Differential cross section measurements at the LHC —

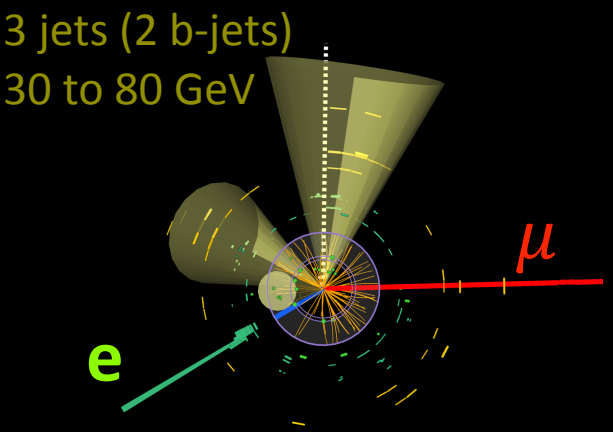
(final state objects: gap fraction, vs njets,... including tt+HF)

Matthias Danninger (University of British Columbia)

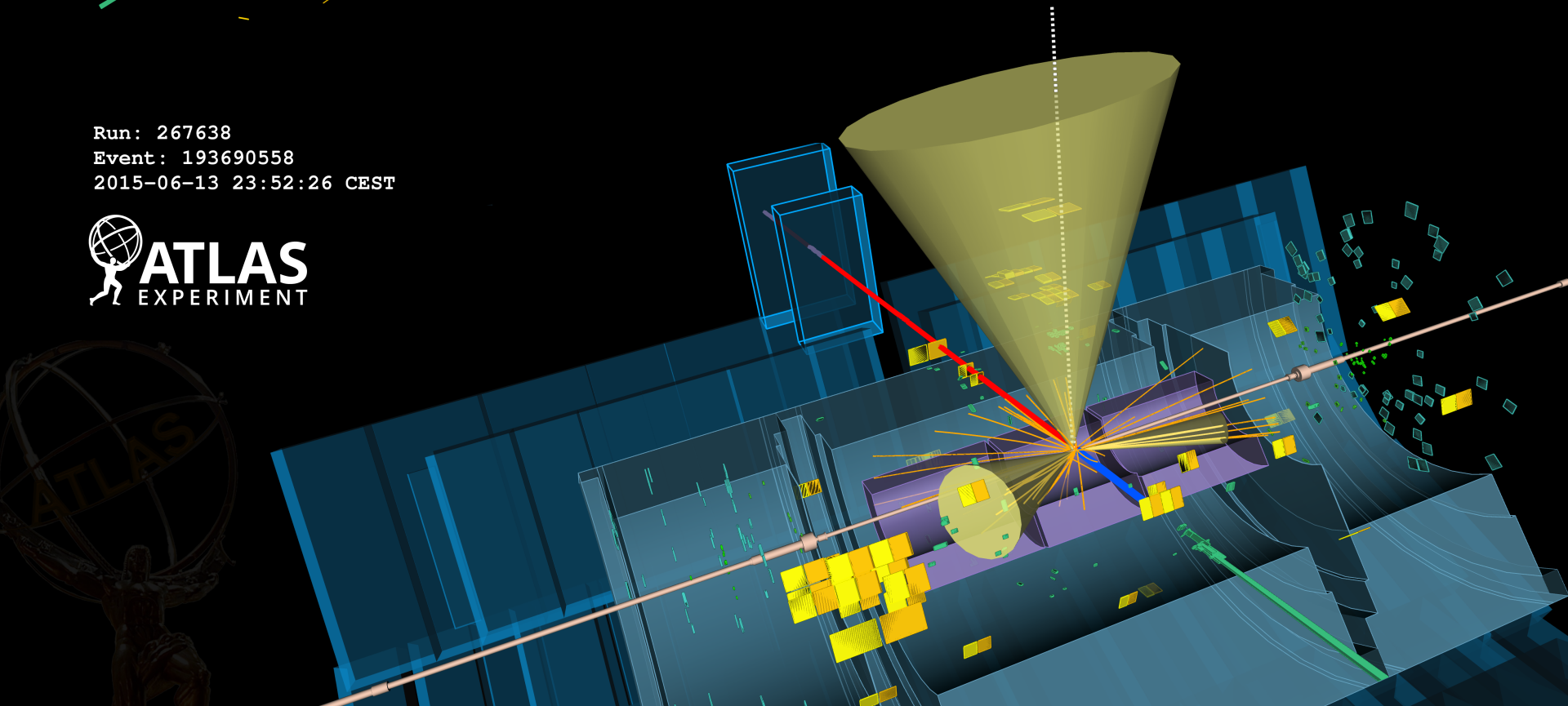
Top2015 - 8th International Workshop on Top Quark Physics, Ischia 2015-09-15

On behalf of the ATLAS and CMS Collaborations

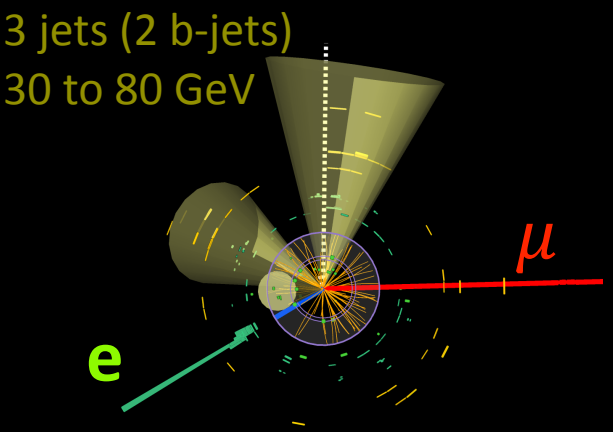
Motivation — new data



13 TeV $t\bar{t}$+jets candidate event
(Dilepton channel)



Cross-section measurements for $t\bar{t}$+jets: Why?



- Detailed study of perturbative QCD at the highest scales
  - ~1/2 of top events used in Run1 measurements have at least 1 additional jet
- Provide input for QCD MC tuning
  - QCD radiation is described by MC models with free model parameters

    —> Reduce MC modelling uncertainties
- Provide a detailed understanding of standard model processes up to TeV-scale
  - Important background for Higgs physics (ttH) and searches for BSM physics (VLQ, SUSY, …)

Fiducial vs. full phase space

Fiducial particle-level differential cross-section:

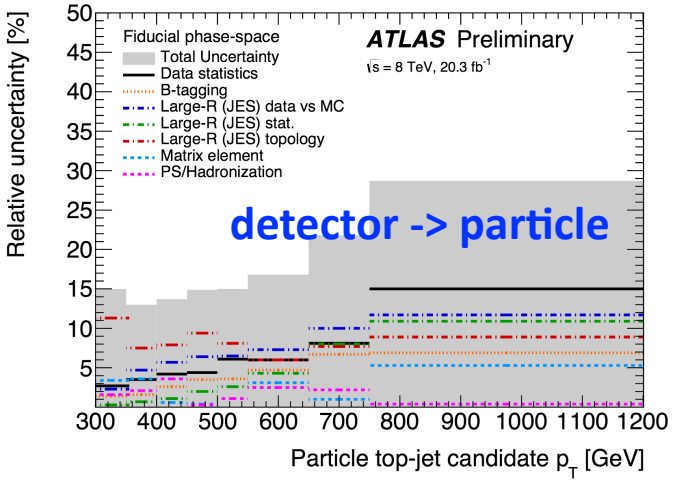
- Fiducial phase-space can match closely the phase space of the detector
- Correct mostly for detector response (resolution & efficiency)
- Less model dependent
  - Often see reduced dependence of measurement on signal modelling
  - Reduced extrapolation outside the fiducial phase space (relative to parton-level)

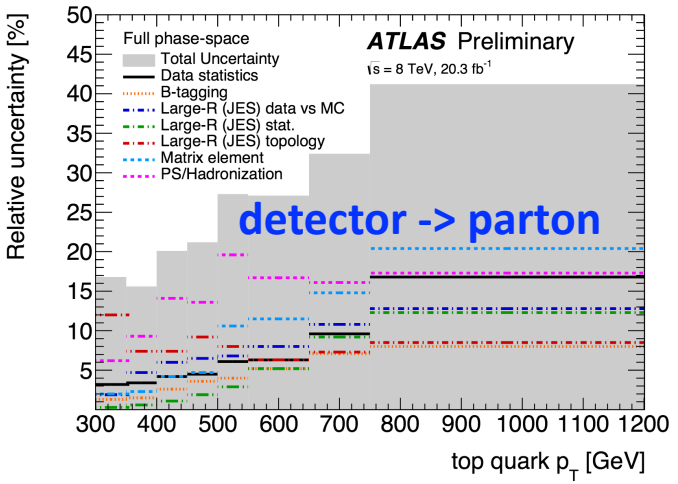
Full phase-space extrapolation:

- Model dependent

ATLAS-TOPQ-2014-15 (boosted top)

Example for illustration





Particle level definitions (incomplete list)

Recommendations for common truth objects definitions is based on particles with $\tau_{\text{particle}} > 3 \times 10^{-11}$ s: *(for further details see* LHCtopWG TWiki*)*

- **Charged leptons (e,μ):**
  Prompt, dressed truth-leptons that are not hadron decay products
  (either directly or via τ decays)
- **Neutrinos:**
  Only neutrinos not from hadron decays (directly or via τ decay) are considered.
- **Particle jets:**
  Clustering of all stable particles, except dressed charged leptons and neutrinos using anti-k_t algorithm (R=0.4, R=0.5 [0.4@13 TeV]);
- **Jet flavour ID:**
  Ghost matching of b-hadrons ($p_T^{had} > 5$ GeV) to truth jets.

Particle level event selections differ between 7 and 8 TeV, and between ATLAS and CMS analyses:

- Selection differences will be highlighted for specific analyses

tt+jets

Associated production measurements:

- Gap-fraction, Dilepton and L+jets at 7 TeV (Eur.Phys.J. C (2014) 74:3014)
- Gap-fraction, Dilepton at 8 TeV (CMS-PAS-TOP-12-041)
- L+jets at 8 TeV (CMS-PAS-TOP-12-042)
- Preliminary 13 TeV results (dilepton & L+jets)
  - CMS-PAS-TOP-15-005
  - CMS-PAS-TOP-15-010

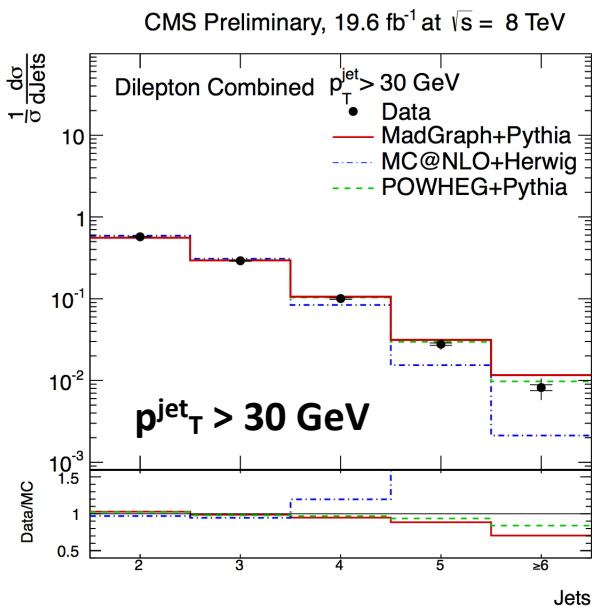
- Gap-fraction, dilepton at 7 TeV (Eur.Phys.J. C72 (2012) 2043)
- L+jets at 7 TeV (JHEP 01 (2015) 20)
- Performance & MC studies:
  - ATL-PHYS-PUB-2015-002
  - ATL-PHYS-PUB-2015-011

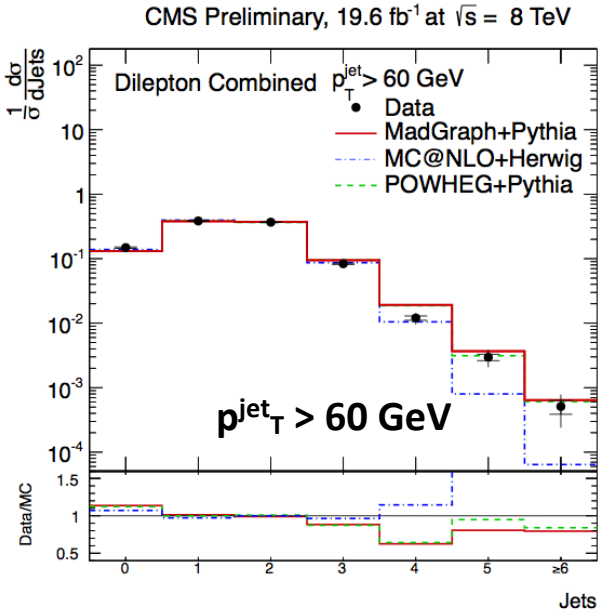
Jet multiplicity in tt events

Dilepton, 8 TeV

CMS-PAS-TOP-12-041

- Jet multiplicity unfolded to particle level
- Normalised cross-section for p_T thresholds of 30, 60, and 100 GeV
- Probing the p_T dependence of the hard emission





Definition:

- =2 lep.
- $|\eta^{lep}|<2.5$, $p_T^{lep}>20$GeV
- $|\eta^{b}|<2.4$, $p_T^{b}>30$GeV
- ≥ 2 b-jet

- MadGraph+Pythia6 & Powheg+Pythia6 showing generally good agreement with data

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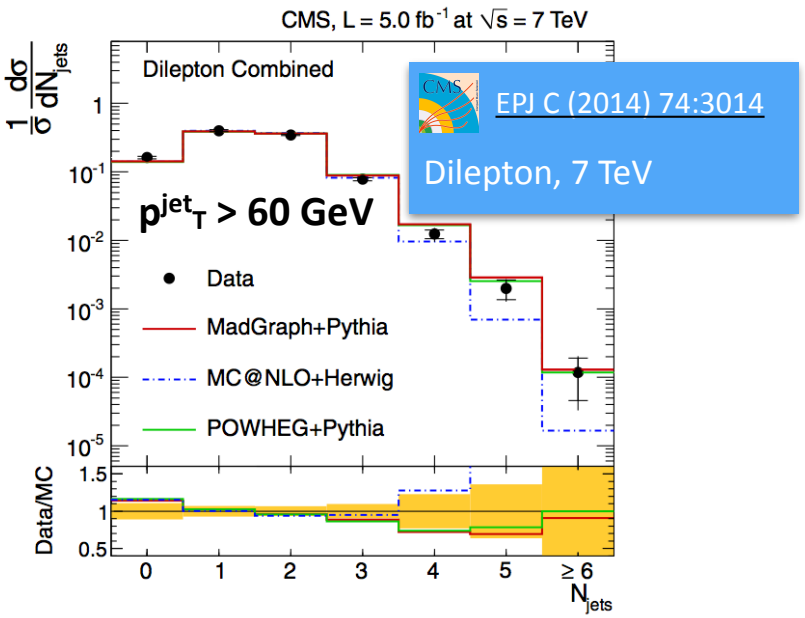
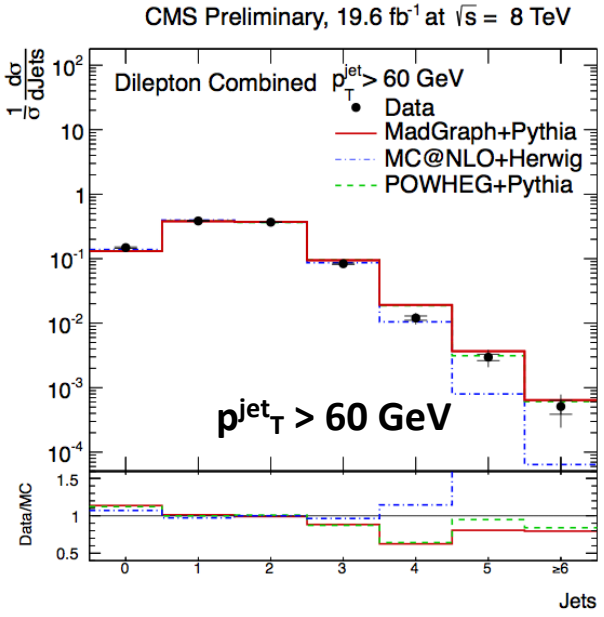


EPJ C (2014) 74:3014

Dilepton, 7 TeV



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- $|\eta^{lep}|$<2.5, p_T^{lep} >20GeV
- $|\eta^{b}|$<2.4, p_T^{b} >30GeV
- ≥ 2 b-jet

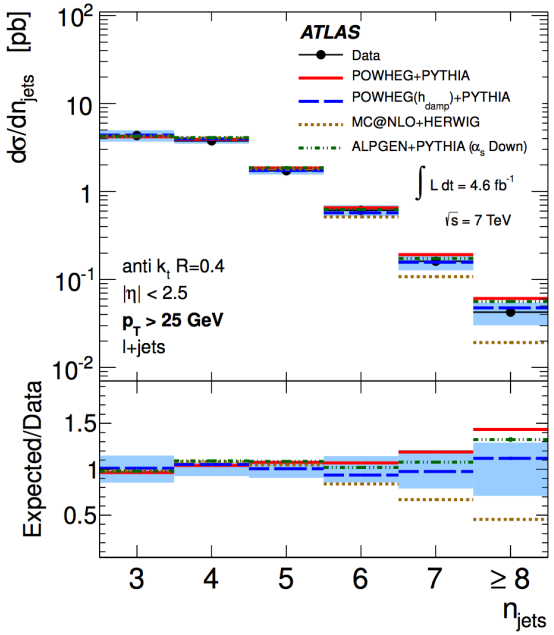
- MadGraph+Pythia6 & Powheg+Pythia6 showing generally good agreement with data
- Consistent results with 7 TeV measurements

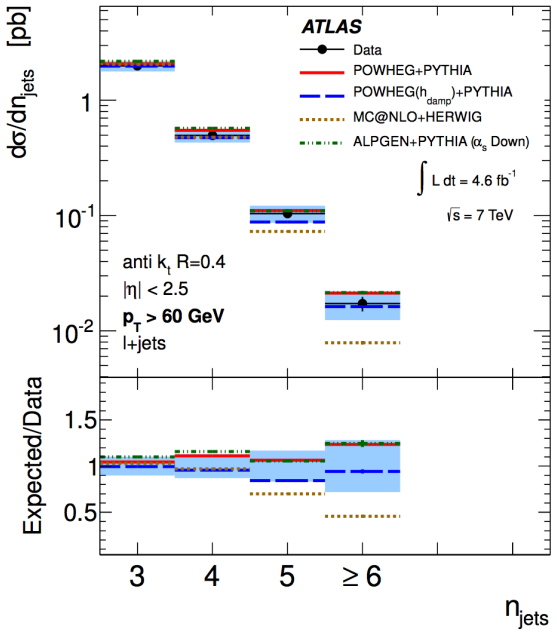
Jet multiplicity in tt events

L+jets, 7 TeV JHEP 01 (2015) 20 *(see also* Eur.Phys.J. C (2014) 74:3014 *)*

- Fiducial particle-level differential cross-section vs jet multiplicity and jet p_T
- Jet multiplicity (up to 8 jets) and jet-p_T spectra (ordered by p_T) unfolded to particle level
- Cross-section derived for p_T thresholds of 25, 40, 60 and 100 GeV

Uncertainty:
10%-30%





Definition ($|\eta|<2.5$):

- 1 lepton
- ≥ 3 jets
- ≥ 1 b-jet

- Model differences increase with jet multiplicity and jet p_T threshold
- PowhegPythia with tuning of hard radiation ($\mathbf{h_{damp}=m_{top}}$) describes data best

Jet multiplicity in tt events

L+jets, 7 TeV JHEP 01 (2015) 20 *(see also* Eur.Phys.J. C (2014) 74:3014 *)*

- Fiducial particle-level differential cross-section vs jet multiplicity and jet p_T
- Jet multiplicity (up to 8 jets) and jet-p_T spectra (ordered by p_T) unfolded to particle level
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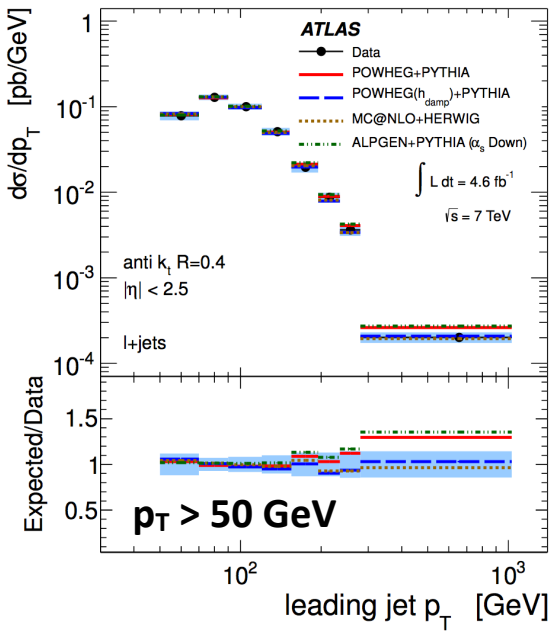
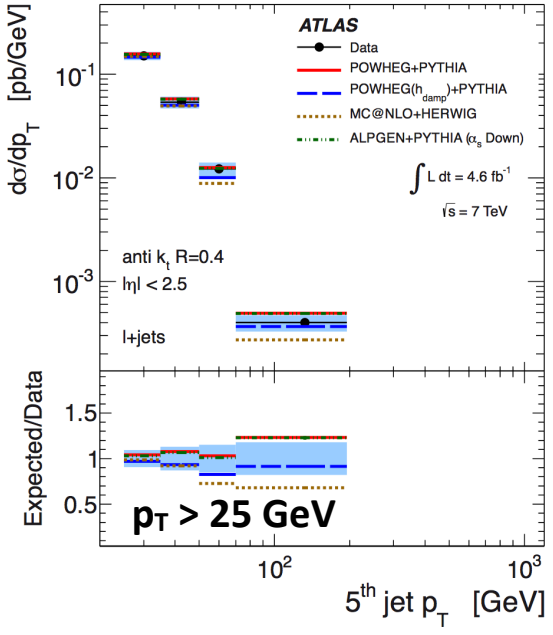
Uncertainty:
10%-16%





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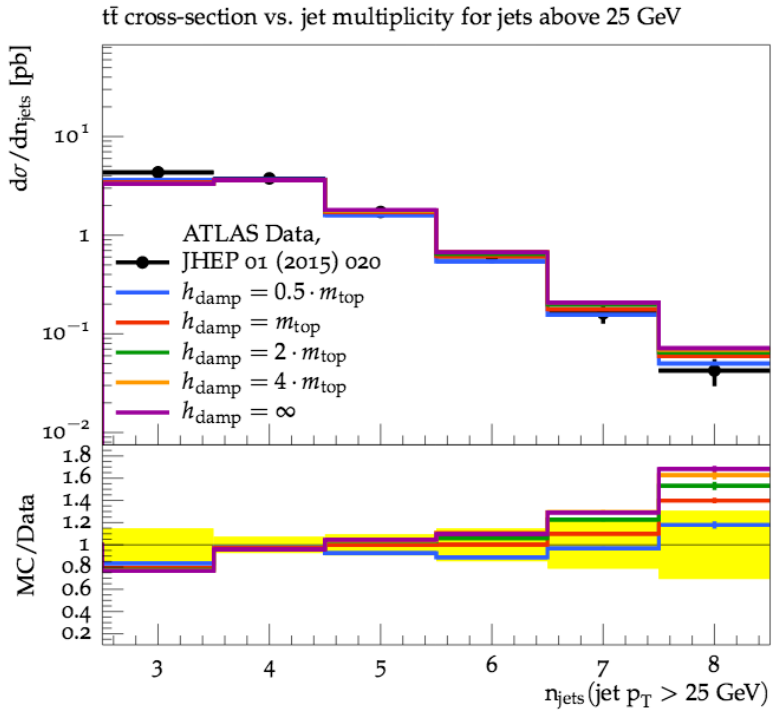
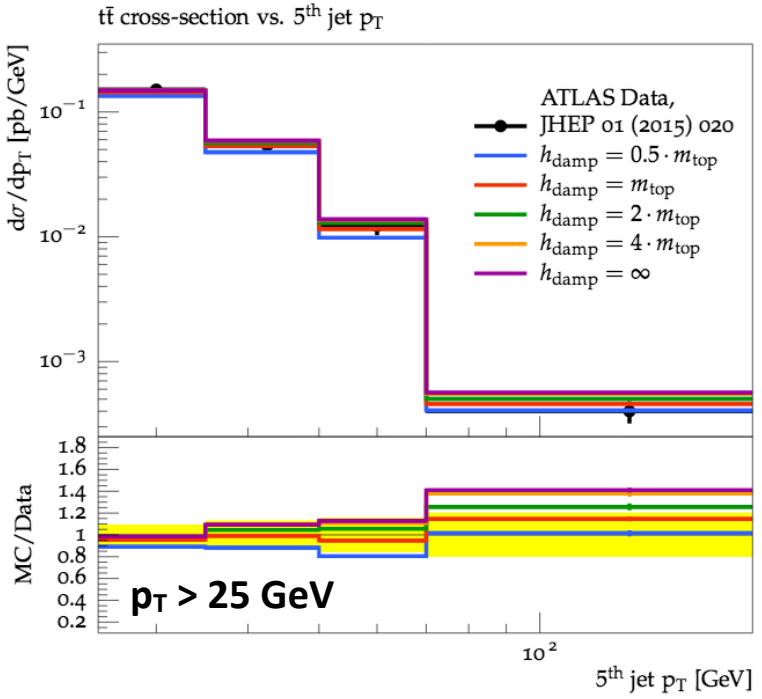
Particle level MC tuning studies

L+jets, 7 TeV, Powheg+Pythia 8 studies

ATL-PHYS-PUB-2015-011





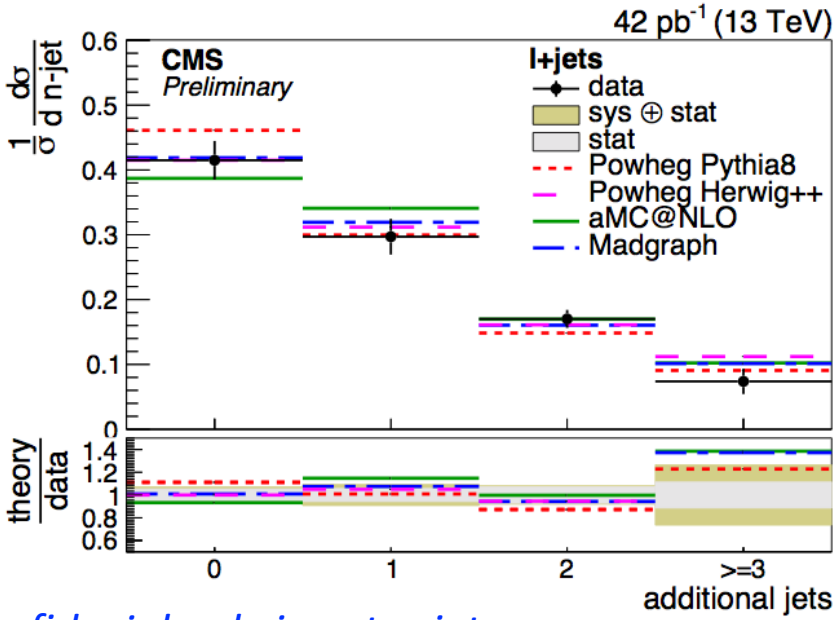
- NLO ME for top pair in Powheg, LO ME for first emission, additional jets from Pythia
- Resumation damping parameter **h_{damp}** controls the p_T matching of 1st add. emission
- Overall best agreement for **$h_{damp} = m_{top}$**
- Studies of PDF sets and generator comparisons presented in the note

First 13 TeV results

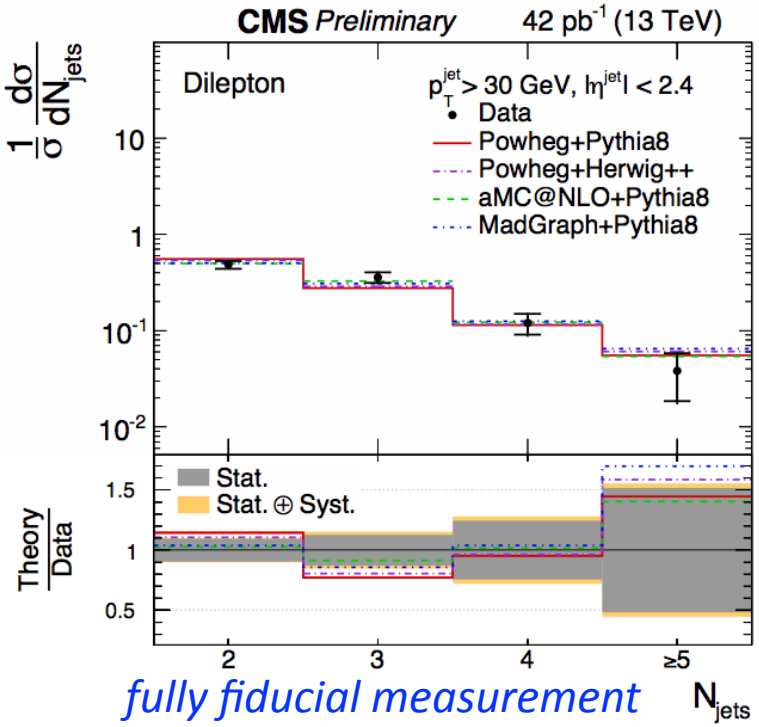
L+jets & Dilepton, 13 TeV

CMS-PAS-TOP-15-005
CMS-PAS-TOP-15-010

- Multiplicity of additional jets not from tt-decays (L+jets analysis)
- Additional jets identified in data by minimizing kinematic χ^2 fit sensitive to tt-system
- Differential cross-section as function of N_{jets} in dilepton analysis are derived in fully fiducial phase space
- Particle- & reconstruction-level jets at 13TeV defined using anti-k_t algorithm with R=0.4



fiducial only in extra jets



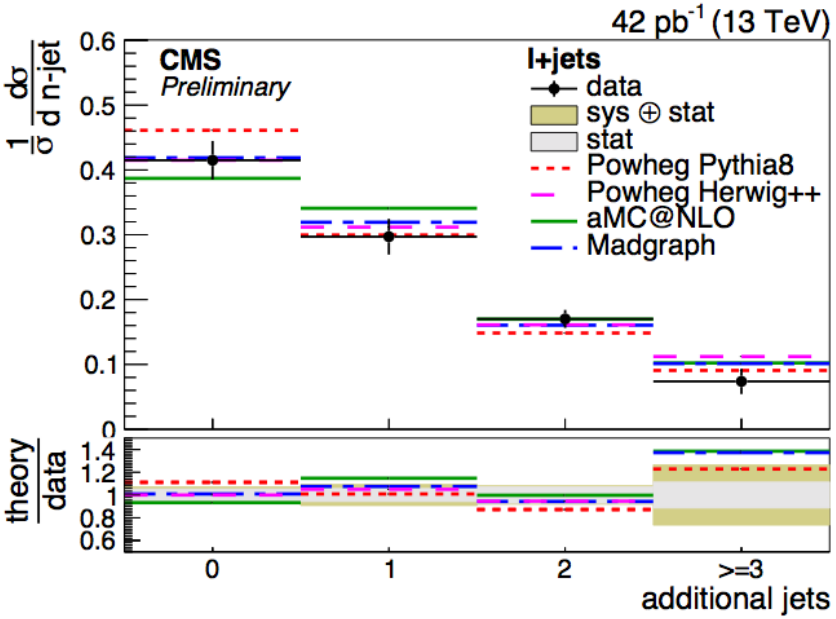
fully fiducial measurement

First 13 TeV results — consistent?

L+jets & Dilepton, 13 TeV

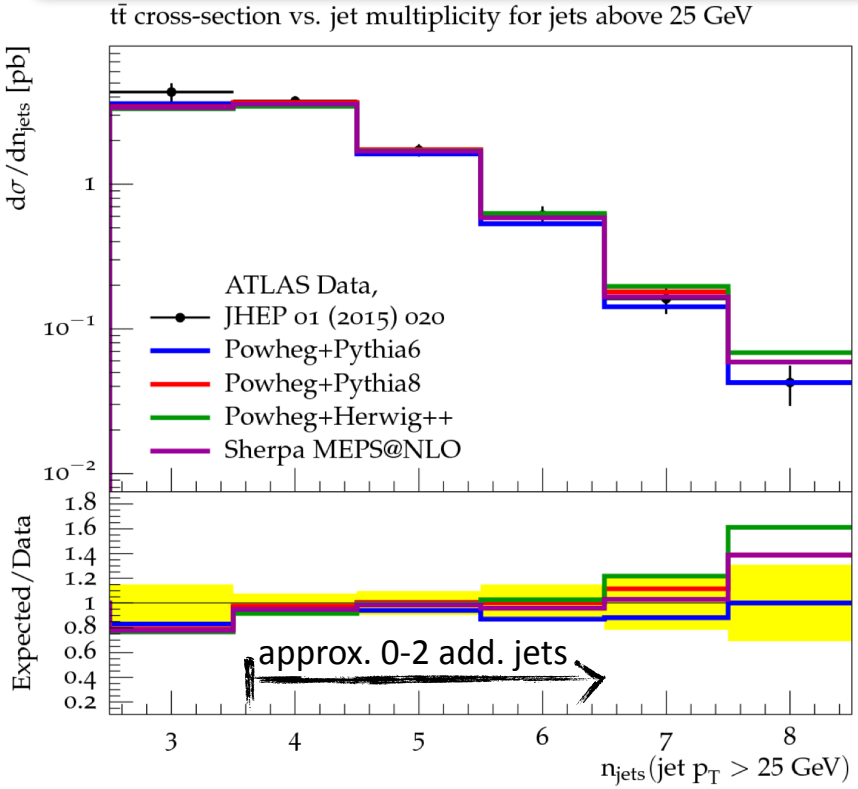
CMS-PAS-TOP-15-005
CMS-PAS-TOP-15-010

- By eye looks like a consistent picture with 7 TeV particle level MC studies?
- Note: n_{jets} is not identical definition (as it's not 'additional jet') but it should be qualitatively comparable.



L+jets, 7 TeV, Particle level MC studies

ATL-PHYS-PUB-2015-011



new results

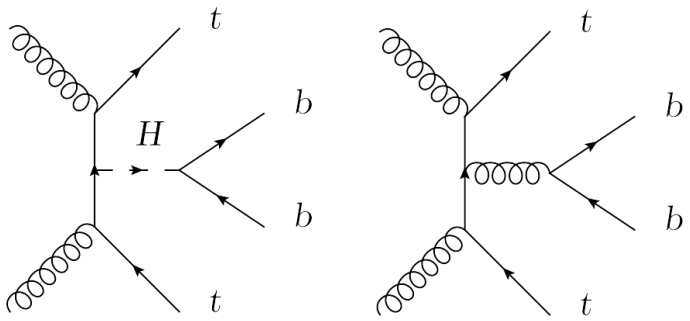
tt+b(b)

Measurements of tt+heavy flavour production:

- Irreducible background process for ttH (H->bb) analysis
- Test of NLO QCD calculations
- Constrain g->bb fragmentation

- Dilepton at 8 TeV (PLB 746 (2015) 132)
- L+jets at 8 TeV (CMS-TOP-13-016)

- Dilepton at 7 TeV (not covered) (PRD 89 (2014) 072012)
- Dilepton and L+jets at 8 TeV (arxiv:1508.06868)



ttH (H->bb) **QCD**

Representative Feynman diagrams

ttb(b) — ATLAS definitions

Dilepton & L+jets, 8 TeV

arxiv:1508.06868

- Measurement of *ttb*, *ttbb*, and ratio R=*ttbb/ttjj* at fully fiducial particle level
- 4 analyses are performed in three complementary fiducial phase-spaces:
- Fit-based analyses made no assumption on the size of other tt-contributions
- Particle-level definitions match closely reconstruction-level cuts

Fiducial Requirement	*ttb* lepton plus jets	*ttb* $e\mu$	*ttbb* dilepton
N_{leptons} ($p_{\text{T}} > 25$ GeV, $\|\eta\| < 2.5$)	1	2	2
Lepton flavours	e and μ	$e\mu$ only	ee, $\mu\mu$ and $e\mu$
$m_{\ell\ell} > 15$ GeV	-	-	yes
$\|m_{ee/\mu\mu} - 91\text{ GeV}\| > 10$ GeV	-	-	yes
N_{jets} ($p_{\text{T}} > 20$ GeV, $\|\eta\| < 2.5$)	≥ 5	≥ 3	≥ 4
$N_{b\text{-jets}}$	≥ 3	≥ 3	≥ 4
$\Delta R_{\ell,j} > 0.4$	yes	yes	yes

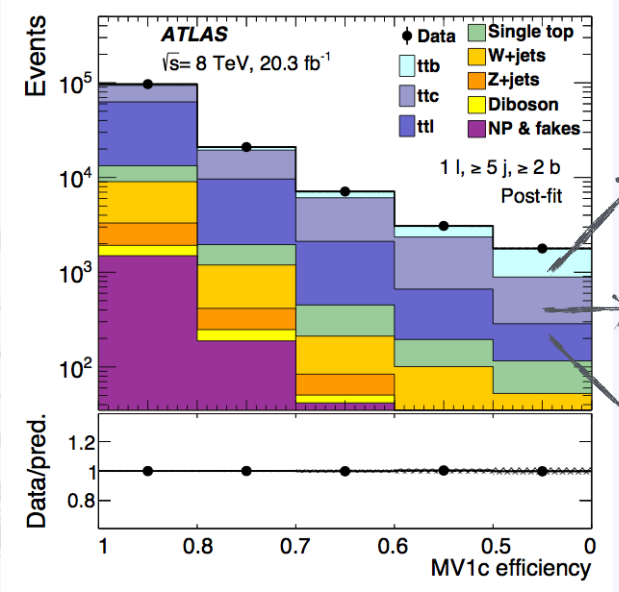
Results:

- Including contributions from ttH and ttV
- Removing contributions from ttH and ttV
  - Allowing direct comparison to QCD predictions
- The ratio R (from *ttbb* dilepton fit-based)

ttb(b) — ATLAS analysis strategy

Dilepton and l+jets ttb

- tt+jets selections:
  - Dilepton (≥3-jets)
  - L+jets (≥5-jets)
- Profile likelihood template fit to the b-tagging discriminator (MV1c) of 3rd highest jet ordered in MV1c
- 3 uncorrelated & unconstrained fit parameters

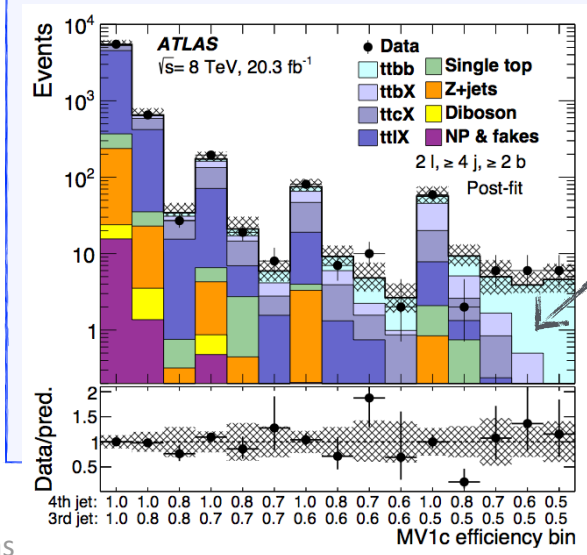


Dilepton ttbb (cut-based)

- High purity tt 4-b-jets selection (tighter b-tag criteria)
  - ttbb 68%, ttbX 16%, other 16%
- Event counting method to extract cross-section
- Correlated scale factor for ttbb and ttbX

Dilepton ttbb (fit-based)

- ≥ 4-jets selection
- Template fit with 3rd and 4th jet in MV1c



- 4 uncorrelated & unconstrained fit parameters
  - **ttbb**
  - **ttbX**
  - **ttcX**
  - **ttlX**

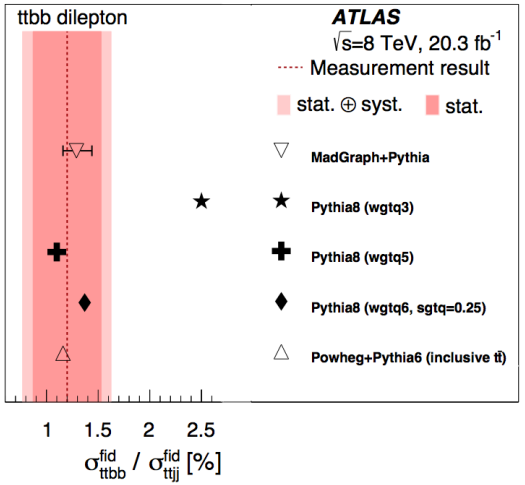
ttb(b) — ATLAS results

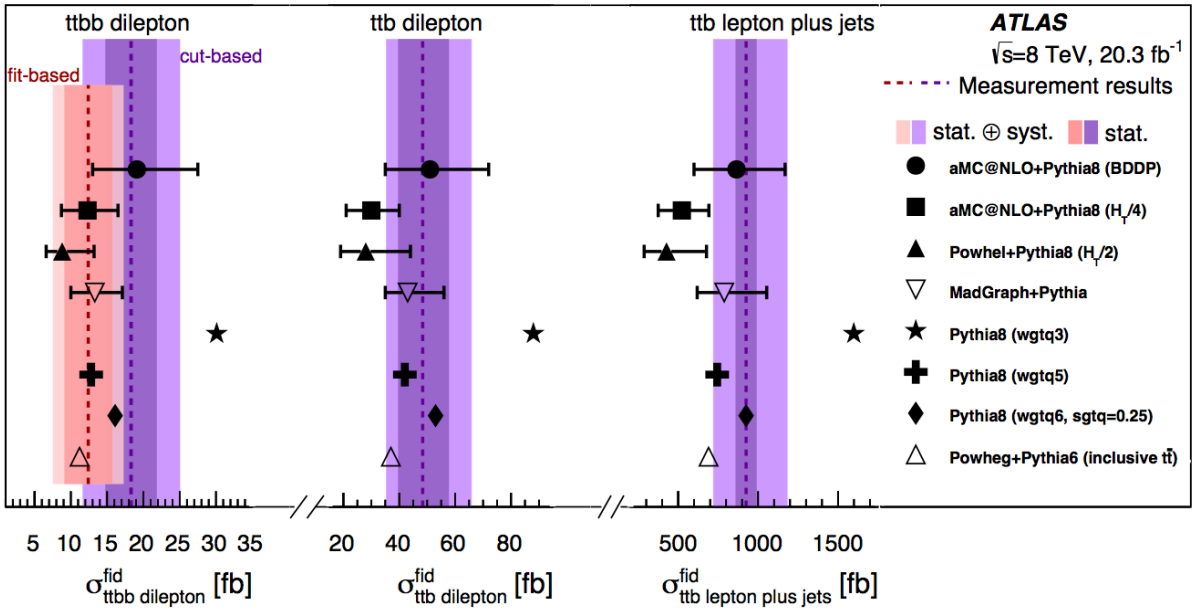
Dilepton & L+jets, 8 TeV

arxiv:1508.06868

- QCD-only results: ttV/H prediction is subtracted (simulation)
- aMC@NLO with 2 different functional forms for renormalization & factorization scales
- Pythia-8 calculations were done with 3 different options for the g → bb splitting, extreme variation disfavoured
- Dominant uncertainties are related to flavour tagging, tt-modelling, and JES uncertainties

Ratio for events >= 4 particle jets





tt+bb @ NLO

tt+bb @ LO+PS

tt+bb from PS: Different Pythia splitting kernels

tt+b @ LO, tt+bb from PS

ttb(b) — CMS (dilepton)

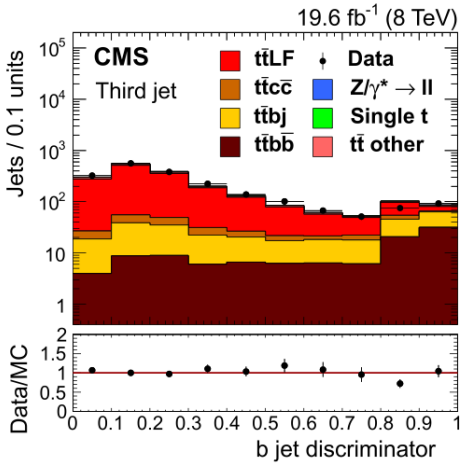
Dilepton, 8 TeV PLB 746 (2015) 132

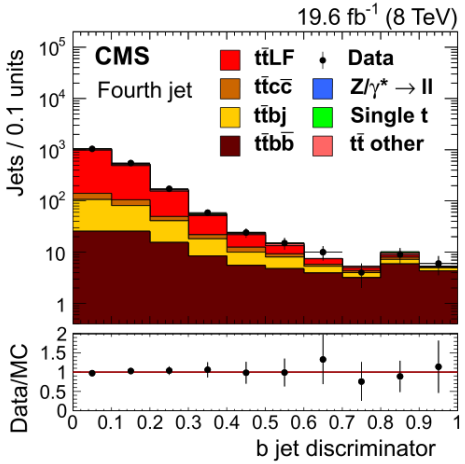
- Measurement of ttbb and ratio R=ttbb/ttjj at fiducial particle level
- Dilepton events with ≥4-jets, ≥2 b-tagged jets
- Simultaneous fit to b-jet discriminator of 3rd and 4th jet in CSV
- Fit 2 free parameters (overall normalisation and R)
  - Ratio of ttbb/ttbX constrained from simulation
  - tt+cX and tt+lX are combined in fit and taken from simulation

Definitions:

Phase Space (PS)	Parton level	Particle level
Visible PS	–	4 (b) jets and 2 leptons (e, μ)
Full PS	t, $\bar{t}$ and 2 (b) jets (not from t or $\bar{t}$)	–

Phase Space (PS)	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible PS (particle)		
Jet $p_T > 20$ GeV/c	$0.029 \pm 0.003 \pm 0.008$	$0.022 \pm 0.003 \pm 0.005$
Full PS (parton)		
Jet $p_T > 20$ GeV/c	$1.11 \pm 0.11 \pm 0.31$	$0.021 \pm 0.003 \pm 0.005$
Jet $p_T > 40$ GeV/c	$0.36 \pm 0.08 \pm 0.10$	$0.022 \pm 0.004 \pm 0.005$
NLO calculation		
Jet $p_T > 40$ GeV/c	0.23 ± 0.05	0.011 ± 0.003



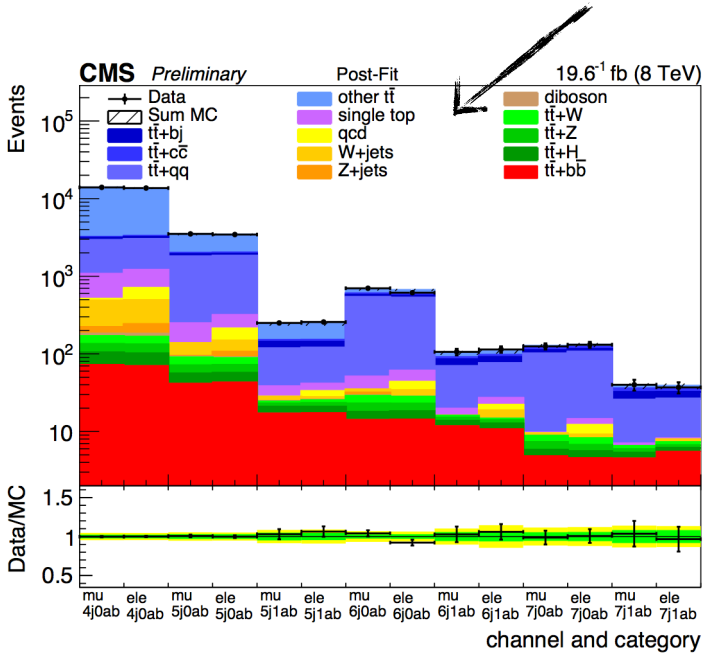


tt+b(b) — CMS (L+jets)

L+jets, 8 TeV CMS-TOP-13-016

- Measurement of tt+bb and ratio R=ttbb/ttjj at parton level
- Jet flavour at parton level defined by flavour of leading quark (hardB) or by the presence of a B-hadron in the list of jet constituents (hadronB)
- Selection: one isolated lepton, ≥4-jets, ≥2 b-tagged jets (jet-p_T > 40 GeV)
- Additional jets identified in data by minimizing kinematic χ^2 fit sensitive to tt-system
- Fit to measured b-jet discriminator in 7 jet categories for each lepton channel (14 total)
- Fit has 3 free parameters
  - ttbb+ttbX ; ttcc+ttqq; other-tt

	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
hardB:	
this analysis	$0.012 \pm 34\%$
theory NLO[4]	$0.011\ ^{+39\%}_{-13\%}$
MADGRAPH +PYTHIA	$0.007 \pm 10\%$
hadronB:	
this analysis	$0.015 \pm 32\%$
CMS dilepton[3]	$0.022 \pm 29\%$
MADGRAPH +PYTHIA	$0.009 \pm 14\%$



new results

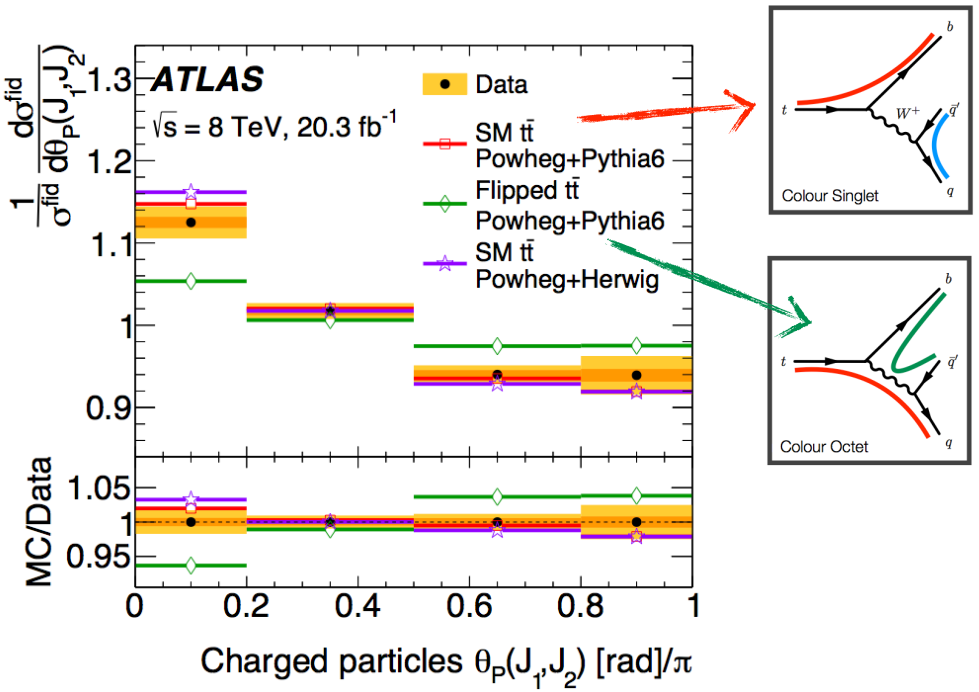
Jet Pull Angle

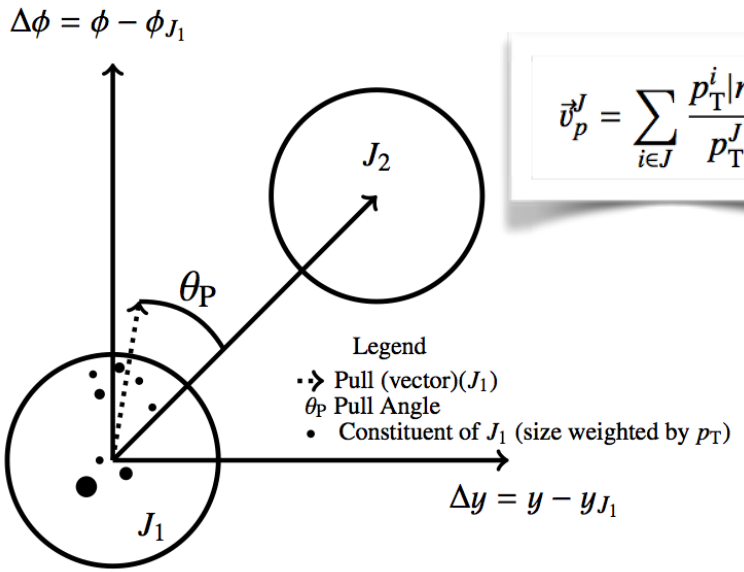
Measurements of colour flow using the jet pull angle

- L+jets at 8 TeV (arxiv:1506.05629)

Color flow using jet pull angle

- Distribution & orientation of energy inside jets provides experimental handle on colour flow (**q** and **g** initiating the jets)
- tt L+jets sample ideal to study colour flow W->jj di-jet resonance is pure color singlet (θ_P~0)
- Normalised fiducial cross-section unfolded to particle level





$$\vec{v}_p^J = \sum_{i \in J} \frac{p_T^i |r_i|}{p_T^J} \vec{r}_i.$$

Results:

- The jet pull angle is found to correctly characterise the *W* boson as a colour singlet.
- Data disfavouring an alternative colour–octet model at greater than 3σ

Conclusions

- Run1 measurements are being finalized
- First preliminary 13 TeV results
- Many different observables related to QCD radiation in top pair events have been measured
  - $t\bar{t}$+j production with veto on additional central jets — "gap-fraction" not discussed in this talk *(di-leptonic)*
- Results show discriminating power between MC models and tuning parameters

  —> Important input for top pair modelling at 13 TeV
- Significant advances in the measurement of tt+heavy flavour production (precision ~25%)

  —> Valuable input on background models for Higgs measurements and BSM searches

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

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

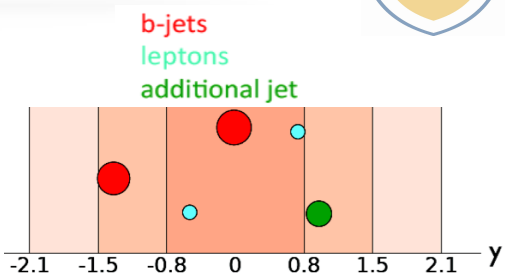
Additional material

jet veto analysis

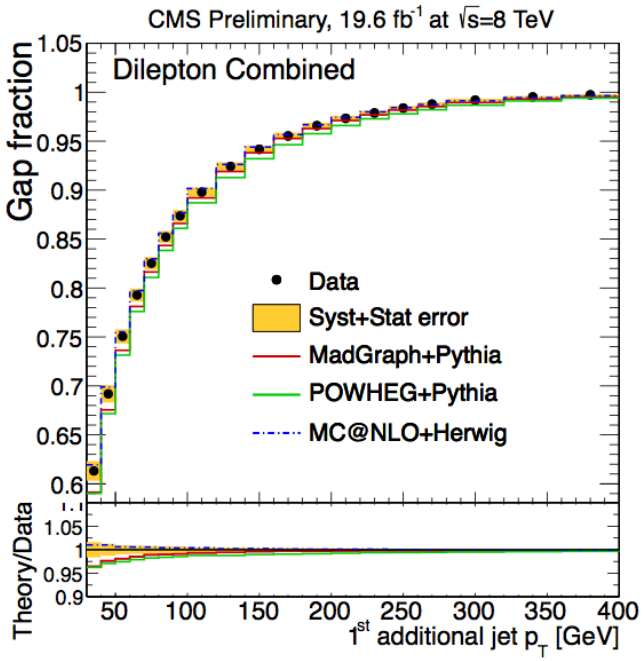
Dilepton, 7 & 8 TeV

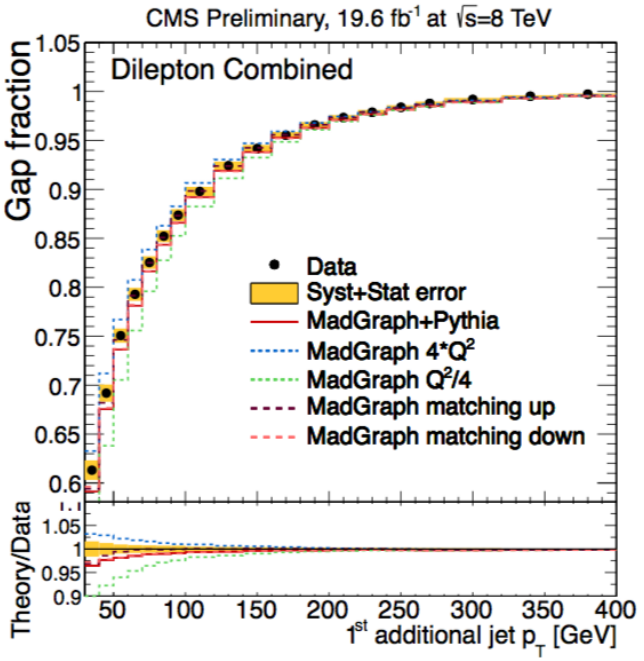
CMS-PAS-TOP-12-041 (8TeV)

Eur.Phys.J. C72 (2012) 2043 (7TeV)



- "Gap-fraction" analysis in fiducial phase space (2 lepton, 2 b-jets)
- Jet veto is used to quantify the jet activity from hard radiation produced in association with the tt-system
- Events are vetoed if they contain an additional jet with p_T or $\sum$ (add. jet-p_T) above a threshold in a central rapidity interval
- $f(X_0) = \frac{N(X < X_0)}{N_{total}}$, where X = additional jet-p_T **or** $\sum$ (add. jet-p_T)



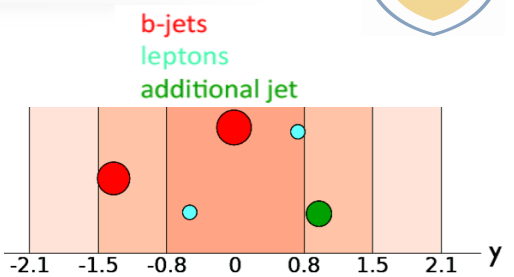


jet veto analysis

Dilepton, 7 & 8 TeV

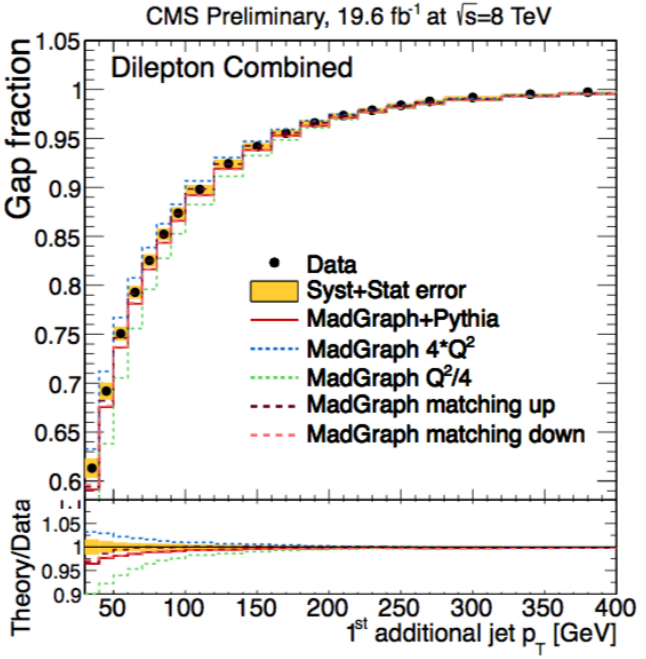
CMS-PAS-TOP-12-041 (8TeV)

Eur.Phys.J. C72 (2012) 2043 (7TeV)



- "Gap-fraction" analysis in fiducial phase space (2 lepton, 2 b-jets)
- Jet veto is used to quantify the jet activity from hard radiation produced in association with the tt-system
- Events are vetoed if they contain an additional jet with p_T or $\sum$ (add. jet-p_T) above a threshold in a central rapidity interval
- $f(X_0) = \frac{N(X < X_0)}{N_{\text{total}}}$, where X = additional jet-p_T **or** $\sum$ (add. jet-p_T)

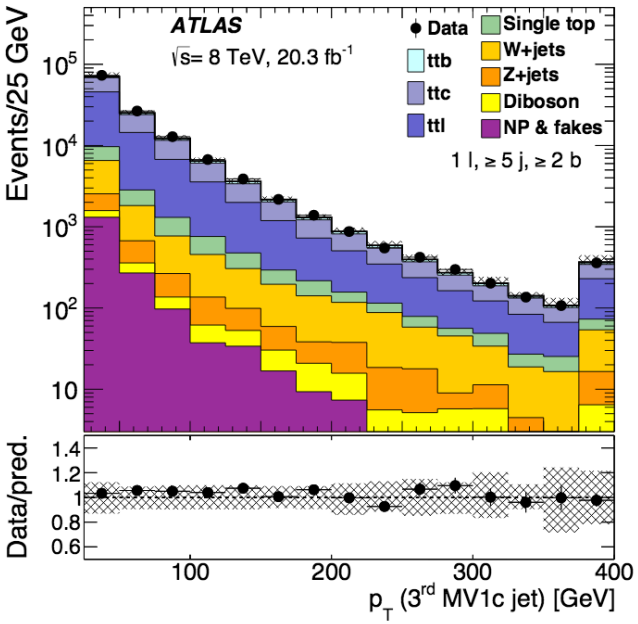
- Can be used to constrain α_S and ISR/FSR variations
- Scale variations provide a conservative envelope with respect to the nominal prediction
- Similar conclusions from ATLAS results



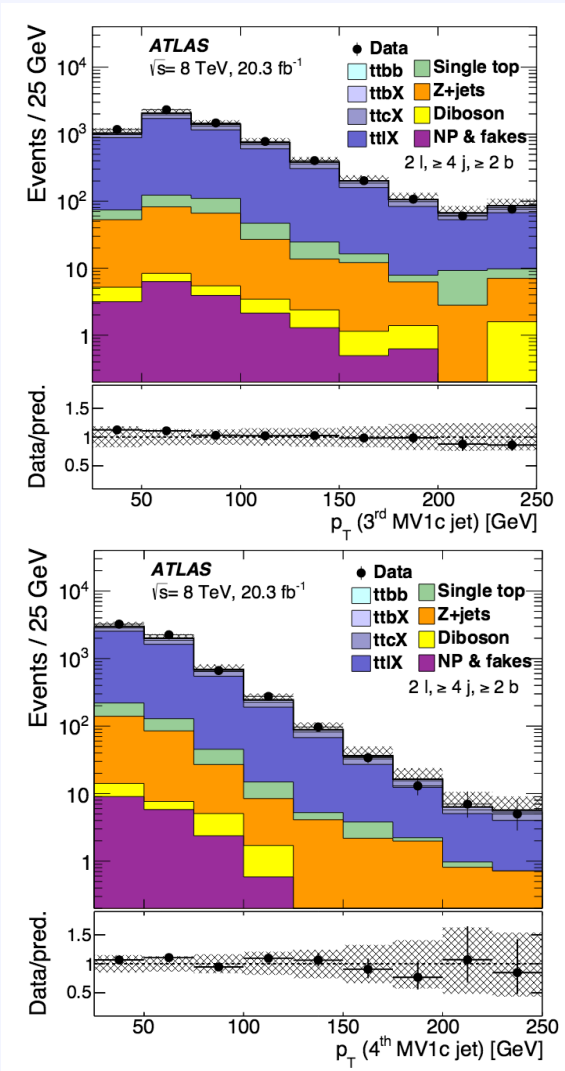
ttb(b) — Modelling of "extra-jets"

p_T distributions of fitted "extra-jets" are well modelled in Powheg+Phythia6 with $h_{damp}=m_{top}$

l+jets ttb



Dilepton ttbb (fit-based)



Jet multiplicity in tt events

L+jets, 7 TeV JHEP 01 (2015) 20

- Fiducial definition:

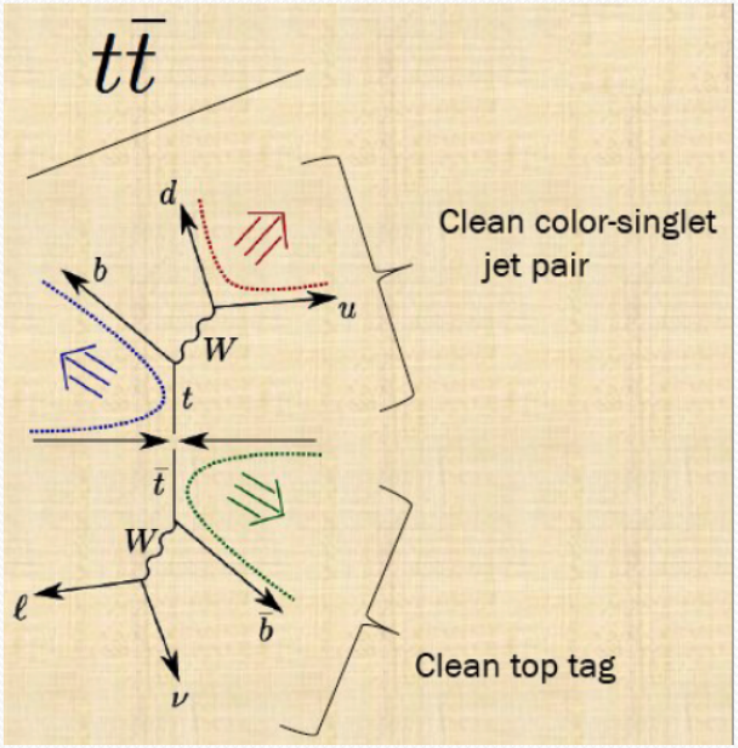
$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV & $m_{\mathrm{T}}(W) > 35$ GeV
One or more b-jets
Three or more jets with $p_{\mathrm{T}} > 25$ GeV & $\lvert\eta\rvert < 2.5$
e (μ) with $p_{\mathrm{T}} > 25$ GeV & $\lvert\eta\rvert < 2.5$
No additional e (μ) with $p_{\mathrm{T}} > 15$ GeV & $\lvert\eta\rvert < 2.5$
No μ (e) with $p_{\mathrm{T}} > 15$ GeV & $\lvert\eta\rvert < 2.5$
No jet-jet pair with $\Delta R < 0.5$
No jet-electron or jet-muon pair with $\Delta R < 0.4$

Table 3. Fiducial-volume definition for the electron (muon) channel of the $t\bar{t}$+jets cross-section measurement with the jet p_{T} threshold of 25 GeV. These conditions were applied on reconstruction-level and particle-level objects, with the exception of the electron where a veto on the η-region corresponding to the barrel-endcap transition region was applied on the reconstruction level (as described in section 3.1), but not included in the fiducial-volume definition. The jet p_{T} threshold in the jet multiplicity distributions was increased to 40, 60 and 80 GeV, for the corresponding cross-section measurements.

Leading jet with $p_{\mathrm{T}} > 50$ GeV & $\lvert\eta\rvert < 2.5$
2^{nd} leading jet with $p_{\mathrm{T}} > 35$ GeV & $\lvert\eta\rvert < 2.5$

Table 4. Additional fiducial-volume requirements implemented for the $t\bar{t}$ cross-section with respect to the jet p_{T}. These requirements were made in addition to those given in table 3 and were applied to the electron and the muon channel.

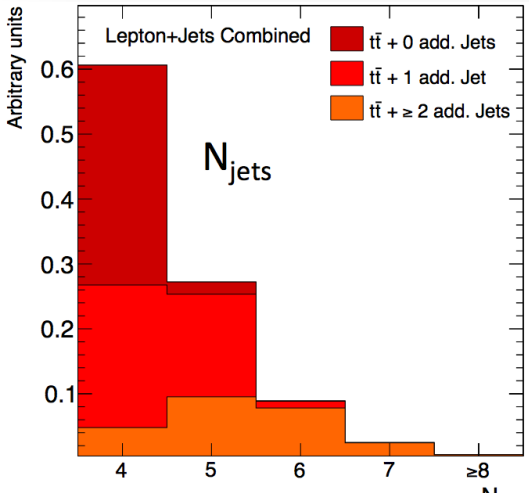
Color flow using jet pull angle



- W➔jj decay is pure color singlet
- Each of the two b quarks is color connected to one of the beam remnants in a color-octet pattern

Taken from Cecilia E. Gerber (LHCP slide)

Additional Jet multipl. & event level observables



- Determine jets not from top/anti-top decay through template fit
- Event classification at truth level:
  dR(jet, top decay product)<0.5
  Top decay products: 2 b quarks, jets and lepton from W decay
- Additional jet definition in data:
  Reconstruct tt system by minimising

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

L+jets, 7 TeV

Eur.Phys.J. C (2014) 74:3014