Recent Results on Top Quark Physics at CMS

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DESY

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Motivation for top quark physics

- The top quark plays a special role in the electroweak sector and in QCD
  - Heaviest elementary particle known to date
  - Decays before hadronizing: unique window on "bare" quark
  - Top and W masses constrain the Higgs mass

➔ A tool for precise SM studies in the LHC energy regime

- Special role in various beyond SM extensions
  - New physics might be preferentially coupled to top
  - Non-standard couplings between top and gauge bosons
  - New particles can produce/decay to tops

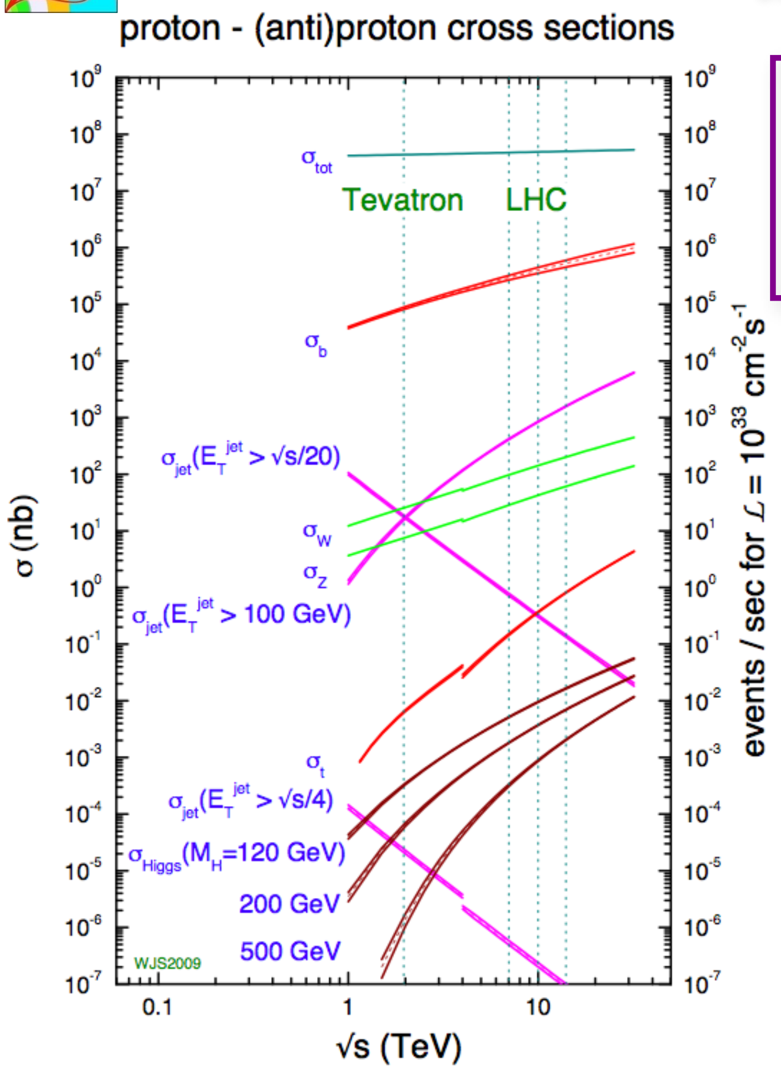
➔ A sensitive probe to new physics

- In addition:

➔ A major source of background for many searches

➔ A tool to understand/calibrate the detector, as all sub-detectors involved

Introduction

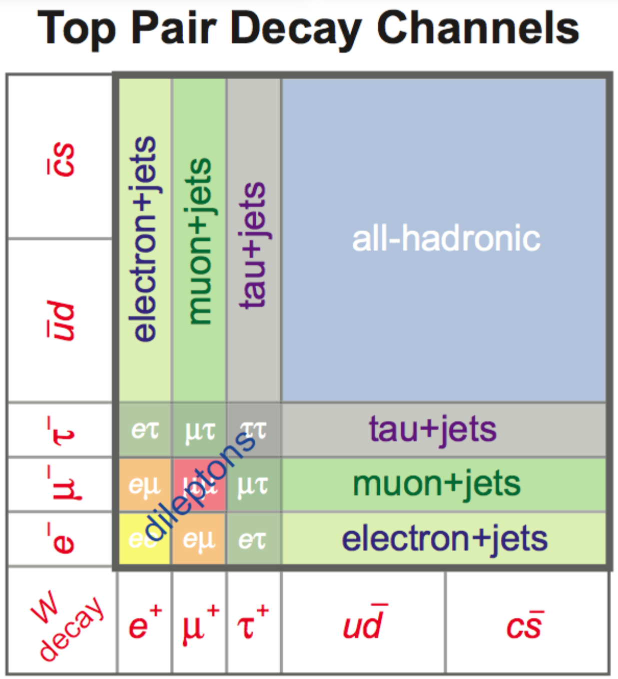


σ_{tt} (LHC) ~ × 20 σ_{tt}(Tevatron)

gg fusion dominates at LHC over $q\bar{q}$

μ/e + jets ~ 34%
1l + 2 b-jets + 2 light-jets +1ν
Good rate, manageable bkg
Main background: W+jets

all-hadronic ~ 46%
High rate, huge bkg
Main background: QCD



dileptons (μ/e) ~ 6%
2l + 2 b-jets + 2ν
Low rate, low background
Main bkg: Drell-Yan

taus ~ 14%
Low rate, high bkg
Main bkg: W+jets, QCD

CMS top quark measurements on 2010 data

CMS public results on the full 2010 pp dataset at $\sqrt{s}$ = 7 TeV: $\mathcal{L}$ **= 35.9 ± 1.4 pb^{-1}**

- Top quark pair cross section measurements:
  - in dileptons (**arXiv:1105.5661** **(*)**)
  - in l+jets without b-tag (**arXiv:1106.0902** **(*)**), with b-tag (**CMS-PAS TOP-10-003**)
  - combination of cross section measurements (**CMS-PAS TOP-11-001**)
- Single top quark cross section measurement (**arXiv:1106.3052** **(*)**)
- Other top quark properties:
  - top mass in dileptons (**arXiv:1105.5661** **(*)**) and in l+jets (**CMS-PAS TOP-10-009**) **NEW !**
  - top pair invariant mass and searches for new physics (**CMS-PAS TOP-10-007**)
  - top pair charge asymmetry (**CMS-PAS TOP-10-010**)

(*) accepted by JHEP, ***(*) submitted to EPJC,*** ***(*) submitted to PRL***

All results shown in this talk are available here:

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

$\sigma(t\bar{t})$ in dileptons arXiv:1105.5661

- First measurement already with only 3 pb^{-1} !

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- Simple *cut-and-count* experiment requiring 2 OS isolated high-p_T leptons, Z veto, jets, E_T^{miss}

- Dedicated data-driven estimates for Drell-Yan and other background events with leptons

- 9 measurements:

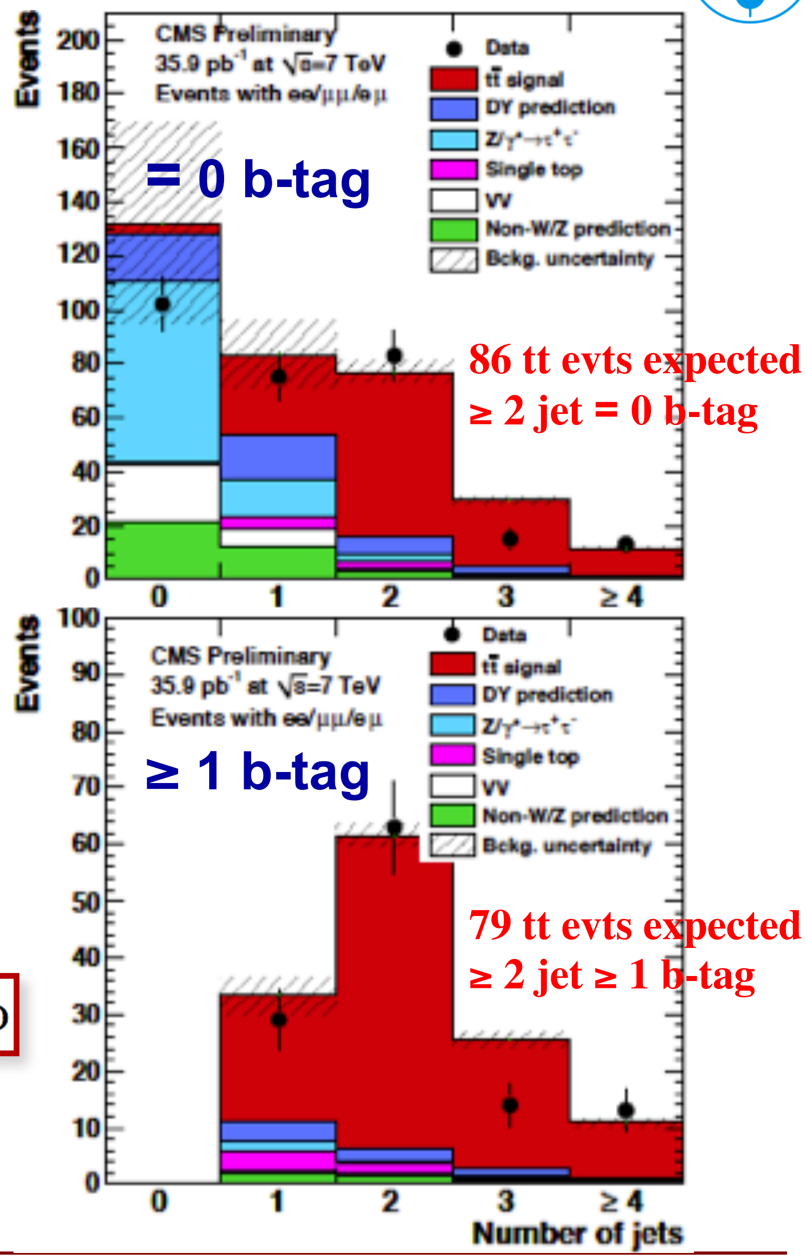
3 channels: **ee, μμ, μe**

3 selections:
- N(jets) ≥ 2, = 0 b-tag
- N(jets) ≥ 2, ≥ 1 b-tag
- N(jets) = 1, = 0-btag

- Combined cross section: 14% precision

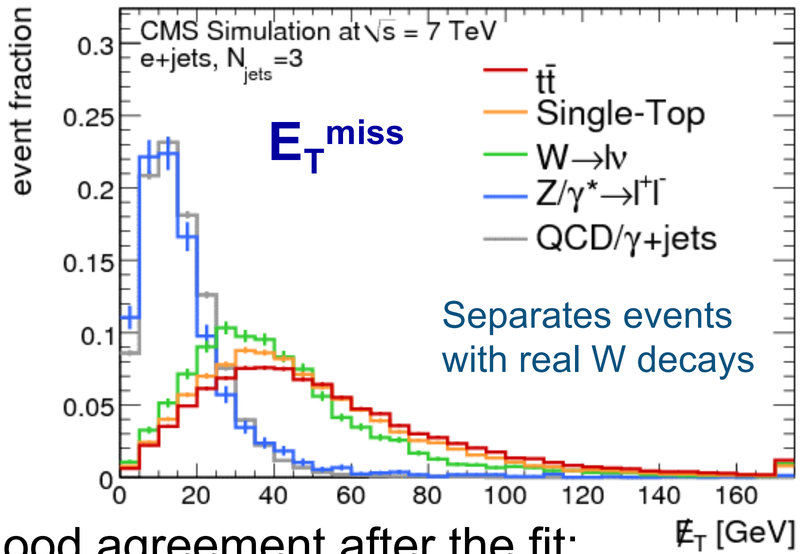
$$\sigma_{t\bar{t}} = 168 \pm 18(\mathrm{stat}) \pm 14(\mathrm{syst}) \pm 7(\mathrm{lumi})\ \mathrm{pb}$$

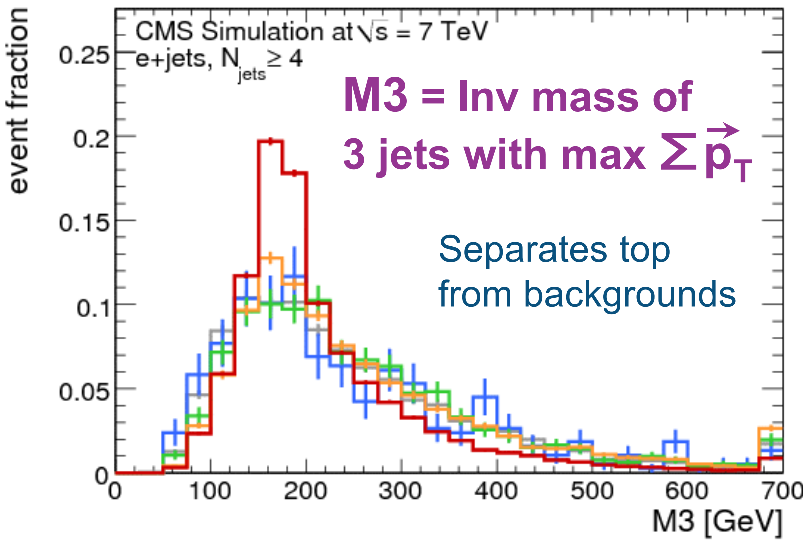
Major systematics: background modelling and b-tagging efficiency



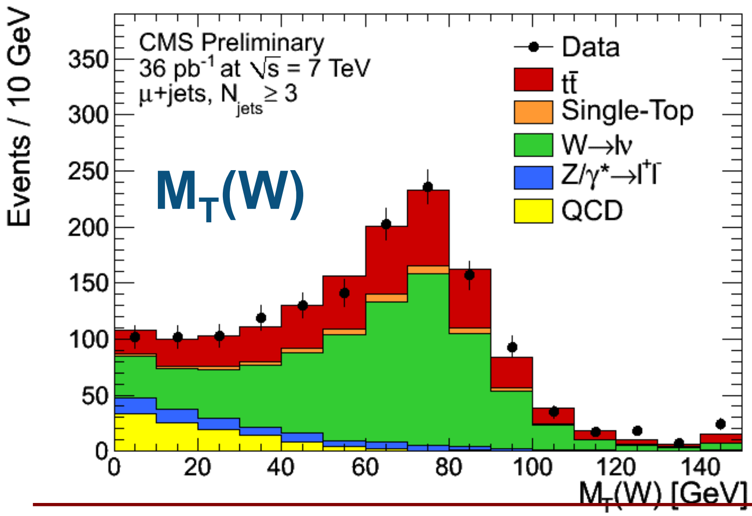
$\sigma(t\bar{t})$ in l+jets without b-tag arXiv:1106.0902

- 1 isolated high-p_T μ/e, veto on additional leptons, ≥ 3 jets (no E_T^{miss} requirement)
- Simultaneous binned likelihood fit to **E_T^{miss} with 3 jets** and **M3 with ≥ 4 jets**





- Good agreement after the fit:



- Measured cross sections:

μ+jets: $\sigma_{t\bar{t}} = 168^{+42}_{-35}(\text{stat.} + \text{syst.}) \pm 7(\text{lumi.})\,\text{pb}$

e+jets: $\sigma_{t\bar{t}} = 180^{+45}_{-38}(\text{stat.} + \text{syst.}) \pm 7(\text{lumi.})\,\text{pb}$

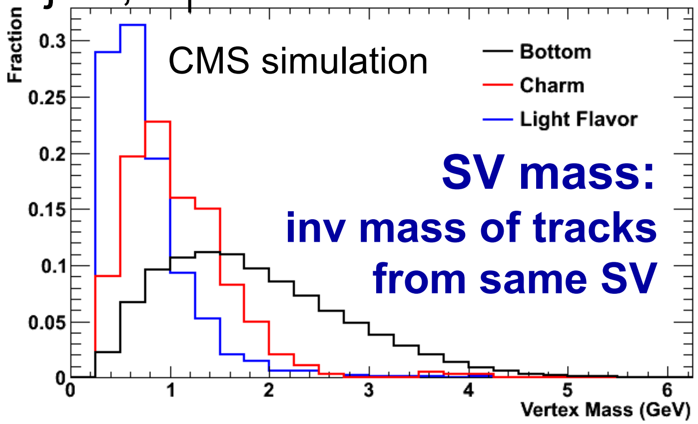
- Combined result: 22% precision

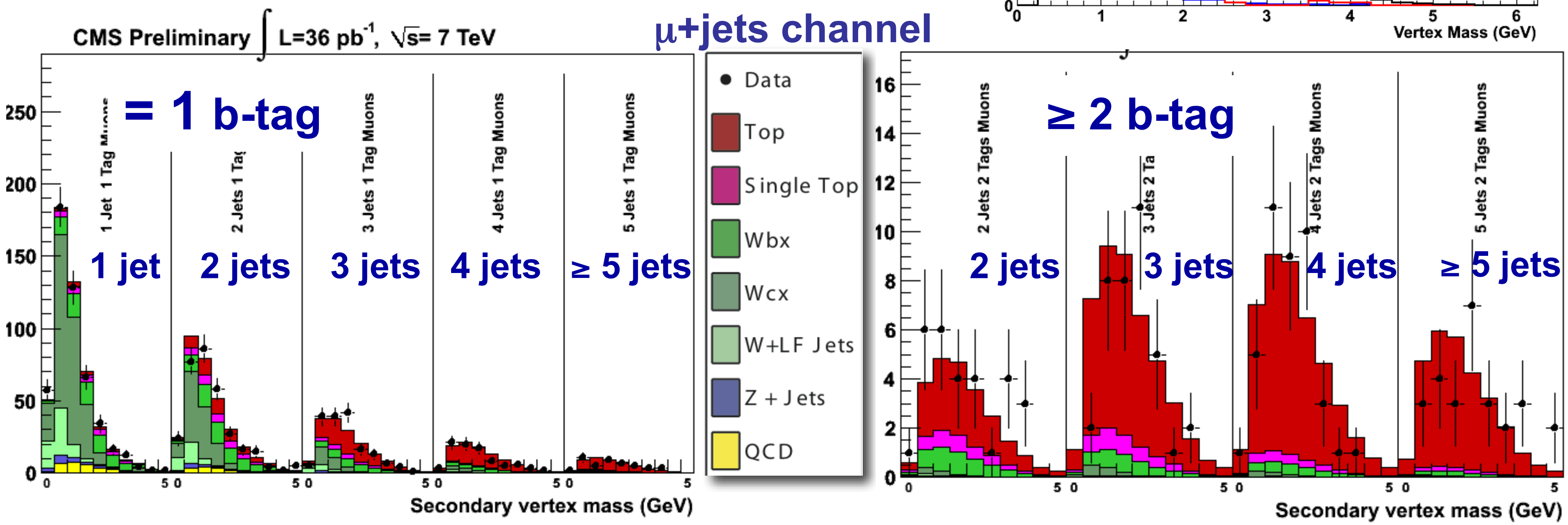
$$\sigma_{t\bar{t}} = 173^{+39}_{-32}(\text{stat} + \text{syst}) \pm 7(\text{lumi})\,\text{pb}$$

Main systematics: jet energy scale (JES)

$\sigma(t\bar{t})$ in l+jets with b-tag CMS-PAS TOP-10-003

- 1 isolated high-p_T μ/e, veto on additional leptons, ≥ 3 jets, E_T^{miss}
- Use only b-tagged events based on displaced secondary vertex
- Binned likelihood fit to secondary vertex (SV) mass
  → separates light from heavy flavour
- Measurement in 9 different jet & b-tag multiplicities





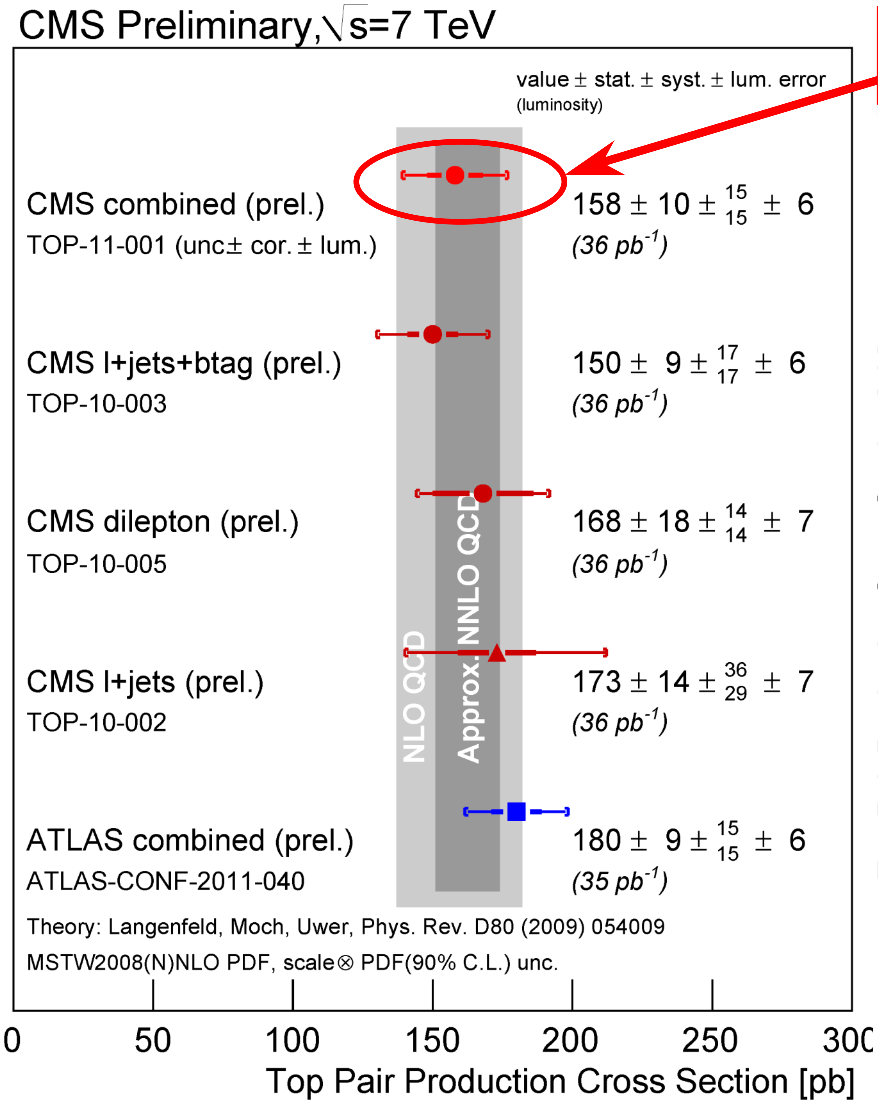
- Combined μ+jets & e+jets cross section: 13% prec.

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

Main systematics, determined from the fit, due to JES, Q^2-scale, b-tag efficiency

Combination of σ(tt̄) results CMS-PAS TOP-11-001

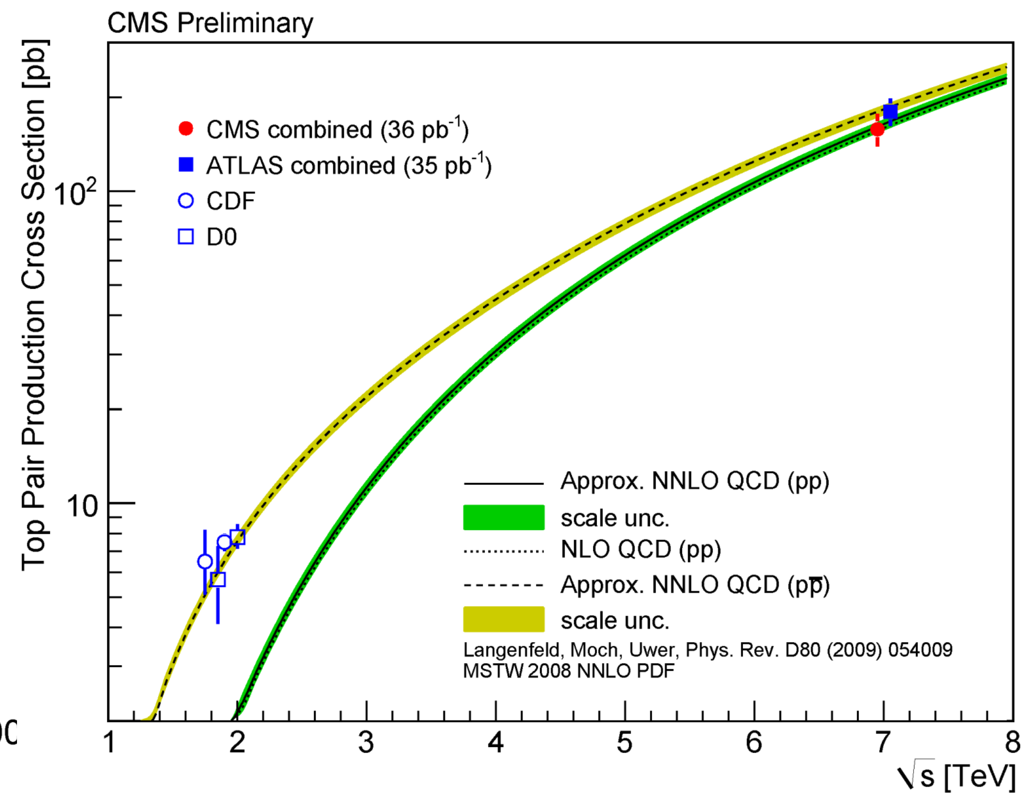
… and comparison with theory predictions



$$\sigma_{t\bar{t}}(\text{CMS}) = 158 \pm 19 \text{ pb.}$$

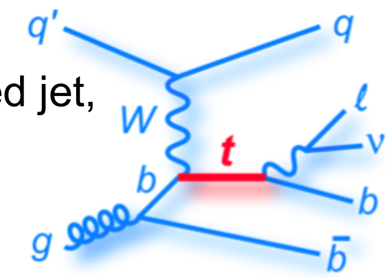
12% precision

All measurements consistent with each other and with SM

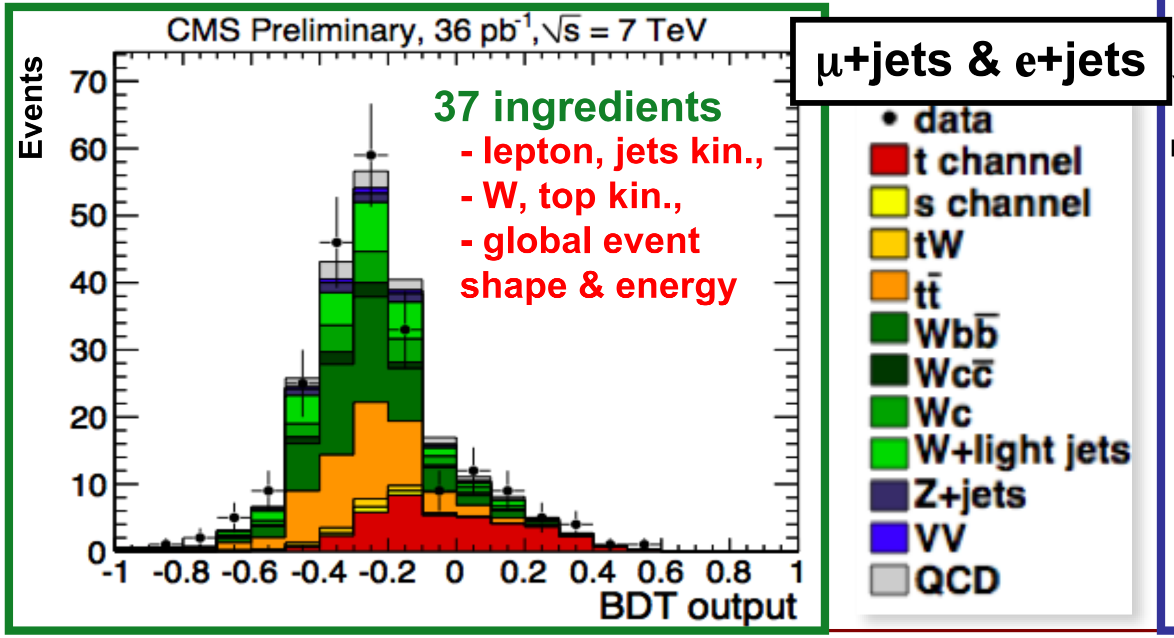


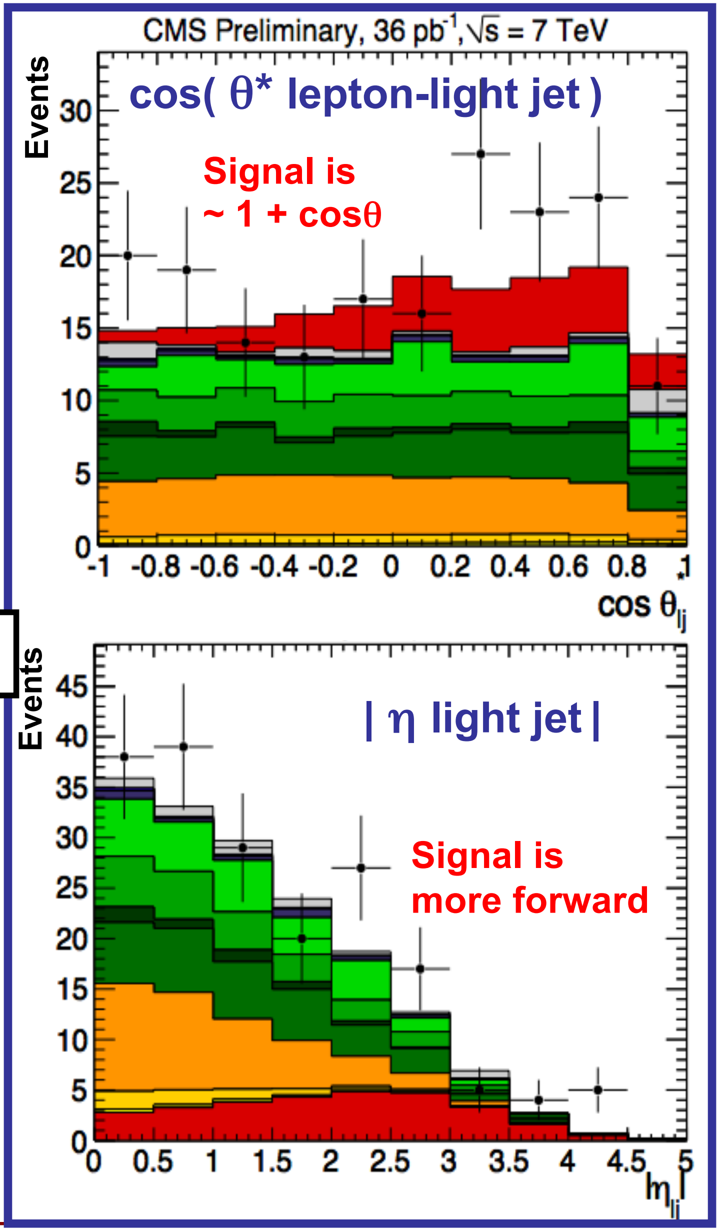
Single top cross section arXiv:1106.3052

- 1st evidence for EWK single top production at LHC!
- t-channel (dominant):
  1 isolated high-p_T μ/e, central b-tagged jet, forward light jet, E_T^{miss}

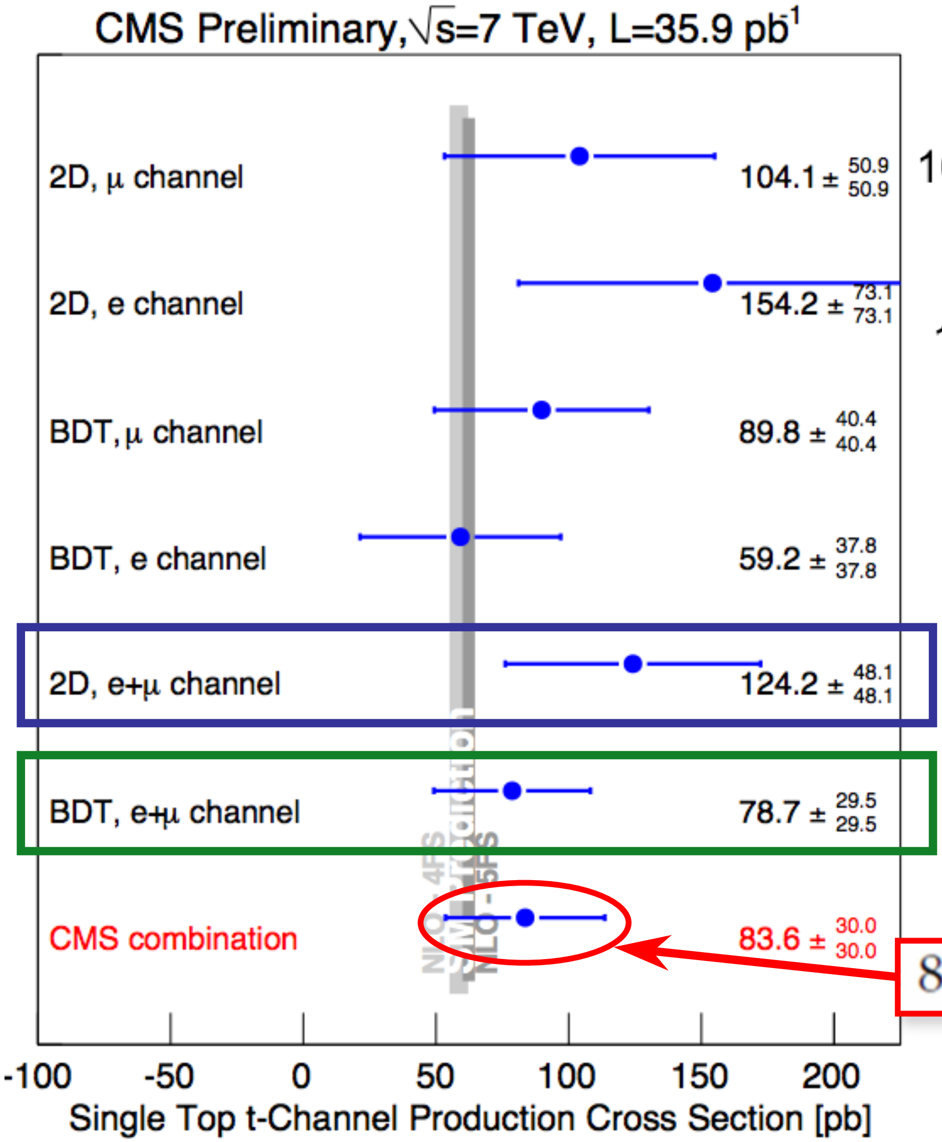


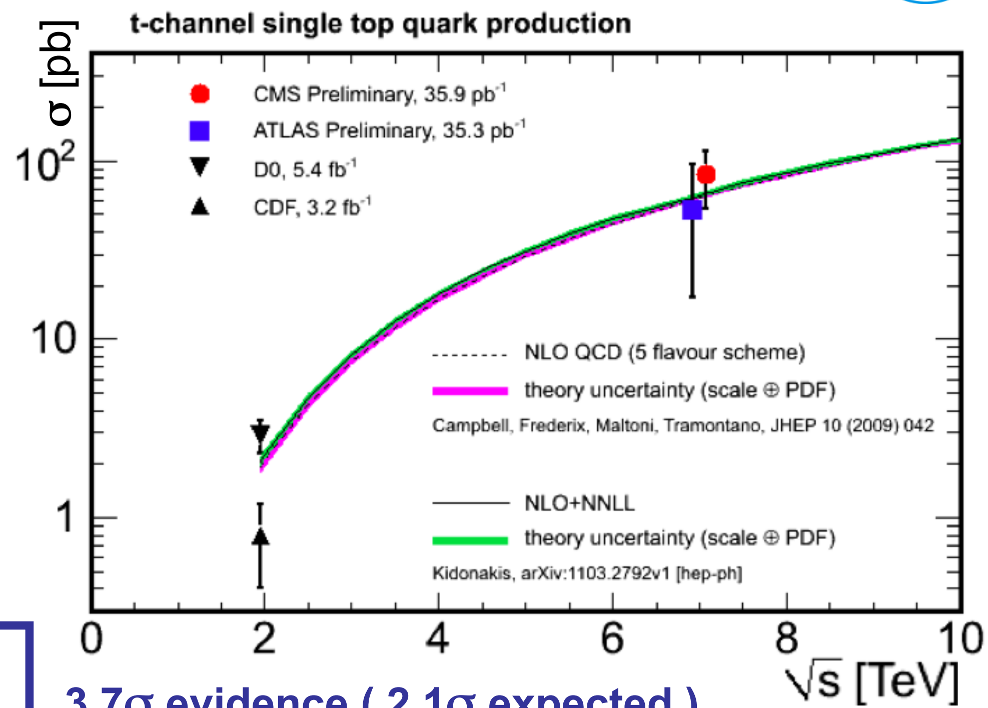
- 2 approaches:
  - 2D likelihood fit to angular signal properties
    → Robust, minimal model dependence
  - 1D likelihood fit to multivariate (BDT) output
    → Fully exploits signal topology, maximizes significance





Single top cross section arXiv:1106.3052





3.7σ evidence (2.1σ expected)

3.5σ evidence (2.9σ expected)

CMS combined cross section: 36% precision

$$83.6 \pm 29.8(stat. + syst.) \pm 3.3(lumi.)\ \text{pb}$$

Main systematics: b-tagging efficiency

All measurements consistent with each other and with SM

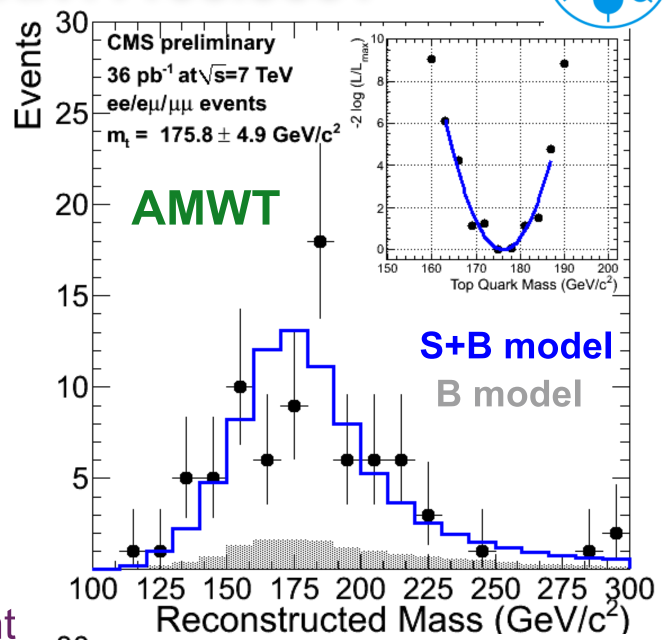
Top mass in dileptons arXiv:1105.5661

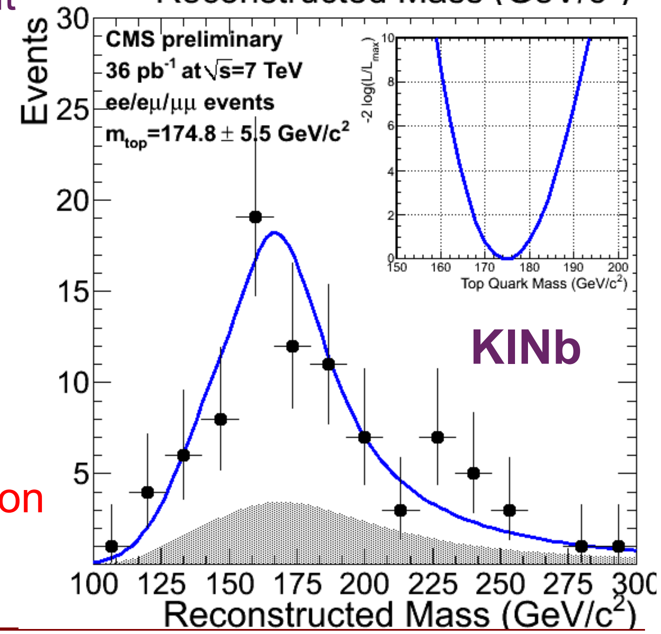
- First top mass measurement at LHC !
- Dilepton (ee, μμ, μe) channel:
  → final state reconstruction still under-constrained after imposing p_T conservation, $m_{top} = m_{antitop}$, M_W constraint
- Two independent methods to constrain further:
  - analytical matrix weighting technique (AMWT)
    Scan values of m_t, weight from PDFs & lepton spectra
  - fully kinematic method (KINb)
    Use p_z(tt) as additional information, b-tag for l-jet assignment
- Template fits to extract m_t from the mass distributions
- Agreement with world average m_t = 173.1 ± 1.1 GeV:

Method	Measured m_{top} (in GeV/c^2)
AMWT	$175.8 \pm 4.9(stat) \pm 4.5(syst)$
KINb	$174.8 \pm 5.5(stat)^{+4.5}_{-5.0}(syst)$
combined	$175.5 \pm 4.6(stat) \pm 4.6(syst)$

4% precision

Dominant systematics: JES





Top mass in l+jets CMS-PAS TOP-10-009 NEW !

Ideogram technique:

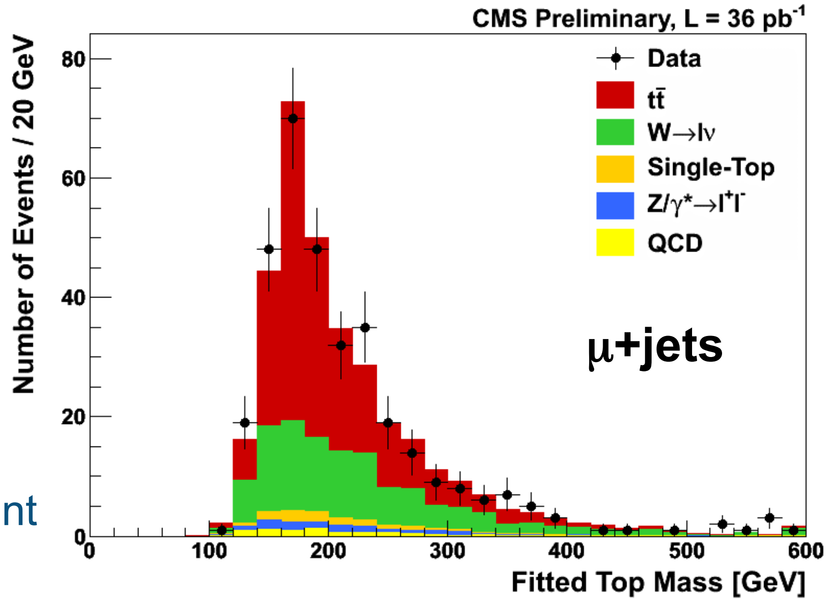
- Constrained kinematic fit of μ/e+jets events requiring $m_{top} = m_{antitop}$ applied to up to 24 jet combinations per event
- Event likelihood as a function of the top quark mass hypothesis taking into account:
  - all possible jet-quark assignments (weighted by χ^2)
  - probability density to be a signal or background event
  - b-tagging information
- Joint likelihood fit over all events to extract m_t
- Combined e+jets & μ+jets:

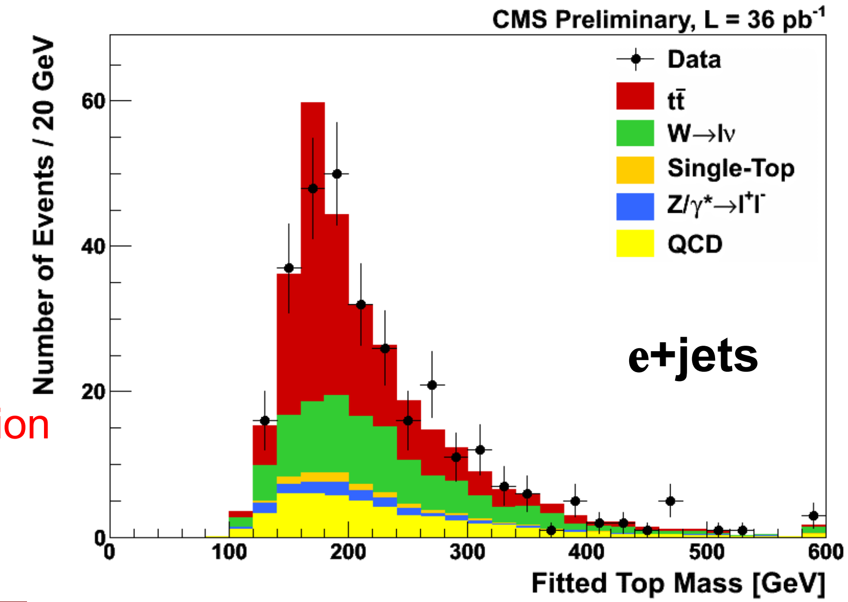
$$m_t = 173.1 \pm 2.1(\text{stat})^{+2.8}_{-2.5}(\text{syst})\ \text{GeV}$$

Dominant systematics: JES

- Combined CMS result (with dilepton): 2% precision

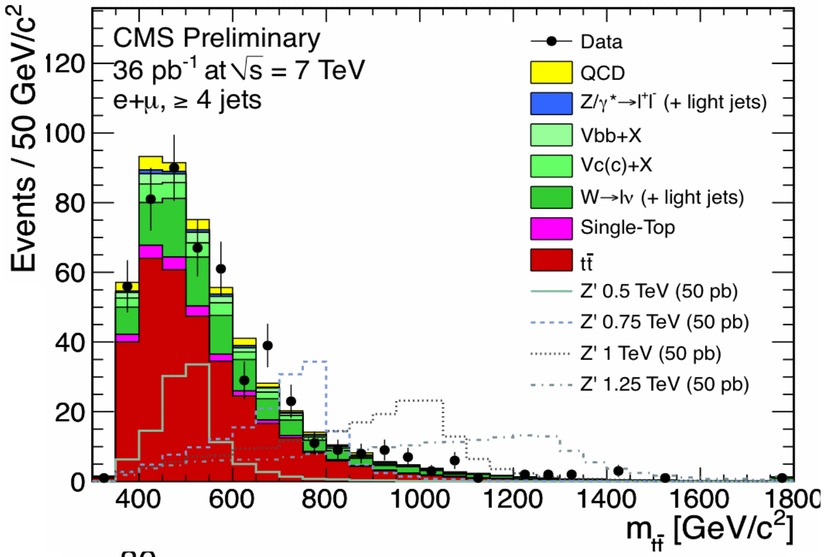
$$m_t = 173.4 \pm 1.9(\text{stat}) \pm 2.7(\text{syst})\ \text{GeV}$$

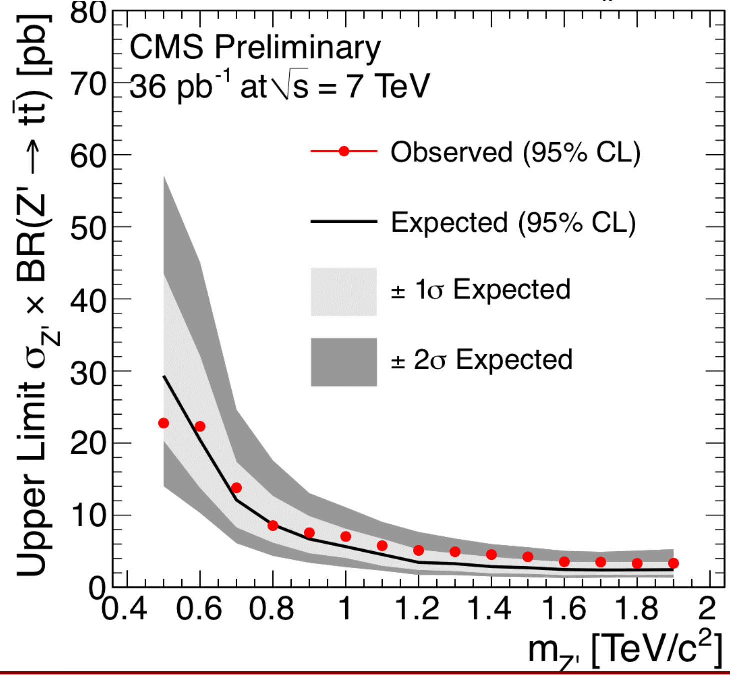




Top-pair invariant mass CMS-PAS TOP-10-007

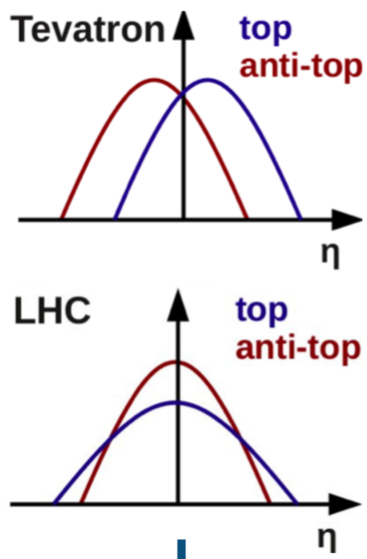
- Search for heavy narrow resonances decaying into top pairs with e/μ+jets in the final state
  → can modify the m_{tt} spectrum from SM predictions
- Energetic & isolated e/μ in an energetic hadronic environment with 2 b-jets
- Reconstruct m_{tt} using a kinematic fit
  - Separate in different lepton flavours and jet & b-tag multiplicities (8 categories)
  - For all relevant processes, use data-driven & MC-based templates
- Likelihood template fit to m_{tt}
- No significant signal observed
  - Limits set for narrow Z'-like particle production at the 95% C.L.
- Already competitive with Tevatron, particularly at higher masses





Charge asymmetry in l+jets CMS-PAS TOP-10-010

Top pair angular production asymmetries are a possible indicator of BSM top production interfering with SM production



- Tevatron: proton-antiproton collider
  - Valence (anti)quarks from certain direction
  - → Forward-backward asymmetry

  Reported a deviation from SM predicted A_{FB} ~ 5%

- LHC: proton-proton collider
  - gg symmetric → SM asymmetries more diluted
  - No valence antiquarks, quarks have higher x on average
  - → Asymmetry in $|\eta_{top}| - |\eta_{antitop}|$=N :

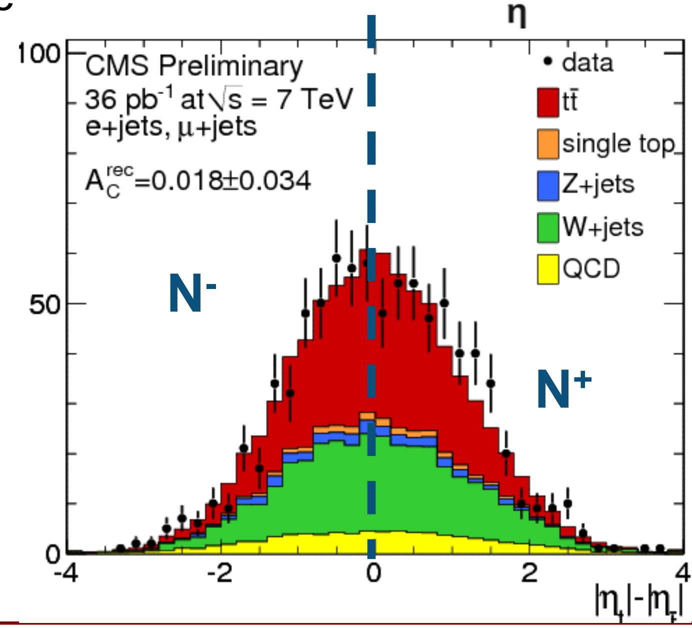
$$A_C = \frac{N^+ - N^-}{N^+ + N^-}$$

- SM prediction: $A_C = 0.0130 \pm 0.0011$
- CMS measurement (unfolded):

$$A_C = 0.060 \pm 0.134(\mathrm{stat.}) \pm 0.026(\mathrm{syst.})$$

Competitive with Tevatron with ~1fb^{-1} of data

First measurement in top pair production in pp !



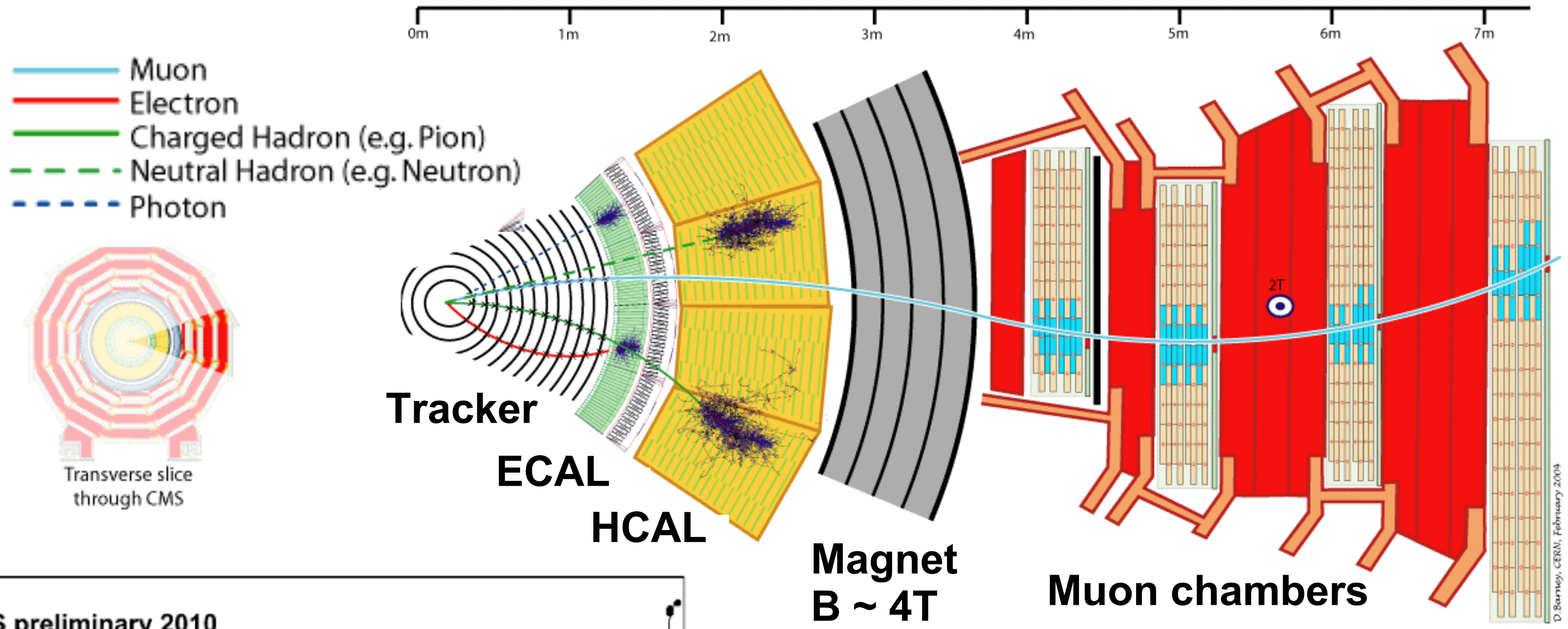
Summary & outlook

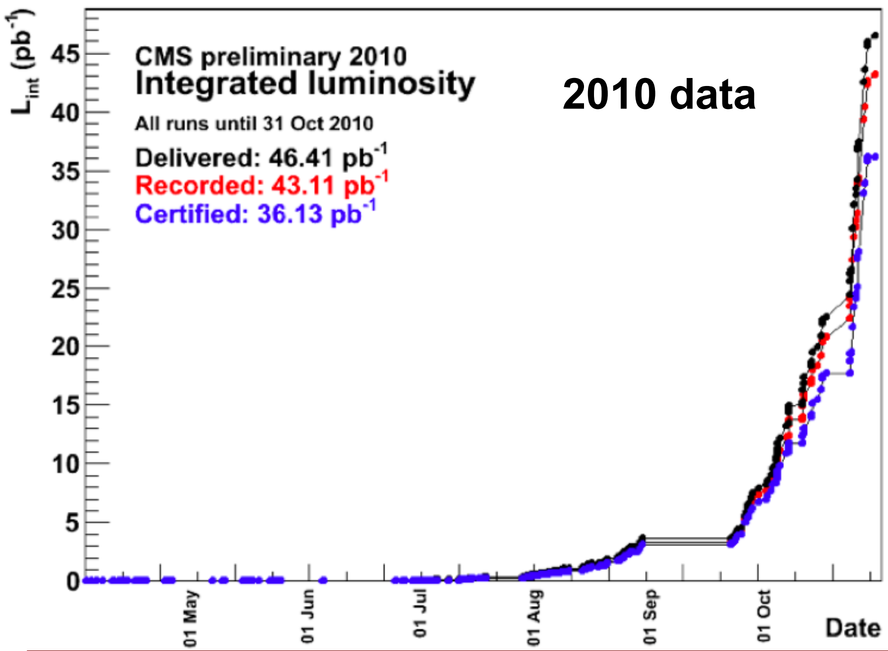
- A lot of interesting results in the top quark sector with only 36 pb^{-1} !
  - **Top-pair cross section in dilepton and lepton+jets channels (12% precision)**
  - **Single top cross section (36% precision)**
  - **Top mass in dilepton and lepton+jets channels (2% precision)**
  - **Top-pair invariant mass ➔ limits on narrow model-independent Z' production**
  - **Charge asymmetry**
- Many new results for summer conferences in the pipeline:
  - **Additional decay channels (all-hadronic, with taus)**
  - **Differential cross sections**
  - **More top-pair and single top properties**
- So far, good agreement with SM predictions, but already ~1 fb^{-1} 2011 data collected

. . . this is only the beginning . . . ☺

Additional information

The CMS experiment





2010 data

~ 100M channels, > 98% operational

Detector	Resolution	Coverage
Tracker	$\sigma(p_T)/p_T$~1.5%p_T+0.005	$\|\eta\|<2.4$
Ecal	$\sigma(E)/E$~3%/√E+0.003	$\|\eta\|<3$
Hcal	$\sigma(E)/E$~100%/√E+0.05 GeV	$\|\eta\|<3$ (b) / 5 (f)
Muon	$\sigma(p_T)/p_T$~1-10%p_T	$\|\eta\|<2.4$

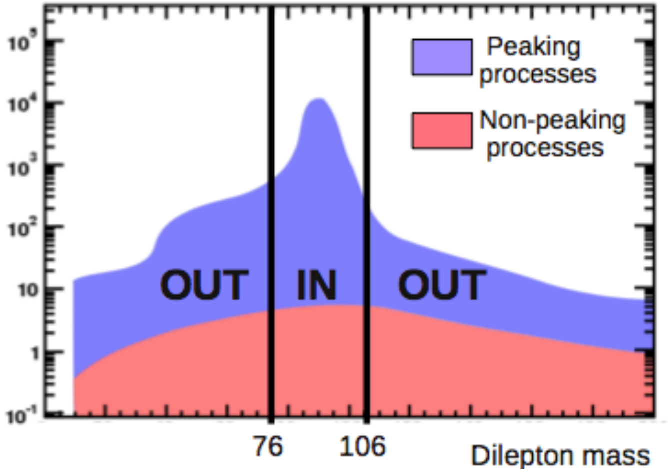
More info: Bckg estimation in dileptons

- Background estimation from simulation:

  single top (tW), semileptonic ttbar, diboson, $Z/\gamma^* \rightarrow \tau^+\tau^-$

- Background estimation from data:

1) Drell-Yan :



Estimation of the contribution outside the Z-veto region using the number of events inside the Z-veto region

$$N^{out}_{Z/\gamma^*} = R_{out/in} \cdot (N^{in}_{\mu^+\mu^-} - k \cdot N^{in}_{e^\pm\mu^\pm})$$

from simulation, $R_{out/in} = N_{out}(\mathrm{DY\ MC}) / N_{in}(\mathrm{DY\ MC})$

non-peaking processes from eμ channel data corrected for lepton eff (k_{ll})

2) Non W/Z decays lepton ("fakes") : QCD multijet, W+jets

Estimation of the contribution of fake leptons, N^{Tight}_{QCD} , using the number of events in a sample with loose identification requirement, N^{Loose}_{QCD}

$$N^{Tight}_{QCD} = R_{TL} \cdot N^{Loose}_{QCD}$$

R_{TL} = Probability that a loose lepton passes the tight selection. Determined from a multijet sample

More info: Bckg estimation in dileptons

Drell-Yan contribution

Sample	$N_{jet} = 1$	$N_{jet} \geq 2$
e^+e^-: $\not{E}_T > 50$ GeV in $N_{jet} = 1$, $\not{E}_T > 30$ GeV in $N_{jet} \geq 2$		
Simulated	0.1 ± 0.1	1.7 ± 0.3
$R_{out/in}$	0.13 ± 0.13	0.14 ± 0.03
Estimate from data	0.2 ± 0.3	3.0 ± 1.8
$\mu^+\mu^-$: $\not{E}_T > 50$ GeV in $N_{jet} = 1$, $\not{E}_T > 30$ GeV in $N_{jet} \geq 2$		
Simulated	1.4 ± 0.3	3.3 ± 0.5
$R_{out/in}$	1.1 ± 0.3	0.22 ± 0.03
Estimate from data	5.2 ± 3.4	7.4 ± 4.1
e^+e^-: with b tagging, $\not{E}_T > 30$ GeV		
Simulated	0.16 ± 0.07	0.6 ± 0.2
$R_{out/in}$	0.08 ± 0.04	0.14 ± 0.05
Estimate from data	0.6 ± 0.5	0.7 ± 0.7
$\mu^+\mu^-$: with b tagging, $\not{E}_T > 30$ GeV		
Simulated	0.8 ± 0.2	1.3 ± 0.3
$R_{out/in}$	0.27 ± 0.08	0.23 ± 0.05
Estimate from data	2.9 ± 1.9	2.6 ± 1.8

Non-W/Z contribution

Selection	$N_{jet} = 1$	$N_{jet} \geq 2$
e^+e^-: $\not{E}_T > 50$ GeV in $N_{jet} = 1$, $\not{E}_T > 30$ GeV in $N_{jet} \geq 2$		
Simulated	1.0 ± 0.3	0.6 ± 0.1
Estimate in data	0.3 ± 0.3	1.1 ± 1.4
$\mu^+\mu^-$: $\not{E}_T > 50$ GeV in $N_{jet} = 1$, $\not{E}_T > 30$ GeV in $N_{jet} \geq 2$		
Simulated	0.1 ± 0.1	0.1 ± 0.1
Estimate in data	0.1 ± 0.3	0.6 ± 1.1
$e^\pm\mu^\mp$:		
Simulated	1.0 ± 0.3	1.6 ± 0.3
Estimate in data	1.3 ± 0.8	1.4 ± 1.6
e^+e^-: with b tagging, $\not{E}_T > 30$ GeV		
Simulated	0.3 ± 0.1	0.3 ± 0.1
Estimate in data	0.3 ± 0.5	0.9 ± 1.2
$\mu^+\mu^-$: with b tagging, $\not{E}_T > 30$ GeV		
Simulated	0.0 ± 0.1	0.1 ± 0.1
Estimate in data	0.1 ± 0.3	0.3 ± 0.8
$e^\pm\mu^\mp$: with b tagging		
Simulated	0.3 ± 0.1	1.0 ± 0.1
Estimate in data	1.3 ± 1.1	0.5 ± 1.1

More info: $t\bar{t}$ cross section in dileptons

Systematics

Table 3: Summary of systematic uncertainties relative to the rate of selected signal events estimated for the full signal selection. All values are in per cent. Systematic uncertainties on the lepton selection are treated separately for e^+e^- and $\mu^+\mu^-$ final states. Except for the lepton selection, values for all modes of a single source are treated as 100% correlated: the negative sign denotes anti-correlation. Different sources are treated as uncorrelated.

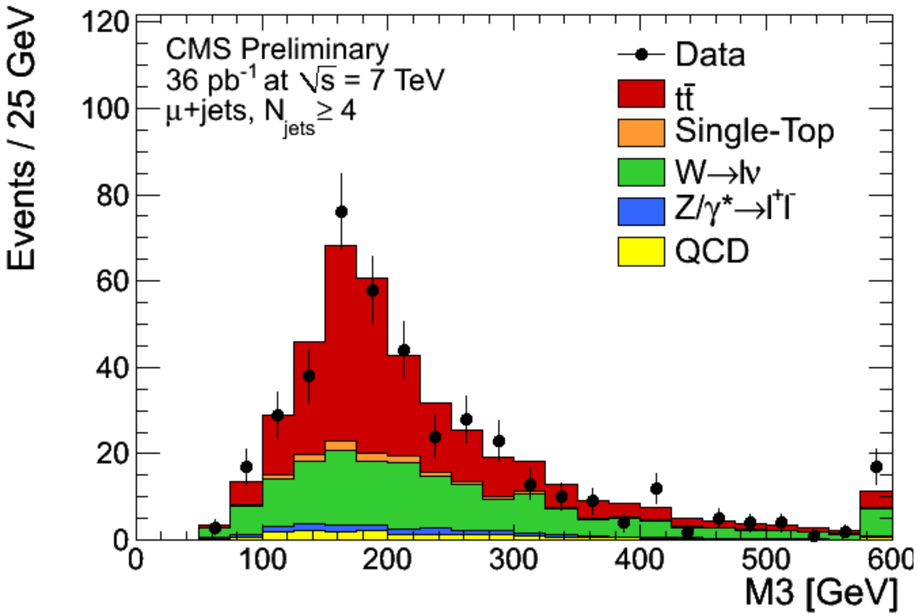
Source	$N_{jet} = 1$ $e^+e^- + \mu^+\mu^-$	$N_{jet} = 1$ $e^\pm\mu^\mp$	$N_{jet} \geq 2$ $e^+e^- + \mu^+\mu^-$	$N_{jet} \geq 2$ $e^\pm\mu^\mp$
Lepton selection	1.91/1.30	1.11	1.91/1.30	1.11
Energy scale	−3.0	−5.5	3.8	2.8
Lepton selection model	4.0	4.0	4.0	4.0
Branching ratio	1.7	1.7	1.7	1.7
Decay model	2.0	2.0	2.0	2.0
Event Q^2 scale	8.2	10	−2.3	−1.7
Top-quark mass	−2.9	−1.0	2.6	1.5
Jet and $\not{E}_T$ model	−3.0	−1.0	3.2	0.4
Shower model	1.0	3.3	−0.7	−0.7
Pileup	−2.0	−2.0	0.8	0.8
Subtotal (before tags)	11.2/11.1	13.1	8.0/7.9	6.2
b tagging ($\geq$ 1 b tag)			5.0	5.0
Subtotal with tags			9.5/9.4	8.0
Luminosity	4	4	4	4

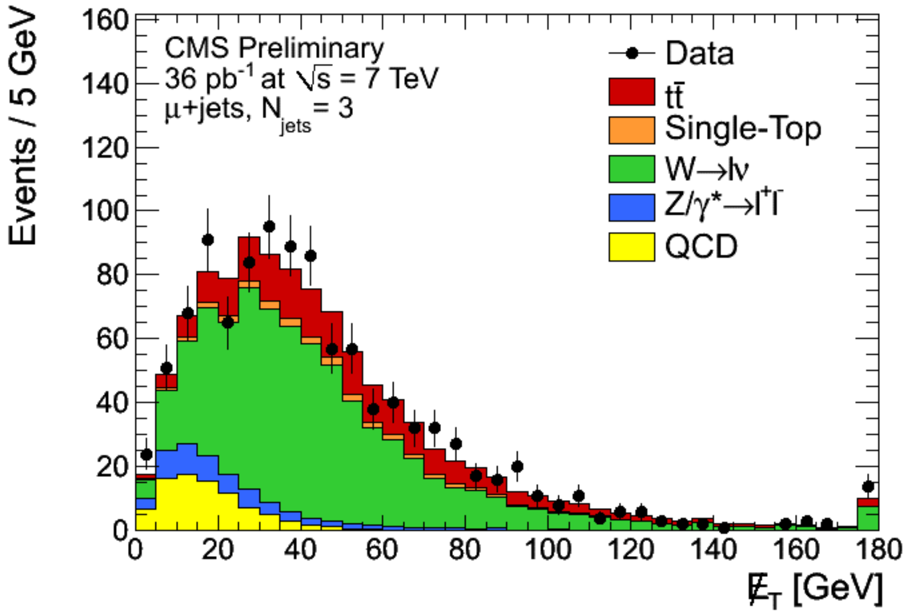
More info: $t\bar{t}$ cross section in l+jets w/o btag

- 2D binned likelihood fit to E_T^{miss} with 3 jets and M3 with ≥ 4 jets
- Templates for E_T^{miss} and M3 for signal and background obtained from simulation, except for QCD (data-driven)

6 parameters floating in the fit: signal + 5 background

	$\beta_{t\bar{t}}$	N_{ST}	N_{W+jets}	N_{Z+jets}	N_{QCD} e+jets	N_{QCD} μ+jets
predicted	1.00	72 ± 4	1069 ± 77	138 ± 10	367 ± 27	58 ± 4
fitted	1.10	76 ± 22	1475 ± 86	184 ± 51	440 ± 44	113 ± 31





More info: $t\bar{t}$ cross section in l+jets w/o btag

Systematics

	stat.+syst. uncertainty	
Stat.+bkg. uncertainty	−8.4%	+8.7%
JES	−17.6%	+20.3%
JER	−8.4%	+8.8%
ISR/FSR variation	−8.6%	+9.0%
Factorization scale	−10.6%	+11.2%
Matching threshold	−9.8%	+10.5%
Branching ratio	−8.6%	+8.9%
Efficiencies (from T&P)	−8.7%	+9.2%
QCD rate & shape	−8.9%	+9.1%
Lepton scale	−8.4%	+8.7%
PDF uncertainty	−8.5%	+8.7%
Pile-up	−9.3%	+9.3%
Total	−19.3%	+23.5%

More info: $t\bar{t}$ cross section in l+jets w btag

- Fit separately lepton flavour (electron, muon), number of jets (1, 2, 3, 4, ≥ 5) and number of tags (1, ≥ 2)

$$\underbrace{\mathcal{N}_i^{\mathrm{pred}}(\mathrm{lept},\mathrm{jets},\mathrm{tag})}_{\text{Number of predicted events}} = \overbrace{k_i}^{\text{Scale factor for the simulated cross section}} \cdot \underbrace{N_i^{\mathrm{MC}}(\mathrm{lept},\mathrm{jets},\mathrm{tag})}_{\text{Number of events predicted by MC corrected for Data/MC discrepancies}} \cdot \prod_X \underbrace{P_i^{\mathrm{X}}(\mathrm{lept},\mathrm{jets},\mathrm{tag}|\overbrace{\mathcal{R}_{\mathrm{X}}}^{\text{Nuisance parameter}})}_{\text{Polynomial functions}}$$

Scale factor for the simulated cross section

Nuisance parameter, where X can be: b-tag efficiency, JES, Q² scale

Number of predicted events

Number of events predicted by MC corrected for Data/MC discrepancies

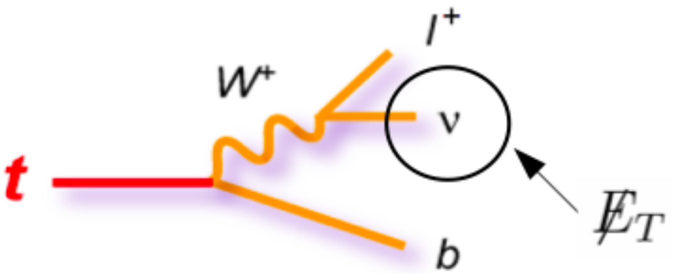
Polynomial functions describing the effect of the nuisance parameter, obtained from MC

- Most important systematics are included as parameters in the fit → their impact is reduced

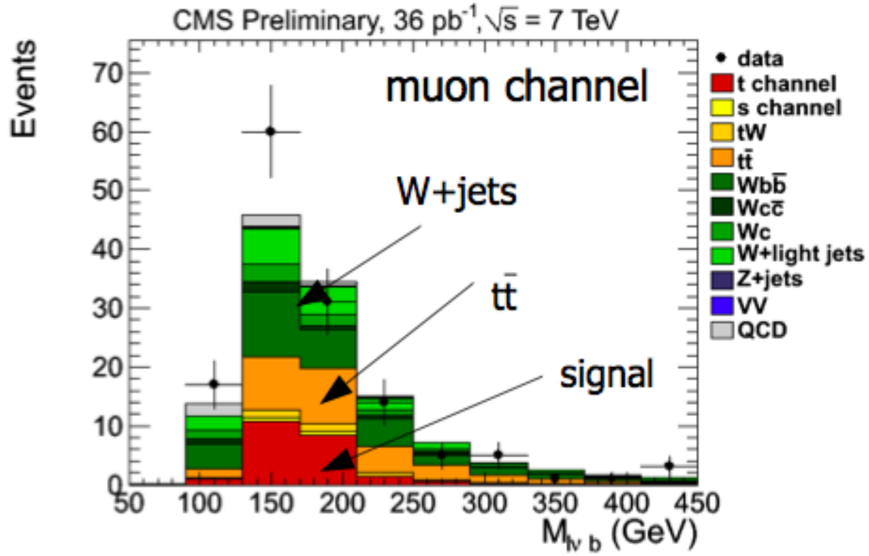
Systematics combined mu/e

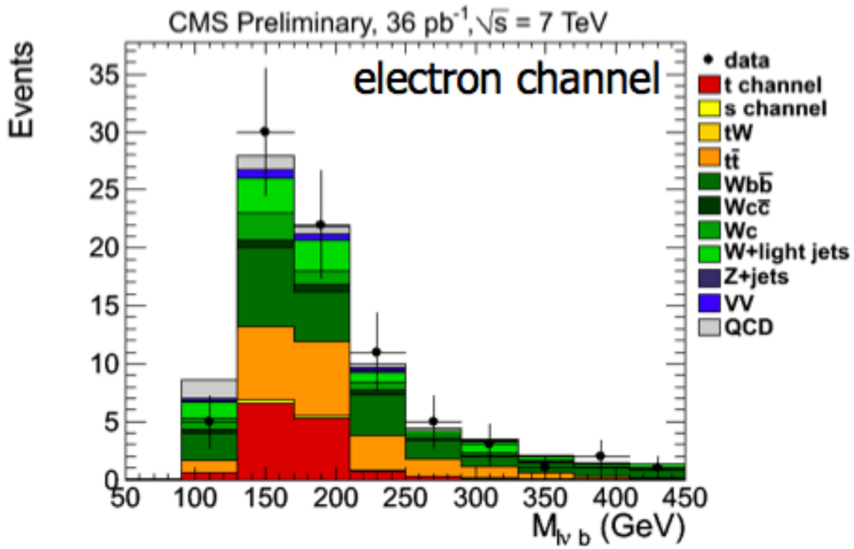
Source	Uncertainty (%)
Systematic uncertainties	
Lepton ID/reco/trigger	3
Unclustered E_T^{miss} resolution	< 1
$t\bar{t}$+ Jets Q^2-scale	2
ISR/FSR	2
ME to PS matching	2
PDF	3.4
Profile likelihood parameters	
Jet energy scale and resolution	7.0
b tag efficiency	7.5
W+Jets Q^2-scale	9.1
Combined	11.6

More info: single top



- Solve neutrino z-momentum
- W boson mass constraint
  - real solutions: smaller |p_z|
  - complex solution: minimally modify MEx and MEy





Still rather small signal to background ratio: Complementary methods

→ Exploit two characteristic features of Single top quark production (**2D analysis**)

→ Use MVA technique Boosted Decision Trees for further separation (**BDT analysis**)

More info: single top

Event yield summary

Process	2D, μ channel	2D, e channel	BDT, μ channel	BDT, e channel
single top, t channel	17.6 ± 0.7 (†)	11.2 ± 0.4 (†)	17.6 ± 0.7 (†)	10.7 ± 0.5 (†)
single top, s channel	0.9 ± 0.3	0.6 ± 0.2	1.4 ± 0.5	1.0 ± 0.3
single top, tW	3.1 ± 0.9	2.4 ± 0.7	3.8 ± 1.1	< 0.1
WW	0.29 ± 0.09	0.23 ± 0.07	0.32 ± 0.10	0.23 ± 0.07
WZ	0.24 ± 0.07	0.17 ± 0.05	0.33 ± 0.10	1.5 ± 0.4
ZZ	0.018 ± 0.005	0.011 ± 0.003	0.020 ± 0.006	< 0.1
$W+$ light partons	18.2 ± 5.5	11.6 ± 2.3	8.4 ± 4.2	7.0 ± 3.5
$Z + X$	1.7 ± 0.5	1.6 ± 0.3	0.7 ± 0.2	0.05 ± 0.03
QCD	0.6 ± 0.3	$2.6^{+3.4}_{-2.6}$	4.9 ± 2.5	5.3 ± 5.3
$VQ\bar{Q}$	20.4 ± 10.2	14.1 ± 7.1	17.6 ± 8.8	11.7 ± 5.8
Wc	$12.9^{+12.9}_{-6.5}$	$9.4^{+9.4}_{-4.7}$	$9.2^{+9.2}_{-4.6}$	$5.9^{+5.9}_{-2.9}$
$t\bar{t}$	20.3 ± 3.6	15.6 ± 2.8	34.9 ± 4.9	22.9 ± 3.2
Total background	78.6 ± 15.2	58.4 ± 11.0	82.4 ± 13.1	55.9 ± 10.2
Signal + background	96.2 ± 15.3	69.6 ± 11.0	100.0 ± 13.2	66.6 ± 10.2
Data	112	72	139	82

More info: single top

Systematics combined mu/e (given in %)

uncertainty	correlation	impact on 2D −	impact on 2D +	impact on BDT −	impact on BDT +
statistical only	60	52		39	
shared shape/rate uncertainties:					
ISR/FSR for $t\bar{t}$	100	−1.0	+1.5	< 0.2	< 0.2
Q^2 for $t\bar{t}$	100	+3.5	−3.5	+0.3	−0.4
Q^2 for V+jets	100	+5.7	−12.0	+2.6	−4.5
Jet energy scale	100	−8.8	+3.6	−5.1	+1.2
b tagging efficiency	100	−19.6	+19.8	−15.2	+14.6
MET (uncl. energy)	100	−5.7	+3.7	−3.9	−0.5
shared rate-only uncertainties:					
$t\bar{t}$ (±14%)	100	+2.0	−1.9	+0.5	−0.6
single top s (±30%)	100	−0.4	+0.5	−0.4	+0.4
single top tW (±30%)	100	+1.1	−1.0	< 0.2	< 0.2
$Wb\bar{b}$, $Wc\bar{c}$ (±50%)	100	−3.0	+2.9	+1.7	−1.9
Wc ($^{+100\%}_{-50\%}$)	100	−3.0	+6.1	−2.4	+4.4
Z+jets (±30%)	100	−0.6	+0.7	+0.4	−0.2
electron QCD (BDT: ±100%, 2D: $^{+130\%}_{-100\%}$)	50	+2.9	−3.7	−1.7	+1.7
muon QCD (BDT: ±50%, 2D: ±50%)	50	< 0.2	< 0.2	−2.1	+2.1
signal model	100	−5.0	+5.0	−4.0	+4.0
BDT-only uncertainties:					
electron efficiency (±5%)	0	—	—	−1.4	+1.4
muon efficiency (±5%)	0	—	—	−3.6	+3.5
V+jets (±50%)	0	—	—	−1.5	< 0.2
2D-only uncertainties:					
muon W+light (±30%)	0	−1.4	+1.4	—	—
electron W+light (±20%)	0	−0.6	+0.7	—	—
W+light model uncertainties	0	−5.4	+5.4	—	—

More info: top mass in dileptons

Fully Kinematic Method (KINb)

- Top quark reconstruction:
  - Solve equations of tt system many times per event
  - Scan kinematic phase space: vary p_T(jet), E_t^{miss} & p_z(tt) independently according to resolution
  - Accept solutions with lowest m(tt) if $|m_{top} - m_{antitop}| < 3$ GeV
  - Choose the l-jet combination with largest number of solutions
  - m_{KIN} = outcome of gaussian fit around most probable value (± 50 GeV)

- Top mass determination:
  - Unbinned likelihood fit to m_{KIN}
  - Free parameters: m_{top}, $N_{sig,}$ N_{bg}
  - Background templates from simulation (shapes fixed); signal template (gaussian + landau) from fit to simulated signal sample

More info: top mass in dileptons

Analytical Matrix Weighting Technique (AMWT)

- Top quark reconstruction:
  - Solve equations of tt system many times per event
  - 8 solutions per event (4 for each of the 2 lepton-jet combination)
  - Scan m_{top} within [100 GeV, 300 GeV] in steps of 1 GeV
  - Assign a weight to each solution according to CTEQ6.1 PDF and the kinematics of the decay:

$$W = f(x)f(\bar{x})p(E^* \mid m_{top})p(\bar{E}^* \mid m_{top})$$

f(x) = PDF (summed over u, d, g)

p($E^*|m_{top}$) = probability of finding the lepton with energy E in the top rest frame by given m_{top}

  - Sum weights of all solutions for a given m_{top} and average for different p_T(jet) within resolution
  - $m_{AMWT} = m_{top}$ with maximum average weight

- Top mass determination:
  - Calculate likelihood for different m_{top}
  - All templates from simulation except Z+jets background, which is taken from data in Z-mass window (fixed)

More info: top mass in dileptons

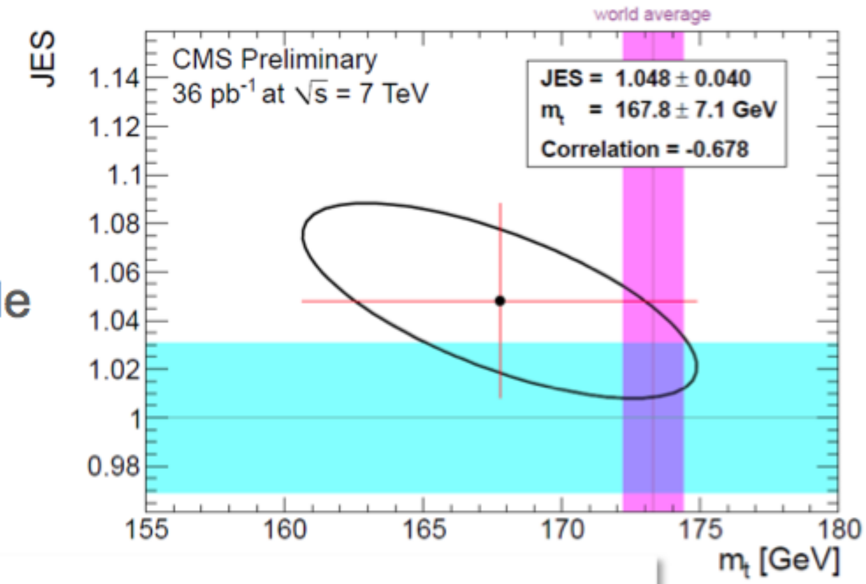
Systematics

Table 2: Summary of the systematic uncertainties (in GeV/c^2) in the measurement of m_{top}, together with their correlations and combined values.

Source	KINb	AMWT	Correlation factor	Combination
jet energy scale	+3.1/-3.7	3.0	1	3.1
b-jet energy scale	+2.2/-2.5	2.5	1	2.5
Underlying event	1.2	1.5	1	1.3
Pileup	0.9	1.1	1	1.0
Jet-parton matching	0.7	0.7	1	0.7
Factorization scale	0.7	0.6	1	0.6
Fit calibration	0.5	0.1	0	0.2
MC generator	0.9	0.2	1	0.5
Parton density functions	0.4	0.6	1	0.5
b-tagging	0.3	0.5	1	0.4

More info: top mass in lepton+jets

- Cross check: simultaneous measurement of m(top) and JES
  - Template method in 2-tag sample
  - using M3 and M2 (mass of untagged jets)
- Central result:



$$m_t = 173.1 \pm 2.1(\mathrm{stat})^{+2.4}_{-2.1}(\mathrm{JES}) \pm 1.4(\mathrm{other\ syst})\ \ \mathrm{GeV}$$

  - Factor two more precise than ATLAS!
- Combined measurement with dileptons

$$m_t = 173.4 \pm 1.9(\mathrm{stat}) \pm 2.7(\mathrm{syst})\ \ \mathrm{GeV}$$

ATLAS result in l+jets:
169.3 +/- 4.0 +/- 4.9 GeV

World average:
173.3 +/- 1.1 GeV

More info: top mass in lepton+jets

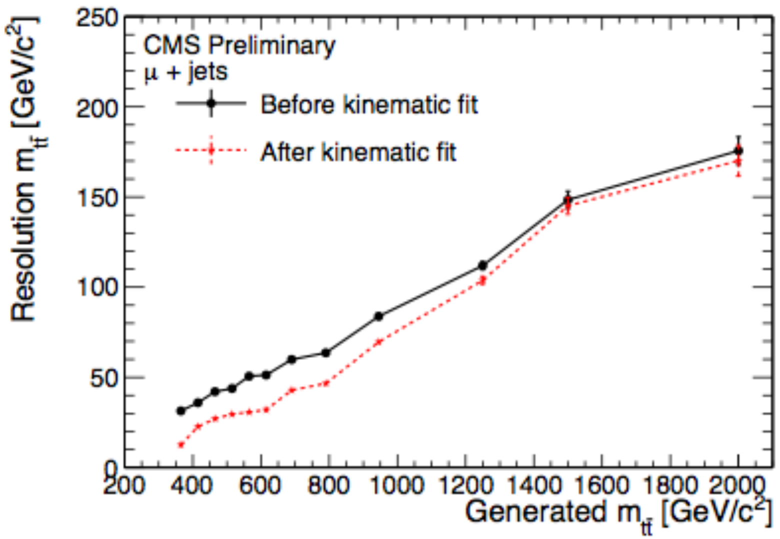
Systematics

Source	Ideogram analysis δm_t (GeV)	Cross-check δJES	 δm_t
JES (overall data/MC)	+2.4-2.1	-	-
JES p_T and η dependence	-	0.004	0.3
light vs b-jet scale	-	0.002	2.6
JER (10% effect)	0.07	0.005	0.2
MET (10% effect)	0.4	-	-
Factorization scale	1.1	0.001	0.9
ME-PS matching threshold	0.4	0.003	0.2
ISR/FSR	0.2	0.008	0.4
Underlying event	0.2	0.001	0.7
Pile-up effect	0.1	0.005	0.2
PDF	0.1	0.002	0.2
Background	0.5	0.007	0.9
B-tagging	0.05	0.003	0.2
Fit calibration statistics	0.1	0.004	0.1
Total systematic uncertainty	+2.8- 2.5	0.015	3.1

More info: top pair invariant mass

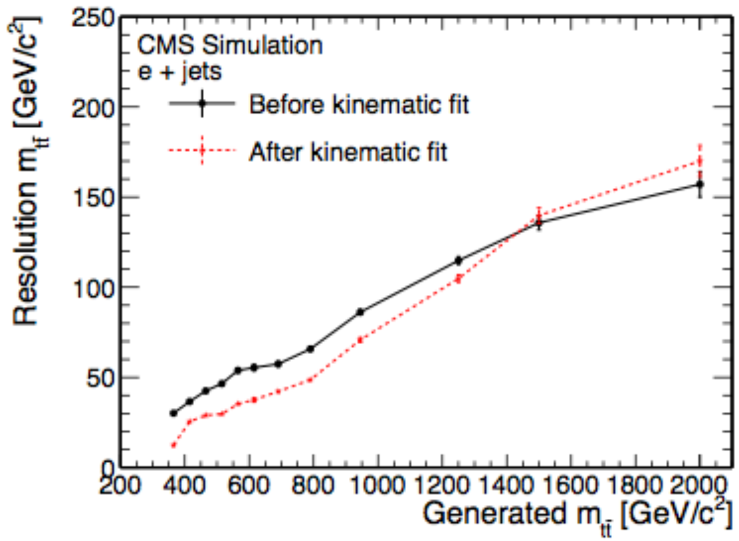
Reconstruction of m_{tt} done in 3 steps:

- Reconstruct leptonic W: $E_T^{miss} = p_T(\nu)$, $p_z(\nu)$ unmeasured
  - Impose W mass constraint: $m_{l\nu} = m_W$ → 2 solutions for $p_z(\nu)$
  - If both real, keep both; if imaginary, modify E_T^{miss} within resolution to give real solution
- Association of jets to hadronic W decay and to the 2 b quarks by χ^2 minimization
  - 5 variables used: m_t^{lep}, m_t^{had}, $p_T(tt)$, H_T fraction (= sum of $E_T^{selected\ jets}$/ sum of $E_T^{all\ jets}$)
- Kinematic fit to improve resolution



resolution μ+jets ←

resolution e+jets →

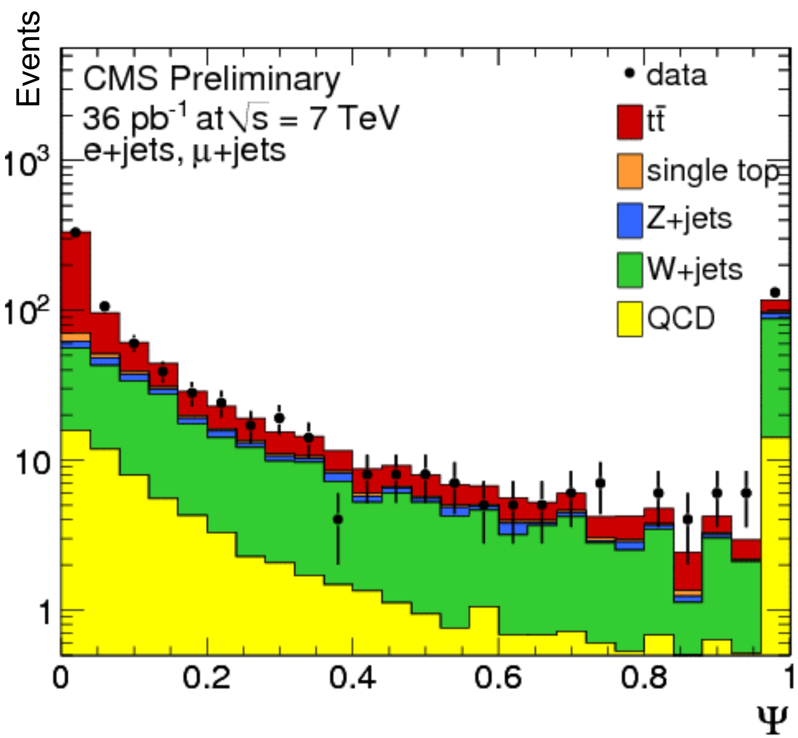


More info: Charge asymmetry

Reconstruction of ttbar final state: (following event selection from TOP-10-002)

- Reconstruct leptonic W: $E_T^{miss} = p_T(\nu)$, $p_z(\nu)$ unmeasured
  - Impose W mass constraint: $m_{l\nu} = m_W$ → 2 solutions for $p_z(\nu)$; if imaginary, take Re
- For each possible 4-jet combination, determine Ψ and take the hypothesis with the smallest value of Ψ :

$$\Psi = \chi^2 (1 - P_b(x_{b_{had}}))(1 - P_b(x_{b_{lep}}))P_b(x_{q_1})P_b(x_{q_2})$$



$$\chi^2 = \frac{(m_{t,had}^{b.p.} - m_{t,had}^{rec})^2}{\sigma^2_{m_{t,had}}} + \frac{(m_{t,lep}^{b.p.} - m_{t,lep}^{rec})^2}{\sigma^2_{m_{t,lep}}} + \frac{(m_{W,had}^{b.p.} - m_{W,had}^{rec})^2}{\sigma^2_{m_{W,had}}}$$

process	electron channel	muon channel
$t\bar{t}$	184 ± 16	231 ± 20
single top	9 ± 3	12 ± 4
W+jets	130 ± 8	159 ± 9
Z+jets	20 ± 6	15 ± 5
QCD	64 ± 6	17 ± 5
total fit result	407 ± 19	434 ± 22
observed data	428	423

More info: Charge asymmetry

Unfolding: correct the measured $|\eta_{top}|-|\eta_{antitop}|$ from several effects:

- Background contributions:
  - use orthogonal samples from diagonalized covariance matrix and subtract them from the measured spectrum: $A_c^{rec}= 0.018 \pm 0.034$ (stat) → $A_c^{rec}= 0.035 \pm 0.070$ (stat)
- Smearing and selection effects:
  - Define matrix $\mathbf{y} = A\,\mathbf{x}$, where $\mathbf{x}$ = true spectrum ; $\mathbf{y}$ = measured distribution
  - A is taken from simulation, measured scale factors from overall selection eff accounted for
  - Equation solved by a generalized inversion process of matrix A