Search for t t̄ resonances at ATLAS and CMS

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on behalf of the ATLAS & CMS collaborations

Top LHC France

Introduction

- The top quark is the heaviest fundamental particle known.
  - Expected to have major role in BSM physics

- Many models (topcolor, extra dimensions, etc.) predict new heavy particles with enhanced coupling to the top quark
  - These particles may decay preferentially into $t\bar{t}$

- ATLAS and CMS are both very active in these searches, and already have results for all-hadronic, semi and di-leptonic final states

- Focus only semi-leptonic final state, on which French groups are mainly involved.

- Public results :
  - ATLAS: ATLAS-CONF-2013-052
  - CMS: B2G-12-006 / Phys. Rev. Lett. 111 (2013) 211804

- Colors: CMS / ATLAS

- Generic Z' resonance: width and cross-section independent of resonance's mass → model independent benchmark.
  - $\Gamma / m_{Z'} = 1.2\,\%$
  - $\Gamma / m_{Z'} = 10\,\%$
  - Generator: MadGraph 4 / Pythia 8
- Kaluza-Klein excitation of SM gluon: width and cross-section fixed by the resonance's mass
  - $\Gamma / m_g = {\sim}15\,\%$
  - Generator: Pythia 8 / MadGraph 4
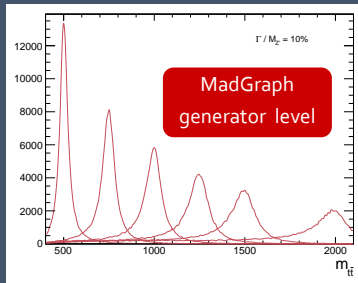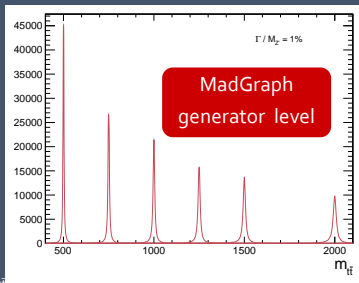
- SM t$\bar{t}$ (irreducible background)
  - MC@NLO + Herwig + CT10
  - Powheg + Pythia + CT10
- Single top
  - MC@NLO + Herwig + CT10 (s and tW channels)
  - AcerMC + Pythia + CTEQ6L1 (t channel)
  - Powheg + Pythia + CT10
- W / Z + jets
  - Alpgen + Pythia + CTEQ6L1
    - Normalization taken from data for W + jets
  - Madgraph + Pythia + CTEQ6L
    - Normalized to NNLO predictions
- Multi-jets
  - Data-driven (matrix method)
  - Estimated from simulation

Analyses strategies

- Similar strategy in both collaborations: the mass range is split in two parts:
  - The resolved regime ($M < 1$ TeV)
  - The boosted regime ($M > 1$ TeV)

- ATLAS has one analysis, but two selections, optimized for resolved and boosted topologies:
  - Events that don't pass the boosted selection are considered resolved
  - Background is estimated on simulation as seen previously

- CMS has two different analyses: one optimized for resolved topologies, and one for boosted topologies
  - The resolved analysis uses a data-driven approach to estimate the background
  - The boosted analysis estimate the background on simulation

Jets / Leptons

- Standard jets: anti-k_T $R = 0.5$, $|\eta| < 2.4$, $R = 0.4$, $|\eta| < 2.5$

- ATLAS uses special jet reconstruction for boosted analysis, in order to stay efficient even in boosted regime:
  - anti-k_T $R = 1.0$, $|\eta| < 2.0$
  - Use trimming to mitigate effect of pileup:
    - Recluster the jet with a smaller radius ($R = 0.3$) and k_T algorithm
    - Remove jets with $p_T < 5\,\%$ of fat jet p_T.

Muons	Electrons

Muons

- Isolated
- Boosted: isolated and $\Delta R(\mu, j) > 0.1$
- Resolved: isolated
- Boosted: no isolation requirement

$$\Delta R(\mu, j) > 0.5 \text{ or } p_T^{\text{rel}}(\mu, j) > 25\,\text{GeV}$$

Electrons

- Isolated
- Boosted: isolated and $\Delta R(e, j) > 0.4$
- Resolved: isolated
- Boosted: no isolation requirement

$$\Delta R(e, j) > 0.5 \text{ or } p_T^{\text{rel}}(e, j) > 25\,\text{GeV}$$

Lepton isolation

- ATLAS
  - dynamic cone size to compute isolation : efficient even for boosted objects

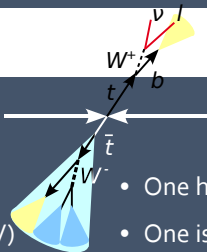$$I = \frac{\sum p_T^{\text{tracks}}}{p_T^{\text{lepton}}} < 5\,\%, R = \frac{10\,\text{GeV}}{E_T}$$

- CMS
  - different cone sizes and thresholds for electrons ($R = 0.3$, $I < 10\,\%$) and muons ($R = 0.4$, $I < 12\,\%$)

$$I = \frac{\sum p_T^{\text{hadrons}} + \sum p_T^{\text{photons}}}{p_T^{\text{lepton}}}$$
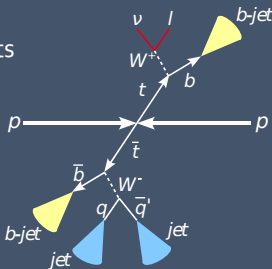
Boosted selection

CMS

- One high-p_T lepton trigger

- One e (μ), $p_T > 35\,\text{GeV}$ (45 GeV)

- At least 2 jets, $p_T > 150/50\,\text{GeV}$

- $\not{E}_t > 50\,\text{GeV}$

- $\not{E}_t + p_T^{\text{lept}} > 150\,\text{GeV}$

- semi-e: triangular cut against multi-jets.

- Four categories: e / μ and
    - 0 b-jet
    - ≥ 1 b-jets

ATLAS

- One high-p_T lepton trigger

- One isolated lepton, $p_T > 25\,\text{GeV}$

- At least one fat jet:
    - $p_T > 300\,\text{GeV}$, $m > 100\,\text{GeV}$
    - $\sqrt{d_{12}} > 40\,\text{GeV}$
    - $\Delta R(\text{jet}, \text{l}) > 2.3$

- At least one standard jet:
    - At least 1 b-tagged jet
    - $\Delta R(\text{jet}, \text{fat jet}) > 1.5$

- semi-e: $\not{E}_t > 25\,\text{GeV}$, $m_T > 25\,\text{GeV}$

- semi-μ: $\not{E}_t > 20\,\text{GeV}$, $\not{E}_t + m_T > 60\,\text{GeV}$

Resolved selection

CMS

- One isolated lepton + 3 jets trigger
- One isolated e / μ, $p_T > 30$ GeV/26 GeV
- At least 4 jets, $p_T > 70/50/30/30$ GeV
- At least 1 b-tagged jet
- $\not{E}_t > 20$ GeV
- Four categories: e / μ and
  - 1 b-jet
  - ≥ 2 b-jets

ATLAS

- **Not selected by the boosted selection**
- One high-p_T lepton trigger
- One isolated lepton, $p_T > 25$ GeV
- If one jet has $m > 60$ GeV:
  - At least 3 jets, $p_T > 25$ GeV (semi-boosted)
- Otherwise
  - At least 4 jets, $p_T > 25$ GeV
- At least 1 b-tagged jet
- semi-e: $\not{E}_t > 25$ GeV, $m_T > 25$ GeV
- semi-μ: $\not{E}_t > 20$ GeV, $\not{E}_t + m_T > 60$ GeV

Selection performances

- **CMS**: selection efficiency on inclusive Z' sample:
  - Resolved analysis: ~3 - 6 % (0.5 to 1.5 TeV)
  - Boosted analysis: ~6 - 11 % (1 to 3 TeV)
- **ATLAS**: selection efficiency on inclusive Z' sample:
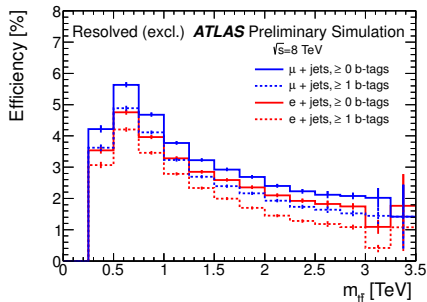
Resolved
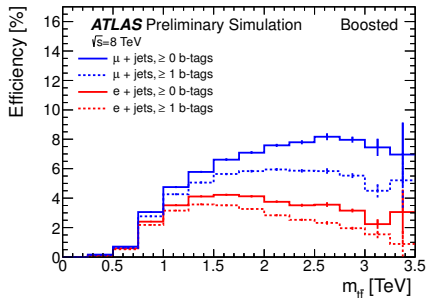
Boosted

- Interpret $\not{E}_t$ as the neutrino. The longitudinal component must be reconstructed.
- We form a quadratic equation using the invariant mass of the lepton and the neutrino, which is constrained to the W mass.
  - Two solutions? Use both in the χ^2 test
  - No solution?
    - Resolved:
      - change $\not{E}_x$ and $\not{E}_y$ synchronously until a solution is found
      - change $\not{E}_x$ and $\not{E}_y$ independently until a solution is found
    - Boosted:
      - keep only real part of the solution
      - change $\not{E}_x$ and $\not{E}_y$ independently until a solution is found

- Choose good jets combination using a χ^2 sorting algorithm

- ATLAS
  - No high mass jet: χ^2 with hadronic W mass, leptonic top mass, (hadronic top mass - hadronic W mass) and Δp_T^{tops}

  - High mass jet: consider it as the hadronic W boson. Remove hadronic W mass term from χ^2

- CMS: χ^2 with hadronic W mass, leptonic and hadronic top mass, and p_T of $t\bar{t}$ system.
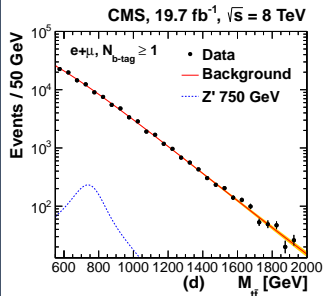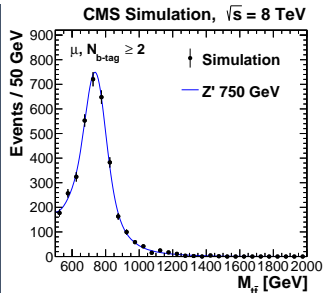
Jets combination choice — boosted analyses

- Choose good jets combination using a χ^2 sorting algorithm

- ATLAS
  - No ambiguity: the fat jet is considered as the hadronic top, and the light jet is the leptonic B jet.

- CMS
  - Exactly one jet on the leptonic side, and at least one jet to the hadronic side
  - χ^2 with leptonic and hadronic top masses.
  - $\chi^2 < 10$

Background modeling — resolved analyses

- Look for a bump in a falling background

- Data-driven estimation for background: fit the data with a functional form

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{t\bar{t}}} = \frac{\left(1 - m/\sqrt{s}\right)^{c_1}}{\left(m/\sqrt{s}\right)^{c_2 + c_3 \ln m/\sqrt{s}}}$$

- Signal shape derived from simulation using a kernel estimation

CMS Simulation, $\sqrt{s}$ = 8 TeV

μ, $N_{b\text{-tag}} \geq 2$

Simulation

Z' 750 GeV

Events / 50 GeV

$M_{t\bar{t}}$ [GeV]

CMS, 19.7 fb^{-1}, $\sqrt{s}$ = 8 TeV

e+μ, $N_{b\text{-tag}} \geq 1$

Data

Background

Z' 750 GeV
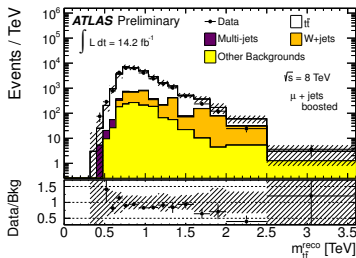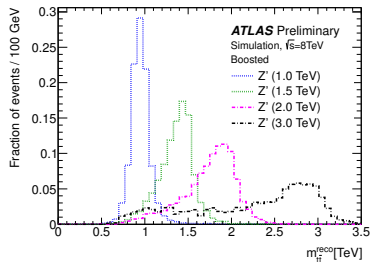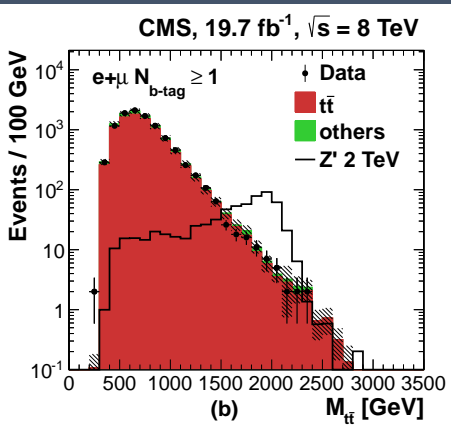
Events / 50 GeV

(d) $M_{t\bar{t}}$ [GeV]

Background modeling — resolved analyses

- Monte-Carlo estimation

- W + jets normalization calculated using W charge asymmetry

- Multi-jets normalized from matrix method
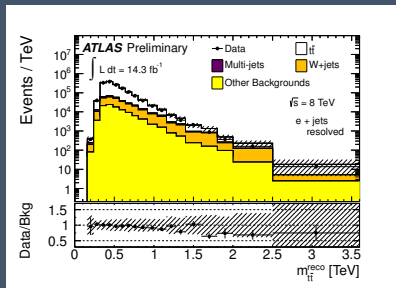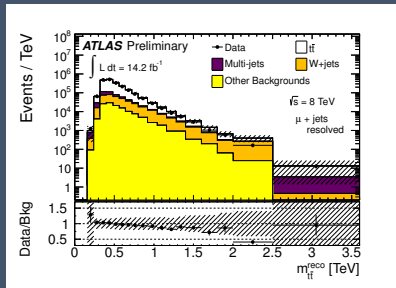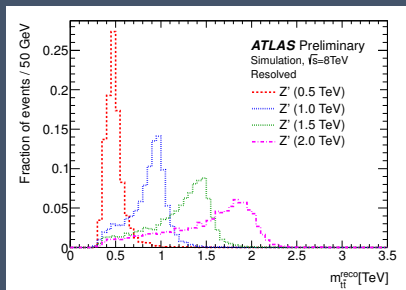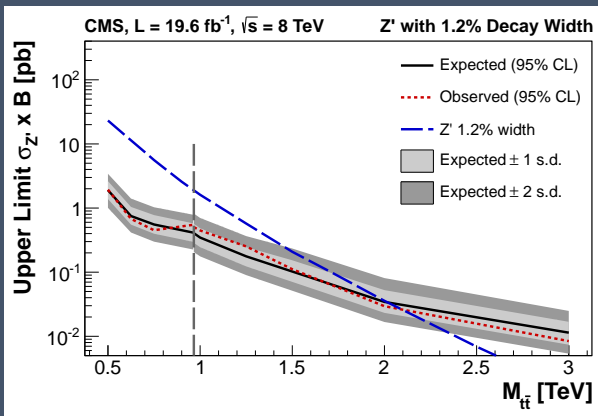
Systematic uncertainties

CMS
(Boosted — Common — Resolved)

- $t\bar{t}$
  - Normalization: 15 %
  - Factorization / renormalization scale
- W + jets
  - Light-flavor jets: 50 %
  - Heavy-flavor jets: 100 %
- Z + jets: 100 %
- Single top: 50 %
- Multi-jets: 100 %
- PDF
- JES, JER, Luminosity
- Signal / background Probability Density Function

ATLAS

- $t\bar{t}$
  - Normalization: 11 %
  - Electroweak corrections: 3 % to 9 %
  - QCD ISR/FSR modeling
  - MC@NLO vs Powheg
  - Factorization / renormalization scale
- W + jets
  - Resolved: 18 % / 16 % (e / μ)
  - Boosted: 22 % / 16 % (e / μ)
- Z + jets: 48 %
- Single top: 7.7 %
- Multi-jets: 50 %
- PDF: up to 40 % at 2 TeV
- JES, luminosity, ...

Results — CMS

- Bayesian method to extract upper limit on $\sigma \times BR$
- Combine limits from both analysis: transition between resolved and boosted analysis based on the sensitivity of the expected limit

CMS, L = 19.6 fb^{-1}, $\sqrt{s}$ = 8 TeV — Z' with 1.2% Decay Width

- Expected (95% CL)
- Observed (95% CL)
- Z' 1.2% width
- Expected ± 1 s.d.
- Expected ± 2 s.d.

Upper Limit $\sigma_{Z'} \times B$ [pb] vs $M_{t\bar{t}}$ [TeV]

Exclude masses below:

- 2.10 TeV (narrow Z')
- 2.68 TeV (large Z')
- 2.54 TeV (KK gluons)

- Bayesian method to extract upper limit on $\sigma \times BR$
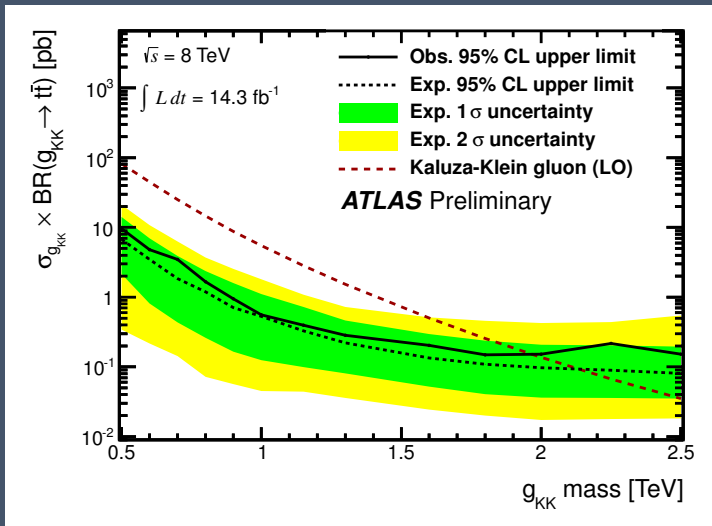- ~6 fb^{-1} **missing compared to CMS**
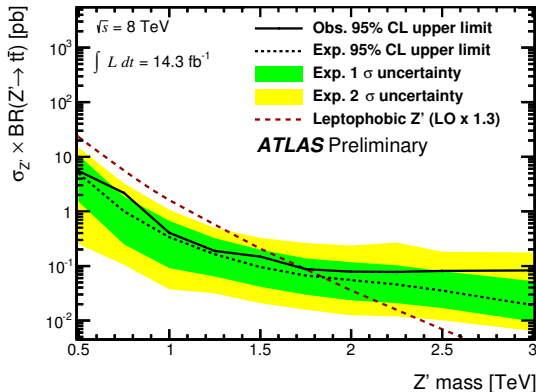
Exclude masses below:
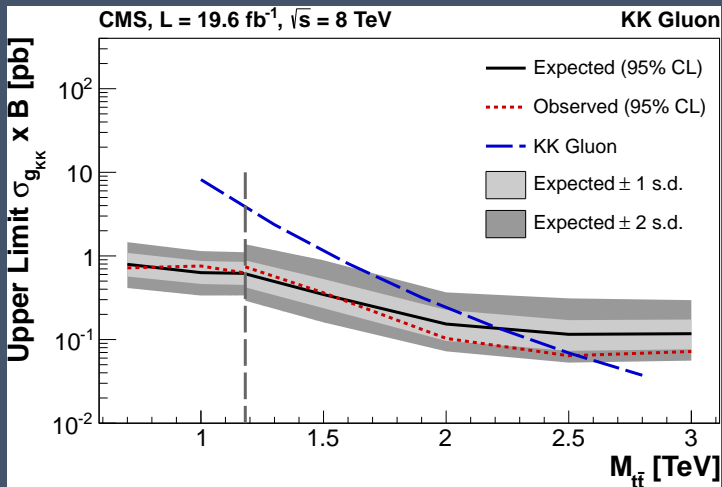- 1.8 TeV (narrow Z')
- 1.9 TeV (KK gluons)

- ATLAS:
  - Grenoble: fat jet selection optimization
  - Clermont: selection optimization, reconstruction performances for resolved selection and analysis coordination

- CMS:
  - Lyon: responsible for resolved analysis

- Both collaborations use similar strategy to improve sensibility over the whole mass range:
  - CMS uses two different analyses and combines limits
  - ATLAS uses one analysis but two different selections

- Main difference comes from boosted topologies
  - ATLAS uses fat jet with grooming
  - CMS loosen isolation criteria on lepton and number of jets

- No sign of new physics is found. We start to reach exclusion limit of ~2 TeV

- CMS is a bit more efficient than ATLAS on exclusion, but comparison is not fair: ~6 fb^{-1} of data is missing. Let's wait for the analysis on the full dataset!

Backup

$$\frac{-1.5}{75} \not{E}_t + 1.5 < \Delta\phi(\text{e or j}, \not{E}_t) < \frac{1.5}{75} \not{E}_t + 1.5$$