

# Top Physics Results at CMS

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On behalf of the CMS Collaboration

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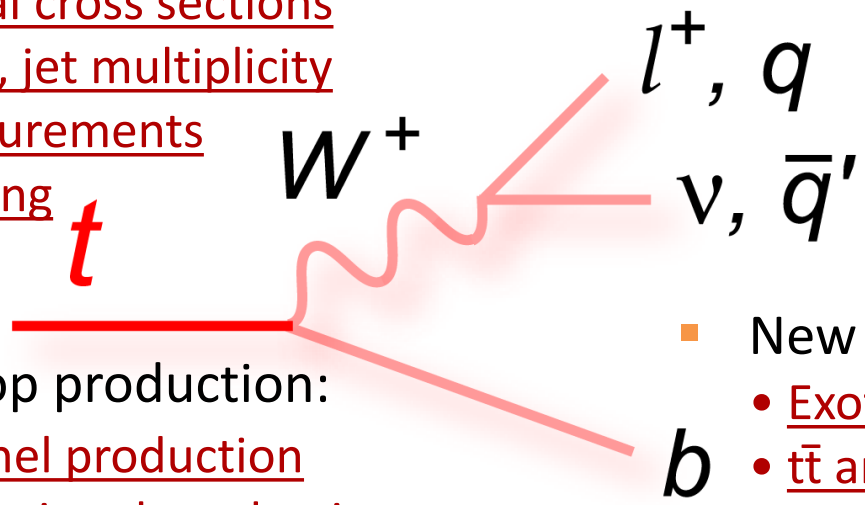
Split (Croatia)

# Motivations

- Unique role in standard model of elementary particles:
  - Very large mass, Yukawa coupling to Higgs close to unity
  - Special role in electroweak symmetry breaking?
  - Sensitive to physics beyond the standard model?
- Precise measurements of top quark properties allow to test the standard model:
  - Top couplings, charge, width, decay branching ratios
- Important background to many physics signals
- Ideal event final states to test many reconstruction tools:
  - Jet energy scale, b-tagging, missing transverse energy

# Top Physics at CMS

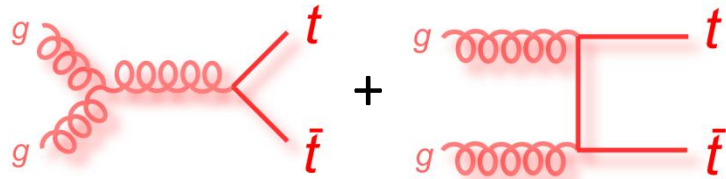
- Top pair production:
  - Inclusive cross sections
  - Differential cross sections
  - Missing  $E_T$ , jet multiplicity
  - $t\bar{t}+X$  measurements
  - Alpha strong
- Production properties:
  - Spin correlation
  - Top polarization
  - Charge asymmetry
- Top properties:
  - top mass
  - top-antitop  $\Delta m$
  - top charge
  - BR( $t \rightarrow Wb$ )
  - W polarization
  - Boson radiation
- Single top production:
  - t-channel production
  - tW associated production
- New physics in top sector:
  - Exotic top decays
  - $t\bar{t}$  and tW resonances
  - Heavy particles decaying to top
- Complete review of CMS results on top physics at:
  - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP>



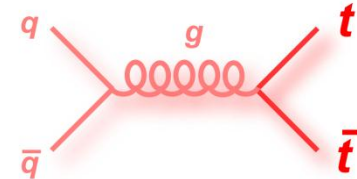
# Top Quark Production and Decay

- Pair production dominant in pp collisions at LHC:

- Gluon fusion:  $\sim 80\%$

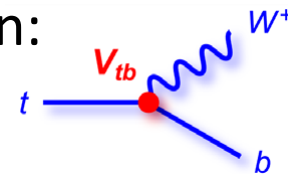


- Quark annihilation:  $\sim 20\%$

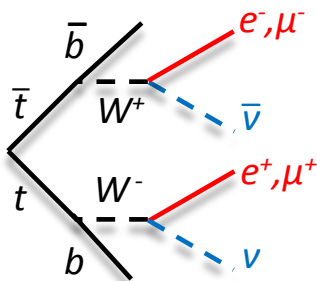


- Decay mainly to  $Wb$  via electroweak interaction:

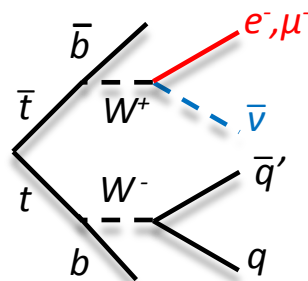
- $BR(t \rightarrow Wb) \sim 100\%$  in SM



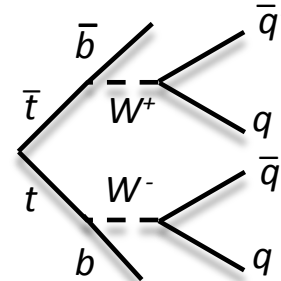
- Observed final states classified according to  $W$  bosons' decays:



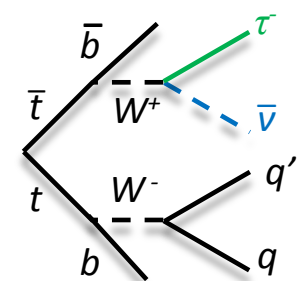
Dilepton ( $\sim 5\%$ )



Lepton+jets ( $\sim 30$ )



All hadronic ( $\sim 46\%$ )



Tau+jets ( $\sim 15\%$ )

# $t\bar{t}$ Event Reconstruction

- Most analyses need a full reconstruction of the  $t\bar{t}$  event:
  - top mass and charge, angular distributions, production asymmetries
- Kinematic fit used to select/weight parton-jet assignments

$$\chi^2 = \sum_{i=\ell, 4 \text{ jets}} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_t)^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - M_t)^2}{\Gamma_t^2}$$

Allow momenta to fluctuate according to their resolution

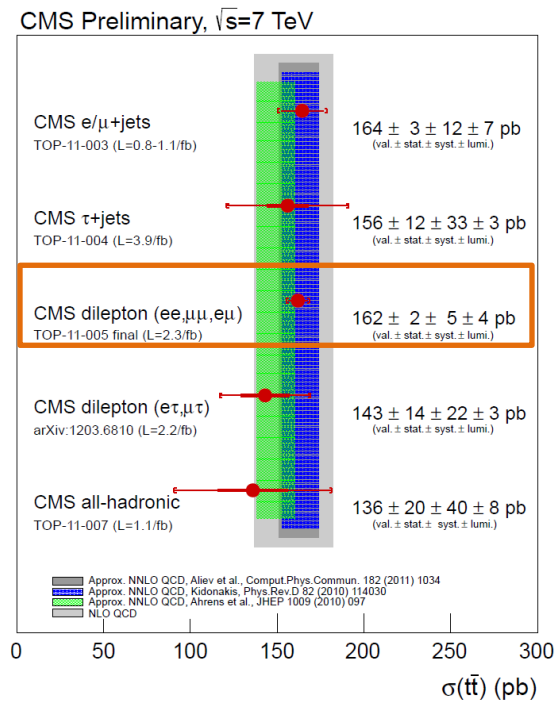
Constrain on W masses

Same mass for top and antitop

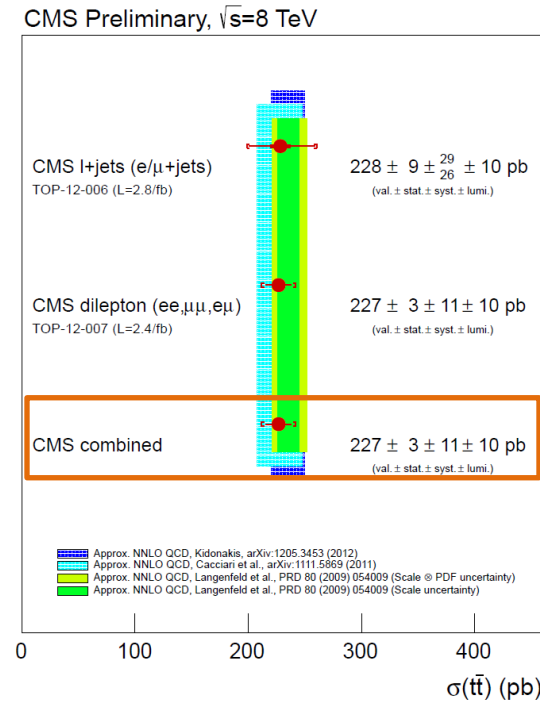
- Dilepton events underconstrained due to the presence of two undetected neutrinos:
  - Use expectation from theory to assign a probability to the solutions (kinematic distributions of the neutrinos, matrix elements)

# $t\bar{t}$ Cross Sections

- Measurements at 7 TeV:
  - Dominated by the very precise dilepton channel (updated result)



- Measurements at 8 TeV:
  - Preliminary results in dilepton and lepton+jets channels

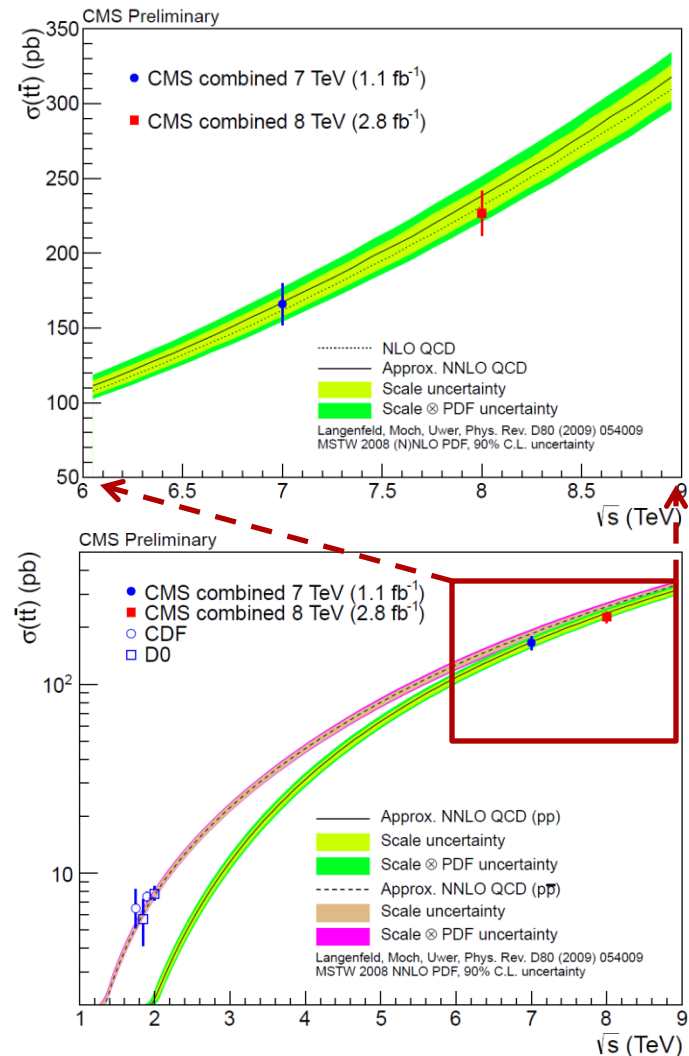


- Exp. precision challenging the approx. NNLO QCD calculations

# $t\bar{t}$ Cross Sections

- Cross section increase with energy agrees with predictions
- Ratio  $R = \sigma(8\text{TeV})/\sigma(7\text{TeV})$ :  

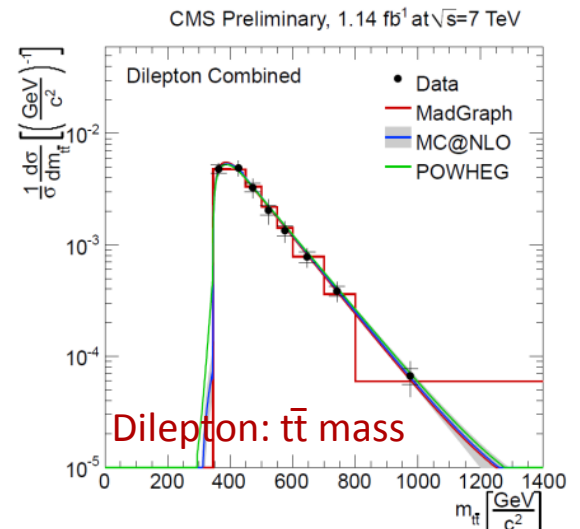
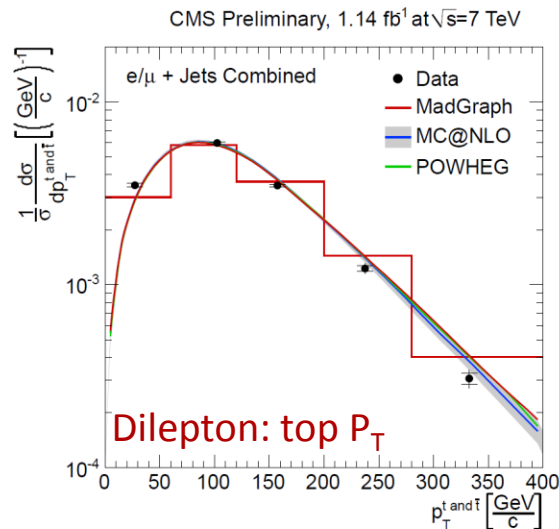
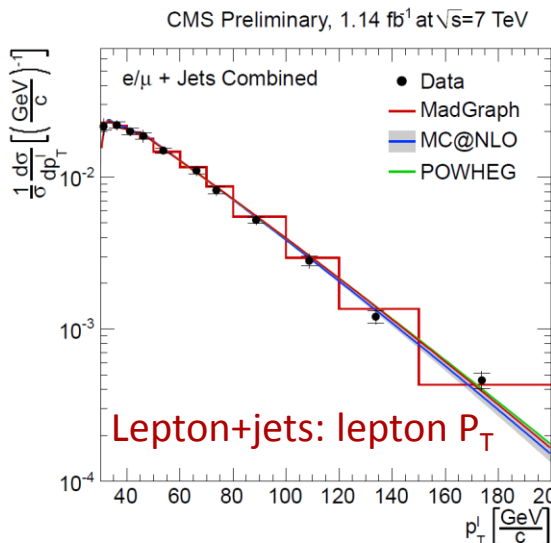
$$R = 1.41 \pm 0.10$$
  - Experimental uncertainties taken as uncorrelated (pessimistic scenario)
  - Theoretical uncertainties assumed to be 100% correlated



# Differential $t\bar{t}$ Cross Sections

TOP-11-013

- Inclusive cross section precision matching theoretical uncertainty
- Differential cross sections test different QCD calculation schemes:
  - Unfolding distributions to parton level
  - Shape measurement: lot of systematic uncertainties cancel out in the normalization

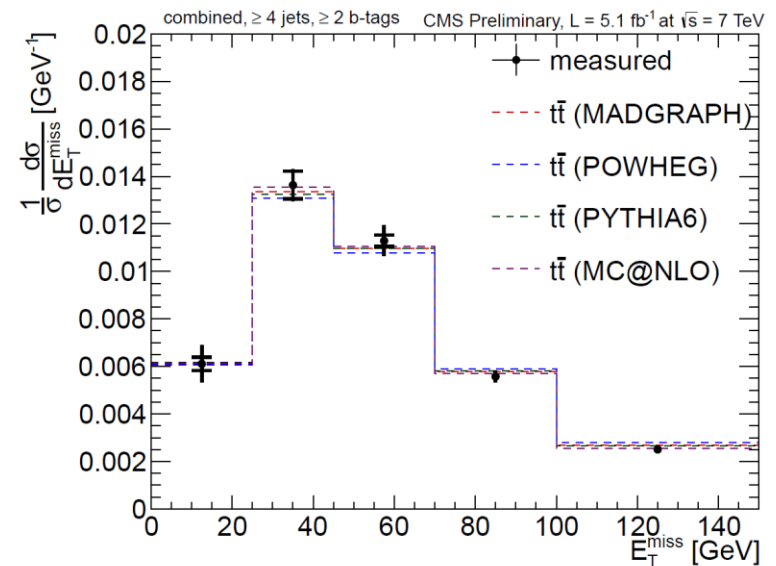
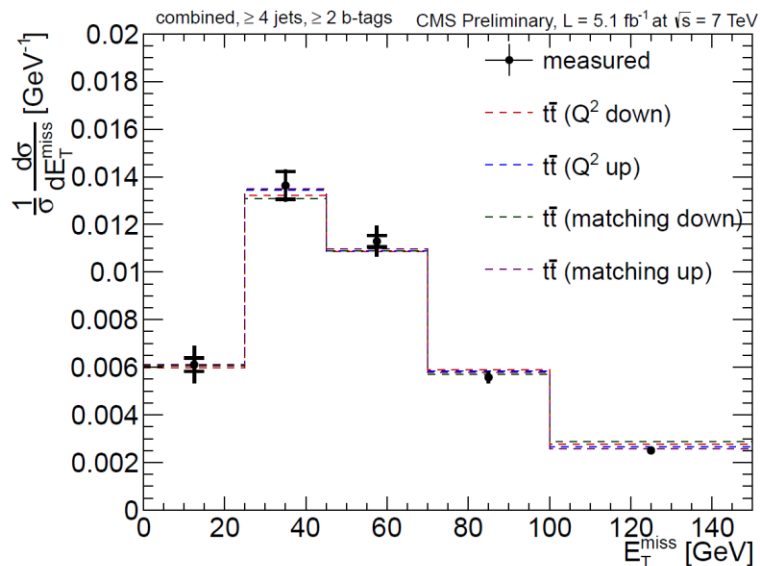




# Missing $E_T$ in $t\bar{t}$ Events

TOP-12-019

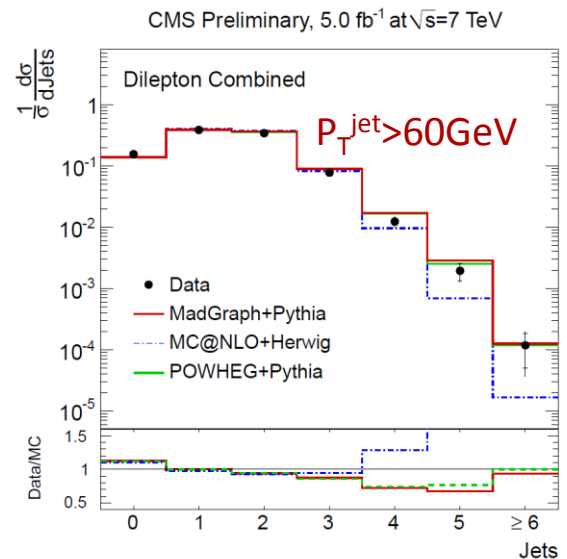
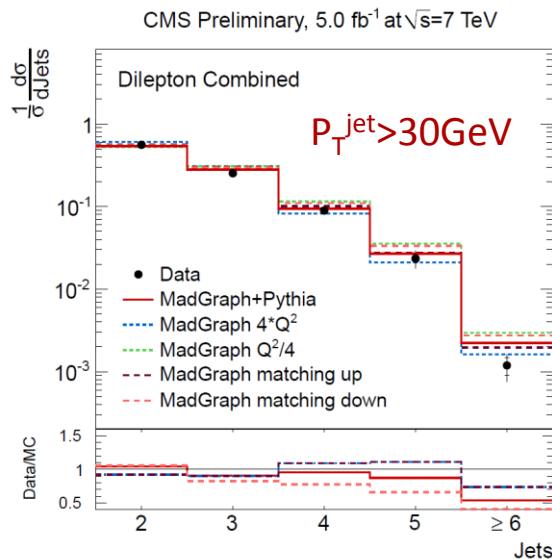
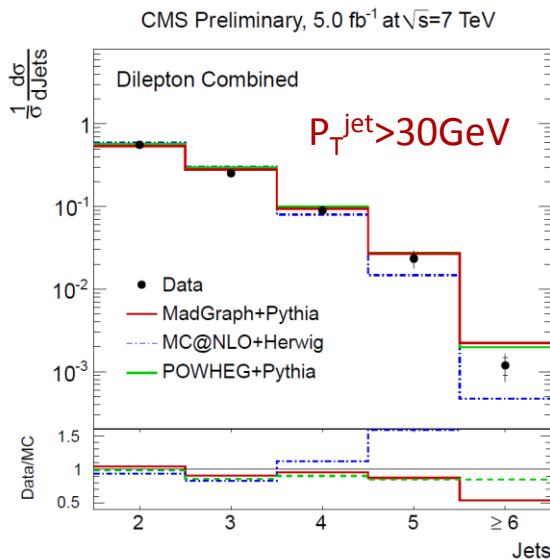
- Test of the current models of top quark pair production
  - $t\bar{t}$  is a major background to many processes involving MET
  - Also sensitive to BSM production of MET with  $t\bar{t}$  pairs
- Selecting  $t\bar{t}$  events in lepton+jets final states
  - Fit to lepton pseudorapidity in bin of missing  $E_T$



# Jet Multiplicity in $t\bar{t}$ Events

TOP-12-023

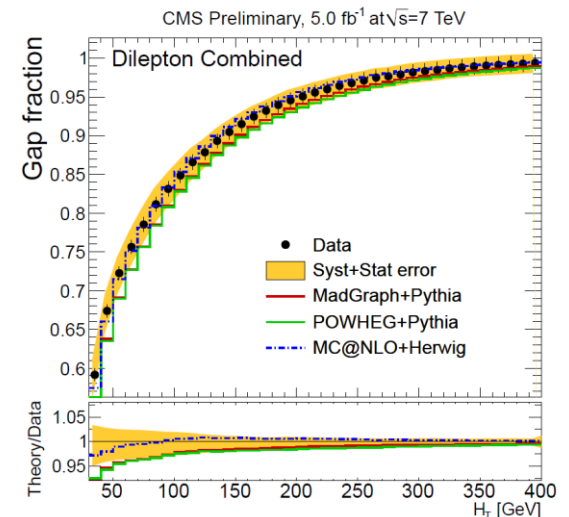
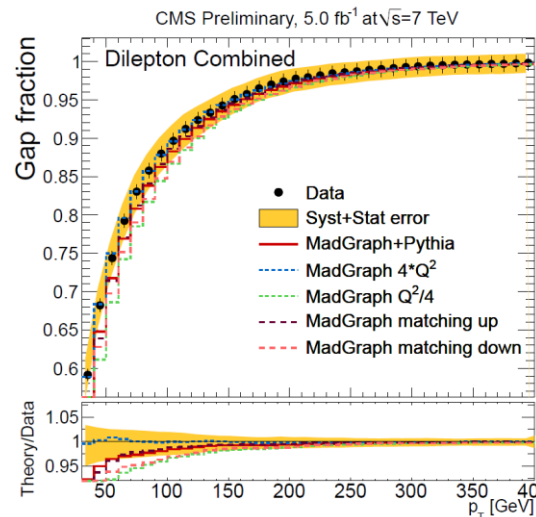
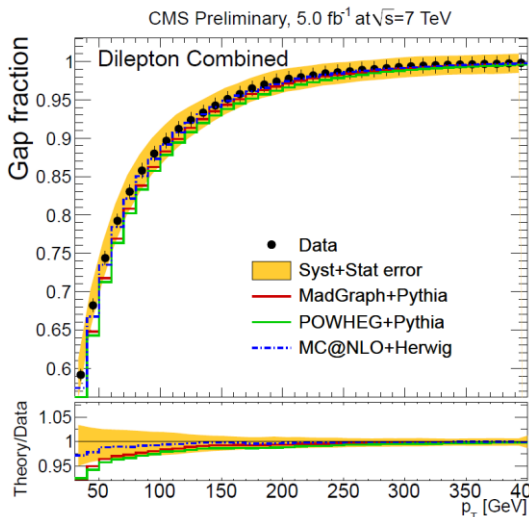
- Differential cross sections for dilepton final state events
  - Test of perturbative QCD calculations at higher order
- Probing higher order effects of different generators using different parameters and shower models



# $t\bar{t}$ +Jets Events

TOP-12-023

- Gap fraction: fraction of events no containing additional jets
- Measured as a function of a threshold on:
  - Transverse momentum of the leading additional jet
  - Scalar sum of the transverse momentum of the additional jets



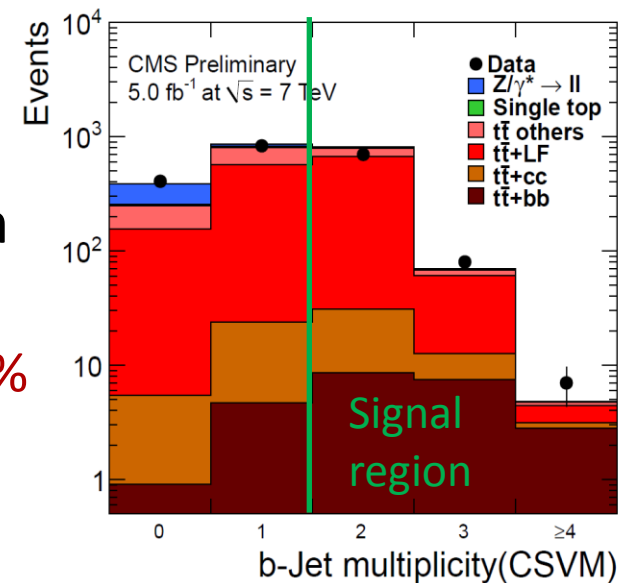
# $t\bar{t}b\bar{b}$ Production

TOP-12-024

- Irreducible background for  $t\bar{t}H \rightarrow t\bar{t}b\bar{b}$  searches
  - Crucial for testing the Yukawa coupling of the new found boson



- Measuring the ratio  $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ :
  - Lot of systematic uncertainties cancel
- Fit to the observed b-tag multiplicity in events with two leptons and four jets:
  - $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 3.6 \pm 1.1(\text{stat.}) \pm 0.9(\text{syst.})\%$
  - NLO QCD: 4.7% (before detector effects)



# $\alpha_s$ from $t\bar{t}$ Cross Section

TOP-12-022

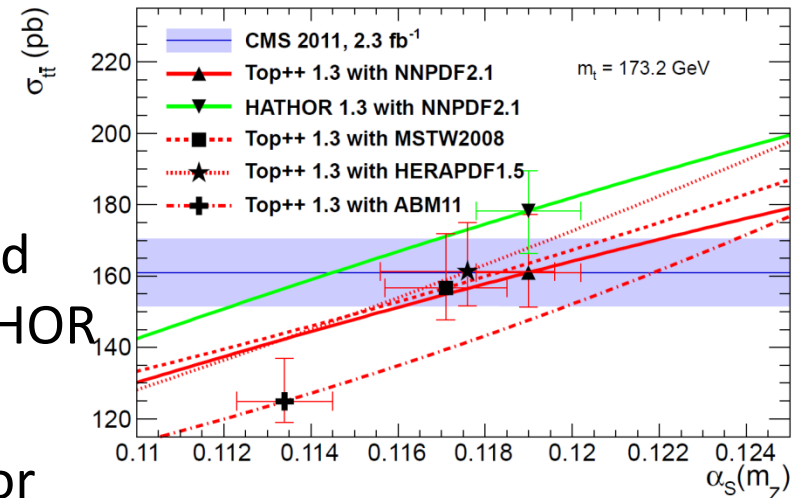
- High precision of  $t\bar{t}$  cross section measurement allows to determine strong coupling constant  $\alpha_s(M_Z)$
- Cross section dependence on  $\alpha_s$  and  $m_t$  determined with Top++ and HATHOR and for different PDFs
- Likelihood function maximization for fixed top mass value ( $m_t = 173.2$  GeV):

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

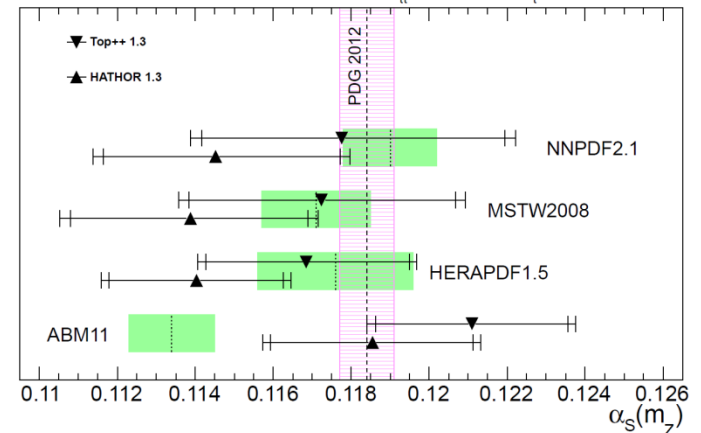
Experimental term (gaussian)

Convolution of PDF (gaussian) and ren./fact. scales (rectangular) terms

- Add uncertainty varying  $m_t$  by  $\pm 1.4$  GeV



2.3 fb<sup>-1</sup> of 2011 CMS data  $\times$  approx. NNLO for  $\sigma_{t\bar{t}}$ ,  $\sqrt{s} = 7$  TeV,  $m_t = 173.2 \pm 1.4$  GeV



# Spin Correlation

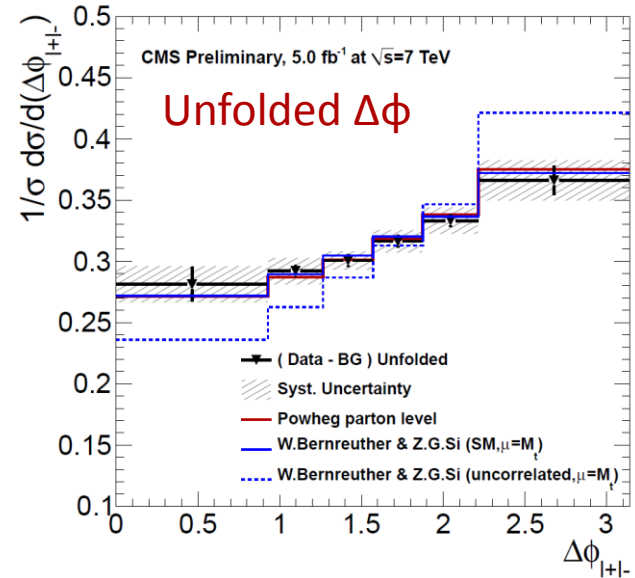
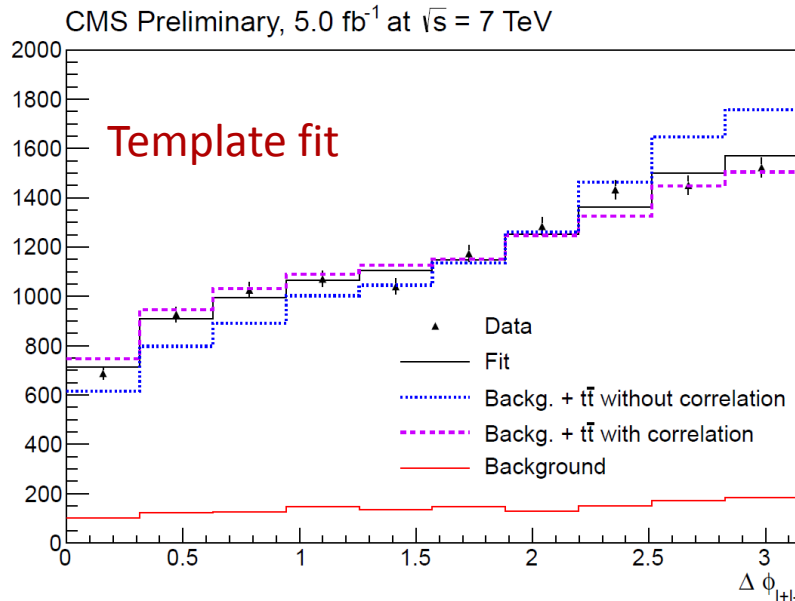
TOP-12-004

- Test of top pair production processes and perturbative QCD

$$A_{\text{hel.}} = \frac{N_{\text{like}} - N_{\text{unlike}}}{N_{\text{like}} + N_{\text{unlike}}} = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}$$

- Fitting lepton azimuthal difference in dilepton final states:

$$A_{\text{hel.}}^{\text{meas.}} = 0.24 \pm 0.02 \text{ (stat.)} \pm 0.08 \text{ (syst.)} \quad (A_{\text{hel.}}^{\text{th.}} = 0.31, \pm \sim 1\%)$$



# Top Polarization

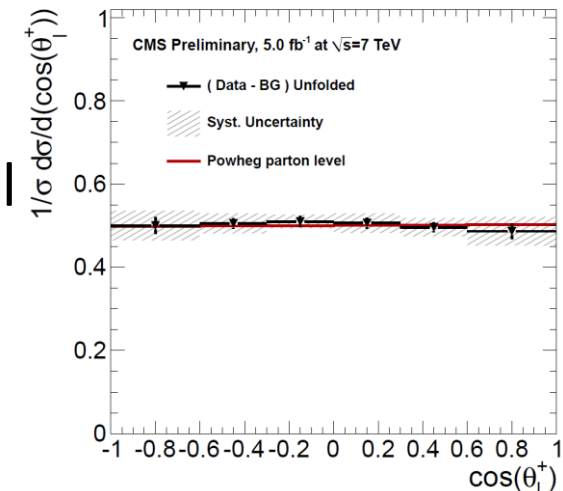
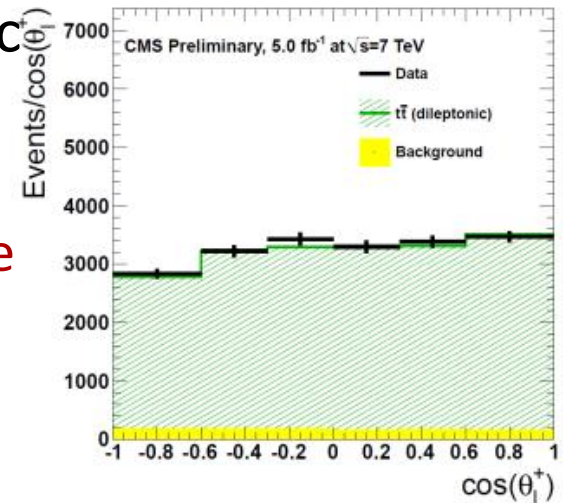
TOP-12-016

- Top polarization  $P_{\hat{n}}$  reflected by kinematic distributions of its decay products:
  - Angle  $\theta_{\hat{n},l}$  between lepton direction in top rest frame and top direction  $\hat{n}$  in  $t\bar{t}$  CM frame
- Fitting the unfolded  $\theta_{l,\hat{n}}$  distributions observed in dilepton final states

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_{l,\hat{n}}} = \frac{1}{2} (1 + 2k_l P_{\hat{n}} \cos\theta_{l,\hat{n}})$$

- Measured  $P_{\hat{n}}$  consistent with parton-level prediction from simulations:

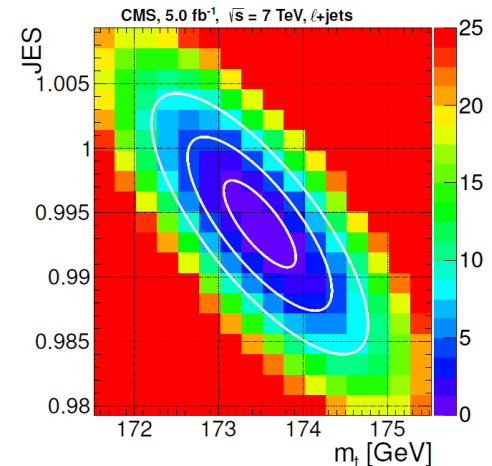
$$P_{\hat{n}} = -0.009 \pm 0.029 \text{ (stat.)} \pm 0.041 \text{ (syst.)}$$



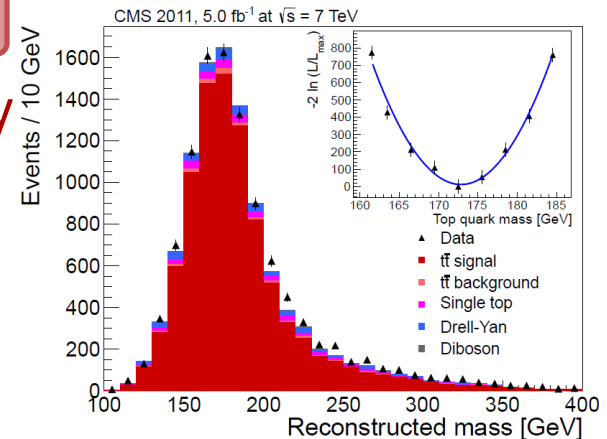
# Top Mass Measurement

- Updated results in the lepton+jets and dilepton channels

- Lepton+jets channel ( $5\text{fb}^{-1}$ ): **TOP-11-015**
  - 2D ideogram method with *in situ* JES calib.
  - Most precise single top mass measurement  
 $m_t = 173.5 \pm 0.4 \text{ (stat.+JES)} \pm 1.0 \text{ (syst.) GeV}$



- Dilepton channel ( $5\text{fb}^{-1}$ ): **TOP-11-016**
  - Neutrino momenta computed analytically
  - Solutions weighted by LO matrix element  
 $m_t = 172.5 \pm 0.4 \text{ (stat.)} \pm 1.5 \text{ (syst.) GeV}$





# Top Mass Measurement

- Results exploiting new techniques or decay channels

- Dilepton channel ( $5\text{fb}^{-1}$ ): TOP-11-027

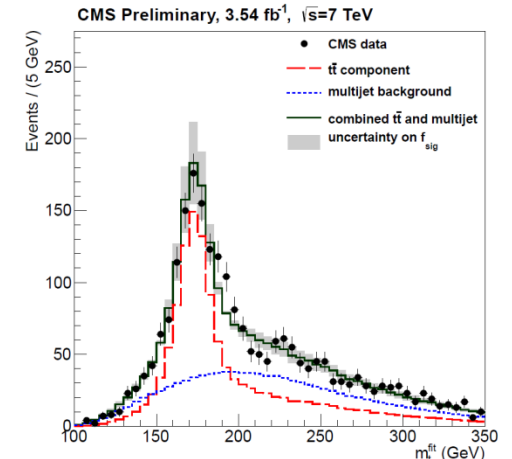
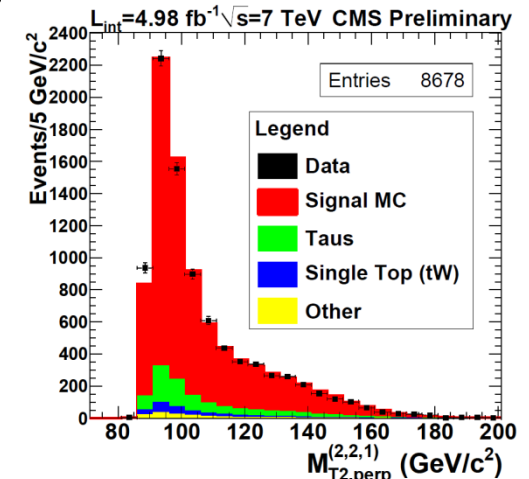
- Kinematic endpoint method
- Technique developed in BSM searches

$$m_t = 173.9 \pm 0.9 \text{ (stat.) } {}^{+1.2}_{-1.8} \text{ (syst.) GeV}$$

- All hadronic channel ( $3.5\text{fb}^{-1}$ ): TOP-11-017

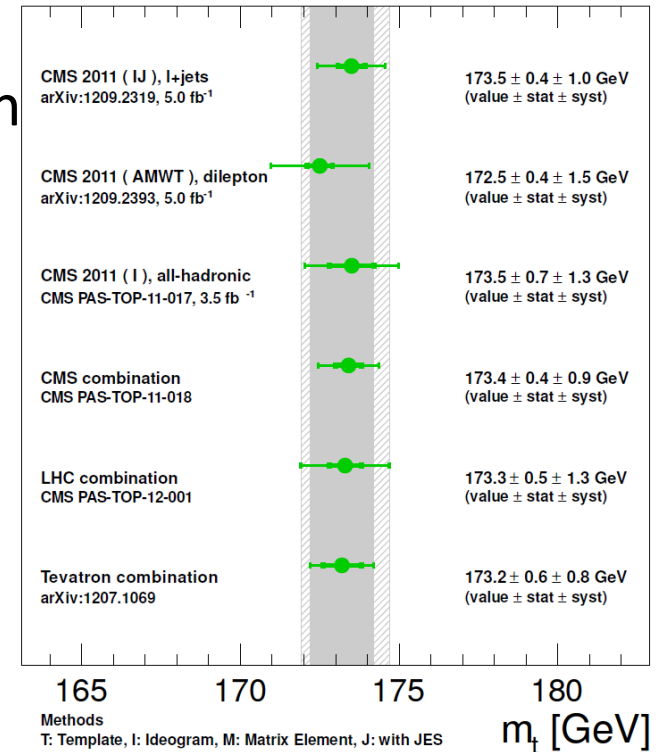
- Similar approach as in lepton+jets channel
- Result with no *in situ* JES calibration

$$m_t = 173.5 \pm 0.7 \text{ (stat.) } \pm 1.3 \text{ (syst.) GeV}$$



# Top Mass Measurement

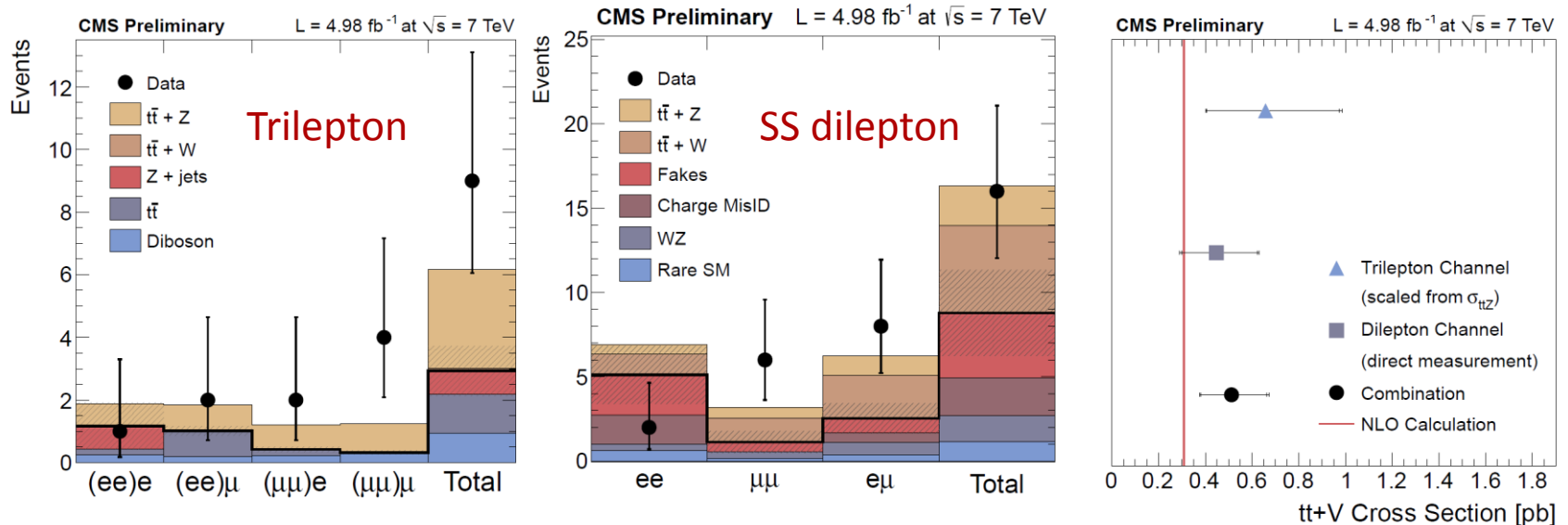
- CMS top mass measurement reached the precision obtained at the Tevatron
- Many ideas to reduce systematics:
  - JES calibrations in situ, b-specific JES
  - ISR/FSR from  $t\bar{t}$ +jets cross sections
  - Constrain theoretical models on data (Color recon., underlying event, PDFs)
  - With large statistics, use well understood regions of phase-space
  - Combine alternative methods with complementary systematics



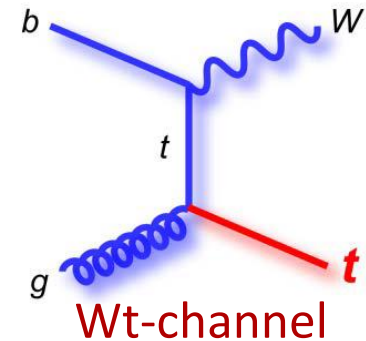
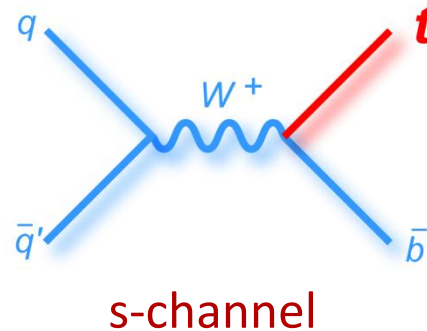
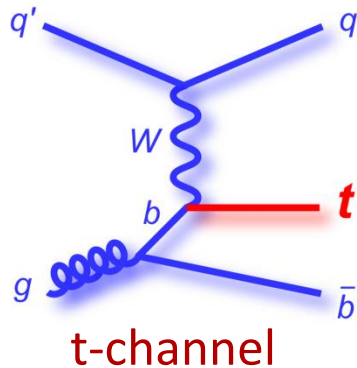
# $t\bar{t}+V$ ( $V=W/Z$ ) Production

TOP-12-014

- Top coupling to weak vector bosons not yet directly measured
- Two independent analyses in lepton+jets  $t\bar{t}$  final states:
  - Trilepton search: designed to select only  $t\bar{t}+Z$  events
  - Same sign dilepton search: sensitive to both  $t\bar{t}+Z/W$  production
- Measured cross sections compatible with NLO calculations



# Single Top Production

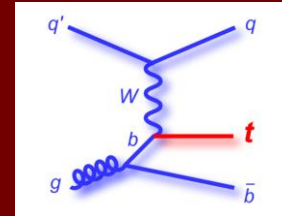


- Test of top EWK coupling, measurement of  $|V_{tb}|$
- Probe for PDFs for b-quarks
- Sensitive to new physics:
  - Anomalous  $W_{tb}$  couplings,  $W'$  or  $H^+$ , FCNC production, 4<sup>th</sup> generation

Kidonakis, approx. NNLO, arXiv:1205.3453v1 (2012)

pp energy	$\sigma(\text{t-channel})$	$\sigma(\text{s-channel})$	$\sigma(\text{Wt-channel})$
7 TeV	$65.9^{+2.6}_{-1.8}$ pb	$4.6 \pm 0.2$ pb	$15.6^{+0.5}_{-0.6}$ pb
8 TeV	$87.2^{+3.4}_{-2.4}$ pb	$5.6 \pm 0.2$ pb	$22.2 \pm 0.8$ pb

# Single Top in the t-Channel



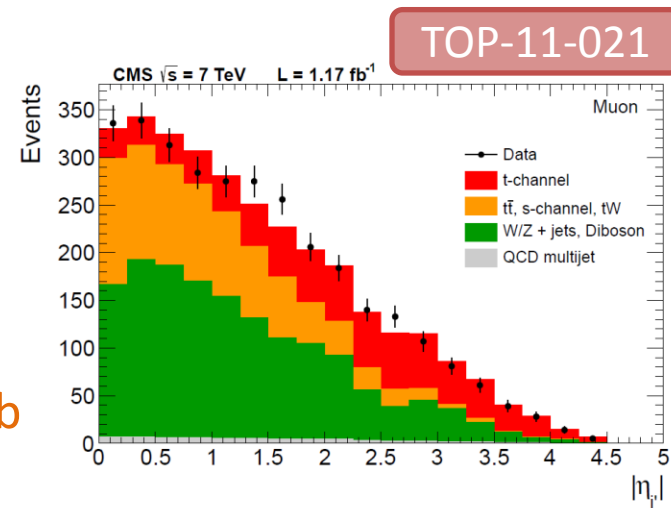
## ■ Cross section measurement at 7 TeV:

### • Two approaches in lepton+jets events:

- Top mass and light jet recoil ( $|\eta'|$ )
- Multivariate discriminators

### • Combined results:

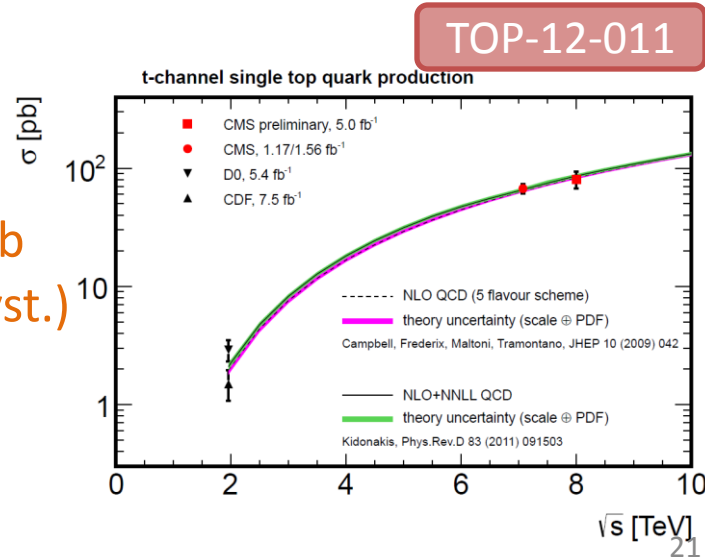
- $\sigma = 67 \pm 4(\text{stat.}) \pm 3(\text{syst.}) \pm 4(\text{th.}) \pm 2(\text{lum.}) \text{pb}$
- $V_{tb} = 1.02 \pm 0.05(\text{exp.}) \pm 0.02(\text{th.})$
- $0.92 < V_{tb} < 1$  @95% CL



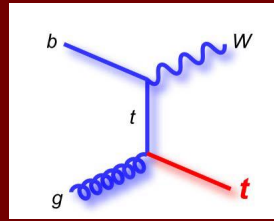
## ■ Cross section measurement at 8 TeV:

### • Only $|\eta'|$ analysis in $\mu$ +jets events:

- $\sigma = 80 \pm 6(\text{stat.}) \pm 11(\text{syst.}) \pm 4(\text{lum.}) \text{pb}$
- $R(8\text{TeV}/7\text{TeV}) = 1.14 \pm 0.12(\text{stat.}) \pm 0.14(\text{syst.})$
- $V_{tb} = 0.96 \pm 0.08(\text{exp.}) \pm 0.02(\text{th.})$
- $0.81 < V_{tb} < 1$  @95% CL

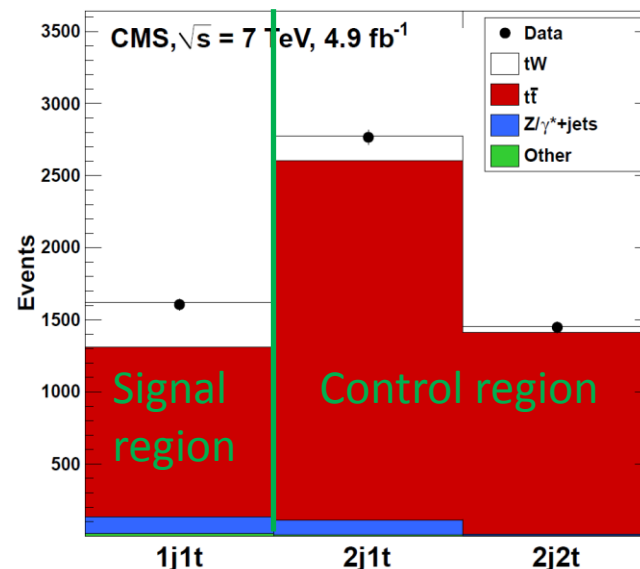
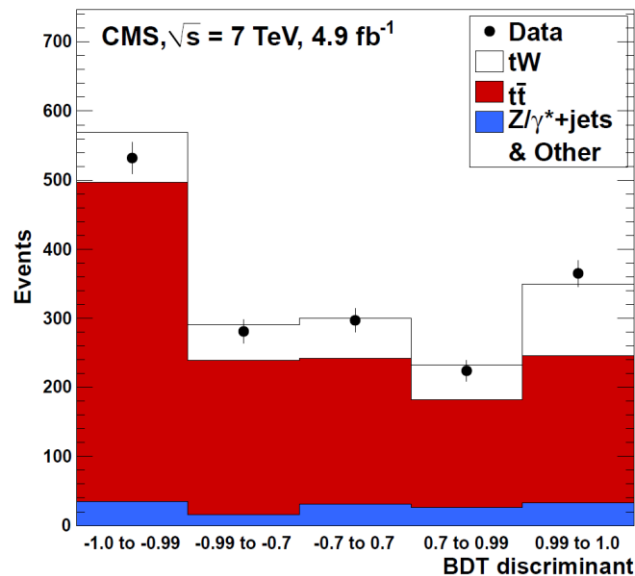


# tW Associated Production



TOP-11-022

- Search for tW associated production in 7 TeV pp collision
  - Decay channel  $tW \rightarrow (bW)W \rightarrow (bl\nu)(l\nu)$
- Binned likelihood fit to BDT output in signal and control regions
  - Excess observed:  $\sigma = 16^{+5}_{-4}$  pb ( $4\sigma$  significance)
  - $V_{tb} = 1.01^{+0.16}_{-0.13}$  (exp.)  $^{+0.03}_{-0.04}$  (th.) ( $0.79 < V_{tb} < 1$  @90% CL)



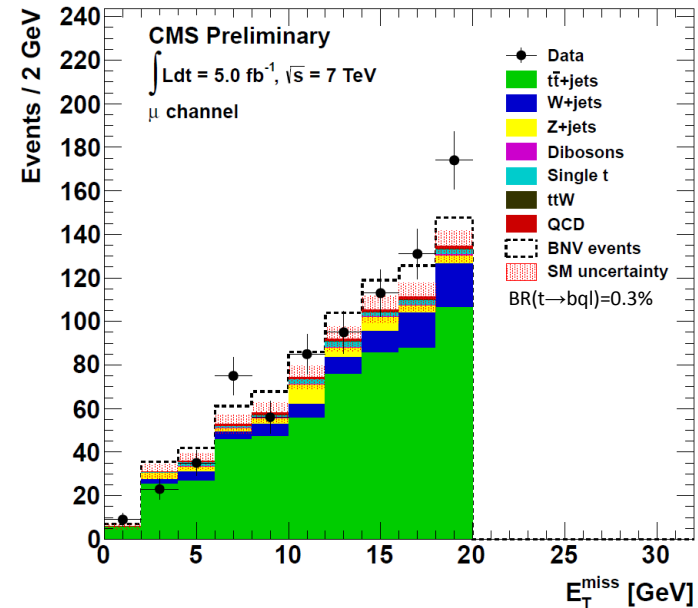
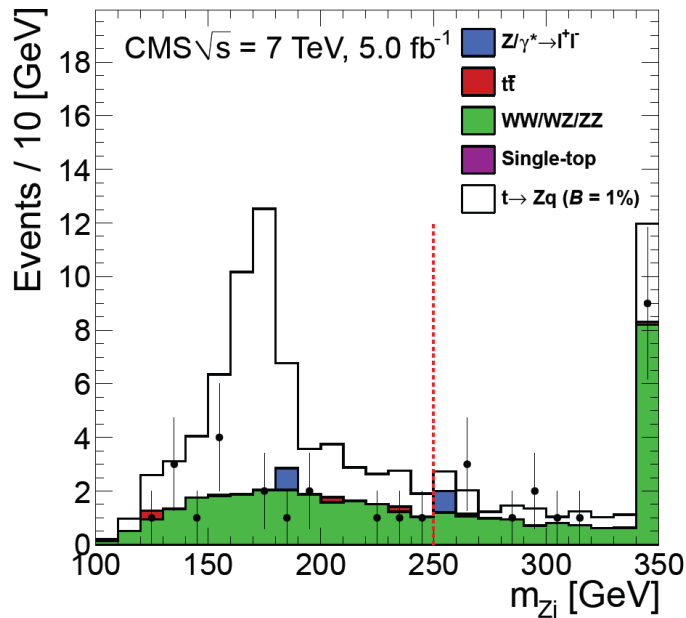
# New Physics in Top Quark Decays

TOP-11-028

B2G-12-002

- Search for FCNC top decays into a Z boson,  $t \rightarrow Zq$ :
  - $t\bar{t} \rightarrow (Wb)(Zq) \rightarrow (bl\nu)(qll)$ : three leptons in the final states
  - $BR(t \rightarrow Zq) < 0.24\%$  @95% CL

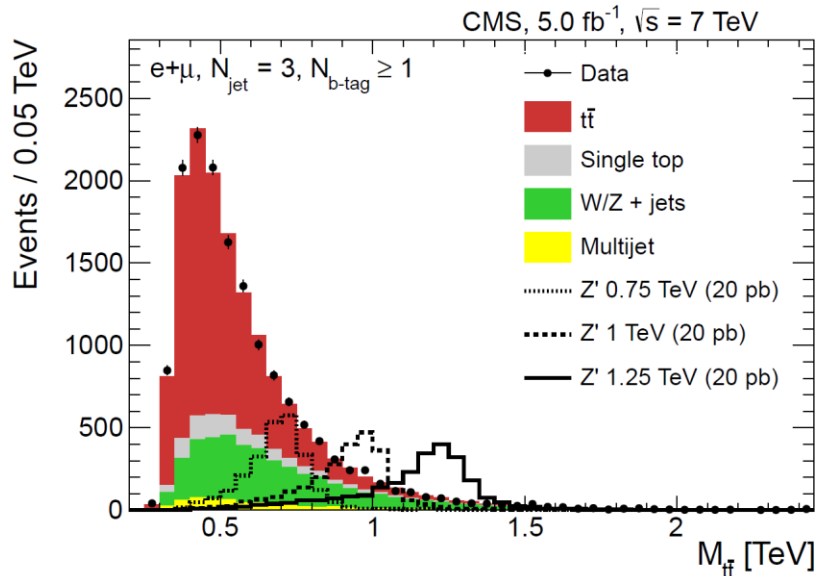
- Search for baryon number violating top decays:
  - $t\bar{t} (Wb)(bql) \rightarrow (bqq)(bql)$ : one charged lepton, no neutrinos
  - $BR(t \rightarrow bql) < 0.67\%$  @95% CL



# New Physics in Top Production

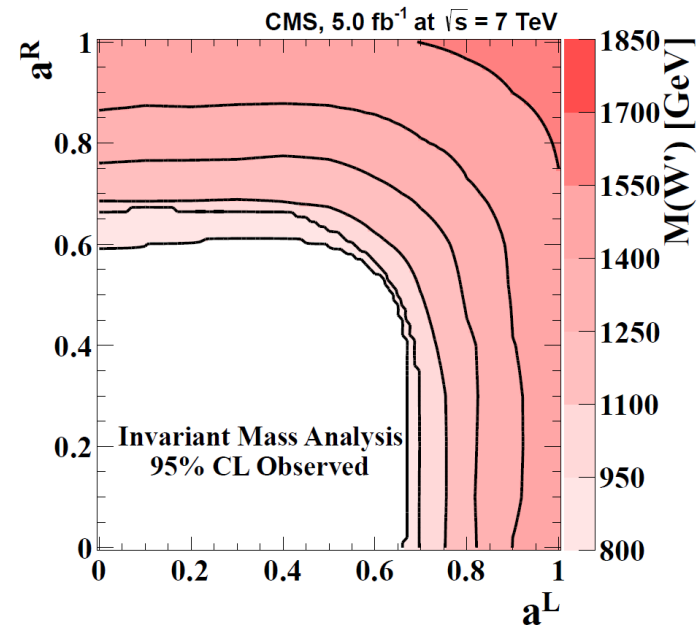
TOP-12-017

- Search for  $t\bar{t}$  resonances:
  - $M_{t\bar{t}}$  in lepton+jets events
  - Lower limits (95% CL):
    - Topcolor  $Z'$ :  $M_{Z'} > 1.49$  TeV
    - KK excited  $g$ :  $M_{g^*} > 1.82$  TeV



EXO-12-001

- $W'$  boson decaying to  $tb$ :
  - $W' \rightarrow tb \rightarrow Wbb \rightarrow l\nu bb$
  - Assuming SM couplings:
    - Right-handed  $W'$ :  $M_{W'} > 1.85$  TeV
    - $M_{W'}$  contours in  $(a^L, a^R)$  plane

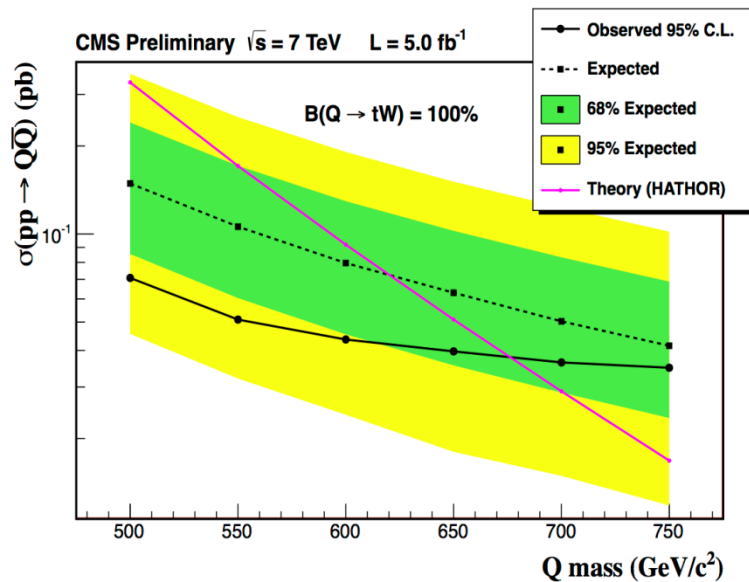




# New Physics in Top Production

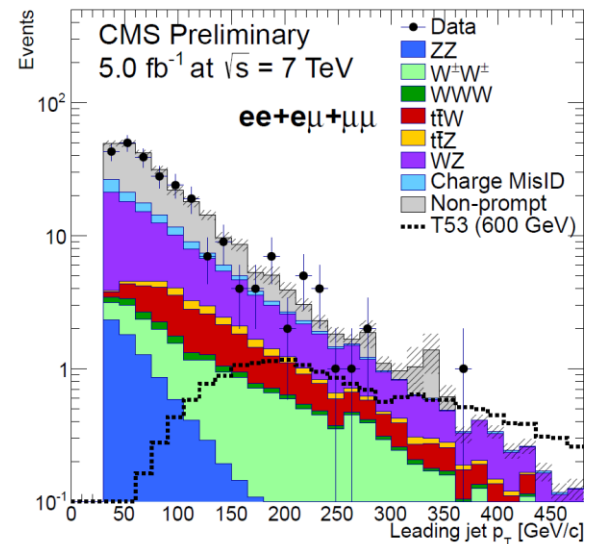
B2G-12-004

- Heavy quark decaying to  $tV$ :
  - $Q\bar{Q} \rightarrow t\bar{t}VV \rightarrow l\nu + \geq 4\text{jets}$
  - No excess over SM observed:
    - $M(Q \rightarrow tW) > 675 \text{ GeV @95\% CL}$
    - $M(Q \rightarrow tZ) > 625 \text{ GeV @95\% CL}$



B2G-12-003

- Heavy top quark partner,  $Q=5/3$ :
  - Same sign dilepton +  $\geq 4$  jets from  $T_{5/3}T_{5/3} \rightarrow (tW)(tW) \rightarrow (bl\nu l\nu)(bqqqq)$ :
    - $M(T_{5/3}) > 645 \text{ GeV @95\% CL}$



# Conclusions

- CMS is investigating top production and properties in pp collisions at center-of-mass energies of 7 and 8 TeV
- High precision measurements on inclusive and differential cross section challenge theoretical models, and can be used to validate their predictions and constrain their parameters
- Measurements of many top properties test the validity of the standard model
- Direct searches for new phenomena constrain the scenarios for beyond standard model physics
- **Expect new results with improved precision and reach from 2012 data**

# Back Up Material

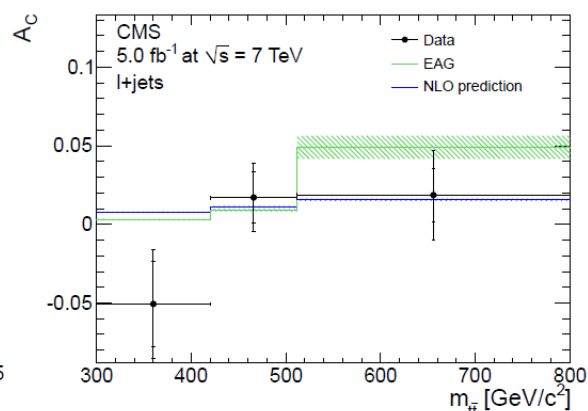
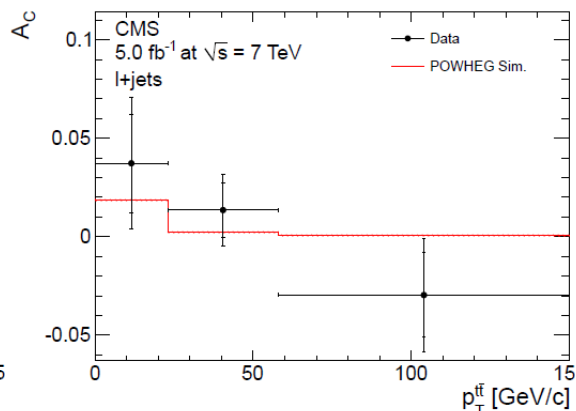
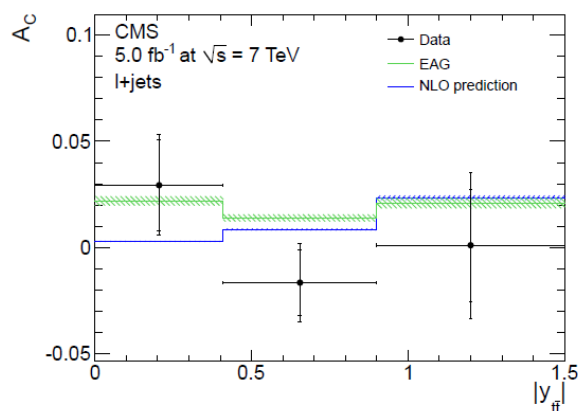
# Charge Asymmetry

TOP-11-030

- Charge asymmetry in  $t\bar{t}$  pair production:
  - Sensitive to BSM top production
  - In pp collisions, antitop expected to be produced more centrally
- CMS measurements compatible with SM predictions:

$$A_C^y = (N_P - N_N) / (N_P + N_N), \quad N_P = N(|y_t| - |y_{\bar{t}}| > 0), \quad N_N = N(|y_t| - |y_{\bar{t}}| < 0)$$

$$A_C^y = 0.004 \pm 0.010 \text{ (stat.)} \pm 0.012 \text{ (syst.)}, \quad A_C^{\text{th}} = 0.0115 \pm 0.0006$$



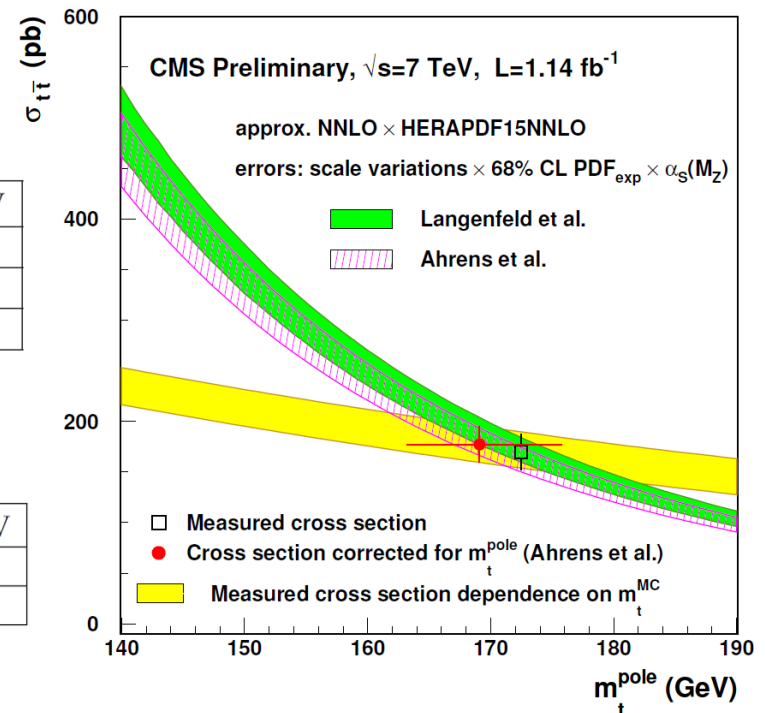
# Top Mass from Cross Section

TOP-11-008

- Exploit strong dependence of top pair cross section on top mass
  - Using cross section measurement from dilepton channel ( $1.14 \text{ fb}^{-1}$ )
- Well defined renormalization scheme:
  - Test of the mass scheme as applied in the MC simulations

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

Approx. NNLO $\times$ HERAPDF15NNLO	$m_t^{\text{pole}} / \text{GeV}$	$m_t^{\overline{\text{MS}}} / \text{GeV}$
Langenfeld et al. [7]	$171.7^{+6.8}_{-6.0}$	$164.3^{+6.5}_{-5.7}$
Ahrens et al. [9]	$169.1^{+6.7}_{-5.9}$	$161.0^{+6.8}_{-6.1}$

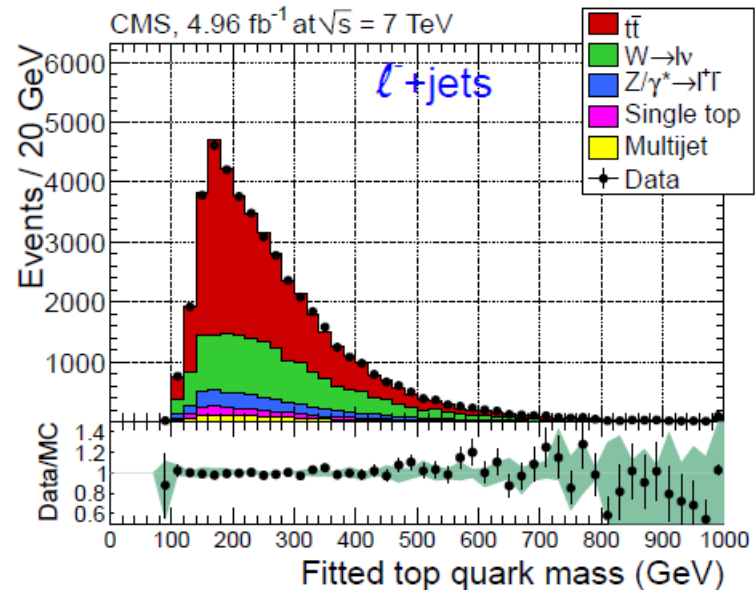
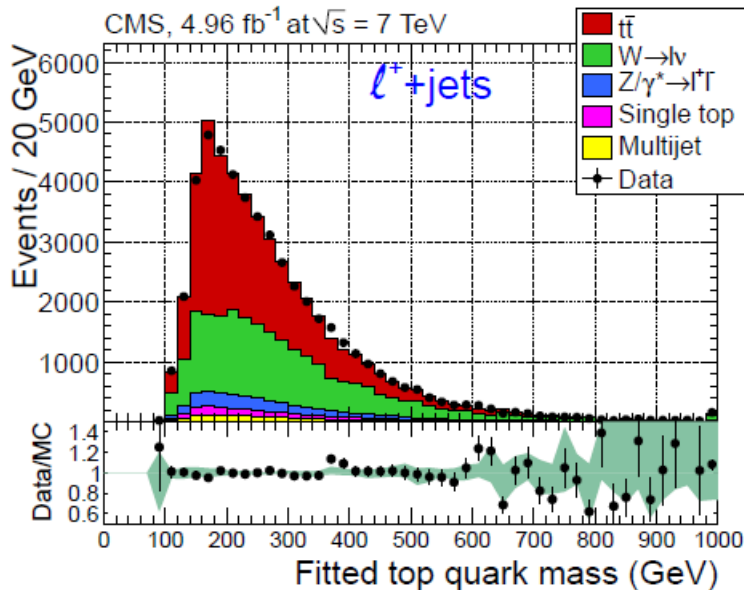


# Top-Antitop Mass Difference

TOP-11-019

- If CPT is conserved, particle and antiparticle must have same mass
  - The top quark is the only one with which we can test this directly
- CMS: reconstruct  $t$  ( $\bar{t}$ ) mass in  $l^-(l^+)+\text{jets}$  events:

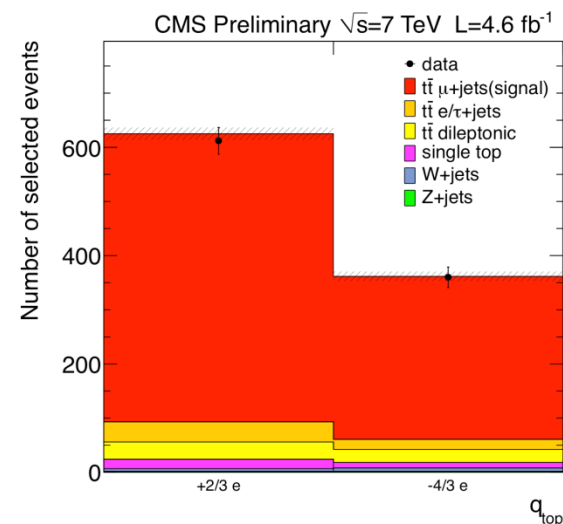
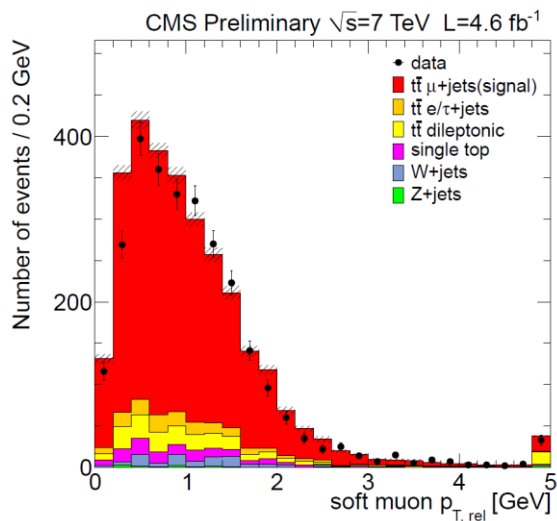
$$\Delta m_t = -0.44 \pm 0.46 \text{ (stat.)} \pm 0.27 \text{ (syst.) GeV}$$



# Top Quark Charge

TOP-11-031

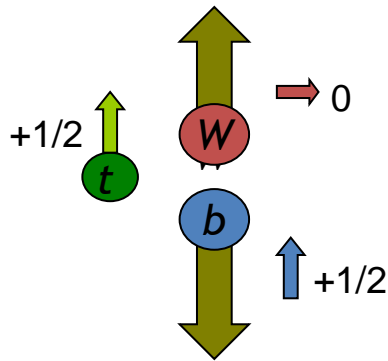
- Constraints on top charge:
  - Top charge reconstructed from the charge of the decay products:
    - W: same charge of muon from  $W^\pm \rightarrow \mu^\pm u$  decay
    - b: flavor from charge of muon in semileptonic decay
- $q=+2/3$  vs  $q_t=-4/3$  hypotheses:
  - Good agreement with SM



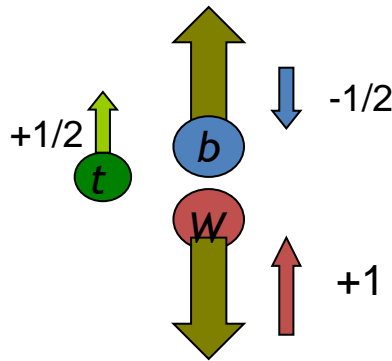
# W Boson Polarization

TOP-11-020

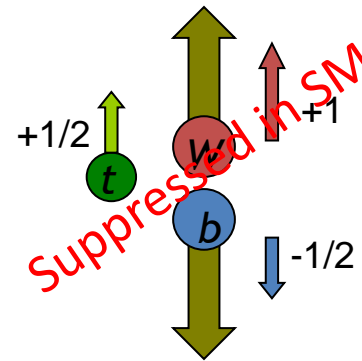
- W boson polarization tests V-A coupling in top decays:



$W_0$  longitudinal:  $F_0 = 0.7$

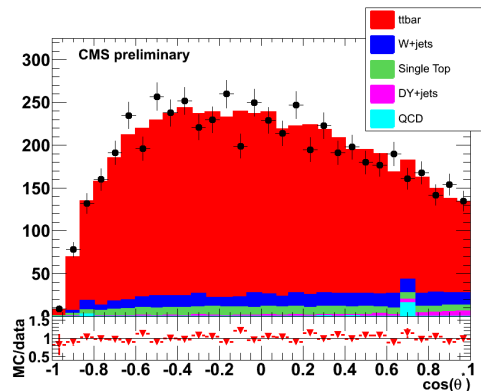
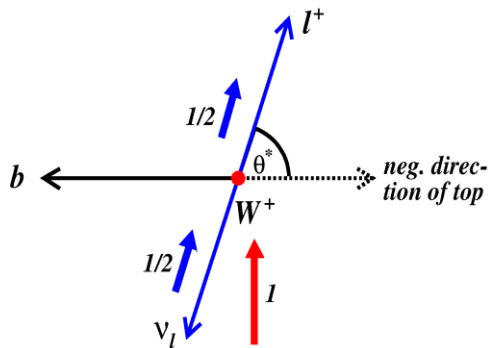


$W_-$  left-handed:  $F_- = 0.3$



$W_+$  right-handed:  $F_+ \approx 0.0$

- CMS measured the W helicity fractions in the  $l\bar{t}$  channel:



- $F_0 = 0.57 \pm 0.07 \pm 0.05$

- $F_- = 0.39 \pm 0.04 \pm 0.03$

- $F_+ = 0.04 \pm 0.04 \pm 0.04$



# Top Quark Decay

TOP-11-029

- Measurement of decay ratio  $R = \text{BR}(t \rightarrow Wb) / \text{BR}(t \rightarrow Wq)$ :
  - Fit to b-tag multiplicity in  $t\bar{t}$  dilepton decays
  - $R = 0.98 \pm 0.04$ ,  $R > 0.85$  @95% CL

