Supersymmetry
Lecture 4

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Universität Freiburg, Sommersemester 2009

Chapter 2: Supersymmetry

2.1 Introduction and Overview
- What is SUSY
- How can we find/measure it?

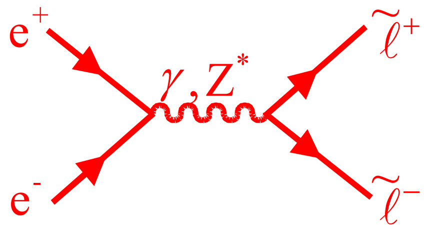
2.2 SUSY Theory/Phenomenology
- SUSY Lagrangian, MSSM
- SUSY interactions, masses, SUSY breaking

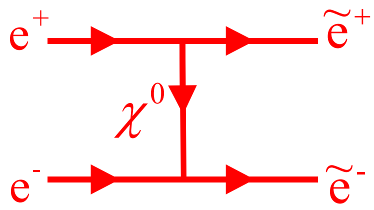
2.3 SUSY searches/measurements at experiments
- past and running experiments
- LHC / future linear collider

2.4 Searches for MSSM Higgs bosons

Direct Searches for Sleptons at LEP

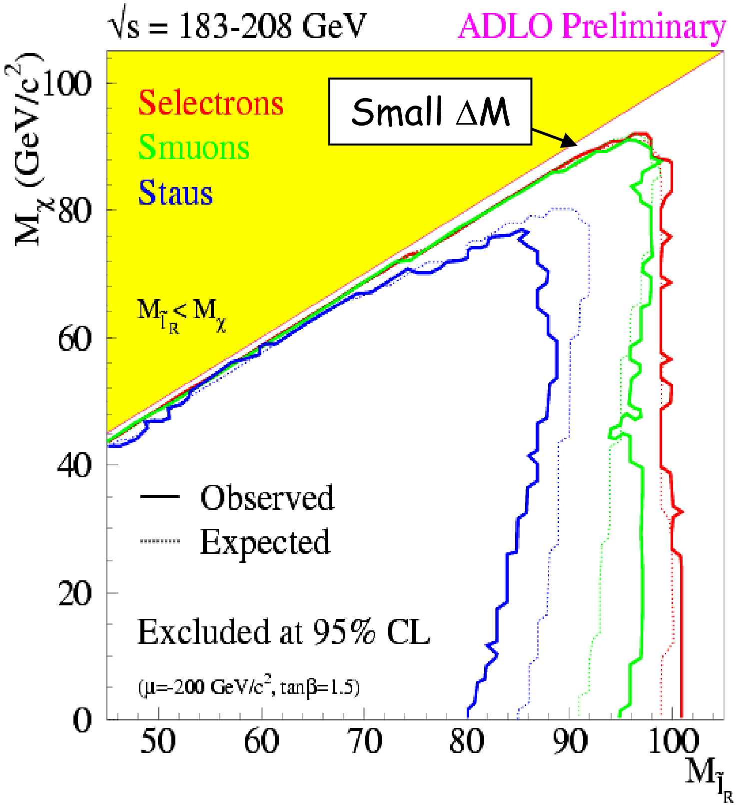
- Clear domain of LEP are
  Slepton & Chargino/Neutralino
  searches (e^+e^-, E_{cm}~ 200 GeV)



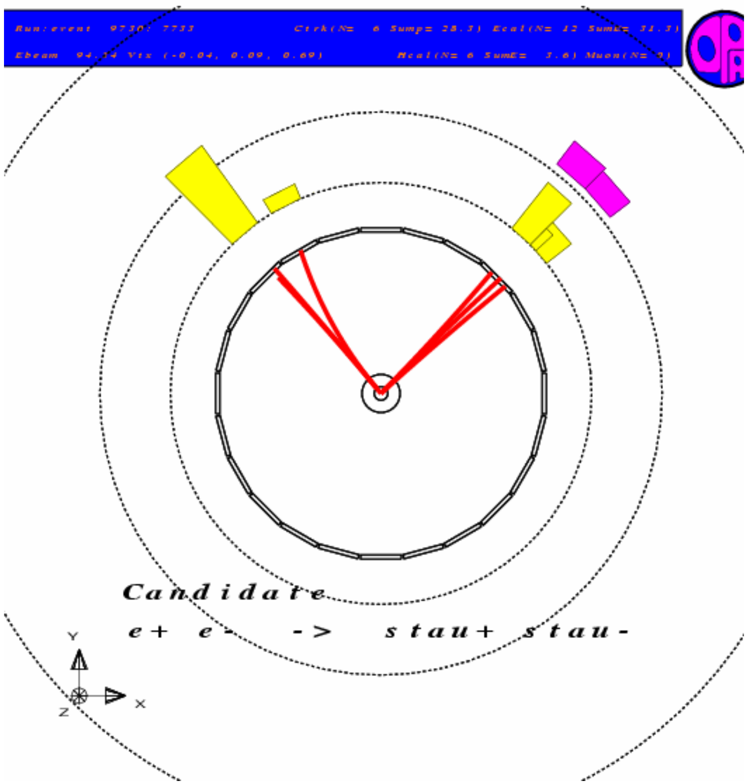


$\tilde{\ell} \rightarrow \ell\, \chi^0_1$ **(2 leptons + missing E)**

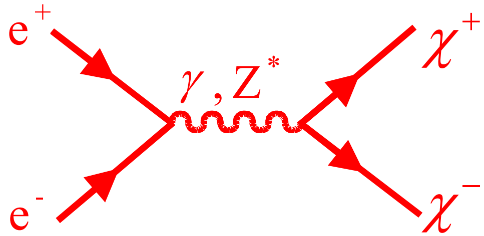
→ Excluded up to masses of
80 … 100 GeV (~ $E_{cm}/2$)



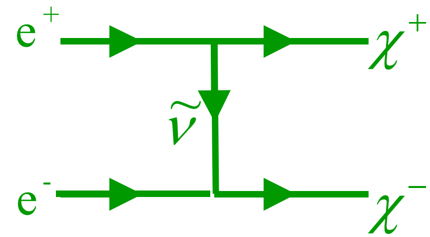
OPAL stau event candidate



Large m_0 ($\tilde{\ell}$ are heavy)



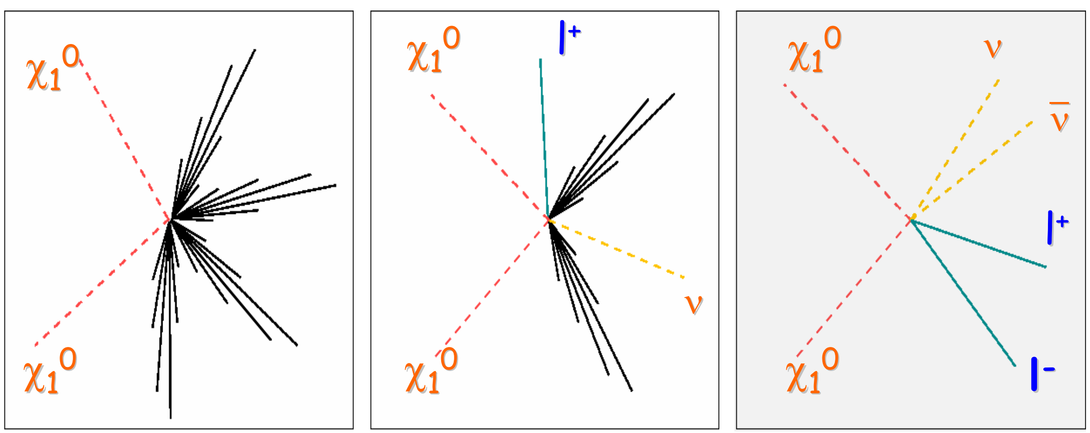
Small m_0 ($\tilde{\ell}$ are light)



$$\chi^+\chi^- \to W^*\chi^0_1 W^*\chi^0_1$$

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

$WW \to qqqq$ $\quad$ $WW \to l\nu qq$ $\quad$ $WW \to l\nu\, l\nu$

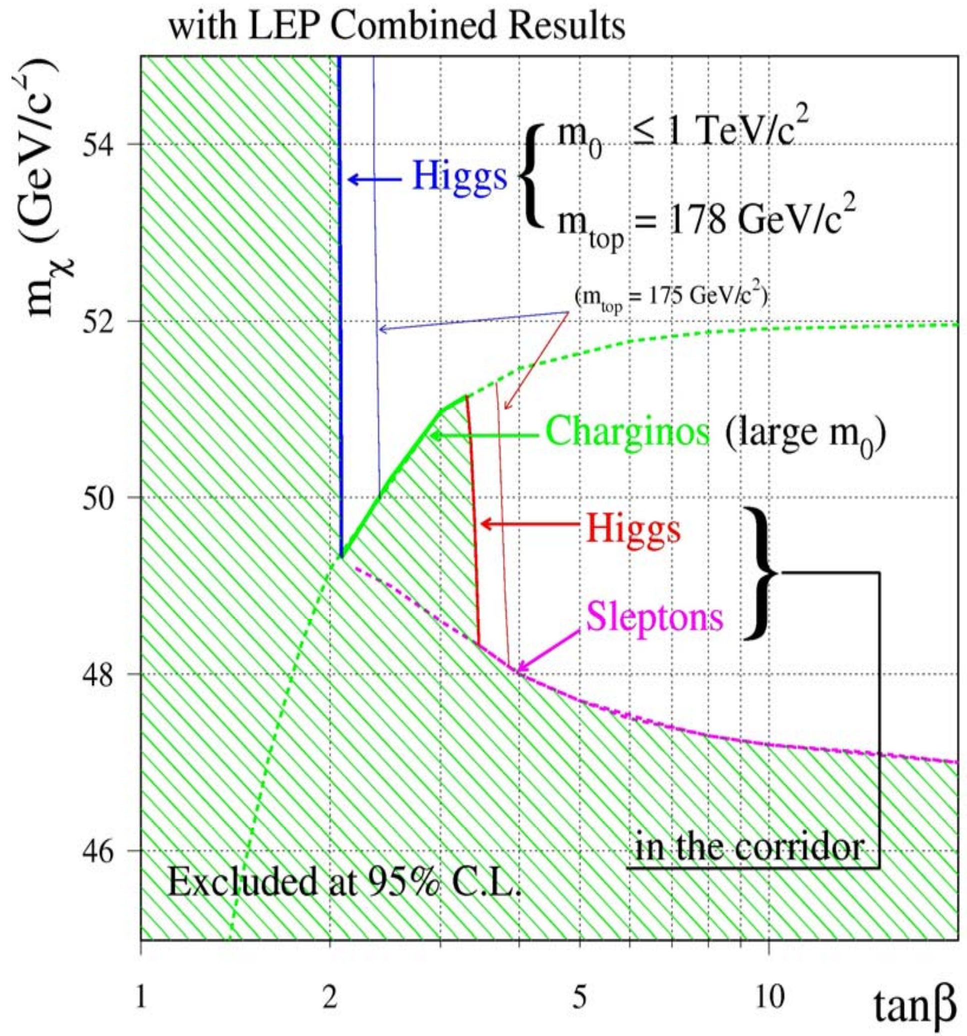


Main SM backgrounds (WW, ZZ production) suppressed by asking for large missing mass or missing E_T in the event.

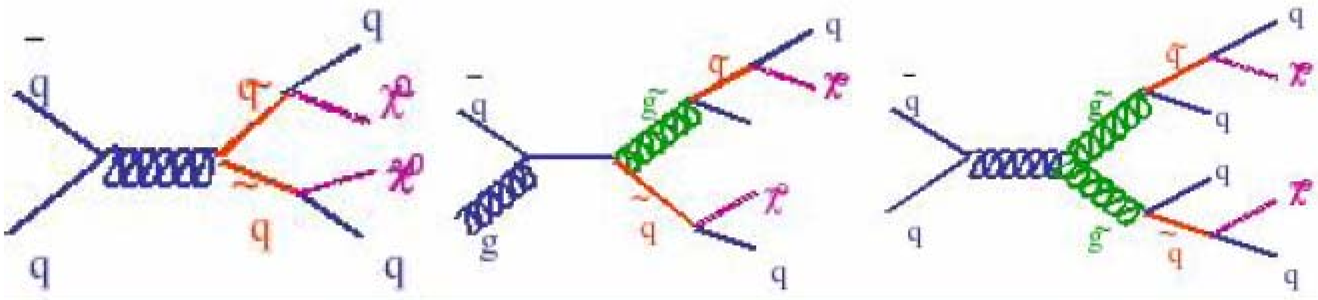
LEP Constraints in the cMSSM

- LEP cMSSM limits:
  - sfermions and charginos excluded up to masses of 80 … 100 GeV
  - tan β > 1.4
  - M_{LSP} > 47 GeV
  - M_h > 114.5 GeV

Limits on mass of LSP in the cMSSM



Direct Searches for Squarks / Gluinos at Tevatron



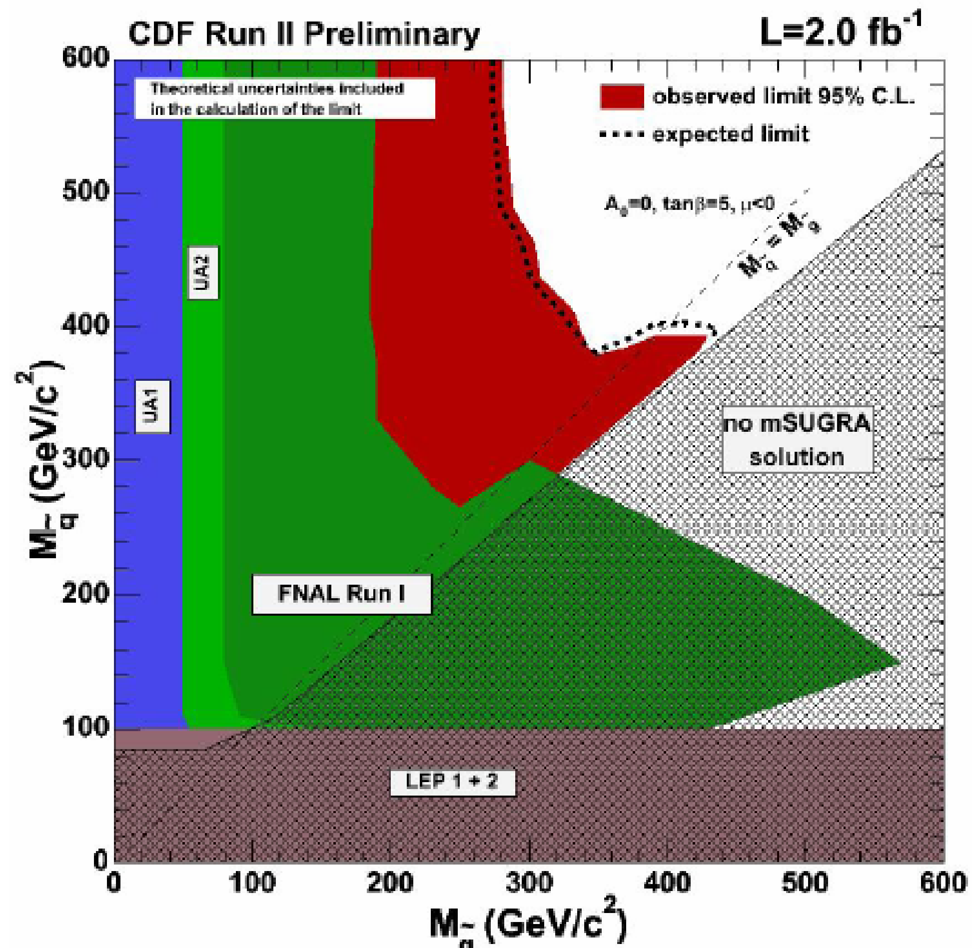
- Clear domain of Tevatron as hadron machine are Squark and gluino searches (p anti-p, E_{cm}~ 2 TeV)

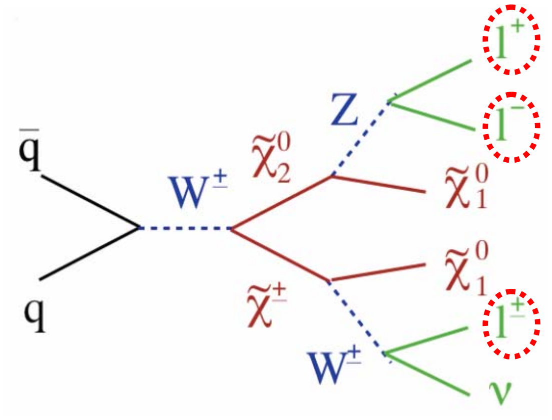
→ Squarks and gluinos excluded up to masses of ~ 300-400 GeV

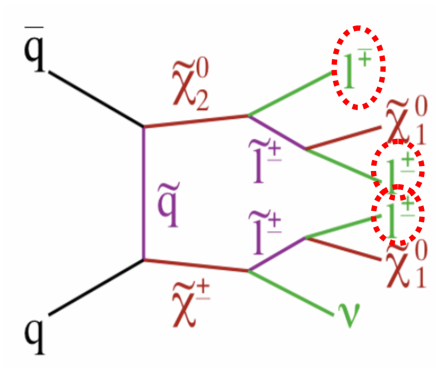
Similar to searches at LHC I

Main differences:

- LHC is pp collider
  → gluon processes dominate!
- E_{cm}(LHC) = 14 TeV !!!



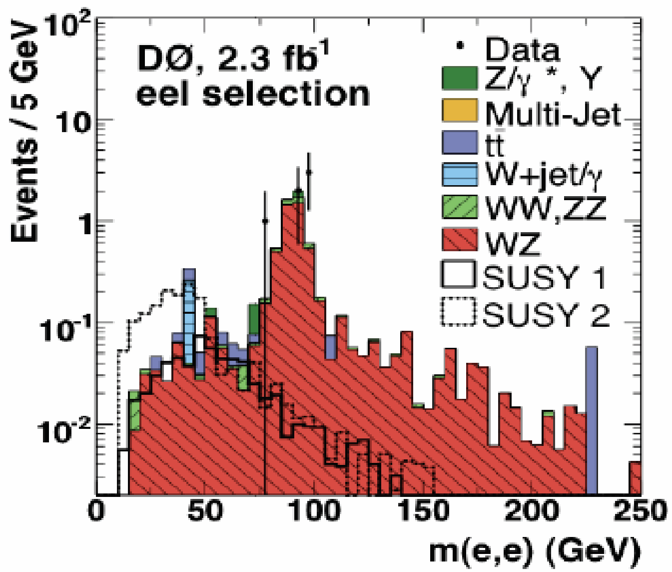




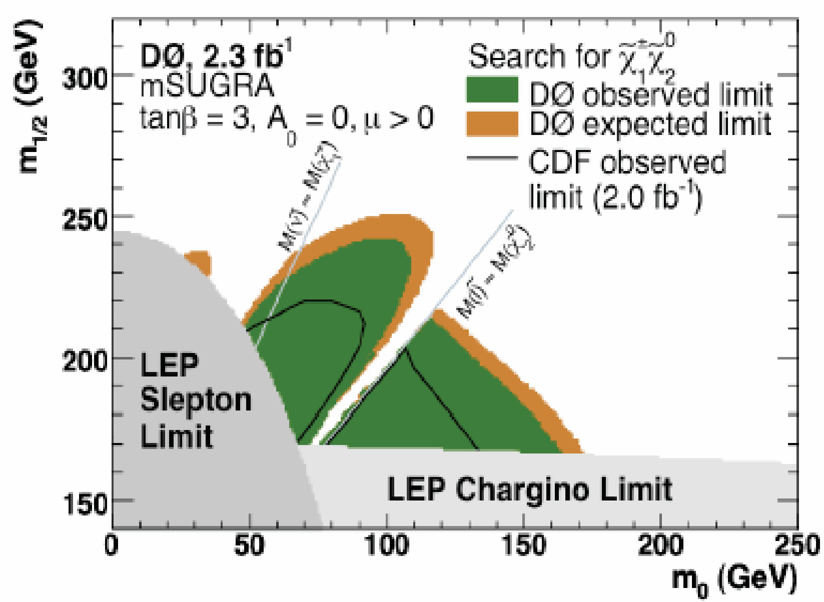
Very clean signature:
- 3 isolated leptons
- $\not\!\!E_T$ due to undetected $\tilde{\chi}_1^0$ and ν

Challenge:
- low cross section: $\sigma \times \mathcal{B}r < 0.5$ pb
- very soft 3rd lepton p_T

e.g. select 2 electrons + additional track (ℓ)

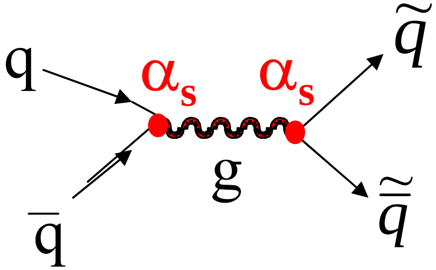


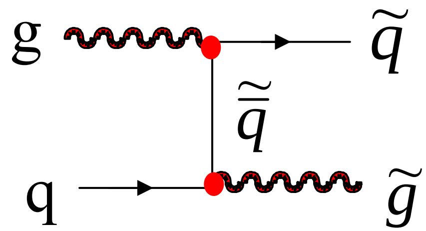
Exclusion limits in mSUGRA

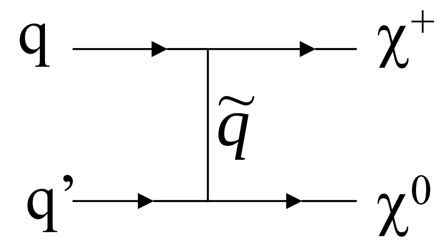


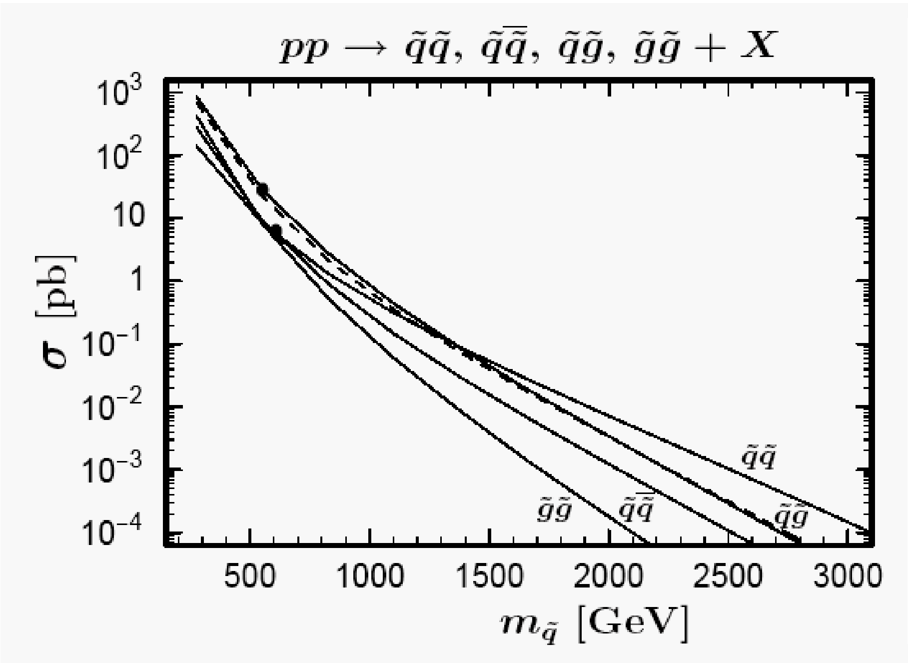
SUSY Searches at the LHC

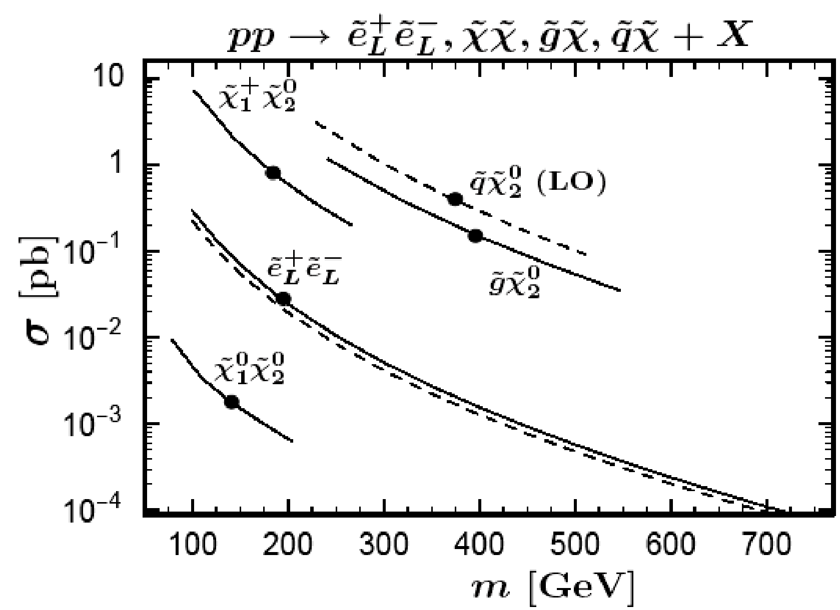
Reminder: SUSY Production and Cross Sections









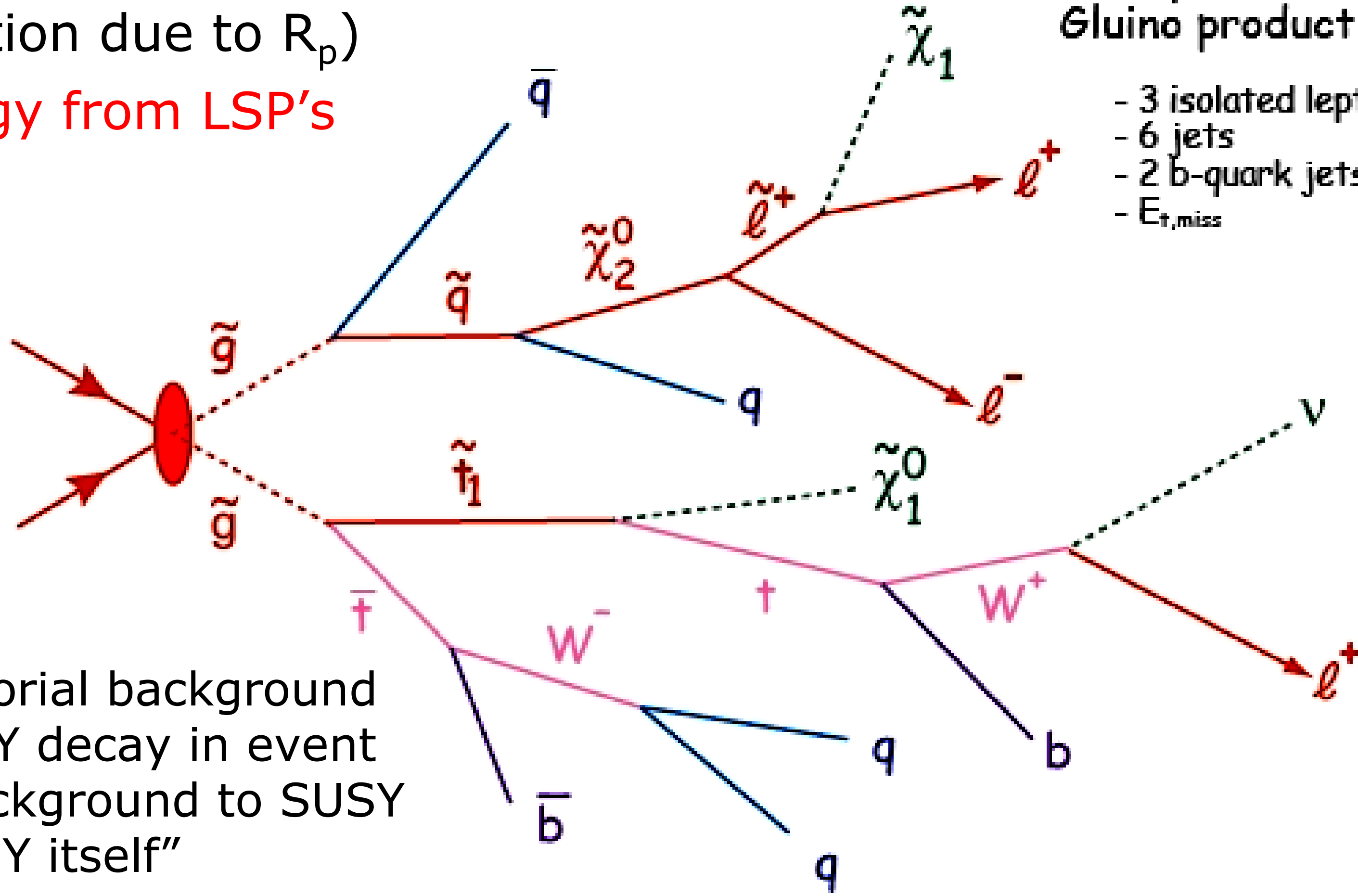


→ Production of gluons and squarks dominates at LHC

- Long, complex decay chains (at the end: SM particles and LSP's)
- Two SUSY decay chains per event
  (pair production due to R_p)
- Missing energy from LSP's

Example:
Gluino production

- 3 isolated leptons
- 6 jets
- 2 b-quark jets
- $E_{t,miss}$



Huge combinatorial background
from second SUSY decay in event
→ "dominant background to SUSY
is SUSY itself"

Typical final states: jets + E_T^{miss} (+ leptons)

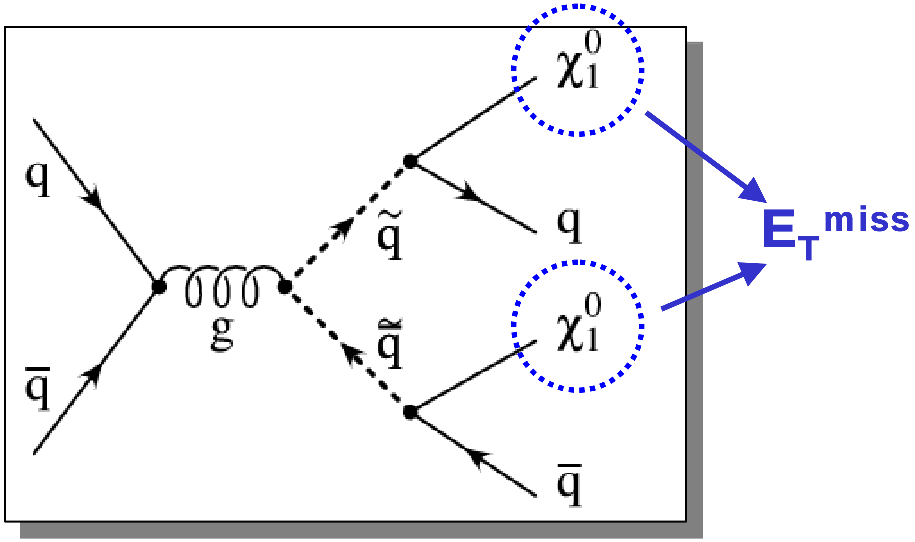
Strategy for SUSY Searches at the LHC

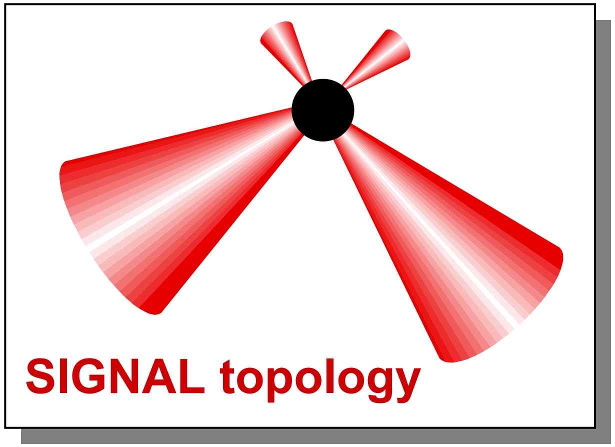
- Step 1: Discovery
  - Look for deviations from the Standard Model
- Step 2: Mass scale
  - Establish the approximate SUSY mass scale
- Step 3: Measurements
  - Determine masses, branching fractions, etc.
- Step 4: Parameter studies
  - Study underlying theory / SUSY model

Inclusive

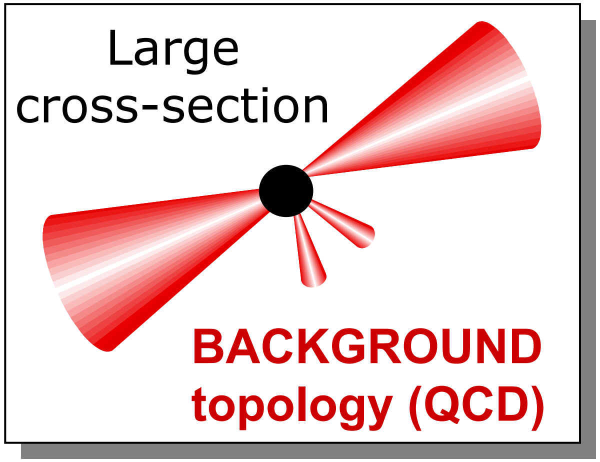
Specific Decays

Discovering SUSY with Jets



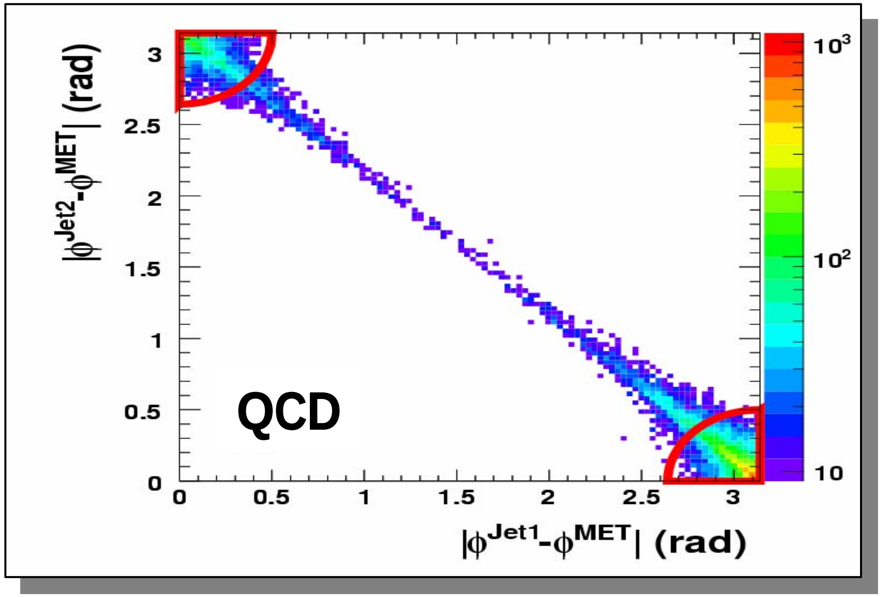


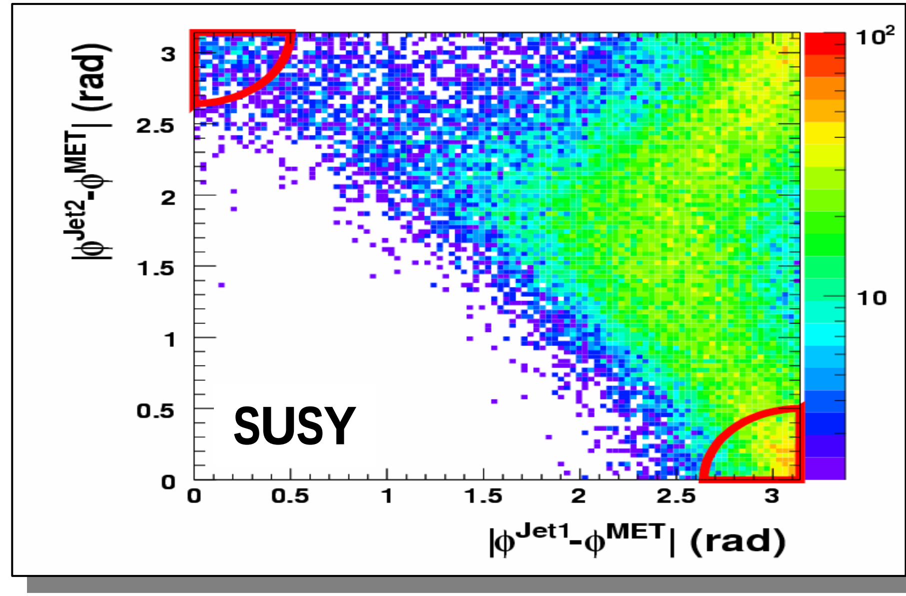
- Select high P_T jets
  - Large signal cross-section
  - Large control statistics

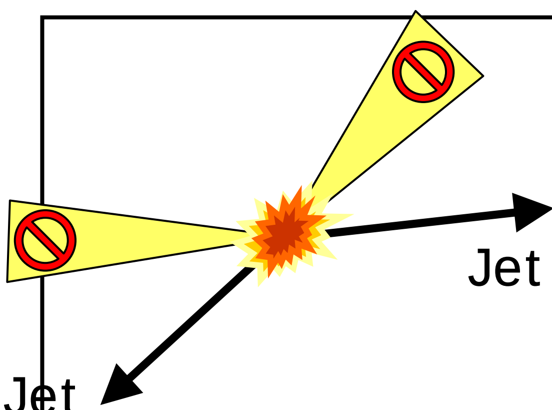


- Relatively "model independent"
  - Does not rely on leptonic cascades
  - Does not rely on hadronic cascades

Suppressing QCD Background







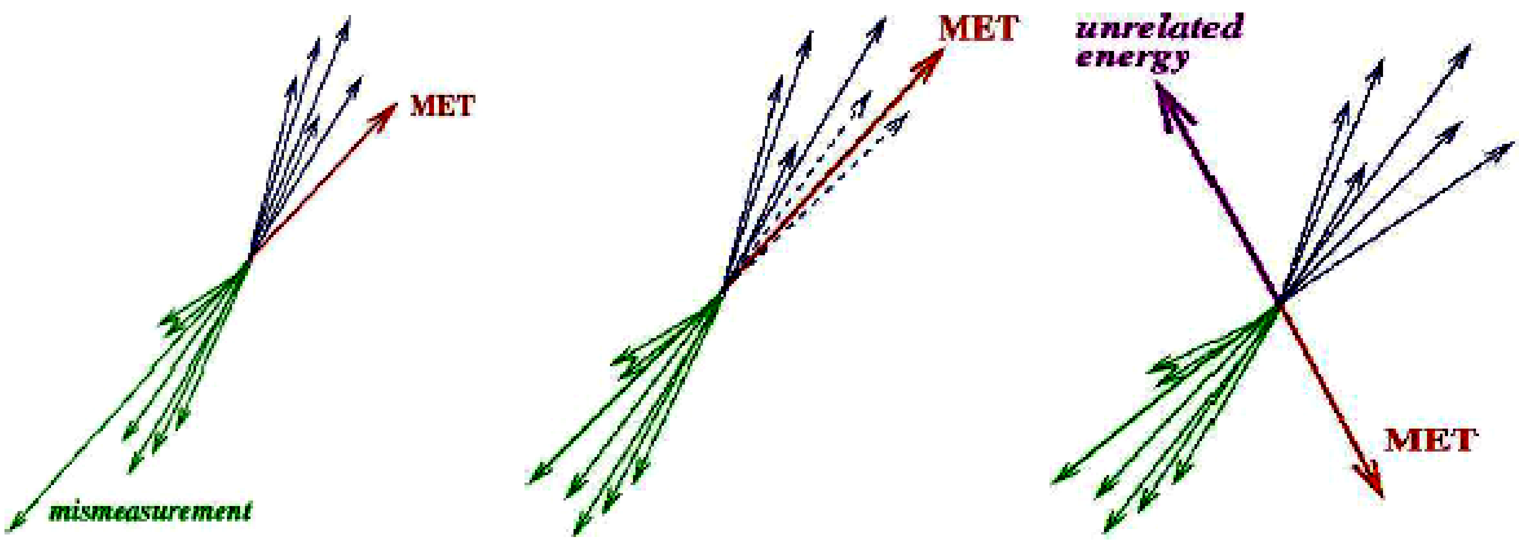
Remove events with missing energy back-to-back with leading jets

Sources of Missing Energy

It is not so easy to "measure" the missing energy, due to difficult limitations in our instruments.

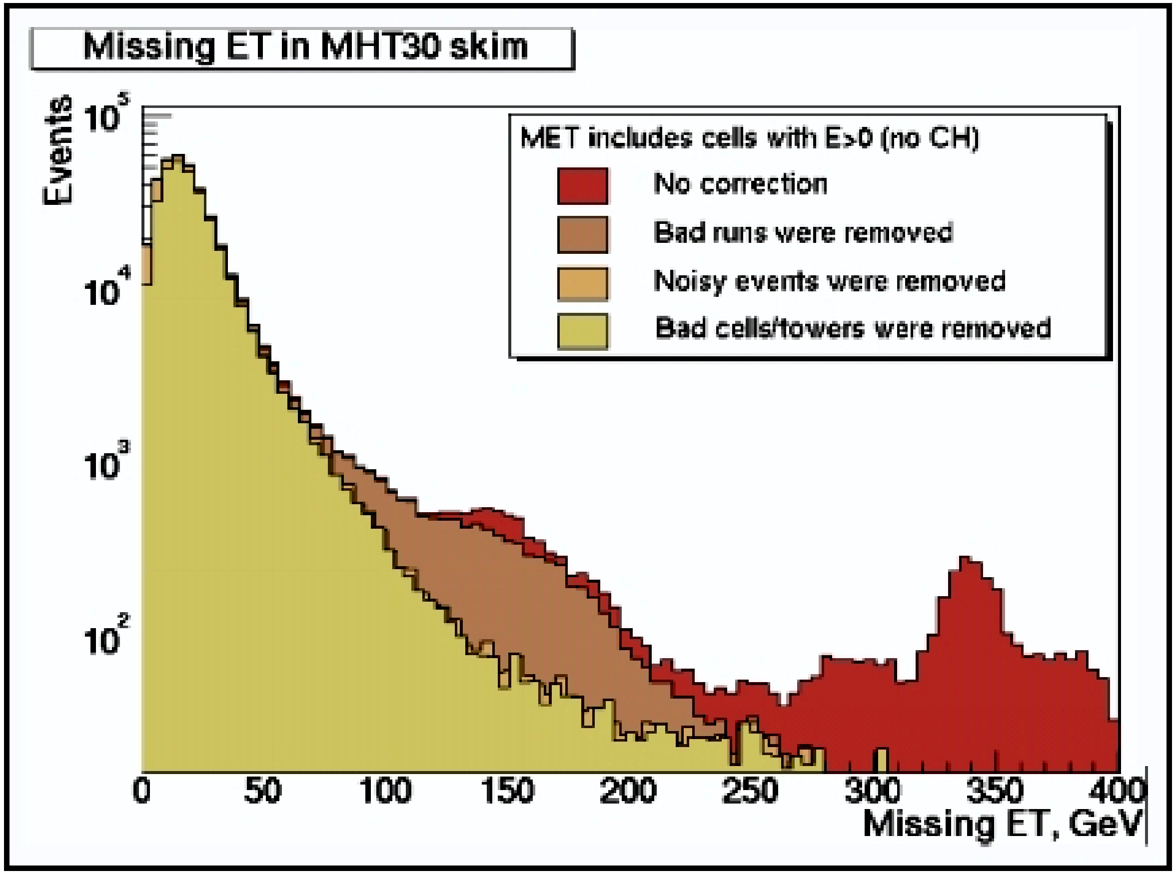
What are the sources of MET?

- calorimeter resolution on the jet energies
- losses of energy in uninstrumented regions ("cracks")
- additional energy unrelated to the primary interaction
- neutrinos and also long-lived neutral kaons plus neutrons
- real LSP's, we hope....

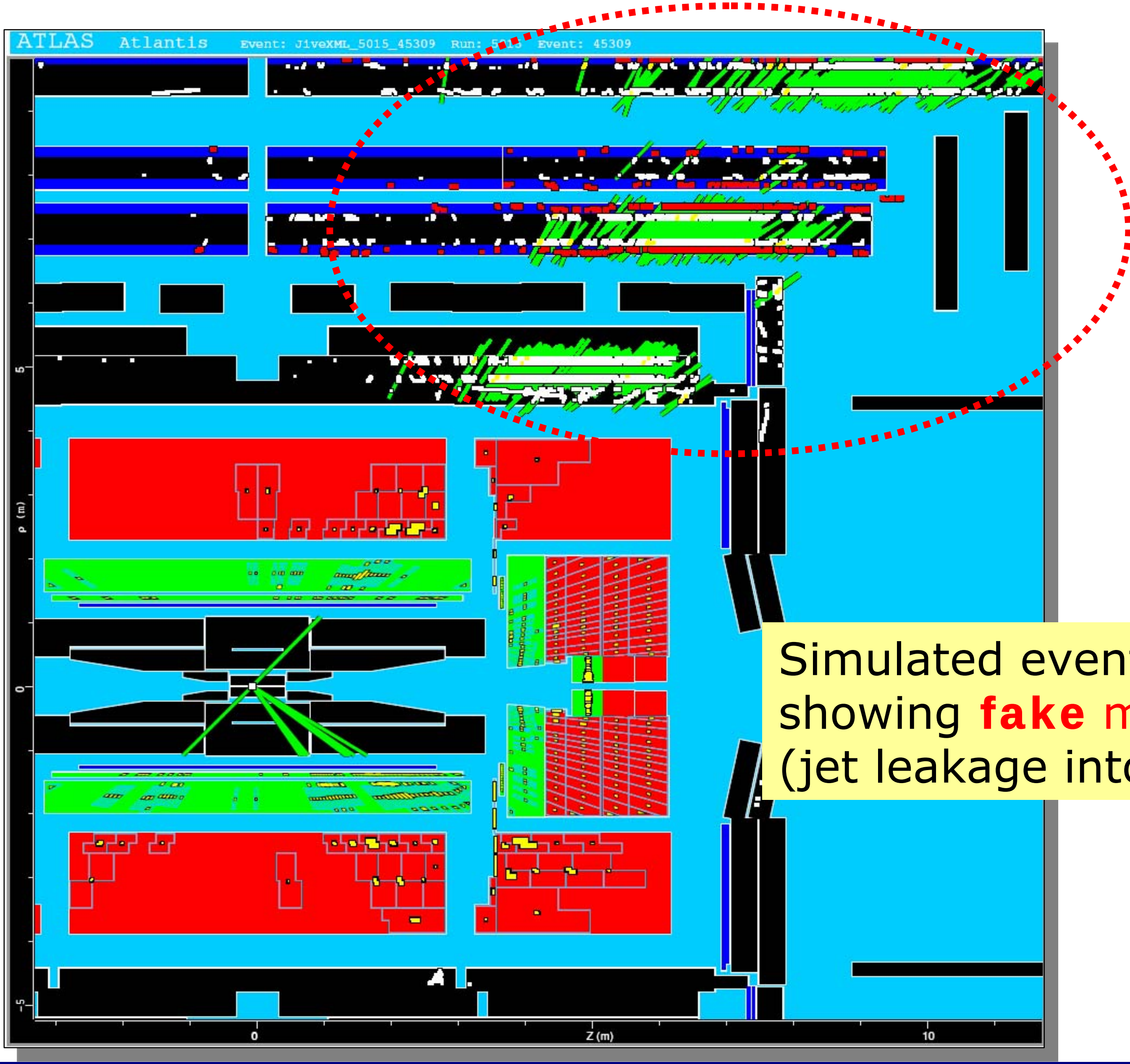


Experimental Challenge: E_T^{miss}

- Lesson learned from the Tevatron experiments:



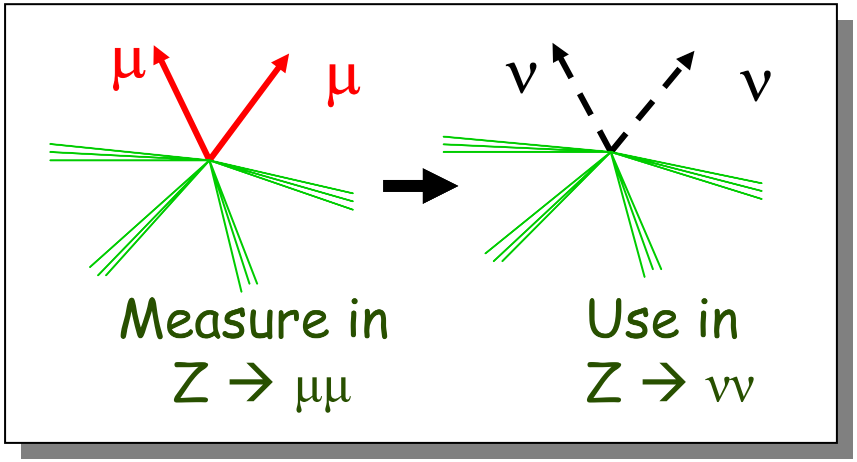
Understanding the Detector !!!

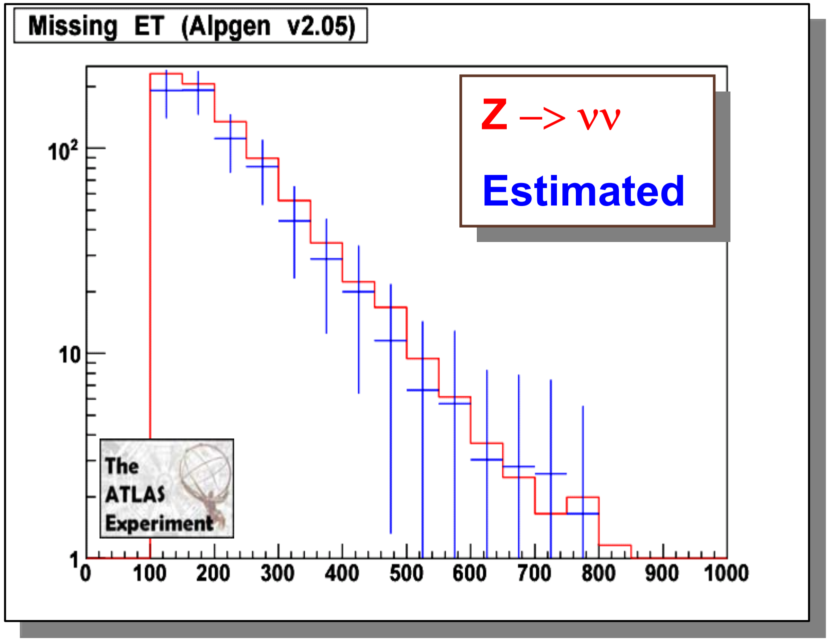


Simulated event in detector showing **fake** missing energy (jet leakage into muon system)

Estimating Backgrounds from Data

- **Example: Z background in SUSY with jets search**
  - **Missing energy + jets from Z^0 decays to neutrinos**
  - **Measure in Z → μμ**
  - **Remove muons from event**
  - **Use for Z → νν**





- **Check: Compare both distributions based on Monte Carlo simulation**
- **If good match → useful technique**
- **Statistics limited**

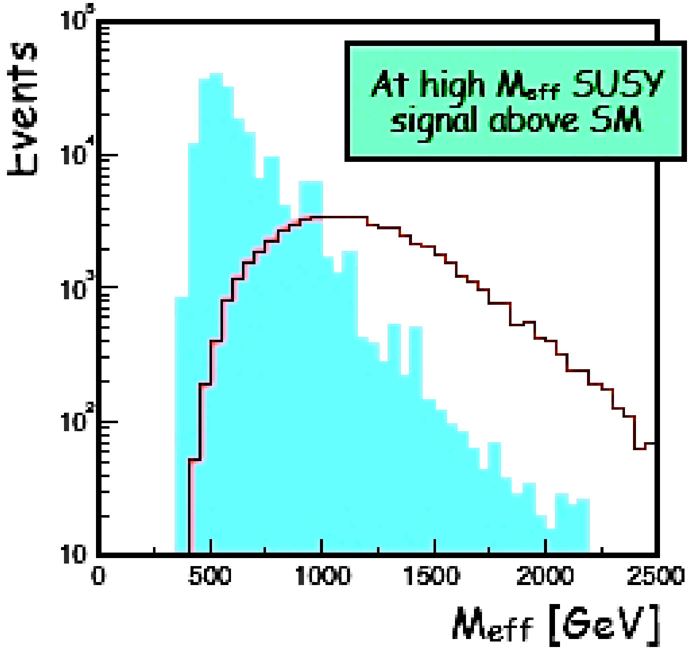
  → Use W → μν in addition?

Inclusive Searches: Effective Mass & Mass Scale

- Select: > 4 jets, $E_{T,miss}$
- Reconstruct effective mass

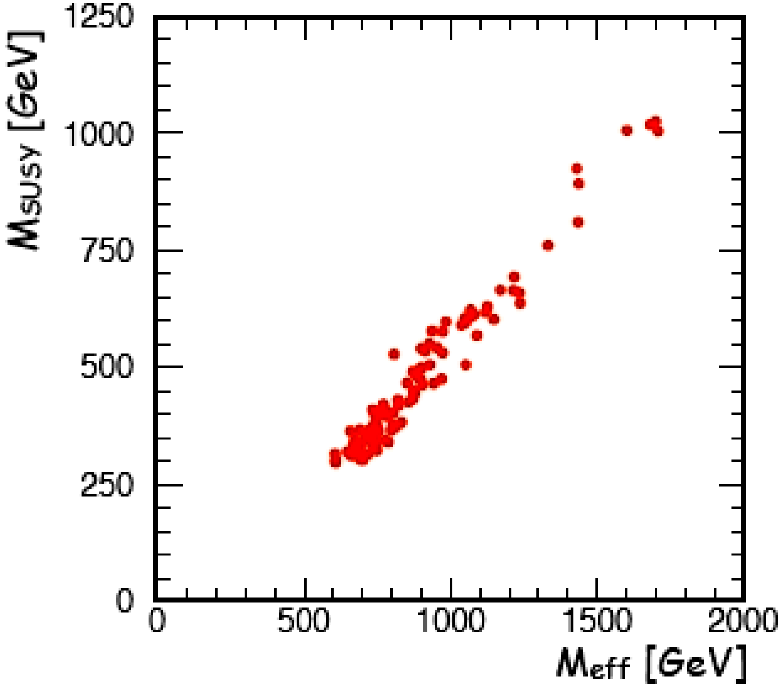
Look at multi-jet and E_T^{miss} final states

$$M_{\mathrm{eff}} = \sum_{i=1}^{4} |P_{T,i}| + |E_{T,\mathrm{miss}}|$$



Inclusive signature for squarks and gluinos

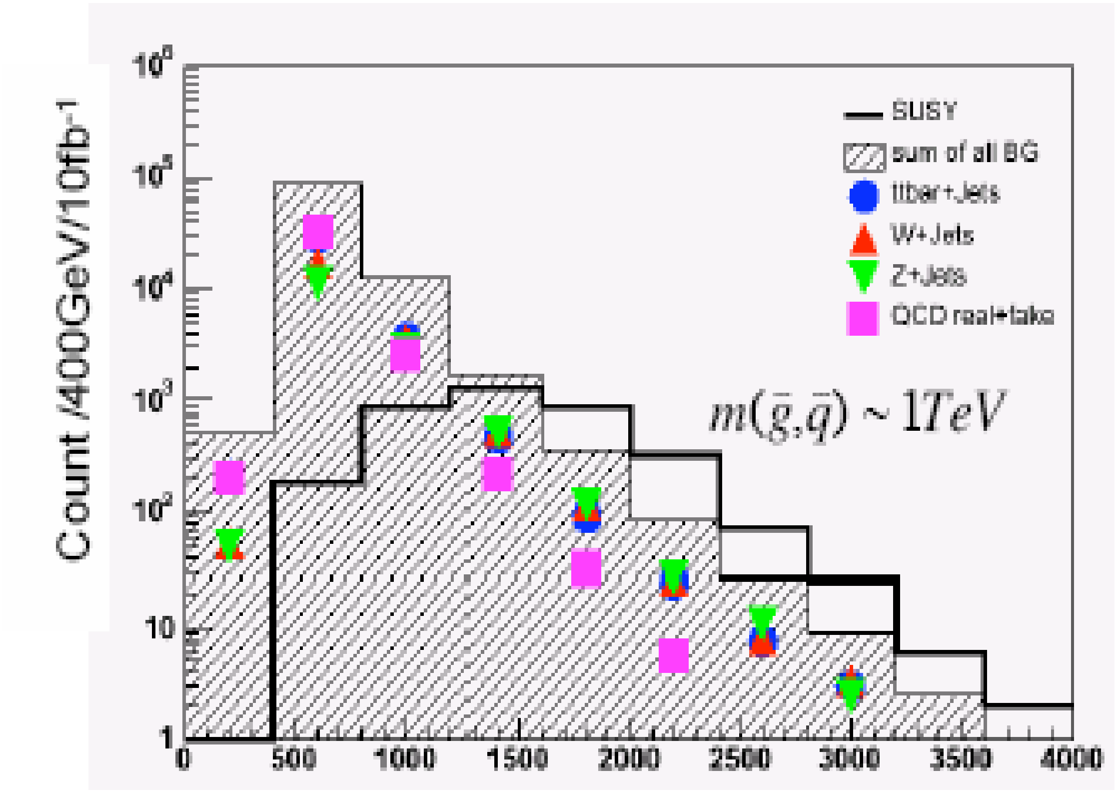
From Simulation



Peaking M_{eff} distribution correlates well with M_{SUSY}

Example: 10 fb^{-1}, m(squark) = 1 TeV

jets + E_T^{miss}

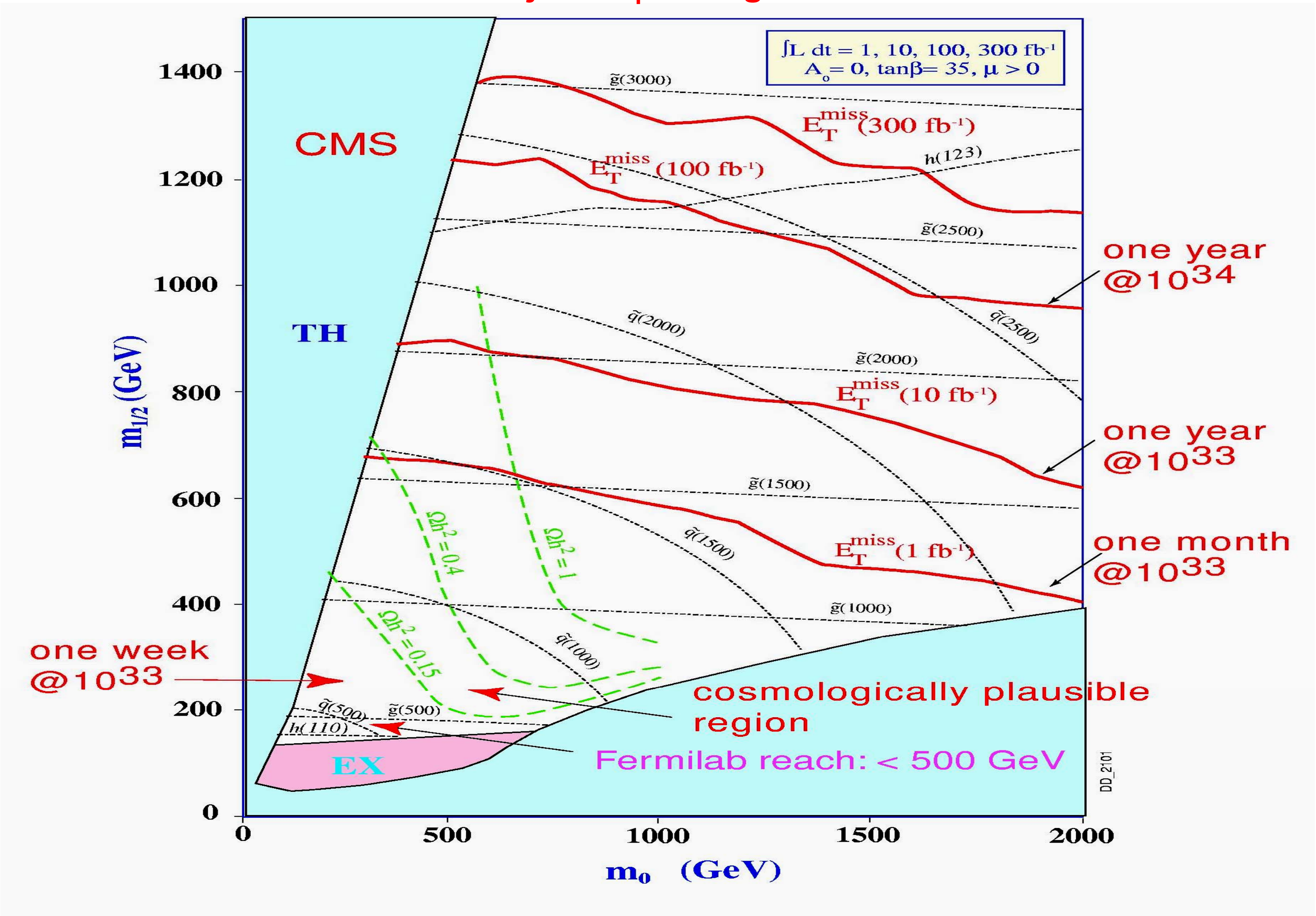


M_{eff}(GeV)

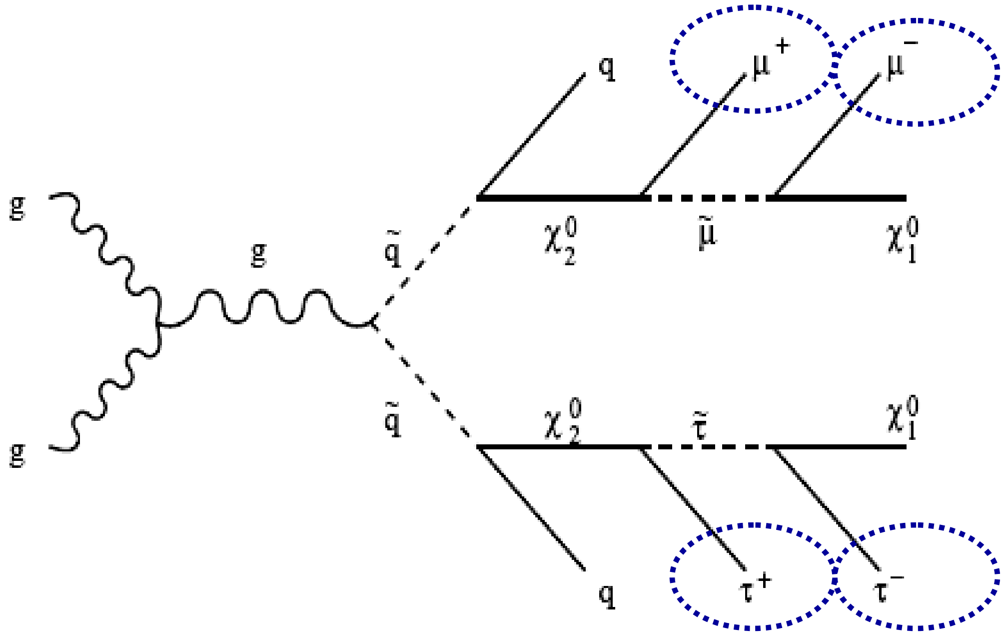
- jet+E_T^{miss} final states are the key for SUSY discovery
- These searches are quite model-independent

LHC Reach for SUSY Masses

Multijet + E_T^{miss} Signature



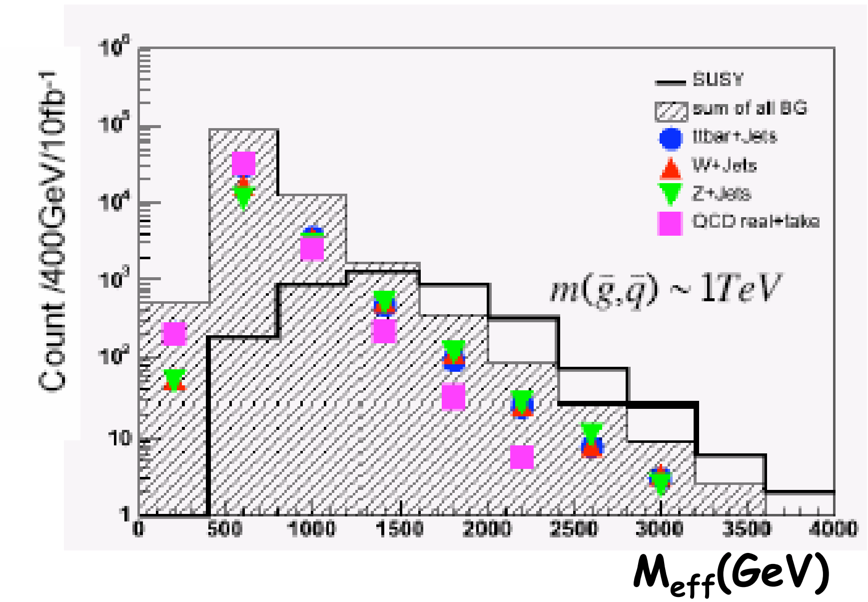
The Case of Charged Leptons



- Charged leptons are a clean signatures in the hadronic environment at the LCH
- But: Branching fraction of neutralinos, charginos into charged leptons smaller than into quarks

Example: 10 fb^{-1}, m(squark) = 1 TeV

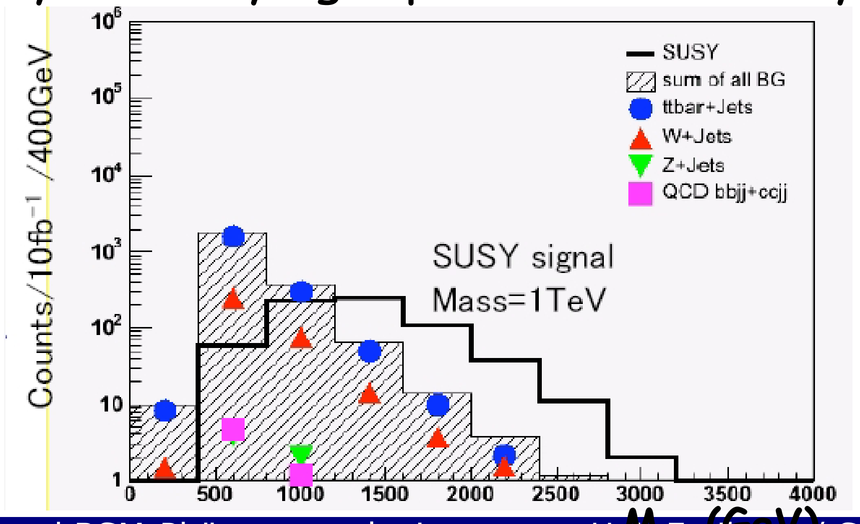
jets + E_T^{miss}



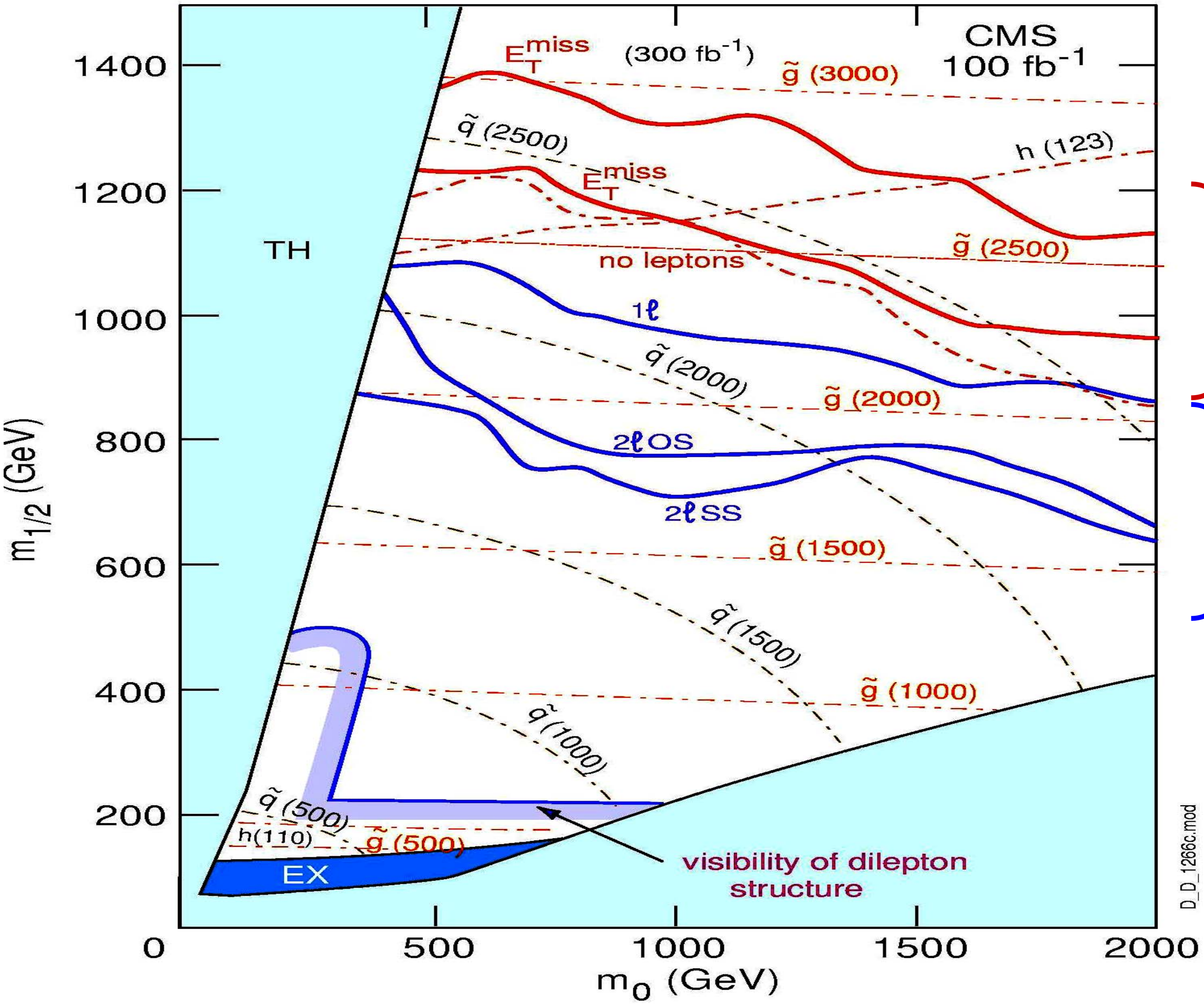
- jet+E_T^{miss} final states are the key for SUSY discovery
- Signal/bkg ratio can be improved by identifying leptons in the decay, e.g.

jets + E_T^{miss} + 1 lepton

→ Lower background, but also much fewer events!



LHC Reach for SUSY Masses

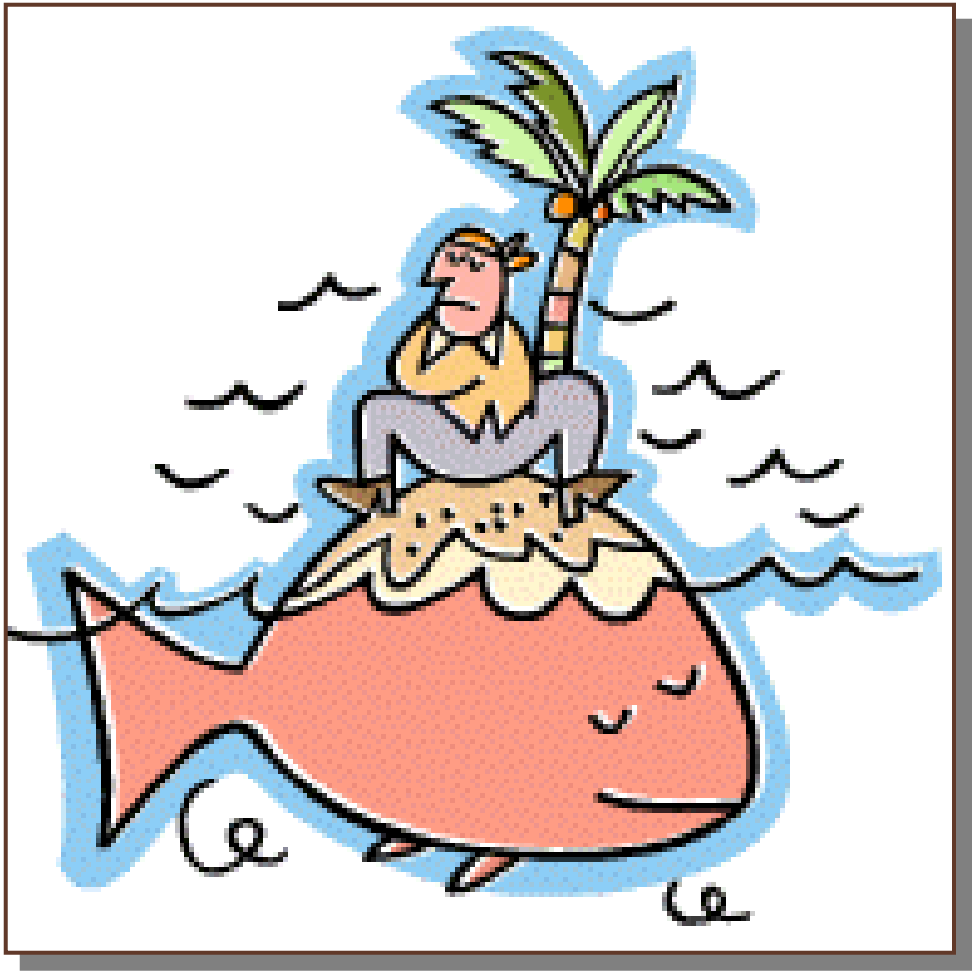


jets + E_T^{miss}

add. lepton(s)

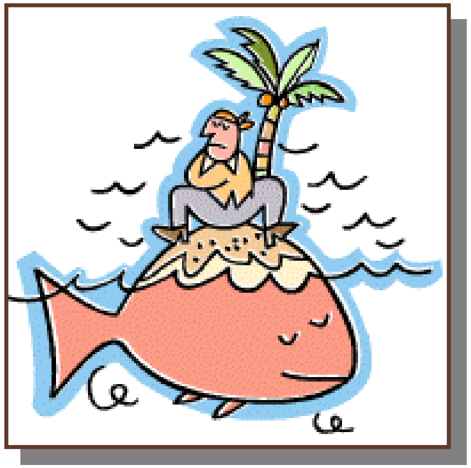
What Might We Know Then?

What Might We Know Then?



Maybe not what we think!

What Might We Know Then?



- "Discovered supersymmetry?"
- Can say, e.g.,
  - Undetected particles produced

    from missing energy
  - Some particles have mass ~ 600 GeV, with couplings similar to QCD

    from M_{eff} & cross-section
  - Some of the particles are colored

    from observation of jets
  - Some particles contain lepton quantum numbers

    from opposite-sign, same-family leptons
  - Lepton flavour ~ conserved in first two generations

    from e vs μ numbers

→ Now need to study exclusive decay chains in detail !

Establishing SUSY Experimentally

Assume an excess seen in inclusive analyses: how does one verify wheteher it is actually SUSY? Need to demonstrate that:

- Every particle has a superpartner
- Their spin differ by $1/2$
- Their couplings are identical
- Mass relations predicted by SUSY hold

Available observables: • Sparticle masses, • BR's of cascade decays, • production cross-sections, • angular decay distributions

Precise measurements of such observable not completely straightforward at the LHC: develop a strategy based on detailed MC study of reasonable candidate models

Measuring Model Parameters

The problem is the presence of a very complex spectroscopy due to long decay chains, with crowded final states. Many concurrent signatures obscuring each other

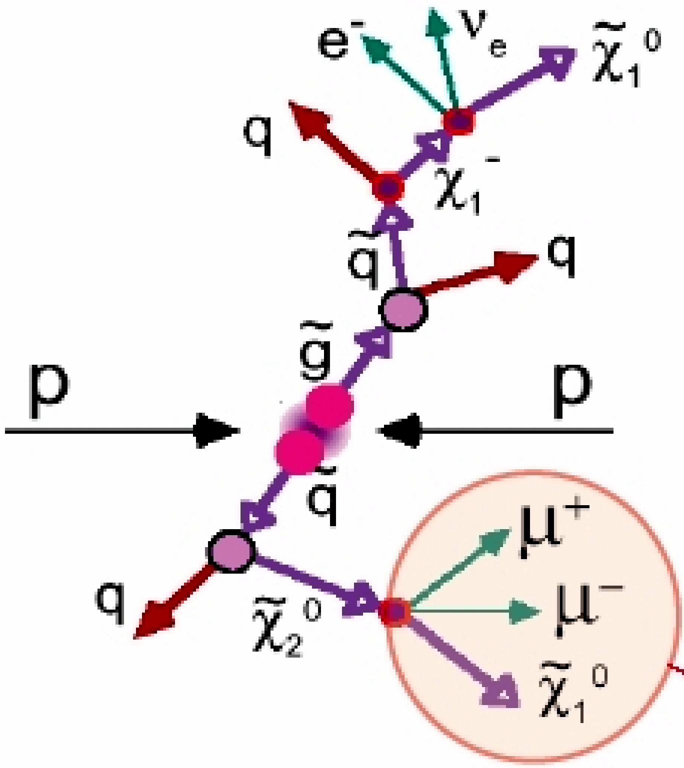
General strategy:

- Choose signatures identifying well defined decay chains
- Extract constraints on masses, couplings, spin from decay kinematics/rates
- Try to match emerging pattern to tentative template models, SUSY or anything else
- Having adjusted template models to measurements, try to find additional signatures to discriminate different options

In last ten years developed techniques for mass and spin measurements in complex SUSY decay kinematics

Progress helped by close collaboration with theory colleagues

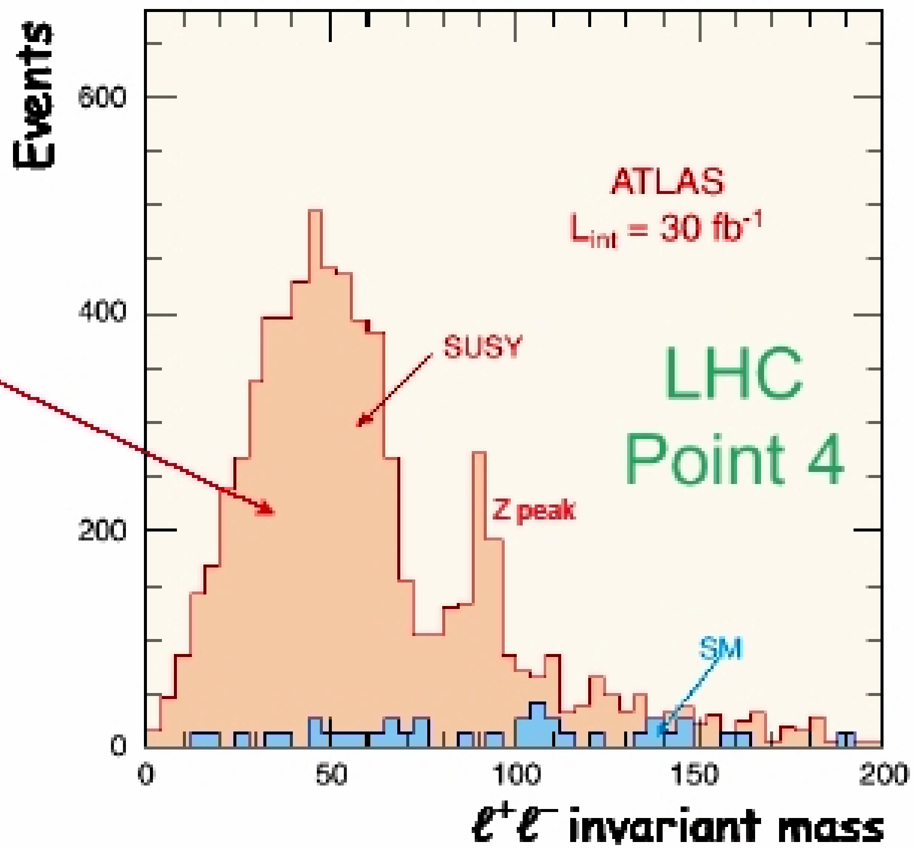
Focus today on explaining most promising techniques for mass and spin measurements



Reconstruction of decay chains

Need to take unobserved LSPs into account

Need to identify specific decay chain [SUSY is background to SUSY]



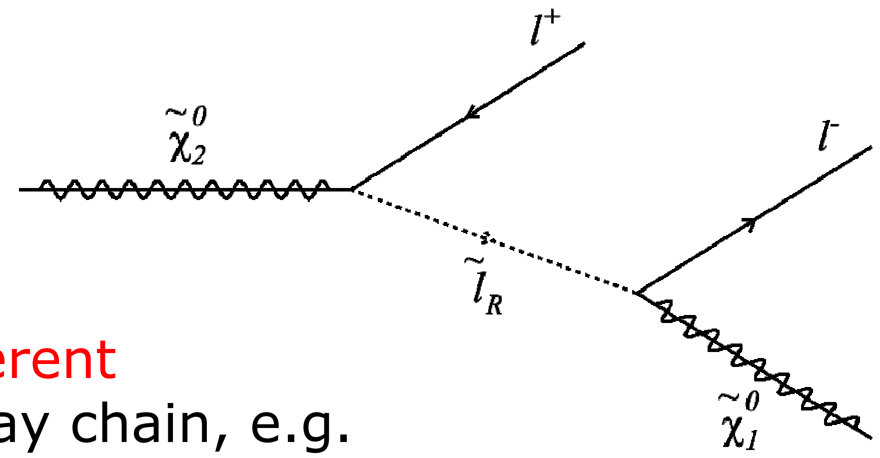
Example for approach

Consider decay $\chi_2^0 \to \chi_1^0 \ell^+ \ell^-$

But: contribution $\chi_2^\pm \to \chi_1^\pm Z$

Endpoint in $\ell^+\ell^-$ invariant mass determines mass difference $\chi_2^0 - \chi_1^0$

Determining SUSY Masses

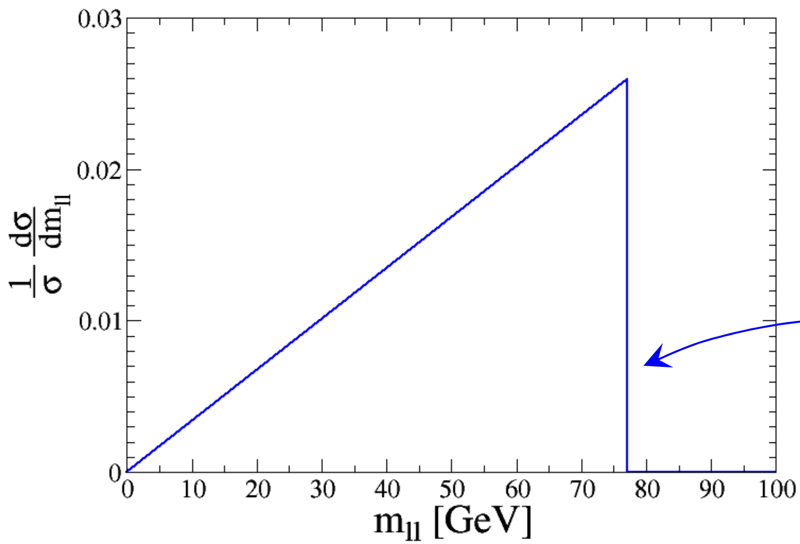


- Reconstruct SUSY masses in decay chain, e.g.
- Cannot reconstruct masses directly due to undetected LSP
- Study invariant masses for different combinations of particles in decay chain, e.g.

$$m_{ll} = m_{ll}^{\mathrm{max}} \sqrt{(1 - \cos\theta)/2}$$

angle between leptons

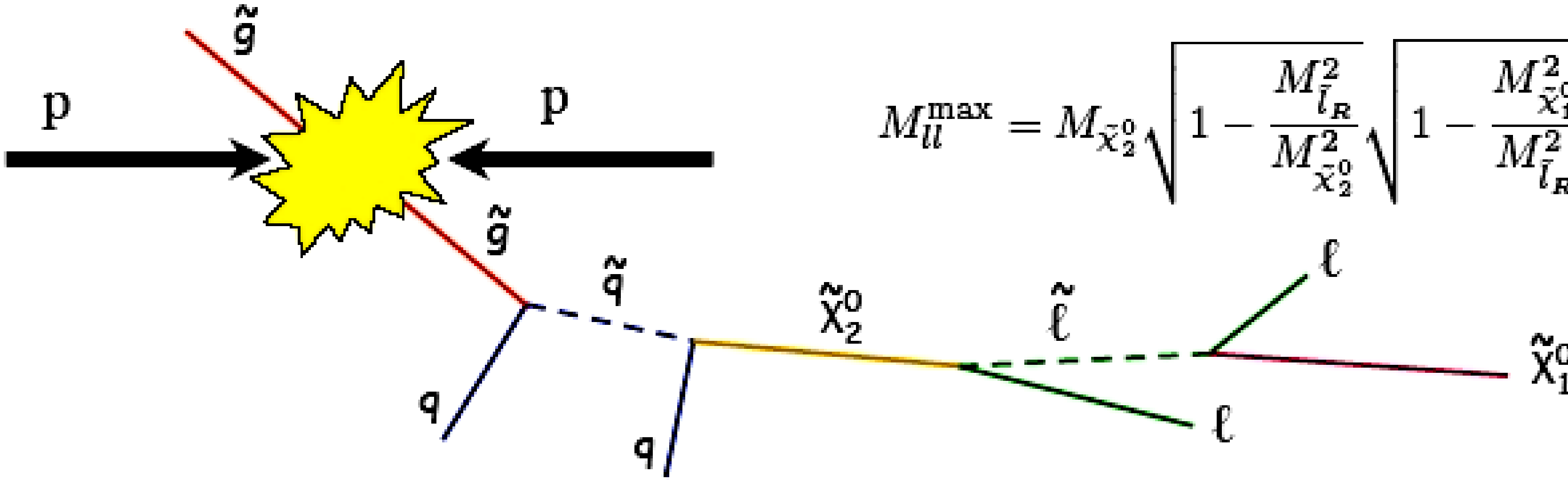
m_{ll} is maximal when leptons are back-to-back in slepton rest frame



Enpoint of inv. mass spectrum:

$$\left(m_{ll}^{\mathrm{max}}\right)^2 = \left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R}\right)\left(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}\right)/m^2_{\tilde{l}_R}$$

Determining SUSY Masses

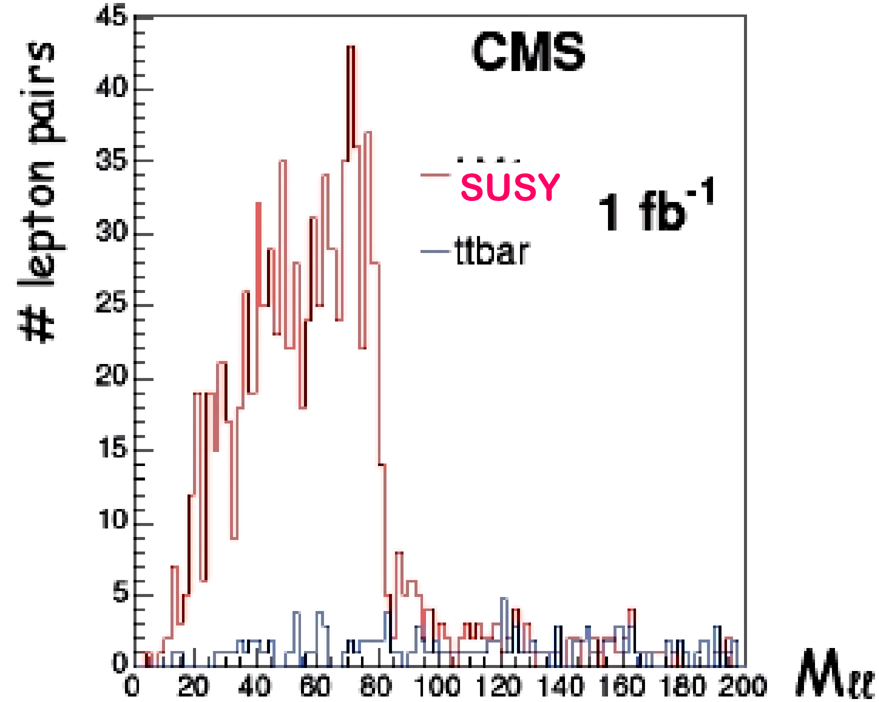


$$M_{ll}^{\max} = M_{\tilde{\chi}_2^0}\sqrt{1-\frac{M_{\tilde{l}_R}^2}{M_{\tilde{\chi}_2^0}^2}}\sqrt{1-\frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{l}_R}^2}}$$

$$M_{lq}^{\max} = \sqrt{\frac{(M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - (M_{\tilde{l}_R}^2)}{M_{\tilde{\chi}_2^0}^2}}$$

$$M_{lqq}^{\max} = \sqrt{\frac{(M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - (M_{\tilde{\chi}_1^0}^2)}{M_{\tilde{\chi}_2^0}^2}}$$

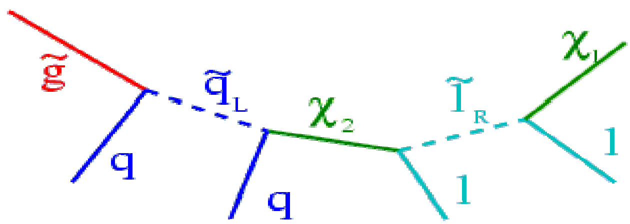
$$M_{qq}^{\max} = \ldots$$



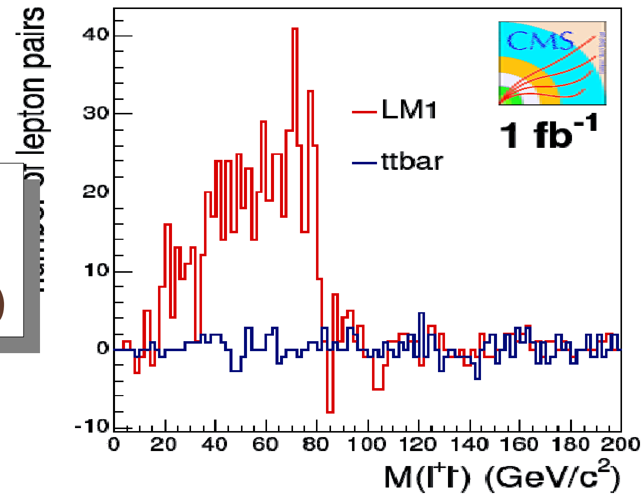
Determine SUSY masses from endpoints of $M_{\ell\ell}$, $M_{\ell q}$ and $M_{\ell qq}$ ...

Mass Determinations: Overview

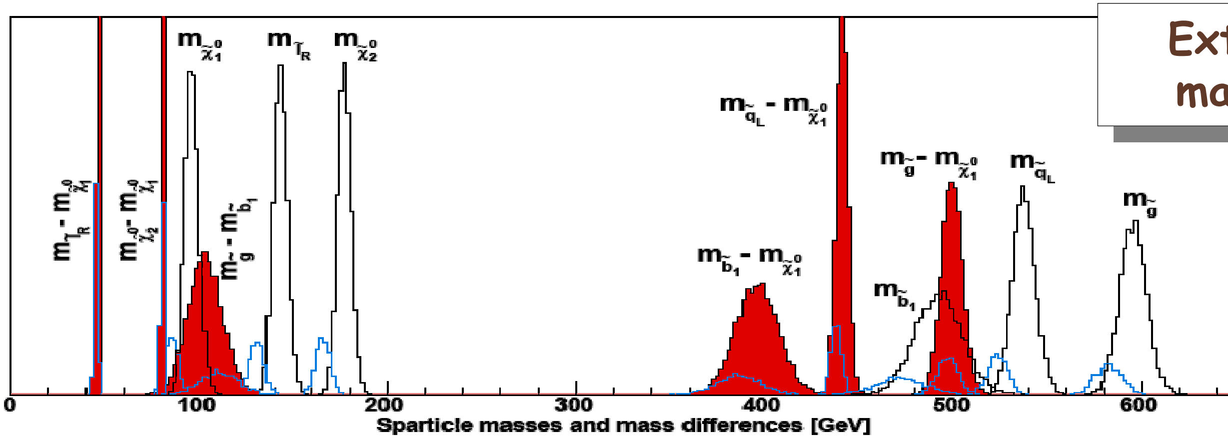
Try various decay chains



Look for sensitive variables (inv. masses, many of them)

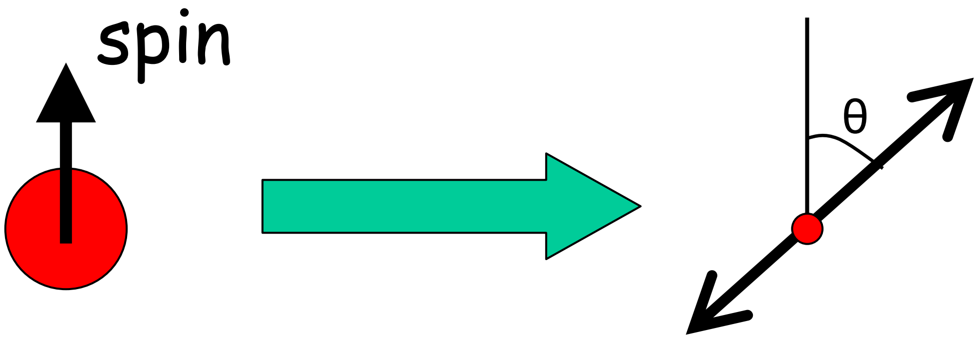


Extract masses

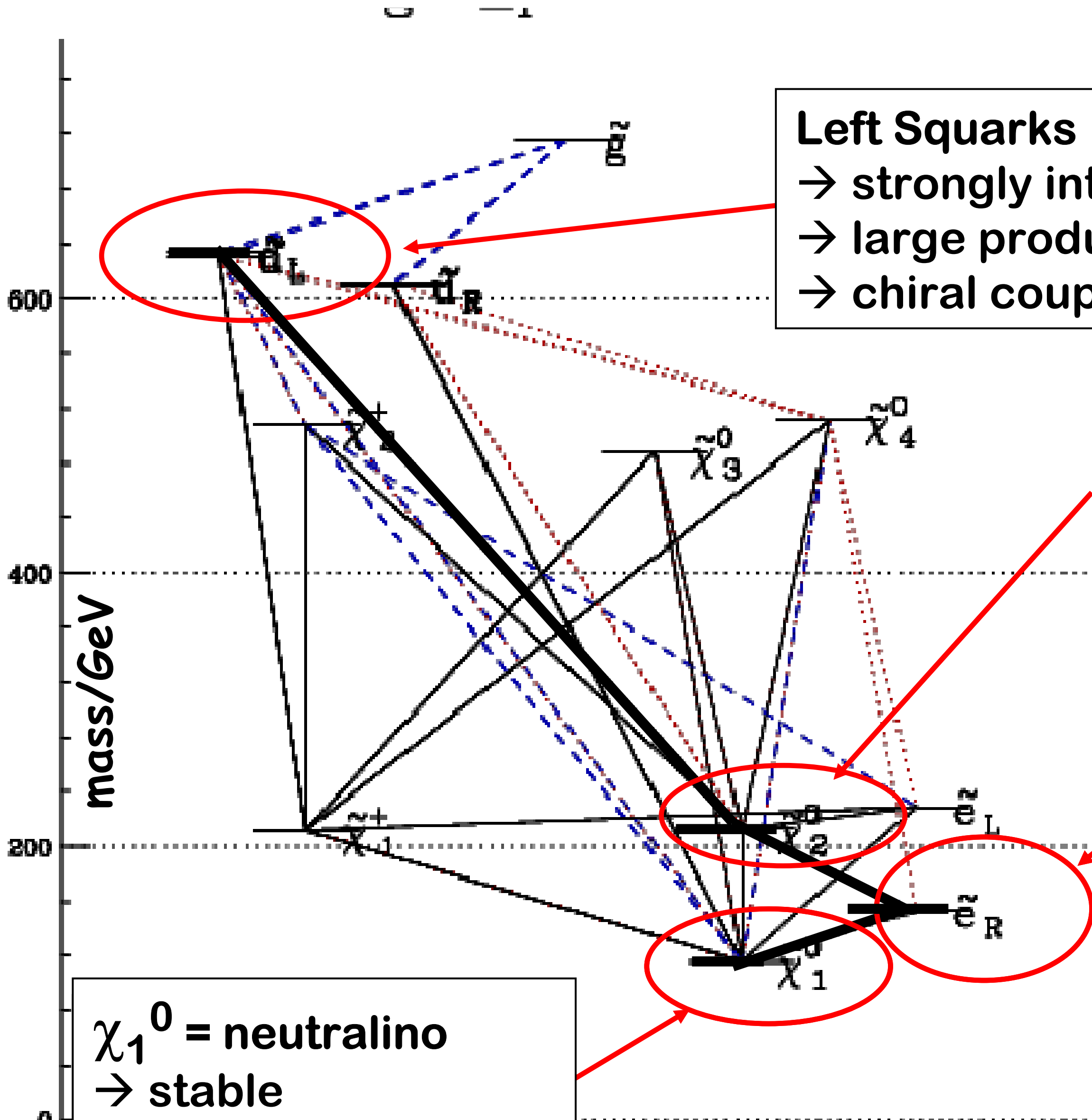


Another Example: Studying Spins of Sparticles

- **Basic recipe:**
  - **Produce polarized particle**
  - **Look at angular distributions in its decay**



Revisiting Typical Particle Spectrum



Left Squarks
→ strongly interacting
→ large production
→ chiral couplings

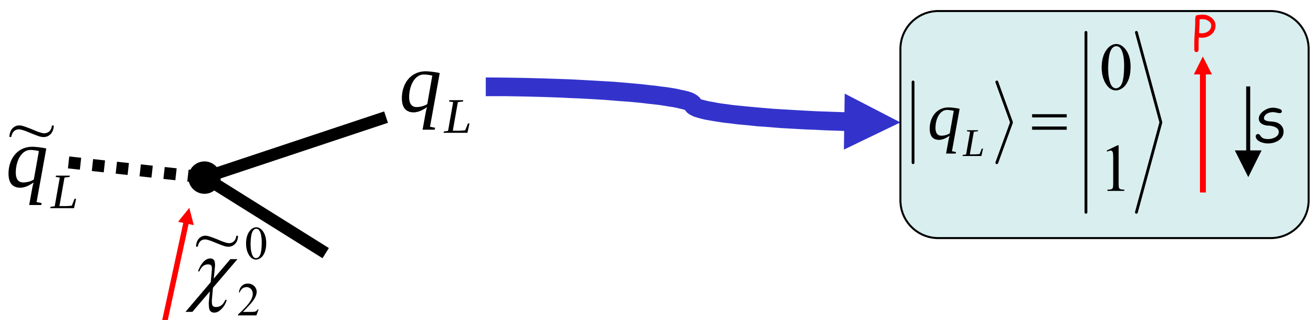
χ_2^0 = neutralino 2
→ (mostly) partner of SM W^0

Right slepton
(selectron or smuon)
→ Decay produces lepton
→ chiral couplings

χ_1^0 = neutralino
→ stable
→ weakly interacting

Some sparticles omitted

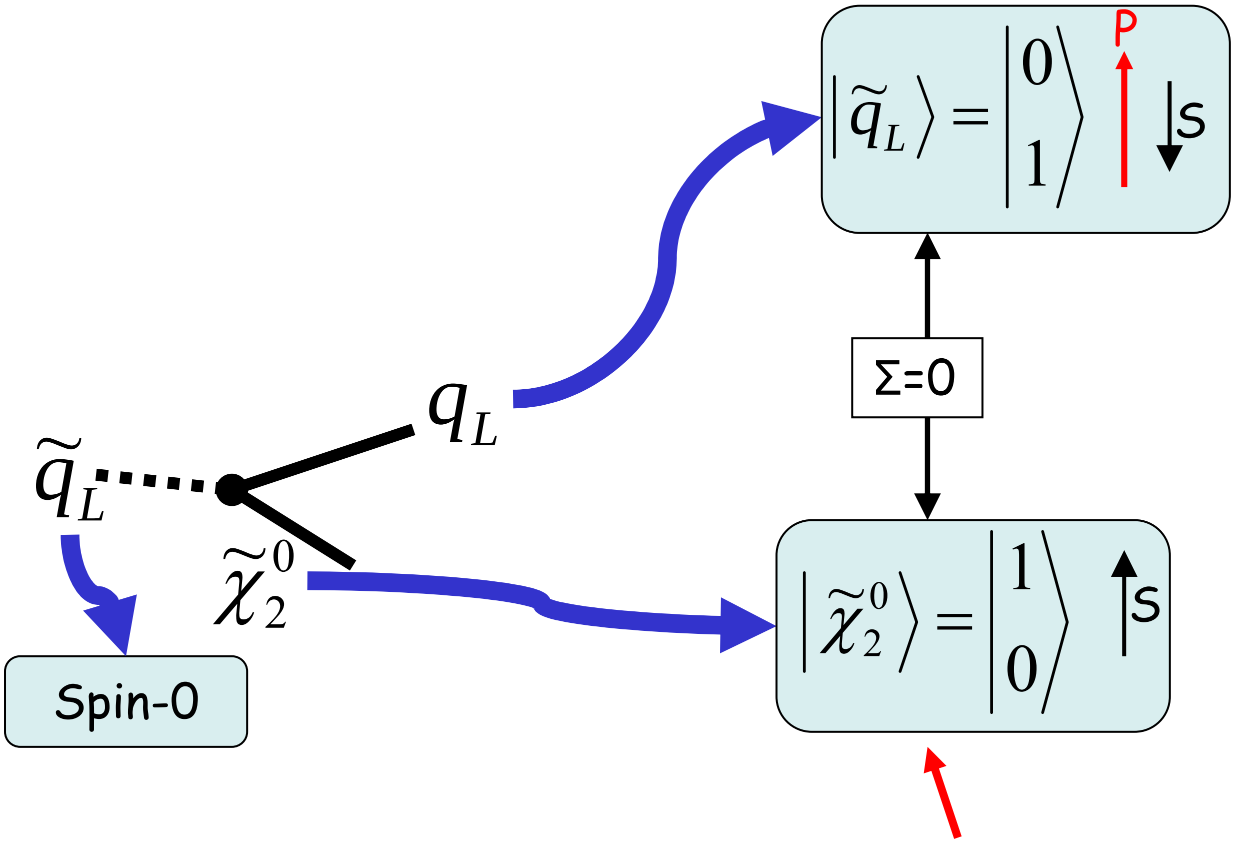
Spin Projection Factors



Chiral coupling

Approximate SM particles as massless
-> okay since m « p

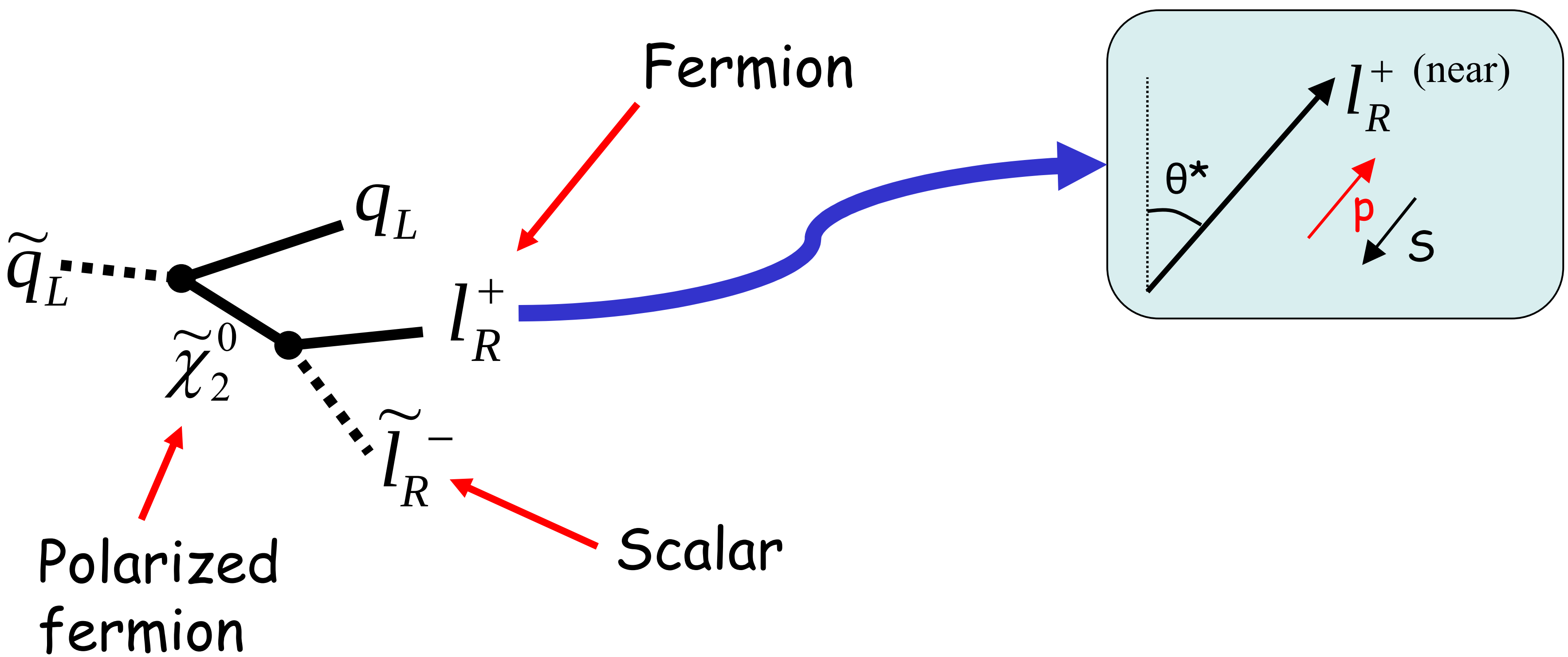
Spin Projection Factors



Produces **polarized** neutralino

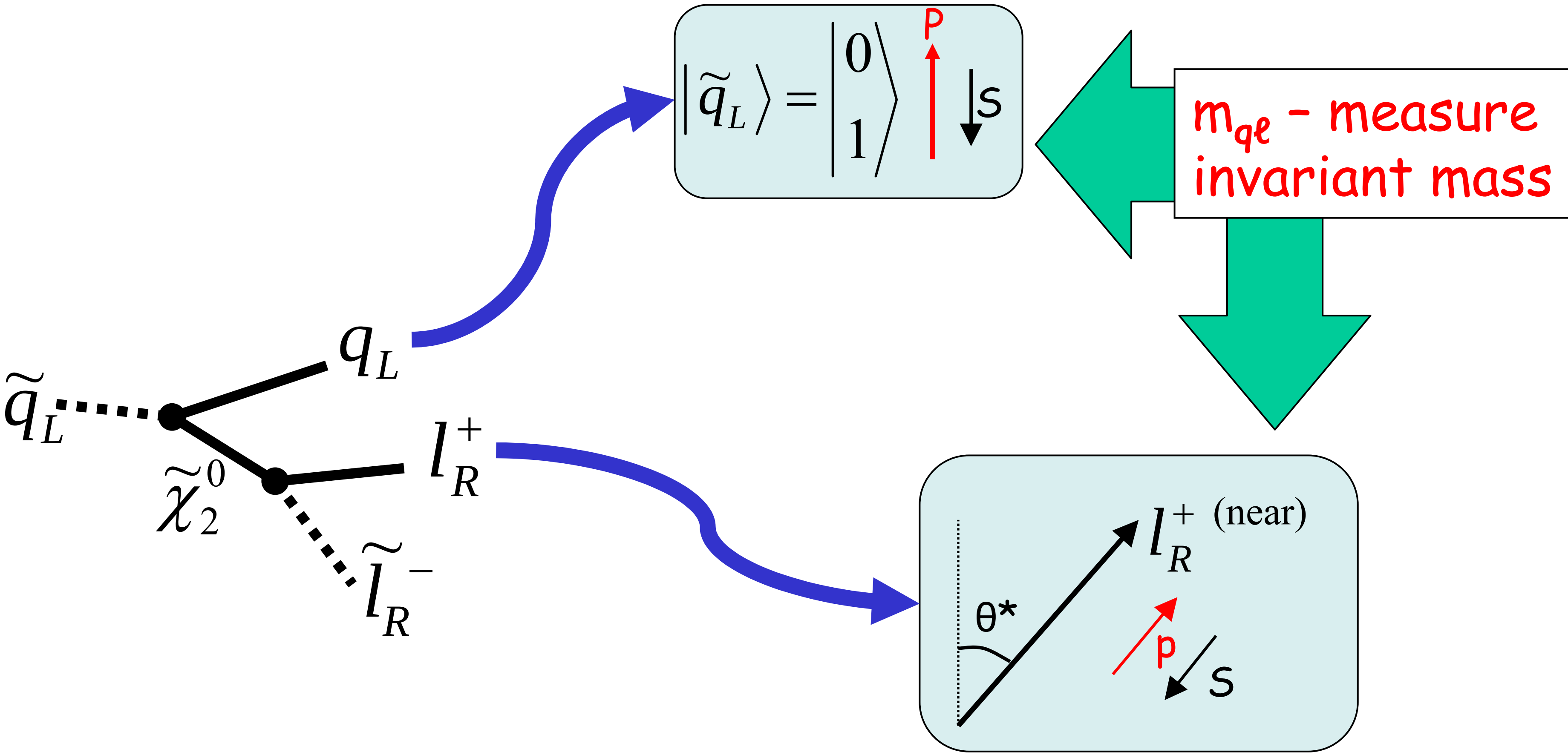
Approximate SM particles as massless
-> okay since m « p

Spin Projection Factors



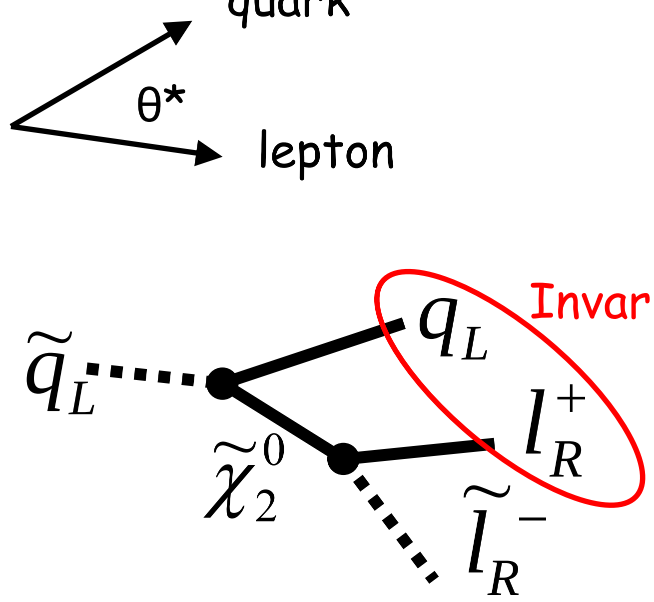
Approximate SM particles as massless
-> okay since m « p

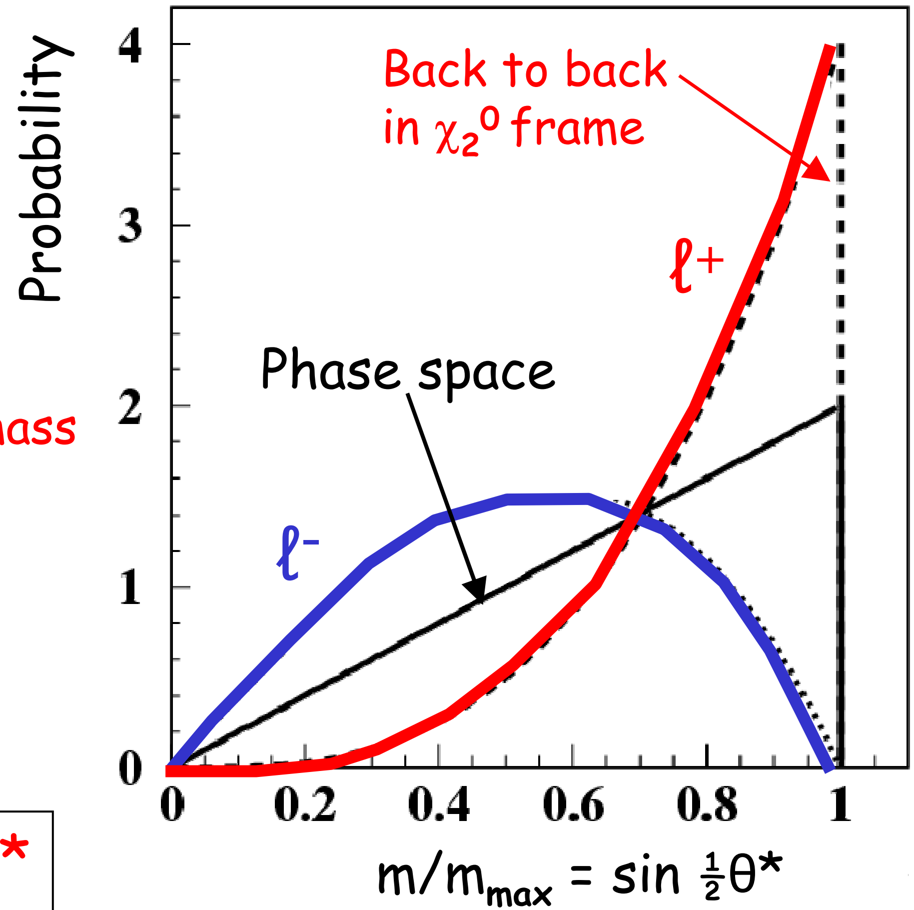
Spin Projection Factors



Approximate SM particles as massless
-> okay since m « p

Lepton(near)-Quark Invariant Mass





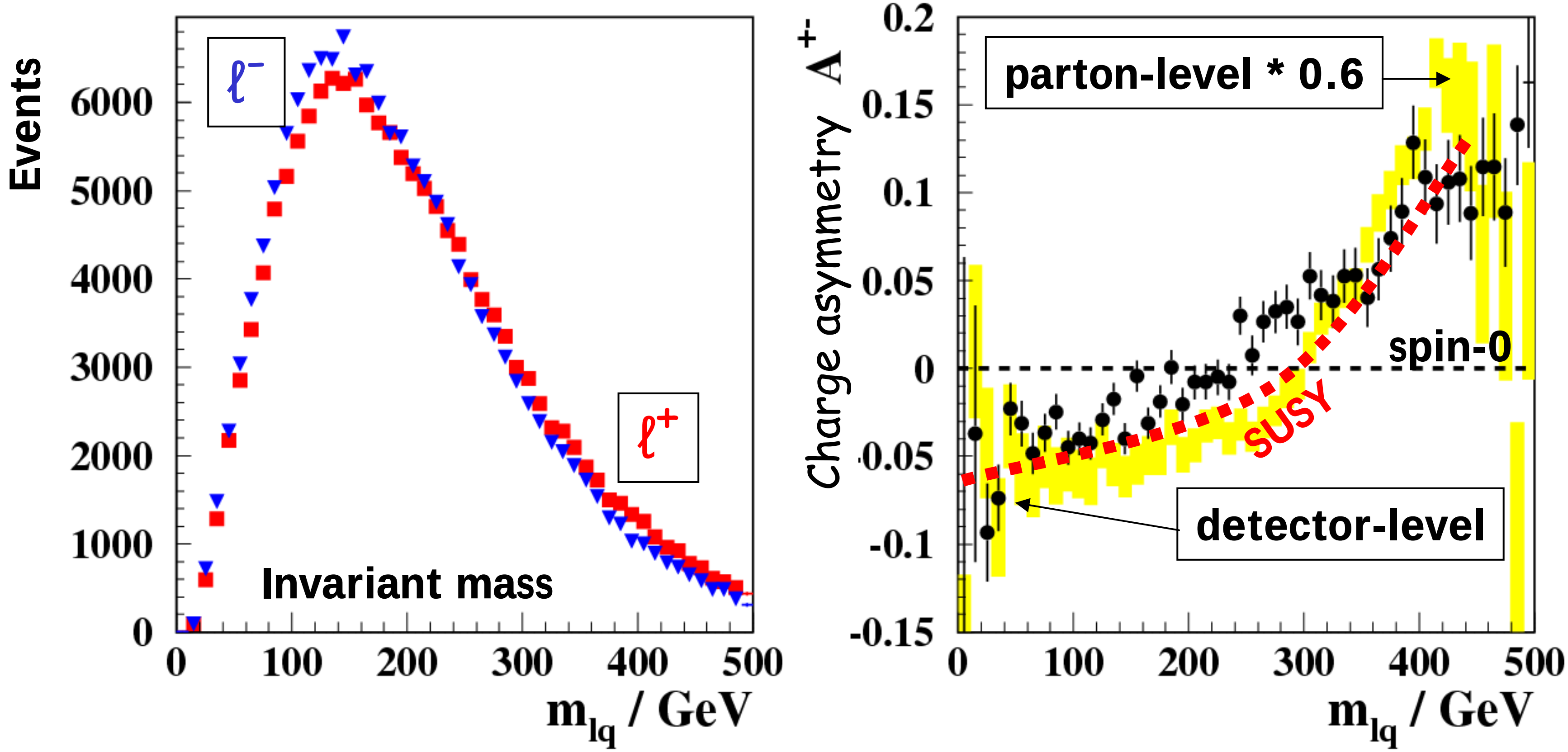
Phase space -> factor of $\sin \frac{1}{2}\theta^*$

Spin projection factor in $|M|^2$:

$\ell^+ q$ -> $\sin^2 \frac{1}{2}\theta^*$

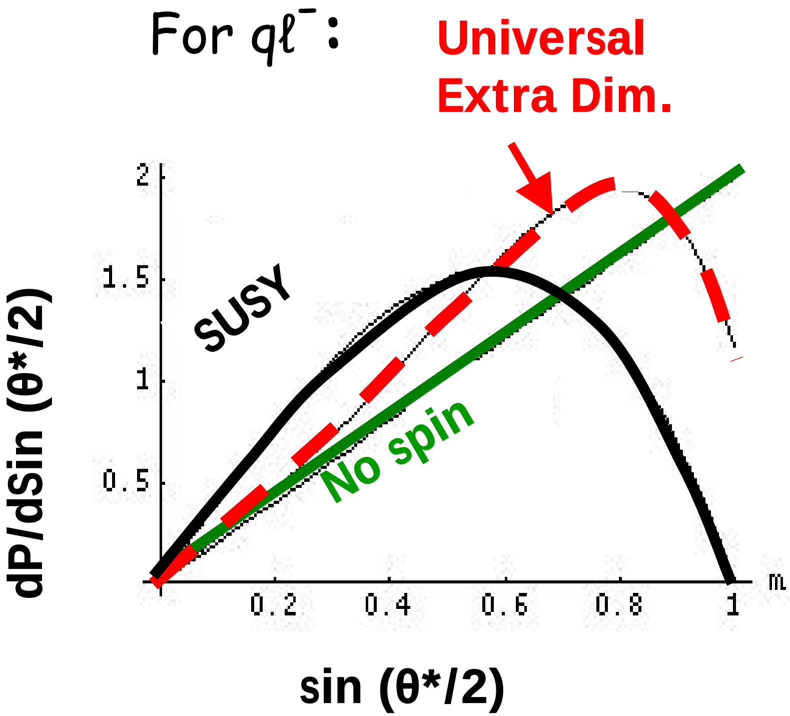
$\ell^- q$ -> $\cos^2 \frac{1}{2}\theta^*$

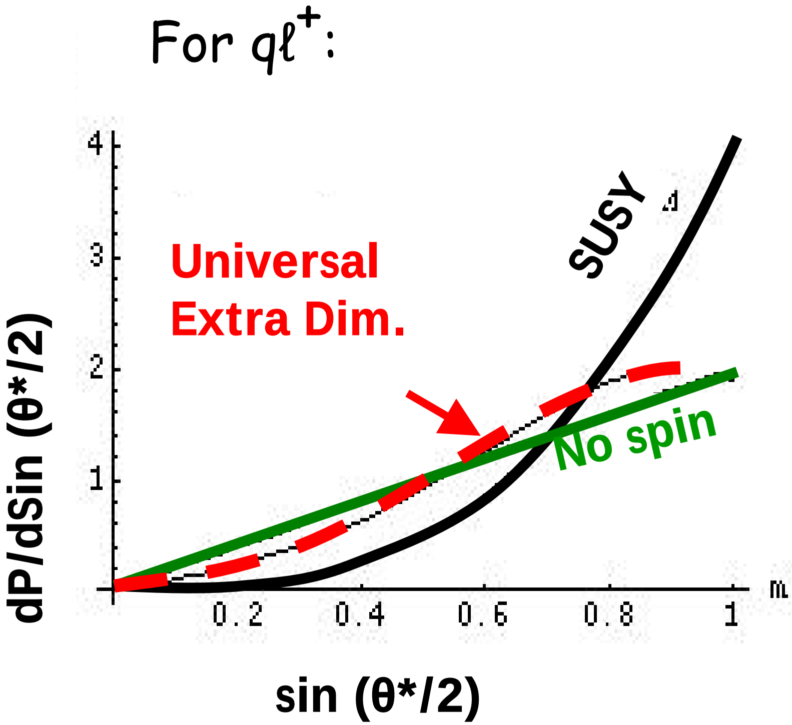
After Detector Simulation



→ Charge asymmetry survives detector simulation
→ Same shape as parton level (but smeared)

Distinguishing between New-Physics Models

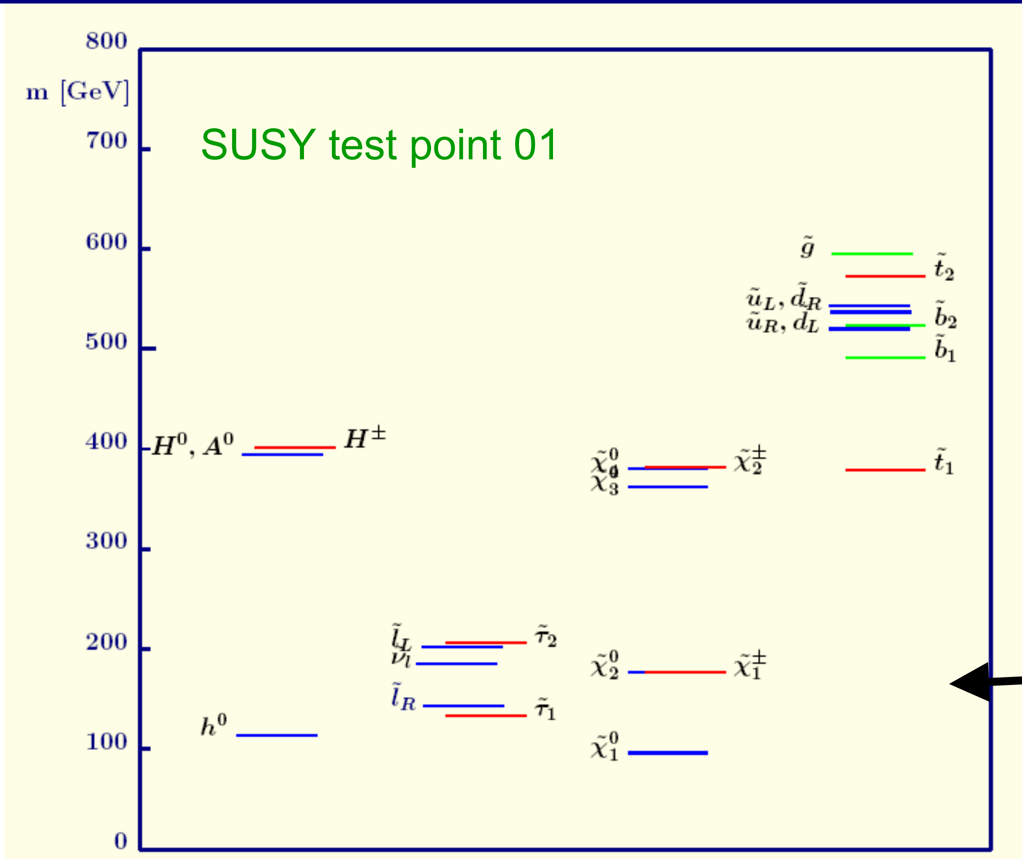


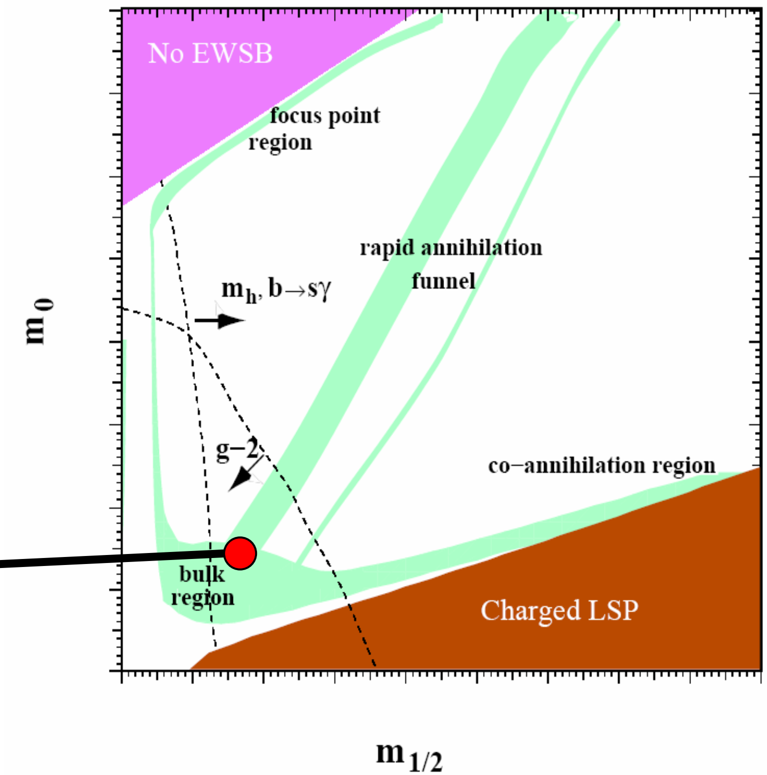


As expected, we can show that SUSY differs from
- all-scalar (no-spin)
- Extra Dimensions

Smillie et al.

Now what – do we know the underlying Model?





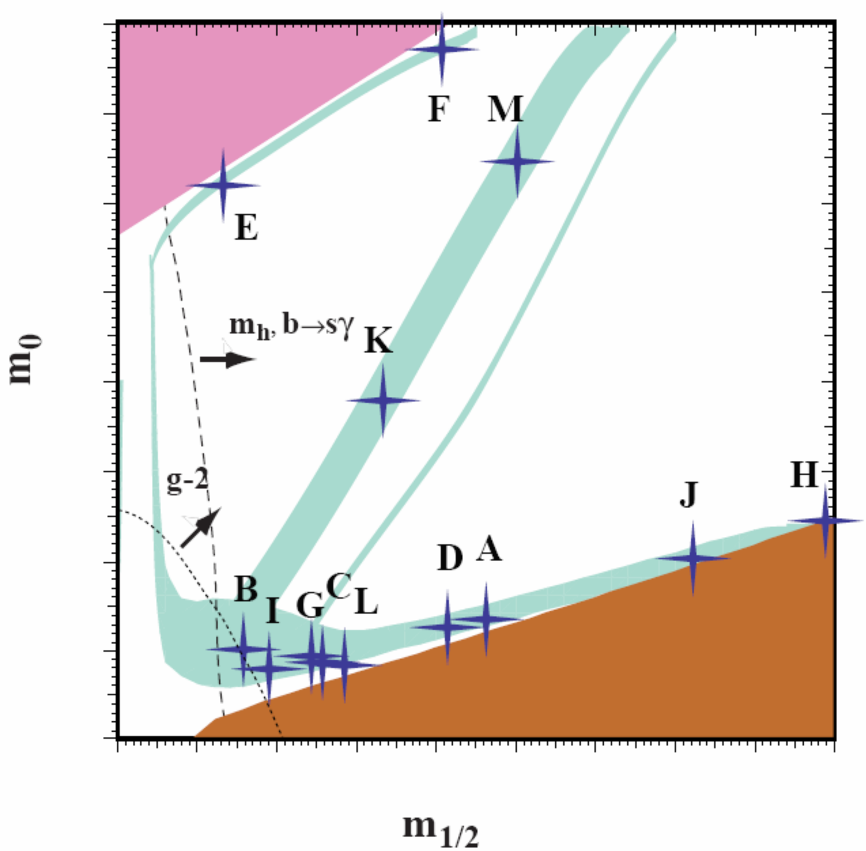
Measure full SUSY spectrum → obtain theory parameters

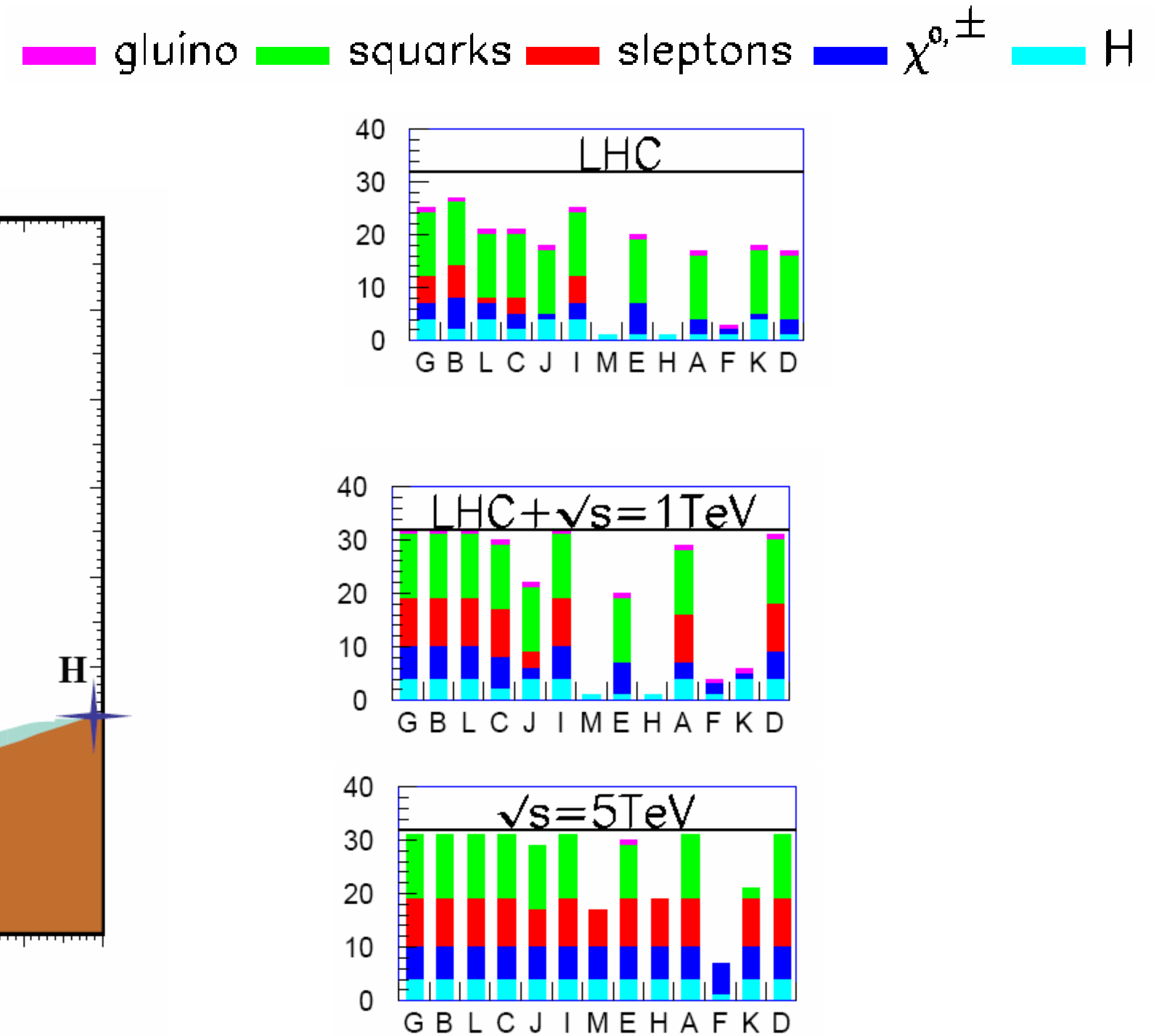
LHC: This will (most likely) not be possible! Discovery (Hadron) Machine

ILC : Precision measurements of electroweakly interactiong sparticles

→ we absolutely need a new high-energy e+e- collider after LHC

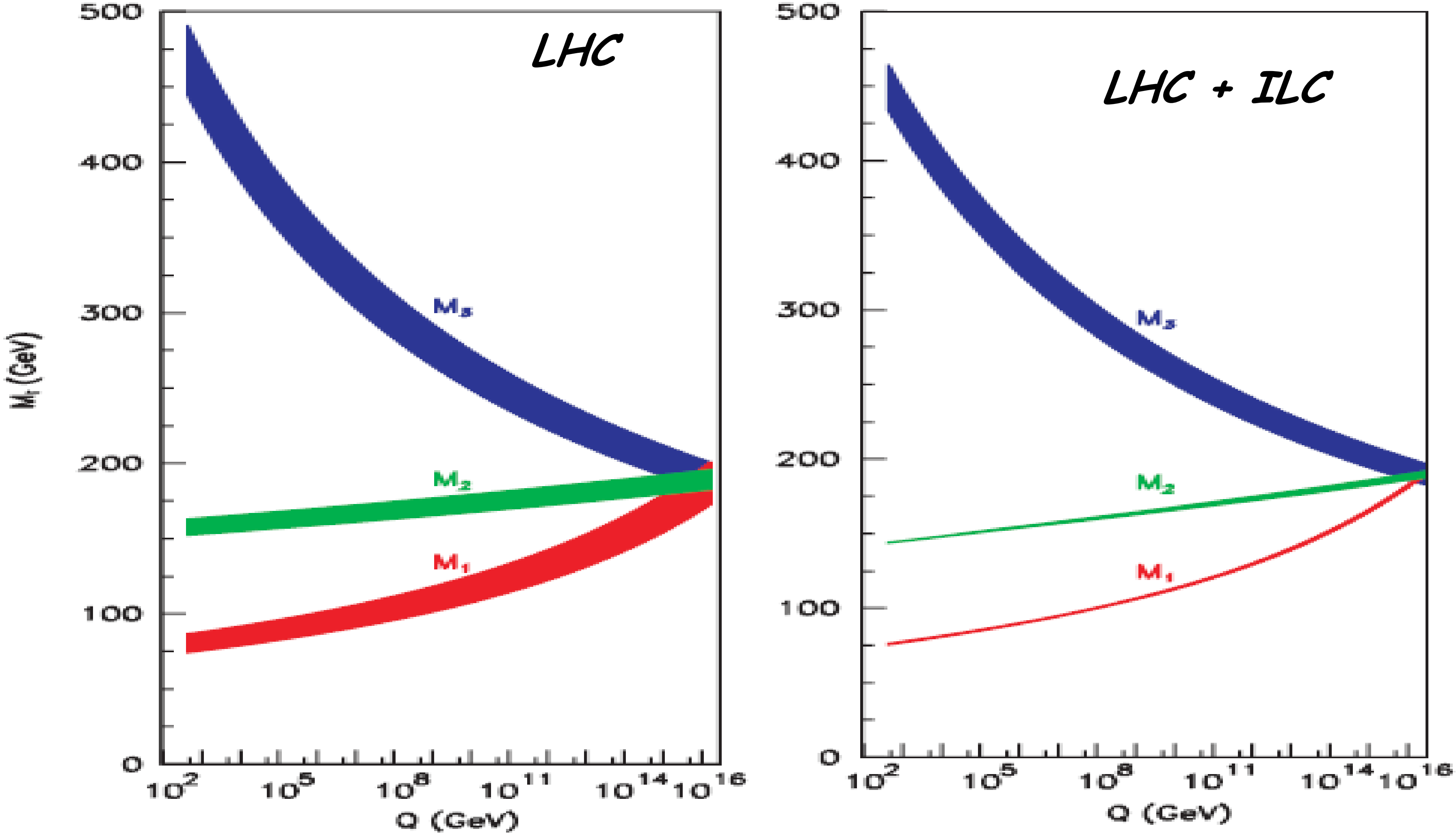
Number of observable SUSY particles:





LHC+ILC: Physics at the GUT Scale

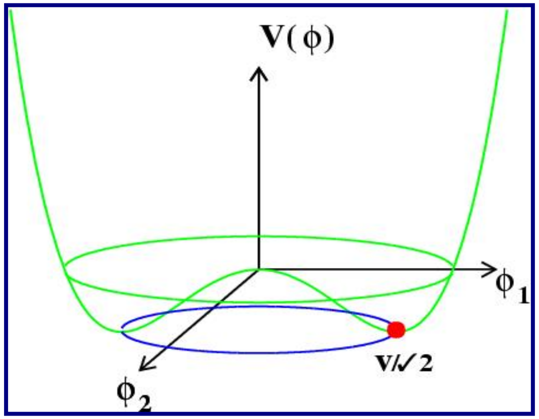
After Discovery: Extrapolation of SUSY Masses to high energies
→Testing GUT ?



The MSSM Higgs Sector

Reminder: Higgs Mechanism in Standard Model

The „Standard"-Solution:



Doublet of 4 scalar fields with

appropiately choosen potential:

$$V = -\mu^2 \,|\phi^+\phi| + \lambda \,|\phi^+\phi|^2 \qquad \mu^2, \lambda > 0$$

minimum not at ϕ=0

→ spontaneous symmetry breaking

Higgs field has two components:

1) omnipresent, homogeneous background field v= 247 GeV

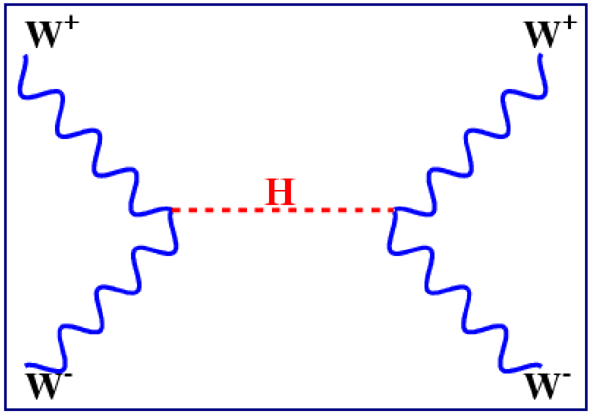
2) Higgs-Boson H with unknown mass $M_H \sim \sqrt{\lambda}\, v$

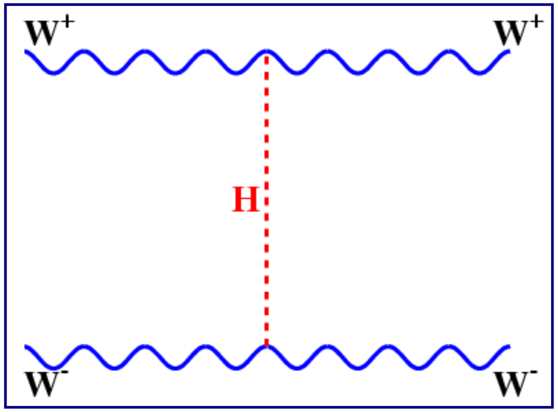
H restores unitarity in WW scattering if

$g_{HWW} \sim M_W$

$g_{Hff} \sim M_f$

and M_H not too large





Electroweak Symmetry Breaking in the MSSM

There are two complex Higgs scalar doublets, (H_u^+, H_u^0) and (H_d^0, H_d^-), rather than one in the Standard Model. The classical scalar potential is:

$$\boxed{\begin{aligned} V \;=\; & (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2) + (|\mu|^2 + m_{H_d}^2)(|H_d^0|^2 + |H_d^-|^2) \\ & + b\,(H_u^+ H_d^- - H_u^0 H_d^0) + \text{c.c.} \\ & + \tfrac{1}{8}(g^2 + g'^2)(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2 \\ & + \tfrac{1}{2} g^2 |H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2 . \end{aligned}}$$

The $|\mu|^2$ parts come from the F-terms. The g^2 and g'^2 parts come from the D-terms. The other terms come from the soft SUSY-breaking Lagrangian.

We must now minimize this potential, and show that it is compatible with the known electroweak symmetry breaking.

First, the freedom to do $SU(2)_L$ gauge transformations allows us to take $H_u^+ = 0$ at the minimum without loss of generality. Then one can show that $\partial V / \partial H_u^+ = 0$ also requires $H_d^- = 0$. So, at the minimum of the potential, $U(1)_{\mathrm{EM}}$ will be unbroken, as required. We are left with. . .

$$\boxed{\begin{aligned} V &= (|\mu|^2 + m^2_{H_u})|H_u^0|^2 + (|\mu|^2 + m^2_{H_d})|H_d^0|^2 - (b\, H_u^0 H_d^0 + \text{c.c.}) \\ &\quad + \tfrac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2. \end{aligned}}$$

A redefinition of the phase of H_u^0 can absorb any phase in b, so take it real and positive. This implies that at the minimum, $H_u^0 H_d^0$ is also real and positive, so H_u^0 and H_d^0 have opposite phases. Since they have opposite weak hypercharges $(\pm\frac{1}{2})$, a $U(1)_Y$ gauge rotation can make them both real and positive at the minimum, without loss of generality.

Must require that $H_u^0 = H_d^0 = 0$ is **not** the minimum. Then:

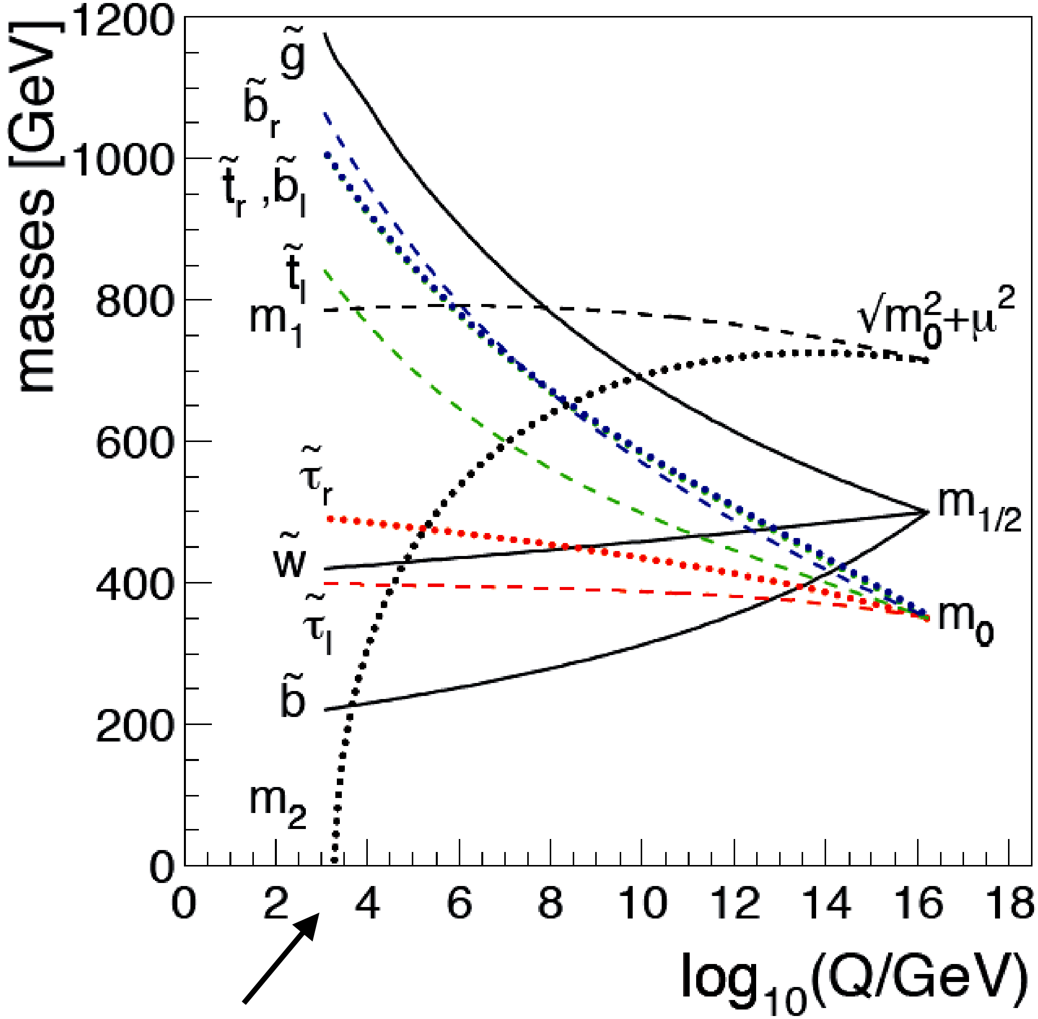
$$b^2 > (|\mu|^2 + m^2_{H_u})(|\mu|^2 + m^2_{H_d}).$$

Also, we need the potential to be bounded from below. This requires:

$$2b < 2|\mu|^2 + m^2_{H_u} + m^2_{H_d}.$$

If these conditions are met, typically with $m^2_{H_u} < 0$ in realistic models, then spontaneous electroweak breaking $SU(2)_L \times U(1)_Y \to U(1)_{\mathrm{EM}}$ occurs.

Reminder: RGE's



RGE drive m_u^2 (=m_2^2) negative due to large top Yukawa coupling

→ triggers EWSB

Electroweak Symmetry Breaking in the MSSM

The resulting Higgs VEVs can be parameterized:

$$\boxed{\begin{aligned} &v_u = \langle H_u^0 \rangle, \qquad v_d = \langle H_d^0 \rangle, \qquad \text{where} \\ &v_u^2 + v_d^2 = v^2 = 2m_Z^2/(g^2 + g'^2) \approx (174\,\mathrm{GeV})^2 \\ &\tan\beta \equiv v_u/v_d. \end{aligned}}$$

The conditions for a minimum, from $\partial V/\partial H_u^0 = \partial V/\partial H_d^0 = 0$, are:

$$|\mu|^2 + m_{H_u}^2 = b\cot\beta + (m_Z^2/2)\cos 2\beta$$
$$|\mu|^2 + m_{H_d}^2 = b\tan\beta - (m_Z^2/2)\cos 2\beta$$

These allow us to eliminate two parameters in favor of m_Z^2 and $\tan\beta$.

The quark and lepton masses are related to these VEVs by:

$$y_t = \frac{m_t}{v\sin\beta}, \qquad y_b = \frac{m_b}{v\cos\beta}, \qquad y_\tau = \frac{m_\tau}{v\cos\beta}, \qquad \text{etc.}$$

If we want the Yukawa couplings to avoid getting non-perturbatively large up to very high scales, we must have:

$$1.5 \lesssim \tan\beta \lesssim 55$$

The "μ Problem"

Solve for outputs m_Z and $\tan\beta$, using Lagrangian parameters as inputs:

$$\tan\beta = r + \sqrt{r^2 - 1}$$

$$m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2}{\sqrt{1 - 1/r^2}} - 2|\mu|^2 - m_{H_d}^2 - m_{H_u}^2$$

where

$$r = (2|\mu|^2 + m_{H_d}^2 + m_{H_u}^2)/2b.$$

Without miraculous cancellations, we expect that all of the (mass)^2 parameters appearing in these equations should be within an order of magnitude of m_Z^2. However, μ is a SUSY-**respecting** parameter appearing in the superpotential, while $m_{H_u}^2$, $m_{H_d}^2$ and b are SUSY-**breaking** parameters. Why should they be comparable in size?

Define mass-eigenstate Higgs bosons: $h^0, H^0, A^0, G^0, H^+, G^+$ by:

$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \underbrace{\begin{pmatrix} h^0 \\ H^0 \end{pmatrix}}_{\text{CP even}} + \frac{i}{\sqrt{2}} \begin{pmatrix} \sin\beta & \cos\beta \\ -\cos\beta & \sin\beta \end{pmatrix} \underbrace{\begin{pmatrix} G^0 \\ A^0 \end{pmatrix}}_{\text{CP odd}}$$

$$\begin{pmatrix} H_u^+ \\ H_d^{-*} \end{pmatrix} = \begin{pmatrix} \sin\beta & \cos\beta \\ -\cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$$

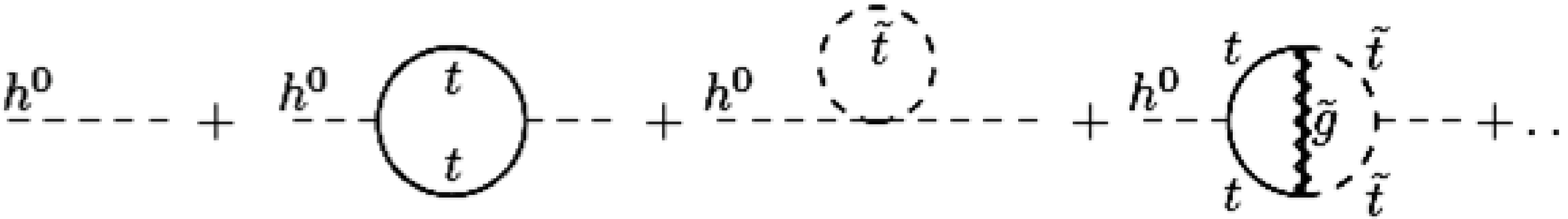
Now, expand the potential to second order in these fields to obtain the masses:

$$\boxed{\begin{aligned} m_{A^0}^2 &= 2b/\sin 2\beta \\ m_{h^0,H^0}^2 &= \tfrac{1}{2}\left(m_{A^0}^2 + m_Z^2 \mp \sqrt{(m_{A^0}^2 + m_Z^2)^2 - 4 m_Z^2 m_{A^0}^2 \cos^2 2\beta}\right), \\ m_{H^\pm}^2 &= m_{A^0}^2 + m_W^2 \end{aligned}}$$

The mixing angle α obeys $\tan 2\alpha = \left(\frac{m_{A^0}^2 + m_Z^2}{m_{A^0}^2 - m_Z^2}\right) \tan 2\beta$, and is traditionally chosen to be negative. The Goldstone bosons have $m_{G^0} = m_{G^\pm} = 0$; they are absorbed by the Z, $W^\pm$ bosons to give them masses, as in the Standard Model.

Radiative Corrections to Higgs Mass in SUSY

$$m_{h^0}^2 = m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2} y_t^2 m_t^2 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \ldots$$

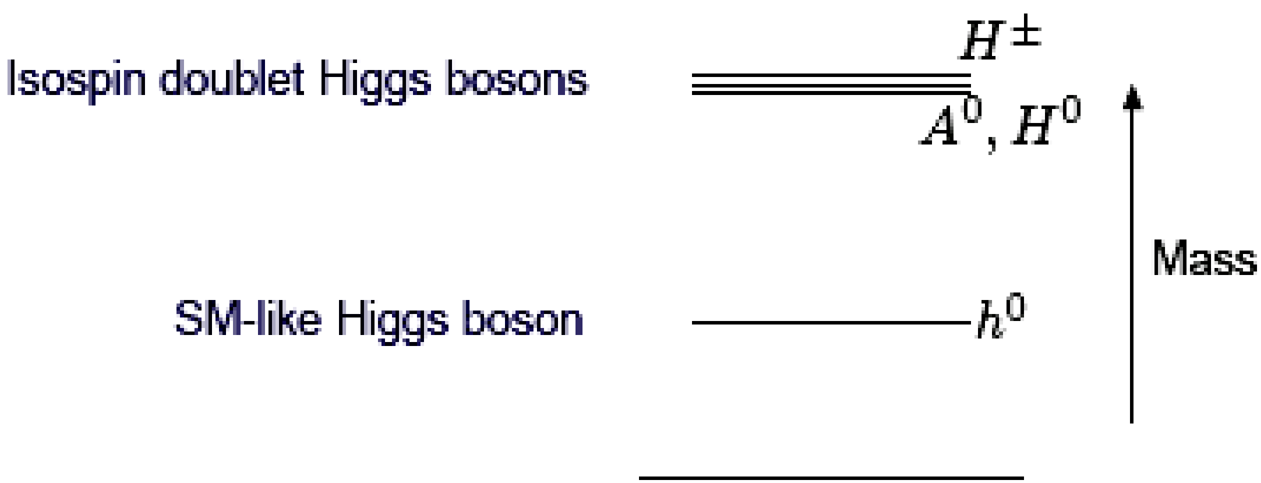


At tree-level:	m_Z^2	pure electroweak
At one-loop:	$y_t^2 m_t^2$	top Yukawa comes in
At two-loop:	$\alpha_S y_t^2 m_t^2$	SUSYQCD comes in
At three-loop:	$\alpha_S^2 y_t^2 m_t^2$	

At a future International Linear Collider, one might be able to measure m_{h^0} to within 50 MeV or better. This will require three-loop calculations to match theory to experiment!

If $m_{A^0} \gg m_Z$, then:

- h^0 has the same couplings as would a Standard Model Higgs boson of the same mass
- $A^0, H^0, H^{\pm}$ form an isospin doublet, and are much heavier than h^0



Many models of SUSY breaking approximate this decoupling limit.

MSSM Higgs Bosons Phenomenology

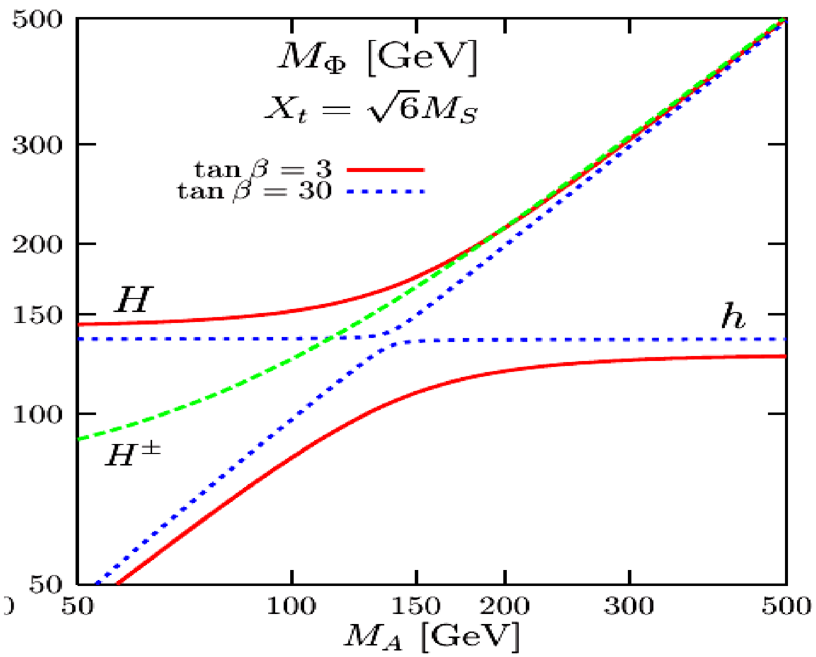
- Modified couplings $g_{MSSM} = \xi\, g_{SM}$

ξ	**t**	**b / τ**	**W / Z**
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\alpha-\beta)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\alpha-\beta)$
A	$\cot\beta$	$\tan\beta$	-----

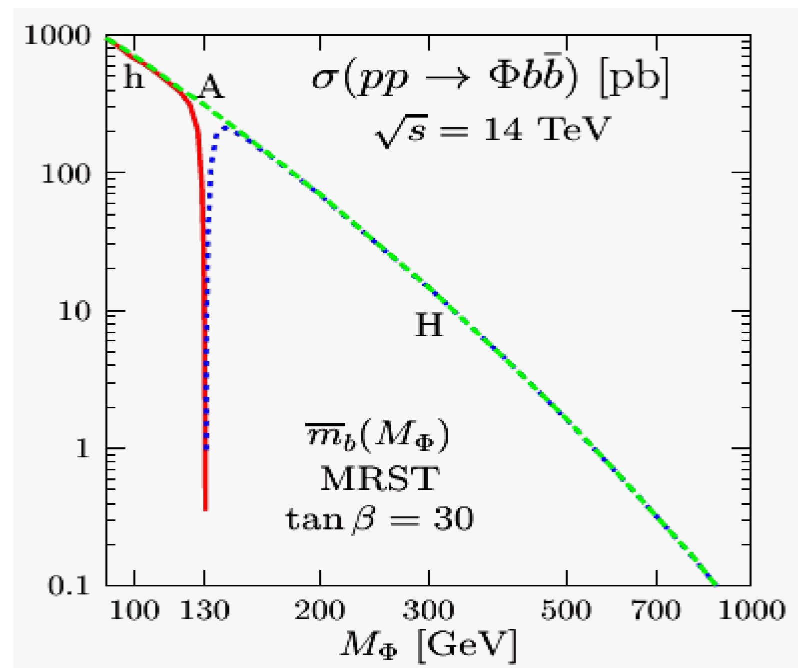
α = mixing btw. CP-even neutral Higgs bosons

- no coupling of A to W/Z
- small $\alpha \rightarrow$ small BR($h\rightarrow\tau\tau$,bb)
- large $\beta \rightarrow$ large BR($h,H,A\rightarrow\tau\tau$,bb)

- Higgs boson mass pattern

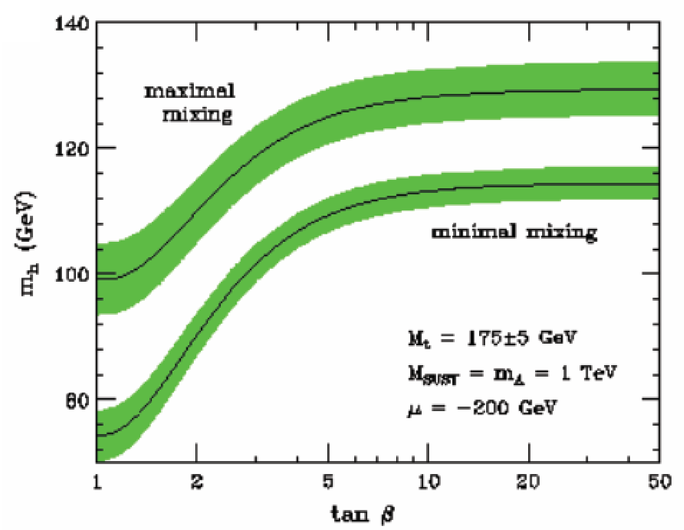


- New production mode: b(b)Higgs



Constraints on the Higgs Sector

- MSSM bounds



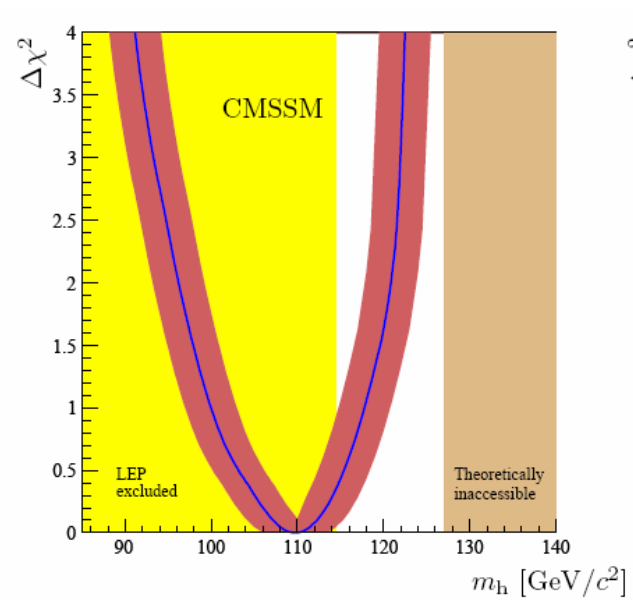
Constrained MSSM:

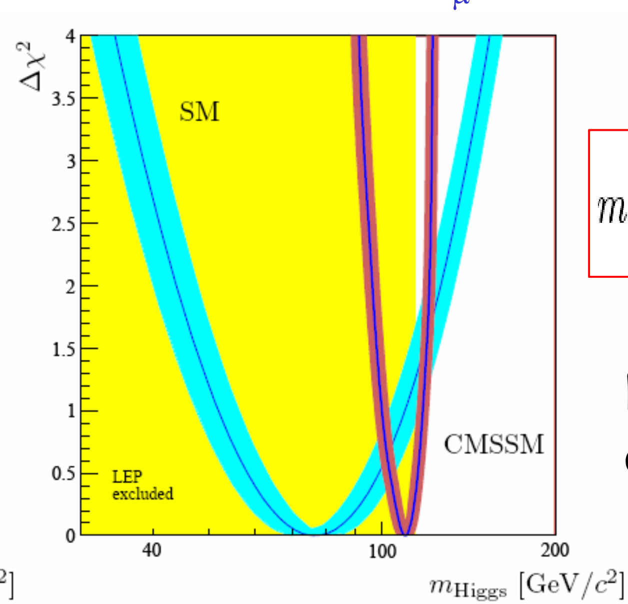
M_h < 133 GeV for m_t=175 GeV, M_{SUSY}=1TeV

General MSSM:

M_h < 150GeV

- EW precision data, dark matter density, a_μ, b → sγ in cMSSM(mSUGRA)



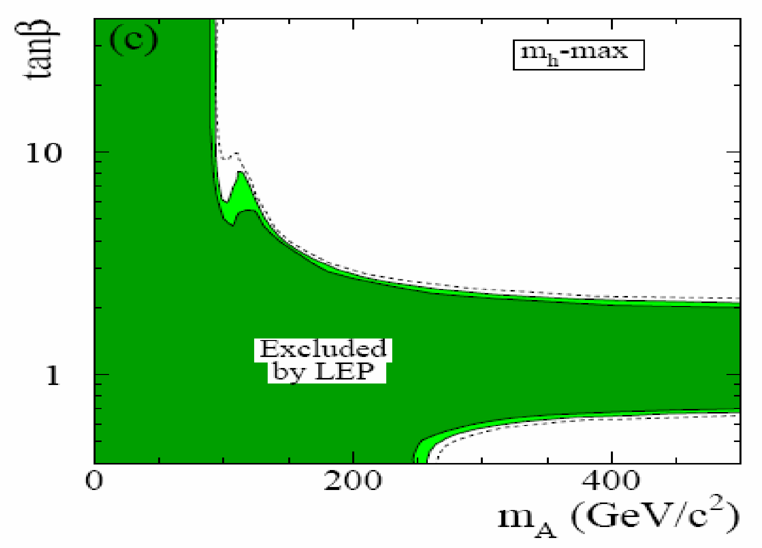


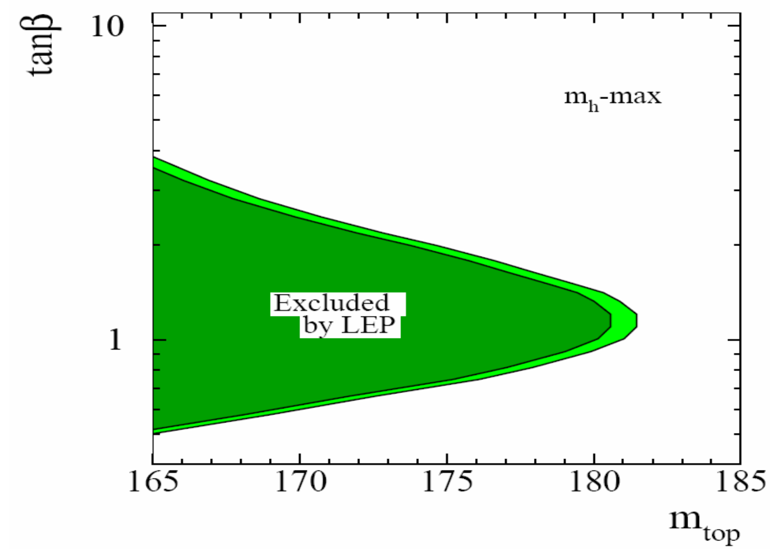
$$m_h^{CMSSM} = 110^{+8}_{-10}\,(\text{exp.}) \pm 3\,(\text{theo.})\ \text{GeV}/c^2$$

precision from dark matter, a_μ, b → sγ constraints

Constraints on the Higgs sector: Direct searches

- LEP: $M_{h/A} <\sim M_Z$ excluded at 95%CL

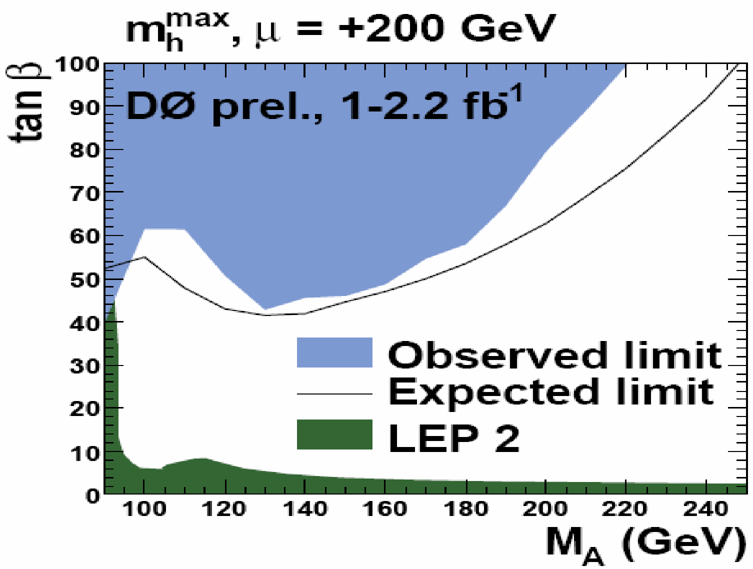




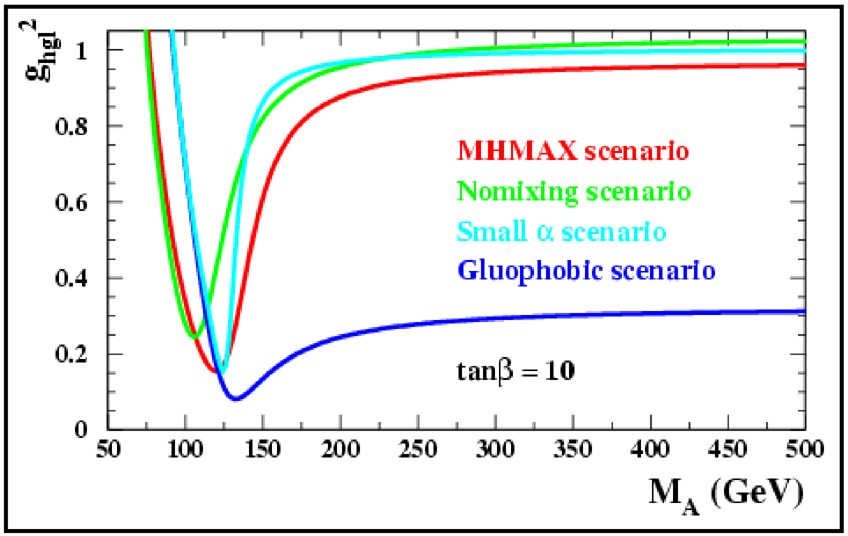
- TEVATRON:

  largest sensitivity at large tan β

  via bbH, H→ττ

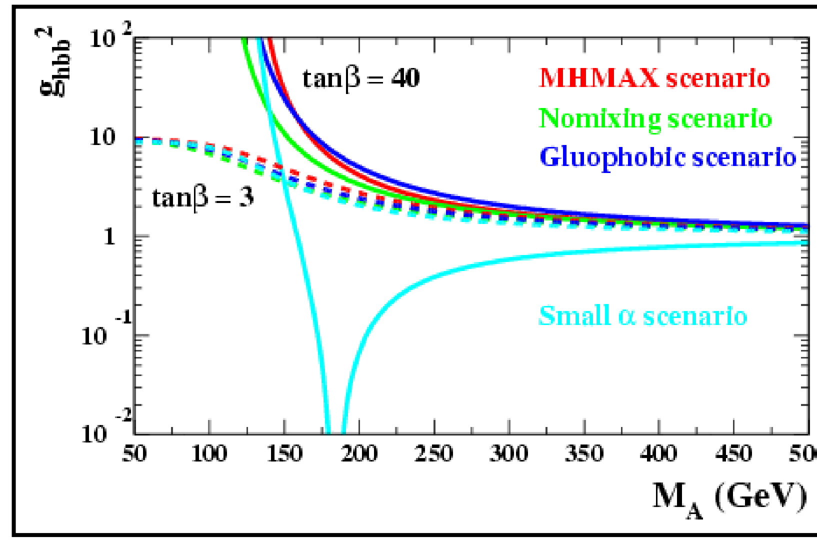


- MHMAX scenario: maximal m_h < 133 GeV → conservative LEP exclusion
- Nomixing scenario: small m_h < 116 GeV → difficult for LHC
- Gluophobic scenario
  small $g_{h,gluon}$ m_h < 119 GeV



theo. aim: harm discovery via
gg→ h, h→gg and h→ZZ→4 l

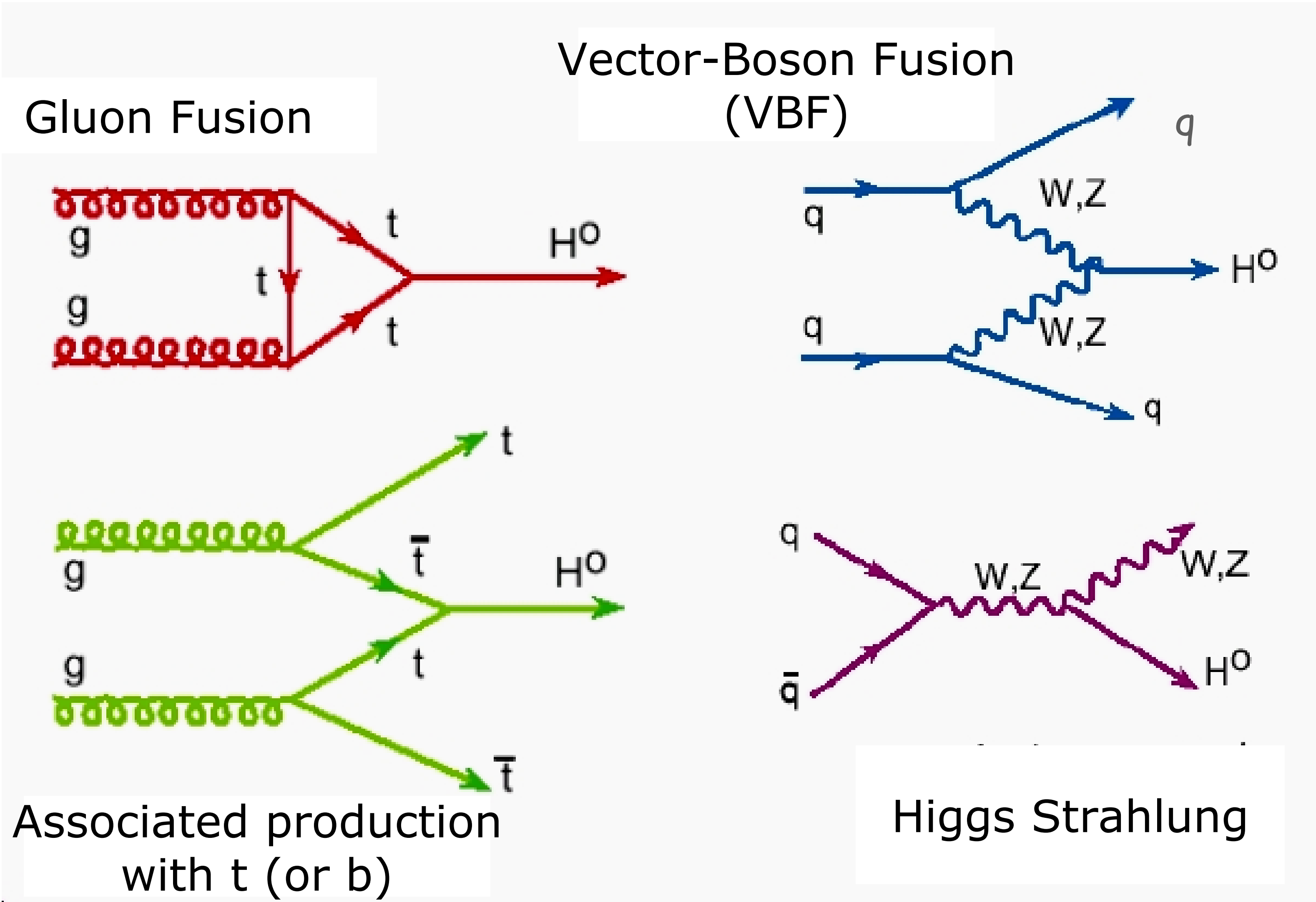
- Small a scenario
  small g_{hbb} and g_{htt} m_h <123 GeV



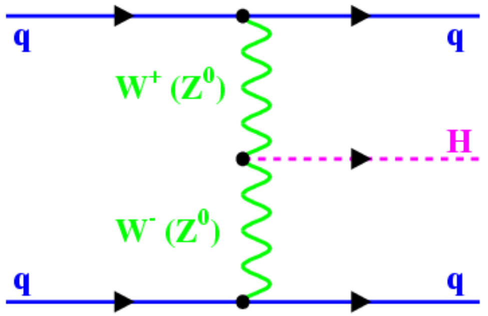
theo. aim: harm discovery via
VBF, h→tt tth, h→bb

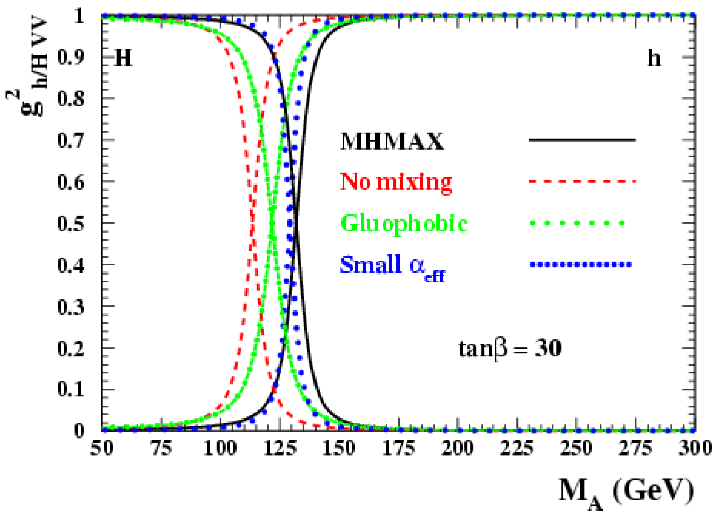
- mainly influence masses and couplings of h
- phenomenology of heavy states very similar

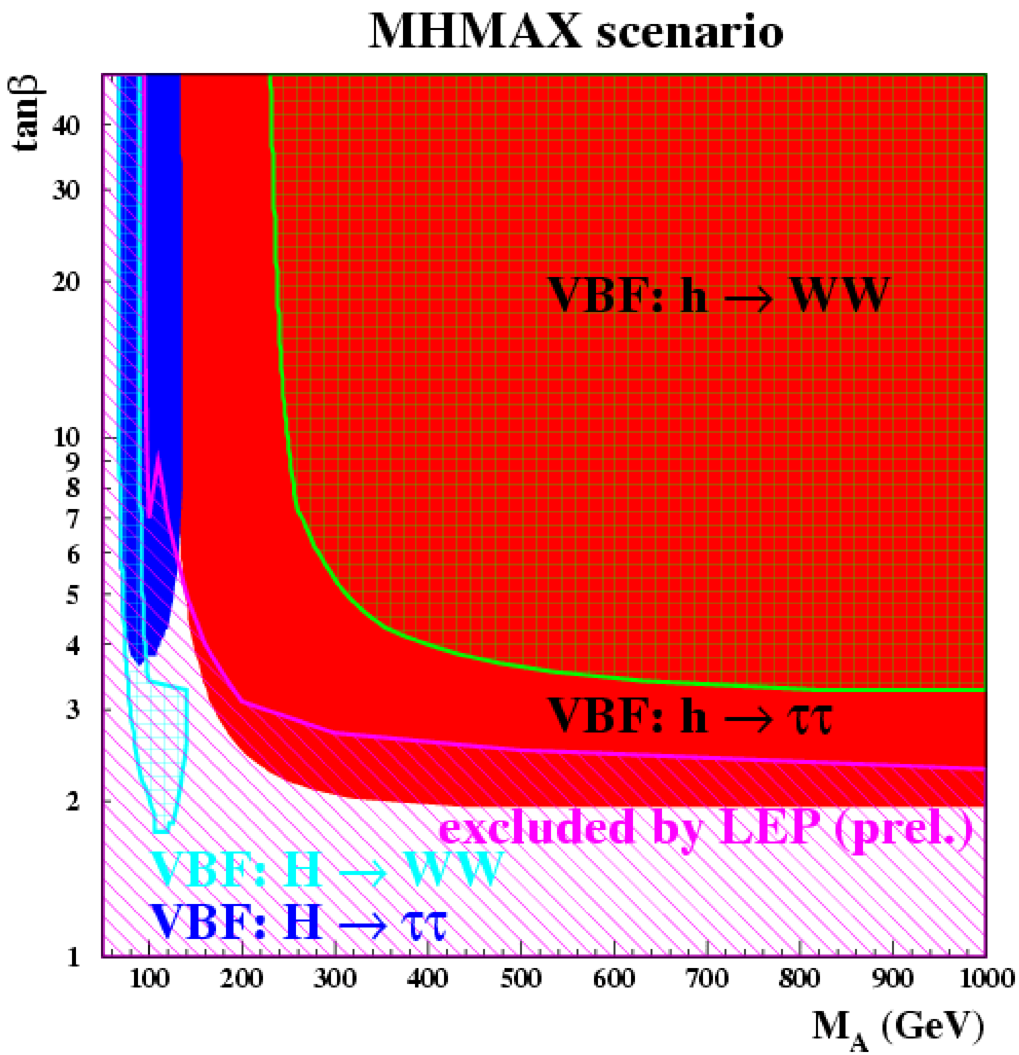
Higgs Production at LHC



h / H in Vector-Boson Fusion (30 fb^{-1})





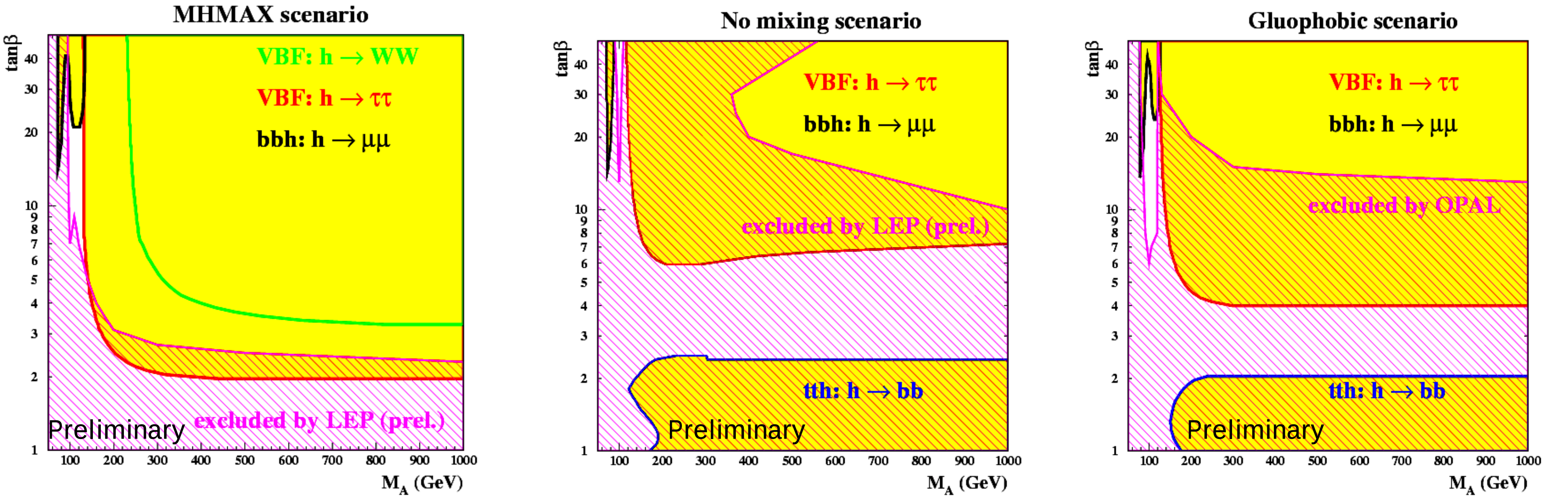


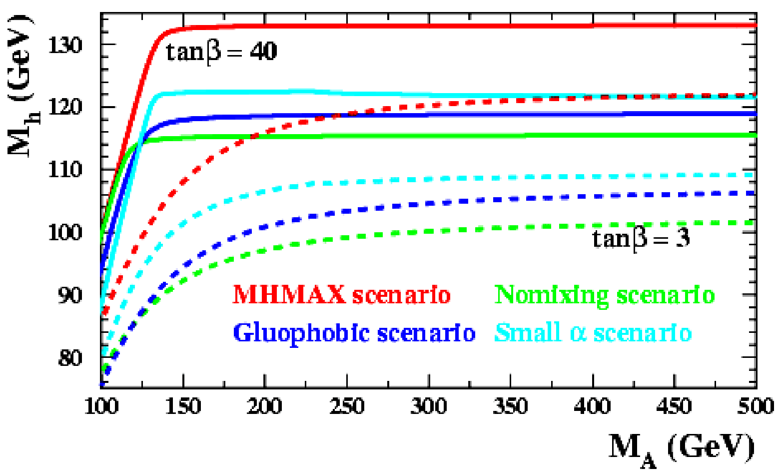
- Studied for M_H>110 GeV at low lumi running
- Same conclusion in other benchmark scenarios

h or H observable with 30 fb^{-1}

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

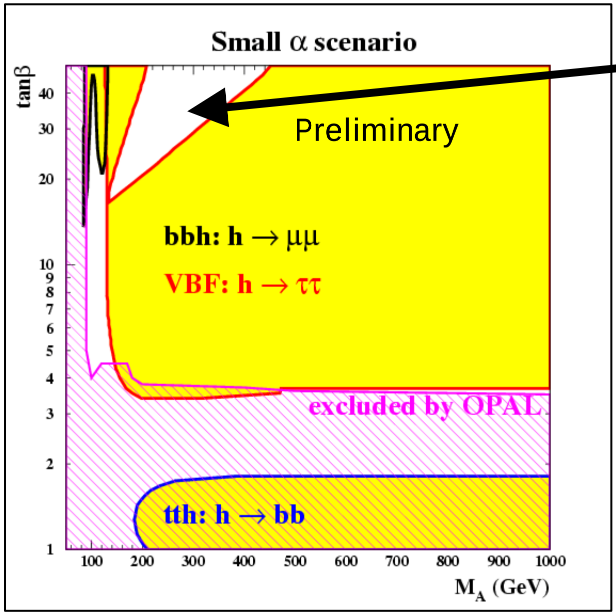
Observable channels: VBF with h→μμ/WW , bbh with h→μμ , tth with h→bb



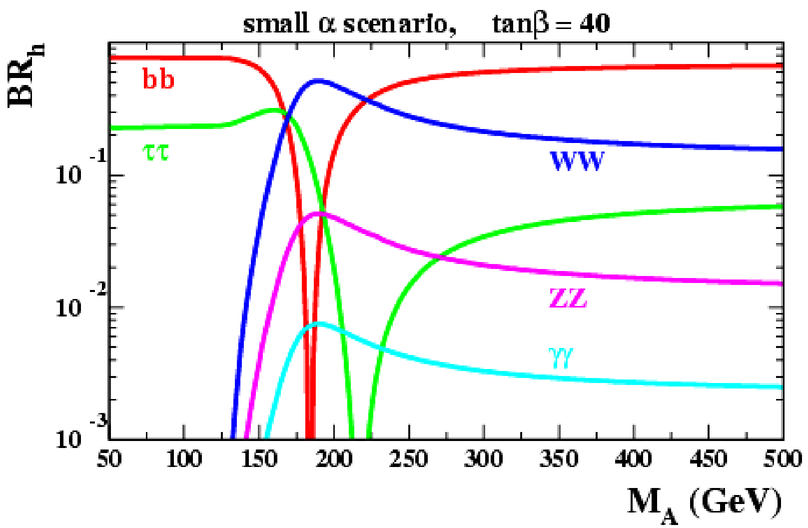


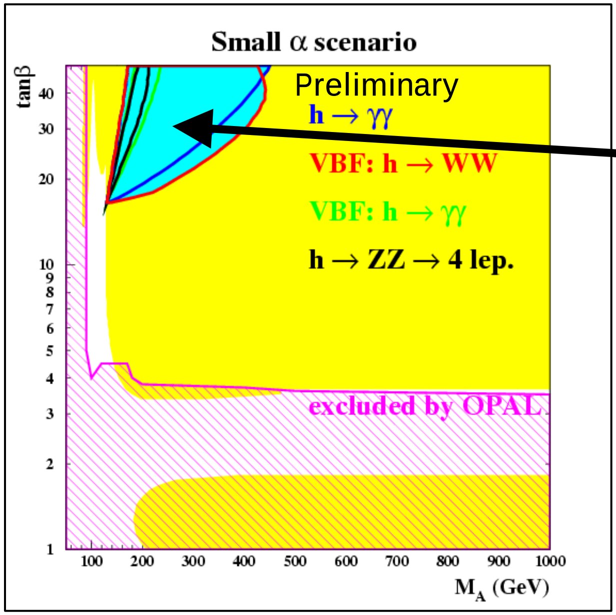
Differences mainly due to different m_h for same (tanβ, M_A) point (up to 17 GeV difference)

Light Higgs h in Small-α Scenario (30 fb^{-1})



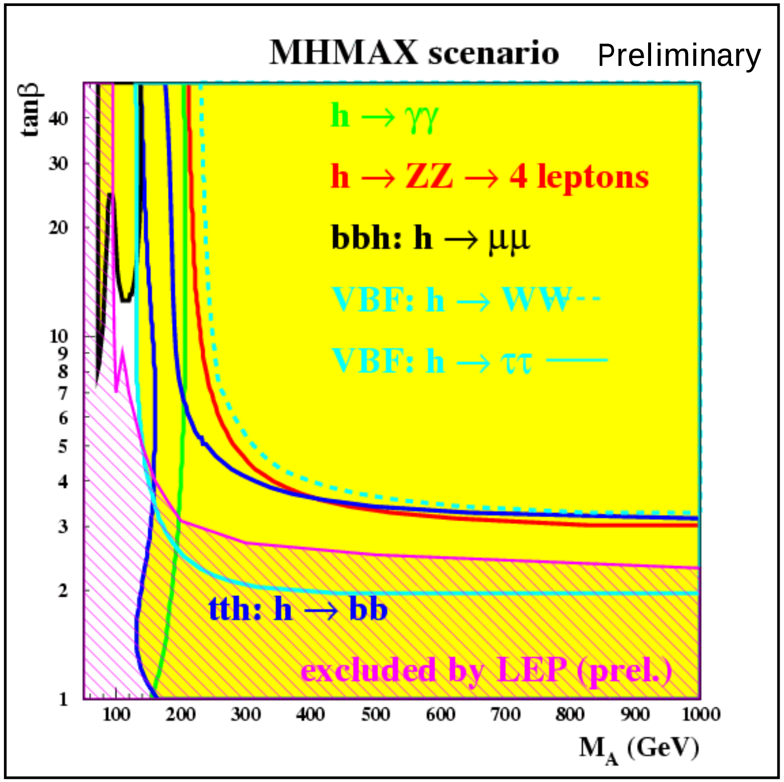
- Hole due to reduced branching ratio for H → ττ

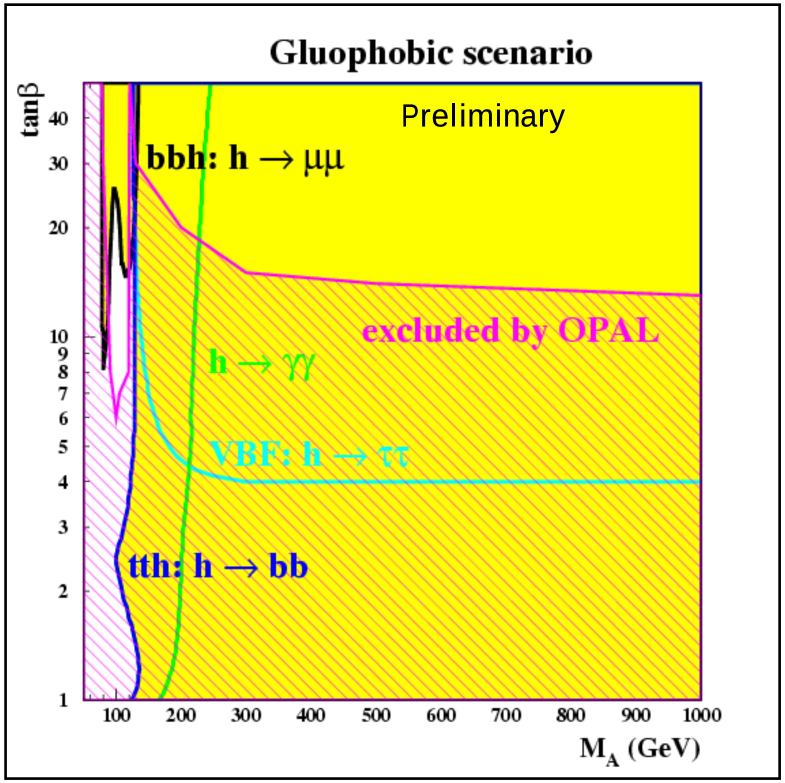




- Covered by enhanced BR to gauge bosons
- Complementarity of search channels almost guarantees observability of h

Light Higgs h (300 fb^{-1}, VBF only 30 fb^{-1})

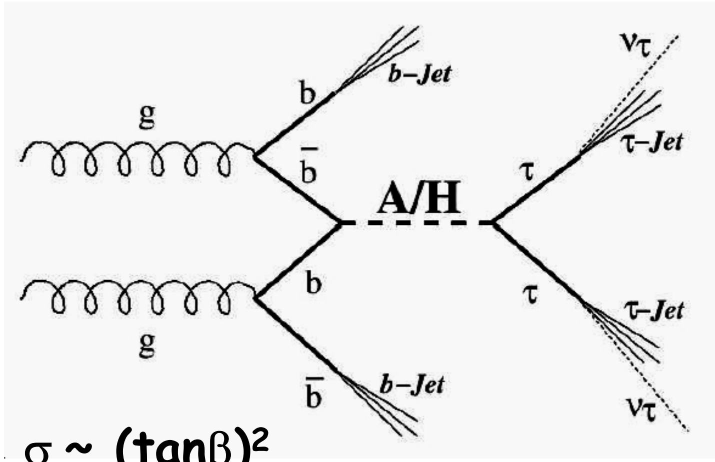




- Also h → γγ, h → ZZ → 4 leptons (tth → bb) contribute
- Large area covered by several channels
  → discovery and parameter determination possible
- Small area uncovered at m_h = 90 to 100 GeV
- h → γγ sensitive in gluophobic scenario due to VBF, Wh, tth production

Heavy Neutral Higgs Bosons H / A

- Most promising: bbH/A, H/A → $\tau\tau$, $\mu\mu$



$\sigma \sim (\tan\beta)^2$

- $\tau\tau$ → lep lep (both τ decay leptonically)
- $\tau\tau$ → lep had (1 had., 1 lept. τ decay)
- $\tau\tau$ → had had (2 hadronic τ decays only for large M>450 GeV due to QCD bkg)

Same bkgs as in VBF

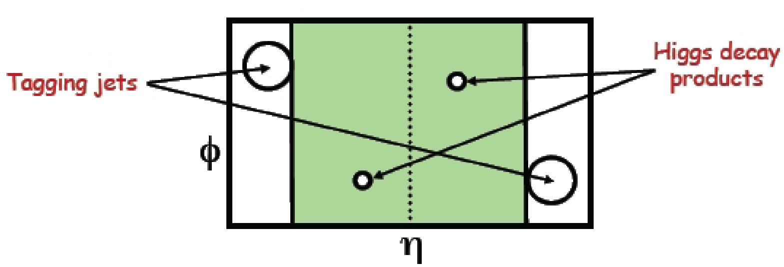
Same H → $\tau\tau$ mass reco. and bkg estimate

But:

- no forward jets and no central-jet veto

- b-tagging instead of b-veto

Reminder: VBF



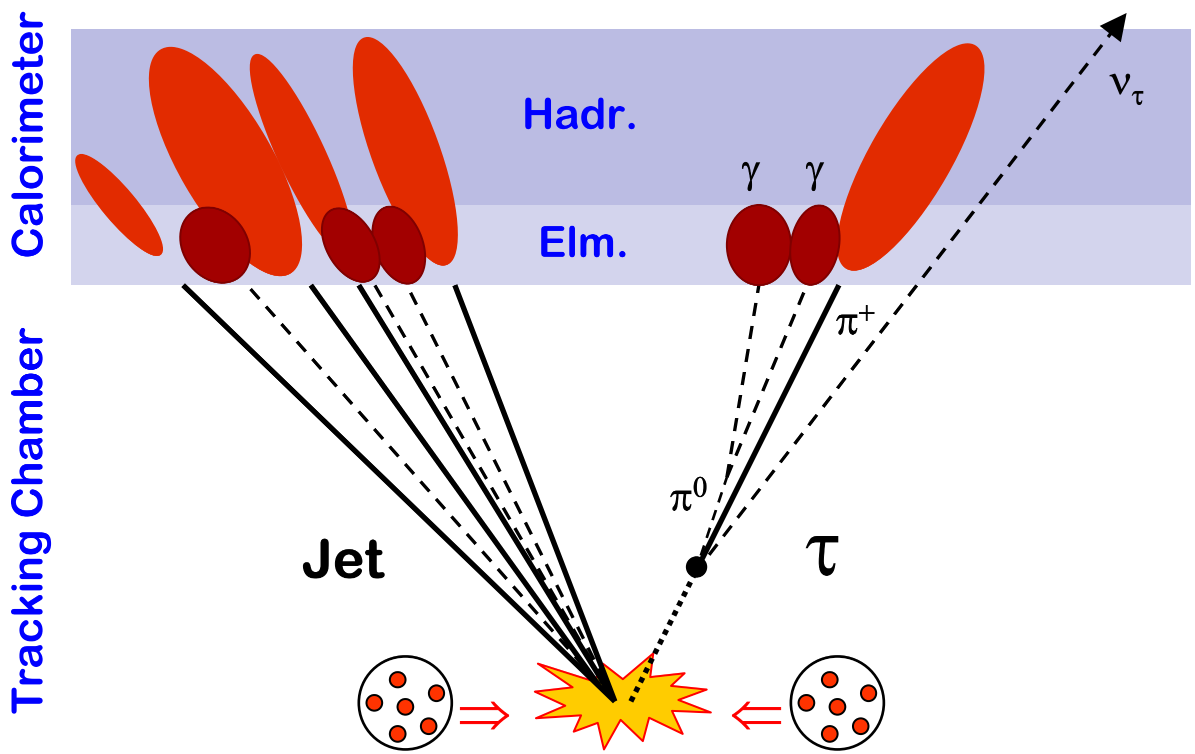
Excursion: Identification of τ Leptons

- τ **decays:**

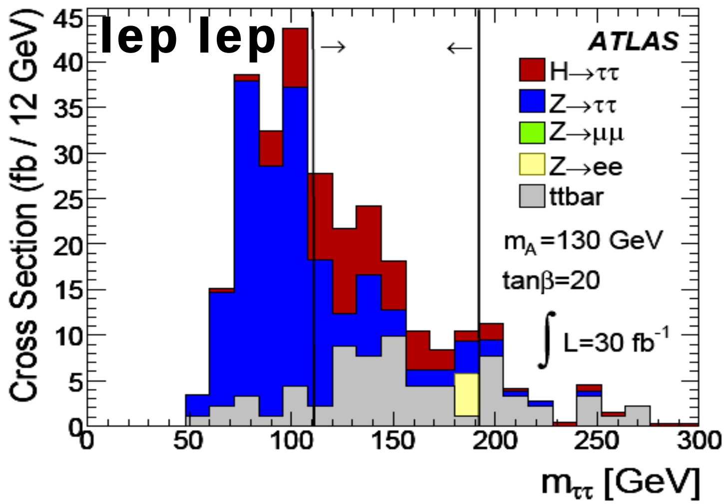
$$\tau^{\pm} \rightarrow e^{-}\overline{\nu_e}\nu_\tau \qquad 17\,\%$$

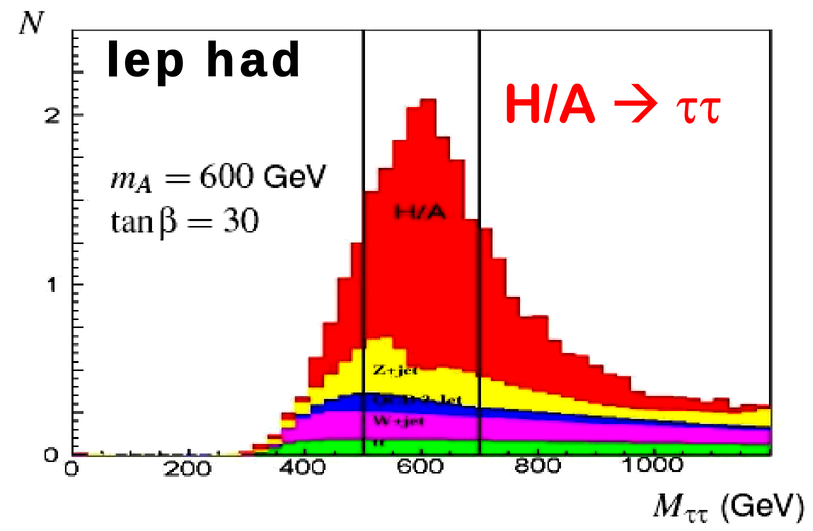
$$\boxed{\begin{array}{ll} \tau^{\pm} \rightarrow \pi^{\pm}(n\pi^0)\nu_\tau & 47\,\% \\ \tau^{\pm} \rightarrow 3\pi^{\pm}(n\pi^0)\nu_\tau & 15\,\% \end{array}}$$

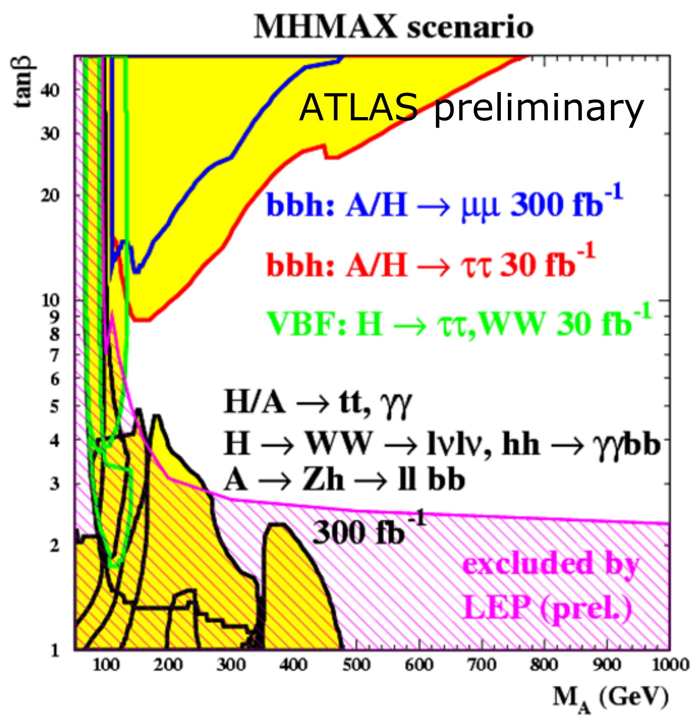
- **Main dackground for hadronic τ decays: ets from q,g scattering**



Heavy Neutral Higgs Bosons H / A





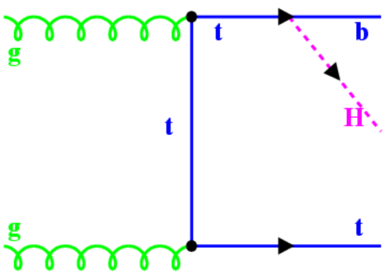


- **Goal: After a few years, reach** **mass resolution of a few %**
- **Determine from signal rate:**

$$\sigma_{prod} \times BR(H^0/A^0 \rightarrow \tau\tau)$$

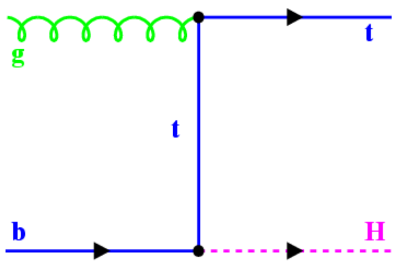
Charged Higgs Bosons $H^\pm$

low mass: $m_{H\pm} < m_t$

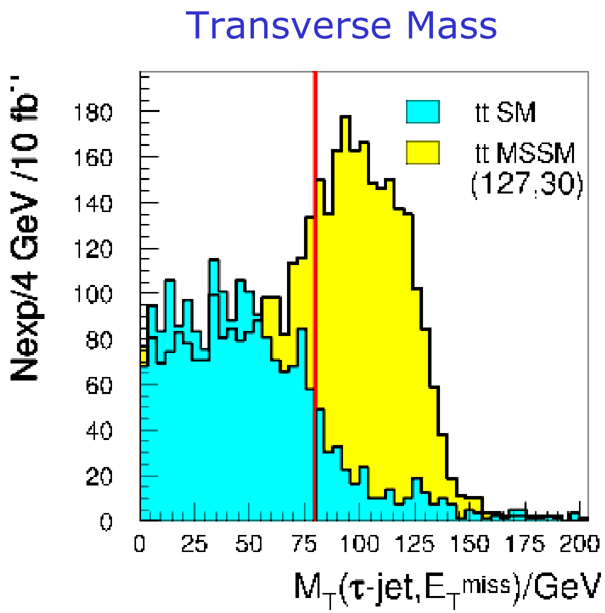


$gg \rightarrow tt \rightarrow H^\pm bt$

high mass: $m_{H\pm} > m_t$

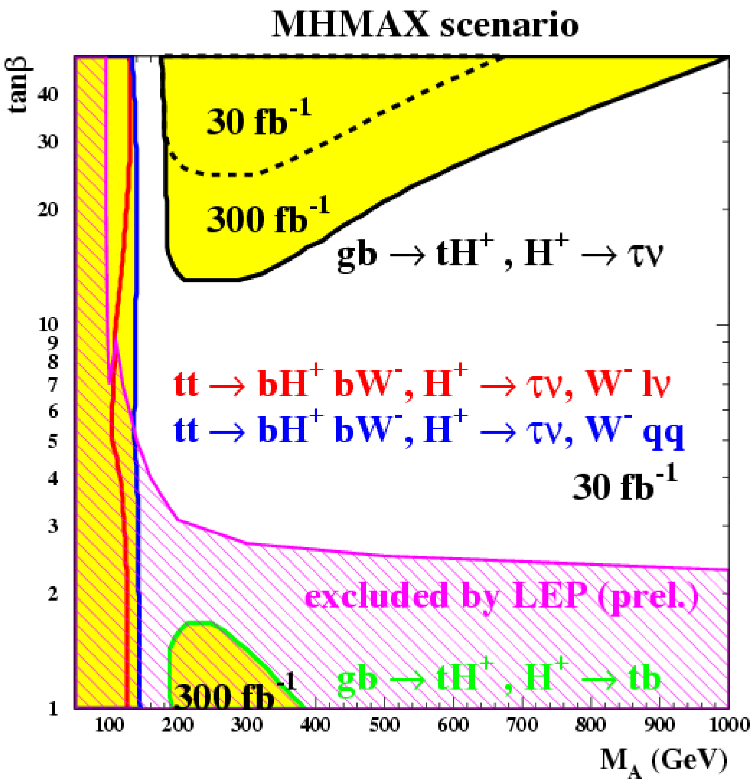


$gb \rightarrow H^\pm t$



$H^\pm \rightarrow \tau^\pm \nu$

$t \rightarrow bW \rightarrow bqq$



- Backgrounds: tt, single t, W+jets, QCD
- tt production dominant background
- Systematic uncertainties:

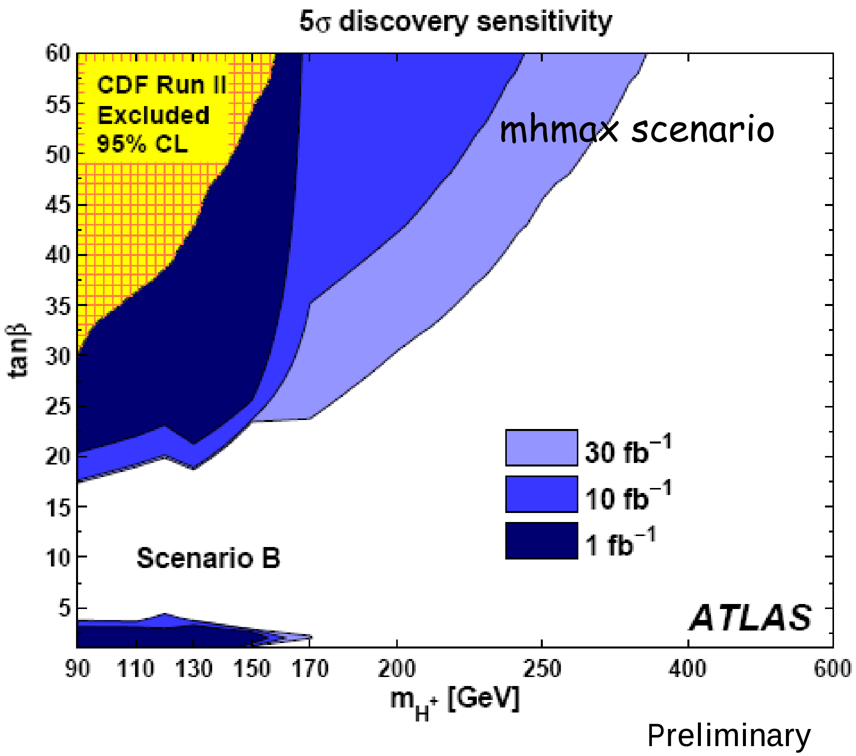
  theo: 15% for tt cross section

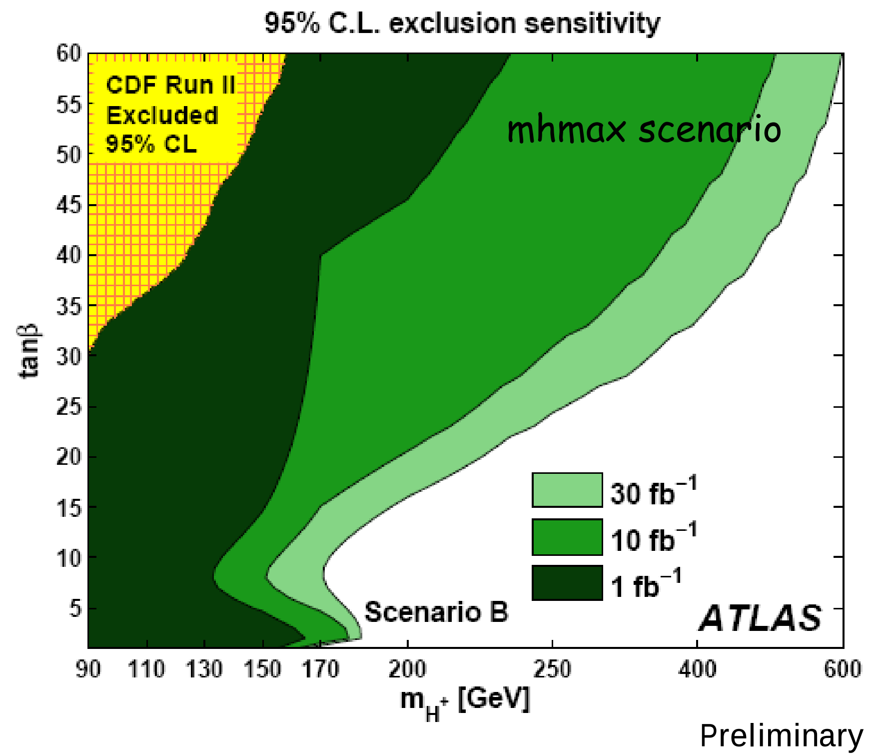
  exp.: 15 to 40% for signal and bkg

  (E scale, b-tagging, …)

  → exctract bkg from data control sample

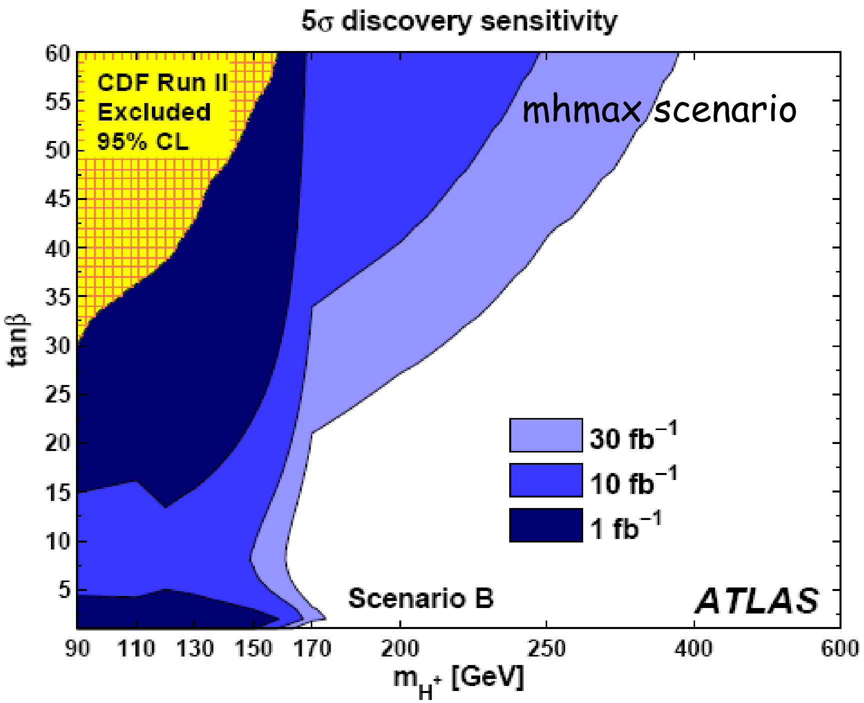
Charged Higgs Sensitivity in mhmax Scenario



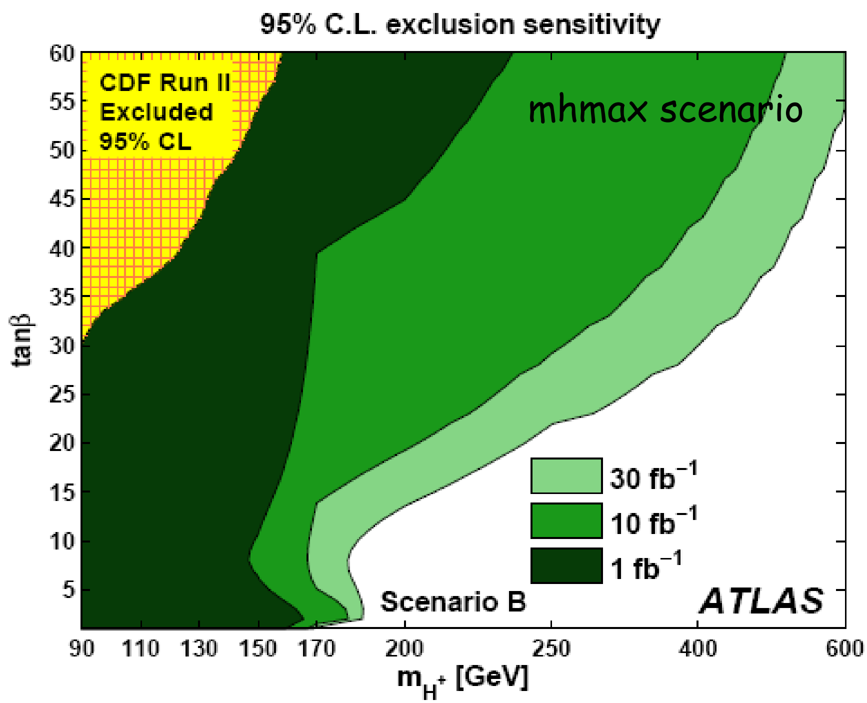


- Most difficult region at intermediate tanβ as coupling H^{+-}tb smallest

Charged Higgs Sensitivity in mhmax Scenario



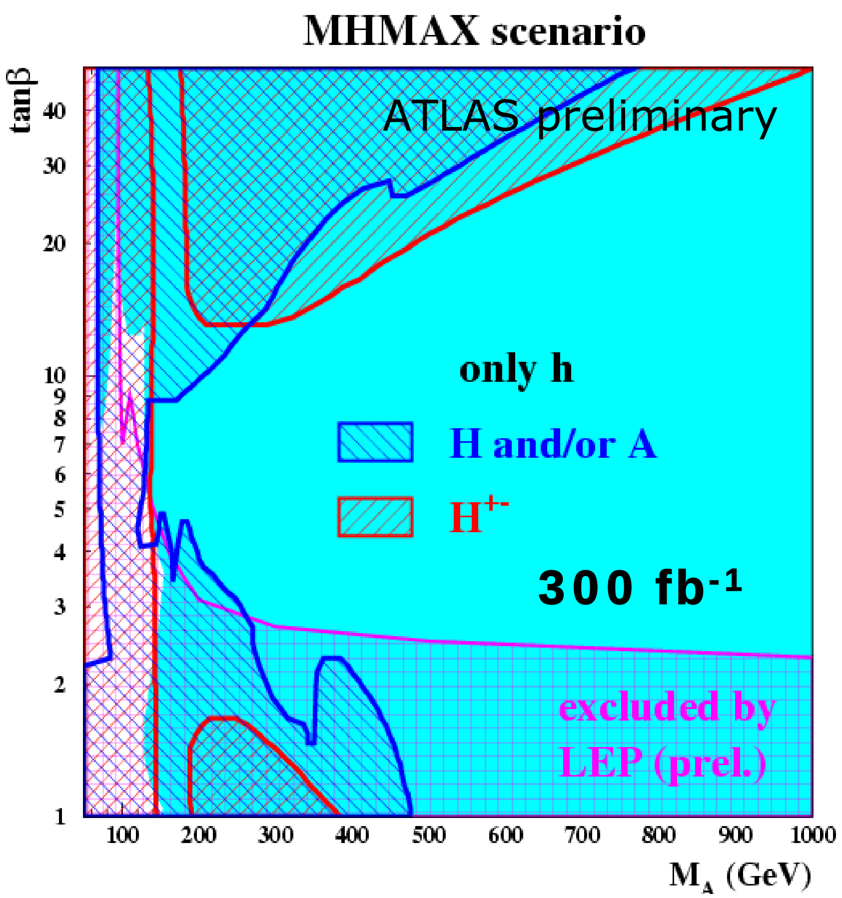
Preliminary



Preliminary

- Most difficult region at intermediate tanβ as coupling H^{+-}tb smallest
- If statistical uncertainties from limited MC neglected → gap closed

Overall MSSM Higgs Discovery Potential



- At least one Higgs boson observable for whole parameters space in all (CP-conserving) benchmark scenarios
- Significant area where only lightest Higgs boson h is observable
- Discrimination between h, H, A via
  - investigation of properties of observed Higgs
  - observation in SUSY cascades or H/A → SUSY decays

• Similar results in other benchmark scenarios

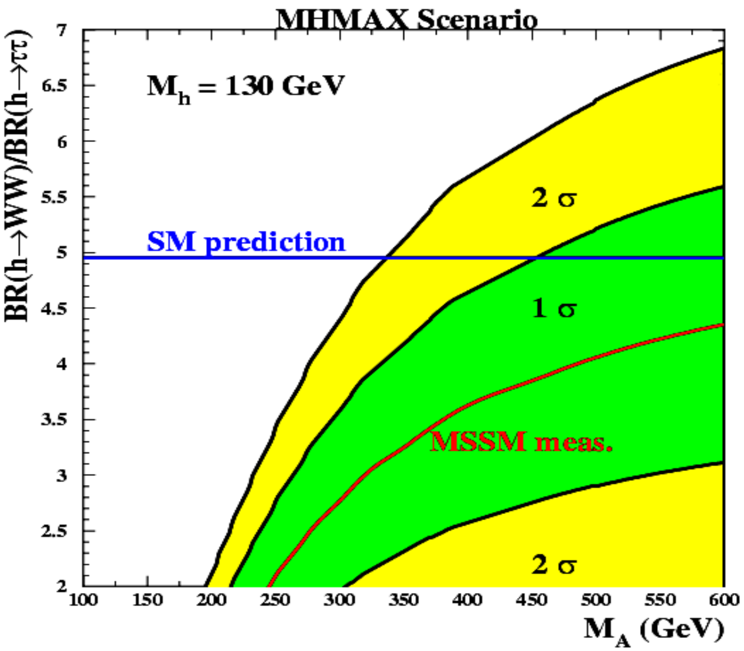
(VBF channels , H/A→$\tau\tau$ only shown for 30fb^{-1})

SM or MSSM Higgs (i.e. Extended Higgs Sector) ?

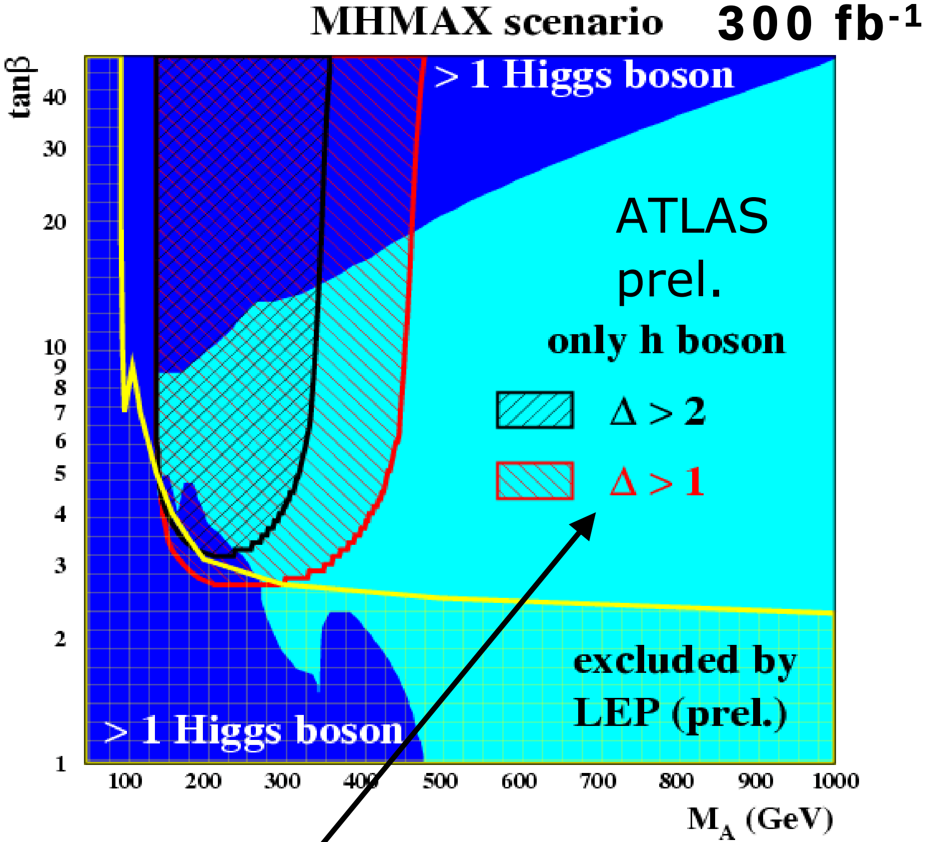
Discrimination via VBF

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

Compare expected measurement of R in MSSM with SM prediction



Assumes M_h precisely known (syst. uncertainties neglected)



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