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Search for exotic production of top quarks with same-sign leptons

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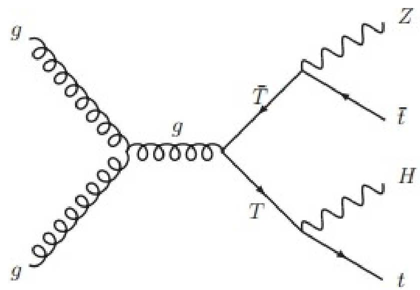
Introduction

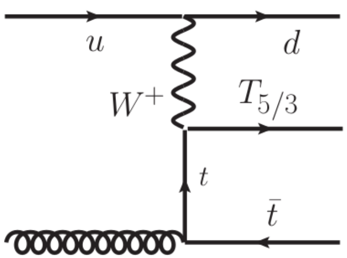
- Search for exotic **top** quark production is theoretically motivated
  - Top mass, radiative Higgs correction, Higgs stability …
- **Same-sign leptons** can be the signature of many exotic top production:
  - Same-sign tops tt or $\bar{t}\bar{t}$, ≥3t, $t\bar{t}$+extra bosons
  - Leading to $l^{\pm}l^{\pm}(l) + bjets\ + jets\ +\ Et_{miss}$
  - Low background from the standard model

- Today, I will present **4 analyses** from **ATLAS** and **CMS**:
  - Search for top quark partners with charge 5/3 at 13TeV **(CMS T5/3):** Link
  - Search for new physics in same-sign dilepton events at 13TeV **(CMS Susy)**: link
  - Search for supersymmetry at 13TeV with jets and two same-sign leptons or three leptons (**ATLAS Susy)** : link
  - Analysis of events with b-jets and a pair of leptons of the same charge at 8TeV (**ATLAS VLQ**) : link
    - Will soon be published with 13TeV data

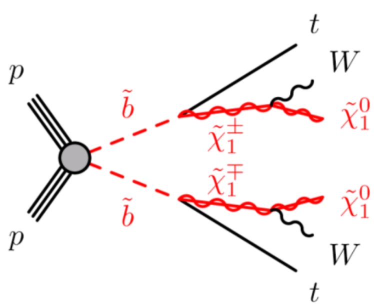
BSM Models (1): VLQ and SUSY

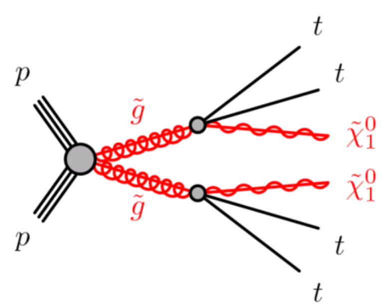
- Vector Like Quark (VLQ) signatures: $t\bar{t} + X$
  - Double production: TT, BB or $T_{5/3}T_{5/3}$
    - Limit in m_Q and Br($Q \rightarrow qV$)
      - *T→Zt, Ht or Wb*
      - *B→Zb, Hb or Wt*
      - $T_{5/3}$→Wt
  - Single production:
    - Limit in m_Q and coupling *C*
  - Large jet activities (H_T)





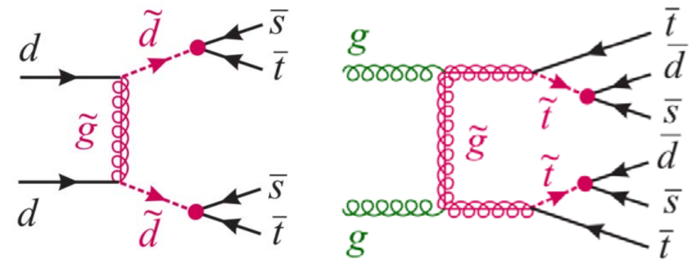
- Supersymmetric signature: $t\bar{t} + X + \ E^T_{miss}$
  - Light gluino and 3rd generation squark motivated by naturalness
    - Large production of $\tilde{g}\tilde{g}, \tilde{t}\tilde{t}$ and $\tilde{b}\tilde{b}$
    - And large Br($\tilde{g} \rightarrow \tilde{t}t$)
  - Two signals producing top quarks:
  - Large MET from neutralino





BSM Models (2): RPV and 4tops

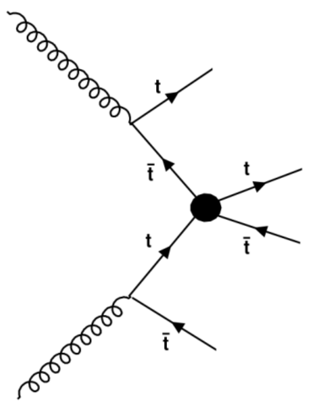
- Baryonic number violation search: *same-sign tops*
  - Low energy constraint (proton stability) implies $\Delta B=2$ processes involving top quarks
  - Possible realization with R-**parity violation SUSY**:
  - No neutralino (low MET) but high jet activities



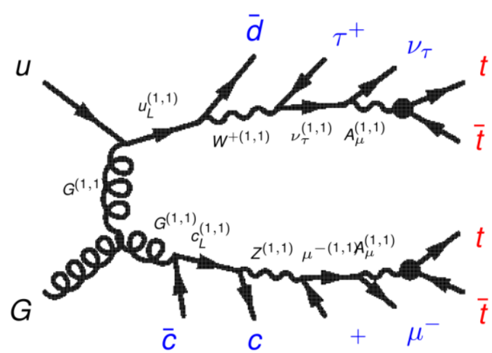
- Four tops signature: $t\bar{t}t\bar{t}$

- Effective theory:

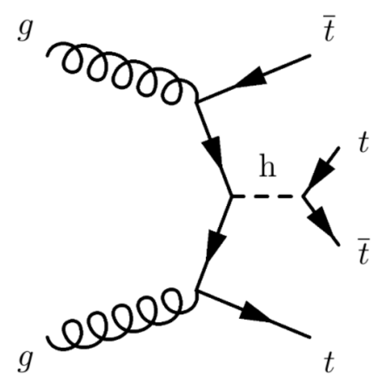
$$\mathcal{L}_{4t} = \frac{C_{4t}}{\Lambda^2}\left(\bar{t}_R\gamma^\mu t_R\right)\left(\bar{t}_R\gamma_\mu t_R\right)$$



- Extra-dimension
  - Universal Extra Dimension



- 2HDM type-II



Selections:

- All analyses require **same-sign leptons** or **3 leptons**
  - + additional cuts on jet activities, Number of jets/b-jets, MET**…**
- General feature:
  - **CMS T5/3** and **ATLAS VLQ** cuts optimized for the search of **energetic** tops
    - High jet activities cut and high lepton Pt (25-30GeV)
  - **CMS Susy** and **ATLAS Susy** cuts optimized for **massive** neutralinos (compressed scenario):
    - High MET cut and low lepton Pt (10GeV)
  - Additional cuts are also required on N_{bjets}, N_{jets} , M_T^{min}, M_{eff}, $N_{constuents}$ …
- Signal region:
  - **CMS T5/3** and **ATLAS Susy** analysis use **inclusive** signal regions
  - **CMS Susy** and **ATLAS VLQ** analysis use **several** signal regions **split** in different kinematic cut requirements

ATLAS Susy

Table 1: Summary of the event selection criteria for the signal regions (see text for details).

Signal region	$N_{\text{lept}}^{\text{signal}}$	$N_{b\text{-jets}}^{20}$	N_{jets}^{50}	E_T^{miss} [GeV]	m_{eff} [GeV]
SR1b	≥ 2	≥ 1	≥ 4	>150	>550
SR3b	≥ 2	≥ 3	-	>125	>650

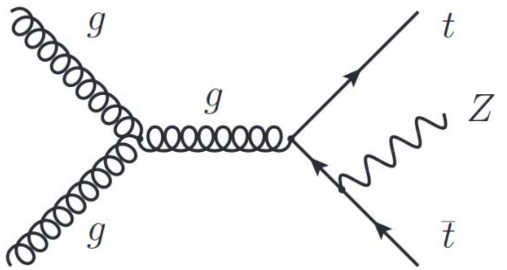
CMS T5/3

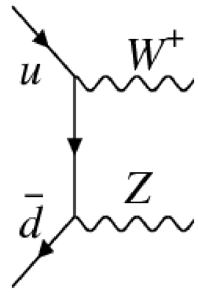
N_{lep}	HT	MeT	$N_{lep+jet}$
≥2	>900 GeV	> 0 GeV	≥5

- More detailed signal region description in backup

Background composition

1) **True same-sign/three leptons**
   - From Standard Model
   - Dominant: $t\bar{t} + V$ and VV
   - Simulated by *Monte-Carlo* method

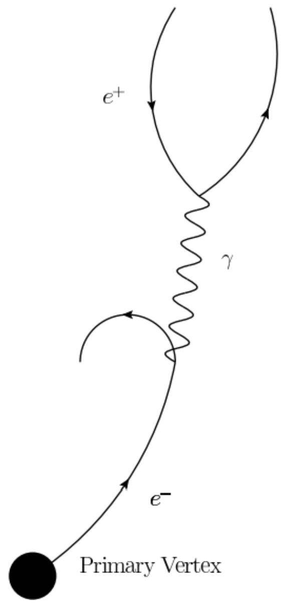




2) **Fake/non-prompt lepton**
   - Light jet reconstructed as lepton
   - Lepton coming from heavy-flavor jet
   - Estimated by *data-driven* method

3) **Charge mis-identification**
   - Detector effect
   - Negligible for muon
   - Two sources:
     - **Tracker** charge reconstruction efficiency
     - Electron from **photon conversion**
   - Estimated by *data-driven* method

Photon conversion:



Fake/non-prompt lepton estimation method

- **Lepton definition:**
  - The fake estimation methods rely on the definition of lepton criteria: **loose** and **tight** criteria
    - For electrons, the identification and isolation are used
    - For muons, the isolation criteria is used
- **Matrix method:**

$$\begin{pmatrix} N_t \\ N_{\bar{t}} \end{pmatrix} = M \begin{pmatrix} N_{real} \\ N_{fake} \end{pmatrix} \quad M = \begin{pmatrix} \epsilon_r & \epsilon_f \\ (1-\epsilon_r) & (1-\epsilon_f) \end{pmatrix}$$

t=tight
$\bar{t}$=loose but not tight

  - N_{fake} is estimated by weighting N_t and $N_{\bar{t}}$ with the elements of M^{-1}
  - Generalized for 2 and 3 leptons
- **Tight-to-loose method:**
  - ϵ_{TL} : probability that a **fake** loose lepton is tagged as **tight** $(\sim\epsilon_f)$
  - N_{fake} estimated by
    - selecting events with ≥1 loose but not tight lepton
    - Weight them by $\epsilon_{TL}/(1-\epsilon_{TL})$
  - Equivalent to Matrix Method by considering that $\epsilon_r \approx 1$

Real and fake efficiency measurement and systematic

- **Efficiency estimation:**
  - ϵ_r estimated on enriched **real** lepton region
    - *Single lepton* region: High MET and MT (W+jets)
    - *Dilepton* region: Z mass window (Z->ll)
  - ϵ_f estimated on enriched **fake** lepton region
    - *Single lepton* region: Low MET and MT (multijet background)
    - *SS Dilepton* region: Tight muon + 1 loose lepton (V+jets and ttbar)
    - Real lepton contribution are subtracted from fake region
  - Usually parameterized in **Pt** and **|η|** of the leptons
    - And sometimes other parameters like triggers, N_{bjets} ... etc

- Systematic uncertainties: around **35-60%**
  - Fake composition (light jet, c-jets, b-jets) can be different in other regions
    - Alternative control region or truth matching studies
  - Other kinematic dependences
  - Statistical uncertainty from fake/real lepton control regions
  - Real lepton bkg removal in fake region
  - Closure tests or comparison with other methods

Charge mis-identification background

- Based on the **charge flip rates ϵ**
  - Defined as the probability of one electron to have its charge mis-identified
  - **Parameterized** on Pt and |η|
- Charge mis-identification bkg estimated by **weighting opposite-sign** dielectron events by:

$$w = \frac{\epsilon_1(1-\epsilon_2)+\epsilon_2(1-\epsilon_1)}{(1-\epsilon_1)(1-\epsilon_2)+\epsilon_1\epsilon_2}$$

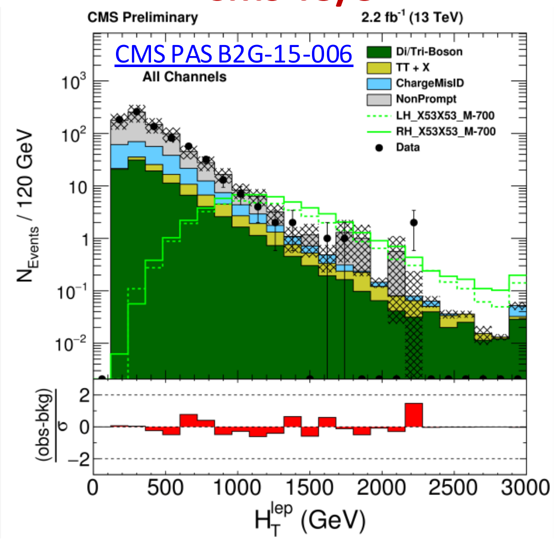
ϵ_1 charge flip rate of 1st electron
ϵ_2 charge flip rate of 2nd electron

- Charge flip rate estimation on enriched pp→Z→ee data events:
  - $m_{ee} \in [m_z - X, m_z + X]$
  - Count the number of e^+e^- and same-sign $e^\pm e^\pm$
  - Charge flip rates estimated by Likelihood minimization $\mathcal{L}(\epsilon|N, N_{ss})$
- Systematic uncertainties: around **20-30%**
  - Statistical uncertainty from likelihood minimization
  - Kinematic dependences
  - Closure tests on MC V+jets samples
  - Invariant mass cuts variations

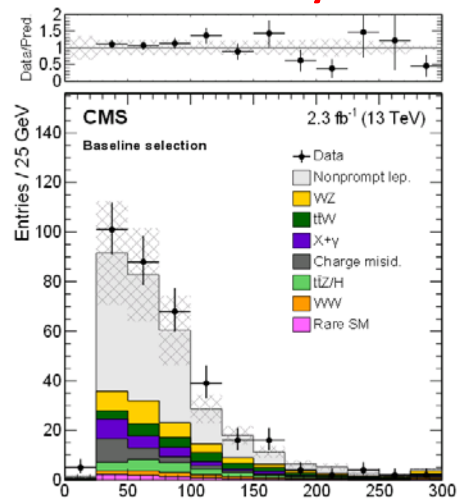
Validation plots

- Validation plots at pre-selection level:

CMS T5/3

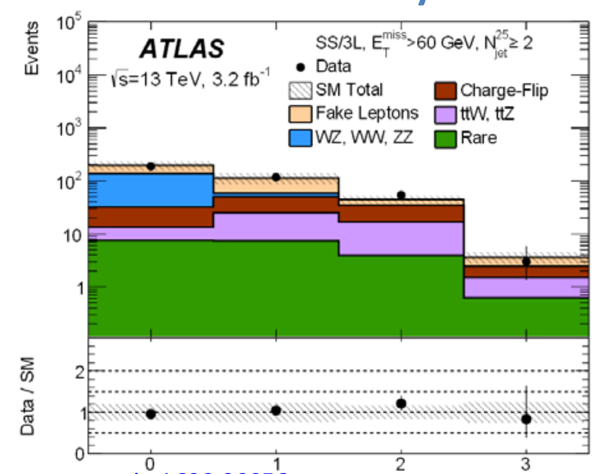


CMS Susy



arxiv:1605.03171v1

ATLAS Susy



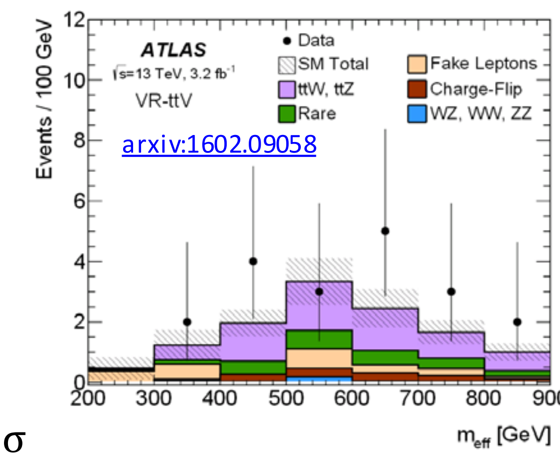
arxiv:1602.09058

- Control regions **ATLAS Susy** :

	VR-WW	VR-WZ	VR-ttV	VR-ttZ
Observed events	4	82	19	14
Total background events	3.4 ± 0.8	98 ± 15	12.1 ± 2.7	9.7 ± 2.5
Fake/non-prompt leptons	0.6 ± 0.5	8 ± 6	2.1 ± 1.4	0.6 ± 1.0
Charge-flip	0.26 ± 0.05	–	1.14 ± 0.15	–
$t\bar{t}W$	0.05 ± 0.03	0.25 ± 0.09	2.4 ± 0.8	0.10 ± 0.03
$t\bar{t}Z$	0.02 ± 0.01	0.72 ± 0.26	3.9 ± 1.3	6.3 ± 2.1
WZ	1.0 ± 0.4	78 ± 13	0.19 ± 0.10	1.2 ± 0.4
$W^{\pm}W^{\pm}jj$	1.3 ± 0.5	–	0.02 ± 0.03	–
ZZ	0.02 ± 0.01	8.2 ± 2.8	0.12 ± 0.15	0.30 ± 0.19
Rare	0.10 ± 0.05	2.8 ± 1.4	2.3 ± 1.2	1.1 ± 0.6

arxiv:1602.09058

Deviation of 1.5σ

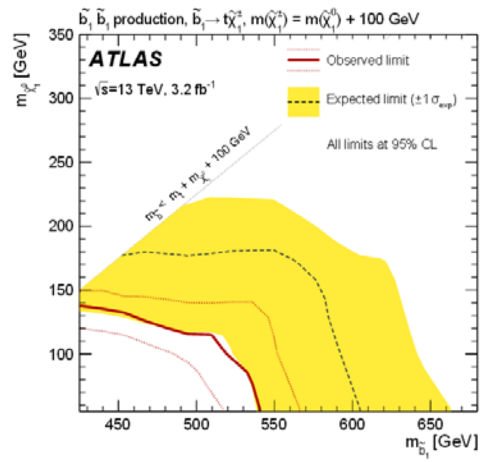


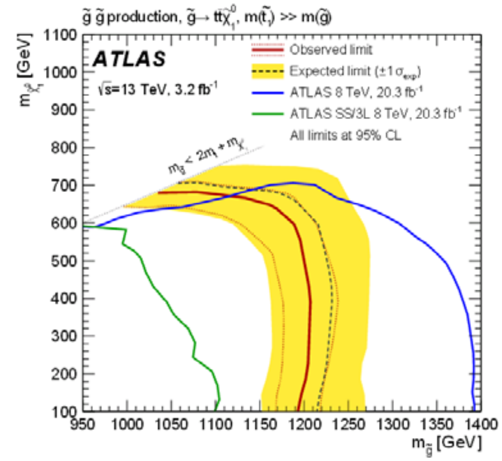
Results: SUSY

- **ATLAS Susy**

arxiv:1602.09058

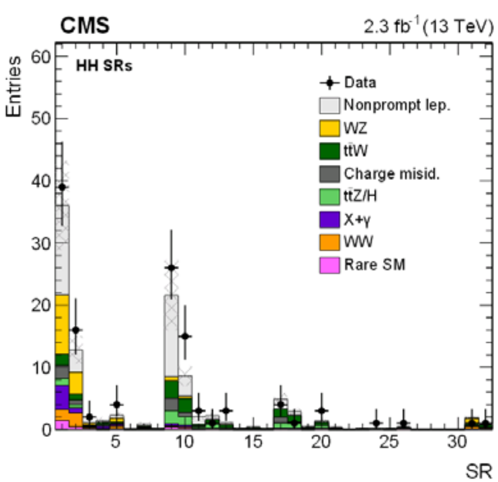
	SR1b	SR3b
Observed events	7	1
Total background events	4.5 ± 1.0	0.80 ± 0.25
$p(s=0)$	0.15	0.36
Fake/non-prompt leptons	0.8 ± 0.8	0.13 ± 0.17
Charge-flip	0.60 ± 0.12	0.19 ± 0.06
$t\bar{t}W$	1.1 ± 0.4	0.10 ± 0.05
$t\bar{t}Z$	0.92 ± 0.31	0.14 ± 0.06
WZ	0.18 ± 0.11	< 0.02
$W^{\pm}W^{\pm}jj$	0.03 ± 0.02	< 0.01
ZZ	< 0.03	< 0.03
Rare	0.8 ± 0.4	0.24 ± 0.14

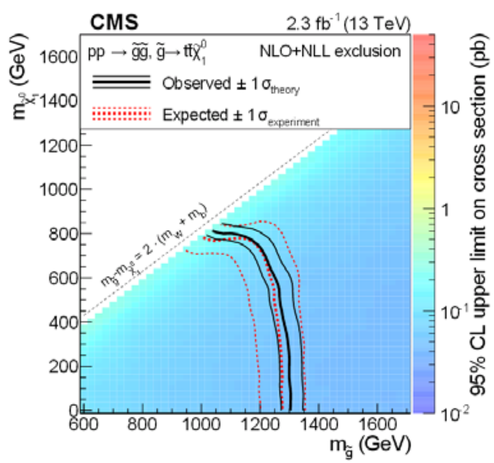


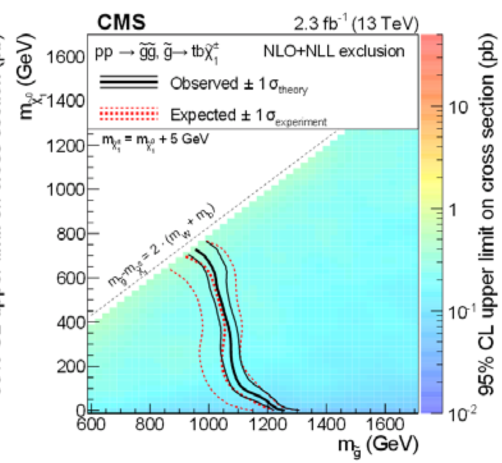


- **CMS Susy**

arxiv:1605.03171v1







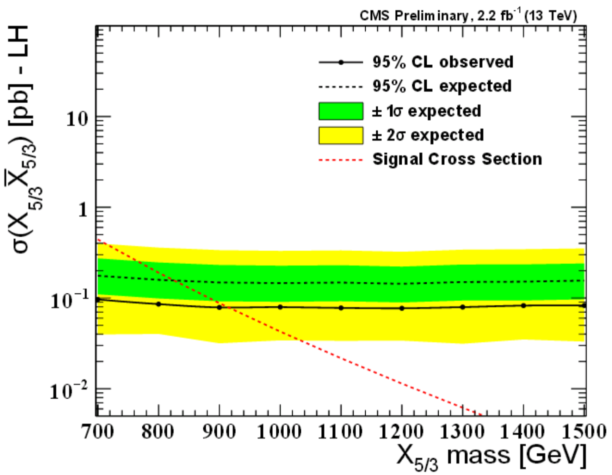
– Better sensitivity for CMS because of the exclusives SRs

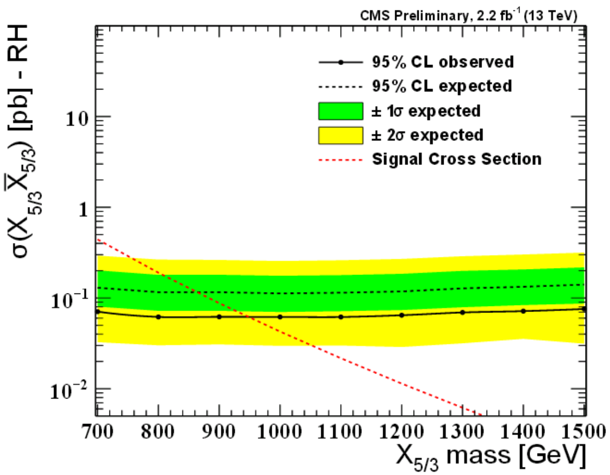
Results: T5/3

- **CMS T5/3**

CMS PAS B2G-15-006

Channel	PSS MC	NonPrompt	ChargeMisID	Total Background	800 GeV $X_{5/3}$	Observed
Di-electron	2.41 ± 0.29	2.16 ± 1.91	1.90 ± 0.60	6.47 ± 2.02	4.38	7
Electron-Muon	2.98 ± 0.36	5.20 ± 3.21	0.54 ± 0.18	8.72 ± 3.24	9.14	3
Di-muon	0.70 ± 0.12	2.09 ± 1.69	0.00 ± 0.00	2.80 ± 1.70	3.55	1
All	6.09 ± 0.67	9.45 ± 5.49	2.44 ± 0.76	17.98 ± 5.58	17.06	11





- 100-200GeV of improvement compared to 8TeV
- Results combined with 1 lepton analysis

Conclusion

- Same-sign lepton is a **well-motivated** signature for the search of new physics involving top quarks
  - Supersymmetry, vector-like quarks …
- **Different** selection strategy for each analysis
- Imply to use sophisticated **data-driven technique** to estimate fake and charge mis-identification background
  - Handled in a different way for each analysis
- **No deviation** found at 13TeV
  - Exclusion limits set for supersymmetric and T5/3 models
- **New results** will be published soon:
  - **ATLAS VLQ** search on going
  - And future 2016 data !
- I hope we will find surprising excess ☺

Backup

Selection: Susy

ATLAS Susy

Table 1: Summary of the event selection criteria for the signal regions (see text for details).

Signal region	$N_{\mathrm{lept}}^{\mathrm{signal}}$	$N_{b-\mathrm{jets}}^{20}$	N_{jets}^{50}	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	m_{eff} [GeV]
SR0b3j	≥3	=0	≥3	>200	>550
SR0b5j	≥2	=0	≥5	>125	>650
SR1b	≥2	≥1	≥4	>150	>550
SR3b	≥2	≥3	-	>125	>650

CMS Susy

Table 2: SR definitions for the HH selection. The notation (*) indicates that, in order to avoid overlaps with SR31, an upper bound $E_{\mathrm{T}}^{\mathrm{miss}} < 300$ GeV is used for regions with $H_{\mathrm{T}} > 300$ GeV.

N_{b}	$M_{\mathrm{T}}^{\mathrm{min}}$ (GeV)	$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	N_{jet}	$H_{\mathrm{T}} < 300$ GeV	$H_{\mathrm{T}} \in [300, 1125]$ GeV	$H_{\mathrm{T}} > 1125$ GeV
0	< 120	50 − 200	2-4	SR1	SR2	SR32
			> 5	SR3	SR4	
		> 200(*)	2-4		SR5	
			> 5		SR6	
	> 120	50 − 200	2-4		SR7	
			> 5		SR8	
		> 200(*)	2-4			
			> 5			
1	< 120	50 − 200	2-4	SR9	SR10	
			> 5	SR11	SR12	
		> 200(*)	2-4		SR13	
			> 5		SR14	
	> 120	50 − 200	2-4		SR15	
			> 5		SR16	
		> 200(*)	2-4			
			> 5			
2	< 120	50 − 200	2-4	SR17	SR18	
			> 5	SR19	SR20	
		> 200(*)	2-4		SR21	
			> 5		SR22	
	> 120	50 − 200	2-4		SR23	
			> 5		SR24	
		> 200(*)	2-4			
			> 5			
> 3	< 120	50 − 200	> 2	SR25	SR26	
		> 200(*)	> 2	SR27	SR28	
	> 120	> 50(*)	> 2	SR29	SR30	
Inclusive	Inclusive	> 300	> 2	——	SR31	

Table 3: SR definitions for the HL selection. The notation (*) indicates that, in order to avoid overlaps with SR25, an upper bound $E_{\mathrm{T}}^{\mathrm{miss}} < 300$ GeV is used for regions with $H_{\mathrm{T}} > 300$ GeV.

N_{b}	$M_{\mathrm{T}}^{\mathrm{min}}$ (GeV)	$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	N_{jet}	$H_{\mathrm{T}} < 300$ GeV	$H_{\mathrm{T}} \in [300, 1125]$ GeV	$H_{\mathrm{T}} > 1125$ GeV
0	< 120	50 − 200	2-4	SR1	SR2	SR26
			> 5	SR3	SR4	
		> 200(*)	2-4		SR5	
			> 5		SR6	
1	< 120	50 − 200	2-4	SR7	SR8	
			> 5	SR9	SR10	
		> 200(*)	2-4		SR11	
			> 5		SR12	
2	< 120	50 − 200	2-4	SR13	SR14	
			> 5	SR15	SR16	
		> 200(*)	2-4		SR17	
			> 5		SR18	
> 3	< 120	50 − 200	> 2	SR19	SR20	
		> 200(*)	> 2	SR21	SR22	
Inclusive	> 120	> 50(*)	> 2	SR23	SR24	
Inclusive	Inclusive	> 300	> 2	——	SR25	

Table 4: SR definitions for the LL selection. All SRs in this category require $N_{\mathrm{jet}} \geq 2$.

N_{b}	$M_{\mathrm{T}}^{\mathrm{min}}$ (GeV)	H_{T} (GeV)	$E_{\mathrm{T}}^{\mathrm{miss}} \in [50, 200]$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV
0	< 120	> 300	SR1	SR2
1			SR3	SR4
2			SR5	SR6
≥ 3			SR7	
Inclusive	> 120		SR8	

Selection VLQ

ATLAS VLQ

Definition			Name	
$e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_j \geq 2$				
$400 < H_{\mathrm{T}} < 700$ GeV	$N_b = 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRVLQ0	
	$N_b = 2$		SRVLQ1	SR4t0
	$N_b \geq 3$		SRVLQ2	SR4t1
$H_{\mathrm{T}} \geq 700$ GeV	$N_b = 1$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100$ GeV	SRVLQ3	
		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 100$ GeV	SRVLQ4	
	$N_b = 2$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100$ GeV	SRVLQ5	SR4t2
		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 100$ GeV	SRVLQ6	SR4t3
	$N_b \geq 3$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRVLQ7	SR4t4

CMS T5/3

- At least two isolated same-sign leptons as defined above with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$. Between each lepton and every top-quark jet, we require $\Delta R > 0.8$.
- Dilepton Z-boson veto: $M(\mathrm{ee}) < 76\,\mathrm{GeV}$ or $M(\mathrm{ee}) > 106\,\mathrm{GeV}$. This selection applies only to the dielectron channel. If the muon charge is mismeasured, its momentum will also be mismeasured so a selected muon pair from a Z boson will not fall within this invariant mass range.
- Trilepton Z-boson veto: $M(\ell\ell) < 76\,\mathrm{GeV}$ or $M(\ell\ell) > 106\,\mathrm{GeV}$ where $M(\ell\ell)$ is the invariant mass of either one of the selected leptons and any other same flavor opposite-sign lepton in the event with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$ that satisfies the loose lepton criteria.
- $N_c \geq 7$, where N_c is the number of constituents identified in the event. For the purpose of this selection, each AK5 jet and each lepton counts as one constituent. Since a W-boson jet is assumed to correspond to a W boson, each such jet counts as two constituents, corresponding to the W-boson decay products. Likewise, each top-quark jet represents a top quark and counts as three constituents.
- $H_{\mathrm{T}} > 900\,\mathrm{GeV}$, where H_{T} is the scalar sum of the p_{T} of all selected jets and leptons in the event.

Fake/non-prompt lepton: method

	ATLAS Susy	ATLAS VLQ	CMS Susy	CMS T5/3
Method	Matrix Method	Matrix Method	Tight-to-loose	Matrix Method
Fake lepton region	Dilepton: 1μ+1lepton	Single lepton: Low MT, ETmiss	Single lepton: Low MT, ETmiss	Single lepton: Low MT, ETmiss
Real lepton region	Dilepton: Z mass window	Single lepton: High MT, ETmiss		Dilepton: Z mass window
Parametrization	Pt / $\|\eta\|$	Pt / $\|\eta\|$/N_{bjet}/trigger	Pt / $\|\eta\|$/trigger	No param
Validation	Alternative fake estimate	Closure tests	Alternative rate measurement	Closure tests

Charge mis-identification: Method

- Based on the **Charge flip rates ϵ**
  - Defined as the probability of one electron to have its charge mis-identified
  - **Parameterized** on Pt and |η|
- Then, assuming a **true** number of **opposite-sign** dielectron events, we have:

$$N_{SS}^{reco} = N_{OS}^{true}(\epsilon_1(1-\epsilon_2)+\epsilon_2(1-\epsilon_1))$$
$$N_{OS}^{reco} = N_{OS}^{true}((1-\epsilon_1)(1-\epsilon_2)+\epsilon_1\epsilon_2)$$

ϵ_1 charge flip rate of 1st electron
ϵ_2 charge flip rate of 2nd electron

- N_{SS}^{reco} can be estimated by weighting N_{OS}^{reco} by:

$$w = \frac{\epsilon_1(1-\epsilon_2)+\epsilon_2(1-\epsilon_1)}{(1-\epsilon_1)(1-\epsilon_2)+\epsilon_1\epsilon_2}$$

- Charge flip rate estimation on enriched pp→Z→ee data events:
  - $m_{ee} \in [m_z - X, m_z + X]$
    - ex: X=10GeV in **CMS T5/3**
  - Count the number of e^+e^- and same-sign $e^\pm e^\pm$
  - Charge flip rates estimated by Likelihood minimization

$$\mathcal{L}(\epsilon|N,N_{ss}) = Poisson(N_{ss}|N,\epsilon)$$