A search for $t\bar{t}$ resonances using 3.2 fb^{-1} of proton-proton collisions at $\sqrt{13}$ TeV: Boosted analysis

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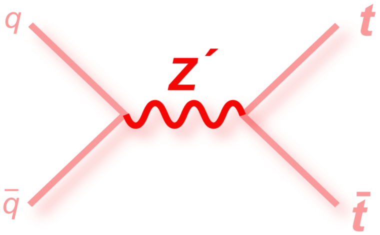
Introduction

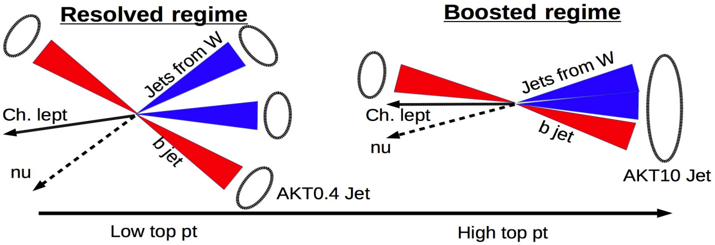
- **General search for $X \rightarrow t\bar{t}$**
- **Benchmark model used for Moriond 2016**: Top colour-assisted $Z'_{TC2} \rightarrow t\bar{t}$
  - Spin 1, Color singlet, narrow width (1.2% and 3%)



- **Plan to include other benchmarks:**
  - Scalar resonance (2HDM) including the interference with SM ttbar
  - KK graviton

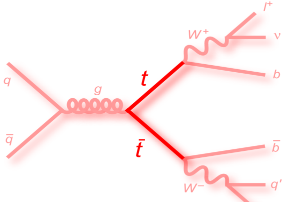
Event topology

- Top quark decays before hadronization: BR($t \to Wb$) $\sim$ 100 %
- Lepton + jets signature: large BR + reduction of multijet bkg
- The hadronic top quark decays in two kinds of topology
  - Resolved: objets well separated in the detector (work in progress)
  - $\Rightarrow$ Boosted: objects start to overlap (approved for Moriond)

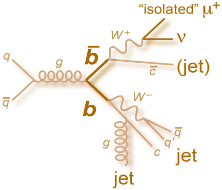


Search for $t\bar{t}$ resonances: backgrounds

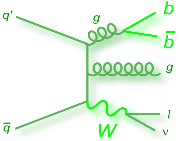
- **SM process which can give to signal like events**
  - **SM ttbar** $\Rightarrow$ main background, MC NLO
  - **W+jets** $\Rightarrow$ MC (normalisation with data-driven techniques)
  - **Single Top, Z+jets, Diboson, ...** $\Rightarrow$ small, MC
  - **Multijets** $\Rightarrow$ small (data-driven)



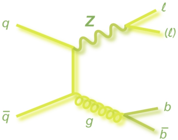
SM ttbar



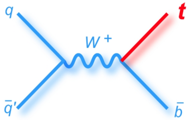
Multi-jets



W+jets



Z+jets



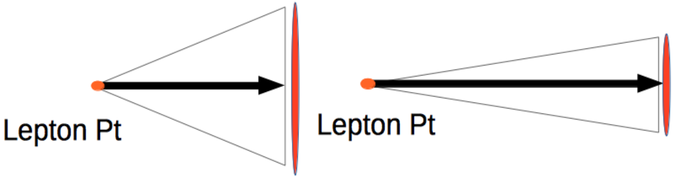
Single-top

Object definition (I): leptons

- Lepton + jets signature: considering only electron and muon channels
  - Electron: $p_T > 30$ GeV and $|\eta| < 2.47$
  - Muon: $p_T > 25$ GeV and $|\eta| < 2.5$

- Lepton isolation **I**, with a cone size which is p_T dependent:

$$\mathbf{I} = \sum_{R} p_T^{trk} \quad \text{with } R = \min\left(\frac{10 GeV}{p_T}, 0.2 \ (0.3)\right)$$



- Good efficiency even at high boosted regimes

- Working point chose with selection efficiency of 99% for all p_T ranges

Object definition (II): jets

- 3 types of hadronic jets are used:

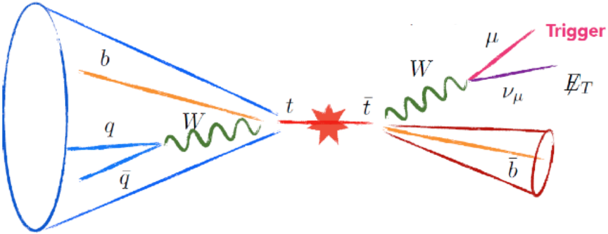
- Small-R jets (anti-k_t with R=0.4):
  - pT $>$ 25 GeV and $| \eta | < 2.5$
  - Removing pileup jets using track and vertex information

- Large-R jets (anti-k_t with R=1.0):
  - Trimming algorithm (f=5%, $R_{sub} = 0.2$)
  - pT $>$ 300 GeV and $| \eta | < 2$
  - Likely to contain the decay products of hadronic top-quark:
    - Top-tagged: based on jet mass and the n-subjettiness ratio τ_{32}
    - Selects top-quark jets with 80% of efficiency

- Track jets (anti-k_t with R=0.2):
  - Better performance in dense environment than calo btagging
  - Track jets likely to contain a b-hadron are identified
  - Btagging efficiency of 70 % for the working point chosen

Analysis selection

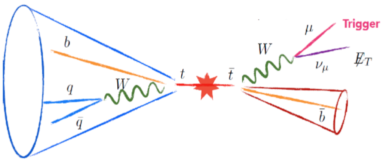
- Event cleaning
- Single lepton triggers
- Exactly 1 electron or muon
- MET $>$ 20 GeV
- MET $+$ MWT [1] $>$ 60 GeV
- $\geq$ 1 "selected jet" of 25 GeV (close to lepton $\Delta R < 1.5$)
- $\geq$ 1 "top-tagged" large-R jets:
  - Away from selected jet: $\Delta R > 1.5$
  - Away from lepton: $\Delta \phi > 2.3$
- $\geq$ 1 b-tagged track jet

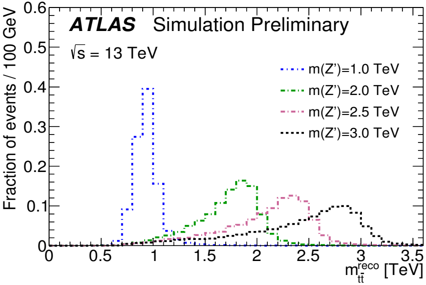


[1] $MWT = \sqrt{p_T^{lep}.MET.2(1 - cos\Delta\Phi(MET, lepton))}$

Invariant mass reconstruction of the $t\bar{t}$ system

- Neutrino's momentum:
  - $p_T^{\nu} = \text{MET}$
  - p_z^{ν} estimated by imposing a mass constrain on the leptonic W boson
- Leading selected jet as the b-jet of leptonic top
- Leading top-tagged large-R jet as the hadronic top
- $m_{t\bar{t}}^{reco}$ = top-tagged large-R jet + selected jet + neutrino + lepton

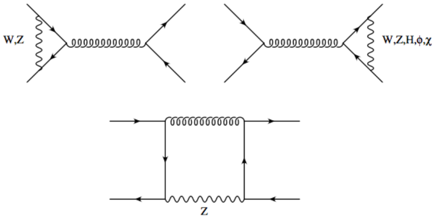




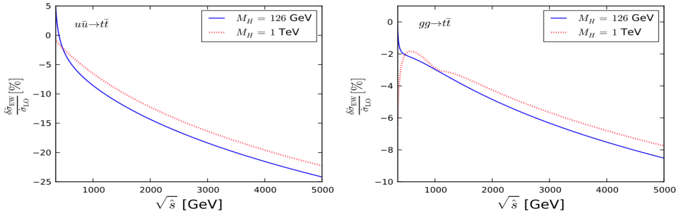
Weak corrections for $t\bar{t}$ production [arXiv:1305.5773]

- Total cross section for top production is dominated by gluon fusion
- In contrast, boosted top quarks are mainly induced by $q\bar{q}$ production

⇒ More significant contribution for quark- than gluon-induced process



- Corrections at partonic level for $q\bar{q}$ and gg processes as functions of parton's energy



- Implementation of weak correction ($M_H = 126$ GeV) to SM $t\bar{t}$ MC
  ⇒ It reduces the overall yields by 4%
- ±10% uncertainty for weak corr.

W+jets normalisation

- Overall normalisation of W+jets bkg: Sherpa MC samples with data-driven scale factors
- SF determined by comparing the W charge-asymmetry in data and MC:

$$A = \frac{N_{W^+} - N_{W-}}{N_{W^+} + N_{W-}}$$

- Charge-asymmetric backgrounds: ttbar +V, single-top and diboson
- Main bkg (ttbar) and others small (Zll, ...) are charge symmetric → substracted
- Overall normalisation SFs:

  Electron channel SF: 0.82 ± 0.18(stat)

  Muon Channel SF: 0.73 ± 0.12(stat)

Multijet bkg estimation

- Composed mostly by non-prompt leptons (semi-leptonic B decays)
- Use matrix "data-driven" method to estimate the multijet bkg
- A looser lepton selection is composed by prompt and "fake" leptons:

$$N_{Loose} = N_{prompt} + N_{multijet}$$

- Prompt and fake contributions are estimated for the lepton selection used in analysis:

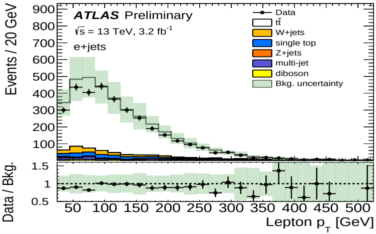
$$N_{Tight} = \epsilon \times N_{prompt} + f \times N_{multijet}$$

- Efficiencies estimated in CRs enriched with isolated lepton (ϵ) and multijet (f)
- Small contribution $\rightarrow$ challenging to find a perfect parametrisation
- Establishing a conservative flat uncertainty of 50%

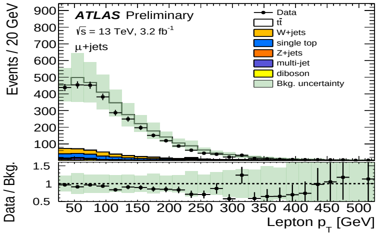
Control plots (I)

- Data-MC disagreements covered by systematic uncertainties (see slide 15)
- p_t of lepton:

electron channel

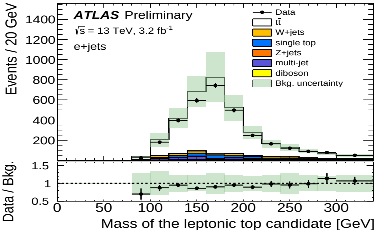


muon channel

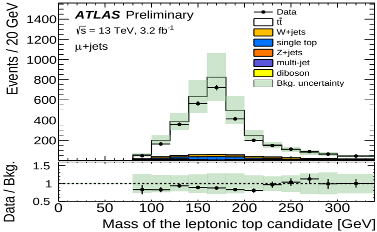


- Leptonic top mass:

electron channel



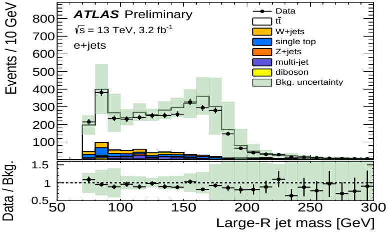
muon channel

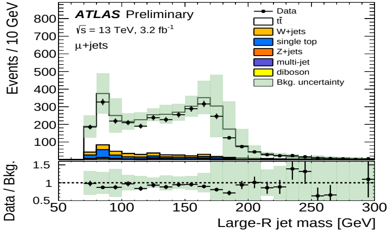


Control plots (II)

- largeR jet mass:

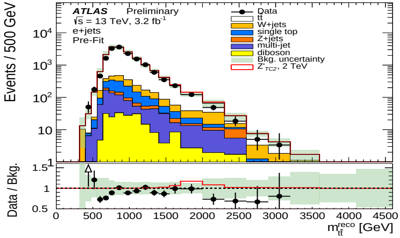
electron channel | muon channel

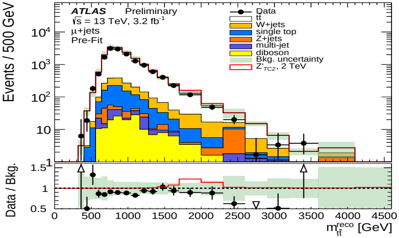




- Mass of ttbar system: low sensitivity at low $m_{t\bar{t}}^{reco}$

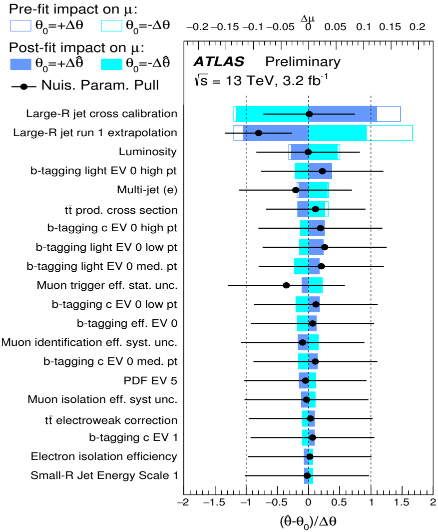
electron channel | muon channel





Nuisance parameter impact on fitted signal strength

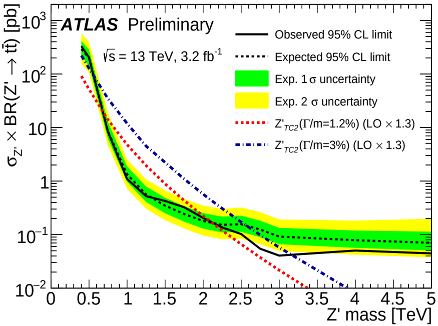
- **Systematic uncertainties:**
  - Large-R jet unc. are dominant
  - 5% luminosity uncertainty (2015 dataset)
  - $t\bar{t}$ background modelling
  - Reconstruction uncertainties of lepton and jets
- Impact of fitted nuisance param. on the fitted signal strength (Z' mass of 2 TeV)
- Impact of the variation of a nuisance param. on the best-fit value



Limit setting

- **Compatibility with SM-only hypothesis tested using BumpHunter:**
  $\Rightarrow$ No significant excess or deficits were found!
- **95% CL cross section limits are set for Z'**
- The hypothesis testing is based on the profile likelihood ratio test statistic

- **Observed upper limits on excluded mass:**
  - Z'($\Gamma/m = 1.2\%$): $0.7 < m_{Z'} < 2.0$ TeV
  - Z'($\Gamma/m = 3.0\%$): $0.7 < m_{Z'} < 3.2$ TeV
- Previous observed limits (run 1 search):
  - Z'($\Gamma/m = 1.2\%$): $0.4 < m_{Z'} < 1.8$ TeV
  - Z'($\Gamma/m = 3.0\%$): $0.4 < m_{Z'} < 2.3$ TeV



Outlook

- Search for $Z' \rightarrow t\bar{t}$ performed with 2015 pp datasets (3.2 fb^{-1})
- No excess or deficits found wrt SM-only hypothesis
- Improving the excluded mass region wrt boosted analysis at Run 1
- Low $t\bar{t}$ mass spectra covered by resolved analysis (diphoton excess at 750 GeV)
  $\Rightarrow$ On going!

Back up

Object definitions

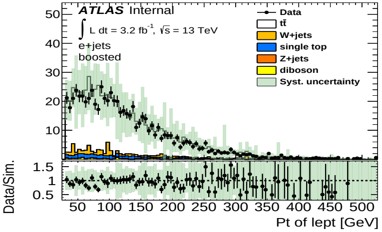
- **Leptons (electron/muon):**
  - $p_T > 30/25$ GeV and $\mid \eta \mid < 2.47/2.5$
  - Track to vertex association cuts
  - Quality requirement: LHTight/Medium
  - p_T dependent isolation: flat eff. 99%)
- **Single (isolated) lepton triggers**
  - e channel:
    * HLT_e24_lhmedium_L1EM18VH (MC)
    * HLT_e24_lhmedium_L1EM20VH (data)
    * HLT_e60_lhmedium
    * HLT_e120_lhloose
  - mu channel:
    * HLT_mu20_iloose_L1MU15
    * HLT_mu50

- **Anti-k_t R=1.0 jet (large-R):**
  - Pre-recommended trimmed jet (f=5%, $R_{sub} = 0.2$)
  - pT $>$ 300 GeV
  - $\mid \eta \mid < 2$
  - top-tagged: 80% eff. for top-jets
- **Anti-k_t R=0.4 jet (small-R):**
  - pT $>$ 25 GeV and $\mid \eta \mid < 2.5$
  - $\mid JVT \mid > 0.64$
- **Track jet bTagging (WP 70 %)**
- Std. OR + p_T dependent variable cone size btw mu-jet
- Scale factors: bTag, lepton and PRW SF

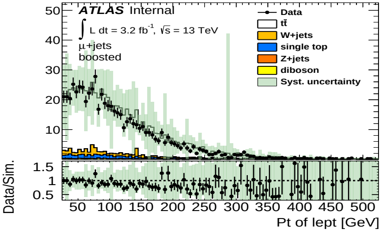
Lepton object definition

- Electron (Muon) with pT > 30 (25) GeV
- Reject crack region electrons
- LHTight electron quality and Medium muon quality
- LooseTrackOnly isolation: ptvarcone20 (ptvarcone30) for electrons (muons)
  $\Rightarrow$ Flat efficiency of 99%
- Track to vertex association (TTVA) cuts:
  $|\ d_0/\sigma_{d_0}\ | < 5(3)$ and $z_0 \times sin(\theta) < 0.5$ mm for electrons (muons)

Boosted e channel

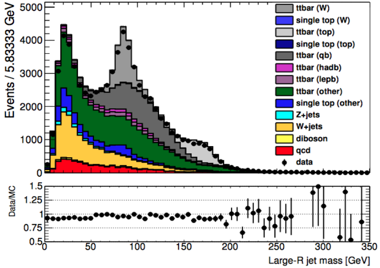


Boosted mu channel

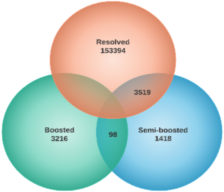


Semi boosted channel

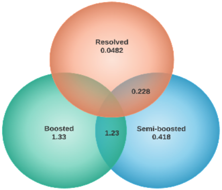
- Semi boosted events could fail boosted and resolved selections
- Goal: find a large-R jet mass window to collect such events
- Using different large-R jet selection based on truth match study:
  - pT > 150 GeV
  - 56 GeV < Mass <168 GeV
- large-R jet selector has 81 % of efficiency



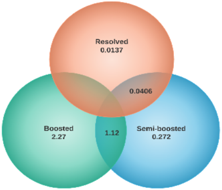
$t\bar{t}$ Total Background Yields



Z' 1TeV Signal/Background



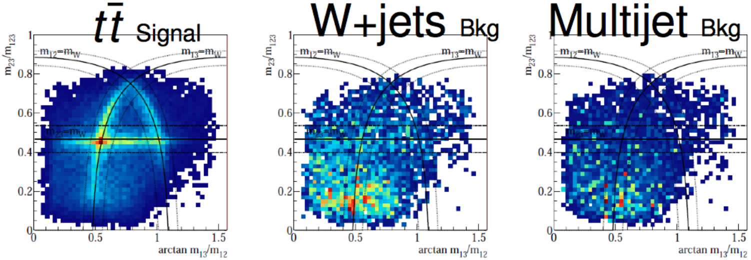
Z' 2TeV Signal/Background



by H. Carson, K. Johns, R. Nayyar, J. Veatch, A. Kilgallon

HEPTopTagger

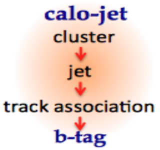
- Full hadronic search to be combined with lepton+jets channel for the paper publication
- Find hadronically decaying top quarks with pT > 200 GeV
  - Obtain 3 sub-jets: testing m_{top}, m_W hypotheses with 2D cuts
  - Using R-scan anti-kt calibrations (R=0.2, 0.3, ..., 0.6)
  - Return 4-vector of top quark candidate
- Running HEPTopTagger using ttbar resonances framework



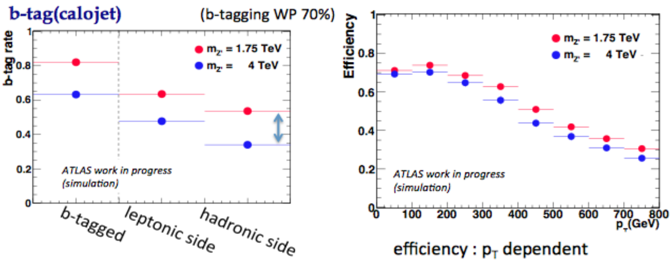
by David Sosa

Track Jet Btagging

- Calo Jets:
  - Used in Run1
  - Built with calorimeter clusters
  - Angular resolution not as fine as for track jets



- Track jets:
  - Building jets from reconstructed tracks
  - Less impact from pile up in dense environment
  - Aim to improve the reconstruction close to the hadronic top decays

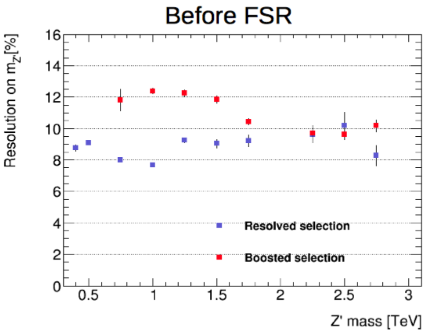


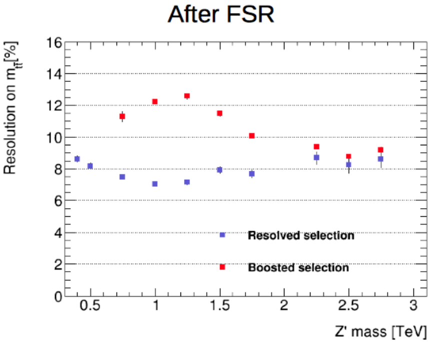
efficiency : p_T dependent

by Aine Kobayashi

Detector resolution

- Match akt4/10 to partons to build mtt_reco and compute the resolution
  - Pure impact of the detector resolution
  - No effect of the reconstructions
  - Comparison with mtt before and after FSR





- Resolved reconstruction closer to "after FSR" than "before FSR", as expected
- Boosted reconstruction worst than resolved, unexpected (was the reverse during run 1)

by Samuel Calvet

Weak corrections for ttbar production

- Leading QCD and weak diagrams

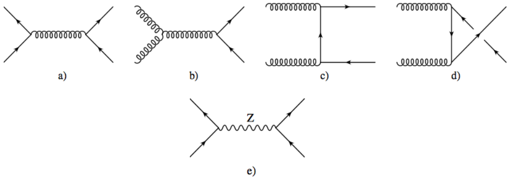


Figure 1: Lowest order QCD (a–d) and weak (e) amplitudes

- Quark-induced production process are preferred for boosted tops

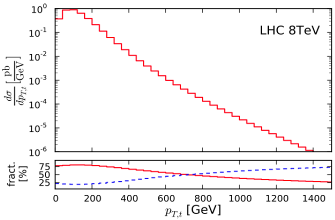


Figure 6: Leading-order differential cross section for the LHC (8 TeV) as a function of p_T. The lower plot shows the fraction from gluon fusion (red,solid) and the fraction from quark–antiquark annihilation (blue, dashed).

Weak corrections for ttbar production

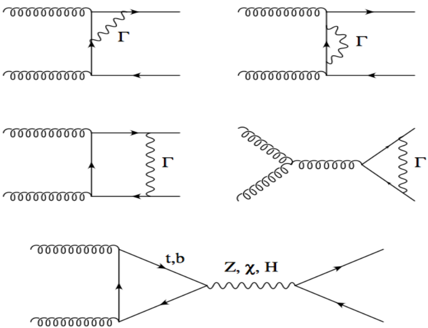


Figure 3: Sample diagrams for the virtual corrections for the gluon-induced process. Γ stands for all contributions from gauge boson, Goldstone boson and Higgs exchange.

W+jets normalisation

- Overall normalisation of W+jets bkg: Sherpa MC samples with data-driven scale factors
- SF determined by comparing the W charge-asymmetry in data and MC
- Charge-asymmetric bkg: ttbar +V, single-top and diboson:

$$CA = N_{Data,W}/N_{MC,W} = \left(\frac{r_{MC}+1}{r_{MC}-1}\right)\frac{(D^{+}_{\text{corr}} - D^{-}_{\text{corr}})}{N_{MC,W}}$$

- $N_{W+} + N_{W-}$: number of W+jets events in data
- r_{MC}: ratio of W+jets events in MC with a positive and negative charged lepton
- $D^{\pm}_{corr}$: number of observed events with a positive (negative) lepton

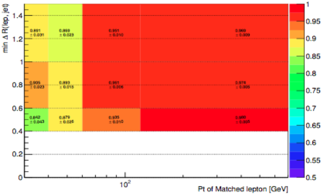
- Other backgrounds are treated as charge-symmetric
- Overall normalisation SFs:

  Electron channel SF: 0.82 $\pm$ 0.18(stat)

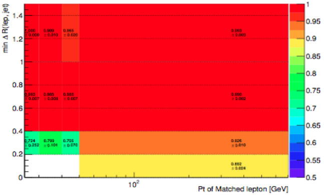
  Muon Channel SF: 0.73 $\pm$ 0.12(stat)

Real eff. measurement

- **Building a pre-selected sample of reco lepton matched to the truth**
  - Tight sample (OR with tight defintion): lepton with quality required by analysis
  - Anti-Tight sample (OR with loose defintion): lepton passing loose quality requirement but failing tight one
  - Loose sample: (no isolation) Anti-Tight + Tight sample
- Using SM ttbar EXOT4 derivations
  $\Rightarrow$ lepton SF estimated from data efficiency measurements
- Real eff. parametrised using lepton pT and min ΔR(lept, jet)
  $\Rightarrow$ Inspired in run 1 results
- Boosted: electron channel muon channel



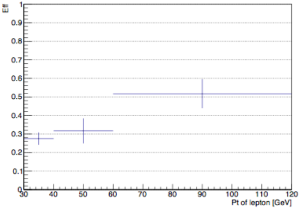
(a) Efficiency ϵ (electrons)



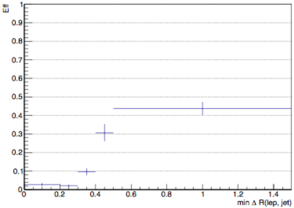
(b) Efficiency ϵ (muons)

1D parametrizacion of fake rates (resolved)

- Rates mostly depends on:
  - Lept PT for e channel
  - ΔR for mu channel
- e channel: lept Pt — mu channel: ΔR



(e) Fake rate f (electron)



(f) Fake rate f (muons)

Systematics (boosted e channel)

Systematics	variation (%)
anti-k_t R=1.0 run 1	12.8
anti-k_t R=1.0 cross calibration	10.9
anti-k_t R=0.4 JER	0.1
anti-k_t R=0.4 JES1	0.8
anti-k_t R=0.4 JES2	0.3
anti-k_t R=0.4 JES3	0.3
b-tagging eff. (E0)	1.4
b-tagging eff. (E1)	0.1
b-tagging eff. (E2)	0.1
b-tagging eff. (E3)	0.0
b-tagging eff. (E4)	0.0
b-tagging c mistag (E0)	0.6
b-tagging c mistag (E1)	0.2
b-tagging c mistag (E2)	0.0
b-tagging c mistag (E3)	0.0
b-tagging extrap.	0.0
b-tagging extrap. (charm)	0.0
b-tagging l mistag (E0)	1.4
b-tagging l mistag (E1)	0.0
b-tagging l mistag (E10)	0.0
b-tagging l mistag (E11)	0.0
b-tagging l mistag (E2)	0.1
b-tagging l mistag (E3)	0.0
b-tagging l mistag (E4)	0.0
b-tagging l mistag (E5)	0.0
b-tagging l mistag (E6)	0.0
b-tagging l mistag (E7)	0.0
b-tagging l mistag (E8)	0.0
b-tagging l mistag (E9)	0.0

Systematics	variation (%)
electron ID	1.1
electron isolation	0.8
electron reconstruction	0.4
electron res.	0.2
electron scale	0.2
electron trigger	0.5
luminosity	5.0
MET res. para.	0.2
MET res. perp.	0.4
MET scale	0.4
muon ID (stat)	0.0
muon ID (syst)	0.0
muon isolation (stat)	0.0
muon isolation (syst)	0.0
muon res. (ID)	0.0
muon res. (MS)	0.0
muon scale	0.0
muon trigger (stat)	0.0
muon trigger (syst)	0.0
single top cross sec.	0.3
tt electroweak corr.	8.6
ttbar gen.	5.2
ttbar ISR/FSR	0.7
ttbar PDF	1.6
ttbar p. shower	7.0
ttbar cross section	5.3
W C/A SF	0.0
Total	22.3

Systematics (boosted mu channel)

Systematics	variation (%)
anti-k_t R=1.0 run 1	12.5
anti-k_t R=1.0 cross calibration	10.8
anti-k_t R=0.4 JER	0.3
anti-k_t R=0.4 JES1	0.8
anti-k_t R=0.4 JES2	0.3
anti-k_t R=0.4 JES3	0.4
b-tagging eff. (E0)	1.3
b-tagging eff. (E1)	0.1
b-tagging eff. (E2)	0.0
b-tagging eff. (E3)	0.1
b-tagging eff. (E4)	0.0
b-tagging c mistag (E0)	0.6
b-tagging c mistag (E1)	0.1
b-tagging c mistag (E2)	0.1
b-tagging c mistag (E3)	0.0
b-tagging extrap.	0.1
b-tagging extrap. (charm)	0.1
b-tagging l mistag (E0)	1.2
b-tagging l mistag (E1)	0.1
b-tagging l mistag (E10)	0.0
b-tagging l mistag (E11)	0.0
b-tagging l mistag (E2)	0.2
b-tagging l mistag (E3)	0.0
b-tagging l mistag (E4)	0.0
b-tagging l mistag (E5)	0.0
b-tagging l mistag (E6)	0.0
b-tagging l mistag (E7)	0.0
b-tagging l mistag (E8)	0.0
b-tagging l mistag (E9)	0.0

Systematics	variation (%)
electron ID	0.0
electron isolation	0.0
electron reconstruction	0.0
electron res.	0.0
electron scale	0.0
electron trigger	0.0
luminosity	5.0
MET res. para.	0.4
MET res. perp.	0.4
MET scale	0.5
muon ID (stat)	0.2
muon ID (syst)	0.7
muon isolation (stat)	0.1
muon isolation (syst)	0.3
muon res. (ID)	0.1
muon res. (MS)	0.1
muon scale	0.0
muon trigger (stat)	1.1
muon trigger (syst)	0.5
single top cross sec.	0.2
tt electroweak corr.	8.7
ttbar gen.	1.6
ttbar ISR/FSR	4.4
ttbar PDF	1.8
ttbar p. shower	8.6
ttbar cross section	5.3
W C/A SF	0.0
Total	22.5

Yields

- Data agrees with MC within the systematic uncertainties
- data/MC fraction is larger in mu channel

Yields in boosted e channel

Type	Yield $\pm$ (stat.$\oplus$syst.)
$t\bar{t}$	3052.8 $\pm$ 852.8
W+jets	234.1 $\pm$ 56.8
single top	190.7 $\pm$ 41.9
Z+jets	20.8 $\pm$ 7.6
diboson	45.7 $\pm$ 10.9
Total	3544.2 $\pm$ 912.1
Data	3363

Yields in boosted mu channel

Type	Yield $\pm$ (stat.$\oplus$syst.)
$t\bar{t}$	2978.2 $\pm$ 848.8
W+jets	219.6 $\pm$ 63.6
single top	172.8 $\pm$ 38.2
Z+jets	16.0 $\pm$ 3.6
diboson	36.6 $\pm$ 8.2
Total	3423.2 $\pm$ 906.2
Data	3073

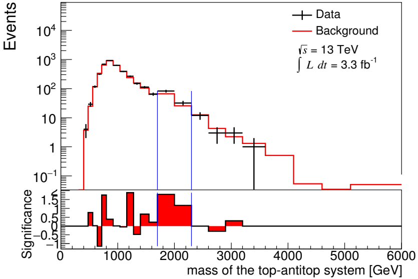
Compatibility with SM-only hypothesis

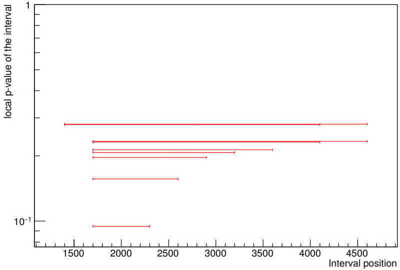
- **BumpHunter used to search for localised excesses or deficits**
- Data and expected background are compared in sliding windows of variable size
- **Smallest Poisson probability (P_i^{min}) corresponds to the most discrepant window**
- Data has been divided in both channels: e+jets and μ+jets
  $\Rightarrow$ Channels are combined in a second step
- **No excess or deficits were found!**

Configuration	Channel	mass range	p-value	σ
excess (syst, postfit)	e	400 - 560	0.331±0.004	0.435 (0.422 - 0.448)
	μ	320 - 560	0.562±0.004	0
	comb.	400 - 560	0.088±0.002	1.350 (1.333 - 1.368)
deficit (syst, postfit)	e	560 - 720	0.134±0.002	1.106 (1.095 - 1.117)
	μ	2600 - 3200	0.092±0.002	1.328 (1.315 - 1.340)
	comb.	no overlap		

Bump hunter studies

- Bump hunter is designed to search for localized excesses or deficits
- Studies below show an example with injected Z' (2TeV) signal with a strength of 0.1
- Validated in the run2 framework





Signal reconstruction at truth level

- Generated Z' mass compared to the mass of the top-antitop system decay products
- Signal peak smeared out due to radiation at high Z' masses
- Radiation effect could reduce the sensitivity of the analysis