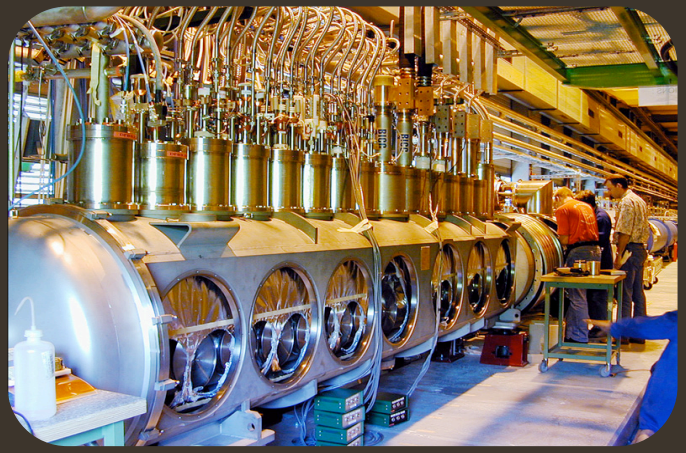
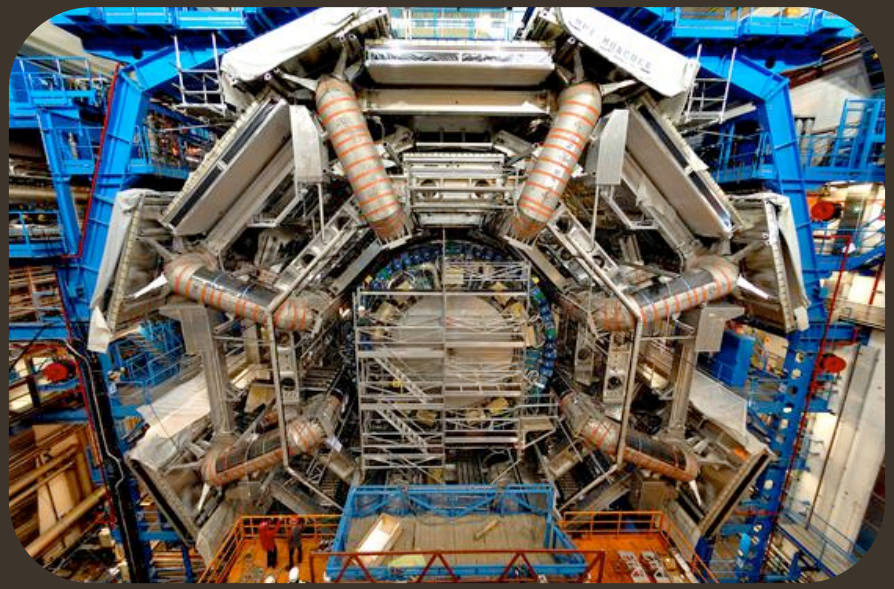
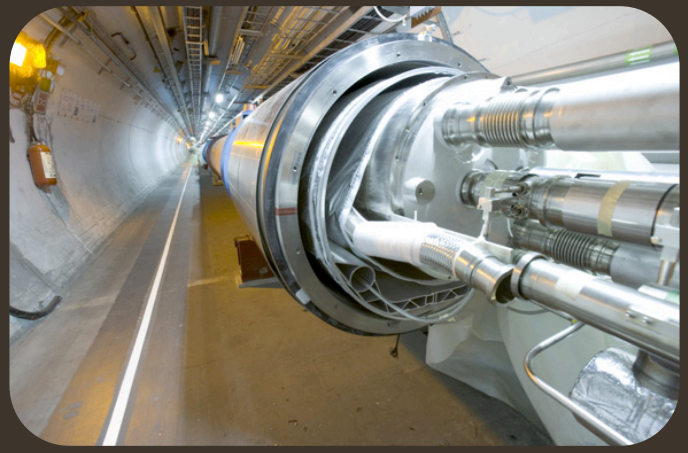


On behalf of ATLAS and CMS

SUSY Searches at the LHC

Oleg Brandt, University of Oxford





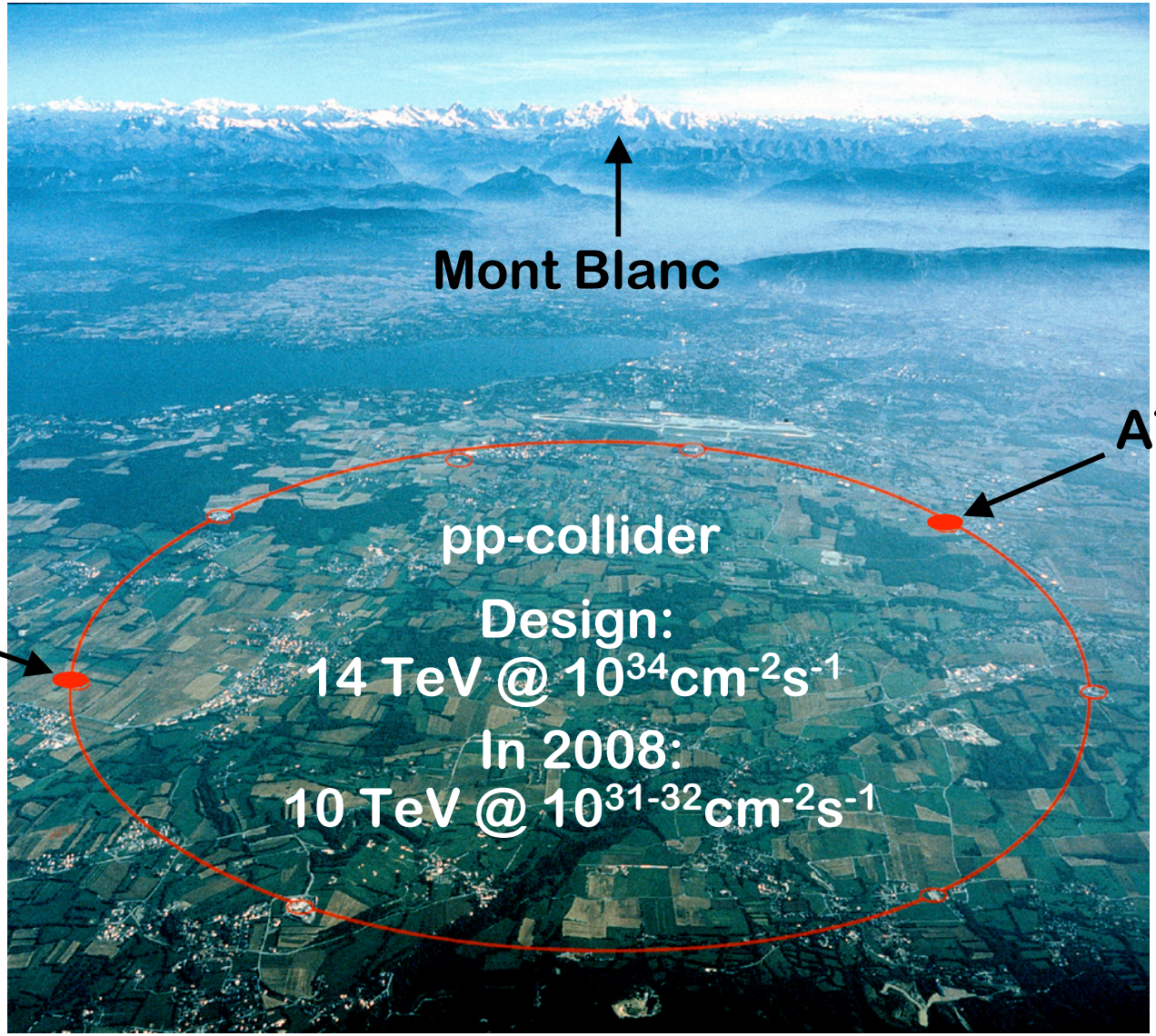
Today's Menu

- The LHC
- ATLAS and CMS
- Generic SUSY search signatures at the LHC:
  - mSUGRA benchmark points at ATLAS and CMS
  - 0, 1, 2, 3-lepton modes
  - Combined Reach for ATLAS and CMS
  - Not covered:
    - Tau, Higgs, Top, Bottom-modes, RPV
- GMSB searches:
  - Prompt diphotons
  - Non-pointing photons
- Massive slepton & R-hadron searches:
  - Online and offline challenges
- Conclusion and outlook

Prelim. Post-TDR Results (ATLAS)

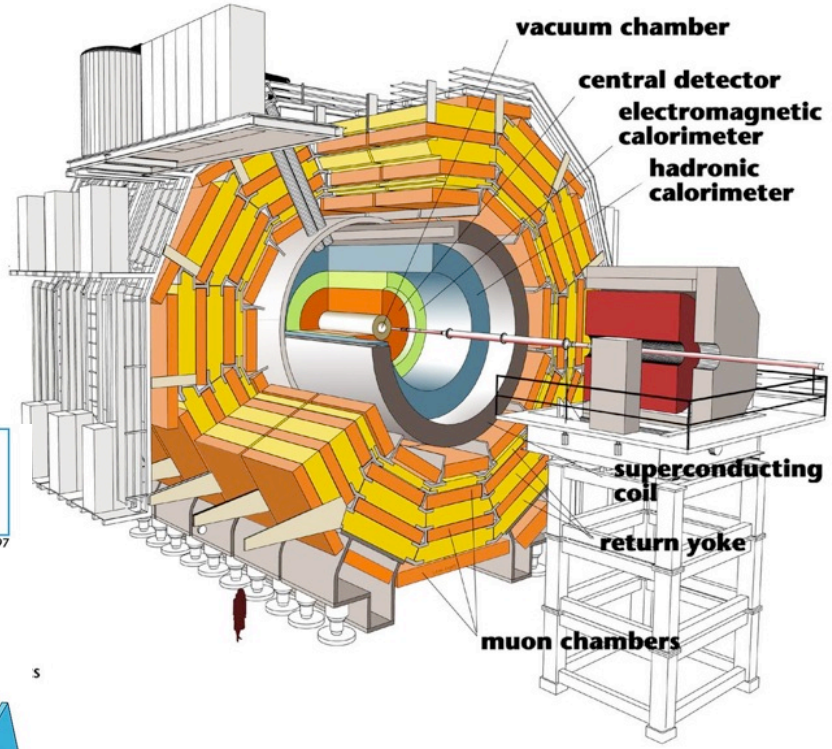
Post-TDR Results for GMSB (CMS)

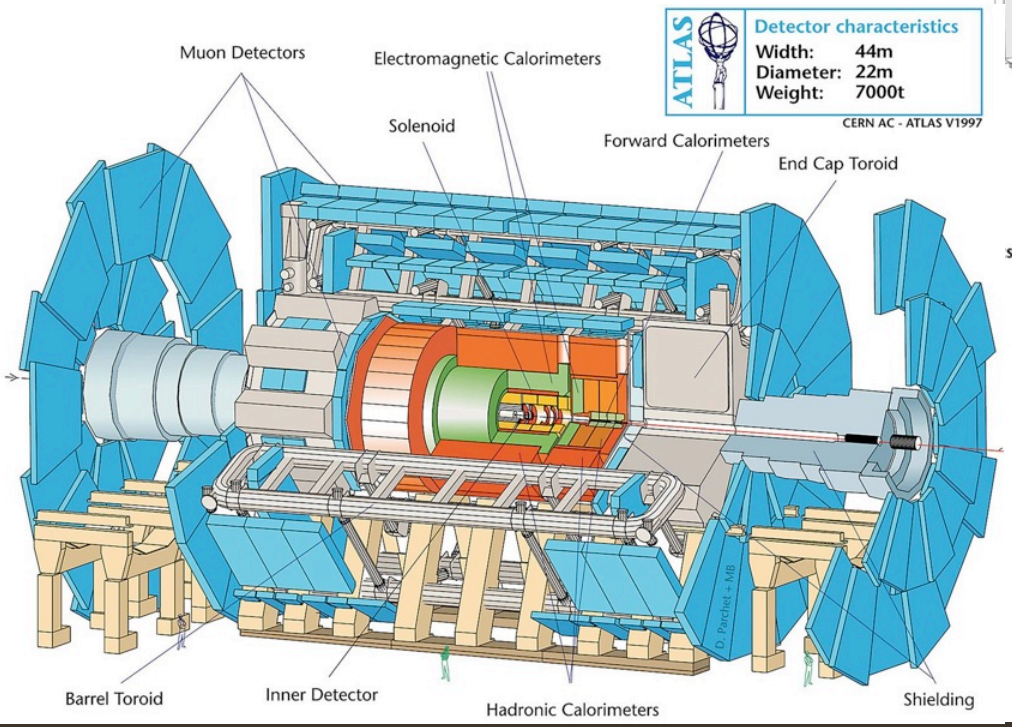
The Large Hadron Collider



The ATLAS and CMS Experiments

Both ATLAS and CMS are multipurpose detectors armed for discovery

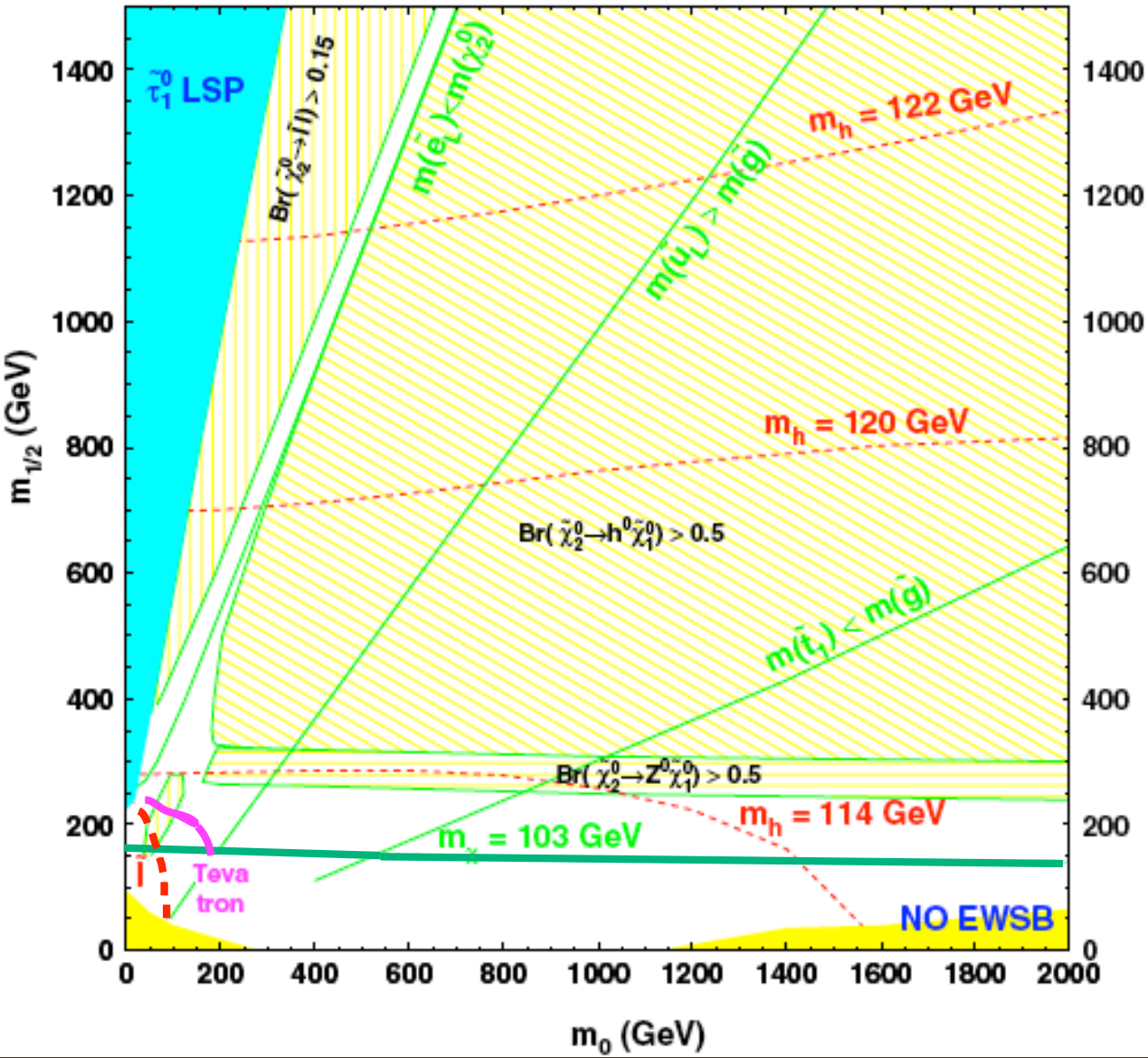




Quite a development from initial „Huge brick with muon chambers“-design!

mSUGRA Benchmark Points at ATLAS and CMS

Exclusion regions for
$A_0 = 0$, $\mu > 0$, $\tan\beta = 10$



mSUGRA Benchmark Points at ATLAS and CMS

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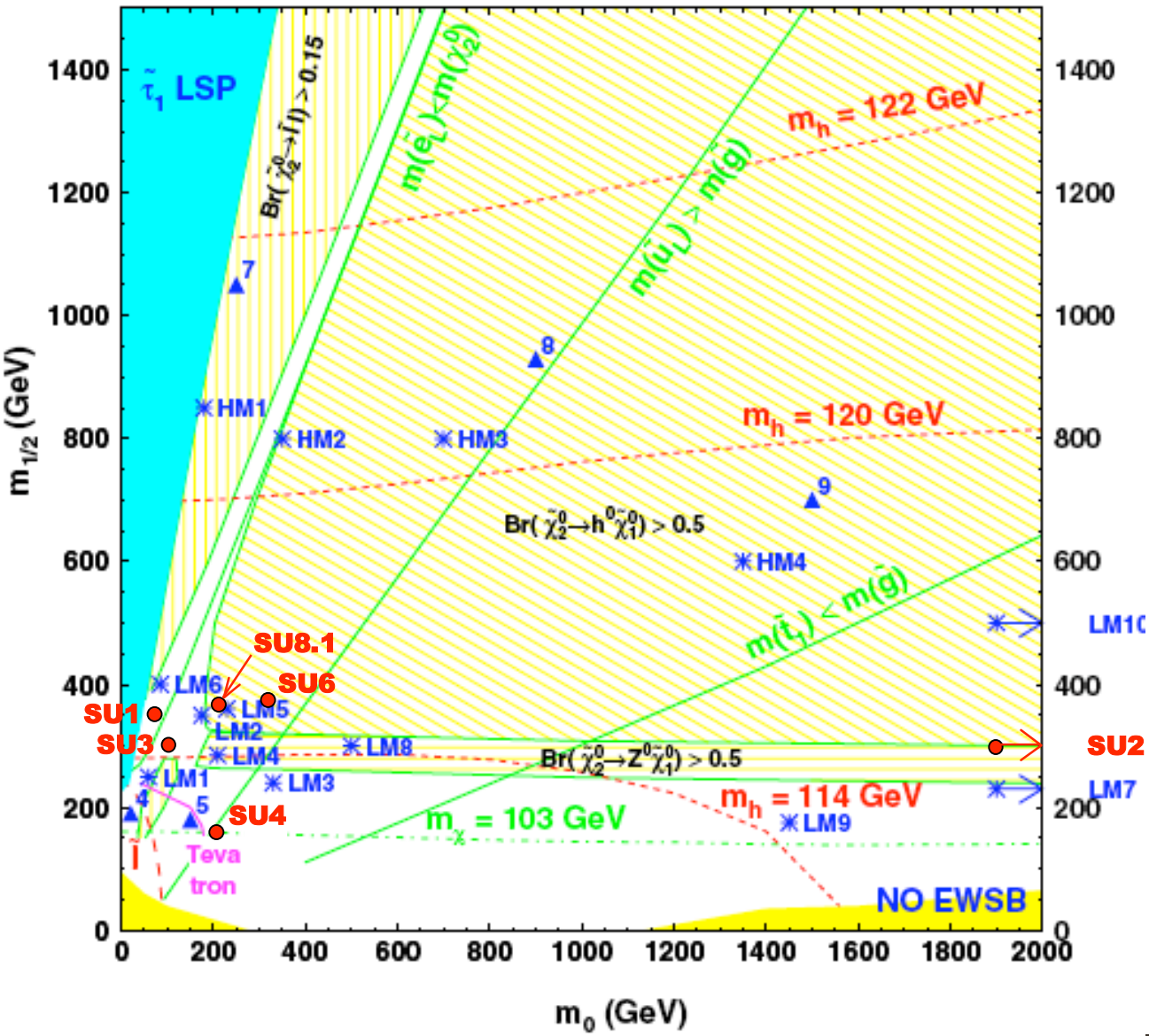
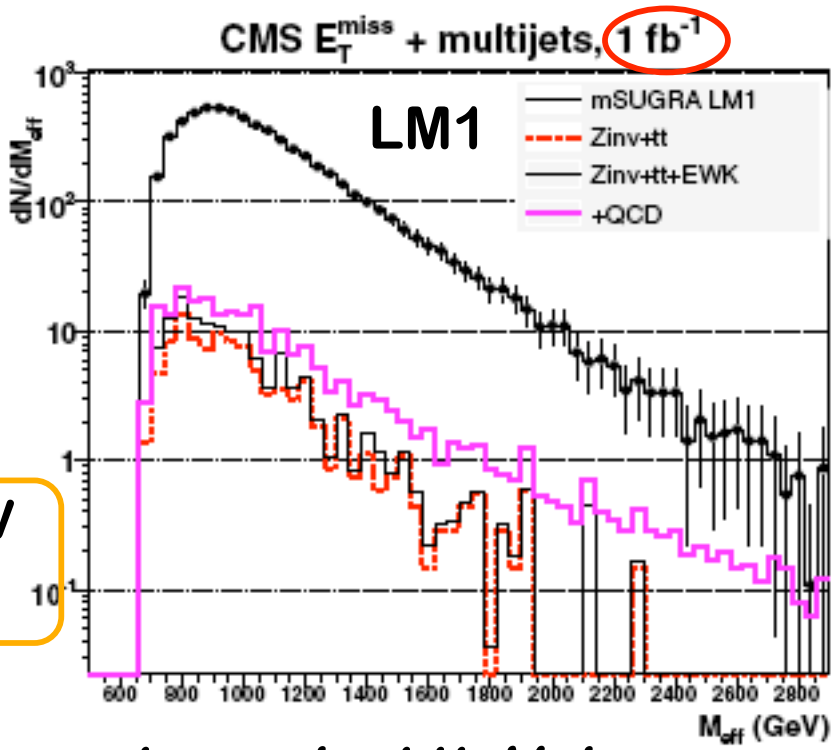


LMx, HMx: CMS
SUx: ATLAS

0-lepton Search: tri-jets (CMS)

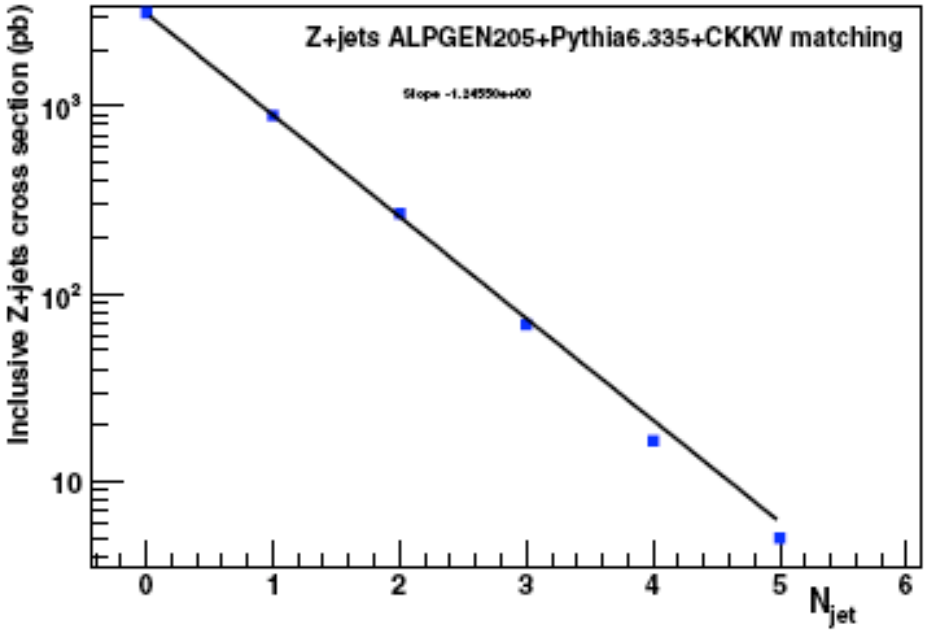
- Best expected mSUGRA reach at CMS
- Potentially high QCD backgrounds
- L1: $E_T^{miss,L1} > 46\,\mathrm{GeV}$, $E_T > 88\,\mathrm{GeV}$, HLT: $E_T^{miss} > 200\,\mathrm{GeV}$
- Cuts:
  - 3 jets:
    - j_1: $E_{T,j(1)} > 180\,\mathrm{GeV}$, $|\eta_d^{1j}| < 1.7$
    - j_2: $E_{T,j(2)} > 110\,\mathrm{GeV}$, $|\eta| < 3$
    - j_3: $E_T > 30\,\mathrm{GeV}$, $|\eta| < 3$
  - $E_T^{miss} > 200\,\mathrm{GeV}$
  - $\delta\phi_{min}(E_T^{miss} - jet) \geqslant 0.3$ rad
  - $\delta\phi(E_T^{miss} - j(2)) > 20°$
  - No isol. tracks with pT > 15 GeV
  - $f_{em(j(1))}$, $f_{em(j(2))} < 0.9$
  - $H_T > 500\,\mathrm{GeV}$



Implicit lepton veto against tt, V+j

Background Estimation from Data (CMS)

- Use the dataset $Z(\to \mu\mu)+\ 2\ \text{jets}$ for normalisation:
  - Estimate the $Z(\to \nu\bar{\nu})+\geqslant 3\ \text{jets}$ contribution from data:
  - Use:
    - $R = \frac{dN_{events}}{dN_{jets}}$ => $Z(\to \mu\mu)+\ 3\ \text{jets}$
    - Ratio of $Z(\to \mu\mu)$ to $Z(\to \nu\bar{\nu})$
    - Require $Z\ \text{boson}\ P_T > 200\,\text{GeV}$ in all samples
  - Similarly, estimate $W(\to \tau\nu)+\geqslant 2\ \text{jets}$:
  - Use:
    - $\rho \equiv \frac{\sigma(pp\to W(\to\mu\nu)+jets)}{\sigma(pp\to Z(\to\mu^+\mu^-)+jets)}$
- Needed data sample:
  - $\sim 1.5\,\text{fb}^{-1}$
- Estimate systematics due to raw E_T^{miss} from data

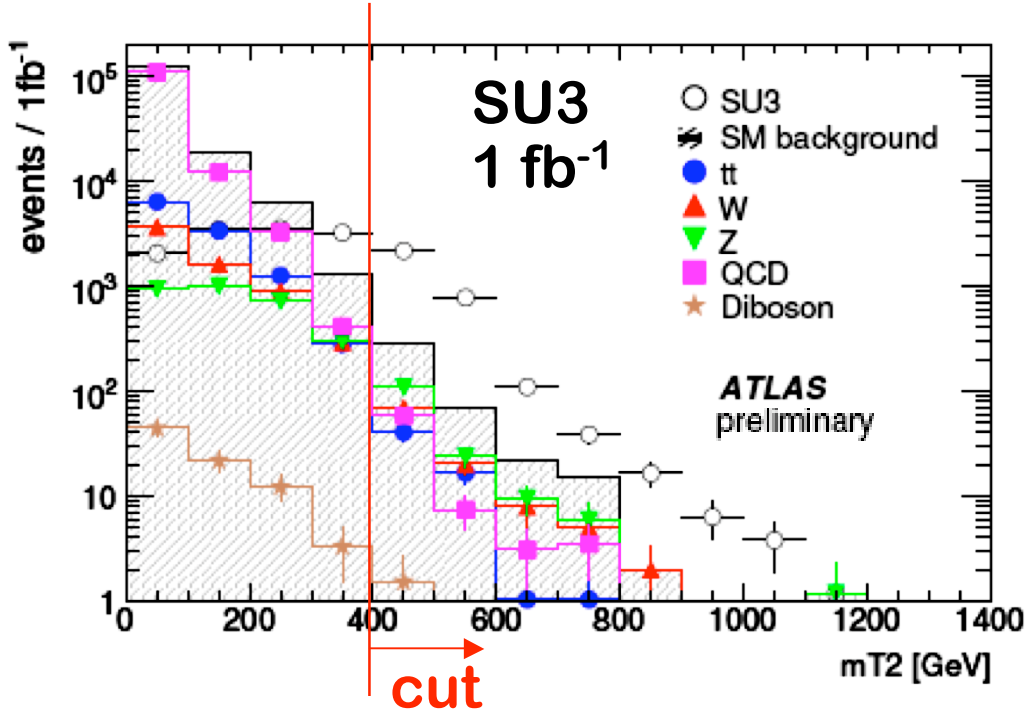


0-lepton Search: di-jets (ATLAS)

- Di-jet search relatively new at ATLAS
- Using new variable m_{T2} (large p_T, $\not{E}_T$ and $\delta\phi$):

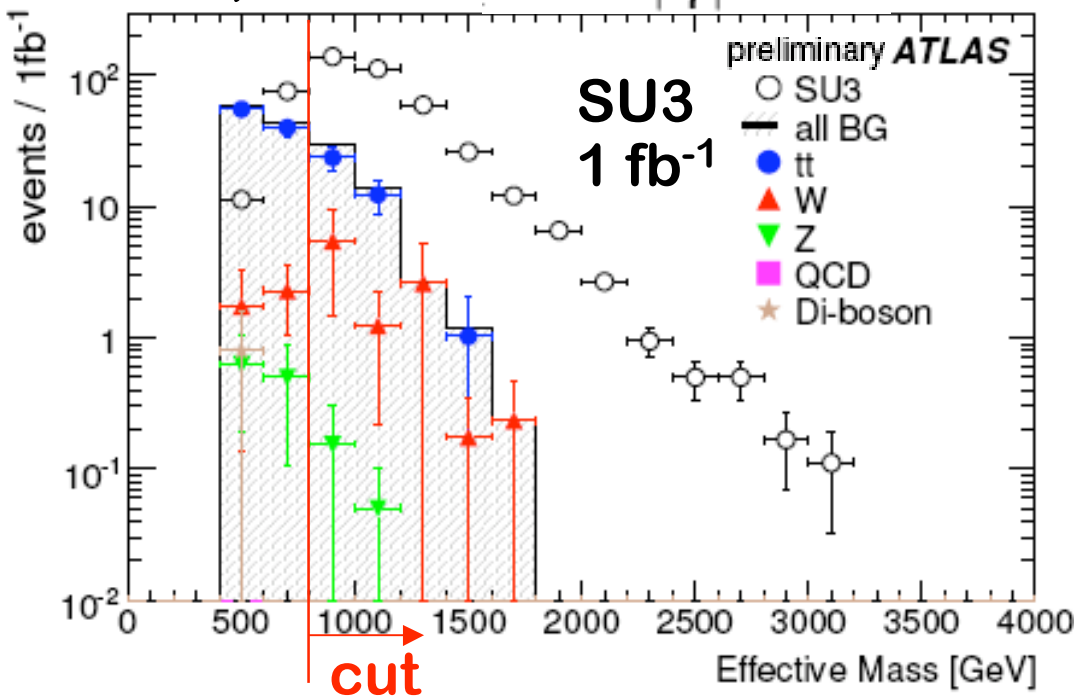
$$m_{T2}^2 \equiv \min_{\not{p}_T^{(1)}+\not{p}_T^{(2)}=\not{E}_T} \left[\max\left\{m_T^2(\mathbf{p}_T^{\alpha}, \not{p}_T^{(1)}; m_\alpha, m_\chi),\ m_T^2(\mathbf{p}_T^{\beta}, \not{p}_T^{(2)}; m_\beta, m_\chi)\right\}\right]$$

- Trigger: $E_T^{\text{jet}} > 70\,\text{GeV}$ and $\not{E}_T > 70\,\text{GeV}$
- Cuts:
  - 2 jets in $|\eta| < 2.5$:
    - j_1: $P_T^{jet1} > 150\ \text{GeV}$
    - j_2: $P_T^{jet2} > 100\ \text{GeV}$
  - $\not{E}_T > 100\ \text{GeV}$
  - $m_{T2} > 400\ \text{GeV}$
  - No isolated leptons



1-lepton Mode: l + jets (ATLAS)

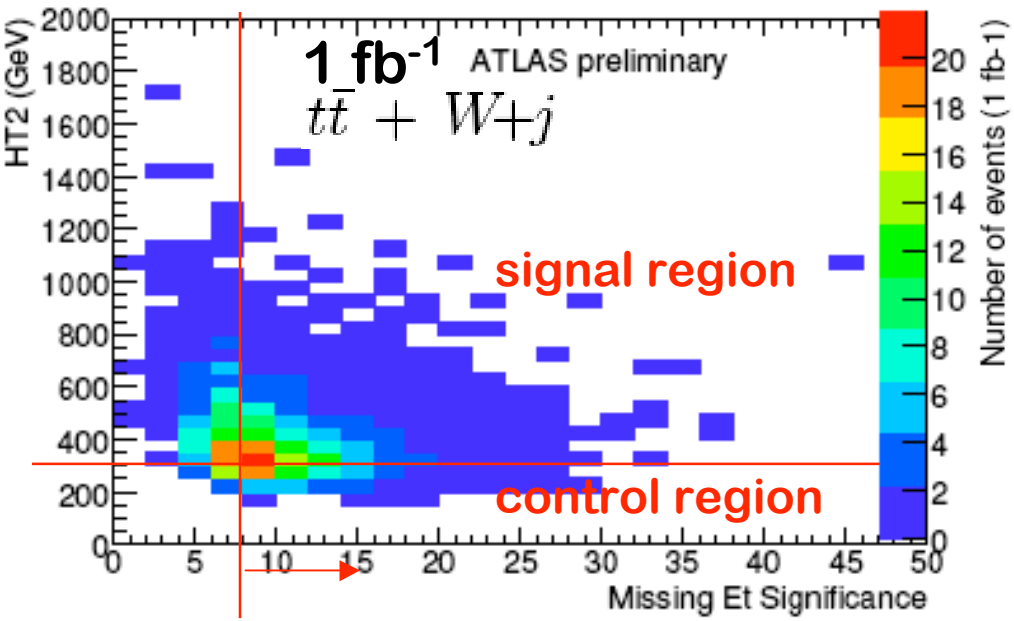
- Sensitivity very close to the 0-lepton mode
- Less prone to QCD systematics
- Trigger: $E_T^{\rm jet} > 70\,{\rm GeV}$ and $\not{E}_T > 70\,{\rm GeV}$
- Cuts:
  - 1 isolated lepton in $|\eta| < 2.5$ and $p_T > 20$ GeV
  - No 2nd lepton with $p_T > 10$ GeV, e veto if $1.37 < |\eta| < 1.52$
  - 4 jets in $|\eta| < 2.5$:
    - j_1: $p_T > 100$ GeV
    - j_2-j_4 : $p_T > 50$ GeV
  - $\not{E}_T > 100$ GeV
  - $\not{E}_T > 0.2 M_{\rm eff}$
  - $S_T > 0.2$
  - $M_T > 100$ GeV
  - $M_{\rm eff} > 800$ GeV

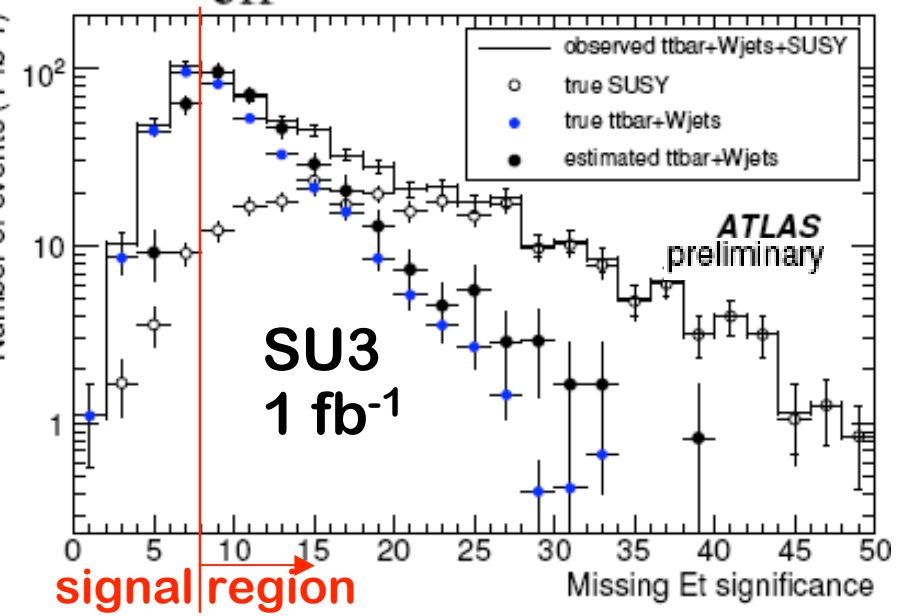


Background estimation (ATLAS)

- Semileptonic tt and W+j reduced due to M_T and $\not{E}_T$ cuts
  - Describe the $\not{E}_T$ distribution with data
  - Use 2 independent variables:
  - $\not{E}_T/[0.49 \cdot \sqrt{\sum E_T}]$ and $\mathrm{HT2} = \sum_{i=2}^{4} p_T^{\mathrm{jet}\,i} + p_T^{\mathrm{lepton}}$ *remove corr. btw* $\not{E}_T$ *and* $p_T^{\mathrm{jet}\,1}$
- Define:
  - Control region: $\mathrm{HT2} < 300\ \mathrm{GeV}$
  - Signal region: $\mathrm{HT2} > 300\ \mathrm{GeV}$ ~ $(M_{\mathrm{eff}}) > 600\ \mathrm{GeV}$

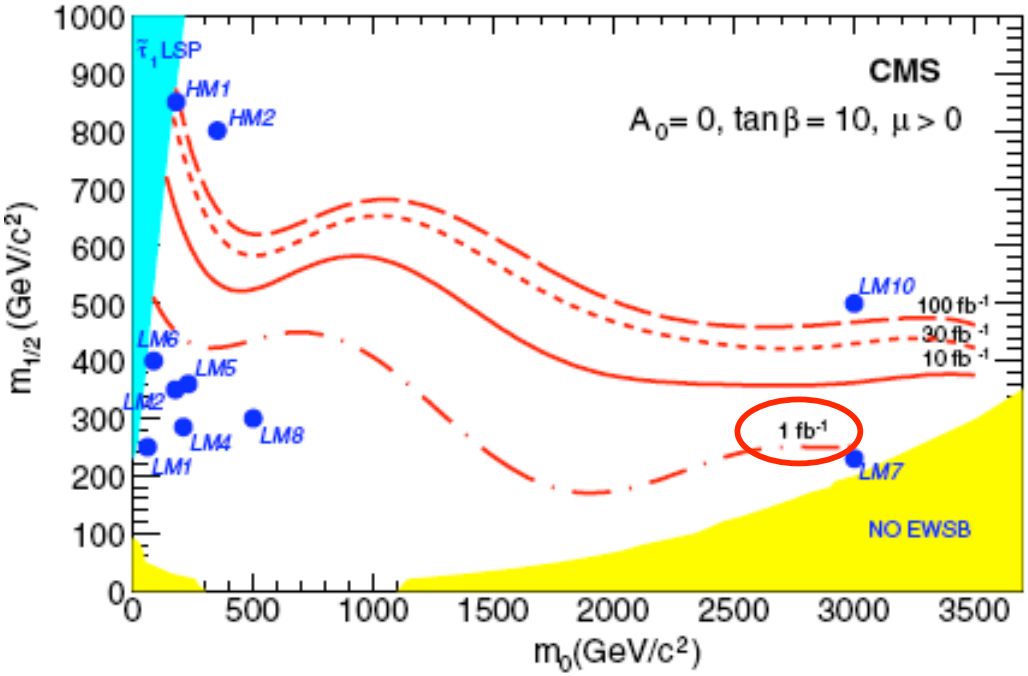
Not shown:
>10 studies on tt, V+j, QCD bgr. estimation





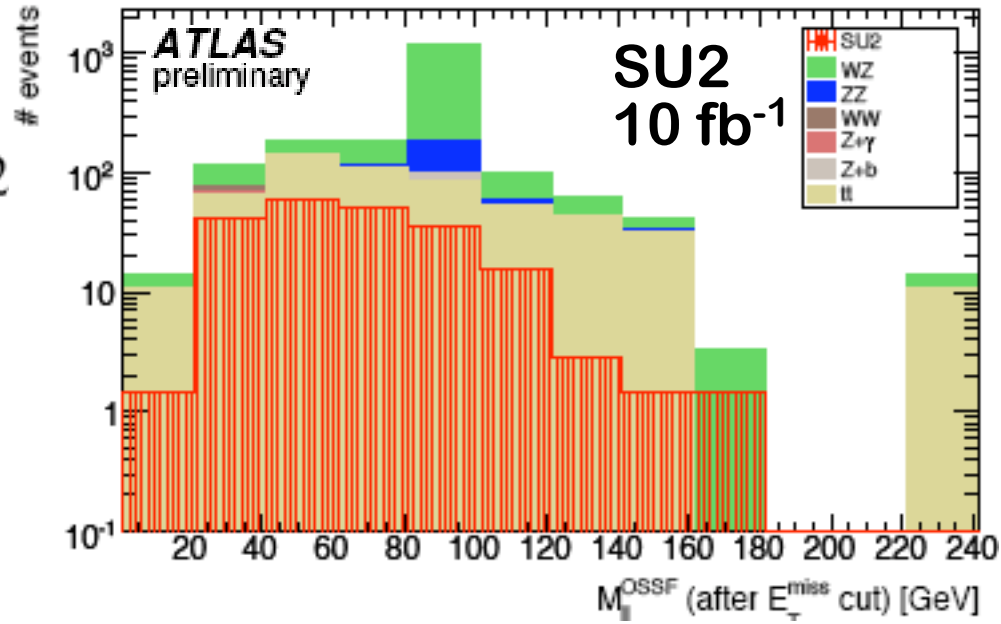
2-lepton Mode: same-sign muons (CMS)

- Striking signature
- Very low SM backgrounds
- Thorough understanding of detector effects needed
- Trigger: HLT: 2 muons with $p_T > 7\,\mathrm{GeV}$
- Cuts:
  - 2 muons with $p_T > 10\,\mathrm{GeV}$:
    - Track and calo isolated
    - Quality cuts
  - $E_T^{j1} > 175\,\mathrm{GeV}$
  - $E_T^{j2} > 130\ \mathrm{GeV}$,
  - $E_T^{j3} > 55\ \mathrm{GeV}$
  - $E_T^{miss} > 200\,\mathrm{GeV}$



3-lepton Mode: Direct Gaugino Production (ATLAS)

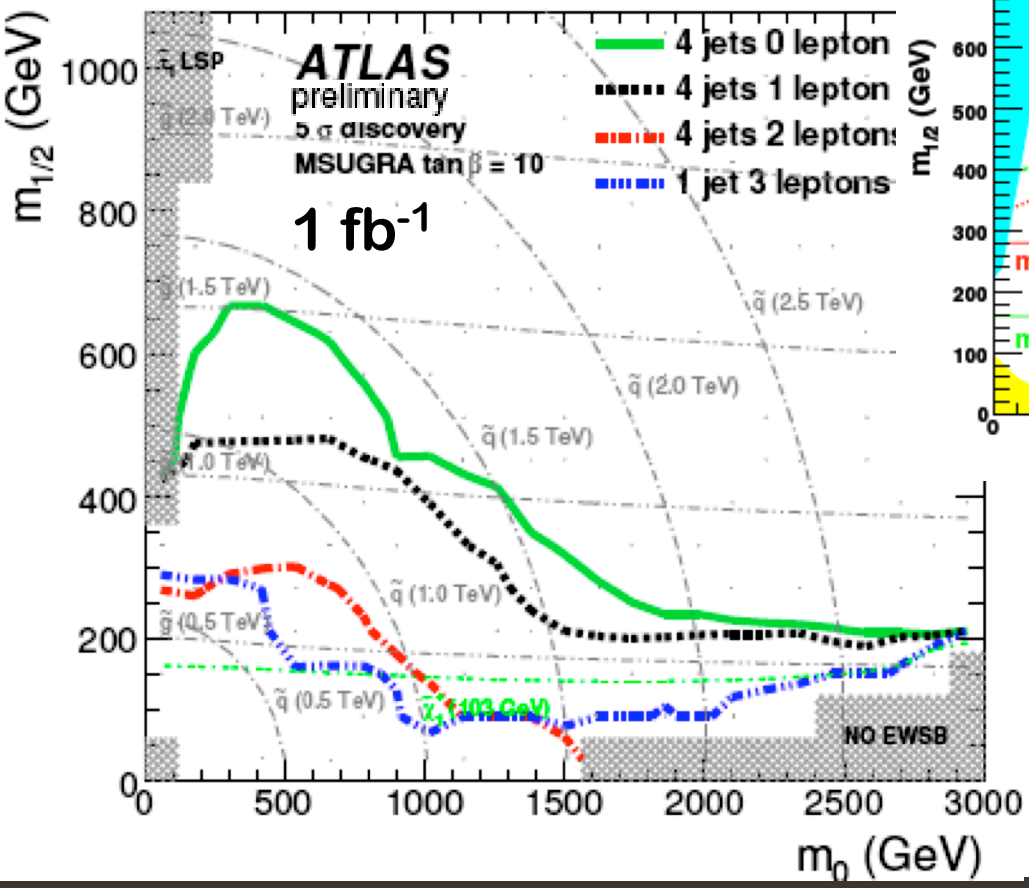
- Does not rely on jets *at all*
  - Arguably best channel for heavy strong SUSY discovery
- Very low systematics (around 5% in total)
- Trigger: $p_T^{e,\,\mathrm{iso}} > 25\,\mathrm{GeV}$ OR $p_T^{\mu,\,\mathrm{iso}} > 20\,\mathrm{GeV}$
- Cuts:
  - leptons: $p_T > 10\,\mathrm{GeV}$
    - e: veto $1.37 < |\eta| < 1.52$
  - At least one OSSF pair
    - $20\,\mathrm{GeV} < M_{OSSF}$
  - 3rd lepton (highest p_T)
  - Track isolation:
    - e: $p_{T\,\mathrm{track,max}}^{\Delta R=0.2} < 2\,\mathrm{GeV}$
    - μ: $p_{T\,\mathrm{track,max}}^{\Delta R=0.2} < 1\,\mathrm{GeV}$
  - No $81.2\,\mathrm{GeV} < M_{OSSF} < 102.2\,\mathrm{GeV}$
  - $\not{p}_T > 30\,\mathrm{GeV}$

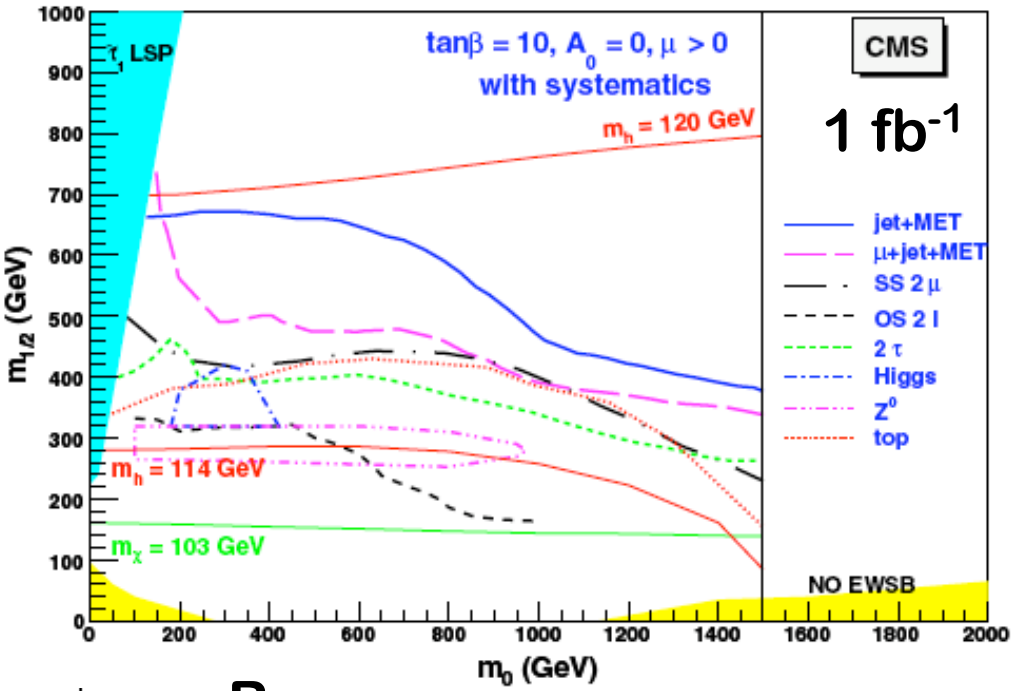


mSUGRA reach at ATLAS & CMS (1 fb^{-1})

$A_0 = 0$, $\mu > 0$, $\tan\beta = 10$, 5σ contours (incl. systematics)

- Assumed uncertainties (ATLAS):
  - QCD: 50%
  - tt, V+j: 20%





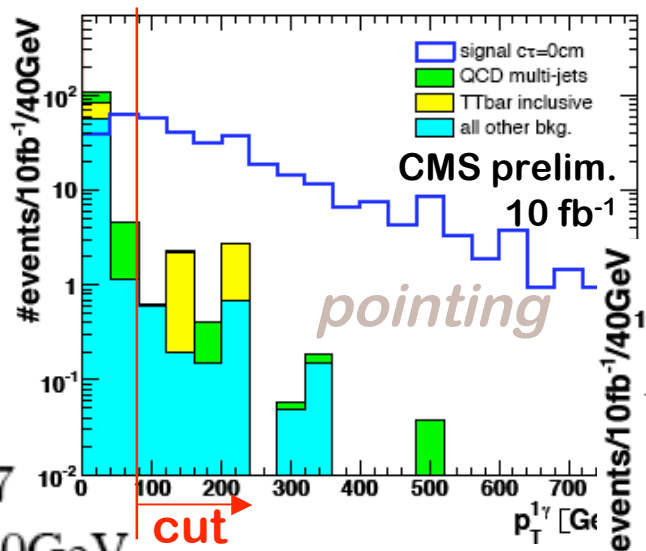
- Beware:
  - Different significance definitions!
  - CMS: syst. uncertainties estimated for 10 fb^{-1} (except 0-lepton: 1 fb^{-1})

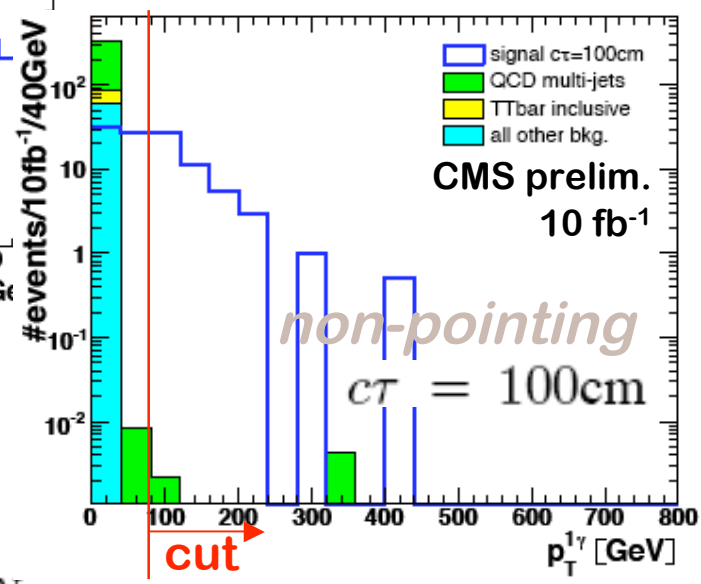
GMSB: (Non-) Pointing Photons (CMS)

- Gauge Mediated Symmetry Breaking (GMSB) parameters:

$$N = 1 \quad \tan\beta = 1 \quad \mathrm{sgn}\,\mu = 1 \quad M_m = 2\Lambda \quad \Lambda = 140\mathrm{TeV}$$

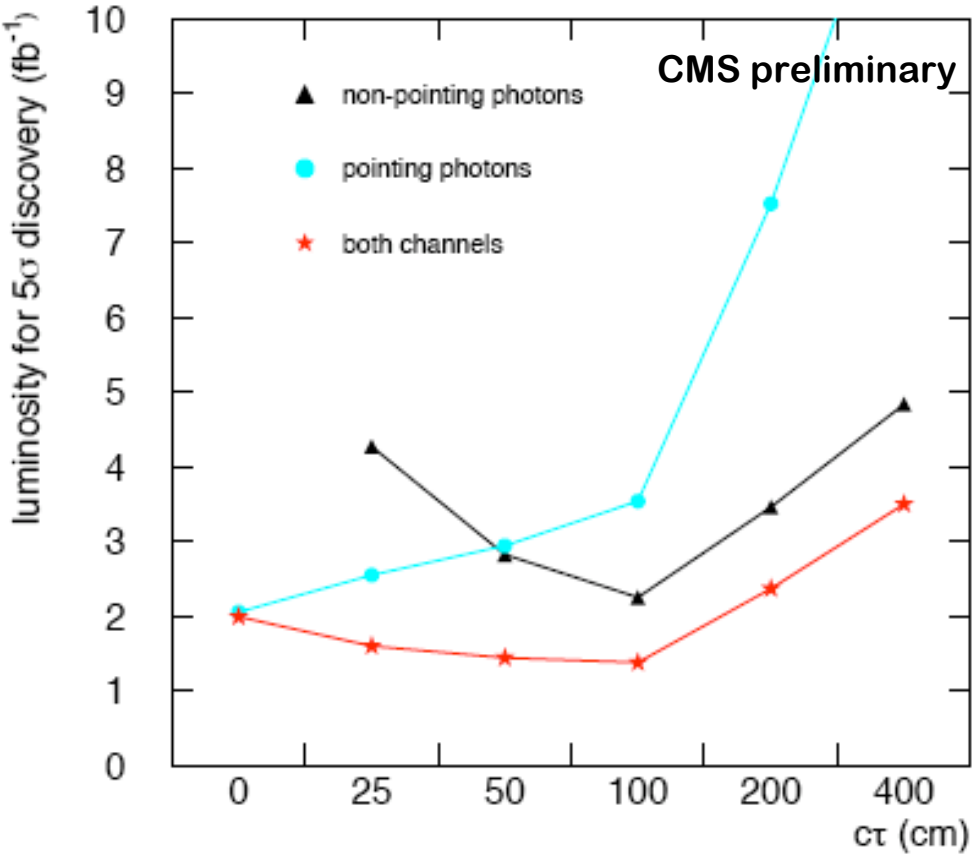
- Trig: $p_T^\gamma > 80\,\mathrm{GeV}$
- Cuts:
  - 1 photon:
  - $p_T^\gamma > 80\,\mathrm{GeV}$
    - Track-isol.
  - 4 jets:
    - j_1: $|\eta^{1j}| < 1.7$
    - j_2-j_4: $p_T^{4j} > 50\mathrm{GeV}$
  - $p_T^{\mathrm{miss}} > 160\mathrm{GeV}$
  - $\phi_{\min}(p_T^{\mathrm{miss}}, p_T^{4j}) > 20°$
  - Cuts based on

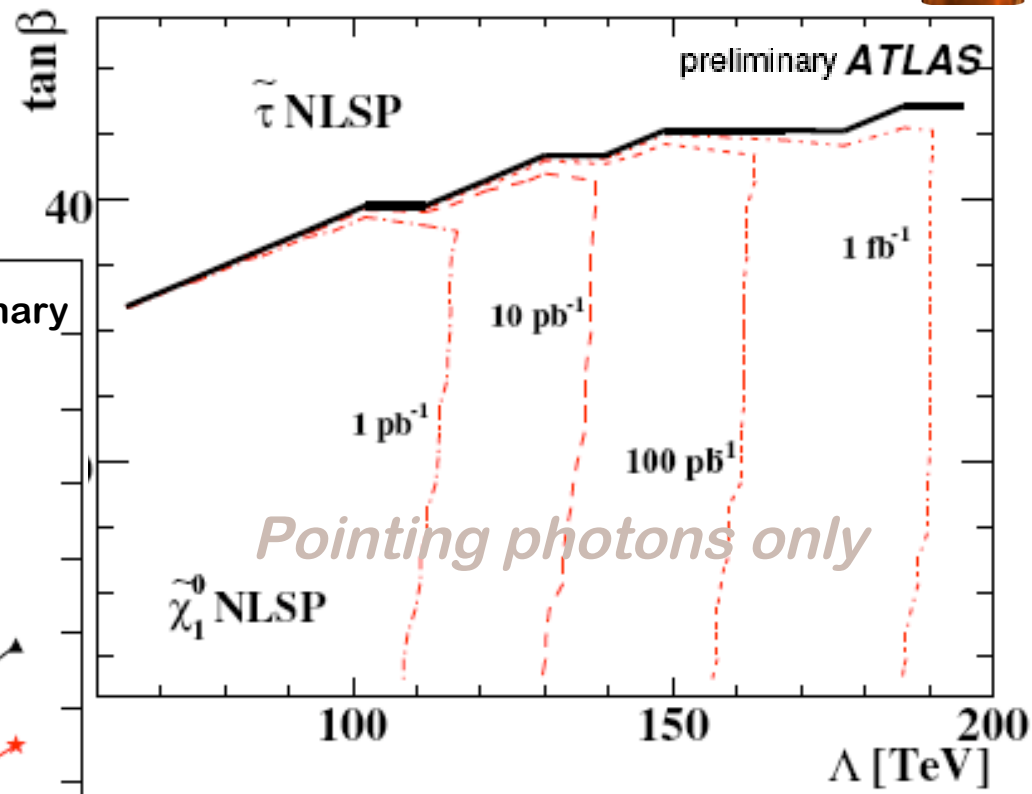




$$COV_{\phi\eta} = \begin{pmatrix} S_{\phi\phi} & S_{\phi\eta} \\ S_{\phi\eta} & S_{\eta\eta} \end{pmatrix} \quad S_{\mu\nu} = \frac{1}{E_\gamma}\sum_{i=1}^{N} E_i \cdot (\mu_i - \langle\mu\rangle)(\nu_i - \langle\nu\rangle)$$

GMSB: Reach at ATLAS and CMS



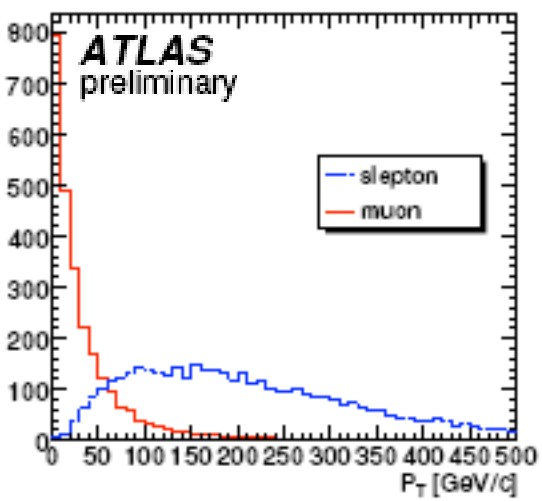


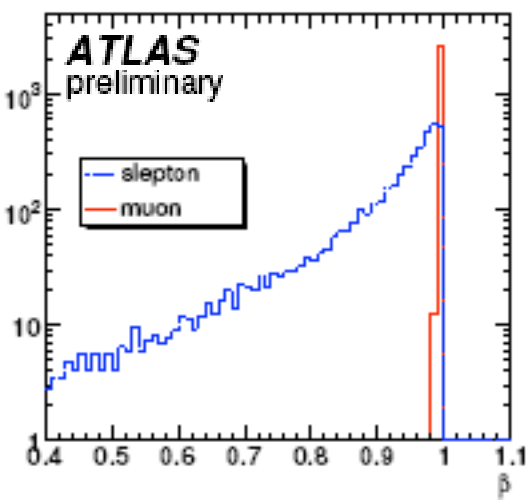
Leptonic (Quasi-) Stable Massive Particles and R-hadrons (ATLAS)

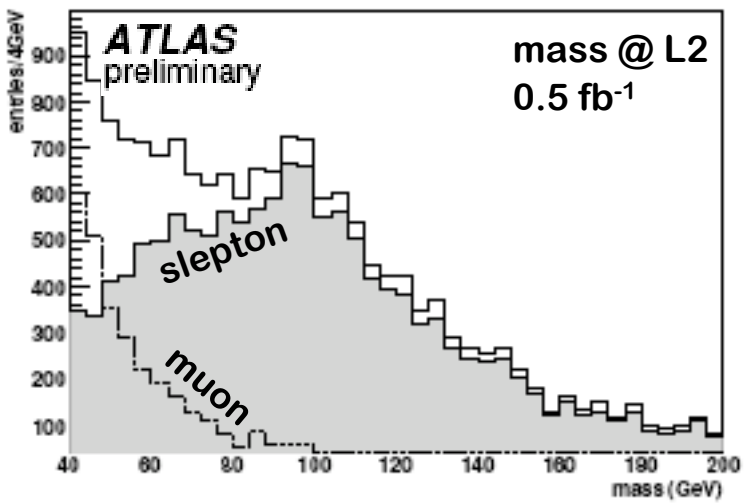
- Many models predict massive leptonic stable particles, eg

Λ [TeV]	M_m [TeV]	$M_{\tilde{\tau}_1}$ [GeV]	N_5	$\tan\beta$	$\arg\mu$	$\sigma_{\rm LO}$ [pb]
30	250	102.3	3	5	+	21.0

- Signature: penetrating tracks with high $p_{\rm T}$, low β
- Signal in parts of detector in different bunch crossings:
  - Online:
    - L1: require regular muon high $p_{\rm T}$ trigger (95% efficient)
    - L2: use TOF information from RPC's (barrel only, ~50% eff.)
      - $p_T > 40\,\mathrm{GeV},\ \beta < 0.97,\ m > 40\,\mathrm{GeV}$

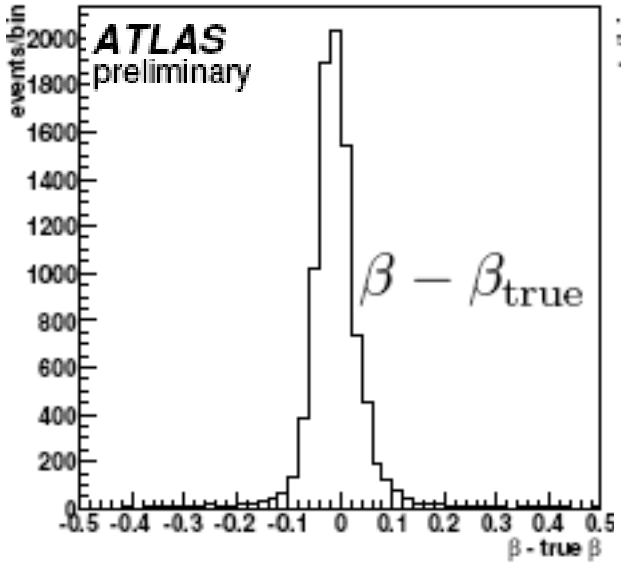


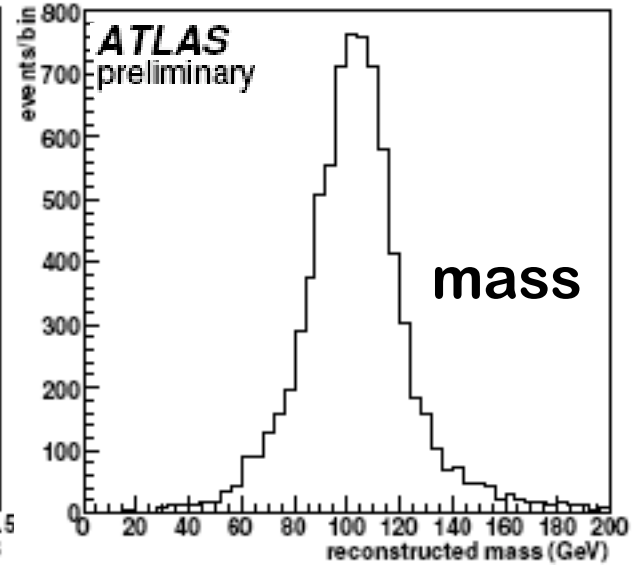




Leptonic (Quasi-) Stable Massive Particles and R-hadrons (ATLAS)

- Dedicated muon-like reconstruction
  - Like at L2 with β and mass constraints
  - Minimise χ^2 w/r/t hit position and time of arrival





- R-hadrons: quasi-stable massive gluinos / squarks
  - Approx. 20 nuclear interactions traversing ATLAS
  - Charge flipping effects / neutral fractions of particle path!
  - Track stubs / unmatched track segments
    - Use various signatures covering cases above

Conclusion / Outlook

- ATLAS and CMS well prepared to look for SUSY:
  - Generic signatures:
    - Analyses ready based on:
      - Hadronic activity
      - Leptonic activity
    - Background estimation methods from data developed
  - More exotic signatures:
    - GMSB in good shape:
      - Prompt / non-pointing photons
      - Massive sleptons
    - R-hadron work progressing well
  - Good prospects for discovery with 1 fb^{-1} (if $M_{SUSY} \lesssim 1TeV$)
- Looking forward to first data!
  - 10 TeV run 2008 -> commisioning
  - 14 TeV and higher luminosity for 2009 expected!
- Expect the Unexpected!

Backup & further discussion

Backup slides following

Definition of Kinematic Variables

- **ATLAS:**
  - $M_{eff} = \sum_{i=1}^{N} p_T^{jet,i} + \sum_{i=1}^{N} p_T^{lep,i} + \not{E}_T$

    4 highest p_T jets in $|\eta| < 2.5$
  - $S_T = \frac{2\lambda_2}{(\lambda_1 + \lambda_2)}$ with $\lambda_1 \lambda_2$ eigenvalues of $S_{ij} = \sum_k p_{ki} p^{kj}$

    all jets with $p_T > 20$ GeV and leptons in $|\eta| < 2.5$
  - $m_{T2}^2 \quad (\mathbf{p}_T^{\alpha}, \mathbf{p}_T^{\beta}, \not{p}_T, m_\alpha, m_\beta, m_\chi)$ defined in:
    - C. Lester, D. Summers, Phys. Lett. B463 (1999) 99
    - A. Barr, C. Lester, P. Stephens, J. Phys. G. 29 (2003) 2343
- **CMS:**
  - $H_T \equiv E_{T(2)} + E_{T(3)} + E_{T(4)} + E_T^{miss}$
    - Where 2, 3, 4 index selected jets sorted by p_T

Definition of Significance Estimators

- **ATLAS:**
  - **Probability for bgr. to fluctuate to N_{data} (all with ROOT):**

$$p = A \int_0^\infty db\, G(b; N_b, \delta N_b) \sum_{i=N_{\text{data}}}^{\infty} \frac{e^{-b} b^i}{i!}$$

    - **With G Gaussian and norm.** $A = \left[\int_0^\infty db\, G(b; N_b, \delta N_b) \sum_{i=0}^{\infty} e^{-b} b^i / i! \right]^{-1}$
  - **Then number of standard deviations:**

$$Z_n = \sqrt{2}\, \mathrm{erf}^{-1}(1 - 2\mathrm{p})$$

  - **For multiple measurements use "Monte Carlo Method" corr.**
- **CMS:**
  - **Program to calculate stat. sign.: ScPf**
  - **Approximation:**

$$S_{c12s} = 2\left(\sqrt{s+b} - \sqrt{b}\right) \frac{b}{b + \Delta b^2}$$

    - **Gaussian background uncertainty assumed**

mSUGRA at ATLAS and CMS

Point	m_0	$m_{1/2}$	$\tan\beta$	$\mathrm{sgn}(\mu)$	A_0
LM1	60	250	10	+	0
LM2	185	350	35	+	0
LM3	330	240	20	+	0
LM4	210	285	10	+	0
LM5	230	360	10	+	0
LM6	85	400	10	+	0
LM7	3000	230	10	+	0
LM8	500	300	10	+	-300
LM9	1450	175	50	+	0
LM10	3000	500	10	+	0
HM1	180	850	10	+	0
HM2	350	800	35	+	0
HM3	700	800	10	+	0
HM4	1350	600	10	+	0

CMS

	M_0 [GeV]	$M_{1/2}$[GeV]	A_0 [GeV]	$\tan\beta$	$\arg\mu$	σ_{LO} [pb]
SU1	70	350	0	10	+	8.15
SU2	3550	300	0	10	+	5.17
SU3	100	300	-300	6	+	20.85
SU4	200	160	-400	10	+	294.46
SU6	320	375	0	50	+	4.47
SU8.1	210	360	0	40	+	6.48

ATLAS

Early SUSY measurements with 1 fb^{-1} (if M_{SUSY} < 1 TeV)

- Need to measure SUSY parameters once discovered
- Example: dilepton edge in decay chain à la:

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

- Three options:
  - (SU4): $m_{\tilde{l}} > m_{\tilde{\chi}_2^0}$: 3-body decay with endpoint $m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$
  - (SU3): $m_{\tilde{l}_R}, m_{\tilde{\tau}_1} < m_{\tilde{\chi}_2^0}$: 2-body decay with triangular shape:

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

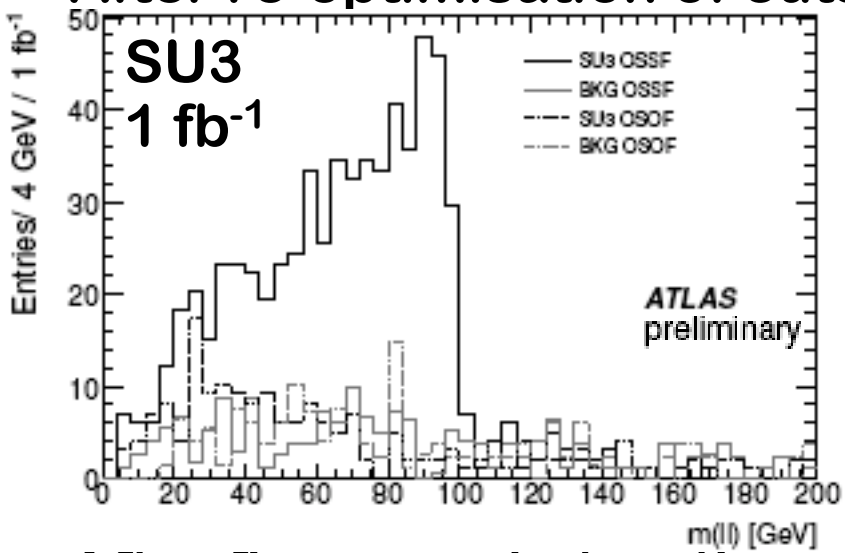
  - (SU1): $m_{\tilde{l}_{L/R}}, m_{\tilde{\tau}_{1/2}} < m_{\tilde{\chi}_2^0}$: 2-body decays, double-triangle
- Control SM background by flavour substraction:
  - $N(e^+e^-)/\beta + \beta N(\mu^+\mu^-) - N(e^{\pm}\mu^{\mp})$ ($\beta = 0.86$ eff. correct'n)
- Re-optimise selection w/r/t the end point:
  - Use as figure of merit (from data):

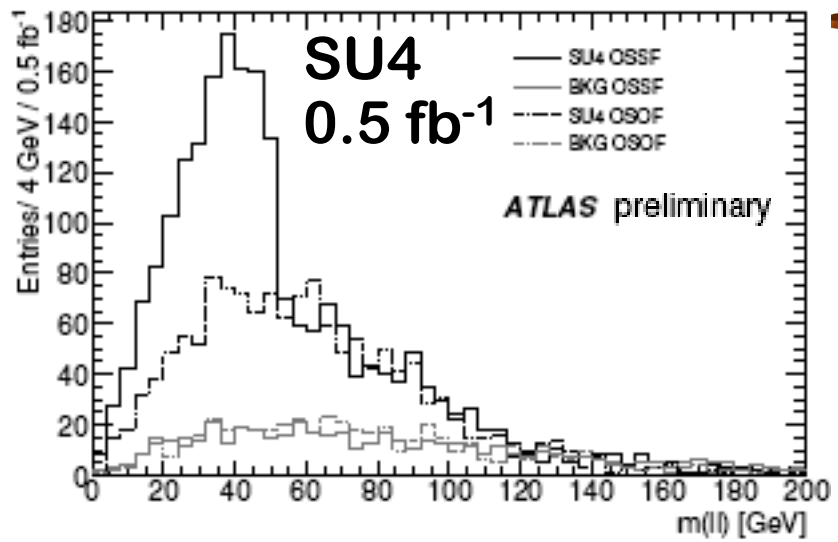
$$S \equiv (N(OSSF) - N(OSOF))/\sqrt{N(OSSF) + N(OSOF)}$$

- Main background (>95%): tt

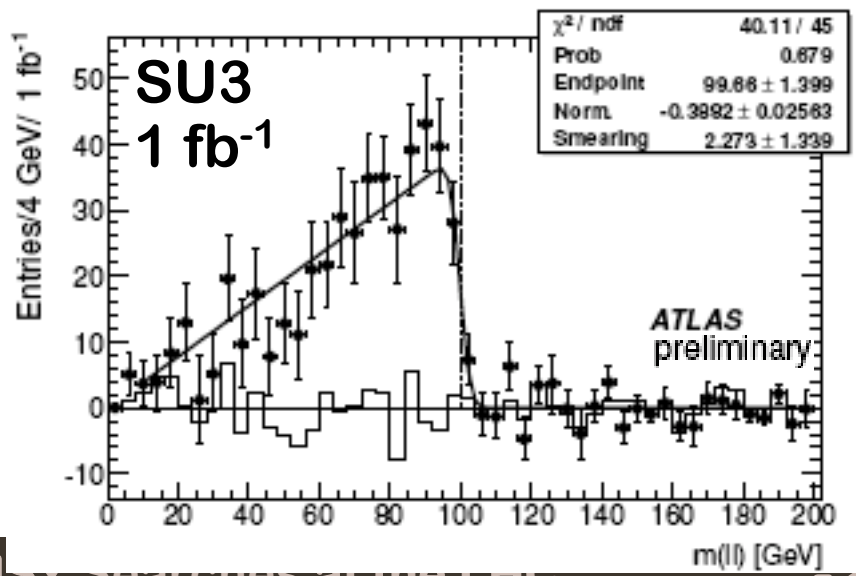
Early SUSY measurements with 1 fb^{-1} (if M_{SUSY} < 1 TeV)

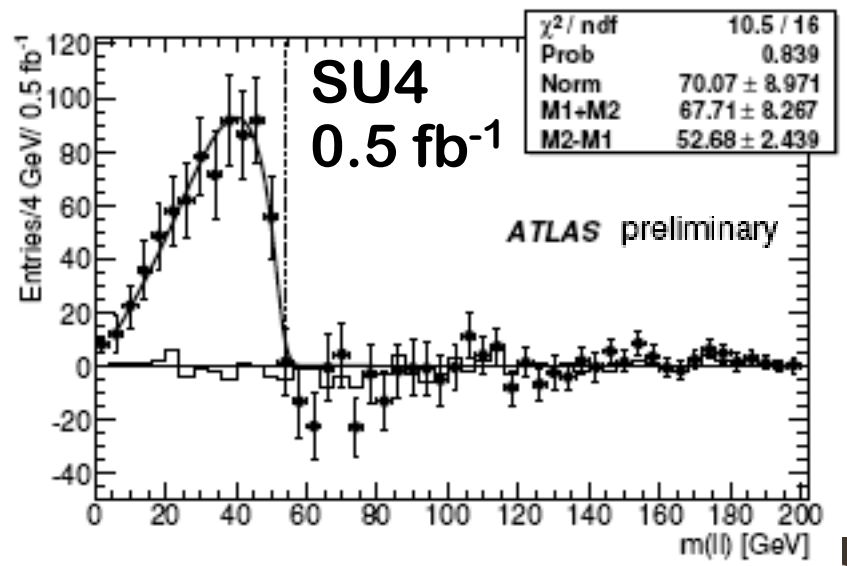
- After re-optimisation of cuts:



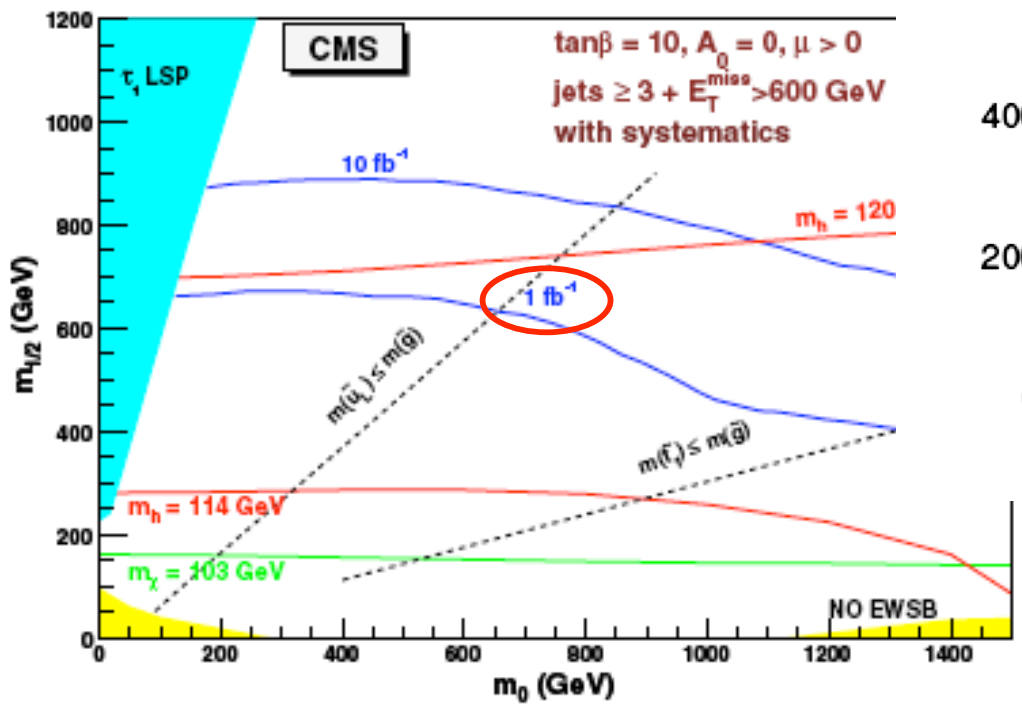


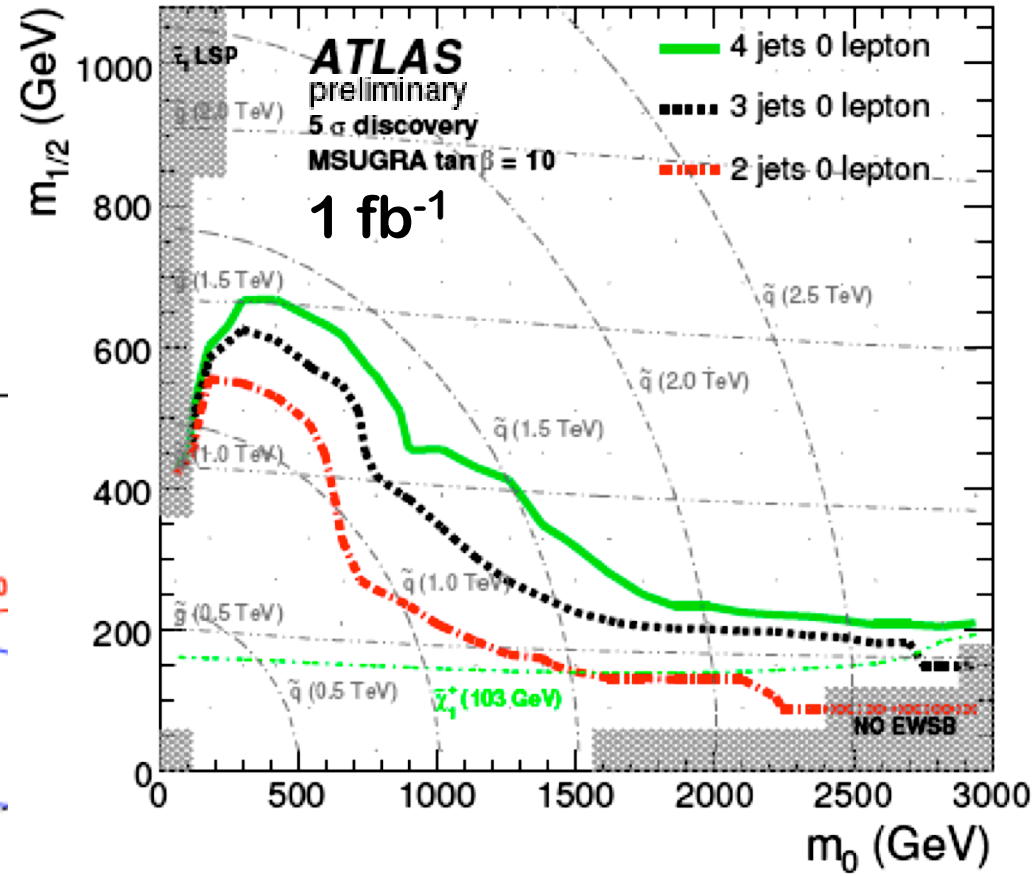
- After flavour substraction:



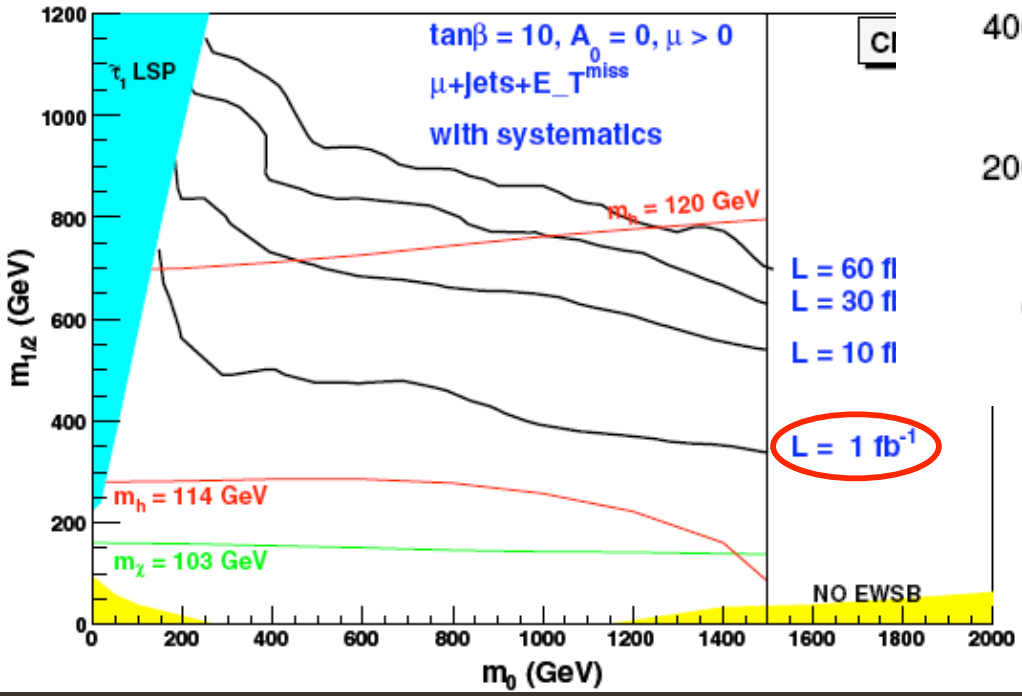


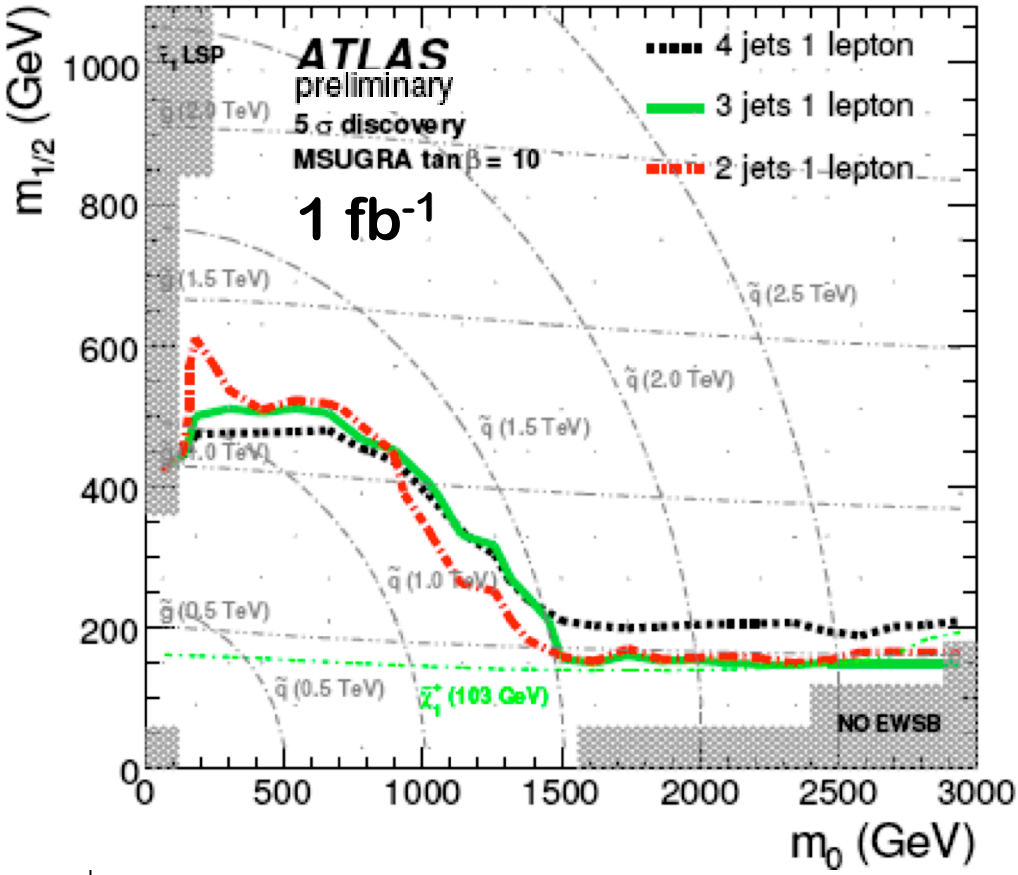
0-lepton reach at ATLAS and CMS





1-lepton reach at ATLAS and CMS



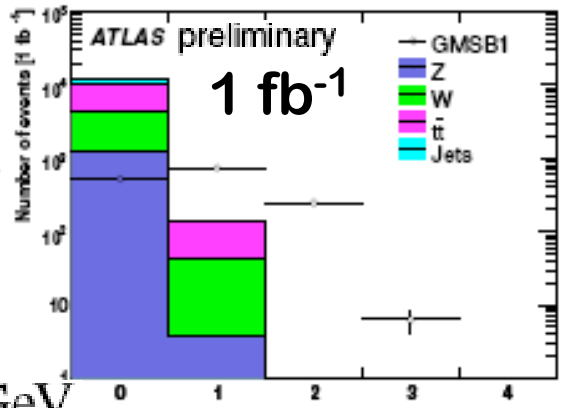


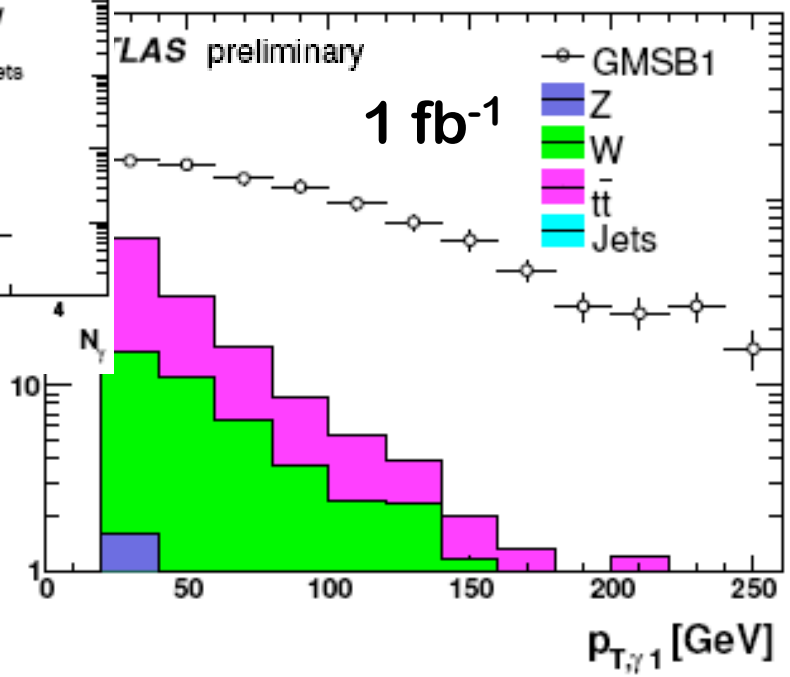
GMSB: Prompt Photons (ATLAS)

- **GMSB point looked at:**

NLO (LO) σ [pb]	Λ [TeV]	M_m [TeV]	C_G	$c\tau$ [mm]	$M_{\tilde{\chi}_1^0}$ [GeV]
7.8 (5.1)	90	500	1.0	1.1	118.8

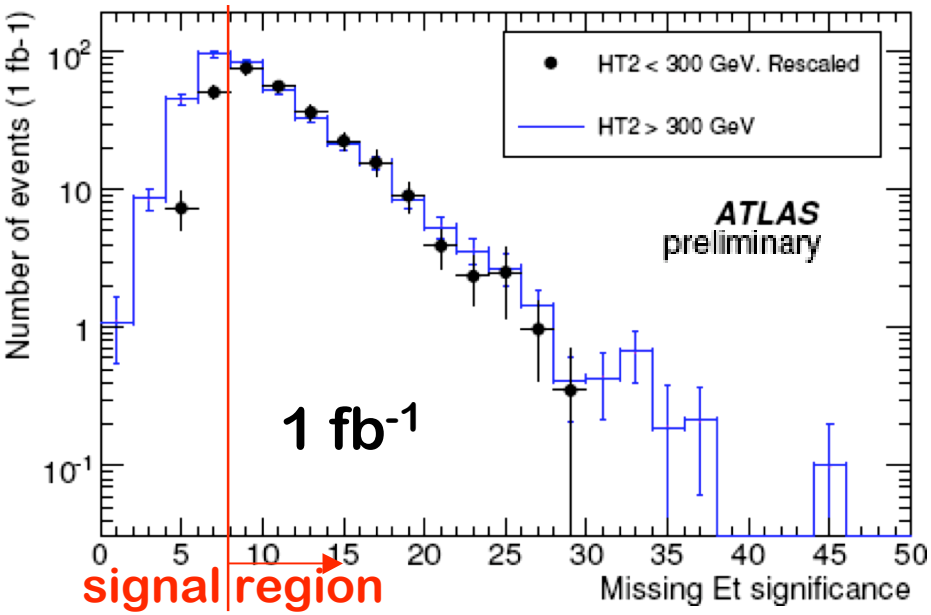
- **Rich signature:** $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$**: 49% (16%)of events have 1 (2)** γ
- **Trigger: g55 OR 2g17i:**
- **Cuts:**
  - **1 or 2 photons:**
    - $p_T > 20$ GeV
    - $|\eta| < 2.5$
  - **4 jets:**
    - j_1: $p_T > 100$ GeV
    - j_4: $p_T > 50$ GeV
  - $\not{E}_T > 100$ GeV
  - $\not{E}_T > 20\% \cdot M_{\text{eff}}$

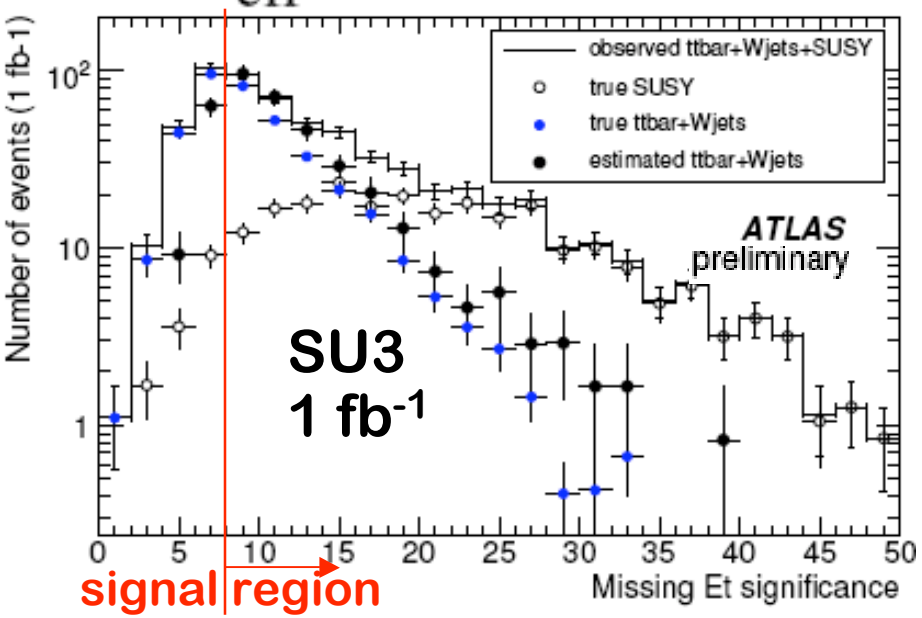




Background estimation (ATLAS)

- Semileptonic tt and W+j reduced due to M_T and $\not{E}_T$ cuts
  - Aim mostly at controlling dileptonic tt
  - Use 2 independent variables:
  - $\not{E}_T/[0.49 \cdot \sqrt{\sum E_T}]$ and $\mathrm{HT2} = \sum_{i=2}^{4} p_T^{\mathrm{jet}\,i} + p_T^{\mathrm{lepton}}$ *remove corr. btw* $\not{E}_T$ *and* $p_T^{\mathrm{jet}\,1}$
- Define:
  - Control region: $\mathrm{HT2} < 300$ GeV
  - Signal region: $\mathrm{HT2} > 300$ GeV ~ $(M_{\mathrm{eff}}) > 600$ GeV





Backup & further discussion