What the LHC Will Teach Us About Low Energy Supersymmetry

Darin Acosta

UNIVERSITY OF FLORIDA

representing

ATLAS & CMS

Outline

Introduction to SUSY, LHC, and the Detectors

Trigger strategies at start-up

Inclusive squark/gluino searches

SUSY Spectroscopy

- ➔ Di-lepton edges
- ➔ squark and gluino reconstruction

Summary

Minimal SuperSymmetry

SUSY

- **Symmetry between bosons and fermions**
  - Squarks/sleptons: $\tilde{q}, \tilde{\ell}$
    scalar counterparts to the fermions
  - Charginos/neutralinos/gluinos: $\tilde{\chi}^{\pm}_{1,2}, \tilde{\chi}^{0}_{1,2,3,4}, \tilde{g}$
    fermion counterparts to SM gauge bosons
  - At least two Higgs doublets (5 scalars): $h, H^0, A, H^{\pm}$
- **Avoids fine-tuning of SM, can lead to GUTs**

MSSM

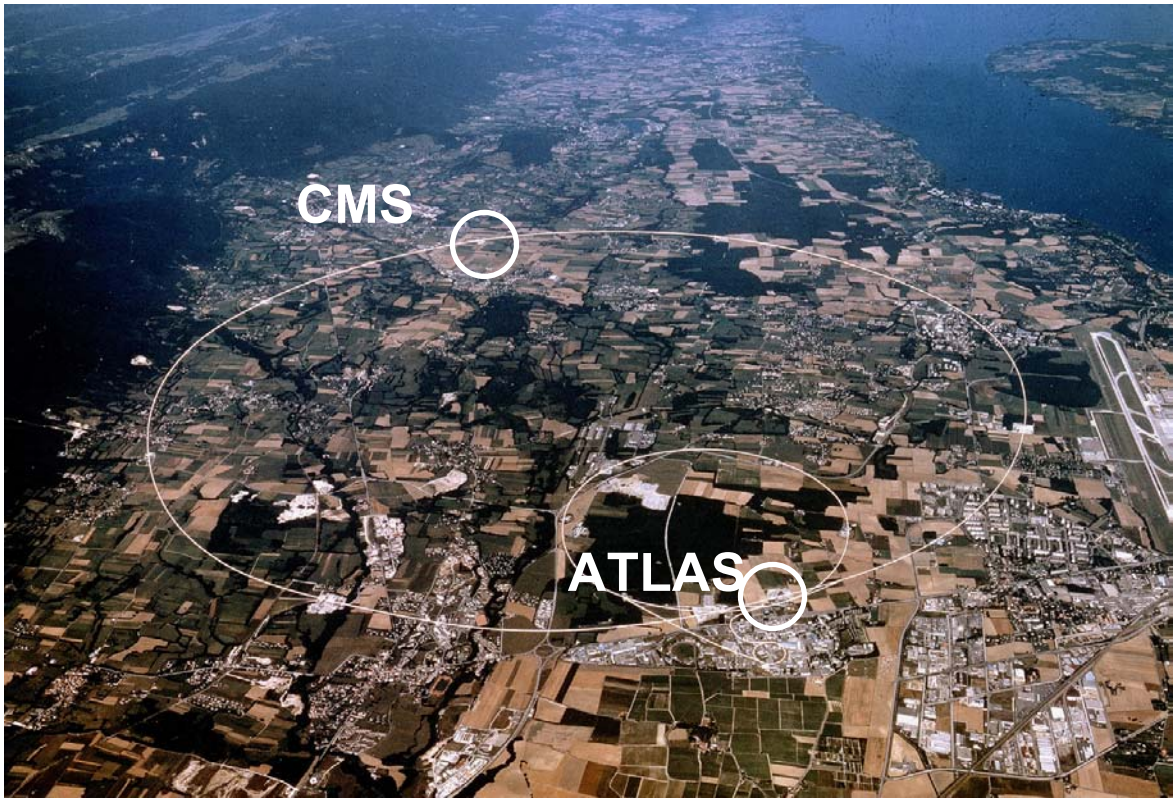
- **Usually consider $R_P \equiv (-1)^{3(B-L)+2S}$ conserved**
  $\Rightarrow$ LSP is stable
- **105 new parameters**

mSUGRA:

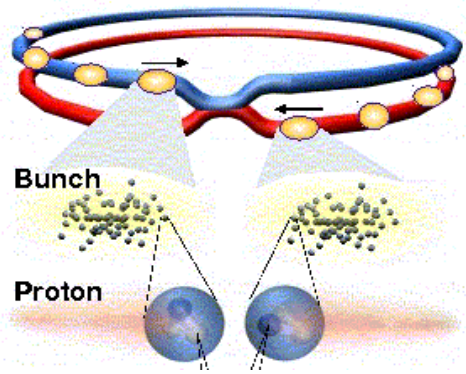
- **Require SUSY to be a local symmetry**
- **Universal gravitational interactions break SUSY at scale $F \sim (10^{11}\ \text{GeV})^2$**
- **5 free parameters**
  - m_0 : Common scalar mass
  - $m_{1/2}$: Common gaugino mass
  - A_0 : Common scalar trilinear coupling
  - $\tan\beta$: Ratio of v.e.v. of Higgs doublets
  - Sign(μ) : sign of Higgsino mixing parameter
- **Typically:** $M(\tilde{\chi}^{\pm}_1) \approx M(\tilde{\chi}^0_2) \approx 2M(\tilde{\chi}^0_1)$

$$M(\tilde{g}) > M(\tilde{q}) > M(\tilde{\chi})$$

Large Hadron Collider (LHC)



R = 4.5 km
E = 7 TeV



Proton-Proton	(2835 x 2835 bunches)
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

Two proton rings housed in same tunnel as LEP

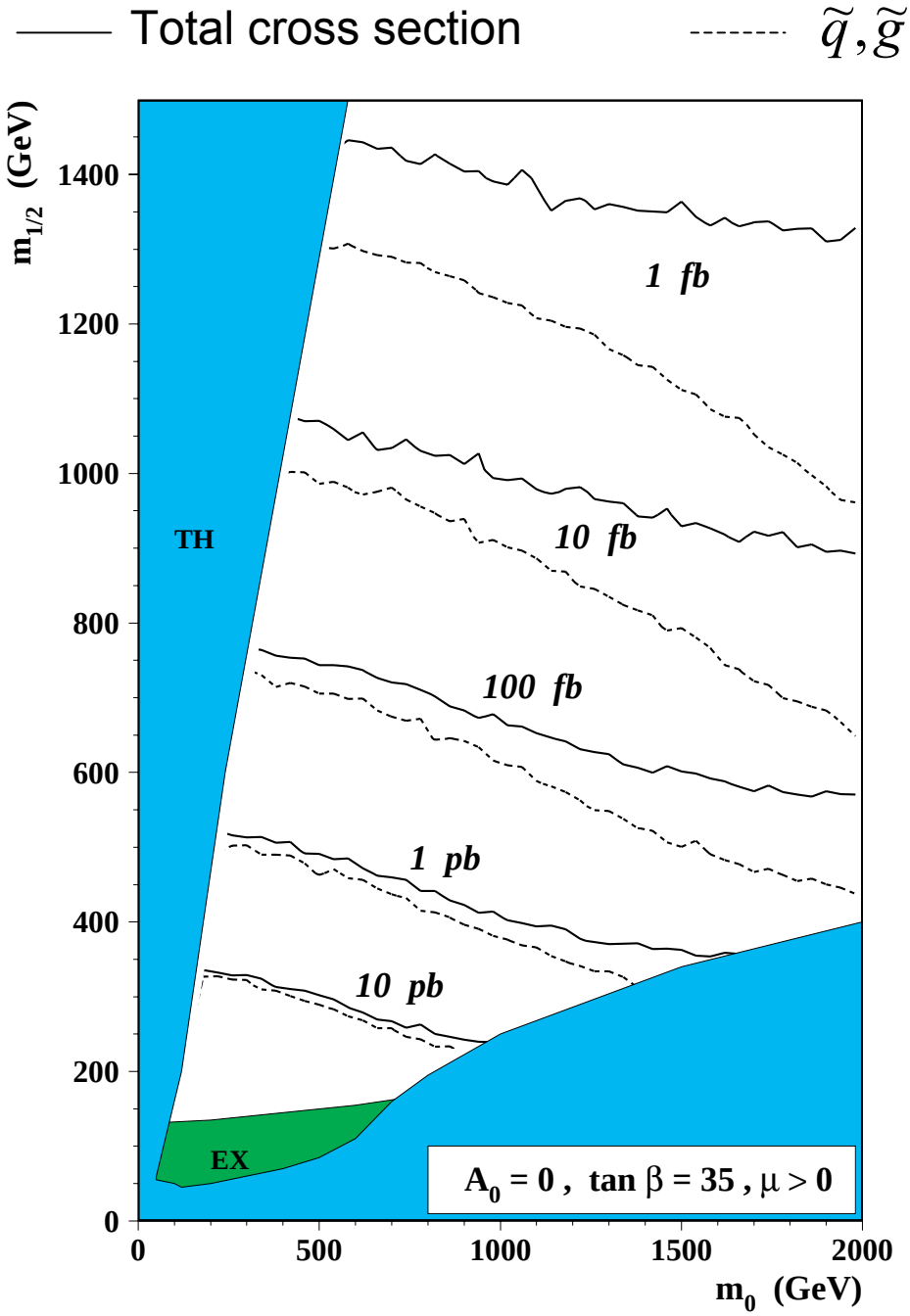
Design luminosity: $L = 10^{34}$ cm^{-2}s^{-1} = 100 fb^{-1}/year

(Pile up: ~20 collisions/crossing)

Start-up luminosity: $L \sim 10^{33}$ cm^{-2}s^{-1} = 10 fb^{-1}/year

Completion: mid 2007

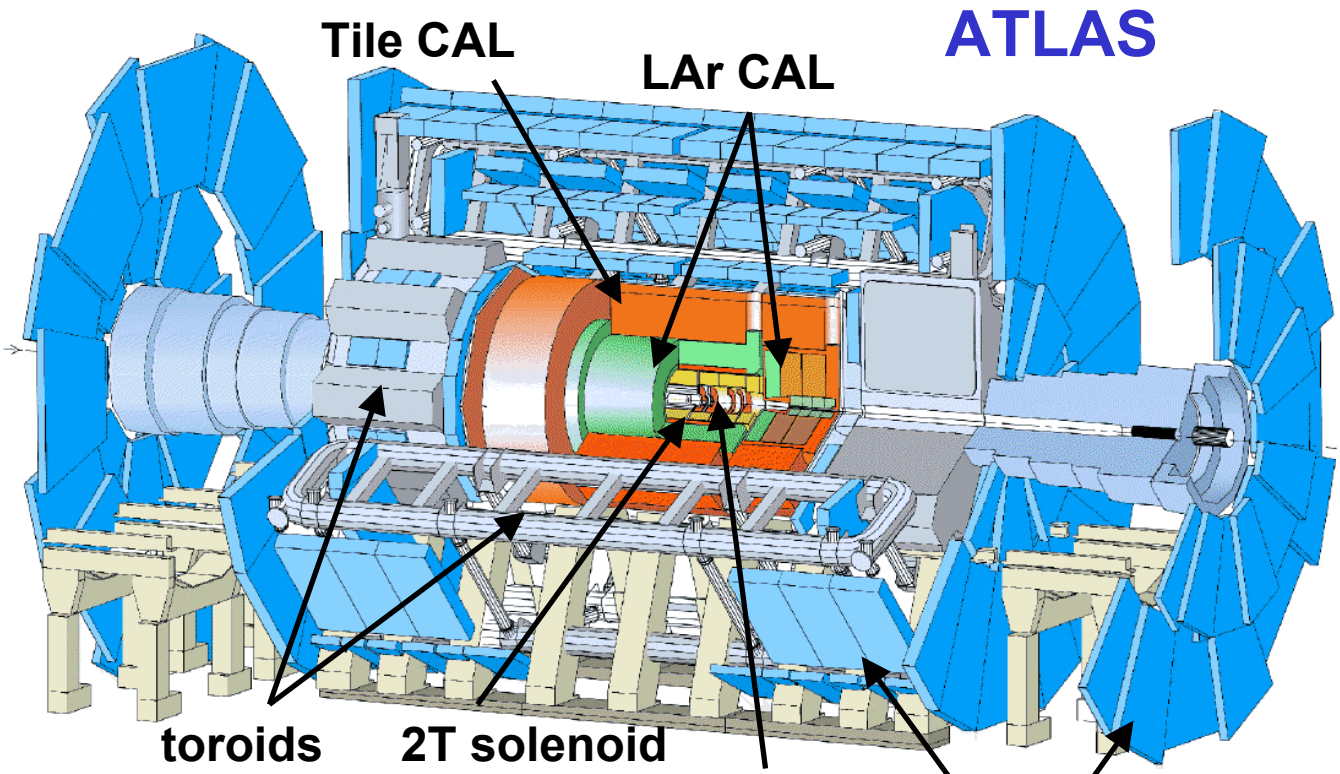
mSUGRA Cross Sections @ LHC

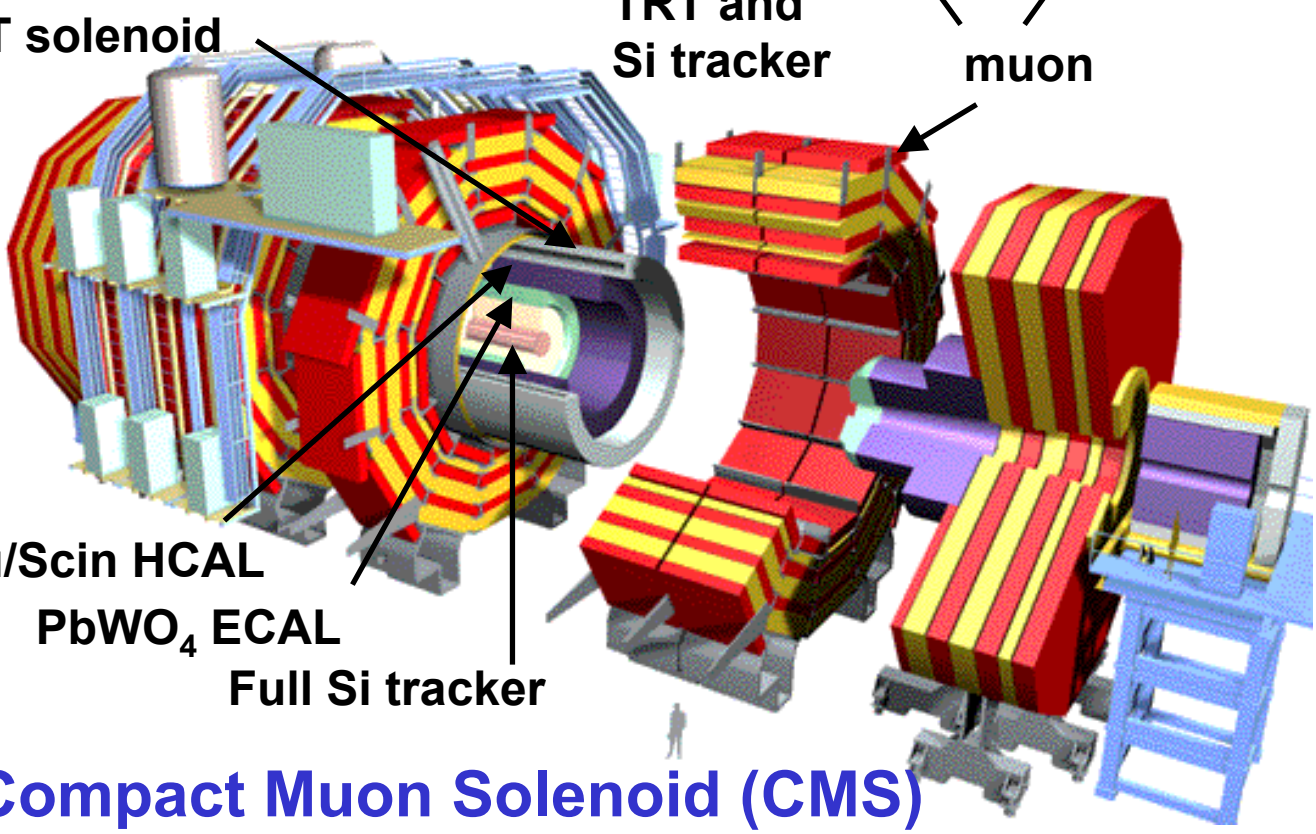


- ➔ Squark/gluino production dominates the total cross-section for low energy SUSY
- ➔ Cross sections don't vary much with μ, $\tan\beta$

Detectors

ATLAS





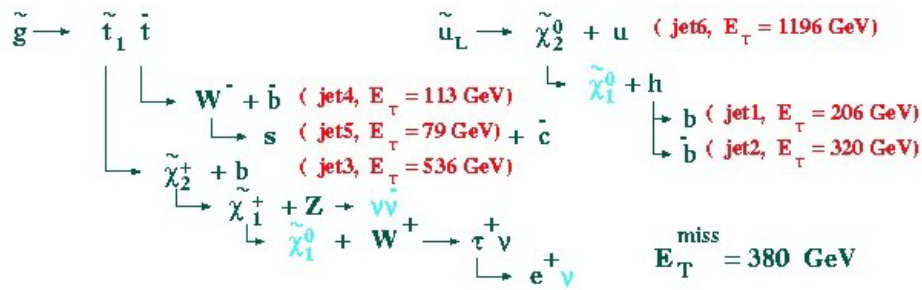
Compact Muon Solenoid (CMS)

SUSY Signatures

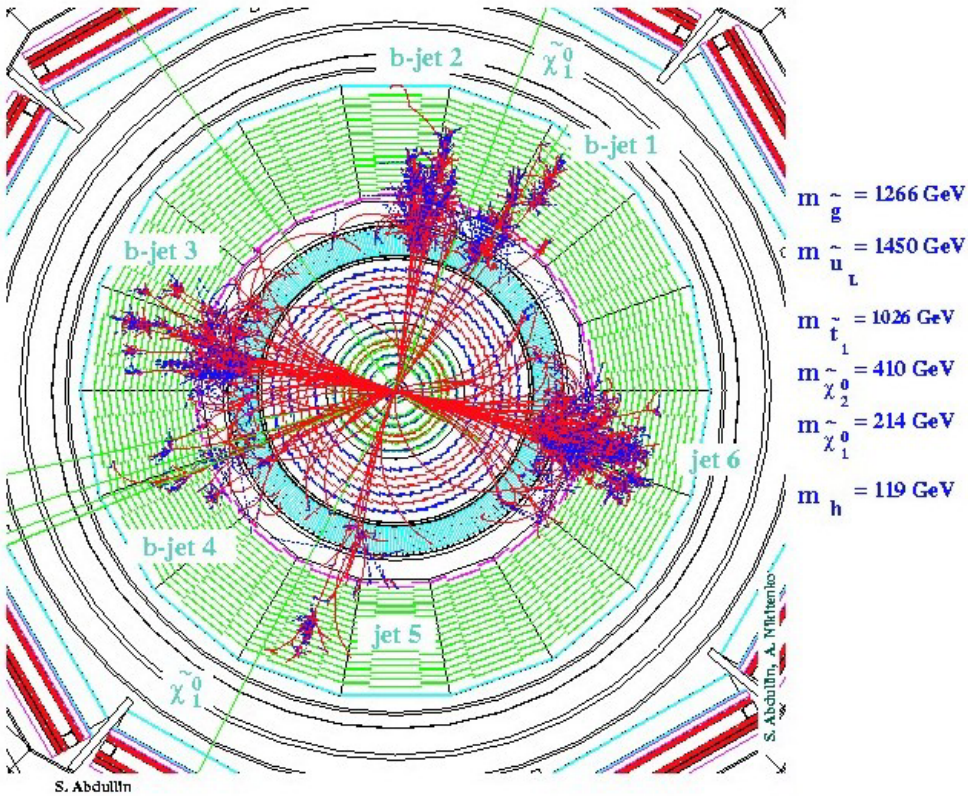
Complex squark/gluino decay chains

- ➔ Many high-E_T jets
- ➔ Heavy-flavor (τ and b, especially at large tanβ)
- ➔ Leptons
  - ➔ From sleptons, charginos, W/Z, and b-jets
- ➔ Missing transverse energy (MET)
  - ➔ From LSP and neutrinos from taus, sneutrinos

Example:



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

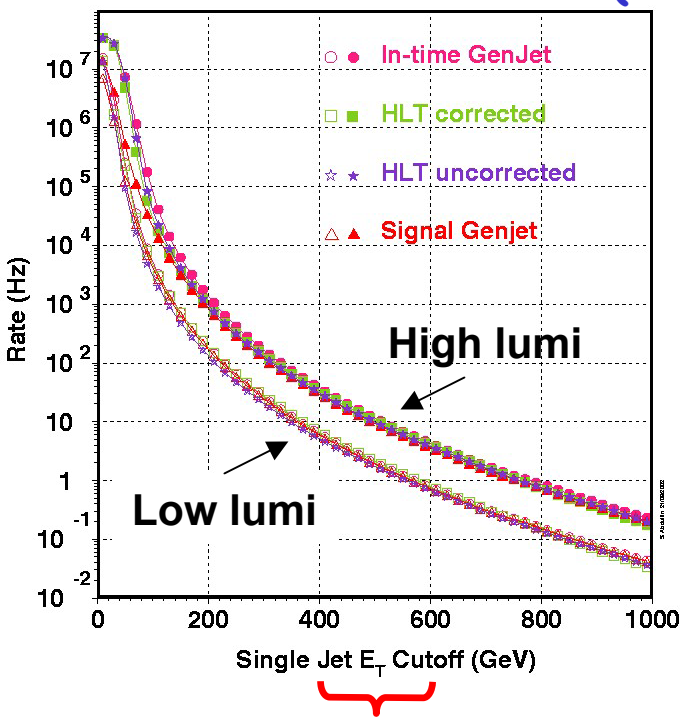


CMS event simulation

Trigger Challenge

Reduce 40 MHz bx rate (1 GHz pp) → O(100 Hz)

➔ Inclusive Jet Rate (cone algorithm, R=0.5):

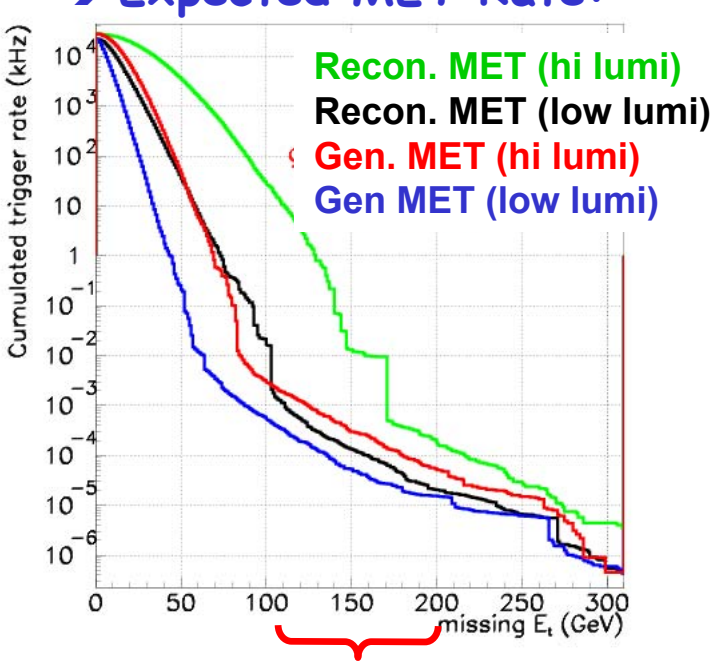


Full GEANT-based detector simulation on QCD background

CMS DAQ Technical Design Report CERN/LHCC 2002-26

Requiring a rate to tape of a ~few Hz implies an inclusive single jet threshold of 400–600GeV, and an inclusive MET threshold of 100–200 GeV

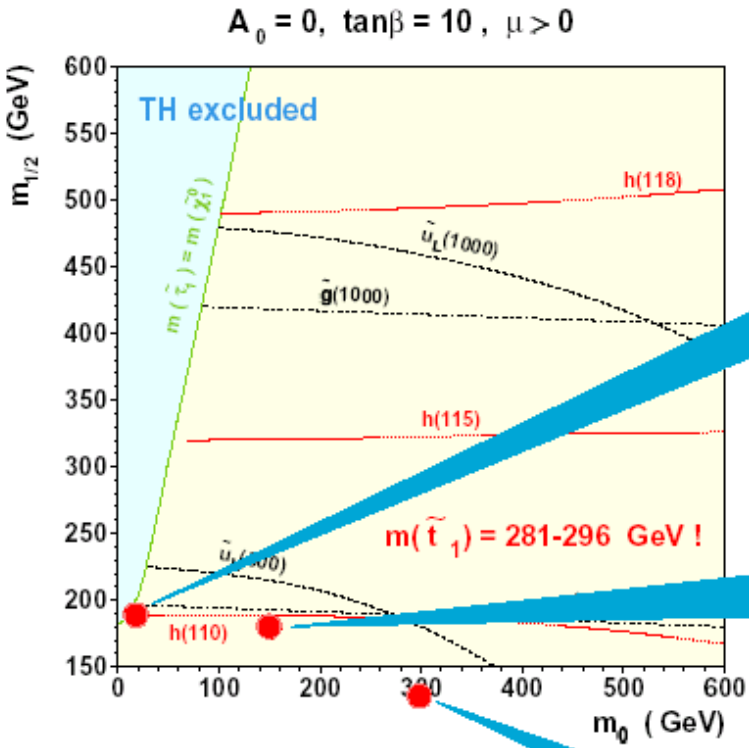
➔ Expected MET Rate:



Reconstructed MET rate below 100 GeV mainly from calorimeter energy resolution

SUSY Trigger Exercise (CMS)

➔ Consider several points in the m_0-$m_{1/2}$ plane near the Tevatron reach (most difficult for LHC)



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

$m(\tilde{\chi}_1^0) = 66$ 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

$m(\tilde{\chi}_1^0) = 45$ 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, more jets, less MET
6 300,130

- Require $\int Ldt < 10\ pb^{-1}$ (1 day of running)

➔ Consider points with and without R_p conservation
  ➔ For $\not{R}_p$ choose most difficult case: $\tilde{\chi}_1^0 \to 3j$

➔ Run full GEANT-based detector simulation on SUSY signals and SM backgrounds to evaluate trigger performance

➔ Optimize efficiency for a rate to tape O(10 Hz)

Example Trigger Strategy (CMS)

Low luminosity case, $L = 2\times10^{33}$ cm^{-2}s^{-1}

Possible triggers at Level-2
(looser requirements at Level-1):

- → 1 jet E_T>180 GeV & MET>120 GeV
- → 4 jets E_T>110 GeV

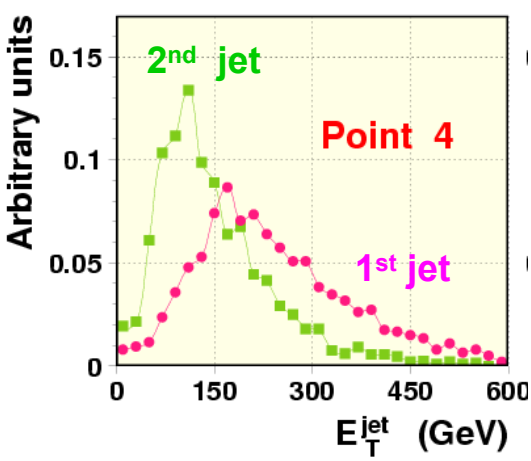
(values at 95% gen. effic.)

Overall efficiencies to pass both trigger levels for the SUSY points are:

→ ε=0.63, 0.63, 0.37, 0.43, 0.38, 0.23

4 5 6 4R 5R 6R

With $\not{R}_P$



Background rate of ~12Hz dominated by QCD

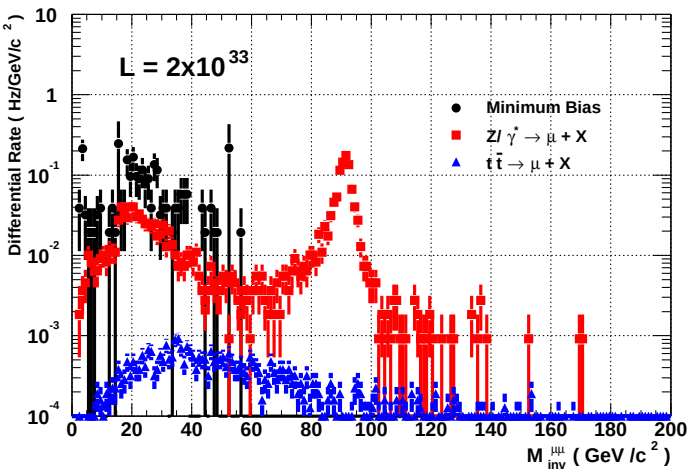
More exclusive triggers involving angular correlations among objects can be added to further improve efficiency

Trigger becomes more efficient at high luminosity since one expects to explore higher masses

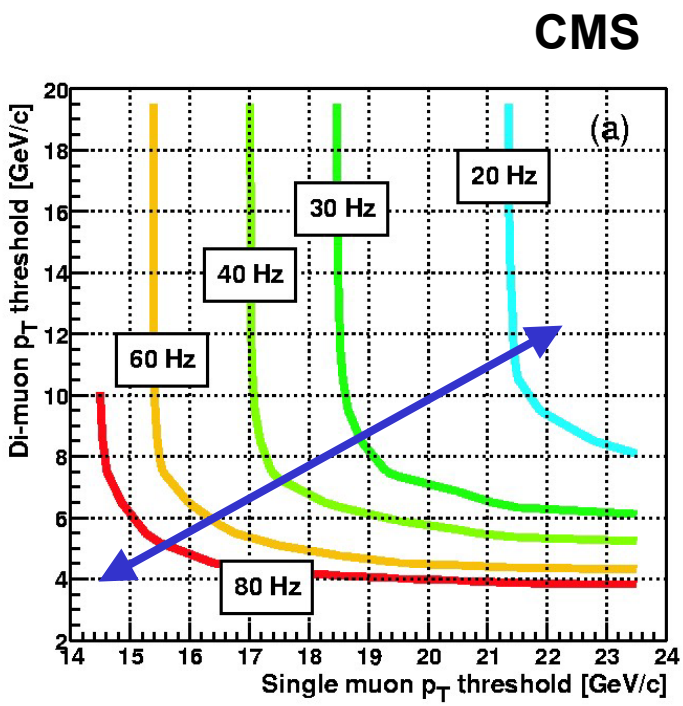
Lepton and Photon Triggers

Anticipated thresholds by ATLAS and CMS for an initial luminosity of $L = 2\times10^{33}$ cm^{-2}s^{-1}

- 1e: P_T > 25 GeV
- 2e: P_T > 15 GeV
- 1μ: P_T > 20 GeV
- 2μ: P_T > 10 GeV
- 1τ: P_T > 85 GeV
- 2τ: P_T > 60 GeV
- 1γ: P_T > 60–80 GeV
- 2γ: P_T > 20–40 GeV



Di-muon invariant mass at Level-3



Sufficient handle on muon trigger rate:

Fast Simulation

Full simulation of signals and backgrounds like that shown for trigger exercise is too CPU intensive for complete SUSY reach determination

- ➔ Require $O(10^8)$ events, but full GEANT simulation takes tens of minutes per event
- ➔ Use physics generators + parameterized detector performance

ATLFAST:

- ➔ Tracks (μ): $\Delta P_T/P_T = 0.4P_T \oplus 1\%$ (P_T in TeV)
- ➔ EM resolution: $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.3\%$ (E in GeV)
- ➔ Jet resolution: $\sigma/E \sim 60\%/\sqrt{E} \oplus 2\%$ (E in GeV)

CMSJET:

- ➔ Tracks (μ): $\Delta P_T/P_T = 0.15P_T \oplus 0.5\%$ (P_T in TeV)
- ➔ EM resolution: $\sigma/E \sim 5\%/\sqrt{E} \oplus 0.5\%$ (E in GeV)
- ➔ Jet resolution: $\sigma/E \sim 100\%/\sqrt{E} \oplus 5\%$ (E in GeV)

Inclusive $\tilde{q}$, $\tilde{g}$ Search

Counting excess events over SM background

- ➔ Discovery mode SUSY search at LHC
- ➔ Explicit sparticle reconstruction not done

6 Analyses:

- ➔ E_T^{miss}: jets+MET, no lepton requirements
- ➔ 0ℓ: no leptons
- ➔ 1ℓ: 1 lepton
- ➔ $2\ell OS$: 2 leptons, opposite sign
- ➔ $2\ell SS$: 2 leptons, same sign
- ➔ 3ℓ: 3 leptons

CMS Study:

Common cuts:

- ➔ MET>200 GeV, ≥2 jets, E_T^{jet} > 40 GeV, $|\eta|<3$

Lepton identification

- ➔ Electron: P_T>20 GeV, isolated, $|\eta|<2.4$
- ➔ Muon: P_T>10 GeV, isolated or not, $|\eta|<2.4$

Vary cuts in 6 categories (~10^4 combinations)

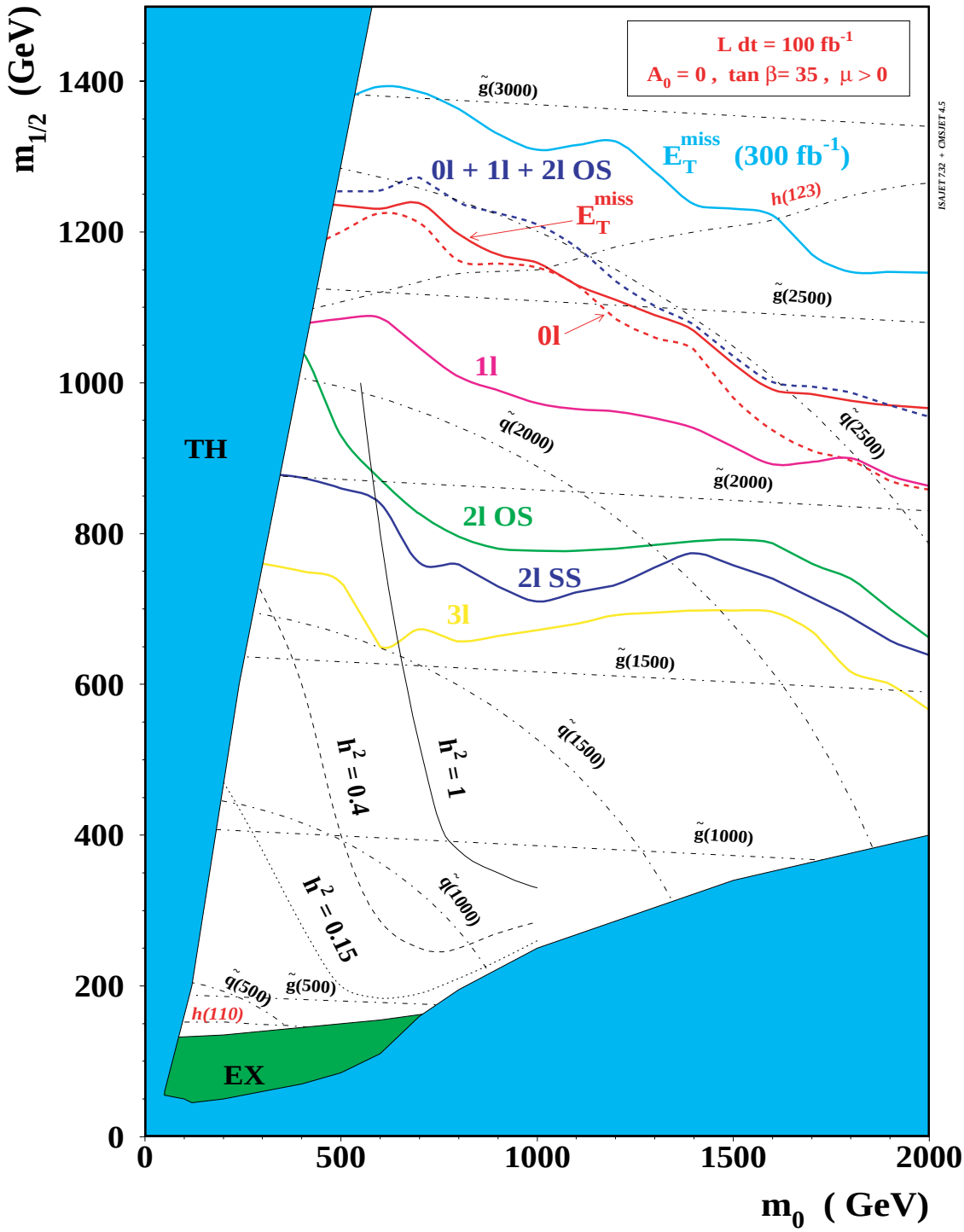
- ➔ #Jets, MET, Jet E_T, $\Delta\phi(\ell,\text{MET})$, Circ., μ Iso.

Optimize $S/\sqrt{(S+B)}$ in a counting experiment

- ➔ Probe 500 (m_0, $m_{1/2}$) points
  - ➔ ~10^6 signal events, ~10^8 QCD, $t\bar{t}$, W/Z+jets

Plot 5σ sensitivity contours

CMS q̃, g̃ Reach

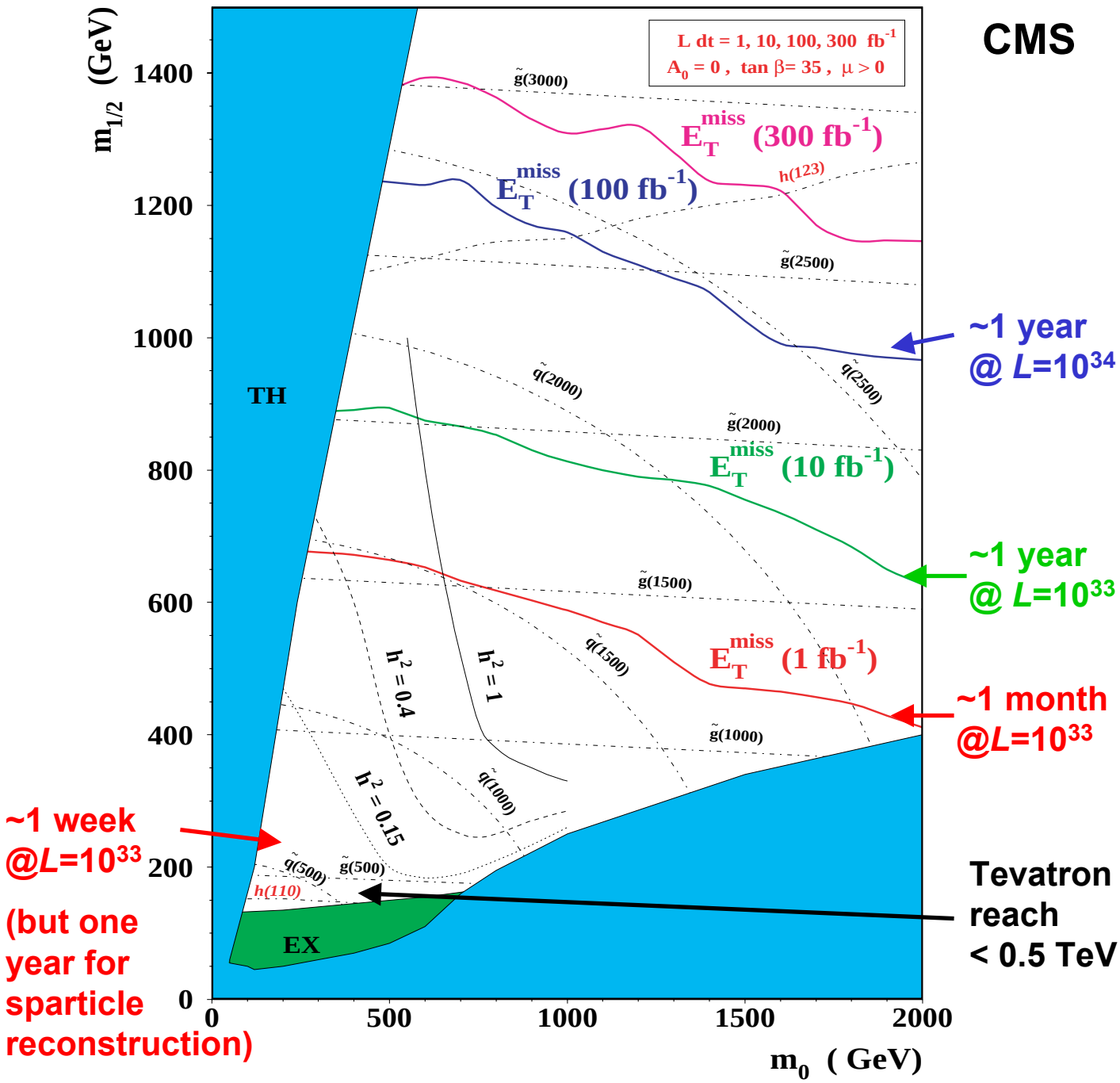


➔ Jets+MET search gives greatest sensitivity

➔ Opposite-sign leptons useful for sparticle recon.

Nucl. Phys. B547 (1999) 60

Jets+MET Reach vs. Luminosity



➔ Squarks/gluinos probed to ~1.5 TeV with 1 fb^{-1}

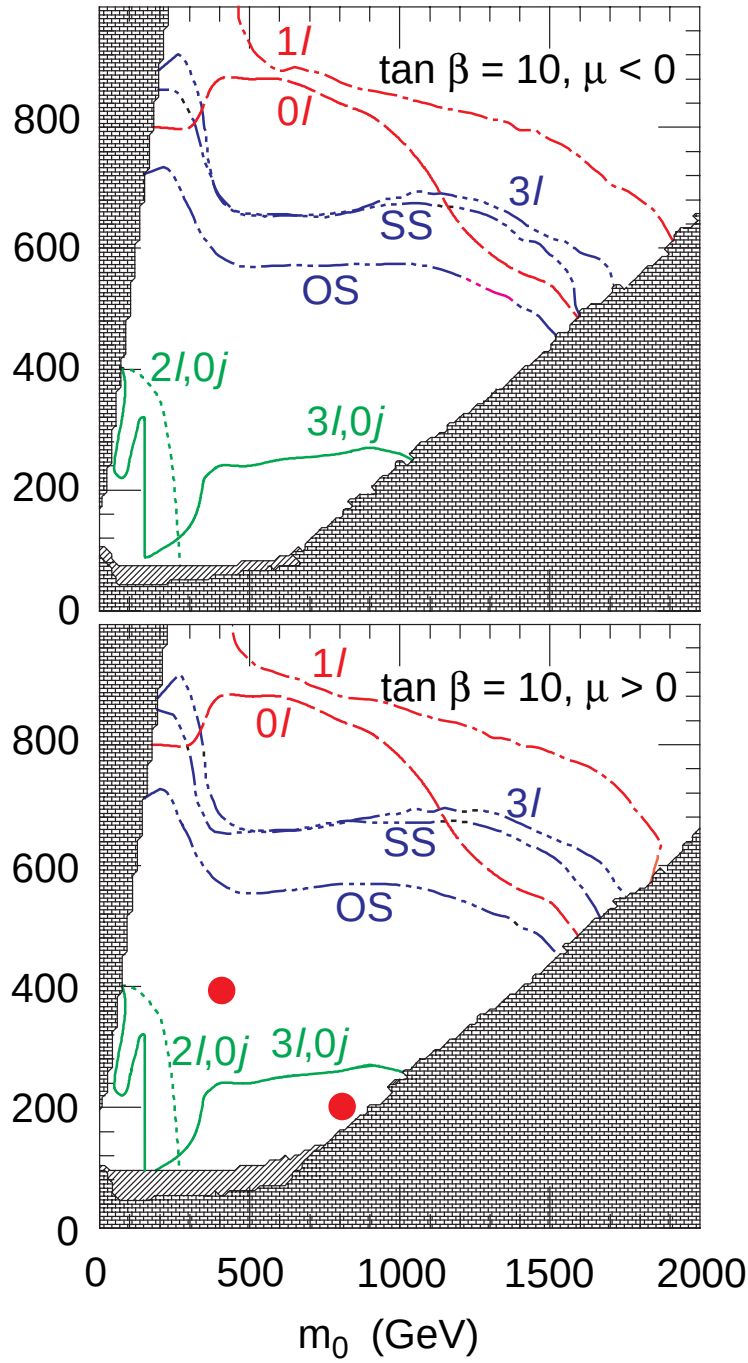
➔ Up to 2.5 TeV at design luminosity (100 fb^{-1})

Other Parameter Choices

ATLAS
TDR 15
CERN/LHCC 99-15

***L*=10 fb^{-1}**

~1 year
@ *L*=10^{33}



➔ Similar cuts and optimization as for CMS study

➔ Sensitivity for lower tanβ also derived, but lower mass Higgs inconsistent with present limits

R-Parity Violation

Non-conservation of $R_P \equiv (-1)^{3(B-L)+2S}$ leads to 3 new terms in SUSY superpotential:

$$W = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} Q_i L_j D_k^c + \lambda''_{ijk} U_i^c L_j^c D_k^c$$

Choose most challenging of baryon number violation (last case): $\tilde{\chi}_1^0 \to 3j$

ATLAS Study of "Point 5"

- ➔ m_0=100 GeV, $m_{1/2}$=300 GeV, tanβ=2, μ>0, A_0=300
- ➔ MET is reduced, but still substantial
- ➔ Number of jets increases
- ➔ Leptons from neutralino decays

Should still be able to explore much of the parameter space as with mSUGRA

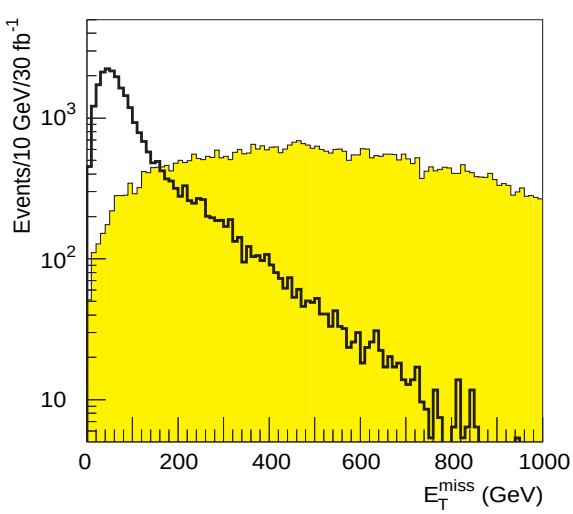


Figure 20-85 E_T^{miss} distribution for SUGRA Point 5 in the case of *R*-parity conservation (shaded histogram) and *R*-parity violation (empty histogram).

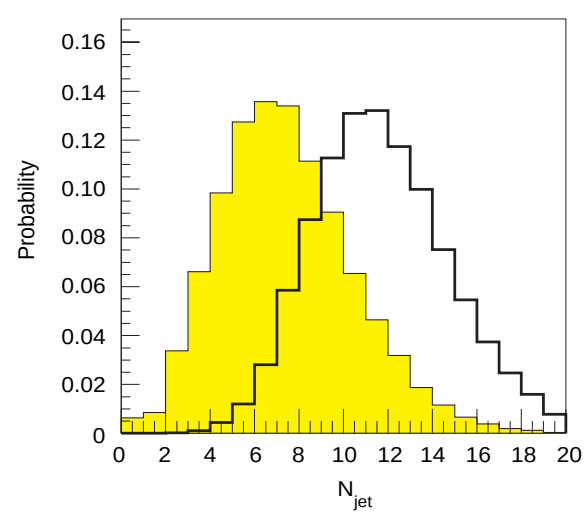


Figure 20-86 Total jet multiplicity ($p_T^{jet} > 15\,\mathrm{GeV}$) distribution for *R*-parity conservation (shaded) and *R*-parity violation at SUGRA Point 5. The jets are reconstructed using a topological algorithm based on joining neighbouring cells.

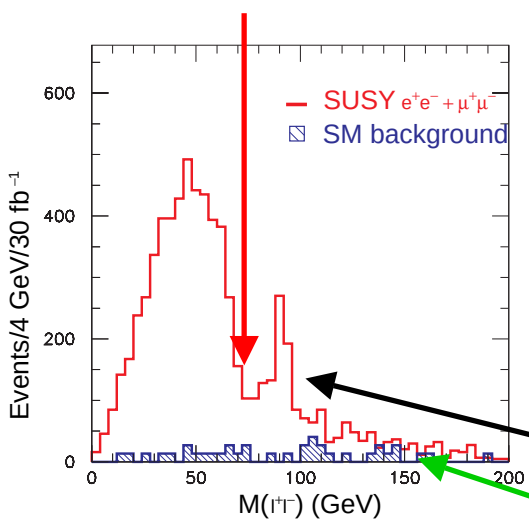
Exclusive Di-Lepton Reconstruction

Measure invariant mass distribution of OS same flavor leptons as evidence for

$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^- \quad \text{or} \quad \tilde{\chi}_2^0 \to \tilde{\ell}^+ \ell^- \to \tilde{\chi}_1^0 \ell^+ \ell^-$$

$\tilde{\chi}_2^0$ can be produced via Drell-Yan $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$, but more prevalent in cascade decays of $\tilde{q}, \tilde{g}$

Endpoint in mass spectrum exhibits sharp edge:



$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$$

ATLAS "Point 4":
m_0=800GeV $m_{1/2}$=200GeV
tanβ=10 μ>0 A_0=0

L=30 fb^{-1}

Some Z^0 from other gauginos

SM background is small

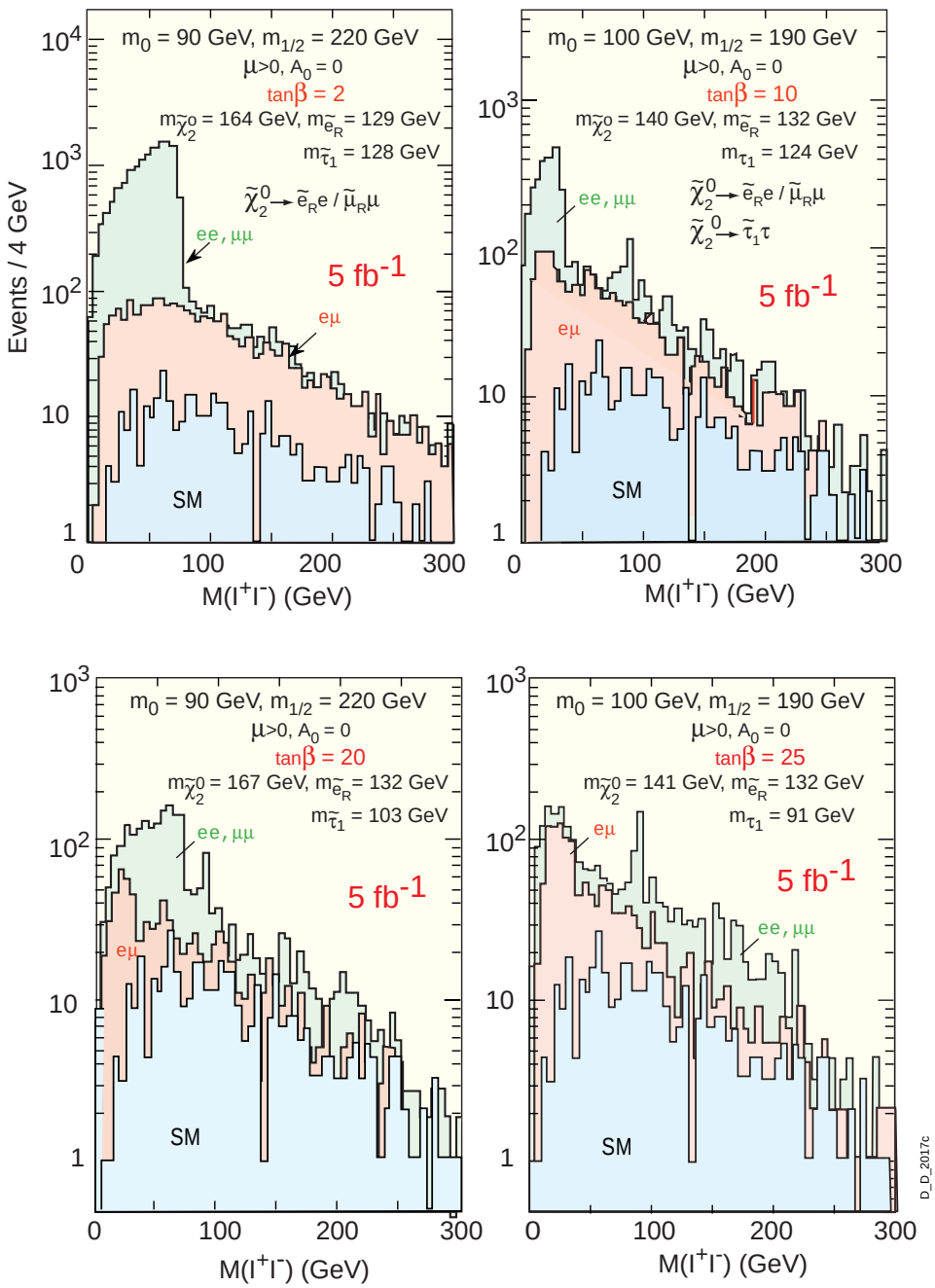
This point selected by:

- ➔ Two OS leptons (e,μ), P_T>(20,10) GeV, |η|<2.5
- ➔ MET>200 GeV, 4 jets: P_T^1>100 GeV, P_T^{234}>50 GeV

3-body decay endpoint: $m_{\ell\ell}^{\max} = m\left(\tilde{\chi}_2^0\right) - m\left(\tilde{\chi}_1^0\right)$

2-body: $m_{\ell\ell}^{\max} = \sqrt{\left(m^2\left(\tilde{\chi}_2^0\right) - m^2\left(\tilde{\ell}\right)\right)\left(m^2\left(\tilde{\ell}\right) - m^2\left(\tilde{\chi}_1^0\right)\right)} / m\left(\tilde{\ell}\right)$

Evolution of Di-Lepton Edges



- ➔ SUSY may reveal itself early through peculiarities in the the di-lepton spectra
- ➔ Structures tend to be less evident with increasing tanβ, where $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tau^+ \tau^-$ dominates

Di-Tau Edge Reconstruction

ATLAS Physics TDR study (Full GEANT simulation) to select *hadronic* tau decays

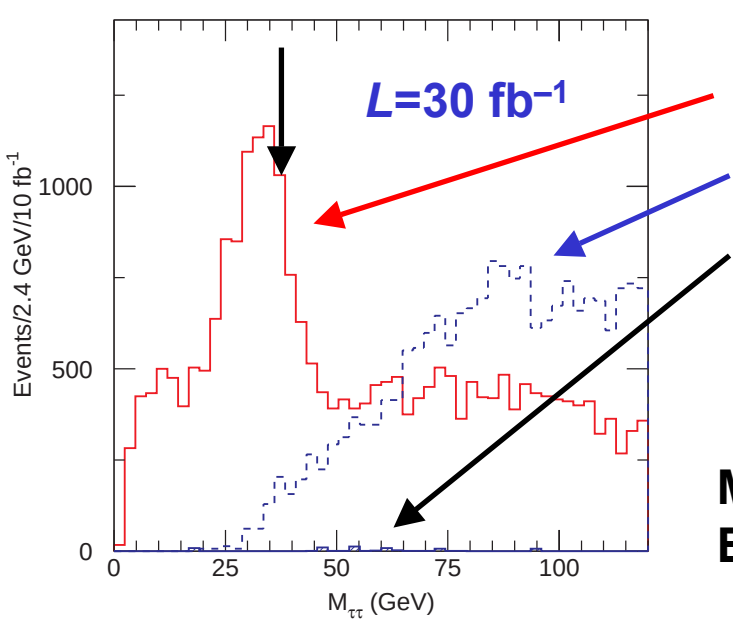
- ➔ Select narrow isolated jets: R_{jet}=0.2, R_{iso}=0.4
- ➔ Require 0.8 GeV < M_{jet} < 3.6 GeV
  - ➔ Biased against 1-prong decays, but improves $M_{\tau\tau}$ resolution (less neutrino momentum)
- ➔ Di-tau efficiency is 41%
- ➔ M_{vis} = 0.66 $M_{\tau\tau}$

Additional event selection cuts

- ➔ 4 jets: E_T^1 > 100 GeV, E_T^{2-4} > 50 GeV,
- ➔ MET>100 GeV, no e,μ leptons with p_T>20 GeV

ATLAS "Point 6":
m_0=200GeV $m_{1/2}$=200GeV
tanβ=45 μ<0 A_0=0

$$BR\left(\tilde{\chi}_2^0 \to \tilde{\tau}\tau\right) = 99.9\%$$

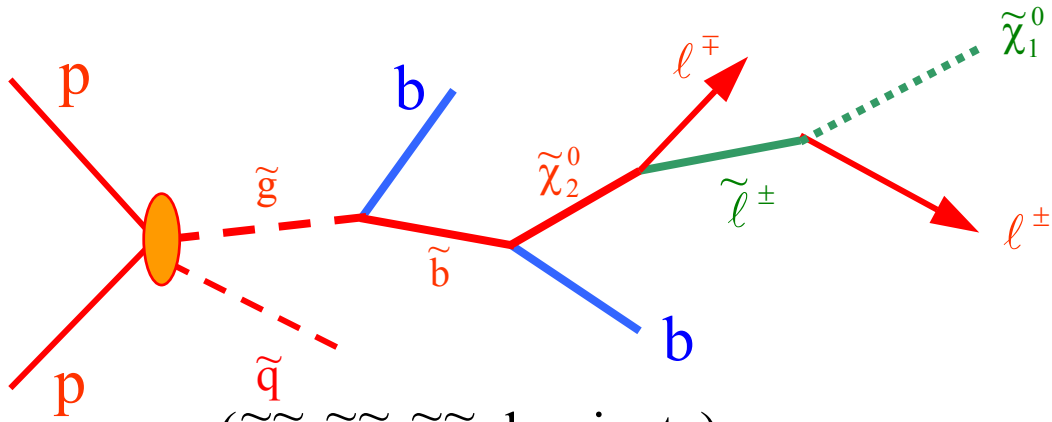


Real τ from SUSY
Fake τ from SUSY
SM background

Mvis = 40 GeV
Expected edge = 60 GeV

Exclusive Sparticle Reconstruction

Completely reconstruct a SUSY decay chain:



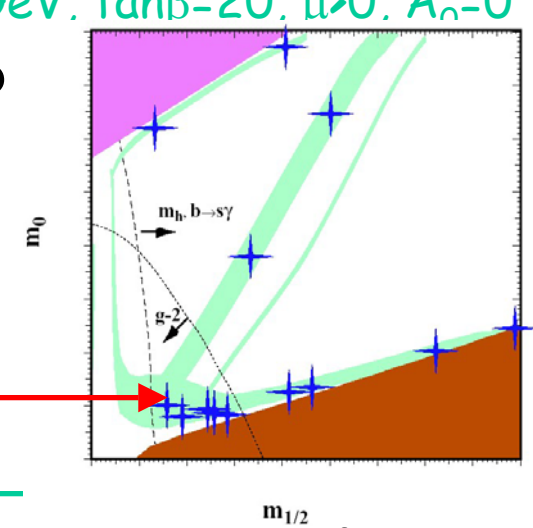
($\tilde{q}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{g}$ dominate)

ATLAS Study

- ➔ "Point 3" of Physics TDR
  - ➔ m_0=200 GeV, $m_{1/2}$=100 GeV, tanβ=2, μ<0, A_0=0

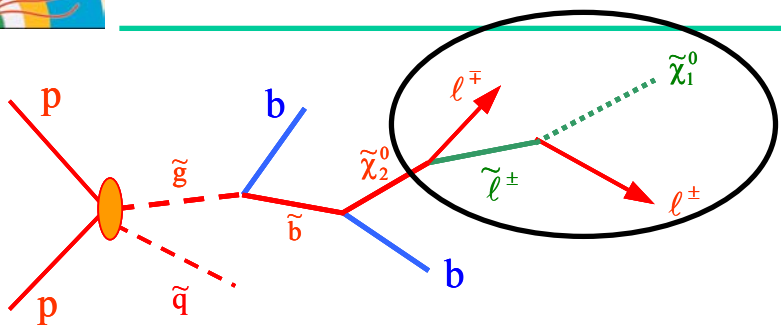
CMS Study [Chiorboli]

- ➔ Investigate Points B & G of "Proposed Post-LEP Benchmarks for SUSY" (hep-ph/0106204)
  - ➔ B: m_0=100 GeV, $m_{1/2}$=250 GeV, tanβ=10, μ>0, A_0=0
    - σ_{TOT}(SUSY) = 58 pb
  - ➔ G: m_0=120 GeV, $m_{1/2}$=375 GeV, tanβ=20, μ>0, A_0=0
    - σ_{TOT}(SUSY) = 6.0 pb



- ➔ ISASUGRA→PYTHIA→CMSJET

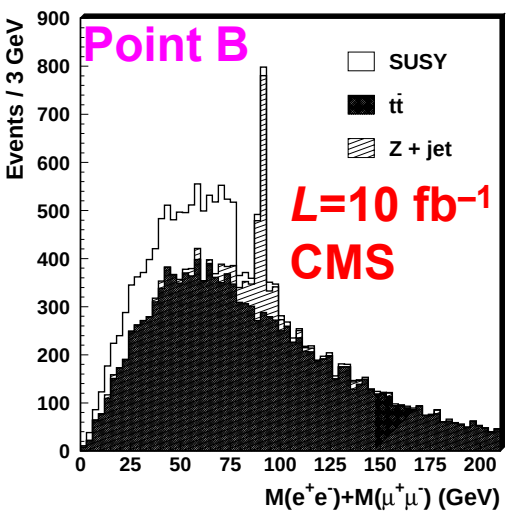
Di-Lepton Edge Reconstruction

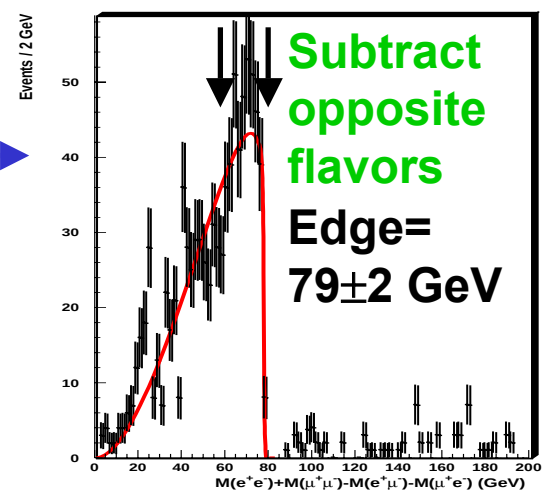


BR=16%

Start with reconstructing $\tilde{\chi}_2^0$ (tanβ not too large)

- ➔ Two OS isolated leptons, P_T>15 GeV, |η|<2.4
- ➔ MET>150 GeV, E(ll)>100 GeV





Select 15 GeV window around di-lepton endpoint

- ➔ $\tilde{\chi}_1^0$ at rest in $\tilde{\chi}_2^0$ rest frame

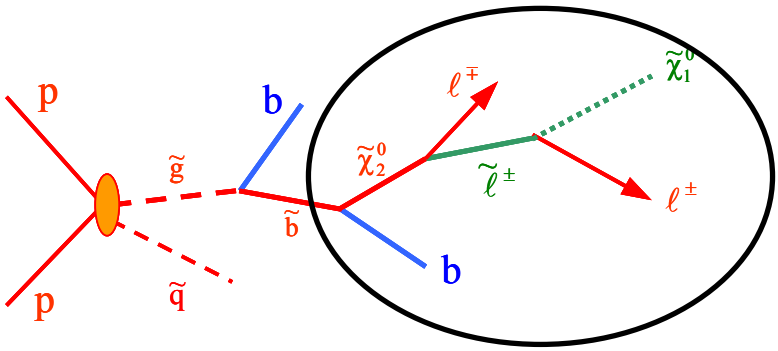
$$\vec{p}\left(\tilde{\chi}_2^0\right) = \left(1 + \frac{m\left(\tilde{\chi}_1^0\right)}{m\left(\ell^+\ell^-\right)}\right)\vec{p}\left(\ell^+\ell^-\right)$$

Can estimate $m\left(\tilde{\chi}_1^0\right)$ from di-lepton endpoint and

$m\left(\tilde{\chi}_2^0\right) \approx 2m\left(\tilde{\chi}_1^0\right)$ Point B: 174 GeV,

but analysis not too sensitive to details

$\tilde{b}$ Reconstruction



BR ~ 5%

Add most energetic b-jet to reconstruct b

- ➔ $E_{b\text{-jet}} > 250$ GeV, $|\eta| < 2.4$
- ➔ b-jet: ≥ 2 tracks with IP significance $> 3\sigma$

Require

- ➔ MET > 150 GeV
- ➔ E(ll) > 100 GeV

Result of fit:

$M(\tilde{b}) = 500 \pm 7$ GeV

$\sigma_M = 42$ GeV

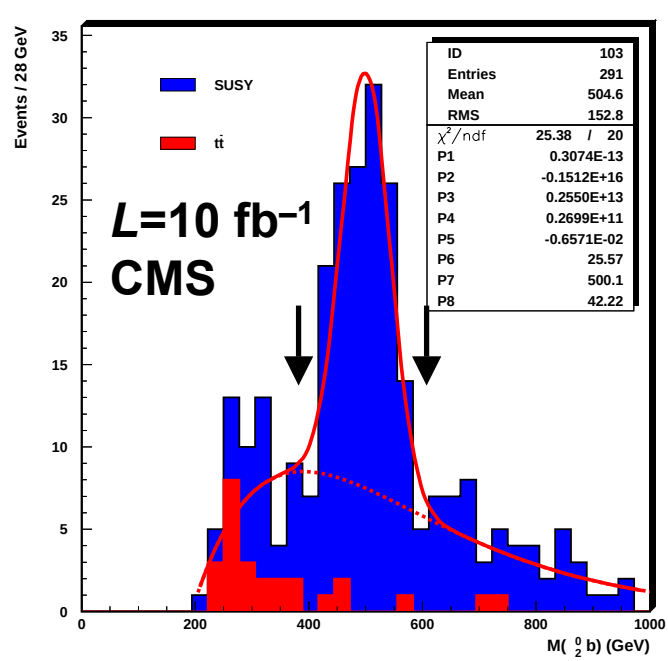
Generated masses:

$M(\tilde{b}_L) = 496$ GeV

$M(\tilde{b}_R) = 524$ GeV

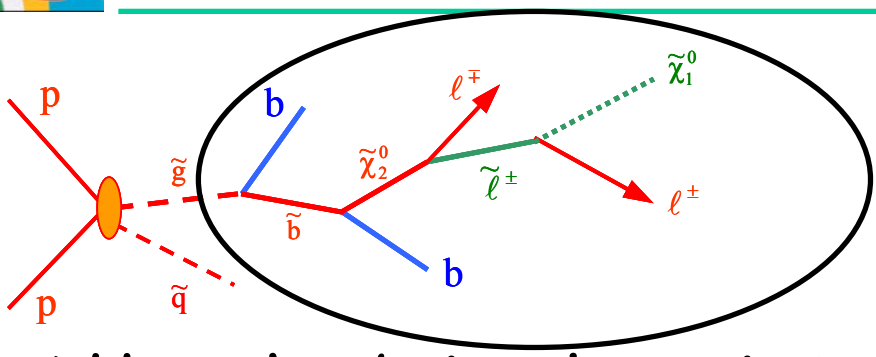
$\sigma \times$ BR dominates

Point B



Mass (GeV)

$\tilde{g}$ Reconstruction



BR ~ 1%

Add another b-jet closest in ϕ to reconstruct $\tilde{g}$

& $400\ \text{GeV} < M(\tilde{b}) < 600\ \text{GeV}$

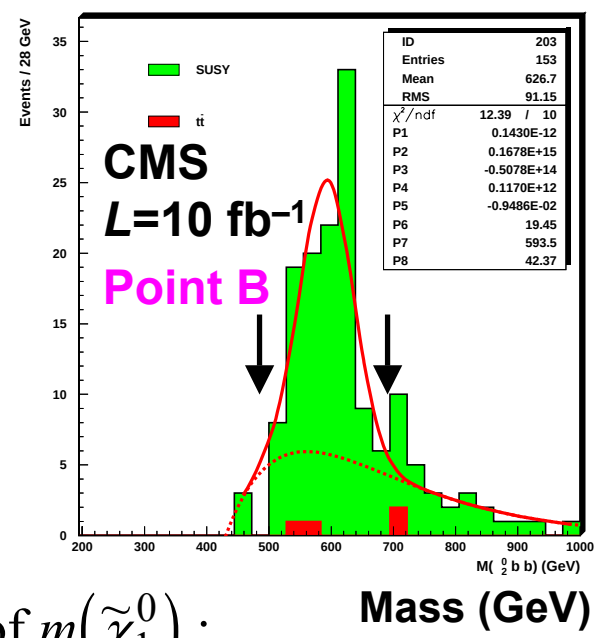
Result of fit:

$M(\tilde{g})$ = 594±7 GeV

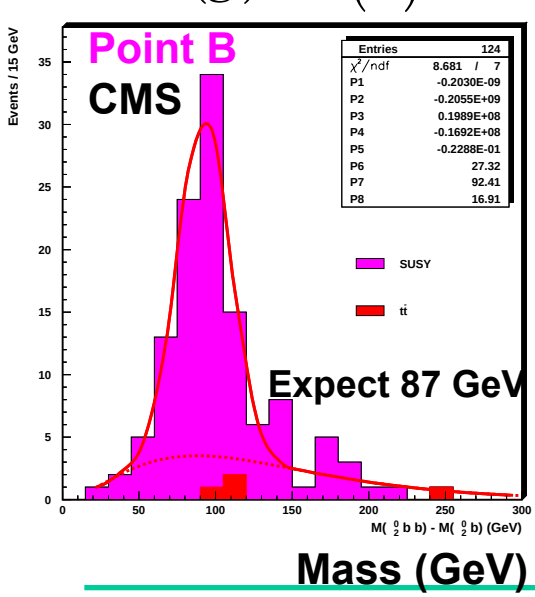
σ_M = 42 GeV

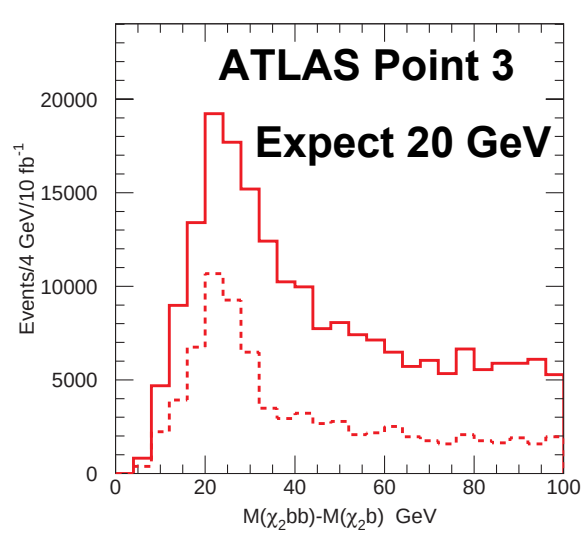
Generated mass:

$M(\tilde{g})$ = 595 GeV

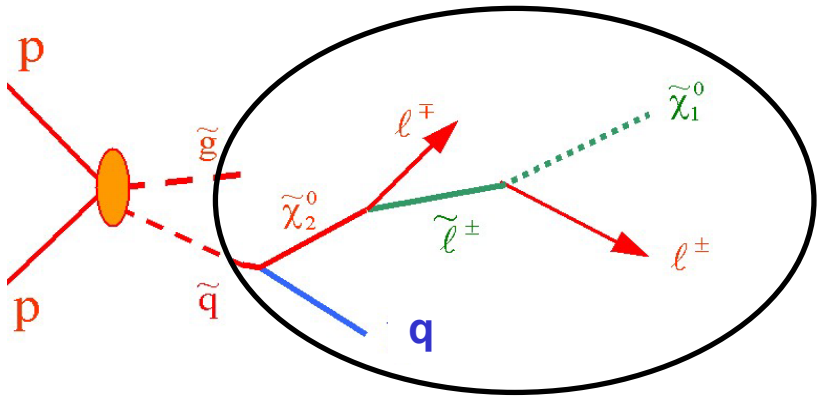


➔ $m(\tilde{g}) - m(\tilde{b})$ is independent of $m(\tilde{\chi}_1^0)$:





$\tilde{q}$ Reconstruction



BR ~ 5%

Same di-lepton edge selection as before

Two jets with p_T>20 GeV, $|\eta|$<2.4

MET > 100 GeV

Veto all b-jets

- ➔ Track with second largest IP significance < 2σ
- ➔ Helps reject sbottom and stop decays

Less luminosity required (1 fb^{-1})

Result of fit:

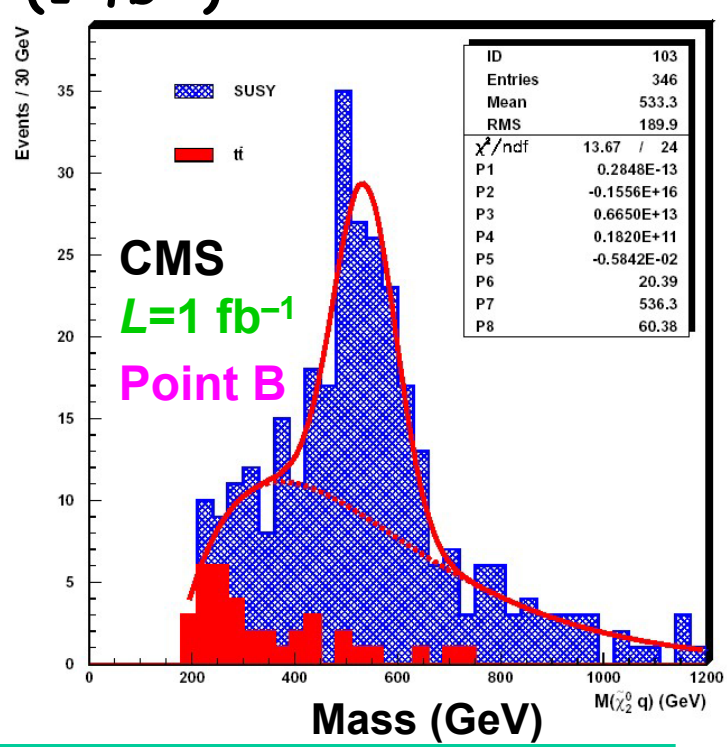
$M(\tilde{q})$ = 536±10 GeV

σ_M = 60 GeV

Generated masses:

$M(\tilde{q}_L)$ = 543 GeV

$M(\tilde{q}_R)$ = 537 GeV



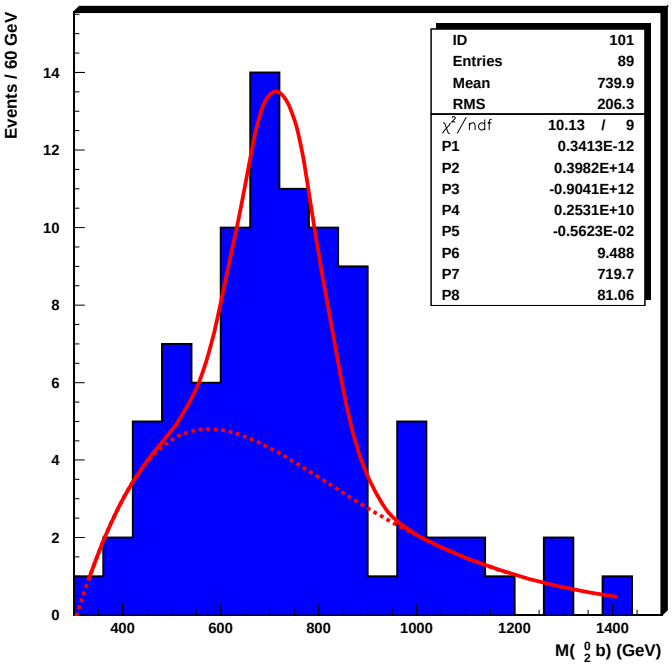
Point G Reconstruction

Cross section 10× smaller
Smaller branching ratios

} Require 300 fb^{-1} >1 year @ 10^{34}

→ $E_{b\text{-}jet}$>350 GeV, MET>350 GeV

sbottom



Result of fit:

$M(\tilde{b})$ = 720 ±26 GeV

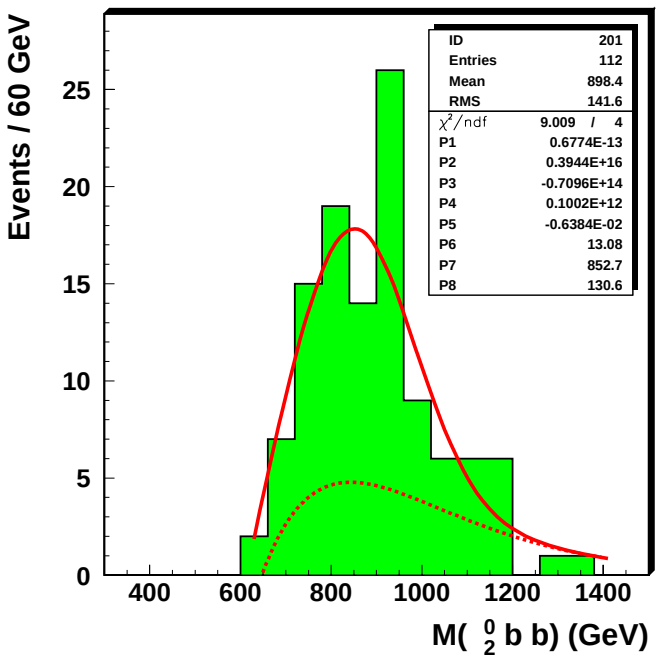
σ_M = 81 GeV

Generated masses:

$M(\tilde{b}_L)$ = 702 GeV

$M(\tilde{b}_R)$ = 748 GeV

gluino



Result of fit:

$M(\tilde{g})$ = 850±40 GeV

σ_M = 130 GeV

Generated mass:

$M(\tilde{g})$ = 860 GeV

Can mSUGRA Escape LHC?

M.Battaglia et al., Eur.Phys.J. C22 (2001) 535 (hep-ph/0106204) proposed several SUSY benchmark points in the post-LEP era

Two of them would lead to sparticles beyond the reach of the LHC except for a light Higgs

→ squark/gluino masses > 2.5 TeV

But most other points covered well

Prospective observability at the LHC

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)	+	+	+	−	+	+	+	+	+	+	−	+	+
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
$\chi_i^0/\chi_j^\pm$	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

↑ Sparticles reconstructed in 10 fb^{-1}

↑ Sparticles reconstructed in 300 fb^{-1}

X ↑ Di-lepton edge not observable

X

If SUSY exists, prospects at LHC look favorable

LHC Summary

Discovery of SUSY, if it exists, is almost assured at the LHC

- → Inclusive mSUGRA squark/gluino discovery reach to 1.5 TeV with 1 fb^{-1}, 2.5 TeV with 100 fb^{-1}
- → Difficult part will be untangling decay chains and measuring mass relations

Possibility to reconstruct squark/gluino/neutralino decays in mSUGRA for several prototype analyses

- → Mass resolution <10% under some assumptions
- → Generally require $\tan\beta<35$
- → Generally require much more data (years)

Trigger strategies identified for efficient coverage

Many more exhaustive SUSY studies at the LHC experiments are available:

- → ATLAS TDR 15 CERN/LHCC 99-15
- → CMS Note 1998/006

Looking forward to studying SUSY spectroscopy before the end of the decade !

Minimal GMSB

Gauge Mediated Symmetry Breaking

- Uses SM gauge interactions instead of gravity to break SUSY
  - Solves FCNC problem
- SUSY breaking scale much less than mSUGRA scale $\sqrt{F} << 10^{11}$ GeV
- Particles get mass from SM gauge interactions at a messenger scale $M_m \sim O(1000\ \text{TeV}) << M_{Pl}$
- n = number of SU(5) messenger fields
  $\Lambda = F / M_m \sim 100$ TeV

$\tilde{G}$ is LSP ($m << 1$ GeV)

NLSP: $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma \quad (n=1,\ \text{low}\ \tan\beta)$

$\tilde{\ell} \rightarrow \tilde{G}\ell \quad (n>1,\ \text{high}\ \tan\beta)$

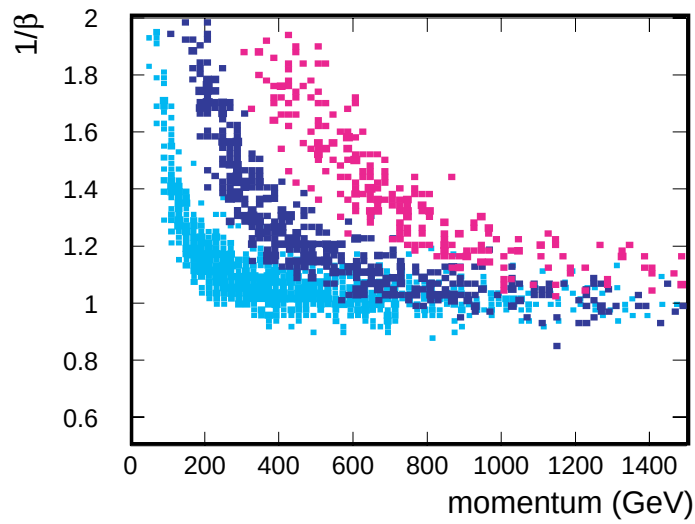
- NLSP lifetime:

$$c\tau \sim 1.3\ \text{m}\left(\frac{100\ \text{GeV}}{M_{\text{NLSP}}}\right)^5\left(\frac{\sqrt{F}}{1000\ \text{TeV}}\right)^4$$

- $c\tau$ >> detector size
  - slepton ($\tilde{\tau}$) is a long-lived heavy lepton (like μ)
  - neutralino leads to MET, like MSSM
- $c\tau$ ~ detector size
  - Measure NLSP lifetime
  - Estimate F
- $c\tau$ << detector size
  - radiative decay with γ

GMSB Heavy Lepton ($\tilde{\tau}$) Search

Use drift-tube muon systems of ATLAS and CMS to measure time-of-flight for heavy leptons (σ ~ 1ns)



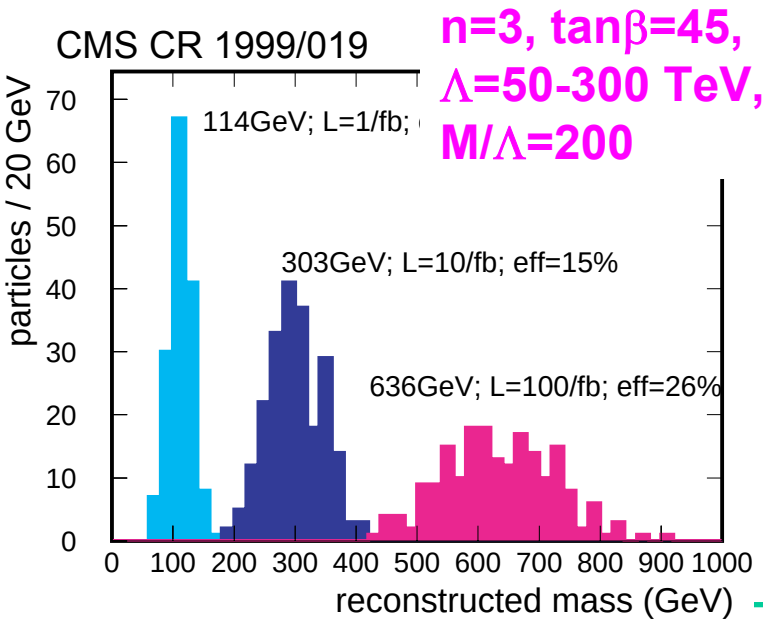
➔ Measure $1/\beta$ and $p \Rightarrow$ reconstruct mass

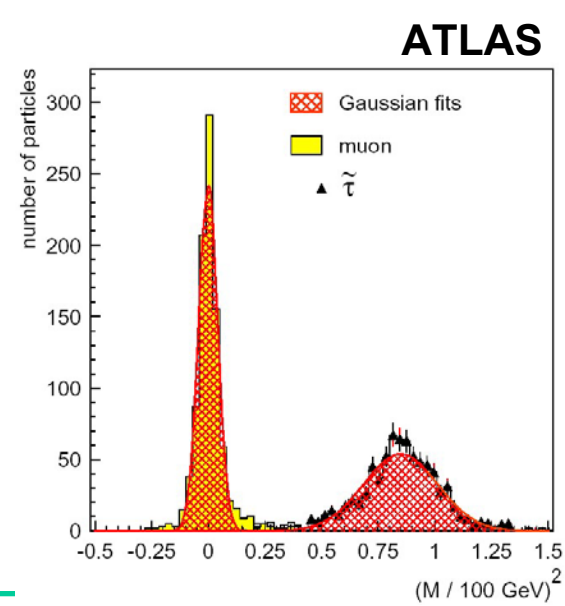
CMS:

➔ Require 2 "muons" with P_T>45 GeV, M>97 GeV

➔ $|\eta|$<1 for CMS drift-tube system

➔ Can measure stau mass from 90–700 GeV:





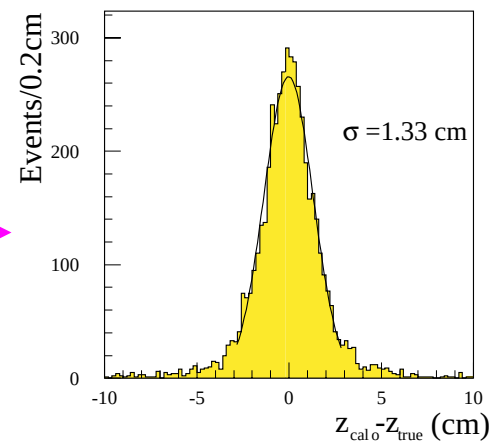
GMSB $\tilde{N}_1$ Lifetime Measurement

Look for $\tilde{N}_1$ decays inside detectors:

1) Electromagnetic showers not pointing to vertex

- ➔ Use fine angular resolution from LAr EM calorimeter (ATLAS) and $PbWO_4$ crystals (CMS)

ATLAS vertex resolution for $H \rightarrow \gamma\gamma$ ⟶

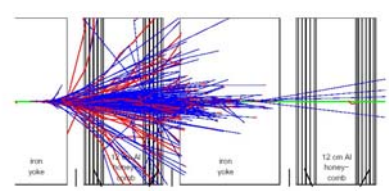
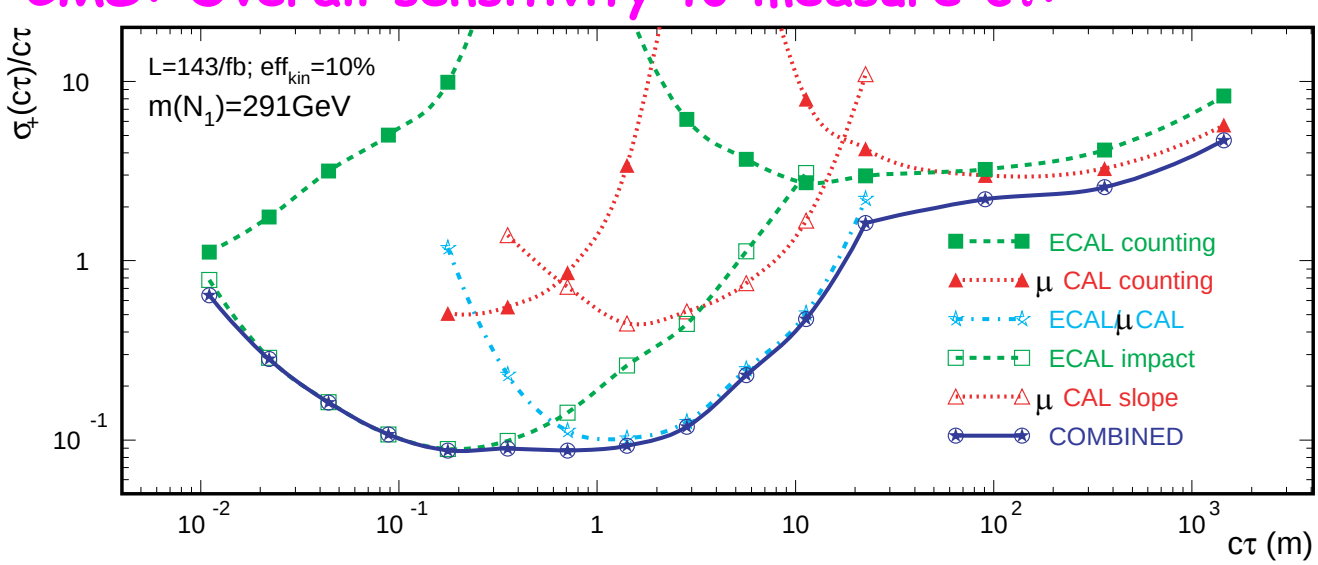


- ➔ ATLAS: if no non-pointing γ's in 30 fb^{-1} $\Rightarrow$ $c\tau$ > 100km

(Λ=90 TeV, M = 500 TeV, n=1)

2) Showers in muon system

- ➔ Identify showers with high hit multiplicity



CMS: Overall sensitivity to measure $c\tau$: