LHC Days in Split

Split, Croatia, 5-9 October 2004

Sparticle reconstruction at LHC

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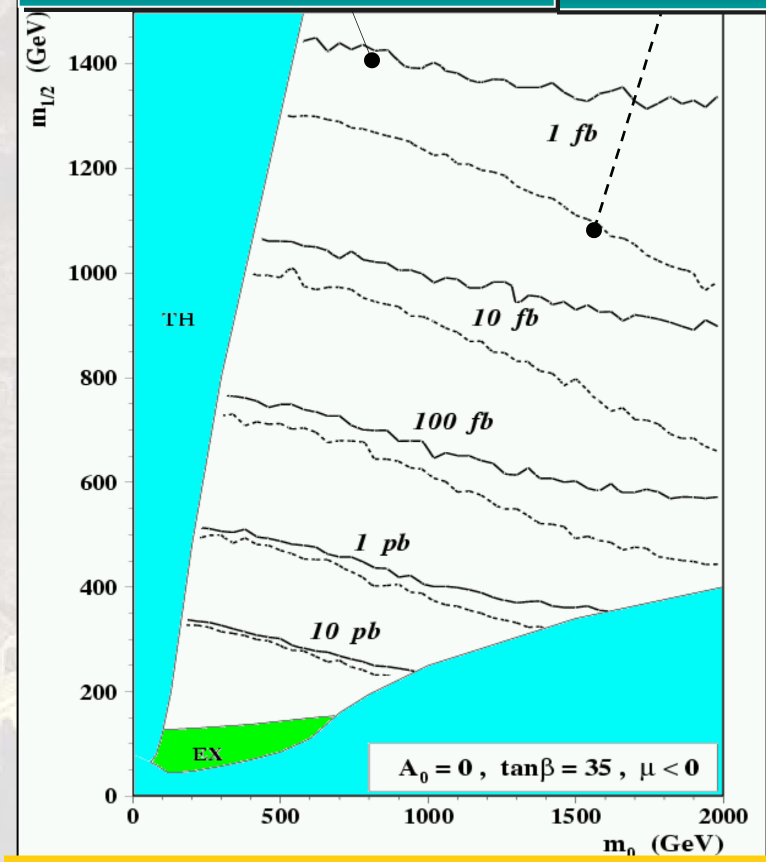
SUSY searches: motivations

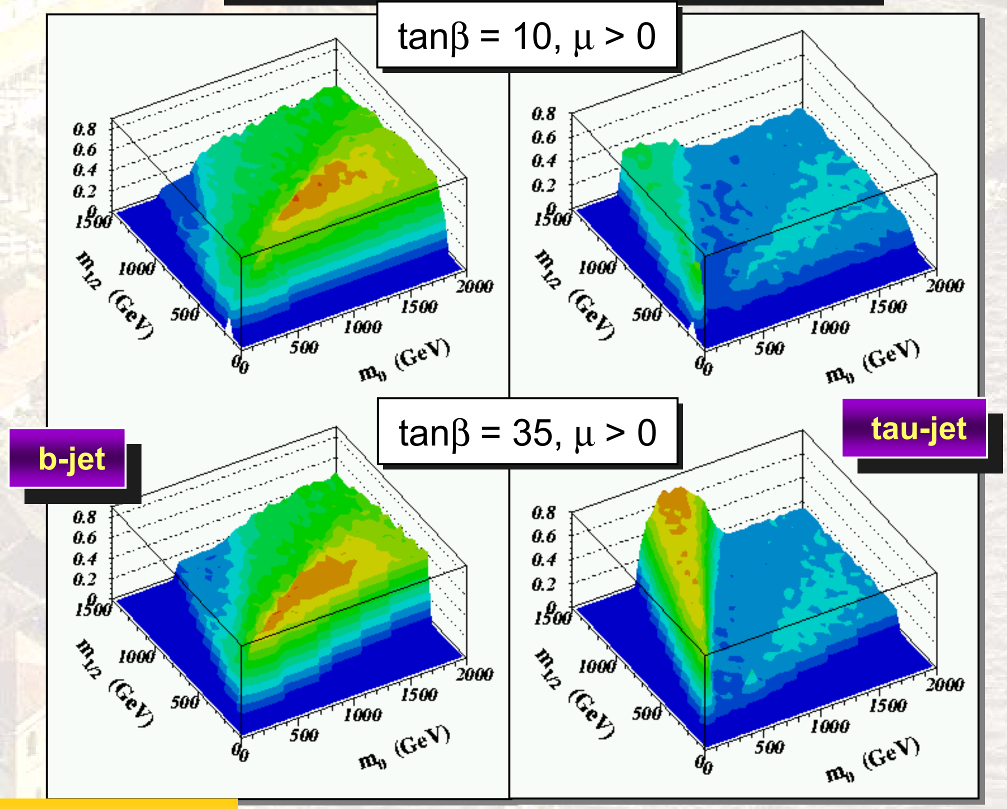
- TeV scale SUSY is an attractive extension of SM
  - solves the hierarchy problems
  - consistent with EW data from LEP, SLC, TeVatron
  - χ_1^0 natural candidate for Cold Dark Matter
- MSSM:
  - Higgs sector two doublets ☞ 5 physical states (h,H,A,$H^{\pm}$)
  - Superpatners with $\Delta J = \pm \frac{1}{2}$ for each SM particles (e.g. $\tilde{q}, \tilde{\ell}$)
    Conserved $R=(-1)^{3(B-L)+2S}$ ☞ LSP stable and sparticles produced in pairs
  - Gaugino superpatners of gauge and Higgs bosons mix to give
    - four neutralinos $\chi_i^0 \Leftrightarrow \tilde{\gamma}, \tilde{Z}, \tilde{H}_1^0, \tilde{H}_2^0$
    - Two charginos $\chi_i^{\pm} \Leftrightarrow \tilde{W}, \tilde{H}^{\pm}$
  - Many new particles are expected ☞ lot of fun @ LHC!
- MSSM however has 105 new parameters!!! Often mSUGRA model used: SUSY breaking through supergravity with only 5 parameters: m_0, $m_{1/2}$, A_0, $\tan\beta$, sgnμ

mSUGRA cross section

Solid line : total cross section | Dashed line : q,g



Probability / event to find at least one object with p_T > 50 geV in $|\eta|<2.4$



- For low $m_{1/2}$ value main contribution from $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$
- In the domains with extremely high $\tilde{g}, \tilde{q}$ masses associated production of $\tilde{g}, \tilde{q}$ with $\tilde{\chi}^0, \tilde{\chi}^\pm$ may dominate
- No big dependence on A_0, tanβ and signμ

Abundant b,τ production (the latter – especially at large tanβ)

First step: discover SUSY?!

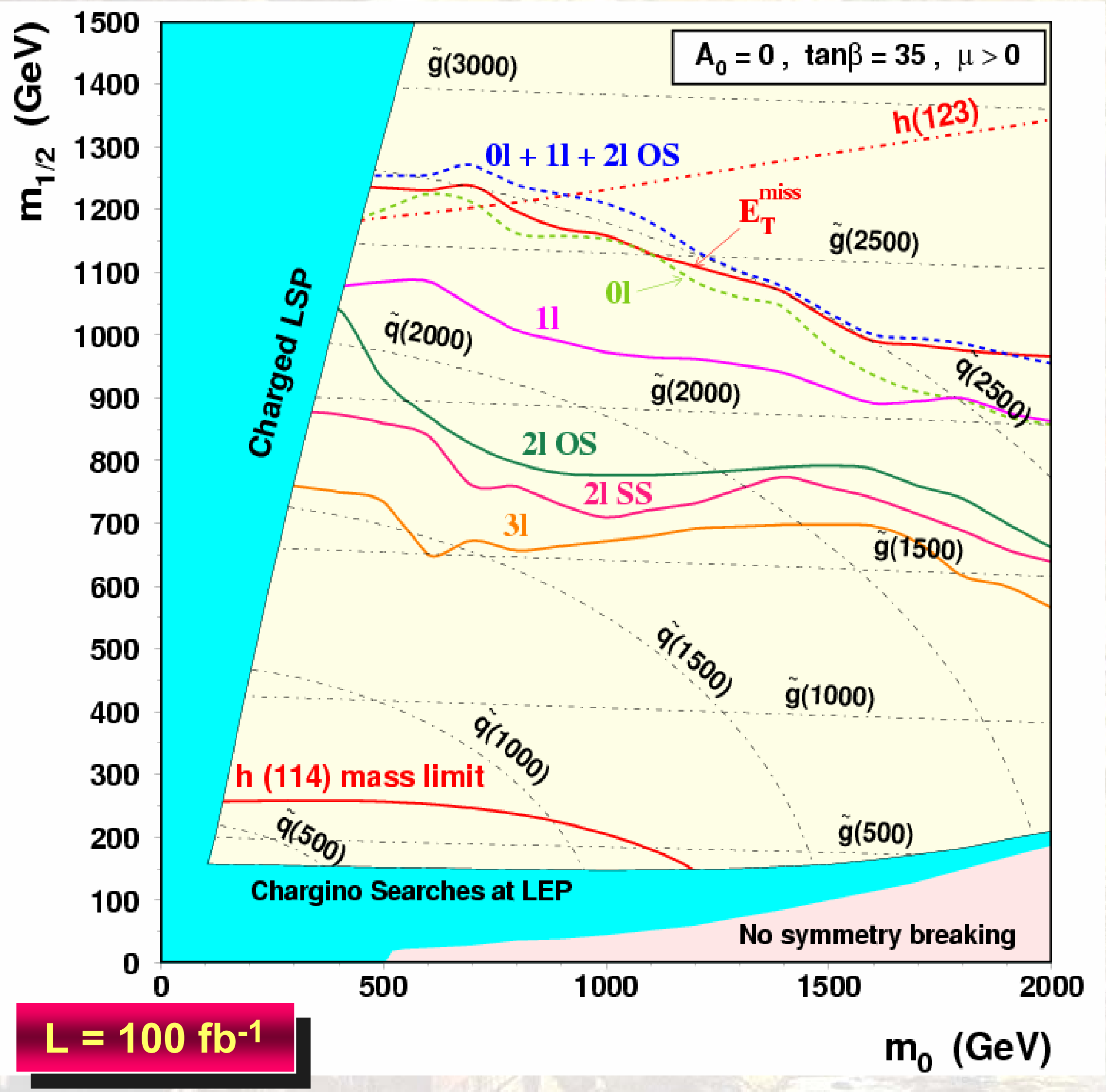
In the past years several inclusive studies done to understand the detector capabilities to discover SUSY

- Counting excess of events over SM expectations
- No explicit sparticle reconstruction done
- Apply kinematical cuts to distinguish signal from bkg
  - Etmiss,Njets ,Nb-jets ,Niso-lep
  - Several different final states analysed
    - E_t^{miss} + jets
    - No lepton + E_t^{miss} + jets
    - 1 l + E_t^{miss} + jets
    - 2 l OS + E_t^{miss} + jets
    - 2 l SS + E_t^{miss} + jets
    - 3 l + E_t^{miss} + jets

S.Abdullin, F. Charles Nucl. Phys. B547 (1999) 60
S. Abdullin et al., J. Phys. G28 (2002) 469
M. Dzelalija et al., Mod. Phys. Lett. A15 (2000) 465

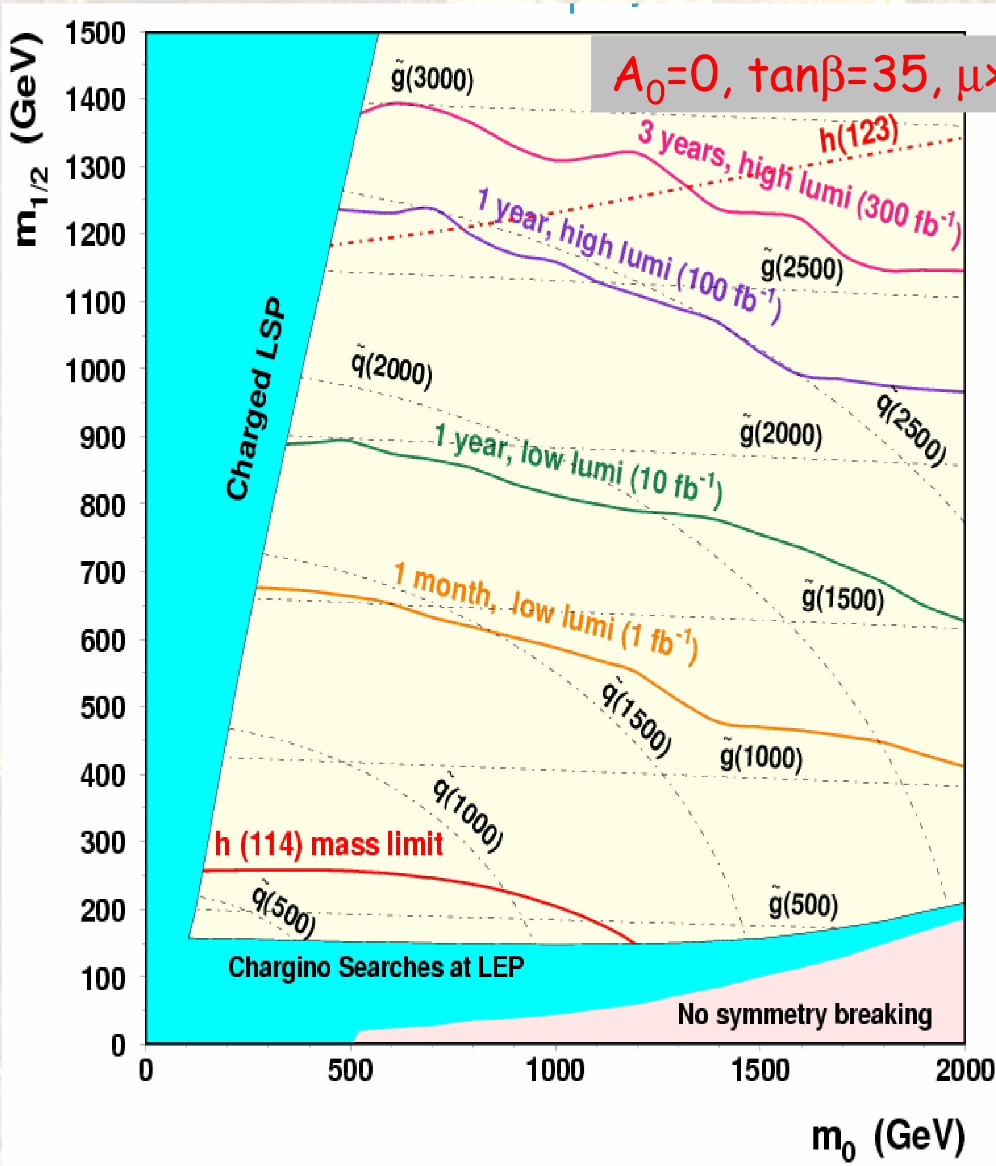
- Chosen criterion of signal observability $\sigma = \frac{S}{\sqrt{S+B}} \geq 5$
- Cuts optimized in order to maximize σ
- Scan in mSUGRA (m_0,$m_{1/2}$) plane (also studies in p-MSSM and AMSB scenario performed)
- Fast MC simulation used: ATLFAST, CMSJET

Inclusive reach in various final states



- Jets+MET gives greatest sensitivity
- 2lOS most useful for sparticle reconstruction

Inclusive SUSY reach vs integrated luminosity



- ✓ If Supersymmetry exists, LHC will probably observe it
- ✓ Most of the cosmologically interesting region covered with 10 fb^{-1}
- ✓ Squark-gluino production dominates the total cross section at low mass scale
- ✓ Squarks and Gluinos detectable up to 2 TeV mass with 100 fb^{-1}
- ✓ Similar reach also in other R conserving scenarios ➡

Expected squark-gluino mass reach

- ≈ 1.5 – 1.8 TeV with 10 fb^{-1}
- ≈ 2.3 – 2.5 TeV with 100 fb^{-1}
- ≈ 2.6 – 3.0 Tev with 300 fb^{-1}
- ≈ 2.8 – 3.2 TeV with 1000 fb^{-1}

S.Abdullin, F. Charles Nucl. Phys. B547 (1999) 60
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But …

It is not enough to observe the excess over the Standard Model…

DISCOVERY → **SUSY SPECTROSCOPY**

This requires a different approach…

Fix a set of points in the parameter space

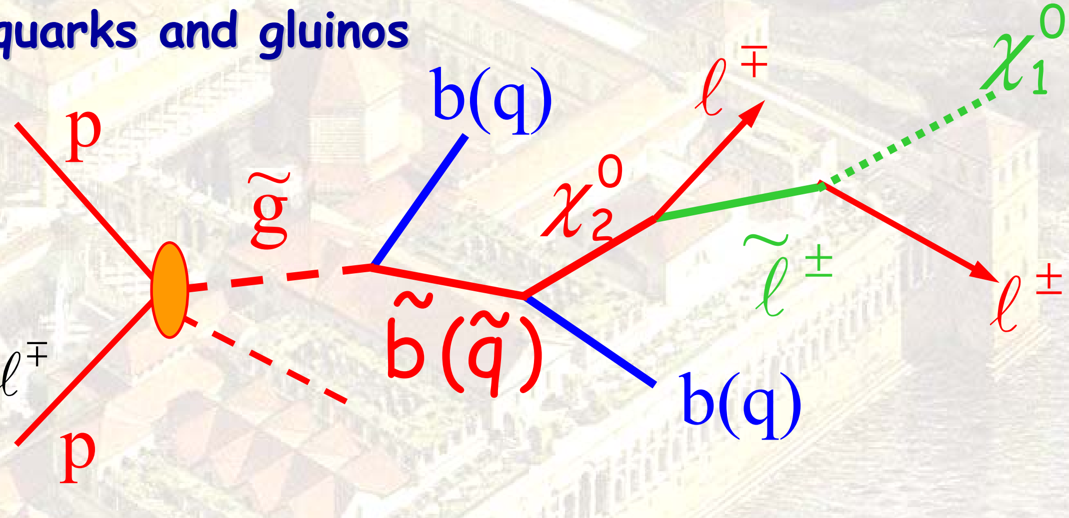
Get information on the spectrum (i.e. end points)

Reconstruct sparticles

Decay chains

Reconstruction of sbottoms, squarks and gluinos

$$pp \to \tilde{g} \to \tilde{b}b$$
$$\hookrightarrow \chi_2^0 b$$
$$\hookrightarrow \tilde{\ell}^{\pm}\ell^{\mp} \to \chi_1^0 \ell^{\pm}\ell^{\mp}$$



$$pp \to \tilde{g} \to \tilde{q}q$$
$$\hookrightarrow \chi_2^0 q$$
$$\hookrightarrow \tilde{\ell}^{\pm}\ell^{\mp} \to \chi_1^0 \ell^{+}\ell^{-}$$

- $\geq$ 2 high p_t isolated leptons OS (leptons = e,μ)
- $\geq$ 2 high p_t b jets
- missing E_t

SM bkg: tt, Z+jet, W+jet, ZZ, WW, ZW, QCD jets

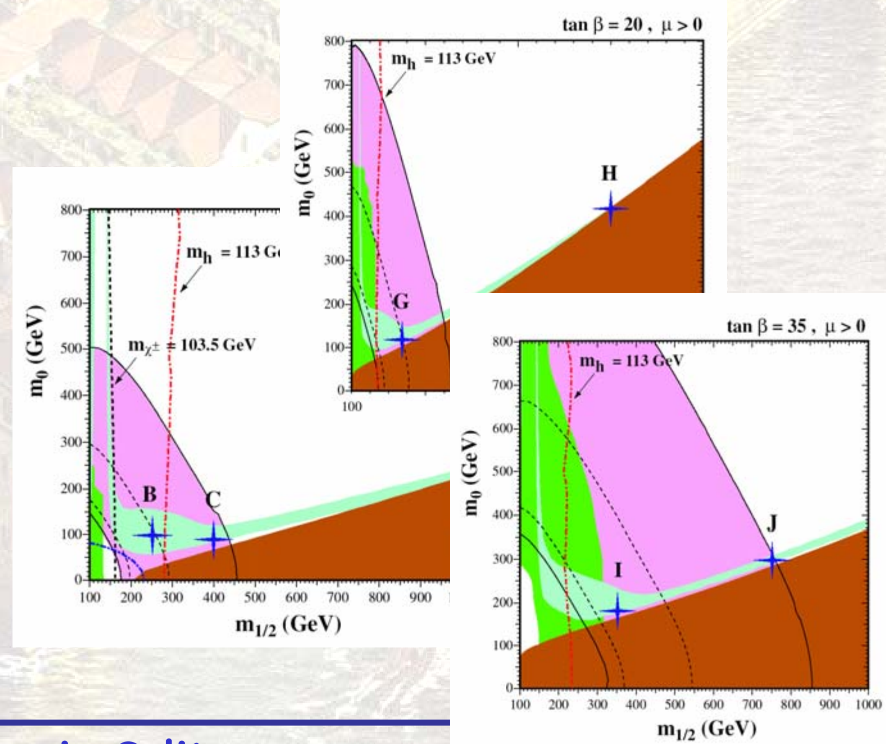
Benchmark points

Proposed Post-LEP Benchmarks for Supersymmetry, M. Battaglia *et al*. (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
sign(μ)	+	+	+	−	+	+	+	+	+	+	−	+	+
$\alpha_s(m_Z)$	120	123	121	121	123	120	122	117	122	119	117	121	116
m_t	175	175	175	175	171	171	175	175	175	175	175	175	175

All masses in GeV/c^2

- **Rather low m_0 and $m_{1/2}$ values in order to have high SUSY cross section**
- **Three different $\tan\beta$ values ($\tan\beta$ = 10, 20, 35) since BR($\chi_2^0 \rightarrow l^+l^- \chi_1^0$) depends critically on $\tan\beta$**



Point B spectra

$m_{1/2} = 250 \quad sign(\mu) = +$

$m_0 = 100 \quad A_0 = 0$

$\tan\beta = 10$

Point B

$\sigma^{TOT}_{SUSY} = 57.77$ pb

g	595.1	t_L	392.9
b_L	496.0	t_R	575.9
b_R	524.0	χ_4^0	361.1
q_L	559	χ_3^0	339.9
q_R	520	χ_2^0	174.4
l_L	196.5	$\chi_2^{\pm}$	361.6
l_R	136.2	$\chi_1^{\pm}$	173.8
		χ_1^0 = LSP	95.6

$pp \rightarrow \tilde{g} \rightarrow \tilde{b}b$ (17% b_L, 10% b_R)

$\hookrightarrow \tilde{\chi}_2^0 b$ (37 % b_L, 25% b_R)

- $\rightarrow \tilde{\chi}_1^0 \ell^+\ell^-$ (0.04 %)
- $\rightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \tilde{\chi}_1^0 \ell^+\ell^-$ (16.4 %)
- $\rightarrow \tilde{\tau}^{\pm}\tau^{\mp} \rightarrow \tilde{\chi}_1^0 \tau^+\tau^-$ (83.2 %)

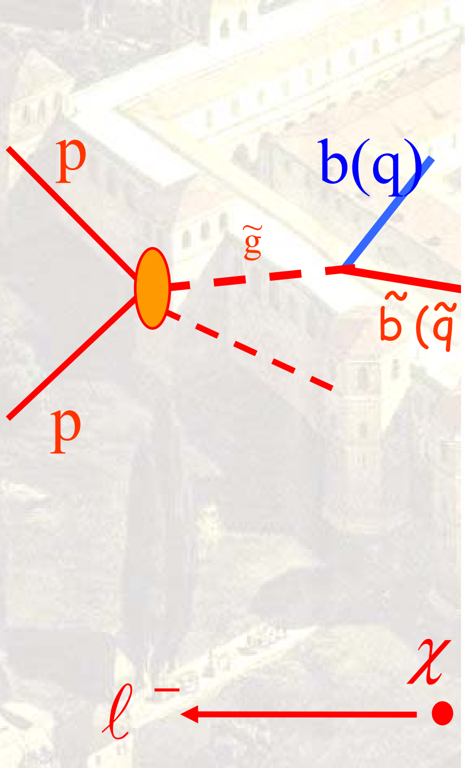
Sbottom reconstruction

- **≥2 isolated leptons, p_T>15 GeV, |η|<2.4**
- **≥ 2 b-jets, p_T>20 GeV, |η|<2.4**

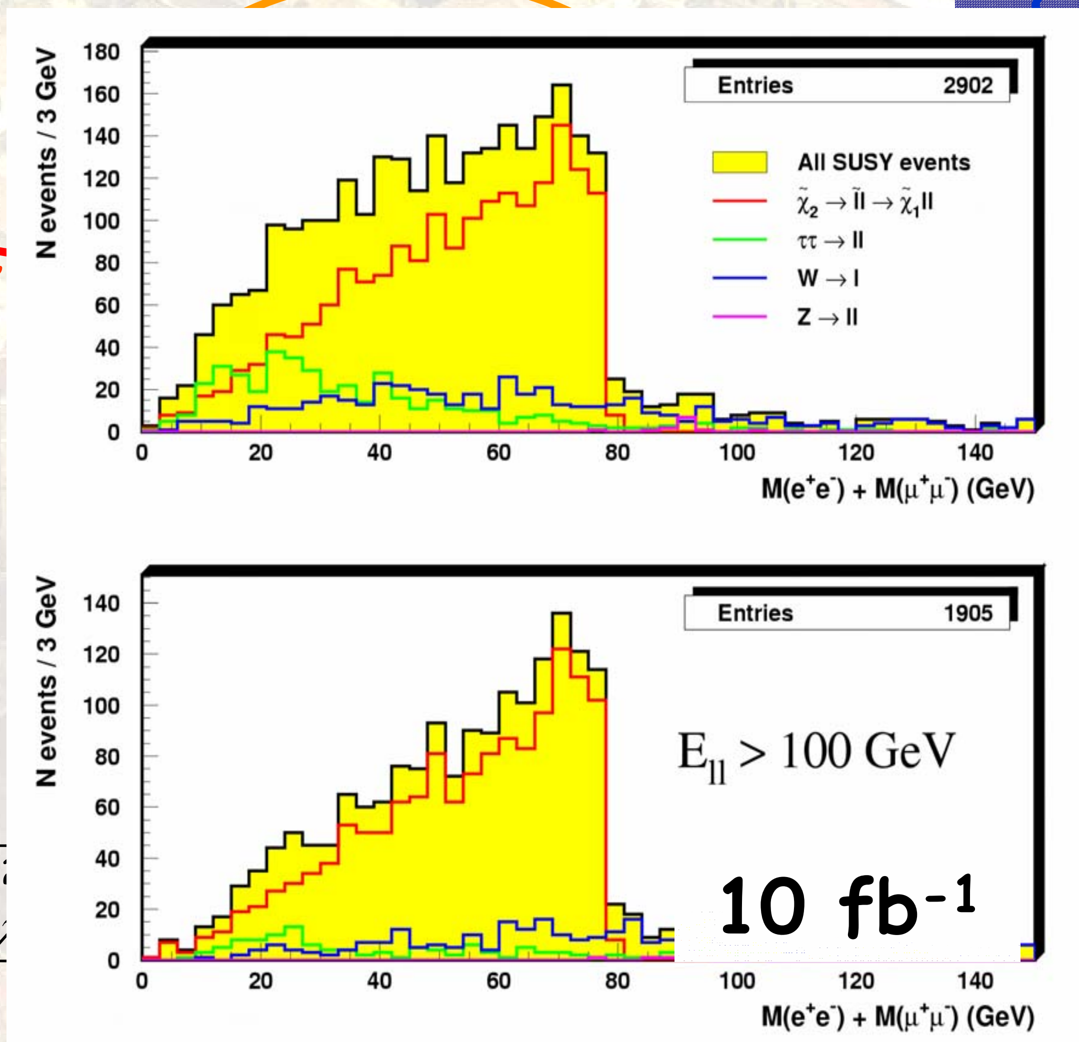
First step: $\chi_2^0 \rightarrow l^+l^- \chi_1^0$

SUSY events

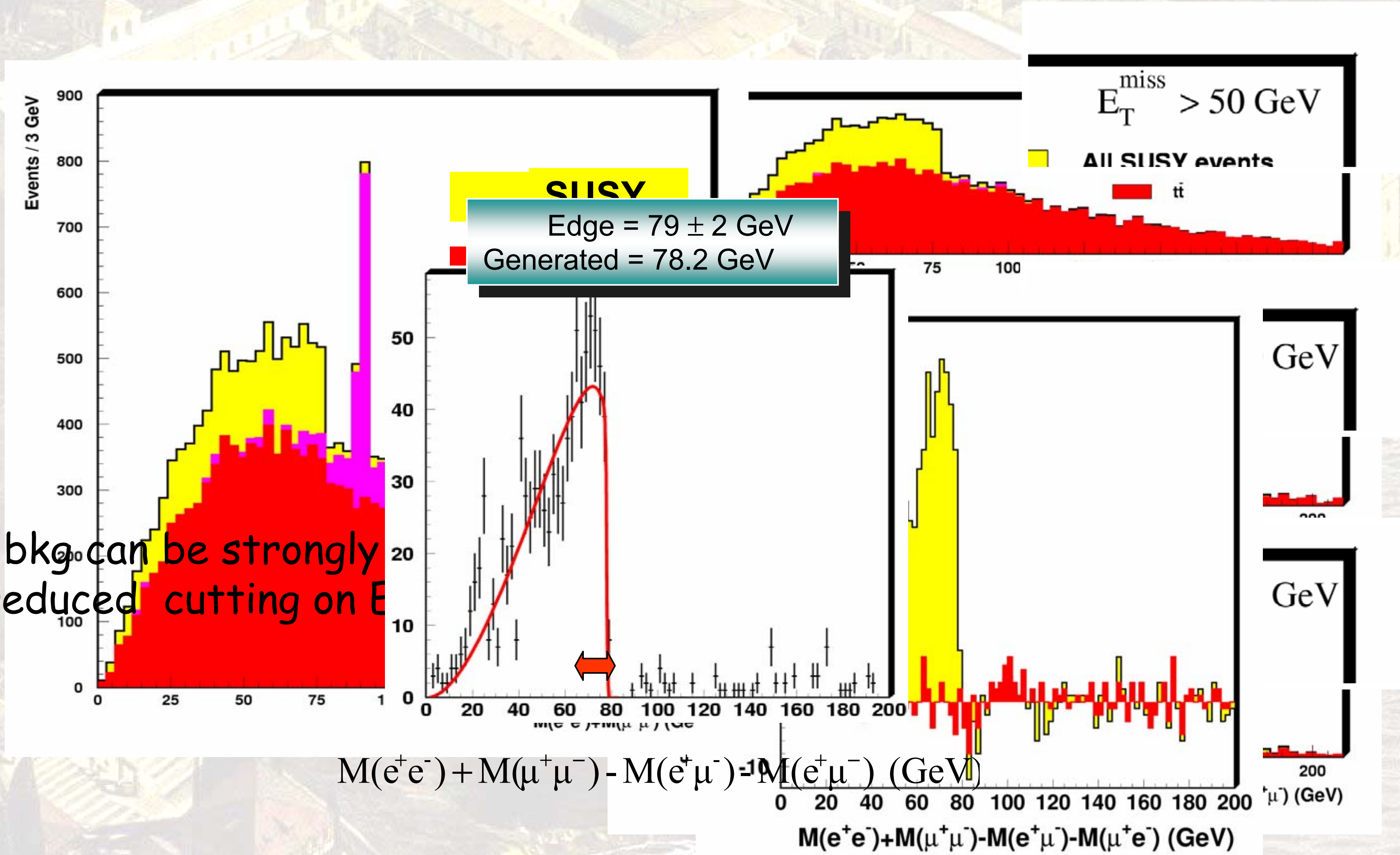
$M(e^+e^-) + M(\mu^+\mu^-)$



$$M^{max}_{\ell^+\ell^-} = \sqrt{(M \ldots}$$



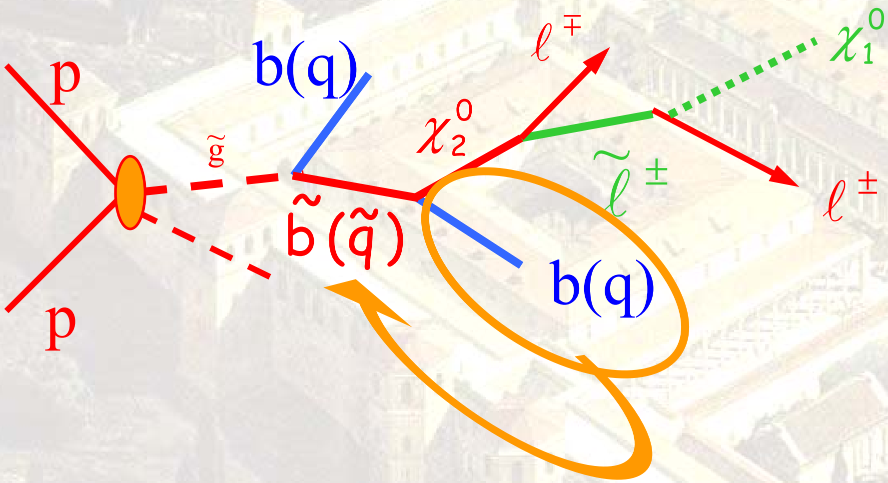
Bkg reduction



SM bkg can be strongly reduced cutting on E

$M(e^+e^-) + M(\mu^+\mu^-) - M(e^+\mu^-) - M(e^+\mu^-)$ (GeV)

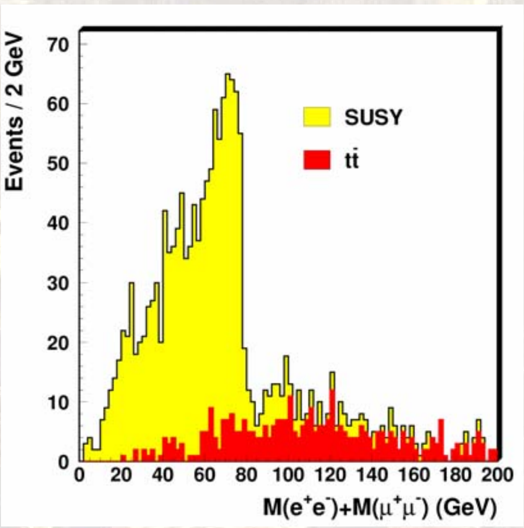
Second step: sbottom (squark) reconstruction



At the end-point:

$$\vec{p}_{\chi_2^0} = \left(1 + \frac{M_{\chi_1^0}}{M_{\ell^+\ell^-}}\right)\vec{p}_{\ell^+\ell^-}$$

χ_1^0 at rest in the χ_2^0 rest frame



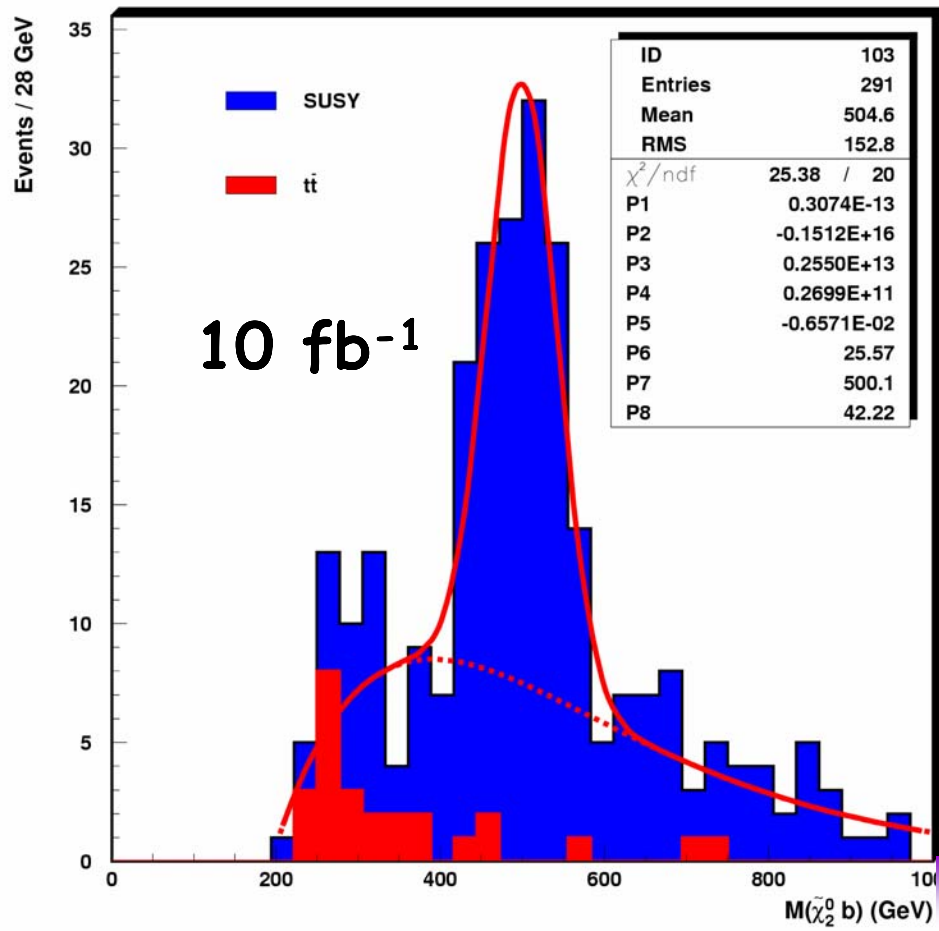
$65\ \text{GeV} < M(\ell^+\ell^-) < 80\ \text{GeV}$

- Assuming $M(\chi_1^0)$ known
- Selecting events "in edge"
- Combining the χ_2^0 obtained from the two leptons with the most energetic (b)-jet in the event

Sbottom mass peak

$$\sigma \bullet BR(pp \to \tilde{b} \to \text{decay chain}) = 0.1\,pb$$

$$\sigma \bullet BR(pp \to \tilde{g} \to \tilde{b} \to \text{decay chain}) = 0.6\,pb$$



Result of the fit:

$M(\tilde{\chi}_2^0 b) = 500 \pm 7$ GeV

$\sigma = 42 \pm 5$ GeV

$$\sigma \bullet BR(\tilde{b}_1 \to \text{decay chain}) = 535\ fb$$

$$\sigma \bullet BR(\tilde{b}_2 \to \text{decay chain}) = 212\ fb$$

Generated masses:

$M(\tilde{b}_L) = 496.0$ GeV

$M(\tilde{b}_R) = 524.0$ GeV

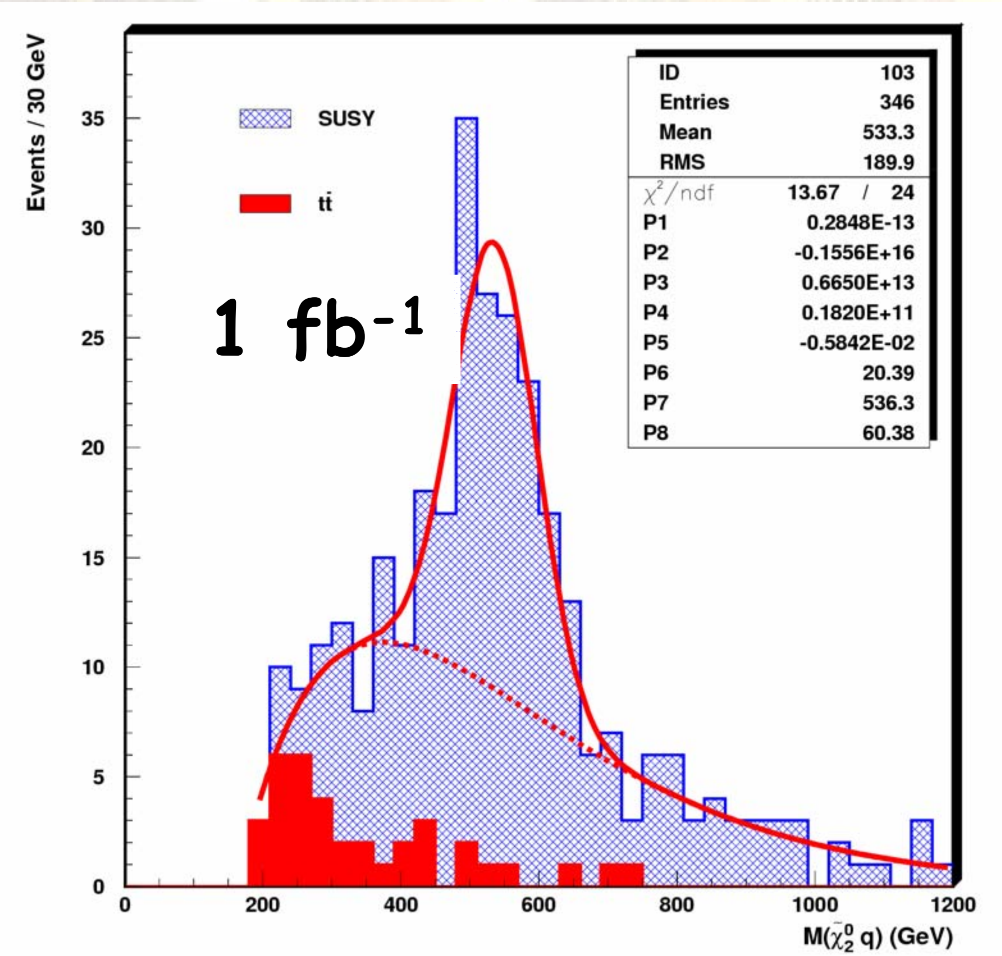
The peak should be considered as the superposition of two peaks

$$\overline{M}(\tilde{b}) = \frac{M(\tilde{b}_1) \bullet \sigma \times BR(\tilde{b}_1) + M(\tilde{b}_2) \bullet \sigma \times BR(\tilde{b}_2)}{\sigma \times BR(\tilde{b}_1) + \sigma \times BR(\tilde{b}_2)} = 503.9\,GeV$$

Squark mass peak

$\sigma \bullet BR(pp \to \tilde{q} \to \text{decay chain}) = 1.4\ pb$

$\sigma \bullet BR(pp \to \tilde{g} \to \tilde{q} \to \text{decay chain}) = 0.5\ pb$



Result of the fit:

$M(\tilde{\chi}_2^0 q) = 536 \pm 10\ GeV$

$\sigma = 60 \pm 9\ GeV$

Generated values

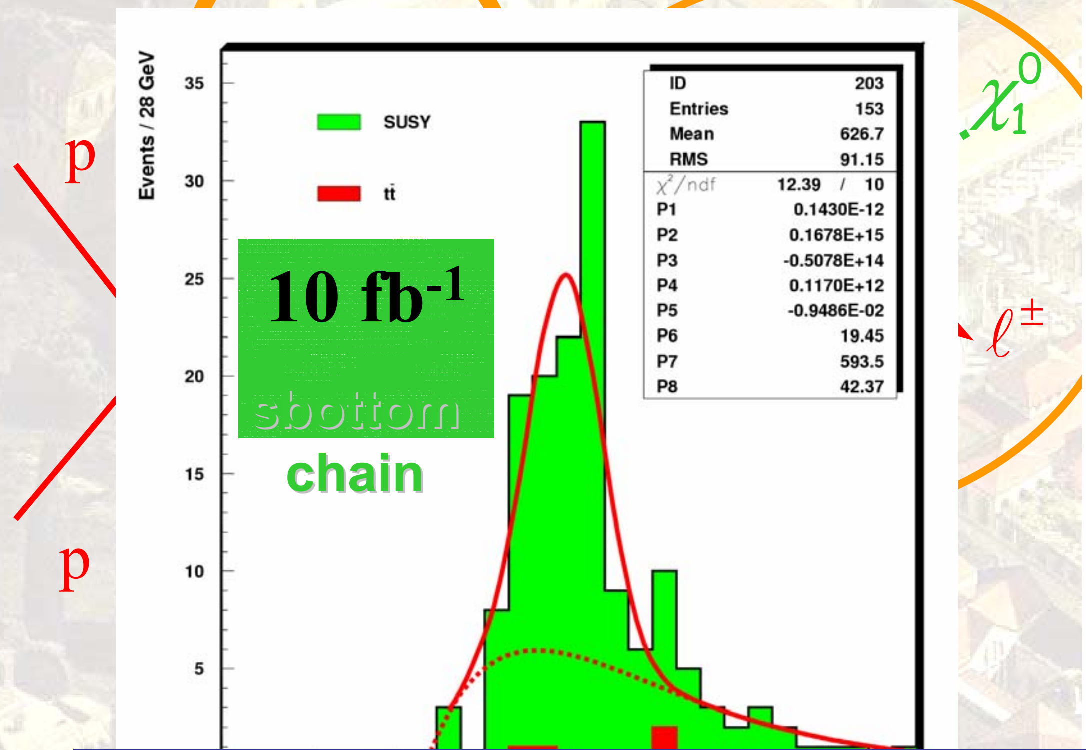
$M(\tilde{d}_L) = M(\tilde{s}_L) = 542.8\ GeV$

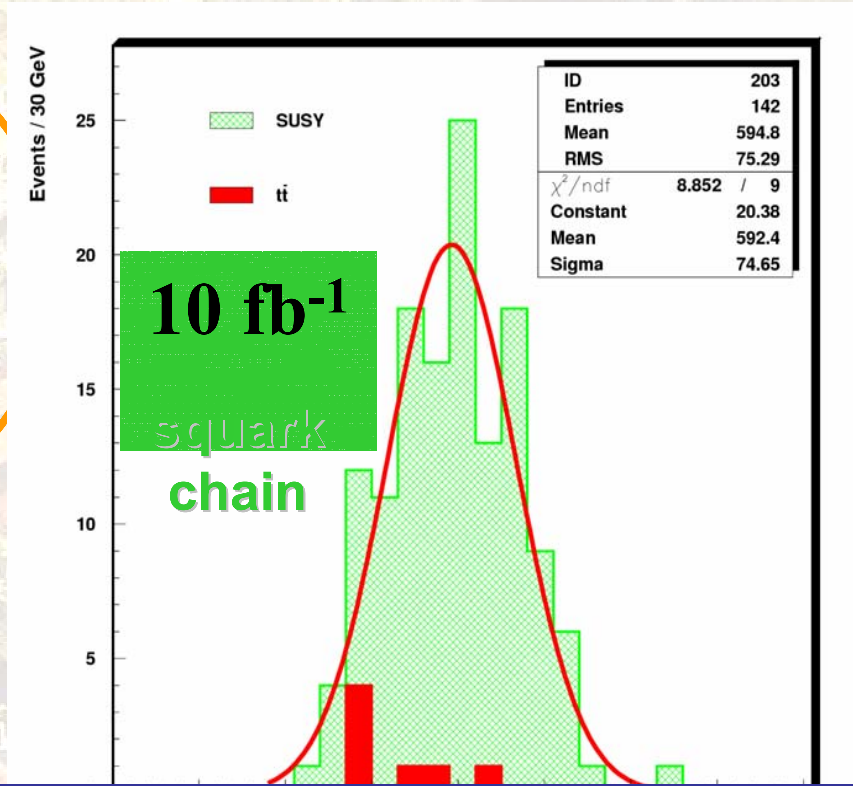
$M(\tilde{u}_L) = M(\tilde{c}_L) = 537.0\ GeV$

$\sigma \bullet BR(\tilde{q}_L \to \text{decay chain}) = 2\ pb$

$\sigma \bullet BR(\tilde{q}_R \to \text{decay chain}) = 60\ fb$

Gluino reconstruction





Two independent (separate) gluino mass measurements

$M(\tilde{\chi}_2^0 bb) = 594 \pm 7\ GeV$

$\sigma = 42 \pm 7\ GeV$

Generated value:

$M(\tilde{g}) = 595.1\ \ GeV$

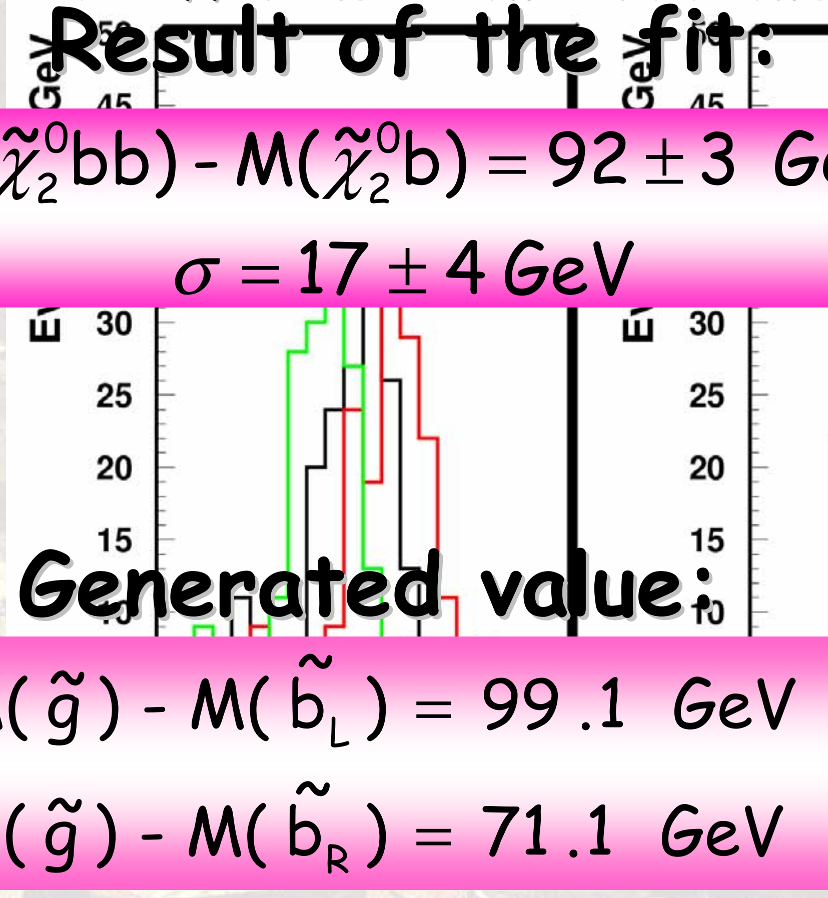
$M(\tilde{\chi}_2^0 qq) = 592 \pm 7\ GeV$

$\sigma = 75 \pm 5\ GeV$

$M(\tilde{g}) - M(\tilde{b})$ estimate

The reconstruction is performed assuming $M(\chi_1^0)$ known but …

The difference between the two masses is independent of $M(\chi_1^0)$



Result of the fit:

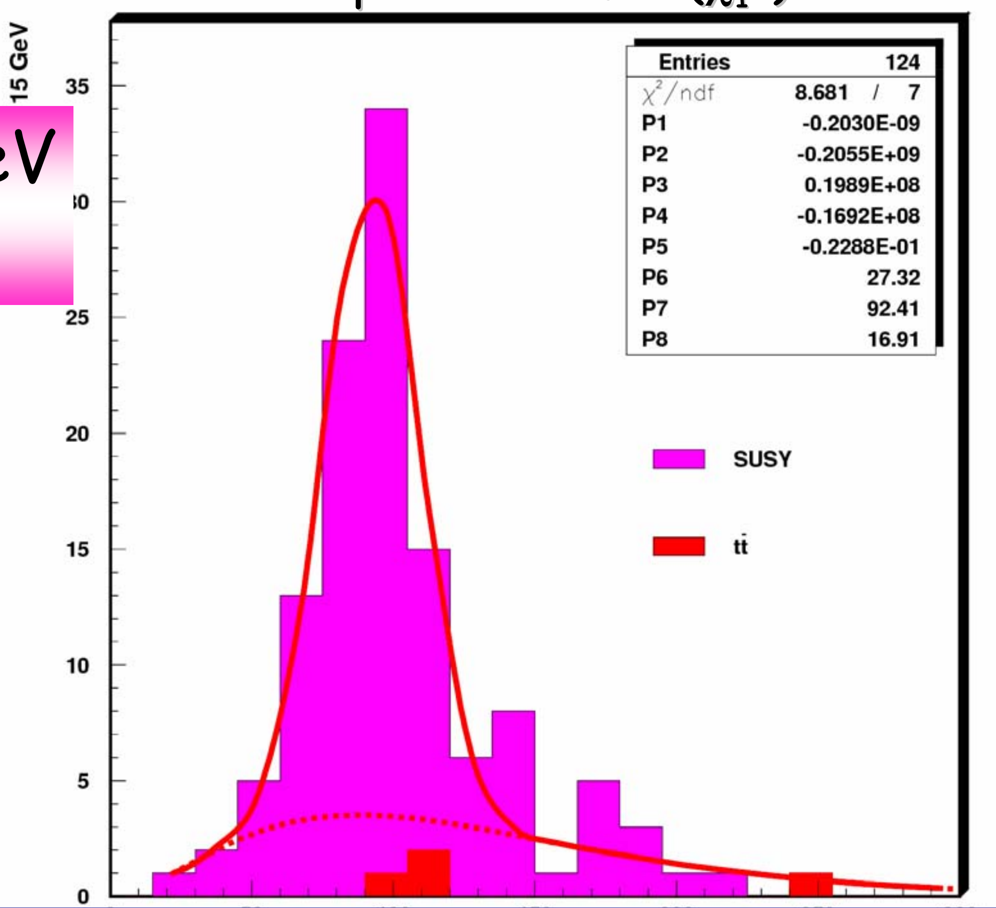
$$M(\tilde{\chi}_2^0 bb) - M(\tilde{\chi}_2^0 b) = 92 \pm 3 \;\; GeV$$

$$\sigma = 17 \pm 4 \; GeV$$

Generated value:

$$M(\tilde{g}) - M(\tilde{b}_L) = 99.1 \;\; GeV$$

$$M(\tilde{g}) - M(\tilde{b}_R) = 71.1 \;\; GeV$$



Worse resolution, but model independent result

Results @ point B

With "well calibrated" and smoothly running detectors

- Squark mass peak can be reconstructed in the first few weeks (resolution ~12%)
- Sbottom and gluino in the first year (resolution ~6÷8%)
- Two independent gluino mass measurements
- The resolutions can be improved with larger statistics (~5÷6% at 300 fb^{-1})

Sbottom Chain (Masses in GeV/c^2)				Squark Chain (Masses in GeV/c^2)			
	10 fb^{-1}	60 fb^{-1}	300 fb^{-1}		10 fb^{-1}	60 fb^{-1}	300 fb^{-1}
M(sbottom)	500±7	502±4	497±2	M(squark)	536±10	532±2	536±1
σ(sbottom)	42±5	41±4	36±3	σ(squark)	60±9	36±1	31±1
M(gluino)	594±7	592±4	591±3	M(gluino)	592±7	595±2	590±2
σ(gluino)	42±7	46±3	39±3	σ(gluino)	75±5	59±2	59±2
M(gl)-M(sb)	92±3	88±2	90±2	M(gl)-M(sq)	57±3	47±2	44±2
σ(gl-sb)	17±4	[illegible]	[illegible]	σ(gl-sq)	[illegible]	[illegible]6±5	11±2

- Errors of the order of 1÷2 GeV/c^2(stat)⊕2÷3 GeV/c^2(calorimeter energy scale)
- Main systematic uncertainty is due to the lack of knowledge on $M(\chi_1^0)$

Model dependence:

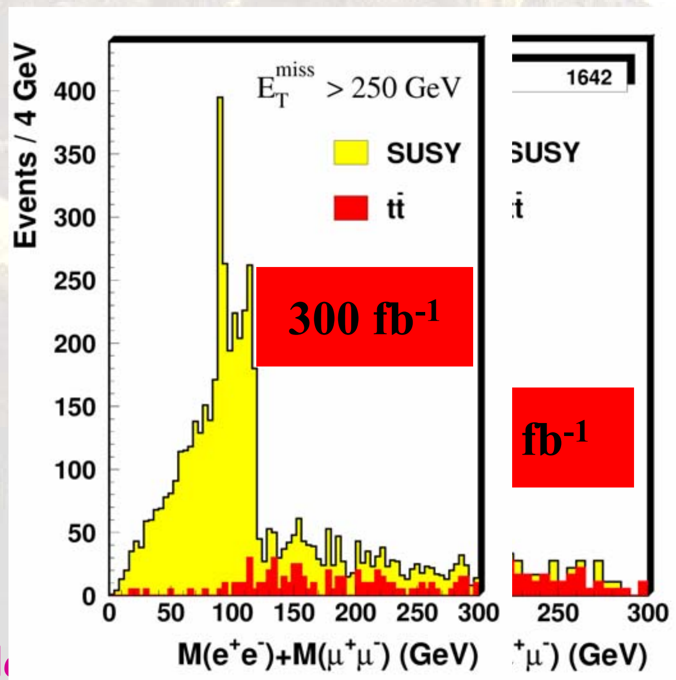
$M_{\chi_1^0}$ assumed to be known

Jet association

Kinematical peculiarities can be exploited (see next slides)

Reconstruction @ point G

$m_0 = 120$ GeV
$m_{1/2} = 375$ GeV
$\tan\beta = 20$
$A_0 = 0$
$\mu > 0$



With respect to the Point B:

✓**Lower total SUSY cross-section**

$\sigma_{SUSY}^{TOT} = 8.25$ pb (≈ 57 pb @ point B)

✓**Lower BR of useful decays**

$BR(\tilde{g} \to \tilde{b}b) = 26.58\%$ (point B 27.48%)

$BR(\tilde{g} \to \tilde{q}q) = 59.92\%$ (point B 67.32%)

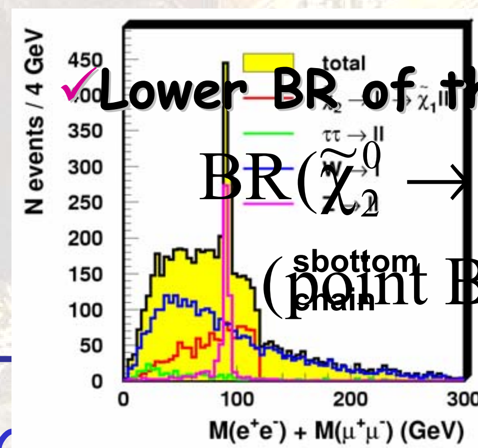
✓**Higher BR's of competitive decays**

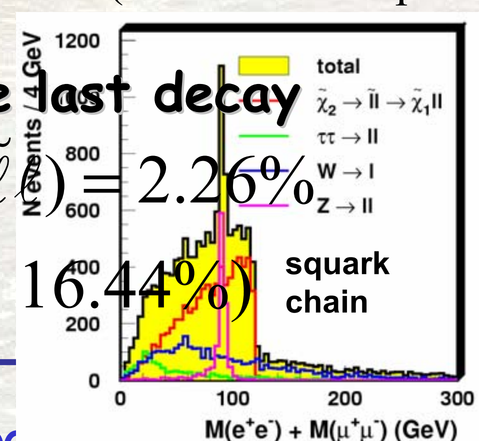
$BR(\tilde{b}_2 \to \tilde{t}W) = 21.52\%$ (point B 2.19%)

$BR(\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 W) = 7.83\%$ (not allowed at point B)

✓**Lower BR of the last decay**

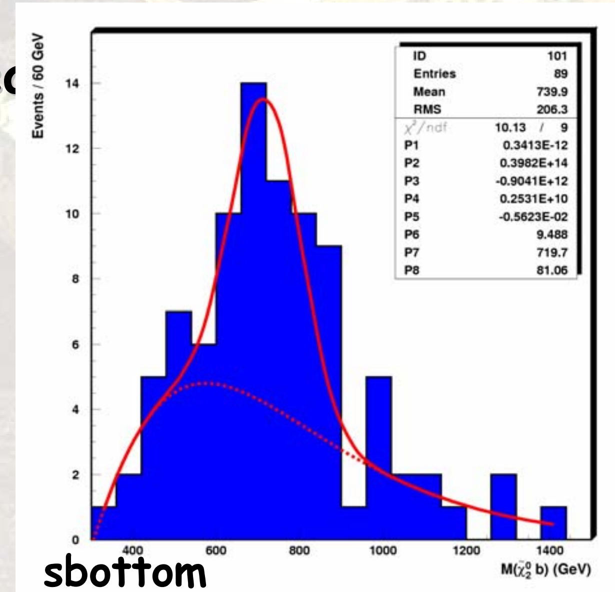
$BR(\tilde{\chi}_2^0 \to \tilde{\ell}\ell) = 2.26\%$ (point B 16.44%)

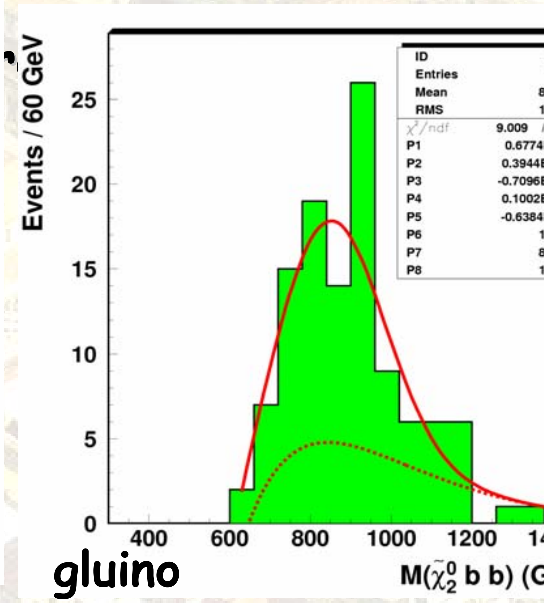


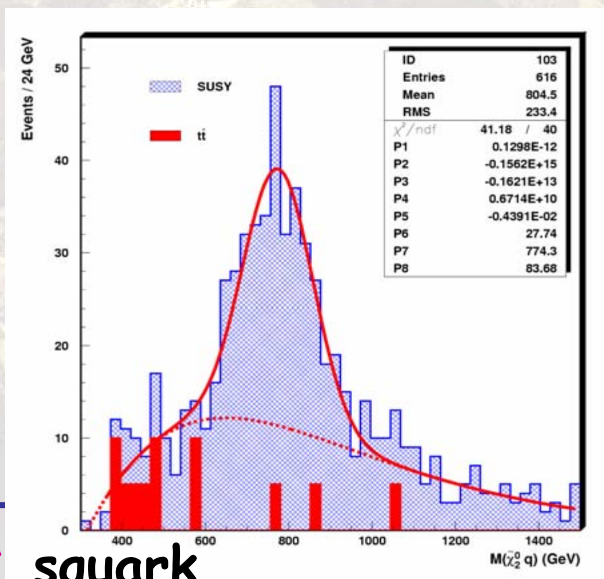


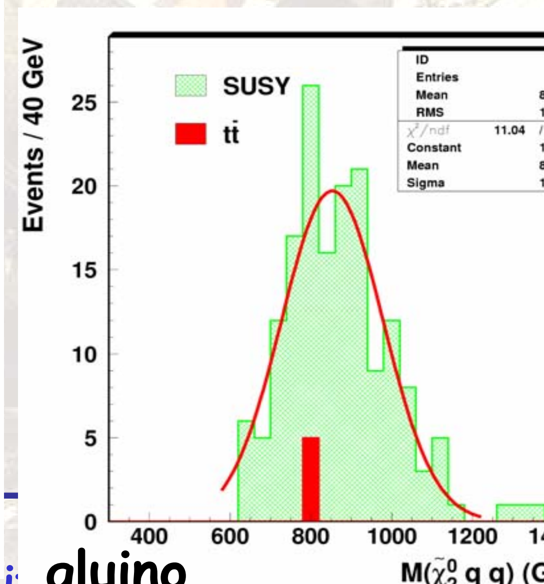
Results @ Point G

Repea...









Sbottom Chain	
	300 fb^{-1}
M(sbottom)	720±26
σ(sbottom)	81±18
M(gluino)	851±40
σ(gluino)	130±43
M(sb)-M(gl)	127±10
σ(sb-gl)	48±11
Squark Chain	
	300 fb^{-1}
M(squark)	774±9
σ(squark)	84±9
M(gluino)	853±11
σ(gluino)	126±11
M(sq)-M(gl)	82±3
σ(sq-gl)	35±3

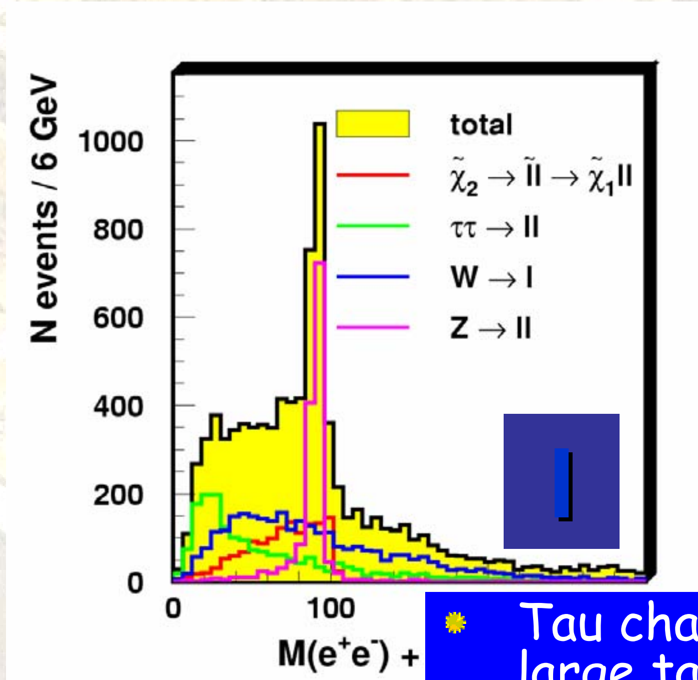
$M(\tilde{g}) - M(\tilde{q})$

M($\tilde{\chi}^0_2$ q q) - M($\tilde{\chi}^0_2$ q) (GeV)

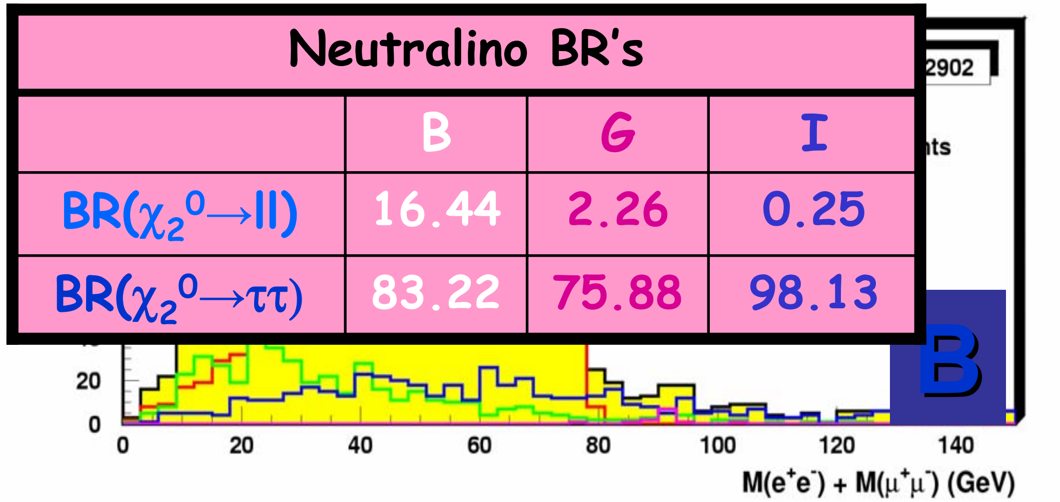
Reconstruction @ point I

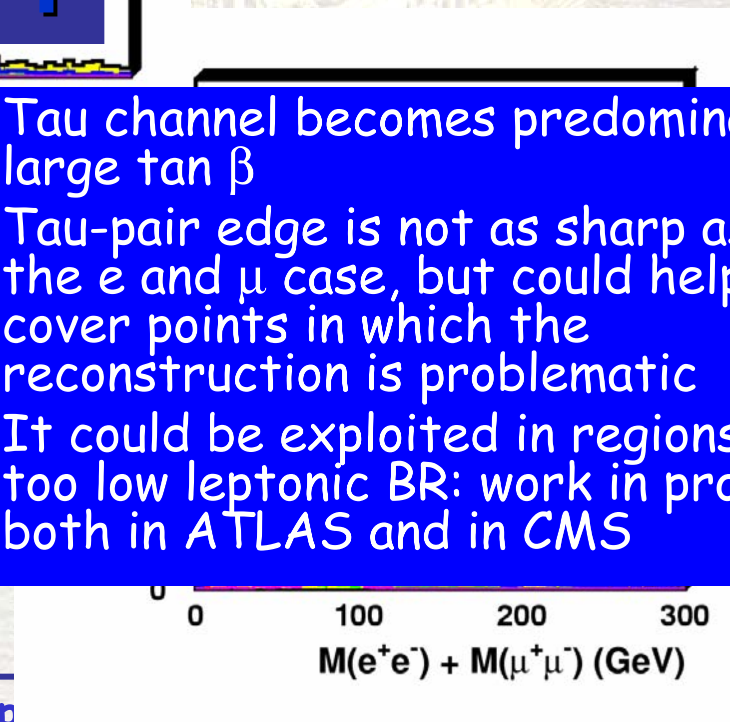
$$m_0 = 180 \text{ GeV}$$
$$m_{1/2} = 350 \text{ GeV}$$
$$\tan\beta = 35$$
$$A_0 = 0$$
$$\mu > 0$$

$$BR(\tilde{\chi}_2^0 \to \tilde{\ell}\ell) = 0.25\%$$



Neutralino BR's			
	B	G	I
$BR(\chi_2^0 \to ll)$	16.44	2.26	0.25
$BR(\chi_2^0 \to \tau\tau)$	83.22	75.88	98.13

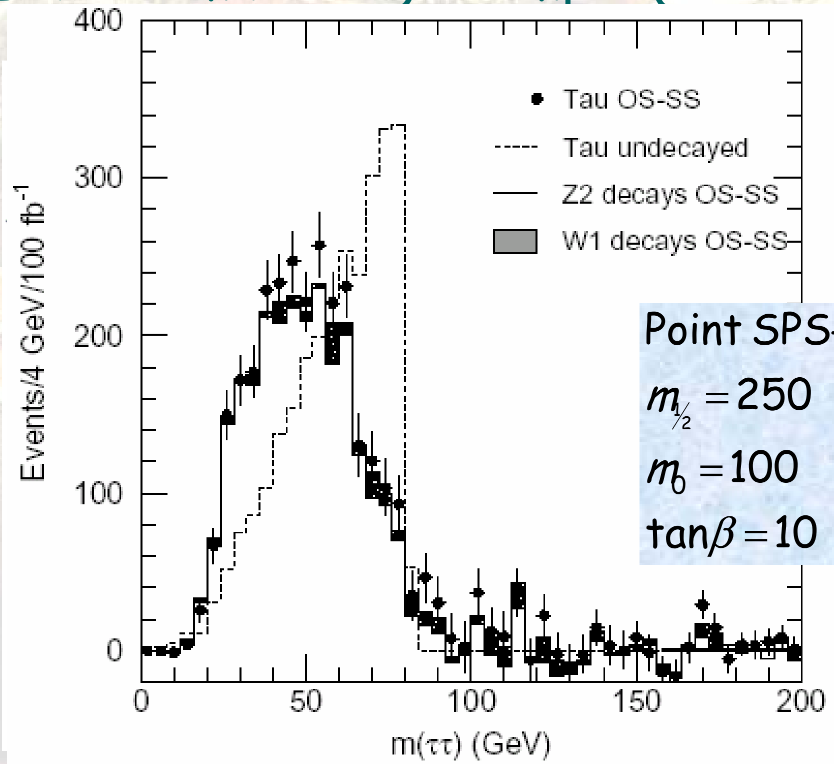




- Tau channel becomes predominant at large tan β
- Tau-pair edge is not as sharp as in the e and μ case, but could help to cover points in which the reconstruction is problematic
- It could be exploited in regions with too low leptonic BR: work in progress both in ATLAS and in CMS

Di-tau lepton edge

- As $\tau \to l \nu \bar{\nu}$ identification is not possible, must rely on hadronic decays – narrow, 1-prong jets (large QCD bkg though)
  - Can typically achieve τ/jet ~100 for ε_τ~50-60 %
- ATLAS Physics TDR study (full GEANT simulation) example ("Point 6") :
  - Narrow isolated jets selection : R_{jet} = 0.2, R_{isol} = 0.4
  - Require 0.8 GeV < M_{jet} < 3.6 GeV (biased against 1-prong, but improves di-tau mass resolution - less neutrino momentum)
  - Di-tau efficiency = 41 %
  - M_{vis} = 0.66 $M_{\tau\tau}$
  - Additional cuts : min. 4 jets : E_T^1 > 100 GeV, E_T^{2-4} > 50 GeV missing E_T > 100 GeV, no e, μ with p_T > 20 GeV



Point SPS-1A

$m_{1/2} = 250$ $sign(\mu) = +$

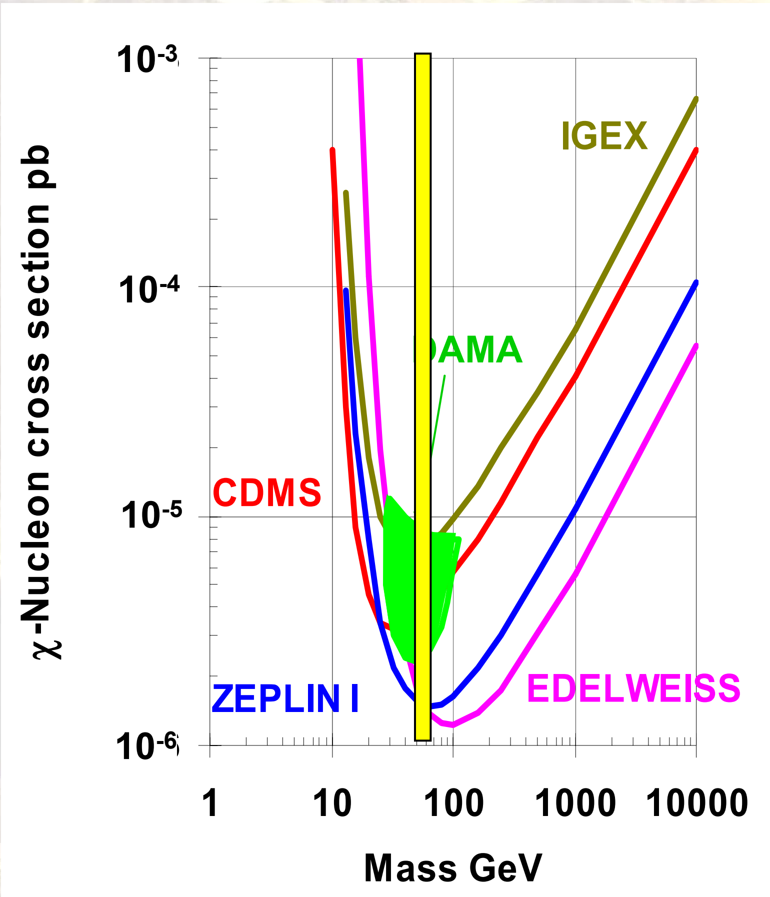
$m_0 = 100$ $A_0 = -100$

$\tan\beta = 10$

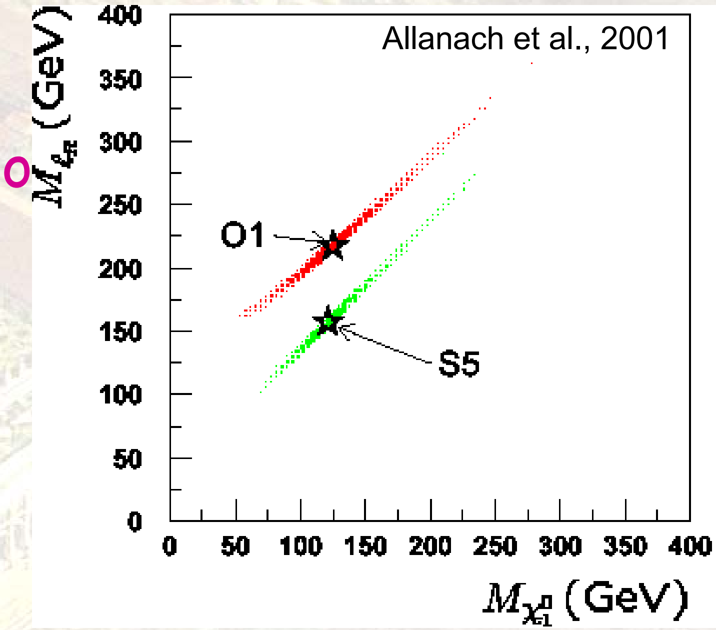
☞ Recent results – even more encouraging…

Why and how to measure the χ_1^0 mass…

1. Use as starting point for other sparticle mass measurements (sbottom, gluino, squark…)



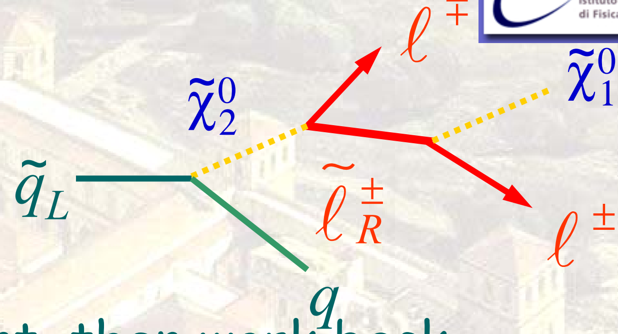
2. Using mass of lightest neutralino and RH sleptons can discriminate between SUSY models differing only in slepton mass.



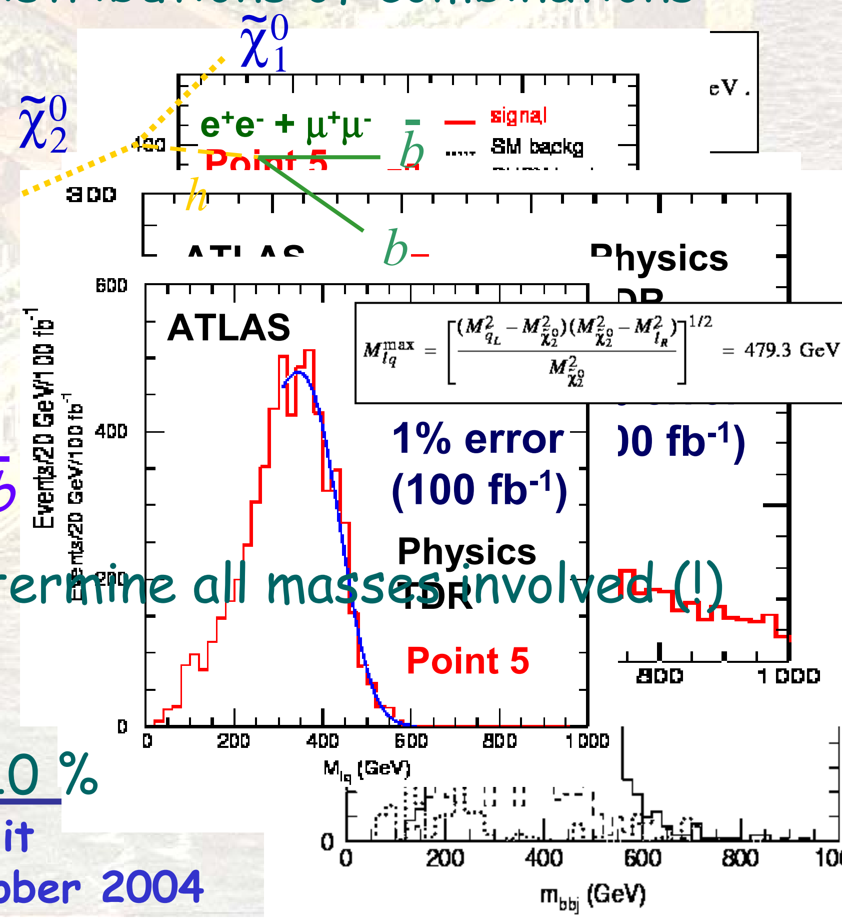
SUSY Dark Matter

3. Lightest Neutralino LSP excellent Dark Matter candidate.
   - Test of compatibility between LHC observations and signal observed in Dark Matter experiments.

Why and how to measure the χ_1^0 mass…



- Long decay chains allow multiple measurements
  - Use kinematics to measure end-points (in general both maximum and minimum value due to 2-body decays)
- Use dilepton signature to tag presence of χ^0_2 in event, then work back up decay chain constructing invariant mass distributions of combinations of leptons and jets
- Starting point : di-lepton OS SF mass edge
- Assume 2 hardest jets are from squarks, combine each of these with leptons to from :
  - Endpoints: M_{llq} $M^{>}_{lq}$, $M^{<}_{lq}$
  - Threshold : T_{llq}, requiring $M_{ll} > M_{ll}^{max}/\sqrt{2}$
  - Also used endpoint from M_{hq} from $h \to b\bar{b}$



- Turns out to have enough constraints to determine all masses involved (!)
- Can measure mass relations to ~1% as a function of LSP mass, determined to ~10 %

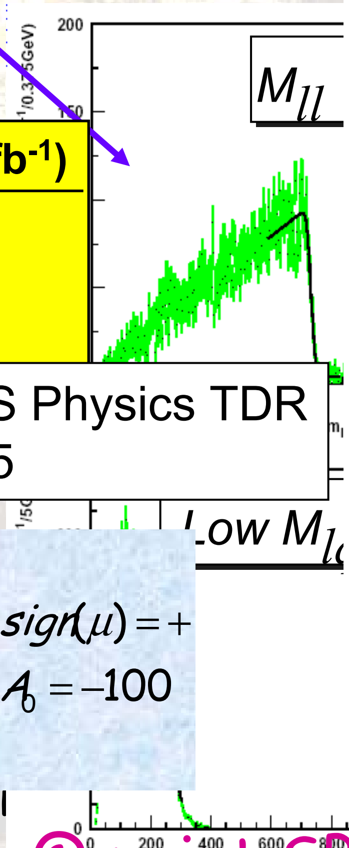
Mass Reconstruction

Combine measurements from edges from different jet/lepton combinations

- Numerical solution of simultaneous edge position equations

Sparticle	Expected precision (100 fb^{-1})
$\tilde{q}_L$	± 3%
$\tilde{\chi}^0_2$	± 6%
$\tilde{l}_R$	± 9%
$\tilde{\chi}^0_1$	± 12%

ATLAS Physics TDR
Point 5



Point 5

$m_{1/2} = 300$ $sign(\mu) = -$

$m_0 = 100$ $A_0 = 300$

$\tan\beta = 2$

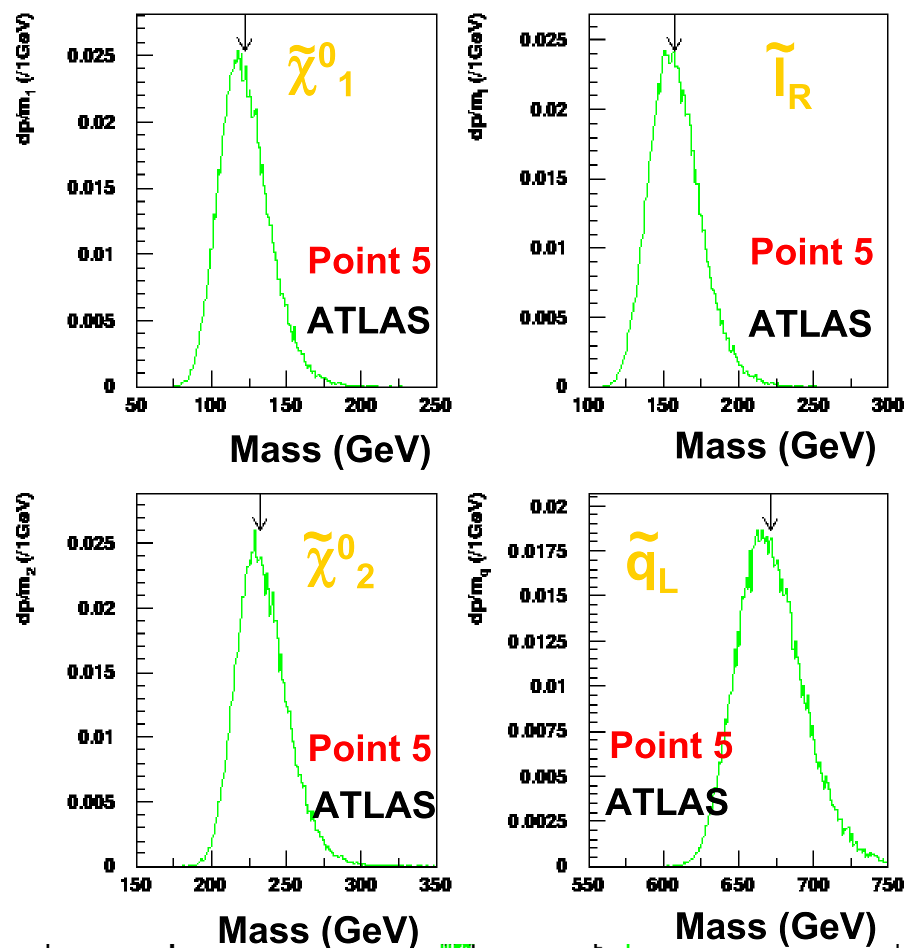
Point SPS-1A

$m_{1/2} = 250$ $sign(\mu) = +$

$m_0 = 100$ $A_0 = -100$

$\tan\beta = 10$

Allanach et al., 2001



Same order precision also @ point SPS1A (similar to "CMS" point B)

Gives sensitivity to masses

Gjelsten et al., ATLAS-PHYS-2004-07

Conclusions

- LHC experiments are expected to explore SUSY in a decisive way.
- The plausible part of mSUGRA-MSSM parameter space will be explored in a number of characteristic signatures
- Strongly interacting SUSY particles can be accessed up to 2TeV for 100 fb^{-1}
- Information on the SUSY spectrum could be obtained with favourable SUSY parameters, already after the first months of data taking (of course, if detectors run smoothly)

- **Low tan β region (like point B, SPS1A, point 5):**
  - first few weeks of LHC running period:
    - reconstruction of squark (resolution ~12%)
  - first year:
    - reconstruction of sbottom and gluino (resolutions ~6÷8%)
    - reconstruction of gluino in the squark chain (independent channel)
  - high integrated luminosity:
    - improvement on the resolutions
    - double fit of the sbottom peak

- **Intermediate tan β (i.e. point G):**
  - first year:
    - dilepton edge hardly visible
    - no reconstruction possible in e,μ channel
  - high integrated luminosity:
    - reconstruction of squarks, sbottom (~11%) and gluino (~15%)
- **High tan β (i.e point I):**
  - no reconstruction possible in the e-μ channel even with high accumulated statistics
  - Reconstruction in the tau channel exploited. Work is going on…

New analyses are going on:

- New benchmark points to be analyzed
- Full reconstruction studies in first priority
- Multi-edge technique to be fully exploited
- Deeper insight to the tau-tau channel
- Systematic uncertainties to be evaluated

Lot of work before LHC start-up!!!