Top quark measurements in CMS

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on behalf of the CMS collaboration

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Outline

- Introduction
- Top pair cross sections
  - top pair, ttbb/ttjj, ttH, ttW/Z
  - SM parameter constraints: α_s, m_t^{pole}
- Single top cross section
- Top quark properties:
  - top mass, spin correlations, $|V_{tb}|$, charge asymmetry, polarisation
- Beyond the Standard Model
  - FCNC

Top quark

The heaviest SM particle: $m_t = 172.2 \pm 0.8$ GeV (CMS combination)

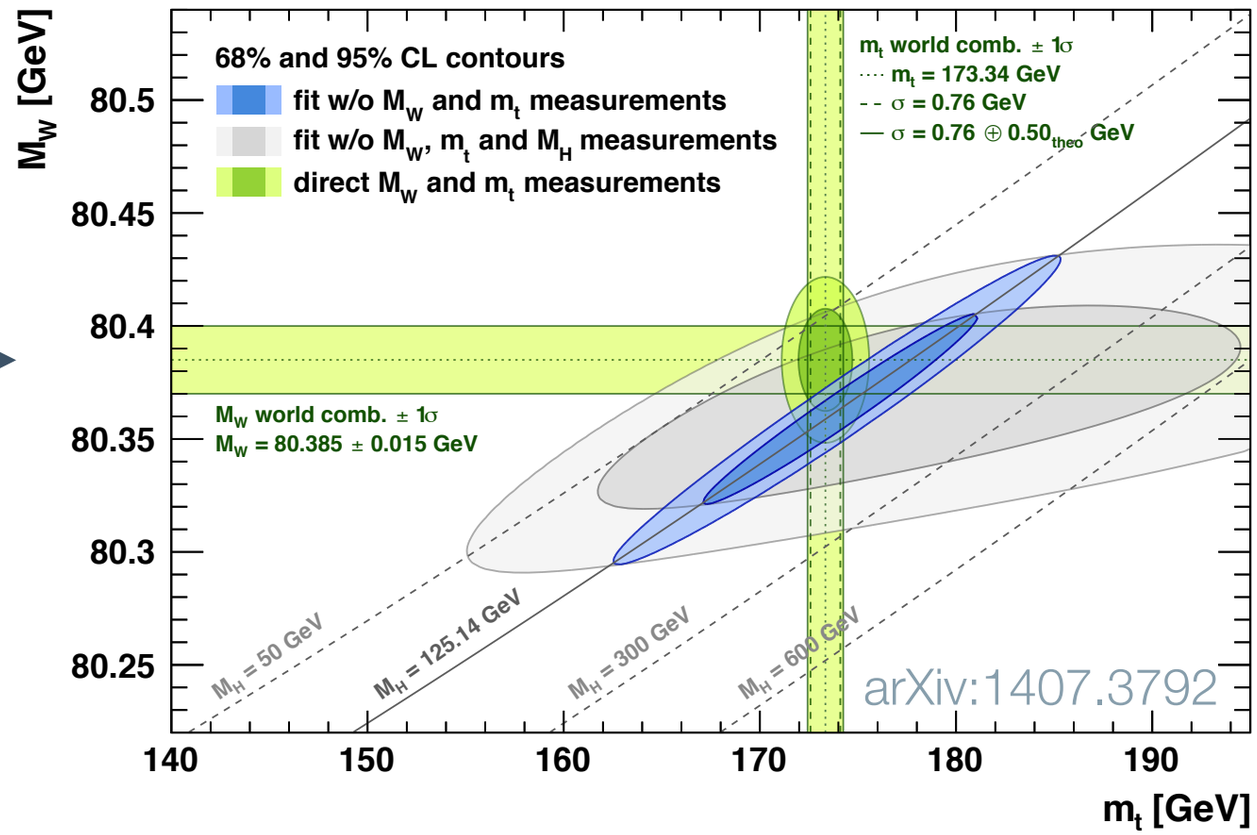
Life time (10^{-25}s) shorter than hadronisation time scale (10^{-24}s)
bare quark properties accessible: mass, $|V_{tb}|$, spin, charge,…

Top quark mass – important Standard Model parameter

The Higgs boson preferentially couples to the top quark

Can be used for testing the SM
consistency of m_H, m_W, m_t →
pQCD precision tests

Main background in many BSM searches



Top quark production

LHC – top quark factory

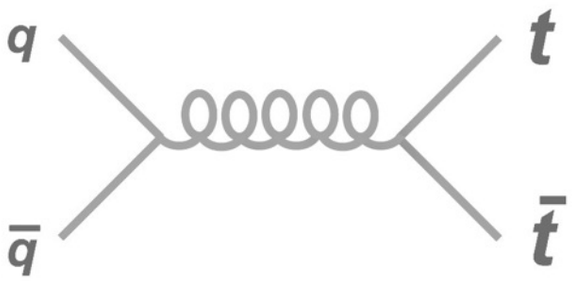
NNLO mt=173.3 GeV

Collider	σ_{tot} [pb]
Tevatron	7.009
LHC 7 TeV	167.0
LHC 8 TeV	239.1
LHC 14 TeV	933.0

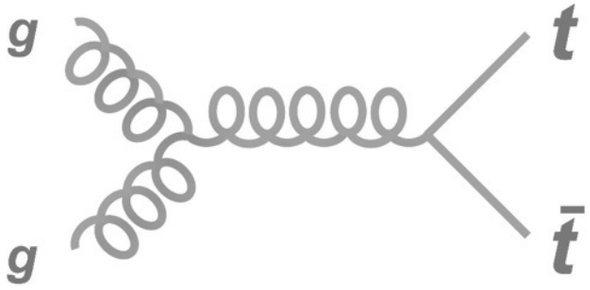
arXiv: 1303.6254

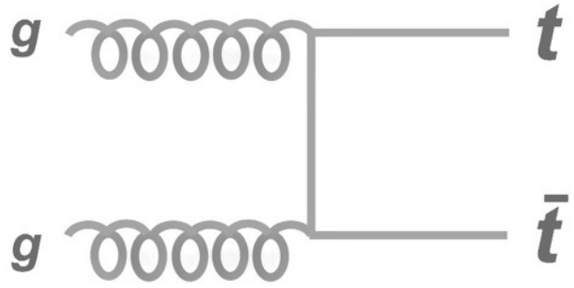
Top pair production: via QCD interactions

85% Tevatron
15% LHC

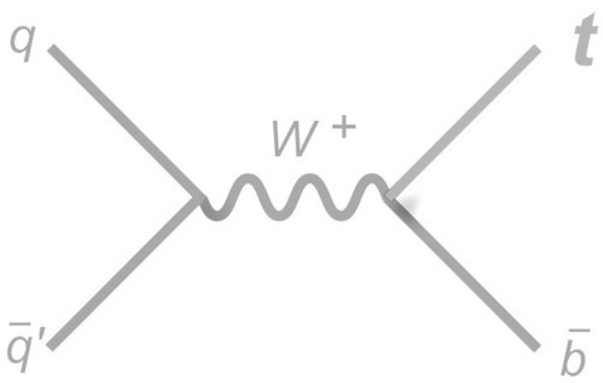


15% Tevatron
85% LHC

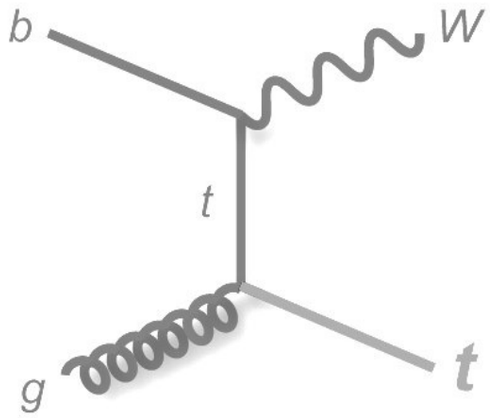




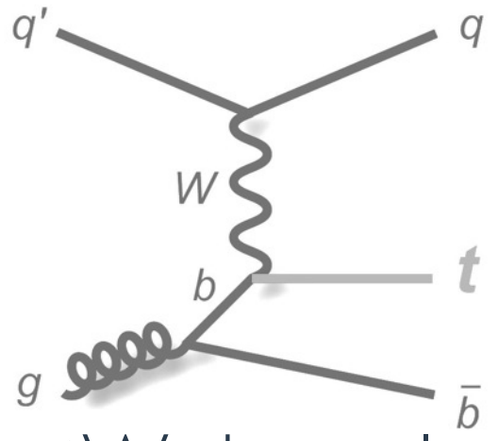
Single top production: via EWK interactions



t-channel



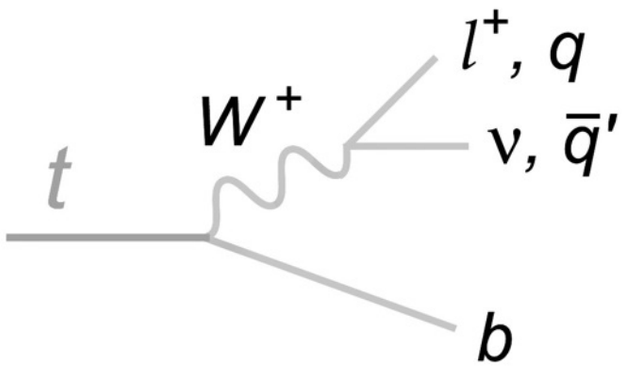
s-channel



tW-channel

Top pair decay signatures

$t \to Wb \sim 100\%$

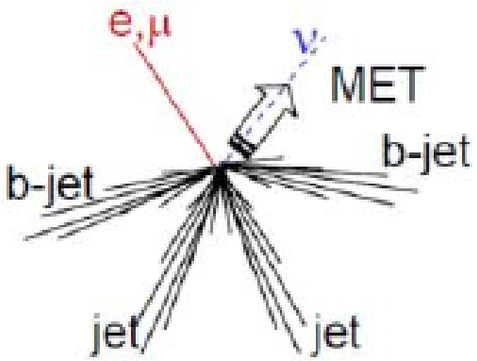


W decay defines final state →

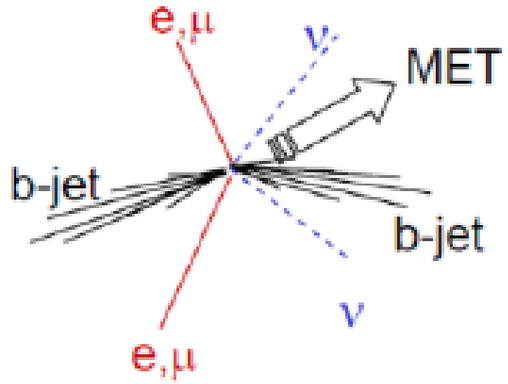
Top Pair Decay Channels

W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
e^-	ee	$e\mu$	$e\tau$	electron+jets	
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
$u\bar{d}$	electron+jets	muon+jets	tau+jets	all-hadronic	
$c\bar{s}$					

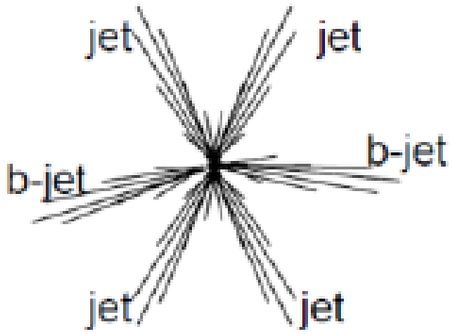
dileptons



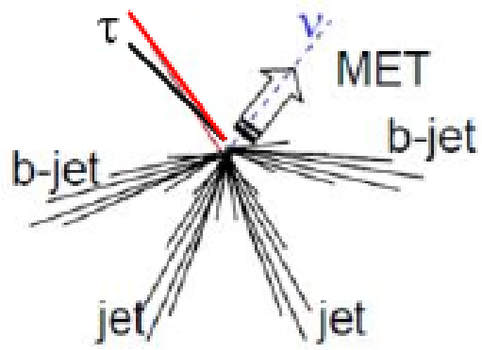
semileptonic [e/μ] BR~30%
Bkg: W+jets, …



dileptonic [e/μ] BR~5%
Bkg: DY+jets, … (small)

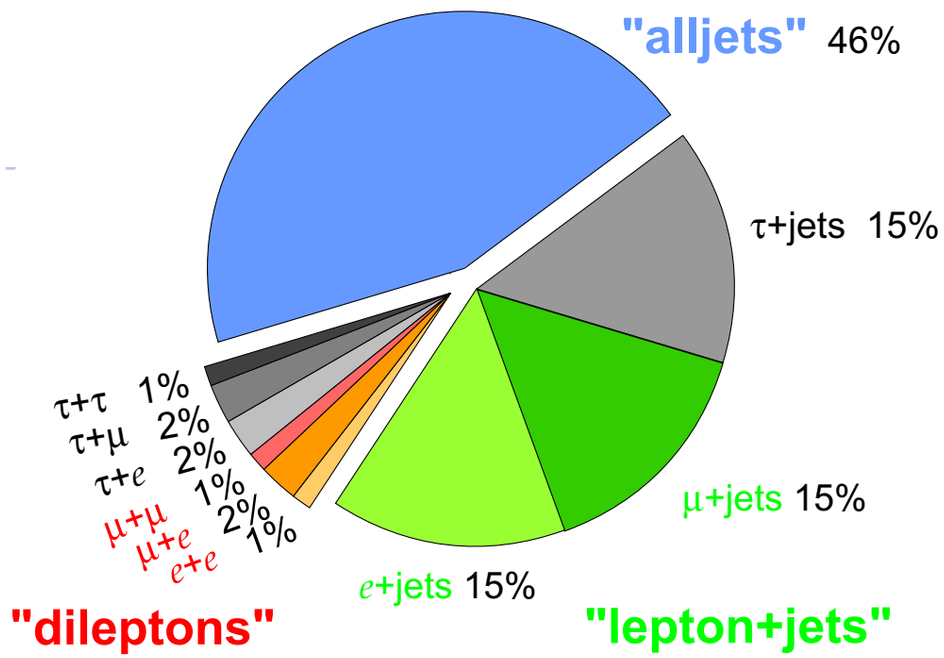


all-hadronic [e/μ] BR~46%
Bkg: QCD multijet, … (large)



τ+jets BR~15%

Top Pair Branching Fractions

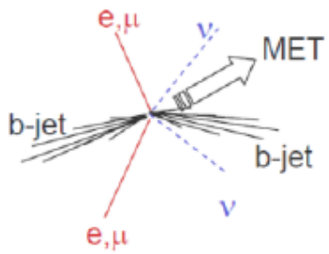


Top pair production

Top pair inclusive cross section

JHEP 02 (2014) 024

dileptonic channel



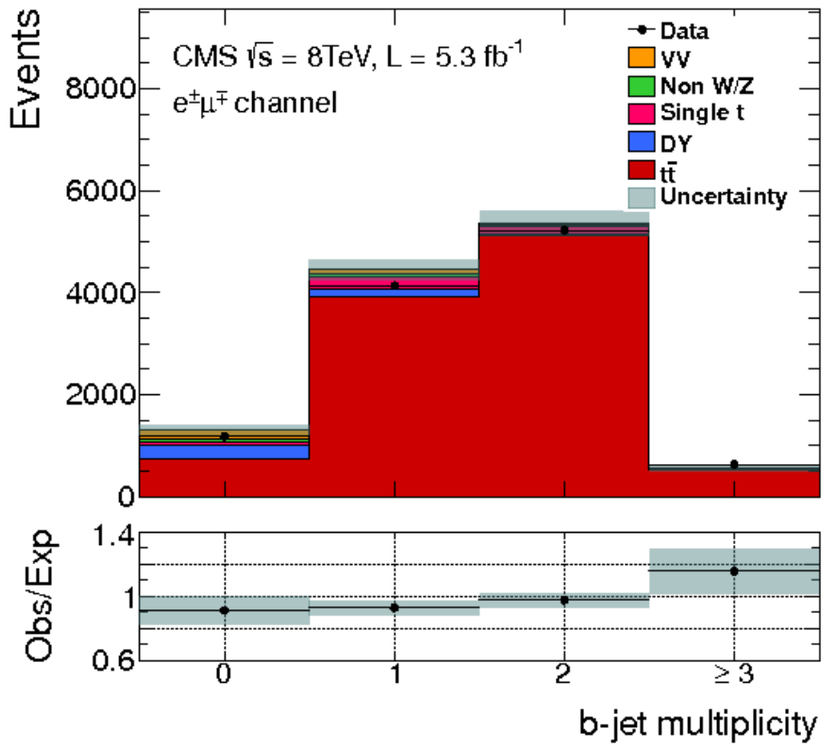
2 oppositely charged isolated high-p_T leptons: **ee**, **eμ**, **μμ** – separately

≥2 jets, ≥1 b-tagged jet

DY and non-W/Z background data estimated

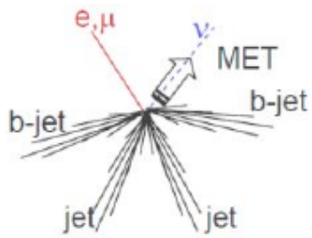
Main systematics: JES, model uncertainties

$$\sigma_{t\bar{t}} = 239.0 \pm 2.1\,(\text{stat.}) \pm 11.3\,(\text{syst.}) \pm 6.2\,(\text{lum.})\,\text{pb}$$



arXiv:1407.6643

e+τ, μ+τ channel



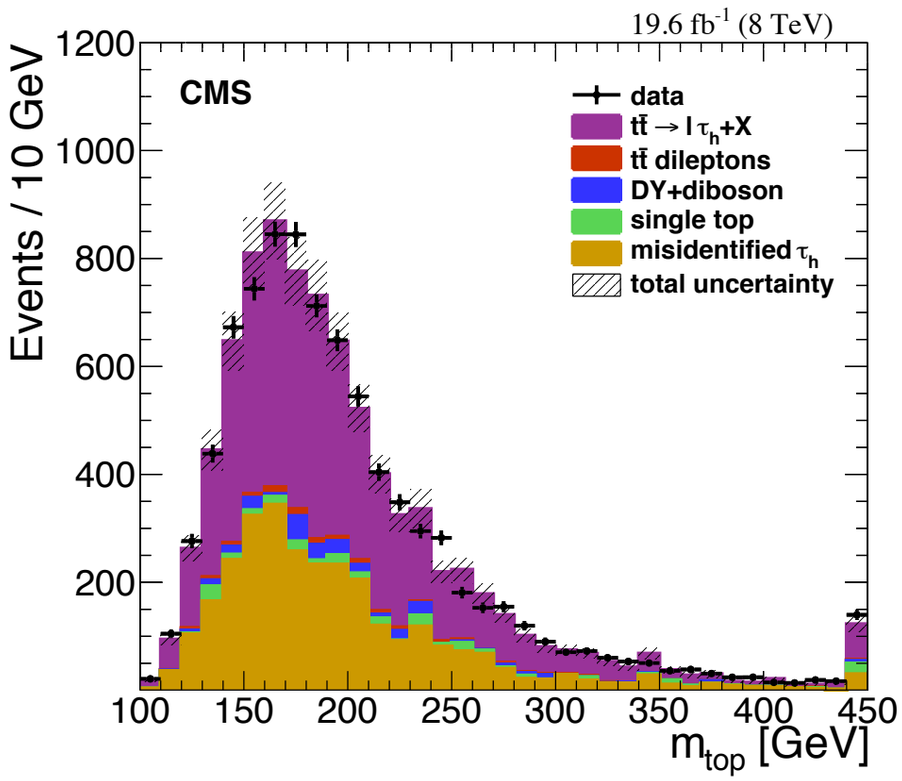
exactly 1 isolated lepton **e/μ**

exactly 1 reconstructed hadronic **τ**

Main background: semileptonic tt
1 jet misidentified as **τ**

$$\sigma_{t\bar{t}} = 257 \pm 3\,(\text{stat}) \pm 24\,(\text{syst}) \pm 7\,(\text{lumi})\,\text{pb}$$

Lepton universality satisfied



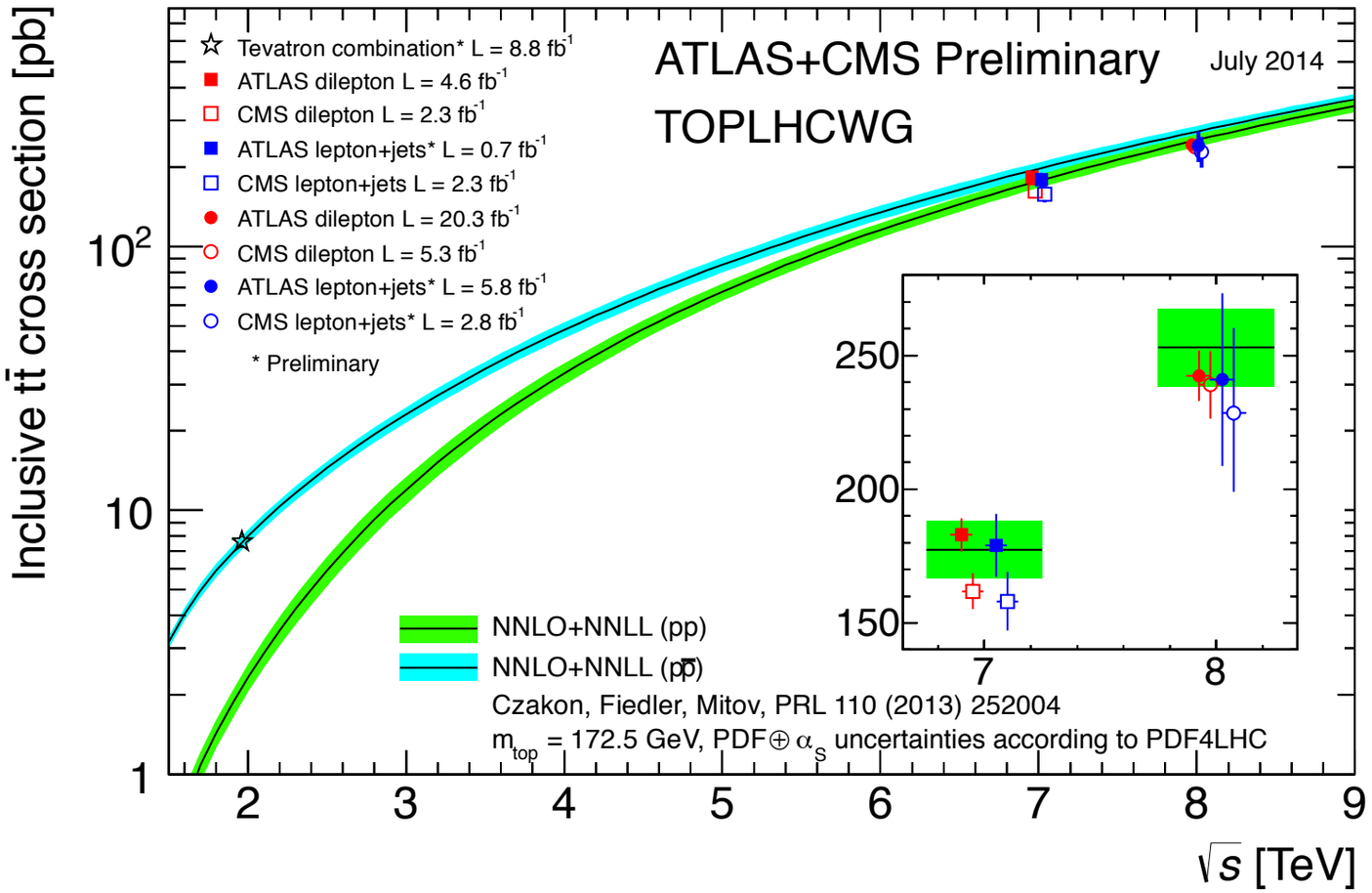
Top pair inclusive cross section

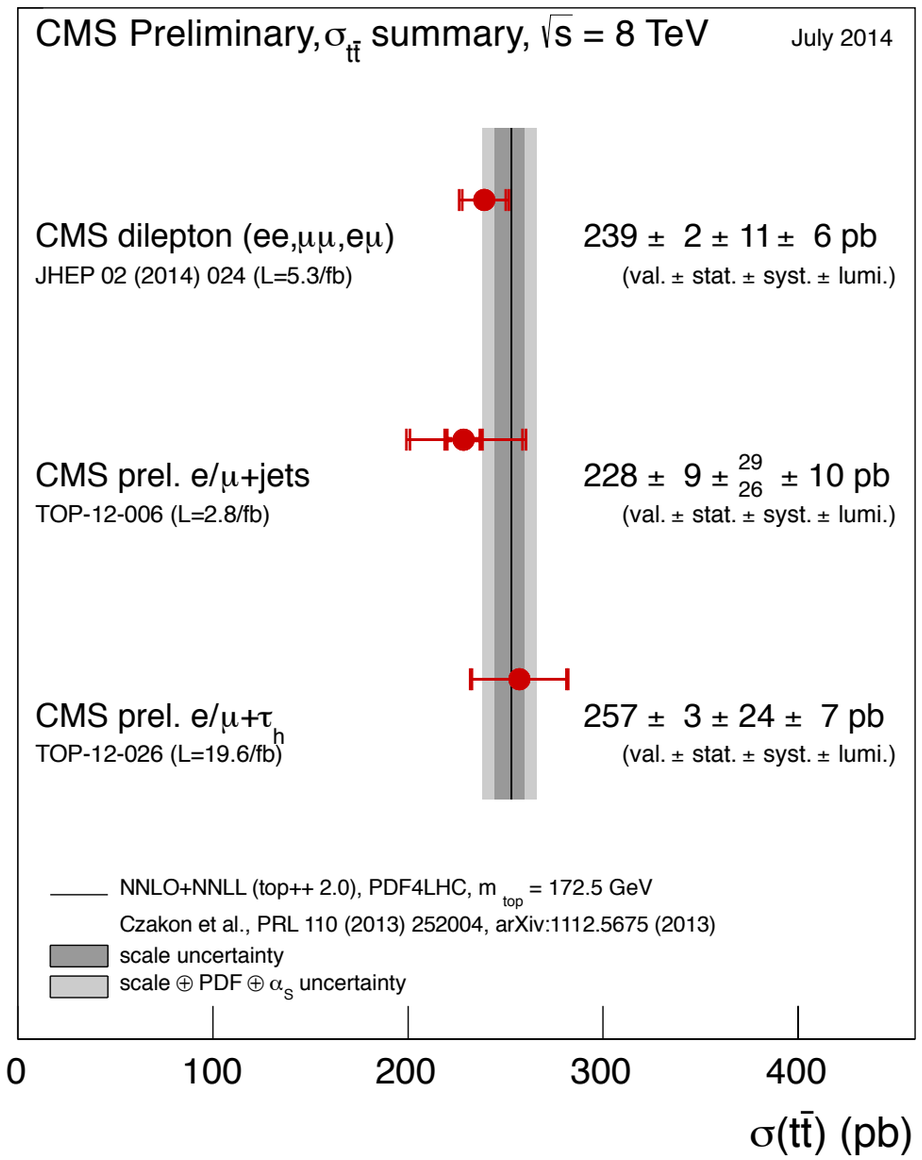
ATLAS+CMS combination of 7TeV and 8TeV measurements

Correlated uncertainties taken into account

Precision driven by the dilepton channel

Limited by systematic uncertainties





Good agreement with theory predictions

Top pole mass and $\alpha_s(m_Z)$

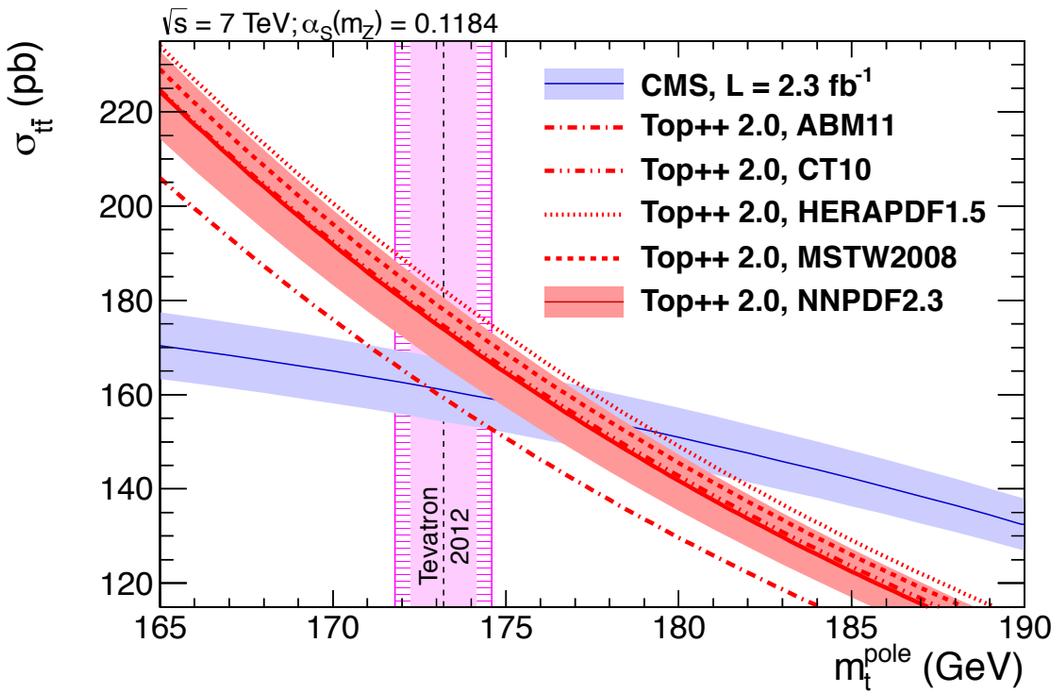
PLB 728 (2013) 496

Top pair production inclusive cross section used to extract:

top pole mass with $\alpha_s(m_Z)$ constrained

$\alpha_s(m_Z)$ with top m_t^{pole} constrained

The first measurement of $\alpha_s(m_Z)$ from ttbar + first full NNLO QCD

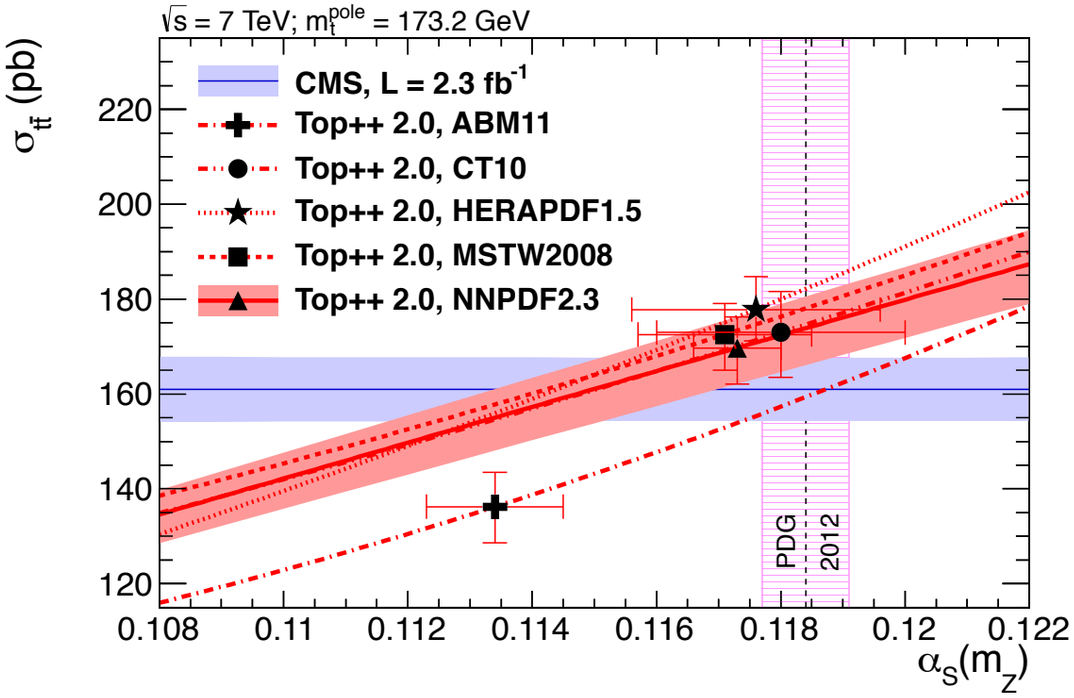


Main systematics:
measured ttbar cross section and PDF

Results: (NNPDF2.3)

$$m_t^{pole} = 176.7^{+3.0}_{-2.8}\,\text{GeV}$$

$$\alpha_s(m_Z) = 0.1151^{+0.0028}_{-0.0027}$$



ABM11 has significantly smaller gluon density and α_s

Top pair differential cross sections

Enhance sensitivity to new physics in tails of the distributions
Important test of SM predictions.

Comparison to different MC generators, theory calculations

~5-10% precision per bin

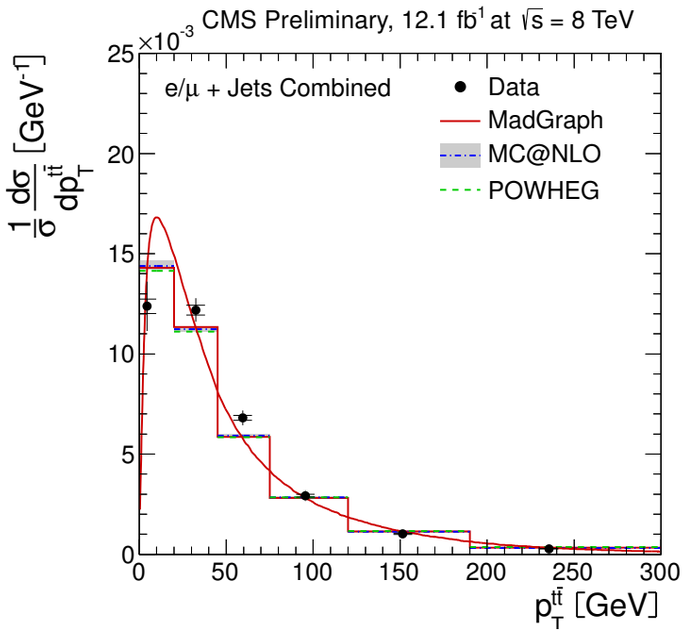
Dominant systematic: signal modelling

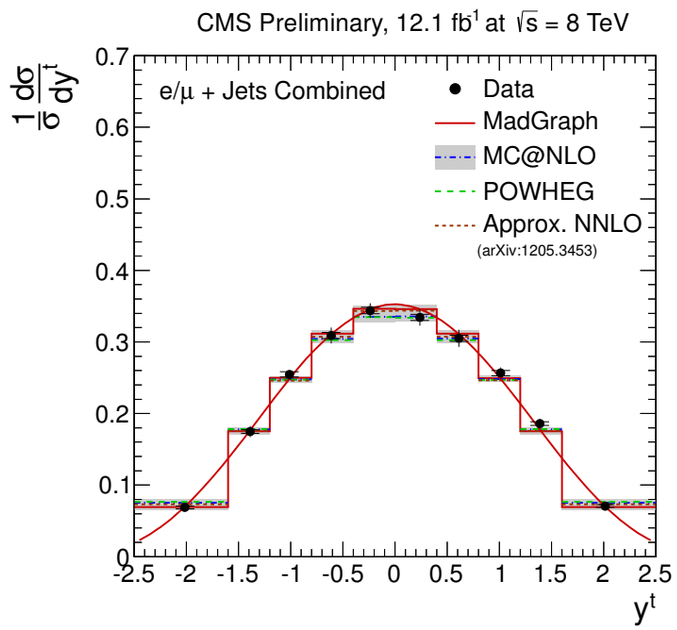
Good description of data

Top quark p_T spectrum harder in MC predictions.

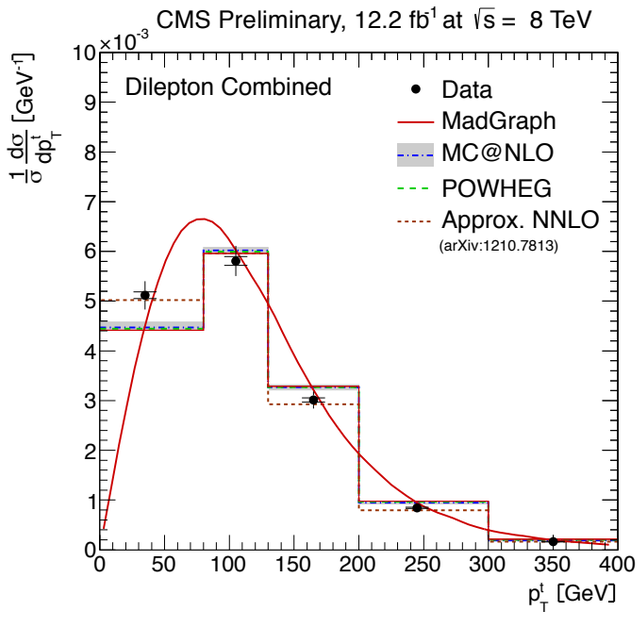
Better description by Approx. NNLO

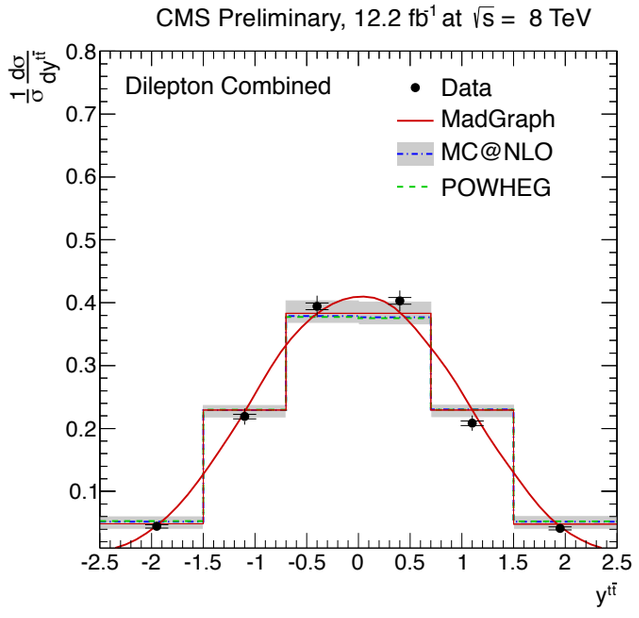
CMS PAS TOP-12-027 — lepton + jets





CMS PAS TOP-12-028 — dilepton





Top pair with additional jets

CMS PAS TOP-12-041

Large fraction of ttbar produced with hard jets from ISR/FSR

Large uncertainty from radiation modelling in MC

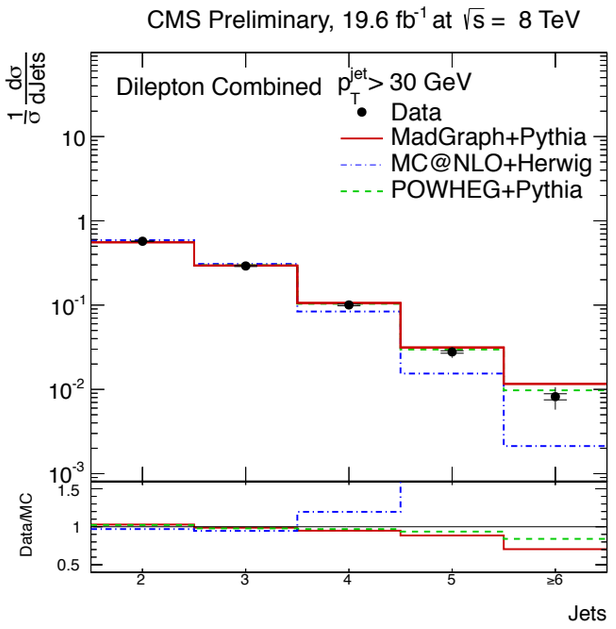
Tuning parameters for MC from measurements

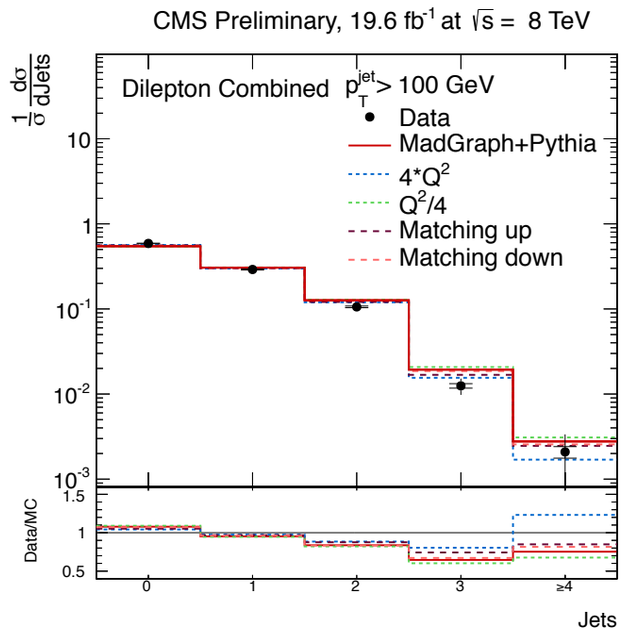
Background to many BSM searches

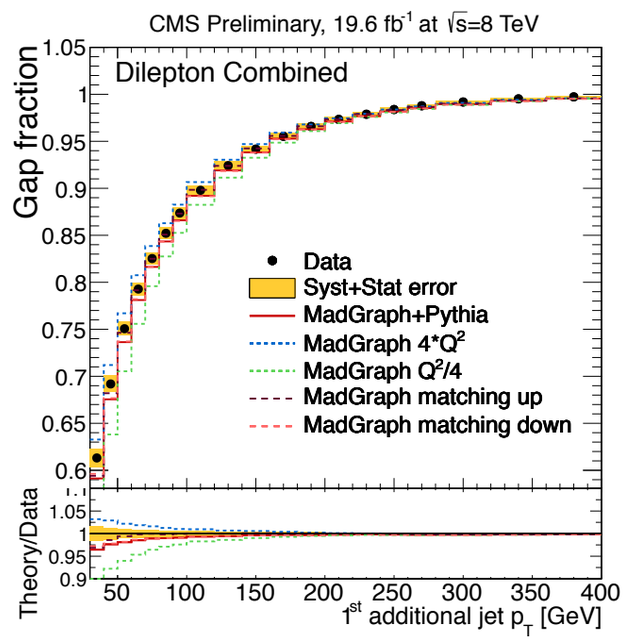
Cross section as a function of additional jet multiplicity with 3 jet p_T thresholds

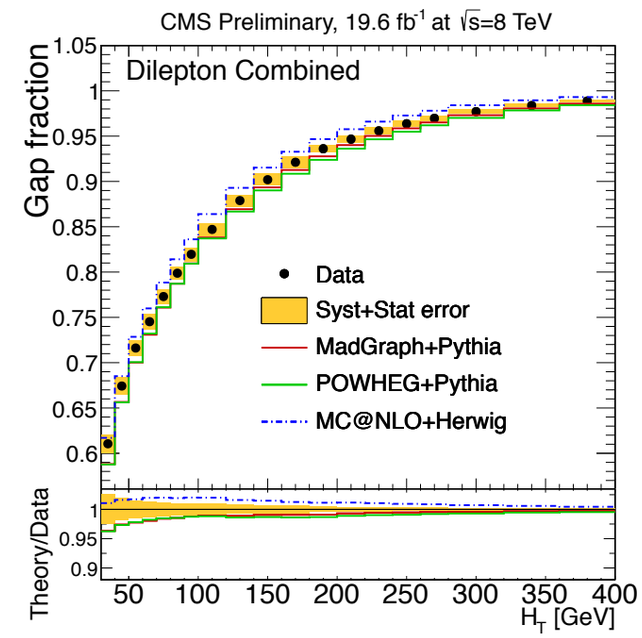
Fraction of events without additional jets with threshold on 1st, 2nd jet p_T, H_T

Differences between theory predictions at low p_T region









Associated tt+X production

tt+tt, tt+bb

CMS PAS TOP-13-012

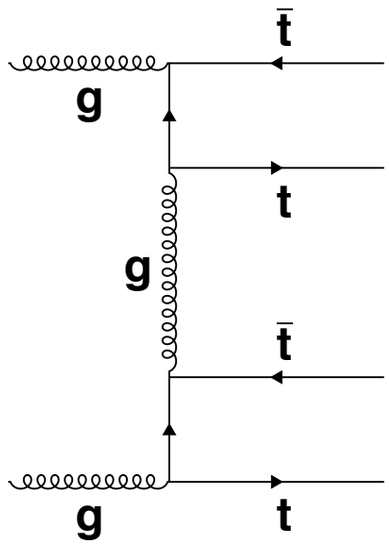
tt+tt has very small cross section in the SM

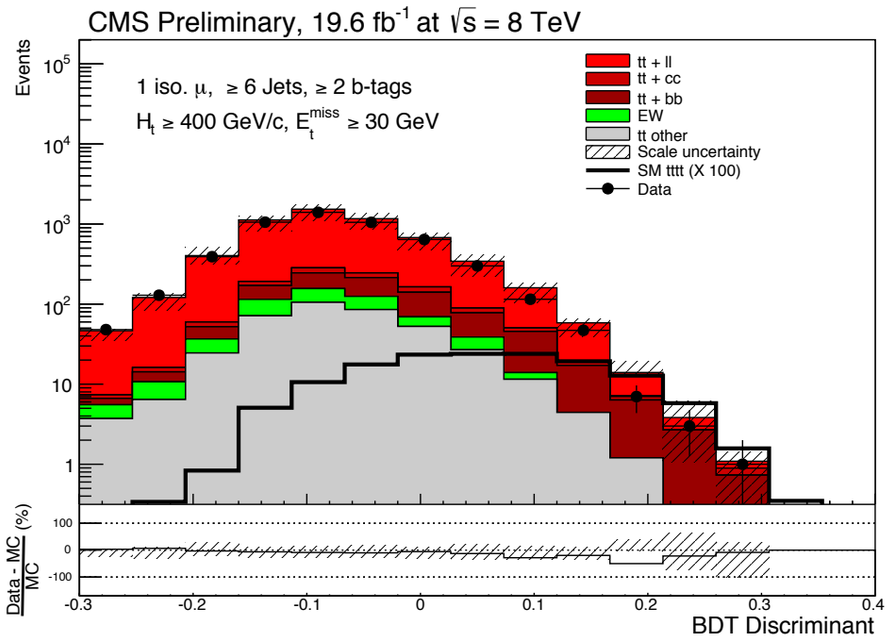
May be enhanced in some new physics scenarios

No deviation from the SM:

Observed: 42^{+18}_{-13} fb

Expected: 63 fb



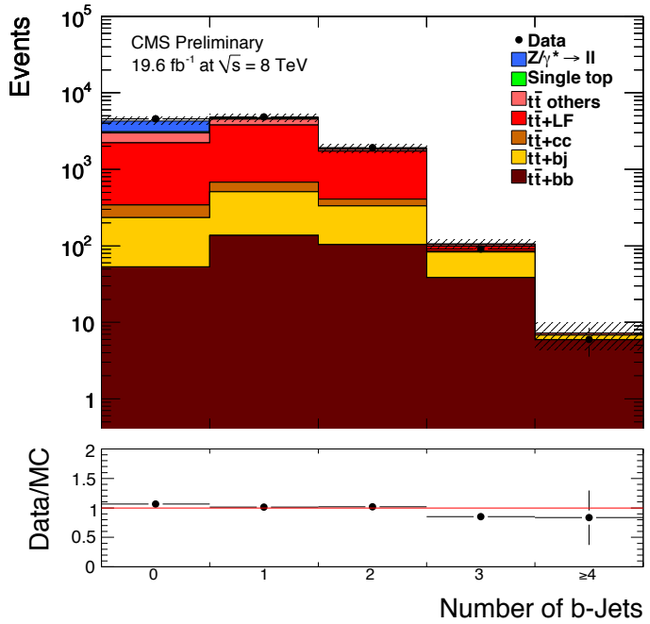


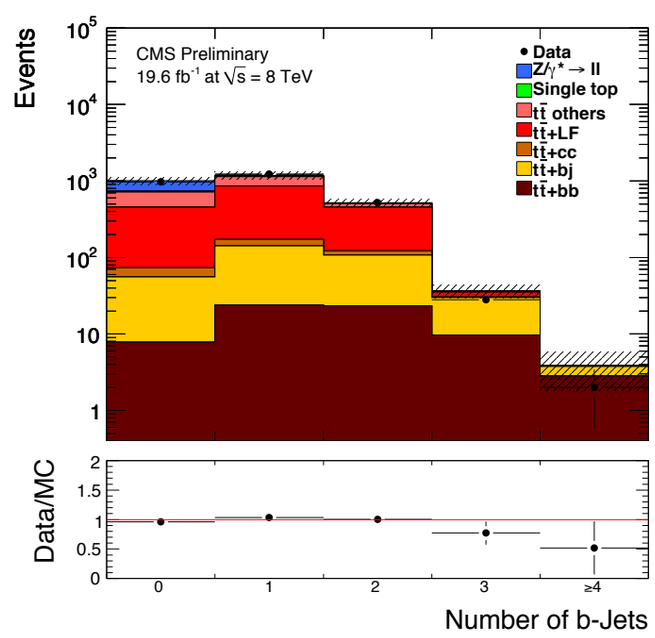
CMS PAS TOP-13-010

tt+bb fraction mismodelled in MC: Madgraph, Powheg

The main (irreducible) background to ttH production

Fit to the measured b-tagging algorithm output





jet p_T > 20 GeV $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.023 \pm 0.003(\text{stat.}) \pm 0.005(\text{syst.})$ x1.44 (1.35) Madgraph

40 GeV $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.022 \pm 0.004(\text{stat.}) \pm 0.005(\text{syst.})$ x1.69 (1.57) (Powheg)

ttH production

arXiv:1408.1682

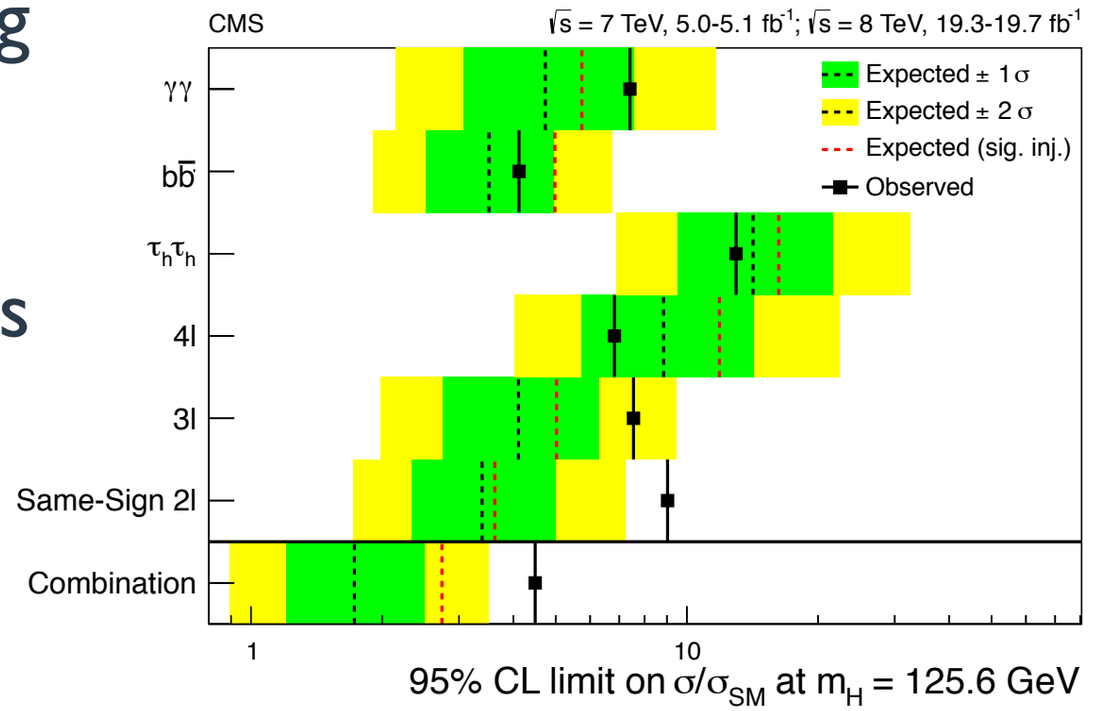
Probe of the top quark Yukawa coupling

Test of t-H coupling

Can be enhanced in some NP scenarios

Analysis separately optimised for each of the H decay modes:

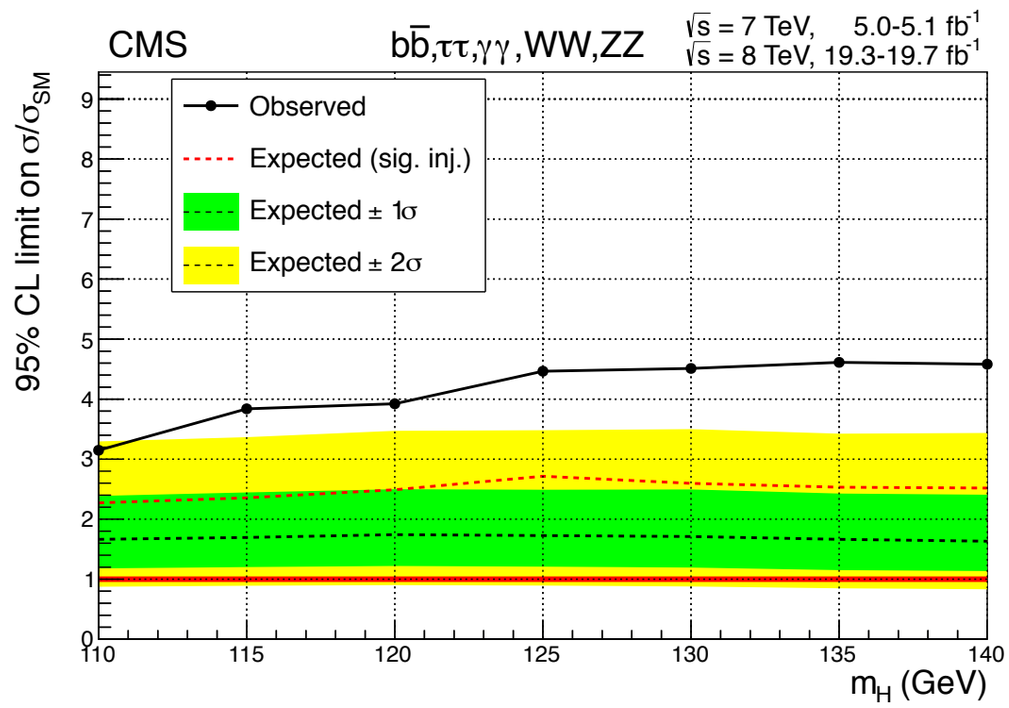
$H \to bb, \tau_h\tau_h, \gamma\gamma, WW, ZZ$



Assumed m_H = 125.6 GeV

Observed excess equivalent to 2σ upward fluctuation

Results don't change significantly with m_H variation around 125 GeV



tt+W/Z

arXiv:1406.7830

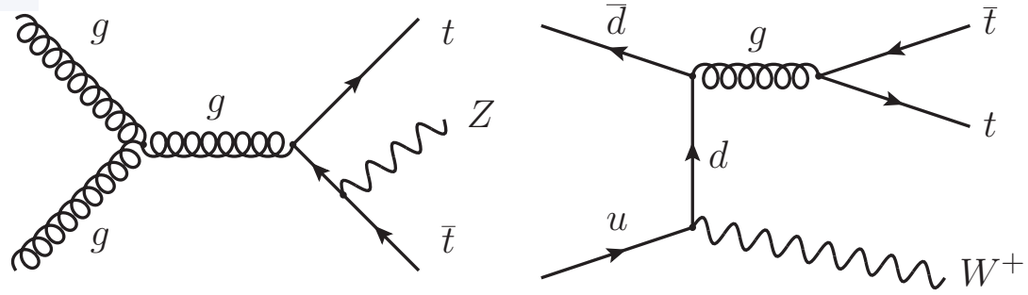
Rare processes in the SM

Measurement of couplings to bosons

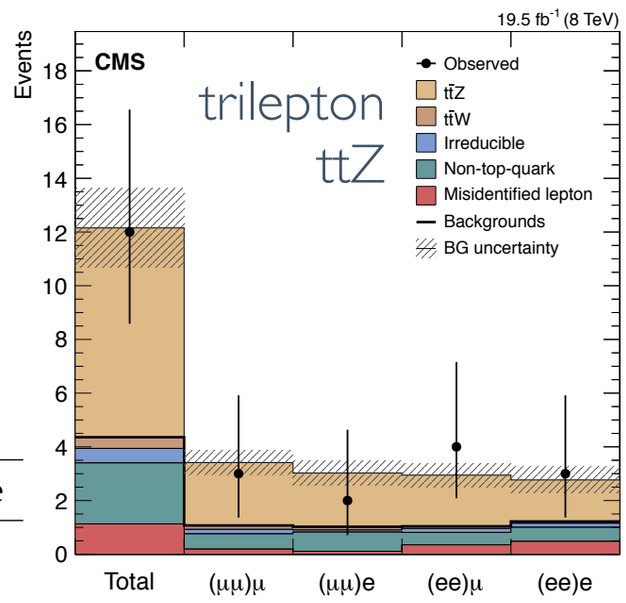
Background for BSM searches

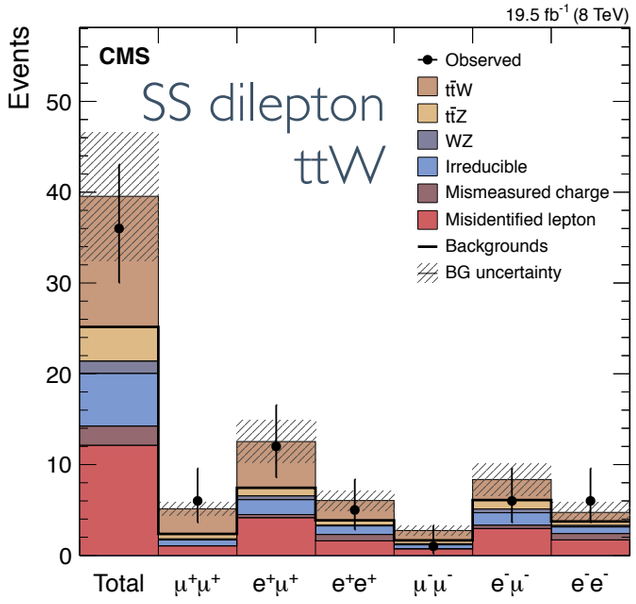
Measurement in 3 channels:

- 2 leptons: ttW
- 3 or 4 leptons: ttZ



Channels used	Process	Cross section	Significance
2ℓ	$t\bar{t}W$	170^{+90}_{-80} (stat) $\pm$ 70 (syst) fb	1.6
3ℓ+4ℓ	$t\bar{t}Z$	200^{+80}_{-70} (stat)$^{+40}_{-30}$ (syst) fb	3.1
2ℓ+3ℓ+4ℓ	$t\bar{t}W + t\bar{t}Z$	380^{+100}_{-90} (stat)$^{+80}_{-70}$ (syst) fb	3.7

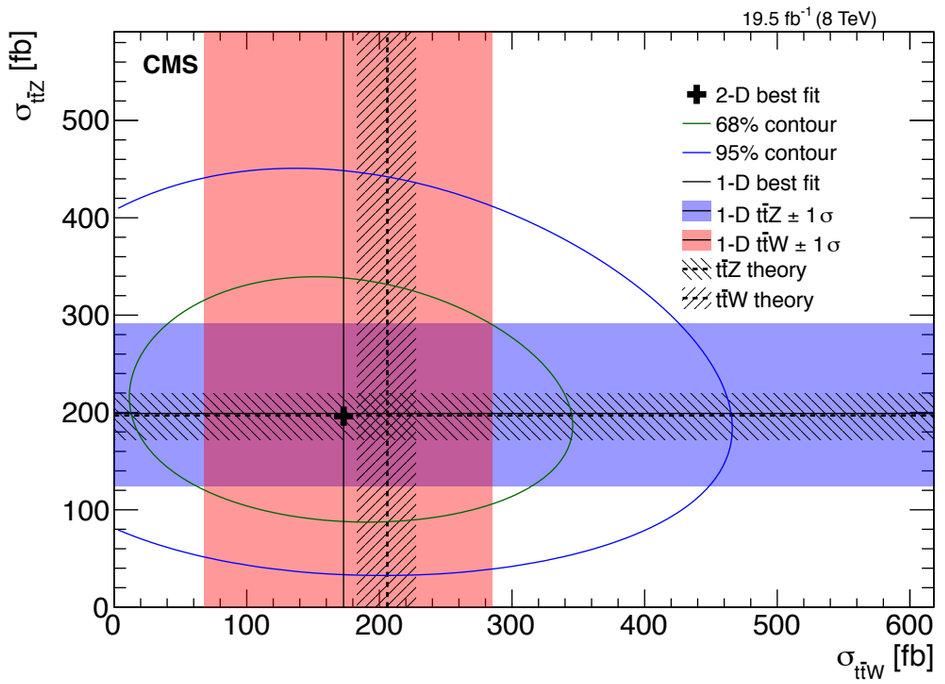




2D fit of the ttW and ttZ cross sections:

Channels used	$t\bar{t}W$ cross section	$t\bar{t}Z$ cross section
2ℓ+3ℓ+4ℓ	170^{+110}_{-100} (total) fb	200 ± 90 (total) fb

Measured cross sections compatible with SM predictions within uncertainties.



Single top

Single top: t-channel

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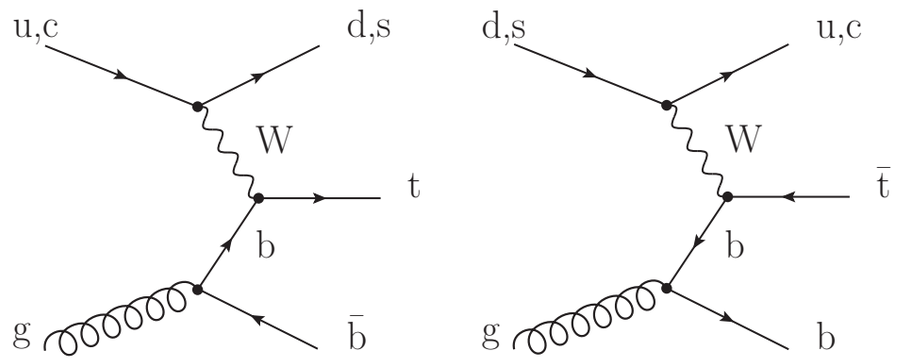


Direct probe of Wtb coupling

Test of SM predictions, search for NP

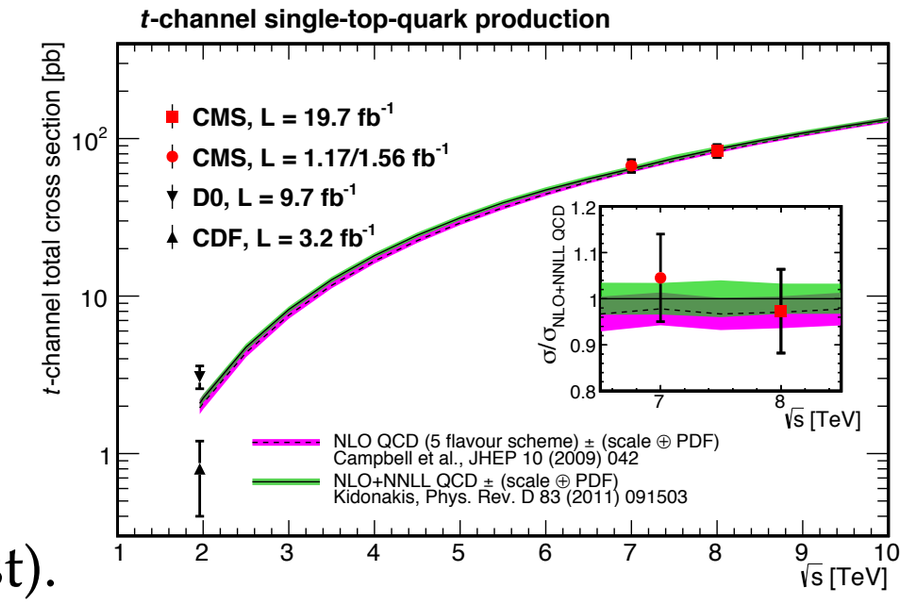
Constraint on u/d PDF models via σ_t/σ_{tbar} ratio

Leptonic decay mode (including $\tau \rightarrow \mu/e$)

Signal region at high $|\eta|$ of light jet

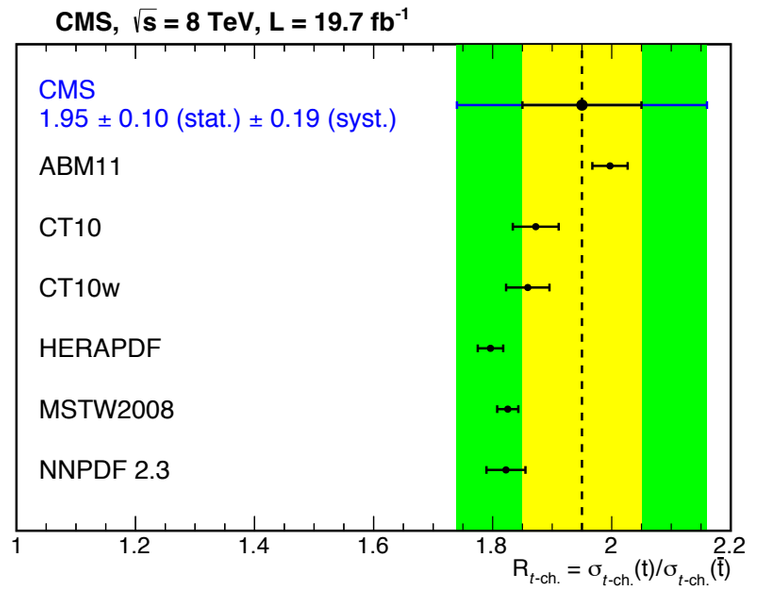
$$\sigma_{t\text{-ch.}} = 83.6 \pm 2.3\,(\text{stat}) \pm 7.4\,(\text{syst})\,\text{pb}.$$

$$R_{t\text{-ch.}} = \sigma_{t\text{-ch.}}(\text{t})/\sigma_{t\text{-ch.}}(\bar{\text{t}}) = 1.95 \pm 0.10\,(\text{stat}) \pm 0.19\,(\text{syst}).$$



Combined with 7 TeV result to determine $|V_{tb}|$

$$|V_{tb}| = 0.998 \pm 0.038\,(\text{exp.}) \pm 0.016\,(\text{theo.})$$



No deviations from the SM observed

Single top: s-channel

CMS PAS TOP-13-009

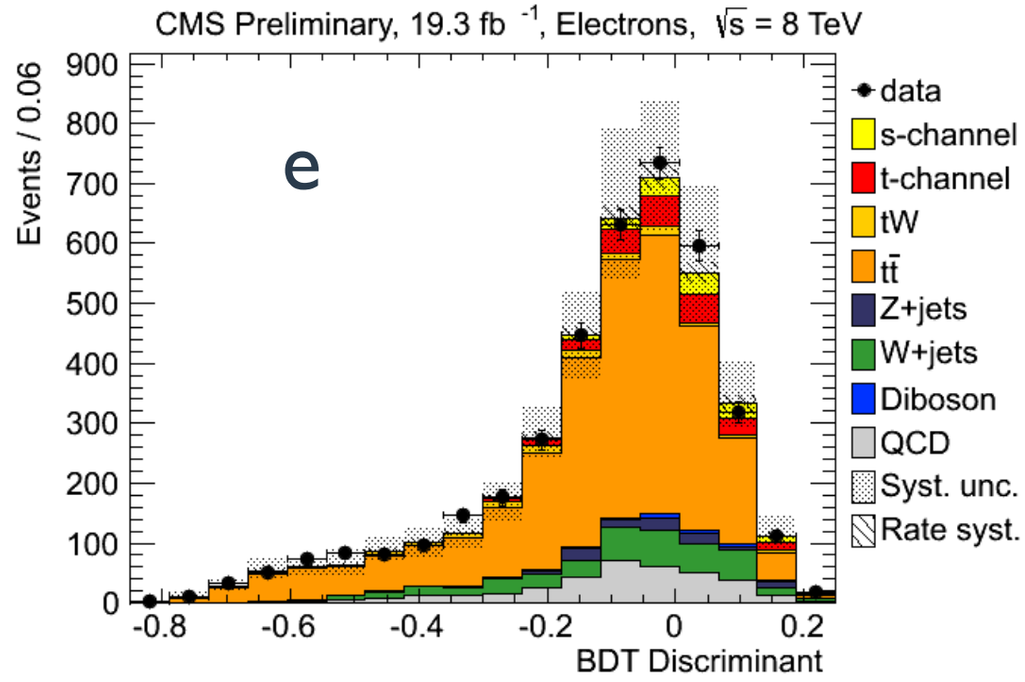
Smallest cross section at LHC

Sensitive to new physics

Leptonic decay mode (including $\tau \rightarrow \mu/e$)

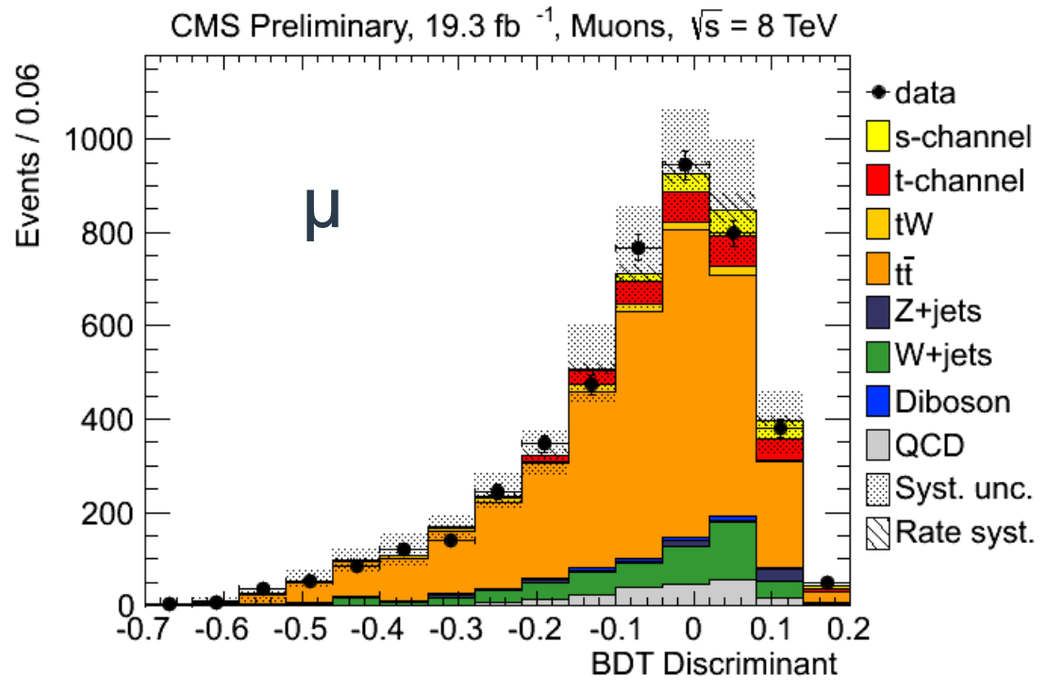
Multivariate analysis based on Boosted Decision Trees

Inclusive cross section: e, μ combined



Upper limit: $\sigma_{s\text{-}ch} < 11.5\ (17.0, 9.0)$ pb observed(expected with SM signal, expected with bkg only)

2.1 (3.1, 1.6) times the SM



Single top: tW channel

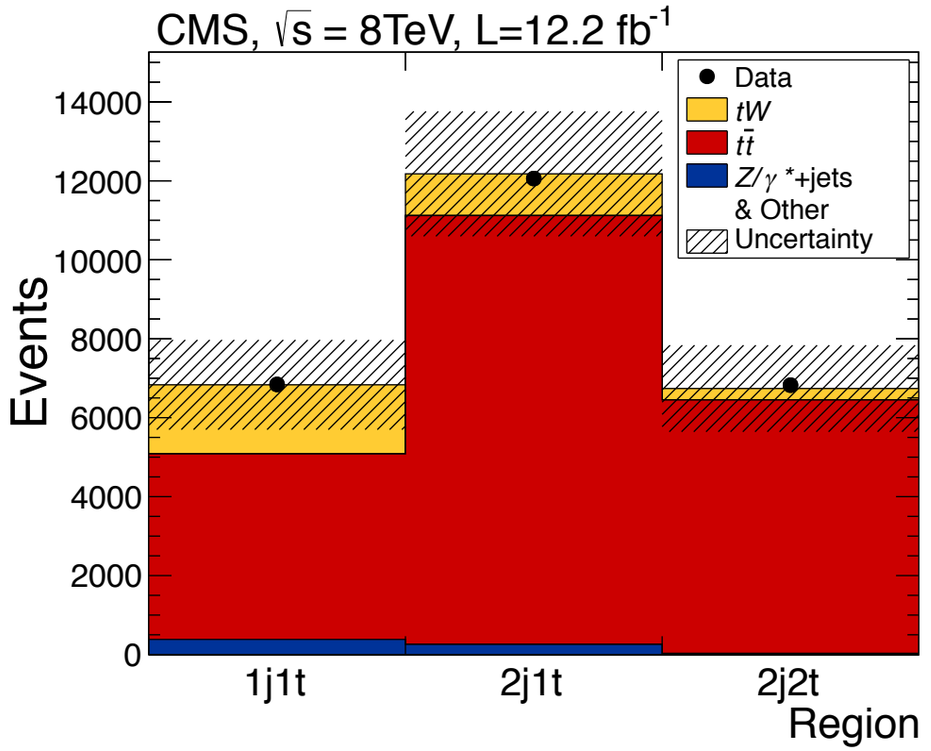
PRL 112 (2014) 231802

Dilepton final state

Dominated by ttbar background

Multivariate analysis based on Boosted Decision Trees

Signal and 2 control regions
defined by jet/b-tagged jet multiplicity



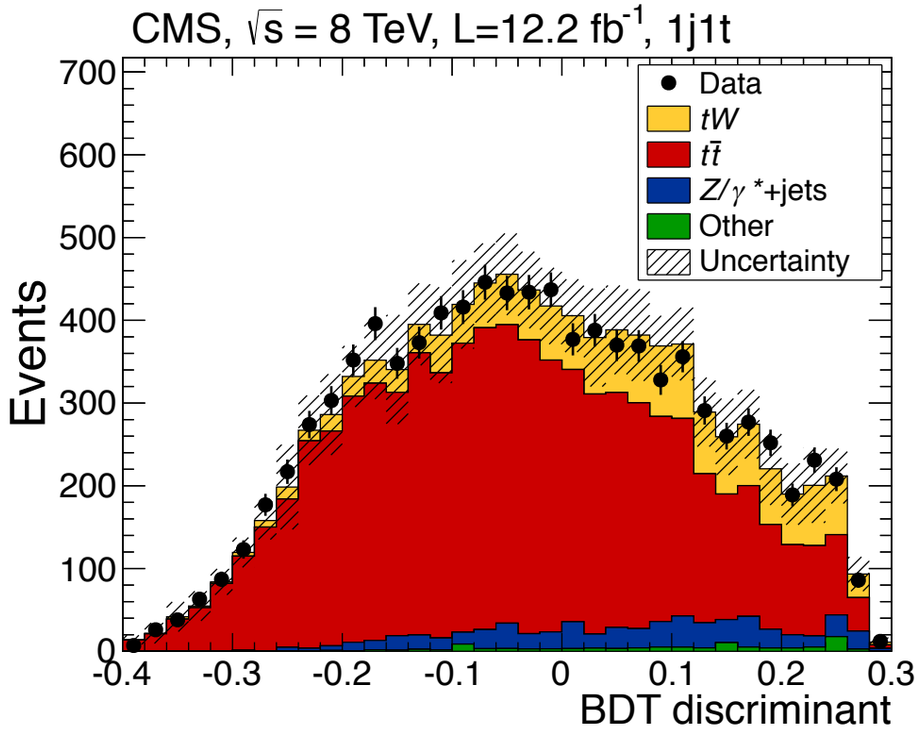
6.1σ significance observed

$\sigma_{tW} = 23.4 \pm 5.4$ pb

$\sigma_{tW} = 22.2 \pm 0.6 \pm 1.4$ pb (appr. NNLO)

$|V_{tb}|$ extracted:

$$|V_{tb}| = \sqrt{\sigma_{tW}/\sigma_{tW}^{th}} = 1.03 \pm 0.12\,(\text{exp}) \pm 0.04\,(\text{th.})$$



Results in agreement with SM predictions

Section

Top quark properties

Top mass: lepton+jets

CMS PAS TOP-14-001

Essential parameter of the SM

Input to fits of global electroweak parameters
Affects the Higgs potential

Selection: semileptonic

exactly 1 isolated lepton (e or μ)

≥ 4 jets (exactly 2 b-tagged)

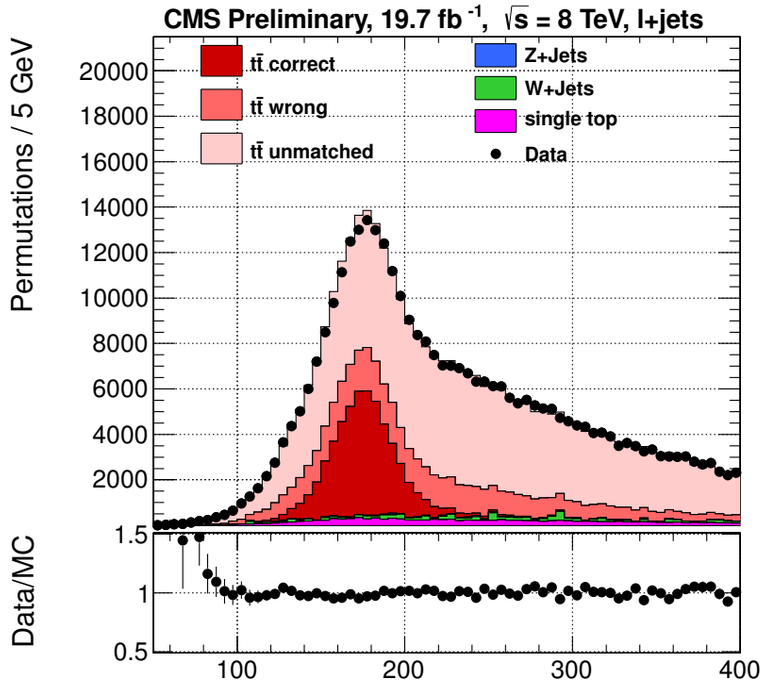
Kinematic fit: m_W=80.4 GeV, $m_t = m_{tbar}$

2 tagged – tt | 2 untagged – W→jj

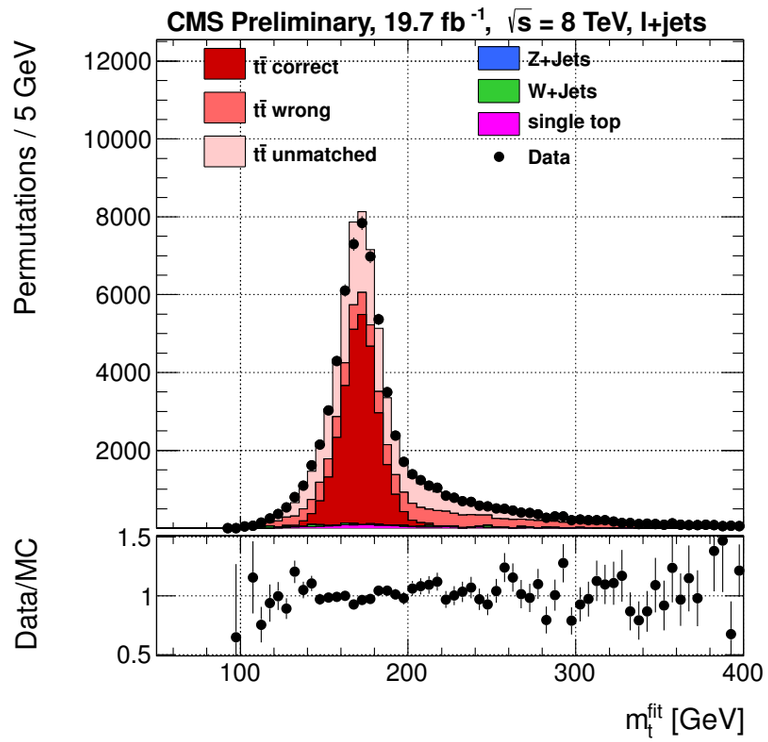
Goodness-of-fit probability (P_{gof}) used to improve jet-parton assignment:

f_{cp} = 13% → 44% (weighted by P_{gof})

≤4 permutations/event [2 x jet, 2 x $p_z(\nu)$]



$P_{gof} > 0.2$



Top mass: lepton+jets

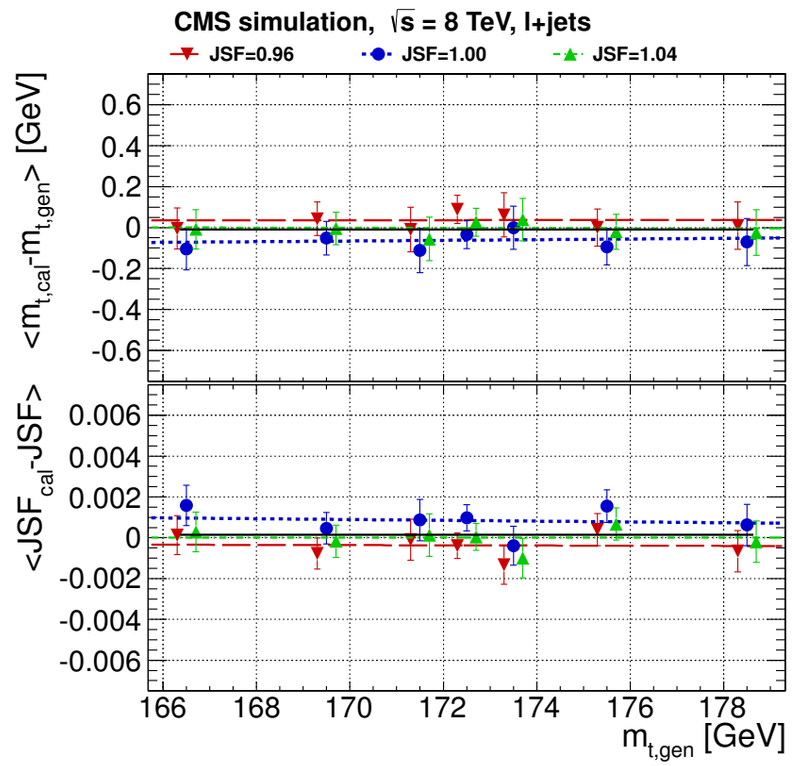
CMS PAS TOP-14-001

Ideogram method for simultaneous determination of m_t, jet energy scale (JSF)

Likelihood fit of m_t from the kinematic fit and reconstructed m_W

Calibrated using MC:

7 simulations of m_t x 3 values of JSF



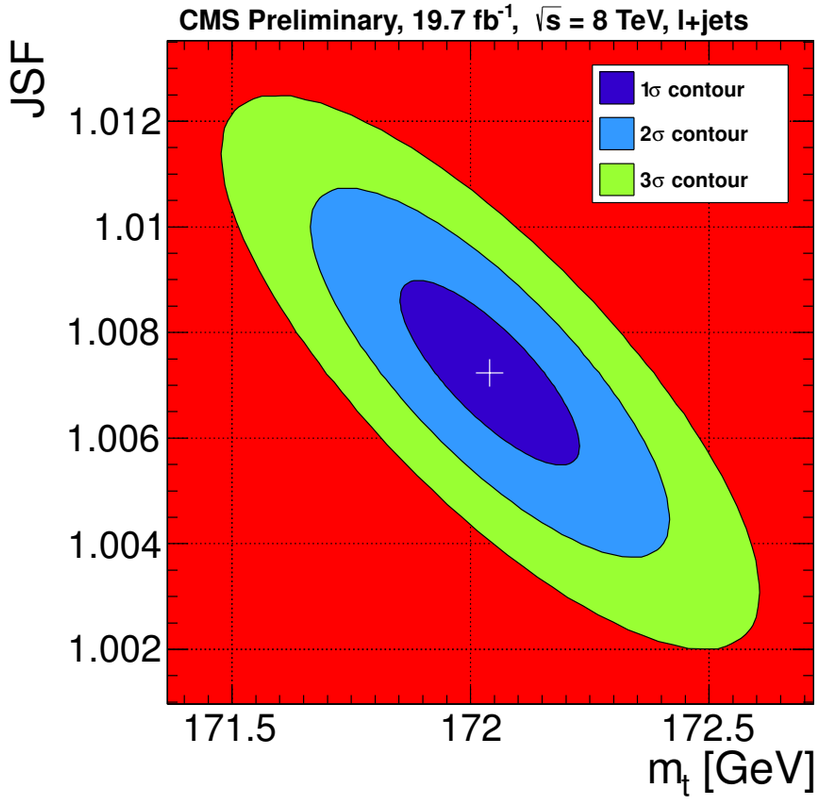
Result from 2D fit:

$$m_t = 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\,\text{GeV},$$
$$\text{JSF} = 1.007 \pm 0.002\,(\text{stat.}) \pm 0.012\,(\text{syst.}).$$

Result from 1D fit (JSF = 1.0) cross check

$$m_t = 172.66 \pm 0.11\,(\text{stat.}) \pm 1.29\,(\text{syst.})\,\text{GeV}$$

Larger systematic uncertainty from JES uncertainty (1.17 GeV)



Top mass: full hadronic

CMS PAS TOP-14-002

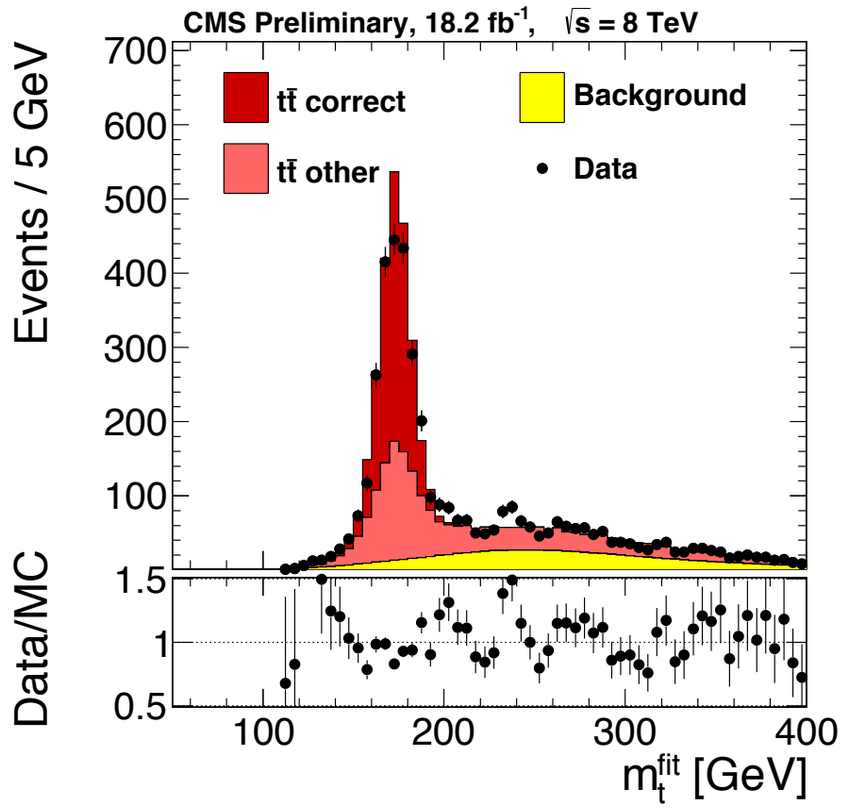
Selection: full hadronic

≥ 6 jets (exactly 2 b-tagged)

Same ideogram method as in lepton+jets

kinematic fit: m_W=80.4 GeV, $m_t = m_{tbar}$

simultaneous determination of m_t and JSF
7 simulations of m_t × 5 values of JSF



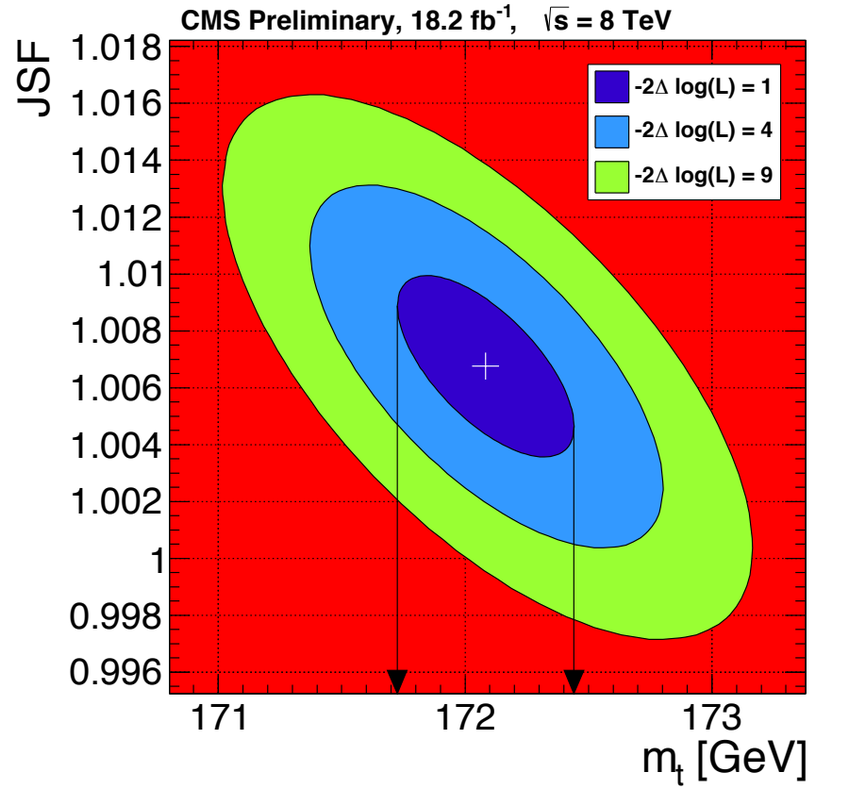
Result from 2D fit:

$$m_{\mathrm{t}} = 172.08 \pm 0.36\,(\mathrm{stat.{+}JSF}) \pm 0.83\,(\mathrm{syst.})\,\mathrm{GeV},$$
$$\mathrm{JSF} = 1.007 \pm 0.003\,(\mathrm{stat.}) \pm 0.011\,(\mathrm{syst.}).$$

Result from 1D fit (JSF = 1.0) cross check

$$m_{\mathrm{t}} = 172.59 \pm 0.27\,(\mathrm{stat.}) \pm 1.05\,(\mathrm{syst.})\,\mathrm{GeV}$$

Results consistent with values obtained from lepton+jets channel



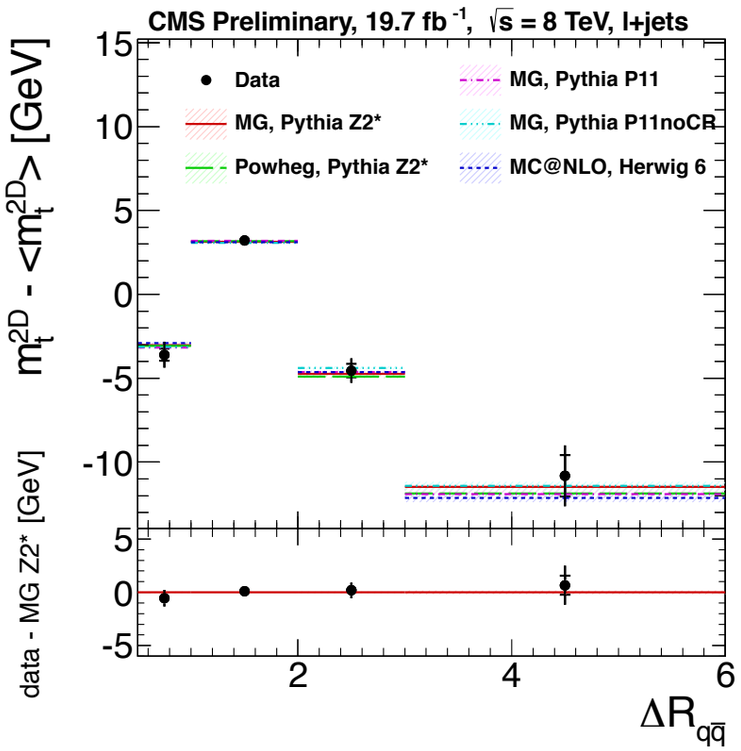
Top mass: kinematic dependence

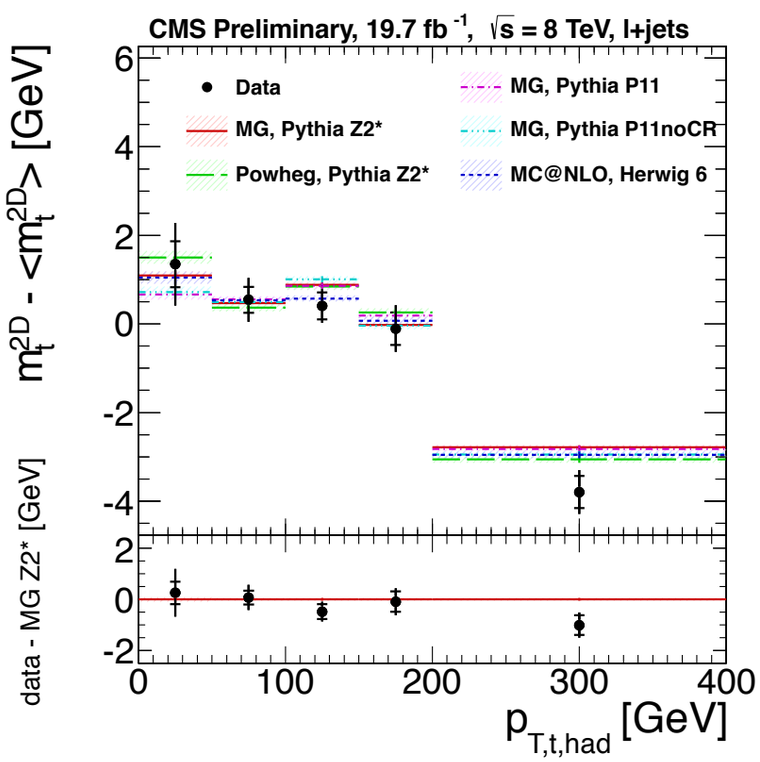
CMS PAS TOP-14-001

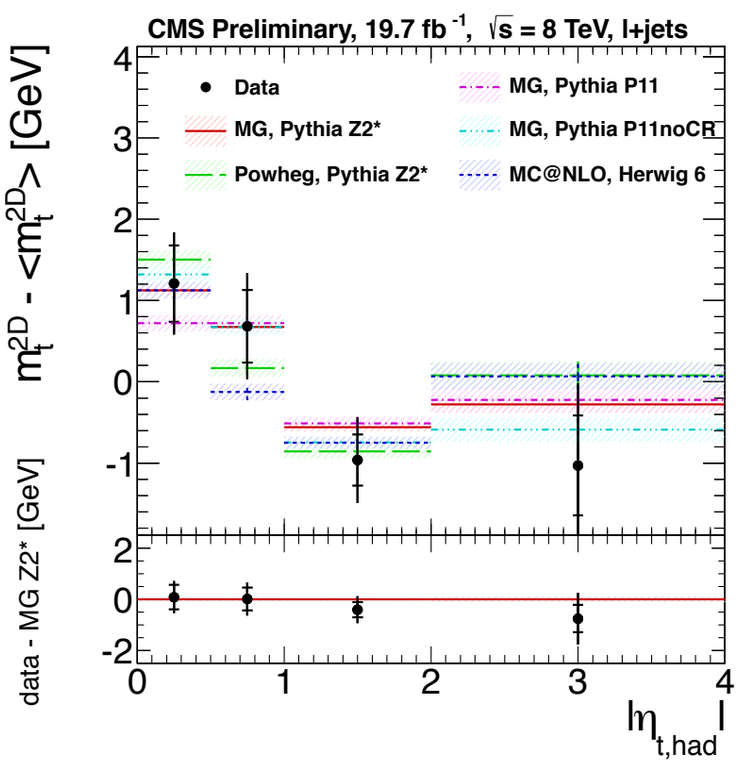
Interpretation of measured m_t observable for electroweak fits – not trivial: difficult to match pole m_t to MC m_t

Can cause biases in differential distributions of the m_t observable

Madgraph + Pythia Z2* tune for the final result determination







Kinematic dependences well described by MC for most observables

Top mass: CMS combination

CMS PAS TOP-14-001

2012 result in lepton+jet channel combined with results on 2010 (dileptonic, semileptonic), **2011** (dileptonic, semileptonic, full hadronic) **data**

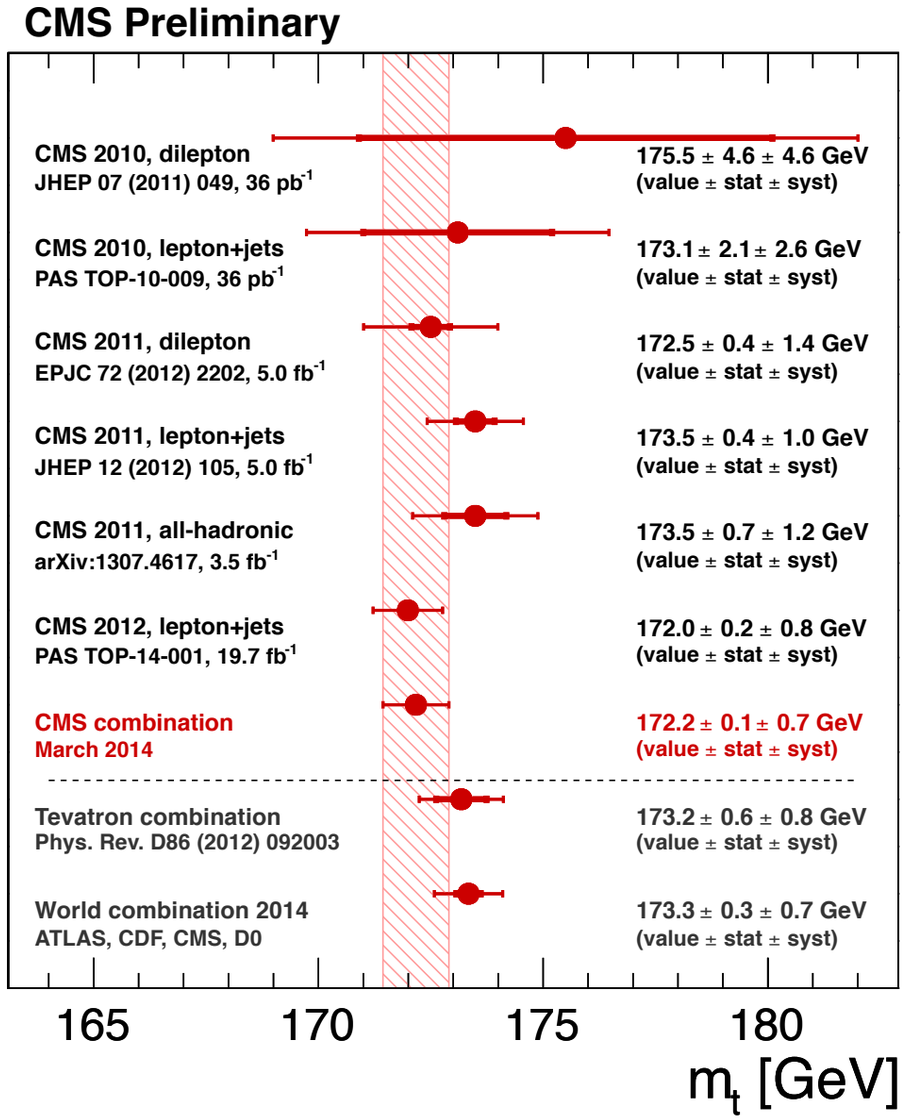
Most systematics assumed to be fully correlated between 5 additional analyses

Experimental uncertainties correlated between analyses using same data

JSF uncertainty treated as uncorrelated

X^2 = 4.1/5 DOF (54% CL)

$$m_t = 172.22 \pm 0.14\,(\text{stat.}) \pm 0.72\,(\text{syst.})\,\text{GeV}$$



Consistent with 2014 World combination: LHC + Tevatron

Top charge asymmetry

CMS PAS TOP-12-033 JHEP 04 (2014) 191

NLO effect due to interference of different qq → tt diagrams

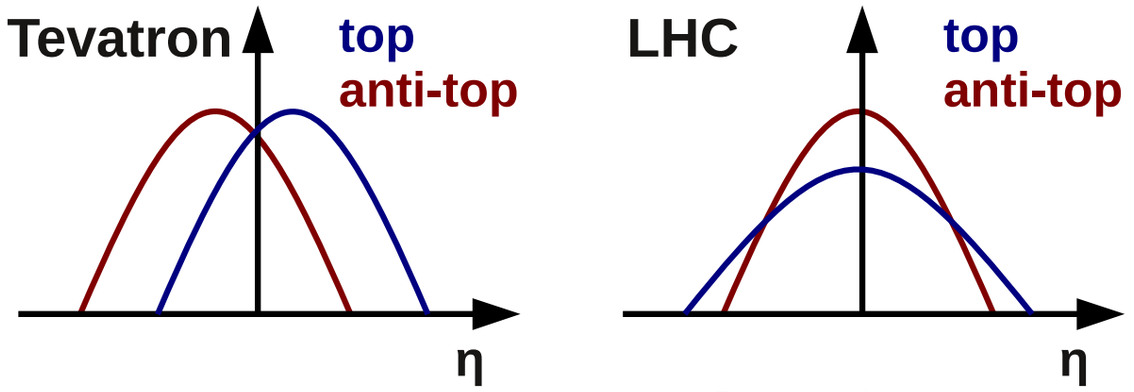
Small in SM; enhanced in NP

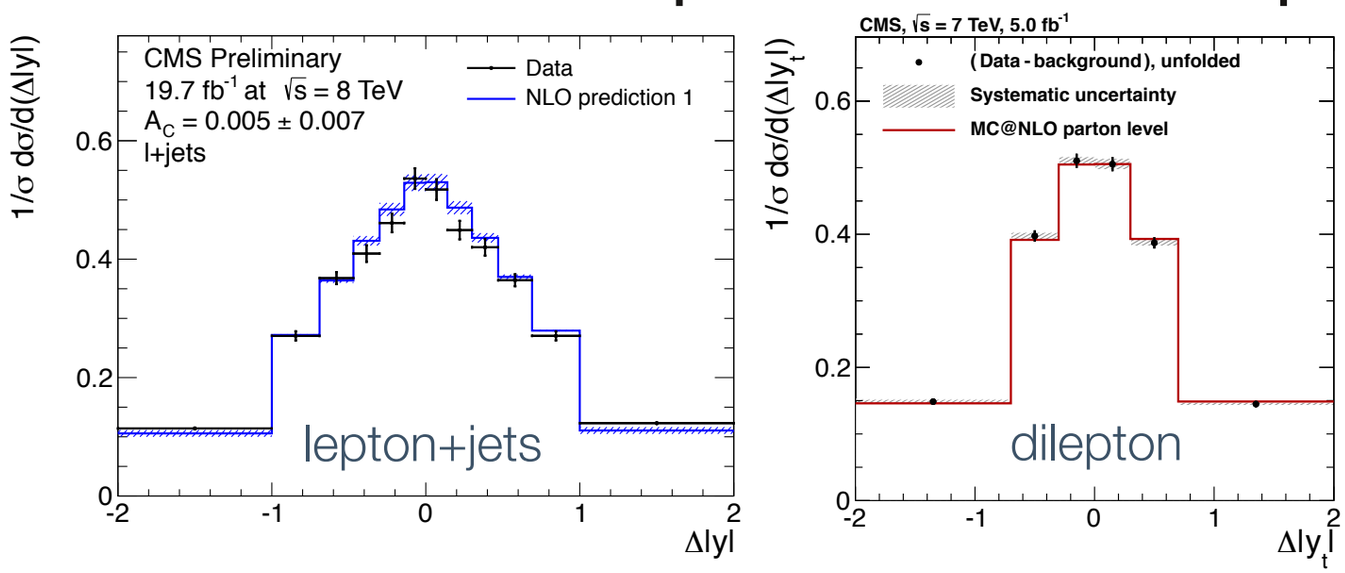
D0 & CDF observed 2σ excess in forward-backward asymmetry

Boost difference at LHC:

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

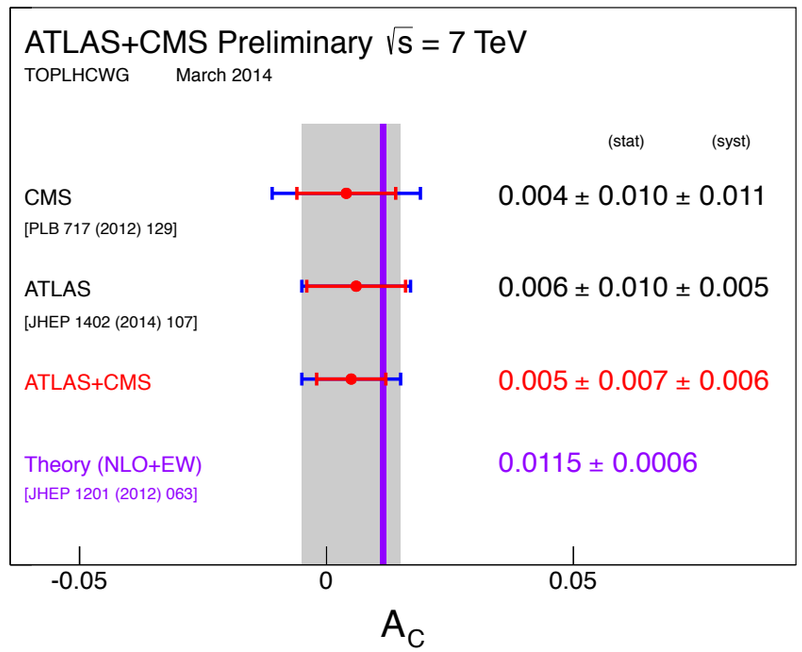
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$





CMS results consistent with NLO prediction

ATLAS and CMS results at 7TeV combined taking correlations into account CMS PAS TOP-14-006



No excess observed at LHC

Top branching fraction and V_{tb}

PLB 736 (2014) 33

BR(t→Wb)/BR(t→Wq) [q=b,s,d]
measured in dilepton channel

Depends on $|V_{tb}|$ and $\Gamma(t)$

D0 reported tension with the SM prediction: $\mathcal{R} = 0.86^{+0.041}_{-0.042}\,(\text{stat}) \pm 0.035\,(\text{syst})$

Parametrised in terms of b-tag multiplicity, b-tagging and misidentification efficiencies

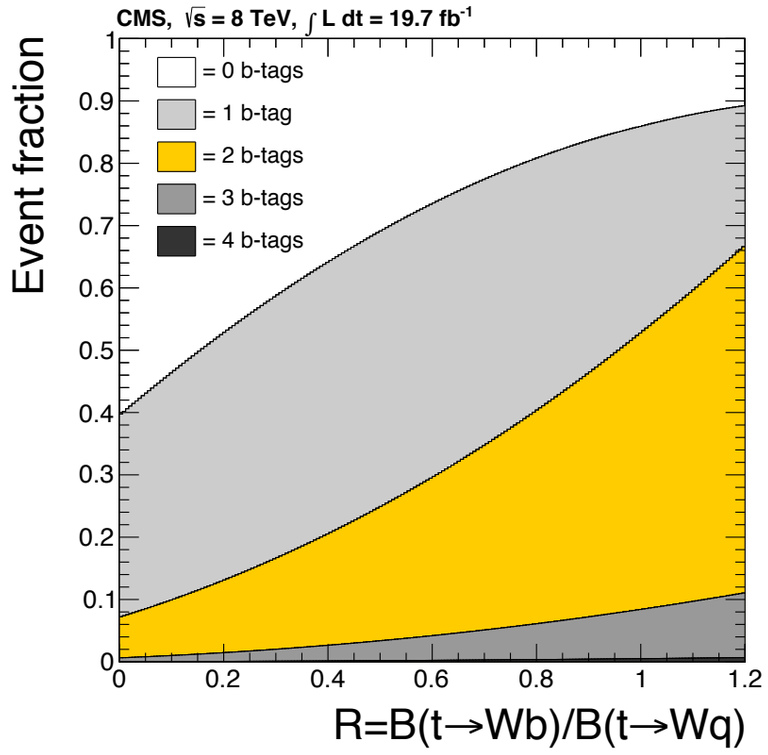
Best fit: $\mathcal{R} = 1.014 \pm 0.003\,(\text{stat}) \pm 0.032\,(\text{syst})$

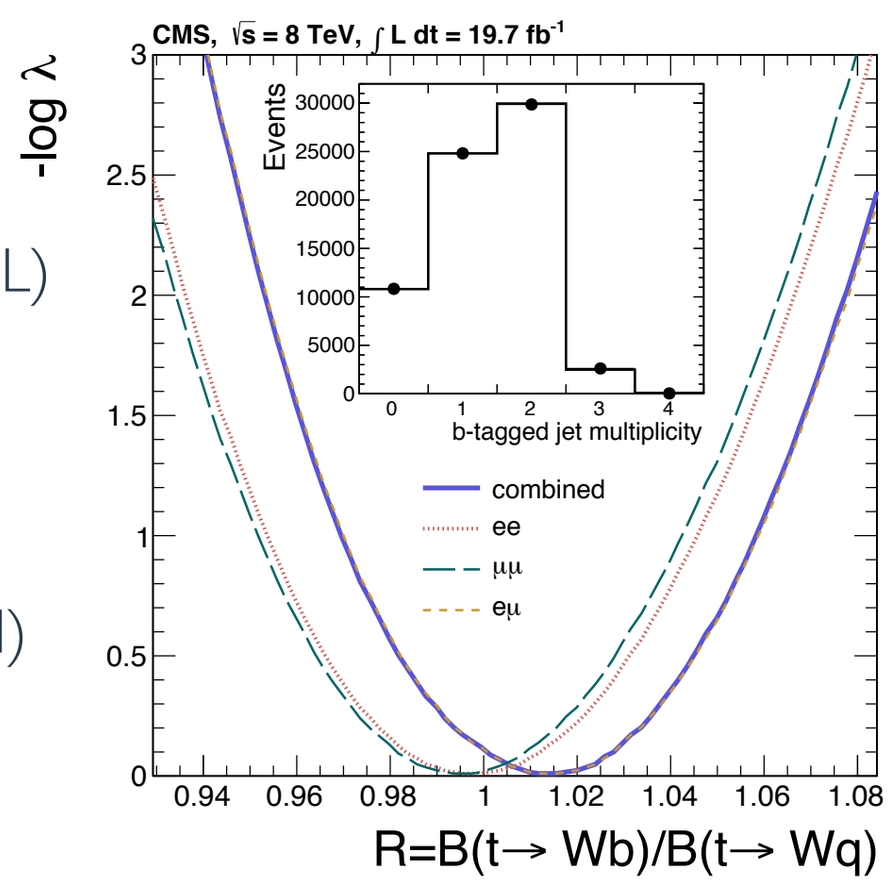
Lower limit: $\mathcal{R} > 0.955 \longrightarrow |V_{tb}| > 0.975$ (95% CL)

Combined with the t-channel single top production cross section to determine Γ_t:

$\Gamma_t = 1.36 \pm 0.02\,(\text{stat})^{+0.14}_{-0.11}\,(\text{syst})\,\text{GeV}$ (1.29 in SM)

Results agree with theoretical expectations





Spin correlations, polarisation

PRL 112 (2014) 182001

Information about spin of the top quark transferred directly to decay products

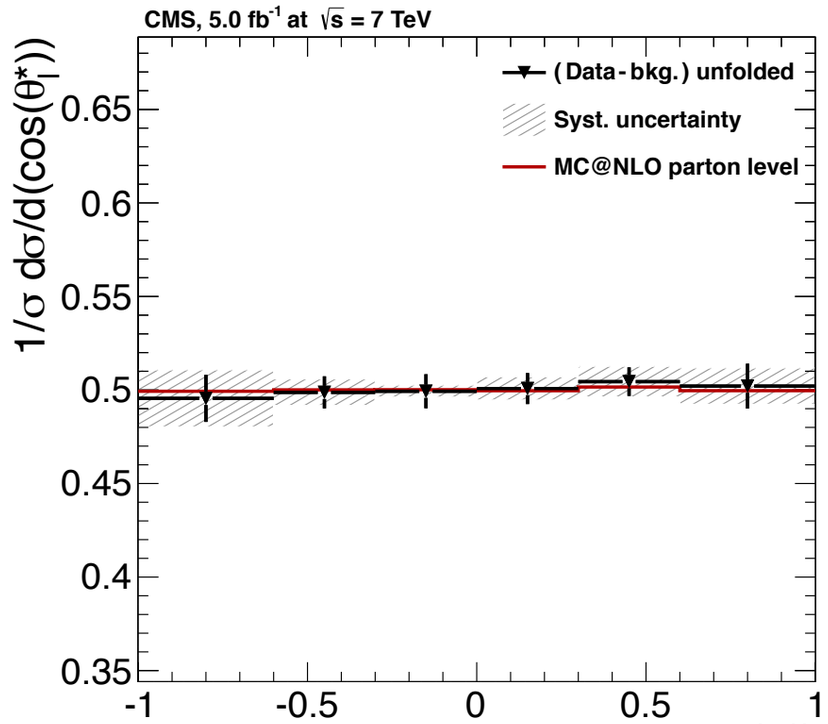
Can be altered by couplings to new particles in BSM models

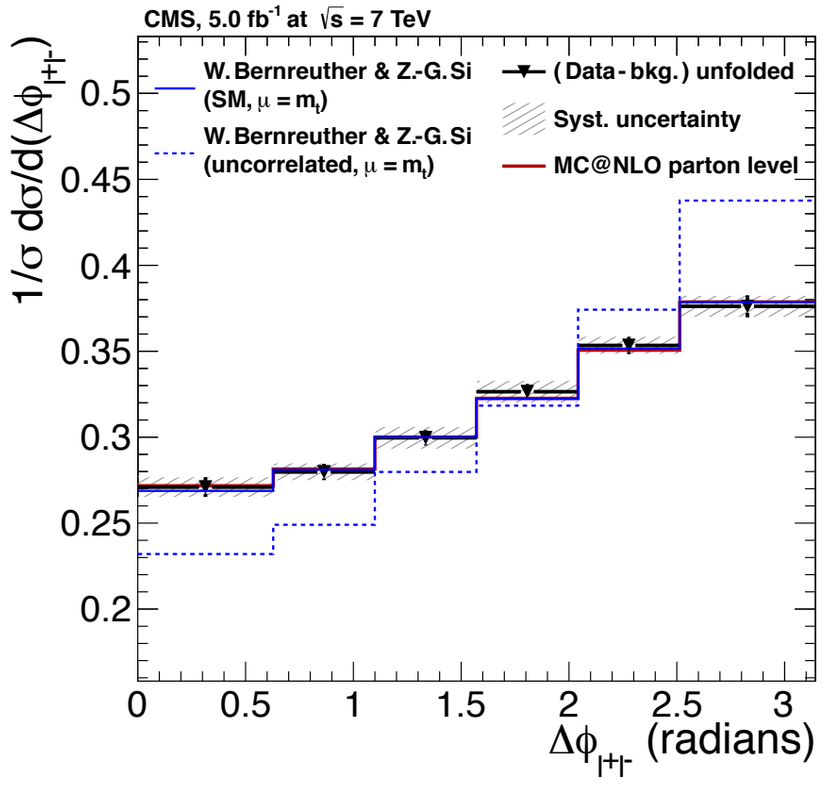
Asymmetry variables defined for polarisation: $A_P = \frac{N\left[\cos(\theta^\star_\ell) > 0\right] - N\left[\cos(\theta^\star_\ell) < 0\right]}{N\left[\cos(\theta^\star_\ell) > 0\right] + N\left[\cos(\theta^\star_\ell) < 0\right]}$

and spin correlation discrimination:

$$A_{\Delta\phi} = \frac{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) - N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) + N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}$$

Asymmetry	Data (unfolded)	MC@NLO	NLO (SM, correlated)
$A_{\Delta\phi}$	$0.113 \pm 0.010 \pm 0.006 \pm 0.012$	0.110 ± 0.001	$0.115^{+0.014}_{-0.016}$
A_P	$0.005 \pm 0.013 \pm 0.014 \pm 0.008$	0.000 ± 0.001	N/A





Indication of presence of spin correlation

No indication of polarisation, in agreement with NLO SM prediction

Section

Beyond the Standard Model

Flavour changing neutral current

CMS PAS TOP-11-028

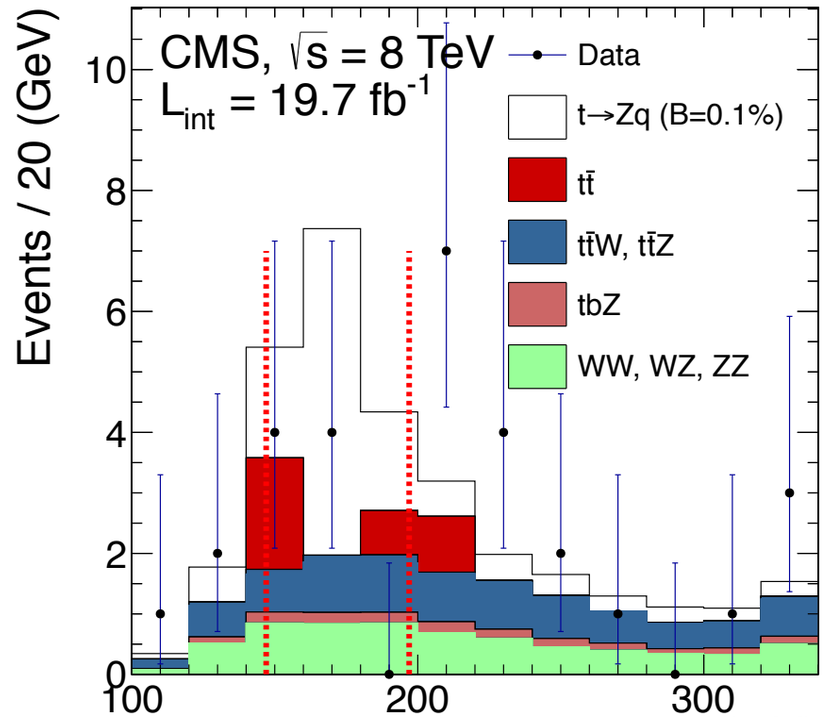
Transition from a quark to a different-flavour quark of the same charge:

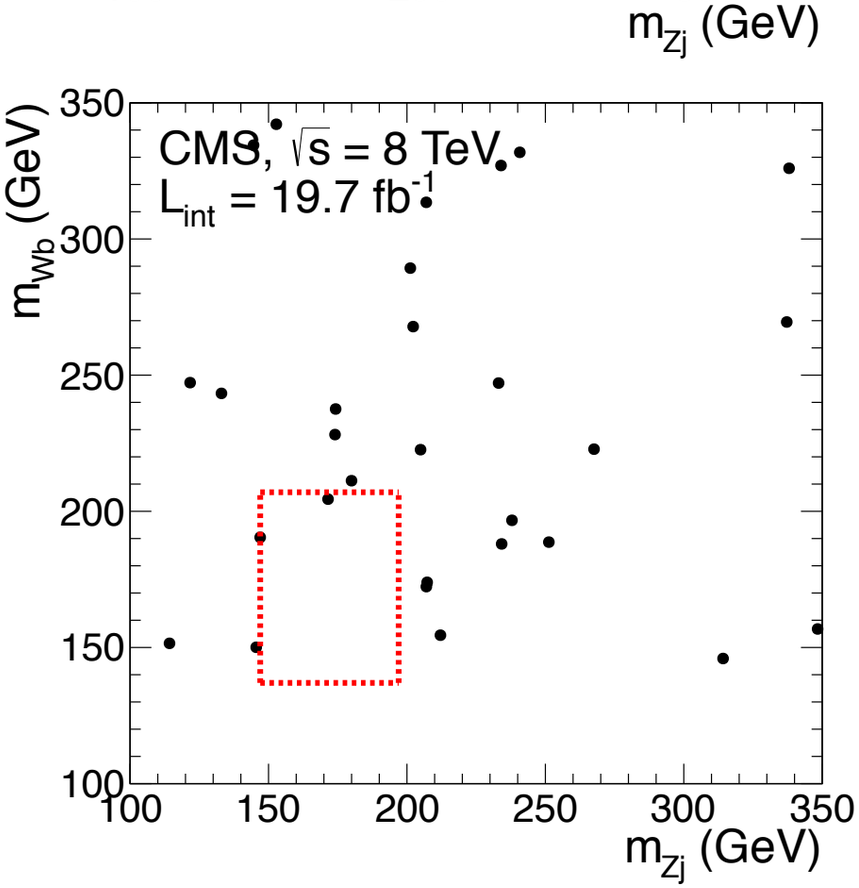
- forbidden at tree level in the SM
- strongly suppressed in higher order diagrams
- can be enhanced in NP models

Search in trilepton t→Zq+Wb decays
Z and W decay leptonically

No evidence of FCNC found

Combination with 7 TeV result excludes BR(t→Zq) > 0.05% (95% CL)





Summary

- CMS has rich program for quark related analyses
- Provide precise test of the Standard Model
- Allow searches for many NP effects
- All analyses of top quark cross sections and properties show good agreement with SM predictions
- Disagreement with NLO predictions in top quark p_T distribution. Better agreement with approx. NNLO calculations
- Most precise top mass obtained from the combination of 2010-2012 CMS measurements: $m_t = 172.2 \pm 0.1 \pm 0.7$ GeV
- Many results on 8 TeV data approaching publication
- Complete list of public CMS results at a dedicated page