PASCOS ’04

Northeastern university, Boston, 16-22 August 2004

Dark Matter At LHC

Stefano Lacaprara

Stefano.Lacaprara@pd.infn.it

INFN and Padova University

Outline

- Dark Matter and SuperSymmetry (SUSY),
- SUSY Scenarios in mSUGRA,
- LHC reach for SUSY,
- Sparticles spectroscopy,
- SUSY Dark Matter with LHC,
- Conclusion

Dark Matter and SUSY

- Large fraction of universe mass is dark (WMAP)

  in units of $\rho_c = 1.86 \cdot 10^{-29}$ g/cm^3

Barion density:	$\Omega_b = 0.044 \pm 0.004$
Dark energy:	$\Omega_\Lambda = 0.73 \pm 0.04$
Dark matter:	$\Omega_m = 0.23 \pm 0.04$

- Dark Matter density: $0.0094 < \Omega_m h^2 < 0.129$ (2σ range)
- SuperSymmetry provide a good candidate for Dark Matter
  - If **R-Parity** is conserved, the lightest supersymmetric particle (LSP) is stable
  - Relic density of LSP can explain (fraction) of Dark Matter
- *"Natural"* candidate from a theory developed to solve different problems!

SUSY scenarios

- Use constrained MSSM: *mSUGRA*
- Only 5 free parameters (105 + 19 SM for generic MSSM)

m_0	universal scalar mass
$m_{1/2}$	universal gaugino mass
$\tan\beta$	ratio of two Higgs doublets *VEV*'s
sign(μ)	Higgs mixing parameter sign
A_0	trilinear SUSY breaking parameter

- LSP is the lightest neutralino: χ_1^0
- NLSP is usually a slepton: $\tilde{\tau}$
- Heaviest SP is usually the gluino: $\tilde{g}$

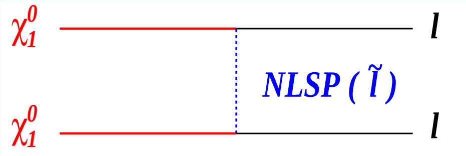
Dark Matter due to relic χ_1^0

Relic density: $\rho_{\chi_1^0} = n_{\chi_1^0} \times m_{\chi_1^0}$

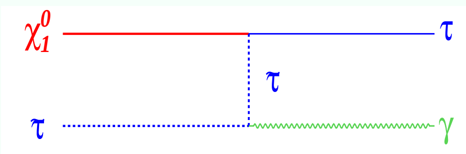
$n_{\chi_1^0}$ depends on LSP annihilation rate at early universe

SUSY scenarios

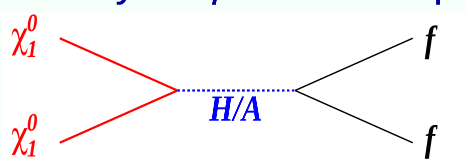
- Bulk:



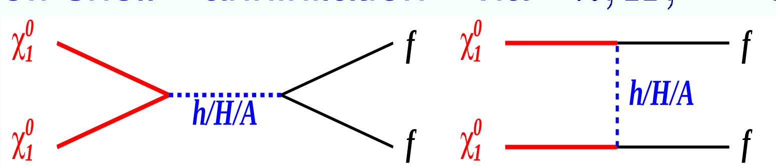
- Co-Annihilation tail: $\tilde{\tau} \to \tau \chi_1^0$ forbidden.
  $\tilde{\tau}$ lives longher

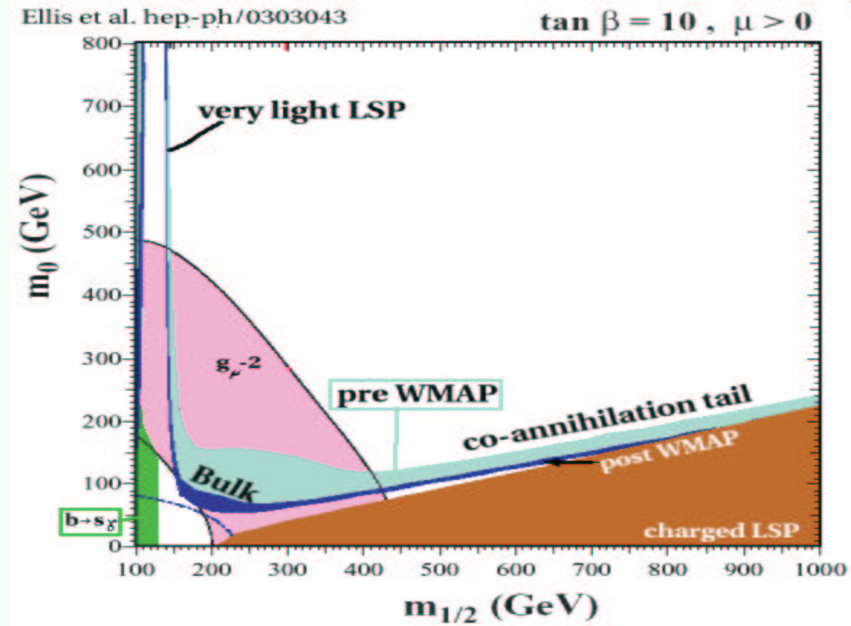


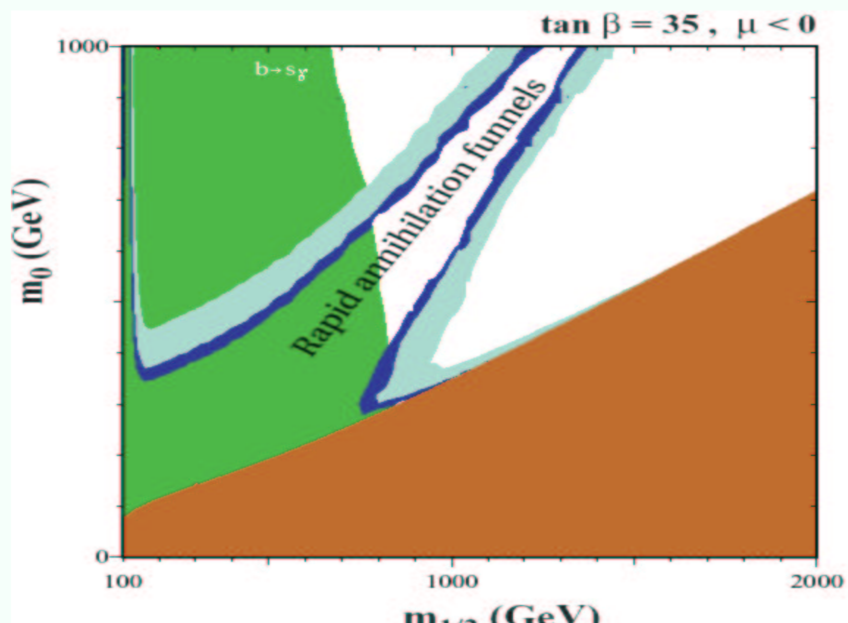
- Funnels (large $\tan\beta$): $m_0 \sim m_{1/2}$,
  $m_{\chi_1^0} \sim 1/2 m_{A/H}$ resonant annihilation (if exactly *on-peak* too rapid)



- Focus point: $\chi_1^0 \sim 100\%$ higgsino
  off-shell annihilation via h, H, A dominant

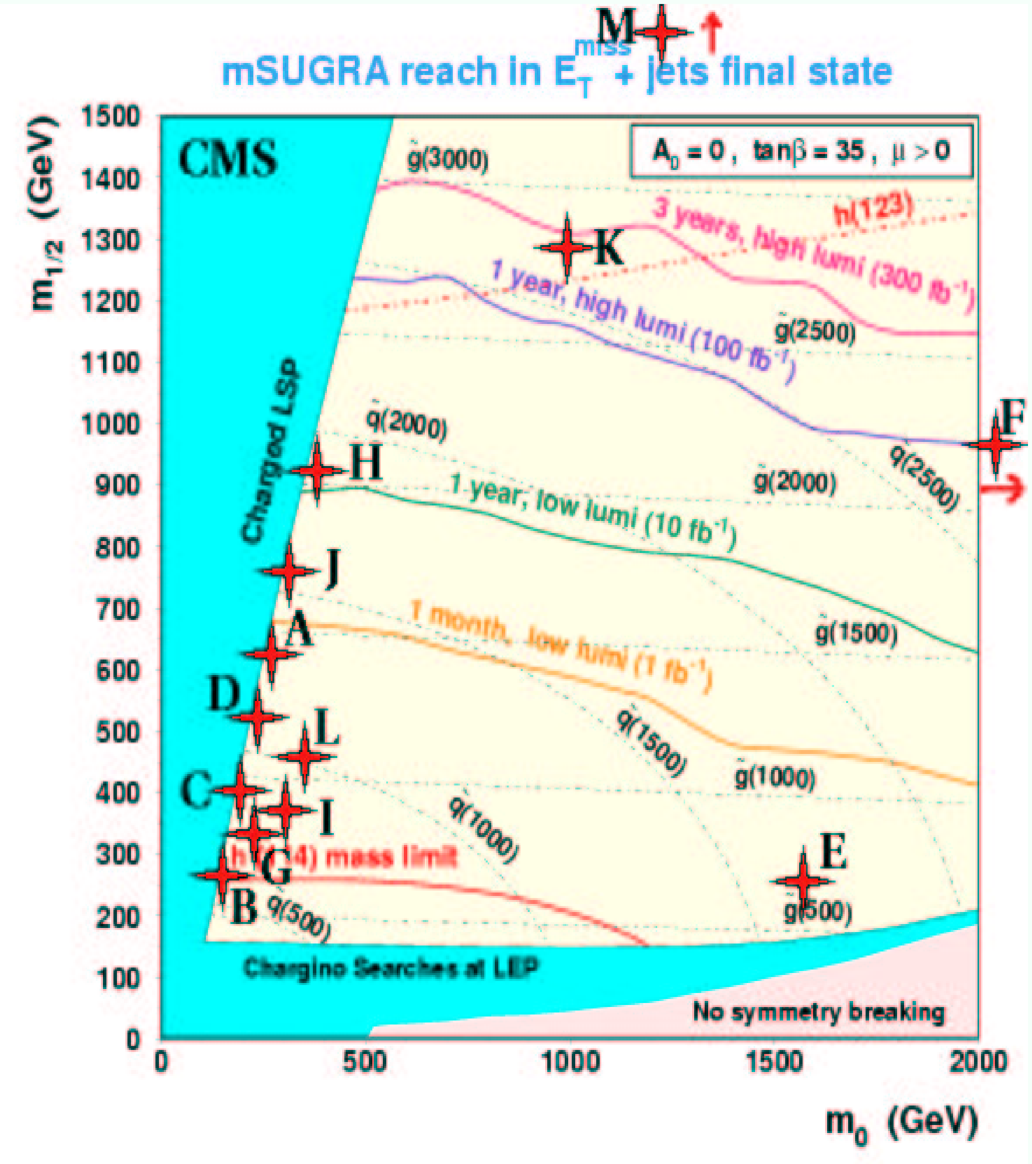






LHC benchmark points

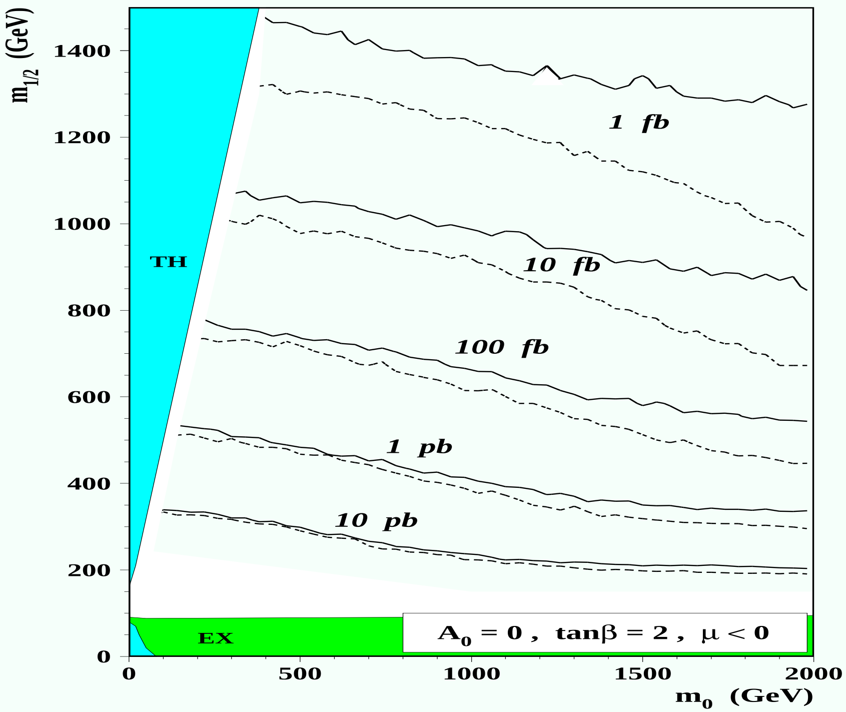
Benchmark points on LHC reach from $\tilde{g}, \tilde{q}$ production (jets+missing E_T)



Point	$m_{1/2}$	m_0	$\tan\beta$	sign(μ)
A	600	140	5	+
B	250	100	10	+
C	400	90	10	+
D	525	125	10	−
E	300	1500	10	+
F	1000	3450	10	+
G	375	120	20	+
H	1500	419	20	+
I	350	180	35	+
J	750	300	35	+
K	1150	1000	35	−
L	450	350	50	+
M	1900	1500	50	+

SUSY discovery @ LHC

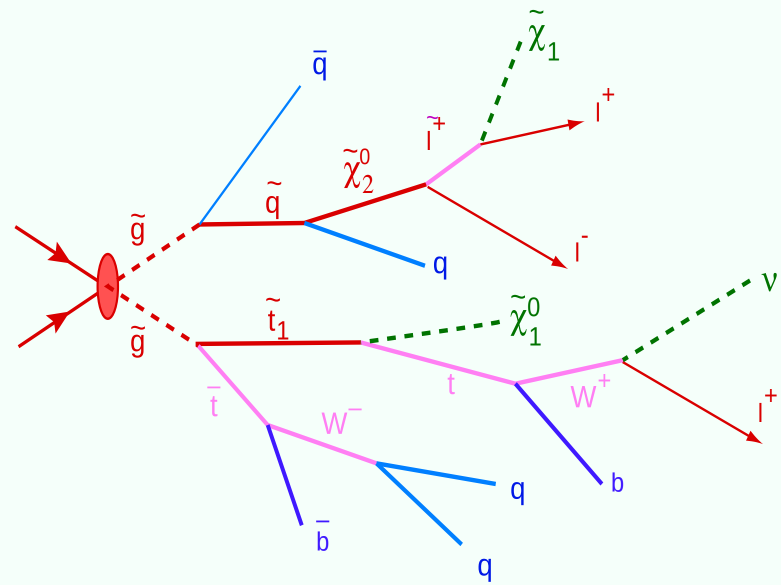
- At LHC dominant production for $\tilde{g}$ and $\tilde{q}$
- Strong production $\Rightarrow$ huge cross section!



- Almost insensitive to $\tan\beta$ and sign(μ)
- Some reference:
  - $\sigma(t\bar{t}) \sim 1$ nb
  - $\sigma(Z \to l\nu) \sim 3$ nb
  - At High Level Trigger: Rate(MET+jets)~ 5 Hz

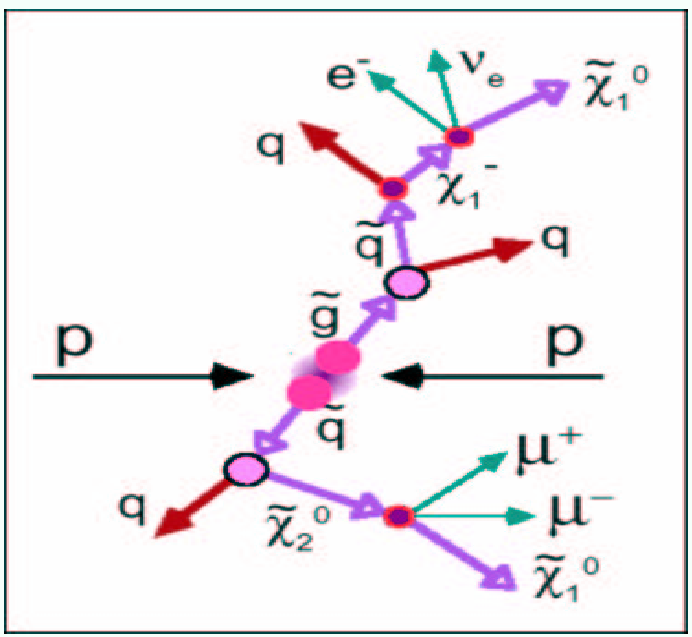
- LHC low luminosity: ($\mathcal{L} = 2$nb^{-1}s^{-1})
- for m_0, $m_{1/2}$ just above limits: SUSY visible at trigger rate!

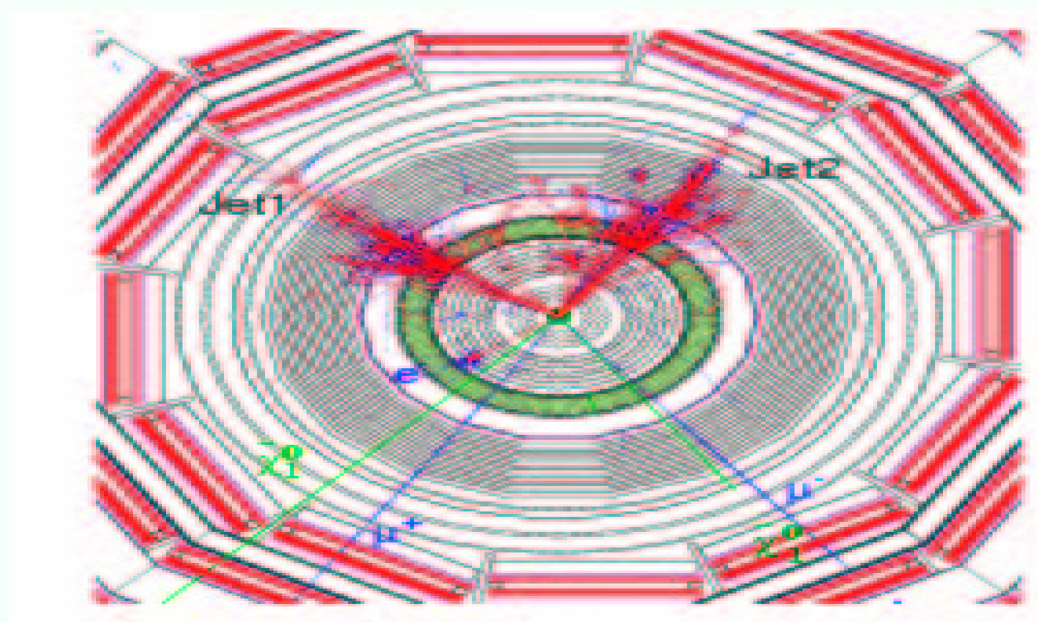
SUSY event topology



Typical SUSY event topology:

- isolated leptons (3)
- b–jets (2)
- jets (4)
- large missing energy





Triggering SUSY events

Trigger strategy is rather simple: many handles (CMS)

- Get maximum trigger efficiency and keep under control trigger rate
- Apply very simple selection to reduce model–dependent bias
- Low lumi:
  - 1 jets $E_T > 180$ GeV & missing $E_T > 123$ GeV
  - 4 jets $E_T > 113$ GeV
  - Efficiency $\epsilon \sim 60 \div 70\%$ for low $M_{\tilde{q}} \sim 400$ GeV
  - Background rate (QCD) ~ 12 Hz
- High lumi:
  - missing $E_T > 239$ GeV
  - 4 jets $E_T > 185$ GeV
  - $\epsilon(M_{\tilde{q}} \sim 2$ TeV$) \sim 75 \div 90\%$
- More complex exclusive trigger possible
- Trigger consider also R_p violating models

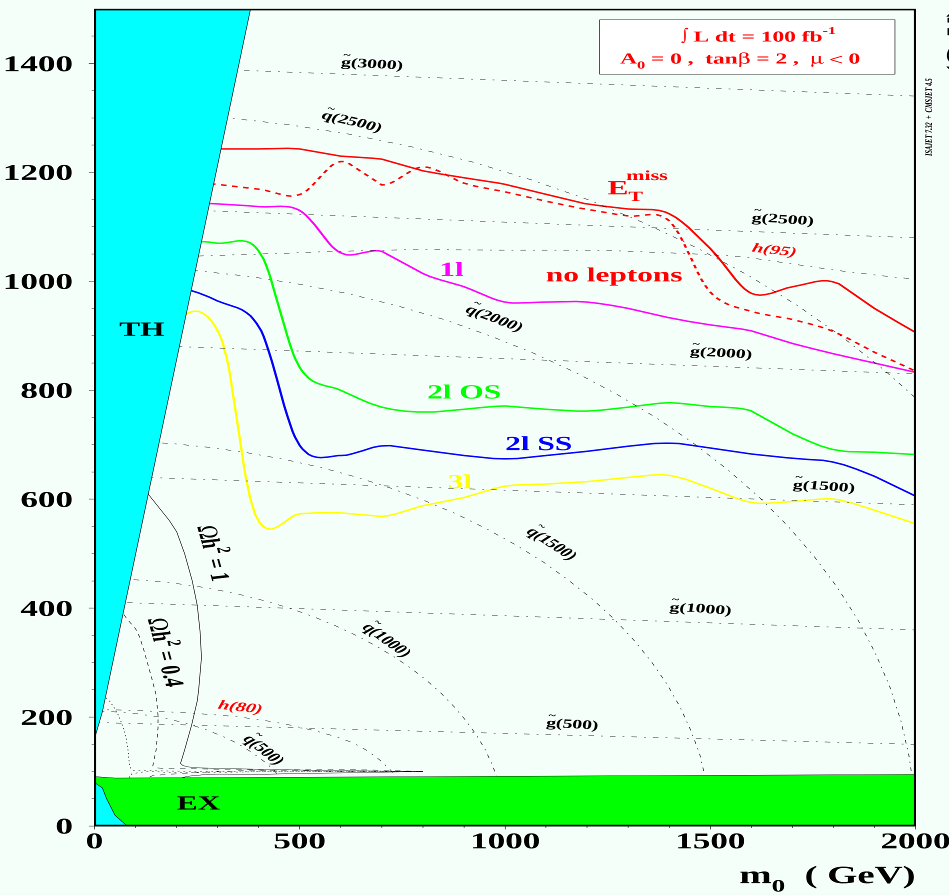
Inclusive SUSY searches

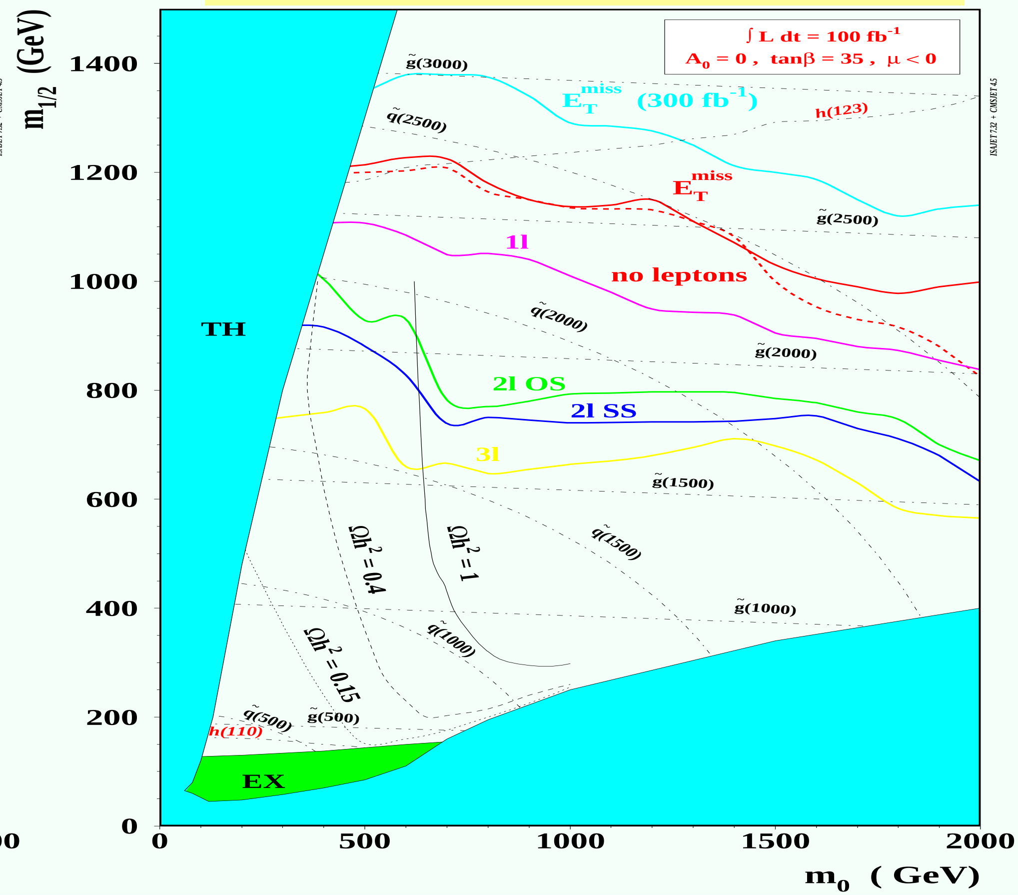
First step: discover SUSY!

Several final states investigated:

Final reach $m_{\tilde{g},\tilde{q}} \sim 2.6 \div 3$ TeV

- E_T^{miss}+jets
- E_T^{miss}+jets+ no leptons
- E_T^{miss}+jets+1 lepton
- E_T^{miss}+jets+2 OS leptons
- E_T^{miss}+jets+2 SS leptons
- E_T^{miss}+jets+3 leptons



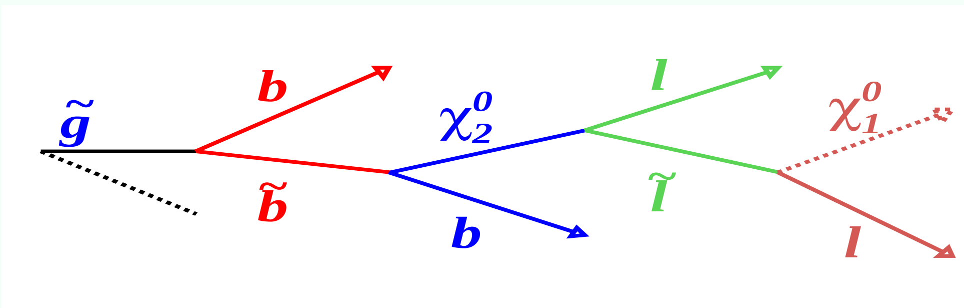


SUSY spectroscopy

Second step: measure sparticle spectrum!

- Use benchmark point **B**:
- $m_0 = 100$ GeV, $m_{1/2} = 250$GeV, $\tan\beta = 10$, $\mu > 0$, $A_0 = 0$
- Most favorable scenario: very light sparticles
- $\sigma^{tot}_{SUSY} \approx 58$pb

Use long decay chains:



- ≥ 2 SFOS isolated leptons
- ≥ 2 $b-$jets
- E_T^{miss}
- Almost SM background free with simple cuts

Start with $\chi_2^0 \rightarrow \chi_1^0 l^+ l^-$ decay

- BR($\chi_2^0 \rightarrow \chi_1^0 l^+ l^-) \approx 0.04\%$
- BR($\chi_2^0 \rightarrow \tilde{l}^{\pm} l^{\mp} \rightarrow \chi_1^0 l^+ l^-) \approx 16.4\%$
- BR($\chi_2^0 \rightarrow \tilde{\tau}^{\pm} \tau^{\mp} \rightarrow \chi_1^0 \tau^+ \tau^-) \approx 83.2\%$

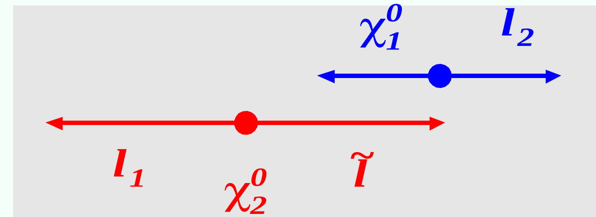
- Final states with $e^{\pm}$ or $\mu^{\pm}$ sizeable
- At larger $\tan\beta$ (*eg* point **G**), BR($\rightarrow \tau^{\pm}) \approx 100\%$ less favorable!

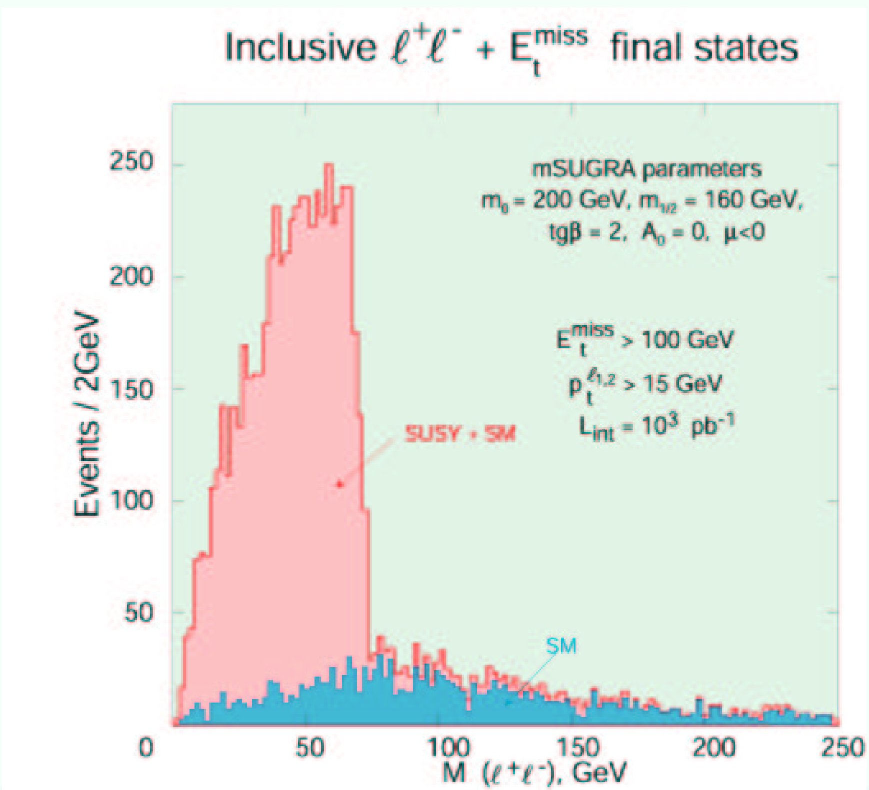
Dilepton mass edge

- Dilepton invariant mass has sharp upper edge
- due to 2 body decay of χ_2^0

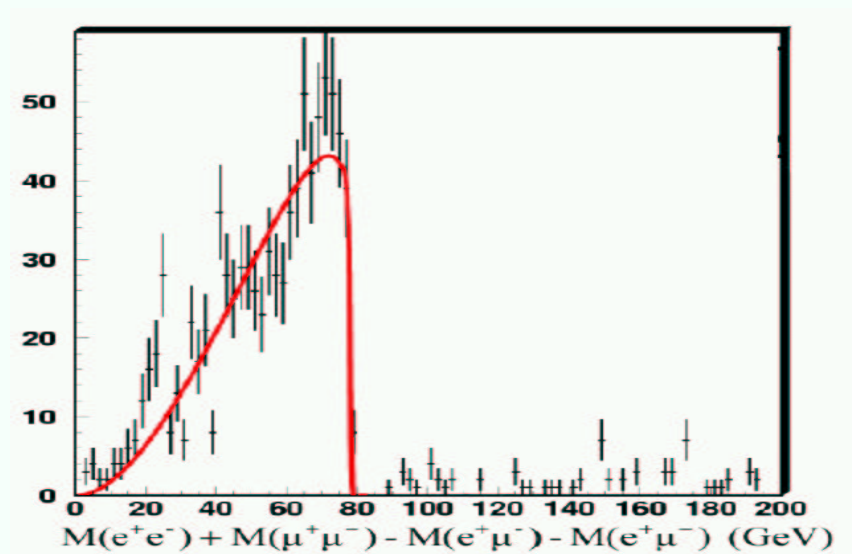
$$M_{ll}^{max} = \frac{1}{m_{\tilde{l}}}\sqrt{\left(m^2_{\chi_2^0} - m^2_{\tilde{l}}\right)\left(m^2_{\tilde{l}} - m^2_{\chi_1^0}\right)}$$

When $l^{\pm}$ back to back in χ_2^0 rest frame





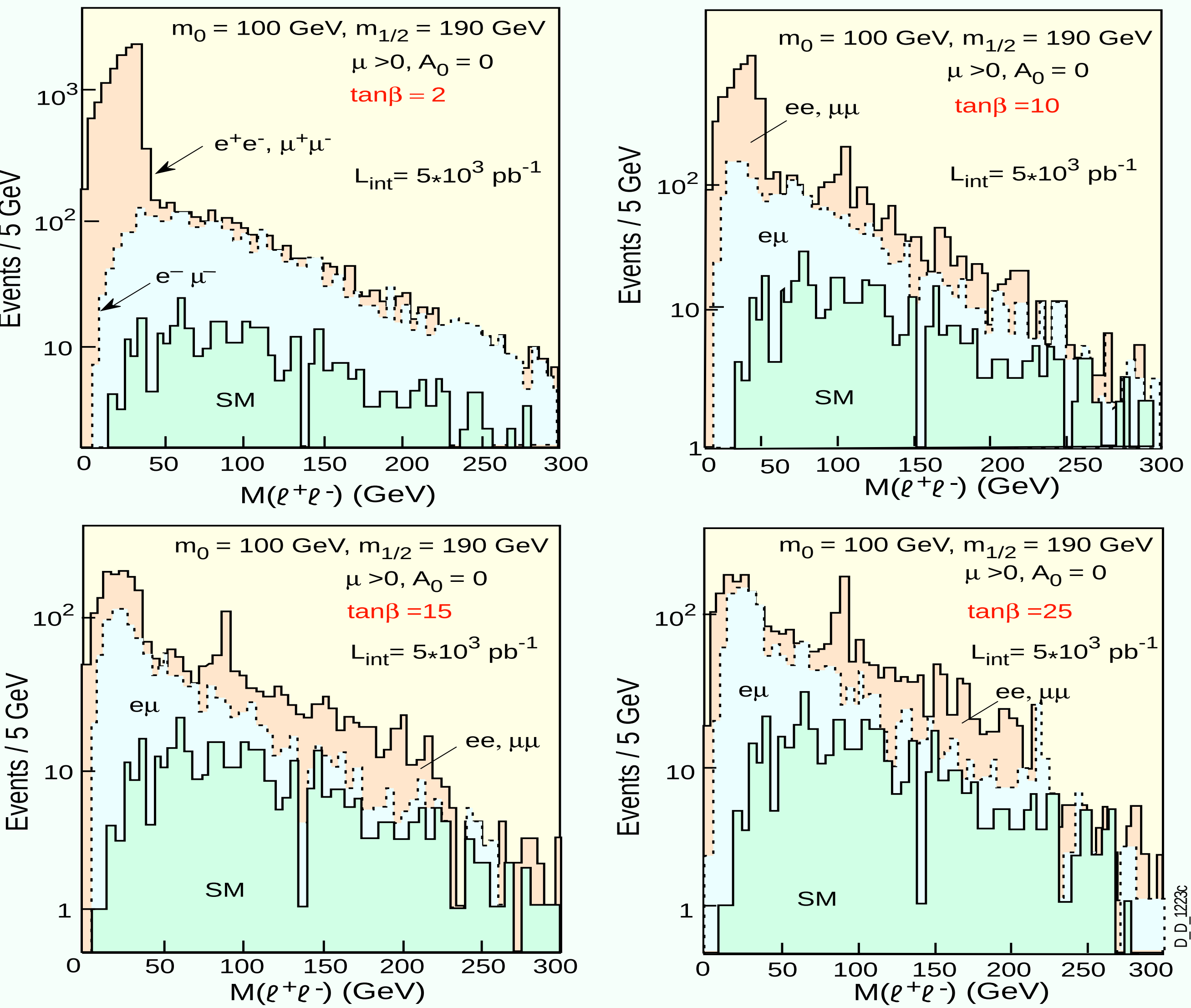
Subtract OFOS leptons reduce background (mostly from SUSY)



Dilepton mass edge vs $\tan\beta$

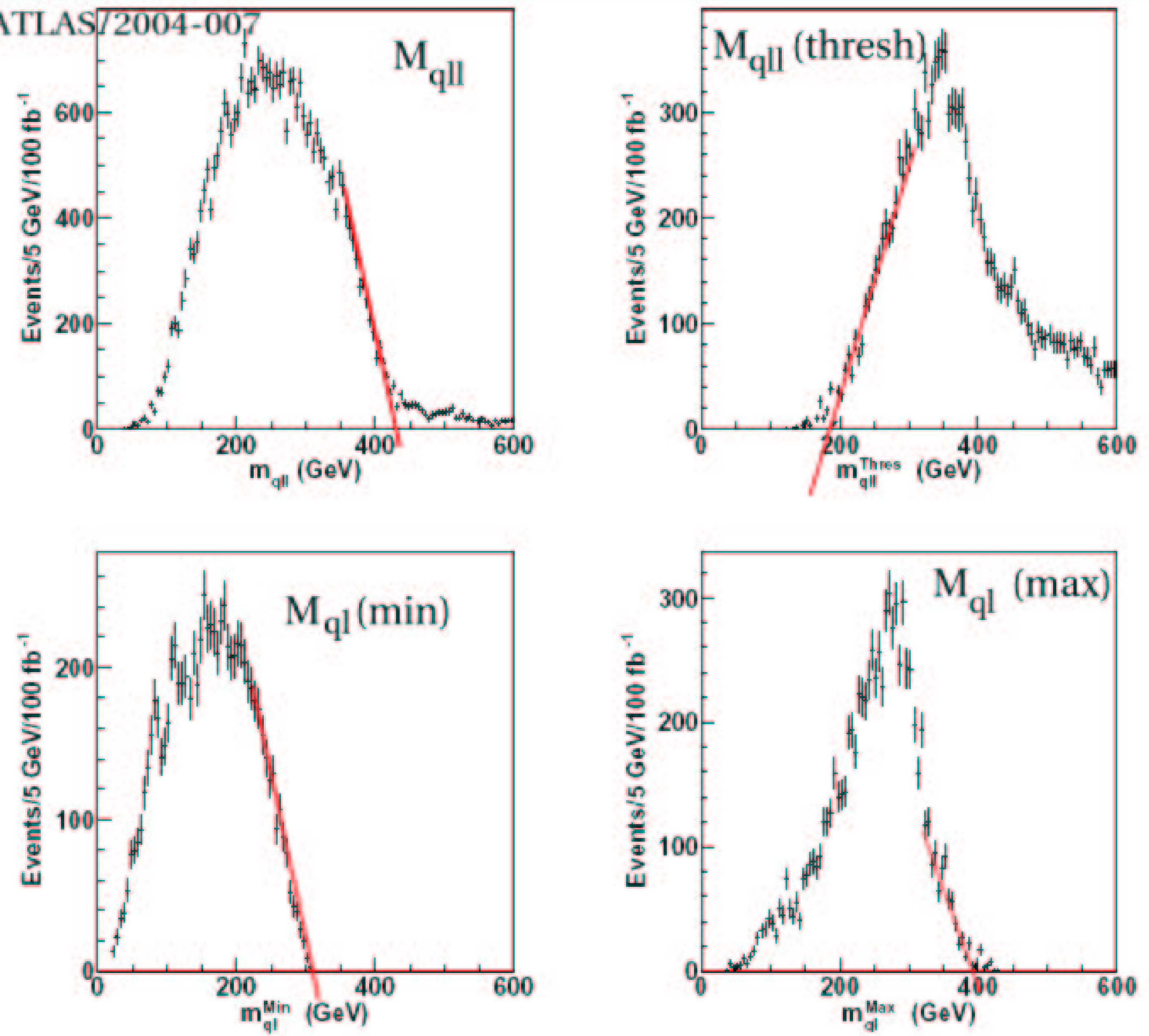
Dilepton invariant mass vs tan β

at fixed $m_0 = 100$ GeV, $m_{1/2} = 190$ GeV, $A_0 = 0$, $\mu < 0$



- Evidence for a M_{ll} edge $\Rightarrow$ SUSY!
- Structure less evident with increasing $\tan\beta$: $\chi_2^0 \rightarrow \chi_1^0\tau^{\pm}$ dominates

Other edges



Edges present for other invariant mass distribution

- M_{qll}
- M_{ql}^{min}
- M_{ql}^{max}
- M_{qll}^{thres}

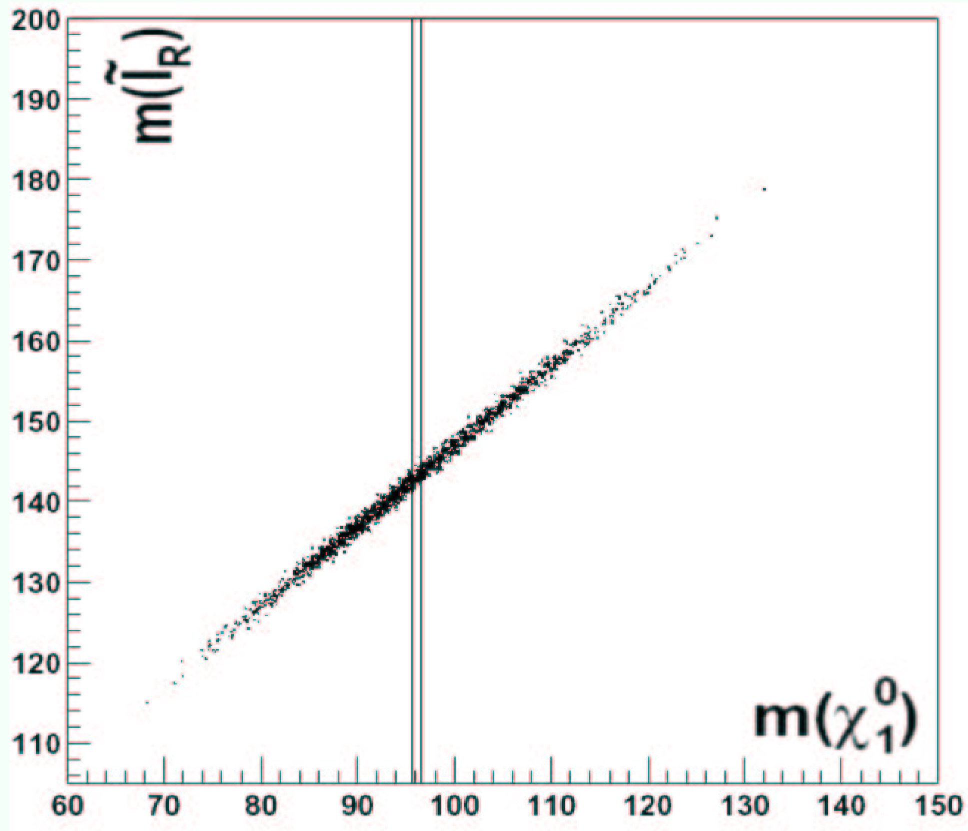
All functions of $m_{\tilde{p}}^{2\,art}$ differences

Error on endpoints: statistical, energy scale, fit model

Fitted values agree well with MC input

Sparticle masses

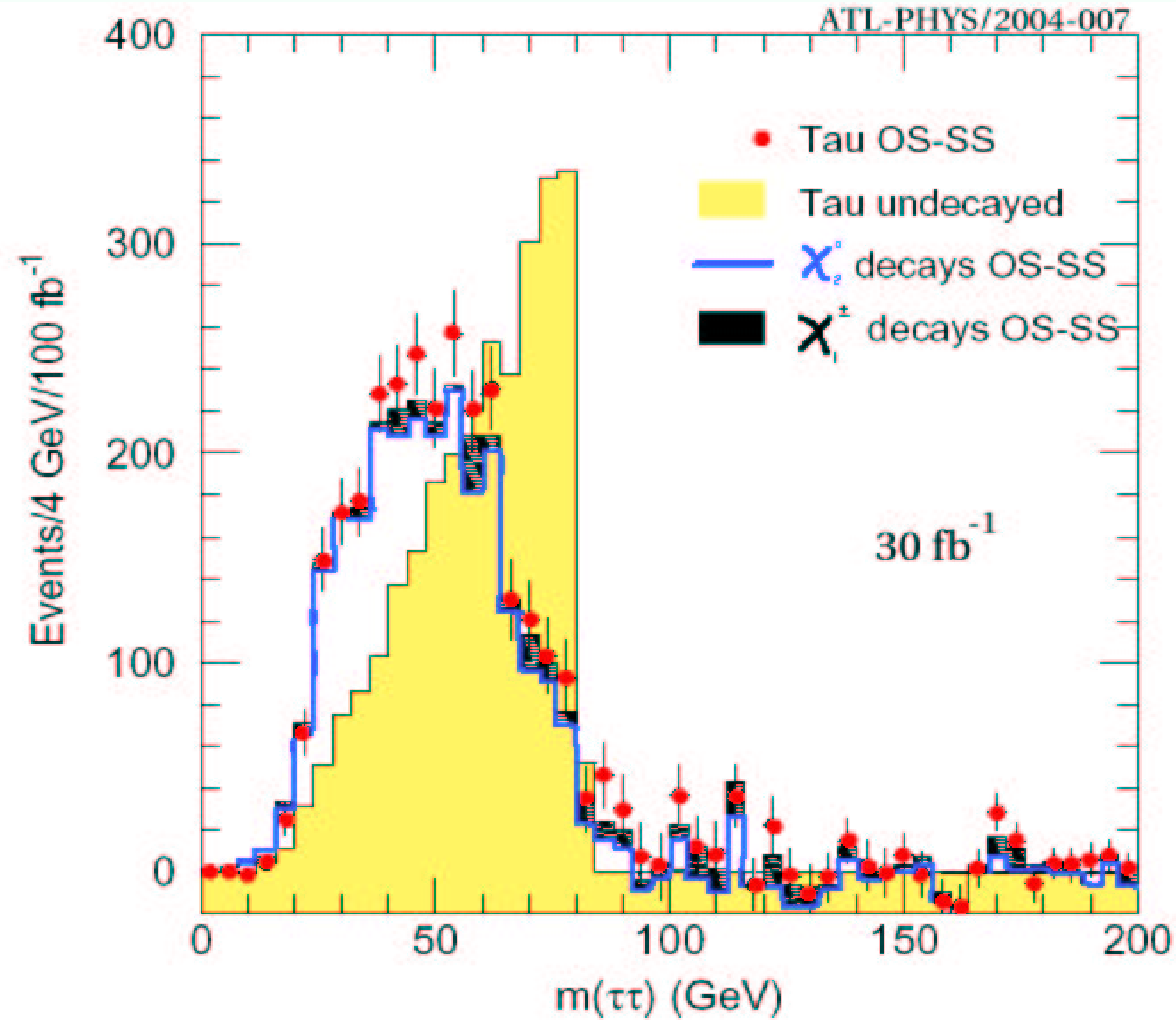
- Use 6 edge measurements: $M_{\tilde{q}_L}, M_{\tilde{b}}, M_{\chi_1^0}, M_{\chi_2^0}, M_{\tilde{l}_R}$
- Edges depends on mass difference $\Rightarrow$ strong dependencies!
- Measure mass relation as a function of $M_{\chi_1^0}$ to $\sim 1\%$
- $M_{\chi_1^0}$ determined to $\sim\ 10\%$
- If $M_{\chi_1^0}$ from extra LHC (*eg* LC) $\Rightarrow$ fix mass scale for all other sparticles!
- Use to measure heavier sparticle masses



$\tilde{\tau}$ reconstruction

- At point **B** dominant χ_2^0 decay mode into $\tilde{\tau}\tau$ ($\sim 80\%$)
- At higher $\tan\beta$ (eg point **G**, point **I**) BR higher

- Study final state with τs
- Use τ hadronic decay: $\tau-$tagged jets
- Subtract same sign τ's to reduce SUSY background
- SM background small
- Edge on $M_{\tau}{}^{\tau}$ invariant mass partially spoiled by ν_τ's
- Distribution sensitive to edge position

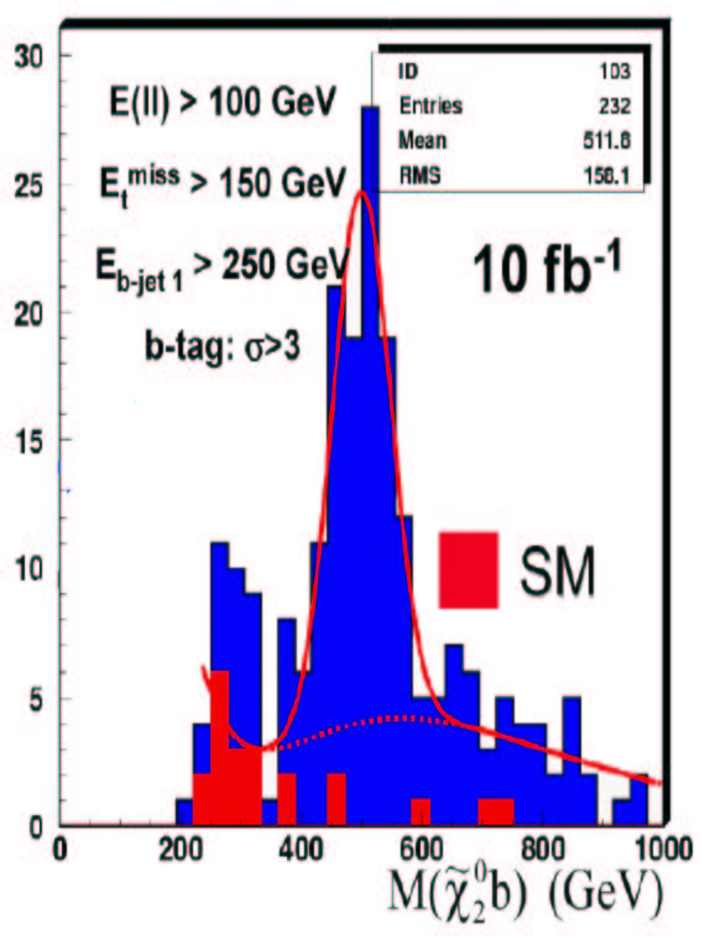


Sbottom reconstruction

- Near the $M_l{}^l$ edge:

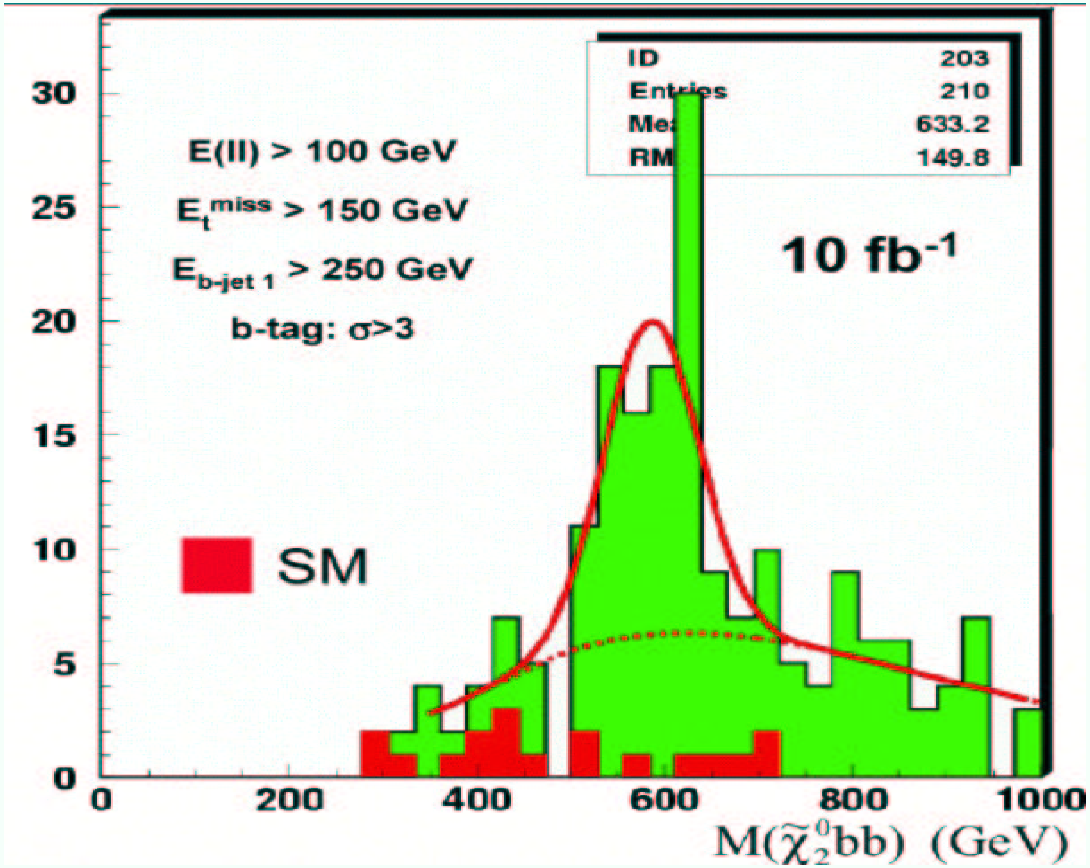
$$\vec{p}_{\chi_2^0} = \left(1 + \frac{M_{\chi_1^0}}{M_{ll}}\right)\vec{p}_{ll}$$

- Need to know $M_{\chi_1^0}$!
- Add most energetic $b-$jet to reconstruct sbottom
- Fit result: $M_{\chi_2^0 b} = 500 \pm 7$ GeV
- Generated: $M_{\tilde{b}_1} = 496$ GeV, $M_{\tilde{b}_2} = 524$ GeV
- With full statistics (300 fb^{-1}) possible to resolve $\tilde{b}_1$ and $\tilde{b}_2$



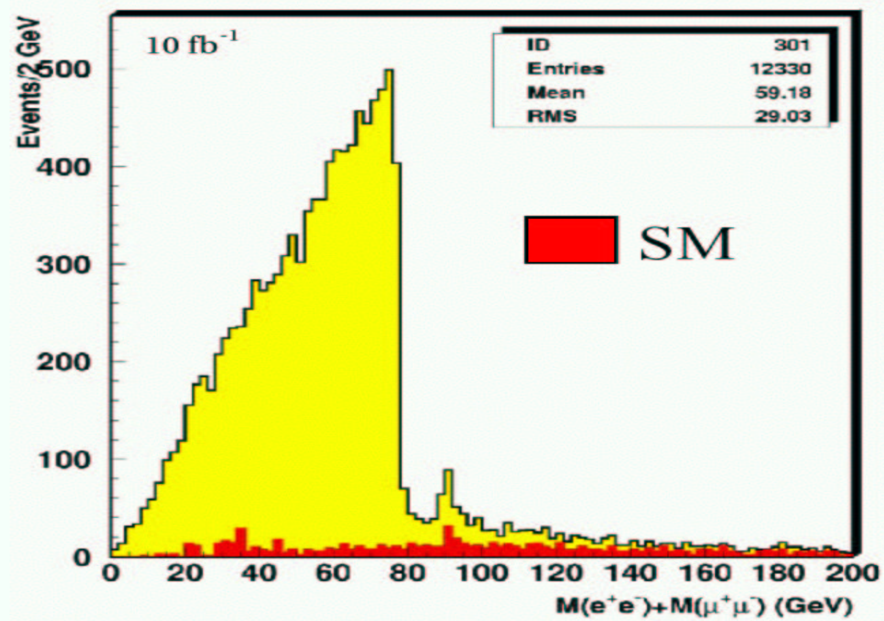
Gluino reconstruction

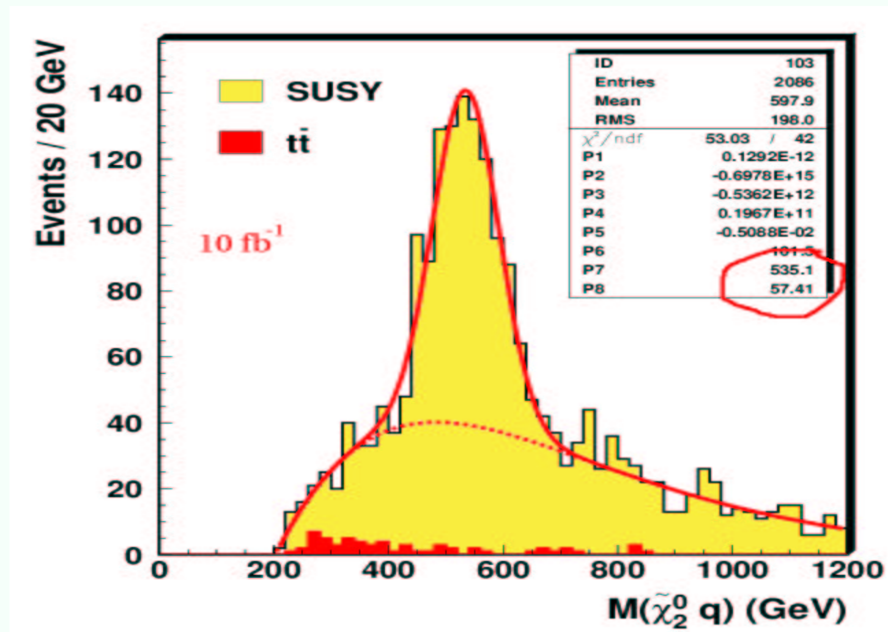
- Combine $\tilde{b}$ with $b-$jet
- Add other $b-$jets (closest in ϕ)
- Get gluino mass peak!
- Fit result: $M_{\chi_2^0 bb} = 594 \pm 7$ GeV
- Generated: $M_{\tilde{g}} = 596$ GeV



Squark reconstruction

- Same procedure also for non b squark ($\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}$)
- Use non $b-$jets
- Higer statistics!
- $\tilde{q}$ mass peak well visible with just 1 fb^{-1}
- Higer combinatorial background
  - Fit result: $M_{\chi_2^0 q} = 535 \pm 3$ GeV
  - Generated:
    - $M_{\tilde{u}_L} = M_{\tilde{c}_L} = 537$ GeV
    - $M_{\tilde{d}_L} = M_{\tilde{s}_L} = 542$ GeV





Mass Relation Method

Alternative approach (ATL-PHYS/2003-039)

Use same decay chain

$$\tilde{g} \rightarrow \tilde{b}b \rightarrow \chi_2^0 bb \rightarrow \tilde{l}bbl \rightarrow \chi_1^0 bbll$$

For each event set of kinematical equations:

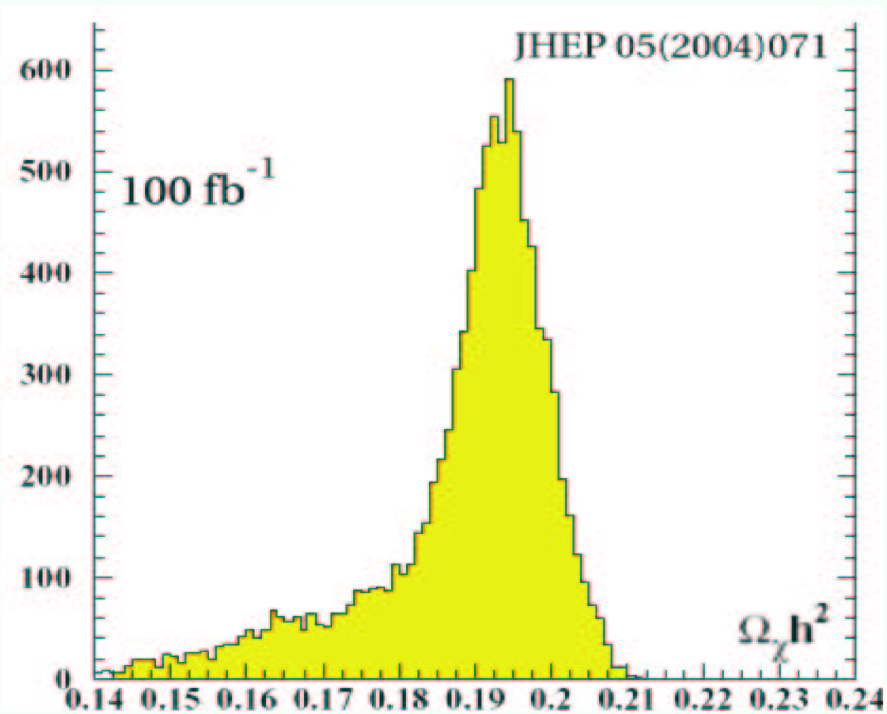
$$\begin{aligned}
m^2_{\chi_1^0} &= p^2_{\chi_1^0} \\
m^2_{\tilde{l}} &= (p_{\chi_1^0} + p_{l_1})^2 \\
m^2_{\chi_2^0} &= (p_{\chi_1^0} + p_{l_1} + p_{l_2})^2 \\
m^2_{\tilde{b}} &= (p_{\chi_1^0} + p_{l_1} + p_{l_2} + p_{b_1})^2 \\
m^2_{\tilde{g}} &= (p_{\chi_1^0} + p_{l_1} + p_{l_2} + p_{b_1} + p_{b_2})^2
\end{aligned}$$

- 5 equations
- 9 unknowns:
  - 5 masses
  - χ_1^0 $4-$momentum

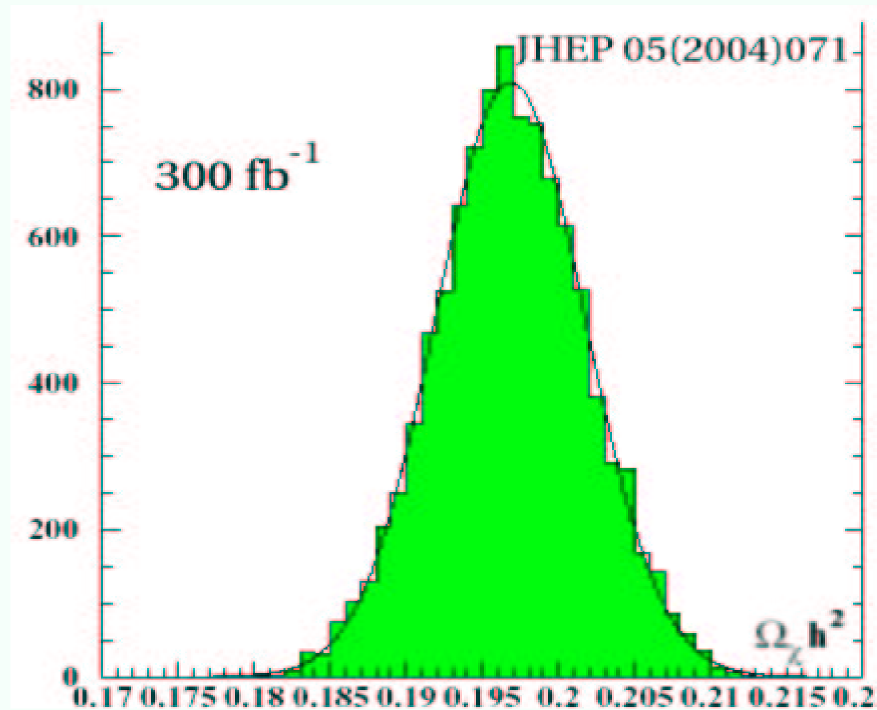
- The masses are the same for all the events!
- With 5 events 25 equation and 25 unknowns (5(m) $+ 5 \times 4$ (p))
- Use all events (not only near edge): increase statistics
- Don't need to know $m_{\chi_1^0}$

Measuring Dark Matter

- Model–dependent mSUGRA fit to all measurements (like SM at LEP)
- Scan on a grid of SUSY models, get best model by χ^2 comparison
- Deduce LSP mass and relic density $\Omega_\chi h^2$
- Generate many simulated experiments for all measurements and expected uncertainties



- Tail at 100 fb^{-1} $\tilde{b}_1, \tilde{b}_2$ not resolved



- Uncertainty $\sigma(\Omega_\chi h^2)/\Omega_\chi h^2 \sim 3\%$
- $\Omega_\chi h^2 = 0.197 \pm 0.003$

More difficult cases

Result presented for **B**: most favourably!

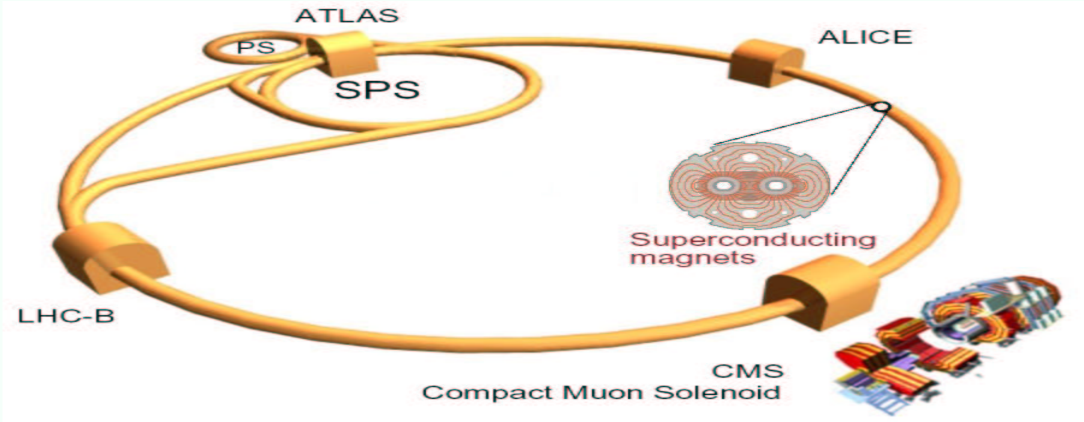
- Bulk region:
  - **G** like **B** but BR$(\chi_2^0 \to \chi_1^0 ll) \approx 2.3\%$ (was 16.4%) and σ smaller (~ 8 pb vs ~ 58 pb)
  - Borderline even with final LHC statistics
  - **I** BR$(\chi_2^0 \to \chi_1^0 \tau\tau) \sim 100\%$!
  - Need work to fully exploit τ's final state
- Coannihilation tail
  - **D,J,L**: BR$(\chi_2^0 \to \chi_1^0 \tau\tau) \sim 100\%$
  - **A,C,H**: similar to **B** but $10 \div 100 \times \int \mathcal{L} dt$
- Focus points and Rapid annihilation funnels
  - $M_{\tilde{g},\tilde{q}}$ very high
  - (Focus Points) Even heavier with with higher M_{top}! ($M_{top} = 180$ GeV D0)
  - Only lighter scalar Higgs h visible at LHC

Conclusion

- LHC will discover SUSY (if exist)
- Most favorable mSUGRA in Bulk region: with ~ 100 fb^{-1} sound estimate for Dark Matter
- Less favorable scenarios: need full statistics (~ 300 fb^{-1}) and more work for $\chi_1^0 \to \tau's$ decay
- Focus points, Rapid annihilation funnels: SUSY spectroscopy $\sim$ hopeless! sparticles too heavy
- Caveat: mSUGRA model, R-parity conserved, ...

Conclusion

- LHC will discover SUSY (if exist)
- Most favorable mSUGRA in Bulk region: with ~ 100 fb^{-1} sound estimate for Dark Matter
- Less favorable scenarios: need full statistics (~ 300 fb^{-1}) and more work for $\chi_1^0 \to \tau's$ decay
- Focus points, Rapid annihilation funnels: SUSY spectroscopy $\sim$ hopeless! sparticles too heavy
- Caveat: mSUGRA model, R-parity conserved, ...
- With a bit of luck, it could be that looking inside the largest microscope (LHC)



Conclusion

- LHC will discover SUSY (if exist)
- Most favorable mSUGRA in Bulk region: with ~ 100 fb^{-1} sound estimate for Dark Matter
- Less favorable scenarios: need full statistics (~ 300 fb^{-1}) and more work for $\chi_1^0 \rightarrow \tau' s$ decay
- Focus points, Rapid annihilation funnels: SUSY spectroscopy $\sim$ hopeless! sparticles too heavy
- Caveat: mSUGRA model, R-parity conserved, ...
- With a bit of luck, it could be that looking inside the largest microscope (LHC) we will see the Universe!