

The background image shows a dirt path leading through a grassy field towards a large, leafy tree on the right. The sky is filled with dramatic, colorful clouds at sunset or sunrise.

CMS Results on Top Physics

Andrew Ivanov

Kansas State University

On behalf of the CMS Collaboration

LHC on the March

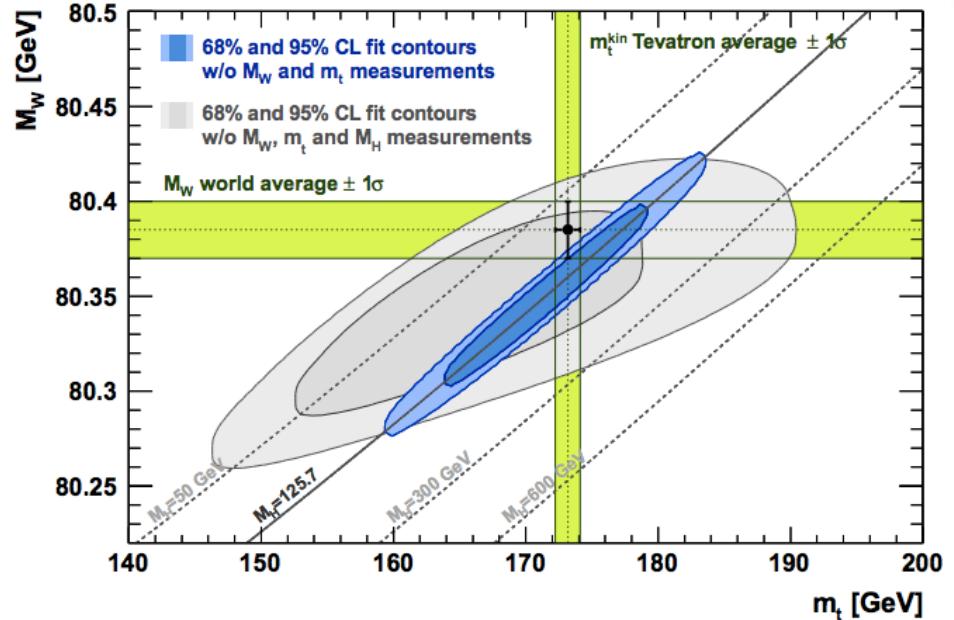
IHEP, Protvino, Russia

November 22, 2012



Top Quark

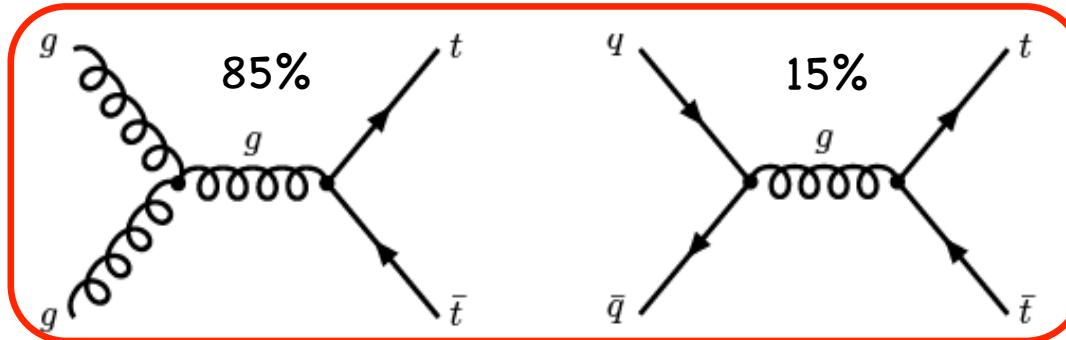
- Heaviest known fundamental particle
- Yukawa coupling is $y_t \sim 1$
- Plays a special role in the EWK symmetry breaking ?
- Precise measurement of mass is crucial for accurate tests of SM
- Decays before hadronization
 - allows to probe spin structure
- Background for new physics events
- Detailed study of kinematic properties might reveal non-SM contributions
 - New particles might decay into top quarks
 - New particles might be produced in top decays





Top Quark Production at LHC

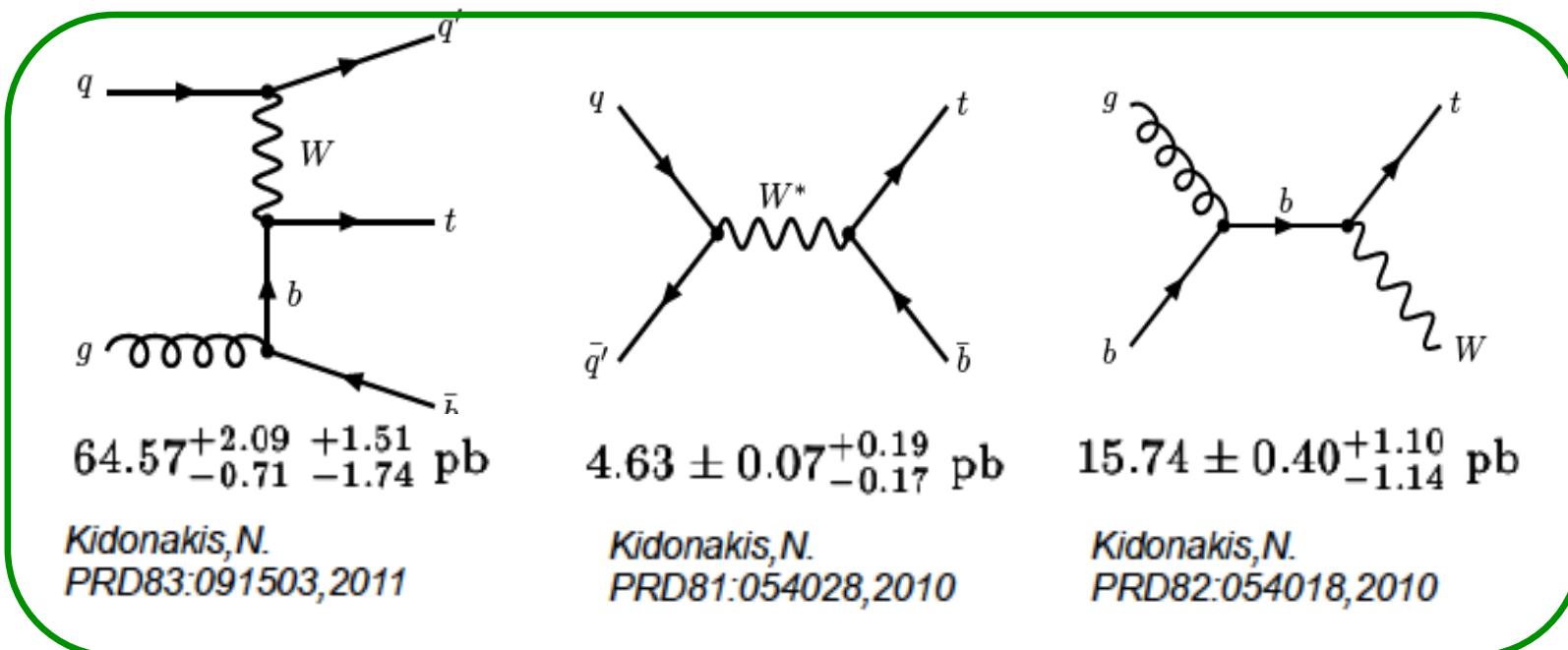
Top Quark Pair Production



165^{+11}_{-16} pb, @ 7 TeV
Aliev, M. et al (X 1.4 @ 8 TeV)
[arXiv/hep-ph:1007.1327](https://arxiv.org/abs/hep-ph/1007.1327)

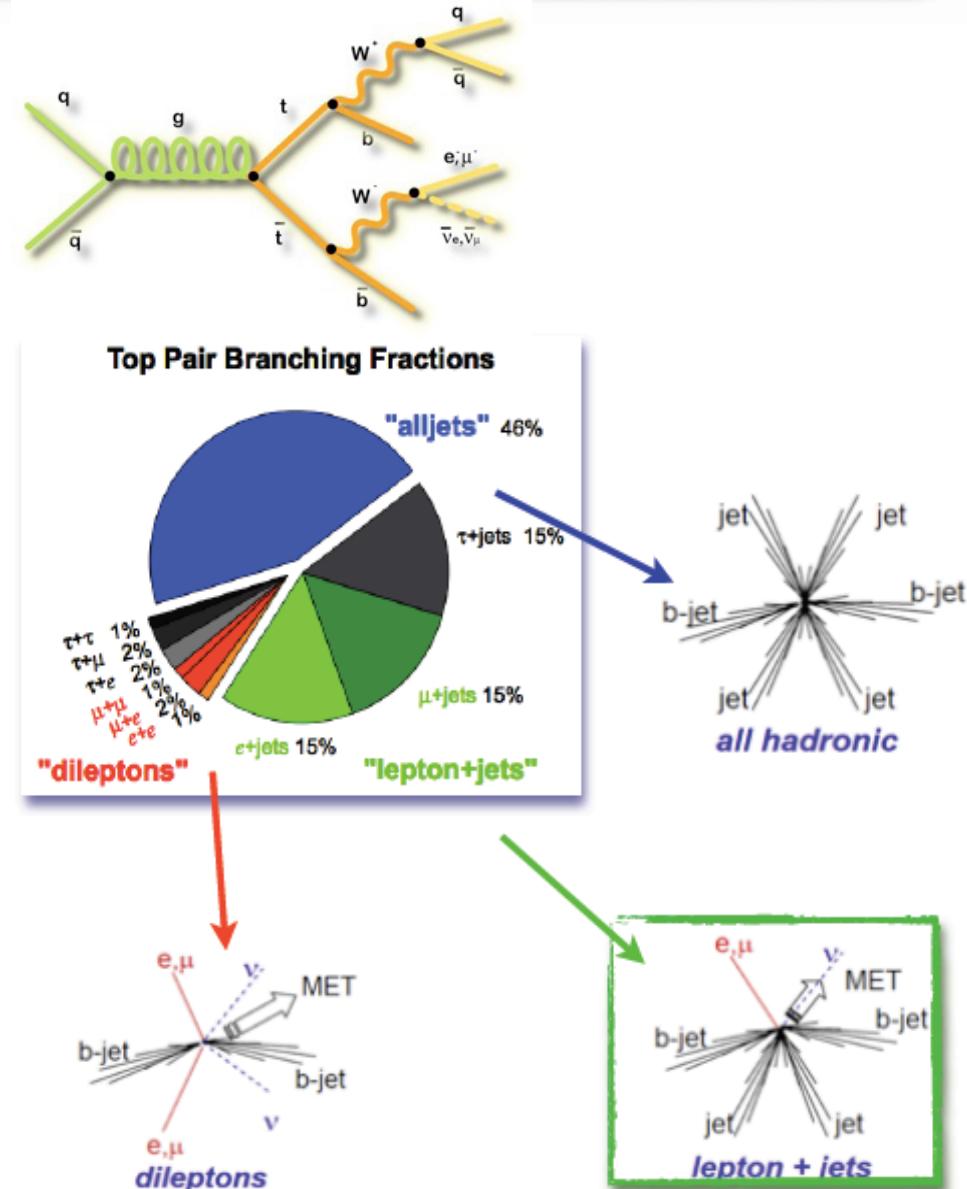
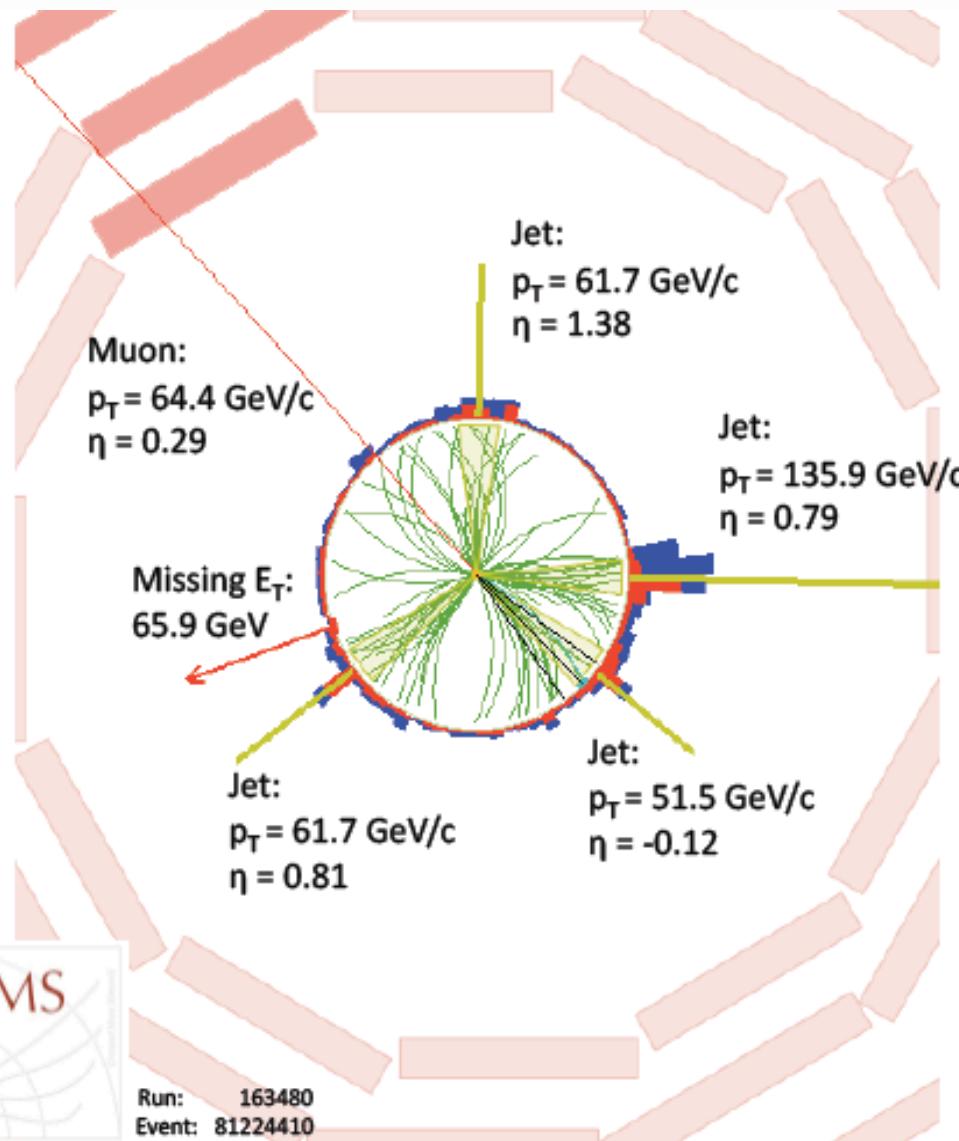
- Approximate NNLO Calculations

Single Top Production





Top Pair Events at LHC

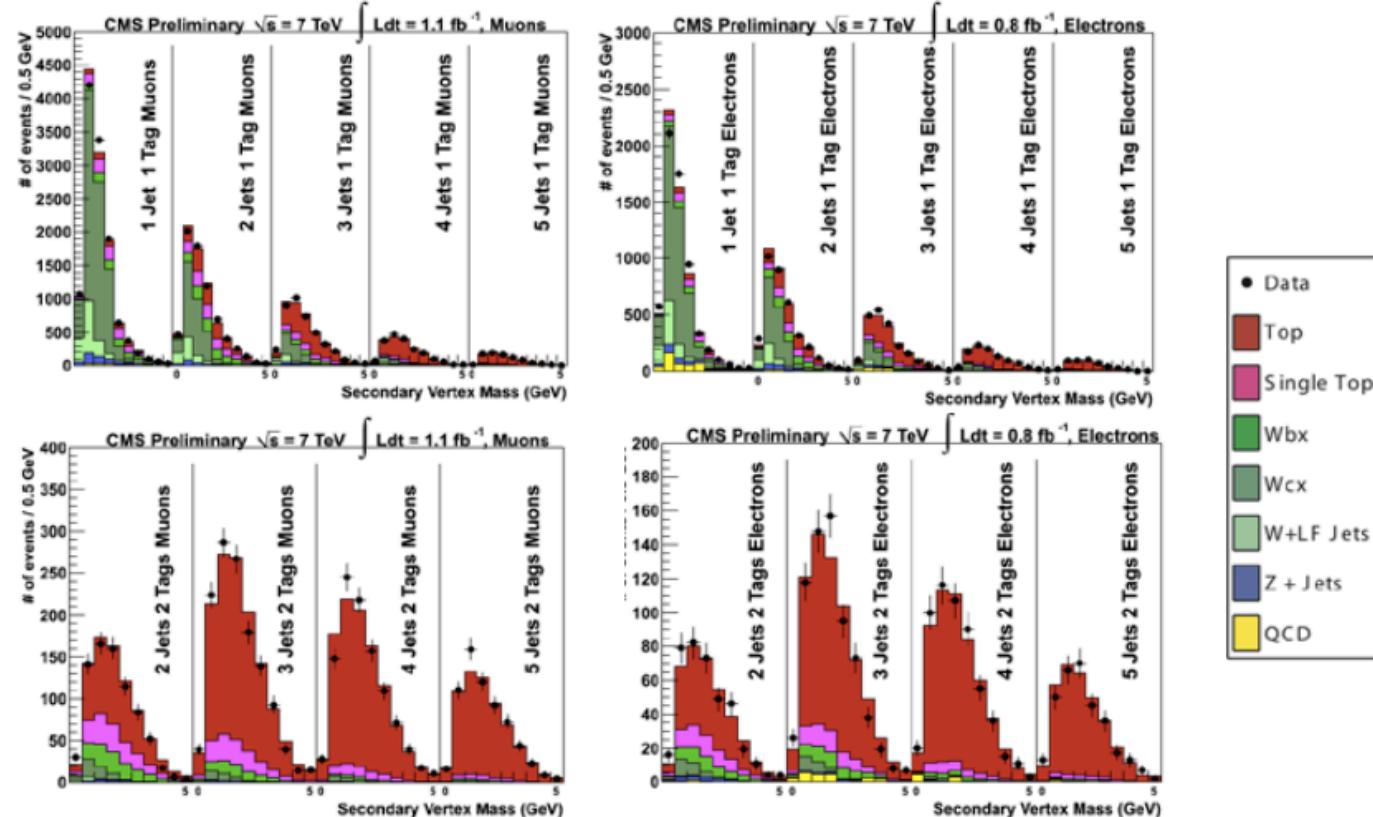




Top Pair Cross Section Lepton + Jets Channel

- Simultaneous likelihood fit across different jet and b-tag multiplicities
- Secondary vertex mass, split into # of jets(1-4,>=5), b-tags(1,>=2)
- Main background: W+jets (light/heavy flavor)

$$\sigma_{tt} = 164.4 \pm 2.8 \text{ (stat.)} \pm 11.9 \text{ (syst.)} \pm 7.4 \text{ (lumi)} \text{ pb}$$



CMS-PAS-TOP-11-003



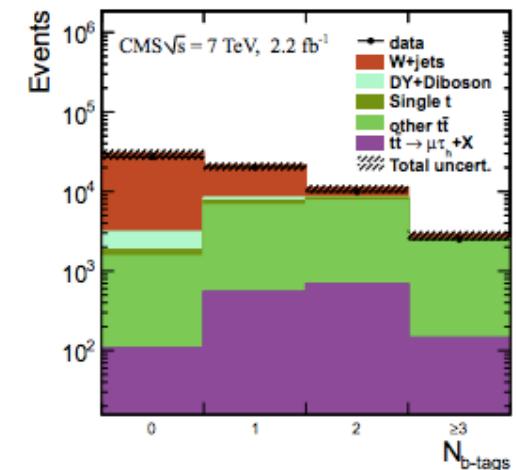
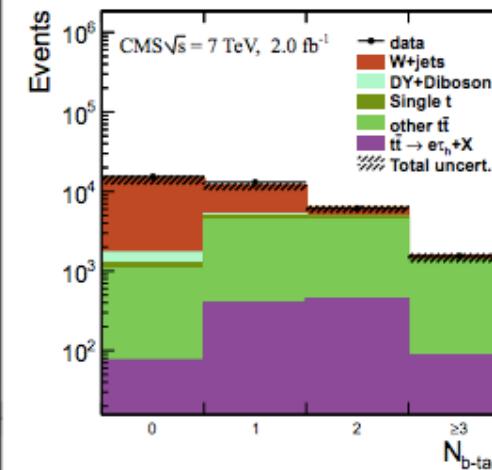
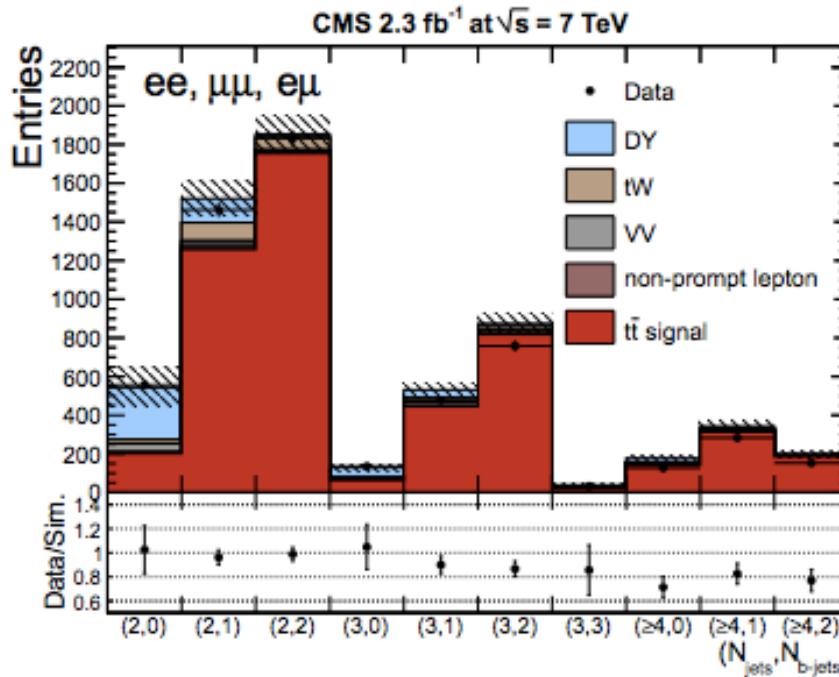
Top Pair Cross Section Dilepton Channel

- $l = e \text{ Or } \mu$, small backgrounds:
 - DY + jets,
 - W+jets via mis-identified second lepton
- Likelihood fit using different jet and b-tag multiplicities

$$\sigma_{tt} = 161.9 \pm 2.5 \text{ (stat.)} \pm 5.1 \text{ (syst.)} \pm 3.6 \text{ (lumi) pb}$$

- Hadronic τ identification
- Matrix method, evaluate p_T, η – dependent fake rate from multi-jets and $W + \geq 1$ jet events

$$\sigma_{tt} = 143 \pm 14 \text{ (stat.)} \pm 22 \text{ (syst.)} \pm 3 \text{ (lumi) pb}$$



arXiv: 1208.2671

22-Nov-2012

ANDREW IVANOV, KSU

arXiv: 1203.6810

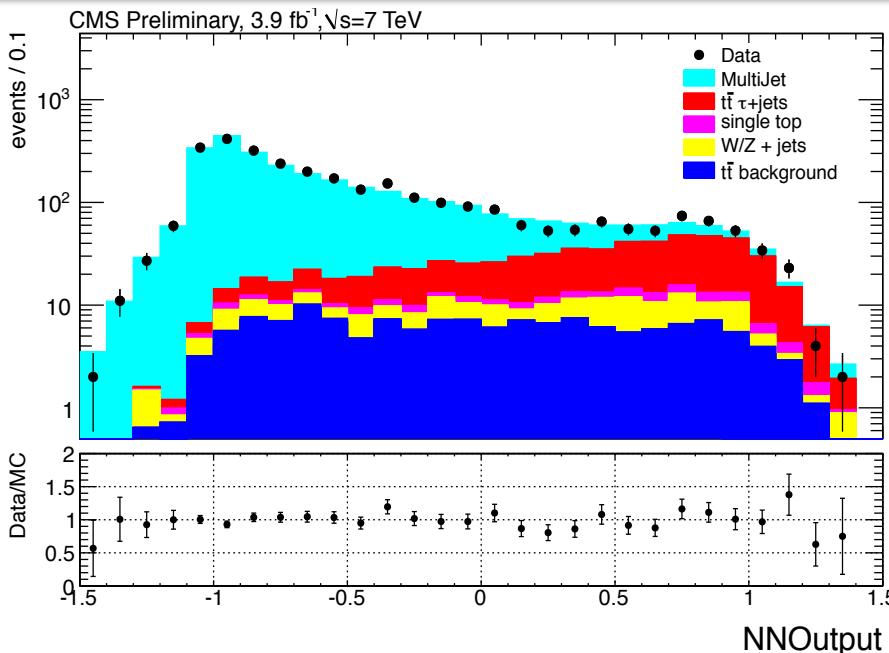


$\tau_h + \text{jets}$ and all-hadronic channels

- τ ID, kinematic event variants and χ^2 , constraining W and top quark masses, used to train ANN
- QCD multi-jet (gluons) shape is obtained from data low met signif. region
- $t\bar{t}\mu + \text{jets}$ from data used to obtain quark-jet shape

CMS-PAS-TOP-11-004

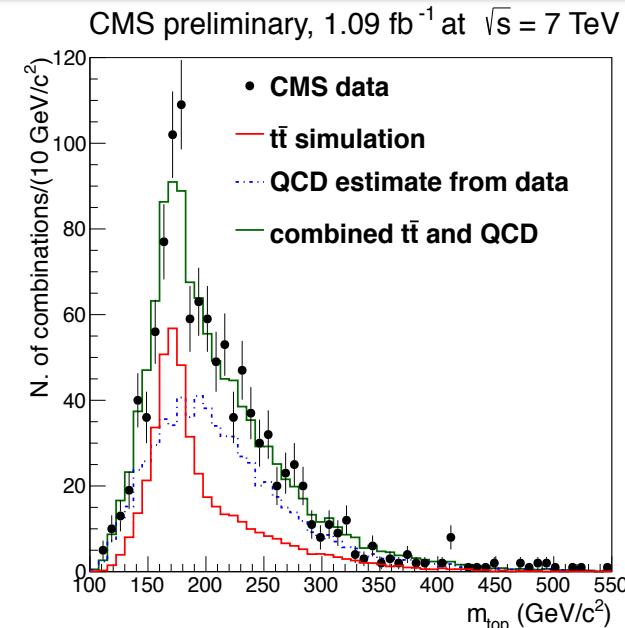
$$\sigma_{t\bar{t}} = 156 \pm 12 \text{ (stat.)} \pm 33 \text{ (syst.)} \pm 3 \text{ (lumi)} \text{ pb}$$



- Multi-jet trigger, ≥ 2 b-tags using combination of high purity taggers
- Fit to reconstructed top quark mass using χ^2
- Multi-jet shape is taken from 0 b-tag region, corrected for b-tag p_T , η -dependent efficiency

CMS-PAS-TOP-11-007

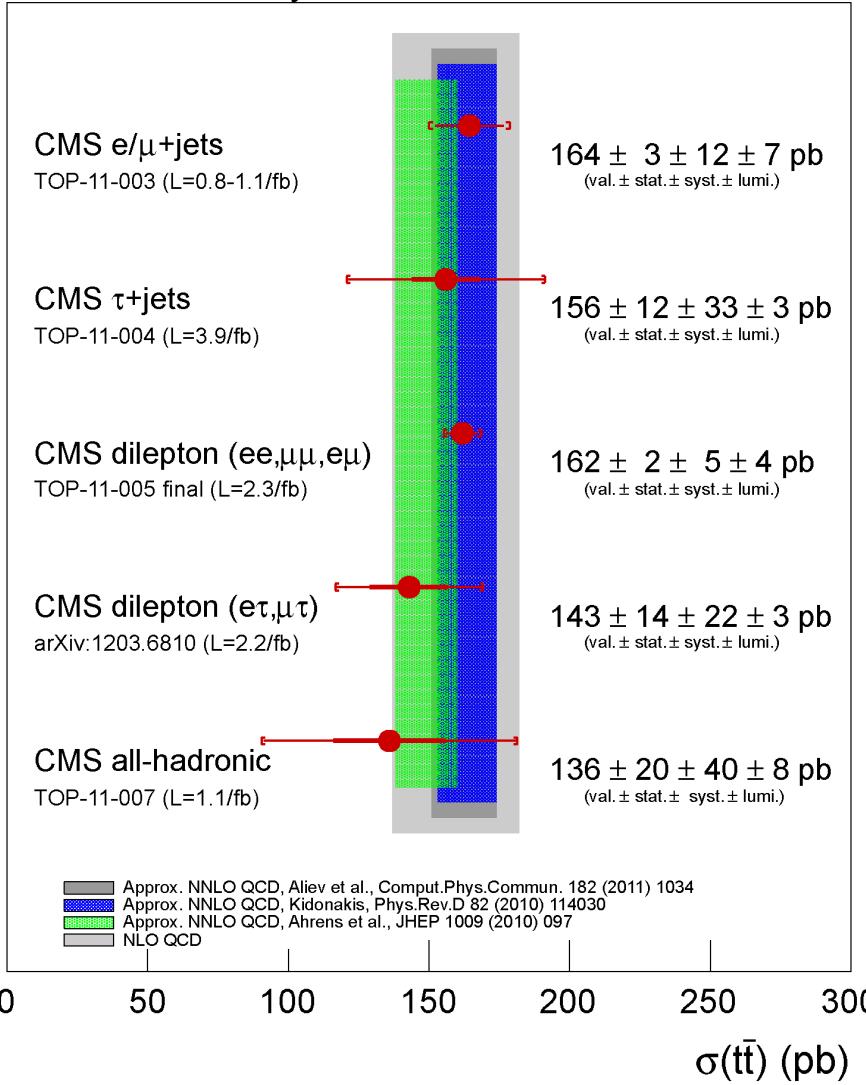
$$\sigma_{t\bar{t}} = 136 \pm 20 \text{ (stat.)} \pm 40 \text{ (syst.)} \pm 8 \text{ (lumi)} \text{ pb}$$



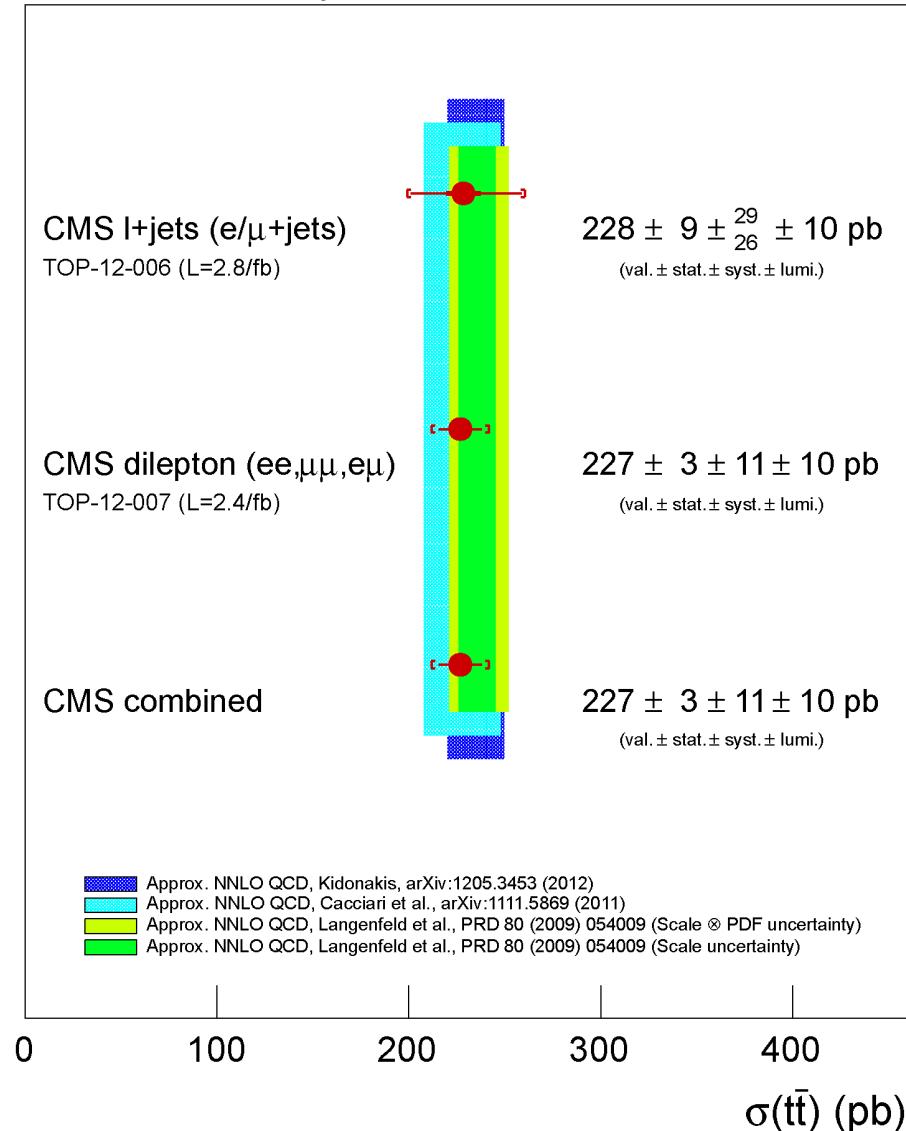


Pair Production Cross Section Summary

CMS Preliminary, $\sqrt{s}=7$ TeV



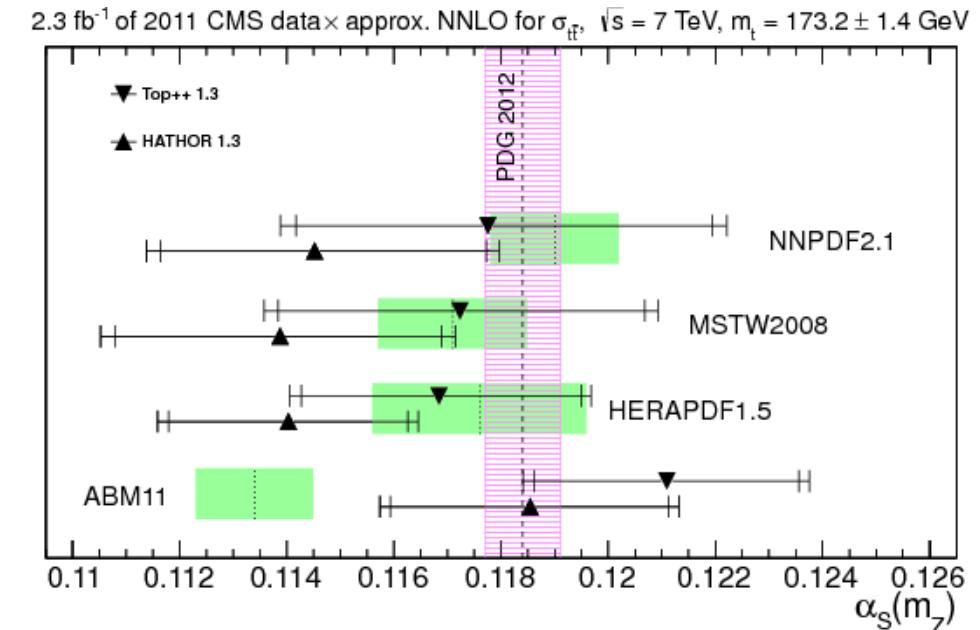
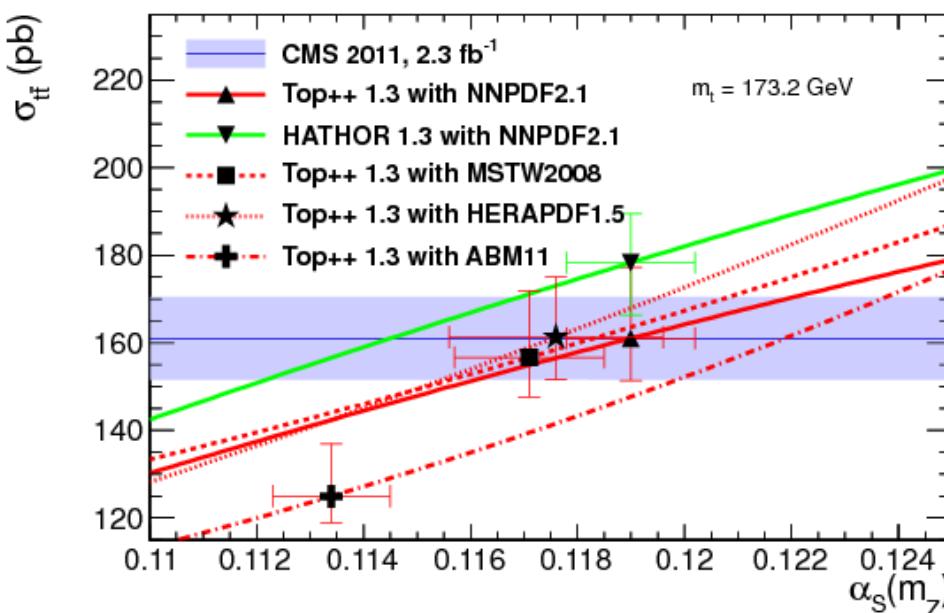
CMS Preliminary, $\sqrt{s}=8$ TeV





First Determination of α_s from Top Cross Section

- Make use of relation $\sigma_{t\bar{t}} = \sigma_{t\bar{t}}(m_t, \alpha_s)$ as an approximate NNLO for given set of PDF and using world average m_t
- Use CMS dilepton cross section as an experimental input



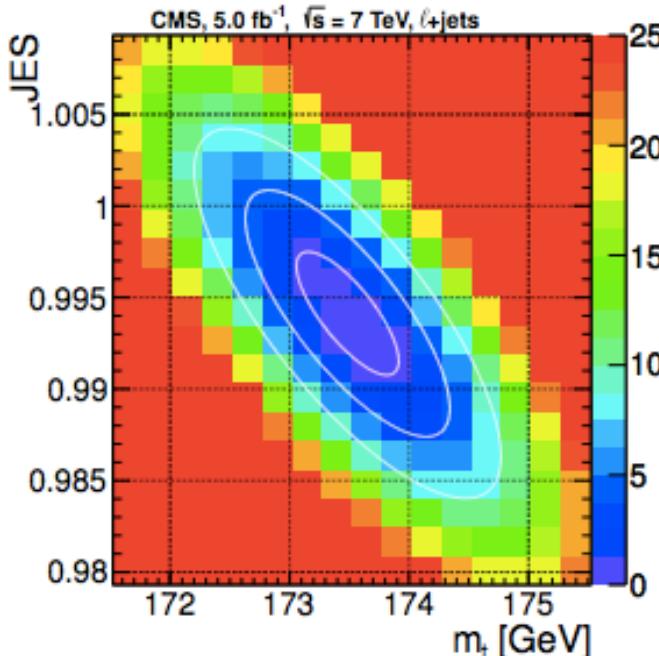
- Obtain strong coupling constant α_s as for each PDF set using likelihood maximization
- First determination from $t\bar{t}$ bar events, similar precision to most precise hadron collider measurements



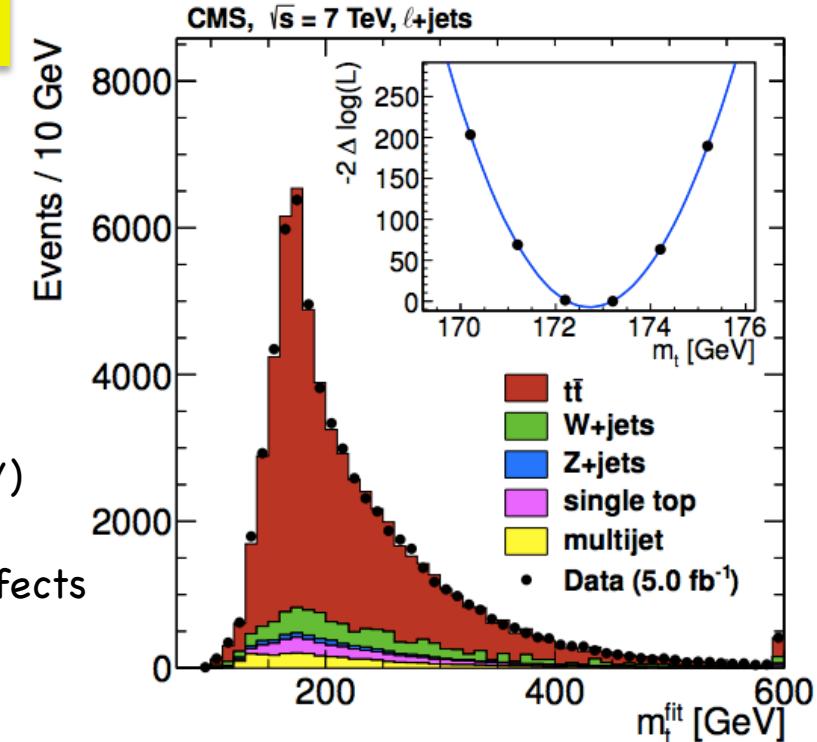
Top Quark Mass Measurements

- Lepton+jets channel
 - JES in-situ calibration: constrain the invariant mass of the two light jets from the W boson decay to m_W
 - Mass reconstructed using kinematic fit
 - Ideogram Method based on 2D likelihood

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



- Main systematics due to
 - b-JES (0.61 GeV)
 - and color reconnection effects (0.54 GeV)



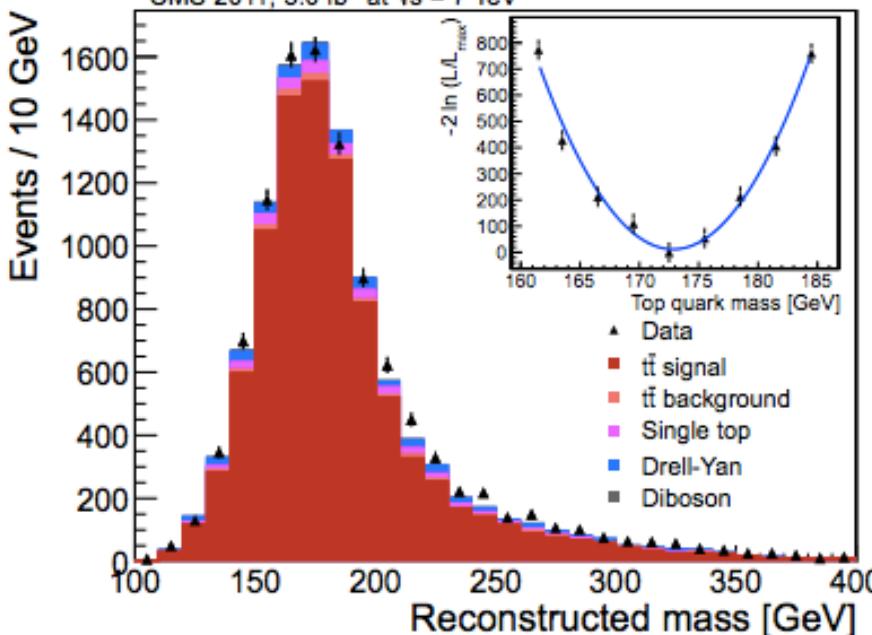
arXiv: 1209.2319



Top Quark Mass Measurements

- Dilepton channel
 - Analytical matrix weighting technique
 - Reconstruction of top quark event using top and W mass constraints
 - Kinematic equations are solved for series of top-quark mass hypotheses

arXiv: 1209.2393



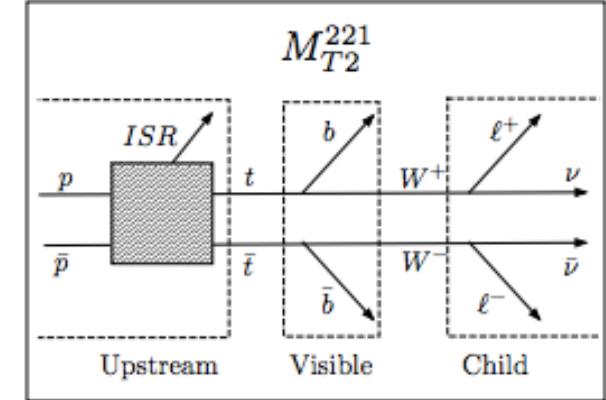
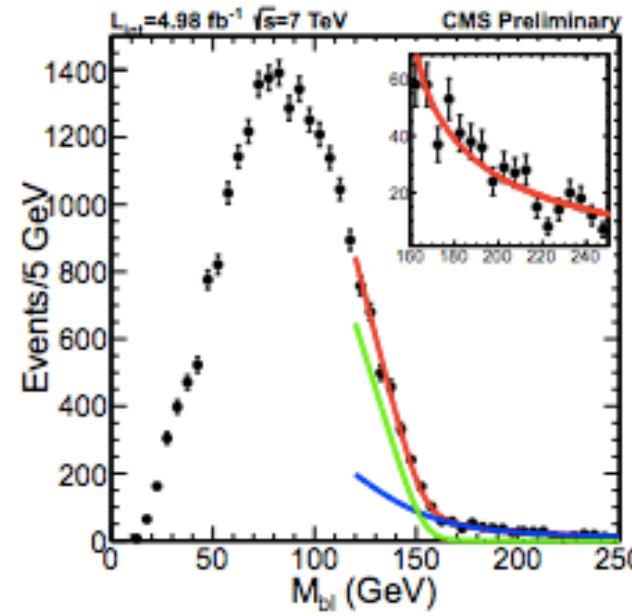
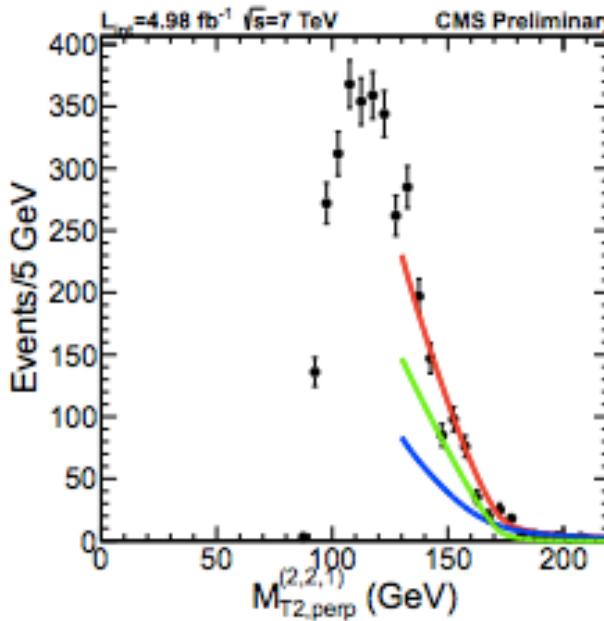
- Main systematics:
 - Jet Energy Scale (0.97 GeV)
 - B-jet Energy Scale (0.76 GeV)

$$m_t = 172.5 \pm 0.4 \text{ (stat.)} \pm 1.5 \text{ (syst.) GeV}$$



Top Quark Mass Measurements

- Dilepton channel
 - Simultaneous fit for both endpoints
 - lower bound for m_t for known m_W
 - m_{bl}^{\max}



- Main systematics
is Jet Energy Scale

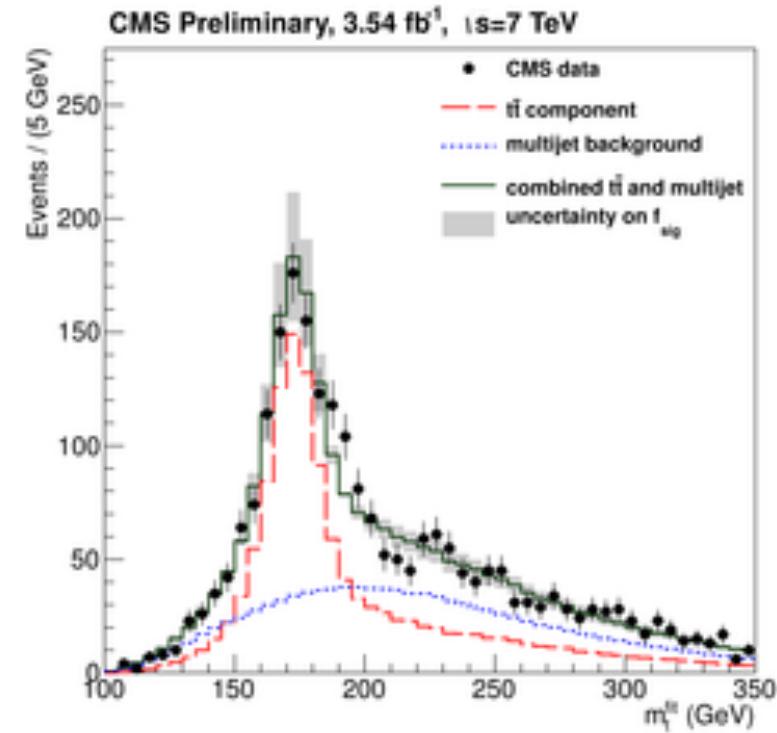
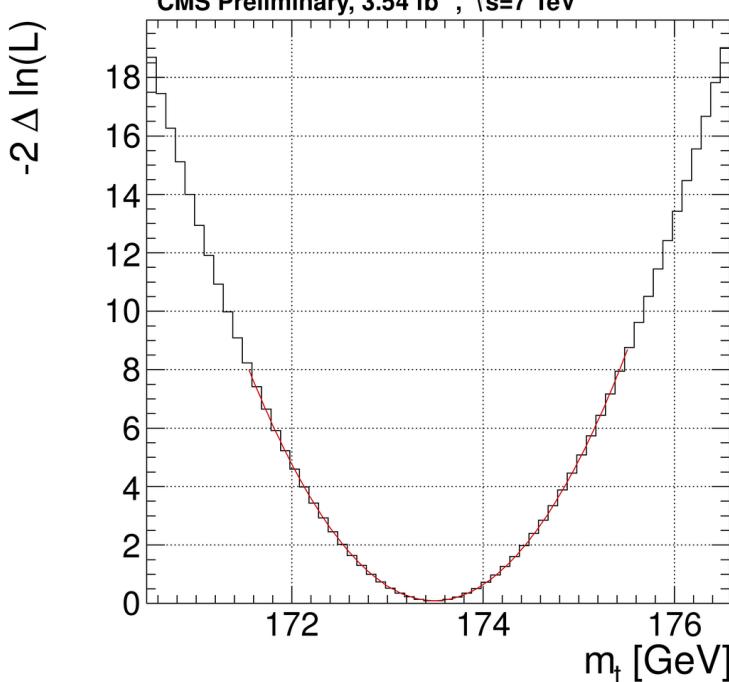
CMS-PAS-TOP-11-027

$$m_t = 173.9 \pm 0.9 \text{ (stat.)}^{+1.2}_{-0.8} \text{ (syst.) GeV}$$



Top Quark Mass Measurements

- All-hadronic channel
 - Kinematic fit using permutations with lowest χ^2
 - Multi-jet background from data



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

- Main systematics is Jet Energy Scale (0.97 GeV)

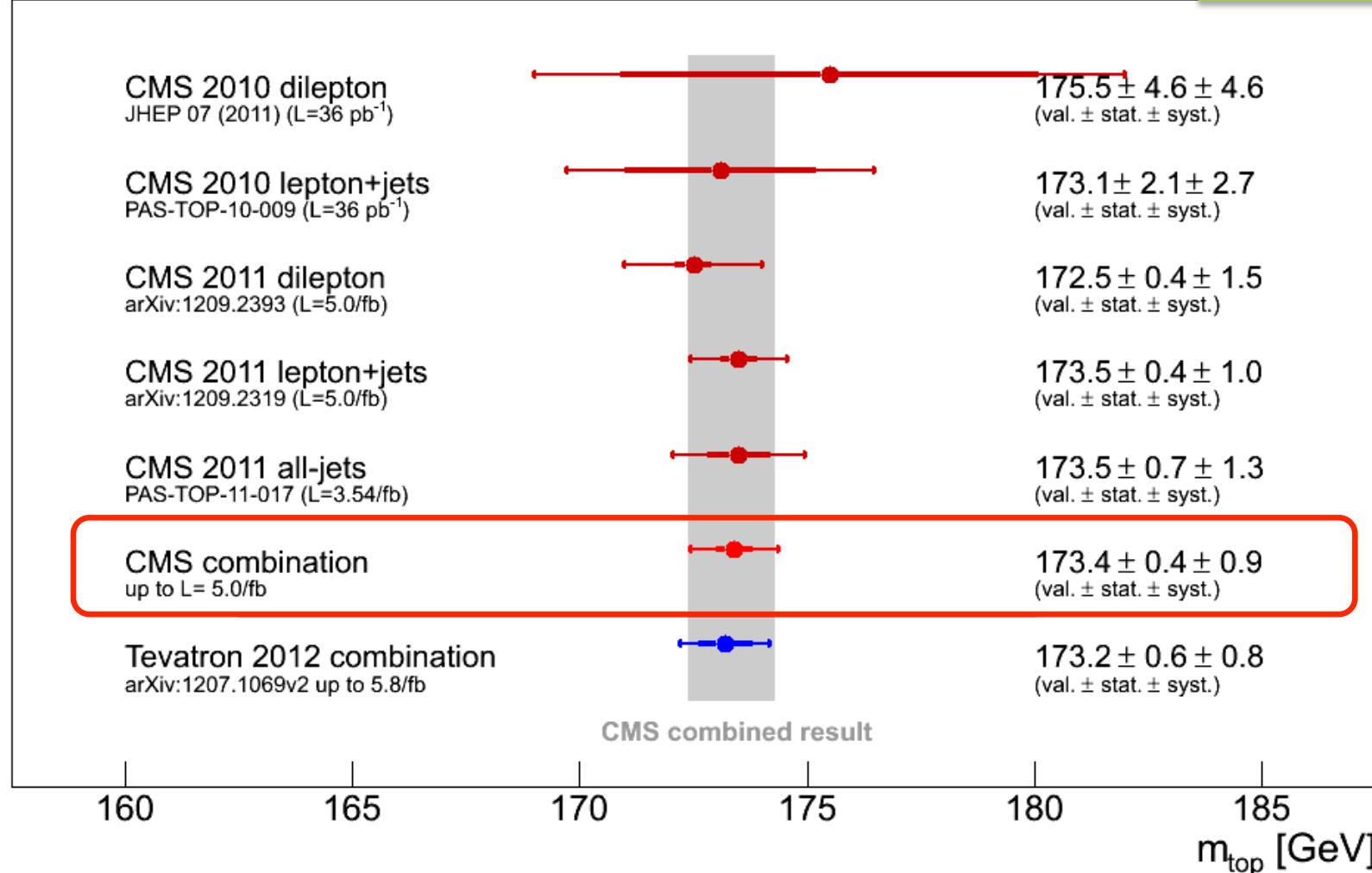
CMS-PAS-TOP-11-017



Top Quark Mass Combination

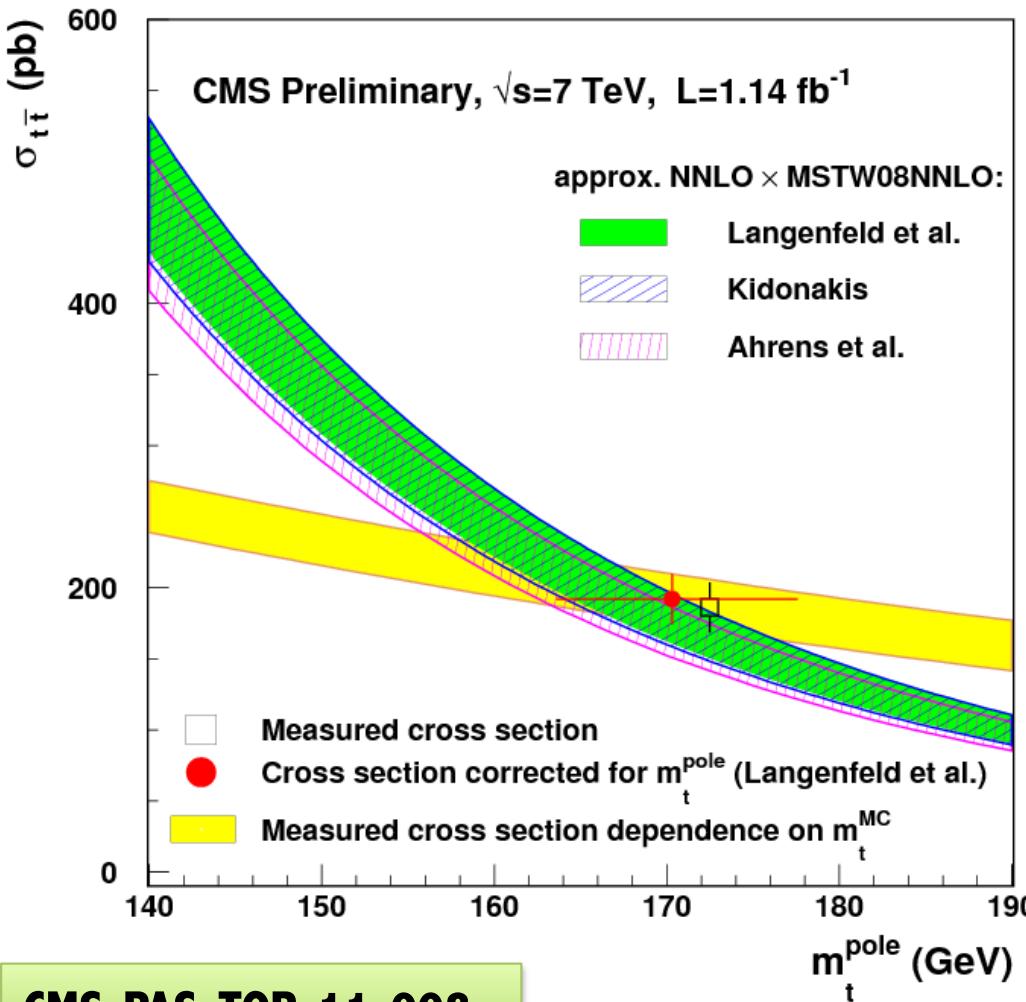
CMS Preliminary

CMS-PAS-TOP-12-001





Indirect Top Quark Mass Measurement



CMS-PAS-TOP-11-008

- Ambiguity in the top quark mass definition : pole mass, MSbar -?
- Direct mass measurement depend on MC, which contain ME at (N)LO QCD and higher order via parton showers
- Extracting the top mass from the inclusive cross section measurement provides an unambiguous definition of m_t
- CMS measurement is based on dilepton channel

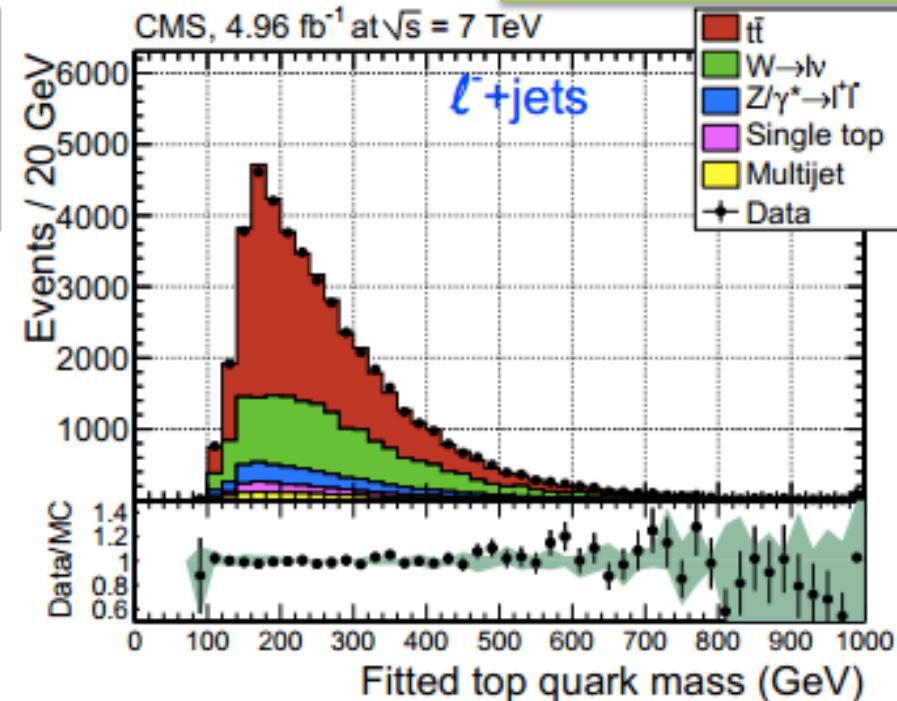
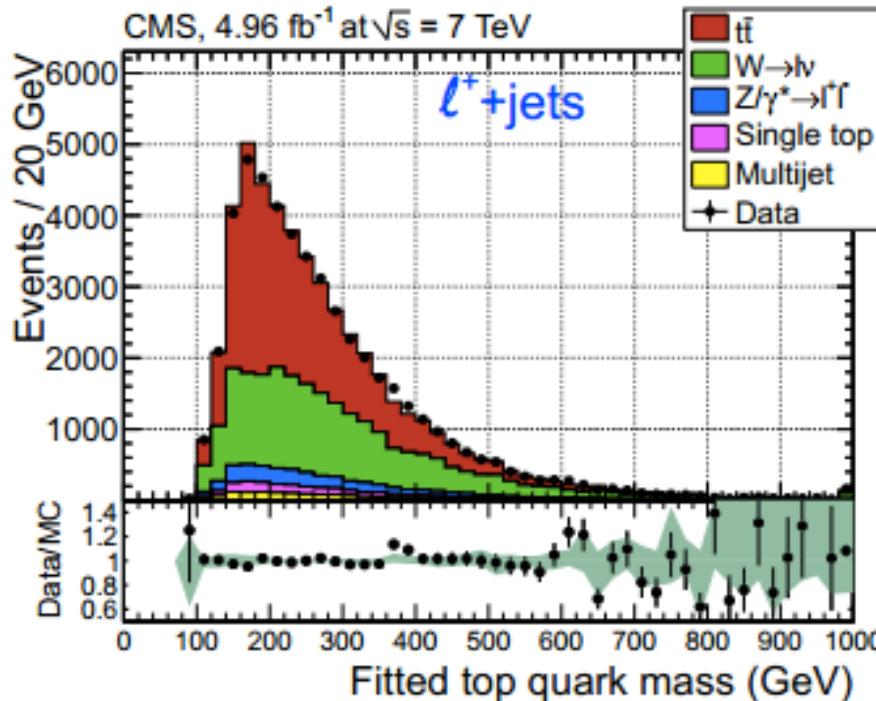


Top-Anti-Top Mass Difference

- Test of CPT invariance
- Split data in 2 samples according to the charge of the lepton
- Mass measurement performed using an ideogram method
- Measurement is statistically dominant

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

JHEP 1206 (2012) (109)

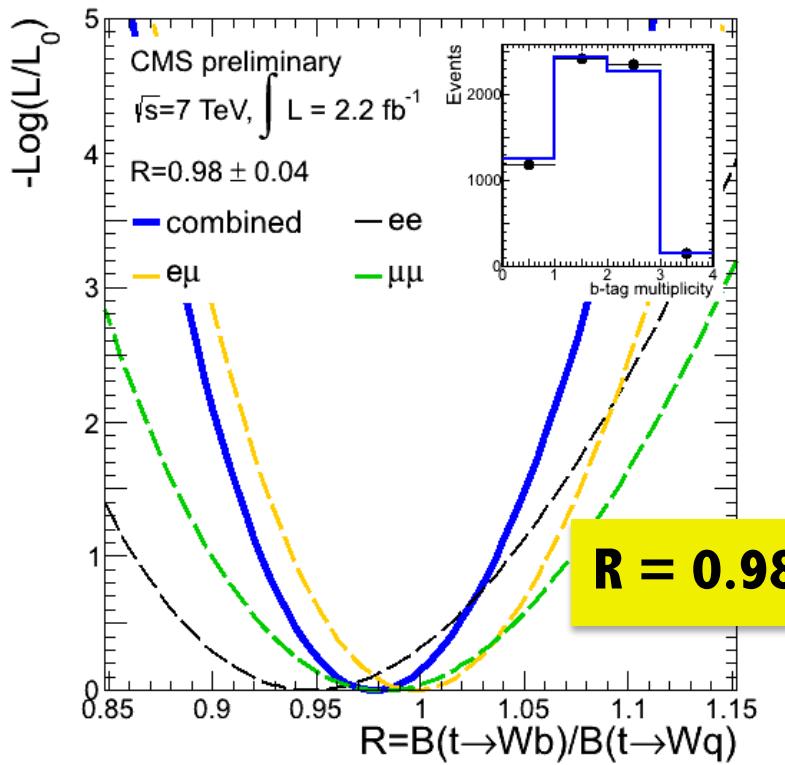




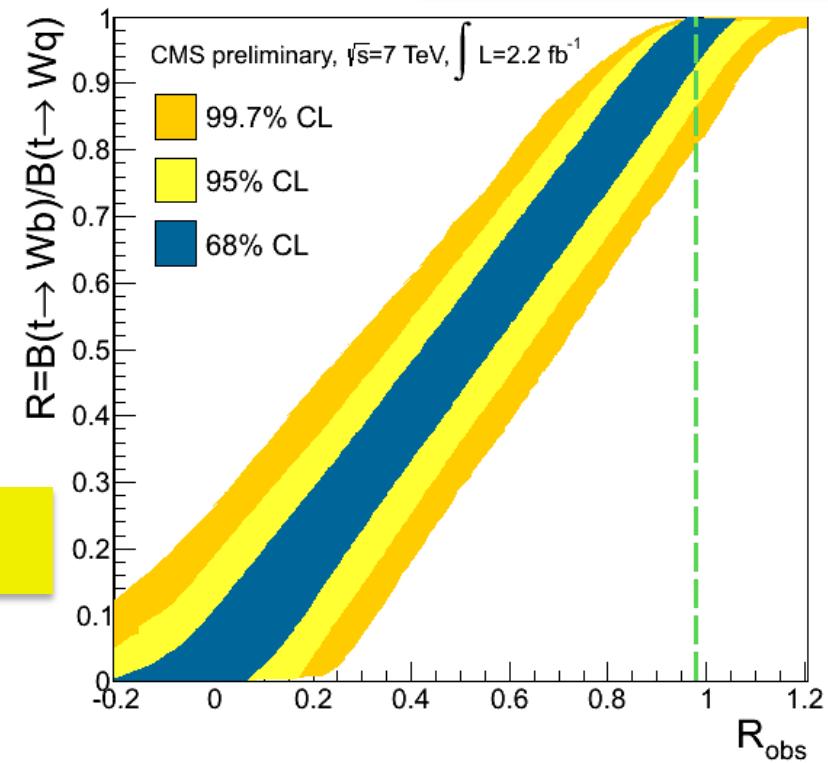
Branching Ratio

$$R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)}$$

- SM expectation $R = 0.998$
- Dilepton channel : categorize events based on lepton flavor, numbers of jets and b-tags
- Binned maximum likelihood fit of b-tag multiplicities

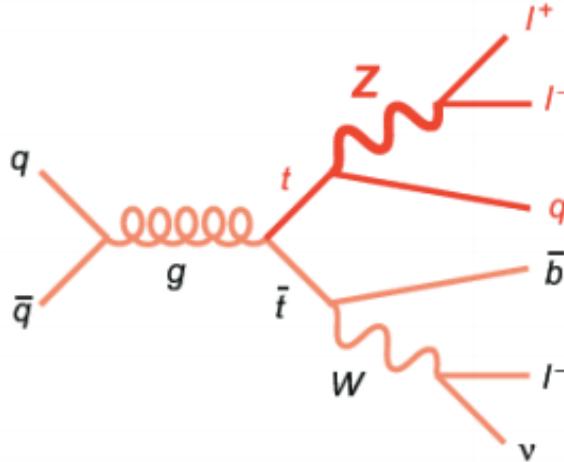


CMS-PAS-TOP-11-029



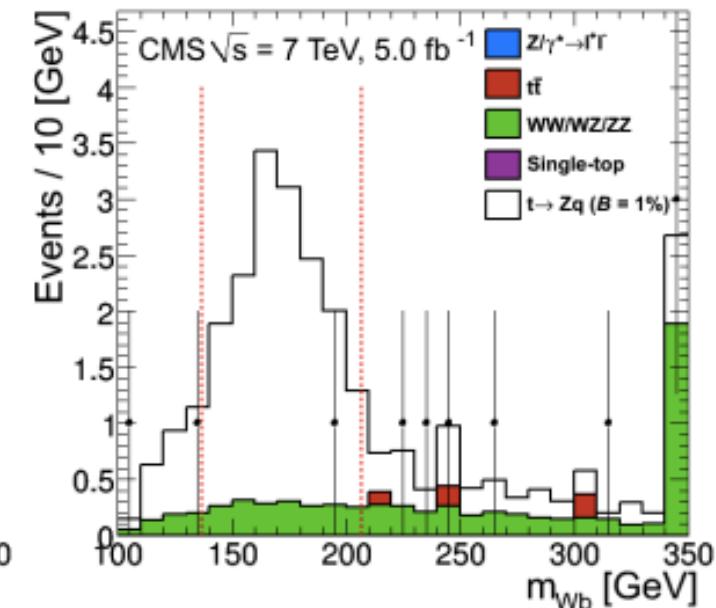
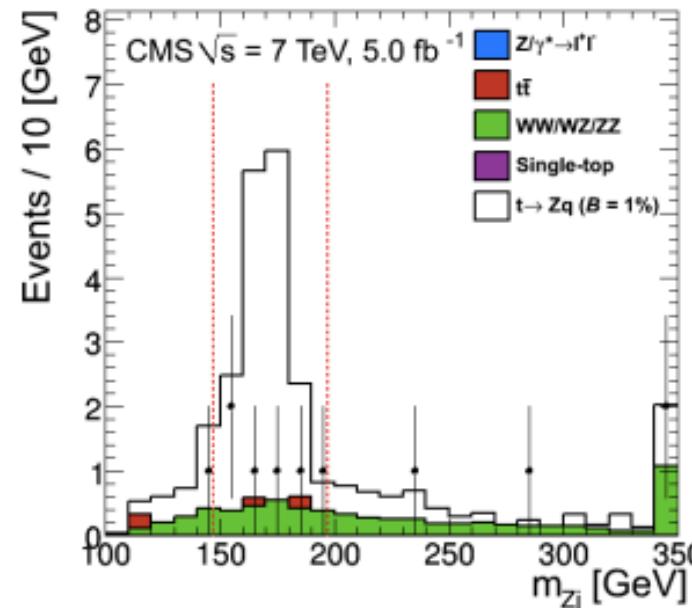


Flavor Changing Neutral Current



- Upper limit using CL_s technique

- Branching ratio is tiny in SM
- Can be significantly enhanced in BSM scenarios
- Event selection : 3 leptons, large scalar p_T sum or mass window near top quark mass under FCNC decay hypothesis

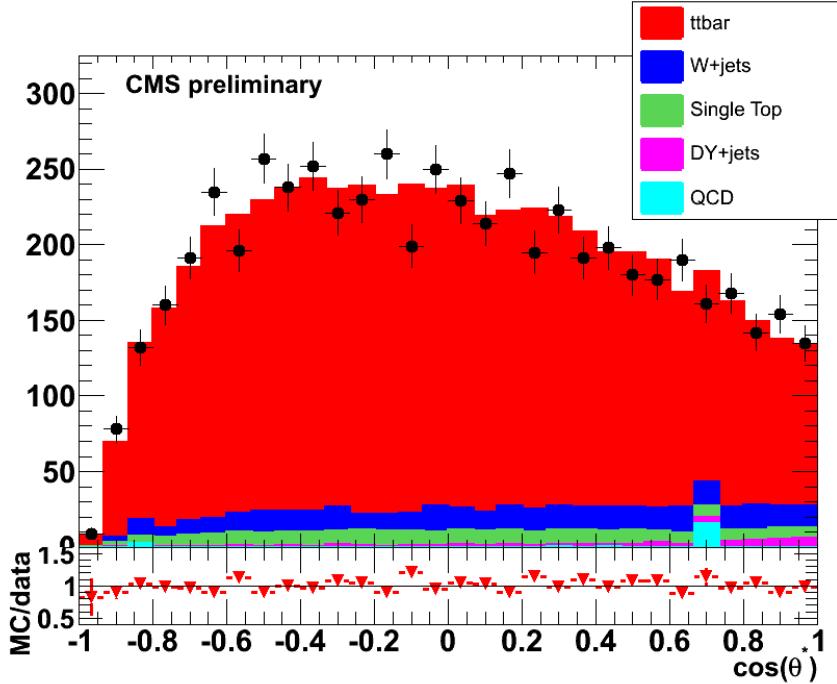


arXiv: 1208.0957

$B(t \rightarrow Zq) < 0.24\% (0.36\%)$ obs. (exp.)

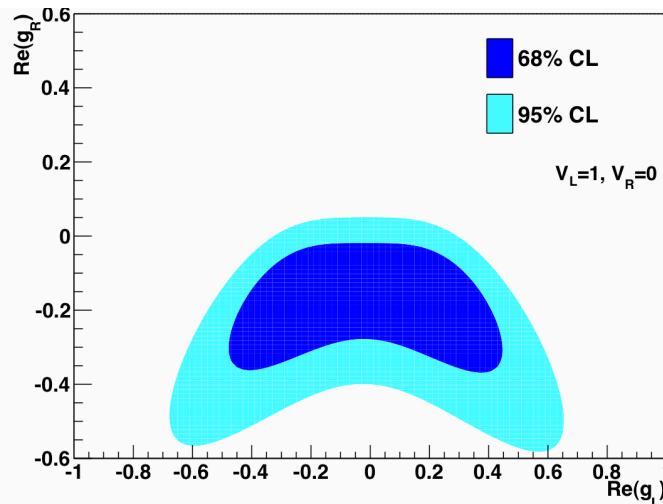


W Boson Helicity



- Kinematic reconstruction of semi-leptonic top events
- Measure helicity fractions and probe anomalous couplings using angle between lepton in W rest frame and W in top rest frame

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



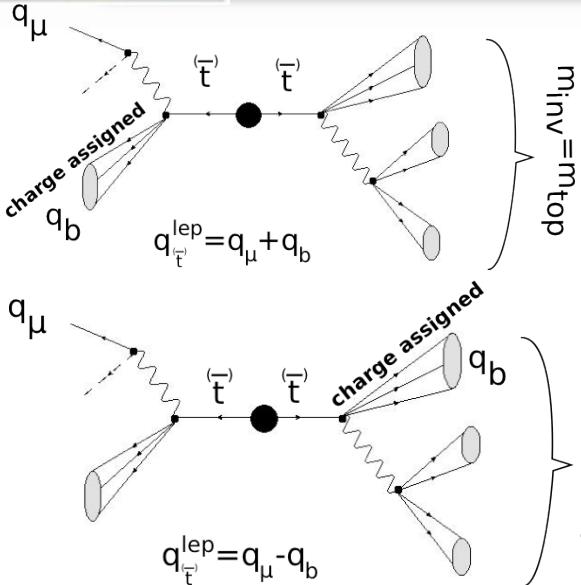
$$F_0 = 0.567 \pm 0.074 \text{ (stat.)} \pm 0.047 \text{ (syst.)}$$
$$F_L = 0.393 \pm 0.045 \text{ (stat.)} \pm 0.029 \text{ (syst.)}$$
$$F_R = 0.040 \pm 0.035 \text{ (stat.)} \pm 0.044 \text{ (syst.)}$$

- Consistent with Standard Model
 $F_0 = 0.7, F_L = 0.3$

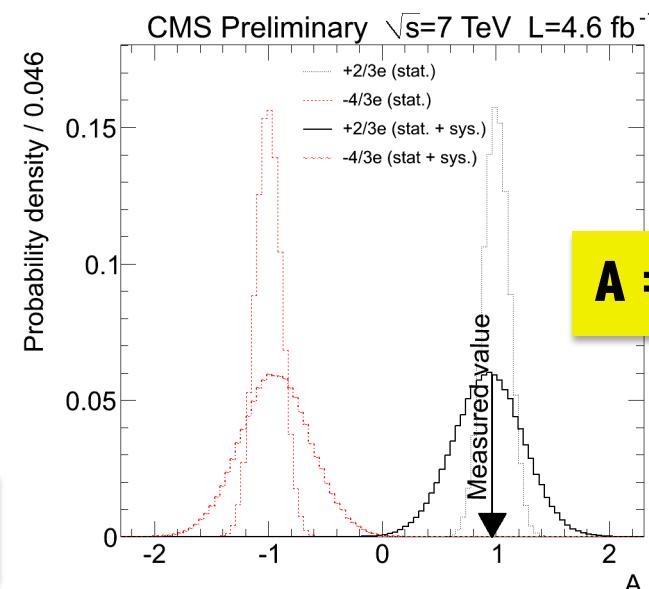
CMS-PAS-TOP-11-020



Top Charge



- Test against hypothesis $Q = -4/3e$
- Determine b-quark charge using soft muons from B-hadron decays
- Top quark charge from event reconstruction
- Measure asymmetry



$$A = \frac{1}{D_S} \frac{N_{SM} - N_{XM} - \langle N_{BG} \rangle D_B}{N_{SM} + N_{XM} - \langle N_{BG} \rangle}$$

$A = 0.97 \pm 0.12 \text{ (stat.)} \pm 0.31 \text{ (syst.)}$

CMS-PAS-TOP-11-031



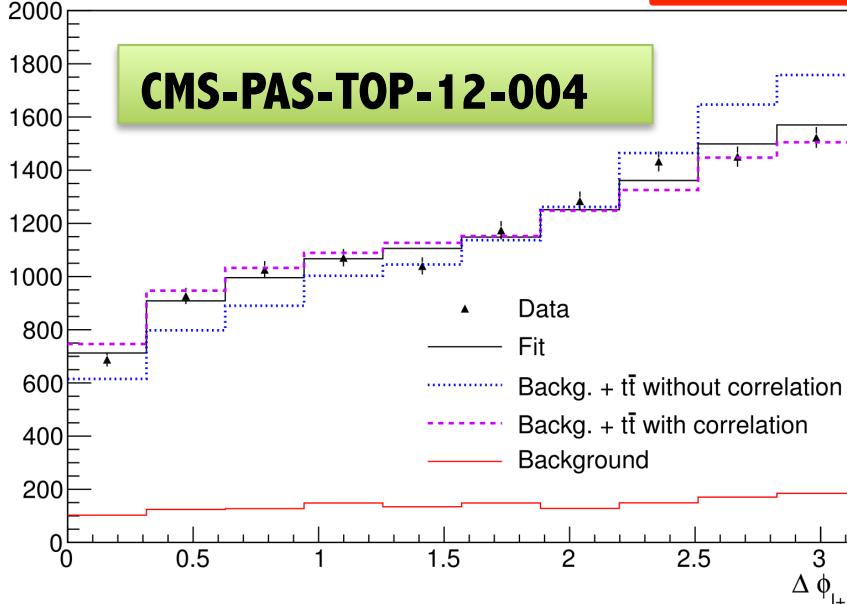
Spin Correlations and Polarization

- Top quark spin information is accessible from decay products
- Use dilepton events
- Measure asymmetry using angular difference between two leptons
- Top quark polarization measured from angular distributions of the leptons in the top quark's rest frame and unfolded to parton level

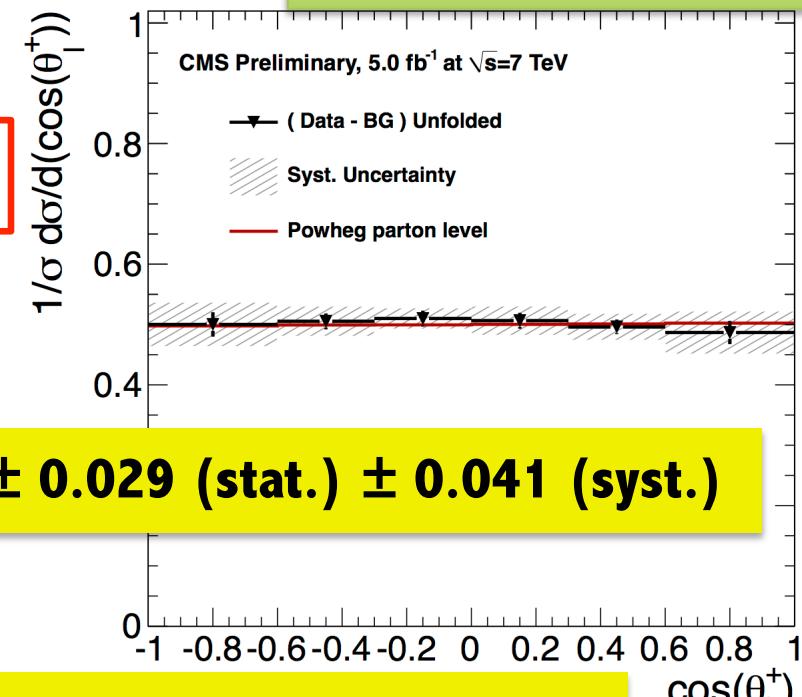
$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\downarrow\uparrow) - N(\uparrow\downarrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\downarrow\uparrow) + N(\uparrow\downarrow)}$$

$$P_n = \frac{N(\cos(\theta_l^+) > 0) - N(\cos(\theta_l^+) < 0)}{N(\cos(\theta_l^+) > 0) + N(\cos(\theta_l^+) < 0)}$$

CMS Preliminary, 5.0 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$



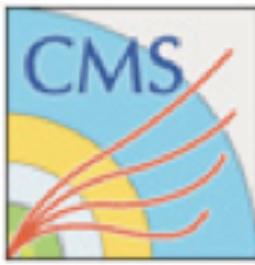
CMS-PAS-TOP-12-016



$P = -0.009 \pm 0.029 \text{ (stat.)} \pm 0.041 \text{ (syst.)}$

$A = 0.24 \pm 0.02 \text{ (stat.)} \pm 0.08 \text{ (syst.)}$

Consistent with Standard Model $A = 0.31$

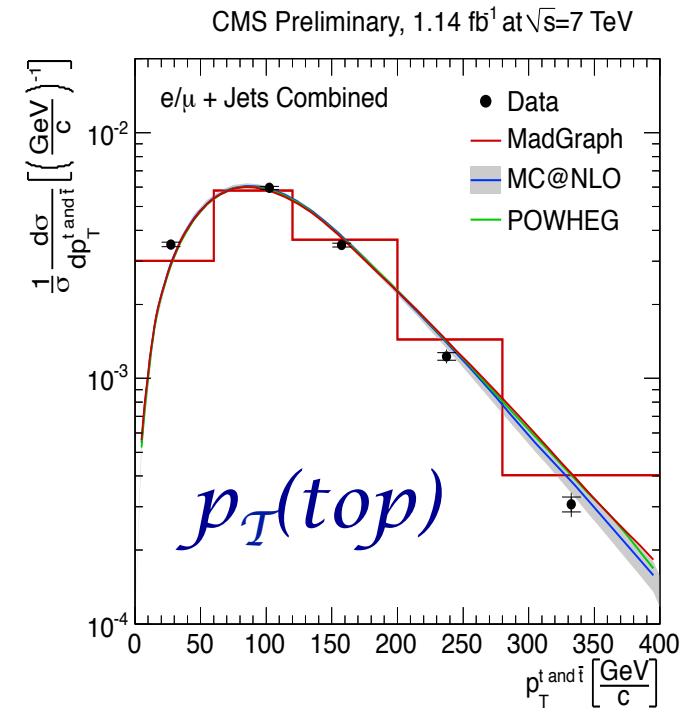
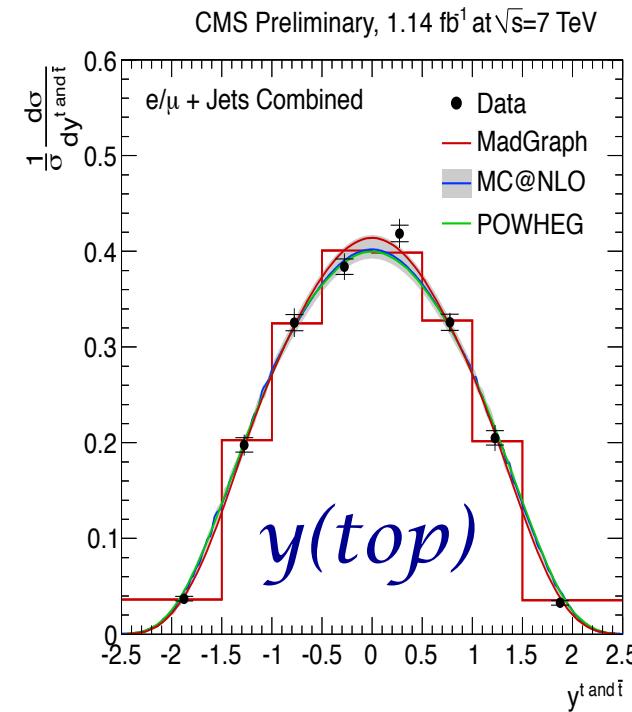
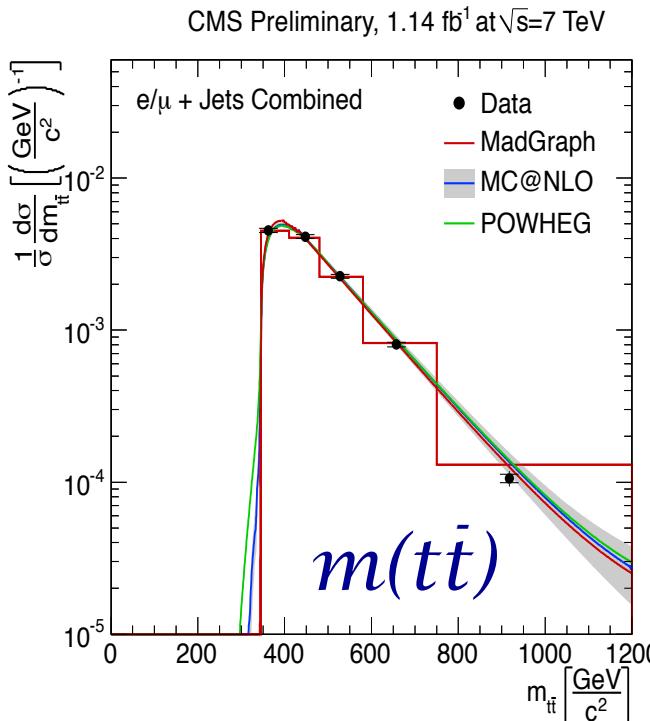


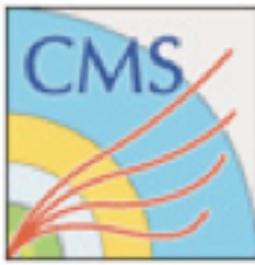
Differential Cross Section

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

- Measure cross section as a function of transverse momentum, (pseudo-)rapidity, invariant mass of final state leptons, reconstructed top quarks, $t\bar{t}$ system
- $t\bar{t}$ events are reconstructed by imposing kinematic constraints
- In DIL channel due to under-constraint, correct solution is found by most probable neutrino energy spectrum and prioritizing b-tagged jets over un-tagged
- Differential distributions are obtained by unfolding using Singular Value Decomposition method (A. Hoecker, V. Kartvelishvili, NIM A 372 (1996) 469)

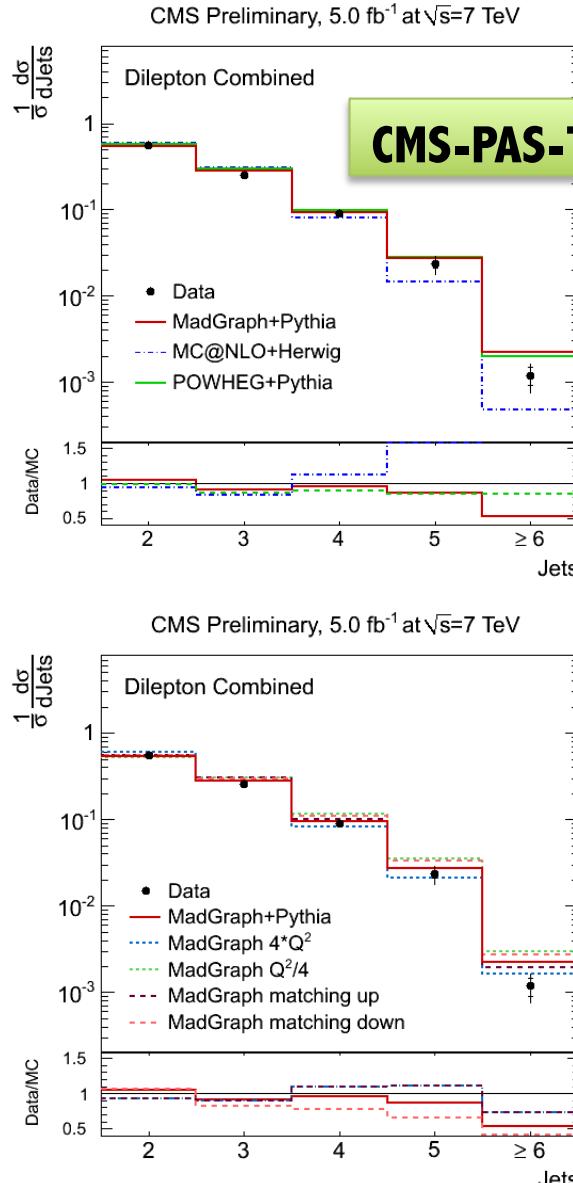
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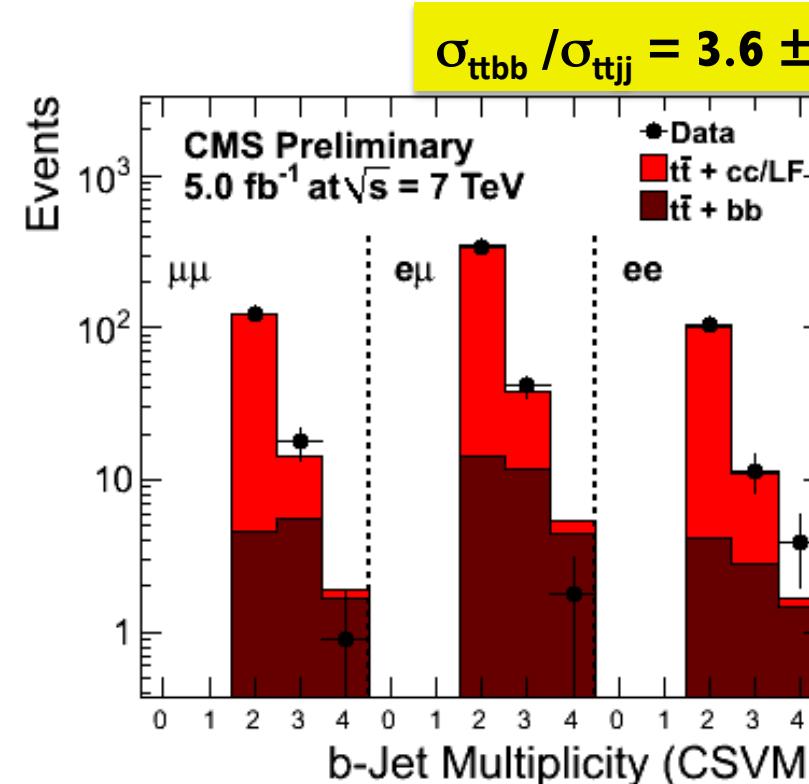


Jet Multiplicity

First Measurement of $\sigma(t\bar{t}bb)/\sigma(t\bar{t}jj)$



- Measurement is performed in dilepton channel using different jet p_T thresholds and compared to different generators and different renormalization/factorization scale and matching parameters
- Correction to the particle level is performed



- Major background for $t\bar{t}+H$
- Somewhat larger than MC predictions
- Madgraph = 1.2%
- Powheg = 1.3%
- Aim to make comparison with NLO QCD

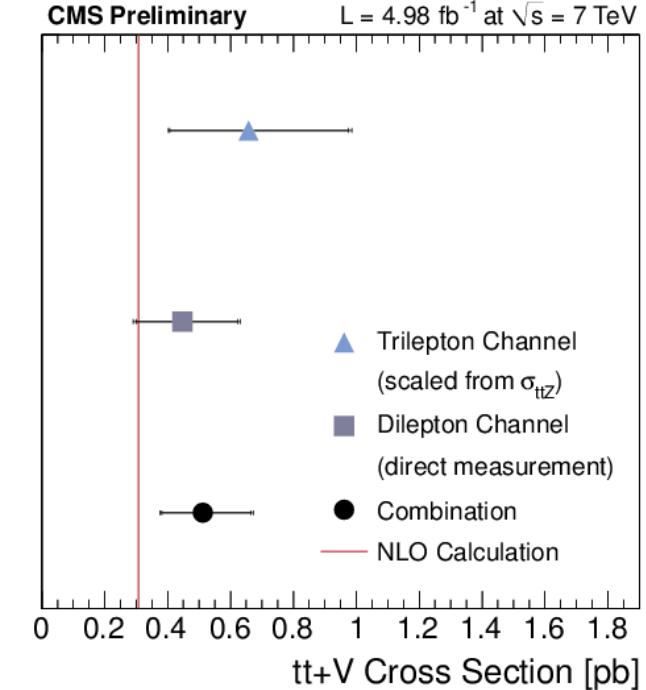
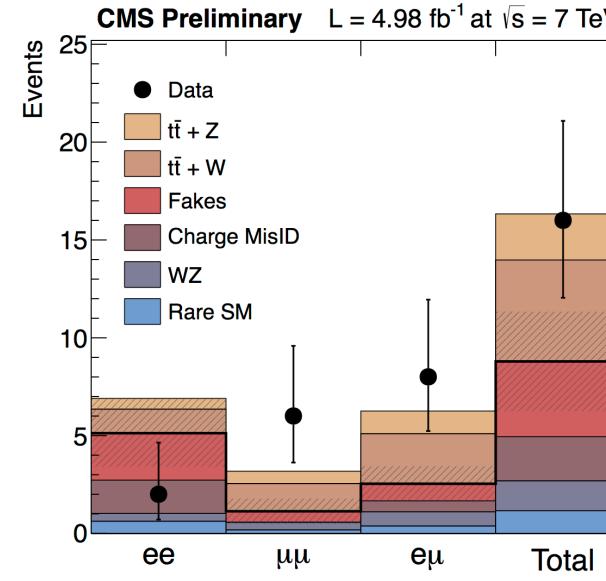
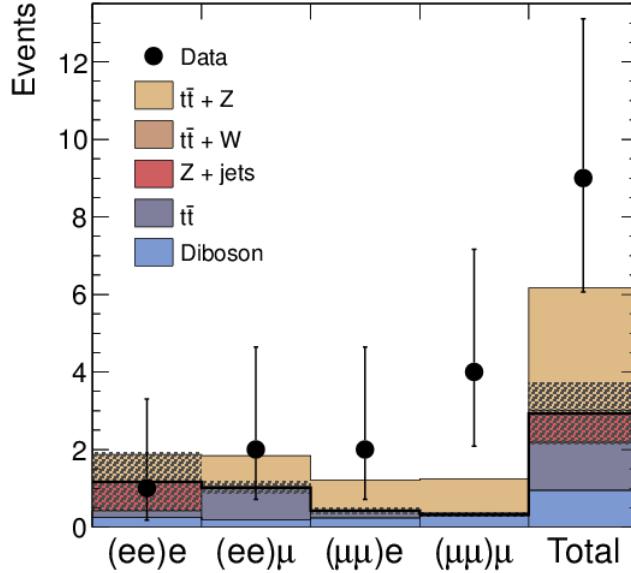
CMS-PAS-TOP-12-024



First Measurement of $\sigma(t\bar{t} + V)$, $V = W / Z$

- Trilepton analysis targets $t\bar{t} + Z$ events
- Same-sign dilepton analysis targets both $t\bar{t} + V$ (W/Z)
- Dedicated cuts optimized for sensitivity to the signal
- 4.7σ evidence for $t\bar{t} + V$

CMS-PAS-TOP-12-014



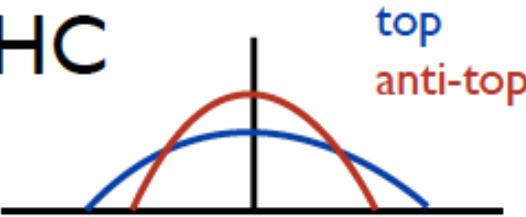
$$\sigma(t\bar{t}+Z) = 0.30 \pm 0.14(\text{stat.}) \pm 0.04(\text{syst.}) \text{ pb (3 l- channel)}$$

$$\sigma(t\bar{t}+V) = 0.51 \pm 0.15(\text{stat.}) \pm 0.05(\text{syst.}) \text{ pb (combined)}$$



Charge Asymmetry

LHC



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

- QCD predictions:
 $A_c^{\Delta y} = 0.0115 \pm 0.0006$

**$A_c = 0.004 \pm 0.010 \text{ (stat.)}$
 $\pm 0.012 \text{ (syst.)}$**

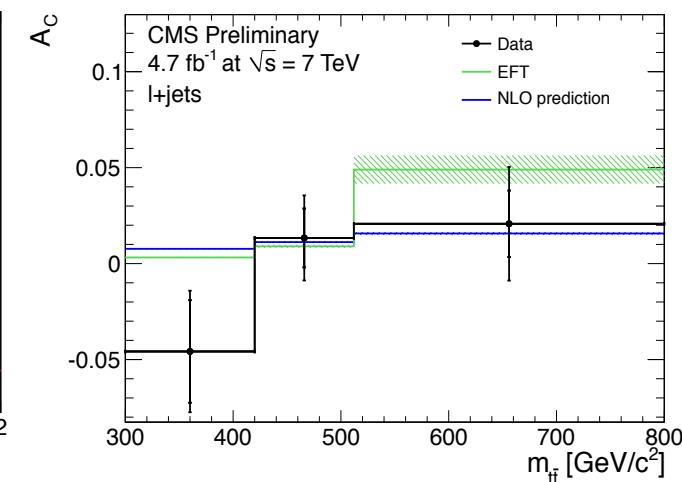
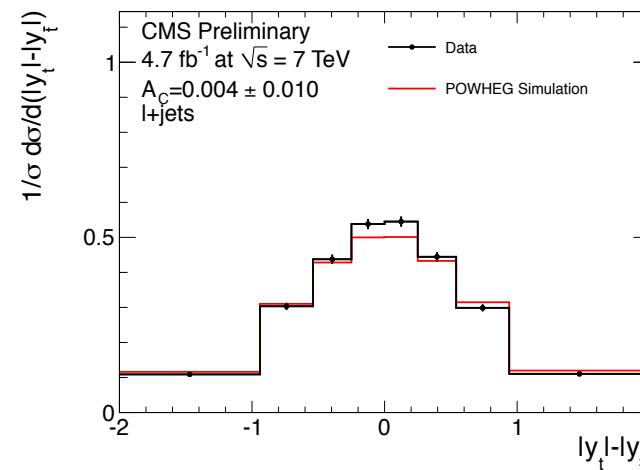
Consistent with
Standard Model !

arXiv: 1207.0065

- CDF reported ~ 3.4 sigma deviation in forward-backward asymmetry for $m(t\bar{t}) > 450$ GeV
- At LHC the charge asymmetry manifests itself in different rapidity widths of top/anti-top quarks
- Explore

$$\Delta|y| = |y_t| - |\bar{y}_t|$$

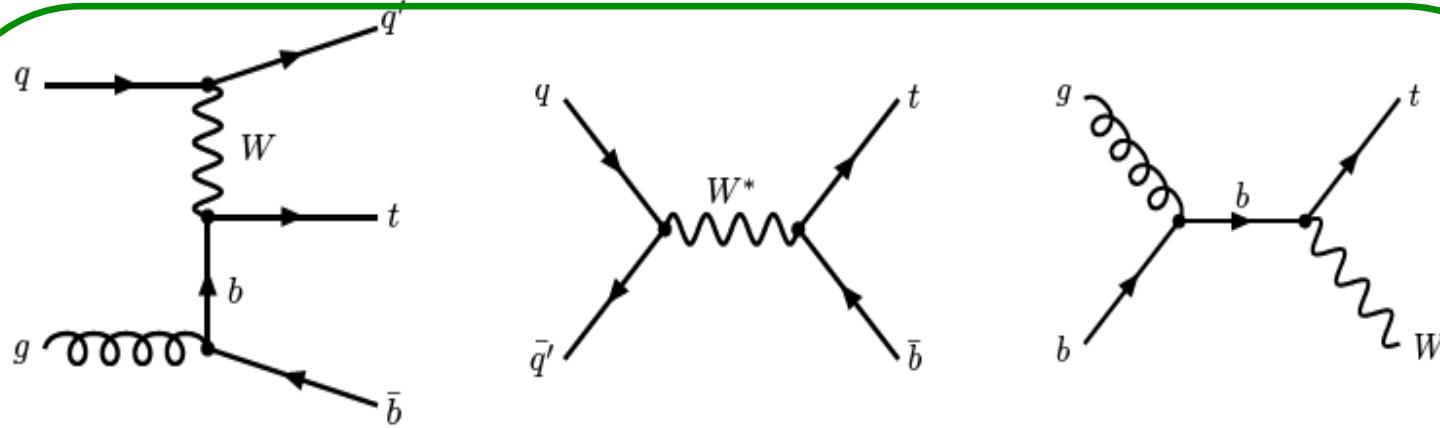
- $t\bar{t}$ events are reconstructed by imposing W/top mass constraints and requirement that b-tagged jet matches jet from top decay
- Reconstructed distributions are corrected to true distributions via a regularized unfolding procedure (Blobel arXiv: hep-ex/0208022), which correct for bin-to-bin migration and efficiency effects





Single Top Production

Single Top Production



$64.57^{+2.09}_{-0.71} {}^{+1.51}_{-1.74}$ pb

Kidonakis, N.
PRD83:091503, 2011

$4.63 \pm 0.07^{+0.19}_{-0.17}$ pb

Kidonakis, N.
PRD81:054028, 2010

$15.74 \pm 0.40^{+1.10}_{-1.14}$ pb

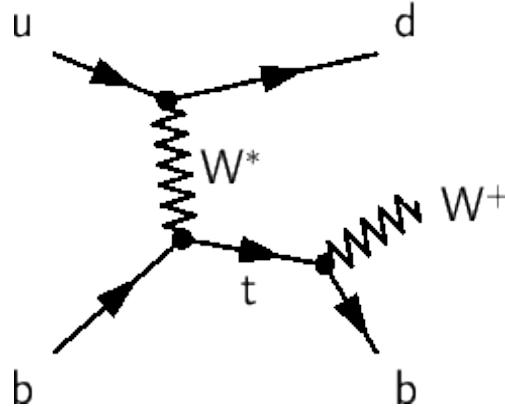
Kidonakis, N.
PRD82:054018, 2010

@ 7 TeV

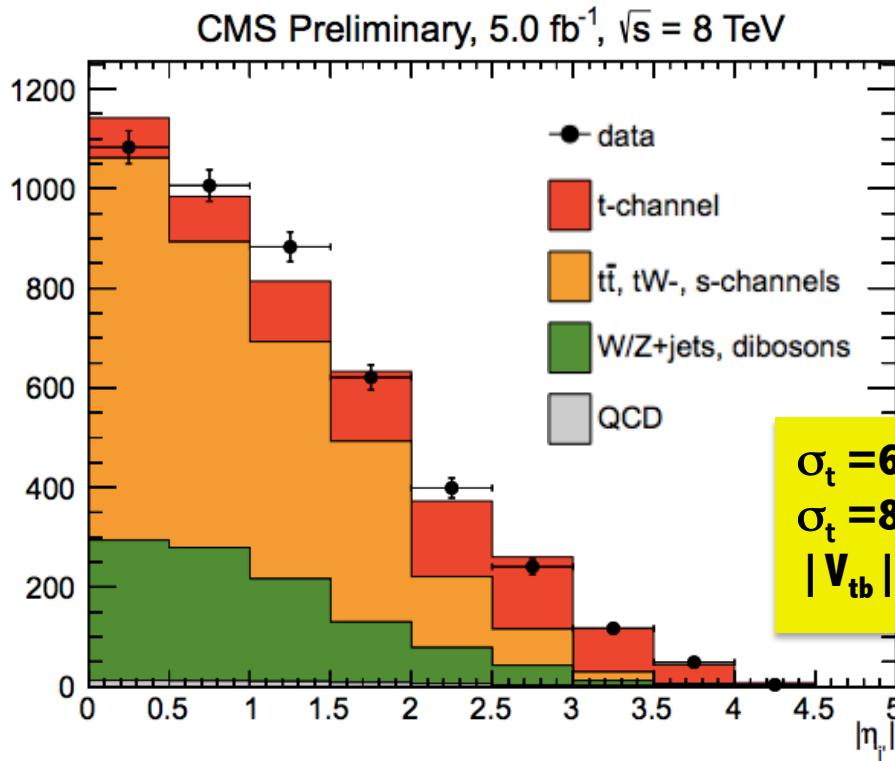
- Weak Interaction : Test of Wtb Vertex
- Direct measurement of V_{tb}
- Can be used to measure the b-quark parton distribution function (PDF)
- Sensitive to new physics : W' , H' , anomalous couplings, etc.



Single Top t-Channel



- Event Selection: = 1 isolated $e(u)$, $p_T > 30(20)$ GeV, $|\eta| < 2.5(2.1)$
- Missing $E_T > 35$ GeV (e) , $m_T(W) > 40$ GeV (μ)
- At least 2 jets with $p_T > 30$ GeV, $|\eta| < 4.5$, at least 1 b-tag
- Other jet and b-tagging multiplicities used as control regions
- Data-driven approach for background estimation

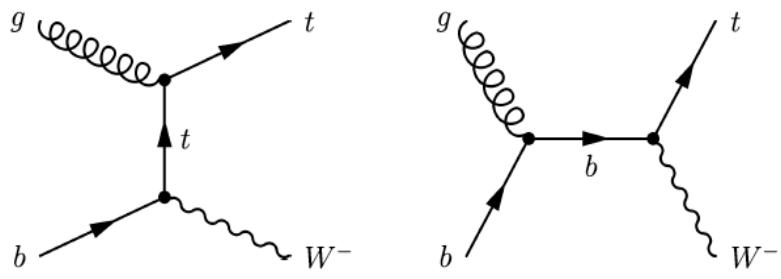


- Max Likelihood fit to pseudo-rapidity of the light (un-tagged jet)
- Plus dedicated multi-variate analyses based on 7 TeV data

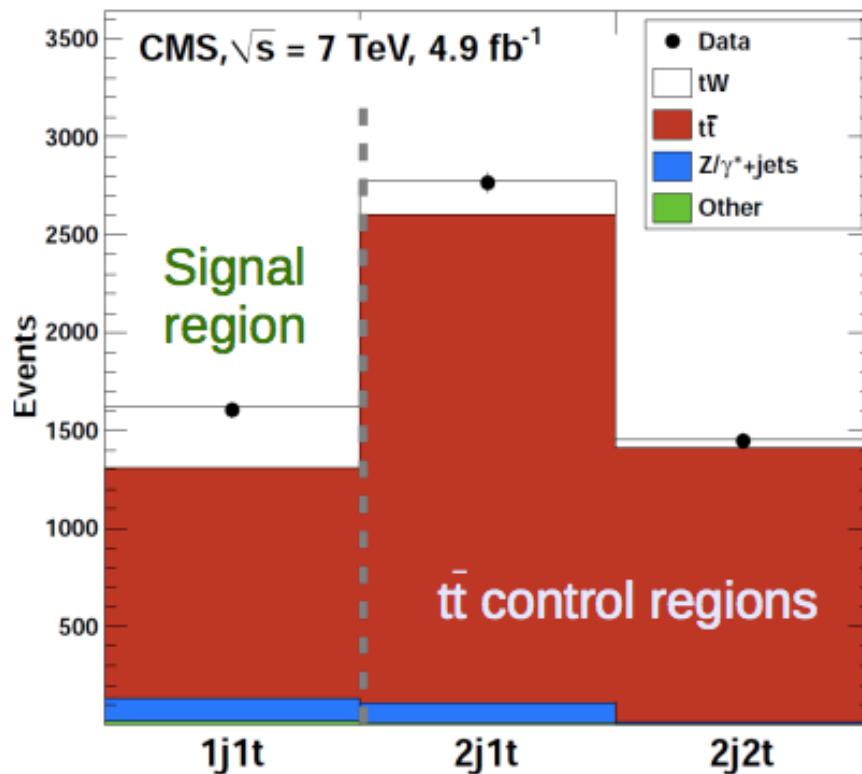
arXiv: 1209.4533



Single Top tW-Channel



- Selection: 2 leptons, $p_T > 20$ GeV
- Missing $E_T > 30$ GeV, = 1 b-tagged jet, $p_T > 30$ GeV
- Z-veto, reject $ee, \mu\mu$ in $m_{ll} = [81,101]$
- Main Backgrounds: Z+jets, ttbar
- ttbar is measured in the control regions ($> = 2$ jets, 1 or 2 b-tags) and extrapolated into the signal region
- Z+jets is estimated using data-driven method by evaluating the number of events in MC "leaking" out of Z-mass window
- Two analyses: cut-and-count approach, and multi-variate boosted decision tree



BDT : $\sigma_t = 16 \pm 6$ pb, at 4.0σ
Cut-based : $\sigma_t = 15 \pm 5$ pb, at 3.5σ
 $|V_{tb}| = 1.01 \pm 0.16$ (exp.) ± 0.04 (th.)

arXiv: 1209.3489

Conclusions

- CMS has a rich top quark physics precision measurements program
- Measurements are systematically limited, starting to constrain theory and validate Monte Carlo models
- All measurements are in good agreement with Standard Model
- CMS Top Results:
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP>

Thank You !