Lecture 2: searches

Lecture 2:

- reminder of motivations behind accelerator and experiment
- existing experimental limits on sparticles
- MSSM sparticle searches at the LHC
- MSSM Higgs searches at the LHC

Why SUSY is a good idea

One of the most appealing extensions of the Standard Model:

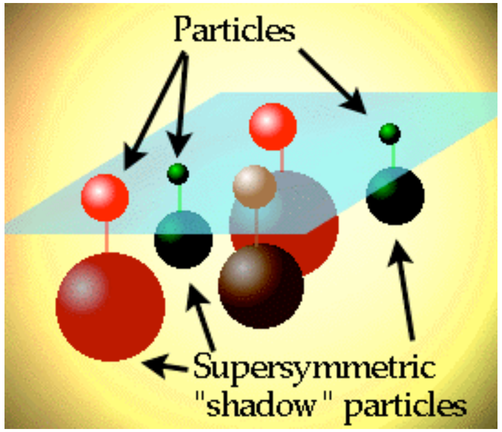
TeV-scale supersymmetry

[= a symmetry between fermions and bosons,
duplicates the SM particle spectrum, but not the couplings]

Solves several problems at once:

- hierarchy problem
- opening towards a theory of gravity
- unification of gauge couplings
- dark matter candidate (=lightest susy particle or LSP)
- allows to explain why the Higgs mechanism works (radiative EWSB)

New sparticles



Need to introduce new particles :

leptons (f)	→	sleptons (b)	$(\tilde{l}, \tilde{q})$
quarks (f)		squarks (b)	
gauge bosons (b)		gauginos (f)	neutralinos
Higgs bosons (b)		higgsinos (f)	charginos

$(\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0)$

$(\chi_1^\pm, \chi_2^\pm)$

(f = fermion, b = boson)

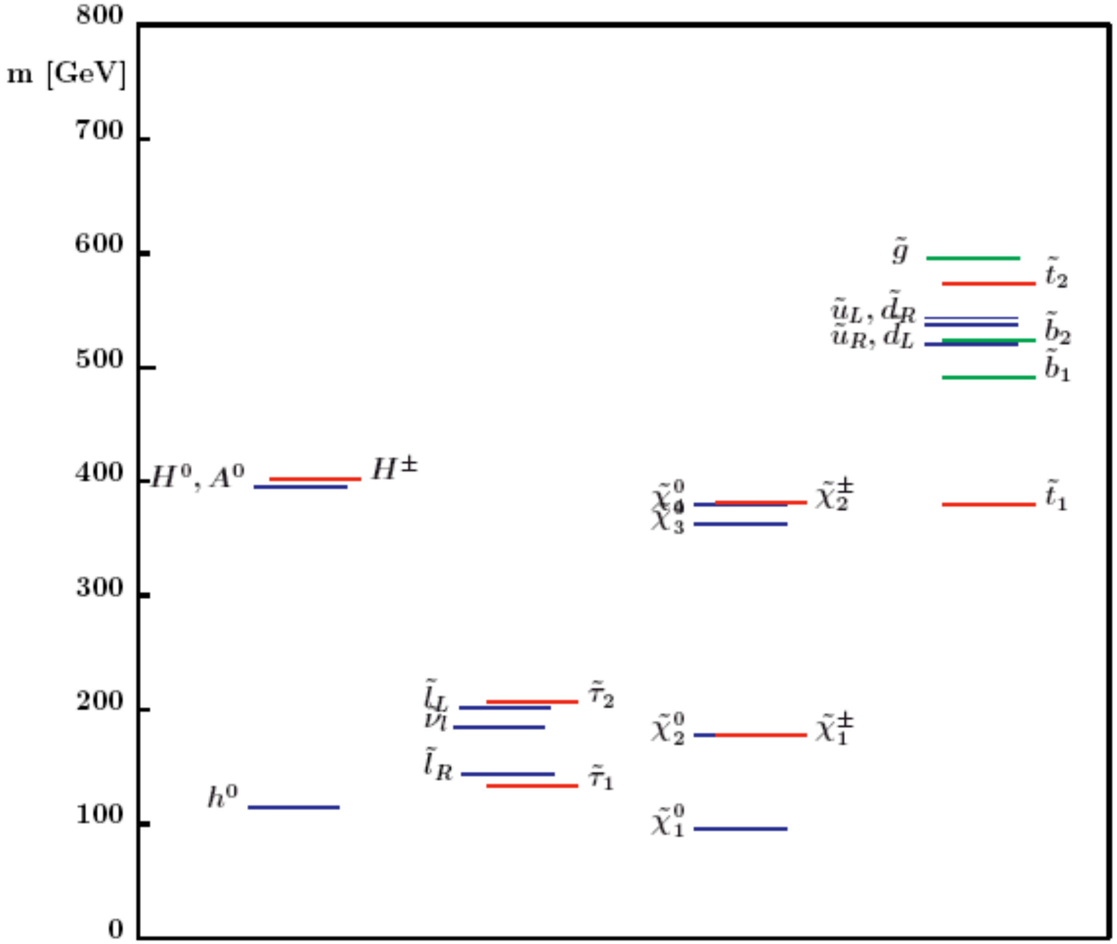
How heavy?

How heavy are the sparticles?

independent arguments for 1 TeV scale:

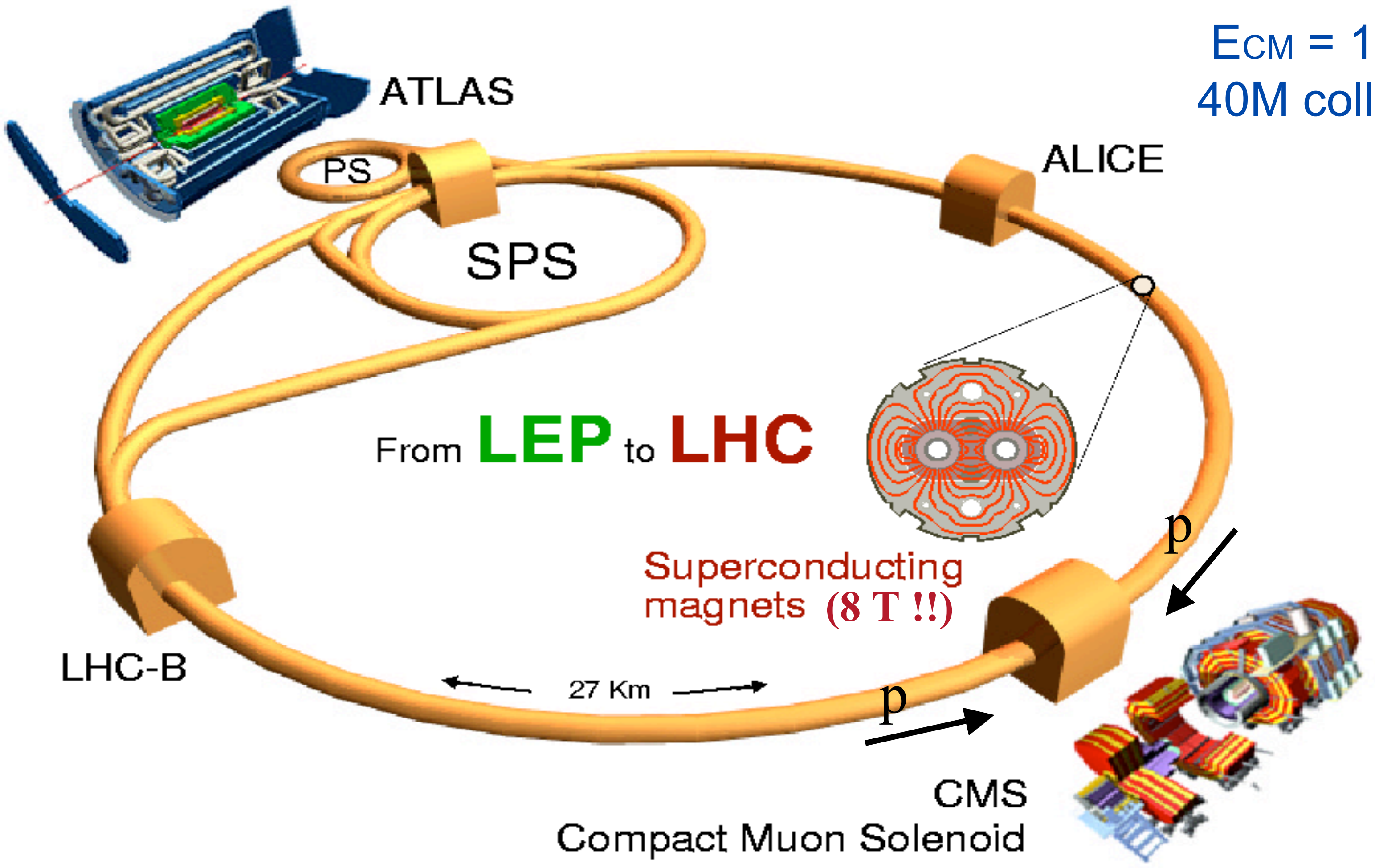
- Gauge coupling unification
- Hierarchy solution
- Dark matter (?)
- EWSB relation

Example spectrum: SPS1a



A new accelerator : LHC

E_{CM} = 14 TeV
40M collisions/s



The Benchmark Reaction: SM Higgs

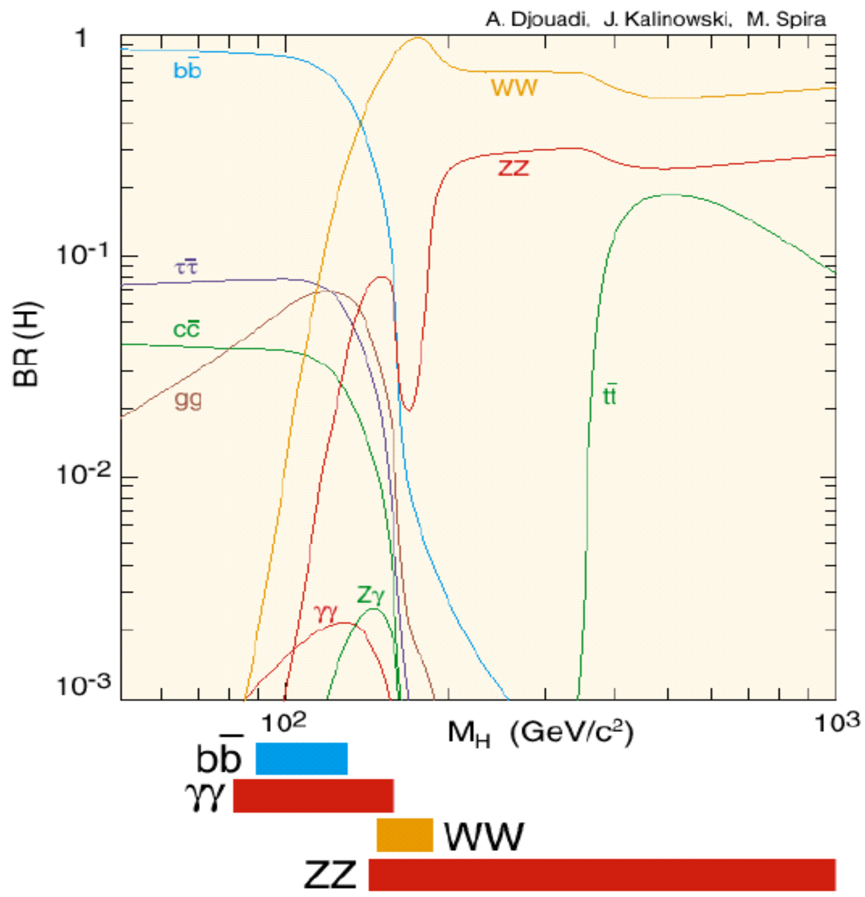
ETH Institute for Particle Physics

Use SM Higgs as a benchmark for new accelerator/detector design

115 GeV < M (Higgs) < ~ 1 TeV

Promising SM Higgs decay modes:

- low mass: $H \rightarrow \gamma\gamma$
- intermediate mass :
  $H \rightarrow WW \rightarrow$ 2 leptons + neutrinos
- high mass : $H \rightarrow ZZ \rightarrow$ 4 leptons



Why LHC?

- LEP (e+e-) not enough energy for new physics
 (limited due to synchrotron radiation)

- upgrade: either larger R or larger m (since $-\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4$)

- so: 1) keep LEP tunnel and go to protons (large m) or
  2) go to a linear collider (large R)

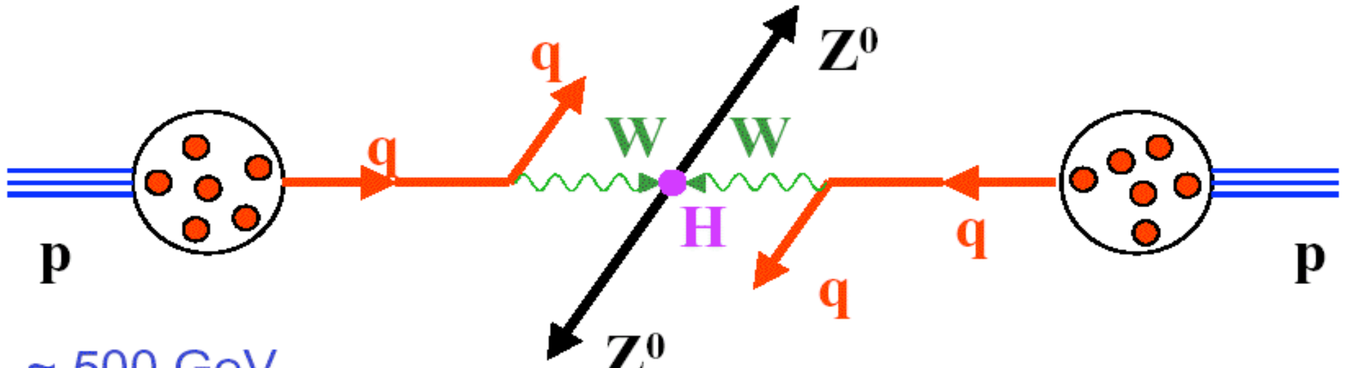
- decided to do 1) first

- energy of LHC determined by bending power magnets:

Design goals of the LHC

Hadron colliders are broad-band exploratory machines

May need to study W_L-W_L scattering at a cm energy of ~ 1 TeV



- ⇨ E_W ~ 500 GeV
- ⇨ E_{quark} ~ 1 TeV
- ⇨ E_{proton} ~ 6 TeV

⇨ **pp collisions at 7 + 7 TeV** → **14 TeV collider**

Event Rate = L.σ.BR

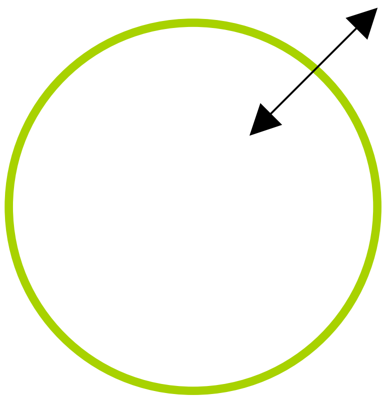
e.g. H(1 TeV) → ZZ → 2e+2μ or 4e or 4μ → $L \sim 10^{34}\ cm^{-2}\ s^{-1}$

For L ~10^{34} , Evts/yr = $\mathbf{10^{34}}\ 10^{-37}.10^{-3}.10^{7}$ ~ 10 /yr !!

LHC energy

Simple calculation:

require that the magnetic field compensates
the centrifugal effect:

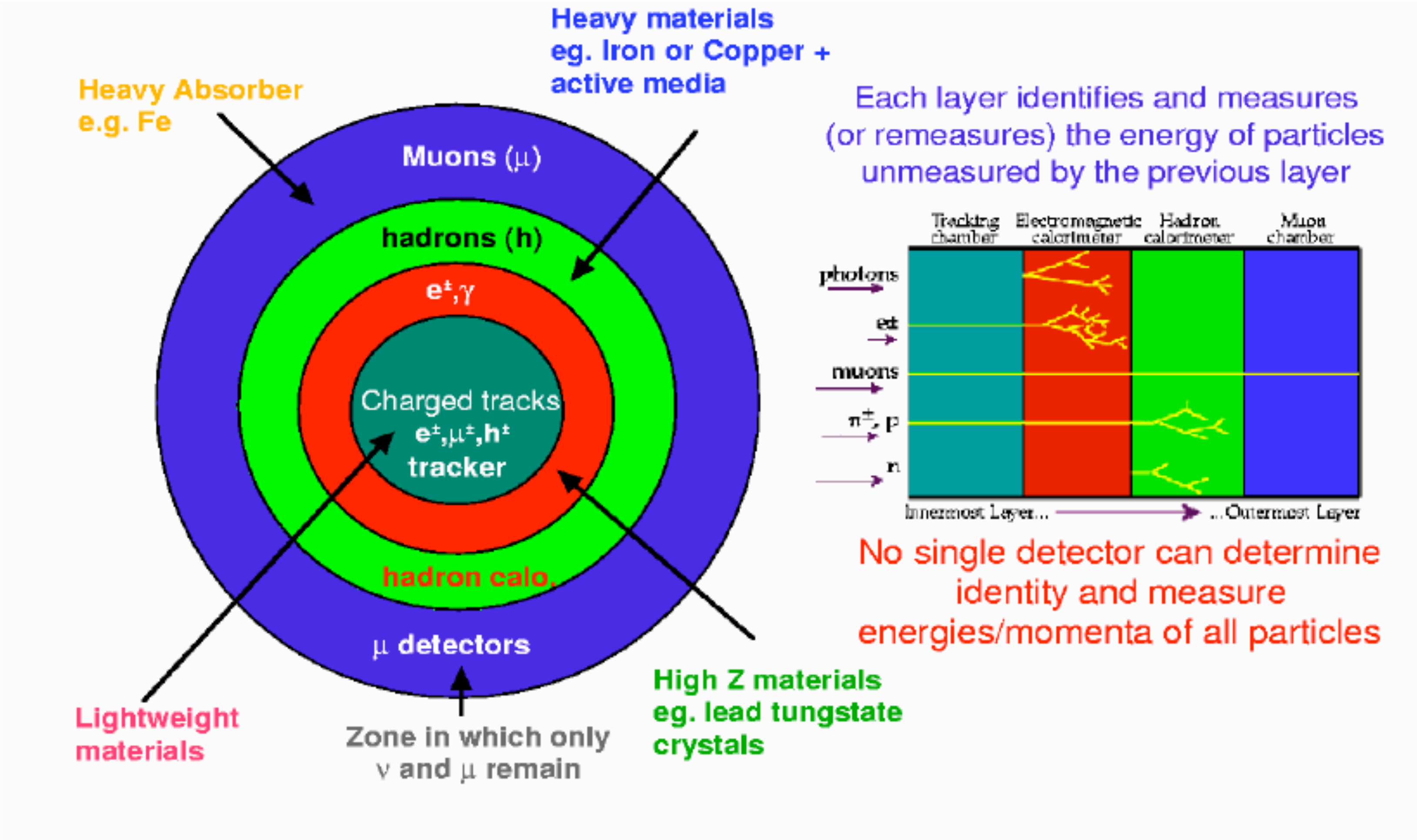


$$F = m\frac{v^2}{R} \quad \leftrightarrow \quad F = qvB$$

$$\Leftrightarrow$$

$$E\,[\mathrm{TeV}] = 0.84\,B\,[\mathrm{T}]$$

Particle Detectors



(CMS) Design Criteria

Very good muon identification and momentum measurement

Trigger efficiently and measure sign of TeV muons dp/p < 10%

High energy resolution electromagnetic calorimetry

~ 0.5% @ E_T ~ 50 GeV

Powerful inner tracking systems

Momentum resolution a factor 10 better than at LEP

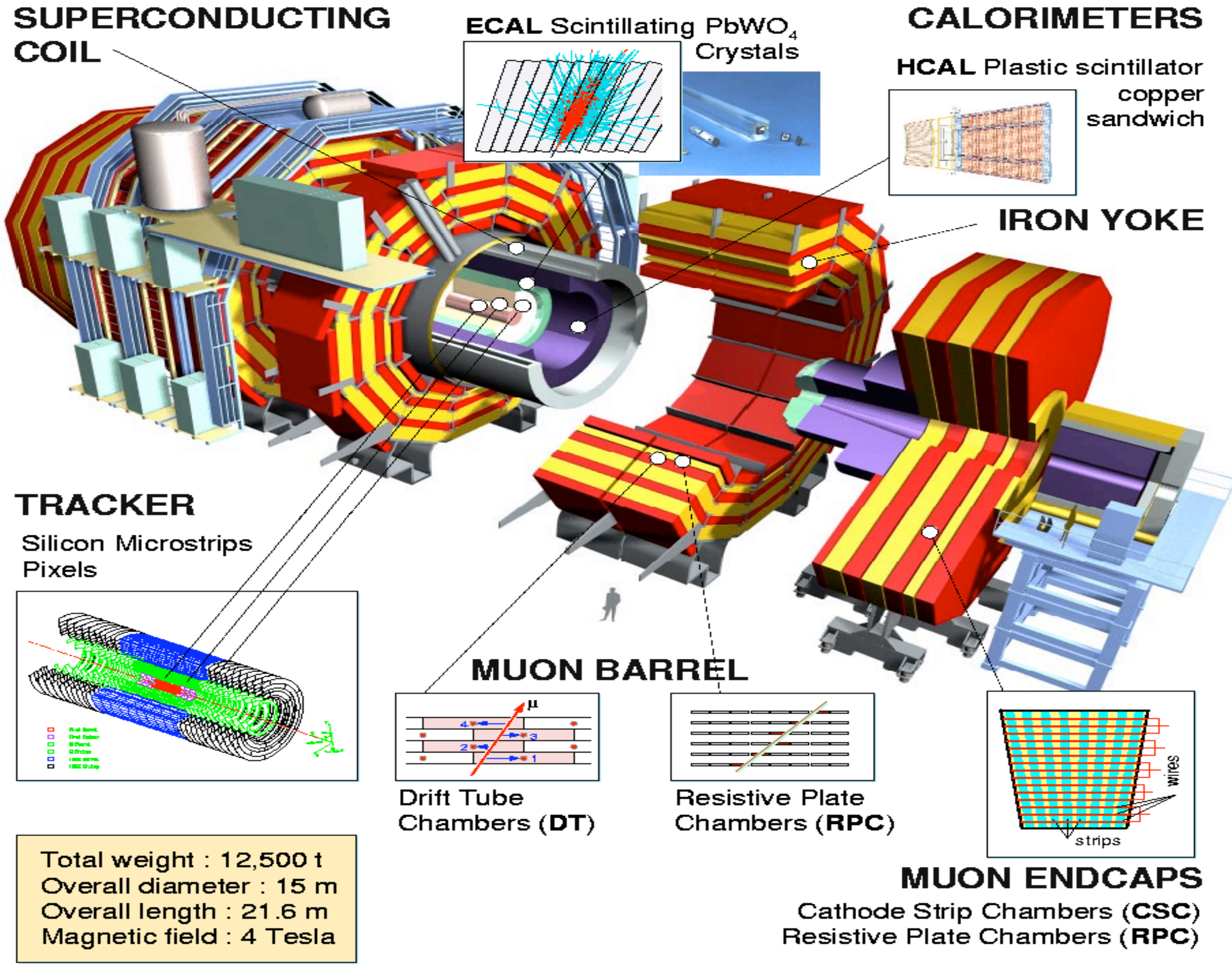
Hermetic calorimetry

Good missing E_T resolution

Transparency from the early 90's

(Affordable detector)

The CMS components



Experimental Challenge

LHC Detectors (especially CMS & ATLAS) are radically different from the ones from the previous generations

High Interaction Rate

pp interaction rate up to **1 billion interactions/s**
Data can be recorded for only ~10^2 out of 40 million crossings/sec
Level-1 trigger decision takes ~2-3 μs
⇨ **electronics need to store data locally (pipelining)**

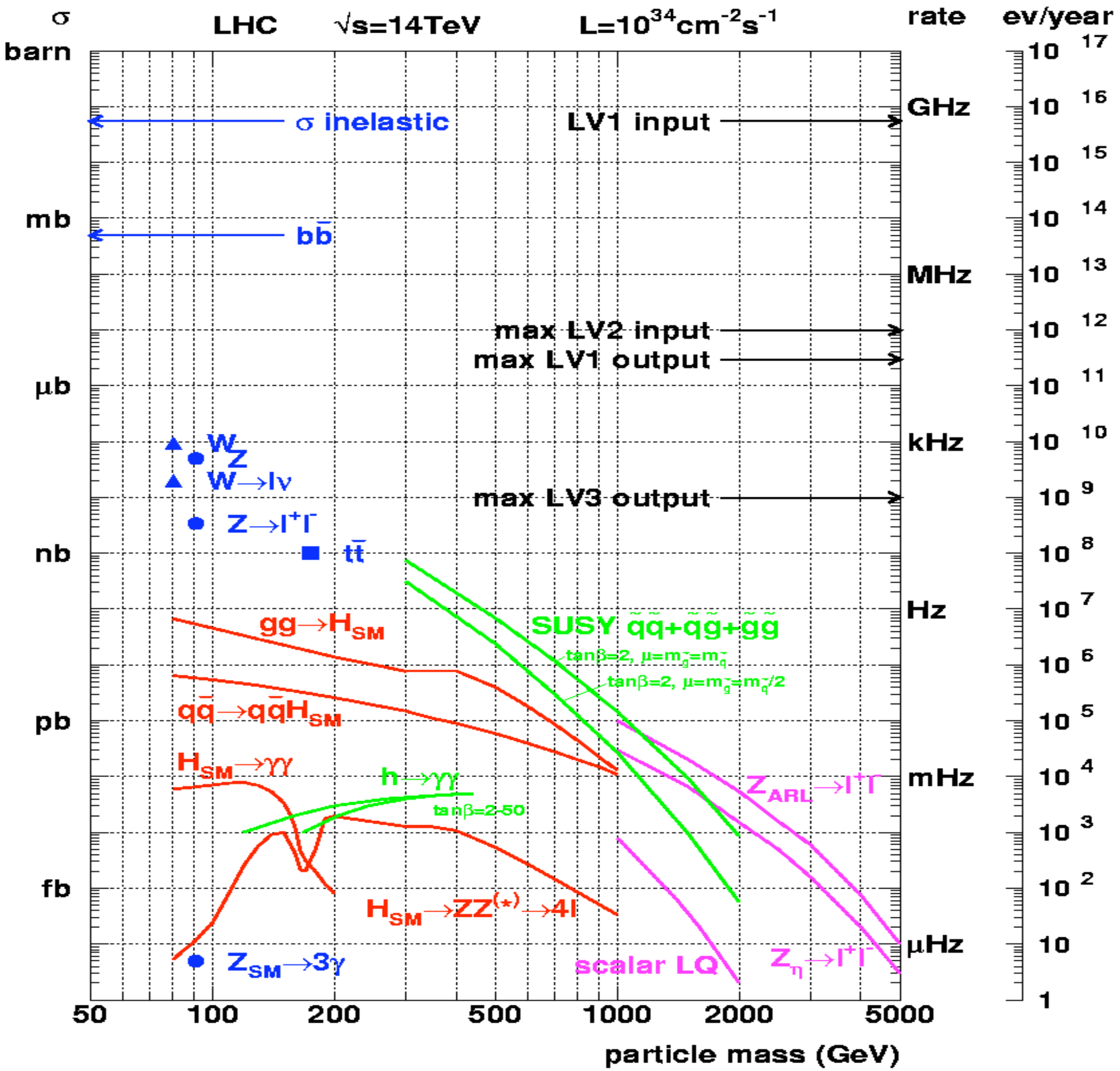
Large Particle Multiplicity

~ <20> superposed events in each crossing
~ 1000 tracks stream into the detector every 25 ns
need highly granular detectors with good time resolution for low occupancy
⇨ **large number of channels (~ 100 M ch)**

High Radiation Levels

⇨ **radiation hard (tolerant) detectors and electronics**

Cross sections @ the LHC



"Well known"processes, don't need to keep all of them …

New Physics!!

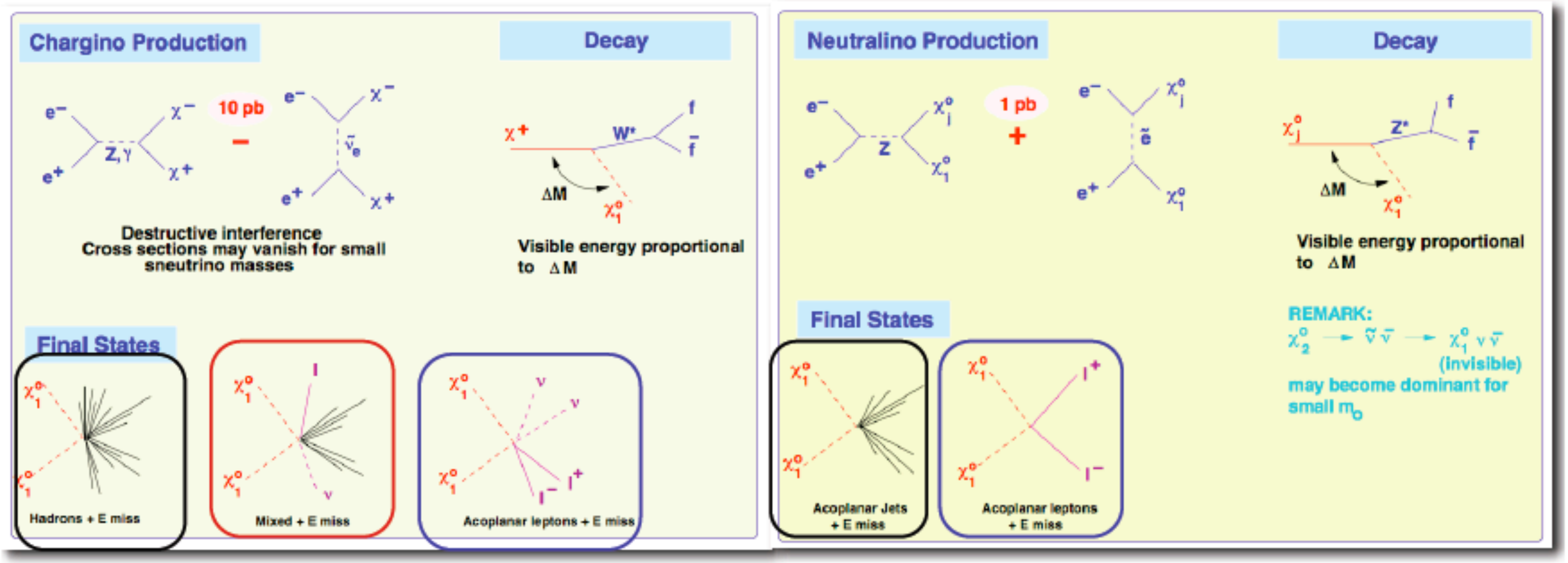
This we want to keep!!

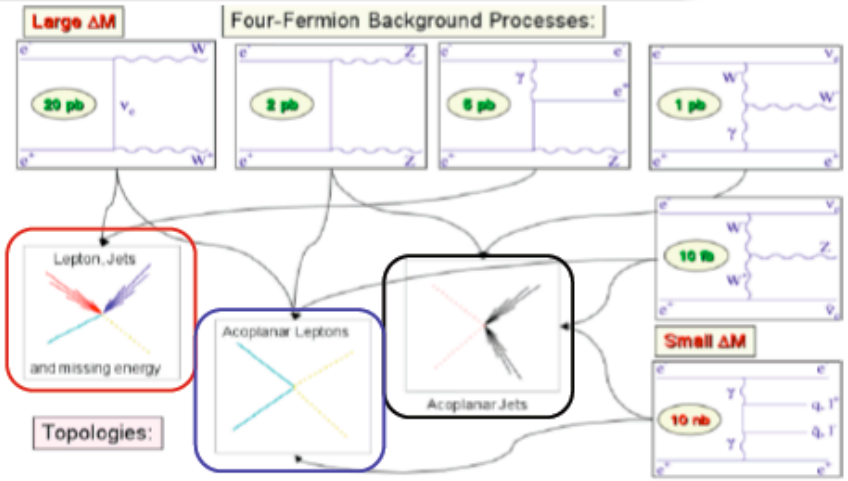
Level-1 trigger table

CMS Level-1 Trigger table ($2x10^{33}$)

Trigger	Threshold (GeV or GeV/c)	Rate (kHz)	Cumulative Rate (kHz)
Isolated e/γ	29	3.3	3.3
Di-e/γ	17	1.3	4.3
Isolated muon	14	2.7	7.0
Di-muon	3	0.9	7.9
Single tau-jet	86	2.2	10.1
Di-tau-jet	59	1.0	10.9
1-jet, 3-jet, 4-jet	177, 86, 70	3.0	12.5
Jet*E_T^{miss}	88*46	2.3	14.3
Electron*jet	21*45	0.8	15.1
Min-bias		0.9	16.0
TOTAL			16.0

LEP sparticle production





Standard Model backgrounds

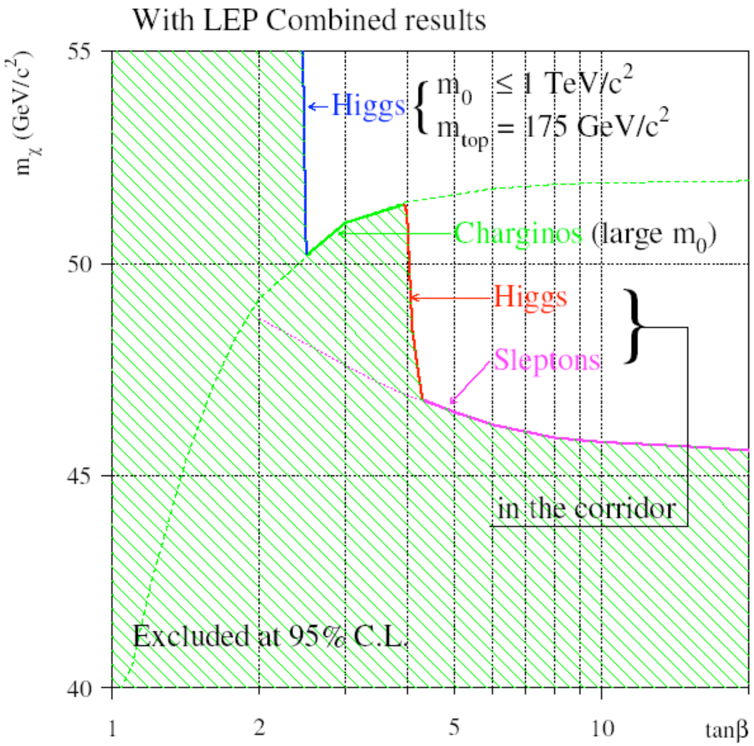
Direct search limits

Channel	M > (GeV)	ΔM	
$\tilde{\nu}$	43.7	EW measts	LEP
$\tilde{e} \rightarrow e\chi_1^0$	99	10 GeV	LEP
$\tilde{\mu} \rightarrow \mu\chi_1^0$	95	10 GeV	LEP
$\tilde{\tau} \rightarrow \tau\chi_1^0$	85	10 GeV	LEP
$\tilde{t} \rightarrow c\chi_1^0$	95	20 GeV	LEP
$\tilde{t} \rightarrow bl\tilde{\nu}$	96	20 GeV	LEP
$\tilde{b} \rightarrow b\chi_1^0$	94	20 GeV	LEP
$\tilde{g} \rightarrow j + E_T^{m}$	233	msugra	Tevatron
$\tilde{q} \rightarrow j + E_T^{m}$	318	msugra	Tevatron
$\chi_1^{\pm} \rightarrow W\chi_1^0$	103.5	Large m_0	LEP
$\chi_1^{\pm} \rightarrow W\chi_1^0$	92.4	Small ΔM	LEP

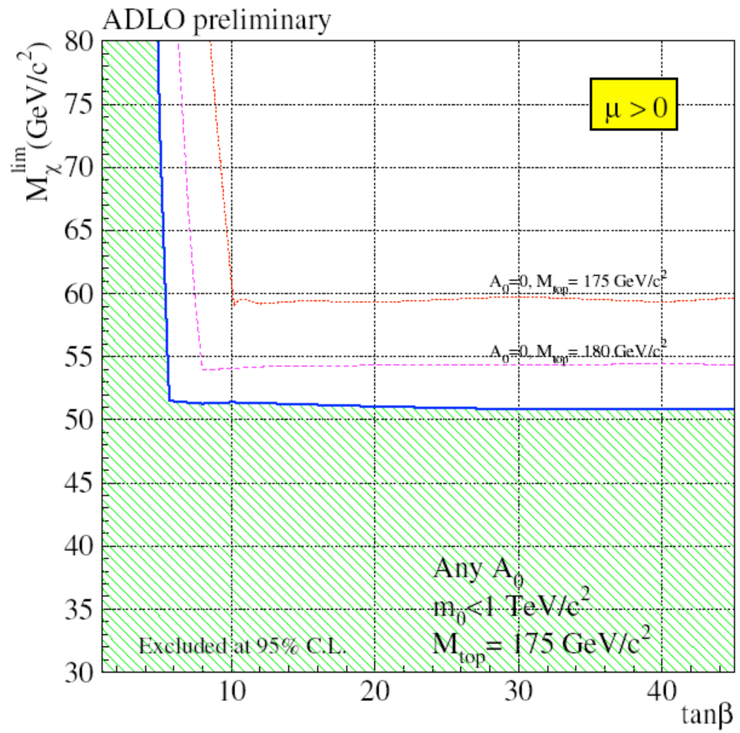
Tevatron: 2005 numbers, LEP: 2004 numbers

Indirect limits on LSP

- In MSSM



- In MSUGRA



$M(\chi^0_1 = LSP) > 45-50$ GeV

Supersymmetry searches at the LHC

- Inclusive signatures:
  discovery, fast but not unambiguous

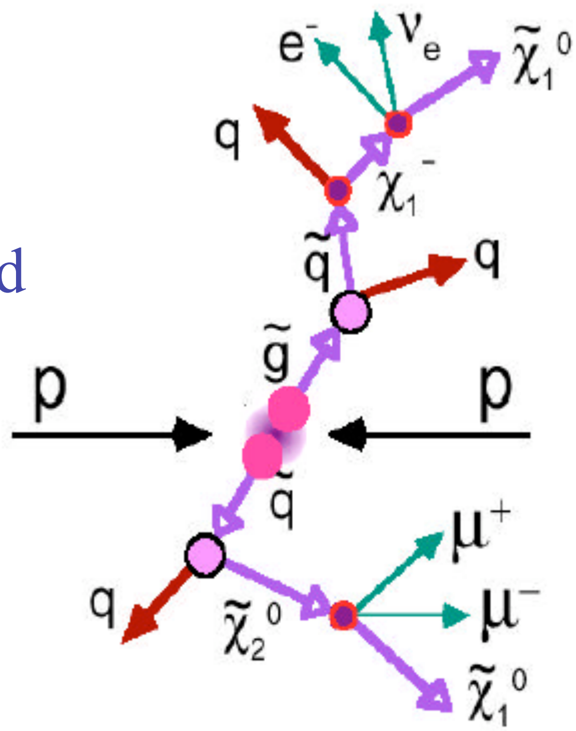
- Exclusive final states & long term measurements:
  towards understanding the underlying model

Generic SUSY signatures

General characteristics of R-parity conserving SUSY:

• sparticles pair produced and LSP stable
→ large amount of missing transverse energy

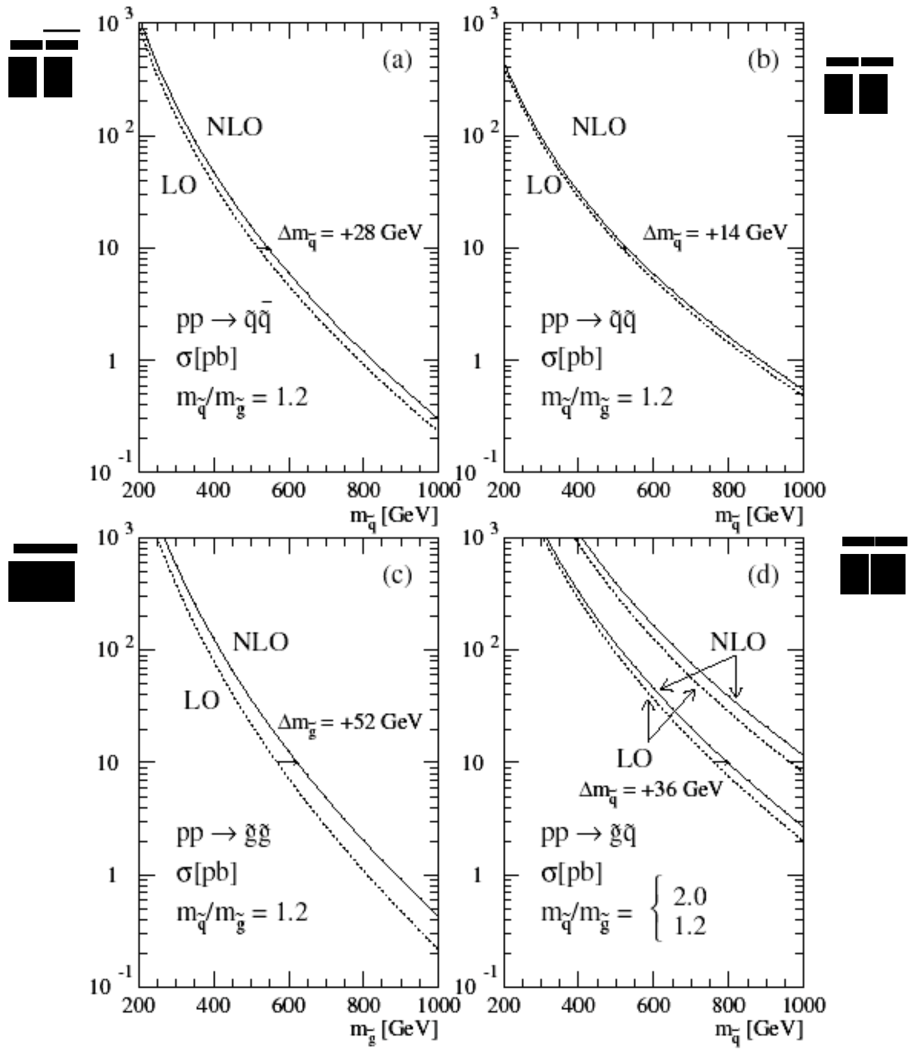
• coloured sparticles are copiously produced and cascade down to the LSP with emission of many hard jets and sometimes leptons



→ Generic SUSY signatures are
E_T^{miss} + multi-jets (and multi-leptons)

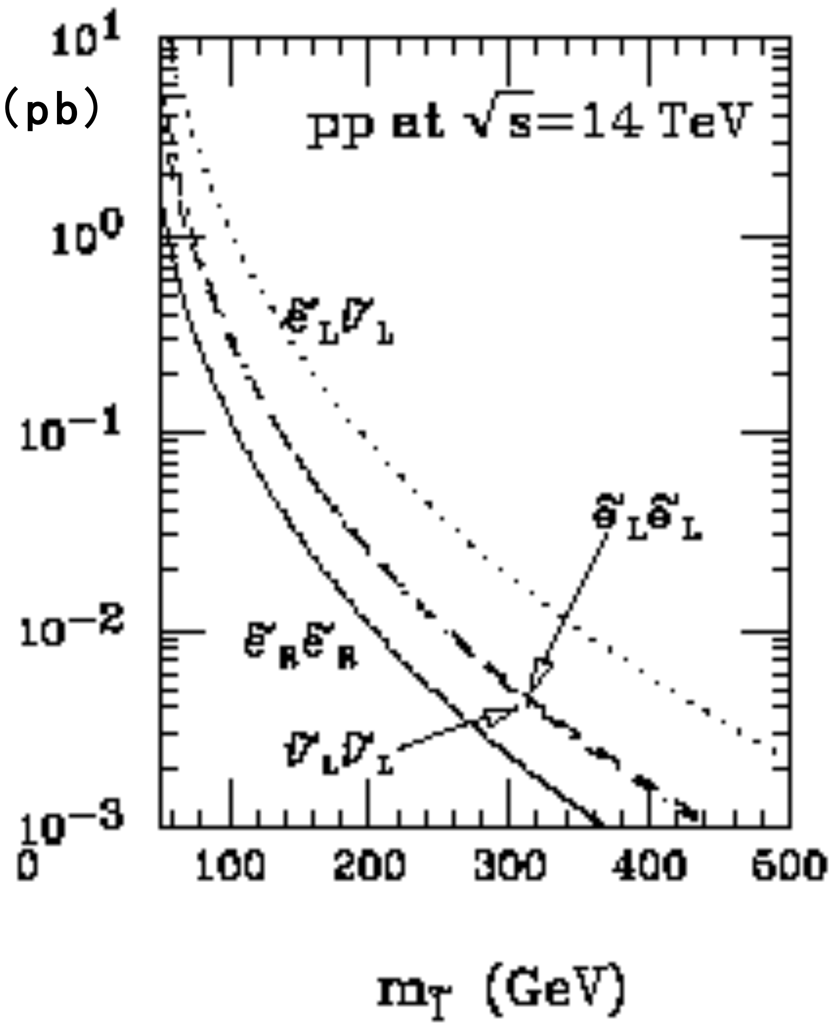
Squark/gluino cross sections

- NLO cross sections at LHC
  - NLO calculation is important: $\sigma_{NLO} \sim (1.1\text{-}1.9)\ \sigma_{LO}$
  - Remaining scale dependence ~15% (uncertainty)
  - At 1 TeV, summed σ > 1 pb
  - 1 fb at ~2.5 TeV



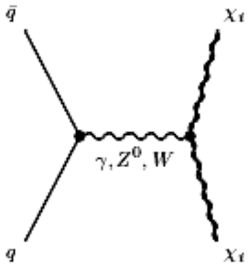
Slepton pair production

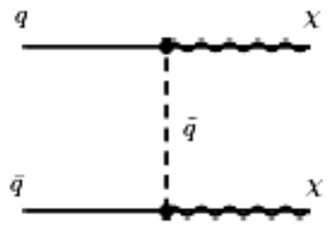
- Slepton pair production at NLO
  - Drell-Yan process mediated by Z* or W*
  - With QCD corrections at LHC σ_{NLO} ~(1.25-1.35) σ_{LO}
  - Cross section is small <1 fb at ~500 GeV

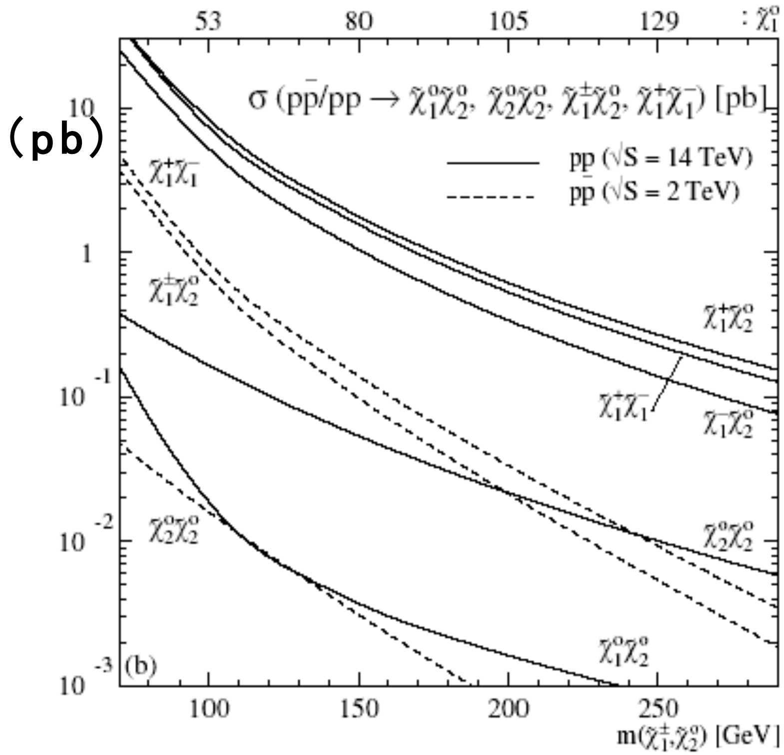


Chargino/neutralino production

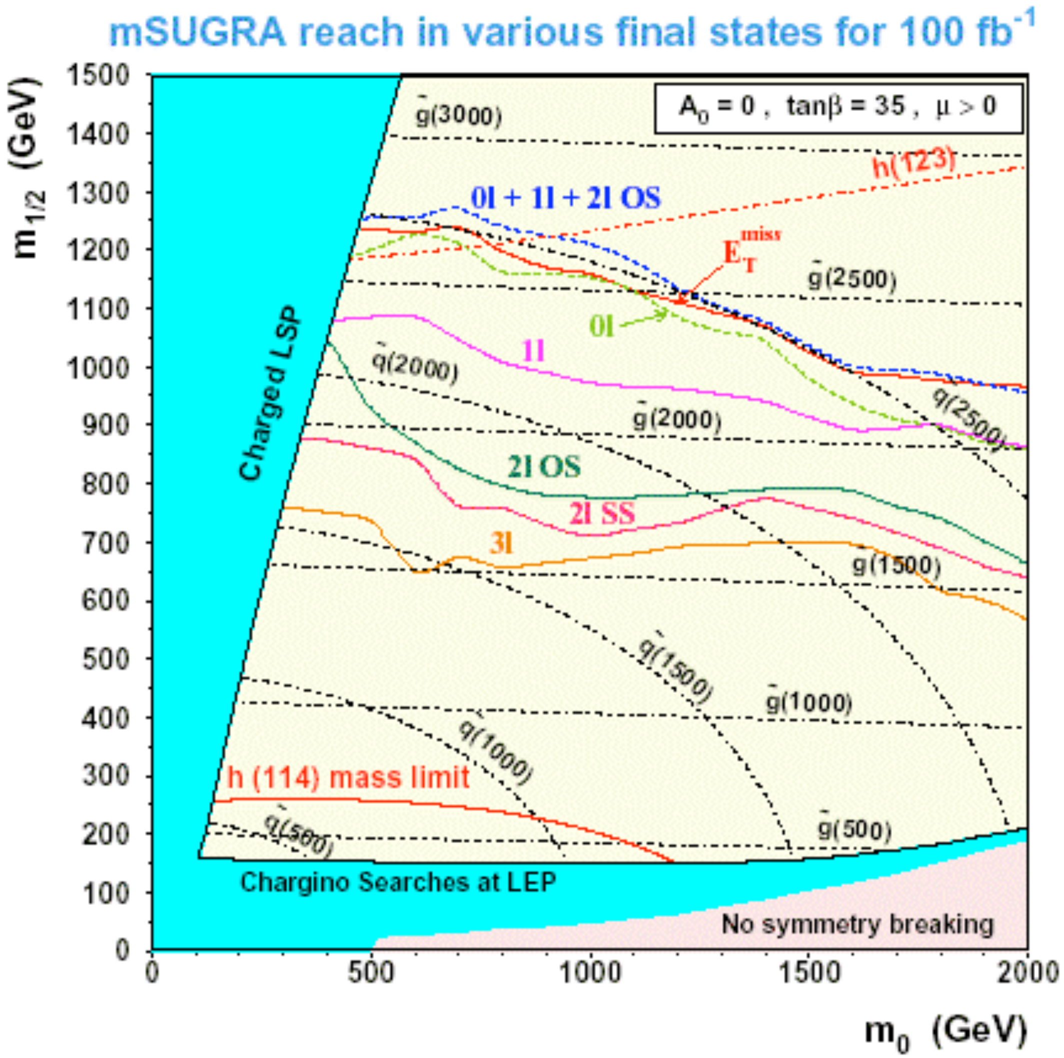
- Chargino/neutralino direct production
  - With QCD corrections at NLO $\sigma_{NLO} \sim (1.1\text{-}1.4)\ \sigma_{LO}$
  - Interesting: $\chi_2^0 \chi_1^\pm$ with $\chi_2^0 \rightarrow \chi_1^0 l^+ l^-$ $\chi_1^\pm \rightarrow \chi_1^0 l^\pm \nu$
  - ➔ trilepton final state







Inclusive SUSY

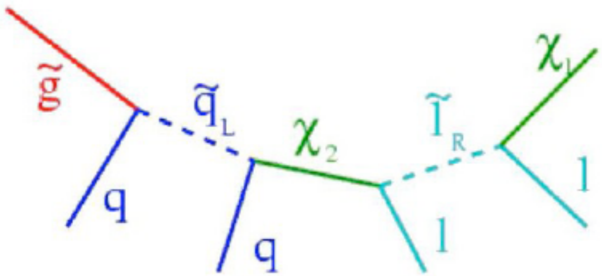


- jets + E_T^{miss}
- 1,2,3 lepton + E_T^{miss}
- opposite sign (OS) or same sign (SS) di-leptons
- often several topologies simultaneously visible

A typical SUSY selection

Event selection :

- large missing E_T (MET): O(> 200 GeV)   (→ LSP)
  - MET challenging to control at startup
- at least 3 hard jets (→ cascade decays)
  - 3 may not always be optimal
- N leptons (according to investigated topology)
  - growing N: reduces QCD background
- angular or event shape variables for background rejection
  - top background probably the most challenging



Main backgrounds: tt+jets, W+jets, Z+jets, QCD (multijet)

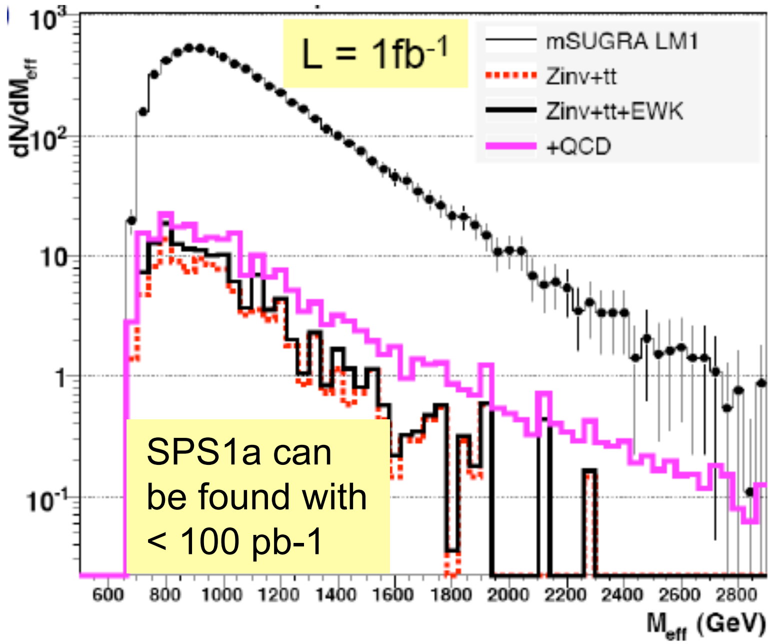
Jets + MET

$N_{leptons}$=0 : largest signal cross section, but beware of QCD!

Efficiency for e.g. SPS1a: 13%

Event Selection:

- MET > 200 GeV
- ≥ 3 jets ($|\eta|$ < 1.7/3/3) with E_T > 180/110/30 GeV
- HT (= $E_{T,j2}$+$E_{T,j3}$+$E_{T,j4}$+MET) > 500 GeV
- indirect lepton veto
- cleanup and QCD rejection (see next slide)



Main backgrounds:

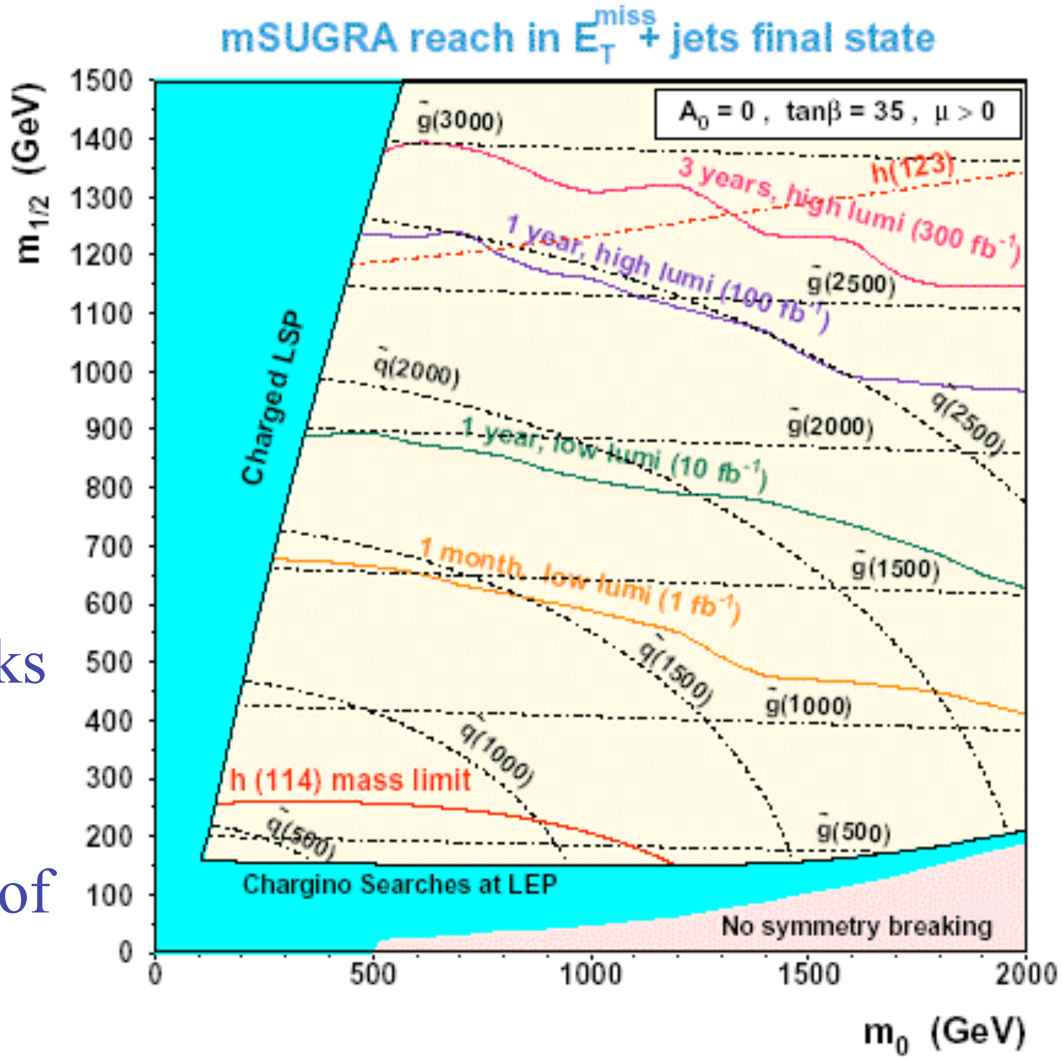
- QCD multijets: MET due to mis-measurements or jet resolution
- Z+jets: Z→νν irreducible
- tt+jets: hadronic or lost lepton(s)
- W+jets: hadronic or lost lepton

Early data: cannot trust simulation → determine backgrounds from data

Jet + MET reach

Signature: E_T^{miss} + jets

- σ ~ 1 pb at 1 TeV
  → physics for startup
- significant reach after 1 yr
- with 300 fb-1, reach squarks and gluinos up to ~ 2.5 TeV
- (need good understanding of detector and backgrounds!)



QCD rejection and cleanup

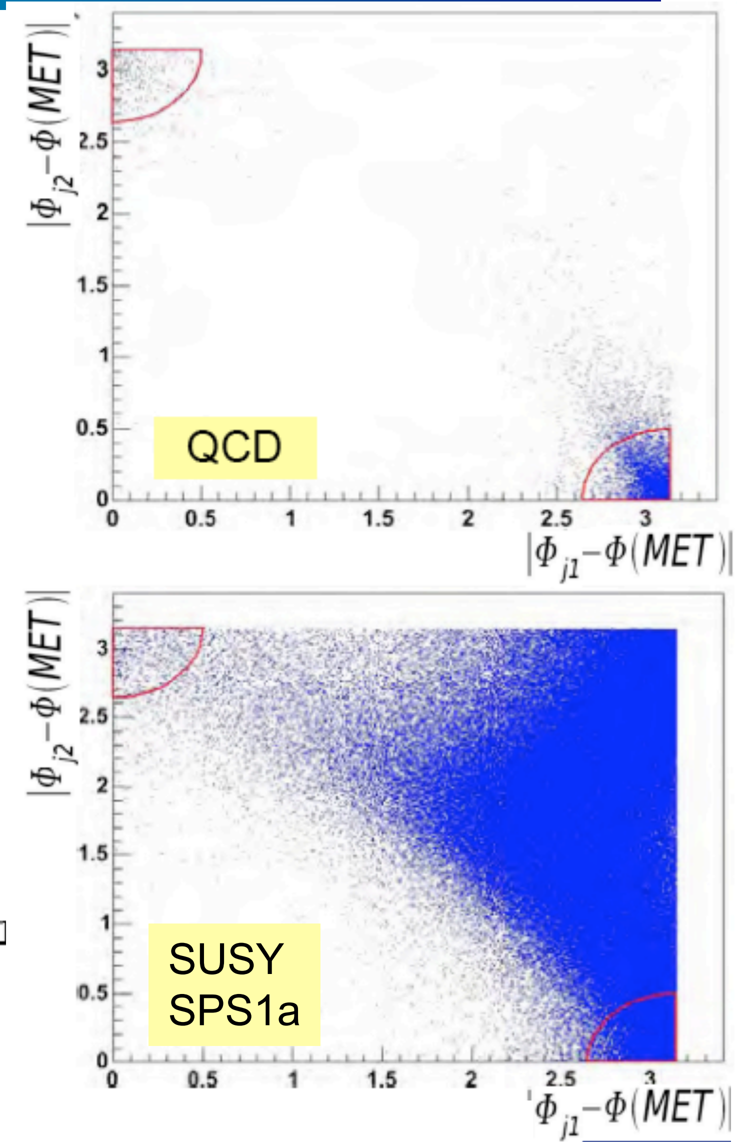
QCD rejection:

- MET in QCD is due to mismeasured jets
- Suppression via topological cuts:

$$R_{1,2}=\sqrt{\Delta\Phi_{1,2}^{2}+(\pi-\Phi_{2,1})^{2}} > 0.5$$

$$\text{with } \Delta\Phi_{1,2}=|\Phi_{j1,j2}-\Phi(MET)|$$

i.e. MET is along or opposite jet



Cleaning against beam halo, cosmics, calo noise:

- good primary vertex
- event electromagnetic fraction: $\frac{\sum_{jets} p_T^j \cdot EMF^j}{\sum p_T^j} > 0.1$
- event charged fraction: $\frac{\sum_{tracks} p_T^t}{p_T^{jet}} > 0.175$

QCD estimation

ETH Institute for Particle Physics

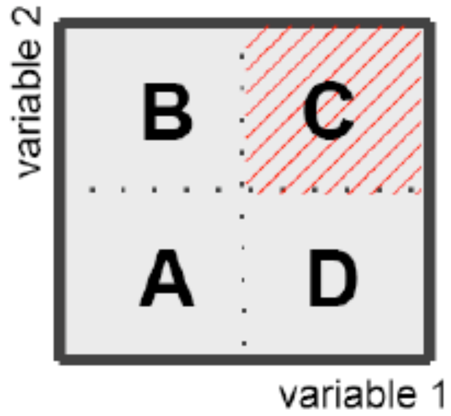
- previous studies (Physics TDR) estimated backgrounds using Monte Carlo

- now, data-driven methods being explored

- often “ABCD” method used:

Idea:
IF variable 1
and variable 2
are uncorrelated:

$$C = D \cdot \frac{B}{A}$$



Avoid signal contamination in A,B,D

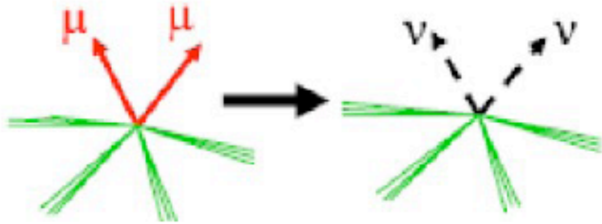
- variables for hadronic search: MET, Rsum, $\Delta\phi(jj)$, $\Delta\phi$(hemisphere), …
- variables for leptonic search: lepton isolation, impact parameter, MET, …
- correlations to be studied

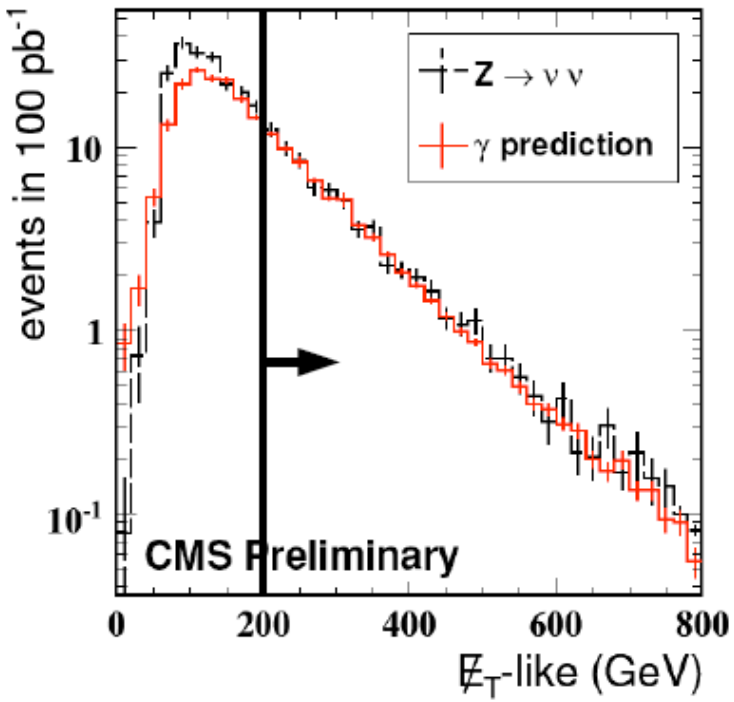
Irreducible: $Z \to \upsilon\upsilon$

Data-driven estimation from Z+jets

"standard candle": use $Z \to \mu\mu$

- replace leptons by neutrinos (and correct for acceptance using MC)
- total uncertainty ~20% for $1 fb^{-1}$
  statistics limited:
  $BR(Z \to \mu\mu) = 1/6\ BR(Z \to \nu\nu)$





New: data-driven estimation from W,γ+jets

assumption: bosonic events at high Pt look similar → use W,γ+jets

- gain in statistics (→ $100 pb^{-1}$ analyses)
  $\sigma(W+2j) = 3\ \sigma(Z+2j) = 0.8\ \sigma(\gamma+2j)$
- complementary to the above (other backgrounds/other triggers)
- beware of signal contamination

$Z \to \nu\nu$ background estimate ($100 pb^{-1}$)	
MC-truth	35
From γ+jets	29 ± 3 (stat) ± 5 (sys)
From W+jets	35 ± 10 (stat) ± 8 (sys) ± 3 (theory)

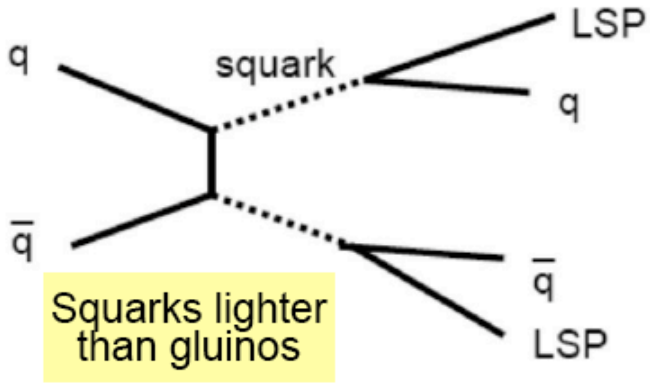
New: di-jet + MET

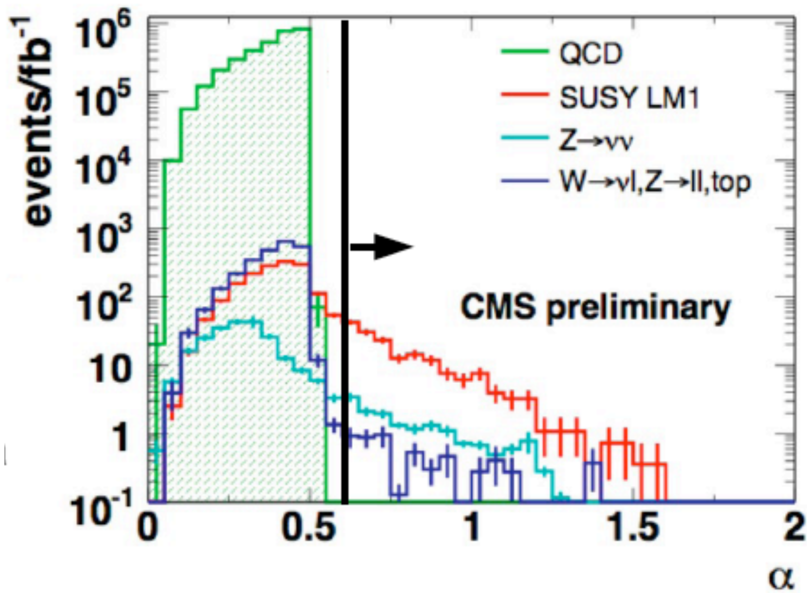
Robust extension of full-hadronic search

Event selection:

- 2 jets with P_T > 50 GeV, lepton veto
- $P_{T,j1}+P_{T,j2}$ > 500 GeV
- angular/acceptance cuts for cleaning
- new variable (Randall/Tucker-Smith):

$$\alpha = \frac{E_{T\ j2}}{M_{j1\,j2}} = \frac{E_{T\ j2}}{\sqrt{2E_1E_2(1-\cos\theta)}} > 0.55$$





Note:

- calorimetric MET not (directly) used
- dominant backgrounds:
  QCD and $Z\to\nu\nu$; estimate from data

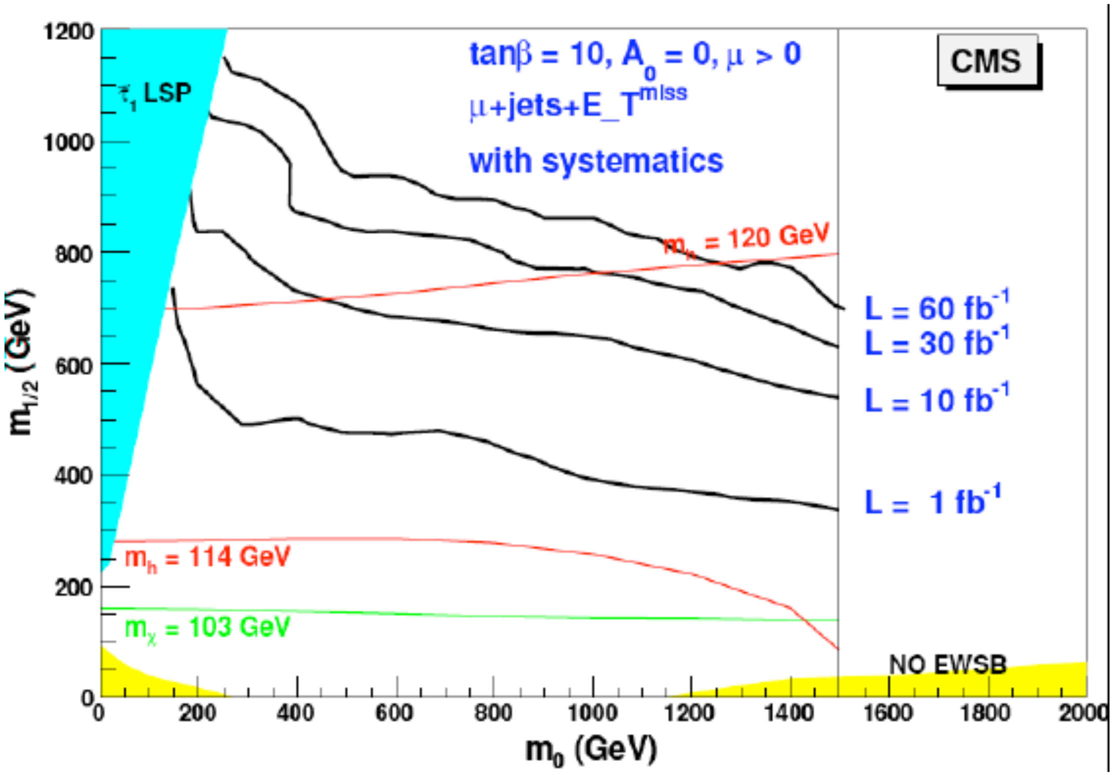
SPS1a discovery within 100 pb^{-1}

Lepton + jet + MET

Event selection:

Cut optimization via genetic algorithm on $10fb^{-1}$

- ≥ 1 isolated muon with P_T> 30 GeV
- $E_{T, j1}$ & $E_{T,j2}$ > 440 GeV, $E_{T,j3}$ > 50 GeV
- MET > 130 GeV
- single/di-muon trigger
- angular cuts for MET cleaning

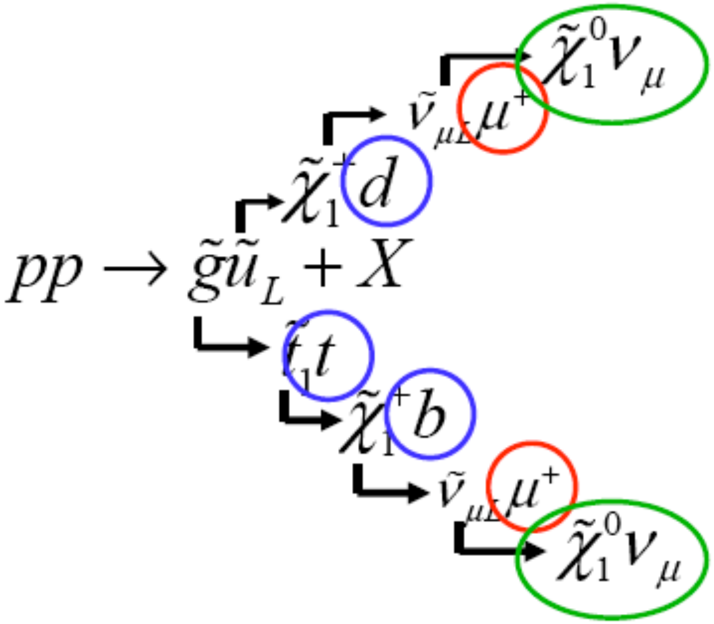


Early SUSY discovery in leptonic channels possible!

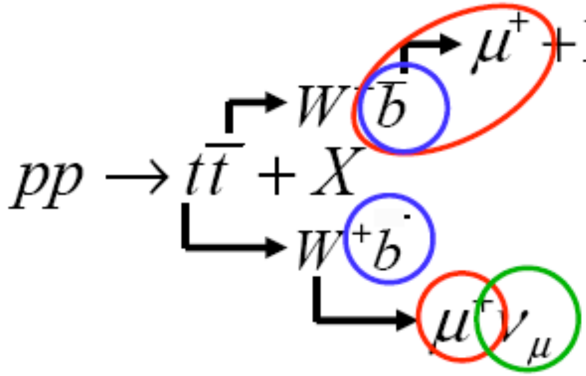
Same-sign dileptons

ETH Institute for Particle Physics

Signal:



Background:

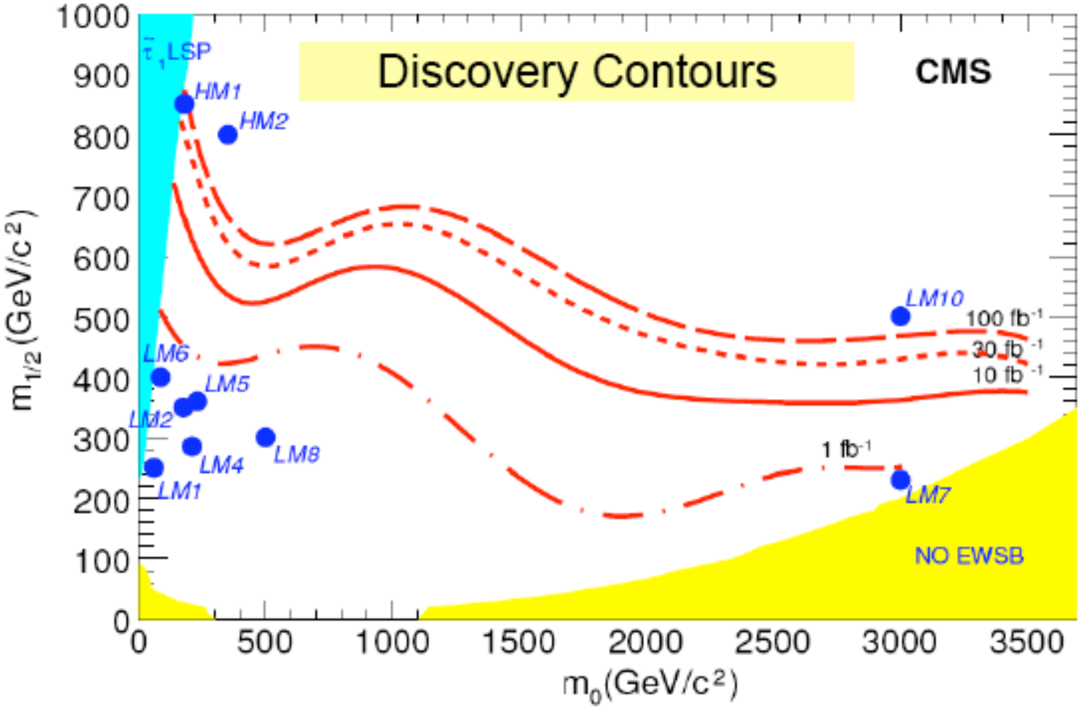


→ ask for 2 SS leptons + hard jets + E_T^{miss}

Same-sign leptons + jet + MET

Event selection:

- ≥ 2 isolated same-sign muons with P_T > 10 GeV
- ≥ 3 jets with E_T > 175/130/55 GeV
- MET > 200 GeV
- single/di-muon trigger



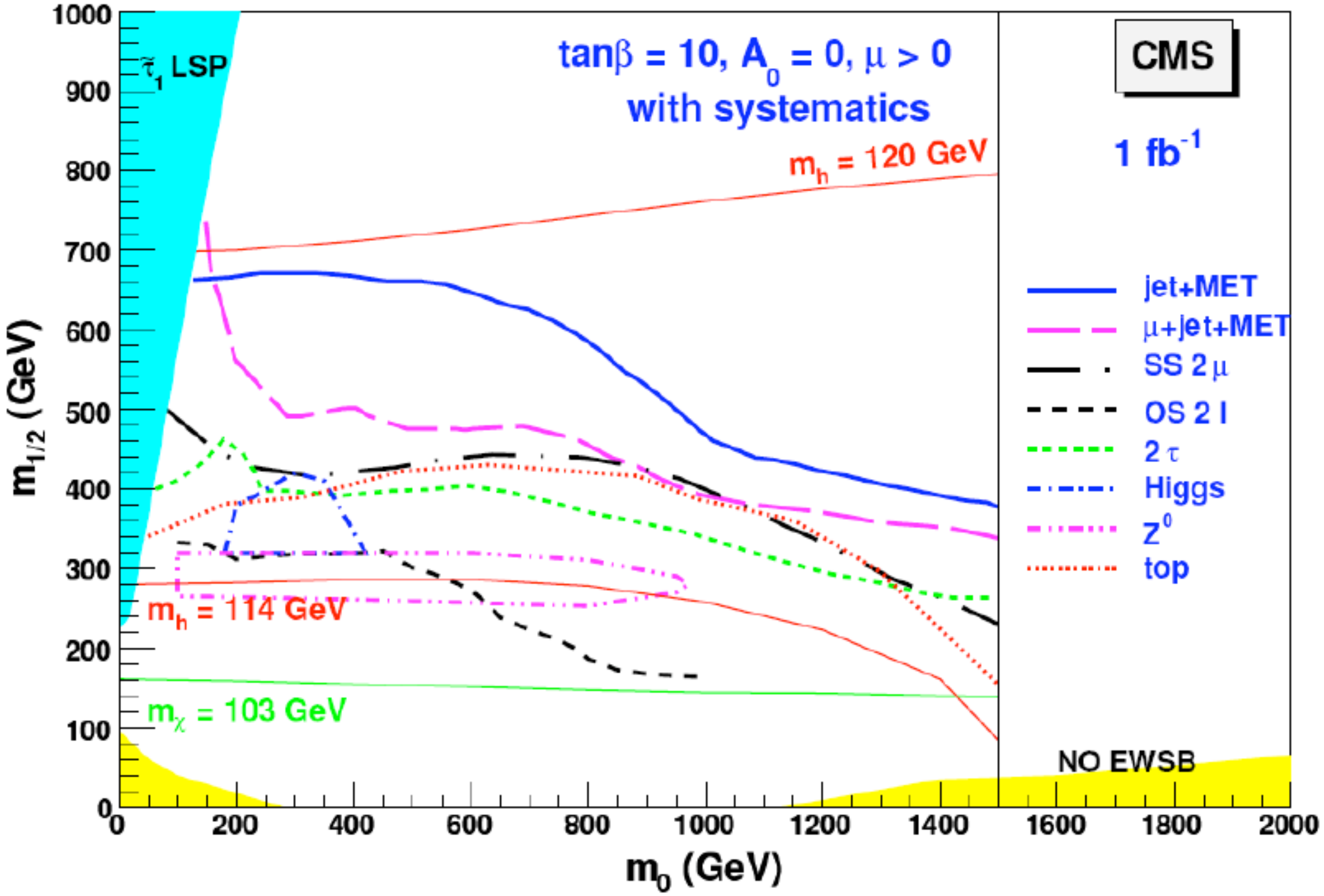
Note:

- almost no SM background
  σ(W+W+): 17 fb
- muon trigger expected to be most robust at startup
- complementary to hadronic channel

SUSY discovery potential

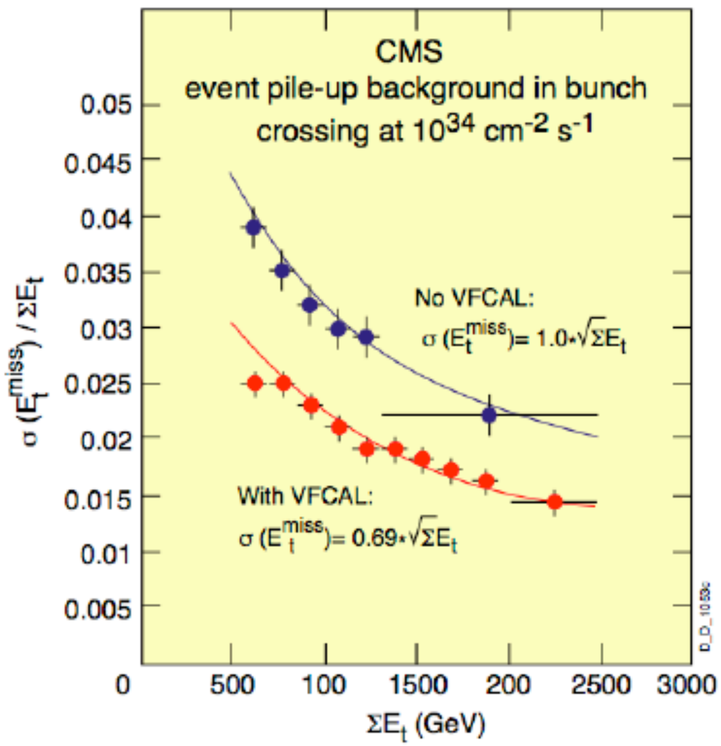
ETH Institute for Particle Physics

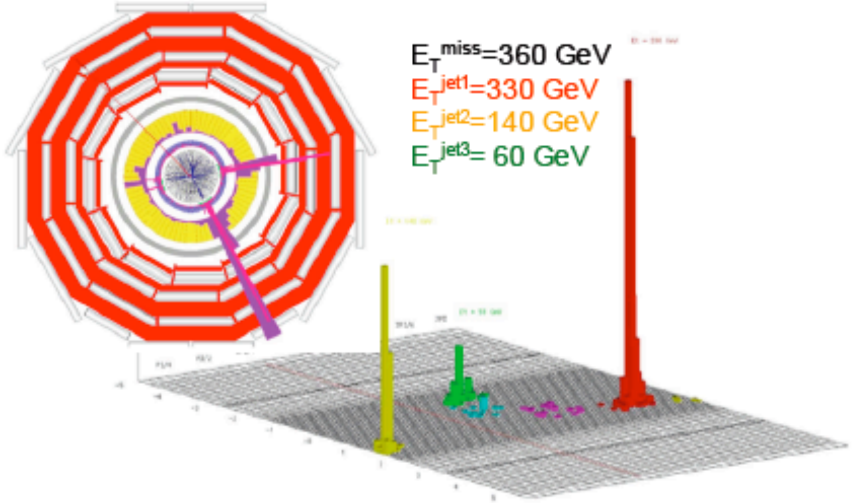
To summarize: many complementary channels for 1 fb^{-1}:

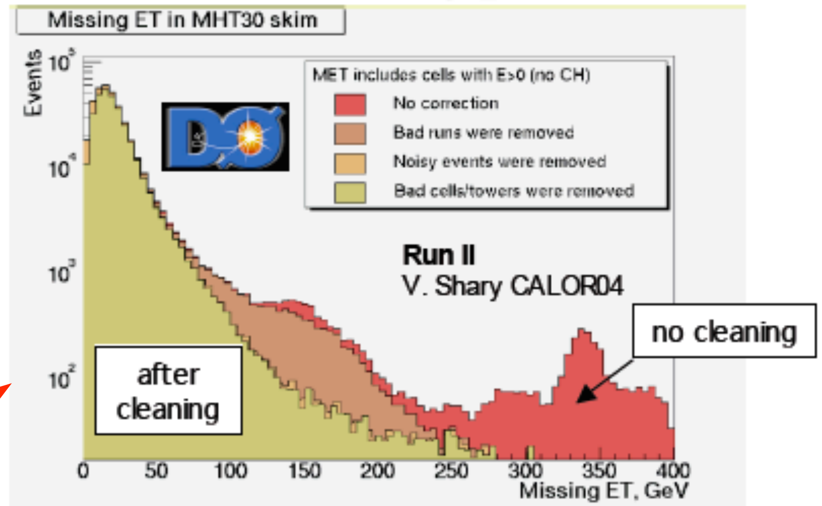


Missing transverse energy

Need large calorimeter coverage and no cracks to avoid "fake" missing-E_T





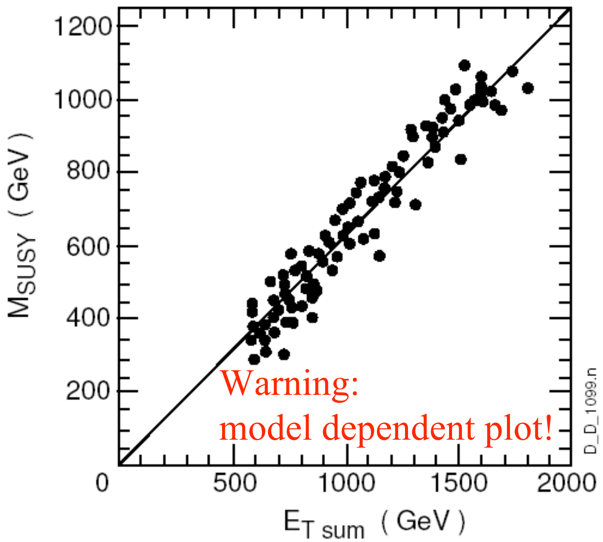


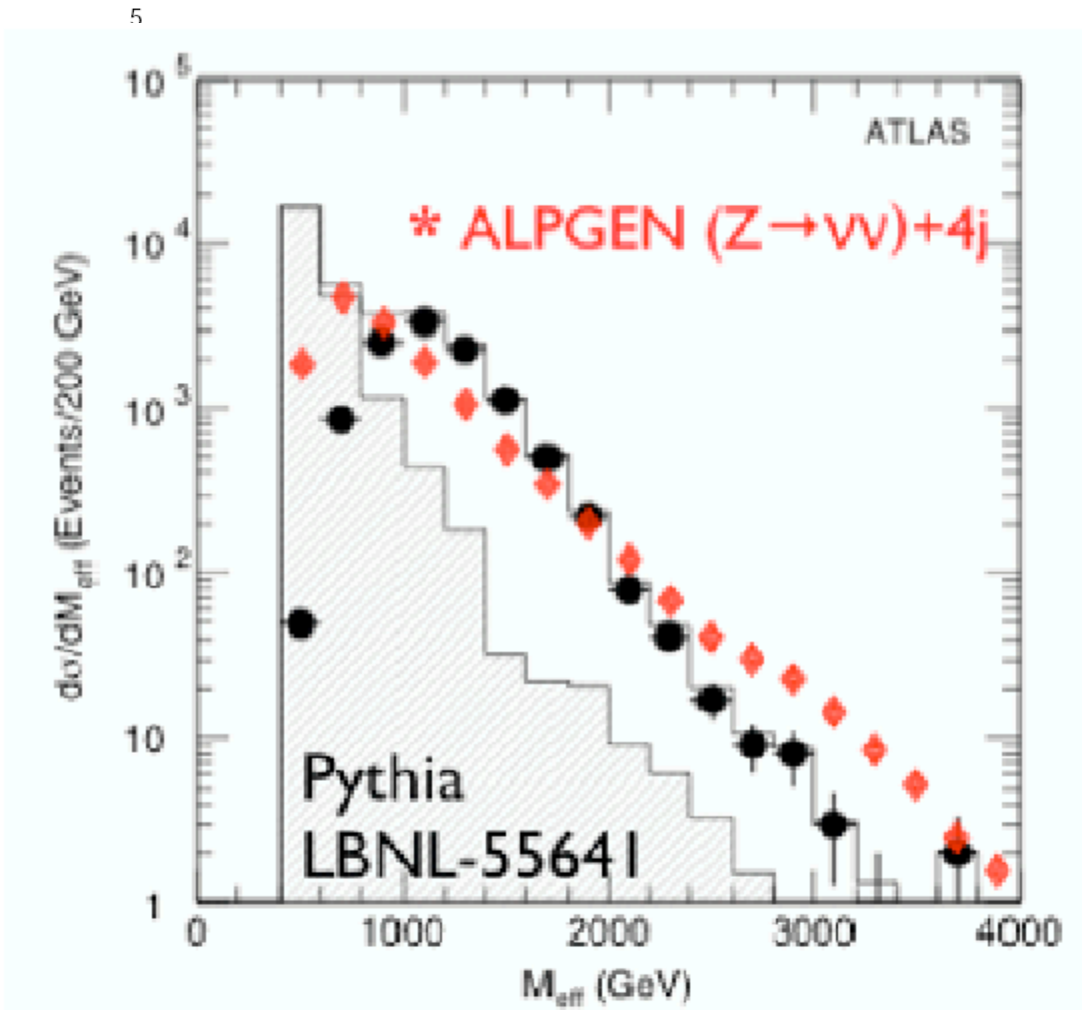
MET cleaning is important!

Et sum

Variable that gives information on the "SUSY scale":

$$E_T^{sum} = E_T^{miss} + \sum_{i=1}^{4} p_{T,i}$$





Exclusive final states

- so far: inclusive measurements

  fast discovery, but does not
  unambiguously single out SUSY

- need to reconstruct sparticle decay chains and masses involved

  need to be prepared for all possible final states

- goal is to measure cross sections, BR's (→ couplings) and even spin of the sparticles

  LHC can not only discover SUSY, but
  also MEASURE its properties (if nature is kind)

Coloured sparticle decays

- Region 1 $m(\tilde{g}) > m(\tilde{q})$

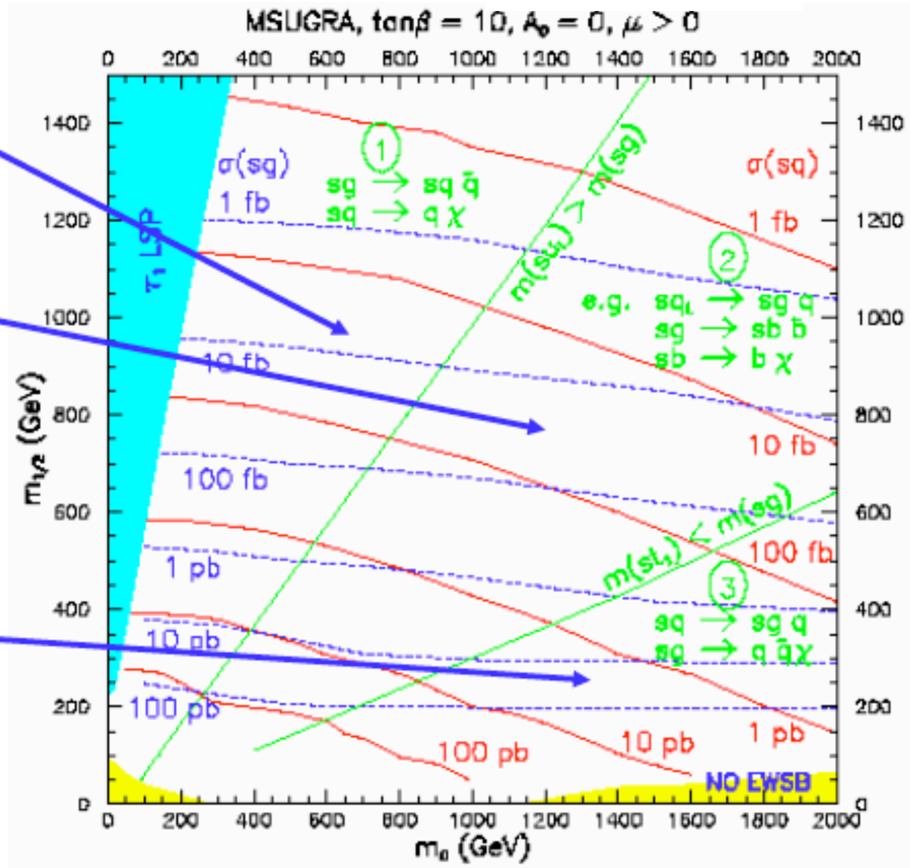
  $\tilde{g} \rightarrow \tilde{q}\bar{q}, \tilde{q} \rightarrow q\chi$

- Region 2, e.g.

  $\tilde{q}_L \rightarrow \tilde{g}q, \tilde{g} \rightarrow \tilde{b}\bar{b}, \tilde{b} \rightarrow b\chi$

- Region 3 $m(\tilde{q}) > m(\tilde{g})$

  $\tilde{q} \rightarrow \tilde{g}\bar{q}, \tilde{g} \rightarrow q\bar{q}\chi$



Neutralino2 decay signatures

Significant fraction of

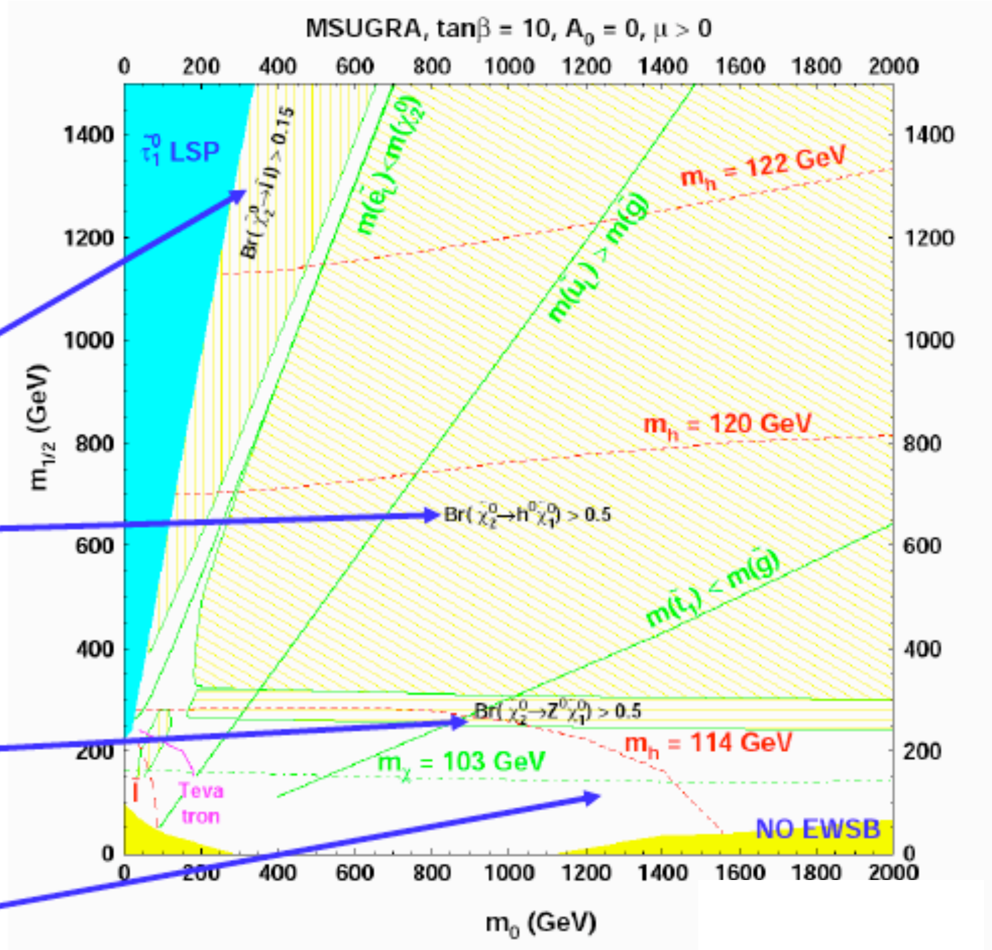
$$\tilde{q} \rightarrow q\chi_2^0$$

$$\chi_2^0 \rightarrow \tilde{l}^{\pm} l^{\mp}$$

$$\chi_2^0 \rightarrow h^0 \chi_1^0$$

$$\chi_2^0 \rightarrow Z^0 \chi_1^0$$

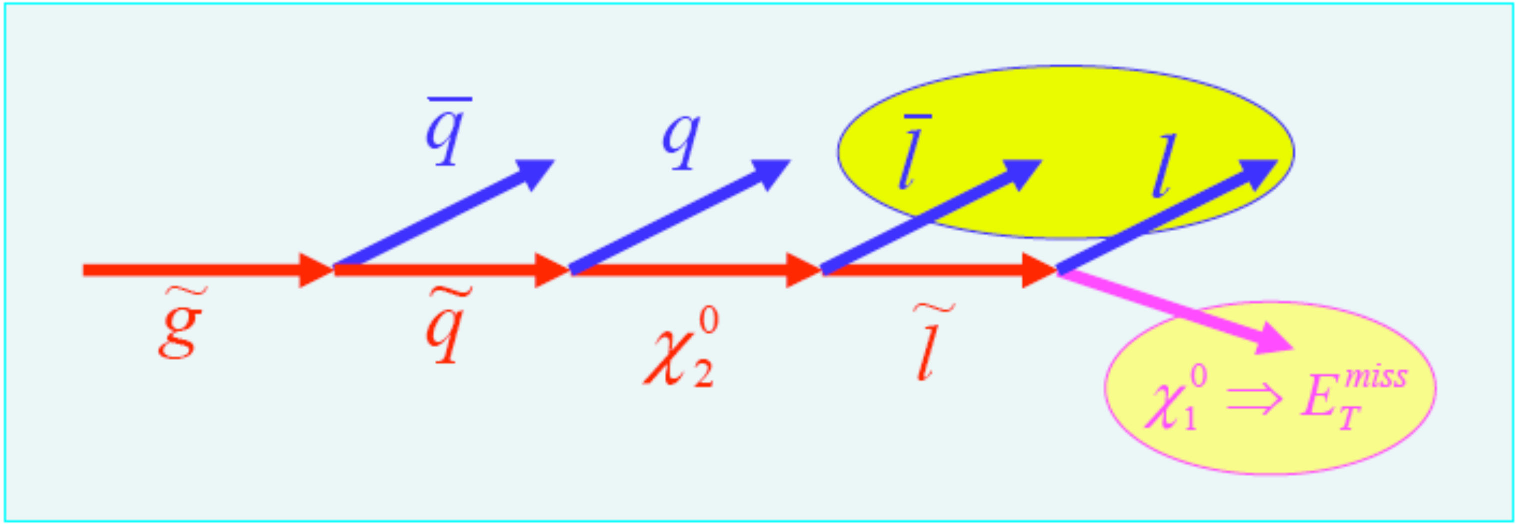
$$\chi_2^0 \rightarrow l^+ l^- \chi_1^0$$



Decay chain to dileptons

CMS

ETH Institute for Particle Physics



Final state:
- 2 high p_t isolated leptons
- 2 high p_t jets
- missing E_t

Kinematic endpoints

Kinematic endpoint technique:
construct lepton/quark upper/lower endpoints
and relate them to the masses in the decay chain

E.g.: $\tilde{q} \rightarrow \chi_2^0 q$

$\quad \hookrightarrow \tilde{\ell}^{\pm} \ell^{\mp} \rightarrow \chi_1^0 \ell^+ \ell^-$

4 unknown masses: $M_{\tilde{q}}, M_{\chi_2^0}, M_{\tilde{l}}, M_{\chi_1^0}$

4 endpoints: $M(ll)^{\max}, M(l1q)^{\max}, M(l2q)^{\max}, M(llq)^{\max}$

→ **all masses can be determined**

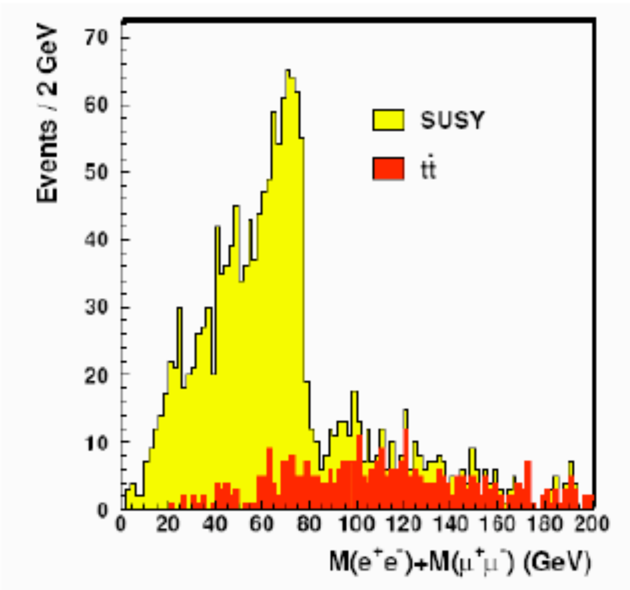
Usually non-linear relations → all masses, not just differences
Extra endpoints, or start from gluino → constraints

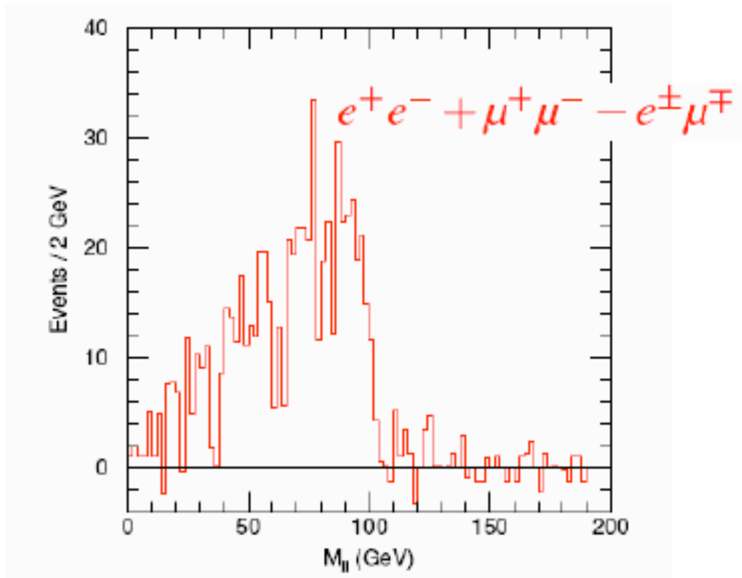
Final states with dileptons (1)

ETH Institute for Particle Physics

- **M(ll):** very sharp end point,
  triangular shape (due to spinless slepton)

$$M_{ll}^{\max} = M_{\chi_2^0}\sqrt{\left(1-\frac{M_{\tilde{l}}^2}{M_{\chi_2^0}^2}\right)\left(1-\frac{M_{\chi_1^0}^2}{M_{\tilde{l}}^2}\right)}$$





Opposite-sign dileptons

- Also use shape information!
- Fit shape + endpoint: $m_{\ell\ell}^{max} = m_{\tilde{\chi}_2^o}\sqrt{1-\frac{m^2_{\tilde{\ell}_R}}{m^2_{\tilde{\chi}_2^o}}}\sqrt{1-\frac{m^2_{\tilde{\chi}_1^o}}{m^2_{\tilde{\ell}_R}}}$

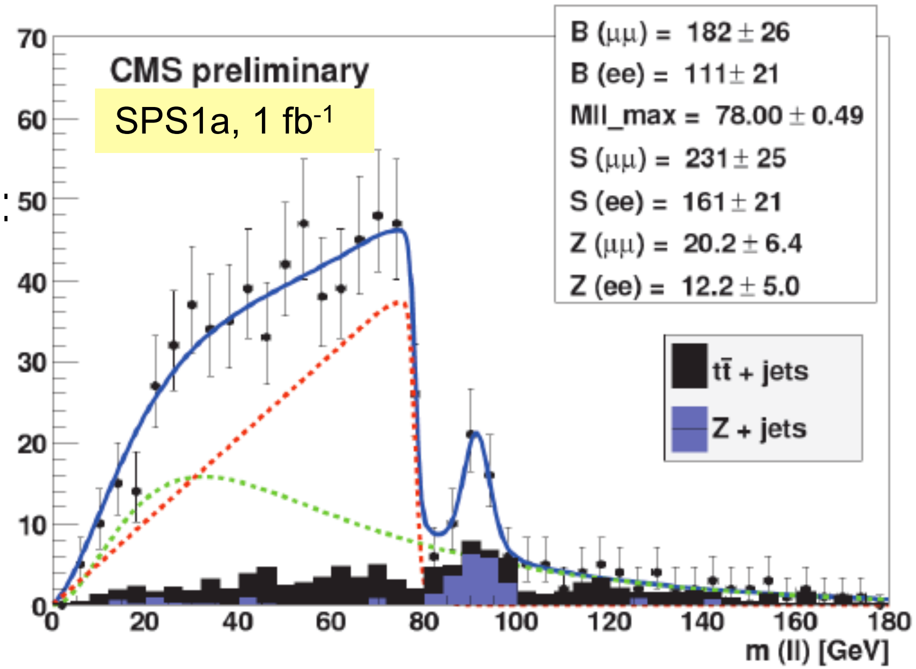
$$\tilde{\chi}_2^o \rightarrow \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^o$$

- Data-driven background estimate:
  tt and diboson background from
  eμ data (BR(ee)=1/2 BR(eμ))
- Unbinned fit to data (7 parameters):

$$F(m) = N_{sig}S(m) + N_{bkg}B(m) + N_Z Z(m)$$

Signal Model | Bkg from data | Z peak

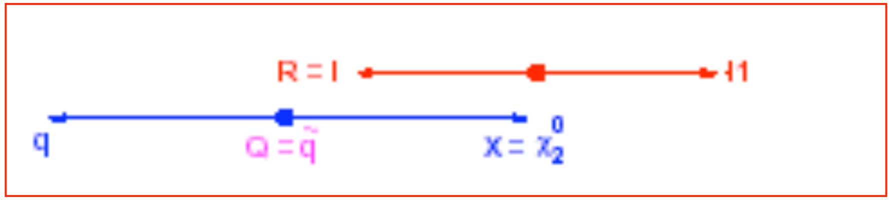
$$\Delta m_{ee}^{max} = \pm 1.07(stat.) \pm 0.36(syst.)GeV$$
$$\Delta m_{\mu\mu}^{max} = \pm 0.75(stat.) \pm 0.18(syst.)GeV$$



Final states with dileptons (2)

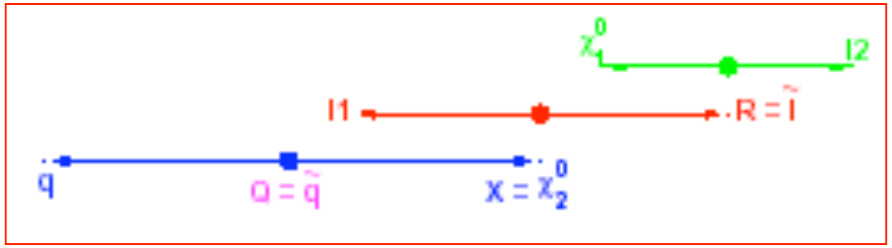
- **M(l1q):**

$$M^{max}_{l1q} = M_{\tilde{q}} \sqrt{\left(1 - \frac{M^2_{\chi_2^0}}{M^2_{\tilde{q}}}\right)\left(1 - \frac{M^2_{\tilde{l}}}{M^2_{\chi_2^0}}\right)}$$



- **M(l2q):**

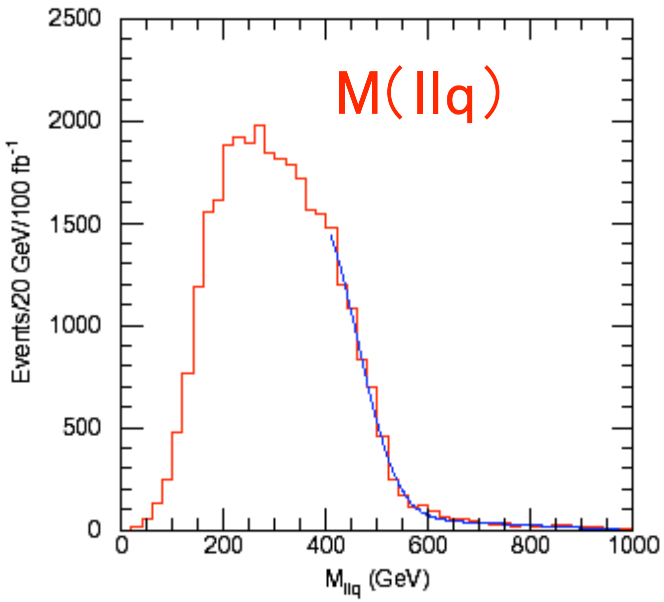
$$M^{max}_{l2q} = M_{\tilde{q}} \sqrt{\left(1 - \frac{M^2_{\chi_2^0}}{M^2_{\tilde{q}}}\right)\left(1 - \frac{M^2_{\chi_1^0}}{M^2_{\tilde{l}}}\right)}$$



➔Can distinguish $M(l1q)^{max}$ from $M(l2q)^{max}$

- **M(llq):**

$$M^{max}_{llq} = M_{\tilde{q}} \sqrt{\left(1 - \frac{M^2_{\chi_2^0}}{M^2_{\tilde{q}}}\right)\left(1 - \frac{M^2_{\chi_1^0}}{M^2_{\chi_2^0}}\right)}$$



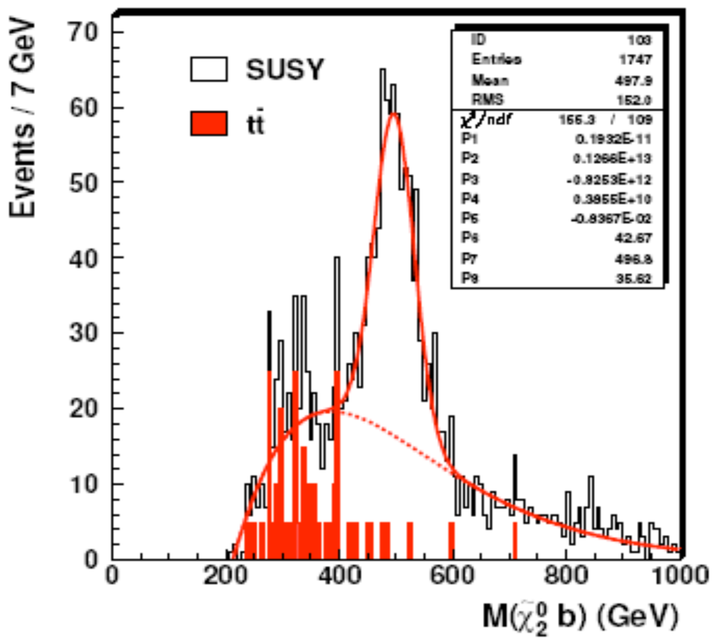
Gluino reconstruction

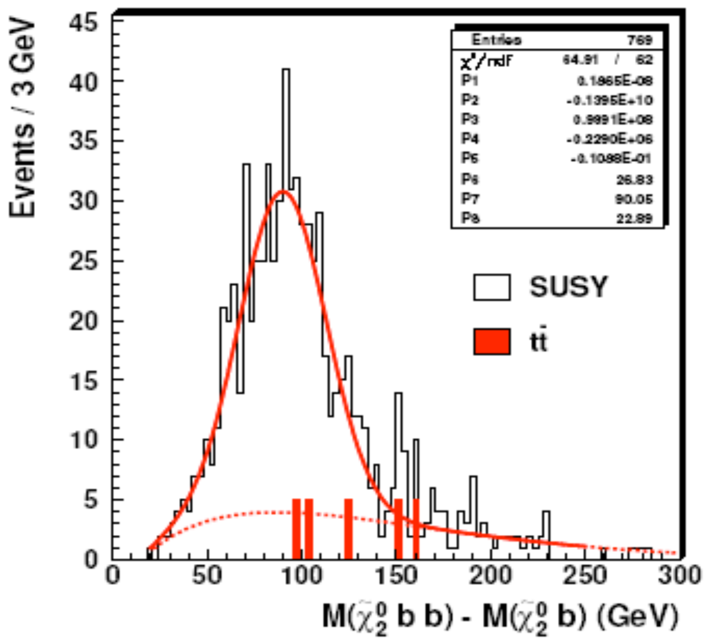
Choose dilepton pairs close to the edge; then

$$\vec{p}_{\tilde{\chi}_2^0} \approx (1 + M_{\tilde{\chi}_1^0} / M_{\ell\ell}) \vec{p}_{\ell\ell}$$

assuming $\tilde{\chi}_1^0$ can be at rest in the frame of $\tilde{\chi}_2^0$

→ can reconstruct $M_{\tilde{q}}$ and $M_{\tilde{g}} - M_{\tilde{q}}$

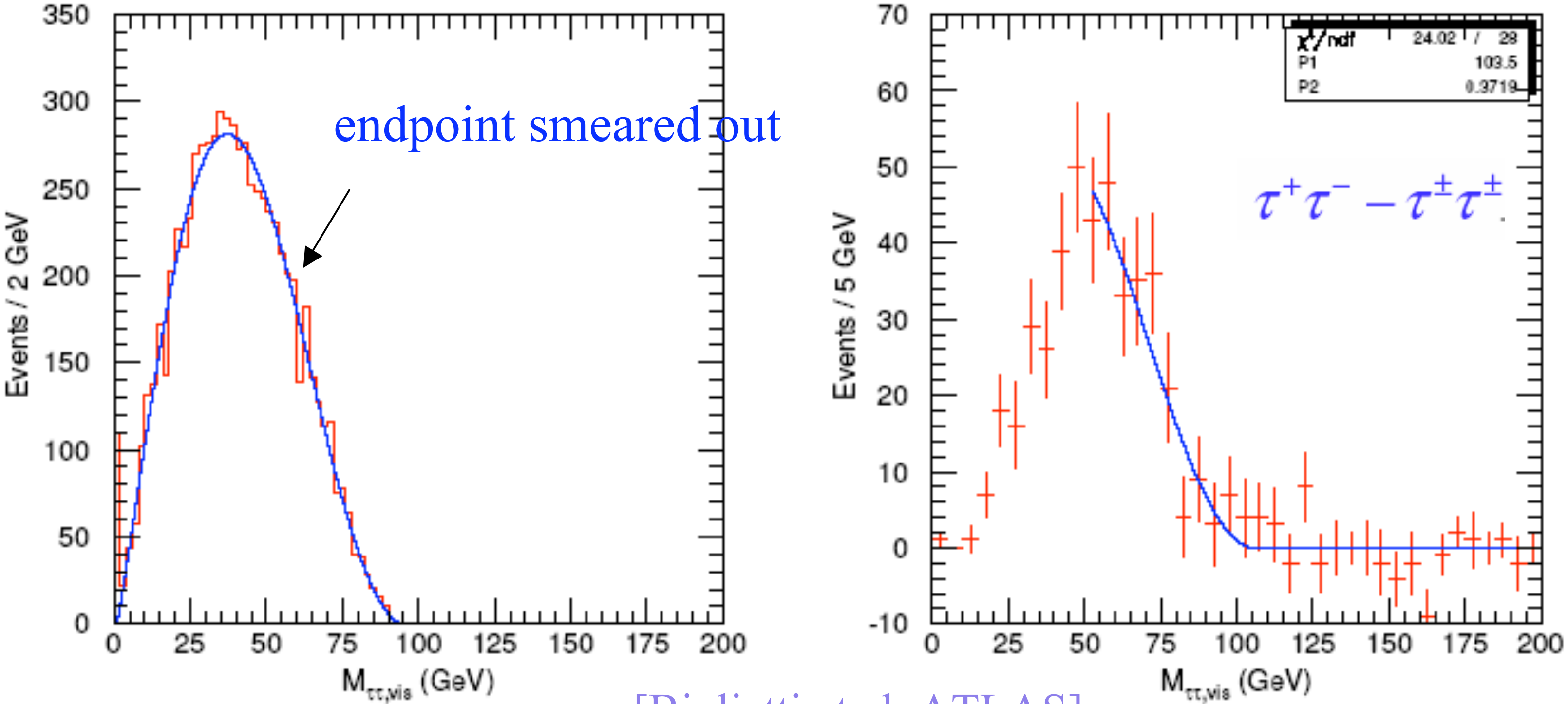




Final state with taus

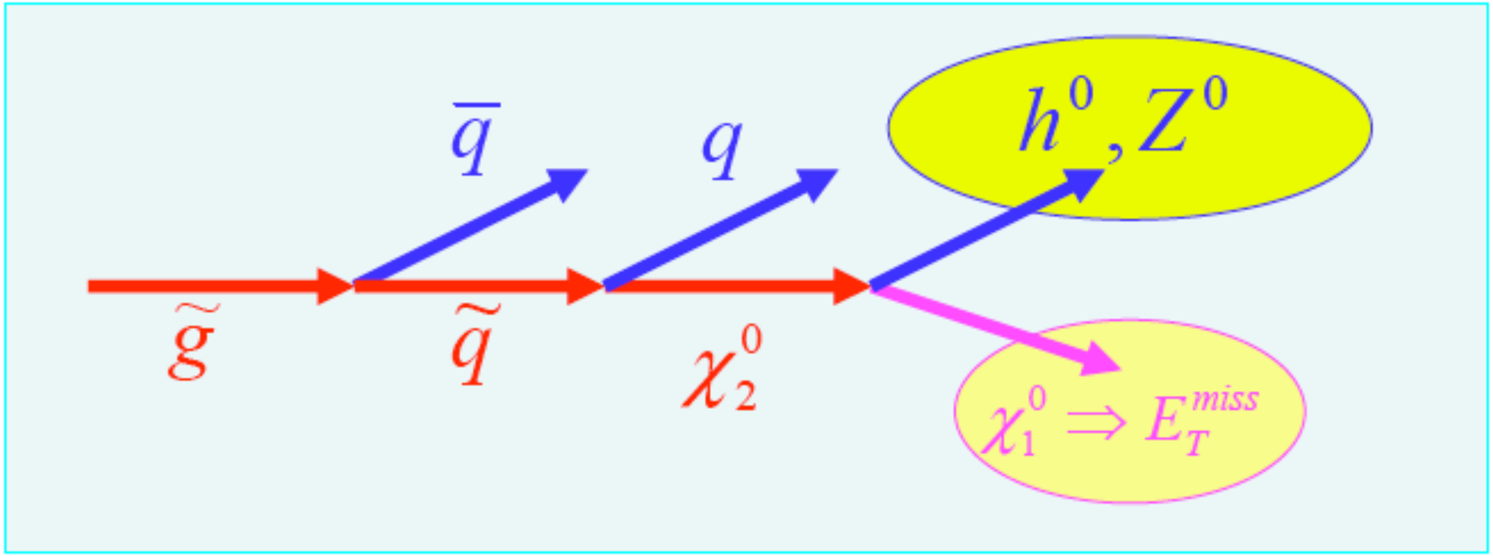
- often $\widetilde{\chi}_2^0$ decays to taus instead of electrons/muons

- can we use hadronic tau final states?



[Biglietti et al, ATLAS]

Decay chain to h^0 or Z^0



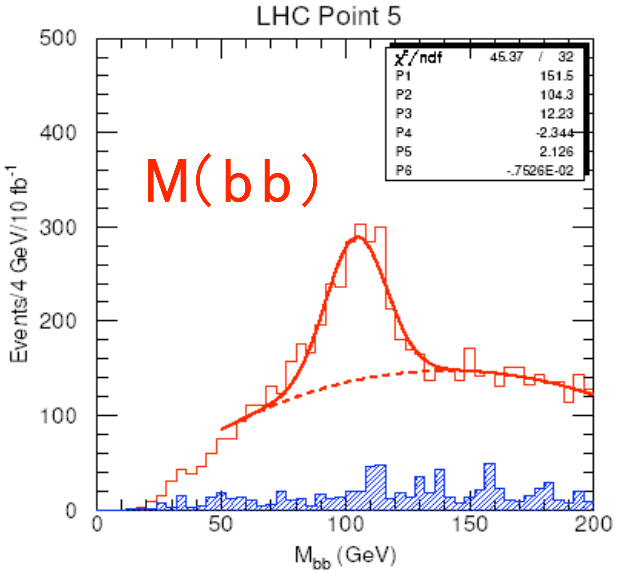
Final states with h^0 or Z^0

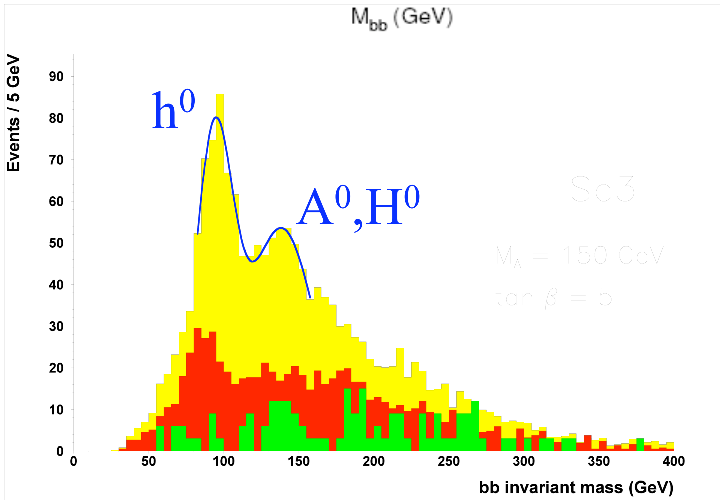
- Higgs peak can be reconstructed from 2 b-jets

  → could be a h^0 discovery channel !
  (even for light H^0 and A^0)

- Z^0 reconstructed from di-lepton decay

- Decay chain is shorter than for di-leptons →
  e.g. start from gluino
  $M(q_1h^0), M(q_2h^0), M(qq), M(qqh^0)$
  to determine 4 masses





GMSB signatures

In GMSB, the light gravitino is the LSP

→ Who is NLSP?

- Neutralino is NLSP

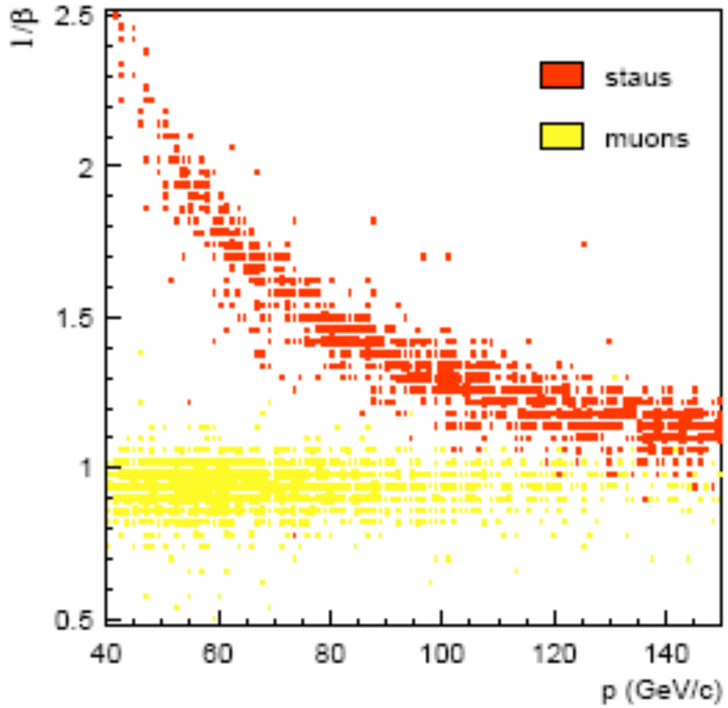
$$\chi_1^0 \rightarrow \gamma + \widetilde{G}$$

- Stau is NLSP

$$\widetilde{\tau}_1 \rightarrow \tau + \widetilde{G}$$

→ $E_T^{miss} + \gamma$, τ or long-lived particles

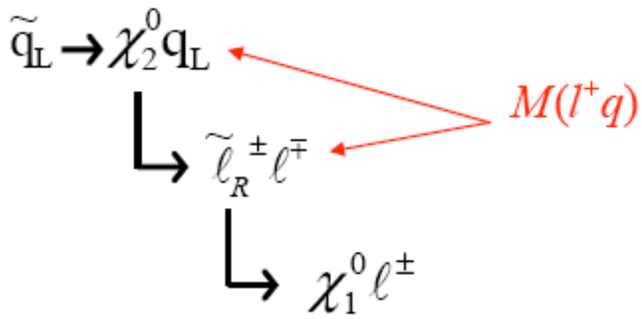
TOF measurement in the CMS muon DT's

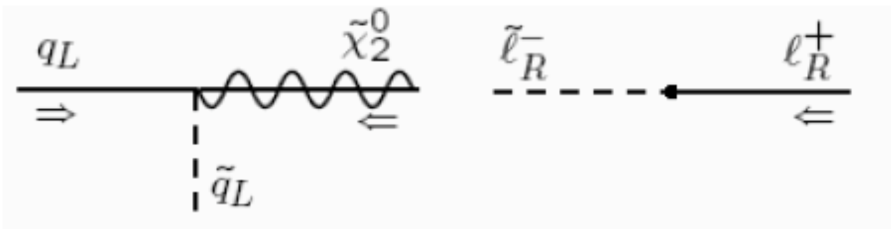


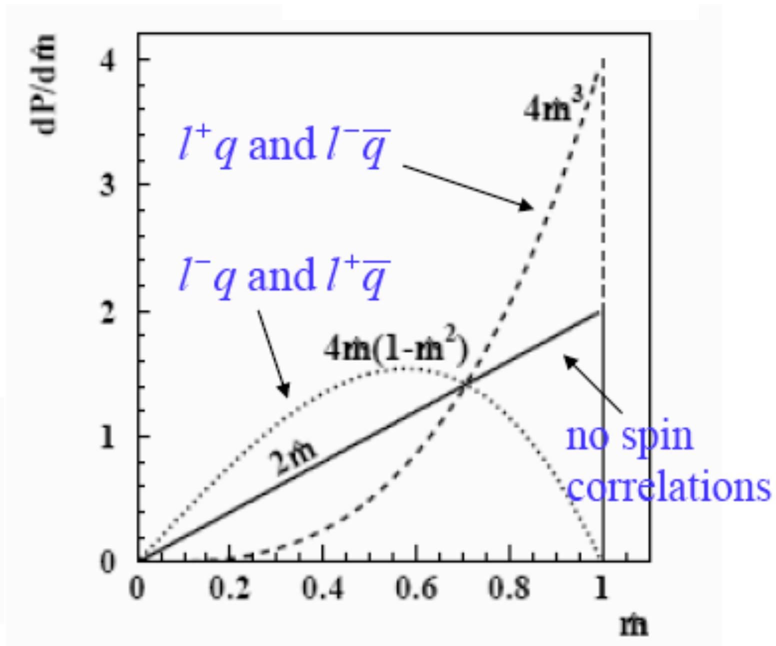
→ dE/dx and TOF

SUSY spin measurement

Make use of spin correlations in decay of squark:





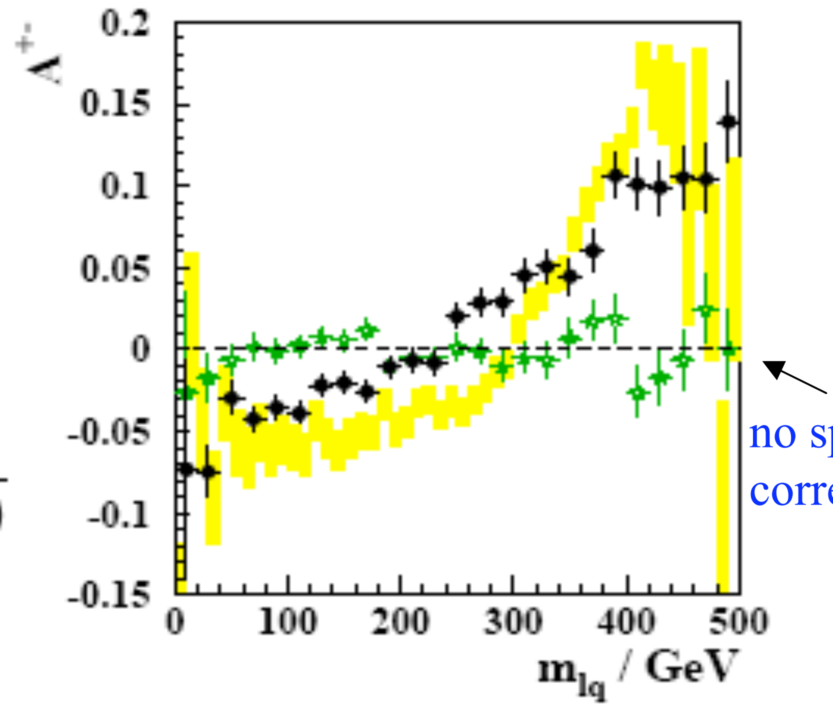


SUSY spin measurements (2)

washes out for antisquarks, but
in *pp* colliders → more squarks produced than antisquarks

→Visible asymmetry:
(500 fb^{-1})

$$A^{+-} \equiv \frac{s^+ - s^-}{s^+ + s^-}, \quad \text{where} \quad s^\pm = \frac{d\sigma}{d(m_{l^\pm q})}$$



no spin correlations

Higgs searches

Lecture 2b:

- reminder of MSSM Higgs phenomenology
- existing experimental limits on Higgs bosons
- Higgs searches at the LHC
- (ongoing Tevatron searches …)

Where are the masses?

Problem with the SM: all particles are massless. Introduction of mass terms ruins the gauge invariance. Oops.

Solution proposed by Brout-Englert-Higgs:

- assume the existence of a scalar field that pervades the universe
- particles interacting with this field acquire mass – the stronger the interaction, the larger the mass
- the particle associated with the Higgs field is the Higgs boson

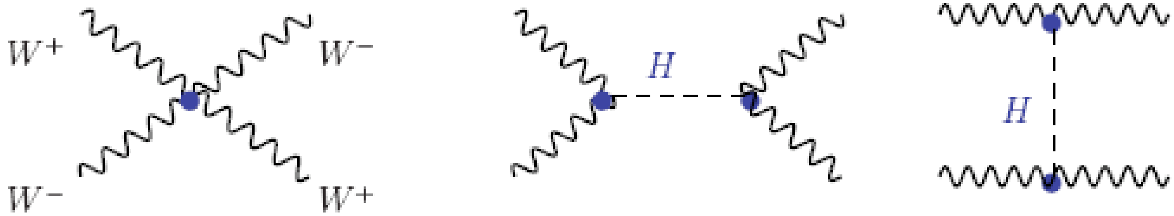
Argument 2 for extra “scalar”

ETH Institute for Particle Physics

Other – independent – argument for a new (effectively) scalar particle:

σ ($W^+W^- \rightarrow W^+W^-$) diverges with energy!

We need something to cancel the divergence: scalar particle H



$$A(W^+W^- \rightarrow W^+W^-) \xrightarrow{s \gg M_W^2} \frac{1}{v^2}\left[s + t - \frac{s^2}{s - M_H^2} - \frac{t^2}{t - M_H^2}\right]$$

Upper bound on scalar mass

In order not to violate unitarity, in the previous formula:

$$M_H \lesssim 870 \text{ GeV}$$

This argument lead to the minimum physics requirement for a post-LEP collider:

The next accelerator must be able to produce particles up to a mass of ~1 TeV

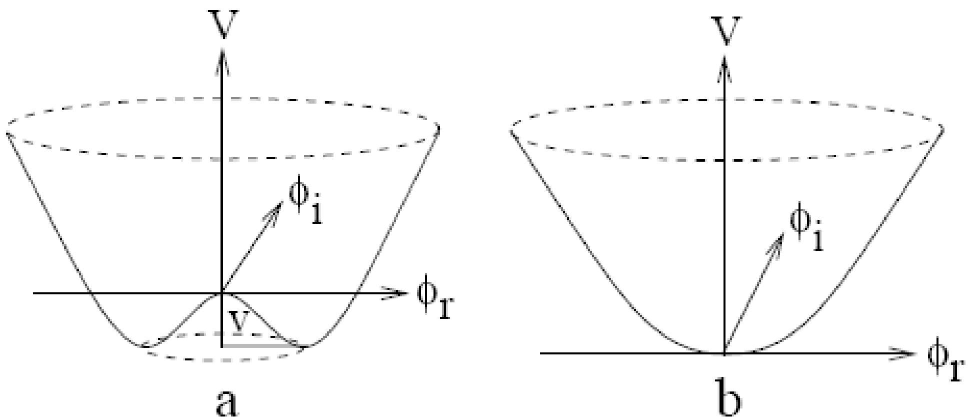
The minimal Higgs Mechanism

1964: Higgs, Englert and Brout propose to add a complex scalar doublet field to the Lagrangian

$$\mathcal{L} = (\partial^\mu \phi^\dagger)(\partial_\mu \phi) - \mu^2 \mid \phi \mid^2 - \lambda \mid \phi \mid^4$$

EWSB if μ^2 negative!

$\mu^2 < 0$ $\mu^2 > 0$



→

$$m_W = \frac{1}{2} g v \qquad (v^2 = \frac{\mu^2}{\lambda})$$

$$m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v$$

$$m_\gamma = 0$$

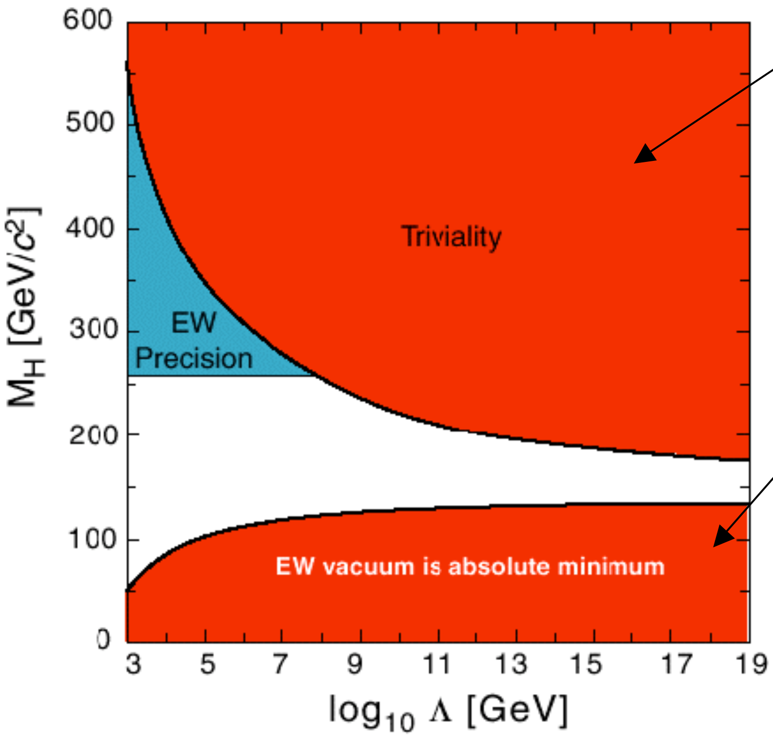
and one extra boson with

$$m_H^2 = -\mu^2$$

Higgs mass limits from theory

ETH Institute for Particle Physics

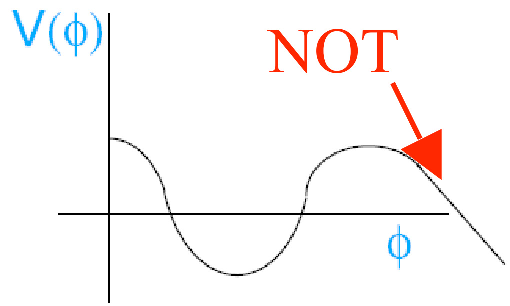
The triviality (upper) bound and vacuum stability (lower) bound as function of the cut-off scale Λ



"triviality" :
Higgs self-coupling remains finite

$$\lambda(Q^2) = \frac{\lambda(Q_0^2)}{1-\lambda(Q_0^2)/16\pi^2 \log(Q^2/Q_0^2)}$$

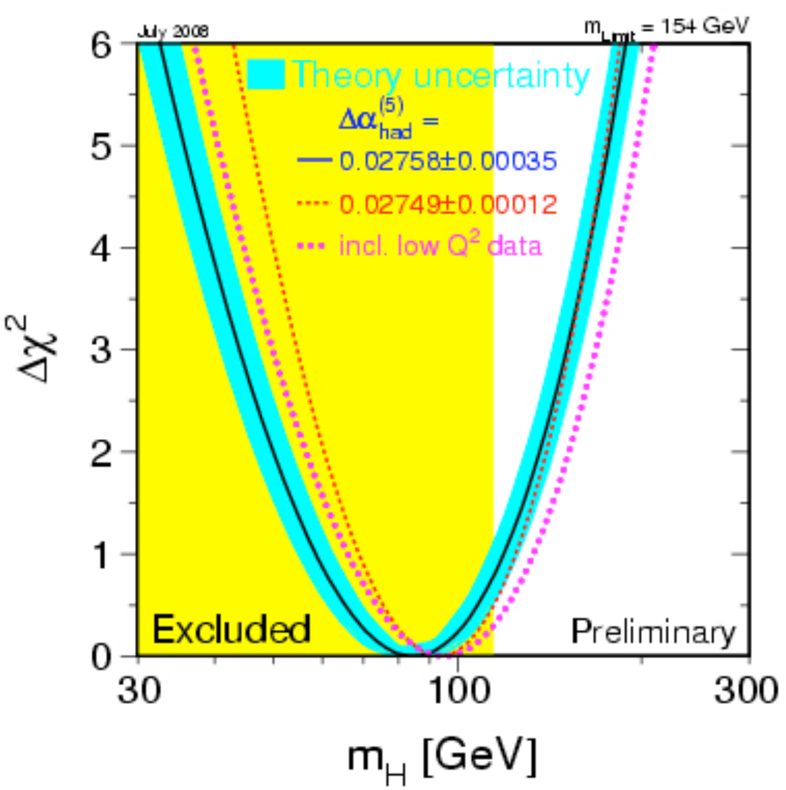
"vacuum stability" :
Higgs potential has a stable minumum

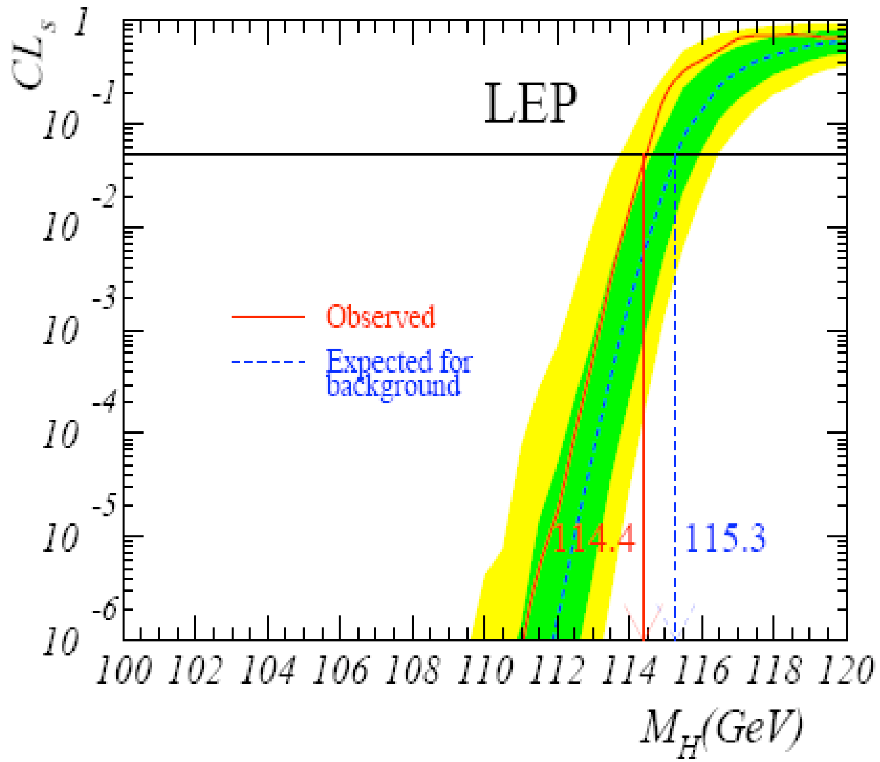


Experiment

Indirect constraints from precision data:

Direct limit from LEP2:





Higgs in MSSM

- In MSSM: 2 Higgs doublets needed
  - to cancel the gauge anomaly (due to higgsinos)
  - to give mass to both up and down type fermions
- 2 Higgs fields → 8 degrees of freedom

  3 are used to make $W^\pm$ and Z^0 massive

  MSSM contains 5 physical Higgs states

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \quad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

$$\tan\beta = \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}$$

  - **2 charged scalars $H^\pm$**

    Mixture of H_d^- and H_u^+, fixed by $\tan\beta$
  - **1 neutral CP-odd A^0**

    Mixture of $\mathrm{Im}(H_d^0)$ and $\mathrm{Im}(H_u^0)$, fixed by $\tan\beta$
  - **2 neutral CP-even h^0 and H^0**

    Mixture of $\mathrm{Re}(H_d^0)$ and $\mathrm{Re}(H_u^0)$, with mixing angle α

→ MSSM Higgs bosons: h^0, H^0, A^0, $H^\pm$

ETH Institute for Particle Physics

Radiative EWSB

All parameters RG evolve, however. In detail, this is a complicated system of differential equations. But schematically, at 1-loop:

$$\frac{dg}{dt} \sim \frac{1}{16\pi^2} g^3$$
$$\frac{dy}{dt} \sim \frac{1}{16\pi^2}\left[g^2 y - y^3\right]$$
$$\frac{dM}{dt} \sim \frac{1}{16\pi^2} g^2 M$$
$$\frac{dA}{dt} \sim \frac{1}{16\pi^2}\left[-g^2 M - y^2 A\right]$$
$$\frac{dm^2}{dt} \sim \frac{1}{16\pi^2}\left[g^2 M^2 - y^2 A^2 - y^2 m^2\right]$$

where $t \equiv \ln(Q_0/Q)$, and *positive* numerical coefficients have been neglected.

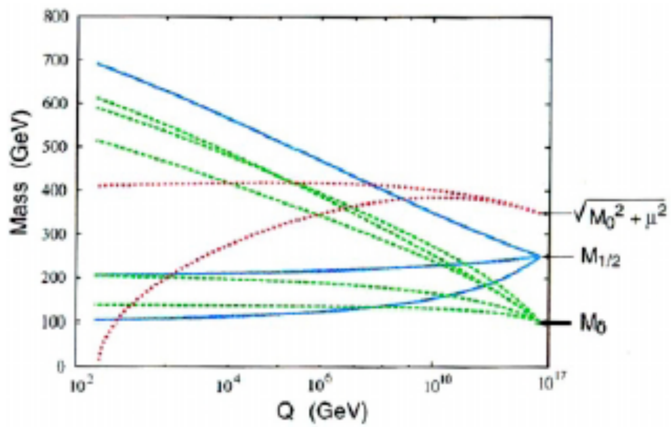
Gauge interactions raise m^2, Yukawa interactions lower m^2.

Recall

$$\mathcal{L} \supset y^u_{ij}\hat{H}_u\hat{Q}_i\hat{U}_j + y^d_{ij}\hat{H}_d\hat{Q}_i\hat{D}_j + y^e_{ij}\hat{H}_d\hat{L}_i\hat{E}_j$$

Top Yukawa coupling enters RGE for H_u but not for H_d. The heavy top quark drives $m^2_{H_u}$ negative.

Example RG trajectories:



Squarks/sleptons (green), gauginos (blue), Higgses (red)

Higgs mass at tree level

- From scalar potential, tree level masses are:

$$m_{H^\pm}^2 = M_W^2 + m_A^2$$
$$m_{H,h}^2 = \frac{1}{2}(m_A^2 + M_Z^2) \pm \frac{1}{2}\sqrt{(m_A^2 + M_Z^2)^2 - 4m_A^2 M_Z^2 \cos^2 2\beta}$$

- Higgs masses depend on only 2 parameters: m_A and $\tan\beta$
  - $\tan\beta \to 1$: $m_h = 0$, $m_H^2 = M_Z^2 + m_A^2$
  - $\tan\beta \to \infty$: m_h, $m_H^0 = \min,\max(M_Z, m_A)$
- Mass hierarchy at tree level:
  - $0 \le m_h \le M_Z|\cos 2\beta|$
  - $m_h \le m_A \le m_H^0$
  - $m_H^0 \ge M_Z$
  - $m_H^\pm \ge M_W$
- Expect light h^0 → observable at LEP2

  But radiative corrections are large, especially on m_h

from b/t yukawa couplings:

$$1.2 \le \tan\beta \le 65$$

Higgs mass radiative corrections

- Top loop corrections: 1-loop leading log approximation

$$\Delta(m_h^2) = \frac{3m_t^4}{4\pi^2 v^2}\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

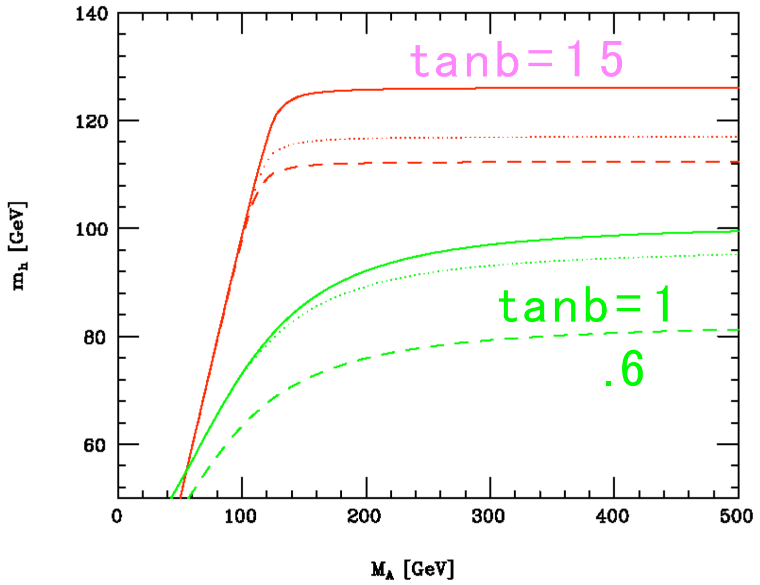
  - Introduces a dependence on top and stop masses
  - More accurate calculation:also on stop mixing $X_t = A_t - \mu\cot\beta$

- In MSSM, **m_h^0 has upper bound**
  - Increases with $\tan\beta$
  - Increases from min $X_t/M_{SUSY}=0$ To max $(X_t/M_{SUSY})^2=6$

$m_h \leq 130$ GeV

(for M_{SUSY} = 1 TeV, m_t=175 GeV)

➔ Lower than preferred SM range



MSSM Higgs sector

• MSSM contains 2 Higgs doublets, therefore 5 physical Higgs states: h^0, H^0, A^0, $H^\pm$

H^0, A^0, $H^\pm$ → ~ degenerate in mass for high m_A

h^0 → looks like H_{SM} (but $m_h < 130$ GeV)

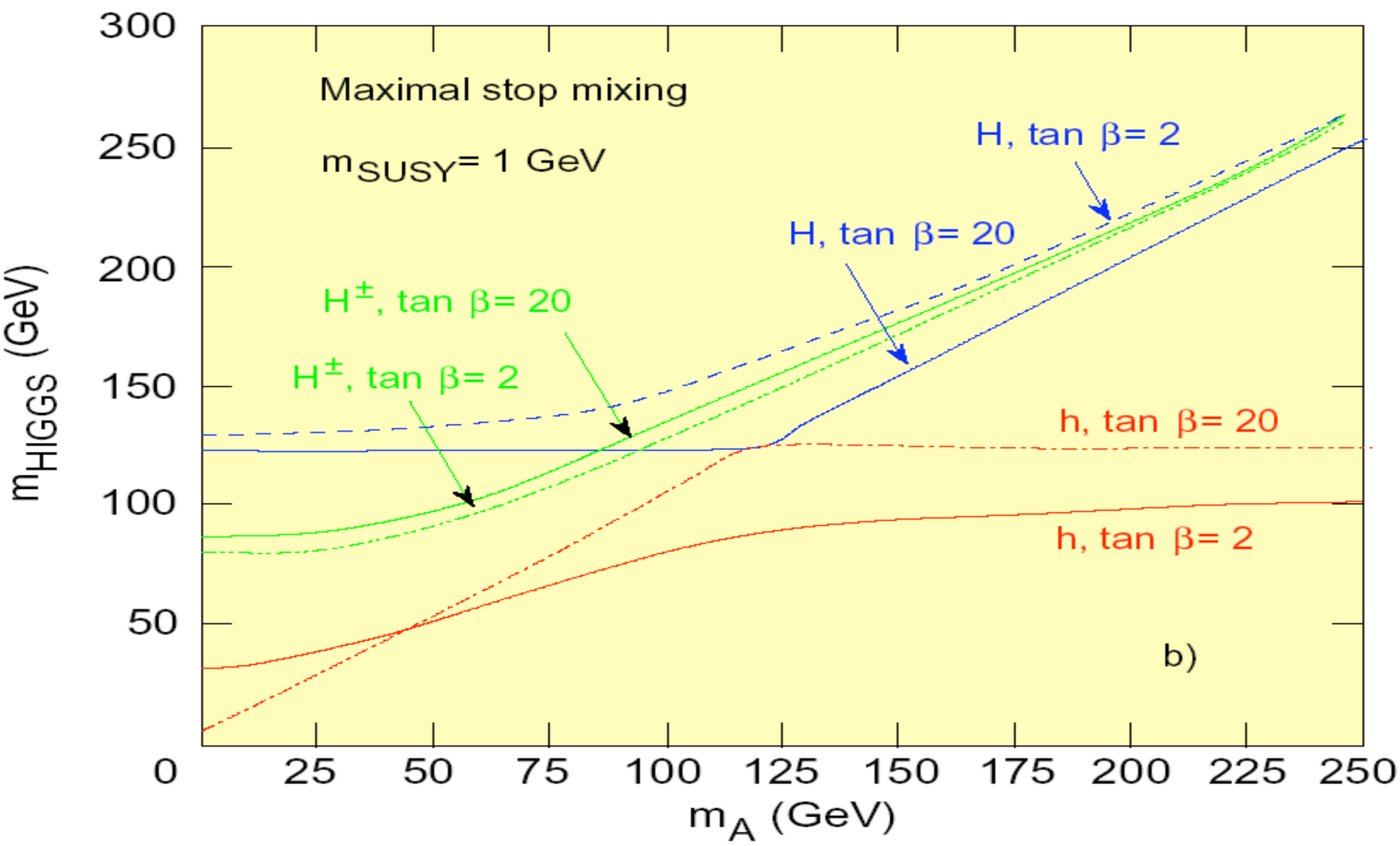
• masses & couplings depend at tree level only on 2 parameters, say m_A & $\tan\beta$: $(1 < \tan\beta < 60)$

$$m^2_{H^\pm} = m^2_{A^0} + m^2_{W^\pm}$$

$$m^2_{h^0,H^0} = \frac{1}{2}\left(m^2_{A^0} + m^2_{Z^0} \mp \sqrt{(m^2_{A^0} + m^2_{Z^0})^2 - 4m^2_{Z^0}m^2_{A^0}\cos^2 2\beta}\right)$$

• radiative corrections can be important (e.g. for h^0 !!)

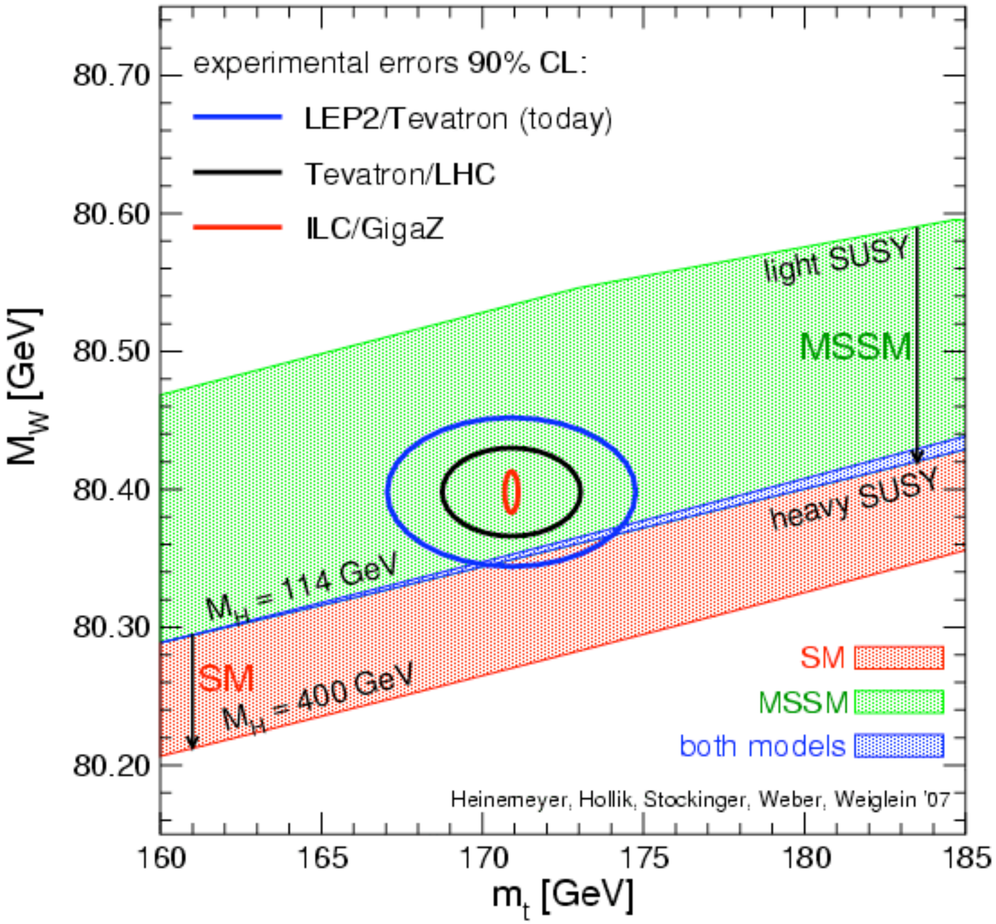
MSSM Higgs masses, summary



LEP Experimental limits

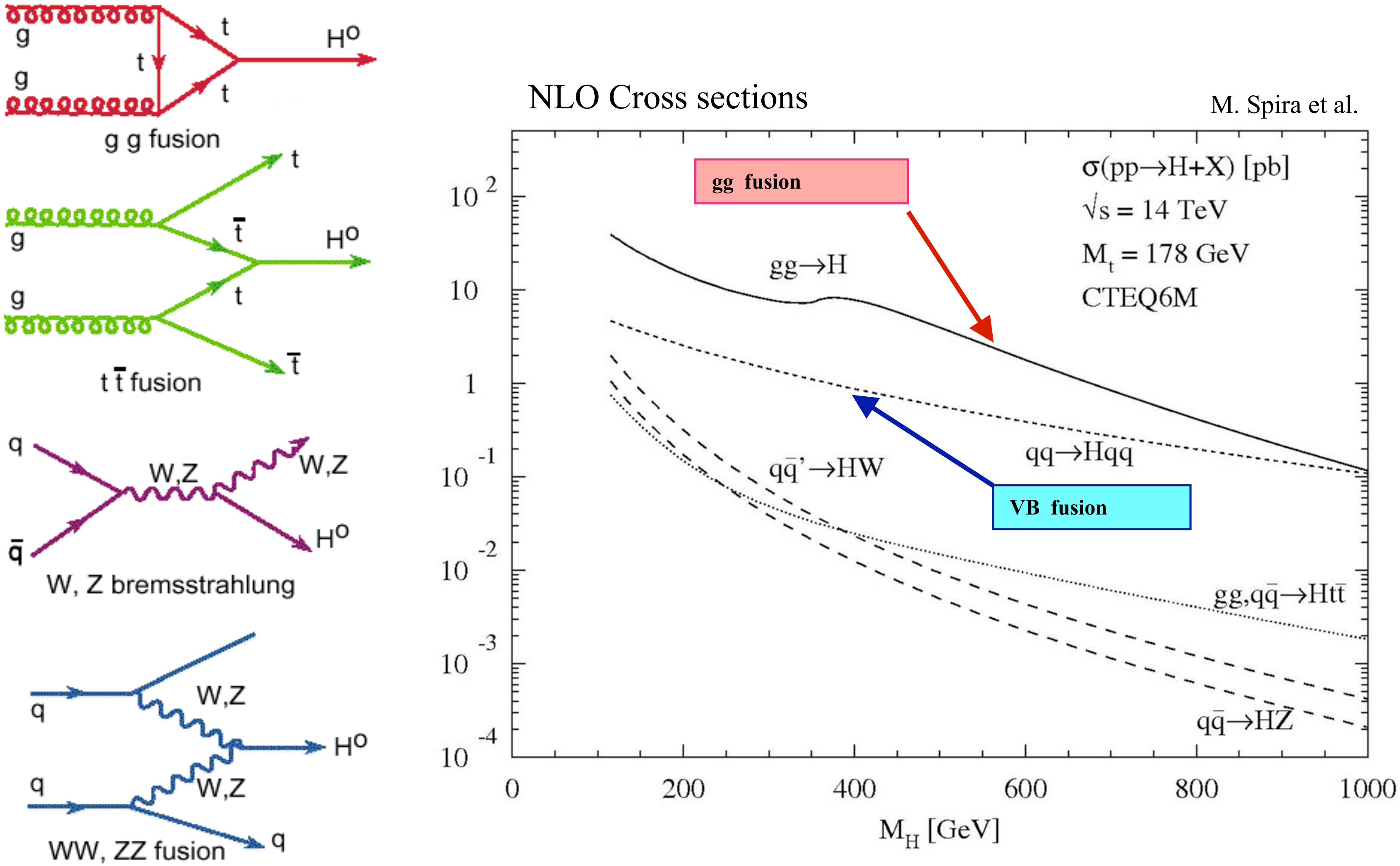
- SM Higgs (LEP)
  - $M_H > 114.4$ GeV @95% CL
- MSSM neutral Higgs bosons (LEP)
  - M_h, $M_A > 92.9$, 93.3 GeV @95% CL
  - $M_{H\pm} > 89.6$ GeV @95% CL for $BR(M_{H\pm} \rightarrow \tau\nu) = 1$
  - $M_{H\pm} > 78.6$ GeV @95% CL for any BR
- Electroweak fits to all high Q^2 measurements give:
  - $M_H = 84^{+34}_{-26}$ GeV
  - $M_H < 154$ GeV @ 95% CL

Precision EW measurements

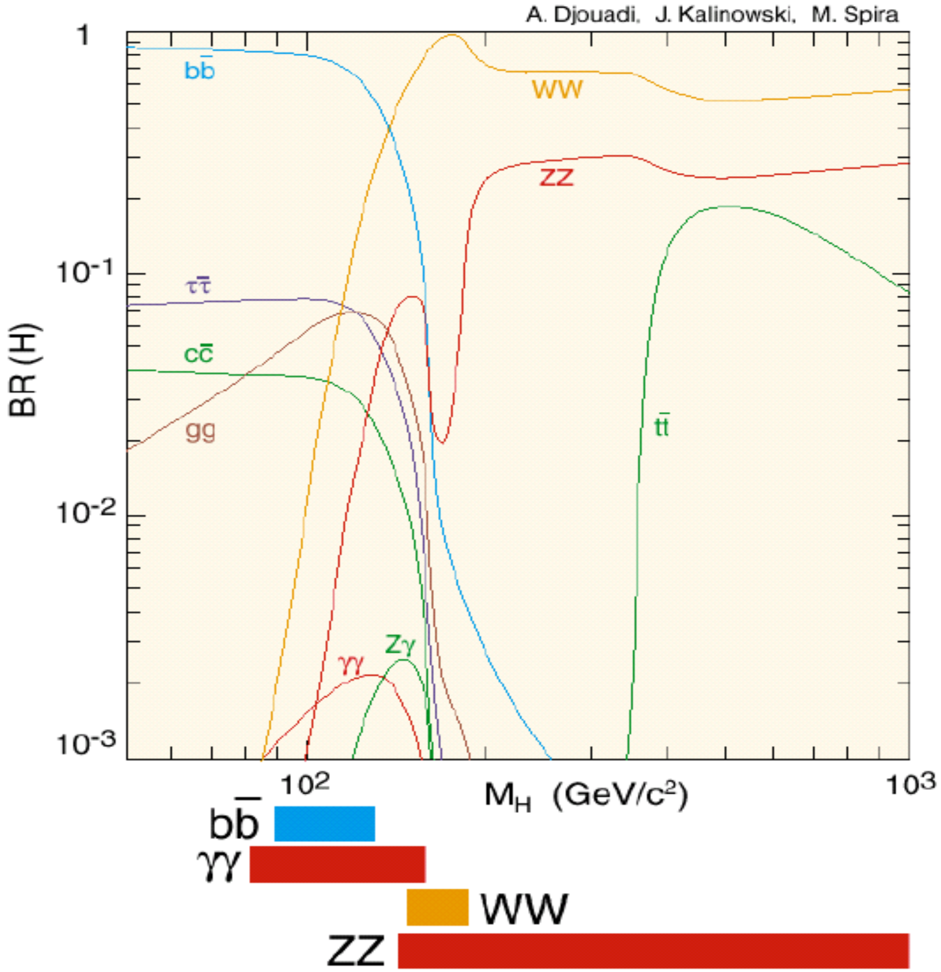


M_t=170.9 GeV
M_W=80.398 GeV

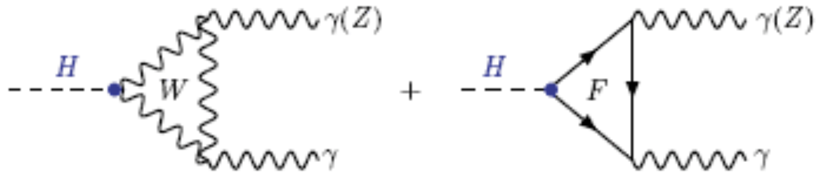
SM Higgs boson production @ LHC



SM Higgs decay modes

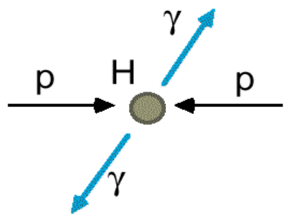


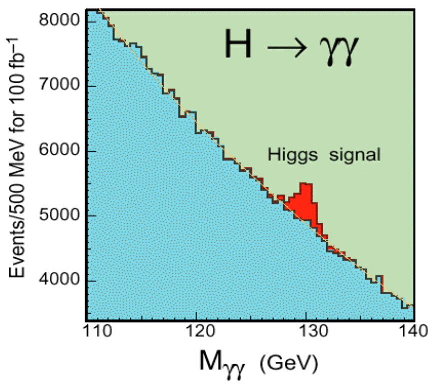
- Higgs couples to m_f^2
  - → b quarks
- until WW and ZZ modes open up (2/1 ratio)
- decay into γγ through loops

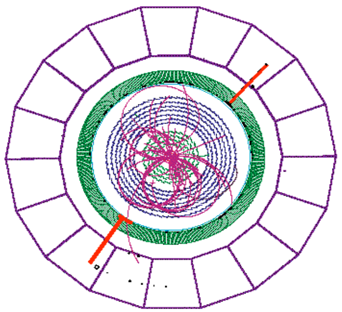


Examples

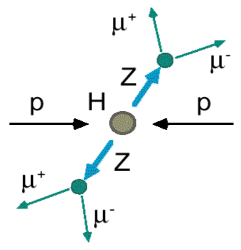
Low M_H < 140 GeV/c²

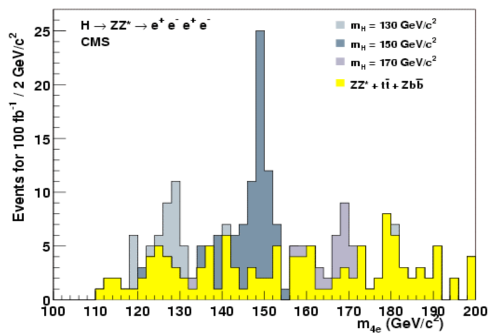


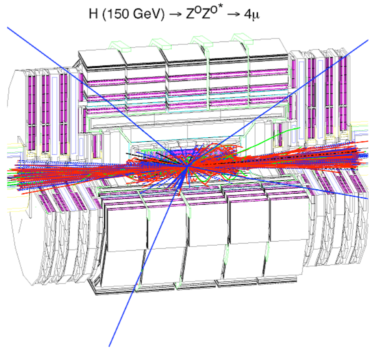




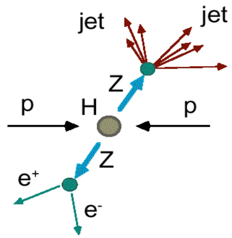
Medium 130<M_H<500 GeV/c²

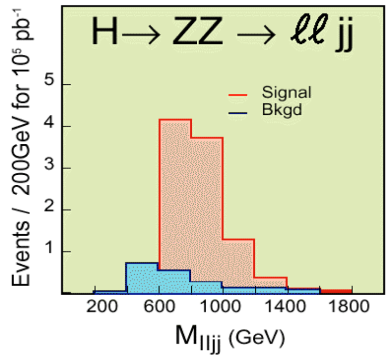


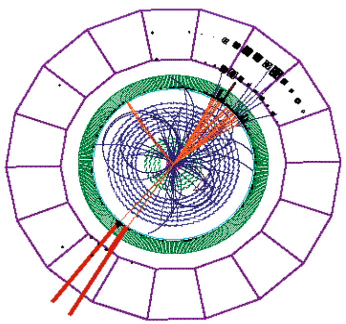




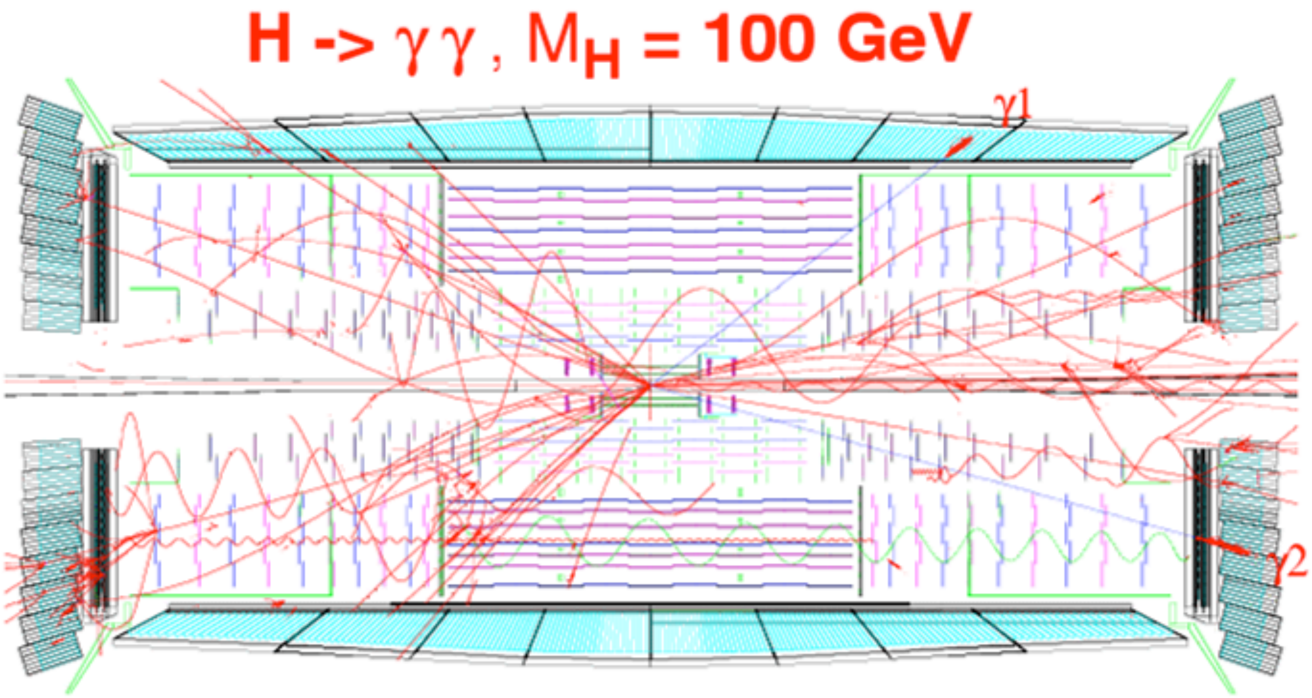
High M_H > ~500 GeV/c²





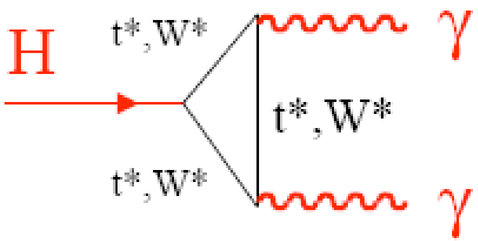


$h \rightarrow \gamma\gamma$



$h \rightarrow \gamma\gamma$

Most promising channel in the range $m_H < 150$ GeV



($\sigma.B \sim 50.10^{-3}$ pb @ $m_H \sim 150$ GeV)

σ.B can be modified by heavy undiscovered fundamental fermions or bosons

Backgrounds are large (2pb/GeV), H natural width is small (~MeV)

⇨ **excellent mass resolution** required

$$\sigma_m/m = 0.5\,[\sigma_{E1}/E_1 \oplus \sigma_{E2}/E_2 \oplus \cot(\theta/2)\Delta\theta]$$

⇨ energy resolution and precise vertex localisation

Typical Cuts

2 isolated photons – $p_T > 25$, 40 GeV with $|\eta| < 2.5$

No track or em cluster with $p_T > 2.5$ GeV in a cone size $\Delta R = 0.3$ around γs

Signal: ~ 1000's of events

High level trigger table

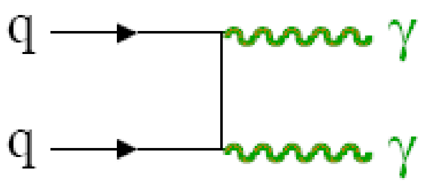
CMS HLT Summary: $2x10^{33}$ $cm^{-2}s^{-1}$

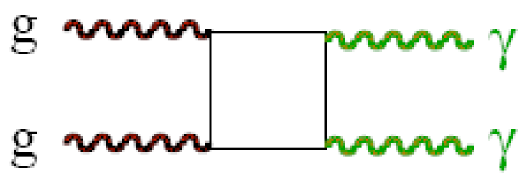
Trigger	Threshold (GeV or GeV/c)	Rate (Hz)	Cuml. rate (Hz)
Inclusive electron	29	33	33
Di-electron	17	1	34
Inclusive photon	80	4	38
Di-photon	40, 25	5	43
Inclusive muon	19	25	68
Di-muon	7	4	72
Inclusive tau-jet	86	3	75
Di-tau-jet	59	1	76
1-jet * E_T^{miss}	180 * 123	5	81
1-jet OR 3-jet OR 4-jet	657, 247, 113	9	89
Electron * jet	19 * 45	2	90
Inclusive b-jet	237	5	95
Calibration etc		10	105
TOTAL			105

$h \rightarrow \gamma\gamma$: backgrounds

Main Backgrounds

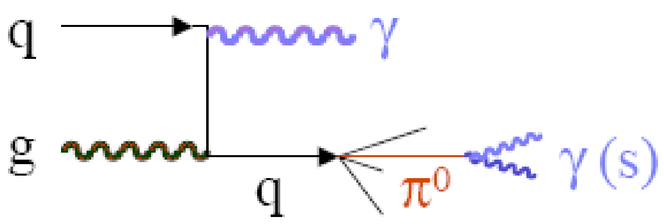
Irreducible: qq annihilation and gg 'box'





$$\frac{\sigma\ (\gamma\gamma)}{\sigma\ (H \rightarrow \gamma\gamma)} \sim 60$$

Reducible: γ-jet and jet-jet

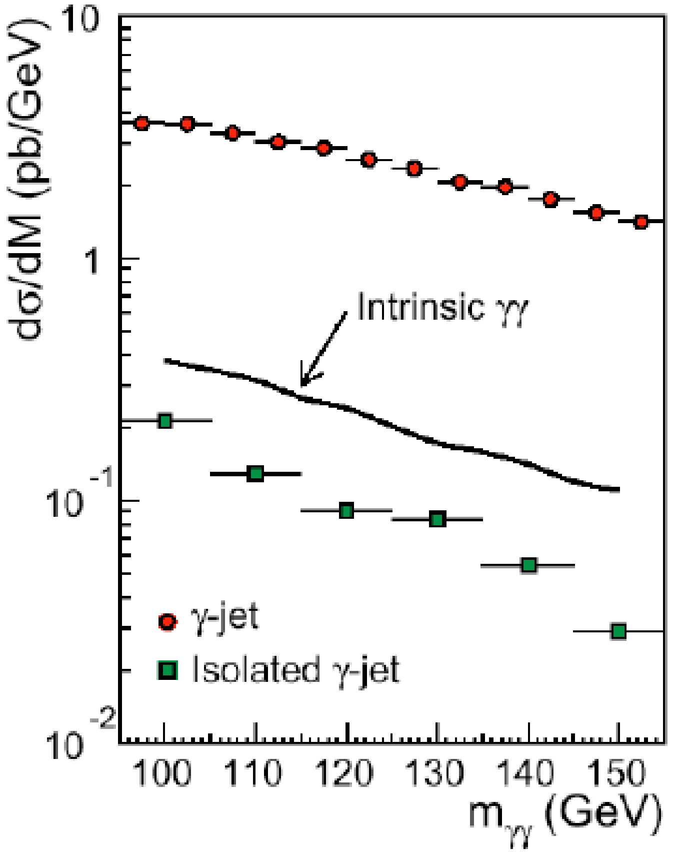


$$\frac{\sigma_{jj}}{\sigma\ (H \rightarrow \gamma\gamma)} \sim 10^8$$

A need large γ-jet separation (essentially γ-π^0 separation) to reject jets faking photons

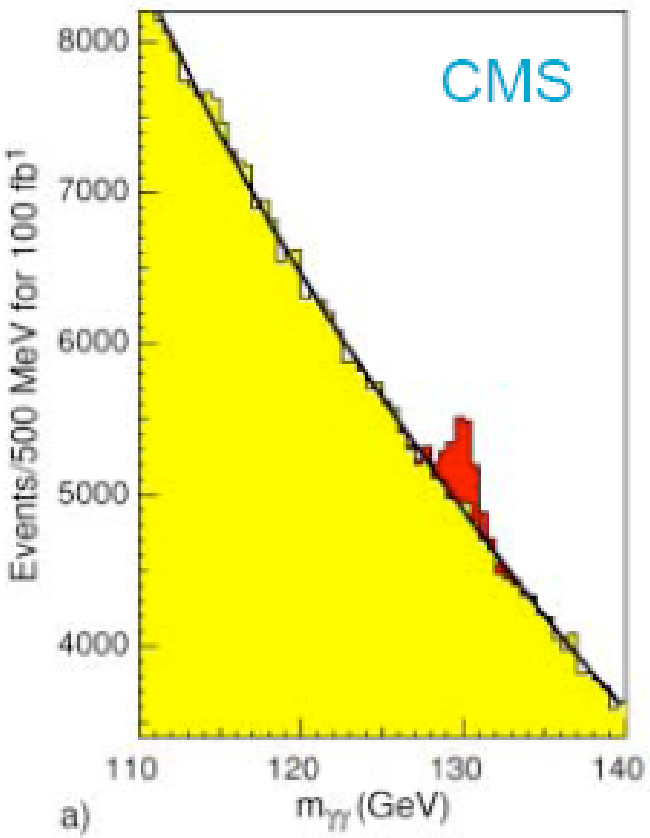
h → γγ

Background rejection:



⇨ (γ–jet + jet-jet) < 40% γγ

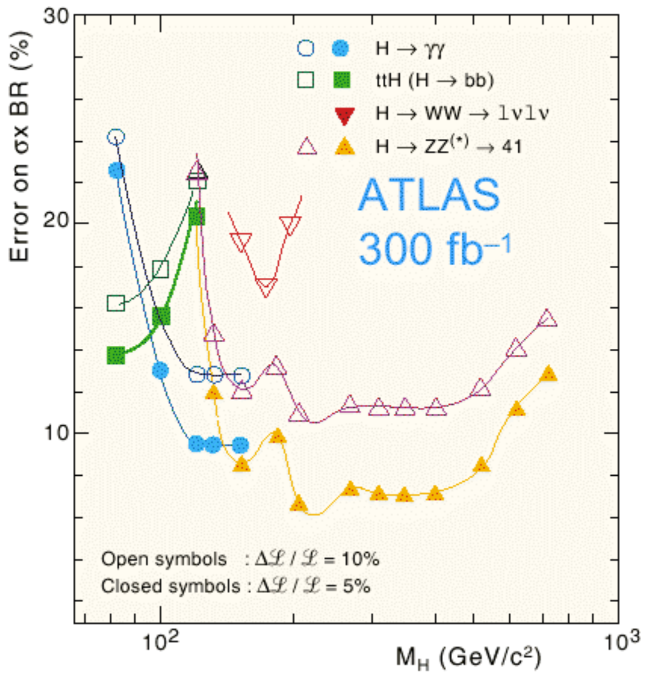
Signal:

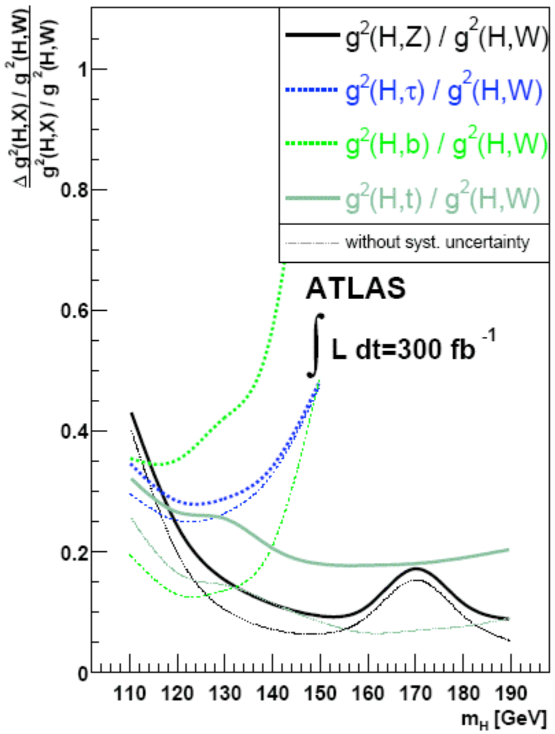


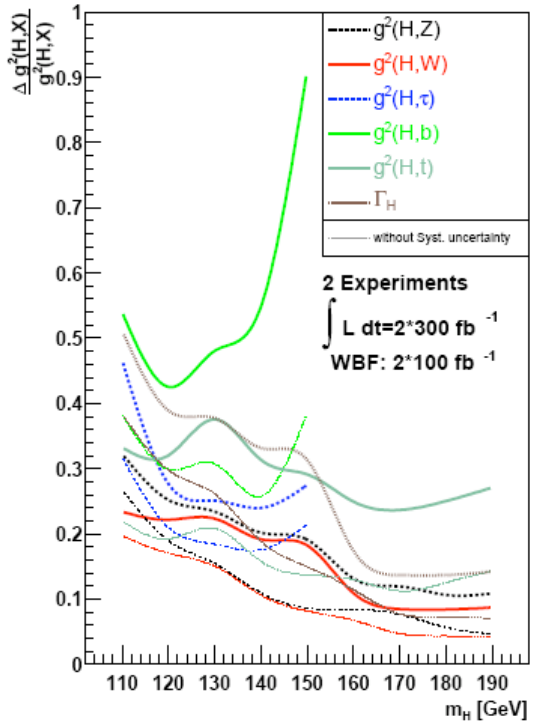
BR's and couplings

Cannot measure total Higgs cross section: no absolute meas. of partial dec. widths

Precision on σ•BR → Ratios of couplings → With "mild" theoretical assumptions→ couplings



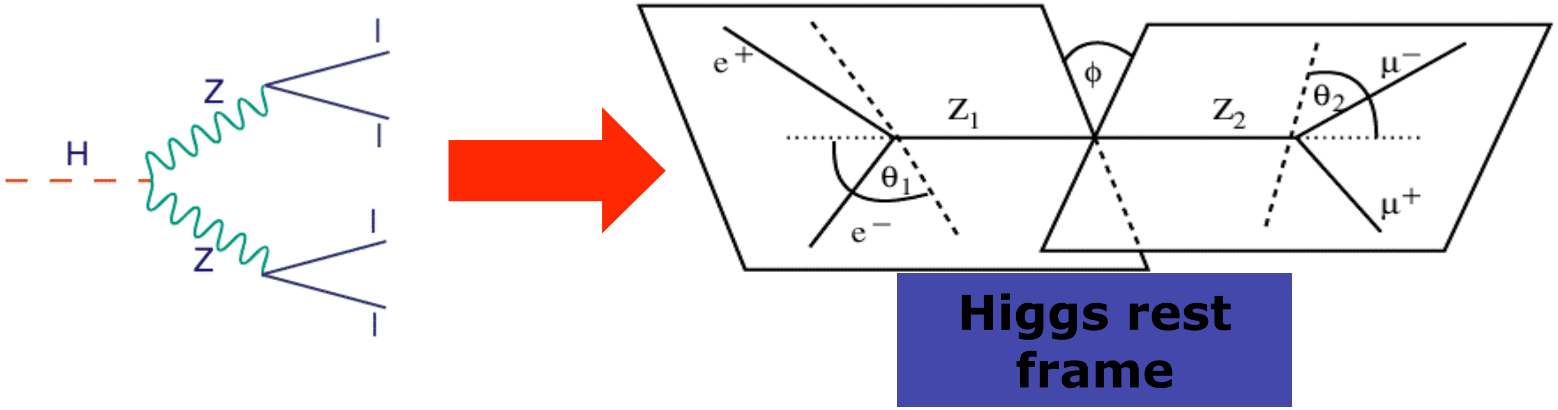




Dominated by luminosity uncertainty

Precision 10-40%

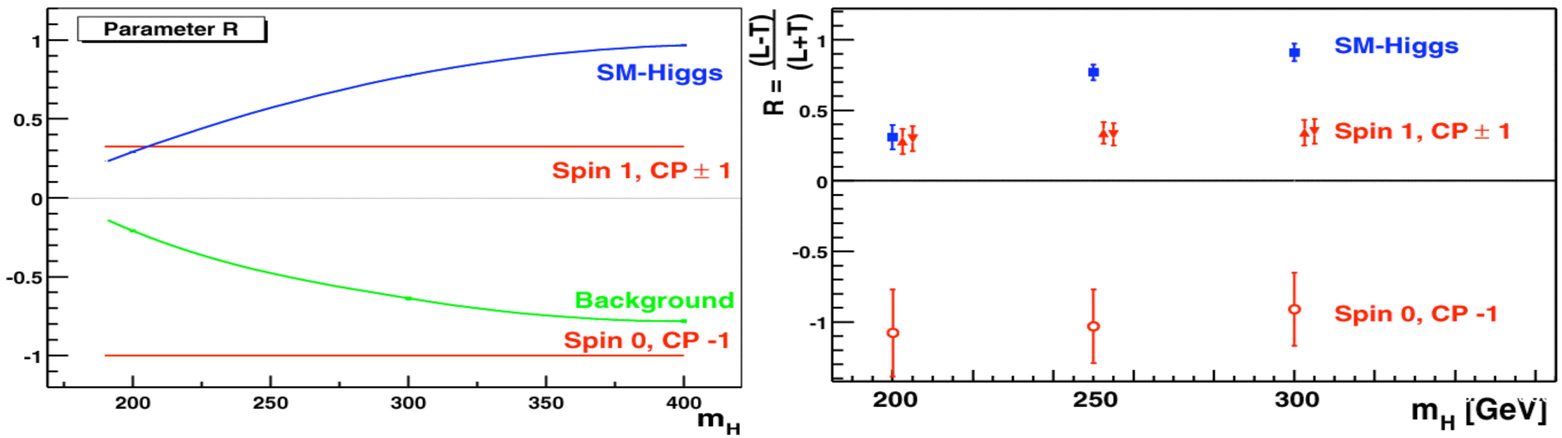
Spin and CP of Higgs



$$F(\phi) = 1 + \alpha \cos\phi + \beta \cos 2\phi$$

$$G(\theta) = L \sin^2\theta + T(1 + \cos^2\theta)$$

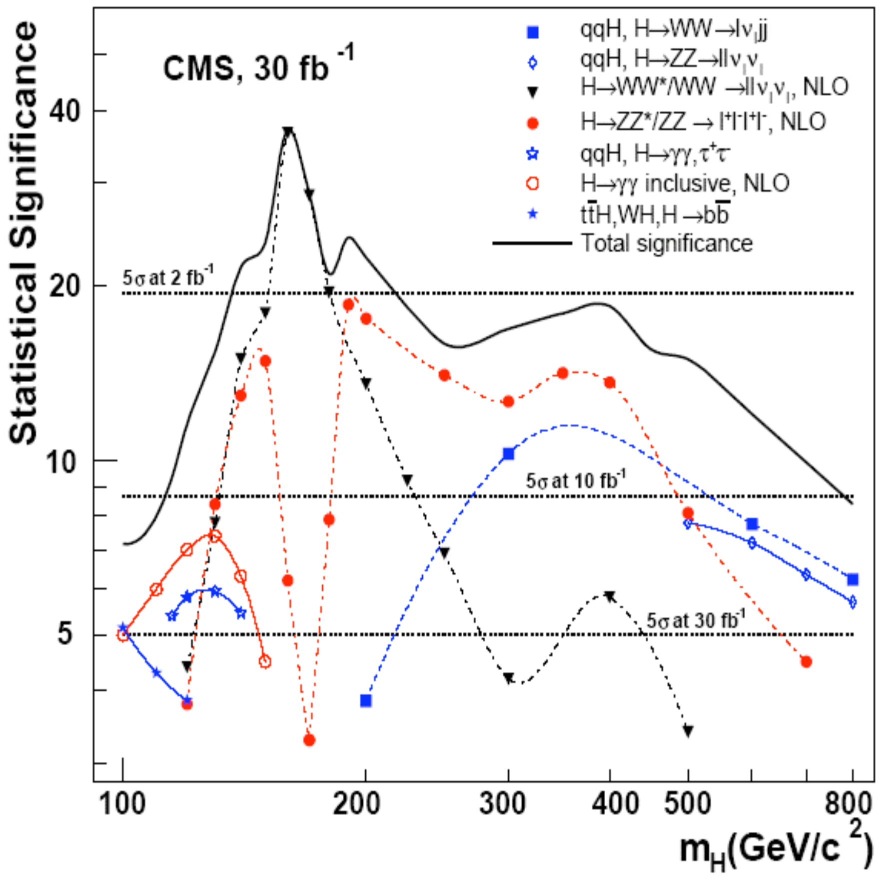
$$R = \frac{L - T}{L + T}$$

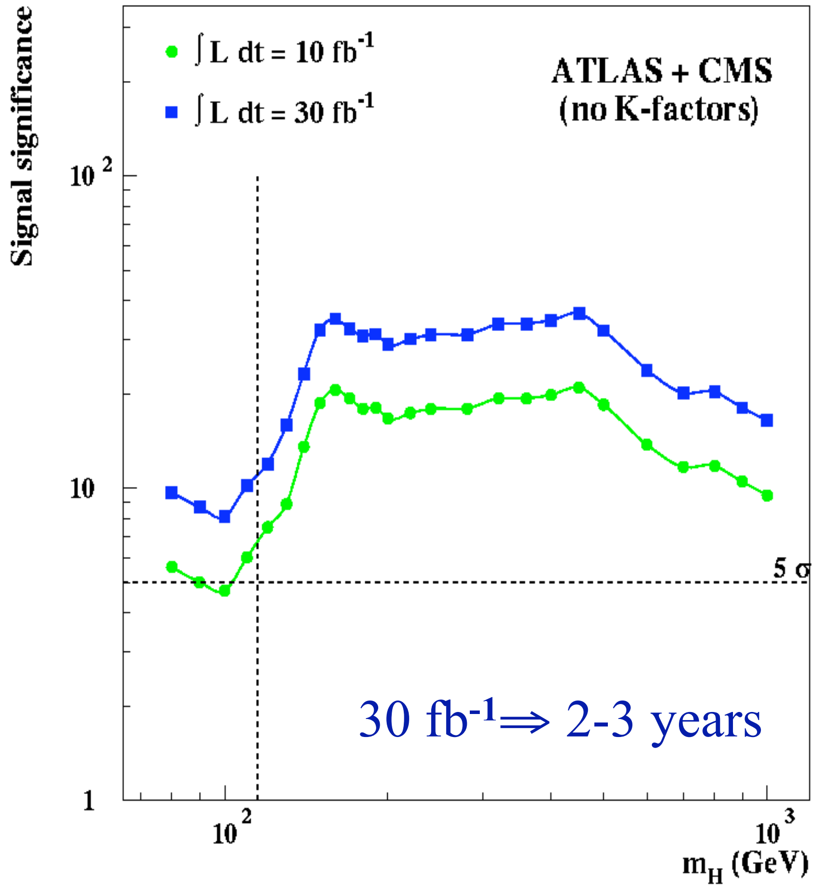


LHC reach for SM Higgs

Different channels

Total sensitivity

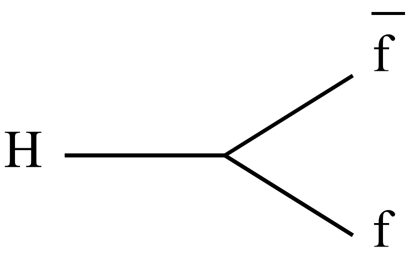




MSSM Higgs Couplings

ETH Institute for Particle Physics

Higgs couplings to fermions:



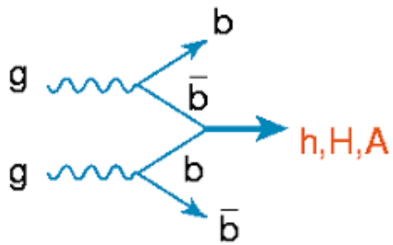
- $g_{h^0 t\bar{t}} \propto m_t \frac{\cos\alpha}{\sin\beta}$
- $g_{h^0 b\bar{b}} \propto m_b \frac{-\sin\alpha}{\cos\beta}$
- $g_{H^0 t\bar{t}} \propto m_t \frac{\sin\alpha}{\sin\beta}$
- $g_{H^0 b\bar{b}} \propto m_b \frac{\cos\alpha}{\cos\beta}$
- $g_{A^0 t\bar{t}} \propto m_t \cot\beta$
- $g_{A^0 b\bar{b}} \propto m_b \tan\beta$

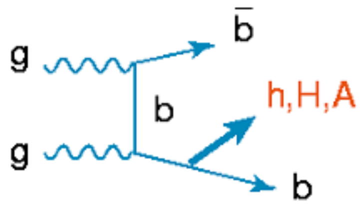
- proportional to mass → 3rd generation favoured
- tan β enhances couplings of H^0/A^0 to down-type fermions

Conventional MSSM A/H channels

… so main production mechanism for A^0 and H^0:

gg ® $A^0, H^0 b\bar{b}$



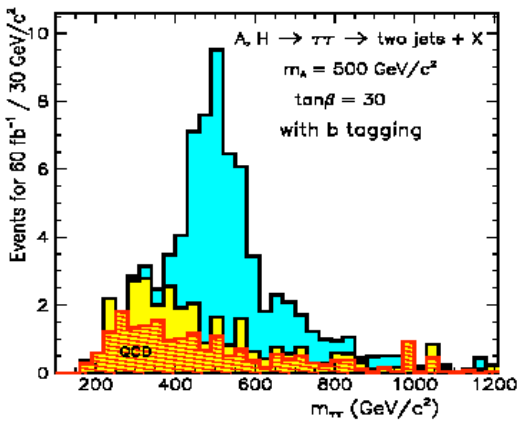


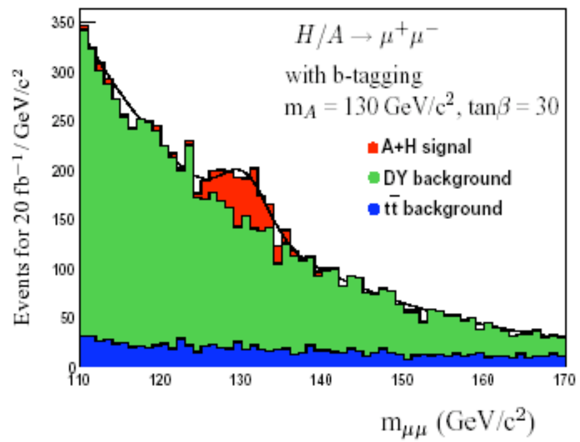
and use decay mode:

A^0, H^0 ® $\tau\bar{\tau}$

A^0, H^0 ® $\mu\bar{\mu}$

(A^0, H^0 ® $b\bar{b}$)

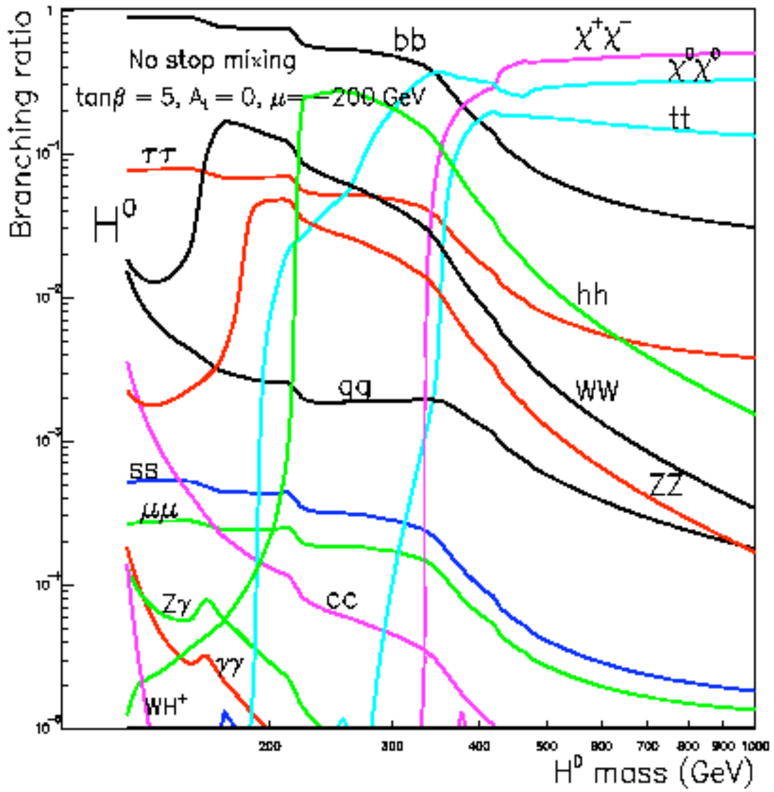




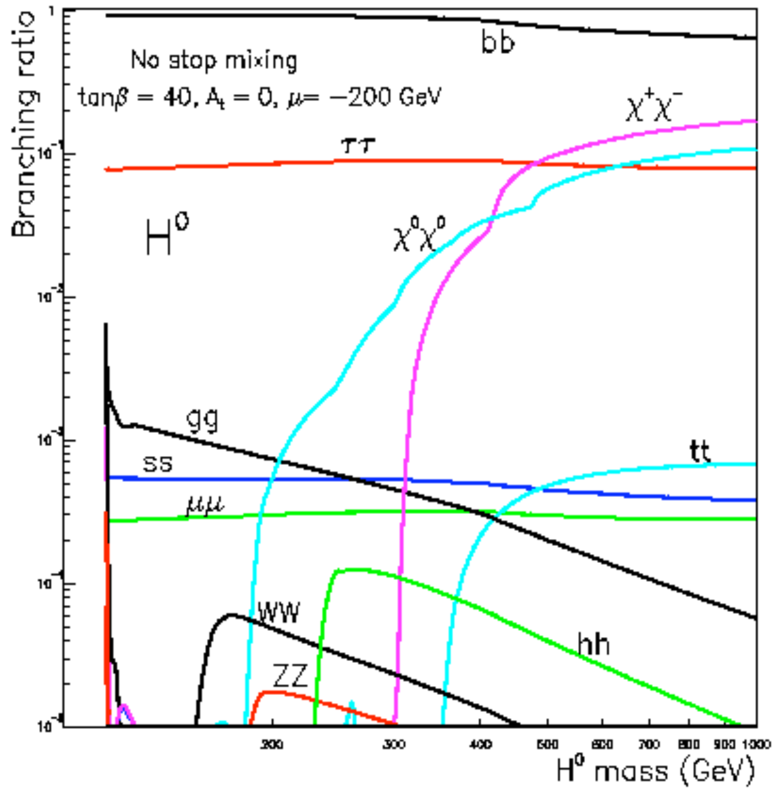
?

A/H branching ratios

low tan β



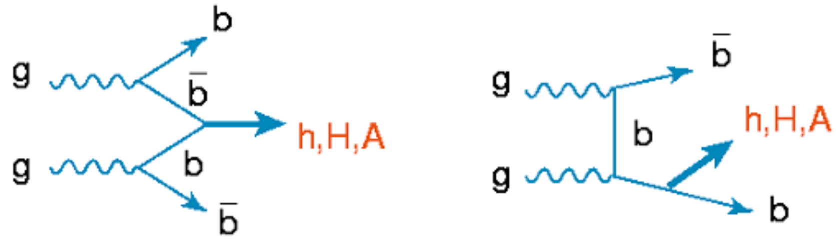
high tan β



(HDECAY)

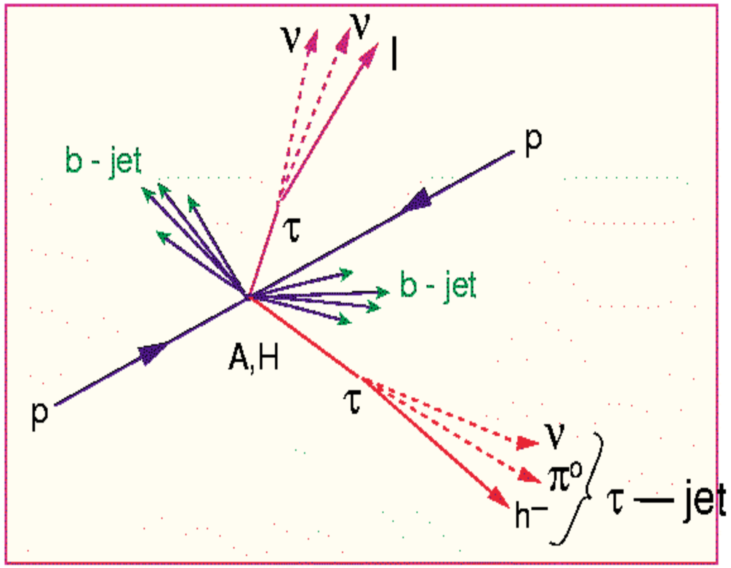
A/H → ττ

Most promising channel:



A/H → ττ

where the taus can decay leptonically or hadronically:



1. lepton + lepton
2. lepton + hadron : $M_A < 350$ GeV
3. hadron + hadron : $M_A > 350$ GeV

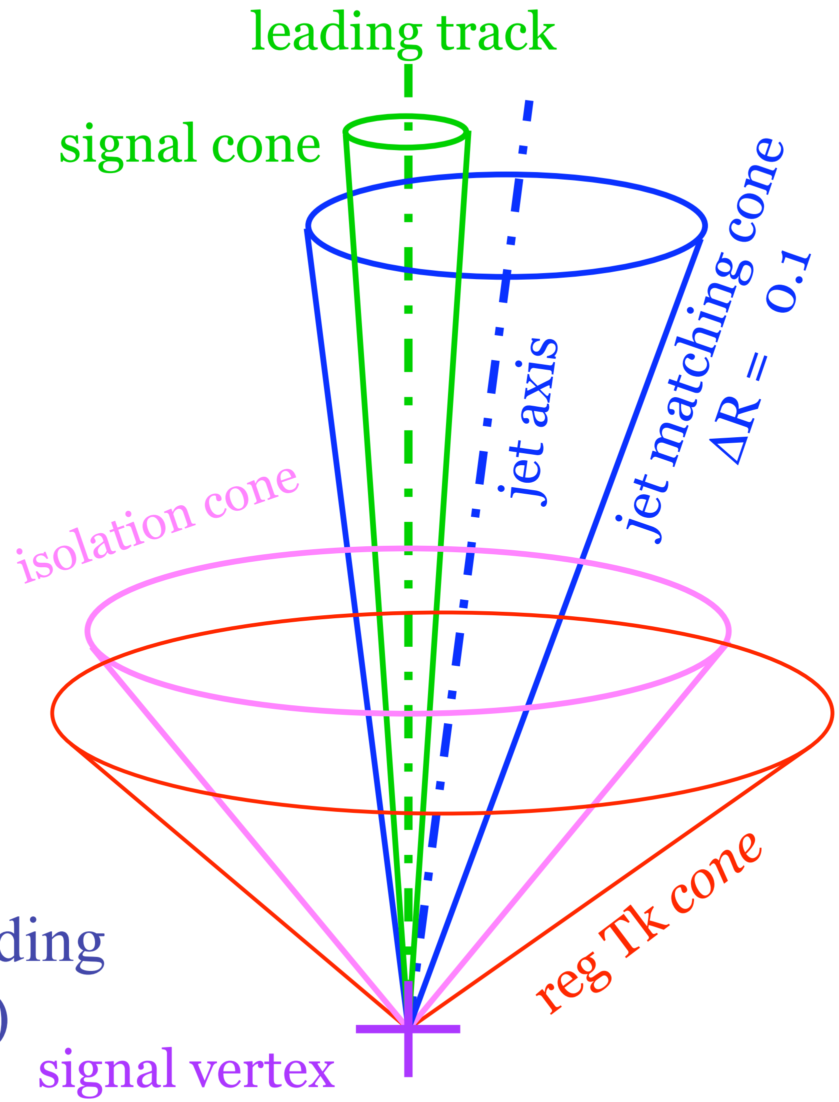
Tau-jet selection

- remember τ branching ratios:
  - $\tau \rightarrow l\, \nu_l\, \nu_\tau$: 35%
  - $\tau \rightarrow \pi^{\pm} + n\, \pi^{0}$'s : 50%
  - $\tau \rightarrow 3\pi^{\pm} + n\, \pi^{0}$'s : 15%

- prefer hadronic decays (for mass rec.) but QCD background is huge

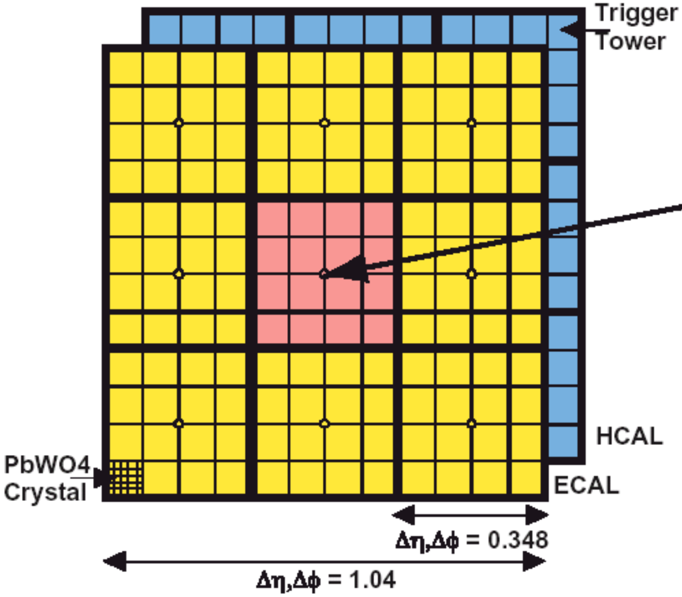
CMS has developed dedicated τ trigger for this!!

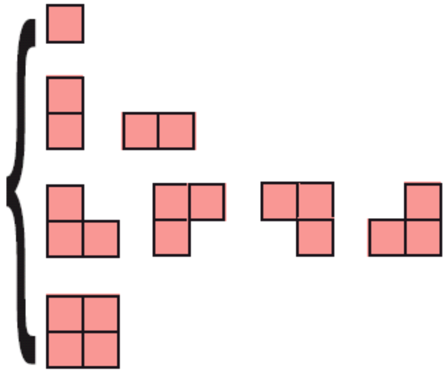
→ look for narrow jet (L1) with leading charged track ($\pi^{\pm}$) (L3)



L1 jet/τ algorithm

Input from E/HCAL: Programmable 8-bit nonlinear scale converted to 10-bit linear scale for sums to obtain jet E_T





τ-veto bit formed by requiring a single contiguous group of less than four active towers in each 4x4 region

Jet or τ E_T

- 12x12 trigger tower E_T sums in 4x4 region steps with central region > others,
- *central region above a programmable threshold*

τ algorithm

- redefine jet as τ-jet if none of the nine 4x4 region τ-veto bits are on

Output

- top 4 τ-jets and top 4 jets in central rapidity, and top four jets in forward rapidity

A/H → ττ : background rejection

ETH Institute for Particle Physics

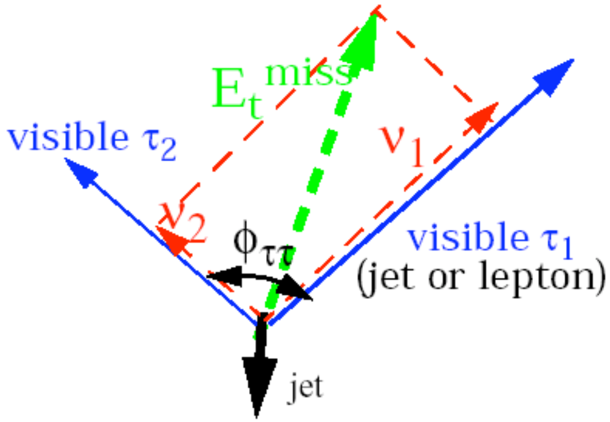
Signal: 2 τ jets + 2 soft b jets

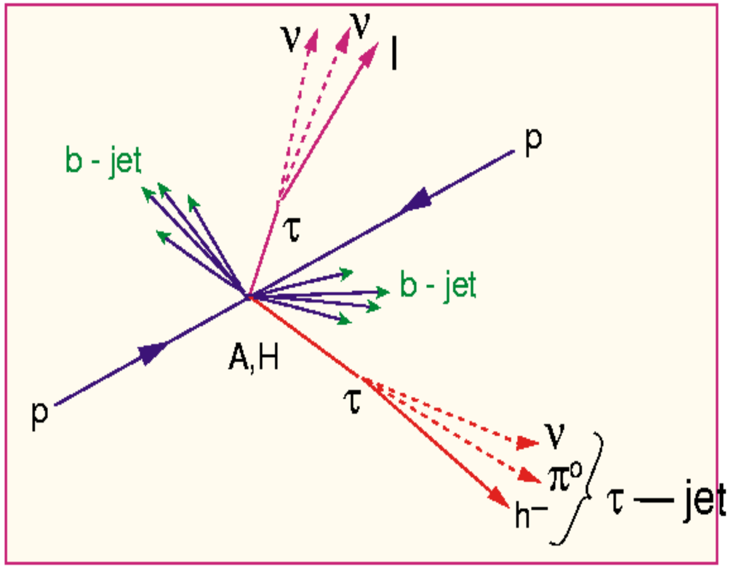
Main backgrounds:		Main rejection techniques:
QCD jets (2 fake τ 's)	⟷	τ-jet ID, E_T^{miss} cut
W + jets (1 real + 1 fake τ)	⟷	τ-jet ID, τ-tagging (IP, vertex)
$t\bar{t}$ (2 real τ 's + 2 hard b's)	⟷	central jet veto
Z, γ* → ττ (2 real τ 's)	⟷	b-tagging

A/H → ττ : mass reconstruction

Assume neutrinos are emitted in the direction of the tau ($M_\tau << E_T^\tau$):

$$E\nu_1 x_1 + E\nu_2 x_2 = E_x^{miss}$$
$$E\nu_1 y_1 + E\nu_2 y_2 = E_y^{miss}$$





$\sigma(M_H) \sim \sigma(E_t^{miss})/\sin(\Delta\phi)$!

back-to-back is the worst case for the mass reconstruction

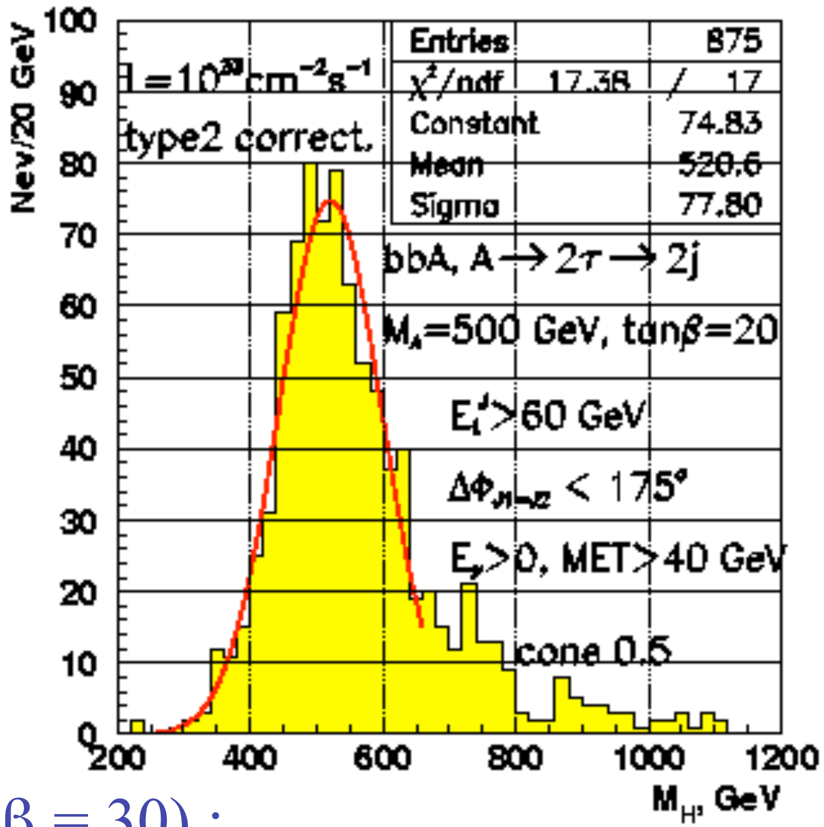
A/H → ττ : mass resolution

A/H → ττ → jj has Gaussian shape with σ(ττ) = 15%
(for m_A = 500 GeV, low lumi)

→ precision on m_A:

$$\sigma(m_A) = \frac{15\%}{\sqrt{n}}$$

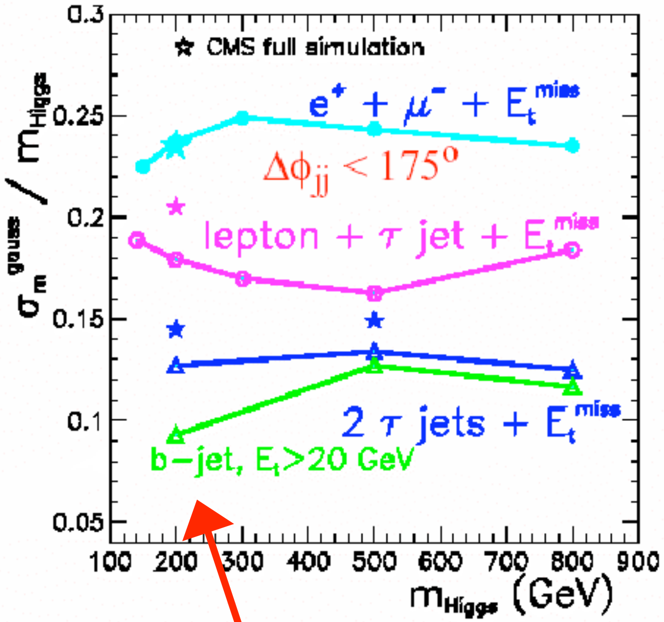
with n the number of events



E.g. at SPS 1b (m_A= 500 GeV, tan β = 30) :
~ 100 events for 30 fb^{-1} : $\sigma(m_A)$ = 1.5% (assuming no background)

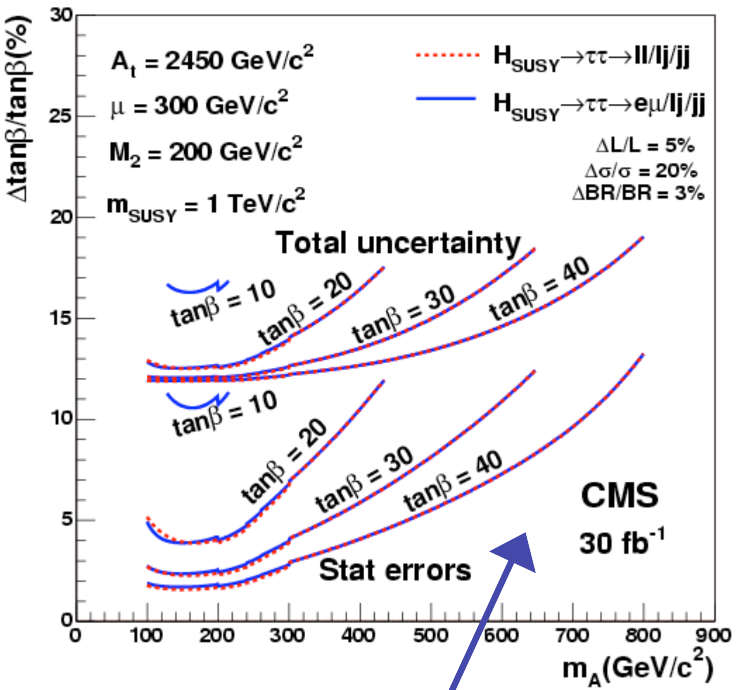
A/H → ττ : mass resolution (2)

Mass resolution for τ channels:



for lower Higgs masses, the mass resolution improves with factor 2 by tagging associated b-jet

m_A known → tan β measurement from rates:



single b-tagging works best

tan β measurement

At large tan(β), σ x Br ~ $\tan^2(\beta)_{eff}$ $f(M_A)$ at fixed μ, M_2, A_t, M_{SUSY}

$$N_S = \tan^2(\beta)_{eff}\ f(M_A)\ L\ \varepsilon_{sel}$$

$$\tan(\beta) = \tan(\beta)_{mes} +/- \Delta_{stat} +/- \Delta_{syst} +/- \Delta_{MCgen}$$

$$\Delta_{syst} = 0.5\ \mathrm{sqrt}(\Delta L^2 + \Delta\sigma_{th}{}^2 + \Delta Br_{th}{}^2 + \Delta\sigma(\Delta M_H)^2 + \Delta\varepsilon_{sel}{}^2 + \Delta B^2)$$

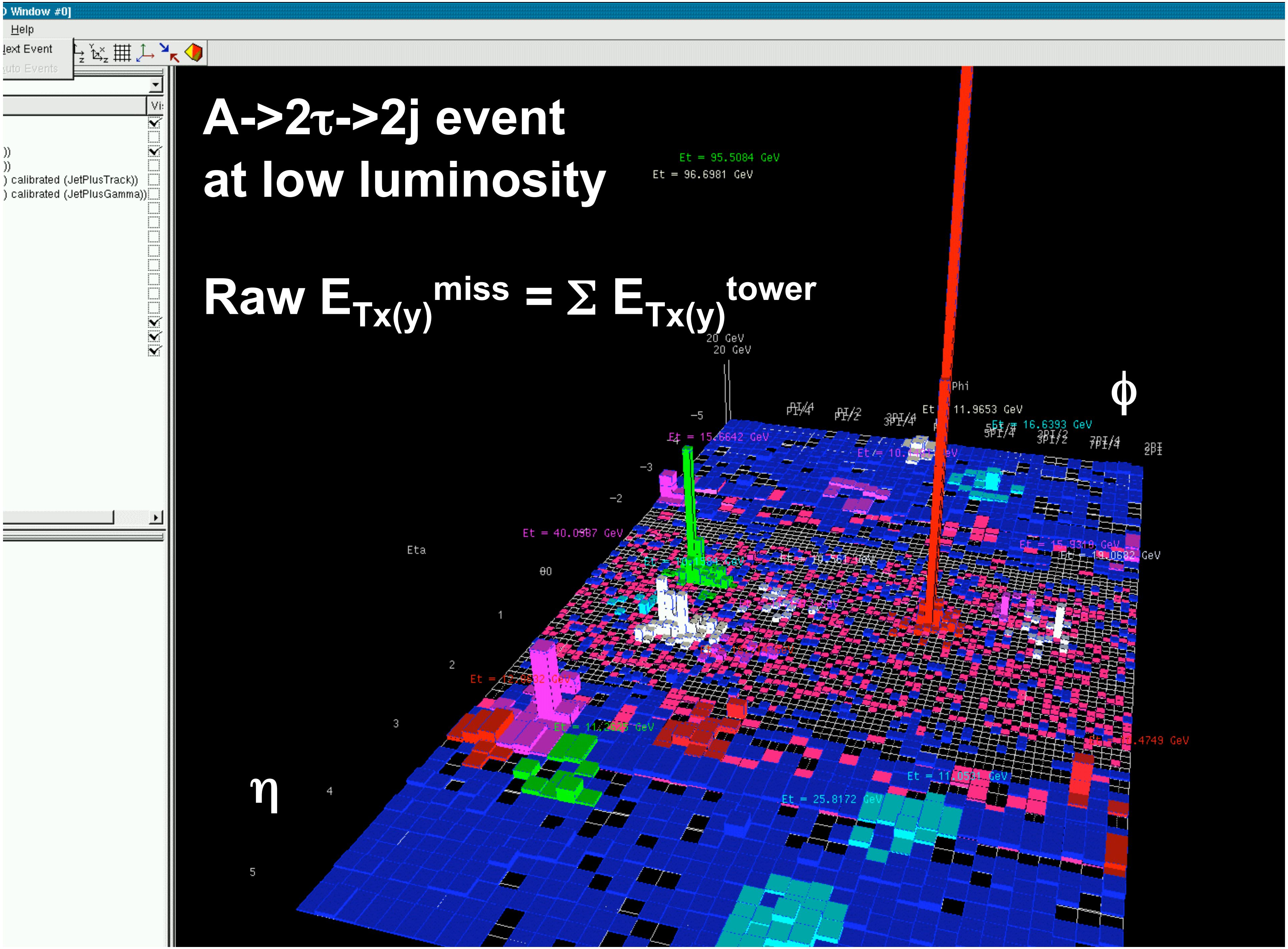
$\Delta\sigma_{th}$ = 20 % due to NLO scale dependence
ΔBr_{th} = 3 % uncertainties of SM input parameters
ΔL = 5 % luminosity uncertainty
$\Delta\sigma(\Delta M_H)$ = 10-12 % due to mass measurement at 5σ discovery limit
$\Delta B = \Delta N_B / N_S$ = 10 % at 5σ discovery limit (preliminary)

$$\Delta\varepsilon_{sel}{}^2 = \Delta\varepsilon_{calo}{}^2 + \Delta\varepsilon_{b\ tag}{}^2 + \Delta\varepsilon_{\tau\ tag}{}^2$$

$\Delta\varepsilon_{b\ tag}$ = 2.0 % (preliminary)
$\Delta\varepsilon_{\tau\ tag}$ = 2.5 % (preliminary)
$\Delta\varepsilon_{calo}$ = 2.9 % (preliminary)

A->2τ->2j event at low luminosity

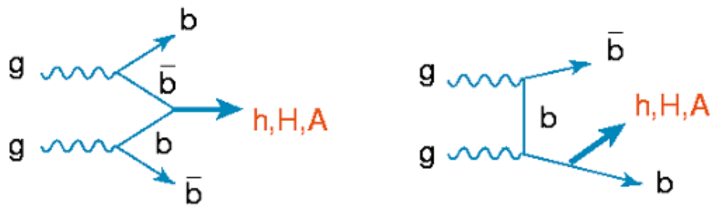
$$\text{Raw } E_{Tx(y)}^{miss} = \Sigma E_{Tx(y)}^{tower}$$



A/H → μμ

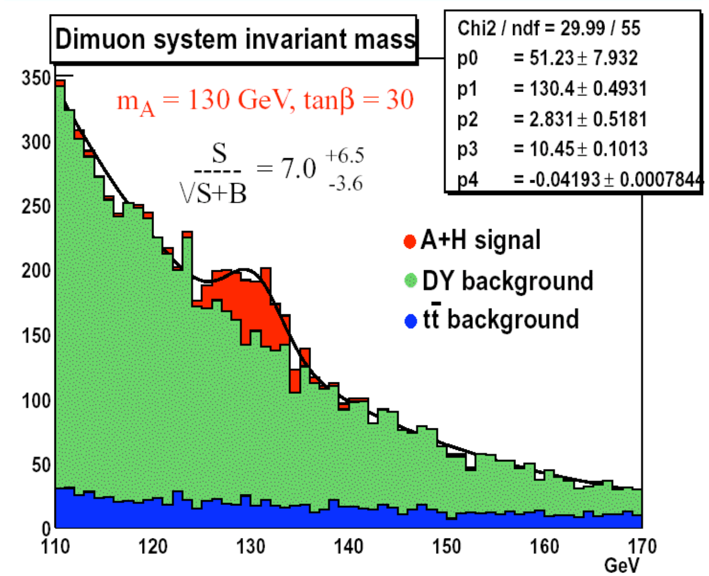
A/H → μμ branching ratio only ~ 3 . 10^{-4} but easy triggering and excellent μ momentum resolution

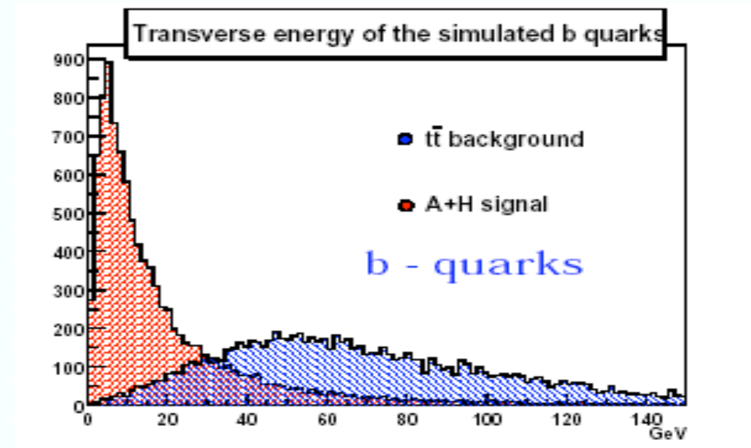
→ feasable at high tan β and low m_A …



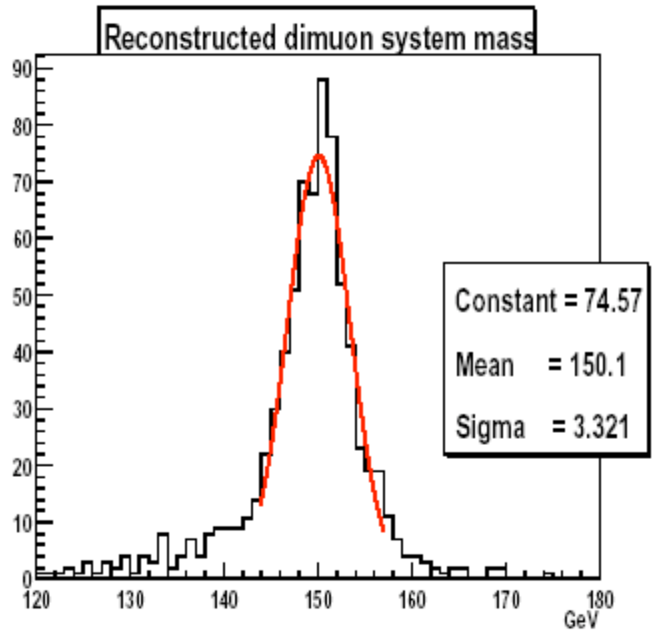
Exploit bbμμ signature (effective against DY background)

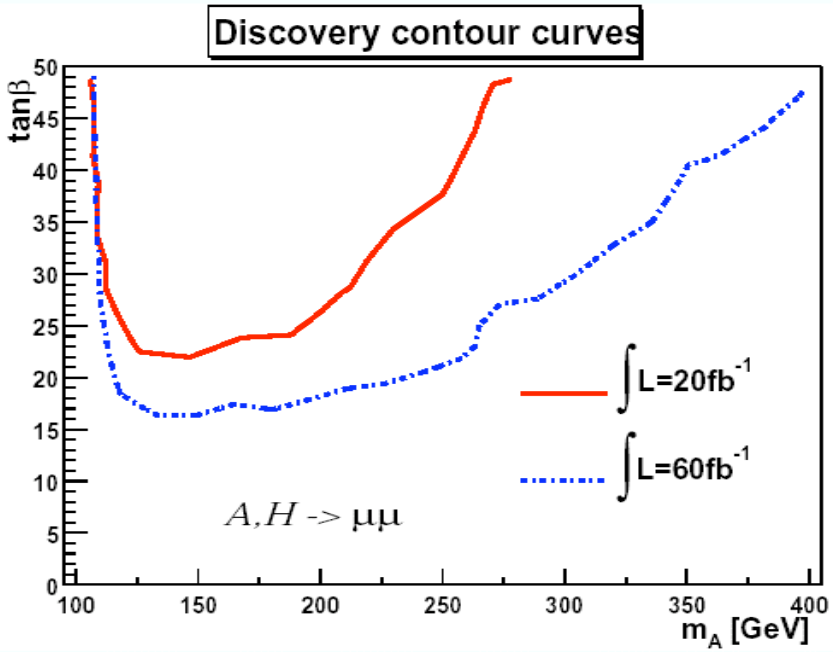
→ need excellent b-tagging





A/H → μμ : mass resolution





μμ mass resolution of 1% :

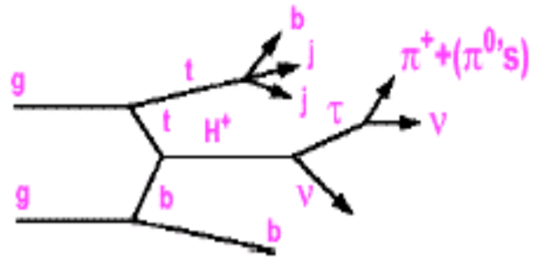
- most precise determination of m_H (and tan β)
- fit to μμ signal shape might allow Γ_H measurement

Charged Higgs bosons

Production:

- in tt events with t -> b$H^{\pm}$ if $m_{H+} < m_{top}$
- through gg -> tb$H^{\pm}$ if $m_{H+} > m_{top}$

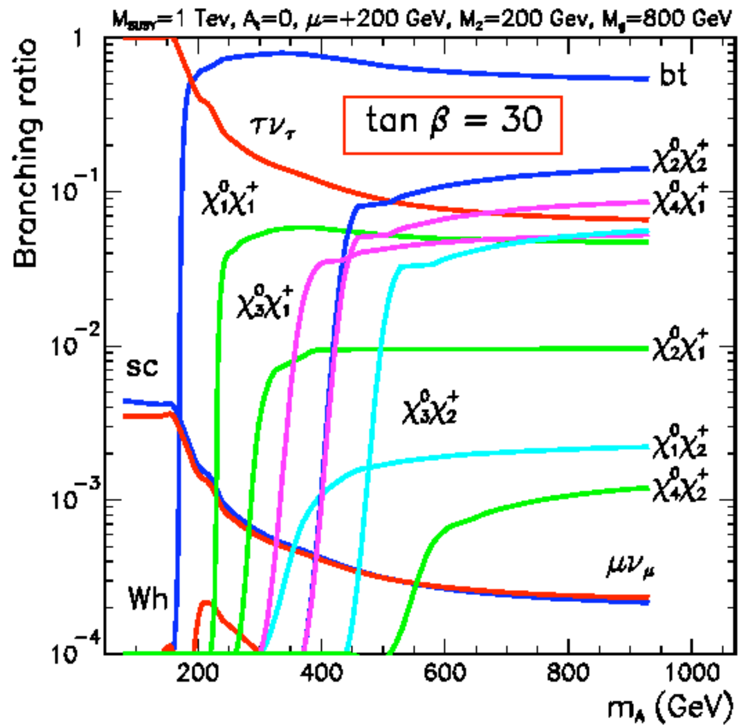
For $m_{H+} > m_{top}$: can use extra top in the event!
(the associated b is usually at large rapidities)



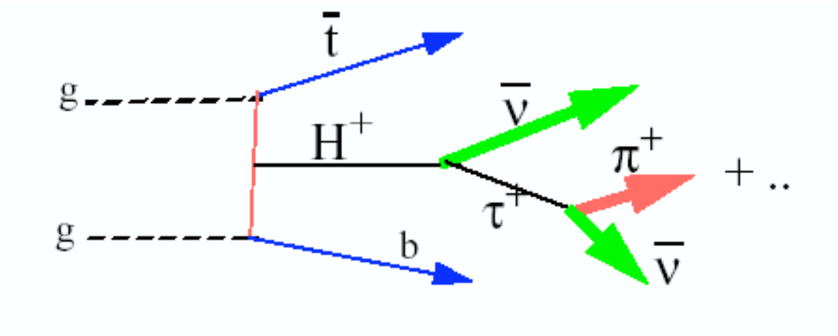
Decay channels:

- $m_{H+} < m_{top}$: BR($H^{\pm}$ → τν) ~100%
- $m_{H+} > m_{top}$ and large tanβ (>10):
  $H^{\pm}$ -> tb dominates
  BR($H^{\pm}$ -> τν) sizeable ~10%

Advantage with $H^{\pm}$ -> τν, τ -> hadrons+n:
Helicity correlations can be exploited
to suppress irreducible backgrounds
from tt, Wt and W+jets with W->τν



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



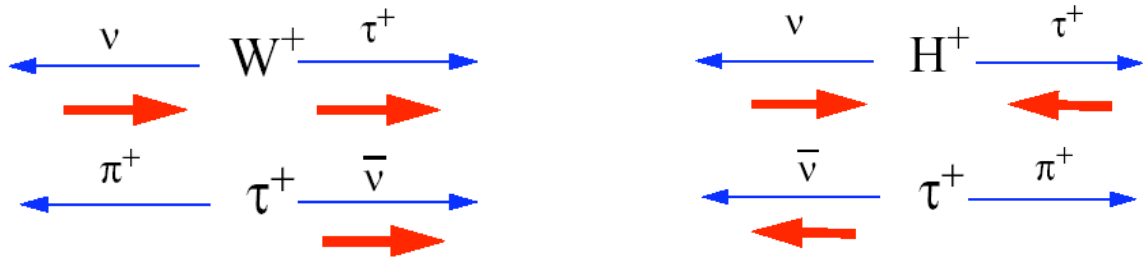
Strategy:

- reconstruct hadronic τ
- reconstruct hadronic top ($t \rightarrow bjj$)

Main backgrounds: $t\bar{t}$, Wtb, W + jets

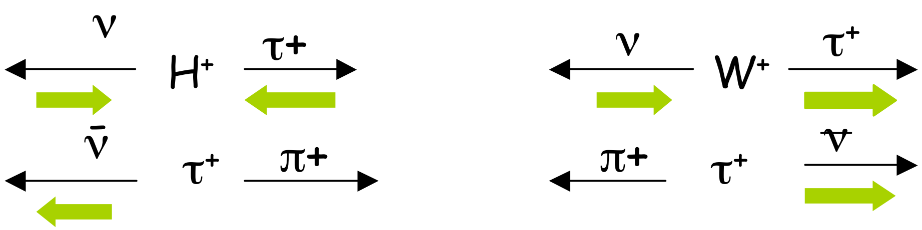
W and $H^{\pm}$ have different spin → exploit τ polarization effects !!

(*D.P. Roy*)



→ harder pions from $H^{\pm}$ …

Spin correlations



Harder pions from $H^+ \to \tau^+\nu$ than from $W^+ \to \tau^+\nu$
(through $\tau \to \pi^+\nu$ and the longidutinal components of ρ and a_1)

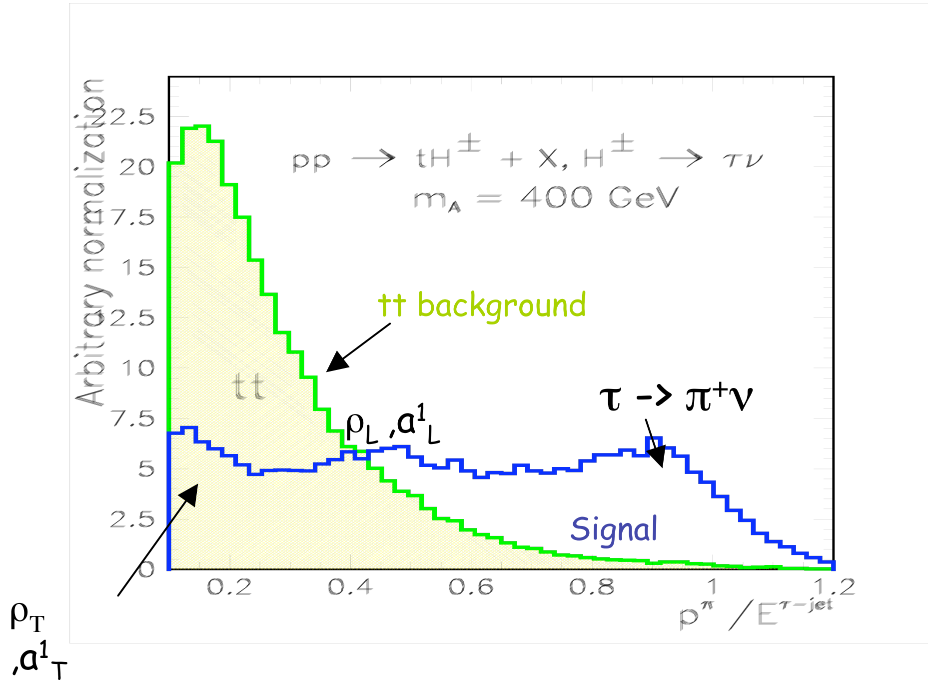
Suppression of backgrounds with genuine τ's from W->τν with a cut in $p^\pi/E^{t\ jet}$

Efficiency with $p^\pi/E^{t\ jet} > 0.8$:

Signal ($m_{H\pm}$ = 400 GeV) ~45%

tt background ~2%

(fast simulation)

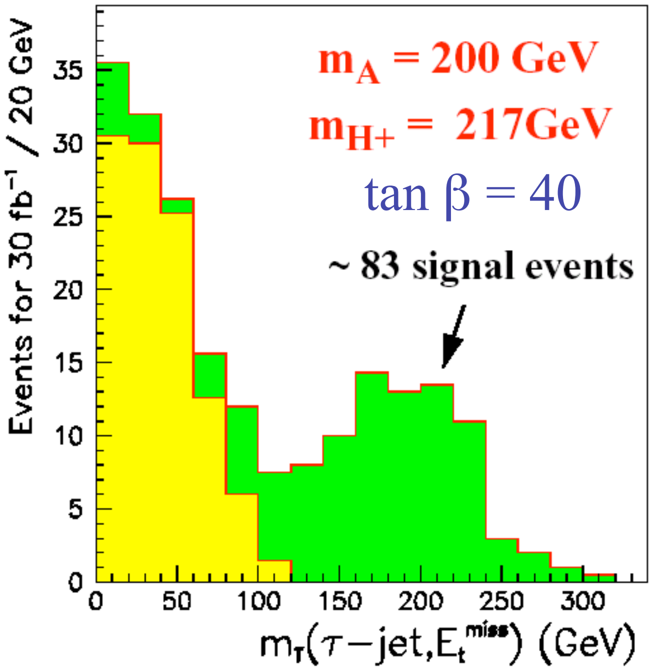


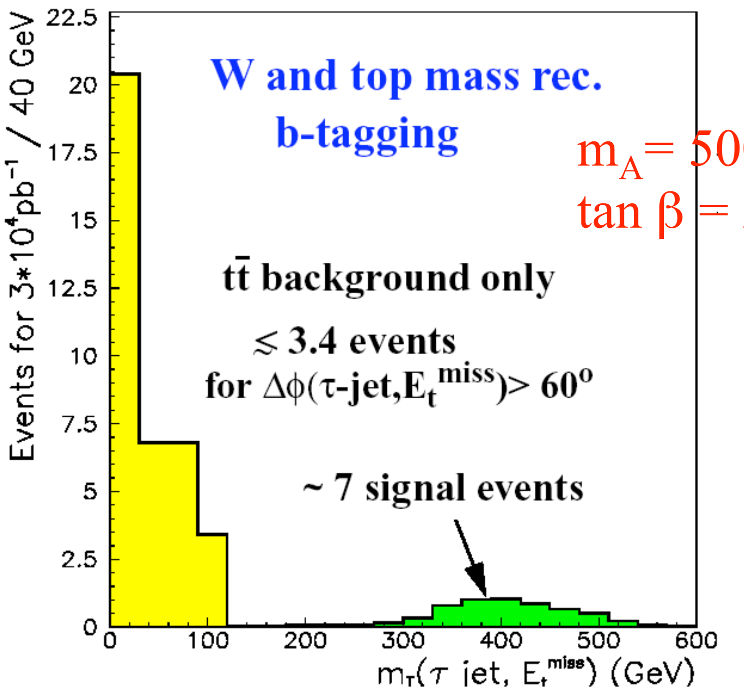
$H^{\pm} \rightarrow \tau\nu$: mass reconstruction

ETH Institute for Particle Physics

τ decays hadronically → only 1 neutrino

→ 2% mass precision possible by fitting Jacobian peak

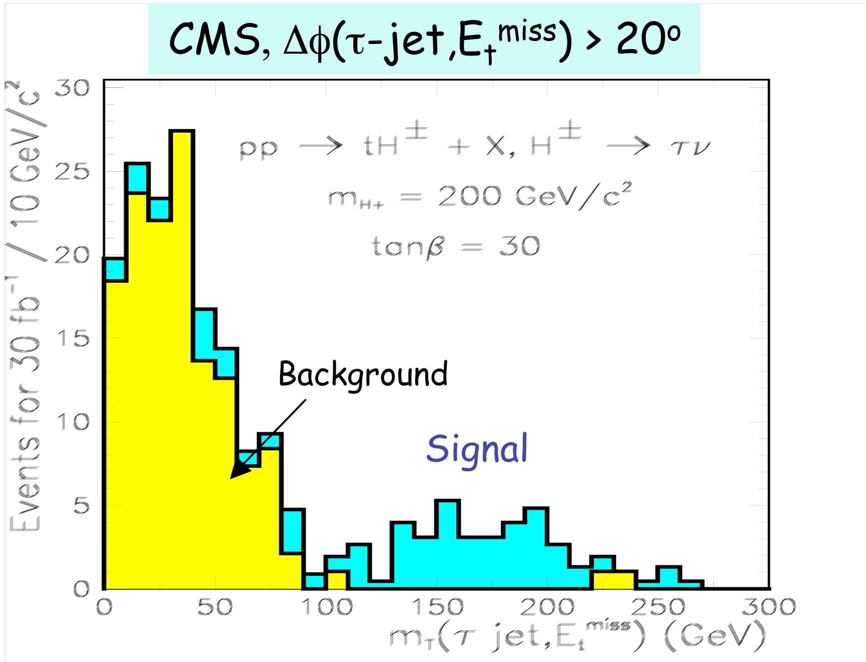


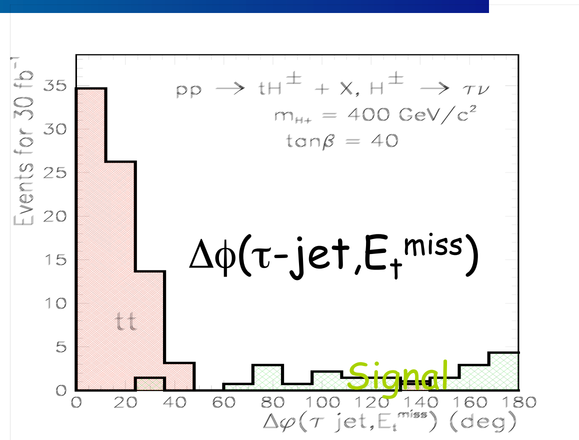


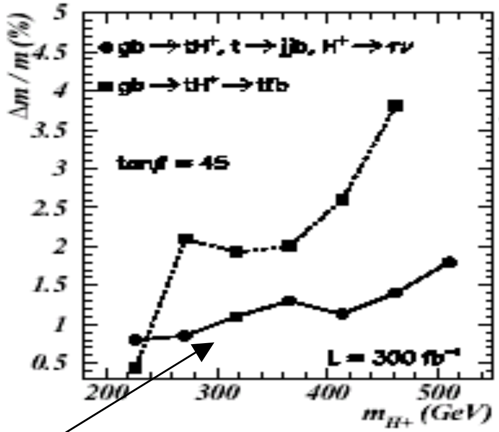
m_A= 500 GeV, tan β = 25

$H^{\pm} \rightarrow \tau\nu$: mass reconstruction

Quasi two-body decay between the τ jet and E_t^{miss} in fully hadronic events → almost background-free situation in $m_T(\tau\text{-jet}, E_t^{miss})$

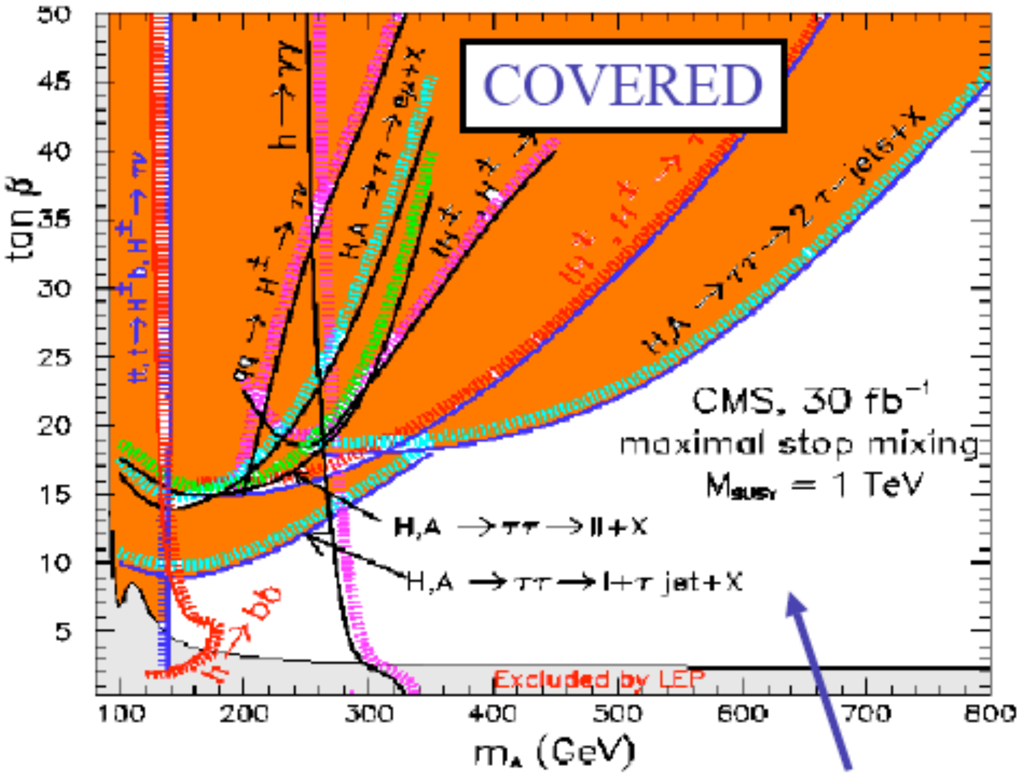






Precision of m_{H+} measurement from $m_T(\tau\text{-jet}, E_t^{miss})$ with likelihood fits: $\Delta m_{H+}/m_{H+} \sim 1 - 1.5\%$

Discovery reach



- discovery of the heavy MSSM Higgses limited to upper triangle in m_A – tan β plot
- note: the h^0 can always be found
- problem is that production mechanism (e.g. bbA^0,H^0) needs tan β enhancement

Need new ideas to cover low tanβ - high m_A region …