SUPERSYMMETRY at the LHC

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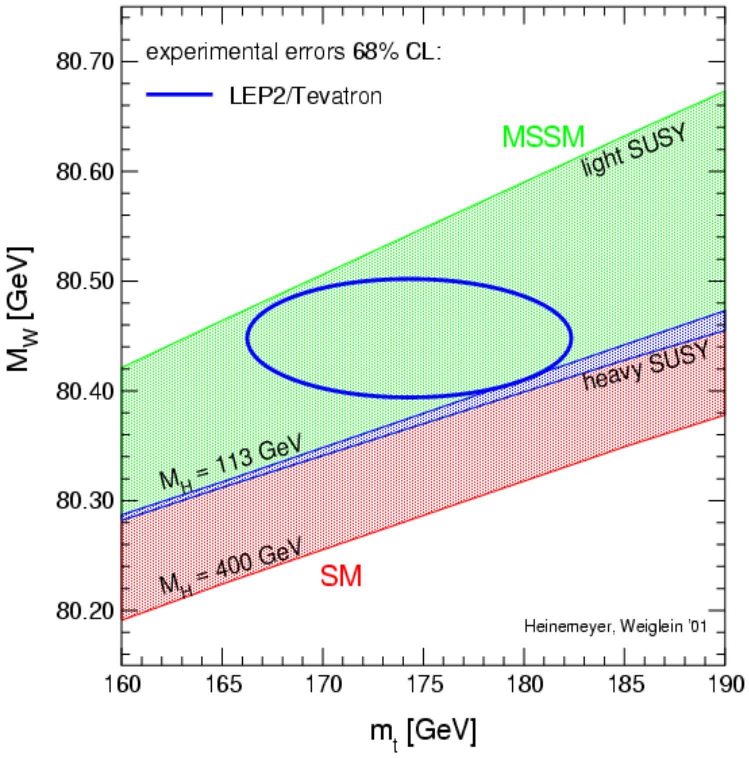
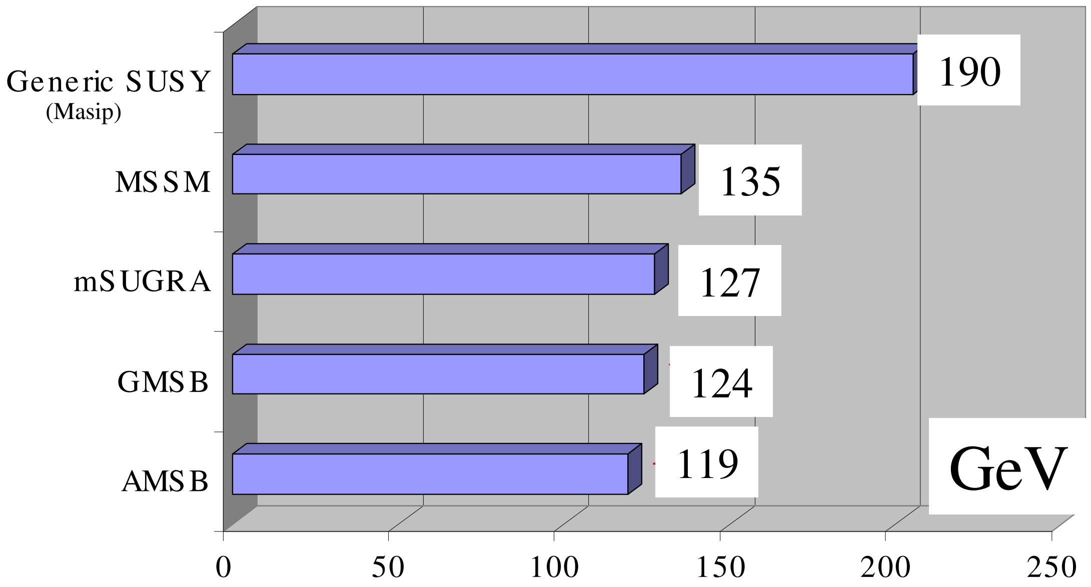
SUSY Higgs bosons: present limits

(see lectures by D.Froidevaux)

A light Higgs boson (preferred by EW data) is typical in SUSY



Upper bound on m_h in various SUSY models



$m_H^{EW} = 81^{+52}_{-33}$ GeV

$m_H^{EW} < 193$ GeV 95% C.L.

from fit of SM to EW data

- Minimal models : 2 Higgs doublets → 5 physical states : $h, H, A, H^{\pm}$

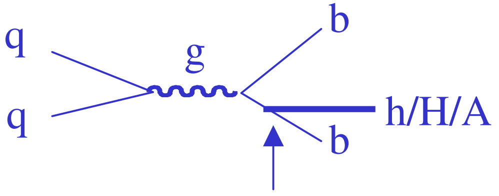
- At tree level SUSY Higgs sector described by two parameters : m_A, $tg\beta$
  Radiative corrections introduce dependence on m_{top}, m_{stop}, stop mixing, etc.

- m_h increases with m_A, $tg\beta$ (for $m_A < 200$, $tg\beta < 10$), m_{top}, m_{stop}, mixing $\tilde{t}_L / \tilde{t}_R$

  m_{top}= 174.3 GeV
  - no mixing : $m_h < 115$ GeV → almost fully excluded by LEP
  - m_h-max scenario : $m_h < 130$ GeV

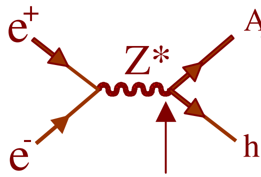
- $H, A, H^{\pm}$ usually heavier and degenerate for $m_A > 200$ GeV

LEP and Tevatron Run 1 are complementary



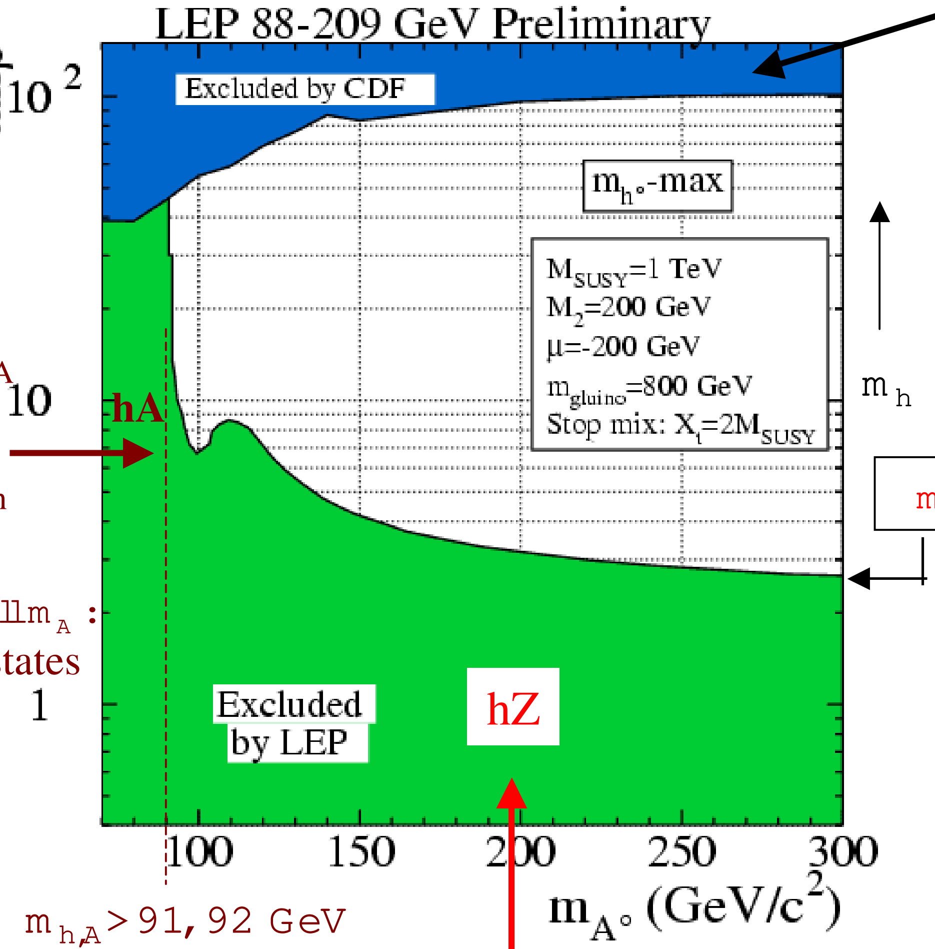
~ $tg^2\beta$

→ large tgβ : 4b final states



~ $\cos^2(\beta-\alpha)$

Large tgβ, small m_A :
4b, bbττ final states
dominate

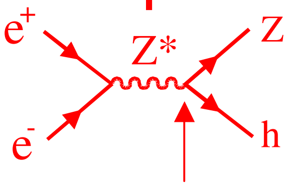


m_h = 114.4 GeV

Note : ~ no sensitivity to
SM-like h in Tevatron Run 1

α ≡ h,H
mixing

$m_{h,A}$ > 91, 92 GeV



~ $\sin^2(\beta-\alpha)$

Large m_A : here h is SM-like
→ SM Higgs searches ZH → qqbb, ννbb, ℓℓbb, qqττ used

Searches for SUSY particles at LEP and Tevatron and present experimental status :

- short reminder of models and parameters
- main searches at LEP and Tevatron
- other constraints

…..a brief overview …

Framework : Supergravity models with R_p conservation

The MSSM parameters

M_1, M_2, M_3 : gaugino SUSY-breaking mass terms (give masses to $\chi^0, \chi^\pm$, gluino)

$m_{\tilde{\ell}_R}, m_{\tilde{\ell}_L}, m_{\tilde{\nu}_L}, m_{\tilde{q}_R}, m_{\tilde{q}_L}$: sfermion SUSY-breaking mass terms

m_A : pseudoscalar Higgs boson mass

$\tan\beta$: ratio of vacuum expectation values of the two Higgs doublets

μ : Higgs mixing parameter

$A_t, A_b, A_\tau, \ldots$: stop/sbottom/stau/... mixing parameters

> 100 parameters → not very predictive ...

→ difficult to use to interpret experimental studies

Introduce some assumptions → Constrained MSSM (CMSSM)

- ☐ Gaugino masses M_1, M_2, M_3 unify to a common gaugino mass $m_{1/2}$ at GUT scale (in the same way as coupling constants of U(1), SU(2), SU(3) unify to α_{GUT})
- ☐ Sfermion masses unify to a common scalar mass m_0 at GUT scale

CMSSM parameters are (usually ...) :

$m_{1/2}, m_0, m_A, \tan\beta, \mu, A_{t,b,\tau \ldots}$

→ widely used to optimize and interpret experimental studies mainly at LEP

- M_1, M_2, M_3 masses run from $m_{1/2}$ at GUT scale to their values at EW scale (through RGE) in the same way as corresponding coupling constants

$$M_i = \frac{\alpha_i}{\alpha_{GUT}} m_{1/2}$$

$M_1 \approx 0.5\, m_{1/2}$; $M_2 \approx 0.8\, m_{1/2}$; $M_3 \approx 3\, m_{1/2}$

at the EW scale

χ^0_1

$\chi^\pm_1, \chi^0_2$

$\tilde{g}$

typically ...

$$m(\tilde{g}) \approx 3.5\, m(\chi^\pm_1, \chi^0_2)$$

$$m(\chi^\pm_1, \chi^0_2) \approx 2\,(\chi^0_1)$$

- Scalar masses depend on m_0, $m_{1/2}$ .... → scalar and gaugino masses are related

Introduce more assumptions → Minimal Supergravity (mSUGRA)

Unify Higgs and sfermion sector at the GUT scale → m_A fixed by m_0, …

Unify all trilinear couplings at the GUT scale to a common A_0

Radiative EW SB → only sign of μ remains free

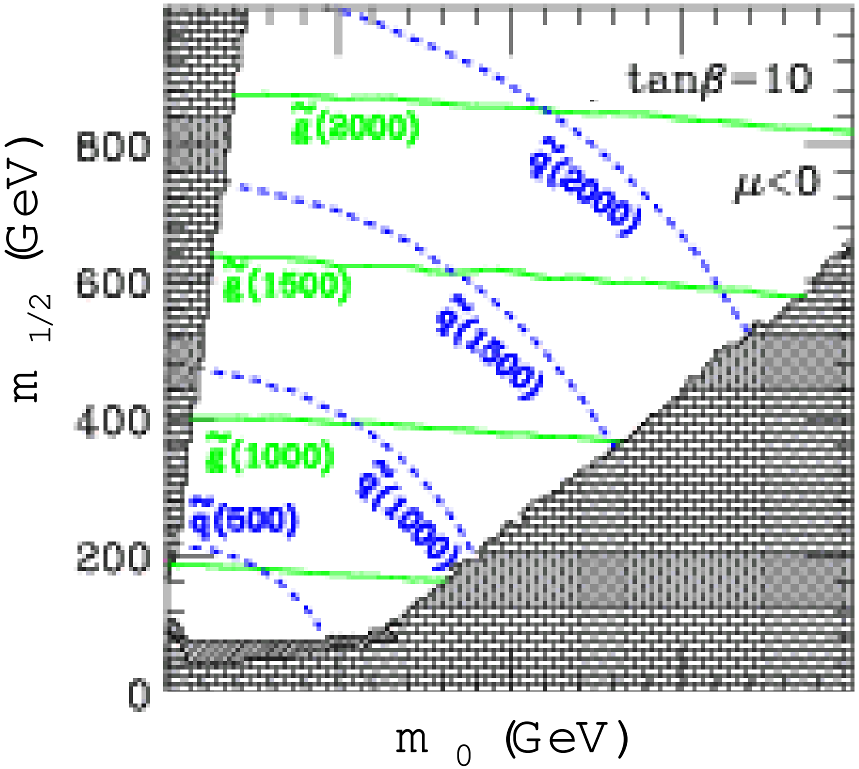
mSUGRA has only 5 parameters :

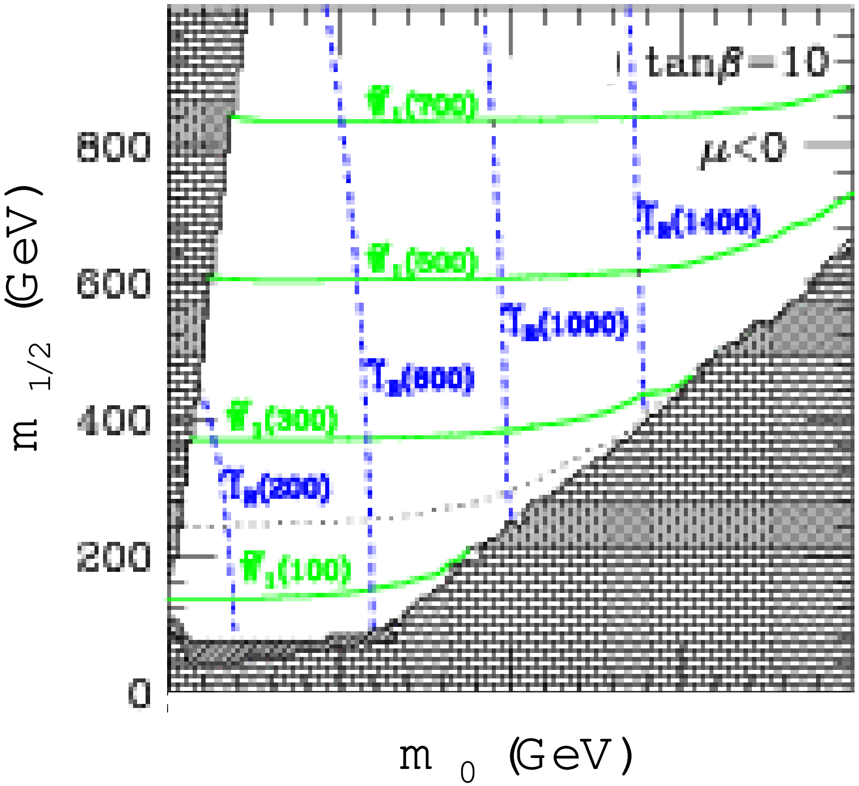
$$\boxed{m_{1/2}, m_0, \tan\beta, \mathrm{sign}(\mu), A_0}$$

→ widely used to optimise and interpret experimental studies mainly at Hadron Colliders

Very predictive but …….. realized in Nature ?

Mass isolines in mSUGRA





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

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

$$m(\chi_1^0) \approx 0.5\, m_{1/2}; \quad m(\chi_2^0, \chi^{\pm}) \approx m_{1/2};$$

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

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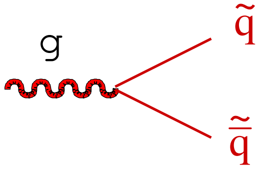
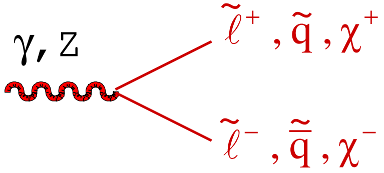
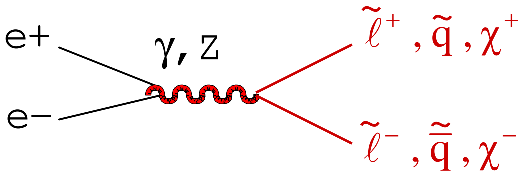
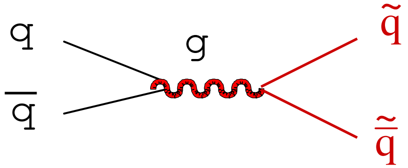
Examples of experimentally useful couplings and processes


g
$\tilde{q}$
$\bar{\tilde{q}}$

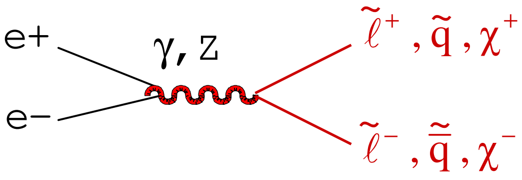

γ, Z
$\tilde{\ell}^+ , \tilde{q} , \chi^+$
$\tilde{\ell}^- , \bar{\tilde{q}} , \chi^-$

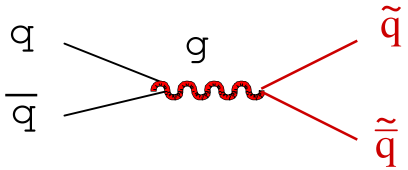
Examples of experimentally useful couplings and processes

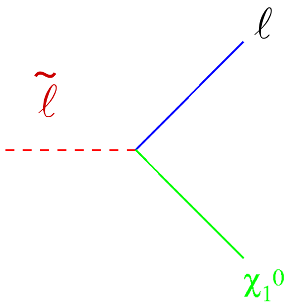

e+
e−
γ, Z
$\tilde{\ell}^+$, $\tilde{q}$, χ^+
$\tilde{\ell}^-$, $\tilde{\bar{q}}$, χ^-

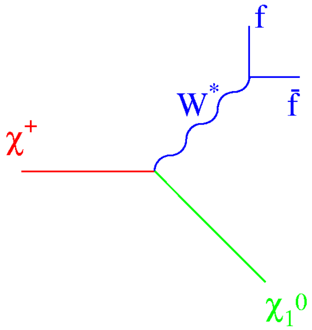

q
$\bar{q}$
g
$\tilde{q}$
$\tilde{\bar{q}}$

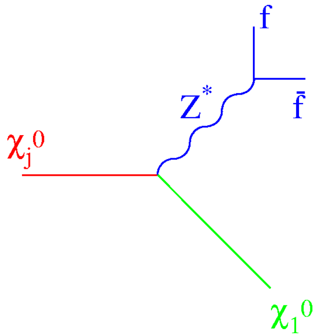
Examples of experimentally useful couplings and processes

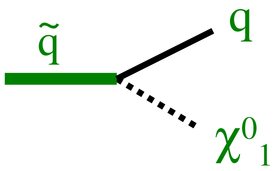

e+
e−
γ, Z
$\tilde{\ell}^+$, $\tilde{q}$, χ^+
$\tilde{\ell}^-$, $\bar{\tilde{q}}$, χ^-


q
$\bar{q}$
g
$\tilde{q}$
$\bar{\tilde{q}}$

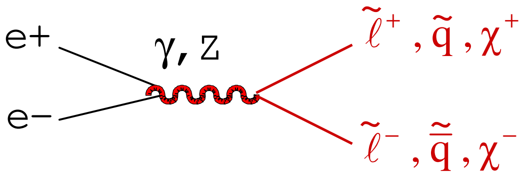

$\tilde{\ell}$
ℓ
χ_1^0

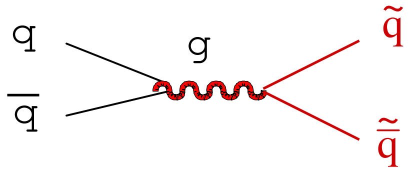

χ^+
W^*
f
$\bar{f}$
χ_1^0

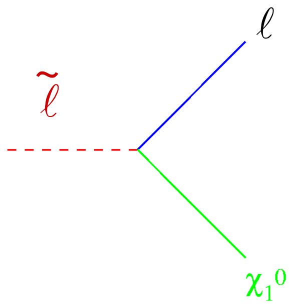

χ_j^0
Z^*
f
$\bar{f}$
χ_1^0

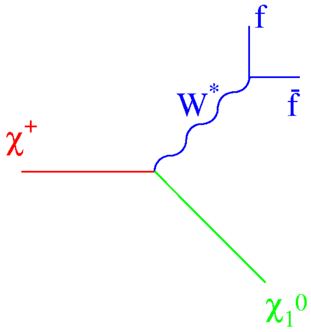

$\tilde{q}$
q
$\chi^0{}_1$

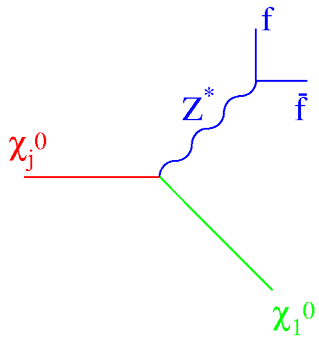
Examples of experimentally useful couplings and processes

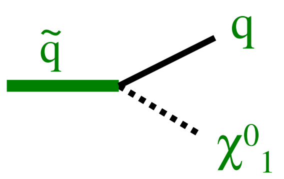

e+
e−
γ, Z
$\tilde{\ell}^+, \tilde{q}, \chi^+$
$\tilde{\ell}^-, \bar{\tilde{q}}, \chi^-$

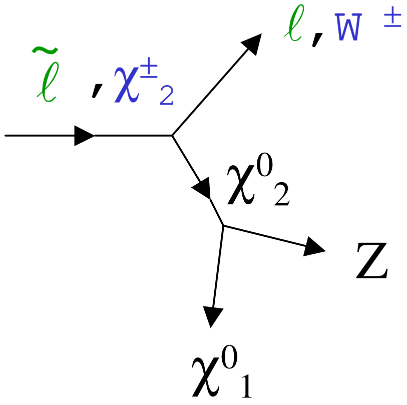

q
$\bar{q}$
g
$\tilde{q}$
$\bar{\tilde{q}}$

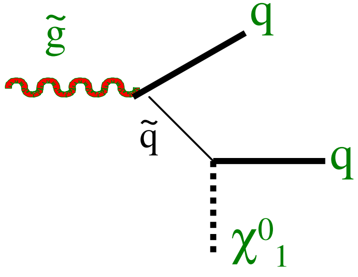

$\tilde{\ell}$
ℓ
χ_1^0

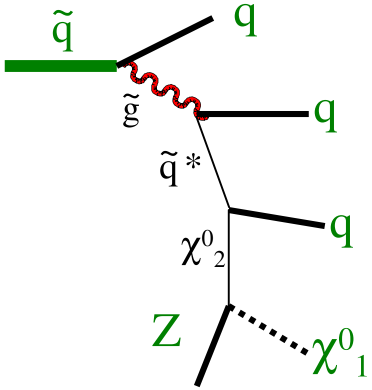

χ^+
W^*
f
$\bar{f}$
χ_1^0


χ_j^0
Z^*
f
$\bar{f}$
χ_1^0


$\tilde{q}$
q
χ^0_1


$\tilde{\ell}, \chi^{\pm}_2$
ℓ, W ±
χ^0_2
Z
χ^0_1


$\tilde{g}$
q
$\tilde{q}$
q
χ^0_1


$\tilde{q}$
q
$\tilde{g}$
q
$\tilde{q}$ *
q
χ^0_2
Z
χ^0_1

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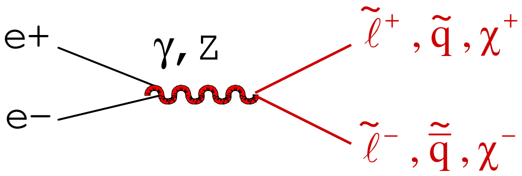
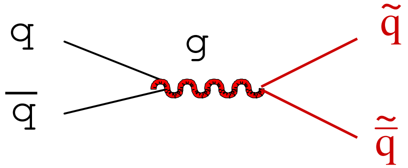
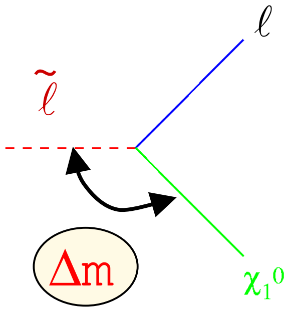
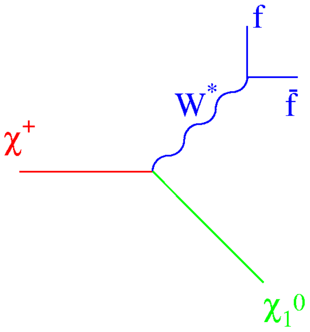
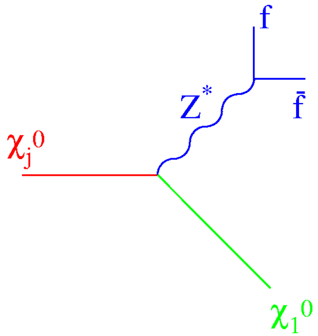
Examples of experimentally useful couplings and processes

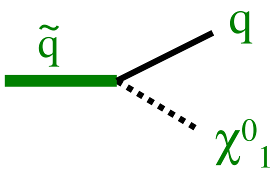

e+
e−
γ, Z
$\tilde{\ell}^+, \tilde{q}, \chi^+$
$\tilde{\ell}^-, \bar{\tilde{q}}, \chi^-$

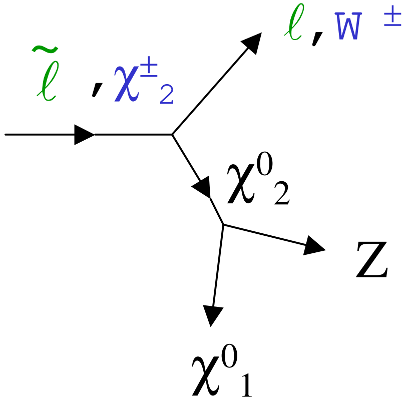

q
$\bar{q}$
g
$\tilde{q}$
$\bar{\tilde{q}}$

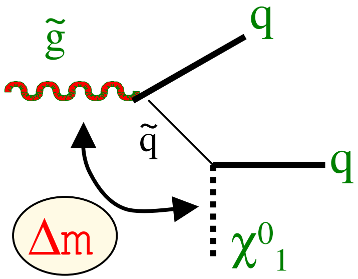

$\tilde{\ell}$
ℓ
χ_1^0
Δm

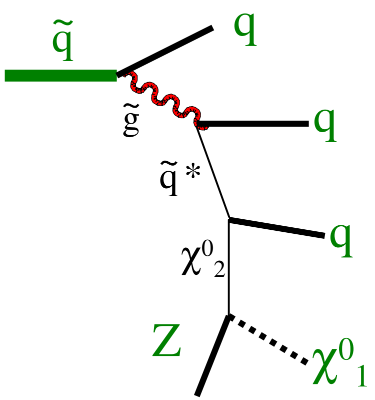

χ^+
W^*
f
$\bar{f}$
χ_1^0


χ_j^0
Z^*
f
$\bar{f}$
χ_1^0


$\tilde{q}$
q
χ^0_1


$\tilde{\ell}$, $\chi^\pm_2$
ℓ, W ±
χ^0_2
Z
χ^0_1


$\tilde{g}$
q
$\tilde{q}$
q
χ^0_1
Δm


$\tilde{q}$
q
$\tilde{g}$
q
$\tilde{q}^*$
q
χ^0_2
Z
χ^0_1

$\chi^0_1 \equiv$ LSP :
stable, weakly interacting
→ not detected
→ missing E in final state

Small Δm : little visible energy in final state

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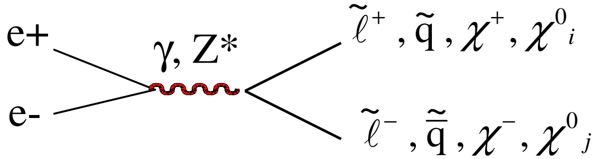
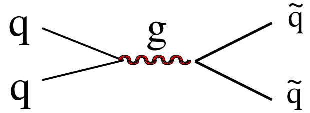
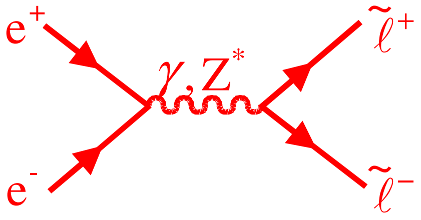
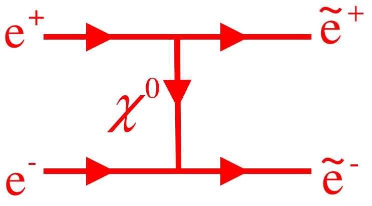
e^+e^- Colliders (LEP) versus Hadron Colliders (Tevatron)

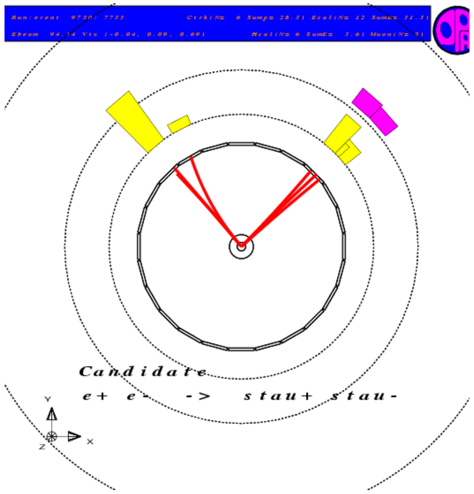
Sparticles produced ~ democratically  e+ e- γ, Z* $\tilde\ell^+, \tilde q, \chi^+, \chi^0_i$ $\tilde\ell^-, \bar{\tilde q}, \chi^-, \chi^0_j$	$\tilde q\tilde q, \tilde q\tilde g, \tilde g\tilde g$ dominates  $\left.\begin{array}{l}\sigma(\tilde q, \tilde g) \approx 100\ \text{pb}\\ \sigma(\tilde e\tilde e) \approx 5\ \text{fb}\end{array}\right\}$ m=150 Gev
Direct decays to LSP dominate: e.g. $\tilde q \to q\chi^0_1, \tilde\ell \to \ell\chi^0_1, \chi^\pm \to W^*\chi^0_1$ → main topology is 2 acoplanar objects + missing E	$\tilde q, \tilde g$ heavy → cascade decays important e.g. $\tilde g \to \tilde q q \to qq\chi^0_2 \to qqZ\chi^0_1$ → high multiplicity high p_T final states
Moderate backgrounds ($\gamma\gamma \to$ ff , WW, ZZ)	Huge backgrounds (QCD, W/Z+jets)
Sensitive to: -- ~ all kinematically accessible $\tilde p$ -- ~ all decay modes -- $\Delta m = m(\tilde p) - m(\chi^0_1) \approx$ GeV (small visible E)	Sensitive to: -- $\tilde q, \tilde g$ (high σ, heavy, clear signature) and $\chi^\pm_1\chi^0_2 \to 3\ell$ (clean signature) -- Δ m >>10 GeV (large visible E needed)
Mass reach $m \le \sqrt{s}/2$ for ~ any sparticle over most accessible parameter space ⊕ Combining more searches → absolute limits (e.g. LSP)	High mass reach for $\tilde q, \tilde g$ (Run 1 ~ 300 GeV) but holes in parameter space → ~ no absolute limit

Slepton searches at LEP



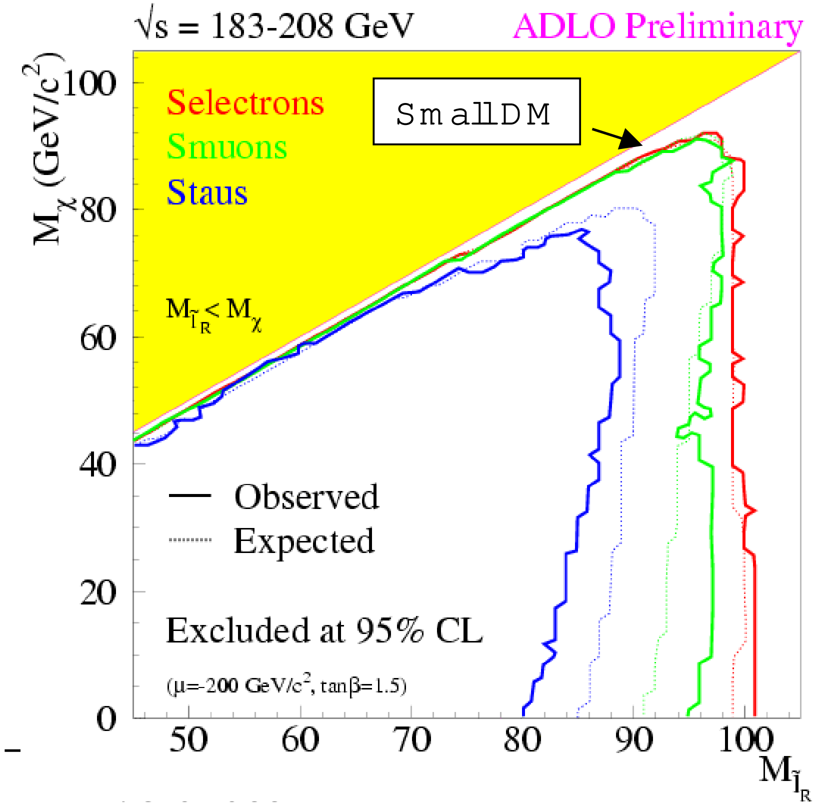


OPAL stau event


Candidate
e+ e- -> stau+ stau-

$\tilde{\ell} \to \ell\, \chi^0_1$ → 2 acoplanar leptons + missing E →

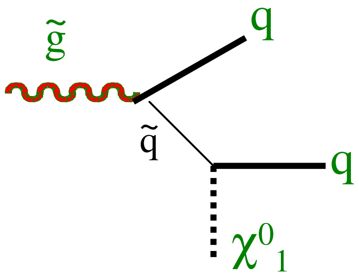
Main background: WW (well known → subtracted)

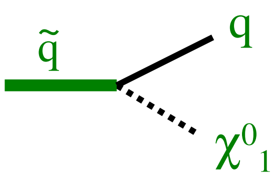


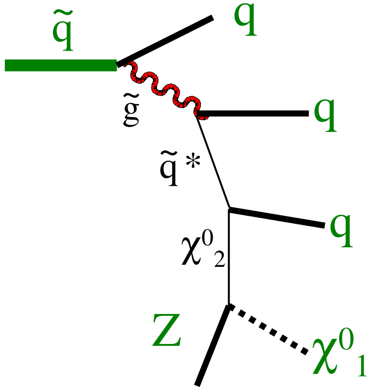
- Scalars: $\sigma \sim \beta^3/s$ → need L to reach kinematic limit
- Smuon and stau limits are ~ model-independent

- Tevatron has no sensitivity (small cross-sections, large backgrounds)

Squark and gluino searches at Tevatron

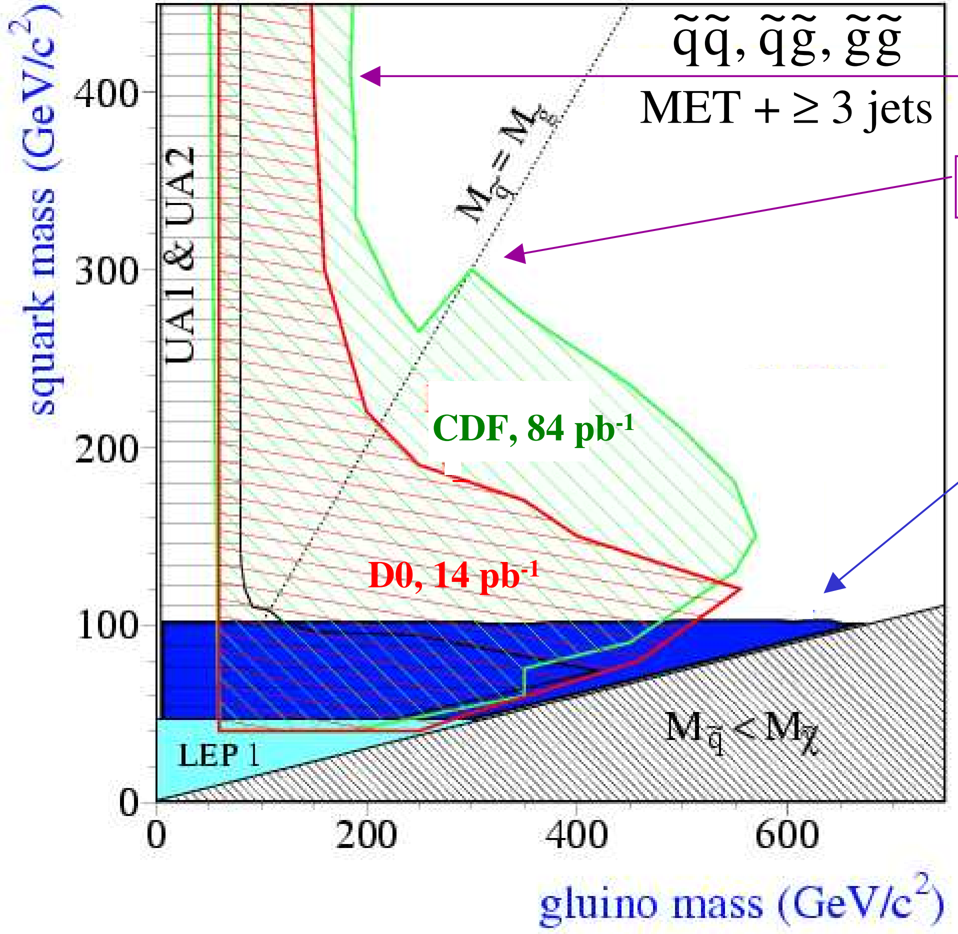

$\tilde{g}$
q
$\tilde{q}$
q
$\chi^0{}_1$


$\tilde{q}$
q
$\chi^0{}_1$


$\tilde{q}$
q
$\tilde{g}$
q
$\tilde{q}$*
q
$\chi^0{}_2$
Z
$\chi^0{}_1$

→ signature for $\tilde{q}\tilde{q}, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$ production at Tevatron is

$E_T{}^{miss}$ (MET) + n jets + m leptons (ℓ = e, μ)



m ($\tilde{g}$) > 195 GeV

m ($\tilde{q}$) ≈ m ($\tilde{g}$) > 300 GeV

2 searches :

MET >70 GeV + 2 jets + 2 ℓ

MET >70 GeV + ≥ 3 jets

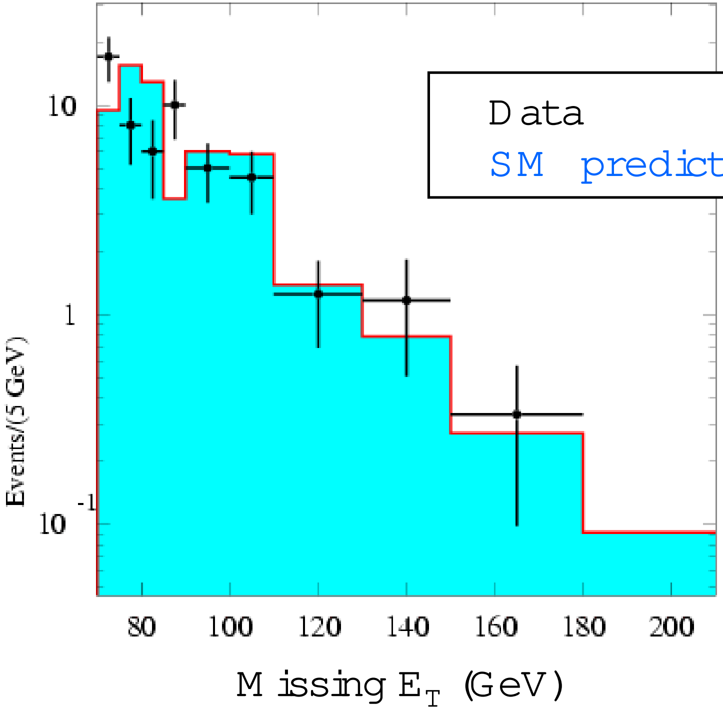
$\tilde{q}\tilde{q}$ searches at LEP

Tevatron not sensitive to $\Delta m (\tilde{q} - \chi^0{}_1) < 25$ GeV

Main backgrounds to SUSY searches in Jets + MET topology at Hadron Colliders from:

- W/Z + jets with $Z \to \nu\nu$, $W \to \tau\nu$; tt; etc.
- QCD multijet events with fake MET from jet mismeasurements (detector resolution, cracks)

CDF, 84 pb^{-1}, MET >70 GeV + ≥ 3 jets sample



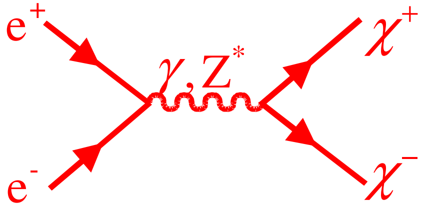
Data : 74 events
SM prediction : 76± 13 events (35 W/Z/tt + 41 QCD)

Understanding the missing E_T spectrum (and tails from instrumental effects) is one of most crucial and difficult experimental issues for SUSY searches at Hadron Colliders

F.Gianotti

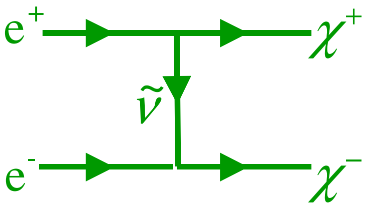
Chargino searches at LEP

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


e^+
e^-
γ, Z^*
χ^+
χ^-

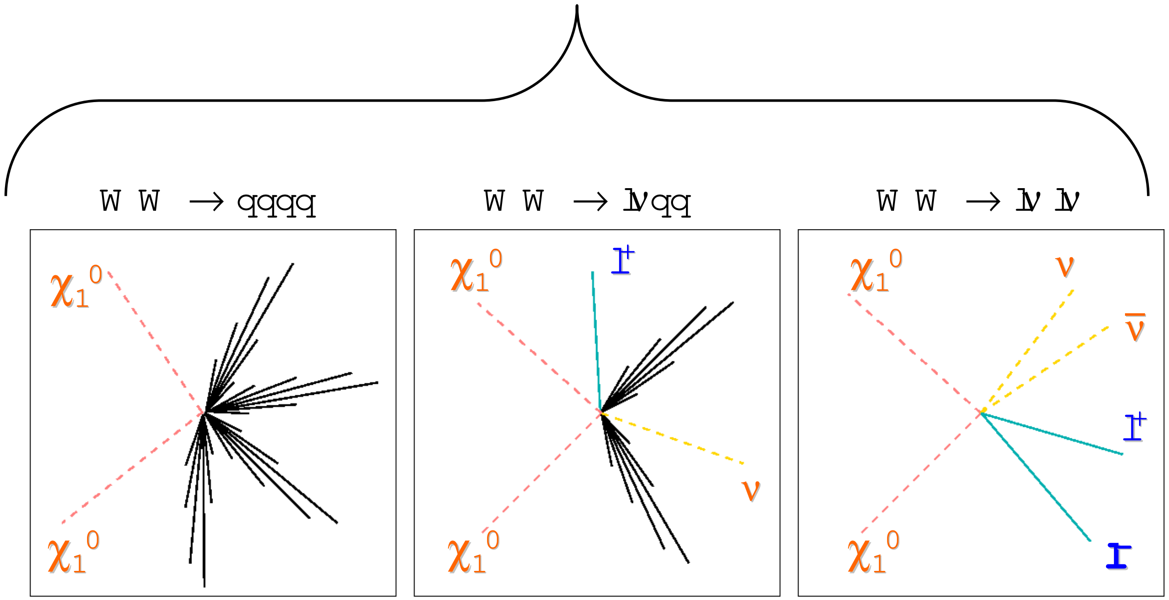
$-$

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


e^+
e^-
$\tilde{\nu}$
χ^+
χ^-

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

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


WW → qqqq

WW → lνqq

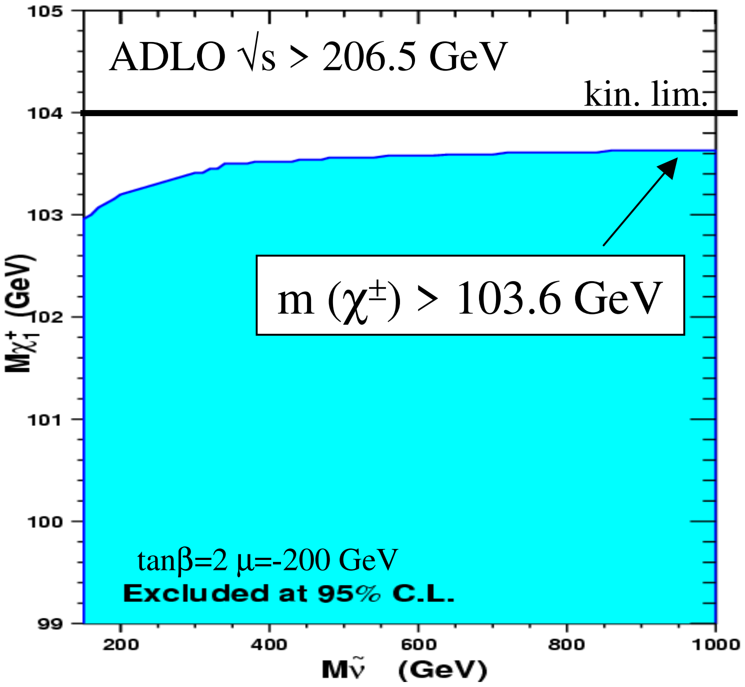
WW → lνlν

χ_1^0
χ_1^0
χ_1^0
l^+
ν
χ_1^0
χ_1^0
ν
$\bar{\nu}$
l^+
l^-
χ_1^0

Main backgrounds (WW, ZZ) can be rejected asking e.g. for a large missing mass in final state

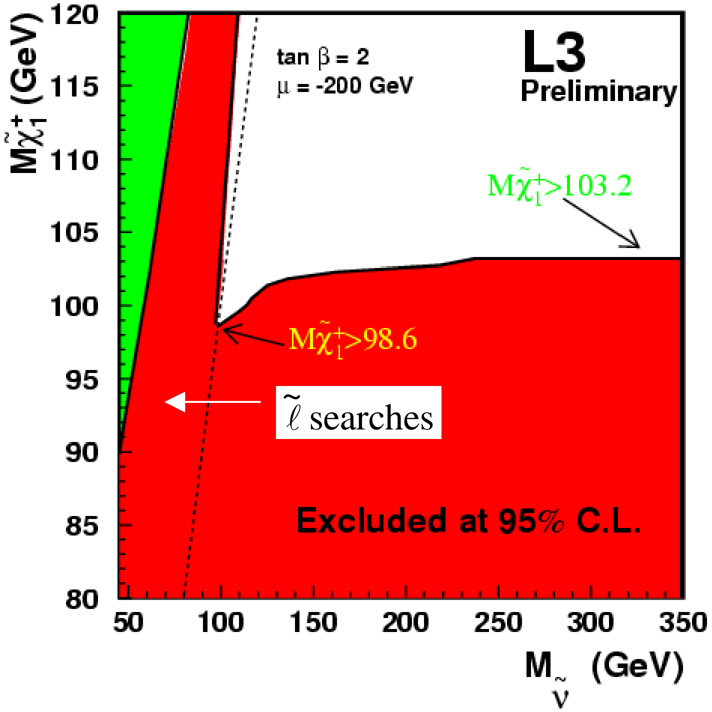
---

"Easy case" : large scalar masses

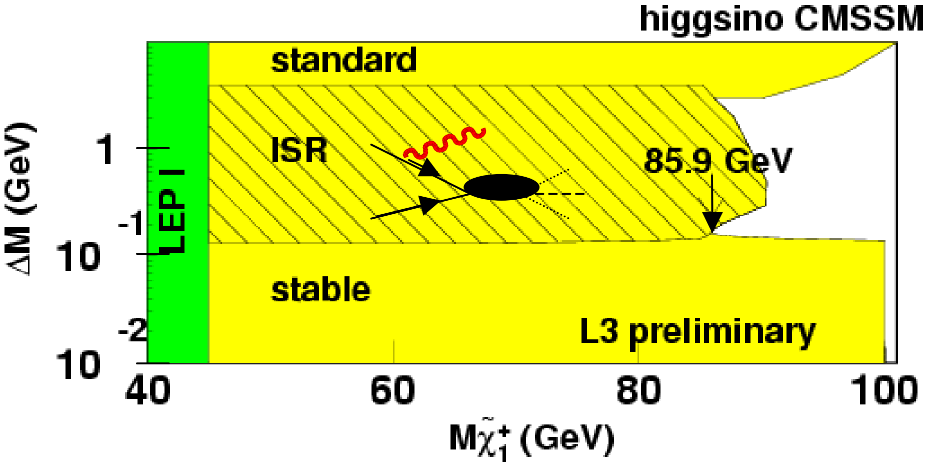


Tevatron Run 1:
searches ($\chi^{\pm}{}_1\,\chi^0{}_2 \to 3\ell$) in
general not competitive

Two difficult cases :
1) small scalar masses



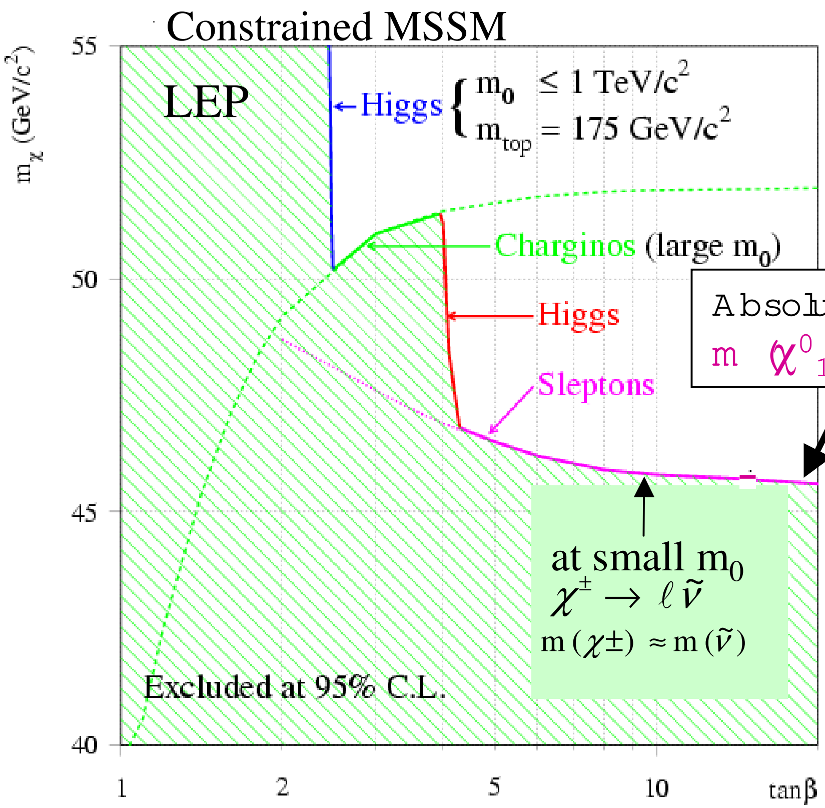
2) very small Δm ($\chi^{\pm} - \chi^0$)



Absolute limit on the LSP at LEP

Cosmological implications : $\chi^0{}_1$ is best candidate for cold dark matter

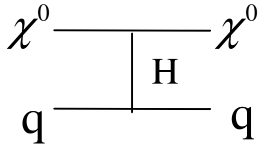
$\chi^0{}_1\chi^0{}_1$ production not observable → indirect limit from interplay of constraints in parameter space from other searches (e.g. $\tilde{\ell}\tilde{\ell}, \chi^+\chi^-, h$)

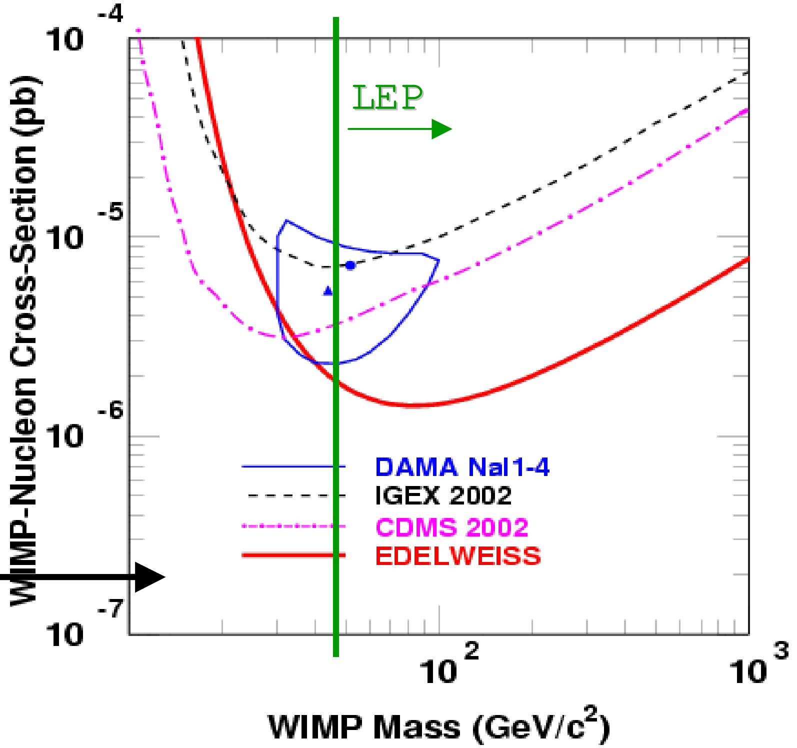


Absolute limit
$m(\chi^0{}_1) > 45$ GeV

Direct searches for cold dark matter (WIMPS) through neutralino-nuclei scattering

e.g.

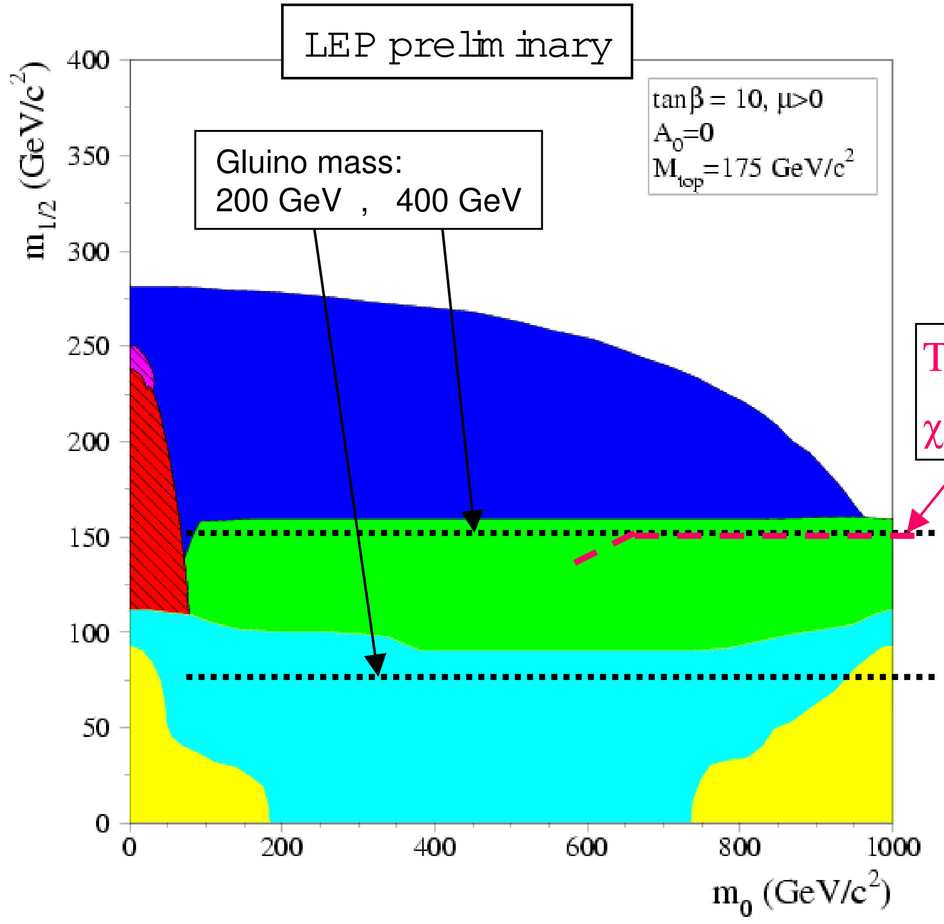




Interplay/complementarity between accelerator limits and dark matter experiments

F. Gianotti

Interpretation of results : constraining the mSUGRA parameter space ...



Gluino mass:
200 GeV , 400 GeV

Tevatron Run 2 (2 fb^{-1})
$\chi_1^+\chi_2^0 \rightarrow 3l^\pm$ + MET searches

Regions excluded by:

1. *Theory*
2. *Z width from LEP1*
3. *Charginos*
4. *Sleptons*
5. *Higgs*
6. *Stable staus*

mSUGRA : m_h depends on m_0, $m_{1/2}$

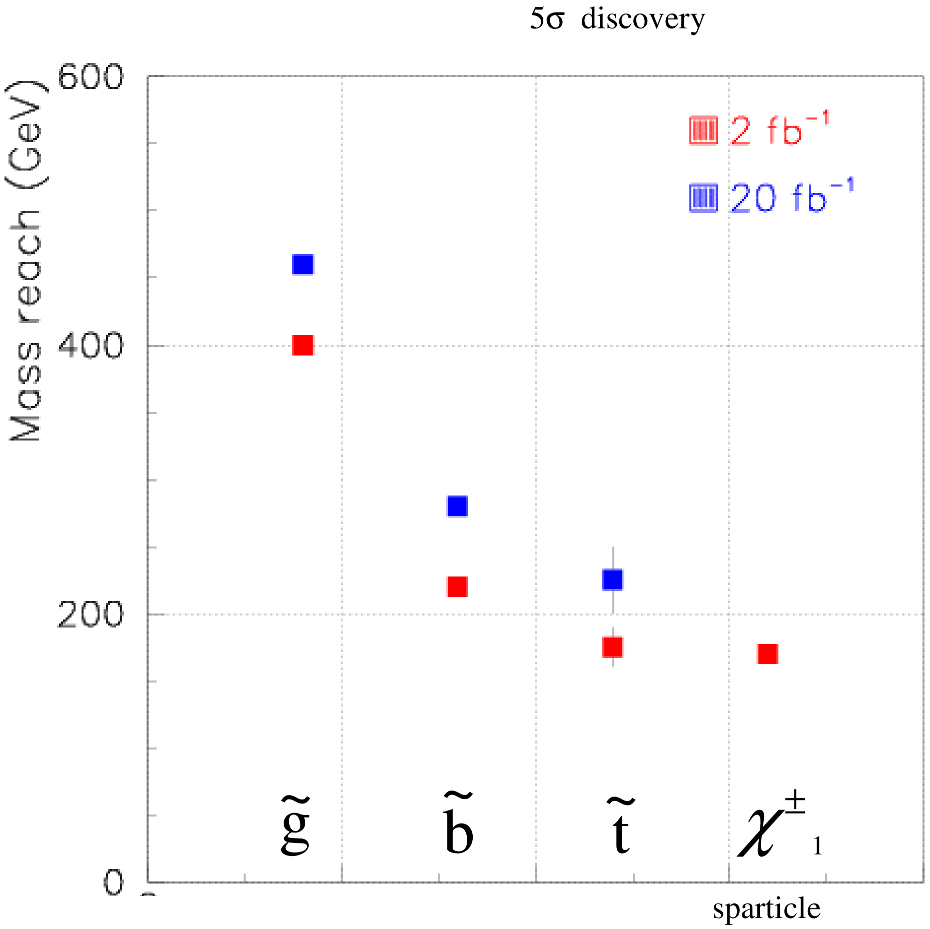
Note :

$$m(\tilde{g}) \approx 3\, m_{1/2}$$
$$m(\chi^{\pm}_1) \approx m_{1/2}$$

➡

$m(\chi^{\pm}) > 100$ GeV limit (from LEP) provides similar constraint on parameter space as m(gluino) > 400 GeV (reach of Tevatron Run 2 ...)

Sprospects at the Tevatron Run 2

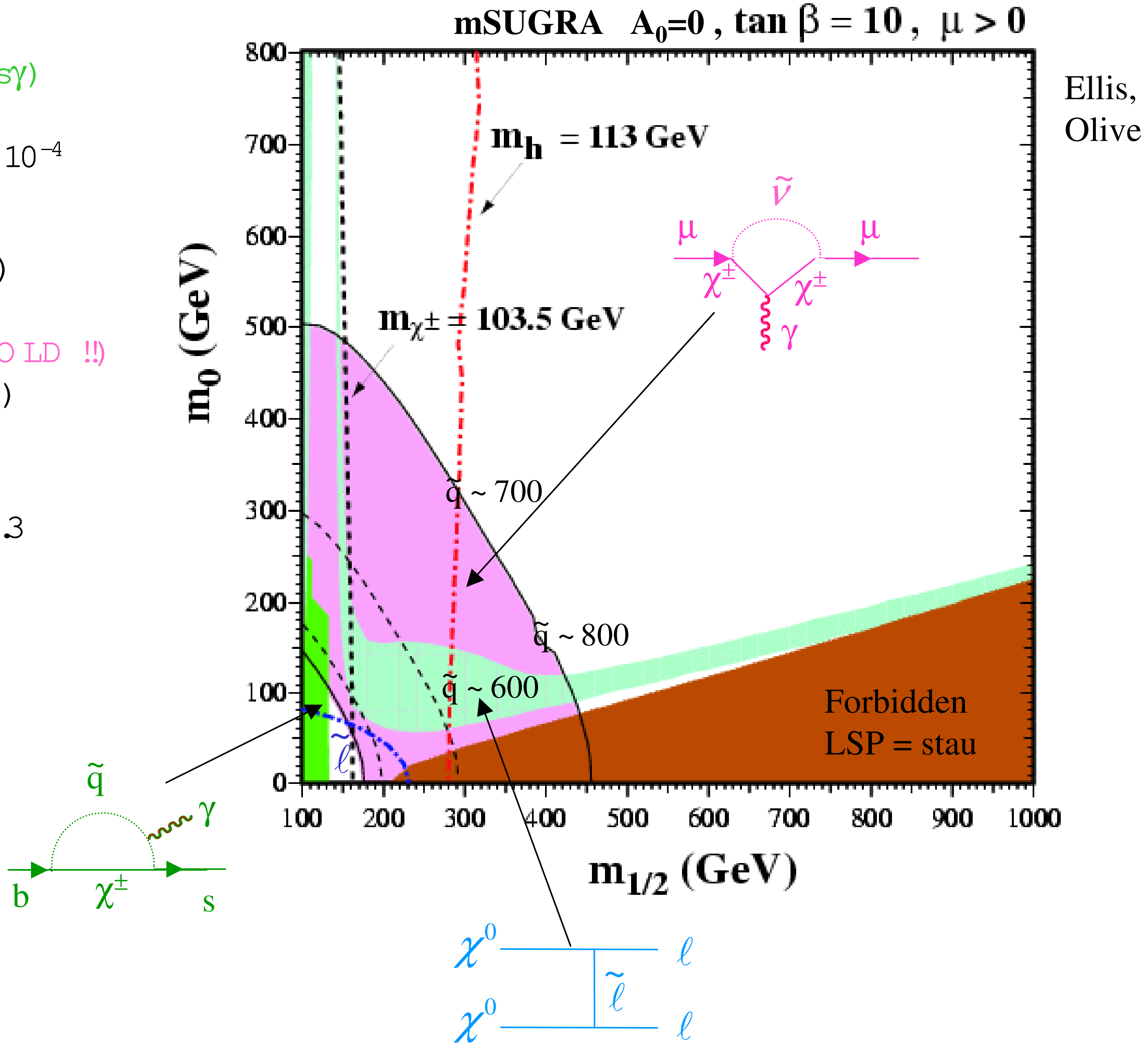


Combining Colliders with other "constraints"….

🟩 Disfavoured by BR $(b \rightarrow s\gamma)$
from CLEO, BELLE
BR $(b \rightarrow s\gamma) = (3.2 \pm 0.5) \bullet 10^{-4}$
used here

🟪 Favoured by $g_\mu-2$ (E821)
assuming that
$\delta\alpha_\mu = (43 \pm 16) \bullet 10^{-10}$ (OLD !!)
is from SUSY ($\pm$ 2 σ band)

🟦 Favoured by cosmology
assuming $0.1 \leq \Omega_\chi h^2 \leq 0.3$



Brief introduction to the LHC :

— the environment
— the main physics challenges
— ATLAS and CMS detectors
— examples of performance relevant to SUSY

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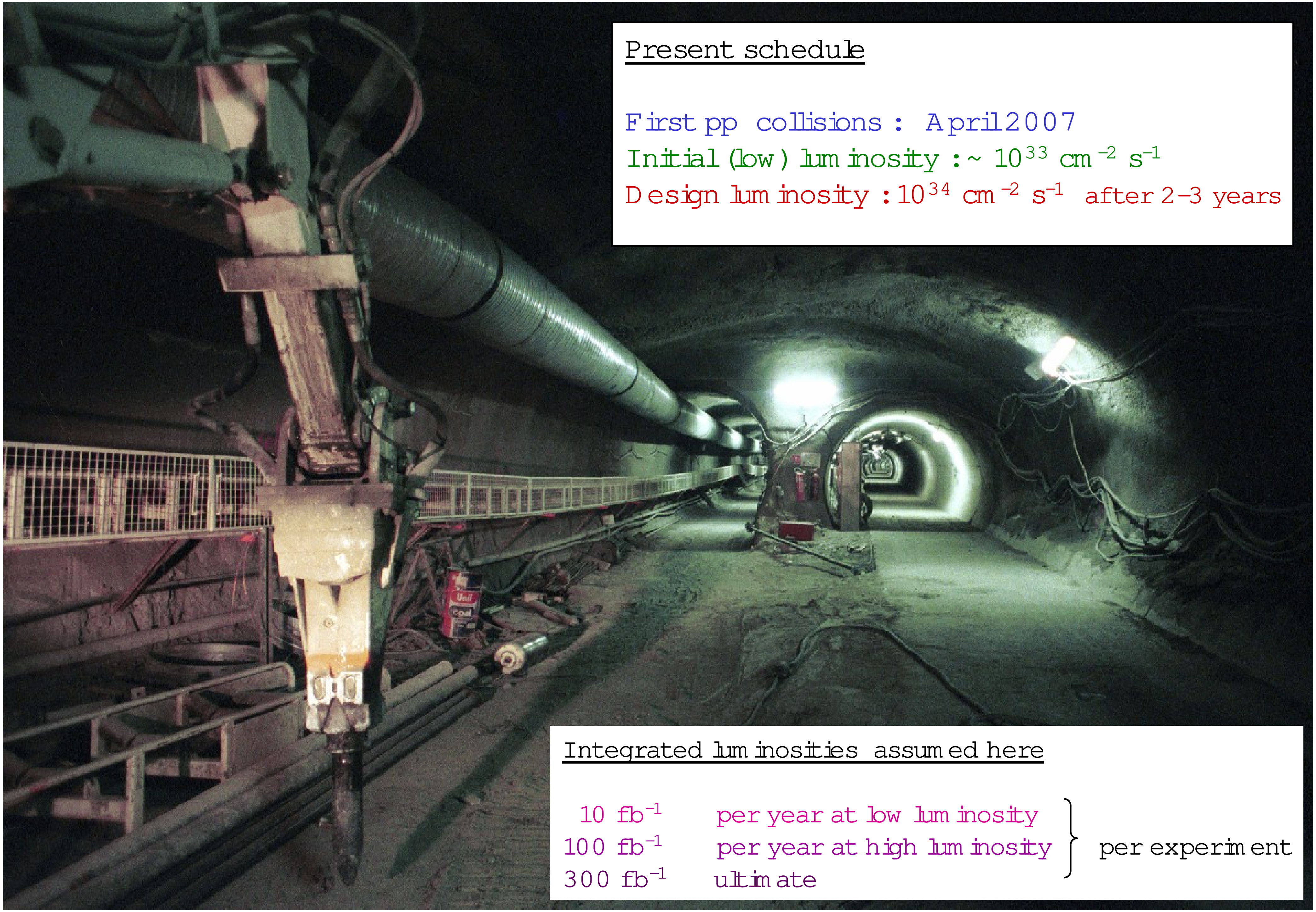


Present schedule

First pp collisions : April 2007

Initial (low) luminosity : ~ 10^{33} cm^{-2} s^{-1}

Design luminosity : 10^{34} cm^{-2} s^{-1} after 2-3 years

Integrated luminosities assumed here

10 fb^{-1}	per year at low luminosity	per experiment
100 fb^{-1}	per year at high luminosity	
300 fb^{-1}	ultimate	

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

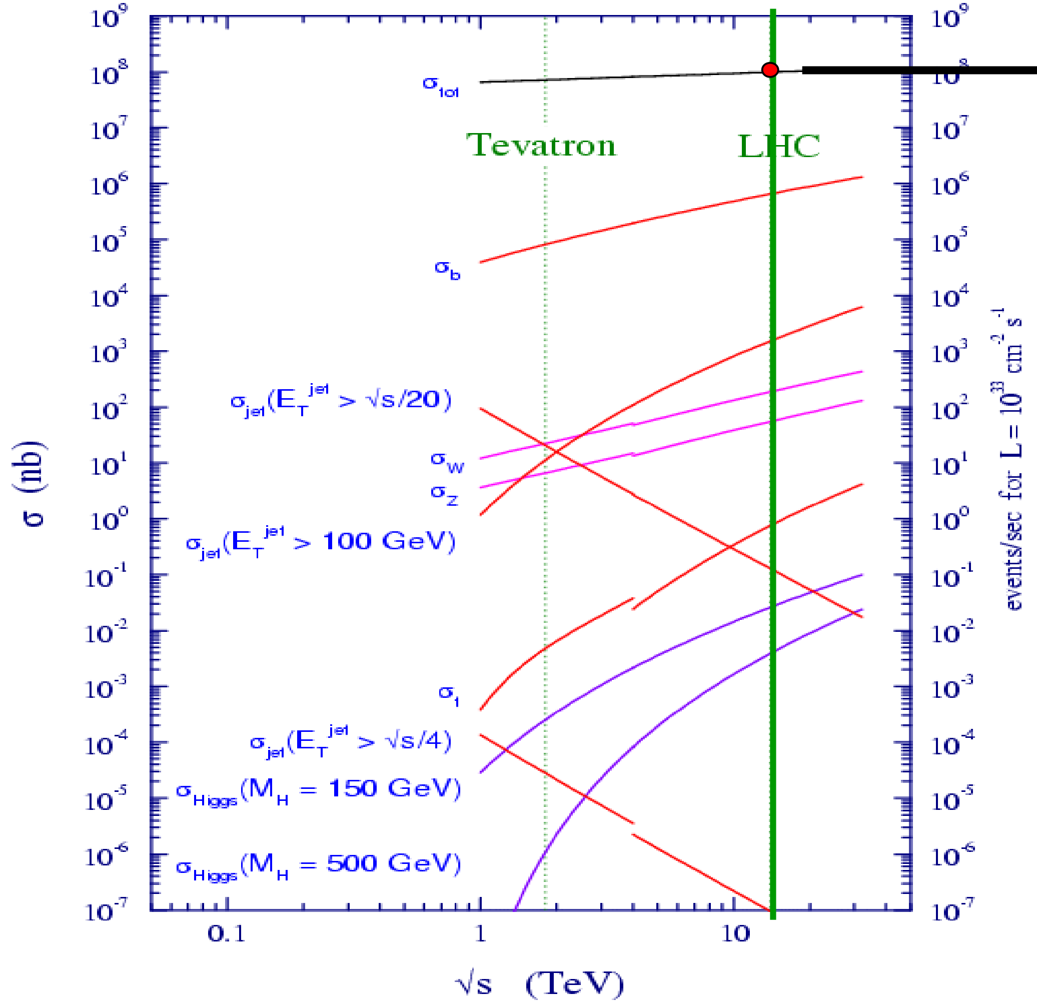
Process	Events/s	Events / year ($10\ \mathrm{fb}^{-1}$)	Total statistics collected at previous machines by 2007
$W \to e\nu$	15	10^{8}	10^{4} LEP / 10^{7} Tevatron
$Z \to ee$	1.5	10^{7}	10^{7} LEP
$t\bar{t}$	1	10^{7}	10^{4} Tevatron
$b\bar{b}$	10^{6}	$10^{12} - 10^{13}$	10^{9} Belle/BaBar ?
H m=130 GeV	0.02	10^{5}	?
$\tilde{g}\tilde{g}$ m = 1 TeV	0.001	10^{4}	—
Black holes m > 3 TeV (M_D=3 TeV, n=4)	0.0001	10^{3}	—

→ — LHC is a B-factory, top factory, W/Z factory, Higgs factory, SUSY factory, …
— ultimate mass reach for singly-produced particles : ≈ 5 TeV

However… .this is not for free … ⇒ two main problems

pile-up

❶

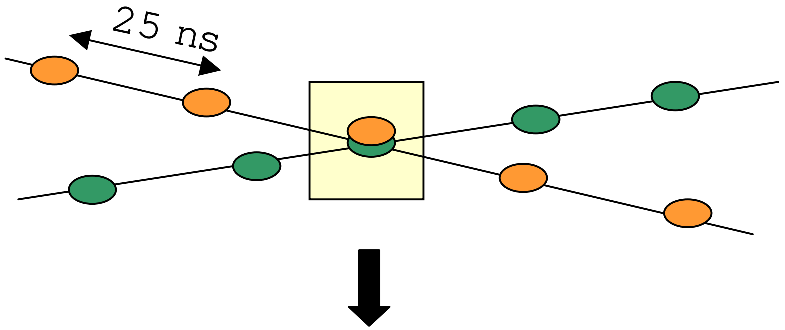


Event rate in ATLAS, CMS :

$N = L \times \sigma_{inelastic}(pp) \approx 10^{34}\ cm^{-2}\ s^{-1} \times 70\ mb$

$\approx 10^9$ interactions/s

Proton bunch spacing : 25 ns

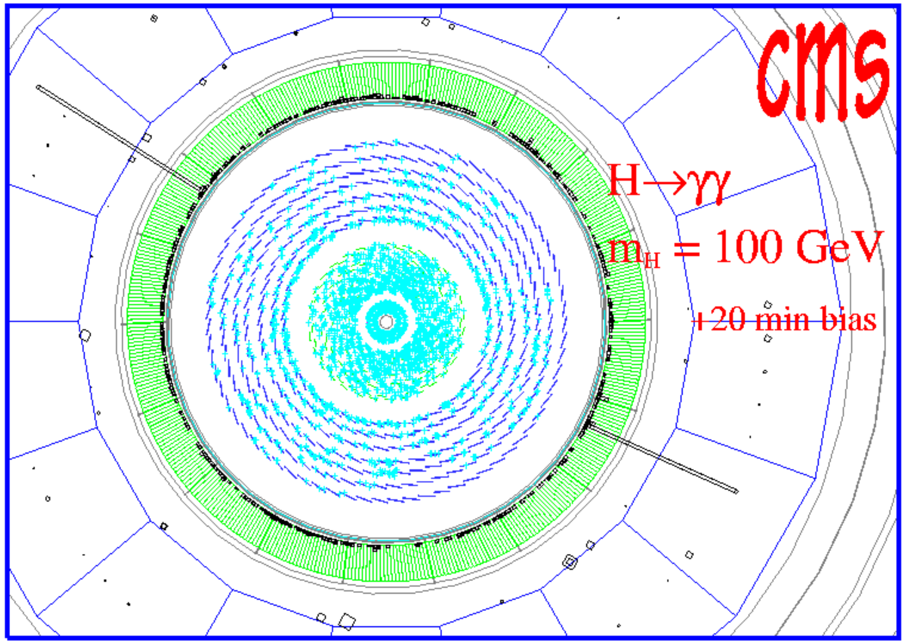


~ 25 inelastic (low-p_T) events ("minimum bias") produced on average in the detectors at each bunch crossing → pile-up

At each crossing : ~1000 charged particles produced over $|\eta| < 2.5$

However : $<p_T> \approx 500$ MeV → applying p_T cut allows extraction of interesting events

⬇



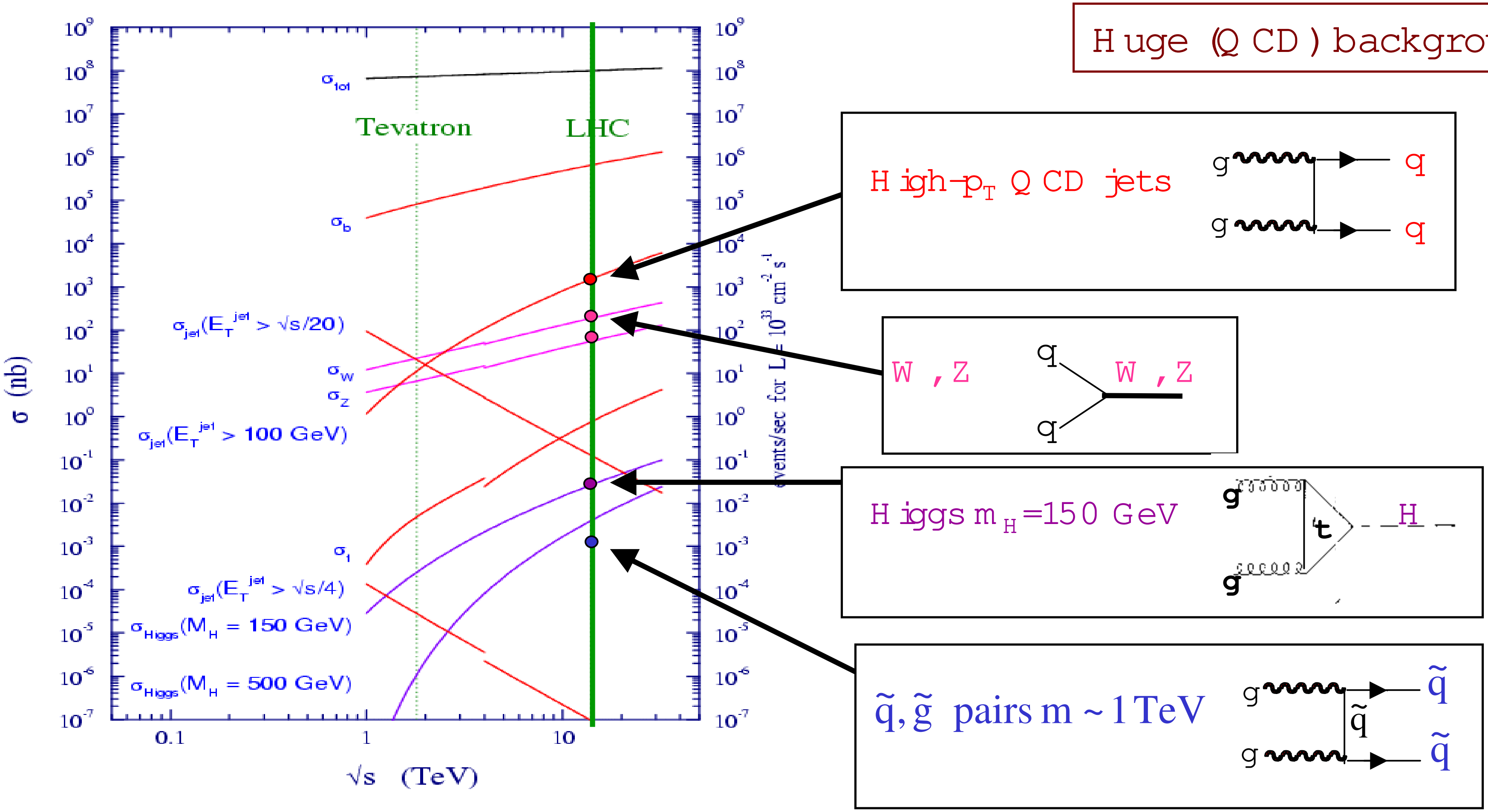
- Impact on detector requirements:
  - — fast response : ✍ 50 ns
  - — granularity → 10^8 channels
  - — radiation resistance (up to 10^{16} n/cm^2/year in forward calorimeters)

- Impact on physics:
  - — general performance deterioration (lower efficiencies, higher fakes, worse resolutions)
  - — tracking and pattern recognition more challenging
  - — additional contribution to calorimeter energy resolution (e.g. big impact on missing E_T resolution !)

Note : quiet environment at low luminosity (Tevatron-like)

Huge (QCD) backgrounds

❷



High-p_T QCD jets

W, Z

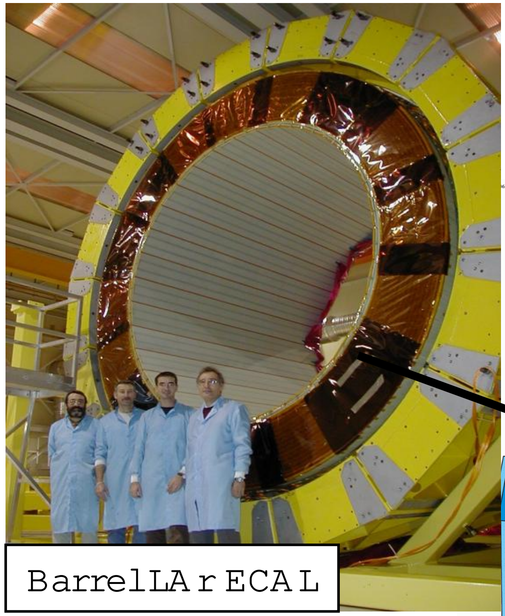
Higgs m_H=150 GeV

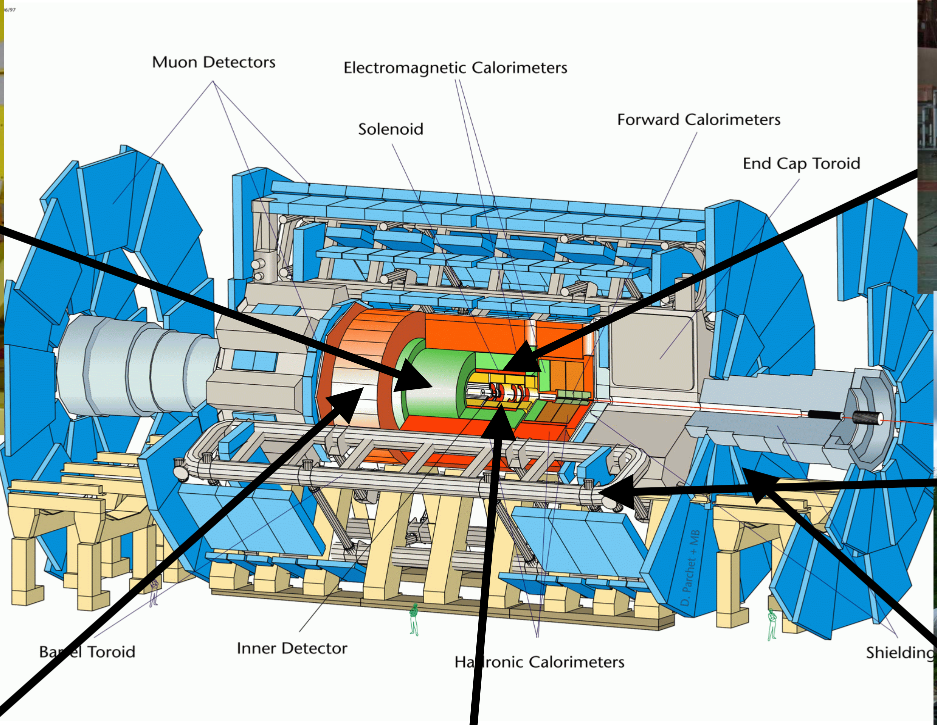
$\tilde{q}, \tilde{g}$ pairs m ~ 1 TeV

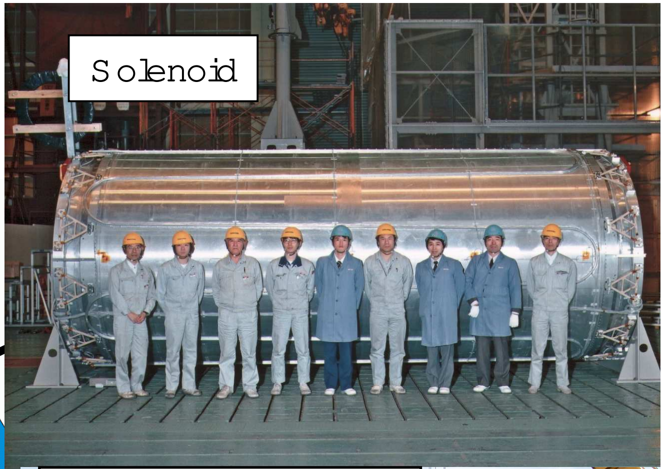
- No hope to observe light objects (W, Z, H?) in fully-hadronic final states → rely on ℓ, γ
- Fully-hadronic final states can be triggered at affordable rate and possible signals (e.g. SUSY) extracted from backgrounds only with hard O (100 GeV) p_T cuts → works only for heavy objects
- Mass resolutions of ~ 1% (10%) needed for ℓ, γ (jets) to extract tiny signals from backgrounds
- Excellent particle identification: e.g. e/jet ratio $p_T > 20$ GeV is 10^{-3} (10^{-5}) at $\sqrt{s} = 2$ TeV (14 TeV)
  → $e^{\pm}$ identification in ATLAS, CMS must be ~ 100 times better than CDF, D0

Note: dynamic range ~ 1 GeV → few TeV

ATLAS

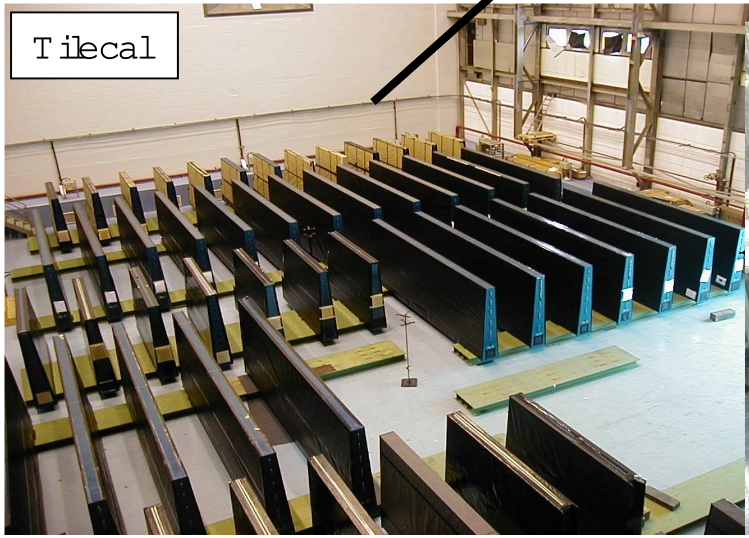

Barrel LAr ECAL


Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding


Solenoid

Barrel coil cryostat

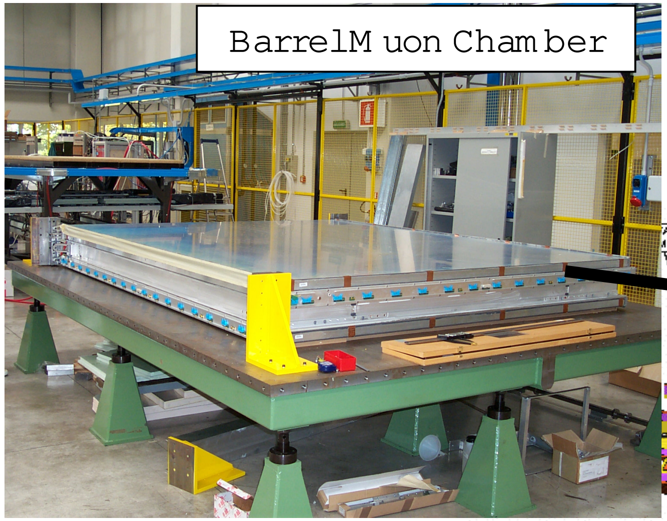
Length : ~40 m
Radius : ~10 m
Weight : ~ 7000 tons

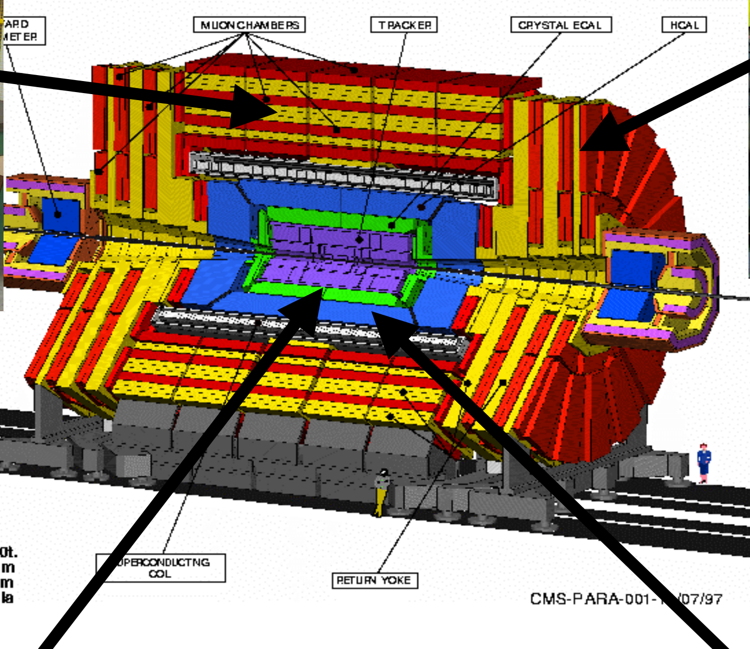

Tilecal

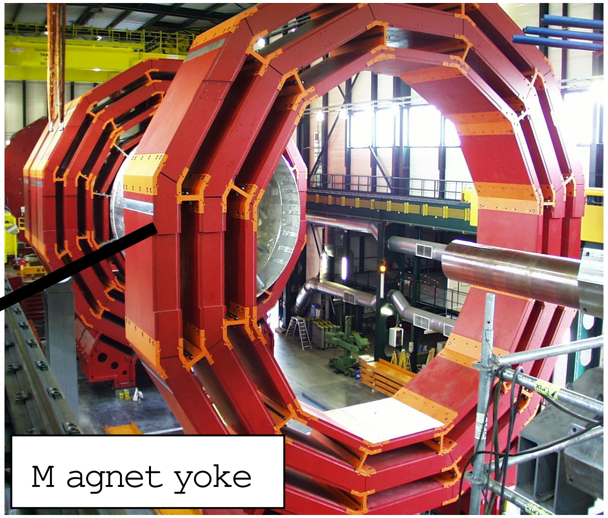
TRT end-cap wheel

Muon end-cap chamber

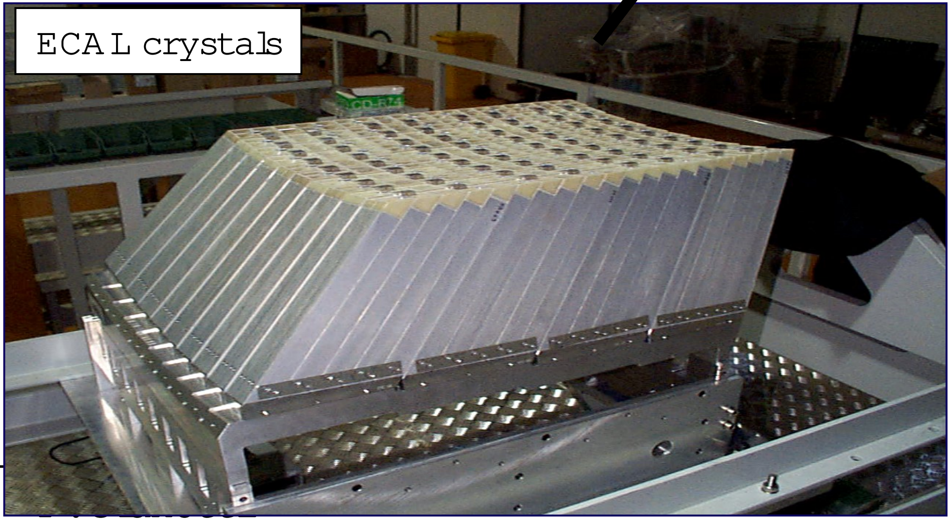
CMS

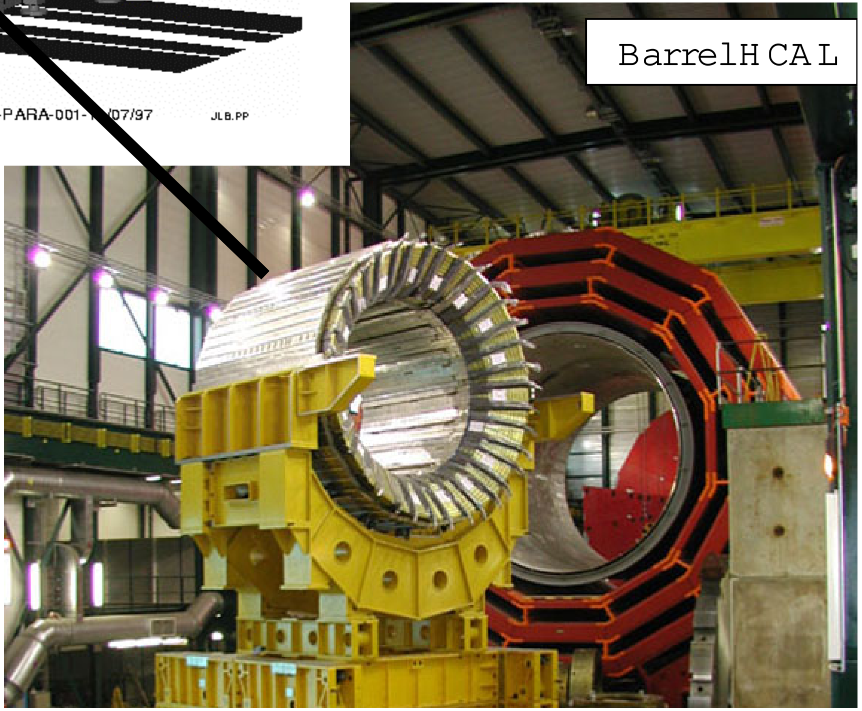

Barrel Muon Chamber


ARD
METER
MUON CHAMBERS
TRACKER
CRYSTAL ECAL
HCAL
Y
Z
X
Total weight : 12,500t.
Overall diameter : 15.00 m
Overall length : 21.60 m
Magnetic field : 4 Tesla
UPERCONDUCTING
COIL
RETURN YOKE
CMS-PARA-001-/07/97
JLB.PP


Magnet yoke

Length : ~20 m
Radius : ~7 m
Weight : ~ 13000 tons


ECAL crystals


Barrel HCAL

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels + strips TRD → particle identification $B= 2T$ $\sigma/p_T \sim 5\times10^{-4}\ p_T(\mathrm{GeV}) \oplus 0.01$	Si pixels + strips No particle identification $B= 4T$ $\sigma/p_T \sim 1.5\times10^{-4}\ p_T\ (\mathrm{GeV}) \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 3\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7\ \%$ at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

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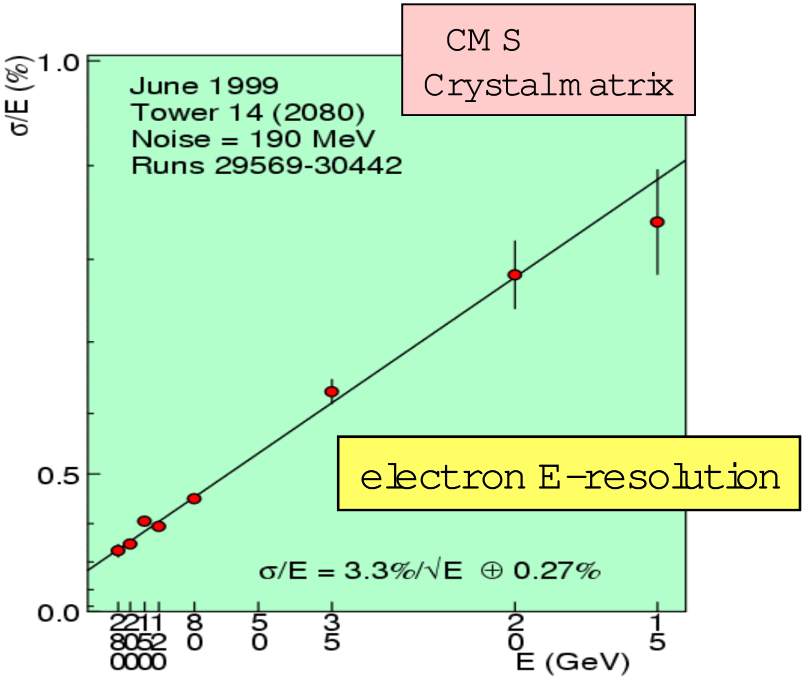
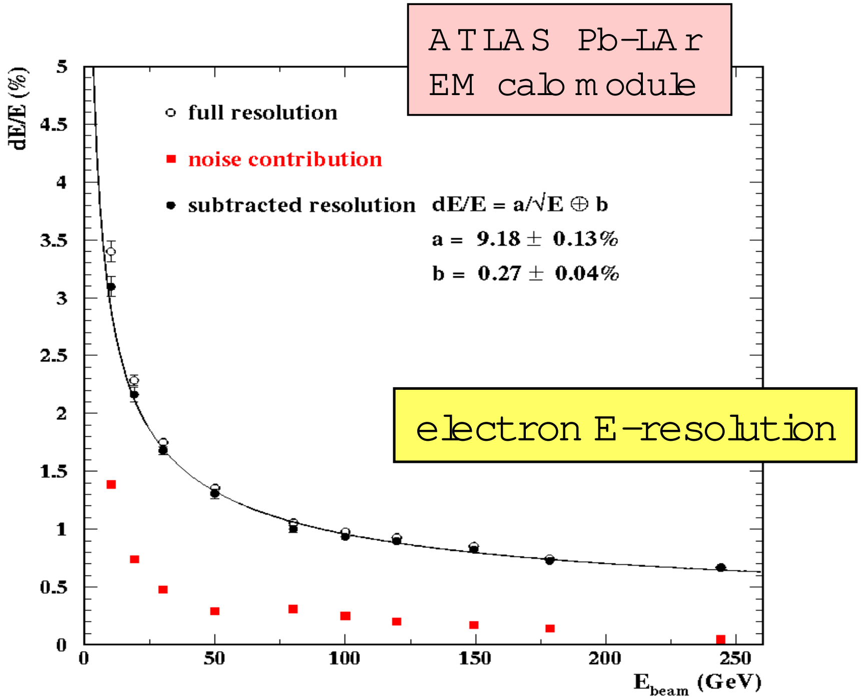
F.Gianotti



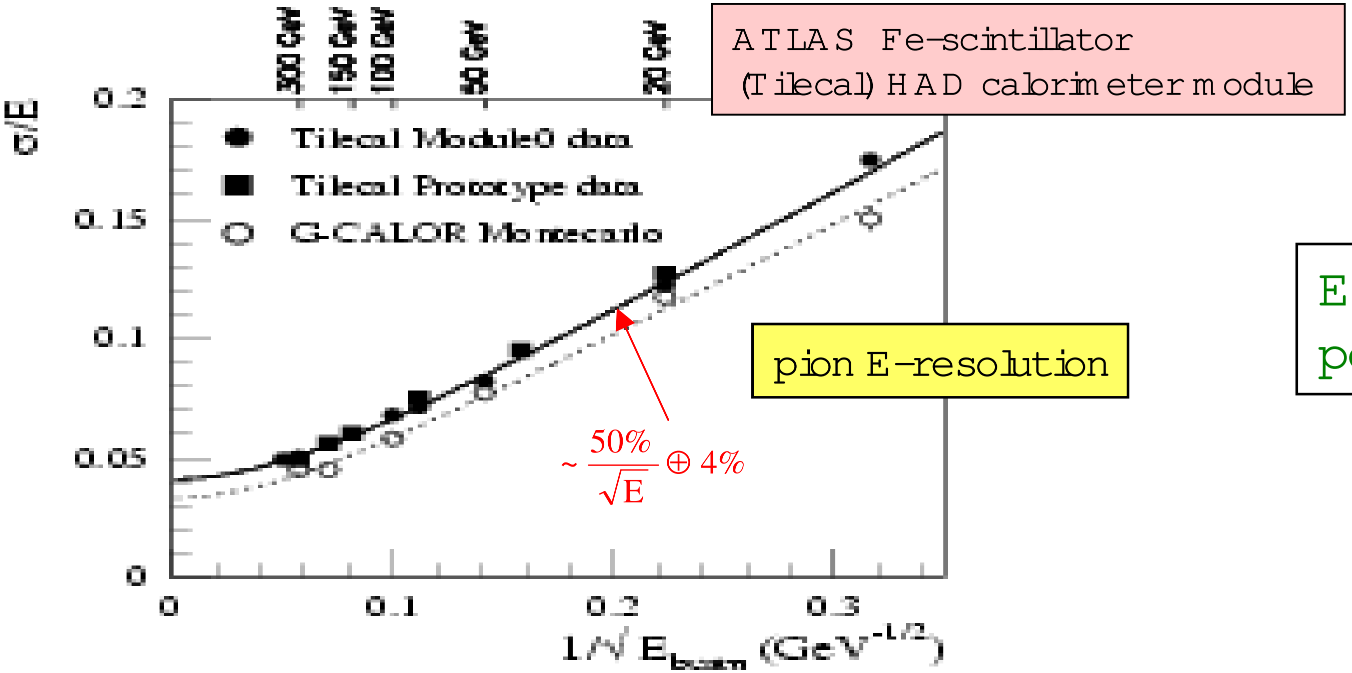
CMS Crystal matrix

electron E-resolution



ATLAS Pb-LAr EM calo module

electron E-resolution



ATLAS Fe-scintillator (Tilecal) HAD calorimeter module

pion E-resolution

$$\sim \frac{50\%}{\sqrt{E}} \oplus 4\%$$

Examples of test beam performance results

Examples of performance and issues relevant to SUSY studies

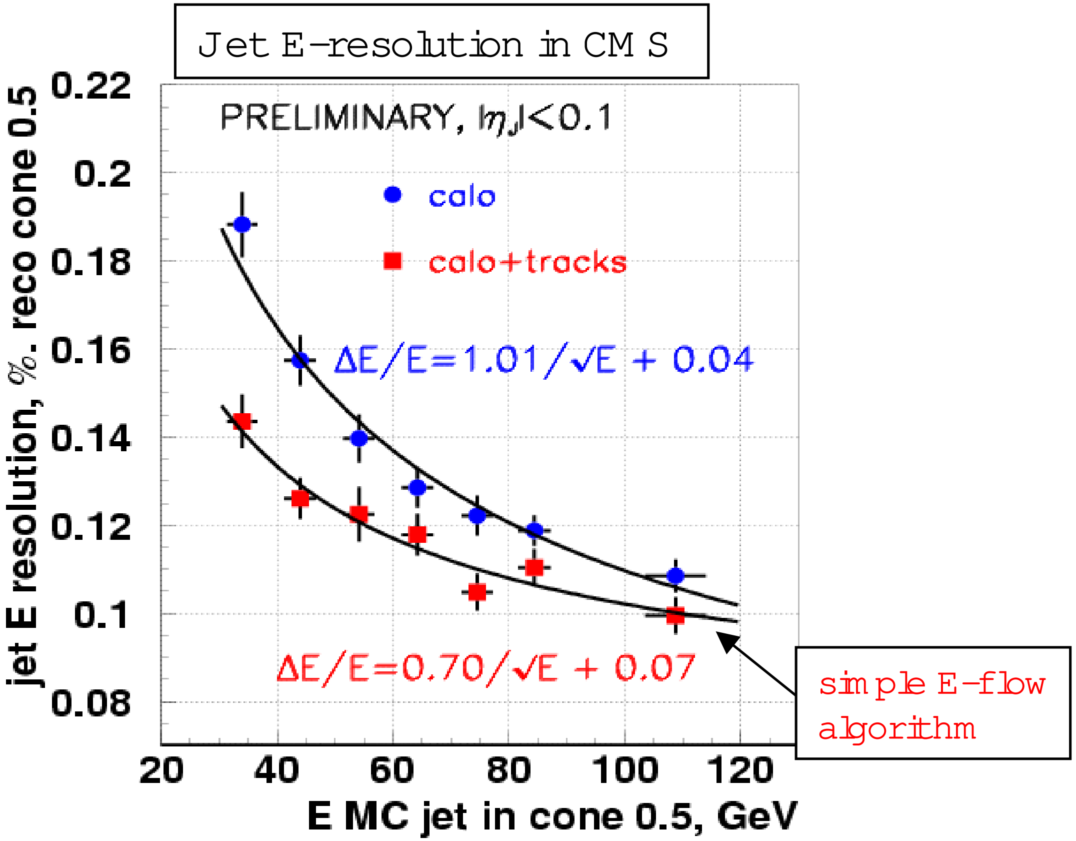
from full GEANT simulations of ATLAS, CMS

❶ Good E-resolution of (hadronic) calorimetry:

— reduces fake MET from detector resolution in QCD multijet events

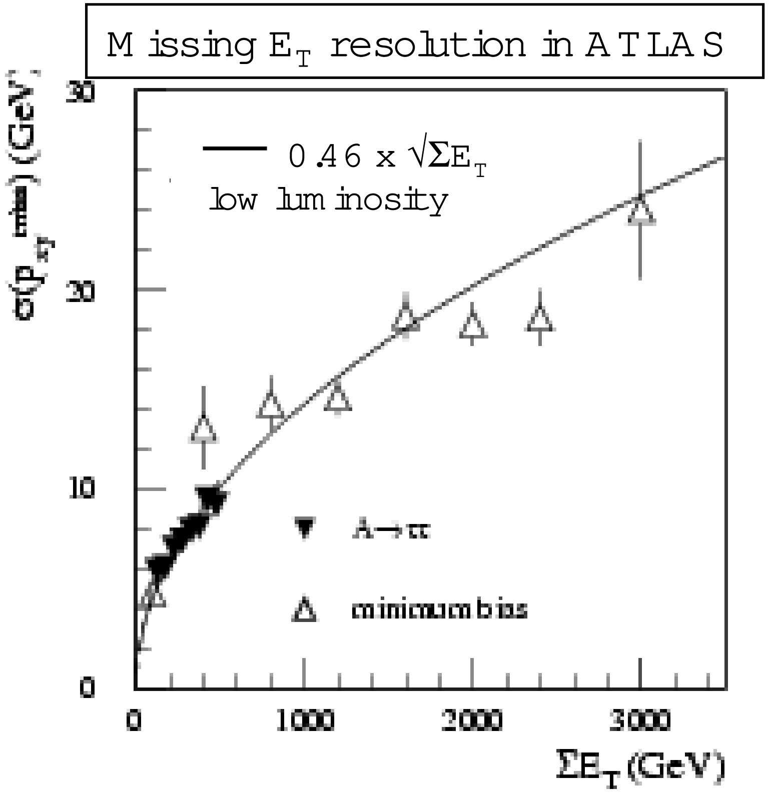
— narrow mass peaks: W → jj, h → bb, t → bjj from SUSY cascade decays; A/H → ττ, etc.

— etc.



Jet E-resolution in CMS

simple E-flow algorithm



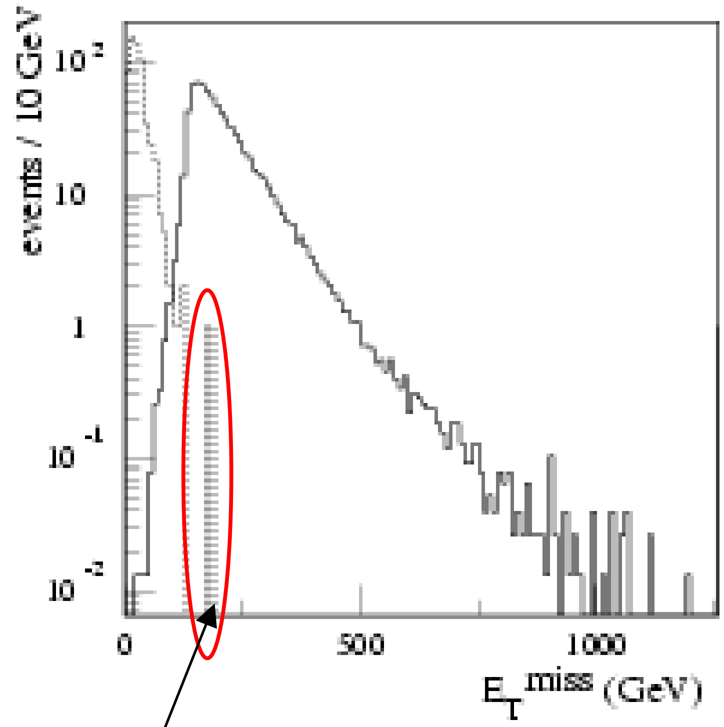
Missing E_T resolution in ATLAS

High lumi: MET resolution is ~ 2 worse

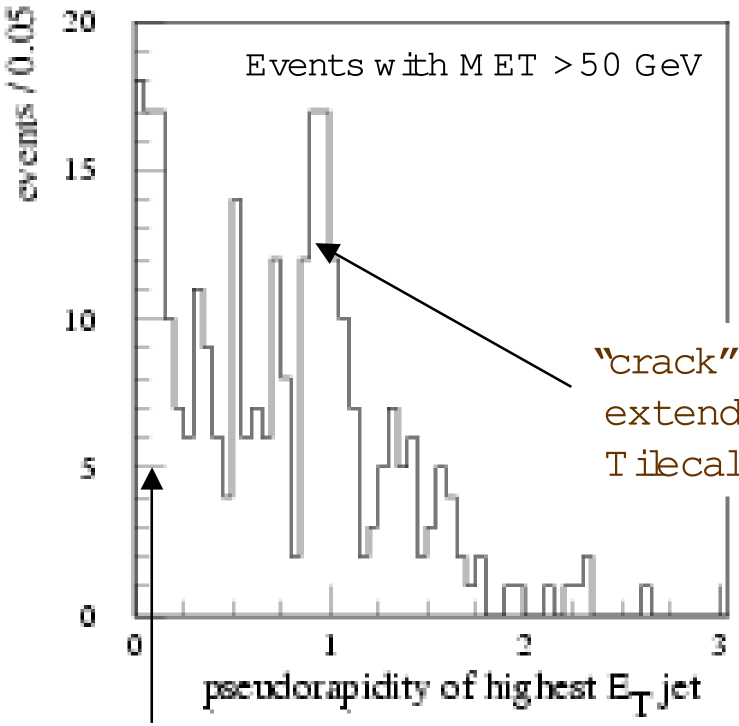
❷ Hermetic calorimetry coverage : $|\eta| < 5$, minimal cracks and dead material

→ minimise fake MET from lost or badly measured jets

ATLAS study : full simulation of Z + jet(s) events, with $Z \rightarrow \mu\mu$ and p_T (Z) > 200 GeV



2 events with MET > 200 GeV contain a high-p_T neutrino

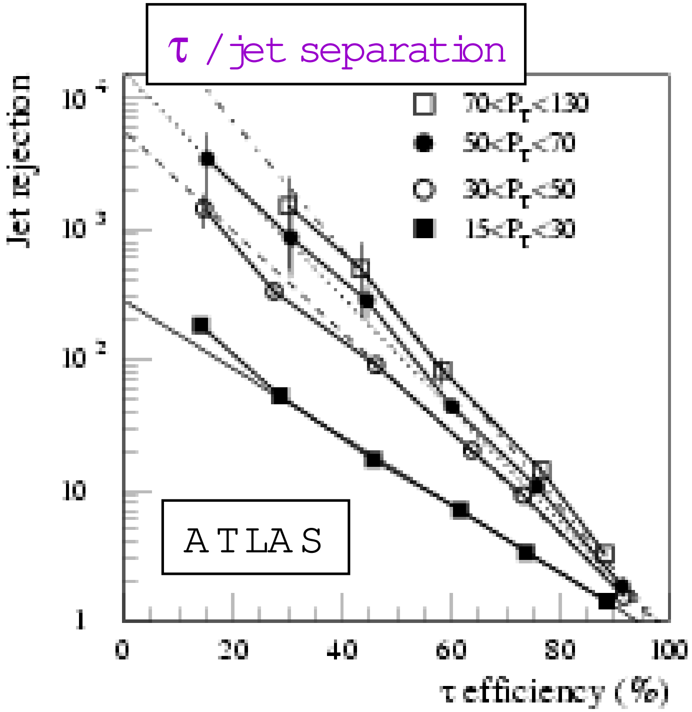


"crack" barrel/ extended barrel Tilecal

Particles parallel to Tilecal scintillating tiles

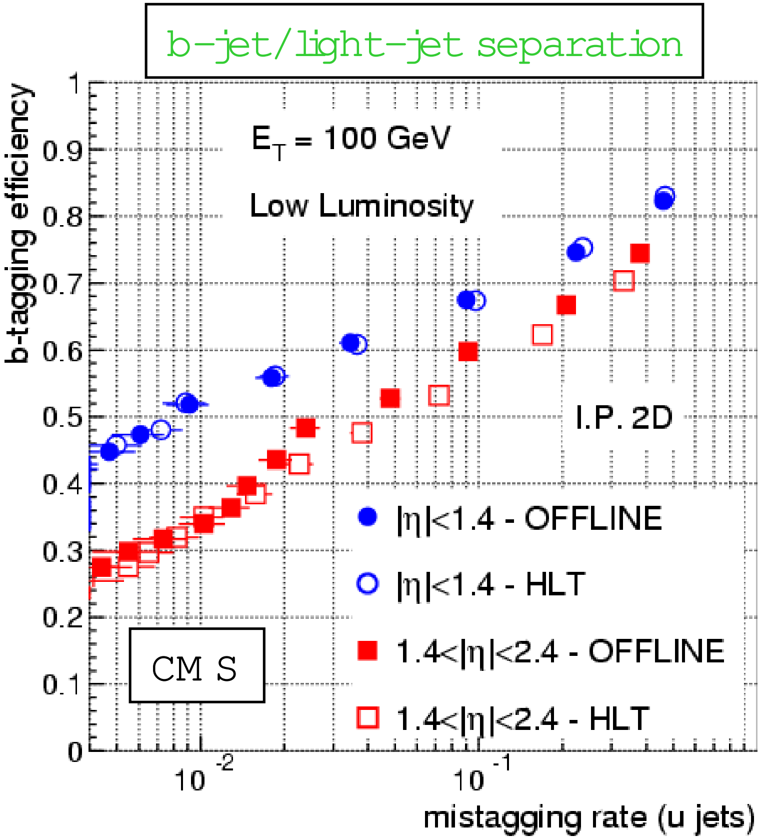
❸ Powerful b-tagging and τ-identification:

- τ's and b-jets expected in sparticle and SUSY Higgs decays (especially at large tanβ)
- in general 3rd generation could play a special role in New Physics



From full simulation of τ's from A → ττ events and QCD jets

τ's are identified as narrow and low multiplicity jets in calorimeters and tracker



From full simulation of QCD b-jets and u-jets

b-jets are identified from tracks with large impact parameter

❹ Precise knowledge of absolute lepton, jet and missing E_T energy scales:

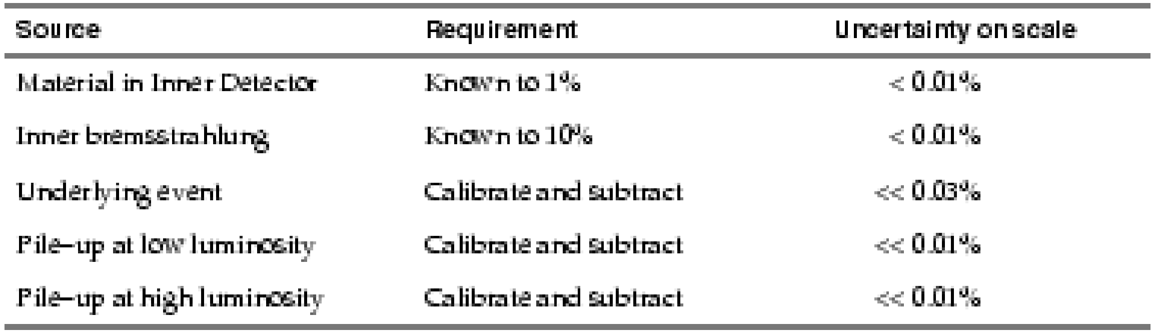
→ for precise measurements of SUSY events, e.g. end-points of kinematic distributions, $A/H \rightarrow \mu\mu$ mass, etc. (in many cases statistical error is negligible)

Can only be achieved with *in situ* calibration with data samples

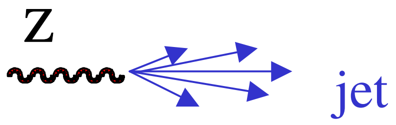
ℓ-scale

- mainly from $Z \rightarrow \ell\ell$ events (1 evt/s per species at 10^{33})
- ~ 1 ‰ uncertainty achieved by CDF, D0 (dominated by statistics of control samples)
- LHC goal: 0.2 ‰ to measure m_W to ~ 15 MeV (1 ‰ assumed here)

ATLAS: full simulation study of uncertainty on $Z \rightarrow ee$ scale

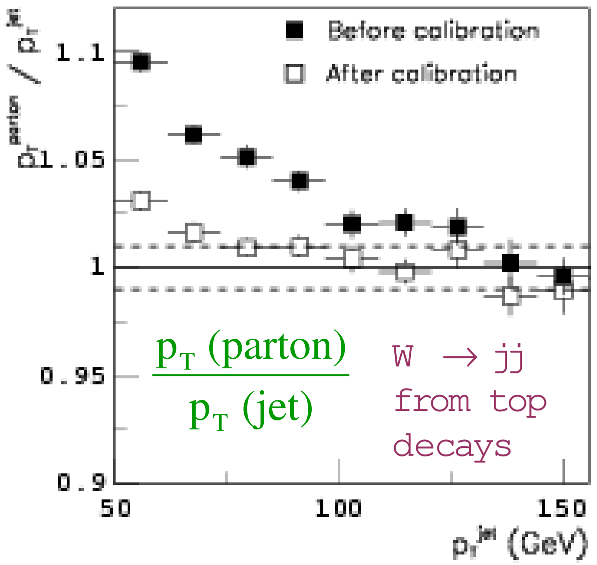


Source	Requirement	Uncertainty on scale
Material in Inner Detector	Known to 1%	< 0.01%
Inner bremsstrahlung	Known to 10%	< 0.01%
Underlying event	Calibrate and subtract	<< 0.03%
Pile-up at low luminosity	Calibrate and subtract	<< 0.01%
Pile-up at high luminosity	Calibrate and subtract	<< 0.01%



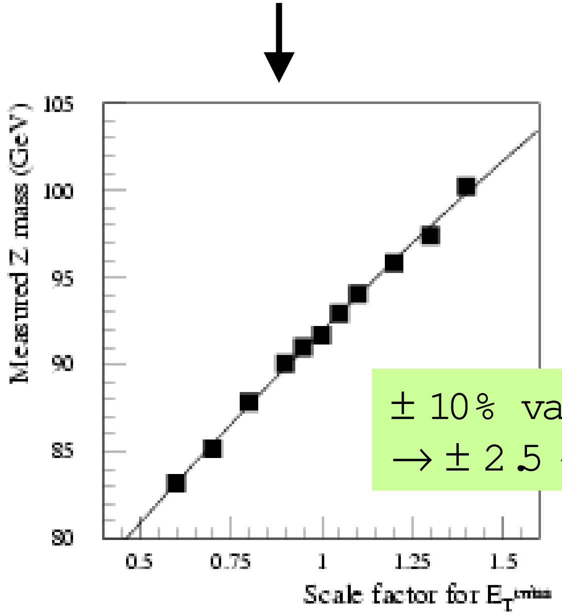
Jet-scale

- mainly from Z (→ ℓℓ) + 1 jet asking p_T (jet) = p_T (Z)
  and from W → jj in tt → bW bW → bℓν bjj events asking $m_{jj} = m_W$
- ~ 3 % uncertainty achieved by CDF, D0 (not enough tt statistics at Tevatron)
- LHC goal: ~ 1 % to measure m_{top} to ~ 1 GeV
- main systematics: FSR, underlying event, etc.



Missing ET scale

- mainly from Z → ττ → ℓ-hadrons + ν 's
- sensitivity of reconstructed Z mass to MET scale



ATLAS,
full simulation

± 10 % variation on MET scale
→ ± 2.5 % variation of m_Z

- m_Z can be measured to 1% with 4000 evts (30 fb^{-1})
  → MET scale can be constrained to ~ 5%

The LHC potential for SUSY :

— inclusive searches

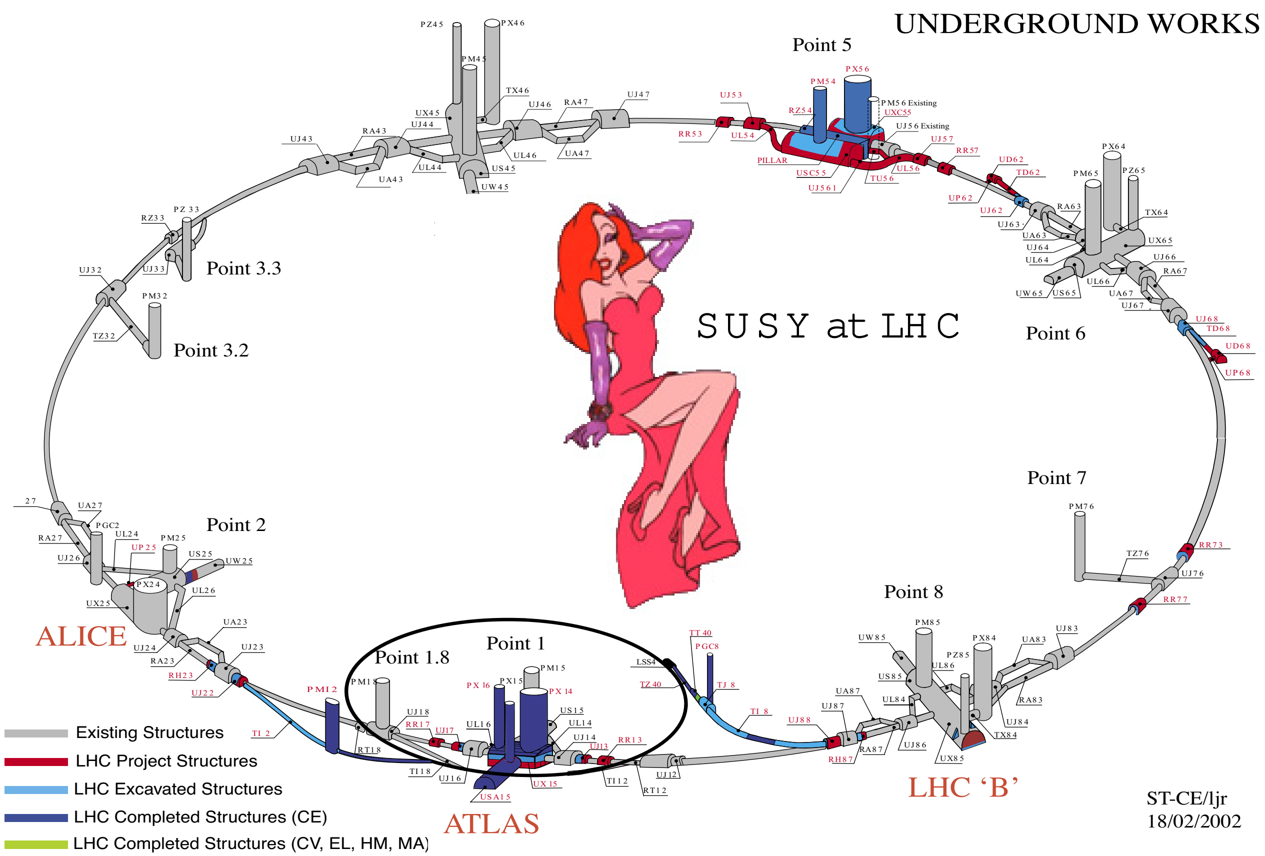
— precise measurements

— constraining the underlying theory

— general "lessons"

— what the LHC can and cannot do ...

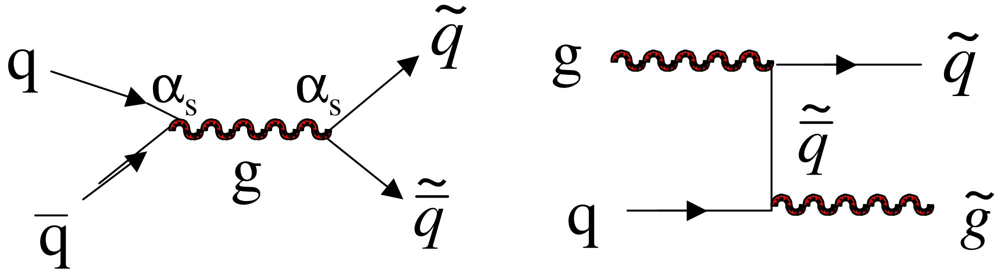
Framework : Supergravity with
R-parity conservation unless
otherwise stated


UNDERGROUND WORKS
SUSY at LHC
Point 5
Point 6
Point 7
Point 8
Point 1
Point 1.8
Point 2
Point 3.2
Point 3.3
ALICE
ATLAS
LHC 'B'
Existing Structures
LHC Project Structures
LHC Excavated Structures
LHC Completed Structures (CE)
LHC Completed Structures (CV, EL, HM, MA)
ST-CE/ljr
18/02/2002

Sparticle production at LHC

- Squarks and gluinos produced via strong processes → large cross-section

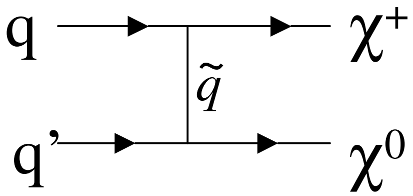
E.g.:


q
α_s
α_s
$\tilde{q}$
g
$\bar{q}$
$\tilde{\bar{q}}$
g
$\tilde{q}$
$\tilde{\bar{q}}$
q
$\tilde{g}$

M (GeV)	*σ (pb)*	*Evts/yr*
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

- Charginos, neutralinos, sleptons direct production occurs via electroweak processes
→ much smaller rate (produced more abundantly in squark and gluino decays)

E.g.

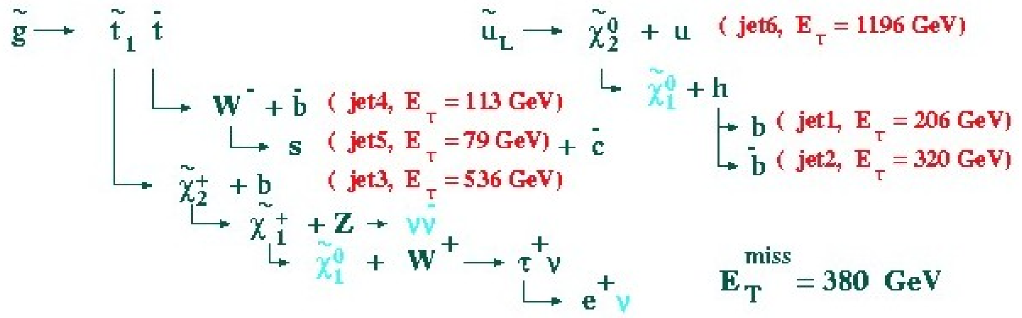

q
q'
$\tilde{q}$
χ^+
χ^0

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

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

$\tilde{q}$, $\tilde{g}$ heavy → cascade decays favoured

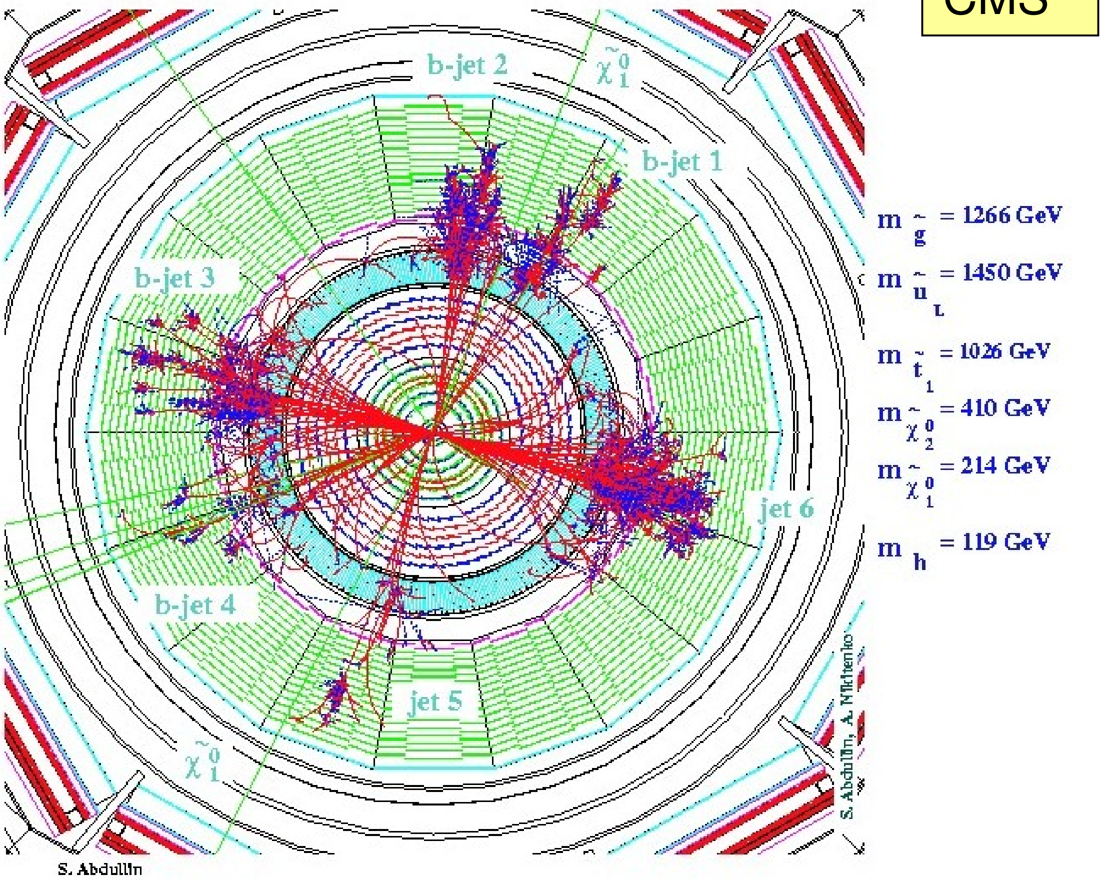
Example :


$\tilde{g} \rightarrow \tilde{t}_1 \bar{t}$
$W^- + \bar{b}$ (jet4, E_T = 113 GeV)
s (jet5, E_T = 79 GeV) + $\bar{c}$
$\tilde{\chi}_2^+ + b$ (jet3, E_T = 536 GeV)
$\tilde{\chi}_1^+ + Z \rightarrow \nu\bar{\nu}$
$\tilde{\chi}_1^0 + W^+ \rightarrow \tau^+ \nu$
$e^+ \nu$
$\tilde{u}_L \rightarrow \tilde{\chi}_2^0 + u$ (jet6, E_T = 1196 GeV)
$\tilde{\chi}_1^0 + h$
b (jet1, E_T = 206 GeV)
$\bar{b}$ (jet2, E_T = 320 GeV)
E_T^{miss} = 380 GeV

$m_0 = 1000$ GeV
$m_{1/2} = 500$ GeV
$\tan\beta = 35$ $\mu > 0$ $A_0 = 0$

$m(\tilde{q}, \tilde{g}) \sim 1\,\text{TeV}$

CMS


b-jet 2
$\tilde{\chi}_1^0$
b-jet 1
b-jet 3
jet 6
b-jet 4
jet 5
$\tilde{\chi}_1^0$
$m_{\tilde{g}}$ = 1266 GeV
$m_{\tilde{u}_L}$ = 1450 GeV
$m_{\tilde{t}_1}$ = 1026 GeV
$m_{\tilde{\chi}_2^0}$ = 410 GeV
$m_{\tilde{\chi}_1^0}$ = 214 GeV
m_h = 119 GeV
S. Abdullin, A. Nikitenko
S. Abdullin

→ spectacular signatures
→ easy to extract SUSY signal from SM backgrounds at LHC (in most cases ...)

Inclusive SUSY (mainly $\tilde{q}, \tilde{g}$) searches

- Should be the most easy, fast and model-independent SUSY discovery mode at LHC

- Six topologies studied :

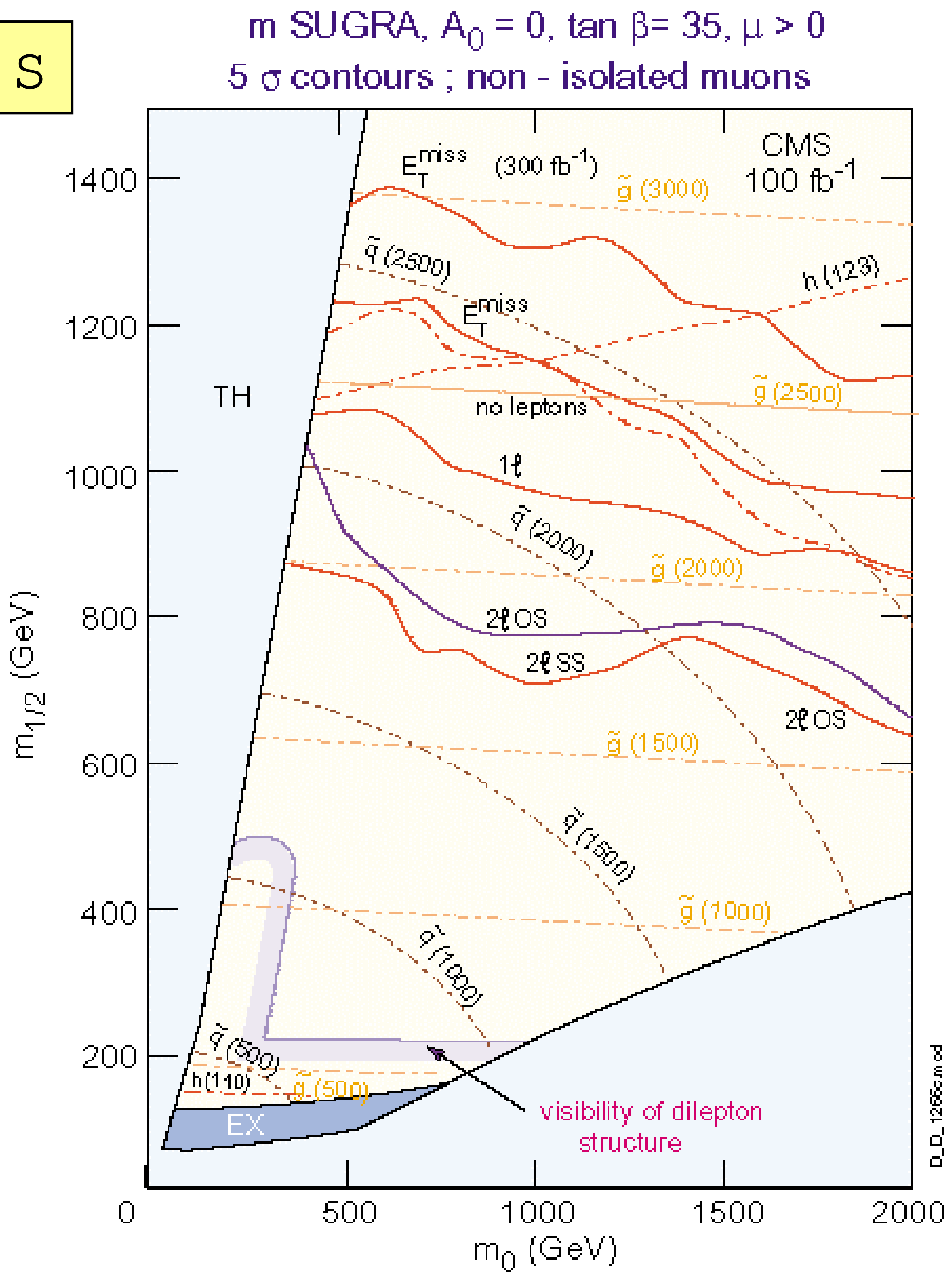
  — Jets + MET : no lepton requirement
  — 0ℓ : no leptons
  — 1ℓ : 1 lepton
  — 2ℓOS : 2 opposite-sign leptons
  — 2ℓSS : 2 same-sign leptons
  — 3ℓ : 3 leptons

- Main backgrounds : tt, W/Z + jets, QCD multijets

- Typically cuts are applied on number and E_T of jets, MET and MET isolation, event transverse sphericity, etc.

- Should also allow first and fast determination of general event properties (lepton multiplicity, "exotic" features like photons or stable heavy particles, etc.), and estimates of SUSY "mass scale" and SUSY inclusive cross-section
  → first indications of candidate models (to be investigated more fully with subsequent exclusive analyses) in rather model-independent way

CMS



Common cuts:

— ≥ 2 jets, $E_T^{j} > 40$ GeV $|\eta| < 3$

— MET > 200 GeV

Leptons :

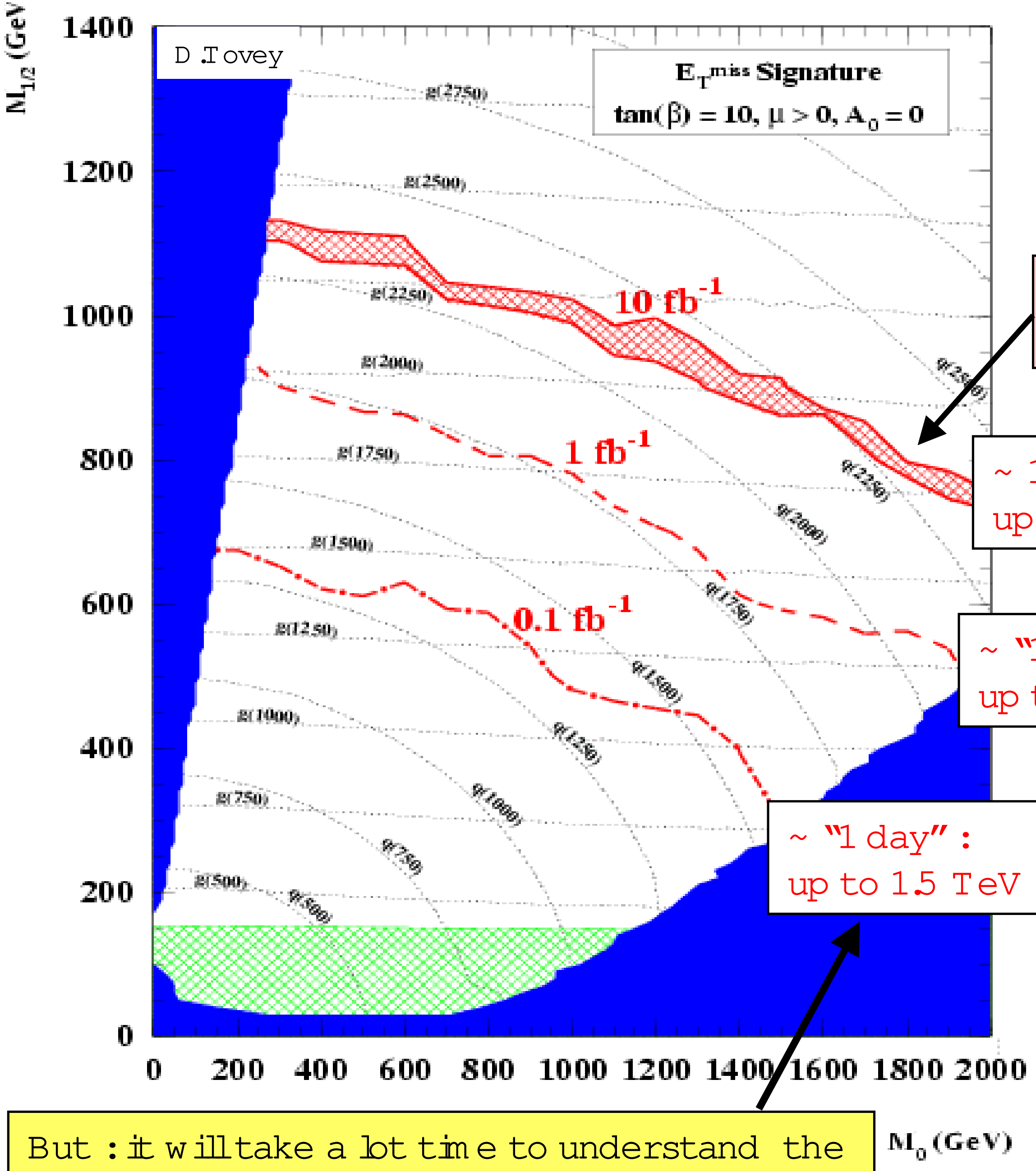
— $e^{\pm}$: $E_T^{e} > 20$ GeV $|\eta| < 2.5$ (isolated)

— $\mu^{\pm}$: $E_T^{\mu} > 10$ GeV $|\eta| < 2.5$ (isolated or not)

Jets + MET gives highest (and most model-independent) reach.

Lepton signatures are more model-dependent (e.g. a lot of τ's at large tanβ)

Discovery reach vs time with most powerful Jets + MET signature



ATLAS
5σ discovery curves

band indicates factor ± 2 variation in background estimate

~ 100 days :
up to 2.3 TeV

~ "10 days" :
up to 2 TeV

~ "1 day" :
up to 1.5 TeV

But : it will take a lot time to understand the detectors and the backgrounds …

Discovery reach for squarks/gluinos

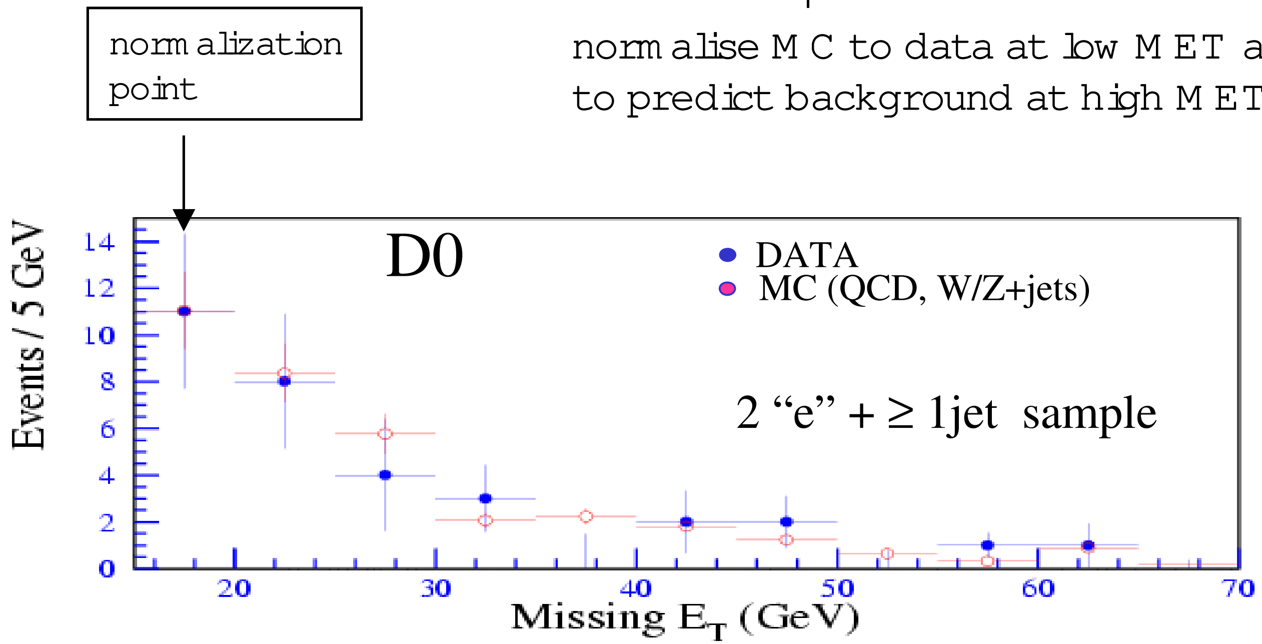
Time	mass reach
1 month at 10^{33}	~ 1.3 TeV
1 year at 10^{33}	~ 1.8 TeV
1 year at 10^{34}	~ 2.5 TeV
ultimate (300 fb^{-1})	~ 2.5 – 3 TeV

Backgrounds will be estimated using as much as possible data (control samples) and Monte Carlo

Background process (examples …)	Control samples (examples …)
Z (→ νν) + jets	Z (→ ee, μμ) + jets
W (→ τν) + jets	W (→ eν, μν) + jets
tt→ bℓνbjj	tt→ bℓν bℓν
QCD multijets	lower E_T sample

Additional handles from changing (loosening ..) cuts, varying the number of leptons, etc., which will change the background composition.

normalise MC to data at low MET and use it to predict background at high MET in "signal" region



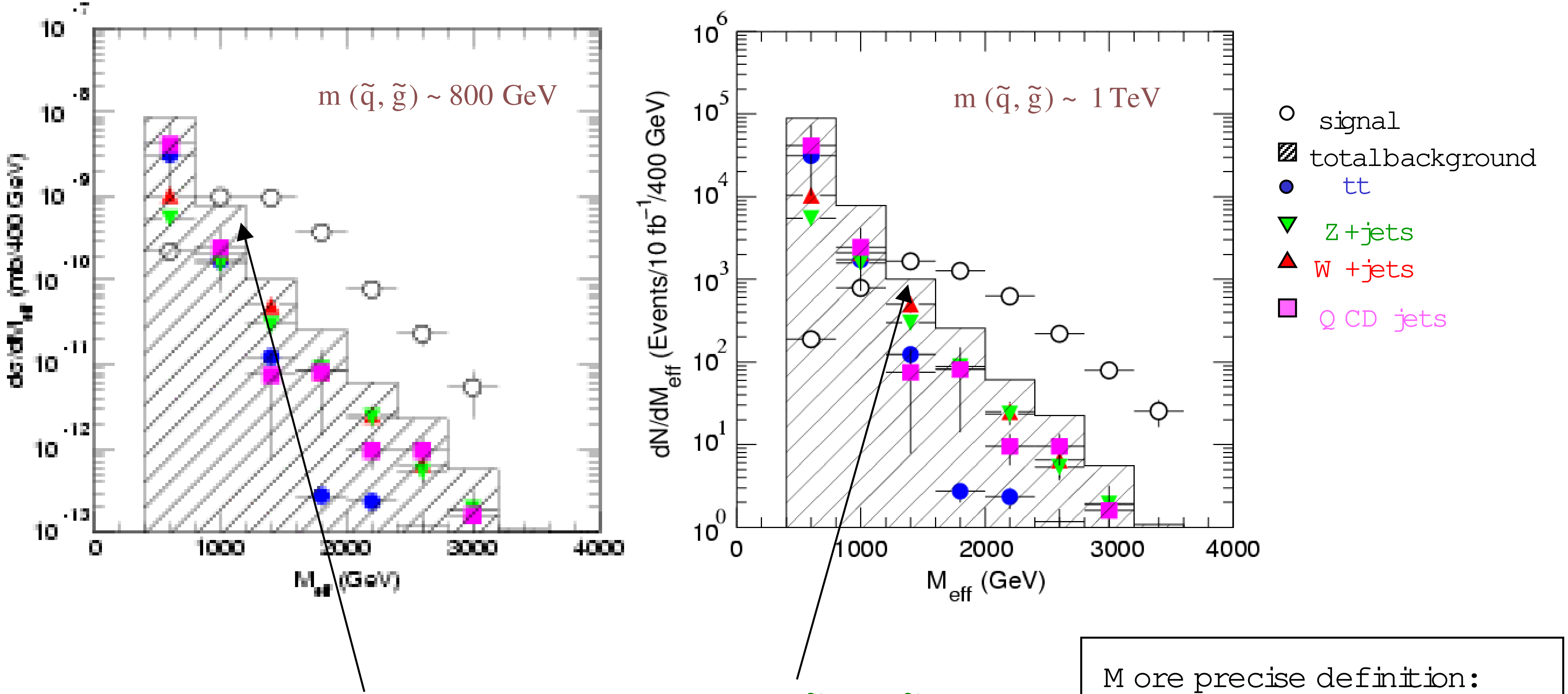
A lot of data will most likely be needed !

First/fast determination of SUSY mass scale and cross-section

Use e.g. the "effective mass":

$$M_{eff} = E_T^{miss} + \sum_{i=1}^{4} p_T\,(jet_i) \quad (GeV)$$

Best sensitivity from
Jets+MET+0ℓ topology



Peak position correlated to $M_{SUSY} \approx \min\,(m(\tilde{q}), m(\tilde{g}))$

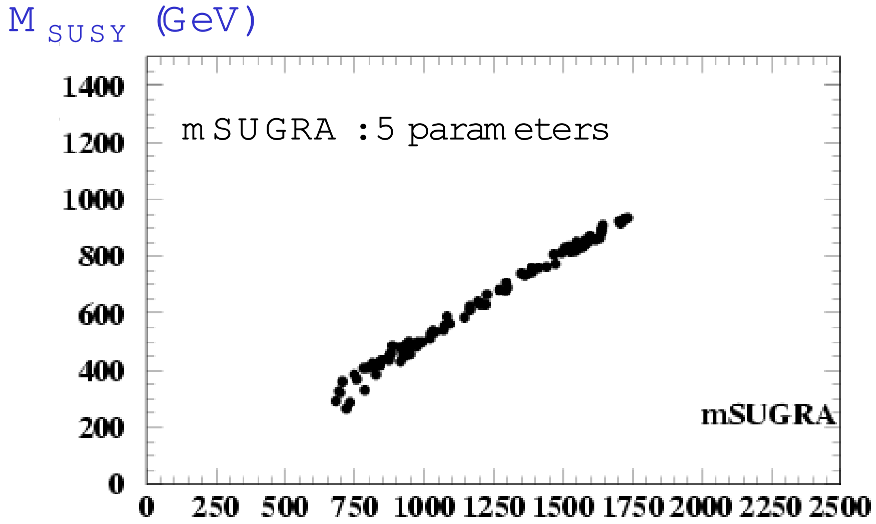
Area under the peak correlated to SUSY cross-section

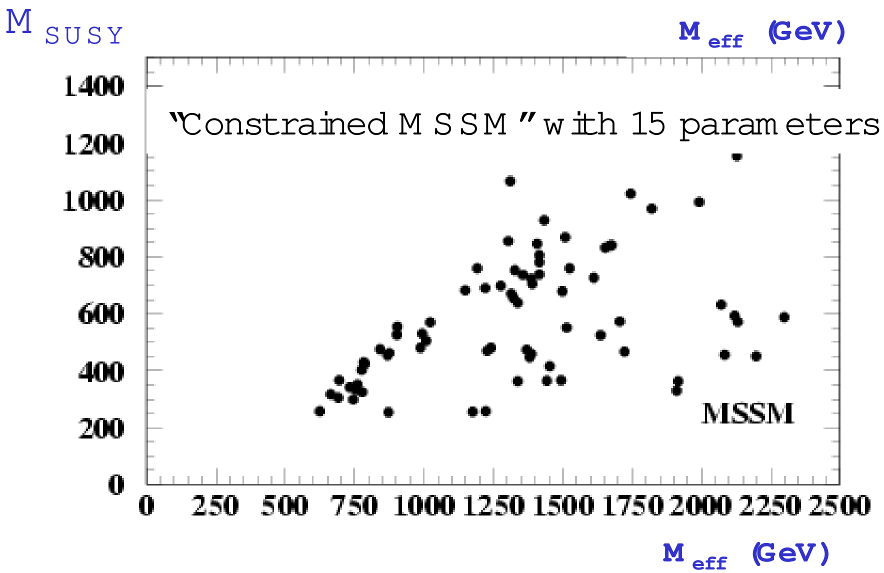
More precise definition:

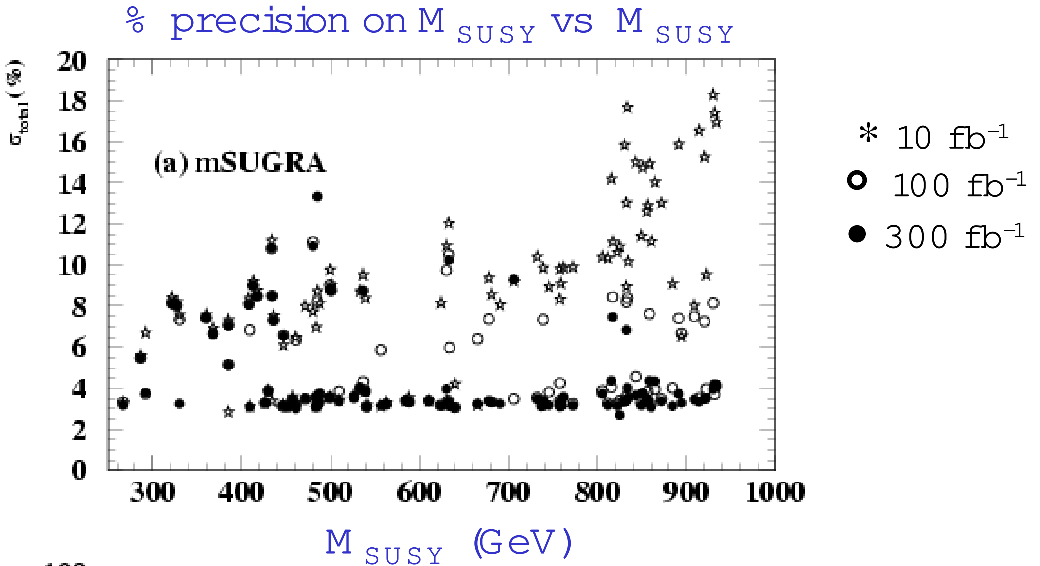
$$M_{SUSY} \approx \frac{\sum_i \sigma_i \tilde{m}_i}{\sum_i \sigma_i} - \frac{m^2\,(LSP)}{\frac{\sum_i \sigma_i \tilde{m}_i}{\sum_i \sigma_i}}$$

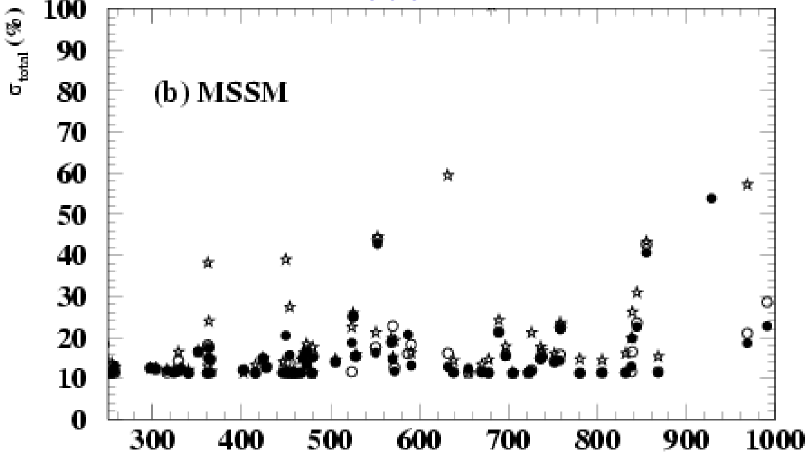
SUSY mass scale (~ model-independent)

D.Tovey









conservative !

Intrinsic spread from model parameters (infinite statistics, no experimental error):

~ 2 % mSUGRA

~10 % constrained MSSM

Including experimental uncertainties (~50% from background subtraction, ~1.5% from E-scale):

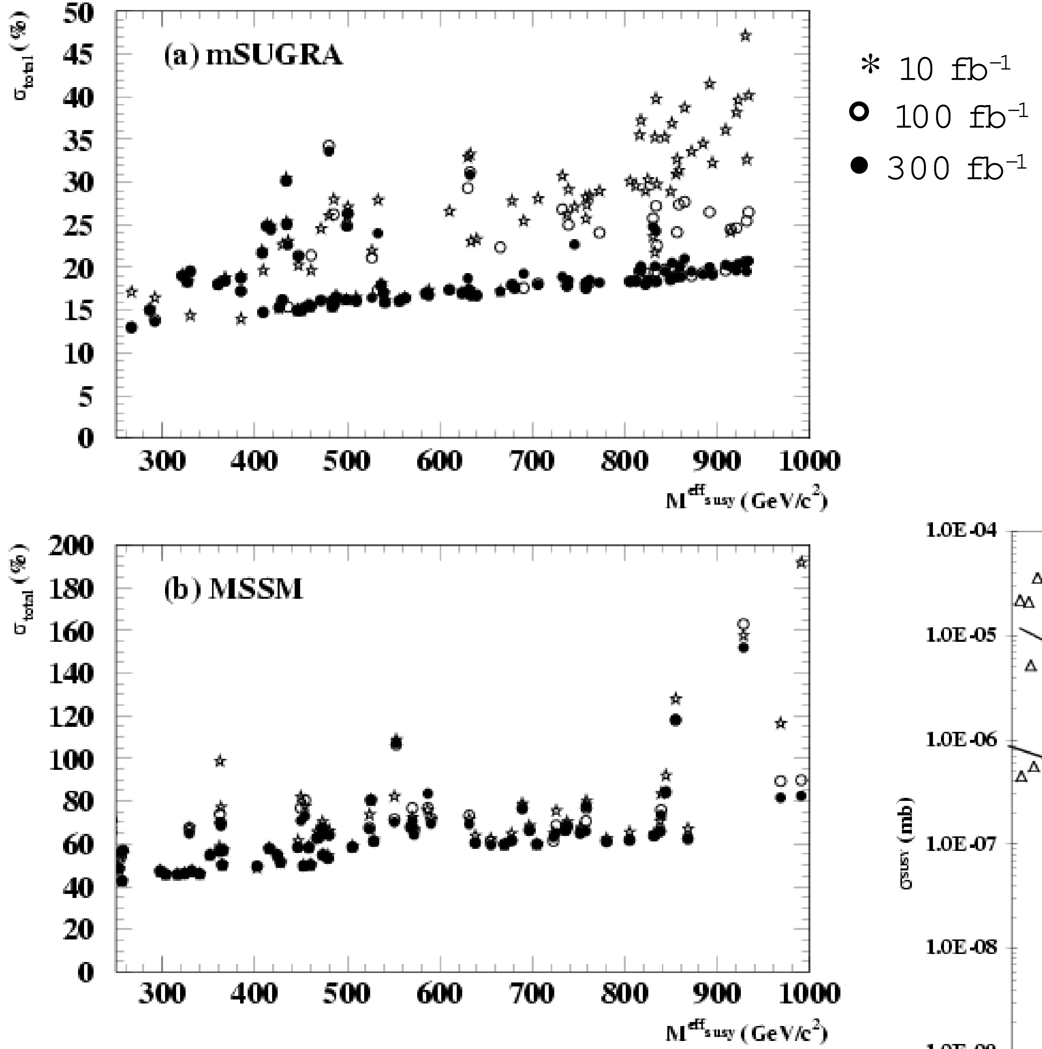
≤ 20% (10%) mSUGRA for 10 (100) fb^{-1}

≤ 60% (30%) constrained MSSM for 10 (100) fb^{-1}

SUSY cross-section (more model-dependent)

D.Tovey

Precision on measured SUSY cross-section vs M^{eff}_{SUSY}

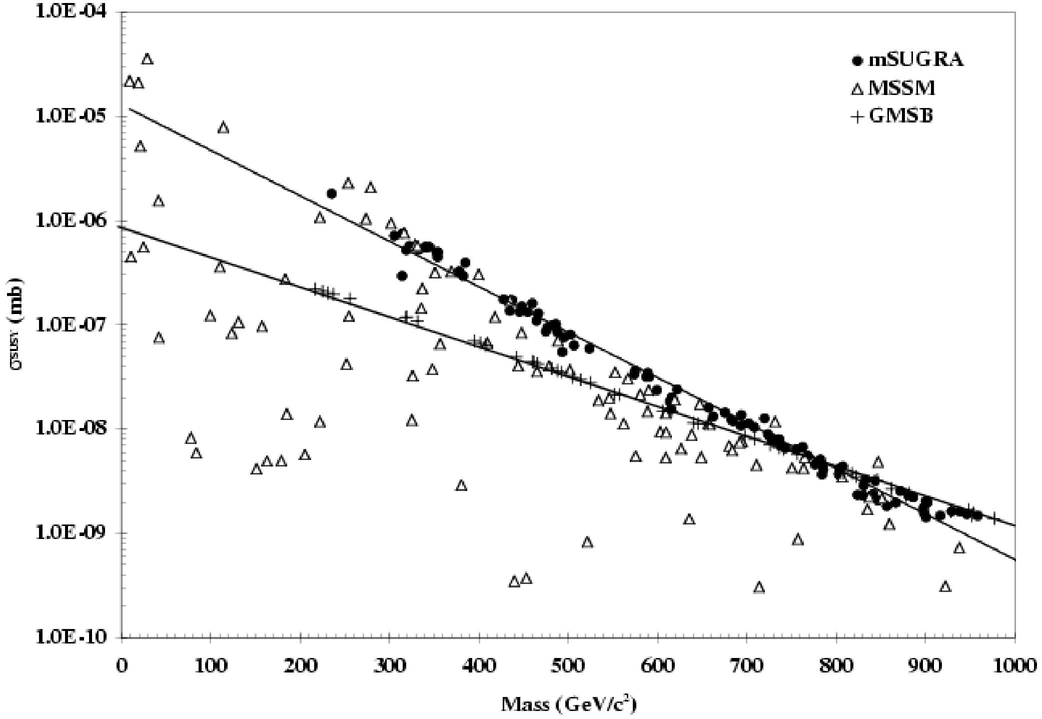


Including experimental uncertainties :

$\leq$ 30% mSUGRA for 300 fb^{-1}

$\leq$ 80% constrained MSSM for 300 fb^{-1}

Theoretical SUSY cross-section vs M^{eff}_{SUSY}



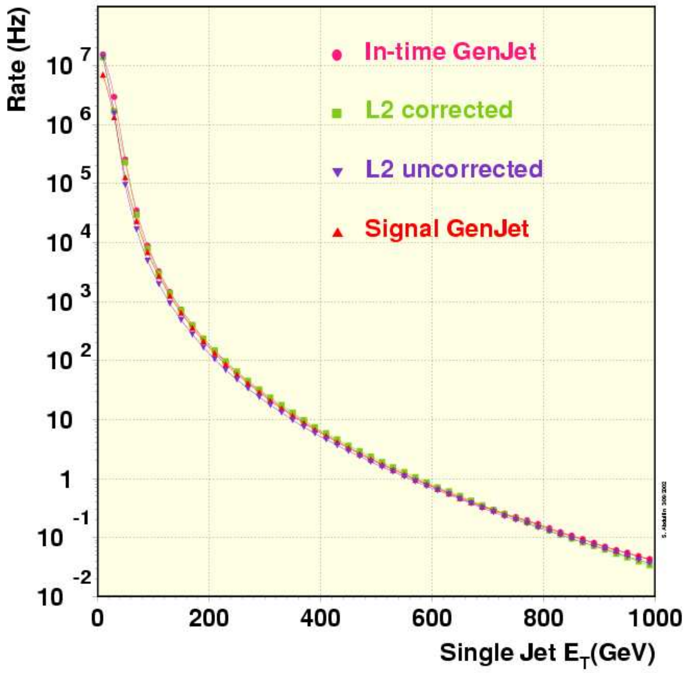
F.Gianotti

Can we trigger on SUSY events ?

dictated by offline
Computing cost

- LHC trigger must reduce 1 GHz pp interactions → 100-200 Hz to storage
- No problems for SUSY triggers in most cases: SM rate acceptable for SUSY-like final states
- Potential exception : Jets + MET signature for light masses close to Tevatron limit, where low thresholds on jets and MET needed → potentially large rate from QCD

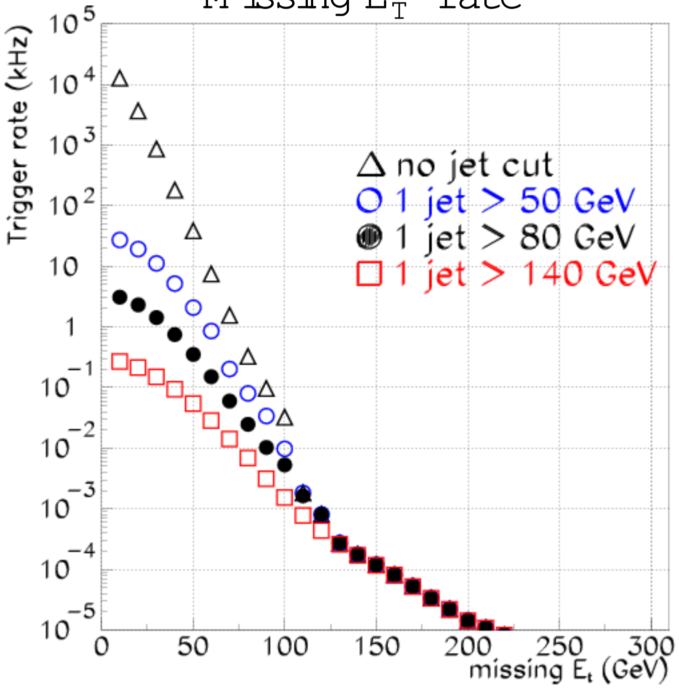
Inclusive jet rate (cone ΔR=0.5)



CMS : full GEANT
simulation of
QCD background
(for DAQ TDR)

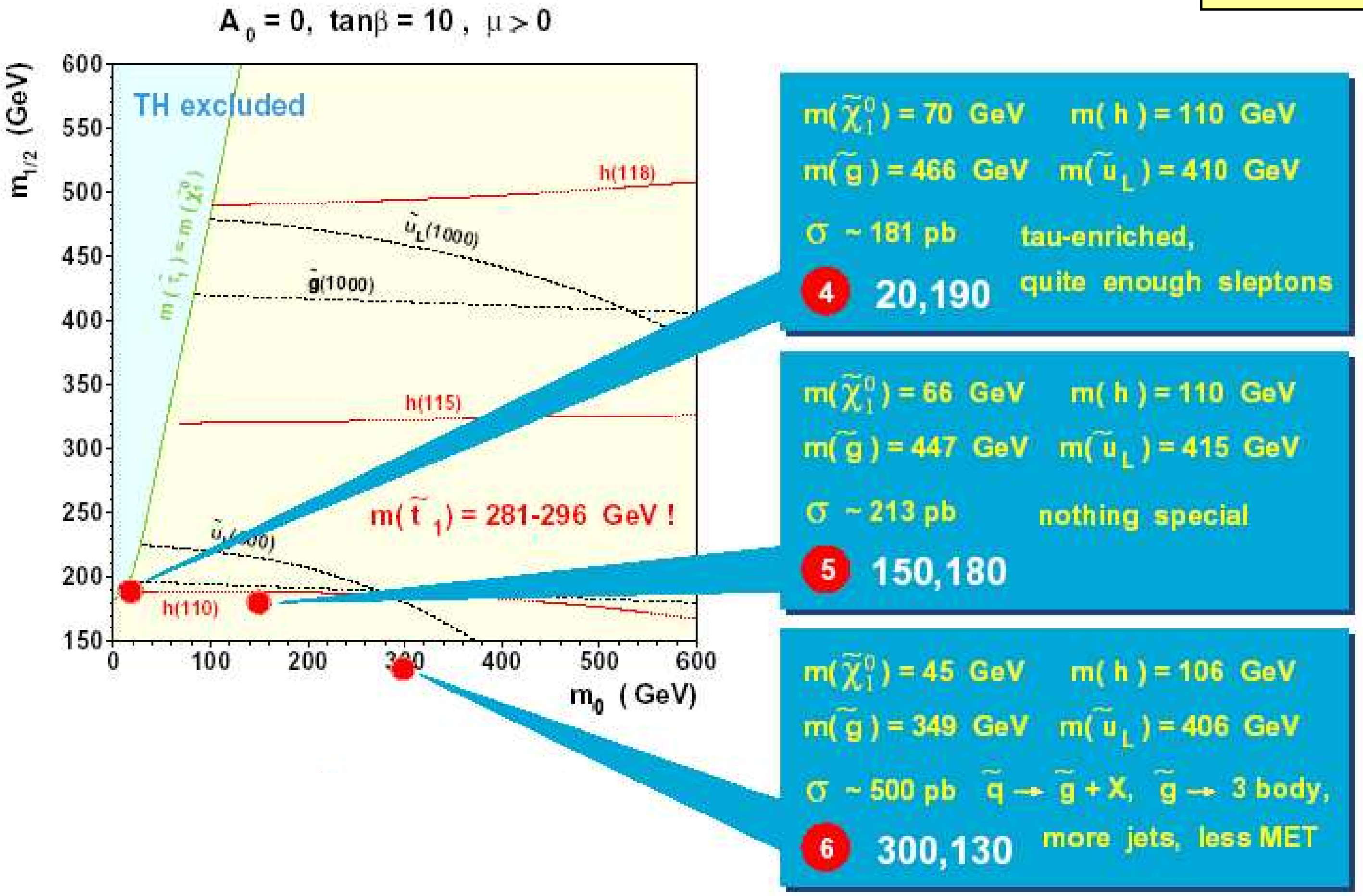
$\mathcal{L}=2\times10^{33}$

Missing E_T rate



→ Achieving a rate of few Hz requires few hundred GeV thresholds or multi-object triggers with many jets or jets + MET

CMS : SUSY trigger exercise



$m(\tilde{\chi}^0_1) = 70$ GeV $m(h) = 110$ GeV
$m(\tilde{g}) = 466$ GeV $m(\tilde{u}_L) = 410$ GeV
$\sigma \sim 181$ pb tau-enriched,
④ 20,190 quite enough sleptons

$m(\tilde{\chi}^0_1) = 66$ GeV $m(h) = 110$ GeV
$m(\tilde{g}) = 447$ GeV $m(\tilde{u}_L) = 415$ GeV
$\sigma \sim 213$ pb nothing special
⑤ 150,180

$m(\tilde{\chi}^0_1) = 45$ GeV $m(h) = 106$ GeV
$m(\tilde{g}) = 349$ GeV $m(\tilde{u}_L) = 406$ GeV
$\sigma \sim 500$ pb $\tilde{q} \to \tilde{g} + X$, $\tilde{g} \to$ 3 body,
⑥ 300,130 more jets, less MET

- Consider points in parameter space close to Tevatron reach (most difficult for LHC trigger)
- With and without R_P conservation. For R_p-violation choose most difficult case : $\chi^0_1 \to 3j$
- Full GEANT simulation of SUSY signal and SM backgrounds
- Optimize efficiency for a rate to storage of 3 Hz

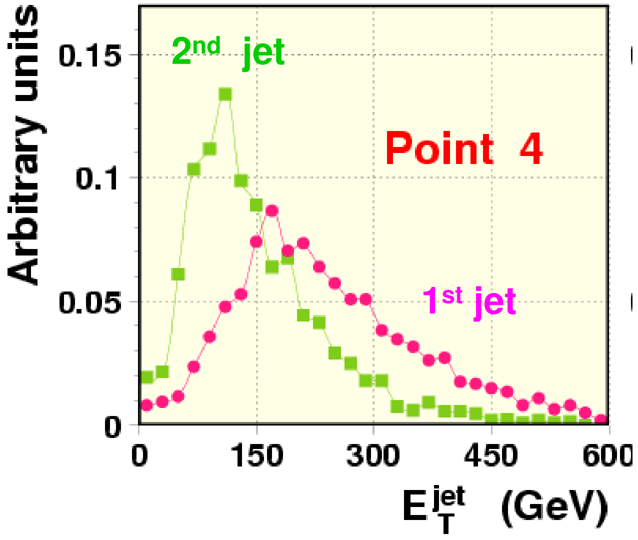
- MET >170 GeV
- 3 jets > 60 GeV and MET > 110 GeV
- 4 jets > 120 GeV
- 1 jet > 190 GeV, MET>90 GeV, and $\Delta\phi(j1,j2) < \pi - 0.5$
- 2 jets>40 GeV, MET>100 GeV, and $\Delta\phi(j1,j2) < \pi - 0.5$
- 4 jets>80 GeV, MET>60 GeV, and $\Delta\phi(j1,j2) < \pi - 0.5$

Possible jets and MET triggers at LVL2 for $L = 2 \times 10^{33}$

Efficiency for SUSY points:

$$\varepsilon = 0.78,\ 0.74,\ 0.54,\ 0.38,\ 0.27,\ 0.17$$

$$④ \quad ⑤ \quad ⑥ \quad \underbrace{\text{4R} \quad \text{5R} \quad \text{6R}}_{\text{With } \not{R}_P}$$



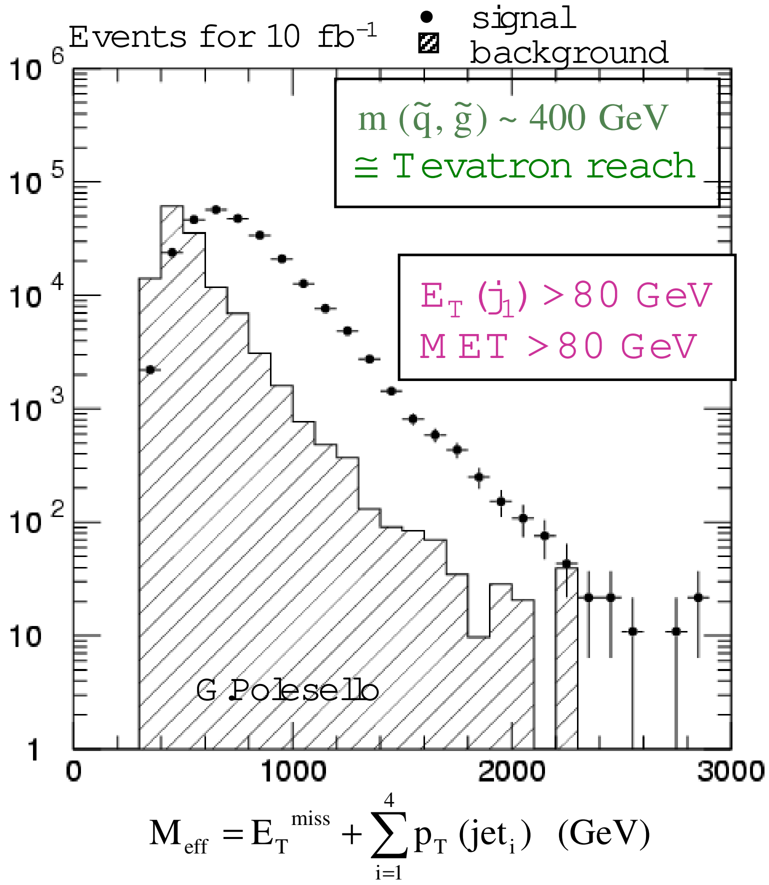
Trigger rate of ~ 3 Hz dominated by QCD

Even in the most difficult cases, we should be able to trigger on SUSY events

However: even lower thresholds needed in some cases to

— observe unbiased shape of SUSY signal emerging from background and measure M_{SUSY}

— study background and systematic effects (pre-scaling at lower thresholds should be ok here)



Higher offline cuts than these
would cut the signal peak

ATLAS uses Jet + MET trigger with
$p_T^{\,j} > 70$ GeV and MET > 70 GeV
(+ MET isolation). Rate ~ 20 Hz at 2×10^{33}

Note: because of lack of resources (→ staging of parts of LHC detectors and trigger being considered) not easy to keep such an inclusive approach (which is necessary for robust physics ....)

F.Gianotti

Precise measurements of SUSY masses and parameters

- Inclusive searches :
  - — SUSY discovery → must be as model-independent as possible
  - — first estimate of SUSY mass scale and cross-section
  - — first indications about model from inclusive features : e.g. GMSB (if many γ's or heavy stable charged particles), R_p-violation or conservation (from MET spectra), large tanβ (many τ's), etc.

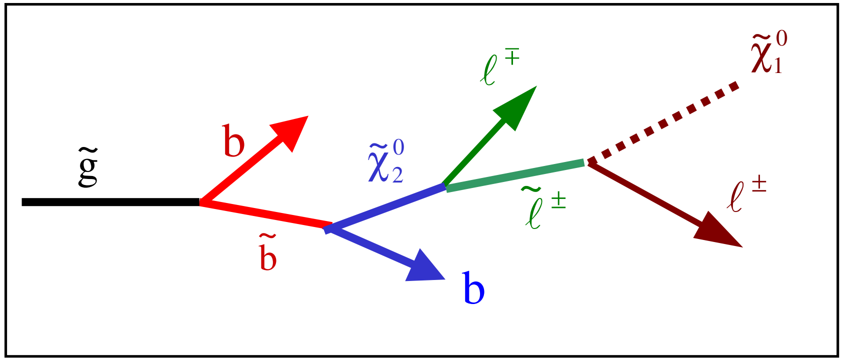
- To progress further, measure as many sparticles (masses, decay modes, etc.) as possible → constrain fundamental parameters of theory

- One example shown in detail here : "LHC Point 5" of mSUGRA
  - — how data analysis could be carried out step by step
  - — determination of sparticle masses and model parameters
- A few other examples for mSUGRA with/without R_p-violation and for GMSB

— Deduce some "model-independent lessons"

— Deduce what the LHC can do and cannot do (in general...)

General strategy and starting point



- Select exclusive decay chains

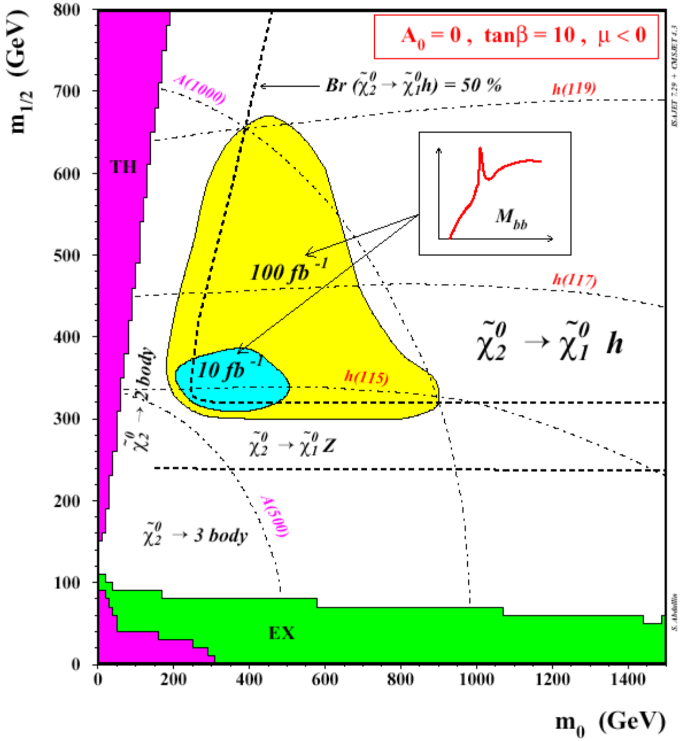
- χ^0_1 is invisible → no mass peak can be reconstructed directly

However: constrain combinations of masses by measuring mass distributions (in particular kinematic end-points) of visible sparticles.

- In general, the longer the decay chain the stronger the constraints (→ GMSB better than SUGRA)

- Starting point is end of decay chain, i.e. χ^0_2 decay ($\chi^{\pm}$ less useful)

Then go up the chain to the primary squark and gluino.



- Most useful decay modes of χ^0_2 (BR depend on involved masses, $\chi^0_{1,2}$ field composition, etc.) :

$\chi^0_2 \to h\ \chi^0_1$

$\chi^0_2 \to Z\ \chi^0_1 \to \ell\ell\ \chi^0_1$

$\chi^0_2 \to \tilde{\ell}\ell \to \ell\ell\ \chi^0_1$ (gives enhanced leptonic BR)

$\chi^0_2 \to \ell\ell\ \chi^0_1$ 3 – body decay through $Z^*, \tilde{\ell}^*$

In particular $\chi^0_2 \to \tilde{\tau}\tau$ can dominate at large $\tan\beta$

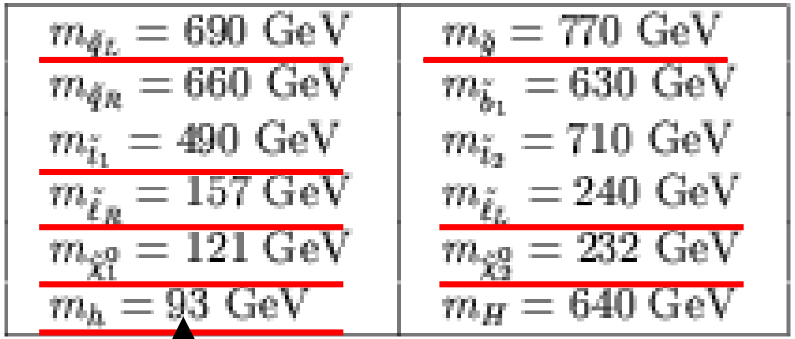
"LHC Point 5"

$m_0 = 100$ GeV, $m_{1/2} = 300$ GeV,
$A_0 = 300$ GeV, $\tan\beta = 2$, $\mu > 0$

ATLAS study

Inside region favoured by cosmology: gives correct relic neutralino density (light sleptons)

SUSY spectrum



$m_{\tilde{q}_L} = 690$ GeV	$m_{\tilde{g}} = 770$ GeV
$m_{\tilde{q}_R} = 660$ GeV	$m_{\tilde{b}_1} = 630$ GeV
$m_{\tilde{t}_1} = 490$ GeV	$m_{\tilde{t}_2} = 710$ GeV
$m_{\tilde{\ell}_R} = 157$ GeV	$m_{\tilde{\ell}_L} = 240$ GeV
$m_{\tilde{\chi}_1^0} = 121$ GeV	$m_{\tilde{\chi}_2^0} = 232$ GeV
$m_h = 93$ GeV	$m_H = 640$ GeV

Excluded by LEP. Limit can be evaded raising $\tan\beta \to 6$ ($m_h \to 114.8$ GeV) with ~ no impact on phenomenology except that BR ($\chi^0_2 \to$ stau-tau)~75 %

Here goal is illustration → we ignore LEP limit

Large $\tan\beta$ region discussed later

Total SUSY cross-section : ≈ 19 pb

$\tilde{q}\tilde{q} \sim 5$ pb

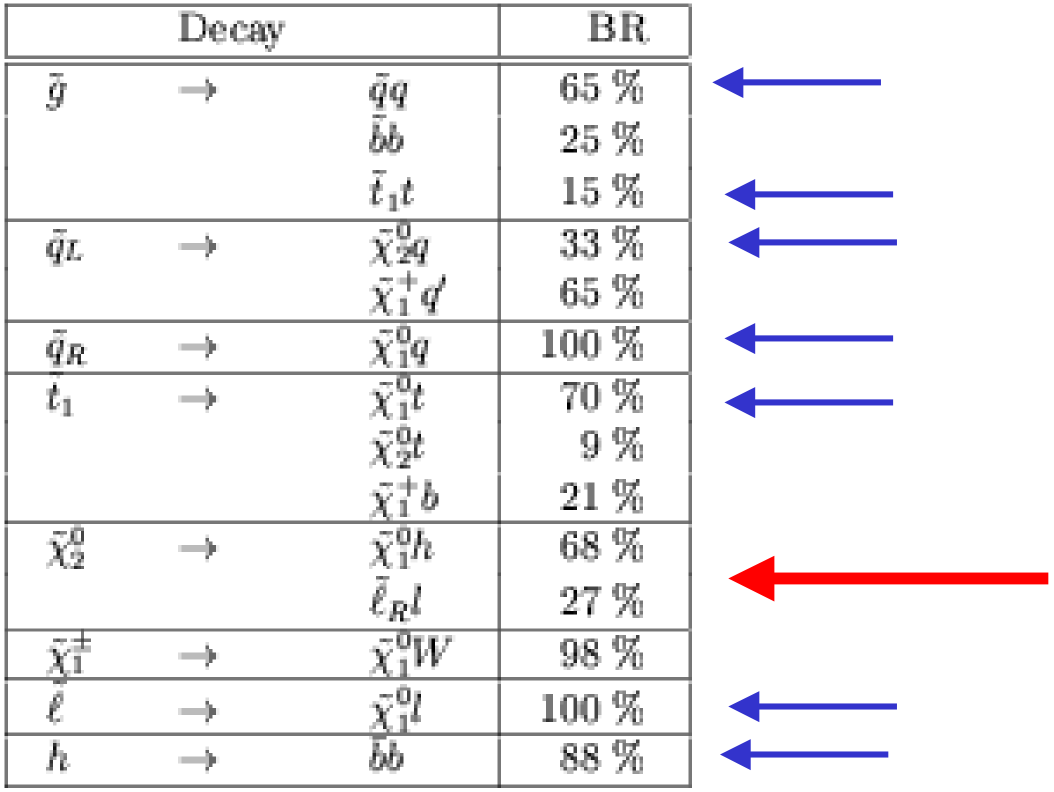
$\tilde{q}\tilde{g} \sim 8$ pb

$\tilde{g}\tilde{g} \sim 2$ pb

$\tilde{t}_1\tilde{t}_1 \sim 0.7$ pb

$\tilde{\ell}\tilde{\ell} \sim 65$ fb

Main decay modes



Decay			BR
$\tilde{g}$	$\rightarrow$	$\bar{q}q$	65 %
		$\bar{b}b$	25 %
		$\tilde{t}_1 t$	15 %
$\tilde{q}_L$	$\rightarrow$	$\tilde{\chi}_2^0 q$	33 %
		$\tilde{\chi}_1^+ q'$	65 %
$\tilde{q}_R$	$\rightarrow$	$\tilde{\chi}_1^0 q$	100 %
$\tilde{t}_1$	$\rightarrow$	$\tilde{\chi}_1^0 t$	70 %
		$\tilde{\chi}_2^0 t$	9 %
		$\tilde{\chi}_1^+ b$	21 %
$\tilde{\chi}_2^0$	$\rightarrow$	$\tilde{\chi}_1^0 h$	68 %
		$\tilde{\ell}_R l$	27 %
$\tilde{\chi}_1^\pm$	$\rightarrow$	$\tilde{\chi}_1^0 W$	98 %
$\tilde{\ell}$	$\rightarrow$	$\tilde{\chi}_1^0 l$	100 %
h	$\rightarrow$	$\bar{b}b$	88 %

Start from bottom of chain ⇒ look for:

$$\chi^0{}_2 \rightarrow h\,\chi^0{}_1 \rightarrow bb\,\chi^0{}_1$$

$$\chi^0{}_2 \rightarrow \tilde{\ell}_R \ell \rightarrow \ell\ell\chi^0{}_1$$

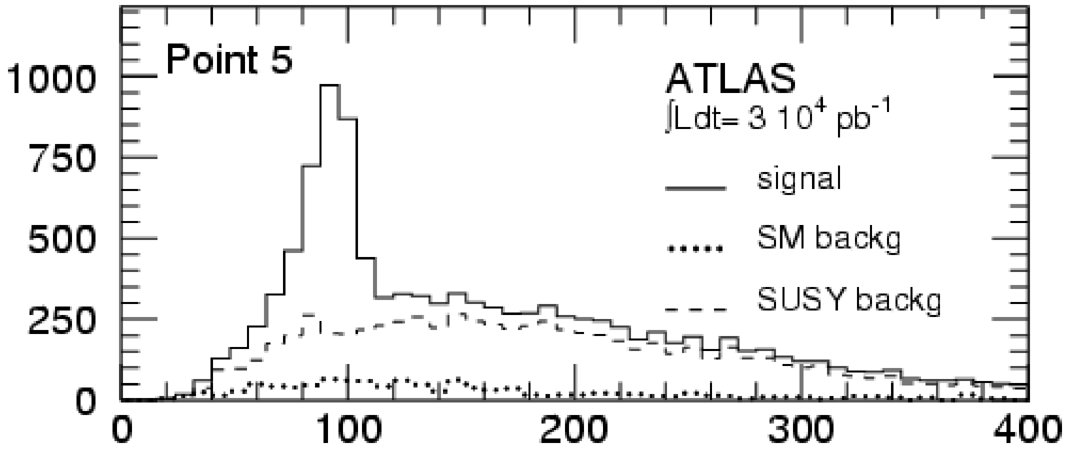
Main source of $\chi^0{}_2$: $\boxed{\tilde{q}_L \rightarrow q\chi^0{}_2}$

❶ Reconstruction of h → bb

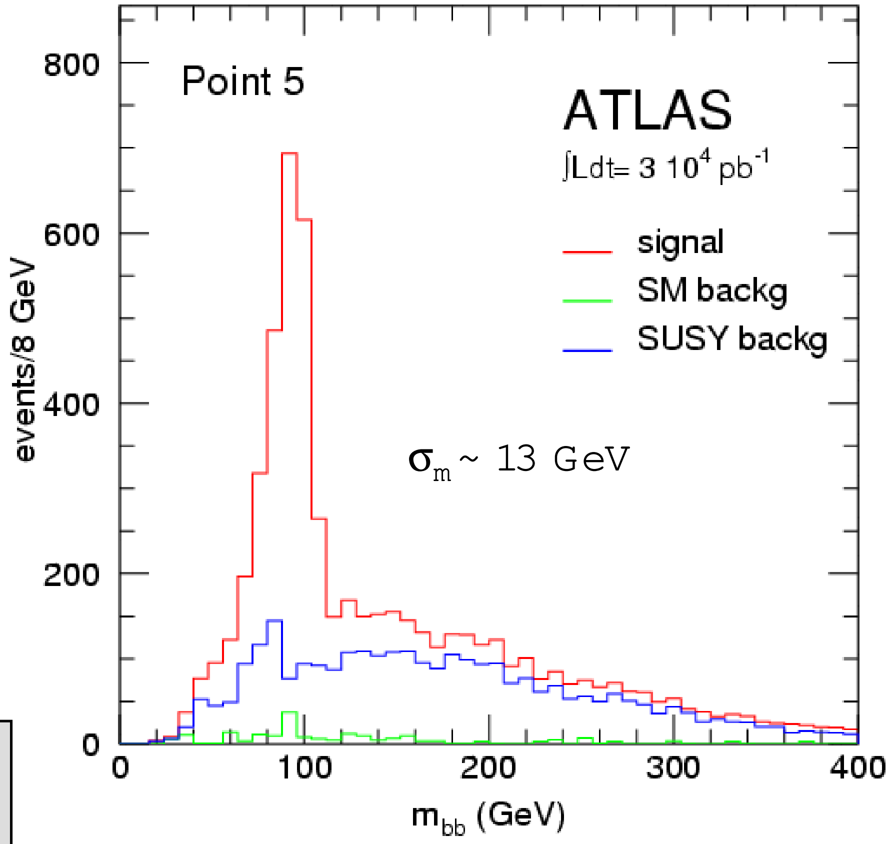
Select events with :

- MET > 300 GeV
- 2 b-tagged jets p_T > 50 GeV

} ~ model-independent



After additional cuts (e.g. lepton veto)



m_h can be measured to:

— ~ 1% from h → bb
  (dominated by systematics on b-jet scale)

— ~ 2‰ from h → γγ
  (γ scale known to 1‰ but low rate → need 300 fb^{-1})

In general, for exclusive channels main background to SUSY is SUSY !

F.Gianotti

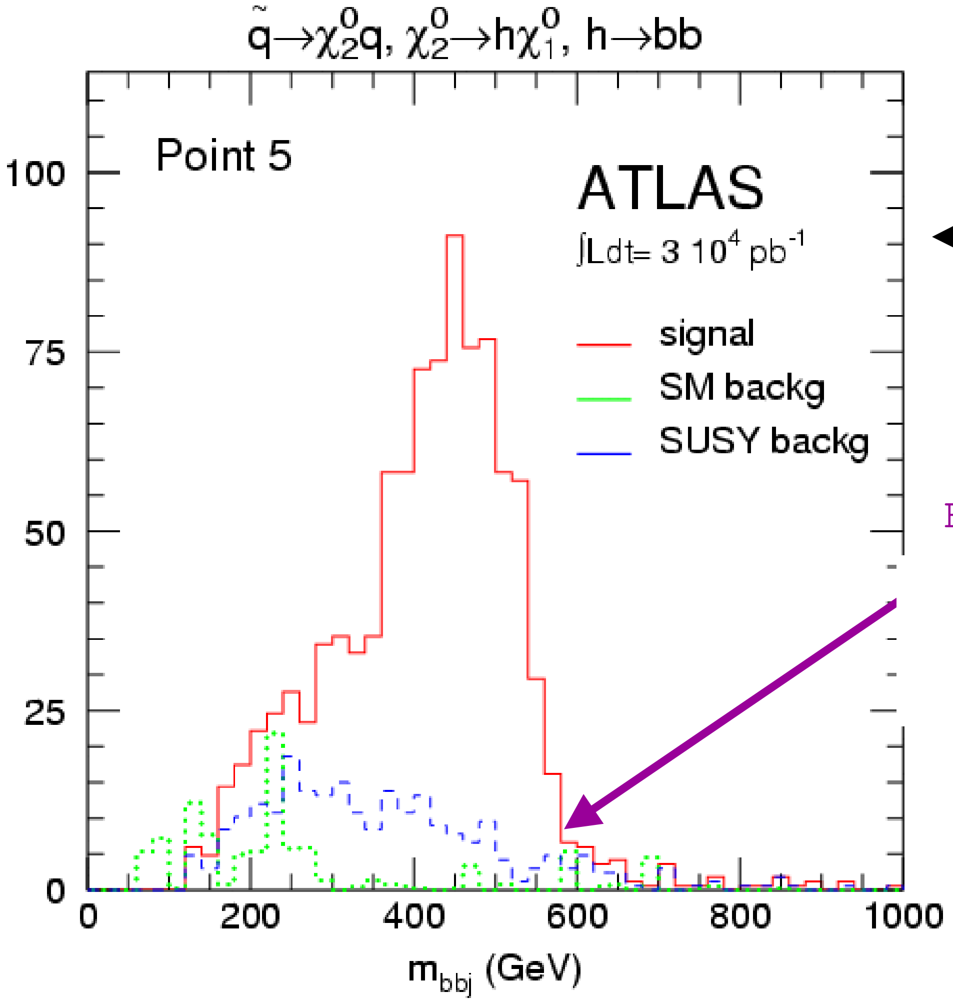
❷ Reconstruction of $\tilde{q}_L \rightarrow q\,\chi^0{}_2$

$\hookrightarrow h\,\chi^0{}_1$

$\hookrightarrow bb$

$\tilde{q}_L$ from $\tilde{q}_L\tilde{q}, \tilde{q}_L\tilde{g}, \tilde{g}\tilde{g}\ (\tilde{g} \rightarrow \tilde{q}_L q)$ production

$$\boxed{m\,(\tilde{q}_L, \chi^0{}_2, \chi^0{}_1) = 690, 232, 121\,\text{GeV}}$$



- Select events with $m_{bb} = m_h \pm 25$ GeV
- Form invariant mass of bb pair with two hardest jets in final state
- Plot minimum of two m_{bbj} masses

End-point clearly visible (due to 2-body kinematics):

$$(M_{hq}^{max})^2 = M_h^2 + (M_{\tilde{q}}^2 - M_{\tilde{\chi}_2^0}^2)\left[\frac{M_{\tilde{\chi}_2^0}^2 + M_h^2 - M_{\tilde{\chi}_1^0}^2 + \sqrt{(M_{\tilde{\chi}_2^0}^2 - M_h^2 - M_{\tilde{\chi}_1^0}^2)^2 - 4M_h^2 M_{\tilde{\chi}_1^0}^2}}{2M_{\tilde{\chi}_2^0}^2}\right]$$

Can be measured to ≈ 1.5% for 30 fb^{-1}

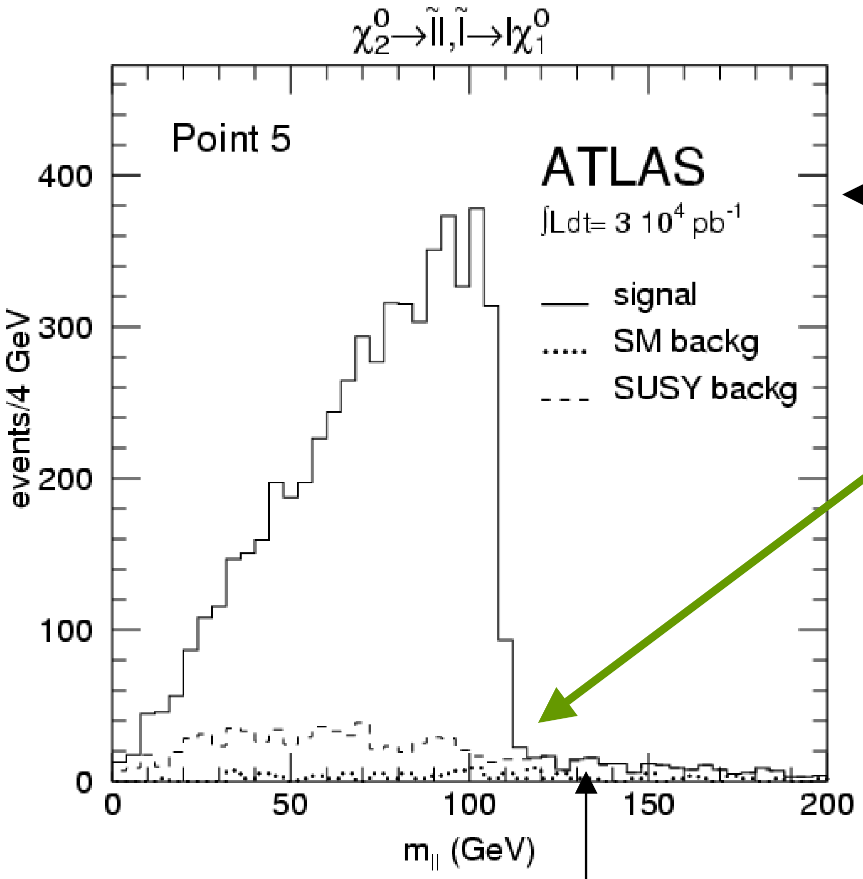
→ constraint on combination of $\tilde{q}_L, \chi^0{}_2, \chi^0{}_1$ masses

If $\chi^0{}_{1,2}$ masses known, squark left mass can be measured to ± 7 GeV (jet scale !) for 300 fb^{-1}

❸ Reconstruction of $\chi^0_2 \rightarrow \tilde{\ell}_R \, \ell$
$\qquad\qquad\qquad\qquad \hookrightarrow \ell \, \chi^0_1$

$\ell = e, \mu$

$\boxed{m(\chi^0_2, \tilde{\ell}_R, \chi^0_1) = 232,\ 157,\ 121\ \text{GeV}}$



Select events with :

- MET > 300 GeV
- ≥ 2 jets p_T > 150 GeV
- 2 opposite-sign same-flavour leptons p_T > 10 GeV

End-point due to decay kinematics :

$$M_{ll}^{max} = M(\tilde{\chi}^0_2)\sqrt{1-\frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}^0_2)}}\sqrt{1-\frac{M^2(\tilde{\chi}^0_1)}{M^2(\tilde{l}_R)}} = 108.93\ \text{GeV}$$

Can be measured to ≈ 0.5% for 30 fb^{-1}

→ constraint on combination of $\chi^0_2, \tilde{\ell}_R, \chi^0_1$ masses

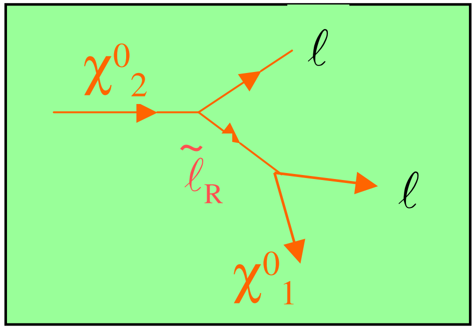
Background can be subtracted using OS-OF pairs :
$e^+e^- + \mu^+\mu^- - (e^+\mu^- + e^-\mu^+)$

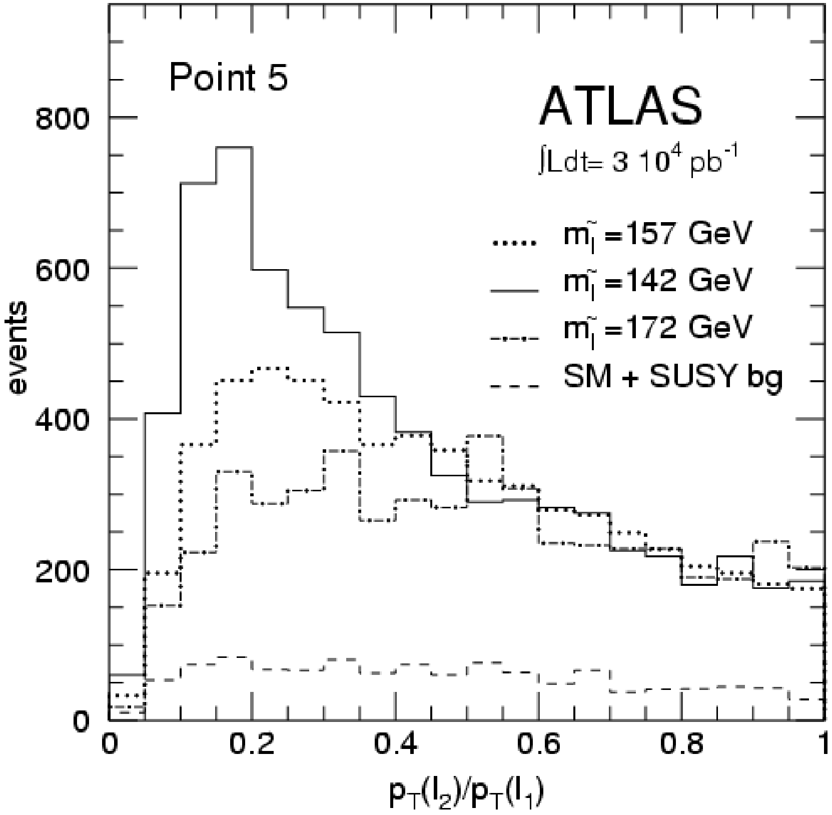
If $\chi^0_{1,2}$ masses known, slepton right mass can be measured to ± 0.5 GeV for 300 fb^{-1}

Note :

- difference in edge position for e^+e^- and $\mu^+\mu^-$ distributions would indicate $m(\tilde{\mu}_R) \neq m(\tilde{e}_R)$
  → precise measurement of end-point crucial → sensitivity to ≈ ‰ mass difference expected
- evidence for 2-body $\chi^0{}_2 \to \tilde{\ell}_R \ell$ (rather than 3-body $\chi^0{}_2 \to \ell^+\ell^-\chi^0{}_1$) from large signal rate
  (same order as for $h \to bb$)

Furthermore ...





Ratio of lepton p_T's sensitive to distance of slepton mass from $\chi^0{}_1$ and $\chi^0{}_2$ masses

$$\boxed{m\,(\chi^0{}_2,\, \tilde{\ell}_R,\, \chi^0{}_1) = 232,\ 157,\ 121\ \text{GeV}}$$

For fixed $m(\chi^0{}_1)$ and $m(\chi^0{}_2)$, distribution sensitive to a few GeV variation of slepton mass

❹ Reconstruction of $\tilde{q}_L \to q\,\chi^0_2$

$\hookrightarrow \tilde{\ell}_R\,\ell$

$\hookrightarrow \ell\,\chi^0_1$

$m(\tilde{q}_L, \chi^0_2, \tilde{\ell}_R, \chi^0_1) = 690, 232, 157, 121\,\text{GeV}$

$\tilde{q}_L$ produced from

- -- $\tilde{q}_L\,\tilde{q}_L$
- -- $\tilde{q}_L\,\tilde{q}_R$ $(\tilde{q}_R \to q\chi^0_1)$
- -- $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$ with $\tilde{g} \to \tilde{q}_L\,q$

$\Delta m(\tilde{q}_L - \chi^0_2) \approx 460\,\text{GeV}$

$\Delta m(\tilde{q}_R - \chi^0_1) \approx 540\,\text{GeV}$

$\Delta m(\tilde{g} - \tilde{q}_L) \approx 80\,\text{GeV}$

⇒ hardest jets in the event from $\tilde{q}_{L,R}$ decays

❶ $m(\ell^+\ell^-)$ distribution constrains combination of $m(\chi^0_2)$, $m(\tilde{\ell}_R)$, $m(\chi^0_1)$

❷ combine $\ell^+\ell^-$ with each of two hardest jets → $m(\ell^+\ell^- j)$

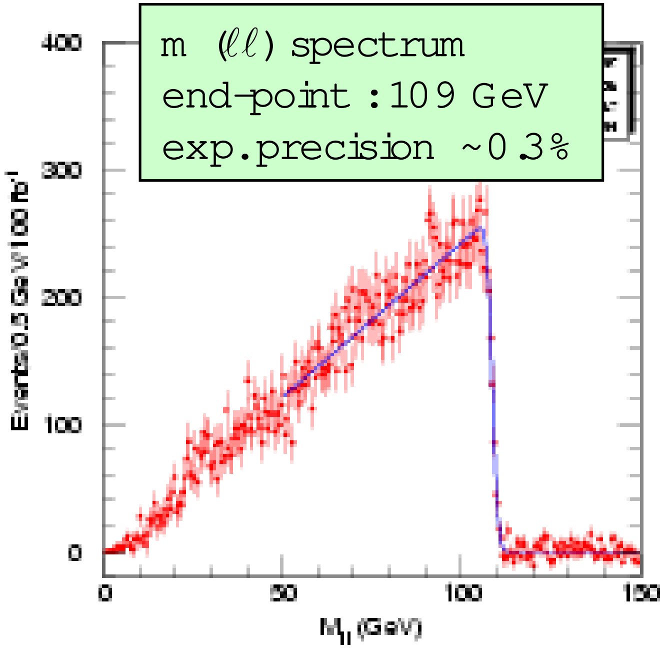
— the smaller of two $m(\ell^+\ell^- j)$ should be smaller than end-point of squark left decay chain

— the larger of two $m(\ell^+\ell^- j)$ should be larger than "threshold" of squark left decay chain

→ these mass spectra and edges constrain combination of $m(\tilde{q}_L)$, $m(\chi^0_2)$, $m(\tilde{\ell}_R)$, $m(\chi^0_1)$

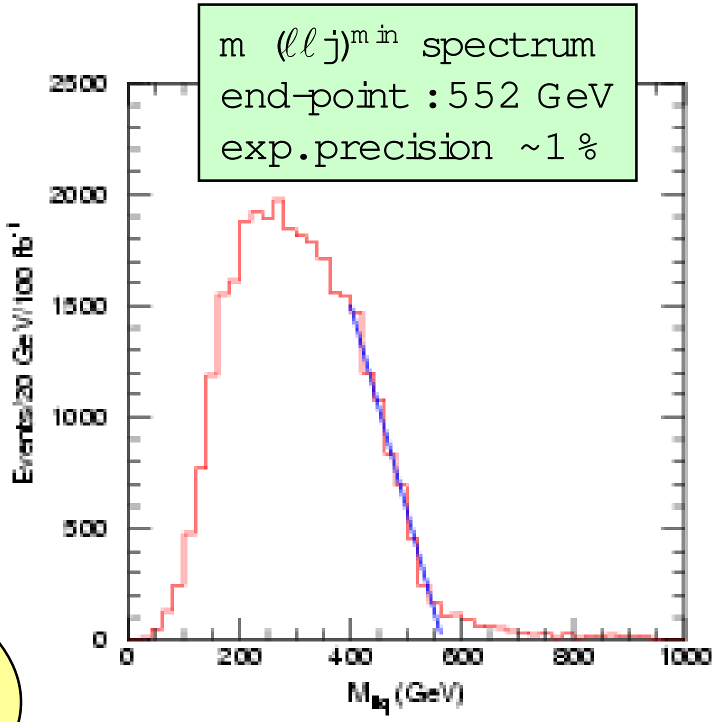
❸ for smaller $m(\ell^+\ell^- j)$ combination, plot the two possible $m(\ell^\pm j)$ combinations

→ distribution constrains (through the "right" combination where ℓ is from χ^0_2)
combination of $m(\tilde{q}_L)$, $m(\chi^0_2)$, $m(\tilde{\ell}_R)$



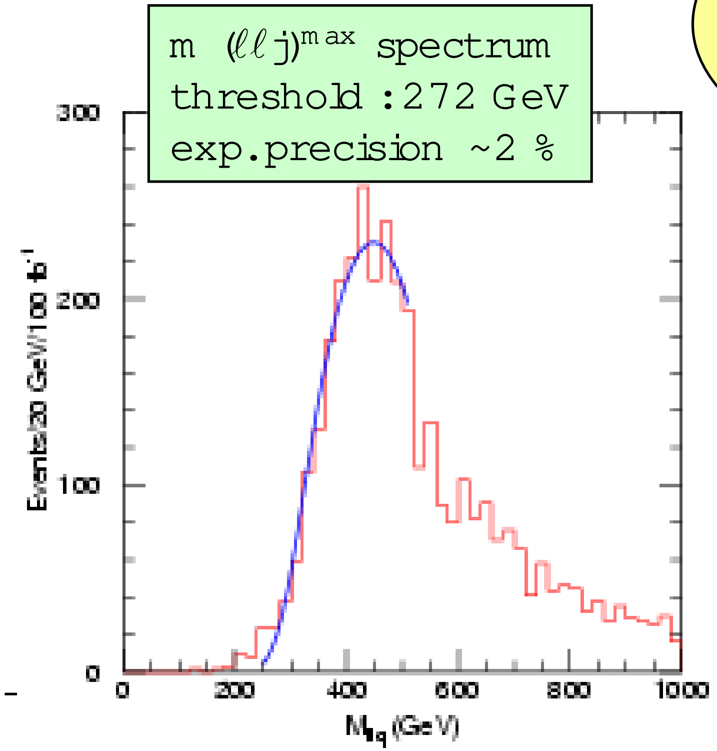
$m(\ell\ell)$ spectrum
end-point : 109 GeV
exp. precision ~0.3%

ATLAS
100 fb^{-1}

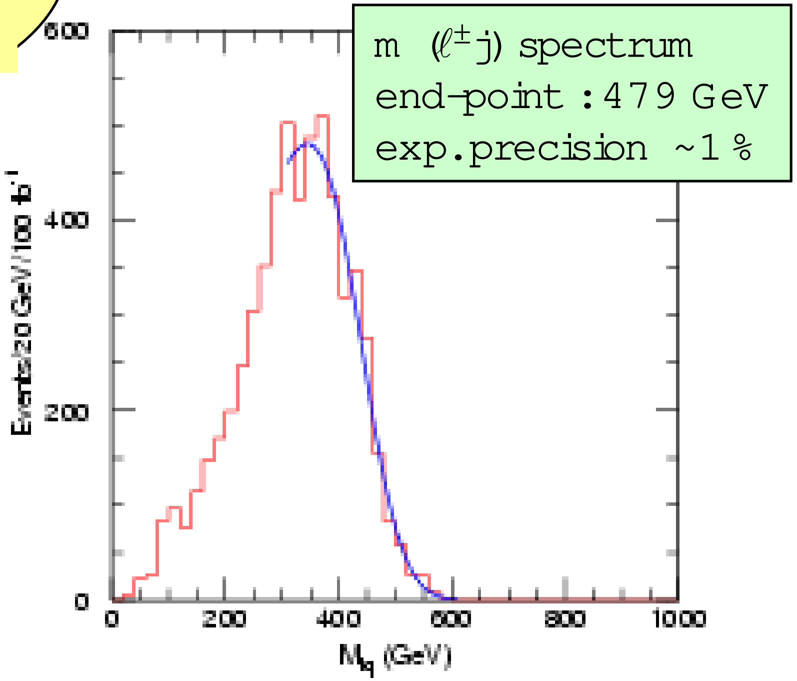


$m(\ell\ell j)^{min}$ spectrum
end-point : 552 GeV
exp. precision ~1%

$$\tilde{q}_L \to q\,\chi^0_2$$
$$\hookrightarrow \tilde{\ell}_R\,\ell$$
$$\hookrightarrow \ell\,\chi^0_1$$



$m(\ell\ell j)^{max}$ spectrum
threshold : 272 GeV
exp. precision ~2%



$m(\ell^{\pm} j)$ spectrum
end-point : 479 GeV
exp. precision ~1%

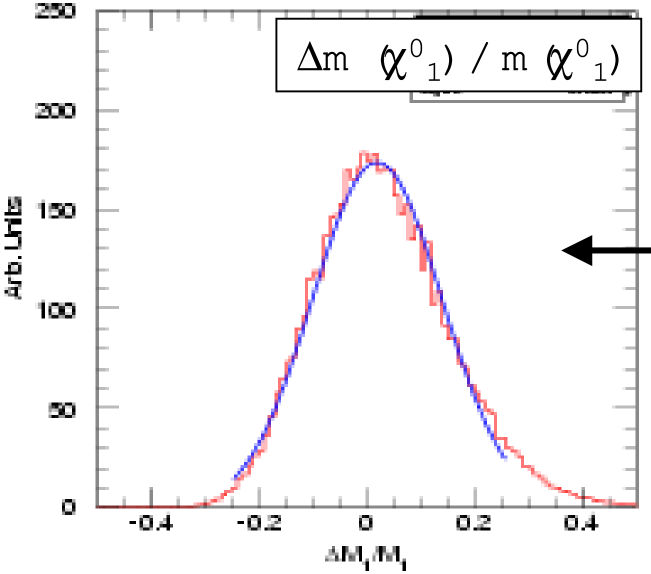
$\tilde{q}_L \to q\,\chi^0_2$

$\chi^0_2 \to h\,\chi^0_1$, $h \to bb$

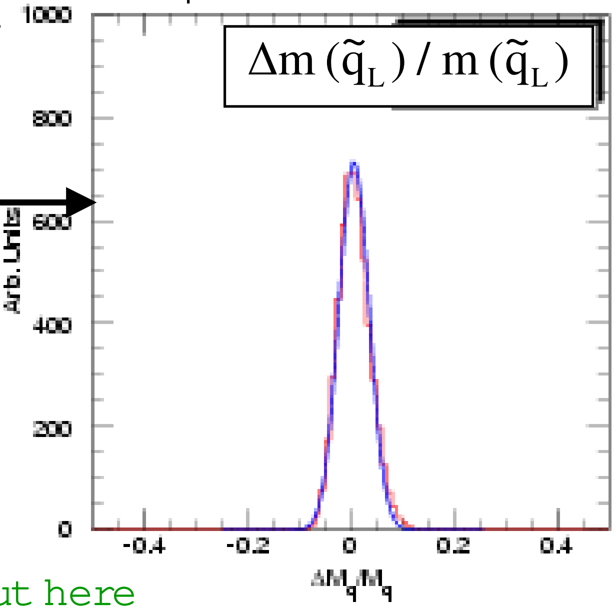
$\chi^0_2 \to \tilde{\ell}_R\,\ell$, $\tilde{\ell}_R \to \ell\,\chi^0_1$

Putting all constraints together: $m(bbj)$, $m(\ell\ell)$, $m(\ell\ell j)^{max}$, $m(\ell\ell j)^{min}$, $m(\ell j)$

Sparticle mass	Expected precision 100 fb^{-1}
squark left	± 3%
χ^0_2	± 6%
slepton mass	± 9%
χ^0_1	± 12%



$$\frac{m\,(\text{reconstructed}) - m\,(\text{true})}{m\,(\text{true})}$$



- These errors larger than from fit within mSUGRA (see later ..), but here ~ no assumptions about underlying model. Constraints just from kinematics distributions.
- Interpretation (e.g. squark left is source of χ^0_2 and not squark right) is model dependent, but in most cases more general than mSUGRA
- In general, long decay chains give multiple constraints on masses through kinematic distributions

❺ Reconstruction of $pp \to \tilde{\ell}^+ \tilde{\ell}^- \to \ell \chi^0{}_1 \ell \chi^0{}_1$

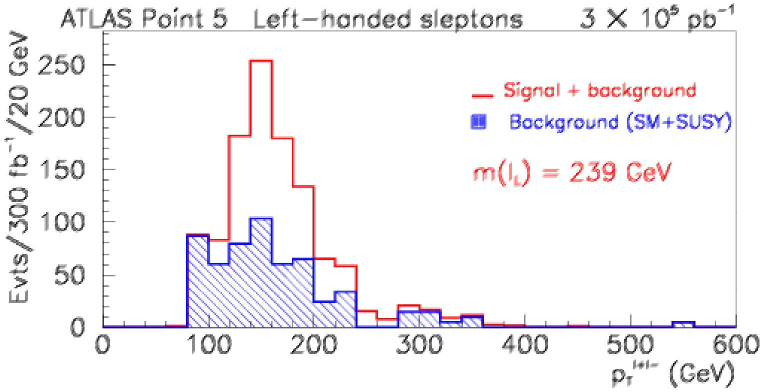
$m(\tilde{\ell}_R, \tilde{\ell}_L) = 157, 240$ GeV

- $\sigma \approx 65$ fb $\qquad \ell = e, \mu$

  $BR(\tilde{\ell} \to \ell \chi^0{}_1) = 100\%$ → look for 2 acoplanar leptons and no jet activity

- Event selection :
  - — MET > 120 GeV
  - — 2 OS-SF leptons $p_T > 30$ GeV
  - — $\Delta\varphi_{\ell\ell} < 2.5$ (to reject WW)
  - — no jets $p_T > 40$ GeV (to reject tt, SUSY background)

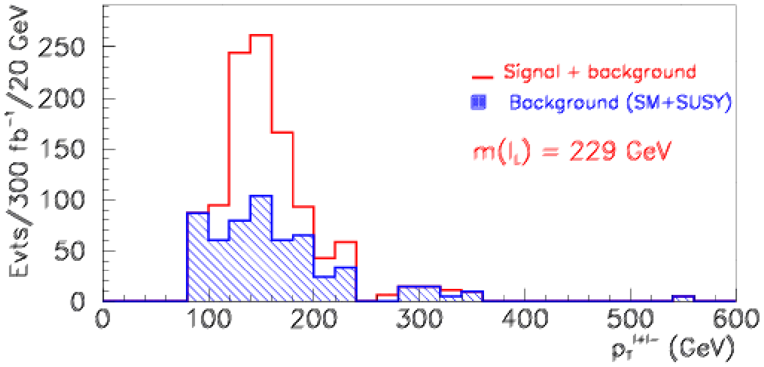
these hard cuts kill $\tilde{\ell}_R \tilde{\ell}_R$



p_T distribution of lepton pair provide constraint on combination of $\tilde{\ell}_L$ and $\chi^0{}_1$ masses

Tiny rate : S = 600 evts, B = 280 evts for 300 fb^{-1}

→ need ultimate LHC luminosity



If $\chi^0{}_1$ mass known, slepton left mass can be measured to few GeV for 300 fb^{-1}

This is one of few cases where direct $\tilde{\ell}^+ \tilde{\ell}^-$ production (small cross-section, large backgrounds) observable at LHC. Typical reach $m(\tilde{\ell}) < 350$ GeV

❻ Reconstruction of tt pairs → $\tilde{g}, \tilde{t}$ masses

- In general, observation of tt pairs in SUSY events could be sign of $\tilde{t}\tilde{t}$ direct production or $\tilde{g} \rightarrow \tilde{t}t$ ($\tilde{b} \rightarrow t\,\chi^{\pm}$ can also contribute)

- Direct production has small cross-section because of structure functions (no tt pairs in the proton sea) → large signal would indicated that $\tilde{g} \rightarrow \tilde{t}t$ is open

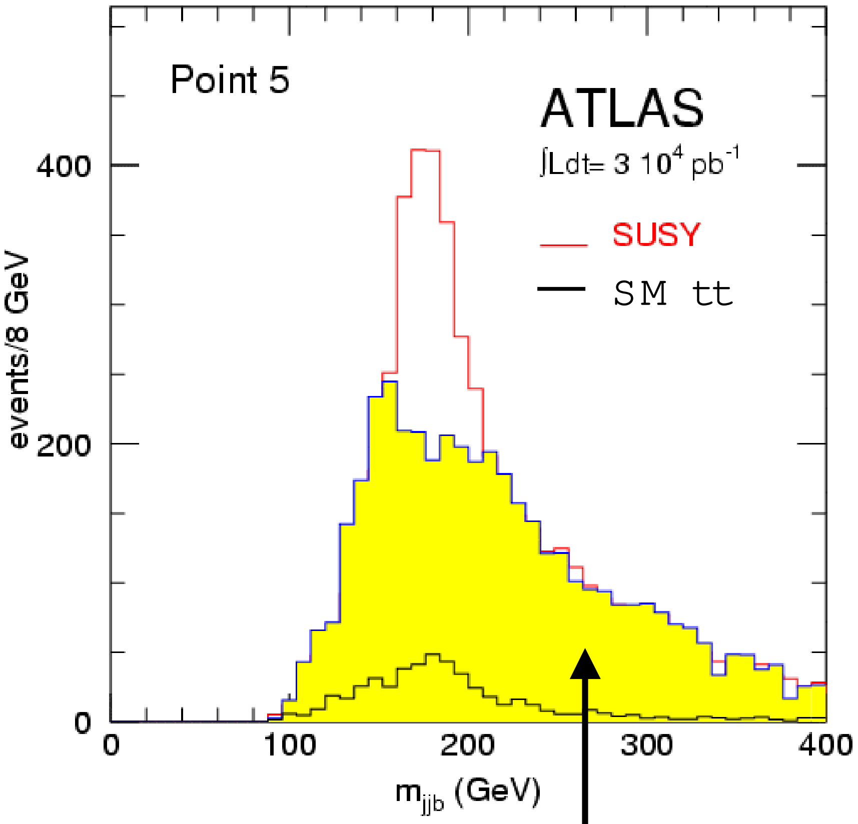
- SM tt production can be rejected asking fully-hadronic t → b jj decays and large MET

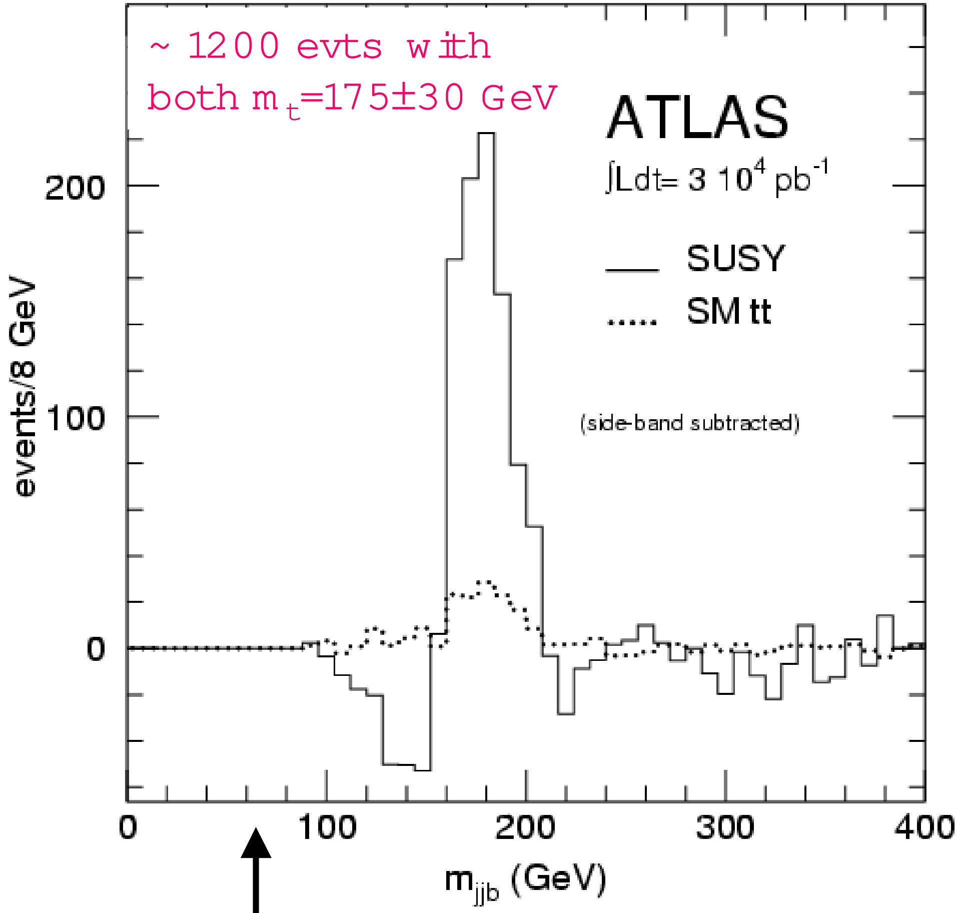
- To look for a tt signal at Point 5 (rather model-independent cuts) :

— 2 b-tagged jets $p_T > 30$ GeV, ≥ 4 additional jets $p_T > 30$ GeV
MET > 200 GeV , no charged lepton

— All jj pairs with $m_{jj} = m_W \pm 15$ GeV considered and two m_{jjb} reconstructed for each jj pair
— Pairing that minimises $\chi^2 = (m_{jjb}^{(1)} - m_t)^2 + (m_{jjb}^{(2)} - m_t)^2$ chosen

Inclusive tt sample at Point 5





Estimated SUSY combinatorial from side-bands of m_W spectrum. After subtraction

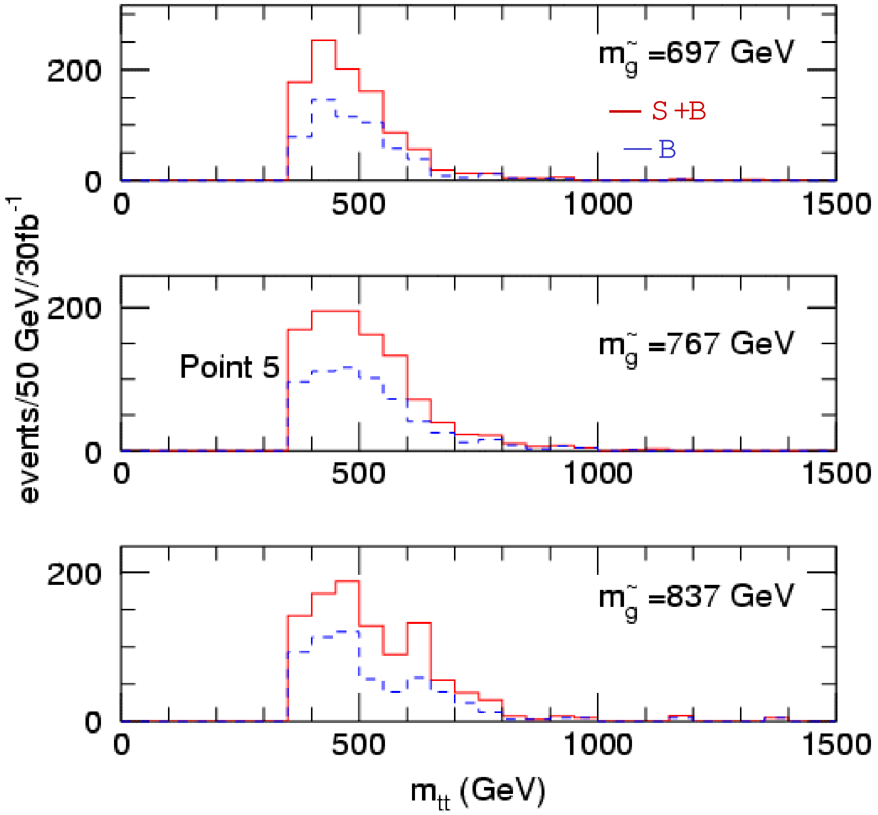
Such a large signal indicates that $\tilde{g} \to \tilde{t}t$ is open

F.Gianotti

From this inclusive tt sample, try to get some sensitivity to:

$\tilde{g} \rightarrow \tilde{t}t$

- additional activity in the event
  → ask additional jet $p_T > 300$ GeV
- m_{tt} distribution sensitive to gluino mass



Direct $\tilde{t}\tilde{t} \rightarrow t\chi^0_1\ t\chi^0_1$

- no additional activity → veto additional jets
- low rate : $\sigma \times BR \approx 300$ fb, $\varepsilon \approx 1\%$
  → need 300 fb^{-1}
- p_T (top) distribution sensitive to stop mass

constraints on combination of
$\tilde{g}, \tilde{t}, \chi^0_1$ masses

Summary of measurements for Point 5

ATLAS

Measured quantity	Value (GeV)	Error (GeV) 30 fb^{-1}	Error (GeV) 300 fb^{-1}
m_h	92.9	1.0	0.2
M_{hj}^{max}	552.5	10.0	5.5
M_{hq}^{min}	346.5	17.0	17.0
$M_{\ell\ell}^{max}$	108.9	0.5	0.1
$M_{\ell j}^{max}$	478.1	11.5	5.0
$M_{\ell j}^{max}/M_{\ell\ell j}^{max}$	0.86	0.06	0.02
$M_{\ell\ell j}^{min}$	271.8	14.0	5.4

Particles directly observable:

$\tilde{q}_L$, $\tilde{q}_R$, $\tilde{g}$, $\tilde{t}_1$, $\tilde{\ell}_R$, $\tilde{\ell}_L$, h, χ_2^0

Note: not all possibilities of mass combinations explored ...

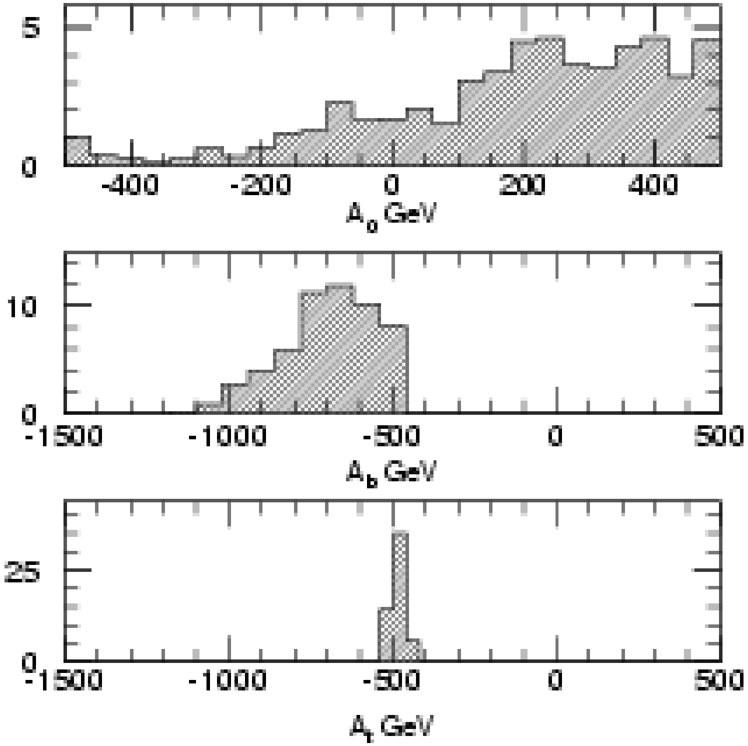
Next step : global fit of mSUGRA to all experimental measurements

⇒ determine parameters of underlying model

	30 fb^{-1}	300 fb^{-1}
m_0	$100.0^{+4.1}_{-2.2}$ GeV	100.0 ± 1.3 GeV
$m_{1/2}$	300.0 ± 2.7 GeV	300.0 ± 1.5 GeV
$\tan\beta$	2.00 ± 0.1	2.00 ± 0.05
μ	+	+
A_0	unconstrained	unconstrained

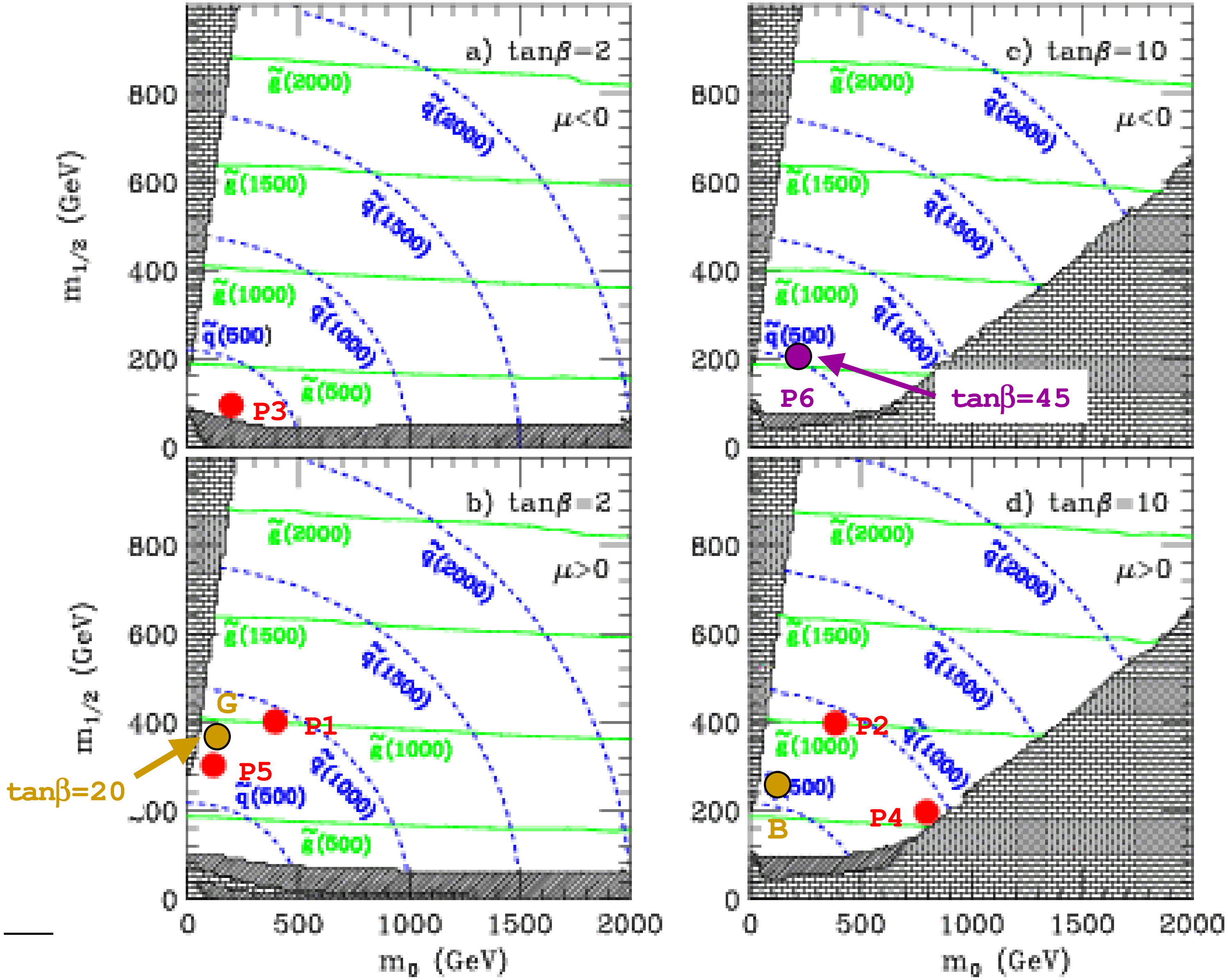
LHC Point 5

Mixing parameters at the EW scale (A_t, A_b, A_τ), determined from measurements of stop, sbottom, stau final states, are little sensitive to A_0 at GUT scale (RGE cause them to evolve to ~ fixed points with little dependence on A_0)



Other mSUGRA points studied in detail:

P1–P5 : 5 original "LHC Points" ('96)
P6 : very large tanβ point
B, G : from "post-LEP" benchmark (CMS study)



Very large tanβ models : ex. "Point 6 "

$m_0 = 200$ GeV, $m_{1/2} = 200$ GeV,
$A_0 = 300$ GeV, $\tan\beta = 45$, $\mu < 0$

BR $(\tilde{g} \to \tilde{b}_1 b) \approx 55\,\%$ BR $(\tilde{b}_1 \to b\,\chi_2^0) \approx 40\,\%$

BR $(\chi_2^0 \to \tilde{\tau}_1 \tau) = 100\%$

$m(\tilde{\tau}_1) \sim 132$ GeV

$m(\chi_{1,2}^0) \sim 81, 152$ GeV

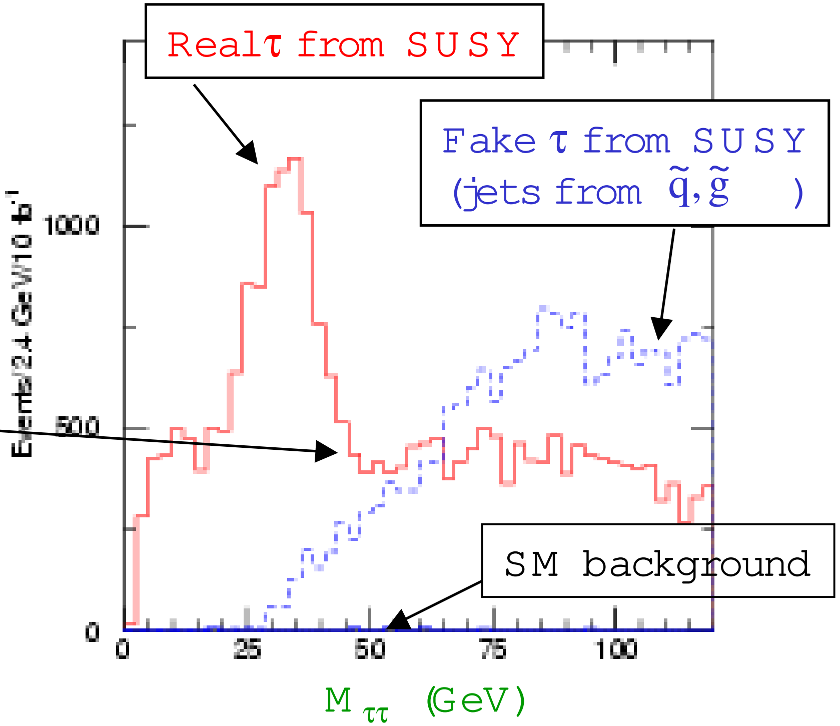
$m(\tilde{g}) \sim 540$ GeV, $m(\tilde{b}_1) \sim 390$ GeV

↑

experimentally more difficult than $\chi_2^0 \to h\,\chi_1^0$, $\tilde{\ell}\ell$
because of additional neutrinos

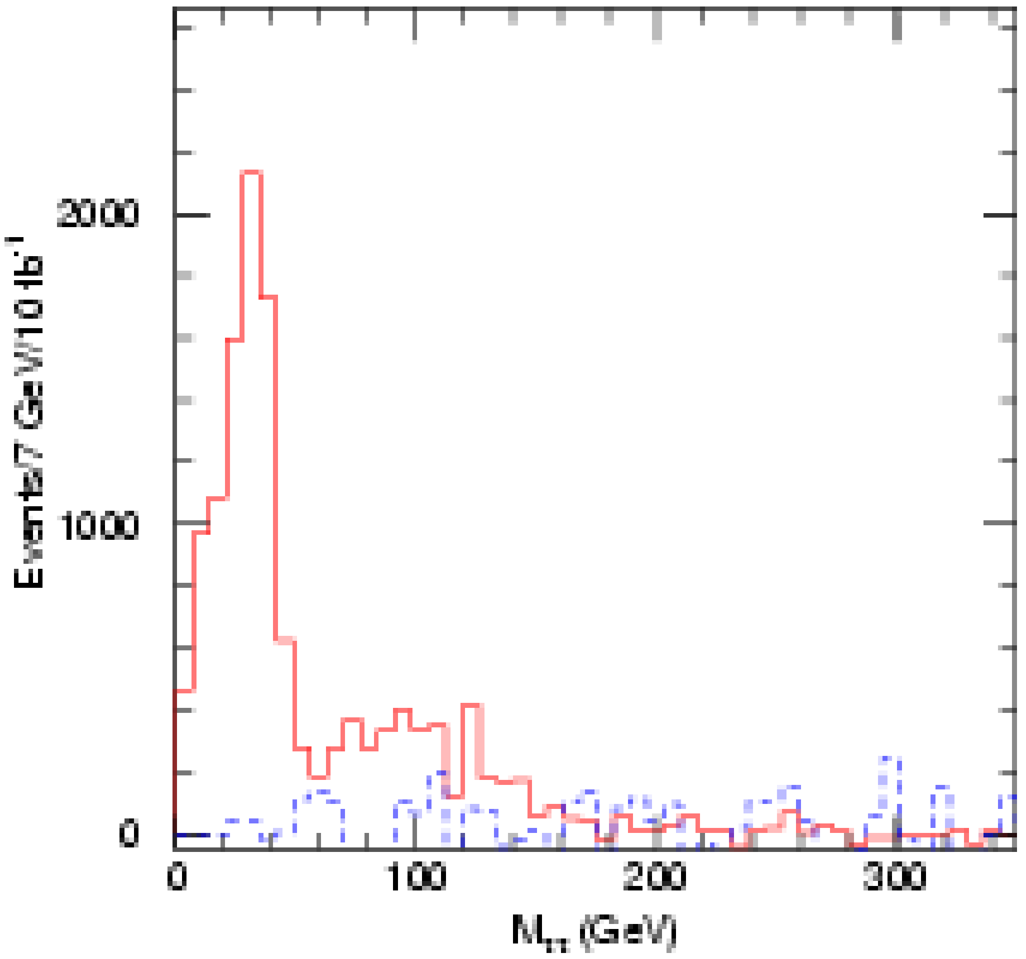
- Select events with two OS hadronic taus $p_T > 20$ GeV + high-p_T jets + MET
- Reconstruct $M_{\tau\tau} \equiv$ invariant mass of two τ-jets
[$M_{\tau\tau}$ (rec.) ~ 0.7 $M_{\tau\tau}$ (true) because of escaping ν's]

Expect end-point at $M_{\tau\tau}^{max} = 59.6$ GeV



- Background can be subtracted by looking at distribution for $\tau^+\tau^- - \tau^\pm\tau^\pm$
- End-point can be measured to ~ 5%
- Then combine $\tau\tau$ with b-jet ⇒ reconstruct $\tilde{b}_1 \to b\,\chi_2^0$
- Exclusive measurements possible (at least for light SUSY ...) but with smaller precision

Background-subtracted distribution : $\tau^+\tau^- - \tau^\pm\tau^\pm$



Expected precision on mSUGRA parameters for 5 LHC Points and large tanβ Point

ATLAS
300 fb^{-1}

Point	m_0 (GeV)	$m_{1/2}$ (GeV)	tgβ
1	400 ± 100 (25%)	400 ± 8 (2%)	2 ± 0.02 (1%)
2	400 ± 100 (25%)	400 ± 8 (2%)	10 ± 1.2 (12%)
3	200 ± 5 (2.5%)	100 ± 1 (1%)	2 ± 0.02 (1%)
4	800 ± 35 (4%)	200 ± 1.5 (0.8%)	10 ± 0.6 (6%)
5	100 ± 1.3 (1.3%)	300 ± 1.5 (0.5%)	2 ± 0.05 (2.5%)
6 tanβ = 45	218 ± 30, 242 ± 25 (~ 10%)	196± 8, 194 ± 6 (3.5%)	44 ± 1.1, 45± 1.7 (~ 3%)

sign μ determined
except Point 6

A_0 ~ unconstrained
except Point 6

μ = +, −

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Remarks :

- Only mass distributions used here. Much more information will be available in data:
  cross-sections, branching ratios, many additional distributions → we will use everything
  → many more constraints. In this respect, these results are conservative.

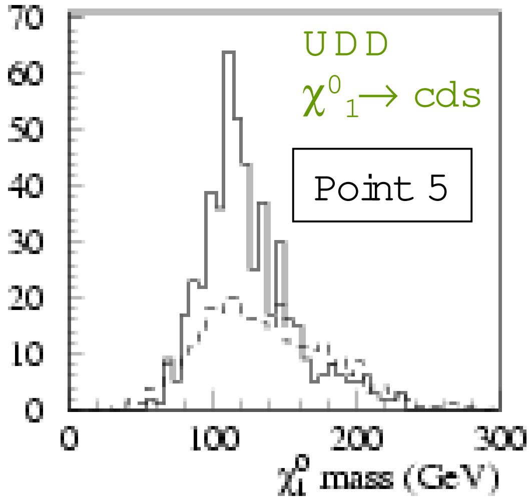
- In addition, these 6 Points are not particularly "LHC-friendly" (chosen by J.Ellis ...)

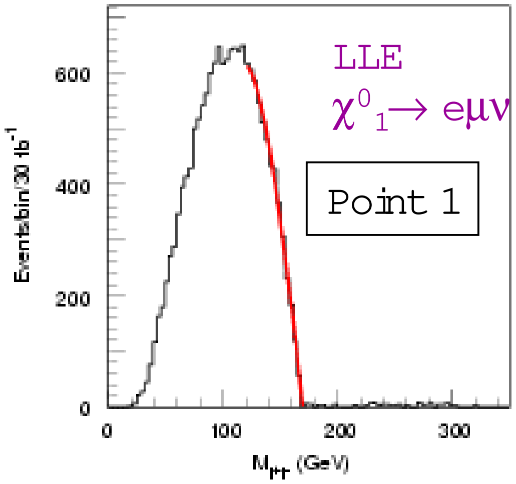
- Constrained models like mSUGRA can artificially improve expected precision
  on model parameters because of high correlations between masses, etc.
  However :
  - impossible in practice to work in general MSSM (~ 100 parameters, not predictive enough)
    without experimental data to provide guidance
  - constrained models nevertheless provide useful benchmarks for study of LHC potential,
    detector performance, main analysis strategies

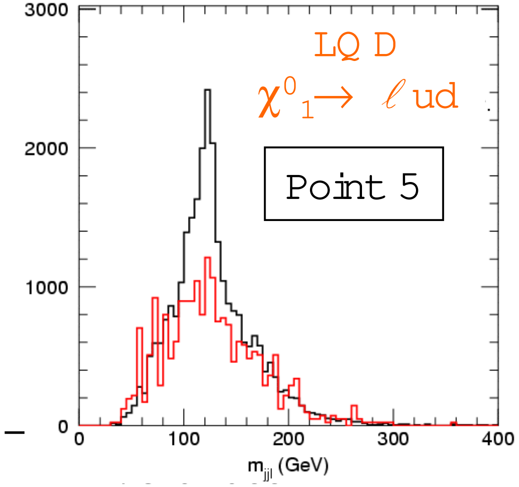
R-parity violating SUSY

- Considered case: only χ^0_1 decays violating R-parity ($\lambda \sim 10^{-2}$)
- MET signature lost but χ^0_1 mass can be reconstructed in many cases → full reconstruction of masses in decay chains.

⇒ Precision measurements and constraints of underlying theory equal/better to/than R_P-conserving mSUGRA, except in few cases (e.g. LLE with $\chi^0_1 \to \tau\ell\nu$)







χ^0_1 measured to (30 fb^{-1}):
≈ % UDD
≈ % LQD
≈ ‰ LLE

More work needed to optimise $\chi^0_1 \to$ jjj reconstruction (algorithms, etc.) for light masses (~100 GeV)

Gauge-Mediated SUSY Breaking

$\mathrm{LSP} \equiv \tilde{G}$ $m(\tilde{G}) < \mathrm{KeV}$ escapes detection

Phenomenology depends on nature and lifetime of NLSP: $c\tau \approx 100\,\mu\mathrm{m} \left(\frac{100}{m\,(\mathrm{NLSP})}\right)^5 \left(\frac{F}{100\,\mathrm{TeV}}\right)^4$

$\mathrm{NLSP} \equiv \tilde{\ell} \rightarrow \ell\,\tilde{G}$

$c\tau \ll L_{det}$ leptons + MET

$c\tau \approx L_{det}$ kinks in inner detector

$c\tau \gg L_{det}$ heavy stable charged particles

$\mathrm{NLSP} \equiv \chi_1^0 \rightarrow \gamma\,\tilde{G}$

$c\tau \ll L_{det}$ two photons + MET

$c\tau \approx L_{det}$ non-pointing photons

$c\tau \gg L_{det}$ missing E_T

In most cases easier than SUGRA (4 Points studied)

— additional/exotic signatures from NLSP decay

— long decay chains

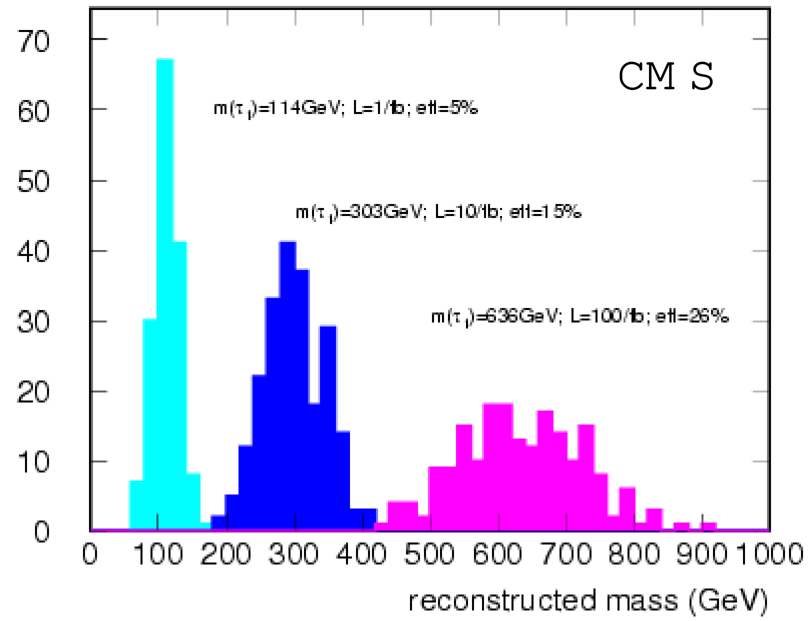
→ parameters constrained to ~ % in minimal models

(no SUGRA solution found)

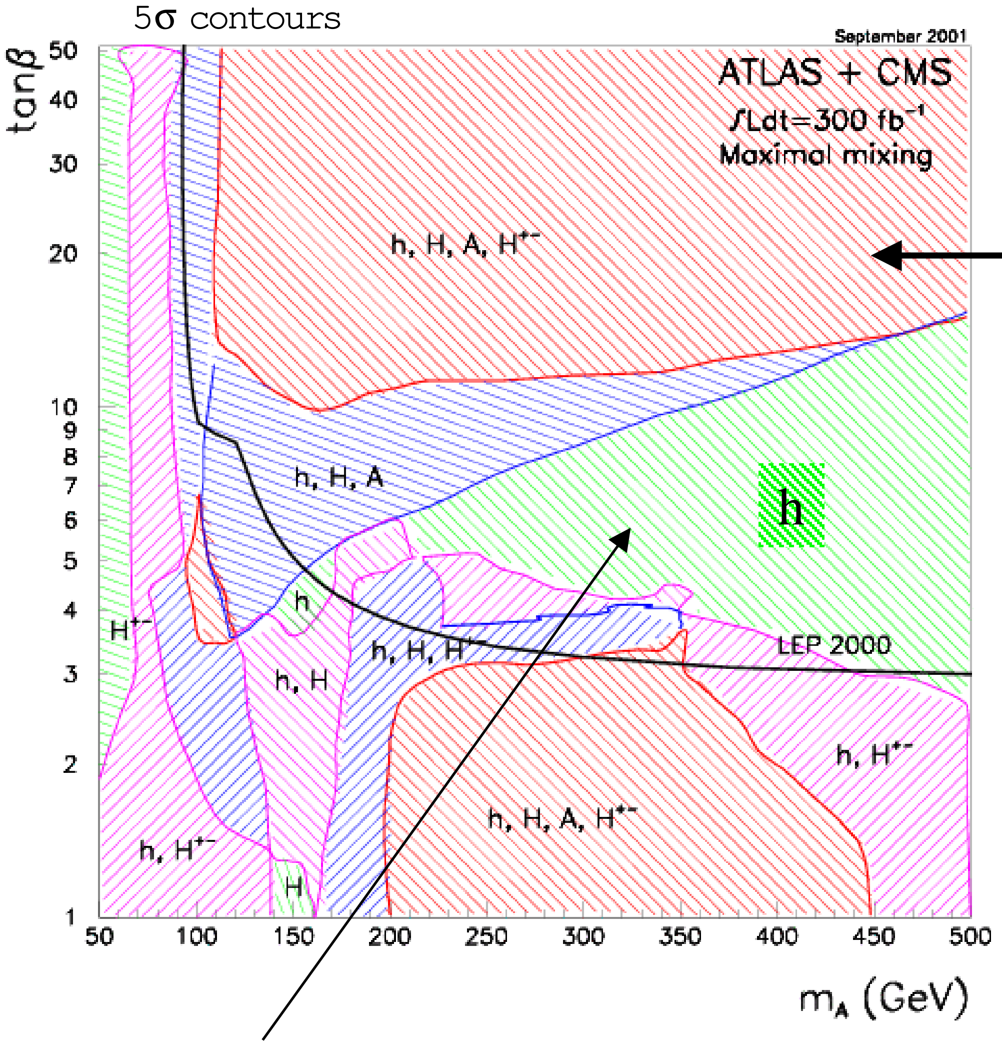
$\mathrm{NLSP} \equiv \tilde{\tau}_1,\ c\tau \sim 1\,\mathrm{Km}$

Stable, slow ($\beta < 1$) charged particles → give delayed signal in muon chambers ($\sigma_t \sim 1$ ns)

m measured from β and p



SUSY Higgs sector at the LHC



Assuming decays to SM particles only

$H, A \rightarrow \mu\mu, \tau\tau$
$H^{\pm} \rightarrow \tau\nu$, tb

▨ 4 Higgs observable
▨ 3 Higgs observable
▨ 2 Higgs observable
▨ 1 Higgs observable

Here only h (SM-like) observable at LHC, unless $A, H, H^{\pm} \rightarrow$ SUSY

$\rightarrow$ LHC may miss part of the MSSM Higgs spectrum

Observation of full spectrum may require high-E ($\sqrt{s} \approx 2$ TeV) Lepton Collider

Can we deduce some general "model-independent" lessons from these studies ?

❶ SUSY should be discovered at LHC up to $m(\tilde{q},\tilde{g}) \approx 2.5\,\mathrm{TeV}$

❷ h should be discovered, mass should be measured to 0.1% – 1%

❸ Several precise measurements of SUSY events should be possible :

— If squark and gluino masses are not both ≫ 1 TeV
(otherwise statistics may be too small to select exclusive chains)

— $\chi^0{}_2$ decay [$\chi^0{}_2 \to h\,\chi^0{}_1, \chi^0{}_2 \to \ell\ell\chi^0{}_1$] excellent starting point for moderate tanβ.
For tanβ > 20 : BR ($\chi^0{}_2$ → stau-tau) → 100% ⇒ reduced measurements/precision expected

— Kinematic distributions (peaks, edges) provide constraints on combination of masses which depend only on the involved masses. If decay chains long enough, these masses can be reconstructed in "model-independent" way from pure kinematics.
Observability of these chains and their interpretation IS model-dependent.

— In general, more powerful measurements in GMSB (richer topologies, longer decay chains) and R_p-violating models ($\chi^0{}_1$ mass can be reconstructed directly)

— A large amount of information will be available in the data (only partially exploited here) and all possible distributions will be used.

Note : ATLAS and CMS very powerful and multi-purpose detectors
(see e.g. case of "new" GMSB signatures)

❹ So … after initial discovery phase, one could :

- — Look for general features : Is there large MET ? Are there many leptons ? Are there "exotic" signatures (many γ's, heavy stable charged particles, kinks in tracker, etc.) ? Are there many b-jets and taus (could indicate large tanβ) ?
- — Look for / reconstruct semi-inclusive topologies, e.g. :
  - — $h \to bb$ peaks
  - — $\ell^+\ell^-$ peaks, edges, …
  - — tt pairs and their spectra → may indicate stop, sbottom in final state
- — Look for n leptons + MET and nothing else:
  - — $\ell^+\ell^-$ + MET may indicate slepton-pair production
  - — 3ℓ + MET may indicate $\chi^{\pm}{}_1\chi^0{}_2 \to 3\ell$
  - — 4ℓ + MET may indicate $A/H \to \chi^0{}_2\,\chi^0{}_2 \to 4\ell$
- — Explore Higgs sector (e.g. look for $\mu\mu$ and $\tau\tau$ peaks)
- — etc. etc.

- At each step we should narrow spectrum of possible models and get guidance to go on
- Joint effort theory/experiments will be essential
- More complicated signatures (e.g. involving combinations of jets) require much more work …

Note : to test this strategy, LHC experiments are planning to do "blind search" simulation studies before LHC start-up

What the LHC can do and cannot do … ..

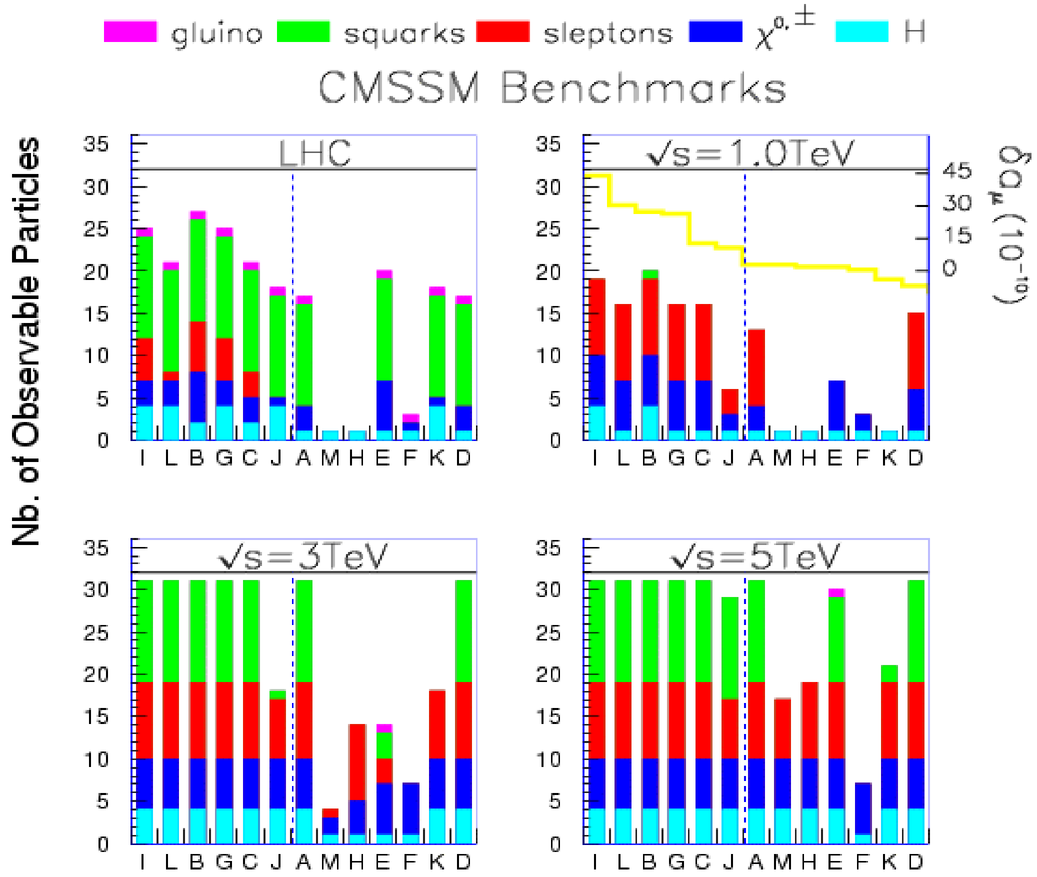
Note : these are few examples/indications and not absolute principles …

Set of mSUGRA benchmark points compatible with present constraints [hep-ph/0106204]

Model	A	B	C	D	E	F	G	H	I	J	K	L	M
$m_{1/2}$	600	250	400	525	300	1000	375	1500	350	750	1150	450	1900
m_0	140	100	90	125	1500	3450	120	419	180	300	1000	350	1500
$\tan\beta$	5	10	10	10	10	10	20	20	35	35	35	50	50
$\text{sign}(\mu)$	+	+	+	−	+	+	+	+	+	+	−	+	+
h^0, H^0, A	1	1	1	1	1	1	3	1	3	3	3	3	1
$H^\pm$	0	1	1	0	0	0	1	0	1	1	1	1	0
$\chi^0_i/\chi^\pm_j$	3	6	3	3	6	1	3	0	3	1	1	3	0
sleptons	0	6	3	0	0	0	5	0	5	0	0	1	0
squarks	12	12	12	12	12	0	12	0	12	12	12	12	0
gluino	1	1	1	1	1	1	1	0	1	1	1	1	0

In general, the LHC can … (examples …)	In general, the LHC cannot … (examples …)
Observe h, measure m_h Discover $\tilde{q}, \tilde{g}$ up to ~ 2.5 TeV	Observe A, H, $H^\pm$ over full parameter space Disentangle squark flavours for first two families
Observe $\tilde{t}$ from $\tilde{g} \to \tilde{t}t$ if $m(\tilde{g}) \leq 1$ TeV	Observe direct $\tilde{t}$ production if $m(\tilde{t}) > 600$ GeV
Observe $\tilde{\ell}$ production (direct or from decays) up to m ~ 350 GeV	Observe heavy $\tilde{\ell}$
Observe some gauginos (in particular χ^0_2)	Observe and measure the full gaugino spectrum (in particular $\chi^\pm$)
Constrain model parameters at 1% -10% level	Constrain model parameters to < 1%

Complementarity between LHC and future e^+e^- Colliders



In general:

- LHC most powerful for $\tilde{q}$ and $\tilde{g}$ (strongly interacting) but can miss some EW sparticles (gauginos, sleptons) and Higgs bosons

- Depending on $\sqrt{s}$, LC should cover part/all EW spectrum (usually lighter than squarks/gluinos) → should fill holes in LHC spectrum. Squarks could also be accessible if $\sqrt{s}$ large enough.

LC can perform precise measurements of masses (to ~ 0.1%), couplings, field content of sparticles with mass up to ~ $\sqrt{s}/2$, disentangle squark flavour, etc.
(see lectures by M. Battaglia)

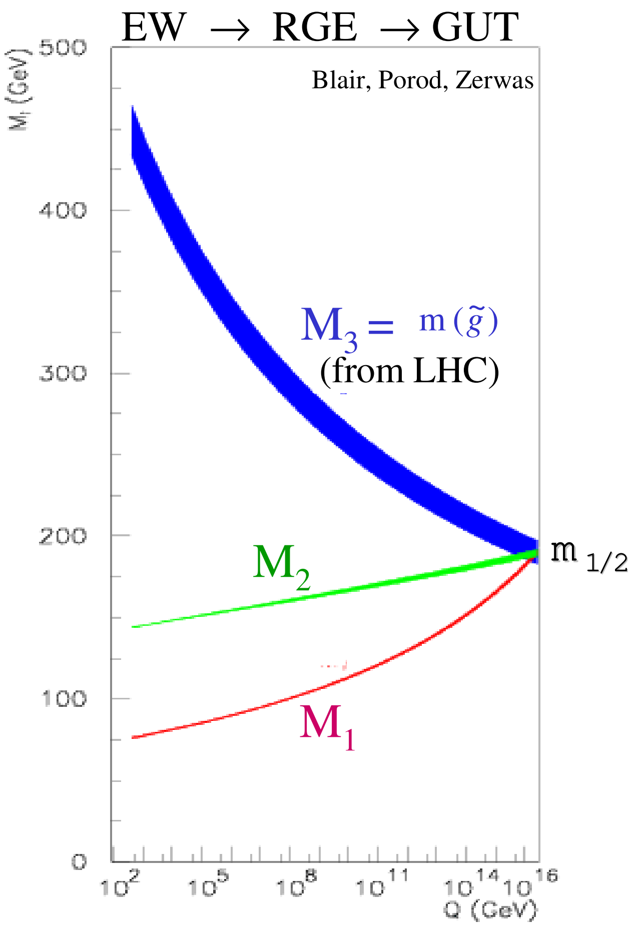
Combining both Colliders

From precise measurements of e.g. gaugino masses at EW scale :

M_3 from LHC (precision ~ %)

M_1, M_2 from LC (precision ~ ‰)

reconstruct theory at high E



Conclusions

- If SUSY exists at the TeV scale, it should be "easy" and "fast" to discover it at the LHC.
  Ultimate LHC reach for squarks and gluinos: m ≈ 2.5 TeV

- The main challenge is therefore not to discover SUSY, but to observe the full spectrum and perform precise measurements.

- Discovery of squarks, gluinos, h should be "granted" in most cases, observation of heavy Higgs bosons and EW sparticles is more model-dependent
  → LHC may leave holes in the SUSY spectrum.

- Several precise measurements of sparticle mass combination should be possible, and should allow the underlying theory to be constrained.
  Typical accuracies: 1–10% (demonstrated in minimal models).

- Several model-independent searches (e.g. semi-inclusive topologies) and analysis techniques (kinematic distributions) have been developed.
  Given also the large amount of information in the data, in particular in the rich cascade decays of squarks and gluinos, it is possible that a similar accuracy can be achieved in more general models than mSUGRA and mGMSB.

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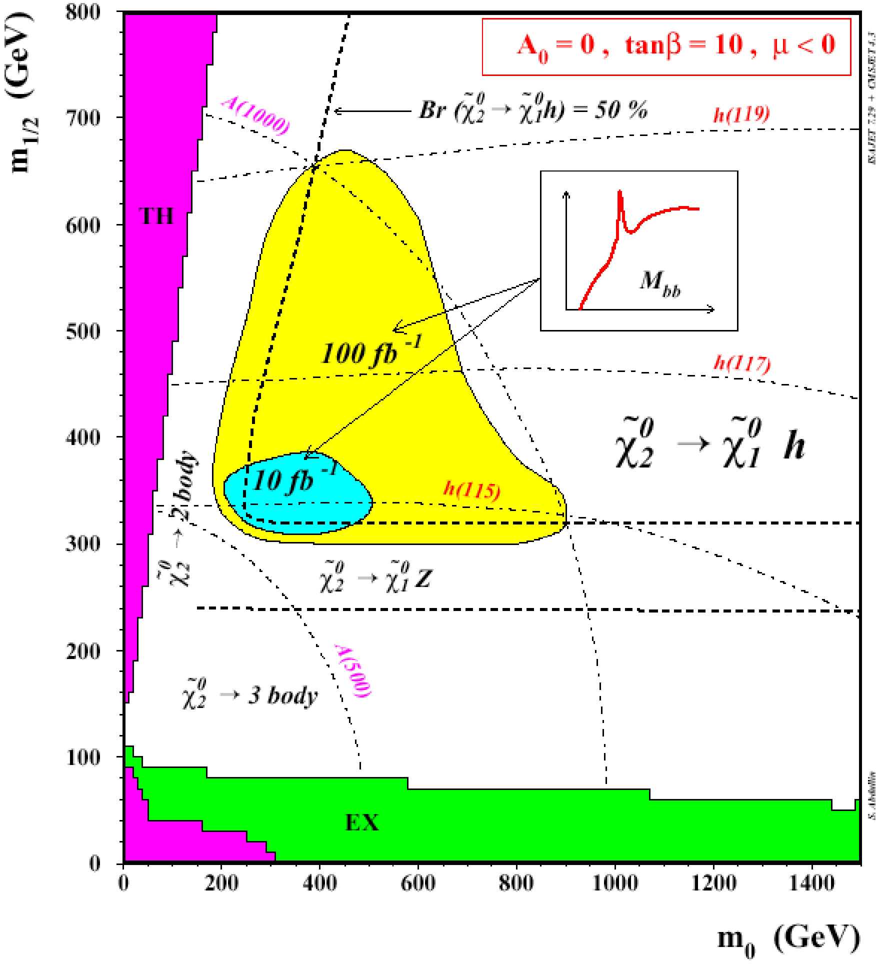
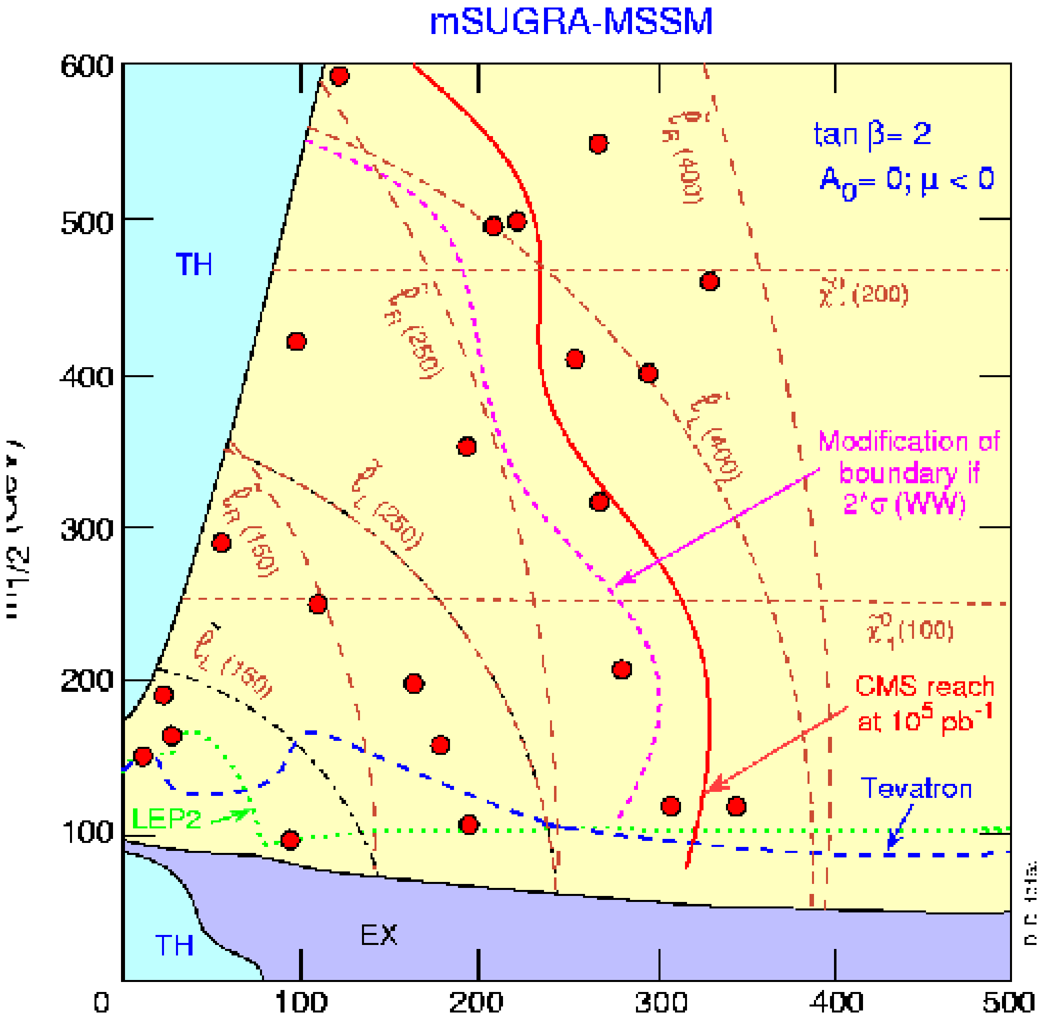
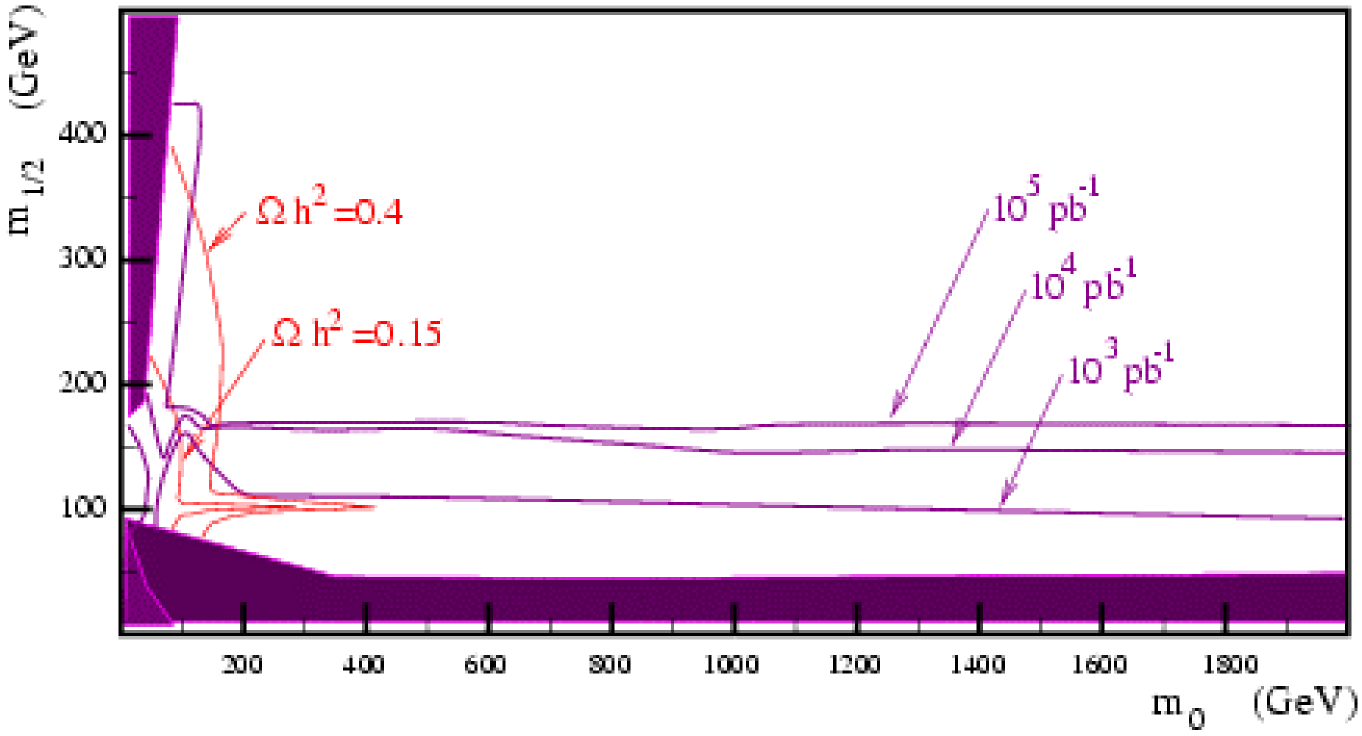


Slepton mapping of parameter space




m $_{1/2}$ (GeV)
400
300
200
100
$\Omega h^2 = 0.4$
$\Omega h^2 = 0.15$
10^5 pb^{-1}
10^4 pb^{-1}
10^3 pb^{-1}
200
400
600
800
1000
1200
1400
1600
1800
m $_0$ (GeV)