Karlsruhe Institute of Technology

Top Production with N-jets and with Jet-Vetoes at the CMS Experiment

Jet Vetoes and Jet Multiplicity Observables at the LHC - Durham - July 2013

Alexis Descroix on behalf of the CMS Collaboration | 17/07/2013

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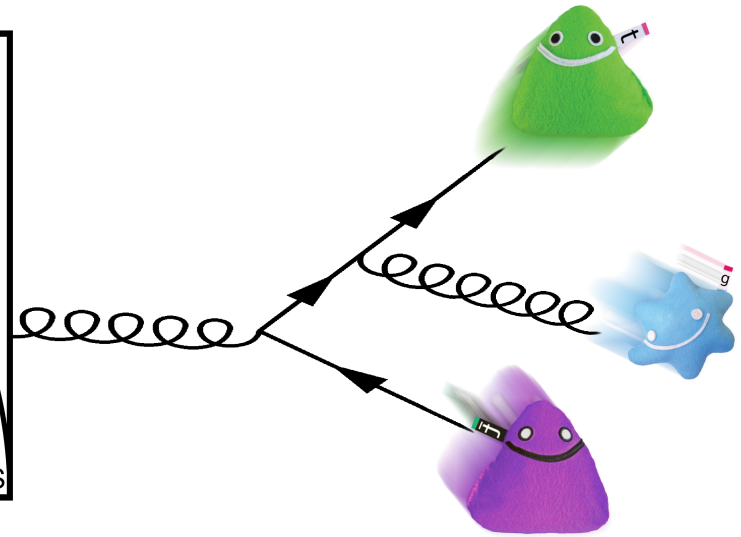
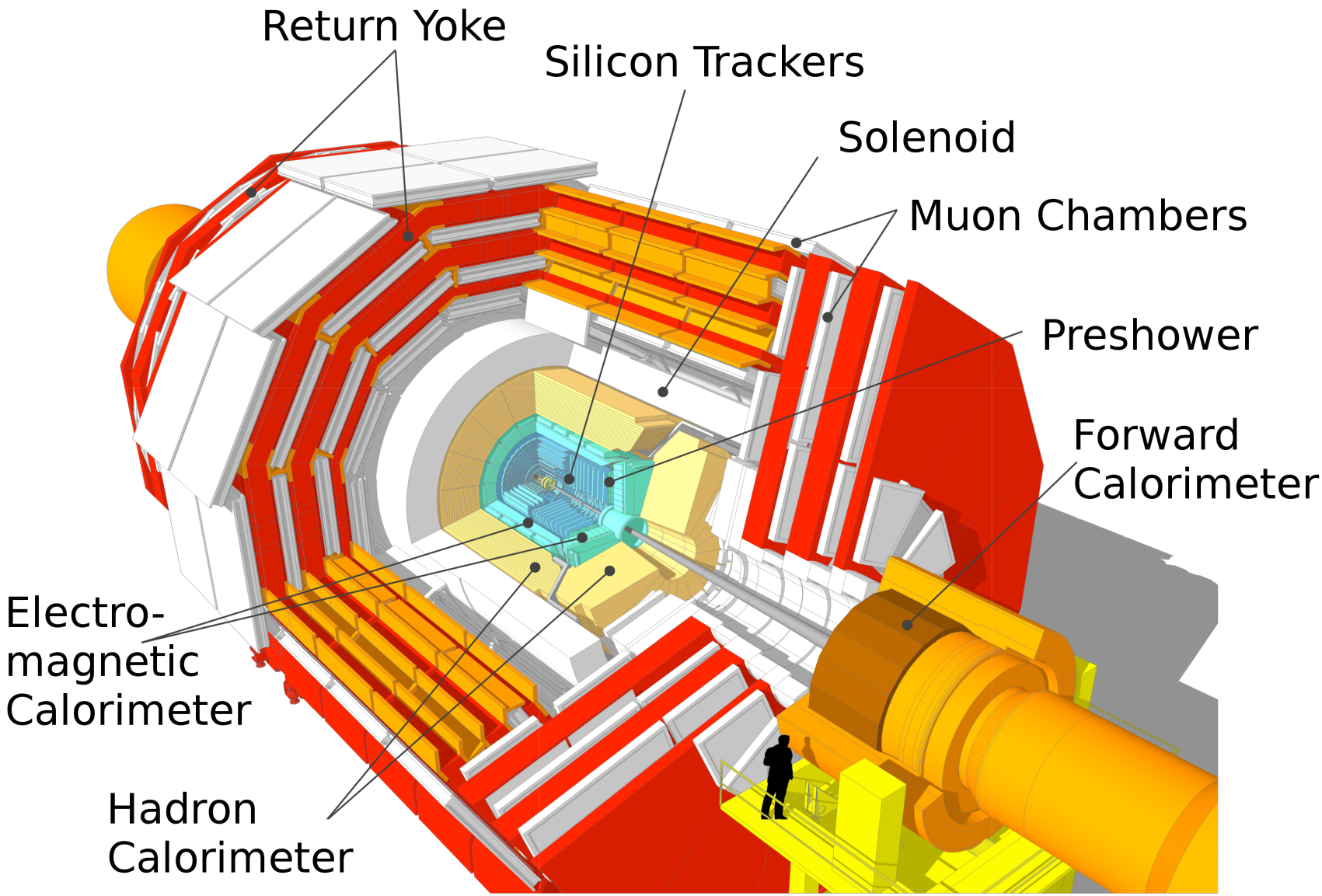
BMBF FSP-CMS



Introduction

- At the LHC a large fraction of top quark pair events ($t\bar{t}$) are produced with additional jets
- Investigating these processes is very interesting
  - Test perturbative QCD at top quark energy scale
  - Constrain modeling uncertainties in MC
  - Anomalous $t\bar{t}$ + jets production can be sign of new physics
  - Background to $t\bar{t}$ production with Higgs or with other bosons and BSM
- This presentation gives an overview of measurements of $t\bar{t}$ events with jets at CMS:
  - Measurement of the jet multiplicity in $t\bar{t}$ events
  - Investigation of the properties of additional jets:
    - Kinematic properties of additional jets
    - Veto on additional jets
    - Measurement of the additional parton multiplicity

The Compact Muon Solenoid Experiment

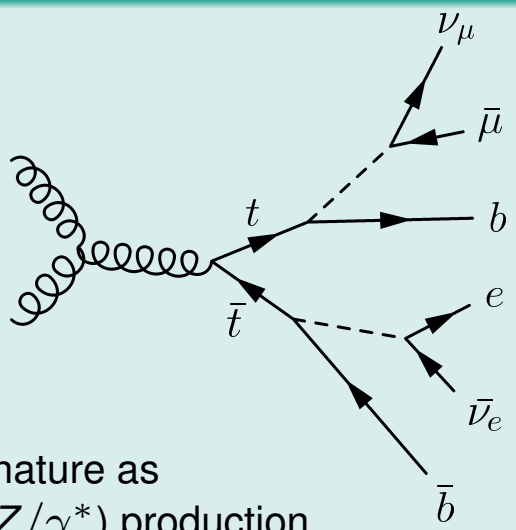


Investigated Processes: $t\bar{t}$ Events

- $t\bar{t}$ produced at LHC mostly with gluons in initial state
- Top quarks decay almost always into a *W* boson and a bottom quark
- $t\bar{t}$ decay signature depends on decays of both *W* bosons
  - Dilepton channel: *ee*, $e\mu$, and $\mu\mu$
    two prompt leptons ✓, two unmeasured neutrinos ✗
  - Lepton+Jets channel: *e*+jets and μ+jets
    one prompt lepton ✓, 4 jets ✗

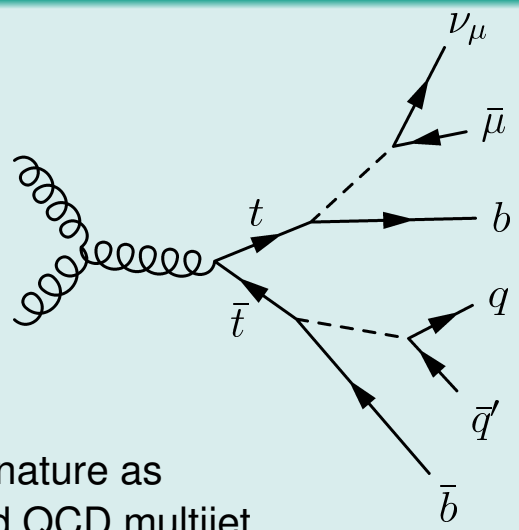
✓: easy
✗: challenging

Dilepton Channel



Similar signature as
Drell-Yan (Z/γ^*) production

Lepton+Jets Channel



Similar signature as
W+jets and QCD multijet

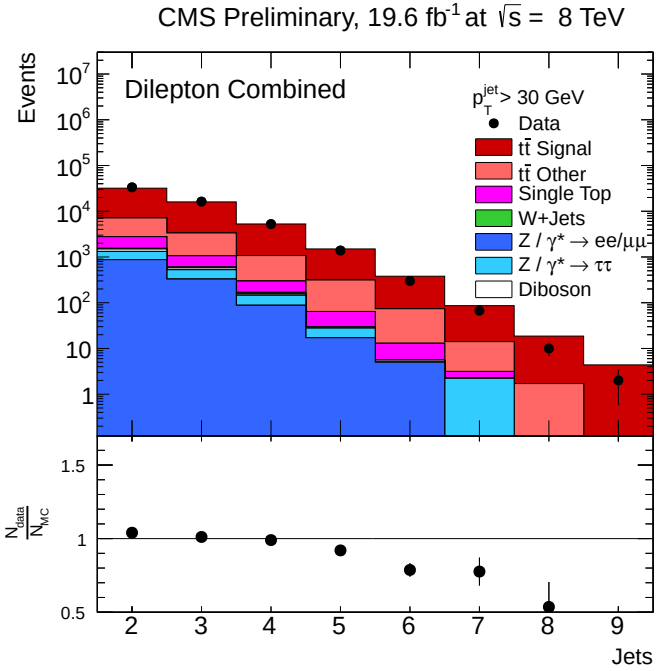
Analyzed Samples

- Datasets from 2011 (7 TeV, 5.0 fb^{-1}) and 2012 (8 TeV, 19.6 fb^{-1})
- Simulation of standard $t\bar{t}$ sample with LO generator:
  - Matrix element from MADGRAPH ($t\bar{t}$ + 0,1,2,3 jets)
  - Interfaced via MLM with PYTHIA for parton showering
  - Fact./renorm. scale: $Q^2 = m_t^2 + \sum p_T^2$
- Comparison available with NLO $t\bar{t}$ generators:
  - POWHEG+PYTHIA
  - MC@NLO+HERWIG
- Modeling/correction of dominant backgrounds with data-driven methods: Drell-Yan (dilepton), W+jets and QCD multijet (lepton+jets)
- Other backgrounds well modeled with MC:
  - MADGRAPH+PYTHIA (W+jets, and Drell-Yan)
  - POWHEG+PYTHIA (single top)
  - PYTHIA (diboson and QCD multijet)

Event Selection

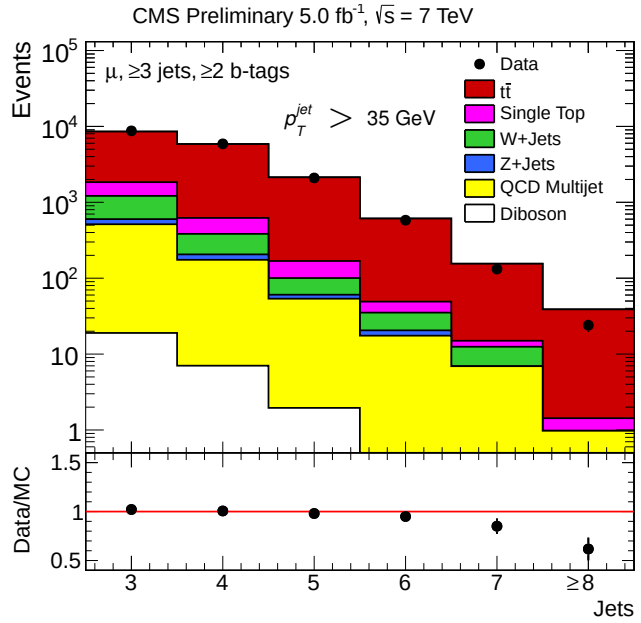
Dilepton Channel

- ≥ 2 leptons with opposite charge ($p_T > 20$ GeV)
- QCD veto, if $m_{\ell\ell} < 20$ GeV
- ≥ 2 jets ($p_T > 30$ GeV), one identified as b-jet
- *ee* and $\mu\mu$ case: $E_T^{miss} > 40$ GeV and $|m_{\ell\ell} - m_Z| > 15$ GeV
- Kinematic reconstruction of $t\bar{t}$ system



Lepton+Jets Channel

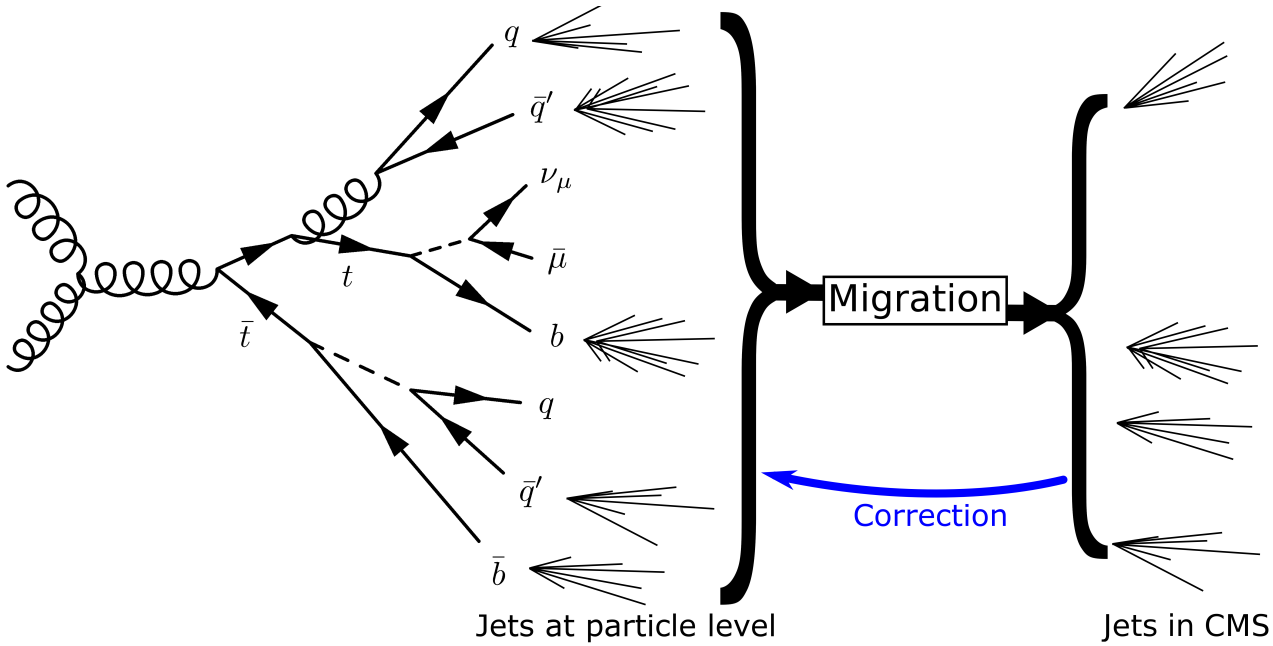
- Only one lepton ($p_T > 30$ GeV) + veto against additional leptons (looser cuts)
- $\geq 3(4)$ jets with $p_T > 35(30)$ GeV
- ≥ 2 selected jets identified as b-jets



Measurement of the Differential Cross-Section as a Function of the number of Jets

Correction Back to Particle Level

- Subtract background from data $\rightarrow N^i_{data} - N^i_{bkg}$
- Migration from particle level to detector level to be corrected



- Invert migration effects back to particle level with MADGRAPH $\rightarrow N^i_{t\bar{t}}$
- Correction within the visible phase-space

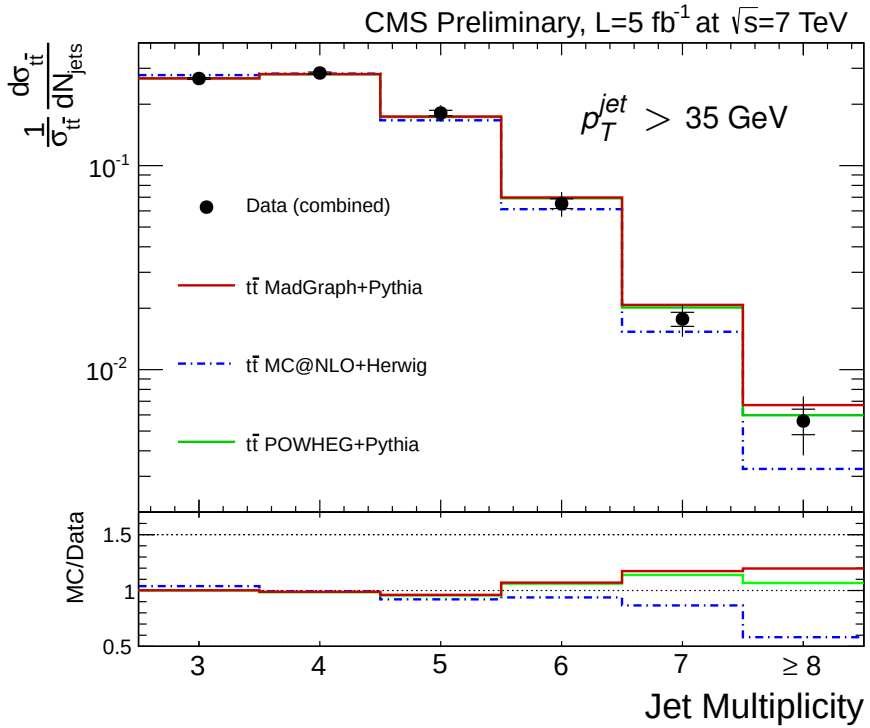
Differential Cross-Section and Theory Comparisons

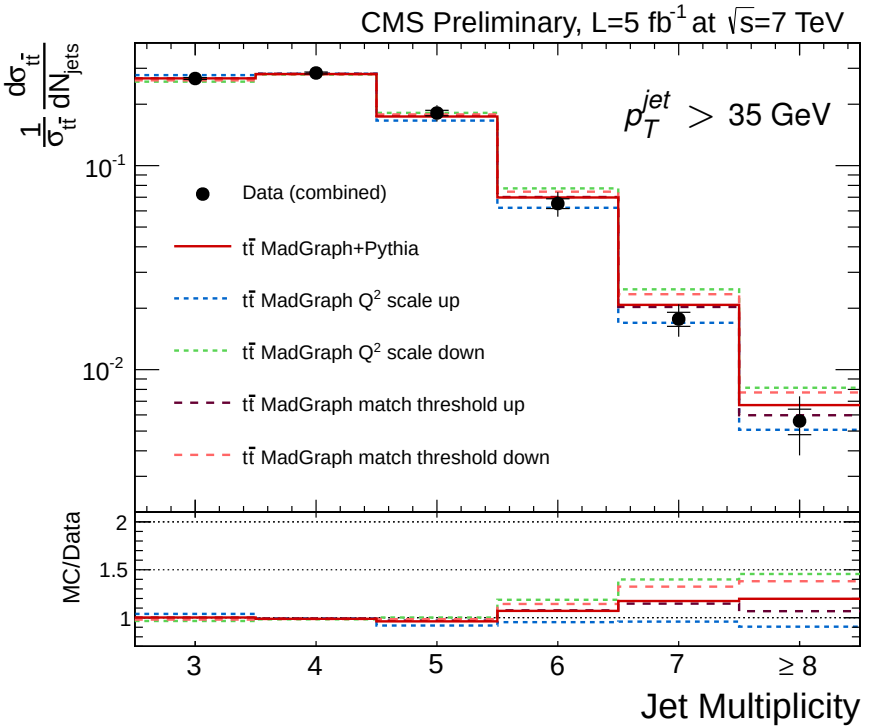
- Calculation of the differential cross-section

$$\frac{1}{\sigma_{t\bar{t}}}\frac{d\sigma_{t\bar{t}}}{dN_{jets}} = \frac{1}{\sigma_{t\bar{t}}}\frac{N^{i}_{t\bar{t}}}{\mathcal{L}}, \text{ with measured cross-section: } \sigma_{t\bar{t}}$$

- Normalization to $\sigma_{t\bar{t}}$ reduces systematic uncertainty
- Combine results and compare to predictions from:
  - POWHEG+PYTHIA
  - MC@NLO+HERWIG
  - MADGRAPH+PYTHIA with Q^2 scale varied to $4 \cdot Q^2$ and $1/4 \cdot Q^2$
  - MADGRAPH+PYTHIA with matrix-element/parton-showering matching threshold varied to 40 and 10 GeV (nominal is 20 GeV)
- Systematic uncertainties estimated by repeating the measurement with varied assumptions on sources, most important ones are:
  - Jet energy uncertainties
  - Modeling uncertainties (Q^2 scale, matching threshold, and hadronization uncertainty)

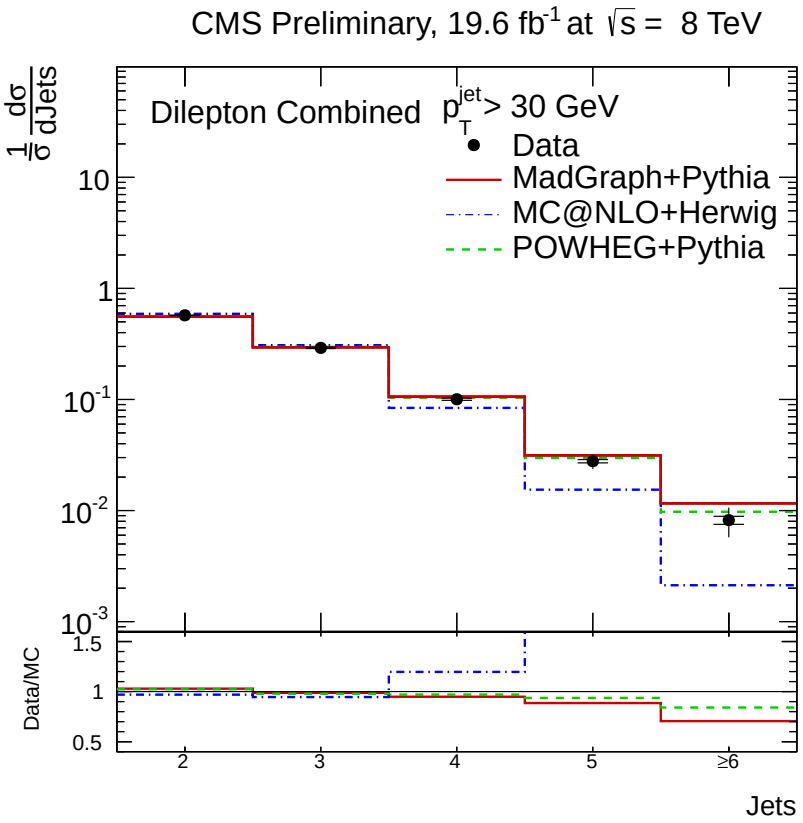
Differential Cross-Section in Lepton+Jets Channel (7 TeV)

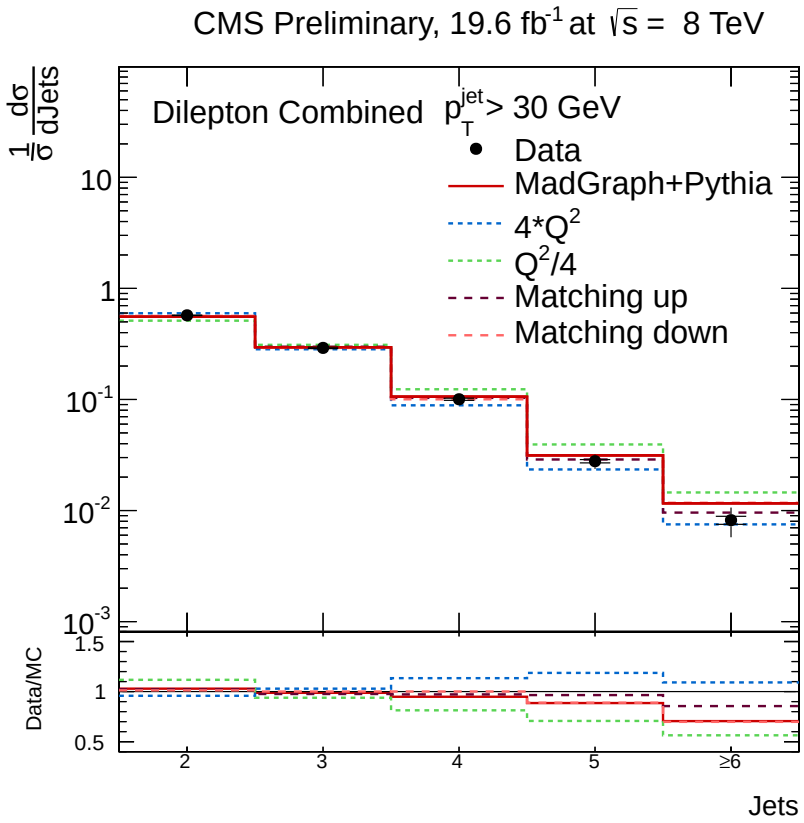




- Good agreement of data with predictions from MADGRAPH+PYTHIA and POWHEG+PYTHIA
- MC@NLO+HERWIG: jet multiplicity lower than data
- MADGRAPH+PYTHIA: best description for larger Q^2/match threshold

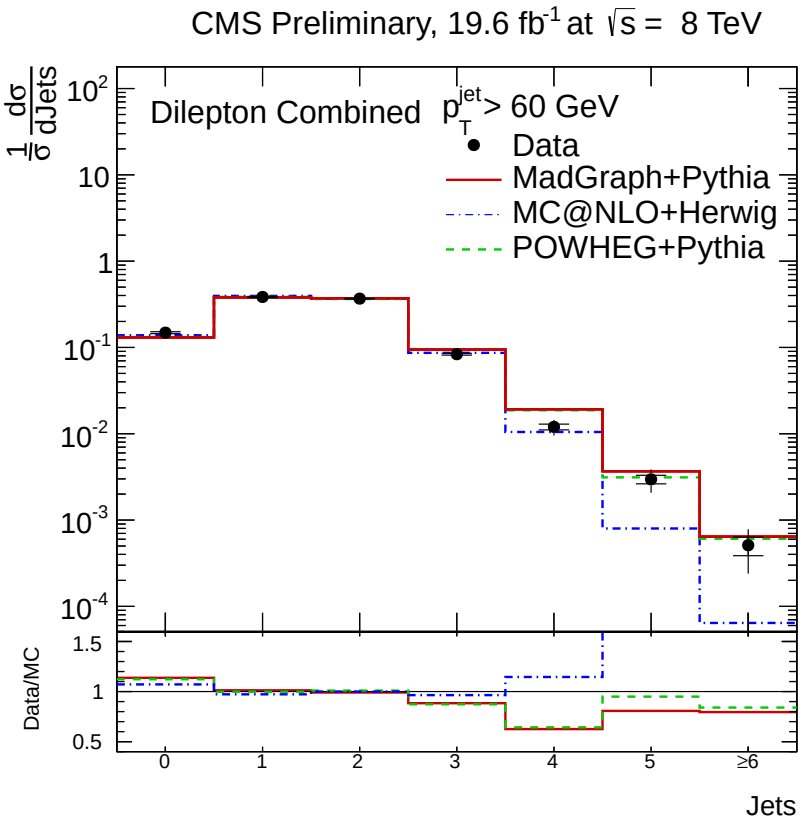
Differential Cross-Section in Dilepton Channel (8 TeV)

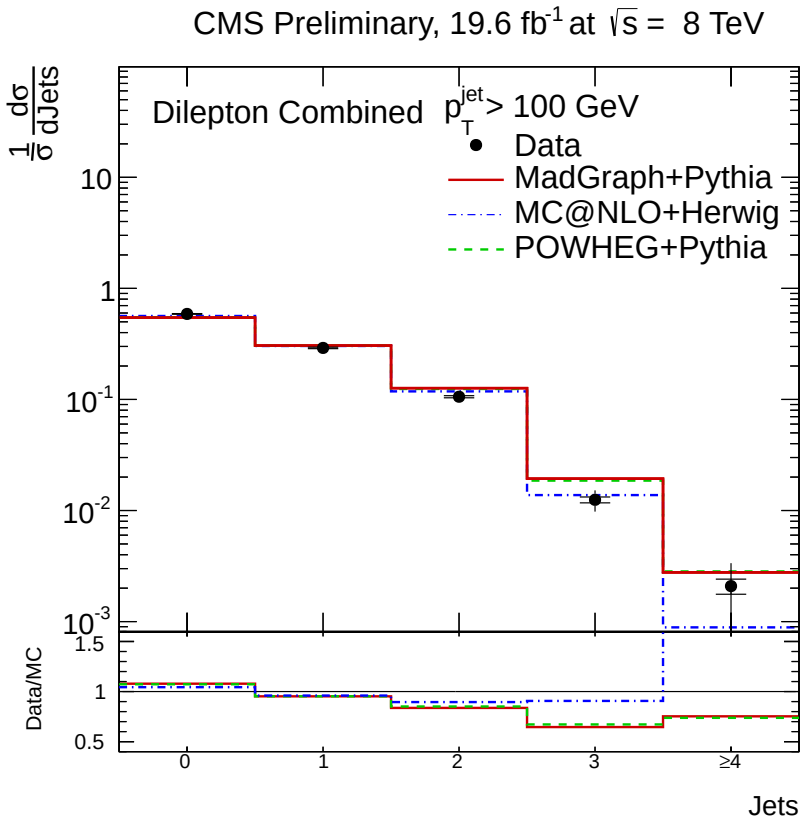




- Consistent with results in dilepton and lepton+jets channels at 7 TeV

Differential Cross-Section in Dilepton Channel (8 TeV) with Higher Jet p_T Threshold



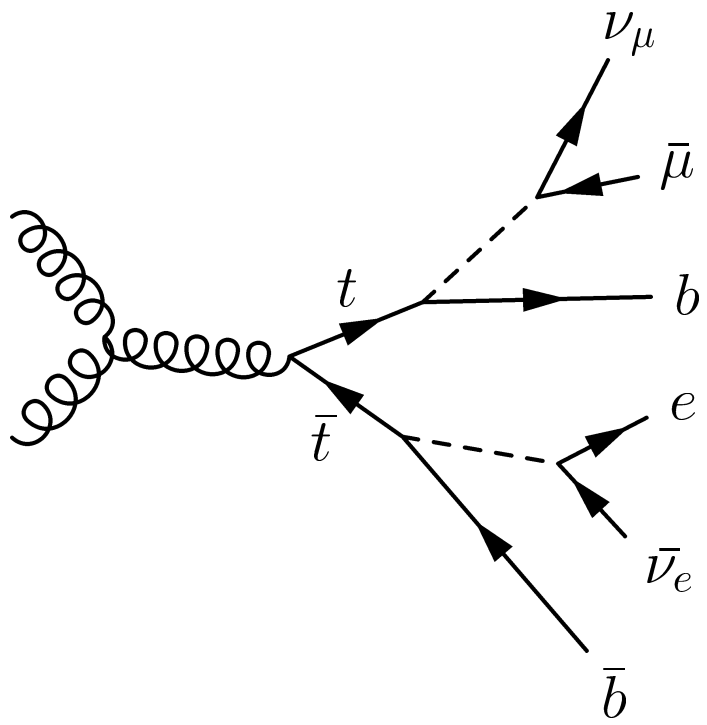


- Different behavior of MC@NLO confirmed at higher jet p_T

KINEMATICS OF ADDITIONAL JETS - DILEPTON CHANNEL

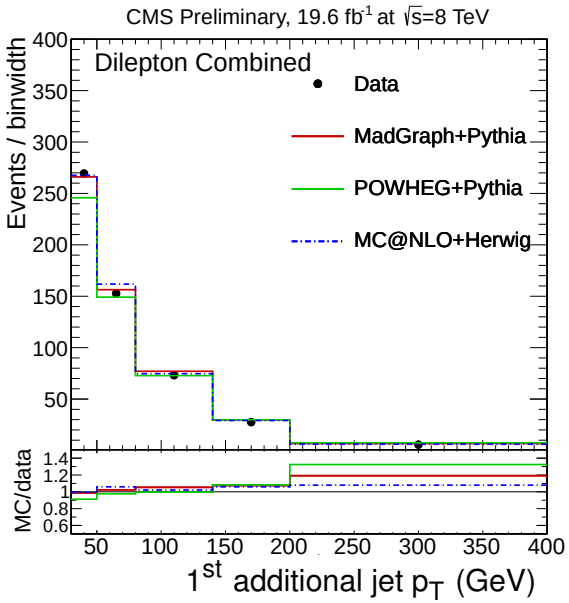
Definition of Additional Jets in Dilepton Channel

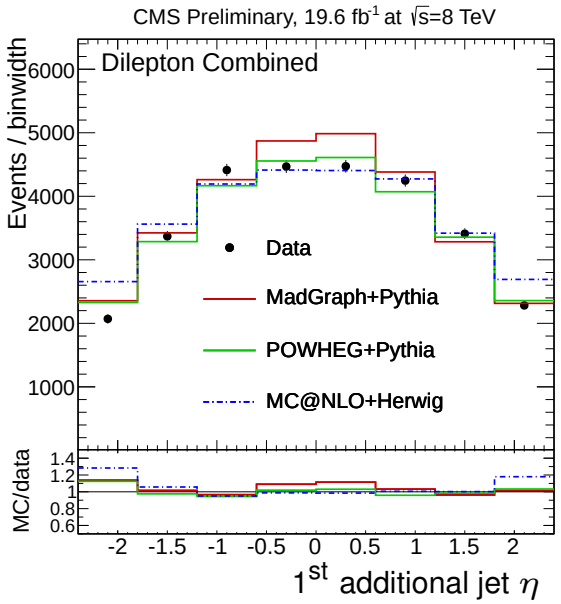
- The kinematic reconstruction of the $t\bar{t}$ system assigns the jets from the $t\bar{t}$ decay
  - Kinematic constraints allow to solve the two-neutrino ambiguity
  - Jet assignment is not straightforward $\Rightarrow$ choice made with b-jet identification and neutrino energy spectrum

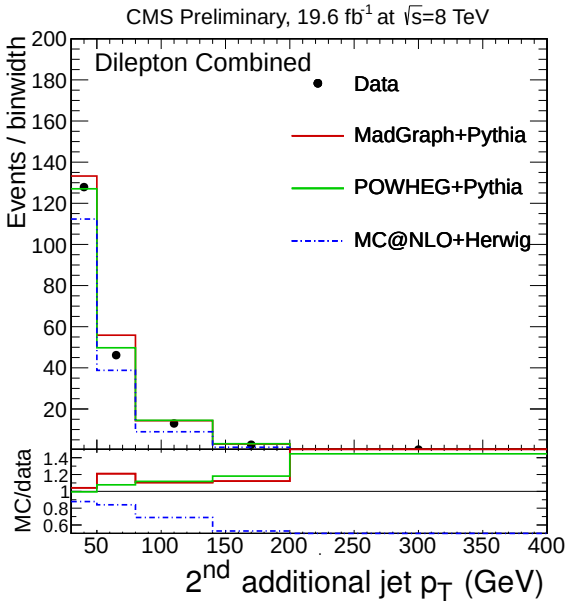


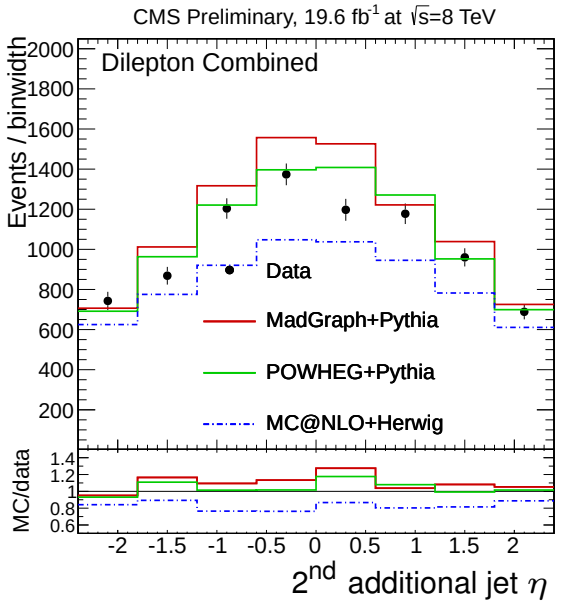
- Study of kinematic properties of additional jets:
  - Subtract background from data, no correction back to particle level
  - MC distribution scaled with measured $t\bar{t}$ cross-section

Kinematics of Additional Jets







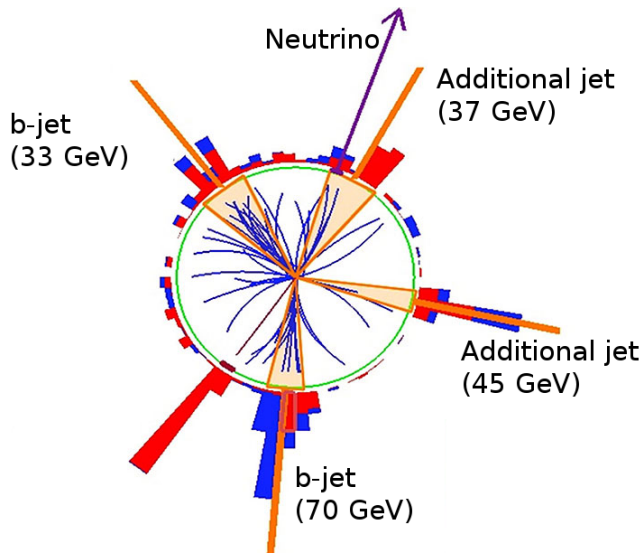


- Good agreement for first additional jet
- η of second additional jet: MC@NLO less central

VETO ON ADDITIONAL JETS - DILEPTON CHANNEL

Definition of Veto on Additional Jets

- A veto variable is calculated: gap fraction $f(p_T) = \frac{N(p_T)}{N_{total}}$
- $N(p_T)$: number of selected events without any additional jet fulfilling a kinematic veto on p_T
- N_{total}: total number of selected events
- Veto on p_T of the 1st, the 2nd and the scalar sum of all additional jets

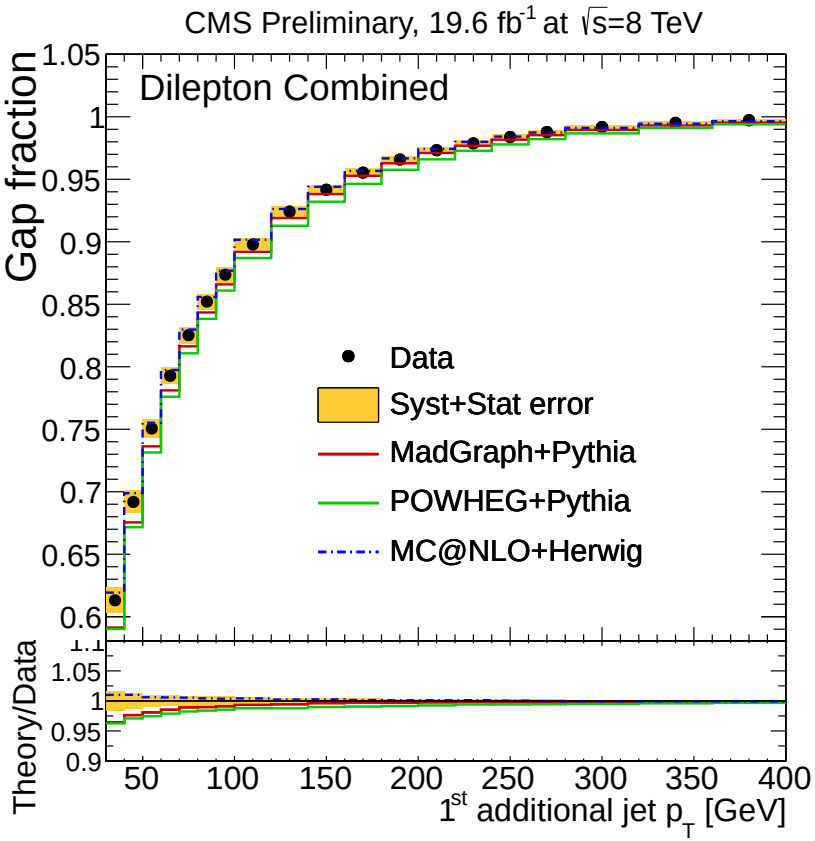


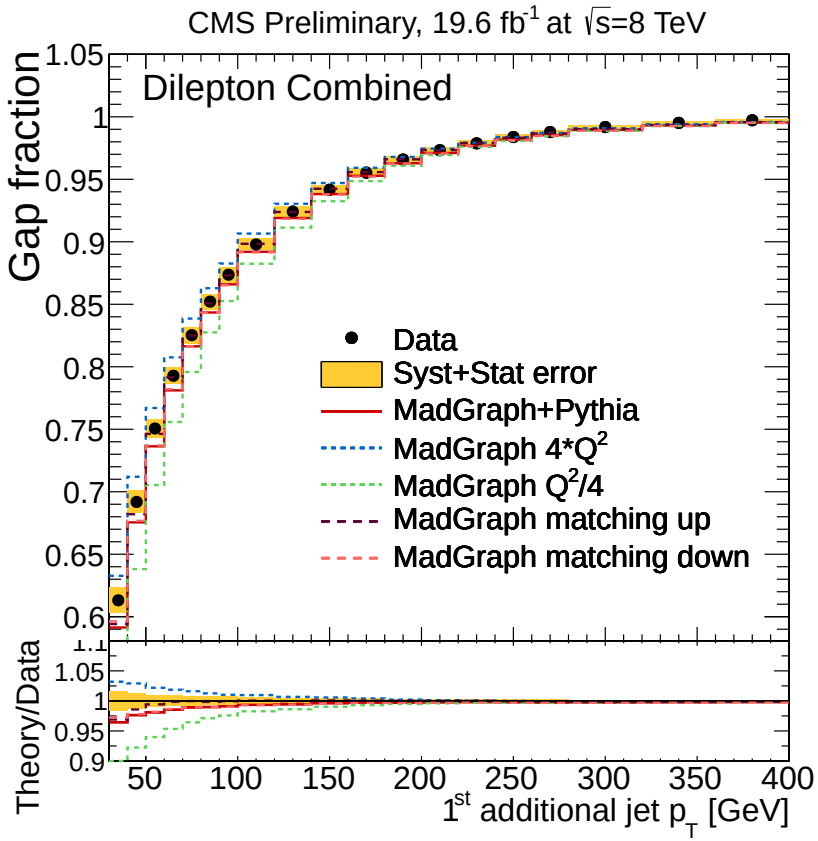
[lepp.cornell.edu]

- Threshold on p_T of 1st add. jet at 40 GeV $\rightarrow$ event vetoed
- Threshold on p_T of 1st add. jet at 50 GeV $\rightarrow$ event counted

- Veto varied in a wide range of p_T
- Correction back to particle level within visible phase space

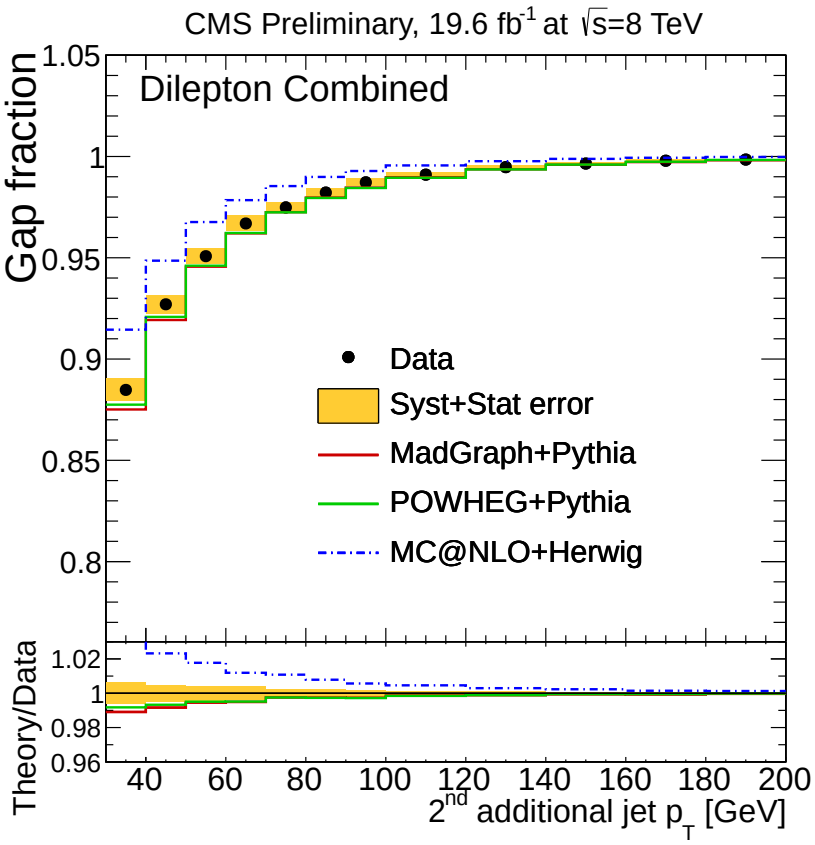
$f(p_T)$ of First Additional Jet

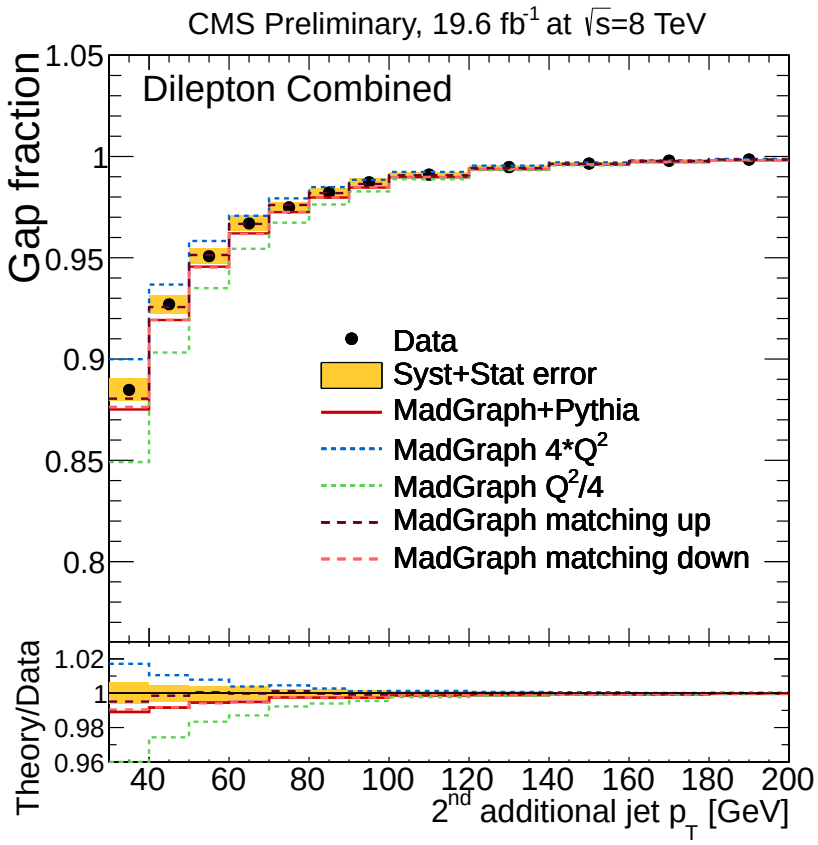




- MC@NLO+HERWIG shows better agreement with data than MADGRAPH+PYTHIA and POWHEG+PYTHIA
- MADGRAPH+PYTHIA Q^2 scale down variation decreases agreement
- Other variations from MADGRAPH+PYTHIA describe data well

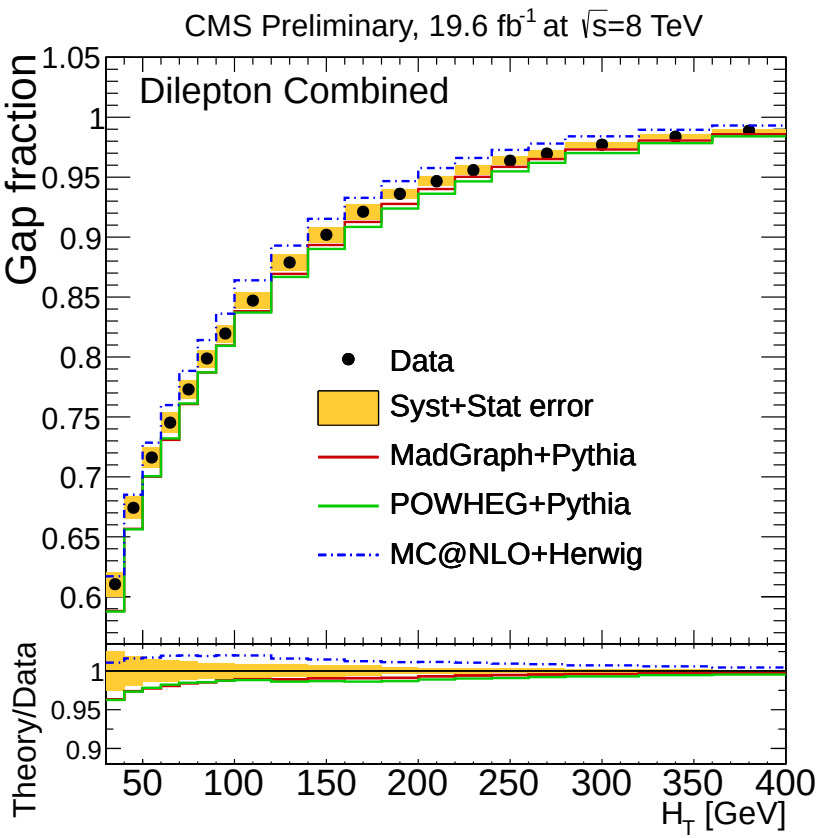
$f(p_T)$ of Second Additional Jet

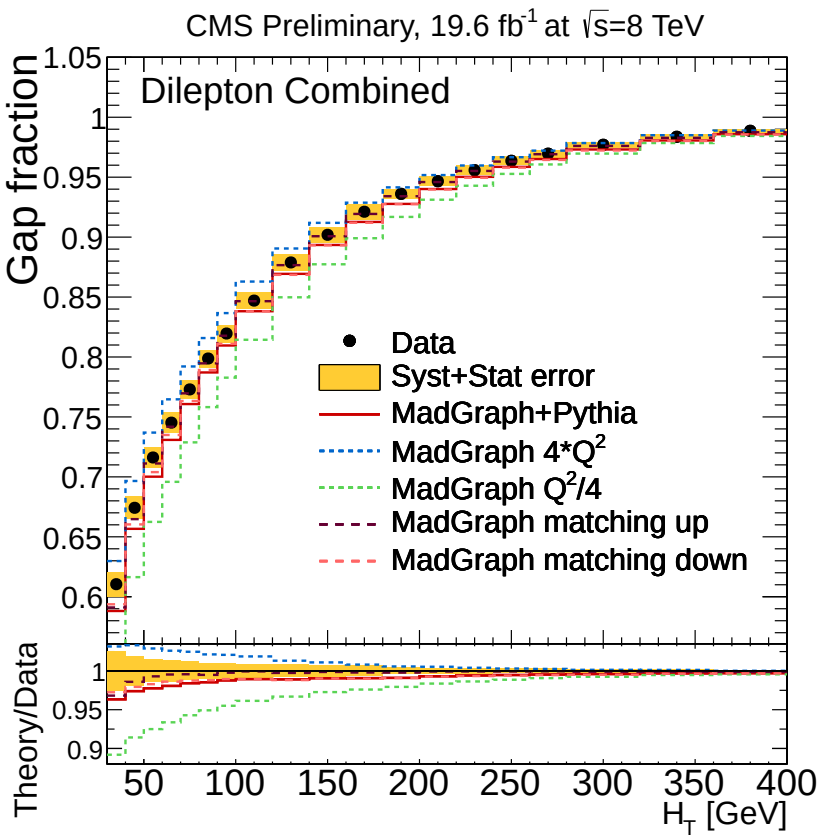




- MC@NLO+HERWIG shows higher gap fraction values than data
- Better agreement with MADGRAPH+PYTHIA and POWHEG+PYTHIA
- MADGRAPH+PYTHIA Q^2 scale down variation shows too low values

$f(H_T)$ of Additional Jets





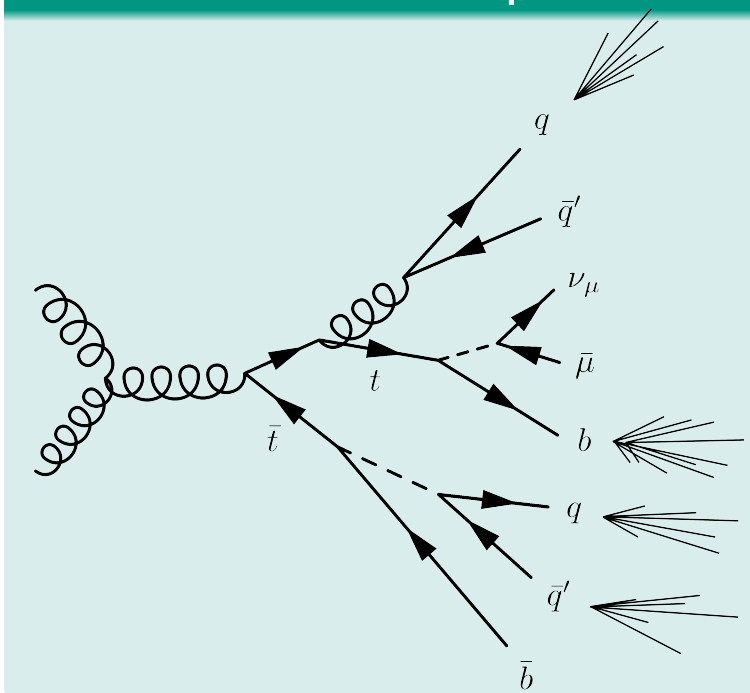
- MC@NLO+HERWIG predictions above data, MADGRAPH+PYTHIA and POWHEG+PYTHIA predictions below data
- MADGRAPH+PYTHIA matching up agrees the best with data

Measurement of the Differential Cross-Section as a function of the number of Additional Partons - Lepton+Jets Channel

Definition of Additional Jets - Event Classification

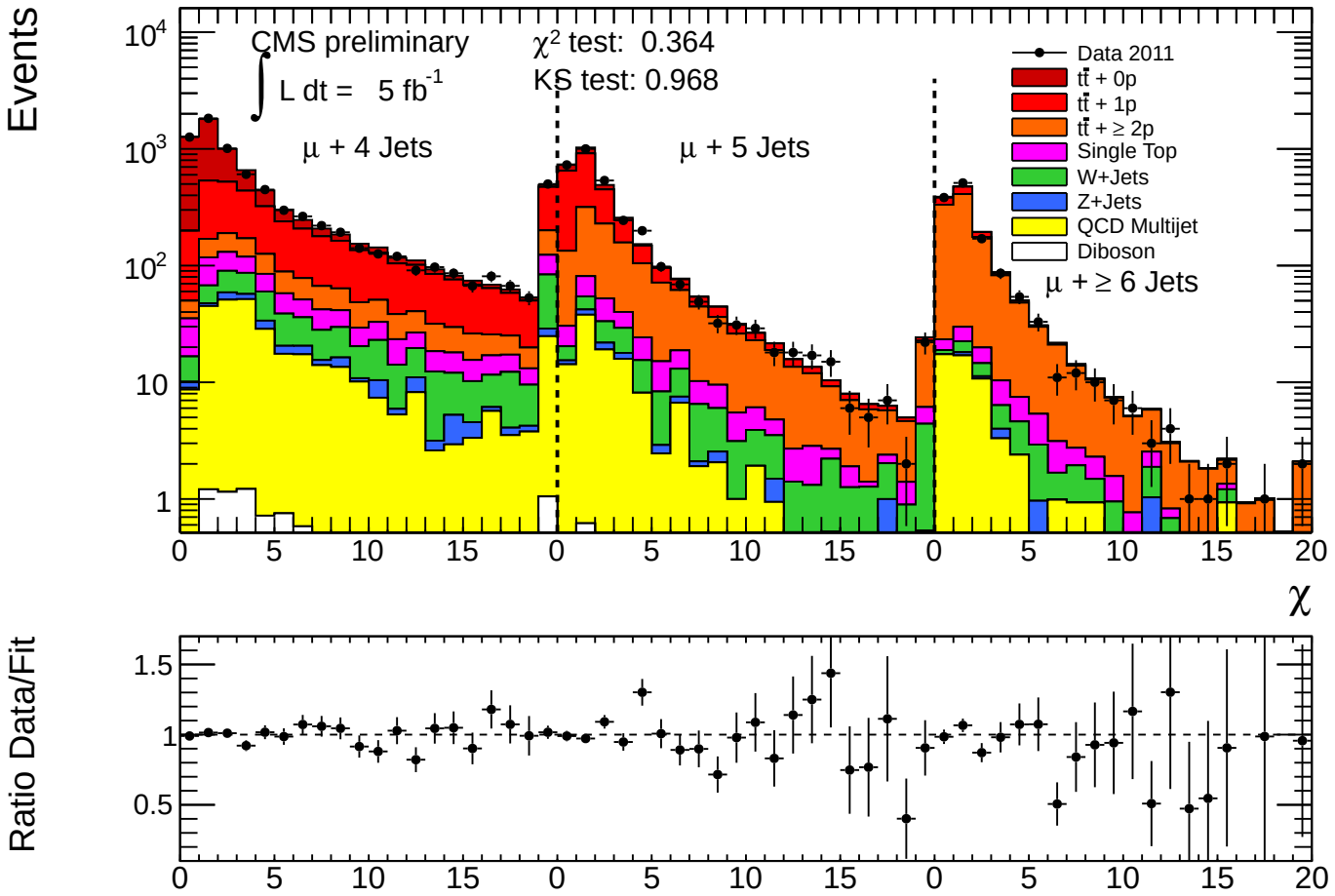
- $t\bar{t}$ MC events are classified using MC information
- Introduce a cut on distance ΔR between jets and $t\bar{t}$ decay products:
  - two b quarks
  - two light quarks
  - prompt lepton
- Jets with $\Delta R > 0.5$ count as additional radiated partons
  $\Rightarrow$ classification of events in
  $t\bar{t}$ + 0, 1 and $\geq$ 2 additional partons
- Extracting rates of these $t\bar{t}$ classes from data via a template fit of χ, from event reconstruction

One additional parton



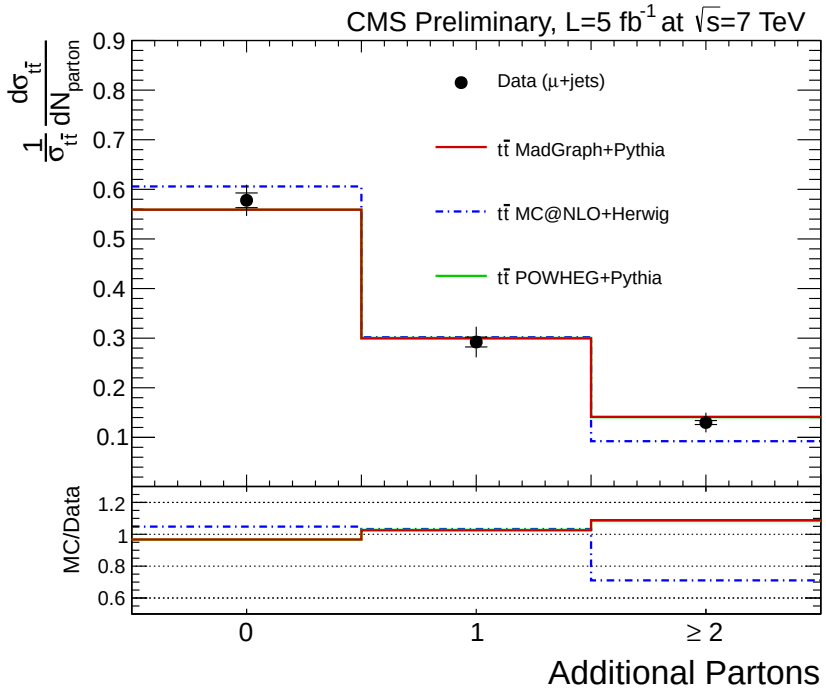
$$\chi = \sqrt{\left(\frac{m_{W^{had}}^{rec} - m_{W^{had}}^{true}}{\sigma_{W^{had}}}\right)^2 + \left(\frac{m_{t^{had}}^{rec} - m_{t^{had}}^{true}}{\sigma_{t^{had}}}\right)^2 + \left(\frac{m_{t^{lep}}^{rec} - m_{t^{lep}}^{true}}{\sigma_{t^{lep}}}\right)^2}$$

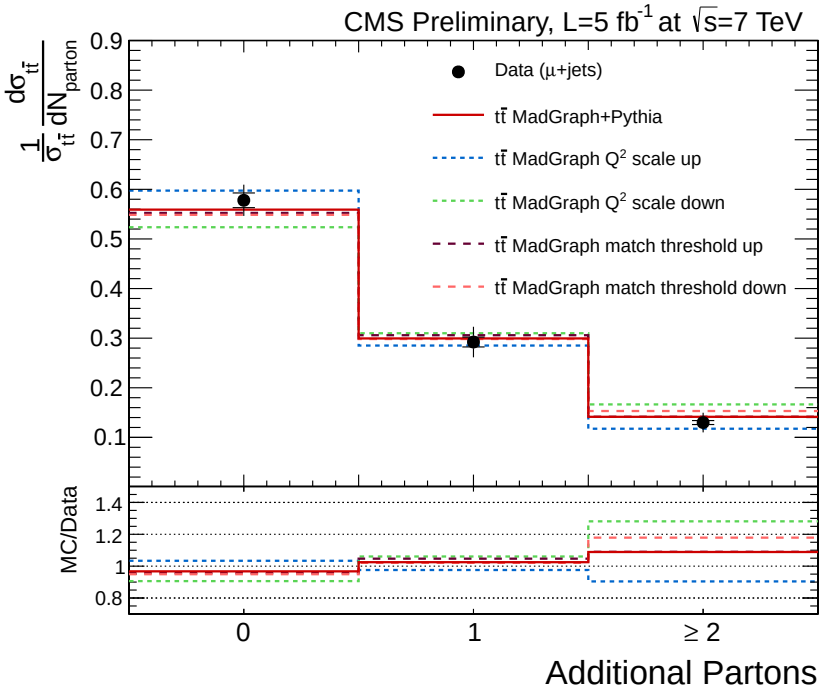
Template Fit Results



- Simultaneous fit in three jet multiplicity parts, $t\bar{t}$ classes show different shapes $\rightarrow$ separation power
- The fit performs well and checks have proved its stability

Results of Differential Cross-Section with Template Fit





- Extract results with MADGRAPH prediction for the $t\bar{t}$ classes
- Systematic uncertainties evaluated with pseudo-data, same assumed sources
- Like jet multiplicity results at 7 and 8 TeV:
  - best agreement with MADGRAPH+PYTHIA and POWHEG+PYTHIA
  - MC@NLO shows discrepancies
  - Visible sensitivity to scale and matching uncertainties

Conclusion and Outlook

- Good agreement between all measurements:
  - Multiplicity of jets and of additional partons
  - Additional jet kinematic
  - Gap fraction of additional jets
- MADGRAPH+PYTHIA predictions agree mostly well with data
- Modeling uncertainty (Q^2 and matching) often larger than precision $\Rightarrow$ could be reduced
- MC@NLO+HERWIG produces fewer jets. Comparison with POWHEG+HERWIG required (sample now available)
- Working towards comparisons with NLO+Parton Showering multileg generators like aMC@NLO and SHERPA

Public results presented today can be found here:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

- TOP-12-018 (lepton+jets channel, 7TeV)
- TOP-12-023 (dilepton channel, 7TeV)
- TOP-12-041 (dilepton channel, 8TeV)

Thanks for your attention