SEARCH FOR SUPERSYMMETRY LHC

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Based on review paper in UFN(2004, v.47,643) and CMS Physics TDR, v.2

OUTLINE

- 1. Introduction
- 2. Search for supersymmetry(MSSM model)
- 3. Search for flavour lepton violation in neutralino decays
- 4. Conclusions

1.Introduction

LHC(Large Hadron Collider)

Start: 2008

Two proton beams with total energy

$E = 14$ TeV

Low luminosity stage with $L_{low} = 10^{33}\ cm^{-2}s^{-1}$

Remember: Nev = sigma Lt

with total luminosity $L_t = 10\ fb^{-1}$ per year Remember: 1 fb = $10^{-39}\ cm^2 s^{-1}$

Two big detectors:

CMS(Compact Muon Solenoid)

ATLAS(A Toroidal LHC Apparatus)

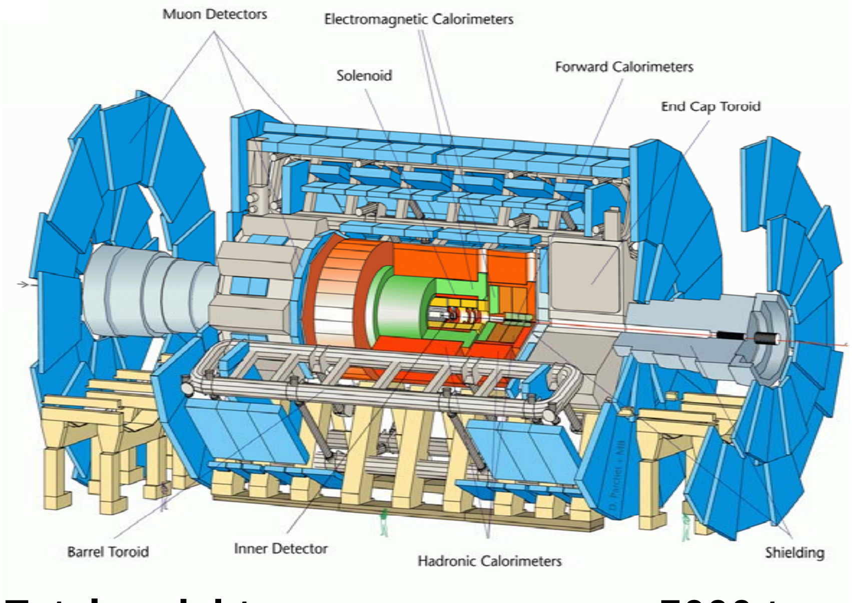
In this talk we review the search for supersymmetry

to be done at LHC(CMS)

ATLAS and CMS Experiments

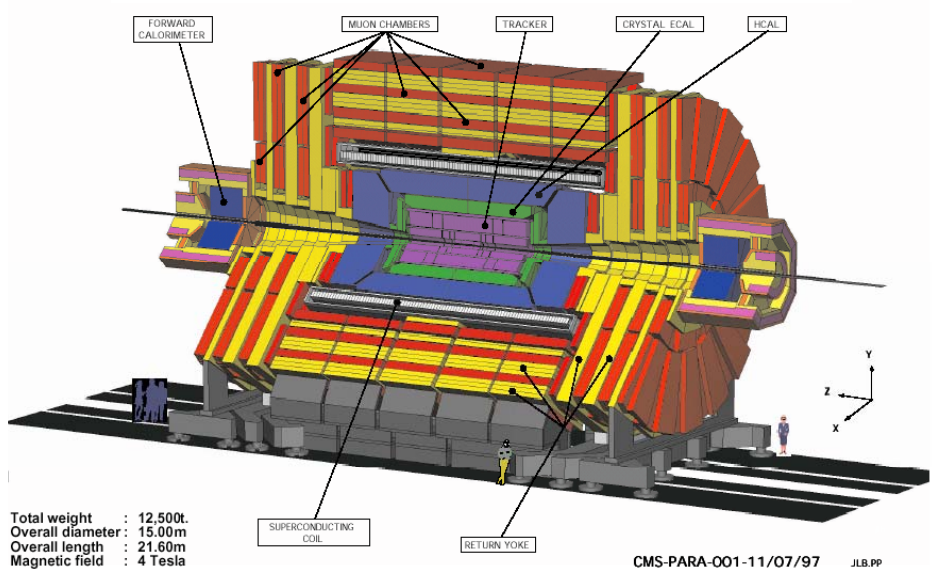
Large general-purpose particle physics detectors

A Large Toroidal LHC ApparatuS



Total weight	**7000 t**
Overall diameter	**25 m**
Barrel toroid length	**26 m**
End-cap end-wall chamber span	**46 m**
Magnetic field	**2 Tesla**

Compact Muon Solenoid



Total weight	**12 500 t**
Overall diameter	**15.00 m**
Overall length	**21.6 m**
Magnetic field	**4 Tesla**

Detector subsystems are designed to measure:
energy and momentum of γ ,e, μ, jets, missing E_T up to a few TeV

3. Search for supersymmetry

- Y.A.Golfand and E.P.Likhtman
- D.V.Volkov and V.P.Akulov
- J.Wess and B.Zumino

- Why we like SUSY?
- elegant theory
- technical solution of the gauge hierarchy problem
- dark matter → LSP is natural candidate
- consistent string theories are superstring
- theories

SUSY, rules of the game

MSSM – minimal supersymmetric standard model based on $SU_c(3) \otimes SU_L(2) \otimes U(1)$ gauge group. For each known particle → superanalog superparticle (the same mass and internal quantum numbers, difference only in spin)

g (gluon, s = 1) → $\tilde{g}$ (gluino , s = ½)

quarks (s = ½) → squarks (s = 0)

leptons (s = ½) → sleptons (s = 0)

gauge bosons (photon, Z- and W-bosons) (s =1) → gaugino (s = ½)

SUSY, rules of the game

H_1, H_2 (two Higgs doublets) (s = 0) → Higgsino (s =1/2)

As a result of gaugino and higgsino mixing

In mass spectrum:

two chargino $\chi_1^{\pm}, \chi_2^{\pm}$ (s = ½)

four neutralino $\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$ (s = ½)

R-parity conservation postulate → to get rid of dangerous terms leading to fast proton decay.

For ordinary particles R = +1

SUSY, rules of the game

For sparticles R = -1

R-parity is conserved by construction

Two important consequences:

1. At supercolliders sparticles are pair produced

2. The lightest sparticle (LSP) is stable: χ_1^0
→ dark matter candidate

- Note that SUSY models with R-parity violation are possible

MSUSGRA model

So SUSY has to be broken and in general masses of sparticles (squarks, sleptons, gluino, gaugino, Higgsino) are arbitrary that makes analysis extremely difficult

For LHC most calculations were done within so called MSUGRA model →

Squark, slepton, higgsino masses are universal at GUT scale → m_0

Gaugino masses also universal→ $m_{1/2}$

Sparticle production

- From cosmology and astrophysics → LSP is weakly interacting neutral particle. As a result LSP escapes from detection (analog of neutrino) → SUSY events are characterized by nonzero transverse missing momentum

  In real life SUSY has to be broken

1. gravity mediated SUSY breaking
2. gauge mediated SUSY breaking

Sparticle production

- At LHC sparticles can be produced via reactions:

$$gg, qq, qg \to \tilde{g}\tilde{g}, \tilde{q}\tilde{g}, \tilde{q}\tilde{q}$$

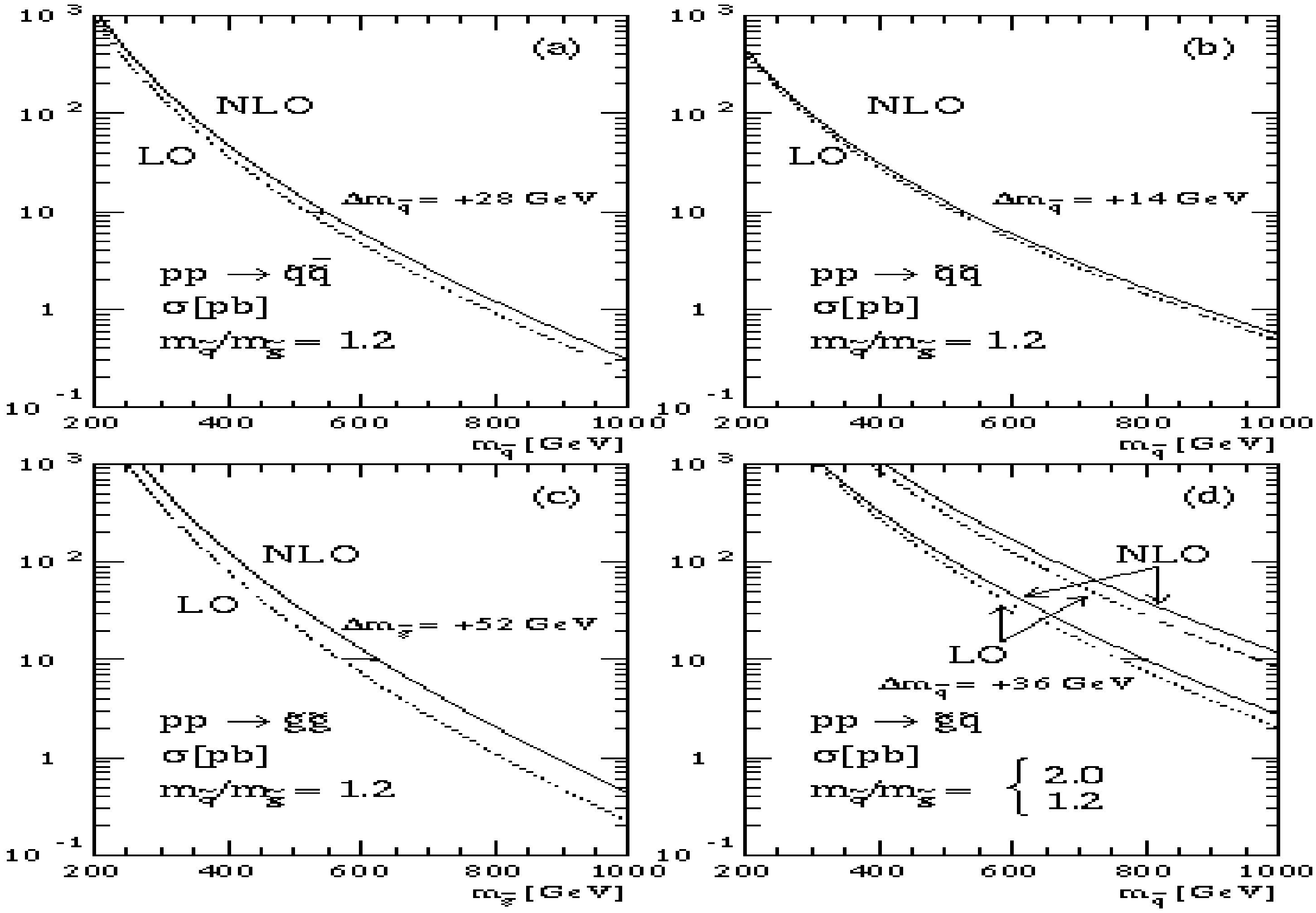
$$qq \to \chi_i^{\pm}\chi_j^{\mp}, \chi_i^{\pm}\chi_j^{0}, \chi_i^{0}\chi_j^{0}$$

$$qq, qg \to \tilde{g}\chi_i^{0}, \tilde{g}\chi_i^{\pm}, \tilde{q}\chi_i^{0}, \tilde{q}\chi_i^{\pm}$$

$$qq \to \tilde{l}\tilde{\nu}, \tilde{l}\tilde{l}, \tilde{\nu}\tilde{\nu}$$

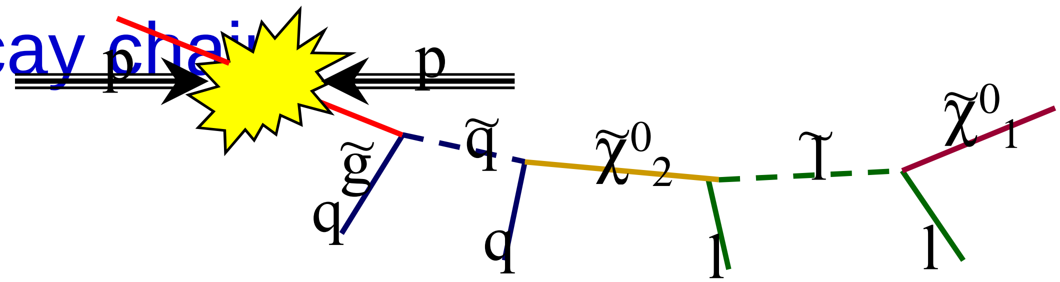
For squarks and gluino with masses O(1) TeV squark and gluino cross sections O(1) pb

The total SUSY cross sections



LHC SUSY Searches

Typical Signature/decay chain



- Strongly interacting sparticles (squarks, gluinos) dominate production.
- Heavier than sleptons, gauginos etc. g cascade decays to LSP.
- Potentially long decay chains and large mass differences
  - **Many high p_T objects observed (leptons, jets, b-jets).**
- If R-Parity conserved LSP (lightest neutraliño in mSUGRA) stable and sparticles pair produced.
  - **Large E_T^{miss} signature (c.f. Wglν).**

SUSY Searches

- Inclusive searches to detect SUSY with first data
- Exclusive studies – performed with more data to determine model parameters e.g. masses etc from end point measurements…

Susy signatures

As a result of squark, gluino decays and chargino and neutralino decays the most interesting signatures for the search for SUSY at LHC are:

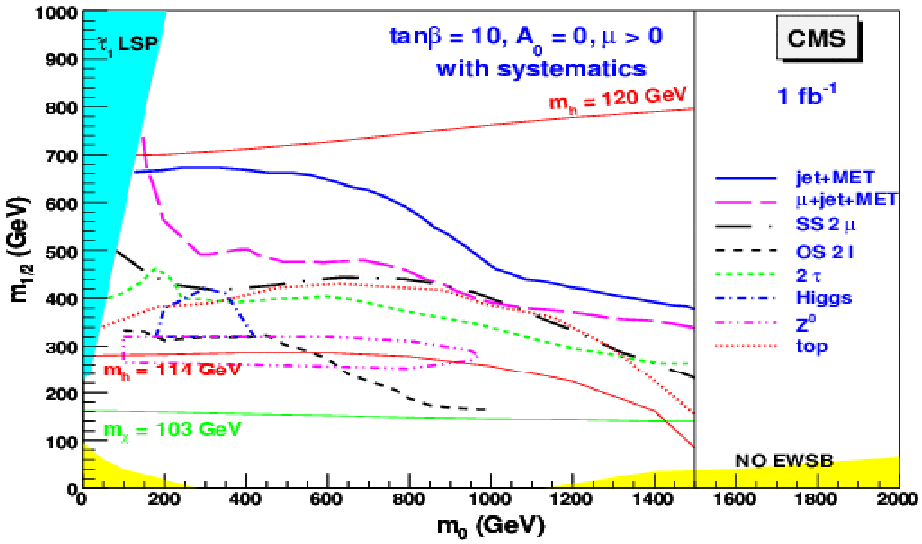
- multijets plus E_T^{miss} events
- 1l plus jets plus E_T^{miss} events
- 2l plus jets plus E_T^{miss} events
- 3l plus jets plus E_T^{miss} events
- 4l plus jets plus E_T^{miss} events

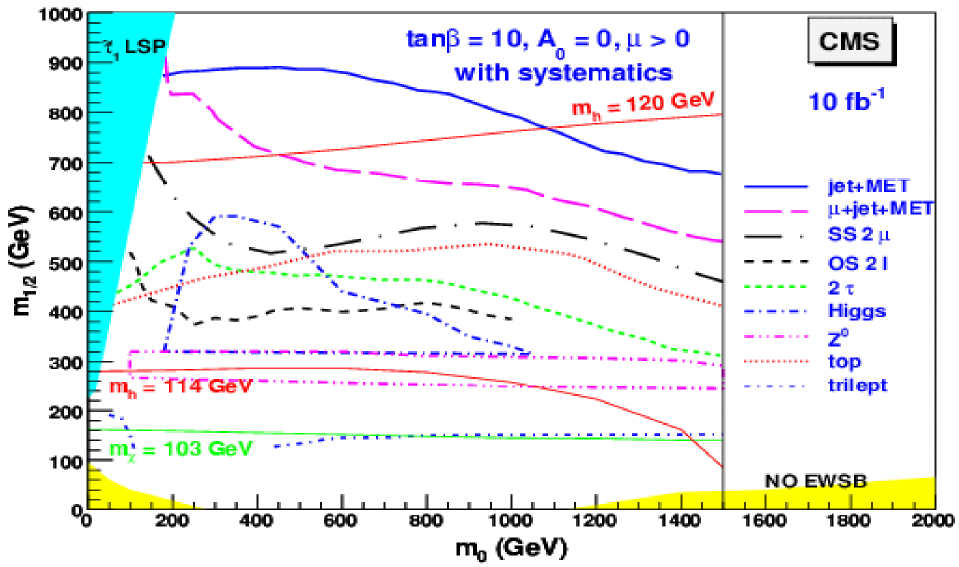
Recent CMS full simulation results

- SUSY signatures:
- 1. E^{miss}_T + n > 2 jets
- For tan(beta) =10, m_0 = 60 GeV, $m_{1/2}$=250
- GeV, sign(mu) = +1
- The 5 sigma discovery is for L_t=2 pb^{-1}

  first 8 hours of LHC work !!!
- 2. The same sign dimuons + E^{miss}_T + n>2
- Jets
- For L_t =10 fb^{-1} SUSY masses up to 1.5 TeV

CMS SUSY discovery potential

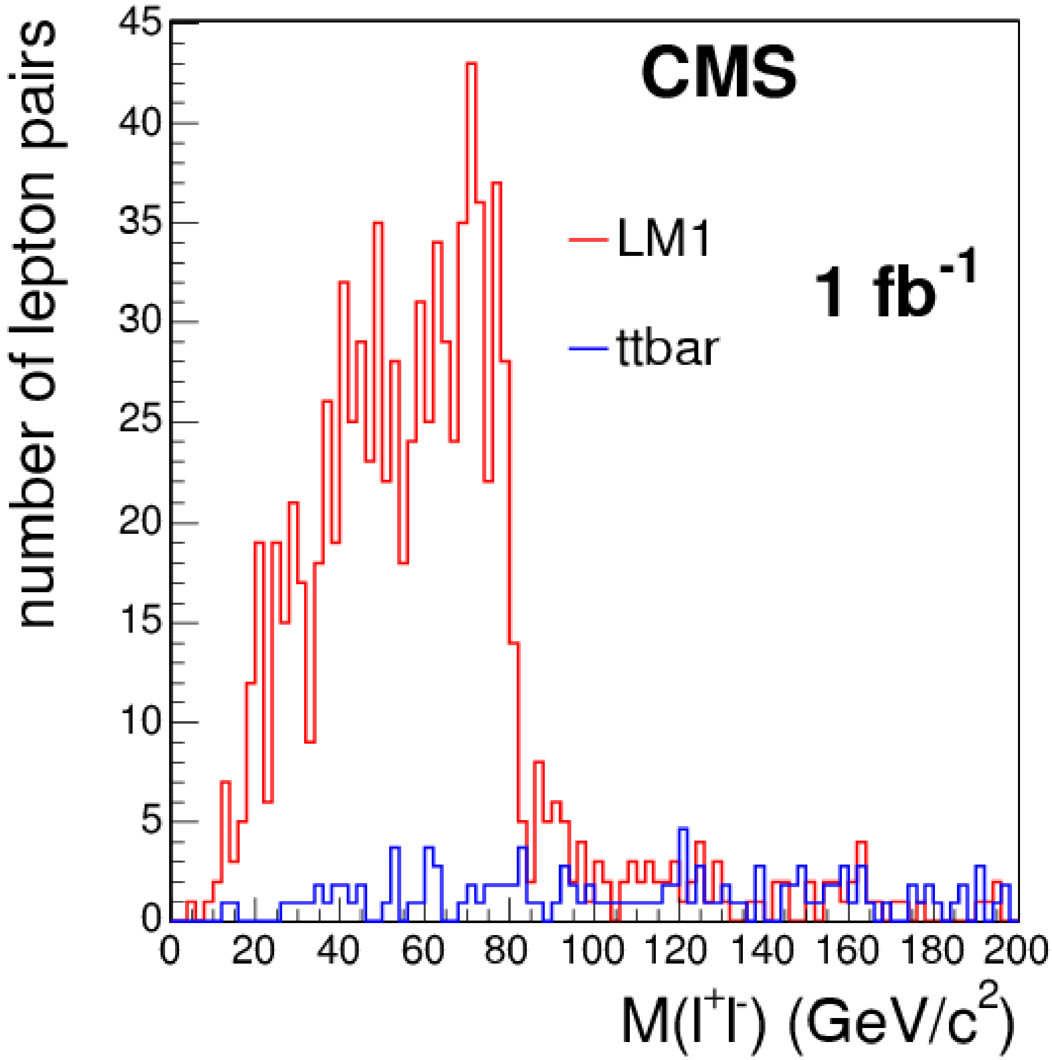




Recent CMS full simulation results

- 2. Single muon + E^{miss}_{T} + n>2 jets
- For L_t = 100 fb^{-1} 5 sigma discovery for
- SUSY masses up to 2TeV.
- 3. Opposite same sign leptons + E^{miss}_{T}
- + n>2 jets
- Basically similar to signature with single muon

Dilepton invariant mass distribution for LM1 test point



LHC SUSY discovery potential

- The main conclusion is that for MSUGRA model LHC will be able to discover SUSY with squark and gluino masses up to 2 .5 TeV for $L_{tot} = 100\ fb^{-1}$
- Chargino and neutralino pairs produced through DY mechanism $pp \to \chi_1^{\pm}\chi_2^{0}$ may be detected through their leptonic decays

$$\chi_1^{\pm}\chi_2^{0} \to lll + E_T^{miss}$$

The signature: 3 isolated leptons without jet activity. LHC is able to detect such DY production with masses up to 200 GeV

Determination of spartile masses

In many cases LHC is able not only to discover SUSY but to determine SUSY breaking parameters (combinations of sparticle masses). For instance, using $l^+ l^-$ invariant mass distribution in reaction

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

it is possible to determine the combination

$$M_{\chi_2^0} - M_{\chi_1^0}$$

as endpoint in edge structure with 2-3 percent accuracy

[redacted]

For $\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0 \ell^+ \ell^-$ find triangular mass distribution with

$$M(\ell^+\ell^-) \leq \sqrt{\frac{\left(M^2(\tilde{\chi}_2^0) - M^2(\tilde{\ell})\right)\left(M^2(\tilde{\ell}) - M^2(\tilde{\chi}_1^0)\right)}{M^2(\tilde{\ell})}}\,.$$

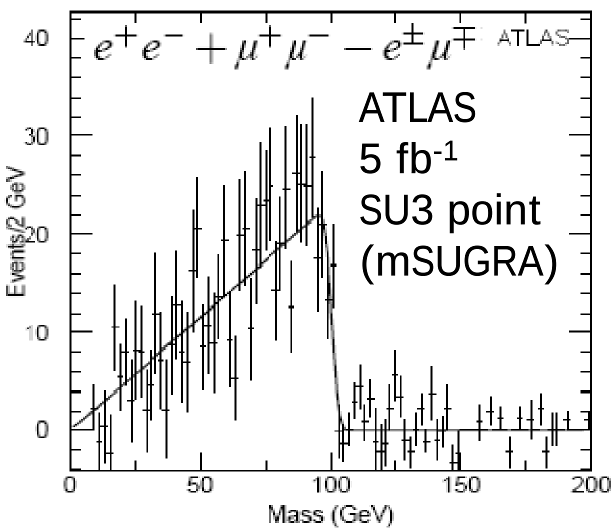
<u>If no flavour violation</u>, we expect same-flavour (ee, mm) pairs only for signal and an equal number of same-flavour and opposite-flavour pairs for background (leptons from two different decay chains, either for SUSY or SM events)

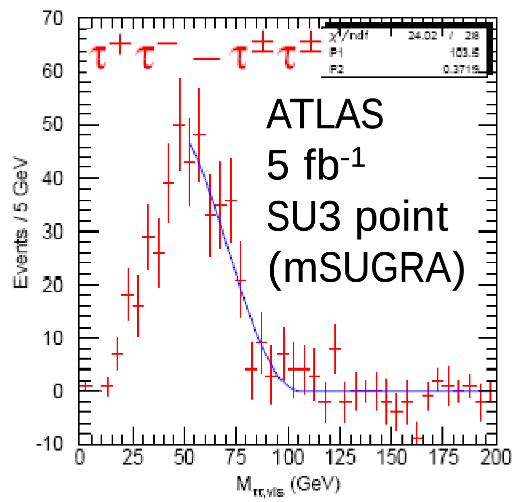
The edge in tt invariant mass can also be measured using the visible decay products of the taus

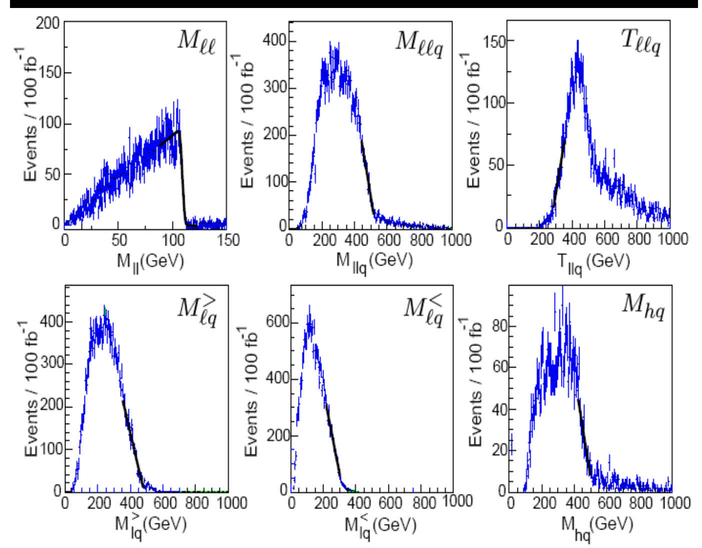
[redacted]

$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\ell}_R^{\pm} \ell^{\mp} q \to \tilde{\chi}_1^0 \ell \;\; \ell \;\; q$$

[redacted]







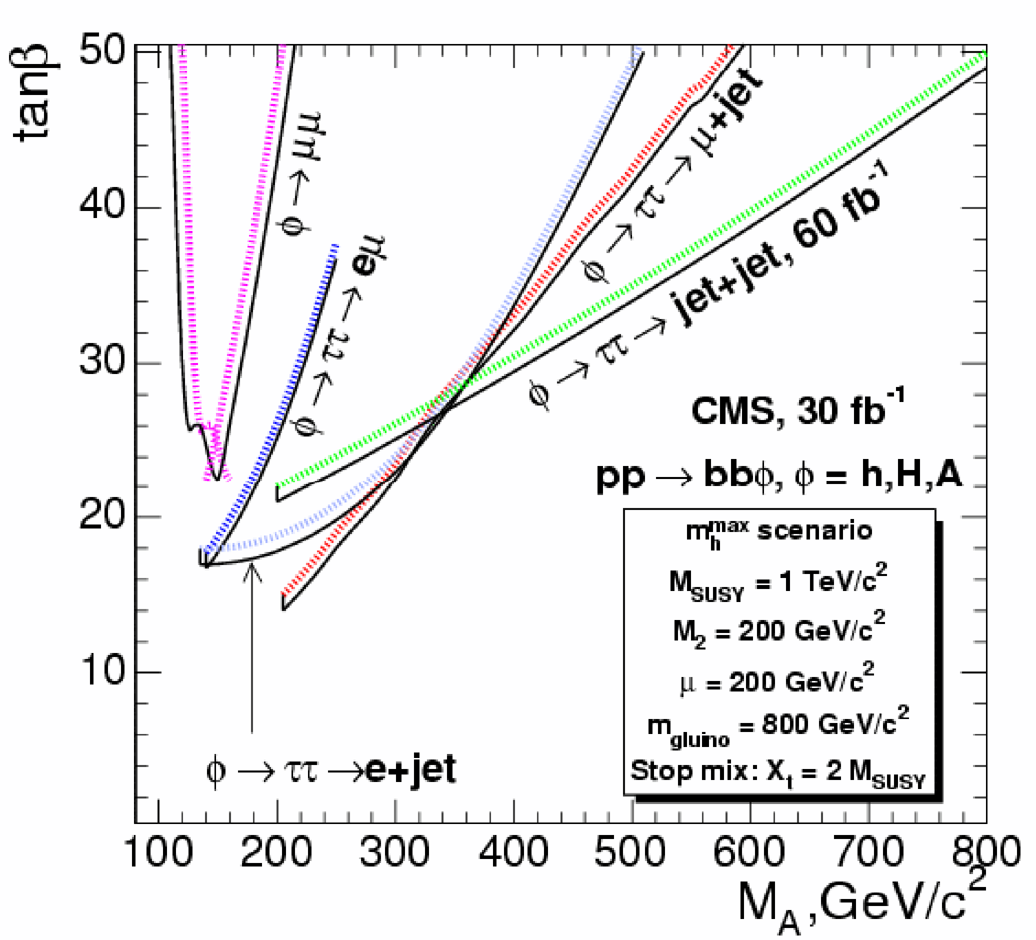
MSSM Higgs boson searches

- In the MSSM there are 4 Higgs bosons
  h, H, A, $H^{+/-}$ the lightest scalar h for
  $m_A > m_h^{max}$ (decoupling regime) is
  SM-like Higgs boson.
  The production of H and A proceeds
  mainly through $gg \rightarrow H/A$ and
  $gg/qq \rightarrow bbH/A$
- At large tan(beta) bbH/A production
  dominates and it is ~90% for tan(beta) >10
  and m_A > 300 GeV

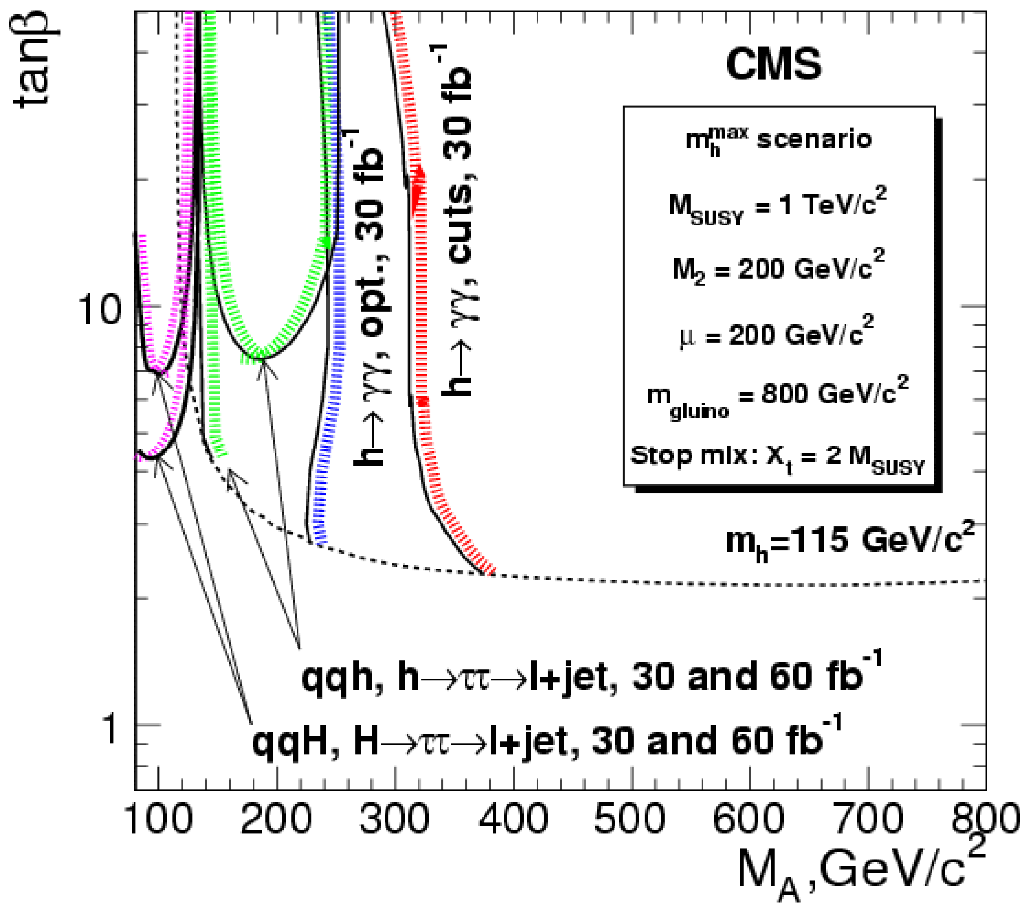
The MSSM Higgs boson signatures

- Light charged Higgs boson $m_{H+/} < m_{top}$ is produced in tt events with $t \rightarrow H^{+/} b$
- The most important production mechanisms for $m_{H+/} > m_{top}$ are
  $gb \rightarrow tH^{+}$, $gg \rightarrow tbH^{+/}$, $qqbar \rightarrow H^{+/}$
  with cross sections $\sim \tan^2$(beta)
- The H,A $\rightarrow$b,bbar decay dominates at large tan(beta). The branching to $\tau^+\tau^-$ is ~10% and to $\mu^+\mu^-$ is about $3{*}10^{-4}$

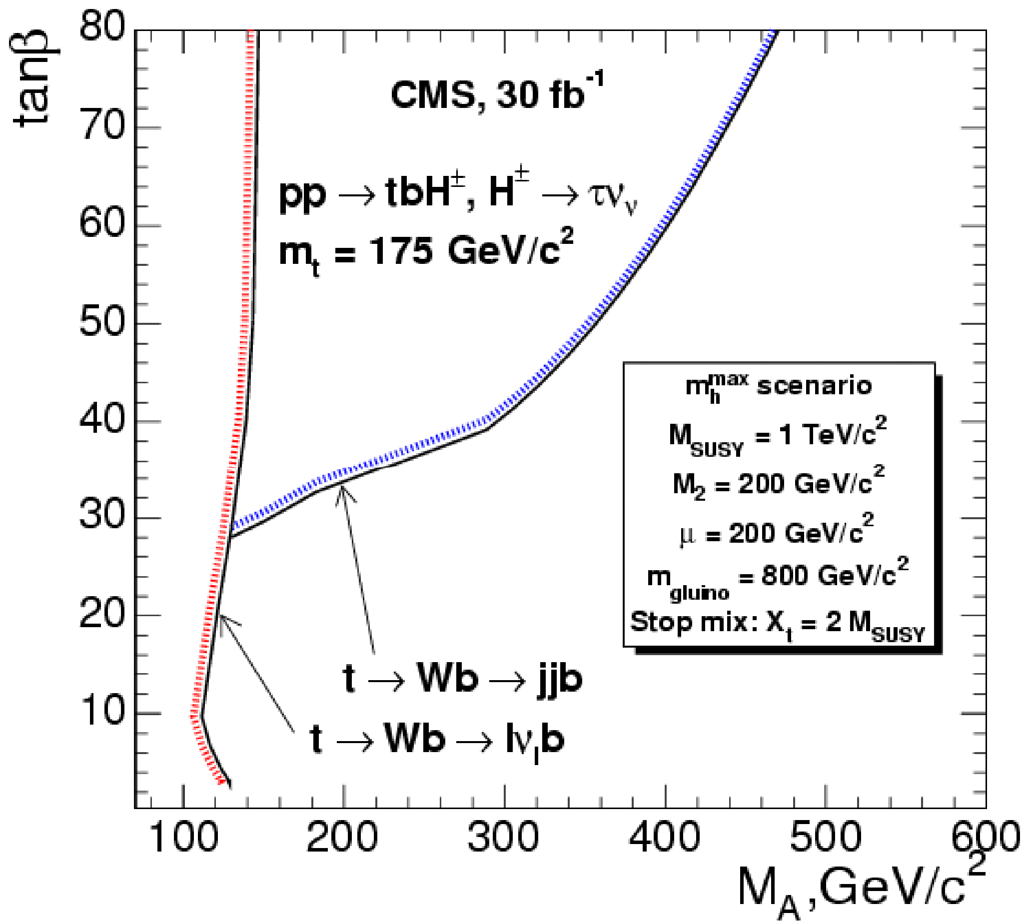
MSSM Higgs boson discovery potential



MSSM light Higgs discovery potential



Charged Higgs discovery potential



Recent CMS full simulation results

- 1. H/A → mu mu decay signature
- For L_t = 30 fb^{-1} 5 sigma discovery for tan(beta) > 25 and $M_{A/H}$ < 250 GeV
- 2. H/A → tau tau decay signature
- For L_t = 30 fb^{-1} 5 sigma discovery for
- tan(beta) > 20 and $M_{A/H}$ < 500 GeV
- 3. H/A →bb channel, looks hopeless.
- The ratio N_S/N_B = 0.03 is small

Recent CMS full simulation results

- 4. A → Zh , Z→ l+l-, h → bb decay sign.
- At L_t = 30 fb^{-1} 5 sigma discovery for

tan(beta) < 3 and 250 GeV <$M_{A/H}$<350 GeV

5.Charged Higgs boson

H+/- → tau+/- nu - the single discovery signature. Discovery possible for tan(beta) > 20 and $M_{A/H}$ <300 GeV for L_t = 30 fb^{-1}

Conclusions

- ✓ CMS & ATLAS have significant discovery potential
- ✓ LHC will be able to discover SUSY with squark and gluino masses up to 2.5 TeV and measures sparticle masses

Conclusions

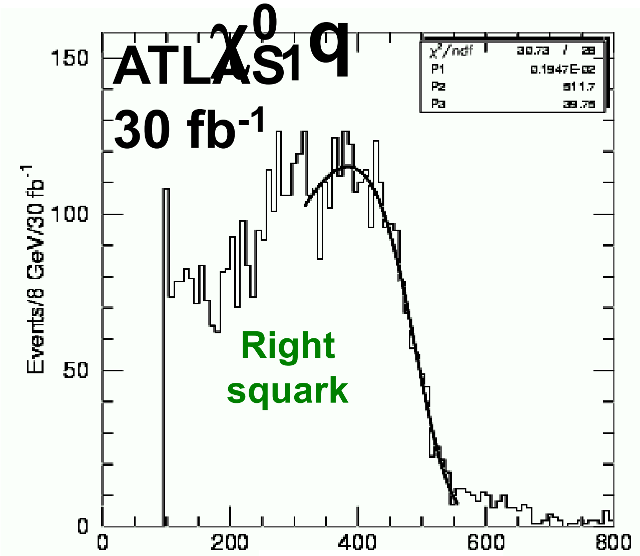
- At any rate after LHC we will know the mechanism of electroweak symmetry breaking (Higgs boson or something more exotic?) and the basic properties of the matter structure at TeV scale.

Backup

- Additional slides

Other mass measurements

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



MT2 (GeV)

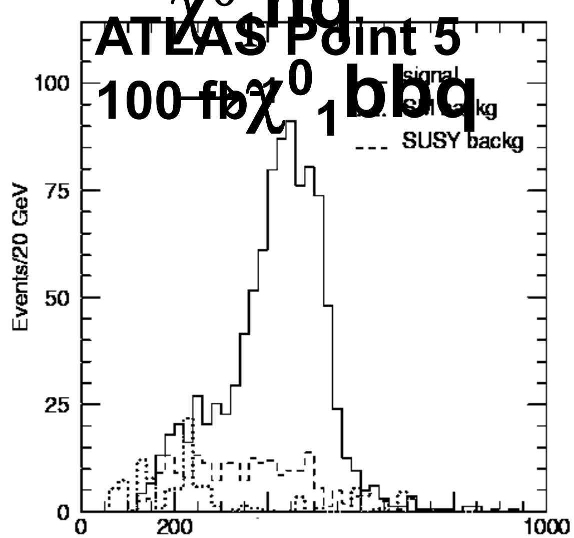
2 hard jets and lots of E_T^{miss}

Reconstruct with

$$M_{T2}^2 = \min_{\not{p}_1 + \not{p}_2 = \not{p}_T} \left[\max \left\{ m_T^2(p_T^{\ell_1}, \not{p}_1), m_T^2(p_T^{\ell_2}, \not{p}_2) \right\} \right]$$

$m(\tilde{q}_R)-m(\chi^0_1) = (424.2 \pm 10.9)$ GeV

$\tilde{q}_L \to \chi^0_2 q \to \chi^0_1 hq \to \chi^0_1 bbq$

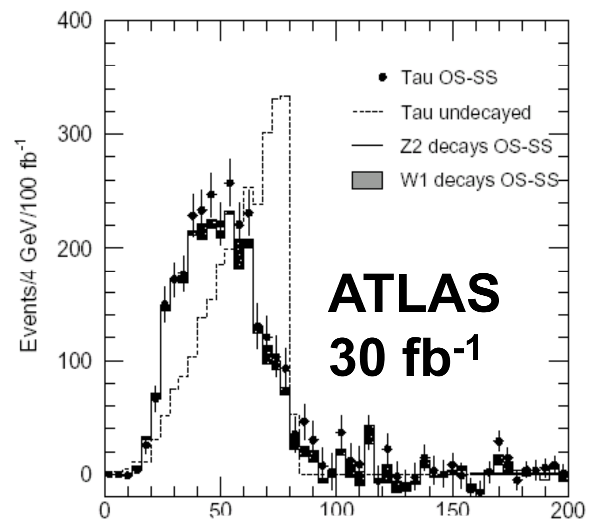


M(bbq) (GeV)

Two body decay of χ^0_2 to higgs and χ^0_1.

Reconstruct higgs mass (2 b-jets) and

$\chi^0_2 \to \tilde{\tau}\tau \to \chi^0_1\ \tau\tau$



M(ττ) (GeV)

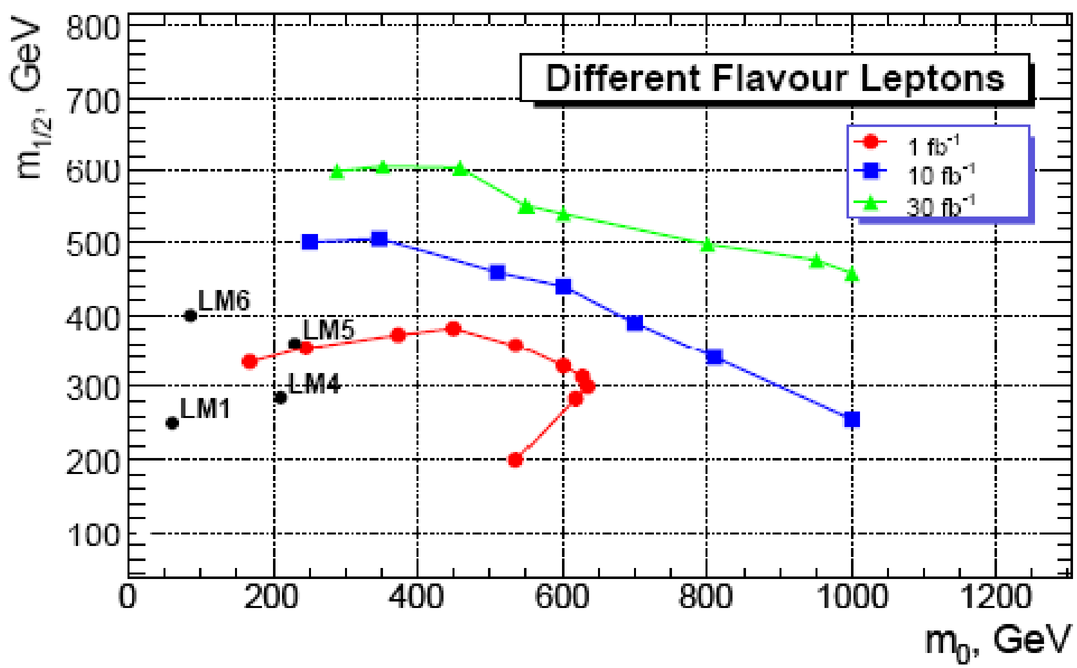
Tau decay dominates neutralino BR at large tanβ.

No sharp edge because of ν, but end-point can still be measured.

Using the $e^{\pm}m^{-}+E^{T}_{miss}$ signature in the search for Supersymmetry and lepton flavour violation in neutralino decay

A search was performed using the CMS detector simulation. The optimal cut set was found to be:

- Isolated leptons with p_t > 20 GeV
- EtMiss > 300 GeV



[redacted]

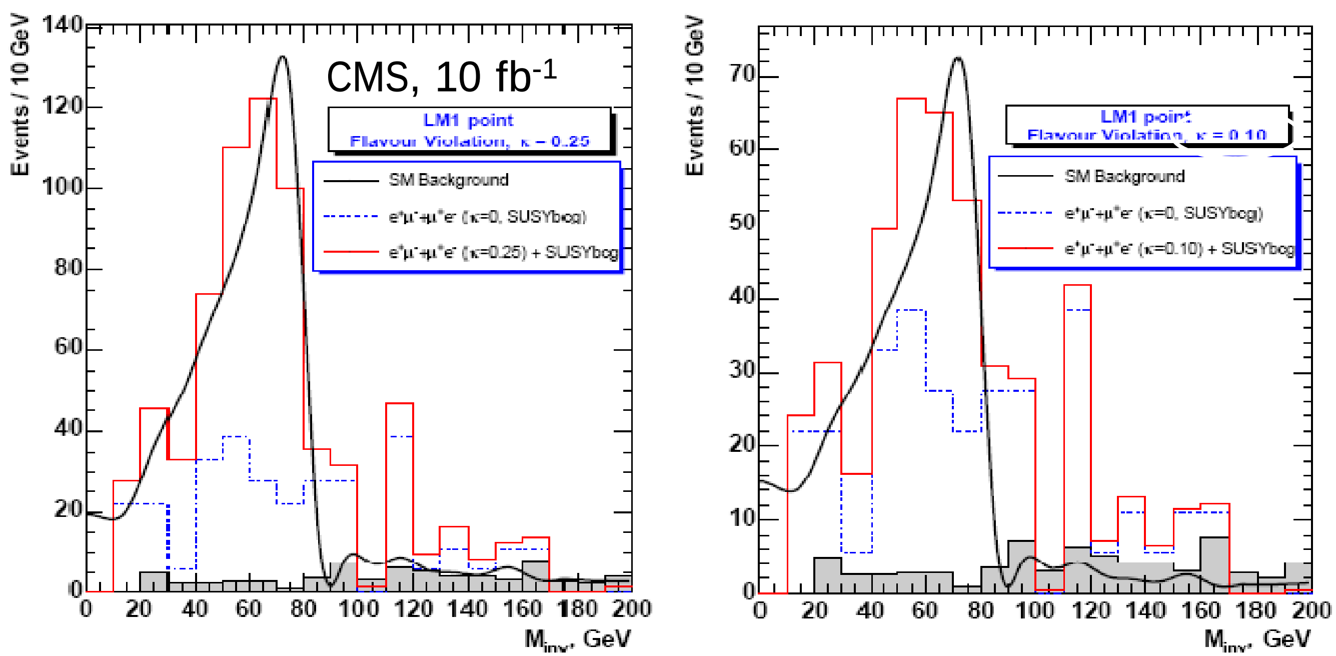
$$\mathrm{BR}(\ell_i \ell_j) \equiv \mathrm{BR}(\tilde{\chi}_2^0 \to \ell_i \ell_j \tilde{\chi}_1^0).$$

[redacted]

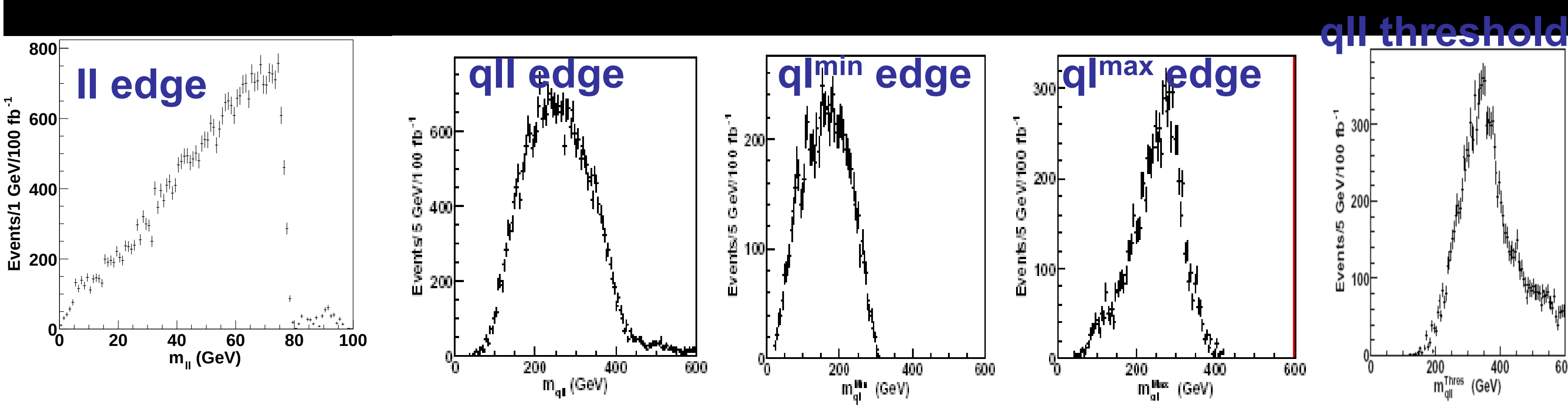
$$\kappa = 2x \sin^2\theta \cos^2\theta,$$

[redacted]

$$x = \frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\Delta m^2_{\tilde{e}\tilde{\mu}} + \Gamma^2},$$



SUSY (s)lepton flavour studies with ATLAS



Gjelsten, Lytken, Miller, Osland, Polesello, ATL-PHYS-2004-007

SPS1a (bulk region)
m_0= 100 GeV,
$m_{1/2}$= 250 GeV,
A_0= -100 GeV,
$\tan(\beta)$=10 , μ>0

Expected errors on the masses

$\Delta m(\chi_1^0)$= 4.8 GeV, $\Delta m(\chi_2^0)$= 4.7 GeV,
$\Delta m(l_R)$ = 4.8 GeV, $\Delta m(q_L)$= 8.7 GeV

5 relations
4 masses

Lepton flavour violation at LHC

Using $\mu^{\pm}e^{\mp}+E_T^{miss}$ signature in the search for Supersymmetry and Lepton Flavour Violation in neutralino decays

Studying $\mu^{\pm}e^{\mp}$ signature in chargino decays

This signature is also interesting irrespective to the lepton flavour number violation due to SUSY cascade decays contribution and it is possible to use it as SUSY discovery signature.

For example:

$$
\begin{aligned}
pp \;\longrightarrow\; & \tilde{q}\,\overline{\tilde{q}} + \ldots \\
& \quad\hookrightarrow\; q\tilde{\chi}_1^{+} \\
& \hookrightarrow q\tilde{\chi}_1^{-} \quad \hookrightarrow\; e^{+}\nu\chi_1^{0},\ \mu^{+}\nu\chi_1^{0} \\
& \qquad\quad \hookrightarrow\; e^{-}\nu\chi_1^{0},\ \mu^{-}\nu\chi_1^{0}
\end{aligned}
$$

We studied it as a SUSY discovery signature.

Neutralino decays. Lepton Flavour Violation.

Normal decays of neutralino (1) and decays of neutralino in the case of Lepton Flavour Violation (2)

$$pp \rightarrow \tilde{q}\overline{\tilde{q}} + \ldots$$

$$\hookrightarrow q\tilde{\chi}_2^0$$

$$\hookrightarrow e^+e^-(\mu^+\mu^-) + \chi_1^0 \quad (1)$$

$$\hookrightarrow \mu^+e^-(\mu^-e^+) + \chi_1^0 \quad (2)$$

(2) Flavour lepton number violation in slepton decays:

Krasnikov N.V. Mod.Phys.Lett. A9 (1994) 791;
Phys.Lett. B388 (1996) 783
Arkani-Hamed N. et al Phys.Rev.Lett. 77 (1996) 1937

Kinematical Cuts and Significances Estimators

After optimization the following set of cuts was chosen:

Cuts for SUSY search

- Two isolated leptons with $p_T^{lept} > 20\ GeV$ and $|\eta| < 2.4$
- $E_T^{miss} > 300\ GeV$

These cuts were chosen to have high significance values (S_{c12},S_{cL}) and high signal to background ratio.

Significances estimators:

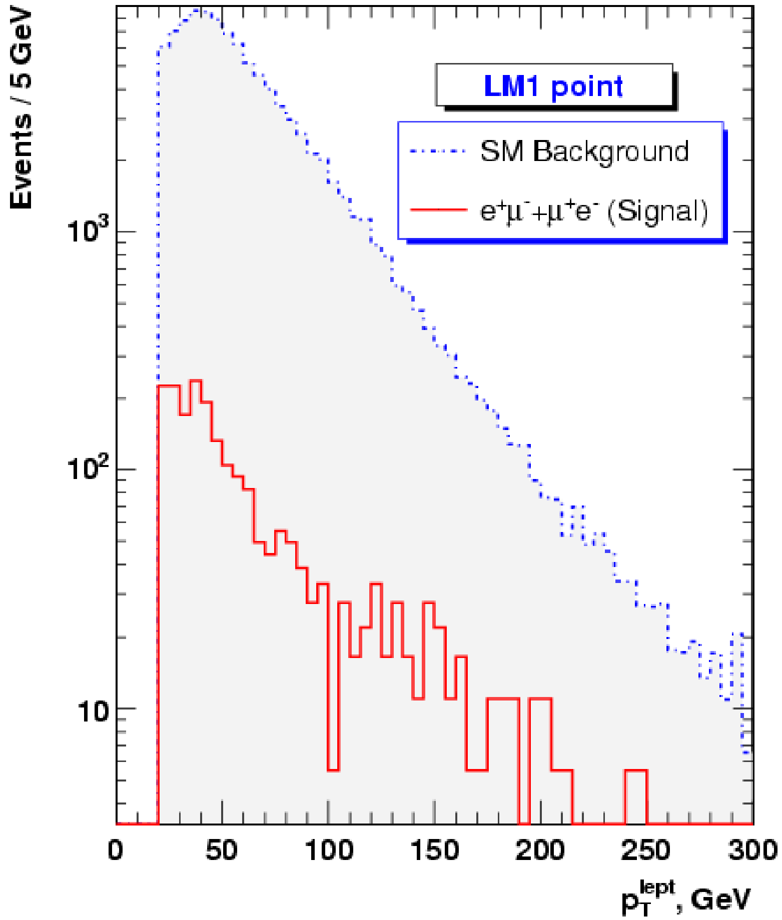
- $S_{c12} = 2\times(\sqrt{N_S+N_B} - \sqrt{N_B})$ S.I.Bityukov, N.V.Krasnikov, NIM A452(2000) 518
- $S_{cL} = \sqrt{2\times((N_S+N_B)\times\ln(1+N_S/N_B)-N_S)}$

V.Bartsch and G.Quast CMS NOTE 2005/004 & R.Cousins et al. CMS NOTE 2005/002

$\mu^{\pm} e^{\mp}$: Signal (LM1) & SM Background

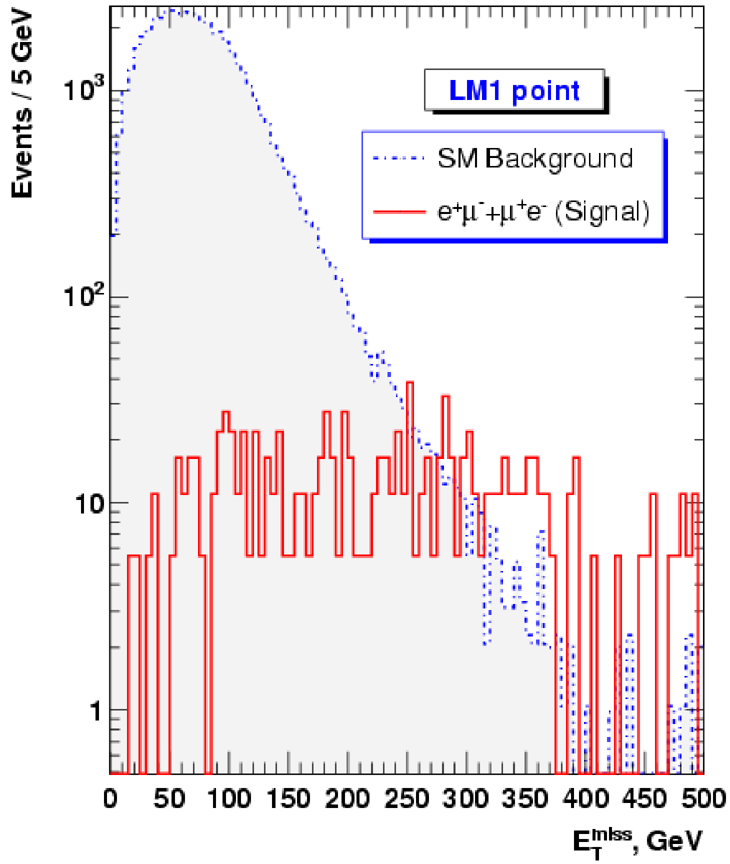
Process	2 isolated leptons, $p_T^{lept} > 20$ GeV	$E_T^{miss} > 300$ GeV
ttbar	39679	79
WW	4356	4
WZ	334	2
Z + jet	1082	6
Wt	3823	2
Zbbbar	4390	0
DY2tau	7564	0
SM background	60184	93
LM1 signal	1054	329

Signal (LM1) and SM Background



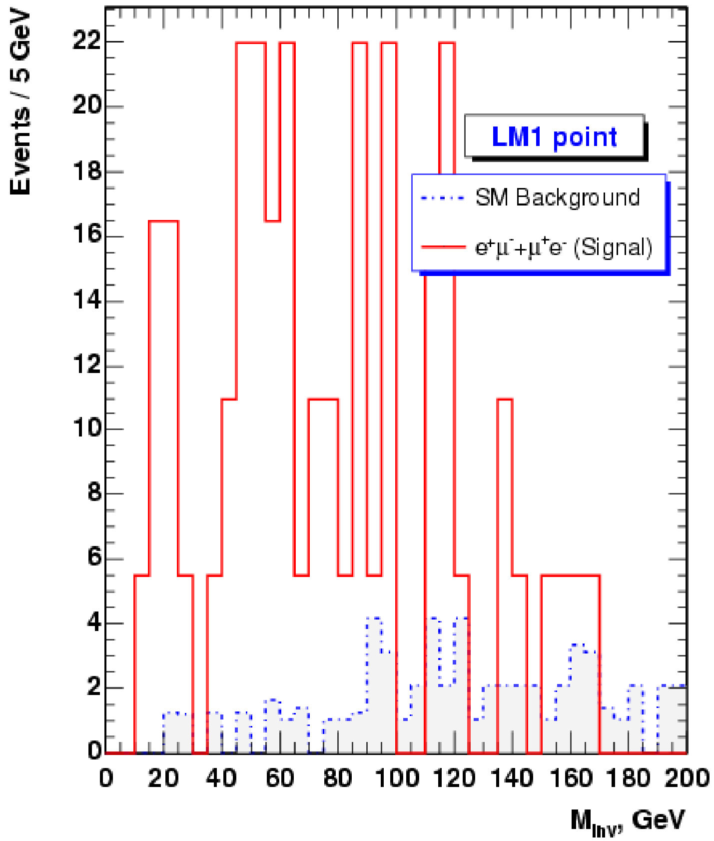
Distribution of p_T^{lept} after selection of two isolated leptons for $\mu^{\pm}e^{\mp}$ with p_T^{lept} > 20 GeV.

Signal (LM1) and SM Background



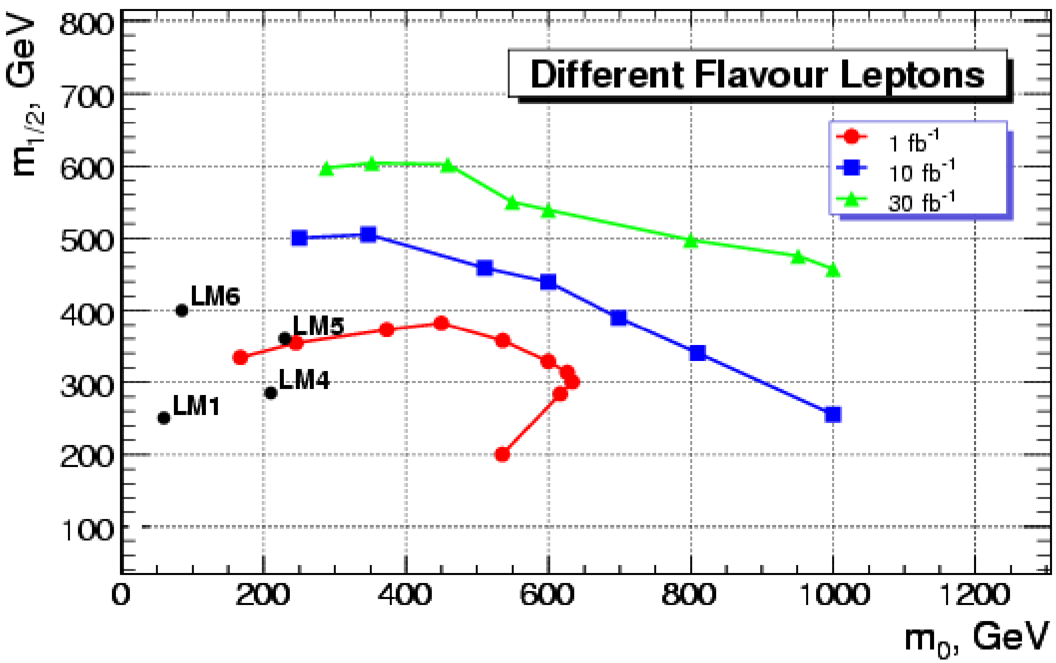
Distribution of E_T^{miss} after selection of two isolated leptons for $\mu^{\pm}e^{\mp}$ with p_T^{lept} > 20 GeV.

Signal (LM1) and SM Background



The dilepton mass M_{inv} after selection of two isolated leptons with p_T^{lept} > 20 GeV and E_T^{miss} > 300 GeV for $\mu^{\pm}e^{\mp}$.

Discovery Plot for tanβ =10, sign(μ)=+, A=0



Discovery plot for $e^{\pm}\mu^{\mp}$.

Lepton Flavour Violation for LM1 Point

In the case of LFV neutralino decays

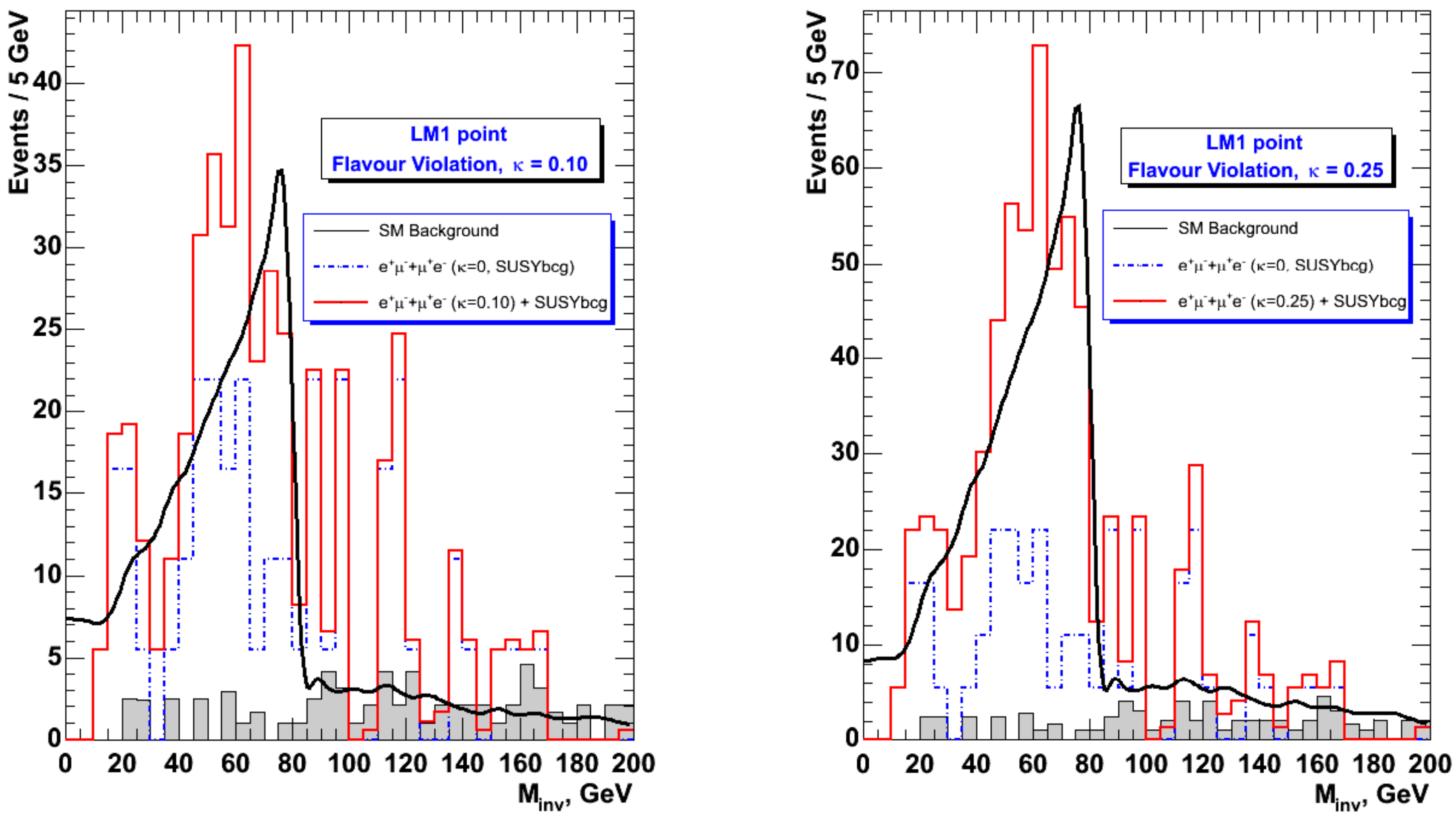
$$\tilde{\chi}_2^0 \rightarrow \tilde{l}l' \rightarrow e\mu\tilde{\chi}_1^0$$

as a consequence the edge structure will appear for the distribution on $m_{inv}(e, \mu)$. The presence of such structure will indicate the existence of LFV.

To study LFV a special sample of events with 100% flavour violation was prepared and fractions of these events were added to LM1 events to simulate LFV behavior.

Distribution on Invariant Mass for Flavour Violating κ = 0.10 & 0.25

$$Br(\chi_2^0 \to \mu^{\pm} e^{\mp} \chi_1^0) = \kappa \times Br(\chi_2^0 \to e^+ e^- \chi_1^0, \mu^+ \mu^- \chi_1^0)$$



Superimposed curves are fits to the Invariant mass distribution for 100% LFV.

LM1 Lepton Flavour Violation Bound

To define Br of LFV for LM1 the following set of cuts was used:

- Two isolated leptons with $p_T^{lept} > 40$ GeV and $|\eta| < 2.4$
- $E_T^{miss} > 200$ GeV
- $M_{inv}(l^+ l^-) < 85$ GeV

The use of an additional cut

$$M_{inv}(e, \mu) < 85 \text{ GeV}$$

allows to reduce both SM and SUSY backgrounds and increase LFV discovery potential. It is possible to discover LFV in neutralino decays with $\kappa > 0.04$ at 5 sigma level for L = 10 fb^{-1} assuming we know the magnitudes of both SM and SUSY backgrounds. Here κ means

$$Br(\chi_2^0 \to \mu^{\pm} e^{\mp} \chi_1^0) = \kappa \times Br(\chi_2^0 \to e^+ e^- \chi_1^0, \mu^+ \mu^- \chi_1^0)$$

and actual value is $Br(\chi_2^0 \to \mu^{\pm} e^{\mp} \chi_1^0) \approx 0.005$ with respect to all neutralino decays.

$\mu^{\pm}e^{\mp}$: LFV Signal (LM1) & Background

Process	2 isolated leptons, $p_T^{lept} > 40$ GeV	$E_T^{miss} > 200$ GeV	$M_{inv} < 85$ GeV
ttbar	20715	422	19
WW	1966	18	0
WZ	188	2	0
Z Z	30	0	0
Wt	2136	33	0
Zbbbar	680	20	0
DY2tau	244	0	0
Total SM bcg	25959	495	19
LM1(SUSY bcg)	433	230	71
LFV signal (LM1)	2454	1619	1421

Conclusions

The use of the $e^{\pm}\mu^{\mp} + E_T^{miss}$ signature allows:

- For the CMS test points LM1-LM9 for $L = 10\ fb^{-1}$ it is possible to discover SUSY for all LM points except the LM7 one.

- To discover the Lepton Flavour Violation in neutralino decays for the point LM1 with Br > 0.005 with respect to all neutralino decays.

LM1 flavour violation bound

The use of additional cut m_{inv}(e mu) <

85 GeV allows to reduce both SM and SUSY backgrounds and increases

LFV discovery potential. It is

possible to discover at 5 sigma level

LFV in neutralino decays with Br up to 0.04 (Br < 0.04)

provided , we know the magnitude of

both SM and SUSY backgrounds

Conclusion

1. The use of e mu signature allows to discover:
   a. SUSY
   b. Flavour lepton violation in neutralino decays
      with LFV Branching up to 0.04
      for LM1 point.