Measurements of Differential $t\bar{t}$ Cross Sections at the LHC

Flera Rizatdinova (Oklahoma State University)

7th Workshop On The CKM Unitarity Triangle
28 Sep - 2 Oct 2012, Cincinnati, Ohio

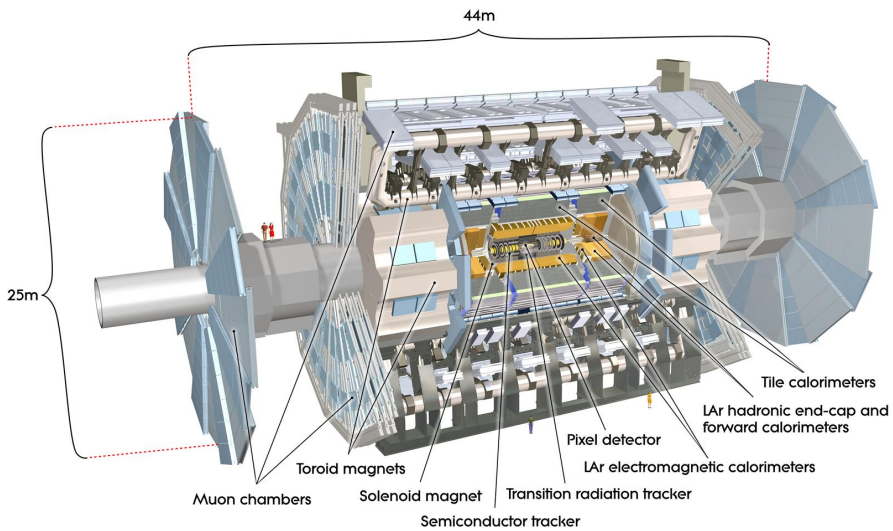
Outline

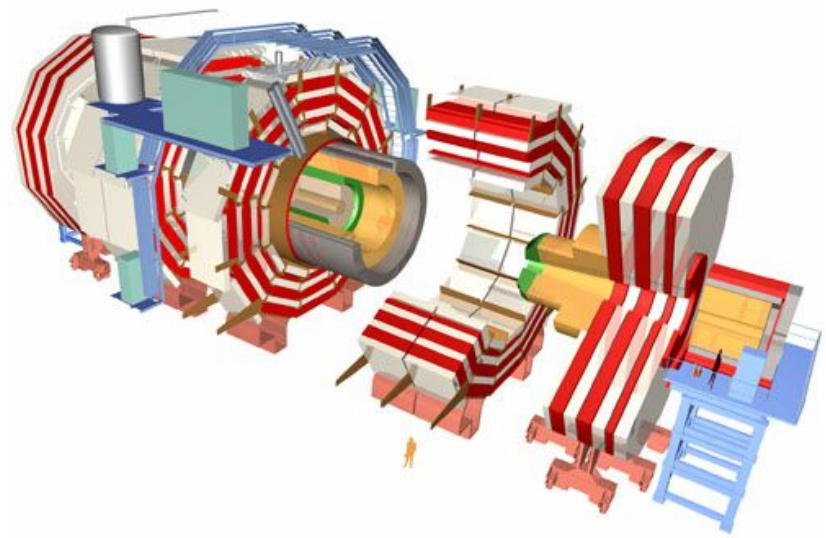
- Introduction
- Results of measurements:
  - Differential cross section as a function of jet multiplicity
  - $t\bar{t}$+additional jets cross section
  - Top quark pair relative differential cross-sections
  - Measurement of $t\bar{t}$ production with a veto on additional central jet activity (gap fraction)
  - Associated production of vector bosons with top-antitop pairs
  - Associated production of b-quark pairs with top-quark pairs
- Conclusions

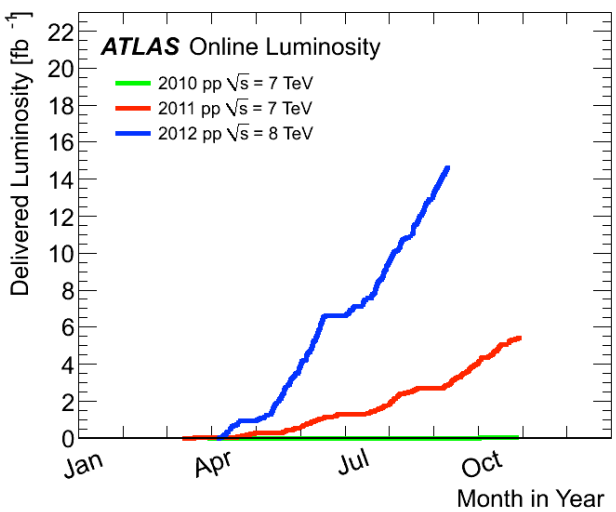
Motivation for differential cross sections measurements

- Large statistics of $t\bar{t}$ events at LHC provides a great opportunity to study the details of the $t\bar{t}$ production mechanism
  - Sensitive to new physics
  - Precise description of hard interactions at the LHC, including initial and final state radiations
  - Production of top-antitop pairs in association with hard jets or vector bosons is main background to many searches of new physics
  - Tuning of the Monte Carlo generators, which will help in reducing the systematic uncertainties in future physics measurements
- From theoretical side, complete calculations at NLO are available for comparison to data

ATLAS and CMS experiments







- Both experiments are doing great in terms of data taking
  - 92-94% of delivered data is recorded in years 2011/2012
  - ~85-90% is used for physics analyses
  - This talk contains results based on 2011 data, pp collisions at $\sqrt{s}$=7 TeV

Selections in lepton+jets channel

- ATLAS selections
  - the unprescaled single-electron or single-muon trigger fired;
  - jets: $p_T > 25$ GeV and $|\eta| < 2.5$
  - exactly one reconstructed lepton matching the trigger
    - **Muon:** p_T>20 GeV, $|\eta|$<2.5, $E_{Tmiss} > 20$ GeV and $m_{T,W}+E_{Tmiss} > 60$ GeV
    - **Electron:** p_T>25 GeV, $|\eta|$<2.47, excluding $1.37 < |\eta| < 1.52$. $E_{Tmiss} > 30$ GeV and $m_{T,W} > 30$ GeV

- CMS selections
  - single-muon trigger; single electron + ≥3 jets trigger fired;
  - at least 4 jets with $p_T > 30$ GeV and $|\eta| < 2.4$, at least one of them is tagged as a b-jet
  - exactly one reconstructed lepton matching the trigger
    - **Muon:** p_T>20 GeV, $|\eta|$<2.1,
    - **Electron:** p_T>30 GeV, $|\eta|$ <2.5

Selections in dilepton channels

- ATLAS selections
  - the unprescaled single-electron or single-muon trigger;
  - at least two jets with $p_T > 25$ GeV and $|\eta| < 2.5$
  - exactly two oppositely charged leptons matching the trigger
    - **Muon:** $p_T>20$ GeV, $|\eta|<2.5$,
    - **Electron:** $p_T>25$ GeV, $|\eta|<2.47$, excluding $1.37 < |\eta| < 1.5$
  - $|m_{ll}-m_Z|>10$ GeV and $E_{T,miss}>60$ GeV in ee,μμ channels;
  - Sum of lepton and jet $E_T > 130$ GeV in eμ

- CMS selections
  - dilepton trigger with additional isolation cuts
  - at least 2 jets with $p_T > 30$ GeV and $|\eta| < 2.4$, at least one of them is tagged as a b-jet
  - $|m_{ll}-m_Z|>15$ GeV and $E_{T,miss}>30$ GeV in ee,μμ channels;
  - at least two isolated oppositely charged leptons (if more than two leptons, lepton pair with highest p_T is considered)
    - **Muon:** $p_T>20$ GeV, $|\eta|<2.1$,
    - **Electron:** $p_T>30$ GeV, $|\eta|<2.5$

Differential $t\bar{t}$ cross section as a function of jet multiplicity, $1/\sigma_{tt} \cdot d\sigma_{tt}/dN_{jets}$

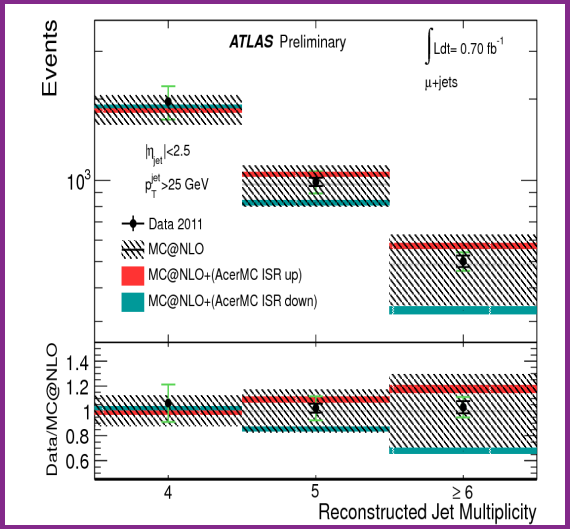
- At the LHC energies, the fraction of $t\bar{t}$ events produced with additional hard jet(s) is high
  - Need detailed understanding and description of $t\bar{t}$ production
- Reconstructed jet multiplicity in $t\bar{t}$ events is measured by ATLAS and CMS; differential cross section by CMS
  - ATLAS: lepton+jets channel using integrated luminosity $\mathcal{L} = 0.7\ fb^{-1}$
  - CMS: dilepton channel using $\mathcal{L} = 5\ fb^{-1}$
- Additional jets definition:
  - CMS: jets in the kinematic region which are not identified by kinematic reconstruction as part of the $t\bar{t}$ system

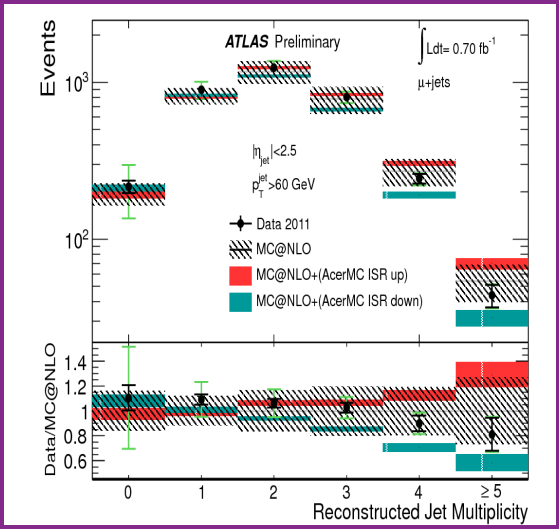
Reconstructed jet multiplicity

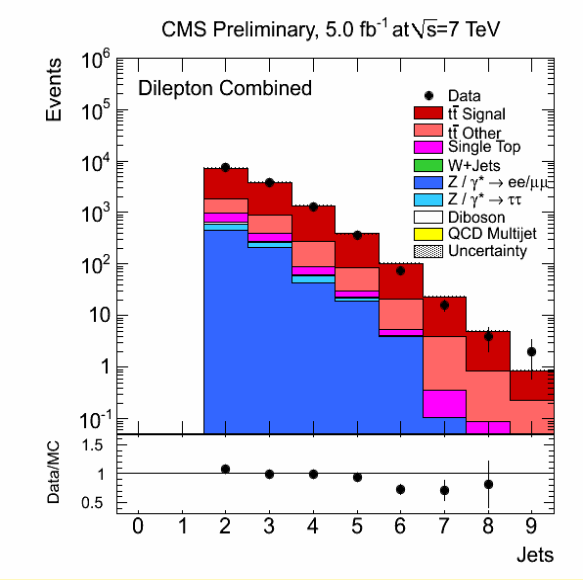
8

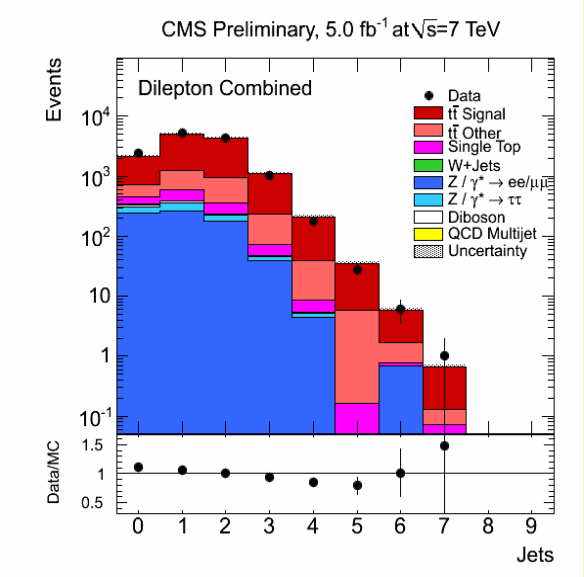
ATLAS-CONF-2011-142

- ATLAS:
  - μ+jets channel
  - Left: jets with p_T>25 GeV; right: jets with p_T> 60 GeV









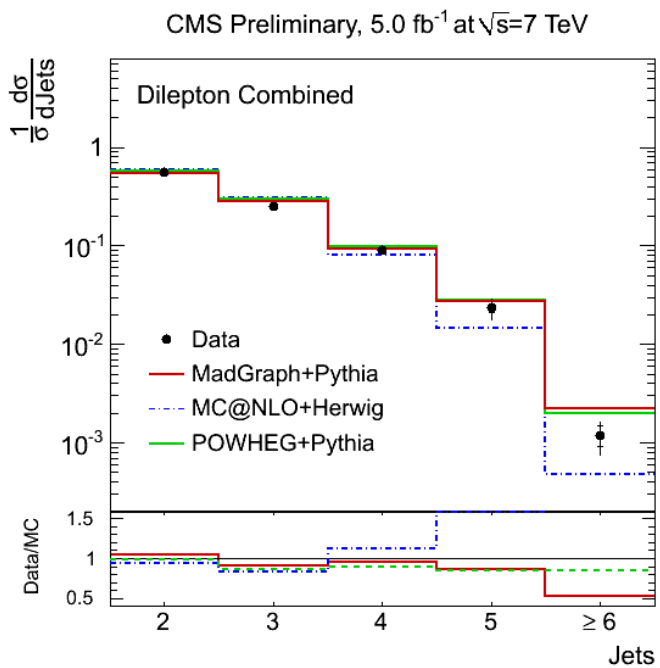
CMS-PAS-TOP-12-023

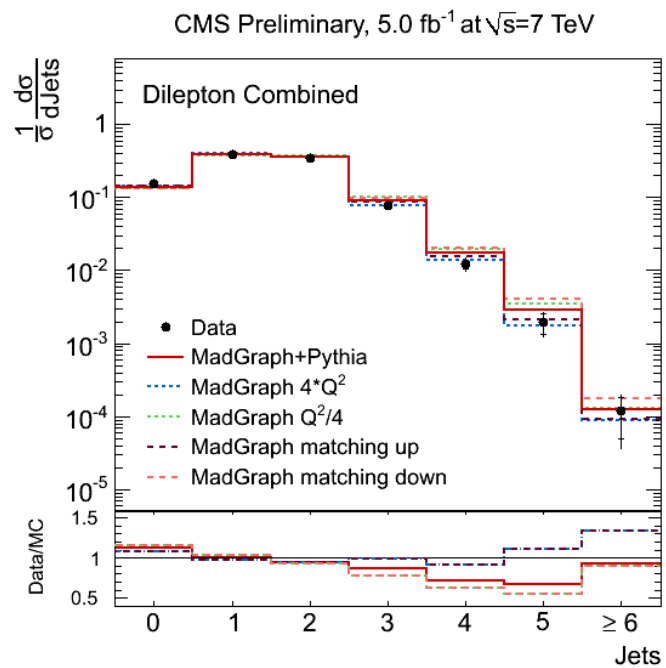
- CMS:
  - Dimuon channel (combination of ee, eμ, and μμ channels)
  - Left: jets with p_T>20GeV, right: jets with p_T>60 GeV

CMS-PAS-TOP-12-023

Results on $1/\sigma_{tt} \cdot d\sigma_{tt}/dN_{jets}$ measurement

- Presented cross section is measured in the kinematic phase space at particle level:
  - Leptons: $|\eta| < 2.4$ and $p_T > 20$ GeV
  - Both b-jets from the top quark decays: $|\eta_b| < 2.4$ and $p_{T,b} > 30$ GeV.
  - A jet at particle level: reconstructed using anti-kT clustering algorithm with size parameter R = 0.5 from all stable particles (including neutrinos)





Eur.Phys.J. C72 (2012) 2043
CMS-PAS-TOP-12-023

Gap fraction measurement

- Measurement of jet activity is sensitive to the theoretical description of quark and gluon radiation
  - Helps to constrain the MC generator modelling, better understanding of ttbar production as a background to other processes, including new physics
- Measurements were performed by ATLAS and CMS
  - ATLAS data sample: $\mathcal{L}$= 2.05 fb^{-1} ; CMS data sample: $\mathcal{L}$ = 5 fb^{-1}
  - both experiments look at dilepton channel ll (l=e/μ)
  - ATLAS: requiring two jets to be tagged as b-quark jets; CMS: at least 1 jet to be tagged as a b-jet
  - corrections for detector effects applied
- Results compared to the theoretical models implemented in MC@NLO, Powheg, Alpgen and Sherpa MC generators

Eur.Phys.J. C72 (2012) 2043

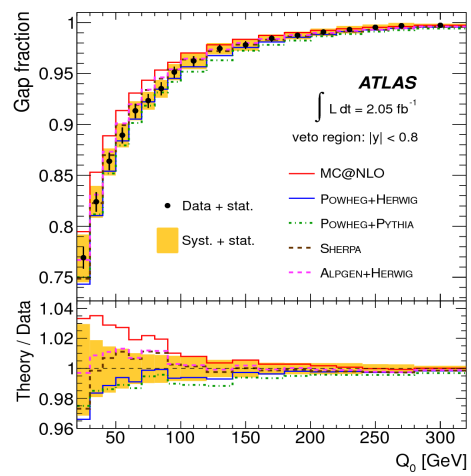
Definitions of the gap fraction

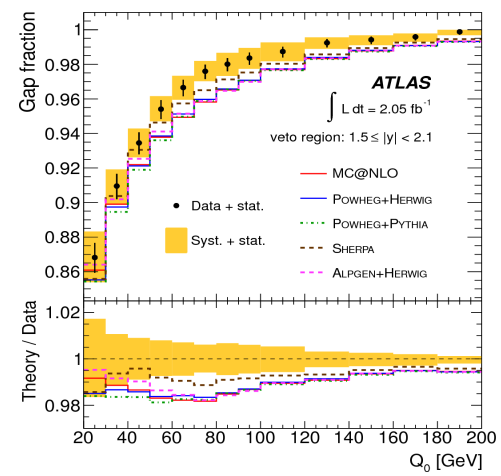
- Additional jets:
  - ATLAS: any jet except two tagged b-jets
  - CMS: jets in the kinematic region which are not identified by kinematic reconstruction as part of the $t\bar{t}$ system
- Definition 1: $f(Q_0) = \frac{\sigma(Q_0)}{\sigma}$ - sensitive to the leading p_T emission
  - Q_0 is the p_T threshold for jets, $\sigma(Q_0)$ is the cross section of $t\bar{t}$ events produced without additional jets in the fiducial region, and σ is the inclusive ttbar cross section in the fiducial region
- Definition 2: $f(Q_{sum}) = \frac{\sigma(Q_{sum})}{\sigma}$ -sensitive to all hard emissions accompanying the $t\bar{t}$ system
  - Q_{sum} is scalar sum of transverse momenta of all additional jets in the event
- ATLAS measured it as a function of jet p_T in rapidity intervals $|y|<0.8$; $0.8 \le |y| < 1.5$; $1.5 \le |y| < 2.1$ and $|y|<2.1$

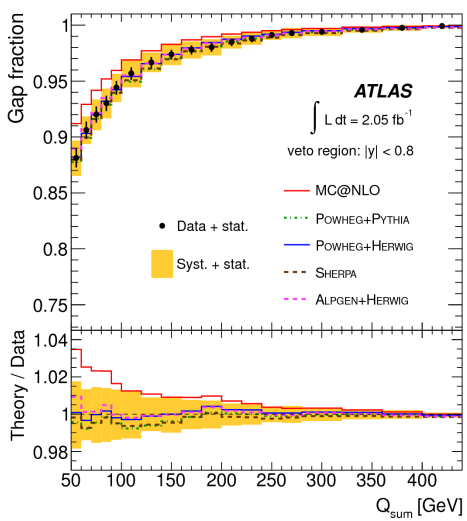
Eur.Phys.J. C72 (2012) 2043

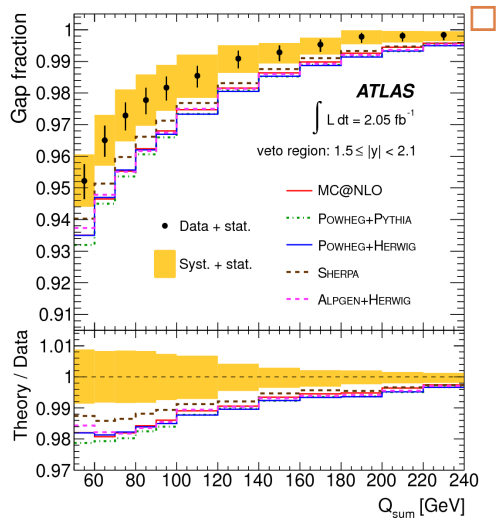
ATLAS results on gap fraction measurement

- Gap fraction definition 1:
  - In |y|<0.8, MC@NLO predicts less jets than observed in data
  - In the most forward rapidity interval, none of the predictions agrees with the data for all values of Q_0







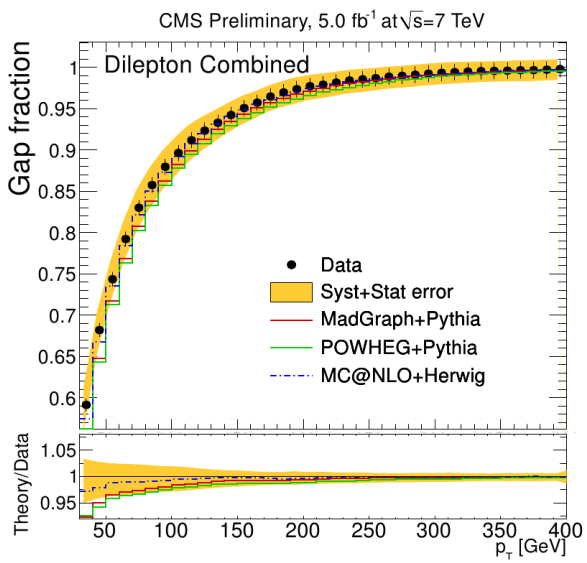


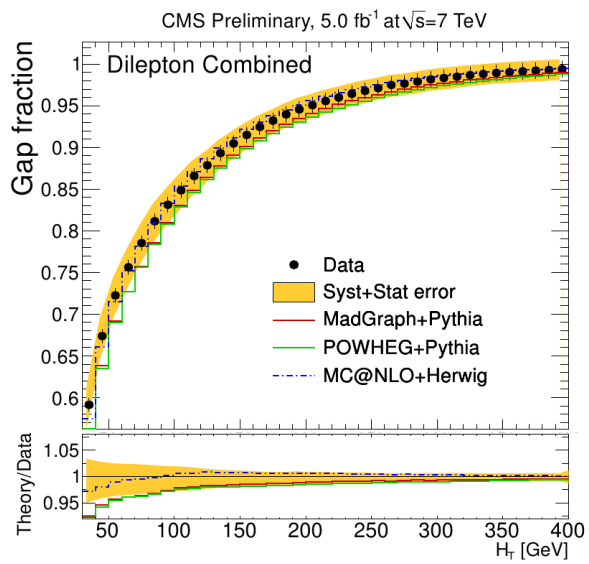
- Gap fraction definition 2:
  - Similar behavior as in case of Q_0
  - Parton shower for subsequent emissions in NLO generators is performing as well as ones in LO generators

CMS-PAS-TOP-12-023

CMS results on gap fraction measurement

- Measurements done as a function of the p_T of the leading additional jet and the scalar sum of the transverse momentum of the additional jets, H_T





Good agreement between data and MadGraph+Pythia, Powheg+Pythia.

ATLAS-CONF-2012-083

$t\bar{t}$+jets cross section $\sigma(t\bar{t}$+jets) measurement

- One of the major backgrounds to the $t\bar{t}H$ channel, heavy charged Higgs searches and some other new physics searches
- Can be compared to theoretical calculations
- Definition of additional jets:
  - **Definition 1:** particle jets with p_T>5 GeV that have not been matched to the top quark decay products were declared as additional jets in the event
  - **Definition 2:** all events with at least 5 jets were considered as events with additional jets
- Analysis was done:
  - on data sample corresponding to $\mathcal{L}$= 4.7 fb^{-1} at 7 TeV
  - in single lepton channel (e/μ) with veto on any other reconstructed lepton
  - using likelihood method

ATLAS-CONF-2012-083

σ($t\bar{t}$+jets): Results

- $t\bar{t}$ +jets cross section and its ratio to inclusive $t\bar{t}$ cross-section according to definition 1:

$$\sigma_{t\bar{t}+jets} = 102 \pm 2(\text{stat.})^{+23}_{-26}(\text{syst.})\ \text{pb}$$

$$\frac{\sigma_{t\bar{t}+jets}}{\sigma_{t\bar{t}}} = 0.51 \pm 0.01(\text{stat.}) \pm 0.08(\text{syst.})$$

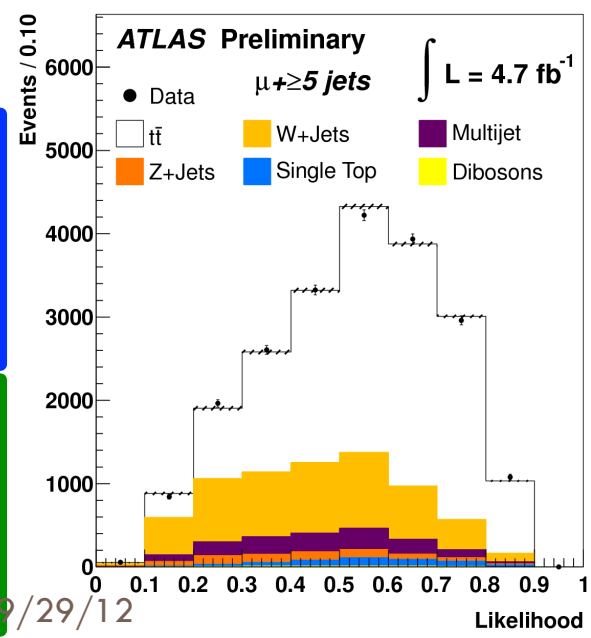
- Cross sections in fiducial volumes defined by kinematic selections:

$$\sigma^{fiducial}_{t\bar{t}+jets \to e+jets} = 2.59 \pm 0.09(\text{stat.})^{+0.26}_{-0.46}(\text{syst.})\ \text{pb}$$

$$\sigma^{fiducial}_{t\bar{t}+jets \to \mu+jets} = 3.48 \pm 0.08(\text{stat.})^{+0.43}_{-0.61}(\text{syst.})\ \text{pb}$$

$$\sigma^{fiducial}_{t\bar{t}+X \to e+\geq 5\,jets} = 4.09 \pm 0.18(\text{stat.})^{+0.62}_{-0.85}(\text{syst.})\ \text{pb}$$

$$\sigma^{fiducial}_{t\bar{t}+X \to \mu+\geq 5\,jets} = 5.27 \pm 0.16(\text{stat.})^{+1.04}_{-1.20}(\text{syst.})\ \text{pb}$$



CMS-PAS-TOP-12-024

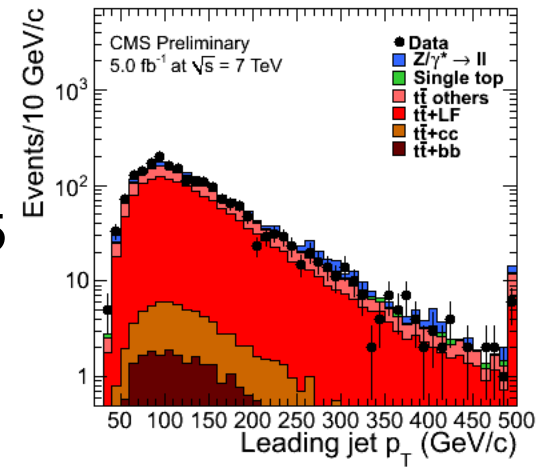
Associated production of $t\bar{t}b\bar{b}$

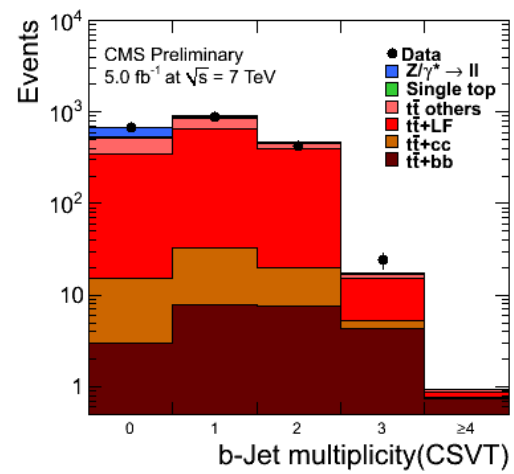
- Irreducible background to $t\bar{t}H$ channel
  - $t\bar{t}H$ is the most promising channel to measure the Yukawa coupling of Higgs boson and top quark
- This channel has not been observed yet by any other experiment
- Can provide a good test for NLO QCD calculations
- Analysis was performed
  - in dilepton mode using $\mathcal{L}$ = 5 fb^{-1}
  - in the fiducial region defined by selection criteria
- Results are presented as a ratio of $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$, where j is referred to any additional jet in $t\bar{t}$ events

CMS-PAS-TOP-12-024

Associated production of $t\bar{t}b\bar{b}$

- Definition of $t\bar{t}b\bar{b}$ at the particle level:
  - Particle jets are built recombining all final state particles (excluding neutrinos)
  - Particle jets selection: p_T>20 GeV, $|\eta|$<2.5, R_{ij}>0.5
  - b-jets are jets with b-hadrons
- Event selection:
  - at least two opposite sign leptons, M_{ll}>12 GeV
  - ee/μμ: $|M_{ll}-M_Z|$>12 GeV, MET>30 GeV
  - ≥4 jets, ≥2 b-tagged jets
- Fit the b-tagged jet multiplicity distribution in data to a sum of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ templates
- Correct to particle level





$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$= 3.6±1.1(stat.)±0.9(syst.)%

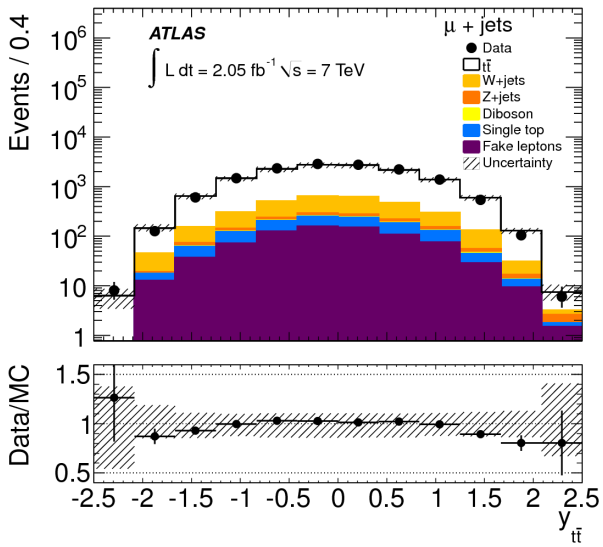
Measurement of the $t\bar{t}$ relative cross sections $1/\sigma_{tt} \cdot d\sigma_{tt}/dx_{tt}$

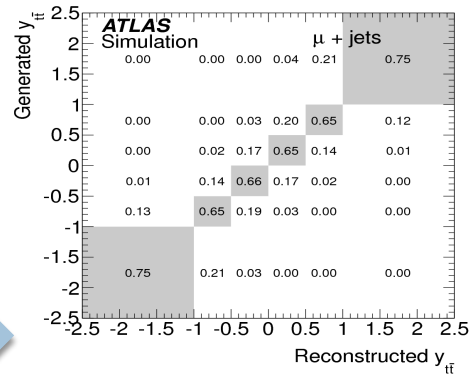
arXiv:1207.5644
CMS-PAS-TOP-11-013

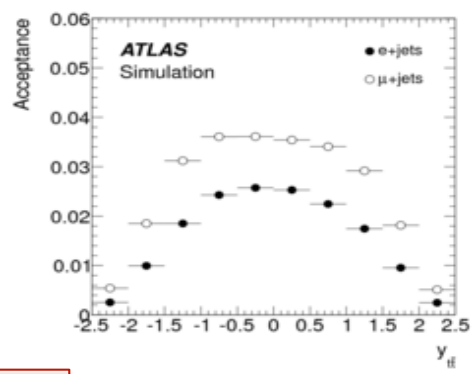
- Detailed studies of the $t\bar{t}$ system in terms of:
  - mass of $t\bar{t}$ system (sensitive to new scalars), its transverse momentum (sensitive to QCD radiation) and rapidity distributions (sensitive to gluon distributions)
- Results were obtained:
  - on data sample corresponding to $\mathcal{L}$= 2.05 fb^{-1} (ATLAS) / $\mathcal{L}$=1.14 fb^{-1} (CMS)
  - in single lepton channel (e/μ) (ATLAS, CMS) and in dilepton channel (CMS)
  - by applying corrections for detector effects after the background subtraction and were normalized to the total inclusive $t\bar{t}$ cross-section
    - CMS used bin-by-bin corrections with requirements of purity and stability
    - ATLAS unfolding is on the next page

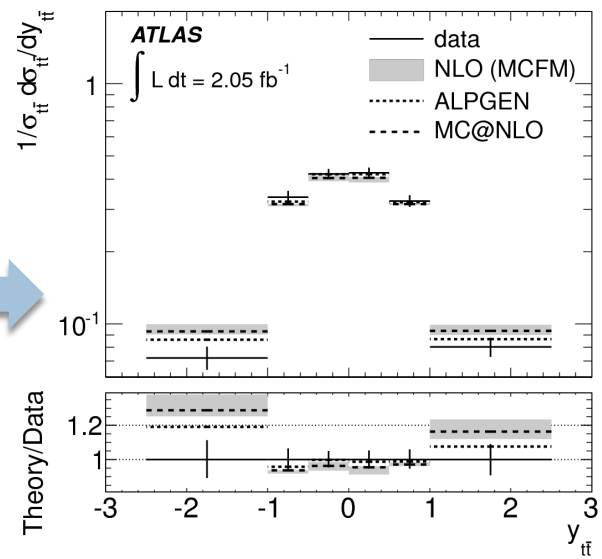
arXiv:1207.5644, submitted to Eur. Phys. J. C

ATLAS Unfolding procedure





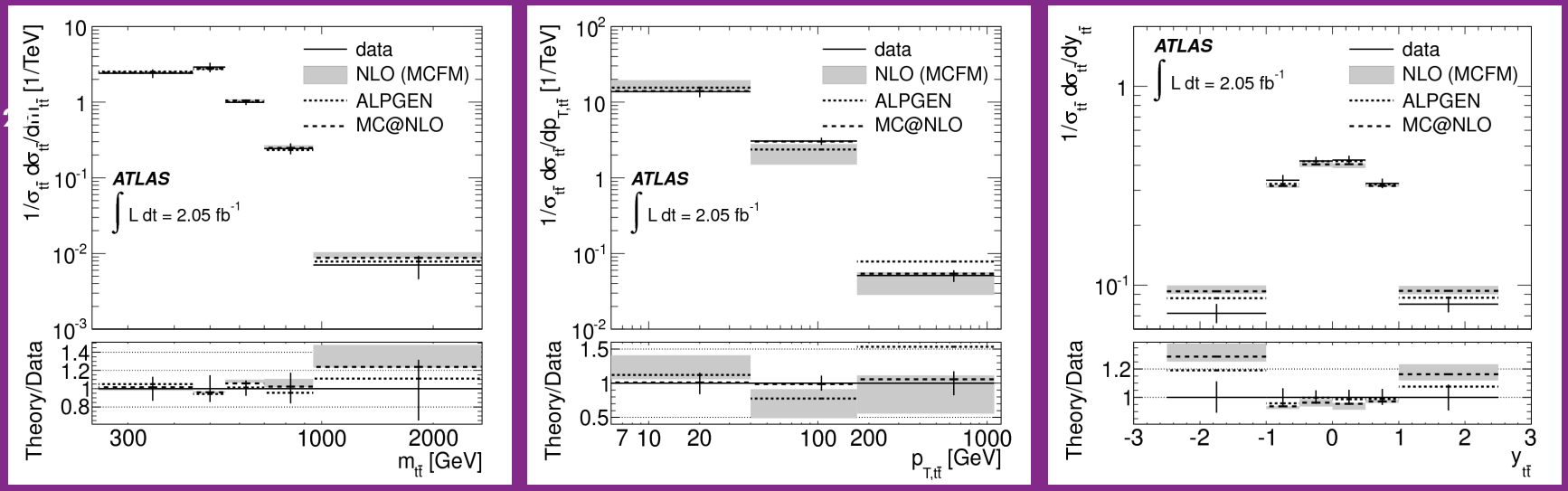




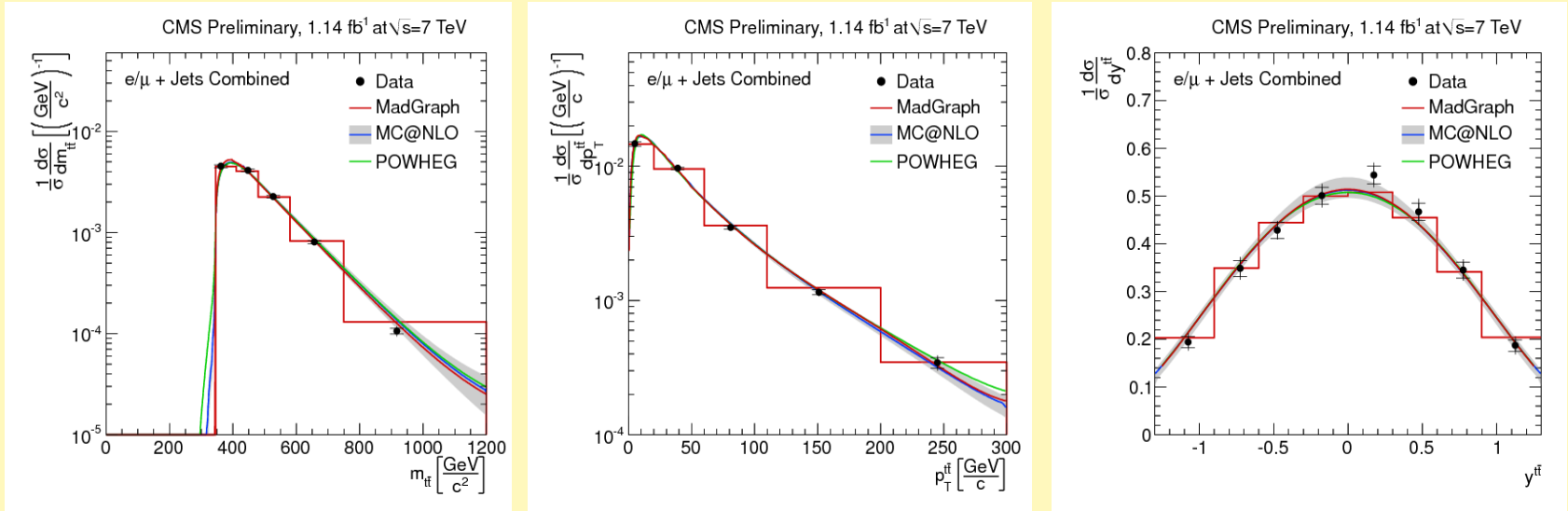
$$\sigma_j = \frac{\sum_i \left(M^{-1}\right)_{ji} \left(N_i - B_i\right)}{A_j L}$$

Here M_{ij} is the bin migration matrix, N_i is the number of observed events in bin i, B_i is the number of background events , A_j is the acceptance and L is luminosity.

ATLAS and CMS results on $1/\sigma_{tt} \cdot d\sigma_{tt}/dx_{tt}$



arXiv:1207.5644



CMS-PAS-TOP-11-013

Good agreement between data and different models

CMS-PAS-TOP-12-014

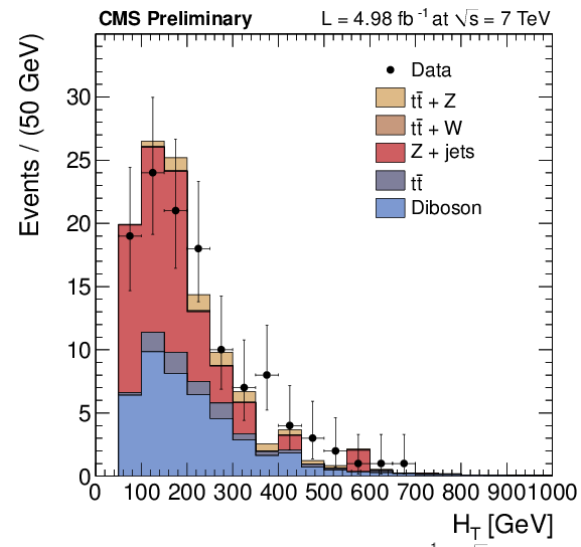
Measurement of Vector Boson Production associated with $t\bar{t}$

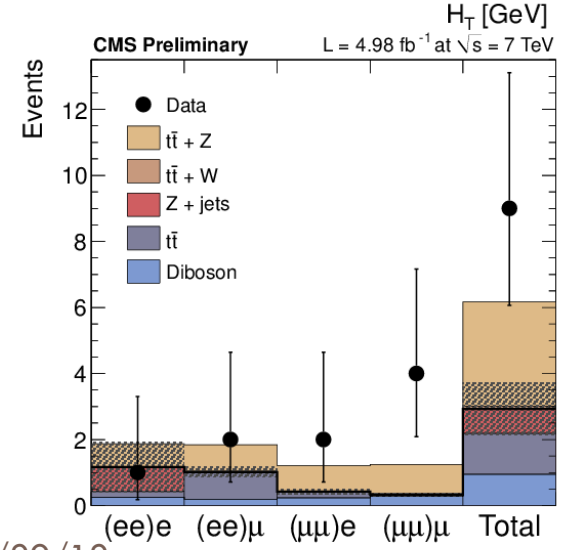
- Probe anomalous top quark couplings which could indicate presence of new physics
- Best theoretical prediction at $\sqrt{s}$=7 TeV (NLO):
  - $\sigma(tt+W)=0.169^{+0.029}_{-0.051}$ pb
  - $\sigma(tt+Z)=0.139$ pb
- The first measurement done by CMS using 5.0 fb^{-1} of 7 TeV data.
- Channels:
  - trileptons: $ttZ \rightarrow (t \rightarrow bl\nu)(t \rightarrow bjj)(Z \rightarrow ll)$, $l=e,\mu$
  - same sign leptons: $ttW \rightarrow (t \rightarrow bl^{\pm}\nu)(t \rightarrow bjj)(W \rightarrow l^{\pm}\nu)$, $ttZ \rightarrow (t \rightarrow bl^{\pm}\nu)(t \rightarrow bjj)(Z \rightarrow l^{\pm}l^{\mp})$

CMS-PAS-TOP-12-014

Vector Boson Production associated with $t\bar{t}$: trilepton channel

- Selection:
  - Z-candidate: ee/μμ with $p_T(l)>20$ GeV
  - $81<M(ll)<101$ GeV, $p_T(ll)>35$ GeV
  - Third e/μ, $p_T>10$ GeV
  - 3 jets ($p_T>20$ GeV, $|\eta|<2.4$), 2 of them tagged
  - $H_T(\text{jets})>120$ GeV
- Backgrounds: ttbar, dibosons
- Count the number of observed events less the background





9 events observed, 2.9±0.8 background

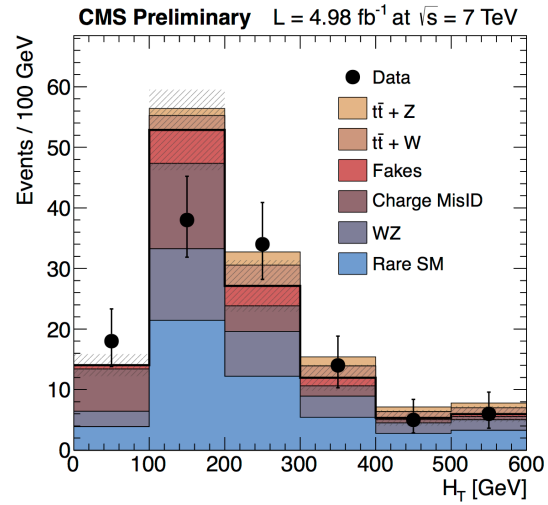
Signal significance 3.66σ

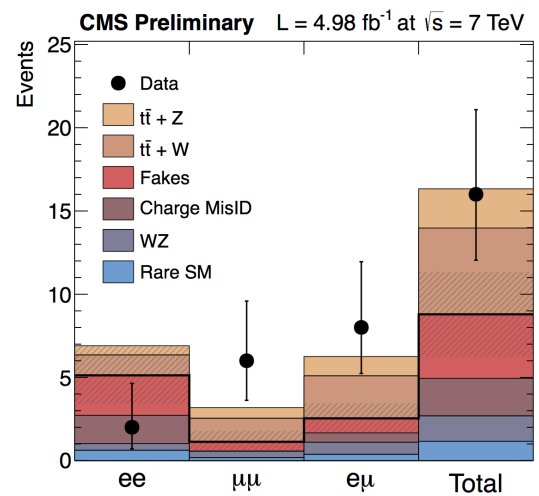
$$\sigma_{t\bar{t}Z} = 0.30^{+0.14}_{-0.11}(\text{stat.})^{+0.04}_{-0.02}(\text{syst.})\ \text{pb}$$

CMS-PAS-TOP-12-014

Vector Boson Production associated with $t\bar{t}$: same sign lepton channel

- Selection:
  - Two same sign isolated leptons (e,μ), p_T(l1)>55 GeV, p_T(l2)>30 GeV
  - M(ll)>8 GeV
  - 3 jets (p_T>20 GeV, |η|<2.4), no b-tagging
- Backgrounds: instrumental (fakes, charge misID), dibosons, other SM
- Count the number of observed events less the background





16 events observed, 8.8±2.5 background

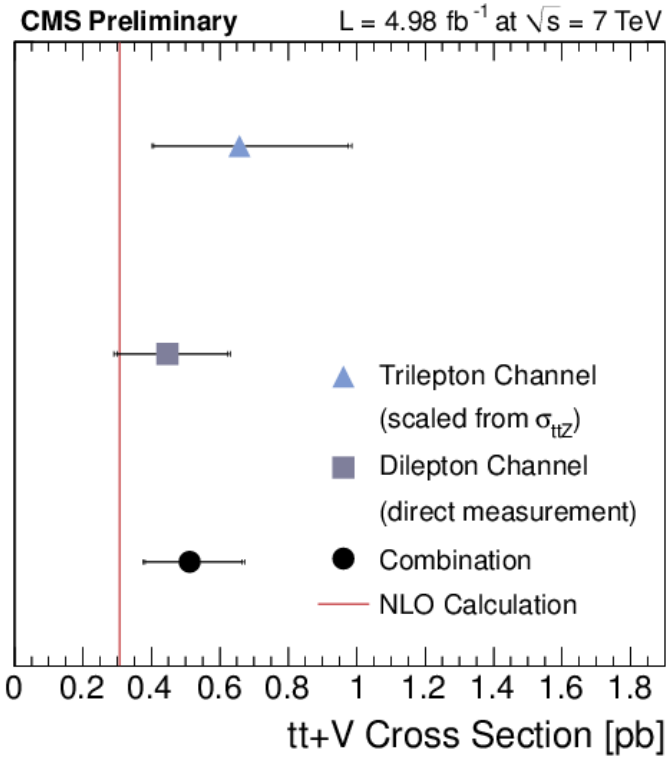
Signal significance 2.99σ

$$\sigma_{t\bar{t}V} = 0.45^{+0.17}_{-0.15}(\text{stat.})^{+0.06}_{-0.05}(\text{syst.})\ \text{pb}$$

CMS-PAS-TOP-12-014

Vector Boson Production associated with $t\bar{t}$: the combination

- Seven channels combined by multiplying individual likelihoods
- The result is somewhat large but compatible with NLO calculation of 0.308 pb



Signal significance 4.67σ

$$\sigma_{t\bar{t}V} = 0.51^{+0.15}_{-0.13}(\text{stat.})^{+0.05}_{-0.04}(\text{syst.})\ \text{pb}$$

Conclusions

- LHC is a top factory, providing a huge statistics of top quark events
- Measurements in the top quark sector become precision tests for the Standard Model and various theoretical calculations
- Many differential distributions have been measured with high accuracy, providing valuable information about details of the $t\bar{t}$ production, which is important for further searches for new physics
- New measurements at 8 TeV cm energy and on the larger data sets are on the way!

Back-up slides

Data driven methods for multijet background estimation (ATLAS)

Lepton + jets channel

- Matrix method:

$$N^{loose} = N^{loose}_{real} + N^{loose}_{fake}$$
$$N^{tight} = \varepsilon_{real} N^{loose}_{real} + \varepsilon_{fake} N^{loose}_{fake}$$

  - Two samples selected with different lepton isolation criteria, loose and tight
  - Efficiencies determined on Z→ ll samples
- Jet-electron method:
  - Jet-electron model is based on a sample selected with jet trigger
  - Jets with high EM fraction are used to model fake electrons

Dilepton channel

- Matrix method:
  - Similar to lepton+jets, but has 4 equations, related combinations of loose and tight leptons
  - Efficiencies are determined on Z→ ll samples
  - Fake lepton probabilities determined in electron and muon channels with two methods using different relaxing criteria

Kinematic top quark pair reconstruction (CMS)

- l+jets: from constrained kinematic fit
  - 4-momenta of all objects (lepton and up to 5 leading jets) are varied within their resolutions
  - Constraints are: W mass, $m_t = m_{\bar{t}}$, $E_T^{\nu} = E_T^{miss}$
- Dilepton channel:
  - Same constraints as in l+jets channel
  - Remaining ambiguities are resolved by prioritizing solutions with two or one b-jets over solutions with non-tagged jets

ATLAS-CONF-2012-083

$\sigma(t\bar{t}+jets)$: Selection

- Selection of the events:
  - Muon: p_T>20 GeV, E_{Tmiss} > 20 GeV and $m_{T,W}+E_{Tmiss}$ > 60 GeV
  - Electron: p_T>25 GeV, E_{Tmiss} > 30 GeV and $m_{T,W}$> 30 GeV
  - at least 4 jets with p_T>25 GeV

- Backgrounds:
  - W+jets – by far dominant
  - Z+jets, diboson+jets and single top production: used their theoretical cross sections
  - Multijet background: used data-driven methods, matrix method and jet-electron method