Differential $t\bar{t}$ cross section measurements at the LHC

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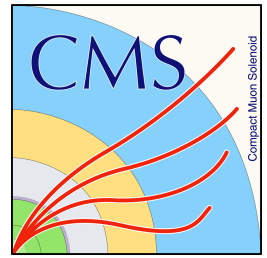


TOP2015, Ischia

15.09.2015

The high number of top quark pairs produced at the LHC allows for precise differential measurements:

- good opportunity to test the standard model (QCD)
- sensitive to physics beyond SM.
- important background for many searches.

What is meant by $t\bar{t}$? The two conventions:

- **Parton level**:
  look at MC decay chain and select the top quark. Usually directly before it decays into b and W (after radiation)
- **Particle level (pseudo-tops)**:
  the pseudo-top definition consists of directly measurable quantities. No extrapolation into full phase space.

Particle level (pseudo-tops)

Particle definition consists of directly measurable quantities:

- jets of stable particles (no partons)
- b jets are jets containing b hadrons (e.g. by ghost-matching)
  re-cluster jets including b hadrons ($p_{\mathrm{T}} > 5\,\mathrm{GeV}$) with momentum scaled to negligible value.
- leptons (not from hadronic decays) corrected for non-measurable radiative effects
  add prompt-photons in $\Delta R < 0.1$

Pseudo-top definition:

- kinematic and fiducial selection of particles similar to detector acceptance.
- algorithm to define the pseudo-top pair using constraints of M_{t}, M_W, separations, p_{T}, ...

In general different definitions used in various analyses.

+ based on well defined quantities.
+ defined in detectable phase space. $\rightarrow$minimizes theoretical uncertainties (on the experimental side.)
+ easier comparison to future MCs (improved parton shower, hadronization, ...)
- not directly comparable to ME calculations.
- "true" top kinematics are smeared $\rightarrow$could be less sensitive to new effects.

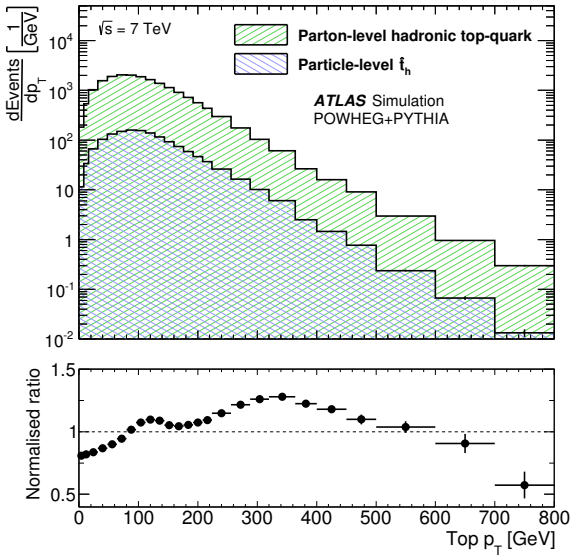
ATLAS: JHEP 06 (2015) 100 (arXiv:1502.05923), 4.6 fb^{-1}, 7 TeV

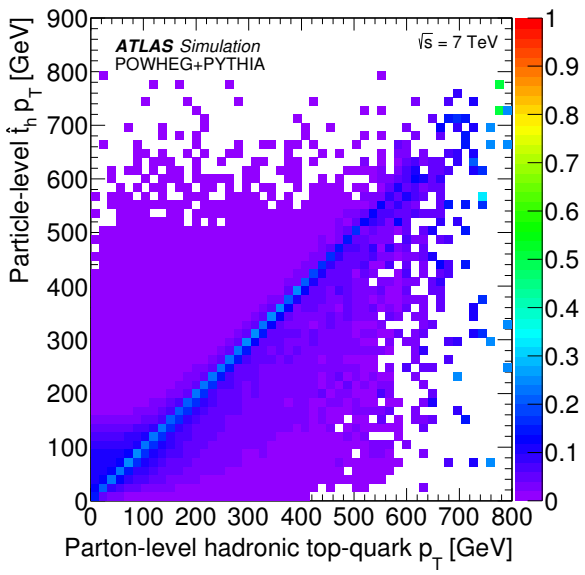
Definition of the pseudo-top constituents:

- electrons, muons, and jets: $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, $|\eta| < 2.5$
- exactly one lepton (not from hadron)
- at least four jets, at least 2 b jets.
- $E_{\mathrm{T}}^{\mathrm{miss}} > 30\,\mathrm{GeV}$, $M_T(W) > 35\,\mathrm{GeV}$ (defined by lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$)

Definition of the pseudo-top system:

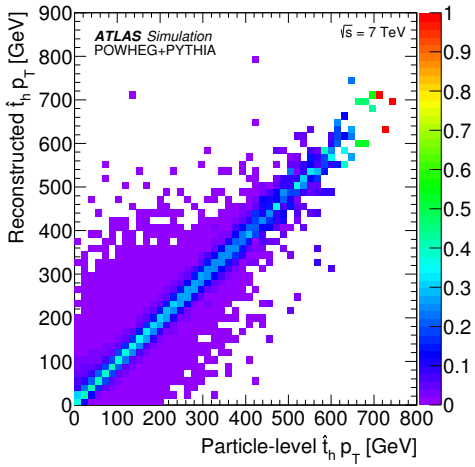
- two hardest b jets belong to pseudo-top pair system.
- the b jet closer to lepton (ΔR) is part of the leptonic decay.
- the two remaining jets with highest p_{T} are the hadronically decaying W.





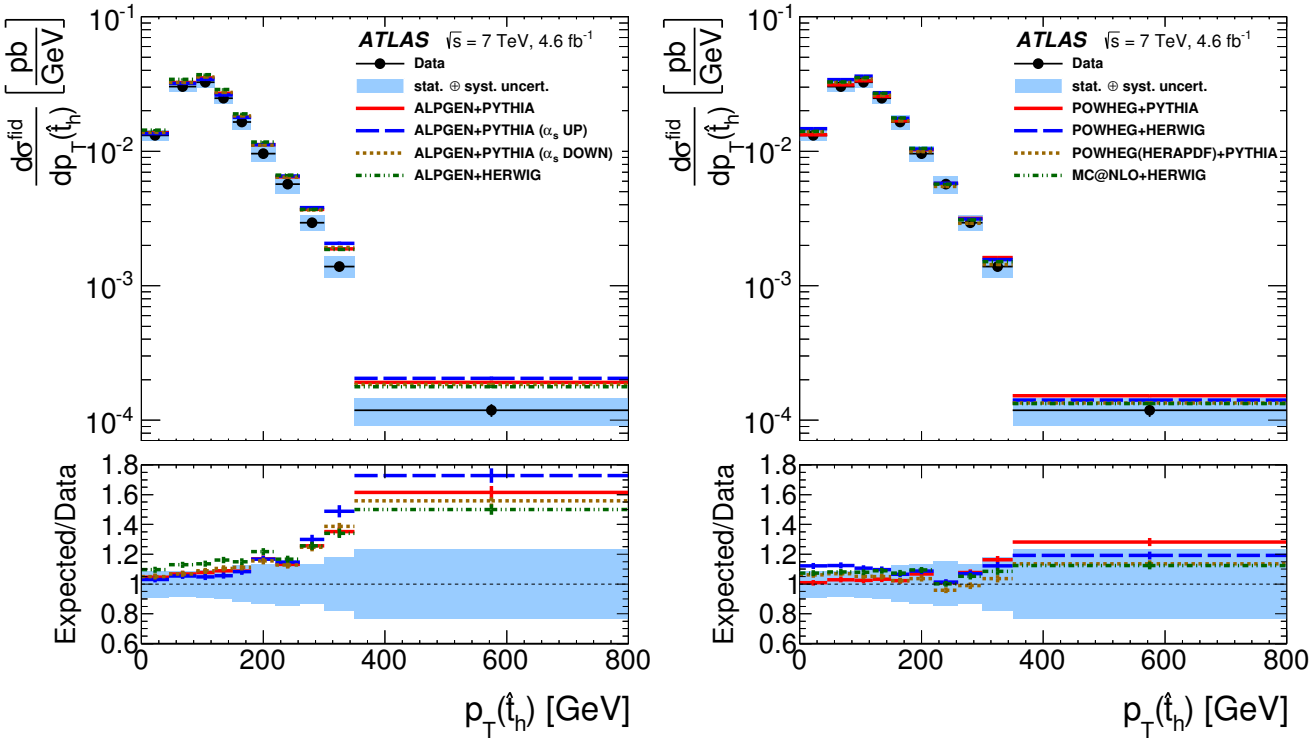
Pseudo-top reconstruction

- same kinematic selection on reconstructed objects
- veto on additional leptons $p_{\mathrm{T}} > 15\,\mathrm{GeV}$



After background subtraction and unfolding:

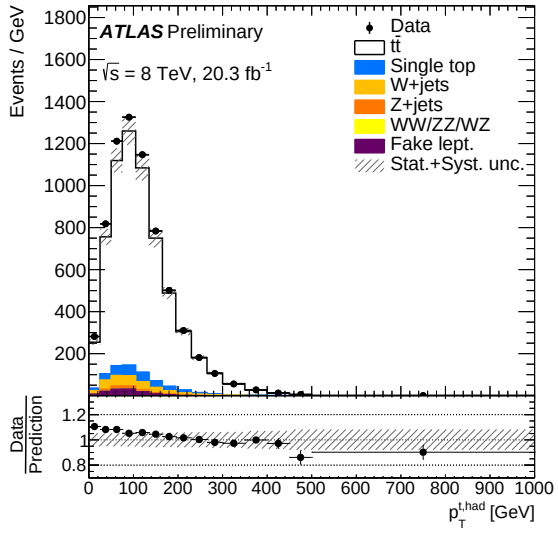
- uncertainty dominated by systematics in b-tagging, jet energy scale, initial and final state parton shower.
- $\rightarrow$softer $p_{\mathrm{T}}(\mathrm{t})$ observed, especially compared to Alpgen.

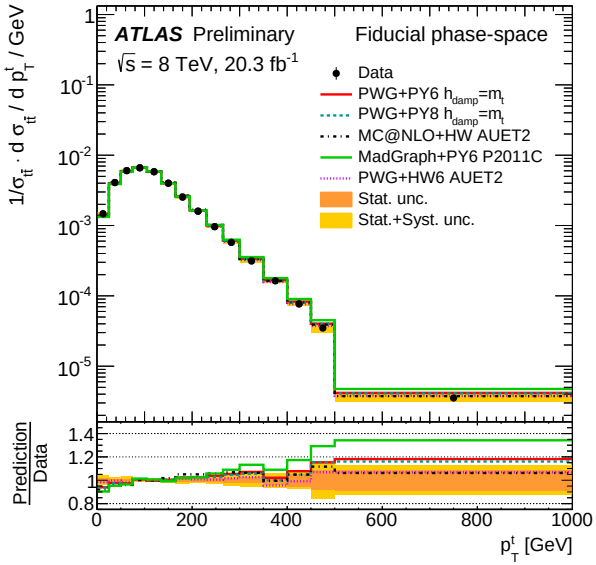


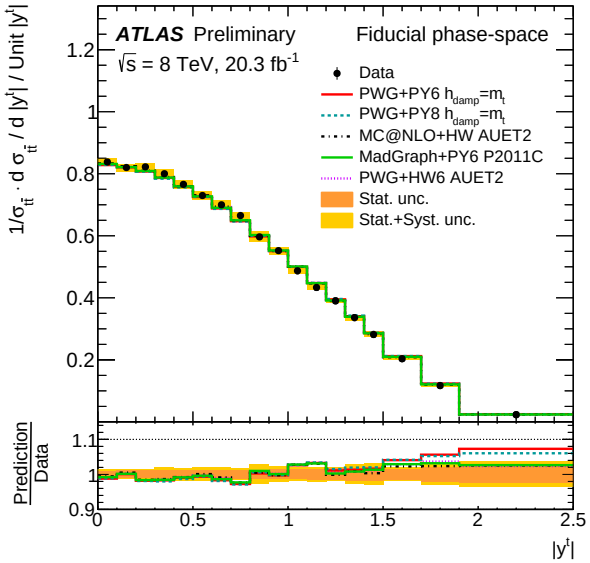
NEW ATLAS: TOPQ-15-06, 20.3 fb^{-1}, 8 TeV

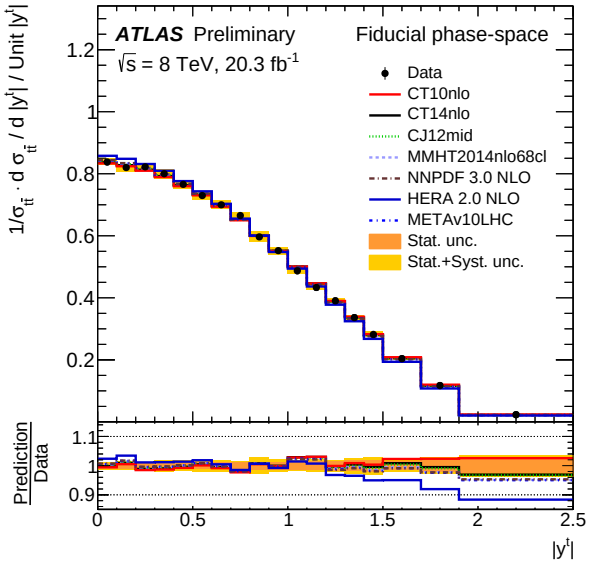
Particle and parton level measurement
Definitions of particles and pseudo-top very similar to 7 TeV.

- $p_{\mathrm{T}}(\mathrm{t})$ again softer than predicted.
- rapidity very sensitive to PDF.





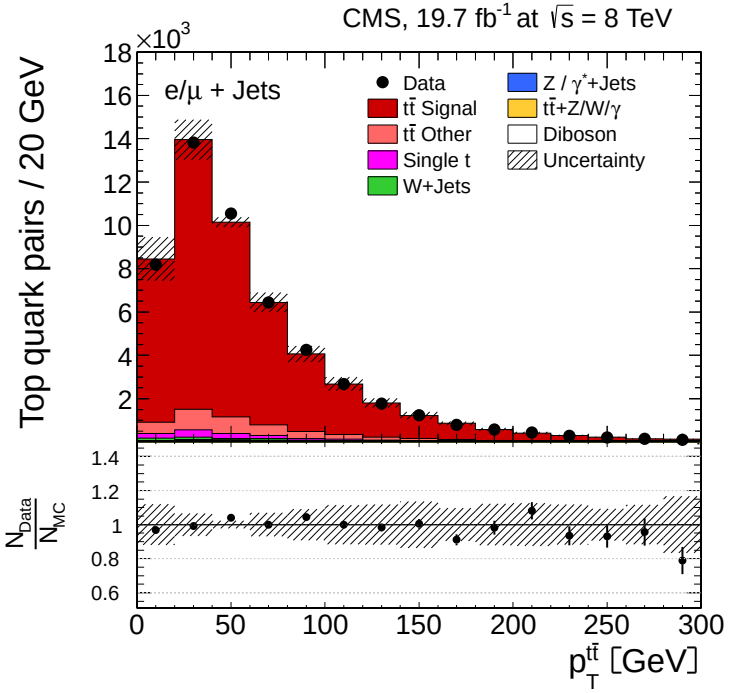




CMS: CERN-PH-EP-2015-117 (arXiv:1505.04480), 19.7 fb^{-1}, 8 TeV

l+jets (e/μ) selection:

- lepton $p_{\mathrm{T}} > 33\,\mathrm{GeV}$, $|\eta| < 2.1$
- $>= 4$ jets $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 2.4$, 2 b-tagged, 2 non-tagged.

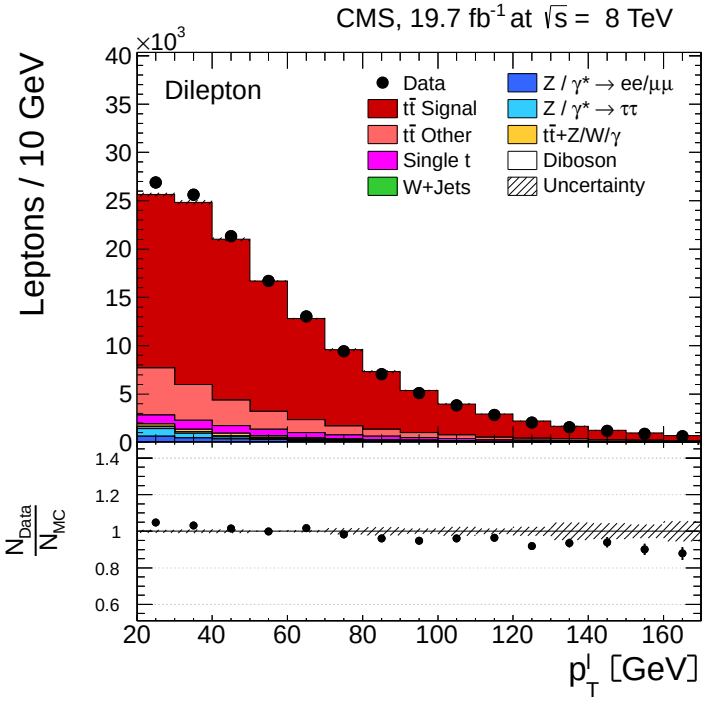


l+jet reconstruction:

- use kinematic fit with smearing according to resolution including permutations of up to five jets.
- first step: M_{t}, M_W constraints for jet association.
- second step: repeat fit without M_{t} constraints to improve kinematics.
- $\rightarrow$after cut on χ^2 result of the fit: 87% correctly reconstructed.

dilepton ($ee, e\mu, \mu\mu$) selection:

- two leptons $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $|\eta| < 2.4$
- exclude Z boson mass window.
- $>= 2$ jets $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 2.4$, $>= 1$ b-tagged
- $E_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}$

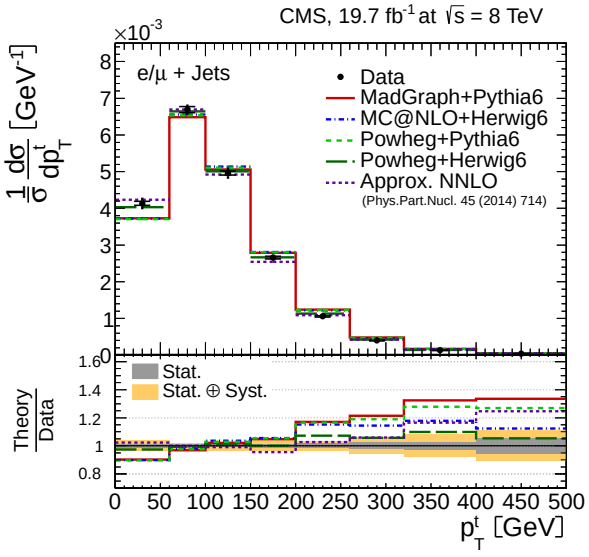


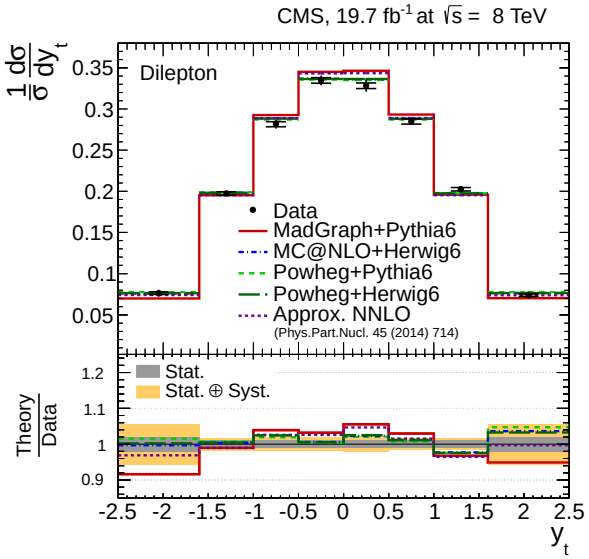
dilepton reconstruction:

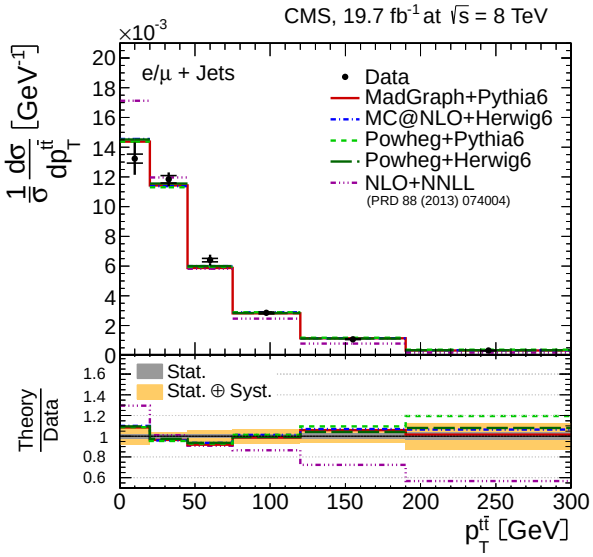
- algebraic reconstruction of neutrino momenta:
  - event p_{T} balance, M_{t}, M_W constraints.
  - smearing according to detector resolution to increase number of solvable events $\rightarrow$94%.

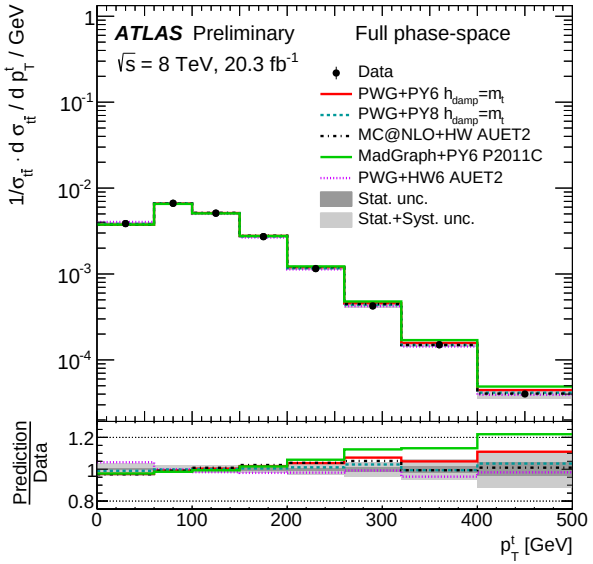
differential cross sections at parton level:

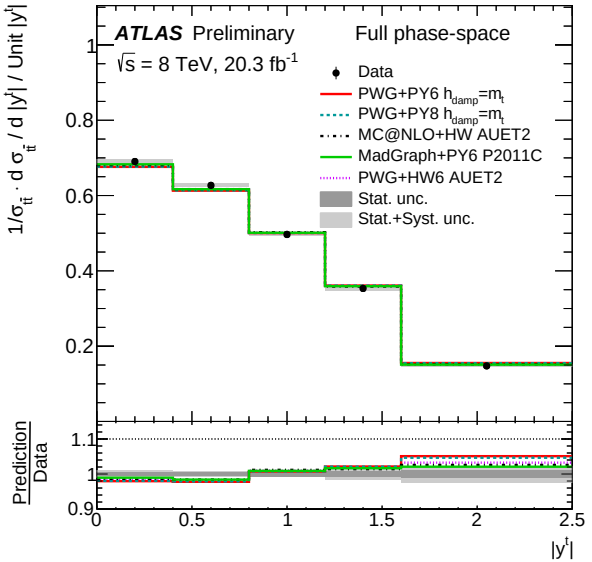
Main sys. uncertainty: parton shower/hadronization, jet energy scale.

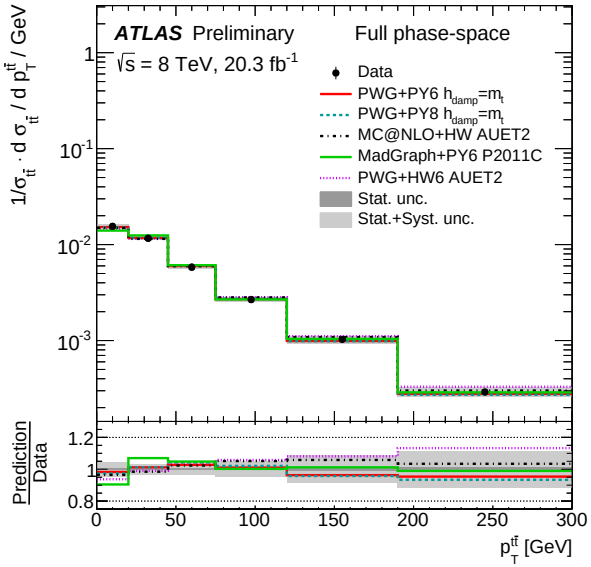






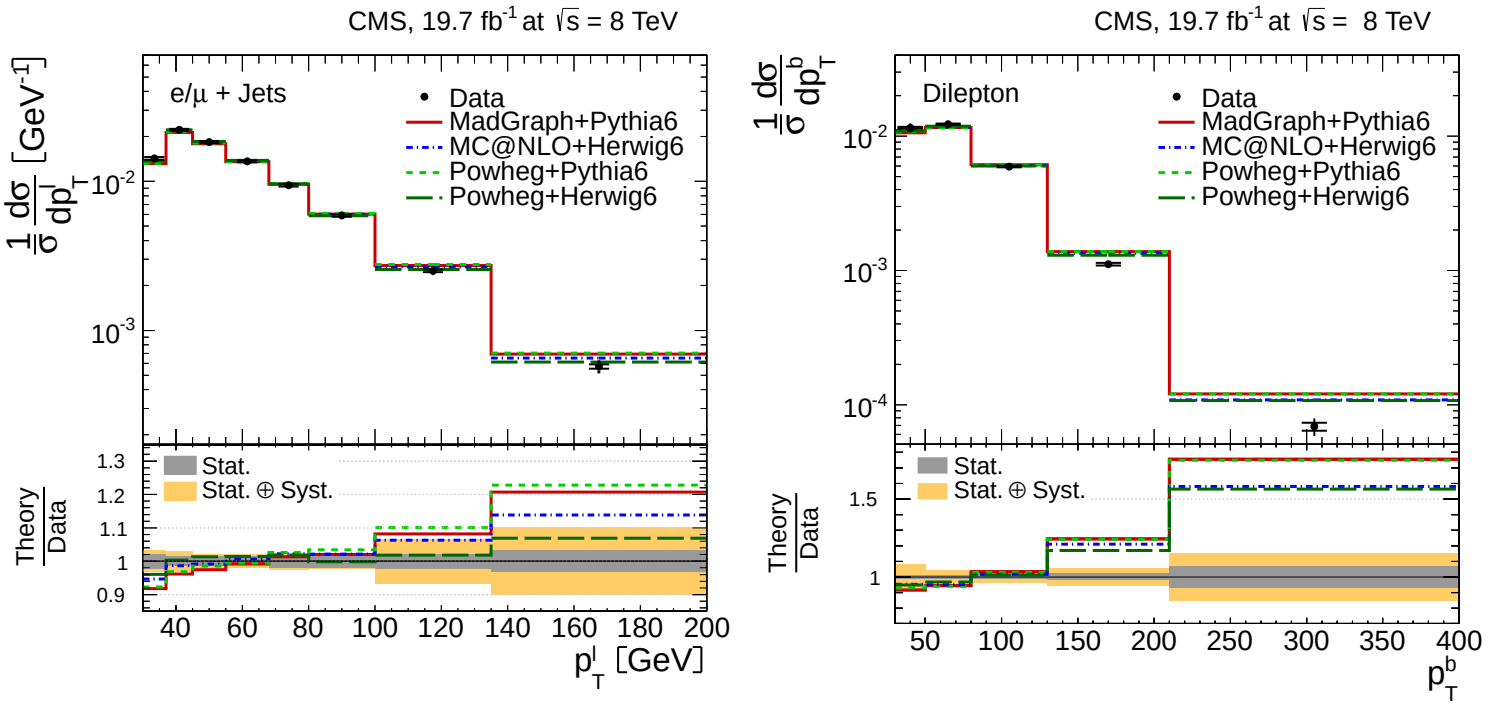






p_T, $|\eta|$ of leptons and b jets are measured on particle level within detector acceptance:

- l+jets: one lepton $p_T > 33\,\text{GeV}$ $|\eta| < 2.1$
- dilepton: two leptons $p_T > 24\,\text{GeV}$ $|\eta| < 2.4$
- b jets: two jets with highest p_T that contain decay products of b hadron.



Main sys. uncertainty: parton shower/hadronization (comparison between Pythia6 and Herwig).

$\rightarrow$softer p_T spectrum also confirmed by measurements of decay products.

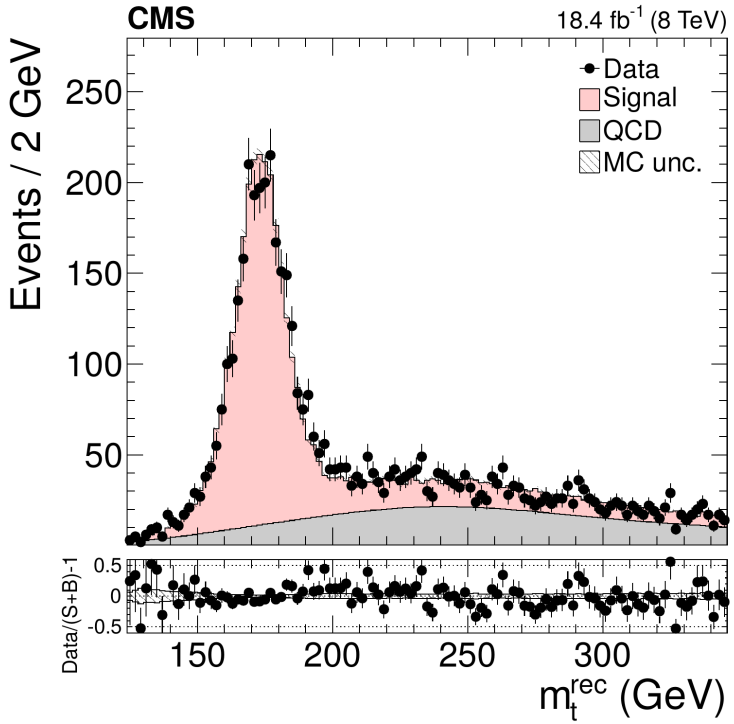
NEW CMS: TOP-14-018, 18.4 fb^{-1}, 8 TeV

Selection:

- $>=$ 6 jets $p_{\text{T}} > 40\,\text{GeV}$, $|\eta| < 2.4$
- $>=$ 4 jets $p_{\text{T}} > 60\,\text{GeV}$
- $>=$ 2 b jets

Reconstruction:

- kinematic fit with smearing according to resolution including all combinations.
- constraints: $m_W = 80.4\,\text{GeV}$, equal m_t.
- fit probability $> 15\%$, $\Delta R(b, b) > 2.0$

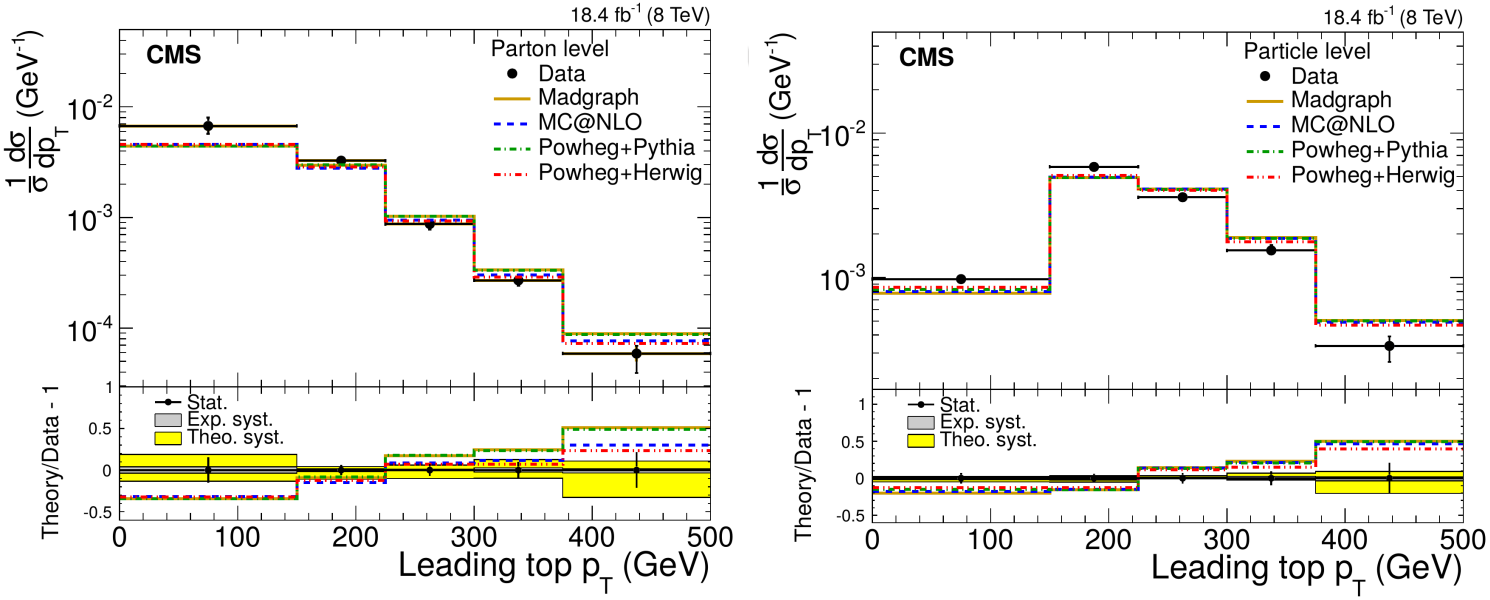


QCD background estimation:

- same selection and reconstruction in multi-jet events, but veto b jets
  $\rightarrow$QCD-enriched sample ($< 1\%$ $t\bar{t}$) with same shapes as background in main selection.
- QCD normalization from template fit on m_t in each bin.

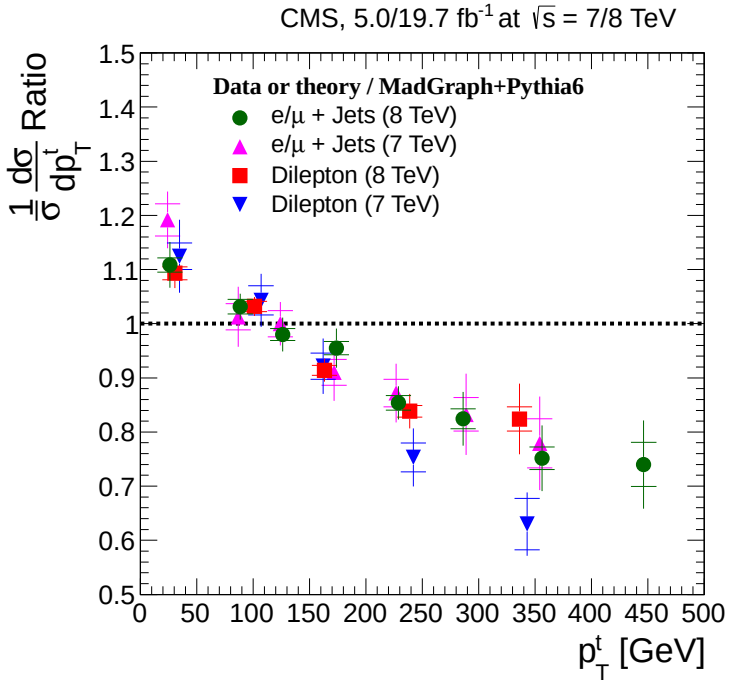
All-hadronic final state:

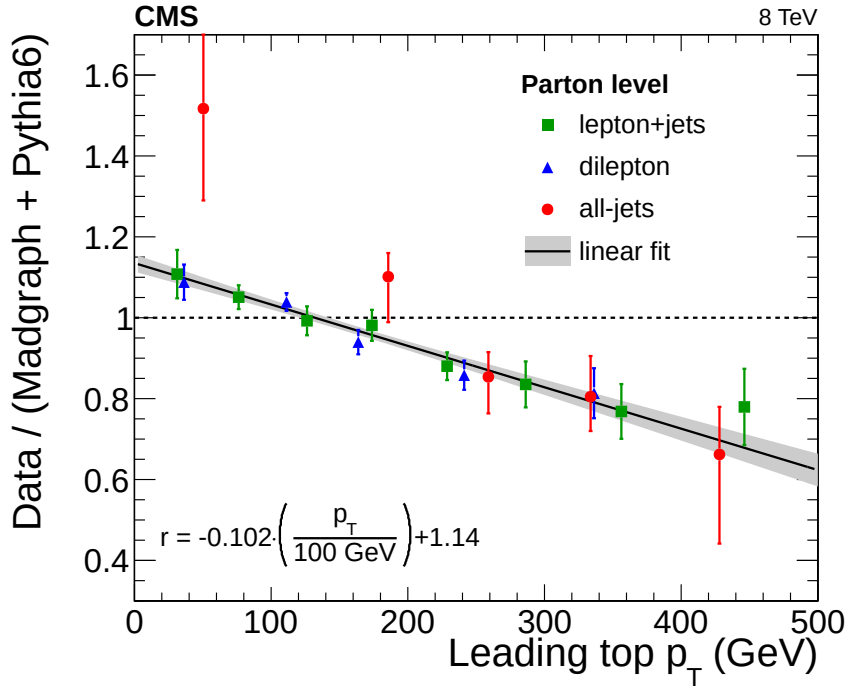
- parton level: large extrapolation →dominant theo. uncertanities.
- particle level: in detector acceptance →reduced theo. uncertanities.



→softer p_{T} spectrum also confirmed by all-hadronic measurement.

All 7 TeV and 8 TeV measurement show softer $p_{\mathrm{T}}(\mathrm{t})$ spectrum:
CMS: EPJ C73 (2013) 2339 (arXiv:1211.2220), 7 TeV
ATLAS: Phys. Rev. D 90, 072004 (arXiv:1407.0371), 7 TeV



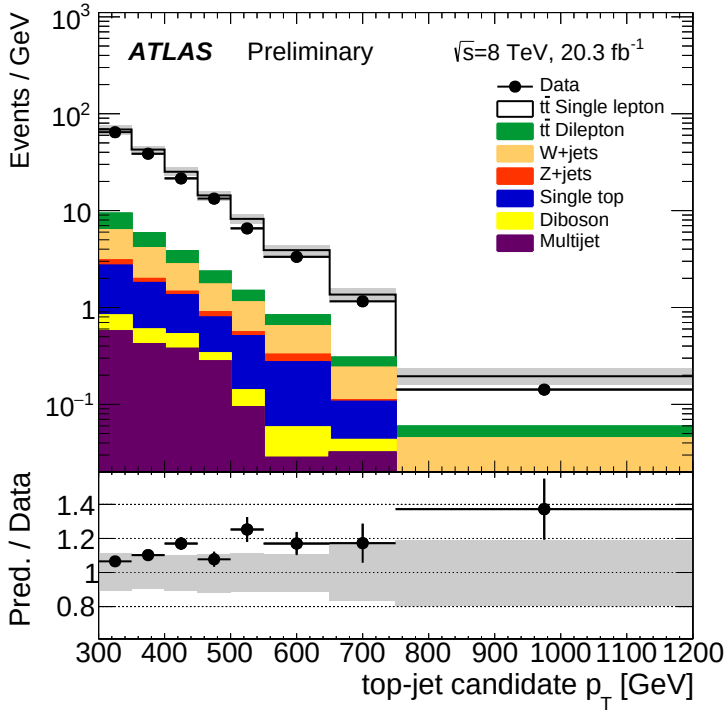


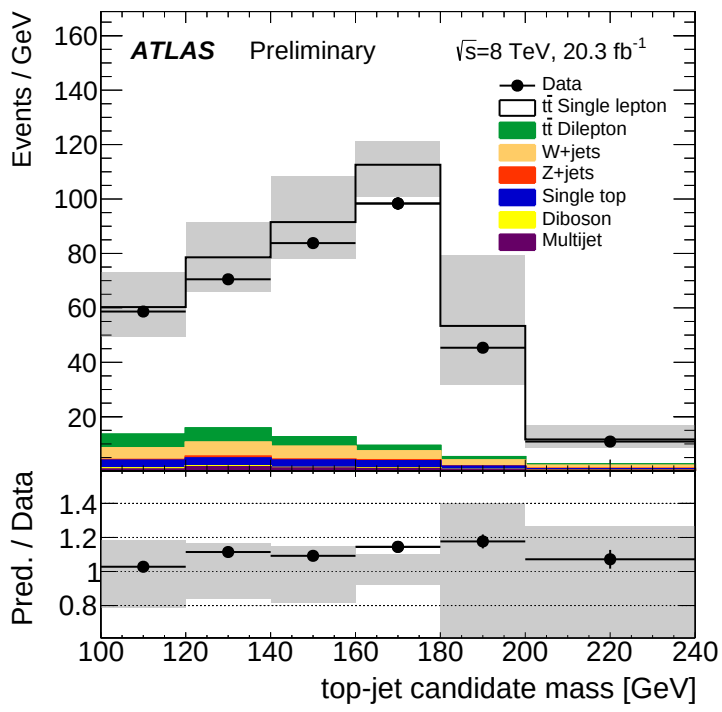
NEW ATLAS: TOPQ-2014-15, ATLAS-CONF-2014-057, 20.3 fb^{-1}, 8 TeV

Particle, parton level measurements for $p_{\text{T}}(\text{t}) > 300$ GeV in e/μ+jets.

Optimization necessary to identify close by top decay products:

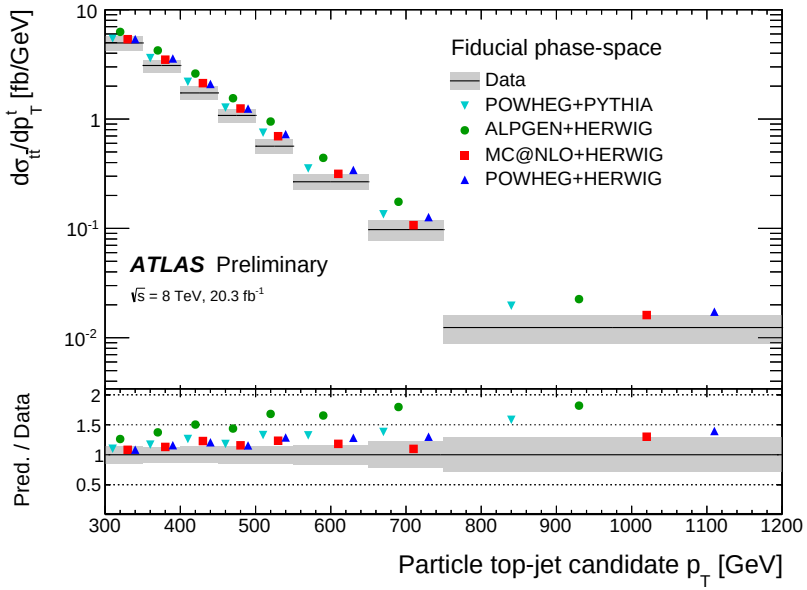
- exactly 1 lepton: $p_{\text{T}} > 25\ GeV$, isolation cone size $\propto 1/p_{\text{T}}$
- at least 1 jet: $p_{\text{T}} > 25$ GeV, $\Delta R(j, l) < 1.5$
- at least 1 fat jet ($R = 1.0$), $p_{\text{T}} > 300$ GeV, $M_j > 100$ GeV, $\Delta R(j, l) > 2.3$
- k_T splitting scale of fat jet: $\sqrt{d_{12}} = \min(p_{\text{T}}(j_1), p_{\text{T}}(j_2))\Delta R(j_1, j_2) > 40$ GeV
- at least 1 b-tag: the leading small jet close to lepton or a small jet with $\Delta R(j, j_{\text{large}}) < 1.0$

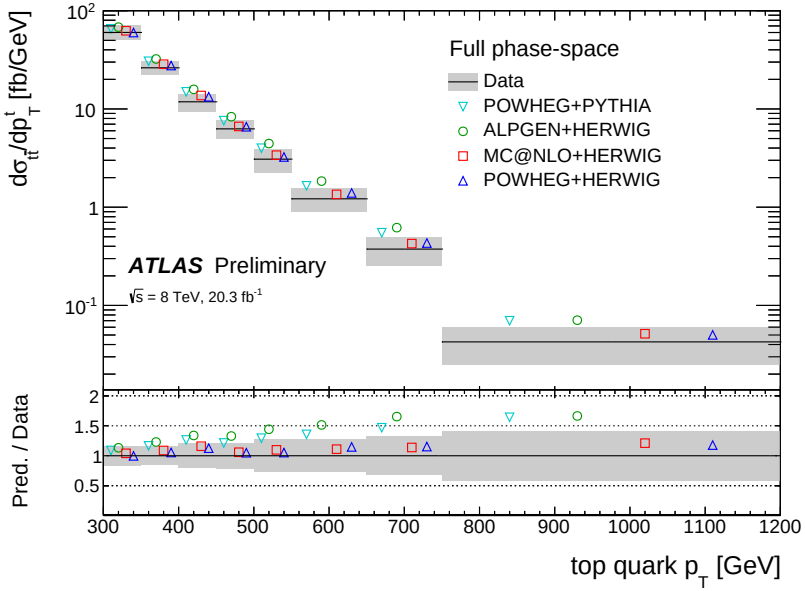




Particle, parton level measurements for $p_{\mathrm{T}}(\mathrm{t}) > 300\,\mathrm{GeV}$ in e/μ+jets.

- dominant background W+jets: determined from lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ selection plus b/c-jets and extrapolated using MC predictions.
- dominant uncertainties particle level: jet energy scale, statistics
- dominant uncertainties parton level: signal modeling, jet energy scale, statistics



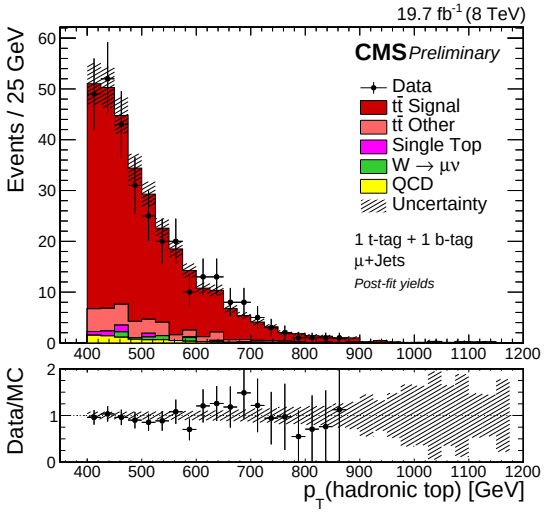


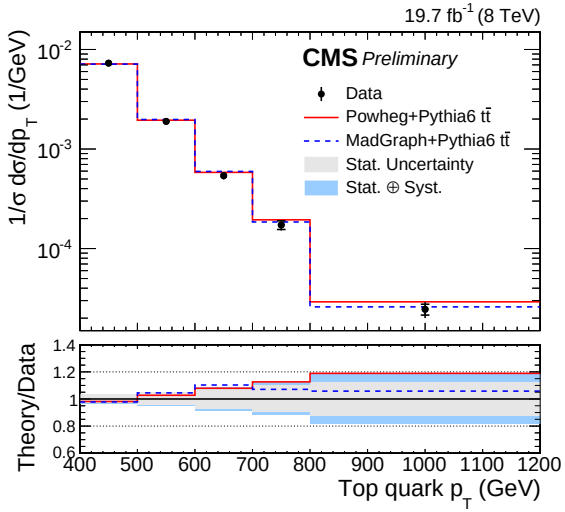
→MC overestimates the production of high p_{T} tops.

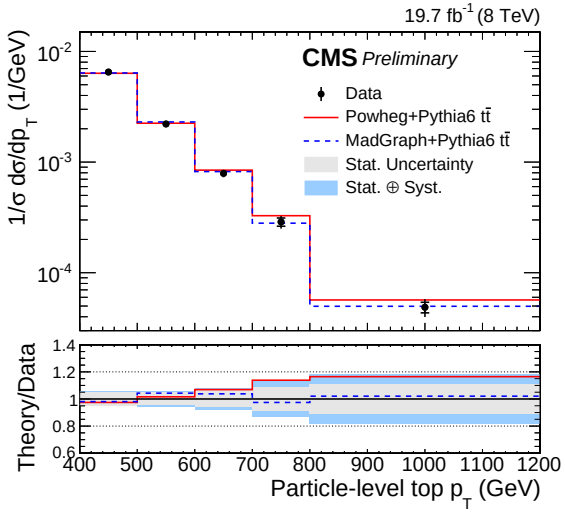
CMS: CMS-PAS-TOP-14-012, 19.7 fb^{-1}, 8 TeV

Particle, parton level measurements for $p_{\mathrm{T}}(\mathrm{t}) > 400$ GeV in e/μ+jets.

- 1 muon(electron) $p_{\mathrm{T}} > 45(35)$ *GeV*, no isolation required
- anti-k_T ($R = 0.5$): $p_{\mathrm{T}} > 30$, $\Delta R(j, l) < \pi/2$, $0.5 < \Delta R(j, l)$ or $p_{\mathrm{T,rel}}(j, l) > 25$ GeV
- Cambridge-Aachen ($R = 0.8$) jet: $140 < M_j < 250$ GeV, $p_{\mathrm{T}} > 400$ GeV
- decluster jet recursively until up to four subjets with $\Delta R > 0.4 - 0.04 p_{\mathrm{T}}$ and $p_{\mathrm{T}}(\mathrm{subjet}) > 0.05 \cdot p_{\mathrm{T}}$
- t-tag: at least three subjets with $M_{jj} > 50$ GeV.







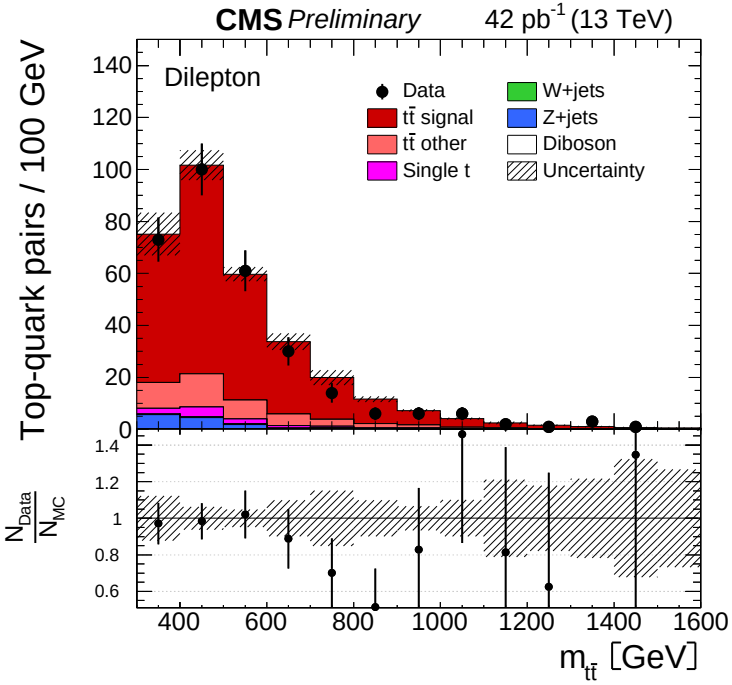
→Again Powheg+Pythia6 predicts harder p_{T} spectrum, but Madgraph+Pythia6 is more compatible.

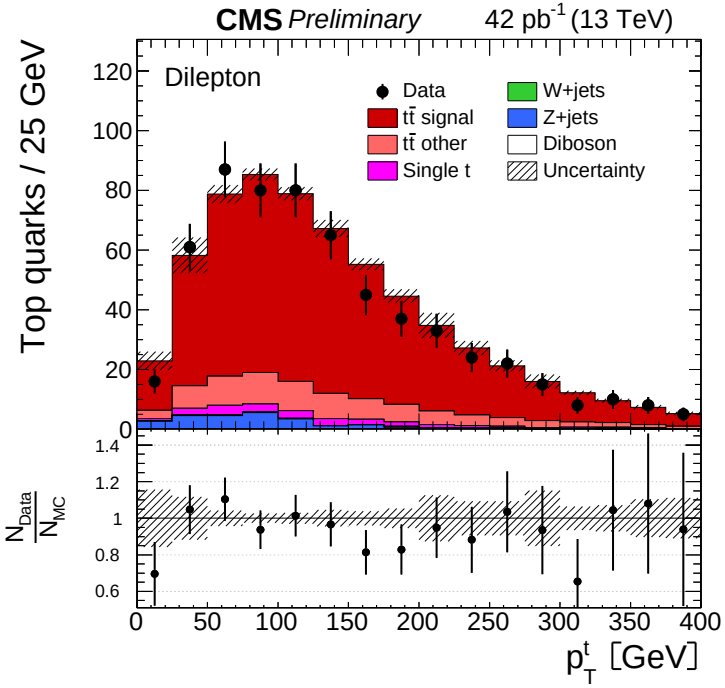
Particle-level cross section: measured. 1.28 ± 0.16 pb, prediction 1.49 pb(NNLO norm. Powheg).

NEW CMS: CMS-PAS-TOP-15-010, 42 pb^{-1}, 13 TeV

Parton level measurements of $t\bar{t}$ variables in dilepton channels ($ee, e\mu, \mu\mu$).

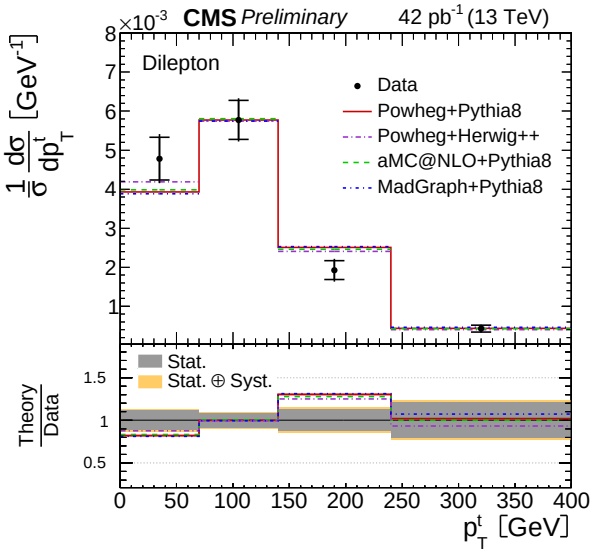
- two leptons with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $|\eta| < 2.4$. Drell-Yan mass window excluded.
- at least two jets $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 2.4$. At least 1 b-tagged.
- same algebraic reconstruction with smearing as in 8 TeV analysis.
- about 300 observed events; 80% signal.

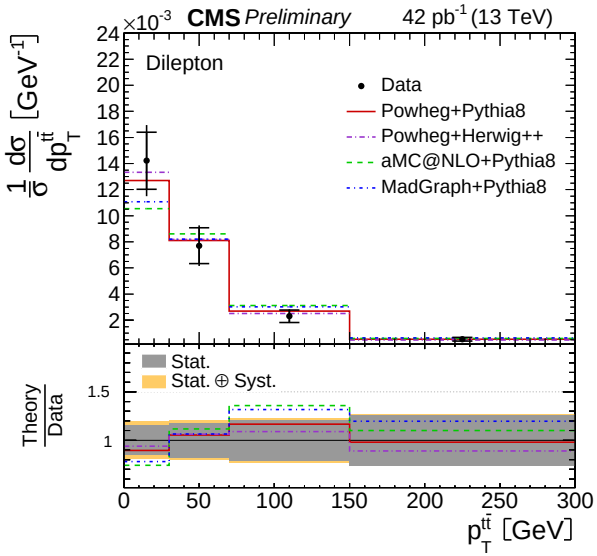


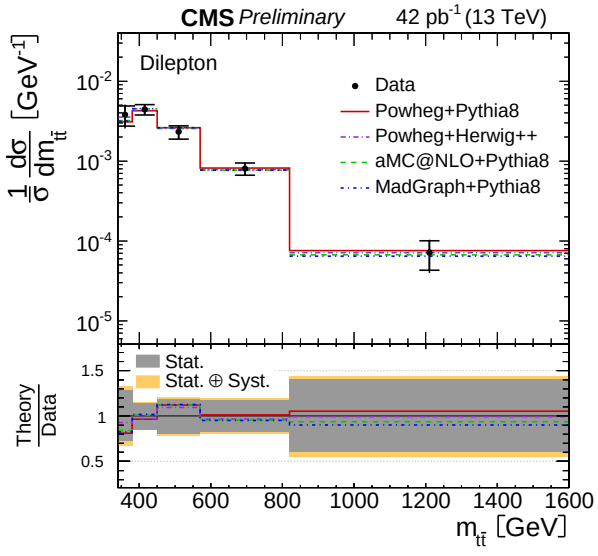


Parton level measurements of $t\bar{t}$ variables in dilepton channels ($ee, e\mu, \mu\mu$).

- unfolded and extrapolated to full phase space.
- uncertainty dominated by statistics.
- new MC setup: MG5_aMC@NLO (+0,1,2 jets at NLO matched to PS), parton shower with Pythia8 or Herwig++, NNPDF 3.0 NLO.



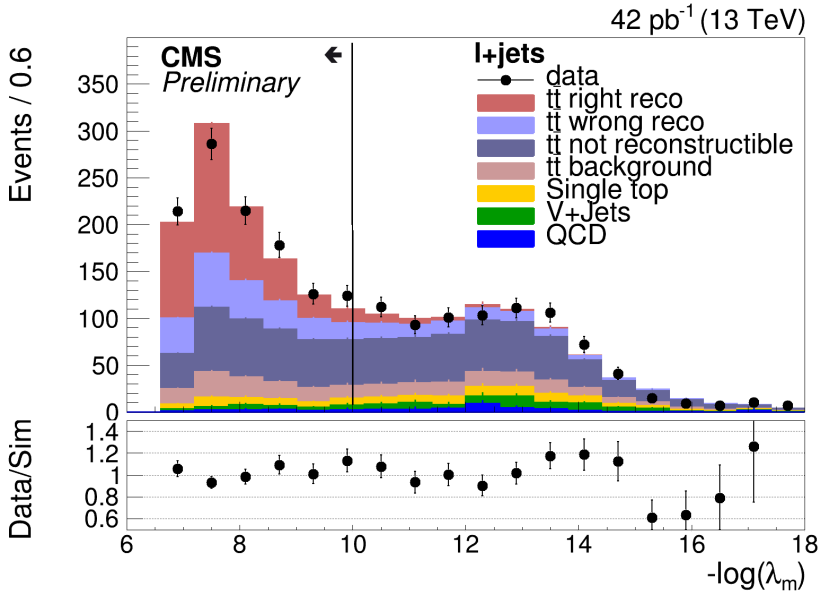


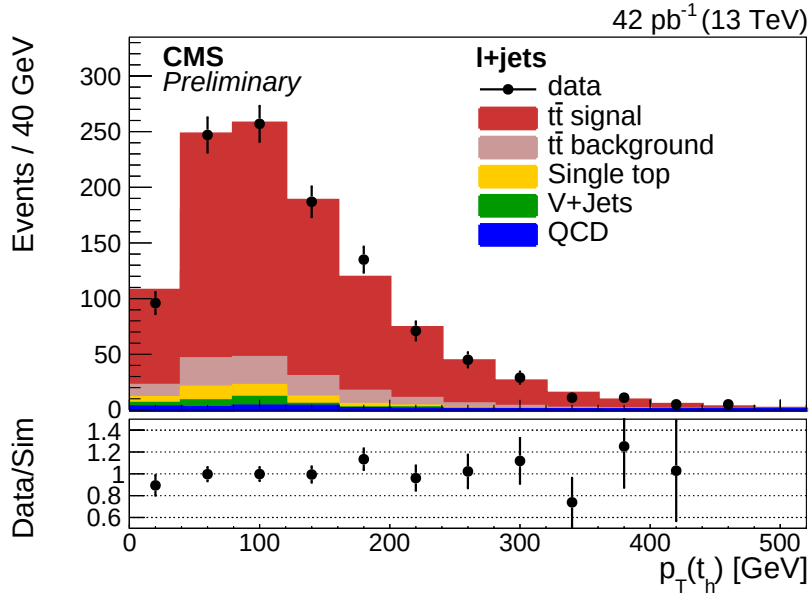


NEW CMS: CMS-PAS-TOP-15-005, 42 pb^{-1}, 13 TeV

Parton level measurements of $t\bar{t}$ variables in l+jets channel (e/μ).

- 1 lepton with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 2.1$.
- at least 4 jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, $|\eta| < 2.4$. At least 1 b-tagged.
- use mass constraints of M_{t}, M_W on leptonic side to obtain neutrino momentum (Nucl.Instrum.Meth 736 (2014), 169), and correct b-jet.
- calculate probability λ_m according to 2D mass distributions of M_{t}, M_W on hadronic side to obtain best permutation of jets.
- cut $-\log(\lambda_m) < 10$: 1100 event 83% signal.

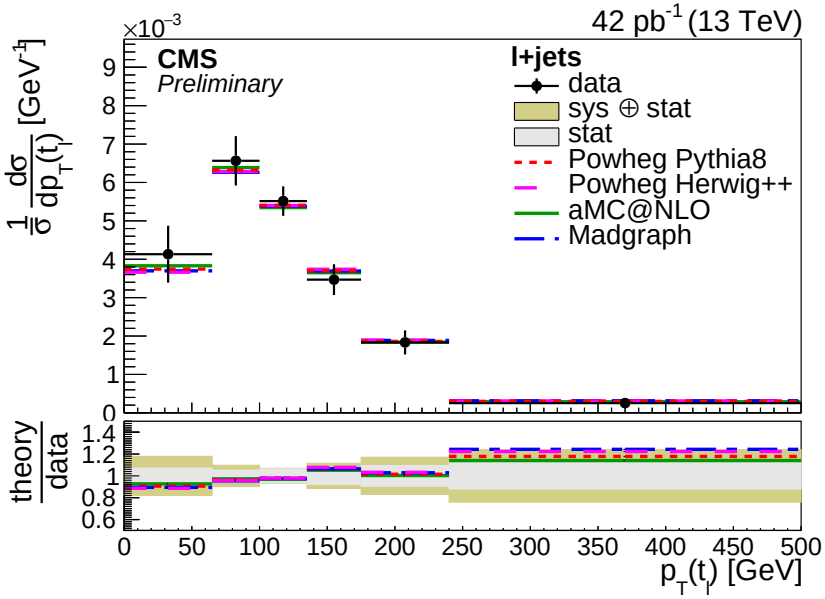


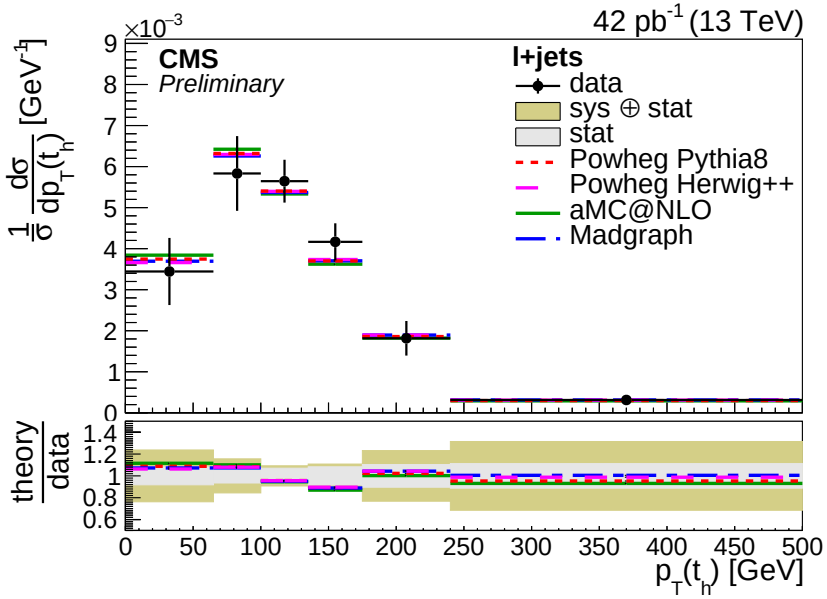


Parton matched to jet with highest p_{T} in $\Delta R < 0.4$

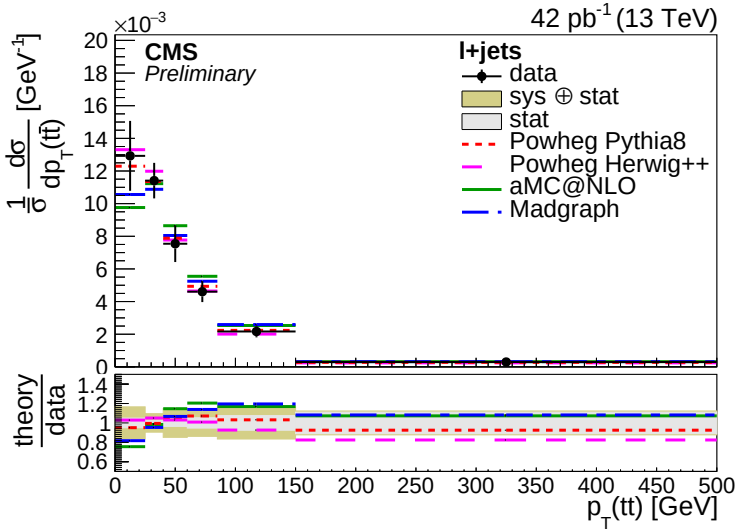
Parton level measurements of $t\bar{t}$ variables in l+jets channel (e/μ).

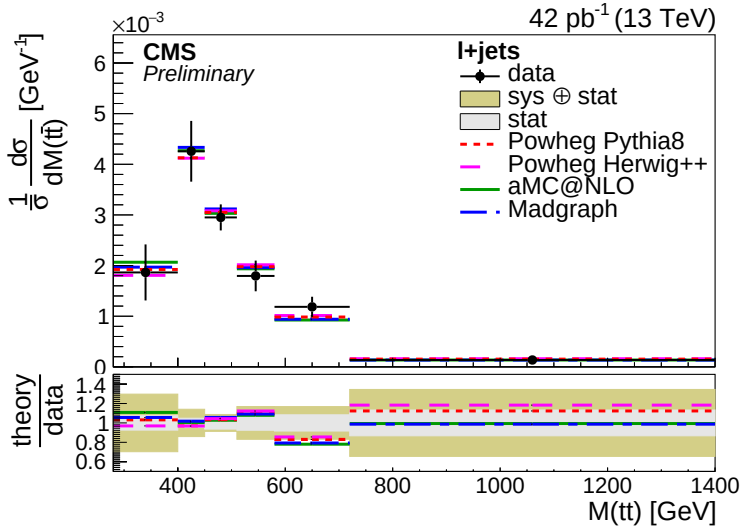
- unfolded and extrapolated to full phase space.
- uncertainty dominated by statistics and parton shower/hadronization (Pythia8 vs. Herwig++).
- with new MC: difference in p_{T} (t) smaller than in previous measurements, but not yet conclusive.





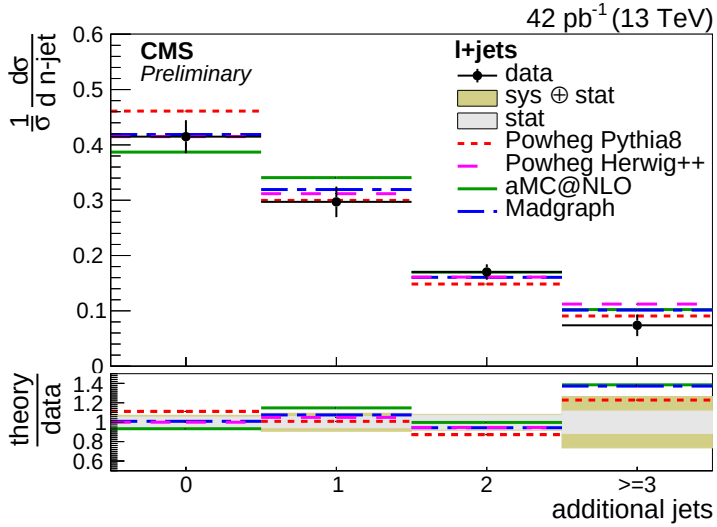
Parton level measurements of $t\bar{t}$ variables in l+jets channel (e/μ).





- $p_{\mathrm{T}}(t\bar{t})$ better described by Powheg than by MG5_aMC@NLO or Madgraph (+ 0,1,2,3 jets LO).

Additional jets defined at particle level in detector acceptance: $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, $|\eta| < 2.4$.



ATLAS and CMS: many analyses on differential $t\bar{t}$ measurements at various center of mass energies (13 TeV!).

- analyses available with pseudo-top, particle, and parton level definitions to provide a variety of interfaces with theory.
- special techniques needed and developed to measure high p_{T} tops ($> 300\,\mathrm{GeV}$).
- a softer $p_{\mathrm{T}}(\mathrm{t})$ spectrum is observed in all analyses (13 TeV?).
- besides experimental uncertainties large impact of parton shower and hadronization models.

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