TOP-QUARK MEASUREMENTS AT THE LHC

Results from 2010/2011 and Prospects for the Next Years

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on behalf of the ATLAS and CMS Collaborations
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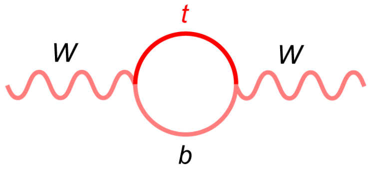
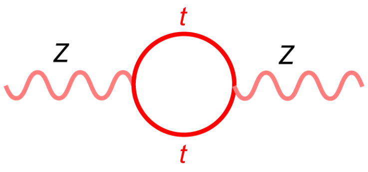
HELMHOLTZ ASSOCIATION

DESY

The Top Quark: A Unique Particle

- Heaviest known particle (173 GeV)
- Dominant contribution to radiative corrections for processes within the SM (Higgs) and beyond

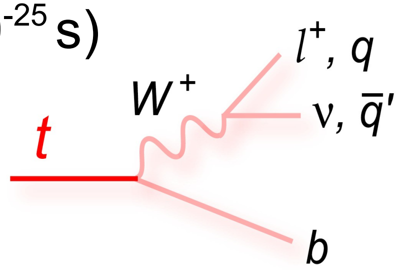




- Special role in electroweak-symmetry breaking?

  Yukawa coupling ≈ 1
- Several models predict new particles preferentially coupling to top quarks

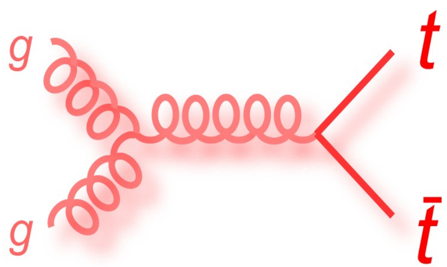
- Decays into Wb before hadronizing ($5 \cdot 10^{-25}$ s)

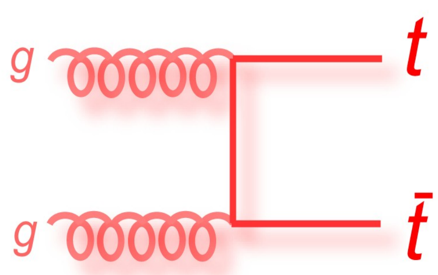


- Allows to study a "bare" quark (e.g.: spin information passed to its decay products)

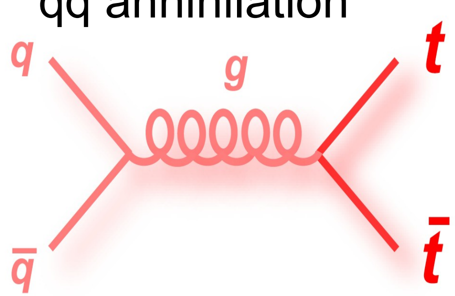
The Top Quark: Production and Decay

- Heaviest known particle (173 GeV)
- At the LHC: mainly produced in pairs from gg fusion



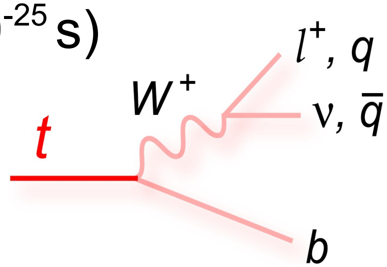


also:
$q\bar{q}$ annihilation

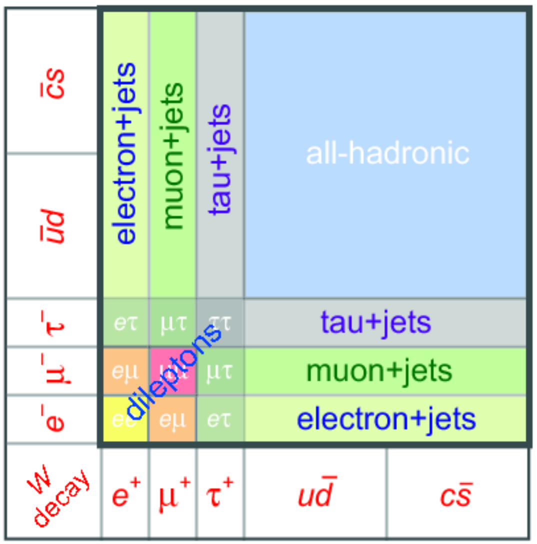


- Single top quarks produced via electroweak interaction (but with much smaller S/B)

- Decays into Wb before hadronizing ($5 \cdot 10^{-25}$ s)



- Events classified according to W decays



Top-Quark Measurements

- Cross section for $t\bar{t}$ production:
  - Lepton+jets, dileptonic, fully-hadronic channels
- Properties:
  - Charge Asymmetry
  - Spin correlations
  - W helicity fractions
  - Mass
  - Charge
- Cross sections for production of single-top quarks:
  - s- and t-channel, associated tW production
- Searches:
  - FCNC, $m_{t\bar{t}}$ resonances, ...

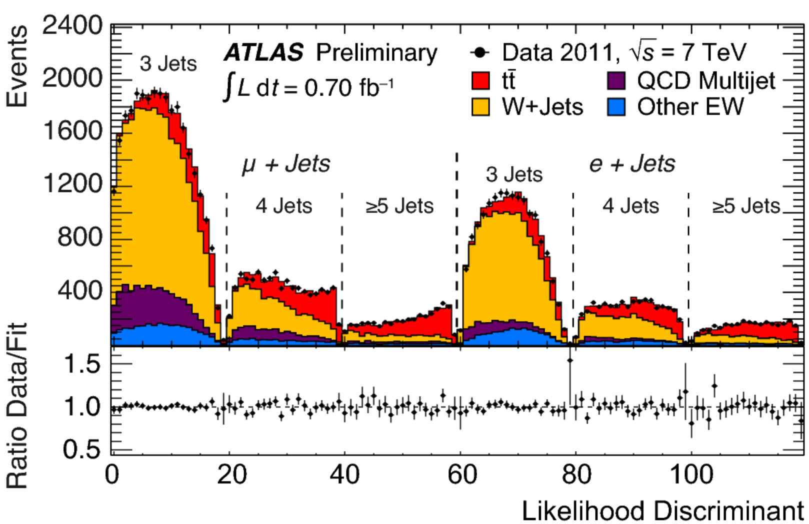
Most results shown today from 0.7 fb^{-1} (ATLAS) and 1.1 fb^{-1} (CMS) of data, all of them taken at $\sqrt{s}$ = 7 TeV

Pair Cross Section from the Lepton+Jets Channel

Both experiments: e+jets and μ+jets events; categorization according to jet multiplicities; profile likelihood (systematics as nuisance parameters, i.e. data itself used to constrain the uncertainties)

ATLAS: CONF-2011-121

Fit to multivariate discriminant;
3,4,≥5 jets, no b-tag information

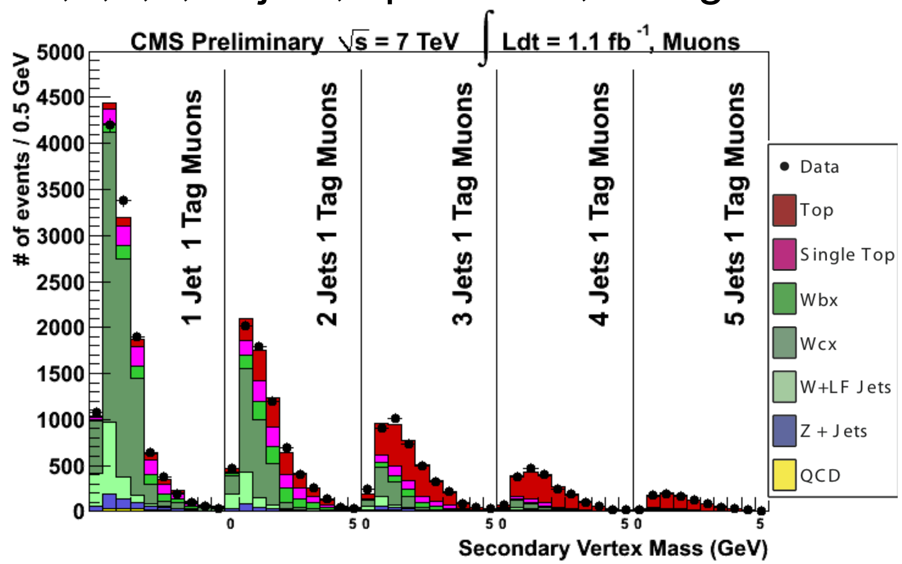


$$\sigma_{t\bar{t}} = 179.0 \pm 3.9\,(\mathrm{stat}) \pm 9.0\,(\mathrm{syst}) \pm 6.6\,(\mathrm{lumi})\ \mathrm{pb}$$

$\delta\sigma/\sigma$ = 6.6% from 0.7 fb^{-1}

CMS: PAS-TOP-11-003

Fit to secondary-vertex mass;
1,2,3,4,≥5 jets; split into 1,≥2 tags



$$\sigma_{t\bar{t}} = 164.4 \pm 2.8(\mathrm{stat.}) \pm 11.9(\mathrm{syst.}) \pm 7.4(\mathrm{lum.})\ \mathrm{pb}$$

$\delta\sigma/\sigma$ = 8.7% from 0.8-1.1 fb^{-1}

Pair Cross Section from the Dileptonic Channel (ee, μμ, eμ)

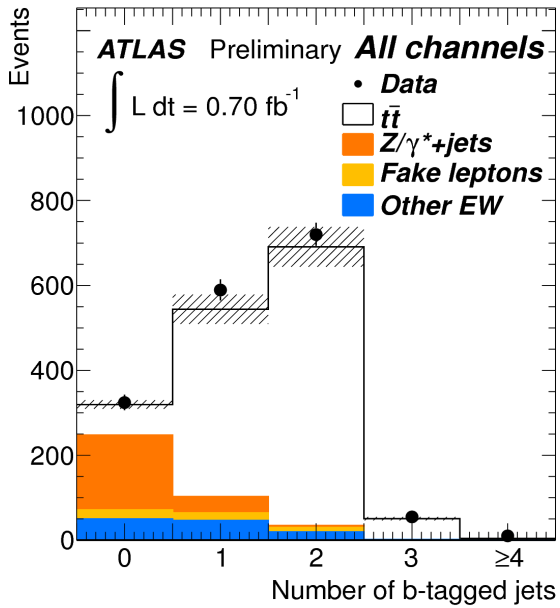
- Cut-and-count measurements
- Requiring significant MET for ee and μμ; vetoing Z-mass region
- Very pure $t\bar{t}$ sample after requiring at least 1 b-tagged jet

ATLAS: CONF-2011-100 (0.7 fb^{-1})

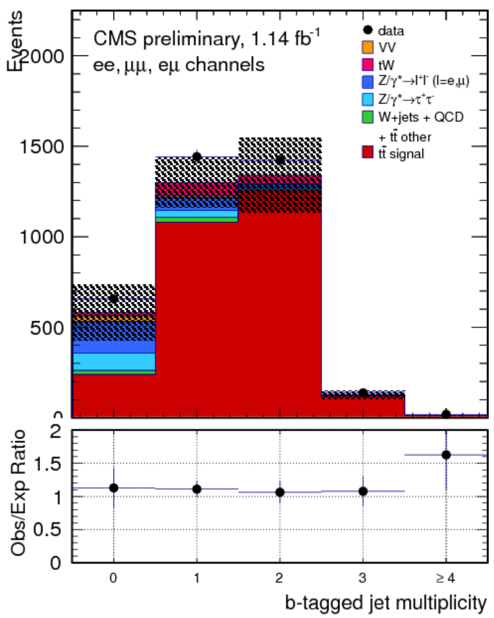
$$\sigma_{t\bar{t}} = 183 \pm 6(\text{stat.})^{+18}_{-14}(\text{syst.})^{+8}_{-7}(\text{lum.})\ \text{pb}$$

CMS: PAS-TOP-11-005 (1.1 fb^{-1})

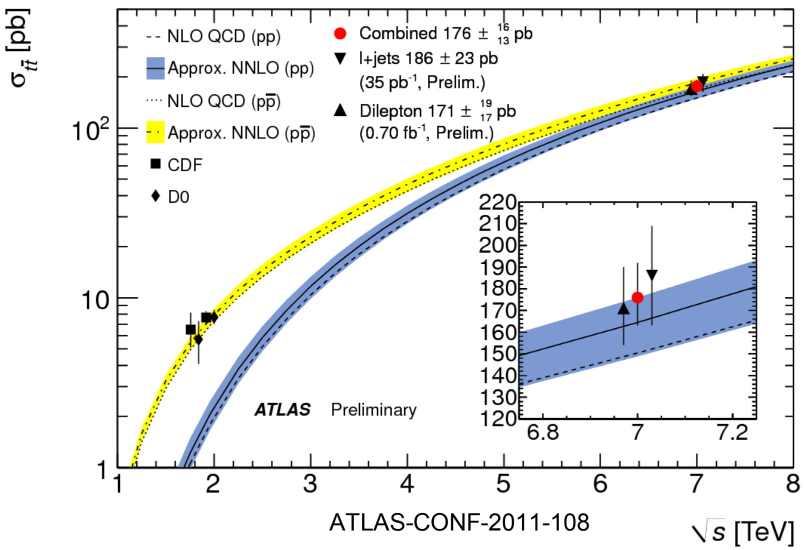
$$\sigma_{t\bar{t}} = 169.9 \pm 3.9\ (\text{stat.}) \pm 16.3\ (\text{syst.}) \pm 7.6\ (\text{lumi.})\text{pb}$$



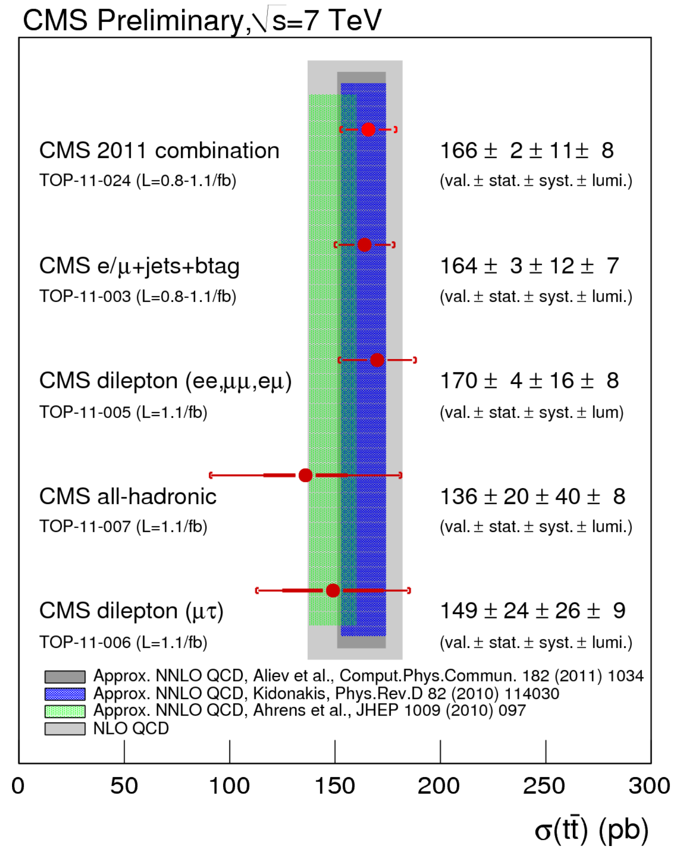
δσ/σ ≈ 11%



Summary of Pair Cross Sections and Comparison to Theory



ATLAS-CMS combination in preparation



- All channels: δ(stat) < δ(syst)
- Consistent results between ATLAS and CMS
- Measurements agree with approx. NNLO QCD
- Uncertainties from lepton+jets and dileptonic channels already at same level as uncertainties of theory predictions
- Fully-hadronic and μτ channels confirm fermion universality and are important benchmarks for many searches

Differential Cross Sections

Allow for precise tests of perturbative QCD and constraints on BSM effects

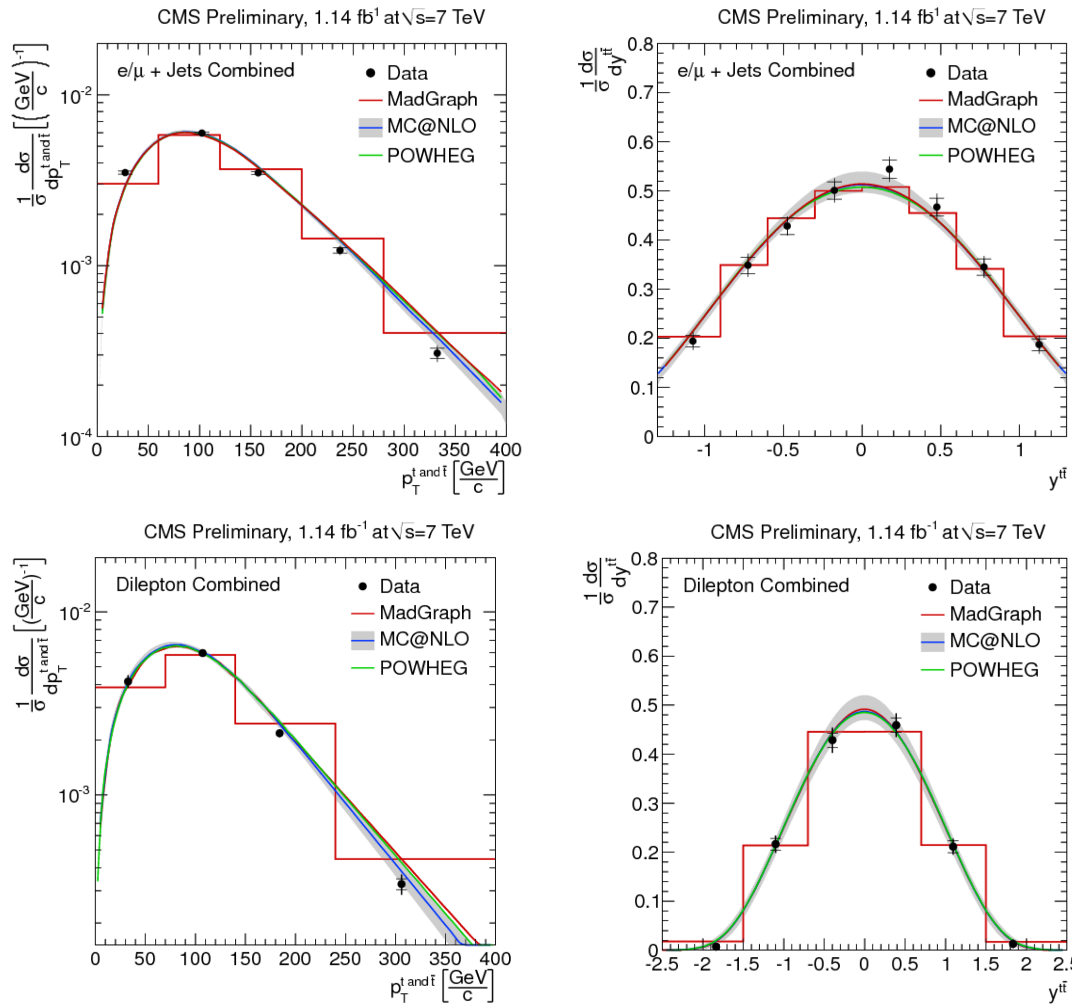
CMS: PAS-11-013

Normalized differential cross sections in lepton+jets and dileptons as a function of...

- $p_T(l)$, $\eta(l)$, $p_T(ll)$, $m(ll)$
- $p_T(t/tbar)$, $y(t/tbar)$
- $p_T(ttbar)$, $y(ttbar)$
- $m(ttbar)$

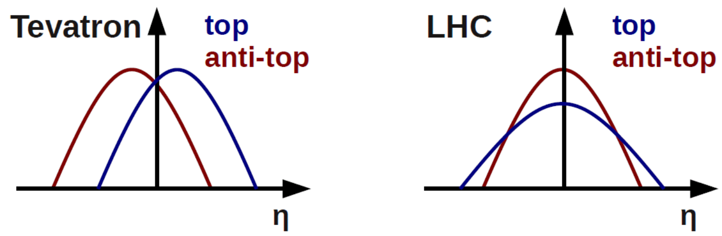
Good Agreement with SM (including NLO models) so far

Higher-order predictions only available for some distributions

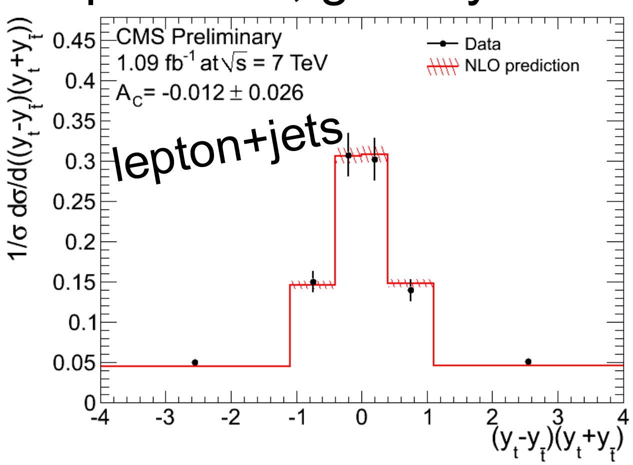


$t\bar{t}$ Charge Asymmetry

- $q\bar{q} \rightarrow t\bar{t}$: (anti-)top quarks preferably emitted in direction of (anti-)quark; small NLO effect! not present at LO and not in $gg \rightarrow t\bar{t}$



- $t\bar{t}$ production via new exchange bosons could enhance the asymmetry
- Tevatron: asymmetry higher than predicted by SM; especially at high $m_{t\bar{t}}$
- LHC: symmetric initial state; but quarks have higher momentum than anti-quarks; central-peripheral instead of forward-backward asymmetry
- Measurement: likelihood technique to reconstruct t and $\bar{t}$ from decay products; get asymmetry from unfolded distribution of sensitive variable



CMS: PAS-TOP-11-014 (1.1 fb^{-1})

$$A_C^{\eta} = -0.016 \pm 0.030\,(\text{stat.})^{+0.010}_{-0.019}(\text{syst.}) \qquad A_C^{\eta}(theo.) = 0.013 \pm 0.001$$

$$A_C^{y} = -0.013 \pm 0.026\,(\text{stat.})^{+0.026}_{-0.021}(\text{syst.}) \qquad A_C^{y}(theo.) = 0.011 \pm 0.001$$

ATLAS: CONF-2011-106 (0.7 fb^{-1})

$$A_C = -0.024 \pm 0.016\,(\text{stat.}) \pm 0.023\,(\text{syst.})$$

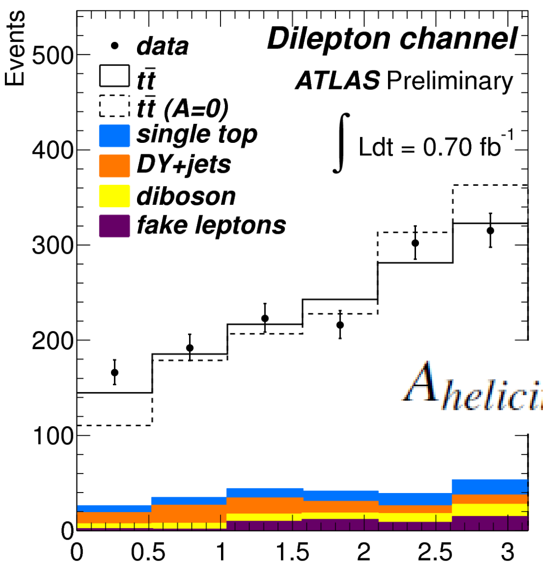
SM prediction: 0.006

$t\bar{t}$ Spin Correlations / W Polarization

- $t\bar{t}$ unpolarized but spins correlated
- Short lifetime: no spin flip before decay; correlation handed over
- Correlation strength:

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

ATLAS: CONF-2011-117 (0.7 fb^{-1})



Template fit to $\Delta\varphi$(ll) in dileptonic channel

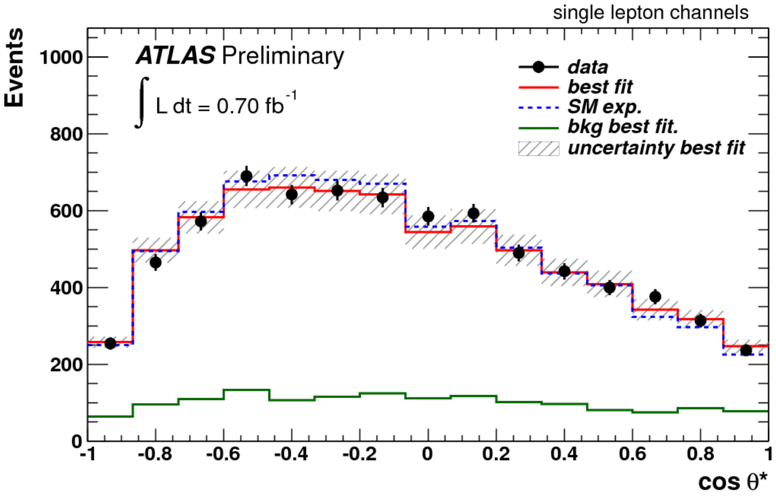
$$A_{helicity} = 0.34^{+0.15}_{-0.11}$$

NLO QCD:
A = 0.32

Different regime and quantization axis than Tevatron; complementary test of the spin!

- W polarization can be obtained from Θ*: angle between lepton and b-quark in the W rest frame

ATLAS: CONF-2011-122 (0.7 fb^{-1})
lepton+jets and dileptons



- Extract helicity fractions F_0, F_L, F_R; constrain anomalous Wtb coupl.

Top-Quark Mass via Ideogram/Template Method

CMS: PAS-TOP-10-009 l+jets (36 pb^{-1})

- Kinematic fit with lepton, MET and 4 leading jets
- Include all 12 jet combinations and 2 neutrino solutions in final likelihood, assigning weights according to number of b-tags and χ^2 of kinematic fit

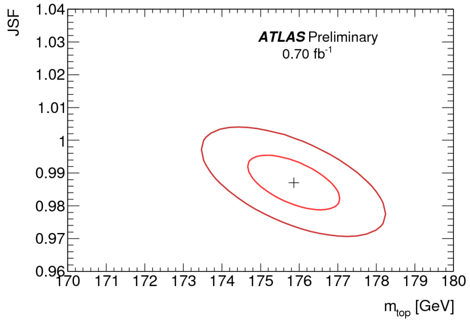
$$\mathcal{L}_{event}\left(x|m_t, f_{t\bar{t}}\right) = f_{t\bar{t}} P_{t\bar{t}}\left(x|m_t\right) + \left(1 - f_{t\bar{t}}\right) P_{bkg}\left(x\right)$$

- Ideograms calibrated using MC samples with varied m_t

$$m_t = 173.1 \pm 2.1(\text{stat})^{+2.8}_{-2.5}(\text{syst})\ \text{GeV}.$$

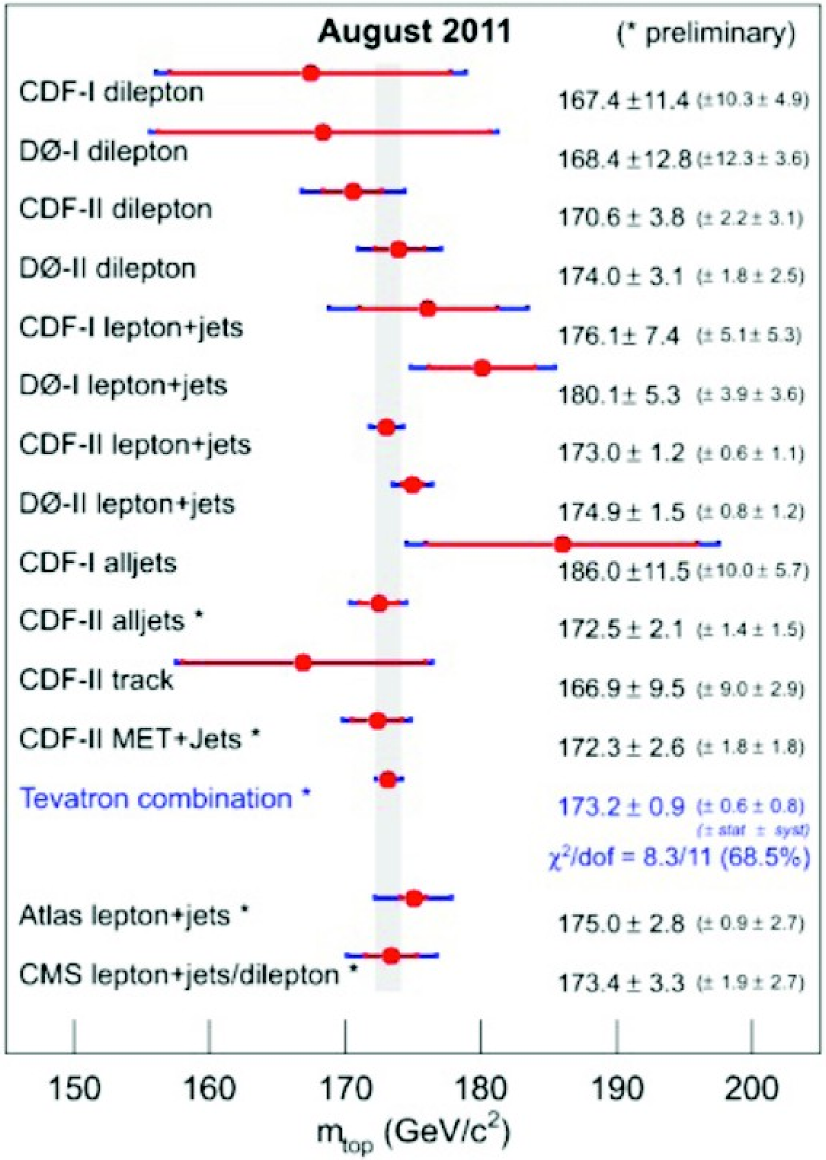
ATLAS: CONF-2011-120 l+jets (0.7 fb^{-1})

- Reconstruct hadronic decay branch: combine all possible light-jet pairs with a tagged jet, choose combination with max. p_T
- MC templates for shape of m_{jjb} and m_{jj} with varied m_t and jet energy; simultaneously fit m_t and jet scale factor in data:



m_t = 175.9 ±0.9(stat) ±2.7(syst) GeV

Top-Quark Mass: Comparison to Tevatron



Courtesy of Frédéric Déliot

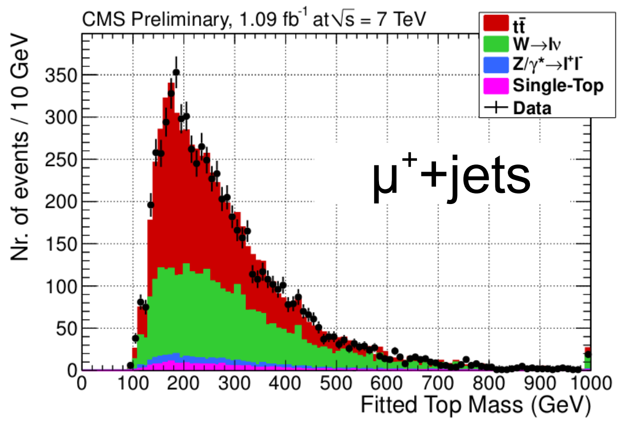
ATLAS-CMS combination in preparation

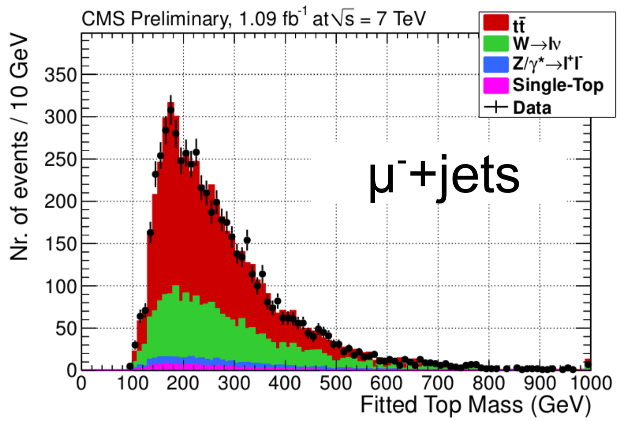
$t\bar{t}$ Mass Difference

- Test of CPT invariance: particle and anti-particle must have same mass
- 2σ deviation recently reported by CDF

CMS: PAS-TOP-11-019 (1.1 fb^{-1})

- Ideogram method (with modified kinematic fitter)
- Compare fitted masses from hadronic side of μ$^+$+jets and μ$^-$+jets events





$$\Delta m_t^{\text{measured}} = -1.20 \pm 1.21\ (\text{stat}) \pm 0.47\ (\text{syst})\ \text{GeV}$$

- Consistent with SM (Δm=0) and already more precise than Tevatron
- Still statistically limited (uncertainties from jet energy largely cancel)

Top-Quark Mass from the Cross Section

Mass-dependence of predicted cross section allows extracting m_t from measured cross section

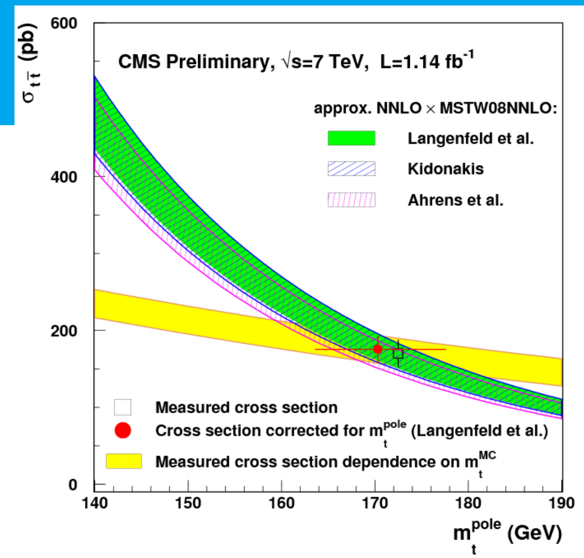
- Most-probable mass results from joint likelihood: theory ⊗ experiment
- 3 different predictions at approximate NNLO
- Unambiguous mass definitions! → More than cross check for direct mass measurements

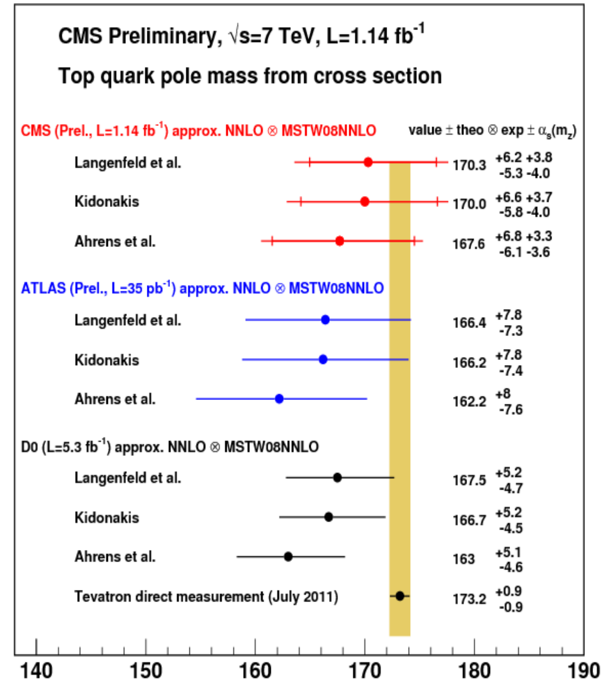
ATLAS: CONF-2011-054

Using lepton+jets cross section from 35 pb^{-1}; extracting pole masses

CMS: PAS-TOP-11-008

Using dileptonic cross section from 1.1 fb^{-1}; extracting masses in pole and $\overline{\text{MS}}$ scheme; testing different proton PDFs; including α_s uncert.





Top-Quark Charge and $t\bar{t}\gamma$ Production

- SM top-quark decay: $t^{(2/3)} \rightarrow b^{(-1/3)} + W^{(+1)}, W^{+} \rightarrow \ell^{+} + \nu_{\ell}$

  Possible exotic charge: $\tilde{t}^{(-4/3)} \rightarrow b^{(-1/3)} + W^{(-1)}, W^{-} \rightarrow \ell^{-} + \bar{\nu}_{\ell}$

ATLAS: CONF-2011-141

Using lepton+jets events (e or μ; large MET; 4 jets; 1 b-tag) in 0.7 fb^{-1}; charge of W from the lepton; charge of b-quark either from summing weighted charges of tracks in the jet or from charge of soft muon in jet

Exotic charge of -4/3 exluded at more than 5 std. dev. (as DØ and CDF)

- Measuring $\sigma_{t\bar{t}\gamma}$ (or $\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}}$) will give a direct handle on Q_t (for known α_{em})

ATLAS: CONF-2011-153

L+jets events (e or μ; large MET; 4 jets; 1 b-tag) that have an isolated photon with p_T > 8 GeV: 122 candidate events in 1.0 fb^{-1} ($f_{sig} \approx 38\%$)

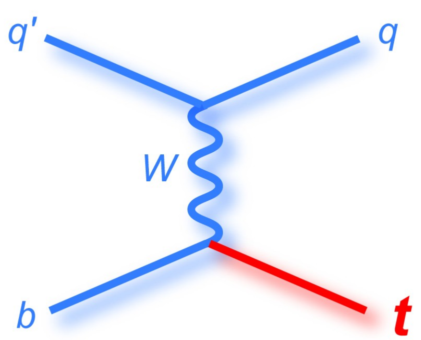
$\sigma_{t\bar{t}\gamma} \cdot \mathrm{BR} = 2.0 \pm 0.5\,(\mathrm{stat.}) \pm 0.7\,(\mathrm{syst.}) \pm 0.08\,(\mathrm{lumi.})\,\mathrm{pb}$ [SM pred.: 2.1±0.4 pb]

Observed (expected) significance: 2.7 (3.0) standard deviations

Production of Single Top Quarks

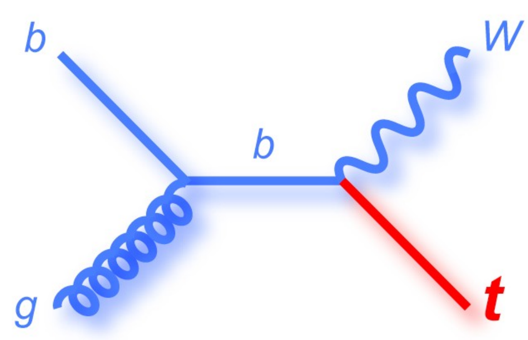
- 3 production modes for single top quarks:

t-channel



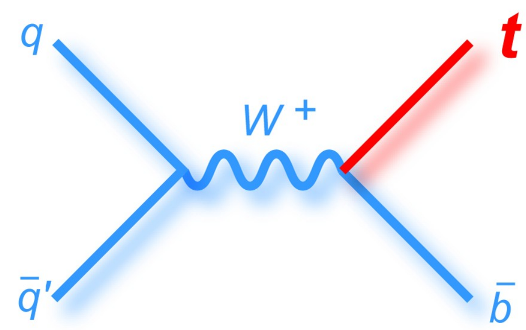
65 ± 3 pb

associated tW production



16 ± 1 pb

s-channel



4.6 ± 0.3 pb

[Approx. NNLO predictions]

- Smaller cross section than pair prod.; higher backgrounds (fewer jets)
- s-channel particularly challenging!

  Observed (expected) limit from ATLAS-CONF-2011-118 with 0.7 fb^{-1}:

  σ_s < 26.5 (20.5) pb at 95% CL

Single Top Quarks in the t-Channel

CMS: TOP-10-008

- Requiring e or μ; reasonable $m_T(W)$; 2 or 3 jets; 1 b-tag
- Combination of 2D measurement with angular variables and multivariate analysis (36 pb^{-1}):

$$83.6 \pm 29.8(\text{stat}+\text{syst}) \pm 3.3(\text{lumi})\ \text{pb}$$

Observed (expected) significance: 3.5 (2.9) standard deviations

- Testing unitarity of CKM matrix:

$$|V_{tb}| = \sqrt{\frac{\sigma^{\text{exp}}}{\sigma^{\text{th}}}} = 1.14 \pm 0.22(\text{exp}) \pm 0.02(\text{th})$$

when assuming $|V_{td}|,|V_{ts}| \ll |V_{tb}|$; and

$|V_{tb}|>0.62$ at 95% CL when $0 \leq |V_{tb}|^2 \leq 1$

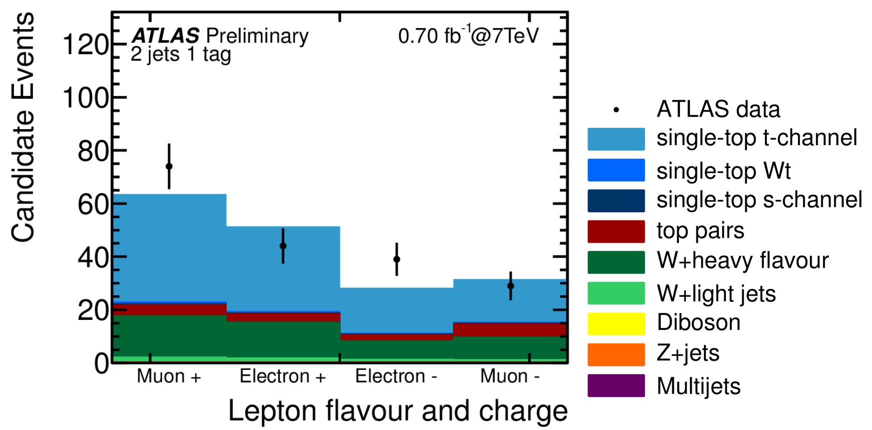
[Phys. Rev. Lett. 107, 091802 (2011)]

ATLAS: CONF-2011-101

- Requiring e or μ; significant MET; 2 or 3 jets; 1 b-tag
- Cut-and-count method (0.7 fb^{-1}):

$$\sigma_t = 90^{+9}_{-9}(\text{stat})^{+31}_{-20}(\text{syst}) = 90^{+32}_{-22}\ \text{pb}$$

Observed (expected) significance: 7.6 (5.4) standard deviations



Single Top Quarks from Associated tW Production

- Event signature very similar to $t\bar{t}$!
- Both experiments look for dileptonic events: 2 opposite-sign leptons; Z-mass veto for ee and μμ; MET; 1 jet
- Cut-and-count measurements

ATLAS: CONF-2011-104

No use of b-tagging

Observed (expected) limit from 0.7 fb^{-1}:

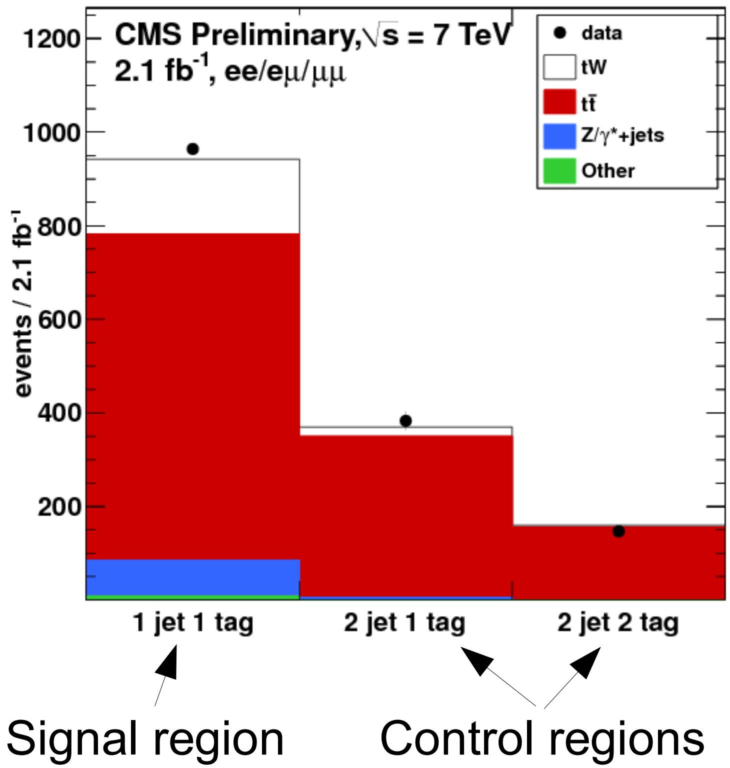
σ_{tW} < 39.1 (40.6) pb at 95% CL

CMS: PAS-TOP-11-022

From 2.1 fb^{-1}: $\sigma_{tW} = 22^{+9}_{-7}$ (stat+syst) pb

Observed (expected) significance:

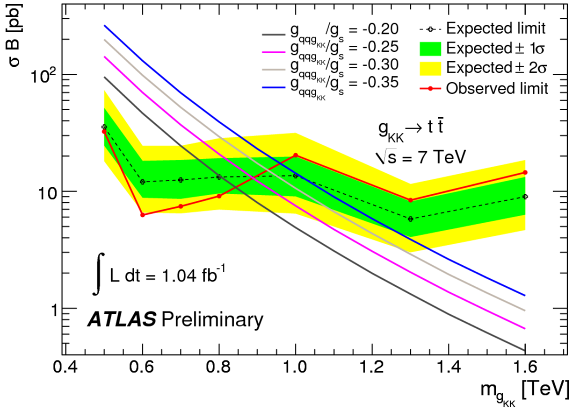
2.7 (1.8) standard deviations



Searches

- Numerous $t\bar{t}$-related searches already carried out by ATLAS and CMS (mainly in lepton+jets and dileptonic channel)

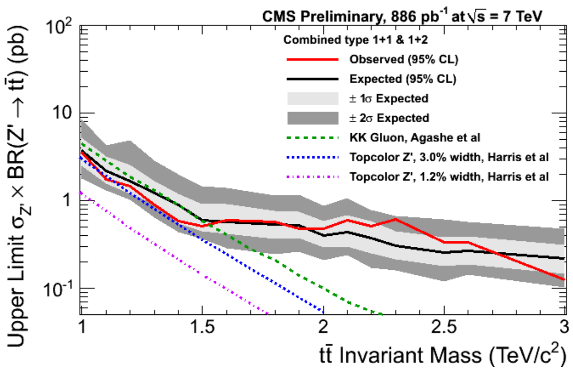
  Examples:
  - Z'; heavy gluons (like Kaluza-Klein)
  - FCNC; same-sign tt pairs



ATLAS-CONF-2011-123

- In some cases, can use standard $t\bar{t}$ selection & reconstruction techniques and, e.g., “simply” look for resonances in the $m_{t\bar{t}}$ spectrum

- Some processes result in high boost of $t\bar{t}$ system: whole top-quark decay contained within a single jet → need special algorithms (sub-jets, top-tagging)



CMS-PAS-EXO-11-006

- No hints for new physics found so far; improving limits

Prospects for the Next Years

See also Andrea Giammanco's talk at TOP2011

- Work on the main systematics
- New/additional measurements
- Increased center-of-mass energy
- Increased beam intensities / collision rates

2012: 15 fb^{-1} at $\sqrt{s}$ = 8 TeV ?

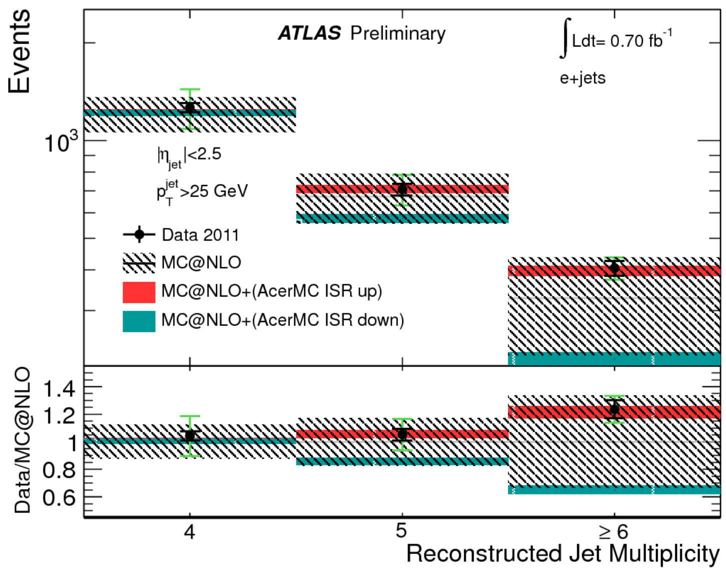
2015: switch to $\sqrt{s}$ = 13 TeV ?

2017: 150 fb^{-1} accumulated ?

Prospects: Main Systematic Uncertainties

- *Large statistics:* will reduce uncertainties of data-driven estimates for, e.g., backgrounds and allow for tighter selections (increased purity)
- Jet energy scale and b-tagging: already better than originally expected; precision will still improve; $t\bar{t}$ events themselves helping
- Modeling uncertainties (ISR/FSR, matching scales, etc.): data itself will constrain parameters

  Example (ATLAS-CONF-2011-42): Measuring $t\bar{t}$+jets as a function of jet multiplicity allows testing ISR model



- Proton PDF: (differential) $t\bar{t}$ cross sections should constrain the gluon at high x; b-quark component could be tested with single top quarks

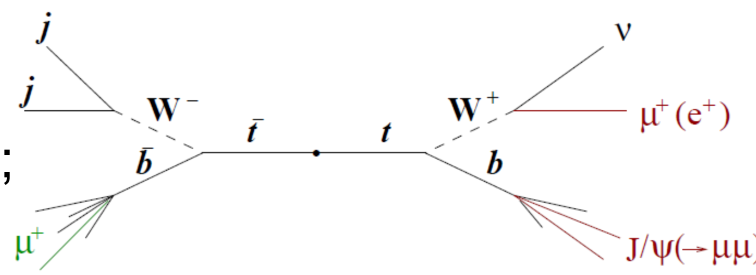
Prospects: Additional Measurements

- Large data sets will allow for many new differential measurements and access to rare $t\bar{t}X$ production modes
- Measurements of the top-quark mass:

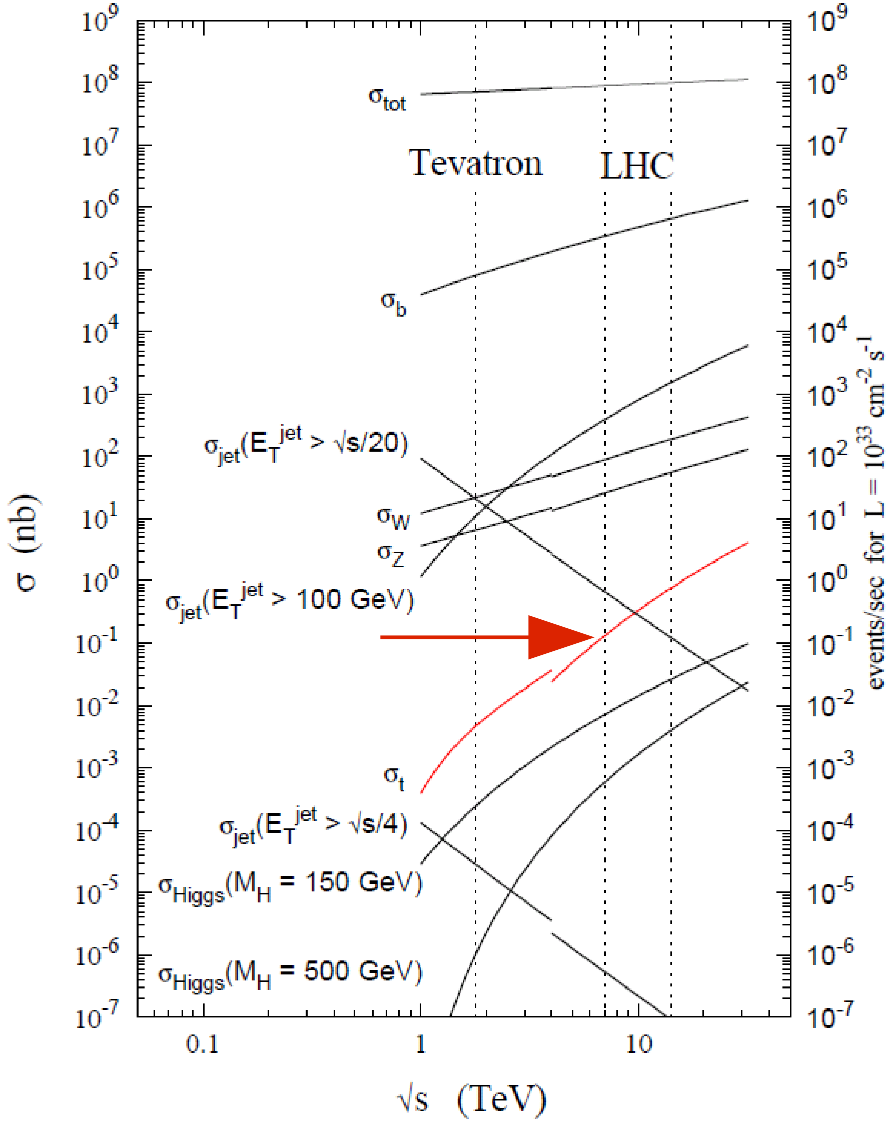
  Might become competitive with Tevatron but will be very hard to do better

  Some techniques not yet used (at the LHC):

  - Lepton p_T: extracted m_t closer to pole mass (W emitted before QCD enters the game)? statistics limited at the Tevatron
  - b-Hadron decay length: At the Tevatron, systematics dominated by background estimates (had to use lepton+jets with lower purity to get enough statistics)
  - M(l,J/ψ): low rate but very clean; not used at Tevatron; ~900 events in 10 fb^{-1} at 7 TeV; small systematics expected (CMS Physics TDR II)



Prospects: Increased Center-of-Mass Energy



- Running at higher $\sqrt{s}$ less crucial for SM $t\bar{t}$ than for Higgs and BSM searches but still helps
- Compared to 7 TeV, $\sigma_{t\bar{t}}$ increases by 43% when going to 8 TeV and by factors of ~5 for 13 or 14 TeV
- Main backgrounds (e.g. W+jets) increase less steeply → better S/B
- In addition, could take advantage of different dependencies on $\sqrt{s}$: simultaneously fit data at different energies with background ratios $\sigma_{bkg}(E)/\sigma_{bkg}(E')$ constrained to SM prediction

Prospects: Increased Intensities / Rates

- Total trigger rates of the experiments have to be kept stable:

  Increased interaction rates require to tighten trigger thresholds and/or use more complex triggers, combining different trigger objects like leptons, jets, b-tags and MET ("cross triggers")

  Problematic mainly for fully-hadronic channels (and τ)

- Already in 2011, up to 30 pile-up interactions per event (9 on average); might get > 40 pile-up interactions soon (~25 on average?)

  Pile-up degrades jet and MET resolutions as well as lepton, vertex-finding and b-tag efficiencies

  However, first studies suggest manageable impact on top-quark measurements

  For example: reconstructed top-quark mass depends linearly on number of reconstructed vertices → easy to correct for

  Remaining losses in resolution / sensitivity compensated by gain in integrated luminosity, i.e. signal statistics

Summary and Conclusions

- Top quarks offer unique possibilities
  - to test QCD and electroweak predictions
  - to look for new physics
- The LHC has started to be a real “top factory”
- Huge physics program: cross sections, properties, searches
- Many results already competitive with Tevatron
- Effort on improving the systematics (e.g. data-driven profiling techniques)
- Large statistics will allow tradeoff for the benefit of systematics and enable several new measurements
- Encouraging prospects for the upcoming LHC running periods

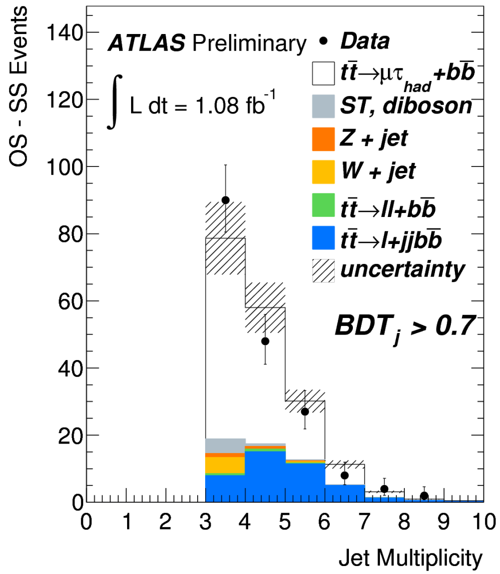
Further Reading

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

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

Pair Cross Section from the μτ Channel

- Selecting μτ events with hadronic τ decays
- Requiring at least 1 b-tagged jet and opposite charge of μ and τ
- Main challenge: determination of τ fake rates and ID efficiency

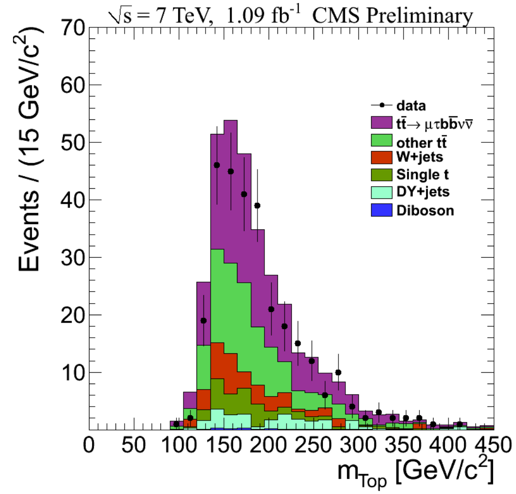


ATLAS: CONF-2011-119

Cutting on a multivariate discriminant (BDT)

$$\sigma_{t\bar{t}} = 142 \pm 21\ (\text{stat.}) \pm^{20}_{16}\ (\text{syst.}) \pm 5\ (\text{lumi.})\ \ \text{pb}$$

$\delta\sigma/\sigma$ = 21% from 1.1 fb^{-1}



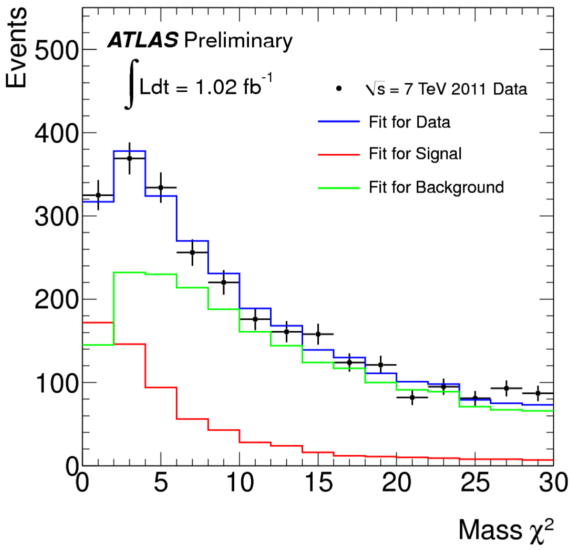
CMS: PAS-TOP-11-006

$$\sigma_{t\bar{t}}^{\tau-dil} = 148.7 \pm 23.6(\text{stat.}) \pm 26.0(\text{syst.}) \pm 8.9(\text{lumi.})\ \text{pb}$$

$\delta\sigma/\sigma$ = 24% from 1.1 fb^{-1}

Pair Cross Section from the Fully-Hadronic Channel

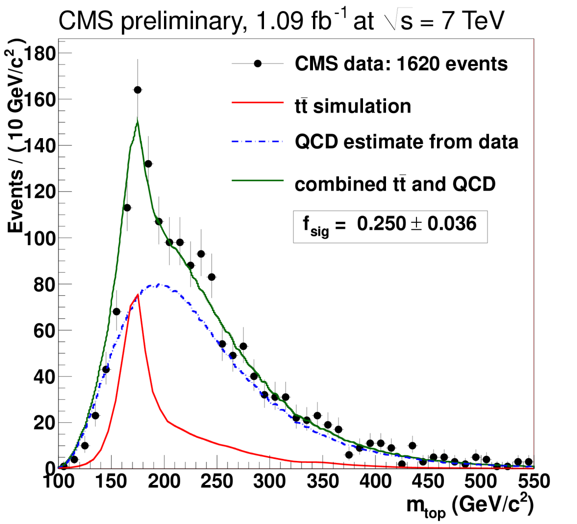
- Requiring 2 b-tagged jets before performing a kinematic fit to test the $t\bar{t}$ hypothesis
- Shapes of resulting χ^2 (ATLAS) and m_t (CMS) distributions used to determine the signal fraction
- Main challenge: background modeling (estimate QCD at high jet multiplicities from data)



ATLAS: CONF-2011-140

$$\sigma(pp \to t\bar{t}) = 167 \pm 18\ (\text{stat.})\ \pm 78\ (\text{syst.})\ \pm 6\ (\text{lum.})\ \text{pb}$$

$\delta\sigma/\sigma$ = 48% from 1.0 fb^{-1}



CMS: PAS-TOP-11-007

$$\sigma_{t\bar{t}} = 136 \pm 20\ (\text{stat.}) \pm 40\ (\text{sys.}) \pm 8\ (\text{lumi.})\ \text{pb}$$

$\delta\sigma/\sigma$ = 33% from 1.1 fb^{-1}