Measurement of Differential Cross Sections in Top Pair Production with the CMS Detector

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ULRICH HUSEMANN on behalf of the CMS Collaboration
Differential Cross Sections: Why?

- **Properties** of the top quark:
  - Detailed **test of perturbative QCD** (and MC generators) at the highest scales
  - Search for **BSM physics** involving top quarks

- Top quarks as a **tool**:
  - **Detailed understanding** of TeV-scale standard model processes → benefit for **Higgs physics** and **searches** for BSM physics
  - Extraction of **parton distribution functions**

- This presentation: **differential cross section results from the CMS experiment**
  - $t\bar{t}$ differential cross sections and jet multiplicity
  - Event-level observables in $t\bar{t}$ events
Differential Cross Sections: How?

- General strategy of differential cross section measurements
  1. Object reconstruction and tight event selection (lepton+jets, dilepton) → pure $t\bar{t}$ sample
  2. Top quark kinematic reconstruction
  3. Background subtraction
  4. Corrections: detector acceptance, resolution → regularized unfolding techniques
  5. Comparison with theory (visible or full phase space)

Normalized Differential Cross Section: Master Formula

$$\frac{1}{\sigma} \frac{d\sigma_i}{dX} = \frac{1}{\sigma} \frac{\text{unfold}(s^X_i - b^X_i)}{\Delta^X_i \cdot \int \mathcal{L} \, dt}$$

Object Reconstruction

Top Kinematic Reconstruction

Theory Comparison

[arXiv:1505.04480 [hep-ex], submitted to EPJC]
Visible Phase Phase & Observables

- **Acceptance** corrections:
  - Limitation for cross section measurements: **extrapolation** from limited detector acceptance to **full phase space** with theory/simulation tools
  - Measurement of differential cross sections in **visible phase space** (aka fiducial cross sections) → reduced dependence of measurement on signal/background **modeling**
  - Corrections to level of **stable particles**
    (some analyses: parton-level information on tops)

- **Observables** in differential cross section measurement:
  - **Directly** measured quantities, e.g. kinematics of leptons and b jets: **visible** phase space → comparison with Monte Carlo (MC) simulations
  - **Reconstructed** quantities (top and t\(\bar{t}\) system): **visible** and **full** phase space → comparison with **MC** and **calculations** (e.g. fixed-order NNLO)
Leptons and b-Jets

- Measurement in **visible** phase space

- **Leptons** (left):
  - Example: e/µ+jets
  - \( p_T \) spectrum slightly softer in data

- **b-Jets** and \( b\bar{b} \) system (right):
  - Example: dilepton
  - \( \eta_b \) slightly less central in data

- Good description of all distributions:
  - Powheg+Herwig6
All distributions corrected to parton level (before decay, but after radiation)

Top kinematics (left):
- Examples: top transverse momentum and rapidity
- Generally good agreement with MC and calculations up to approx. NNLO
- Measured $p_T$ spectrum softer than most MC predictions, best description by Powheg+Herwig6

$t\bar{t}$ kinematics (right):
- $p_T^{t\bar{t}}$ well described (except NLO+NNLL calculation)
- $m_{t\bar{t}}$ tails in data lower than predictions
Consistency of Results

- **Results consistent among all CMS measurements**
  - $e/\mu$+jets vs. dilepton
  - 7 TeV vs. 8 TeV

- **Comparison with ATLAS results:**
  - Generally *good* agreement
  - Some *differences* in low top $p_T$ region (under investigation at LHCTOPWG)
Jet Multiplicity in $t\bar{t}$ Events

- $t\bar{t}$+jets:
  - Results from 7 TeV and 8 TeV data
  - $e/\mu$+jets & dilepton

- Main results:
  - Jet multiplicity (unfolded to particle level)
  - Comparison with MC generators → good agreement with MadGraph and Powheg
  - Comparison with $Q^2$ scale variations (MadGraph)
Jet Multiplicity in $t\bar{t}$ Events

- $t\bar{t}$+jets:
  - Results from 7 TeV and 8 TeV data
  - $e/\mu$+jets & dilepton

- Additional results:
  -Multiplicity of additional jets (not matched to top partons)
  -Gap fractions:

$$f(X_0) = \frac{N(X < X_0)}{N_{\text{total}}}$$

$(X = p_T$ of two additional jets, $H_T)$
Event-Level Observables in $t\bar{t}$

- Event-level observables (e.g. $E_{T}^{\text{miss}}$, $H_{T}$) sensitive to rare processes (e.g. $t\bar{t} + W/Z/H$) and new physics in lepton + multijet final states

- Analysis strategy:
  1. Standard lepton+jets event selection with $\geq 2$ b-tagged jets $\rightarrow$ pure $t\bar{t}$ sample
  2. Split samples into bins of event-level observables
  3. Obtain top content from fit to lepton $|\eta|$ distribution
  4. Correct for leptons from tauonic top decays and single top process
  5. Correct for migration effects (regularized unfolding)
Event-Level Observables in $t\bar{t}$

- Observables:
  - Missing transverse energy $E_T^{\text{miss}}$ (previous slide)
  - Scalar sum of transverse momenta: all jets ($H_T$), all objects ($S_T$)
  - $W \rightarrow l\nu$ decay: transverse momentum ($p_T^W$), transverse mass ($m_T^W$)

- Results: **good agreement** with MC generators
Summary and Conclusions

- Towards precision top physics: differential cross sections

- This presentation: CMS results with LHC Run 1 data on
  - Differential cross sections as a function of lepton and b-quark kinematics
  - Kinematics of top quark and $t\bar{t}$ system
  - Modeling of QCD radiation: jet multiplicity in $t\bar{t}$ events
  - Event-level observables in $t\bar{t}$ events
  - Generally good agreement with standard MC generators, working on remaining discrepancies with ATLAS and theory/MC community
Outlook: First Tops at 13 TeV

Event Display: $\mu$+Jets Event with Two b-Tags

[CMS DP-2015/019]
Outlook: First Tops at 13 TeV

Kinematic Distributions: $H_T$ and Hadronic Top Mass

[ CMS DP-2015/019 ]
Bibliography

- Please refer to the original publications for more details

- Differential cross sections:
  - arXiv:150504480, submitted to EPJC (8 TeV), additional material (8 TeV)
  - EPJ C73 (2013) 2339 (7 TeV)

- Jet multiplicity:
  - CMS-PAS-TOP-12-041 (8 TeV)
  - EPJ C74 (2014) 3014 (7 TeV)

- Event-level observables:
  - CMS-PAS-TOP-12-042 (8 TeV)
  - CMS-PAS-TOP-12-019 (7 TeV)

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