Latest results on inclusive $t\bar{t}$ cross sections in CMS

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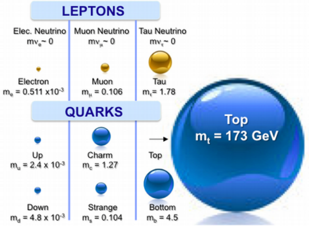
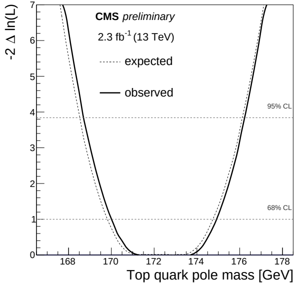
The top quark: key to QCD, EWK, Higgs and new physics

- The most massive known particle
- It decays before hadronisation: study the properties of the bare quark

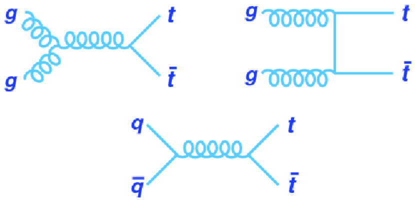
- Measuring $\sigma_{t\bar{t}}$ is the first fundamental step for understanding top physics
- Test QCD predictions and help constraining the PDFs (especially gluon distribution)
- Determination of m$_t$ or α_s (see J. Kieseler's talk)
- Main background for Higgs and many searches for New Physics
- May provide insight into physics BSM: deviation in the ratio of cross section at 13 TeV/ 8TeV, searches for stop quark production





Top quark production in pp collisions at the LHC

$t\bar{t}$ production mainly by gluon fusion
($\sim$80% at 7-8 TeV)

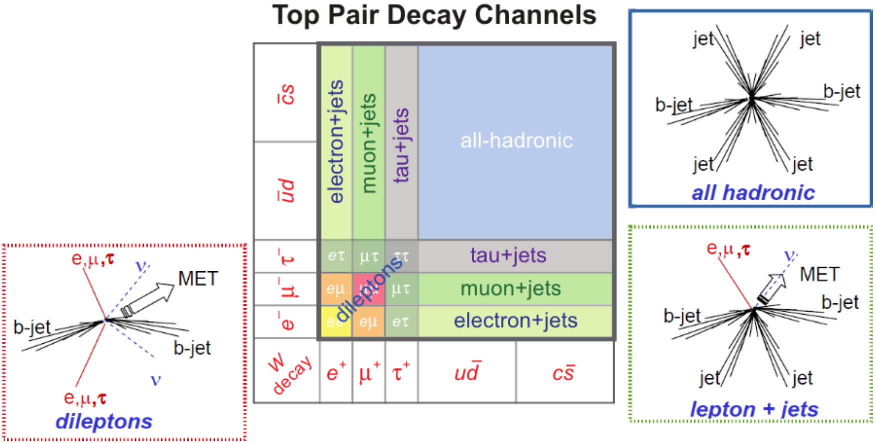


Full NNLO+NNLL calculation
[arXiv:1303.6254]

$\sqrt{s}$ (TeV)	σ (m_t = 172.5 GeV)
5	$68.9 \pm 1.9(\mathrm{scale}) \pm 2.7(\mathrm{PDF} + \alpha_S)$
7	$177.3^{+4.7}_{-6.0}(\mathrm{scale}) \pm 9.0(\mathrm{PDF} + \alpha_S)$
8	$252.9^{+6.4}_{-8.5}(\mathrm{scale}) \pm 11.7(\mathrm{PDF} + \alpha_S)$
13	$832^{+20}_{-29}(\mathrm{scale}) \pm 35(\mathrm{PDF} + \alpha_S)$

Top quark decay signatures

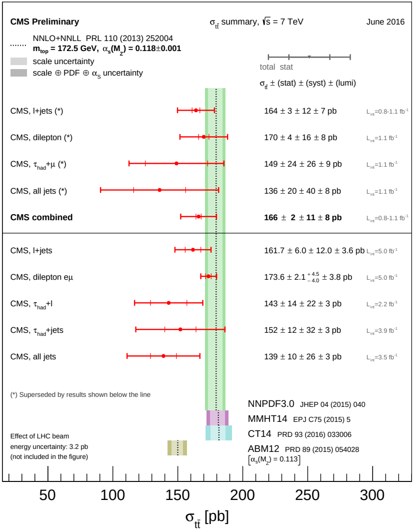
In the SM $t \rightarrow Wb$ almost 100%, W decay defines final state

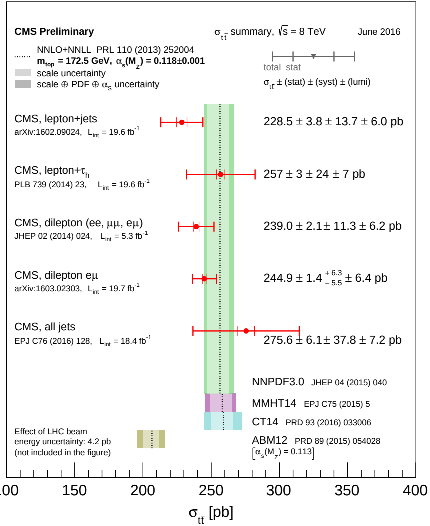


Here: measurements in the three channels (new preliminary result/paper since TOP2015)

Overview of cross section measurements: 7 and 8 TeV

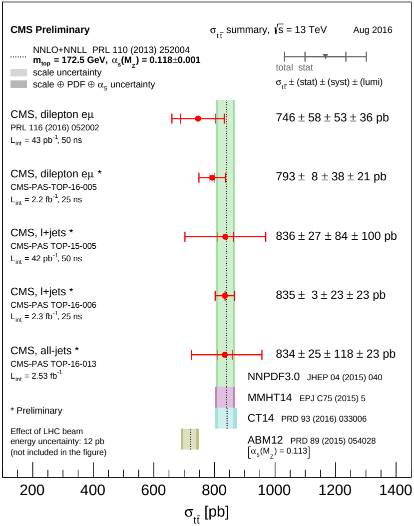
A fine crop of measurements



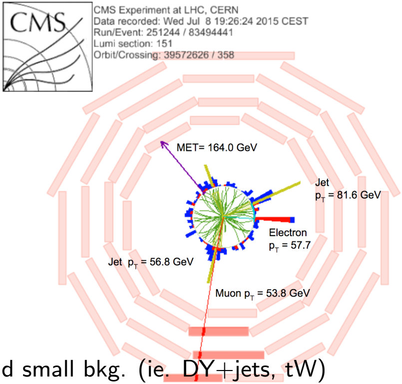


Overview of cross section measurements: 13 TeV

- L = 42/pb - 2.5/fb (2015 data)
- Measurements available in the $e\mu$ and l+jets channel and fully hadronic
- Precision around 4%!



Dilepton decay channel: $e\mu$

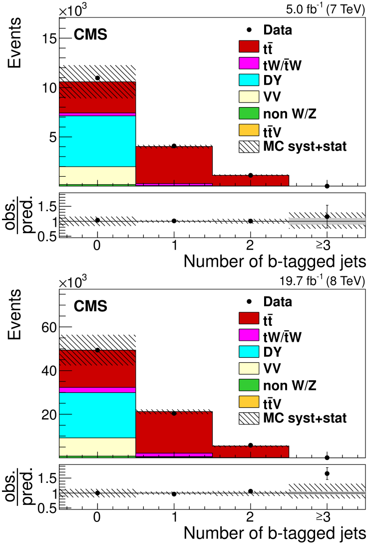


- e/μ: BR~2.5% and small bkg. (ie. DY+jets, tW)
- Measurements at 5, 7, 8 (full data set) and 13 TeV (2015 data)

  Not shown here: early measurement with 42/pb - Phys. Rev. Lett. 116, 052002 (20)
- Events selected using dilepton triggers (Mu8*Mu17*, Ele8*Ele17*)
- One isolated opposite charge $e\mu$ pair (typically $p_T > 20$ GeV, e$\mu > 20$ GeV)

$e\mu$ 7 and 8 TeV [JHEP 08 (2016) 029]

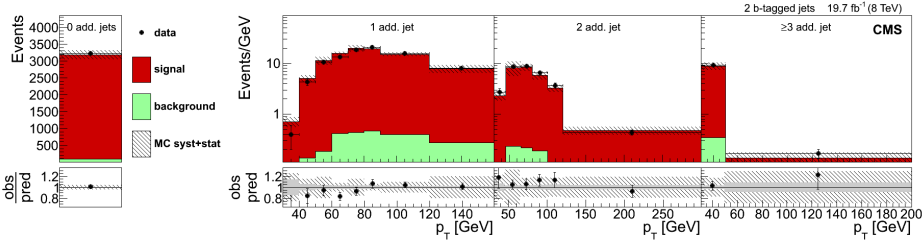
- Reference signal $t\bar{t}$: Madgraph+Pythia6
- One isolated opposite charge $e\mu$ pair
- Jets (p > 30 GeV, $|\eta| < 2.5$)
- b-tagged jets identified with low mistag rate
- No minimum requirement on jets, b-jets!



$e\mu$ 7 and 8 TeV [JHEP 08 (2016) 029]

- Simultaneous 7 & 8 TeV binned likelihood fit with systematics as nuisance parameters:
  - N b-tagged jet and additional non-tagged Njets categories
  - Fit to the softest non-tagged jet p_T distribution in each category
- Large constraints on JES, extra radiation, b-tagging, etc.
- Main uncertainties: luminosity, trigger and lepton Id. eff, DY
- Uncertainties correlated between 7 and 8 TeV data

Figure: 8TeV post-fit distribution, 2 b-tagged jets category



Results: fiducial cross section

$\sigma^{vis}_{t\bar{t}}$ defined with events containing an $e\mu$ pair, with $p_T > 20$ and $|\eta| < 2.4$.

- $\sigma^{vis} = 3.03 \pm 0.04(\text{stat}) \pm^{0.08}_{0.07} (\text{syst}) \pm 0.07(\text{lumi})$ pb at $\sqrt{s} = 7$ TeV (3.5%)
- $\sigma^{vis} = 4.23 \pm 0.02(\text{stat}) \pm^{0.11}_{0.09} (\text{syst}) \pm 0.11(\text{lumi})$ pb at $\sqrt{s} = 8$ TeV (3.6%)

Dominant uncertainties: luminosity, trigger and lepton Id. efficiencies, DY

Source	Uncertainty [%]	
	7 TeV	8 TeV
Trigger	1.2	1.2
Lepton ID/isolation	1.4	1.5
Lepton energy scale	0.1	0.1
Jet energy scale	0.7	0.9
Jet energy resolution	0.1	0.1
Single top	0.9	0.6
DY	1.2	1.2
$t\bar{t}$ other	0.1	0.1
$t\bar{t} + V$	0.0	0.1
Diboson	0.2	0.6
W+jets	0.0	0.0
QCD	0.0	0.0
B-tag	0.5	0.5
Mistag	0.2	0.1
Pileup	0.3	0.3
Q^2 scale	0.3	0.3
ME/PS matching	0.2	0.1
MG+PY → PH+PY	0.2	0.4
Hadronization (JES)	0.6	0.8
Top p_T	0.3	0.3
Color reconnection	0.1	0.0
Underlying event	0.0	0.1
PDF	0.2	0.7
Luminosity	2.2	2.6
Statistical	1.2	0.6

Full phase space

- $\sigma = 173.6 \pm 2.1(\text{stat}) \pm^{4.5}_{4.0}(\text{syst}) \pm 3.8(\text{lum})$ **pb** at $\sqrt{s} = 7$ TeV (3.6%)
- $\sigma = 244.9 \pm 1.4(\text{stat}) \pm^{6.3}_{5.5}(\text{syst}) \pm 6.4(\text{lum})$ **pb** at $\sqrt{s} = 8$ TeV (3.7%)

- Ratio between 8 and 7 TeV results:

$R_{t\bar{t}} = 1.41 \pm 0.06$

→ Very good agreement with ratio in l+jets channel (next slides)

$R_{t\bar{t}} =$

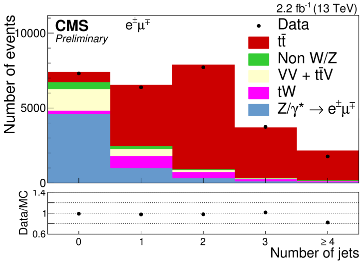
$1.43 \pm 0.04(\text{stat}) \pm 0.07(\text{syst}) \pm 0.05(\text{lumi})$

- Model uncertainties cannot be constrained: full variation

Source	Uncertainty [%]	
	7 TeV	8 TeV
Total (vis)	$\pm^{3.6}_{3.4}$	$\pm^{3.7}_{3.4}$
Q^2 scale (extrapol.)	$\mp^{0.0}_{0.4}$	$\pm^{0.2}_{0.1}$
ME/PS matching (extrapol.)	$\pm^{0.1}_{0.1}$	$\pm^{0.3}_{0.3}$
Top p_T (extrapol.)	$\pm^{0.5}_{0.3}$	$\pm^{0.6}_{0.3}$
PDF (extrapol.)	$\pm^{0.2}_{0.1}$	$\pm^{0.2}_{0.1}$
Total	$\pm^{3.6}_{3.5}$	$\pm^{3.7}_{3.5}$

13 TeV $e\mu$ [CMS-TOP-16-005]

- Counting experiment
- Reference signal $t\bar{t}$: Powheg+Pythia8
- Selection:
  - One isolated opposite charge $e\mu$ pair ($m_{e\mu} > 20$GeV)
  - $\geq$2 jets
  - $\geq$1 b-tagged jets
- Background estimation
  - tW, ttV and diboson from MC
  - DY MC prediction normalized to Z peak in data
  - Non W/Z: estimated from same-sign control region with scale factor from MC

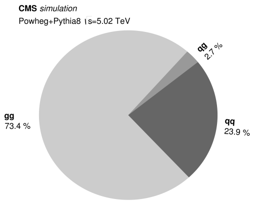


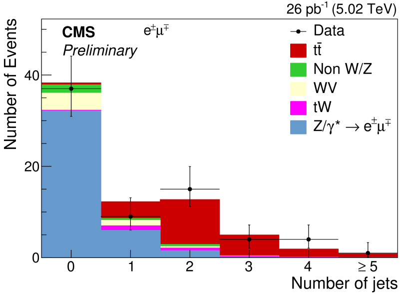
Source	Number of $e^{\pm}\mu^{\mp}$ events
Drell–Yan	$24 \pm 9 \pm 4$
Non-W/Z leptons	$109 \pm 50 \pm 33$
Single top quark	$463 \pm 6 \pm 145$
VV	$15 \pm 2 \pm 5$
$t\bar{t}$ V	$31 \pm 1 \pm 10$
Total background	$642 \pm 52 \pm 149$
$t\bar{t}$ dilepton signal	$10199 \pm 14 \pm 462$
Data	10368

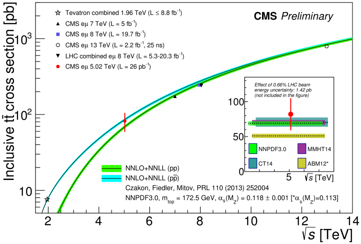
$\sigma_{t\bar{t}} = 793 \pm 8(stat) \pm 38(syst) \pm 21(lum.)$ **pb** (5.6%)

5.02 TeV: eμ [CMS-PAS-TOP-16-015]

- Potential to constrain high-x gluon PDF
- Similar approach as measurement at 13 TeV
- No b-tagging requirements
- Dominated by statistical uncertainties (25%)





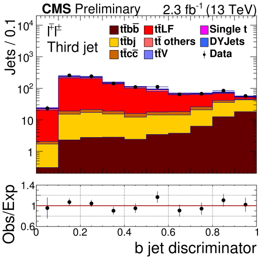


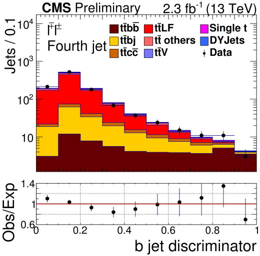
$$\sigma_{t\bar{t}} = 82 \pm 20(stat) \pm 5(syst) \pm 10(lum.)\ \mathbf{pb}$$

→ Poster by J.R. Gonzalez

$t\bar{t}+b\bar{b}$: ratio of b- to light-flavour jets [CMS-TOP-16-010]

- Comparison with NLO QCD calculations
- Irreducible bkg. for $t\bar{t}$+H($b\bar{b}$)
- Measure ratio $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$: large cancellation of uncertainties
    - Selection: dilepton events with ≥4 jets with $p_T >$ 20 GeV, ≥2 b–tagged jets
    - Signal extraction by fit to the measured b-tagging algorithm discriminators
    - Corrected to particle level
    - Dominant systematic: b efficiency

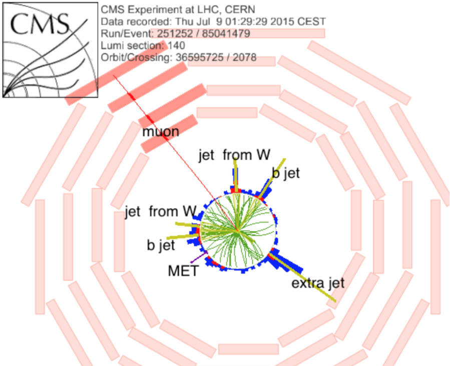




Phase Space	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Measurement			
Visible	$0.085 \pm 0.012 \pm 0.029$	$3.5 \pm 0.1 \pm 0.7$	$0.024 \pm 0.003 \pm 0.007$
Full	$3.9 \pm 0.6 \pm 1.3$	$176 \pm 5 \pm 33$	$0.022 \pm 0.003 \pm 0.006$
Simulation (POWHEG)			
Visible	0.070 ± 0.009	5.1 ± 0.5	0.014 ± 0.001
Full	3.2 ± 0.4	257 ± 26	0.012 ± 0.001

→ Also: new results $t\bar{t}t\bar{t}$ (CMS-PAS-TOP-16-016, See L. Beck's talk)

Decay channel: l+jets

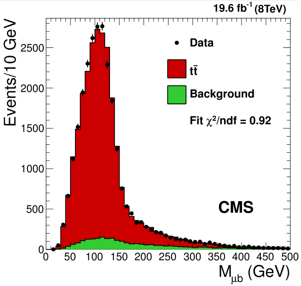


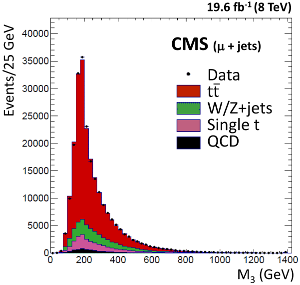
- e/μ +jets: BR$\sim$30% and manageable bkg. (ie. W+jets)
- Measurements at 7, 8 TeV (full data set) and 13 TeV (2015 data)
- Events selected using single leptons triggers ($p_{\mathrm{T}} > 20 - 27$ GeV)
- One isolated e or μ (typically lepton $p_{\mathrm{T}} > 30$ GeV), veto additional leptons

l+jets 7 and 8 TeV [arXiv:1602.09024]

- 1 isolated high-p_T μ/e, $\geq$4 jets, $\geq$1 b-tagged jet
- Fit to M_{lb}
- Cross check: fit to M3 (three-jet combination with the highest p_T)
- The results from the two lepton+jets channels are combined using the BLUE method.
- QCD background shape from data
- Main syst.: JES, b-tag, Q^2 & matching scales

Analysis	Generator	Channel	σ at $\sqrt{s} = 8$ TeV
M_{lb}	MADGRAPH	μ+jets	228.9 ± 3.4 ± 13.7 ± 6.0 pb
		e+jets	234.6 ± 3.9 ± 15.2 ± 6.2 pb
		Combined	228.5 ± 3.8 ± 13.7 ± 6.0 pb
M_{lb}	POWHEG	Combined	237.1 ± 3.9 ± 14.2 ± 6.2 pb
M_3	MADGRAPH	Combined	227.1 ± 2.5 ± 19.1 ± 6.0 pb
M_3	POWHEG	Combined	238.4 ± 2.8 ± 20.0 ± 6.2 pb
Analysis	**Generator**	**Channel**	**σ at $\sqrt{s} = 7$ TeV**
M_{lb}	MADGRAPH	μ+jets	157.7 ± 5.5 ± 13.2 ± 3.4 pb
		e+jets	165.8 ± 6.5 ± 12.8 ± 3.6 pb
		Combined	161.7 ± 6.0 ± 12.0 ± 3.6 pb





7 & 8 TeV: fiducial and boosted cross sections

- Measurement at particle level, visible phase space: Exactly one muon or electron with p_T >32 GeV and $|\eta| < 2.1$, one neutrino with p_T >40 GeV, and at least four jets with p_T >40 GeV:

  $\sigma = 3.80 \pm 0.06(\mathrm{stat}) \pm 0.18(\mathrm{syst}) \pm 0.10(\mathrm{lumi})$ pb at $\sqrt{s} = 8$ TeV

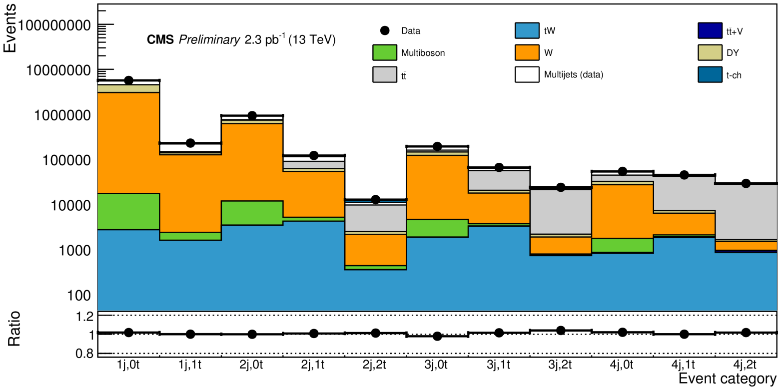
Sneak preview: cross sectios in the boosted regime [arXiv:1605.00116]

- Inclusive cross section also measured in the boosted regime $p_T^t > 400$ GeV
  $\sigma = 1.44 \pm 0.10(\mathrm{stat} + \mathrm{syst}) \pm 0.29(\mathrm{theory}) \pm 0.04(\mathrm{lumi})$ pb

→ See K. Kousouris' talk

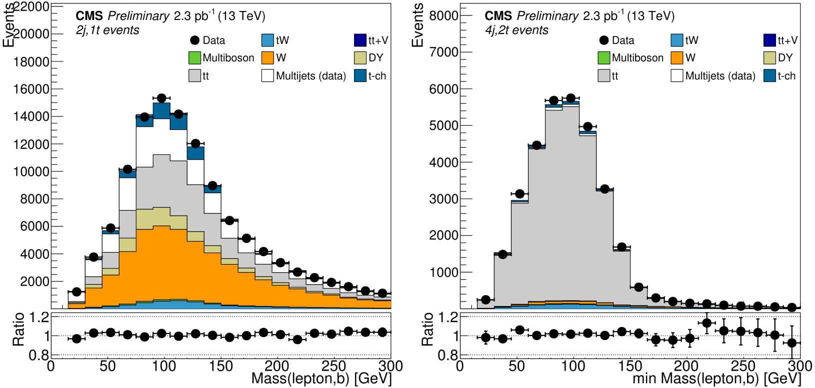
l+jets 13 TeV [CMS-PAS-TOP-16-006]

- Require only 1 lepton and at least 1 jet
- Divide the analysis in different categories by counting the jets and b-tags
- Low jet/b-tag categories to constrain backgrounds while high jet/b-tag to fit the signal
- W+jets and QCD estimated from data



l+jets 13 TeV [CMS-PAS-TOP-16-006]

- Simultaneous binned likelihood fit with systematics as nuisance parameters (log-normal distributions):
  - Fit to M_{lb} or min(M_{lb})
  - Shape fit in 44 lepton flavour and charge, b-tagged jet, Njets categories
- Data-driven background estimate included in the fit
- Pole quark mass extracted simultaneously in the fit (see J. Kieseler's talk)



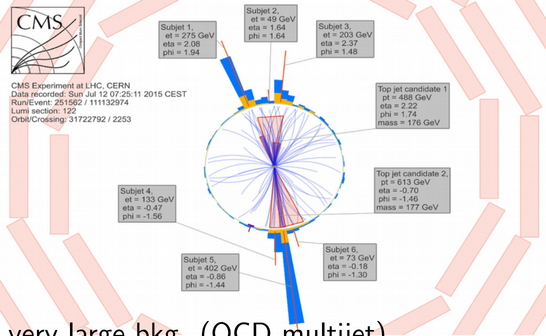
l+jets 13 TeV [CMS-PAS-TOP-16-006]

- Statistical uncertainty 0.3%
- Large constraints on JES, extra radiation, b-tagging, etc.
- Main uncertainties: W+jets bkg. modelling, luminosity
- Uncertainty in the extrapolation reduced (1.5%) by requiring only one jet in the selection (∼0.7% in the eμ channel at 8 TeV)

Source	**Cut-in-Categories**	**Shape**
Statistics	0.004	0.003
Experimental uncertainties		
Jet energy scale/resolution	0.003	0.001
b-tagging	0.004	0.004
Pileup	0.001	$<$ 0.001
Lepton efficiency	$<$0.001	$<$0.001
Lepton energy scale	0.002	0.001
W model	0.020	0.020
QCD multijets	0.018	0.009
Other backgrounds	0.004	0.004
Theory uncertainties		
$t\bar{t}$ model	0.011	0.002
top p_T	0.006	0.005
parton shower scale	0.012	0.001
QCD scale	0.004	0.002
Single top quark model	0.008	0.002
Top quark mass	$<$ 0.001	0.001
Total	**0.034**	**0.023**

$\sigma = 834.7 \pm 2.5(stat) \pm 20.7(syst) \pm 22.6(lumi) \pm 12.5(extrapol)$ (3.9%)

Decay channel: all jets

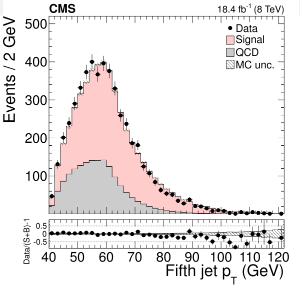


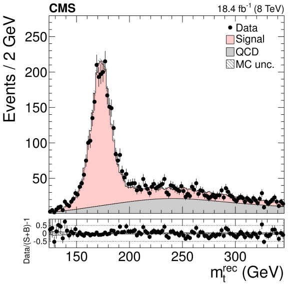
- BR∼46%, very large bkg. (QCD multijet)
- Measurements at 8 TeV (full data set) and 13 TeV (2015 data)
- Multijet trigger event selection
- Signature: ≥6 jets, ≥2 b-tagged jets

8 TeV [Eur. Phys. J. C 76 (2016) 128]

- Reconstruction of $t\bar{t}$ system
- Background: mostly QCD multijet
- Unbinned maximum likelihood fit to m_t extract signal and background normalizations
- Uncertainties:

Source	
Background modeling	±4.9%
JES	−7.0, +6.8%
JER	±3.5%
b tagging	±7.3%
Trigger efficiency	−2.2, +2.0%
Underlying event	±4.4%
Matching partons to showers	−4.2, +2.4%
Factorization and renormalization scales	−0.5, +3.8%
Color reconnection	±1.4%
Parton distribution function	±1.5%
Hadronization	±2.0%
Total systematic uncertainty	−13.7, +13.7%
Statistical uncertainty	±2.3%
Integrated luminosity	±2.6%





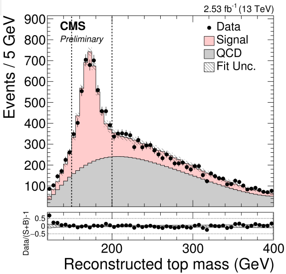
$\sigma_{t\bar{t}} = 275.6 \pm 6.1(stat) \pm 37.8(syst) \pm 7.2(lum.)$ **pb** (13.6%)

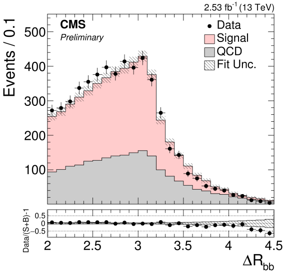
13 TeV [CMS-PAS-TOP-16-013]

- Performed also in the boosted regime!
- Similar strategy in the resolved regime as at 8 TeV: Unbinned maximum likelihood fit to m_t (χ^2, m_t range slightly different)
- Dominant uncertainties: JES, b-tagging

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

$$\sigma_{t\bar{t}} = 834 \pm 25(stat)^{+118}_{-104}(syst) \pm 23(lum.)\ \mathbf{pb}$$ (13%)





Boosted regime: $\sigma_{t\bar{t}} = 727 \pm 46(stat)^{+115}_{-112}(syst) \pm 8(lum.)$ pb

Summary

From Run I: first ever top quark factory

- Precision regime: $\Delta\sigma_{t\bar{t}} <4\%$ (full NNLO same precision as data)
- Measurement in the fidual phase space $\Delta\sigma_{t\bar{t}} <3\%$
- Determined ratio of full phase space cross sections

... to (the beginning of) Run II

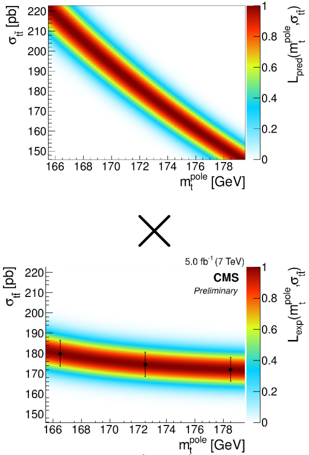
- Results already in several channels, different regimes
- Measurements with $\sim$2.3/fb reaching similar precision, dominated by luminosity
- Better precision expected with the larger data set: combinining l+jets, dilepton, splitting and fitting the data in further different categories (lepton charge, number of jets, b-jets), etc...

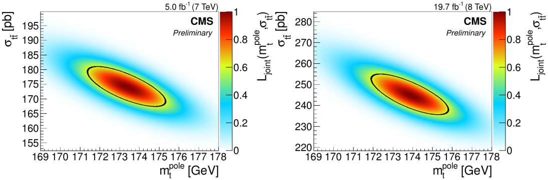
Excellent agreement between channels, $\sqrt{s}$, and NNLO+NNLL predictions

BACKUP

Top quark pole mass extraction

- Mass dependence of predicted σ allows determining m_t from measured $\sigma(t\bar{t})$
  - m_t^{pole} extracted by comparing the most precise predicted and measured cross sections
  - Final result: combination of 7 and 8 TeV





Combined:

	m_t
NNPDF3.0	$173.6 \pm^{1.7}_{1.8}$ GeV
MMHT2014	$173.9 \pm^{1.8}_{1.9}$ GeV
CT14	$174.1 \pm^{2.1}_{2.2}$ GeV

8 TeV: CMS τ_h+lepton [Phys. Lett. B 739 (2014) 23]

Selection:

- 1 isolated high-p_T μ/e, $\geq$3 jets, $\geq$1 b-tagged jet

  1 τ_h candidate

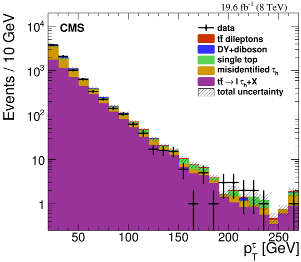
  MET cut

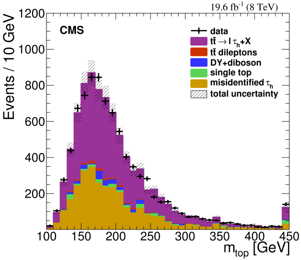
- Reconstruction of m_t for additional separation

Main uncertainties:

τ_h Identification	6%
τ_h Mis-Identifcation	4.3%
Factorization Scale	2.9%
Total systematic	9.5%
Total statistical	1%
Luminosity	2.6%

- Dependence on m_t described by a linear variation





$\sigma_{t\bar{t}} = 257 \pm 3(stat) \pm 24(syst) \pm 7(lum.)$ **pb**