Spin Correlation and W Helicity in Top Events with ATLAS

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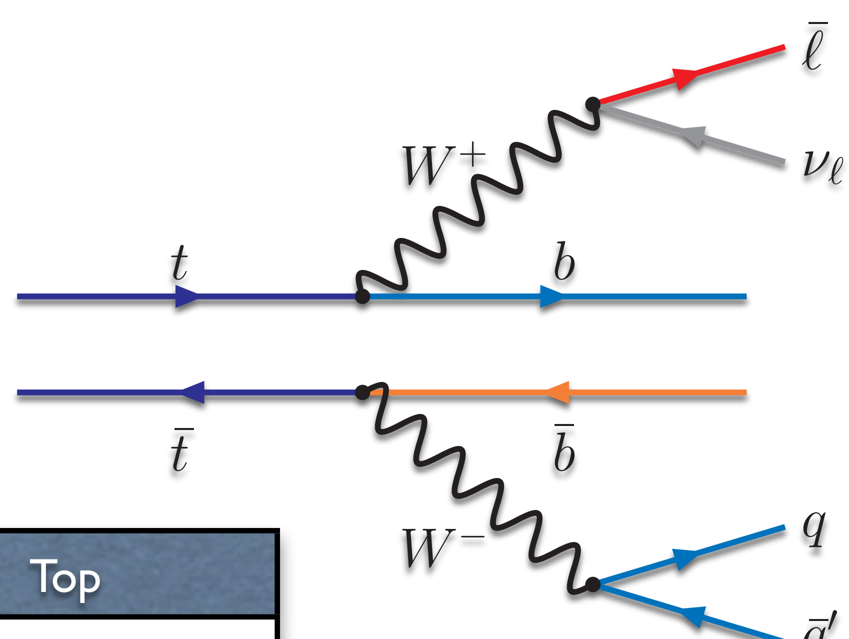
Motivation

- Sensitive test of perturbative QCD and the SM prediction of top-quark decays
  - understanding of important background for many BSM and SM Higgs searches
  - as decays before hadronisation (lifetime $5 \cdot 10^{-25}$s) it gives access to a bare quark
- Top quark events are produced (mostly gg-fusion) in abundance at the LHC
  - allows precision measurements of several SM quantities
  - can also be used for calibration (e.g. b-tagging)
- Some of the most basic quantities of the elementary particles are their mass (lifetime), charge and spin and also their couplings

Production

Cross Section
Top Spin Polarization
Spin Correlation
Anomalous couplings
Resonance Production



Decay

Branching Ratios
$|V_{tb}|$
Anomalous Couplings
Rare/non-SM Decays
W Polarization

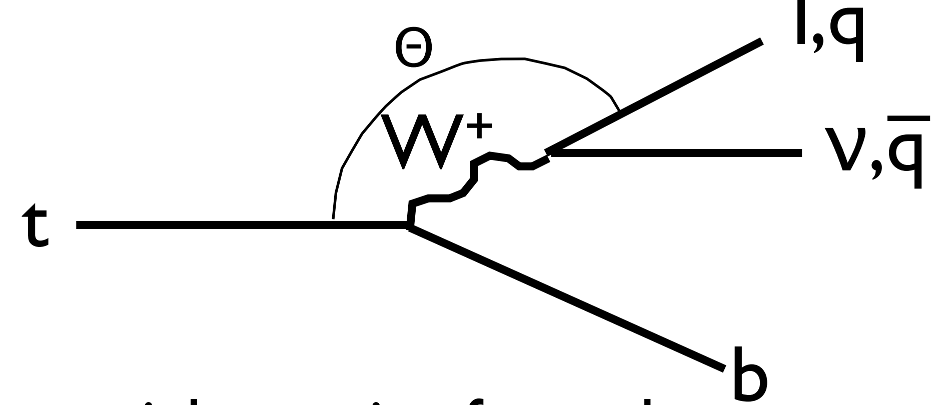
Top

Mass Spin Charge
Lifetime Width

Polarisation Power

- Spin information can be accessed via the angular momentum of the top quark decay products

$$\frac{1}{N}\frac{dN}{d\cos(\theta_i)} = \frac{1}{2}\left[1 + \alpha_i \cos(\theta_i)\right]$$



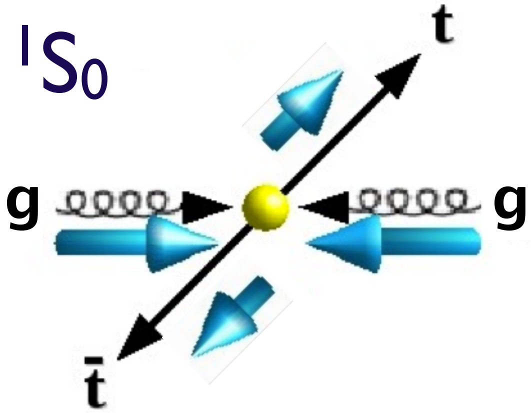
- Amount of spin information a daughter particle carries from the parent top is encoded in α_i

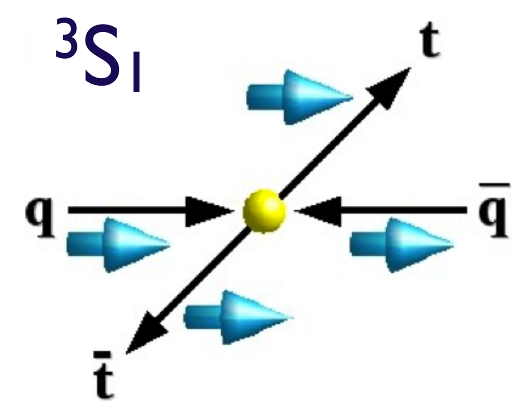
	b-quark	W^+	l^+	d/s quark	u/c quark
α(LO)	-0.41	0.41	1	1	-0.31
α(NLO)	-0.39	0.39	0.998	0.93	-0.31

- Largest fractions are carried by leptons and down-type quarks
  - dilepton channel: simple to tag leptons, but event reconstruction required to define spin basis
  - lepton+jets channel: event reconstruction less challenging but critical to tag the down-type quark with high efficiency

Spin Correlation

- Short lifetime → can access spin via decay particles
- Strength of the correlation may differ for BSM models (e.g. H^+ contribution)
- For spin-1/2 top particles two states possible → $^1S_0$ and $^3S_1$





- In gg-fusion at threshold top pair produced in $^1S_0$ state ($t_L t_L$ and $t_R t_R$)
  - at high energies dominant production is $^3S_1$ state ($t_L t_R$ and $t_R t_L$)
- In qq-annihilation produced in $^3S_1$ state
- Asymmetry parameter, A, describing difference between like and unlike spin configuration depends on quantization axis

$$A = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}} = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$
$$\text{where } C = A\alpha_1\alpha_2$$

- At the LHC no axis for 100% correlation
  - for helicity basis A is predicted to be $A_{hel} \approx 0.326$
  - complementary to Tevatron measurement

Bernreuther, Brandenburg, Si, Uwer, Nucl. Phys. B690, 81 (2004)

Template Fit

Phys. Rev. Lett. 108, 212001 (2012)

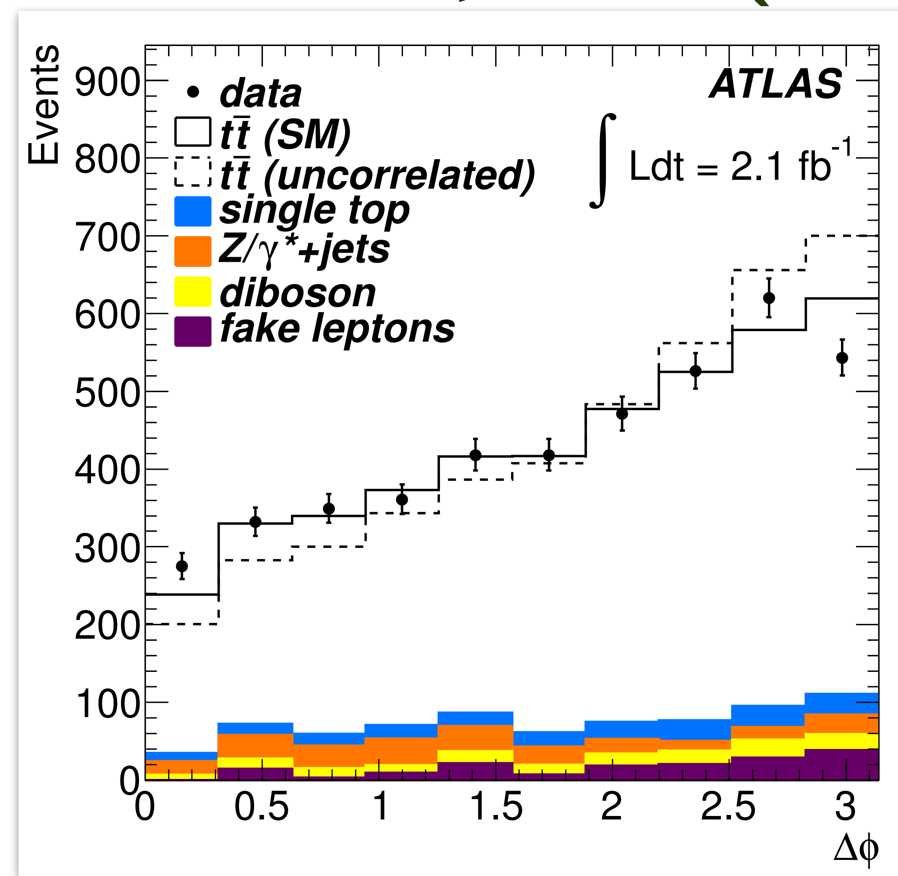
- In dilepton channel almost 100% of correlation carried by the two leptons
- Opening angle between leptons carry information about spin correlation

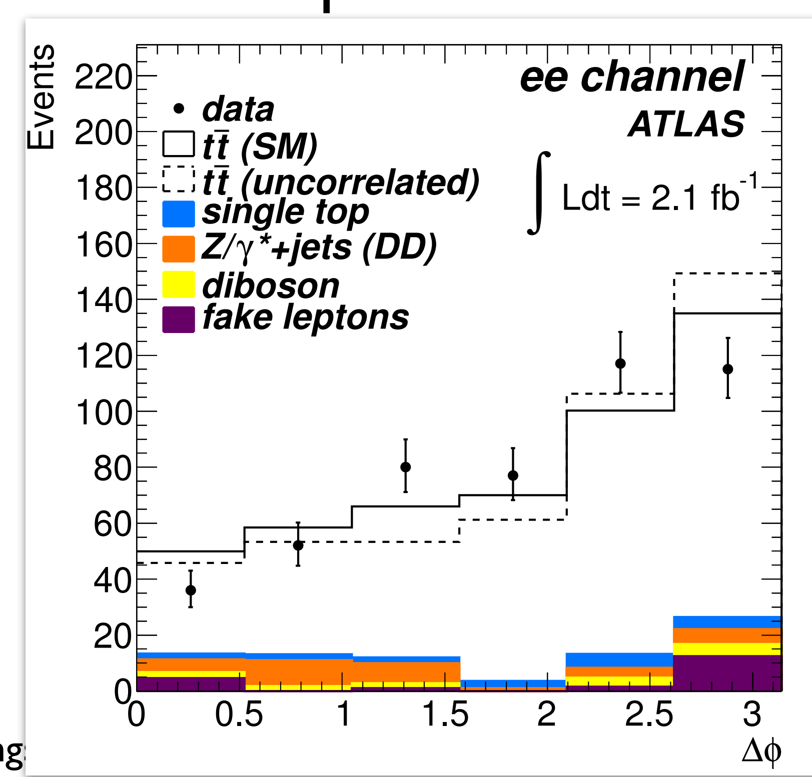
    G. Mahlon and S. Parke, Phys. Rev. D81 (2010) 074024

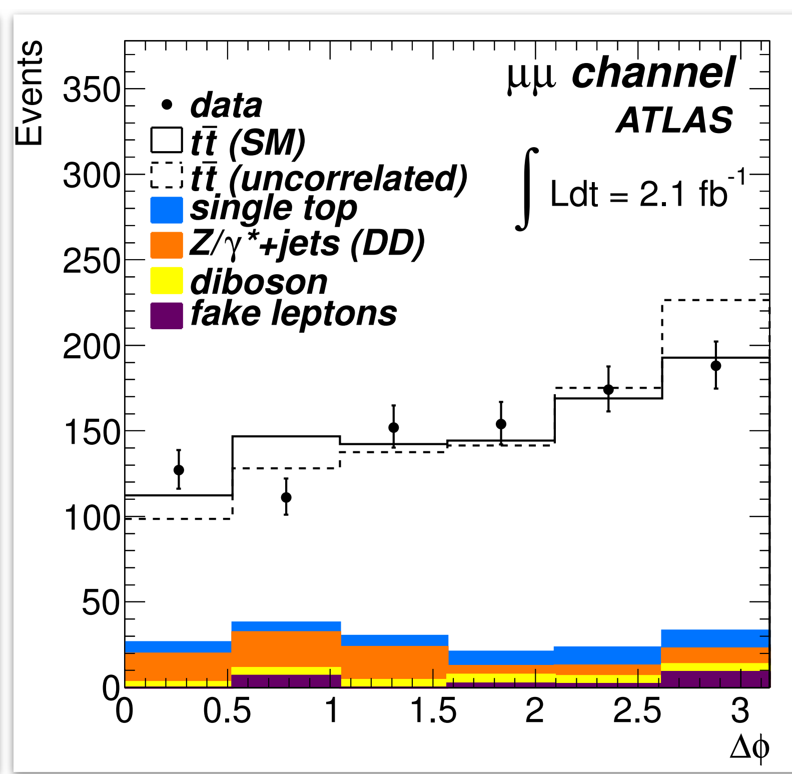
- Template fit separately performed for the three dilepton channels and in a combined fit

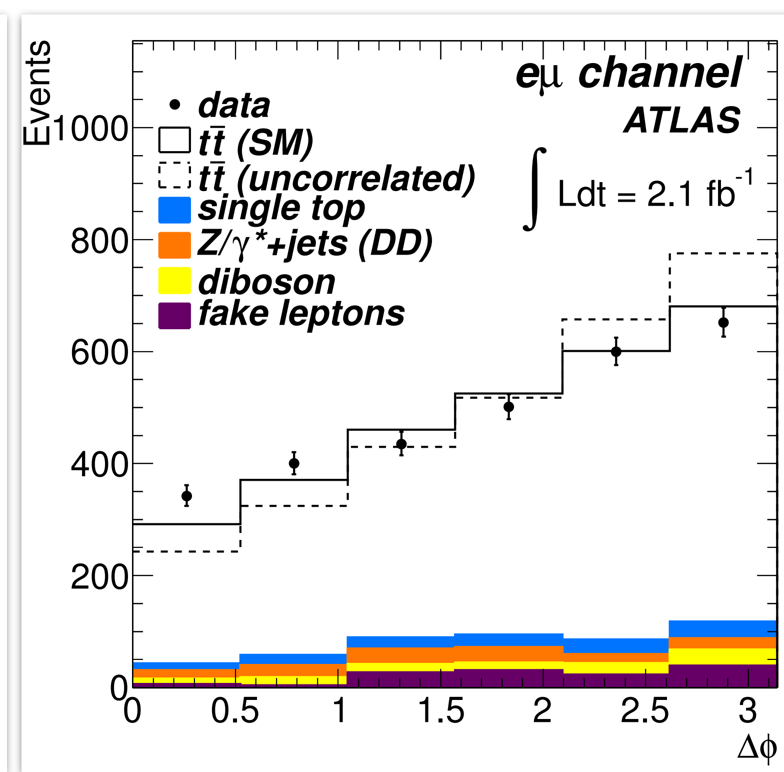
$$f^{SM}=N_{SM}/(N_{SM}+N_{UC})$$
$$A^{SM}=A^{SM}_{theo}\cdot f_{SM}$$

- Combined result gives correction factor of **f=1.30** to the input SM correlation





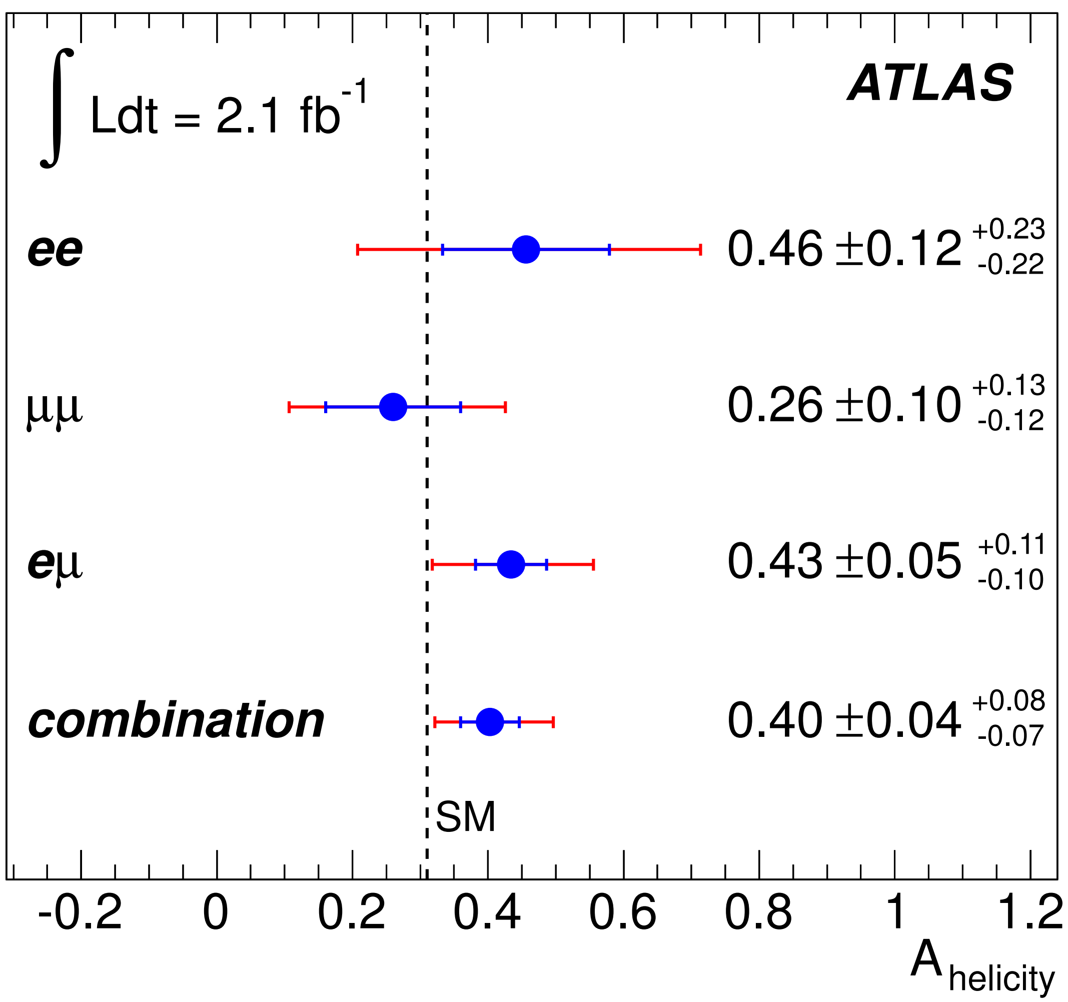


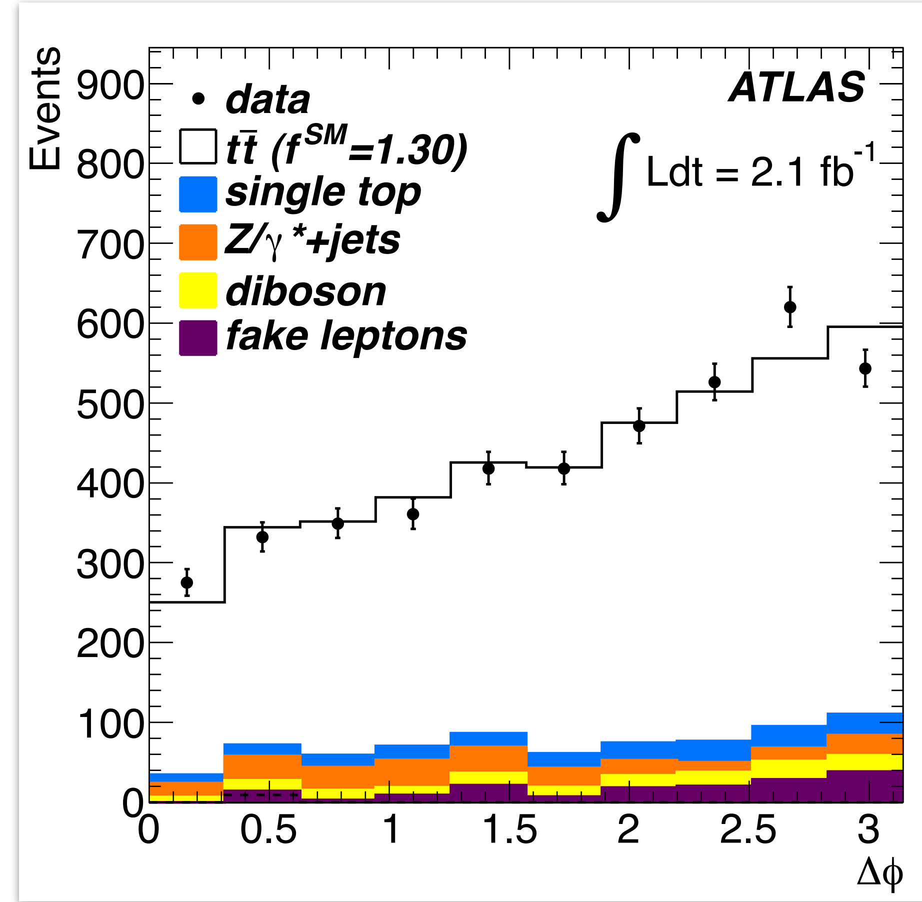


Results

Phys. Rev. Lett. 108, 212001 (2012)

- Figures show control plots for best fit and scaling parameter transformed to helicity parameter
- Main systematics arising from JES and shape of background (fakes) templates





(best fit with scaling applied)

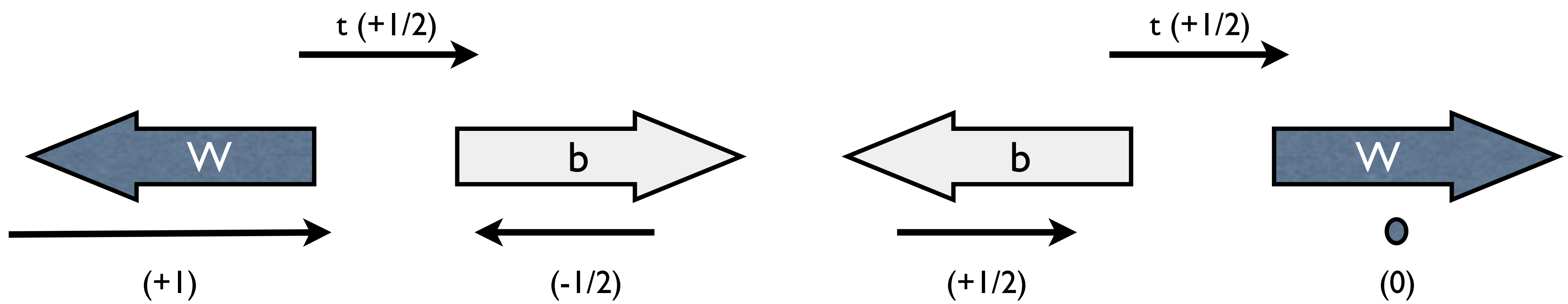
The data are **inconsistent with zero** (or negative) spin correlation with a significance of **5 standard deviations**

→first observation of spin correlation!

Helicity

- Top quarks decay as left-handed fermions through the V-A weak interaction
- Helicity of W boson in the decay is constraint to 0, +1, -1 (massive particles have 2S+1 states)

- Angular momentum conservation → only left handed and longitudinal W helicity configuration allowed



- The relative fractions of the three contributions (F_0, F_L and F_R):

		SM prediction
Negative helicity:	$F_L = \Gamma(t \rightarrow W_{(h=-1)} b)/\Gamma(t \rightarrow Wb)$	~ 30 %
Zero helicity:	$F_0 = \Gamma(t \rightarrow W_{(h=0)} b)/\Gamma(t \rightarrow Wb)$	~ 70%
Positive helicity:	$F_R = \Gamma(t \rightarrow W_{(h=+1)} b)/\Gamma(t \rightarrow Wb)$	~ 0 %

$$F_L + F_0 + F_R = 1$$

- Sensitivity to anomalous (non-SM) couplings

A. Czarnecki, J. G. Korner, and J. H. Piclum, Phys. Rev. D 81 (2010) 111503

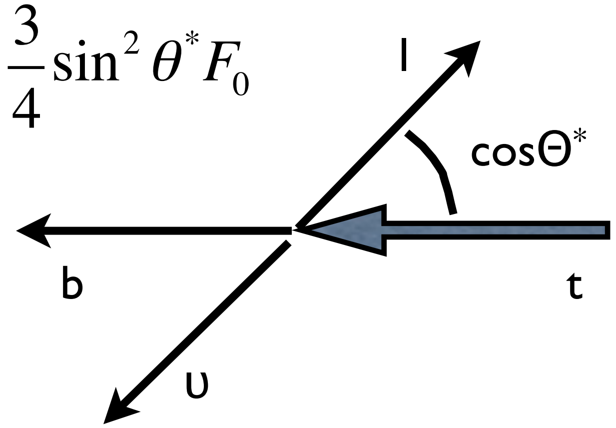
W-Helicity Templates

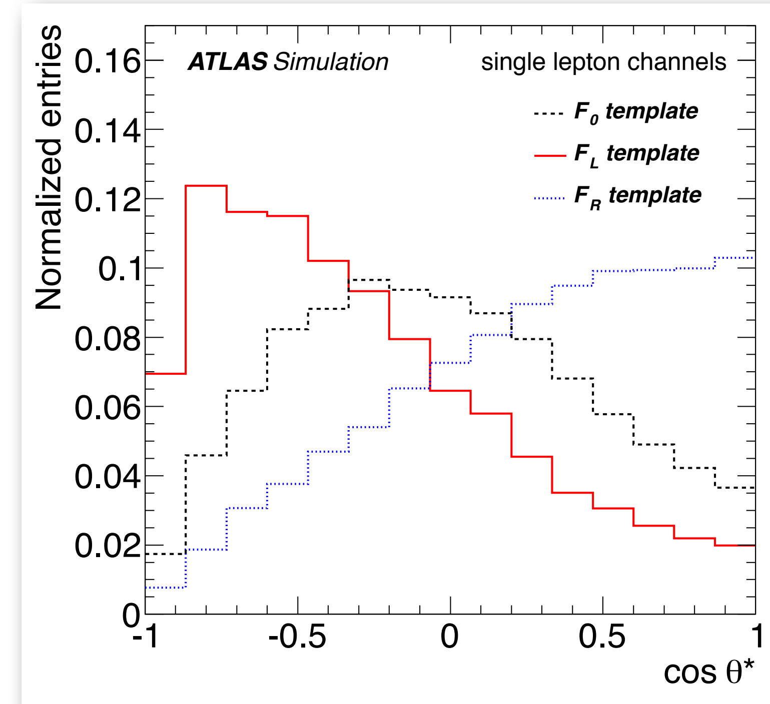
arXiv:1205.2484v1

- The Wtb vertex is defined by the electroweak interaction and has V-A structure
- W bosons are produced as real particles → polarisation can be longitudinal-, left- and right-handed

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

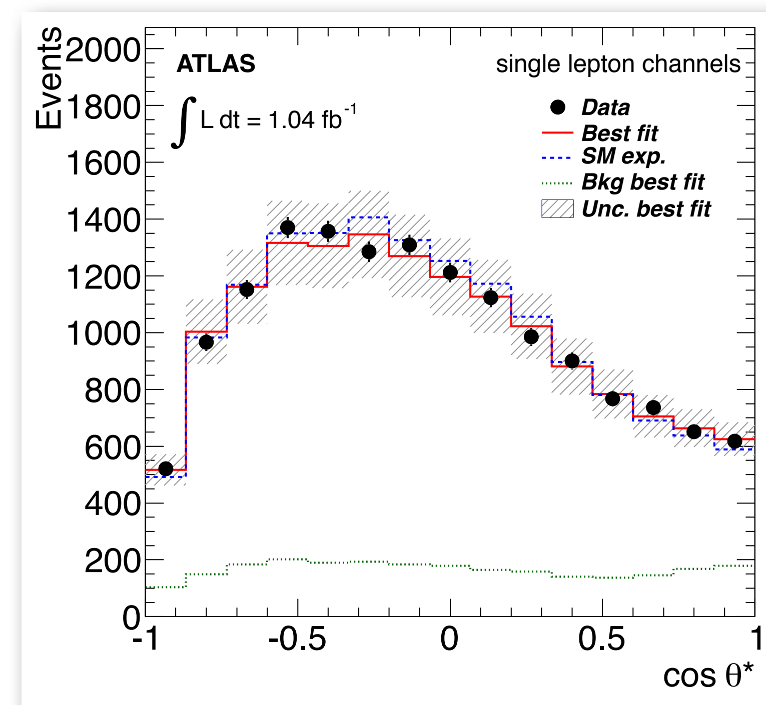
$$\Gamma \equiv \Gamma(t \rightarrow W^+ b) = \Gamma_R + \Gamma_L + \Gamma_0$$





  - angle between lepton and negative top quark direction

- Two different methods used:
  1. template fit using distributions for different signal and background contributions
  2. counting events after bkg subtraction above and below z=±(1-2^{2/3}) in unfolded distribution



$$A_z = \frac{N(\cos\theta^* > z) - N(\cos\theta^* < z)}{N(\cos\theta^* > z) + N(\cos\theta^* < z)}$$

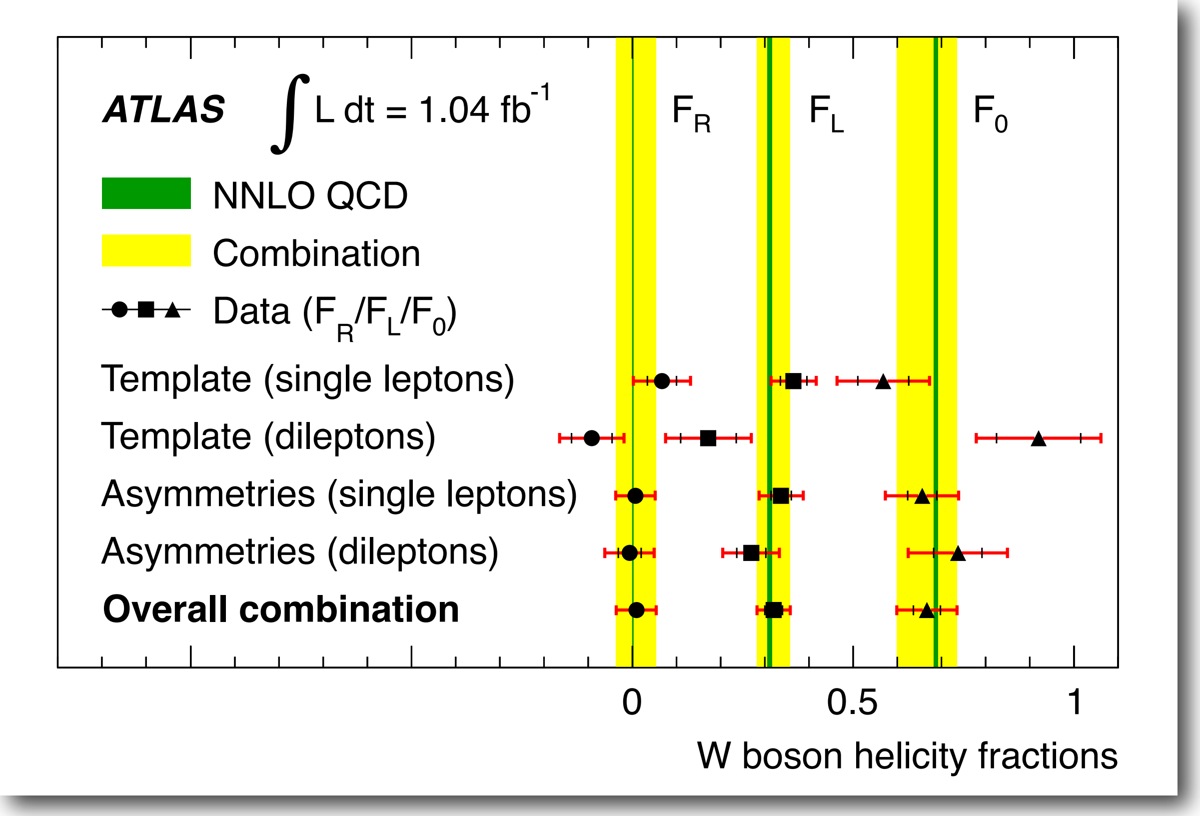
Helicity - Combined Results

arXiv:1205.2484v1

- Results of four measurements combined using BLUE method:

	Combined Result	NNLO
F_0	0.67±0.03 (stat+syst)	0.687±0.005
F_L	0.32±0.02 (stat+syst)	0.311±0.005
F_R	-0.01±0.01 (stat+syst)	0.0017±0.0001

- Main systematics from lepton ID, JES and from method-specific uncertainties



No significant deviations from NNLO QCD predictions observed supporting the model of a **pure V-A structure** of the Wtb vertex

→Most precise measurement of hel. fractions!

Effective Lagrangian

arXiv:1205.2484v1

- New physics can be parametrized in terms of an effective Lagrangian (above the electroweak symmetry breaking scale of v=246 GeV)

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_{\rm L}P_L + V_{\rm R}P_R)\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_{\rm L}P_L + g_{\rm R}P_R)\,t\,W_{\mu}^{-} + \text{h.c.}\,,$$

J. A. Aguilar-Saavedra, Nucl. Phys. B 812 (2009) 181
J. A. Aguilar-Saavedra, Nucl. Phys. B 821 (2009) 215

where

$$V_{\rm L} = V_{tb} + C_{\phi q}^{(3,3+3)}\frac{v^2}{\Lambda^2}\,, \quad V_{\rm R} = \frac{1}{2}C_{\phi\phi}^{33*}\frac{v^2}{\Lambda^2}\,, \quad g_{\rm L} = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2}\,, \quad g_{\rm R} = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}\,.$$

- couplings V_R, g_L and G_R absent in the SM at tree-level

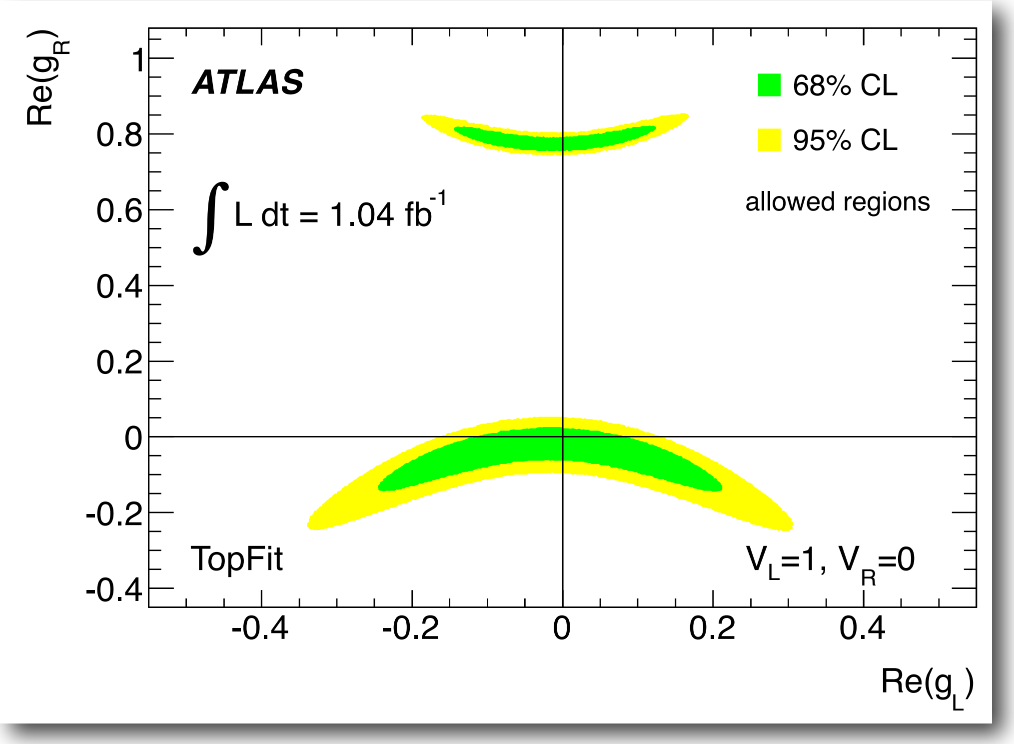
- Measured limits at 95 % CL are:

$$\text{Re}\,(V_{\rm R}) \in [-0.20, 0.23] \rightarrow \frac{\text{Re}\,(C_{\phi\phi}^{33})}{\Lambda^2} \in [-6.7, 7.8]\ \ \text{TeV}^{-2}$$

$$\text{Re}\,(g_{\rm L}) \in [-0.14, 0.11] \rightarrow \frac{\text{Re}\,(C_{dW}^{33})}{\Lambda^2} \in [-1.6, 1.2]\ \ \text{TeV}^{-2}$$

$$\text{Re}\,(g_{\rm R}) \in [-0.08, 0.04] \rightarrow \frac{\text{Re}\,(C_{uW}^{33})}{\Lambda^2} \in [-1.0, 0.5]\ \ \text{TeV}^{-2}$$

$$\frac{\text{Re}\,(C_{uW}^{33})}{\Lambda^2} \in [-0.9, 2.3]\ \ \text{TeV}^{-2}$$ (F_L=0)



(2D limit assuming V_R=0)

Summary

- Top physics (at the LHC) provides the possibility to test the SM in various ways

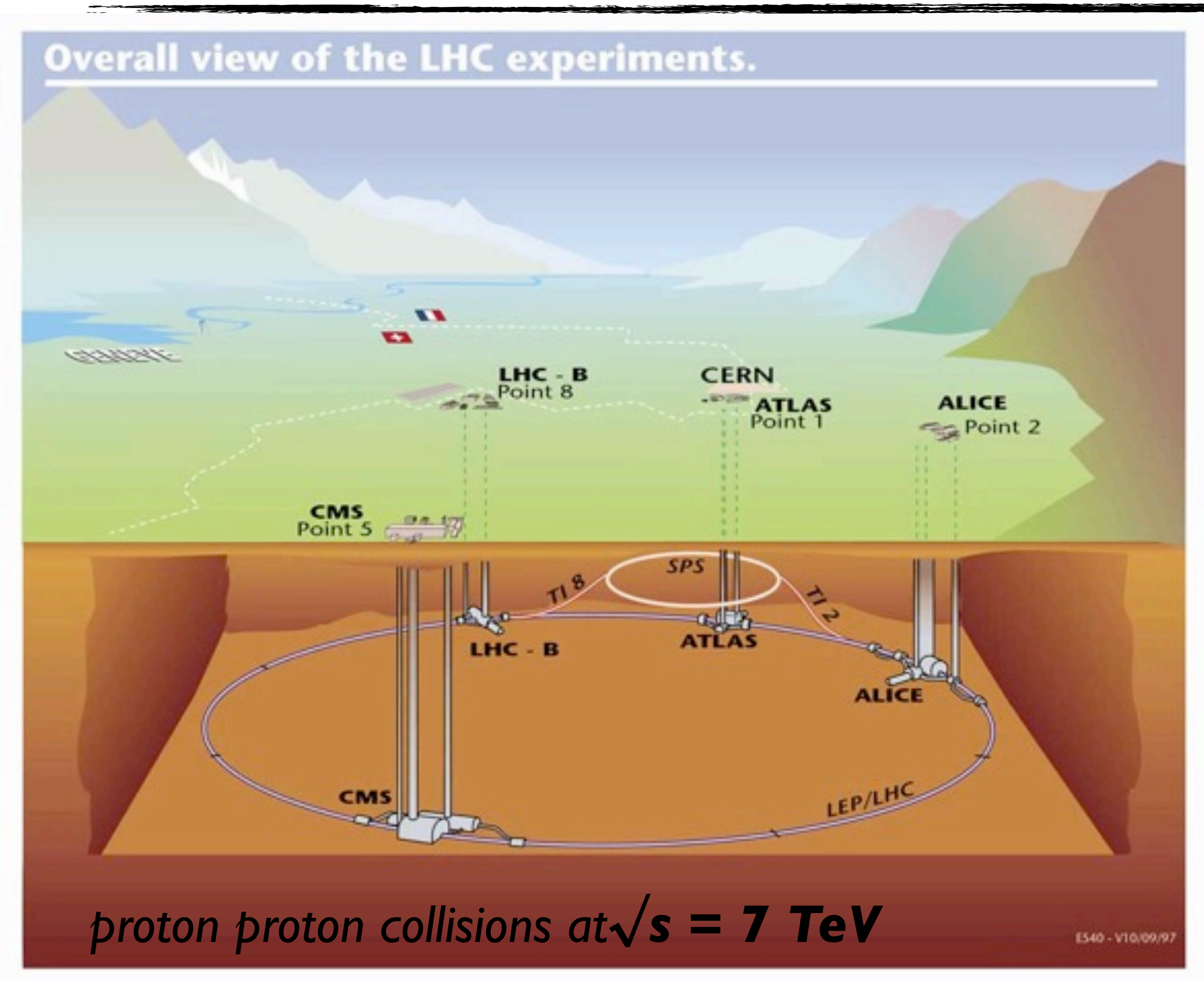
- Two analysis from top properties presented:
  1. *"Observation of spin correlation in tt events from pp collisions at $\sqrt{s}$ = 7 TeV using the ATLAS detector"*
  2. *"Measurement of the W boson polarization in top quark decays with the ATLAS detector"*

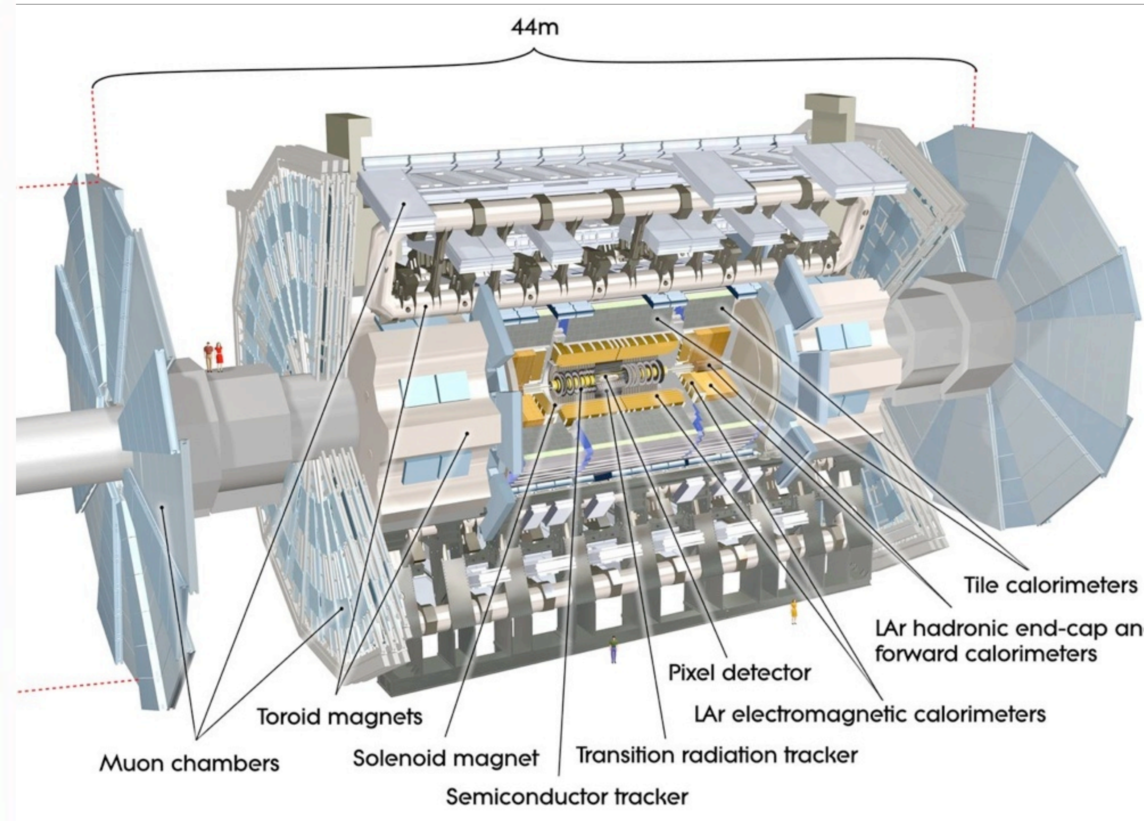
- No significant deviation from SM prediction observed
  1. hypothesis of zero spin correlation excluded with 5 sigma
  2. helicity measurements supports model of pure V-A Wtb vertex structure

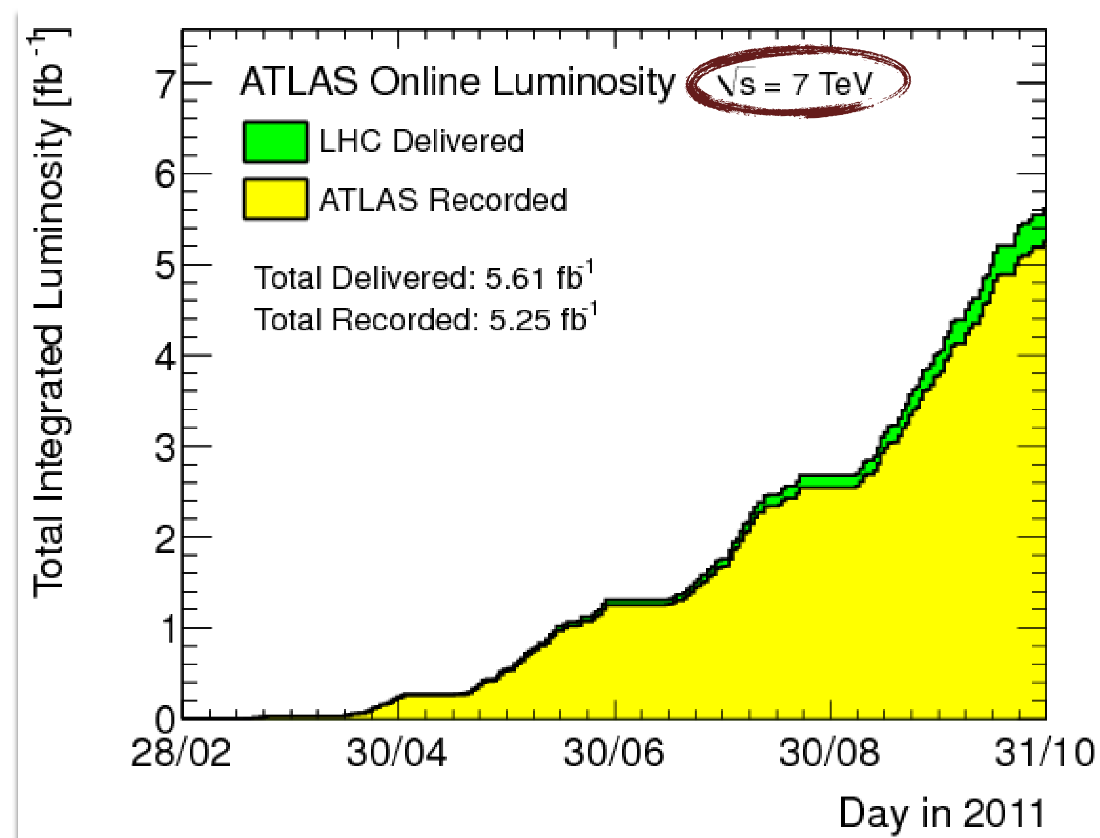
Thanks for your attention!

Backup

The Usual Pictures





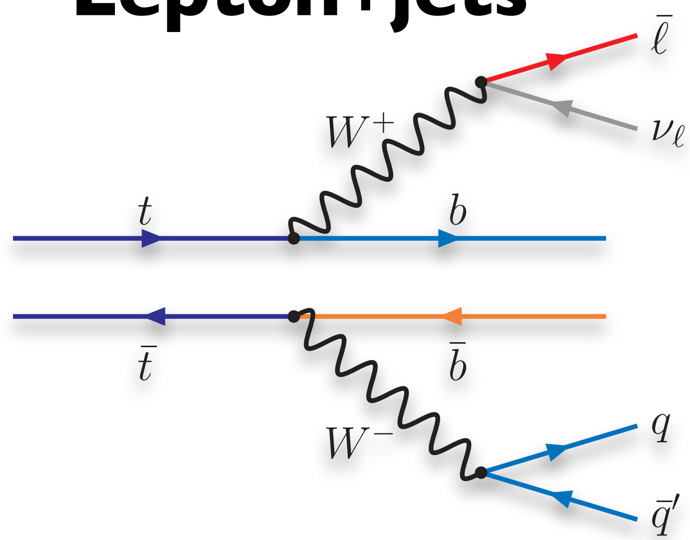


- More than 5 fb^{-1} recorded in 2011
- Will present analyses with 2.1/1 fb^{-1}
- Both using 7 TeV (we have 8 TeV in 2012)

$t\bar{t}$ Selection

- Single lepton and dilepton events selected by lepton triggers and require to have a good primary vertex (at least 5 tracks associated to it)

Lepton+jets



One lepton

- p_T > 25 (20) GeV
- $|\eta|$ <2.5 (and transition cuts for e)

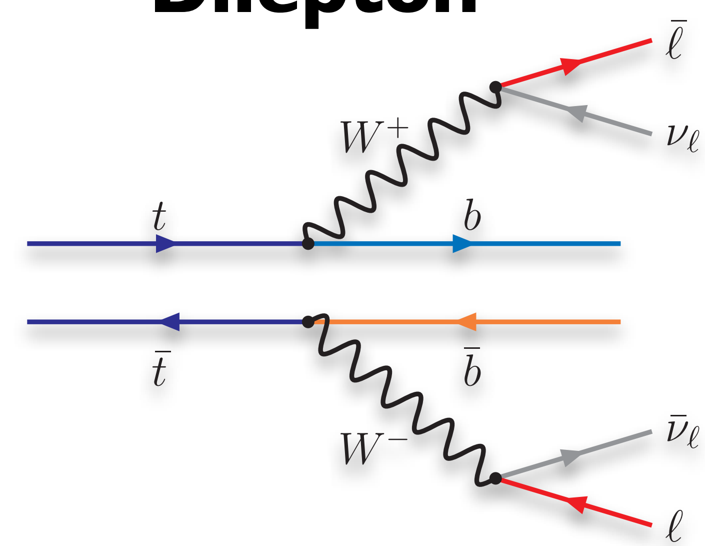
At least four Jets (anti-kt R=0.4)

- p_T > 20 GeV
- $|\eta|$ <2.5

Background Rejection

- (e): E_T^{Miss}>35 GeV and m_T^W >25
- (μ): E_T^{Miss}>20 GeV and $E_T^{Miss}+m_T^W$>60 GeV

Dilepton



Two oppositely charged leptons

- p_T > 20 (25) GeV
- $|\eta|$ <2.5 (2.47 and transition cuts)

At least two Jets (anti-kt R=0.4)

- p_T > 25 GeV
- $|\eta|$ <2.5

Background Rejection

- (ee, μμ): E_T^{Miss}>60 GeV, m_{ll} > 15 GeV and $|m_{ll}-m_Z|$>10 GeV
- (eμ): H_T>130 GeV
- (Tl): E_T^{Miss}>60 GeV, H_T>150 GeV and $|m_{Tl}-m_Z|$>10 GeV

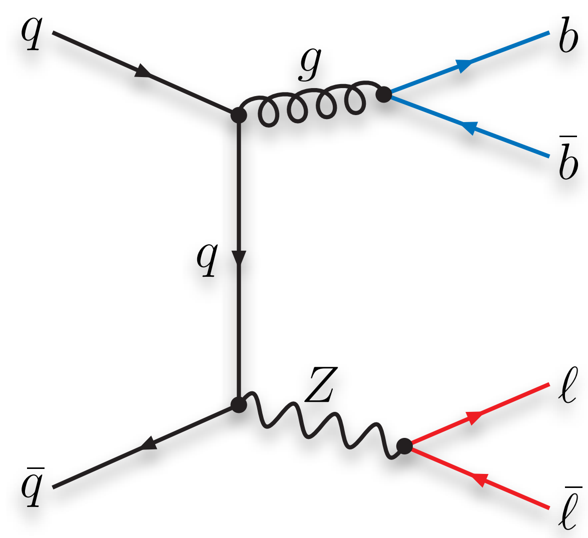
Event Reconstruction

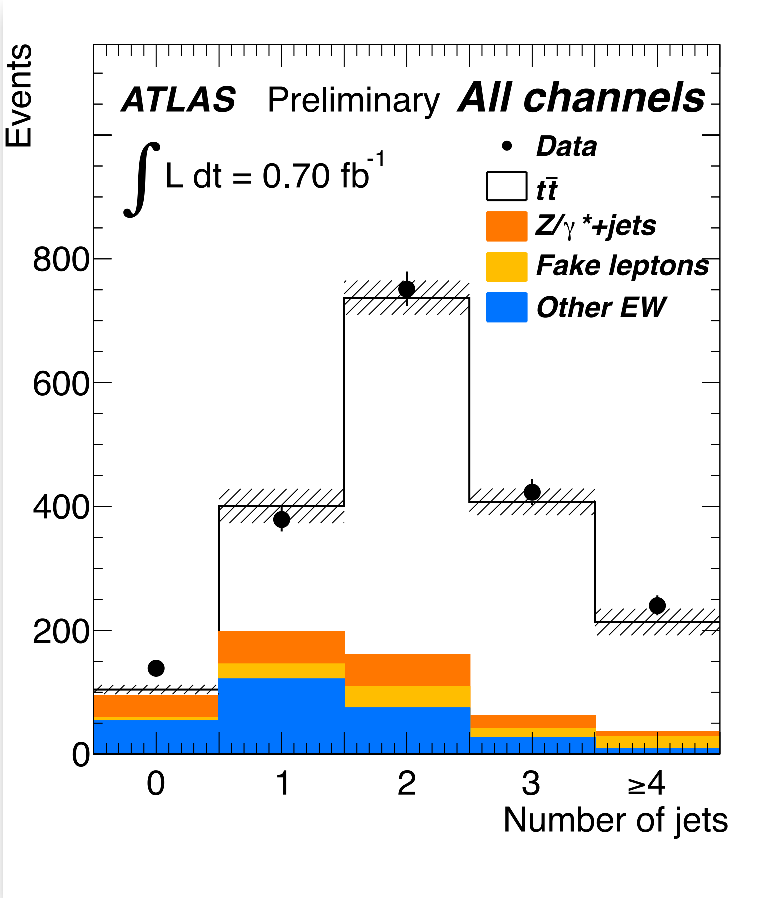
- To associate reconstructed objects to truth partons and to determine event kinematic full event reconstruction necessary
  - for some analysis like W helicity or spin correlation reference frame has to be defined for boosting
- In lepton+jets channel missing information (z-component) of the neutrino can be reconstructed using MET and constraints from know top and W masses
- For more clean dilepton environment system is under constraint and in general several solutions exist

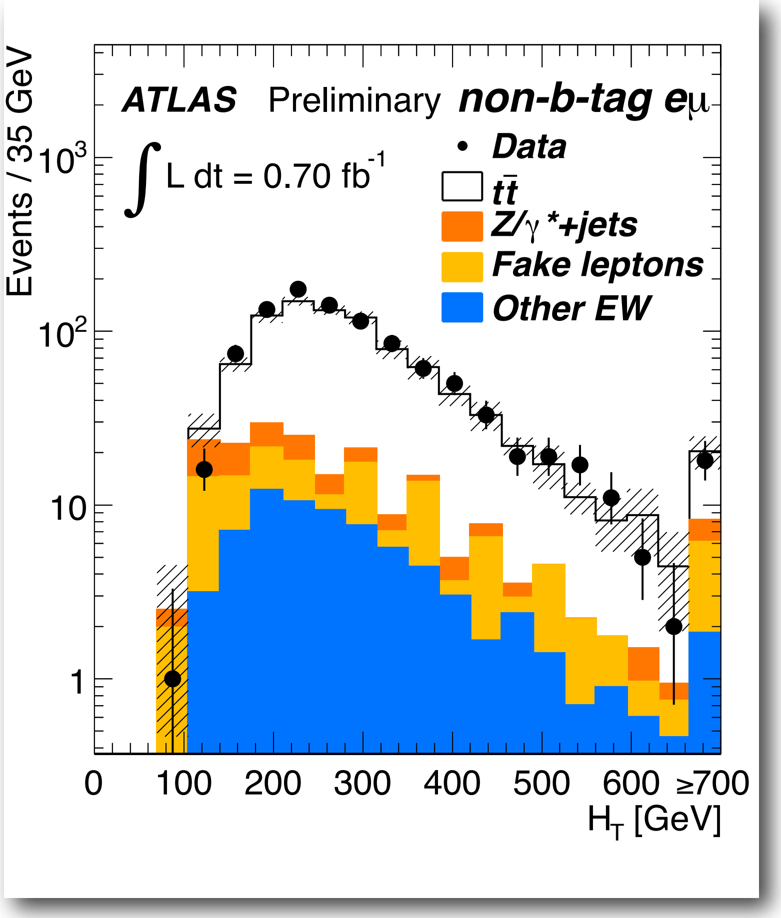
Lepton+Jets	Dilepton
Neutrino momentum unknown → use constraints from 1. transverse momentum (MET) 2. Top mass 3. W mass (and additional input from b-tagging for jet-permutations) Use chi2 minimization or kinematic likelihood fit to find best solution $\chi^2 = \frac{(m_{\ell\nu \mathrm{j_a}} - m_\mathrm{t})^2}{\sigma_\mathrm{t}^2} + \frac{(m_{\mathrm{j_b j_c j_d}} - m_\mathrm{t})^2}{\sigma_\mathrm{t}^2} + \frac{(m_{\ell\nu} - m_\mathrm{W})^2}{\sigma_\mathrm{W}^2} + \frac{(m_{\mathrm{j_c j_d}} - m_\mathrm{W})^2}{\sigma_\mathrm{W}^2}$	Two neutrino momenta unknown → same constraints as for lepton+jets Up to four remaining solutions due to under-constraint system Take solution with minimal product of neutrino momenta Alternative is ME approach ..... $\begin{aligned} p_x^{\nu_1} + p_x^{\nu_2} &= \not{E}_\mathrm{x}, \\ p_y^{\nu_1} + p_y^{\nu_2} &= \not{E}_\mathrm{y}, \\ (p_{\ell_1} + p_{\upsilon_1})^2 &= m_\mathrm{W}^2, \\ (p_{\ell_2} + p_{\upsilon_2})^2 &= m_\mathrm{W}^2, \\ (p_{W_1} + p_{j_1})^2 &= m_\mathrm{t}^2, \\ (p_{W2} + p_{j_2})^2 &= m_\mathrm{t}^2. \end{aligned}$

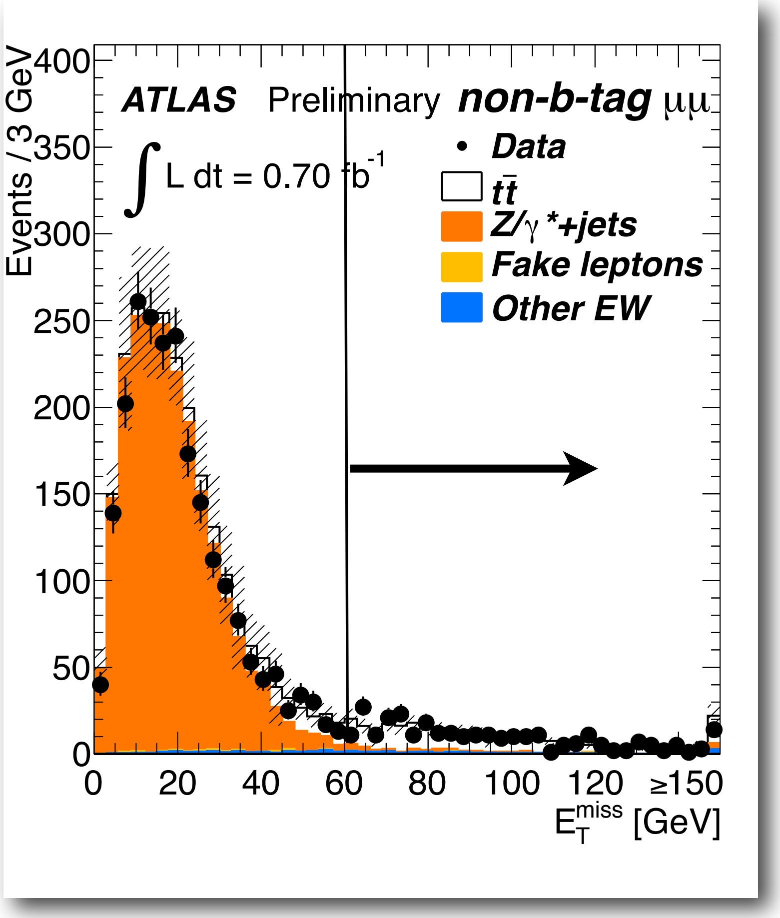
Background Estimate

- Due to cut on two good leptons main background is from Z decay or from events with at least one fake lepton
- To evaluate the Z/γ^{*}+jets background the MC prediction for the number of events in the SR is normalized to the data using the events measured in CR ($|m_{ll}-m_Z|<10$ GeV and $E_T^{Miss}>30$ (35) GeV)
- The yield of fake leptons is determined from data using a matrix-method (put dileptons into four categories using loose and tight definitions for both leptons)

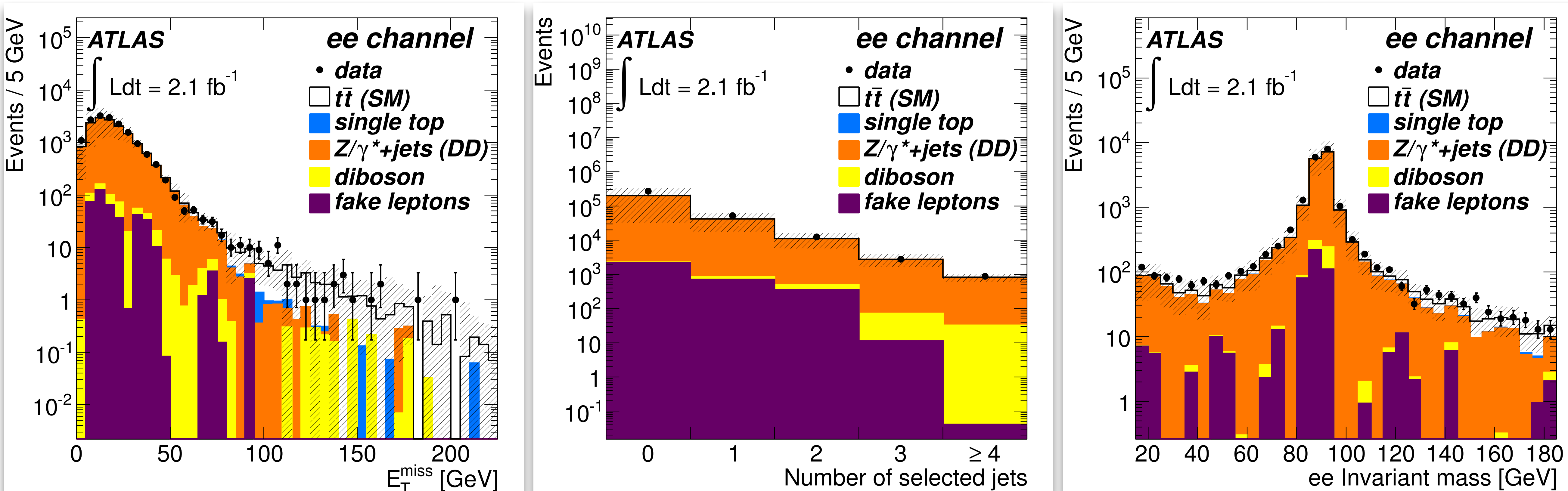








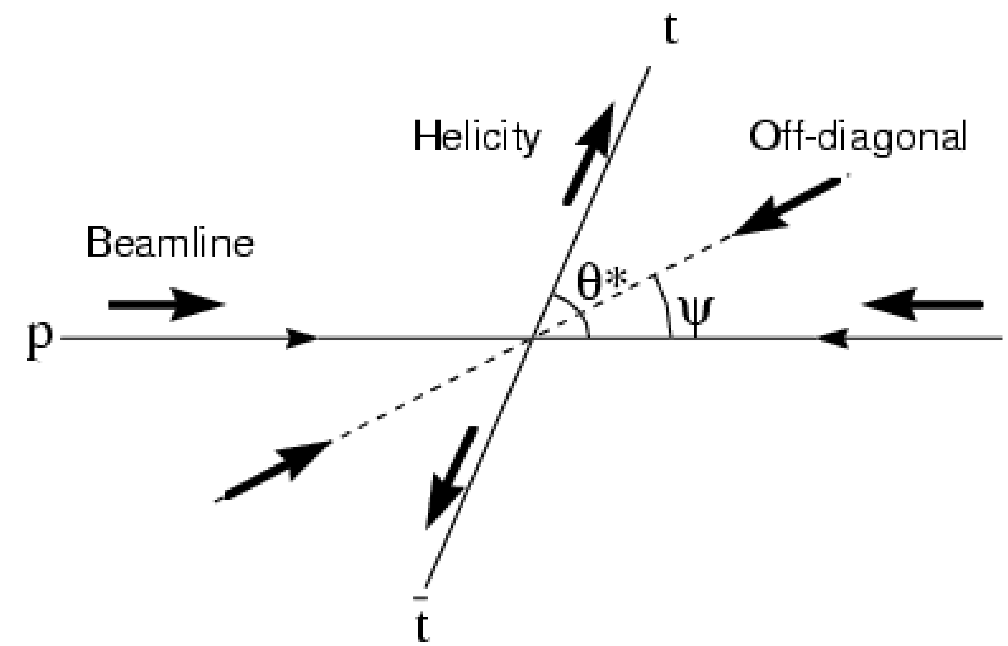
Background Enriched Control Plots

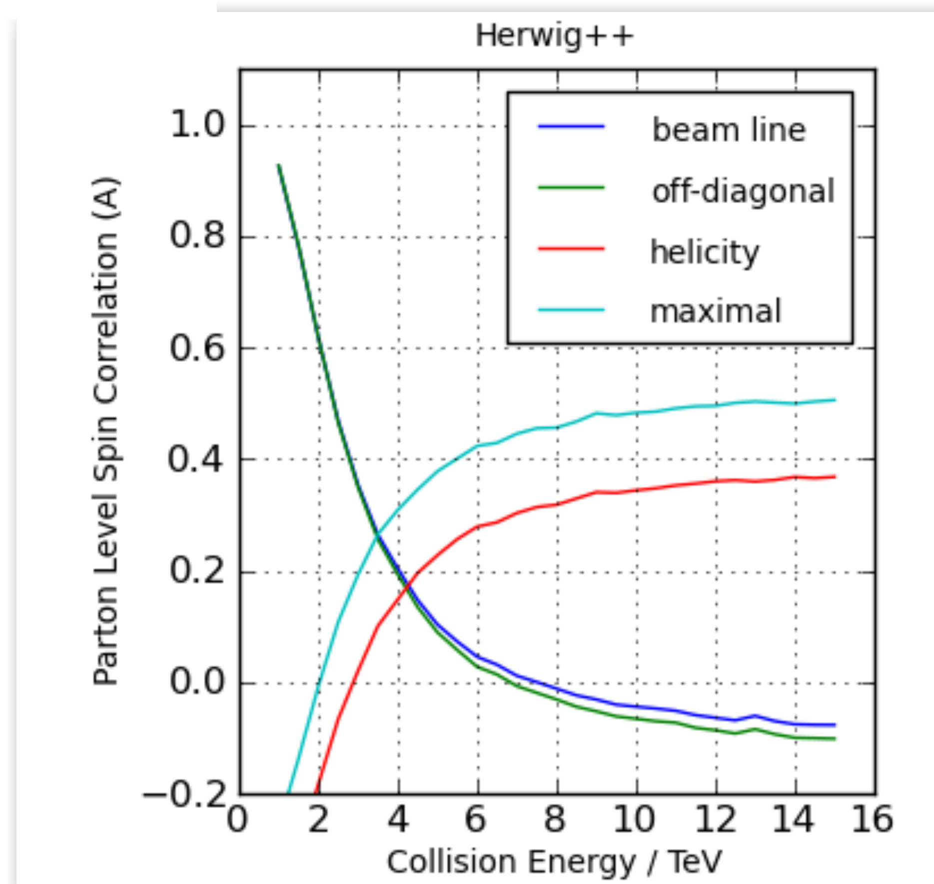


- Control plots for background enriched (mainly DY) region
  - ETMiss for events with at least two jets for ee inside the Z mass window
  - Number of jets with same Z mass window cut and ETMiss<60 GeV
  - Invariant dilepton mass for events with at least two jets and ETMiss< 60 GeV

Spin Basis

- Number of unlike spin combinations of the top pair depends on choice of spin basis
- Spin correlation strength (A) depends on collision energy
- For Tevatron off-diagonal basis is best choice, where up to 90 % of top pairs have unlike-sign spin
- For LHC beam-line and off-diagonal basis have very poor strength
- Helicity (or more complicated maximal) basis provide possibility to extract spin correlation
- Center-of-mass dependence is not very large





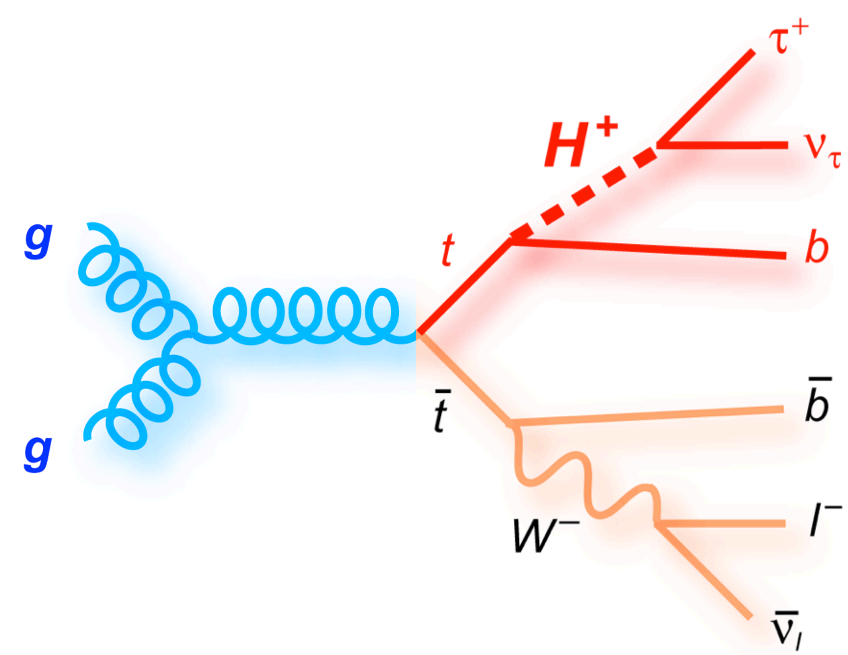
maximal basis requires matrix solving (eigenvectors of spin density matrix)

Beam-Axis (Tevatron): NLO QCD: A = 0.78
Bernreuther, Brandenburg, Si, Uwer, Nucl. Phys. B690, 81 (2004)

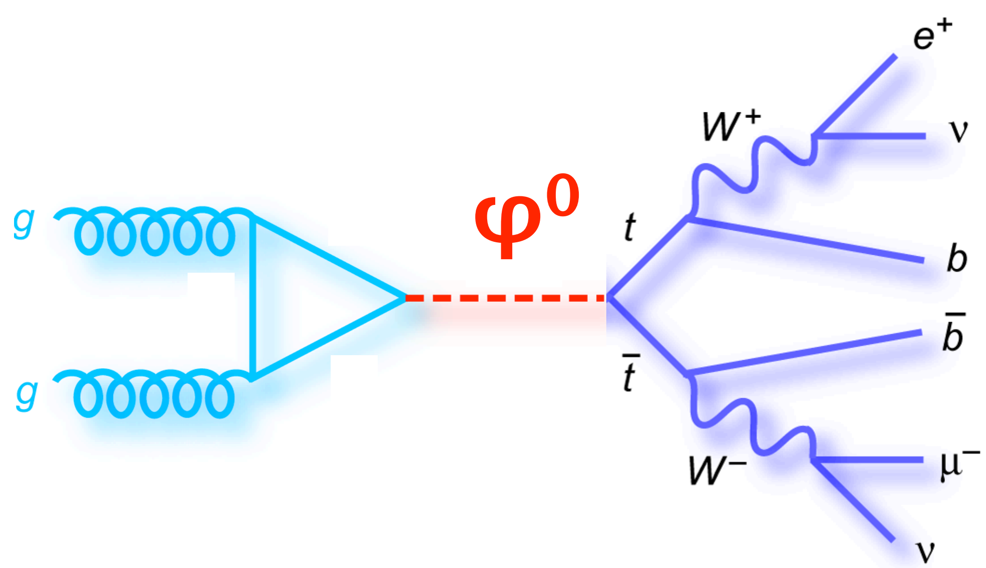
Helicity-Axis (LHC): NLO QCD: A = 0.32
Uwer, Phys. Lett., B609:271–276, 2005

Spin Correlation - BSM

- Several BSM scenarios predict different top decay/production mechanisms yielding in a different spin polarization

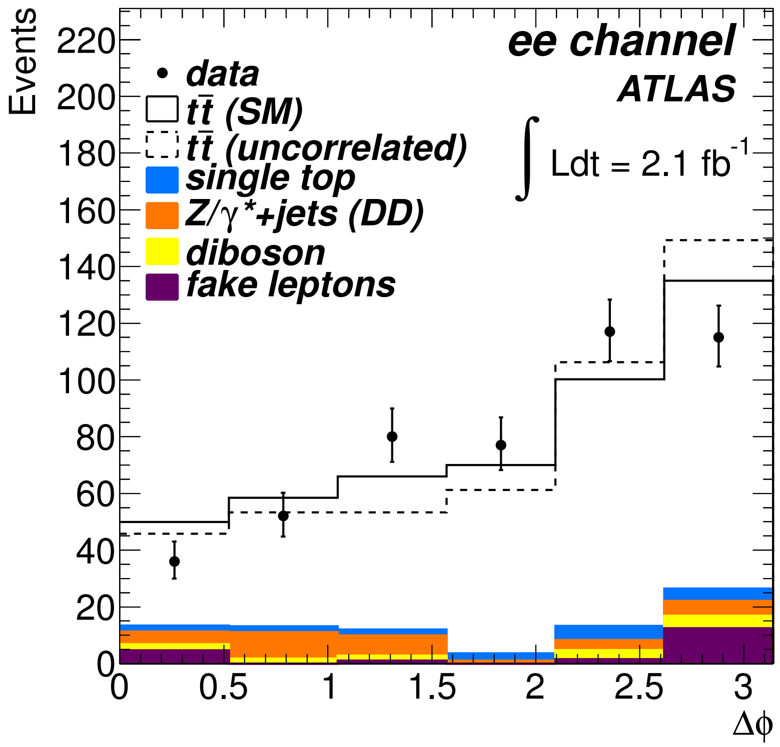


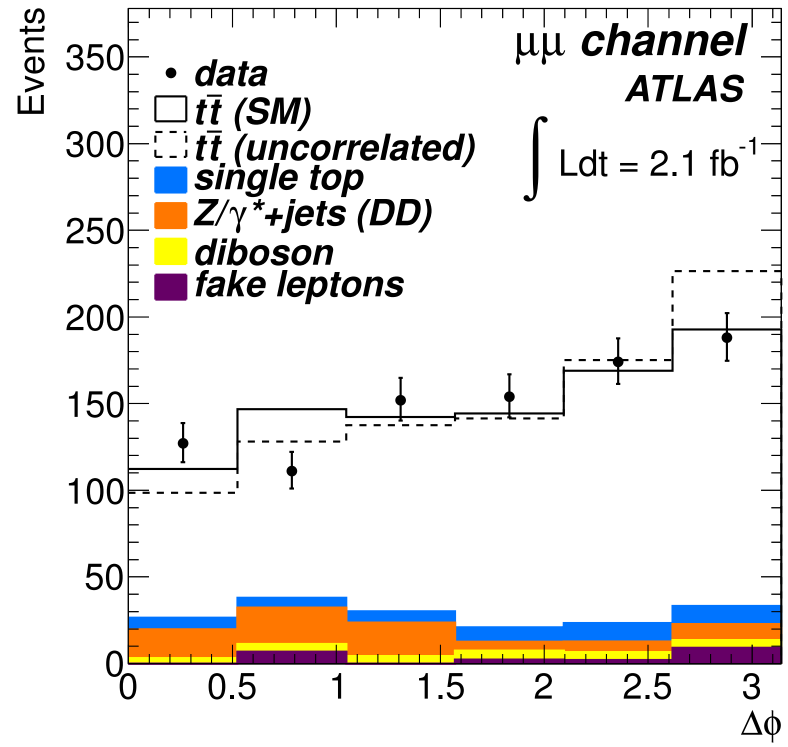
charged Higgs, b', ...

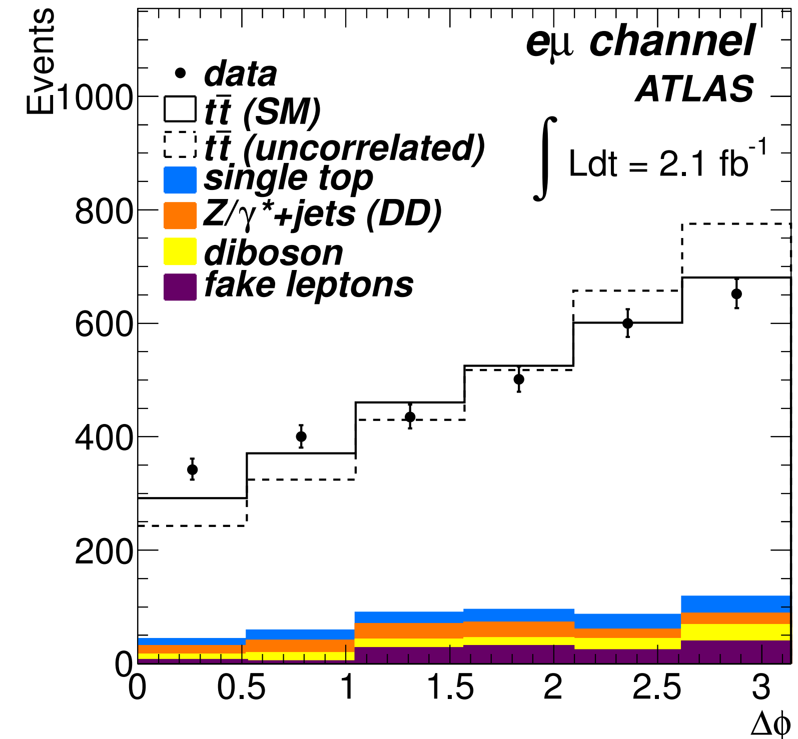


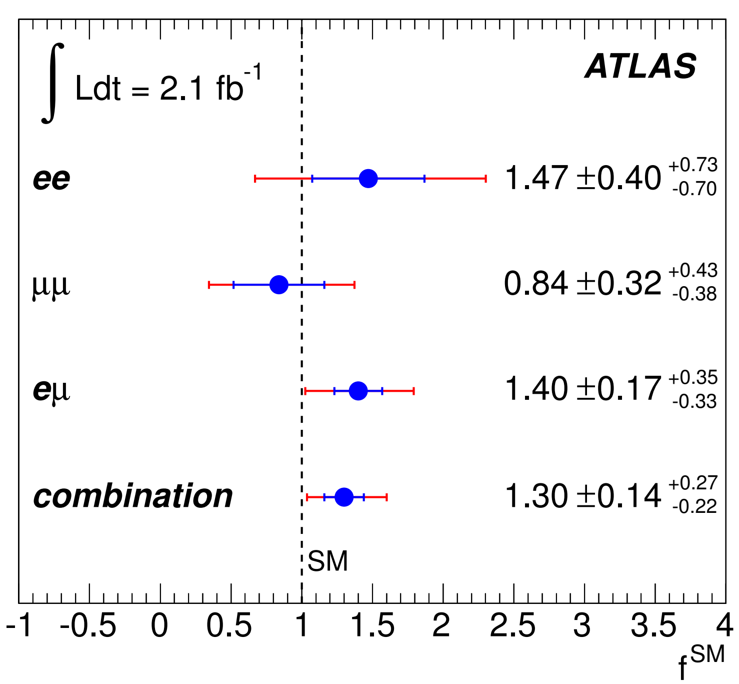
Higgs, KK gravitons, Z', stop pairs, ...

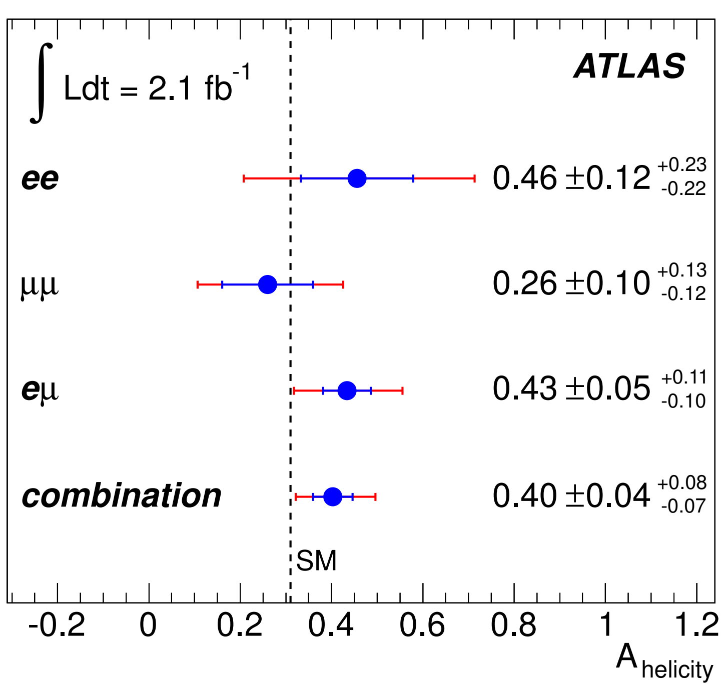
Spin Correlation - Channels

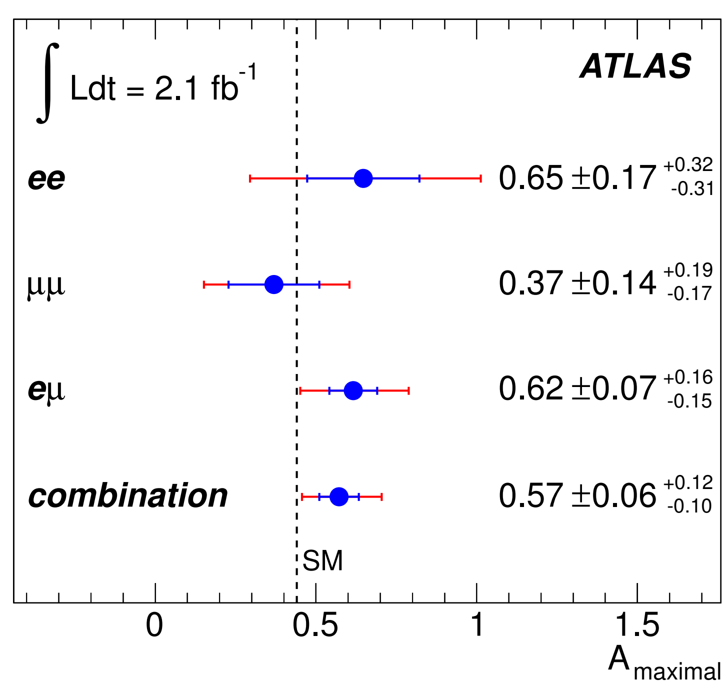












Spin Correlation - Systematics

Uncertainty source	Δf^{SM}
Data statistics	± 0.14
MC simulation template statistics	± 0.09
Luminosity	± 0.01
Lepton	± 0.01
Jet energy scale, resolution and efficiency	± 0.12
NLO generator	± 0.08
Parton shower and fragmentation	± 0.08
ISR/FSR	± 0.07
PDF uncertainty	± 0.07
Top quark mass	± 0.01
Fake leptons	$+0.16/-0.07$
Calorimeter readout	± 0.01
All systematics	$+0.27/-0.22$
Statistical + Systematic	$+0.30/-0.26$

Helicity - Asymmetry Method

- Extracting information about the polarization states of the W bosons evaluating angular asymmetries
$$A_z = \frac{N(\cos\theta^* > z) - N(\cos\theta^* < z)}{N(\cos\theta^* > z) + N(\cos\theta^* < z)}$$
- For z=0 this transforms into forward-backward asymmetry which is directly related to the helicity fractions by $A_{FB} = \frac{3}{4}[F_R - F_L]$
- Using the normalization constraint it is possible to define two independent asymmetries which fully constrain the three fractions (with $\beta = 2^{1/3} - 1$)

$$F_R = \frac{1}{1-\beta} + \frac{A_\beta - A_{-\beta}}{3\beta(1-\beta^2)}$$

$$F_L = \frac{1}{1-\beta} - \frac{A_{-\beta} - A_\beta}{3\beta(1-\beta^2)}$$

$$F_0 = -\frac{1+\beta}{1-\beta} + \frac{A_\beta - A_{-\beta}}{3\beta(1-\beta^2)}$$

- This provides an alternative method to extract helicity fractions

W Helicity - Systematics

Source	Uncertainties		
	F_0	F_L	F_R
Signal and background modelling			
Generator choice	0.012	0.009	0.004
ISR/FSR	0.015	0.008	0.007
PDF	0.011	0.006	0.006
Top quark mass	0.016	0.009	0.008
Misidentified leptons	0.020	0.013	0.007
W+jets	0.016	0.008	0.008
Other backgrounds	0.006	0.003	0.003
Method-specific uncertainties	0.031	0.016	0.035
Detector modelling			
Lepton reconstruction	0.013	0.006	0.007
Jet energy scale	0.026	0.014	0.012
Jet reconstruction	0.012	0.005	0.007
b-tagging	0.007	0.003	0.004
Calorimeter readout	0.009	0.005	0.004
Luminosity and pileup	0.009	0.004	0.005
Total systematic uncertainty	0.06	0.03	0.04