Top quark production at hadron colliders

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– Lund, 13th-18th June 2016 –

Outline

Introduction

↓

Inclusive measurements

↓

Differential measurements –resolved topology–

↓

Differential measurements – boosted topology –

↓

$t\bar{t}+X$ measurements

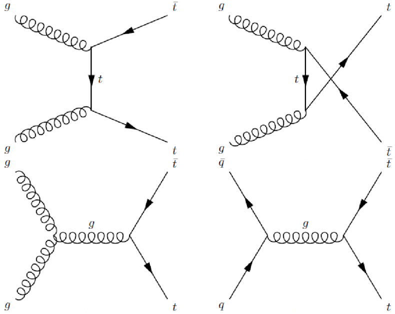
↓

Summary and Discussion

Top-Quark Pair Production

- $q\bar{q}$-annihilation or gg-fusion
- $gg \rightarrow t\bar{t}$ dominates at the LHC

  $\hookrightarrow$ ratio $gg/q\bar{q}$ changes with centre-of-mass energy



Why do we make these precision measurements?

- need to test pertubative QCD prediction
- enhanced cross-section possible in new production mechanisms
- many BSM searches have similar final states

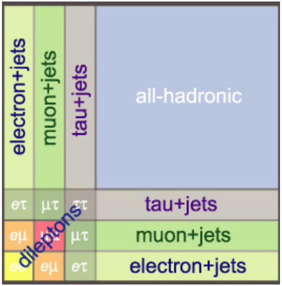
  $\hookrightarrow$ has to be well understood to increase discovery potential

How can we identify Top-Quark pairs?

Top-Quark Decay:

- BR($t \to Wb$) $\approx$ 1
- final state defined by W decay
- W decays to $l\nu_l$ or $q\bar{q}'$

➔ *b*-tagging crucial!



dilepton:

- signature: two jets, $l^+, l^-, \nu_l, \bar{\nu}_l$
- pro: clean signal
- con: kinematically underconstrained

all hadronic:

- signature: six jets
- pro: largest branching ratio
- con: large multijet background

lepton+jets:

- signature: four jets, l, ν_l
- pro: good signal/background ratio
- con: dominated by jet/modelling unc

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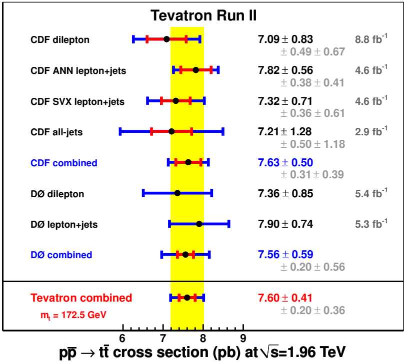
1. Introduction
2. **Inclusive measurements**
3. Differential measurements –resolved topology–
4. Differential measurements – boosted topology –
5. $t\bar{t} + X$ measurements
6. Summary and Discussion

Top-quark pair production at the Tevatron

➔ Combination: limited by statistics, signal modelling and luminosity

↪ relative uncertainty of 5.4 % (used up to 8.8 fb-1) ▸ Phys. Rev. D 89, 072001

↪ already close to unc. on theoretical cross-section prediction of 4 %



Updated D0 result: ▸ Sub. to PRD

➔ updated to full 9.7 fb-1 data set

➔ profile LH fit to extract σ

➔ $\sigma = 7.26 \pm 0.13$ (stat) $^{+0.57}_{-0.50}$ (syst) pb

➔ total uncertainty dominated by systematics

NEW: Top-quark pair production @ 5 TeV

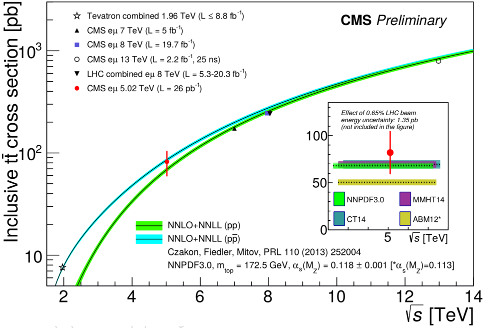
CMS-PAS-TOP-16-015

➔ analysis performed in $e\mu$-channel, using 26 pb-1 of data

➔ $\sigma = 82 \pm 20$(stat.) $\pm$ 5(syst.) $\pm$ 10(lumi.) pb

➔ 28% relative uncertainty

Source	Number of events $e^{\pm}\mu^{\mp}$
Drell–Yan	1.6 ± 0.4
Non W/Z	1.0 ± 0.9
tW	0.89 ± 0.02
WV	0.41 ± 0.02
Total background	3.9 ± 0.8
Signal ($t\bar{t} \rightarrow e\mu$)	16.7 ± 0.2
Data	24



Top-quark production at the LHC

How are top quarks produced?

$\hookrightarrow$ top-quark pairs: strong interaction

$\hookrightarrow$ single top production: weak interaction ▸ Talk from Kirill

8 TeV, NNLO+NNLL

$\sigma = 253^{+13}_{-15}$ pb

$\hookrightarrow$ 5.9% unc.

factor 3.3

13 TeV, NNLO+NNLL

$\sigma = 832^{+40}_{-46}$ pb

$\hookrightarrow$ 5.5% unc.

Top quark is heaviest particle: mass close to EWSB scale

$\hookrightarrow$ large production rate allows for precision measurements

$\hookrightarrow$ crucial to test at highest energies

$\hookrightarrow$ increasing importance of boosted regime

NEW: Dilepton $e\mu$ channel @ ATLAS, 13 TeV ▸ 1606.02699v1

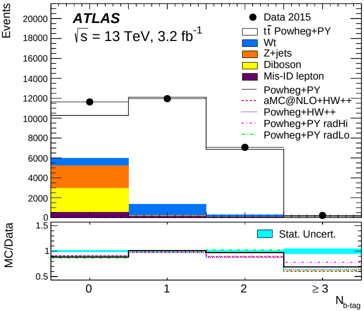
- e and μ with oppos. charge (OS)
- same-sign (SS) region for fake lepton estimate
- events with one/two b-tagged jets

$$N_1 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1-C_b\epsilon_b) + N_1^{\mathrm{bkg}}$$
$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b^2 + N_2^{\mathrm{bkg}}$$

$\hookrightarrow$ $\epsilon_{e\mu} \hat{=}$ preselection efficiency

$\hookrightarrow$ $\epsilon_b \hat{=}$ eff. for b-jet to be tagged and fall into acceptance

$\hookrightarrow$ $C_b \hat{=}$ tagging correlation coeff.



Final result:

$818 \pm 8\,(\mathrm{stat}) \pm 27\,(\mathrm{syst}) \pm 19\,(\mathrm{lumi}) \pm 12\,(\mathrm{beam})$ pb

$\hookrightarrow$ 4.4 % uncertainty

$\hookrightarrow$ systematics dominated by modelling uncertainties

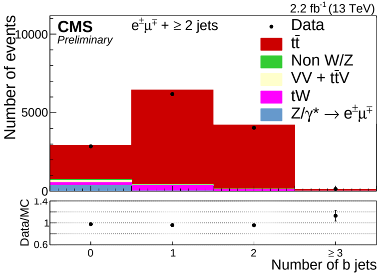
Dilepton $e\mu$ channel @ CMS, 13 TeV

CMS-PAS-TOP-16-005

- exactly one e and μ with OS
- SS region for fake lepton estimate
- at least one b-tagged jet

$$\sigma = \frac{N^{\text{data}} - N^{\text{Bkg}}}{\epsilon \cdot \mathrm{A} \cdot L}$$

Source	Number of $e^{\pm}\mu^{\mp}$ events
Drell–Yan	$24 \pm 9 \pm 4$
Non-W/Z leptons	$109 \pm 50 \pm 33$
Single top quark	$463 \pm 6 \pm 145$
VV	$15 \pm 2 \pm 5$
$t\bar{t}$ V	$31 \pm 1 \pm 10$
Total background	$642 \pm 52 \pm 149$
$t\bar{t}$ dilepton signal	$10199 \pm 14 \pm 462$
Data	10368



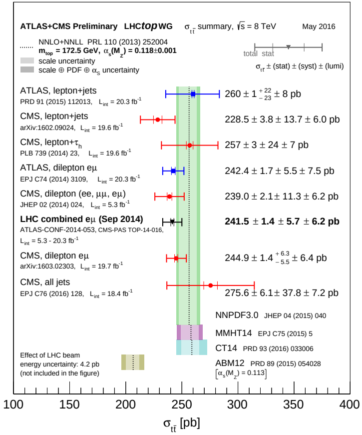
Final result:

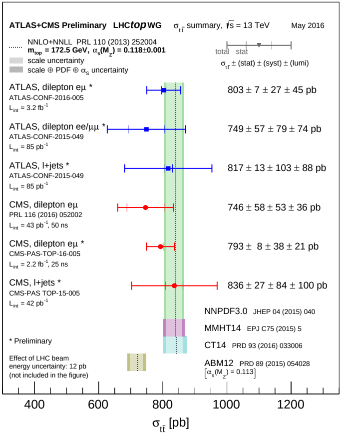
$793 \pm 8\,(\text{stat.}) \pm 38\,(\text{sys}) \pm 21\,(\text{lumi})$ pb

$\hookrightarrow$ 5.6 % uncertainty

$\hookrightarrow$ dominated by hadronisation, JES and lepton eff. uncertainties

Inclusive measurements @ 8 and 13 TeV





➔ 8 TeV: combined LHC $e\mu$ result: 3.5% precision

➔ 13 TeV: most precise result from ATLAS $e\mu$ channel: 4.4%

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Differential cross-section measurements

- want to test predictions in different parts of phase space
- unfold to parton-level and stable particle level
- allows to compare results from different experiments
- make fiducial measurements

  ↪ allows to test different models

  ↪ helps to constrain systematic uncertainties

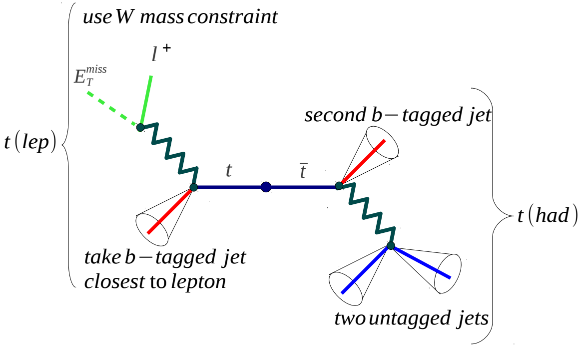
Distributions unfolded to:

➔ parton level: top after radiation, but before decay

➔ particle level: stable leptons and jets clustered from stable particles

Pseudo-top algorithm

- want to fully reconstruct $t\bar{t}$ event from final state objects
- run same algorithm on particle and detector level



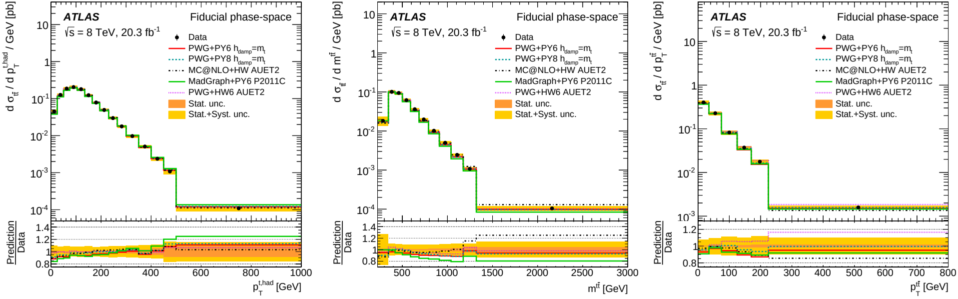
➔ Unfolding to particle level: generator independent studies possible

Differential cross-section @ ATLAS, 8 TeV ▸ arXiv:1511.04716

➔ unfolded to parton and stable particle level with Powheg+Pythia6

➔ lepton+jets channel, event reconstructed with pseudo-top alg.

➔ transverse top quark momentum softer in data than in MC



Differential cross-section @ CMS, 8 TeV

Eur. Phys. J. C 75 (2015) 542

Reconstruction lepton+jets channel

➔ use kinematic fitting algorithm with up to 5 jets

➔ veto *b*-tagged jets in position of light quarks and vice versa

↪ allows to reduce number of permutations in the fit

➔ cut on χ^2 probability to keep mainly well reconstructed events

Reconstruction dilepton channel

➔ use algebraic reconstruction method

➔ smear energies and directions of leptons and jets 100 times

↪ allows to recover events without neutrino solution

➔ calculate weight per solution and sum over all 100 cases

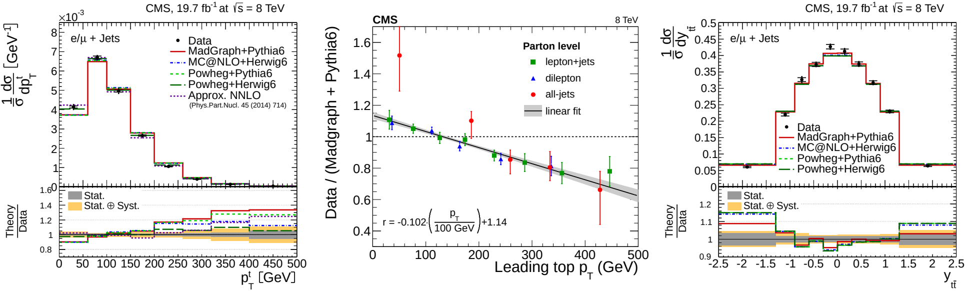
↪ take solution with maximum sum of weights

➔ weight is based on expected m_{lb} mass spectrum

Differential cross-section @ CMS, 8 TeV

▸ Eur. Phys. J. C 75 (2015) 542

- ➔ unfolded to parton and stable particle level with Madgraph5+Pythia6
- ➔ top quark p_T softer in data than in MC, data more central
- ➔ larger deviation at higher momentum
- ➔ see deviation in all three channels (middle) ▸ Eur. Phys. J. C 76 (2016) 128



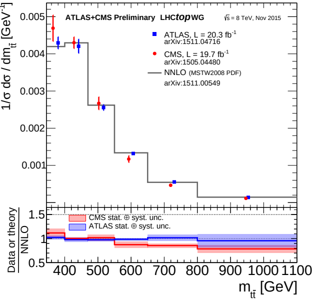
Comparison with NNLO predictions @ 8 TeV

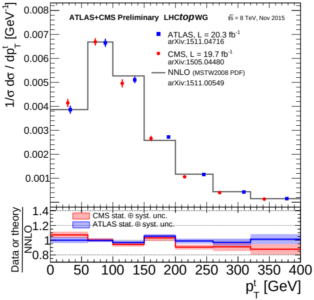
➔ compare now unfolded ATLAS and CMS data with NNLO predictions

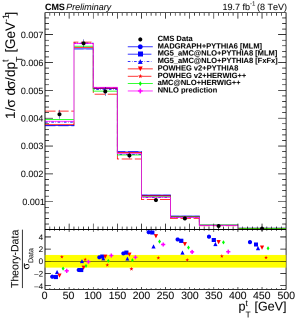
➔ $m_{t\bar{t}}$ and top p_T distributions (unf. to parton level):

↪ NNLO prediction harder than CMS data, good agreement for ATLAS

➔ large differences between generators predictions ▸ CMS-TOP-15-011







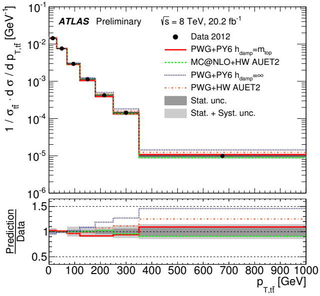
NEW: Diff. measurements, dilepton @ ATLAS, 7 & 8 TeV

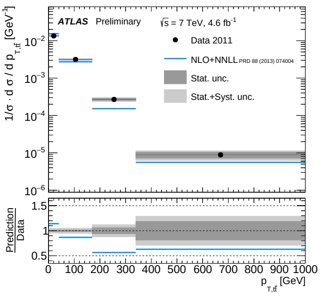
➔ unfolded to parton level, $\geq$ 2 jets and $\geq$ 1 *b*-tag

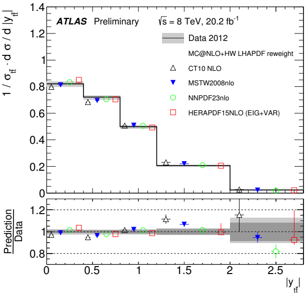
➔ improved $t\bar{t}$-p_{T} modelling with $h_{\mathrm{damp}} = m_{\mathrm{top}}$

↪ large descrepancy for NLO+NNLL calculation (also visible in 7 TeV)

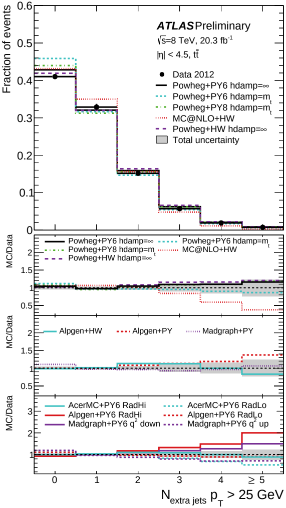
➔ better agreement for rapidity when moving to NNPDF or HERAPDF







NEW: Jet production in $e\mu b\bar{b}$ events @ ATLAS, 8 TeV



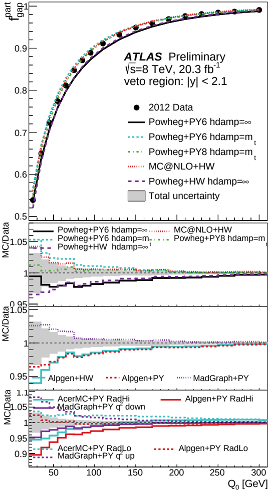
➔ additional jet multiplicity
↪ largest difference for MC@NLO

➔ count events which do not have jets above threshold Q_0 (gap fraction)
↪ best agreement for Powheg+Pythia8 ($h_{\mathrm{damp}} = m_{\mathrm{top}}$)

NLO+PS

Multileg

LO and RadHi/Low



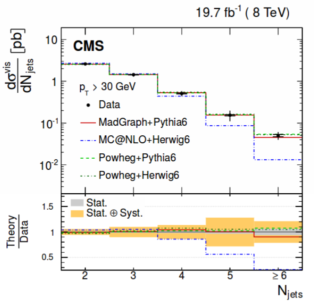
➔ jet gap fraction helps to better understand radiation systematic

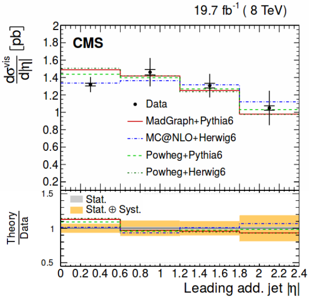
Differential measurements, dilepton @ CMS, 8 TeV ▸ arXiv:1510.03072

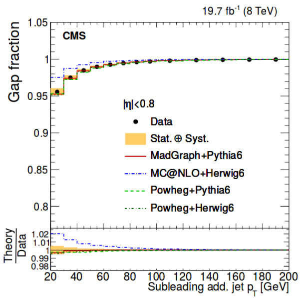
➔ unfolded to parton and stable particle level with Madgraph5+Pythia6

➔ best modelling with Powheg/Madgraph5+Pythia6 setup

➔ MC@NLO+Herwig6 has a lower jet multiplicity and largest deviation for jet gap fraction







Measurements with new 13 TeV data @ ATLAS

ATLAS-CONF-2015-065

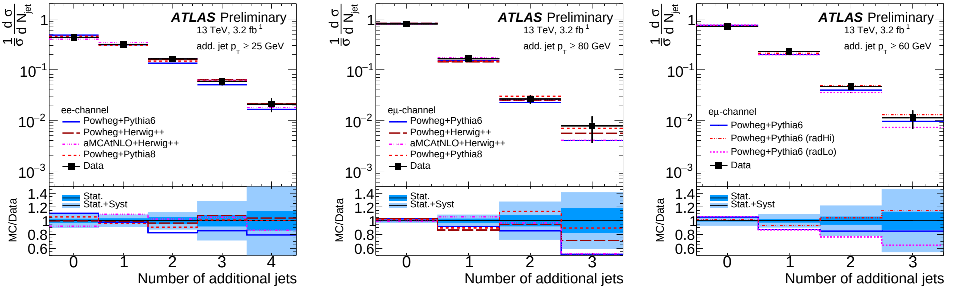
➔ exactly two high p_T leptons and two b-tagged jets

➔ measure jet multiplicity for different jet p_T thresholds

➔ distributions were unfolded to particle level

➔ distributions in agreement with data within uncertainties

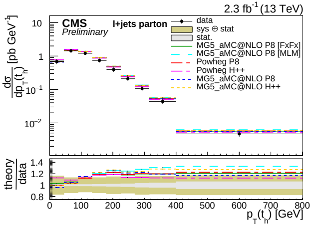
➔ uncertainties expected to improve in the future

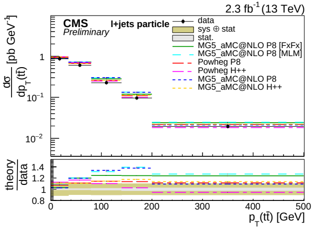


Differential distributions (l+jets) @ CMS, 13 TeV

CMS PAS TOP-16-008

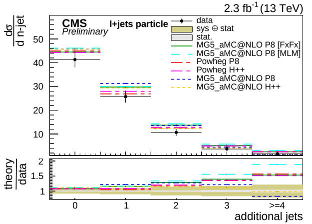
➔ use now NLO+PS setups as baseline: Powheg+Pythia8/Herwig++

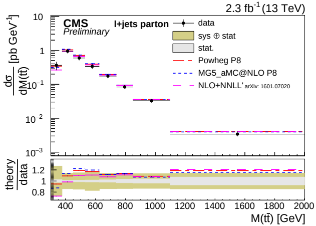




➔ data momentum distributions are softer than expected

➔ data shows less jets than the MC generators





Differential distributions (dilepton) @ CMS, 13 TeV

▸ CMS PAS TOP-16-011

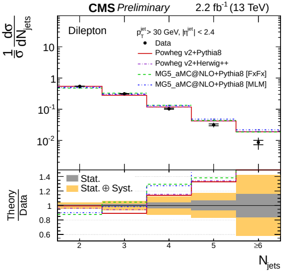
➔ performed in fiducial and full phase space

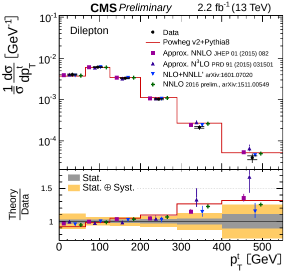
➔ data shows less jets than the MC generators

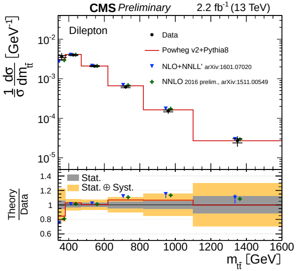
➔ larger variations between NLO+PS setups for $p_{\mathrm{T}}(t\bar{t})$

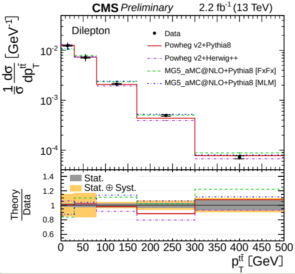
➔ top p_{T} in data softer than in NLO+PS MC

$\hookrightarrow$ but data in good agreement with NNLO predictions









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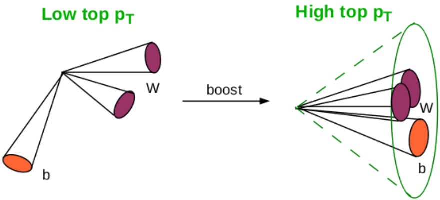
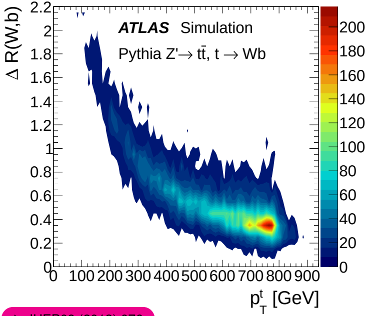
Differential measurements in boosted regime

- ➔ at large transverse top momentum: decay products strongly collimated
- ➔ top can be identified as one large-radius jet
- ➔ allows to reduce combinatorial background
- ➔ especially important for BSM searches





▸ JHEP09 (2013) 076

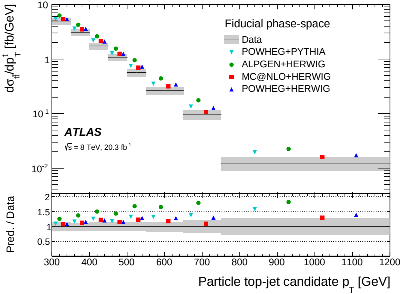
Boosted differential cross-sections @ ATLAS

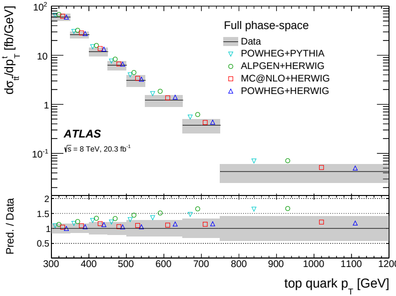
▸ Phys. Rev. D 93, 032009 (2016)

➔ $p_{\mathrm{T}} >$300 GeV, trimmed large-R (1.0) jets

➔ $m_{\mathrm{jet}} >$ 100 GeV, use substructure to identify top candidates

➔ take hardest top-tagged jet as hadronic top quark candidate





➔ uncertainty 13-29%, dominated by large-R JES

➔ parton-level result: relies more on MC

↪ larger systematic uncertainties

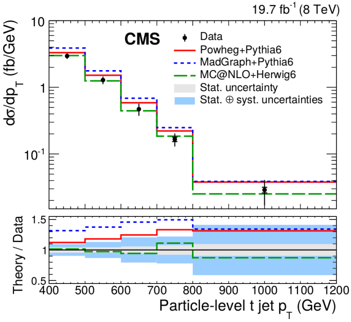
➔ same trend as in resolved analysis

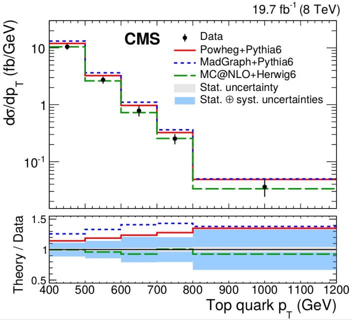
Boosted differential cross-sections @ CMS ▸ arXiv:1605.00116

➔ $p_T > 400$ GeV, trimmed large-R (0.8) jets

➔ $140 < m_{jet} < 250$ GeV, use subjet info to identify top candidates

➔ take hardest top-tagged jet as hadronic top quark candidate





➔ Powheg+Pythia6: σ about 14% higher

$\hookrightarrow$ still within uncertianties

➔ large overestimation from Madgraph+Pythia

➔ same trends as in resolved analysis

NEW: 13 TeV analysis in all-hadronic final state

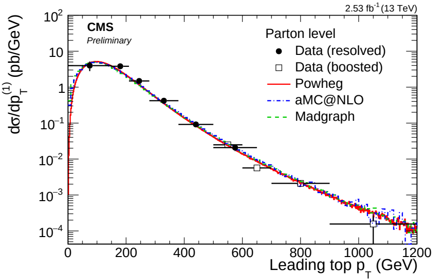
CMS-PAS-TOP-16-013

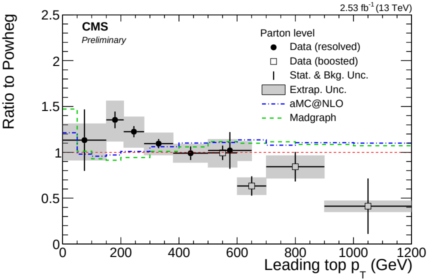
➔ study resolved+boosted topology

➔ resolved: use kinematic fit for reconstruction

➔ inclusive cross-section:

$\hookrightarrow 834 \pm 25(\text{stat.})^{+118}_{-104}(\text{syst.}) \pm 23(\text{lumi.})$ pb





Resolved	Boosted
lepton veto AK4 jets $p_T > 30$ GeV and $\lvert\eta\rvert < 2.4$ $N_{jets} \geq 6$ $H_T > 500$ GeV, $p_T^{(6)} > 45$ GeV at least two b-tagged jets $\Delta R_{bb} > 2.0$ kin. fit probability > 0.02 $150 < m_t < 200$ GeV	lepton veto AK8 jets $p_T > 200$ GeV, $\lvert\eta\rvert < 2.4$, $m_{SD} > 50$ GeV $N_{jets} \geq 2$ $p_T^{(1)} > 450$ GeV both jets should contain one b-tagged subjet $\mathcal{F} > 0$ $150 < m_{SD}^{(1)} < 200$ GeV

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$t\bar{t} + X$ measurements

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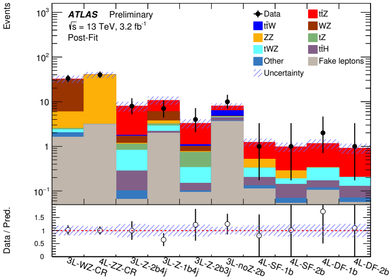
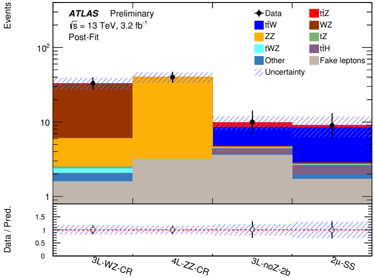
Measurement of $t\bar{t} + W/Z$ with ATLAS @ 13 TeV ATLAS-CONF-2016-003

➔ processes have been first observed at ATLAS and CMS @ 8 TeV

➔ extract σ using binned profile LH fit

➔ include various signal and control regions





Results:

➔ $\sigma_{t\bar{t}Z} = 0.9 \pm 0.3$ (stat.) $\pm\, 0.1$ (syst.) pb

➔ $\sigma_{t\bar{t}W} = 1.4 \pm 0.7$ (stat.) $\pm\, 0.3$ (syst.) pb

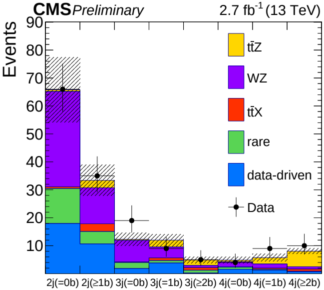
➔ measurement statistically limited

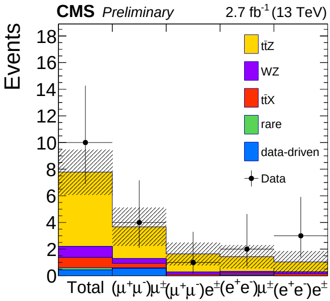
Measurement of $t\bar{t}+Z$ with CMS @ 13 TeV CMS-PAS-TOP-16-009

➔ processes have been first observed at ATLAS and CMS @ 8 TeV

➔ extract σ using binned profile LH fit

➔ include 3 and 4 lepton final states





Results:

➔ $\sigma_{t\bar{t}Z} = 1.1 \pm 0.4\,(\text{stat.}) \pm 0.2\,(\text{syst.})$ pb

➔ significance 3.6 standard deviation

➔ measurement statistically limited

Top observation @ LHCb experiment

▸ Phys. Rev. Lett. 115 (2015)

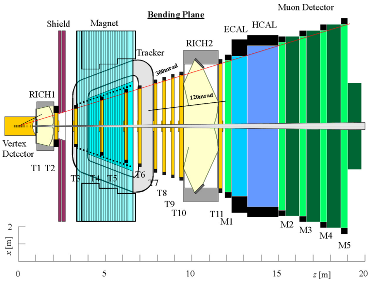
Why measure top at LHCb?

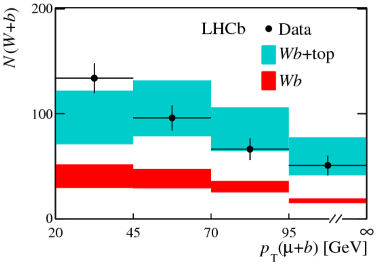
➔ production via *gg*-fusion:

↪ smaller than for ATLAS & CMS

➔ gluon PDF: higher *x* accessible

➔ look at differential distributions





How can we measure it?

➔ have 75% pair and 25% single top

➔ measure both processes together

↪ $\mu + b$ final state

➔ main background: di-jet and *Wb*

Top production @ LHCb

▸ Phys. Rev. Lett. 115 (2015)

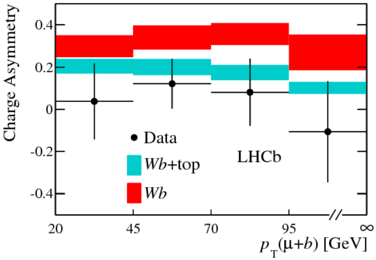
Event selection:

- ➔ μ: $2 \leq \eta \leq 4.5$ and $p_T > 25$ GeV
- ➔ j: $2.2 \leq \eta \leq 4.2$, p_T : 50–100 GeV
- ➔ $p_T(\mu + j) > 20$ GeV

➔ BDT based *b*-tagging

➔ profile LH fit to $p_T(\mu + j)$ spectrum

➔ measure cross-section and charge asymmetry



Summary:

- ➔ top observation with 5.4σ at LHCb
- ➔ in good agreement with prediction
- ➔ first observation in forward region!

Outline

Introduction

Inclusive measurements

Differential measurements
–resolved topology–

Differential measurements
– boosted topology –

$t\bar{t} + X$ measurements

Summary and Discussion

Summary

- top-quark pair production at the LHC

  ↪ many high precision measurements (incl. cross-sections)

  ↪ also important statistically limited measurements and searches like $t\bar{t}+b\bar{b}$ (backup), $t\bar{t}+V$, $t\bar{t}H$ (backup)

- quick turnaround of analyses with full 13 TeV data

- see similar trends in top p_{T} and rapidity as in 7 and 8 TeV data

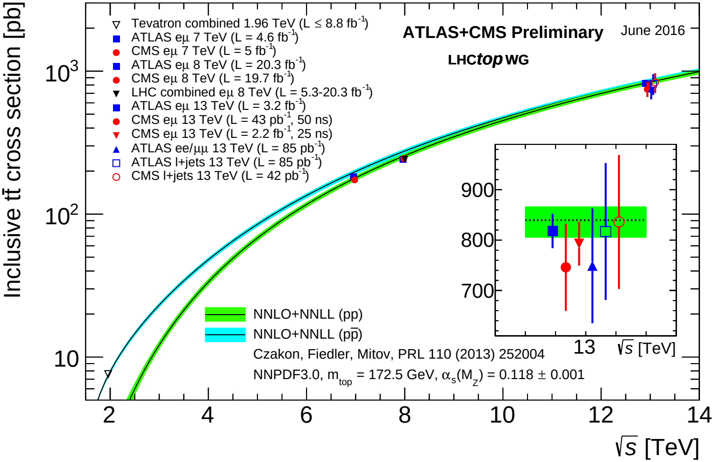
- need to better understand $t\bar{t}$ modelling of data

  ↪ allows to constrain systematic uncertainties

- this year: will get more data than ever before

  ↪ will allow us to test boosted regions and to look at double-differential distributions

Plenty of more data in 2016: challenge best theory predictions!

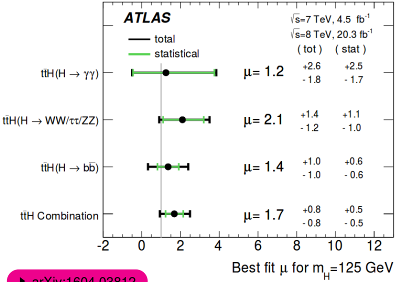


Thank you for your attention!

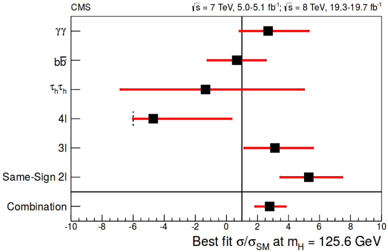
Search for $t\bar{t}+H$ production

Combination note

- ➔ ATLAS+CMS combination @ 8 TeV
- ➔ expected production rate:
  - ↪ 0.129 pb @ 8 TeV (NLO)
- ➔ signal strength: $\mu_{t\bar{t}H} = 2.3^{+0.7}_{-0.6}$



arXiv:1604.03812



JHEP 09 (2014) 087

First 13 TeV results @95 % C.L.:

- ➔ CMS multilepton channel:

CMS-PAS-HIG-15-008

↪ $\sigma < 3.3\ (2.6)\ \sigma_{\rm SM}$ obs. (exp.)

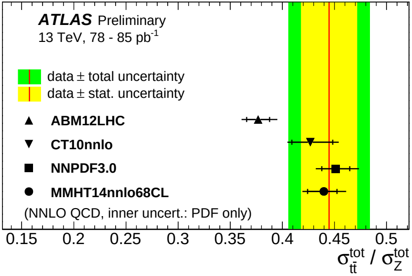
Ratio of $t\bar{t}/Z$ cross-sections ATLAS-CONF-2015-049

➔ new cross-section measurements:

↪ 9% uncertainty from luminosity

↪ would cancel out in ratio to other xsec

$$R_{t\bar{t}/Z} = \frac{\sigma_{t\bar{t}}}{0.5(\sigma_{Z\to ee} + \sigma_{Z\to\mu\mu})}$$



Theoretical calculations:

FEWZ for σ_{Z+jets}

↪ Comp. Ph. Comm. 182 2388

Top++ for $\sigma_{t\bar{t}}$

↪ Comp. Ph. Comm. 185 2930

Final result:

$R_{t\bar{t}/Z} = 0.445 \pm 0.027\,(\text{stat}) \pm 0.028\,(\text{syst})$

↪ 8.8 % uncertainty

↪ systematics dominated by modelling uncertainties

$t\bar{t}b\bar{b}$ production in ATLAS @ 8 TeV ▸ Eur. Phys. J. C (2016) 76:11

➔ large uncertainties on NLO predictions
➔ need experimental measurements to better understand process!

Fiducial $t\bar{t}+b$ cross-section

➔ $e\mu$ & lepton+jets channel

➔ two (one) leptons, ≥ 3 (5) jets, ≥ 3 *b*-tagged jets

➔ use *b*-tagging discriminant to extract $t\bar{t}$+*b*/*c*/*l*

Fiducial $t\bar{t}+b\bar{b}$ cross-section

➔ dilepton channel: cut- and fit-based, ≥ 4 *b*-tagged jets

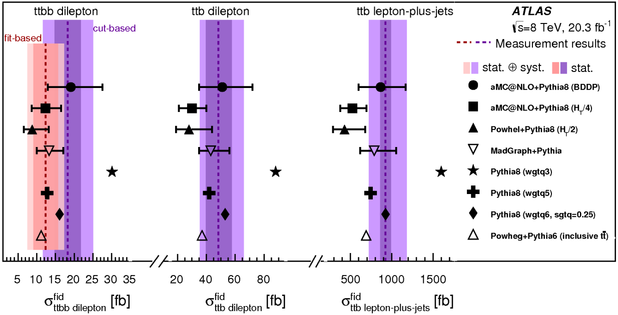
➔ use *b*-tagging discr. to extract $t\bar{t}+b\bar{b}$, $t\bar{t}+bX$, $t\bar{t}+cX$, $t\bar{t}+lX$

$\sigma(t\bar{t}+b\bar{b})/\sigma(t\bar{t}+jj)$ ratio in dilepton channel

➔ allows to cancel some uncertainties

Results for fiducial cross-sections

▸ Eur. Phys. J. C (2016) 76:11



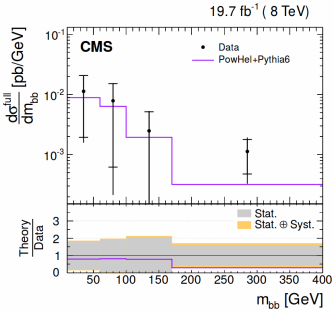
QCD only measurements (subtract $t\bar{t}H$ and $t\bar{t}V$)

- measurement at 8 TeV still limited by statistics
- uncertainty on $t\bar{t}+b$: 25% (lepton+jets) and 32% (dilepton)
- uncertainty on $t\bar{t}+b\bar{b}$: 35% (cut-based) and 36% (fit-based)
- most generators: good agreement with data
  $\hookrightarrow$ extreme option with highest rate of $g\rightarrow b\bar{b}$: strongly disfavoured

Measurement of $t\bar{t}+b\bar{b}$ at CMS @ 8 TeV

▸ Phys. Lett. B 746 (2015) 132

Phase Space (PS)	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible PS (particle)			
Jet $p_T > 20\,\mathrm{GeV}/c$	$0.029 \pm 0.003 \pm 0.008$	$1.28 \pm 0.03 \pm 0.15$	$0.022 \pm 0.003 \pm 0.005$
Full PS (parton)			
Jet $p_T > 20\,\mathrm{GeV}/c$	$1.11 \pm 0.11 \pm 0.31$	$52.1 \pm 1.0 \pm 6.8$	$0.021 \pm 0.003 \pm 0.005$
Jet $p_T > 40\,\mathrm{GeV}/c$	$0.36 \pm 0.08 \pm 0.10$	$16.1 \pm 0.7 \pm 2.1$	$0.022 \pm 0.004 \pm 0.005$
NLO calculation			
Jet $p_T > 40\,\mathrm{GeV}/c$	0.23 ± 0.05	21.0 ± 2.9	0.011 ± 0.003



Summary inclusive:

➔ LH fit using *b*-tagging discriminant

➔ main unc: *b*-tagging, JES/JER, scale

➔ statistical uncertainties still large

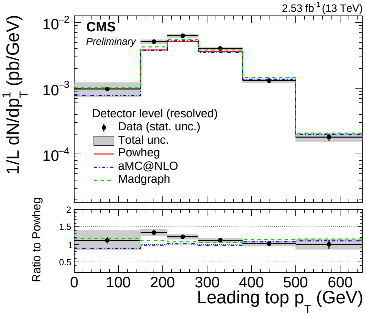
➔ agrees within 1.6σ with prediction

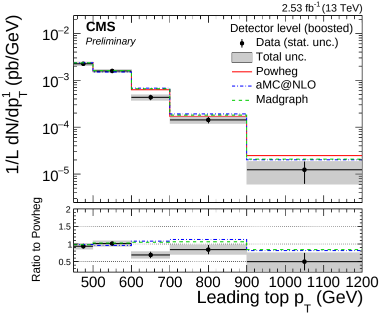
▸ CMS-TOP-12-041

➔ underestimate total $t\bar{t}b\bar{b}$ cross-section by factor of 2

NEW: 13 TeV analysis in all-hadronic final state ▸ CMS-PAS-TOP-16-013

- ➔ resolved: use kinematic fit, cut on probability and reconstructed top mass
- ➔ QCD: taken from CR, extrapolated to SR, small impact on boosted
- ➔ build Fisher-discr. from τ_{32} and τ_{31}
- ➔ cut on softdrop mass of leading jet





Resolved	Boosted
lepton veto	lepton veto
AK4 jets	AK8 jets
$p_T > 30$ GeV and $\|\eta\| < 2.4$	$p_T > 200$ GeV, $\|\eta\| < 2.4$, $m_{SD} > 50$ GeV
$N_{jets} \geq 6$	$N_{jets} \geq 2$
$H_T > 500$ GeV, $p_T^{(6)} > 45$ GeV	$p_T^{(1)} > 450$ GeV
at least two b-tagged jets	both jets should contain one b-tagged subjet
$\Delta R_{bb} > 2.0$	$\mathcal{F} > 0$
kin. fit probability > 0.02	$150 < m_{SD}^{(1)} < 200$ GeV
$150 < m_t < 200$ GeV	

NEW: 13 TeV analysis in all-hadronic final state ▸ CMS-PAS-TOP-16-013

Uncertainties on inclusive measurements:

Analysis	Resolved	Boosted
Source	(%)	(%)
QCD background modeling	−1.0, +6.6	−2.7, +2.4
Subdominant backgrounds	±4.0	±4.0
Jet energy scale	−8.2, +9.0	−1.8, +1.6
Jet energy resolution	−0.7, +0.8	$\pm < 1$
b tagging	−5.5, +6.2	−10.5, +12.9
Trigger efficiency	−2.9, +3.2	−1.1, +0.9
Scale (μ_F and μ_R)	−1.5, +0.0	−1.5, +0.0
PDF	±1.0	±1.0
Parton shower	−5.0, +2.5	−7.0, +3.0
NLO generator	±2.0	±7.0
Total systematic	−12.4, +14.1	−15.4, +15.8
Statistical	±3.0	±6.3
Integrated luminosity	±2.7	±2.7

Substructure variables

Subjettiness: measure for compatibility of jet with the assumption that it has i subjets:

$$\tau_i = \frac{1}{\sum_k p_{T,k} R} \sum_k p_{T,k} \min(\Delta R_{1k}, ..., \Delta R_{ik}) \qquad (1)$$

➔ R is distance parameter of current jet
➔ ΔR is distance betwen subjet and other constituents
➔ For top-quarks: i=3, for QCD: less subjets: take ratio τ_{32}

CMS:
➔ at least three subjets, min. invariant mass of each subjet-pair > 50 GeV, total invariant mass between 140 and 250 GeV, $p_T > 400$ GeV

ATLAS:
➔ $m > 100$ GeV, $\sqrt{d_{12}} > 40$ GeV, $p_T > 300$ GeV
➔ $\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2})\Delta R_{12}$ (large for jets with two hard subjets)

$t\bar{t}+V$ measurements at 8 TeV

➔ ATLAS: 2,3 and 4 lepton FS

➔ results statistically limited

➔ in signal enriched regions: use NN

➔ at 13 TeV: cross-section increased by factor of 4

Result ATLAS:

	$t\bar{t}W$ significance		$t\bar{t}Z$ significance	
Channel	Expected	Observed	Expected	Observed
2ℓOS	0.4	0.1	1.4	1.1
2ℓSS	2.8	5.0	-	-
3ℓ	1.4	1.0	3.7	3.3
4ℓ	-	-	2.0	2.4
Combined	3.2	5.0	4.5	4.2

Result CMS: ▸ Link Paper

$t\bar{t}Z$	$t\bar{t}W$		$t\bar{t}Z$	
Channel	Exp.	Obs.	Exp.	Obs.
OS (2l)	–	–	1.8	2.1
SS (2l)	3.4	4.9	–	–
3 l	1.0	1.0	4.6	5.1
4 l	–	–	2.7	3.4
Combined	3.5	4.8	5.7	6.4

Reconstruction dilepton channel

- problem: dilepton final state kinematically underconstrained
- we know: momenta of leptons and b-quarks and the top mass
- neutrino weighting: sample neutrino η and compute weight
- with assumed neutrino η: get in total 4 solutions
- for each solution calculate weight:

$$w_i^{\nu} = \exp(\frac{-(p_x - p_x^{\nu} - p_x^{\bar{\nu}})^2}{2\sigma^2})\exp(\frac{-(p_y - p_y^{\nu} - p_y^{\bar{\nu}})^2}{2\sigma^2}) \qquad (2)$$

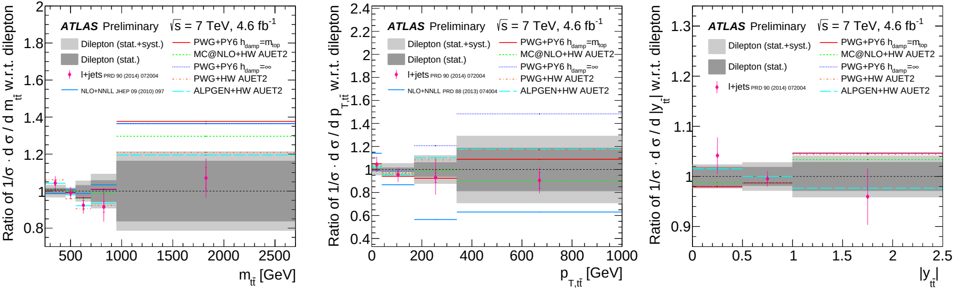
NEW: Diff. measurements, dilepton @ ATLAS, 7 & 8 TeV

➔ unfolded to parton level, $\geq$ 2 jets and $\geq$ 1 b-tag

➔ improved $t\bar{t}$-p_{T} modelling with $h_{\mathrm{damp}} = m_{\mathrm{top}}$

$\hookrightarrow$ large descrepancy for NLO+NNLL calculation (also visible in 7 TeV)

➔ better agreement for rapidity when moving to NNPDF or HERAPDF



Jet gap fraction measurement

Definition:

Fraction of events without additional jet activity in a certain rapidity or mass region above a defined p_{T} threshold.

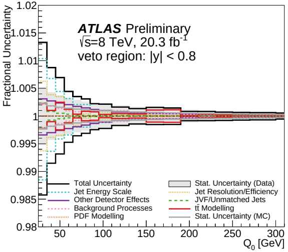
For leading additional jet:

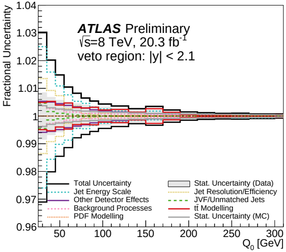
$$f_{\mathrm{gap}}(Q_0) = \frac{n(Q_0)}{N_{t\bar{t}}} \quad (3)$$

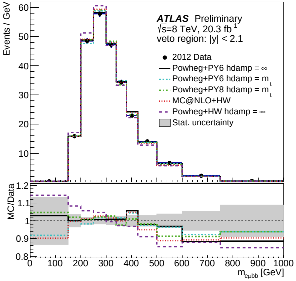
For scalar sum p_{T} of all additional jets:

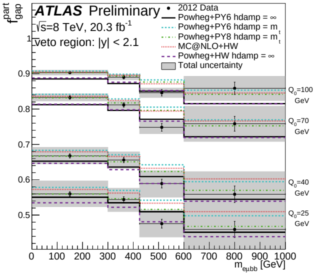
$$f_{\mathrm{gap}}(Q_{\mathrm{sum}}) = \frac{n(Q_{\mathrm{sum}})}{N_{t\bar{t}}} \quad (4)$$

Jet gap fraction



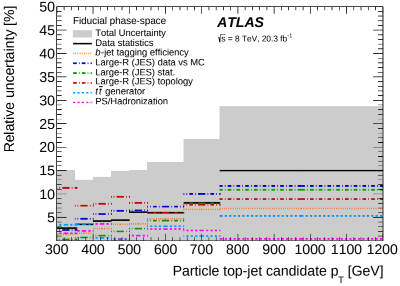


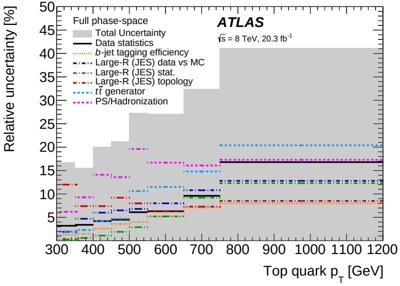




Boosted differential: uncertainties

▸ Phys. Rev. D 93, 032009 (2016)



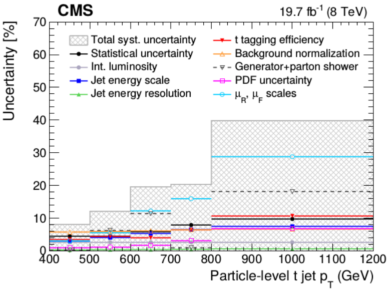


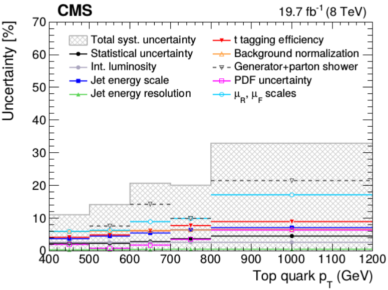
➔ parton level measurement relies more on MC information

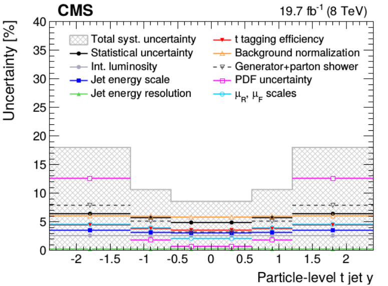
↪ larger uncertainties than for particle level result

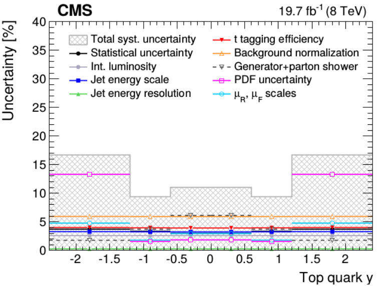
Boosted differential cross-sections @ CMS

arXiv:1605.00116









LHCb measurement: more details

➔ higher fraction of $q\bar{q}$ and qg scattering

↪ larger charge asymmetries, sensitive to BSM physics

➔ estimate W+jets from fit to $p_{T,\mu}/p_{T,j_\mu}$ ratio in data

➔ GEC: global event cuts to reduce influence of high-occupancy events in trigger (90% eff. of cuts)

source	uncertainty
GEC	2%
$p_T(\mu)/p_T(j_\mu)$ templates	5%
jet reconstruction	2%
SV-tag BDT templates	5%
b-tag efficiency	10%
trigger & μ selection	2%†
jet energy	5%†
$W \to \tau \to \mu$	1%†
luminosity	1–2%†
Total	14%
Theory	10%

➔ σ(7TeV, 1fb-1) $= 239 \pm 53$(stat) ± 33(syst) ± 24(theory) fb

➔ σ(8TeV, 2fb-1) $= 289 \pm 43$(stat) ± 40(syst) ± 29(theory) fb