

# Search for the SM (and BSM) production of four top quarks in the ATLAS detector at the LHC

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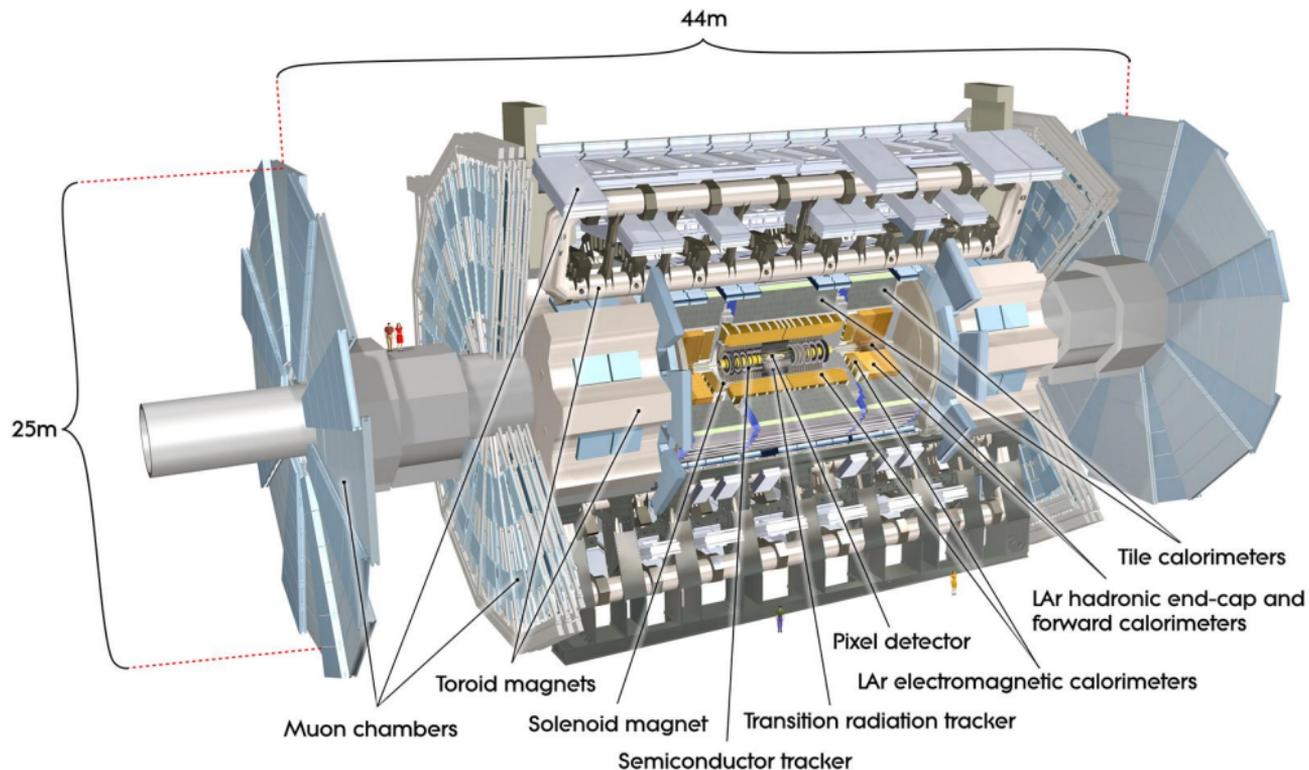
# Table of Contents

- 1 ATLAS @ LHC
- 2 Motivation and models
- 3 Event selection
- 4 Background Modeling
- 5 Results

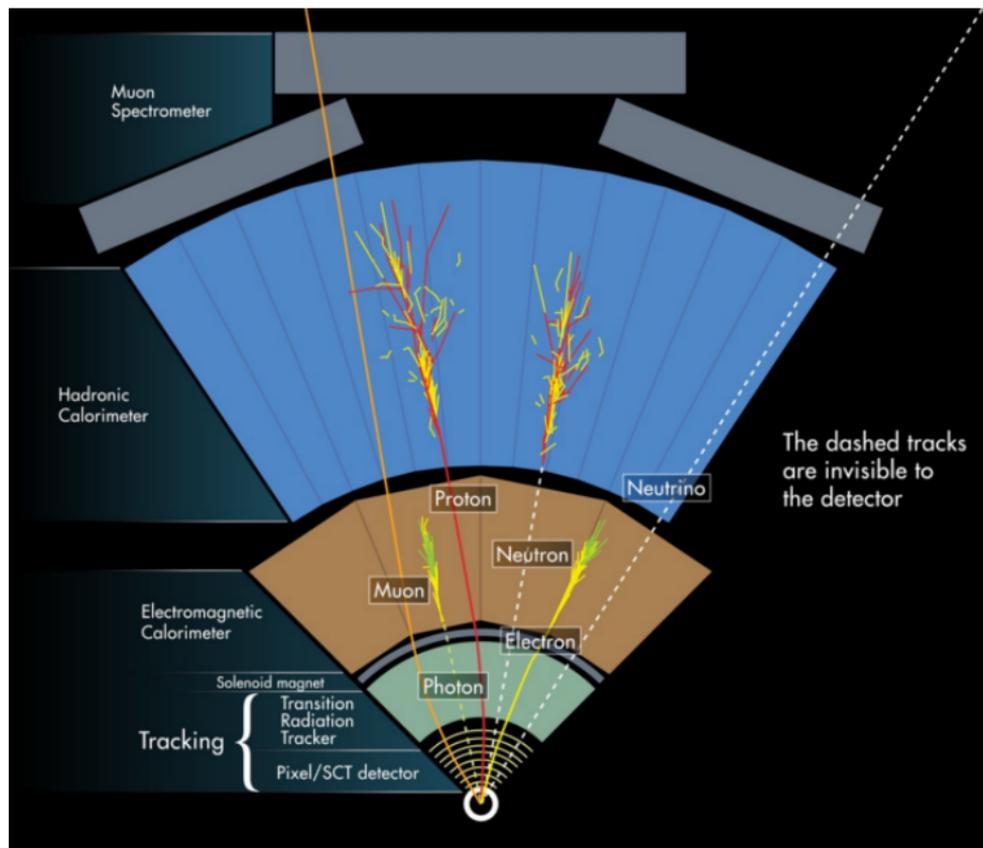
# The Large Hadron Collider



# The ATLAS detector



# Particle detection in ATLAS



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# Why four tops?

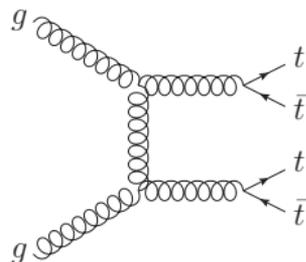


Top quark: **heaviest elementary particle** currently known

Four top production:  $t\bar{t}t\bar{t}$ , an **extremely rare process**

→  $\sigma_{t\bar{t}t\bar{t}} = 9.2 \text{ fb}$  at 13 TeV

⇒ Only  $\sim 700$   $t\bar{t}t\bar{t}$  events occurred since 2015!  
(compare that to the **40 million events per second**)



- **Goal:** Measure the  $t\bar{t}t\bar{t}$  cross-section  
→ **Very sensitive** to several **Beyond Standard Model theories**



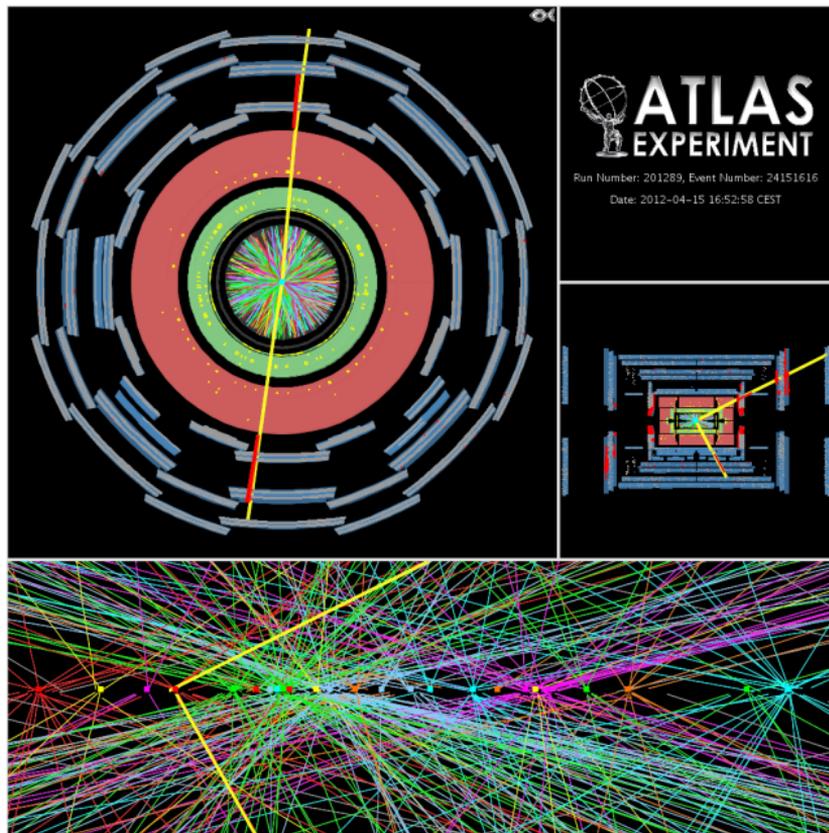
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# Event selection

- **40 000 000 events/second** produced in ATLAS, with  $\sim$  **33 collisions/event**
- but a few  $\sim$  **100  $t\bar{t}\bar{t}$  events per year** only!

⇒ **Need to perform some smart event selection**

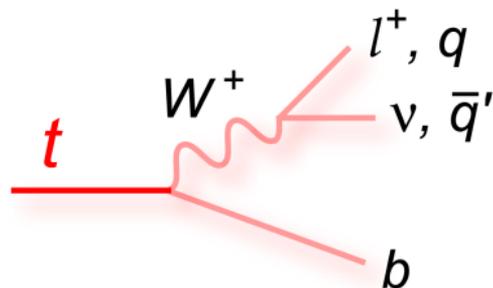
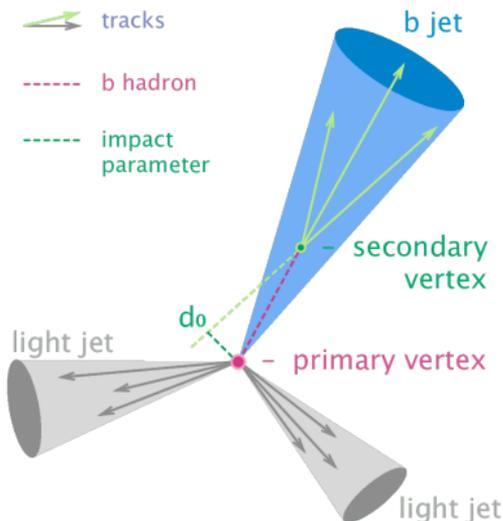


# The $t\bar{t}\bar{t}\bar{t}$ final state

- Top decay:  $t \rightarrow Wb$  ( $\sim 100\%$ )

$\implies$  Final state  $4t \rightarrow 4W + 4b$

- W decay:  $W \rightarrow \begin{cases} l\nu_l & (\sim 30\%) \\ qq' & (\sim 70\%) \end{cases}$



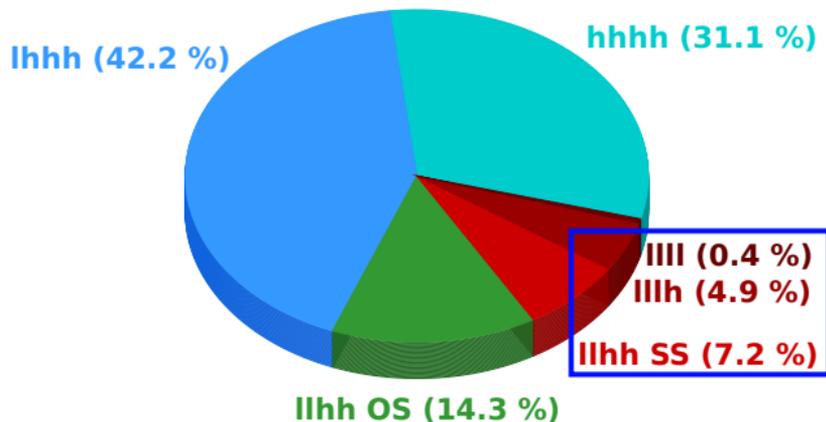
## Concerning jets

- quarks  $\rightarrow$  **jets** in the detector (parton shower + hadronization)
- **b-jets** are special (displaced vertex)  $\rightarrow$  **b-tagging** techniques

# The $t\bar{t}t\bar{t}$ final state: you said 4W?

2 interesting channels:

- **single lepton channel**
- **same-sign dilepton channel**  
(including **trilepton**)



$WWW$  decays branching fractions

- Choose events with **two leptons of the same electric charge** ( $e$  or  $\mu$ )
  - Only  $\sim 10\%$  of signal events
  - But very small background contamination!

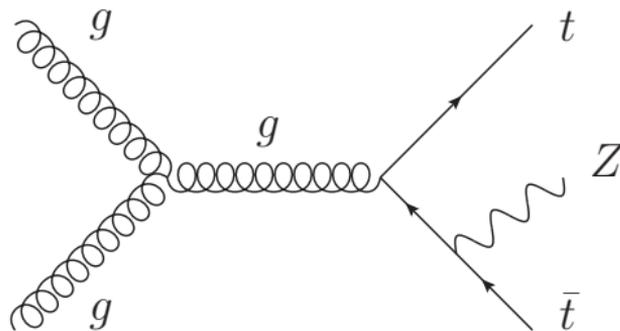
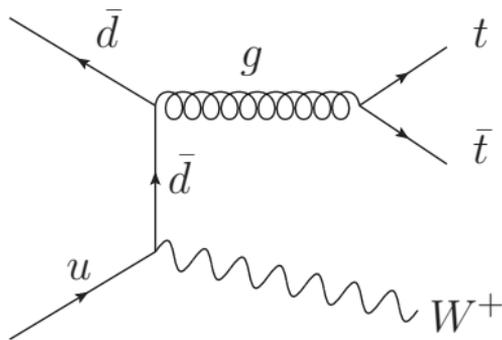
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■ **Physical processes** producing same-charge leptons:

- Top quark pair + W boson:  $t\bar{t}W$
- Top quark pair + Z boson:  $t\bar{t}Z$
- Other smaller processes

⇒ estimated by **Monte-Carlo simulations**



# Background Modeling - instrumental backgrounds

## ■ Wrong identification of leptons in the detector

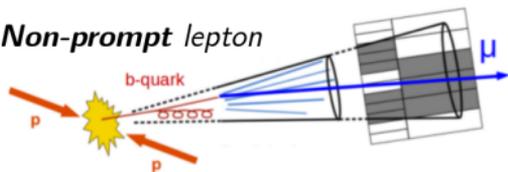
### ■ Electron charge mis-identification

- **Error** on the **charge** of an electron  
→ e.g.  $e^+$  instead of  $e^-$
- Photon conversion
- High  $p_T$  electron

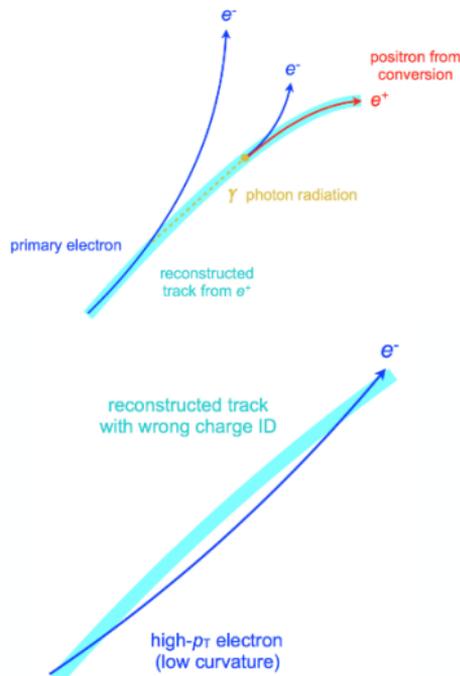
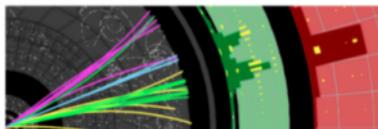
### ■ Fake/Non-prompt leptons

- Lepton from hadron decay
- Jet misidentified as lepton

*Non-prompt lepton*



*Fake lepton* - jet wrongly reconstructed as a lepton



- 2 types of backgrounds:
  - **Physical processes** producing exactly the particles we're looking for
  - **Instrumental backgrounds**: charge mis-identification, fake leptons

$$N_{\text{bkg}} = N_{\text{physical}} + N_{\text{charge misID}} + N_{\text{fakes}}$$

Analysis: **estimate**  $N_{\text{bkg}}$  as best as possible

→ then **compare**  $N_{\text{bkg}} + N_{4\text{tops}(\text{theory})}$  **to**  $N_{\text{observed same-sign events}}$

→ if  $N_{\text{bkg}} + N_{4\text{tops}(\text{theory})} \neq N_{\text{observed same-sign events}} \Rightarrow$  **BSM physics?**

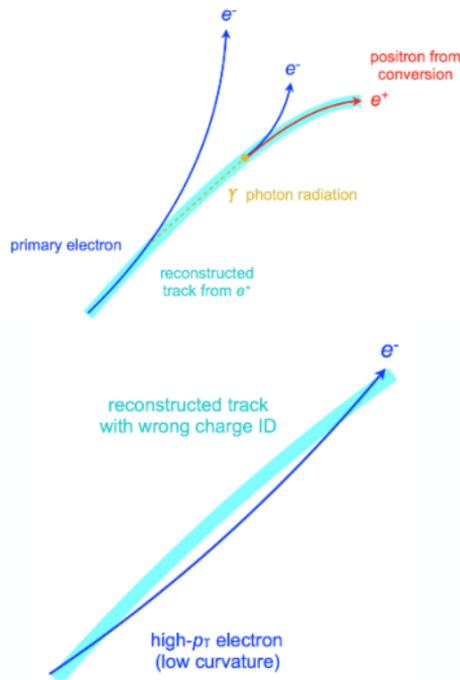
# Charge mis-ID background estimation

- Effect: select events with leptons having **opposite charge instead of same charge**
- Probability of mis-identification: **charge flip rate  $\epsilon$**   
→ **Estimated from data** ( $Z \rightarrow e^+e^-$  decays)
- **Probability** to select opposite-sign event:

$$P_{OS \rightarrow SS} = \epsilon_i(1 - \epsilon_j) + \epsilon_j(1 - \epsilon_i)$$

- Apply weights on **opposite-sign events in real data** to estimate charge mis-ID background:

$$N_{SS(\text{estimate})}^{ij} = \frac{\epsilon_i + \epsilon_j - 2\epsilon_i\epsilon_j}{1 - \epsilon_i - \epsilon_j + 2\epsilon_i\epsilon_j} N_{OS(\text{observed})}^{ij}$$



# Fake/Non-prompt background estimation

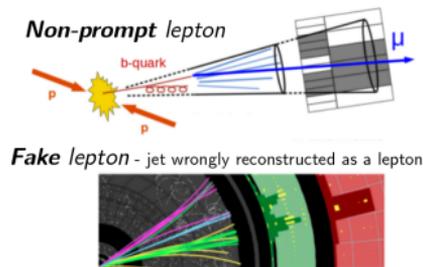
- We **select only isolated leptons** to remove fakes
- **Probabilities**  $\epsilon_{real}/\epsilon_{fake}$  that real/fake leptons are selected as isolated  
→ **estimated from real data** using specific selection
- Example with 1 lepton (blue = measured, red = unknown)

$$N^{tot} = N_{real} + N_{fake}$$

$$N^{iso} = \epsilon_{real} N_{real} + \epsilon_{fake} N_{fake}$$

⇒ Estimation of fakes background:

$$N_{isolated\ fakes} = \epsilon_{fake} N_{fake} = \frac{\epsilon_{fake}}{\epsilon_{real} - \epsilon_{fake}} (\epsilon_{real} N^{tot} - N^{iso})$$



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# Results

- Results using **2015 data:  $3.2 \text{ fb}^{-1}$**  ▶ ATLAS-CONF-2016-032
- **No excess** of data VS estimated background  
→ set **95 % Confidence Level** limits for each model
- Limit on  $\sigma_{t\bar{t}t\bar{t}} < 95 \text{ fb}$  (theory = 9.2 fb)

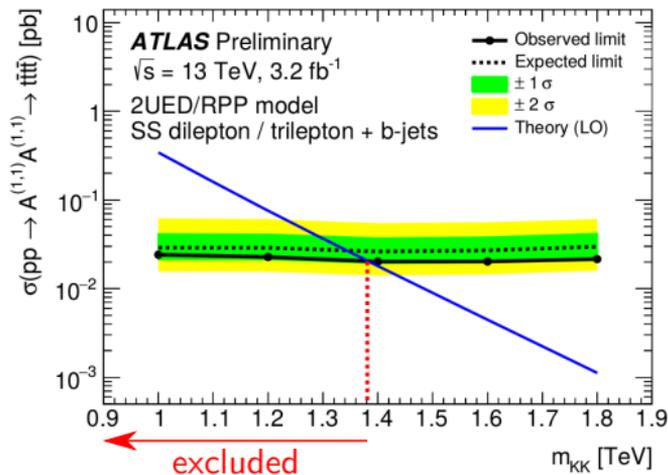
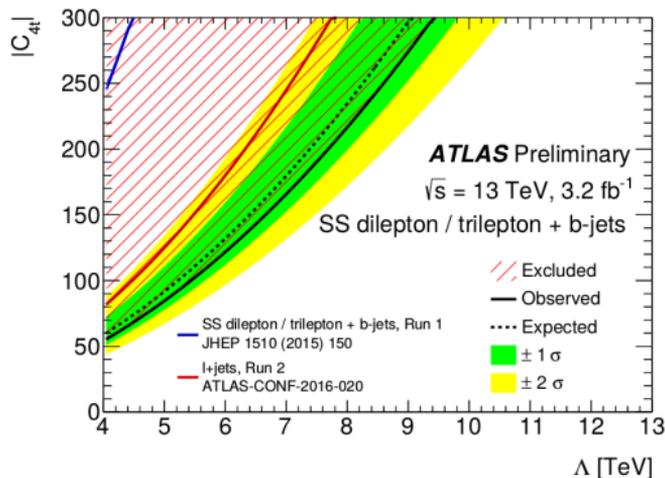


Figure: Expected and observed limits on 4 top CI (left) and UED (right) models

# Conclusion

- Study of **4 top quarks production** at the LHC with the ATLAS detector  
→ using **same-sign leptons + b-jets**
- Several BSM models were tested, along with the SM production
- Instrumental backgrounds are the tricky point of this analysis
- Our limit on 4top SM (theory = 9.2 fb)  
→  $\sigma_{t\bar{t}t\bar{t}} < 95 \text{ fb}$
- **Best result** to date from our competitors CMS, with  $10\times$  more data: [arXiv:1710.1061](https://arxiv.org/abs/1710.1061)  
→  $\sigma_{t\bar{t}t\bar{t}} < 41.7 \text{ fb}$
- New ATLAS results coming soon!

# BACKUP

# Signal Regions

## Event topology

- Large total energy:  $H_T = \sum_{leptons} p_T + \sum_{jets} p_T$
- Large number of b-jets:  $N_b$
- Missing energy (neutrinos):  $E_T^{miss}$

→ We actually make **8 different selections**, and combine them statistically (each one optimized for a given model)

Definition		Name
$e^\pm e^\pm + e^\pm \mu^\pm + \mu^\pm \mu^\pm + eee + ee\mu + e\mu\mu + \mu\mu\mu, N_{jets} \geq 2$		
$400 < H_T < 700 \text{ GeV}$	$N_b = 1$	$E_T^{miss} > 40 \text{ GeV}$
	$N_b = 2$	
	$N_b \geq 3$	
$H_T \geq 700 \text{ GeV}$	$N_b = 1$	$40 < E_T^{miss} < 100 \text{ GeV}$
		$E_T^{miss} \geq 100 \text{ GeV}$
	$N_b = 2$	$40 < E_T^{miss} < 100 \text{ GeV}$
		$E_T^{miss} \geq 100 \text{ GeV}$
	$N_b \geq 3$	$E_T^{miss} > 40 \text{ GeV}$

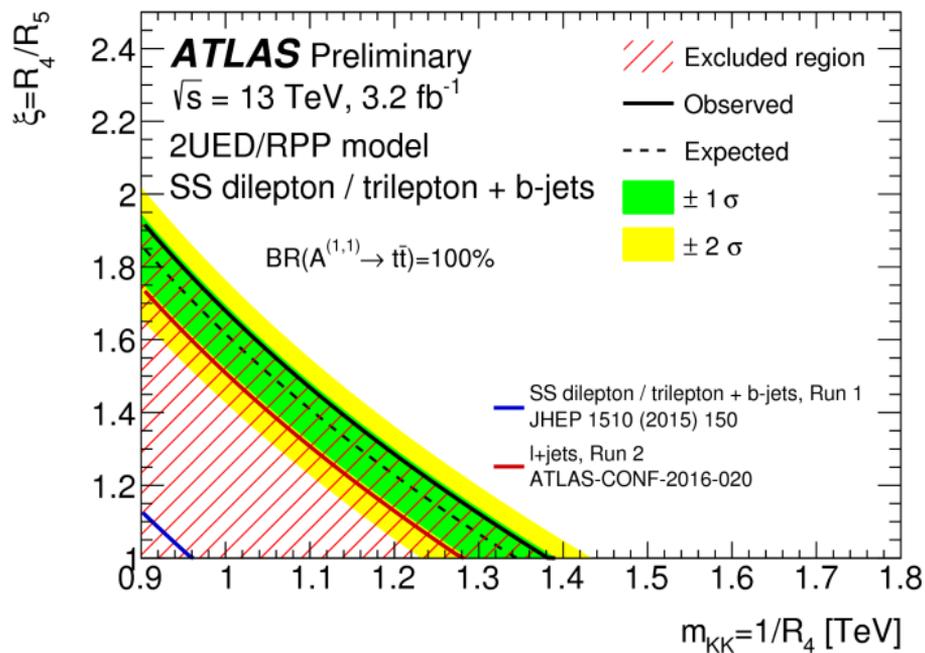
- **Example for 2 leptons** with real (fake) efficiencies called  $r$  ( $f$ ):

$$\begin{pmatrix} N^{tt} \\ N^{\bar{t}\bar{t}} \\ N^{\bar{t}t} \\ N^{t\bar{t}} \end{pmatrix} = \mathbf{M} \begin{pmatrix} N_{rr}^{ll} \\ N_{rf}^{ll} \\ N_{fr}^{ll} \\ N_{ff}^{ll} \end{pmatrix} \quad \mathbf{M} = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1 \bar{r}_2 & r_1 \bar{f}_2 & \bar{f}_1 \bar{r}_2 & \bar{f}_1 \bar{f}_2 \\ \bar{r}_1 r_2 & \bar{r}_1 f_2 & f_1 r_2 & f_1 f_2 \\ \bar{r}_1 \bar{r}_2 & \bar{r}_1 \bar{f}_2 & \bar{f}_1 \bar{r}_2 & \bar{f}_1 \bar{f}_2 \end{pmatrix}$$

what we measure      what we need      transformation matrix



# Limit UED in 2 dimensions



# Systematics on bkg

Source	Signal region							
	SR0	SR1	SR2	SR3	SR4	SR5	SR6	SR7
Cross section	8	11	26	13	9	27	23	57
Jet energy scale	1	1	3	1	1	3	2	4
Jet energy resolution	<1	2	2	2	<1	1	<1	3
<i>b</i> -tagging efficiency	1	2	5	3	1	2	2	7
Luminosity	1	1	1	1	1	1	1	1
Fake/non-prompt leptons	17	7	15	13	26	13	17	17
Charge misID	8	3	7	5	3	6	5	8

# Systematics on signal (4top SM)

Source	Signal region							
	SR0	SR1	SR2	SR3	SR4	SR5	SR6	SR7
Jet energy scale	2	12	2	6	4	3	3	3
Jet energy resolution	16	6	7	16	14	11	1	2
<i>b</i> -tagging efficiency	8	5	5	21	14	15	5	5
Lepton ID efficiency	1	1	1	4	2	2	2	1
Luminosity	2	2	2	2	2	2	2	2

# Yields

## 4 top signals yields normalized to $100 \text{ fb}^{-1}$

	SR0	SR1	SR2	SR3	SR4
Fake/Non-prompt	$16.3 \pm 9.5$	$4.2 \pm 3.3$	$1.0 \pm 0.9$	$1.8 \pm 1.4$	$7.1 \pm 4.5$
Charge mis-ID	$18.1 \pm 4.1$	$14.9 \pm 3.5$	$1.2 \pm 0.3$	$1.5 \pm 0.4$	$2.1 \pm 0.5$
$t\bar{t}W/Z/W^+W^-$	$10.1 \pm 1.4$	$9.2 \pm 1.3$	$1.0 \pm 0.3$	$2.2 \pm 0.3$	$3.1 \pm 0.5$
Dibosons	$5.8 \pm 1.0$	$0.5 \pm 0.2$	$0.03 \pm 0.07$	$1.6 \pm 0.4$	$1.8 \pm 0.4$
Other bkg.	$2.0 \pm 1.0$	$1.7 \pm 0.9$	$0.3 \pm 0.2$	$0.3 \pm 0.2$	$0.5 \pm 0.3$
Total bkg.	$52 \pm 11$	$31 \pm 5$	$3.6 \pm 1.0$	$7.4 \pm 1.5$	$15 \pm 5$
$t\bar{t}\bar{t}$ (SM)	$0.5 \pm 0.1$	$0.8 \pm 0.1$	$0.9 \pm 0.1$	$0.2 \pm 0.1$	$0.5 \pm 0.1$
$t\bar{t}\bar{t}$ (CI)	$0.26 \pm 0.04$	$0.6 \pm 0.1$	$0.6 \pm 0.1$	$0.24 \pm 0.05$	$0.9 \pm 0.1$
UED 1.2 TeV	$<0.01$	$<0.01$	$<0.01$	$0.3 \pm 0.1$	$3.8 \pm 0.8$
$T\bar{T}$ 0.75 TeV	$0.2 \pm 0.1$	$0.31 \pm 0.1$	$0.04 \pm 0.04$	$0.9 \pm 0.2$	$3.7 \pm 0.4$
Data	51	37	3	4	11

	SR5	SR6	SR7
Fake/Non-prompt	$1.4 \pm 0.9$	$2.6 \pm 1.8$	$0.0 \pm 0.6$
Charge mis-ID	$1.4 \pm 0.4$	$1.6 \pm 0.5$	$0.6 \pm 0.2$
$t\bar{t}W/Z/W^+W^-$	$2.3 \pm 0.6$	$3.0 \pm 0.7$	$0.8 \pm 0.4$
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$t\bar{t}\bar{t}$ (CI)	$0.6 \pm 0.1$	$2.2 \pm 0.2$	$5.2 \pm 0.4$
UED 1.2 TeV	$0.6 \pm 0.1$	$6.6 \pm 0.7$	$10.1 \pm 0.8$
$T\bar{T}$ 0.75 TeV	$1.3 \pm 0.2$	$5.0 \pm 0.5$	$3.2 \pm 0.4$
Data	6	3	2

# Results - detailed

- Results using **2015 data:  $3.2 \text{ fb}^{-1}$**  ▶ ATLAS-CONF-2016-032
- **No excess** of data VS estimated background  
→ set **95 % Confidence Level** limits for each model
- Observed (expected) limit on  $\sigma_{t\bar{t}\bar{t}\bar{t}} < \mathbf{95 \text{ fb}}$  ( $\mathbf{107 \text{ fb}}$   $^{+50\%}_{-30\%}$ ) (theory = 9.2 fb)

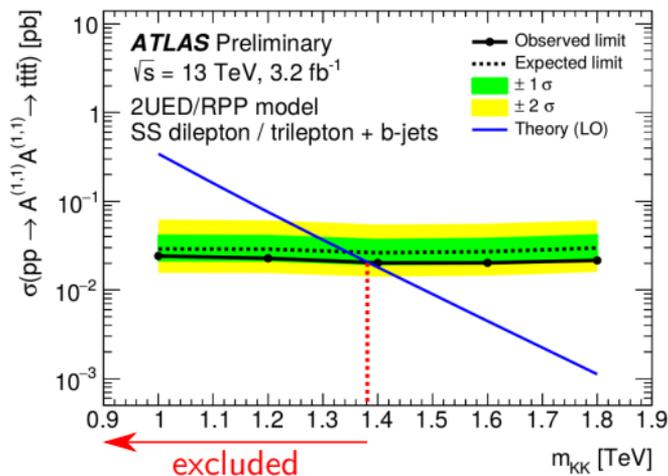
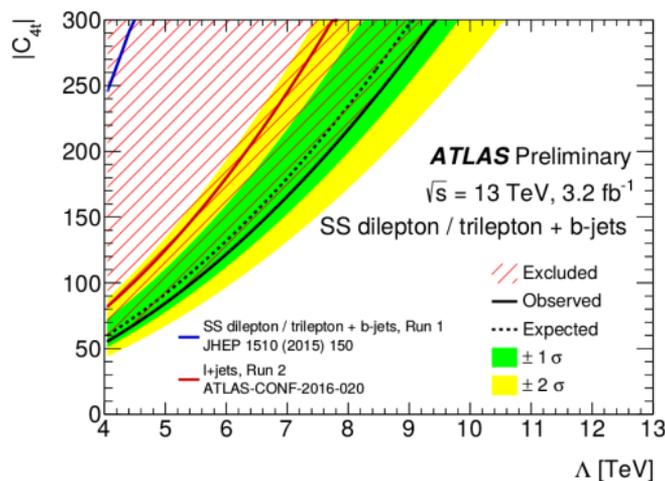


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- Instrumental backgrounds are the tricky point of this analysis
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→  $\sigma_{t\bar{t}t\bar{t}} < \mathbf{95\text{ fb}}$  ( $\mathbf{107\text{ fb}}$   $^{+50\%}_{-30\%}$ )
- **Best result** to date from our competitors CMS, with  $10\times$  more data: [arXiv:1710.1061](https://arxiv.org/abs/1710.1061)  
→  $\sigma_{t\bar{t}t\bar{t}} < \mathbf{41.7\text{ fb}}$  ( $\mathbf{20.8\text{ fb}}$ )
- New ATLAS results coming soon!