measurements of the top-quark mass and properties at CMS

Kruger 2014

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why are we interested in the top-quark?

it’s by a margin the heaviest of all SM particles

-> might hint at new physics

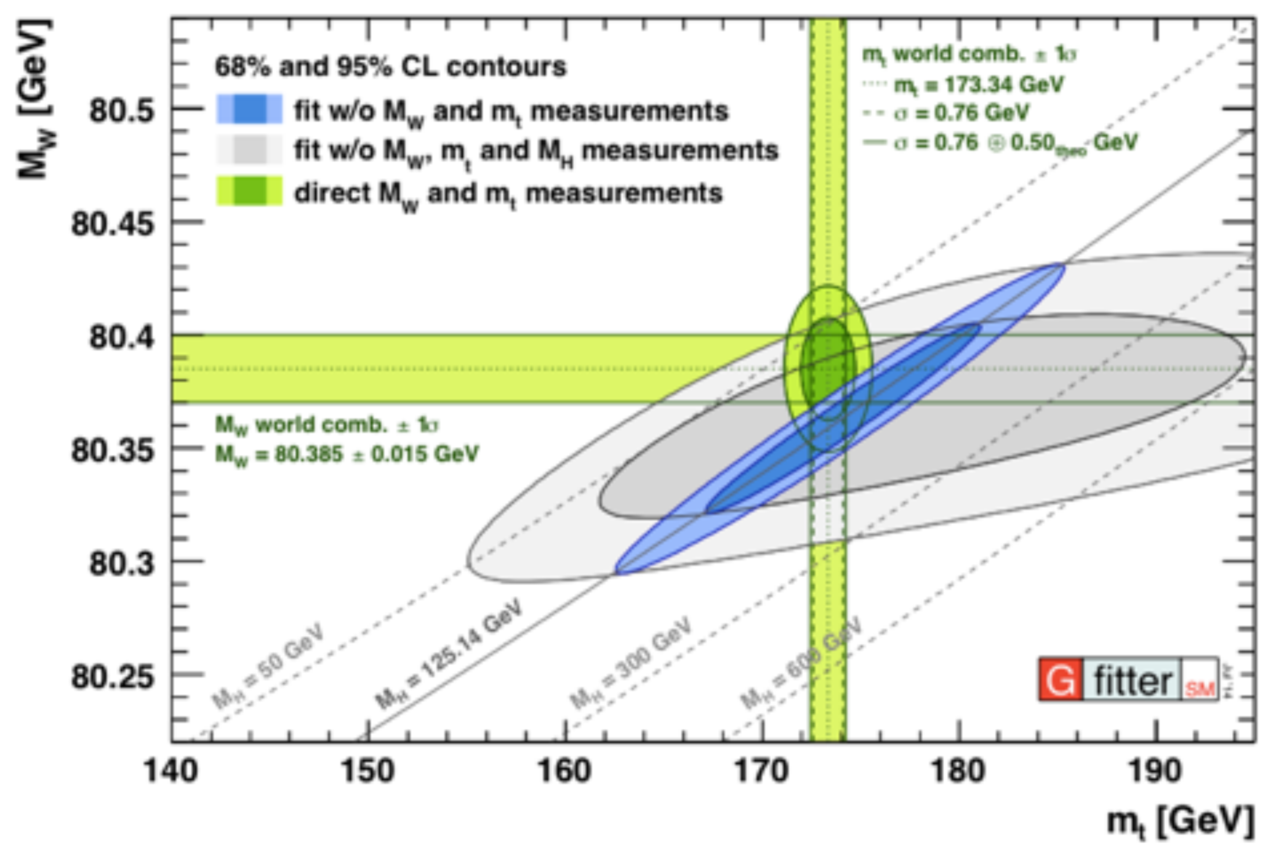
its mass is one of the least precisely known parameters of the SM

-> only quark that decays before hadronization

-> together with m_W and m_H it can constrain the SM/new physics

measuring properties gives insight into the weak sector

-> CKM matrix for example



arXiv:1407.3792

what are we going to talk about?

focus on new measurements out of CMS!

measurements of the top-quark mass

-> different final states and different methods

combination of various top-mass measurements

-> combining many results from CMS

-> world combination including Tevatron

CMS measurement of top quark properties

-> Wb/Wq ratio

-> W helicity

-> tt+boson

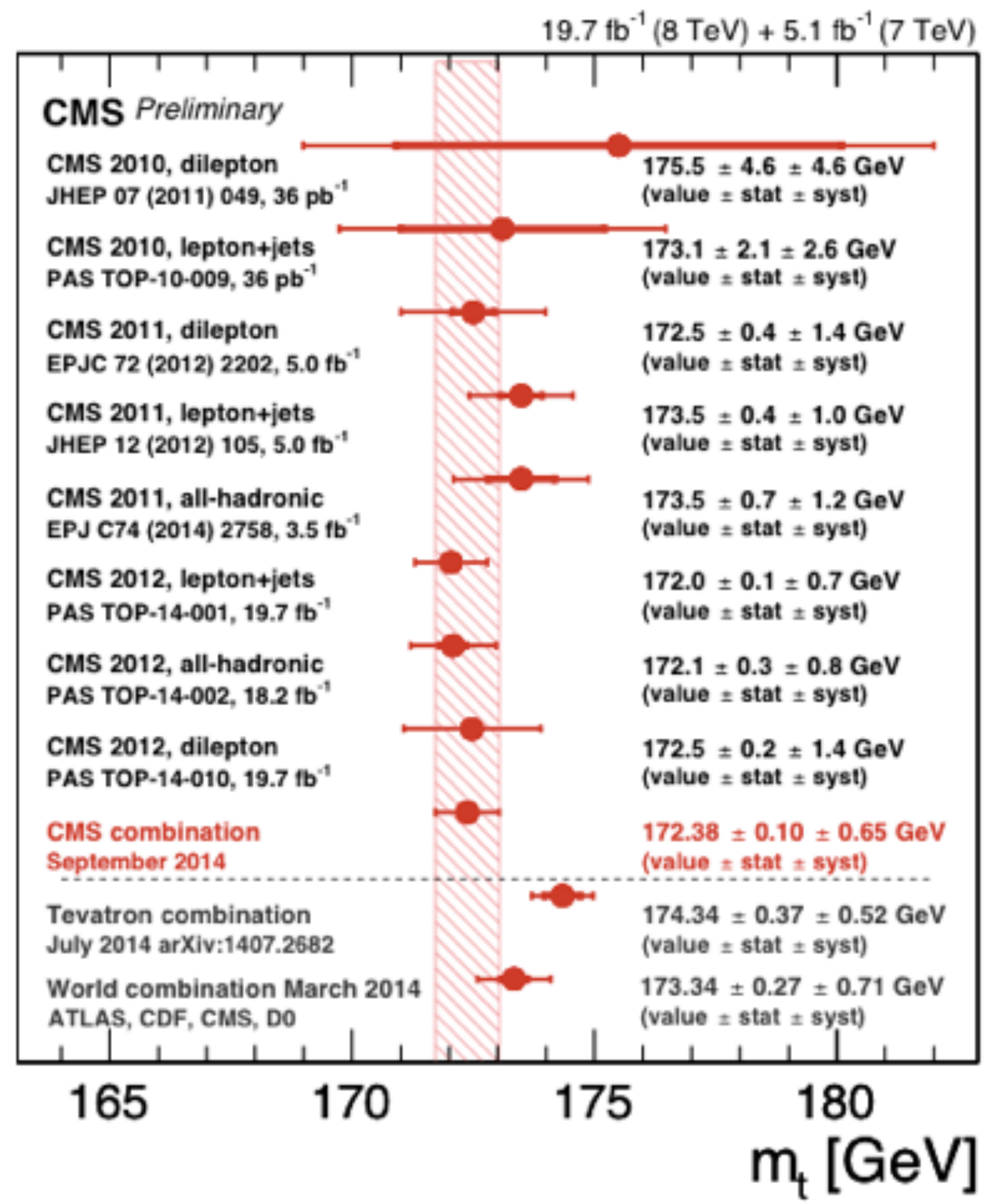
so what about the top mass?

fundamental parameter of the standard model

-> it's also a free parameter, so it has to be determined experimentally

-> it affects many theoretical predictions

-> but we can measure it directly!



the CMS combination of m_t is currently 172.38 ± 0.66 GeV

-> 3.8‰ relative error!

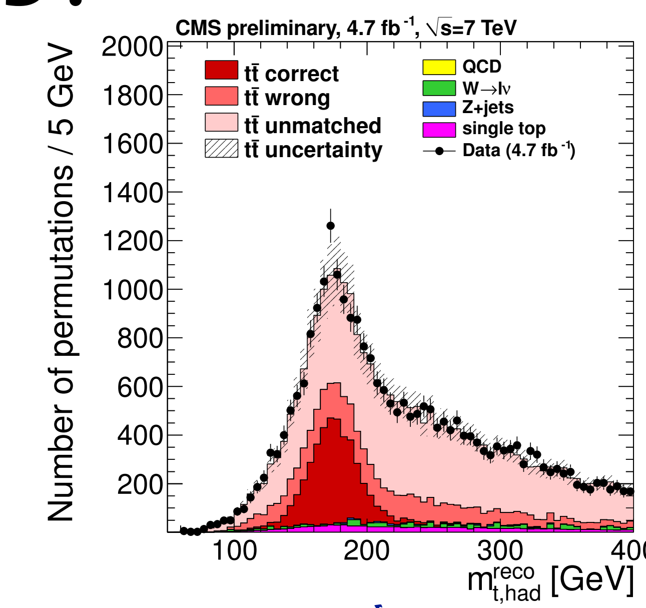
-> first combination of LHC+Tevatron:

173.34 ± 0.76 GeV (4.4‰ rel.err.)

CMS measurements in all the relevant decay modes at 7 and 8 TeV

-> talk about 8 TeV today

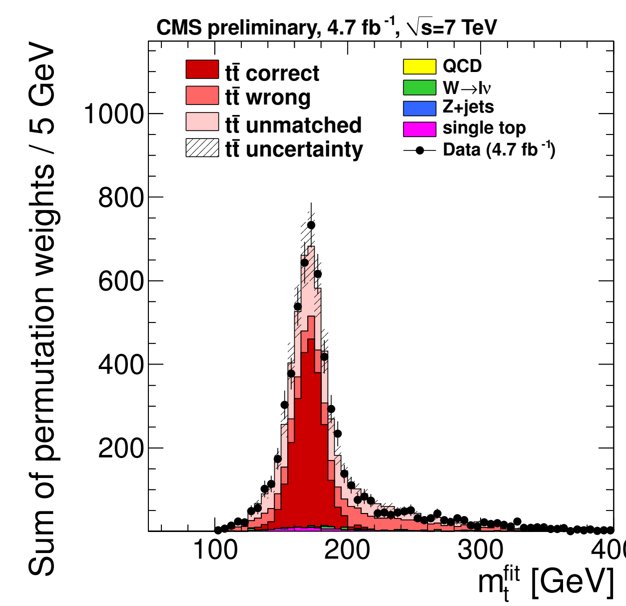
how to measure the top quark mass?



many 'conventional' methods employed

-> kinematic fit to the ttbar hypothesis

-> construct ideograms/templates from MC

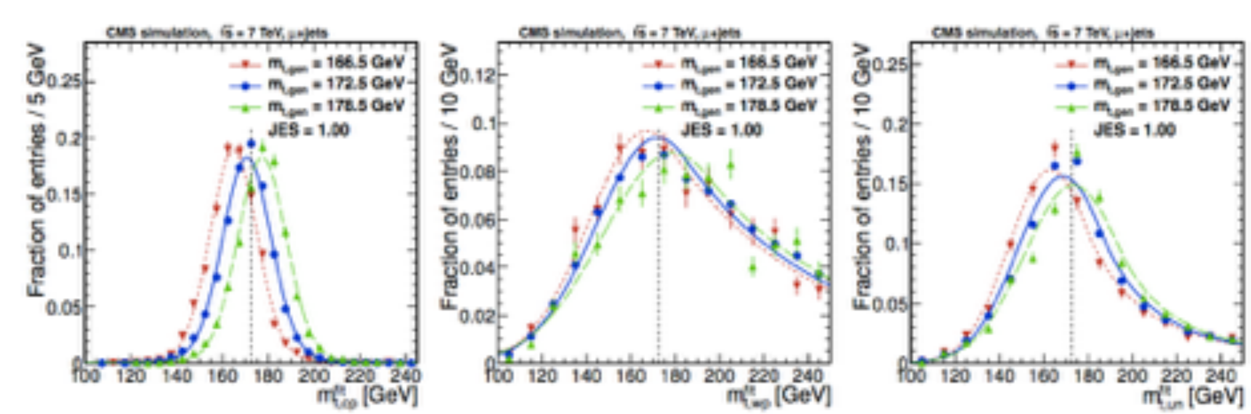


some 'alternative' approaches

-> such as from the b-lifetime

-> by fitting the shape of m_{lb}

examples of both in this talk!



measuring m_t from m_{lb}

CMS-PAS-TOP-14-014

a di-leptonic measurement without reconstructing the top

-> instead make use of a relation between m_{lb} and m_t

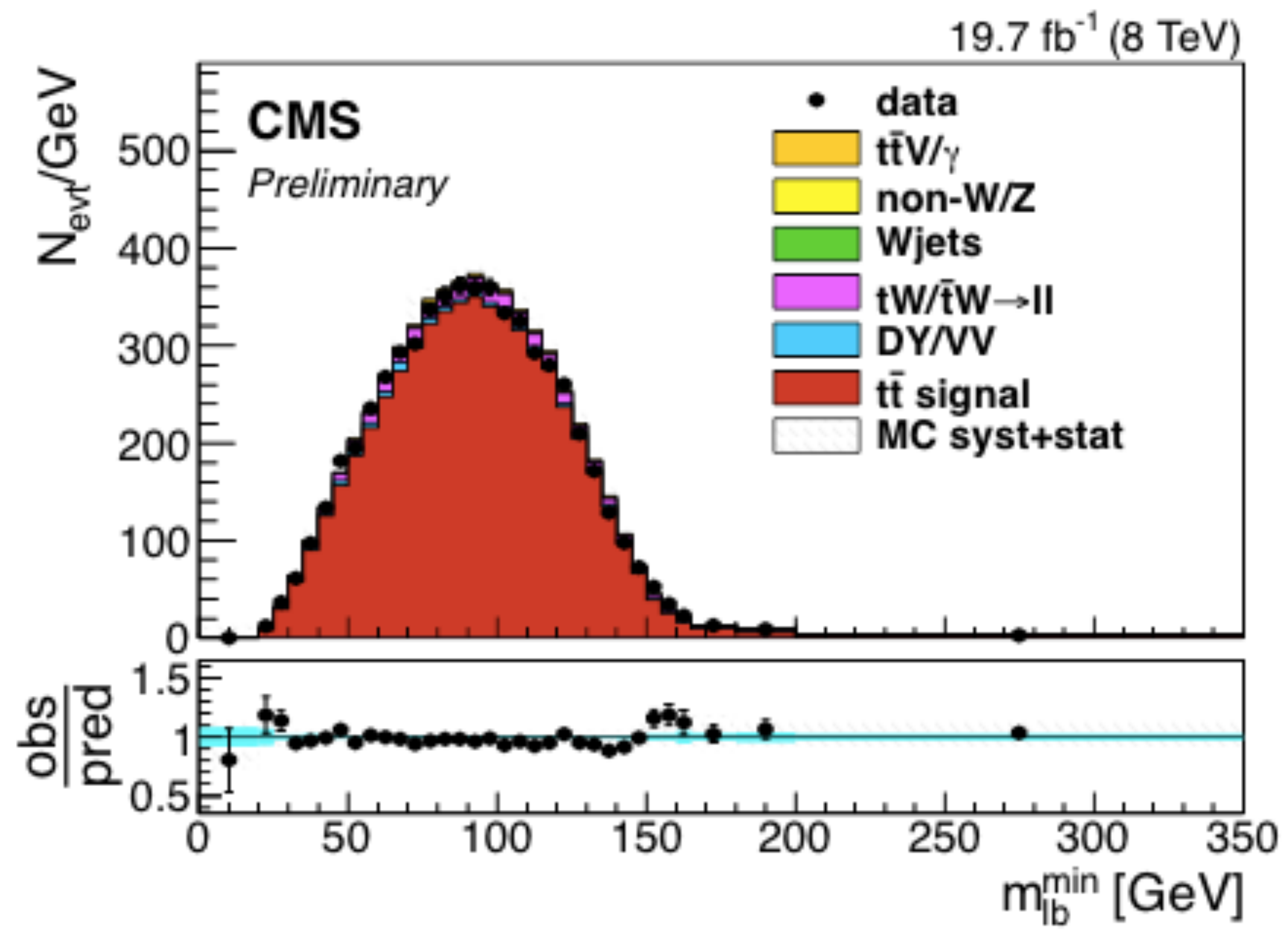
$$m_{lb}^2 = \frac{m_t^2 - m_W^2}{2}(1 - \cos\theta_{lb}) \xrightarrow{\text{endpoint}} \max(m_{lb}) \approx \sqrt{m_t^2 - m_W^2}$$

~ 153 GeV (if m_t~173)

select $e^{\pm}\mu^{\mp}$ events with at least two jets and one b-jet

-> use the minimal m_{lb} with highest p_T b-jet

-> correct assignment in roughly 85%



perform a template fit to the data

i.e. measuring the MC mass

build different templates from MC and fit the distribution to it

-> calculate the χ^2 of data and MC

extract a top mass of 172.3 ± 1.3 GeV

also compare the data to fixed order in QCD from MCFM

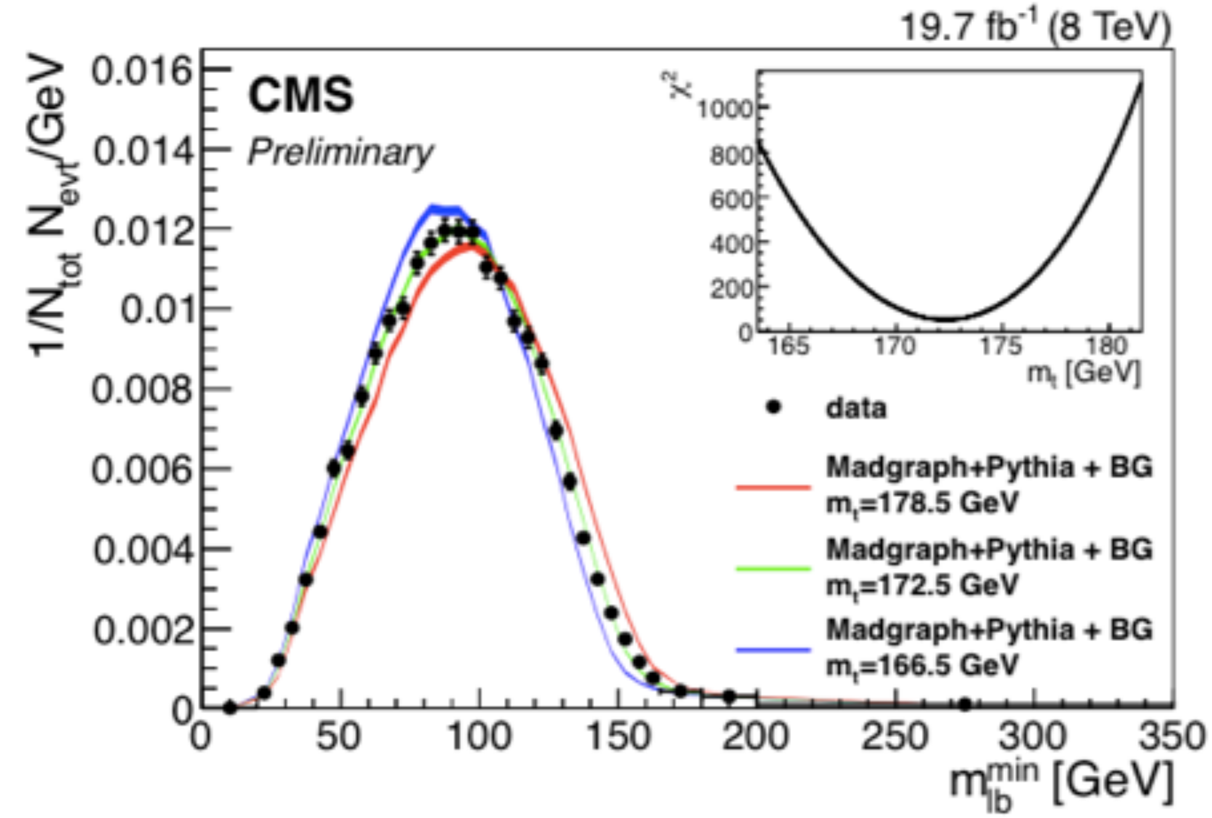
-> observe very similar results

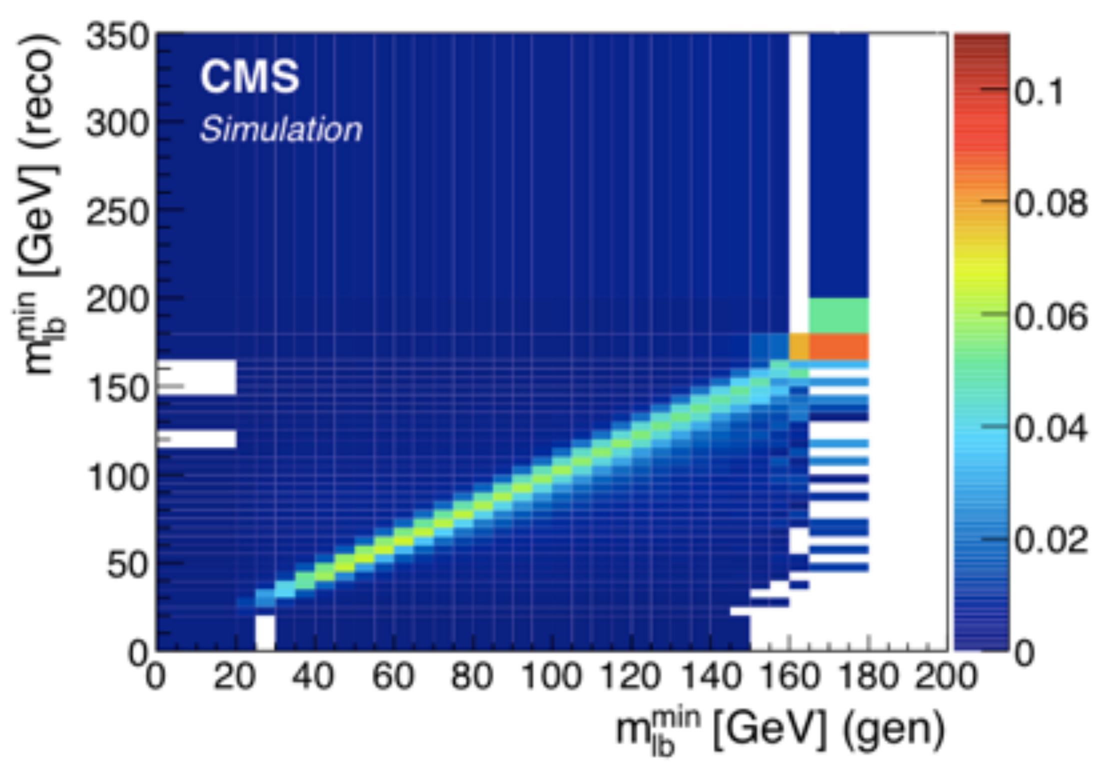
-> publish response matrix for the first time!

very similar results from MCFM:

-> m_t in LO: **171.5 ± 1.1 GeV**

-> m_t in NLO: **171.4 ± 1.1 GeV**





measuring m_t very precisely: lepton plus jets

CMS-PAS-TOP-14-001

the most precise measurement to date! it's a rather well defined final state

-> kinematically fit the decay products to ttbar hypothesis

-> measuring m_t and a jet energy scale factor (JSF) at the same time!

-> JSF constrained from the known W-mass

very pure sample with low backgrounds!

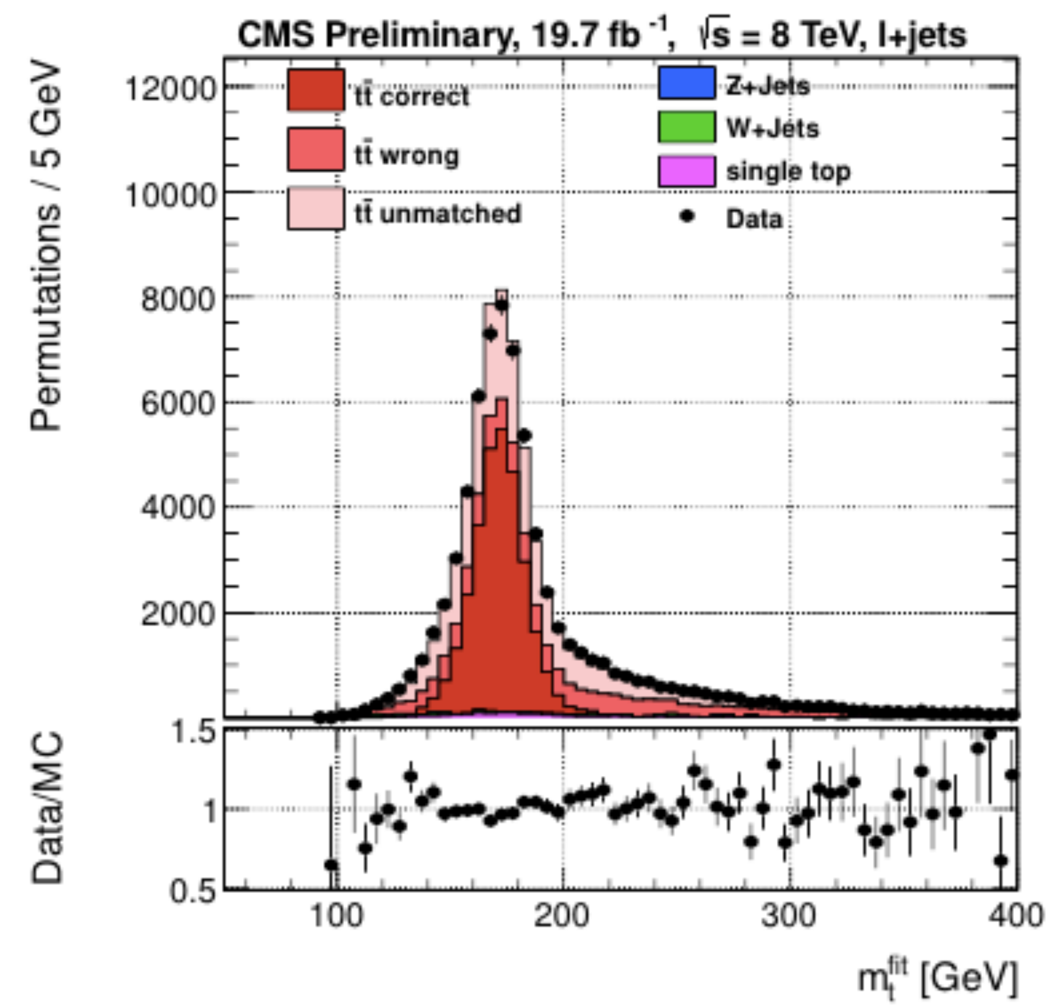
-> **1 lepton, >=4 jets, ==2 b-jets**

-> require a goodness of fit prob. of > 0.2

largest systematic uncertainty due to flavor dependent jet energy scale

-> compare `PYTHIA` and `HERWIG++`

-> validate this by using different ME



2D fit to m_t and JSF

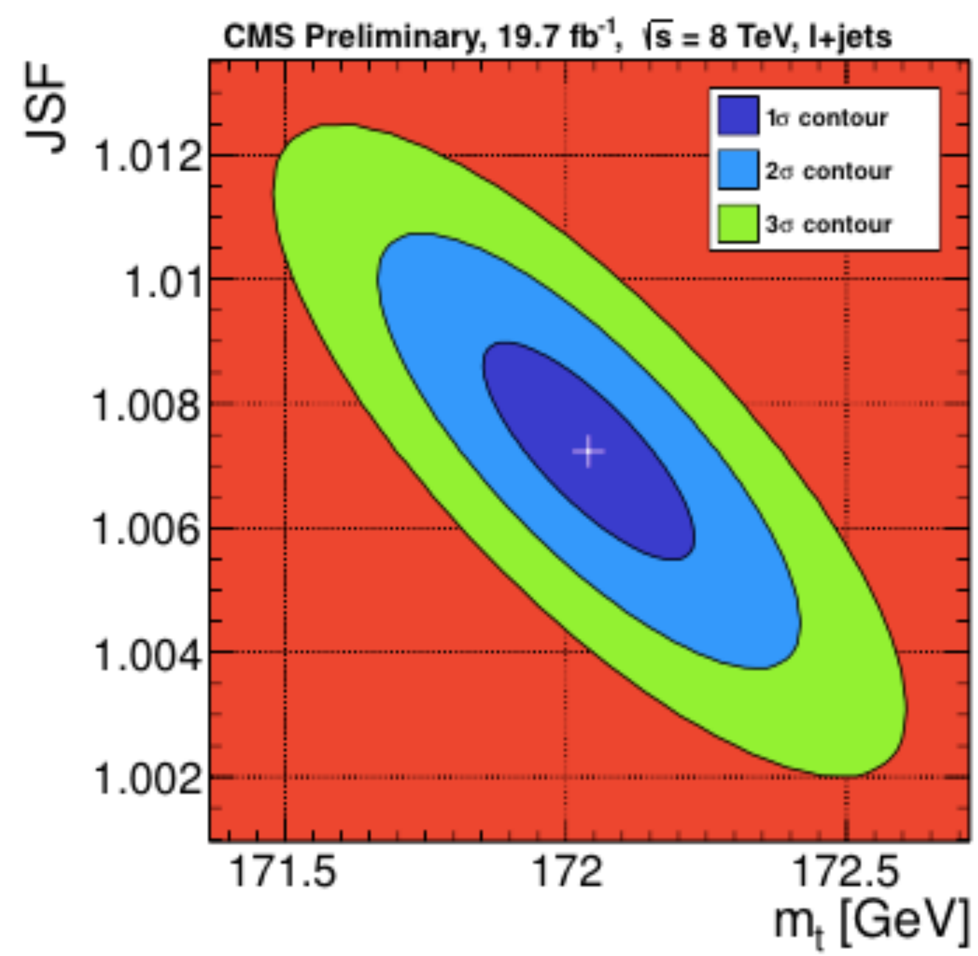
use the ideogram method to extract maximum information

results in a measured top mass of 172.04 ± 0.19 (stat.) ± 0.75 (syst.) GeV

-> most precise measurement we have!

-> overall JSF fitted to 1.007 ± 0.002 (stat.) ± 0.012 (syst.)

-> removing the 2D fit (and JSF =1) would result in **m_t = 172.66 ± 0.11 ± 1.29 GeV**



compared with other measurements

-> m_{lb}: 172.3 ± 1.3 GeV

-> world: 173.3 ± 0.3 ± 0.7 GeV

-> well within errors!

adding a lepton to the final state

CMS-PAS-TOP-14-010

this analysis was performed blind!

-> 2 leptons of either flavor and opposite charge, >=2 jets, of which one b-tagged

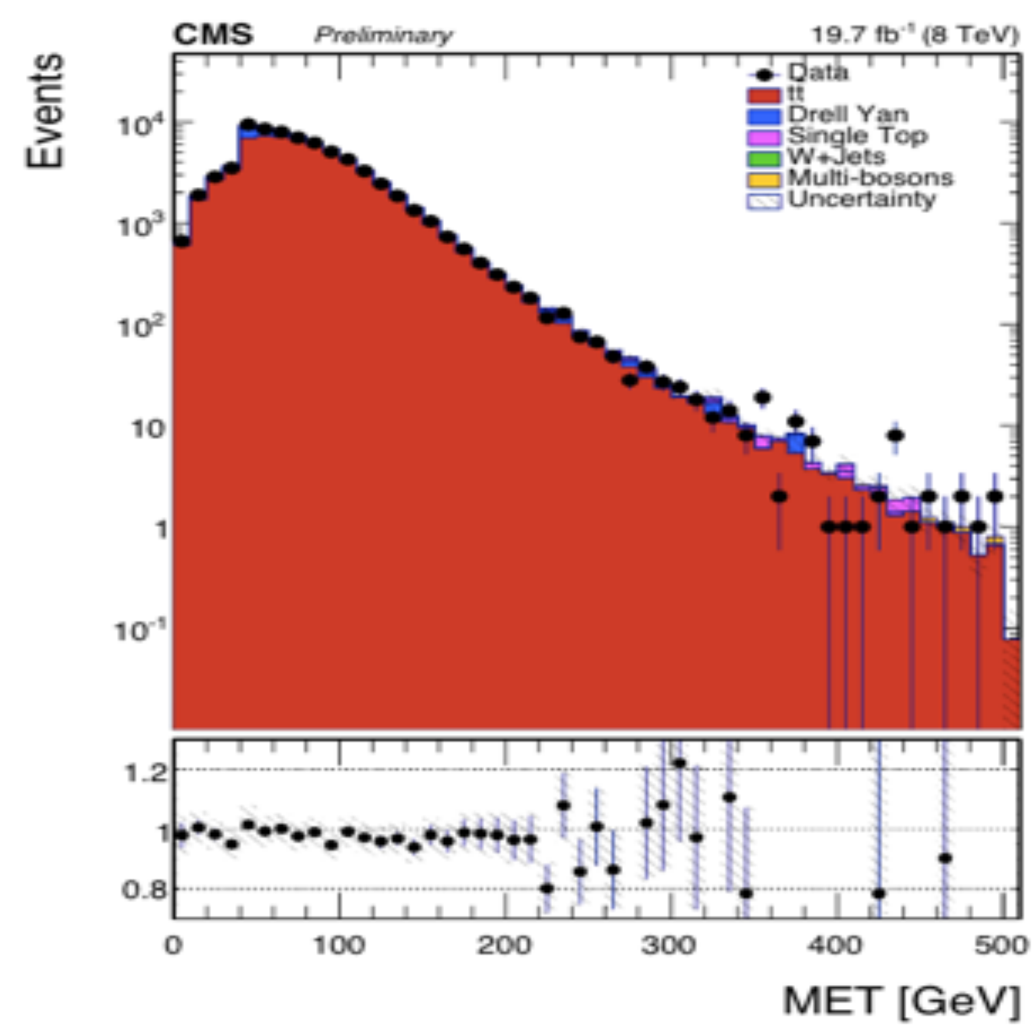
adding another neutrino makes life a bit more complicated

-> 8 solutions for every event and every top mass hypothesis

-> re-reconstruct every event 500 times smearing the jets

-> recovery of 95% of events

-> take solution with highest weight



working with roughly 70’000 events

-> statistically very sound. purity of 90%

fitting the MC mass

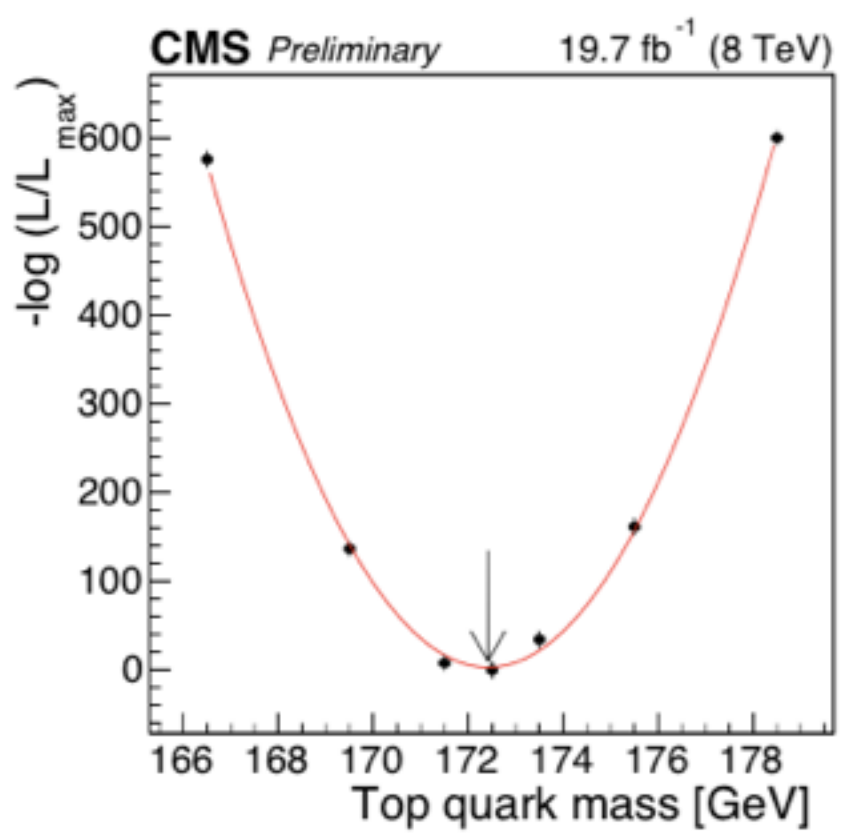
fit the MC and data and retrieve a mass of 172.47 ± 0.17 (stat.) ± 1.40 (syst.) GeV

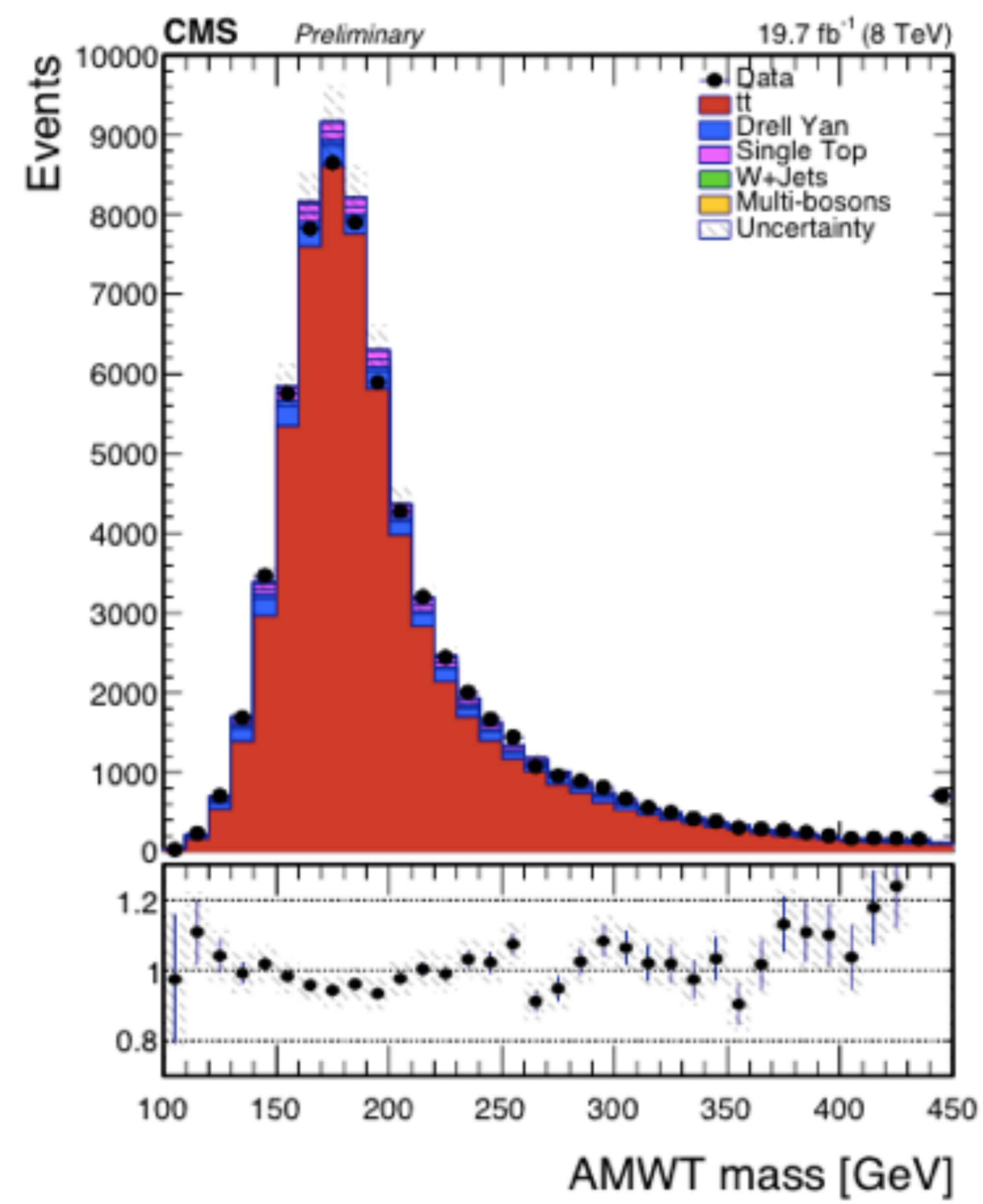
-> remarkable agreement with the previous results

-> larger errors though

leading systematics from MC

-> factorization and renormalization scale, JES, and b-fragmentation dominate





going all hadronic

CMS-PAS-TOP-14-002

smallest branching ratio penalty, but a lot of jets and trigger

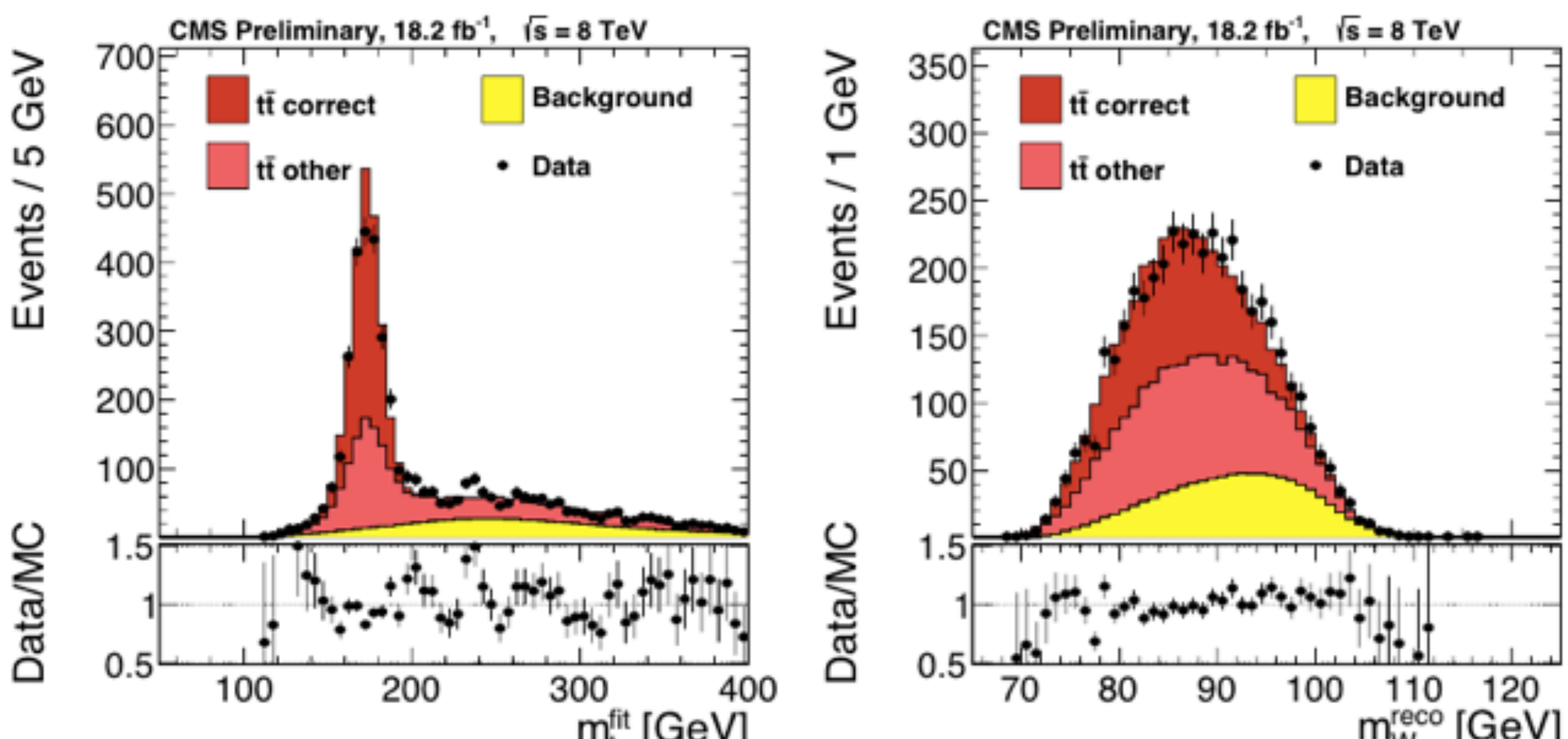
-> events with 6 jets, high thresholds due to trigger (4x60 + 2x30)

-> roughly 4'500 events

very similar analysis strategy to the previous two

-> kinematic fit to the tt hypothesis

-> fitting again 2D with JSF by constraining W-masses



again a template fit

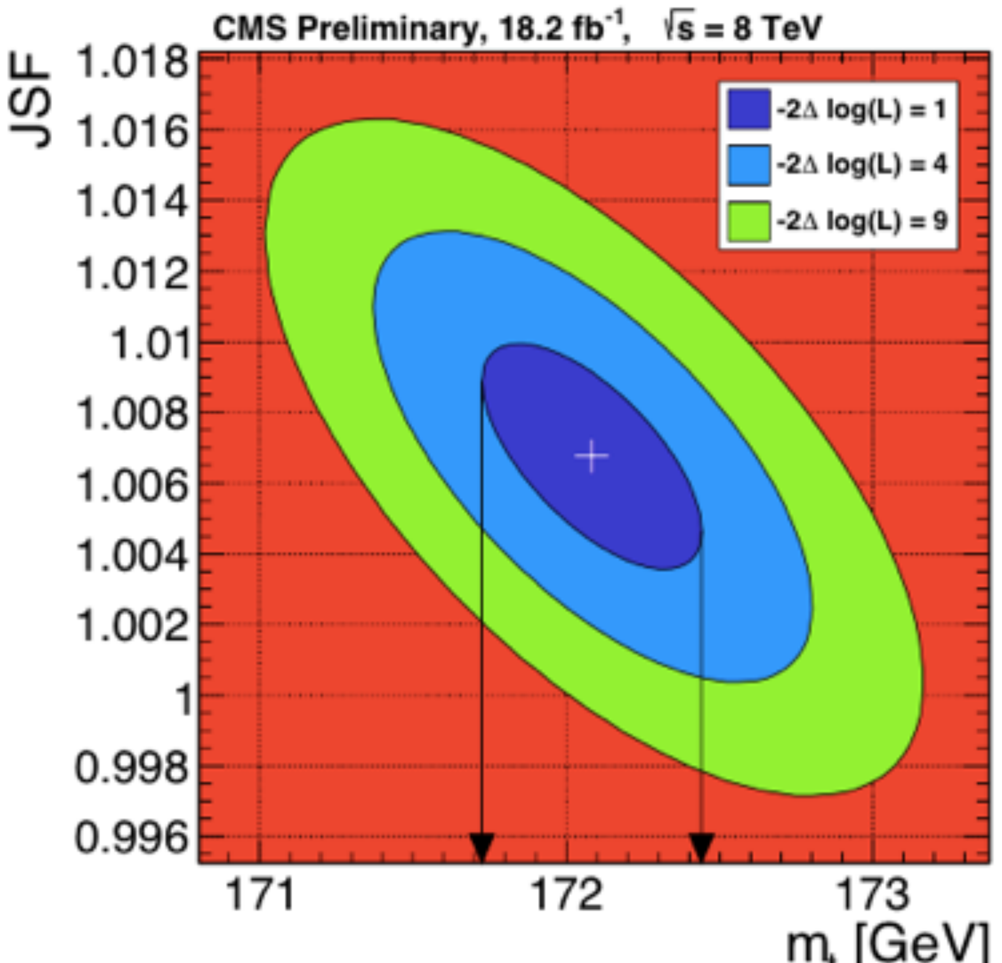
fitting the MC mass again from templates at different masses

-> systematics now dominated by JES and pileup and hadronization

mass: 172.08 ± 0.36 (stat.) ± 0.83 (syst.) GeV

-> JSF fitted to 1.007 ± 0.003 ± 0.011 (again)

-> m_t(JSF=1): **172.59 ± 0.27 ± 1.05 GeV**



again, impressive consistency with other CMS measurements!

-> learn something about jet energy scales in CMS as well!

combining the measurements of all final states within CMS

CMS-PAS-TOP-14-015

combining results from 3 years of running

-> **(36 pb^{-1} + 5 fb^{-1})** @ 7 TeV **+ 20 fb^{-1}** @ 8 TeV

using a method called BLUE (best linear unbiased estimator)

-> the tricky part is getting the correlations of systematics right!

		2010		2011			2012		
		di-l	$l+$jets	di-l	$l+$jets	all-jets	di-l	$l+$jets	all-jets
2010	di-l	1.00							
	$l+$jets	0.20	1.00						
2011	di-l	0.15	0.26	1.00					
	$l+$jets	0.09	0.15	0.37	1.00				
	all-jets	0.10	0.16	0.62	0.31	1.00			
2012	di-l	0.08	0.19	0.26	0.13	0.16	1.00		
	$l+$jets	0.07	0.10	0.22	0.39	0.27	0.27	1.00	
	all-jets	0.06	0.08	0.16	0.29	0.24	0.26	0.52	1.00

not actual values

	Correlations ρ_{year}	Correlations ρ_{chan}	Combined uncertainty
Experimental uncertainties			
In-situ JSF factor	0	0	0.10
Inter-calibration JES component	1	1	0.01
MPF *in-situ* JES component	1	1	0.05
Uncorrelated JES component	0	1	0.14
Other JES uncertainties	0	0	0.00
Lepton energy scale	1	1	0.02
E_T^{miss} scale	1	1	0.06
Jet energy resolution	1	1	0.17
b-tagging	1	1	0.03
Trigger	0	0	0.04
MHI(Pileup)	0	1	0.20
Background Data	0	0	0.05
Background MC	1	1	0.07
Fit calibration	0	0	0.05
Modeling of hadronization			
Flavor JES component	1	1	0.05
Flavor-dependent hadronization uncertainty	1	1	0.36
b fragmentation and B branching fractions	1	1	0.14
Modeling of the hard scattering process and radiatio			
Parton distribution functions	1	1	0.06
Renormalization and factorization scales	1	1	0.17
ME-PS matching threshold	1	1	0.16
ME generator	1	1	0.13
Top quark p_T	1	1	0.12
Modeling of non-perturbative QCD			
Underlying event	1	1	0.16
Color reconnection	1	1	0.18
Statistical uncertainty			0.10
Total systematic uncertainty			0.65
Total uncertainty			0.65

combined mass:

172.38 ± 0.10 (stat.) ± 0.65 (syst.) GeV

-> this is significantly better than the world average!

short summary on m_t

from σ_{ttbar}: PLB 728 (2014) 496–517
b-lifetime: CMS-PAS-TOP-12-030
combin.: CMS-PAS-TOP-12-015

very nice and precise measurements from CMS out lately

-> very, very consistent among themselves

					δm/m
m_{lb}	172.30	±	1.30	GeV	7.5 ‰
from σ_{ttbar}	176.70	±	3.80	GeV	21.5 ‰
b-lifetime	173.50	±	3.27	GeV	18.8 ‰
l+jets	172.04	±	0.77	GeV	4.5 ‰
ll+jets	172.47	±	1.41	GeV	8.2 ‰
jets	172.08	±	0.85	GeV	5.0 ‰
combined	172.38	±	0.66	GeV	3.8 ‰

+ 2010 and 2011 versions

most accurate single measurement has less than half a percent error!

-> reach 3.8 per mill precision after combination!

properties of the top quark

many nice features measurable only with the top-quark

-> it's the only quark that decays before hadronization

some interesting measurements from a SM perspective

-> ratio of **t->bW/qW** — measuring V_{tb}

-> W-helicity measurements

-> tt+X

-> spin correlations

-> couplings of the top quark to other particles (esp. higgs)

-> top-pair charge-asymmetry

we can derive limits on new physics from the top's properties

-> anomalous couplings

-> contradict/confirm some interesting measurements

measuring the ratio bW/qW

PLB 736 (2014) 33-57

unitarity of the CKM matrix provides information on the ratio

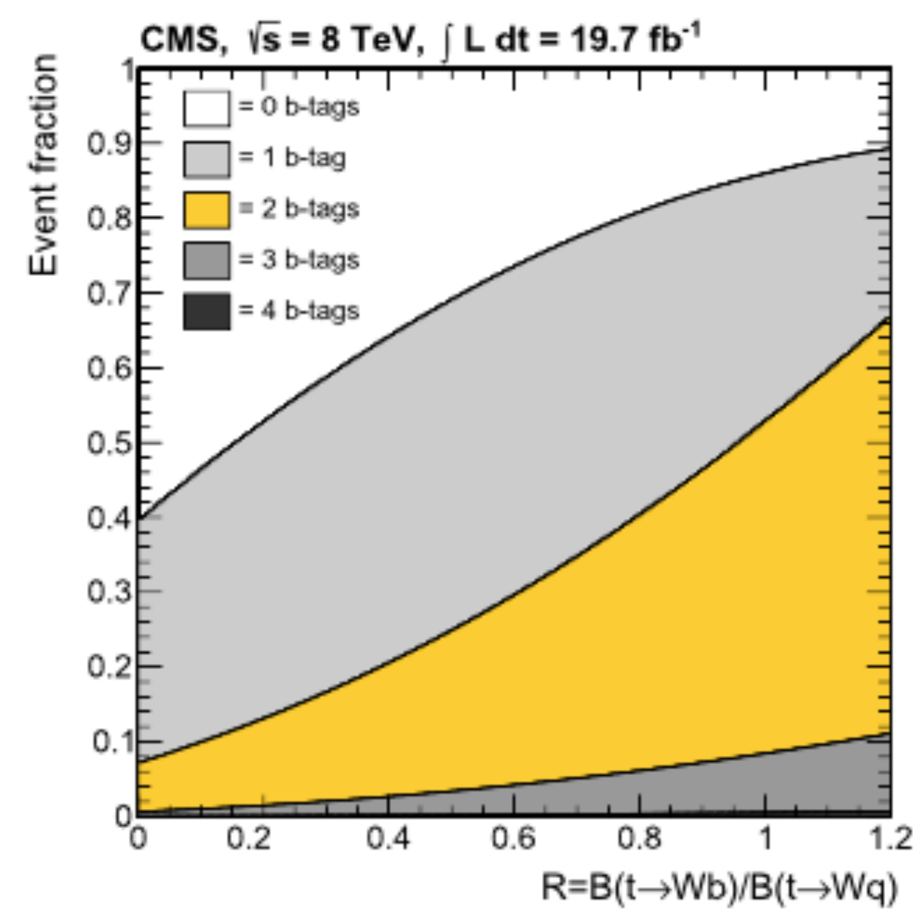
-> measuring V_{ub} and V_{cb} gives a **very** stringent limit on **$|V_{tb}| = 0.999146^{+0.000021}_{-0.000046}$**

-> the ratio and V_{tb} are essentially the same thing: $R = |V_{tb}|^2$

additional interest comes from the Tevatron/DØ

-> overall ratio **R = 0.90 ± 0.04** **->** $|V_{tb}| \sim 0.95$

-> di-lepton tt: **R = 0.86 ± 0.054** **->** $|V_{tb}| \sim 0.93$



measured at CMS on 8 TeV data

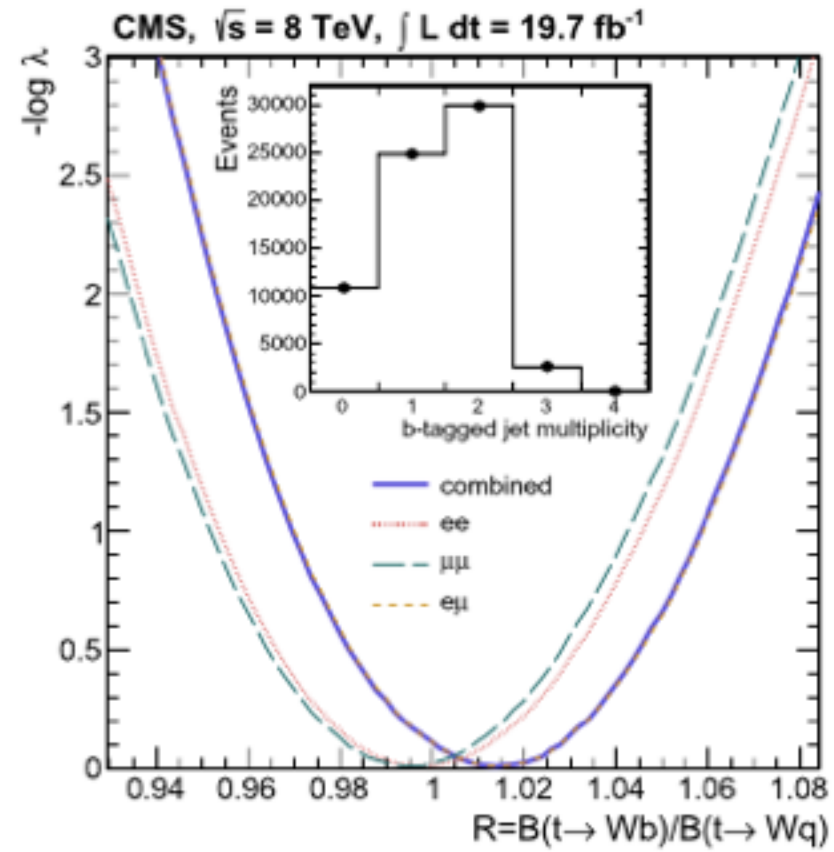
-> also in di-leptonic channel

-> two opposite charge leptons and at least two jets

extracting R from the (b-)jet multiplicity

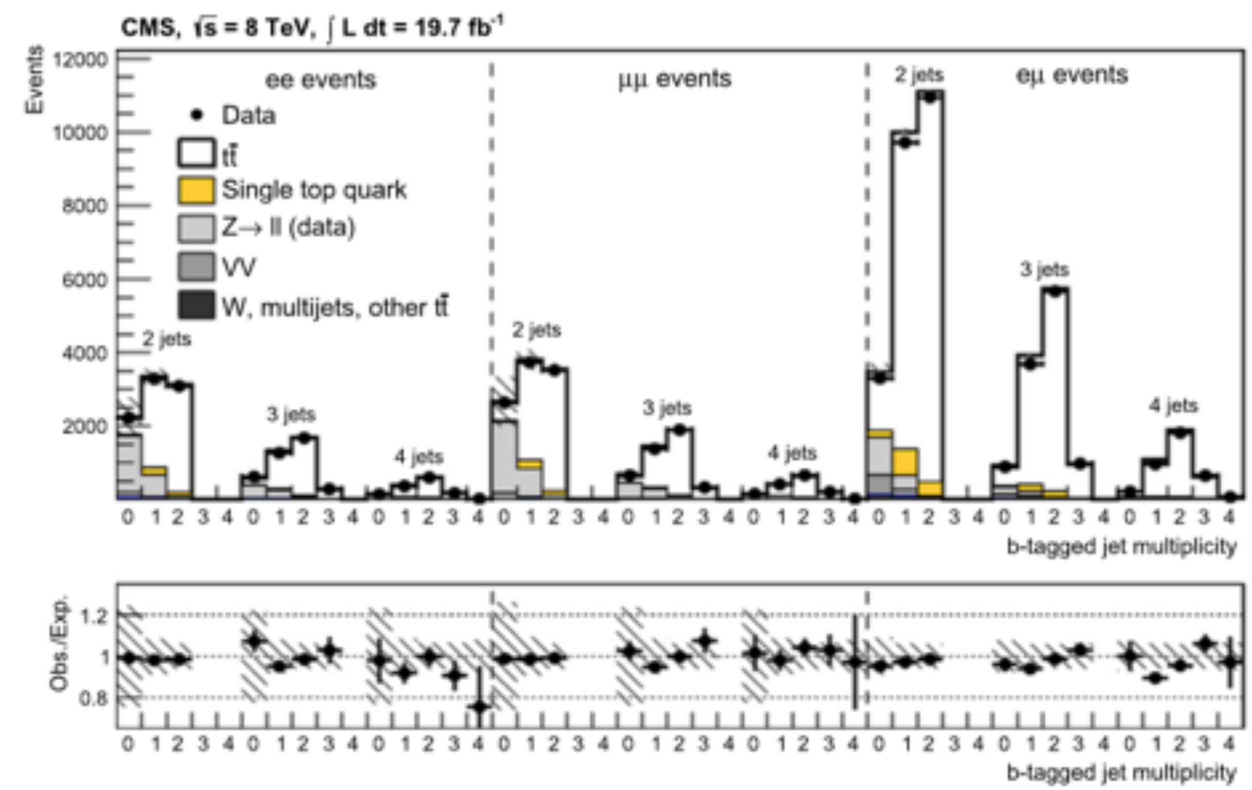
if we know ε_b and ε_q we can write a probability to observe n-bjets

-> this is then proportional to R



systematics dominated by uncertainty on tagging efficiency

-> top mass uncertainty also contributes



measure the ratio from fitting the b-multiplicities

-> extract ratio

R = 1.015 ± 0.003 (stat.) ± 0.031 (syst.)

$|V_{tb}|$ ~ 1.007

-> very consistent with CKM unitarity

spin information in single tops - the W helicity

arXiv:1410.1154

top decays before hadronization, so spin information is relatively directly observable

-> the W boson has either longitudinal or left- or right-handed helicity

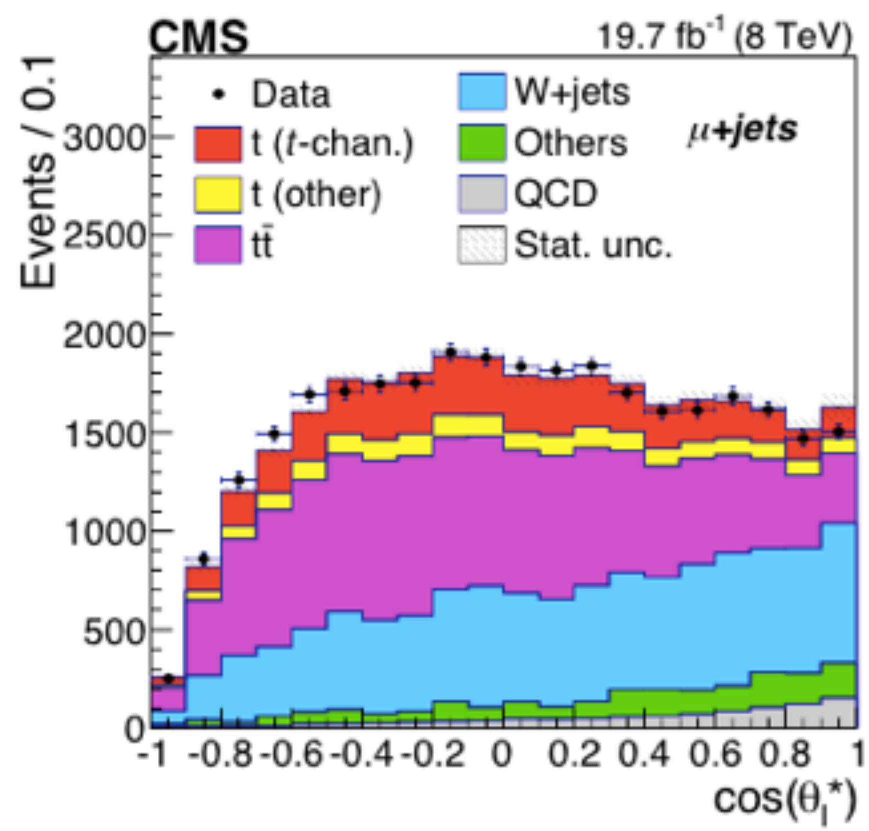
-> the SM predicts the helicity fractions (F_i) with good accuracy

helicity angle between W in top restframe and down-fermion in W restframe

-> prob. distr. func. for this angle

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

-> fit the distribution of $\cos(\theta_l)$ to the data

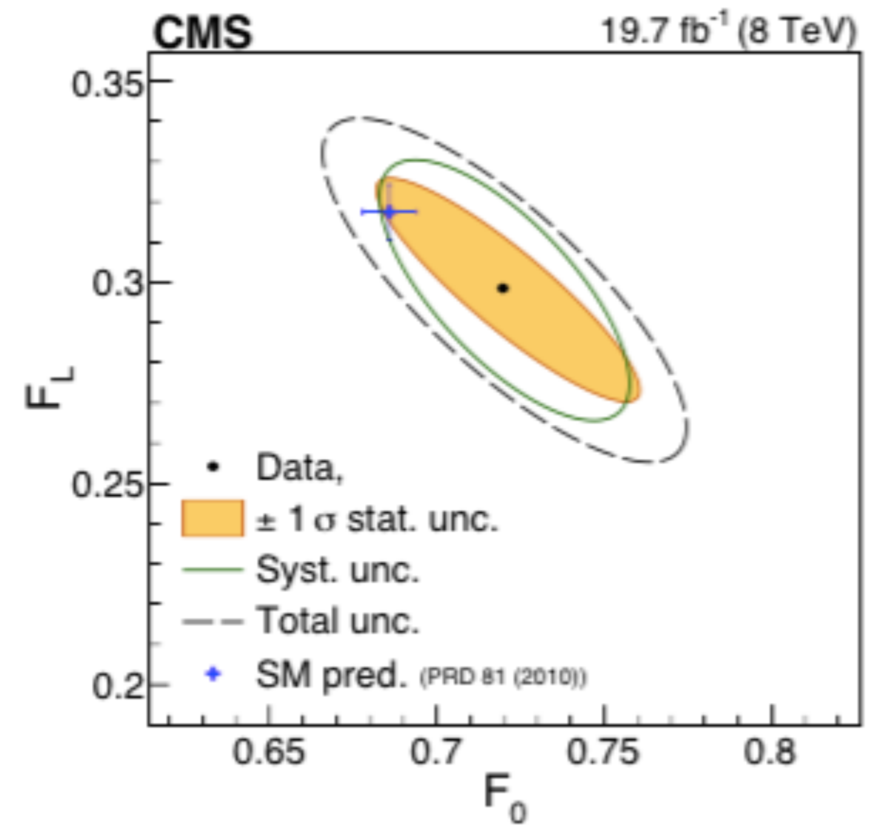


==1 lepton, ==2 jets (1b), not very pure

-> but the contamination are tops as well, so

-> this is a new measurement with single tops, the one from ttbar has been out for a long time!

spin information in single tops - the W helicity



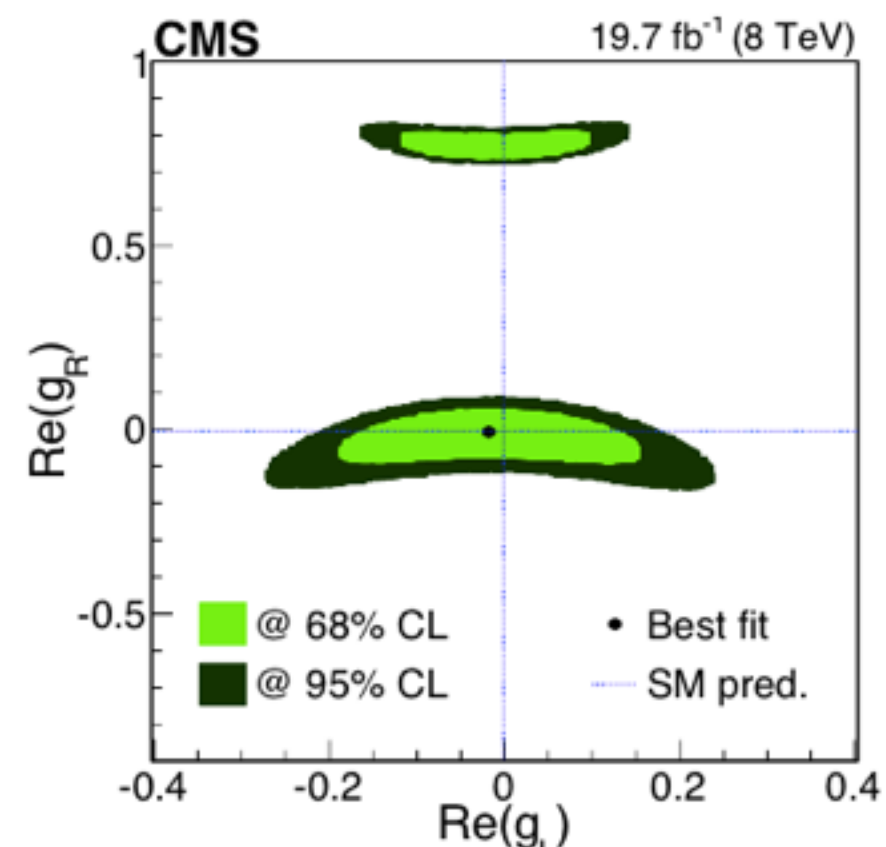
distributions in data agree well with expectation

-> W+jets contribution is free in the fit

-> F_R constrained by $\Sigma F_i = 1$

systematic uncertainties dominated by MC modeling and limited statistics

-> set limits on anomalous tWb couplings



	F_L	F_0	F_R
theory	0.311 ± 0.005	0.687 ± 0.005	0.0017 ± 0.0001
CMS	0.298 ± 0.043	0.720 ± 0.054	-0.018 ± 0.022
CMS (tt)	0.350 ± 0.026	0.659 ± 0.027	-0.009 ± 0.021

measuring tt+W/Z

tt+V: EPJC (2014) 74:3060

eventually measure tt-W/Z/higgs couplings

-> so far only cross section measurements

tt+W/Z measured in leptonic final states

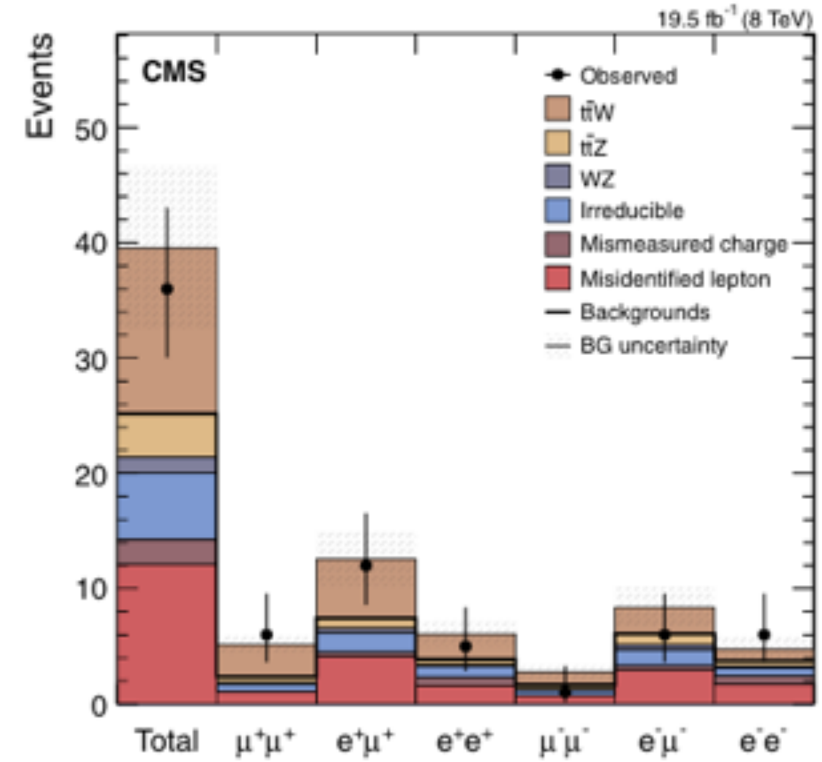
-> same-sign, tri-, quadleptons

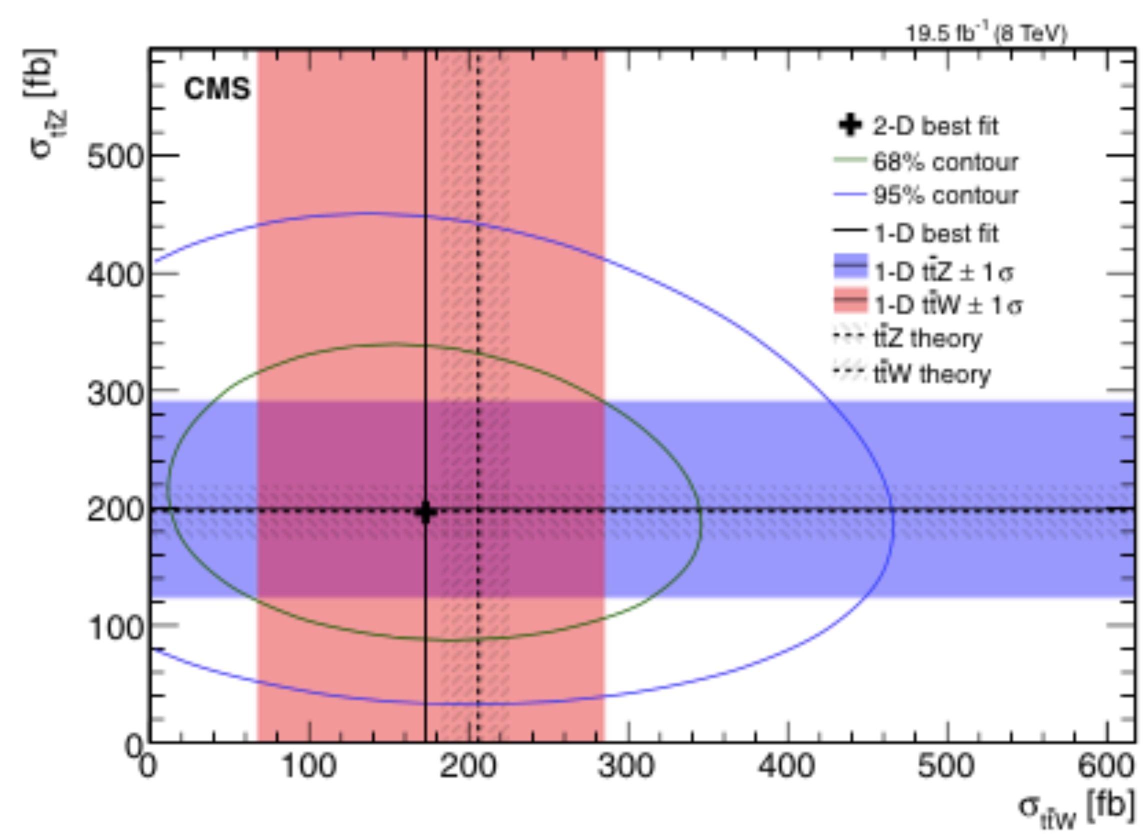
-> nine signal regions in total

perform a simultaneous fit to both components!

-> obtain good agreement with SM

	measured	theory
σ_{tt+W}	$170\ ^{+100}_{-10}$ fb	$206\ ^{+21}_{-23}$ fb
σ_{tt+Z}	$200\ ^{+90}_{-90}$ fb	$197\ ^{+22}_{-25}$ fb





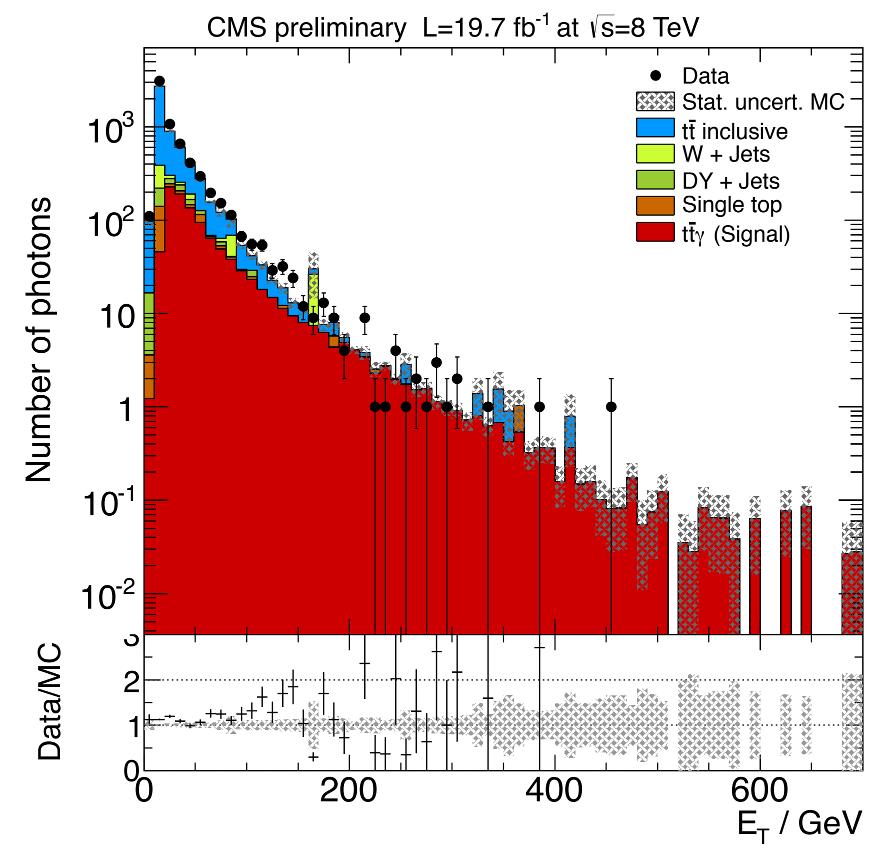
measuring tt+gamma

CMS-PAS-TOP-13-011

statistically much easier than massive bosons

-> measure in muon+photon events though

-> one muon, 4 jets, 2 b-jets,



systematics dominated by background modeling

-> top quark p_T spectrum and scale uncertainties as well

measure ratio R = $\sigma_{ttbar+\gamma} / \sigma_{ttbar} = (1.07 \pm 0.28) \times 10^{-2}$

-> extract cross section from ttbar cross section measurement

	measured	theory
$\sigma_{ttbar+photon}$	2.4 ± 0.63 pb	1.8 ± 0.5 pb

summary of all things top

top quark mass precision has reached < 1 % precision!

-> can help constrain the SM and new physics alike

-> results from CMS systematically lower than Tevatron results

top quark properties seem very standard-model-like!

-> W helicity and V_{tb} just two of the interesting measurements

-> charge asymmetry, ttbar spin correlations, jet multiplicities just some examples of what's more to come

the top quark continues to be a nice playing field at the LHC

-> statistical errors are becoming less and less important

-> we're on the way to measure top-W/Z/higgs/gamma couplings in run2!

surely some exciting times ahead for top physics!

the end

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