Top results at LHC

Luca Lista

INFN

up

charm

top

down

strange

bottom

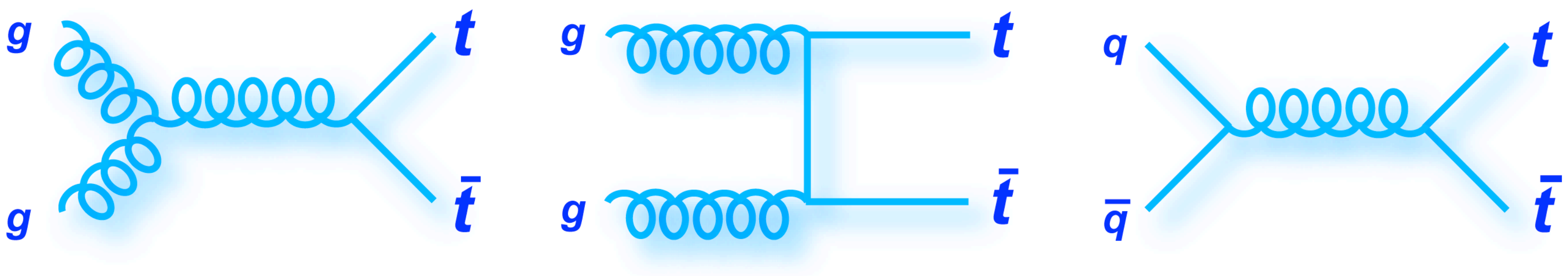
[*] not on scale

Outline

- Top quark production at LHC:
  - $t\bar{t}$ cross section measurements
  - α_s from $t\bar{t}$ cross section
  - Single-top production
- Top quark mass measurements
  - Mass from lepton+jets, dileptons, all hadronic
  - Mass difference
- Top quark properties
  - W polarization
  - Spin correlation
  - FB/charge asymmetry
- New physics with top quark

Top pair production at LHC

- Hadronic production mechanisms



$\sqrt{s}$	σ_{tt} (pb)
7 TeV	$154^{+9}_{-8}(\text{scale}) \pm 4(\text{pdf})$
8 TeV	$220^{+13}_{-11}(\text{scale})^{+5}_{-6}(\text{pdf})$

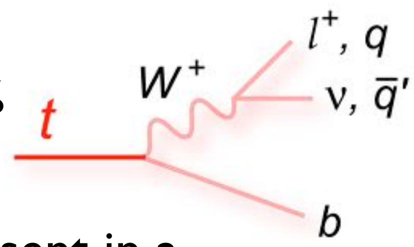
Top++ 1.4[*], m_t = 173.3 GeV, MSTW2008NNLO PDF

Approx. NNLO predictions
Czakon, Mitov: arXiv:1112.5675 (2011)
Cacciari et al.: PLB710,612 (2012)
Baernreuther et al.: PRL109,132001 (2012)
Czakon, Mitov: arXiv:1207.0236 (2012)
[*]Czakon, Mitov: arXiv:1210.6832 (2012)

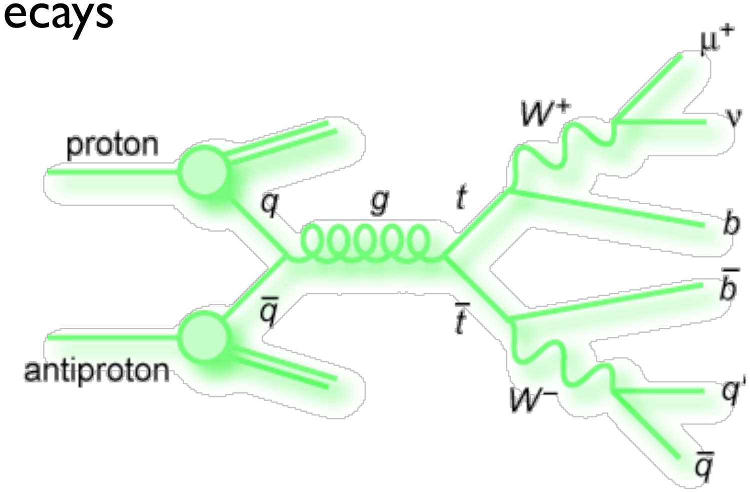
Dominated by gluon fusion at LHC: ~85%
~85% quark-antiquark annihilation at Tevatron

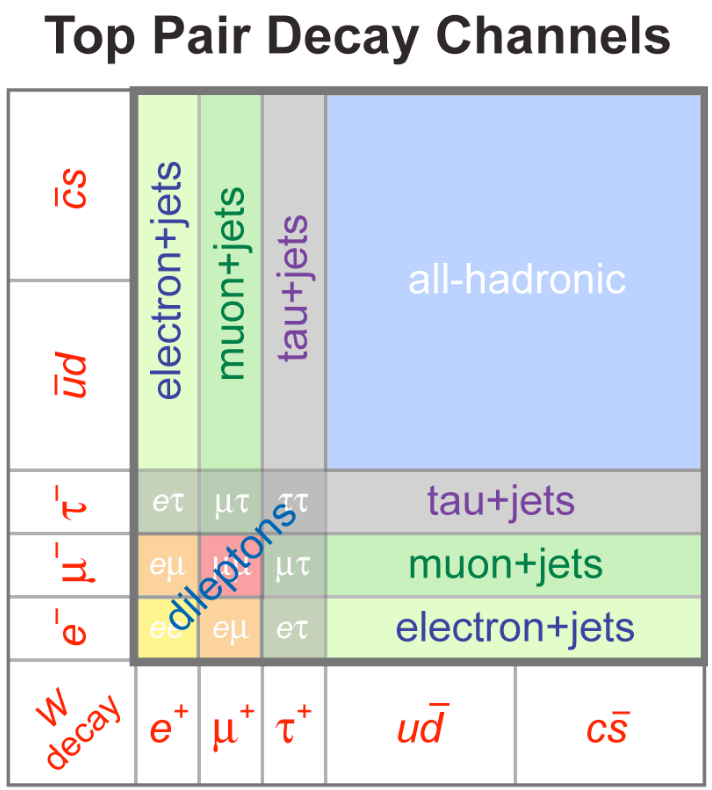
Final states in top pair events

- W decays from t→Wb dictate top event signature
- Possible final states of tt^bar events:
  - Dileptons (e, μ): ~5%
  - Leptons + jets (e, μ): ~30%
  - All hadronic: ~45%
- At least two b-jets are present in a tt^bar event
- Neutrinos from leptonic W decays generate missing E_T (MET)
- Non-b jets are present in W hadronic decays



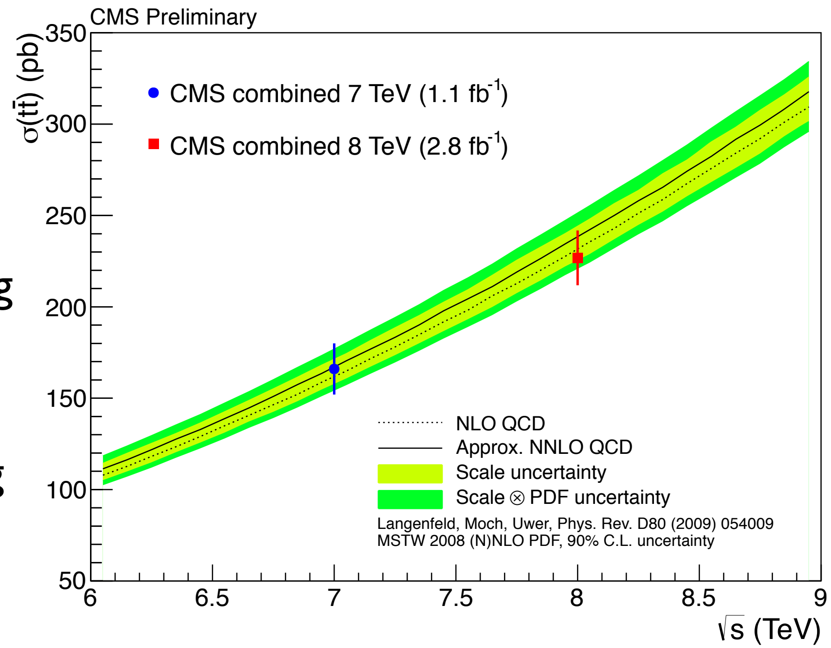
W^+ DECAY MODES	Fraction (Γ_i/Γ)
$\ell^+\nu$	(10.80 ± 0.09) %
$e^+\nu$	(10.75 ± 0.13) %
$\mu^+\nu$	(10.57 ± 0.15) %
$\tau^+\nu$	(11.25 ± 0.20) %
hadrons	(67.60 ± 0.27) %





$t\bar{t}$ cross section

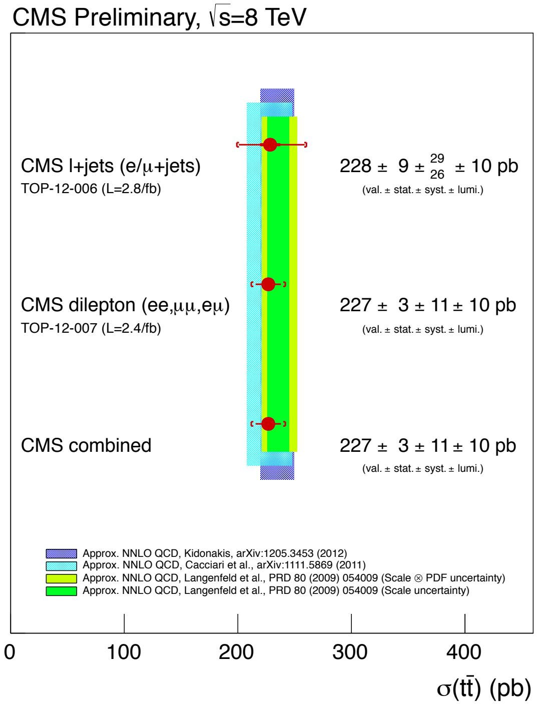
- Precision limited by systematics in lepton+jets and dilepton channels
- Some early measurements with initial data taking have unsurpassed precision thanks to favorable running conditions (lower pile-up)
- All hadronic and $W\rightarrow\tau\nu$, also explored, achieving lower precision.



$\sqrt{s}$	σ_{tt} (pb) [lepton + jets]	
7 TeV	$179.0 \pm 3.9(\text{stat.}) \pm 9.0(\text{syst.}) \pm 6.6(\text{lumi})$	(7%: ATLAS-CONF-2011-121)
7 TeV	$164.4 \pm 2.8(\text{stat.}) \pm 11.9(\text{syst.}) \pm 7.4(\text{lumi})$	(8%, CMS TOP PAS-11-003)
8 TeV	$241 \pm 2(\text{stat.}) \pm 31(\text{syst.}) \pm 9(\text{lumi})$	(13%, ATLAS-CONF-2012-149)
8 TeV	$228.4 \pm 9.0(\text{stat.})^{+29.0}_{-26.0}(\text{syst.}) \pm 10.0(\text{lumi})$	(13%, CMS PAS TOP-12-006)

$\sqrt{s}$	σ_{tt} (pb) [dileptons]	
7 TeV	$176 \pm 5(\text{stat.})^{+14}_{-11}(\text{syst.}) \pm 8(\text{lumi})$	(10%: ATLAS, JHEP05(2012)059)
7 TeV	$161 \pm 2.5(\text{stat.})^{+5.1}_{-5.0}(\text{syst.}) \pm 3.6(\text{lumi})$	(4%: CMS, arXiv:1208.2671 → JHEP)
8 TeV	$227 \pm 3(\text{stat.}) \pm 11(\text{syst.}) \pm 10(\text{lumi})$	(7%: CMS PAS TOP-12-007)

ATLAS, CMS combinations



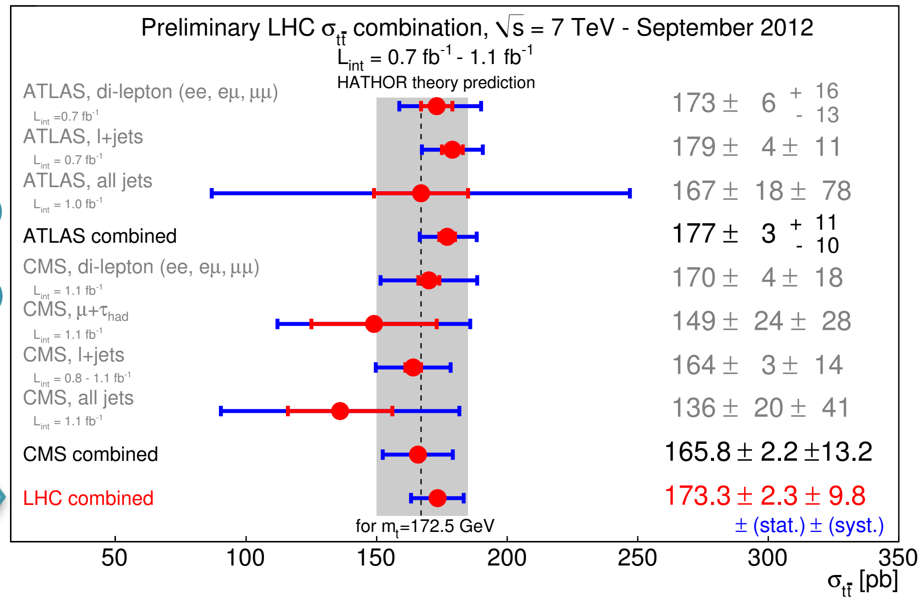
- Combination within the TOPLHC working group
- Combined $t\bar{t}$ cross section at 7 TeV: uncertainty becomes 5.8% (around 10 pb) ➞ about 7% gain compared to the most precise measurement
- Total ATLAS-CMS correlations: 30%

CMS PAS TOP-12-007

$$\frac{\sigma_{t\bar{t}}(8\text{TeV})}{\sigma_{t\bar{t}}(7\text{TeV})} = 1.41 \pm 0.10$$

ATLAS-CONF-2012-134
CMS PAS TOP-12-003

$\sqrt{s}$	σ_{tt} (pb)	
7 TeV	$173.3 \pm 2.3(\text{stat.}) \pm 9.8(\text{syst.})$	(5.8%, LHC)
8 TeV	$227 \pm 3(\text{stat.}) \pm 11(\text{syst.}) \pm 10(\text{lumi})$	(6.7%, CMS)



Improvements expected with new measurements: more statistics, better luminosity uncertainty, studies of robustness under MC mismodeling, fiducial cross-sections

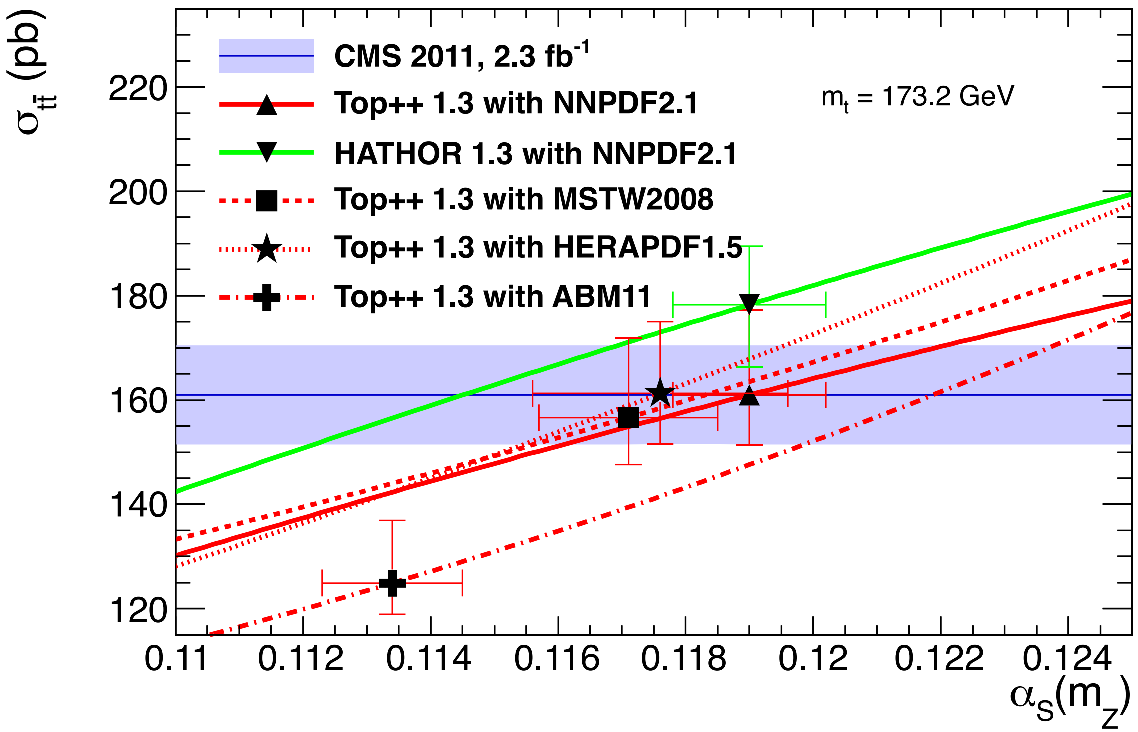
Alpha-strong from cross section

- σ_{tt} prediction depends on m_t and α_s , but m_t and α_s can't be measured simultaneously from σ_{tt} unless using differential studies
- m_t precision very limited when measured from σ_{tt}
- Constraining m_t allows to measure α_s from theoretical predictions (Top++, Hator)

$$\mathcal{L}(\alpha_s) = \int f_{\text{exp}}(\sigma_{t\bar{t}}|\alpha_s) f_{\text{th}}(\sigma_{t\bar{t}}|\alpha_s) d\sigma_{t\bar{t}}$$

Experimental: Gaussian term

Theory: Convolution of a Gaussian (PDF) and a rectangular function (ren./fact. scales)



CMS PAS TOP-12-022

$$\alpha_s(m_Z) = 0.1178^{+0.0046}_{-0.0040}$$

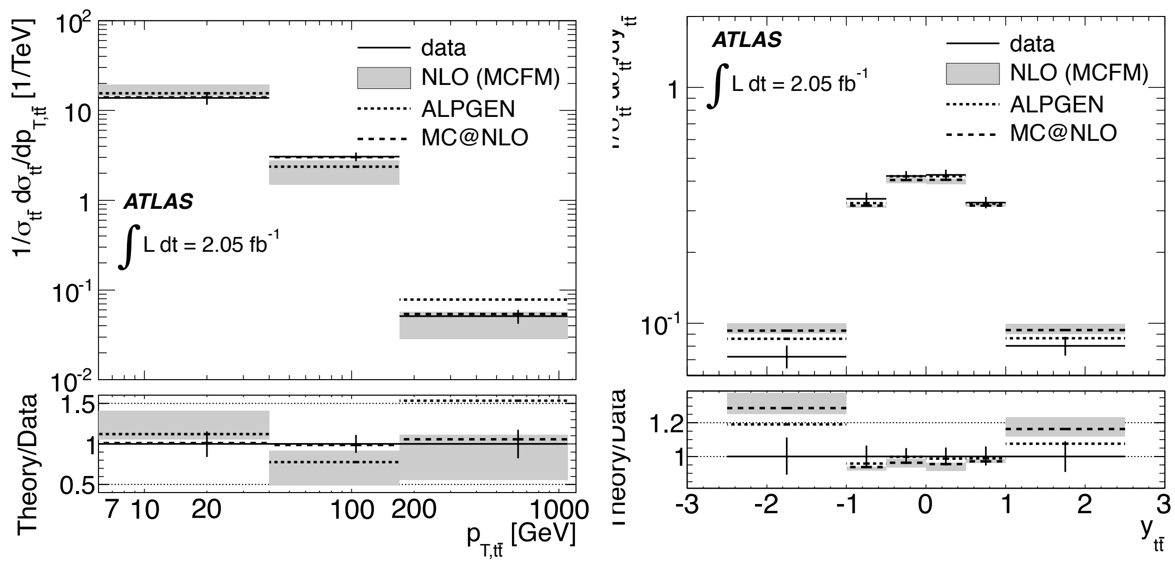
Approx. NNLO σ_{tt} from Top++ with NNPDF2.1 and m_t = 173.2 ± 1.4 GeV

Differential cross section

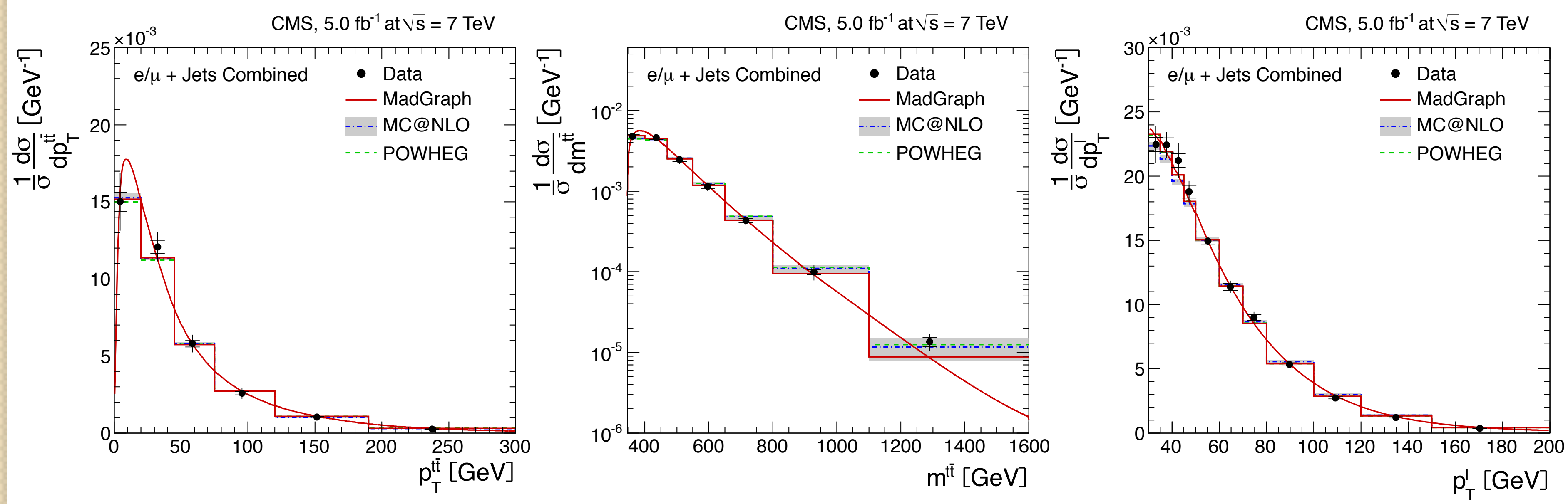
$$\frac{1}{\sigma_{t\bar{t}}}\frac{d\sigma_{t\bar{t}}}{dx}$$

ATLAS: arXiv:1207.5644 → accepted by EPJC

- Test of perturbative QCD predictions
- Explored variables: p_T, y, m of top pair, p_T, y of individual tops, p_T, y, m of lepton pairs
- Good description of data found for AlpGen, Madgraph, MC@NLO, Powheg
- Possible small bias on tt^{bar} y (ATLAS), p_T of reco top (CMS)

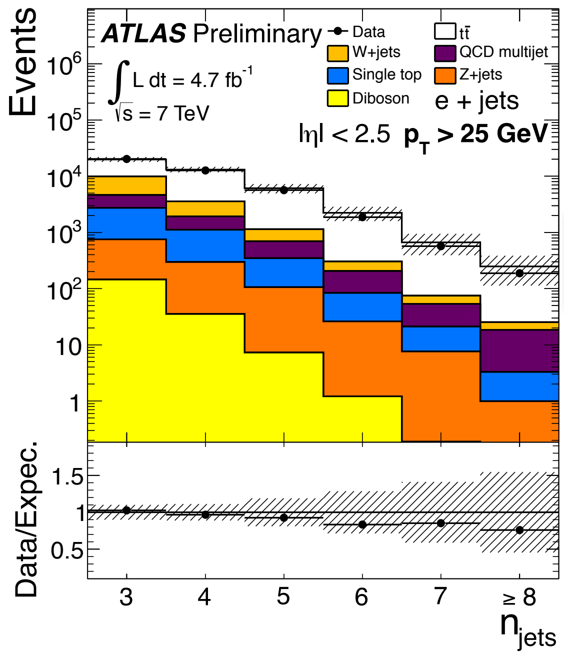


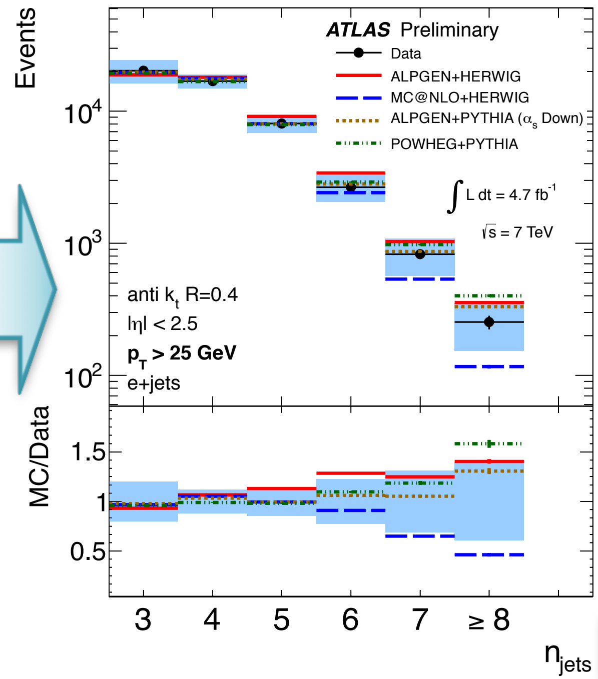
CMS: arXiv:1212.2201 → EPJC



$t\bar{t}$ + jets

CMS PAS TOP-12-023 (dileptons)
CMS PAS TOP-12-018 (l+jets)
ATLAS-CONF-2012-155

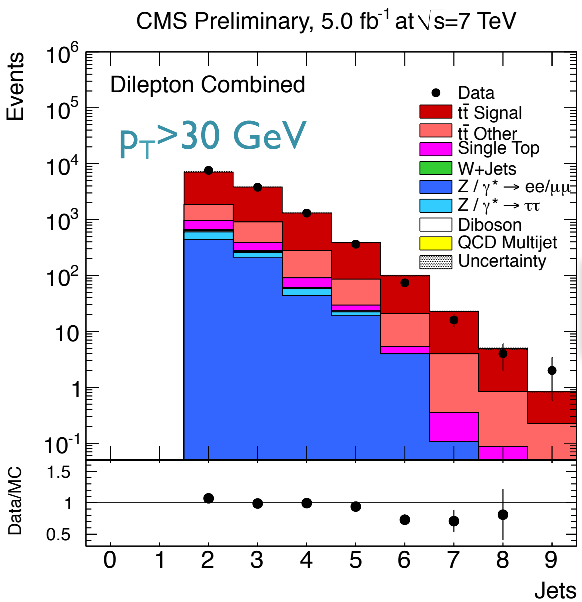


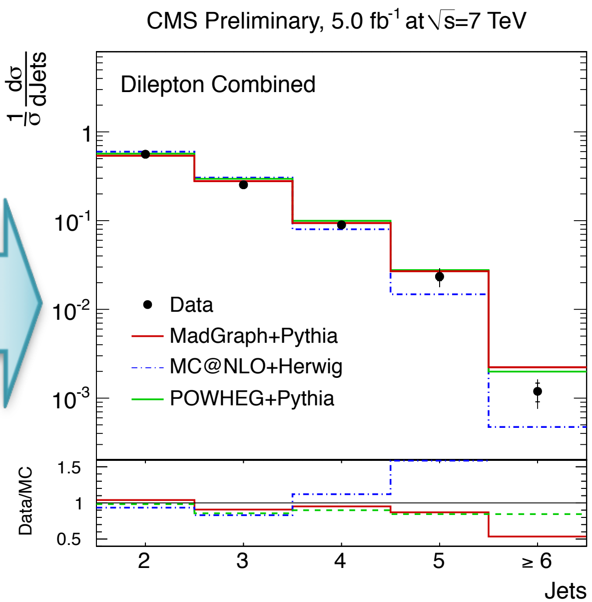


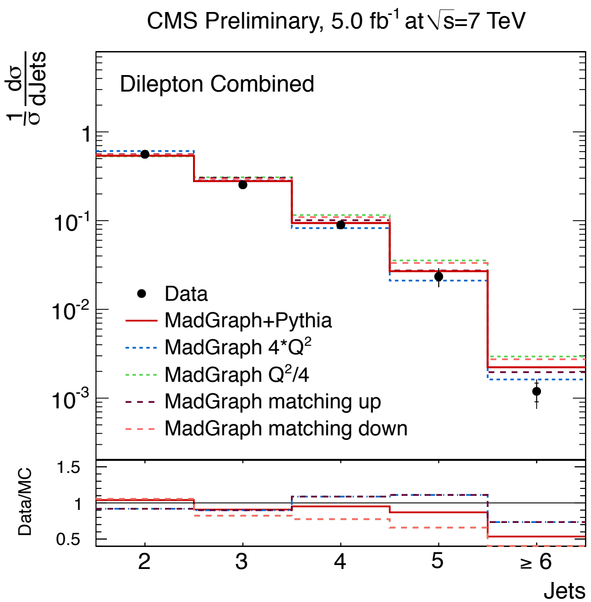
- Dileptons (CMS) and l+jets (ATLAS, CMS) probed in association with extra jets
- Reasonable agreement found with MadGraph, PowHeg, AlpGen, while MC@NLO+Herwig showering predicts lower jet multiplicity than observed
- ATLAS also measured the inclusive $t\bar{t}$+jets cross section (p_T>25 GeV, $|\eta|$<2.5), largely dependent on MC generator

ATLAS-CONF-2012-083

$$\sigma_{t\bar{t}j}/\sigma^{\rm incl}_{t\bar{t}} = 0.54 \pm 0.01({\rm stat.})^{+0.05}_{-0.08}({\rm syst.})$$

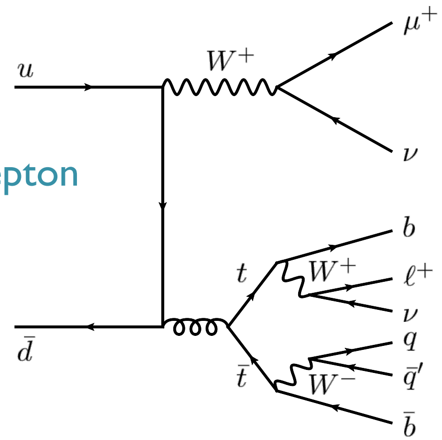






Associated tt^{bar} +W, Z,γ production

- Large data samples allow to measure associated production of top pairs with vector bosons
- CMS: Inclusive search for same-sign dilepton from ttV, V=W, Z, exclusive trilepton search from ttZ. ttW determined from ttV subtracting MC for ttZ
- ATLAS: ttγ l+jets analysis based on template fit of photon isolation
- Results somewhat larger than prediction, but still compatible within uncertainties with NLO calculation (no th. uncert. available for ttZ)



CMS PAS TOP-12-014

$$\sigma(t\bar{t}V) = 0.51^{+0.15}_{-0.13}(\text{stat.})^{+0.05}_{-0.04}(\text{syst.})\text{pb} \quad (4.7\,\sigma)$$

$$\sigma(t\bar{t}Z) = 0.30^{+0.14}_{-0.11}(\text{stat.})^{+0.04}_{-0.02}(\text{syst.})\text{pb} \quad (3.7\,\sigma)$$

$$\sigma(t\bar{t}W) = 0.28^{+0.14}_{-0.12}(\text{stat.}) \pm 0.04(\text{syst.})\text{pb} \quad (2.5\,\sigma)$$

NLO predictions:

$$\sigma(t\bar{t}Z) = 0.139 \pm ??? \text{ pb}$$

$$\sigma(t\bar{t}W) = 0.17^{+0.03}_{-0.05} \text{ pb}$$

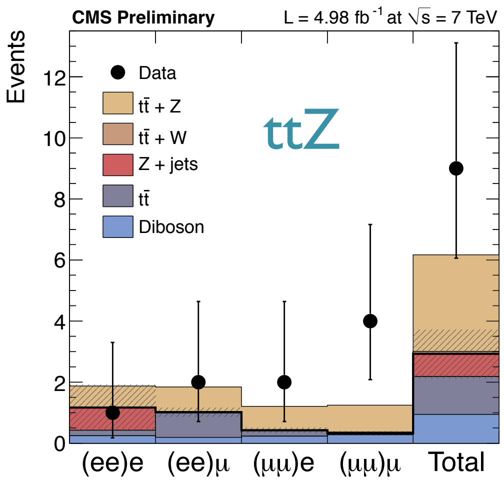
$$\sigma(t\bar{t}\gamma) = 2.1 \pm 0.4 \text{ pb}$$

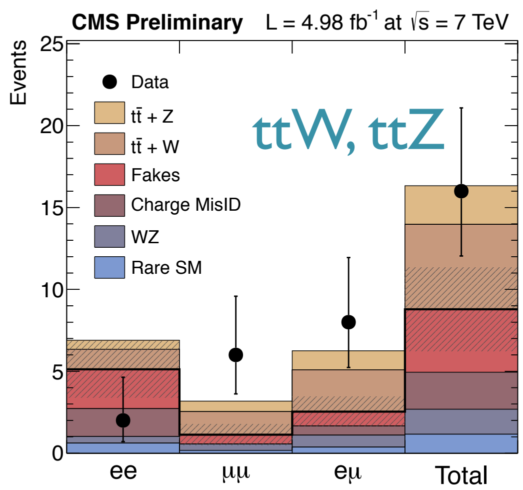
$p_T(\gamma)$>8 GeV

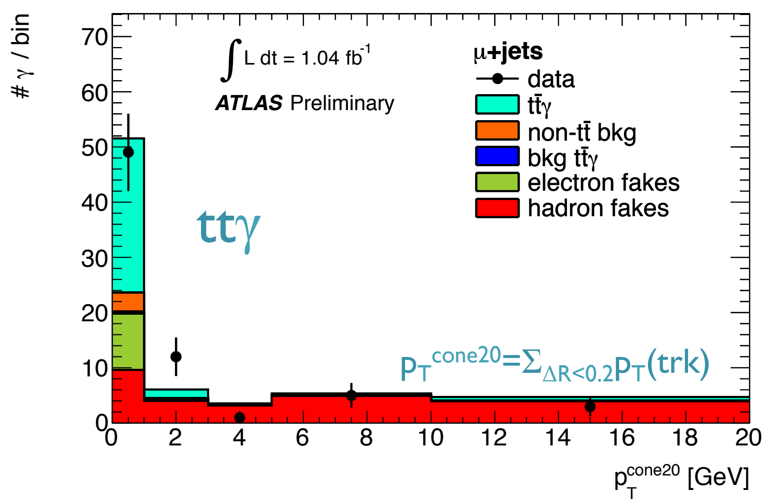
Campbell, Ellis: arXiv:1204.5678
Kardos et al.: PRD85(2012)074022
W. Kilian et al.: EPJC71(2011)1742

$$\sigma(t\bar{t}\gamma) = 2.0 \pm 0.5(\text{stat.}) \pm 0.7(\text{syst.}) \pm 0.08(\text{lumi.}) \text{ pb}$$

ATLAS-CONF-2010-153







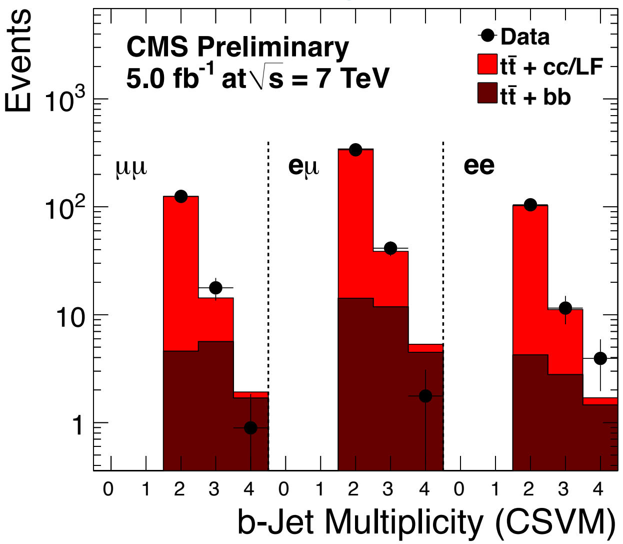
Associated $t\bar{t}$ +$b\bar{b}$ production

- Same final state as ttH Higgs production of which it's an irreducible non-resonant background
- Theoretical predictions suffer from large uncertainties, mainly due to renormalization/factorization scale
- Event selection: two leptons (Z veto applied), ≥4 jets, all with p_T>30 GeV, ME_T>30 GeV applied only in ee, μμ to reduce DY+jets
- Many uncertainties cancel in the ratio ttbb/ttjj, largest uncertainty: mistag efficiency

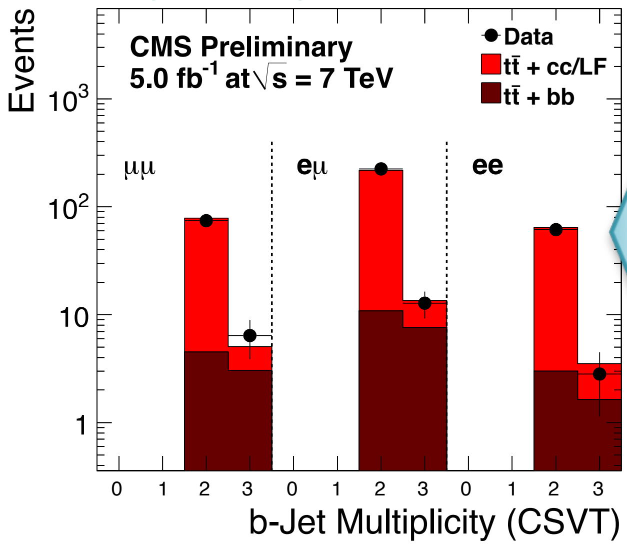
$$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)} = 3.6 \pm 1.1(\mathrm{stat.}) \pm 0.9(\mathrm{syst.})\%$$

p_T>20 GeV, at gen. level

medium b-tag



tight b-tag



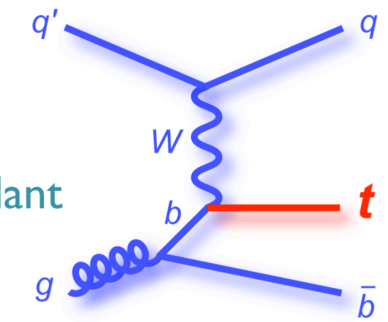
CMS PAS TOP-12-024

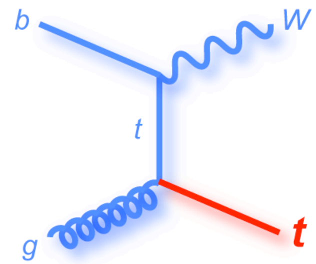
Background and signal yield fit from b-jet multiplicity distributions

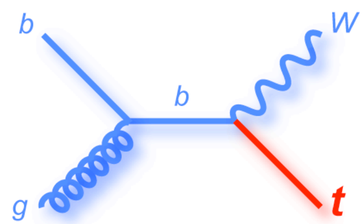
Single top production

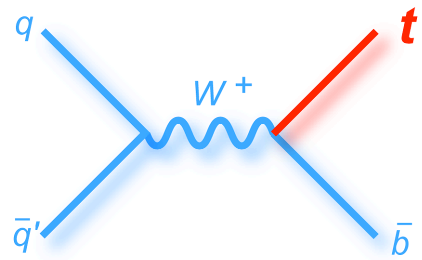
- Electroweak top production, first observed at Tevatron
- Sensitive to new physics: anomalous couplings, W', H^+, 4^{th} generation
- Direct measurement of $|V_{tb}|^2$

t channel most abundant









$\sqrt{s}$	*t* channel	tW channel	*s* channel
7 TeV	64.6 ± 2.4 pb	15.7 ± 1.1 pb	4.6 ± 0.2 pb
8 TeV	87.8 ± 3.4 pb	22.4 ± 1.5 pb	5.6 ± 0.2 pb

Uncertainties: factorization/renormalization scale, PDF

N. Kidonakis: PRD83(2011)091503, PRD81(2010)054028 (2010), PRD82(2010)054018, arXiv:1205.3453

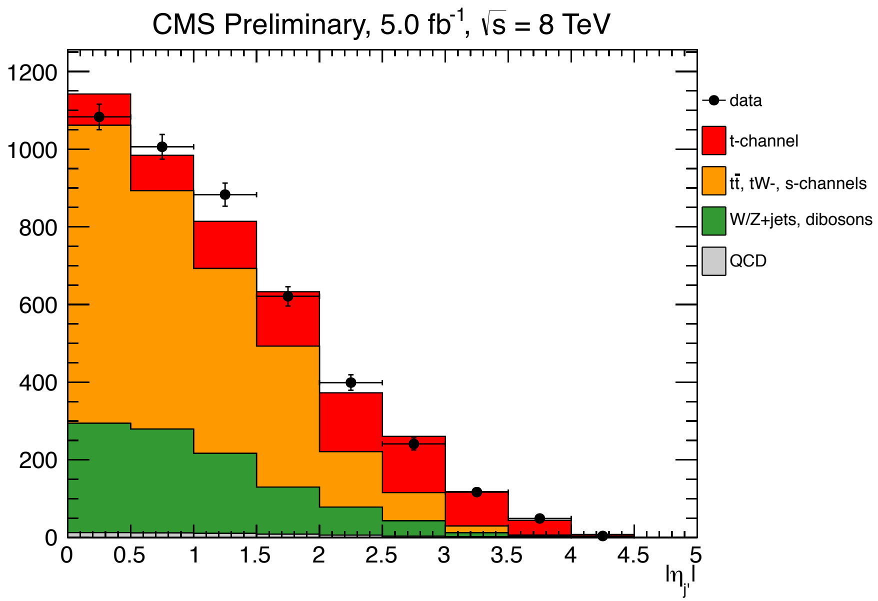
t channel

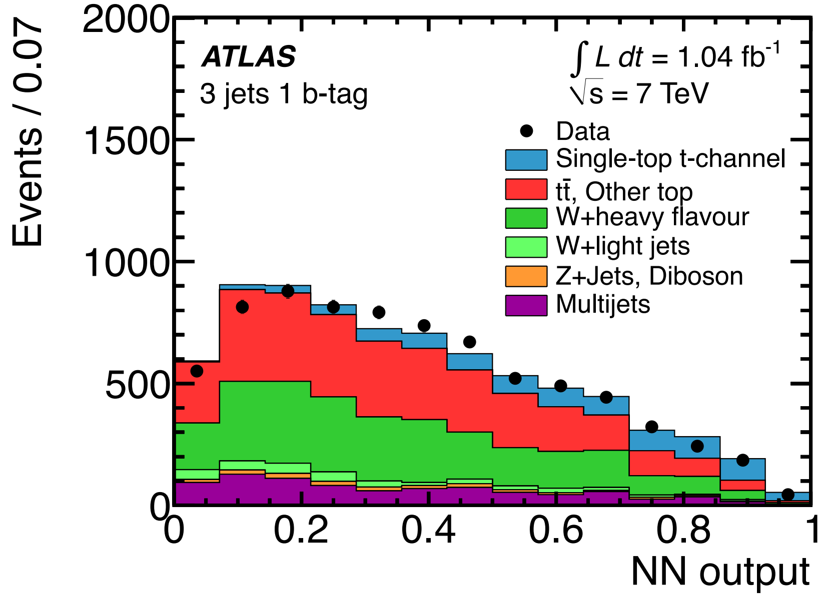
- CMS: single-lepton or lepton + b-jet trigger
- Two analyses combined: fit to $|\eta_{j'}|$ distribution with data-driven background estimate and multivariate (NN, BDT) analyses with in-situ constraint of main systematics
- 8 TeV: $|\eta_{j'}|$ analysis only so far

7 TeV: arXiv:1209.4533, accepted by JHEP
8 TeV: CMS PAS TOP-12-011

- ATLAS: single-lepton trigger
- Multivariate analysis with maximum-likelihood fit of NN output
- Cut-based analysis as crosscheck
- Normalization from data of main backgrounds

7 TeV: PLB717(2012)330
8 TeV: ATLAS-CONF-2012-132





t-channel results

- CMS: Largest syst.: th. uncert. (5%: single top, tt gen.), b-tagging, W+jets modeling, trigger (~2%)
- ATLAS: Largest syst.: ISR/FSR (14%), b-tagging modeling (13%), jet energy scale (6%)

CMS

$\sqrt{s}$	$\sigma_{t\text{-ch.}}$ (pb)	
7 TeV	$67.2 \pm 3.7(\text{stat.}) \pm 4.8(\text{syst.})$	(9%)
8 TeV	$80.1 \pm 5.7(\text{stat.}) \pm 11.0(\text{syst.}) \pm 4.0(\text{lumi})$	(16%)

ATLAS

$\sqrt{s}$	$\sigma_{t\text{-ch.}}$ (pb)	
7 TeV	$83 \pm 4(\text{stat.}) \pm 20(\text{syst.})$	(25%)
8 TeV	$95 \pm 2(\text{stat.}) \pm 18(\text{syst.})$	(19%)

- $|V_{tb}|$ from cross section

$$|V_{\mathrm{tb}} f_{L_V}| = \sqrt{\frac{\sigma_{t\text{-ch.}}}{\sigma^{\mathrm{th}}_{t\text{-ch.}}}}$$

f_{L_V} = 1 in the SM; $\sigma^{\mathrm{th}}_{t\text{-ch.}}$: $|V_{tb}|=1$

$$|V_{\mathrm{tb}}| = 1.020 \pm 0.046(\mathrm{exp.}) \pm 0.017(\mathrm{th.}) \quad \text{7 TeV}$$

95%CL, constr. → $1 \geq |V_{\mathrm{tb}}| > 0.92$

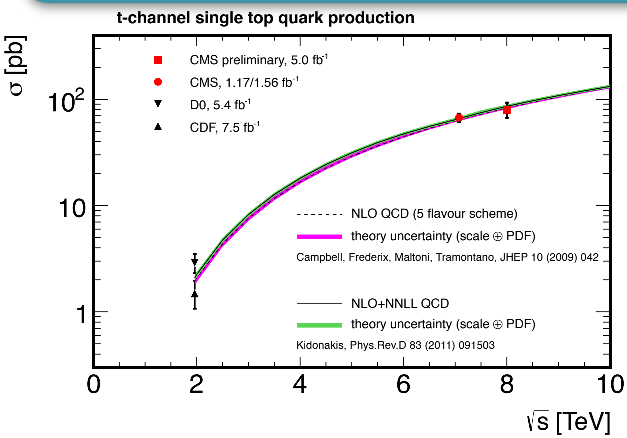
$$|V_{\mathrm{tb}}| = 0.96 \pm 0.08(\mathrm{exp.}) \pm 0.02(\mathrm{th.}) \quad \text{8 TeV}$$

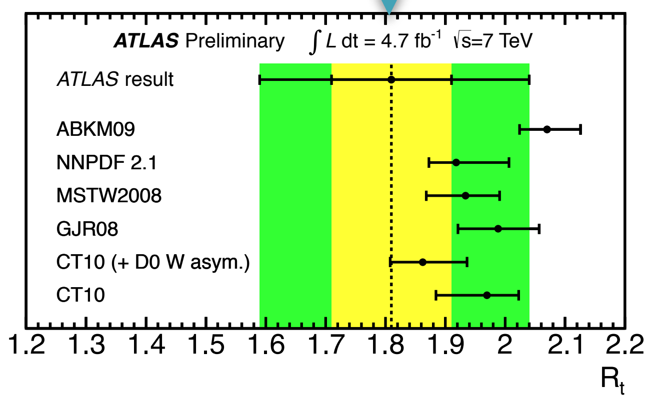
$$1 \geq |V_{\mathrm{tb}}| > 0.80$$

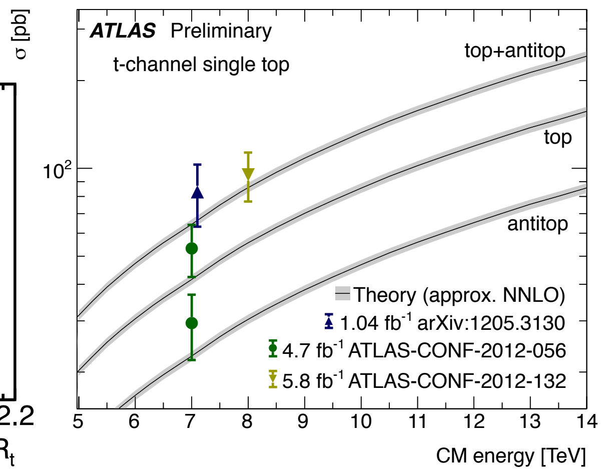
$$\frac{\sigma_t}{\sigma_{\bar{t}}} = 1.81 \pm 0.10(\mathrm{stat.}) \pm 0.20(\mathrm{syst.})$$

$$|V_{\mathrm{tb}}| = 1.13 \pm 0.14 \quad 1 \geq |V_{\mathrm{tb}}| > 0.75 \quad \text{7 TeV}$$

$$|V_{\mathrm{tb}}| = 1.04 \pm 0.11 \quad 1 \geq |V_{\mathrm{tb}}| > 0.80 \quad \text{8 TeV}$$







tW and s channel

arXiv:1209.3489 → PRL

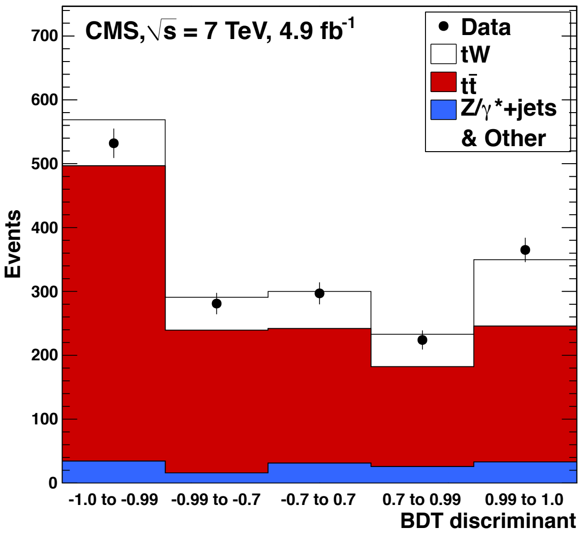
- CMS: 5fb^{-1}, BDT analysis (cut based as cross check) using leptonic t and W decays
- Largest uncert.: statistics (20%), JES (7%) b-tag (up to 4%), theory (tt, tW)

$\sqrt{s}$	σ_{tW} (pb)
7 TeV	16^{+5}_{-4}

(28%)

4.0 σ (3.6 σ expected)

$$|V_{tb}| = 1.01^{+0.16}_{-0.15}(\text{exp.})^{+0.03}_{-0.04}(\text{th.})$$
$$1 \geq |V_{tb}| > 0.79$$ 90% CL, constrained



PLB716(2012)142

- ATLAS: first evidence claimed at 2fb^{-1}, dilepton BDT analysis
- Largest uncert.: statistics (17%), jet energy scale (16%), parton shower model (15%), generator, pile-up

$\sqrt{s}$	σ_{tW} (pb)
7 TeV	$17 \pm 3(\text{stat.}) \pm 5(\text{syst.})$

(34%)

3.3 σ (3.4 σ expected)

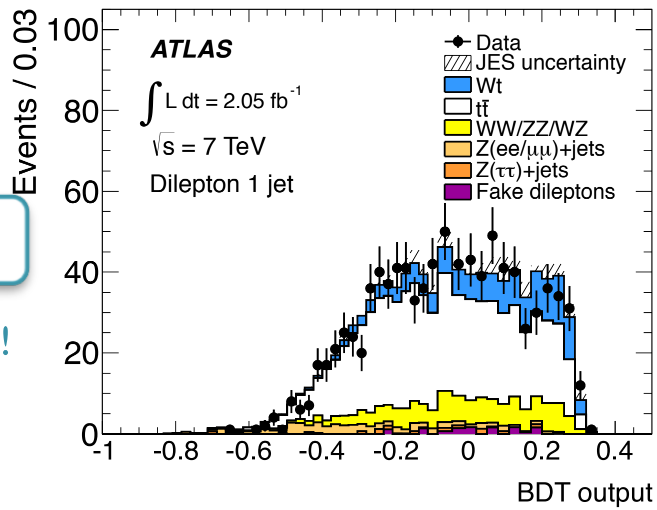
$$|V_{tb}| = 1.03^{+0.16}_{-0.19}$$

- No evidence for s channel
- ATLAS presented an upper limit from a cut-based analysis

$$\sigma_{s\text{-ch.}} < 26.5\,\text{pb}$$ 95%CL

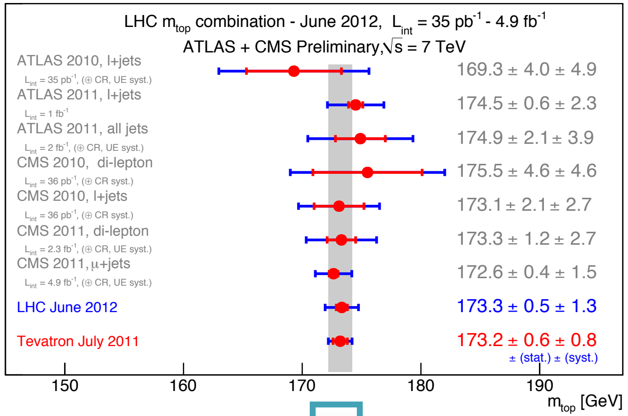
$$\sigma^{\text{th}}_{s\text{-ch.}} = 4.6\,\text{pb}$$ 5.8× SM!

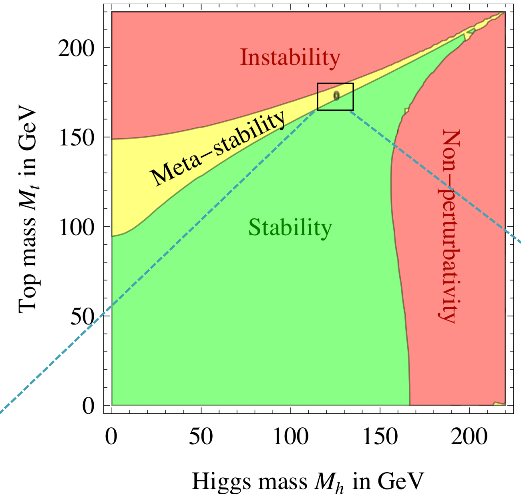
ATLAS-CONF-2011-118



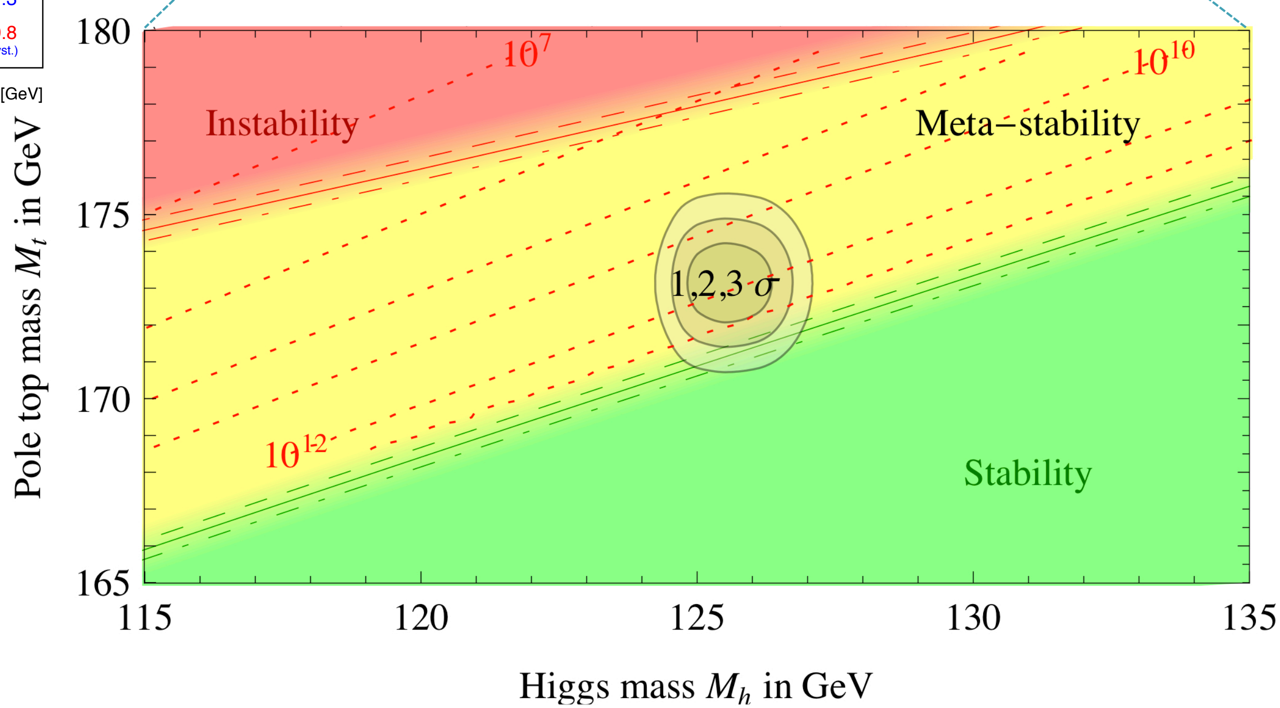
Top quark mass

- Also interesting in the Higgs era!





Degrassi et al: JHEP08(2012)098



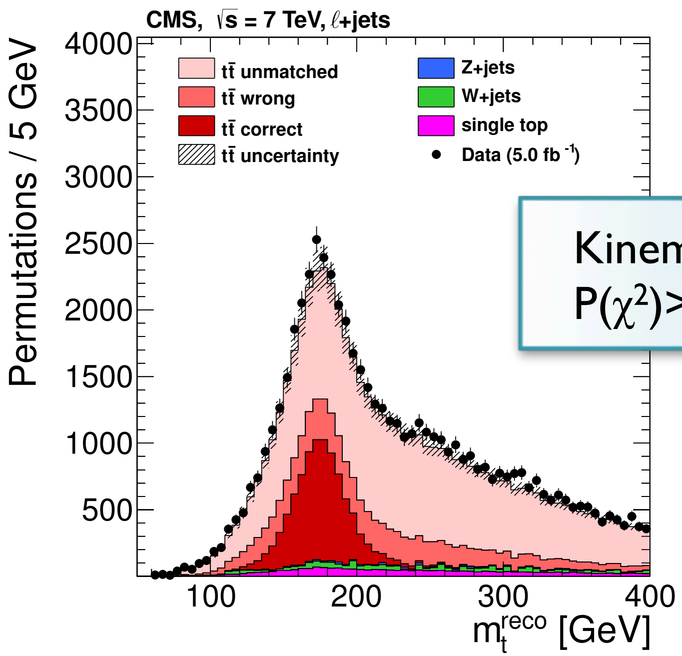
l+jets, ideogram method, CMS

- One isolated lepton, ≥4 jets, ≥2 b-tagged jets
- Kinematic fit: m_W constraint on both W, equal mass of decaying heavy particles

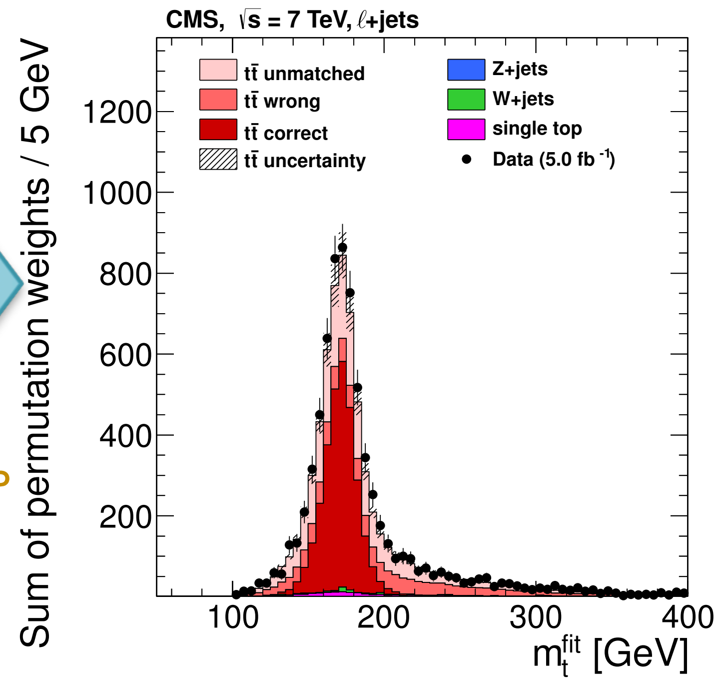
$$P_{\mathrm{gof}} = P\left(\chi^2\right) = \exp\left(-\tfrac{1}{2}\chi^2\right)$$

- Weight permutations by χ^2 probability (>0.2 required)

$$\mathcal{L}\left(m_t, \mathrm{JES}|\mathrm{sample}\right) \propto \prod_{\mathrm{events}} \left(\sum_{i=1}^{n} c\, P_{\mathrm{gof}}(i)\, P\left(m_{t,i}^{\mathrm{fit}}, m_{W,i}^{\mathrm{reco}} | m_t, \mathrm{JES}\right)\right)^{w_{\mathrm{event}}}$$



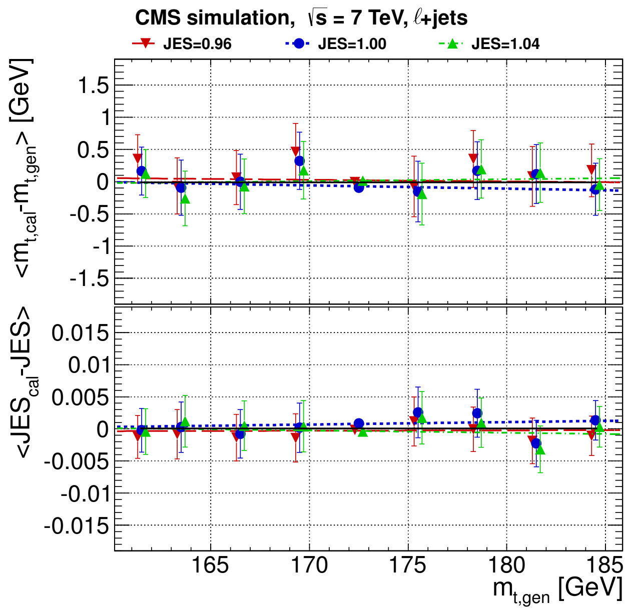
Kinematic fit +
P(χ^2)>0.2, weighting

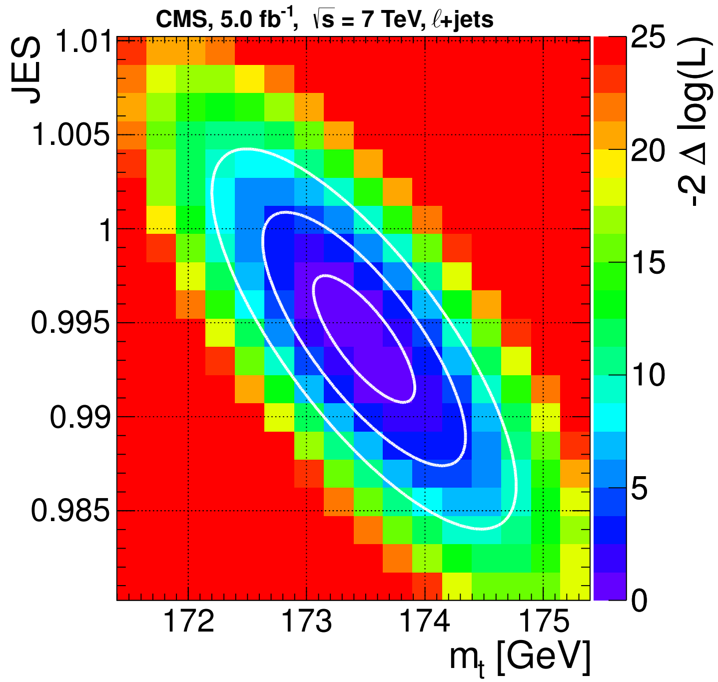


arXiv:1209.2319→JHEP

In-situ constraints

- Residual Jet energy scale and m_t fit simultaneously to reduce syst. uncertainty
- Nominal calibration validated in-situ
- Simulated pseudo-experiments used to scan possible JES/m_t points, correct possible bias, assess coverage





μ+jets: $m_t = 173.22 \pm 0.56\,(\text{stat.+JES}) \pm 1.06\,(\text{syst.})$ GeV, $\text{JES} = 0.999 \pm 0.005\,(\text{stat.}) \pm 0.008\,(\text{syst.})$

e+jets: $m_t = 173.72 \pm 0.66\,(\text{stat.+JES}) \pm 1.00\,(\text{syst.})$ GeV, $\text{JES} = 0.989 \pm 0.005\,(\text{stat.}) \pm 0.007\,(\text{syst.})$

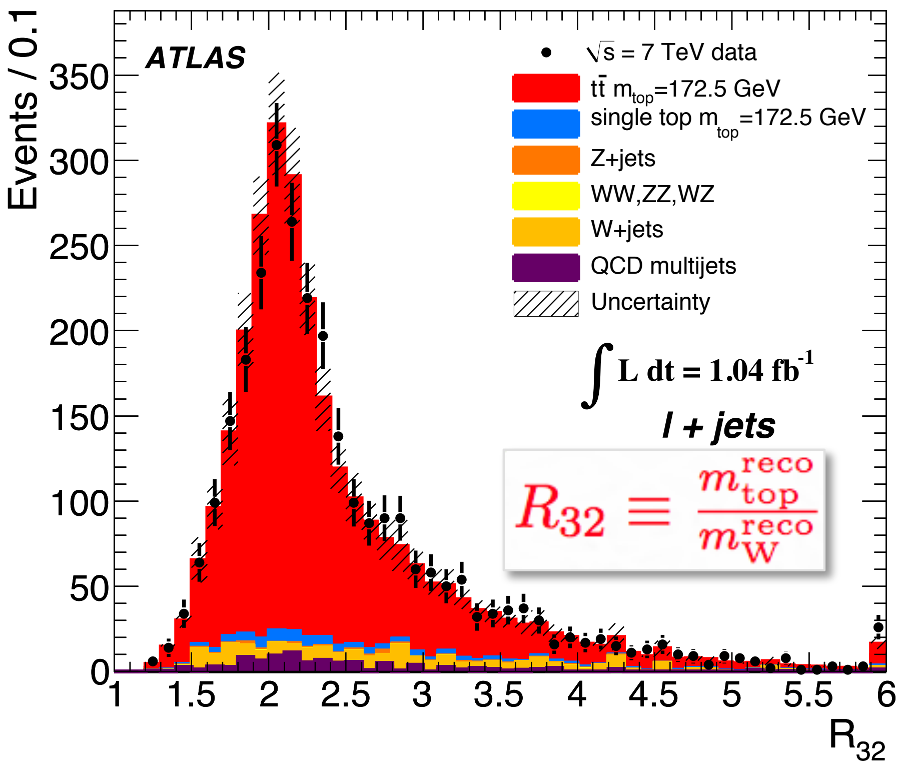
$$m_t = 173.49 \pm 0.43(\text{stat.+JES}) \pm 0.98(\text{syst.})\ \text{GeV}$$

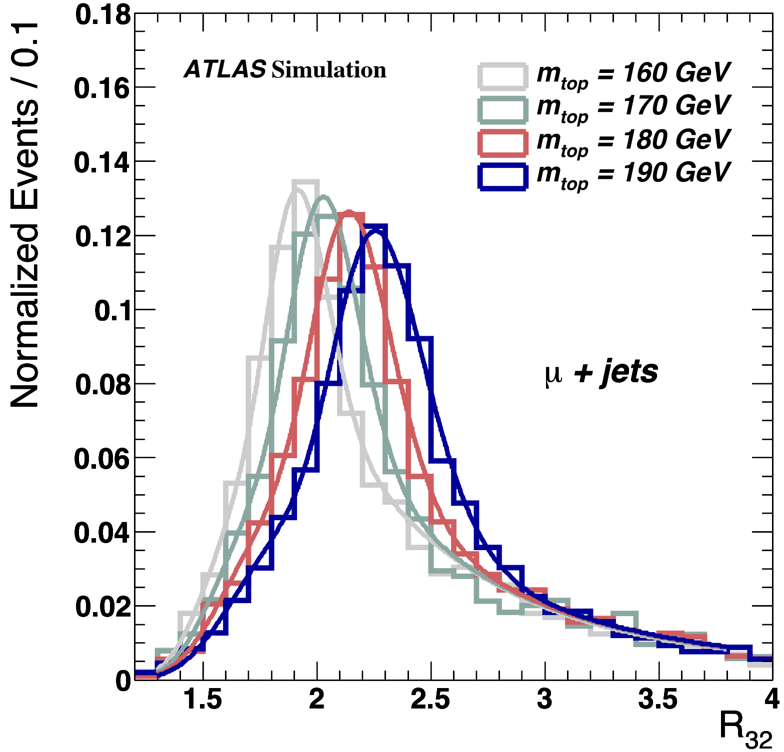
l+jets: template method , ATLAS

- Two measurement: 1D, based on R_{32} and 2D based on both m_t and m_W. Jet assignment in the hadronic hemisphere based on χ^2

$$m_t = 174.5 \pm 0.6(\mathrm{stat.}) \pm 2.3(\mathrm{syst.})\ \mathrm{GeV}$$

EPJC72(2012)2046





Dilepton mass measurement

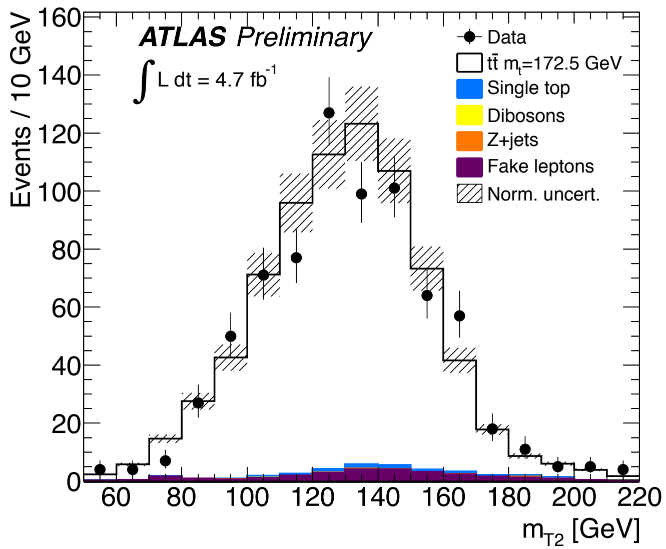
- m_{T2} variable: visible particles and two invisible particles in decay, gives lower bound on parent particle mass
- eμ only used

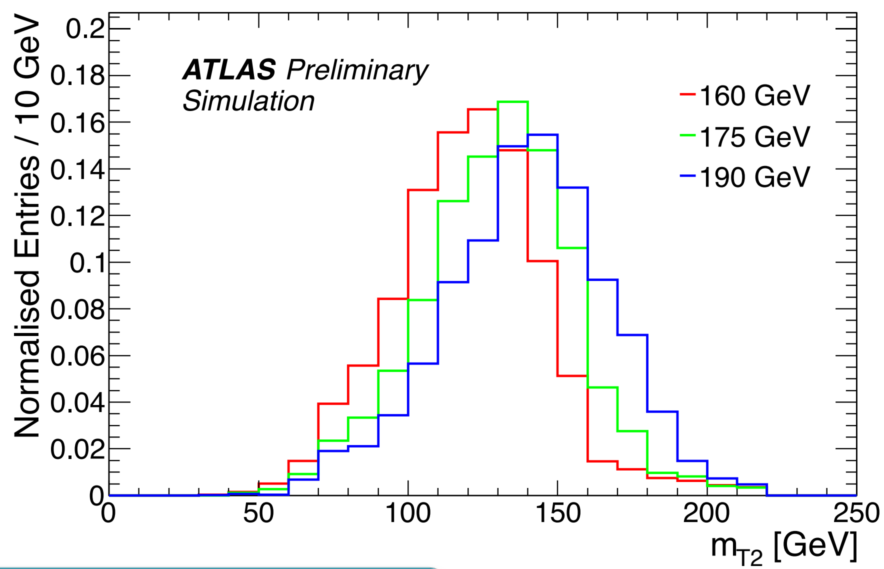
$$m_{T2}(m_{invis}) = \min_{\vec{p}_T^{(1)},\, \vec{p}_T^{(2)}} \left\{ \max\left[m_T(m_{invis}, \vec{p}_T^{(1)}), m_T(m_{invis}, \vec{p}_T^{(2)}) \right] \right\}$$

$$m_T(m_{invis}, \vec{p}_T^{(i)}) = \sqrt{m_{vis}^2 + m_{invis}^2 + 2(E_T^{vis} E_T^{invis} - \vec{p}_T^{vis} \cdot \vec{p}_T^{(i)})}$$

$\vec{p}_T^{(1)}, \vec{p}_T^{(2)}$: trial neutrino momenta

ATLAS-CONF-2012-082

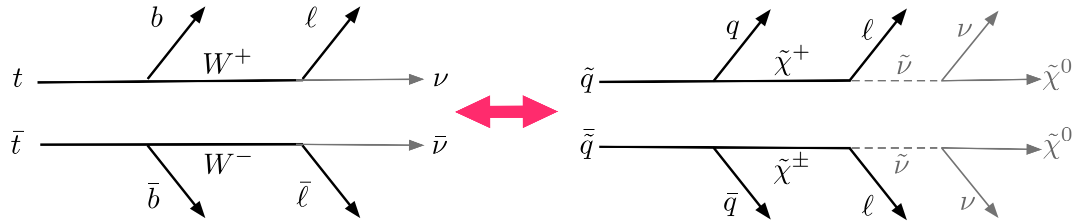


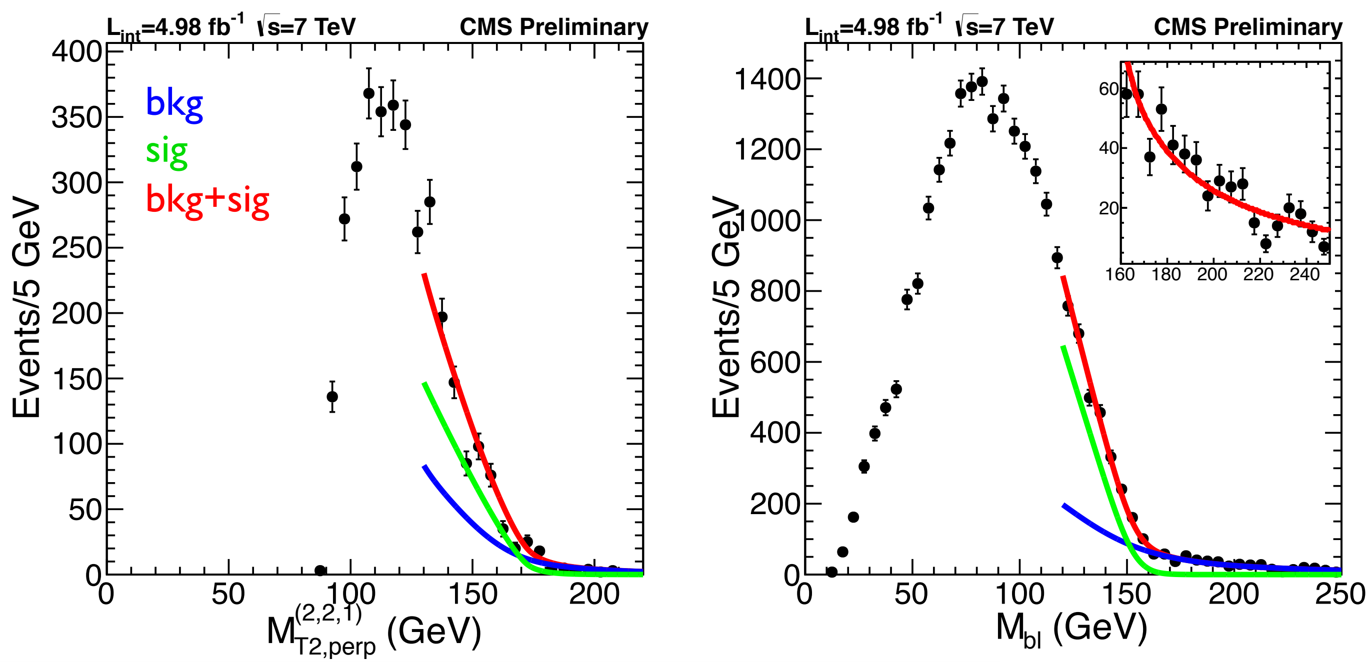


$$m_t = 175.2 \pm 1.6(\text{stat.})^{+3.1}_{-2.8}(\text{syst.})\ \text{GeV}$$

Mass from endpoint spectrum

- Technique similar to new physics scenarios
- Complementary measurement to usual approaches, may allow improvements in the combination thanks to different sources of systematic uncertainties





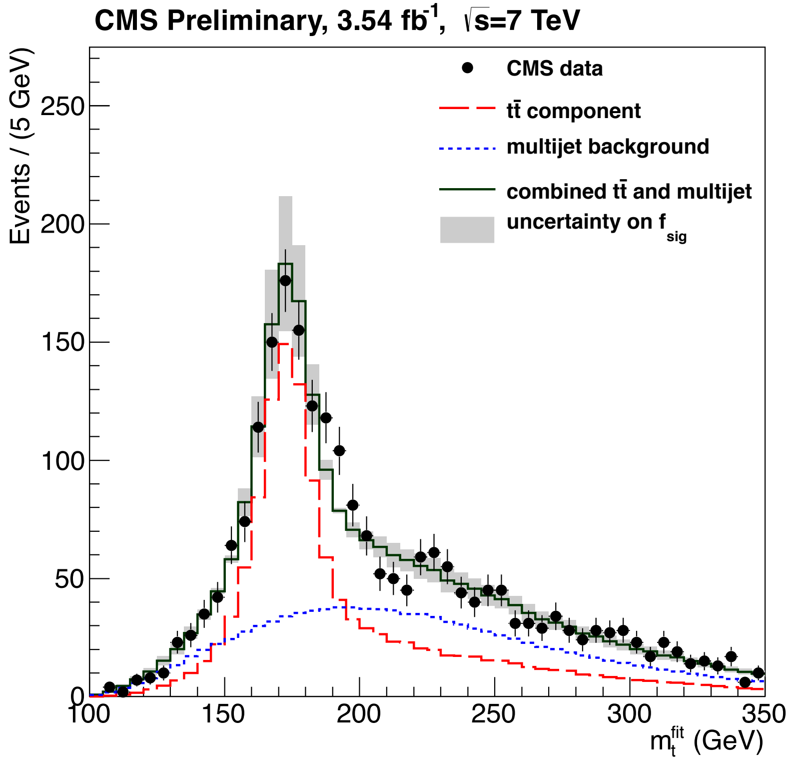
Fit Quantity	Constraint		
	None	$m_\nu = 0$	$m_\nu = 0$ and $M_W = 80.4$
m_ν^2 (GeV^2)	$-556 \pm 473 \pm 600$	(0)	(0)
M_W (GeV)	$72 \pm 7 \pm 9$	$80.7 \pm 1.1 \pm 1$	(80.4)
M_t (GeV)	$163 \pm 10 \pm 11$	$174.0 \pm 0.9 \pm 2$	$173.9 \pm 0.9^{+1.2}_{-1.8}$

CMS PAS TOP-11-027

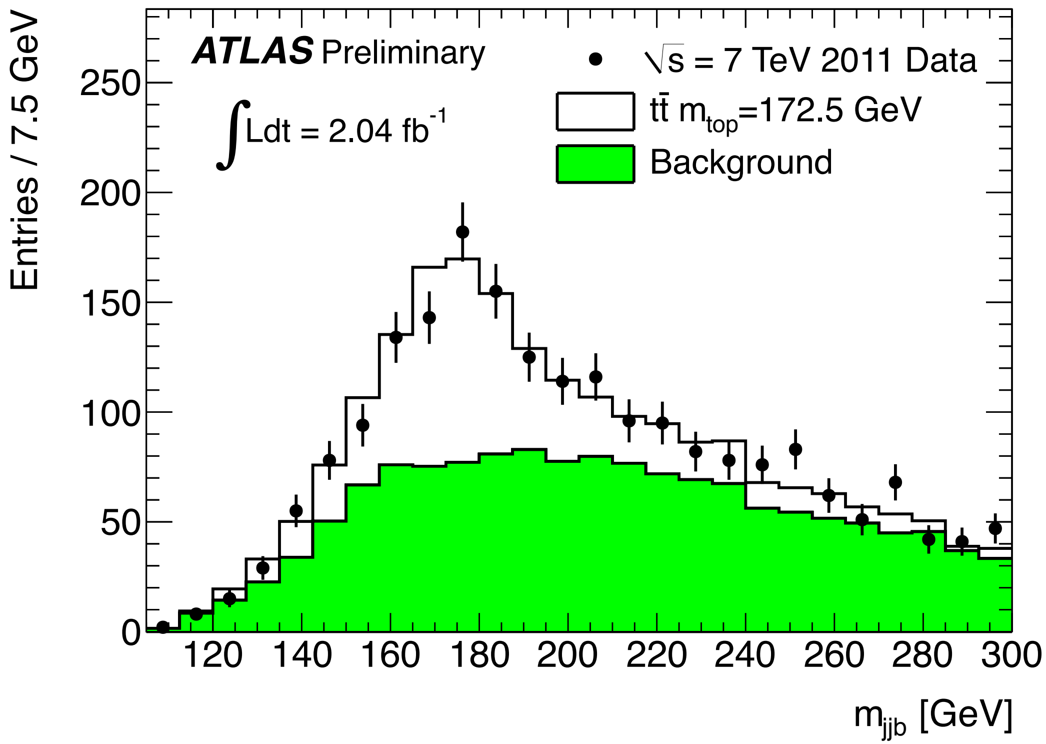
Mass from fully hardonic

- At least 5(ATLAS), 6(CMS) jets (2 b-tagged with p_T>30 GeV)
- Choose permutation with lowest χ^2 after kinematics fit

CMS PAS TOP-11-017



ATLAS-CONF-2012-030



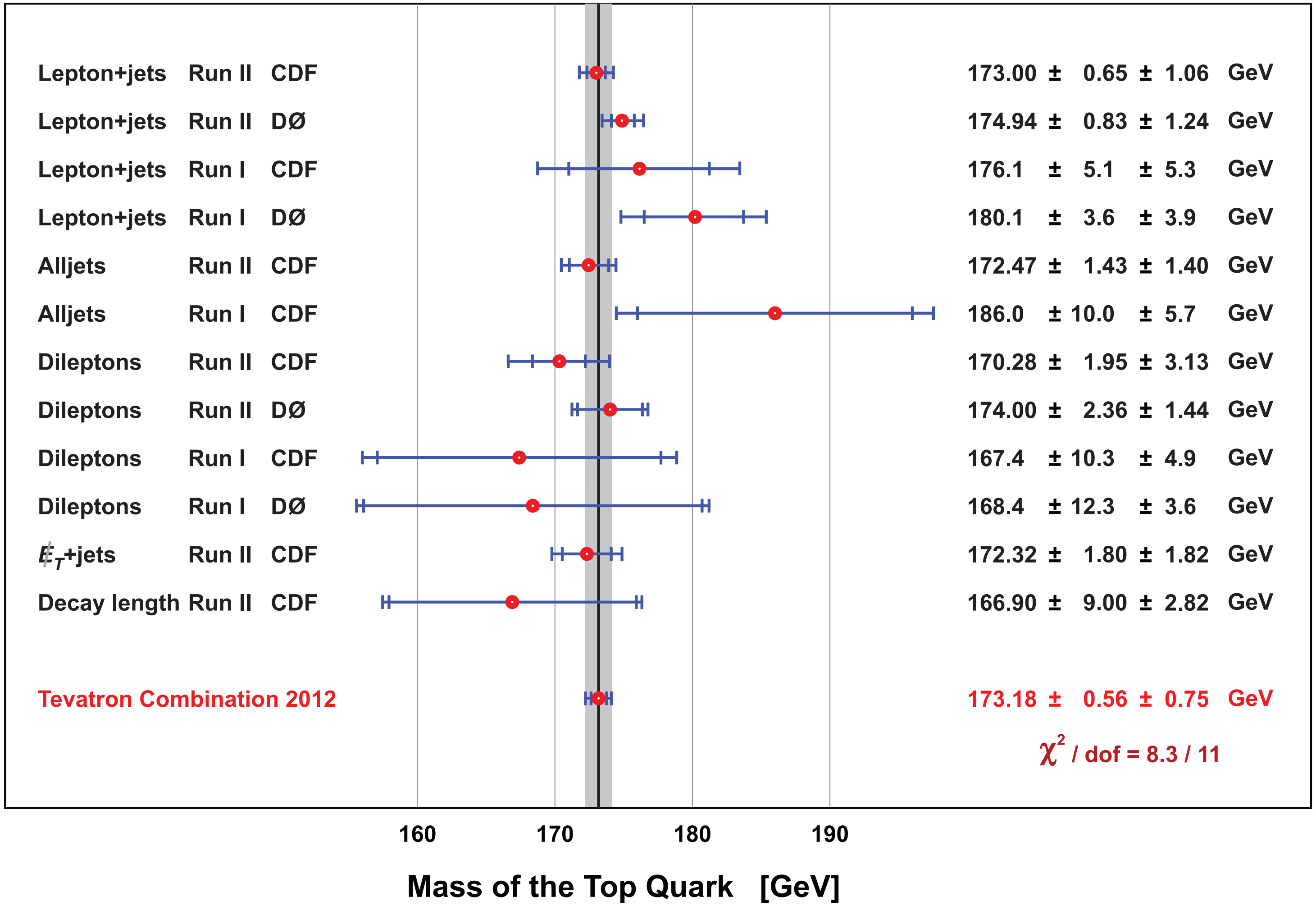
$$m_t = 173.49 \pm 0.69(\text{stat.}) \pm 1.25(\text{syst.})\ \text{GeV}$$

$$m_t = 174.9 \pm 2.1(\text{stat.}) \pm 3.8(\text{syst.})\ \text{GeV}$$

Top mass from Tevatron

- Combined measurement from CDF and D0

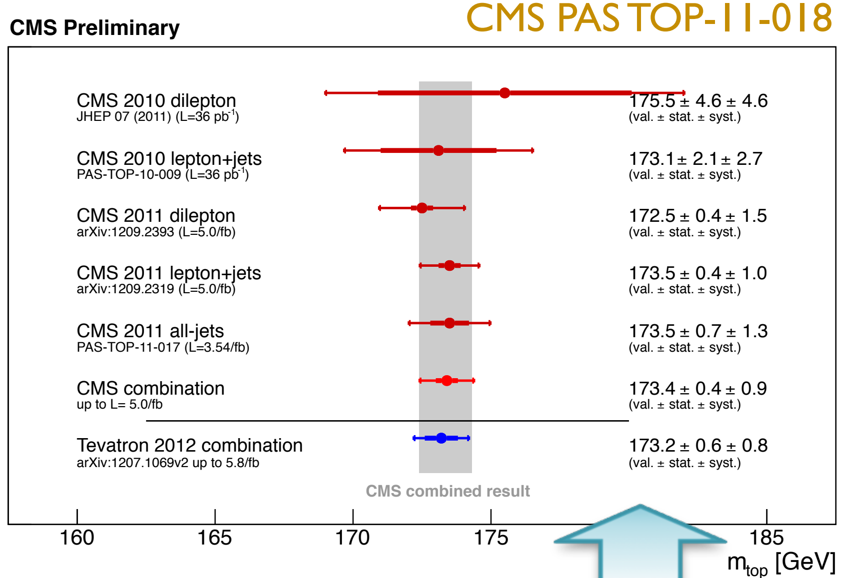
PRD86(2012)092003



LHC Top mass combination

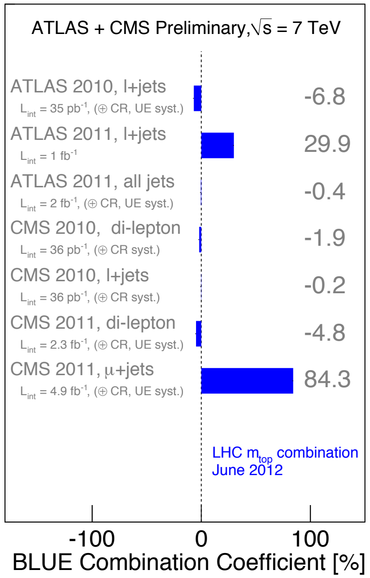
- Combination of all LHC channels within the TOPLHC working group
- BLUE method adopted, categorization of uncertainties and many cross checks
- Relative uncertainty: 0.8%, mostly driven by l+jets result, competitive with Tevatron: ±1.4GeV vs ±1.0 GeV uncertainties
- CMS-only combination updated, final uncertainty is 0.57% (±1.0 GeV)

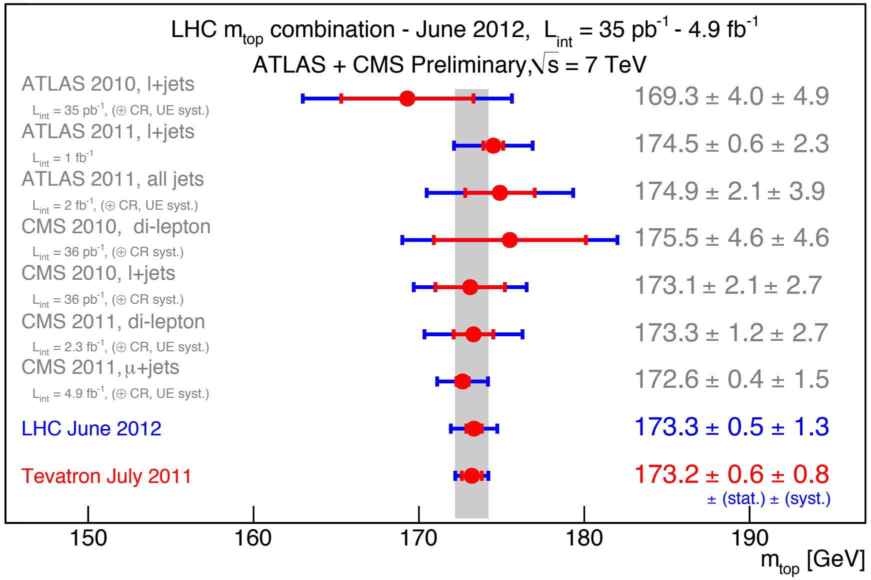
CMS PAS TOP-11-018



Measured m_t	173.36
Statistical Uncertainty	0.38
iJES: *in-situ* JES factor	0.24
bJES: relative b-jet scale	0.55
dJES: η and p_T-dependent JES	0.32
rJES: other uncorrelated JES	0.07
Lepton energy scale	0.03
MC generator	0.01
ISR/FSR	0.03
PDF	0.06
Factorization scale	0.17
ME-PS matching threshold	0.16
Signal	
Jet energy resolution	0.20
b-tagging	0.10
E_T^{miss} scale	0.01
Detector Modeling	
Underlying event	0.15
Background MC	0.07
Background Data	0.07
Fit calibration and MC statistic	0.08
Pile-up	0.09
Color reconnection	0.45
Trigger	0.07
Total Systematic Uncertainty	0.91
Total Uncertainty	0.99

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

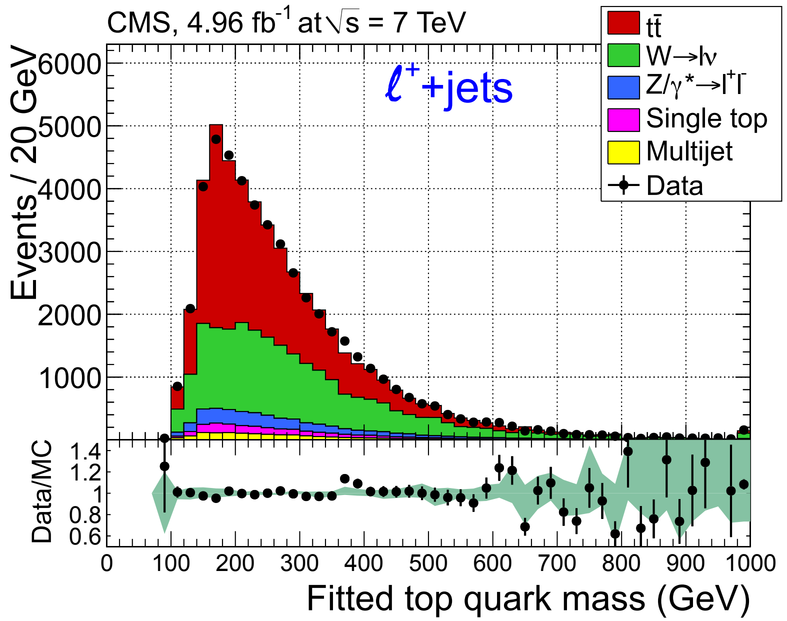


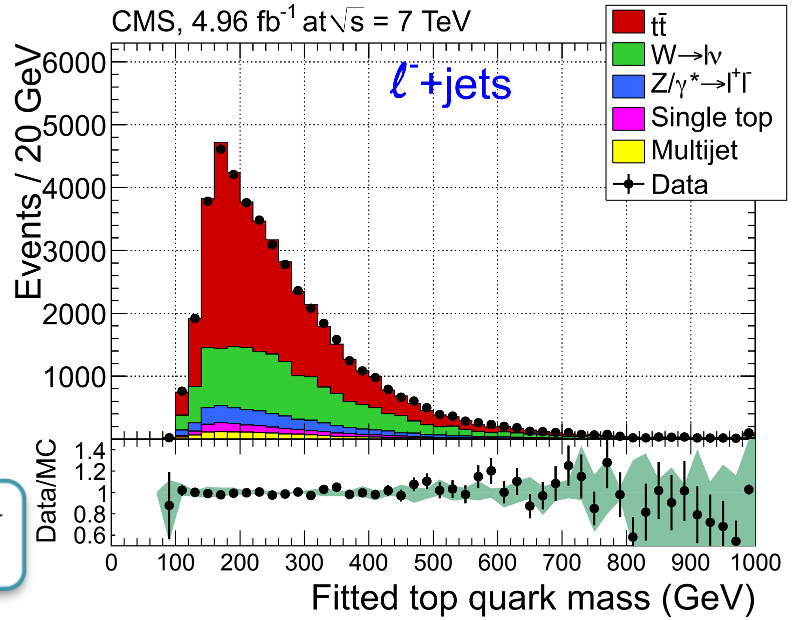


Top mass difference

- Test CPT invariance in the top sector
- Compare e^+/μ^++jets vs e^-/μ^-+jets samples
- Mass reconstructed from hadronic side
  - Kinematic fit (including resolutions)
  - Choose combination with lowest χ^2
- Final measurement from ideogram method: combine μ^- and μ^+ likelihoods separately
- Most systematic effects cancel out
- Largest uncertainties: statistics, b vs b^{bar} jet response and efficiency, method calibration, pileup modeling

CMS: JHEP06(2012)109





CMS: world's best measurement

$$\Delta m_t = -0.44 \pm 0.46\ \text{(stat.)} \pm 0.27\ \text{(syst.)}\ \text{GeV}$$

CDF: PRD84(2011)052005

$$\Delta m_t = 0.8 \pm 1.9\,\text{GeV}$$

D0: arXiv:1210.6131

$$\Delta m_t = -2.0 \pm 1.3\,\text{GeV}$$

W polarization in top decays

- W polarization in t → Wb probes the V−A structure of weak charged current

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}\sin^2\theta^* F_0 + \frac{3}{8}(1-\cos\theta^*)^2 F_{\rm L} + \frac{3}{8}(1+\cos\theta^*)^2 F_{\rm R}$$

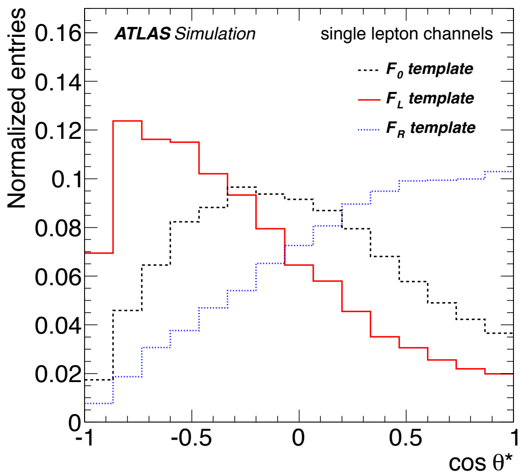
θ^* = angle between lepton and W in the W rest frame

- Possible deviations from the SM predictions and limits on anomalous Wtb couplings are determined
- ATLAS: 1.0 fb^{-1}, lepton+jets + dileptons, combined, CMS: 2.2 fb^{-1}, lepton+jets only

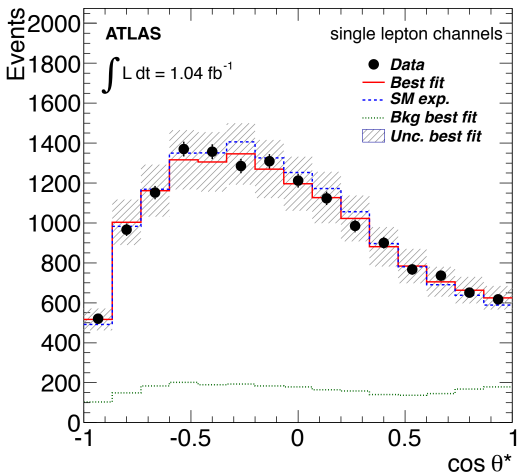
=1 (norm.) = 0 (assumed)

$$\mathcal{L}^{\rm eff.}_{\rm Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(V_{\rm L}P_{\rm L} + V_{\rm R}P_{\rm R})tW^-_\mu - \frac{g}{\sqrt{2}}\bar{b}\frac{-i\sigma^{\mu\nu}q_\nu}{m_{\rm W}}(g_{\rm L}P_{\rm L} + g_{\rm R}P_{\rm R})tW^-_\mu + \text{h.c.}$$

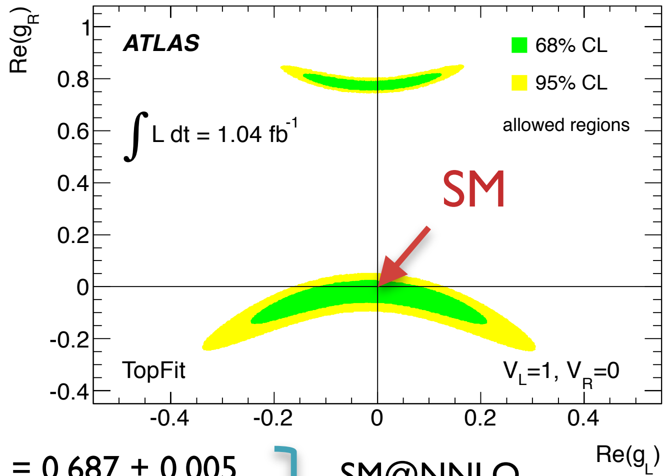
Limits on anomalous coupling determined from $F_0, F_{\rm L}, F_{\rm R}$



JHEP 1206 (2012) 088



CMS-PAS-TOP-11-020



	ATLAS	CMS
F_0	0.67 ± 0.03 (stat.) ± 0.06 (syst.)	0.57 ± 0.07(stat.) ± 0.05(syst.)
$F_{\rm L}$	0.32 ± 0.02 (stat.) ± 0.03 (syst.)	0.39 ± 0.04(stat.) ± 0.03(syst.)
$F_{\rm R}$	0.01 ± 0.01 (stat.) ± 0.04 (syst.)	0.04 ± 0.04 (stat.) ± 0.04(syst.)

F_0 = 0.687 ± 0.005
$F_{\rm L}$ = 0.311 ± 0.005
$F_{\rm R}$ = 0.0017 ± 0.0001

SM@NNLO
Czarnecki et al. PRD81(2010)111503

Spin correlation, polarization

- First observation of spin correlation: 5.1 σ

$$A = \frac{(N(\uparrow\uparrow) + N(\downarrow\downarrow)) - (N(\uparrow\downarrow) + N(\uparrow\downarrow))}{(N(\uparrow\uparrow) + N(\downarrow\downarrow)) + (N(\uparrow\downarrow) + N(\uparrow\downarrow))}$$

- Helicity/maximal basis asymmetry[*], main syst: JER/JES:

$$A_{\mathrm{hel}} = 0.40 \pm 0.04(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{syst.}),\ \ \mathrm{SM{:}}\,0.31$$
$$A_{\mathrm{max}} = 0.57 \pm 0.06(\mathrm{stat.})^{+0.12}_{-0.10}(\mathrm{syst.}),\ \ \mathrm{SM{:}}\,0.44$$

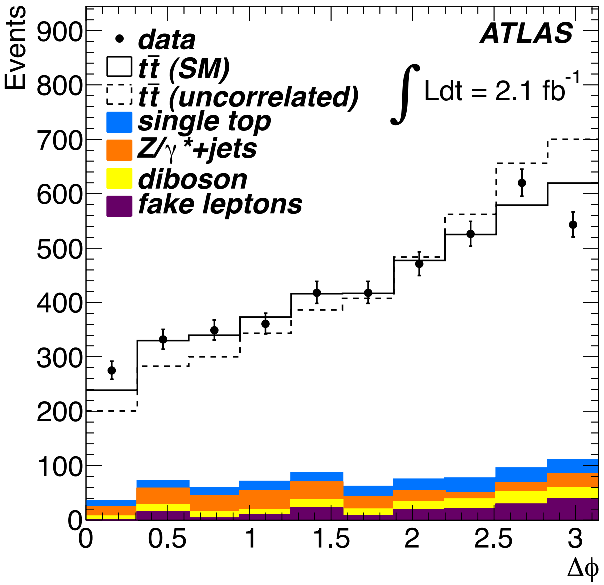
[*] P. Uwer, PPLB609 (2005)271

- Top quark polarization: $f = \frac{1}{2} + \frac{N(\cos\theta_\ell > 0) - N(\cos\theta_\ell < 0)}{N(\cos\theta_\ell > 0) + N(\cos\theta_\ell < 0)}$
- Consistent with SM expectations: f = 0.5

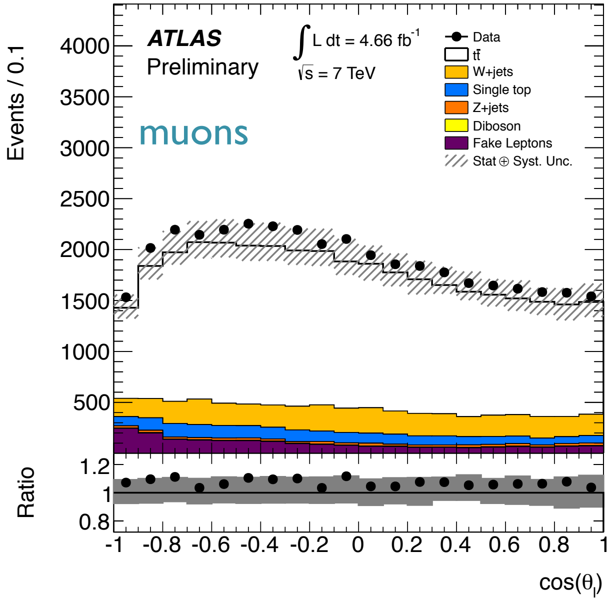
$$f = 0.470 \pm 0.009(\mathrm{stat.})^{+0.023}_{-0.032}(\mathrm{syst.})$$

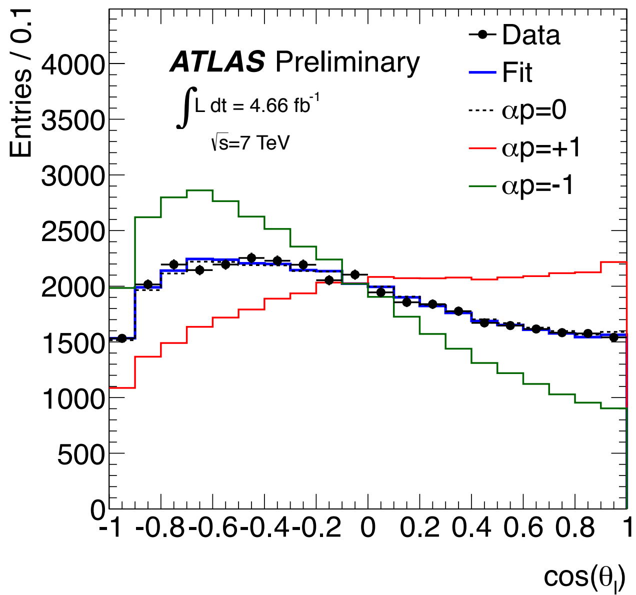
θ_l = lepton polar angle in the top rest frame

PRL108(2012)212001



ATLAS-CONF-2012-133

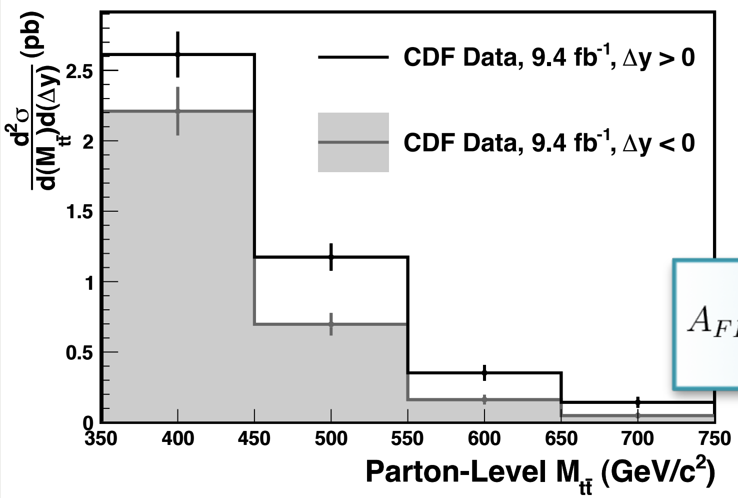




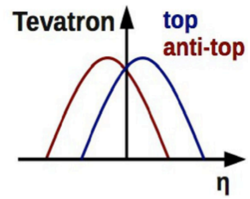
Forward-backward asymmetry

- Possible deviation from SM reported at Tevatron

arXiv:1211.1003 → PRD

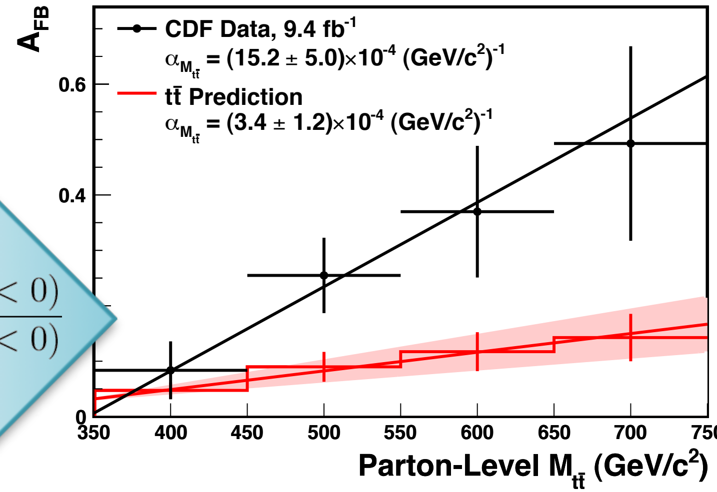


A_{FB}

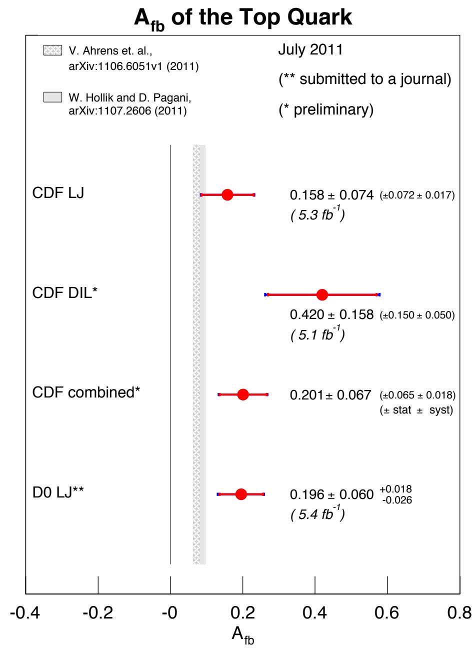


$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

2.4 σ deviation from SM



- Δy distribution in l+jets at D0 and dileptons at CDF confirms a discrepancy at 2~3 σ level
- $\Delta\eta_{ll}$ distribution consistent with SM expectation at D0



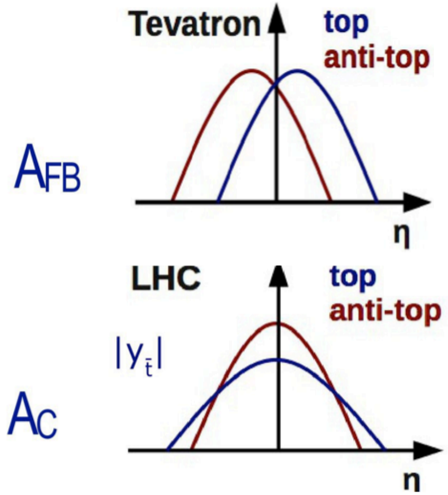
More Tevatron A_{FB} measurements:

CDF: PRD83(2011)112003, CDF note 10436

D0: PRD 84(2011)112005, arXiv:1207.0364

Charge asymmetry at LHC

- LHC data not directly comparable to Tevatron: symmetric pp initial state vs asymmetric pp^{bar}
- Charge asymmetry measured instead of forward backward asymmetry, using top or lepton y



$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)} \quad \begin{cases} \Delta|y| = |y_t| - |y_{\bar{t}}| \\ \Delta|y| = |y_{\ell+}| - |y_{\ell-}| \end{cases}$$

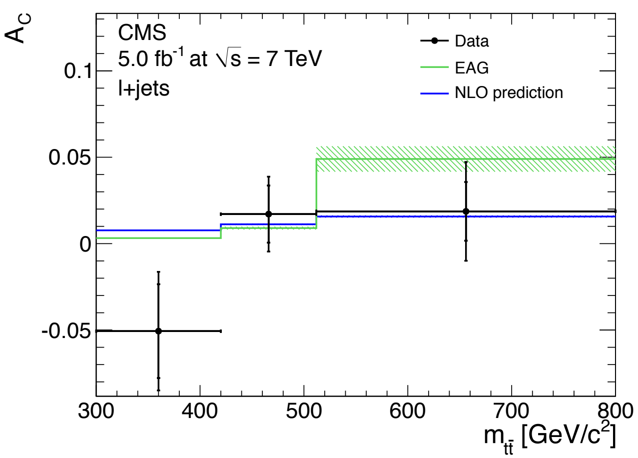
PLB717(2012)129, CMS PAS TOP-12-010

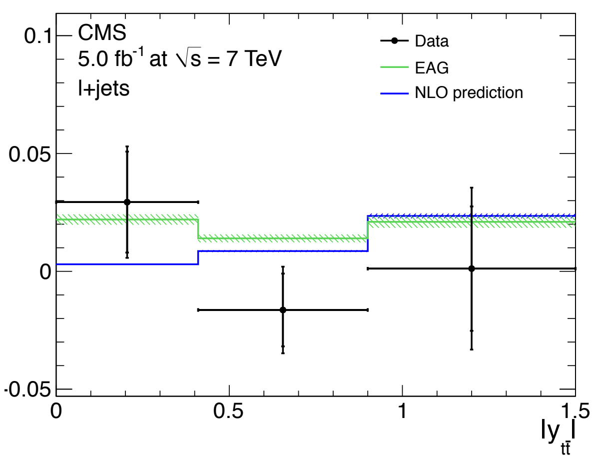
l+jets, ll (inc. and diff. vs tt^{bar} y, p_T and m),

$$A_C^{\ell\ell} = 0.010 \pm 0.015(\text{stat.}) \pm 0.006(\text{syst.})$$
$$A_C^{t\bar{t}} = 0.004 \pm 0.010(\text{stat.}) \pm 0.011(\text{syst.})$$

l+jets, ll inclusive, comb. ATLAS-CONF-2012-057

$$A_C^{\ell\ell} = 0.023 \pm 0.012(\text{stat.}) \pm 0.008(\text{syst.})$$
$$A_C^{t\bar{t}} = 0.029 \pm 0.018(\text{stat.}) \pm 0.014(\text{syst.})$$



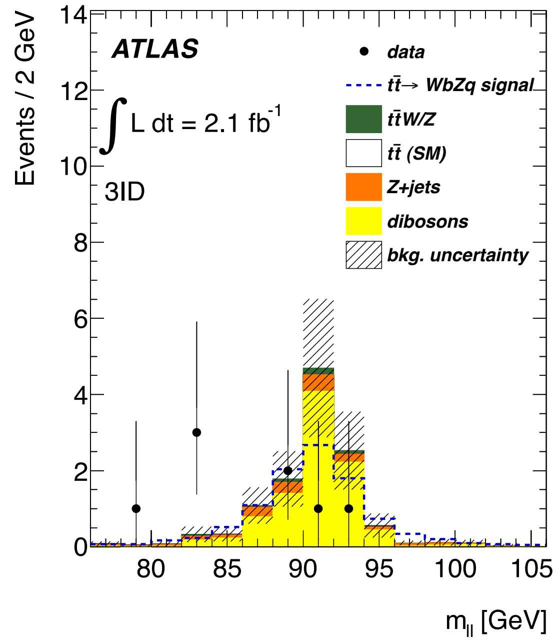


$$A_C^{\ell\ell}(\text{SM}) = 0.004 \pm 0.001$$
$$A_C^{t\bar{t}}(\text{SM}) = 0.006 \pm 0.002$$

- Large deviations from SM disfavored
- Not sensitive yet to distinguish zero from SM prediction

New physics with top: FCNC

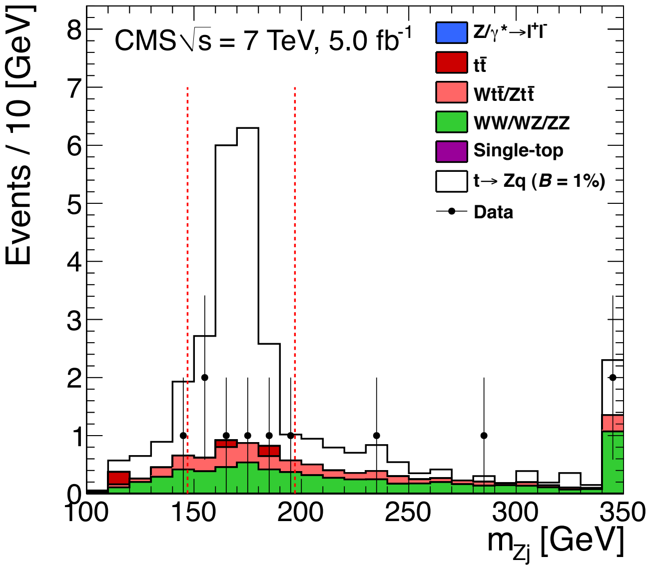
JHEP09(2012)139

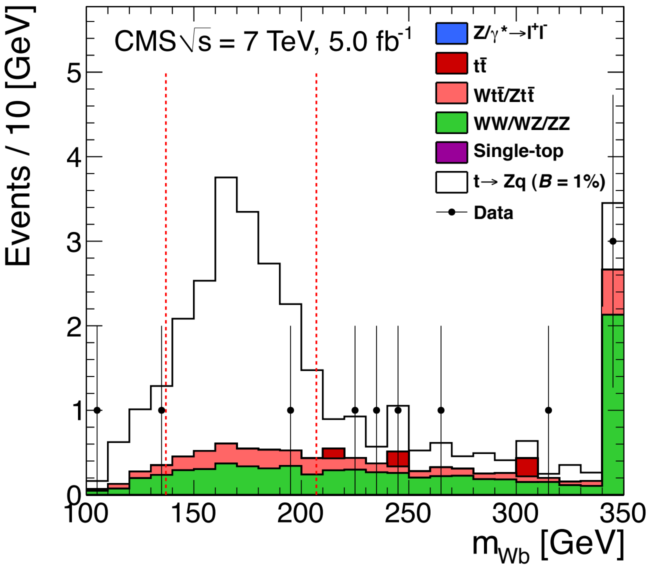


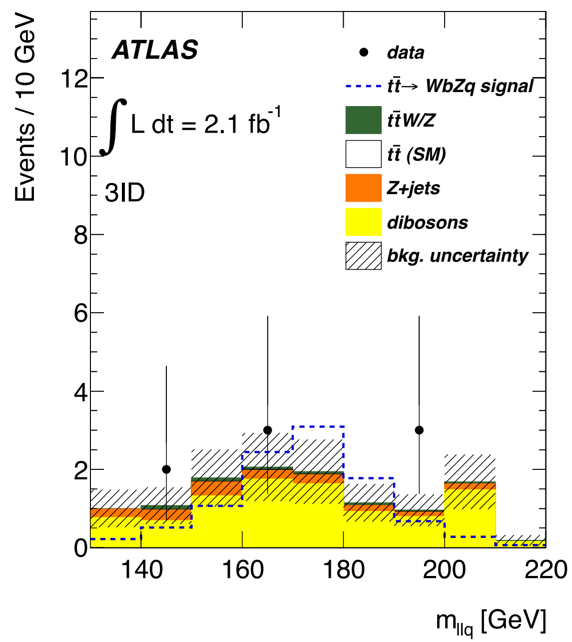
• t→Zq FCNC decay

- Limits achieved:
  - $B(t \to Zq) < 0.24\%$ (CMS, $5fb^{-1}$), $B(t \to Zq) < 0.73\%$ (ATLAS, $2fb^{-1}$)
- Significant improvements achievable using the entire LHC data sample

arXiv:1208.0957→PLB



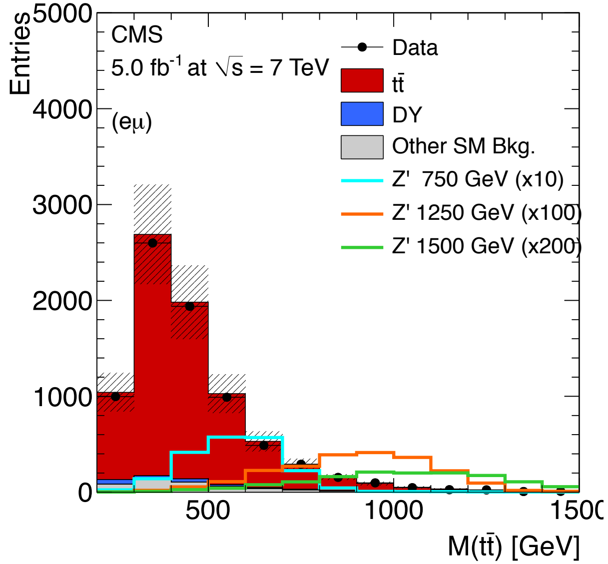




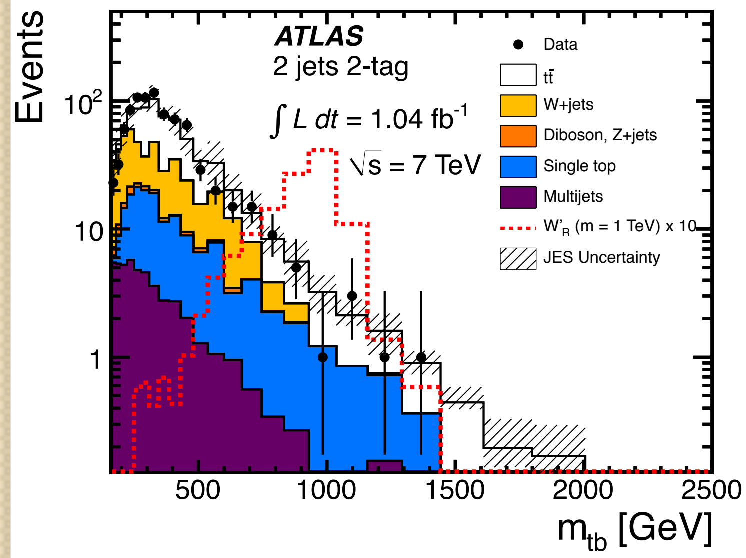
New physics: resonances

- Search for new resonances decaying to tt^{bar} and tb
  - Reached 1.5-2.0 TeV limits on topcolor Z', depending on the assumed width, 1.8 TeV limit on KK gluon*
  - $m_{W'R}$>1.13 TeV decaying into tb (ATLAS)

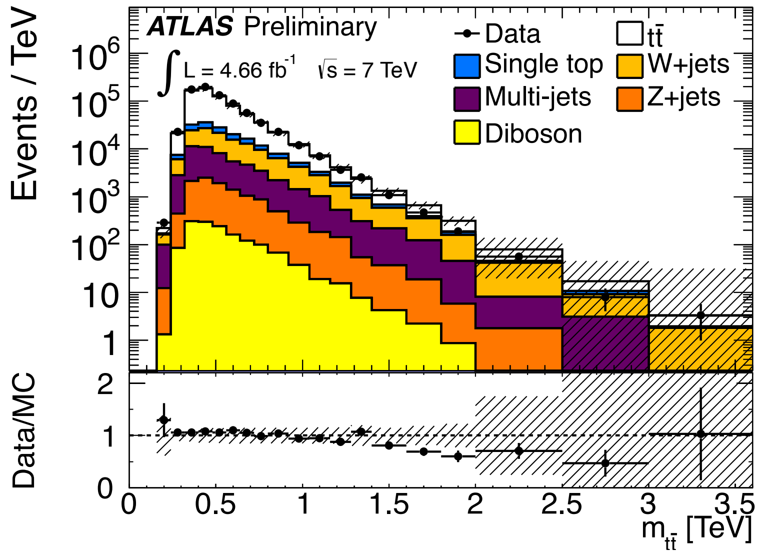
arXiv:1211.3338 →PRD (dilepton)



PRL109(2012)081801



arXiv:1211.2202 →JHEP (fully hadronic)
ATLAS-CONF-2012-136 (l+jets)



Conclusions

- LHC is a top factory, millions of tt^{bar} events have been produced so far at LHC
- Top-pair cross section became a precision measurement, allowing an indirect measurement of alpha-strong
- Single-top cross section moved to the precision regime, allowing differential studies
- Top-mass precision at LHC reached Tevatron, more methods are being pursued in order to reduce combined systematic uncertainties
- Top is also a benchmark to study new physics processes
- More measurements will come from the large data sample achieved so far at 8 TeV

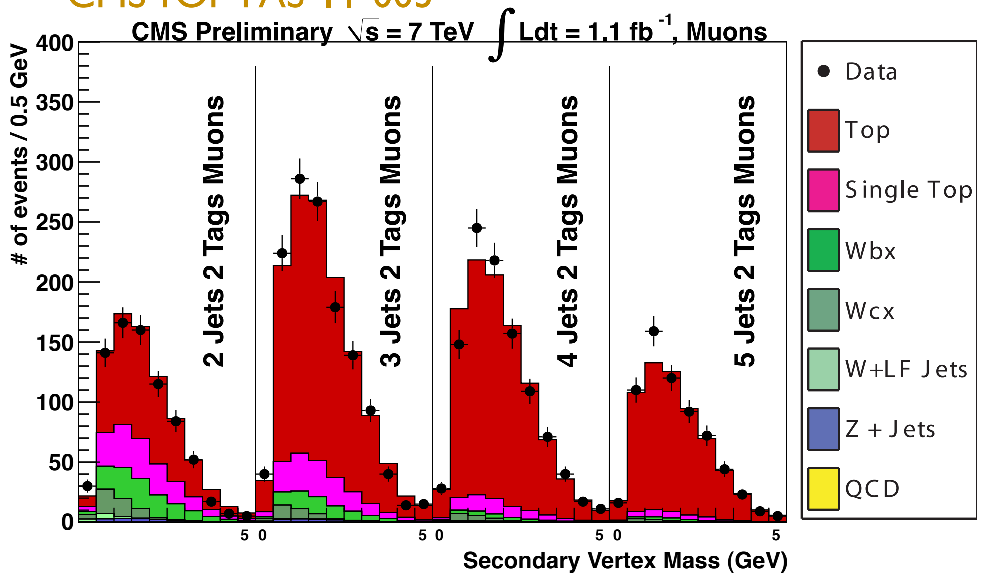
Stay tuned!

Backup

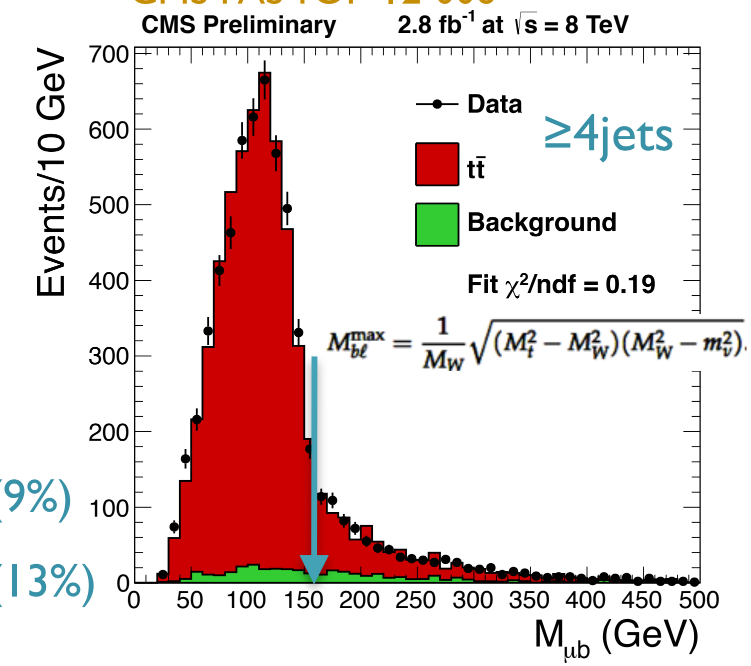
σ ($t\bar{t}$), lepton + jets: CMS

- Events triggered from single lepton, required be isolated and with high p_T
- Vetoed second lepton requiring a looser isolation
- ≥1 jet with high p_T, possibly b-tagged
- MET required
- Main uncertainties:
  - Q^2, matching scale uncertainty, b-tag, Jet energy scale
- 8 TeV: QCD background shape determined from data (isolation SB)

CMS TOP PAS-11-003



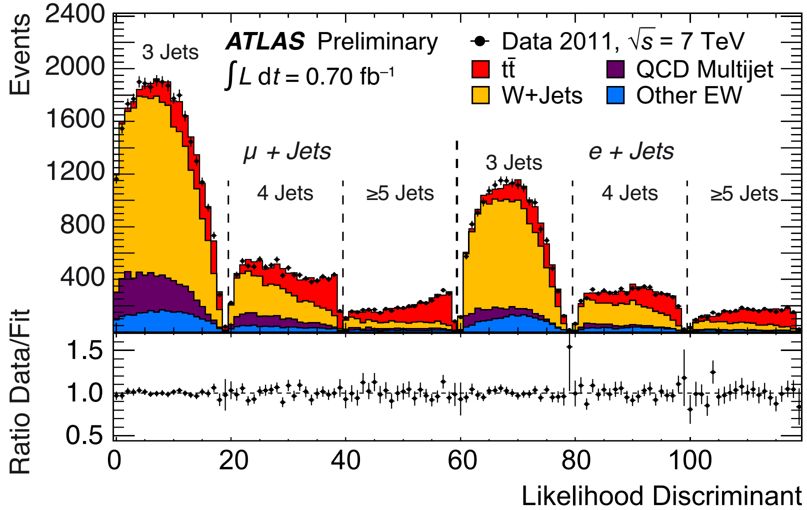
CMS PAS TOP-12-006



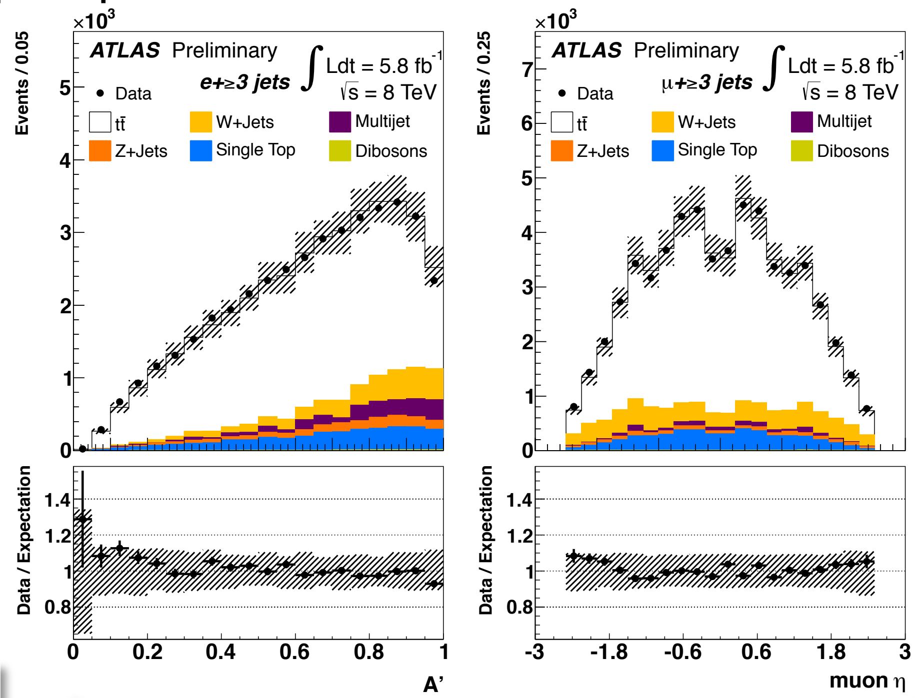
$\sqrt{s}$	σ_{tt} (pb)	
7 TeV	$164.4 \pm 2.8(\text{stat.}) \pm 11.9(\text{syst.}) \pm 7.4(\text{lumi})$	(9%)
8 TeV	$228.4 \pm 9.0(\text{stat.})^{+29.0}_{-26.0}(\text{syst.}) \pm 10.0(\text{lumi})$	(13%)

σ (tt^{bar}), lepton + jets: ATLAS

- Measurement at 7 TeV with 0.7 fb^{-1} with no b-tag requirement, based on a likelihood of four shape variables
- Measurement extended to 4.7fb^{-1}, adding b-tagging, but less precise due to larger background uncertainty due to higher pile-up conditions



ATLAS-CONF-2011-121
ATLAS-CONF-2012-131



$\sqrt{s}$	σ_{tt} (pb)	
7 TeV	179.0 ± 3.9(stat.) ± 9.0(syst.) ± 6.6 (lumi)	(7%: 0.7fb^{-1}, no b-tag)
7 TeV	165 ± 2(stat.) ± 17(syst.) ± 3(lumi)	(11%: 4.7fb^{-1}, with b-tag)
8 TeV	241 ± 2(stat-) ± 31(syst.) ± 9(lumi)	(13%)

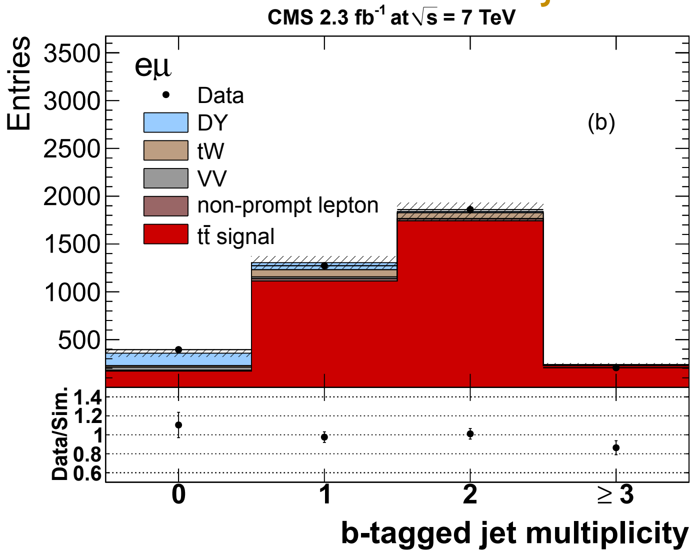
Likelihood discriminator

ATLAS-CONF-2012-149

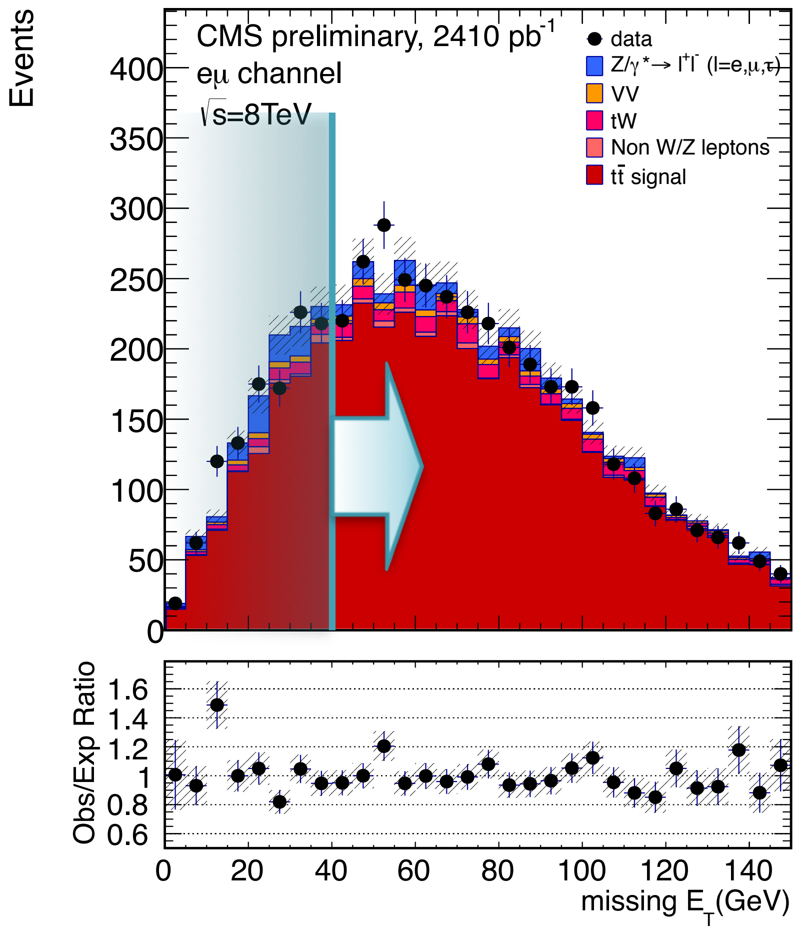
Dilepton channel: CMS

- Dilepton trigger, two high-p_T leptons, Z mass veto
- MET requirement (>40GeV)
- e/μ channel dominates the combined result (lower background)
- Main uncertainties: luminosity, JES, W Branching ratio,

arXiv:1208.2671 → JHEP



CMS PAS TOP-12-007



$\sqrt{s}$	σ_{tt} (pb)	
7 TeV	$161 \pm 2.5(\text{stat.})^{+5.1}_{-5.0}(\text{syst.}) \pm 3.6(\text{lumi})$	(4%)
8 TeV	$227 \pm 3(\text{stat.}) \pm 11(\text{syst.}) \pm 10(\text{lumi})$	(7%)

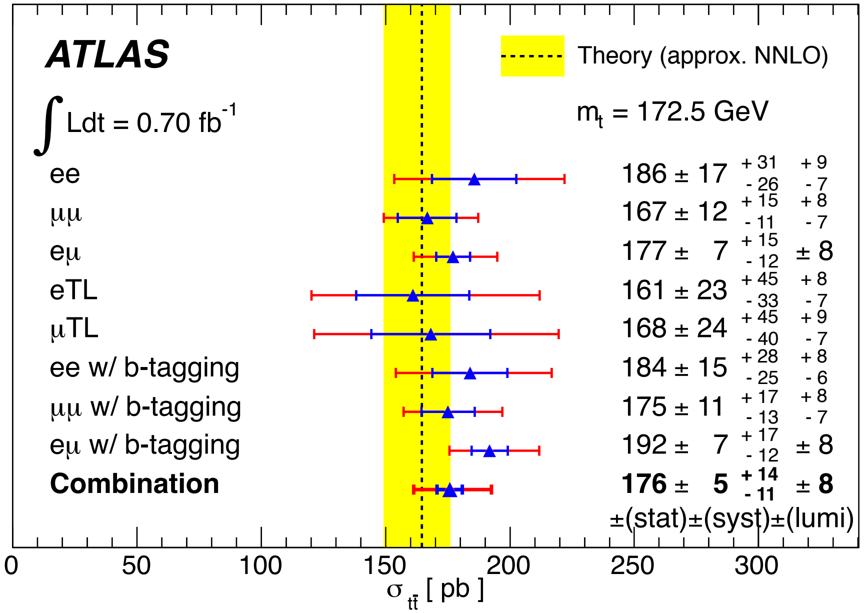
Ratio of combinations at 7, 8 TeV

CMS PAS TOP-12-007

$$\frac{\sigma_{t\bar{t}}(8\text{TeV})}{\sigma_{t\bar{t}}(7\text{TeV})} = 1.41 \pm 0.10$$

Dilepton channel: ATLAS

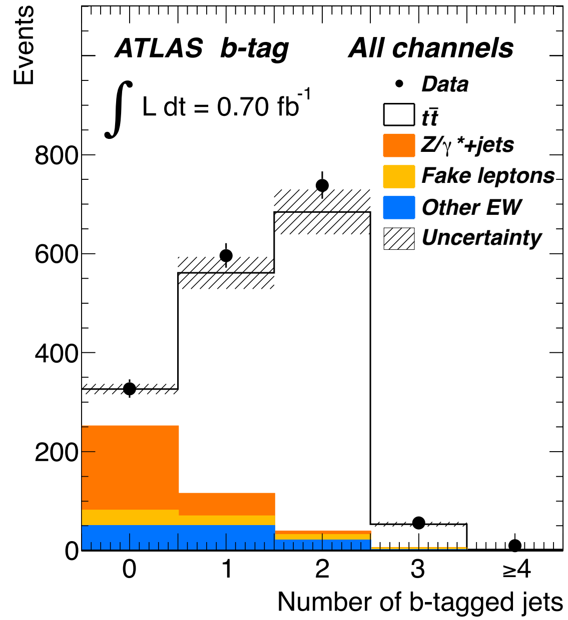
- Single-lepton trigger, two lepton candidates (also high p_T track, 'TL', included), Z mass veto
- MET and H_T (pT sum of selected objects) required
- Main background from Drell-Yan processes, determined from data
- Main uncertainties: luminosity, jet/MET and generator systematics

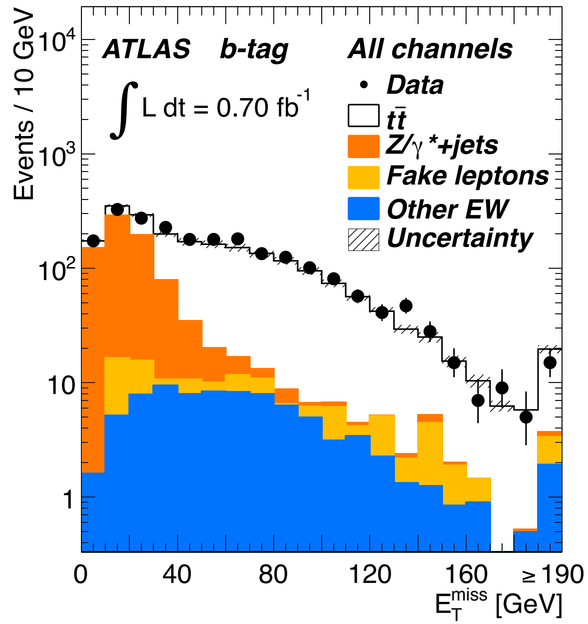


$\sqrt{s}$	σ_{tt} (pb)
7 TeV	$176 \pm 5(\text{stat.})^{+14}_{-11}(\text{syst.}) \pm 8(\text{lumi})$

(10%)

JHEP05(2012)059



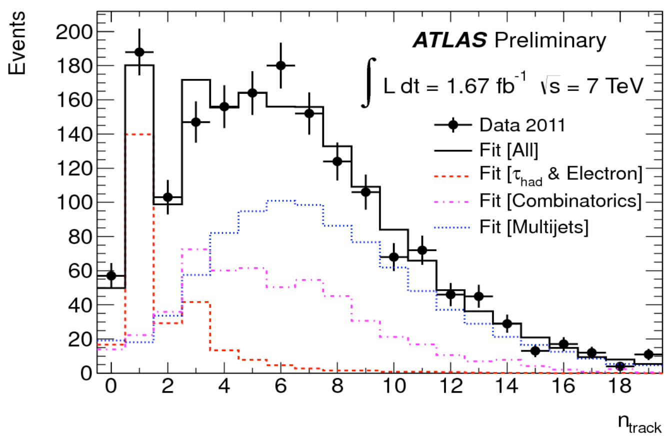


$t\bar{t}$ with W→τν

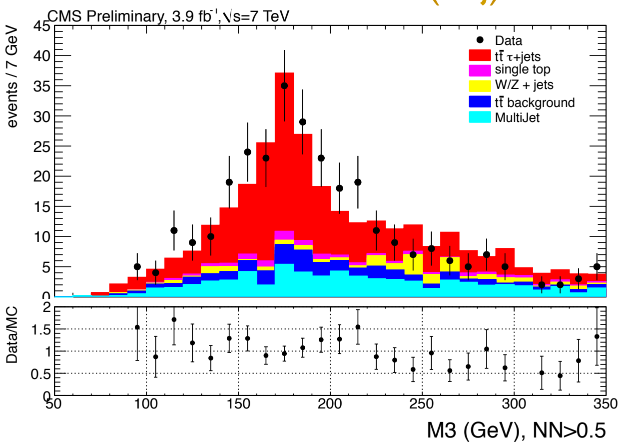
- ATLAS: trigger ≥4 jets, ≥2 b-tags
- Perform binned likelihood fit to the data with the templates; correct for the tau/tau+e fraction with MC

- CMS: trigger on taus
- τ+jets: fit to NN output, fakes modeled from 0-btag data. Main uncert: JES
- τ dilepton: main uncert.: tau fakes, est. from W+jets sample

ATLAS-CONF-2012-032

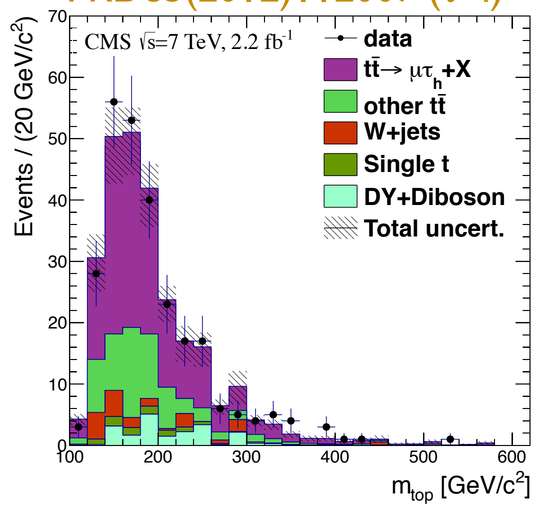


CMS PAS TOP-11-004 (τ+j)



M3=mass of 3 jets with highest E_T

PRD85(2012)112007 (τ+l)



$\sqrt{s}$	σ_{tt} (pb)
7 TeV	$200 \pm 19(\text{stat.}) \pm 43(\text{syst.})$

(τ+jets, 23%)

τ+l combined with other dileptons

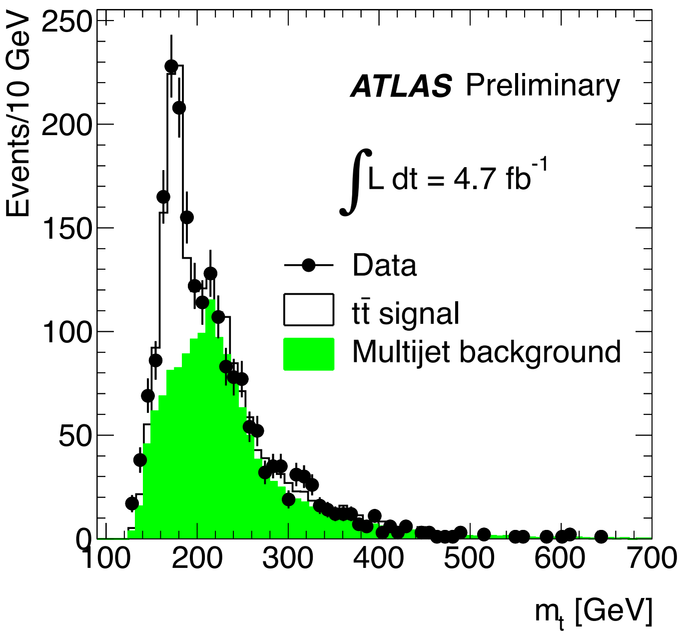
$\sqrt{s}$	σ_{tt} (pb)	
7 TeV	$156 \pm 12(\text{stat.}) \pm 33(\text{syst.}) \pm 3(\text{lumi})$	(τ+jets, 22%)
7 TeV	$143 \pm 14(\text{stat.}) \pm 22(\text{syst.}) \pm 3(\text{lumi})$	(τ+lep, 18%)

All hadronic

- Kinematic fit used to sort jets combinations to reconstruct m_t
- Multijet background modeled from 0-b-tag control region

- ATLAS: Largest uncertainties: JES, b-tag, ISR/FSR, parton shower modeling

ATLAS-CONF-2012-031

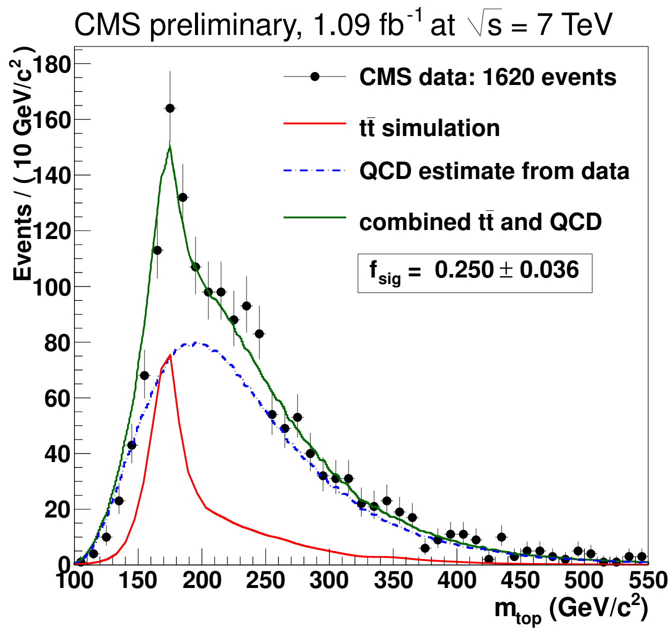


$\sqrt{s}$	σ_{tt} (pb)
7 TeV	$168 \pm 12(\text{stat.})^{+60}_{-57}(\text{syst.}) \pm 6(\text{lumi})$

(35%)

- CMS: Largest uncertainties: b-tag, JES, background modeling

CMS PAS TOP-11-007



$\sqrt{s}$	σ_{tt} (pb)
7 TeV	$136 \pm 20(\text{stat.}) \pm 40(\text{syst.}) \pm 8(\text{lumi})$

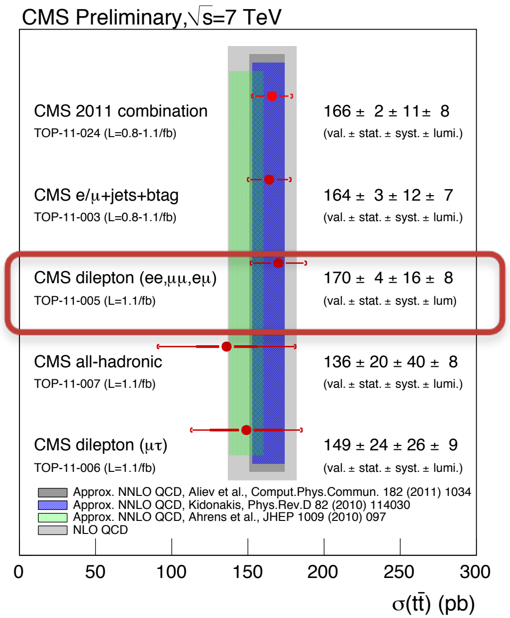
(33%)

σ_{tt} combinations at 7,8 TeV

- CMS combination using 0.8-1.1 fb-1 at 7 TeV
- Combination done using a binned maximum likelihood
- Gain 21% of stat. and 11% of syst. uncertainty compared to the l+jets channel (7 TeV)
- Combination cross-checked with a BLUE method

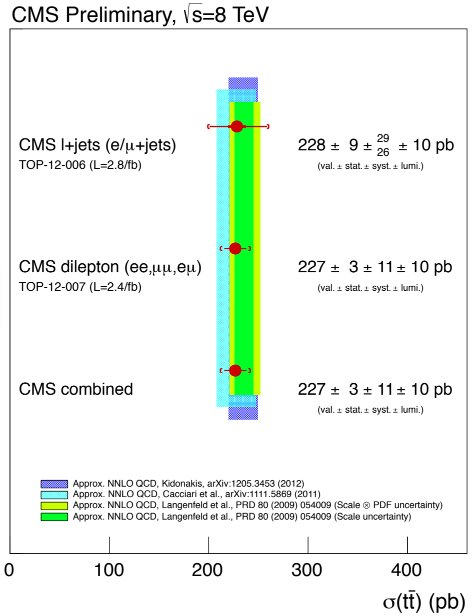
- ATLAS combination using 0.7-1.0 fb-1.
- Combination done using a profile likelihood ratio method.
- Gain 25% of stat. and 11% of syst. uncertainties compared to the l+jets channel

CMS PAS TOP-11-024

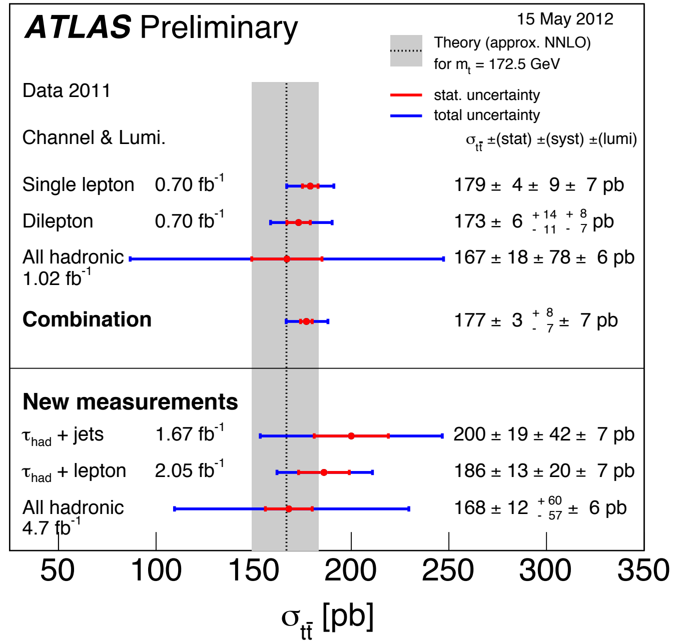


old!

CMS PAS TOP-12-007



ATLAS-CONF-2012-024



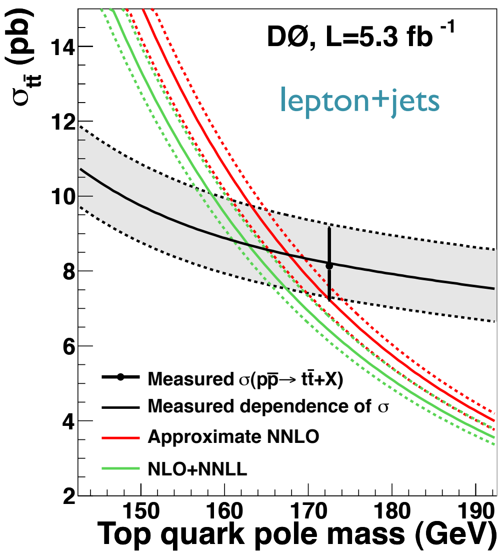
CMS PAS TOP-12-007

$$\frac{\sigma_{t\bar{t}}(8\text{TeV})}{\sigma_{t\bar{t}}(7\text{TeV})} = 1.41 \pm 0.10$$

$\sqrt{s}$	σ_{tt} (pb)	
7 TeV	$177 \pm 3(\text{stat.})^{+8}_{-7}(\text{syst.}) \pm 7(\text{lumi})$	(ATLAS, 7.3%)
7 TeV	$166 \pm 2(\text{stat.}) \pm 11(\text{syst.}) \pm 8(\text{lumi.})$	(CMS, 8.0%)
8 TeV	$227 \pm 3(\text{stat.}) \pm 11(\text{syst.}) \pm 10(\text{lumi})$	(CMS, 6.7%)

m_t from tt^{bar} cross section

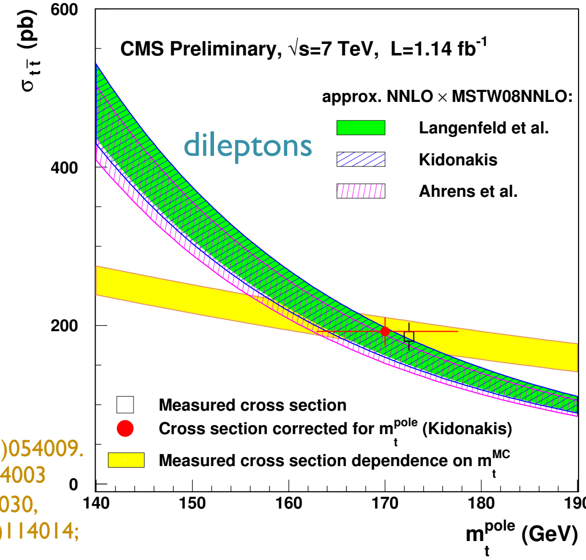
- tt^{bar} cross section has a strong dependence on m_t: pole mass vs MS^{bar} definition matters! The level of precision does not compare with direct measurements so far



D0: PLB703(2011)422 — Pole mass — MS^{bar} mass

Theory prediction	m_t^{pole}(GeV)	m_t^{MS}(GeV)
NLO – Nadolsky et al. [1]	$164.8^{+5.7}_{-5.4}$	-
NLO+NLL, Cacciari et al. [2]	$166.5^{+5.5}_{-4.8}$	-
NLO+NNL, Ahrens, et al. [3]	$163.0^{+5.1}_{-4.6}$	$154.5^{+5.0}_{-4.3}$
Approx. NNLO, Langfeld et al. [4]	$167.5^{+5.2}_{-4.7}$	$160.0^{+4.8}_{-4.3}$
Approx. NNLO, Kidonakis [5]	$166.7^{+5.2}_{-4.5}$	-

[1] Nadolsky, et al. PRD78(2008)013004, Beenakker, et al. PRD40(1989)54
[2] Cacciari et al. JHEP0404(2004)068
[3] Ahrens et al. JHEP1009(2010)097; Nucl. Phys. B (Proc. S.) 205–206 (2010) 48
[4] Langenfeld et al PRD80(2009)054009. Moch, Uwer, PRD78(2008)034003
[5] Kidonakis, PRD82 (2010)114030, Kidonakis, Vogt, PRD68(2003)114014;



CMS TOP-11-008 1.1fb^{-1} — ATLAS-CONF-2011-054 35pb^{-1}

Theory prediction	CMS m_t^{pole}(GeV)	CMS m_t^{MS}(GeV)	ATLAS m_t^{pole}(GeV)
Langfeld et al.+ MSTW08 [4]	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$	$166.4^{+7.8}_{-7.3}$
Kidonakis + MSTW08 [5]	$170.0^{+7.6}_{-7.1}$	-	$166.2^{è7.8}_{-7.4}$
Ahrens, et al. + MSTW08 [3]	$167.6^{+7.6}_{-7.1}$	$159.8^{+7.3}_{-6.8}$	$162.2^{+8.0}_{-7.6}$
Langfeld et al.+ HERAPDF15 [4]	$171.7^{+6.8}_{-6.0}$	$164.3^{+6.5}_{-5.7}$	-
Ahrens, et al. + HERAPDF15 [3]	$169.1^{+6.7}_{-5.9}$	$161.0^{+6.8}_{-6.1}$	-