# Potential for early SUSY discovery at the LHC

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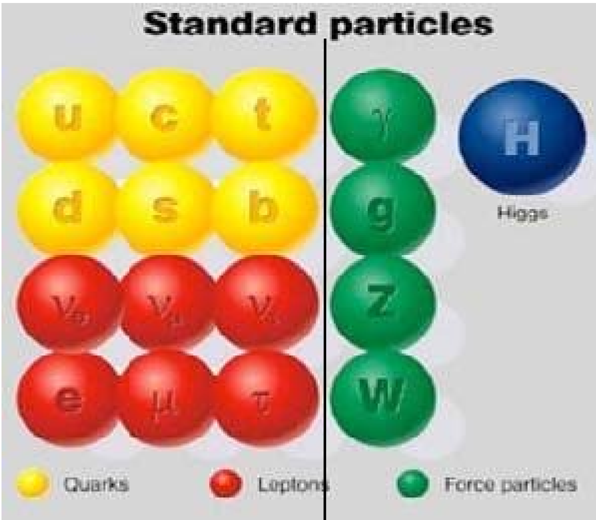
# OUTLINE

- Why Supersymmetry?
- SUSY models and SUSY events
- LHC detectors
- SUSY searches
  - Inclusive SUSY searches
  - Trilepton events
  - Other searches
- SUSY mass spectrum
- Conclusions

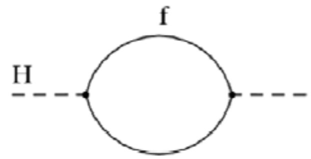
The plots in this talk are the result of the work of many people. – Thanks to all of them!

# Why Supersymmetry?




Spin ½ | Spin 1

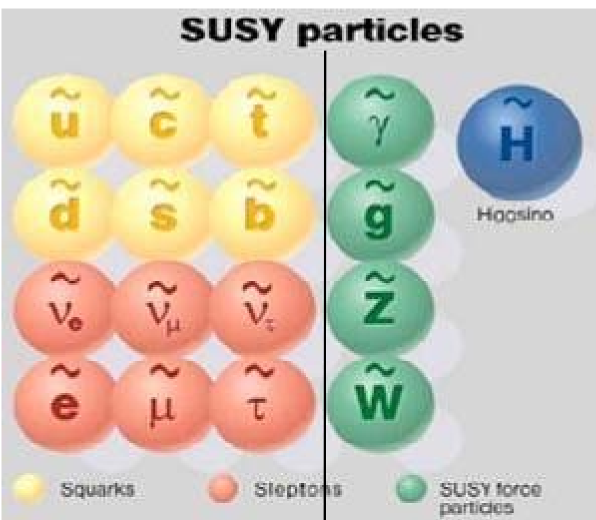
Large fermion loop correction to Higgs mass…




$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots\right]$$

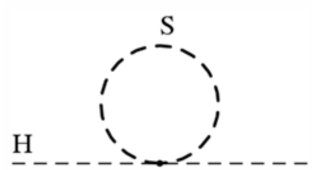
**SUPERSYMMETRY**

**but needs to be broken!**




Spin 1 | Spin ½

… is cancelled by boson loop correction:




$$\Delta m_H^2 = \frac{|\lambda_S|^2}{16\pi^2}\left[\Lambda_{UV}^2 - s m_S^2 \ln(\Lambda_{UV}/m_S) + \ldots\right]$$

# SUSY Breaking

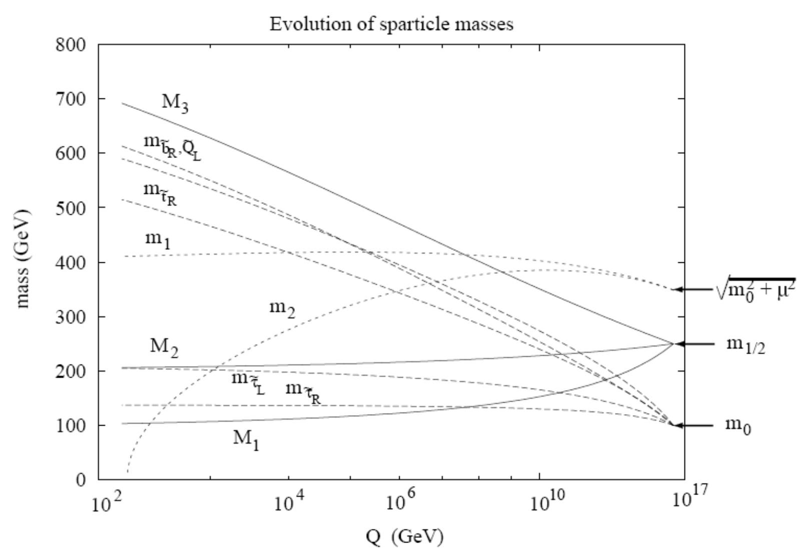
- Huge number of additional mass parameters even in MSSM (ca. 100)
  → parameters have to be constrained in specific models

- No unique way of breaking SUSY → several models ( mSUGRA, GMSB, …)

- Mixing of “pure” gauginos/higgsinos:

$$\left.\begin{array}{l} \left(\tilde{Z}, \tilde{\gamma}, \tilde{H}_u^0, \tilde{H}_d^0\right) \rightarrow \left(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0\right) \\ \left(\tilde{W}^+, \tilde{H}_u^+\right) \rightarrow \left(\tilde{\chi}_1^+, \tilde{\chi}_2^+\right) \\ \left(\tilde{W}^-, \tilde{H}_d^-\right) \rightarrow \left(\tilde{\chi}_1^-, \tilde{\chi}_2^-\right) \end{array}\right\} \text{(ordered by mass)}$$

- in mSUGRA SUSY masses are derived from 5 theoretical mass parameters at GUT scale: $m_{1/2}$, $m_0$, $A_0$, tanβ, sign(μ)




I will consider only so called R-parity conserving models in my talk!

# SUSY benchmark scenarios (ATLAS)

★ **SU1:** $m(\tilde{g}) \approx 830\,\text{GeV},\ m(\tilde{q}) \approx 760\,\text{GeV}$

– Coannihilation region

★ **SU2:** $m(\tilde{g}) \approx 860\,\text{GeV},\ m(\tilde{q}) \approx 3560\,\text{GeV}$

– Focus point

★ **SU3:** $m(\tilde{g}) \approx 720\,\text{GeV},\ m(\tilde{q}) \approx 620\,\text{GeV}$

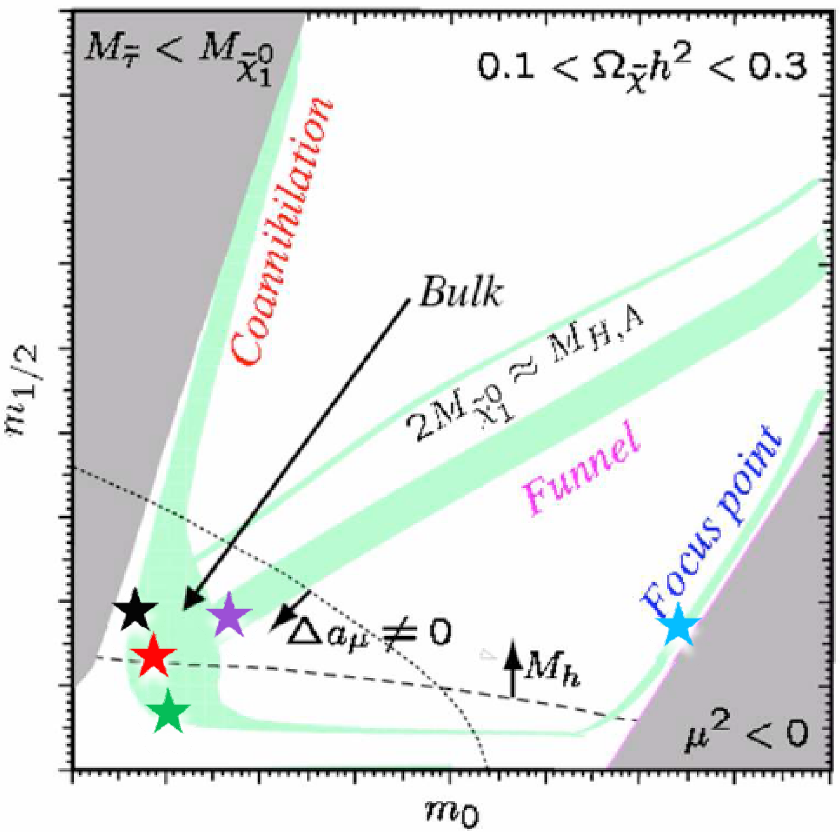
– Bulk point

★ **SU4:** $m(\tilde{g}) \approx 420\,\text{GeV},\ m(\tilde{q}) \approx 420\,\text{GeV}$

– Just beyond Tevatron reach

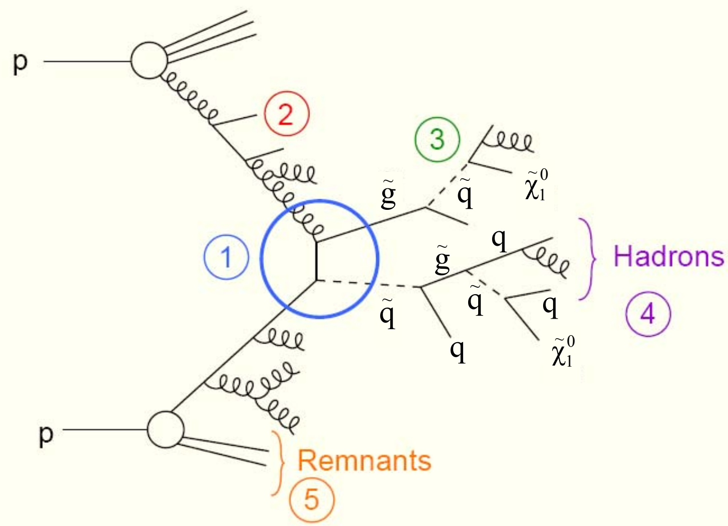
★ **SU6:** $m(\tilde{g}) \approx 890\,\text{GeV},\ m(\tilde{q}) \approx 870\,\text{GeV}$

– Funnel regions




CMS uses somewhat different benchmark scenarios with additional points in the high mass region!

# SUSY events




Event generation in LL - QCD

1) Hard scattering / convolution with PDFs

2) Intial / final state showers

3) Cascade decays

4) Hadronization

5) Beam remnants

**Dominant process: $\tilde{q}\tilde{q}, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$ (squark/gluino pair production)**

SUSY decay cascades down to stable LSP

Neutralinos via $\tilde{q} \to q\,\tilde{\chi}_2^0 \to q\,\ell^{\pm}\tilde{\ell}^{\mp} \to q\,\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$

Signatures:

- Missing energy
  - from Lightest Supersymmetric Particles(LSPs)
  - from neutrinos (e.g. from semileptonic b decays)
- Hard jets (from quarks or gluons)
- Additional hard leptons (0, 1, 2, …)

## CMS (Compact Muon Solenoid)

Large 4T Solenoid

Muon Spectrometer

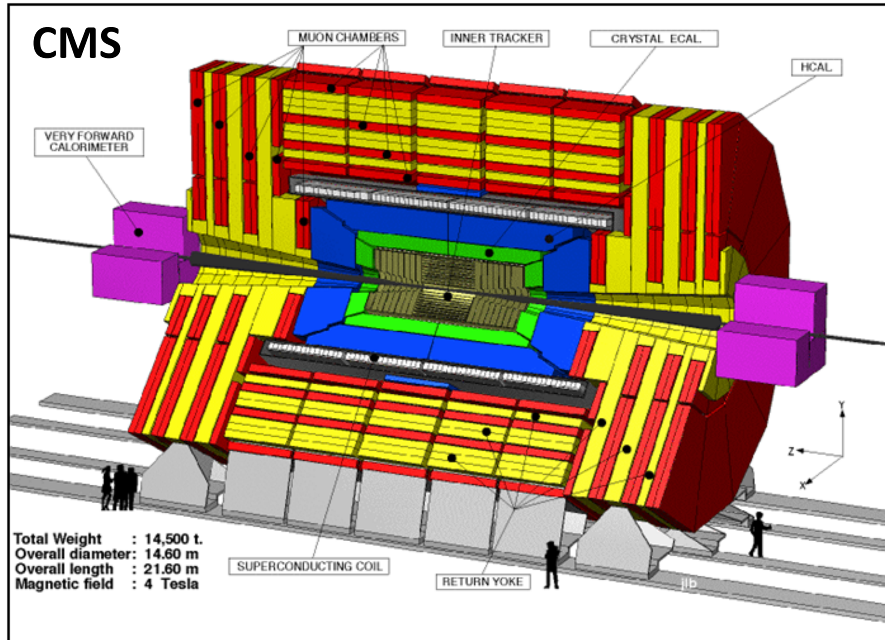
- *Muon Chambers Integrated in Return Yoke*

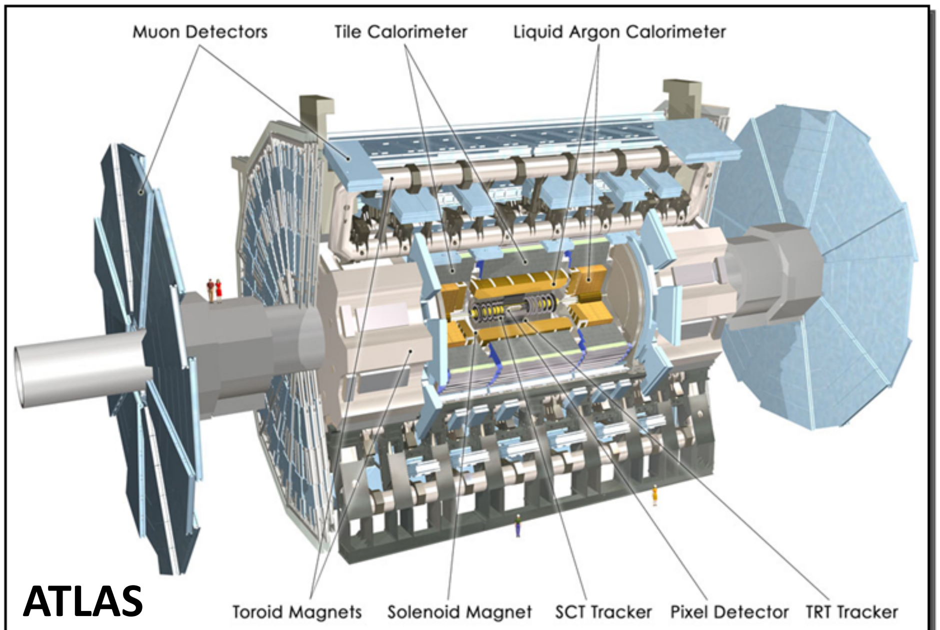
Calorimetry

- *$PbWO_4$ Crystal: Excellent Resolution*

Inner Tracking

- *Pixels: 100$\mu$m (r-$\phi$) x 150$\mu$m (z)*
- *$\Delta$p/p (1 GeV) = 0.007,0.02 ($\eta\approx$0,2.5)*
- *$\Delta$p/p (100 GeV) = 0.015,0.07*




## ATLAS (A Toiroidal LHC ApparatuS)

Muon Spectrometer (3 Large Toroids)

- *High $BL^2$ for Standalone Measurements*

Calorimetry

- *Lateral & Longitudinal Segmentation*

Inner Tracking (Small” 2T Solenoid)

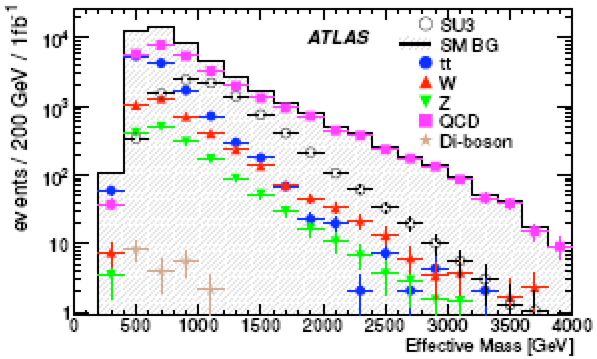
- *Pixels: 50$\mu$m (r-$\phi$) x 400$\mu$m (z)*
- *$\Delta$p/p (1 GeV)= 0.013,0.02 ($\eta\approx$0,2.5)*
- *$\Delta$p/p (100 GeV) = 0.038,0.11*
- *TRT for e/$\pi$ identification*

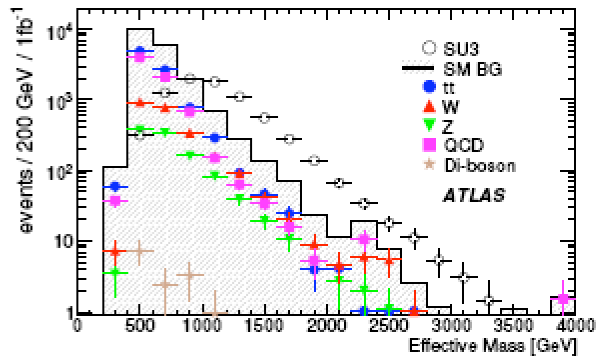
# Inclusive Analysis (no leptons)

**SUSY shape looks like background → Tune your cuts:**

Lum.: 1 $fb^{-1}$

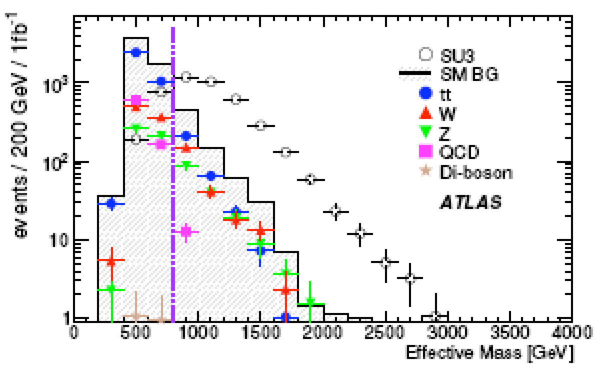
1): 4 jets+$E_T^{miss}$

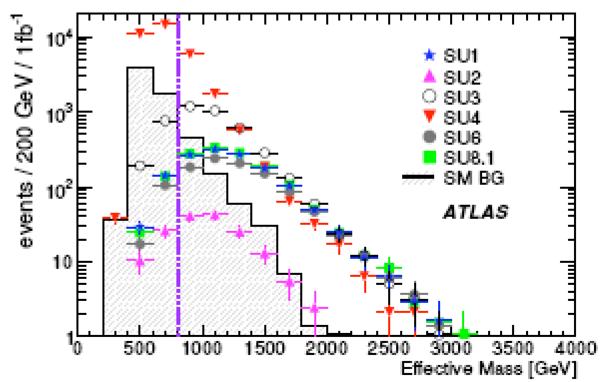



2): 1) + $E_T^{miss} > 0.2\,M_{eff}$

3): 2) + $S_T > 0.2$+more



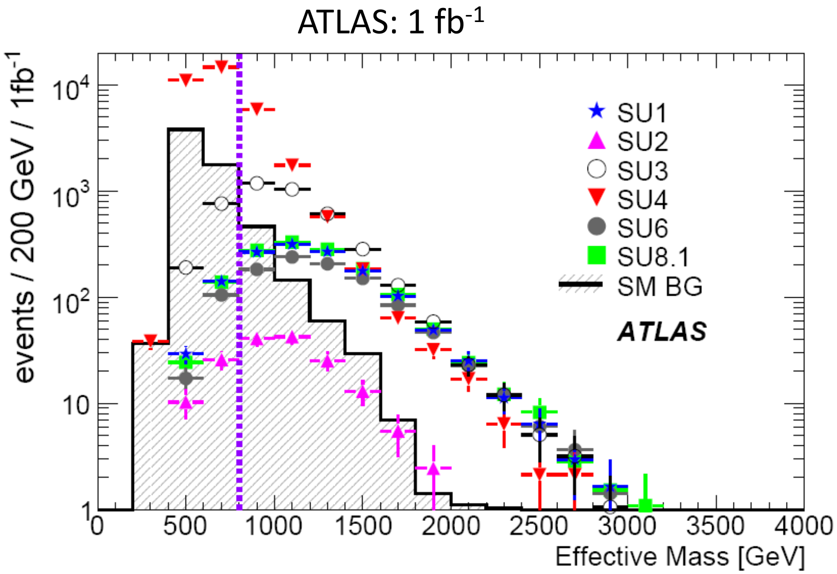



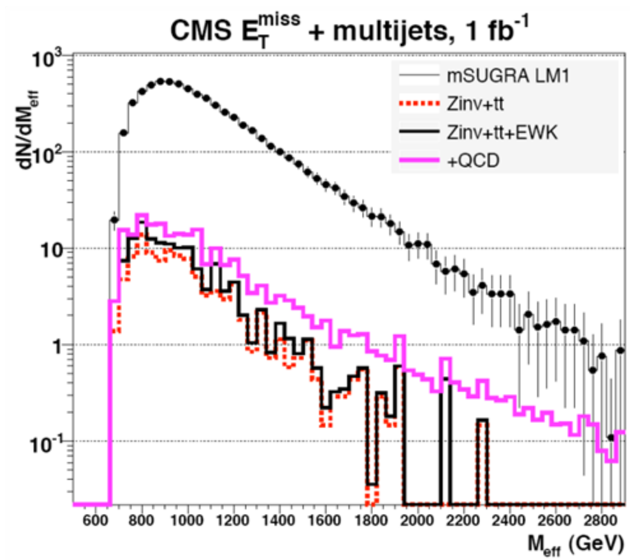

$M_{eff}$: Effective mass with $M_{eff} = \sum_{i=1}^{4} p_T^{jet} + E_T^{miss}$

$S_T$: Transverse Sphericity; $S_T \approx 0$: back to back (QCD); $S_T \approx 1$: spherical

Cuts do not work for all models!

# Inclusive Analysis: Comparison



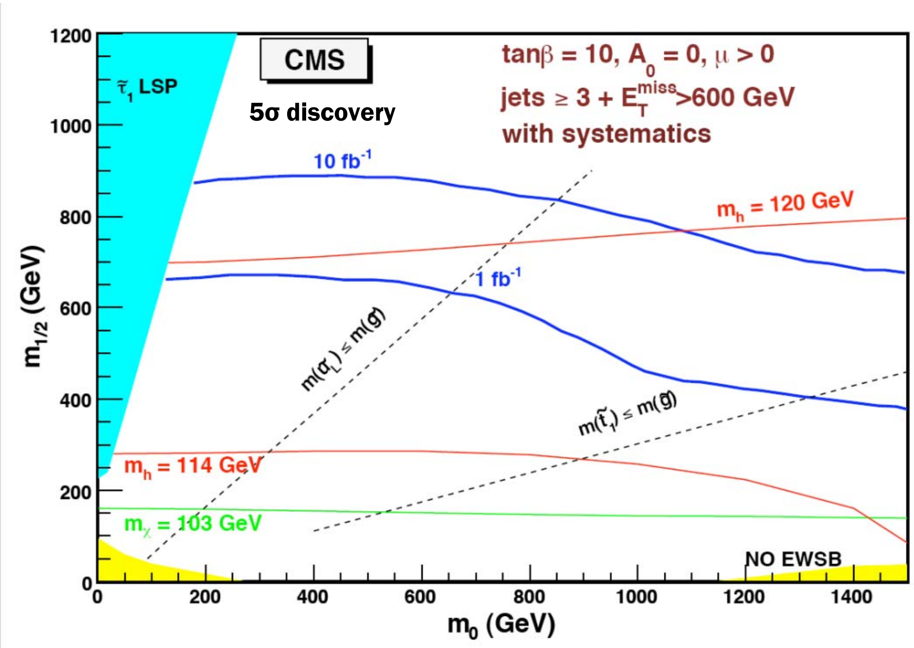



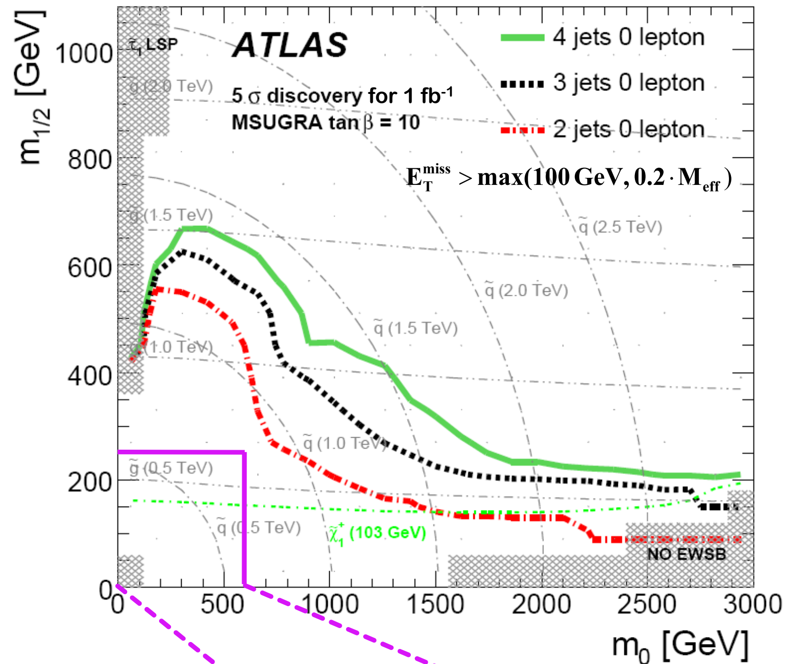

ATLAS has looked at several different benchmark points without optimizing the cuts for each point separately

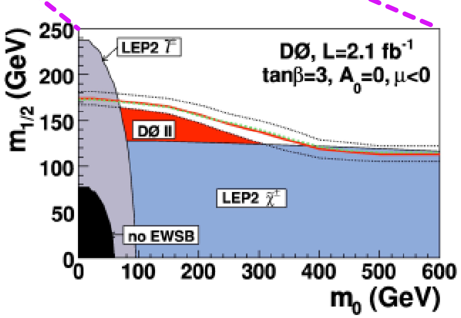
CMS has demonstrated the analysis potential in detail for one particular benchmark point (LM1 ≈ SU4)

Difficult for 1st year:
- $\mathbf{E}_{\mathbf{T}}^{\mathbf{miss}}$ requires that detector is fully understood
- QCD background has big theoretical(!) uncertainty – → it's better to derive this background from data!

# Inclusive Analysis – discovery reach



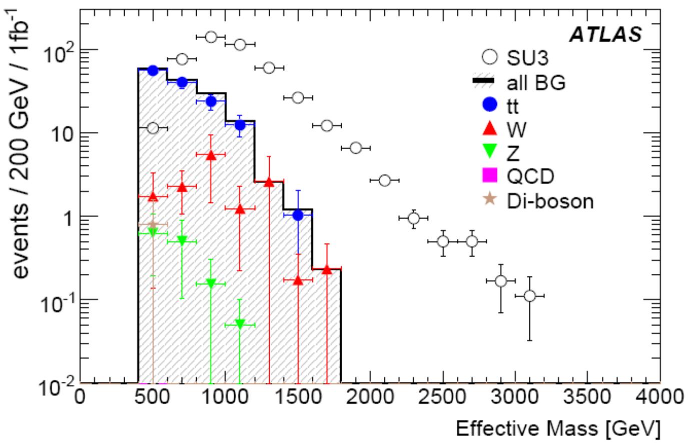

With 1 $fb^{-1}$ at 14 TeV $m_{\tilde{q}} \approx 1\,TeV, m_{\tilde{g}} \approx 1\,TeV$ can be reached
2009 running at 10 TeV: around 0.6 TeV, if(!) we get 1 $fb^{-1}$

These plots depend also on tanβ, but not too much!

Other SUSY breaking models: similar discovery potential

# Inclusive Analysis with leptons

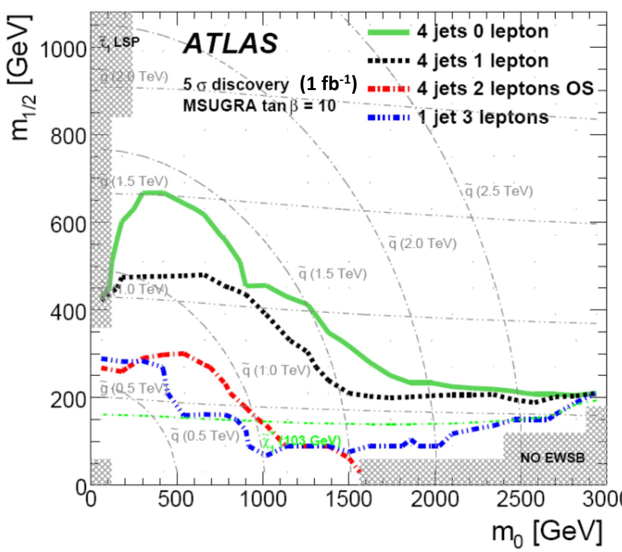
Additional requirement: ≥ 1 isolated lepton ( ≥ 1μ for CMS); e.g. from $\tilde{\chi}_2^\pm \rightarrow \chi_1^0 \ell^\pm \nu$

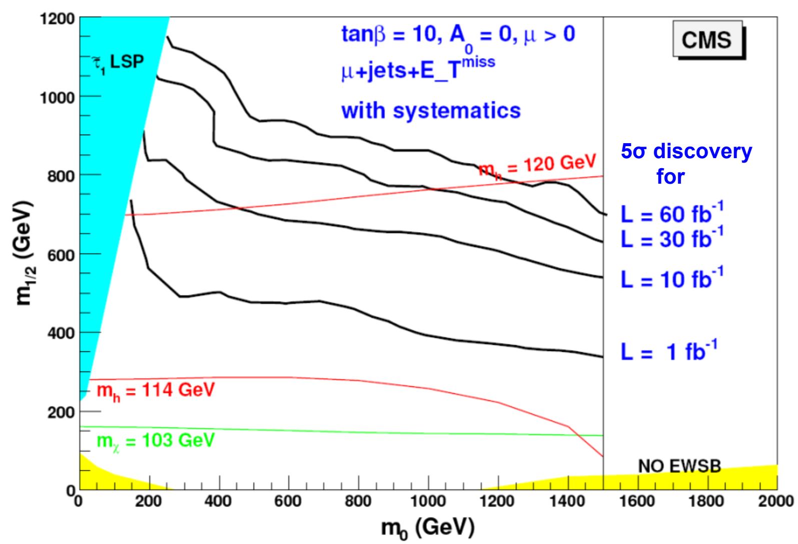



Effective mass now $\mathbf{M}_{\mathrm{eff}} = \sum_{i=1}^{4} \mathbf{p}_{\mathrm{T}}^{\mathrm{jet}} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}} + |\mathbf{p}_{\mathrm{T}}^{\ell}|$

- Less events, but cleaner signal
- QCD background negligible!

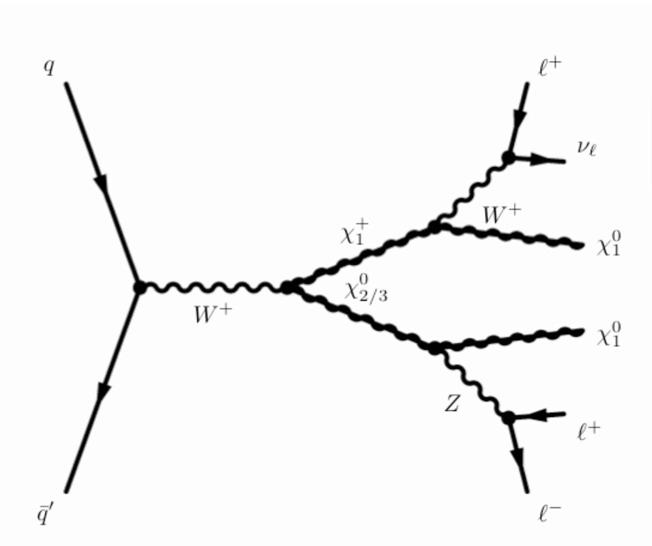
Discovery reach:



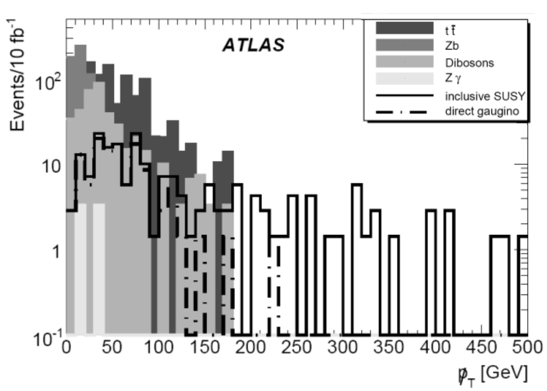
# Trilepton analysis (heavy squarks)

If squarks are heavy (>1TeV), production cross sections are small
→ mainly gauginos are (pair-)produced

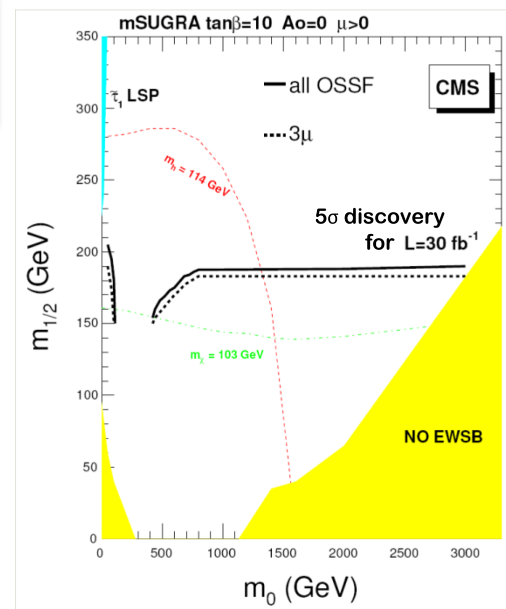



Event selection:

- Require 3 isolated leptons; two OSSF from $\tilde{\chi}_2^0$ decay
- Cut $M_{OSSF}$ around real Z peak (remove background from ZW and Zb events)
- ATLAS: Require $\mathbf{E_T^{miss} > 30\,GeV}$
- CMS: Use neural network



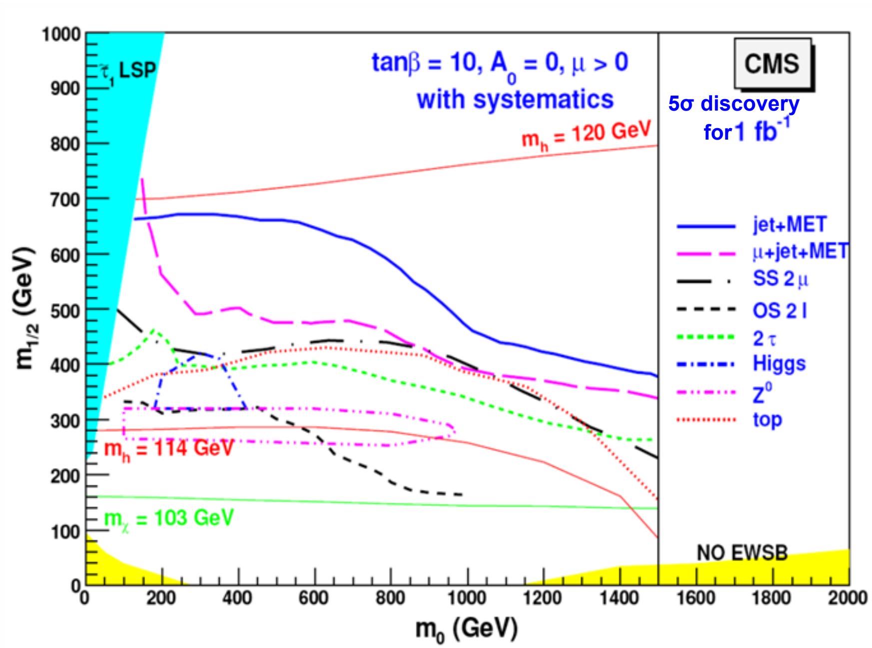

| ATLAS<br>Event selection | Luminosity for 5σ discovery | |
|---|---|---|
| | SU2 | SU3 |
| Inclusive SUSY | 7.1 $fb^{-1}$ | 0.8 $fb^{-1}$ |
| Direct gaugino only | 22.4 $fb^{-1}$ | 92.9 $fb^{-1}$ |



# Other searches

## CMS

**Reach for different analysis channels**

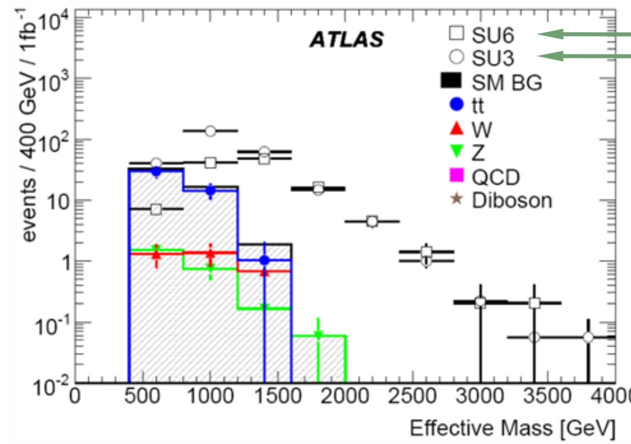



CMS: SS dimuons promising:

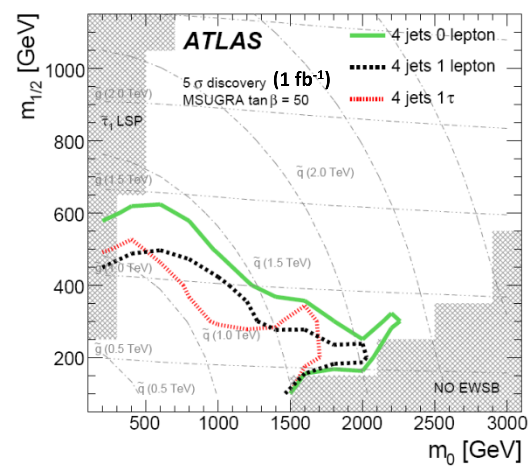
- significance of discovery >14σ for all low mass models

## ATLAS

**Study of inclusive analysis + ≥ 1 reconstructed τ**




(tan β = 50)
(tan β = 6)

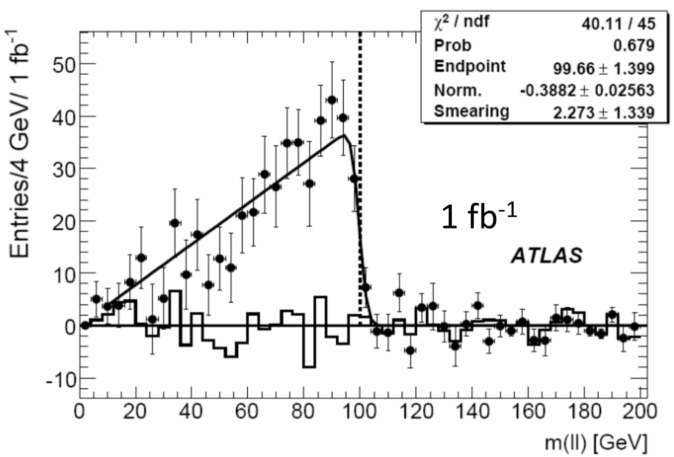


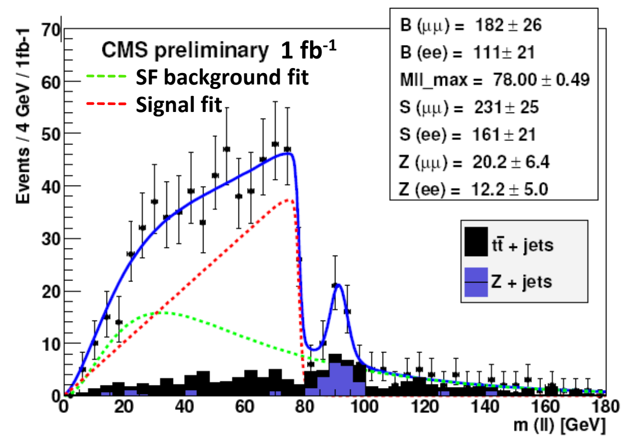

ATLAS:
τ channel about as good as 1-lepton channel!

# SUSY mass spectrum

Consider $\tilde{q}_L \to \tilde{\chi}_2^0\, q \left(\to \tilde{\ell}^{\pm}\, \ell^{\mp}\, q\right) \to \tilde{\chi}_1^0\, \ell^+ \ell^- q$ → Plot $m_{\ell^+\ell^-}$ → Extract edge at $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$

More complicated plots → $m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}, m_{\tilde{q}}, m_{\tilde{\ell}}$ can be obtained separately (but with larger errors)




<u>ATLAS:</u> SS and $Z^0$ background subtracted

<u>CMS:</u> SS and $Z^0$ background fitted

ATLAS result for SU3: 99.3±1.3±0.3 GeV
Theory: 97.9 GeV

CMS result for LM1: 78.00 ± 0.49 GeV
Theory: 78.15 GeV

# Conclusions

- Two powerful experiments: ATLAS and CMS with similar discovery potential
- At 14 TeV and 1 $fb^{-1}$ SUSY can be detected for squark and gluino masses up to 1 TeV
- At 10 TeV masses of about 600 GeV can be found
- Inclusive channels requiring only jets and missing energy have best discovery potential
- For early discoveries inclusive events with 1 lepton are more promising
- If SUSY is realized in the low mass region, also mass parameters can be determined

# Backup slides

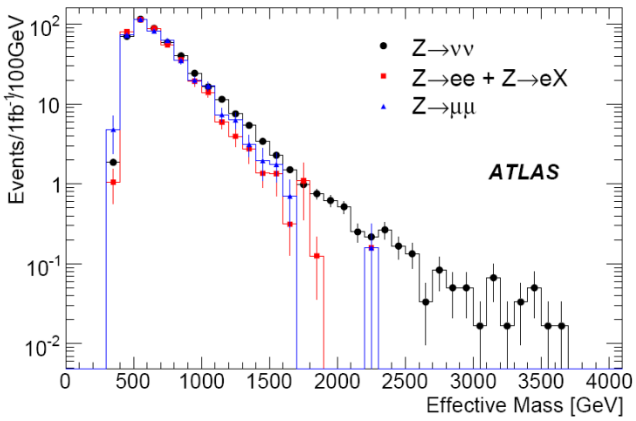
# Background determination from data

**Example 1: Background from Z decays**

- Events with $E_T^{miss}$ have contribution from the process $(Z \to \nu\bar{\nu}) + \text{jets}$
- The decay $Z \to \nu\bar{\nu}$ has similar kinematics as $Z \to e^+e^-$ or $Z \to \mu^+\mu^-$
- The relative rates for the different Z decays are known exactly

Recipe:

- Take measured events that contain $Z \to e^+e^-$ or $Z \to \mu^+\mu^-$
- Delete the electrons or muons
- Weight these events with $\frac{BR(Z \to \nu\bar{\nu})}{BR(Z \to \mu^+\mu^-) + BR(Z \to e^+e^-)} \approx 3$
- Correct for finite acceptance of $e^+, e^-, \mu^+, \mu^-$
  (Acceptance not to see $\nu, \bar{\nu}$ is 100 %!)



# Background determination from data

**Example 2: Background from top/W decays in $M_{eff}$ distribution**

Recipe:

Define (with cuts that do not depend on $M_{eff}$ !) :
- signal region (the region of your cuts) with high SUSY and low background content
- control region (the complement) with high background and low SUSY content

- Find the distribution of $M_{eff}$ in the control region

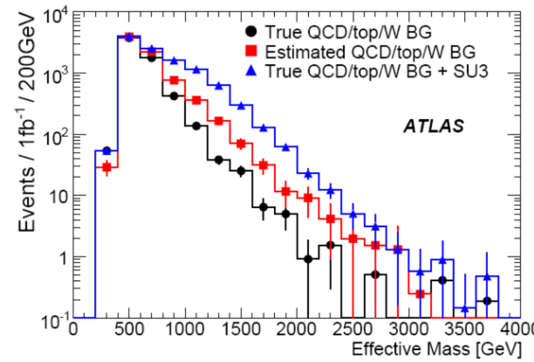
*This should be the $M_{eff}$ distribution of background events (almost, since some SUSY events are still in)*

-Renormalize this and use it as background

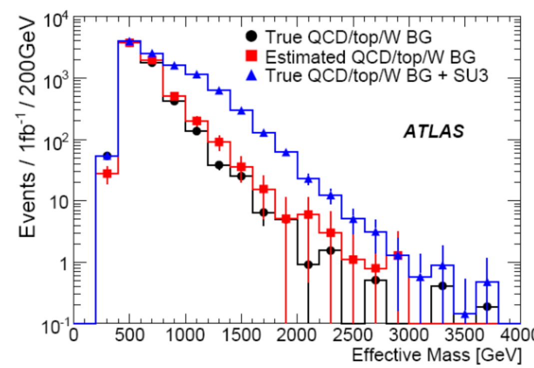
*But this overestimates the background, i.e. underestimates SUSY!*

-Make an Ansatz for the SUSY events as function of the cut variables and subtract from control region

- Get the new background and iterate



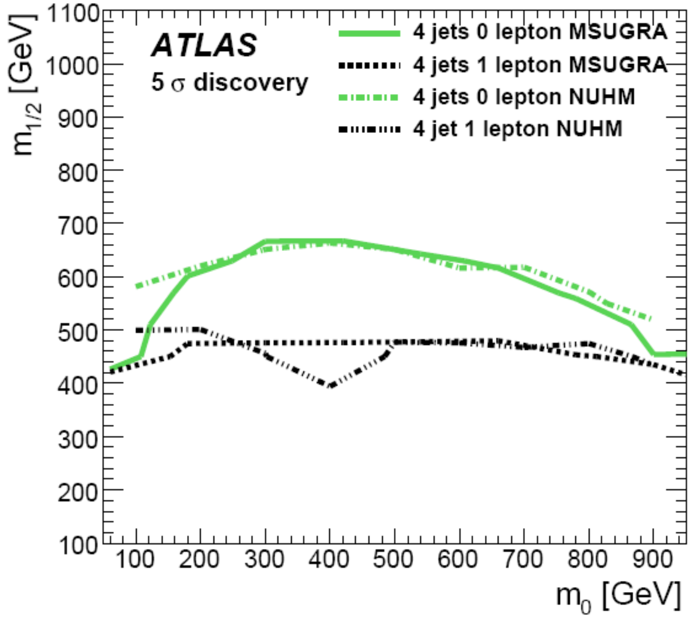

no correction



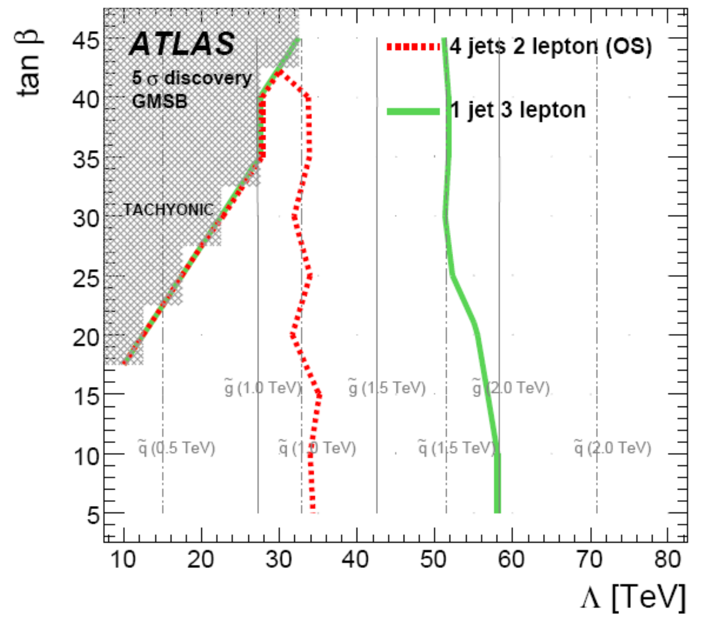

corrected

# Other SUSY models

**Non-Universal Higgs Model (NUHM)**




**Gauge-Mediated Symmetry Breaking (GMSB)**




- Discovery potential of LHC for other models is rather similar to mSUGRA, i.e. squark and gluino masses ≤ 1TeV are reachable with $1fb^{-1}$@14TeV

Similar studies have also been performed by CMS!