Searches for SUSY in all-hadronic & photonic final states at the LHC

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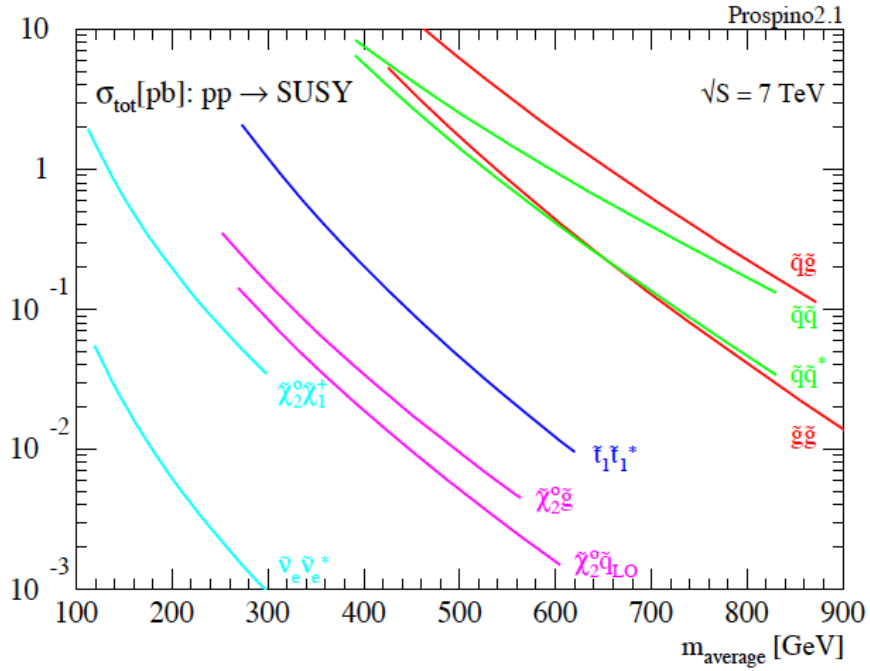
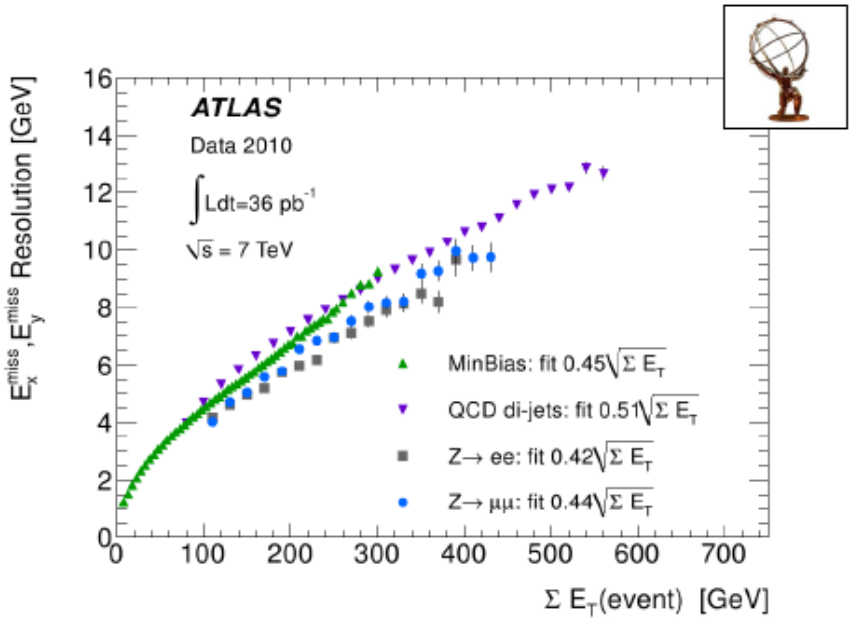
Introduction

- SUSY cross-sections large at the LHC
  - gluinos & squarks dominate
- Decay topologies complex
  - Multiple jets; large H_T
  - Missing transverse energy (MET)
  - Leptons, photons, bjets etc
- This talk: Hadronic + photonic decays

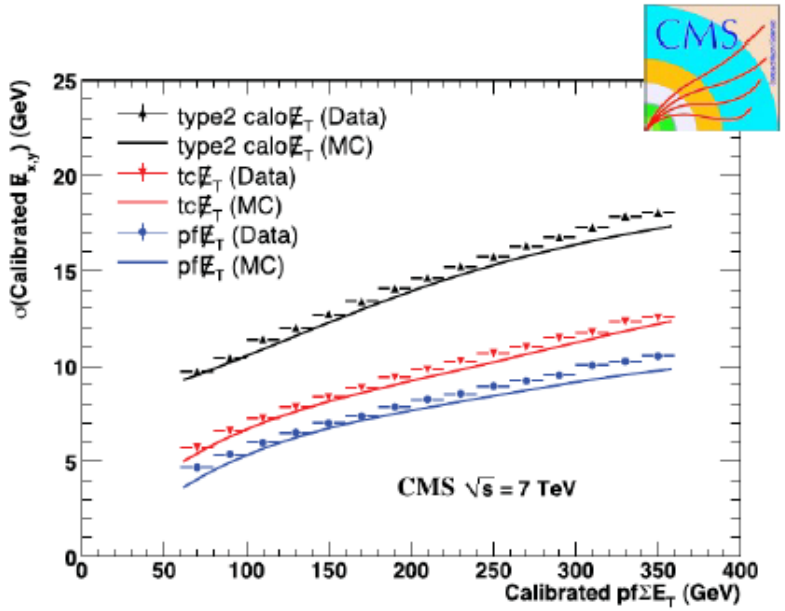


- Basic analysis flow:
  - Find a region where signal is enhanced
  - Estimate the SM background in this region
  - Set limit or make discovery

Missing Transverse Energy



Eur. Phys. J. C72 (2012) 1844



J. Instrum.6 (2011) P09001

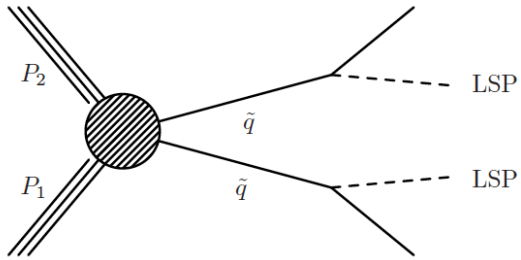
- MET: Key observable in many SUSY searches
  - Can be experimentally challenging
- ATLAS & CMS performance comparable
  - CMS used PF MET in most analyses

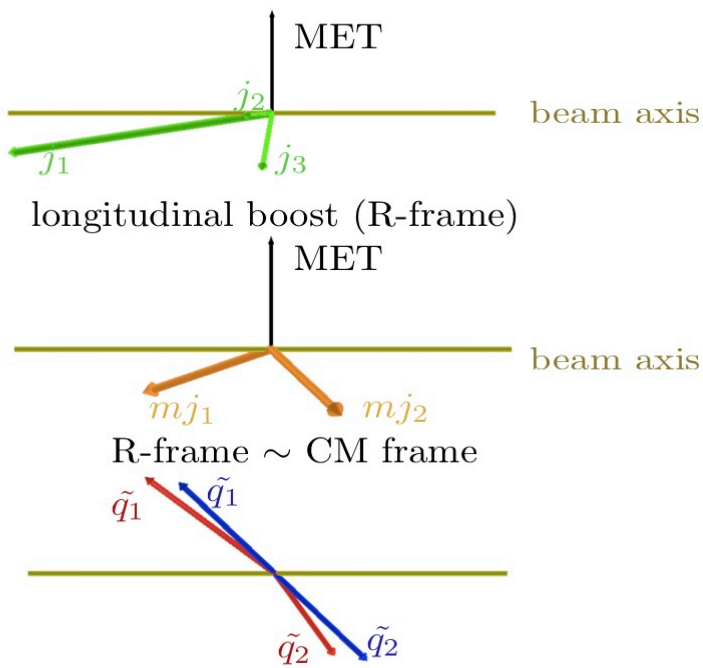
CMS-PAS-SUS-12-005

$$M_\Delta \equiv \frac{M_{\tilde{q}}^2 - M_{\tilde{\chi}}^2}{M_{\tilde{q}}}$$

CMS Razor Inclusive (4.4fb^{-1})

- Assume a pseudo-dijet topology
  - pp → squark squark; squark → quark + LSP
  - Cluster objects into hemispheres
  - Longitudinal boost to *R frame*: ~CM frame



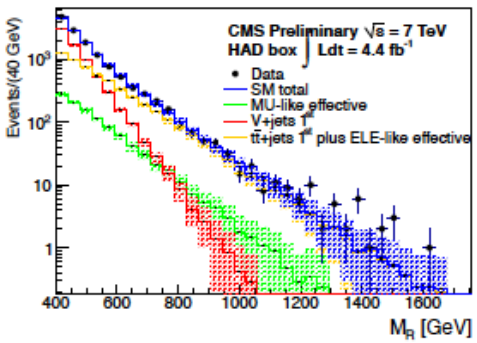


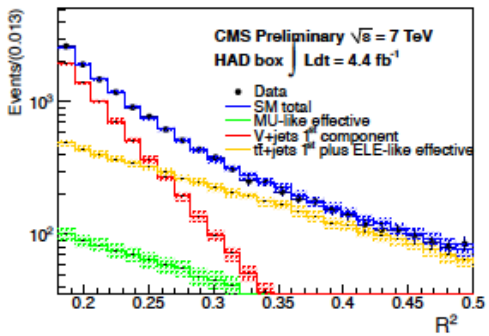
- Razor variables estimate event scale:
  - M_R peaks at M_Δ
  - M_R^T has kinematic edge at M_Δ
  - Ratio, $R = M_R^T/M_R$, removes QCD
- M_R (R^2) exp. when projected over R^2 (M_R)
  - Search for 2D bump on steeply falling SM background

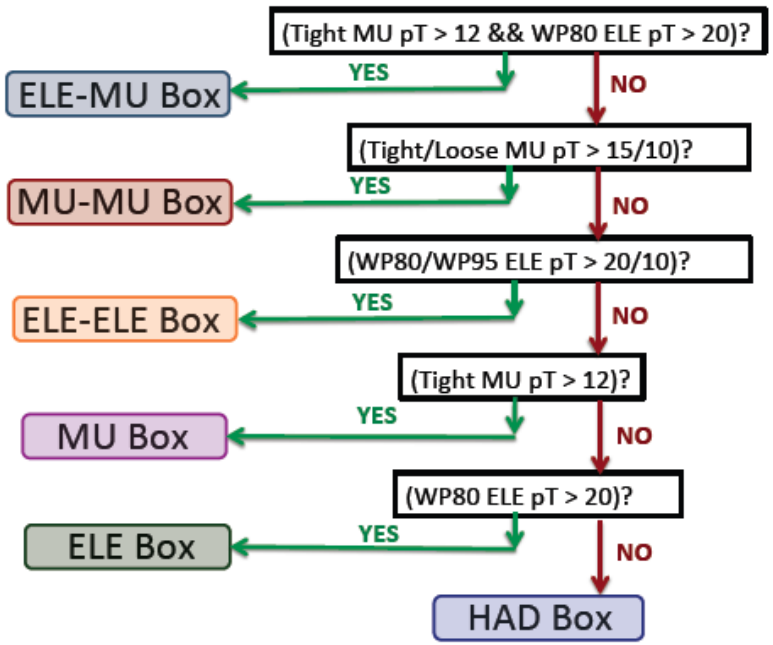
CMS-PAS-SUS-12-005

$$M_\Delta \equiv \frac{M_{\tilde{q}}^2 - M_{\tilde{\chi}}^2}{M_{\tilde{q}}}$$

CMS Razor Inclusive (4.4fb^{-1})





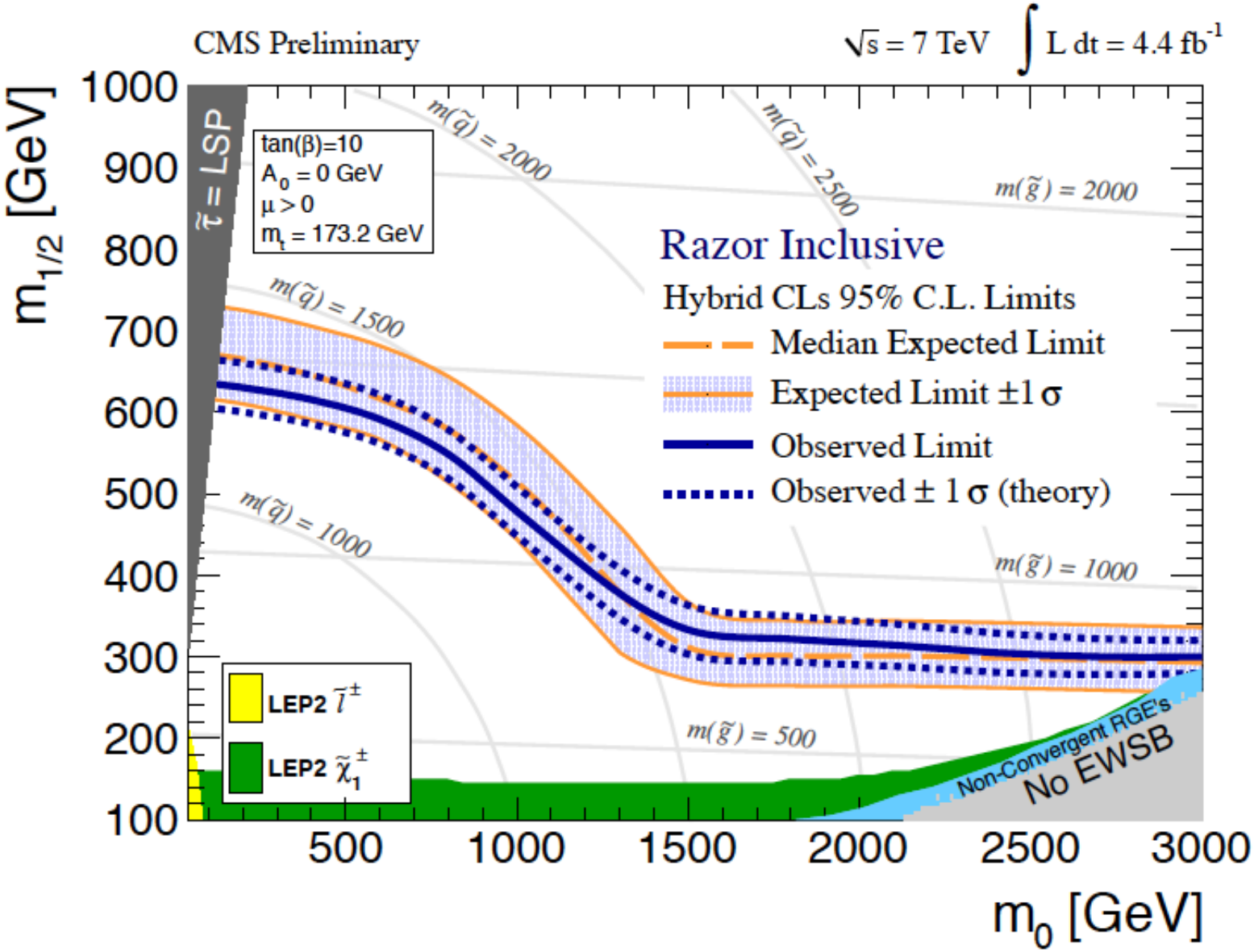


- Exploit M_R/R correlations with unbinned 2D ML fit (minimal MC use)
  - By-process shapes from control region
  - Extrapolate to signal region for model independent limit
- CMSSW: Use signal MC in hypothesis test
  - Combine orthogonal boxes for limit

Online: dedicated R/MR trigger
Offline: ≥2 jets (AK5 60GeV), box cuts
R/M_R: Per box to remove turn-on

$$F_j(M_R, R^2) = \left[k_j(M_R - M_{R,j}^0)(R^2 - R_{0,j}^2) - 1\right] e^{-k_j(M_R - M_{R,j}^0)(R^2 - R_{0,j}^2)}$$

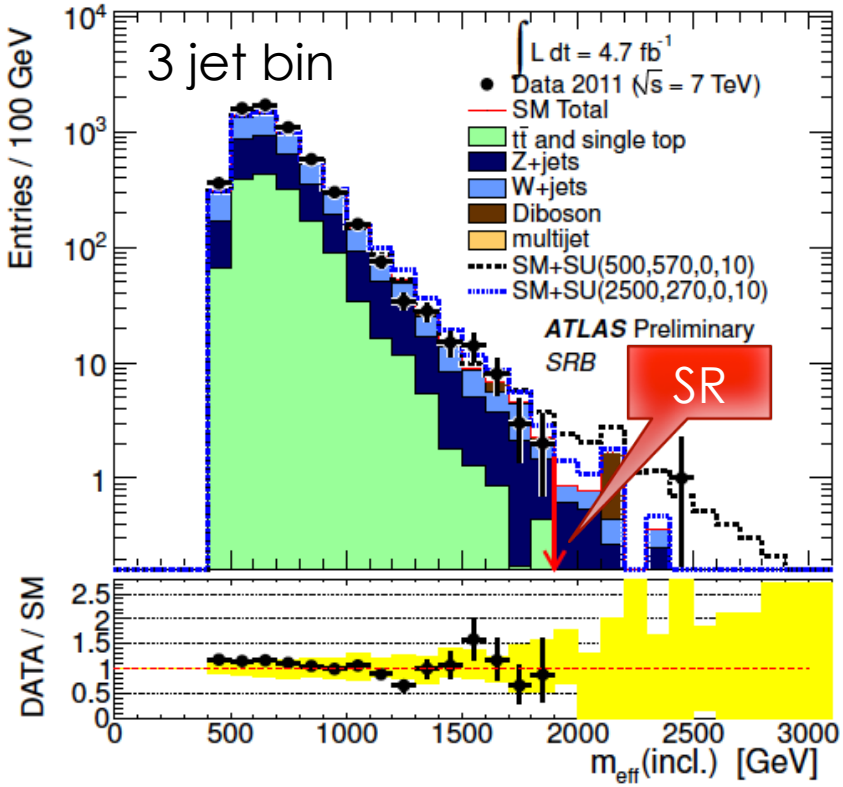
CMS-PAS-SUS-12-005



ATLAS-CONF-2012-033

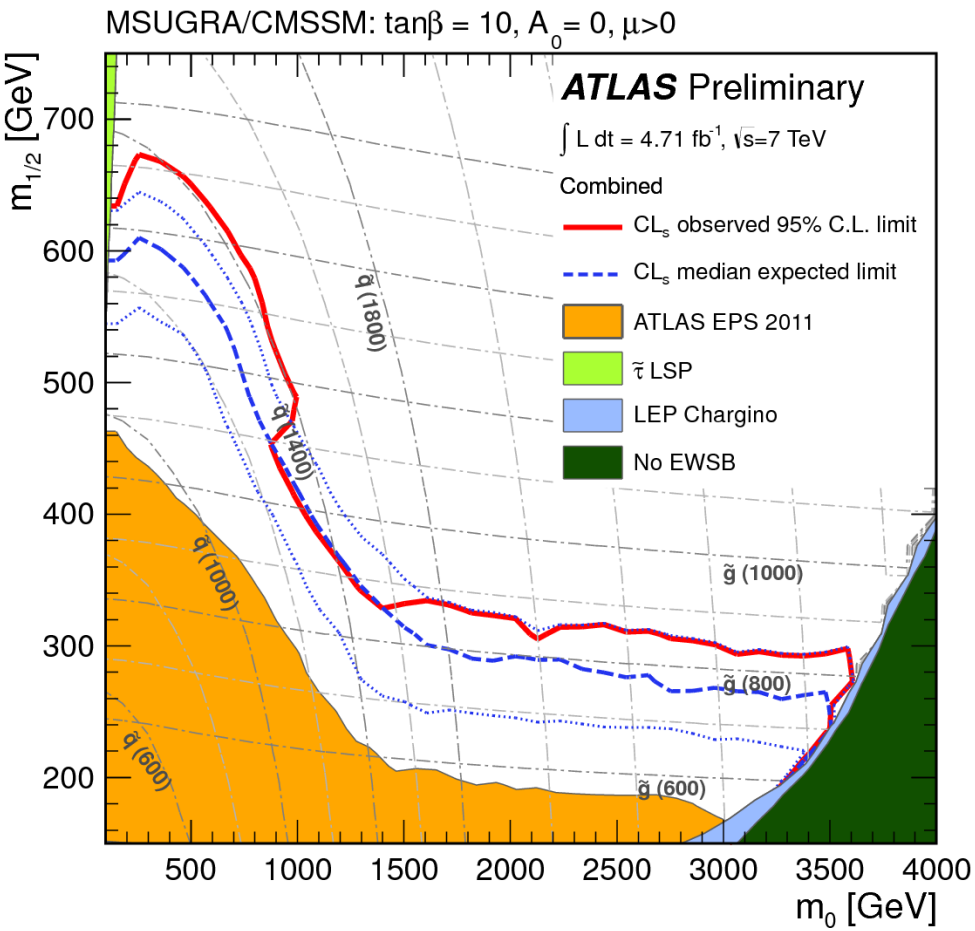
ATLAS 2-6 Jets+MET (4.7fb^{-1})

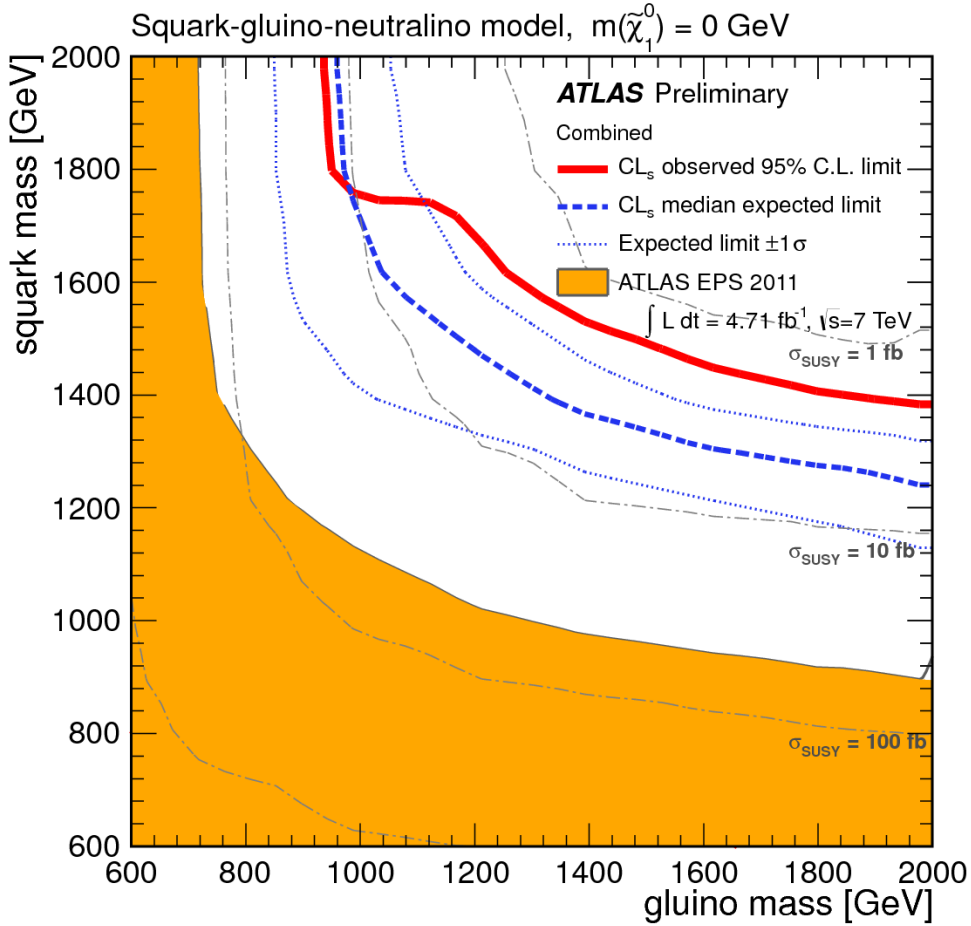
- Veto leptons; search m_{eff} as a function jet multiplicity (2-6)
  - m_{eff} = sum(p_t^{jet}) + MET
- Define 11 SRs; 55 orthogonal CRs
  - CR for each major background
- Extrapolate yields from CRs to SRs with transfer fraction
  - Multjet from data; Others from MC
- Likelihood fit propagates uncertainties
  - Systematics & correlations included



$$N(SR, est, proc) = N(CR, obs, proc) \times \left[\frac{N(SR, raw, proc)}{N(CR, raw, proc)}\right]$$

ATLAS-CONF-2012-033





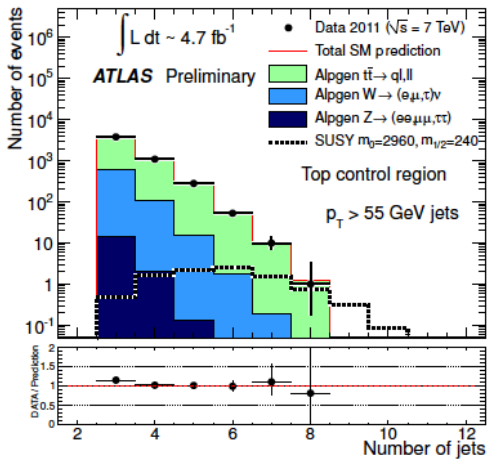
SMS: Directly produced sparticles decay to jets + MET

ATLAS-CONF-2012-033

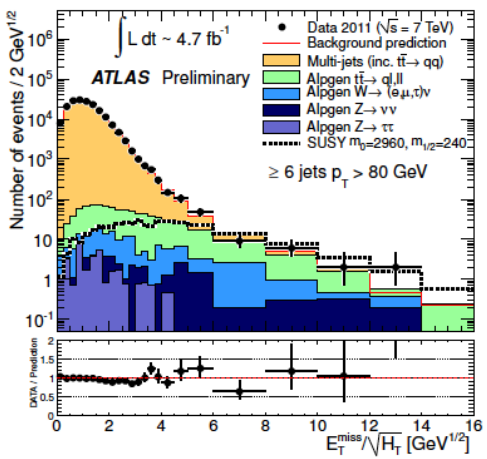
ATLAS 6-9 Jets+MET (4.7fb^{-1})

Signal region	7j55	8j55	9j55	6j80	7j80	8j80
Isolated leptons (e, μ)	=0					
Jet p_T	> 55 GeV			> 80 GeV		
Jet $\lvert\eta\rvert$	< 2.8					
Number of jets	≥ 7	≥ 8	≥ 9	≥ 6	≥ 7	≥ 8
$E_T^{miss}/\sqrt{H_T}$	> 4 GeV$^{1/2}$					

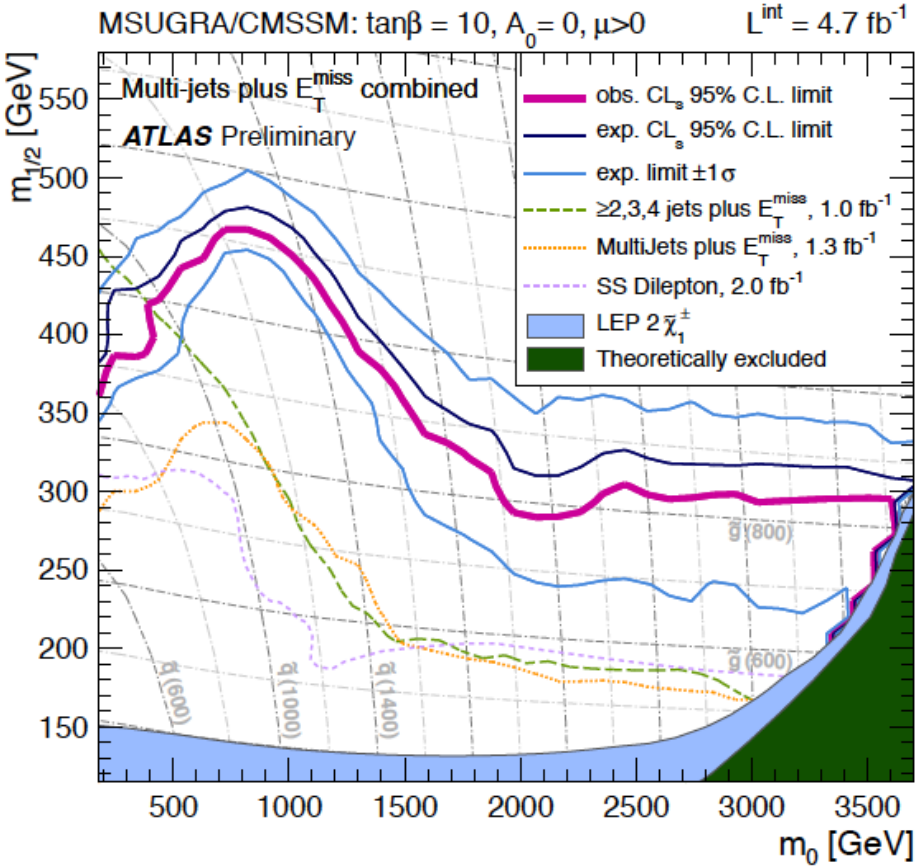
- Analysis targets long decay chains
  - Multijet (dominant): templates from from low jet multiplicity data
  - W, Z, top: MC validated in CRs



Top CR



6j SR



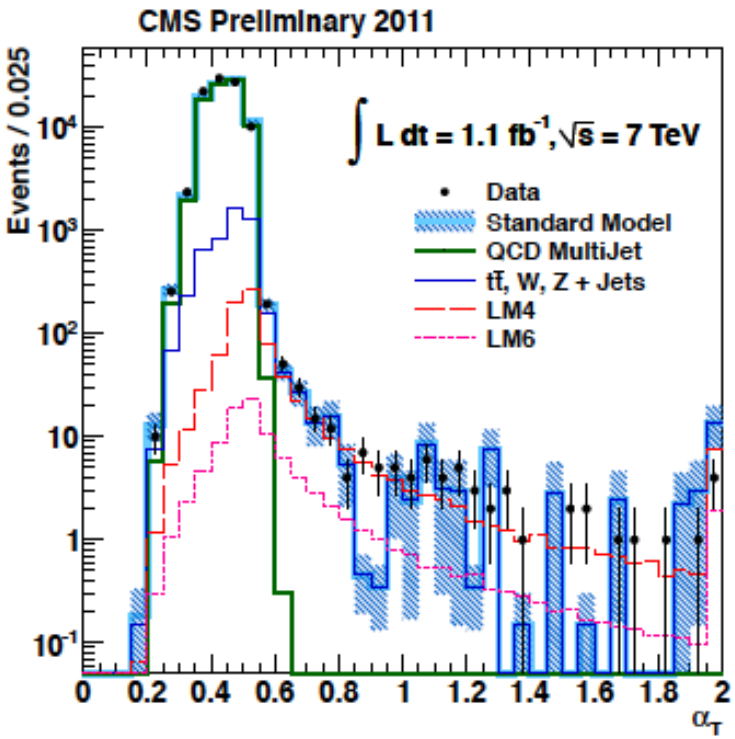
Analysis optimised for small $m_{1/2}$, large m_0 region

CMS-PAS-11-003

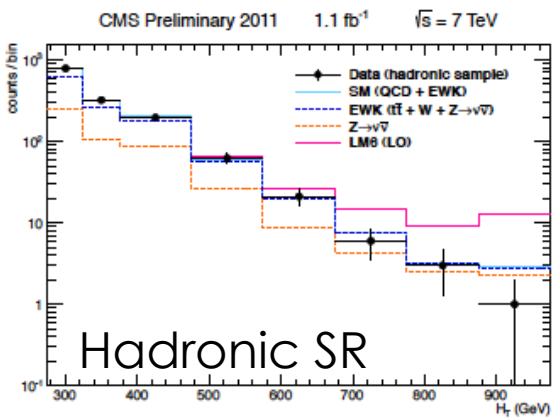
$$\alpha_T = \frac{E_T^{jet_2}}{M_T} = \frac{E_T^{jet_2}}{\sqrt{\left(\sum_{i=1}^{2} E_T^{jet_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{jet_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{jet_i}\right)^2}},$$

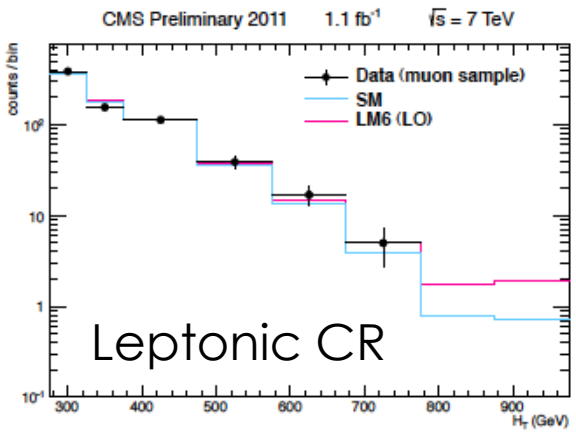
CMS Jets + MET with α_T (1.1fb^{-1})

- Require ≥2 jets (AK5 50GeV), no leptons, H_T > 275 GeV
  - α_T > 0.55 removes QCD
- CRs for major background used:
  - Top & W+Jets: Leptonic W decays
  - Z→νν: γ+jets; remove γ
  - QCD yields compatible with zero



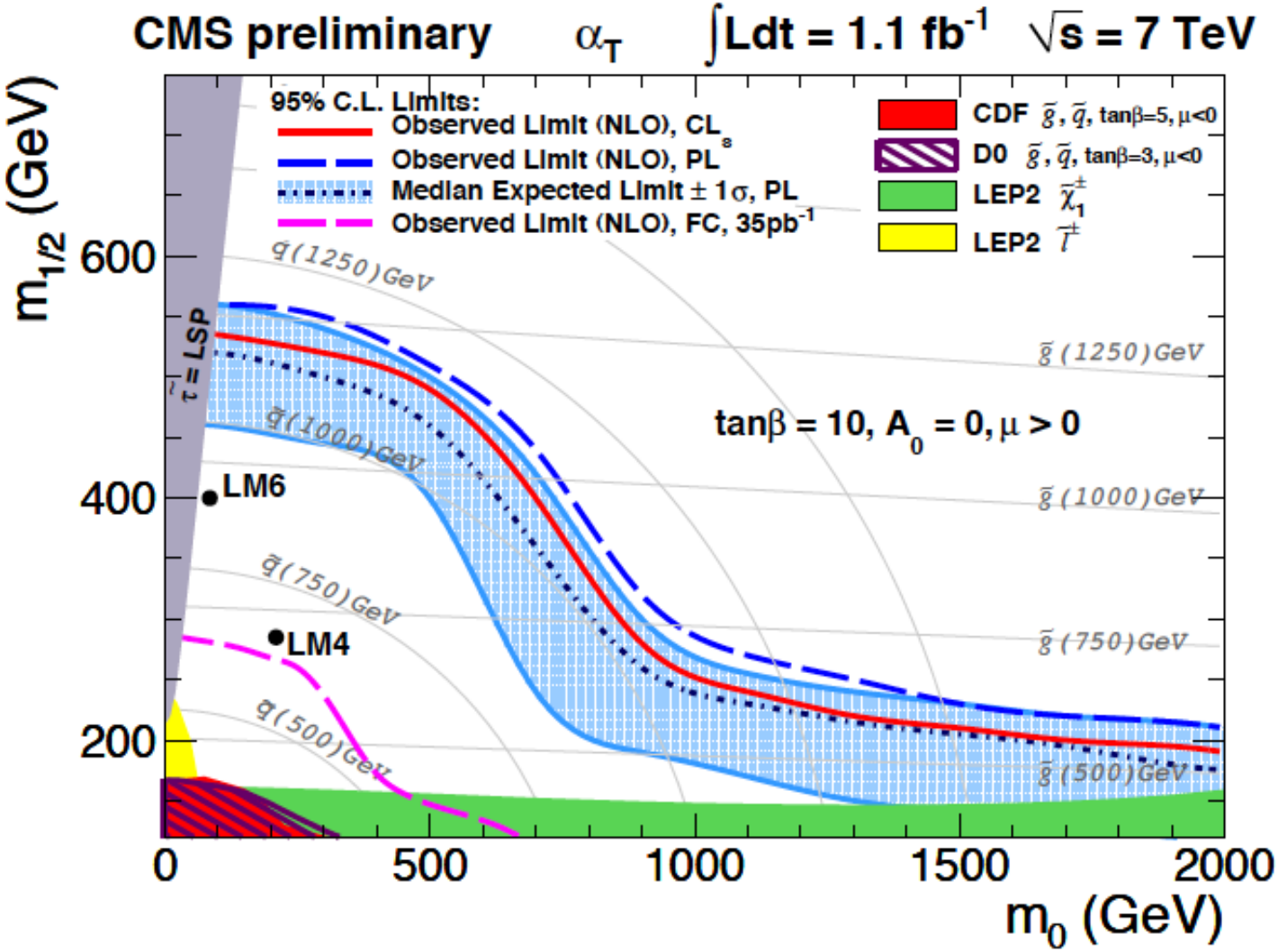
H_T > 375 GeV





CMS-PAS-11-003

CMS Jets + MET with α_T (1.1fb^{-1})

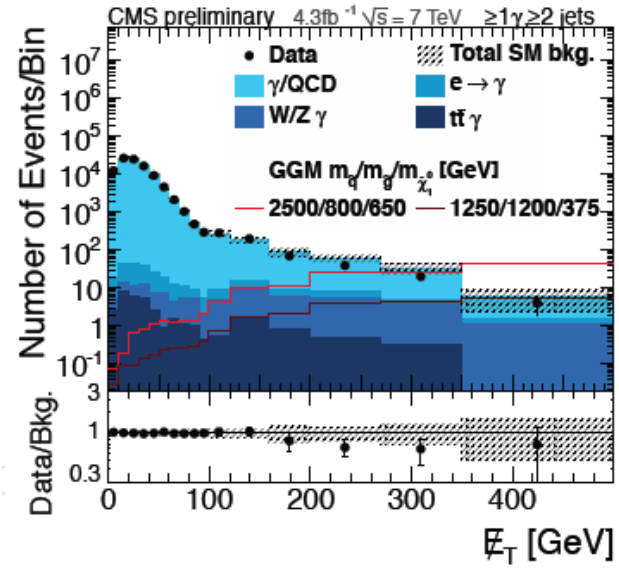


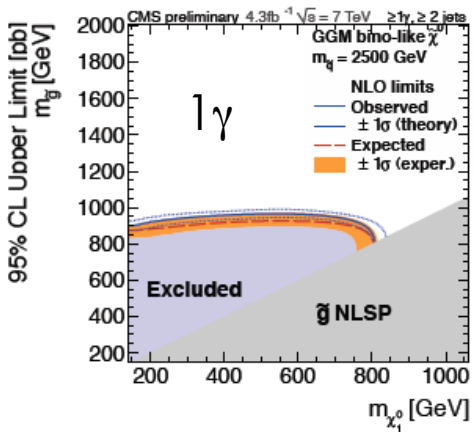
CMS-PAS-12-001

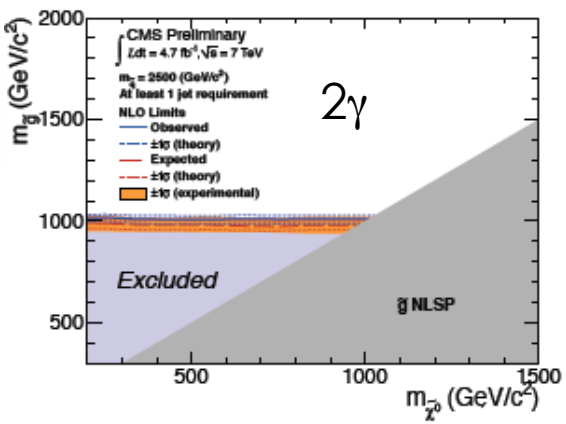
NLSP type	$\gamma + 2\,\text{jets} + E_T^{miss}$	$\gamma\gamma + \text{jet} + E_T^{miss}$
Bino	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{jets} + \gamma + Z + \tilde{G}\tilde{G}$	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{jets} + \gamma\gamma + \tilde{G}\tilde{G}$
Wino	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{jets} + \gamma + Z + \tilde{G}\tilde{G}$ $\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^\pm \to \text{jets} + \gamma + W^\pm + \tilde{G}\tilde{G}$	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{jets} + \gamma\gamma + \tilde{G}\tilde{G}$

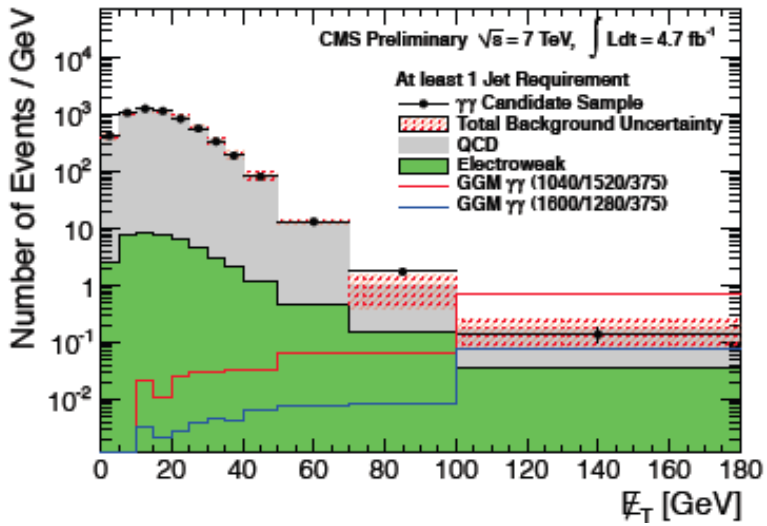
CMS Photons + MET (4.7fb^{-1})

- Search for gauge mediated SUSY
  - Gravitino is lightest SUSY particle
  - Also set limits on UED model
- Two paths: different triggers
  - 2γ (40,25 GeV), 1 jet, MET
  - 1γ (70 GeV), 2 jets, HT>450, MET
- QCD multijet and Z→ee CRs used to model dominant background





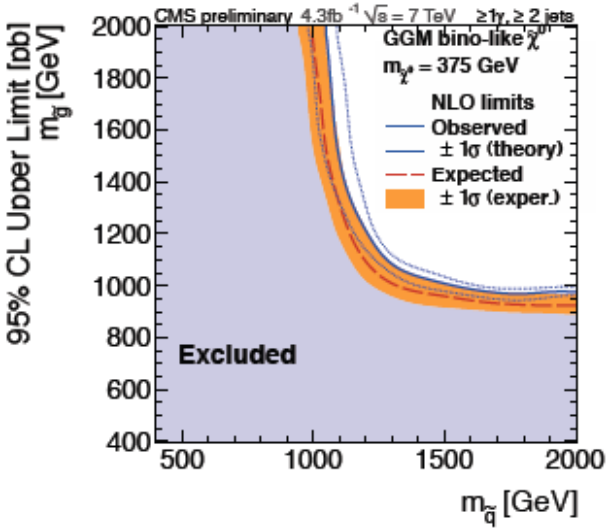




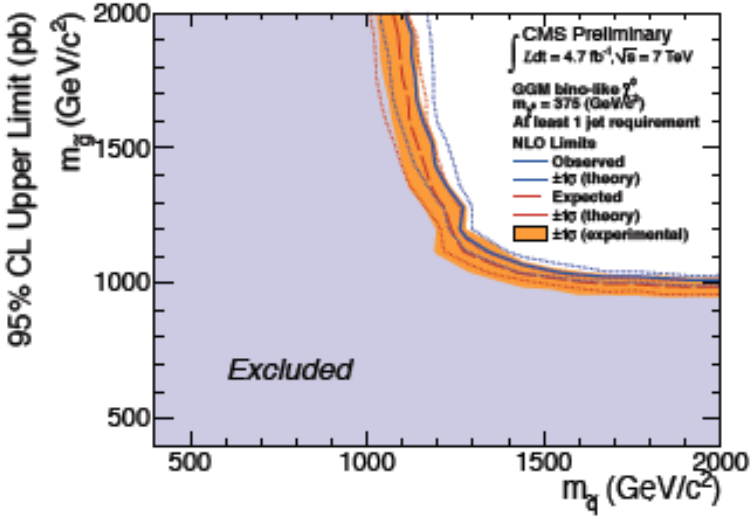
CMS-PAS-12-001

CMS Photons + MET (4.7fb^{-1})

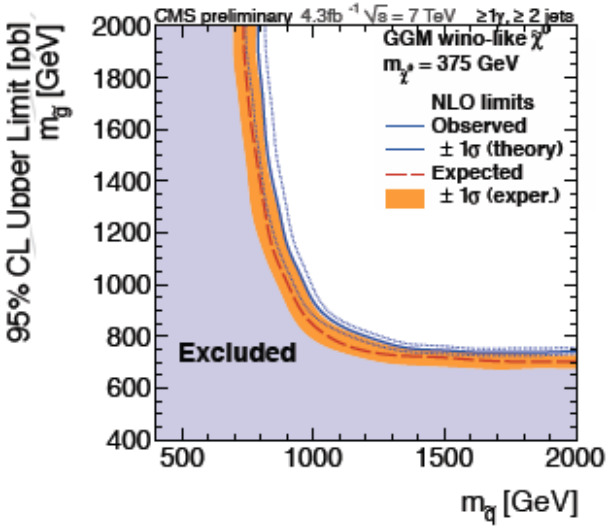
Single photon



Double photon



GGM Bino



GGM Wino

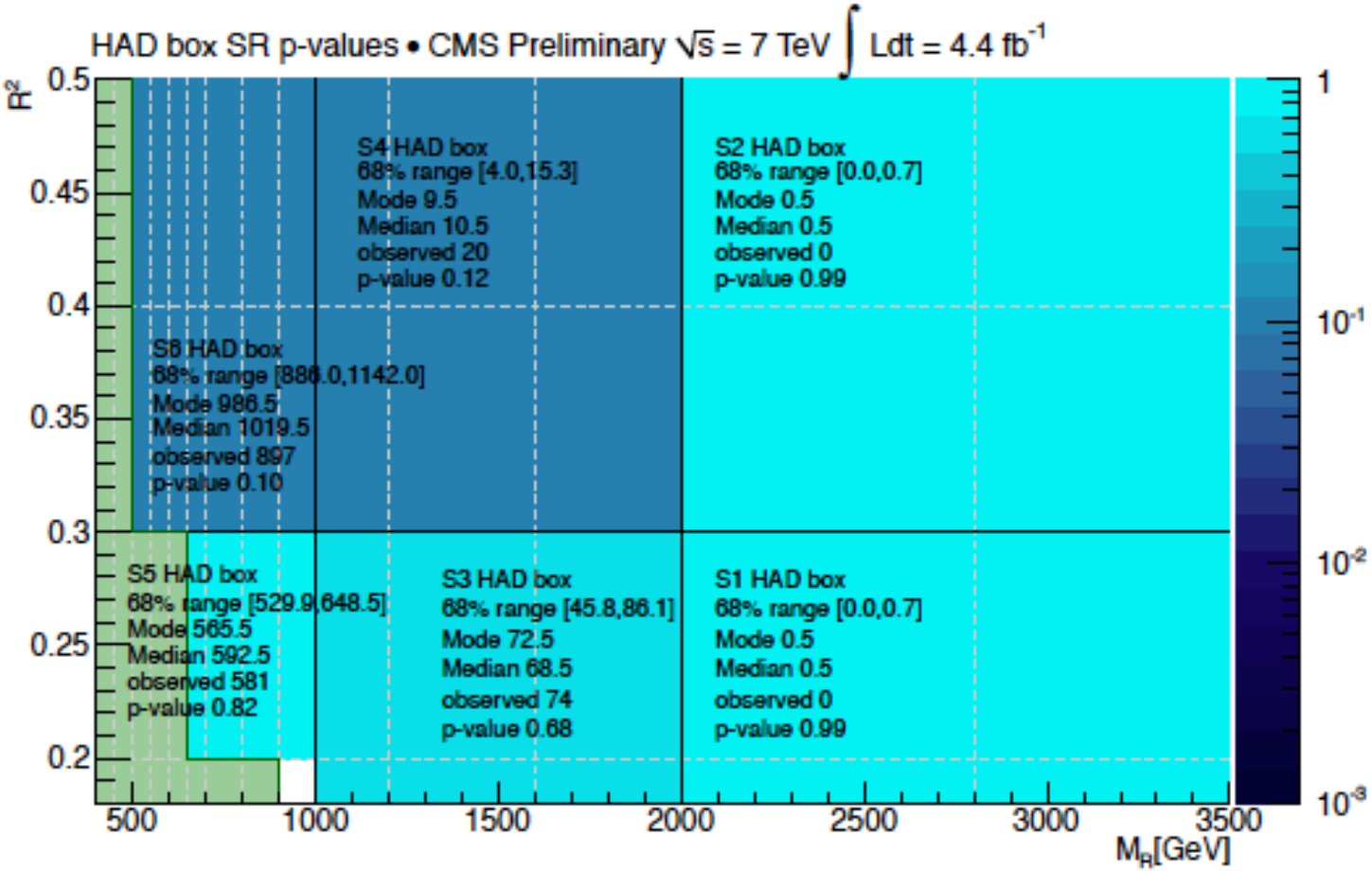
Conclusions

- Hadronic analyses from both ATLAS & CMS presented
  - Common theme is dependence on MET
- So far, no real hint of SUSY has been seen…
  - Other 2011 data analyses in preparation
- The 2012 LHC run brings fresh hope:
  - Higher energies; higher mass scales etc
  - New experimental challenges
- Need to cover all corners of parameter space
  - Mixture of inclusive and targeted analyses planned

Backup

CMS-PAS-SUS-12-005

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}\,, \quad M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss}\cdot(\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$



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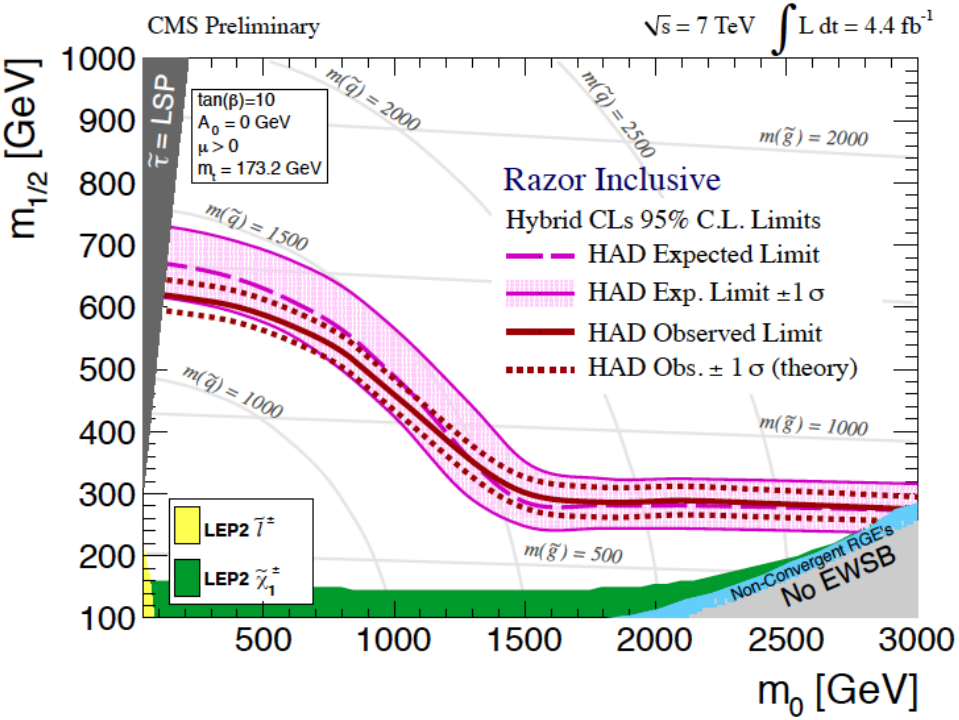
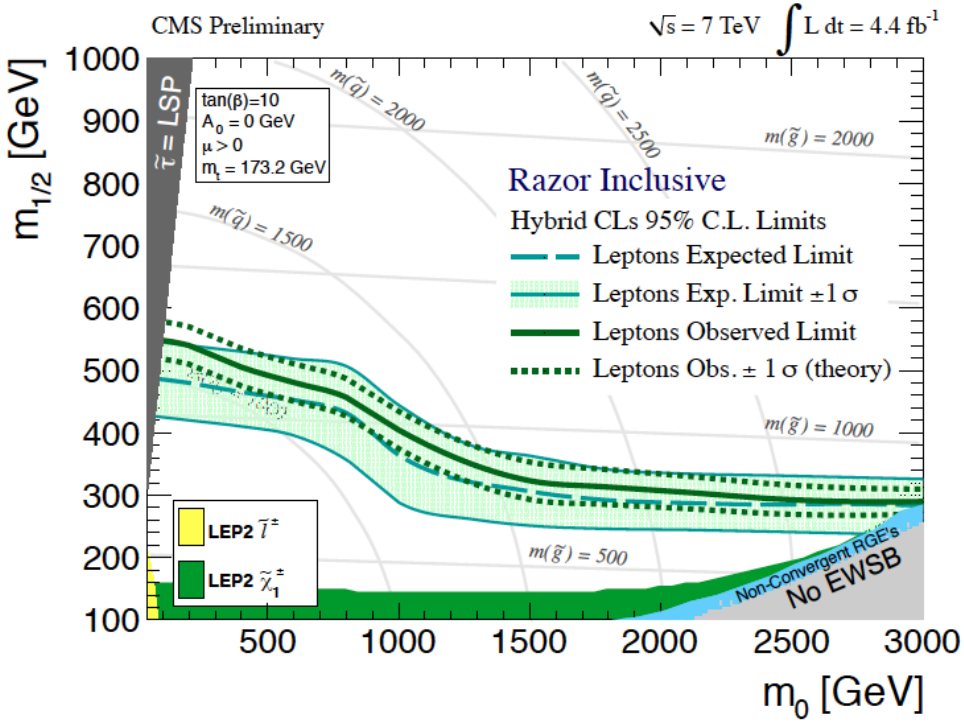
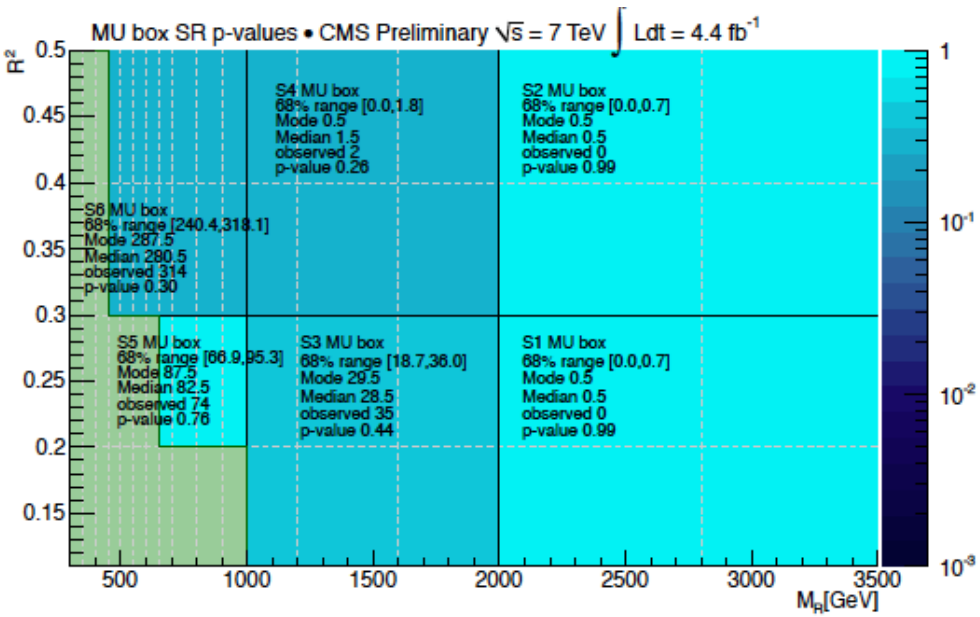
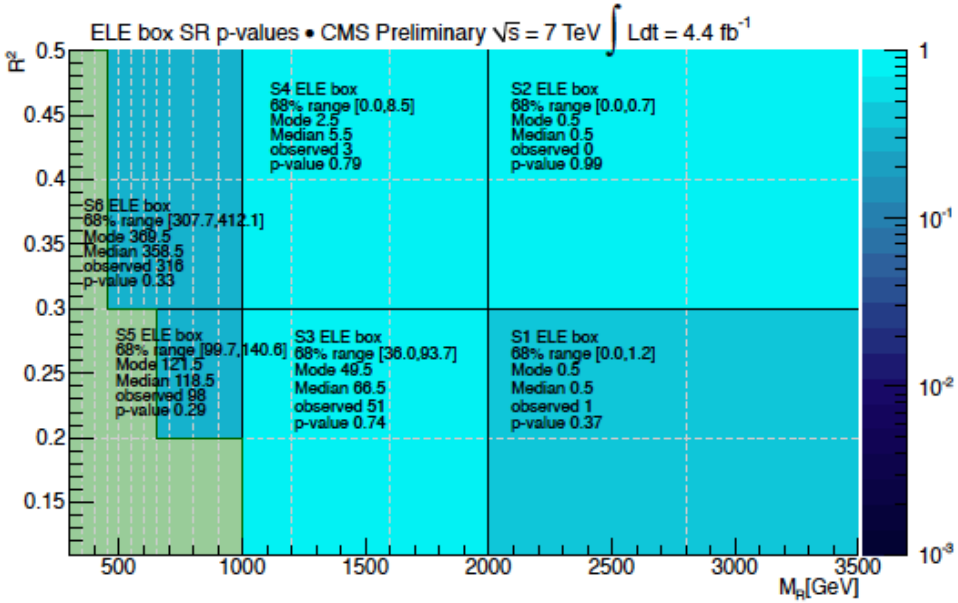




yield systematics	
$\mathcal{L}$[35]	4.5%
cross section	point-by-point
trigger efficiency R^2-M_R	2%
trigger efficiency lepton	3% (lepton, dilepton boxes)
shape systematics	
PDF	point-by-point (up to 30%)
JES	point-by-point (up to 1%)
lepton-id (tag-and-probe)	1% (per lepton)

CMS-PAS-SUS-12-005





Requirement	Channel					
	A	A'	B	C	D	E
E_T^{miss}[GeV] >	160					
$p_T(j_1)$ [GeV] >	130					
$p_T(j_2)$ [GeV] >	60					
$p_T(j_3)$ [GeV] >	–	–	60	60	60	60
$p_T(j_4)$ [GeV] >	–	–	–	60	60	60
$p_T(j_5)$ [GeV] >	–	–	–	–	40	40
$p_T(j_6)$ [GeV] >	–	–	–	–	–	40
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$ >	0.4 ($i = \{1, 2, (3)\}$)			0.4 ($i = \{1, 2, 3\}$), 0.2 (p_T > 40 GeV jets)		
$E_T^{miss}/m_{eff}(N\,j)$ >	0.3 (2j)	0.4 (2j)	0.25 (3j)	0.25 (4j)	0.2 (5j)	0.15 (6j)
m_{eff}(incl.) [GeV] >	1900/1400/–	–/1200/–	1900/–/–	1500/1200/900	1500/–/–	1400/1200/900

Table 1: Cuts used to define each of the channels in the analysis. The E_T^{miss}/m_{eff} cut in any N jet channel uses a value of m_{eff} constructed from only the leading N jets (indicated in parentheses). However, the final m_{eff}(incl.) selection, which is used to define the signal regions, includes all jets with $p_T > 40$ GeV. The three m_{eff}(incl.) selections listed in the final row denote the 'tight', 'medium' and 'loose' selections respectively. Not all channels include all three SRs.

CR	SR Background	CR process	CR selection
CR1a	$Z(\rightarrow \nu\nu)$+jets	γ+jets	Isolated photon
CR1b	$Z(\rightarrow \nu\nu)$+jets	$Z(\rightarrow \ell\ell)$+jets	$\lvert m(\ell,\ell) - m(Z)\rvert < 25$ GeV
CR2	Multi-jets	Multi-jets	Reversed $\Delta\phi(j_i, E_{\mathrm{T}}^{\mathrm{miss}})$ cut
CR3	$W(\rightarrow \ell\nu)$+jets	$W(\rightarrow \ell\nu)$+jets	30 GeV $< m_T(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) <$ 100 GeV, b-veto
CR4	$t\bar{t}$ and single-t	$t\bar{t} \rightarrow bbqq'\ell\nu$	30 GeV $< m_T(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) <$ 100 GeV, b-tag

Table 2: Control regions used in the analysis: the main targeted background in the SR,, the process used to model the background, and main CR cut(s) used to select this process are given.

ATLAS-CONF-2012-033 – Jets+MET with 2-6 jets

Process	Signal Region					
	SRC loose	SRE loose	SRA medium	SRA' medium	SRC medium	SRE medium
$t\bar{t}$+ Single Top	74 ± 13 (75)	66 ± 26 (64)	7 ± 5 (5.1)	11 ± 3.4 (10)	12 ± 4.5 (10)	17 ± 5.8 (13)
Z/γ+jets	70 ± 22 (61)	22 ± 6.4 (13)	31 ± 9.9 (34)	64 ± 20 (69)	17 ± 5.9 (16)	8 ± 2.9 (4.4)
W+jets	62 ± 9.3 (61)	23 ± 11 (23)	19 ± 4.5 (21)	26 ± 4.6 (30)	8.1 ± 2.9 (11)	5.9 ± 3 (4.7)
Multi-jets	0.39 ± 0.4 (0.16)	3.7 ± 1.9 (3.8)	0.14 ± 0.24 (0.13)	0 ± 0.13 (0.38)	0.024 ± 0.034 (0.013)	0.8 ± 0.53 (0.64)
Di-Bosons	7.9 ± 4 (7.9)	4.2 ± 2 (4.2)	7.3 ± 3.7 (7.5)	15 ± 7.4 (16)	1.7 ± 0.87 (1.7)	2.7 ± 1.3 (2.7)
Total	214 ± 24.9 ± 13	119 ± 32.6 ± 11.6	64.8 ± 10.2 ± 6.92	115 ± 19 ± 9.69	38.6 ± 6.68 ± 4.77	34 ± 4.47 ± 5.57
Data	210	148	59	85	36	25
local p-value (Gaus. σ)	0.55(-0.14)	0.21(0.8)	0.65(-0.4)	0.9(-1.3)	0.6(-0.26)	0.85(-1)
UL on N_{BSM}	$58(60^{44}_{83})$	$84(69^{52}_{93})$	$25(28^{20}_{39})$	$29(43^{32}_{60})$	$18(19^{14}_{27})$	$12(16^{12}_{23})$
UL on σ_{BSM} /(fb)	$12(13^{9.3}_{18})$	$18(15^{11}_{20})$	$5.3(6^{4.3}_{8.2})$	$6.2(9.2^{6.7}_{13})$	$3.7(4.1^{3}_{5.7})$	$2.5(3.5^{2.5}_{5})$

Process	Signal Region				
	SRA tight	SRB tight	SRC tight	SRD tight	SRE tight
$t\bar{t}$+ Single Top	0.22 ± 0.35 (0.046)	0.21 ± 0.33 (0.066)	1.8 ± 1.6 (0.96)	2 ± 1.7 (0.92)	3.9 ± 4 (2.6)
Z/γ+jets	2.9 ± 1.5 (3.1)	2.5 ± 1.4 (1.6)	2.1 ± 1.1 (4.4)	0.95 ± 0.58 (2.7)	3.2 ± 1.4 (1.8)
W+jets	2.1 ± 0.99 (1.9)	0.97 ± 0.6 (0.84)	1.2 ± 1.2 (2.7)	1.7 ± 1.5 (2.5)	2.3 ± 1.7 (1.5)
Multi-jets	0 ± 0.0024 (0.002)	0 ± 0.0034 (0.0032)	0 ± 0.0058 (0.0023)	0 ± 0.0072 (0.021)	0.22 ± 0.25 (0.24)
Di-Bosons	1.7 ± 0.95 (2)	1.7 ± 0.95 (1.9)	0.49 ± 0.26 (0.51)	2.2 ± 1.2 (2.2)	2.5 ± 1.3 (2.5)
Total	7 ± 0.999 ± 2.26	5.39 ± 0.951 ± 2.01	5.68 ± 1.79 ± 1.51	6.84 ± 1.7 ± 2.1	12.1 ± 4.59 ± 3.04
Data	1	1	14	9	13
local p-value (Gaus. σ)	0.98(-2.1)	0.95(-1.7)	0.018(2.1)	0.29(0.55)	0.45(0.13)
UL on N_{BSM}	$2.9(6.1^{4.2}_{9})$	$3.1(5.5^{3.8}_{8.3})$	$16(11^{7.6}_{15})$	$10(8.9^{6.4}_{13})$	$12(12^{8.5}_{17})$
UL on σ_{BSM} /(fb)	$0.62(1.3^{0.89}_{1.9})$	$0.65(1.2^{0.8}_{1.8})$	$3.5(2.3^{1.6}_{3.2})$	$2.2(1.9^{1.4}_{2.7})$	$2.6(2.5^{1.8}_{3.5})$

ATLAS-CONF-2012-033 – Jets+MET with 2-6 jets

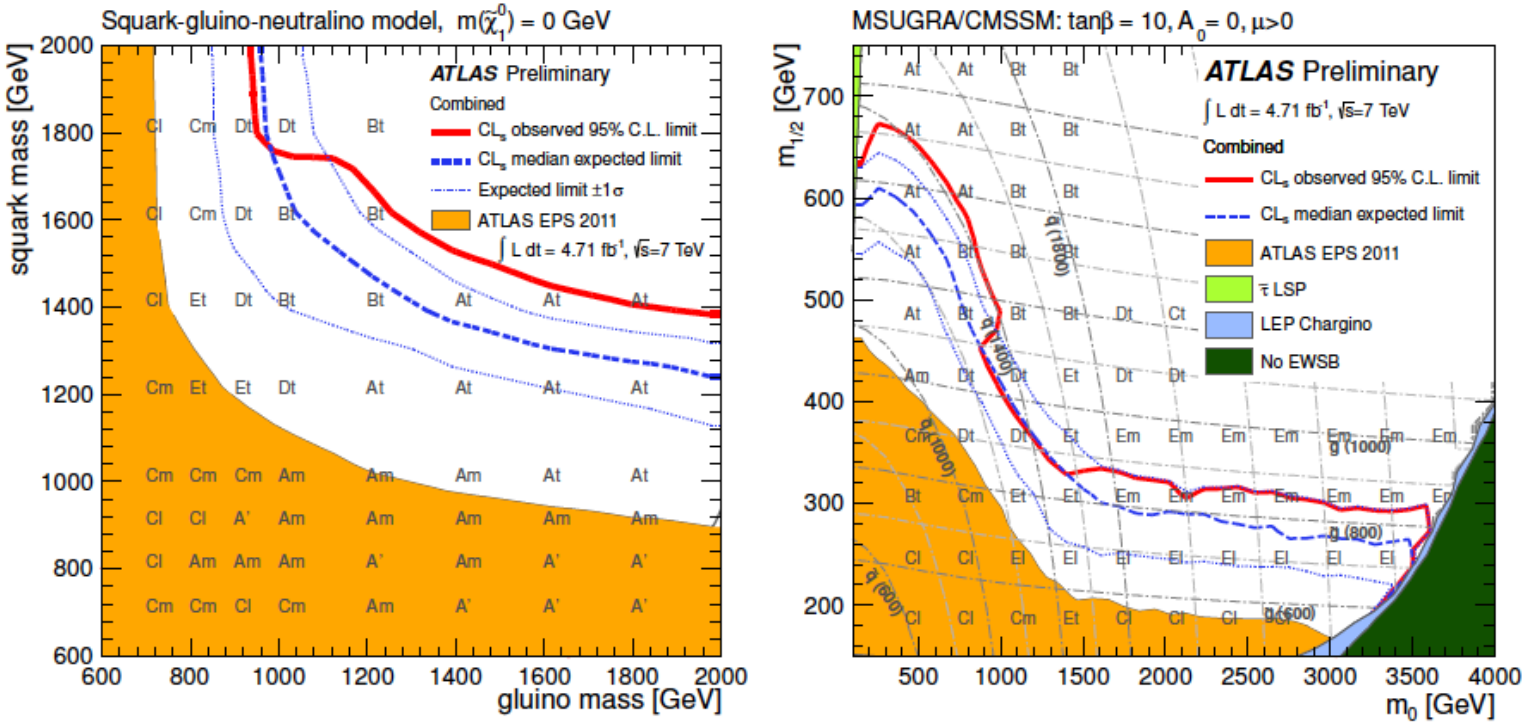


Figure 38: 95% CL_s exclusion limits obtained by using the signal region with the best expected sensitivity at each point in a simplified MSSM scenario with only strong production of gluinos and first- and second-generation squarks, and direct decays to jets and neutralinos (left); and in the (m_0 ; $m_{1/2}$) plane of MSUGRA/CMSSM for $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$ (right). The red lines show the observed limits, the dashed-blue lines the median expected limits, and the dotted blue lines the $\pm 1\sigma$ variation on the expected limits. The labels A-E refer to the channel with the best expected exclusion at each point, while the suffixes l, m and t refer to the loose, medium and tight selections for each signal region. ATLAS EPS 2011 limits are from [17] and LEP results from [59].

	$t\bar{t}$ + jets	W + jets	Z + jets
Muon kinematics	$p_T > 20$ GeV, $\lvert\eta\rvert < 2.4$		
Muon multiplicity	$= 1$		$= 2$
Electron multiplicity	$= 0$		
b-tag jets	≥ 1	$= 0$	—
m_T or $m_{\mu\mu}$	50 GeV $< m_T <$ 100 GeV		80 GeV $< m_{\mu\mu} <$ 100 GeV
VR $\rightarrow$ CR transform	$\mu \rightarrow$ jet		$\mu \rightarrow \nu$
Jet p_T, $\lvert\eta\rvert$, multiplicity (CR)	As in Table 1.		
$E_T^{miss}/\sqrt{H_T}$ (CR)			

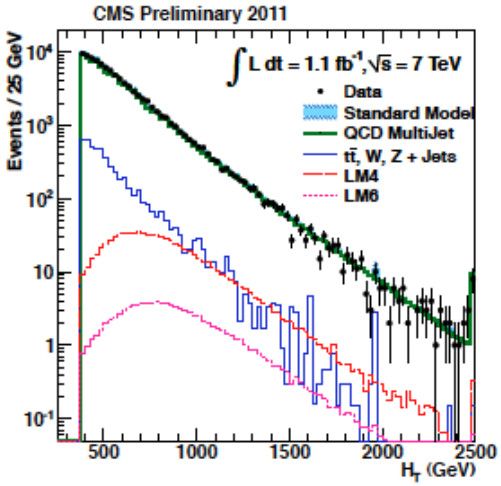
Table 2: Definitions of the validation regions and control regions for the 'leptonic' backgrounds: $t\bar{t}$ + jets, W + jets and Z + jets. The validation regions VR are defined by the first five selection requirements. A long dash '—' indicates that no requirement is made. The control regions CR differ from the VR in their treatment of the muons, and by having additional requirements on jets and $E_T^{miss}/\sqrt{H_T}$, as shown in the final two rows.

Signal region	**7j55**	**8j55**	**9j55**	**6j80**	**7j80**	**8j80**
Multi-jets	91±20	10±3	1.2±0.4	67±12	5.4±1.7	0.42±0.16
$t\bar{t} \to q\ell, \ell\ell$	55±18	5.7±6.0	0.70±0.72	24±13	2.8±1.8	0.38±0.40
W + jets	18±11	0.81±0.72	0+0.13	13±10	0.34±0.21	0+0.06
Z + jets	2.7±1.6	0.05±0.19	0+0.12	2.7±2.9	0.10±0.17	0+0.13
Total Standard Model	**167±34**	**17±7**	**1.9±0.8**	**107±21**	**8.6±2.5**	**0.80±0.45**
Data	**154**	**22**	**3**	**106**	**15**	**1**
$N^{95\%}_{\mathrm{BSM,max}}$ (exp)	72	16	4.5	46	8.4	3.5
$N^{95\%}_{\mathrm{BSM,max}}$ (obs)	64	20	5.7	46	15	3.8
$\sigma^{95\%}_{\mathrm{BSM,max}} \cdot A \cdot \epsilon$ (exp) [fb]	15	3.4	0.96	9.8	1.8	0.74
$\sigma^{95\%}_{\mathrm{BSM,max}} \cdot A \cdot \epsilon$ (obs) [fb]	14	4.2	1.2	9.8	3.2	0.81
p_{SM}	0.64	0.27	0.28	0.52	0.07	0.43

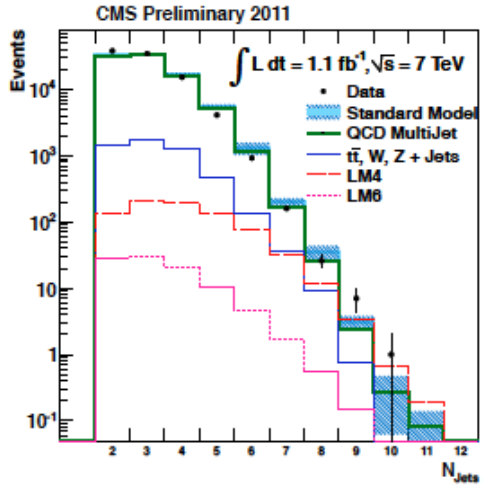
Table 3: Results for each of the six signal regions for an integrated luminosity of 4.7 fb^{-1}. The expected numbers of Standard Model events are given for each of the following sources: multi-jet (including fully hadronic $t\bar{t}$), semi- and fully-leptonic top combined, and W and Z bosons (separately) in association with jets, as well as the total Standard Model expectation. Where small event counts in control regions have not made it possible to determine a central value for the expectation, an asymmetric bound is given instead. The numbers of observed events are also shown. The final five rows show the statistical quantities described in the text. Both the expected (exp) and the observed (obs) values are shown for $N^{95\%}_{\mathrm{BSM,max}}$ and $\sigma^{95\%}_{\mathrm{BSM,max}} \times A \times \epsilon$.

Table 1: Definition of the H_T bins and the corresponding p_T thresholds for the leading, second, and all remaining jets in the event; the number of events passing and failing the α_T cut and the resulting R_{α_T} value, for 1.1 fb^{-1} of data collected in 2011.

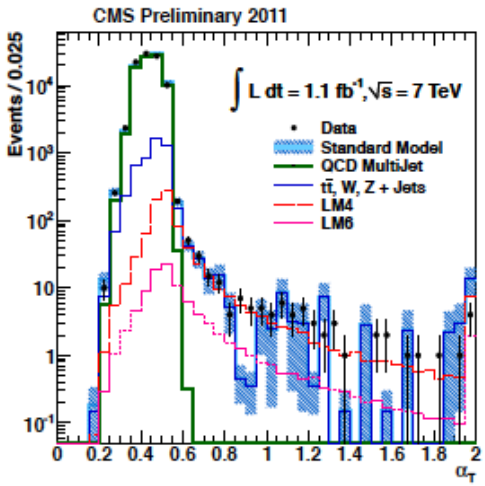
H_T Bin (GeV)	275–325	325–375	375–475	475–575
$p_T^{leading}$ (GeV)	73	87	100	100
p_T^{second} (GeV)	73	87	100	100
p_T^{other}(GeV)	37	43	50	50
$\alpha_T > 0.55$	782	321	196	62
$\alpha_T < 0.55$	$5.73 \cdot 10^7$	$2.36 \cdot 10^7$	$1.62 \cdot 10^7$	$5.12 \cdot 10^6$
$R_{\alpha_T}(10^{-5})$	$1.36 \pm 0.05_{stat}$	$1.36 \pm 0.08_{stat}$	$1.21 \pm 0.09_{stat}$	$1.21 \pm 0.15_{stat}$
H_T Bin (GeV)	575–675	675–775	775–875	875–∞
$p_T^{leading}$ (GeV)	100	100	100	100
p_T^{second} (GeV)	100	100	100	100
p_T^{other} (GeV)	50	50	50	50
$\alpha_T > 0.55$	21	6	3	1
$\alpha_T < 0.55$	$1.78 \cdot 10^6$	$6.89 \cdot 10^5$	$2.90 \cdot 10^5$	$2.60 \cdot 10^5$
$R_{\alpha_T}(10^{-5})$	$1.18 \pm 0.26_{stat}$	$0.87 \pm 0.36_{stat}$	$1.03 \pm 0.60_{stat}$	$0.39 \pm 0.52_{stat}$



(a) Comparison of H_T between data and MC for the hadronic selection for $H_T \geq 375$ GeV and $\not{H}_T > 100$ GeV.

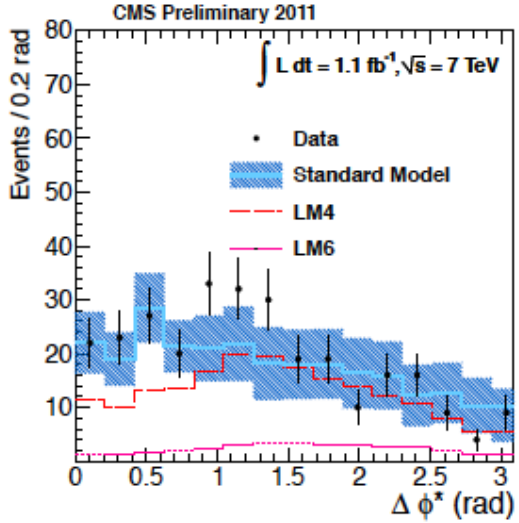


(b) Comparison of the jet multiplicity between data and MC for the hadronic selection, for $H_T \geq 375$ GeV and $\not{H}_T > 100$ GeV.

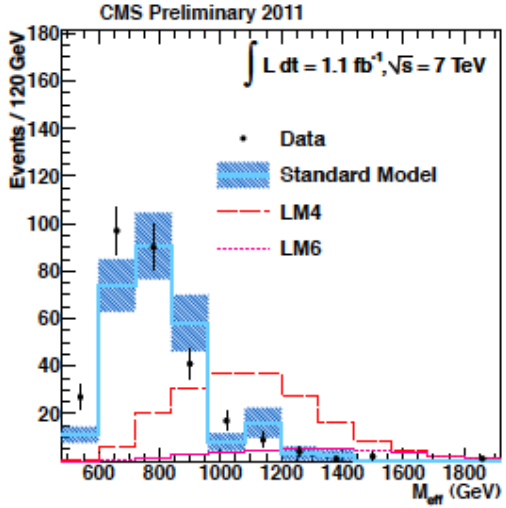


(c) Comparison of the α_T distribution between data and MC for the hadronic selection, for $H_T \geq 375$ GeV and $\not{H}_T > 100$ GeV.

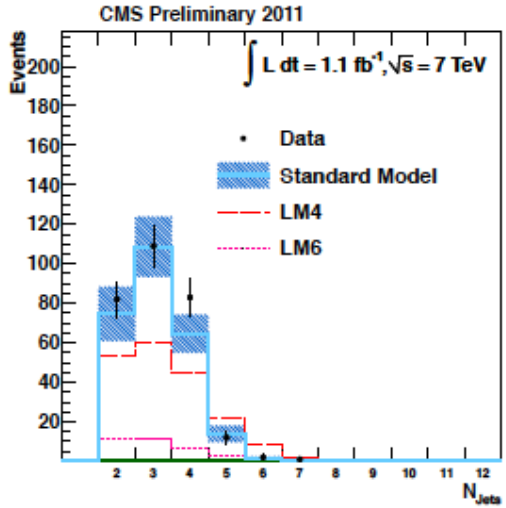
Figure 1: Comparisons of basic quantities before the α_T selection cuts.



(a) $\Delta\Phi^*$ distribution after α_T selection.



(b) The effective mass distribution, $M_{\rm eff} = H_T + \not{H}_T$, of the events passing the α_T selection.



(c) Jet multiplicity after α_T selection.

Figure 2: Comparisons between data and MC after the α_T selection cut.

$$R_{\alpha_T} = N^{\alpha_T > \theta} / N^{\alpha_T < \theta}$$

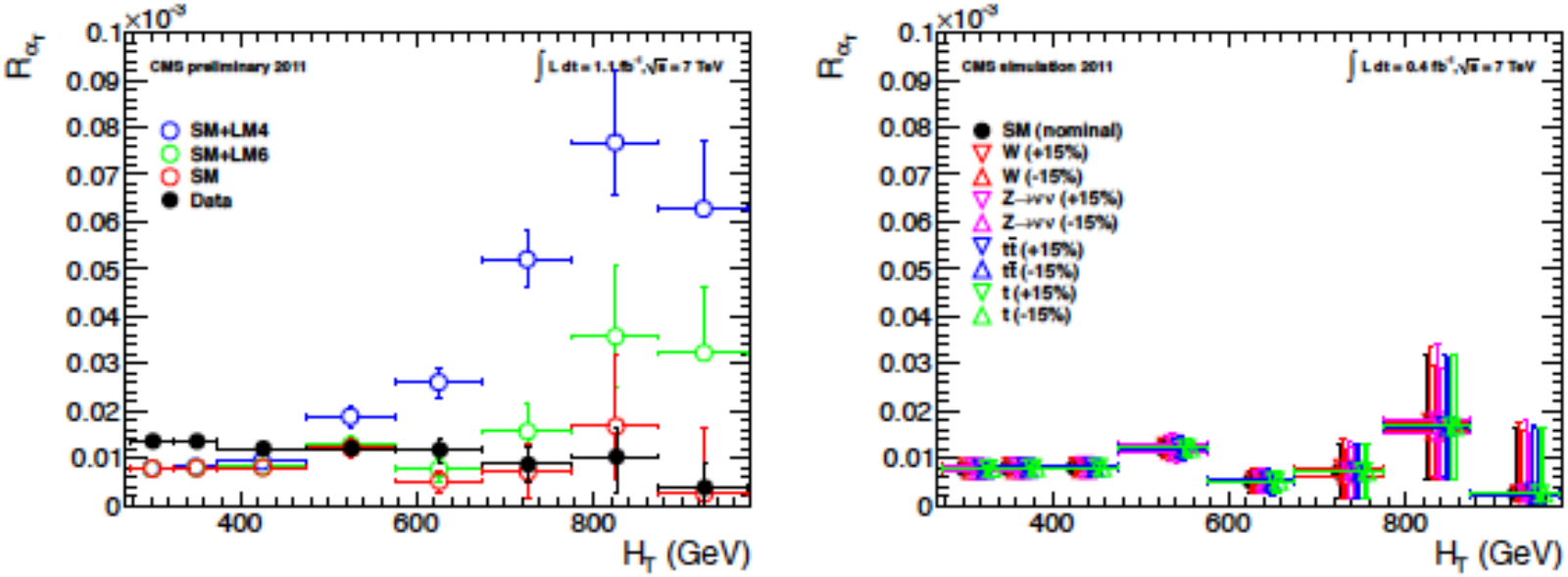


Figure 3: (Left) The dependence of R_{α_T} on H_T for events with $N_{jet} \geq 2$. (Right) Dependence of R_{α_T} on H_T when varying the effective cross-section of the four major EWK background components individually by $\pm 15\%$. (Markers are artificially offset for clarity.)