Top quark pair production cross section at CMS

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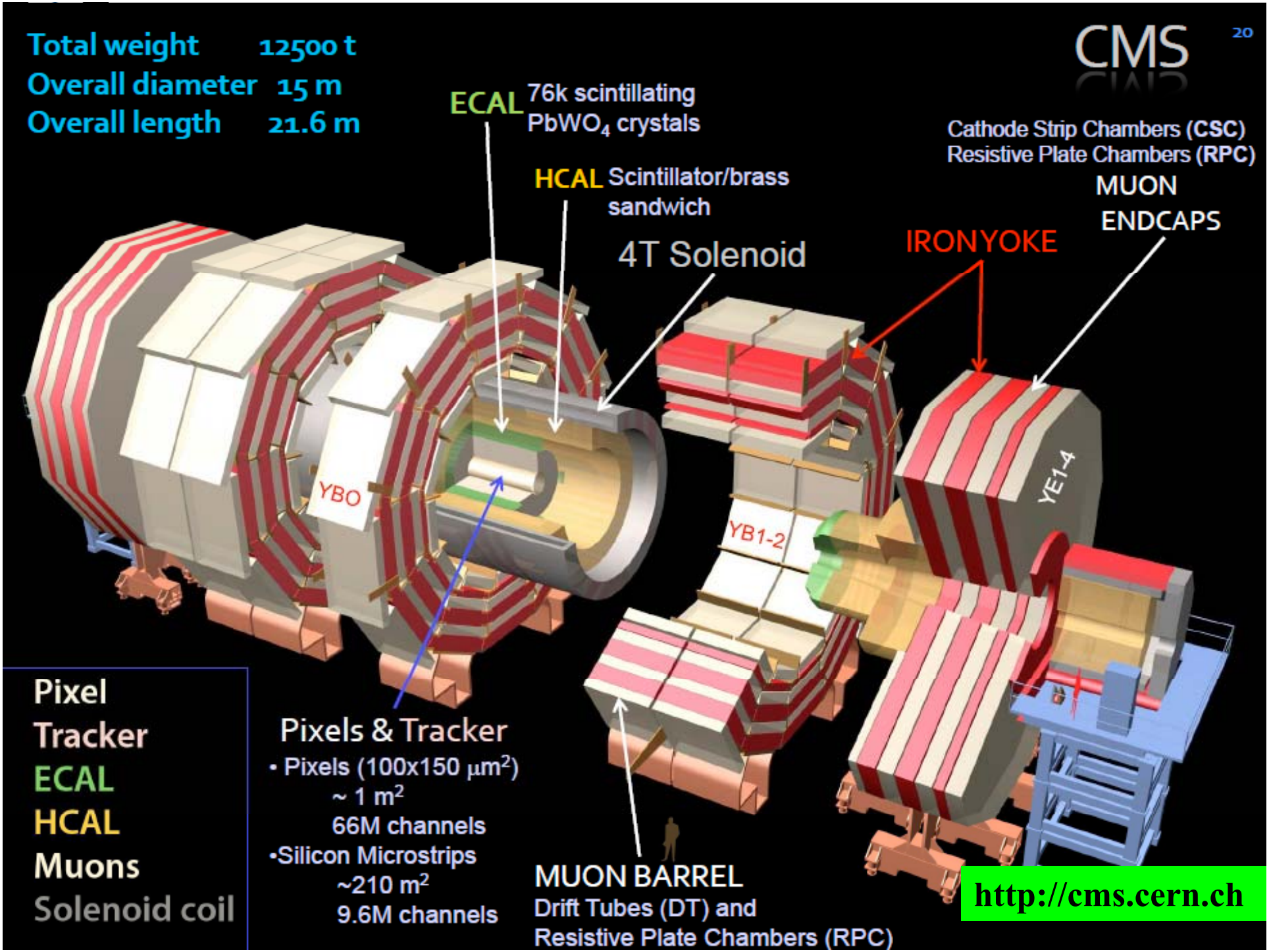
On behalf of the CMS Collaboration

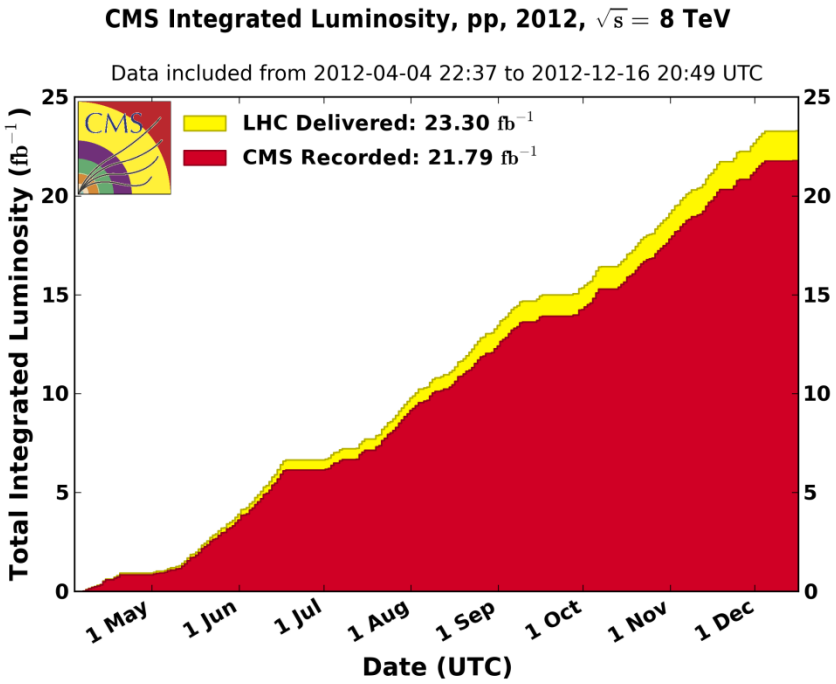
CMS results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP


Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m
CMS
20
ECAL 76k scintillating PbWO4 crystals
HCAL Scintillator/brass sandwich
4T Solenoid
IRONYOKE
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
MUON ENDCAPS
YBO
YB1-2
YE1-4
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm²)
~ 1 m²
66M channels
•Silicon Microstrips
~210 m²
9.6M channels
MUON BARREL
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)
http://cms.cern.ch

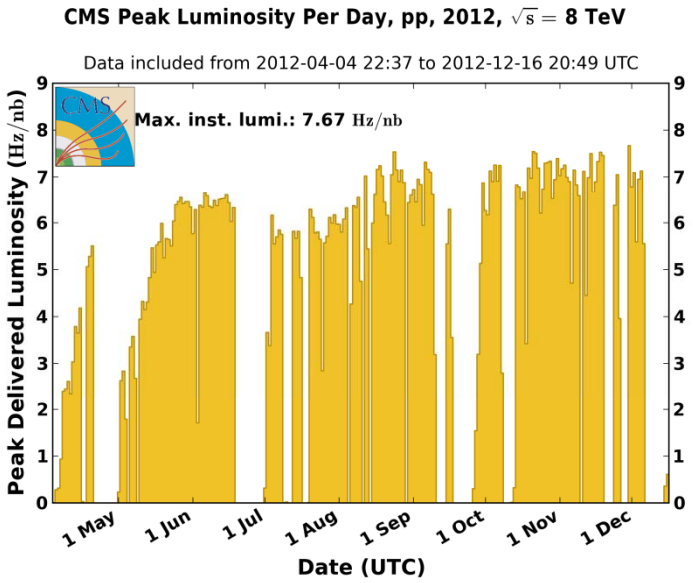
LHC and CMS operation

2012: 23.30 fb^{-1} delivered by LHC and **21.79 fb^{-1}** recorded by CMS
2011: 5.72 fb^{-1} delivered by LHC and **5.20 fb^{-1}** at 7 TeV
2010 at 7 TeV : ~36 pb^{-1}

Uncertainty on integrated luminosity: 2.2% at 7 TeV / 2.6% at 8 TeV



■ **Instantaneous luminosity above $7 \cdot 10^{33}$ cm^{-2}s^{-1}**



Overall data taking efficiency **~94%.**
Average fraction of operational channels per subsystem >98%

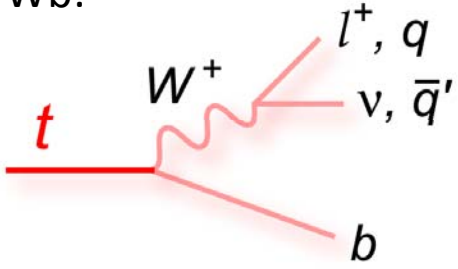
■ **Successfully coping with PileUp at the trigger, DAQ, computing and reconstruction level**

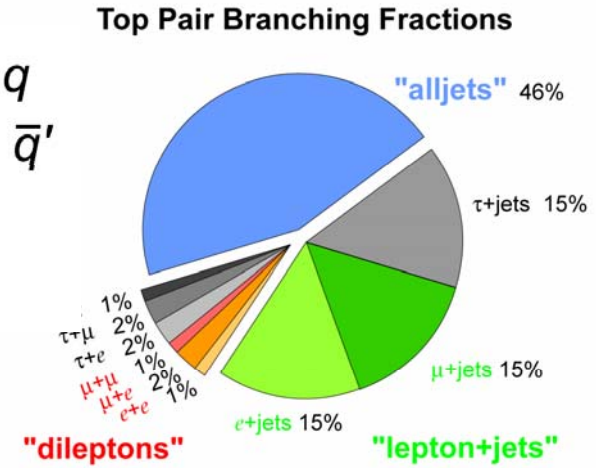
Top production and decay channels

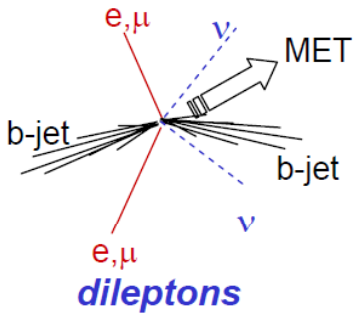
- Production: predominately in top-antitop pairs (ttbar)

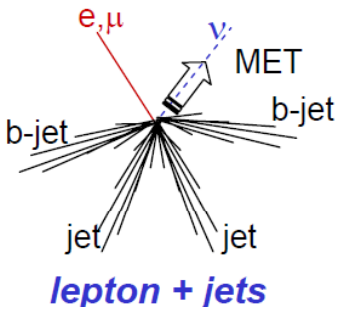
NNLO σ_{tt} for m_{top} = 173.3 GeV (LHC@7TeV) = 172 pb, (LHC@8TeV) = 245 pb

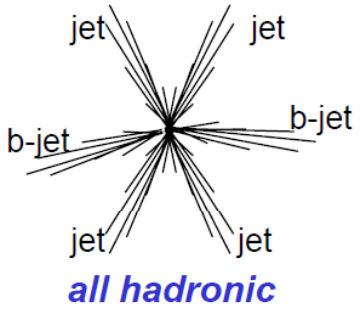
Top quark decays almost exclusively to Wb:











	dileptons	lepton + jets	all hadronic
BR:	~ 5%	~30% (e, μ)	~46%
Bkg:	small	medium	huge
Mainly:	Z+jets dibosons	W+jets	QCD multijets

Selection requirements

- **Trigger**
  - Single/double (isolated) leptons
  - and/or based on hadronic activity

- **Jets**
  - Anti-k_T algorithm with R=0.5
  - p_T> 30-45 GeV $|\eta|$<2.5
  - b-tagging

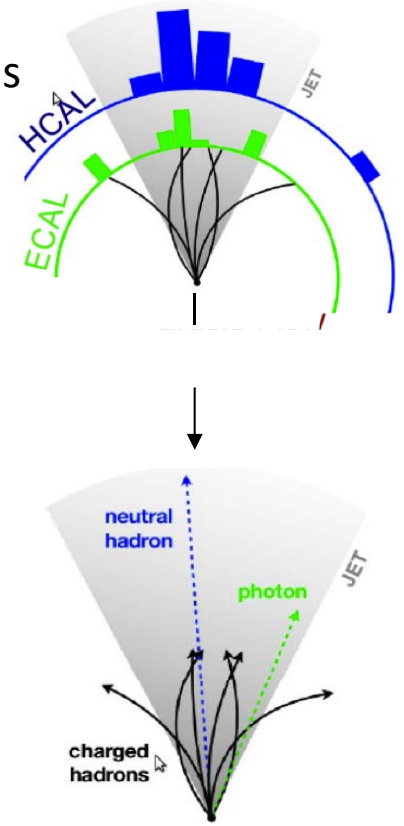
- **Leptons (e,μ,τ) with p_T>20-30 GeV**
  - Isolation in tracker and calorimeters
  - Reconstruction and ID quality cuts

- **Missing transverse energy (E_T^{miss})**
  - In some analyses, > 20-60 GeV

CMS PAS PFT-10-002

"Particle Flow" reconstruction and identification combining information from all subdetectors:

-charged hadrons
-photons
-neutral hadrons
-muons
-electrons

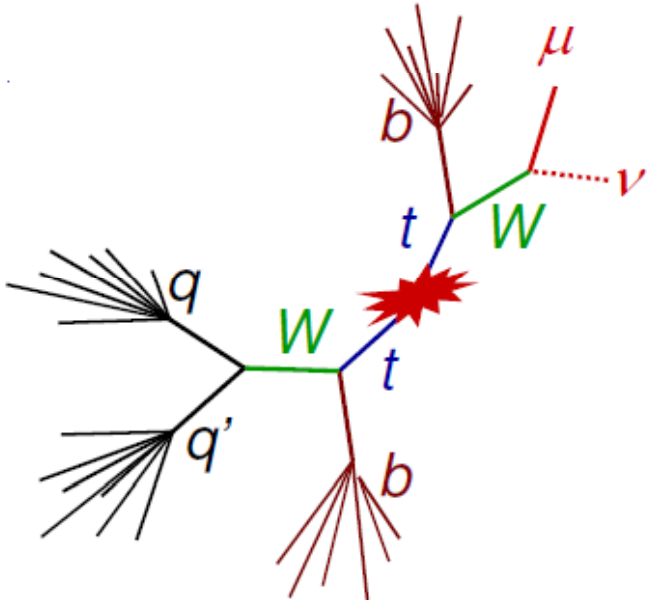


Leptons + jets

$t\bar{t} \rightarrow l\nu qqbb$

Common strategies:

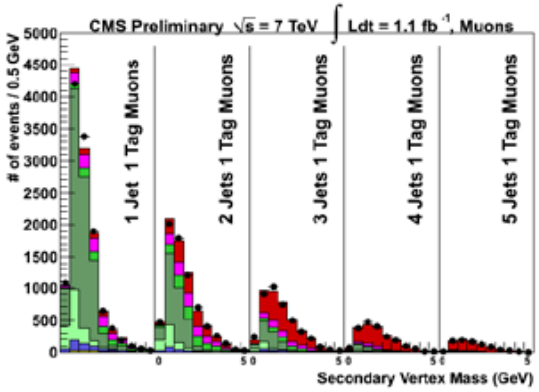
- Trigger
- Require 1 isolated lepton (e, μ)
- high pT (~ 30 GeV)
- veto on additional leptons
- at least 4 jets
- at least 1 b-tagged jet

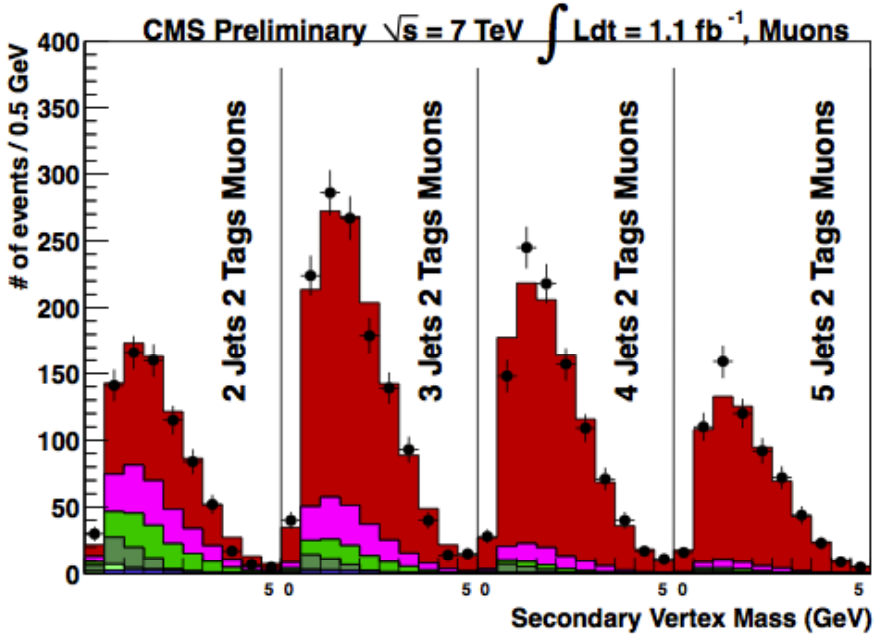


CMS PAS TOP-11-003 2.3 fb^{-1}
Phys. Lett. B 720 (2013) 83

Leptons + jets at 7 TeV

- Multijet shape from MC, normalization from data
- Profile Likelihood fit to Secondary vertex mass in N(jets), N(b-tagged jets) plane
- Some systematic uncertainties treated as nuisance parameters (Q2, b-tag eff.)





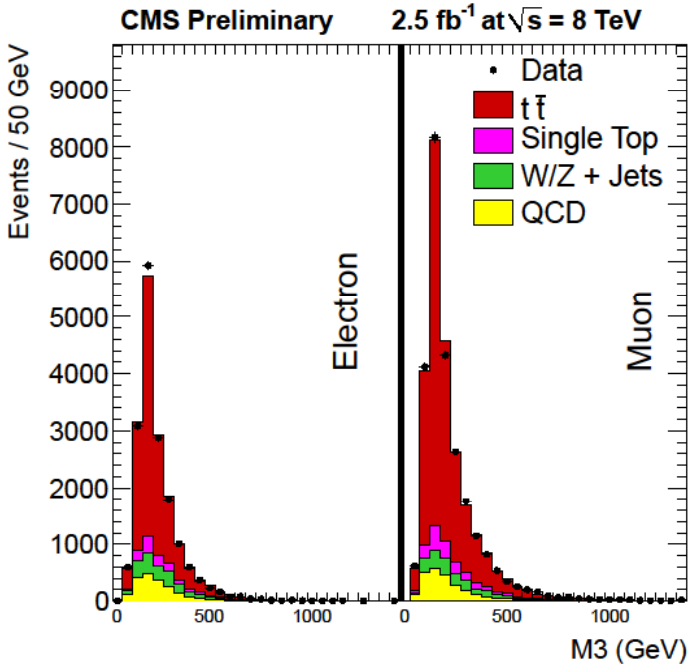
σ_{tt} = (158.1 ± 2.1 (stat.) ± 10.2 (syst.) ± 3.5 (lumi.))pb, $\Delta\sigma_{tt} / \sigma_{tt}$ = 6.9%

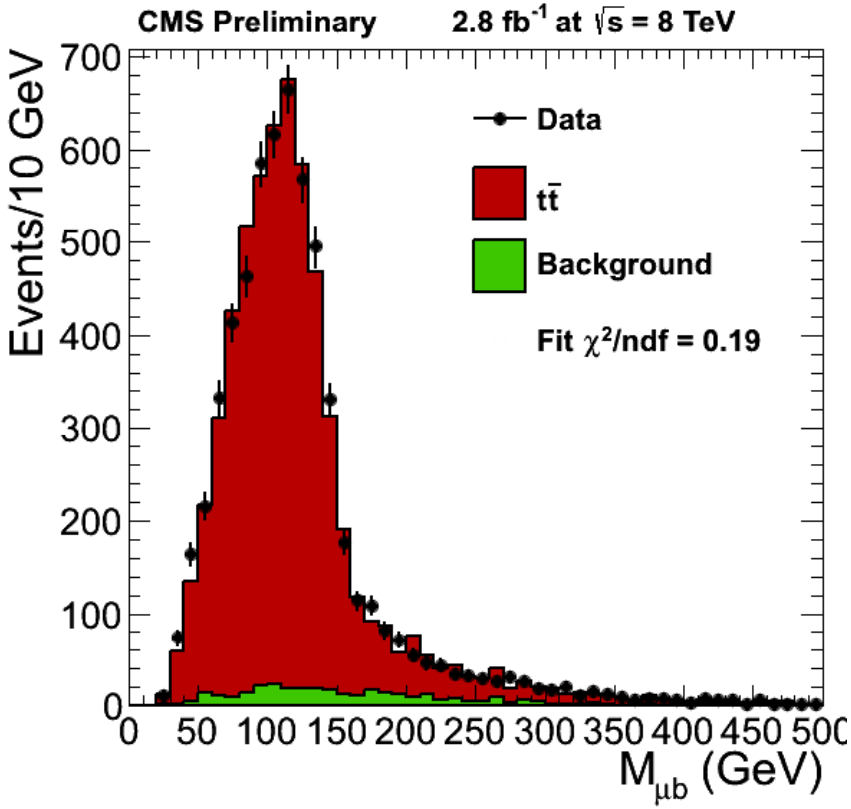
Main systematics: lepton efficiencies 3%, jet energy scale 2.4%

CMS PAS TOP-12-006 2.5-2.8 fb^{-1}

Leptons + jets at 8 TeV

- Binned likelihood fit to M_{lb} distribution
- Related to the leptonic top quark mass
- Cross-check analysis: invariant mass of three-jet combination with highest p_T
- Data driven templates for QCD background: multijet shape and normalization from data





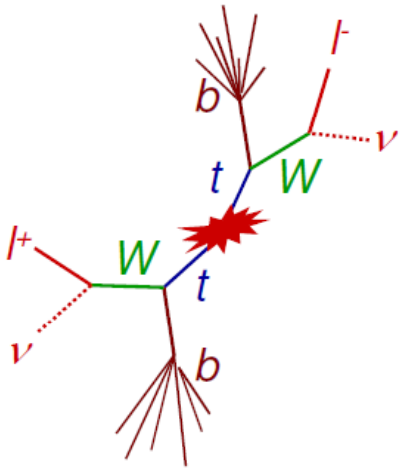
σ_{tt} = (228.4 ± 9.0(stat.) +29-26 (syst.) ± 10.0(lumi.))pb, $\Delta\sigma_{tt} / \sigma_{tt}$ = 14.0%

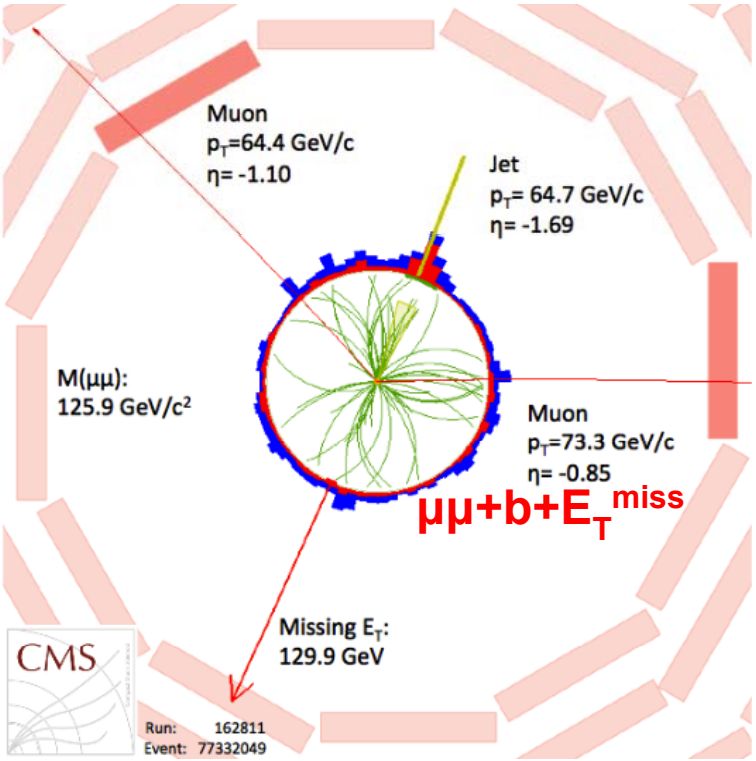
Main systematics: b-tagging efficiency 8%, jet energy scale 5%

Results with 19.6 fb^{-1} expected soon

Dileptons

$t\bar{t} \rightarrow l\nu l\nu bb$





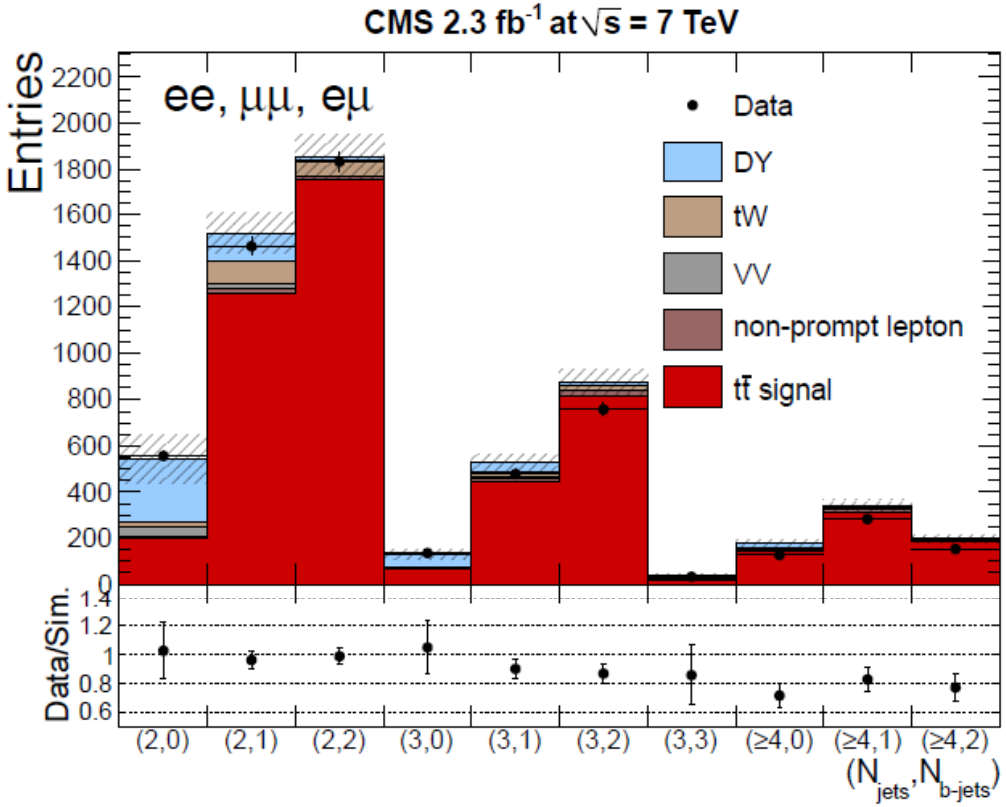
Common strategies:

- 2 OS isolated leptons
- with high pT
- veto Z mass region for ee and μμ
- at least 2 jets
- minimum E_T^{miss}

•DY and QCD lepton backgrounds estimated from data

CMS PAS TOP-11-005 2.3 fb^{-1}
JHEP 11 (2012) 067

Dileptons at 7 TeV



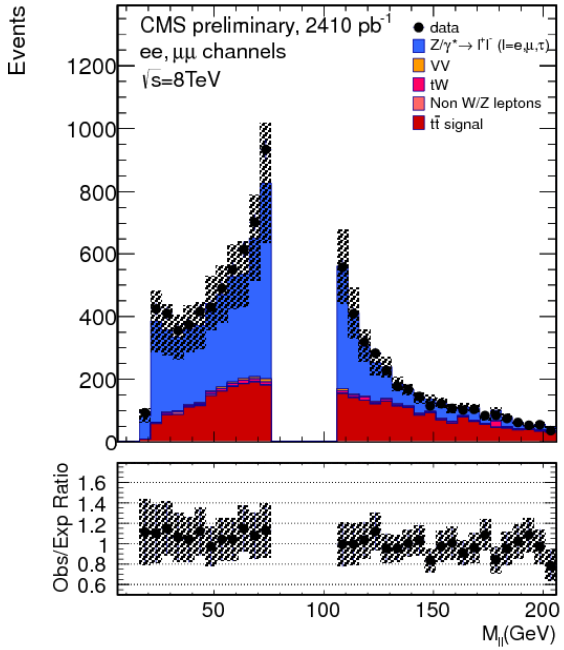
- Profile likelihood fit to jet multiplicity, b-tagged jet multiplicity
- DY events (inside the dilepton invariant mass window) estimated from sidebands
- Cross-check: cut-based analysis requiring 1 b-tagged jet

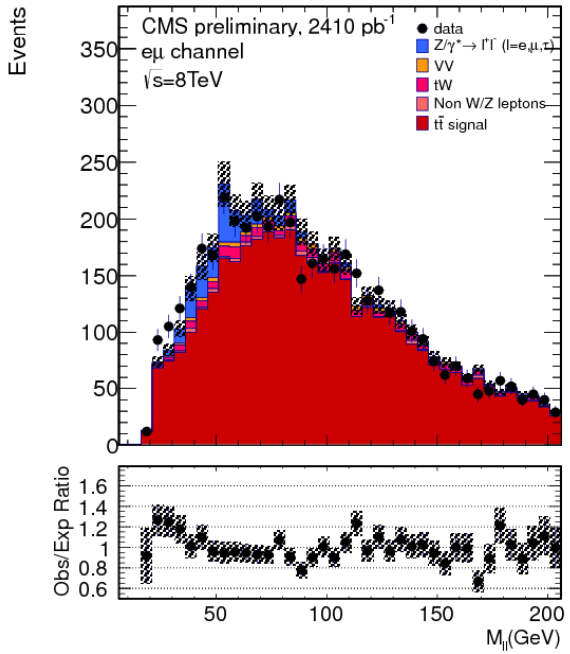
σ_{tt} = (161.9 ± 2.5 (stat.) + 5.1-5.0 (syst.) ± 3.6 (lumi.))pb, $\Delta\sigma_{tt} / \sigma_{tt}$ = 4.2%
Main systematics: lepton efficiencies 1.7%, jet energy scale 1.8%

CMS PAS TOP-12-007 2.4 fb^{-1}

Dileptons at 8 TeV

- Very low background
- Require 1 b-tagged jet
- Cut-based analysis
- DY events (inside the dilepton invariant mass window) estimated from sidebands





σ_{tt} = (226.8 3.1 (stat.) + 10.7 (syst.) 10.0 (lumi.))pb,

$\Delta\sigma_{tt} / \sigma_{tt}$ = 6.6%

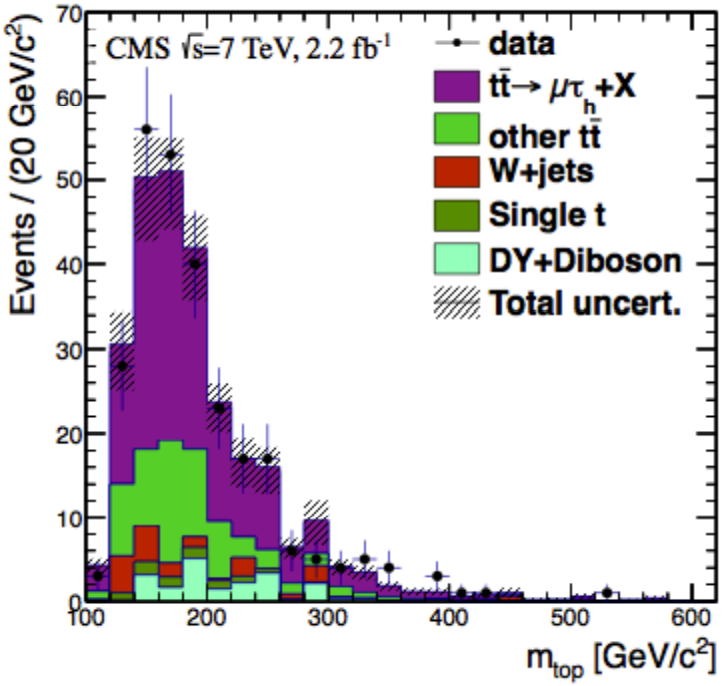
Main systematics: lepton efficiencies 2%, jet energy scale 3%

Results with 19.6 fb^{-1} expected soon

CMS PAS TOP-11-006 2.2 fb^{-1}
Phys. Rev. D85 (2012) 112007

Dileptons (τ, e/μ) at 7 TeV

$t\bar{t} \rightarrow \tau\nu l\nu bb$



- Hadronic tau decays
- Based on PF, uses tracker and ECAL info to reconstruct and identify 1- and 3-prong decays plus photons from π^0 decays

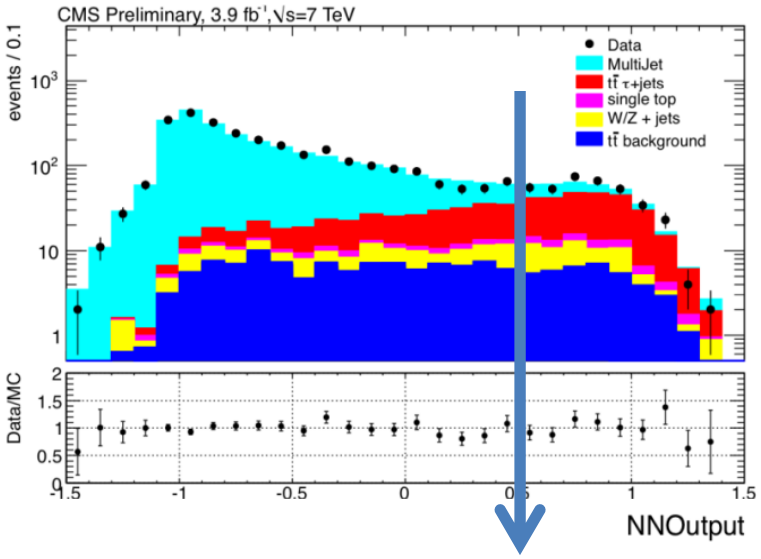
- Profile likelihood fit to jet multiplicity, b-tagged jet multiplicity
- Cross-check: cut-based analysis requiring 1 b-tagged jet

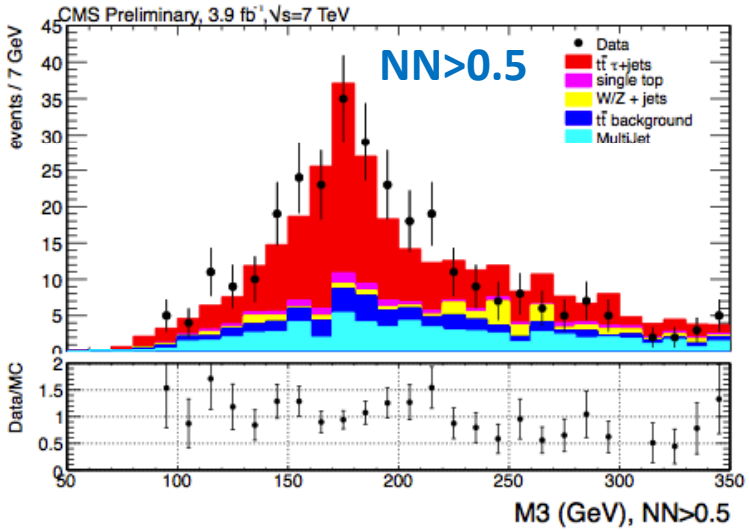
σ_{tt} = (143 ± 14 (stat.) ± 22 (syst.) ± 3 lumi.))pb, $\Delta\sigma_{tt} / \sigma_{tt}$ = 18%
Main systematics: τ identification 6%, jet energy scale 6%

CMS PAS TOP-11-004 3.9 fb^{-1}
Eur.Phys. J C73 (2013) 2382

τ + jets at 7 TeV

tt → τνqqbb





- At least 4 jets
- ≥ one b-tagged jet
- ≥ hadronically decaying τ
- Minimum E_T^{miss}

- Hadronic tau decays

- QCD background extracted from data

- Profile likelihood fit to NN output
- Cross-check: cut-based analysis requiring 1 b-tagged jet

σ_{tt} = (152 ± 12 (stat.) ± 32 (syst.) ± 3 (lumi.))pb, $\Delta\sigma_{tt} / \sigma_{tt}$ = 23%

Main systematics: τ identification 9%, τ energy scale 7%, τ trigger eff. 7%, jet energy scale 11%

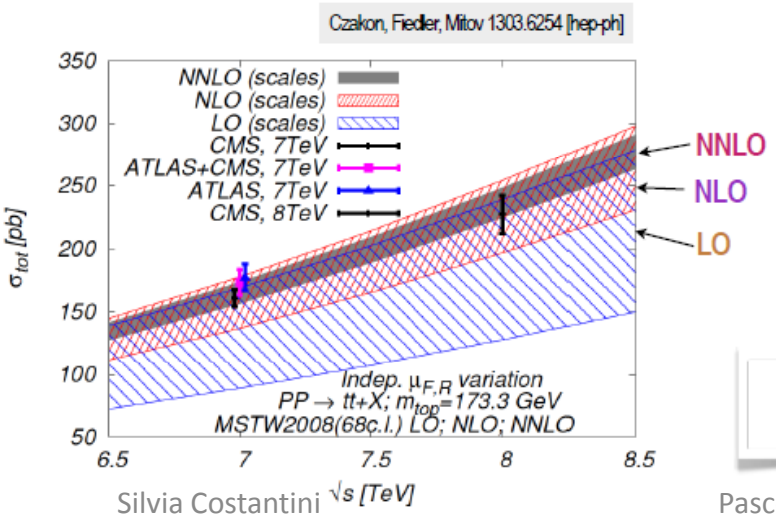
Comparison with theory

- Full NLO matrix element and approximate NNLO calculations for σ_{tot} by several groups

- **Exact NNLO calculations recently available**
- scale uncertainty: ~ 3%

Approx. NNLO calculations, LHC @ 8 TeV

Authors	(σ (tt) ± scale ± PDF) pb
HATHOR, Moch et al. arXiv 1203.6282	202.1 +11.3-14.5 ± 8.5 (ABM11 PDFs)
HATHOR, Moch et al. arXiv 1203.6282	249.9 +14.0-18.2 +6.2-6.3 (MSTW PDFs)
Cacciari et al. ,arXiv 1111.5869	228.6 +18.2-19.8 +5.6-5.9
Kidonakis, arXiv 1205.3453	234 +10-7 ± 12
Ahrens et al., 1105.5824	224.7 +11.8-12.2 +10.8 -11.6
Czakon, Mitov, , 1303.6254	**245.8 +6.2-8.4 ± 6.2**



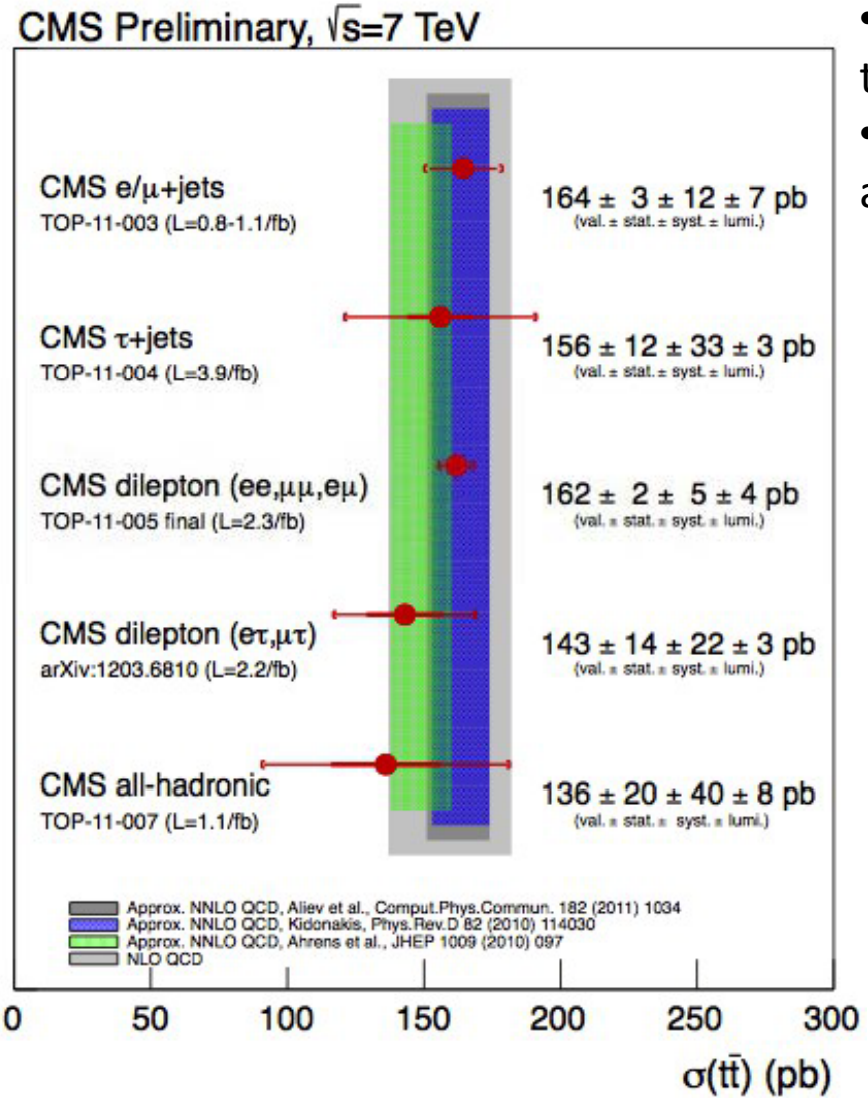
CMS at 8 TeV, $\Delta\sigma_{tt} / \sigma_{tt} = 6.6\%$:

$$\sigma_{t\bar{t}} = 227 \pm 3\ (\text{stat.}) \pm 11\ (\text{syst.}) \pm 10\ (\text{lumi})\ \text{pb}$$

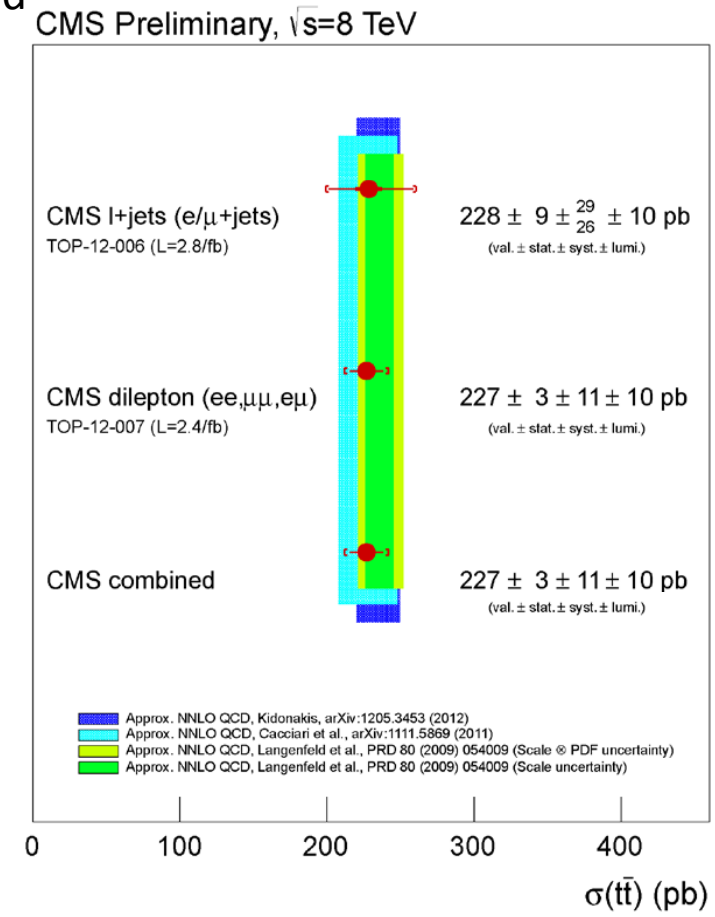
Challenging theory predictions

CMS PAS TOP-11-024
CMS PAS TOP-12-007

Results at 7 and 8 TeV



- Combination with a BLUE method
- Lepton ID, b-tagging, background normalization treated as uncorrelated syst. uncertainties
- PU, BR, JES, JER, theory and luminosity treated as correlated



Differential cross sections

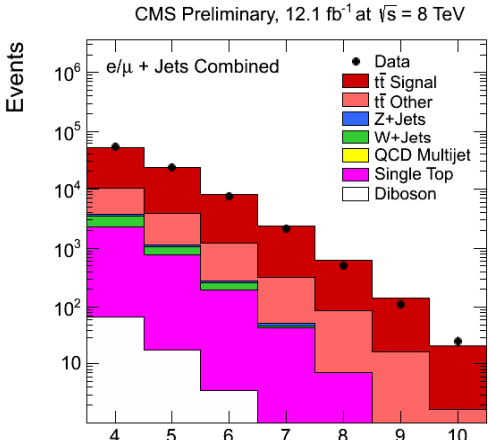
Key measurements to experimental and theoretical precision
Access to higher orders

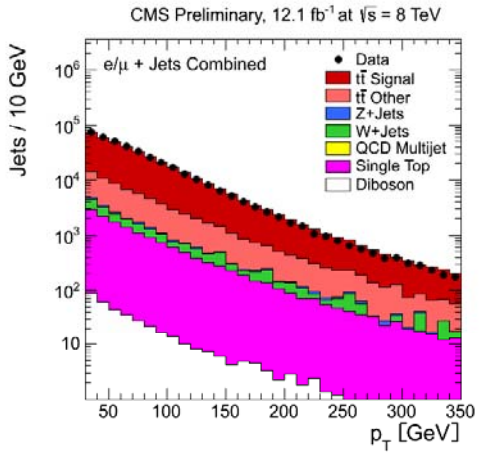
- Differential distributions as a function of various variables: top quark p_T, jet p_T, pseudo(rapidity), M_{lb}, …

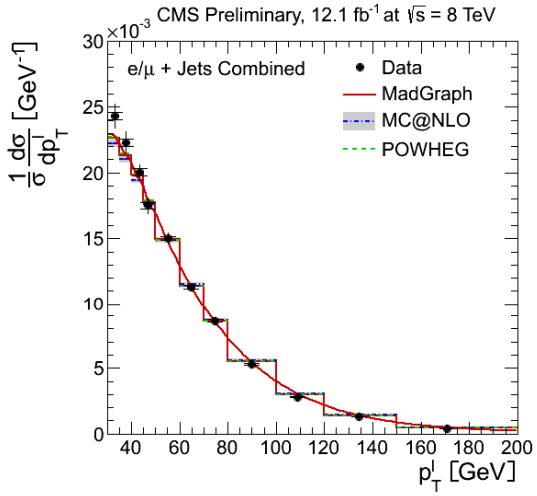
Differential cross sections

l+jets: CMS PAS TOP-12-027 12.1 fb^{-1}

- e/μ + jets
- At least 4 jets with p_T > 30 GeV, 1 lepton with p_T > 30 GeV
- 2 b-tagged jets

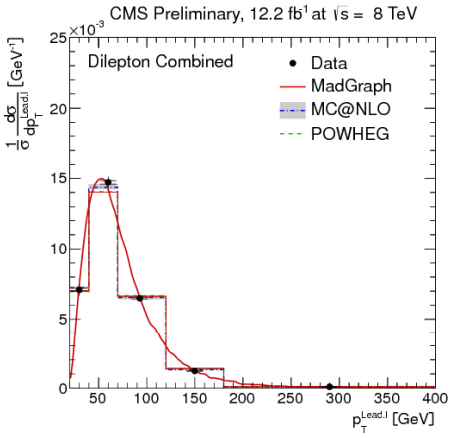






Dileptons: CMS PAS TOP-12-028 12.1 fb^{-1}

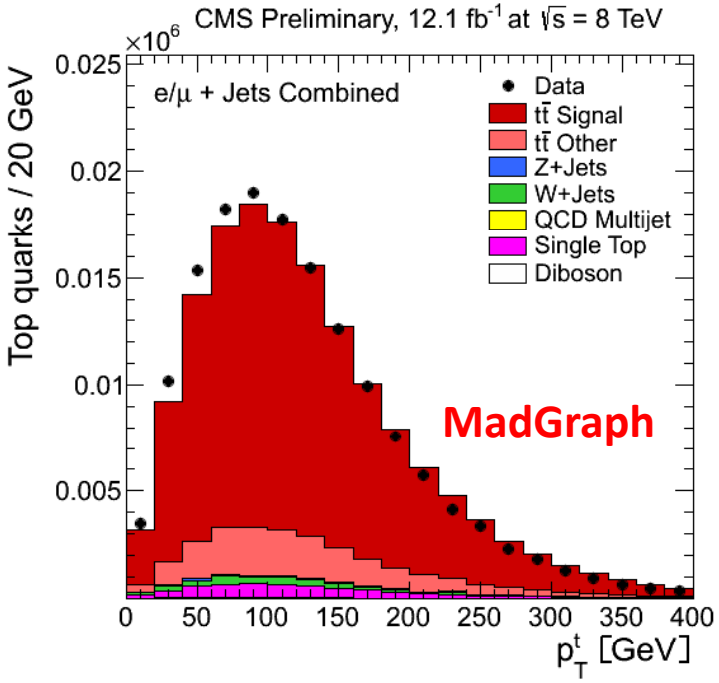
- ee, μμ, eμ
- Two opposite charge, isolated leptons with p_T > 20 GeV
- ee, μμ outide Z mass window (91 ±15) GeV

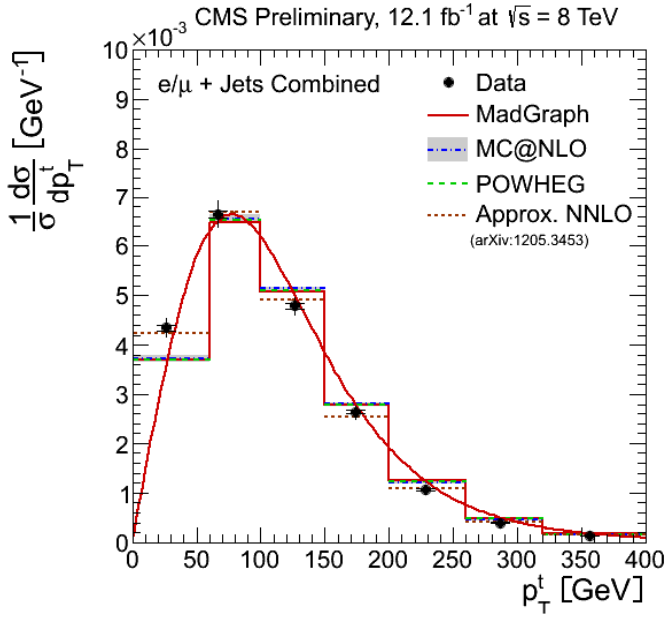


- Good agreement with SM predictions
- More distributions available

Differential cross sections

- Top quark p_T : discrepancies observed between NLO+PS generators and data, as well as between NLO+PS and approx. NNLO predictions.





Shape differences taken into account as systematic uncertainties in recent measurements

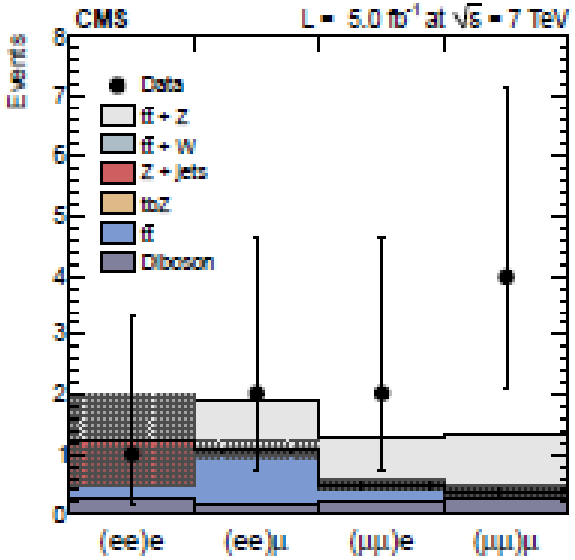
Associated production

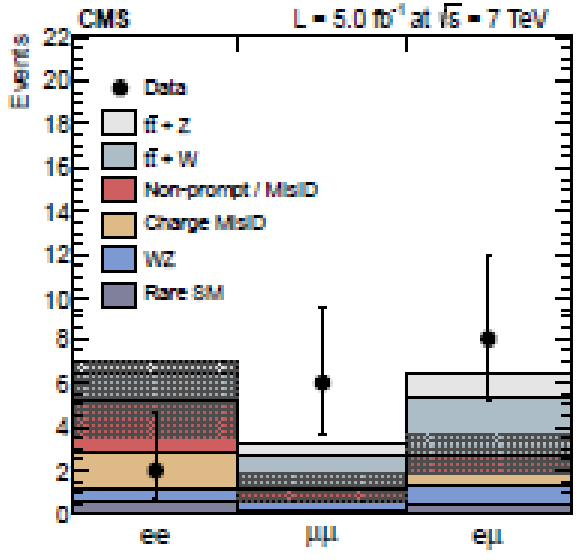
- tt + W/Z
- tt + jets
- tt+bb

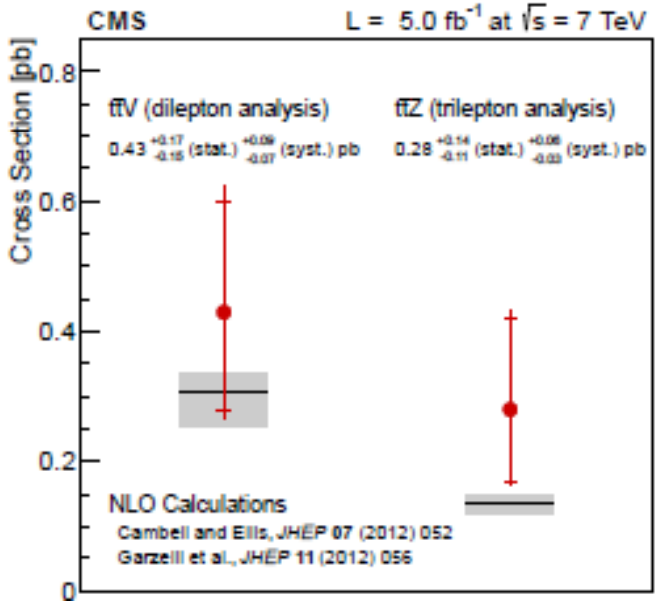
CMS PAS TOP-12-014 5 fb^{-1}
Phys. Rev. Lett. 110 (2013) 172002

tt + W/Z

Associated production of Vector Bosons with top-antitop pairs at 7 TeV
Measurement performed in two independent channels







Trilepton channel,
p_T > 20, 20, 10 GeV
HT > 120 GeV
Exclusive search for ttZ
Only events with 70 < m_{ll} < 110 GeV

Dilepton channel (SS), pT > 55, 30 GeV
HT > 100 GeV
Inclusive search for ttZ, ttW

Compatible with NLO calculations

Combining all 7 channels: ttV signal significance of 4.67 σ

σ_{ttV} = 0.43 +0.17-0.15 (stat.) + 0.09-0.07 (syst.) pb
σ_{ttZ} = 0.28 +0.14-0.11 (stat.) + 0.06-0.03 (syst.) pb

CMS PAS TOP-12-041
19.6 fb^{-1}

tt + jets

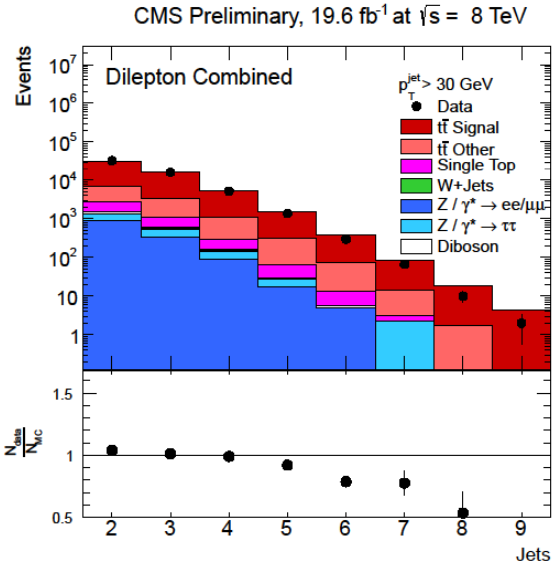
7 TeV results:
CMS PAS TOP-12-023
5 fb^{-1}

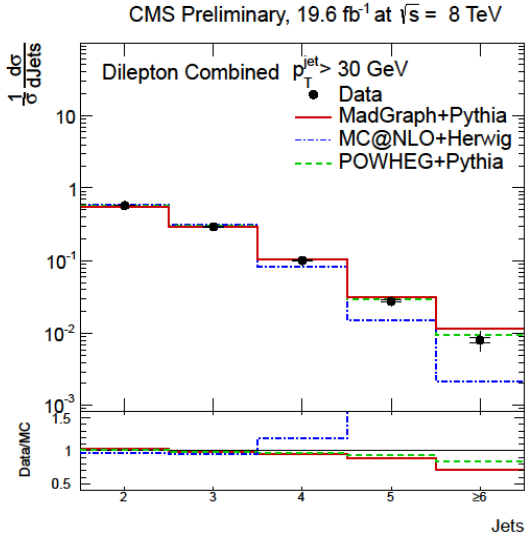
- Differential cross section measured as a function of the jet multiplicity for different jet p_T
- Measurement performed in the ee, eμ, μμ decay channels
- Require at least 2 isolated leptons, $p_T > 20$ GeV, with invariant mass outside Z window

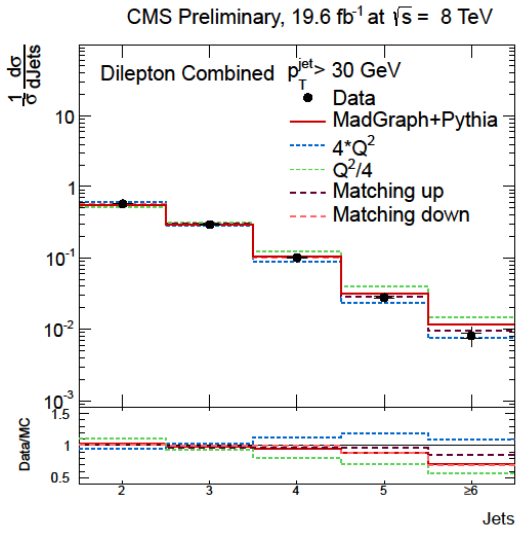
At least 2 jets with $p_T > 30$ GeV

At least 1 b-tagged jet

Reasonable description of the data by NLO generators





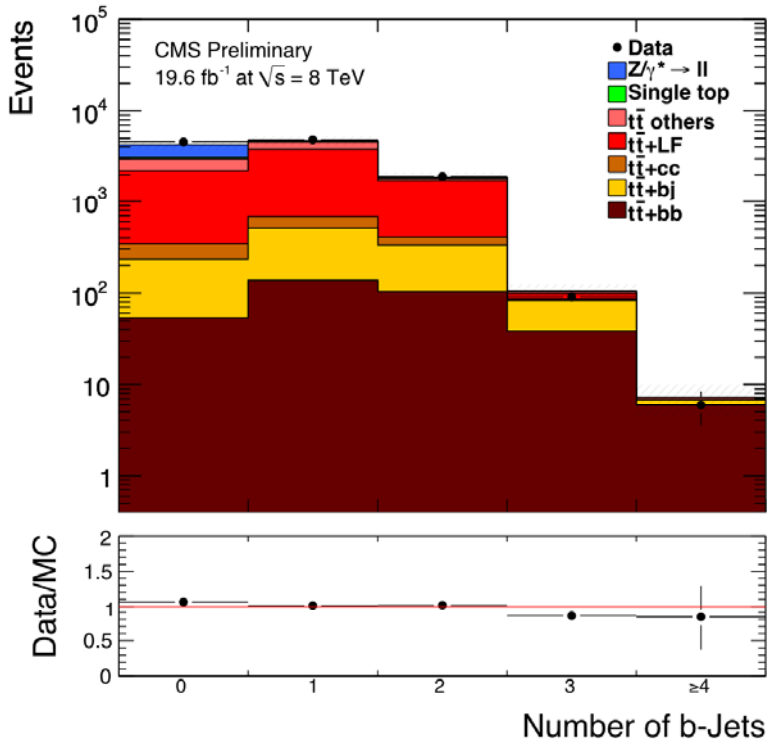


- Slightly higher jet multiplicity predicted by simulation
- Lower multiplicity by MC@NLO +Herwig
- Slightly worse description by MadGraph with $Q^2/4$

CMS PAS TOP-13-010
19.6 fb^{-1}

tt + bb

7 TeV results:
CMS PAS TOP-12-024
5 fb^{-1}



- Study of heavy flavour content in tt events
- Comparison with NLO QCD calculations
- Searches for ttH

- Dilepton events
- ≥ 4 jets with p_T > 20 (40) GeV
- ≥ 2 b-tagged jets

- Measurement performed in the visible phase space

Experimental uncertainties cancel out in the cross section ratio

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = \begin{array}{l} 0.023 \pm 0.003\ (\text{stat.}) \pm 0.005\ (\text{syst.})\ \text{at Jet}\ p_{\text{T}} > 20\ \text{GeV} \\ 0.022 \pm 0.004\ (\text{stat.}) \pm 0.005\ (\text{syst.})\ \text{at Jet}\ p_{\text{T}} > 40\ \text{GeV} \end{array}$$

Summary

- Measurements of with (almost) all experimental signatures at 7 TeV and 8 TeV

- Experimental uncertainties on σ_{tt}: ~4%-7%
- Challenging theory predictions

- New measurements at 8 TeV to appear soon at:

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

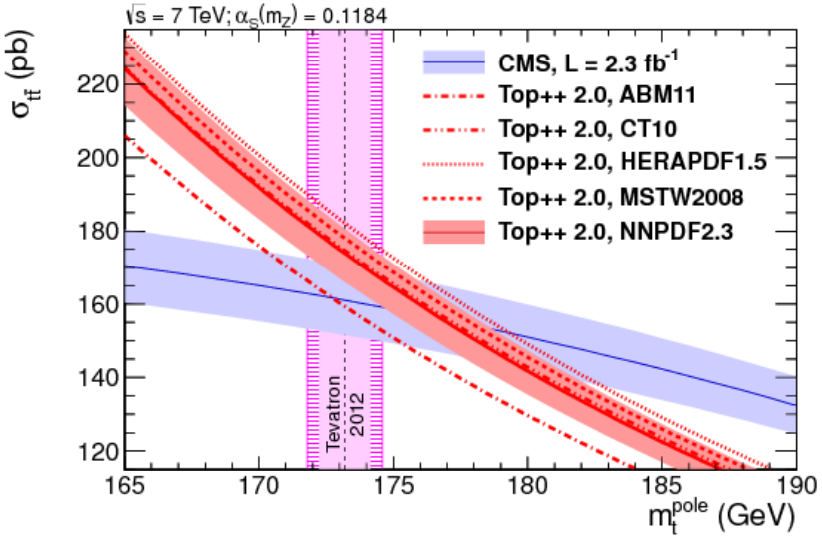
Additional slides

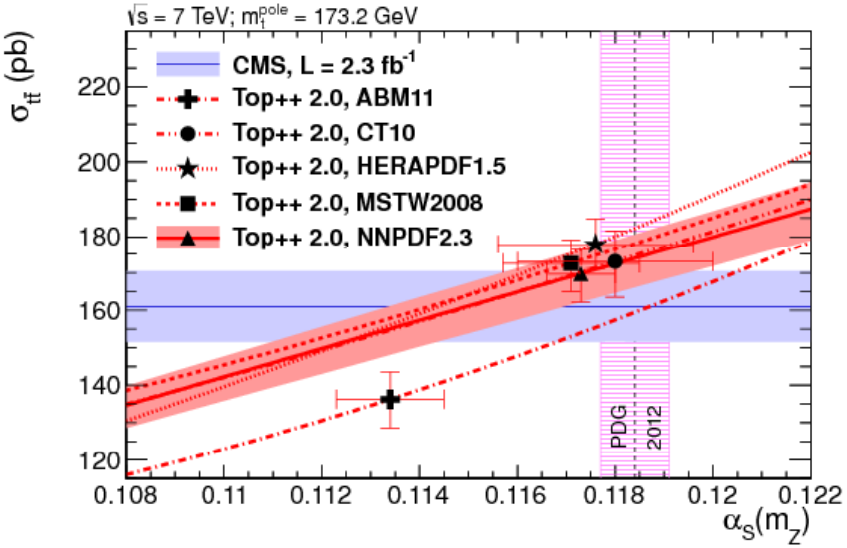
First α_S determination from tt cross section

CMS PAS TOP-11-005 5 fb^{-1}
CMS PAS TOP-12-022
Subm. to Phys. Lett. B

- Approx. NNLO QCD + different PDFs used to extract α_S from the ttbar cross section at 7 TeV. First determination of α_S from t quark production
- With PDF set NNPDF2.3, a pole mass m_t = (176.7 +3.8 −3.4) GeV is obtained when constraining α_S at the m_Z scale
- Alternatively, by constraining m_t to the latest average from direct mass measurements, a value of $\alpha_S(m_Z)$ = 0.1151 +0.0033 −0.0032 is extracted.

Most precise determination at hadron colliders

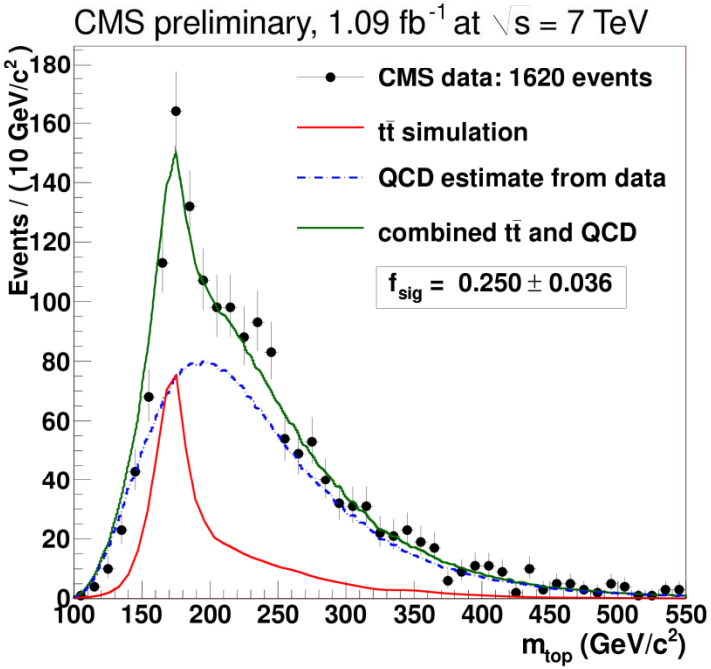




CMS PAS TOP-11-007 3.5 fb^{-1}
JHEP 1305 (2013) 065

Fully hadronic at 7 TeV

$t\bar{t} \rightarrow qqqqbb$



- Very high multijet background
- At least 6 jets
- With different high pt thresholds
- Require 2 b-tagged jet (essential against QCD)
- QCD estimate from data, reweighted from 0 b-tag control region

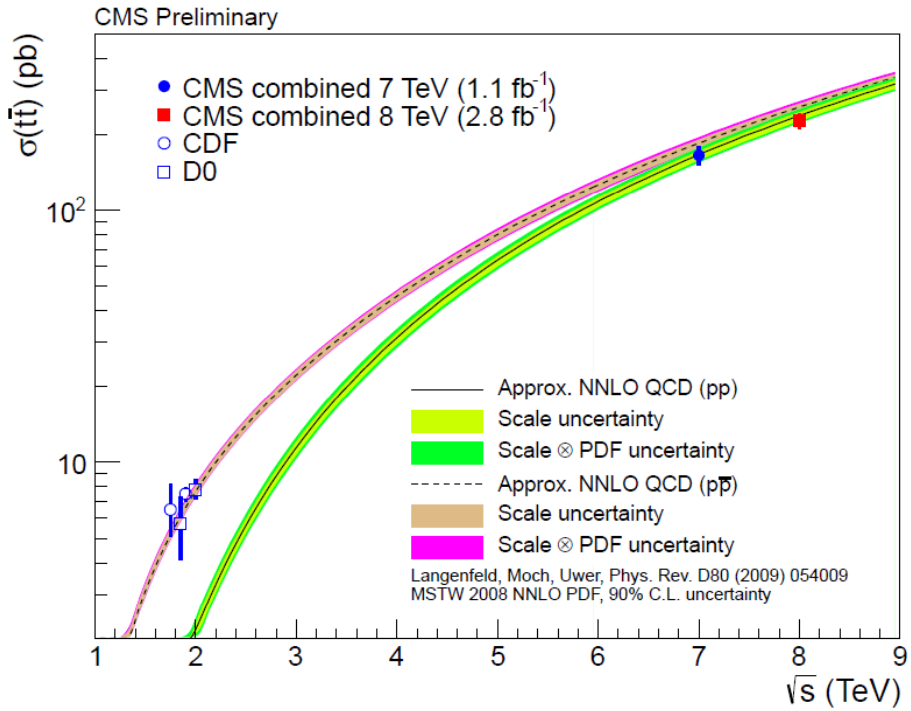
- Unbinned likelihood fit to reconstructed top mass

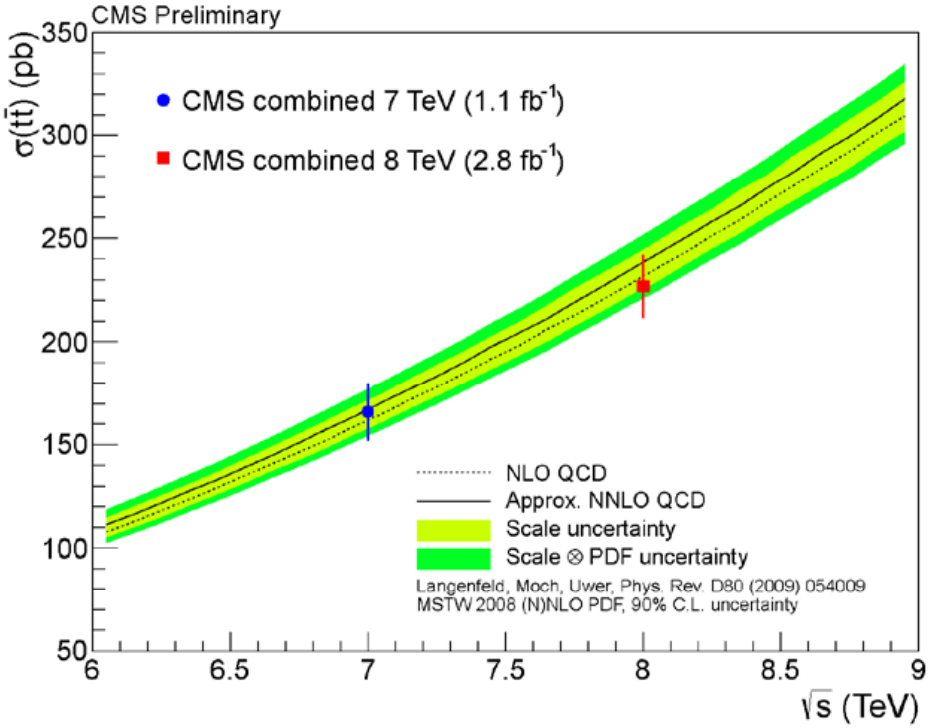
$\sigma_{t\bar{t}}$ = (139 ± 10 (stat.) + 26 (syst.) ± 3 (lumi.))pb,

$\Delta\sigma_{t\bar{t}} / \sigma_{t\bar{t}}$ = 20%

Main systematics: b-tagging efficiency 6%, background contribution, jet energy scale 10%

Results at 7 and 8 TeV (2)
Ratio 8/7 TeV





Ratio $R_{8/7} = (1.41 \pm 0.10)$ in the dilepton channel

Assuming fully correlated theoretical systematic uncertainties
Assuming uncorrelated experimental uncertainties

The systematic uncertainty due to the BR cancels out in the ratio