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

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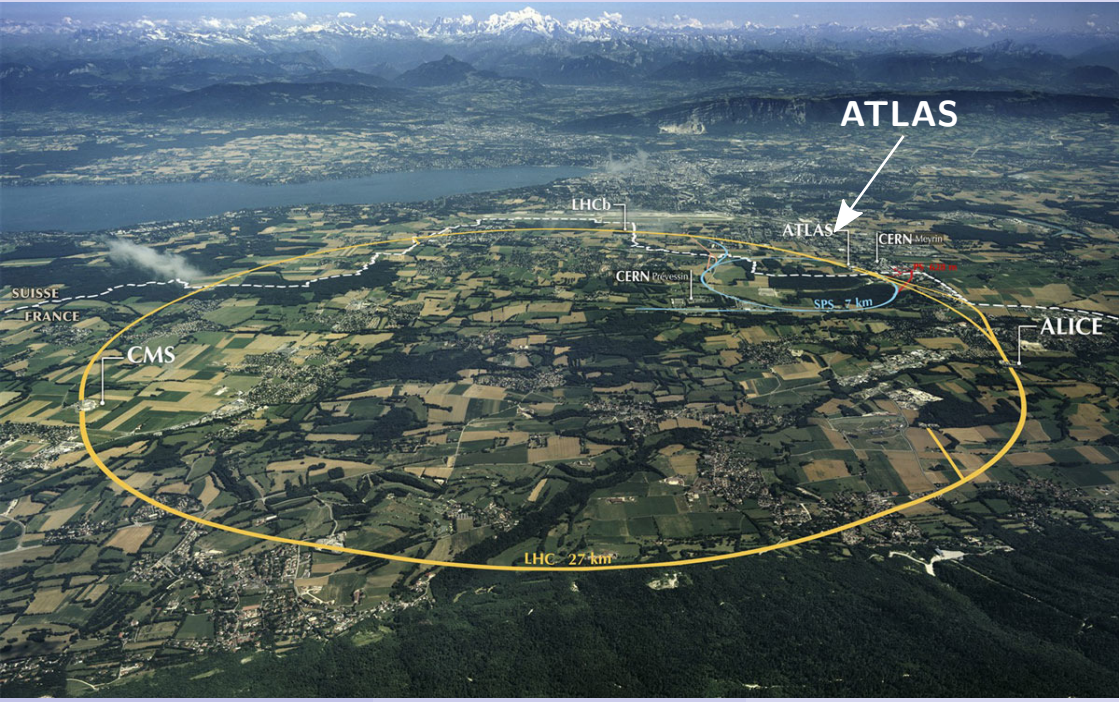
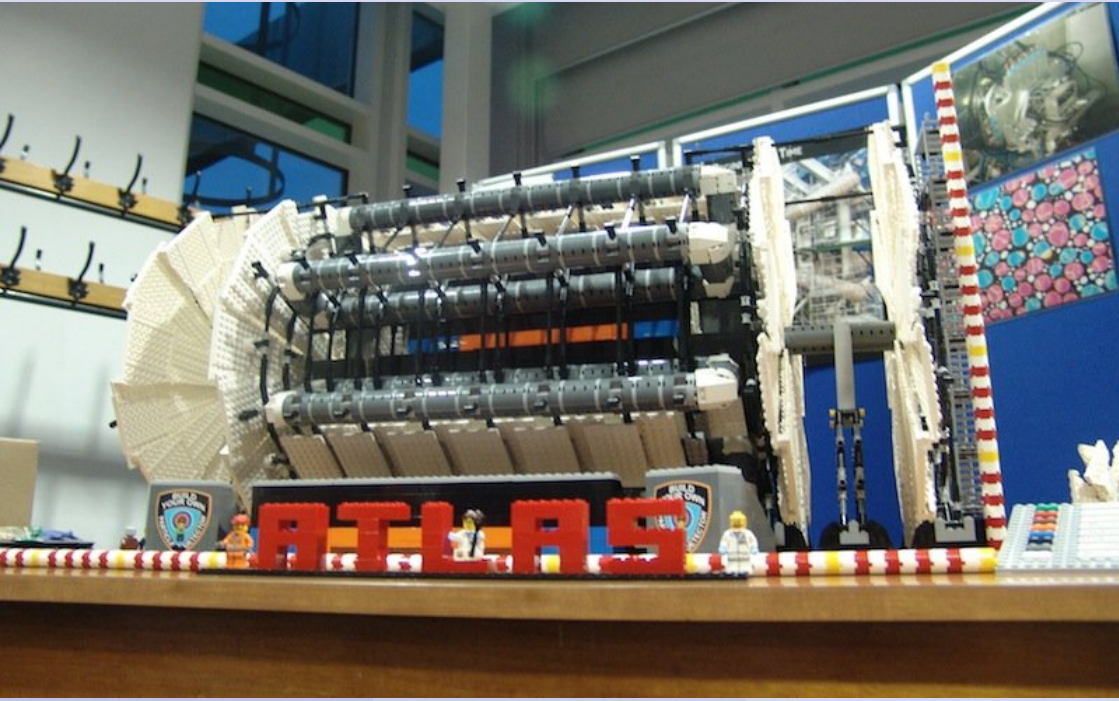
5. Results

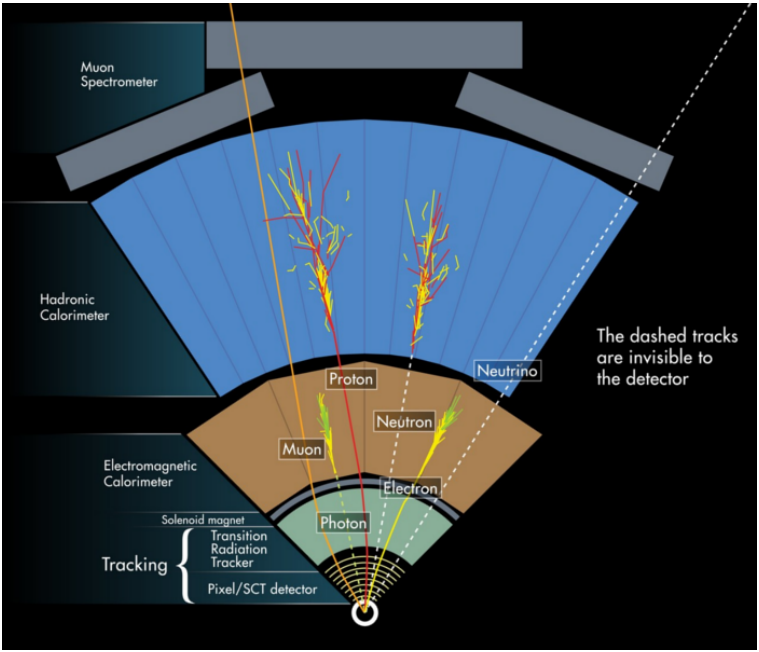
The Large Hadron Collider



The ATLAS detector



Particle detection in ATLAS



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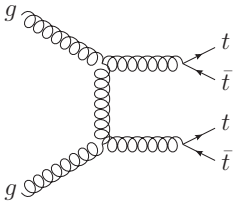
Why four tops?

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

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

$\longrightarrow$ $\sigma_{t\bar{t}t\bar{t}} = 9.2\,\mathrm{fb}$ at 13 TeV

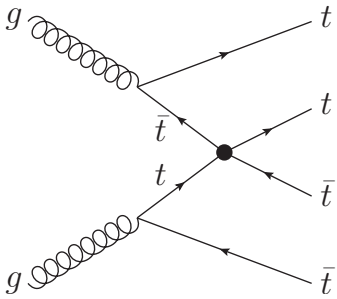
$\Longrightarrow$ Only $\sim$ **300** $t\bar{t}t\bar{t}$ **events** occurred in 2015-2016!
(compare that to the **40 million events per second** produced)



- **Goal**: Measure the $t\bar{t}t\bar{t}$ **cross-section**
  $\longrightarrow$ **Very sensitive** to several **BSM scenarios**
  $\longrightarrow$ **Test the Standard Model** prediction for $\sigma_{t\bar{t}t\bar{t}}$

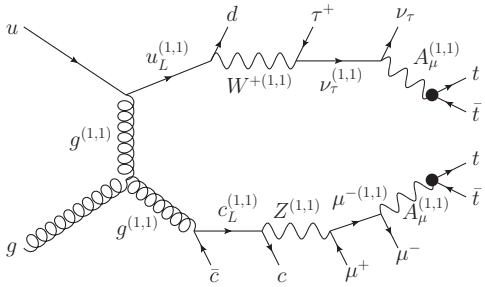
Some BSM models tested

Contact Interaction model



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

Universal extra-dimensions (2UED/RPP)



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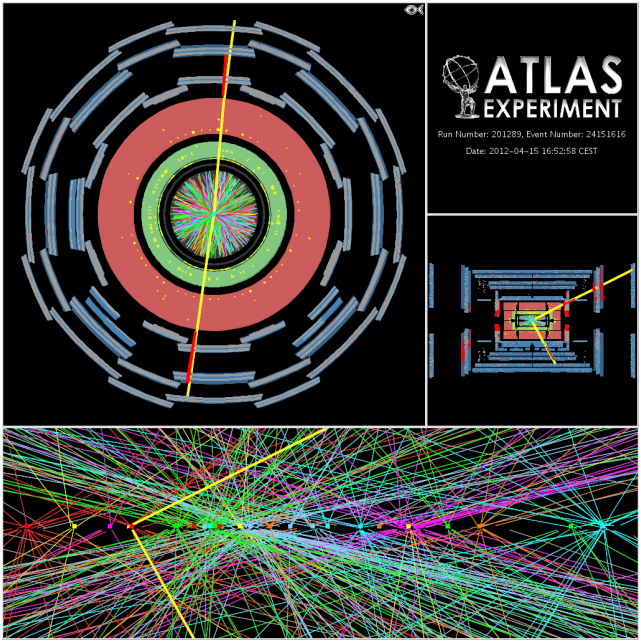
Event selection

- **40 000 000 events/second** produced in ATLAS, with $\sim$ **25 collisions**/event
- but a few $\sim$ **100** $\boldsymbol{t\bar{t}t\bar{t}}$ **events per year** only!

$\Longrightarrow$ **Need to perform some smart event selection**

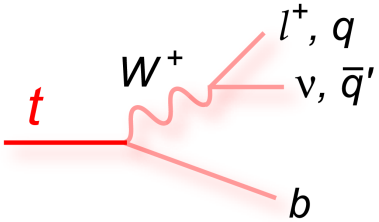


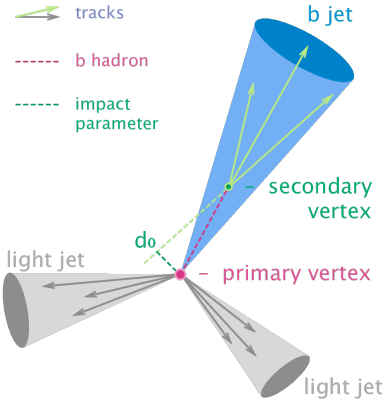
The $t\bar{t}t\bar{t}$ final state

- Top decay: $t \to Wb$ (~ 100 %)

  $\Longrightarrow$ Final state **4t** $\longrightarrow$ **4W + 4b**

- W decay: $W \to \begin{cases} \ell\nu_\ell & (\sim 30\ \%) \\ qq' & (\sim 70\ \%) \end{cases}$





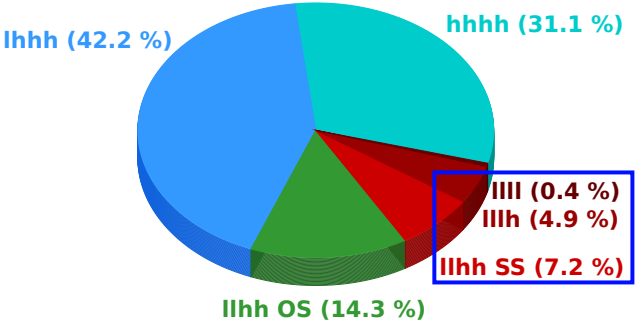
Concerning jets

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



WWWW decays branching fractions

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

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}

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

Definition			Name
$e^\pm e^\pm + e^\pm \mu^\pm + \mu^\pm \mu^\pm + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_{\text{jets}} \geq 2$			
$400 < H_T < 700$ GeV	$N_b = 1$	$E_T^{\text{miss}} > 40$ GeV	SR0
	$N_b = 2$		SR1
	$N_b \geq 3$		SR2
$H_T \geq 700$ GeV	$N_b = 1$	$40 < E_T^{\text{miss}} < 100$ GeV	SR3
		$E_T^{\text{miss}} \geq 100$ GeV	SR4
	$N_b = 2$	$40 < E_T^{\text{miss}} < 100$ GeV	SR5
		$E_T^{\text{miss}} \geq 100$ GeV	SR6
	$N_b \geq 3$	$E_T^{\text{miss}} > 40$ GeV	SR7

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Background Modeling

- We're looking for small deviations from the expected number of background events
  $\longrightarrow$ Primordial to estimate backgrounds
- **2 types of backgrounds**:
  - **Physical processes** producing exactly the particles we're looking for
  - **Instrumental backgrounds**: charge mis-identification, fake leptons

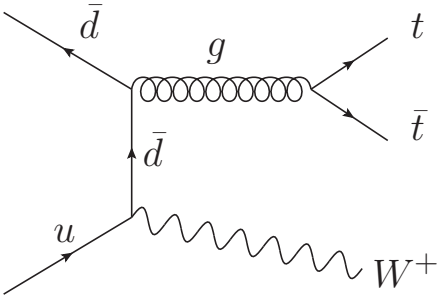
$$N_{\text{bkg}} = N_{\text{physical}} + N_{\text{charge misID}} + N_{\text{fakes}}$$

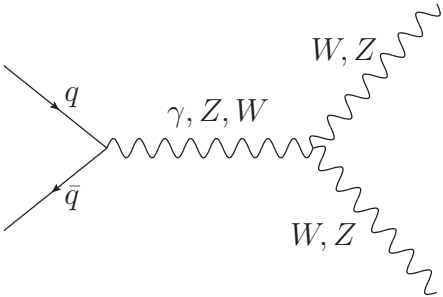
Analysis: estimate N_{bkg} as best as possible
$\longrightarrow$ then **compare** $N_{\text{bkg}} + N_{\text{signal}}$ **to** N_{observed}

Background Modeling - SM backgrounds

- **Physical processes** producing same-charge leptons:
  - Top quark pair + vector boson: $\boldsymbol{t\bar{t}V}$ (V = W or Z)
  - Di-boson production: $\boldsymbol{VV}$ (V = W or Z)
  - (+ 4 top SM when searching for BSM signals)
  - Other (rare): $t\bar{t}H$, $t\bar{t}WW$, VVV, VH, 3 top, tZ, tWZ

$\Longrightarrow$ estimated by **Monte-Carlo simulations**

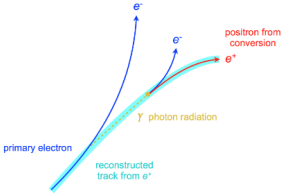




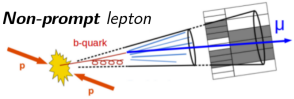
Background Modeling - instrumental backgrounds

- **Wrong identification of leptons** in the detector
  $\longrightarrow$ Coming mostly from $\boldsymbol{t\bar{t}}$ **events badly reconstructed**
  $\longrightarrow$ **Small fraction** of $t\bar{t}$ events, but not negligible since $\boldsymbol{\sigma_{t\bar{t}} \sim 100\,000\,\sigma_{t\bar{t}t\bar{t}}}$!

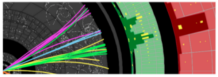
- **Charge mis-identification**
  - **Error** on the **charge** of an electron, e.g. e^+ instead of e^-
    $\longrightarrow$ Select events with leptons having **opposite charge instead of same charge**
  - Negligible for muons

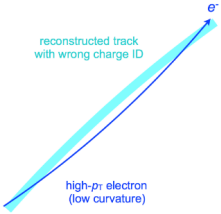


- **Fake/Non-prompt leptons**
  - Leptons from secondary interactions
  - Reconstructed leptons where there is none



***Fake** lepton* - jet wrongly reconstructed as a lepton





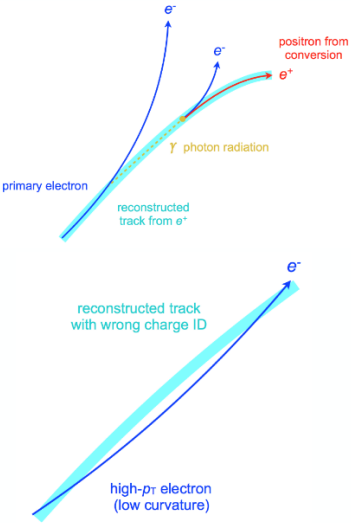
Charge mis-ID background estimation

- Probability of mis-identification: **charge flip rate** ε $\longrightarrow$ **Estimated from data** ($Z \to e^+e^-$ decays)
- **Probability** to select opposite-sign event:

$$P_{OS \to SS} = \varepsilon_i(1-\varepsilon_j) + \varepsilon_j(1-\varepsilon_i)$$

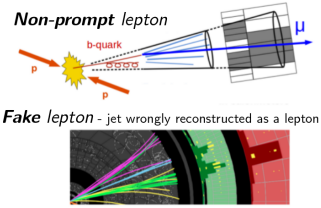
- Look at **opposite-sign events in real data** to estimate charge mis-ID background:

$$N^{ij}_{SS} = \frac{\varepsilon_i + \varepsilon_j - 2\varepsilon_i\varepsilon_j}{1-\varepsilon_i-\varepsilon_j+2\varepsilon_i\varepsilon_j} N^{ij}_{OS(observed)}$$



Fake/Non-prompt background - general principle

- We **select only isolated leptons** to remove fakes
- **Probabilities** $\varepsilon_{real}/\varepsilon_{fake}$ that real/fake leptons are selected as isolated
  $\longrightarrow$ **estimated from real data** using specific selection



- **Example with 1 lepton below**. Similar method for 2 or 3 leptons.
  (in blue what we measure, in red what is unknown)

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

$\Longrightarrow$ Estimation of fakes background:

$$N_{\text{fakes selected}} = \varepsilon_{fake} N_{fake} = \frac{\varepsilon_{\text{fake}}}{\varepsilon_{\text{real}} - \varepsilon_{\text{fake}}} (\varepsilon_{\text{real}} N^{tot} - N^{iso})$$

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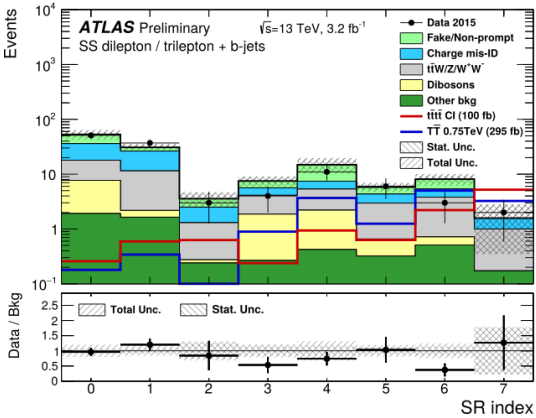
Results

- Results on **2015 data: 3.2 fb^{-1}**
  $\longrightarrow$ ATLAS-CONF-2016-032
  $\longrightarrow$ expecting only ~ 30 $t\bar{t}t\bar{t}$ events with this dataset
- **2016 data analysis almost finished**, using 36.1 fb^{-1} (10$\times$ more!)
- Currently **planning the full Run 2 analysis** (2015 to 2018 data): ~ 120 fb^{-1} expected



- **No observed excess** of data compared to expected background

  $\longrightarrow$ **95 % CL limits** are set to assess the compatibility of each model with observations

Limits - 4 top CI and UED models

- For each of the models
  $\longrightarrow$ set limits above which we're sure at 95 % CL that it doesn't exist

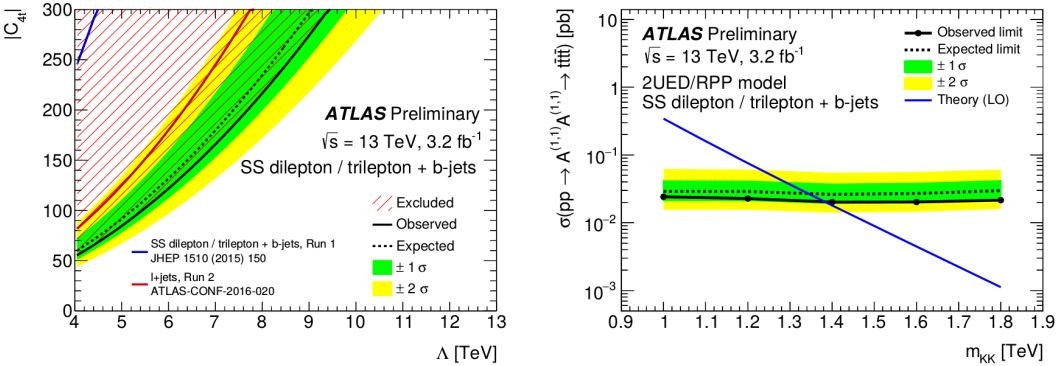


Figure: Expected and observed limits on 4 top CI (left) and UED (right) models

Limits - 4 top SM

- Observed (expected) limit on 4top SM: **95 fb** (**107 fb** $^{+50\ \%}_{-30\ \%}$)
  $\Longrightarrow$ Corresponds to **10**$\times$ (**12**$\times$) the theory
  $\Longrightarrow$ **Need to improve** a lot to get sensitive enough!
- **But!**
  $\longrightarrow$ The dataset is now **10**$\times$ **larger**
  $\longrightarrow$ A whole **new analysis** has been performed **on 2015 - 2016 data**
- **ATLAS results are not public yet**
  $\longrightarrow$ CMS latest results [Sept 2017]
  $\longrightarrow$ Observed (expected) limit on 4top SM : 41.7 fb (20.8 fb-1)
  $\longrightarrow$ Sensitivity: 2.3$\times$ SM prediction

Conclusion

- Study of 4 top quarks production at the LHC with this ATLAS detector
  $\longrightarrow$ 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
- The results with 2015 data only are limited, but we expect large improvements from the ongoing analysis, comparable to CMS results
- We will approach the sensitivity required to observe 4 top production in 2018/2019
  $\longrightarrow$ first evidence of this process?

BACKUP

Fake/Non-prompt background - 2 leptons

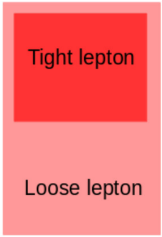
- **Example for 2 leptons** with real (fake) efficiencies called r (f):

$$\begin{pmatrix} N^{\mathrm{tt}} \\ N^{\mathrm{t\bar{t}}} \\ N^{\mathrm{\bar{t}t}} \\ N^{\mathrm{\bar{t}\bar{t}}} \end{pmatrix} = \mathbf{M} \begin{pmatrix} N^{\mathrm{ll}}_{\mathrm{rr}} \\ N^{\mathrm{ll}}_{\mathrm{rf}} \\ N^{\mathrm{ll}}_{\mathrm{fr}} \\ N^{\mathrm{ll}}_{\mathrm{ff}} \end{pmatrix} \qquad \mathbf{M} = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1 \overline{r_2} & r_1 \overline{f_2} & f_1 \overline{r_2} & f_1 \overline{f_2} \\ \overline{r_1} r_2 & \overline{r_1} f_2 & \overline{f_1} r_2 & \overline{f_1} f_2 \\ \overline{r_1 r_2} & \overline{r_1 f_2} & \overline{f_1 r_2} & \overline{f_1 f_2} \end{pmatrix}$$

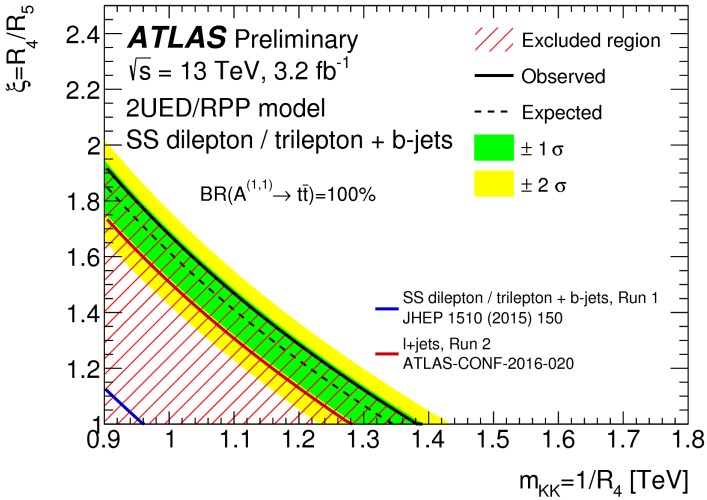
what we measure

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
b-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
b-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 fb^{-1}

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

	SR5	SR6	SR7
Fake/Non-prompt	1.4±0.9	2.6±1.8	0.0 ±0.6
Charge mis-ID	1.4±0.4	1.6±0.5	0.6 ±0.2
$t\bar{t}W/Z/W^+W^-$	2.3±0.6	3.0±0.7	0.8 ±0.4
Dibosons	0.3±0.1	0.2±0.1	0.0 ±0.1
Other bkg.	0.4±0.2	0.7±0.4	0.5 ±0.3
Total bkg.	5.8±1.2	8.1±2.0	1.9 ±0.8
$t\bar{t}t\bar{t}$ (SM)	0.7±0.1	1.8±0.2	3.6 ±0.4
$t\bar{t}t\bar{t}$ (CI)	0.6±0.1	2.2±0.2	5.2 ±0.4
UED 1.2 TeV	0.6±0.1	6.6±0.7	10.1±0.8
$T\bar{T}$ 0.75 TeV	1.3±0.2	5.0±0.5	3.2 ±0.4
Data	6	3	2