Search for new resonances decaying into top-quark pairs using lepton-plus-jets events in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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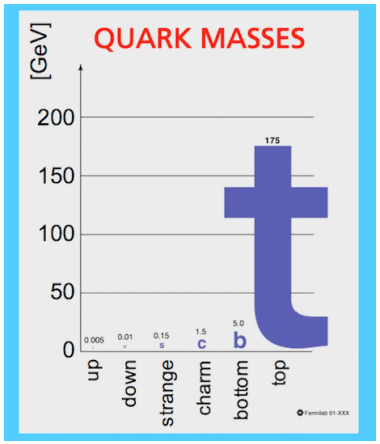
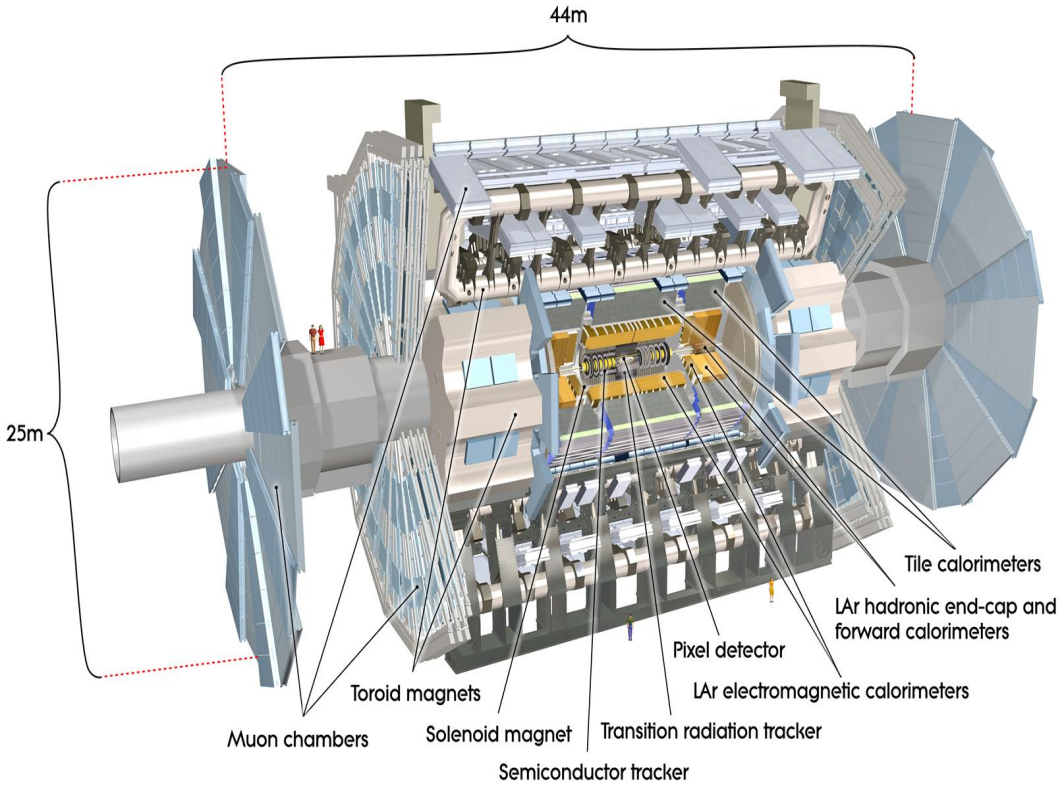
Motivation

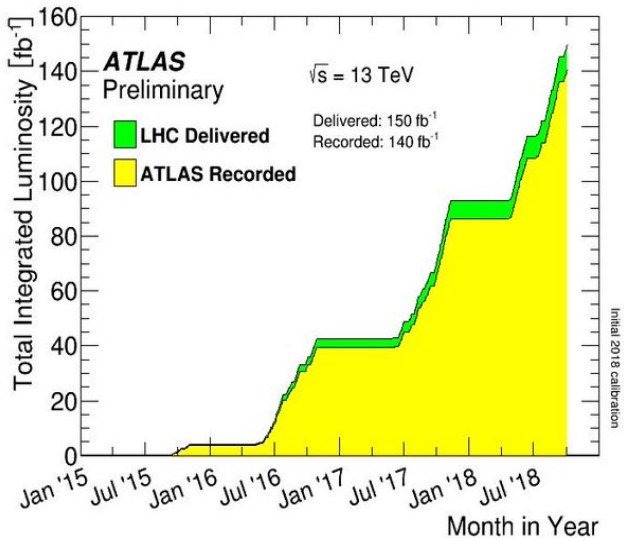
- **BSM physics at the TeV scale is a major goal for LHC.**
- **Top quarks play an important role as a probe for new physics :**
  - heaviest elementary particle in the SM ($\approx$173 GeV)
  - Very large Yukawa coupling with Higgs ≈ 1
- **Many scenarios for BSM physics (exotic models) predict enhanced couplings to third generation quarks :**
  - Top-color model (TC) : Leptophobic TC heavy Z' boson
  - Warped extra-dimensions models (Randall-Sundrum)
  - 2 Higgs Doublet Model (2HDM) : 4 scalars and 1 pseudo-scalar



ATLAS and LHC

- **LHC is a "top factory" : run2 160M top quarks were produced ($\approx$ 20 top/s)**
- **ATLAS detector optimized to find top-quarks**
  - Very good electron and muon reconstruction and identification Present in 39% of top decays
  - Full azimuthal coverage (Nearly 4π) to measure neutrino transverse component via E_T^{miss}
  - High granularity tracking to select displaced vertexes from b-jets

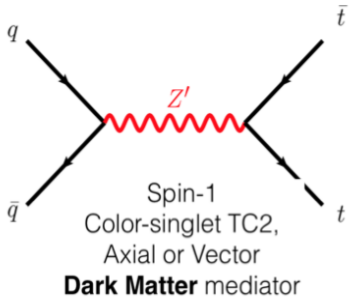


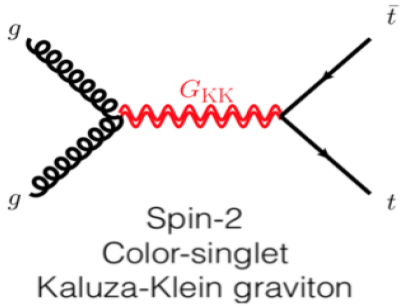


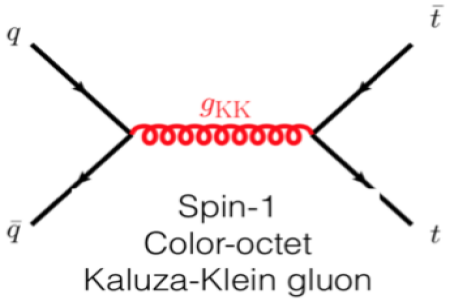
Cumulative luminosity versus time delivered to ATLAS at Run2

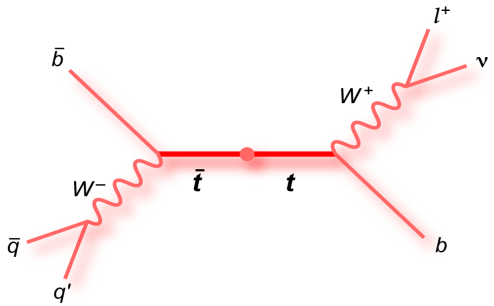
Benchmark Scenarios :

Many BSM scenarios predict new particles (X) decaying into a pair of tops.









Analysis strategy :
Build a model independent analysis

- Select events
- Reconstruct $t\bar{t}$ invariant mass
- Scan $t\bar{t}$ system mass spectrum to find an excess/deficit

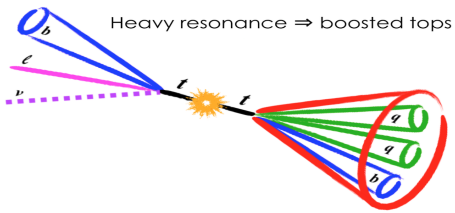
Lepton + jet decay mode :

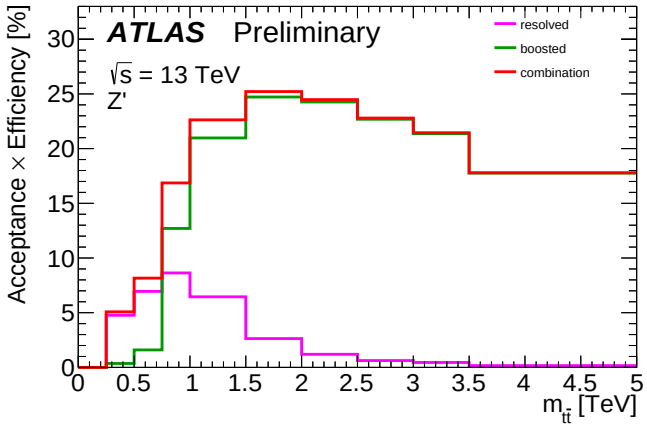
- **Lepton** : Multijet background suppression (trigger more efficient on leptons)
- **Jets** : Keep good statistics level (high branching ratio)

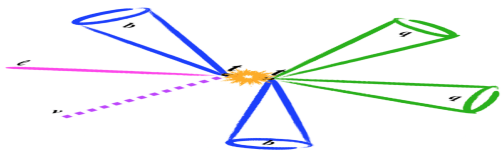
Event selection

Decay topologies in the lepton+jets channel :

- Resolved : relevant at low $m_{t\bar{t}}$
- Boosted : relevant at high $m_{t\bar{t}}$







Boosted Selection :

- Exactly one lepton e or μ
- $E_T^{miss} > 20$ GeV
- $E_T^{miss} + m_T^W > 60$ GeV
- 1 top-tagged large-R jet
- $\geq$ 1 b-tagged and Small-R jet
- Ensure a back-to-back decay

Resolved Selection

- veto boosted selection
- Exactly one lepton e or μ
- $E_T^{miss} > 20$ GeV
- $E_T^{miss} + m_T^W > 60$ GeV
- $\geq$ 4 well separated small-radius jets
- $\geq$ 1 b-tagged 0.2 track-jet
- $Log_{10}(\chi 2) < 0.9$

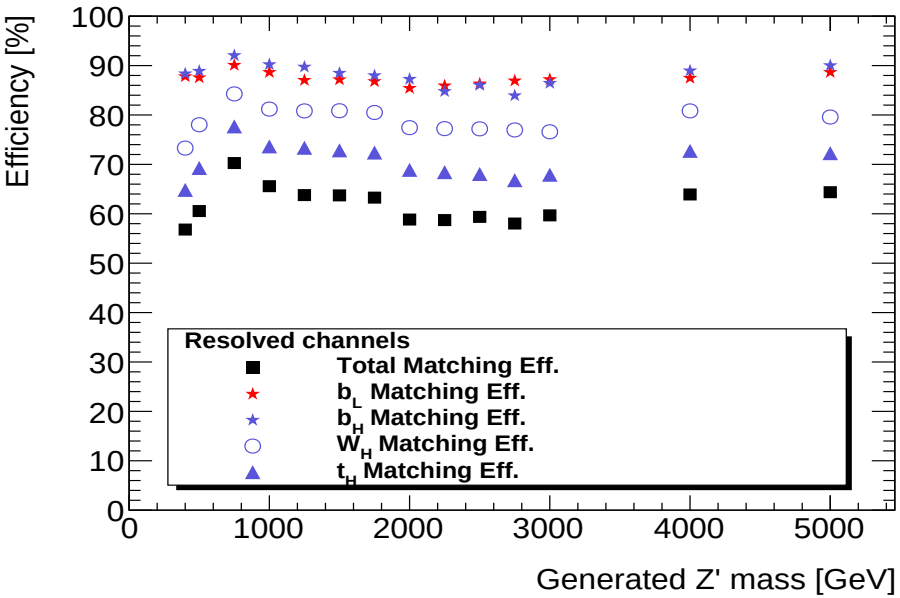
Background

- **SM $t\bar{t}$:**
  - main and irreducible background.
  - estimated from MC
  - re-weighted to include NLO EWK calculations.
- **W+jets :**
  - Shape estimated from MC
  - normalisation : usage of data-driven scale factors
- **Multi-jets :**
  - Data-Driven : Matrix method (more focus in the next slides)
- **Other backgrounds : directly from MC**
  - Z+jets
  - single top
  - Diboson

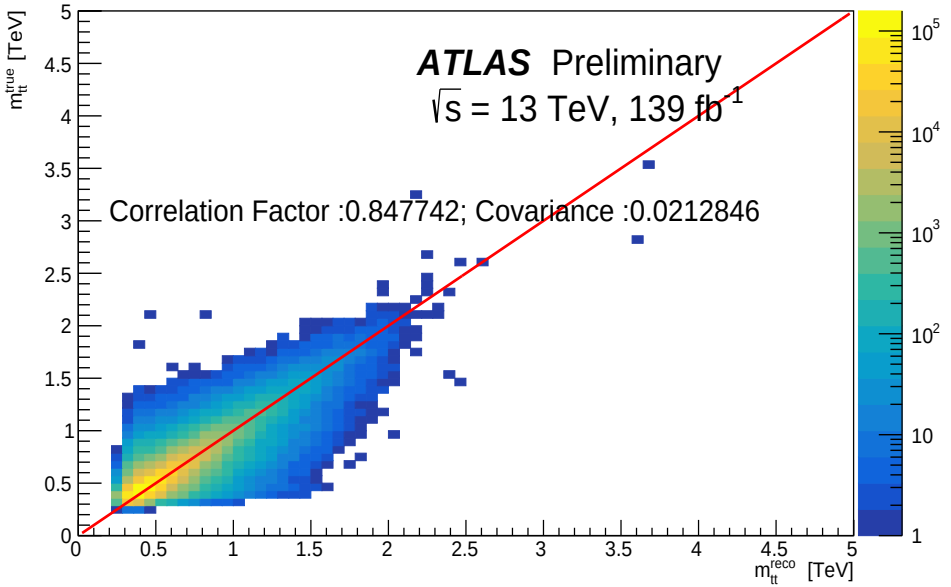
Reconstruction in resolved Topology :

- The $\chi 2$ minimization method aims to select the right combination of jets
- The $\chi 2$ is defined as follows :

$$\chi 2 = \left(\frac{m_{jj}-m_W}{\sigma_W}\right)^2 + \left(\frac{m_{jjb}-m_{jj}-m_{th-W}}{\sigma_{th-W}}\right)^2 + \left(\frac{(pT_{jjb}-pT_{jl\nu})-(pT_{th}-pT_{tl})}{\sigma_{diff-pT}}\right)^2 + \left(\frac{m_{jl\nu}-m_{tl}}{\sigma_{tl}}\right)^2$$



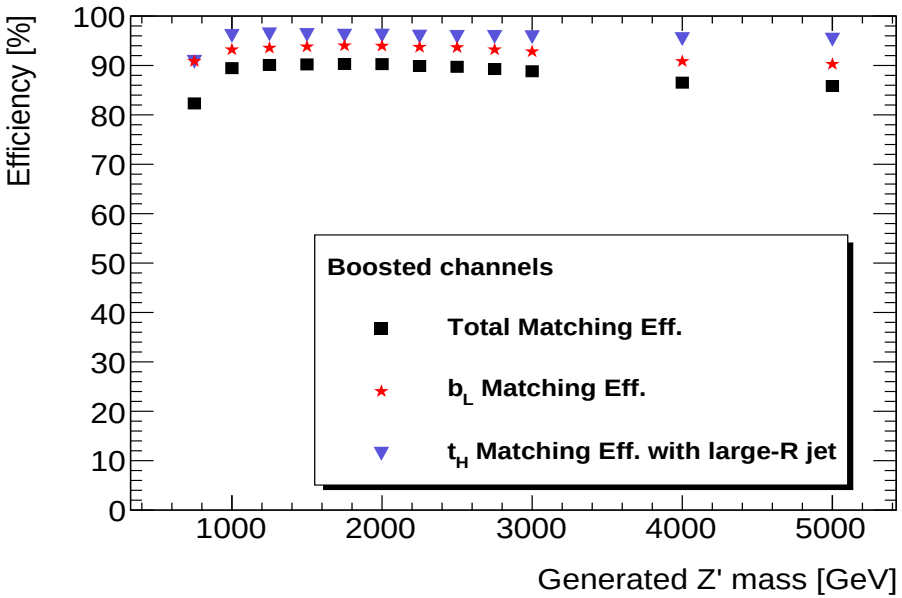
The performance is about 90% determined on parton-matched for Z'_{TC2} signal.



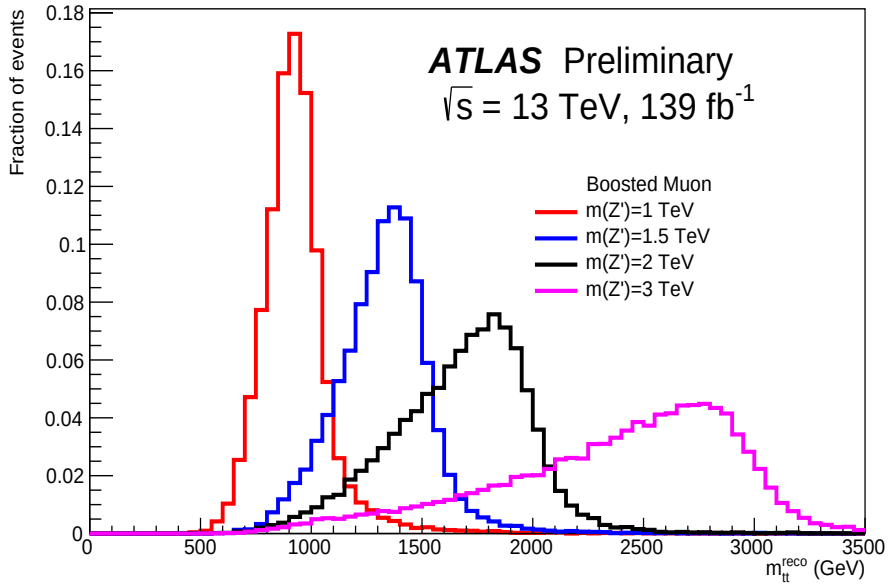
High correlation between truth and reconstructed $m_{t\bar{t}}$

Reconstruction in boosted Topology :

- $m_{t\bar{t}}^{reco}$ is reconstructed from the **leptonic** top candidate and **hadronic** top candidate :
  - **leptonic side : lepton (e/μ) + j_{sel} + ν**
    (Assume neutrinos's p_T = MET and its p_z is estimated from W mass constraint)
  - **hadronic side : highest Large-R jet that passes the top tagging requirements.**



The performance of the reconstruction is about 90%



Reconstructed invariant masses for the boosted Z'_{TC2} signal.

Multijet background estimation via Matrix Method

Matrix Method is used to estimate the background from non-prompt lepton sources, mainly QCD multijet production ($\geq$ 1 b-jet and $\geq$ 4 jets)

- real eff. (ϵ) computed from MC
- fake eff. (f) measured in QCD enriched control region : CR : $E_T^{miss} < 20$ GeV and $E_T^{miss} + m_T^W < 60$ GeV, $\geq$ 4 jets, $\geq$ 1 b-tagged jet
- rates for full run2 dataset are combined to increase statistics
- best parametrization : topetcone20 and lepton pT

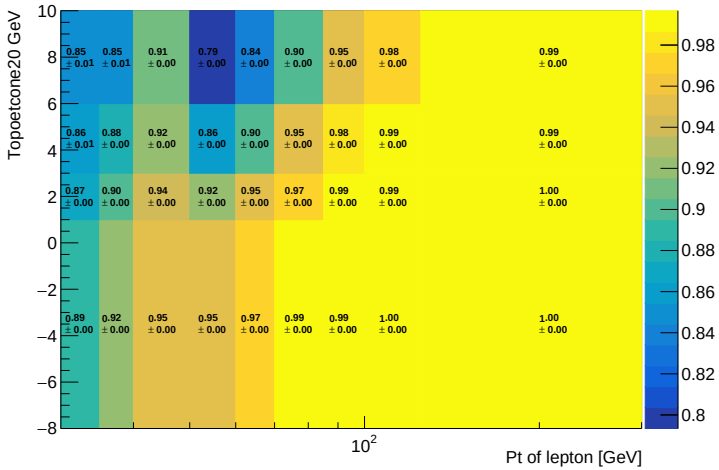
$$N_{loose} = N_{prompt} + N_{QCD}$$
$$N_{tight} = \epsilon \text{ x } N_{prompt} + \text{f x } N_{QCD}$$

Estimation of Multijet background via :

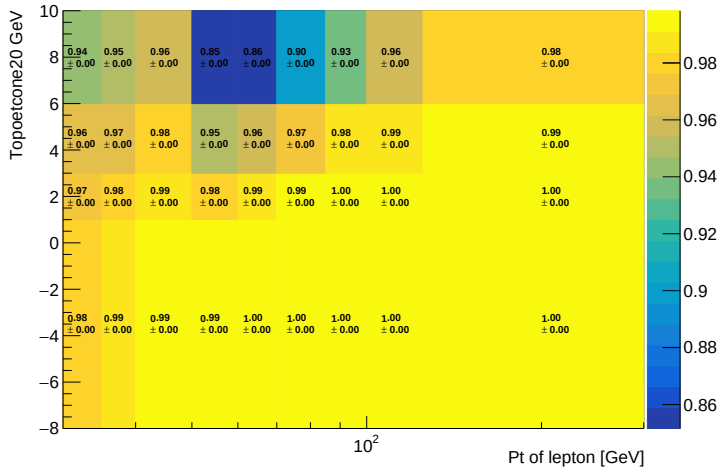
$$fxN_{QCD} = \frac{(\epsilon-1)f}{(\epsilon-f)} N_{tight} + \frac{\epsilon f}{(\epsilon-f)} N_{anti\ tight}$$

Multijet background estimation : rates

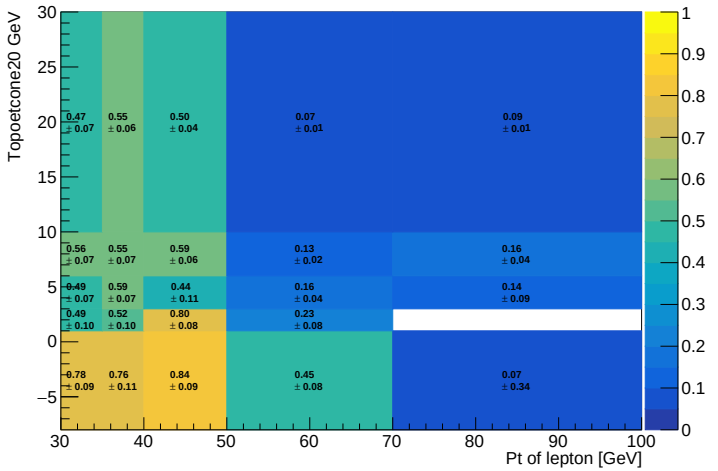
Real : $\Delta R(\mu, jet) < 0.4$



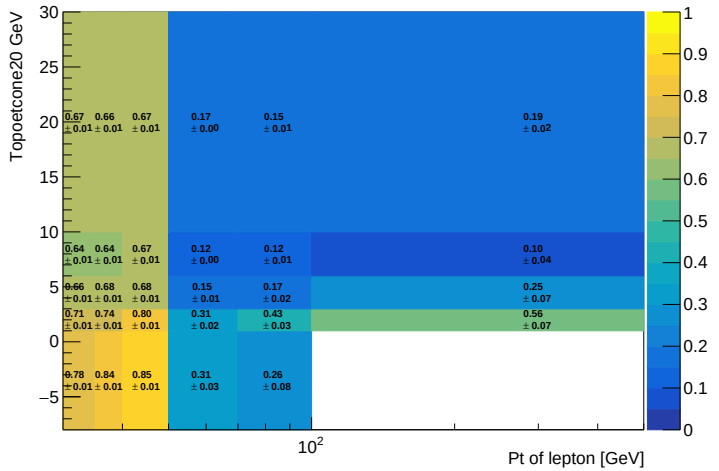
$\Delta R(\mu, jet) \geq 0.4$



Fake : $\Delta R(\mu, jet) < 0.4$

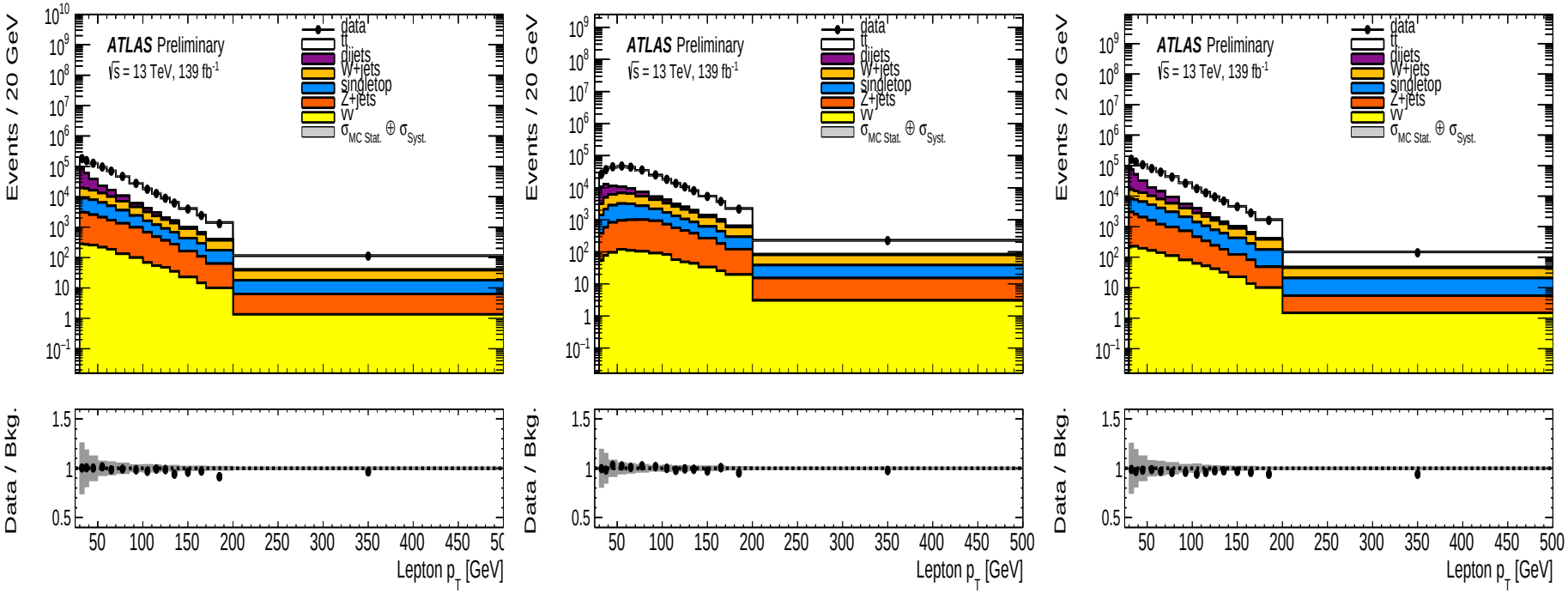


$\Delta R(\mu, jet) \geq 0.4$



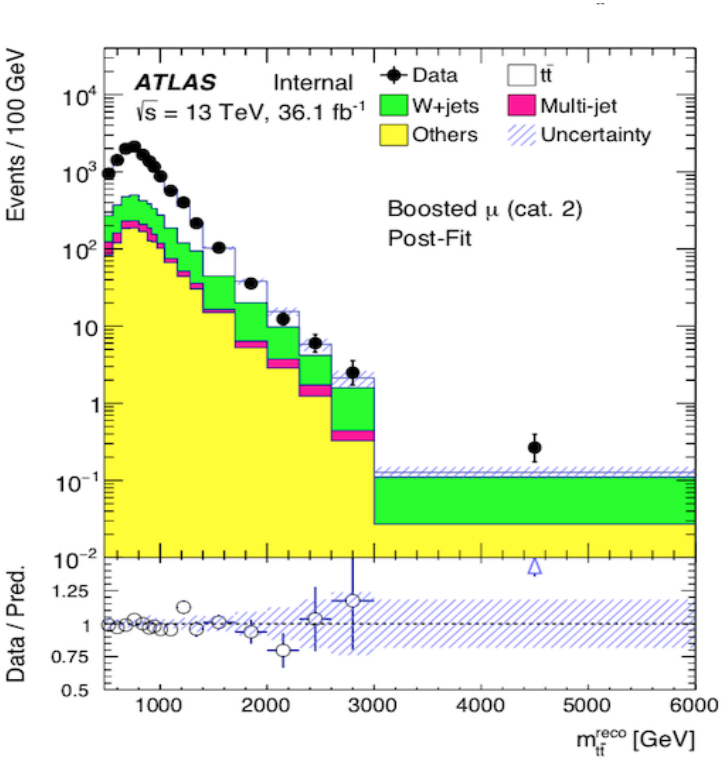
Multijet background estimation : Closure test

CR **VR1** **VR2**

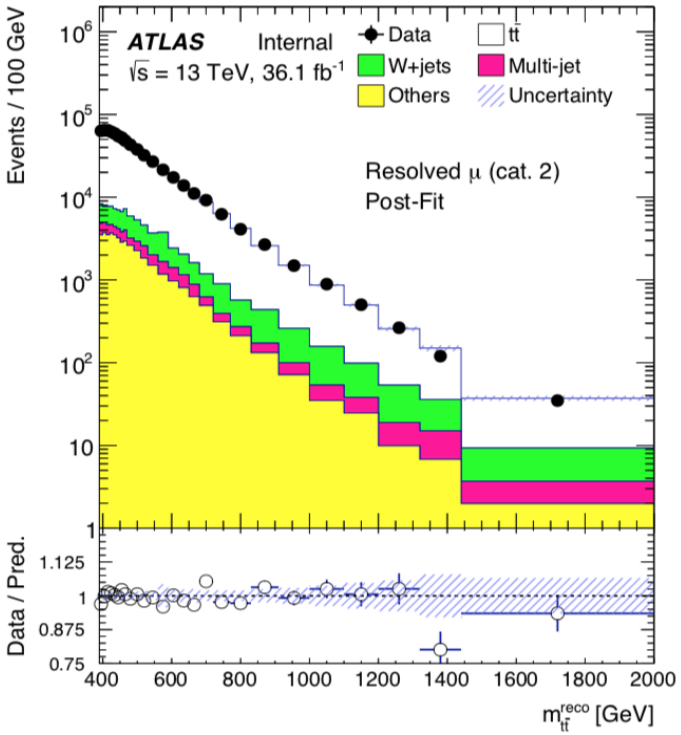


Good agreement between MC prediction and the data for CR and VR's.

$t\bar{t}$ Invariant mass :

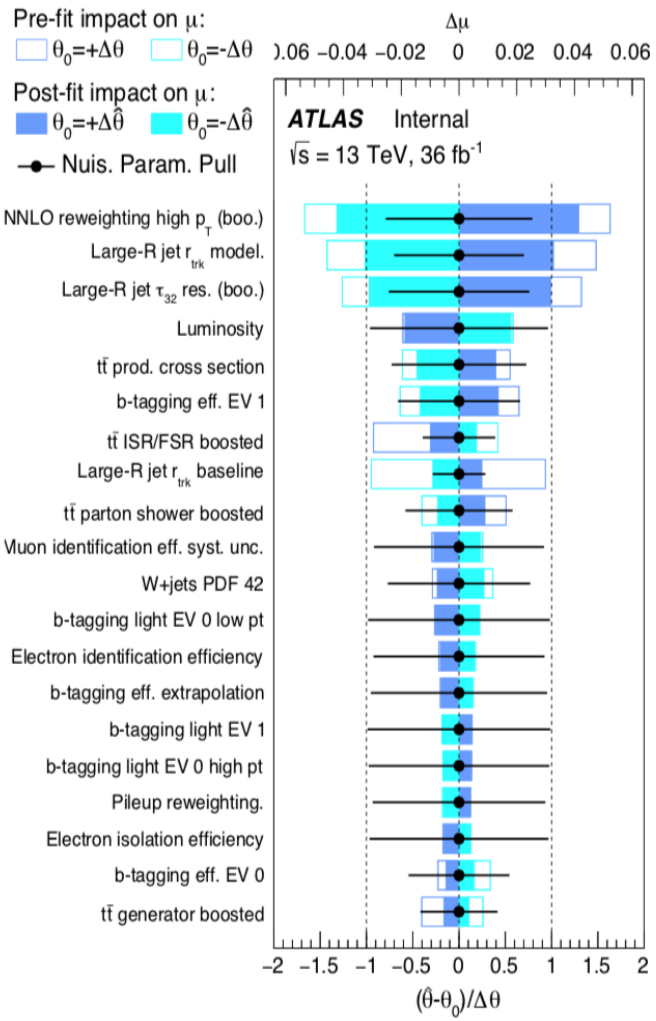


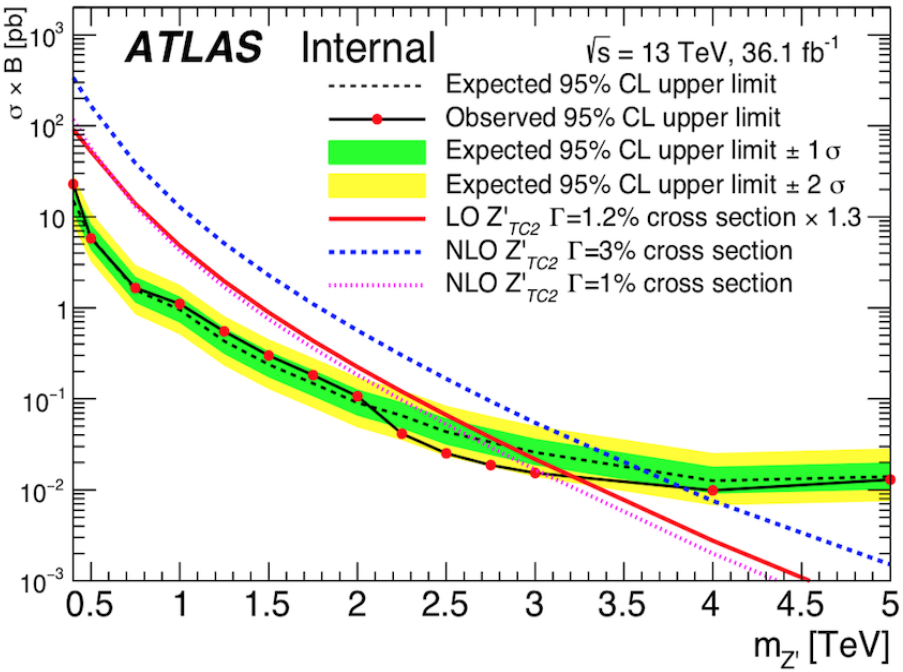
- Good Data-Simulation agreement, within systematic uncertainties.
- **No evidence for a deviation from the Standard Model**



- **Statistical and systematic uncertainties are included as nuisance parameters in the fit**

Systematics and limits for Z' -> $t\bar{t}$:





- **Main systematics from : $t\bar{t}$ modeling, uncertainties in large-R jet energy and luminosity**
- **Expected (observed)** limits (95 % C.L.) are set for Z'_{TC2} Benchmark model :
  - m(Z'_{TC2}) < **2.6** **(3.1)** TeV, Γ/m = 1.2%

Conclusion :

- No sign of new resonances found so far in : the lepton+ jets top-quark pair decay channel.
- 13 TeV data exclude : leptophobic Z' with $m_{Z'} < 3.1$ TeV
- Significant improvement on mass limits from Run-1 for Run-2 searches


BACKUP

Object Definitions :

Jets

Large-R jet
AntiKt-1.0 LCTopo Jets Pre-recommended trimmed jet
(f=5%, R_{sub} = 0.2)
$p_T > 300$ GeV
$|\eta| < 2$
Use for top-tagging

Small-R jet
AntiKt-0.4 EMPFlow Jets
$p_T > 25$ GeV
$|\eta| < 2.5$
Standard JVT cut ($|JVT| > 0.64$)

Track jet (VR track jet)
AntiKtVR30Rmax4Rmin02 Track Jets
Used for b-tagging (DL1r :FixedCutBEff_77, WP 77 %))
$p_T > 10$ GeV
$|\eta| < 2.5$

Leptons

Common Selection
Exactly one lepton e or μ
$E_T^{miss} > 20$ GeV
$E_T^{miss} + m_T^W > 60$ GeV

Muon
MuonQuality Medium
$p_T > 25$ GeV
$|\eta| < 2.5$
Isolation : TightTrackOnly_VarRad
OR Procedure BoostedSlidingDRMu

Electron
ElectronID TightLH
$p_T > 25$ GeV
$|\eta| < 2.5$ excluding crack
($1.37 < |\eta| < 1.52$)
Isolation : TightTrackOnly
OR Procedure ElectronInJetSubtraction

Single-lepton Triggers

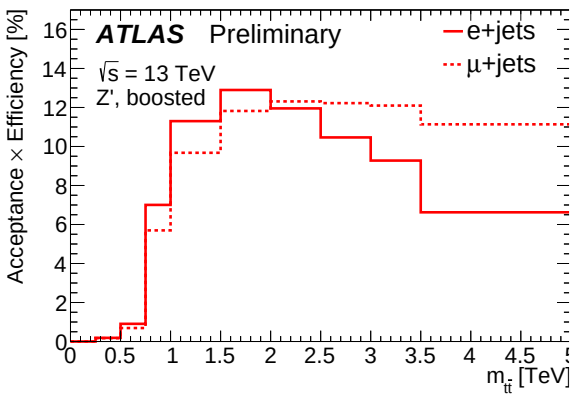
Muon
2015@mu20_iloose_L1MU15_OR_mu50
2016@mu26_ivarmedium_OR_mu50
2017@mu26_ivarmedium_OR_mu50
2018@mu26_ivarmedium_OR_mu50

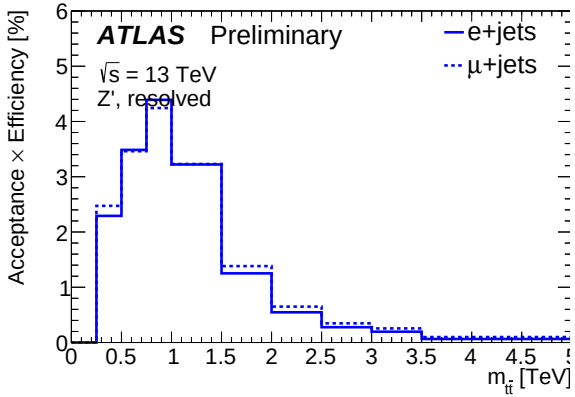
Electron
2015@e24_lhmedium_L1EM20VH_OR_e60_lhmedium_OR_e120_lhloose
2016@e26_lhtight_nod0_ivarloose_OR_e60_lhmedium_nod0_OR_e140_lhloose_nod0
2017@e26_lhtight_nod0_ivarloose_OR_e60_lhmedium_nod0_OR_e140_lhloose_nod0
2018@e26_lhtight_nod0_ivarloose_OR_e60_lhmedium_nod0_OR_e140_lhloose_nod0

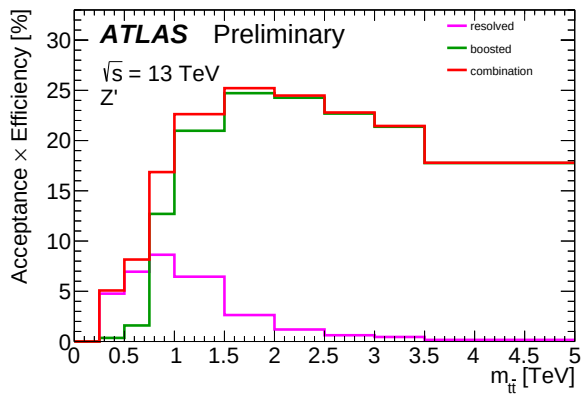
Categories/Acceptance

The events are splited into 4 categories :

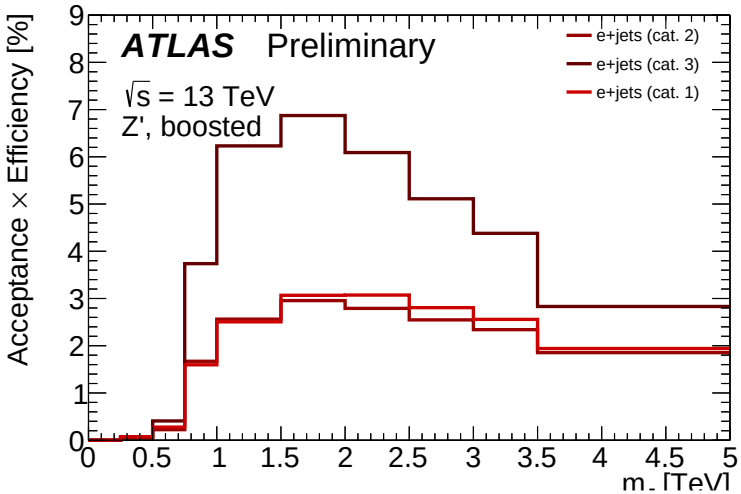
- **Cat 0 : b-tagged jet matching the hadronic nor leptonic top candidates → reject the event from the final signal region.**
- **Cat 1 : only the leptonic top candidate has a matching b-tagged jet**
- **Cat 2 : only the hadronic top candidate has a matching b-tagged jet**
- **Cat 3 : the hadronic top candidate and the leptonic top candidate both have a matching b-tagged jet.**

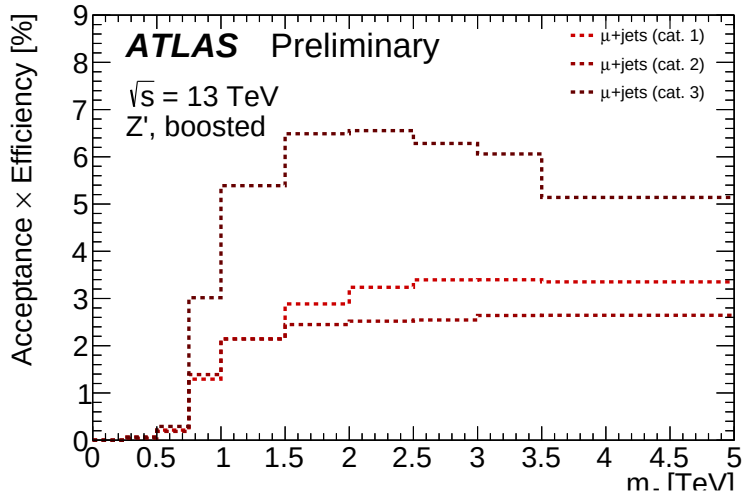


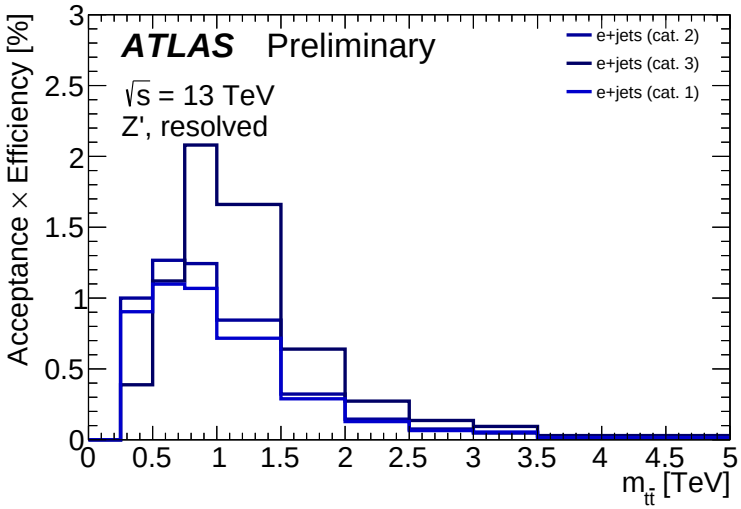


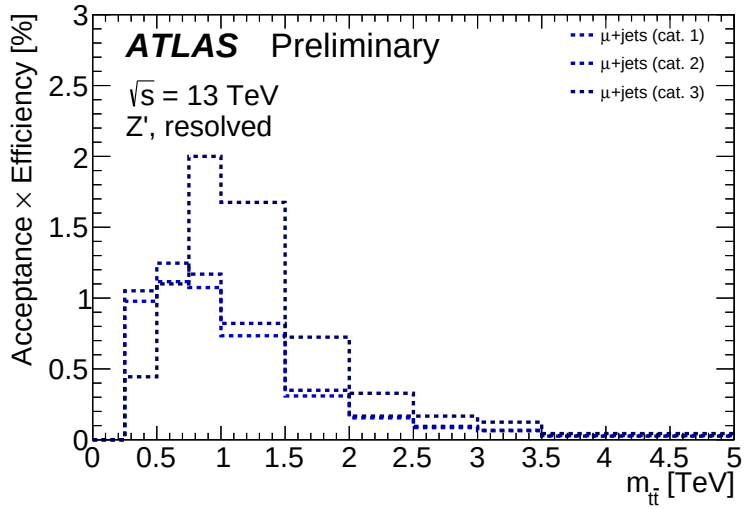


Acceptance x Efficiency (b-Cats)



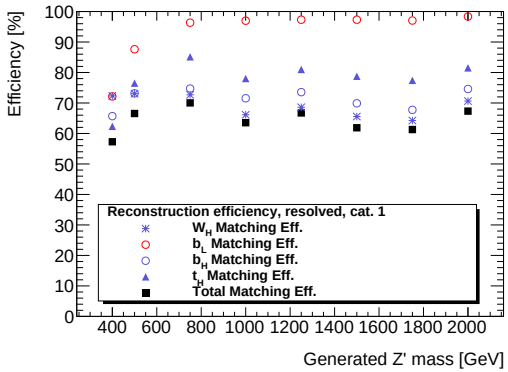




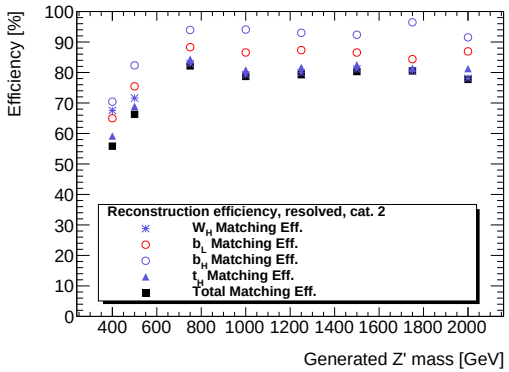


Performance of the reconstruction

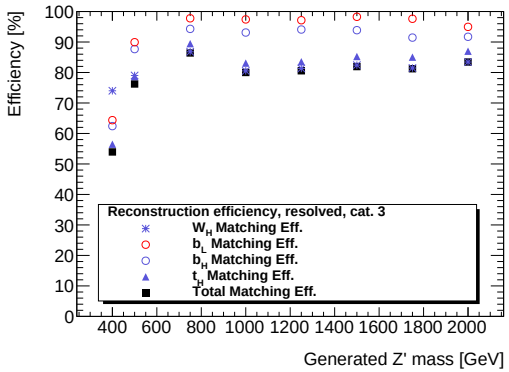
Resolved **Cat 1**



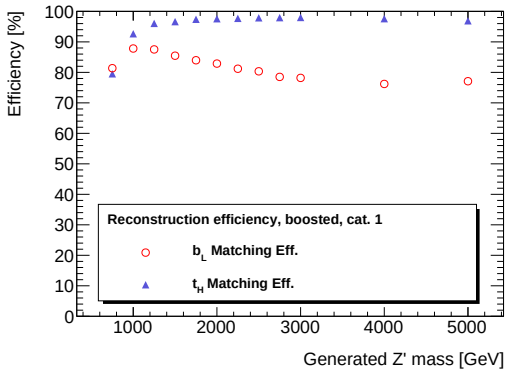
Cat2



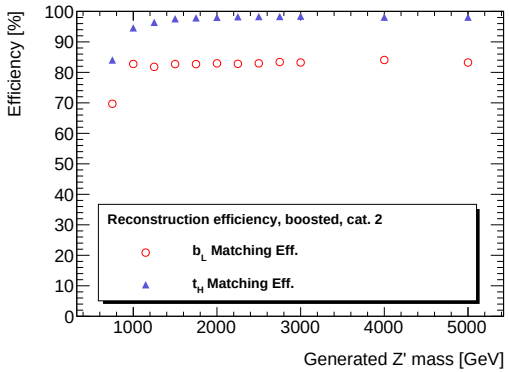
Cat3



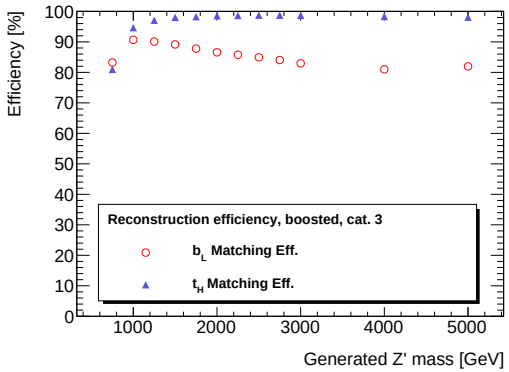
Boosted **Cat 1**



Cat2



Cat3



χ2 Parameters

Measured on a mix of Z'_{TC2} samples (0.5 to 2 TeV)