Top Quark Physics - Experimental Results

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Outline

- Discovery
- Production and decay
- Property measurements
- New physics related to top quark
- Conclusion

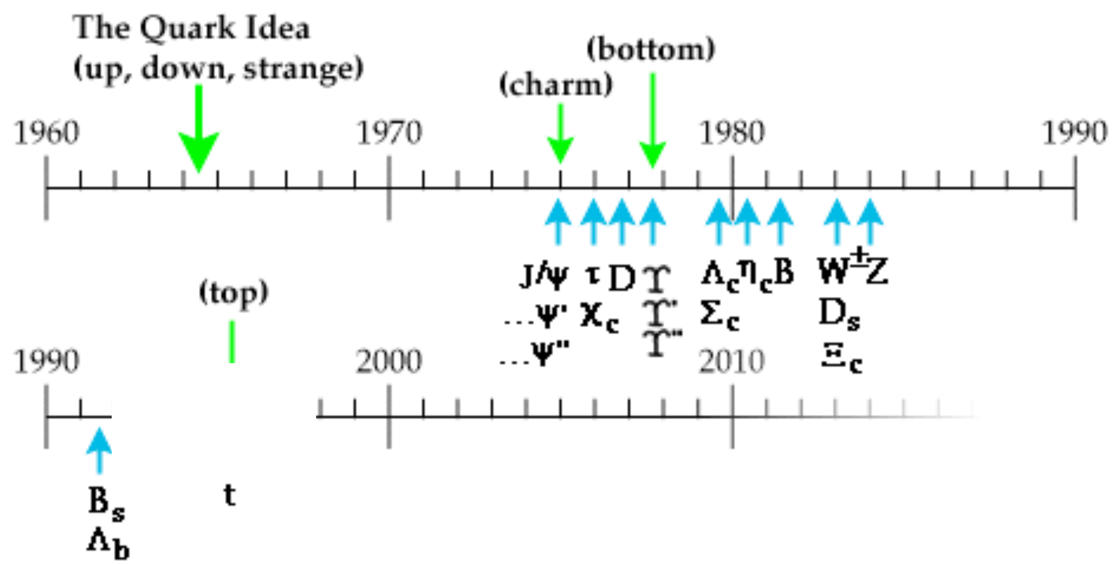
How top quark was discovered?

Top Quark - a Special Fundamental Particle

- Most people have reached a consensus that there exists physics beyond the SM (new physics). One way to probe it is via the top quark.

- In 1977, the bottom quark was discovered. If the SM is correct, it is expected to have a partner - top quark, because of gauge symmetry requirement.

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} \\ b \end{pmatrix}$$



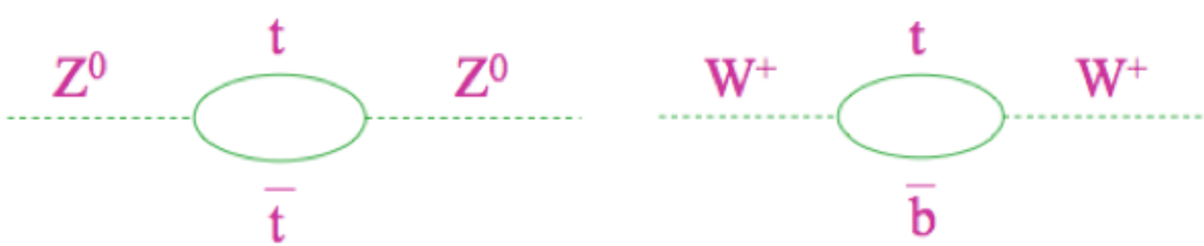
- Given all of the other quarks were discovered within 15 years, top quark was expected to be discovered soon.

Searches in e^+e^- collider I

- PETRA (positron-electron tandem ring at DESY in Germany, $\sqrt{s}$ = ~20 GeV) , late of 1970's
  - if a bound ttbar state were produced, a narrow resonance would be s (anologous to the J/ψ- $c\bar{c}$, ϒ-$b\bar{b}$)
  - if a top quark and antiquark were produced without forming a bound state, the rate of producing hadrons would be larger than in the absence of top quark production
  - if top quarks decay, the angular distribution of decay products is more spherical than that of light quarks
  - the absence of such signatures => top mass > 23 GeV

Searches in e^+e^- collider II

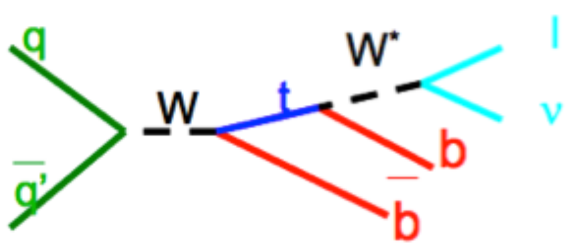
- TRSTAN (Transposable Ring Intersecting Storage Accelerator in Nippon at KEK in Japan)
  - similar techniques employed at PETRA
  - negative results => top mass > 30 GeV
- SLC (Stanford Linear Collider at SLAC in US) and LEP (Large electron-position collider at CERN in Europe)
  - searched for $Z \to t\bar{t}$
  - negative results =>top mass > 45 GeV
- In the SM various Electroweak observables depend on the mass of the top quark



  - Precision measurement of the Z decay -> top mass < 200-220 GeV
- Attention turned to hadron colliders --> reach a higher energy

Searches in Hadron Collider I

- $Sp\bar{p}S$ (super proton-antiproton synchrotron, $\sqrt{s}$ = 540 GeV)
  - searched for e + ≥ 2 jets or μ + ≥ 2 jets



  - by 1985, 12 events were observed
  - expected background 1.6 events, expected signal 10 events (Mtop = 40 GeV)
  - concluded that their results were consistent with a 30-50 GeV top quark. Stopped before claiming discovery

Searches in Hadron Collider II

- 1988, $Sp\bar{p}S$ with larger data sample and improved understanding of the background
- observed 36 events
- expected 35 background events, expected 23 signal events (Mtop = 40 GeV)
- conclude Mtop > 44 GeV

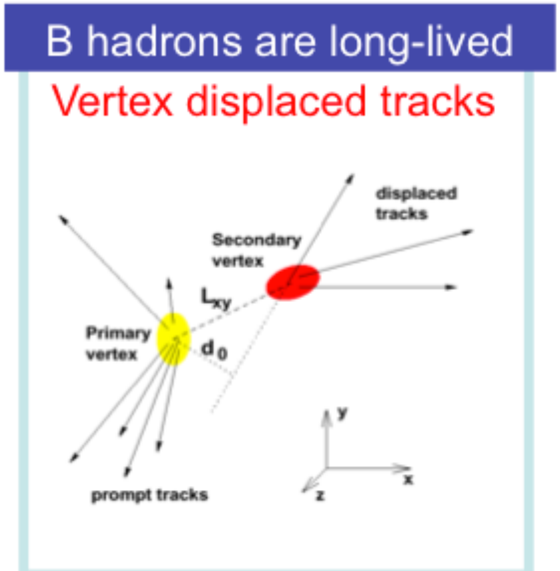
- Tevatron (at Fermilab in US) joins the hunt with a higher center of mass energy $\sqrt{s}$ = 1.8 TeV, about 3 times of that at the $Sp\bar{p}S$

Searches in Hadron Collider III

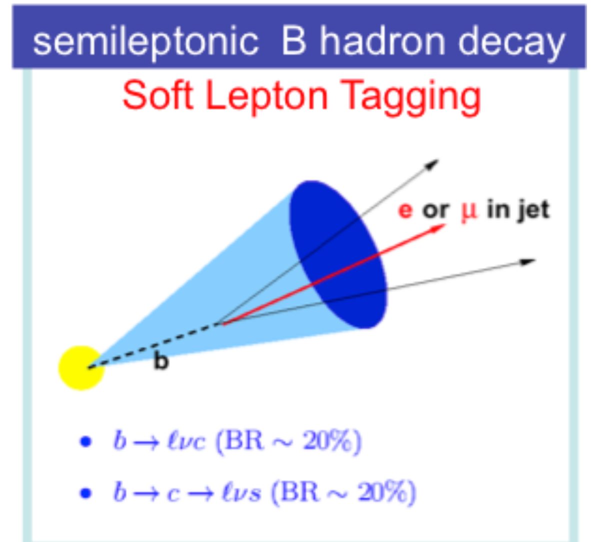
- Start from the hypothesis that Mtop = 40 - 80 GeV (lighter than W)
  - e + missing transverse energy + ≥ 2 jets or e μ + ≥ 2 jets
  - domimant background is W + jets (W is on-shell, while in signal W is off-shell), use MT (lν) - transverse mass of W as discriminant
  - conclude Mtop > 77 GeV
- Start to change the searching strategy
  - Mtop > Mb + Mw
  - W bosons in both background and signal are on-shell, therefore not use MT (lν) as discriminant anymore, add b-tagging
  - search in dilepton channels (ee, eμ , μμ) and single lepton channels
  - in 1992, conclude Mtop > 91 GeV

Searches in Hadron Collider IV

- Two b-tagging methods



more complicated, but more efficient (efficiency ~60%)



simpler, but less efficient (efficiency ~15%)

- In 1993, report excess of events, but not significant (2.8 sigma)

Type	observed	background
DIL	2 events	$0.56^{+0.25}_{-0.13}$
SVX	6 tags	2.3 ± 0.3
SLT	7 tags	3.1 ± 0.3
total	12 events	---

some common events found by both SVX and SLT

Discovery in 1994-1995

VOLUME 73, NUMBER 2 PHYSICAL REVIEW LETTERS 11 JULY 1994

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb^{-1}. We find 12 events consistent with either two W bosons, or a W boson and at least one b jet. The probability that the measured yield is consistent with the background is 0.26%. Though the statistics are too limited to establish firmly the existence of the top quark, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. Under this assumption, constrained fits to individual events yield a top quark mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2. The $t\bar{t}$ production cross section is measured to be $13.9^{+6.1}_{-4.8}$ pb.

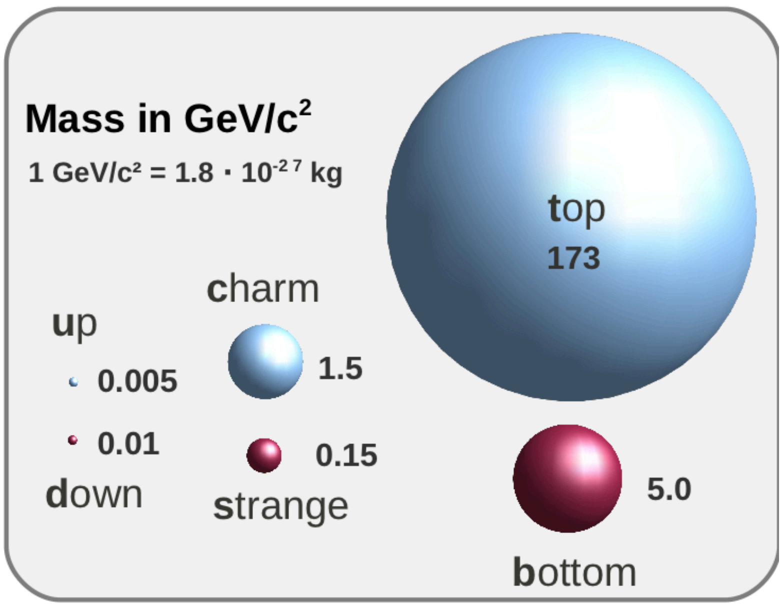
VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of Top Quark Production in $\overline{p}p$ Collisions with the Collider Detector at Fermilab

We establish the existence of the top quark using a 67 pb^{-1} data sample of $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\overline{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be $176 \pm 8(\text{stat}) \pm 10(\text{syst})$ GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

Milestones of Top Quark Discovery

Year	Collider	Particles	References	Limit on m_t
1979–84	PETRA (DESY)	e^+e^-	[50]–[63]	> 23.3 GeV/c^2
1987–90	TRISTAN (KEK)	e^+e^-	[64]–[68]	> 30.2 GeV/c^2
1989–90	SLC (SLAC), LEP (CERN)	e^+e^-	[69]–[72]	> 45.8 GeV/c^2
1984	$Sp\bar{p}S$ (CERN)	$p\bar{p}$	[75]	> 45.0 GeV/c^2
1990	$Sp\bar{p}S$ (CERN)	$p\bar{p}$	[76, 77]	> 69 GeV/c^2
1991	TEVATRON (FNAL)	$p\bar{p}$	[78]–[80]	> 77 GeV/c^2
1992	TEVATRON (FNAL)	$p\bar{p}$	[81, 82]	> 91 GeV/c^2
1994	TEVATRON (FNAL)	$p\bar{p}$	[84, 85]	> 131 GeV/c^2



It was not discovered until 1995, mainly due to its large mass ~173 proton mass.

The heaviest fundamental particle discovered so far!

Things We Learn from Top Quark Discovery

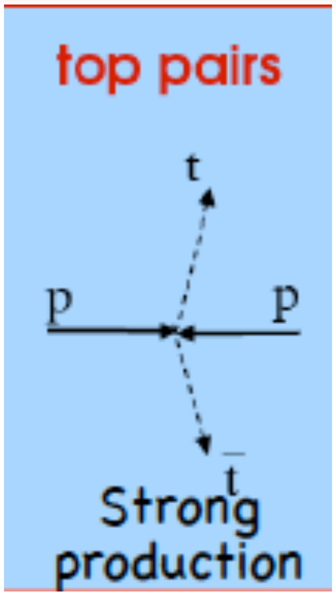
- We need faith and patience. From late of 1970's to 1995, it is a long journey.
  - nothing found --- narrow down searching range (set limit) --- wrong conclusions --- optimize --- evidence --- discovery --- cross check
- We need right machines. The energy has to be high enough to produce such heavy particles. The luminosity has to be high enough to produce enough events.
- We need right searching strategies.
  - sensitive channels - large signal and small background
  - powerful discriminants between signal and background
  - accurate estimates of background

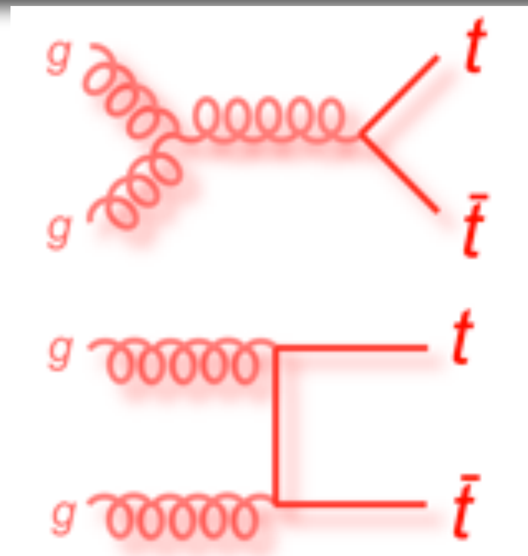
What do we study for top quarks?

- **Production and decay**
  - Produced through strong interaction (dominant) and electroweak interaction
  - Decays predominantly through t→bW
  - Decays before hadronization - access spin information via its decay products
  - Good test of perturbative QCD
- **Properties**
  - Mass, couplings, width, spin, charge and other properties
- **Probe to new physics**
  - Large couplings to the Higgs boston
  - Special role in the Electroweak symmetry breaking in many new physics scenarios

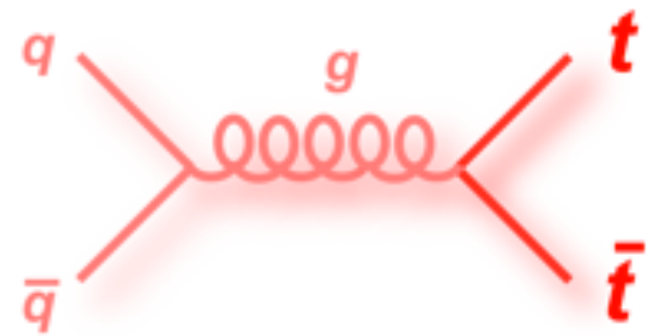
Production and decay

Top Quark Production at the LHC

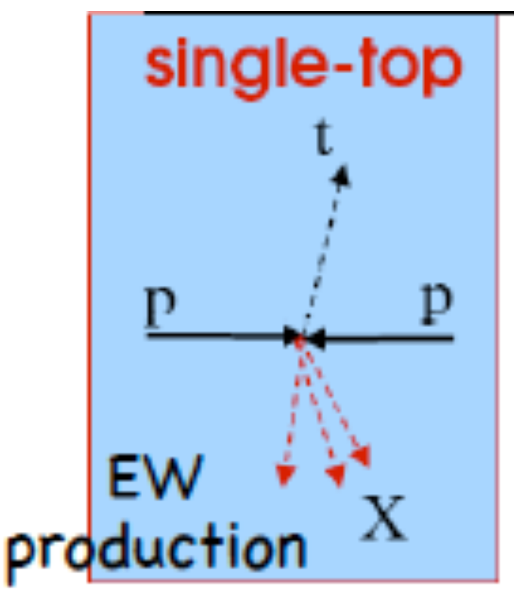


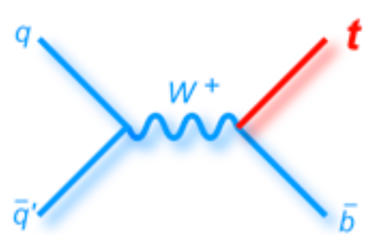


gluon fusion

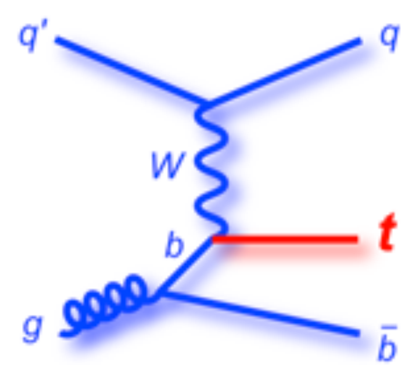


quark and anti-quark annihilation

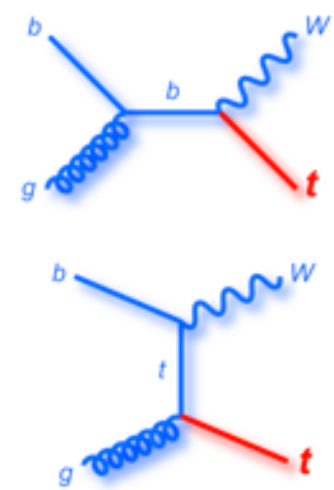




s-channel

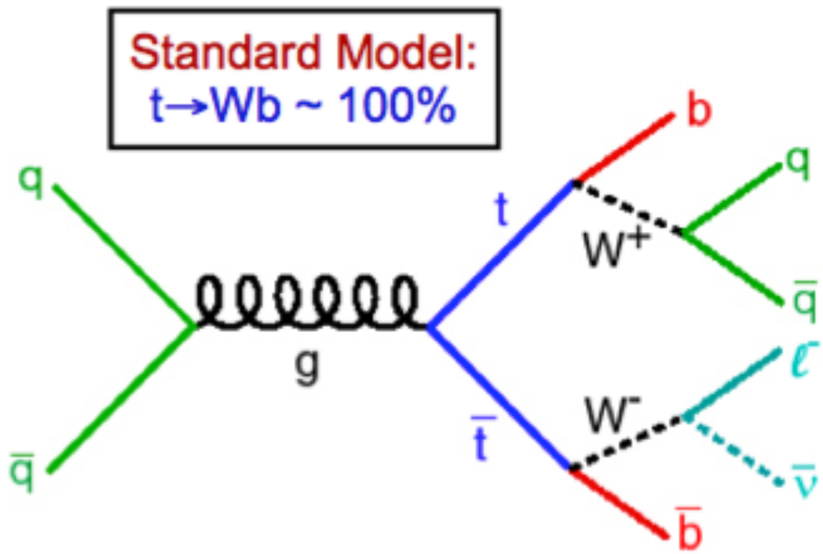


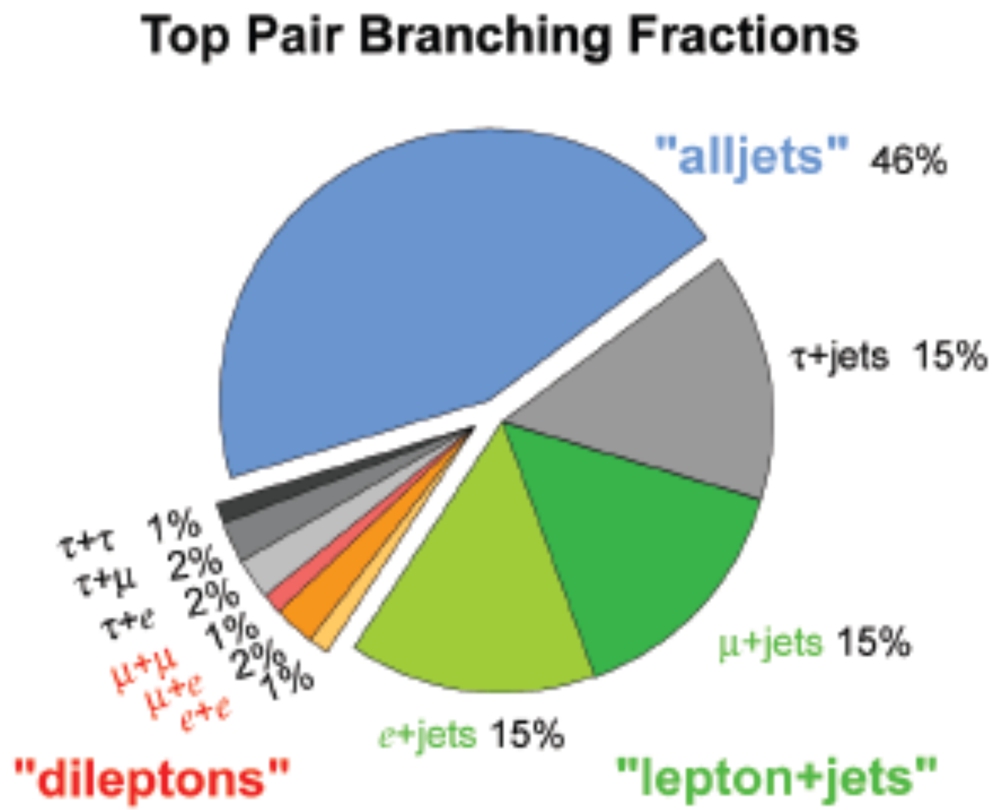
t-channel



associated tW

Top decay





- channels:
  - single lepton: large branching ratio - 30%, moderate background
  - dilepton: small branching ratio - 5%, but clean - small background
  - full hardronic: large branching ratio - 46%, large background too

Cross section -How to Measure?

Number of observed events

just count …

Background

measured from data or calculated from theory

$$\sigma = \frac{N^{obs} - N^{bkg}}{\int \mathcal{L}\, dt \cdot \varepsilon}$$

Luminosity

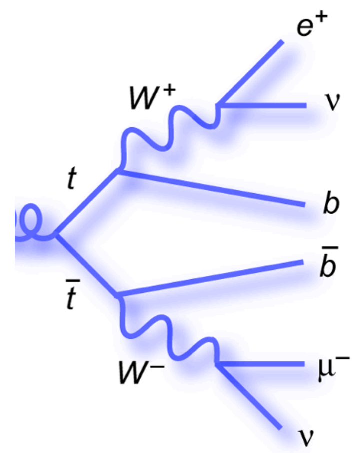
determined by accelerator, triggers, …

Efficiency

many factors, optimized by experimentalist

$t\bar{t}$ Cross Section - Example Analysis

- **2011 and 2012 dataset at $\sqrt{s}$ = 7 TeV and 8 TeV at the ATLAS: 4.6/fb + 20.3/fb**
  - Trigger: single electron or single muon
  - Event selections:
    - an eμ pair
    - at least two jets, one or two of them are b-tagged
  - Background: tW, diboson, Z+jets, W+jets etc
  - Extraction of the cross section: counting number of events with exactly one b-jet and two b-jets respectively



$$N_1 = L\sigma_{t\bar{t}}\ \epsilon_{e\mu} 2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\mathrm{bkg}}$$
$$N_2 = L\sigma_{t\bar{t}}\ \epsilon_{e\mu} C_b {\epsilon_b}^2 + N_2^{\mathrm{bkg}}$$

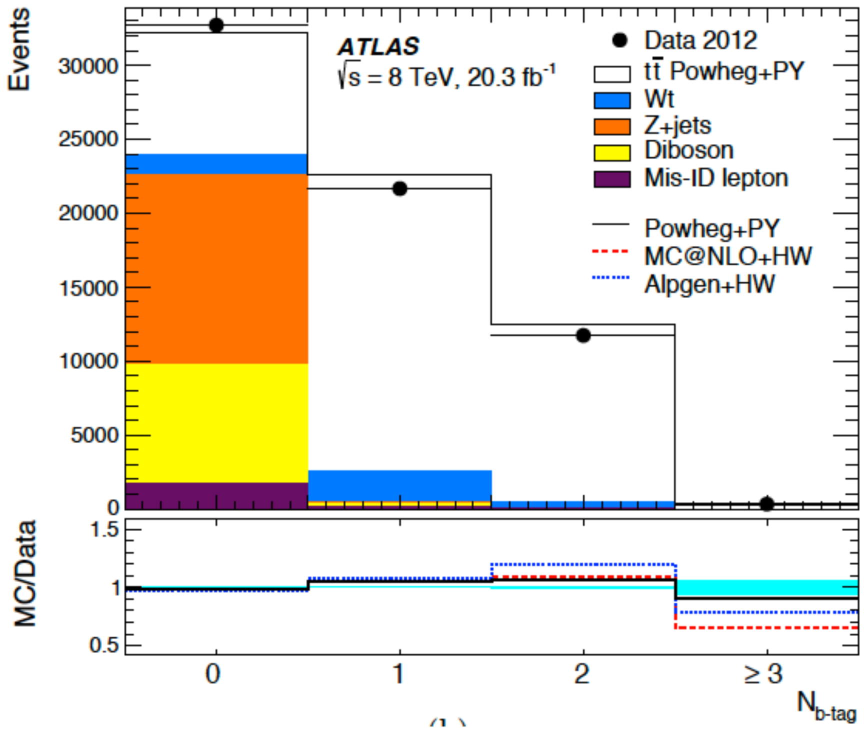
unknown: $\sigma_{t\bar{t}}$ and ϵ_b

b-jet acceptance and efficiency ε_b

$\varepsilon_{e\mu}$ efficiency to pass lepton selection

kinematic correlation C_b of two b-jets taken from MC

$t\bar{t}$ Cross Section - Example Analysis



Event counts	$\sqrt{s}=7$ TeV N_1	$\sqrt{s}=7$ TeV N_2	$\sqrt{s}=8$ TeV N_1	$\sqrt{s}=8$ TeV N_2
Data	3527	2073	21666	11739
Wt single top	326 ± 36	53 ± 14	2050 ± 210	360 ± 120
Dibosons	19 ± 5	0.5 ± 0.1	120 ± 30	3 ± 1
$Z(\to \tau\tau \to e\mu)$+jets	28 ± 2	1.8 ± 0.5	210 ± 5	7 ± 1
Misidentified leptons	27 ± 13	15 ± 8	210 ± 66	95 ± 29
Total background	400 ± 40	70 ± 16	2590 ± 230	460 ± 130

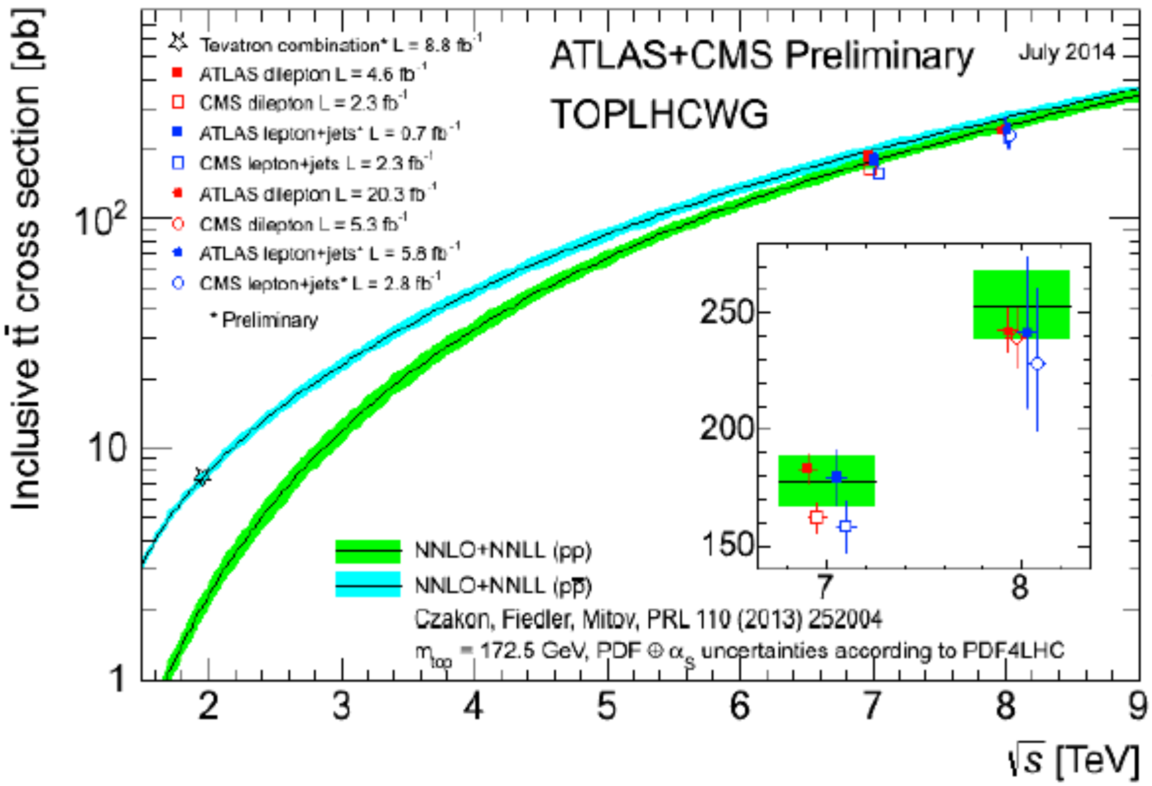
Total inclusive top anti-top cross section

$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\text{pb}\;(\sqrt{s} = 7\text{ TeV})$$

$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\text{pb}\;(\sqrt{s} = 8\text{ TeV})$$

	7 TeV	8 TeV
Precision achieved:	3.5%	4.0%

$t\bar{t}$ Cross Section - Inclusive measurements



Most precise results:

CMS JHEP 02 (2014) 024 JHEP 11 (2012) 067

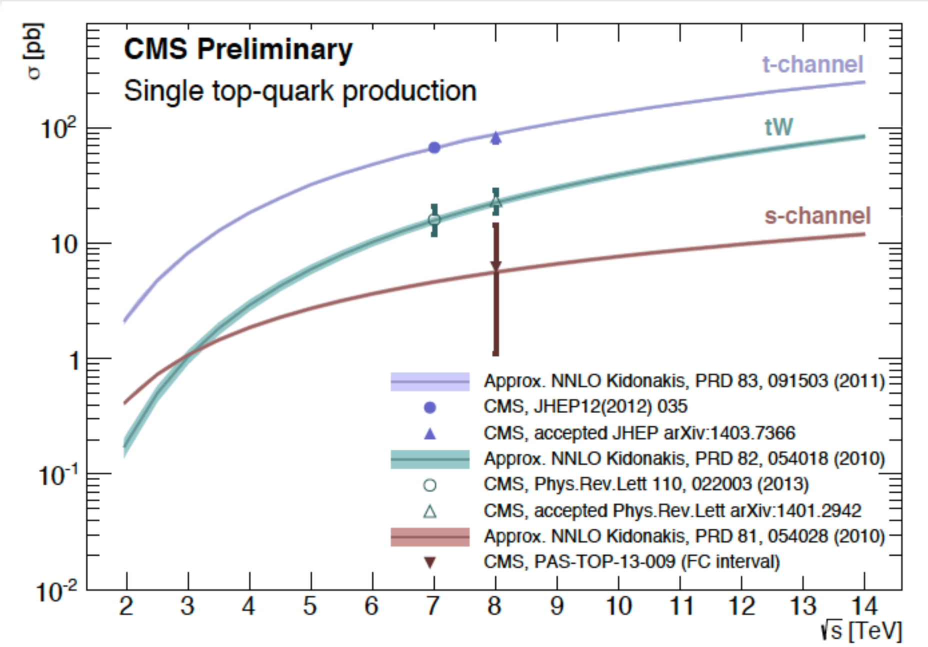
ATLAS arXiv:1406.5375

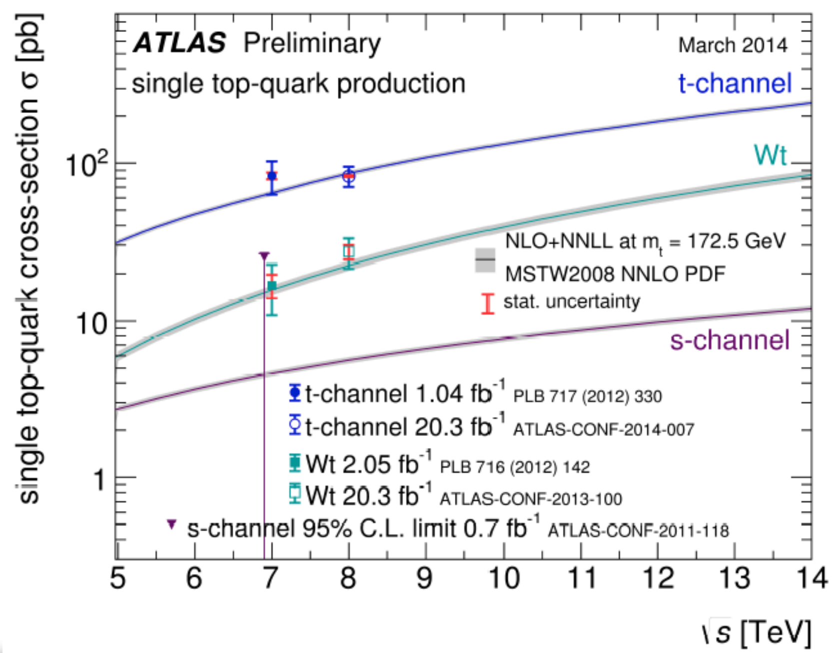
Tevatron combination PRD 89 (2014) 072001

	Tevatron		LHC 8 TeV	
Precision	D0	CDF	ATLAS	CMS
total	7.8%	6.5%	4.3%	5.5%
stat	2.6%	4.0%	0.7%	0.8%
syst	4.3%	4.7%	2.3%	4.7%
lumi	6.1%	2.0%	3.1 %	2.6%

- 7 TeV: about 2 sigma difference between ATLAS and CMS measurements
- 8 TeV: both measurements are in good agreement with NNLO predictions

Single Top Production Cross Section





t-channel: observation is consistent with the SM expectation

tW channel: observation is consistent with the SM expectation

s-channel: very challenging! CMS significance 0.7 sigma; set upper limit 11.5 pb (95% C. L.)

process	seen ?	Tevatron	LHC
t-ch.	yes	16%	10%
Wt-ch.	yes		22%
s-ch.	yes	19%	$<2.1\ \sigma_{SM}$

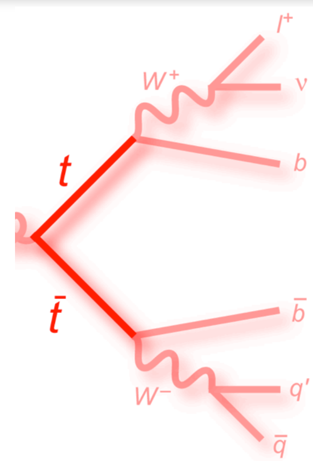
Top quark properties

Top Mass - Measurement Methods

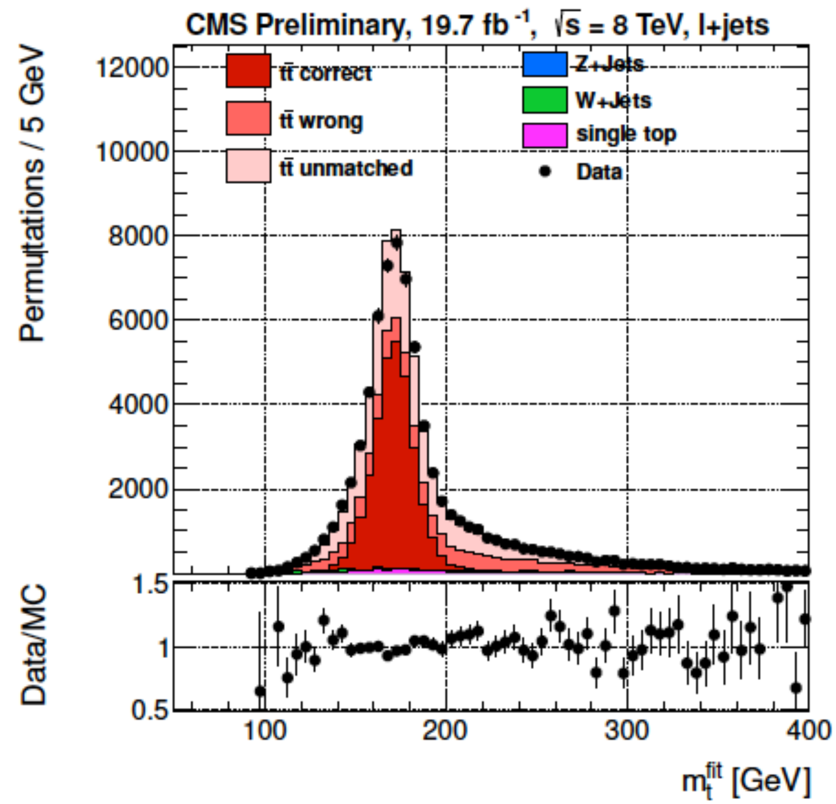
- Direct or standard methods
  - Template: compare data to templates from simulation with different masses
  - Ideogram: Likelihood functions to test compatibility of event kinematics with top decay hypothesis
  - Matrix element: calculate signal and background probability density for all parton-jet assignment as function of Mtop and Jet Energy Scale Factor
- Non-standard methods
  - NLO QCD comparison to tt cross sections
  - Kinematic Endpoints

Top mass - Example Analysis

- **Full 2012 dataset at $\sqrt{s}$ = 8 TeV at CMS: 19.7/fb**
- Trigger: single lepton trigger
- **Event selections**
  - One isolated lepton, at least 4 jets, two of them are b-tagged
- Background
  - single top, W/Z+jets
- Analysis strategy
  - A kinematic fit of the decay products to a ttbar hypothesis, where templates for Mtop distribution of the events with right, wrong and unmatched parton-jet assignments are used
  - Keep those events with the goodness-of-fit probability to be above 20%
  - Fraction of right assignment increased from 13% to 42%



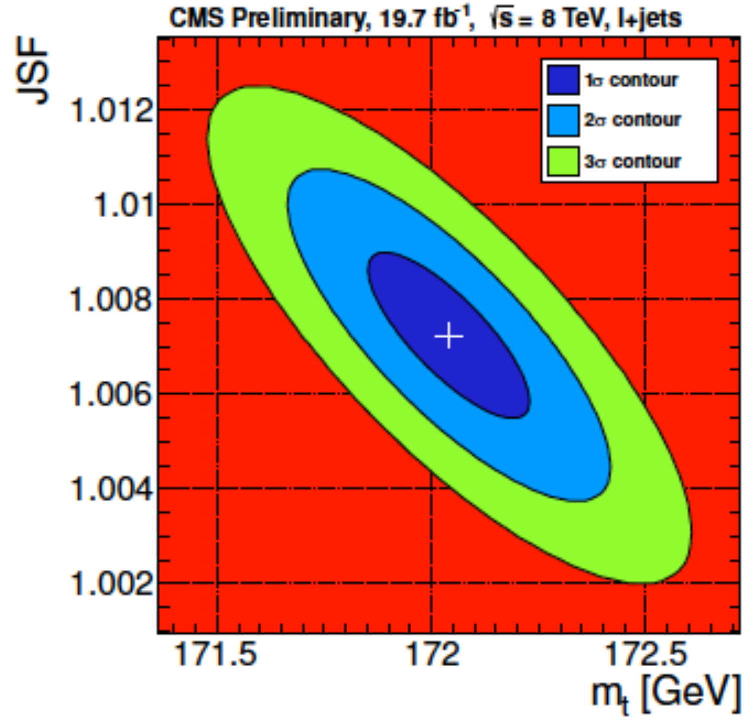
CMS-TOP-14-001



Top mass - Example Analysis

- Ideogram method: 2D likelihood functions for each event to estimate simultaneously the top-quark mass and the jet energy scale (JSF)
  - What are the likelihood functions? Function f (x, λ) describes the probability of the random variable x = (x1, x2,.... xN) with a specific set of parameters λ = (λ1, .. λp). When N measurements are made, the probability to have such N events is given by

$$L = \prod_{j=1}^{N} f\left(\boldsymbol{x}^{(j)}; \boldsymbol{\lambda}\right)$$

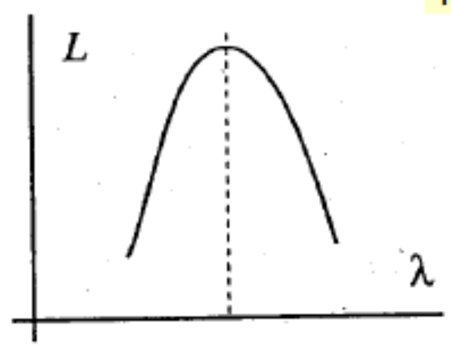


CMS-TOP-14-001

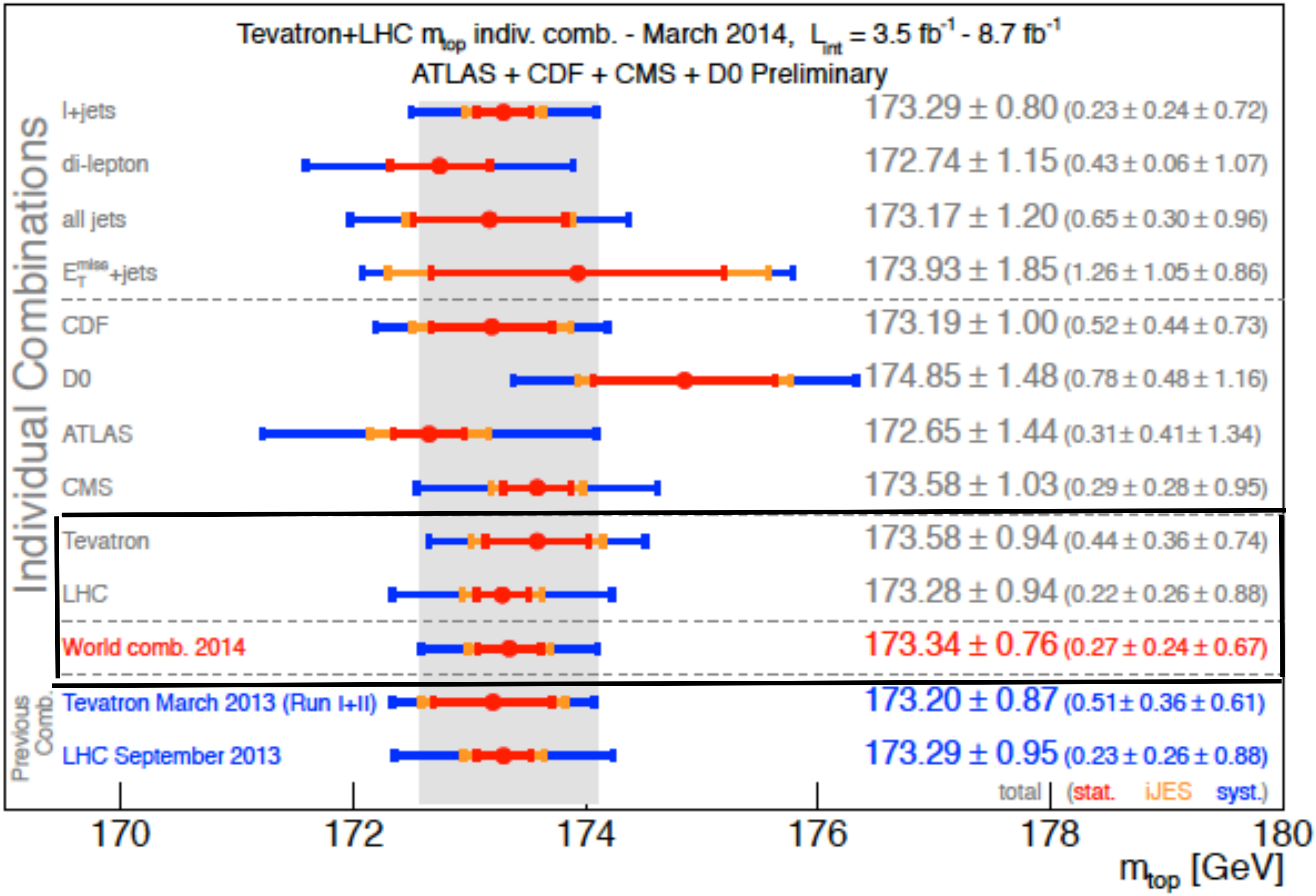
$$m_t = 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\,\text{GeV},$$

precision: 0.45%

  - What are the maximum likelyhood? find λ which make L maximum



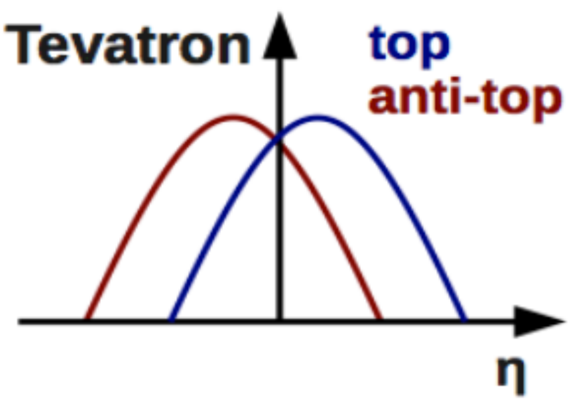
Top mass world average 2014

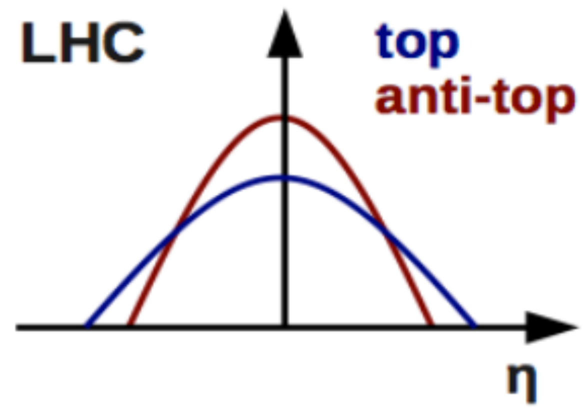


Precision on Mtop 0.44%

$t\bar{t}$ Charge Asymmetry

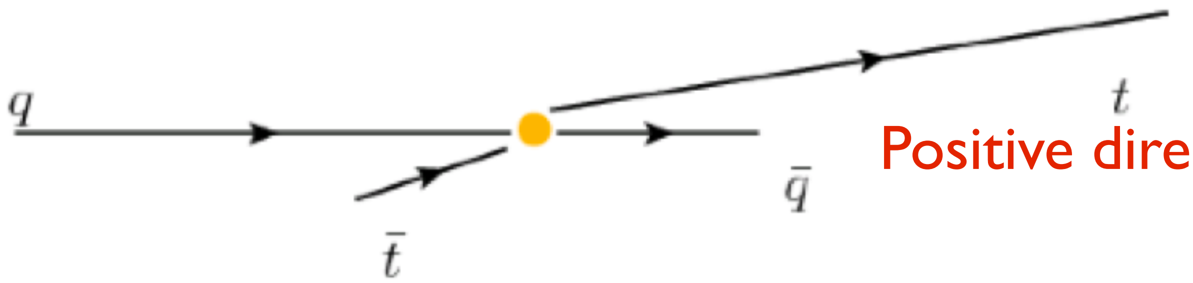
- At Tevatron (proton-antiproton collision), $q\bar{q} \to t\bar{t}$: top quarks are emitted in the direction of the incoming quark, anti-top quarks in the direction of the incoming anti-quark (asymmetry)
- At LHC (proton-proton collision)
  - $gg \to t\bar{t}$ no asymmetry
  - $q\bar{q} \to t\bar{t}$ asymmetry: in pp collisions, the quark in the initial state is a valence quark in most cases and the anti-quarks is a sea quark. Nuclear physicists tell us - valence quarks usually carry much more momenta than sea quarks





$t\bar{t}$ Charge Asymmetry

- At LHC, due to the imbalance of quark and anti-quark, system is boosted, typically along the direction of quark motion. We can define it to be the (event-by-event) forward direction.



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

N^+(N^-): number of events with positive and negative values in the sensitive variable. e.g.

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

- Theoretically
  - SM: only small asymmetry due to ISR/FSR
  - New physics: production mechanism with new exchange particles could enhance the asymmetry

$t\bar{t}$ Charge Asymmetry - Example Analysis

- **2011 dataset at $\sqrt{s}$ = 7 TeV at CMS: 5.0/fb**
- Analysis strategy:
  - The measured distribution is distorted from the true underlying distribution by two factors: (1) bias introduced by detector acceptance and analysis cuts, and (2) effects due to the finite resolution of the measurement.
  - An "unfolding" procedure is incorporated to correct the above effects and yield the parton-level distribution (truth level).
  - The measured distribution b_k is related to the underlying parton-level distribution X_i by:

$$b_k = S_{kj} A_{ji} X_i \quad \Longrightarrow \quad X = A^{-1} S^{-1} b$$

where A is acceptance matrix and S is migration matrix. We obtain them using Monte Carlo simulation.

$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$

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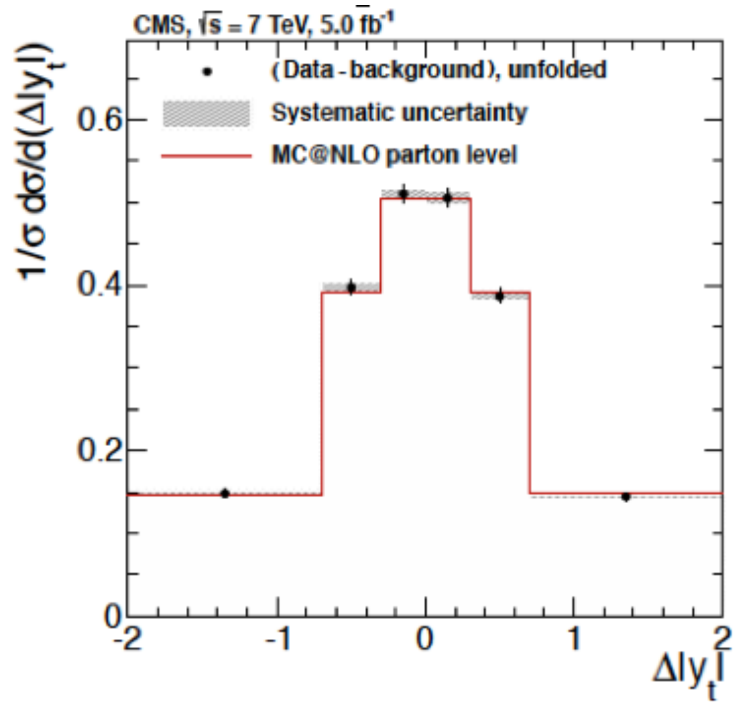
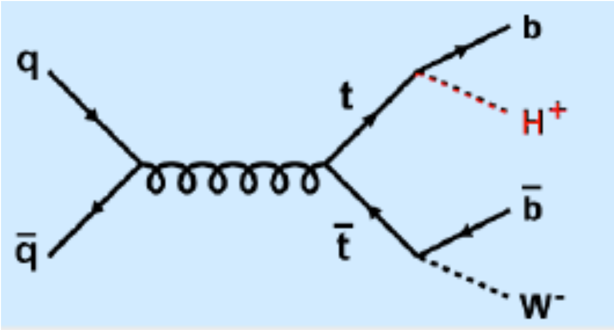


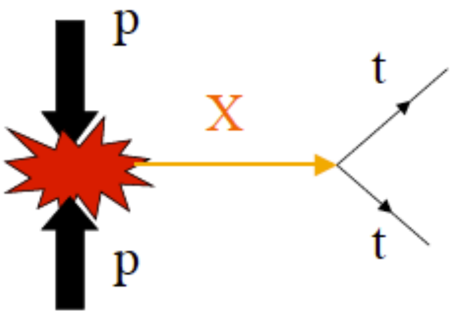
CMS dilepton channel
Ac = -0.010±0.017(stat)±0.008(syst)

Probe for New Physics

New Physics Related to Top Quark

- Wtb anomalous coupling
- Flavor Changing Neutral Current (FCNC)
- Higgs
  - ttH associated production
  - t -> H+
- SUSY: ttbar is the dominant background of stop search
- Exotic
  - top like heavy quark
  - heavy resonance to $t\bar{t}$
  - W' --> tb

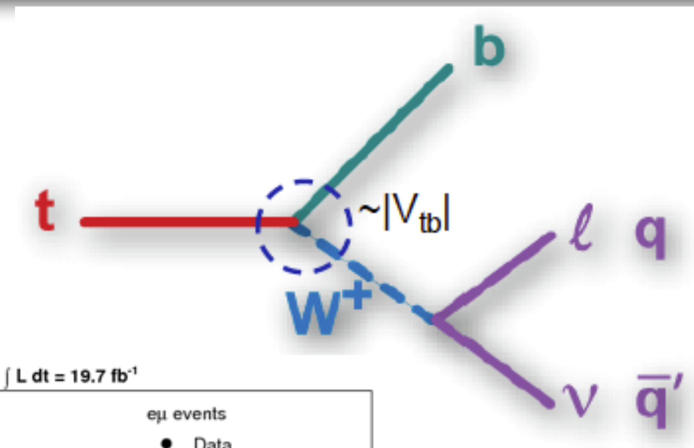




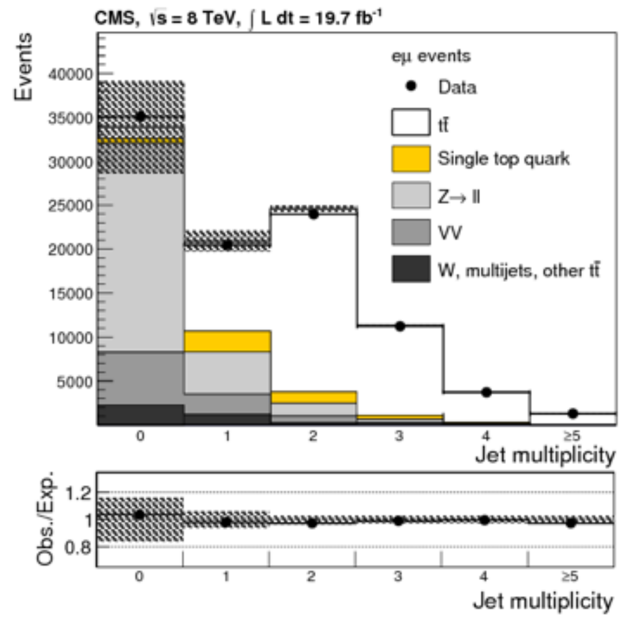
Wtb coupling

- Top decay t--> Wb, but is it really 100%?

$$R = \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} \quad \text{where } q = \{d, s, b\}$$



- In the SM, 0.9980< R < 0.9984
- R< 1 could indicate new physics
- **2012 dataset at √s = 8 TeV at CMS: 19.7/fb**
- Dilepton channel, purity of the signal sample is quantified by measuring the cross section
- R value is measured by fitting the observed b-tagged jet distribution



R = 1.014±0.003(stat)±0.032(syst)

At 95% C.L., R > 0.955, assuming R <=1.

|Vtb| > 0.975, assuming the unitarity of CKM matrix

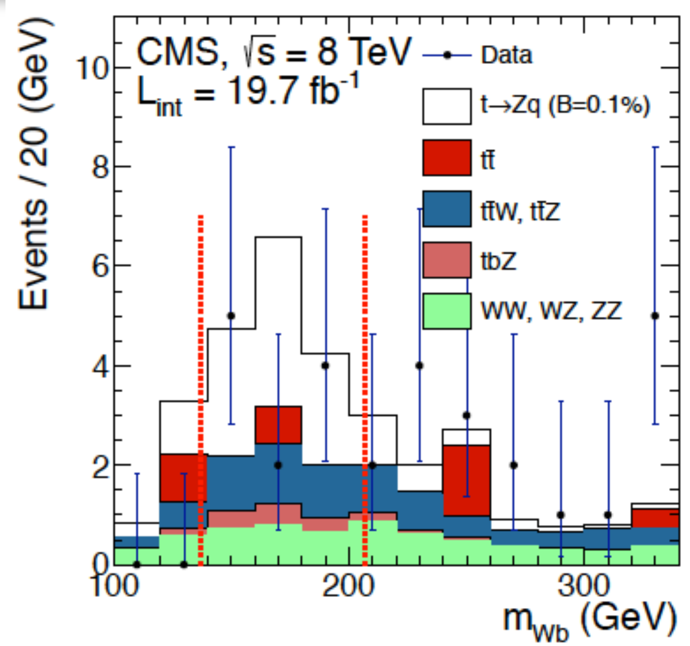
Indirect measurement on top total decay width 1.36±0.02(stat)$^{+0.14}_{-0.11}$ (syst) GeV

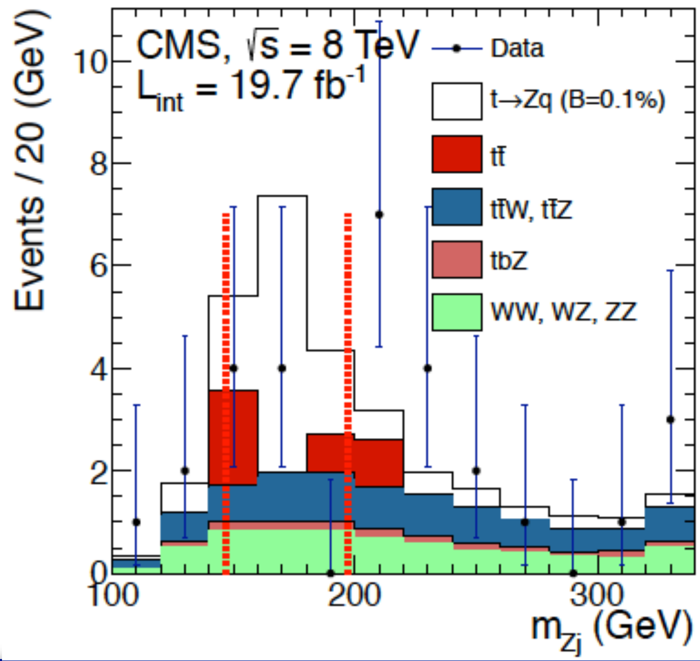
Search for FCNC in top decays

- **Full 2012 dataset at $\sqrt{s}$ = 8 TeV: 19.7/fb**
- t→Zq suppressed in SM but can be enhanced in new physics models
- 3 isolated leptons + at least two jets (exactly one is b-tagged)+MET

Process	Estimation from data	MC prediction
$t \to Zq$ ($\mathcal{B} = 0.1\%$)	—	$6.4 \pm 0.1 \pm 1.3$
Total background	$3.1 \pm 0.8 \pm 0.8$	$3.2 \pm 1.2 \pm 1.5$
Observed events	1	—

$\mathcal{B}(t \to Zq)$	8 TeV	7 TeV + 8 TeV
Expected upper limit	<0.10%	<0.09%
Observed upper limit	<0.06%	<0.05%
1σ boundary	0.06–0.13%	0.06–0.13%
2σ boundary	0.05–0.20%	0.05–0.18%





PRL 112 (2014) 171802

Conclusions

- Top was discovered 25 years ago, since then various experimental studies for top physics have been carried out.
- The production, decay and properties have been measured in good precisions.
- Top physics is not only the tests for the SM, but also good probes to new physics
- In the run I of the LHC, results from the top physics are in good agreement with SM predictions
- Expect rich results from the top physics in the run II of the LHC

Backup

Top polarization in t-channel single-top production

- **Full 2012 dataset at $\sqrt{s}$ = 8 TeV: 19.7/fb**
- One isolated lepton, two jets (one b-tagged), MET
- In t-channel single -top production, top quarks are almost 100% polarized through the V-A coupling structure
- New physics models may alter the coupling structure which affects the top quark polarization

CMS-TOP-13-001

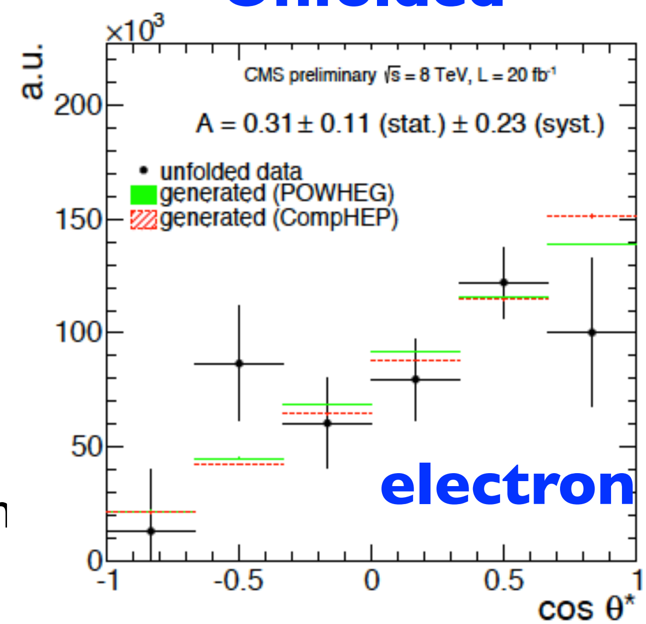
$$A_l = \frac{N(\cos\theta^*_{unfolded} > 0) - N(\cos\theta^*_{unfolded} < 0)}{N(\cos\theta^*_{unfolded} > 0) + N(\cos\theta^*_{unfolded} < 0)}.$$

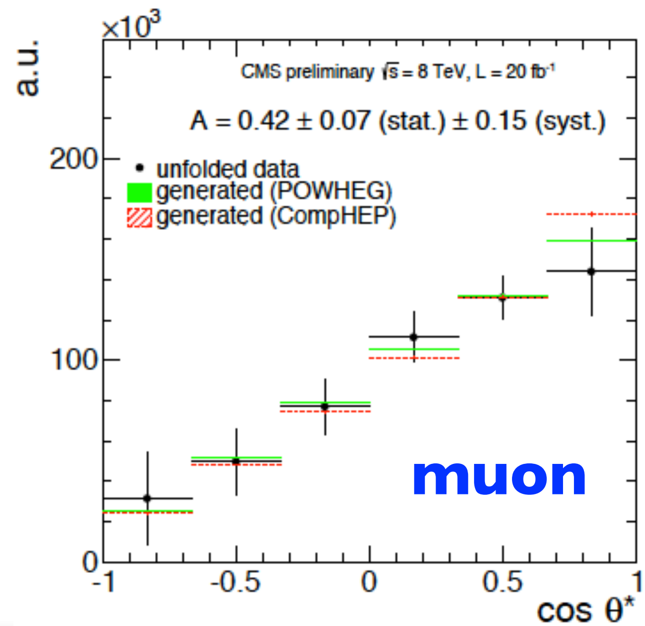
$$A_l \equiv \frac{1}{2} \cdot P_t \cdot \alpha_l$$

Polarization: 0.82±0.12(stat)±0.32(syst)
Asymmetry:

$$A_l^\mu = 0.42 \pm 0.07(stat.) \pm 0.15(syst.),$$
$$A_l^e = 0.31 \pm 0.11(stat.) \pm 0.23(syst.).$$

Unfolded





Top mass at 7 TeV - dilepton

- **Full 2011 dataset at $\sqrt{s}$ = 7 TeV: 5.0/fb**
- Two isolated leptons, at least two b-tagged jets, MET
- Technique is based on edges of M_{T2} distributions
- M_ν^2, M_W and M_t are obtained in a simultaneous fit to three endpoints

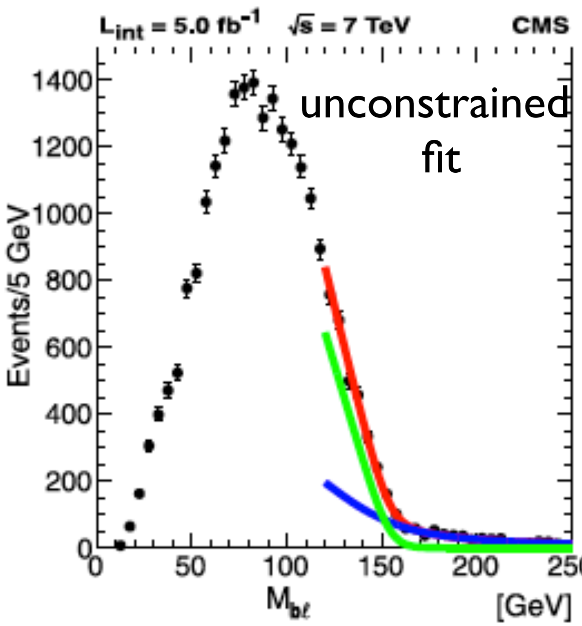
μ_{bb} : lower bound of m_t for known m_W

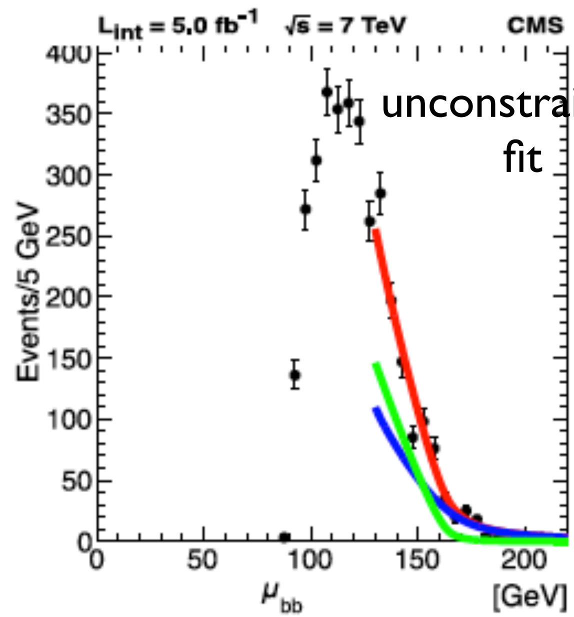
μ_{ll} : endpoint is the W boson mass at $m_\nu = 0$

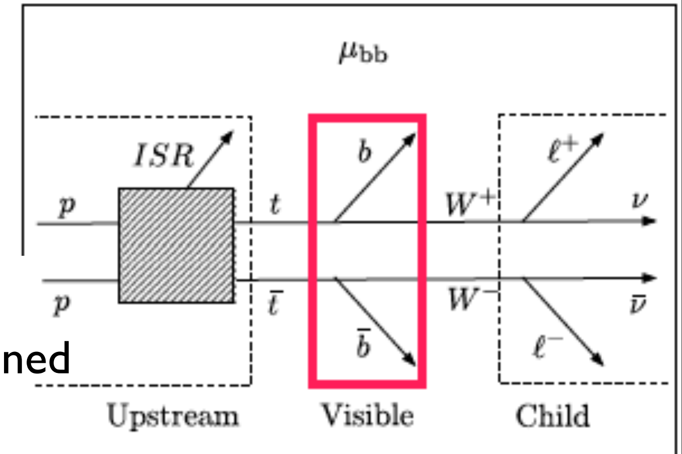
M_{bl} : endpoint is $\sqrt{(m_t^2 - m_W^2)(m_W^2 - m_\nu^2)/m_W^2}$

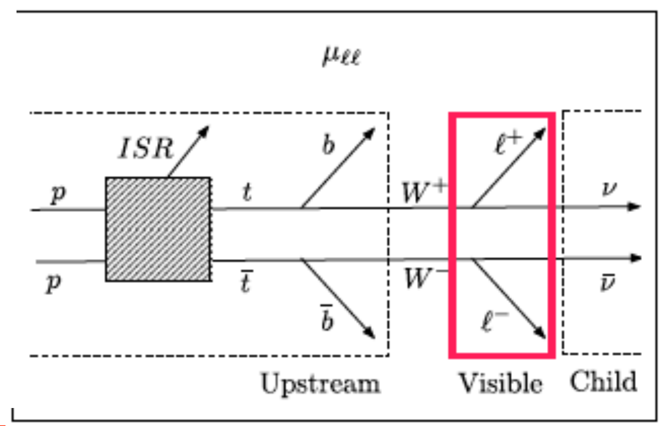
CMS-TOP-11-027

EPJC 73 (2013) 2494





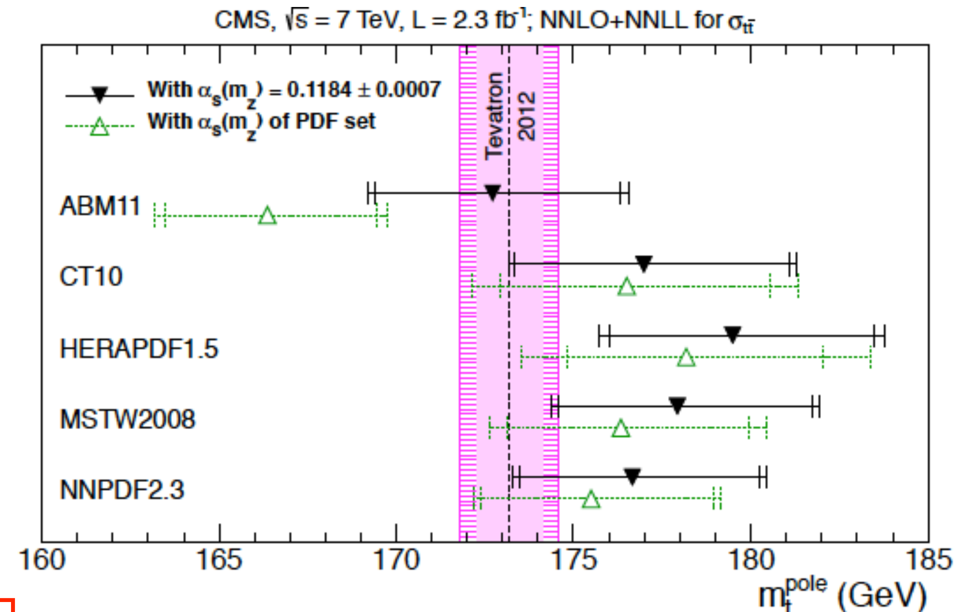


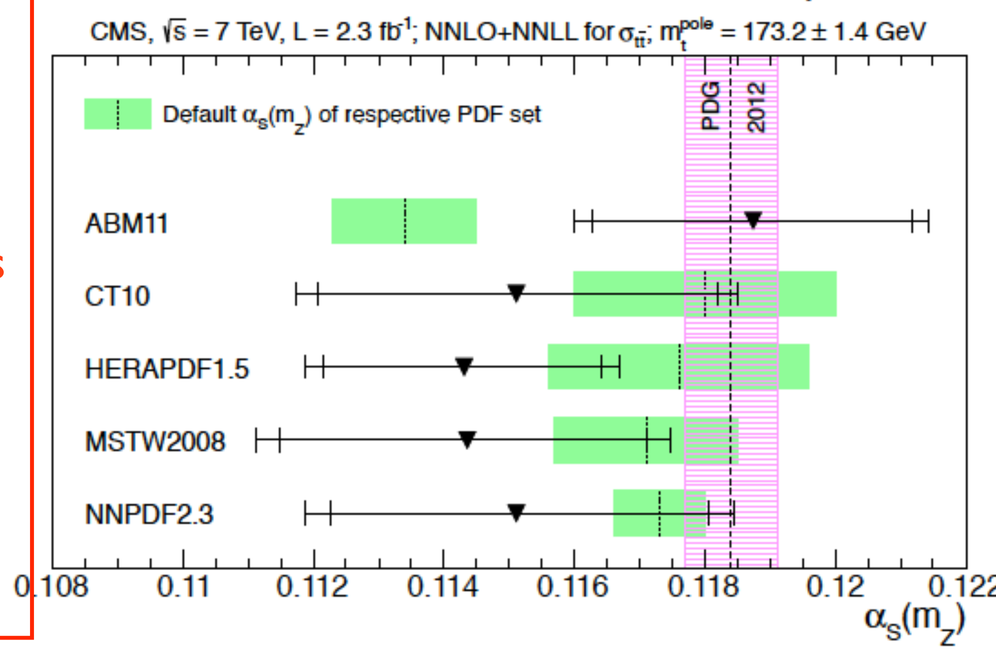


M_t = 173.9±0.9(stat)$^{+1.7}_{-2.1}$(syst) GeV - fixed M_W and M_ν^2

Top mass and alpha_s extracted from ttbar cross section

- **2011 dataset at √s = 7 TeV: 2.3/fb**
- The measured inclusive cross section for top-quark pair production is compared to the QCD prediction at NNLO to determine top pole mass or the strong coupling alpha_s





PLB 728 (2013) 496

Observed cross section in the dilepton channel with 2.3/fb: 161.9 ± 6.7 pb

With the PDF set NNPDF2.3, $M_t = 176.7^{+3.8}_{-3.4}$ GeV when constraining alpha_s (M_z) = 0.1184

alpha_s (M_z) = $0.1151^{+0.0033}_{-0.0032}$ when constraining M_t = 173.2 GeV

Top spin correlation and polarization in ttbar

- **Full 2011 dataset at $\sqrt{s}$ = 7 TeV: 5/fb**
- Dilepton channel, **top kinematics reconstructed** using analytical matrix weighting technique
- An "**unfolding**" procedure is employed to correct acceptance and resolution effects

CMS-TOP-13-003 accepted by PRL

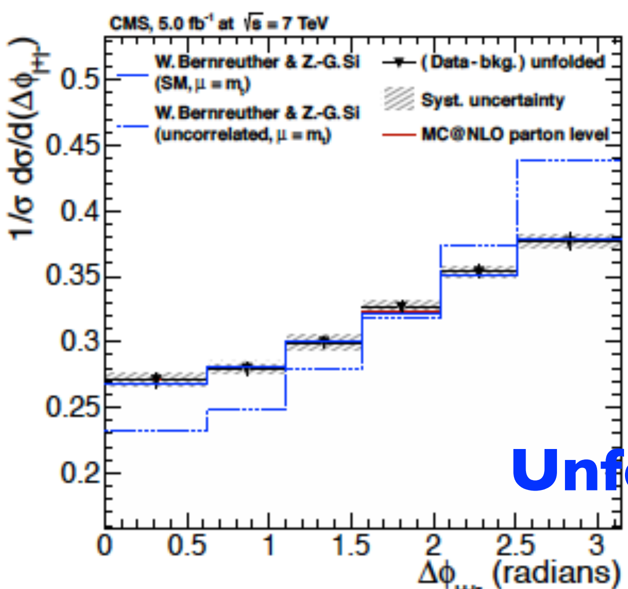
$$A_P = \frac{N(\cos(\theta_\ell) > 0) - N(\cos(\theta_\ell) < 0)}{N(\cos(\theta_\ell) > 0) + N(\cos(\theta_\ell) < 0)}$$

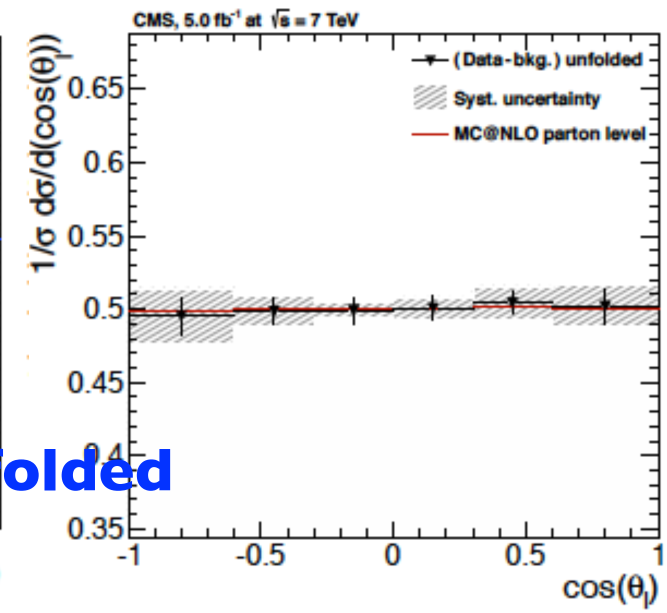
in the helicity basis

$$A_{\Delta\phi} = \frac{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) - N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) + N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}$$

$$A_{c_1c_2} = \frac{N(c_1 \cdot c_2 > 0) - N(c_1 \cdot c_2 < 0)}{N(c_1 \cdot c_2 > 0) + N(c_1 \cdot c_2 < 0)}$$

where c1 = $\cos(\theta_{l+})$ and c2 = $\cos(\theta_{l-})$,





Unfolded

Asymmetry	Data (unfolded)	MC@NLO	NLO (SM, correlated)	NLO (uncorrelated)
$A_{\Delta\phi}$	$0.113 \pm 0.010 \pm 0.007 \pm 0.012$	0.110 ± 0.001	$0.115^{+0.014}_{-0.016}$	$0.210^{+0.013}_{-0.008}$
$A_{c_1c_2}$	$-0.021 \pm 0.023 \pm 0.027 \pm 0.010$	-0.078 ± 0.001	-0.078 ± 0.006	0
A_P	$0.005 \pm 0.013 \pm 0.020 \pm 0.008$	0.000 ± 0.001	N/A	N/A

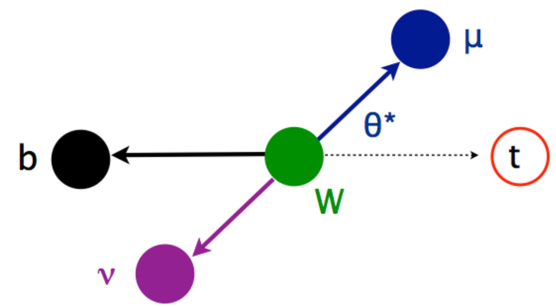
W helicity in top events

- W boson helicity fraction in top-quark decays are sensitive to the Wtb couplings
- Measure W helicity fractions (F_R, F_L, and F_0) using cos(θ*) distribution in ttbar events
- NNLO predictions in the SM: F_L=0.311±0.05, F_0=0.687±0.005, F_R =0.0017±0.0001
  Phys. Rev. D 81 (2010) 111503

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R + \frac{3}{4}\left(\sin\theta^*\right)^2 F_0 \qquad F_L + F_R + F_0 = 1$$

7 TeV

Lepton+jets	FL = 0.310 ± 0.022 (stat.) ± 0.022 (syst.), FR = 0.008 ± 0.012 (stat.) ± 0.014 (syst.), F0 = 0.682 ± 0.030 (stat.) ± 0.033 (syst.) JHEP 10 (2013) 167
Dilepton	FL = 0.288 ± 0.035(stat) ± 0.040(sys), FR = 0.014 ± 0.027(stat) ± 0.042(sys), F0 = 0.698 ± 0.057(stat) ± 0.063(sys) CMS PAS TOP-12-015
Single top	FL = 0.293 ± 0.069(stat.) ± 0.030(syst.), FR = −0.006 ± 0.057(stat.) ± 0.027(syst.), F0 = 0.713 ± 0.114(stat.) ± 0.023(syst.) CMS PAS TOP-12-020
Atlas+CMS combination Lepton+jets and dilepton	FL = 0.359 ± 0.021 (stat.) ± 0.028 (syst.), FR = 0.015 ± 0.034, F0 = 0.626 ± 0.034 (stat.) ± 0.048 (syst.) CMS PAS TOP-12-025



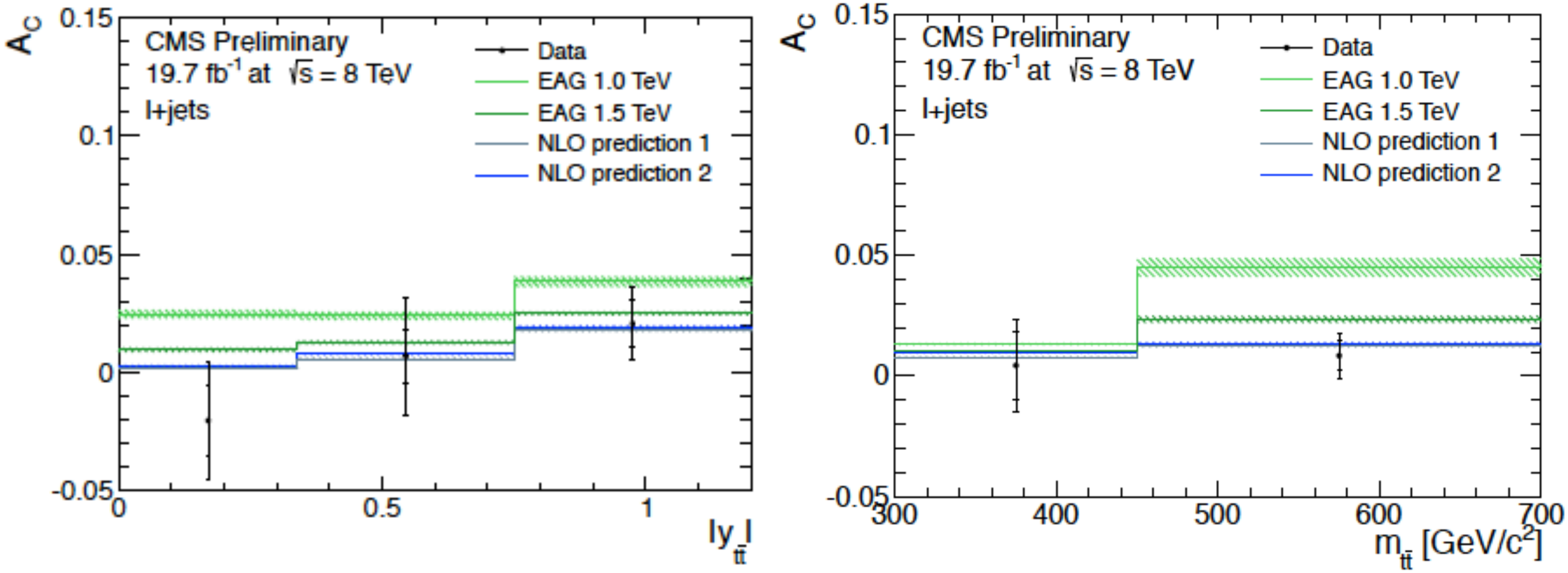
8TeV

Lepton+jets	FL = 0.350 ± 0.010 (stat.) ± 0.024 (syst.), FR = −0.009 ± 0.006 (stat.) ± 0.020 (syst.), F0 = 0.659 ± 0.015 (stat.) ± 0.023 (syst.) CMS PAS TOP-13-008

Top pair charge asymmetry at 8 TeV

- **Full 2012 dataset at $\sqrt{s}$ = 8 TeV: 19.7/fb**
- One isolated lepton, at least 4 jets, at least one jet tagged as b

$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$

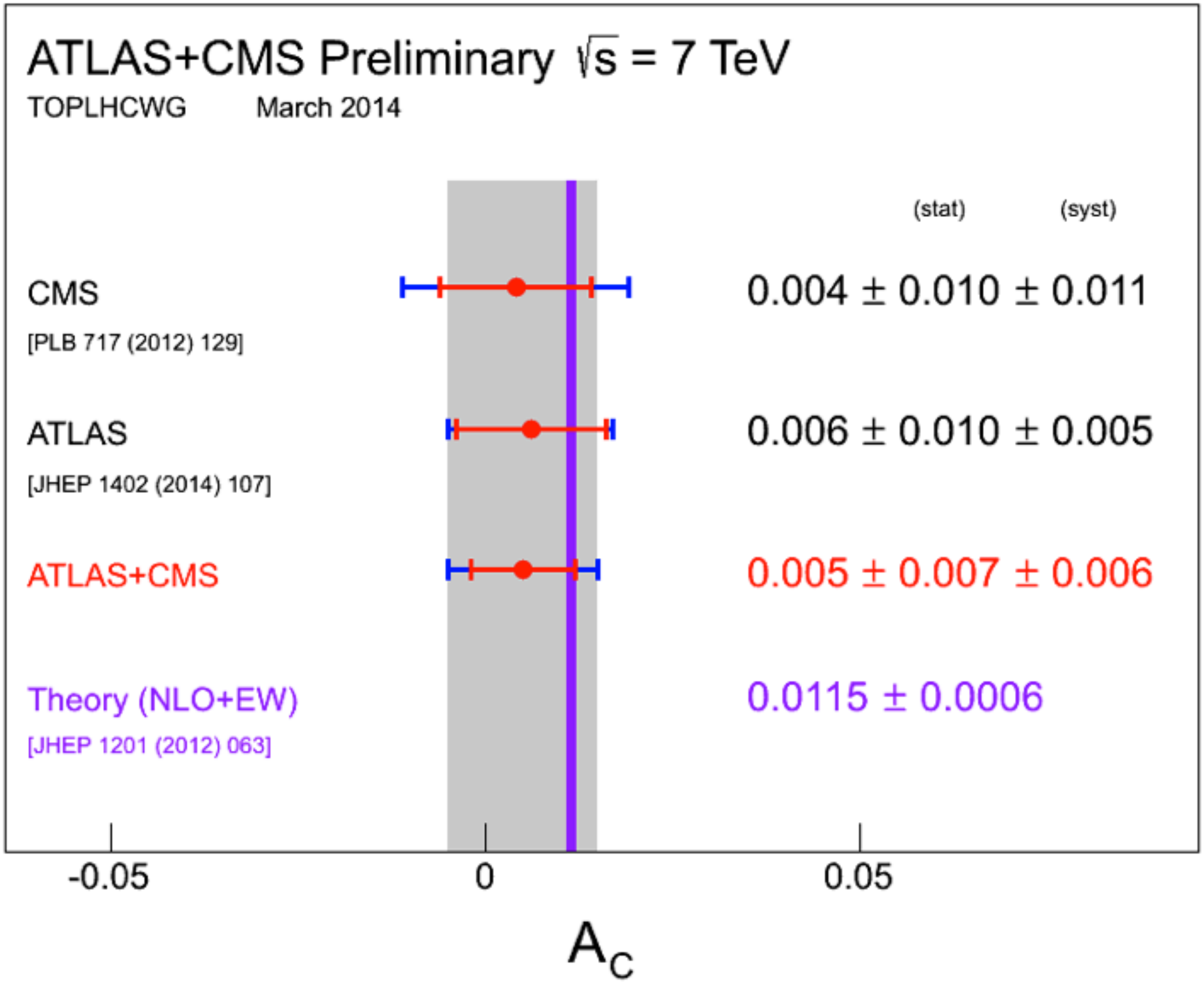


CMS PAS TOP-12-033

Inclusive measurement: 0.005±0.007(stat)±0.006(syst)
NLO: 0.0111 ± 0.0004 Phys. Rev. D **86** (2012) 034026

EAG: Model featuring an effective axial-vector coupling of the gluon: Phys. Rev. D 85 (2012) 074021

Charge Asymmetry - Example Analysis



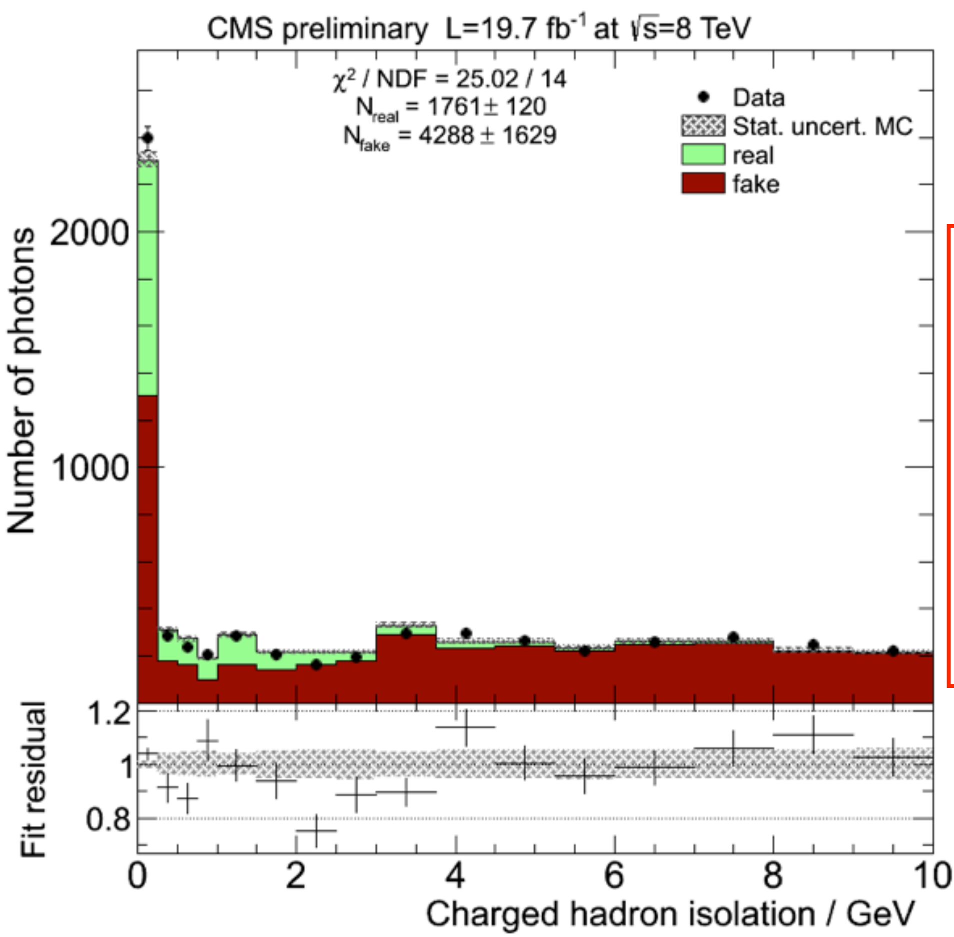
CMS PAS TOP-14-006

ATLAS+CMS: single lepton channel
Ac = 0.005±0.007(stat)±0.006(syst);
NLO: 0.0115 ± 0.0006 JHEP 1201 (2012) 063

TTbar + photon cross section

- **Full 2012 dataset at $\sqrt{s}$ = 8 TeV: 19.7/fb**
- one muon, at least four jets (at least one b-tagged), one γ
- quantity of correctly identified prompt photons is estimated using a binned maximum likelihood template fit

TOP-13-011



$$R = \sigma_{\bar{t}t+\gamma}/\sigma_{\bar{t}t}$$
$$= (1.07 \pm 0.07(\text{stat.}) \pm 0.27(\text{syst.})) \cdot 10^{-2}$$

$$\sigma_{t\bar{t}+\gamma} = R \cdot \sigma^{\text{CMS}}_{\bar{t}t}$$
$$= 2.4 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.})\,\text{pb}$$

$$\sigma^{SM}_{\bar{t}t+\gamma} = 1.8 \pm 0.5\,\text{pb}.$$

$t\bar{t}$ Cross Section - Example Analysis

$\sqrt{s}$ Uncertainty (inclusive $\sigma_{t\bar{t}}$)	7 TeV $\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	7 TeV $\Delta C_b/C_b$ (%)	7 TeV $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	8 TeV $\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	8 TeV $\Delta C_b/C_b$ (%)	8 TeV $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics			1.69			0.71
$t\bar{t}$ modelling	0.71	−0.72	1.43	0.65	−0.57	1.22
Parton distribution functions	1.03	-	1.04	1.12	-	1.13
QCD scale choice	0.30	-	0.30	0.30	-	0.30
Single-top modelling	-	-	0.34	-	-	0.42
Single-top/$t\bar{t}$ interference	-	-	0.22	-	-	0.15
Single-top Wt cross-section	-	-	0.72	-	-	0.69
Diboson modelling	-	-	0.12	-	-	0.13
Diboson cross-sections	-	-	0.03	-	-	0.03
Z+jets extrapolation	-	-	0.05	-	-	0.02
Electron energy scale/resolution	0.19	−0.00	0.22	0.46	0.02	0.51
Electron identification	0.12	0.00	0.13	0.36	0.00	0.41
Muon momentum scale/resolution	0.12	0.00	0.14	0.01	0.01	0.02
Muon identification	0.27	0.00	0.30	0.38	0.00	0.42
Lepton isolation	0.74	-	0.74	0.37	-	0.37
Lepton trigger	0.15	−0.02	0.19	0.15	0.00	0.16
Jet energy scale	0.22	0.06	0.27	0.47	0.07	0.52
Jet energy resolution	−0.16	0.08	0.30	−0.36	0.05	0.51
Jet reconstruction/vertex fraction	0.00	0.00	0.06	0.01	0.01	0.03
b-tagging	-	0.18	0.41	-	0.14	0.40
Misidentified leptons	-	-	0.41	-	-	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	1.56	0.75	2.27	1.66	0.59	2.26
Integrated luminosity	-	-	1.98	-	-	3.10
LHC beam energy	-	-	1.79	-	-	1.72
Total uncertainty ($\sigma_{t\bar{t}}$)	1.56	0.75	3.89	1.66	0.59	4.27