

Non-standard SUSY searches at the LHC

Junjie Zhu

University of Michigan / BNL

On behalf of the ATLAS and CMS Collaborations

May 30, 2013

Outline

- ❑ Non-Standard SUSY → not usual SUSY searches with MET in final states
- ❑ **RPV SUSY searches:**
 - ❑ Four or more leptons
 - ❑ Three or more leptons with at least one b-tagged jet
 - ❑ Different-flavor opposite-sign (DFOS) dilepton
 - ❑ 2×3 jets resonances (resolved or boosted jets)
- ❑ **Long-lived particle searches:**
 - ❑ Non-pointing photons
 - ❑ Disappearing-track
 - ❑ Heavy stable charged particles

- ❑ Signature-based or model-driven searches covering prompt and non-prompt new particle production
- ❑ Only covered a small fraction of non-standard SUSY searches, more results can be found at
 - <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults> (ATLAS)
 - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS> (CMS)

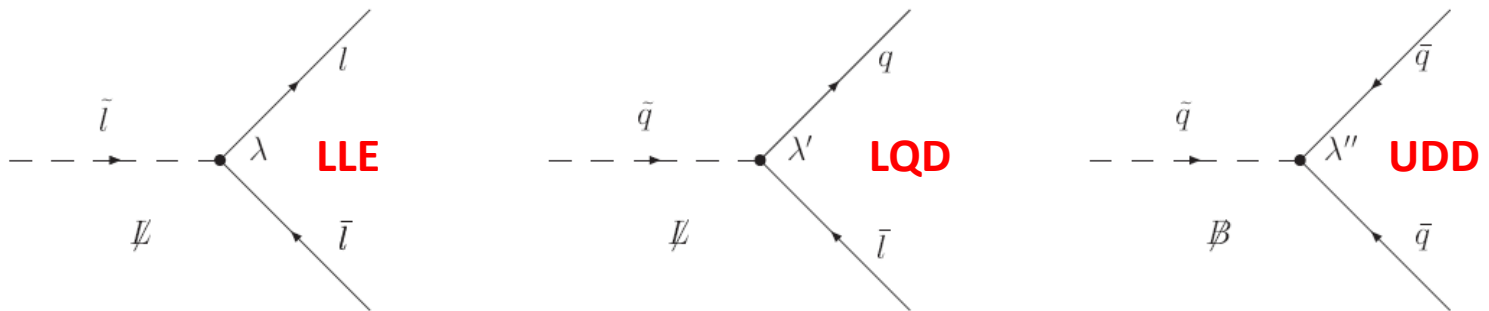
RPV SUSY

- SUSY superpotential with B- and L-num violating terms:

$$W_{\mathcal{R}_p} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

L-num violating
B-num violating

- LLE and LQD terms give lepton final states
- UDD term gives jetty final states, more challenging

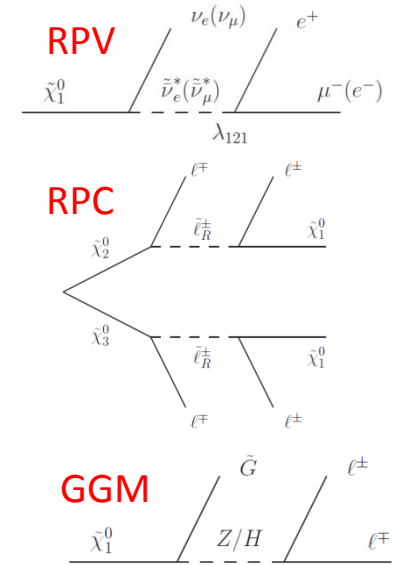


Detector signature	RPV parameters probed
4 charged leptons: $e^+e^+\mu^-\mu^-$	$LL\bar{E}$
3 charged leptons + b-tag	$LL\bar{E}, LQ\bar{D}$
Dilepton resonance	$LL\bar{E} \otimes LQ\bar{D}$
6 resolved jets or 2 merged jets	$\bar{U}\bar{D}\bar{D}$

Four or more charged leptons search

- Generic SUSY search with ≥ 4 leptons (21 fb⁻¹, ATLAS)

SR	$N(\ell = e, \mu)$	$N(\tau)$	Z Candidate	E_T^{miss} [GeV]	m_{eff} [GeV]	Scenario
SR0noZa	≥ 4	≥ 0	extended veto	> 50		RPC
SR0noZb	≥ 4	≥ 0	extended veto	> 75	or > 600	RPV
SR1noZ	$= 3$	≥ 1	extended veto	> 100	or > 400	RPV
SR0Z	≥ 4	≥ 0	request	> 75		GGM
SR1Z	$= 3$	≥ 1	request	> 100		GGM



- Irreducible background: ZWW, ZZ \rightarrow estimated using MC simulation
- Reducible background: \rightarrow data-driven techniques

Signal lepton

Loose lepton, failing one or more of the signal lepton requirements

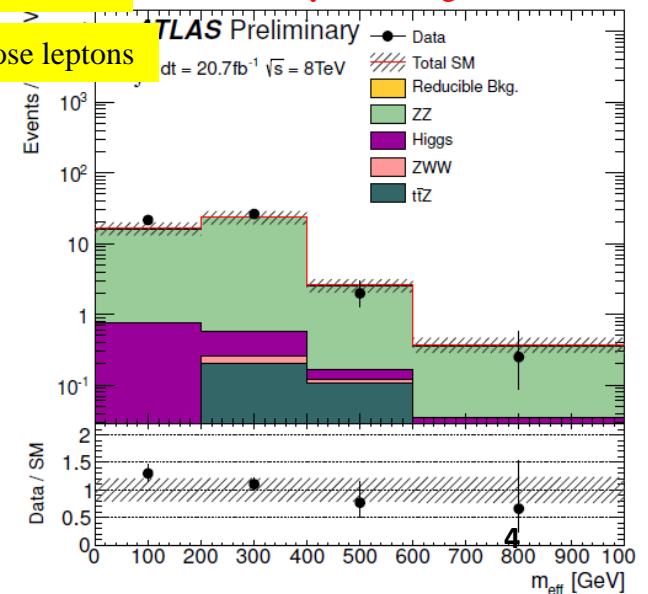
$$[N_{\text{data}}(3\ell_S + \ell_L) - N_{\text{MCirr}}(3\ell_S + \ell_L)] \times F(\ell_L)$$

$$- [N_{\text{data}}(2\ell_S + \ell_{L_1} + \ell_{L_2}) - N_{\text{MCirr}}(2\ell_S + \ell_{L_1} + \ell_{L_2})] \times F(\ell_{L_1}) \times F(\ell_{L_2})$$

Fake ratio of signal to loose leptons

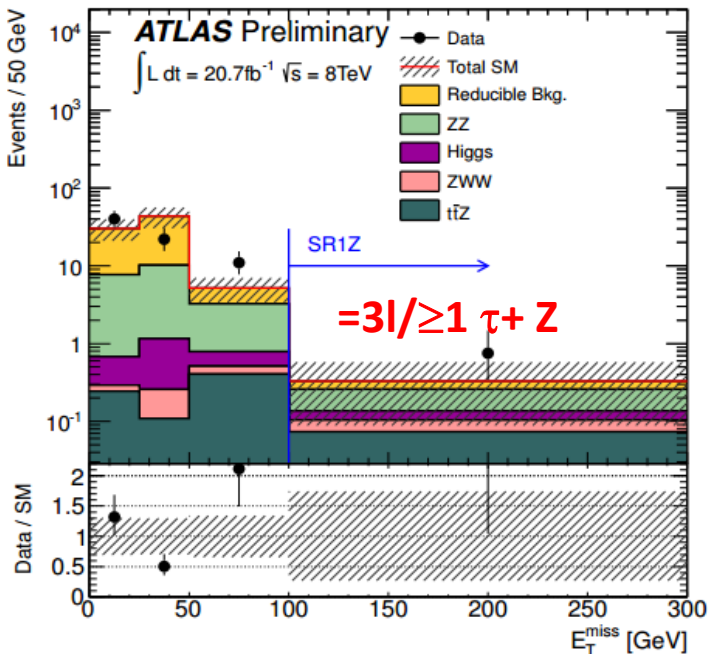
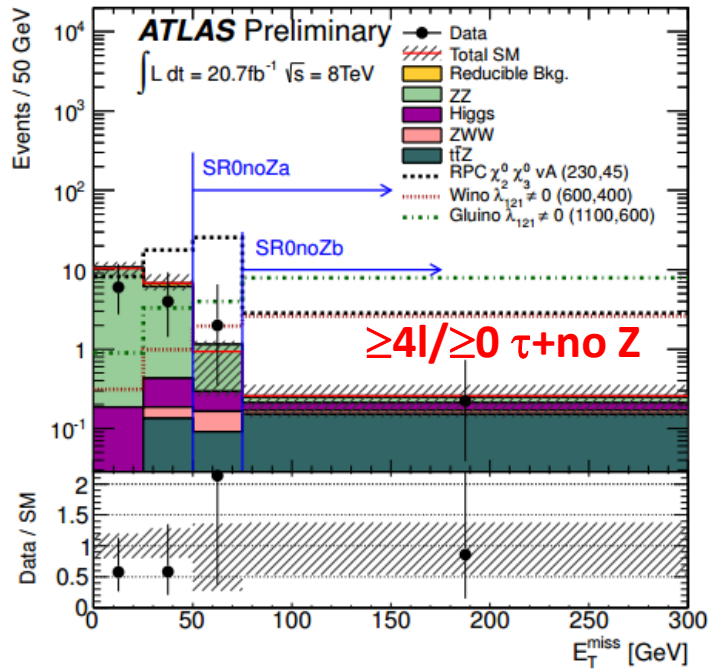
- Background estimation method applied on validation regions with certain selection cuts reversed

VR0Z (MET < 50 and $m_{\text{eff}} < 400$ GeV)
Dominated by ZZ background

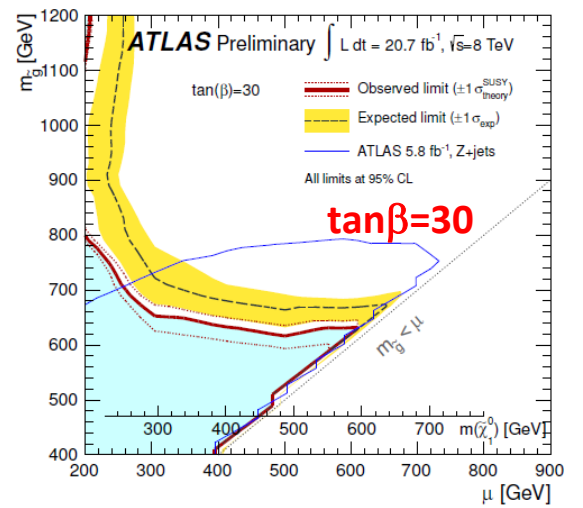
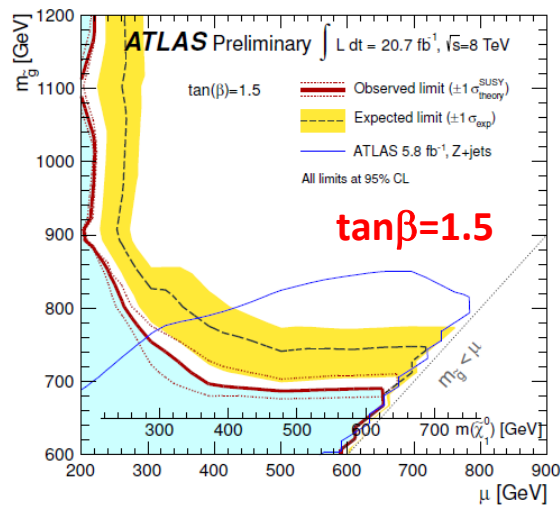
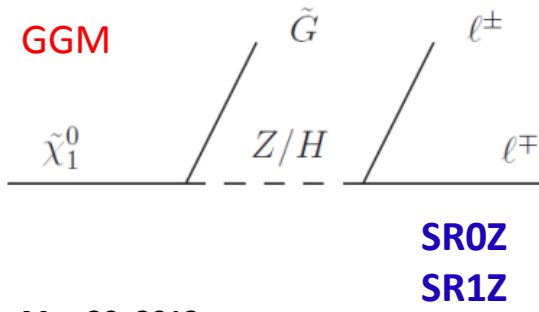
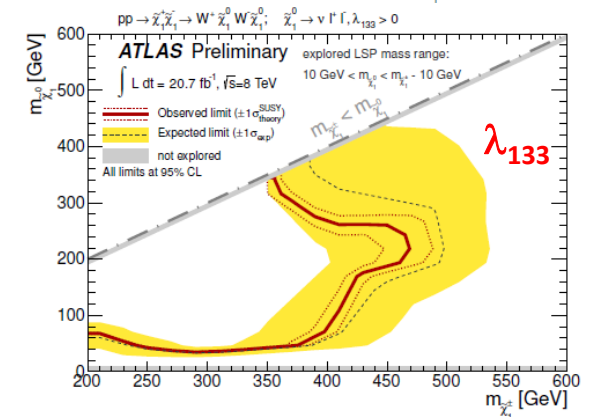
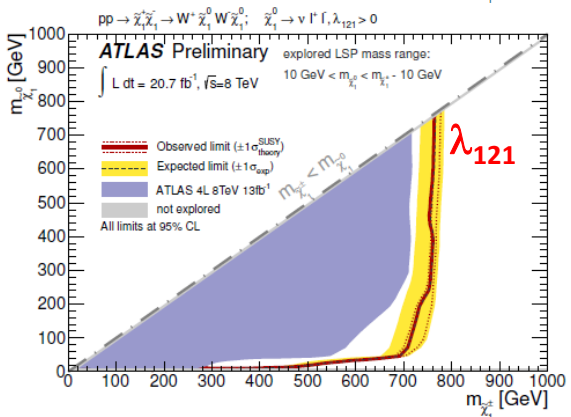
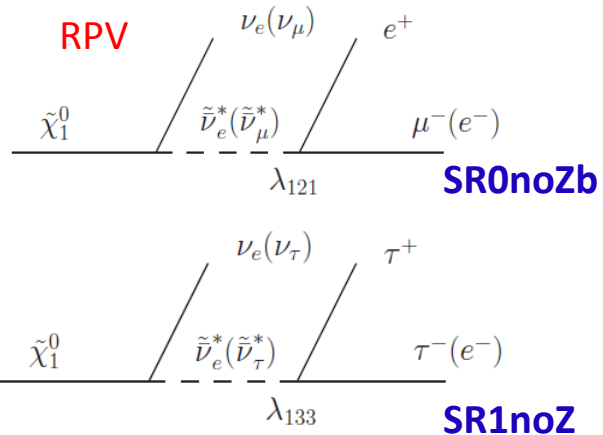
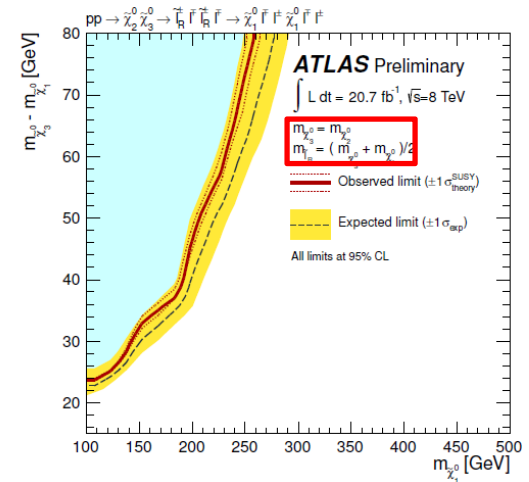
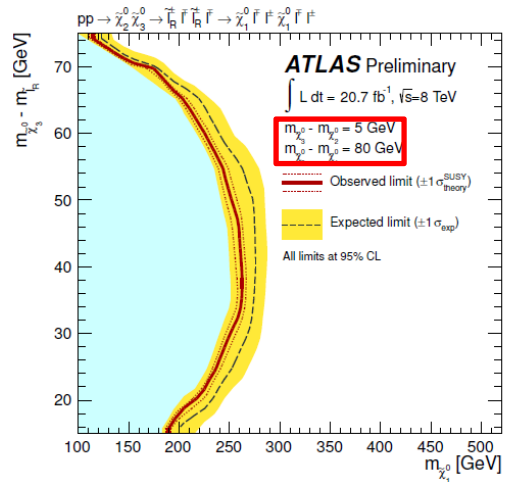
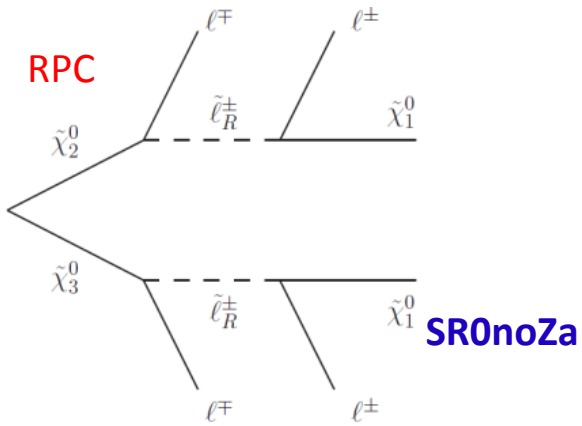


Results

<http://cds.cern.ch/record/1532429>



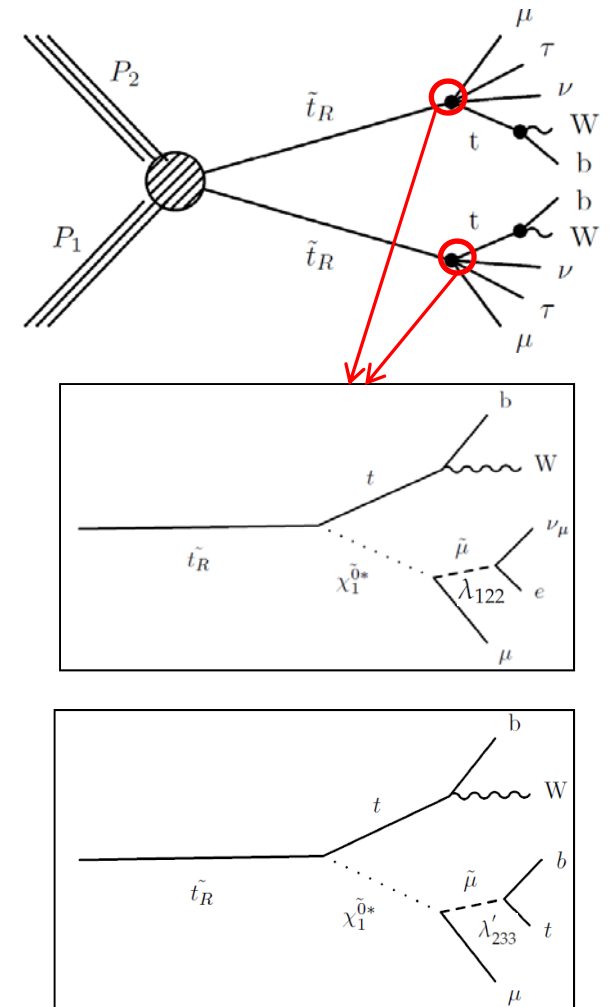
Sample	SR0noZa	SR0noZb	SR1noZ	SR0Z	SR1Z
ZZ	0.6 ± 0.5	0.50 ± 0.26	0.19 ± 0.05	1.2 ± 0.4	0.49 ± 0.10
ZWW	0.12 ± 0.12	0.08 ± 0.08	0.05 ± 0.05	0.6 ± 0.6	0.13 ± 0.13
tZ	0.73 ± 0.34	0.75 ± 0.35	0.16 ± 0.12	2.3 ± 0.9	0.29 ± 0.24
Higgs	0.26 ± 0.07	0.22 ± 0.07	0.23 ± 0.06	0.58 ± 0.15	0.14 ± 0.05
Irreducible Bkg.	1.7 ± 0.8	1.6 ± 0.6	0.62 ± 0.21	4.8 ± 1.8	1.1 ± 0.4
Reducible Bkg.	$0^{+0.16}_{-0}$	$0.05^{+0.14}_{-0.05}$	1.4 ± 1.3	$0^{+0.14}_{-0}$	$0.3^{+1.0}_{-0.3}$
Total Bkg.	1.7 ± 0.8	1.6 ± 0.6	2.0 ± 1.3	4.8 ± 1.8	$1.3^{+1.0}_{-0.5}$
Data	2	1	4	8	3
p_0 -value	0.29	0.5	0.15	0.08	0.13



May 30, 2013

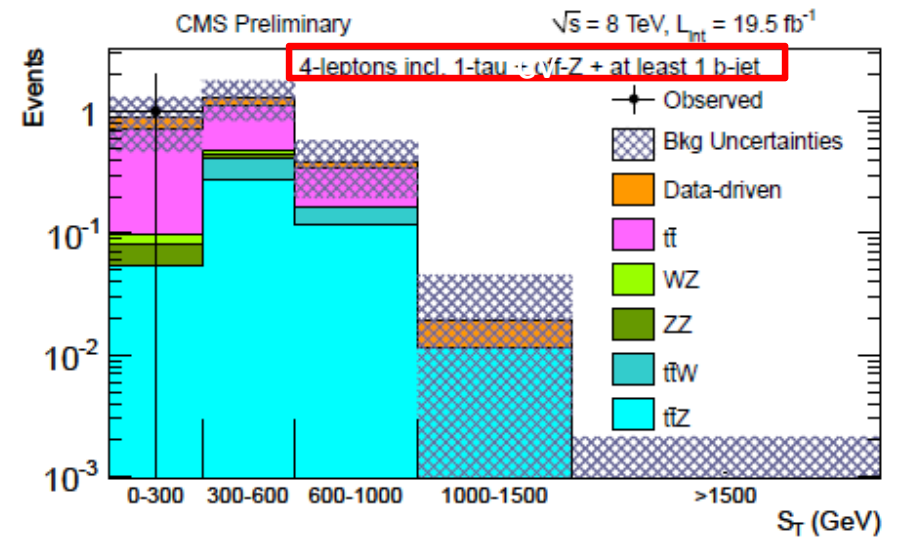
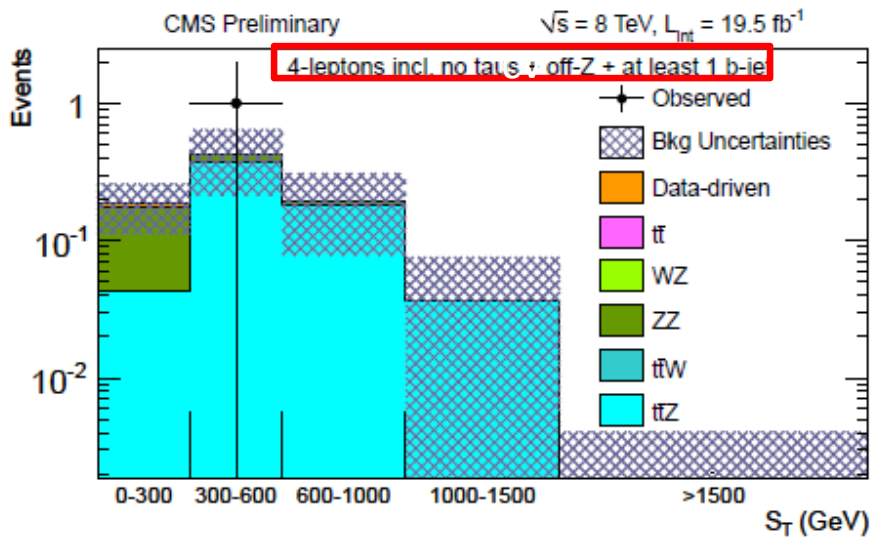
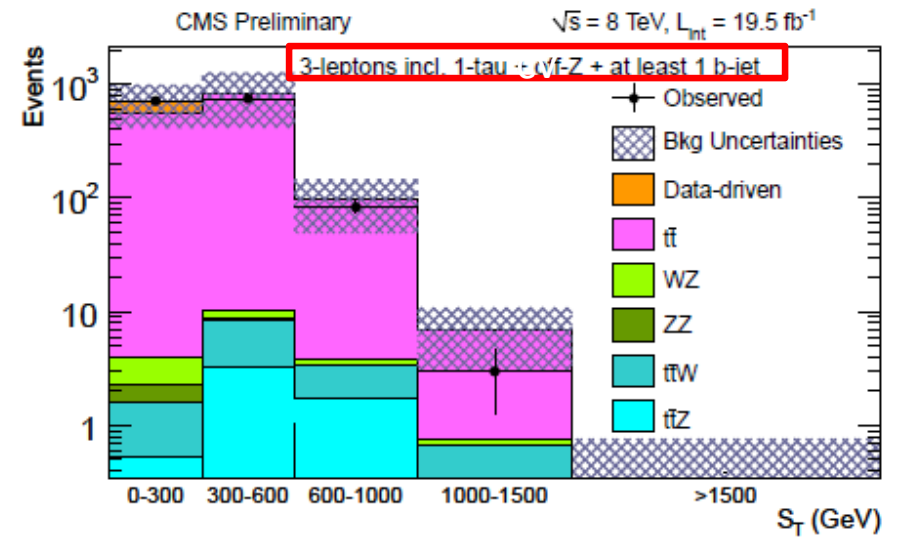
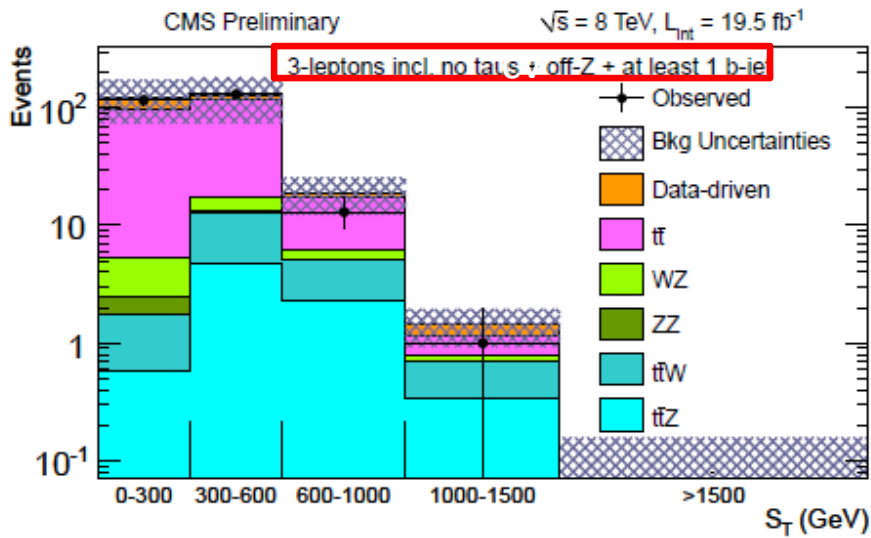
Three or more leptons and b-tag search

- SUSY search with three or more leptons and at least one b-tag jet (20 fb^{-1} , CMS)
- Events separated into four categories based on N_{lep} and N_{τ}
- Irreducible background: WZ, ZZ, ttW and ttZ \rightarrow estimated using MC simulation
- Reducible background:
 - misidentified light leptons
 - misidentified hadronic taus
 - light leptons from asymmetric internal conversions



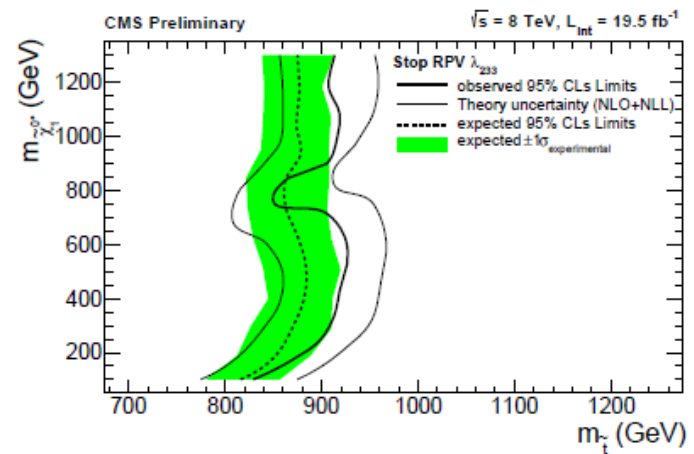
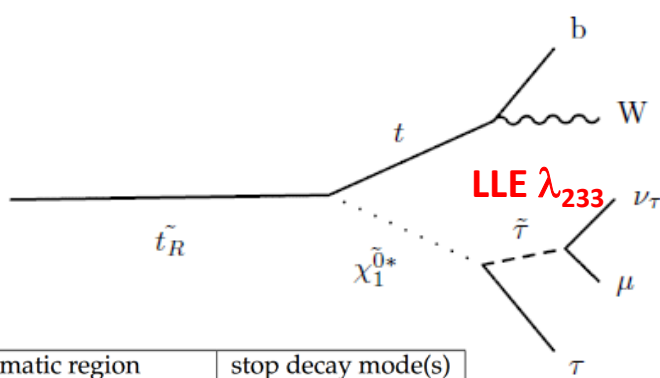
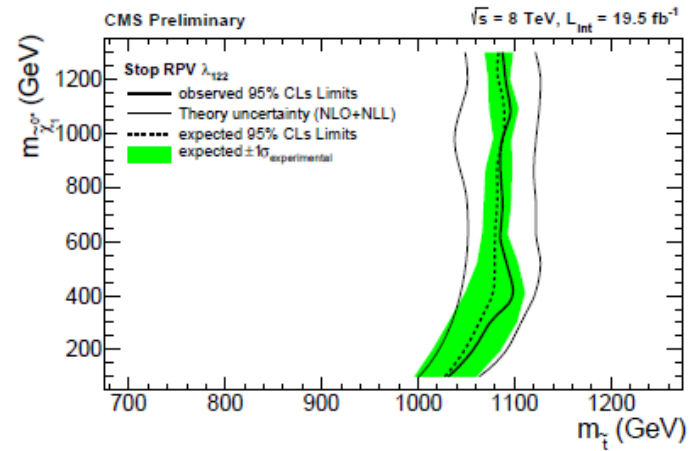
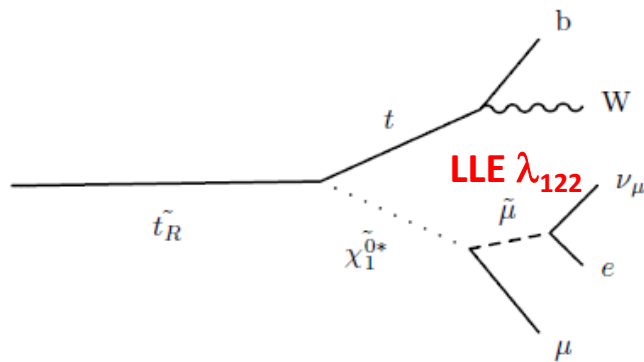
Results

<http://cds.cern.ch/record/1525539>

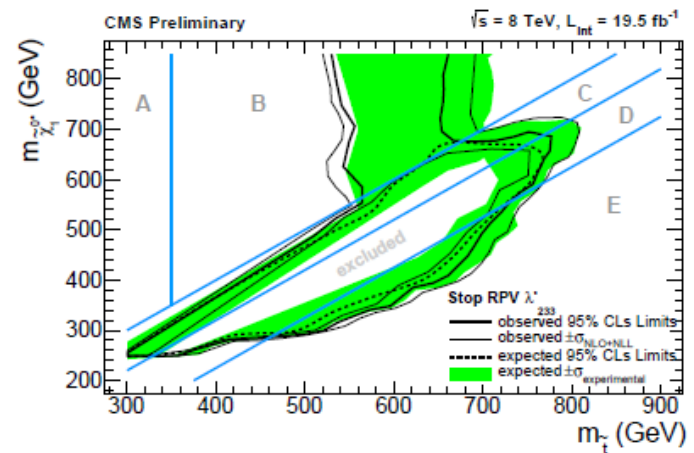
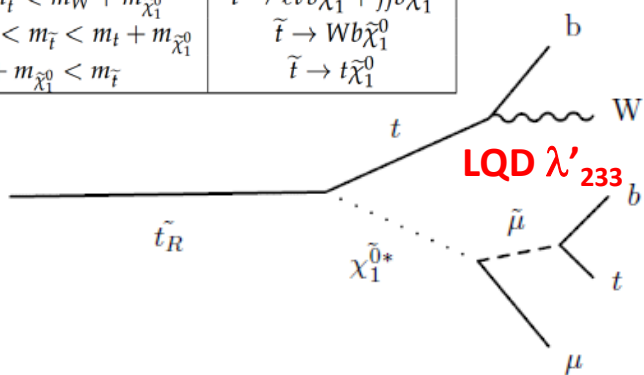


May 30, 2013

S_T : scalar sum of charged lepton pT, jet pT and MET



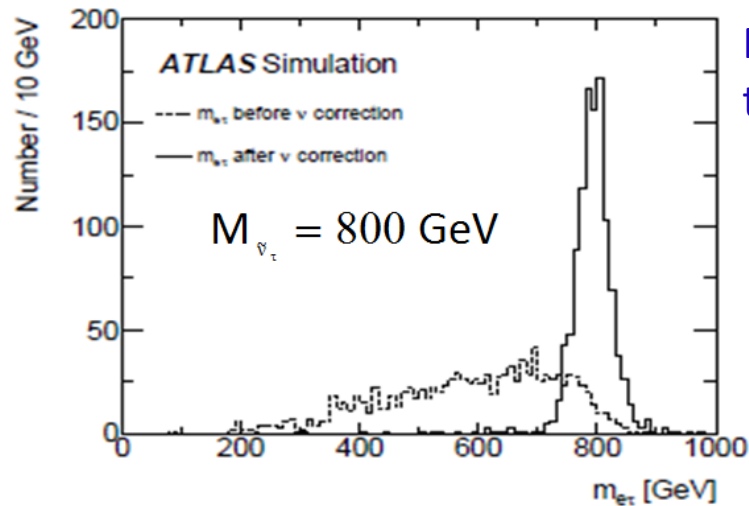
region label	kinematic region	stop decay mode(s)
A	$m_t < m_{\tilde{t}} < 2m_t, m_{\tilde{\chi}_1^0}$	$\tilde{t} \rightarrow t\nu b\bar{b}$
B	$2m_t < m_{\tilde{t}} < m_{\tilde{\chi}_1^0}$	$\tilde{t} \rightarrow t\mu t\bar{b} + t\nu b\bar{b}$
C	$m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_W + m_{\tilde{\chi}_1^0}$	$\tilde{t} \rightarrow \ell\nu b\tilde{\chi}_1^0 + j\nu b\tilde{\chi}_1^0$
D	$m_W + m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_t + m_{\tilde{\chi}_1^0}$	$\tilde{t} \rightarrow Wb\tilde{\chi}_1^0$
E	$m_t + m_{\tilde{\chi}_1^0} < m_{\tilde{t}}$	$\tilde{t} \rightarrow t\tilde{\chi}_1^0$



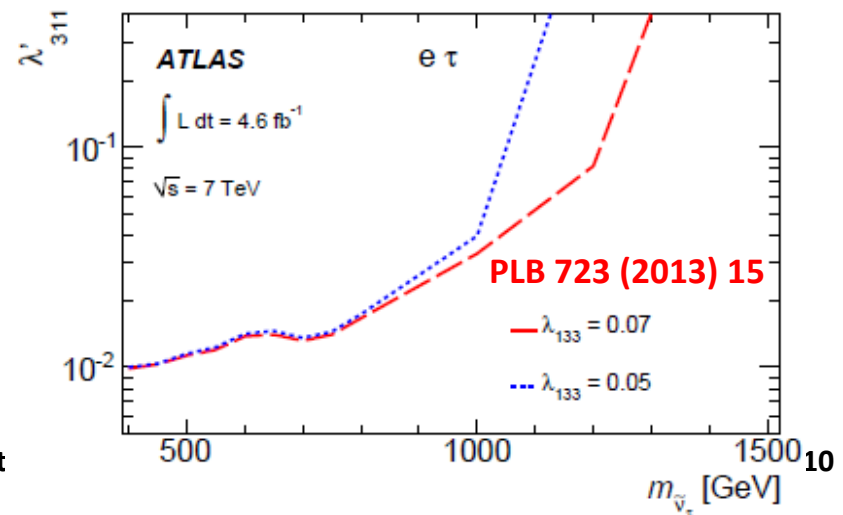
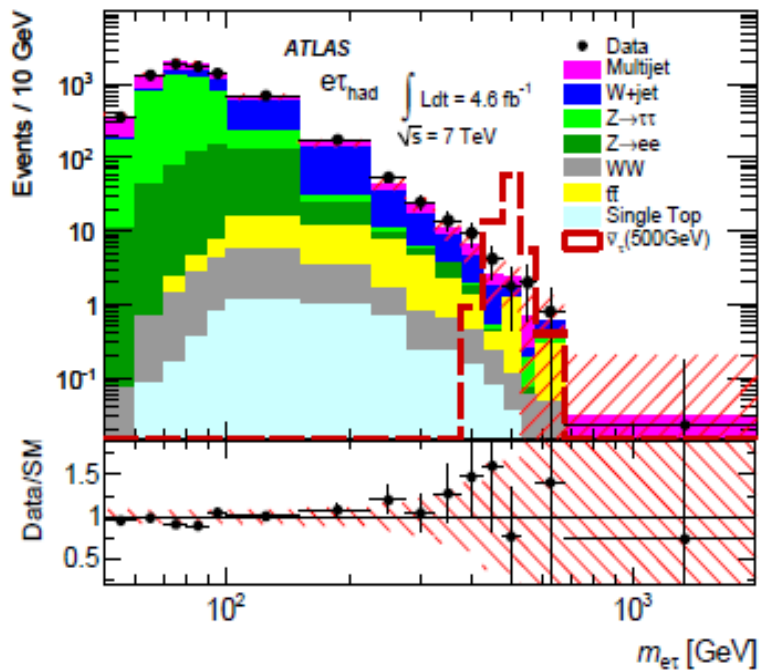
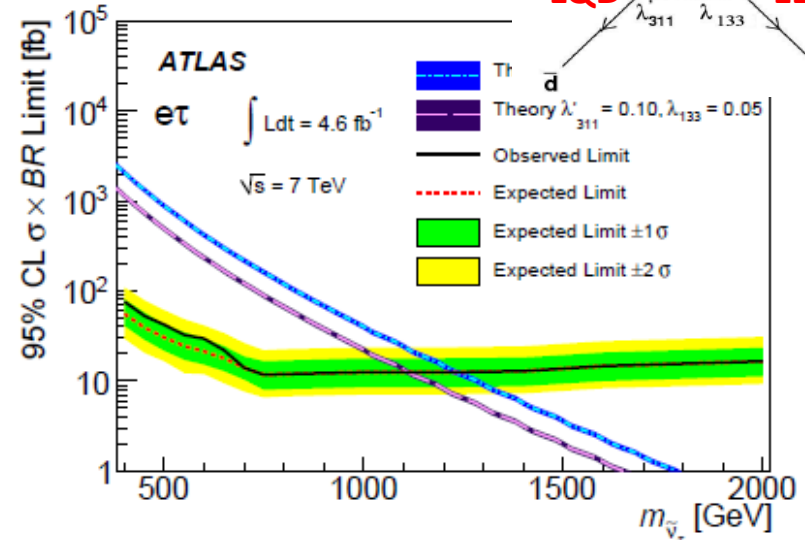
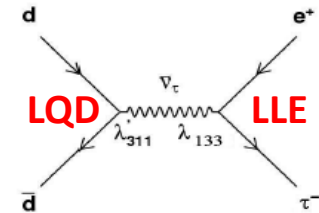
May 30, 2013

DFOS high-mass dilepton resonance search

Stau neutrino search, results obtained for three decay channels ($e\mu$, $\mu\tau$ and $e\tau$)

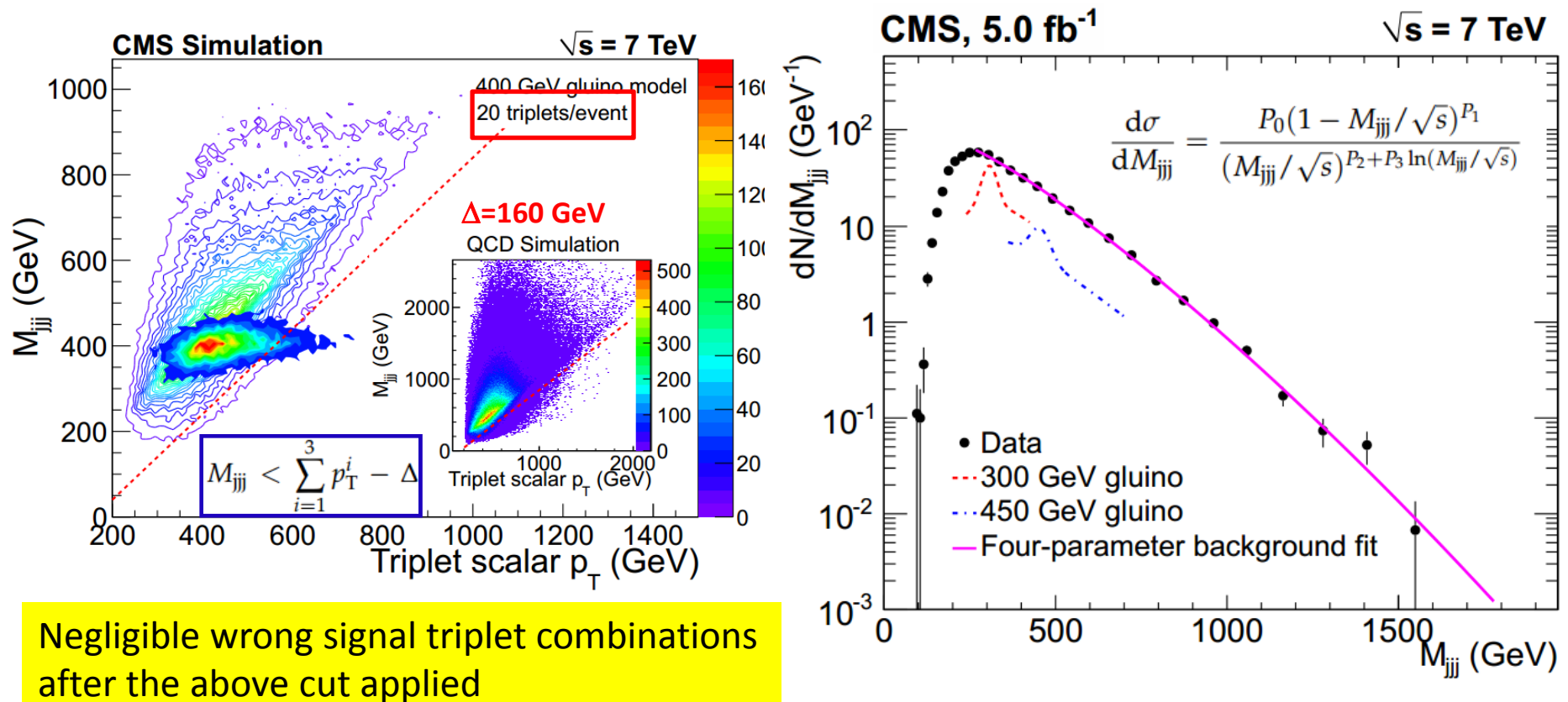


Neutrino correction applied to reconstruct $\mu\tau$ and $e\tau$ masses



2×3 jets resonances search

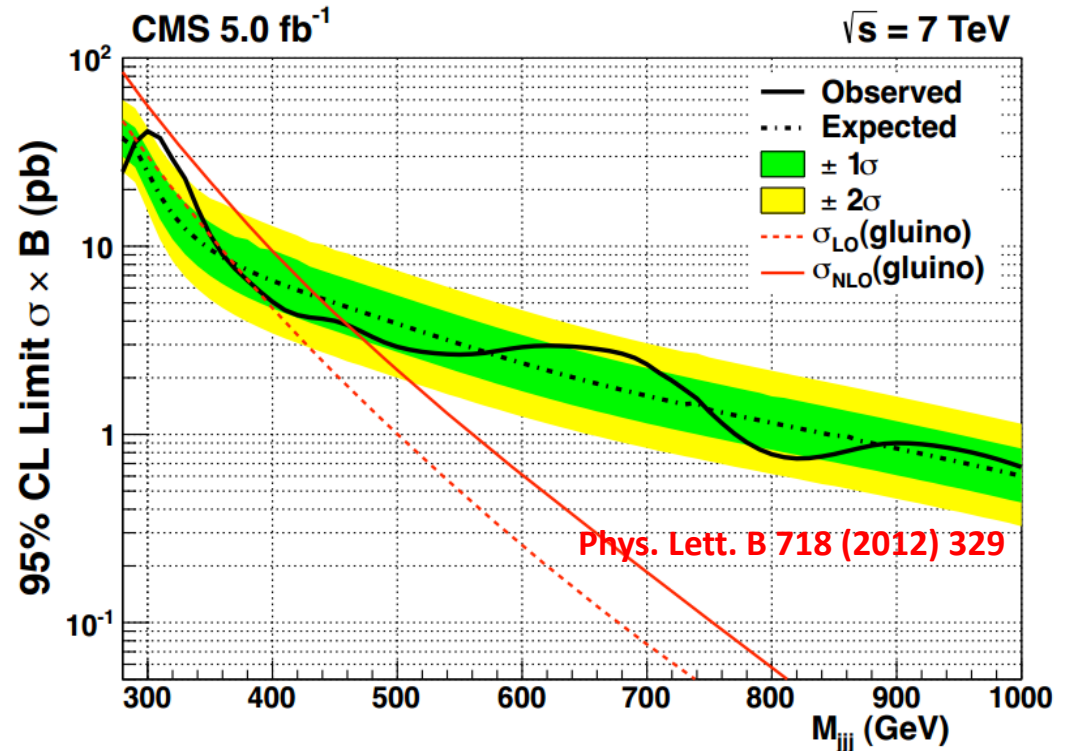
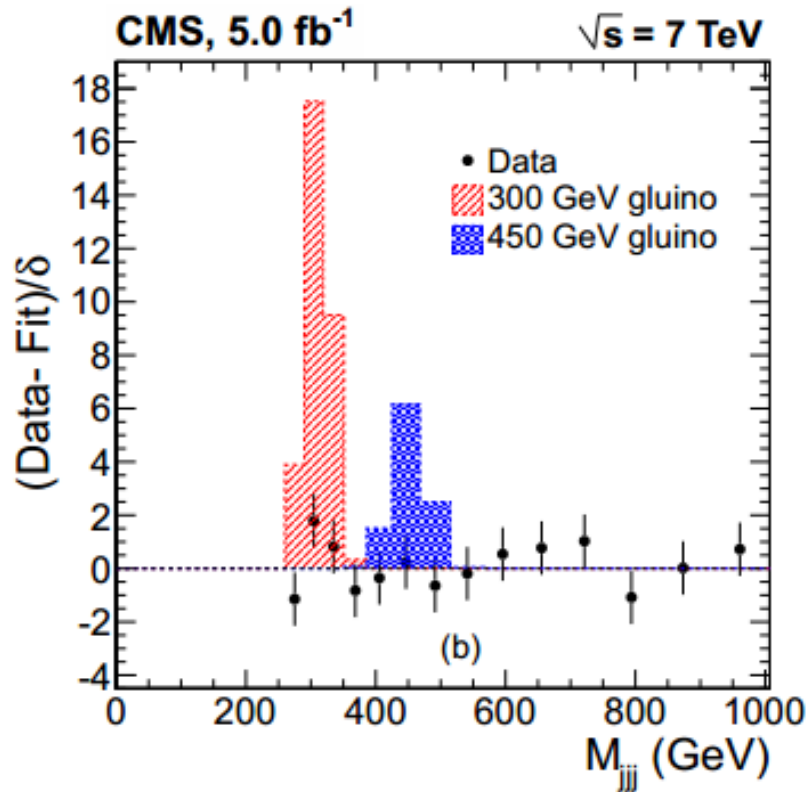
- Pair production of $\tilde{g} \rightarrow \tilde{q}q \rightarrow qqq$ with 6 jets (or 2 merged jets) in final states
- Events triggered with L1 jet $H_T > 350-750$ GeV (for jets with $p_T > 40$ GeV)
- Require ≥ 6 jets with $p_T > 70$ GeV and $H_T > 900$ GeV for HLT
- 20 unique three-jet combinations (triplets) for six highest- p_T jets
- Main backgrounds from QCD multijet and wrong signal triplet combinations



Negligible wrong signal triplet combinations after the above cut applied

Results

- Signal $A \times \varepsilon$ increases from 0.25% to 2.6% for $m(\tilde{g}) = 250 - 1500$ GeV



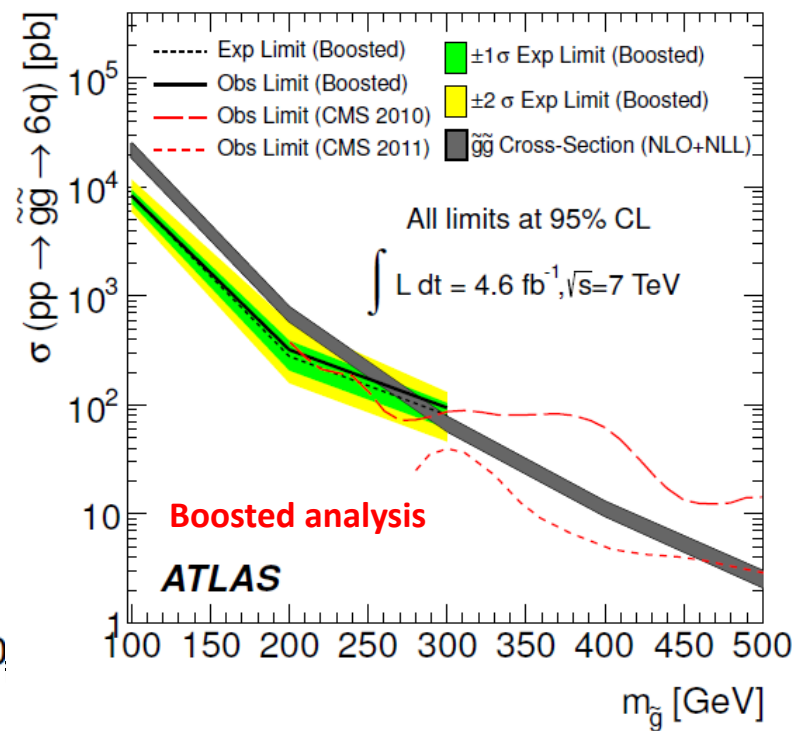
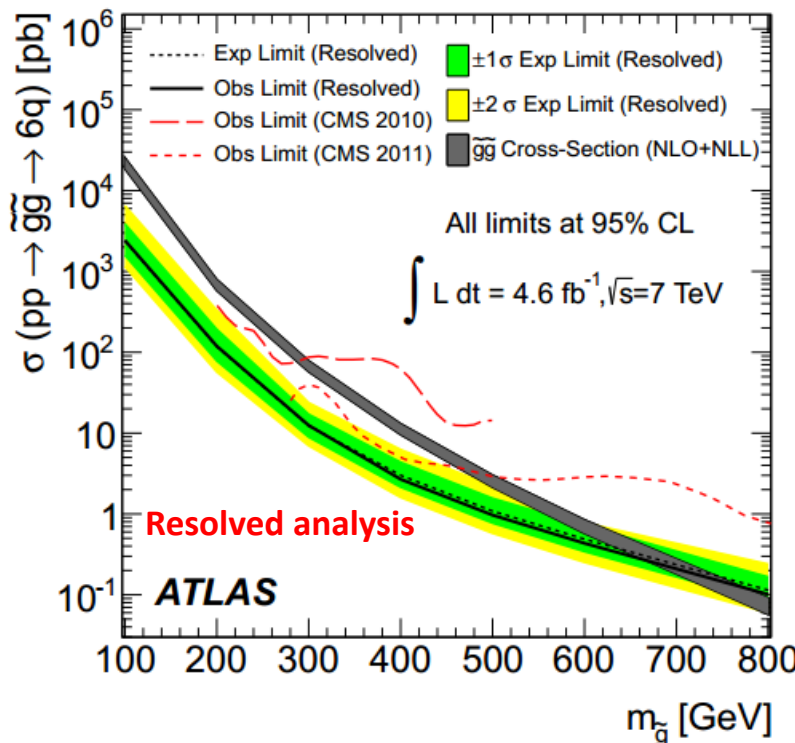
2×3 jets resonances search

- Events triggered with a single-jet trigger ($p_T > 240$ GeV) or a single-jet trigger ($p_T > 100$ GeV) with an additional requirement on H_T of all jets in the event
- Use jet-substructure information to remove background (subject distance):

$$\tau_N = \frac{1}{d_0} \sum_k p_{Tk} \times \min(\delta R_{1k}, \delta R_{2k}, \dots, \delta R_{Nk}), \quad \text{with} \quad d_0 \equiv \sum_k p_{Tk} \times R$$

- Define $\tau_{32} = \tau_3 / \tau_2$, $\tau_{32} \approx 0$ implies a jet is better described by three subjects than one or two

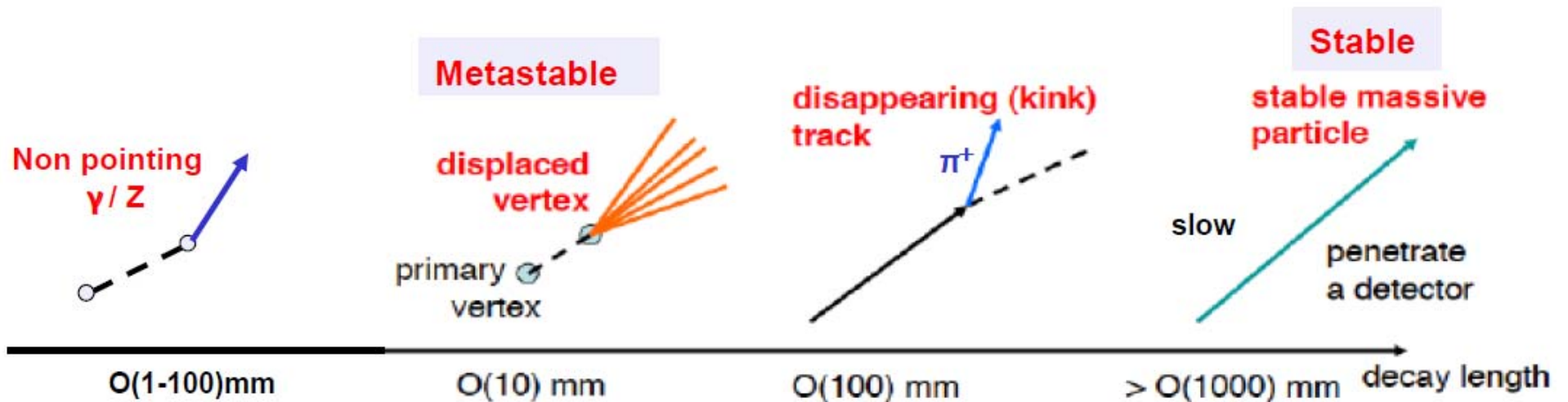
arXiv:1210.4813



Long-lived particle searches

Some examples:

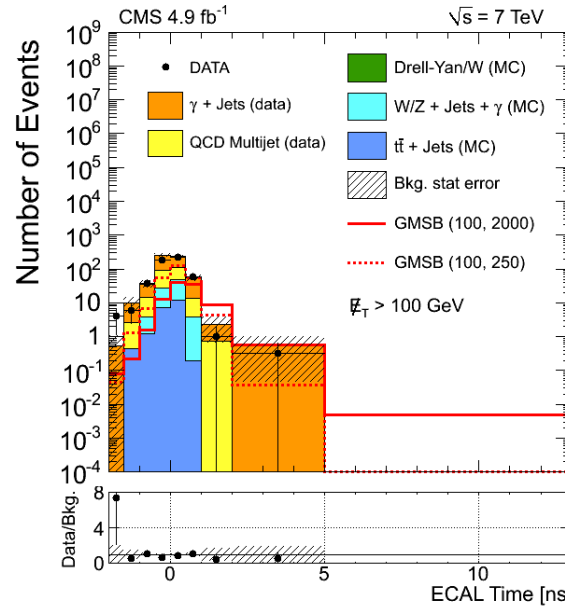
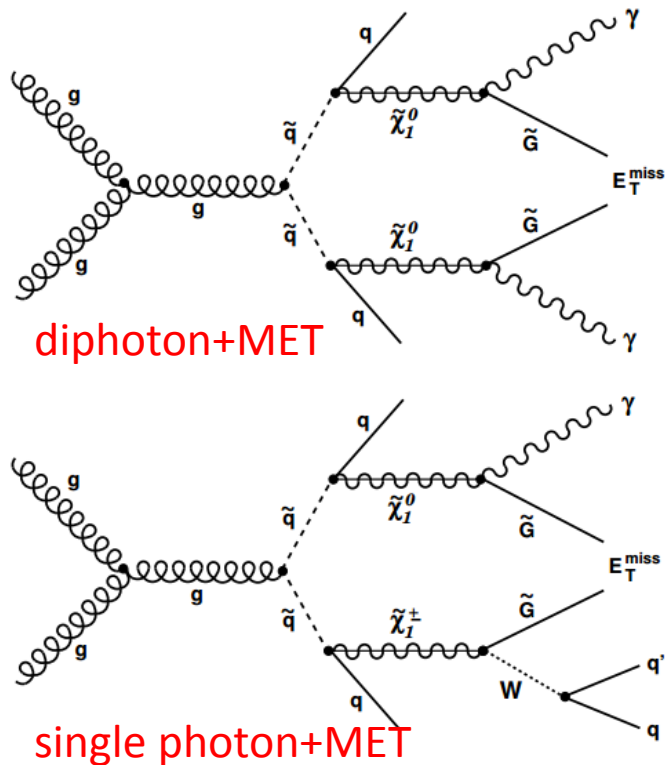
1. Very weak coupling with $\tilde{G}=\text{LSP}$ (GMSB) → Non-pointing γ or Z
2. Lifetime proportional to $\lambda^2, \lambda'^2, \lambda''^2$ (RPV) → Displaced vertex
3. Low mass difference for $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ (AMSB) → Low energy π emitted, kinked track
4. Stable massive particle (mix of 1 and 3) → Sleptons or R-hadron (\tilde{g} or \tilde{q})



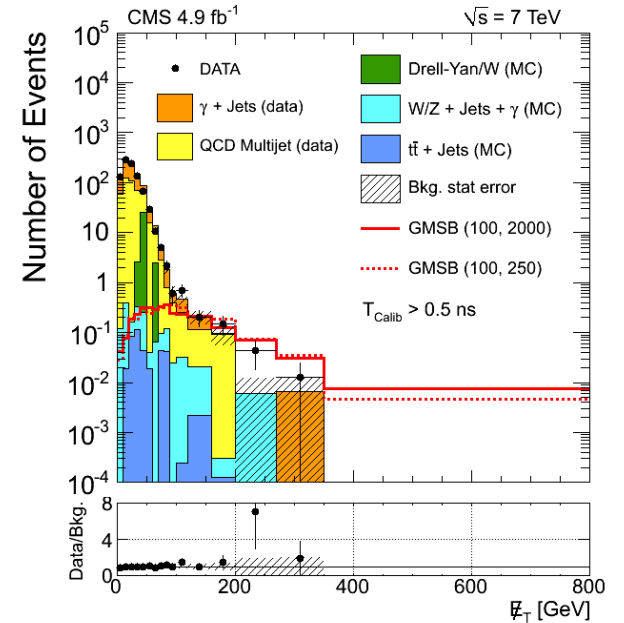
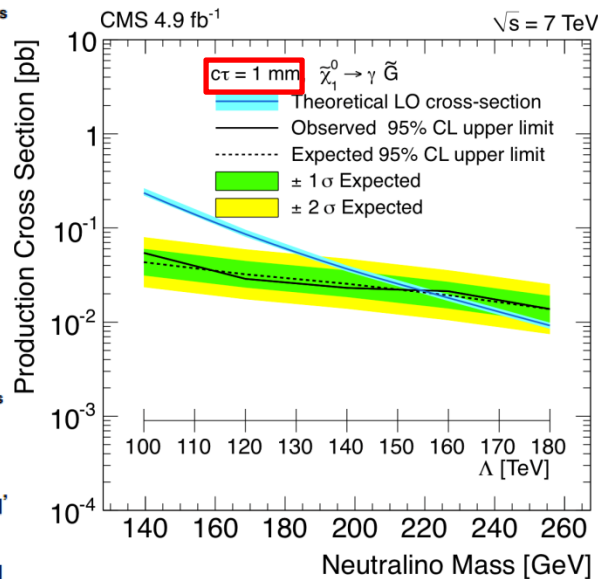
- Different distinguished detector signatures, not presented for SM processes

Non-pointing photons

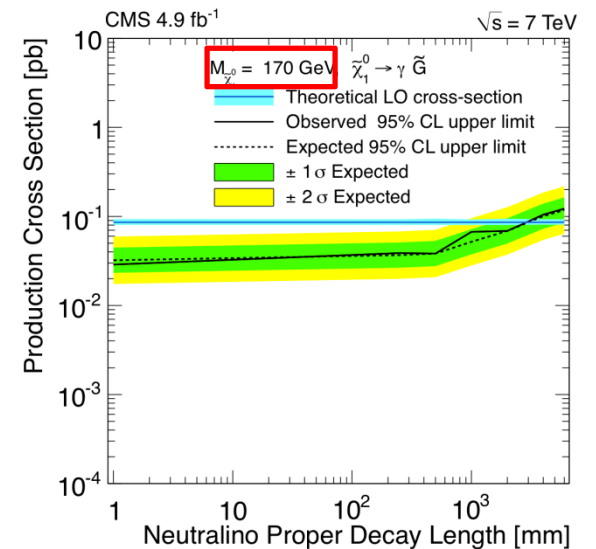
- Search for long-lived GMSB neutralinos with single photon or diphoton with large MET (4.9 fb⁻¹, CMS)
- Photons not pointing back to the PV of the event



After the subtraction of TOF

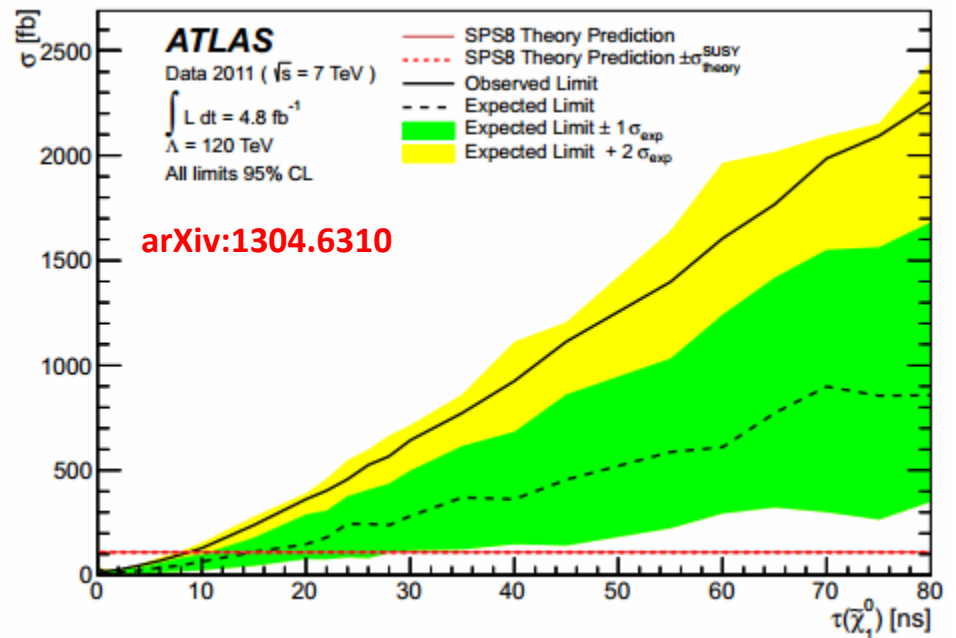
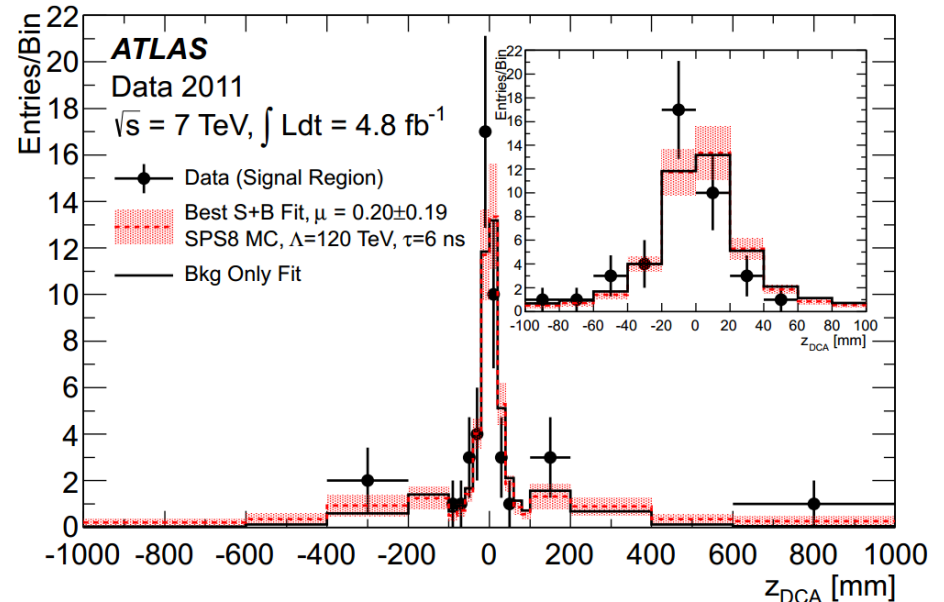
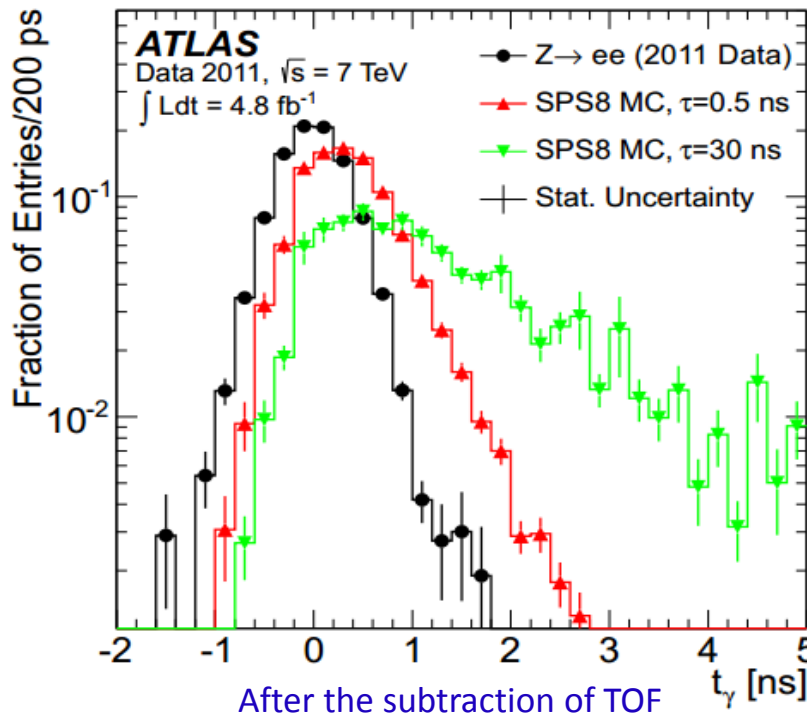


Phys. Lett. 722 (2013) 273



Non-pointing photons

- Similar search with diphoton + MET (4.8 fb^{-1} , ATLAS)
- Use Z_{DCA} (z-coordinate difference between the photon extrapolated position and the PV) and calorimeter timing to improve the search sensitivity

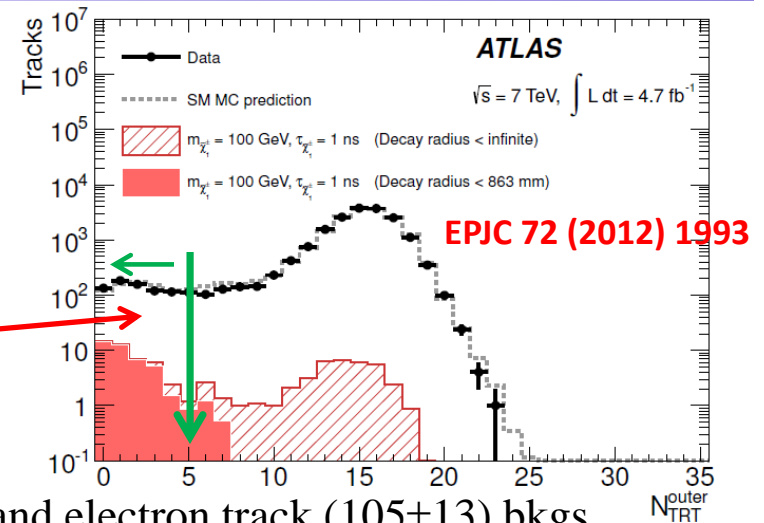


Disappearing tracks

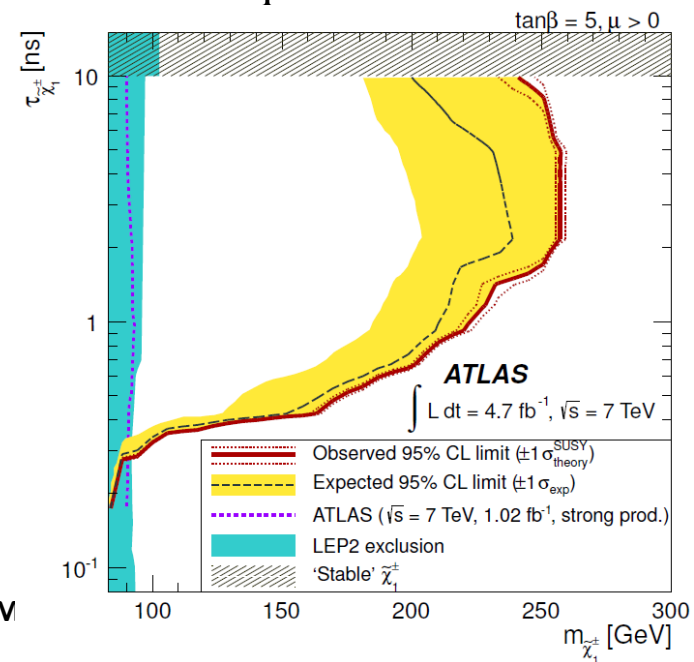
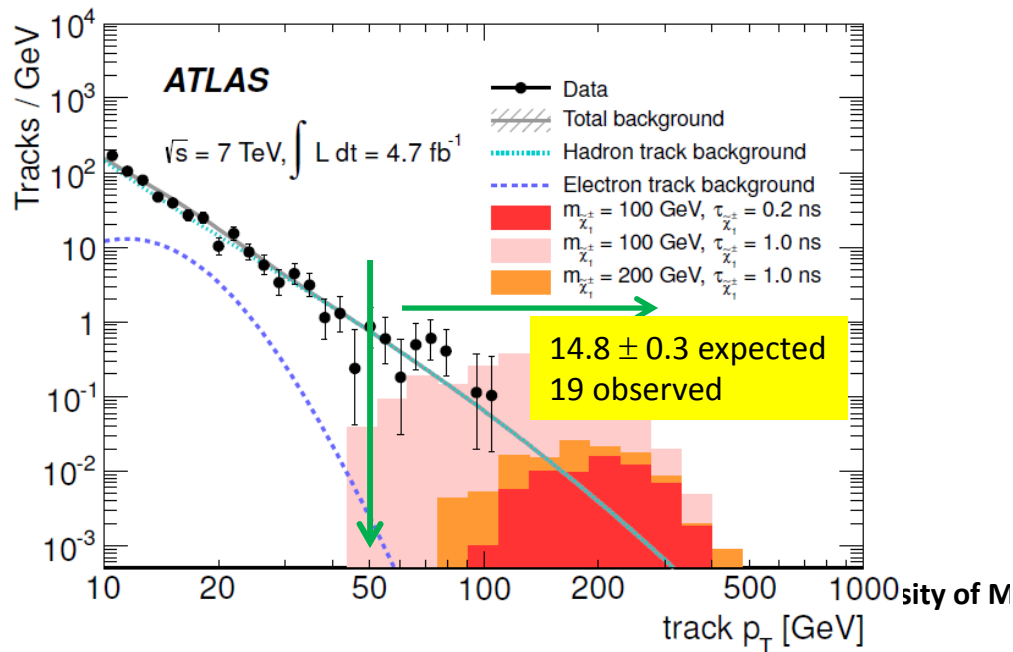
- Anomaly-mediated SUSY breaking (AMSB), soft SUSY breaking caused by loop effects
- Nearly mass degenerate between the lightest chargino ($m_{\tilde{\chi}_1^\pm}$) and neutralino ($m_{\tilde{\chi}_1^0}$), both are winos ($m(m_{\tilde{\chi}_1^\pm}) > m(m_{\tilde{\chi}_1^0})$ by about 160-170 MeV)
- $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + \pi^\pm$ pion with a mean lifetime of \sim ns $\rightarrow \tilde{\chi}_1^\pm$ will have decay lengths exceeding \sim 10 cm and their tracks may have no or few associated hits in the outer region of the tracking system \rightarrow disappearing tracks
- Search for $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0 j$, $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- j$: high p_T jet and disappearing track with large MET

Disappearing tracks

Requirement	Observed	Signal events (efficiency [%])	
		$m_{\tilde{\chi}_1^\pm} = 100$ GeV	$m_{\tilde{\chi}_1^\pm} = 200$ GeV
Quality requirements and trigger	3765627	1983 (3.0)	283.3 (6.7)
Non-collision background rejection	2899498	1958 (3.0)	279.6 (6.6)
Lepton veto	2186581	1906 (2.9)	274.8 (6.5)
Leading jet $p_T > 90$ GeV	2054262	1497 (2.3)	237.7 (5.6)
$E_T^{\text{miss}} > 90$ GeV	1233864	1420 (2.2)	230.2 (5.5)
$\Delta\phi_{\text{min}}^{\text{jet}-E_T^{\text{miss}}} > 1.5$ rad	1191298	1402 (2.1)	227.4 (5.4)
High- p_T isolated track selection	18493	90.5 (0.14)	9.1 (0.26)
Disappearing-track selection	710	42.9 (0.066)	4.1 (0.12)

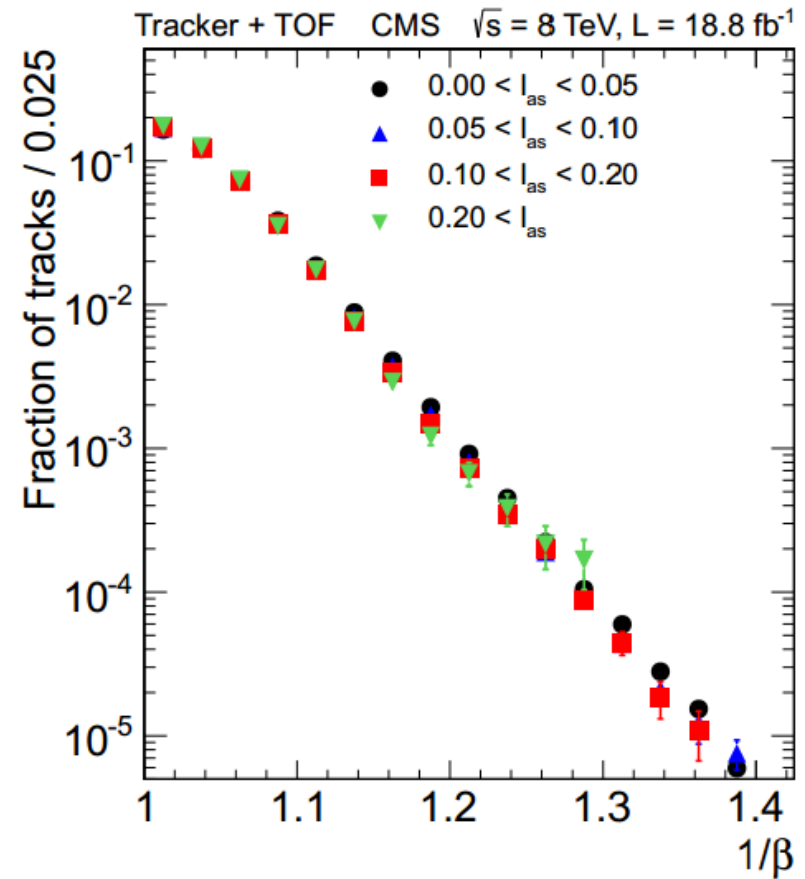
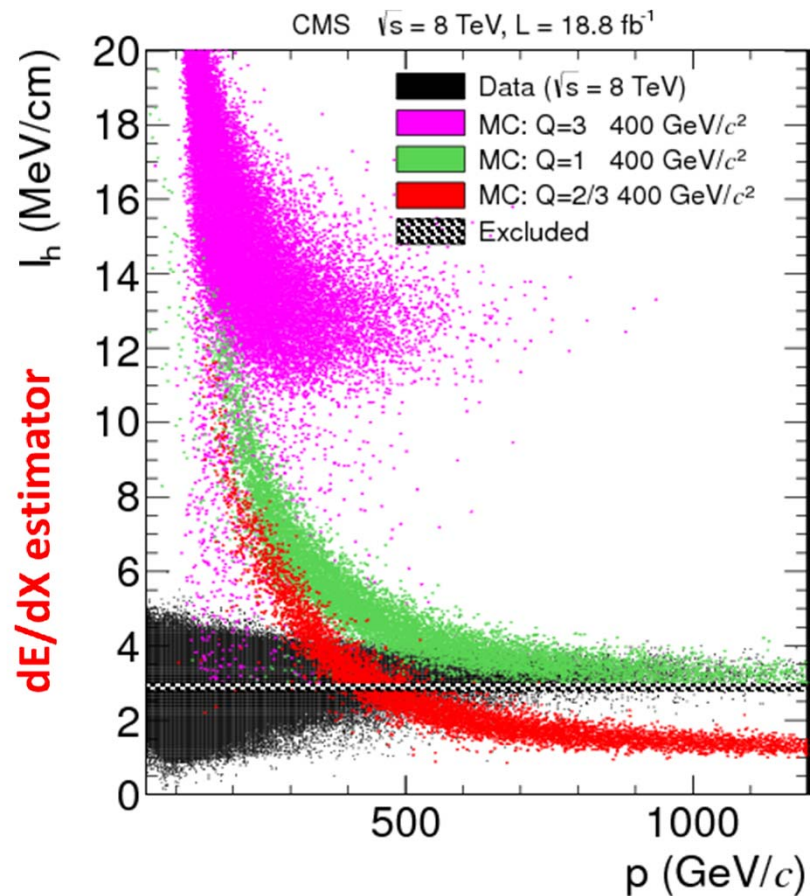


- Hadron track (mainly from $W(\rightarrow\tau\nu)+\text{jets}$) (610 ± 30) and electron track (105 ± 13) bkg
- Background track p_T spectra determined from data-driven techniques

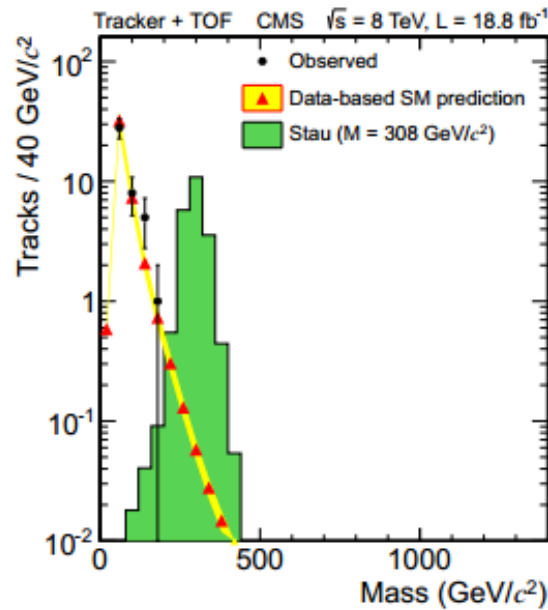
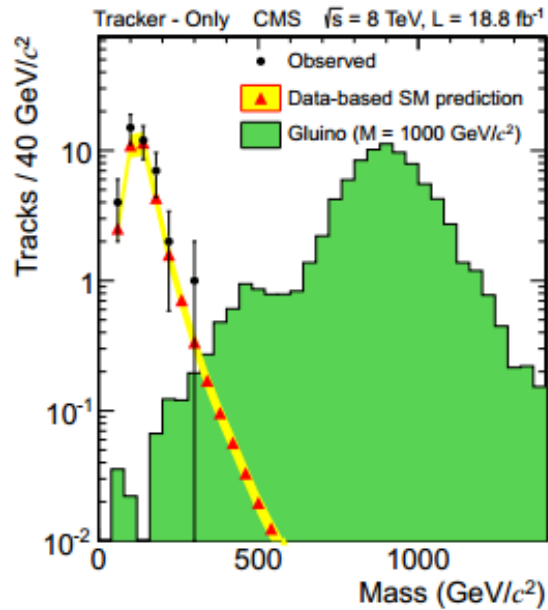


Heavy stable particle search

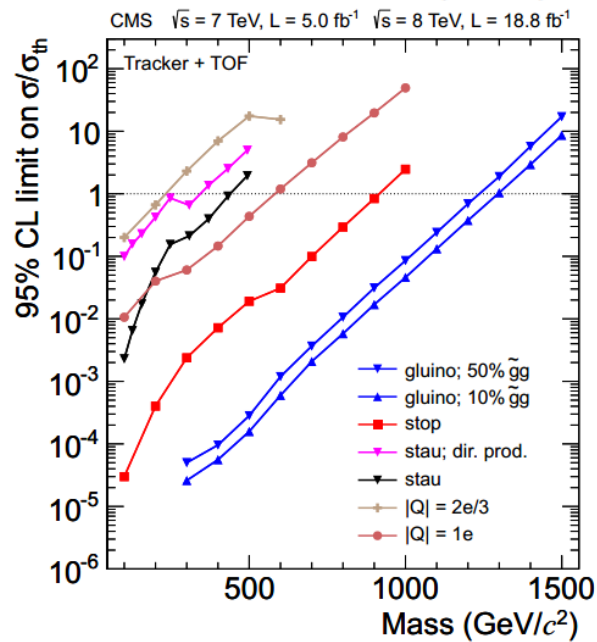
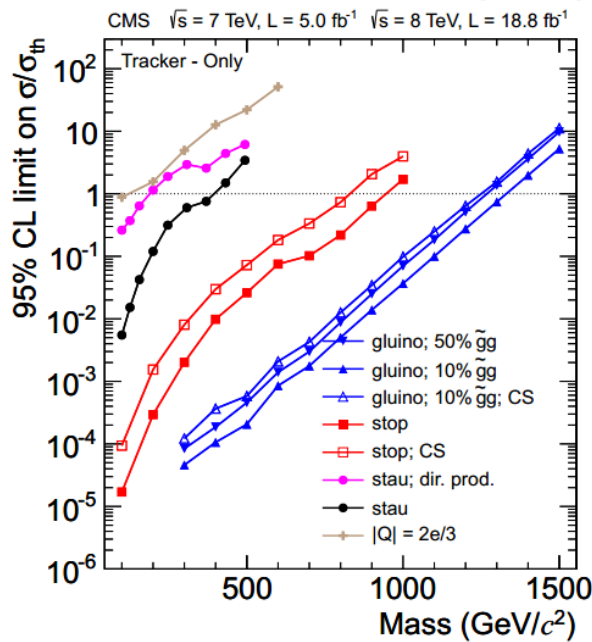
- Long-lived charged sleptons such as light staus in GMSB are reconstructed as muons
- Long-lived coloured particles such as \tilde{q} and \tilde{g} will hadronize forming R-hadrons, bound states composed of the LLP and light SM quarks or gluons



Results

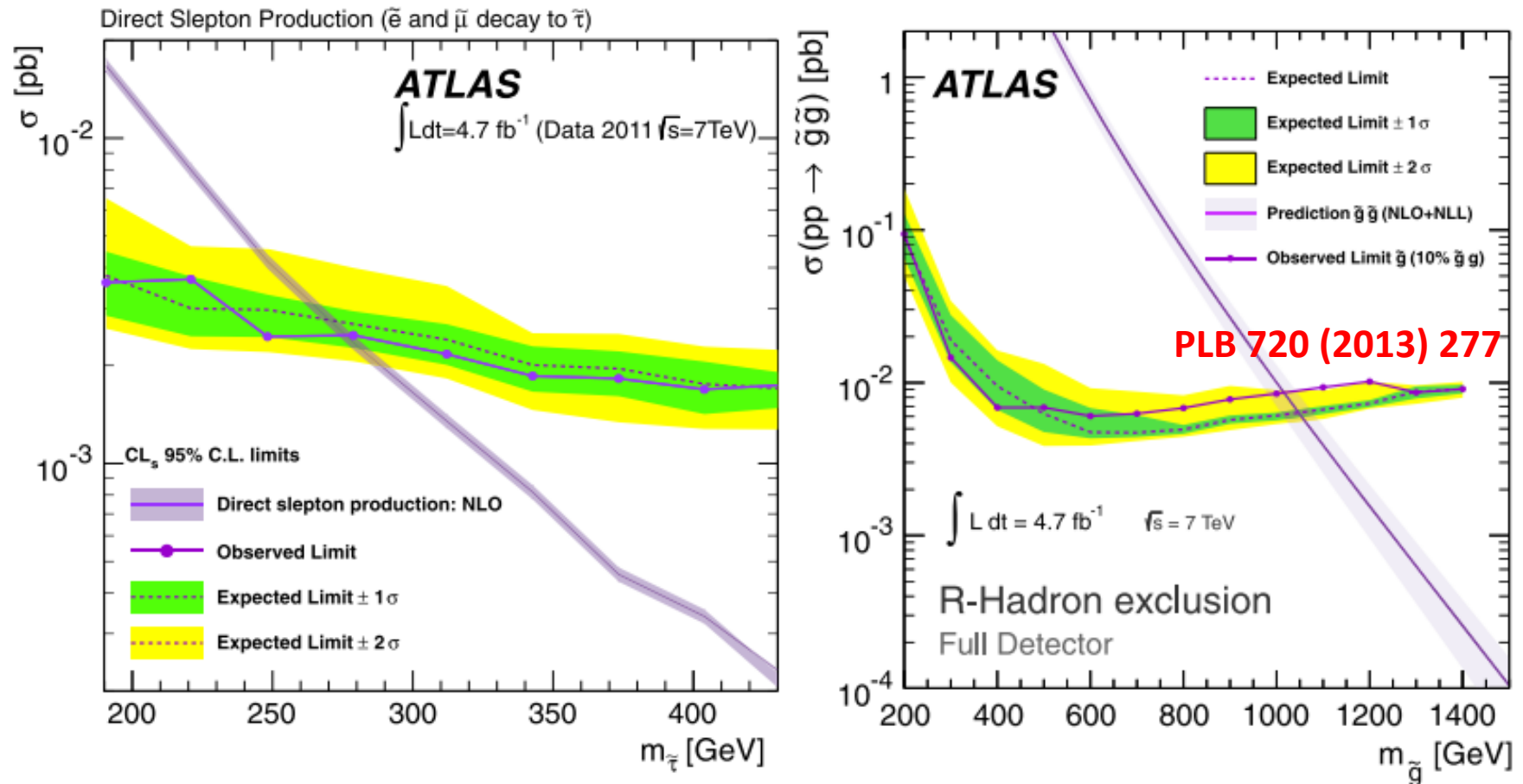


arXiv: 1305.0491



ATLAS search results

- ATLAS also searched for slepton and R-hadron using the timing information in the muon spectrometer or calorimeters and energy loss measurement in the silicon detector



Conclusions

- ❑ Presented non-Standard SUSY searches at ATLAS and CMS
- ❑ Covered a range of interesting final states with leptons, jets, photons, vertices, tracks and muons
- ❑ Some searches are signature-based searches while some are model-driven
- ❑ No data excess observed so far, but extensive studies are ongoing to obtain better sensitivities to all non-Standard SUSY searches