JPS, Kochi
September 20-23 2013

Search for Minimal Universal Extra Dimensions in 8 TeV pp collisions in the ATLAS detector

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Introduction

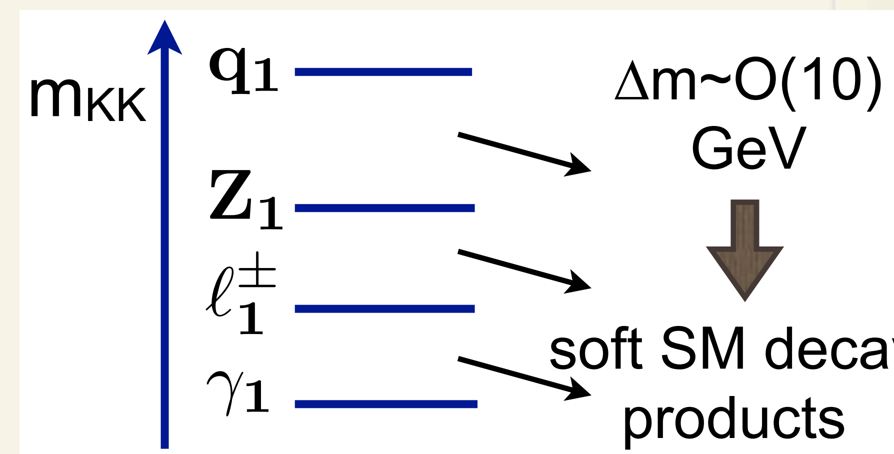
- **Minimal universal extra dimensions** (mUED) is an interesting candidate for physics beyond the standard model (BSM)

- All the SM fields propagate in the **compactified extra dimensions** (only 1 ED assumed in this case)
  - Tower of Kaluza-Klein (KK) states
  - KK masses given by (at the tree level):

$$\mathbf{m_n^2 = \frac{n^2}{R^2} + m_{SM}^2}$$

KK particle (m_n^2) — ***GeV~TeV*** (n^2/R^2) — ***MeV~GeV*** *=> very small contribution to m_n* (m_{SM}^2)

- *R = size of the ED*
- *n = excitation level (n=0 => SM particle)*



  - **The KK particle spectrum is naturally compressed**
  - Low momentum (soft) particles produced in the decays
  - Experimentally challenging signature

- The lightest KK particle is stable
  - **Dark matter candidate**

Parameters of the theory:

$$\mathbf{R^{-1}(\geq 700GeV) \simeq m_\gamma}$$

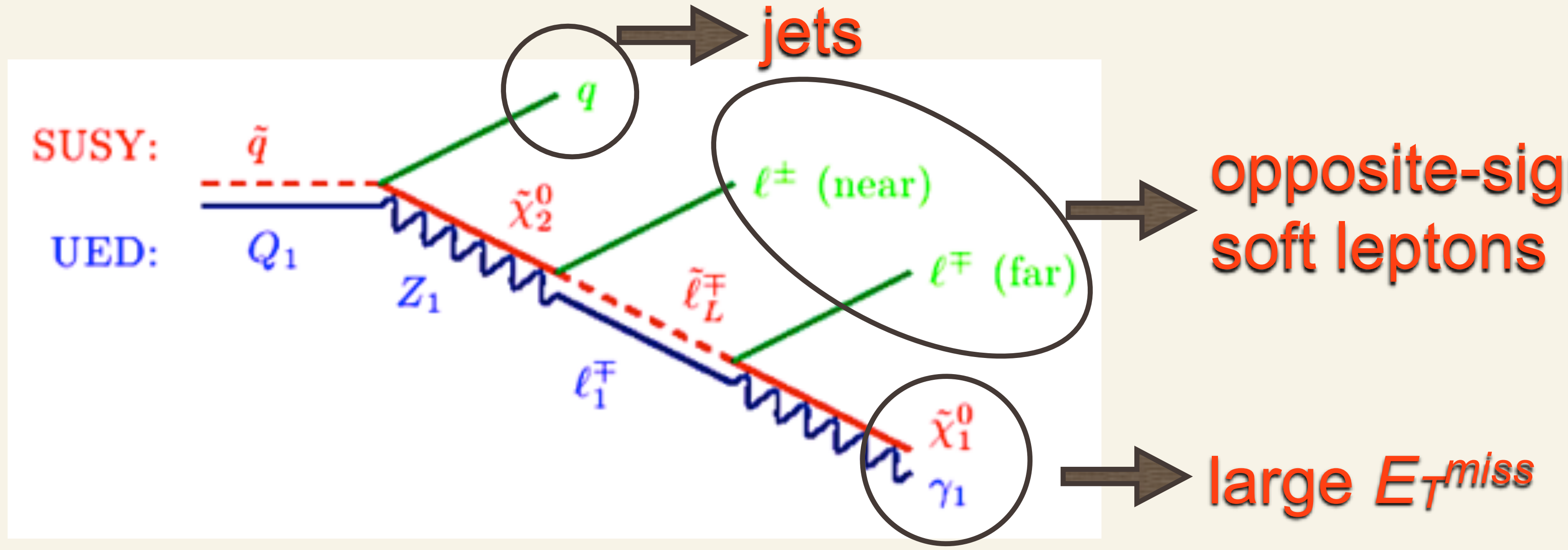
$$\mathbf{\Lambda R \in [3, 40]}$$

Λ: ultra-violet cut-off; small value: small Δm; large value: larger Δm

Typical signature

- Two KK quarks (or gluons) are produced in proton-proton collisions
  - One typically decays hadronically (producing only jets)
  - The other decays leptonically, often to KK Z which, in turn, gives **two opposite sign same-flavour leptons**

- KK gamma is the lightest particle of the model and a dark-matter candidate
  - It doesn't interact with the detector leaving a **missing transverse** (*E_T^{miss}*) **energy signature**



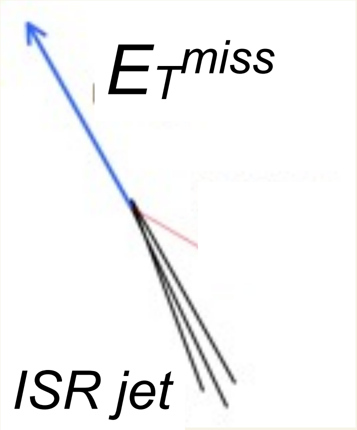
- Large branching fraction to leptons
  - KK W & Z decay to leptons with Br~100%
  - Dilepton channel is a promising signature

$$B(W_1^{\pm} \to \nu_1 L_0^{\pm}) = B(W_1^{\pm} \to L_1^{\pm} \nu_0) = \frac{1}{6}$$
$$B(Z_1 \to \nu_1 \bar{\nu}_0) = B(Z_1 \to L_1^{\pm} L_0^{\mp}) \simeq \frac{1}{6}$$

Event selection

- Full 2012 √s=8 TeV ATLAS dataset (L=20.1 fb^{-1})
- The selection determined by optimising S/√B in the signal region (SR)
  - ➡ Mainly focus on smaller Δm region ($\mathbf{\Delta R \leq 10}$)
  - ➡ Simple **1-bin counting experiment, no shape fitting**

- Baseline selection:
  - **Trigger**: E_T^{miss} > 80 GeV
  - **Two soft muons**: 6 GeV < p_T < 25 GeV
  - **Two** (or more) **jets** - often the leading jet is coming from the initial state radiation (ISR)
  - **Large E_T^{miss}**

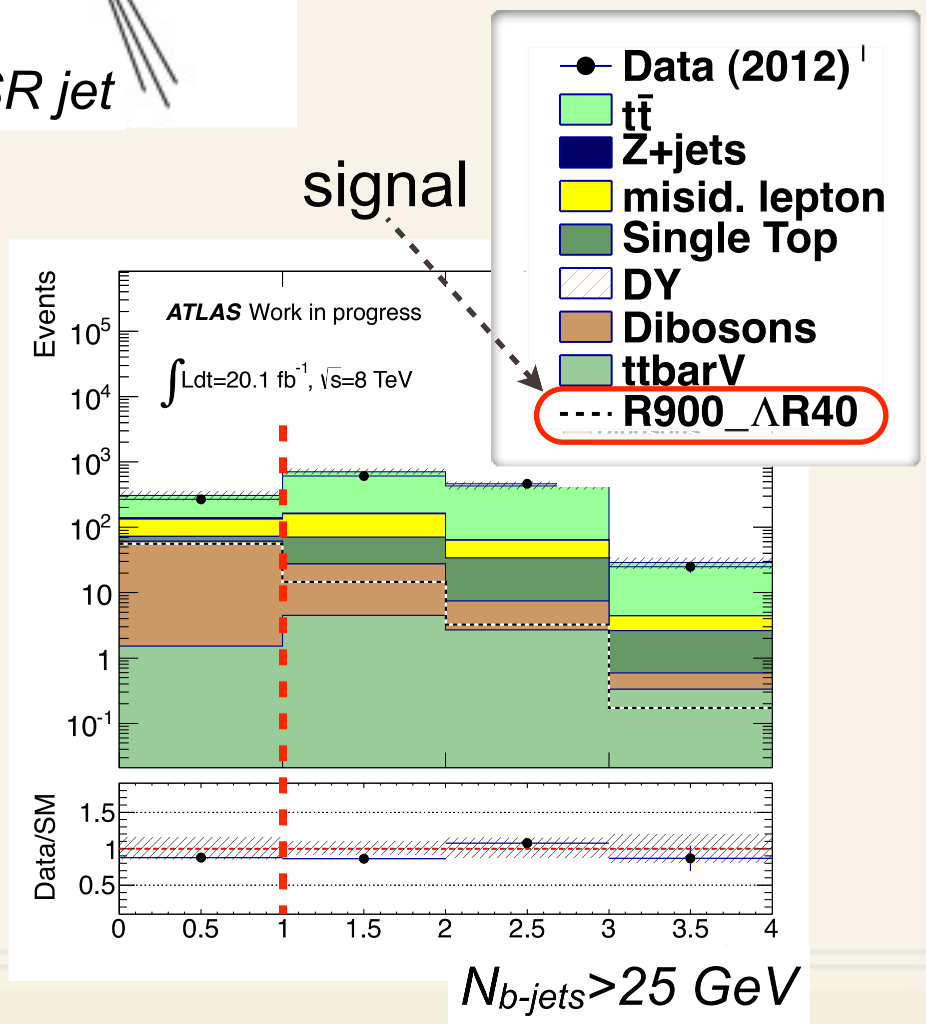


$p_T{}^{jets}$ (GeV)	>70,25
$N_{b-\mathrm{tag}}$	0
E_T^{miss} (GeV)	>170
m_T (GeV)	> 80

- SR definition:
  - **High transverse mass (m_T) region**
    - calculated with 2nd μ

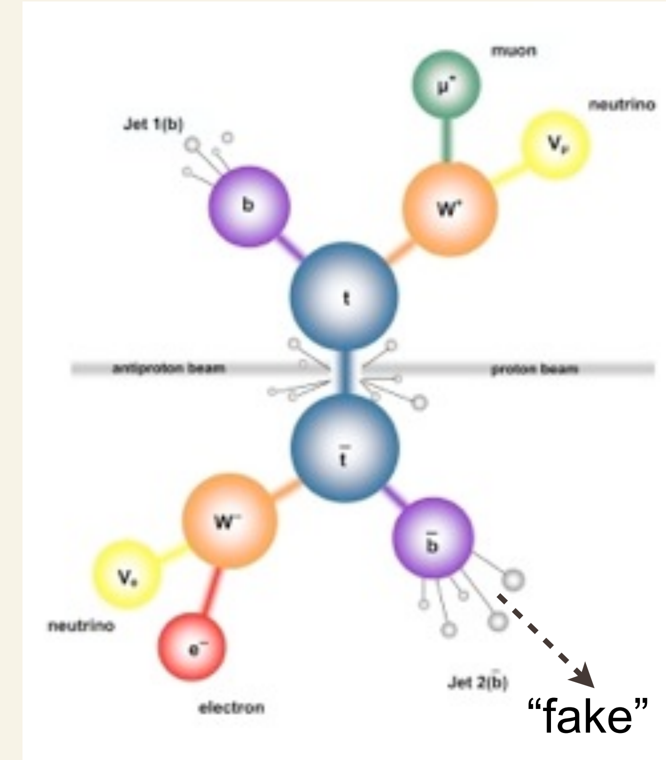
$$m_T = \sqrt{2 p_T^{\ell} E_T^{\mathrm{miss}} (1 - \cos(\Delta\phi(\vec{\ell}, \boldsymbol{p}_T^{\mathrm{miss}})))}$$

  - **B-jet veto** (among 3 leading jets)
  - ➡ These cuts mainly reject the dominant tt-bar background

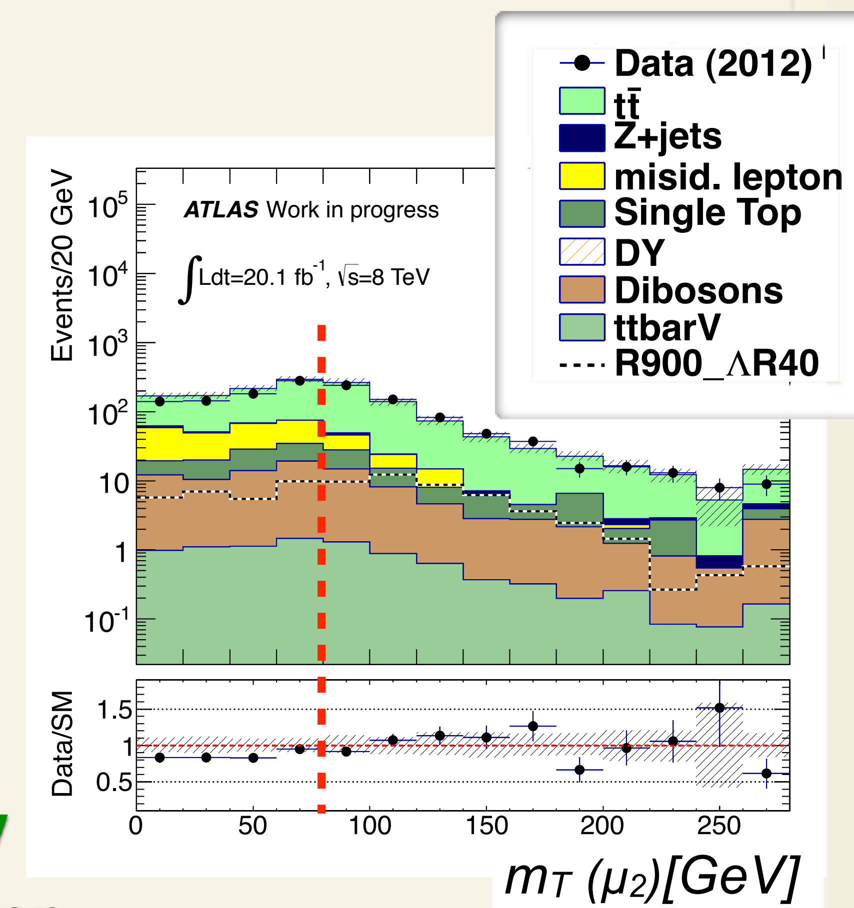


Backgrounds

- **Misidentified** (fake) **muon background** - μ from b- or c-hadron decays or jets misidentified as μ
  - **dominant source: muons form b-jet decays in semileptonic tt-bar events**
  - suppressed by requiring μ to be well isolated
    ➡ define a cone around jet => ΔR to nearest μ > 0.4
  - significant at small μ p_T and small m_T
    ➡ suppressed further by requiring high m_T



- **Dileptonic tt-bar**
  - suppressed by putting an upper cut on muon p_T and by requiring 0 b-jets in the SR



- **Z+jets, Drell-Yan, single-top, diboson & tt-bar+V**
  - minor backgrounds estimated using **only MC simulation**

Misid. μ background

- Estimated in a **fully data-driven way** (the matrix method)
- Based on inverting the muon track-isolation and impact parameter cuts:

$$\frac{\sum \mathbf{p_T}\ \textbf{tracks in a dR = 0.3 cone}}{\mathbf{p_T^{\mu}}} < \mathbf{0.12}$$

$$\textbf{Longitudinal IP}:\ |\mathbf{z_0^{PV}} \sin\theta| \leq \mathbf{0.4\,mm}$$

$$\textbf{Transverse IP}:\ \mathbf{d_0^{PV}}/\sigma(\mathbf{d_0^{PV}}) \leq \mathbf{3}$$

- **Fake rate:** $\mathbf{FR} = \frac{\mathbf{N^{\mu}_{isolated,fake}}}{\mathbf{N^{\mu}_{total,fake}}}$
  - Measured in the di-jet data sample
  - ➡ Low E_T^{miss} and m_T region

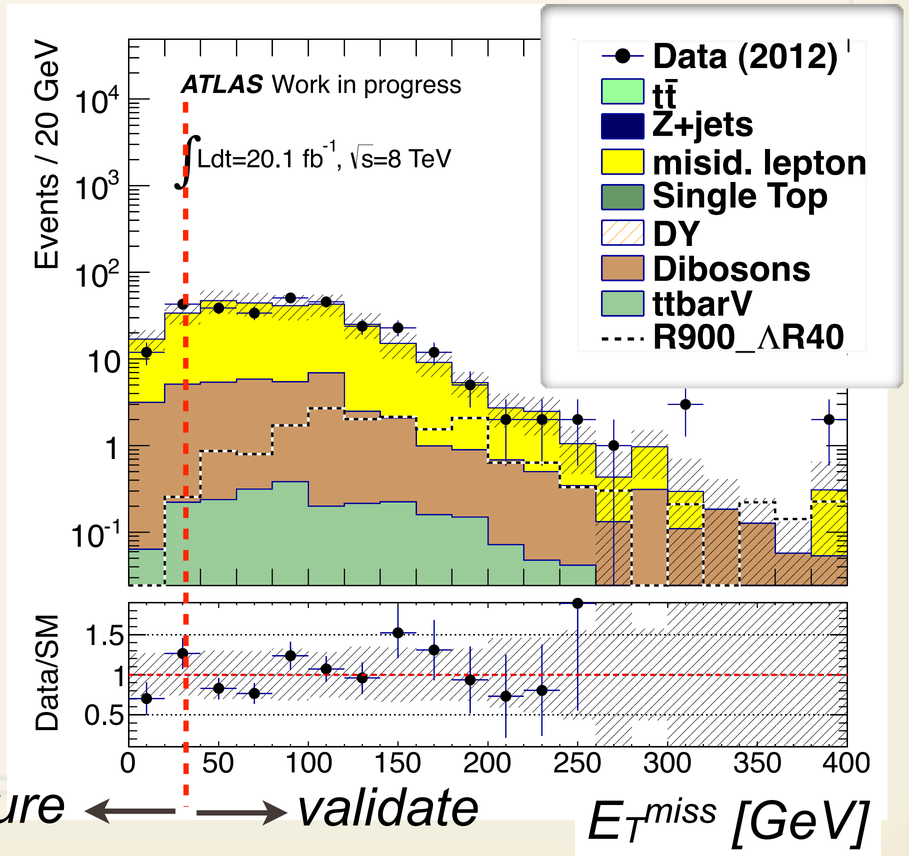
- **Real rate:** $\mathbf{RR} = \frac{\mathbf{N^{\mu}_{isolated,real}}}{\mathbf{N^{\mu}_{total,real}}}$
  - Measured in the Z->μμ data sample

$$\mathbf{N_{iso}} = \mathbf{RR} \times \mathbf{N_{real}} + \mathbf{FR} \times \mathbf{N_{fake}}$$

$$\mathbf{N_{non-iso}} = (\mathbf{1} - \mathbf{RR}) \times \mathbf{N_{real}} + (\mathbf{1} - \mathbf{FR}) \times \mathbf{N_{fake}}$$

- Invert the equations above to extract N_{fake}

- The result is validated in the whole E_T^{miss} range
  - Good agreement with the data



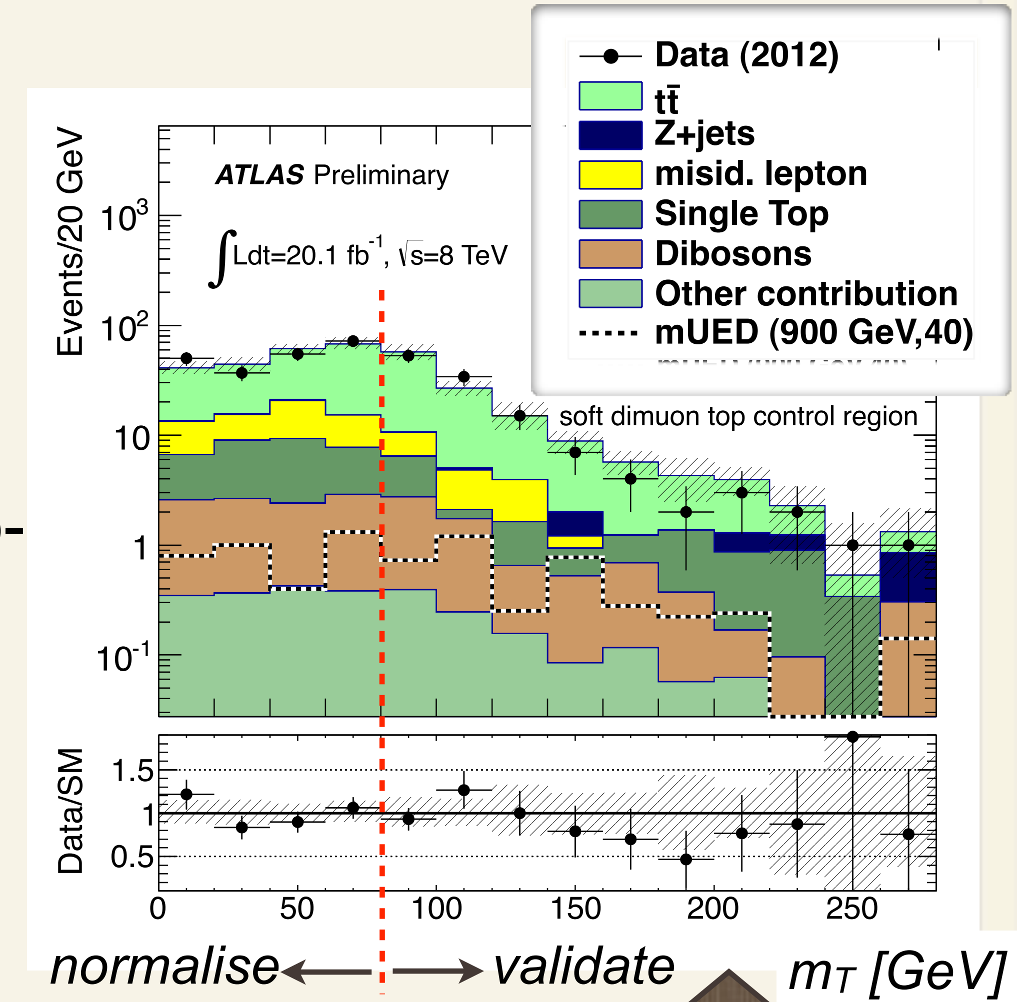
measure ← → validate

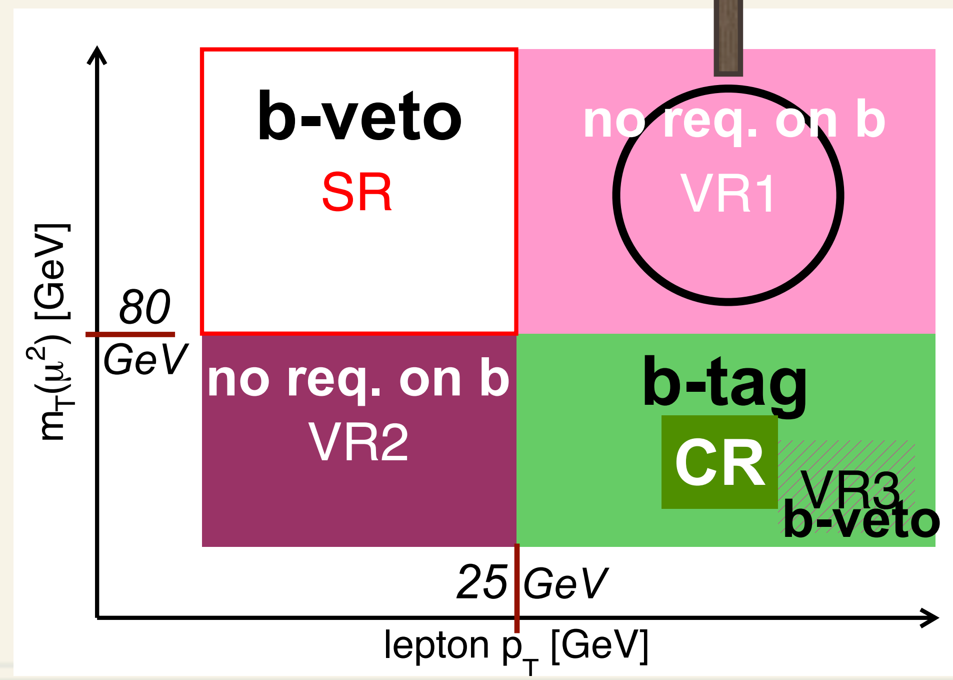
Dileptonic tt-bar

- Estimated in the **semi data-driven way**
- tt-bar normalised to the data in the control region (CR) => orthogonal to the SR
  - tt-bar purity enhanced by requiring at least 1 b-tagged jet
- MC transfer factor is used to extrapolate to the signal region:

$$N_{SR,est.data} = N_{CR,obs.data} \times \frac{N_{SR,MC}}{N_{CR,MC}}$$

- The result of the normalisation is checked in the 3 validation regions (VR)
  - Defined "in between" the CR and SR

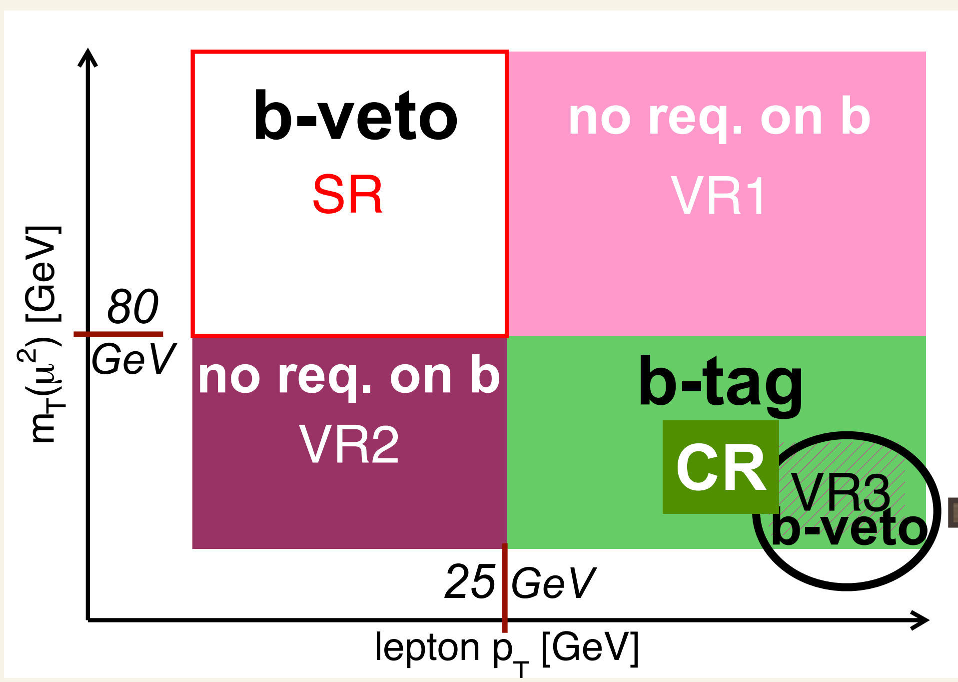


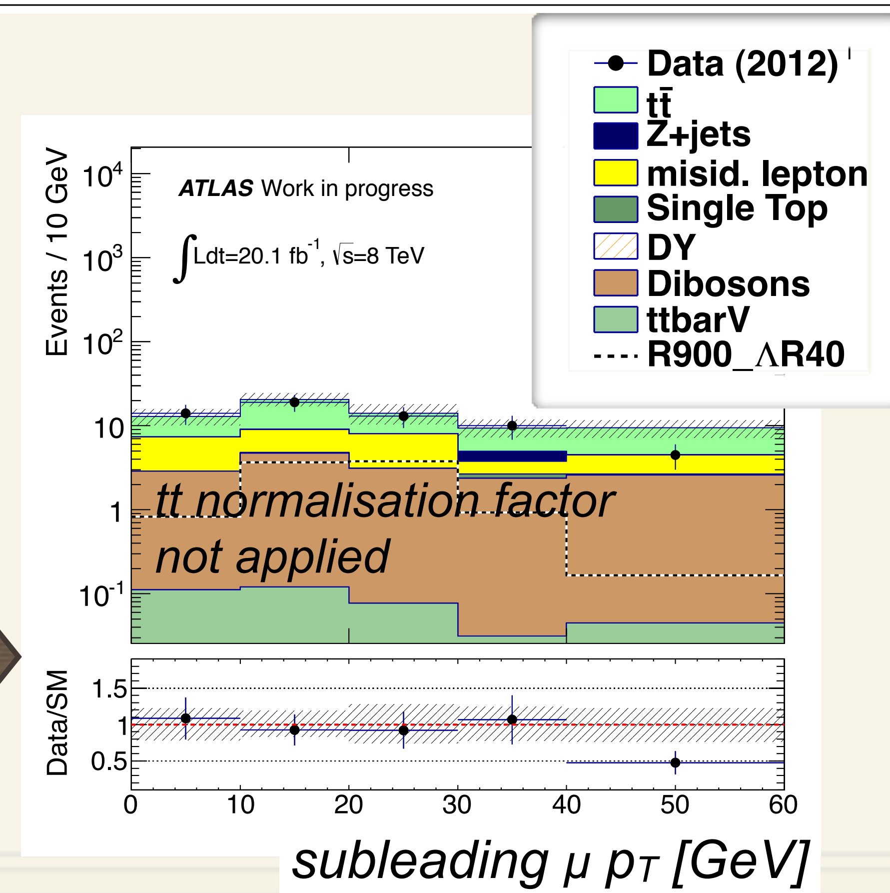


tt-bar estimation validation

- Very good agreement observed in all the validation regions

	VR1	VR2	VR3
Observed events	169	37	65
Estim bkg events	168.27 ± 28.64	36.17 ± 7.84	69.05 ± 14.63
Estim tt-bar events	118.16 ± 28.08	20.61 ± 6.44	30.56 ± 10.15
Misid. lepton events	11.15 ± 5.04	10.44 ± 4.50	18.37 ± 5.87
Diboson events	19.45 ± 9.92	2.50 ± 1.45	17.85 ± 9.25
Single-top events	11.70 ± 6.31	2.09 ± 1.15	$0.53^{+0.73}_{-0.53}$
Z+jets events	5.99 ± 4.31	0.29 ± 0.09	1.22 ± 0.81
tt-bar+V events	1.42 ± 0.61	0.23 ± 0.09	0.43 ± 0.21





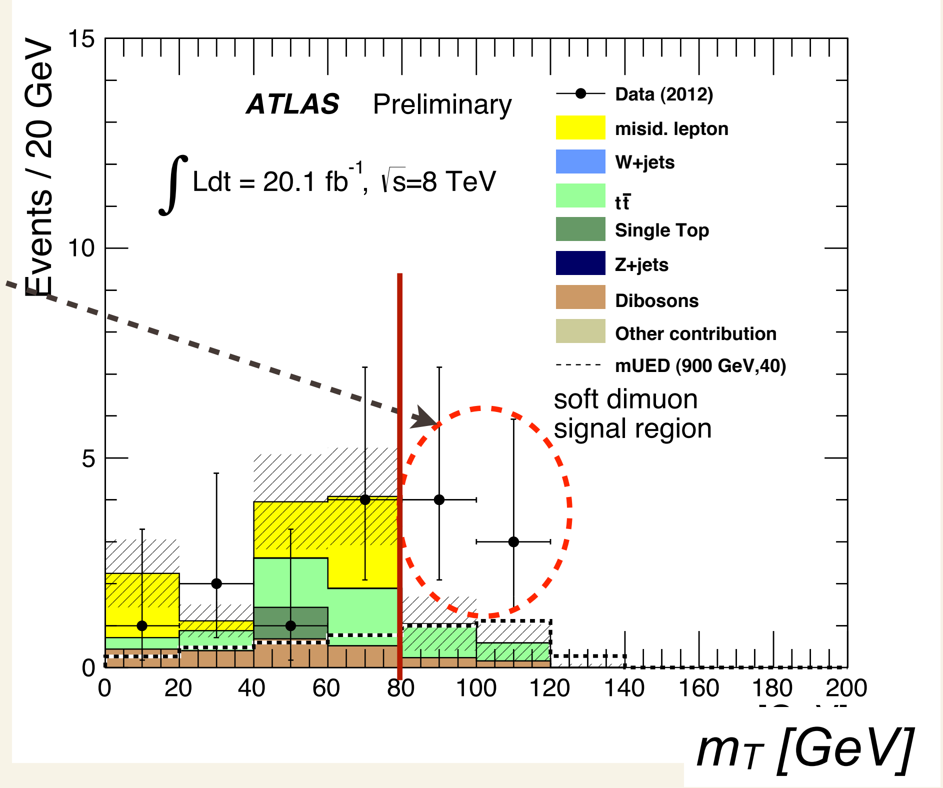
Result

- **No significant deviation** between predicted SM background and observed number of events in the SR
  - Disagreement is at the level of **2.3 sigma**

$p(s=0)$
0.01

p-value for bkg only hypothesis

	Signal region
Observed events	7
Estim. bkg events	1.60 ± 1.04
Estim. tt-bar events	1.20 ± 0.97
Misid. lepton events	$0.00^{+0.27}_{-0.00}$
Diboson events	0.39 ± 0.27
Single-top events	0.00 ± 0.00
Z+jets events	0.00 ± 0.00
tt-bar+V events	$0.01^{+0.06}_{-0.01}$



- Dominant **sources of systematic uncertainty**
  - The uncertainties can be correlated and don't necessarily add up quadratically to the total uncertainty

+/- N_{eve}

tt-bar parton-shower uncertainty	± 0.81 [50.6%]
MC statistics in SR	± 0.45 [27.9%]
B tagging	± 0.30 [19.0%]
tt-bar yield	± 0.20 [12.7%]
Systematics Dibosons	± 0.19 [12.1%]

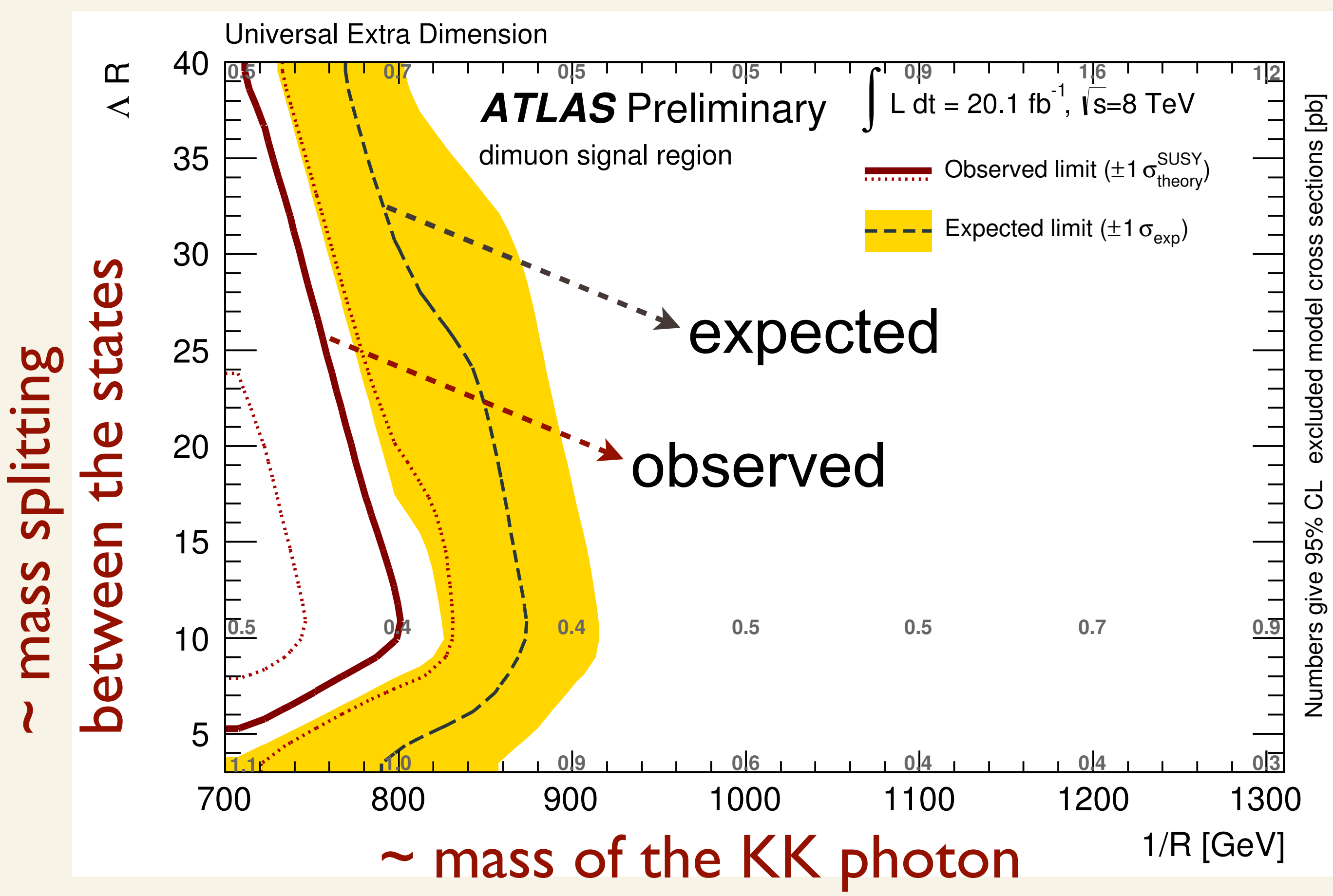
Exclusion

- **Model-independent limits:**
  - Derived using CLs prescription

95% CL upper limits on:

visible x-section	N signal events	
$\langle \epsilon\sigma \rangle^{95}_{obs}$ [fb]	S^{95}_{obs}	S^{95}_{exp}
0.57	11.5	$5.9^{+2.1}_{-1.0}$

- The cross-section upper limits are set for the **mUED model** in the 2D parameter space



Conclusion

- The analysis performed using the full 20.1 fb^{-1} of ATLAS data at $\sqrt{s}$=8 TeV
- The signal region definition optimised specifically for mUED model
  - ➡ soft leptons/jets in the decay chains
  - ➡ dimuon channel is used
- No significant deviation form the standard model expectation is observed
- The limit on the compactification radius of up to 1/R=800 GeV is set, depending on the compression scale ($\mathbf{\Lambda R}$)
- This extends the previous ATLAS limit set by the $\sqrt{s}$=7 TeV 3-lepton analysis into $\mathbf{\Lambda R \leq 10}$ region

Backup

The matrix-method

- Data-driven method to estimate the misidentified lepton background
- Based on inverting the muon isolation:

$$\frac{\sum \mathbf{p_T\ tracks\ in\ a\ dR = 0.3\ cone}}{\mathbf{p_T^{\mu}}} < \mathbf{0.12}$$

$$\mathbf{Longitudinal\ IP}:\ |\mathbf{z_0^{PV}} \sin\theta| \leq \mathbf{0.4\ mm}$$

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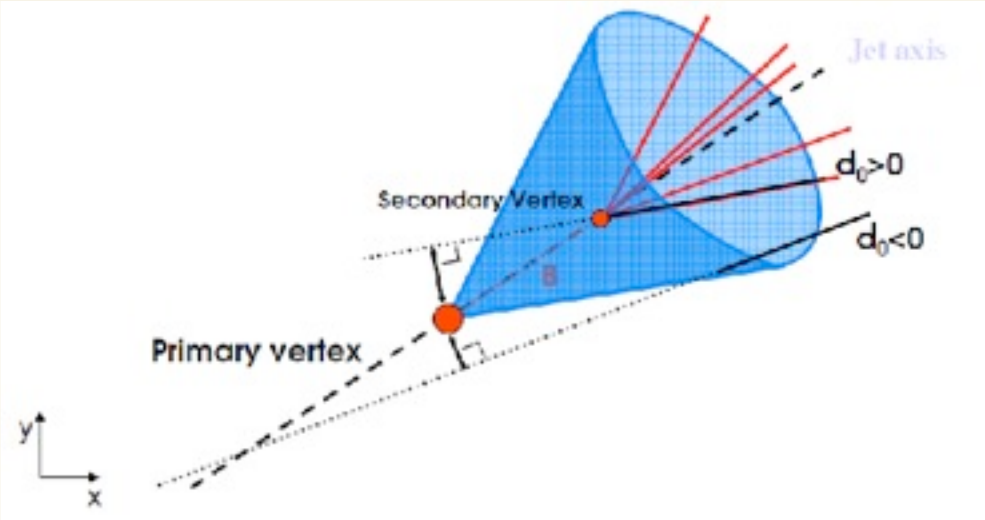
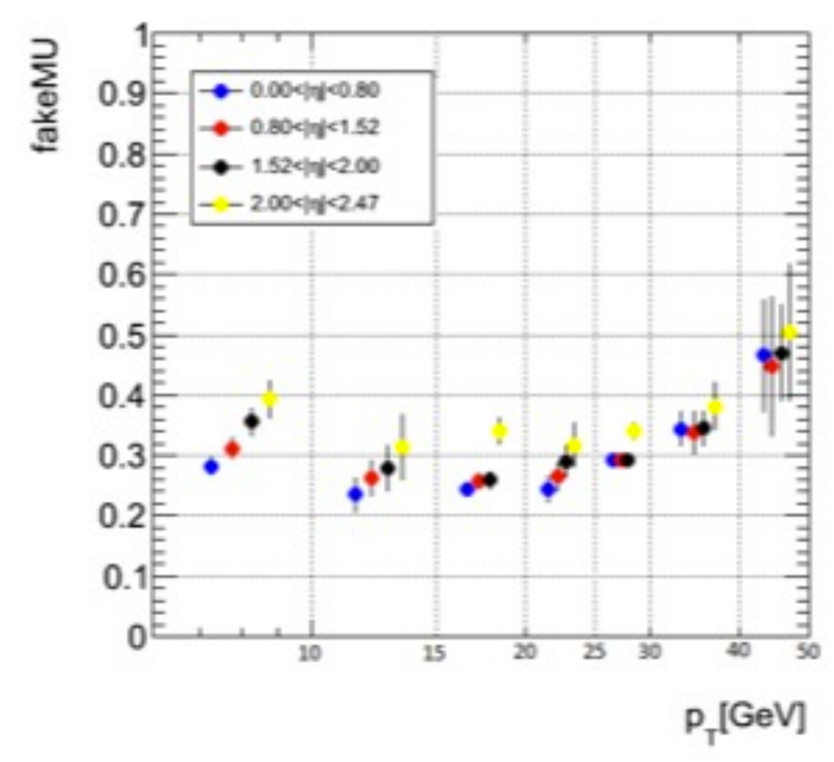


- **Fake rate:**

$$\mathbf{FR} = \frac{\mathbf{N^{\mu}_{isolated,fake}}}{\mathbf{N^{\mu}_{total,fake}}}$$

  - Measured in the di-jet data sample:
    - ✓ E_T^{miss} <30 GeV
    - ✓ m_T<40 GeV



- **Real rate:**

$$\mathbf{RR} = \frac{\mathbf{N^{\mu}_{isolated,real}}}{\mathbf{N^{\mu}_{total,real}}}$$

  - Measured in the Z+jets events in the data

The matrix-method

$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} rr & rf & fr & ff \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)(1-r) & (1-r)(1-f) & (1-f)(1-r) & (1-f)(1-f) \end{bmatrix} \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}$$

Number of tight = isolated & loose = non-isolated muons in our data sample
➡ count it

Fake & real rates
➡ measured

Number of real & fake muons in our data sample
➡ invert the matrix to extract this number

- The result is validated in the whole E_T^{miss} region
  - Good agreement with the data