Top Quark Pair Production Cross Sections at CMS

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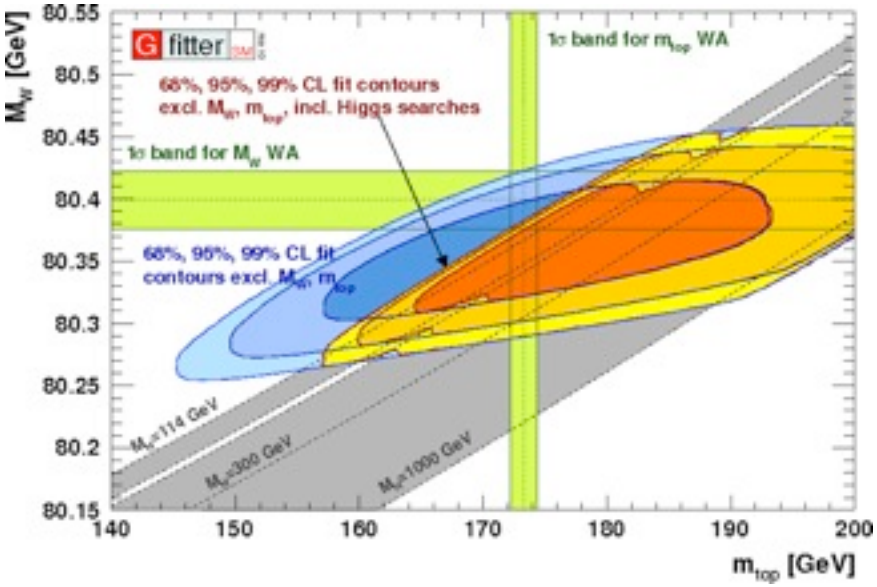
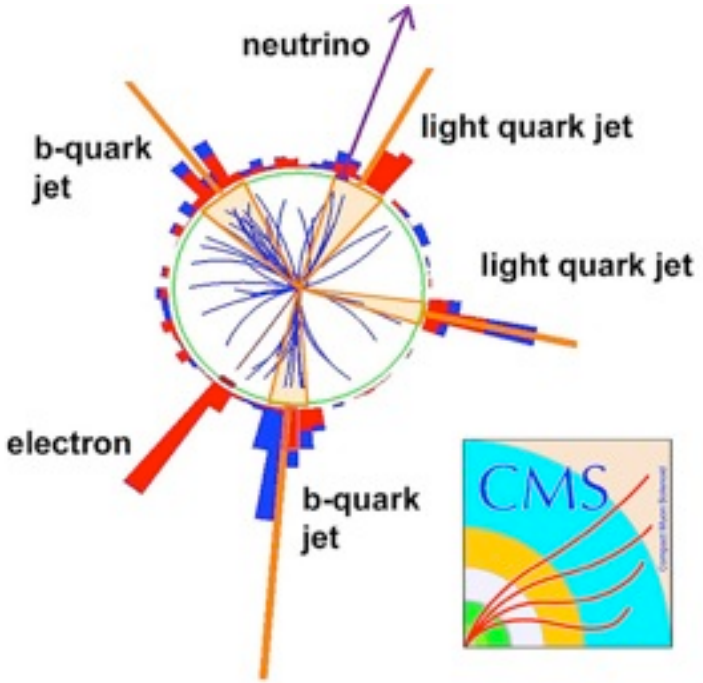
on behalf of the CMS Collaboration

EPS, 21 July 11

Motivation

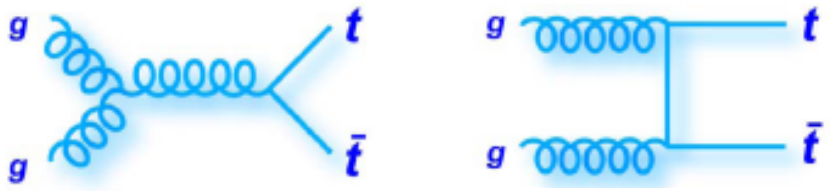
- Top Quark is special
  - heaviest known particle
  - decay before hadronization: "bare quark"
  - maximum sensitivity to Higgs (EWK loop corrections)
- Precision measurements of SM parameters
  - total cross section, differential distributions
  - properties (mass, spin structure, asymmetries, couplings, V_{tb} ...)
- Search for New Physics
  - New physics might preferentially couple / decay to top
  - non-standard couplings ?
- LHC is a top factory with multi TeV scale reach
  > 1 fb^{-1} : > 160k top quark pairs produced in CMS



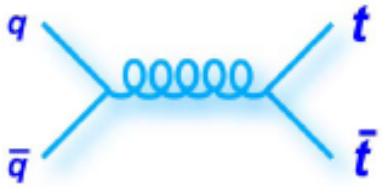


Top Quark Pair Production

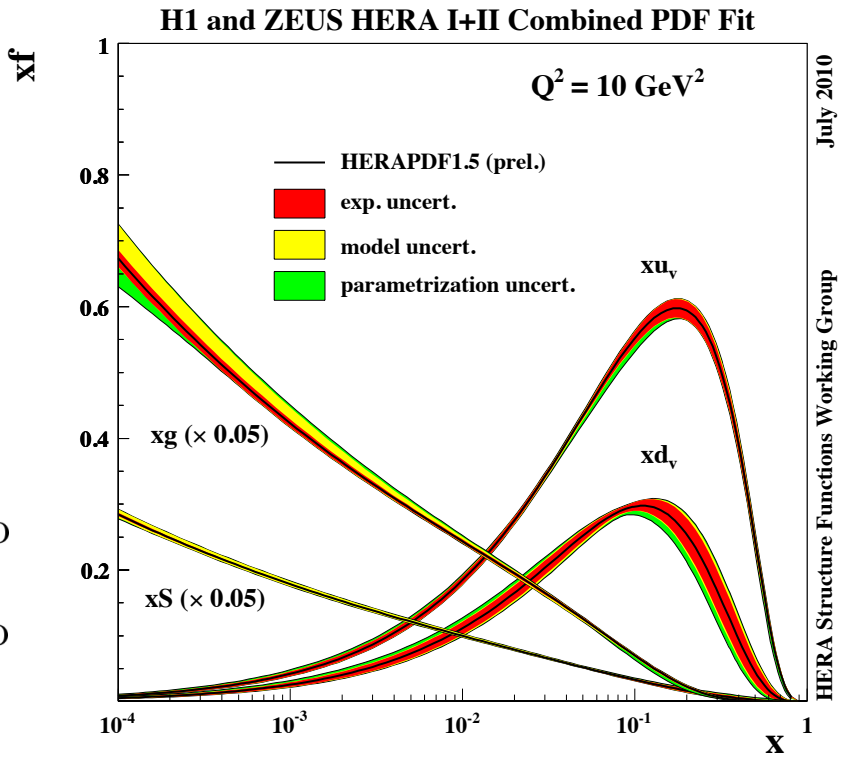
- **Gluon-Gluon Fusion**



- **Quark-Antiquark Annihilation**



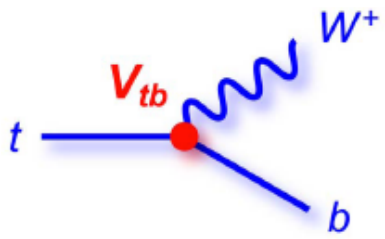
	LHC (7TeV)	Tevatron
σ_{tt}	~160 pb	~7 pb
dominantly	gg	$q\bar{q}$

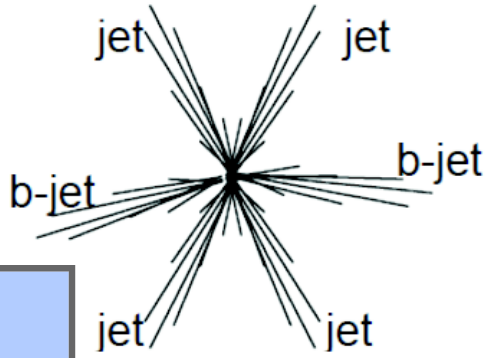


- **Calculations (pp at 7 TeV):**
  - **NLO (MCFM):** $\sigma_{t\bar{t}}^{\mathrm{NLO}} = 158^{+23}_{-24}\ \mathrm{pb}$
  - **approx. NNLO:**
    - **Kidonakis** PRD 82 (2010) 114030 $\sigma_{t\bar{t}} = 163^{+11}_{-10}\ \mathrm{pb}$
    - **Langenfeld et al, Aliev et al** PRD 80 (2009) 054009, CPC 182 (2011) 1034 $\sigma_{t\bar{t}} = 164^{+10}_{-13}\ \mathrm{pb}$

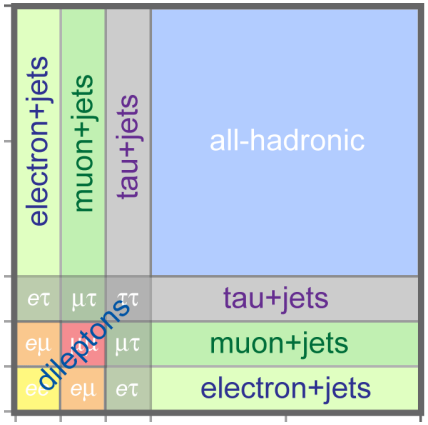
$t\bar{t}$ Decay Channels

- Leptons
  - low background / 'easy' to trigger
  - good resolution
  - low branching ratio
  - missing E_T (neutrinos)
- Hadrons / jets
  - large background / difficult to trigger
  - large branching ratio
  - no missing E_T
- New measurements from CMS presented today:
  - fully hadronic channel
  - μτ dilepton channel





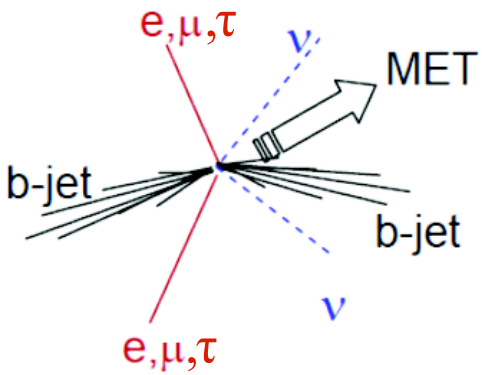
Fully hadronic: BR ~ 45%

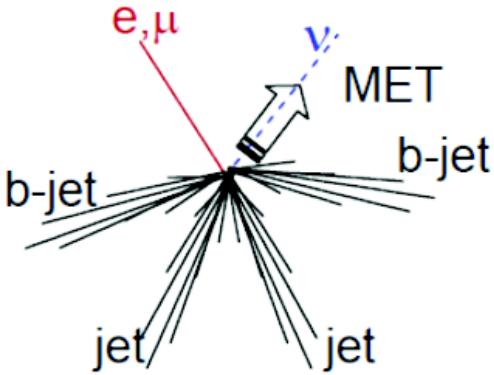


Semileptonic: BR ~ 30%

μμ, μe, ee: BR ~ 5%

τμ,τe: BR ~ 5%





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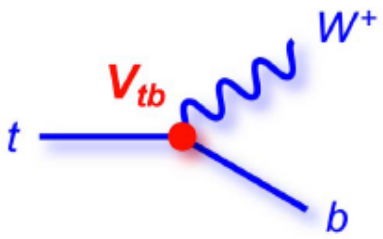

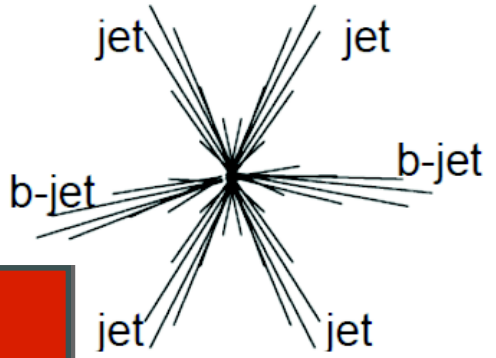

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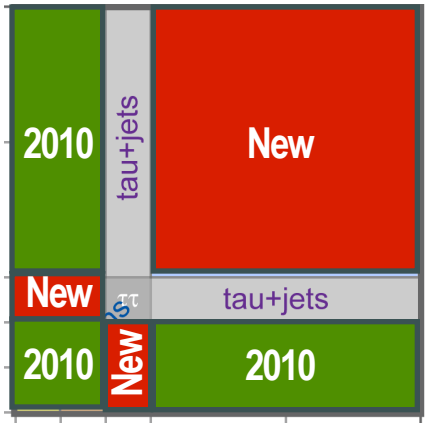

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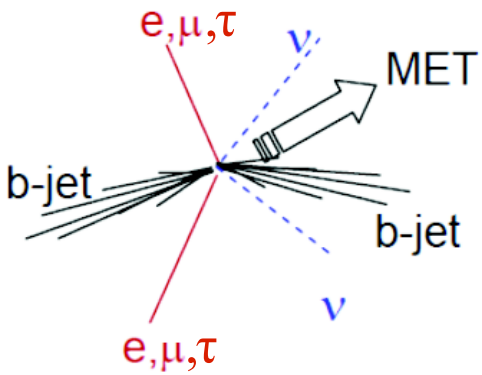
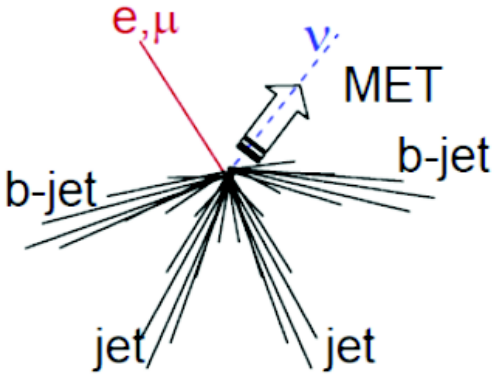
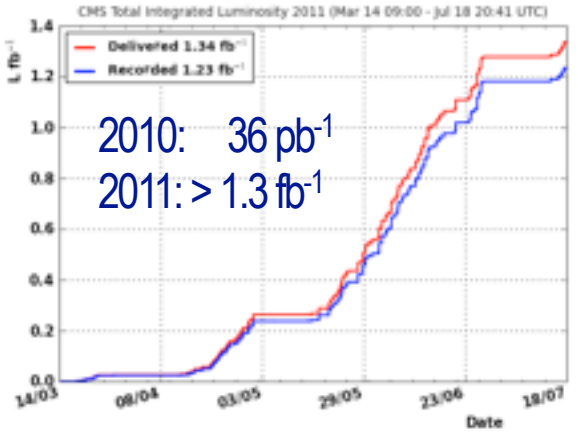




CMS Experiment

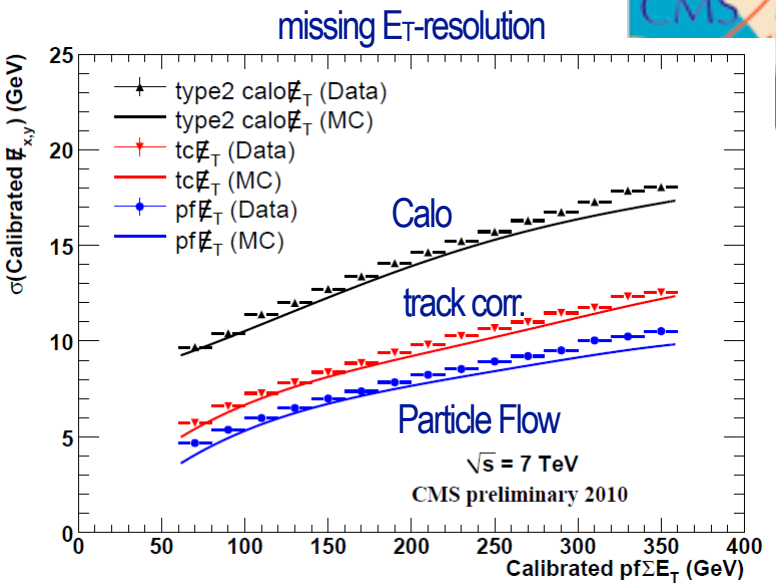


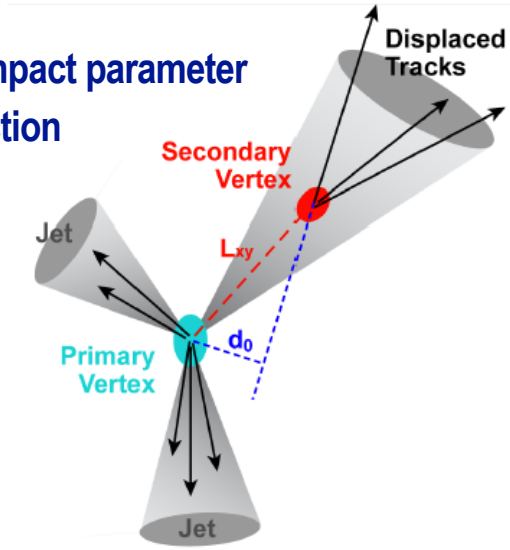
2010: 36 pb^{-1}
2011: > 1.3 fb^{-1}

Total weight: 14000 t
Magnetic field: 3.8 T
Silicon-only track detectors
Crystal EM calorimeter
Muon tracking detectors (within return yoke)
Trigger: L1 100kHz / HLT 300 Hz to tape

Experimental Ingredients

- Leptons (μ or e)
  - very good resolution (< 1% below ~ 100 GeV)
  - isolation cuts against QCD backgrounds
- Jet reconstruction / missing transverse momentum
  - Particle Flow: identification and reconstruction of particles from combined signals/deposits in tracker/ calorimeter and muon systems
- b-tag
  - track counting algorithm
    - count tracks with large impact parameter
  - secondary vertex reconstruction
    - decay length
    - vertex mass





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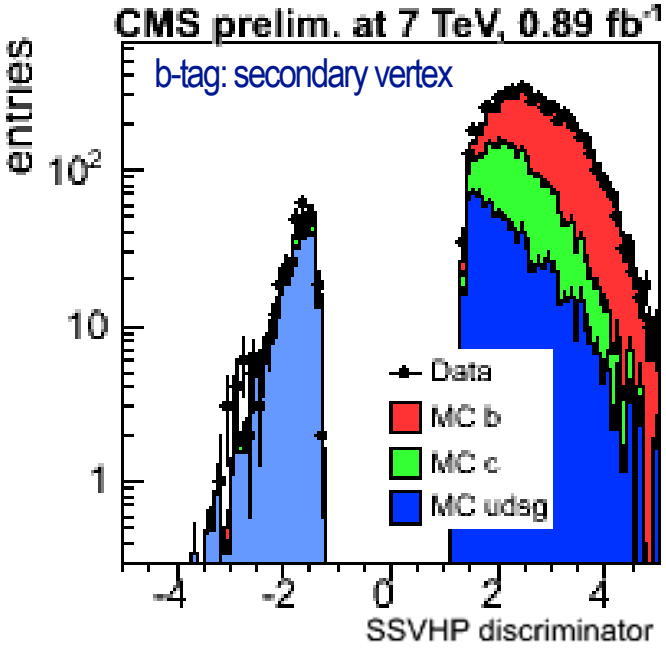
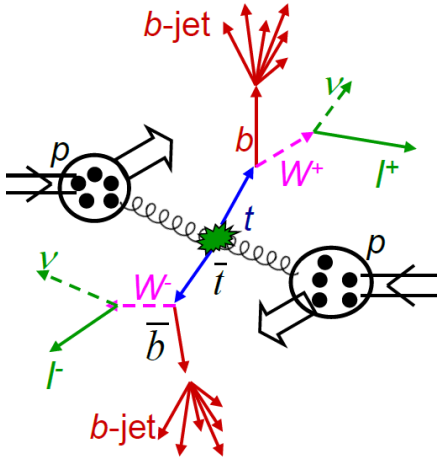


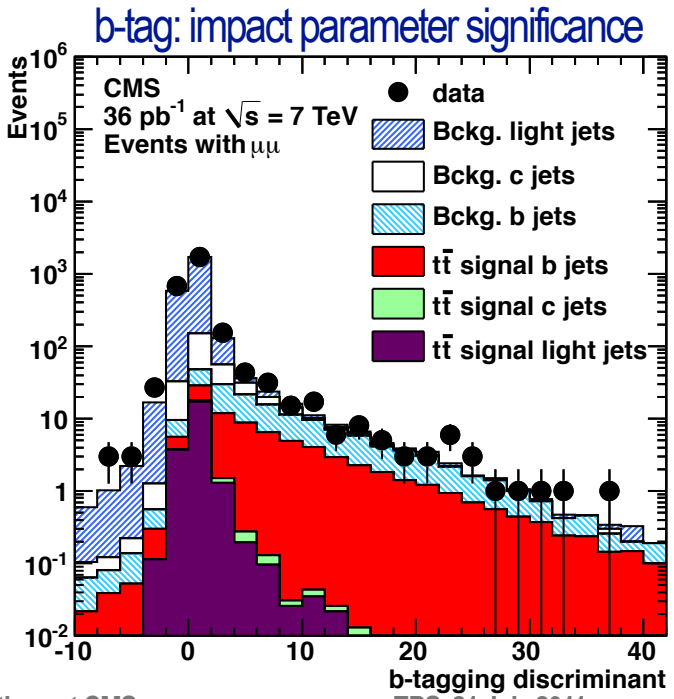
Dileptons (μe,ee,μμ)

2010: 36 pb^{-1}

arXiv: 1105.5661

- Event Selection
  - Inclusive single lepton triggers (p_T>15 (22) GeV for μ(e))
  - ≥2 isolated, opposite charge leptons (ee,μμ,eμ)
    - p_T>20 GeV, |η|<2.4 (μ), 2.5 (e)
    - Lepton ID and conversion rejection efficiency: 99% for μ, 90% for e
    - Relative Isolation < 0.15
  - ≥2 jets
    - Anti-K_T, particle flow
    - P_T>30 GeV, |η|<2.5
  - Z^0 veto (ee,μμ): 76 < $m_{ee,\mu\mu}$ < 106 GeV/c^2
  - Missing E_T (ee,μμ) > 30 GeV
  - b-tag (track counting algorithm) discriminant > 1.7
    - efficiency 80%, mistag 10%





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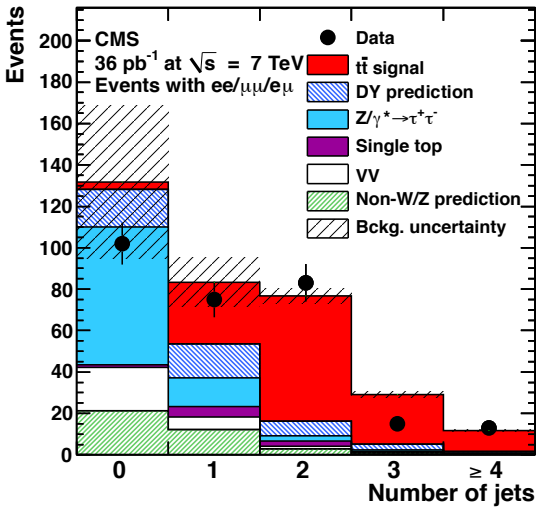
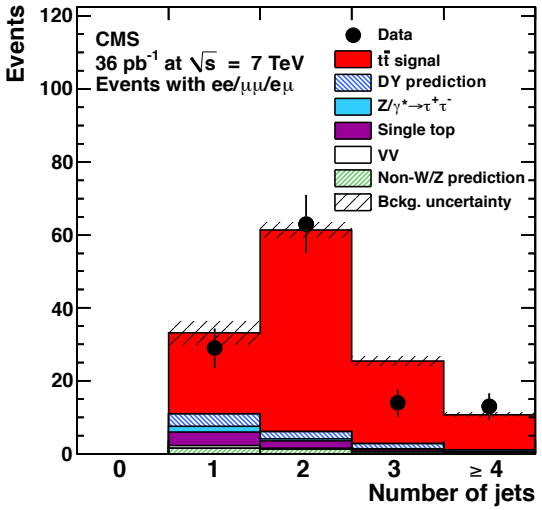
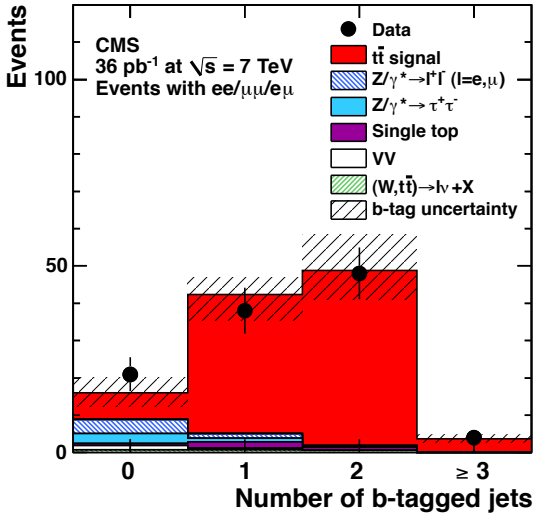


before b-tagging



N(jets) for N(b-tag) ≥ 1



N(b-tag) for N(jets) ≥ 2

- Backgrounds
  - Drell Yan (ee,μμ): estimated from data (using events at Z peak)
  - QCD, W+jets: estimated from data (using tight-to-loose ratio)
- Main systematics:
  - lepton ID
  - jet energy scale
  - top quark mass
  - b-tagging (determined in-situ)

Background free sample of top quark pair events !

Dileptons (μe,ee,μμ)

2010: 36 pb^{-1}

arXiv: 1105.5661

- **Cross section determination:**
  - count number of events above background
  - 3 categories for each mode (ee,μμ,eμ):
    - 1 jet, no b-tagging
    - >2 jets, no b-tagging
    - >2 jets, ≥ 1 b-tag

9 separate measurements

Final state	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
At least two jets, no b-tagging requirement			
Events in data	23	28	60
Simulated backgrounds	1.4 ± 0.3	1.5 ± 0.3	5.2 ± 1.2
$Z/\gamma^\star \to e^+e^-/\mu^+\mu^-$	3.0 ± 1.8	7.4 ± 4.1	–
Non-W/Z	1.1 ± 1.4	0.6 ± 1.1	1.4 ± 1.6
All backgrounds	5.5 ± 2.3	9.5 ± 4.3	6.7 ± 2.0
Total acceptance $\mathcal{A}$ (%)	0.259 ± 0.021	0.324 ± 0.025	0.928 ± 0.057
Cross section (pb)	$189 \pm 52 \pm 29$	$159 \pm 45 \pm 39$	$160 \pm 23 \pm 12$
At least two jets, at least one b-jet			
Events in data	15	24	51
Simulated backgrounds	0.7 ± 0.2	0.8 ± 0.3	2.5 ± 0.7
$Z/\gamma^\star \to e^+e^-/\mu^+\mu^-$	0.7 ± 0.7	2.6 ± 1.8	–
Non-W/Z	0.9 ± 1.2	0.3 ± 0.8	0.5 ± 1.1
All backgrounds	2.3 ± 1.4	3.8 ± 2.0	3.0 ± 1.4
Total acceptance $\mathcal{A}$ (%)	0.236 ± 0.022	0.303 ± 0.028	0.857 ± 0.068
Cross section (pb)	$150 \pm 46 \pm 22$	$186 \pm 45 \pm 25$	$156 \pm 23 \pm 13$
One jet, no b-tagging requirement			
	8	10	18
ınds	1.6 ± 0.4	1.9 ± 0.4	3.6 ± 0.9
$Z/\gamma^\star \to e^+e^-/\mu^+\mu^-$	0.2 ± 0.3	5.2 ± 4.3	–
Non-W/Z	0.3 ± 0.5	0.1 ± 0.4	1.3 ± 1.3
All backgrounds	2.1 ± 0.7	7.1 ± 4.3	4.9 ± 1.5
Total acceptance $\mathcal{A}$ (%)	0.058 ± 0.007	0.074 ± 0.008	0.183 ± 0.024
Cross section (pb)	$282 \pm 135 \pm 45$	$107 \pm 119 \pm 163$	$200 \pm 65 \pm 35$

$$\sigma_{t\bar{t}} = 168 \pm 18\,(\text{stat.}) \pm 14\,(\text{syst.}) \pm 7\,(\text{lumi.})\ \text{pb}$$

systematic uncertainty: ~9%

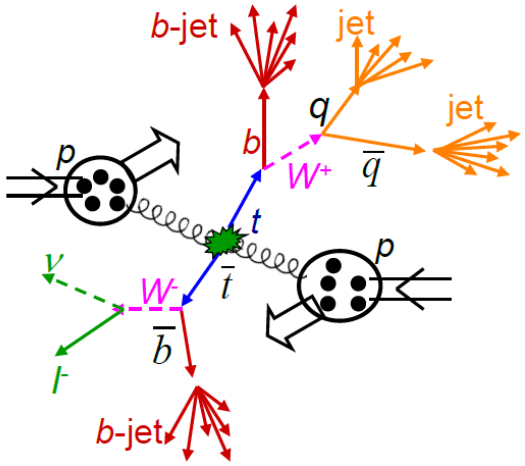
- **Cross section ratio tt/Z:**
  - cancellation of some of the exp.systematics, no luminosity uncertainty
  - anti-correlated PDF uncertainties in Z and tt

$$\frac{\sigma(pp \to t\bar{t})}{\sigma(pp \to Z/\gamma^\star \to e^+e^-/\mu^+\mu^-)} = 0.175 \pm 0.018\,(\text{stat.}) \pm 0.015\,(\text{syst.})$$

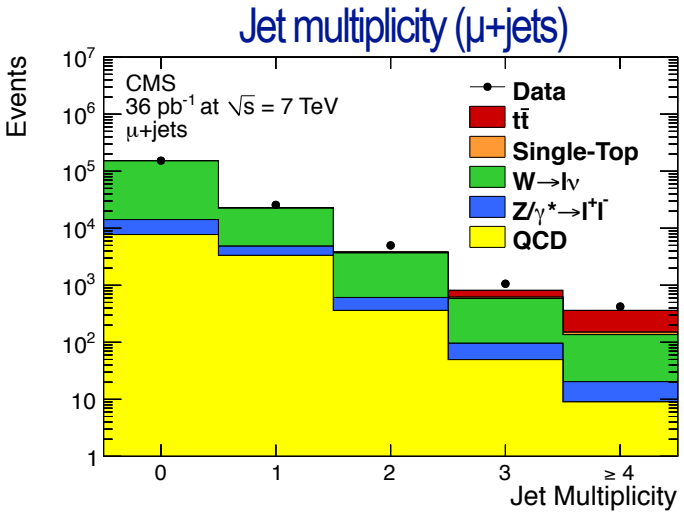
e/μ+jets

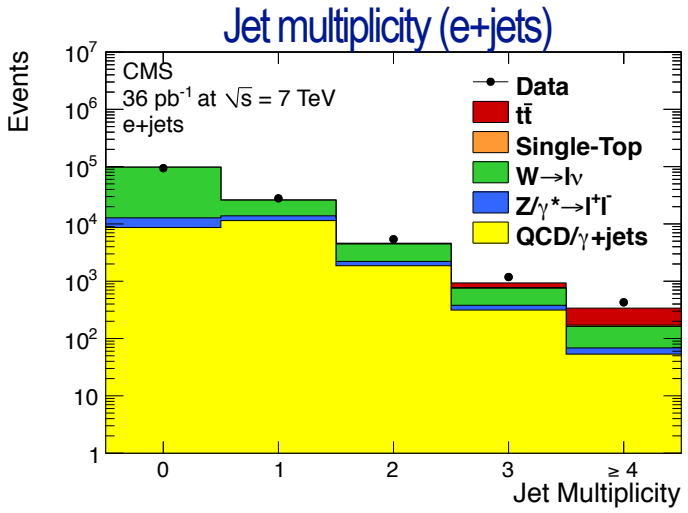
2010: 36 pb^{-1} arXiv: 1106.0902 | CMS-TOP-10-003

- **Event selection:**
  - single lepton triggers (2010 same as for dilepton analysis)
  - exactly one isolated lepton
    - electrons: p_T > 30 GeV, |η|<2.5, relative isolation<0.1, conversion rejection
    - muons: p_T > 20 GeV, |η|<2.1, relative isolation<0.05
  - Jets: p_T>30 GeV, |η|<2.4



- **Two independent analyses:**
  - no b-tag: fit MET and M3 shapes as discriminator variables
  - with b-tag: secondary vertex algorithm, MET > 20 GeV



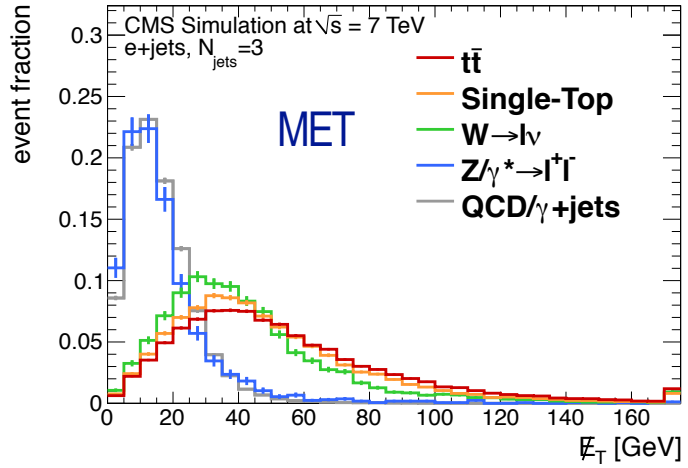


e/μ+jets (no b-tag) 2010: 36 pb^{-1}

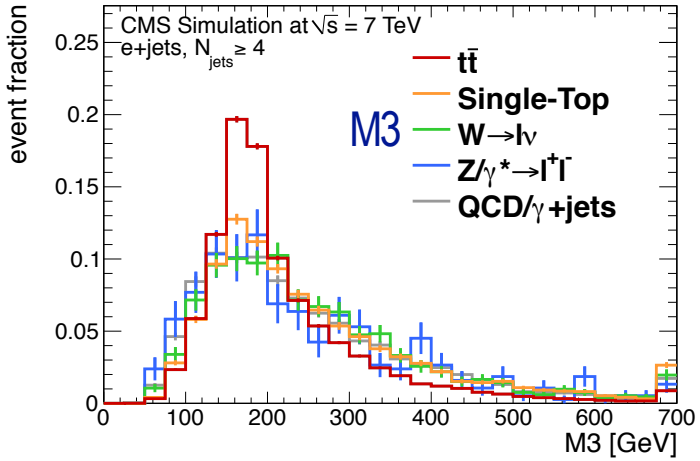
arXiv: 1106.0902

- Simultaneous fit to templates of two distributions in two separate samples
  - N(jets) = 3: MET distribution: separates top quark pair signal from QCD, Z+jets
  - N(jets) ≥ 4: M3 distribution (maximum vectorial sum of 3 jets): signal peaks around top mass

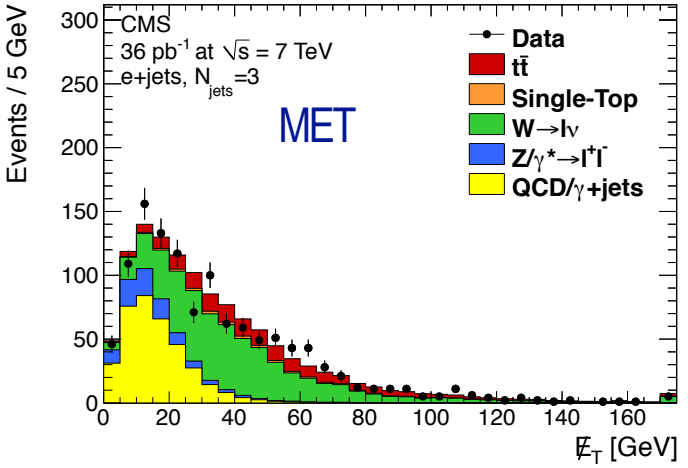
N(jets) = 3

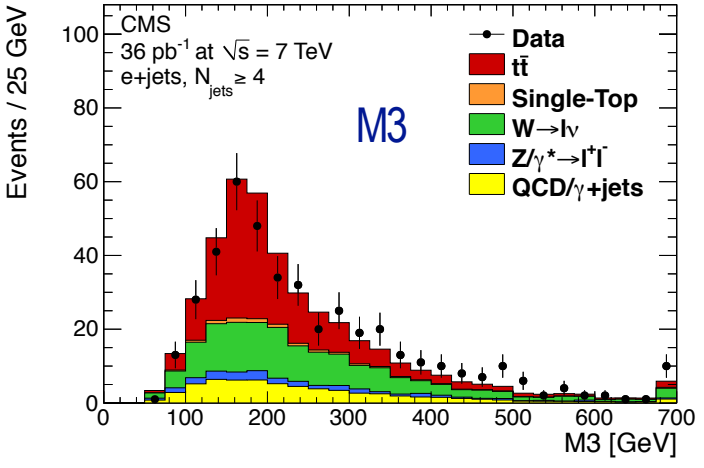


N(jets) ≥ 4



here: e+jets (similar distributions for μ+jets)



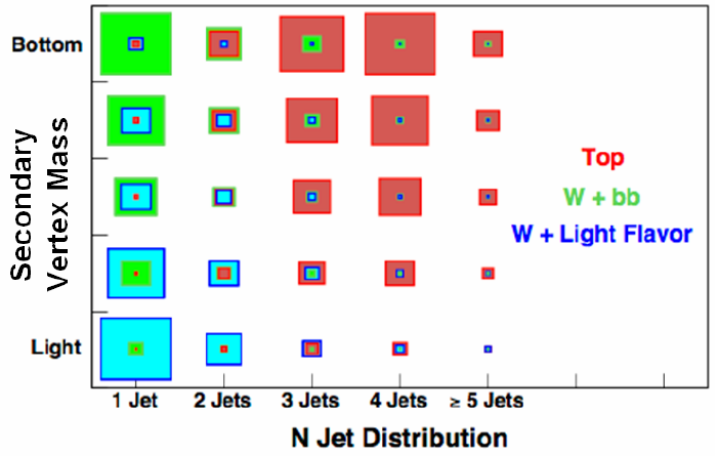


e/μ+jets (b-tag)

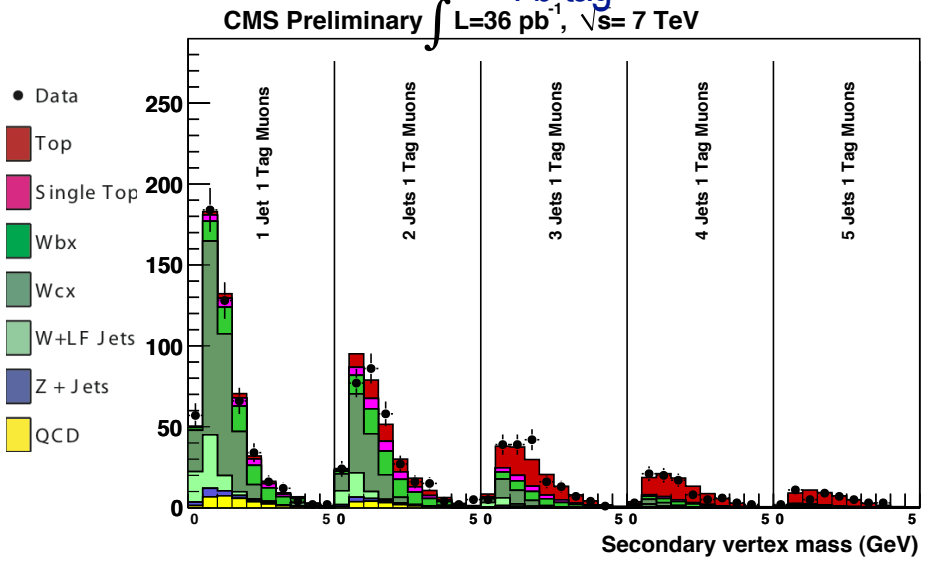
2010: 36 pb^{-1}

CMS-TOP-10-003

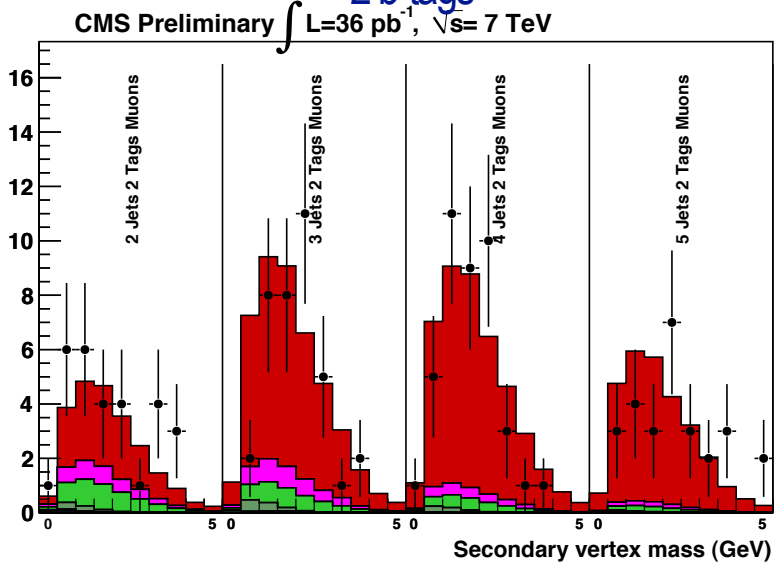
- Binned template fit
  - secondary vertex mass and jet multiplicity
  - separately for 1 b-tag and 2 b-tag events
- Combined in-situ fit of systematic errors



1 b-tag



2 b-tags



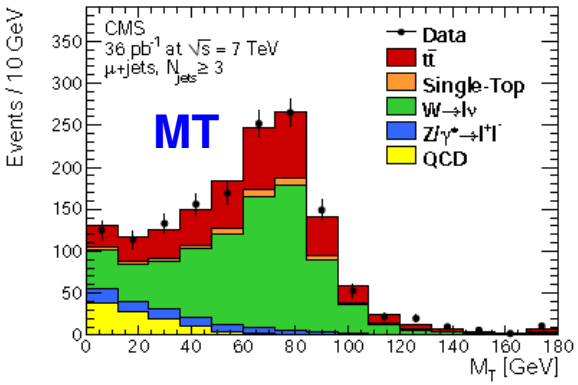
here: μ+jets (similar distributions for e+jets)

e/μ+jets

arXiv: 1106.0902

CMS-TOP-10-003

no b-tag

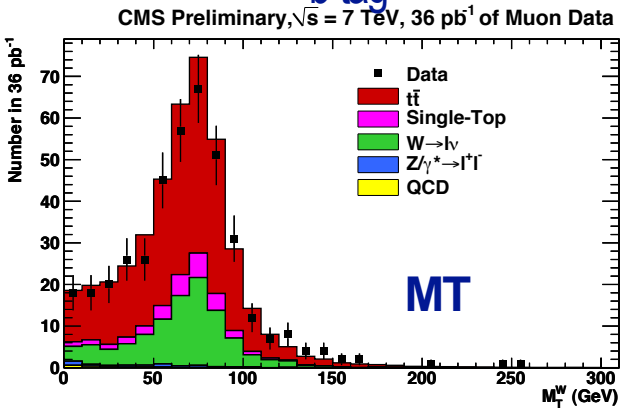


- Cross section from MET and M3
  - ratio W+jet/Z+jets (± 30% within theory pred.)
  - single top (±30% within theory prediction)
- Dominant systematic errors: Jet energy scale, W+jets Q^2-scale
- 4 cross check analyses:
  - counting experiment in μ+jets (B/G scaling)
  - simultaneous fit to jet multiplicity and $p_T(\mu)$
  - fit to η(μ) exploiting W charge asymmetry
  - μ+jets with cut on MET>20 GeV

$$\sigma_{t\bar{t}} = 173^{+39}_{-32}\,(\text{stat.} + \text{syst.}) \pm 7\,(\text{lumi.})\,\text{pb}$$

systematic uncertainty: ~20%

b-tag



- Cross section from SV mass and Jet multiplicity
  - QCD bg (±100% within theory prediction)
  - single top and Z+jets (±30% within theory)
- Dominant systematic errors: Jet energy scale, b-tag, W+jets Q^2-scale
- 3 cross check analyses
  - soft muon tagging in μ+jets
  - counting experiment in e+jets (B/G scaling)
  - neural net with track counting b-tag

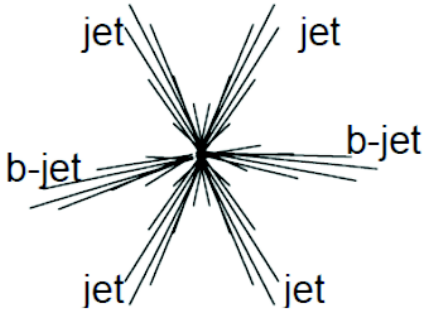
$$\sigma_{t\bar{t}} = 150 \pm 9\,(\text{stat.}) \pm 17\,(\text{syst.}) \pm 6\,(\text{lum.})\,\text{pb}.$$

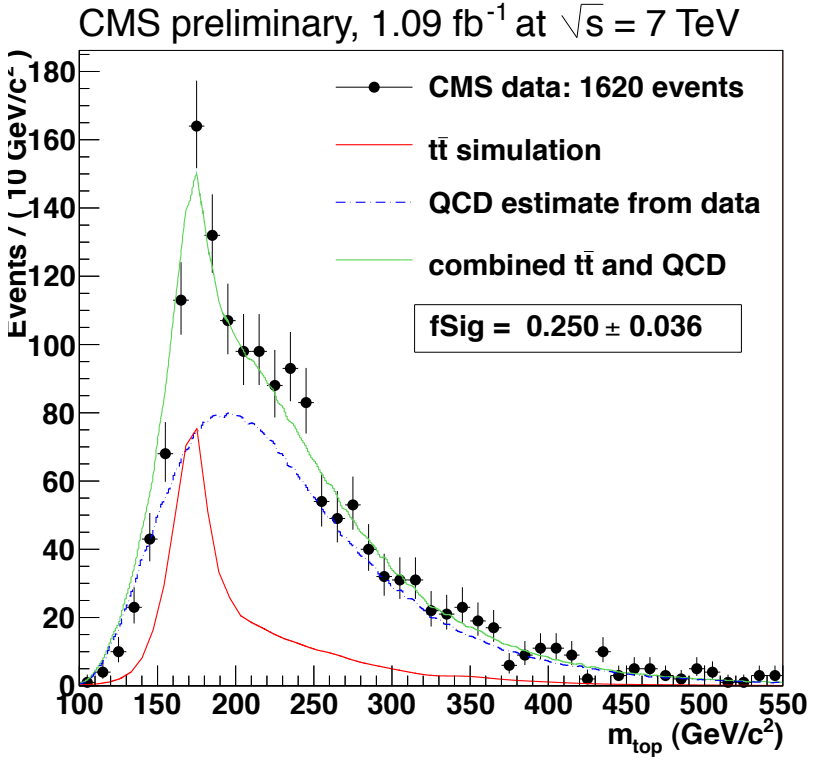
systematic uncertainty: 12%

Hadronic Channel

CMS-TOP-11-007
2011: 1.09 fb^{-1}

- **Event Selection:**
  - Jets (anti-K_T using R = 0.5) within $|\eta|<2.4$
    - ≥ 6 jets with:
      - 4 jets with $p_T > 60$ GeV
      - +1 jet with $p_T > 50$ GeV
      - +1 jet with $p_T > 40$ GeV
    - additional jets considered if $p_T > 30$ GeV
  - ≥ 2 b-tagged jets (high purity):
    - secondary vertex: $N_{tracks} \geq 3$
    - decay length significance $d_B > 2.0$ (efficiency 38%, mis-tag 0.12%)
- **Kinematic Reconstruction:**
  - W from all non-b-tagged jets ($m_W = 80.4$ GeV)
  - reconstruct m(t) from bW pairs ($m_t = m_{tbar}$)
  - select the one combination with minimal χ^2
  - accept event if $P(\chi^2) > 1\%$

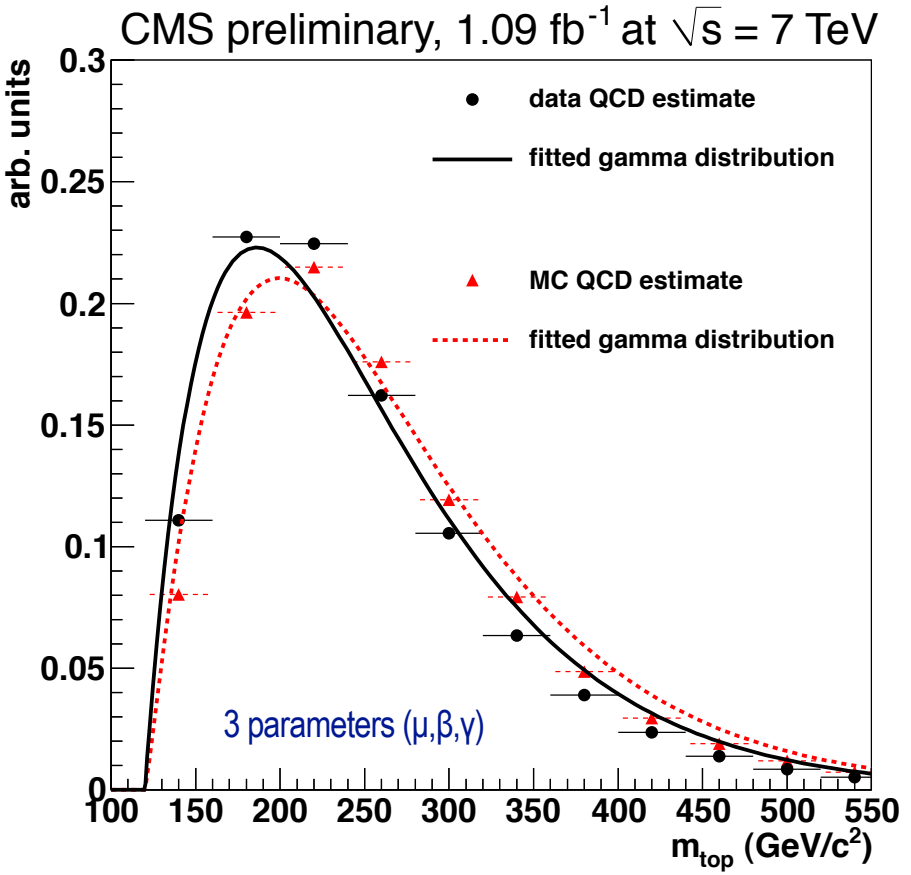




Hadronic Channel

CMS-TOP-11-007
2011: 1.09 fb^{-1}

- Cross section extraction: signal fraction from unbinned likelihood fit to reconstructed top mass distribution
  - signal shape from simulation
  - QCD background shape from data
    - using signal free control sample (0 b-tags)
    - weight non-b-tagged events as function of p_T and η to distribution of b-candidates from kinematic fit
    - systematics: 50% of difference in γ-parameter (±5%)
- Dominant systematics
  - b-tagging (~16%)
  - jet energy scale (~14%)
  - background (~12%)



$$\sigma_{t\bar{t}} = 136 \pm 20\,(\text{stat.}) \pm 40\,(\text{sys.}) \pm 8\,(\text{lumi.})\ \text{pb}$$

systematic uncertainty: 29%

Hadronic Channel (Cross Check)

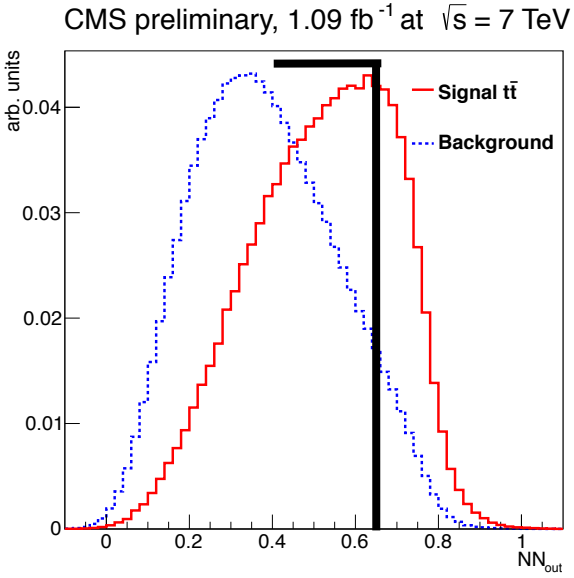
CMS-TOP-11-007

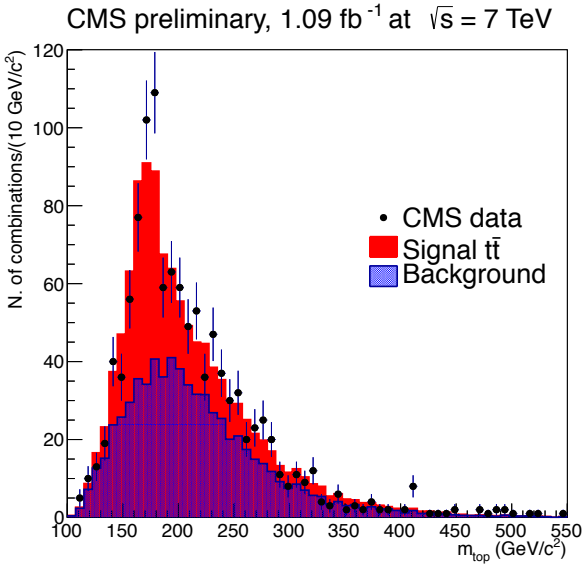
2011: 1.09 fb^{-1}

- **Event Selection**
  - same as main selection: ≥ 6 jets with:
    - 4 jets with p_T > 60 GeV
    - +1 jet with p_T > 50 GeV
    - +1 jet with p_T > 40 GeV
    - veto against more than 8 jets with p_T > 30 GeV
  - ≥ 2 loose b-tags (b-tag track counting algorithm)
- **Neural Network (NN_{out} > 0.65)**
  - 8 input variables: ΣE_T, $\Sigma_3 E_T$, Centrality ($\Sigma E_T/\sqrt{\hat{s}}$), Aplanarity , Sphericity, $E_T^{*1,2}$, $\langle E_T^* \rangle_{3\text{-Njet}}$
- **Kinematic Fit**
  - $\chi^2 \leq 40$
  - ΔR (b-tags) ≥ 1.2
- **Signal fraction from binned max.LL fit to top mass of kinematic fit: 40.3%**

$$\sigma_{t\bar{t}} = 157 \pm 30\ (\text{stat.}) \pm 47\ (\text{sys.}) \pm 9\ (\text{lumi.})\ \text{pb}$$

(cross check result)



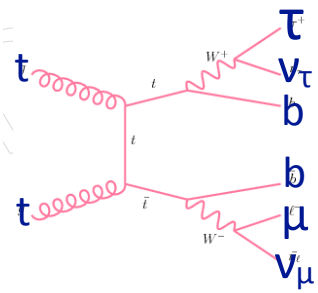


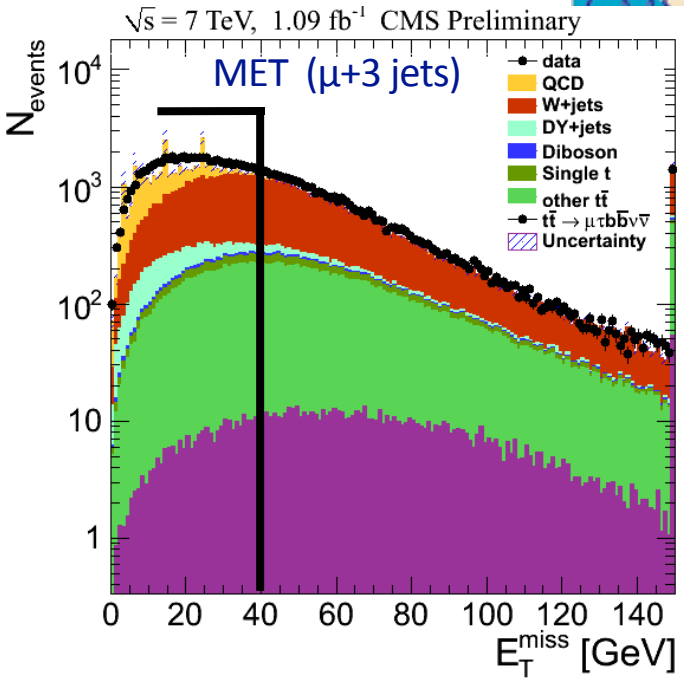
Dilepton (μτ)

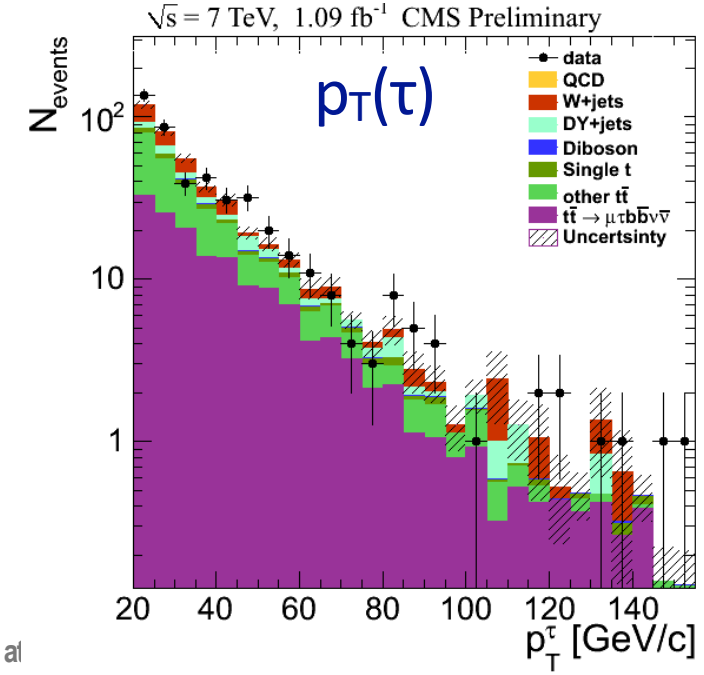
2011 data: 1.09 fb^{-1}
CMS-TOP-11-006

- 1 isolated muon
  - veto against additional isolated μ or e
  - p_T>20 GeV, |η| < 2.1
  - lepton-jet separation: ΔR > 0.3
- ≥ 2 jets
  - p_T>30 GeV, |η|<2.4
- MET> 40 GeV
- ≥ 1 b-tag

- = 1 τ-jet
  - p_T>20 GeV, |η|<2.4, (opp. lepton charge)
  - tau identification τ-jet from hadrons and π^0-strips in a cone ΔR=2.8/p_T
    - charged hadrons (standard Particle Flow)
    - π^0 reconstructed in narrow η-φ 'strips' in ECAL, taking into account photon conversion



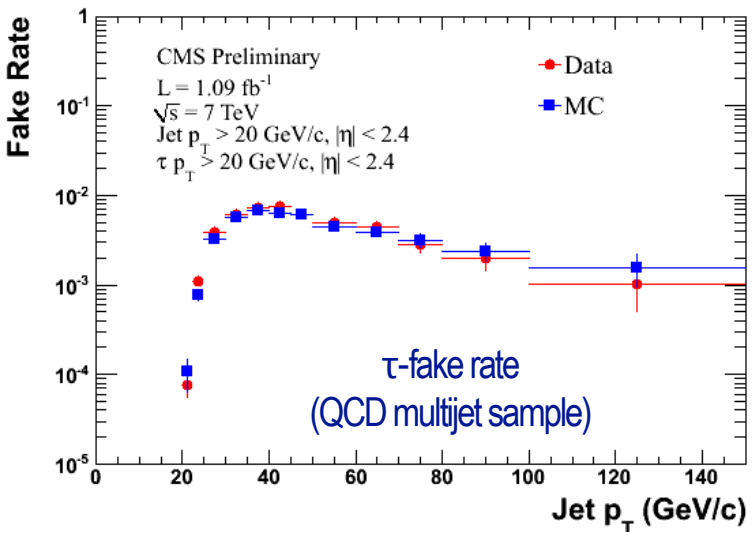


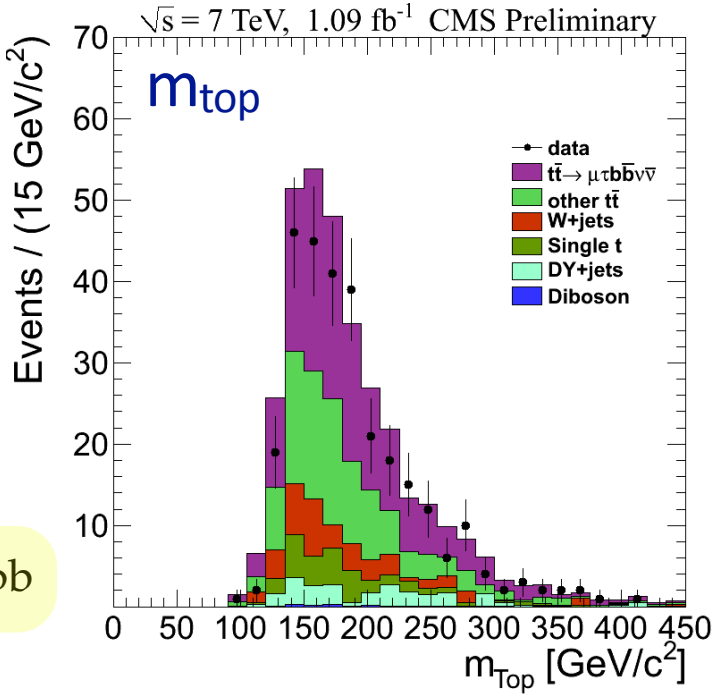


Dilepton (μτ)

2011 data: 1.09 fb^{-1}
CMS-TOP-11-006

- Cross section extraction: count N_{events} above bg
- Backgrounds:
  - τ-fake (estimated from data)
    - mostly from W+jets and tt → l+jets
    - W+ ≥1-jet and multi-jet QCD samples
    - the genuine τ-contribution (18%) within these τ-fake study samples are taken from MC
  - other sources of background (estimated from MC)
    - $Z \rightarrow \tau^+\tau^-$
    - single top
- Dominant systematics
  - τ-fake rate
  - Jet energy scale
  - b-tagging



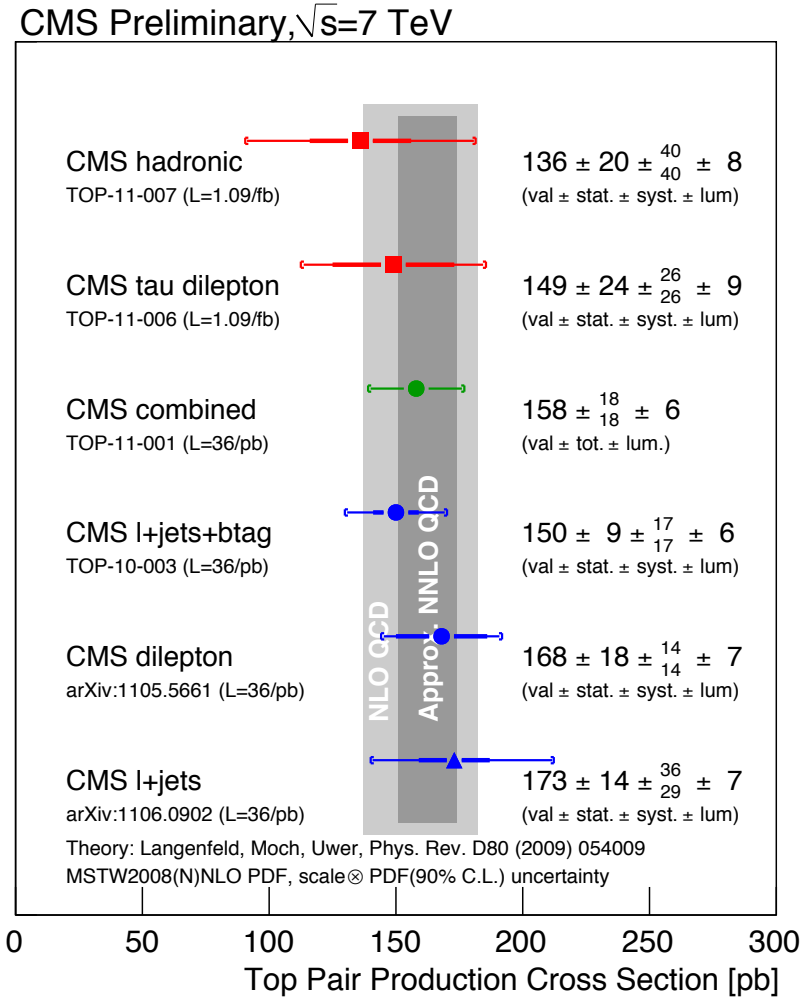


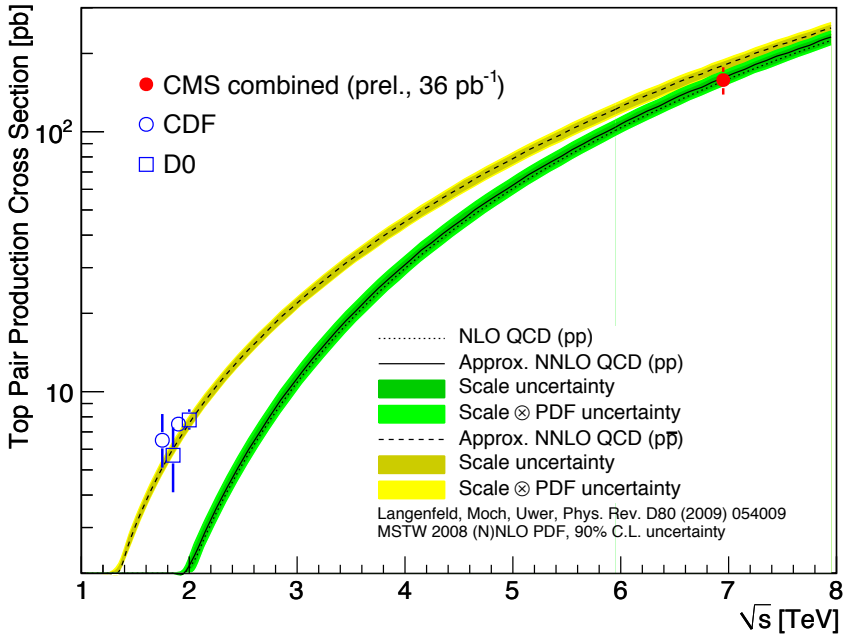
$$\sigma_{t\bar{t}}^{\tau-dil} = 148.7 \pm 23.6(\text{stat.}) \pm 26.0(\text{syst.}) \pm 8.9(\text{lumi.})\ \text{pb}$$

systematic uncertainty: 18%

Combined Results

CMS-TOP-11-001





$$\sigma_{t\bar{t}}^{\mathrm{NLO}}(\mathrm{MCFM}) = 158^{+23}_{-24}\ \mathrm{pb}$$

$$\sigma_{t\bar{t}}^{\mathrm{app.\ NNLO}}(\mathrm{HATHOR}) = 164^{+11}_{-13}\ \mathrm{pb}$$

$$\sigma_{t\bar{t}}^{\mathrm{app.\ NNLO}}(\mathrm{Kidonakis}) = 163^{+11}_{-10}\ \mathrm{pb}$$

'CMS combined': total uncertainty (incl. stat.err.): 12%

relative weights (dilepton / l+jets): 42% / 58%

Data starting to constrain NLO calculations

Summary

- CMS has already performed a full suite of $t\bar{t}$ cross section measurements

- Good agreement with theory, no significant deviations from expectations
- Precision of data already starting to constrain predictions (QCD scales and PDF)

- Two experimentally challenging channels have been measured for the first time (using complete summer 2011 statistics)
  - dilepton channel $\mu\tau$
  - fully hadronic channel

results made possible by excellent CMS detector performance and understanding

- Upcoming top pair cross section measurements:
  - next level of precision
  - differential distributions
  - limited by systematics such as jet energy scale, b-tag, theory uncertainties