Top properties measurements at LHC

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- Introduction/motivation
  - Top quark charge
  - t-tbar spin correlations
  - W polarisation and the Wtb vertex
- Summary / outlook

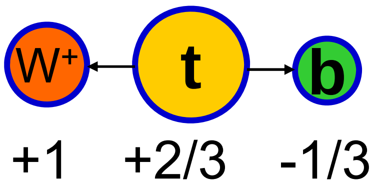
- ATLAS results from CERN-OPEN-2008-20 ('CSC book')
- CMS results from CMS Physics TDR
- Some Tevatron results for comparison…

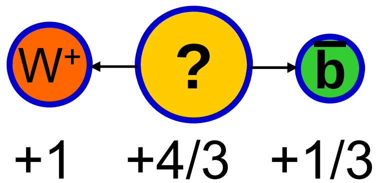
Why measure top properties at the LHC?

- Top exists! Measure its fundamental parameters (mass, charge, couplings,…)
  - Heaviest known quark, least studied, some peculiar properties
    - Decays involve real rather than virtual W
    - Decays before hadronises – spin/polarisation information is preserved
- Top quark beyond the Standard Model
  - Top may be produced in new particle decays (t-tbar resonances, heavy H …)
  - Top quarks may decay in peculiar ways, e.g. $t \rightarrow H^+ b$
    - Careful measurement of the top quark properties may reveal deviations from the SM expectation, signaling new physics
- LHC is a top quark factory
  - At 10^{33} $cm^{-2}s^{-1}$ ('nominal' low luminosity), get 1 top pair/second, or 8M/year
    - 30% of these decay to **$\{e/\mu\}\nu b$ jjb** or **$\{e/\mu\}\nu b\{e/\mu\}\nu b$** final states, good trigger efficiency
  - At 10^{34} $cm^{-2}s^{-1}$ (full LHC design luminosity before SLHC upgrade), get 10 Hz top pairs … O(100M)/year
    - But background from pileup at 10^{34} will make precision studies difficult
  - Analyses of top properties concentrate on 10^{33} scenario (and 14 TeV Ecm)

Top quark charge - SM or exotic?

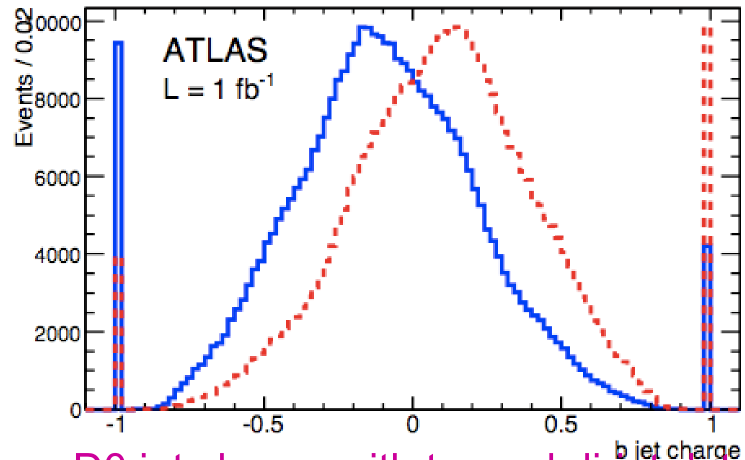
- Object with mass 173 GeV, decays to Wb



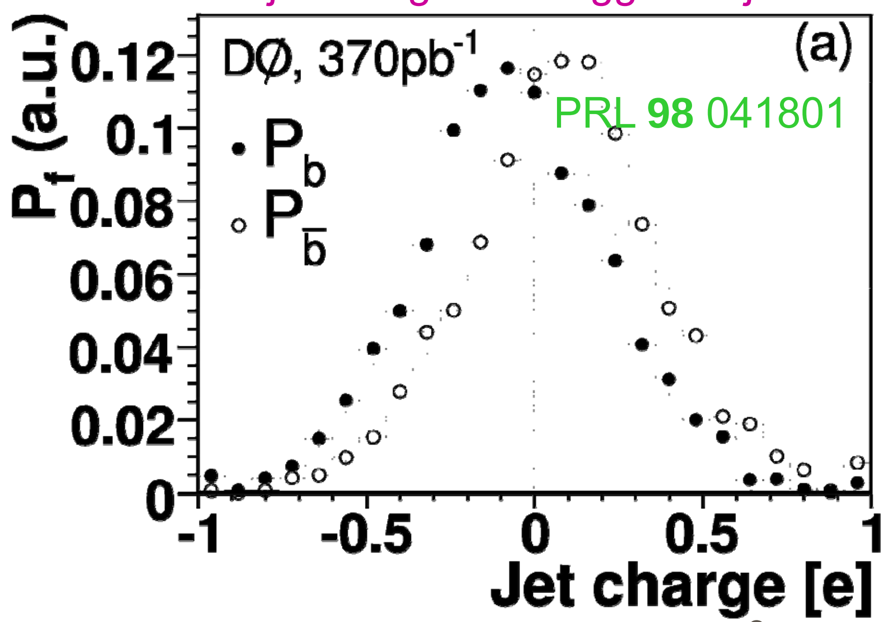


  - Some scenarios with an exotic 4/3e charge object at 175 GeV, real m_{top}>230 GeV
- Measure the top charge (its decay products)
  - Charge of the lepton (±1) ⇒charge of W
  - Charge of the b-quark (±2/3) … infer from **jet charge** of the b-jet
    - Technique familiar from B-oscillation and CP-violation studies, e.g.
    - $Q_{jet}=\sum(\mathbf{p}_{trk}\cdot\mathbf{p}_{jet})^{\kappa} Q_{trk} / \sum (\mathbf{p}_{trk}\cdot\mathbf{p}_{jet})^{\kappa}$ with κ optimised to give best b / b-bar separation
  - Challenges are to **calibrate** jet charge (from b-flavour enhanced dijet data) and **pair** the lepton(s) and b-jet(s) correctly

b/b-bar jet charge in top Monte Carlo



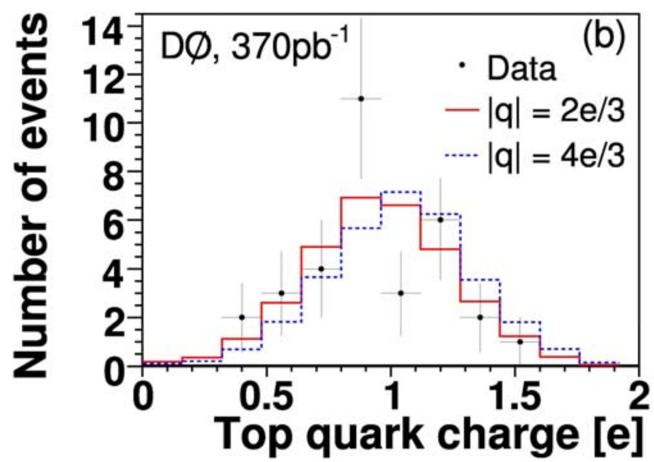
D0 jet charge with tagged di-jet data



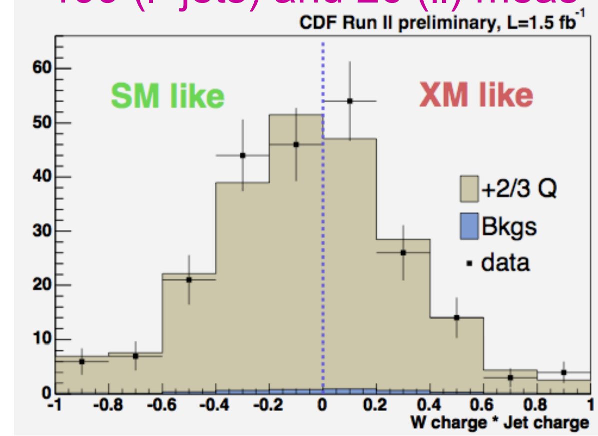
Top charge - Tevatron results

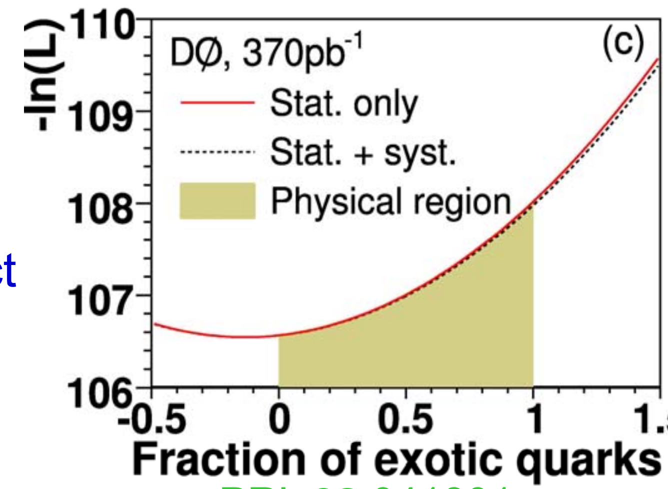
- Tevatron stat-limited results:
  - D0+CDF using l+jet events
    - B-tagging to identify b-jets
    - Association to correct lepton using kinematic fit of t-tbar
  - CDF also using dileptons
    - No b-tagging, use M(bl) of different assignments to determine correct ones
- Both favour SM scenario
  - D0 excludes that **whole sample** is exotic at 92% CL
  - CDF excludes same at 87%, with a 1% prob to falsely reject SM… different interpretation
    - D0 f_{exotic}<0.8 at 90% CL
    - CDF f_{exotic}<0.6 at 95% CL
  - SM highly favoured over XM

16 events, 32 measurements



199 (l+jets) and 26 (ll) meas^{m}





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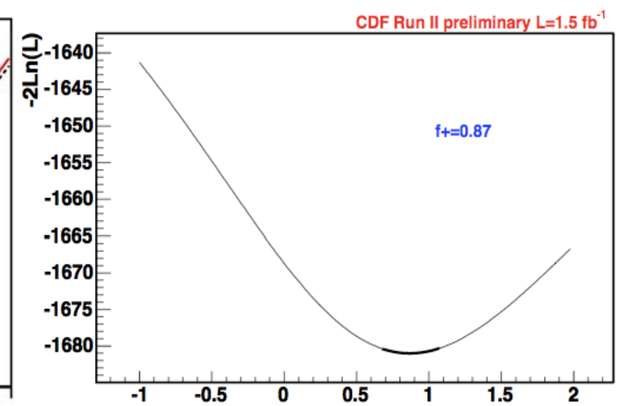


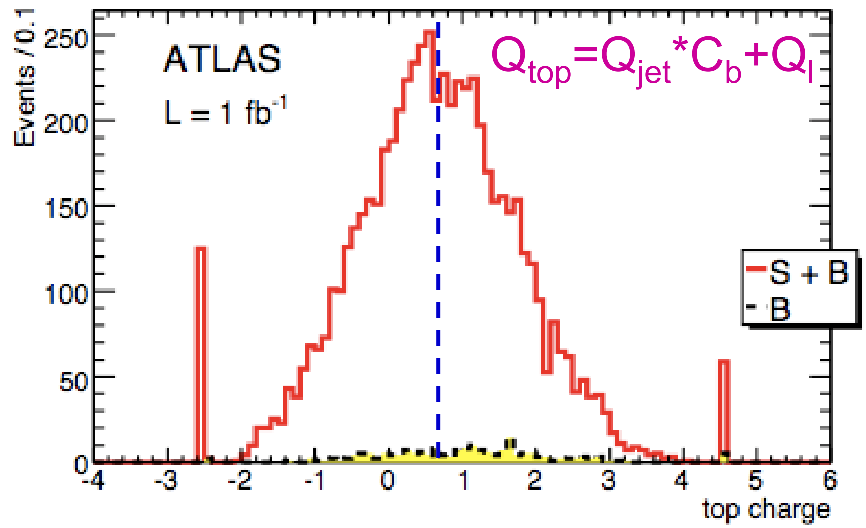
$1-f_{exotic}$

CDF note 8967

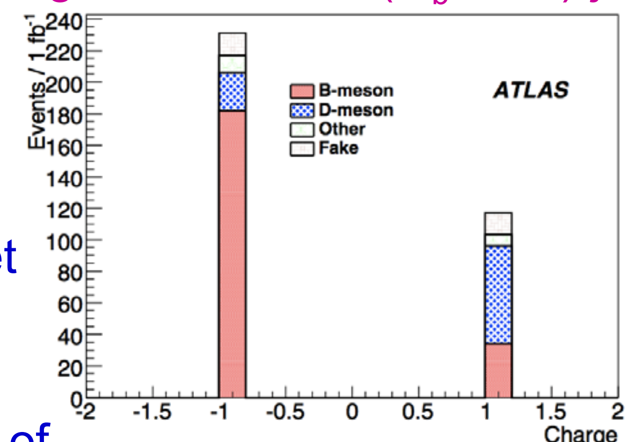
Top charge measurement at LHC

- Statistics good (~6000 l-jet pairs per fb^{-1})
  - Simple selection, require two b-tags in event
    - Using l-bjet pairing based on M(lb) cuts, with 30% efficiency and 86% correct pairing fraction
  - Simple Q_{jet} with κ=0.5; ≥2 tracks p_T>1.5 GeV
  - Can also use b-jets with muons to get Q_b
- Measure $Q_{comb}=Q_{jet}*Q_l$ and $Q_{top}=Q_{jet}*C_b+Q_l$
    - C_b calibrates jet charge: $Q_b=Q_{jet}*C_b$
  - Expect Q_{comb}<0 with 20σ statistical in 1 fb^{-1}
- Systematics for Q_{comb} (%)

Source	Q(jet)	muon
jet scale	0.7	0.3
b-jet scale	1.9	6
Δm_t	1.3	7
PDF	0.6	–
ISR	2.8	15
FSR	7.8	8
Pile-up	–	1.8
Background asymmetry	1	–
S/B ratio	9	–
total	12.5	19.3



Charge of muon in b(Q_b=-1/3)-jet



- Largely data-driven - e.g. understanding of non-ttbar background
- Eventually use tagged di-jet data to measure Q_{jet} performance (C_b) with data
- Will be sensitive to mixture of SM and XM scenarios …

Top-anti-top spin correlations

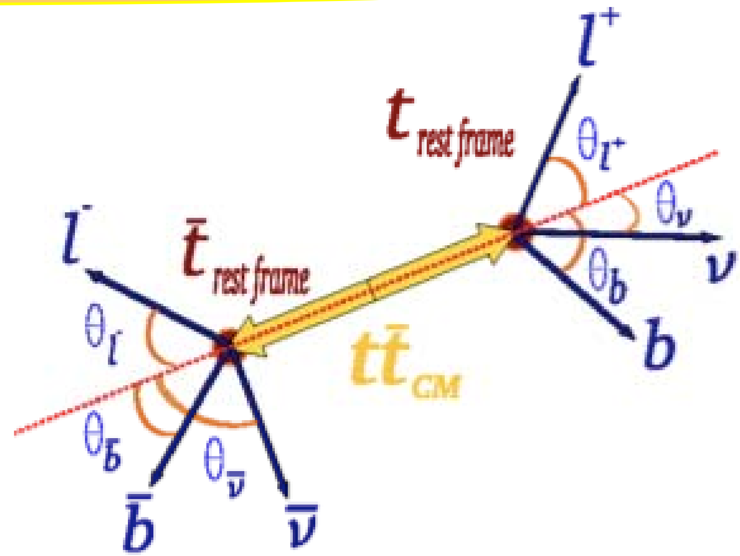
- Top quarks produced ~unpolarized in SM
  - But spin of t and t-bar are correlated - depends on production mechanism (qq vs gg) and energy
    - Measuring spin correlation gives info on production
- Parameterise with an asymmetry A

$$A = \frac{\sigma(t_\uparrow \bar{t}_\uparrow) + \sigma(t_\downarrow \bar{t}_\downarrow) - \sigma(t_\uparrow \bar{t}_\downarrow) - \sigma(t_\downarrow \bar{t}_\uparrow)}{\sigma(t_\uparrow \bar{t}_\uparrow) + \sigma(t_\downarrow \bar{t}_\downarrow) + \sigma(t_\uparrow \bar{t}_\downarrow) + \sigma(t_\downarrow \bar{t}_\uparrow)}$$

- Since top decays before hadronisation, spin information is preserved in decay product angles
  - Angle θ defined between top quark direction in t-tbar rest frame, and decay product in t rest frame

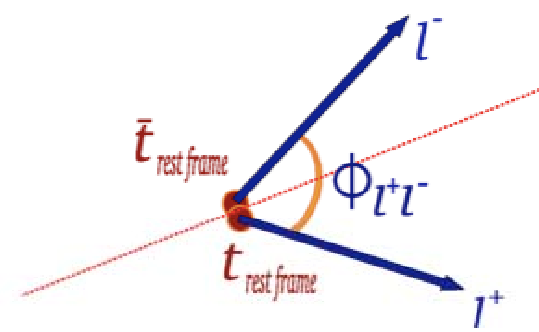
$$\frac{1}{N}\frac{d^2N}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - A|\alpha_1\alpha_2|\cos\theta_1\cos\theta_2)$$

  - θ_1, θ_2 measured using a decay product from each top quark 1,2; α_1, α_2 are analysing powers
    - α: Correlation between top and decay product
    - 1 for lepton; -0.41 for b, 0.51 for lower E q from W



- Can also look at opening angle
  - Useful in particular for dileptons

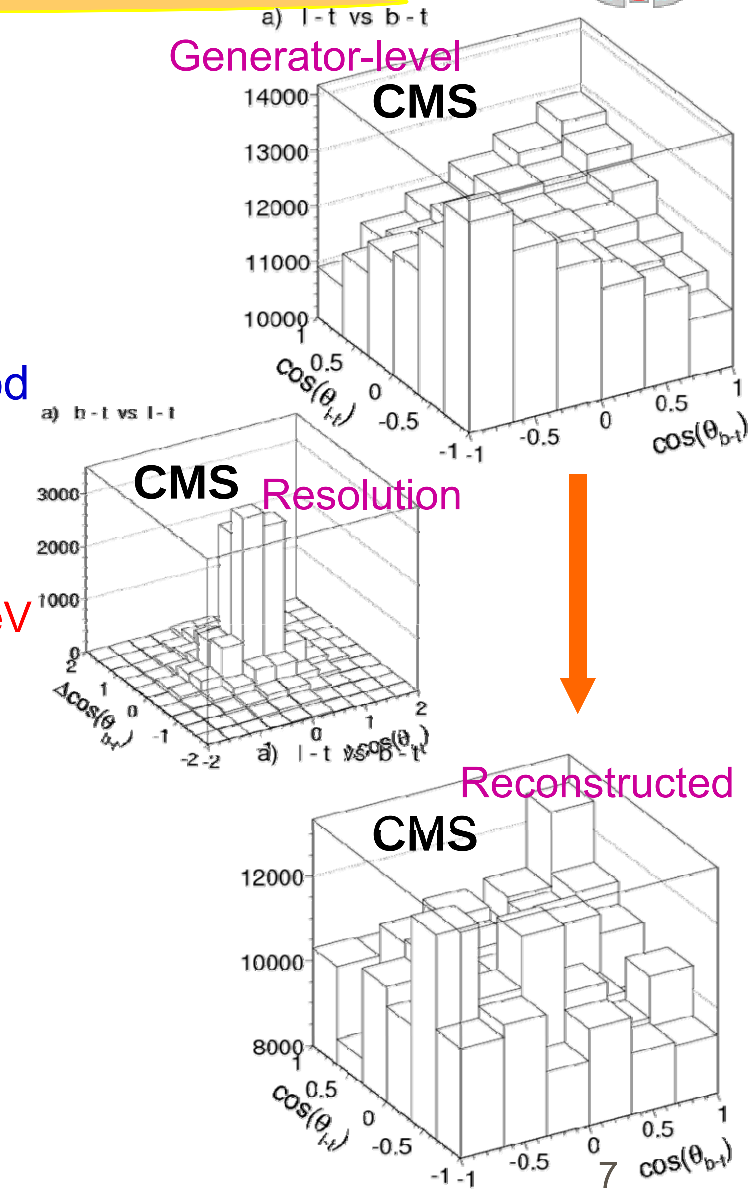
$$\frac{1}{N}\frac{dN}{d\cos\Phi} = \frac{1}{2}(1 - A_D|\alpha_1\alpha_2|\cos\Phi)$$



Angular reconstruction

- Experimentally, choose two ‘analyser particles’
  - E.g. lepton and lower-energy quark from W decay
  - Need to fully reconstruct event (t/tbar 4-vectors)
    - Including estimate of neutrino from missing E_T vector
  - Typically require lepton+≥4 jets, 2-b-tagged jets, using mass requirements and/or kinematic fits to ensure good event reconstruction
    - CMS study shows S/B of 4.5, background dominated by mis-reconstructed top decays
    - Expect around 10k reconstructed events per fb^{-1} @ 14TeV
- Resolution and acceptance effects modify the expected distributions
  - Correct using a 6x6 matrix (CMS approach)
    - Ratio of reconstructed to selected events in each bin
  - Background must also be subtracted … then fit distribution according to

$$\frac{1}{N}\frac{d^2N}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - A|\alpha_1\alpha_2|\cos\theta_1\cos\theta_2)$$



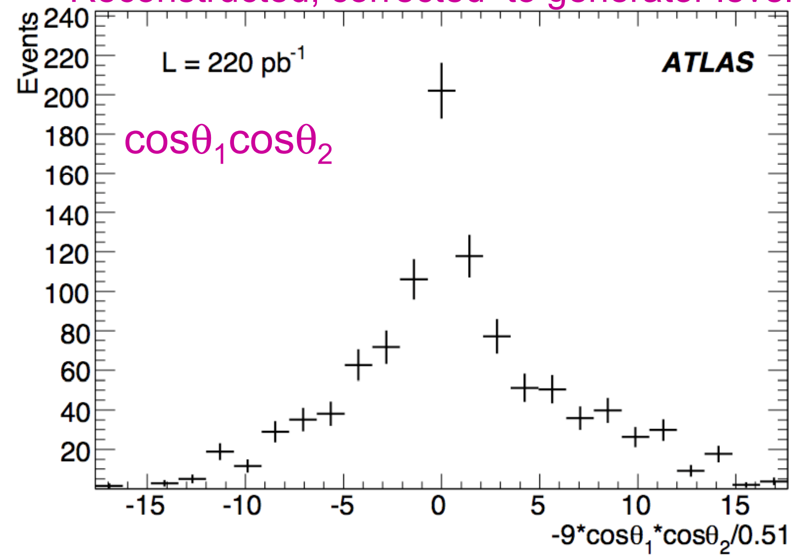
Angular reconstruction and results

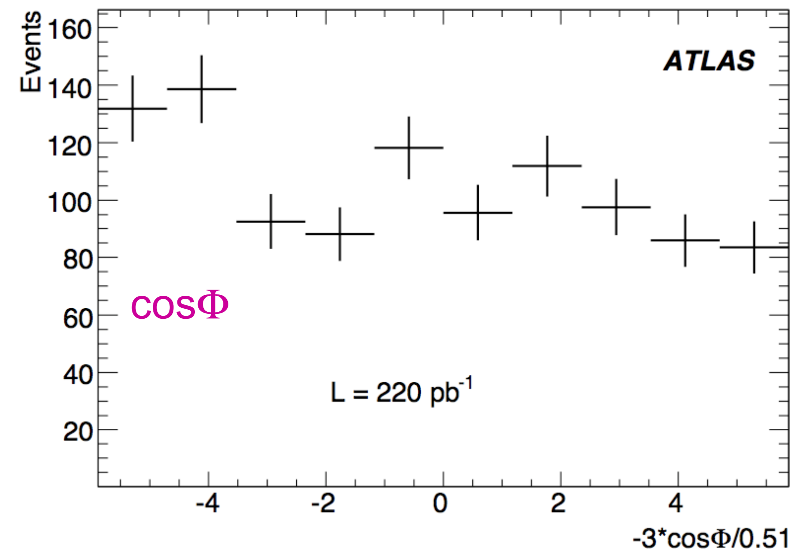
- Alternative approach based on means (ATLAS)
  - Means of $\cos\theta_1\cos\theta_2$ and $\cos\Phi$ distributions are estimators of A and A_D
  - Make 1D-distributions and correct bin-by-bin back to generator level to extract spin correlation
- Estimated statistical/systematic uncertainties

Expt	Measurement	Int L	stat	syst
ATLAS	A(q-l) ≈ 0.42	1 fb^{-1}	0.17	0.18
ATLAS	A_D(q-l) ≈ -0.29	1 fb^{-1}	0.11	0.09
CMS	A(b-l)	10 fb^{-1}	0.027	0.076
CMS	A(q-l)	10 fb^{-1}	0.021	0.041

- Require O(10 fb^{-1}) to make clear 5σ observation
  - Good control of systematics will be essential
    - B-tagging efficiency, jet energy scale, ISR/FSR …
    - Need time and data to understand t-tbar reconstr^n

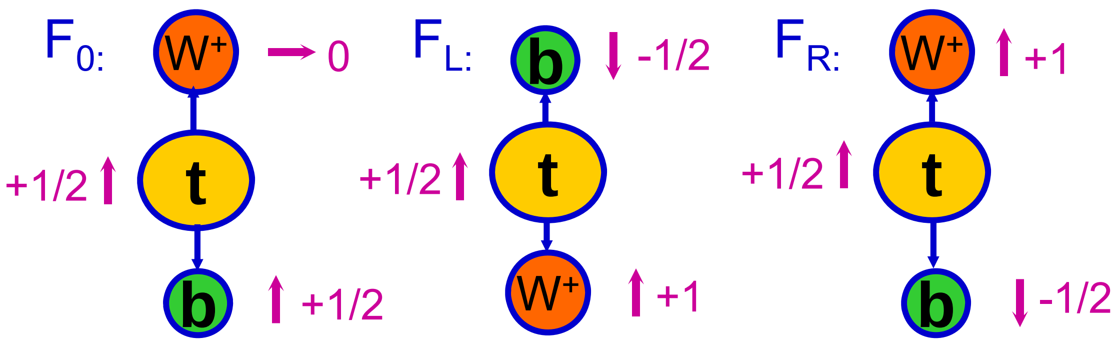
Reconstructed, corrected to generator level



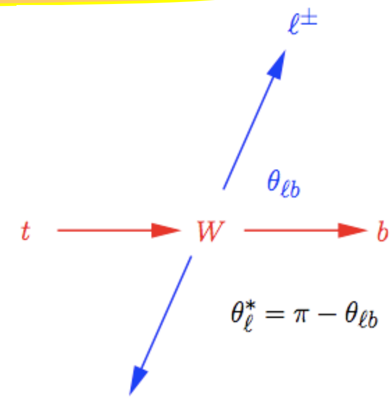


W polarisation in top quark decays

- W in top decay produced with different helicities



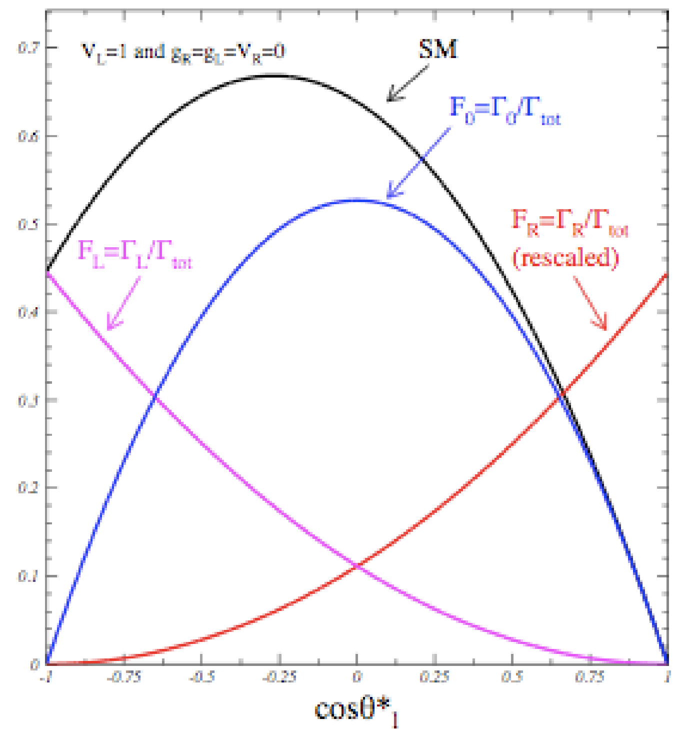
$F_R \neq 0$ only if $m_b > 0$



- Can be measured using the angle θ_l^*
  - Angle between W in top frame and lepton in W frame

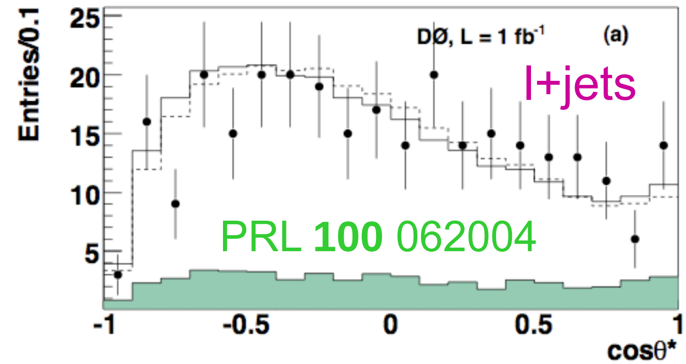
$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*_\ell} = \frac{3}{2}\left[F_0\left(\frac{\sin\theta^*_\ell}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\theta^*_\ell}{2}\right)^2 + F_R\left(\frac{1+\cos\theta^*_\ell}{2}\right)^2\right]$$

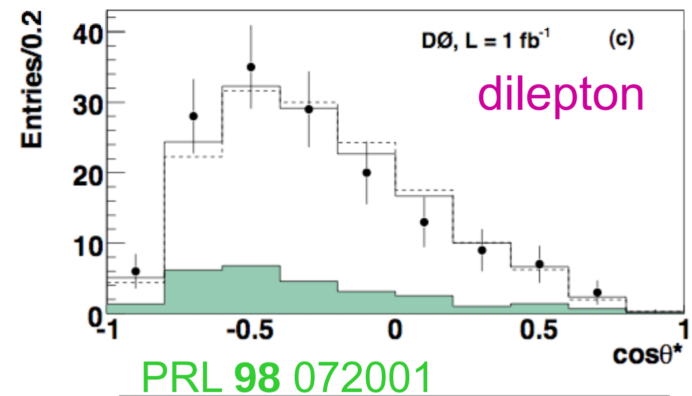
  - In SM, $F_0 \approx 0.695$, $F_L \approx 0.305$, $F_R \approx 0.001$
    - Driven by m_t/m_W and V-A structure of weak interaction
    - Extensions to SM can result in enhanced F_L and/or F_R
  - Attempt to reconstruct the $\cos\theta_l^*$ distribution and fit the fractions of longitudinal, left and right polarised W

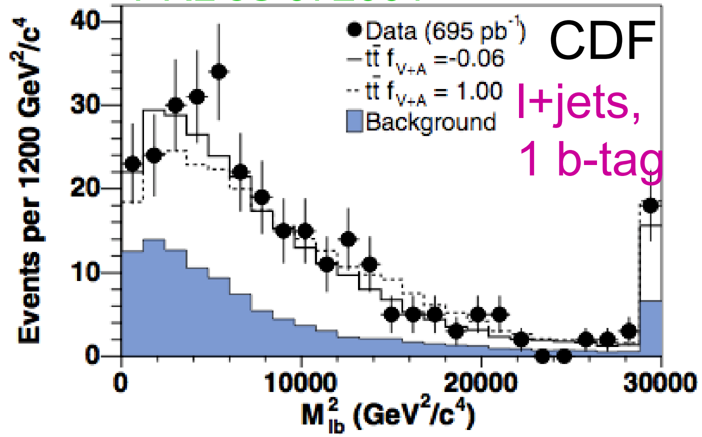


W polarisation studies at the Tevatron

- Various methods used to measure W polarisation
  - Reconstruction of $\cos\theta_l^*$ (extract F_0 and F_R)
    - Needs full event reconstruction, including missing E_T
    - As for spin correlations, can fit reconstructed $\cos\theta_l^*$ distribution to Monte Carlo templates for F_0, F_L, F_R, or correct for detector effects and fit at 'generator' level
  - Measurements done with l+jets and dilepton events
    - Some 'marginal' consistency (2-3σ) between channels (in both CDF and D0)
    - Can also use jet from hadronic W boson decay - measure $|\cos\theta^*|$ - information on F_0
  - Other techniques used to avoid using missing E_T
    - Charged lepton p_T spectrum and m_{lb} have sensitivity to the F_R fraction - difficult to fit all simultaneously
    - Full 'matrix element' fit as used for the top mass, varying F_0 with F_R fixed to zero
- Samples typically O(100s) events - limited statistics
  - Systematics dominated by signal/bkg modelling

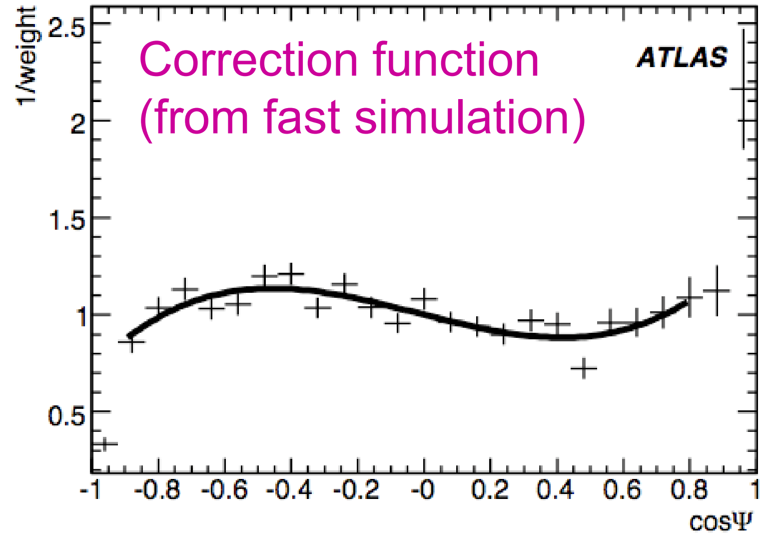


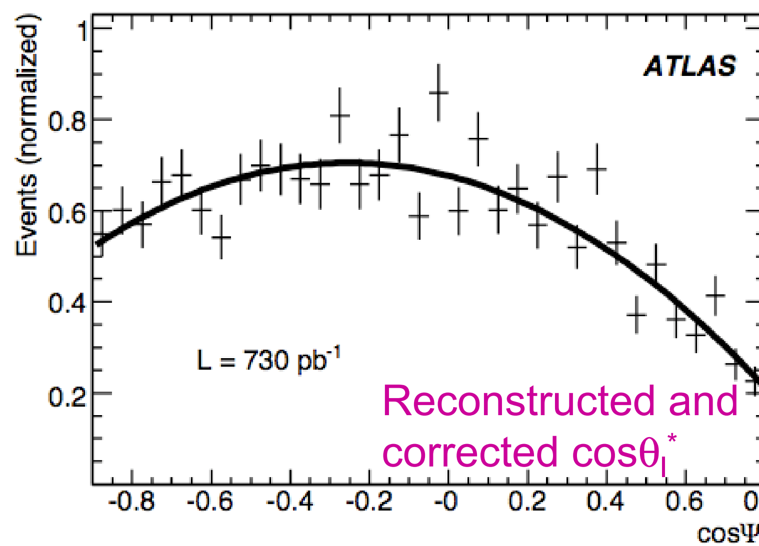




W polarisation studies at LHC

- Studies concentrated on the $\cos\theta_l^*$ method
  - ATLAS - combined analysis with spin correlations
  - Select events with lepton + ≥4 jets and missing E_T, with two jets b-tagged
  - Expect around 10k events per fb^{-1}
    - Main background from t-tbar decays involving τ (around 10%); single top and W+jets < 5%
  - Reconstruct $\cos\theta_l^*$ distribution and correct back to 'generator' level with correction weight function
    - Exclude extremes of distribution where correction is largest
    - Uncertainty / control of correction function is significant source of systematics
  - Also exploring template-based methods to perform fit directly to reconstructed distributions
  - With enough statistics, can extract F_0 and F_R
    - And hence F_L via $F_0+F_L+F_R=1$



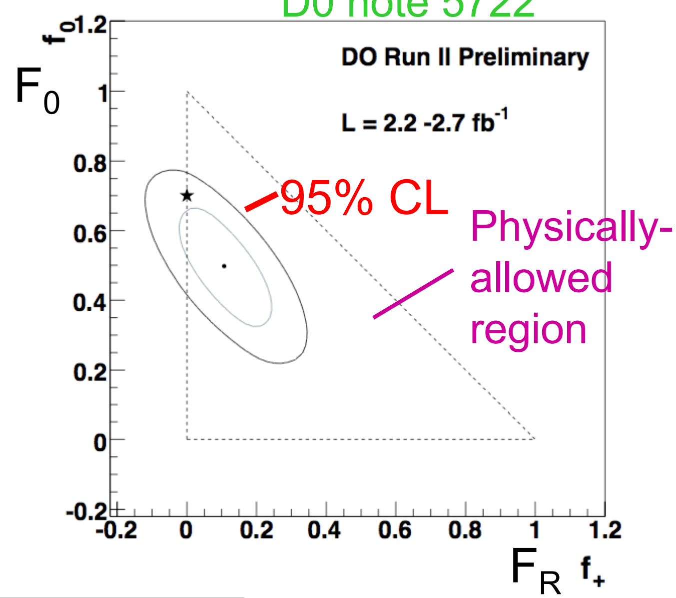


W polarisation results and prospects

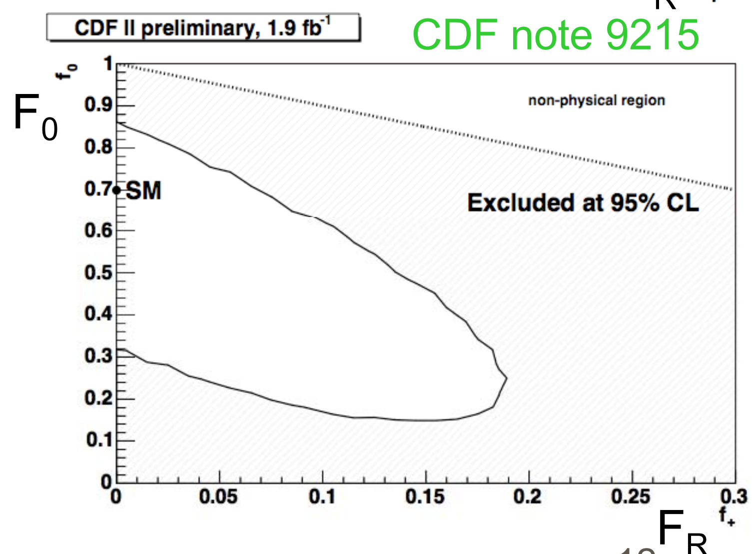
- Some representative results and expectations
  - Using $\cos\theta_l^*$, other methods also used

Expt	fb^{-1}	F_0	F_L	F_R
CDF lj	1.9	±0.16		±0.07
D0 lj+ll	2.7	±0.11 ±0.09		±0.06±0.05
ATLAS lj	1	±0.02 ±0.03	±0.04 ±0.03	±0.02 ±0.02
CMS lj	10	±0.02 ±0.02		

D0 note 5722



CDF note 9215



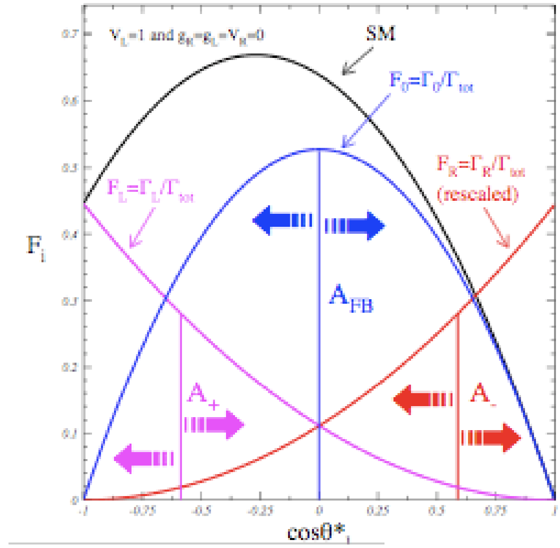
- Tevatron results already providing significant constraints … but statistics limited
  - LHC should give precision measurements (in particular for F_R)
  - Ultimate precision will depend on careful control of systematics

Wtb vertex anomalous couplings

- More general parameterisation of Wtb vertex:

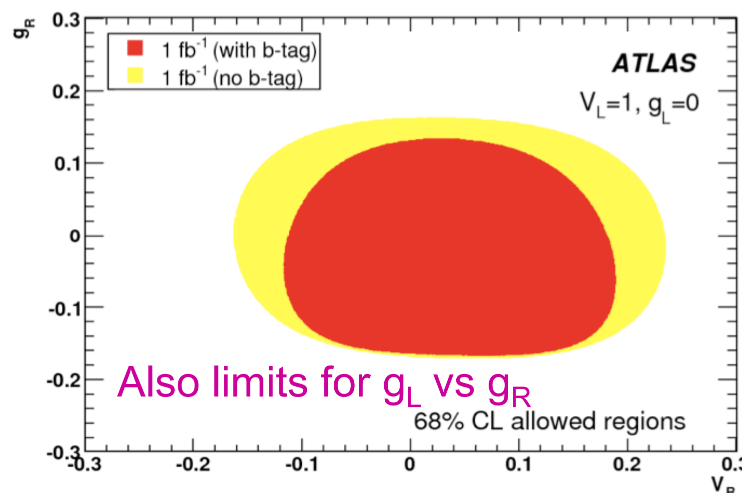
$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)\,t\,W^{-}_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)\,t\,W^{-}_{\mu}$$

  - Anomalous couplings sensitive to ratios $\rho_{L,R}=F_{L,R}/F_0$
  - Can also study asymmetries in the $\cos\theta_l^*$ distribution, A_{FB}, A_+ and A_-
    - Each asymmetry insensitive to one parameter F_0,F_L,F_R
  - Measure using corrected $\cos\theta_l^*$ distribution in 1 fb^{-1} of ATLAS l+jet events; statistical and systematic errors:



	ρ_L	ρ_R	A_{FB}	A_+	A_-
No b-tag	±0.05 ±0.27	±0.008 ±0.017	±0.025 ±0.080	±0.024 ±0.074	±0.012 ±0.021
b-tag	±0.05 ±0.16	±0.007 ±0.012	±0.026 ±0.033	±0.028 ±0.052	±0.014 ±0.027

  - B-tagging helps reduce systematic errors



- Combined fit for couplings, eventually also include s/t channel single top x-sec

Summary and outlook

- The LHC 'top factory' offers an excellent opportunity for precision studies of top quark properties
  - Comprehensively exclude the q=4/3e exotic 'top quark' with < 1 fb^{-1}
    - Sensitivity to small add-mixtures of exotic states as the luminosity increases
  - Studies of top spin correlations and the Wtb vertex require good detector understanding and 1-10 fb^{-1} to reach maturity
    - With O(1 fb^{-1}), can substantially improve on Tevatron constraints on W polarisation
    - Start to measure more parameters, add in constraints from single top
    - Will need > 1 fb^{-1} to make unambiguous observation of t-tbar spin correlations
- Most of these studies require full reconstruction of t-tbar final state
  - Can start to refine techniques, understand resolution and systematics as soon as a significant sample of t-tbar events is recorded and isolated
    - Can also greatly benefit from large samples of e.g. Z events for calibration purposes
  - 100-200 pb^{-1} data is certainly enough to make good progress - first year of data will be very valuable
- … Top properties studies can start from the beginning of LHC data taking