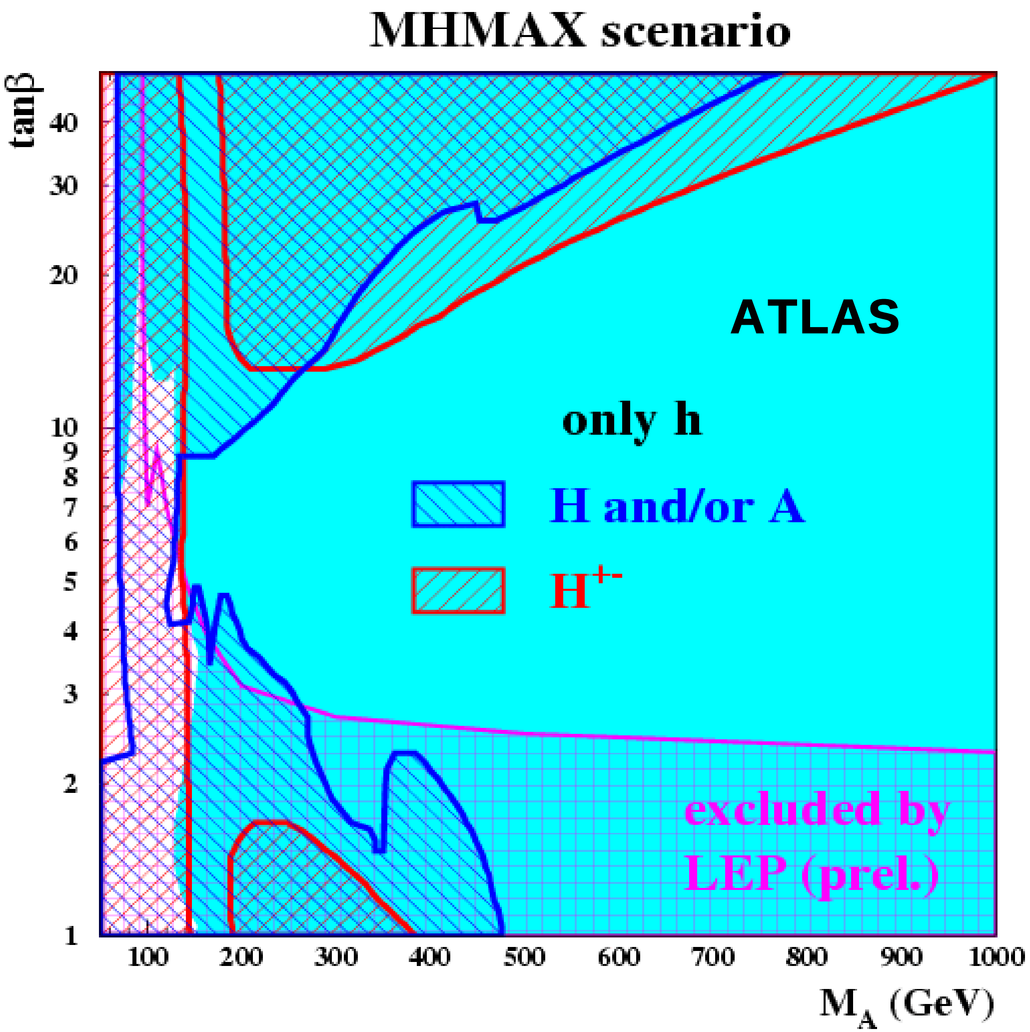
Charged H^{+-} -> $\tau\nu$

at large masses

5σ discovery contours



Overall Discovery Potential: 300 fb^{-1}

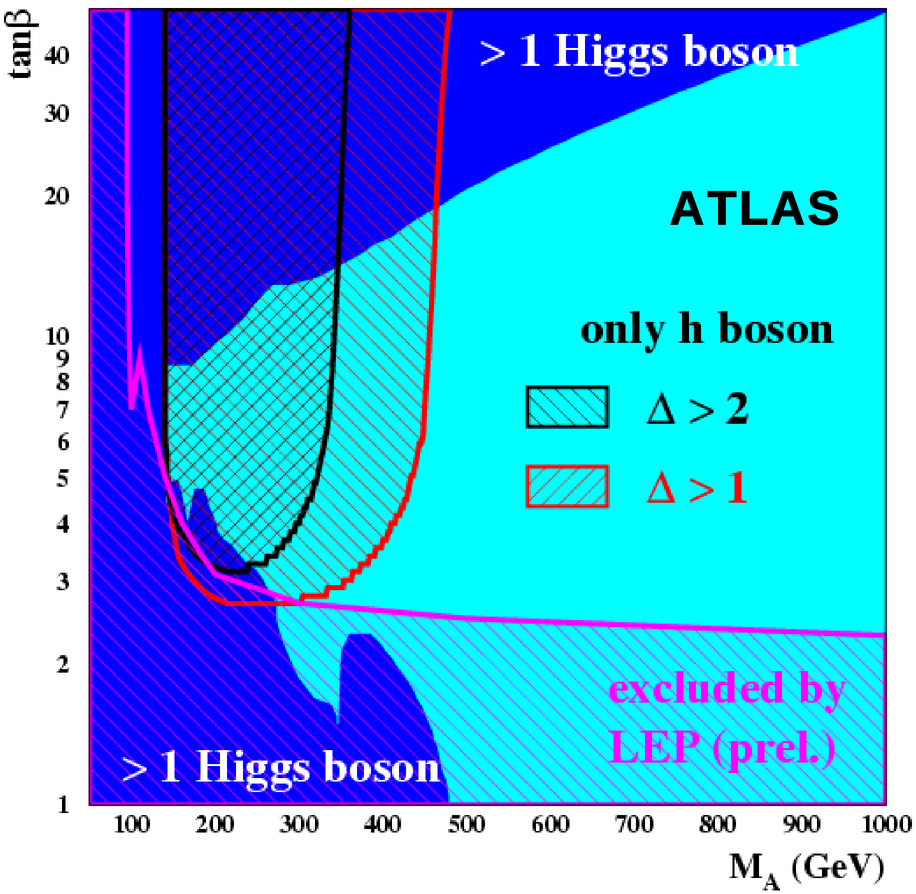


- Whole plane covered for at least one Higgs
- Large wedge area (intermediate tan β) where **only h** is observed
- No direct evidence for higgs beyond SM

→Can we distinguish between SM and extended Higgs sectors by parameter measurements?

SM or Extended Higgs Sectors?

MHMAX scenario



First look using rate measurements from VBF channels ($30fb^{-1}$)

$$R = \frac{BR(h \to \tau\tau)}{BR(h \to WW)}$$

Deviation from SM expectation

$$\Delta = |R_{MSSM} - R_{SM}| / \sigma_{exp}$$

potential for discrimination seems promising!

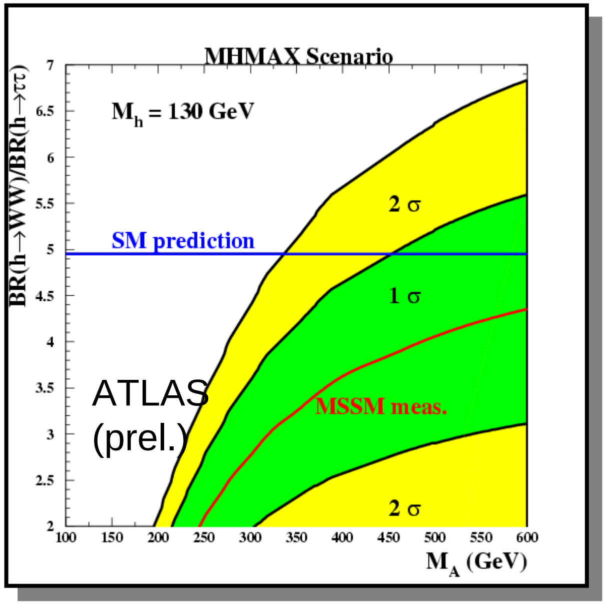
- **only statistical errors considered**
- **assumes Higgs mass exactly known**

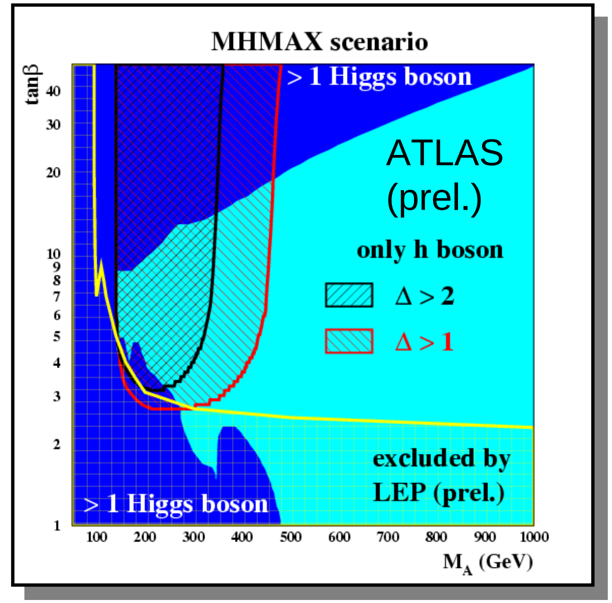
SM or extended Higgs Sector ?

- estimate of sensitivity from rate measurements in VBF channels (30 fb^{-1})
- compare expected measurement of R in MSSM with prediction from SM

$$R = \frac{BR(h \to WW)}{BR(h \to \tau\tau)}$$

$$\Delta = |R_{MSSM} - R_{SM}| / \sigma_{exp}$$



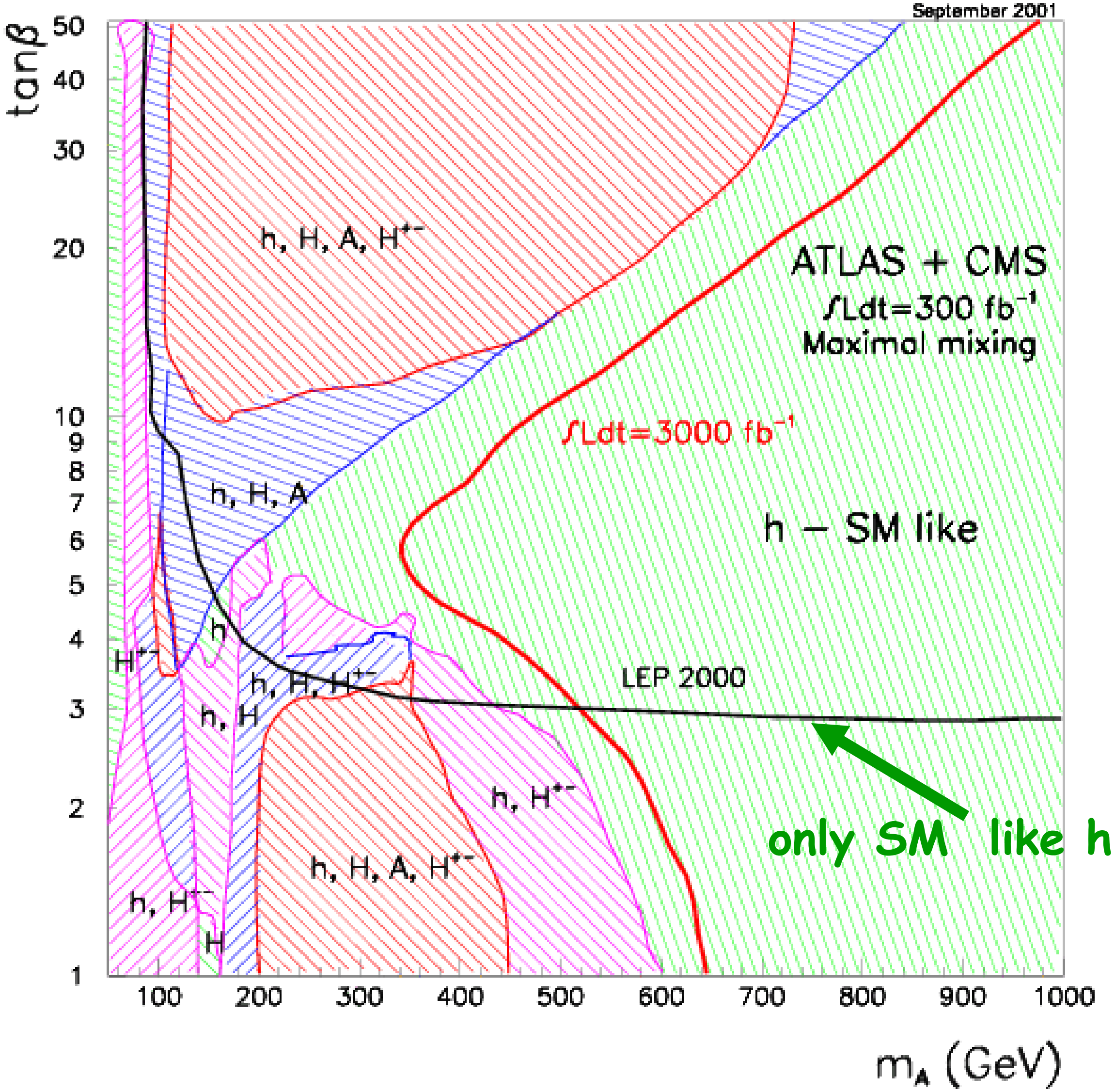


- only statistical errors
- assume M_h exactly known

potential for discrimination

- seems promising
- needs further study incl. sys. errors

Conclusions on MSSM Higgs sector



- **Discovery potential well understood** **with assumption of heavy SUSY particles.**

- **Several overlapping channels, studies extended to m_A=1 TeV range.**

■ (red)	4 Higgs
■ (blue)	3 Higgs
■ (pink)	2 Higgs
■ (green)	1 Higgs

Conclusions

- SM / MSSM Higgs could be discovered with ~ 10 – 30 fb^{-1}
  - Discovery of SM possible with 10 fb^{-1}
  - MSSM parameter space covered with 30 fb^{-1}

- Precise measurements of Higgs parameters with 300 fb^{-1} :

masses to 0.1 – 1%, width to ~ 5-30%,
couplings to 10-30%

Outline

- Introduction to Hadron Collider Physics
- LHC and ATLAS detector
- Test of Standard Model at LHC
  - Parton distribution function
  - QCD + jet physics
  - Electroweak physics (Z/W –bosons)
  - Top physics
- Search for Higgs boson
- **Supersymmetry**
- Conclusions

Introduction to Supersymmetry

Relates fermions and bosons:

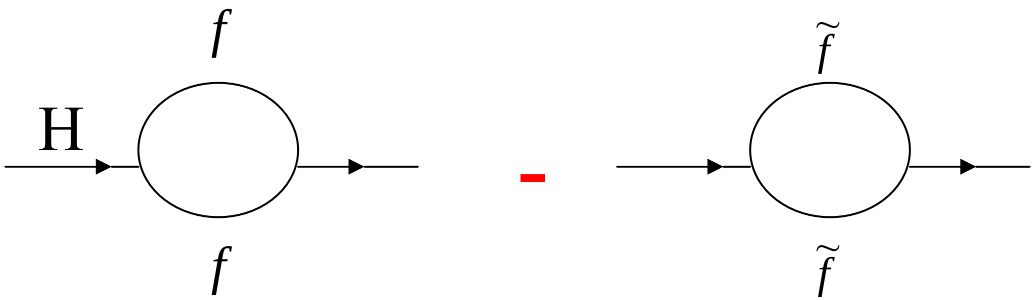
for each particle *p* with spin s, there exists a SUSY partner with spin s-1/2.

Ex. : q (s=1/2) → (s=0) squarks

Z (s=1) → (s=1/2) zino

Motivations:

- unification of fermions and bosons is attractive
- solves problems of SM, e.g. divergence of Higgs mass :



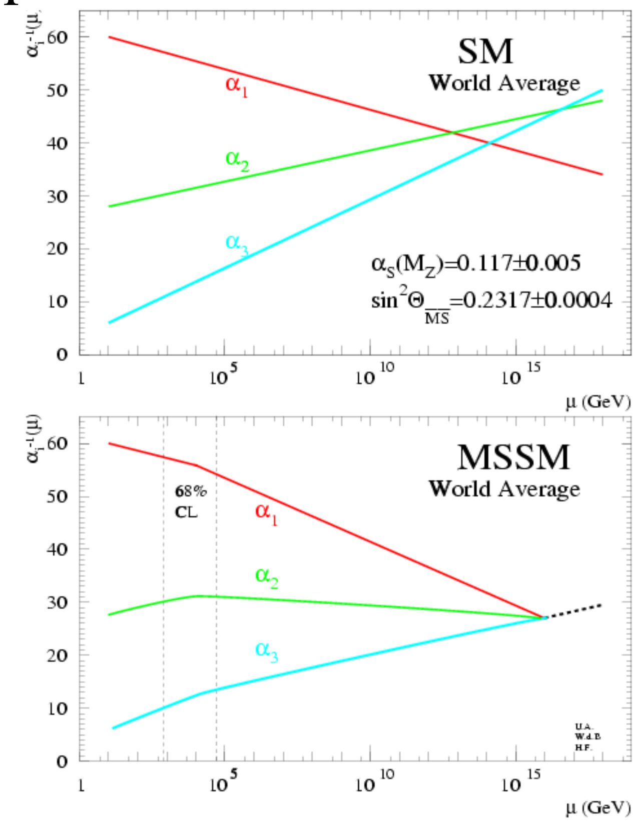
Fermion and boson loops cancel, provided $m_{SUSY} \leq$ TeV.

Introduction to Supersymmetry

Particle content of the Standard Model nicely explained in GUT

SU(5) -> SU(3) x SU(2) x U(1)

Measured coupling constants unify at GUT scale in SUSY but not in SM.



SM

SUSY

QED

Weak

QCD

➢SUSY provides a good candidate for dark matter in the Universe: the Lightest SUSY Particle (LSP)

Introduction to Supersymmetry

Does not contradict predictions of SM at low energy

→ not ruled out by present experiments.

Predicts a light Higgs

However: no experimental evidence for SUSY as yet

Either SUSY does not exist

OR

m_{SUSY} large (>> 100 GeV) → not accessible to present machines

LHC should say "final word" about SUSY if $m_{SUSY} \leq$ a few TeV

➢ **Minimal Supersymmetric Standard Model (MSSM)** is the supersymmetric extension of Standard Model with minimal particle content and R-parity conservation.

Particle spectrum in Supersymmetry

SM	Supersymmetry: weak eigenstates	name	mass eigenstates	
q	$\tilde{q}_L, \tilde{q}_R$	s–Quark	$\tilde{q}_1, \tilde{q}_2$	
ℓ	$\tilde{\ell}_L, \tilde{\ell}_R$	s–Lepton	$\tilde{\ell}_1, \tilde{\ell}_2$	
ν	$\tilde{\nu}$	s–Neutrino	$\tilde{\nu}$	
g	$\tilde{g}$	gluino	$\tilde{g}$	
$W^{\pm}$	$\tilde{W}^{\pm}$	wino		
H_1^+	$\tilde{H}_1^+$	higgsino	$\tilde{\chi}^{\pm}_{1,2}$	Chargino
H_2^-	$\tilde{H}_2^-$	higgsino		
W^0	$\tilde{W}^0$	wino		
B^0	$\tilde{B}^0$	bino		
H_1^0	$\tilde{H}_1^0$	higgsino	$\tilde{\chi}^0_{1,2,3,4}$	Neutralino
H_2^0	$\tilde{H}_2^0$	higgsino		

Each SM particle gets SUSY partner

spin differ by 1/2

2 Higgs doublets for up- and down- quarks

Equal number of bosons and fermions solve hierarchy problem
-> corrections to Higgs mass ~ SUSY mass scale

(S)particle reminder

	SM+ MSSM Higgs	SUSY	
Spin-1/2	quarks (L&R) leptons (L&R) neutrinos (L&?)	squarks (L&R) sleptons (L&R) sneutrinos (L&?)	Spin-0
Spin-1	γ, Z^0 → B, W^0 $W^\pm$ gluon	Bino Wino^0 $\text{Wino}^\pm$ gluino	Spin-1/2
Spin-0	h^0 H^0 A^0 $H^\pm$	$\tilde{H}^0$ $\tilde{H}^\pm$	Spin-1/2

After Mixing (Spin-1/2):

- 4 x neutralino
- gluino
- 2 x chargino

Extended higgs sector (2 doublets)

SUSY breaking

SUSY particles not yet observed -> SUSY broken
SUSY may be broken „by hand" or in the hidden sector
EW requires spontaneus breaking (Higgs mechanism)

<u>Gravitation</u>

$M \sim M_P \sim 10^{18}$ GeV
$\sqrt{F} \sim 10^{11}$ GeV

hidden SUSY sector
$\sqrt{F} \sim \sqrt{\frac{M}{G_F^{1/2}}}$

<u>Gauge</u>

$10^3 < M < 10^{15}$ GeV
$10^3 < \sqrt{F} < 10^{10}$ GeV

visible particle spectrum
e, $\mu, \tau, \ldots$ **, W,Z**
$\tilde{e}, \tilde{\mu}, \tilde{\tau}, \ldots \tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0$

$M_{\tilde{G}} \sim 2,5$ TeV

$M_{\tilde{G}} < 1$ GeV $\rightarrow$ LSP

short or long lived NLSP

MSSM parameters

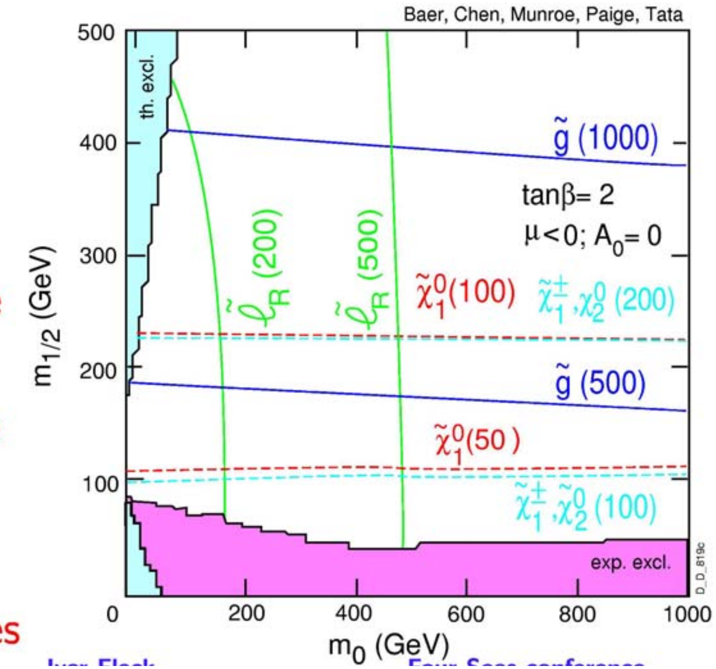
- M_{susy},sfermion mass at EW scale
- M_2, $SU(2)_L$ gaugino mass at EW scale
- μ, supersymmetric Higgs boson mass parameter.
- tan β, the ratio of the two Higgs fields doublets
- A_0, a universal trilinear higgs-squarks coupling at EW scale. It is assumed to be the same for up-type squarks and for down types quarks.
- m_A, mass of CP-odd Higgs boson.
- M_{gluino}, it affects loop corrections for stop and bottom

minimal SUGRA

all 3 coupling constants meet at $\sim 10^{16}$ GeV
$\rightarrow$ can be embedded in Grand Unified Theories (GUT)

common masses for sfermions and gauginos at GUT scale

- m_0 : common mass for sfermions at GUT scale
- $m_{1/2}$: common masses for gauginos at GUT scale
- A_0 : common trilinear Higgs-sfermion-sfermion coupling at GUT scale
- μ : mixing of Higgs doublets
- $\tan\beta = \frac{\langle \nu_2 \rangle}{\langle \nu_1 \rangle}$: ratio of Higgs vacuum expectation values



$\rightarrow$ 5 free parameters: m_0, $m_{1/2}$, A_0, sign(μ), $\tan\beta$
determine all masses, cross-sections, branching ratios

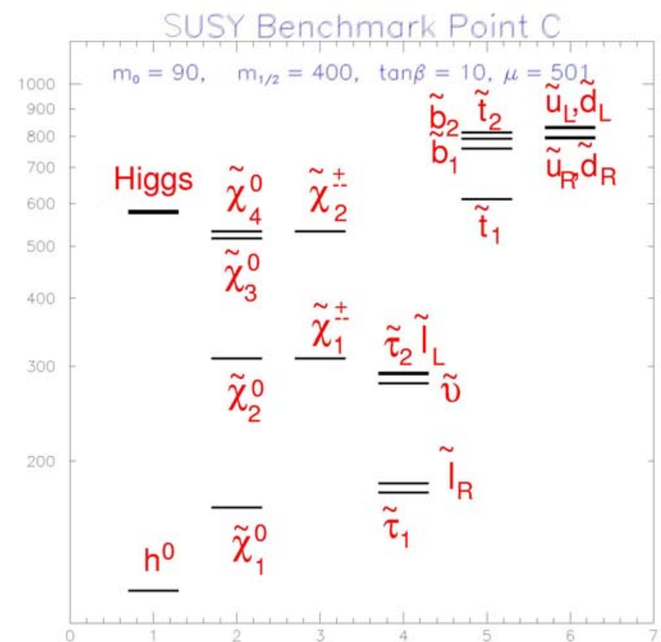
$m^2(\tilde{\ell}_R) \approx m_0^2 + 0.15\ m_{1/2}^2$ $\quad m^2(\tilde{\ell}_L) \approx m_0^2 + 0.52\ m_{1/2}^2$

$m(\tilde{\chi}_1^0) \approx 0.45\ m_{1/2}$ $\quad m(\tilde{\chi}_2^0) \approx m(\tilde{\chi}_1^\pm) \approx 0.9\ m_{1/2}$

$m^2(\tilde{g}) \approx 6.25\ m_{1/2}^2$ $\quad m^2(\tilde{q}) \approx m_0^2 + 6\ m_{1/2}^2$

for $m_0 > 0.45\ m_{1/2}$ sleptons heavier than $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$

3rd generation sparticles lighter due to mixing and large Yukawa couplings



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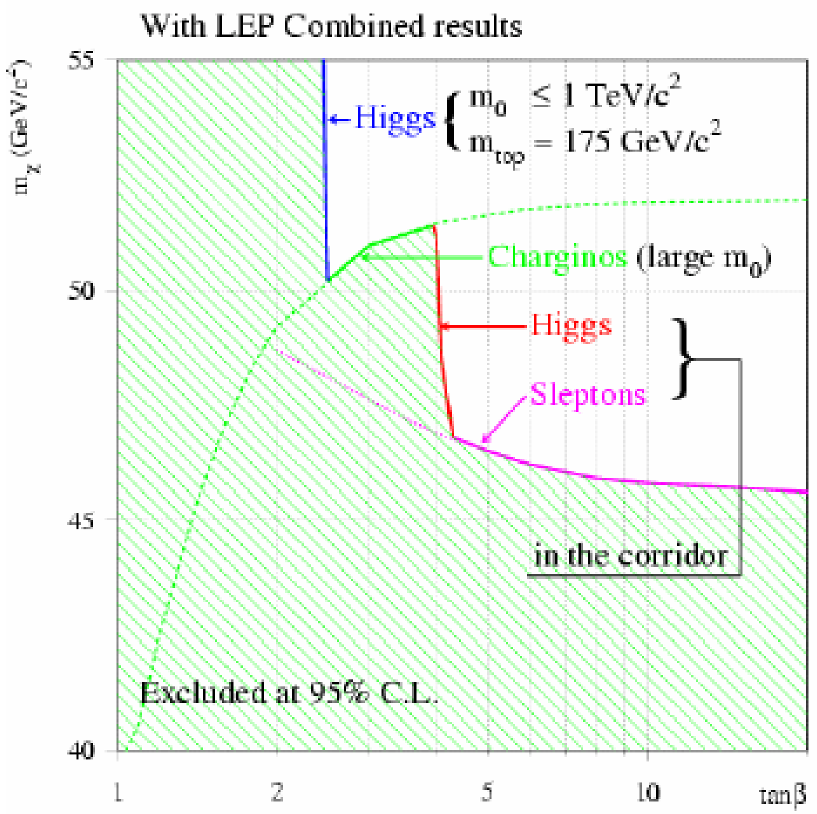
Present limits

Mass sleptons and charginos $\left\{ \begin{array}{l} \tilde{\ell}(\tilde{e},\tilde{\mu},\tilde{\tau}) \\ \chi_1^{\pm}, \chi_2^{\pm} \end{array} \right.$ $>$ 90-100 GeV LEP II

Mass squarks and gluinos $\left\{ \begin{array}{l} \tilde{q} \\ \tilde{g} \end{array} \right\}$ 250 GeV Tevatron Run 1

Mass neutralino $\left\{ \chi^0_{1,2,3,4} \right\}$ ~ 45 GeV LEP II

Present limits



LEP II on mass of lightest supersymmetric particle

Lightest supersymmetric particle = neutralino

LSP = $\chi^0{}_1$

R-parity

new discrete multiplicative symmetry in SUSY models

$$R_p = (-1)^{2S+3B+L}$$

S: spin, B: baryon number, L: lepton number

$$\begin{aligned} R_p &= 1 \quad \text{for SM particles} \\ R_p &= -1 \quad \text{for SUSY particles} \end{aligned}$$

superpotential contains R-parity conserving and violating terms

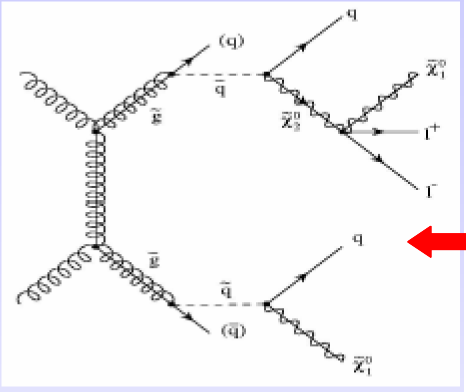
	R_p	$\not{R}_p$
SUSY particles produced in	pairs	pairs or singly
the LSP is the LSP	$\tilde{\chi}_1^0$ is stable	any sparticle decays
experimental signature	$\not{E}_T^{miss}$	E_T

Exclusion limits under assumption of R_p-conservation are not valid under $\not{R}_p$-violation.

Hunting for SUSY

•Squarks and gluinos are strongly Produced

➢**Sparticles decay through cascade to the lightest SUSY particle (LSP)**



Jets
Leptons
E_T^{miss}

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

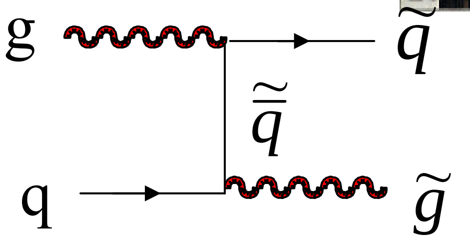
2. Establish the SUSY mass scale use inclusive variables, e.g. effective mass distribution.

3. Determine model parameters (difficult)

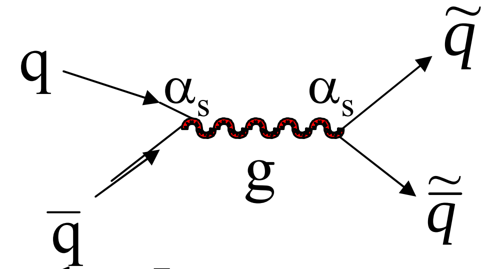
Strategy: select particular decay chains and use kinematics to determine mass combinations.

Production of SUSY particles at LHC

•Squarks and gluinos produced via strong processes
$\rightarrow$ large cross-section

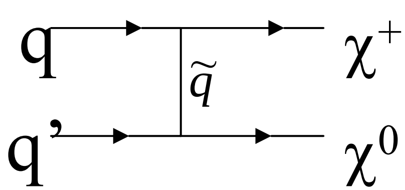


$\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ are dominant SUSY processes at LHC if kinematically accessible



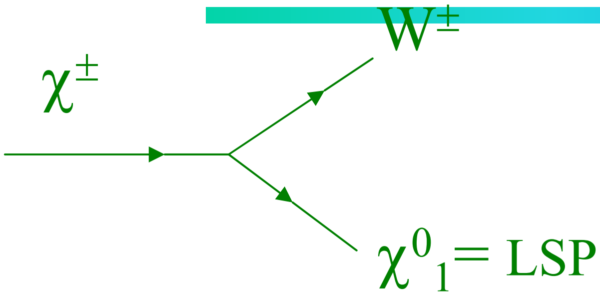
m ~ 1 TeV $\sigma \sim 1$ pb $\rightarrow 10^4$ events per year produced at low L

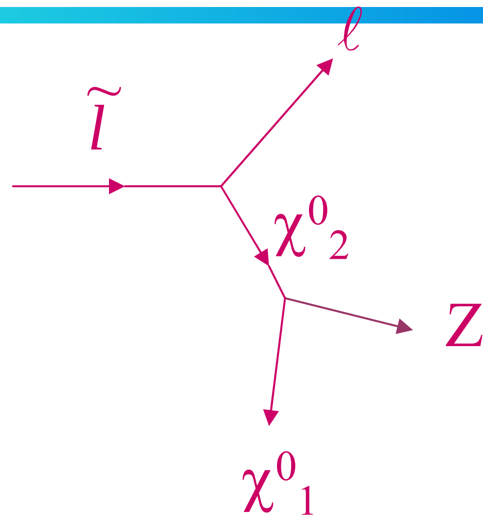
•Charginos, neutralinos, sleptons produced via electroweak processes $\rightarrow$ much smaller rate

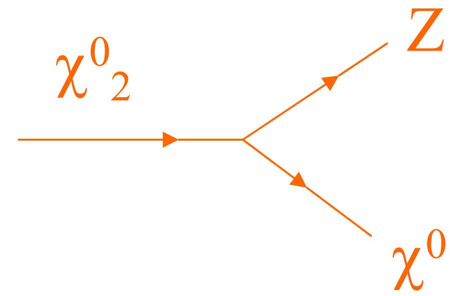


$\sigma \approx$ pb $m_\chi \approx 150$ GeV

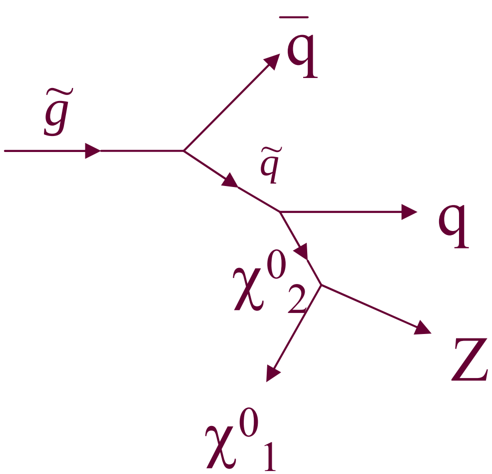
Decays of SUSY particles







$\tilde{q}$, $\tilde{g}$ heavier → more complicated decay chains



Cascade decays

involving many leptons and /or jets

+ missing energy (from LSP)

Decays of SUSY particles

Exact decay chains depend on model parameters (particle masses, etc.)

However : whatever the model is, we know that

$\tilde{q}, \tilde{g}$ are heavy (m > 250 GeV)

decays through cascades favoured

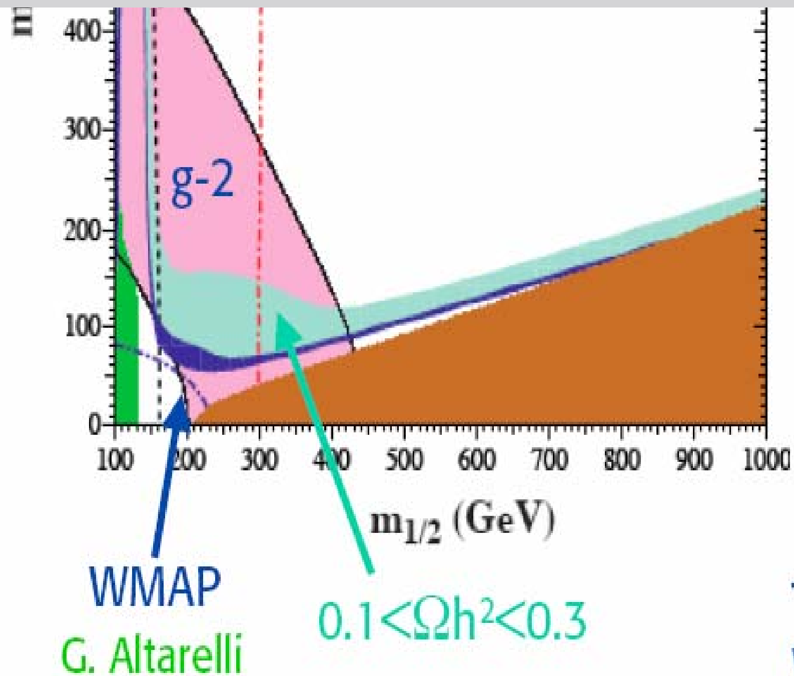
⇒ **many high-p_T jets/leptons/W/Z in the final state + E_T^{miss}**

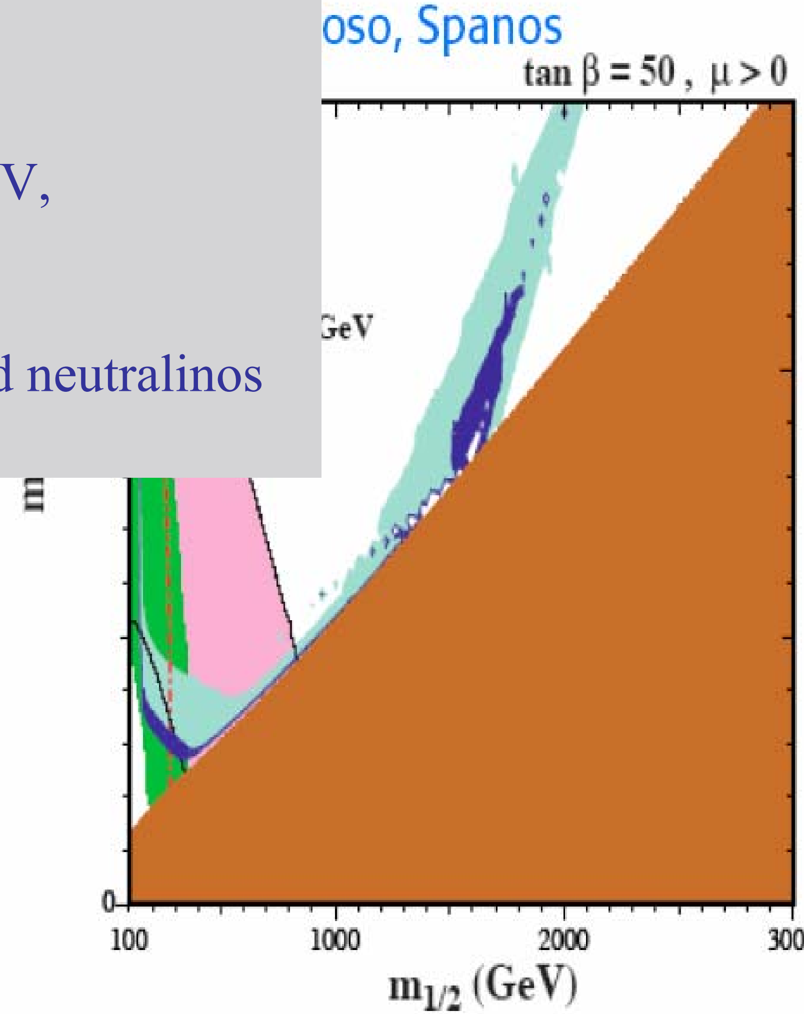
at LHC will be easy to extract SUSY signal from SM background

In the **coannihilation point**:

m_0 =70GeV,$m_{1/2}$,350 GeV, A_0= 0 GeV,
tan (β)= 10 sign(μ) = +

Small difference between sleptons and neutralinos
soft leptons in the final state





This is for the CMSSM
With less constraints more space

Detector performances

- Precise jets measurements, leptons, E^{miss}_T
- Large kinematical coverage

Required performances:

- **Lepton** measurement: $p_T \sim$ GeV, $\rightarrow$5 TeV ($b \rightarrow \ell X$….)
- **Mass Resolution** (m ~ 100 GeV)

~ 1% ($H \rightarrow \gamma\gamma$, 4 ℓ)

~ 10% ($W \rightarrow jj$, $H \rightarrow bb$)

- **Calorimetric coverage** $|\eta| < 5$ (E^{miss}_T, forward jet tag)
- **Particle Identification**

$\varepsilon_b \sim 50\%$ $R_j \sim 100$ ($H \rightarrow bb$, SUSY)

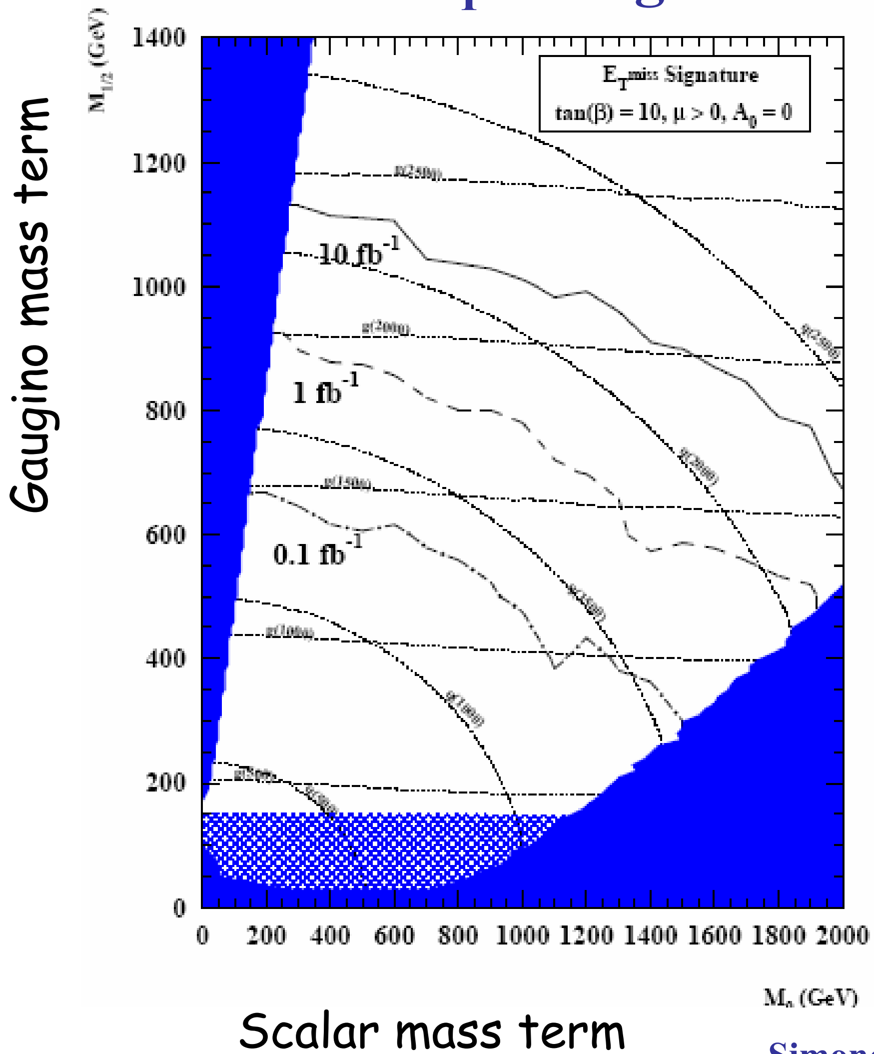
$\varepsilon_\tau \sim 50\%$ $R_j \sim 100$ ($A/H \rightarrow \tau\tau$)

$\varepsilon_\gamma \sim 80\%$ $R_j \sim 10^3$ ($H \rightarrow \gamma\gamma$)

$\varepsilon_e > 50\%$ $R_j \sim 10^5$

SUSY Discovery

Reach from E_T ^{miss} signature



- SUSY cascade decays give rise to many inclusive signatures:
- leptons, b-jets, t's ...
- Final discovery limit ~ 2.5 TeV squark or gluino
- Initially will be limited by detector uncertainties, not SUSY statistics!
- Also need to understand SM backgrounds

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Tovey, Eur.Phys J. directC4 (2002)N4

SUSY Discovery - mSUGRA

- SUSY cascade decays give rise
- to many inclusive signatures:
- leptons, b-jets, t's

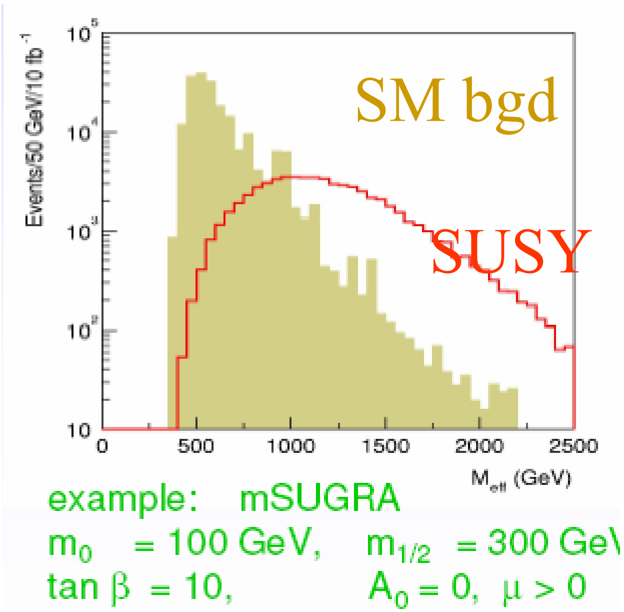
..

- Final discovery limit ~ 2.5 TeV squark or gluino
- Initially will be limited by detector uncertainties, not SUSY stats!
- Also need to understand SM backgrounds

Squarks and Gluinos

- Strongly produced, cross sections comparable to QCD cross sections at same Q^2
- If **R-parity conserved**, cascade decays produced distinctive events: Multiple jets, leptons and E_T^{miss}

$$M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$$



Analysis example:

- N_{jet} >=4
- E_T>100,50,50 50 GeV
- E_T^{miss} > 100 GeV

- Limits reachable at LHC for squarks an gluinos:

$1 fb^{-1} \rightarrow$ M ~ 1500 GeV

$10 fb^{-1} \rightarrow$ M ~ 1900 GeV

$100 fb^{-1} \rightarrow$ M ~ 2500 GeV

Inclusive measurement

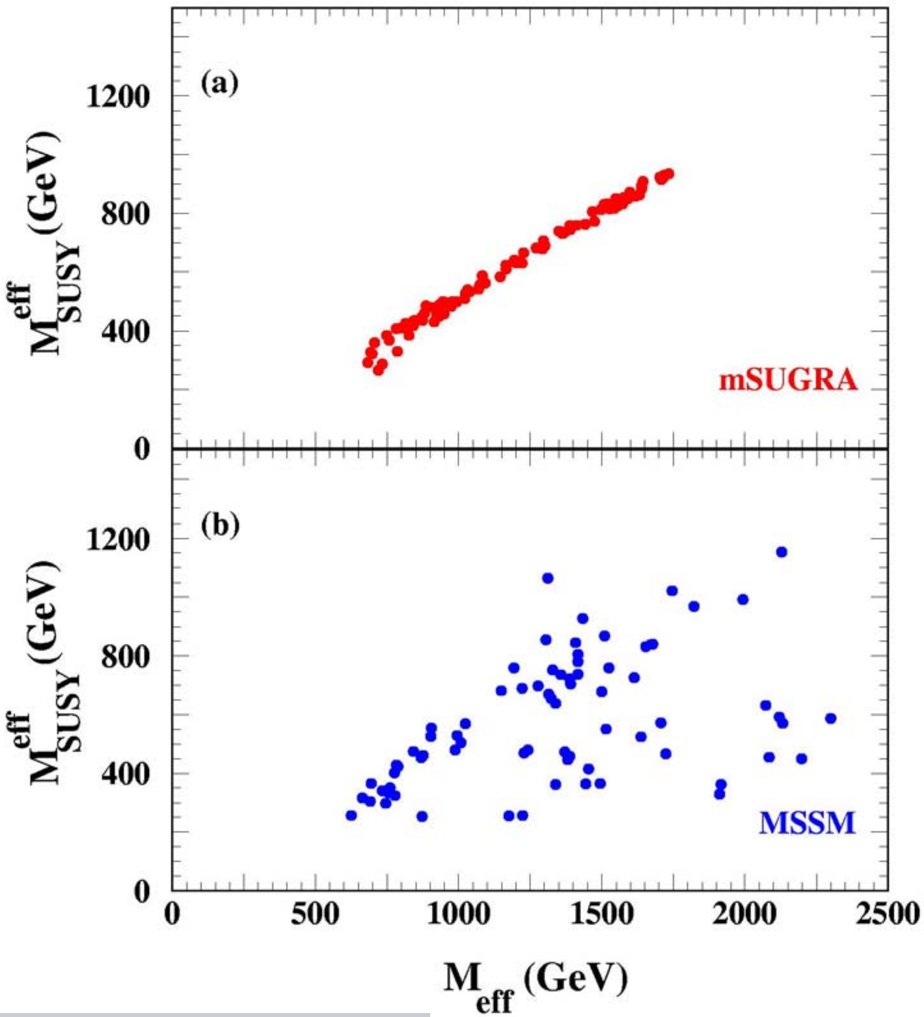
Define averaged produced SUSY mass

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

$$M_{\rm SUSY}^{\rm eff} \equiv M_{\rm SUSY} - \frac{M^2(\tilde\chi_1^0)}{M_{\rm SUSY}}$$

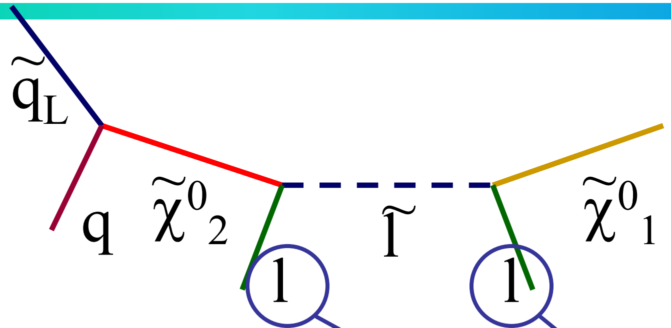
$$M_{eff} = E_T^{miss} + \Sigma_1^4\, p_T^{jet}$$

Good correlation with M_{eff} for SUGRA, not bad even with MSSM



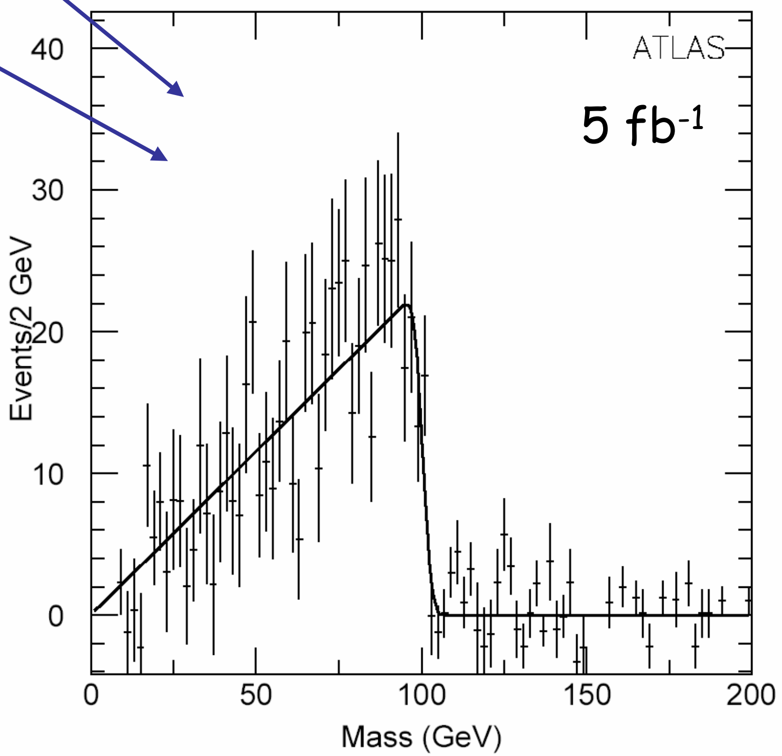
M_{eff} distribution for SUSY signal shows a peak

Slepton, squark, neutralino masses



$M(\chi_2)-M(\chi_1) \approx 105$ GeV

- Apply corrections for electron and muon energy scale and efficiency
- Flavor Subtracted mass to remove the contribution from uncorrelated SUSY decays: $e^+e^- + \mu^+\mu^- - e^+\mu^- - e^-\mu^+$



Accurate measurement of edge position difference for ee/μμ gives the sleptons mass difference

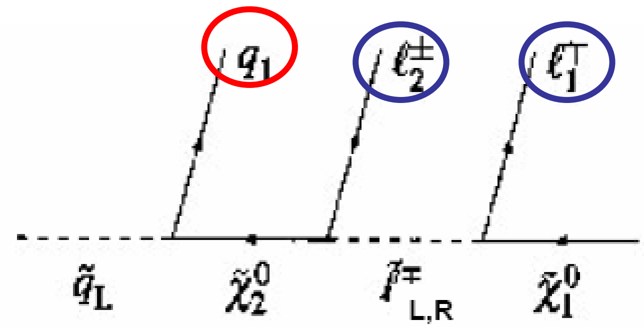
An example

Coannihilation point

Signature:

•Leptons (e^+,e^-,μ^+,μ^-)

•One soft lepton



762 264 255, 154 137

Δm ≈ 20 GeV Δm ≈ 10 GeV

$\tilde{q}_L \to \tilde{\chi}_2^0 q$	32%
$\tilde{\chi}_2^0 \to \tilde{l}_{L,R} l$	6%, 3%
$\tilde{l}_{L,R} \to \tilde{\chi}_1^0 l$	100%

Endpoints:

$M(\ell\ell)$, $M(\ell\ell q)$, $M^{high}(\ell q)$, $M^{low}(\ell q)$

Method: subtraction of wrong sign pairs:

(e^+,e^-,μ^+,μ^-) -

($e^+,\mu^-,- e^-,\mu^+$)

$M(\ell\ell)$

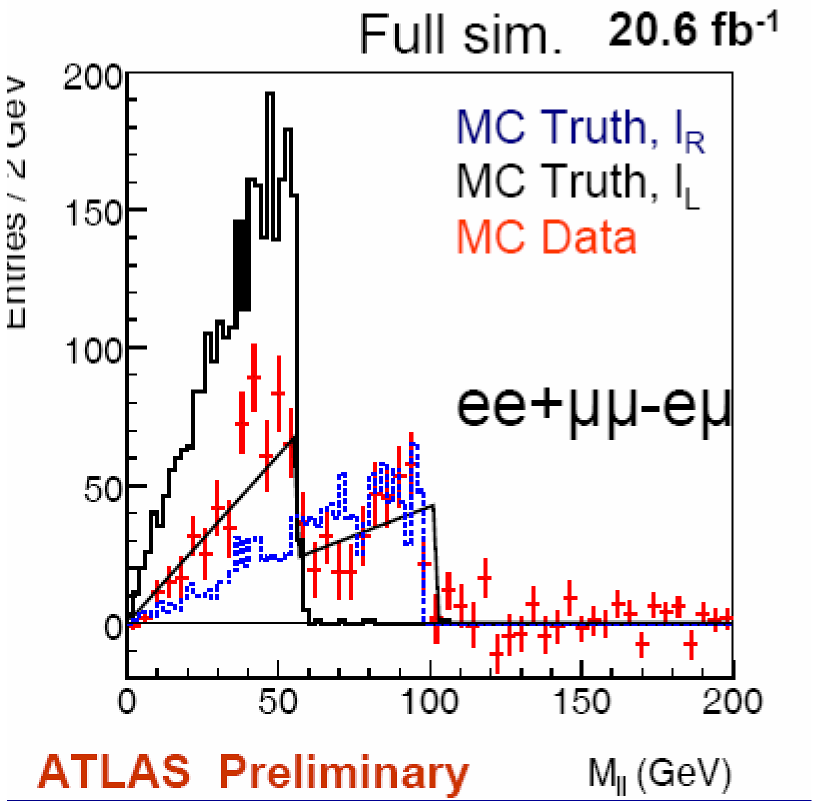
No cuts in E_T^{miss}, P_T^{jet}

Expected endpoints:

$M(\ell\ell)^{max}$=58.19GeV (L)

$M(\ell\ell)^{max}$=100.9GeV (R)

$$M_{ll}^{max} = \left[\frac{(M^2_{\tilde\chi^0_2} - M^2_{\tilde l_{L,R}})(M^2_{\tilde l_{L,R}} - M^2_{\tilde\chi^0_1})}{M^2_{\tilde l_{L,R}}} \right]^{1/2}$$

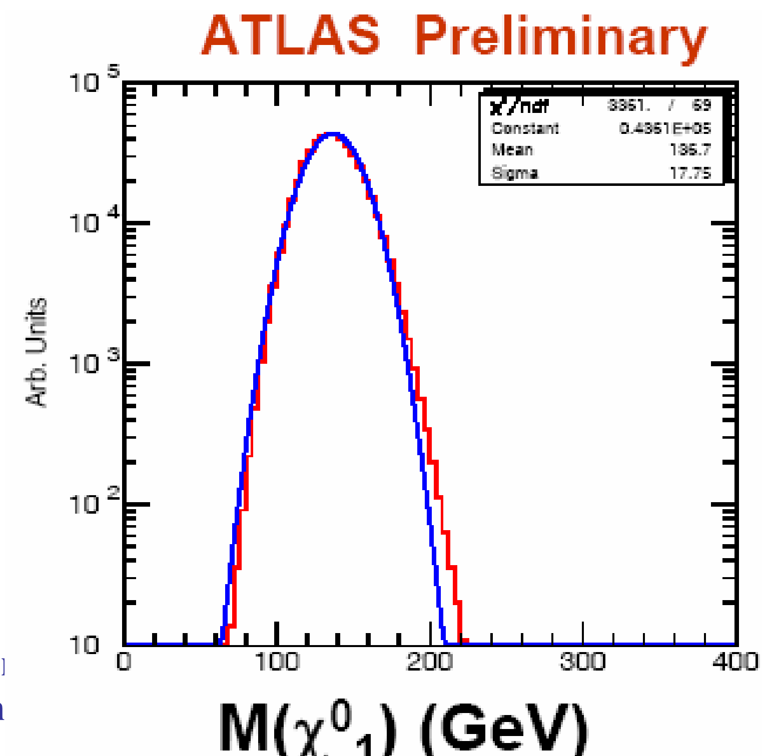


Neutralino

➤ **Fitted all end points :** (preliminary only)

- assuming 1% on lepton jet endpoint

~ 10% error in lightest neutralino mass



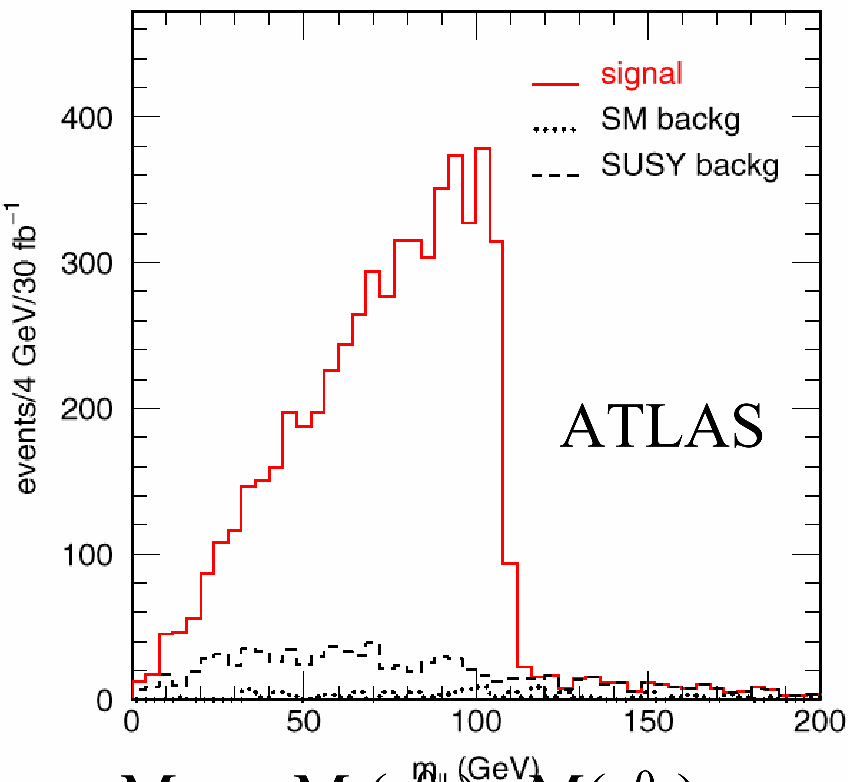
Mesurement of slepton mass difference

If $m_q \approx 900$ GeV $m_g \approx 700$ GeV
$m_{\chi\pm} \approx 230$ GeV $m_{\chi 0} \approx 120$ GeV
("point 5")

$\tilde{\chi}_2^0 \rightarrow \tilde{l}_R^{\pm} l^{\mp} \rightarrow \tilde{\chi}_1^0 l^+ l^-$

Cuts:

- $E_T^{miss} > 300$ GeV
- $e^+ e^- (\mu^+ \mu^-)$ pair with $p_T > 10$ GeV
- At least 2 jets $p_T > 150$ GeV



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

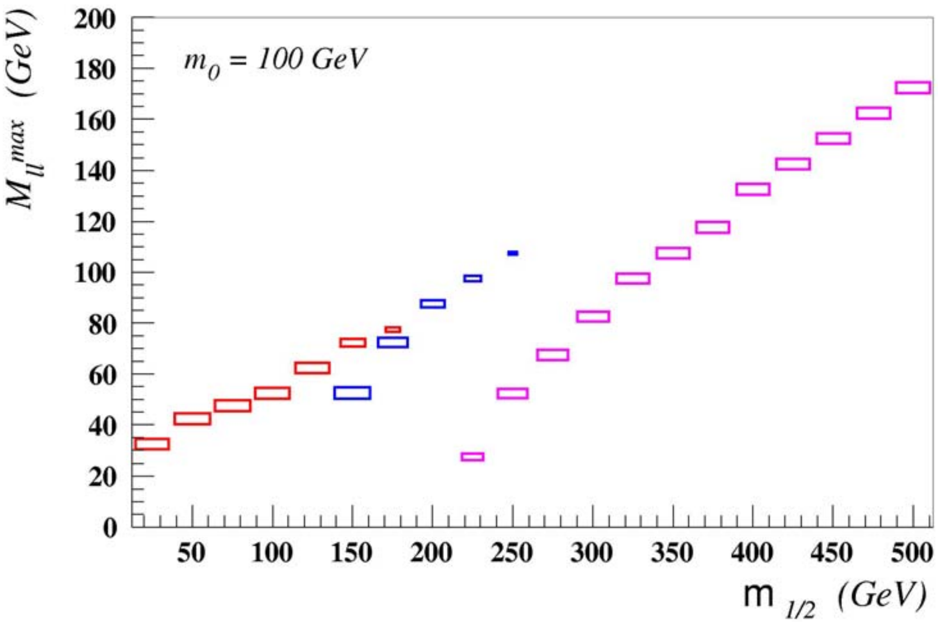
5800 events with 30 fb^{-1}
(880 SUSY BG and 120 SM)
Accurate measurement of edge position difference for ee/μμ gives the sleptons mass difference

$m_{1/2}$ mass determination

Gaugino mass term

endpoint in $m(\ell^+\ell^-)$ has good correlation with $m_{1/2}$

but correlation depends on decay chain



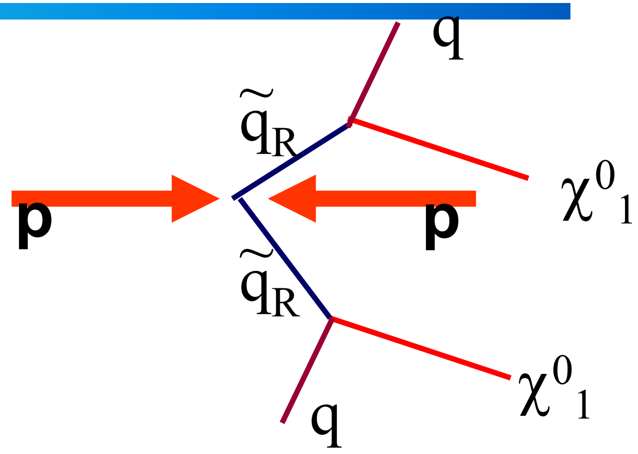
$$\tilde{\chi}_2^0 \to \ell^+\ell^- \ \tilde{\chi}_1^0$$

$$\tilde{\chi}_2^0 \to \ell\tilde{\ell}_R \to \ell^+\ell^- \ \tilde{\chi}_1^0$$

$$\tilde{\chi}_2^0 \to \ell\tilde{\ell}_L \to \ell^+\ell^- \ \tilde{\chi}_1^0$$

SUSY measurements - mass

- Mass measurements from exclusive cascade decays
- Mass differences well measured
  - Typically limited by detector performance
    - Of order 1%
- Error in overall mass scale
  - Unknown missing energy
    - Of order 10%



Estimate of s-quark mass using the transverse momentum mass

$$M_{T2}^2 = \min [\max \{ m_T^2(p_{T,j1}, \not{E}_{T1}, M(\tilde{\chi}_1^0)), m_T^2(p_{T,j2}, \not{E}_{T2}, M(\tilde{\chi}_1^0)) \}]$$

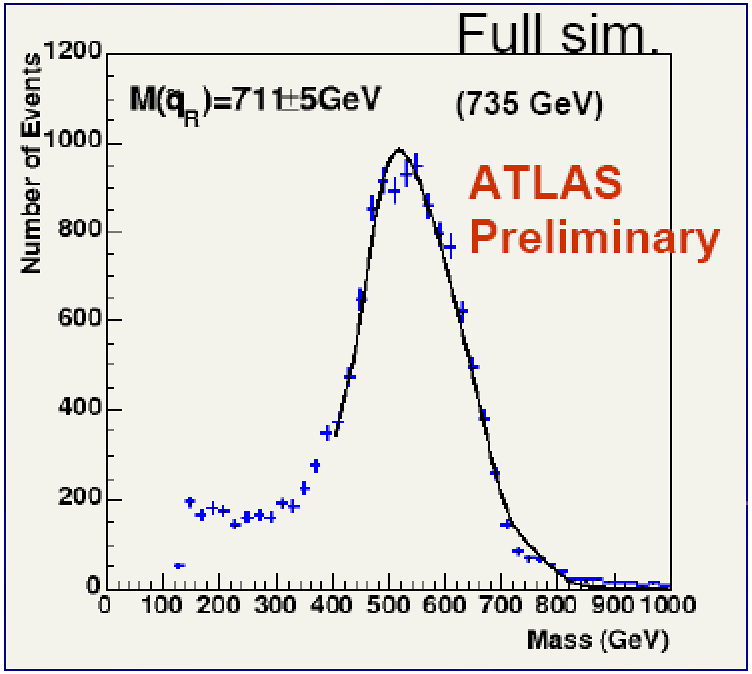
Squark mass

<u>Cuts:</u>

E_T^{miss} >400 GeV

2 jets with p_T > 200 GeV

$\Delta R(j_1,j_2)$ >1

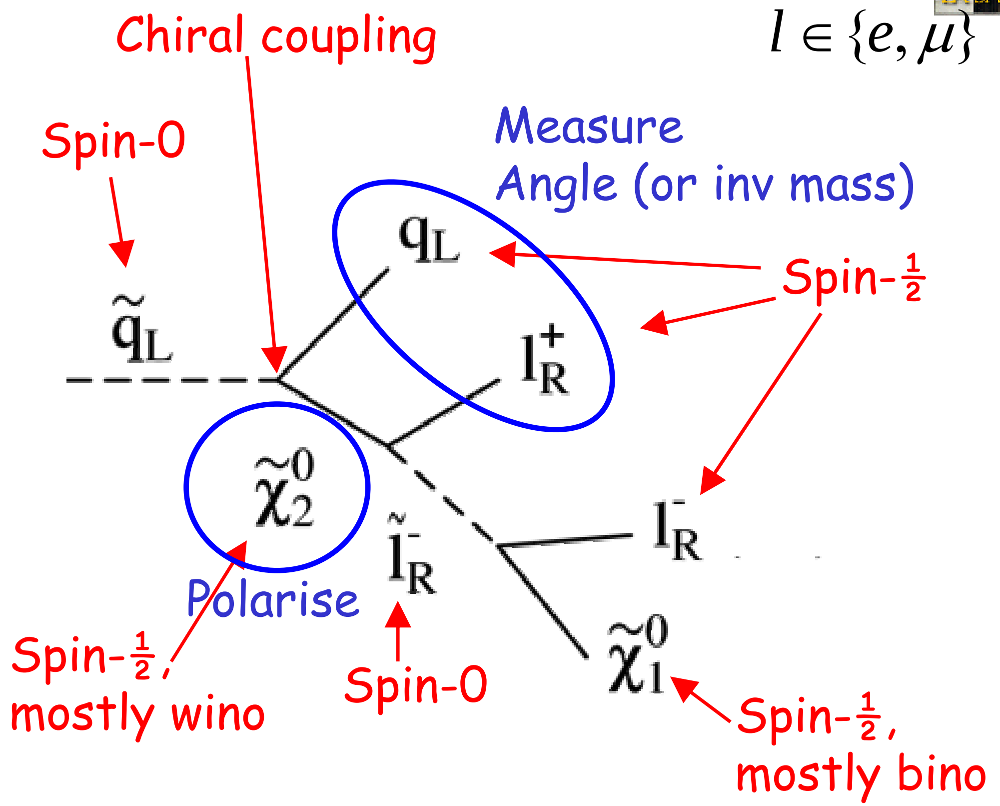


$M(\chi_1^0)$ known M(squark) is obtained from endponit of M_T^2 mass

SUSY SPIN @ LHC

- SUSY particles have spin differing by ½ from SM
- "Discovering SUSY" means measuring spins of new particles
- Possible at LHC?
- Investigation of mSUGRA "Point 5"

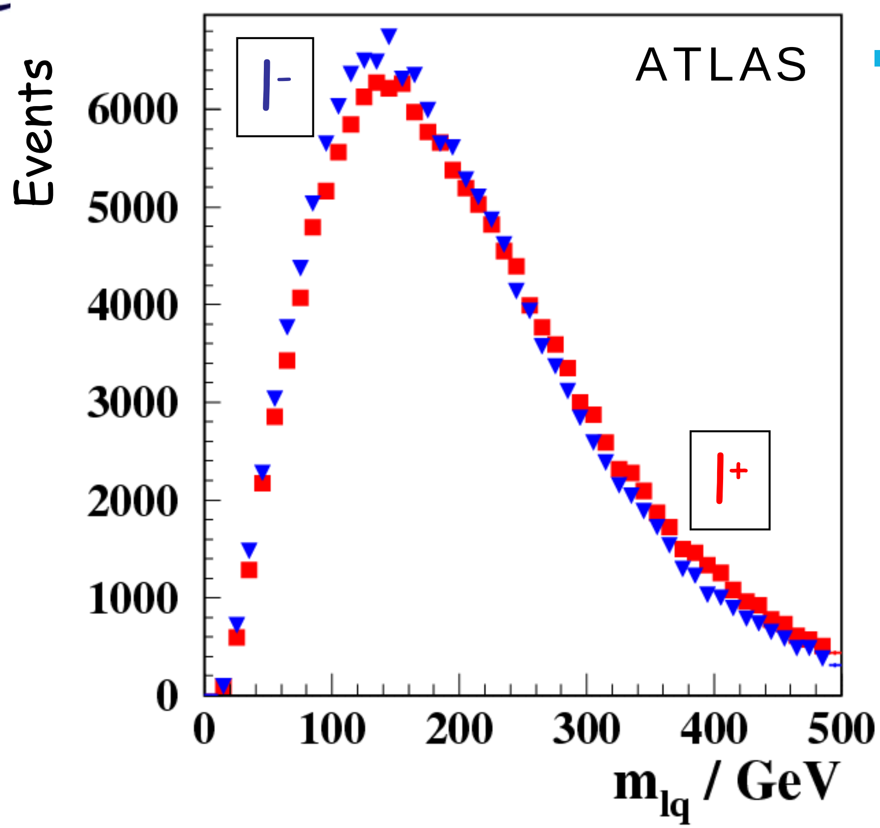
$l \in \{e, \mu\}$



Final state = jet + l^+ + l^- + E_T
(+ decay of other sparticle)

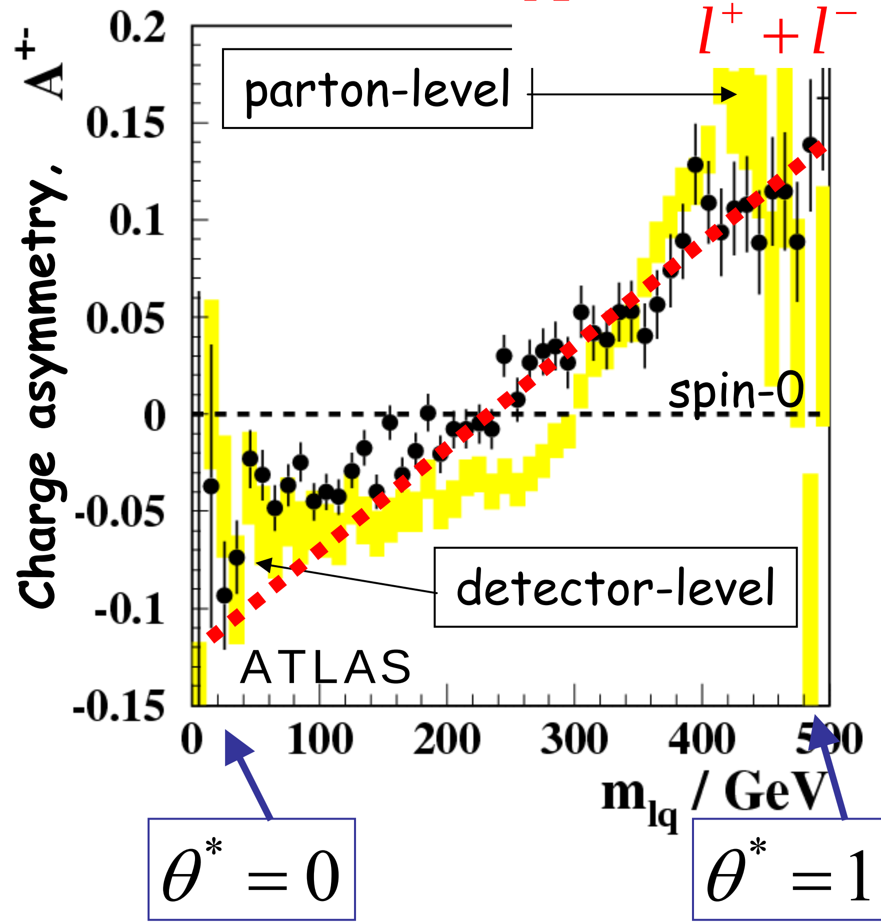
Similar technique allows measurement of tanβ from muon/electron asymmetry

SUSY spin – observable distributions



Lepton+jet invariant mass

$$A^{+-} = \frac{l^+ - l^-}{l^+ + l^-}$$



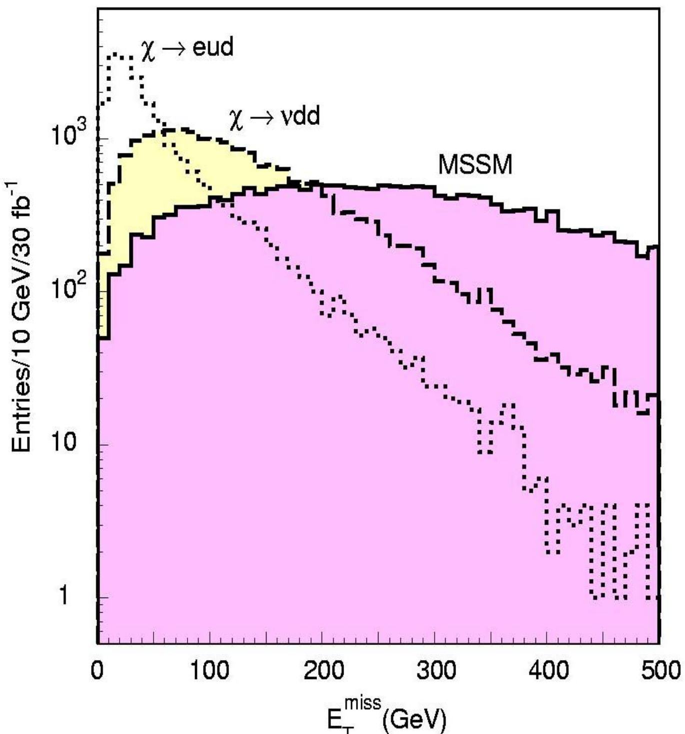
-> Measure **spin-1/2** nature of **neutralino-2**

-> Also can measure **scalar** nature of **slepton**

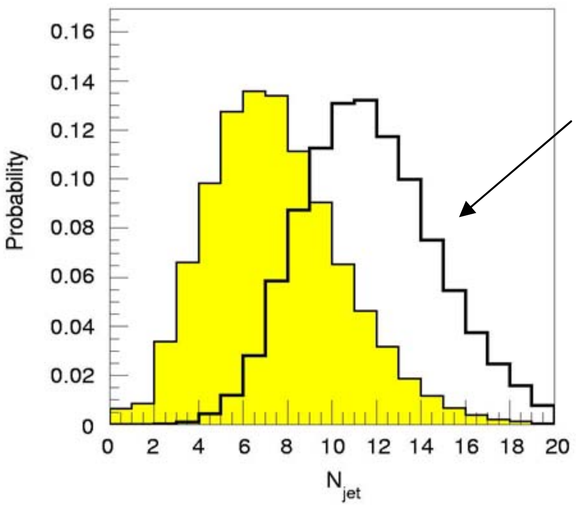
-> Success at several distinct points in parameter space

SUSY with R-parity breaking

R-parity conserved



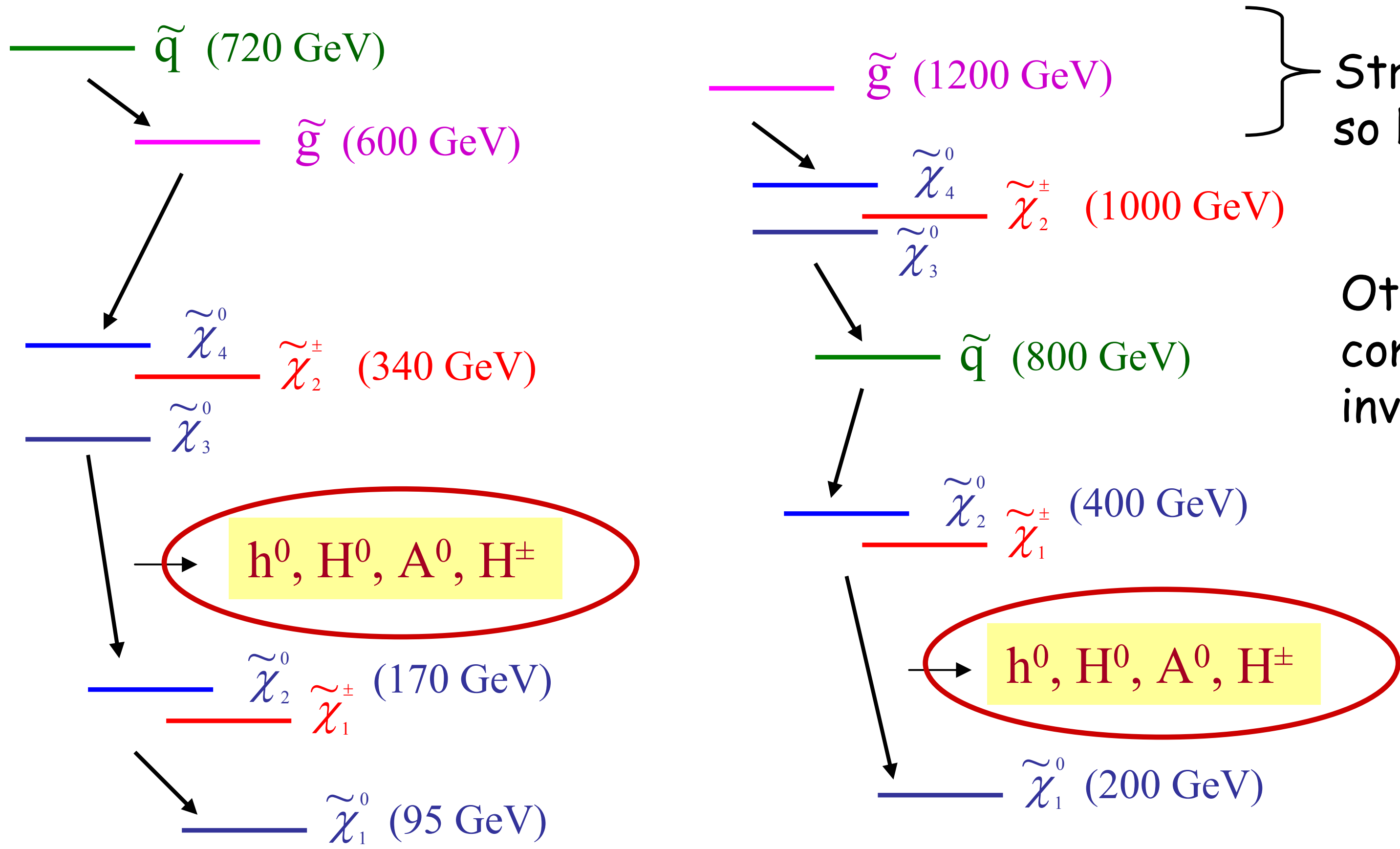
In case of baryon number violation -> increased number of jets



R-parity broken

➢SUSY particles can decay in standard model particle

SUSY produces Higgs



Strongly interacting, so high rate

Other points & combinations also investigated

- Provided Heavy higgs are <1$\tilde{5}$0 GeV -> produced
- Missing energy + jet/lepton + higgs decay->bb
- Apply very simple (general) analysis

Remarks on SUSY detection

➢**Uncertainties on jet and lepton energy scale dominate over Statistical error**

LHC experiments can exploit large statistics of resonances of known mass ($Z \to \ell\,\ell$,$W \to jj$) to achieve *in-situ* calibration.

➢**Lepton scale** from $Z \to \ell\,\ell$ (2 ev/s at 10^{33}) by imposing Z mass constraint → **LHC goal: 0.1%**

Dominant systematic:

•$Z \to ee$: knowledge of inner detector material (goal 1%)
Modelling inner detector bremsstrahlung (goal 10%)

•$Z \to \mu\mu$:Dominate by Inner Detector scale. Requires precise mapping of magnetic field and material.

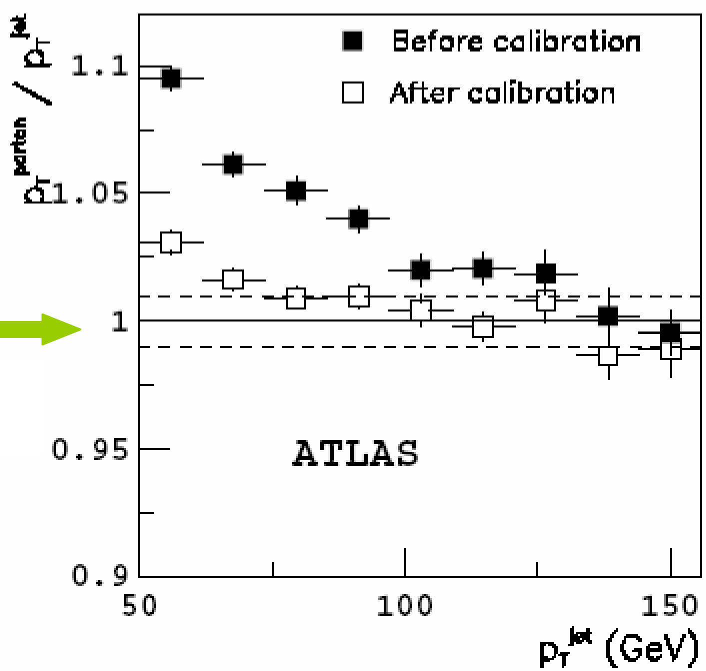
Remarks on SUSY detection

➢ **Jet scale** from:

- $Z \rightarrow (\ell\,\ell)$ +jet, by requiring $P_T(jet) = P_T(Z)$
- $Z \rightarrow jj$ and in the decay $tt \rightarrow bWbW$, by requiring $m_{jj} = m_W$

→ **LHC goal: 0.1%**

Dominant systematic:
Final-State-Radiation (FSR)
cone used to collect energy →



Conclusions (of SUSY part)

- **If SUSY exists at the TeV scale, ATLAS should find it easily.**
- **Despite missing LSP, precision measurements of masses will be also possible.**

Initial program:

- search for multijet + E_T^{miss} excess over SM.
- if found can select SUSY sample with simple cuts
- look for events with multi-leptons, b-jets, tau-jets, photons
- look for events with special features like long-lived sleptons

Use these results to guide further analyses.