Top Quark Physics at LHC

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(on behalf of the ATLAS, CMS collaborations)

QCD@LHC, East Lansing (US)

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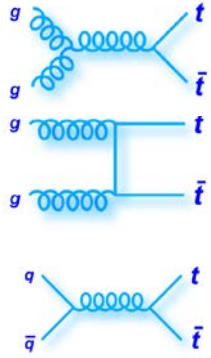
Outline

- ttbar total cross section at 7 and 8 TeV
- Differential ttbar cross sections
- Top quark mass
- Charge asymmetry
- Measurements of ttbar+X (X=photon, W, Z)
- W helicity and spin correlations
- Single top production (t,tW channels)

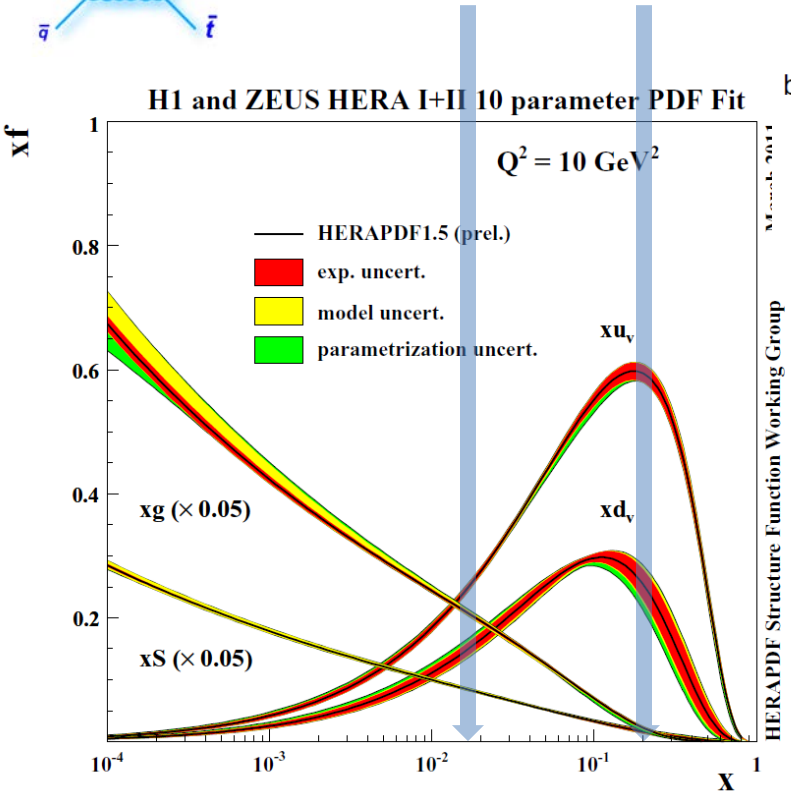
ATLAS results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
CMS results:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
See also:
F.-P. S., “Top Quark Physics at the LHC: A Review of the First Two Years”, IJMPA 27, 17 (2012) 1230016, arXiv:1206.4484

Top quark pair production and decay

Production:

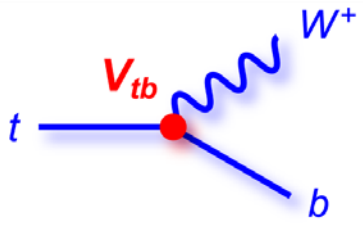


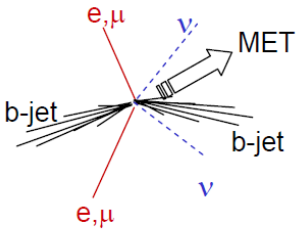
	LHC	Tevatron
gg	~85%	~10%
qq	~15%	~90%



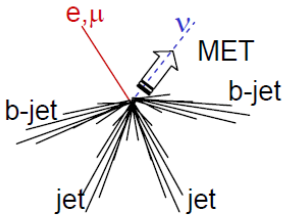
Decay:

Almost 100%

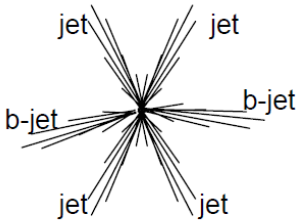




dileptons



lepton + jets



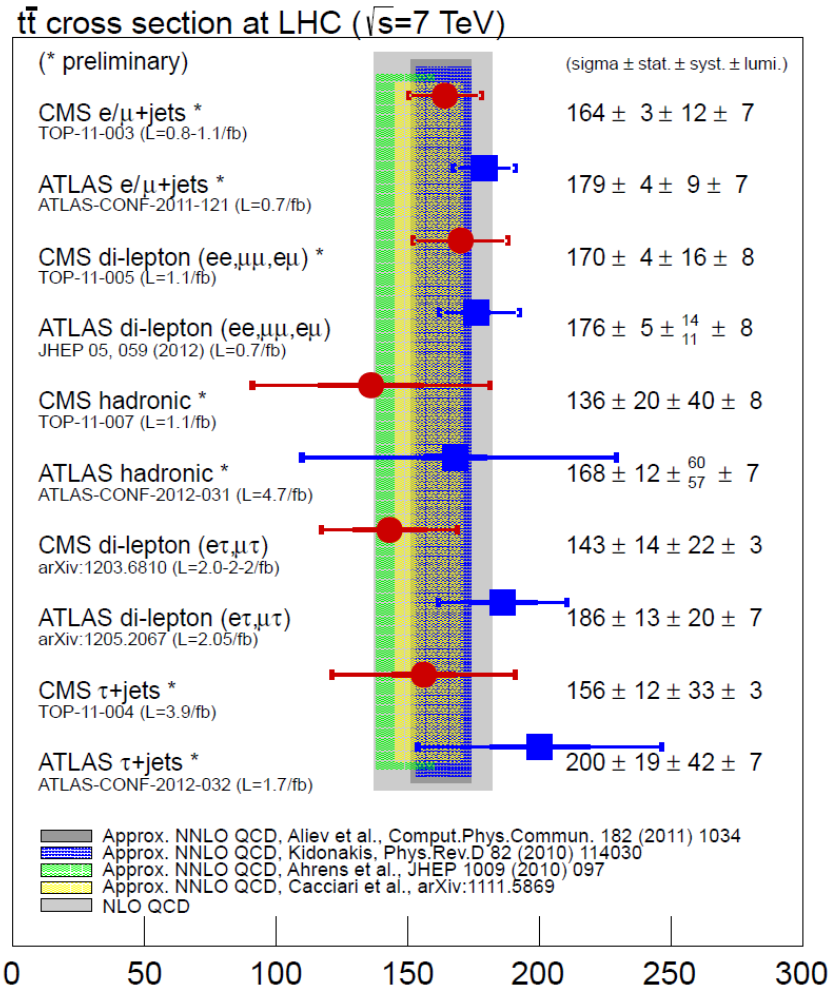
all hadronic

	dileptons	lepton + jets	all hadronic
BR:	~5%	~30%	~46%
Bkgd:	few (mainly Z+jets)	moderate (mainly W+jets)	huge (mainly QCD)

Total cross section at 7 TeV

Approx. NNLO theory calculations	
Authors	Cross Section @ 7 TeV [pb] (+-scale +-PDF)
NLO QCD (MCFM)	160 +20-21 +8-9
Kidonakis	163 +7-5 +9-9
Aliev et al. (HATHOR)	164 +5-9 +9-9
Ahrens et al.	155 +8-9 +8-9
Beneke et al.	163 +7-8 +15-14
Cacciari et al. (TOP++)	159 +12-14 +4-4
Moch et al.	175 +10-13 +5-5

- Measurements in all channels
- Good agreement data vs theory
- Exp. precision starting to challenge approx NNLO
- Measure also xs in fiducial volume?



CMS Combination (~8%)

$$\sigma_{t\bar{t}} = 165.8 \pm 2.2\ (\text{stat.}) \pm 10.6\ (\text{syst.}) \pm 7.8\ (\text{lum.})\ \text{pb}$$

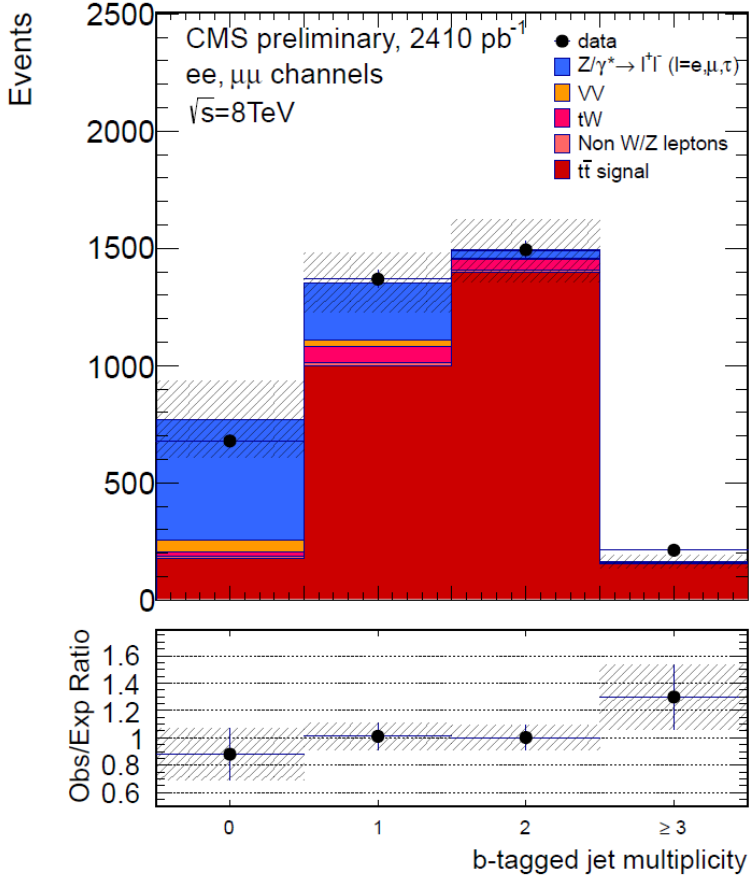
ATLAS Combination (~6%)

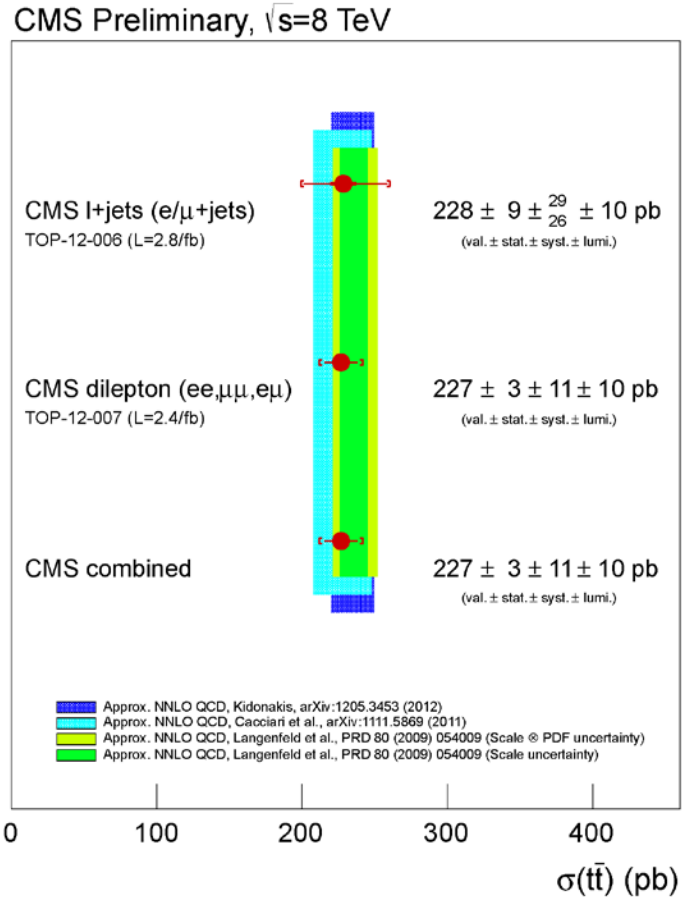
$$\sigma_{t\bar{t}} = 177 \pm 3\ (\text{stat.})^{+8}_{-7}\ (\text{syst.}) \pm 7\ (\text{lum.})\ \text{pb}$$

… and at 8 TeV

CMS PAS TOP-12-006
CMS PAS TOP-12-007

CMS measurements using first part of 2012 data
Both di-lepton and lepton+jets channels





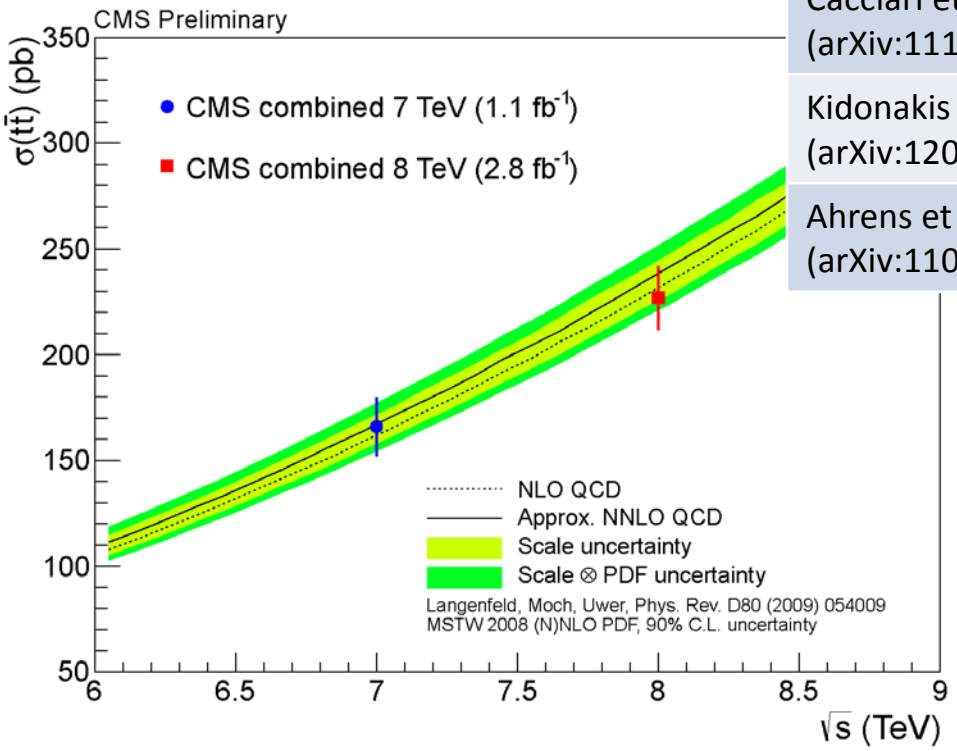
$$\sigma_{t\bar{t}} = 227 \pm 3\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 10\,(\text{lumi})\ \text{pb}$$

Good agreement with theory observed (looking fwd to full NNLO)

Cross section rise with energy

Cross section rise with energy confirmed

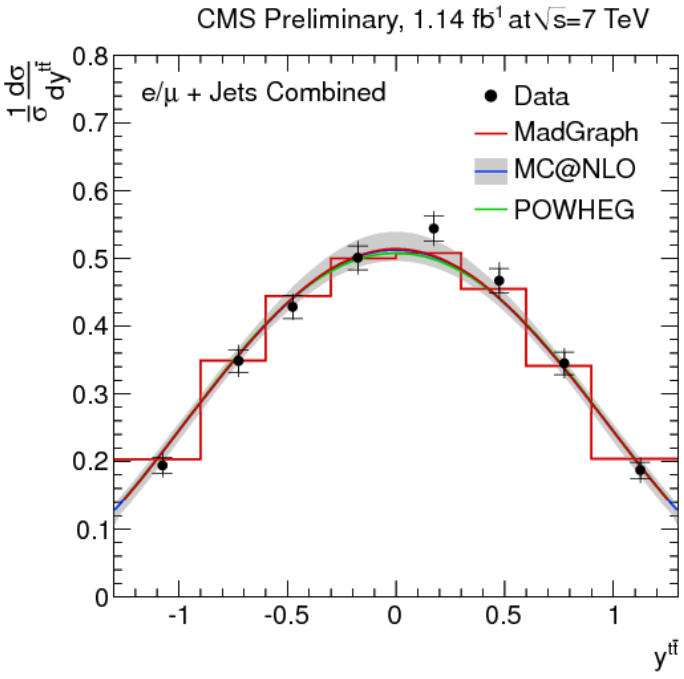
Authors	Cross section at 8 TeV [pb] (+-scale +-PDF)	Details
Moch et al. (arXiv:1203.6282)	250 +14-18 +6-6	MSTW 68%CL , m_t=173 GeV
Moch et al.	203 +11-15 +9-9	ABM11 68%CL
Cacciari et al. (arXiv:1111.5869)	229 +18-20 +6-6	M_t=173.3 GeV, MSTW 68%CL
Kidonakis (arXiv:1205.3453)	234 +10-7 +12-12	MSTW 90%CL
Ahrens et al. (arXiv:1105.5824)	225 +12-12 +11-12	MSTW 90%CL, mt=173.1 GeV

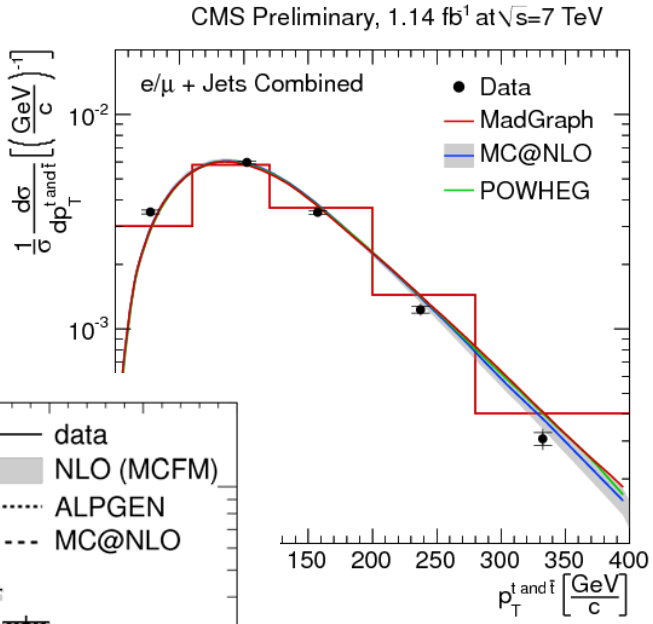


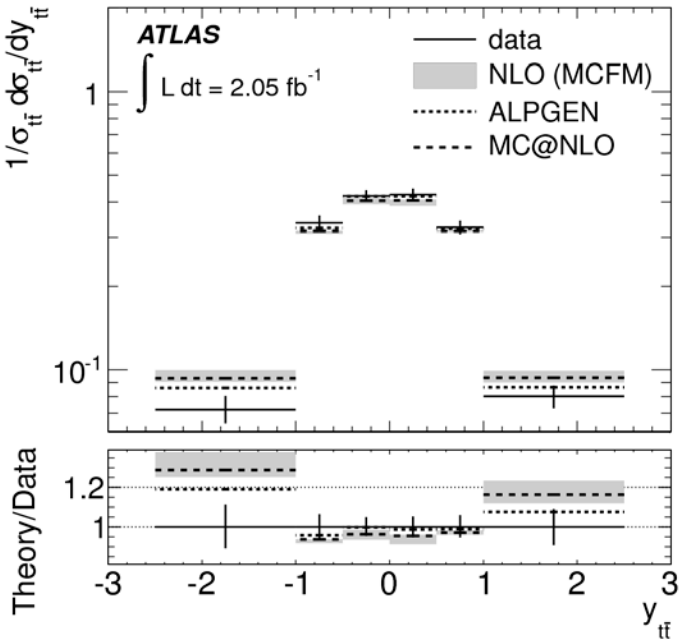
- R(8 TeV / 7 TeV) = 1.41 +/- 0.10 exp. unc. uncorrelated (pessimistic)
- Plan also double ratios e.g. tt/Z(8) / tt/Z(7) – sensitive to new physics (see e.g. Mangano, Rojo)

Differential cross sections

- CMS, PAS TOP-11-013, L=1.14/fb (di-leptons & l+jets, visible PS)
- ATLAS, arXiv:1207.5644, L=2.05/fb (l+jets, full PS)
- Unfolded to parton level
- normalized: cancellations of many systematic uncertainties

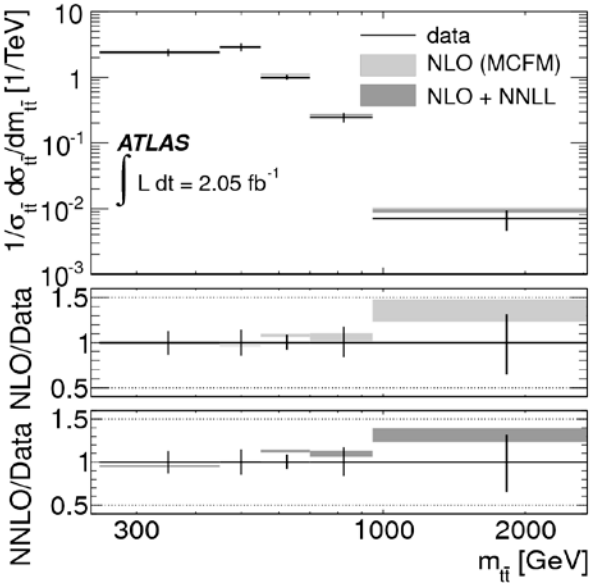


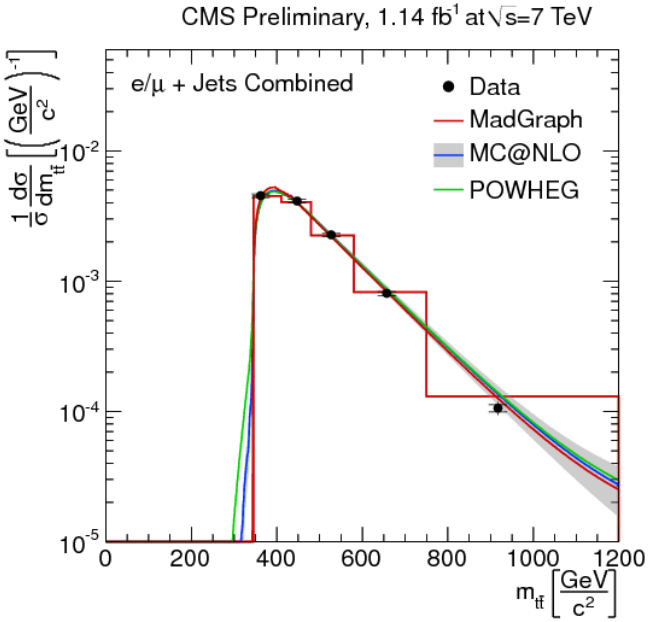


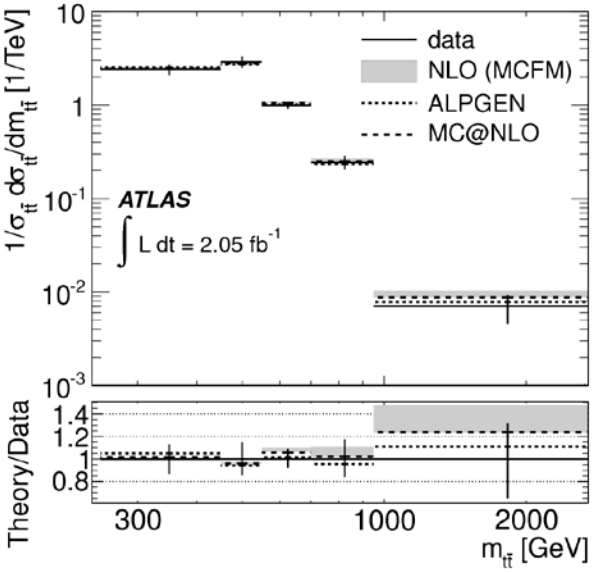


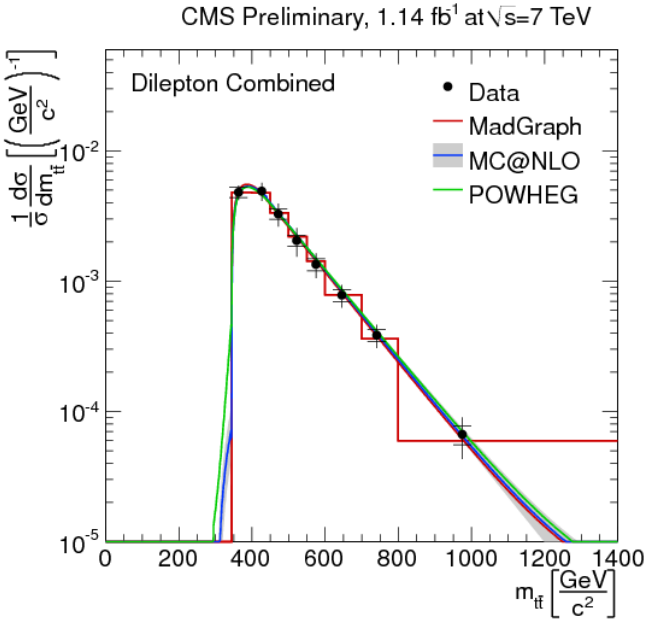
Good agreement with Madgraph, ALPGEN, MCFM, MC@NLO, POWHEG

vs M(tt)









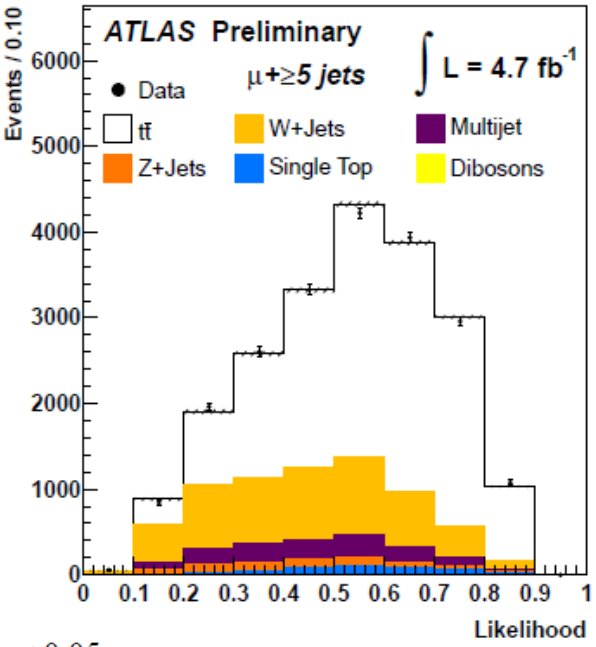
Good agreement with MCFM, ALPGEN/MADGRAPH, MC@NLO and NLO+NNLL (Ahrens)

Cross section for ttbar+jet

ATLAS-CONF-2012-083

Principle of measurement:

- Measurement of N(tt) vs jet multiplicity ==4,>=5 (likelihood for W+jets separation)
- Solve matrix equation to determine sigma(tt) and sigma(tt+jet)
- Quote inclusive cross section or within fiducial region (pt,eta of jets, leptons, MET)



Two definitions of sigma(tt+j) (using particle jets with Pt>25 GeV)

1. Jet with no partons from ttbar decay within dR=0.4

$$\sigma_{t\bar{t}j} = 102 \pm 2(\text{stat.})^{+23}_{-26}(\text{syst.})\ \text{pb} \qquad \sigma_{t\bar{t}j}/\sigma^{\text{incl}}_{t\bar{t}} = 0.54 \pm 0.01(\text{stat.})^{+0.05}_{-0.08}(\text{syst.})$$

2. At least five particle jets (model independent)

$$\sigma^{\text{fiducial}}_{t\bar{t}j\to e+\text{jets}} = 2.59 \pm 0.09(\text{stat.})^{+0.26}_{-0.46}(\text{syst.})\ \text{pb}, \qquad \sigma^{\text{fiducial}}_{t\bar{t}X\to e+\geq 5\text{jets}} = 4.09 \pm 0.18(\text{stat.})^{+0.62}_{-0.85}(\text{syst.})\ \text{pb},$$

$$\sigma^{\text{fiducial}}_{t\bar{t}j\to \mu+\text{jets}} = 3.48 \pm 0.08(\text{stat.})^{+0.43}_{-0.61}(\text{syst.})\ \text{pb}, \qquad \sigma^{\text{fiducial}}_{t\bar{t}X\to \mu+\geq 5\text{jets}} = 5.27 \pm 0.16(\text{stat.})^{+1.04}_{-1.20}(\text{syst.})\ \text{pb}.$$

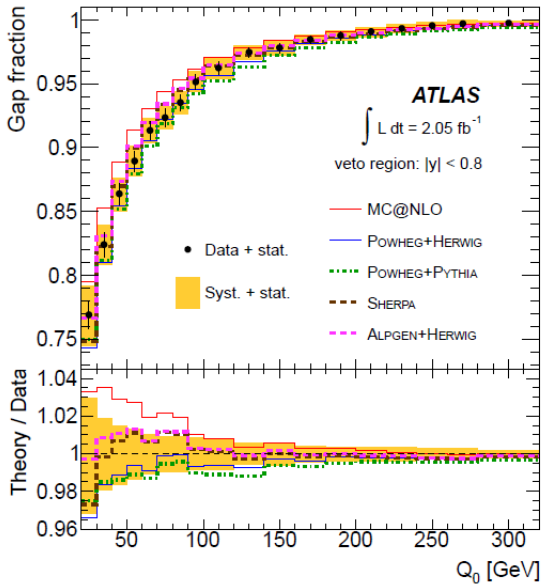
Aim at comparison with NLO QCD (e.g. Dittmaier, Uwer, Weinzierl; Melnikov et al.)

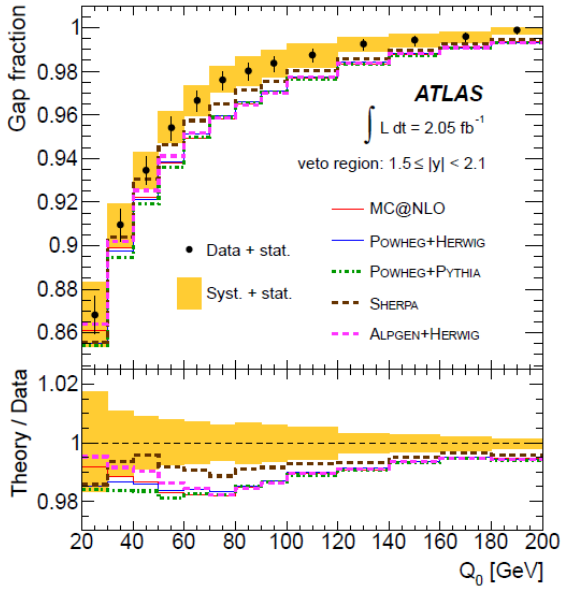
ttbar with veto on extra jets

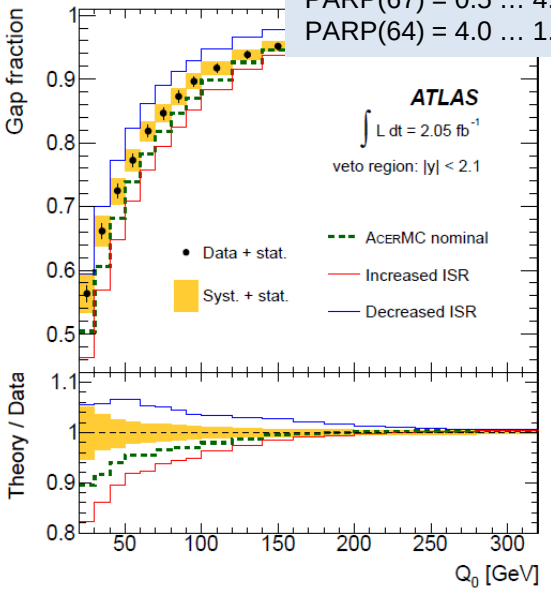
Di-lepton channel using L=2.05/fb of 7 TeV data (arXiv:1203.5015)

- Fraction of ttbar events with no extra jet above a given Pt cut
- Corrected for detector effects, compared with ME+PS (ALPGEN,SHERPA, ACERMC) and NLO (MC@NLO, POWHEG) generators
- Exp. uncertainties often smaller than spread between models

PYTHIA ISR low norm high
PARP(67) = 0.5 … 4.0 … 6.0
PARP(64) = 4.0 … 1.0 … 0.25







Central region:
Too few jets from MC@NLO

Fwd region:
All models produce too many jets

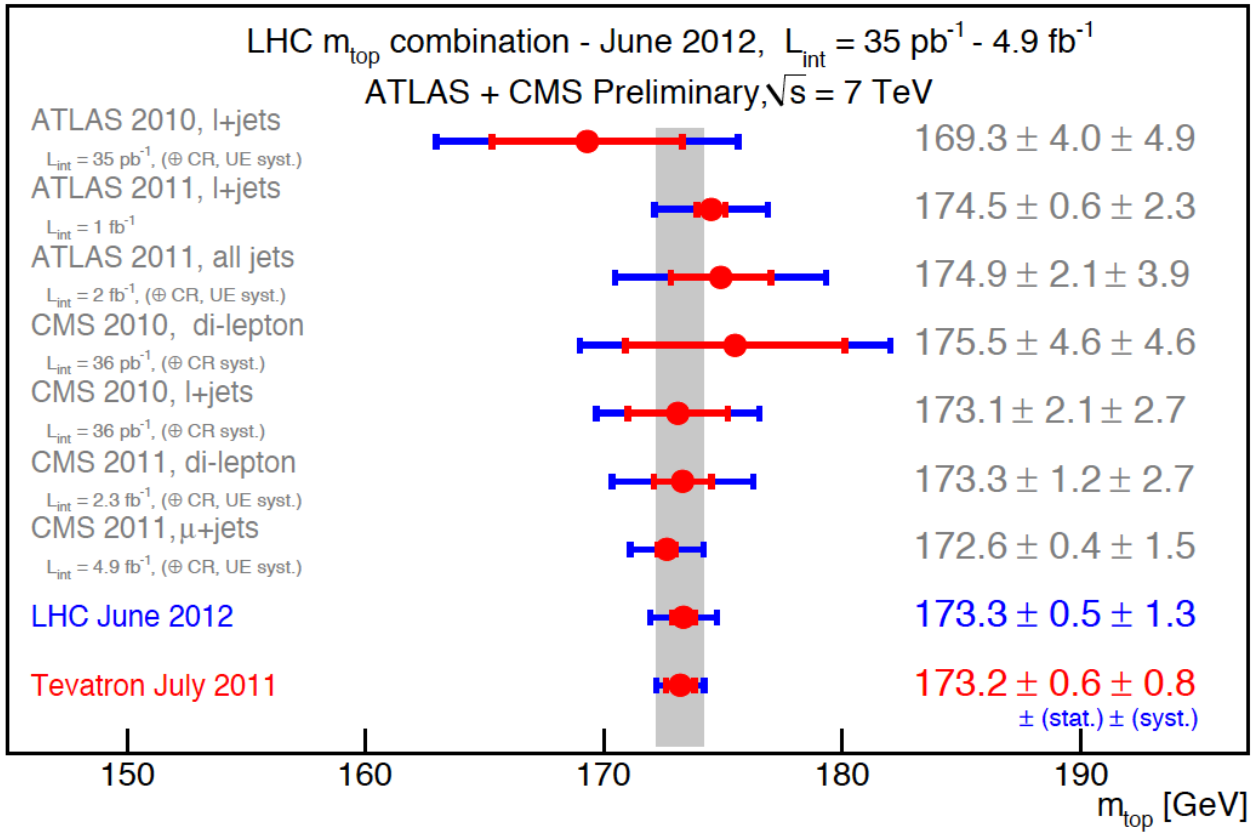
Can constrain parameters of QCD radiation model (ISR/FSR/Q^2)

Room for tuning / need for higher orders

LHC top quark mass

First LHC combined result in top quark physics!

CMS PAS TOP-12-001
ATLAS CONF-2012-095



- Based on conventional measurement techniques (template, ideogram etc.)
- 0.8% precision, quickly approaching Tevatron precision
- Dominating systematics: (b-)JES, ISR/FSR Q2, CR, UE

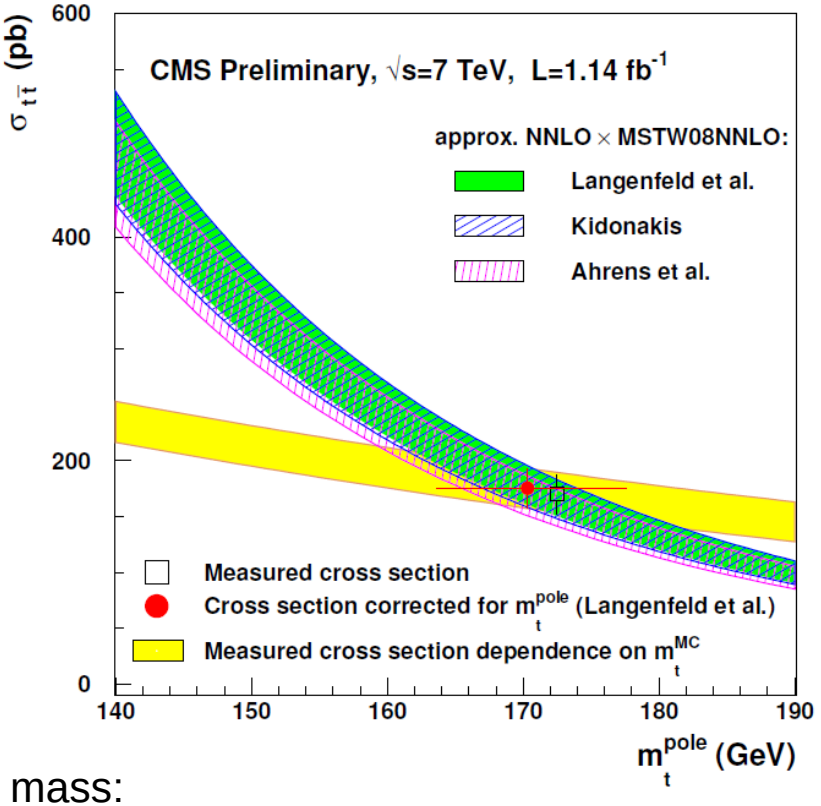
Top mass prospects

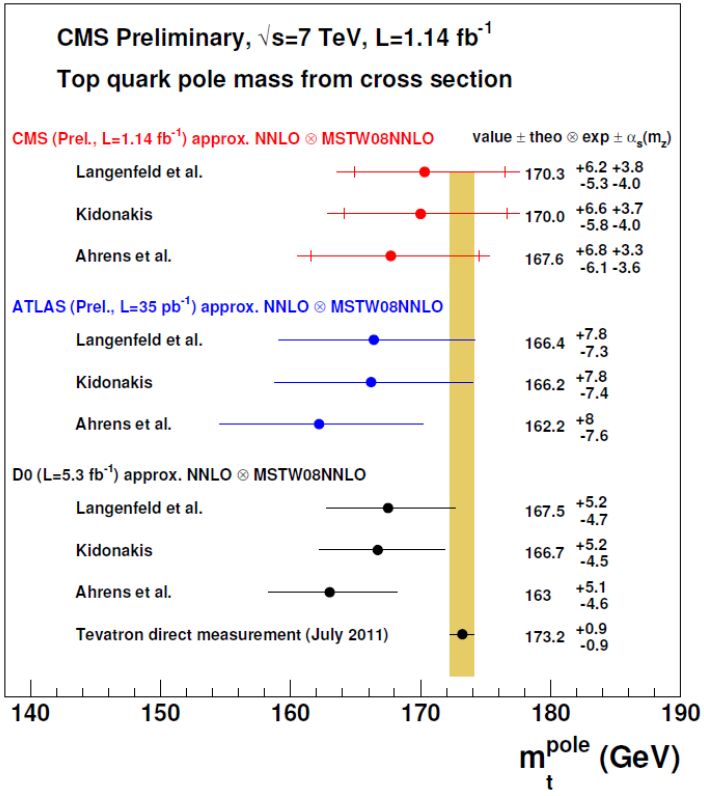
- TOPLHCWG working on this and other combinations (e.g. ttbar and single top cross section)
- Future combinations aiming at harmonized methodologies for evaluation of systematics (experimental and theoretical)
- Potential for further reduction of systematic uncertainties
  - Experimental:
    - Large L allows to constrain to well-understood regions of phase space
    - In-situ determination of (b-)jet energy scale
    - Alternative methods with complementary systematics
      - e.g. lepton pt, d0 of B-hadron, M(J/Psi->ll + l(W))
      - M(l, b-jet), M(ttbar) (NLO(+NNLL) QCD predictions available)
  - Theoretical
    - Understand better CR and UE uncertainties, e.g. by means of differential mtop measurements (e.g. mtop vs pt-top)
    - New developments in tools (e.g. Matrix Element Method @ NLO)

Mass from Cross Section

Exploit strong dependence of theory xsec on mtop
Well defined renormalization scheme

ATLAS CONF-2011-054
CMS PAS TOP-11-008





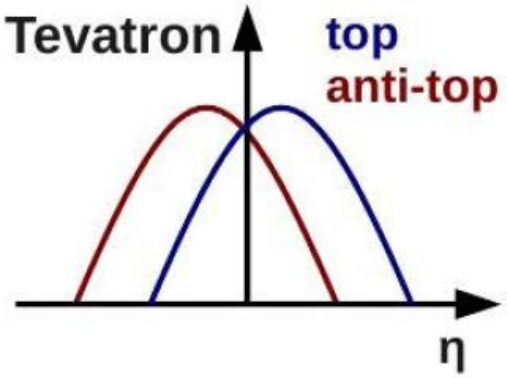
MSbar mass:

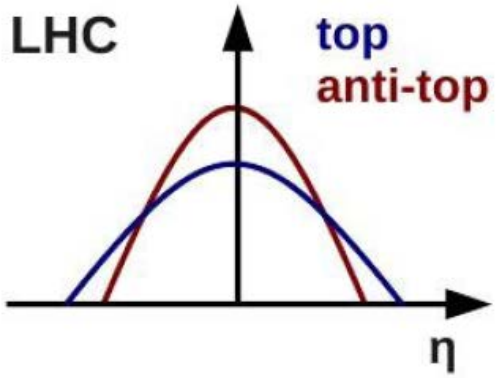
Approx. NNLO × MSTW08NNLO	m_t^{pole} / GeV	$m_t^{\overline{\text{MS}}}$ / GeV
Langenfeld et al. [7]	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis [8]	$170.0^{+7.6}_{-7.1}$	–
Ahrens et al. [9]	$167.6^{+7.6}_{-7.1}$	$159.8^{+7.3}_{-6.8}$

(can also measure alpha-s from xsec)

Charge Asymmetry

Tevatron: $\Delta y = y_t - y_{\bar{t}}$ LHC: $\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$





$$A_C = \frac{N^+ - N^-}{N^+ + N^-}$$

- SM: non-zero Ac appears at NLO QCD due to interference of ISR-FSR and Born-Box diagrams
- CDF/D0 observed larger than predicted Ac at Tevatron
- Many new physics models put forward (e.g. Axigluons, new weak bosons, extra dimensions etc.) [must accommodate ttbar cross section, M(ttbar), EWK and same-sign-top limits etc.]

- Asymmetry at LHC diluted due to large fraction of gg initial states

Unfolded charge asymmetry

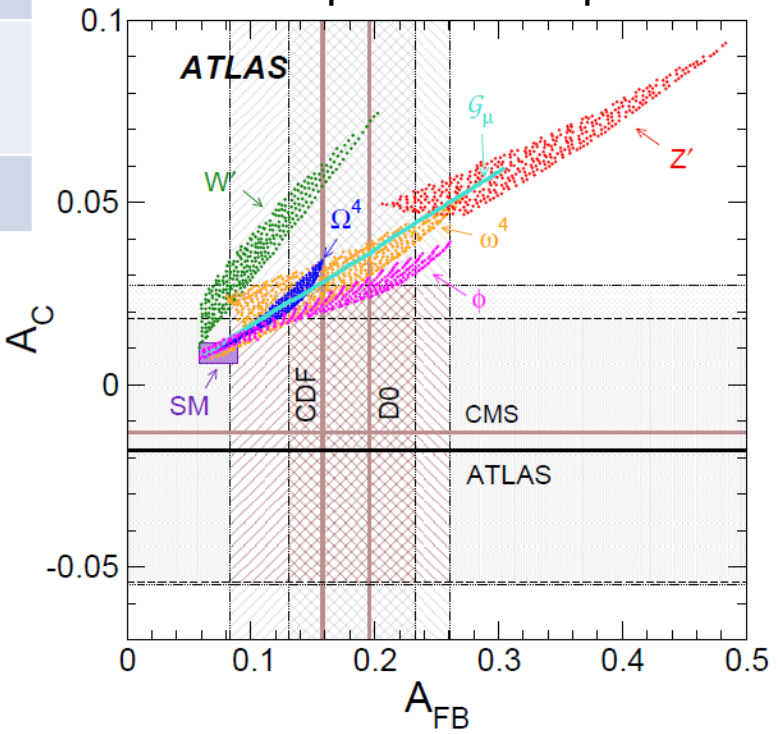
Measurement	Ac $\Delta\lvert y\rvert \equiv \lvert y_t\rvert - \lvert y_{\bar{t}}\rvert$
CMS, L=1.1/fb, l+jets (arXiv:1112.5100)	-0.013 +/- 0.028 +/- 0.030
CMS, L=5.0/fb, l+jets (arXiv:1207.0065)	0.004 +/- 0.010 +/- 0.011
ATLAS, L=1.04/fb, l+jets (arXiv:1203.4211)	-0.019 +/- 0.028 +/- 0.024
ATLAS, L=4.7/fb, dilepton (ATLAS-CONF-2012-057)	0.057 +/- 0.024 +/- 0.015
ATLAS combination	0.029 +/- 0.018 +/- 0.014

All measurements consistent with zero

Also consistent with SM predictions

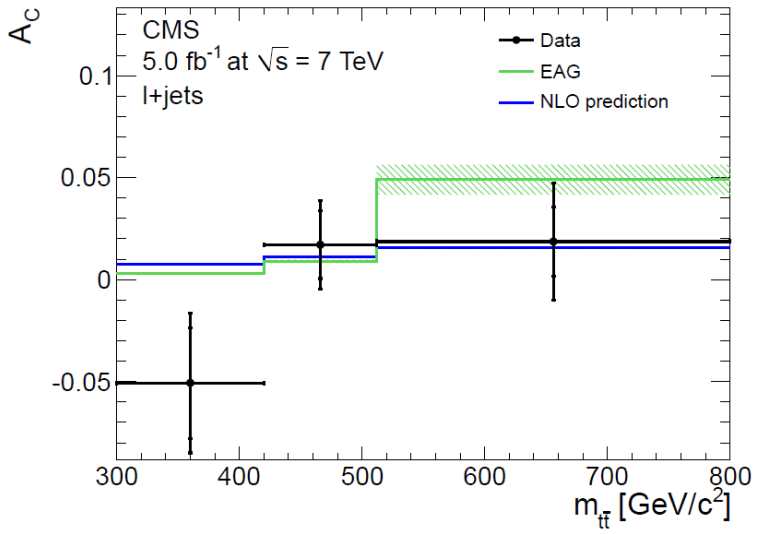
MC@NLO Ac=0.006 +/- 0.002
Kuehn, Rodrigo: Ac=0.0115 +/- 0.0006
(arXiv:1109.6830)

Constraining NP parameter space …

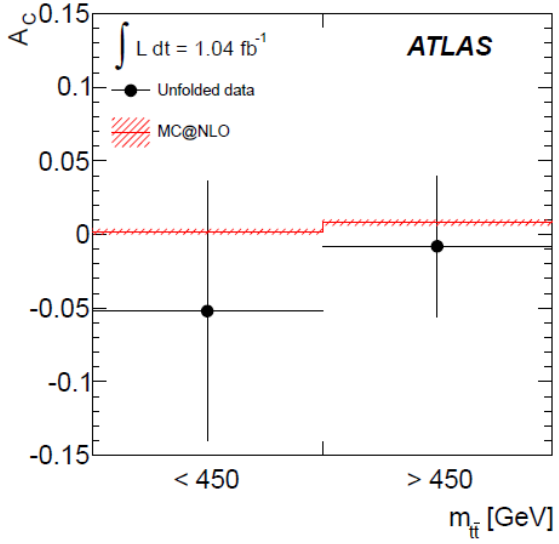


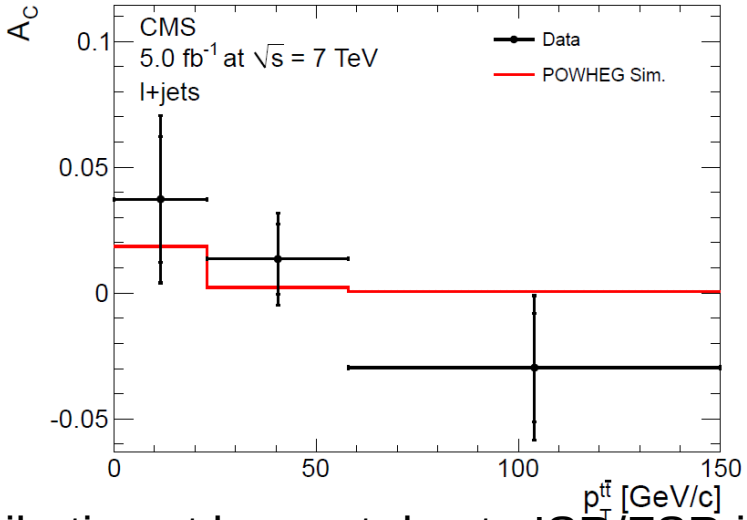
ATLAS also measured dilepton asymmetries (no need to reconstruct ttbar system)

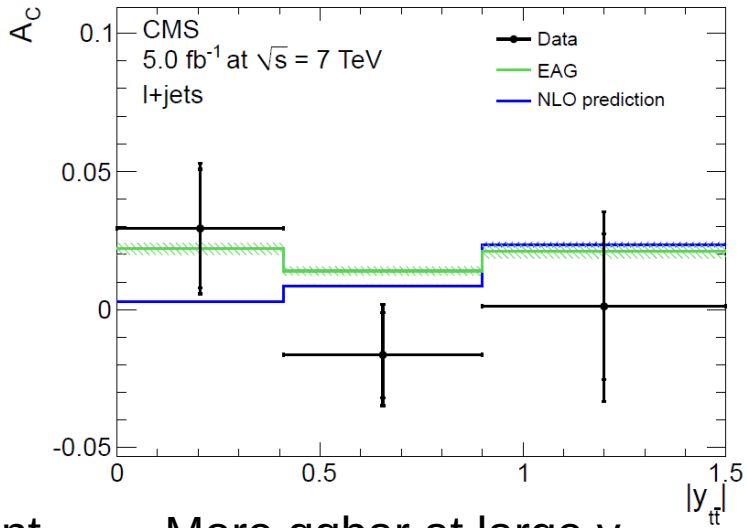
Differential Ac measurements



Large M(tt): more qqbar; new physics?





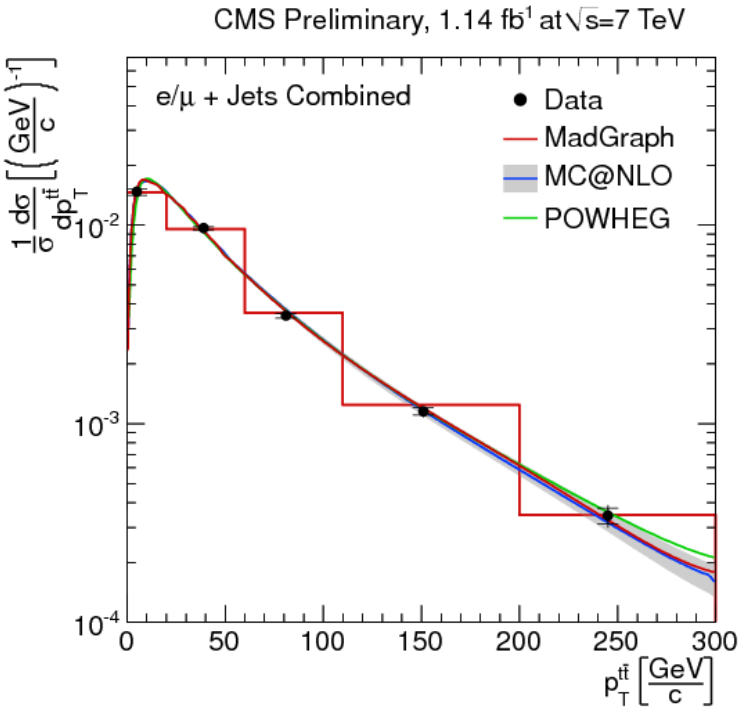


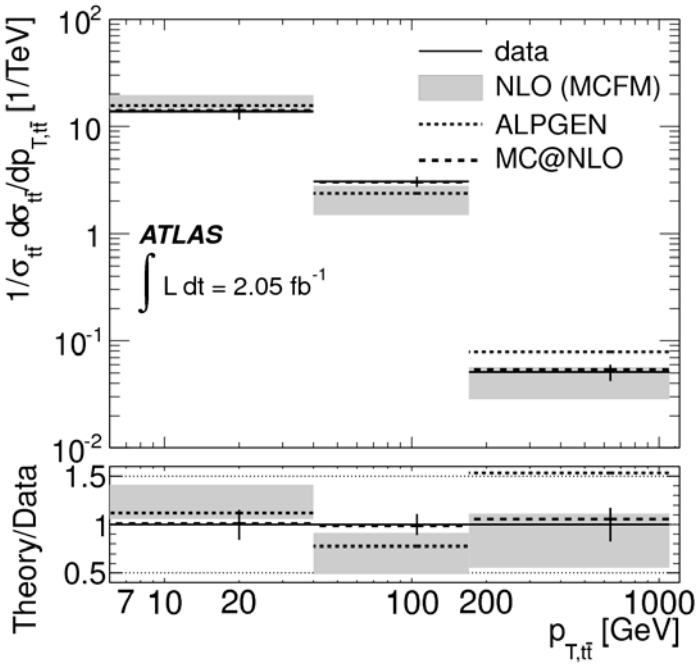
Neg. contribution at large pt due to ISR/FSR int.

More qqbar at large y

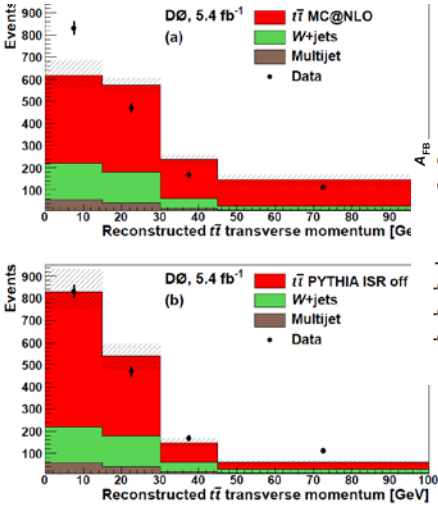
So far consistent with Standard Model …

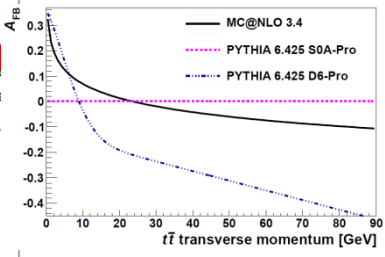
Differential cross section vs Pt(tt)





- Good agreement with expectation
- NB D0 observed softer distribution … correlated with larger A_FB?
- No indication at LHC, but different energy and production mode, and limited resolution

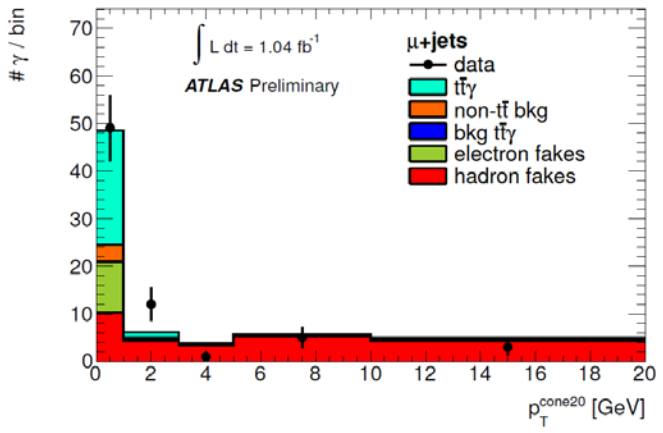




ttbar+X (X=gamma,W,Z)

Goal: Measure couplings with bosons …

tt+gamma (ATLAS-CONF-2011-153):

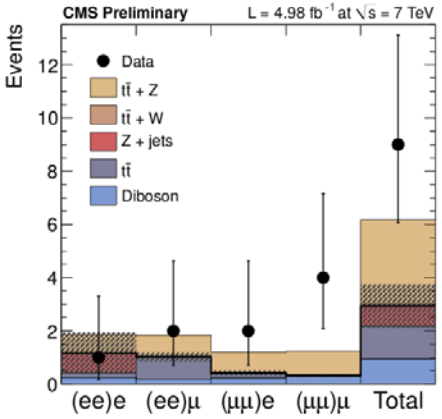


$$\sigma_{t\bar{t}\gamma} \cdot \mathrm{BR} = 2.0 \pm 0.5\,(\mathrm{stat.}) \pm 0.7\,(\mathrm{syst.}) \pm 0.08\,(\mathrm{lumi.})\,\mathrm{pb}$$

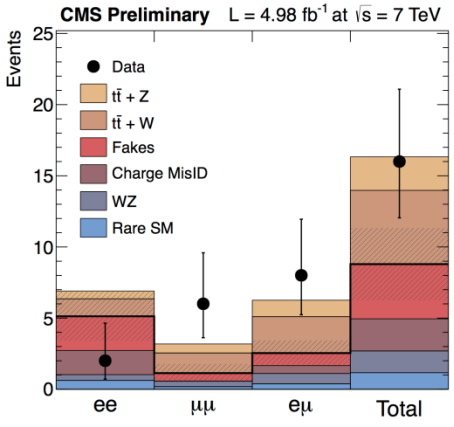
Pt(gamma)>8 GeV

Consistent with NLO QCD:
(using LO * k=2.55 from Melnikov, Schulze)

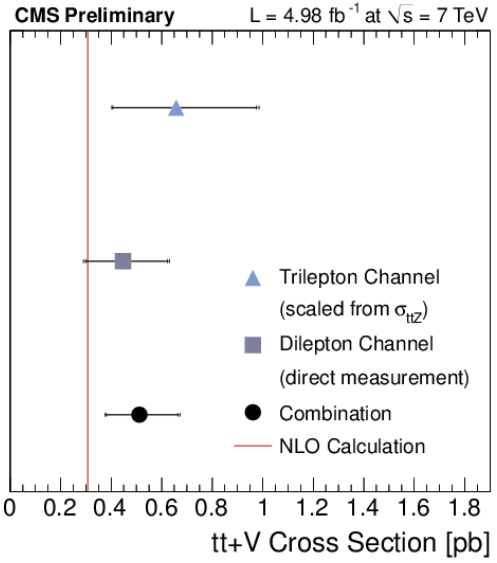
tt+W/Z (CMS PAS-TOP-12-014):



Trileptons



Dileptons



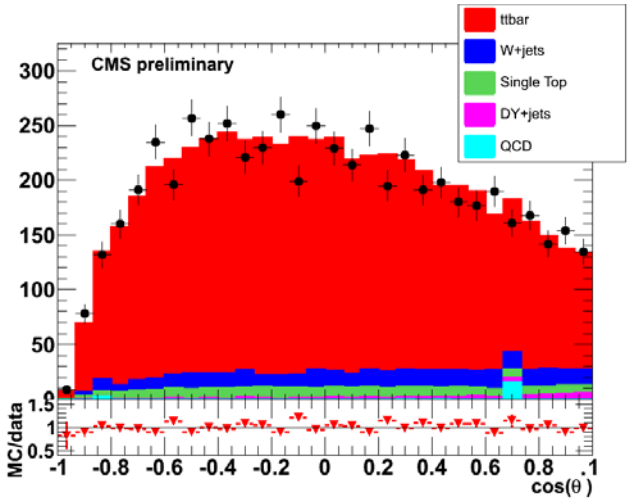
Consistent with NLO QCD

W helicity in top decays

ATLAS arXiv:1205.2484
CMS PAS TOP-11-020

Obtain helicity fractions from fit to cos(theta*) distribution
(angle between lepton and b-quark direction in W-boson rest frame)

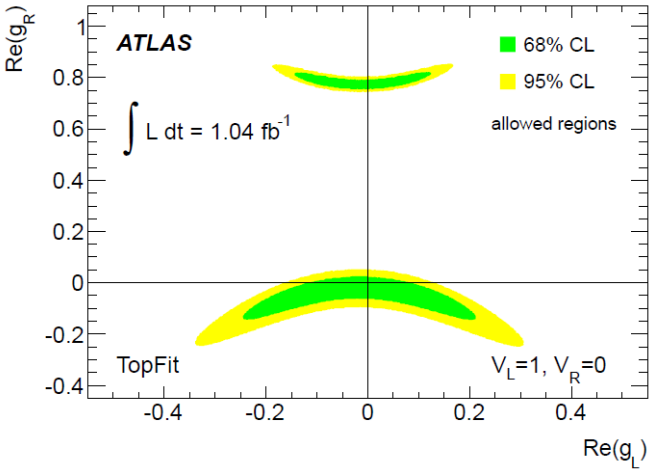
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1+\cos\theta^*)^2 F_R + \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{4}(1-\cos^2\theta^*)F_0$$



Measurement	ATLAS (l + jets + di-lepton)	CMS (l + jets, prelim.)
F_0	$0.67 \pm 0.03 \pm 0.06$	$0.57 \pm 0.07 \pm 0.05$
F_L	$0.32 \pm 0.02 \pm 0.03$	$0.39 \pm 0.05 \pm 0.03$
F_R	$0.01 \pm 0.01 \pm 0.04$	$0.04 \pm 0.04 \pm 0.04$
F_0 ($F_R = 0$)	$0.66 \pm 0.03 \pm 0.04$	$0.64 \pm 0.03 \pm 0.05$
$\mathrm{Re}\, V_R$	$\in [-0.20, 0.23]$	—
$\mathrm{Re}\, g_L$	$\in [-0.14, 0.11]$	—
$\mathrm{Re}\, g_R$	$\in [-0.08, 0.04]$	$-0.07 \pm 0.05^{+0.07}_{-0.08}$
$\frac{\mathrm{Re}(C_{uW}^{33})}{\Lambda^2}$ [TeV^{-2}]	$\in [-0.9, 2.3]$	$-0.81 \pm 0.62^{+0.85}_{-0.95}$

Extract limits on anomalous couplings at Wtb vertex

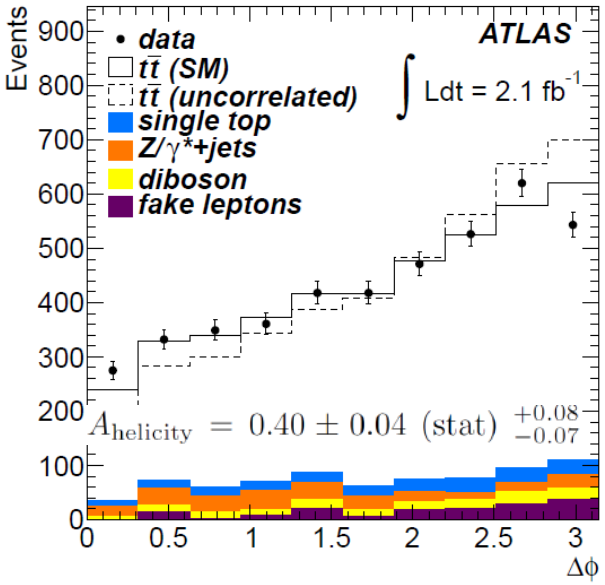
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(V_L P_L + V_R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(g_L P_L + g_R P_R)tW_\mu^- + \mathrm{h.c.}$$

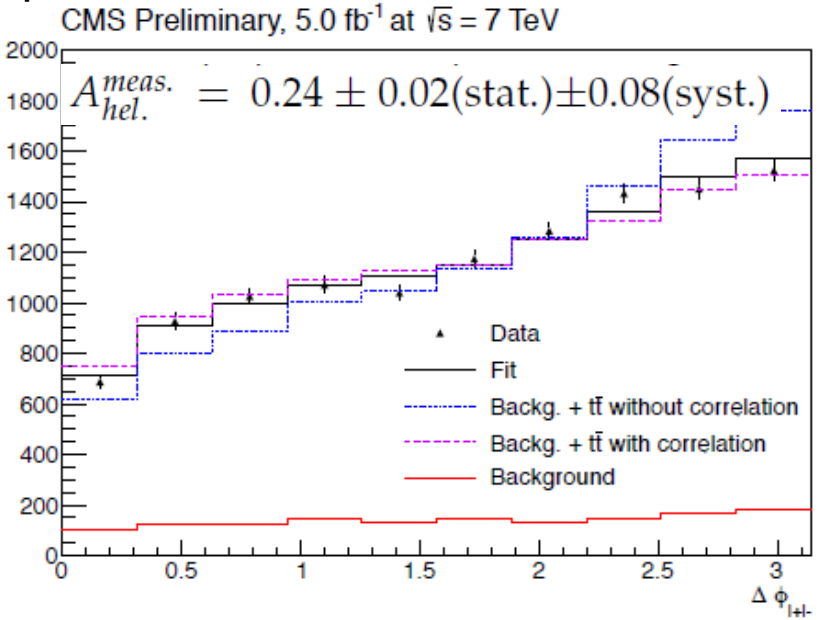


Already competitive with Tevatron
Future: combined fits with single top measurements

ttbar spin correlation

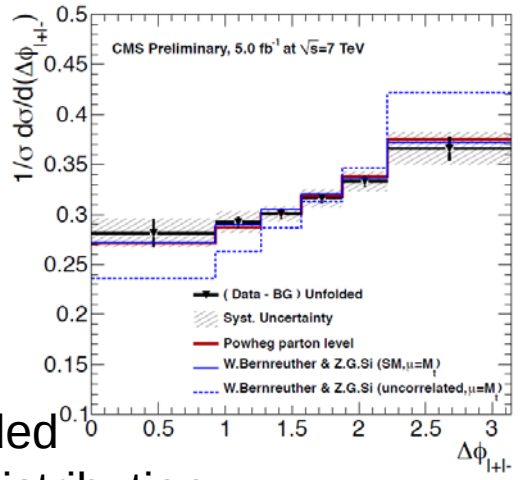
Use dilepton final state and the lepton azimuthal difference as sensitive variable





ATLAS, L=2.1/fb
arXiv:1203.4081
(first observation, 5.1sigma)

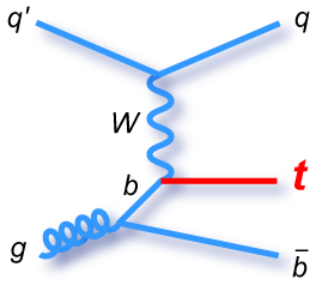
CMS, L=5/fb
TOP-12-004



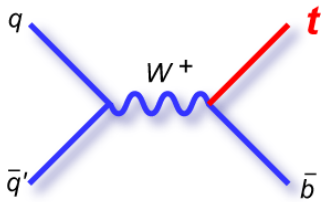
SM: A_hel = 0.31 (Bernreuther et al.)
Helicity basis: spin analyzing vector =
direction of flight of top quark in ttbar rest frame
May be altered by new physics contributions

CMS: unfolded differential distribution

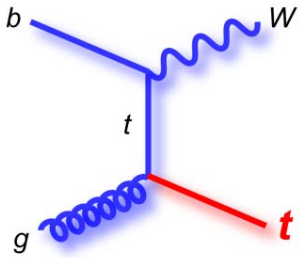
Single top production



t-channel

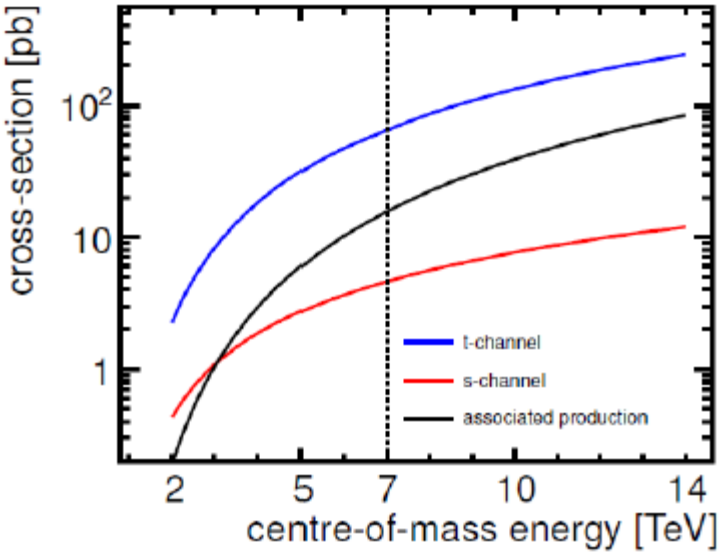


s-channel



tW-channel
(associated production)

- EWK production of top quarks: test Wtb vertex, measurement of |Vtb|
- PDF sensitivity: b-PDF (t-channel), u/d ratio from R(t/tbar)
- Searches for NP at Wtb vertex, 4th gen, H+, W', FCNC



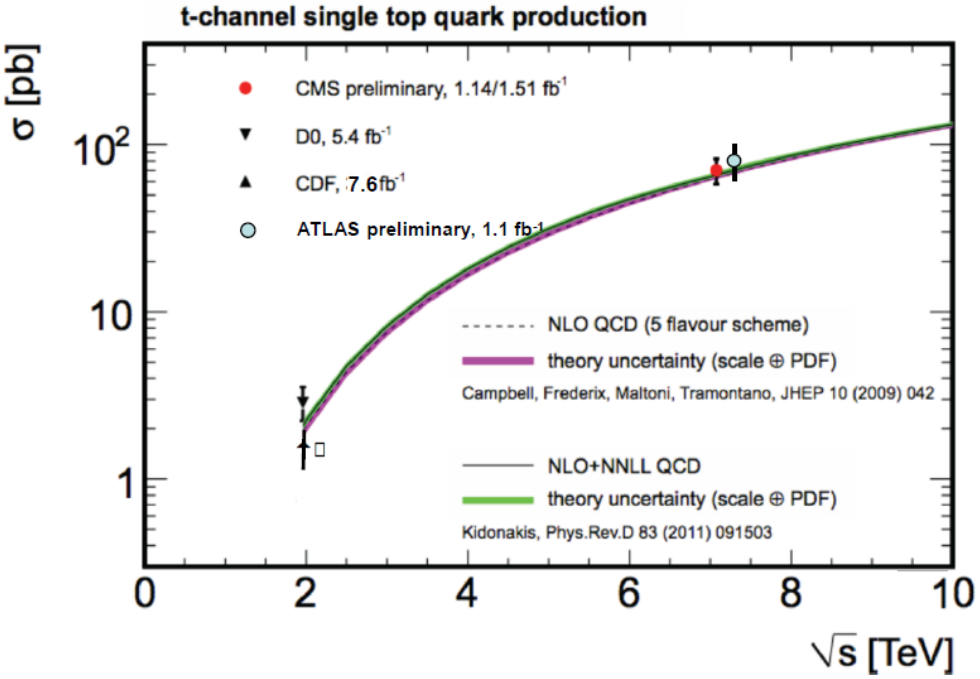
t-channel	$64.6^{+2.7}_{-2.0}$ pb
Wt	15.7 ± 1.1 pb
s-channel	4.6 ± 0.2 pb

Kidonakis, NLO+NNLL:
t-channel: PRD 83 (2011) 091503
s-channel: PRD 81 (2010) 054028
tW-channel: PRD 82 (2010) 054018

Single top t-channel

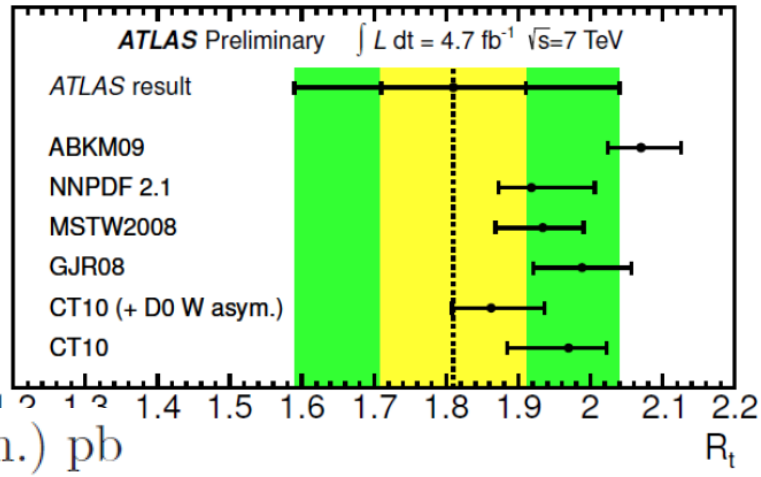
Measurements cut-based or MVA

CMS 2010: arXiv:1106.3052
CMS 2011: PAS-TOP-11-021
ATLAS 2011: arXiv:1205.3130
ATLAS-CONF-2012-056 (R(t/tbar))



Top/antitop ratio (ATLAS):

$$\sigma_t(t) = 53.2 \pm 10.8\,\text{pb}$$
$$\sigma_t(\bar{t}) = 29.5^{+7.4}_{-7.5}\,\text{pb}$$
$$R_t = 1.81^{+0.23}_{-0.22}.$$



ATLAS 2011, 1.04/fb

$$\sigma_{t\text{-ch}} = 83 \pm 4\ (\text{stat.})^{+20}_{-19}\ (\text{syst.})\ \text{pb}$$

CMS 2011, <1.5/fb

$$\sigma_{t\text{-ch}} = 70.2 \pm 5.2\ (\text{stat.}) \pm 10.4\ (\text{syst.}) \pm 3.4\ (\text{lum.})\ \text{pb}$$

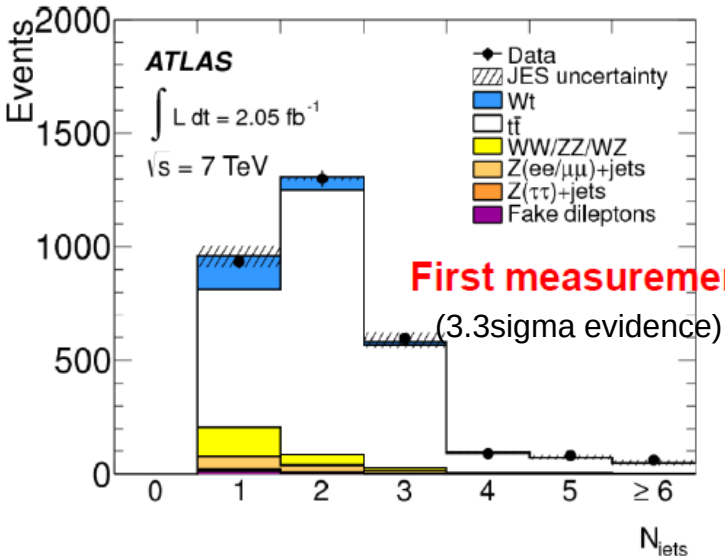
Future: 8 TeV, measure differential cross sections

tW-channel

ATLAS 2011, L=2.05/fb
arXiv:1205.5764

Problem of signal definition:

- At NLO, interference with top pair production
- Two approaches studied (POWHEG, MC@NLO)
  - Diagram removal (DR): remove doubly resonant contributions
  - Diagram subtraction (DS): subtract gauge invariant term which locally cancels tt contribution
- Treat difference as systematic (few %)

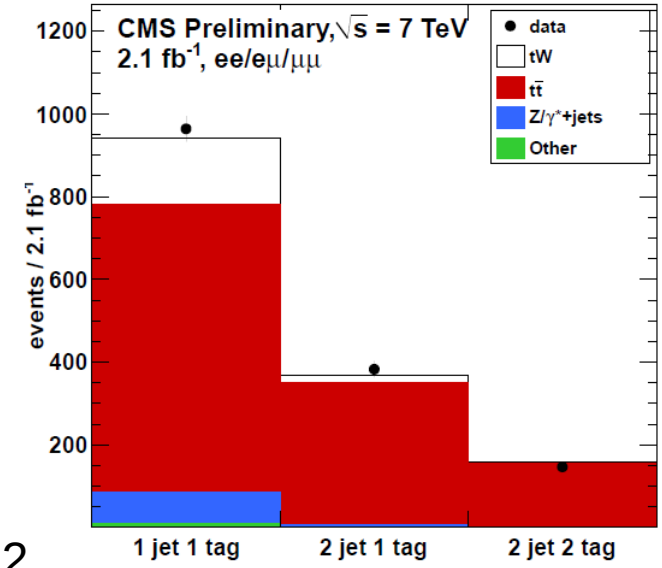


First measurement !

(3.3sigma evidence)

ATLAS: $\sigma = 16.8 \pm 2.9\ (\text{stat.}) \pm 4.9\ (\text{syst.})$ pb

CMS: $\sigma = 22\ ^{+9}_{-7}\ (\text{stat.} + \text{syst.})$ pb



CMS 2011, L=2.1/fb
CMS-PAS-TOP-11-022

Instead of conclusions: Shopping list

- More precise inclusive and more differential cross sections
  - Validate MC models (and variations), compare with (N)NLO
    - NB Understanding ISR in gg->ttbar important also for gg->H
  - Constraints on mtop and/or alpha(s)
  - PDF constraints: g from ttbar, b and u/d from single top (differential measurements!)
- More differential Ac, leptonic asymmetries
- Mass measurements
  - Methods with orthogonal systematics / differential mtop (-> CR)
  - Consistency of global EWK fit incl H(125 GeV)
- tt+gamma/W/Z: couplings to bosons
- tt+jet(s), tt+bb (for ttH), eventually tt+tt (e.g. SUSY)
- Searches (not discussed here)
  - FCNC; W'; ttbar resonances; new physics in spin correl., Ac …