LHC France 2-6 April 2013, Annecy

Top/W polarization in single top production
from ATLAS and CMS

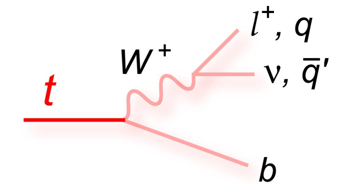
Xiaohu SUN, LPSC, Grenoble

To be presented

- W polarization measurement in helicity basis with single top events
  - Known as W helicity measurements
- CP-violation probe by the forward-backward asymmetry with W polarization in normal basis with single top events

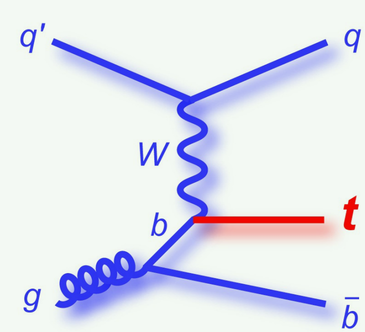
- A few words on polarization
- **What is polarization**: a momentum is produced in a prefered direction, "polarized"
- **How to study**: use angles to probe the prefered (polarized) direction
  - As people say, the polarized angular distribution

What is Top/W polarization?

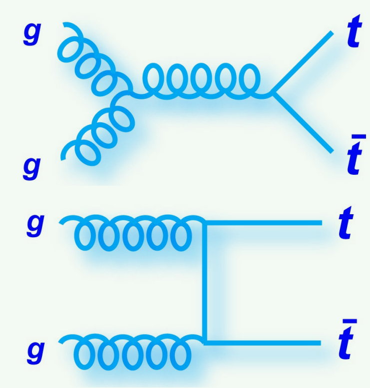


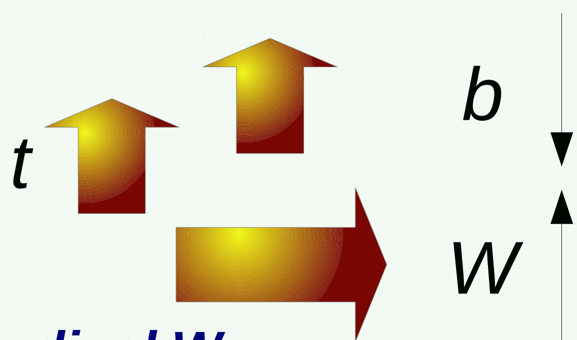
- **Top/W polarization**: decaying children are produced in a polarized direction
- **The left-handed Wtb vertex causes top/W polarization**
- For top polarization, **why use single top**?
  - Single top is highly polarized
  - Top pair is not polarized (F. Déliot talk)
- For W polarization
  - with single top (this talk)
  - with top pair (F. Déliot talk)

Weak interaction



Strong interaction

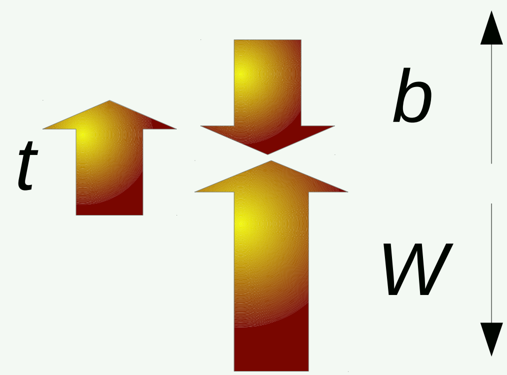




~70% Longitudinal W

spin

momentum
in top rest frame



~30% Left-handed W

spin

momentum
in top rest frame

- **Goal**:
  - Probe Wtb vertex: constraints on anomalous couplings beyond SM

Polarizations constrain Wtb interaction

- The most general effective Lagrangian describing **Wtb vertex**

$$\mathcal{L}_{tWb}^{anom.} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + H.C$$

  - SM: $V_L = V_{tb}$ almost 1, anomalous couplings V_R g_L g_R equal to 0
  - Beyond SM: non-zero anomalous couplings

- **How to constrain anomalous couplings?**
  - CMS measured W polarization fractions in helicity basis to **constrain anomalous couplings**

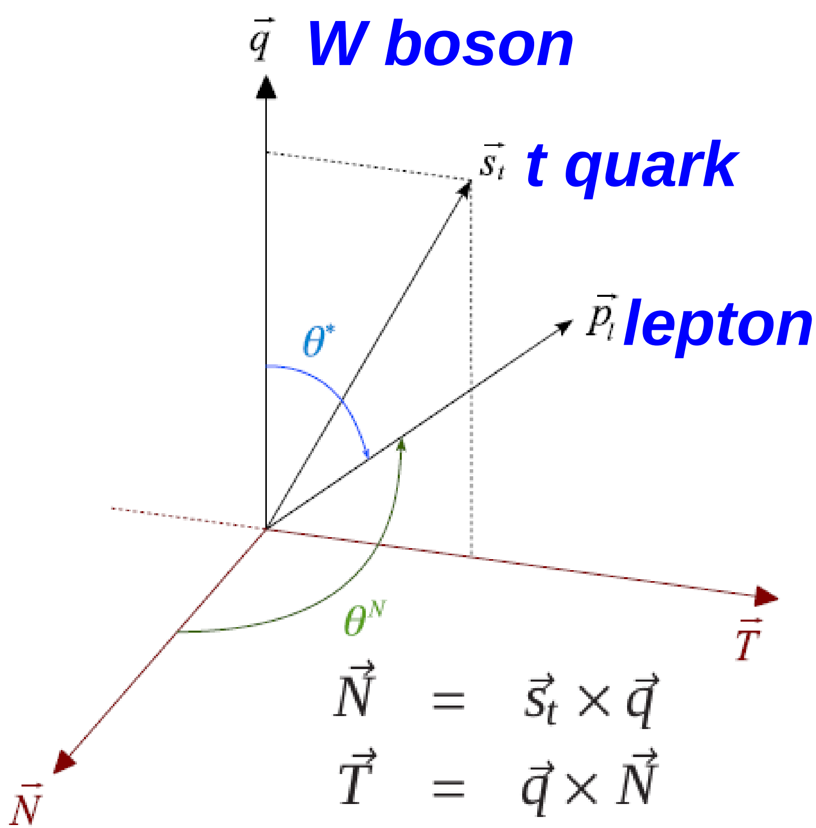
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l^*} = \frac{3}{8}(1-\cos\theta_l^*)^2 F_L + \frac{3}{8}(1+\cos\theta_l^*)^2 F_R + \frac{3}{4}\sin^2\theta_l^* F_0$$

  - ATLAS measured the forward-backward asymmetry in W polarization with normal basis to **probe CP-violation**

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^{T,N}} = \frac{3}{8}(1+\cos\theta_\ell^{T,N})^2\, F_+^{T,N} + \frac{3}{8}(1-\cos\theta_\ell^{T,N})^2\, F_-^{T,N} + \frac{3}{4}\sin^2\theta_\ell^{T,N}\, F_0^{T,N}$$

W polarization with θ*/θ^T/θ^N

- Traditionally, W polarization is measured with cosθ* in helicity basis
  - The angle between lepton momentum in W boson rest frame and W boson momentum in top quark rest frame
  - W helicity fractions are used to constrain anomalous couplings



$$\vec{N} = \vec{s}_t \times \vec{q}$$
$$\vec{T} = \vec{q} \times \vec{N}$$

Normal basis

- Paper [Nucl. Phys. B840 (2010) 349-378] explored new bases for W polarization measurements
  - s_s = top spin axis
  - q = W boson momentum in top rest frame
- Measure W polarization with
  - cosθ^T in transverse basis
  - cosθ^N in normal basis
  - ATLAS defines A^N_{FB} with cosθ^N
  - cosθ = cosθ^N $$A_z \equiv \frac{N_{evt}(\cos\theta > z) - N_{evt}(\cos\theta < z)}{N_{evt}(\cos\theta > z) + N_{evt}(\cos\theta < z)}$$
  - z = 0

CP-violation probe with A^N_{FB}

- **Analysis: Measure A^N_{FB} to constrain anomalous couplings and to probe CP-violation**

$$\mathcal{L}^{anom.}_{tWb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW^-_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW^-_{\mu} + H.C$$

$$A^N_{\mathrm{FB}} = 0.64\, P\, \mathrm{Im}\, g_R$$

[Nucl. Phys. B840 (2010) 349-378]

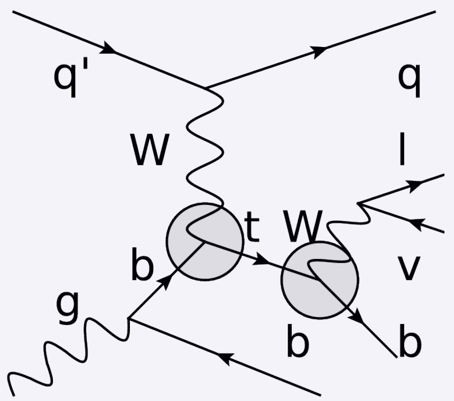
Constrain imaginary part of g_R

Non-zero A^N_{FB} indicates CP-violation

- A^N_{FB} is very sensitive to the imaginary part of g_R, for small values of g_R and taking V_L=1 V_R=g_L=0, one has the relation between the A^N_{FB} and Im g_R above
- CP violation can be probed by the non-zero imaginary part of anomalous coupling g_R
- Therefore, a non-zero A^N_{FB} indicates CP-violation

Signal and backgrounds

Signal



- Exactly one lepton (CMS uses only muon)
- High missing transverse energy
- Exactly two jets
- Exactly one of the two jets is tagged

(J. Donini talk)

Backgrounds

Data driven

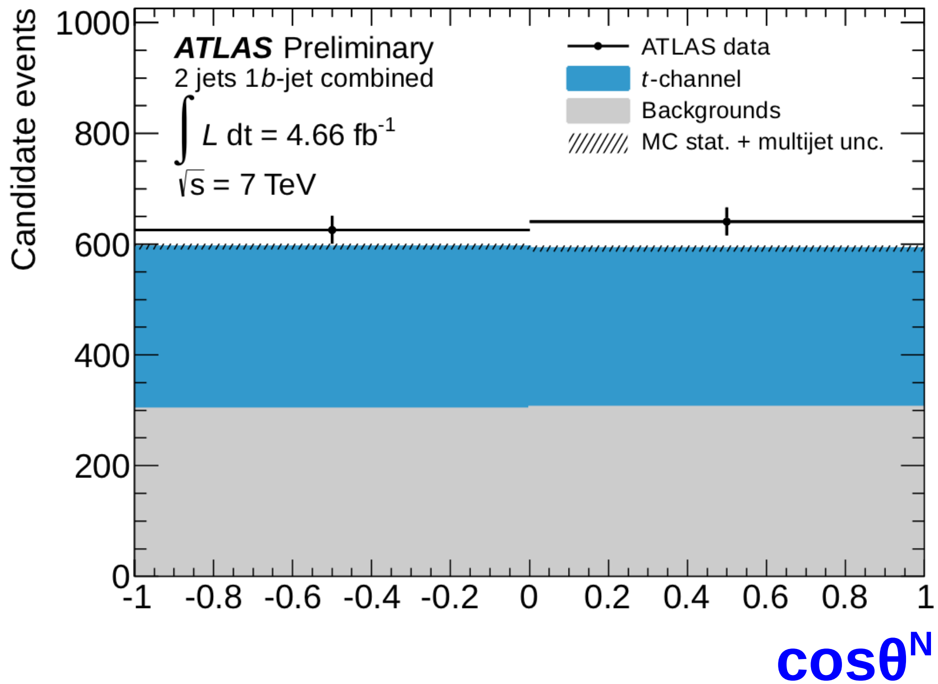
- QCD multijet background
  - Electron channel: JetElectron model for the shape modeling, fit to E^{miss}_{T} for normalization
  - Muon channel: Matrix method
- W+jets background
  - MC for modeling
  - Fit to control region for normalization

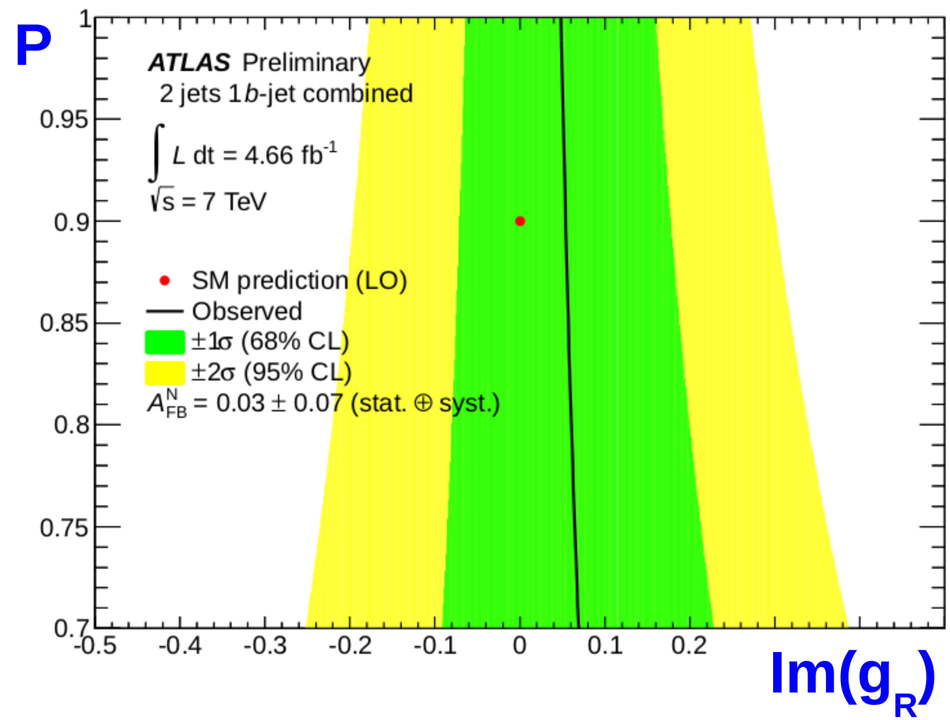
- QCD multijet background
  - Normalization is given in the fit to transverse mass of W
  - Model is given from data by inverting isolation requirements
- W+jets background
  - Normalization is given in the simultaneous fit with W helicity fraction extraction
  - Model is from control region (2jet0tag)

- **Theoretical prediction** and **Monte carlo** simulation
  - s channel, Wt channel, top pair,
  - Z+jets, Diboson(WW, WZ, ZZ)

Result: CP-violation probe with A^{N}_{FB}

$$A^{\mathrm{N}}_{\mathrm{FB}} = 0.64\, P\, \mathbb{I}(g_{\mathrm{R}})$$





[ATLAS-CONF-2013-032]

$$N_j^{\mathrm{unfolded}} = \frac{M_{ji}^{-1}(N_i^{\mathrm{data}} - N_i^{\mathrm{bkg}})}{A_j}$$

Unfolding method (2 bins)

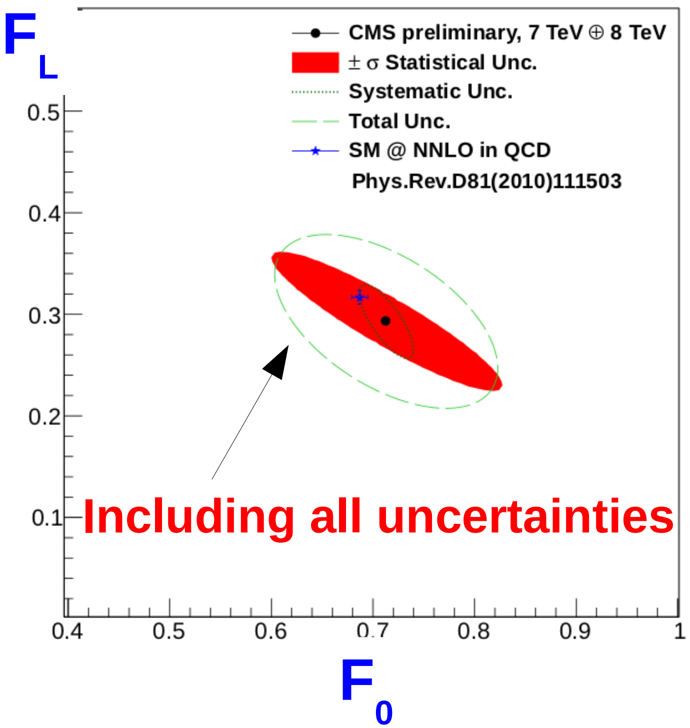
$$A^{\mathrm{N}}_{\mathrm{FB}} = 0.031 \pm 0.065\,(\mathrm{stat.})\,^{+0.029}_{-0.031}\,(\mathrm{syst.})$$

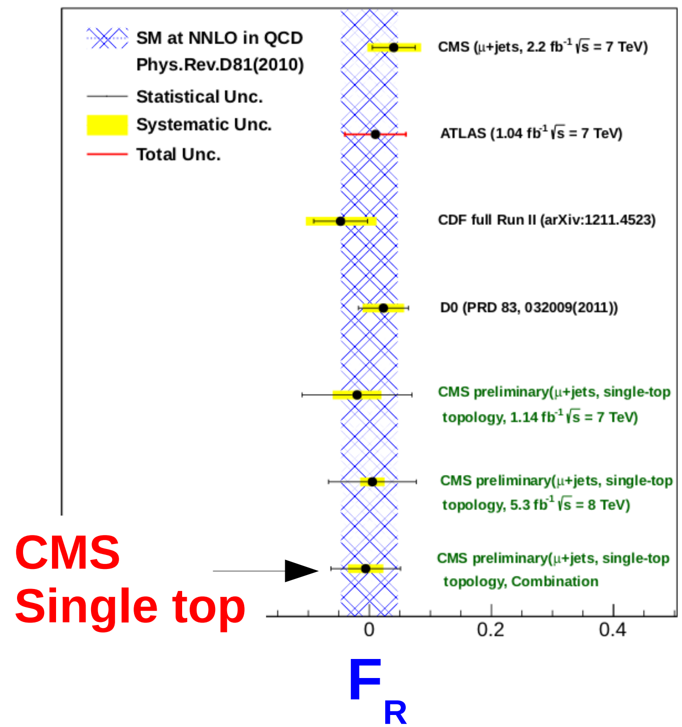
$\mathbb{I}(g_{\mathrm{R}})$ are determined to be $[-0.20, 0.30]$ at 95% confidence level
assuming P = 0.9 in SM

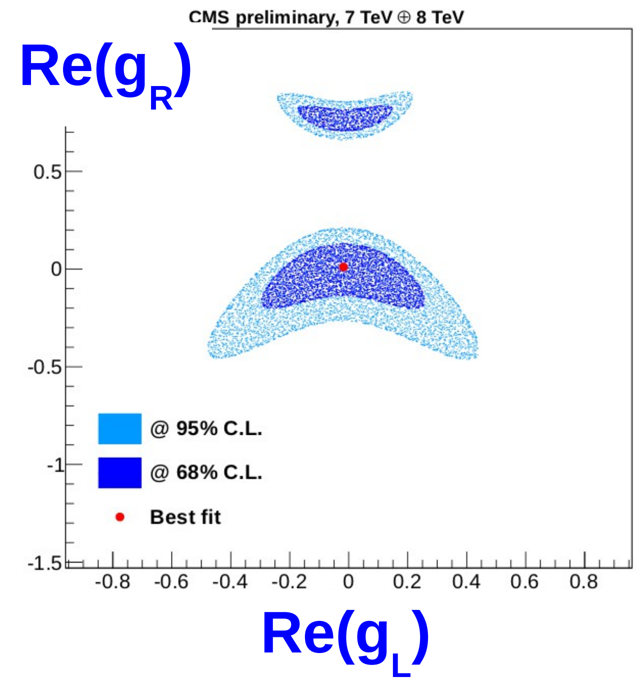
Dominant uncertainties

- statistics
- generator
- bkg normalization
- JER JES

Result: W polarization in helicity basis







$$F_L^{\text{Comb.}} = 0.293 \pm 0.069(\text{stat.}) \pm 0.030(\text{syst.}),$$
$$F_0^{\text{Comb.}} = 0.713 \pm 0.114(\text{stat.}) \pm 0.023(\text{syst.}),$$
$$F_R^{\text{Comb.}} = -0.006 \pm 0.057(\text{stat.}) \pm 0.027(\text{syst.}),$$

[CMS PAS TOP-12-020]

The measured polarizations are used to set limits on Wtb anomalous couplings.

The best fit values

g_L = -0.014 and g_R = 0.007

Conclusions

- ATLAS gave the first measurement on forward-backward asymmetry A^N_{FB} in W polarization with **normal basis** which constrains anomalous couplings in Wtb vertex and shows no evidence of CP-violation in top quark decay.
- CMS gave the first measurements on W polarization in **helicity basis** with single top topology which helps to constrain anomalous couplings in Wtb interaction.
- A little about the future
  - Determine the top polarization to improve A^N_{FB} measurement
  - Simultaneously fit to cross section and polarization observables
  - Perform a combination (top pair W helicity is available) including single top A^N_{FB} and W helicity to strongly constrain anomalous couplings
  - Explore polarizations in other bases (transverse basis)?

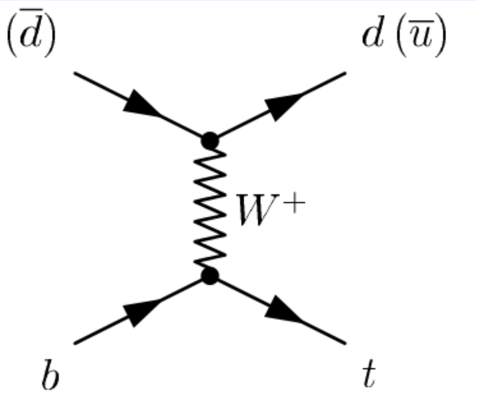
Thank you all!

Thanks to the meeting organizers for arranging everything
and giving me the possibility to give the talk here!

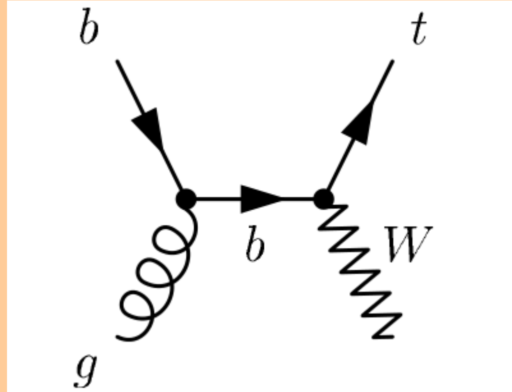
Thanks to the people working on the LHC
and to the people working on ATLAS and CMS for their excellent work!

Backup slides

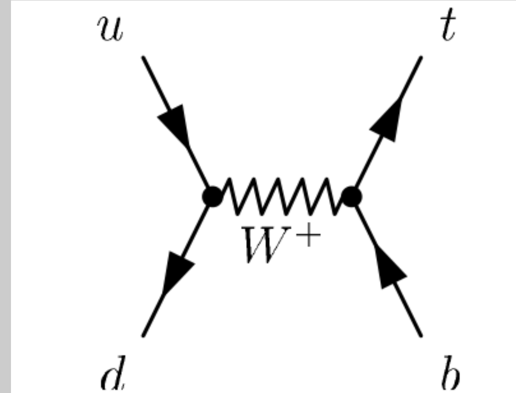
Three production modes



(a) t-channel production



(b) Associated Wt production



(c) s-channel production

First observations:
At TEVATRON
D0, CDF (2009) s+t

First observations:
At LHC
ATLAS (05-2012)
CMS (09-2012)

First observations:
At TEVATRON
D0, CDF (2009) s+t

7 TeV	64.57 pb	15.74 pb	4.63 pb
8 TeV	87.8 pb	22.4 pb	5.6 pb
increase	~ 40%	~ 40%	~ 20%

Single top first observations

- First observations (s+t combined) at TEVATRON
  - D0 [Phys. Rev. Lett. 103, 092001 (2009)]
  - CDF [Phys. Rev. Lett. 103, 092002 (2009)]

PRL **103,** 092001 (2009) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2009

Observation of Single Top-Quark Production

V. M. Abazov,[36] B. Abbott,[74] M. Abolins,[64] B. S. Acharya,[29] M. Adams,[50] T. Adams,[48] E. Aguilo,[6] M. Ahsan,[58]
G. D. Alexeev,[36] G. Alkhazov,[40] A. Alton,[64,*] G. Alverson,[62] G. A. Alves,[2] L. S. Ancu,[35] T. Andeen,[52] M. S. Anzelc,[52]
M. Aoki,[49] Y. Arnoud,[14] M. Arov,[59] M. Arthaud,[18] A. Askew,[48,†] B. Åsman,[41] O. Atramentov,[48,†] C. Avila,[8]
J. BackusMayes,[81] F. Badaud,[13] L. Bagby,[49] B. Baldin,[49] D. V. Bandurin,[58] P. Banerjee,[29] S. Banerjee,[29] E. Barberis,[62]
A.-F. Barfuss,[15] P. Bargassa,[79] P. Baringer,[57] J. Barreto,[2] J. F. Bartlett,[49] U. Bassler,[18] D. Bauer,[43] S. Beale,[6] A. Bean,[57]
M. Begalli,[3] M. Begel,[72] C. Belanger-Champagne,[41] L. Bellantoni,[49] A. Bellavance,[49] J. A. Benitez,[64] S. B. Beri,[27]
G. Bernardi,[17] R. Bernhard,[23] I. Bertram,[42] M. Besançon,[18] R. Beuselinck,[43] V. A. Bezzubov,[39] P. C. Bhat,[49]
D. Edmunds,[64] J. Ellison,[47] V. D. Elvira,[49] Y. Enari,[76] S. Eno,[60] P. Ermolov,[38,||||] M. Escalier,[15] H. Evans,[53]

(Received 4 March 2009; revised manuscript received 10 April 2009; published 24 August 2009)

We report observation of the electroweak production of single top quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV based on 2.3 fb^{-1} of data collected by the D0 detector at the Fermilab Tevatron Collider. Using events containing an isolated electron or muon and missing transverse energy, together with jets originating from the fragmentation of b quarks, we measure a cross section of $\sigma(p\bar{p} \to tb + X, tqb + X) = 3.94 \pm 0.88$ pb. The probability to measure a cross section at this value or higher in the absence of signal is 2.5×10^{-7}, corresponding to a 5.0 standard deviation significance for the observation.

DOI: 10.1103/PhysRevLett.103.092001 PACS numbers: 14.65.Ha, 12.15.Hh, 12.15.Ji, 13.85.Qk

PRL **103,** 092002 (2009) PHYSICAL REVIEW LETTERS

Observation of Electroweak Single Top-Quark Production

T. Aaltonen,[24] J. Adelman,[14] T. Akimoto,[56] B. Álvarez González,[12,t] S. Amerio,[44b,44a] D. Amide
A. Annovi,[20] J. Antos,[15] G. Apollinari,[18] A. Apresyan,[49] T. Arisawa,[58] A. Artikov,[16] W. Ashm
A. Aurisano,[54] F. Azfar,[43] W. Badgett,[18] A. Barbaro-Galtieri,[29] V. E. Barnes,[49] B. A. Barnett,
V. Bartsch,[31] G. Bauer,[33] P.-H. Beauchemin,[34] F. Bedeschi,[47a] D. Beecher,[31] S. Behari,[26] G. Belletti
D. Benjamin,[17] A. Beretvas,[18] J. Beringer,[29] A. Bhatti,[51] M. Binkley,[18] D. Bisello,[44b,44a] I. Biz
C. Cuenca Almenar,[8,v] J. Cuevas,[12,t] R. Culbertson,[18] J. C. Cully,[35] D. Dagenhart,[18] M. Datta,[18] T. Davies,[22]

(Received 4 March 2009; published 24 August 2009)

We report the observation of single top-quark production using 3.2 fb^{-1} of $p\bar{p}$ collision data with $\sqrt{s} = 1.96$ TeV collected by the Collider Detector at Fermilab. The significance of the observed data is 5.0 standard deviations, and the expected sensitivity for standard model production and decay is in excess of 5.9 standard deviations. Assuming $m_t = 175\ \text{GeV}/c^2$, we measure a cross section of $2.3^{+0.6}_{-0.5}$(stat + syst) pb, extract the CKM matrix-element value $|V_{tb}| = 0.91 \pm 0.11$(stat + syst) $\pm$ 0.07(theory), and set the limit $|V_{tb}| > 0.71$ at the 95% C.L.

Cross sections

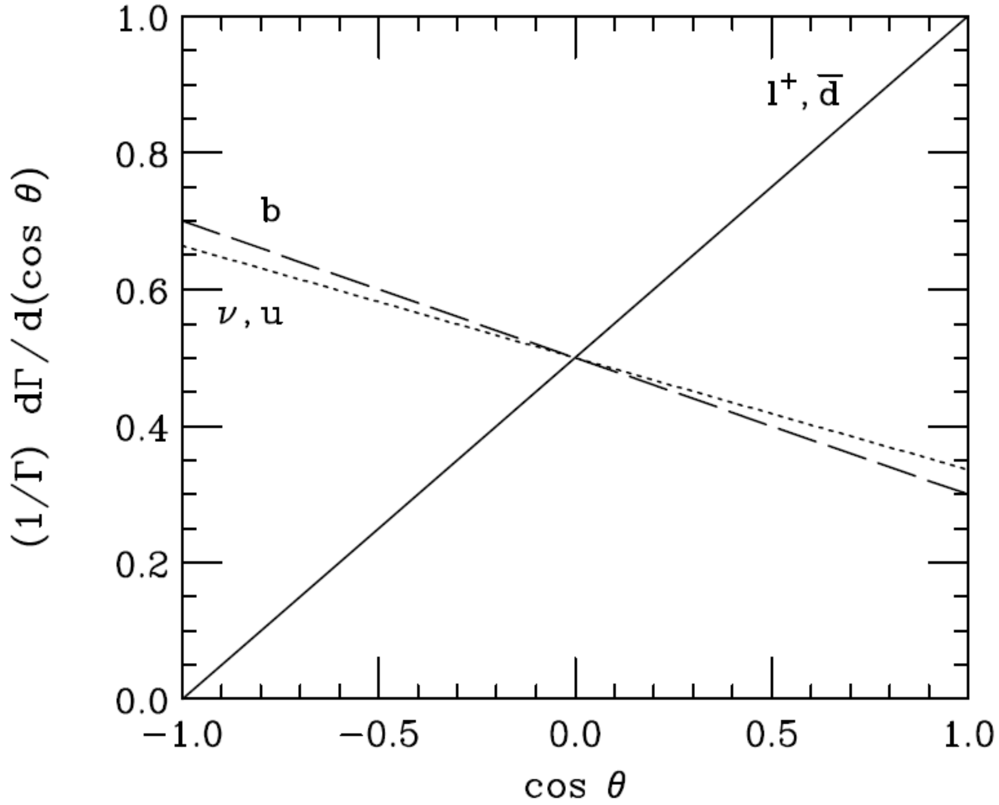
- Cross sections at the center of mass energy X TeV

Collider	s-channel σ_{tb}	t-channel σ_{tqb}	tW-channel σ_{tW}
Tevatron $p\bar{p}$ (1.96 TeV)	1.05 pb	2.08 pb	0.22 pb
LHC pp (7 TeV)	4.63 pb	64.6 pb	15.7 pb
LHC pp (8 TeV)	5.55 pb	87.1 pb	22.2 pb

Collider (energy)	process	approx σ
Tevatron $p\bar{p}$ (run II 1.96 TeV)	$t\bar{t}$	~7 pb
LHC pp (7 TeV)	$t\bar{t}$	~165 pb
LHC pp (8 TeV)	$t\bar{t}$	~235 pb
LHC pp (7 TeV)	single t (total)	~ 85 pb
LHC pp (8 TeV)	single t (total)	~ 115 pb

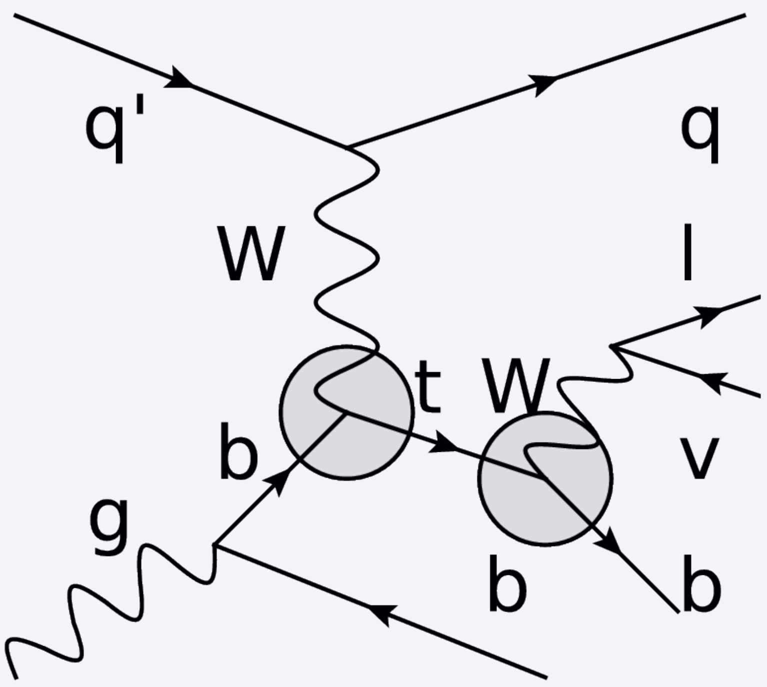
Top polarization

- The angle could be calculated with different decaying children from top: b quark, W boson, lepton, neutrino



arXiv:hep-ph/9811219

CP-violation - event selection



Pretag sample

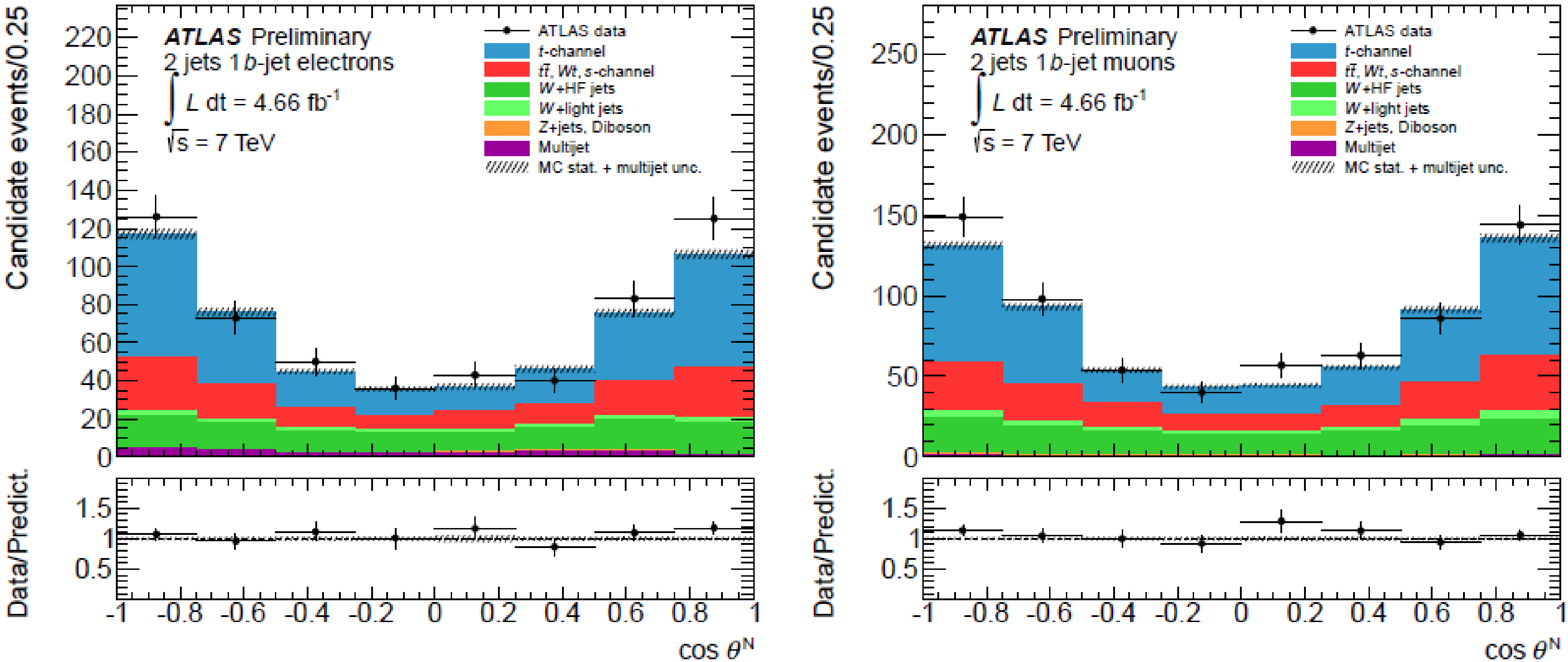
- Exactly one lepton with p_T > 25 GeV
- Exactly two jets
  - Jet p_T > 30 GeV, |η|<4.5
  - With crack removal p_T > 35 GeV at 2.75<|η|<3.5
- Retangular cut
  - MET > 30 GeV MTW > 30 GeV
- QCD rejection
  - p_T(lepton) > 40 ∓ (40/π − 1)(φ(leading-jet, lepton) ± π) GeV

Tagged sample

- Exactly one btagged jets among the two jets
  - Central |η|<2.5
  - JetFitterCOMBNNc cut at 55% btagging efficiency

Extractly A^{N}_{FB} with tagged samples
& | η (light jet)| > 2 & H_T>210 GeV
& m_{top} within 150-190 GeV & | Δη(light jet, b-jet)| > 1

CP-violation - $\cos\theta^N$



[ATLAS-CONF-2013-032]

CP-violation - event yield

	Electron		Muon	
	Preselection	Selection	Preselection	Selection
t-channel	1703 ± 9	262 ± 3	2053 ± 10	318 ± 4
s-channel	114 ± 2	3 ± 0	147 ± 2	5 ± 0
Wt-channel	574 ± 15	14 ± 3	700 ± 17	15 ± 2
Top quark pair	4065 ± 13	114 ± 2	4740 ± 15	140 ± 2
Diboson	121 ± 2	1 ± 0	142 ± 2	2 ± 0
Z+jets	196 ± 9	4 ± 1	190 ± 7	3 ± 1
W+HF jets	5226 ± 57	106 ± 8	7686 ± 65	137 ± 8
W+light jets	1339 ± 58	15 ± 8	1919 ± 70	23 ± 6
Multijet	1100 ± 500	20 ± 10	550 ± 280	6 ± 3
Total expected	14400 ± 600	539 ± 19	18130 ± 290	649 ± 12
S/B	0.13	0.95	0.13	0.96
ATLAS data	14738	576	17966	691

[ATLAS-CONF-2013-032]

CP-violation - uncertainties

[ATLAS-CONF-2013-032]

Source	ΔA_{FB}^{N}
t-channel generator	+0.024 / −0.024
$t\bar{t}$ generator and parton shower	+0.010 / −0.010
Background normalisation	+0.008 / −0.008
Jet energy resolution	+0.007 / −0.007
Jet energy scale	+0.005 / −0.009
Lepton id, reco., trigger and scale	+0.004 / −0.006
PDFs	+0.003 / −0.003
Unfolding	+0.003 / −0.003
E_{T}^{miss}	+0.002 / −0.004
b-tagging	+0.002 / −0.002
W+jets shape	+0.001 / −0.001
ISR/FSR	+0.001 / −0.001
Jet reconstruction efficiency	+0.001 / −0.001
Luminosity	+0.001 / −0.001
Jet vertex fraction	<0.001 / <0.001
Total systematic	+0.029 / −0.031

Lumi uncer input 1.8% 2011

W helicity - Reweighting

- The weight $W(\cos\theta^*_{l,gen}; \vec{F}^{nonSM})$

$$\frac{\rho^{nonSM}(\cos\theta^*_{l,gen})}{\rho^{SM}(\cos\theta^*_{l,gen})} = \frac{\frac{3}{8}(1-\cos\theta^*_{l,gen})^2 F_L^{nonSM} + \frac{3}{8}(1+\cos\theta^*_{l,gen})^2 F_R^{nonSM} + \frac{3}{4}\sin^2\theta^*_{l,gen} F_0^{nonSM}}{\frac{3}{8}(1-\cos\theta^*_{l,gen})^2 F_L^{SM} + \frac{3}{8}(1+\cos\theta^*_{l,gen})^2 F_R^{SM} + \frac{3}{4}\sin^2\theta^*_{l,gen} F_0^{SM}}$$

- The pdf of cosθ* of signal after reconstruction

$$\rho(\cos\theta^*_{l,reco}|\vec{F}) \propto \int \mathrm{d}\cos\theta^*_{l,gen}\ W(\cos\theta^*_{l,gen}; \vec{F})\ \rho(\cos\theta^*_{l,gen}|\vec{F}^{SM})\ \mathcal{R}(\cos\theta^*_{l,gen}, \cos\theta^*_{l,reco})$$

Transfer matrix

- Binned likelihood function $\mathcal{L}(\vec{F}) = \prod_{i\in bins} \frac{(n_i^{MC;\vec{F}})^{n_i^{data}}}{n_i^{data}!} \times e^{n_i^{MC;\vec{F}}}$

$$n_i^{MC;\vec{F}} = n_i^{bkg-other} + N_{Wjets} \times \beta_i^{Wjets} + f \times n_{i,rw}^{signal}$$

Parameters to be fit, 3 in total

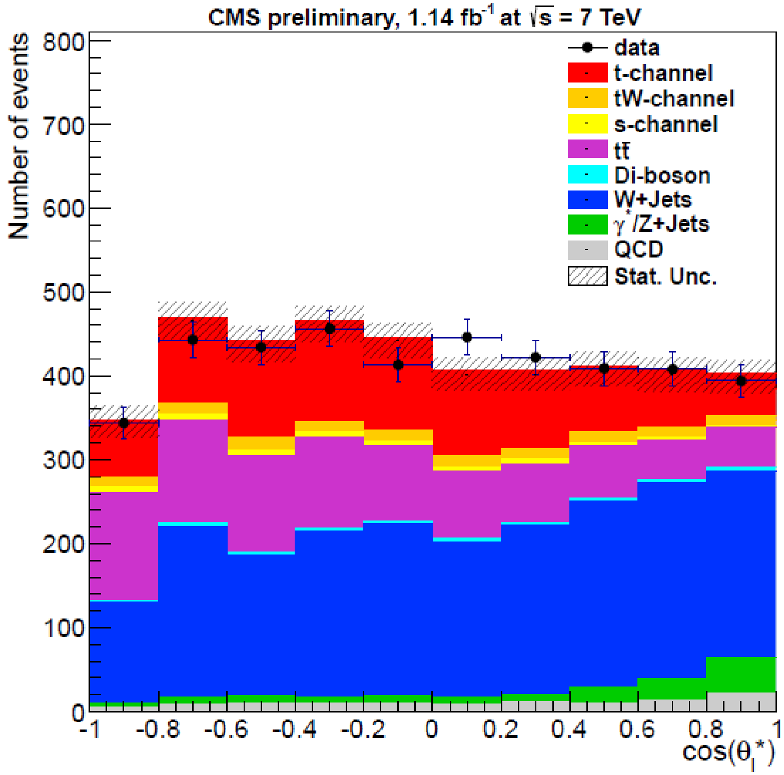
- Wjets normalization and (F_L, F_0) are fit simultaneously
  - Signal normalization is fixed to 1 according to cross section measurement

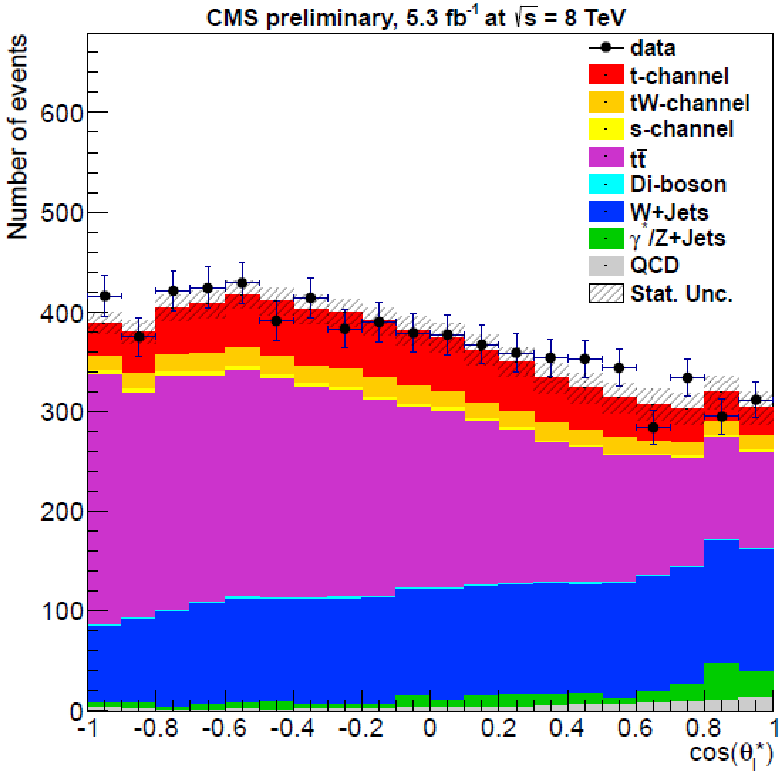
W helicity - event selection

Event selection (only muon events are used in *7(8) TeV* analysis)

- Exactly one isolated muon with p_T>20(26)GeV and |η|<2.1
- Exactly two jets with p_T>30GeV and |η|<4.5 for 7TeV
  - Both jet with p_T>60GeV for 8TeV
- MTW > 40(50) GeV
- Exactly one btagged jet (mistag rate ~0.1%)

W helicity - cosθ*





[CMS PAS TOP-12-020]

W helicity - event yield

Process	Event yield at 7 TeV	Event yield at 8 TeV
single top (t)	910±4	954±5
single top (tW)	131±1	328±6
single top (s)	56±1	64±0
$t\bar{t}$	867±5	3541±11
Diboson	38±1	29±1
W+jets	1953±30	2133±22
DY+jets	145±4	207±14
QCD	107±4	78±39
Total expected	4206±31	7334±49
Data	4196	7401

[CMS PAS TOP-12-020]

W helicity - uncertainties

	$\sqrt{s} = 8\,\text{TeV}$		$\sqrt{s} = 7\,\text{TeV}$	
Systematic source	ΔF_L	ΔF_0	ΔF_L	ΔF_0
JES	0.006	0.006	0.020	0.020
JER	0.008	0.003	0.015	0.010
unclustered energy	0.013	0.003	0.015	0.015
pileup	0.002	0.003	0.004	0.000
b-flavored scale factor	0.004	0.006	0.009	0.009
non-b-flavored scale factor	0.004	0.007	0.002	0.001
single-top generator	0.008	0.014	0.004	0.004
Q^2 scale	0.009	0.012	0.040	0.007
m_{top}	0.005	0.006	0.010	0.010
PDF	0.005	0.005	0.000	0.000
$t\bar{t}$ normalization	0.002	0.003	0.008	0.008
QCD shape	0.002	0.002	0.004	0.004
W+jets shape	0.008	0.010	0.010	0.010
integrated luminosity	0.003	0.003	0.007	0.007
SM W-helicity reference	0.004	0.003	0.001	0.002
total systematic uncertainty (w/o generator)	0.022	0.021	0.054	0.035
total systematic uncertainty	0.024	0.026	0.054	0.035

[CMS PAS TOP-12-020]