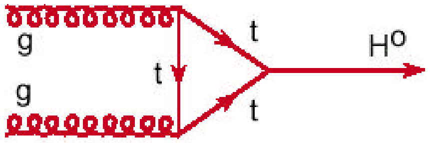
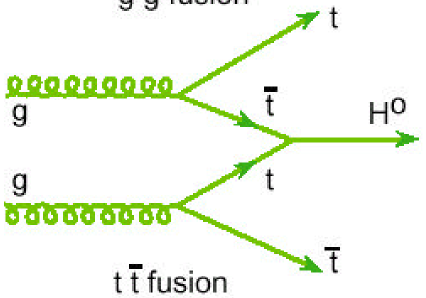
Standard Model Higgs

SM Higgs (I)

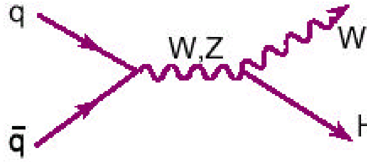
Production mechanisms & cross section



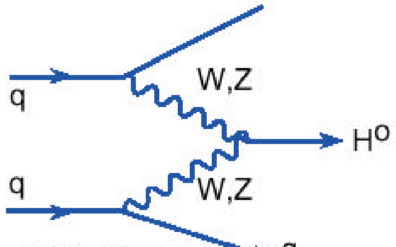
g g fusion



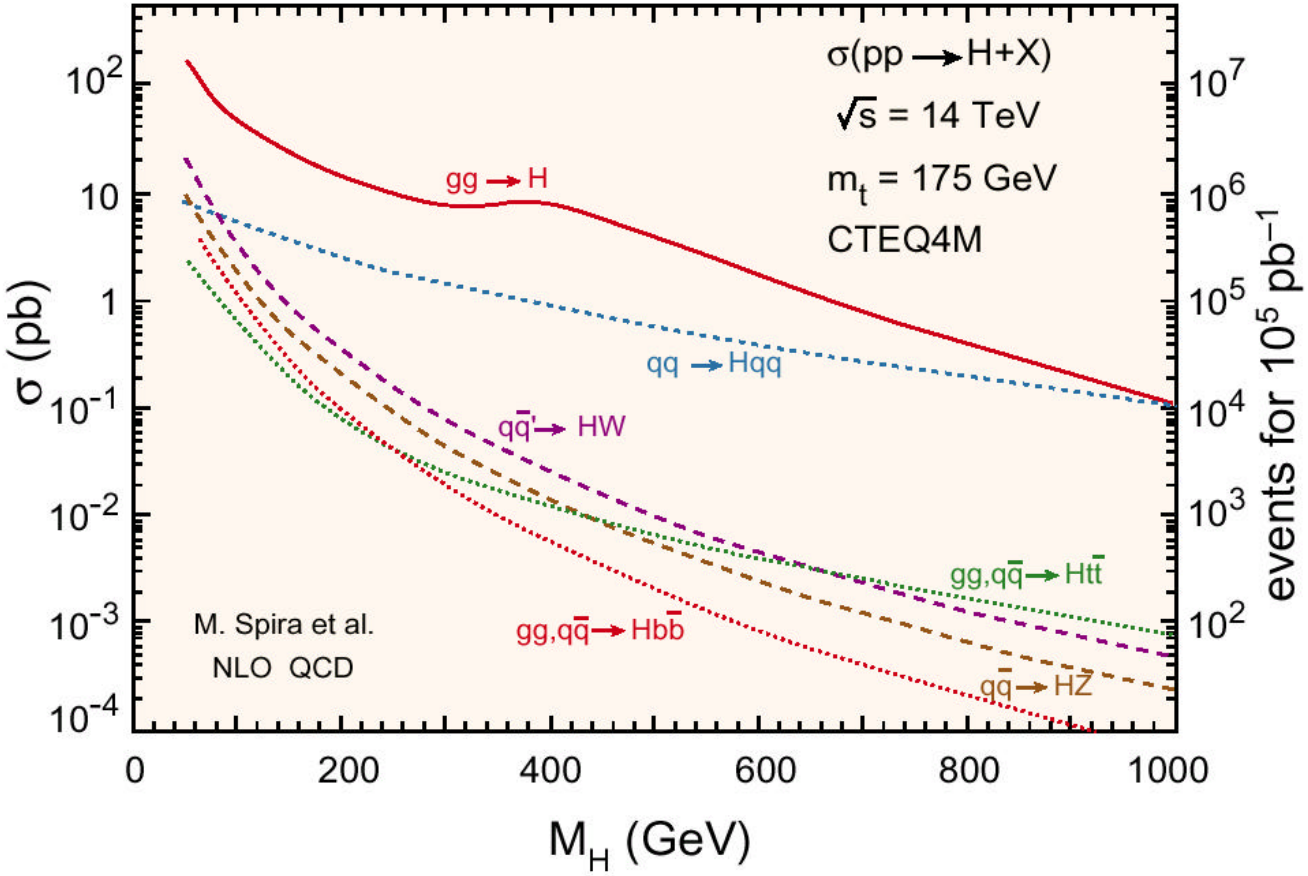
t $\bar{t}$ fusion



W, Z bremsstrahlung



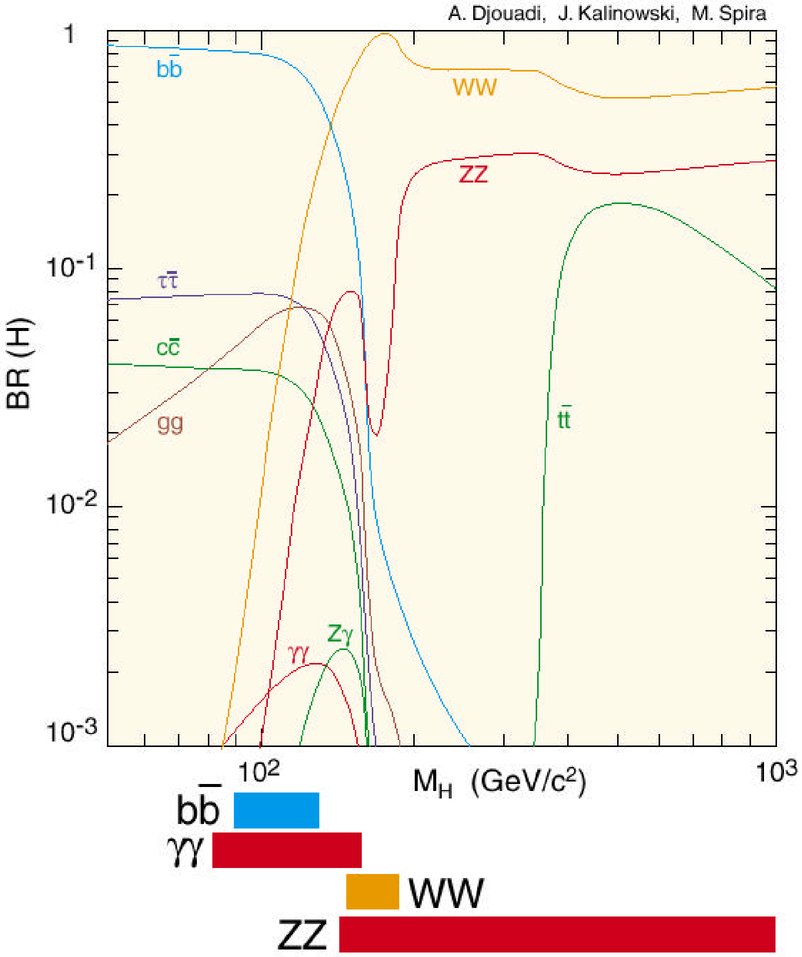
WW, ZZ fusion



SM Higgs (II)

Decays & discovery channels

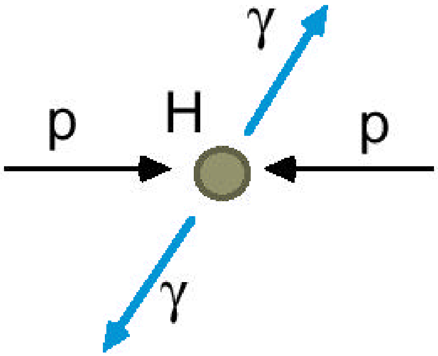
- Higgs couples to m_f^2
  - Heaviest available fermion (b quark) always dominates
  - Until WW, ZZ thresholds open
- Low mass: b quarks→ jets; resolution ~ 15%
  - Only chance is EM energy (use $\gamma\gamma$ decay mode)
- Once $M_H > 2M_Z$, use this
  - W decays to jets or lepton+neutrino (E_T^{miss})

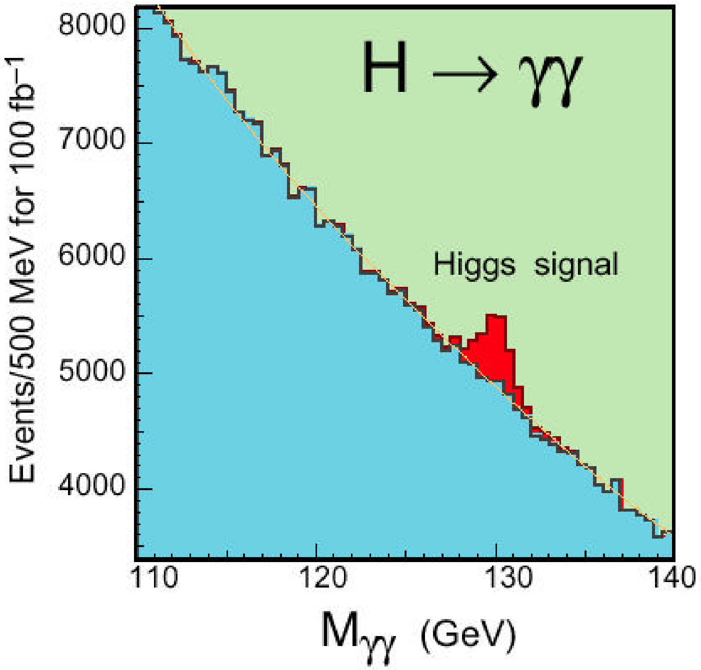


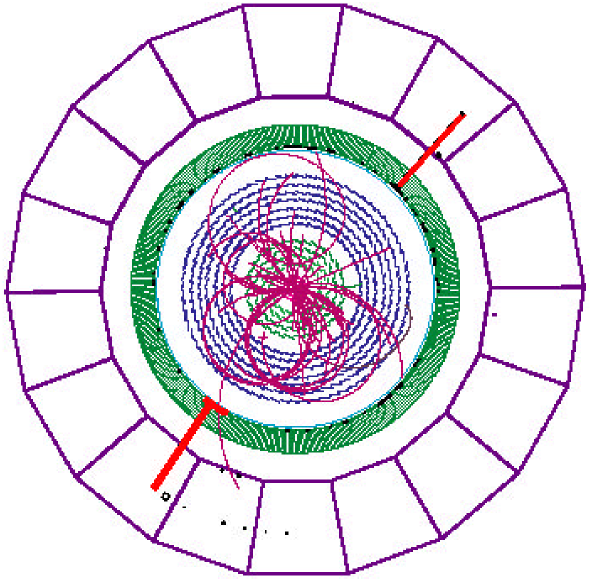
Low mass Higgs (M_H<140 GeV/c^2)

$H \rightarrow \gamma\gamma$: decay is rare ($B \sim 10^{-3}$)

- But with good resolution, one gets a mass peak
- Motivation for LAr/$PbWO_4$ calorimeters
- CMS: at 100 GeV, $\sigma \approx 1$GeV
  - S/B ≈ 1:20



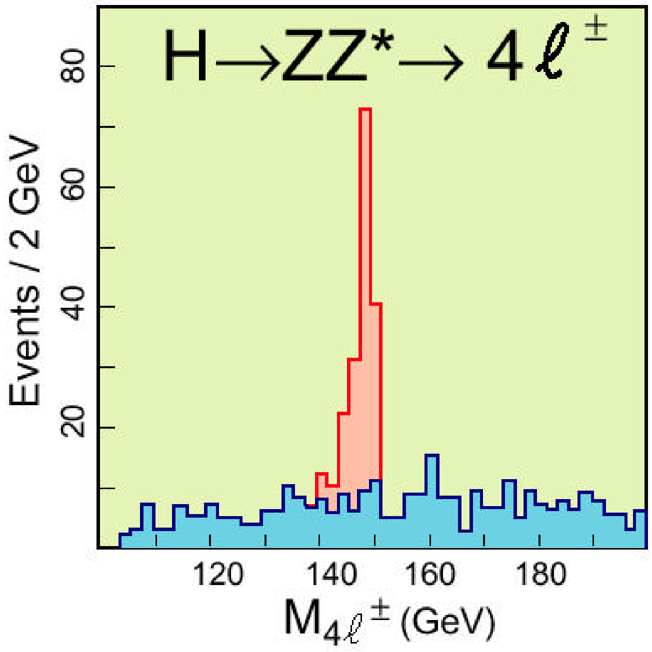


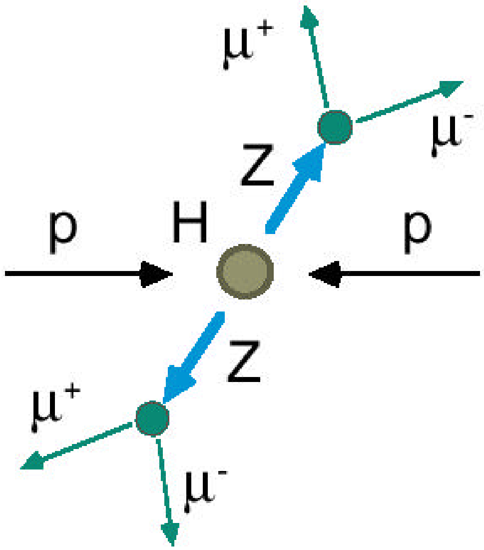


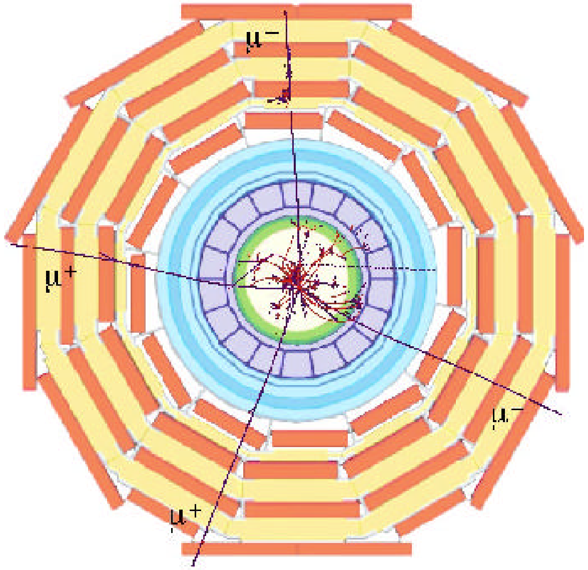
Intermediate mass Higgs

$H \rightarrow ZZ \rightarrow \lambda^+\lambda^- \lambda^+\lambda^-$ (λ =e,μ)

- Very clean
  - Resolution: better than 1 GeV (around 100 GeV mass)
- Valid for the mass range $130 < M_H < 500$ GeV/c^2



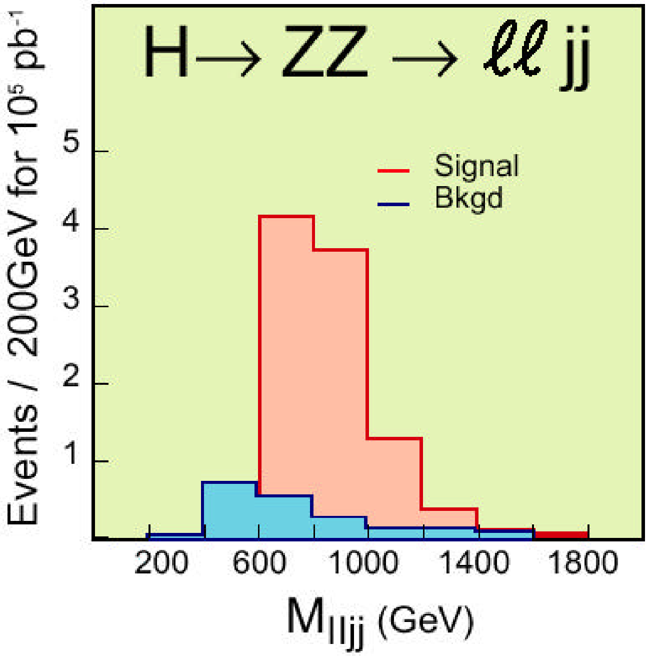


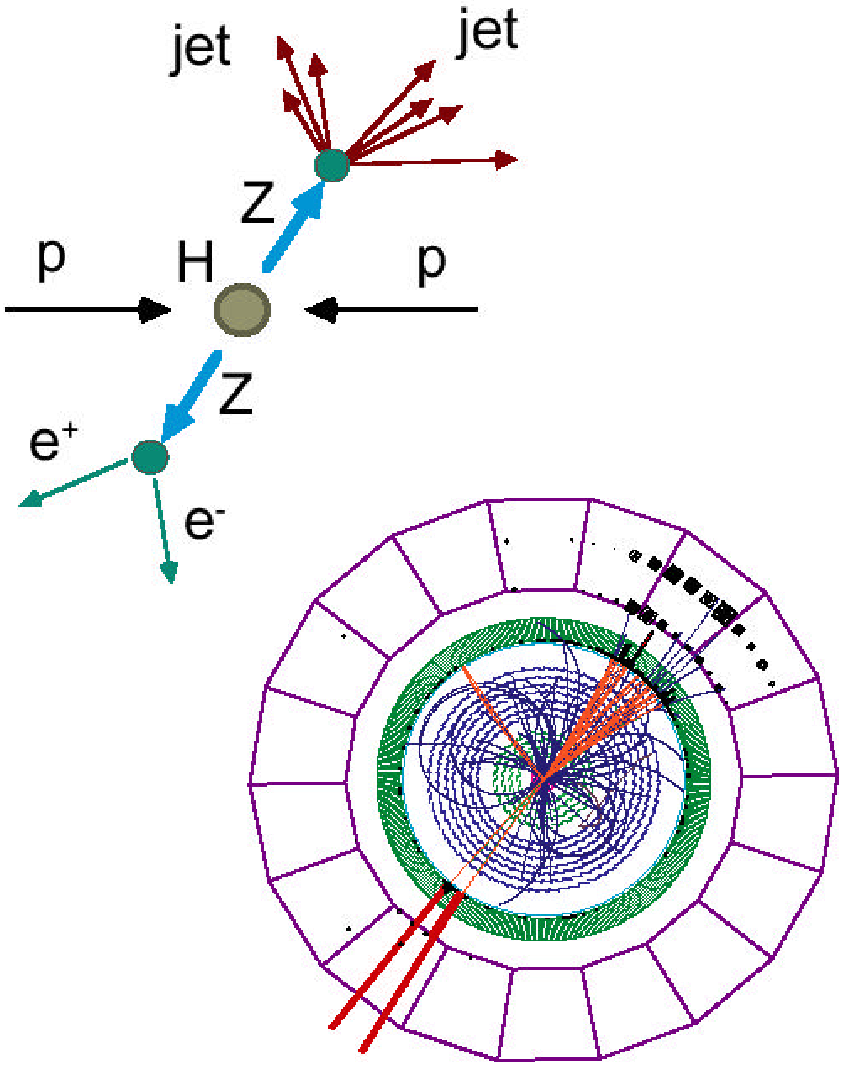


High mass Higgs

$H \to ZZ \to \lambda^+\lambda^-$ jet jet

- Need higher Branching fraction (also $\nu\nu$ for the highest masses ~ 800 GeV/c^2)
- At the limit of statistics

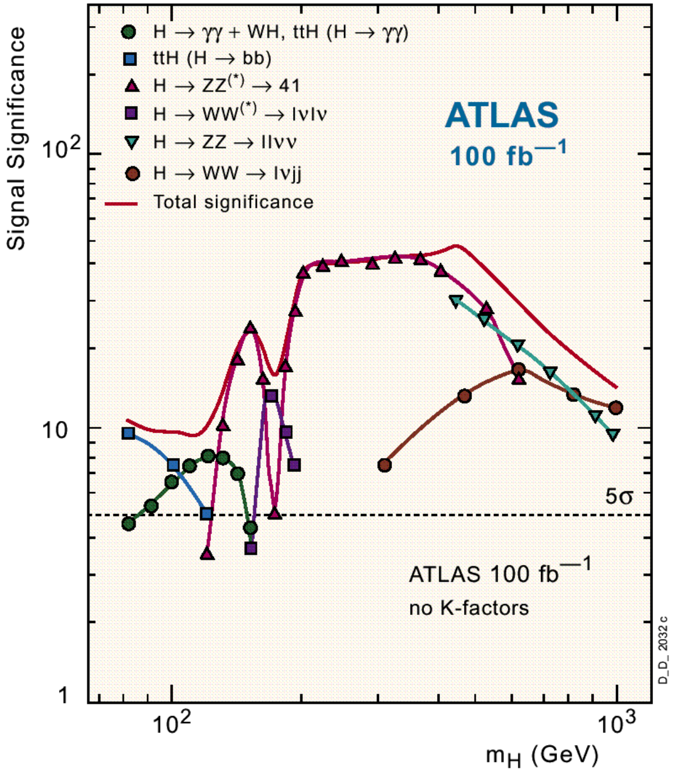


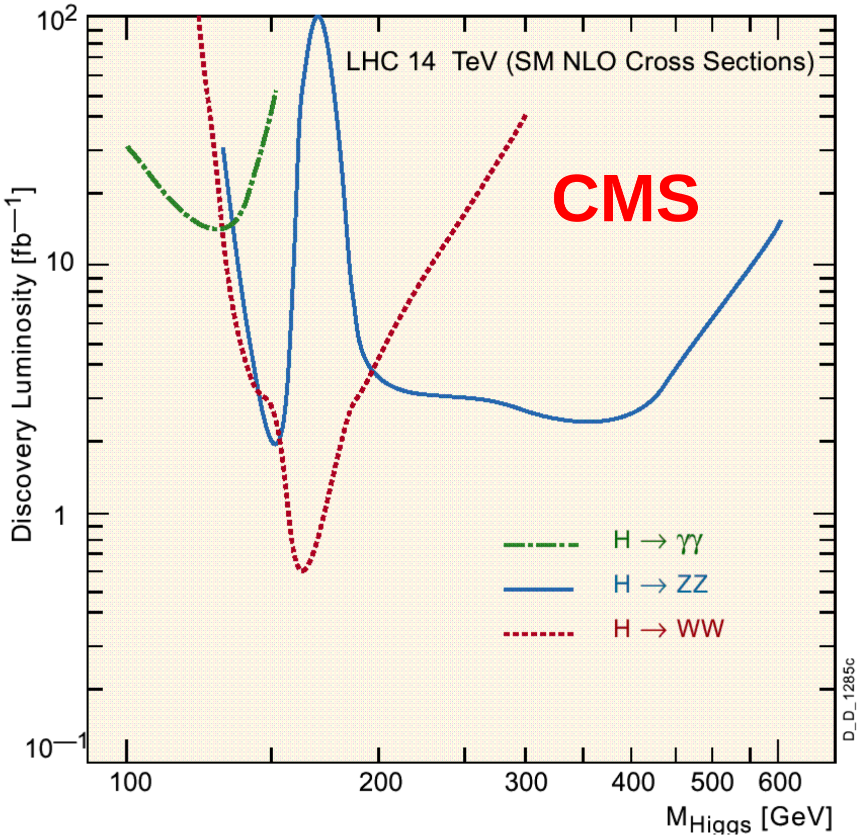


Higgs discovery prospects @ LHC

The LHC can probe the entire set of “allowed” Higgs mass values;

- in most cases a few months at low luminosity are adequate for a 5σ observation



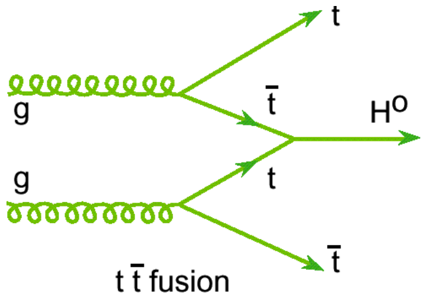


Status of H® $b\bar{b}$ (I)

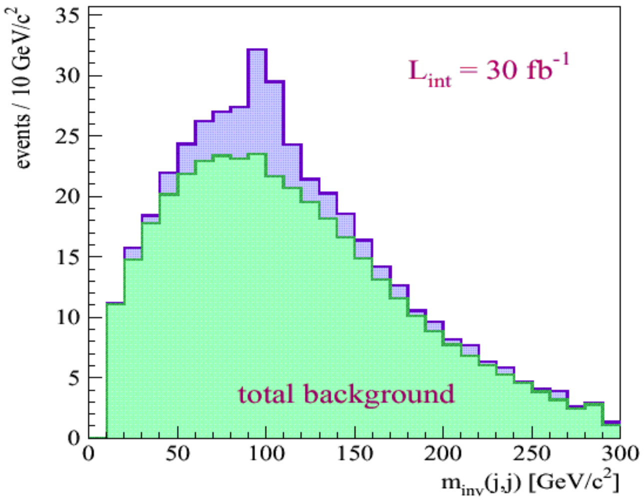
Low mass Higgs; useful for coupling measurement

H→ $b\bar{b}$ in $t\bar{t}$ H production

- σ.Br=300 fb
- Backgrounds:
  - Wjjjj, Wjj$b\bar{b}$
  - $t\bar{t}$ jj
  - Signal (combinatorics)
- Tagging the t quarks helps a lot
  - Trigger: t →b(e/μ)ν
  - Reconstruct both t quarks
- In mass region 90GeV<M($b\bar{b}$)<130GeV, S/B =0.3



$t\bar{t}H^0$: $S + B$ (100 GeV)



Status of H® $b\bar{b}$ (II)

H→ $b\bar{b}$ in WH production

Big background subtraction

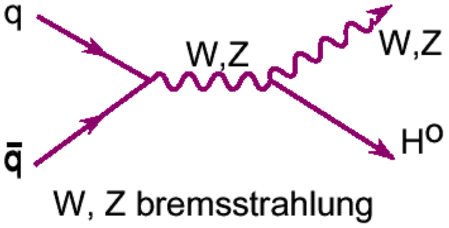
Mainly: Wjj, $t\bar{t}$ (smaller: tX,WZ)

Example (below) at 105:

– in mass region

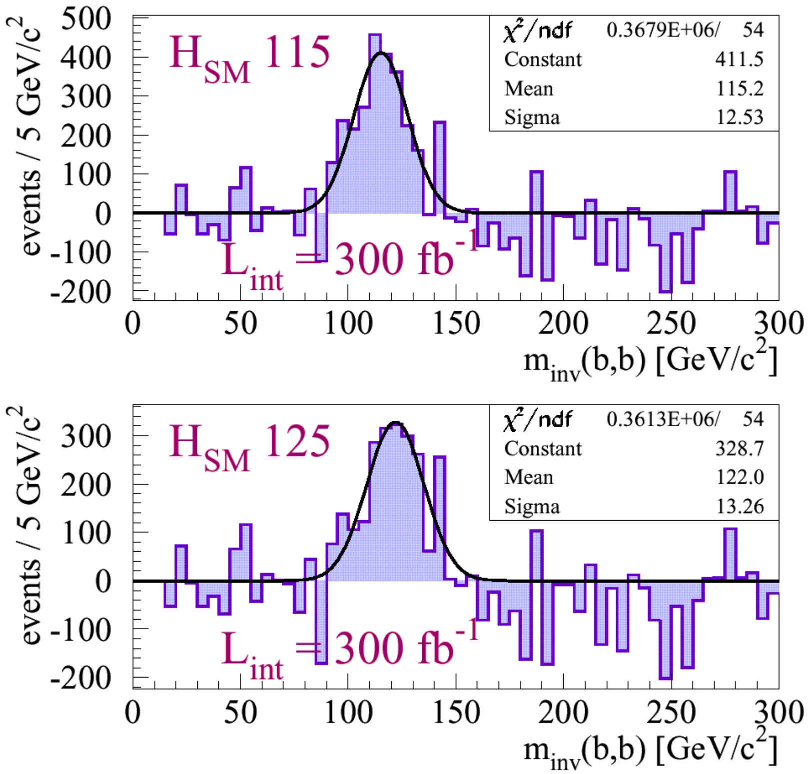
88GeV<M($b\bar{b}$)<121GeV,

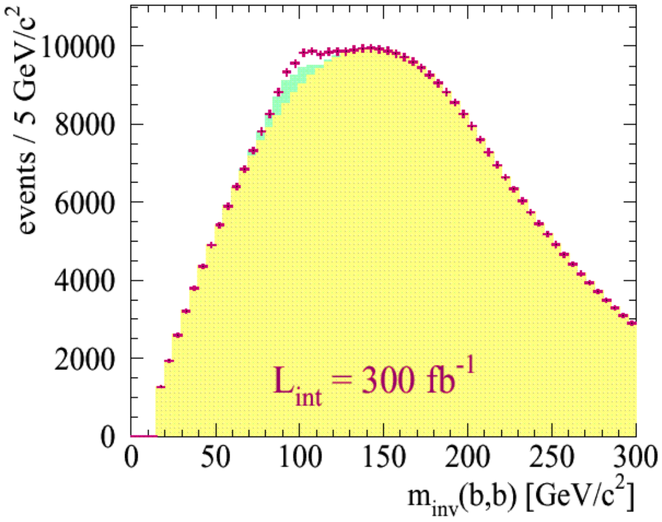
S/B =0.03



W, Z bremsstrahlung

After bkg subtraction

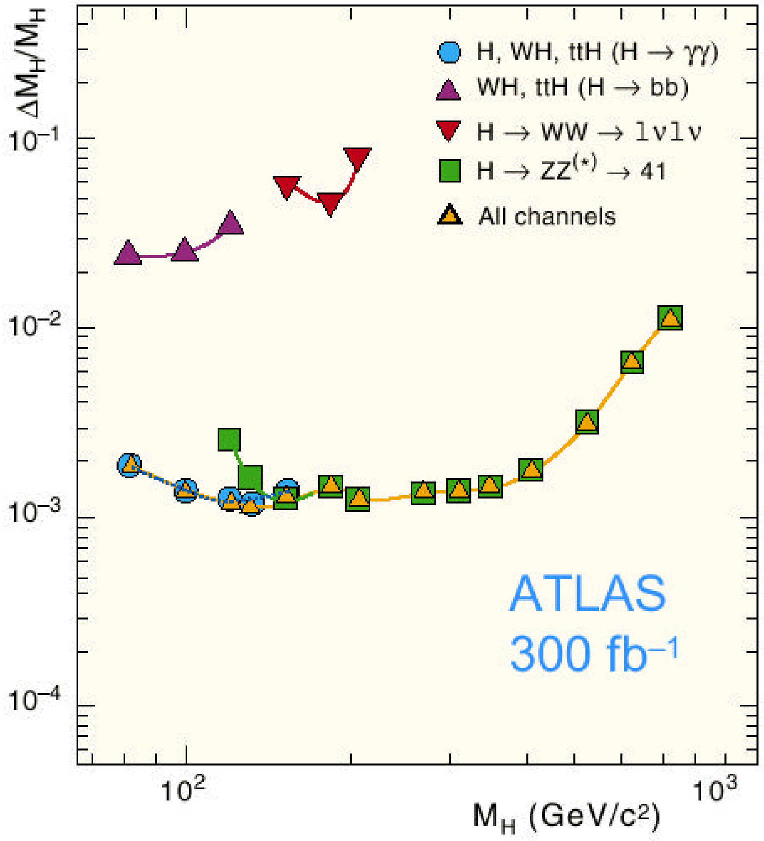




SM Higgs properties (I): mass

Mass measurement

- Limited by absolute energy scale
  - leptons & photons: 0.1% (with Z calibration)
  - Jets: 1%
- Resolutions:
  - For $\gamma\gamma$ & $4l$ ~ 1.5 GeV/c^2
  - For bb ~ 15 GeV/c^2
- At large masses: decreasing precision due to large Γ_H
- CMS ~ ATLAS

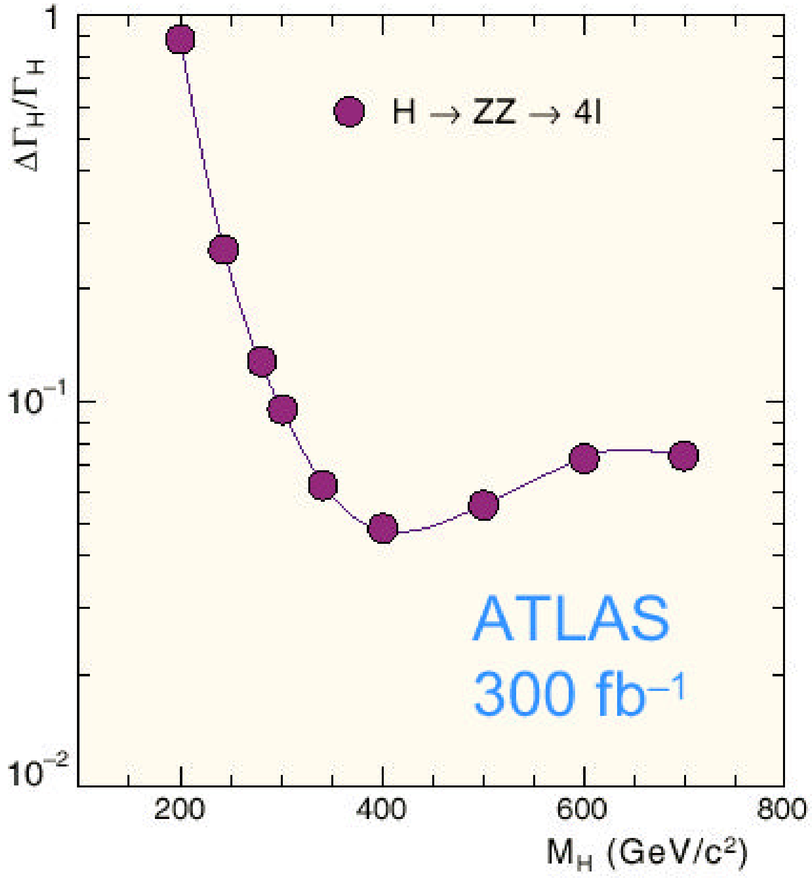


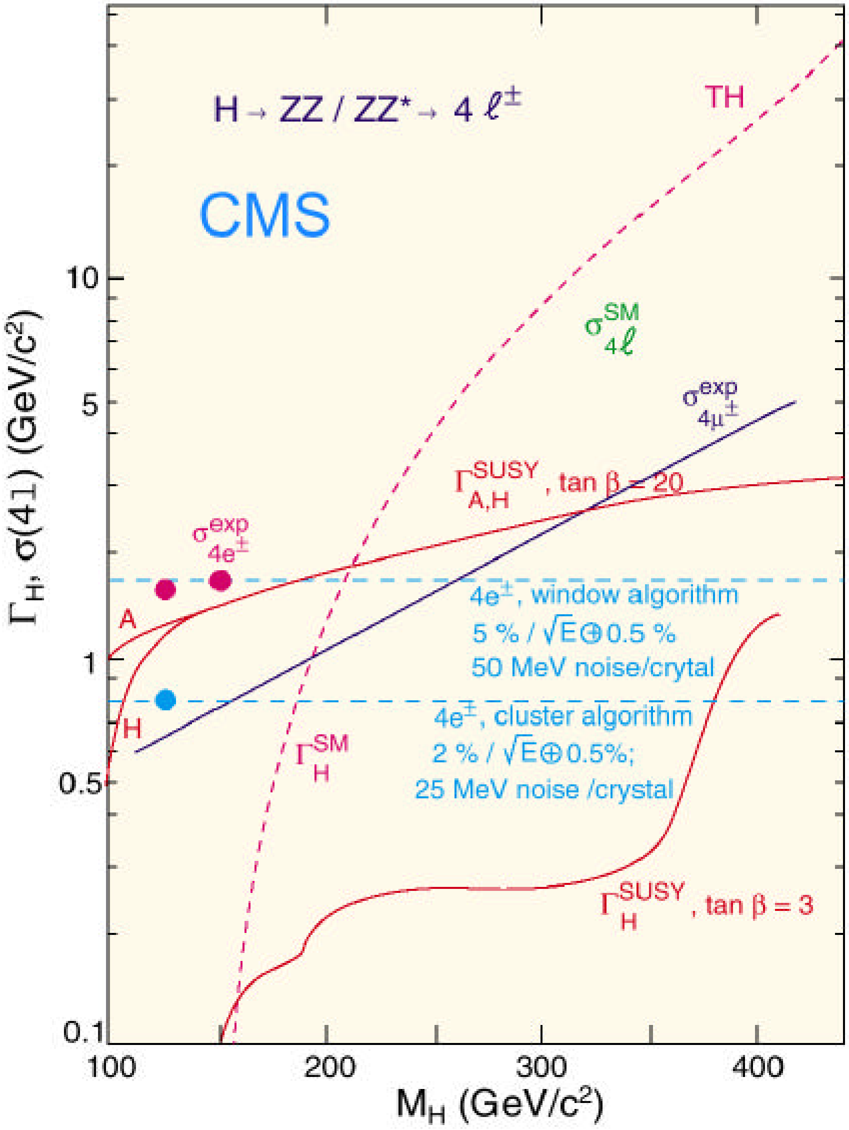
SM Higgs properties (II): width

Width; limitation:

Possible for $M_H>200$

Using golden mode (4λ)

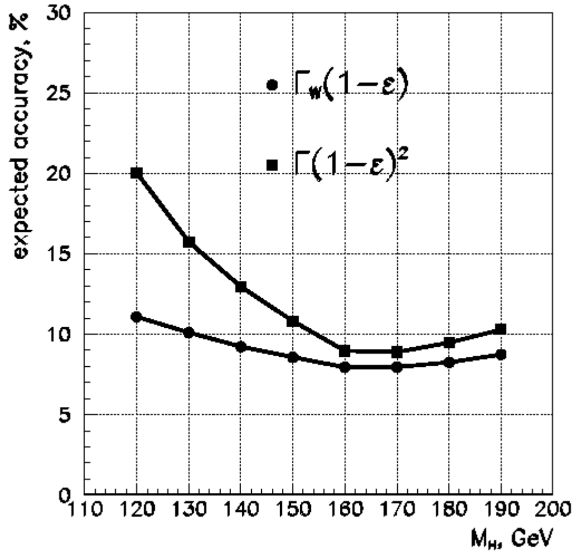




SM Higgs; width for $M_H<2M_Z$

Basic idea: use qq→qqH production (two forward jets+veto on central jets)

- Can measure the following: $X_j = \Gamma_W\Gamma_j/\Gamma$ from qq→qqH →qqjj
  - Here: j = γ, τ, W(W*); precision~10-30%
- One can also measure $Y_j= \Gamma_g\Gamma_j/\Gamma$ from gg→H→jj
  - Here: j = γ, W(W*), Z(Z*); precision~10-30%
- Clearly, ratios of X_j and Y_j (~10-20%) → couplings
- But also interesting, if Γ_W is known:
  - $\Gamma = (\Gamma_W)^2/X_W$
  - Need to measure H → WW*
  - $\varepsilon=1-(B_b+B_\tau+B_W+B_Z+B_g+B_\gamma)<<1$
  - $(1-\varepsilon)\Gamma_W= X_\tau(1+y)+X_W(1+z)+X_\gamma+X_g$
  - $z= \Gamma_W/\Gamma_Z$; $y= \Gamma_b/\Gamma_\tau=3\eta_{QCD}(m_b/m_\tau)^2$



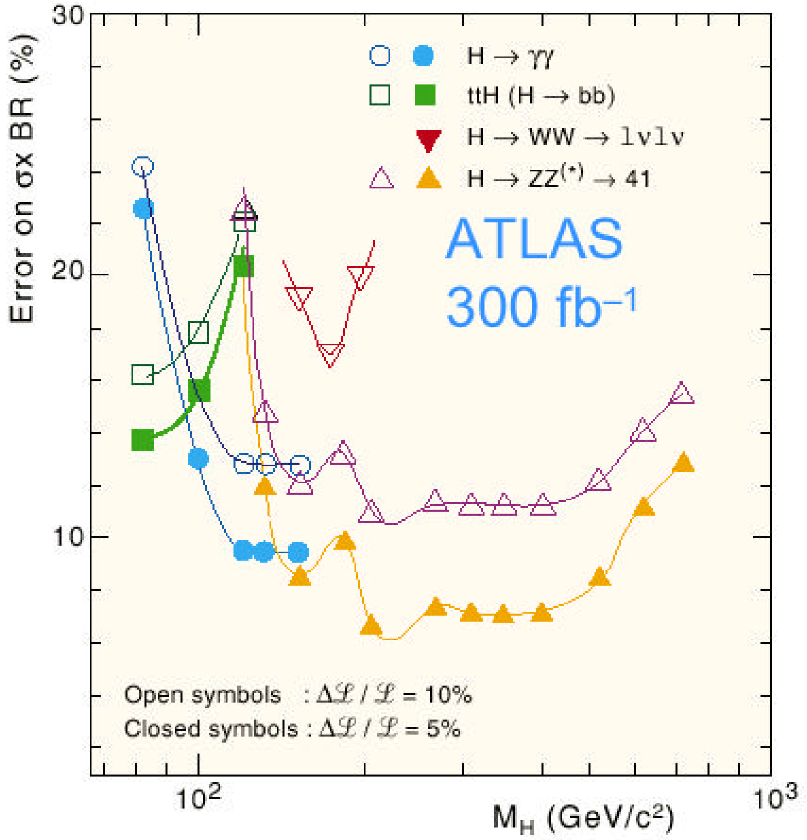
SM Higgs properties (III)

Biggest uncertainty(5-10%): Luminosity

Relative couplings statistically limited

Small overlap regions

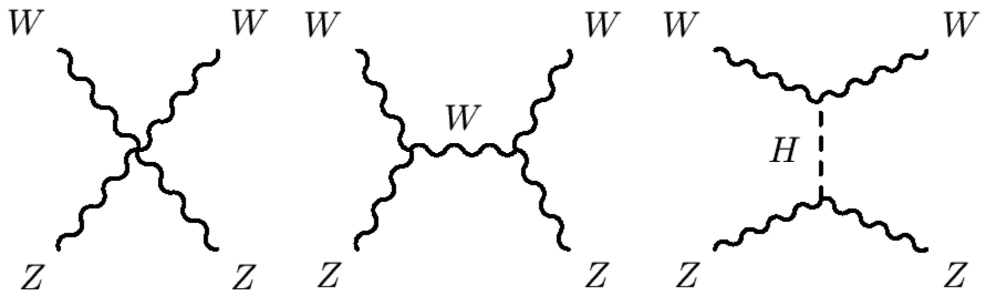
Measure	Error	M_H range
$\frac{(\quad \to gg)}{(\quad \to \quad \bar{}\ )}$	30%	80–120
$\frac{(\quad \to gg)}{(\quad \to \quad {}^{*})}$	15%	125–155
$\frac{s(\quad \bar{}\quad)}{s(\qquad)}$	25%	80–130
$\frac{(\quad \to \quad {}^{(*)})}{(\quad \to \quad {}^{(*)})}$	30%	160–180



Strong boson-boson scattering

Example: $W_L Z_L$ scattering

- W, Z polarization vector e^m satisfies: $e^m p_m=0$;
  - for $p_m=(E,0,0,p)$, $e^m=1/M_V(p,0,0,E) \approx P^\mu/M_V+O(M_V/E)$
- Scattering amplitude ~ $(p_1/M_W)\ (p_2/M_Z)\ (p_3/M_W)\ (p_4/M_Z)$, i.e. $\sigma \sim s^2/M_W^2 M_Z^2$



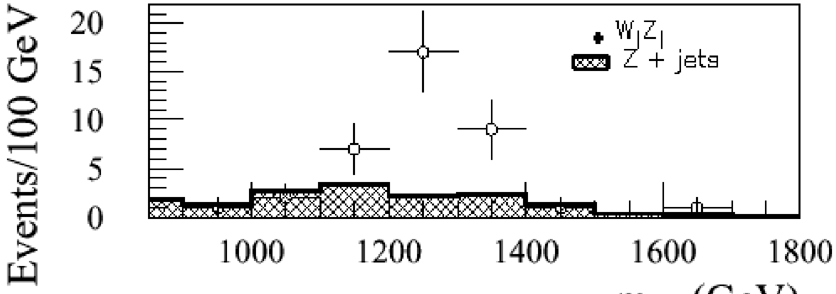
- Taking $M_H \rightarrow \infty$ the H diagram goes to zero $(\sim 1/M_H^2)$
- Technicalities: diagrams are gauge invariant, can take out one factor of s
  - but the second always remains (non-abelian group)
- Conclusion: to preserve unitarity, one must switch on the H at some mass
  - Currently: $M_H \leq 700$ GeV

The no Higgs case: $V_L V_L$ scattering

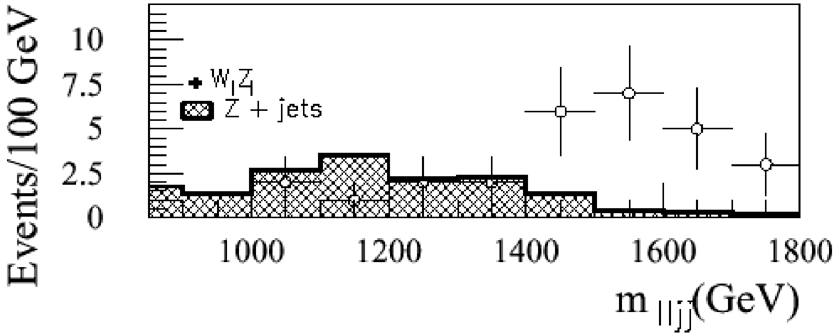
Biggest background is Standard Model VV scattering

Analyses are difficult and limited by statistics

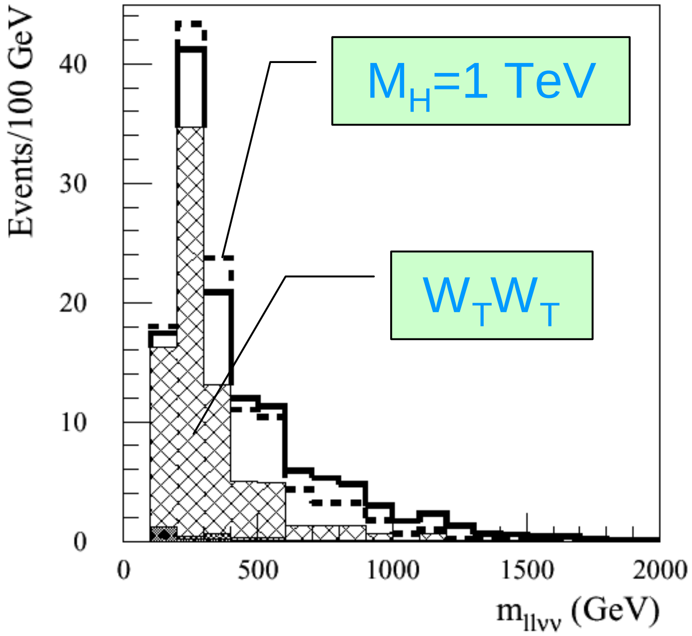
Resonant WZ scattering
at 1.2 & 1.5 TeV



L=300 fb^{-1}



Non-resonant W^+W^+ scattering



M_H=1 TeV

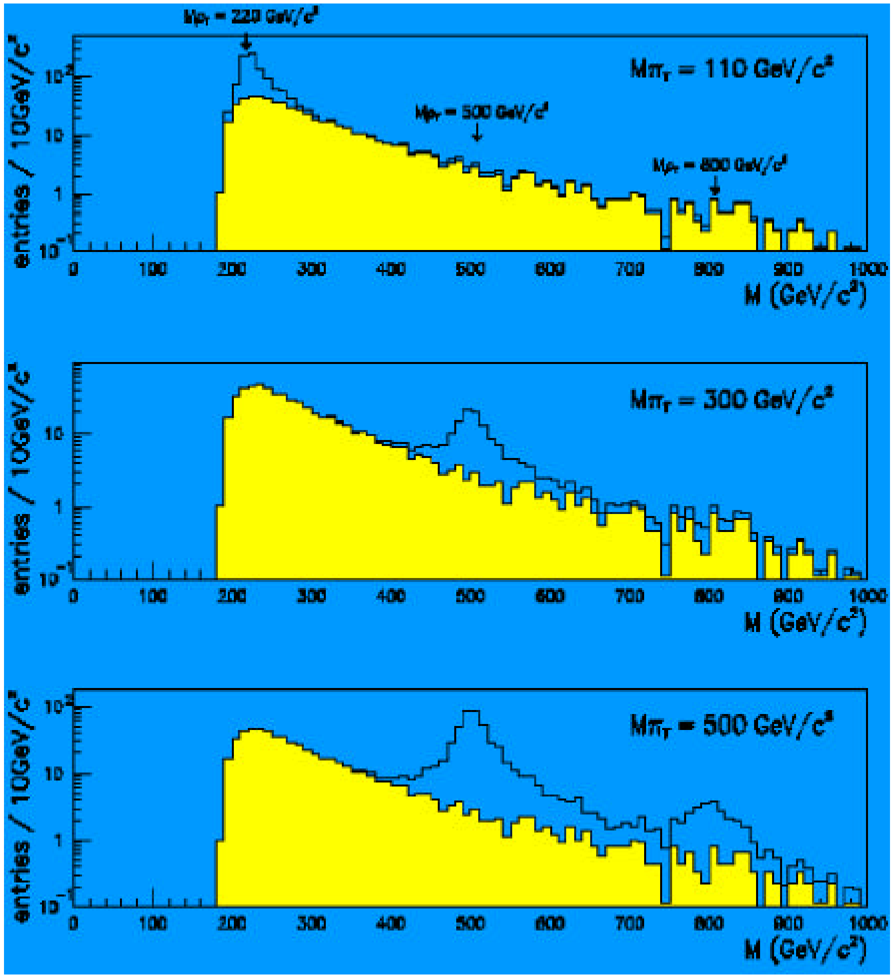
$W_T W_T$

Other resonances/signatures

Technicolor; many possibilities

- Example: $\rho_T^{\pm} \rightarrow W^{\pm} Z^0 \rightarrow \lambda^{\pm} n \lambda^{+} \lambda^{-}$ (cleanest channel…)
- Many other signals ($b\underline{b}$, $t\underline{t}$ resonances, etc…)
- Wide range of observability

ATLAS; 30 fb^{-1}

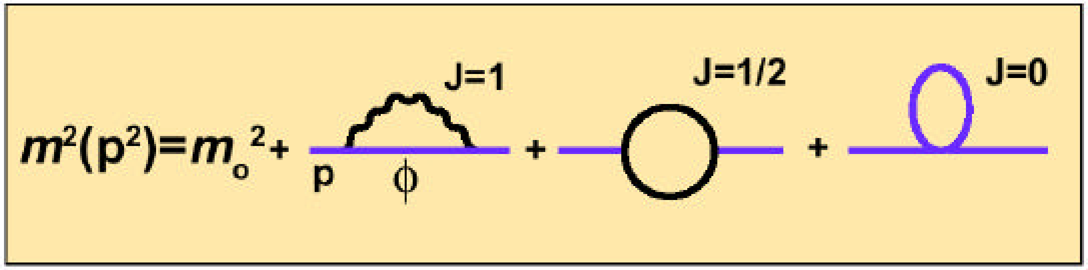


Supersymmetry

SUSY Higgses

Problems with the Higgs

Quadratic divergence of its mass



$$(\quad) = \quad (\Lambda\quad) + \quad \int^{\Lambda}$$

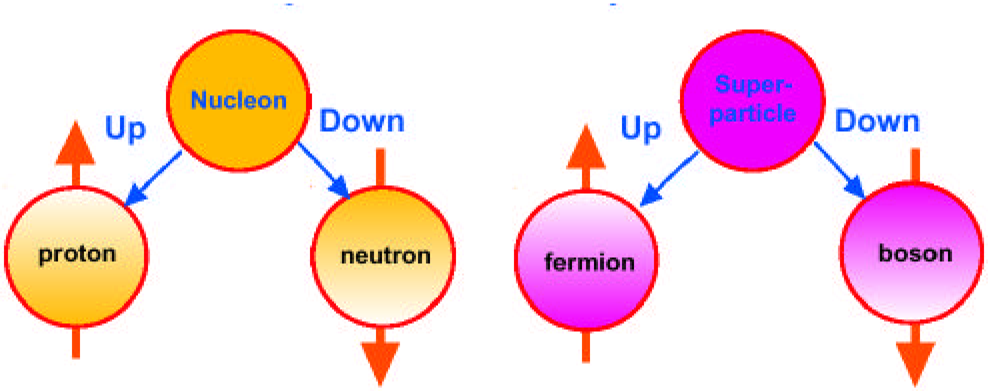
Λ is a cutoff momentum

Put simply: why is the Higgs mass low?

Supersymmetry (SUSY)

One possible solution:

for every particle there exists a partner particle with ½ spin difference



Isotopic symmetry

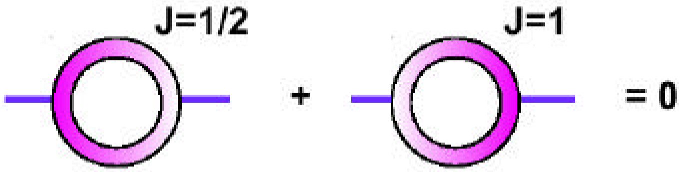
Proton and Neutron:
different states of a
generalized particle (Nucleon)

Supersymmetry :

Fermion and Boson:
different states of a
generalized entity (Superparticle)

With SUSY, infinities disappear:

As long as $M_p = M_{sp}$



Supersymmetry World

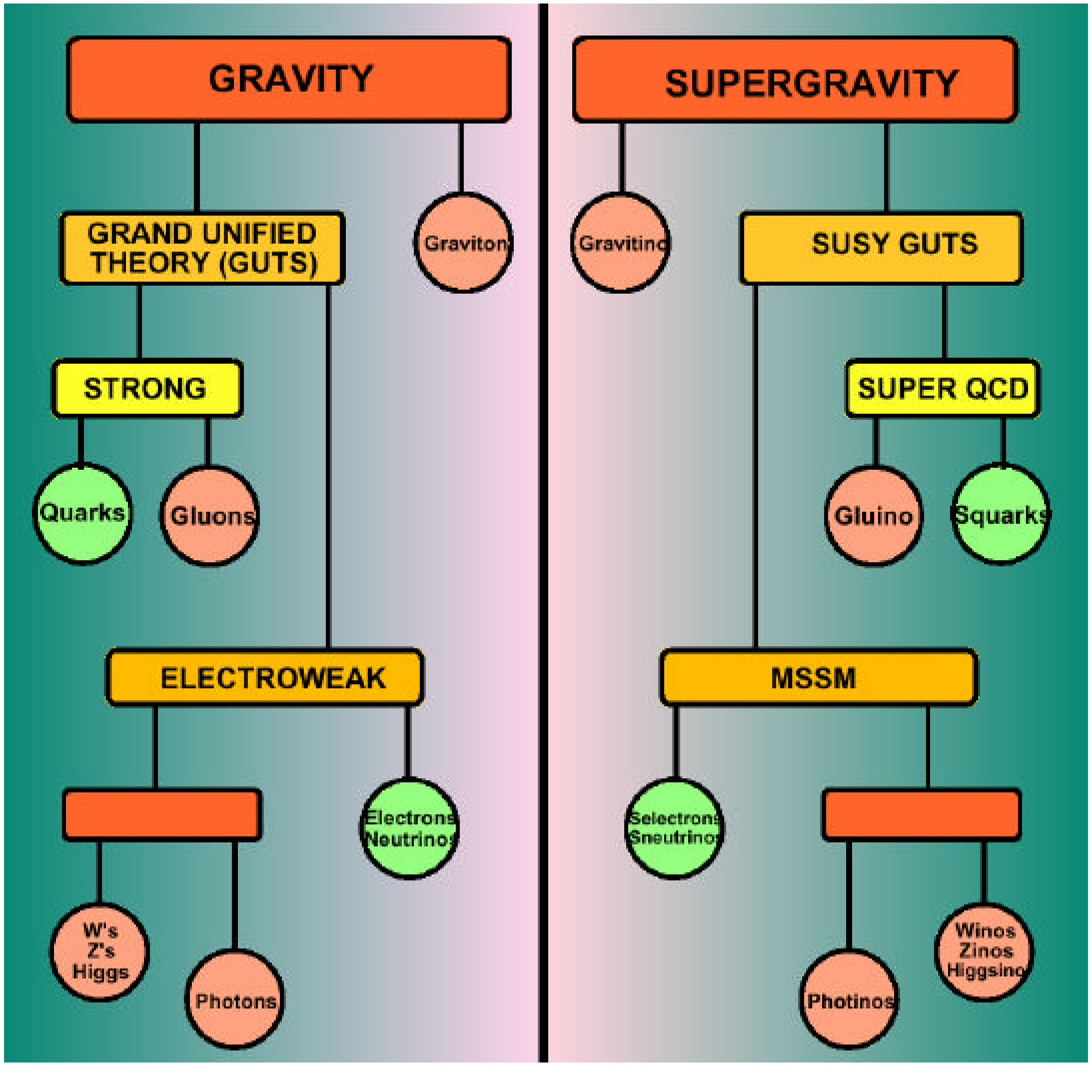
SUSY doubles the particle spectrum

It must also be broken

- To explain why unseen till now
- If broken at E_{SUSY}:

$$(\quad)=$$

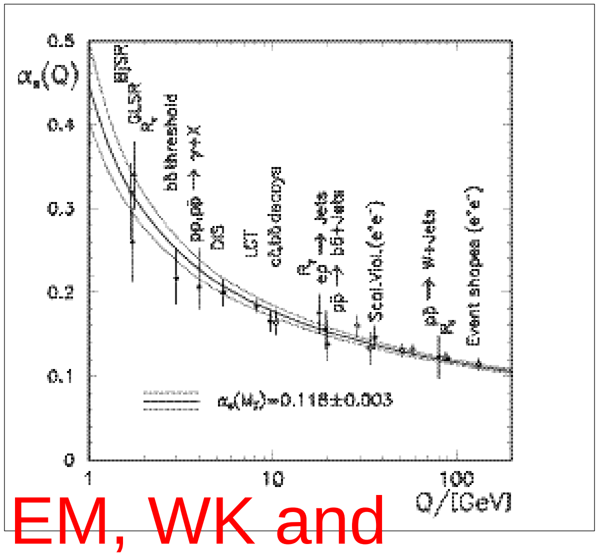
$$(\Lambda\quad)+\qquad\int$$



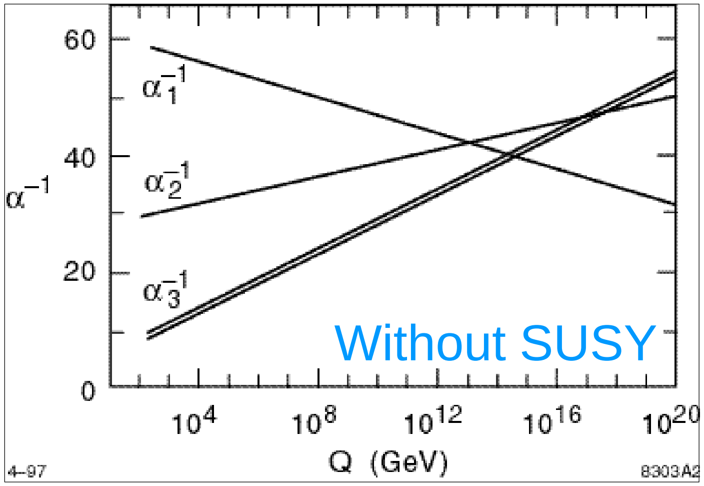
Supersymmetry and Unification

Couplings “run” with Q^2:

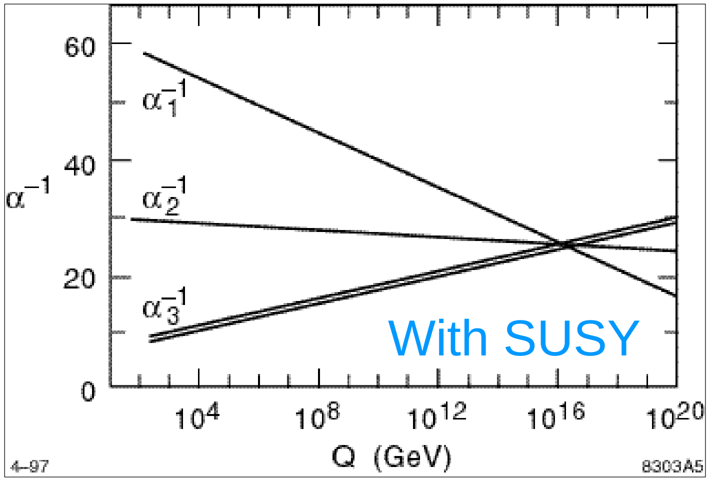
Loop diagrams (quantum corrections) make the coupling between the force and matter particles dependent on the energy at which the interaction occurs



Extrapolating the couplings for the EM, WK and strong interactions:



Without SUSY



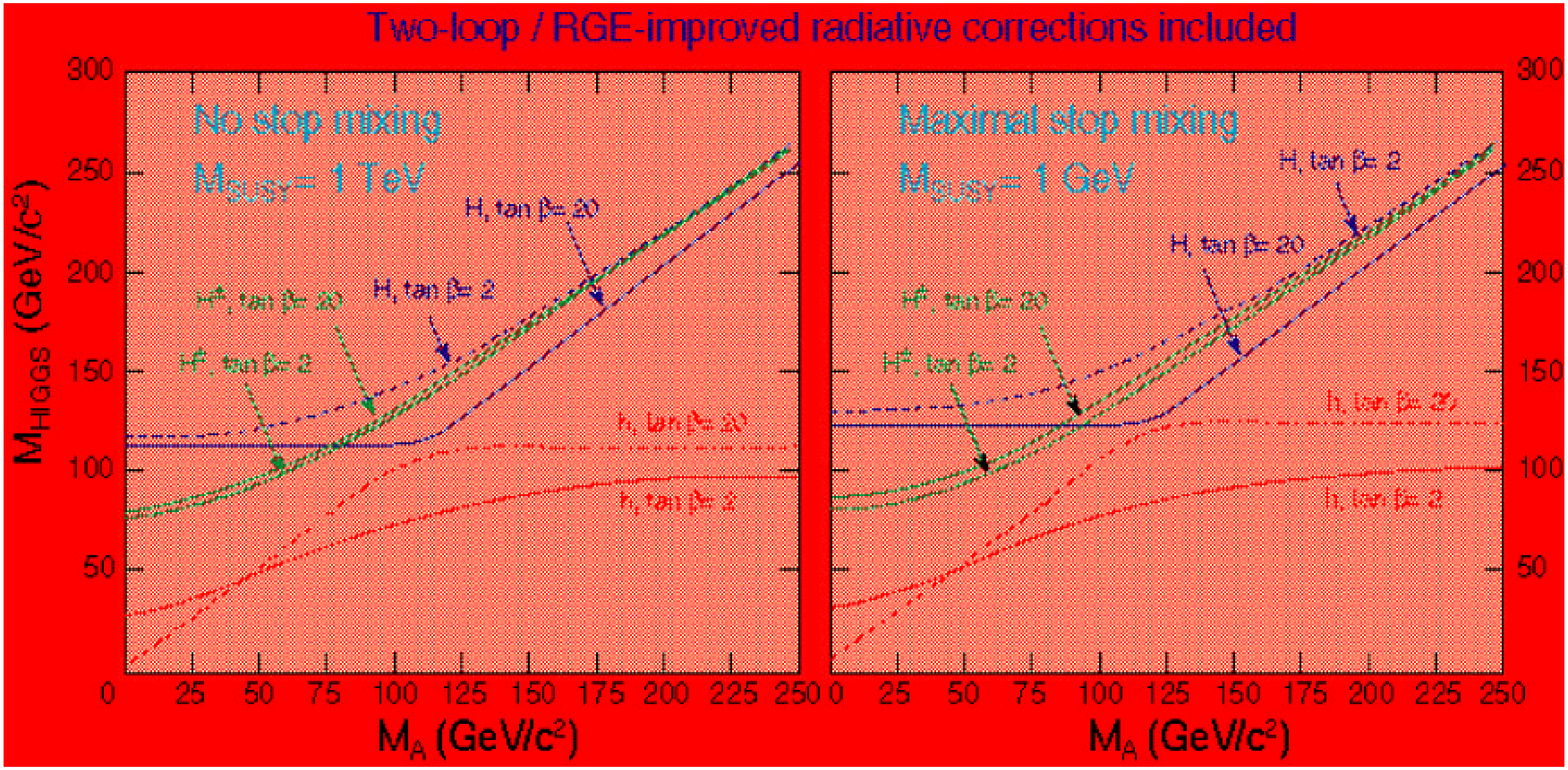
With SUSY

MSSM Higgses: phenomenology

- Complex analysis; 5 Higgses ($H^{\pm}$;H^0,h^0,A^0)
  - At tree level, all masses & couplings depend on only two parameters; tradition says take M_A & tanβ
  - Modifications to tree-level mainly from top loops
    - Important ones; e.g. at tree-level, $M_h < M_Z \cos\beta$; radiative corrections push this to 150 GeV.
  - Important branch 1: SUSY particle masses
    - (a) M>1 TeV (i.e. no decays of the Higgses to them); well-studied
    - (b) M<1 TeV (i.e. allows decays of the Higgses to them); “new”
  - Important branch 2: stop mixing; value of tanβ
    - (a) Maximal–No mixing
    - (b) Low (1.5) and high (˜30) values of tanβ

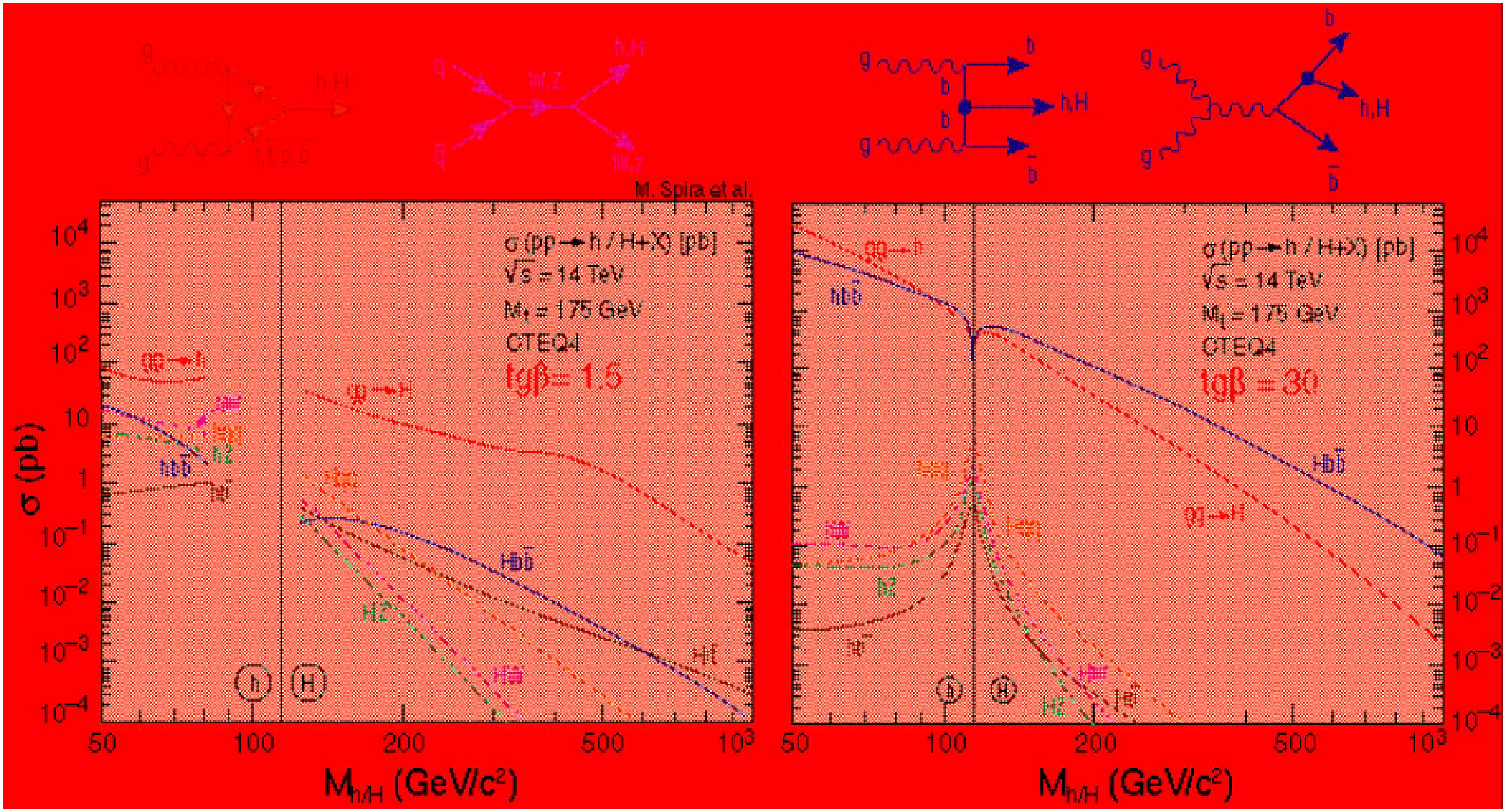
MSSM Higgses: masses

Mass spectra for M_{SUSY}>1TeV



MSSM: h/H production

Biggest branch is tanβ



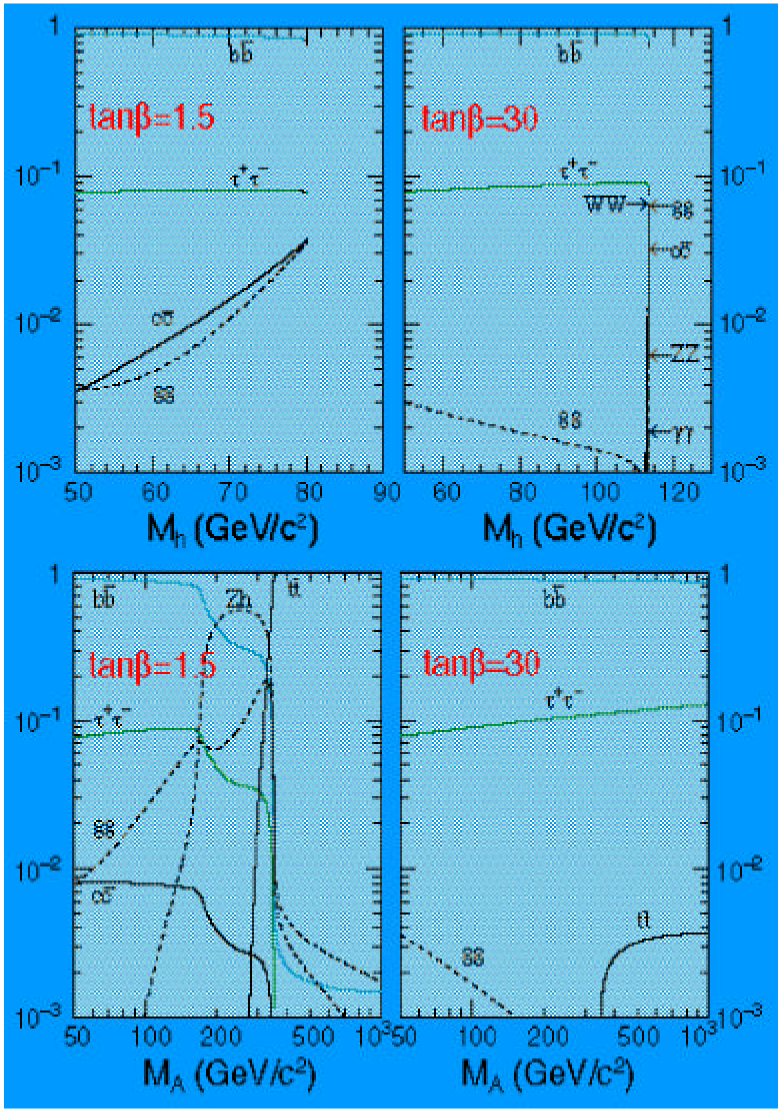
MSSM: h/A decay

h is light

- Decays to $b\bar{b}$ (90%) & $\tau\tau$ (8%)
  - Decays to cc, gg suppressed

H/A "heavy"

- Decays to top open (low tanβ)
- Otherwise still to $b\bar{b}$ & $\tau\tau$
- Negative: WW/ZZ channels suppressed; lose golden modes for H



No mixing

Higgs channels considered

Channels currently being investigated:

- H, $h \to \gamma\gamma$, $b\bar{b}$ ($H \to b\bar{b}$ in WH, $t\bar{t}H$)
- $h \to \gamma\gamma$ in WH, $t\bar{t}h \to l\,\gamma\gamma$

(very) important and hopeful

- h, H $\to$ ZZ*, ZZ $\to$ 4 l
- h, H, A $\to \tau^+\tau^- \to (e/\mu)^+ + h^- + E_T^{miss}$
  - $\to e^+ + \mu^- + E_T^{miss}$
  - $\to h^+ + h^- + E_T^{miss}$

inclusively and in $b\bar{b}H_{SUSY}$

- $H^+ \to \tau^+ \nu$ from $t\bar{t}$
- $H^+ \to \tau^+ \nu$ and $H^+ \to t\bar{b}$ for $M_H > M_{top}$
- A $\to$ Zh with $h \to b\bar{b}$; $A \to \gamma\gamma$
- H, A $\to \tilde{\chi}^0_2\tilde{\chi}^0_2, \tilde{\chi}^0_i\tilde{\chi}^0_j, \tilde{\chi}^+_i\tilde{\chi}^-_j$
- $H^+ \to \tilde{\chi}^+_2\tilde{\chi}^0_2$

new and promising

- qq $\to$ qqH with $H \to \tau^+\tau^-$

using OO code (tough…)

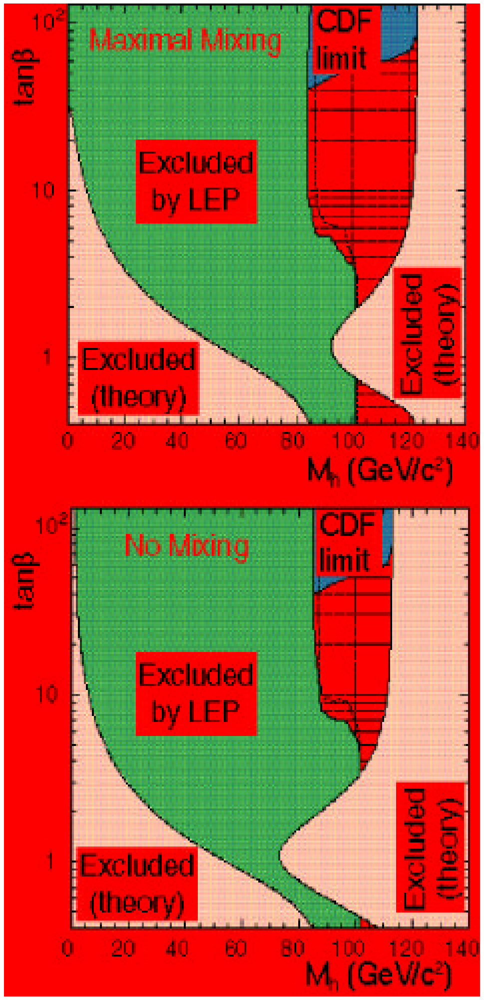
- $H \to \tau\tau$, in WH, $t\bar{t}H$

work started; tough…

MSSM Higgses: last (published) results

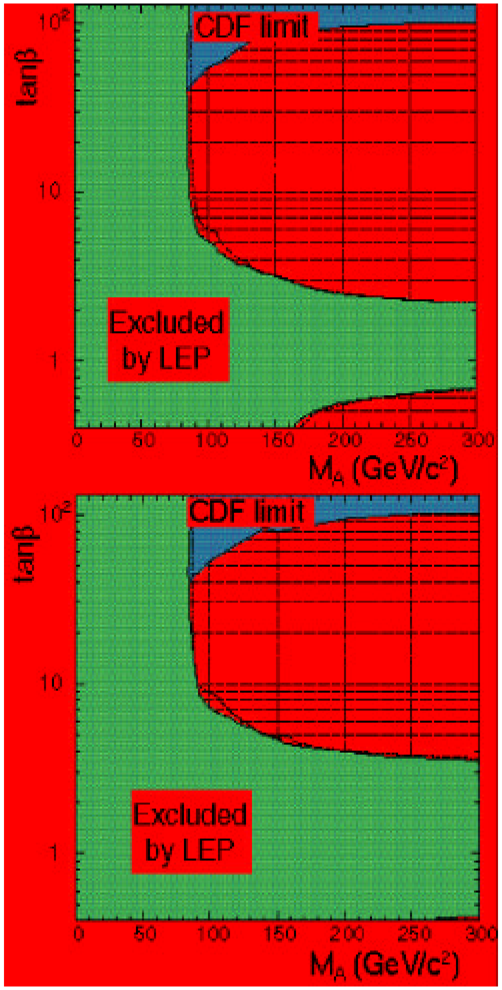
Little room for h left; A is still “open”

- Maximal mixing:
  - $M_h>84\ \mathrm{GeV}/c^2$
  - exclude $0.8<\tan\beta<1.9$
- No mixing:
  - $M_h>84\ \mathrm{GeV}/c^2$ (95%CL)
  - exclude $0.5<\tan\beta<3.2$



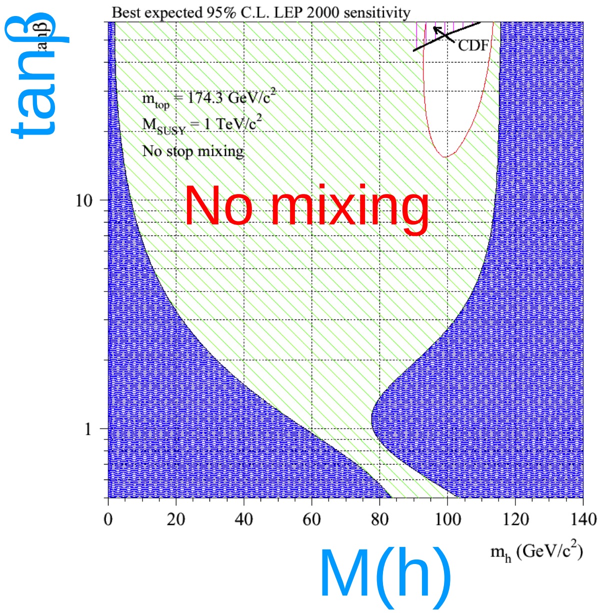
$M_A>84\ \mathrm{GeV}/c^2$

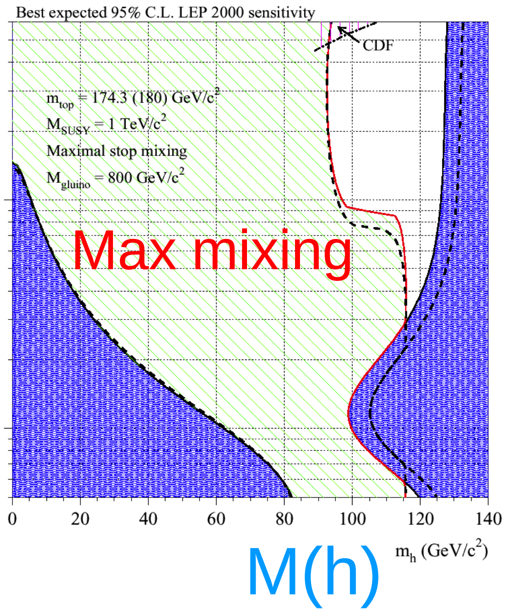
$M_A>85\ \mathrm{GeV}/c^2$

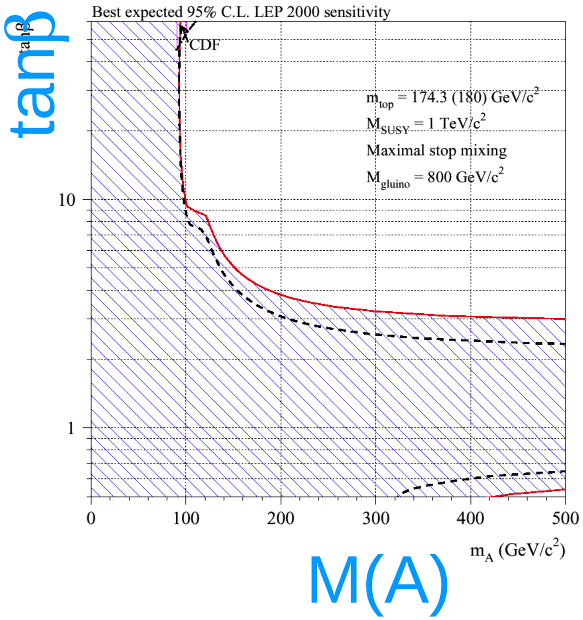


MSSM Higgses: expected LEP reach

Taking 208 GeV and actual luminosity recorded





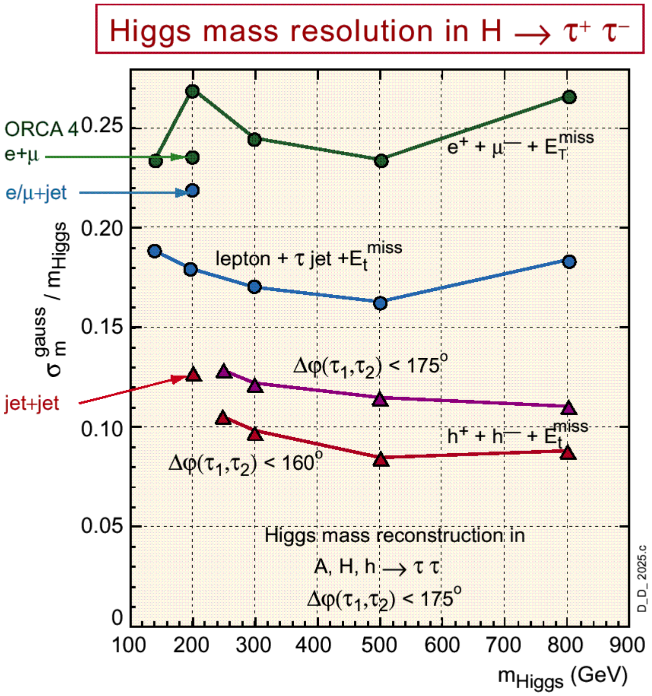


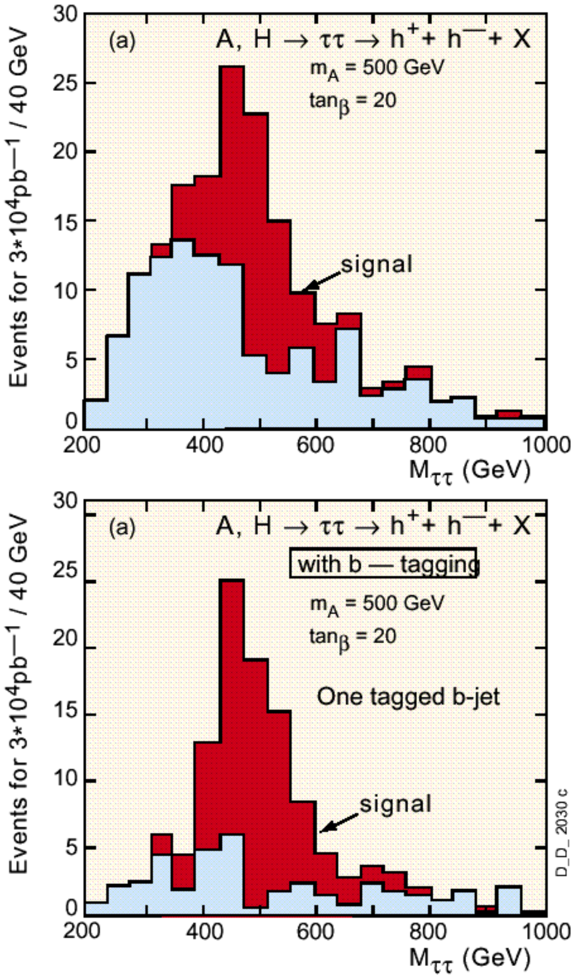
H,A® t t

Most promising modes for H,A

τ's identified either in hadronic or leptonic decays

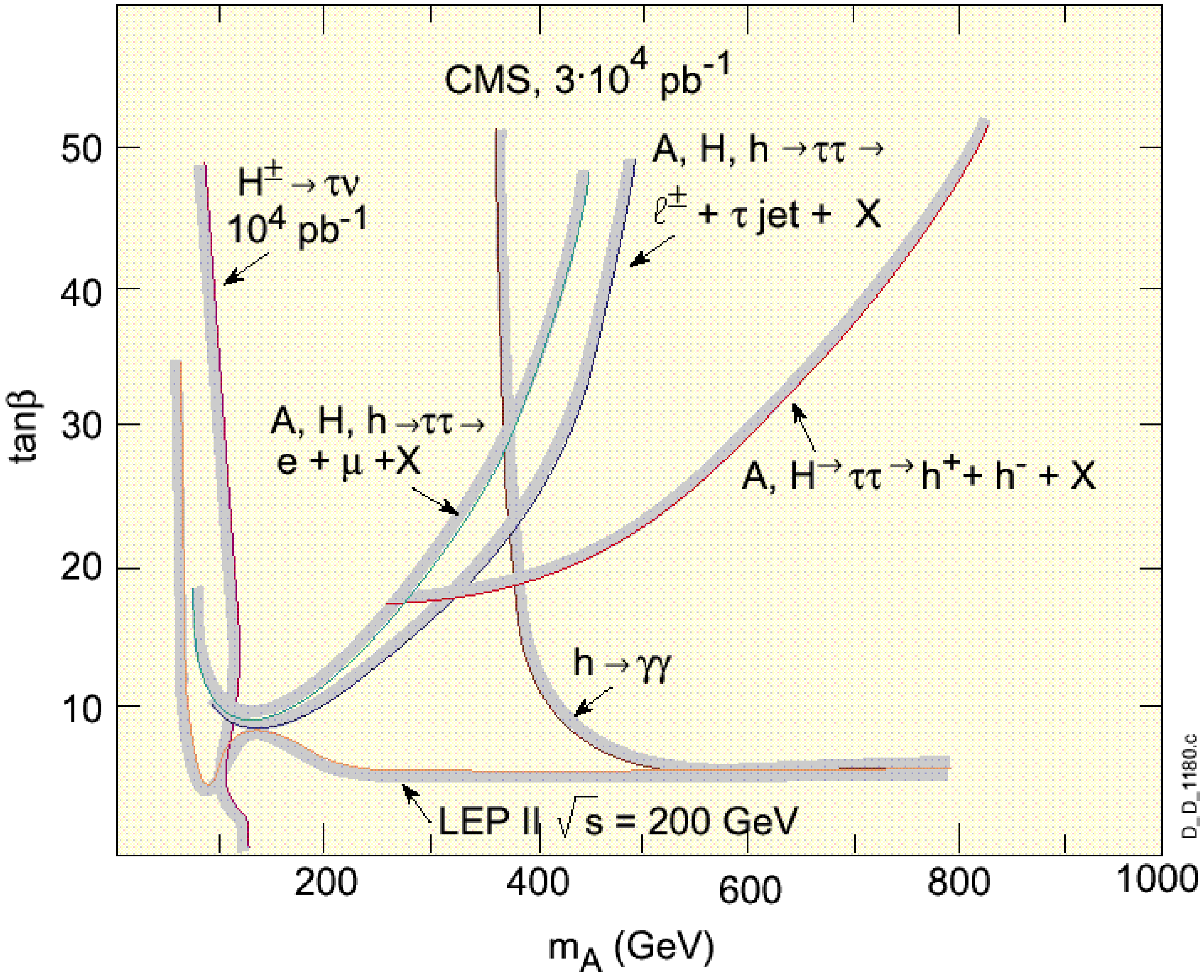
Mass reconstruction: take lepton/jet direction to be the τ direction





H, A reach via t decays

Contours are 5σ; M_{SUSY}=1 TeV



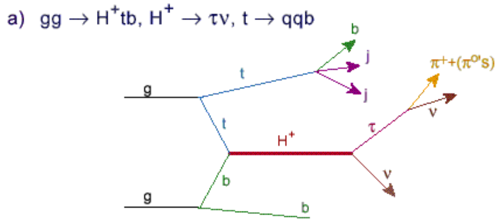
H^+ detection

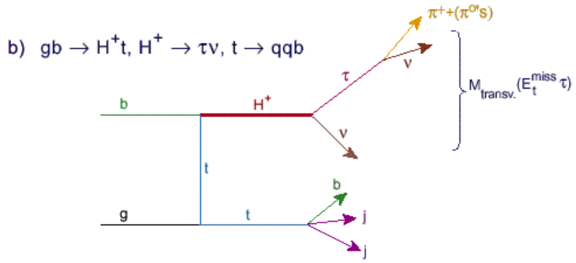
Associated top-H^+ production:

Use all-hadronic decays of the top (leave one "neutrino")

H decay looks like W decay → Jacobian peak for τ-missing E_T

In the process of creating full trigger path + ORCA analysis



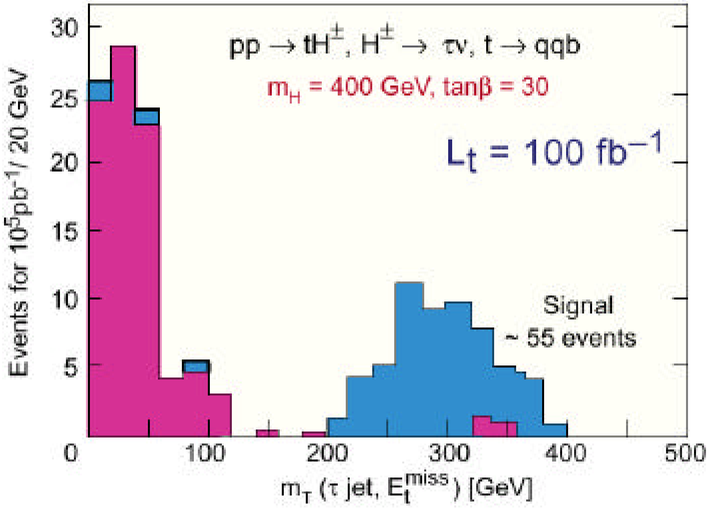


E_T(jet)>40

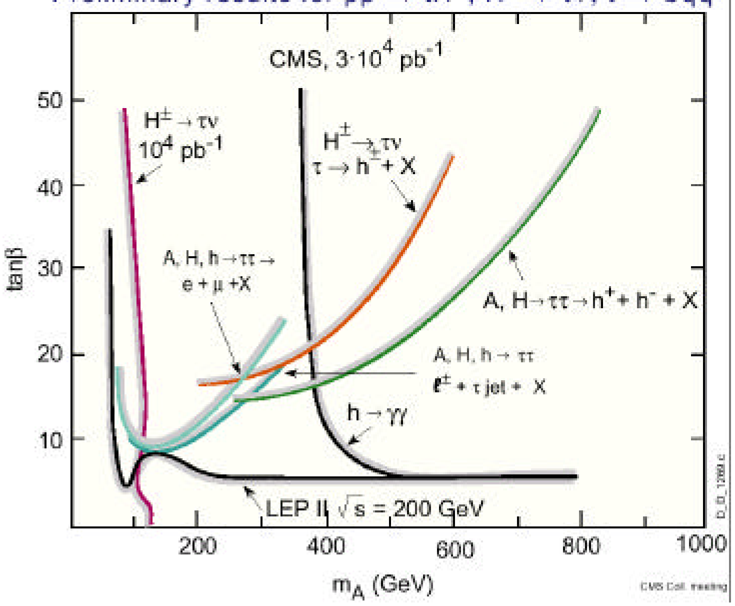
$|\eta|<2.4$

Veto on extra jet, and on second top

Bkg: $t\bar{t}H$



Preliminary results for $pp \to tH^\pm$, $H^\pm \to \tau\nu$, $t \to bqq$



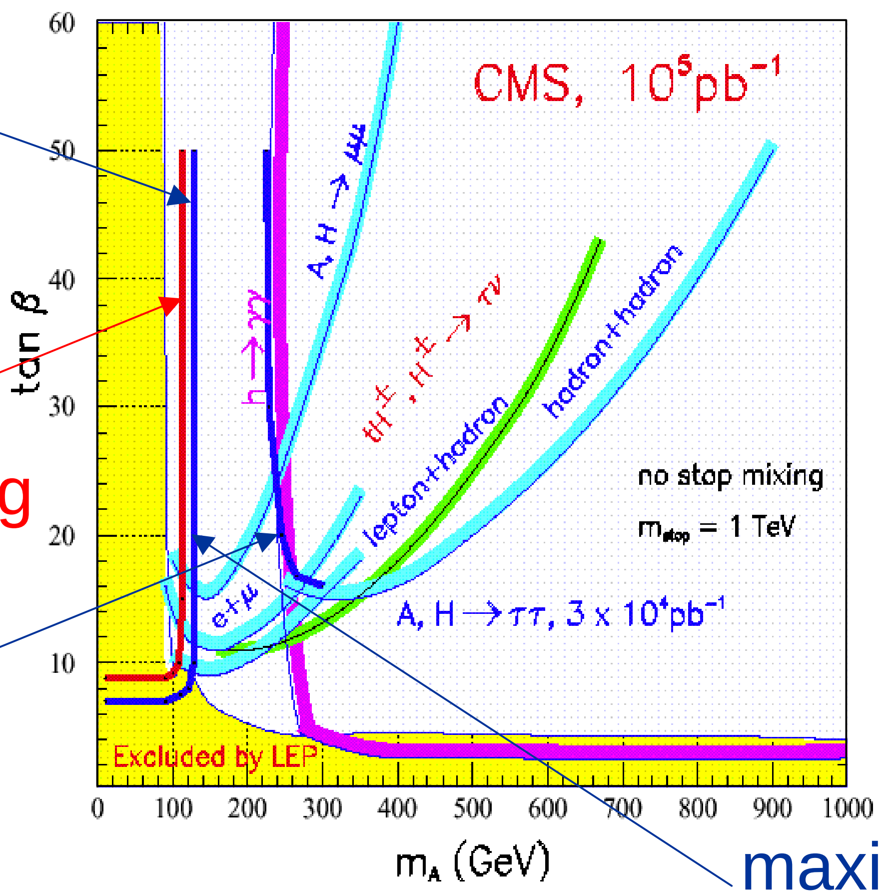
SUSY reach on tanb-M_A plane

Adding $b\bar{b}$ on the τ modes can “close” the plane

Wh

(e/μ)ν

$b\bar{b}$



No stop mixing

maximal stop mixing with 30 fb^{-1}

maximal stop mixing with 300 fb^{-1}

MSSM Higgs reach; M_{SUSY}~1TeV

Summary:

$\rightarrow gg \quad - \left\{ \quad - \right.$

$\rightarrow \quad ^{(*)} \rightarrow \quad 1$

$\rightarrow tt \rightarrow (1/ \quad) + \quad ^{\text{miss}}$

$, \quad , \quad \rightarrow mm$; same for $b\bar{b}H_{\text{SUSY}}$

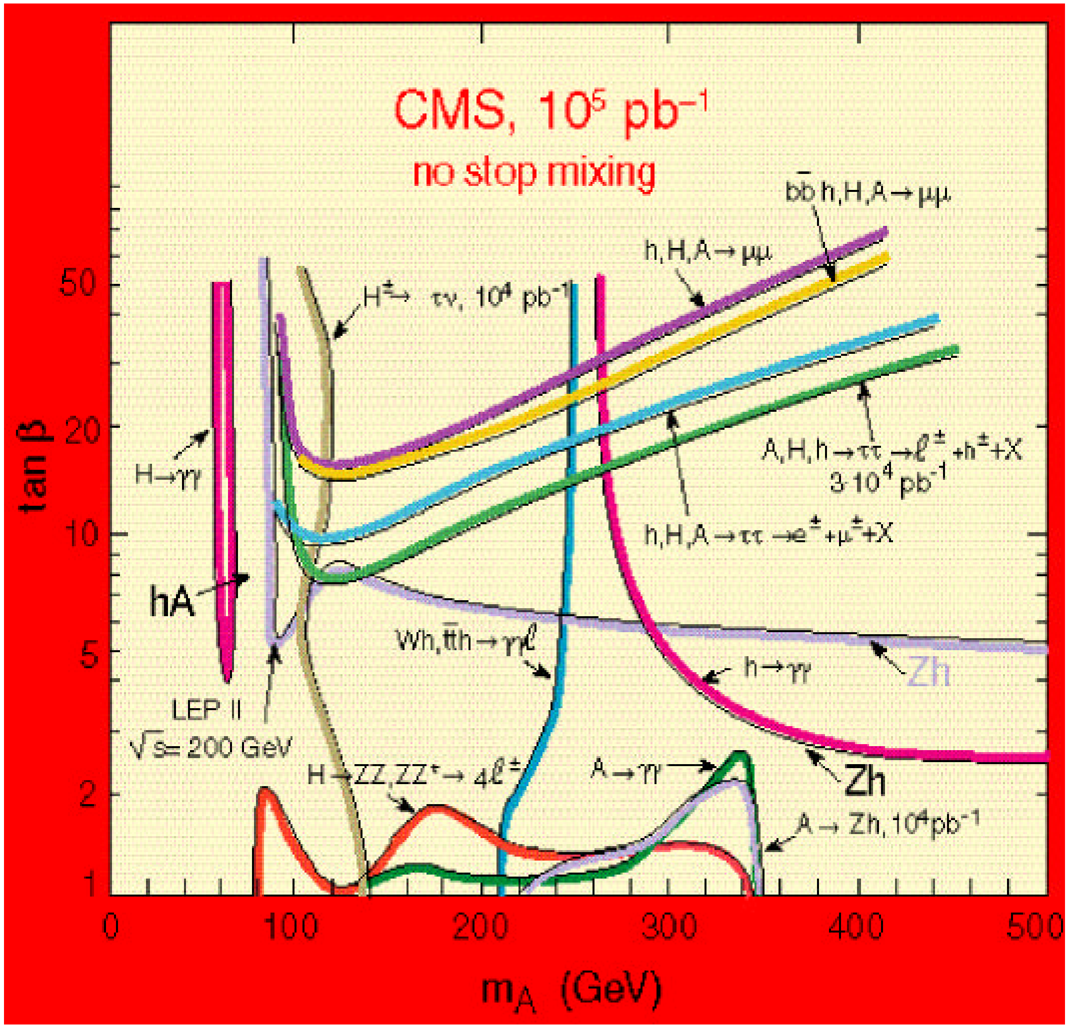
$$H^{\pm} \rightarrow t^{\pm}n \begin{cases} \text{from } t \rightarrow Hb \\ \text{from } H \rightarrow tb \end{cases}$$

$A \rightarrow gg$

$A \rightarrow Zh$

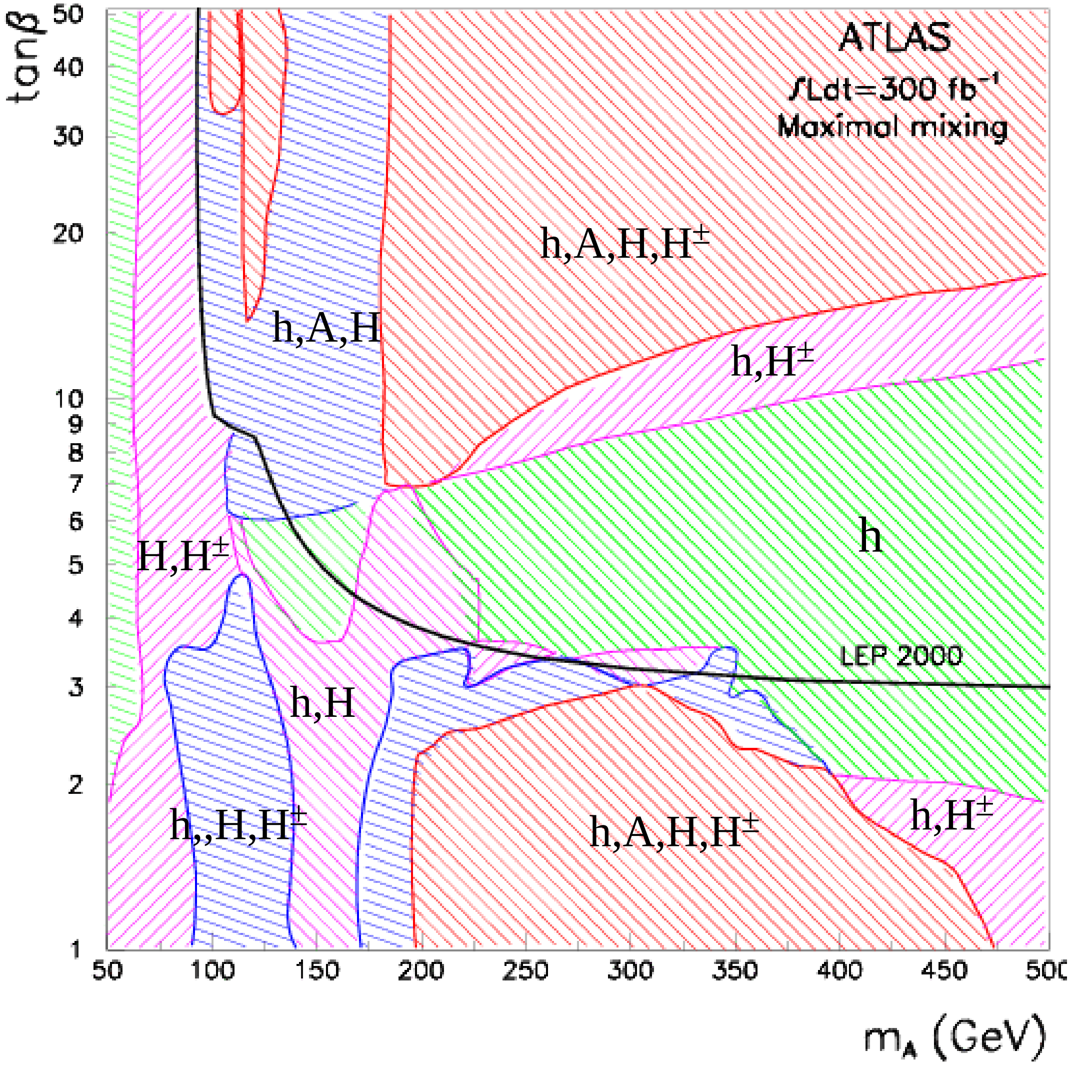
$H \rightarrow hh$

$A/H \rightarrow t\bar{t}$



Observability of MSSM Higgses

MSSM Higgs bosons



- 🟥 4 Higgs observable
- 🟦 3 Higgs observable
- 🟪 2 Higgs observable
- 🟩 1 Higgs observable

5σ contours

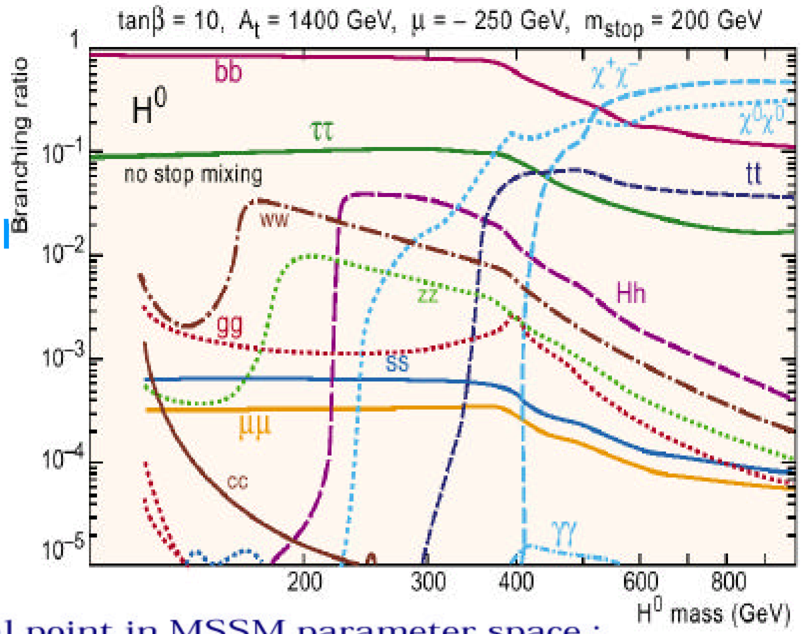
Assuming decays to SM particles only

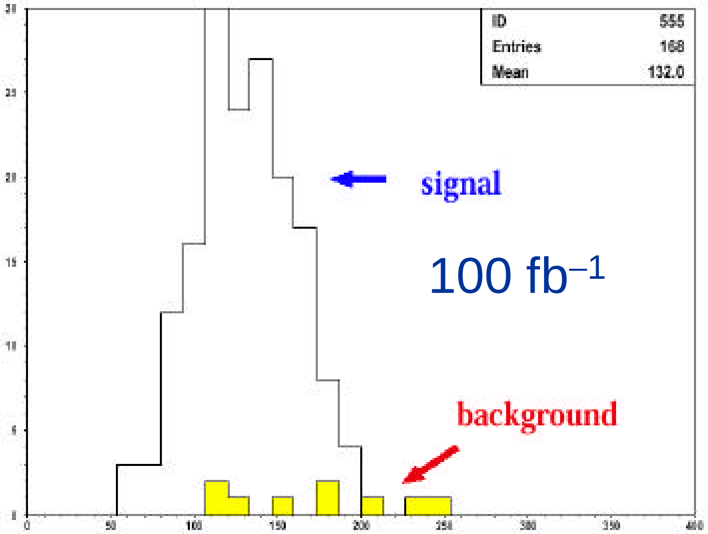
If SUSY charg(neutral)inos < 1 TeV (I)

Decays $H^0 \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_2, \tilde{\chi}^+_i\tilde{\chi}^-_j$ become important

Recall that $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 l^+ l^-$ has spectacular edge on the dilepton mass distribution

Example: $\tilde{\chi}^0_2\tilde{\chi}^0_2$. Four (!) lepton (isolated); plus two edges





Four-lepton mass

Central point in MSSM parameter space :

$M_{A,H} = 350$ GeV　$\tan\beta = 5$

$M_{\tilde{l}} = 250$ GeV　$\mu = -500$ GeV

$M_{\tilde{\chi}^0_1} = 60$ GeV　$M_{\tilde{\chi}^0_2} = 110$ GeV

$M_{\tilde{q}} = M_{\tilde{g}} = 1$ TeV

If SUSY charg(neutral)inos < 1 TeV (II)

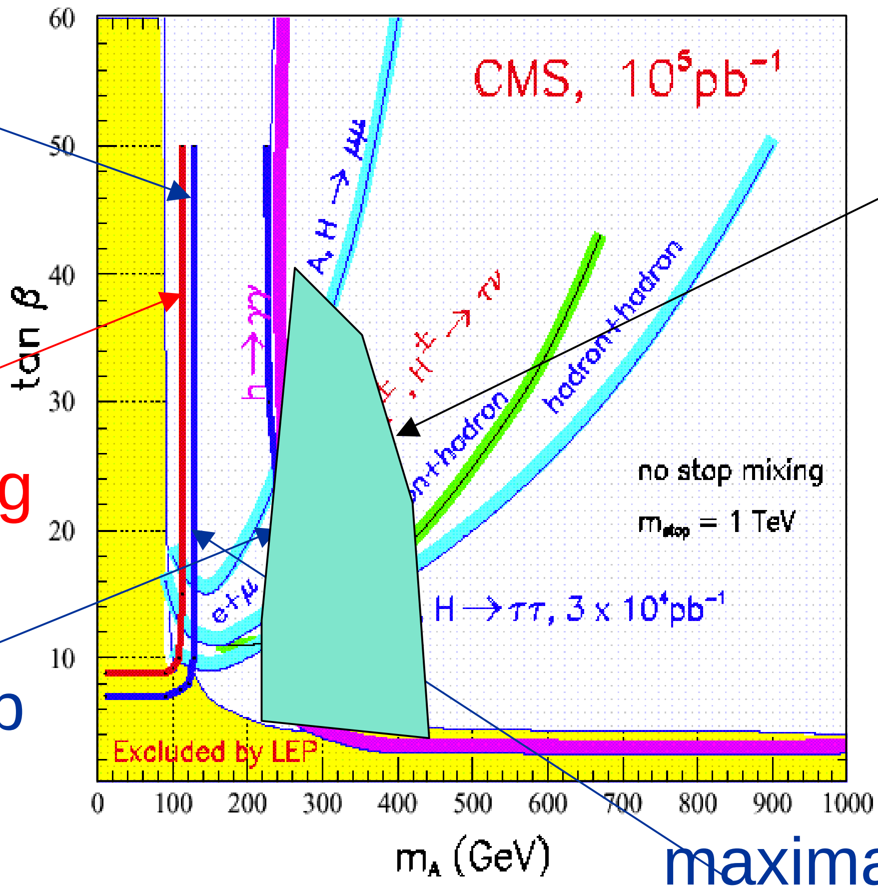
Adding $b\bar{b}$ on the τ modes can “close” the plane

Wh

(e/μ)ν $b\bar{b}$

No stop mixing

maximal stop mixing with $30\ fb^{-1}$



Area covered by $H^0 \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_2$, →4l eptons $100\ fb^{-1}$

maximal stop mixing with $300\ fb^{-1}$

MSSM: Higgs summary

- At least one ϕ will be found in the entire M_A-tanβ plane
  - latter (almost) entirely covered by the various signatures, however:
  - Full exploration requires 100 fb^{-1}
  - Difficult region: $3<\tan\beta<10$ and $120<M_A<220$; will need:
    - $>$ 100 fb^{-1} or h→bb decays
    - Further improvements on t identification?
  - Intermediate tanβ region: difficult to disentangle SM and MSSM Higgses (only h is detectable)

Sumersymmetry

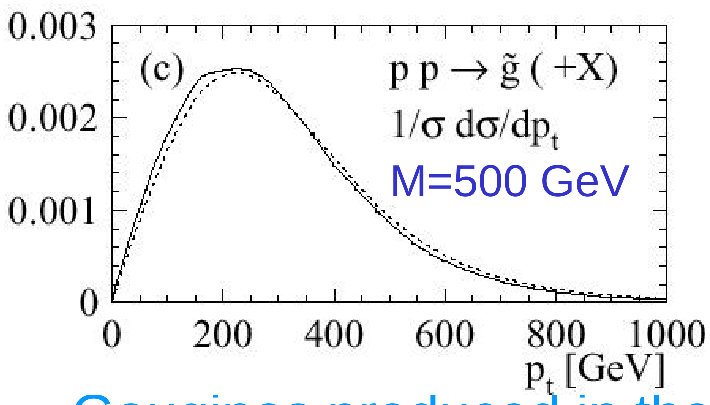
Sparticles

SUSY @ LHC

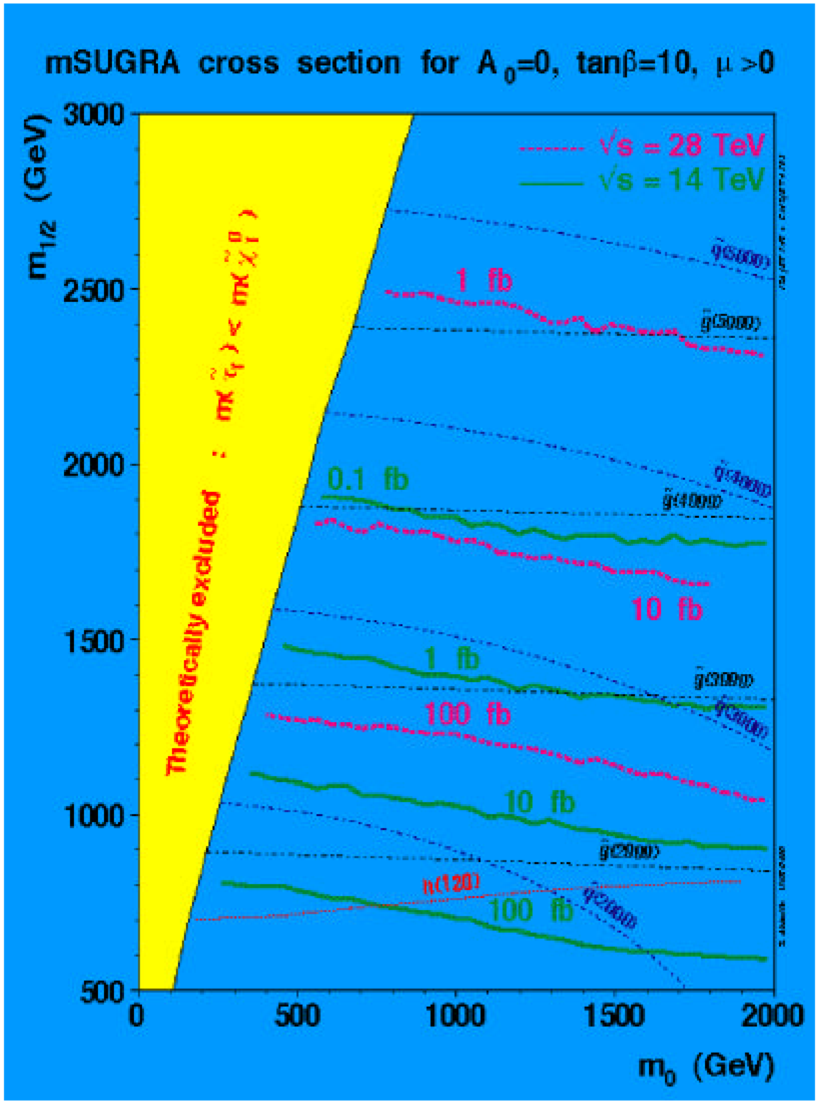
Simplest SUSY

Ample cross section for direct squark and gluino production

M_{sp}(GeV)	s (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3



Gauginos produced in their decay; example: q_L ® $c_2^0 q_L$



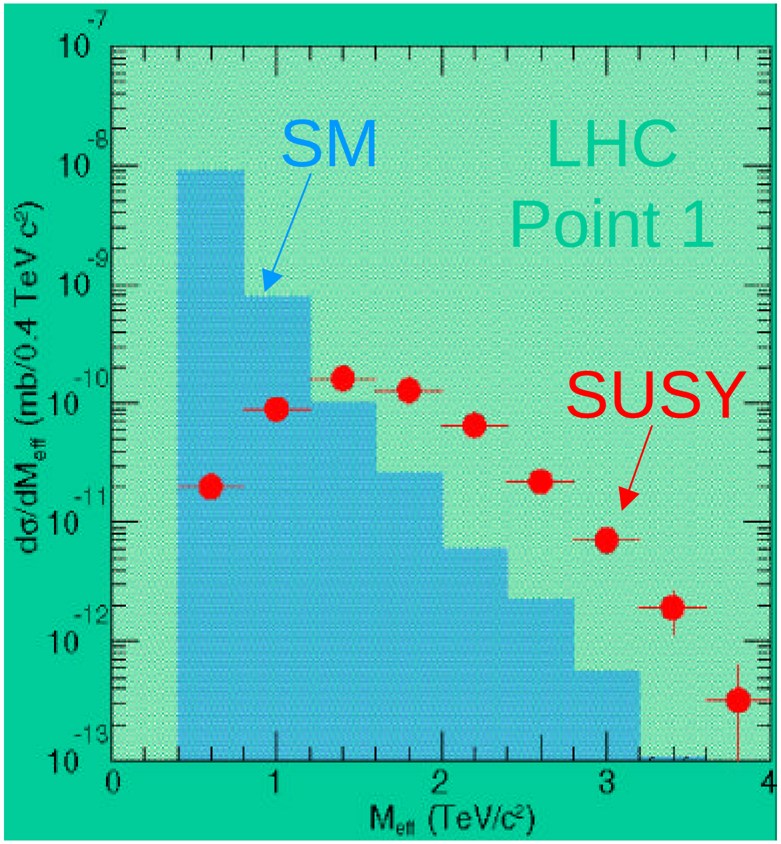
SUSY mass scale

Events with ≥ 4jets + E_T^{miss}

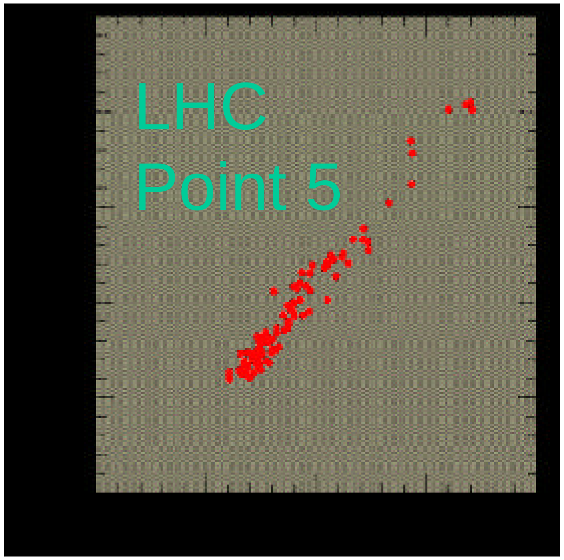
Clean: S/B~10 at high M_{eff}

Establish SUSY scale (σ ≈ 20%)

$$M_{\text{eff}} = \sum_{j=1}^{4} P_{\text{T},j} + E_{\text{T}}^{\text{miss}}$$



Effective mass "tracks" SUSY scale well



SUSY decays

Squarks & gluinos produced together with high σ

Gauginos produced in their decays; examples:

$\tilde{q}_L \text{®} \tilde{c}_2^0 q_L$ (SUGRA P5)

$\tilde{q}$ ® $\tilde{g}\ q$ ® $\tilde{c}_2^0 q\bar{q}$ (GMSB G1a)

Two “generic” options with c^0:

(1) $c_2^0 \rightarrow c_1^0 h$ (~ dominates if allowed)

(2) $c_2^0 \rightarrow c_1^0 \lambda^+ \lambda^-$ or $c_2^0 \rightarrow \lambda^+ \lambda^-$

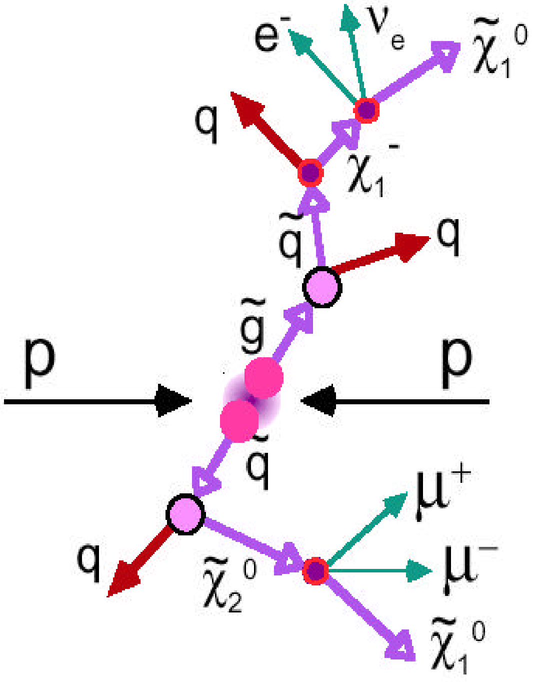
Charginos more difficult

Decay has ν or light q jet

Options:

Look for higgs (to b$\bar{\text{b}}$)

Isolated (multi)-leptons



SUSY

- Huge number of theoretical models
  - Very complex analysis; MSSM-124
  - Very hard work to study particular scenario
    - assuming it is available in an event generator
  - To reduce complexity we have to choose some “reasonable”, “typical” models; use a theory of dynamical SYSY breaking
    - mSUGRA
    - GMSB
    - AMSB (in less detail)
  - Model determines full phenomenology (masses, decays, signals)

SUGRA

Five parameters

- All scalar masses same (m_0) at GUT scale
- All gaugino masses same ($m_{1/2}$) at GUT scale
- tanβ and sign(μ)
- All tri-linear Higgs-sfermion-sfermion couplings common value A_0 (at GUT scale)

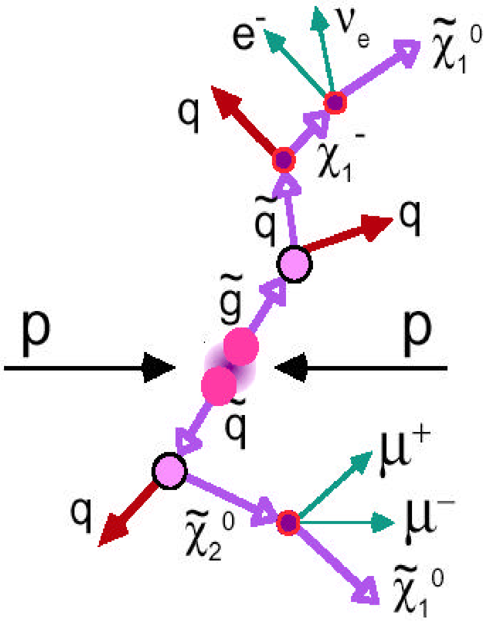
Full "particle table" predictable

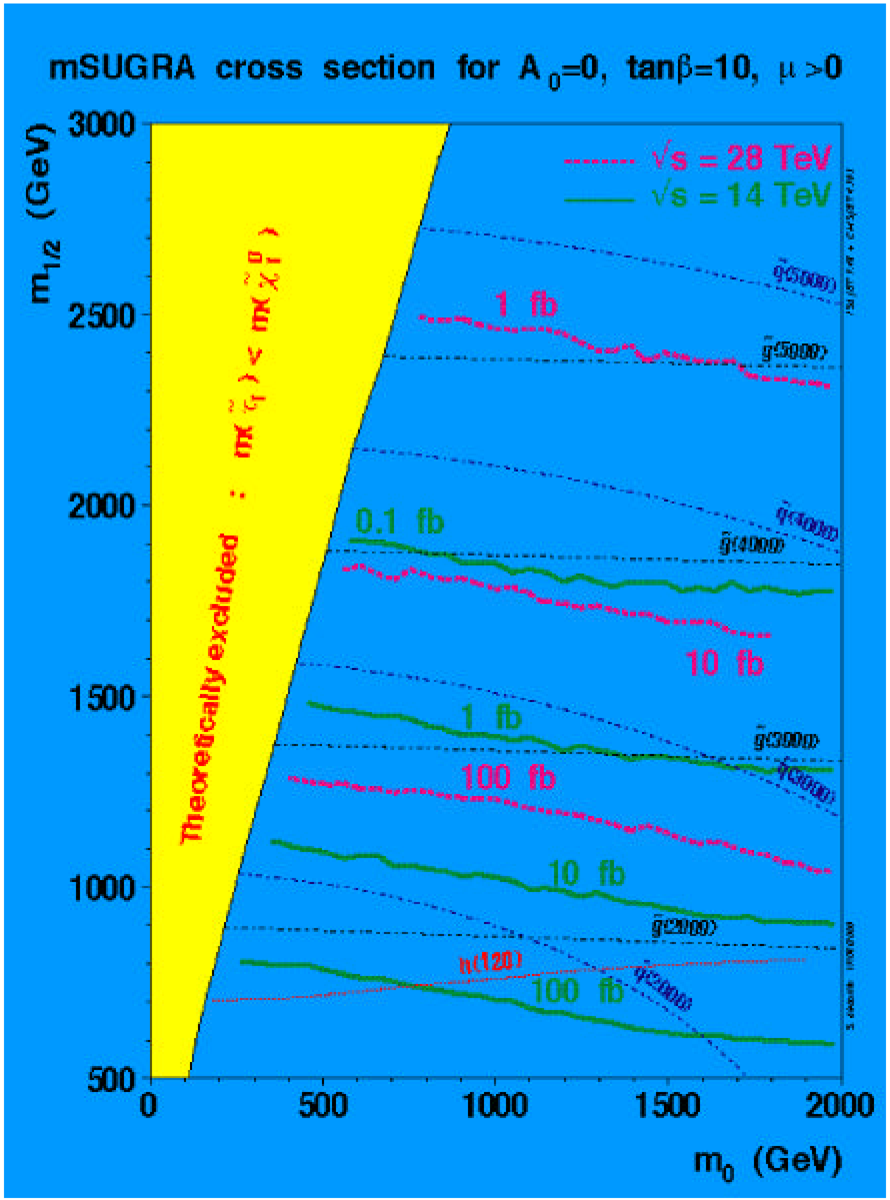
- 26 RGE's solved iteratively
- Branches: R parity (non)conservation
- Extensions: relax GUT assumptions (add parameters)

mSUGRA

Simplest SUSY

- Ample cross section for squark and gluino production
- Gauginos produced in their decay; example: $\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q_L$





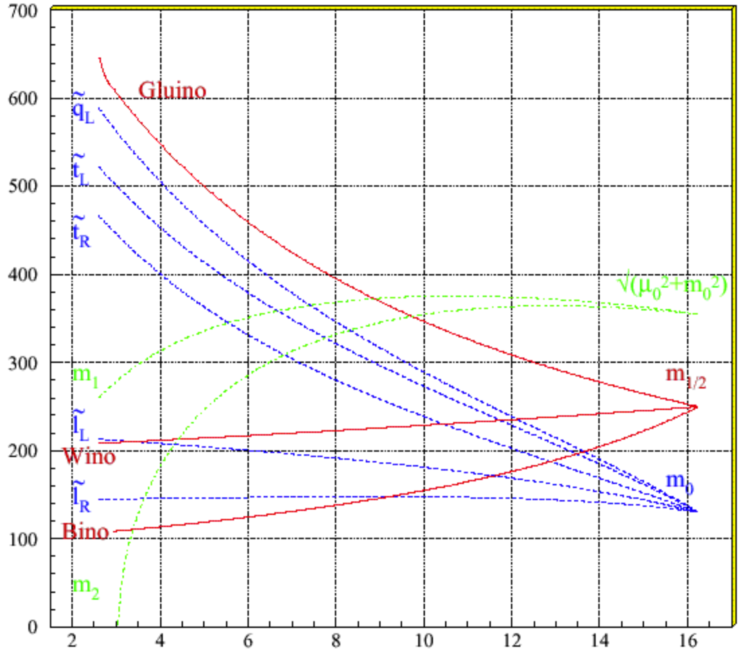
SUGRA spectroscopy

Basic assumption: mass universality

- Scalar masses: m_0;
- gaugino masses: $m_{1/2}$;
- Higgs masses: $(m_0^2+\mu^2)^{1/2}$

RGE: run masses down to EWK scale

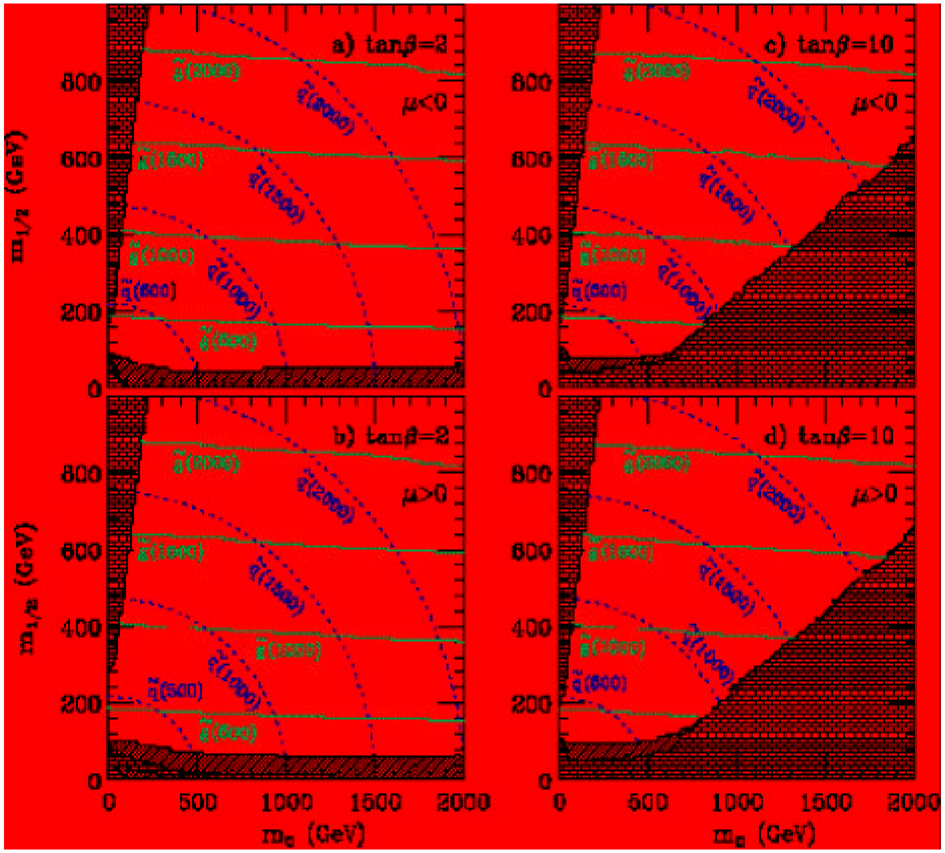
- M(squark): large Increase (due to α_3)
- M(slepton): small increase (due to α_1, α_2)
- Gauginos: gluino is fast-rising; B-ino, W-ino mass decreases
- Mixing leads to charginos (2) and neutralinos (4)

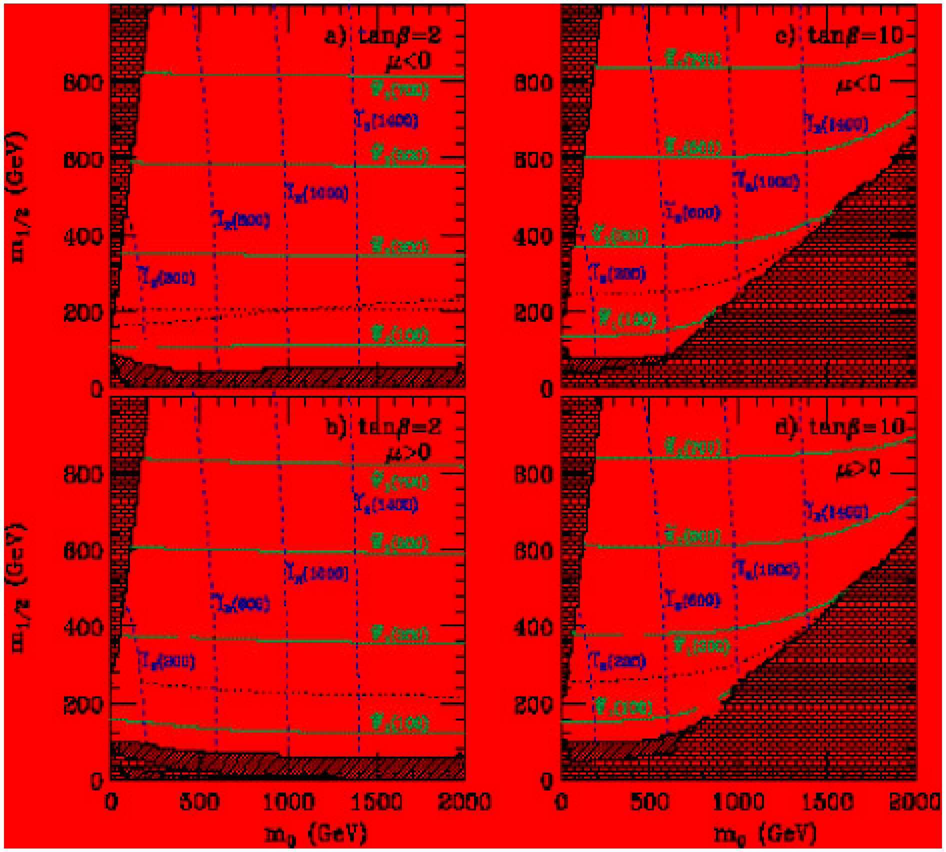


Higgs: strong top coupling drives $\mu^2<0$; Symmetry Breaking mechanism arises naturally in mSUGRA(!)

Sparticles in SUGRA

Contours of fixed g̃/q̃ and χ̃/λ̃ mass





$$m(\tilde{g}) \approx 3m_{1/2}$$

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

$$m(\tilde{\chi}_1^0) \approx m_{1/2}/2;\ m(\tilde{\chi}_2^0, \tilde{\chi}^{\pm}) \approx m_{1/2};$$

$$m(\tilde{\lambda}_L^{\pm}, \tilde{\lambda}_R^{\pm}) \approx \sqrt{m_0^2 + (0.5, 0.15)m_{1/2}^2}$$

SUGRA: the five LHC points

Defined by LHCC in 1996

- Points 1,3,5: light Higgses
  - LEP-excluded (3; less for 1,5)
  - Restore with larger tanβ
- Points 1&2:
  - Squark/gluinos ~ 1TeV
- Point 4: at limit of SB
  - Small μ^2, large χ,ϕ mixing
  - Heavy squarks
- Point 5: cosmology-motivated
  - Small $m_0 \rightarrow$ light sleptons
  - $\rightarrow$ increase annihilation of χ_1^0
  - $\rightarrow$ reduce CDM

P	*M_0*	*$M_{1/2}$*	*A_0*	*tanb*	*s(m)*
1	400	400	0	2	+
2	400	400	0	10	+
3	200	100	0	2	–
4	800	200	0	10	+
5	100	300	300	2.1	+

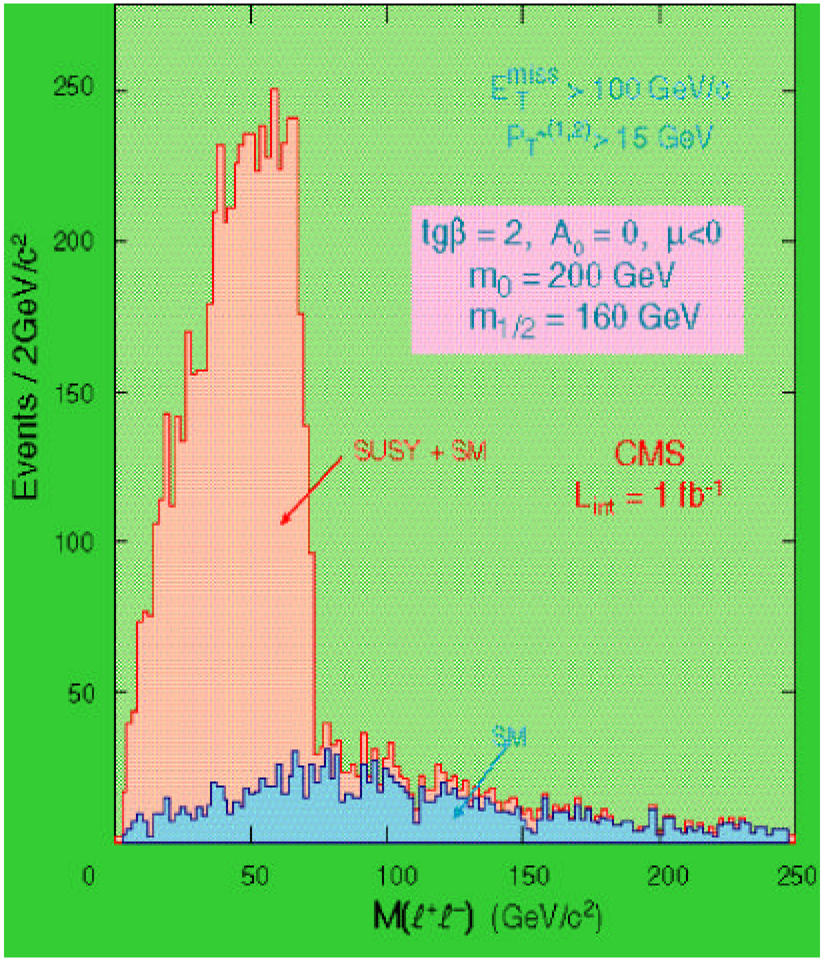
Sparticles (e.g. SUGRA)

- Formidable number of options
  - Five parameters
    - All scalar masses same (m_0) at GUT scale
    - All gaugino masses same ($m_{1/2}$) at GUT scale
    - tanβ and sign(μ)
    - All tri-linear Higgs-sfermion-sfermion couplings common value A_0 (at GUT scale)
- Full "particle table" predictable
  - 26 RGE's solved iteratively
  - Branches: R parity (non)conservation
  - Extensions: relax GUT assumptions (add parameters)

Experimentally: spectacular signatures

“Prototype”: $\tilde{c}_2^0$ ® $\tilde{c}_1^0\lambda^+\lambda^-$

- Straightforward:
  - dileptons + E_T^{miss}
- Example from P3
  - SM even smaller with b’s
  - Also works at other points
  - But additional SM (e.g. Z^0)
- ΔM measurement easy
  - Position of edge; accurate



Dileptons @ other points

Multi-observations

Main peak from $\tilde{c}_2{}^0 ® \tilde{c}_1{}^0\lambda^+\lambda^-$

Measure Δm as before

Also peak from Z^0 through $\tilde{c}_2{}^0 ® \tilde{c}_1{}^0 Z^0$

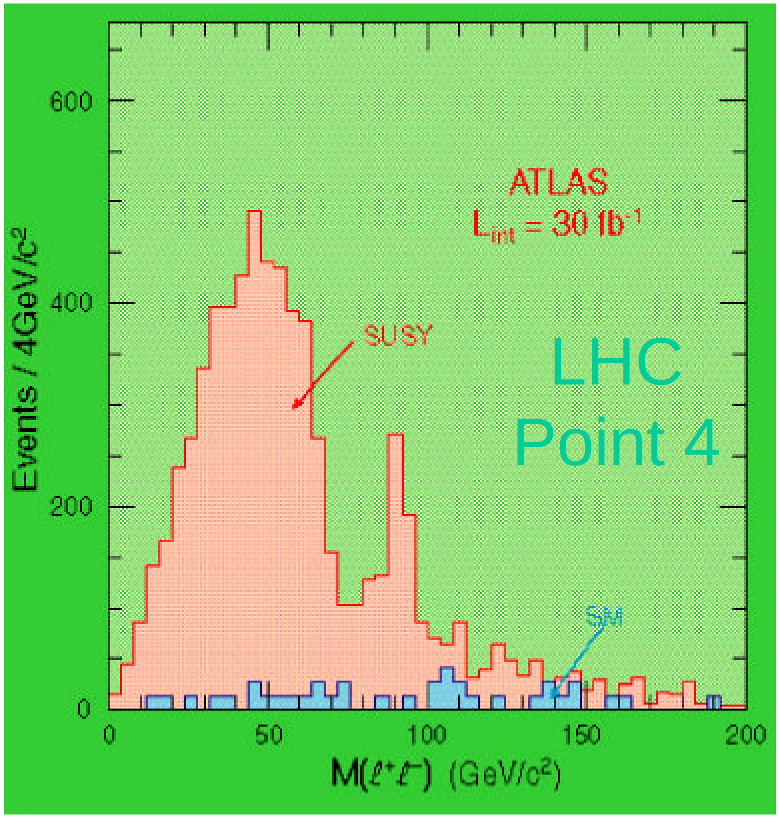
Due to heavier gauginos

P4 at “edge” of SB

→ small μ^2 →

(a) $c^\pm$ and $\tilde{c}^0$ are light

(b) strong mixing between gauginos and Higgsinos



At P4 large Branching fractions to Z decays:

e.g. B($\tilde{c}_3 ® \tilde{c}_{1.2} Z^0$)˜ 1/3; size of peak/$P_T$(Z)→info on masses and mixing of heavier gauginos (model-dependent)

Determining SUSY parameters

From the edges of the spectra

@ P5: $\tilde{q}_L$ ® $q\tilde{c}_2^0 \to q\tilde{\lambda}\lambda \to q\lambda^+\lambda^-$

ATLAS example:

2 isol, OS leptons+=4jets+E_T^{miss}

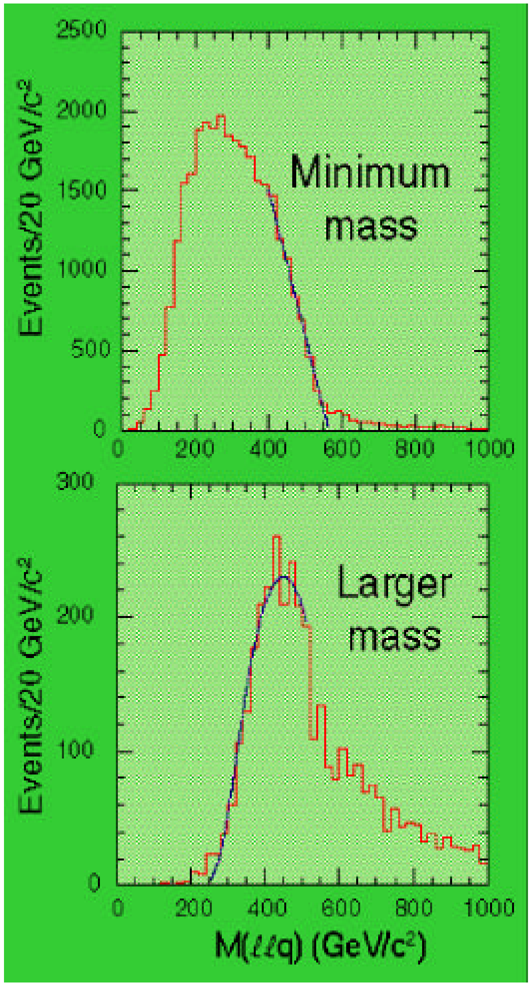
Combine leptons with 2 harder jets

$$M^{\max}_{\lambda\lambda q} = \left[\frac{\left(M^2_{\tilde{q}_L} - M^2_{c_2^0}\right)\left(M^2_{c_2^0} - M^2_{c_1^0}\right)}{M^2_{c_2^0}} \right]^{1/2} \approx 550$$

Similarly, minimum at 270 GeV/c^2

Both min & max visible

Example shown: eμ subtracted



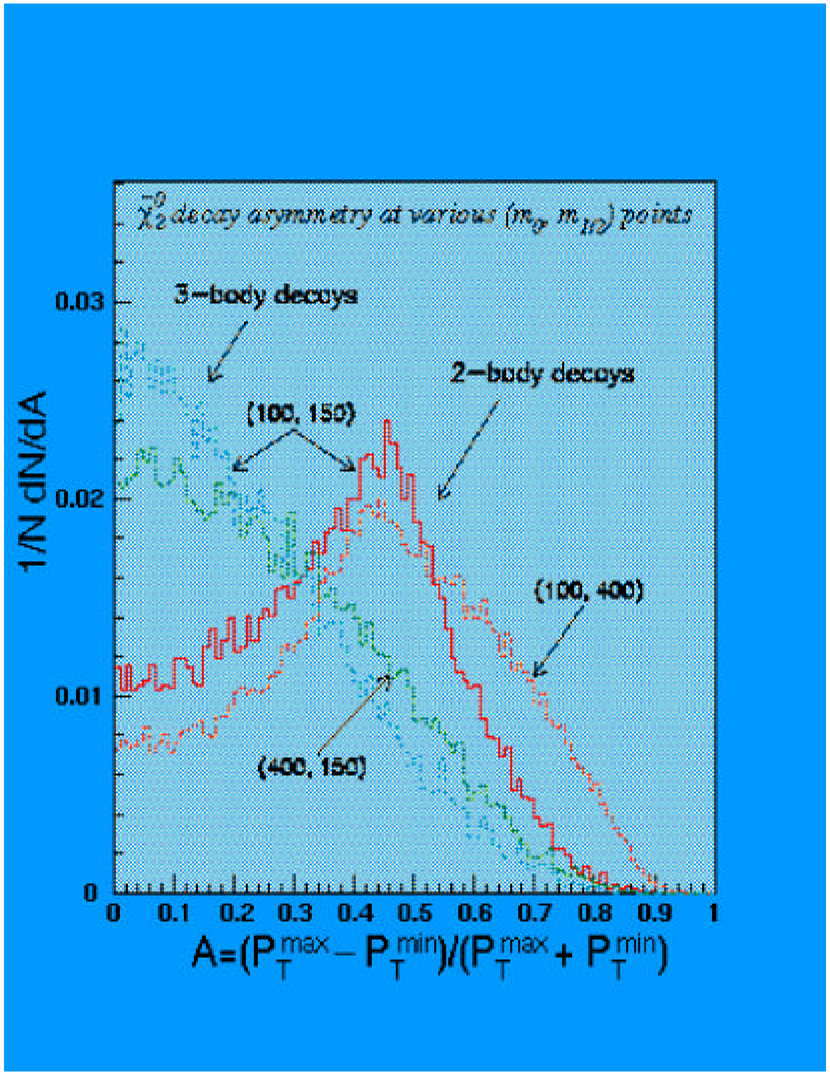
Distinguishing 2 & 3-body decays

Two scenarios can be disentangled directly

From asymmetry of two leptons:

$$A = \frac{P_{\mathrm{T}}^{\max} - P_{\mathrm{T}}^{\min}}{P_{\mathrm{T}}^{\max} + P_{\mathrm{T}}^{\min}}$$

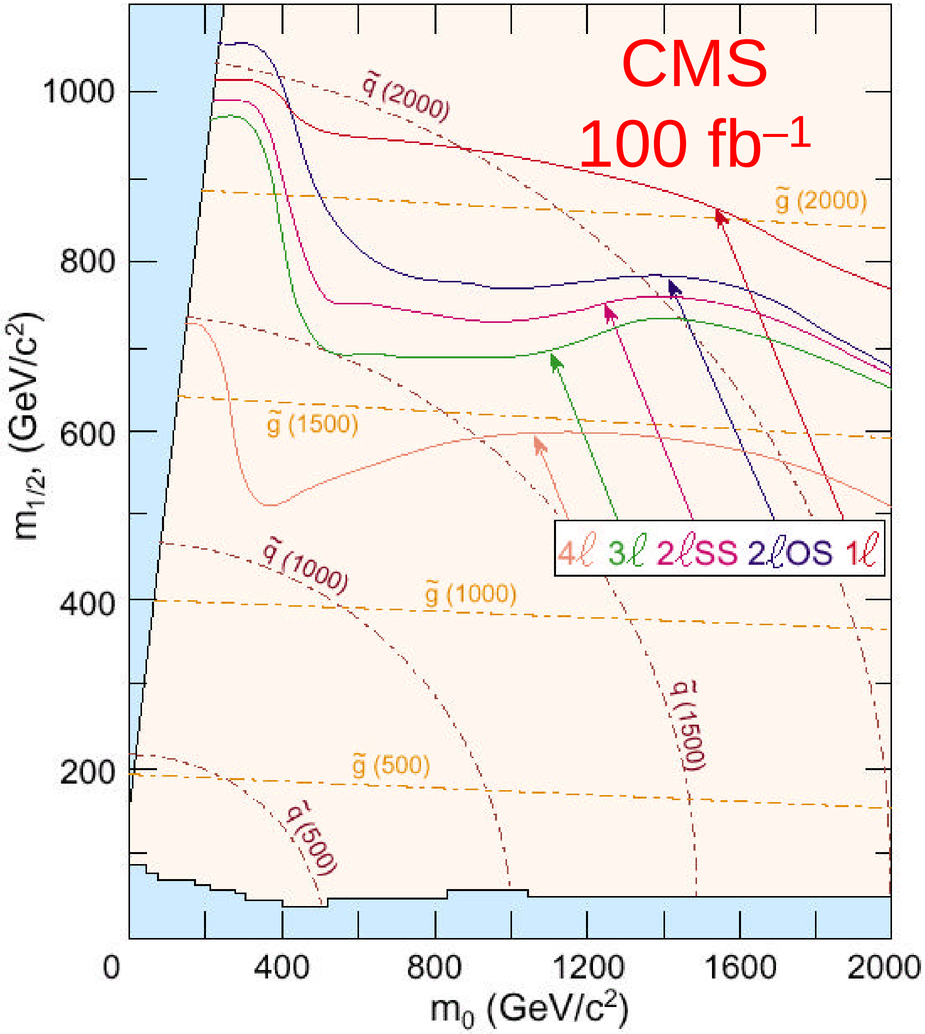
In analogy with τ decays



SUGRA reach

Example from Point 1

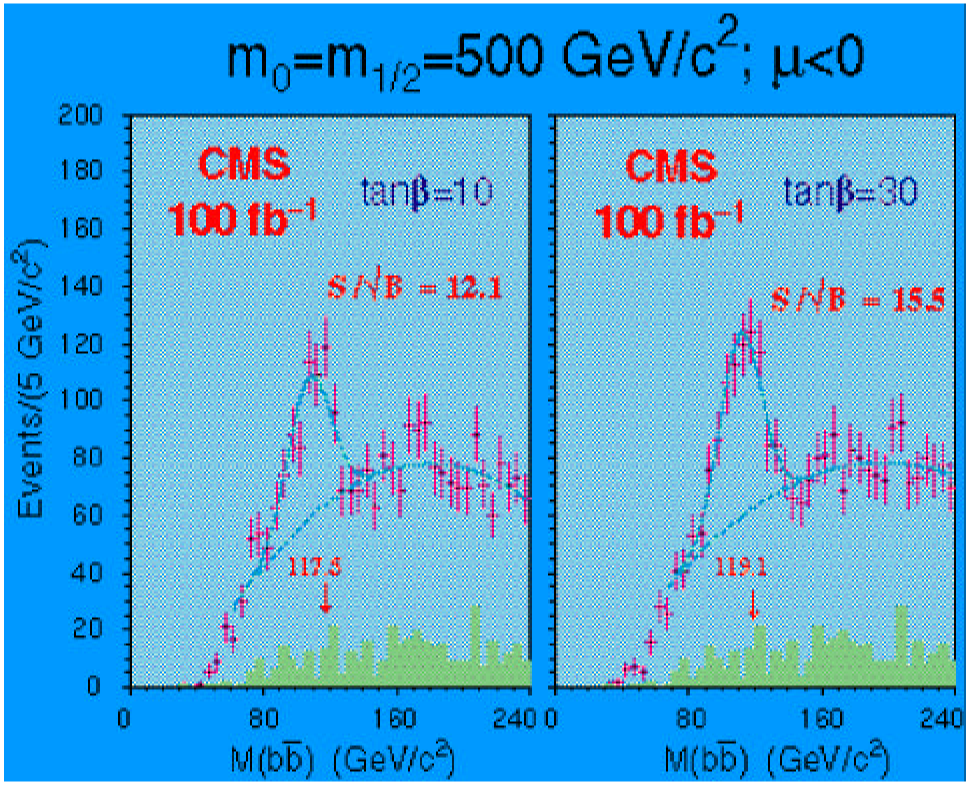
- $\tan\beta=2; A_0=0; \mathrm{sign}(\mu)=-$
- But look at entire m_0-$m_{1/2}$ plane
- Example signature:
  - N (isolated) leptons + = 2 jets + E_T^{miss}
  - 5σ (σ=significance) contours
- Essentially reach is ~2 (1) TeV/c² for the m_0 ($m_{1/2}$) plane



The other scenario: c_2^0® c_1^0h

Followed by *h*®*b$\bar{b}$*: *h* discovery at LHC

- E.g. at Point 1, ≈20% of SUSY events have *h*®*b$\bar{b}$*
  - But squarks/gluinos heavy (low cross sections)
- b-jets are hard and central

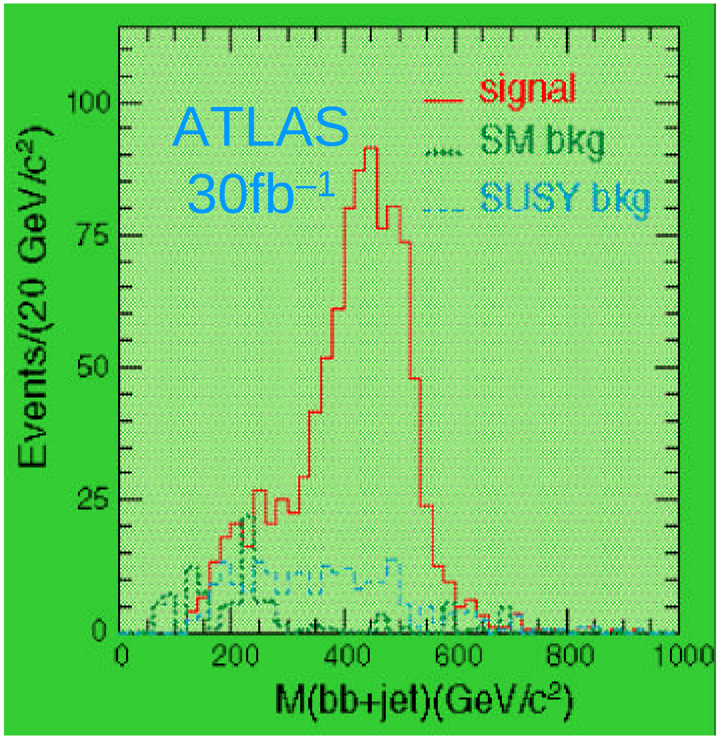


- Expect large peak in (b-tagged) di-jet mass distribution
- Resolution driven by jet energy measurement
- Largest background is other SUSY events!

Building on the h

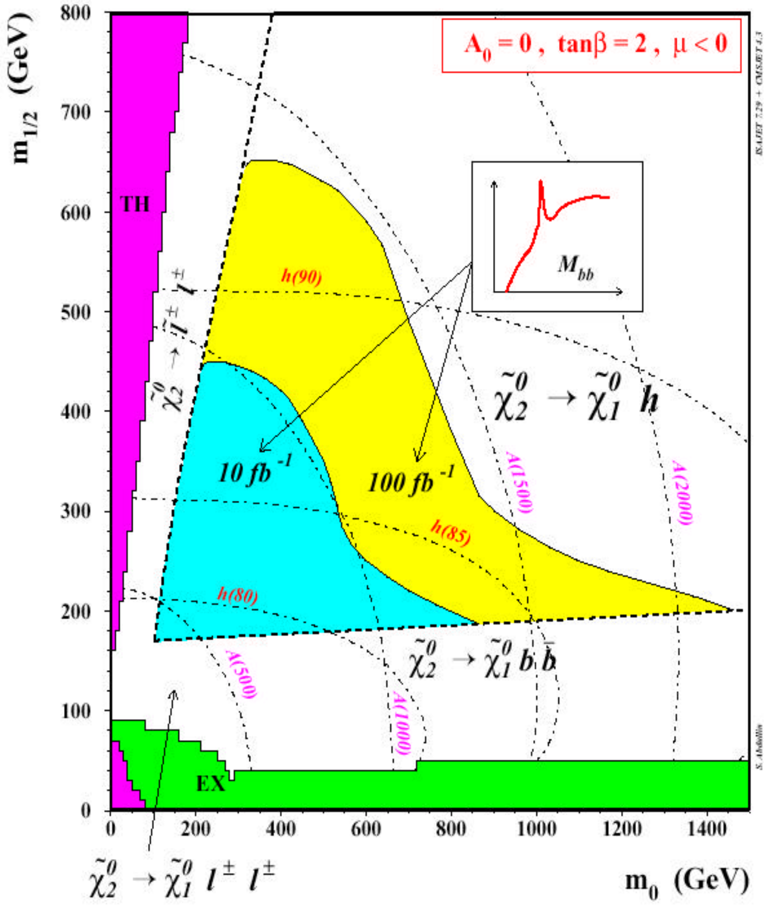
In analogy with adding jets to $c_2^0 \rightarrow c_1^0 \lambda^+ \lambda^-$

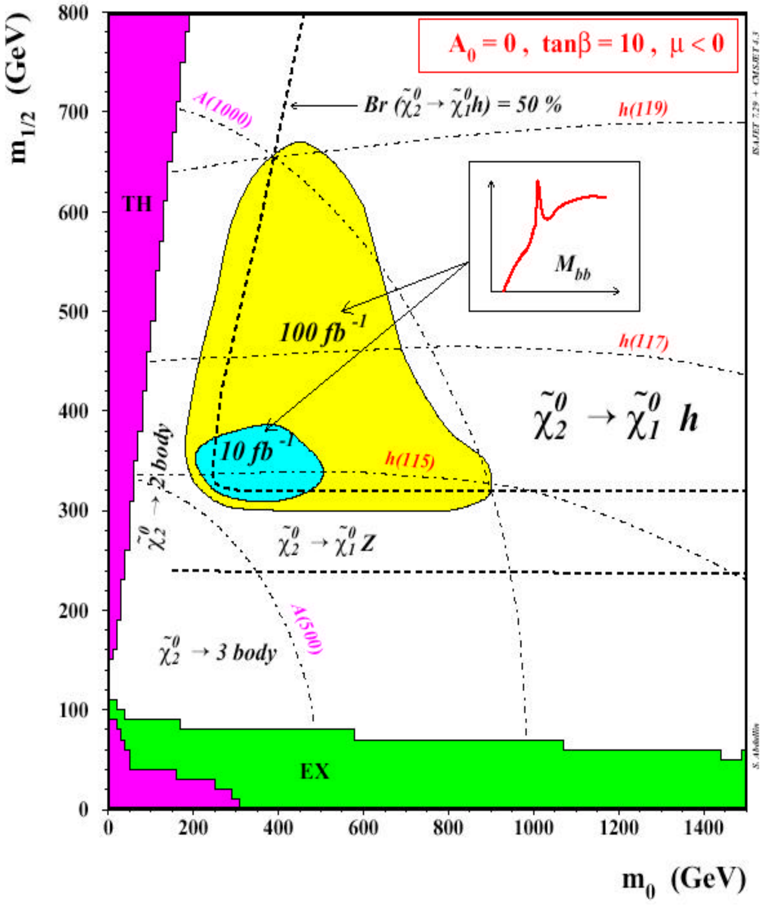
- Select mass window (e.g. 50 GeV) around h
- Combine with two highest E_T jets; plot shows min. mass
- Again, use kinematic limits
  - Case shown: max ˜ 550 GeV/c^2
- Beyond this:
  - Model dependence



Observability of decays into h

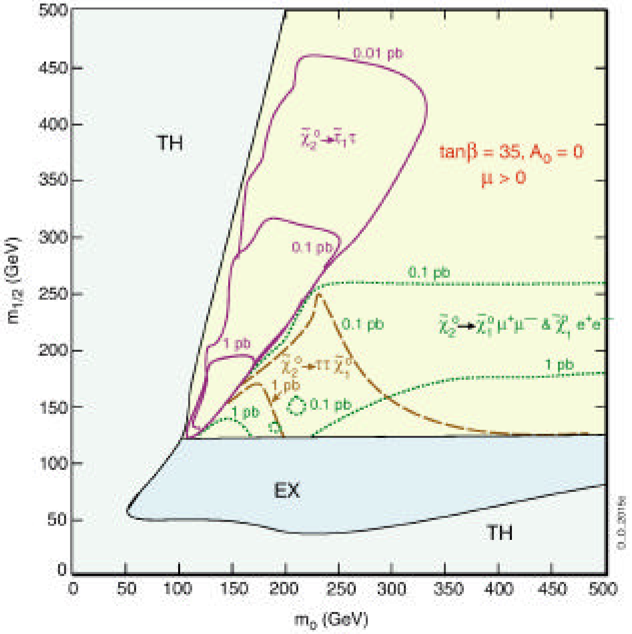
Examples from CMS (tanβ=2&10)

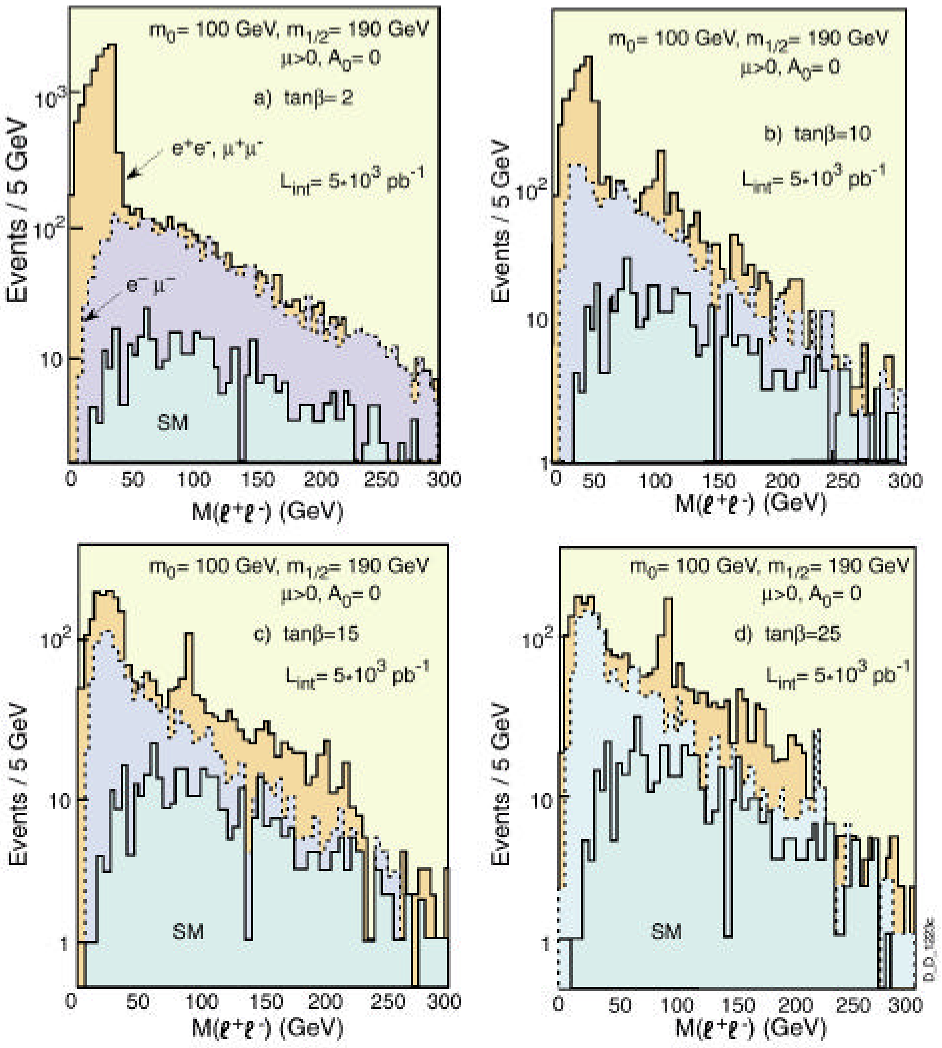




Varying tanb

τ modes eventually become important





At tanβ>>1 only

2-body $\tilde{c}_2^0$ decays

(may be): $\tilde{c}_2^0 ® \tilde{t}_1 t ® \; t t \tilde{c}_1^0$

Visible eμ excess over SM;

for dilepton edge: need ττ mass

SUSY parameters; SUGRA

Point/Lumi	m_0 (GeV)	$m_{1/2}$ (TeV)	$\tan\beta$	$s(\mu)$
P1 @100fb^{-1}	400±100	400±8	2.00±0.08	ok
P2 @100fb^{-1}	400±100	400±8	10±2	ok
P4 @100fb^{-1}	800±50	200±2	10±2	ok
P5 @10fb^{-1}	100±4	300±3	±0.1	ok

Essentially no information on A_0

(A_{heavy} evolve to fixed point independent A_0)