Top quark production at CMS

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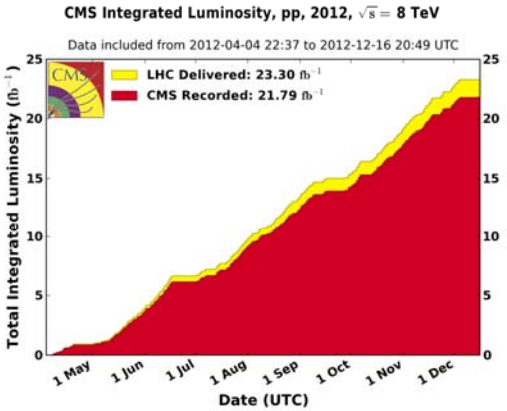
On behalf of the CMS Collaboration

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

Outline

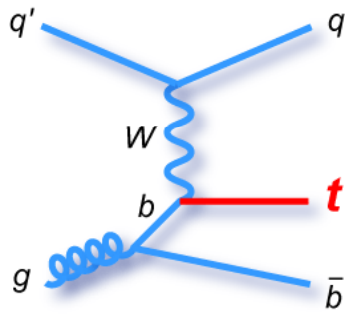
- **Single top production**
  - t-channel
  - tW-channel
  - |Vtb| extraction
  - s-channel
- **Top quark pair production**
  - Lepton + jets channel
  - Dilepton channel
  - Channels with taus
- **Differential cross sections**
- **Associated production**
  - tt + W/Z
  - tt + jets
  - tt + bb
- **First α_S determination from tt cross section**



- Showing mainly 8TeV results
- Several 7TeV results in the appendix

Single top production and decay

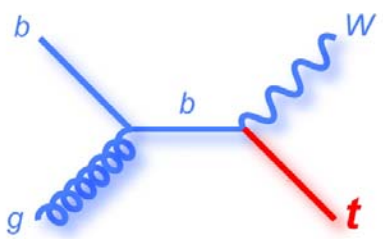
- EW single top quark production via charged current processes
- In each channel: cross section σ proportional to $|V_{tb}|^2$

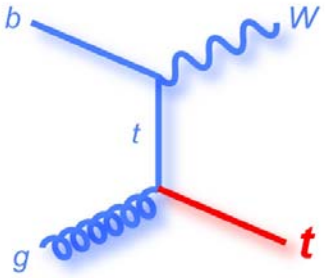


t-channel

Largest σ

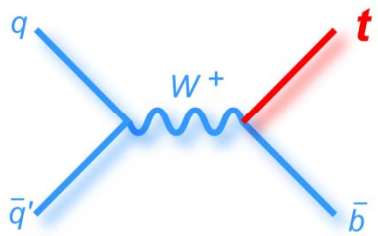
Precision measurements





tW-channel

Observed



s-channel

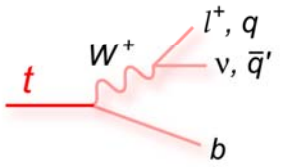
Searches

Limits set

Approx. NNLO
N. Kidonakis
arXiv:1205.3453

	t-channel	tW-channel	s-channel
σ (pb) at 7 TeV	64.6 ± 2.1	15.6 ± 1.2	4.59 ± 0.19
σ (pb) at 8 TeV	87.1 ± 2.8	22.2 ± 1.5	5.55 ± 0.22

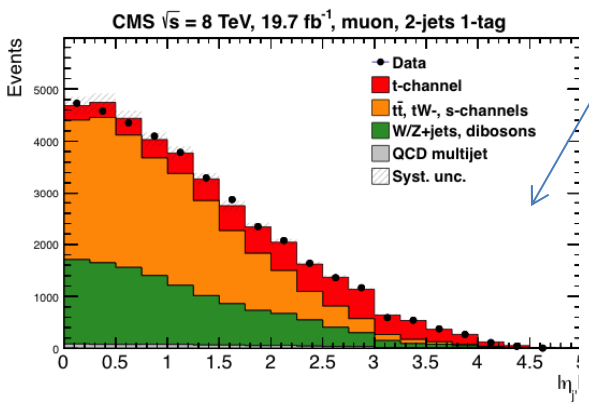
Top quark decays almost exclusively to Wb:

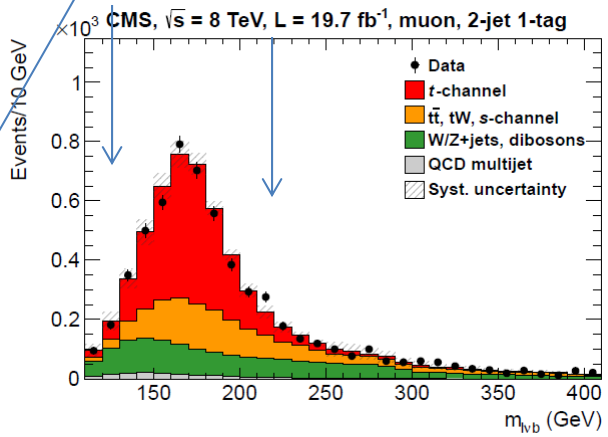


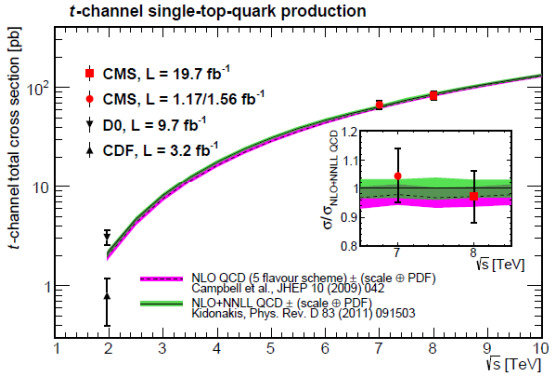
t-channel cross section at 8 TeV

CMS PAS TOP-12-038 19.7 fb^{-1}
JHEP 06 (2014) 090

- Lepton + jets final state from leptonic top decay: t → Wb → lνb
- require 1e or 1μ, 2jets-1tag, in top mass window (130 < $m_{l\nu b}$ < 220 GeV)
- Cross section extracted from fit to the pseudorapidity η of the light jet
- Background shapes for W+jets and tt estimated from control regions in data (side band in $m_{l\nu b}$ and 3jets-2tag)







- **$\sigma_{t\text{-channel}}$ = 83.6 ± 2.3 (stat.) ± 7.4 (syst.) pb (incl.)**
- **$R_{8/7}$ = 1.24 ± 0.08 (stat.) ± 0.12 (syst.)**

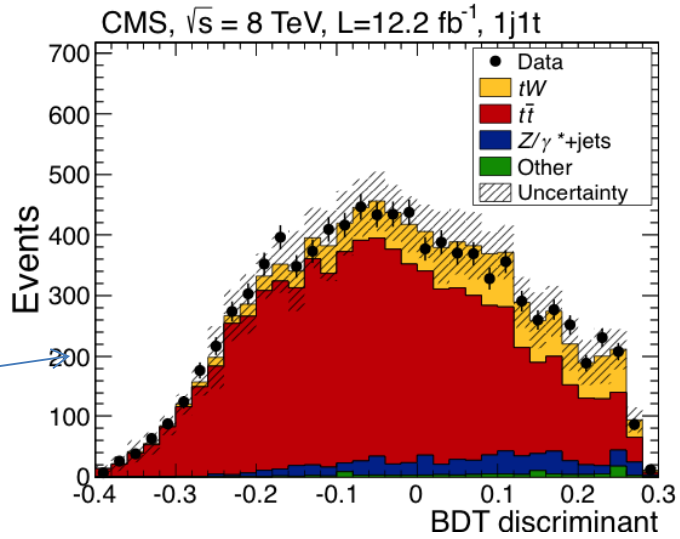
$$\sigma_{t\text{-ch.}}(t) = 53.8 \pm 1.5\,(\text{stat}) \pm 4.4\,(\text{syst})\,\text{pb},$$
$$\sigma_{t\text{-ch.}}(\bar{t}) = 27.6 \pm 1.3\,(\text{stat}) \pm 3.7\,(\text{syst})\,\text{pb}.$$

Total syst: 8.9%. Main systematics: Signal modeling (5.7%) JES,JER,MET (4.3% in total)

tW-channel at 8 TeV

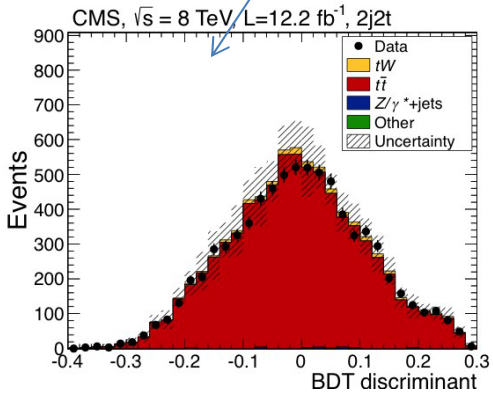
CMS PAS TOP-12-040 12.2 fb^{-1}
PRL 112 (2014) 231802

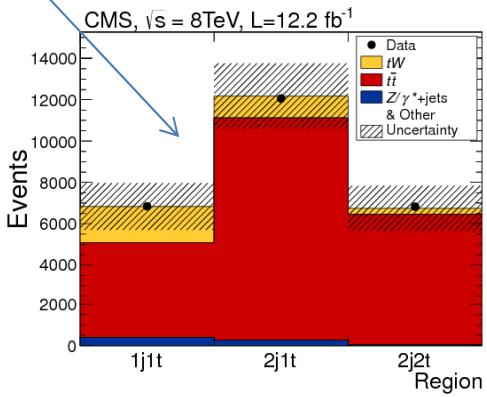
- tW associated production observed for the first time at CMS
- Evidence reported at 7 TeV by ATLAS and CMS
- Cleanest signature when both t and W decay leptonically:
- 2 opposite sign isolated leptons in the final state
- Main background processes: tt, and also Z -> ll
- Multivariate discriminant to distinguish signal from tt
- Jet counting to define signal enriched region (2leptons, 1jet-1tag) and two control regions (2jets, 1 or 2 tags)
- Two cross-checks analyses: consistent results



Signal significance: **6.1σ**
(5.4±1.4σ expected)

σ_{tW} = 23.4±5.4 pb



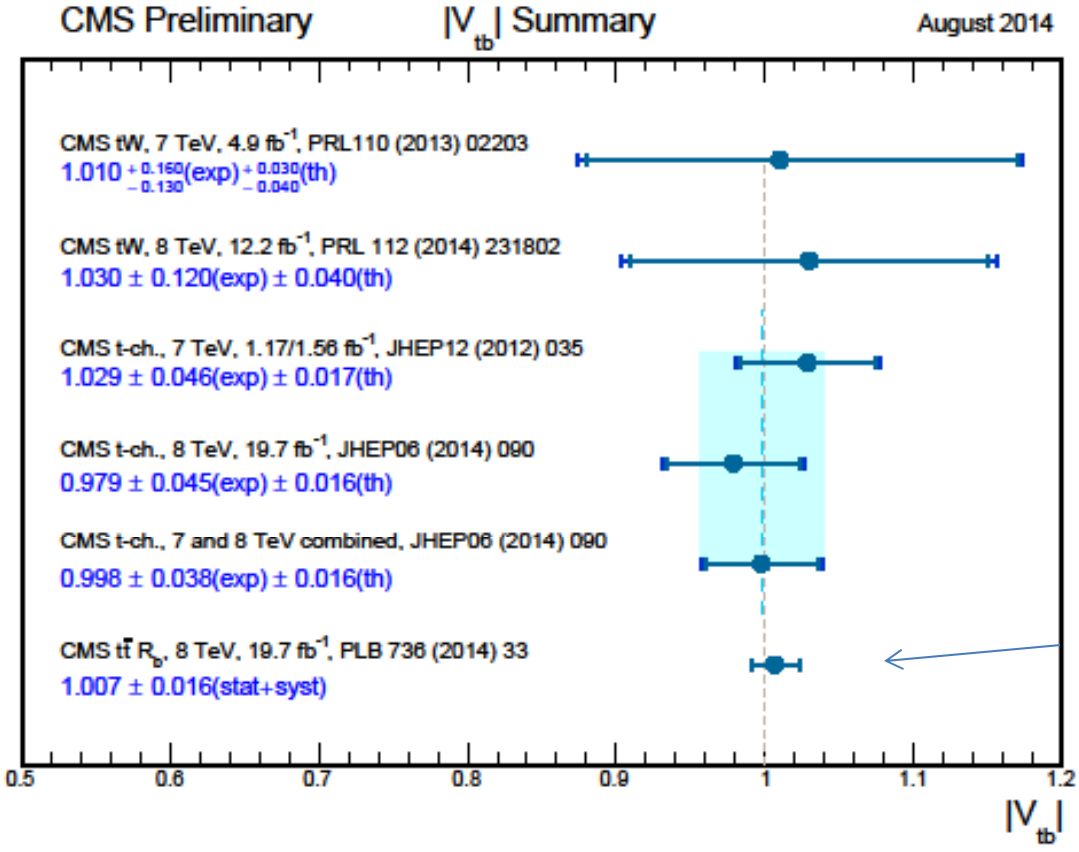


$|V_{tb}|$ extraction

JHEP 12 (2012) 035
JHEP 06 (2014) 090

- Single top events provide the possibility to directly probe the Wtb vertex and measure |Vtb|
- Measurements both in the t-channel and in the tW-channel
- Method: assuming |Vtd| and |Vts| << |Vtb| → $|V_{tb}| = \sqrt{(\sigma / \sigma_{th})}$

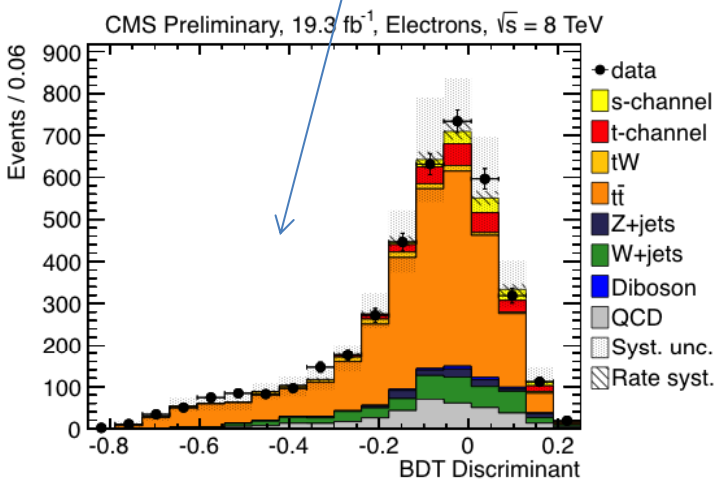
  σ_{th} : SM prediction calculated assuming |Vtb| = 1

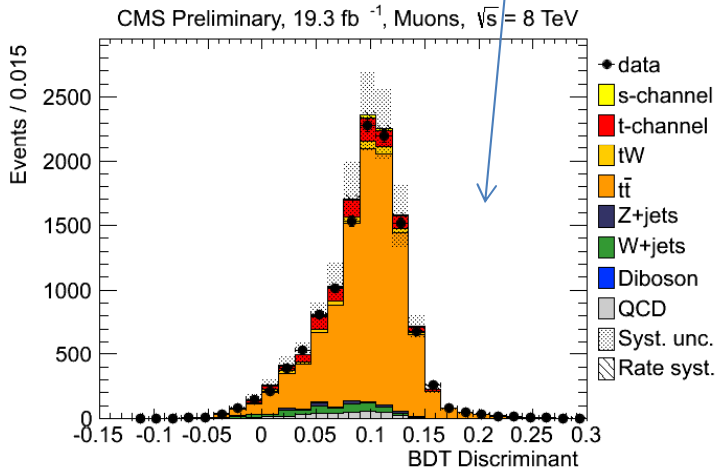


From R = B(t->Wb)/B (t->Wq)
In dilepton channel

s-channel search at 8 TeV

- The smallest cross section among 3 processes
- **1 top and 1 b-jet** in the final state: selection based on **leptonic t decay**
- **Lepton +jets** signature:
  - signal region: with 1 e or 1 mu, MET, 2-btag jets (2jets-2tags)
  - Control region to separate tt: require 1 additional jet (3jets-2tags)
- **Overwhelming background** from tt, multijets, W+jets and t-channel





$\sigma_{s\text{-ch}}$. = 6.2±5.4(exp.)±5.9(th.) pb combined

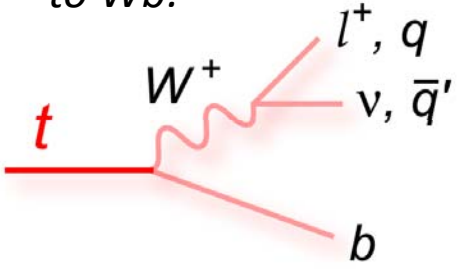
68% CL intervals (Feldman-Cousins): $\sigma_{s\text{-ch.}} = 6.2^{+8.0}_{-5.1}$ pb

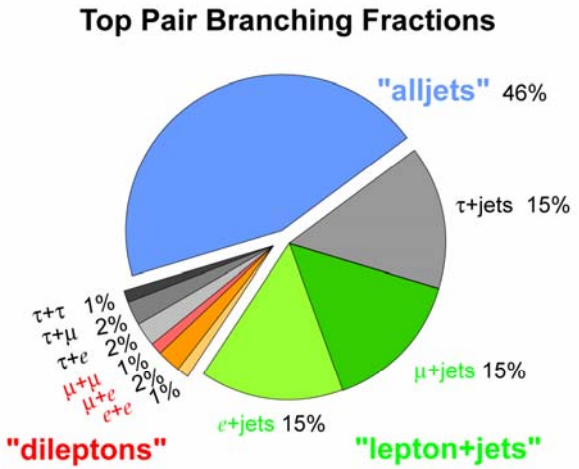
Top quark pair production and decay channels

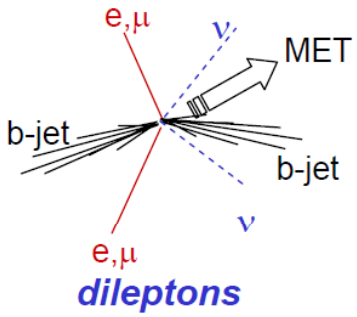
- Top quark pair production: predominately in top-antitop pairs (tt) via strong interactions

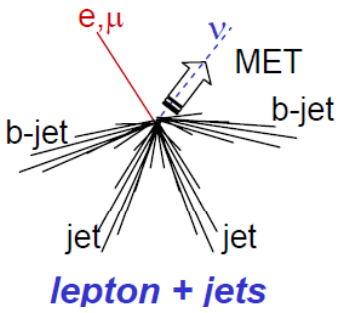
NNLO σ_{tt} for m_{top} = 173.3 GeV
(LHC@7TeV) = 172 pb,
(LHC@8TeV) = 245 pb

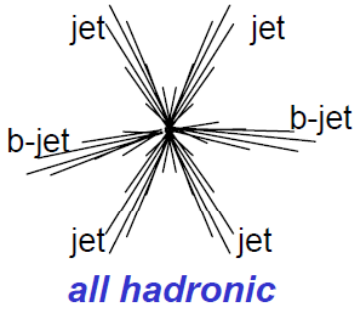
Top quark decays almost exclusively to Wb:







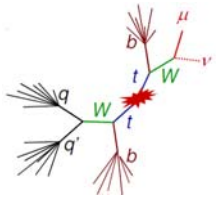




	dileptons	lepton + jets	all hadronic
BR:	~ 5%	~30% (e, μ)	~46%
Bkg:	small	medium	huge
Mainly:	Z+jets dibosons	W+jets	QCD multijets

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

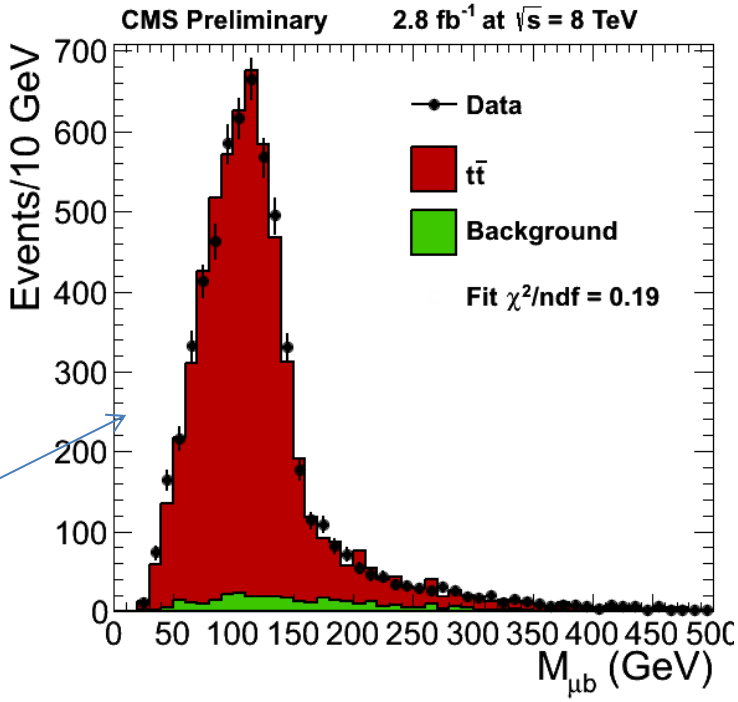
Leptons + jets at 8 TeV



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

Common strategies:

- Trigger: isolated lepton
- Require 1 isolated lepton (e, μ)
- high p_T (~25-30 GeV)
- **veto** on additional leptons
- at least 4 jets
- at least 1 b-tagged jet



- 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%

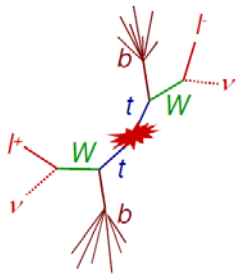
Main systematics: b-tagging efficiency 8%, jet energy scale 5%

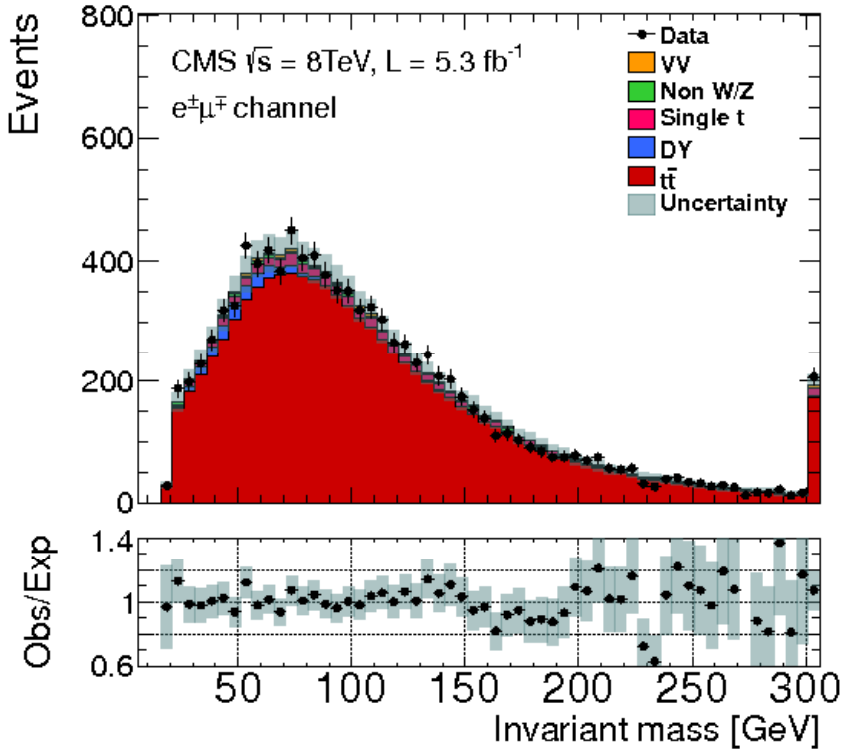
Results with 19.6 fb^{-1} expected soon

CMS PAS TOP-12-007 5.3 fb^{-1}
JHEP 02 (2014) 024

Dileptons at 8 TeV

$tt \rightarrow lvlvbb$





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}

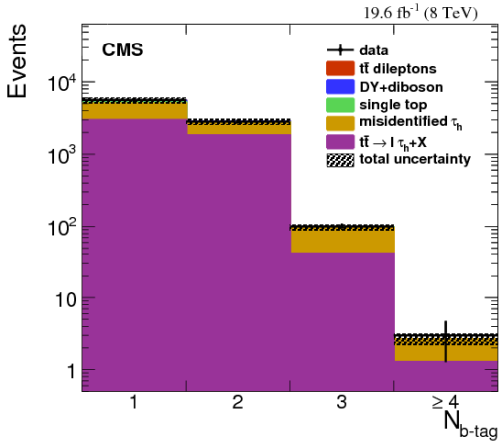
- Very low background
- Require 1 b-tagged jet
- Cut-based analysis
- DY events (inside the dilepton invariant mass window) estimated from sidebands

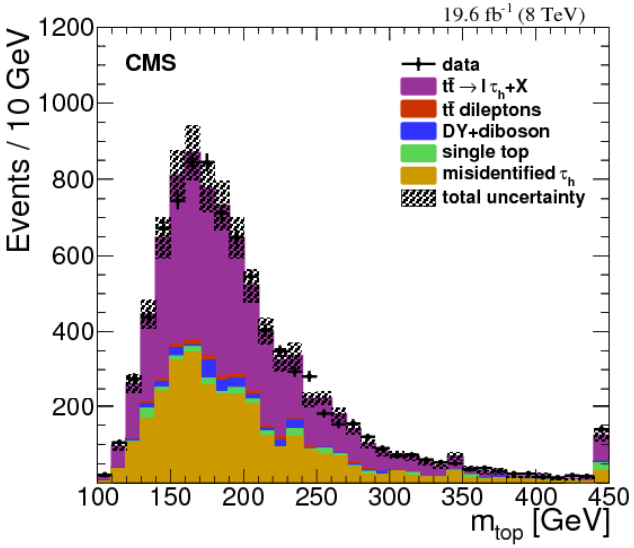
σ_{tt} = (239 2 (stat.) + 11 (syst.) 6 (lumi.))pb,
$\Delta\sigma_{tt} / \sigma_{tt}$ = 5.3%
Main systematics: lepton efficiencies 2%, jet energy scale 3%

Results with 19.6 fb^{-1} expected soon

CMS PAS TOP-12-026 19.6 fb^{-1}
PLB 739 (2014) 23

Dileptons (τ, e/μ) at 8 TeV





tt → τνlνbb

- 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

- Require 1 isolated electron or muon, at least 2 jets, at least one of which is b-tagged
- Largest background contribution estimated from data: tt with W -> jets, with one jet misidentified as τ

σ_{tt} = (257 ± 3 (stat.) ± 24 (syst.) ± 7 lumi.)) pb, $\Delta\sigma_{tt} / \sigma_{tt}$ = 9.8%
Main systematics: τ identification 6%, τ energy scale 2.5%

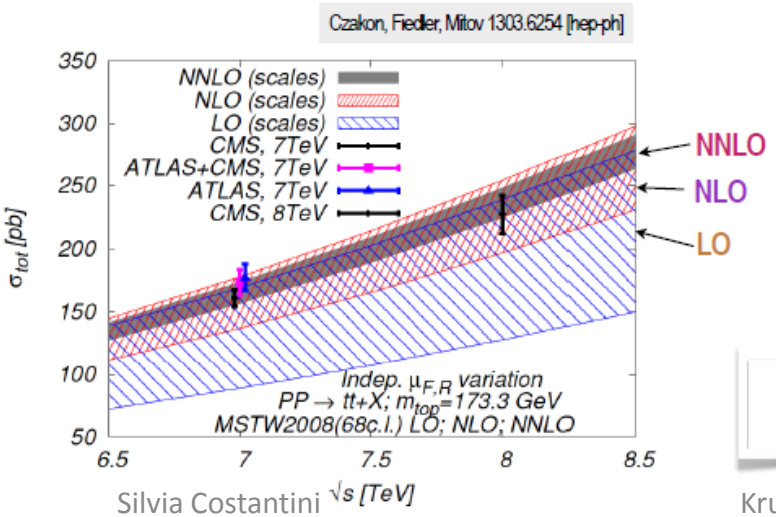
Comparison with theory

- Full NLO matrix element and approximate NNLO calculations for σ_{tot} by several groups
- **Exact NNLO calculations now 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 et al., 1303.6254	**245.8 +6.2-8.4 ± 6.2**

For m_t = 173.3 GeV



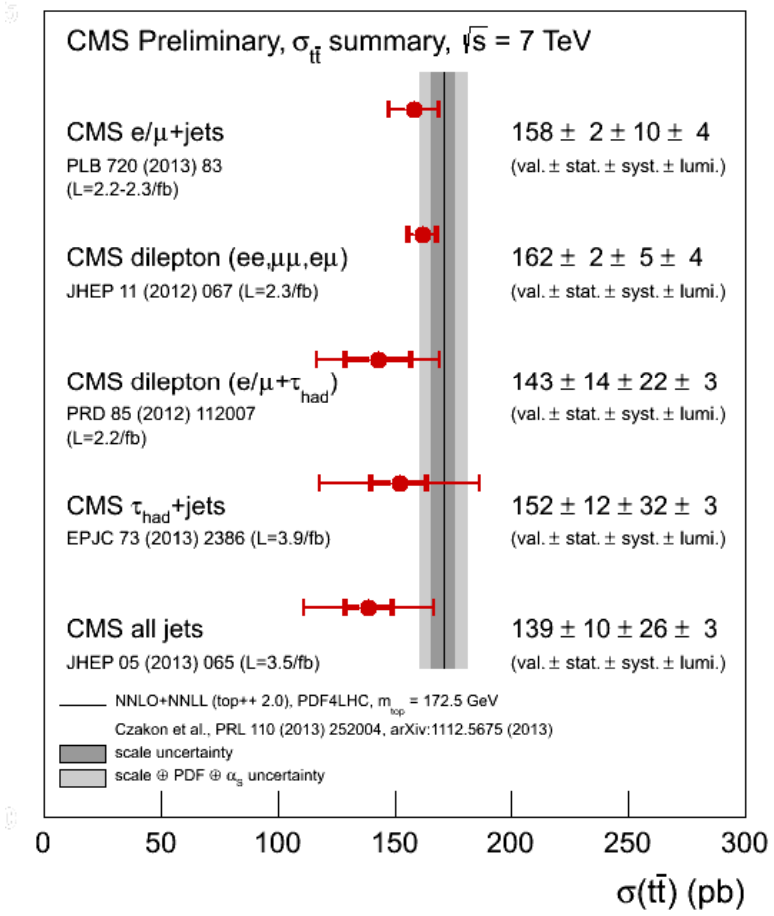
CMS at 8 TeV, $\Delta\sigma_{tt} / \sigma_{tt}$ = 6.6% :

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

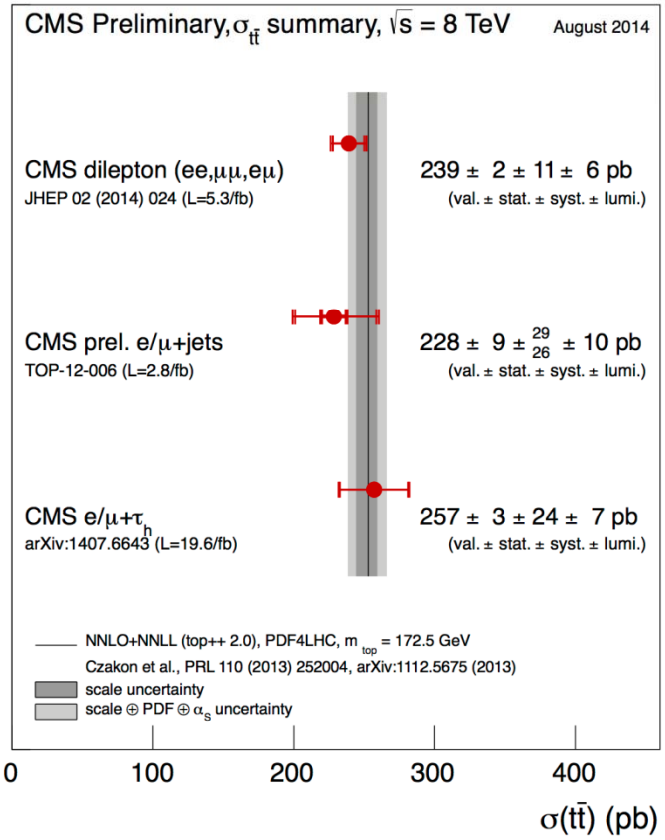
Challenging theory predictions

Results at 7 and 8 TeV

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



- 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

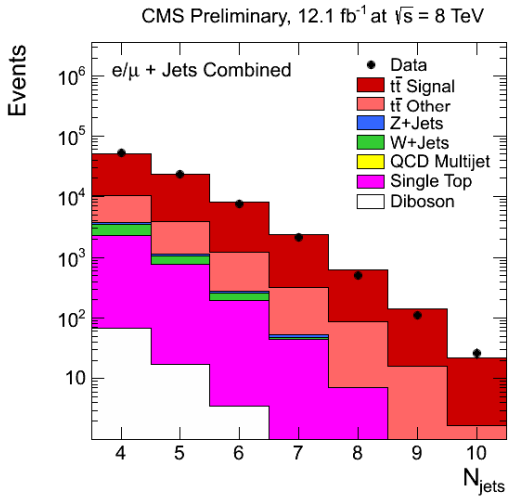
Key measurements to experimental and theoretical precision
Access to higher orders

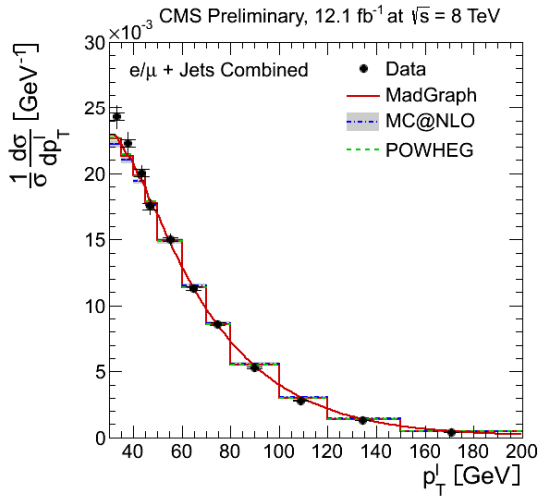
l+jets: CMS PAS TOP-12-027 12.1 fb^{-1}

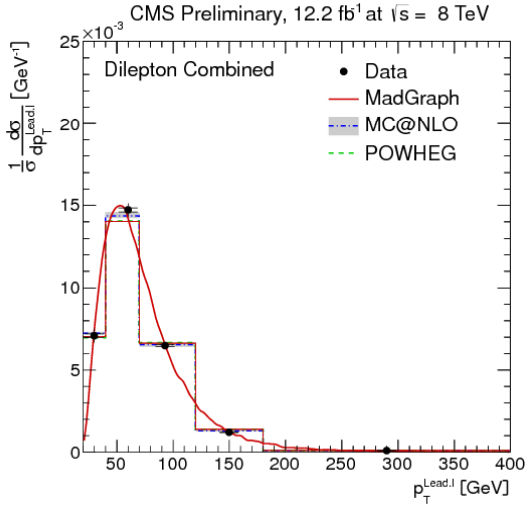
- e/μ + jets
- At least 4 jets with p_T > 30 GeV, 1 lepton with p_T > 30 GeV
- 2 b-tagged jets

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 outside Z mass window (91 ±15) GeV
- 1 b-tagged jet



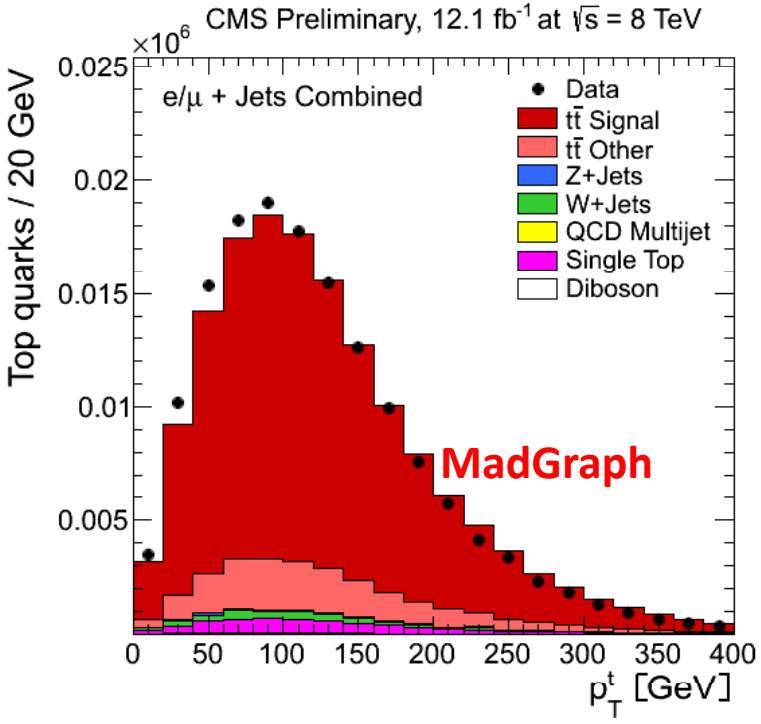


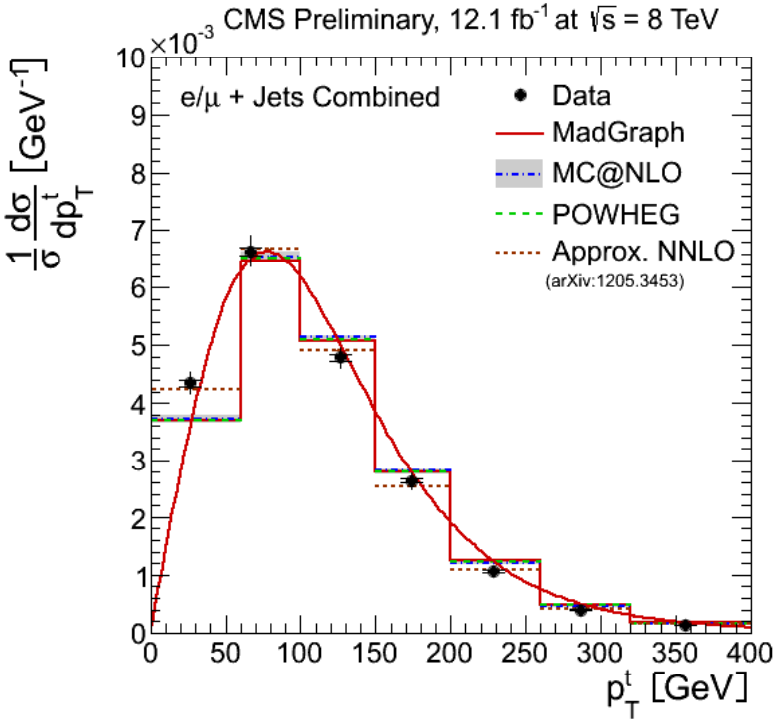


- **Good agreement with SM NLO predictions**
- More distributions available: top quark p_T, jet p_T, pseudo(rapidity), M_{lb}, …

Differential cross sections

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



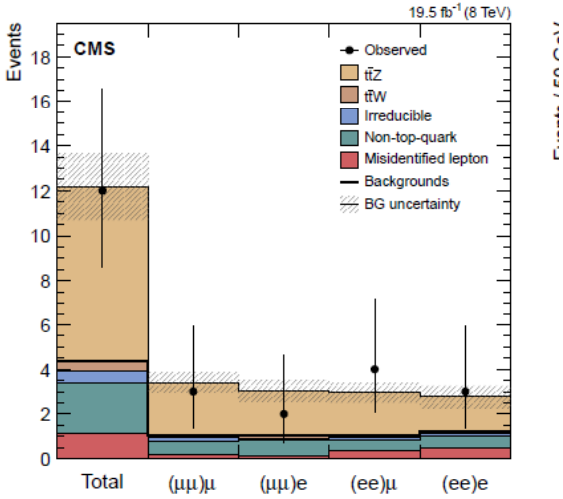


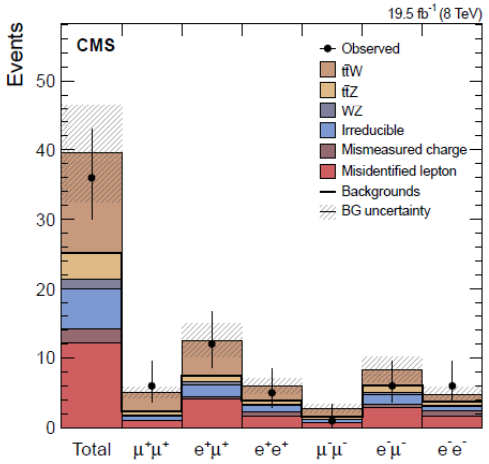
Shape differences taken into account as systematic uncertainties in recent measurements

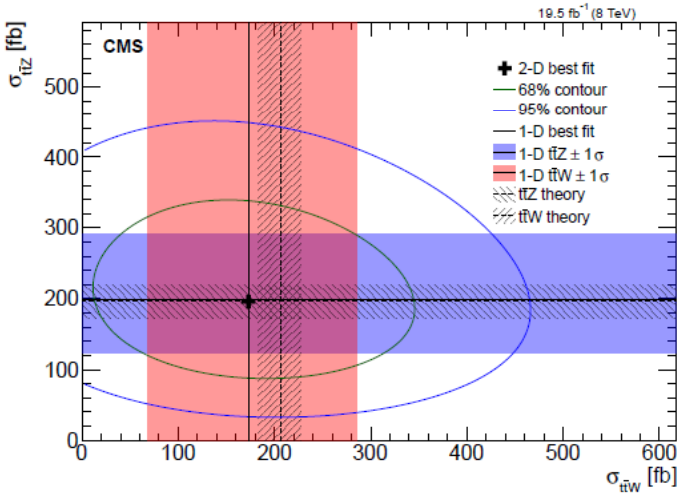
tt + W/Z

CMS PAS TOP-12-036 19.5 fb^{-1}
EPJC 74 (2014) 3060

Associated production of Vector Bosons with top-antitop pairs at 8 TeV







Tri- lepton channel
p_T > 20 GeV
2 b-tagged jets
Exclusive search for ttZ
Only events with m_{ll} outside Z window

New channel with 4 leptons

Dilepton channel (SS), 2 pT > 40 GeV
HT > 155 GeV
1b-tagged jet
Inclusive search for ttZ, ttW

Compatible with SM predictions

Combining all channels: ttV signal significance of 3.7 σ

σ_{ttW}= 170 +90-80 (stat.) +- 70 (syst.) pb
σ_{ttZ} = 200 + 80-70 (stat.) + 40-30 (syst.) pb

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

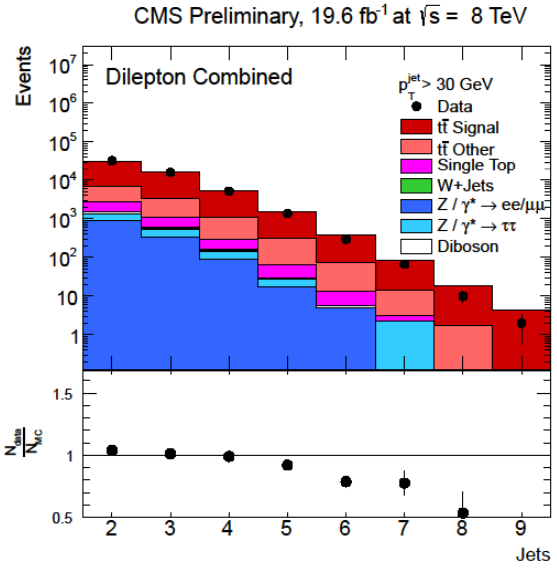
tt + jets

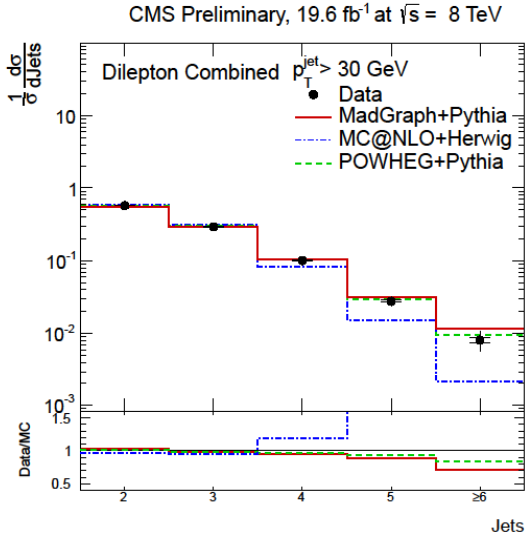
7 TeV results:
CMS PAS TOP-12-023
5 fb^{-1}

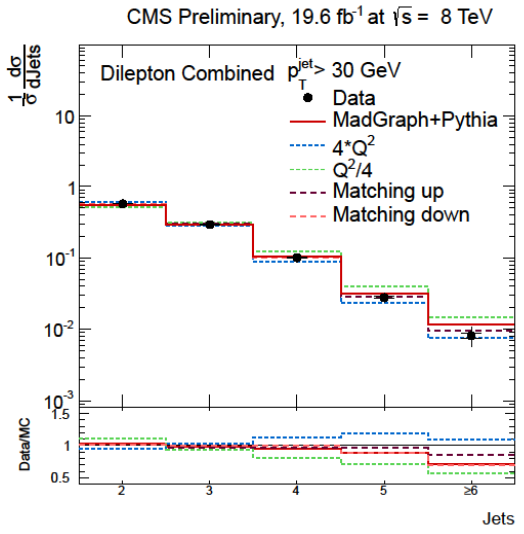
- Differential cross section measured as a function of the jet multiplicity for different jet p_T
- Measurement performed in the ee, eμ, μμ decay channels
- Require at least 2 isolated leptons, p_T > 20 GeV, with invariant mass outside Z window

At least 2 jets with p_T > 30 GeV
At least 1 b-tagged jet

Reasonable description of the data by NLO generators





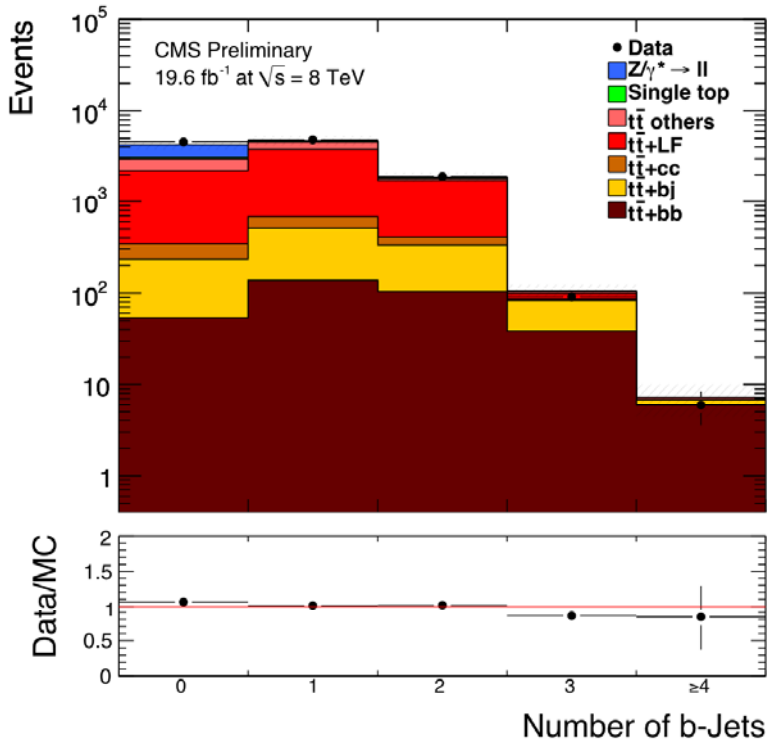


- Slightly higher jet multiplicity predicted by NLO simulation
- Lower multiplicity by MC@NLO +Herwig
- Slightly worse description by MadGraph with $Q^2/4$

CMS PAS TOP-13-010
arXiv:1411.5621 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

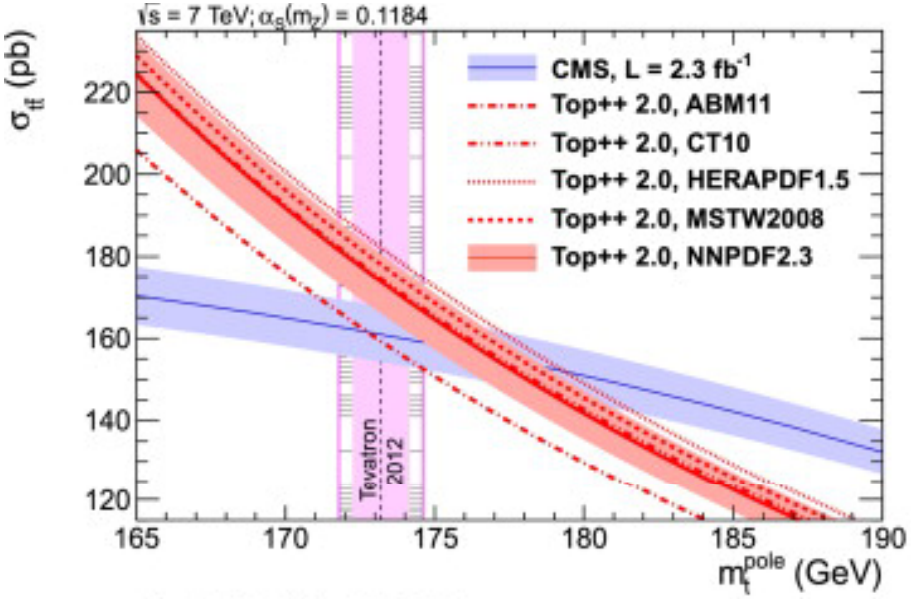
$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = \begin{array}{l} 0.023 \pm 0.003\ (\text{stat.}) \pm 0.005\ (\text{syst.}) \text{ at Jet } p_{\mathrm{T}} > 20\ \text{GeV} \\ 0.022 \pm 0.004\ (\text{stat.}) \pm 0.005\ (\text{syst.}) \text{ at Jet } p_{\mathrm{T}} > 40\ \text{GeV} \end{array}$$

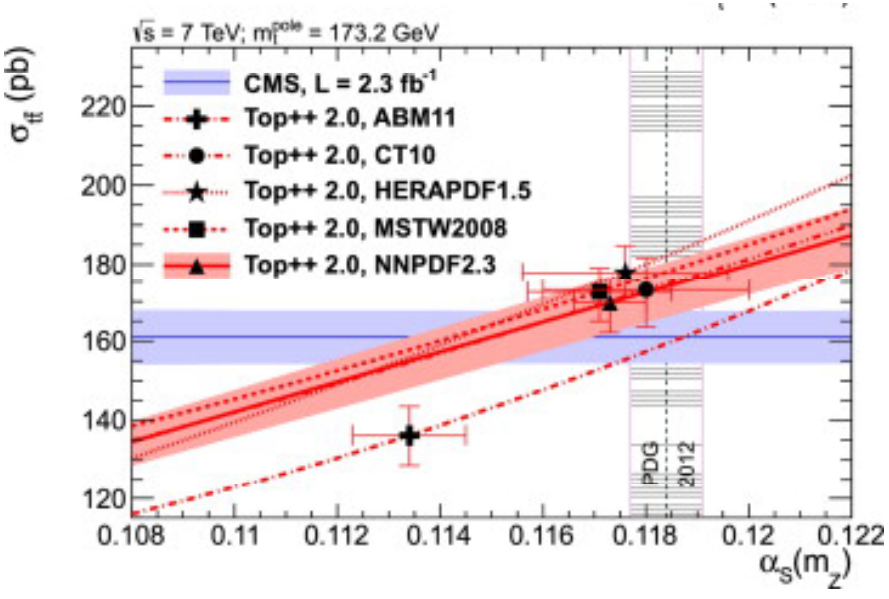
First α_S determination from tt cross section

CMS PAS TOP-12-022 5 fb^{-1}
PLB 728 (2014) 496

- 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 +3.0 −2.8) 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 +0.0028 −0.0027 is extracted.

Most precise determination at hadron colliders





Summary

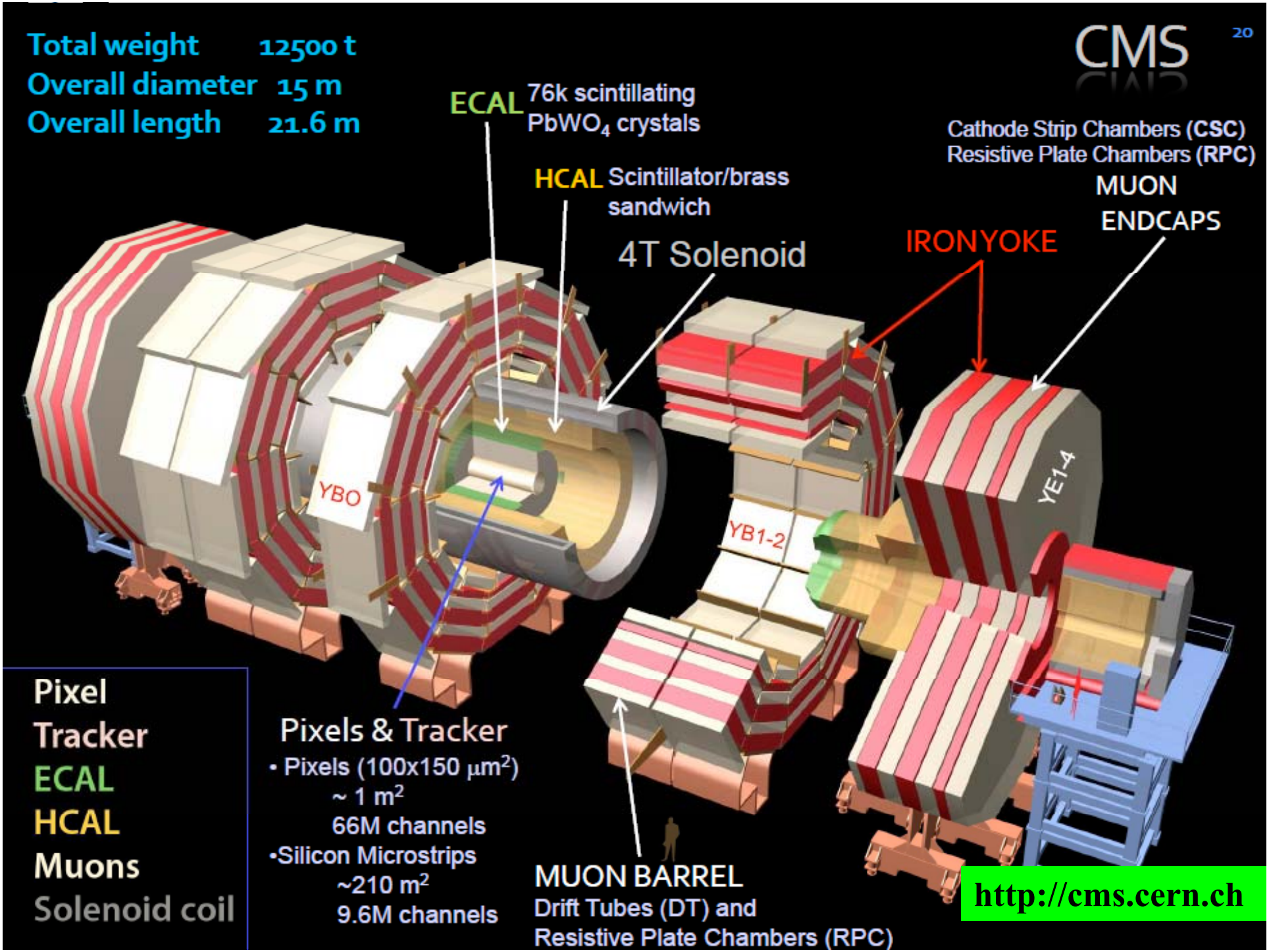
- Measurements of (almost) all experimental signatures at 7 TeV and 8 TeV

- Precision measurements in single top t-channel
- Experimental uncertainties on σ_{tt}: ~4%-7%
- Challenging theory predictions

- CMS top quark results at:

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

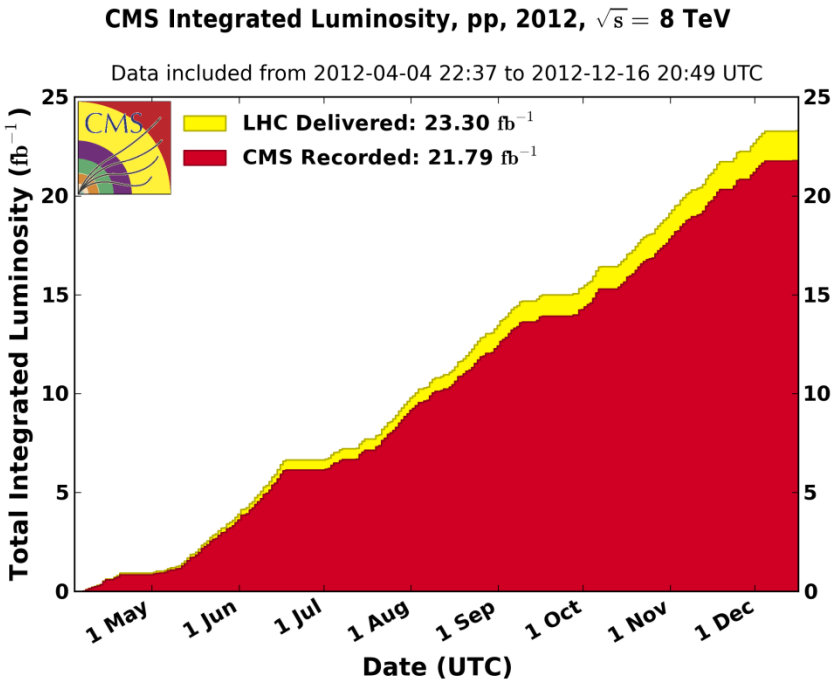
Additional slides


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

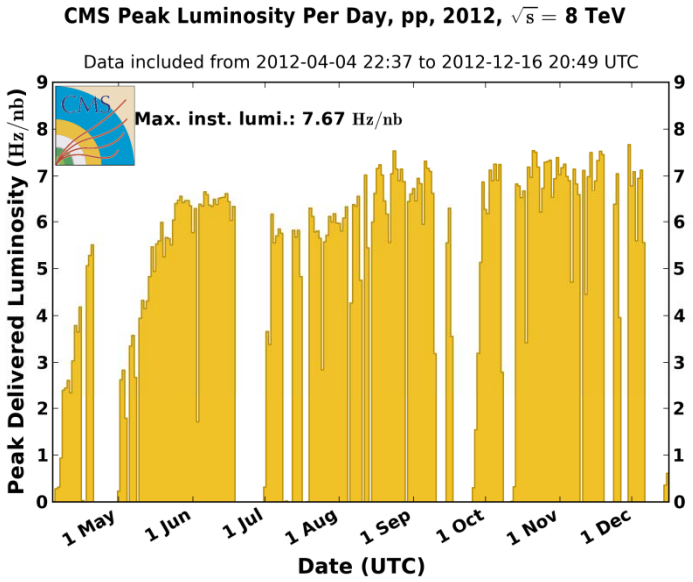
LHC and CMS operation

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**

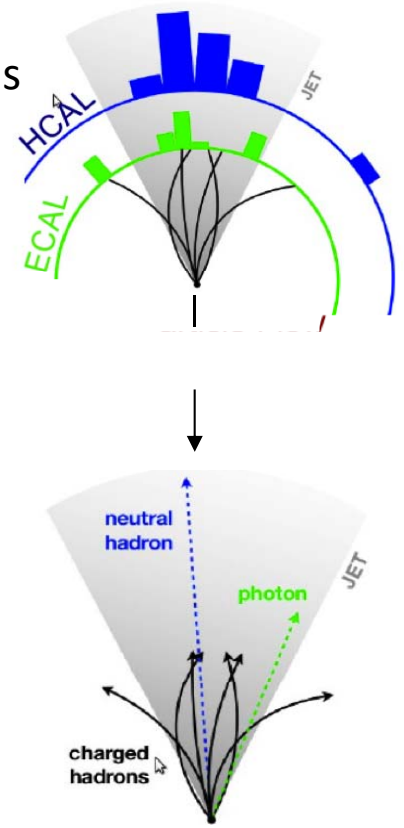
Common selection requirements

- **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 |η|<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

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

CMS PAS PFT-10-002

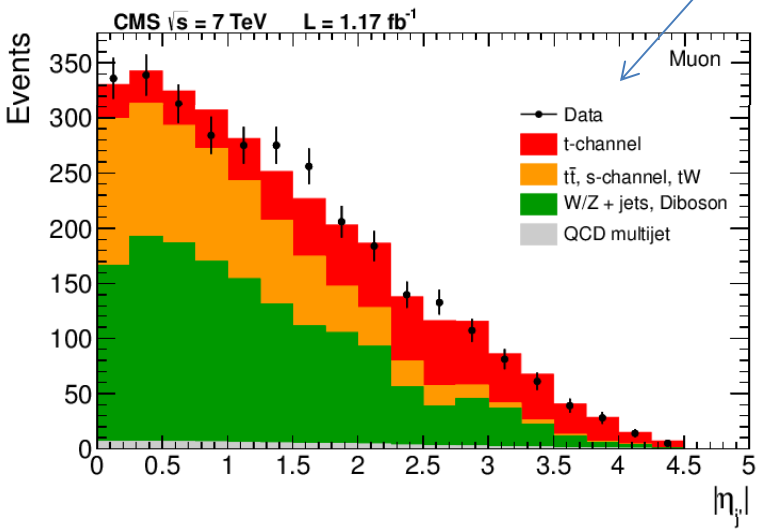
-charged hadrons
-photons
-neutral hadrons
-muons
-electrons

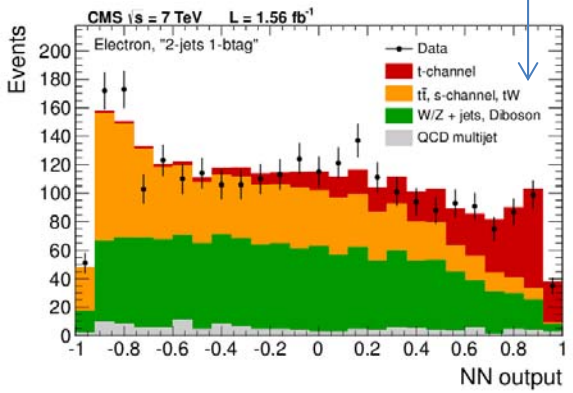


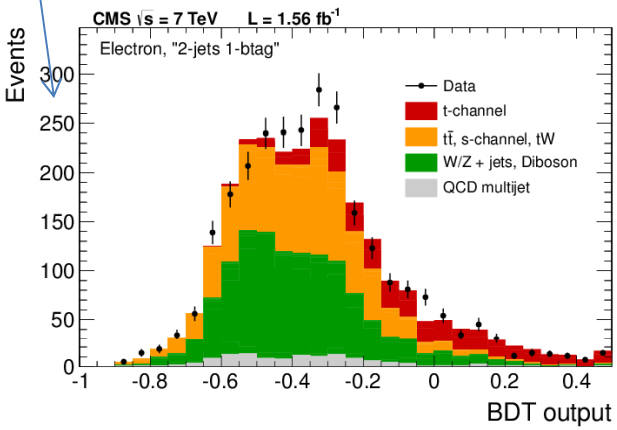
t-channel cross section at 7 TeV

CMS PAS TOP-11-021 1.17 fb^{-1} (mu) and 1.17 fb^{-1} (ele) **JHEP 12 (2012) 035**

- Lepton + jets final state from leptonic top decay: t → Wb → lvb
- Three analyses giving consistent results: fit to the pseudorapidity η of the light jet (as for 8 TeV) plus two multivariate analyses using a Boosted Decision Tree (BDT) or a Neutral Network (NN) discriminant







Combined result:

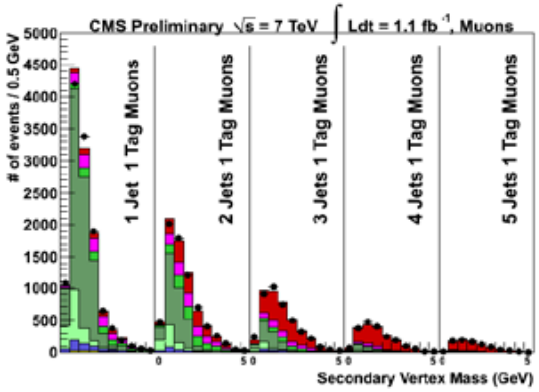
$\sigma_{t\text{-}ch}$ = 67.2 ± 6.1 pb

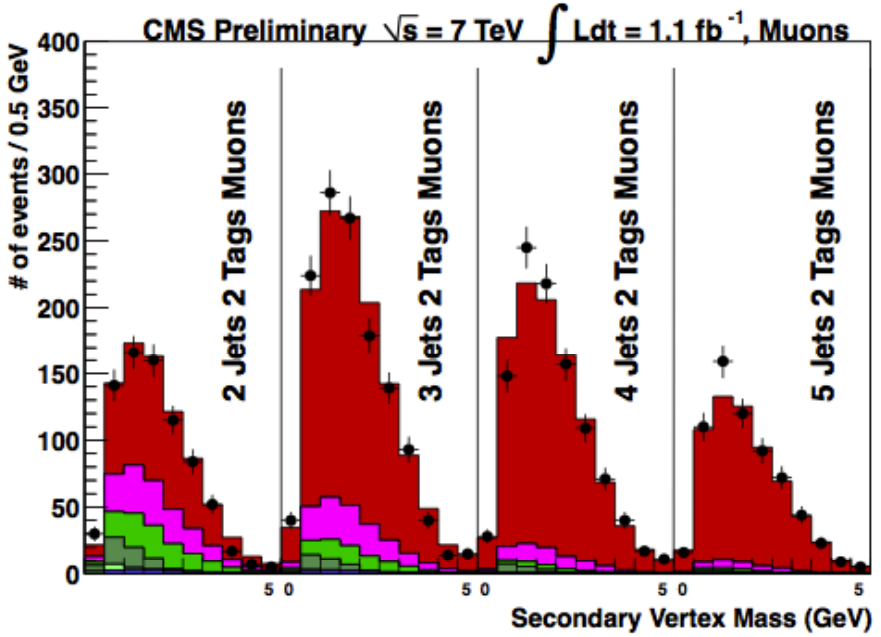
Total systematic uncertainties in the range 8%-10% for the 3 analyses

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 (Q^2, b-tag eff.)



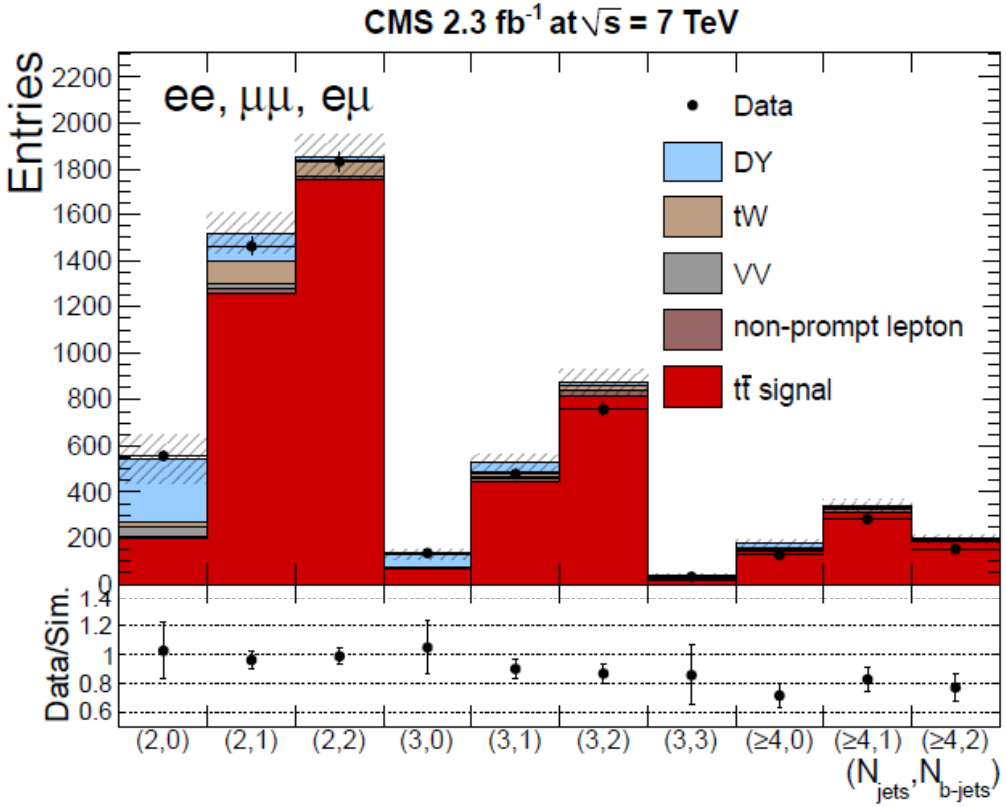


σ_{tt} = (158.1 ± 2.1 (stat.) ± 10.2 (syst.) ± 3.5 (lumi.))pb, $\Delta\sigma_{tt} / \sigma_{tt}$ = 6.9%

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

CMS PAS TOP-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

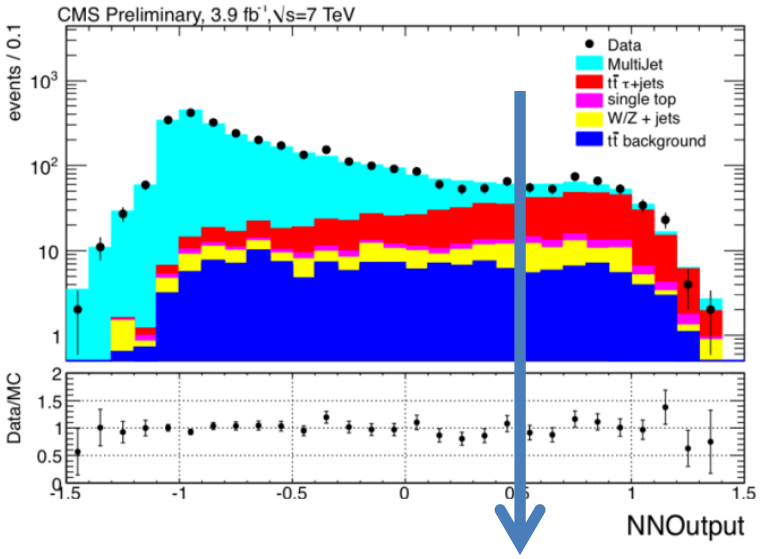
σ_{tt} = (161.9 ± 2.5 (stat.) + 5.1-5.0 (syst.) ± 3.6 (lumi.))pb, $\Delta\sigma_{tt} / \sigma_{tt}$ = 4.2%

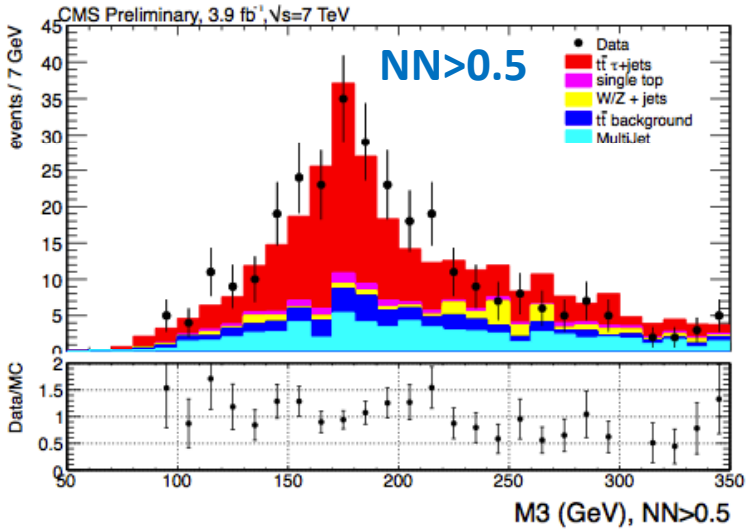
Main systematics: lepton efficiencies 1.7%, jet energy scale 1.8%

CMS PAS TOP-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
- ≥ one 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

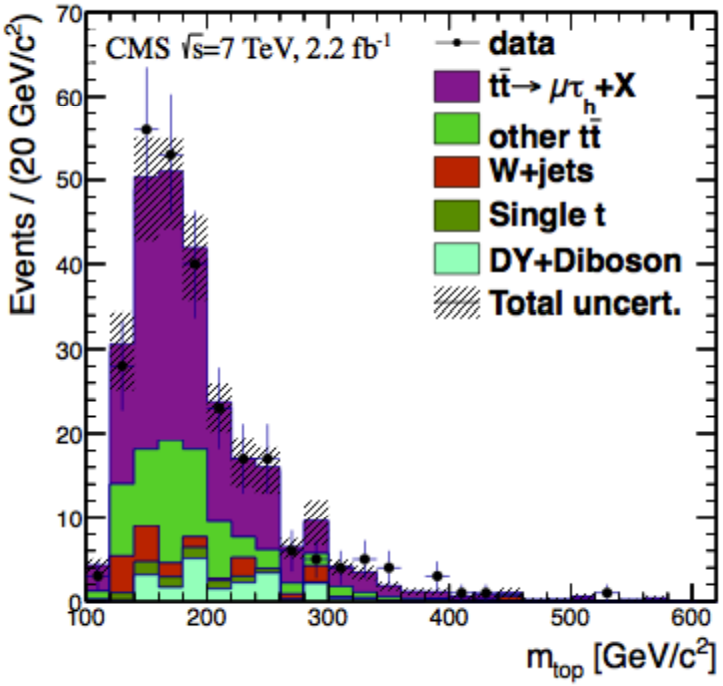
σ_{tt} = (152 ± 12 (stat.) ± 32 (syst.) ± 3 (lumi.)) pb, $\Delta\sigma_{tt} / \sigma_{tt}$ = 23%

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

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

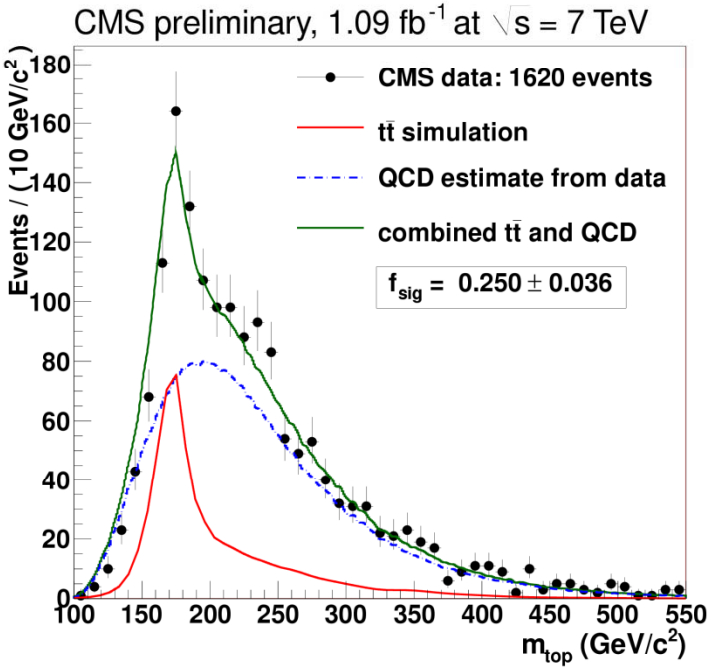
- Profile likelihood fit to jet multiplicity, b-tagged jet multiplicity
- Cross-check: cut-based analysis requiring 1 b-tagged jet

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-11-007 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,

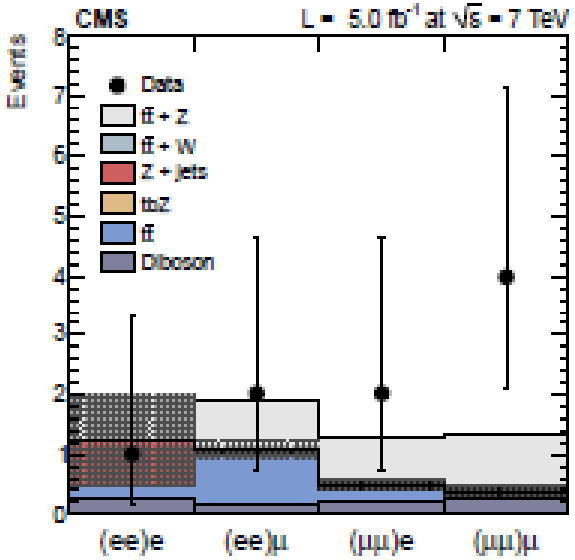
$\Delta\sigma_{t\bar{t}} / \sigma_{t\bar{t}}$ = 20%

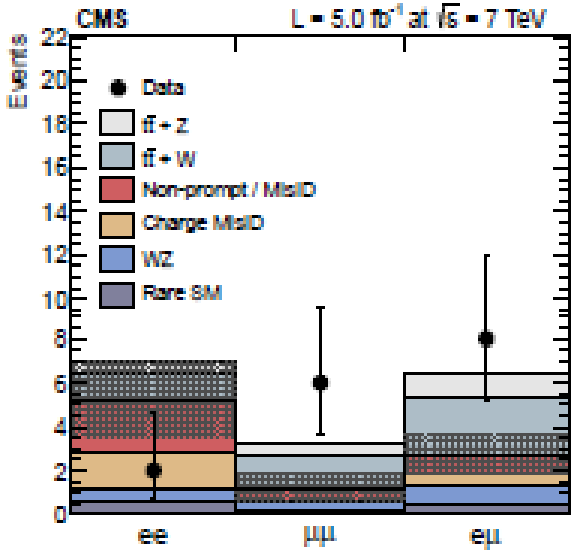
Main systematics: b-tagging efficiency 6%, background contribution, jet energy scale 10%

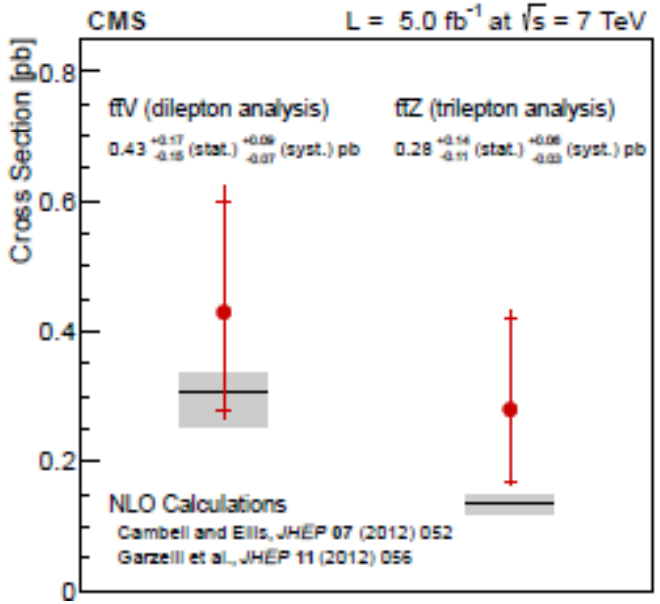
tt + W/Z at 7 TeV

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

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
2 b-tagged jets
Exclusive search for ttZ
Only events with 70 < m_{ll} < 110 GeV

Dilepton channel (SS), pT > 55, 30 GeV
HT > 100 GeV
1b-tagged jet
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