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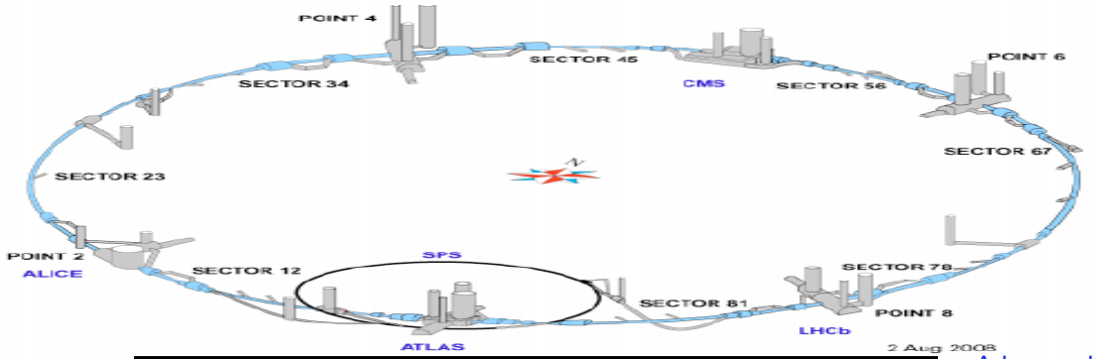

SUSY at LHC

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CMS/ATLAS Search I'm Feeling Lucky

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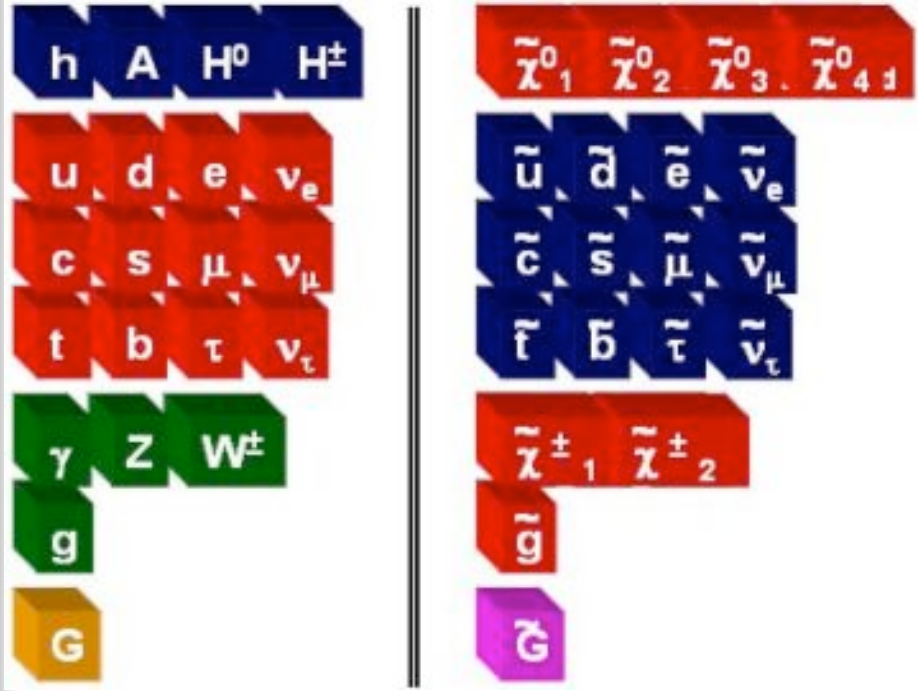
Outline

- Theoretical background
  - What is SUSY?
- Experimental apparatus
  - Highlights of the CMS and ATLAS experiments
- Strategy
  - SM background, inclusive searches, specific measurements
- Conclusions

What is SUSY?

- ***SUSY*** (or supersymmetry): each fermion has a boson superpartner, and vice versa.
  - ***Solves hierarchy*** *and fine-tuning problems in SM*
  - ***SUSY is broken****: sparticles not seen (sparticles heavier than particles)*
- ***MSSM****: Simplest SUSY model consistent with SM*
  - *R-parity conservation*
    - $R=(-1)^{2S+3B+L}$
    - *Sparticles produced in pairs, decay to an odd number of LSPs*
    - ***Lightest sparticle (LSP) stable***
      - ***dark matter candidate***
  - *Soft SUSY breaking*
    - *mSUGRA, GMSB, AMSB*



SUSY phenomenology

mSUGRA

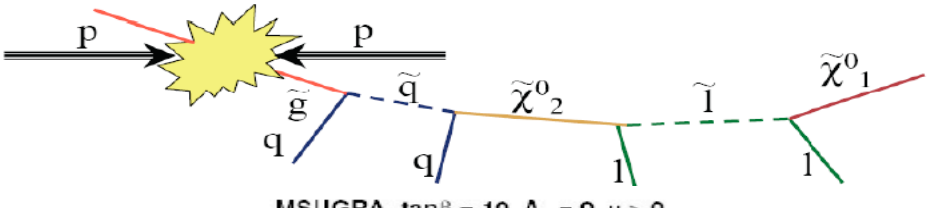
- gluino/squark production and cascade decay
- neutralino χ_1^0 is the LSP
- Parameters: m_0, $m_{1/2}$, A_0, tanβ, sgn(μ)

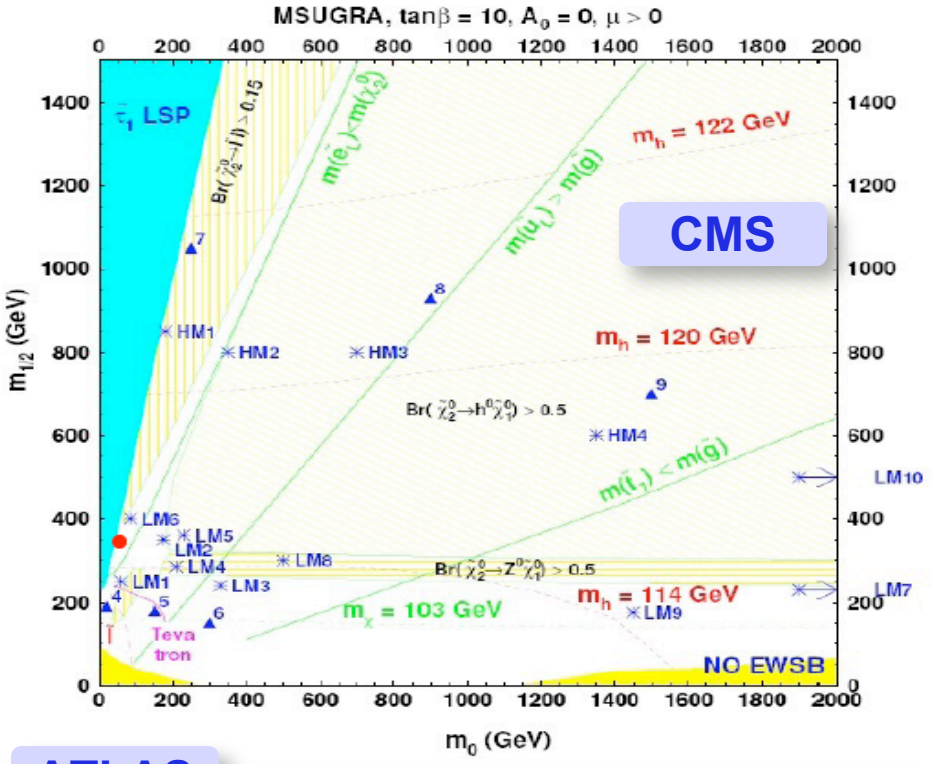
GMSB

- gravitino is the LSP
- NLSP neutralino→gravitino+γ
- NLSP slepton→gravitino+lepton
- Parameters: N, Λ, tanβ, M_m, sgn(μ)

Analysis Strategy

- *Typical SUSY events have:*
  - *very energetic jets*
  - *large missing E_T (ν)*
  - *leptons, photons*
- Study a set of benchmark points
  - *cover well the phase space beyond Tevatron limits*





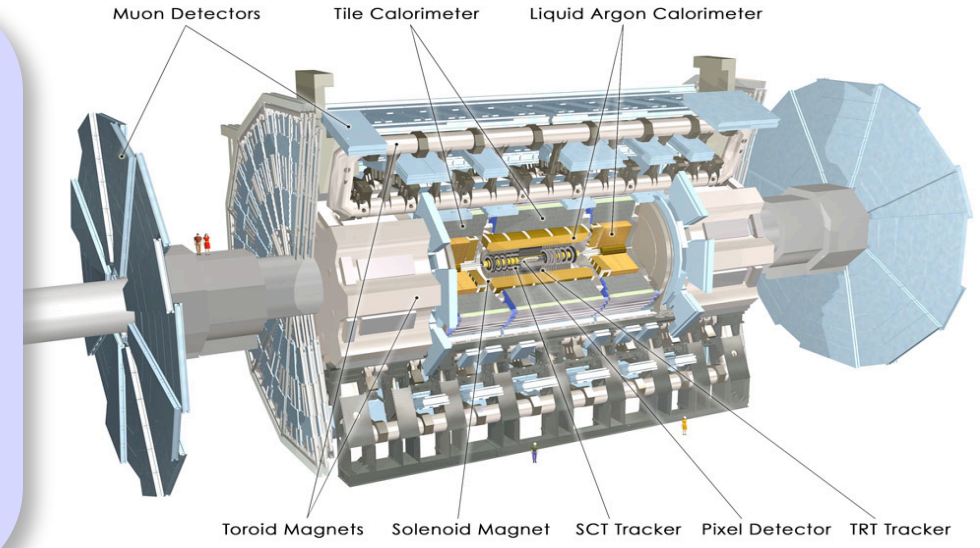
ATLAS

	SU1	SU2	SU3	SU4	SU8
m_0	70	3550	100	200	210
$m_{1/2}$	350	300	300	160	360
A_0	0	0	−300	−400	0
$\tan\beta$	10	10	6	10	40
$\mathrm{sign}\,\mu$	+	+	+	+	+

CMS and ATLAS experiments

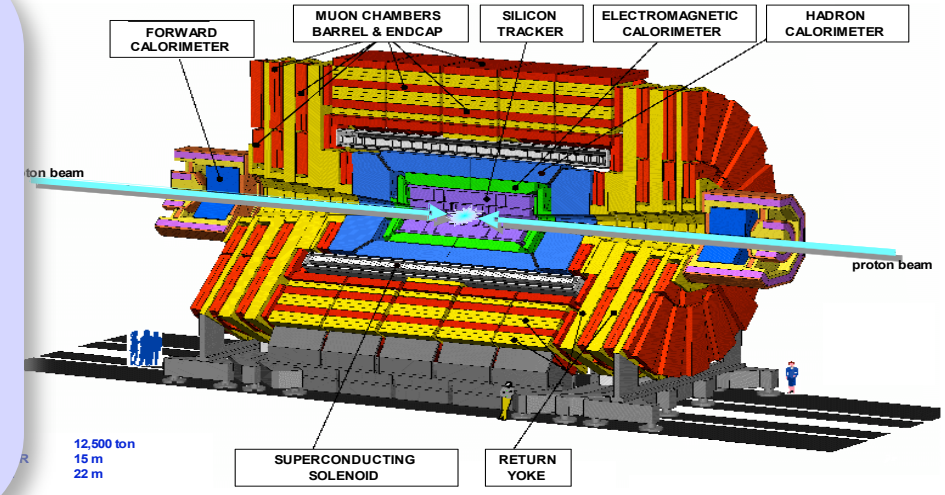
ATLAS detector highlights

- Magnetic field: 2T solenoid + toroid (0.5T barrel, 1T endcap)
- Inner Tracker: Si (pixels, strips) +TRT
  - $\sigma/p_T \sim 5\times10^{-4} p_T \oplus 0.001$
- EM Calorimeter: LAr+Pb
  - $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$
- HAD Calorimeter: Fe+scint/Cu+Lar
  - $\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$
- Muon: drift tube/cathode strip/resistive plate
  - $\sigma/p_T \sim 10\%$ @ 1TeV/c



CMS detector highlights

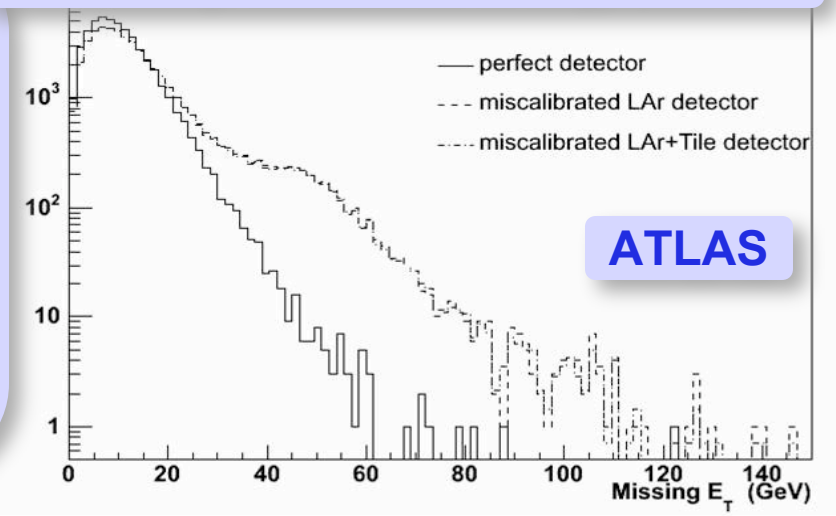
- Magnetic field: 4T solenoid + return yoke
- Inner Tracker: Si (pixels, strips)
  - $\sigma/p_T \sim 1.5\times10^{-4} p_T \oplus 0.005$
- EM Calorimeter: PbWO4 crystals
  - $\sigma/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
- HAD Calorimeter: Brass+scintillator
  - $\sigma/E \sim 100\%/\sqrt{E} \oplus 5\%$
- Muon: drift tube/cathode-strip/resistive plate
  - $\sigma/p_T \sim 5\%$ @ 1TeV/c



MET clean-up

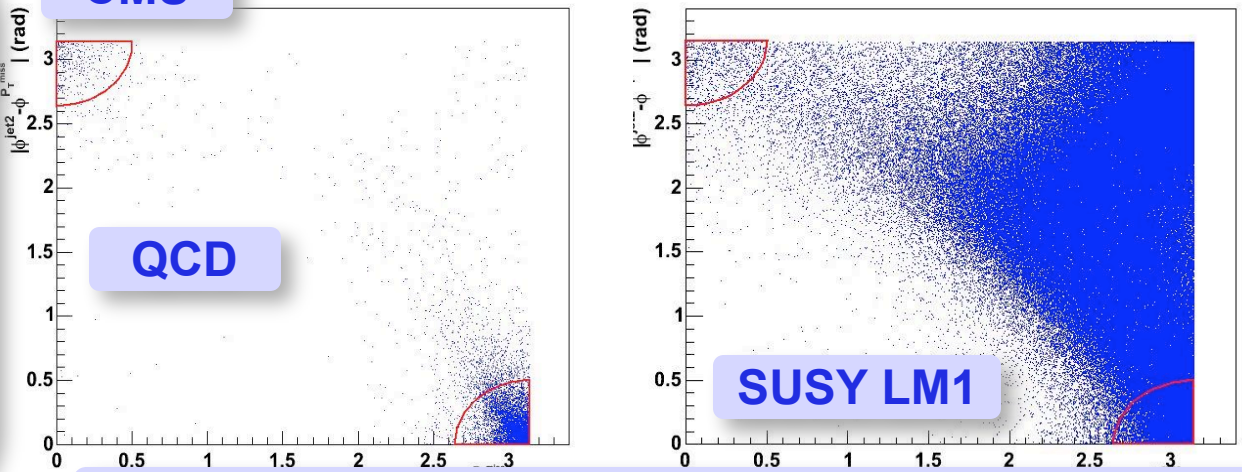
- ***Missing Transverse Energy*** (MET) is the discriminating observable for SUSY search
- *Crucial to fully understand its background sources*
  - cracks, cosmics, beam halo, electronic noise, SM processes
- **CMS** clean-up cuts
  - EEMF = $(\Sigma P_t^{jets} EMF^{jets})/(\Sigma P_t^{jets}) > 0.1$
  - ECHF = $<(\Sigma P_t^{tracks})^{jet}/P_t^{jet})>_{jets} > 0.175$

Missing Transverse Energy (MET)



- **Clean-up fake MET**
- Fake MET along jets
  - mis-measurements, noise, dead cells, backgrounds
- "True" MET comes from LSP, ν
- *Removes ~80% QCD*
- *Keeps ~90% SUSY*

CMS



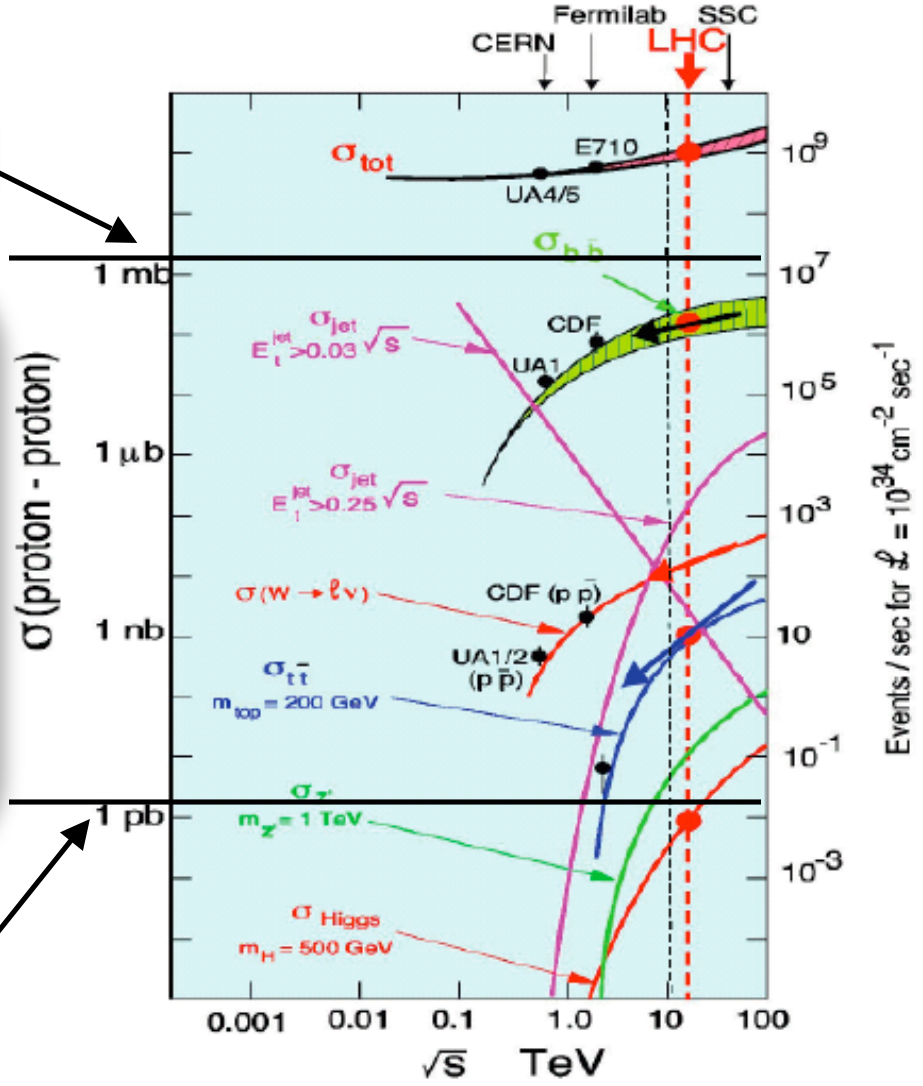
Δφ between jets and MET vector for jet 1 and jet 2

SM background

- *SM processes are dominant*
  - QCD cross-section ~ 5.6×10^{10} pb
  - Z+jets cross-section ~ 15×10^{3} pb
  - Ttbar cross-section ~ 800 pb
  - SUSY LM1 cross-section ~ 42 pb
- *Develop data-driven methods to estimate the backgrounds*
  - Minimizes systematic errors from differences between data and MC
  - Self-calibrating

SM QCD

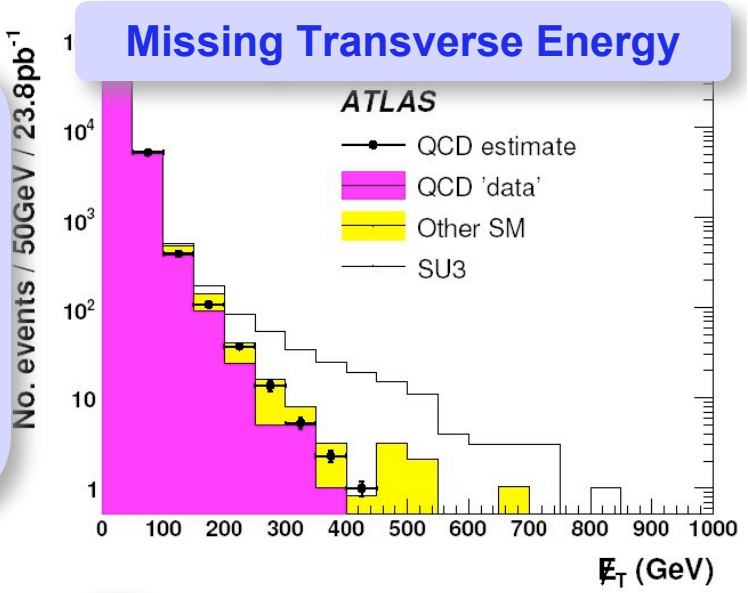
SUSY LM1



QCD background

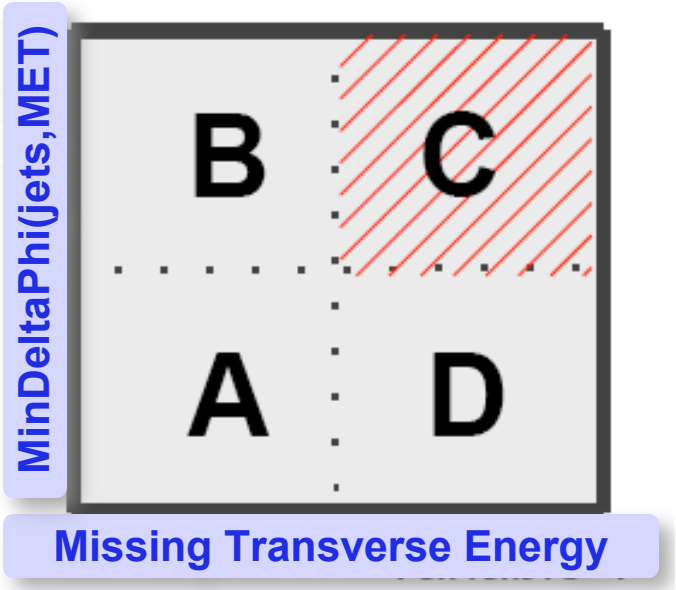
Smearing Method

- Select multi-jet events with MET along one of the jets
- *Define response* $R=1-p_T^{jet}\cos(jet,MET)\,/|p_T^{jet}+MET|^2$
- *Parametrize R* in a subset of events *MET > 60 GeV*
- *Smear jets with R in events from orthogonal subset*
- Normalize to size of QCD data with low MET

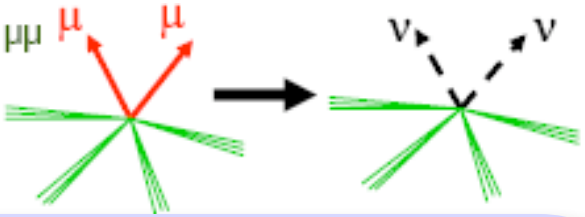


ABCD Method

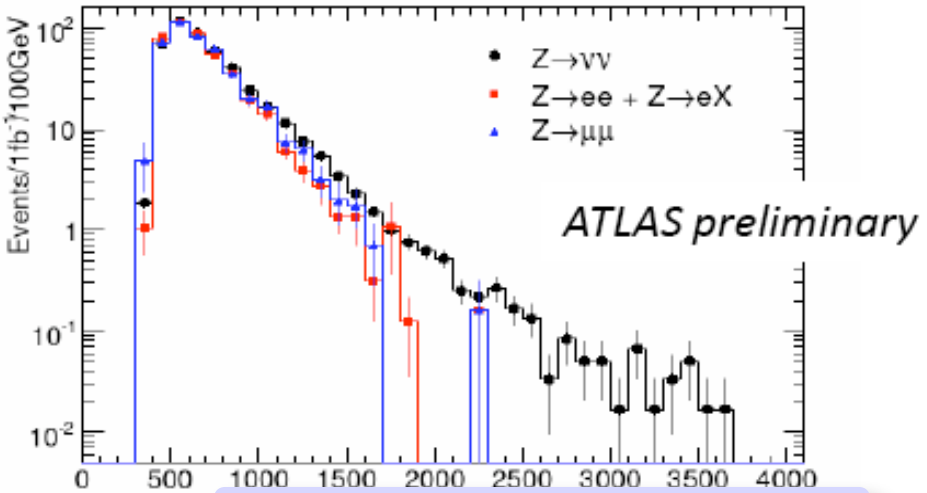
- Find two observables *uncorrelated for QCD*
- Divide the plane in four regions A,B,C,D
  - C is the signal region
- *The numbers of QCD events satisfy: C = D x B/A*
- It is crucial to have *little signal content* in the other 3 regions
  - *Difficult to find such observables*
  - *Otherwise need to remove signal from A,B,D*



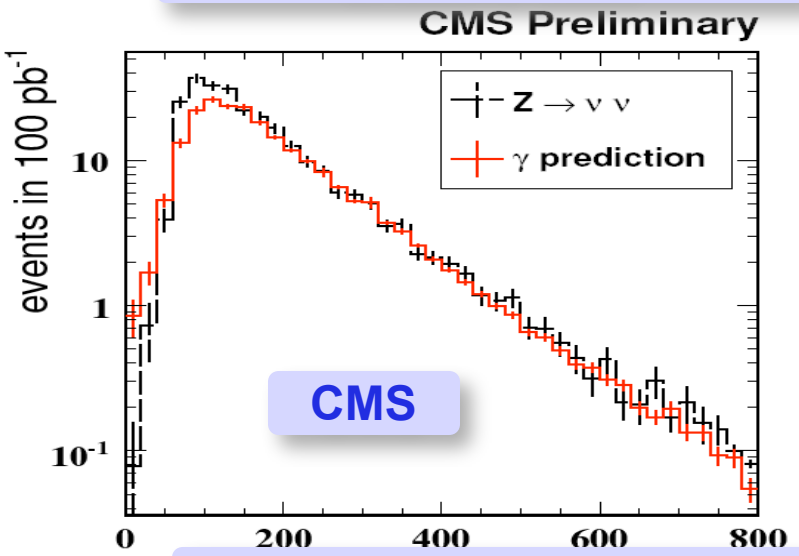
Z->νν background



- ***Use Z(→ee or μμ)+jets events***
  - Lepton ID efficiency determined in data (tag&probe method)
  - Cons: small cross-section
  - Pros: little background, low systematics
  - *5% accuracy with 1.5 fb^{-1}*
- ***Use photon+jets events***
  - After removing photon, similar shape for MET > 150 GeV
  - Pros: Large cross-section
  - Cons: uncert. on normalization
  - *10% accuracy with 100pb^{-1}*



Effective Mass



Missing Transverse Energy

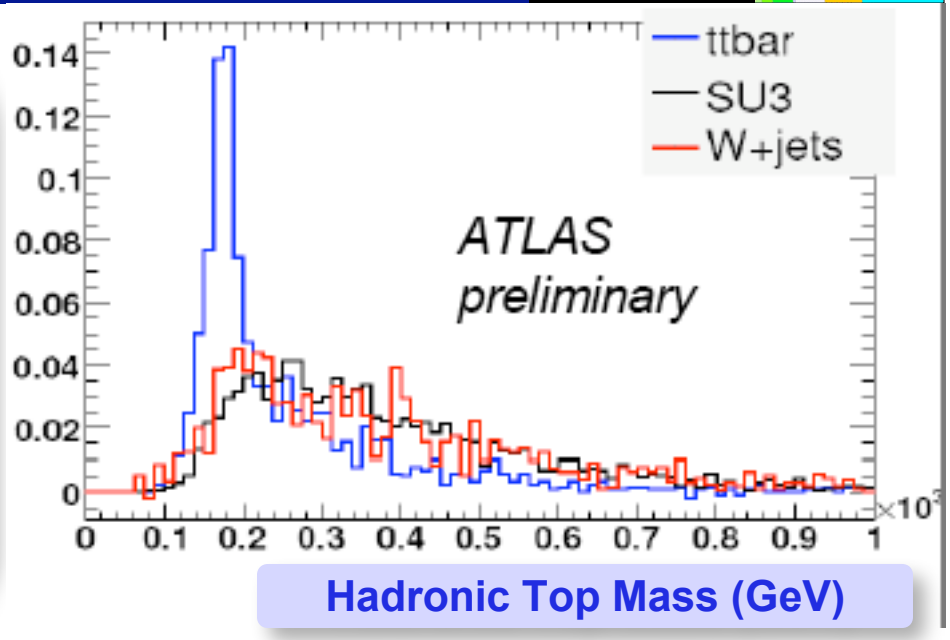
Ttbar background

Semileptonic ttbar

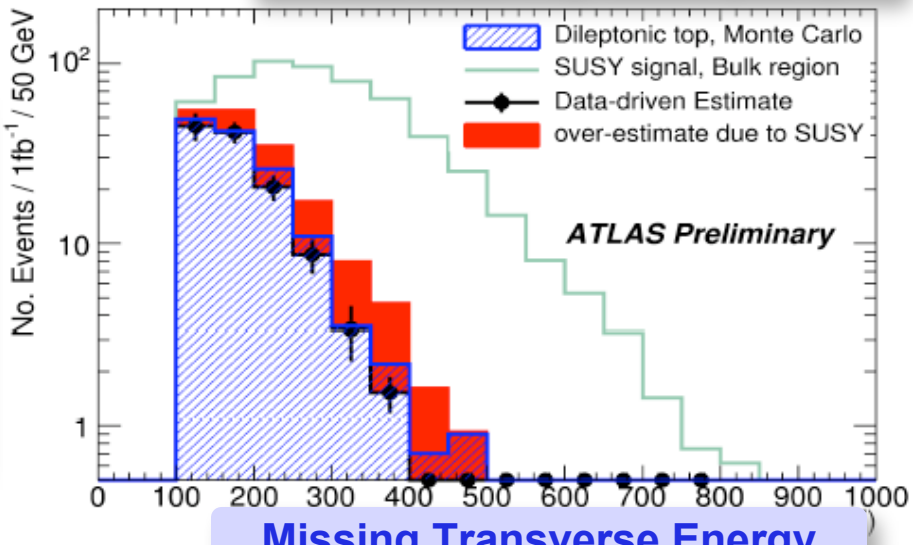
- W bosons and top quarks from jet pairs and triplets with masses closest to world averages
- Control sample in data
  - M_{top} within 25 GeV of world avg
  - M_W within 15 GeV of world avg
- Extrapolate to signal region using simulation

Dileptonic ttbar

- One lepton not seen
  - Hadronic τ, out-of-acceptance, inside jet
- Control sample
  - 2 leptons, 3 jets
  - Remove 1 lepton
  - Remove SUSY with MC
- Normalization in low MET region



Hadronic Top Mass (GeV)



Missing Transverse Energy

Inclusive searches

- Analyses covered in this talk:
  - Jets+MET
  - Dijets
  - Jets+MET+leptons
  - Same-sign muons
  - Trileptons

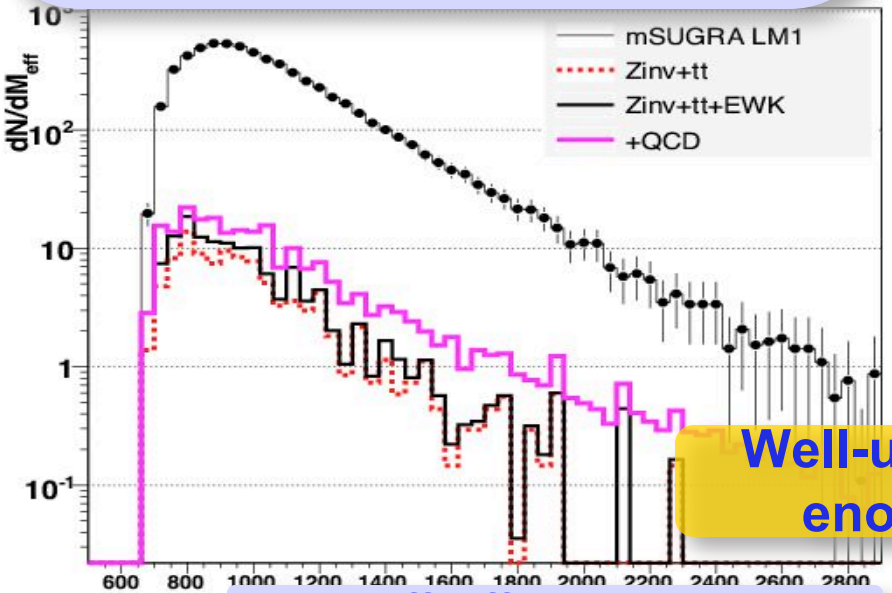
Jets+MET+0 leptons

CMS event selection

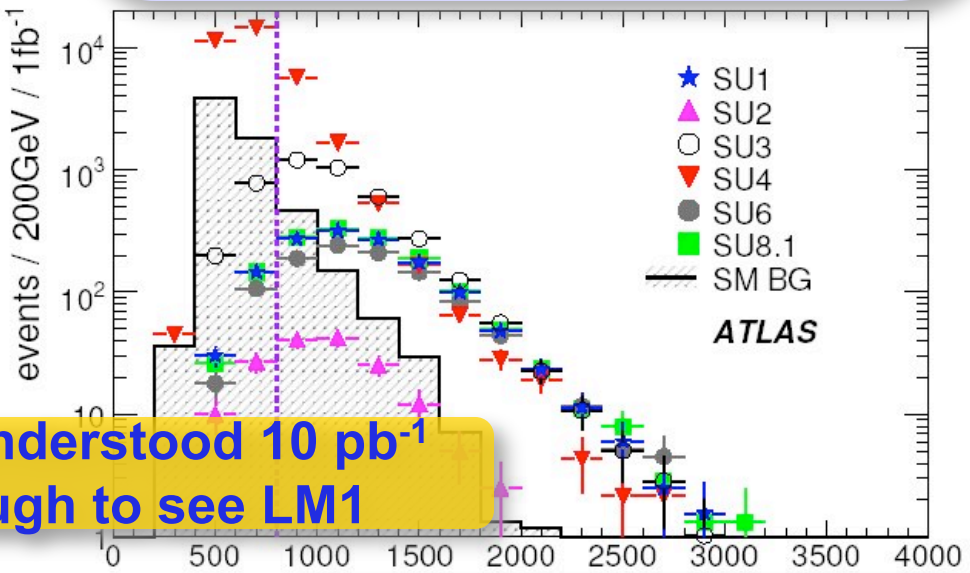
- Trigger
  - L1 HT (sum of L1jets) > 200 GeV
  - HLT HT>350 GeV & MET>65 GeV
- Offline
  - At least 3 jets: 180, 110, 30 GeV
  - $|\eta| < 3$, $|\eta_{1st\ jet}|<1.7$, EM fraction<0.9
  - QCD rejection: angle of jets & MET
  - Veto on loosely isolated tracks
  - MET > 200 GeV and HT > 500 GeV

ATLAS event selection

- Trigger
  - jet Pt>70 GeV, MET > 70 GeV
- Offline
  - At least 4 jets: 100, 100, 50, 50 GeV
  - Transverse sphericity > 0.2
  - Veto on electrons/muons
  - MET > 100 GeV
  - MET/Meff > 20%
    - Meff=HT+MET



Meff (effective mass)

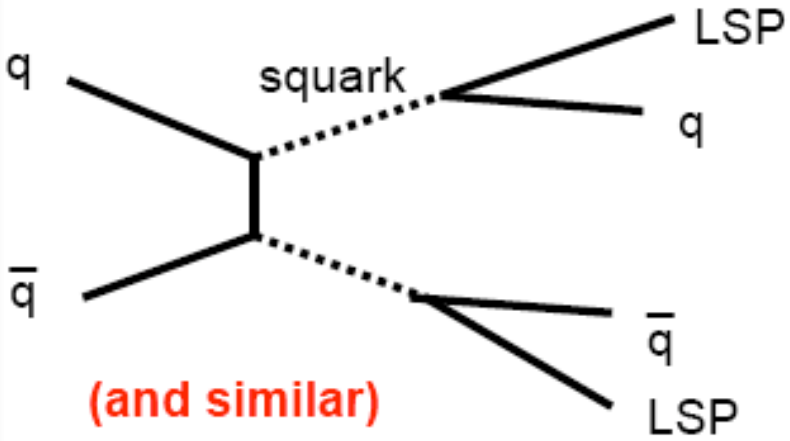


Meff (effective mass)

Well-understood 10 pb^{-1} enough to see LM1

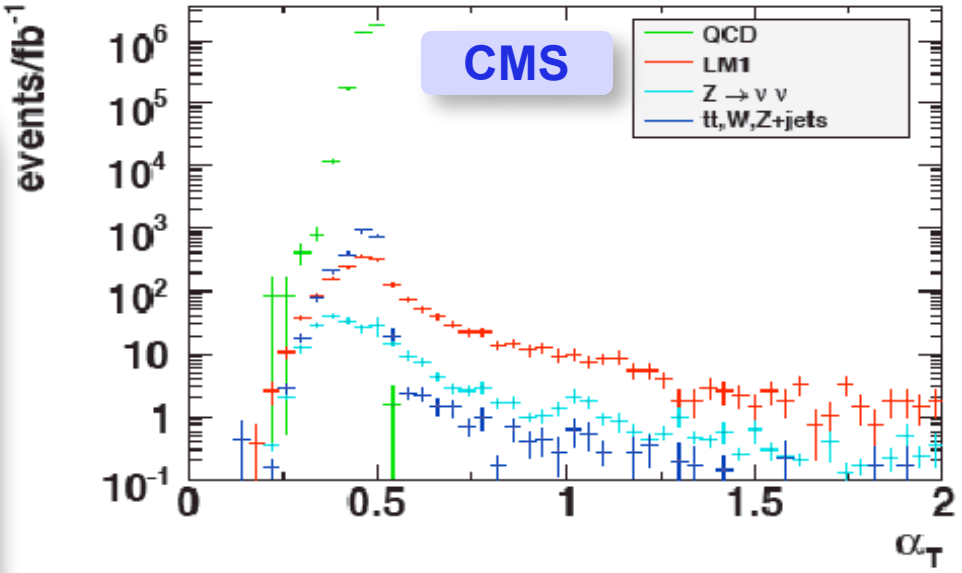
Dijets+0 leptons

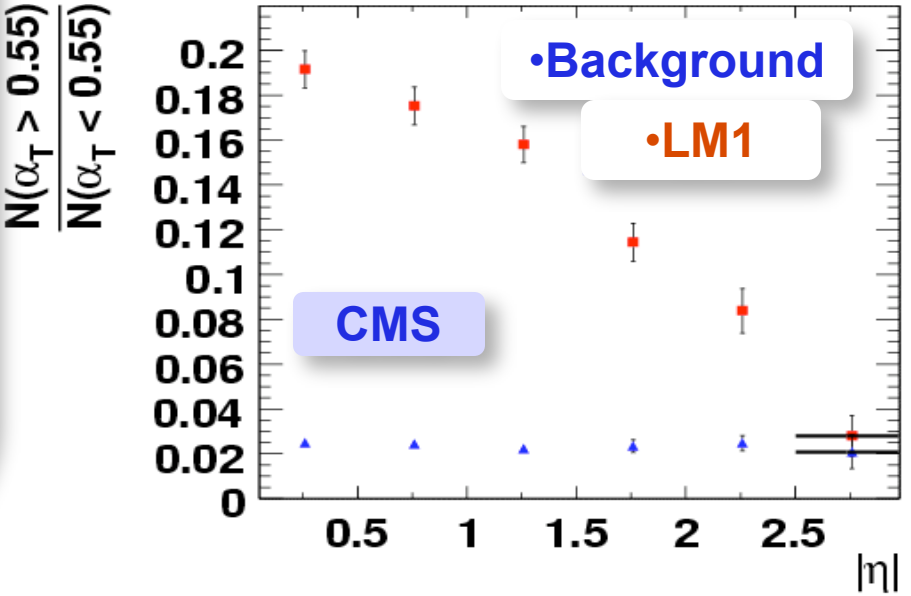
- Extend the search for SUSY in a *new hadronic channel*
  - 2 jets + MET
- Proposed in a recent preprint by L.Randall, D.Tucker-Smith
  - *Two squarks decay straight to two quarks and two neutralinos*
    - Mass squark < mass gluino
- Main background is dijet QCD
  - *Introduce a variable α*
    - $\alpha = E^{2nd\text{-}jet}/M(j1,j2)$
  - *Expect α < 0.5 for QCD*
- Possibility to constrain the squark and neutralino masses



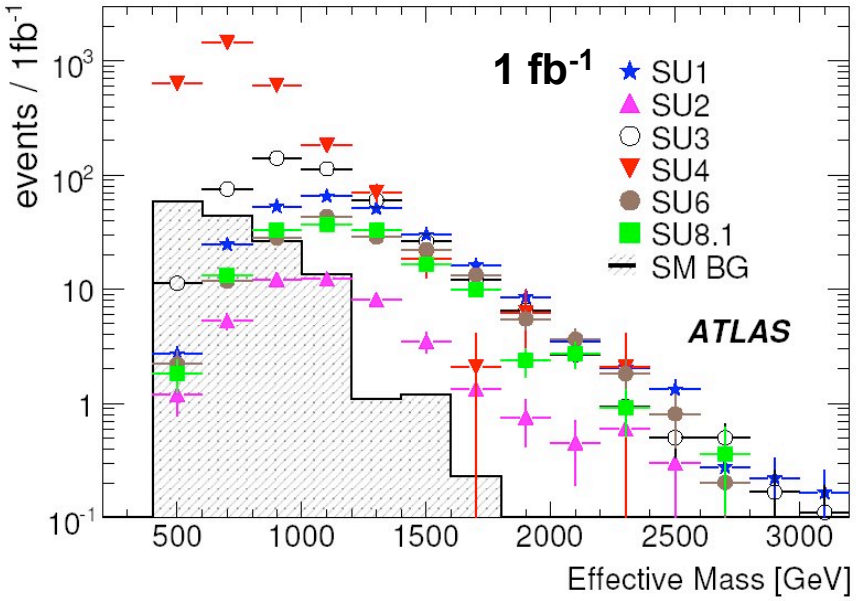
Dijets+0 leptons

- *Event Selection*
  - 2 jets with Pt > 50 GeV
    - 3rd jet Pt < 50 GeV
  - Lepton Pt < 10 GeV
  - HT > 500 GeV
  - α_T < 0.55 ($\alpha_T = E_T^{2nd\text{-}jet}/M_T(j1,j2)$)
- *No cut on MET!*
- *Background*:
  - Dijet QCD greatly reduced by the cut on α_T
    - Jets mostly back-to-back and well-balanced
  - Z->νν+jets as discussed
  - Others: data-driven method
    - ABCD type with α_T and $|\eta|$
- ***Expect S/B ~ 6***
  - LM1@1fb^{-1} ~400 events



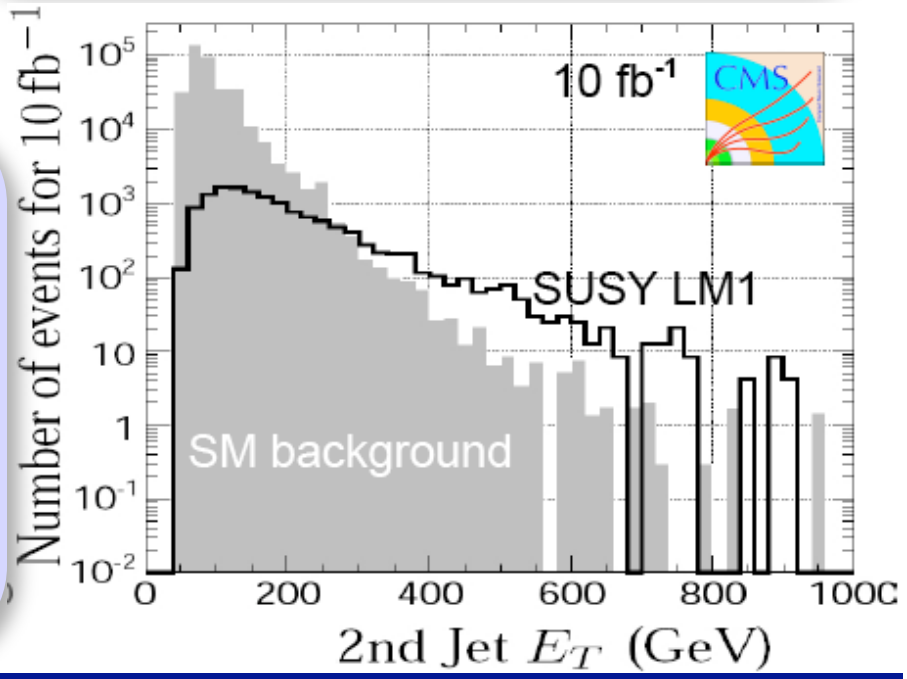


Jet+MET+1 lepton



ATLAS event selection

- 4 jets (>100, 50, 50, 50 GeV)
- MET > 100 GeV, > 0.2 M_{eff}
- S_T > 0.2
- Isolated e or μ, p_T > 20 GeV
- No other e or μ (p_T > 10 GeV)
- M_T (l,ν) > 100 GeV

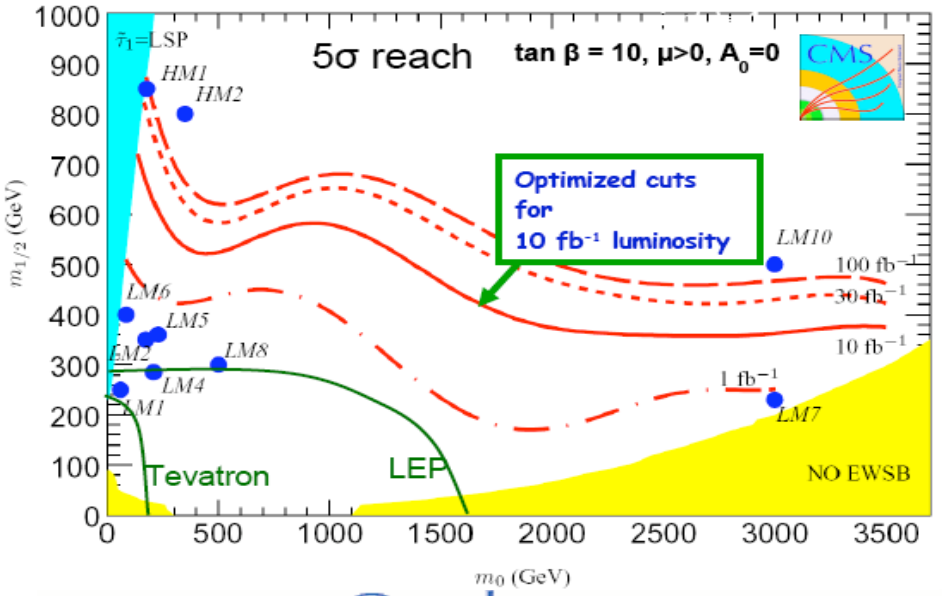


CMS event selection

- Concentrate on muon channel
- Optimised cuts with genetic algorithm
- MET > 130 GeV, E_T^{j1} and E_T^{j2} > 440 GeV
- $|\eta^{j1}| < 1.9$, $|\eta^{j2}| < 1.5$,
- $\cos[\Delta\varphi(j1,j2)]<0.2$, cuts on $\Delta\varphi$(jets,MET)
- ***Excellent sensitivity for all LM benchmark points***

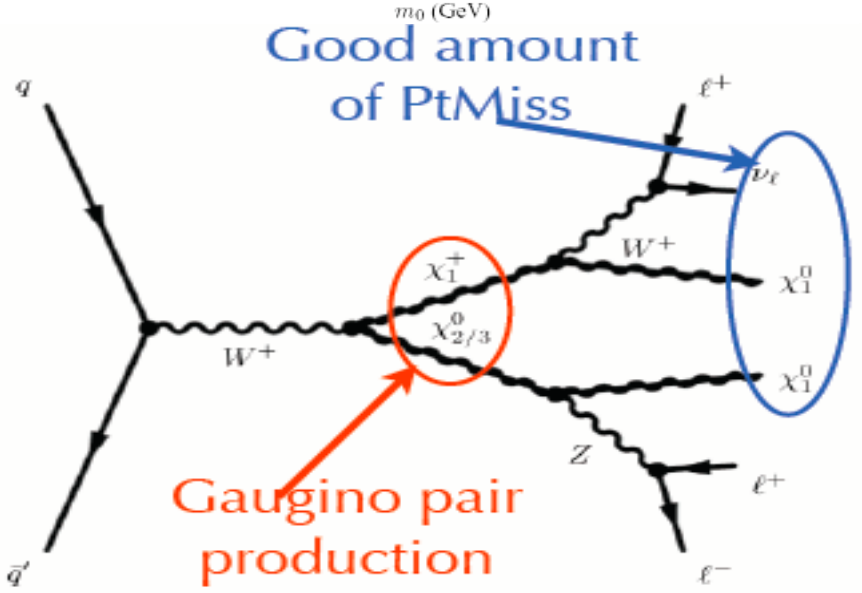
Other leptonic signatures

- *Same-sign dimuons*
  - Rare process in SM, natural in SUSY
  - MET > 100 GeV (ATLAS)
    - 200 GeV (CMS)
  - At least 4 jets Pt >50 GeV
  - 2 isolated SS μ's Pt > 20GeV (ATLAS)
    - 10 GeV (CMS)
  - Backgrounds (ttbar, W/Z+jets, dibosons, QCD) with SS μ from semileptonic decay of b's

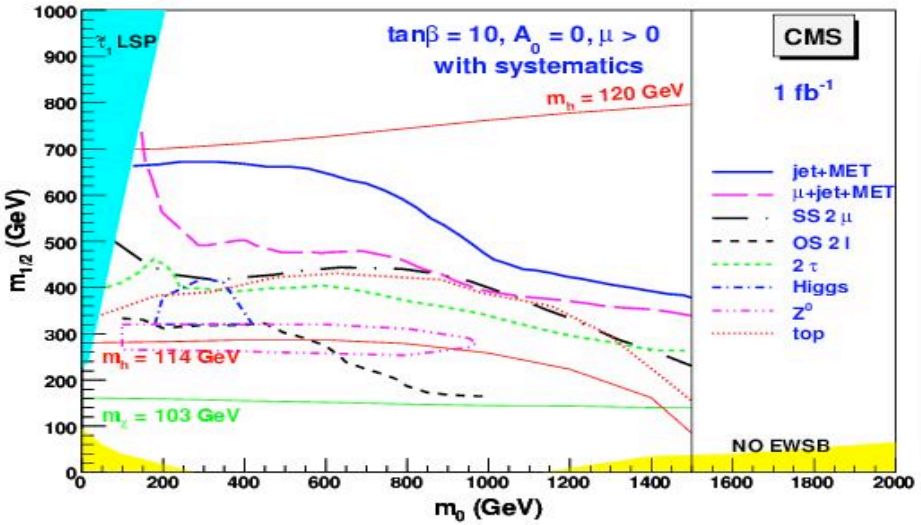


Tri-leptons

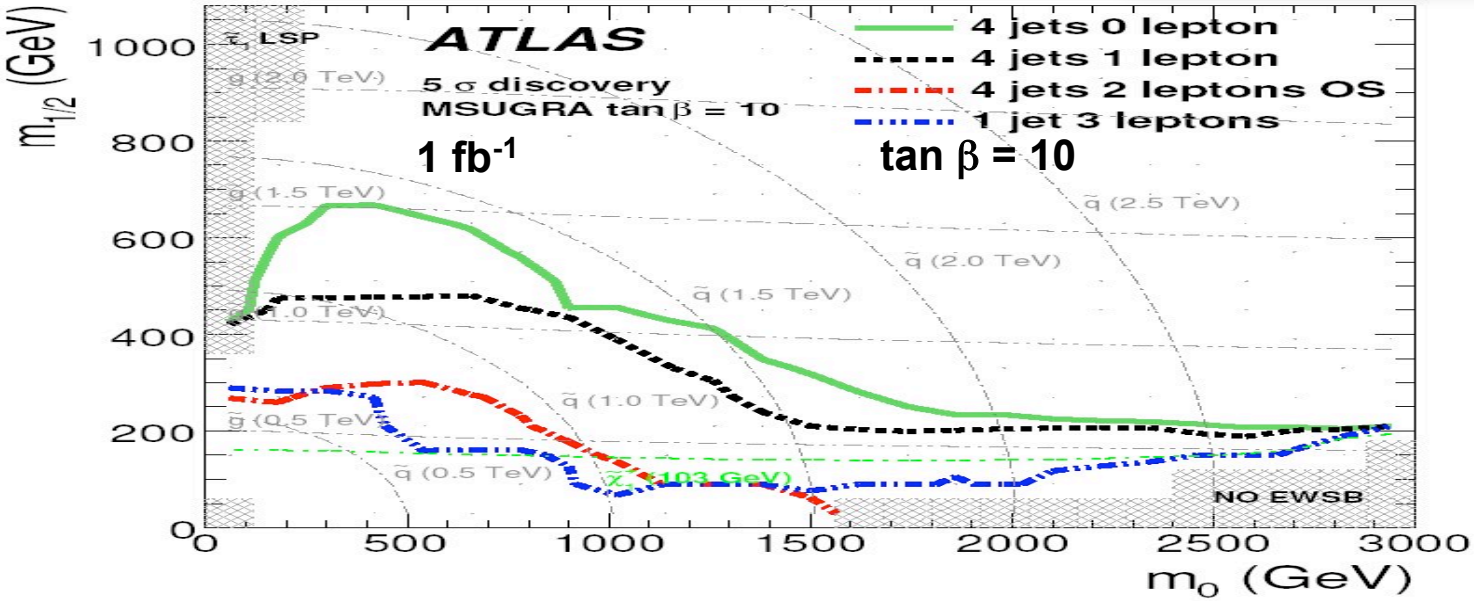
- 3 isolated e,μ Pt>10GeV & MET>30GeV
- Backgrounds: ttbar, Z+b, dibosons
- ATLAS:
  - Studied SU2 ($\chi_1^{\pm} \rightarrow \chi_1^0 l^{\pm}\nu$, $\chi_2^0 \rightarrow \chi_1^0 l^+ l^-$)
  - For 5σ needs ~7 fb^{-1} for inclusive SUSY+direct gaugino production
  - or ~22 fb^{-1} for only direct gaugino prod.
- CMS: LM9 5.8σ with 30 fb^{-1}



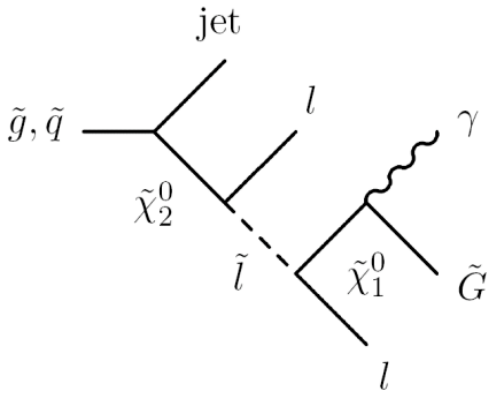
mSUGRA Sensitivity reach

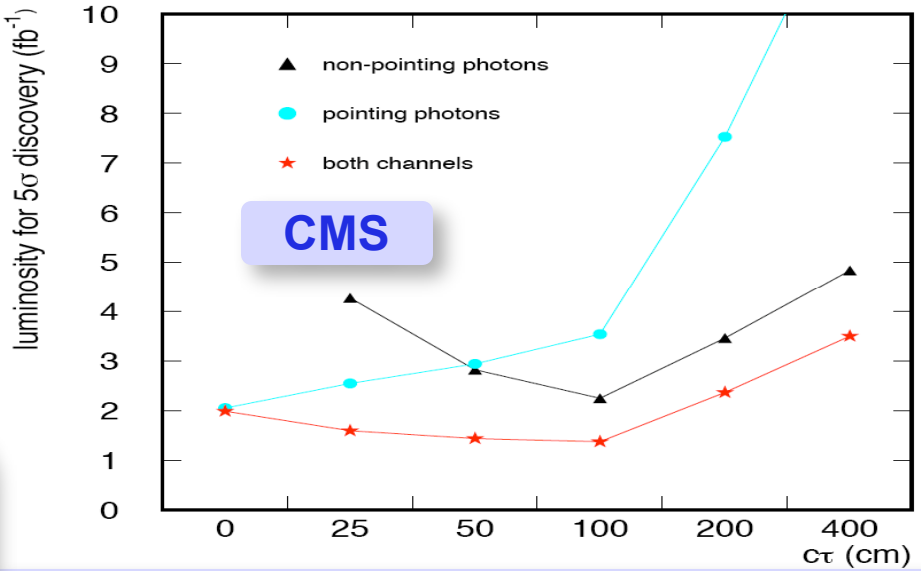


- **The potentials of CMS and ATLAS are very similar.**
- Largely determined by signal and background cross sections
- *With 1 fb^{-1}, we cover a large part of mSUGRA phase space favored by EWK, heavy-flavor, and low energy precision data!*



GMSB: Neutralino is NLSP

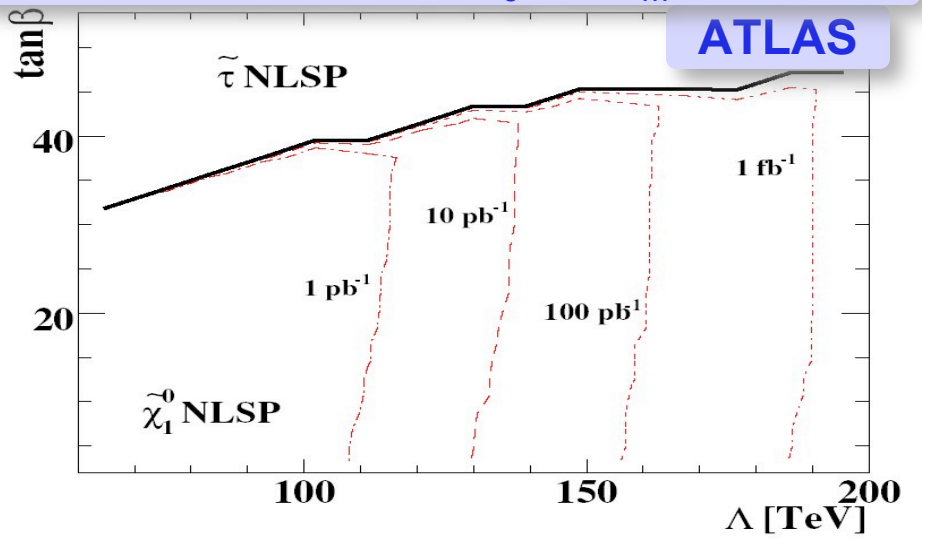




CMS analysis
- Trigger on single photons
- Offline photons with Pt > 80 GeV
- At least 4 jets and large MET
- *Discovery possible with 1fb^{-1}*
  - GMSB SPS8 line: N=1, tan β=1, M=2Λ

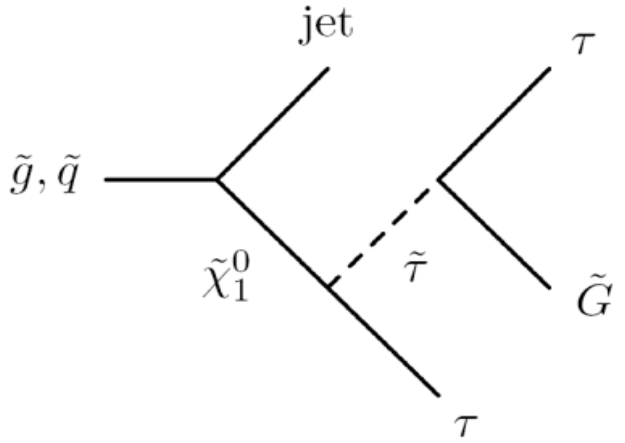
ATLAS analysis
- MET>100 GeV or > 0.2 Meff
- At least 4 jets with Pt > 50 GeV
- Jet1 Pt > 100 GeV
- 2 photons Pt > 20 GeV and |η|<2.5

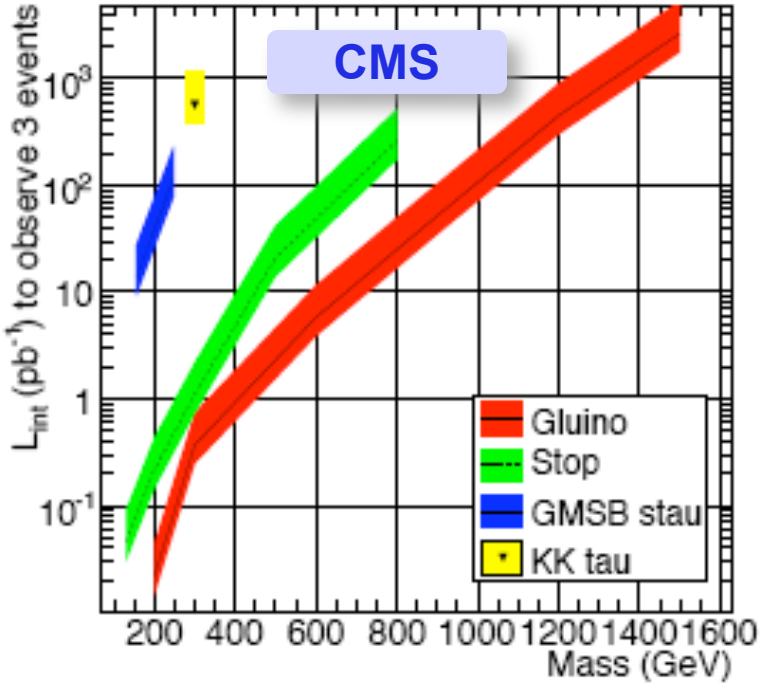
Reach in Λ and tan β (N_5=1, M_m=500 TeV)

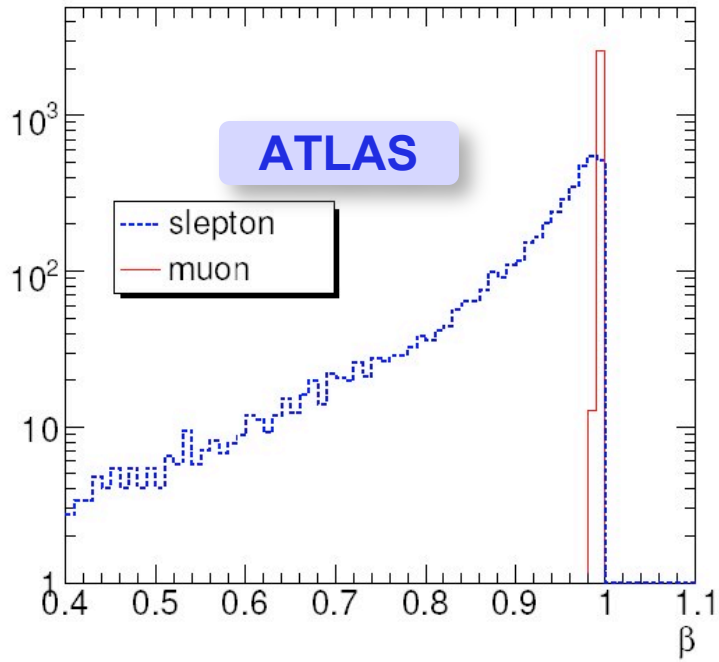


GMSB: Slepton is NLSP

- Slepton is NLSP and decays outside detector
- Massive, semi-stable particles: β could be <1
- SM background flat: β=1
- *Goal: measure β and p → derive mass*
  - $1/\beta$ ~ sqrt(KdE/dx) (K measured from protons)
- 100pb^{-1} enough in the case of a 200 GeV stau





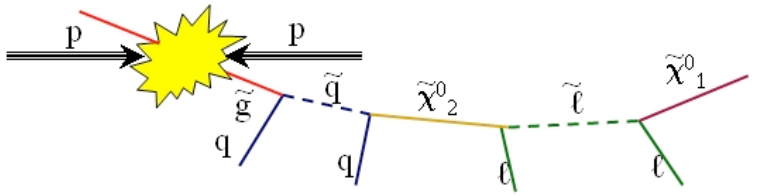


Exclusive searches

- Once an excess is observed: what is the underlying physics?
- Need to measure as many parameters as possible.
- Provide as much input as possible: edges, cross sections, branching fractions, ratio tau's/(e+μ), rate of top and bottom quarks in events, …
  - There will probably still be ambiguities
- *In this talk: only studies involving the masses of the SUSY particles*

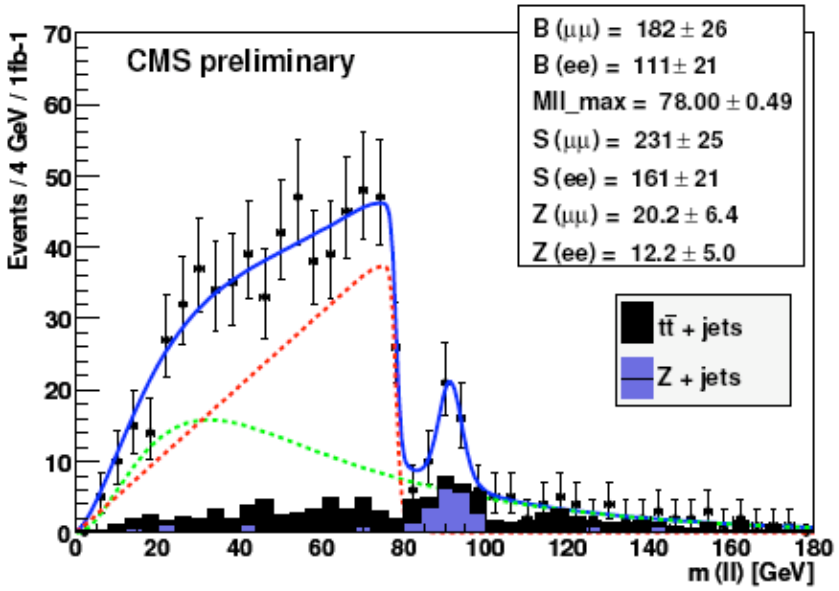
Dilepton mass edge

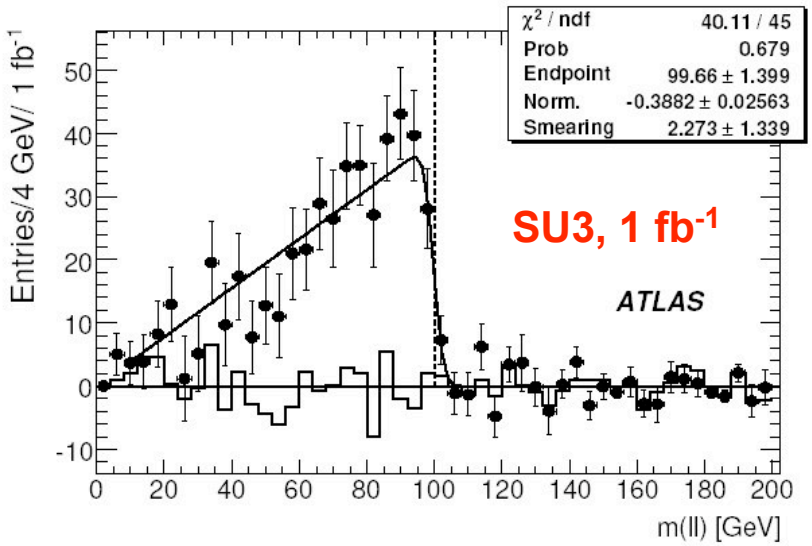
- Select a suitable decay chain
- Measure *invariant mass of leptons pair*
  - edge sensitive to SUSY masses
- *Sensitivity for 1fb^{-1}*
  - CMS LM1: M_{ll}^{edge}~ (78 ± 0.5) GeV
  - ATLAS SU3: M_{ll}^{edge}~ (100 ± 1.5) GeV



$$\tilde{q}_L \to \tilde{\chi}_2^0 q(\to \tilde{\ell}^{\pm}\ell^{\mp}q) \to \tilde{\chi}_1^0 \ell^+\ell^- q$$

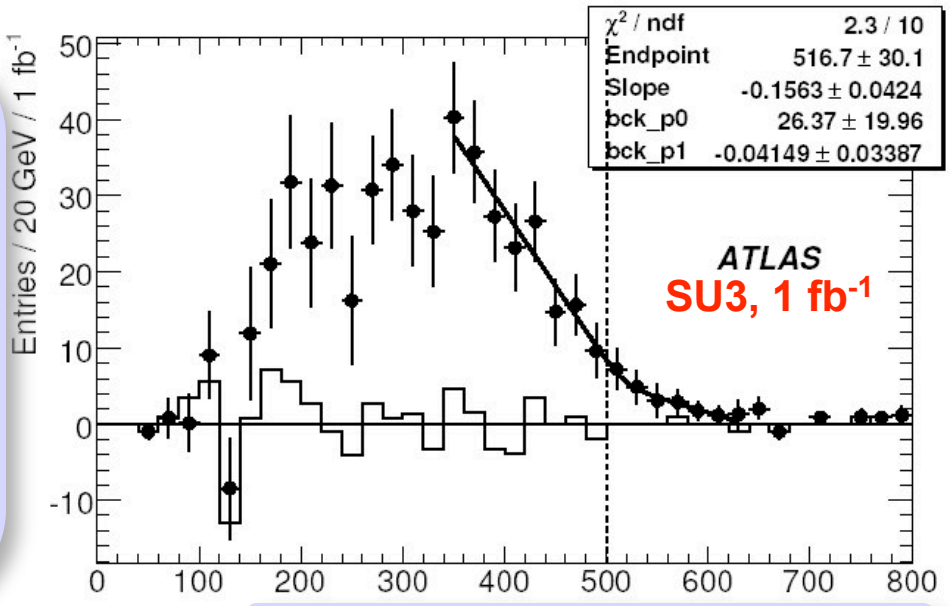
$$m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0}\sqrt{1-\left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2}\sqrt{1-\left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}$$





Lepton(s) + jets mass edge

- Include the quark going up the decay chain
- Compute dilepton+jet mass
- Good estimates for the masses of the SUSY particles with 1 fb^{-1}
  - ATLAS SU3 M_{llq}^{edge} ~ 517±30 GeV



Dilepton+jet mass

Conclusion

- Within the next year(s) expect to discover SUSY or to push its mass scale so high that it is no longer a natural solution of the hierarchy problem.
- Many expected SUSY signatures have been studied
  - Very promising prospects already exist with little luminosity
- A variety of tools in place ready to be applied
- Both CMS and ATLAS will need data to complete the understanding of the detectors, trigger, reconstruction, and SM backgrounds
  - Expect to accomplish that with 1-2 fb^{-1} (next year?) which will allow us to characterize a very interesting region of SUSY parameter space.