Top Quark Properties at the ATLAS Experiment

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on behalf of the

ATLAS Collaboration

Les Rencontres de Physique de la Vallée d'Aoste

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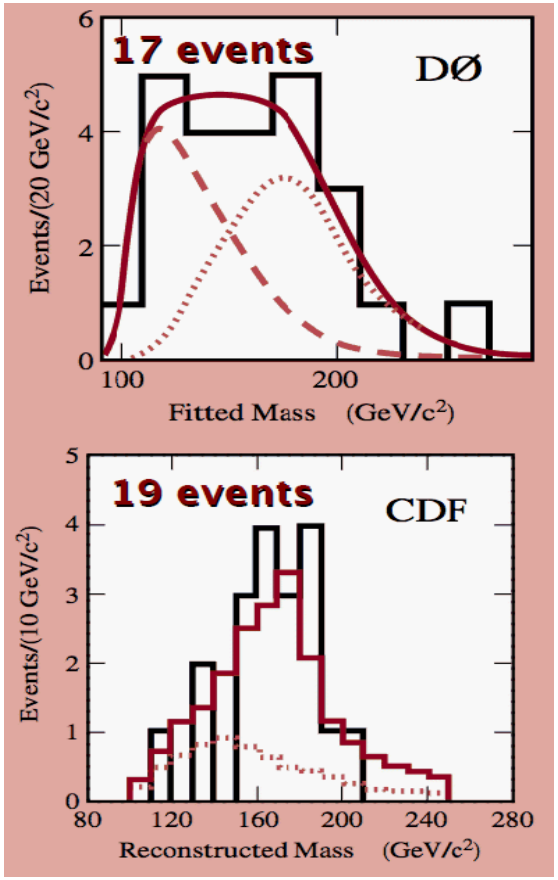
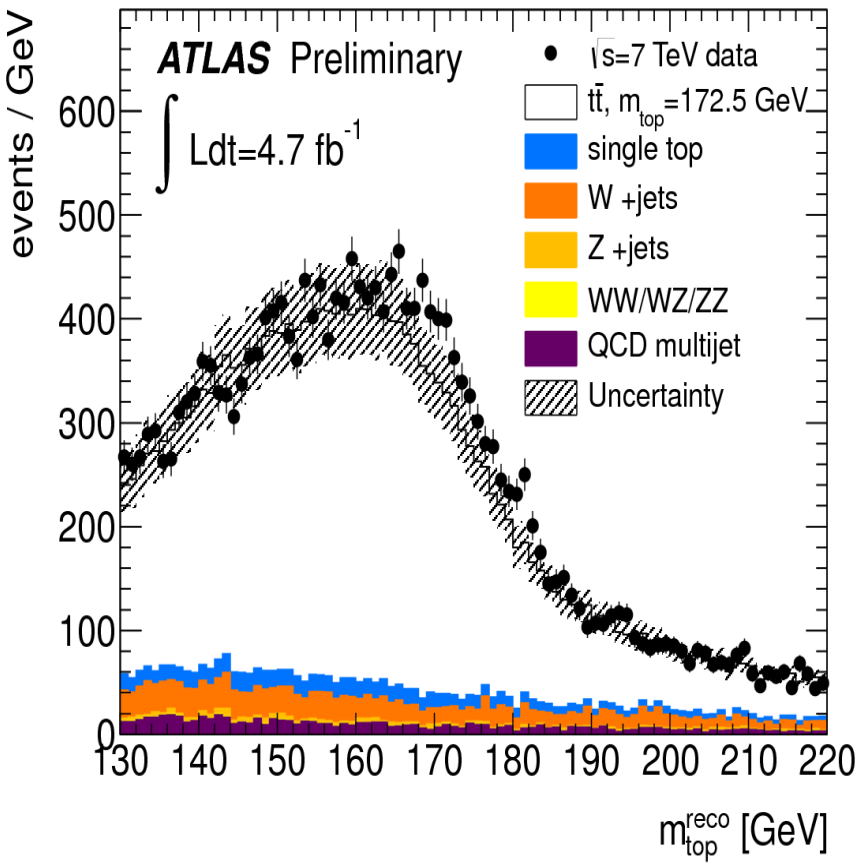
La Thuile, Italy

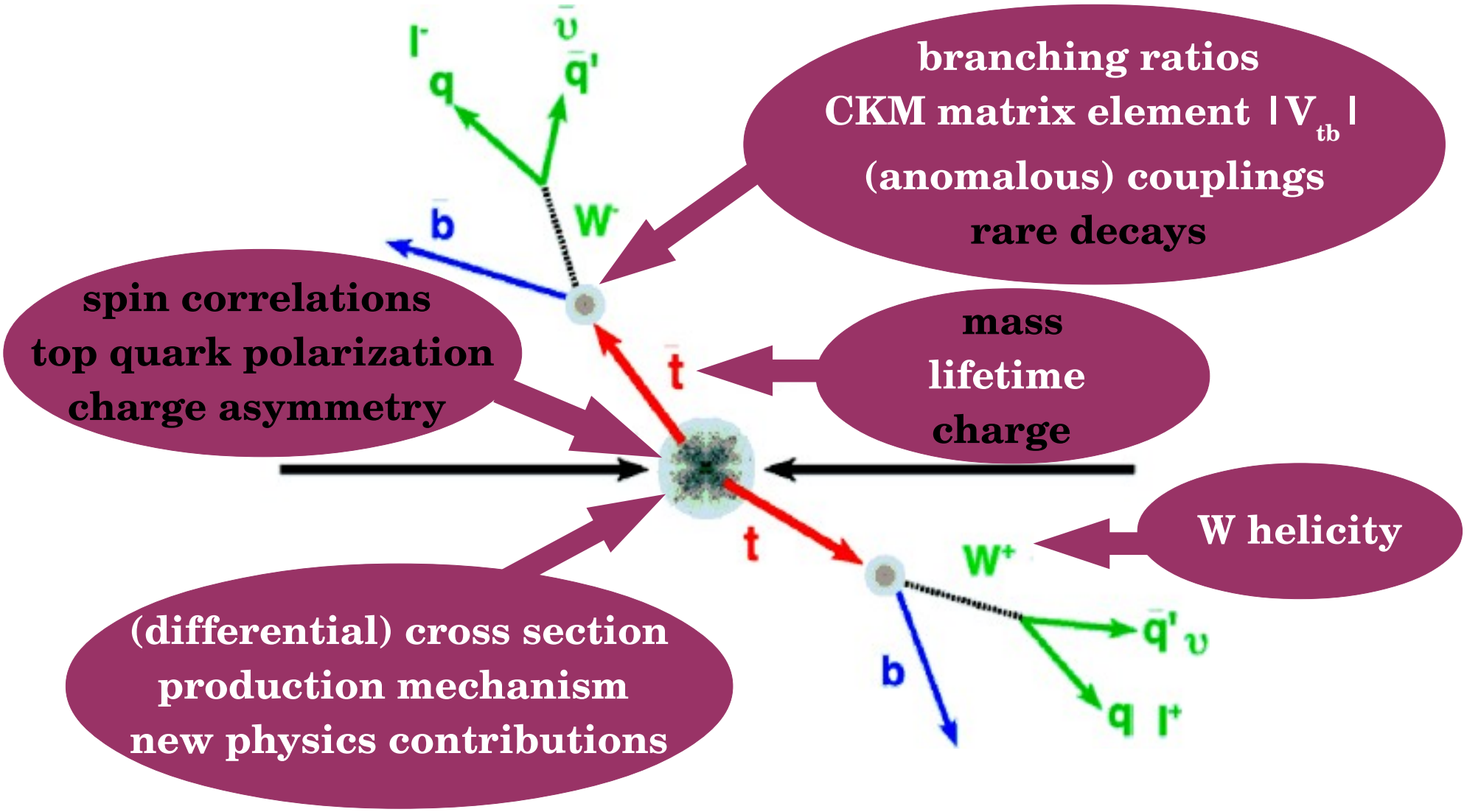
19 Years After its Discovery …

… top quark physics is more varied than ever before





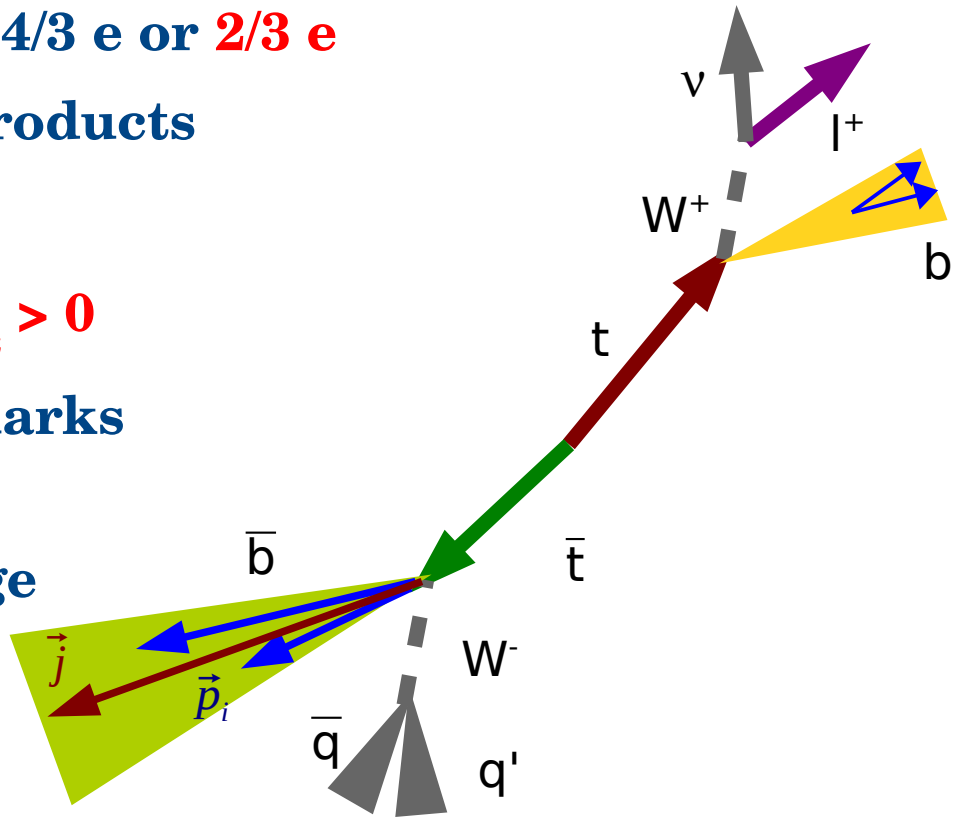
Top Quark Physics – An Overview



Top Quark Charge

- top quark charge could be either -4/3 e or 2/3 e
- deduction from charge of decay products
  - for an SM top (2/3 e): $Q_l \cdot Q_{b\text{-jet}} < 0$
  - for an exotic top (-4/3e): $Q_l \cdot Q_{b\text{-jet}} > 0$
- require 2 jets as coming from b quarks
- lepton charge directly measured;
  b-jet charge from weighted average

$$Q_{b-jet} = \frac{\sum_i Q_i (\vec{p}_i \vec{j})^k}{\sum_i (\vec{p}_i \vec{j})^k}$$

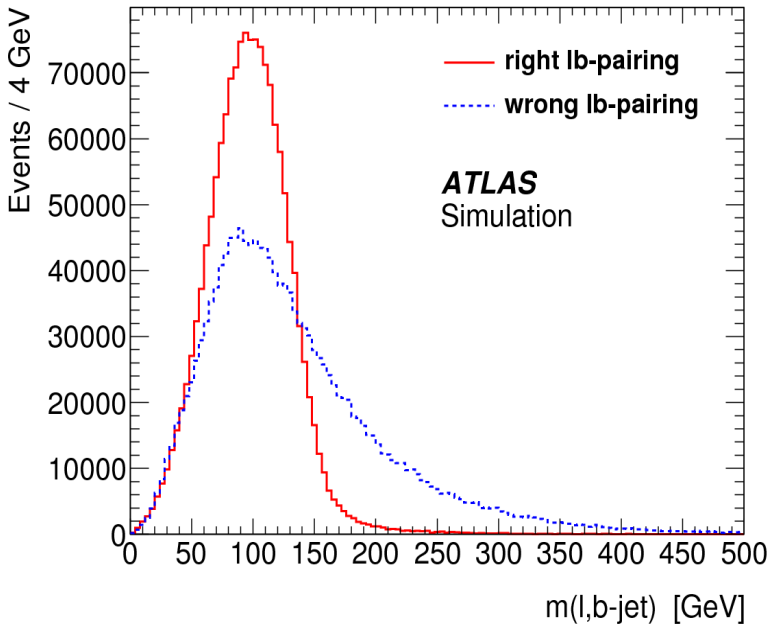


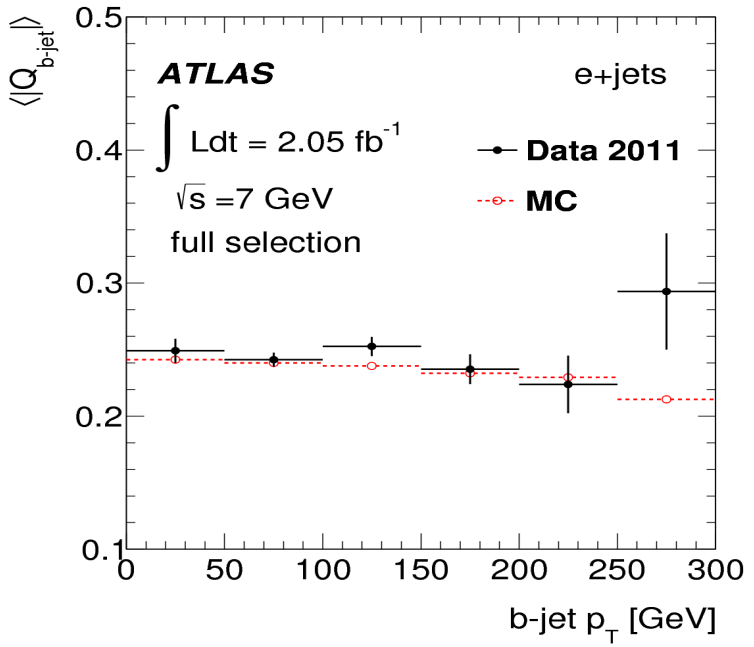
  - up to 10 tracks with p_T>1GeV and ΔR<0.25
  - optimial choice for $t\bar{t}$: κ=0.5

→ high demands on flavor and charge tagging

Top Quark Charge: Performance

- improved performance pairing lepton and proper b jet
  - $m(l,b\ jet_{1/2})<155$ GeV and $m(l,b\ jet_{2/1})>155$ GeV
  - → 87% purity (ε=0.28)
- charge weighting insensitive to b-jet p_T and pile-up
- data well described by MC simulations



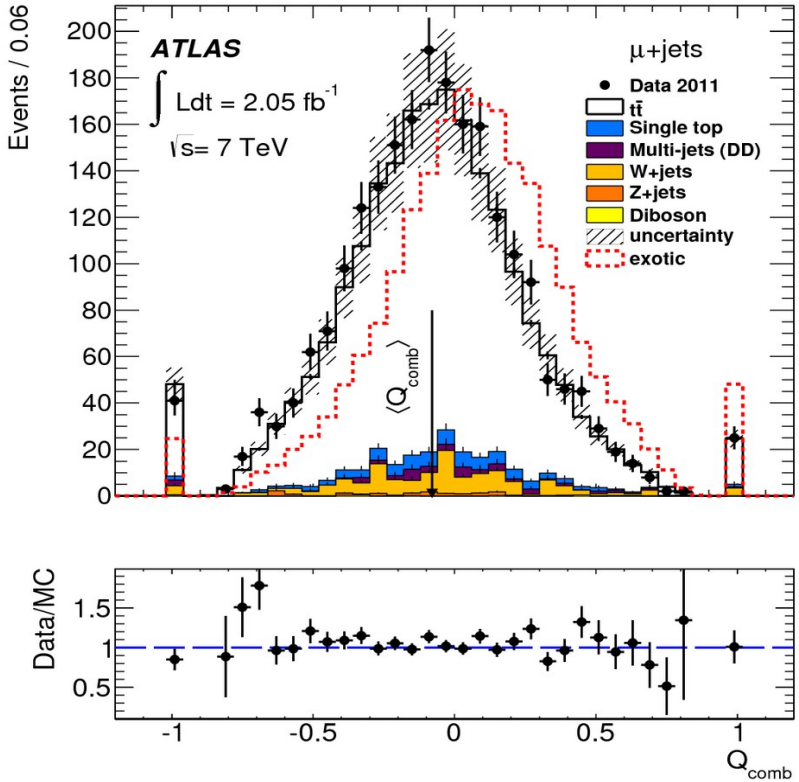


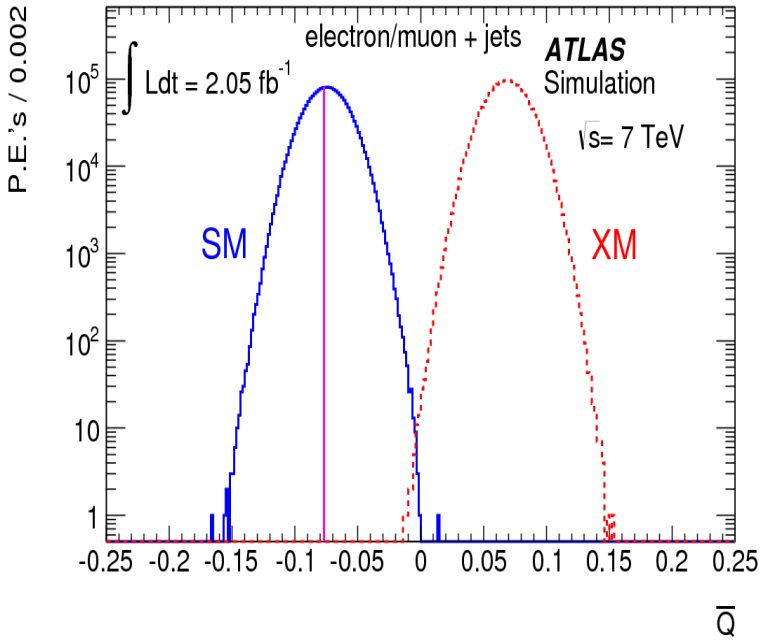
Top Quark Charge: Results

- 2.05 fb^{-1} of 7 TeV single-lepton events

$$Q_{top} = 0.64 \pm 0.02\,(stat) \pm 0.08\,(syst)$$

- exotic quark with –4/3e excluded with more than 8.9 σ
- most precise measurement

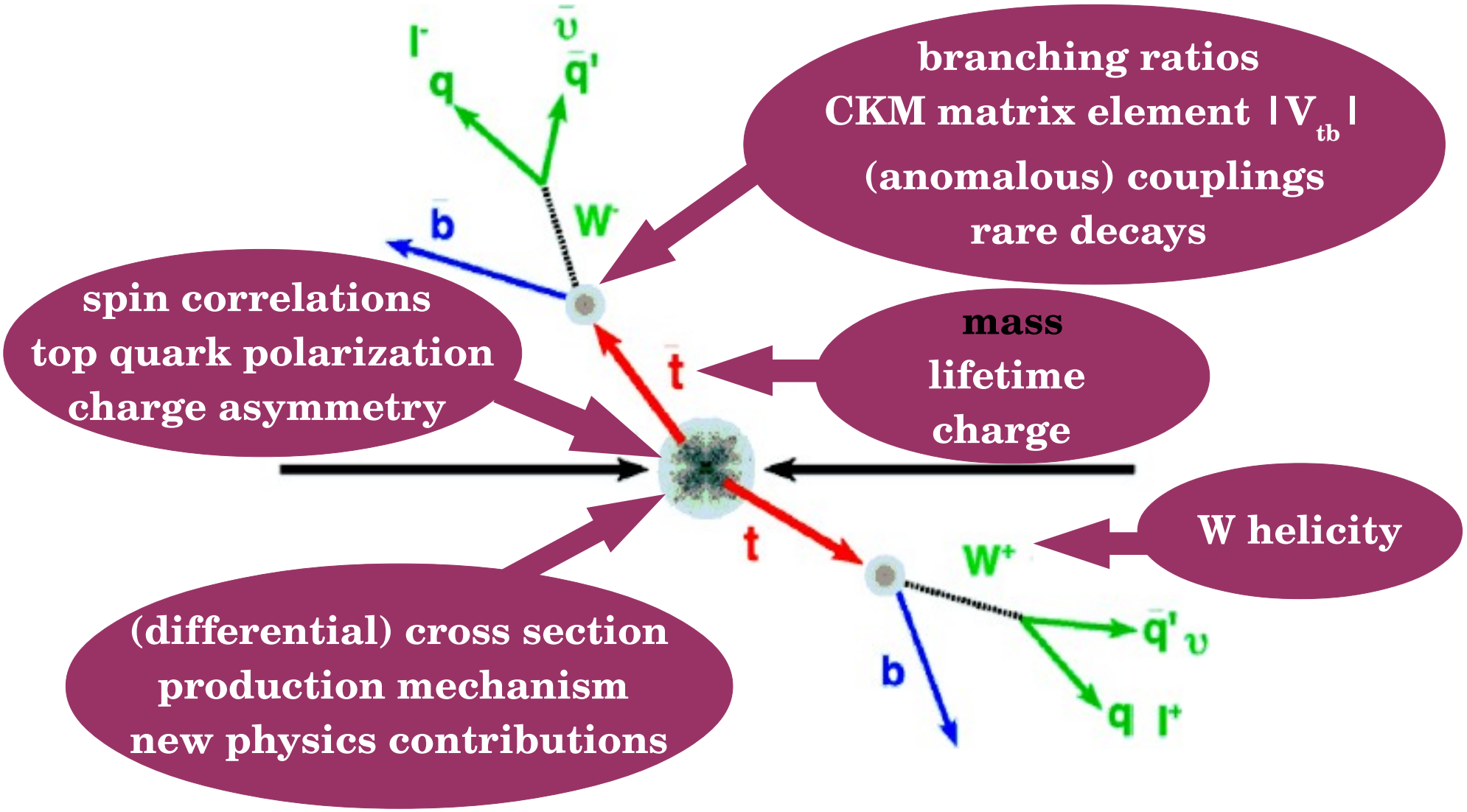




- largest systematic uncertainty from jet energy scale (JES)
  - purity of (l,b jet)-pairing degrades at low b-jet p_T

  and from hadronization model
- JHEP11(2013)031

Top Quark Physics – An Overview



Dilepton Top Quark Mass

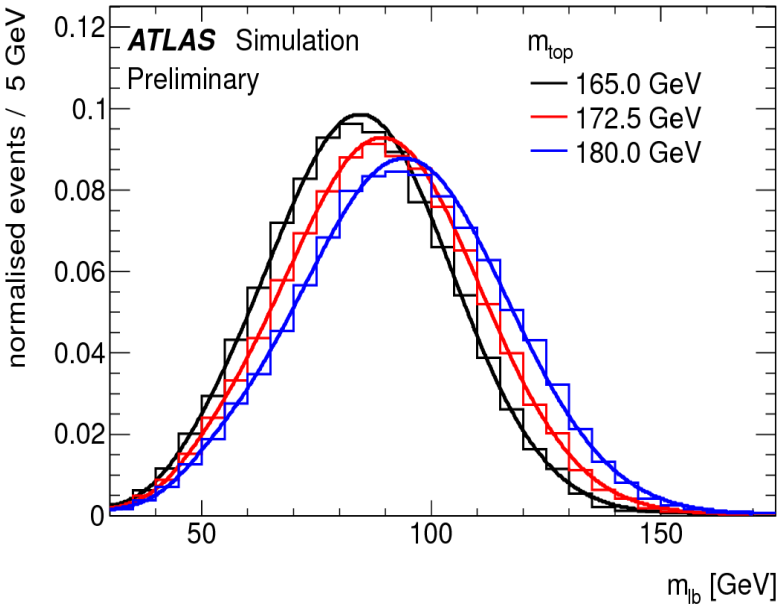
- **template measurement based on m_{lb}**
  - **pick jet-lepton assignment with lowest (m_{lb}(pair 1)+m_{lb}(pair 2))**
  - **~80% proper assignment**
  - **no full event reconstruction → reduced sensitivity to additional jets**
- **unbinned maximum likelihood fit**

$$L(m_{lb};m_t,r)=\prod_{i=1}^{N}(1-r)\,P_{sig}(m_{lb};m_t)+r\,P_{bkg}(m_{lb})$$

- **4.7 fb^{-1} @ 7 TeV (~2900 events, 96% purity)**

m_t = 173.09 ± 0.64 (stat) ± 1.50 (syst) GeV

- **largest systematic uncertainty:**
  JES/bJES: 0.89/0.71 GeV
- **ATLAS-CONF-2013-077**



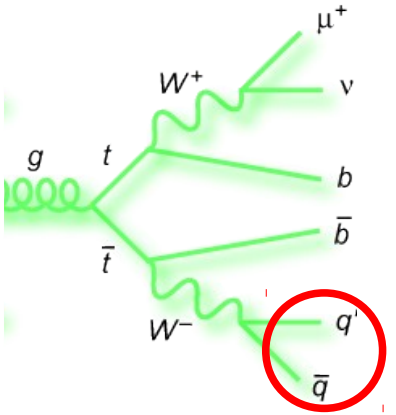
3-Dim Top Mass Measurement

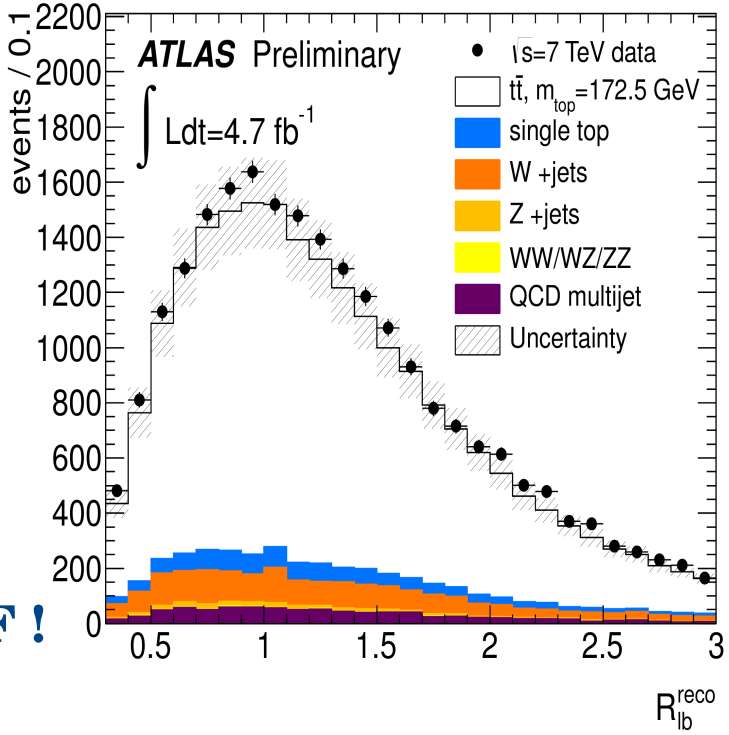
- measurement in single-lepton channel based on reconstructed **top** and **W mass** (to additionally constraint JSF)
- **ratio of light and b jets** explored to calibrate overall b-to-light jet energy scale (bJSF):

$$R_{lb}^{reco} = \frac{p_T^{bhad} + p_T^{blep}}{p_T^{jet1,W} + p_T^{jet2,W}}$$

  - R_{lb}^{reco} **uncorrelated with** m_t **and** m_W
  - well described by MC simulations
- **4.7 fb^{-1} @ 7 TeV (~23000 events, 82% purity):**

  $m_t = 172.31 \pm 0.75\,(stat) \pm 1.35\,(syst)$ GeV
- total uncertainty reduced from 2 to 1.5 GeV
- world's first m_t measurement with in-situ bJSF !
- ATLAS-CONF-2013-046





Systematic Uncertainties and Improvements

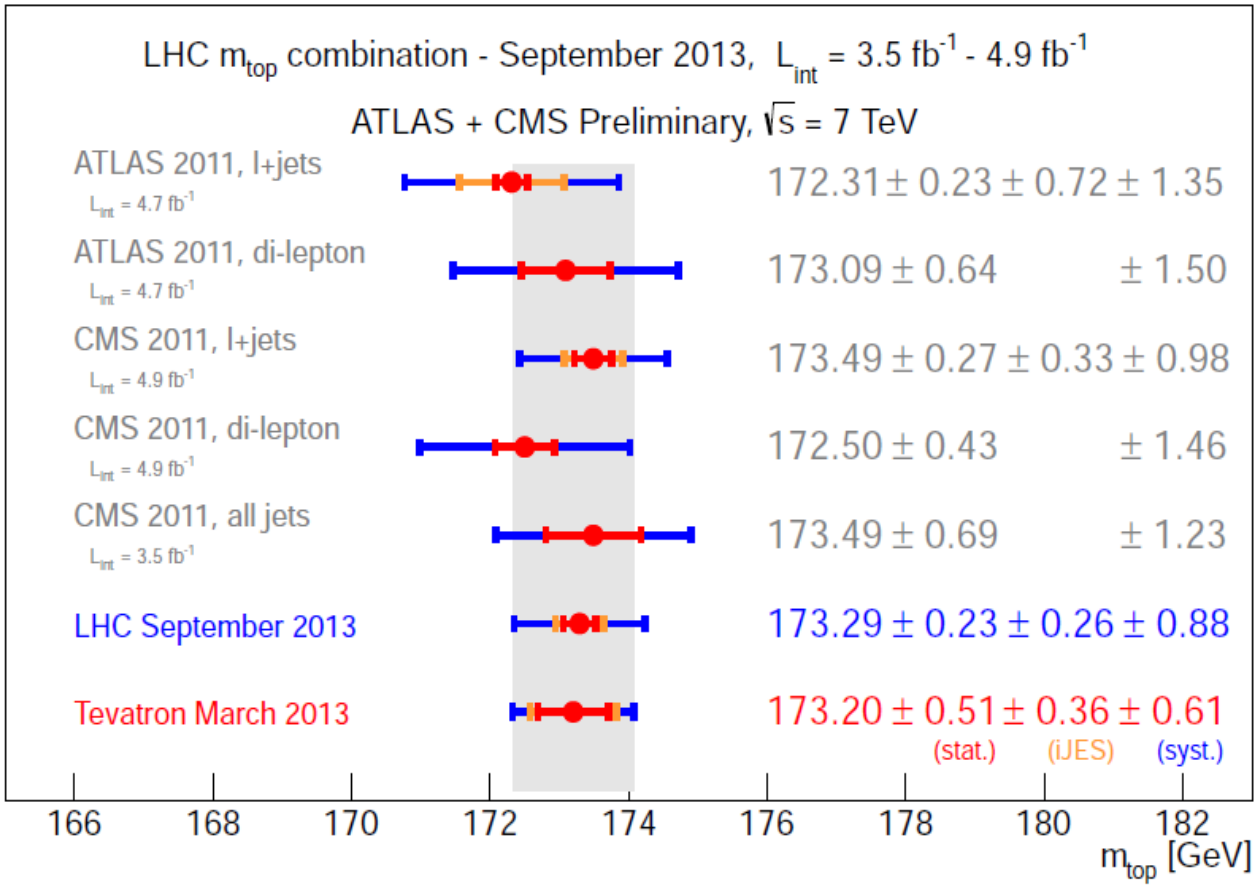
	3d-analysis		
	m_{top} [GeV]	JSF	bJSF
Measured value	172.31	1.014	1.006
Data statistics	0.23	0.003	0.008
Jet energy scale factor (stat. comp.)	0.27	n/a	n/a
bJet energy scale factor (stat. comp.)	0.67	n/a	n/a
Method calibration	0.13	0.002	0.003
Signal MC generator	0.19	0.005	0.002
Hadronisation	0.27	0.008	0.013
Underlying event	0.12	0.001	0.002
Colour reconnection	0.32	0.001	0.004
ISR and FSR (signal only)	0.45	0.017	0.006
Proton PDF	0.17	0.000	0.001
single top normalisation	0.00	0.000	0.000
W+jets background	0.03	0.000	0.000
QCD multijet background	0.10	0.000	0.001
Jet energy scale	0.79	0.004	0.007
b-jet energy scale	0.08	0.000	0.002
Jet energy resolution	0.22	0.006	0.000
Jet reconstruction efficiency	0.05	0.000	0.000
b-tagging efficiency and mistag rate	0.81	0.001	0.011
Lepton energy scale	0.04	0.000	0.000
Missing transverse momentum	0.03	0.000	0.000
Pile-up	0.03	0.000	0.001
Total systematic uncertainty	1.35	0.021	0.020
Total uncertainty	1.55	0.021	0.022

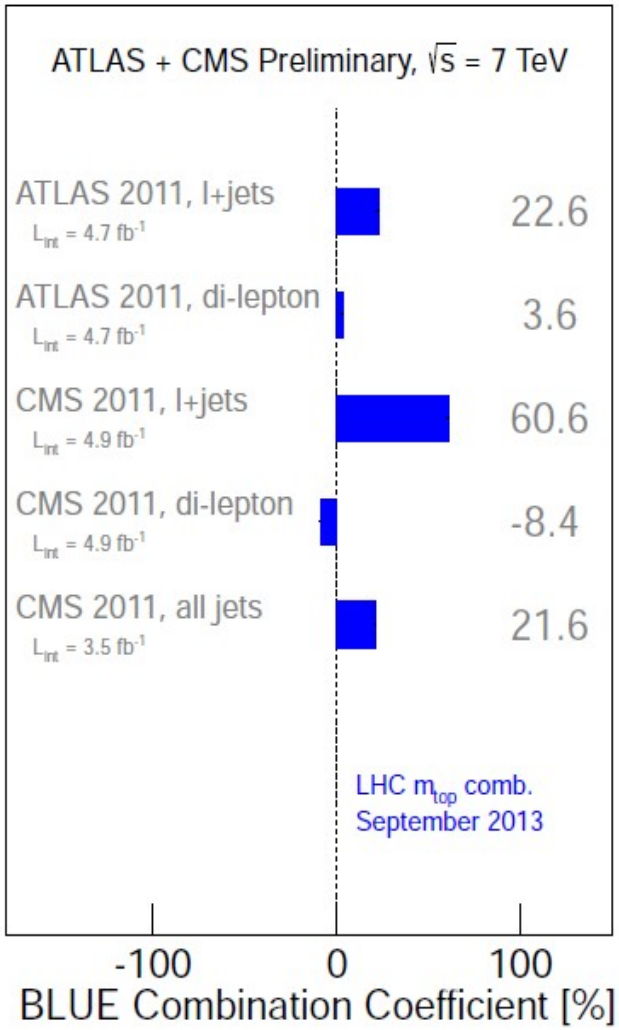
higher statistics

split into different regions

avoid double-counting (e.g. modeling)

LHC Mass Combination





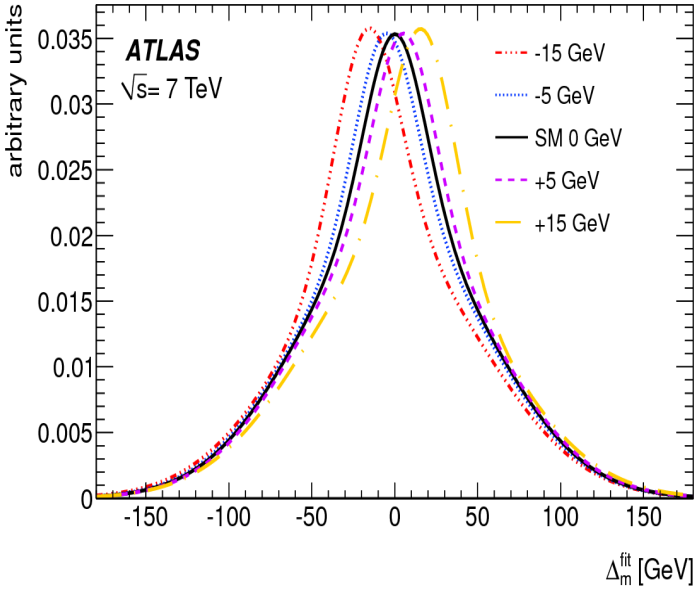
excellent agreement of LHC and Tevatron results

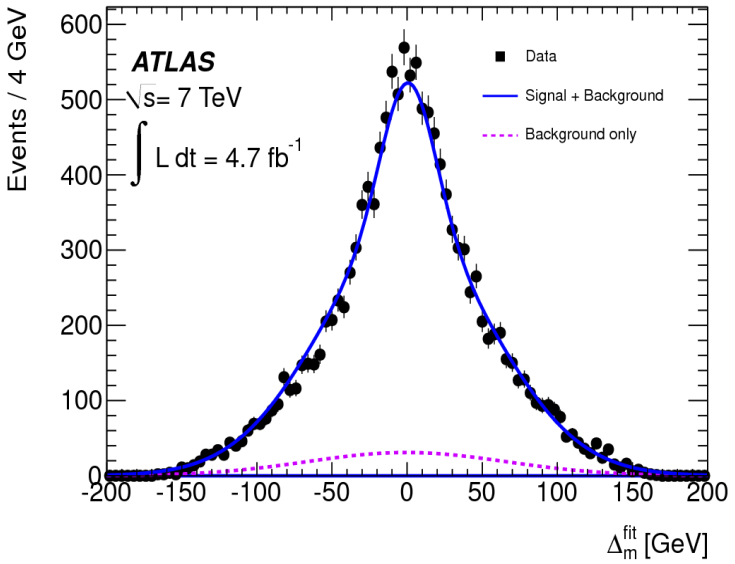
Mass Difference

- are top and antitop masses equal ?
  - probe of CPT symmetry
- templates with various mass differences and average mass of 172.5 GeV
- kinematic fit of $t\bar{t}$ events with $\Delta m_{t\bar{t}}$ as free parameter
- unbinned likelihood fit using 4.7 fb^{-1} of single-lepton events @ 7 TeV:

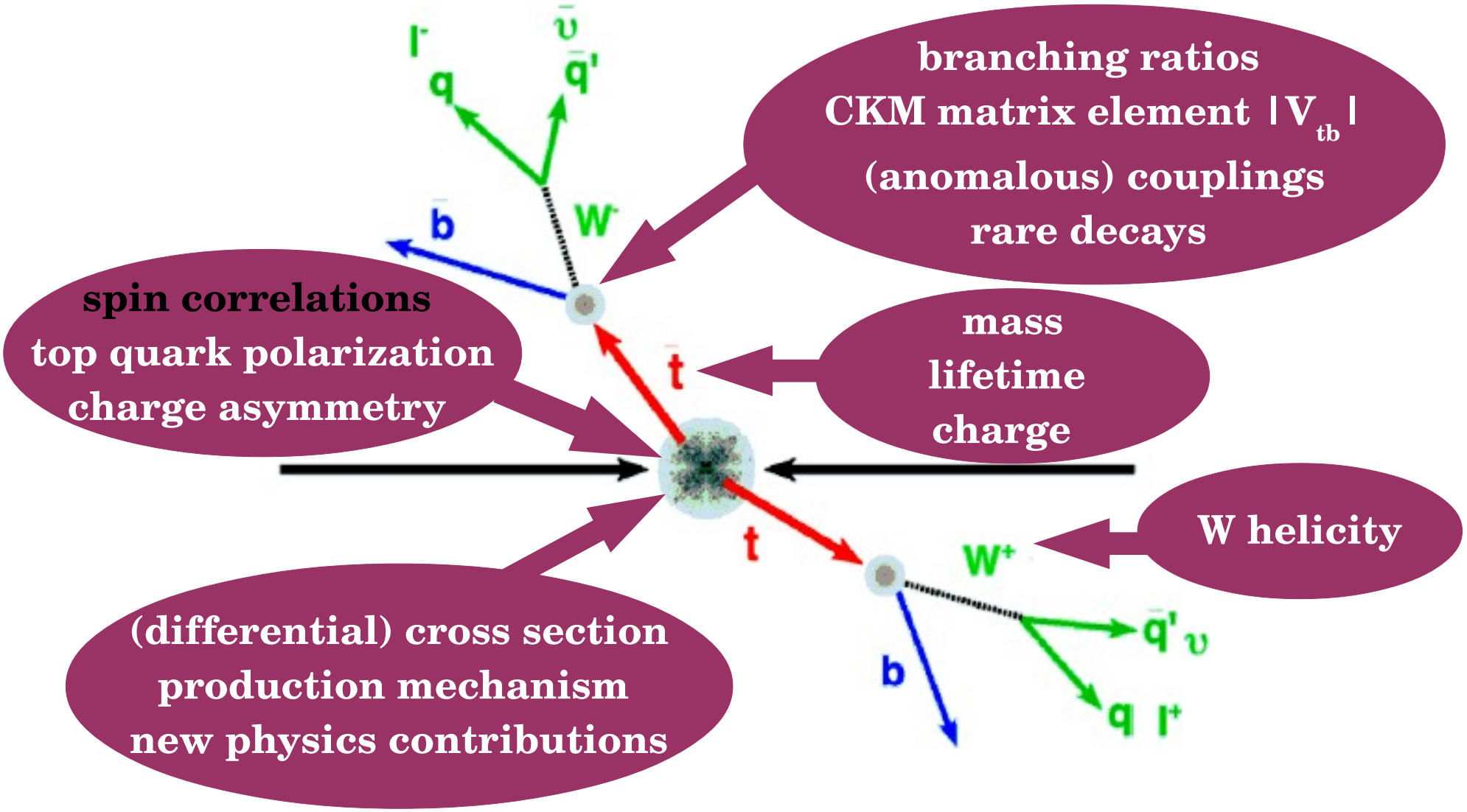
$$\Delta m_{t\bar{t}} = 0.67 \pm 0.61(stat) \pm 0.41(syst)\ GeV$$

- well consistent with SM expectation
- result limited by statistics
- largest systematic (0.34 GeV) from fragmentation and B hadron decay
- PLB 728C (2014) 363-379





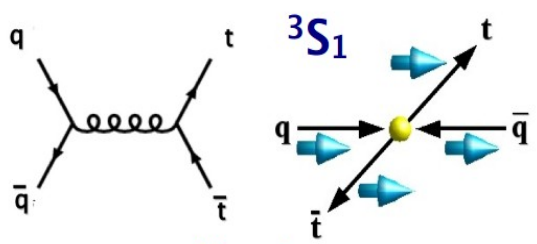
Top Quark Physics – An Overview



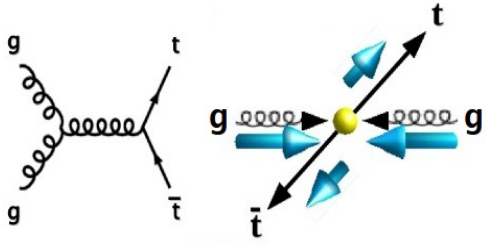
Spin Correlation in $t\bar{t}$ Events

- **SM predicts correlated top quark spins**
- **correlation strength A:**

$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$



Tevatron



LHC

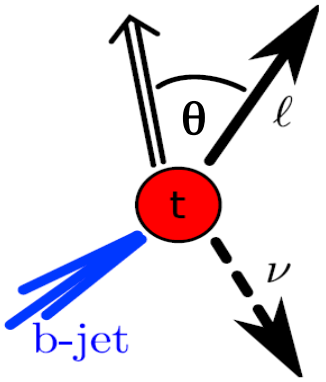
- **depends on production mode → different for Tevatron ($p\bar{p}$) and LHC (pp)**
- **choice of spin basis**

Basis	Helicity	Maximal
A(SM)	0.31	0.44

- **short lifetime → spin visible in angles of decay products ($\alpha \sim 1$ for down-type particles)**

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i} = \frac{1}{2}(1 + \alpha_i \cos\theta_i)$$

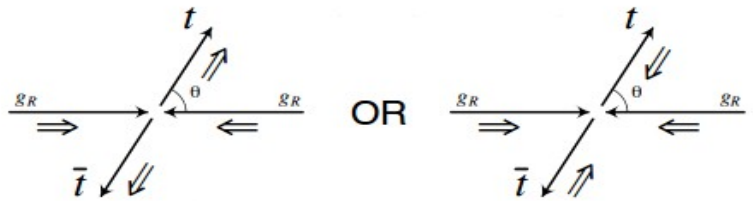
- **probes full chain from production to decay of top**



Observation of Spin Correlation

- $t\bar{t}$ @ LHC dominated by like-helicity-gluon fusion for low $\hat{s}$

$t/\bar{t}$ right-handed left-handed



$(1+\beta)^2 : (1-\beta)^2$

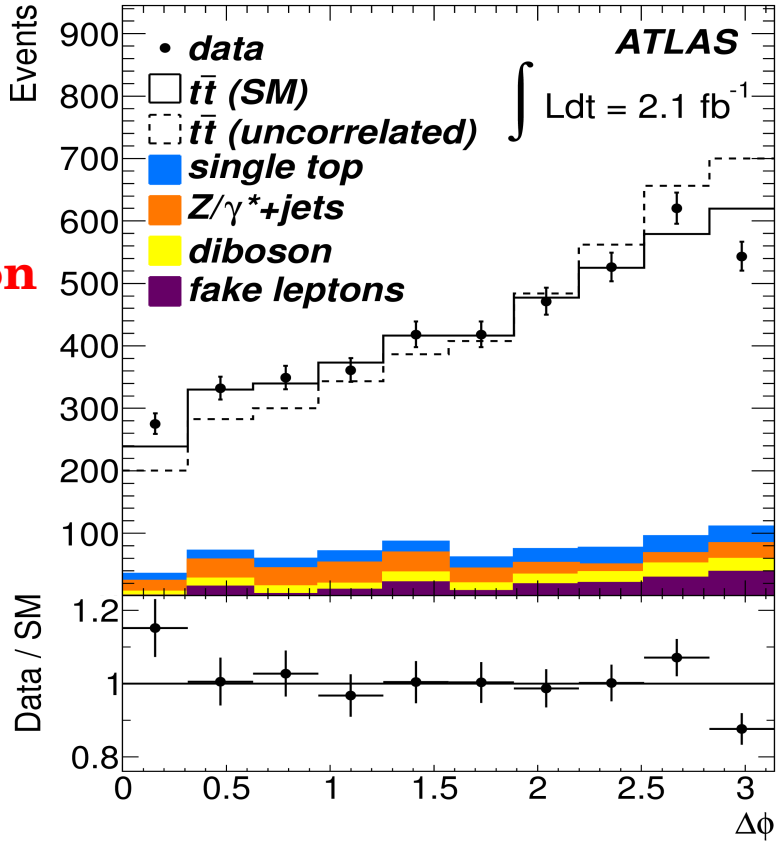
→ leptons show strong azimuthal correlation

→ no need to fully reconstruct $t\bar{t}$ system

- template fit of correlated and uncorrelated prediction to data
- 2.1 fb^{-1} of dilepton events:

$$A_{heli} = 0.40 \pm 0.04\,(stat) \pm 0.08\,(syst)$$

- excellent agreement with SM $A_{heli} = 0.31$
- first observation of spin correlation
- PRL 108 (2012) 212001



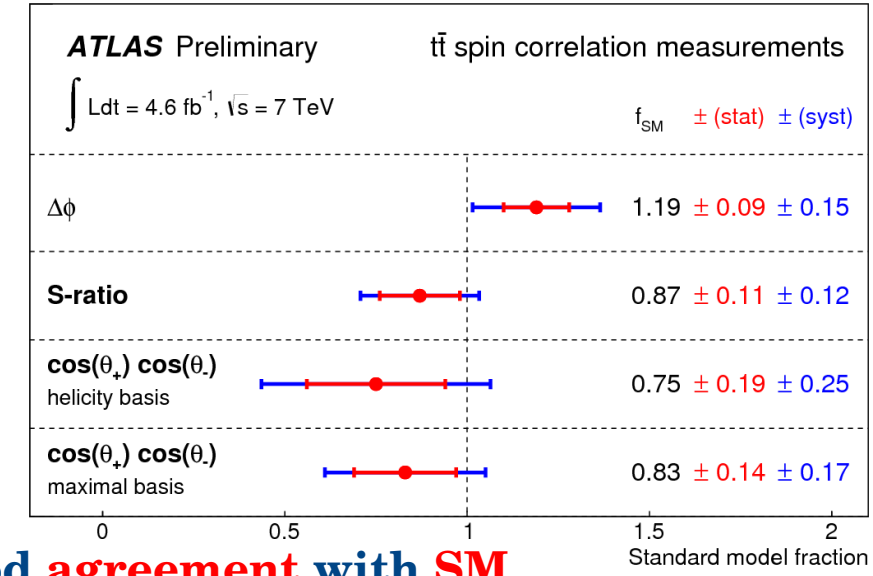
New Observables @ LHC

- **S-ratio from gg→tt̄ matrix elements**

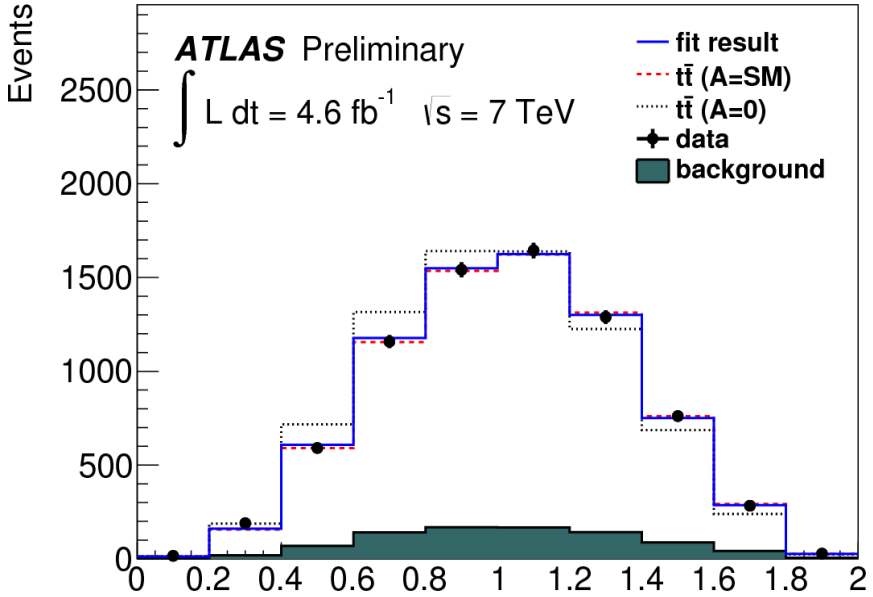
$$S = \frac{\left(|M|^2_{RR} + |M|^2_{LL}\right)_{corr}}{\left(|M|^2_{RR} + |M|^2_{LL}\right)_{uncorr}}$$

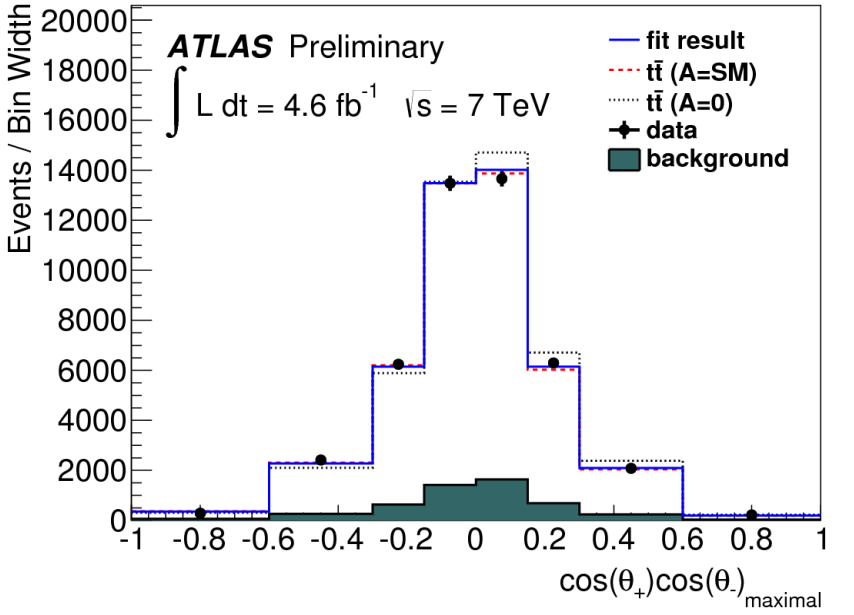
- **double differential cross section in cos θ (helicity and maximal basis)**

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



- **good agreement with SM**
- **ATLAS-CONF-2013-101**





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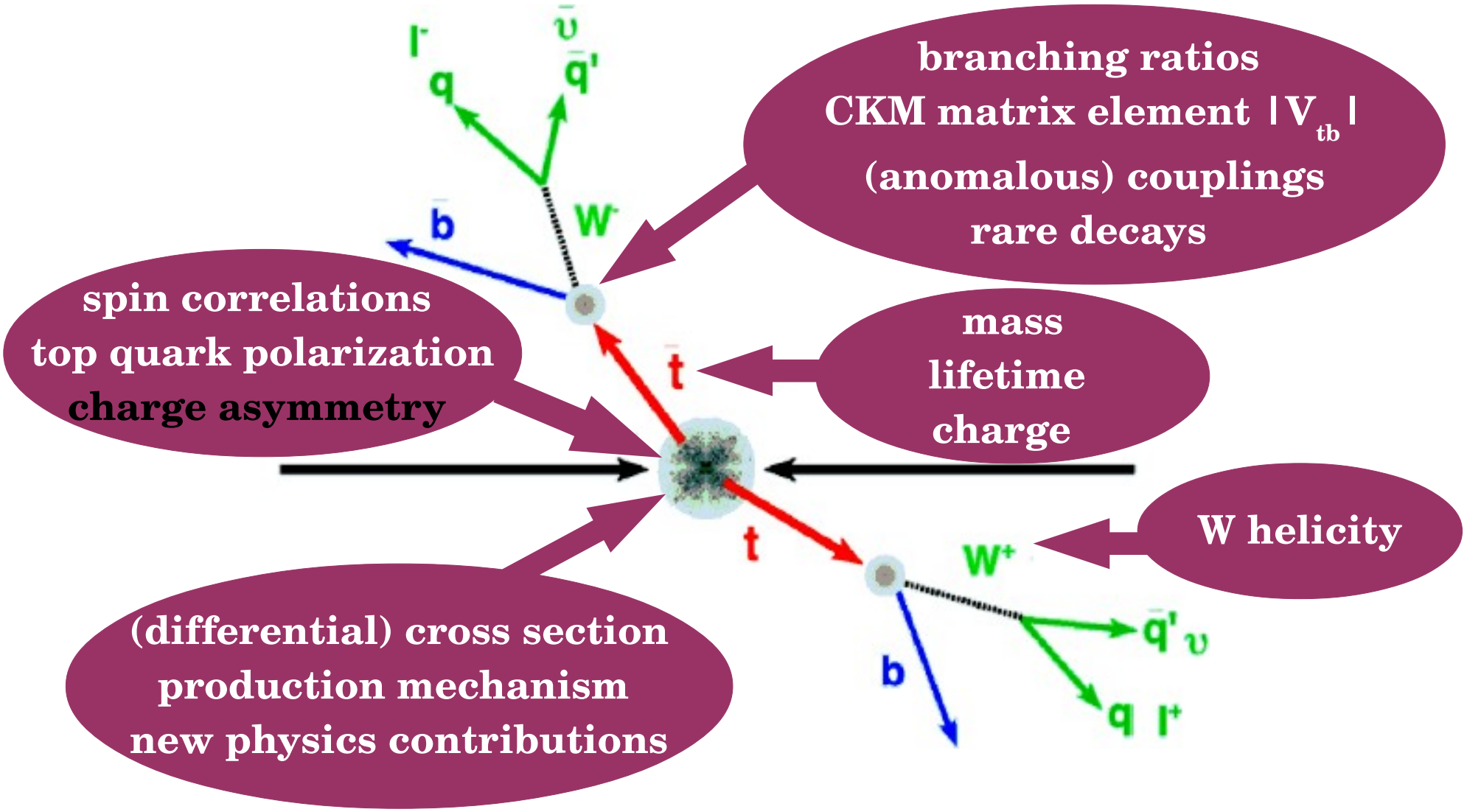
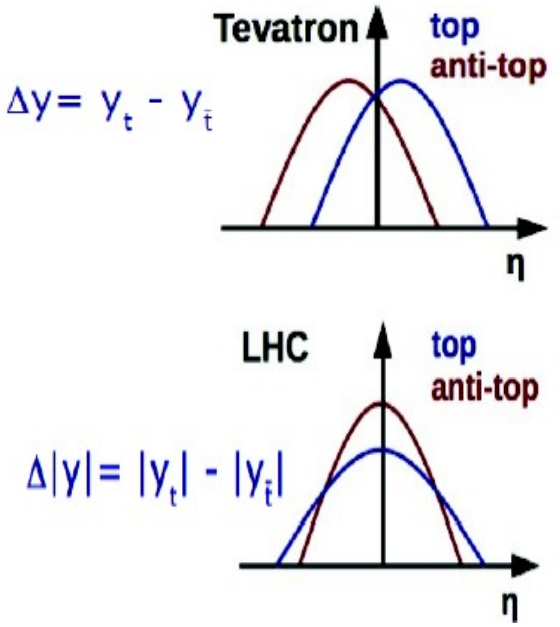


Top Production Asymmetry at LHC

- top (antitop) follows preferentially direction of incoming quark (antiquark) in $t\bar{t}$ rest frame
- on average the quark (antiquark) has higher (smaller) momentum in pp → boost in lab frame drives top (antitop) in forward/backward (central) region



- $t\bar{t}$ asmmetry at LHC:

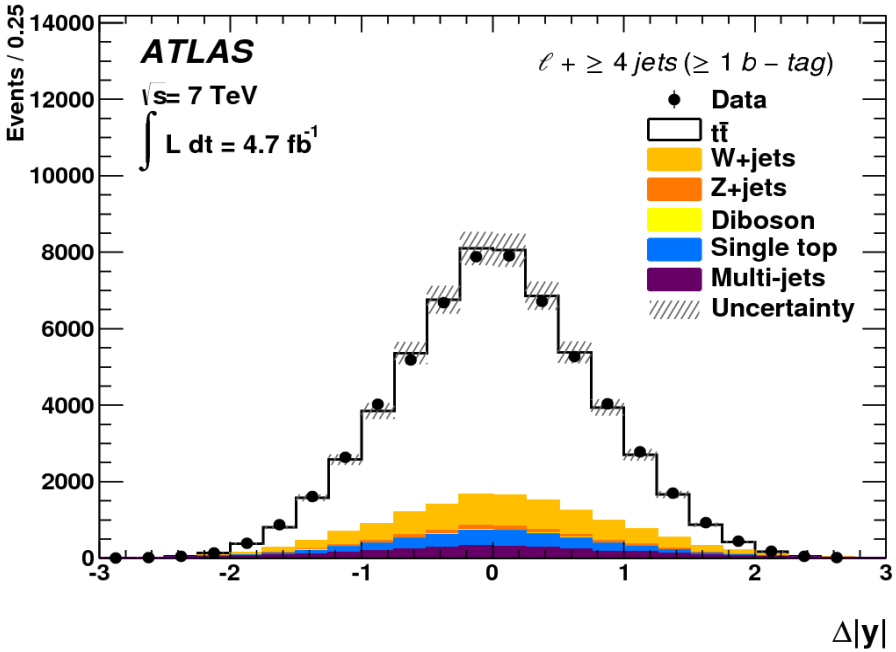
$$A_C = \frac{N(\Delta|y_{t\bar{t}}|>0) - N(\Delta|y_{t\bar{t}}|<0)}{N(\Delta|y_{t\bar{t}}|>0) + N(\Delta|y_{t\bar{t}}|<0)}$$

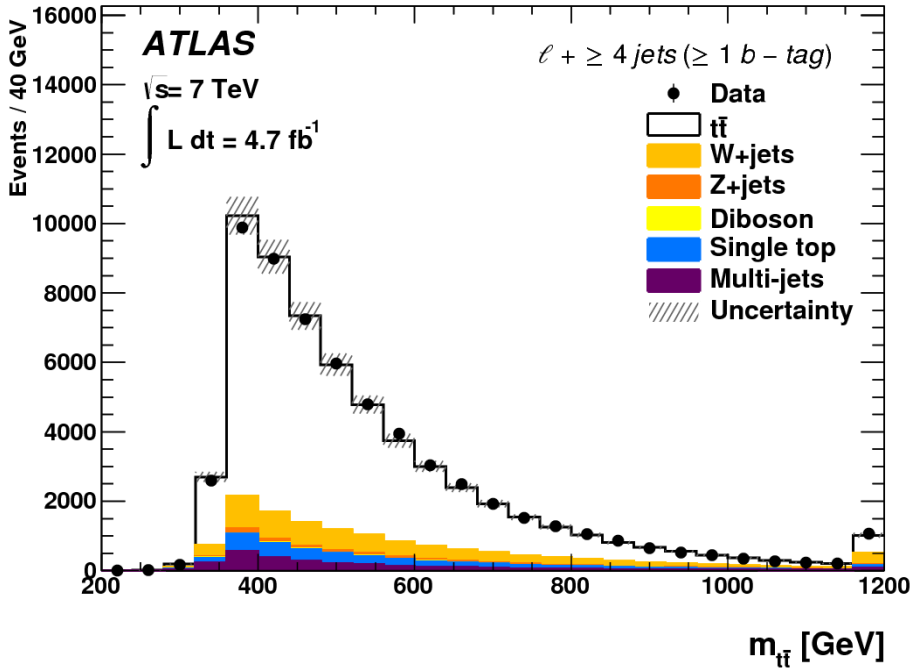
A_C = 1.23 ± 0.05 % @ NLO QCD+ew. corr.

PRD 86 (2012) 034026

A_C at ATLAS

- measurement based on 4.7 fb^{-1} of 7 TeV single-lepton events
- kinematic likelihood fit to reconstruct $t\bar{t}$ system
- cut on likelihood to reject badly reconstructed event





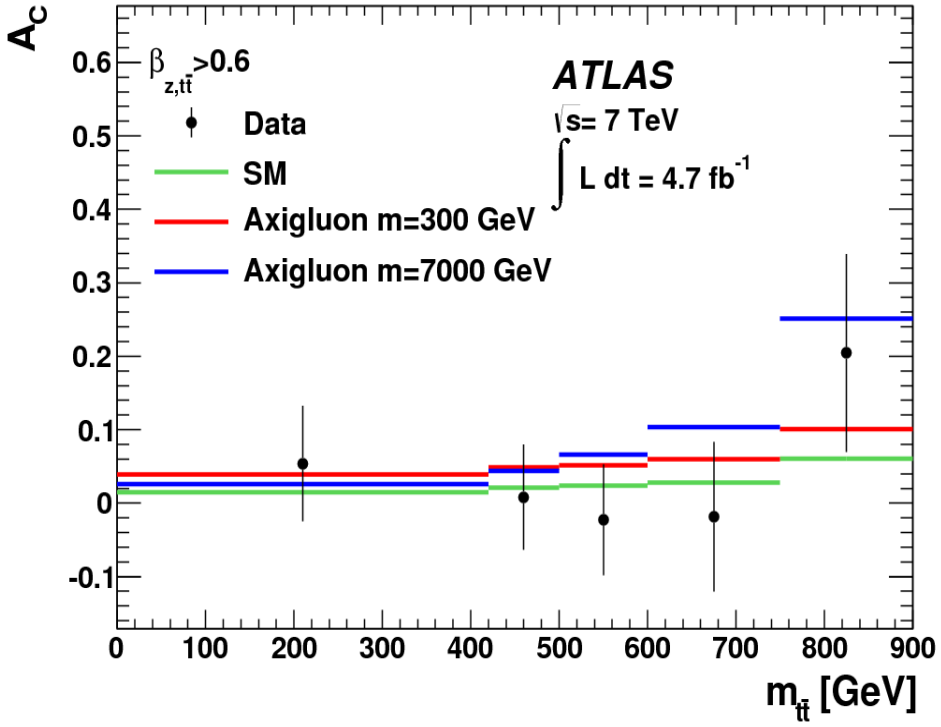
- results corrected for resolution and acceptance effects using Bayesian unfolding

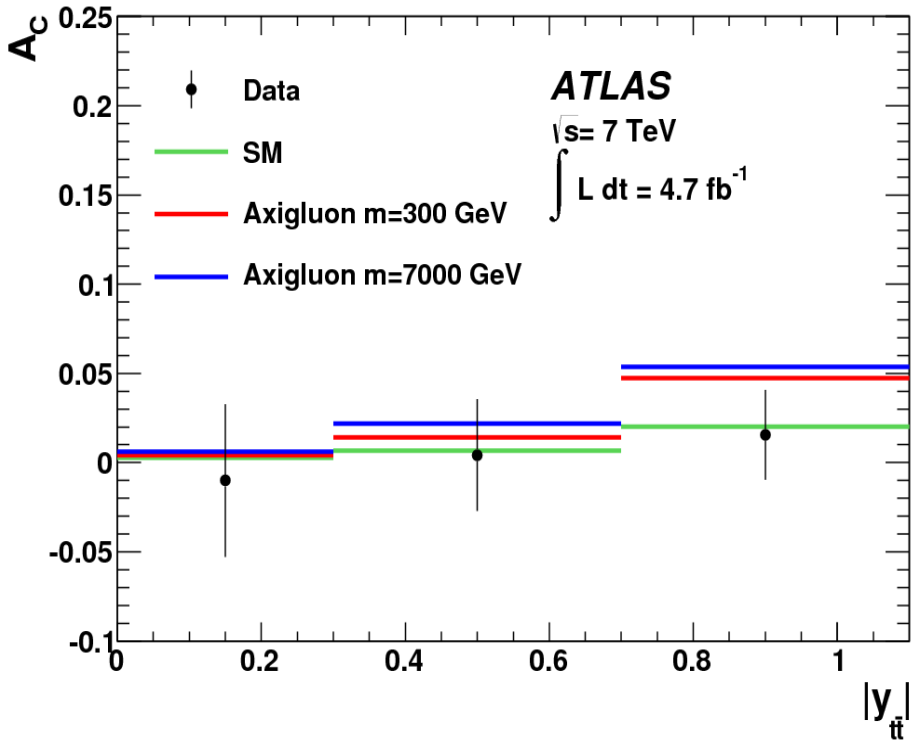
$$A_C = 0.6 \pm 1.0 \text{ (stat+syst) } \%$$

- measurements statistically limited
- good agreement with SM prediction
- arXiv:1311.6724 [hep-ex]

Kinematic Dependencies of A_C

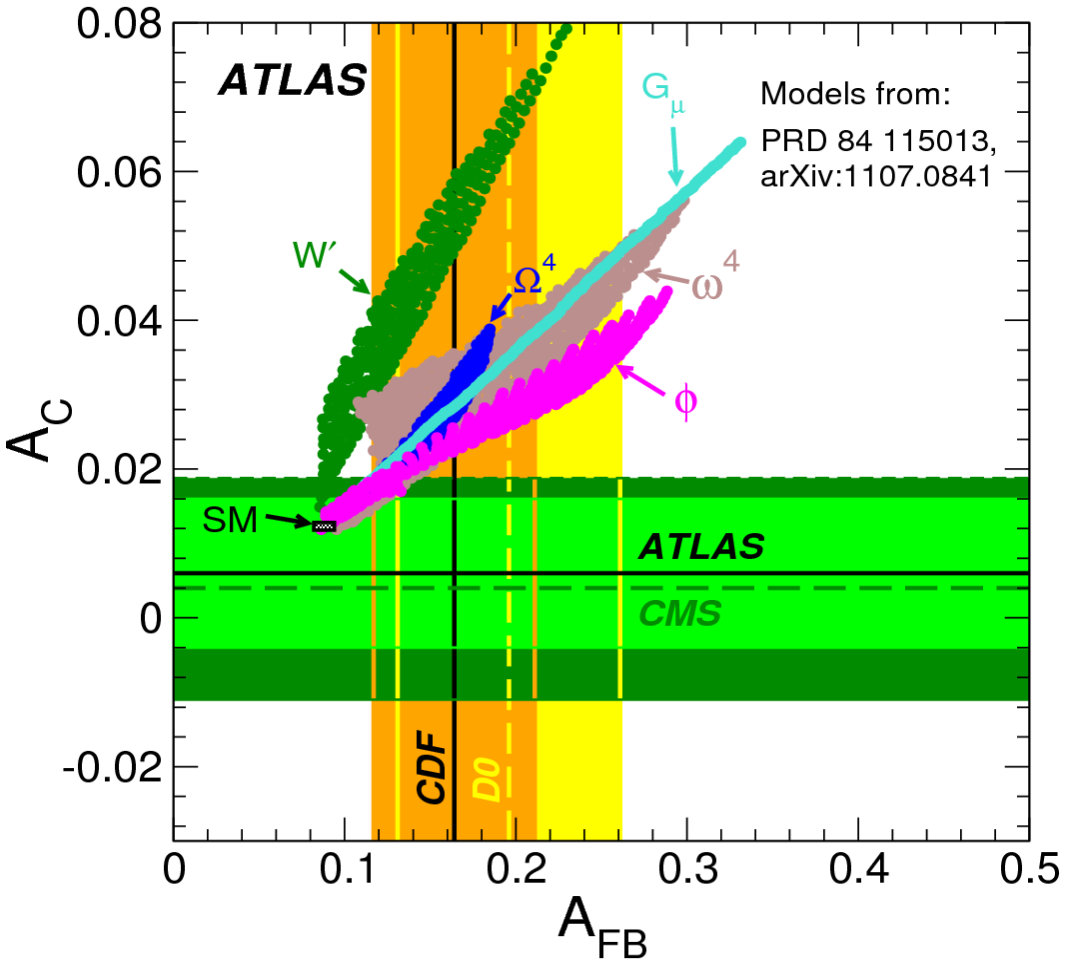
- interesting as new physics yields different $m_{t\bar{t}}$ or $y_{t\bar{t}}$ dependency
- comparison to SM and s-channel axigluons (tuned to Tevatron A_{FB})





→ no significant deviation from the SM prediction

Forward-Backward vs. Charge Asymmetry



PRD 84 (2011) 115013

- **W':**
  right-handed couplings, contributing in $d\bar{d} \to t\bar{t}$
- **G_μ:**
  heavy axi-gluon in s-channel
- **Ω^4:**
  charge 4/3 scalar, color-sextett contributing in u-channel $u\bar{u} \to t\bar{t}$
- **ω^4:**
  charge 4/3 scalar, color-triplett contributing in u-channel $u\bar{u} \to t\bar{t}$
- **ϕ:**
  scalar with SM Higgs quantum numbers

- **some of the models disfavored by current measurements**

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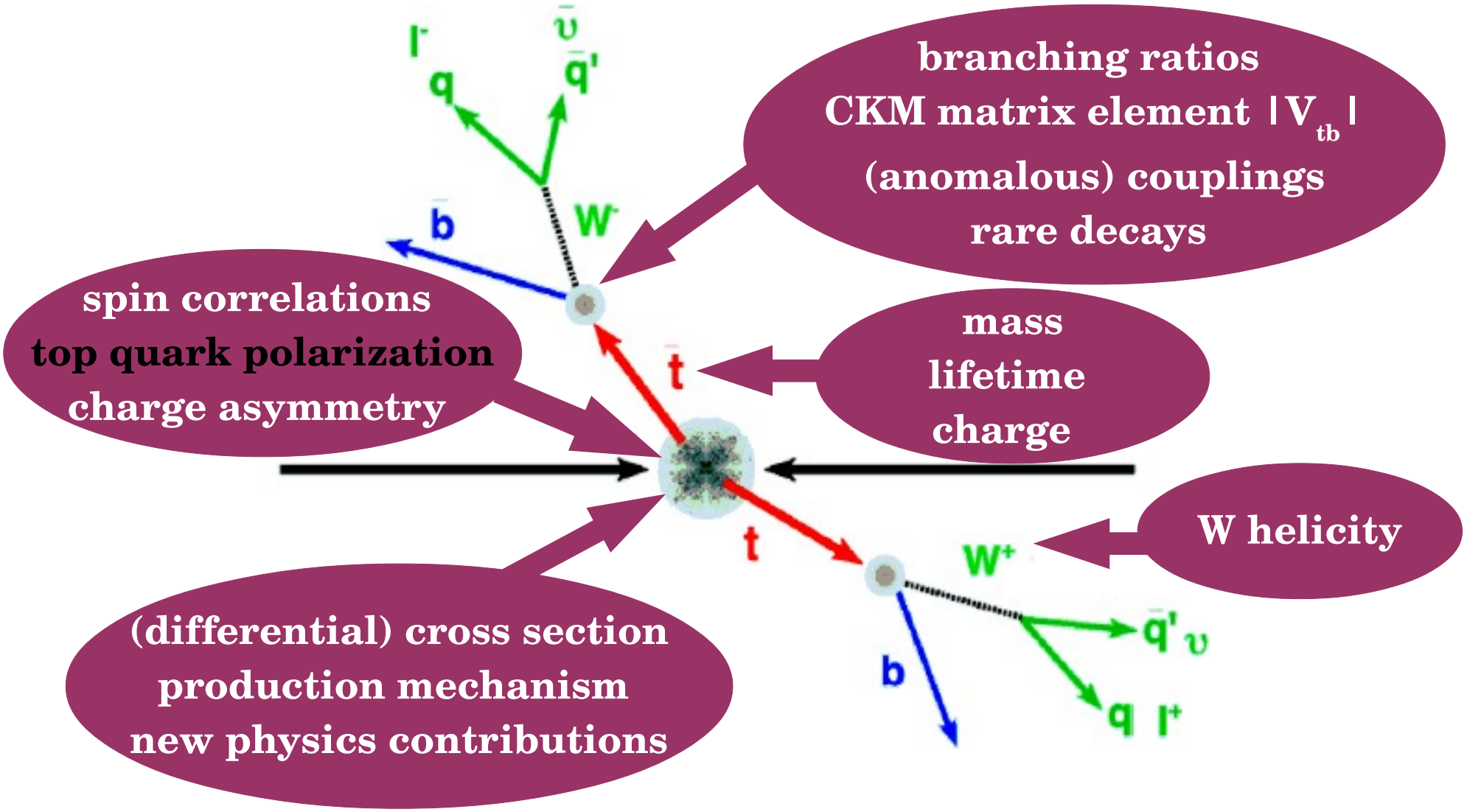
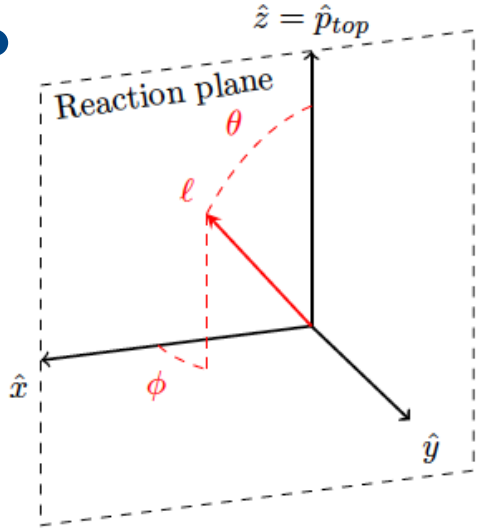


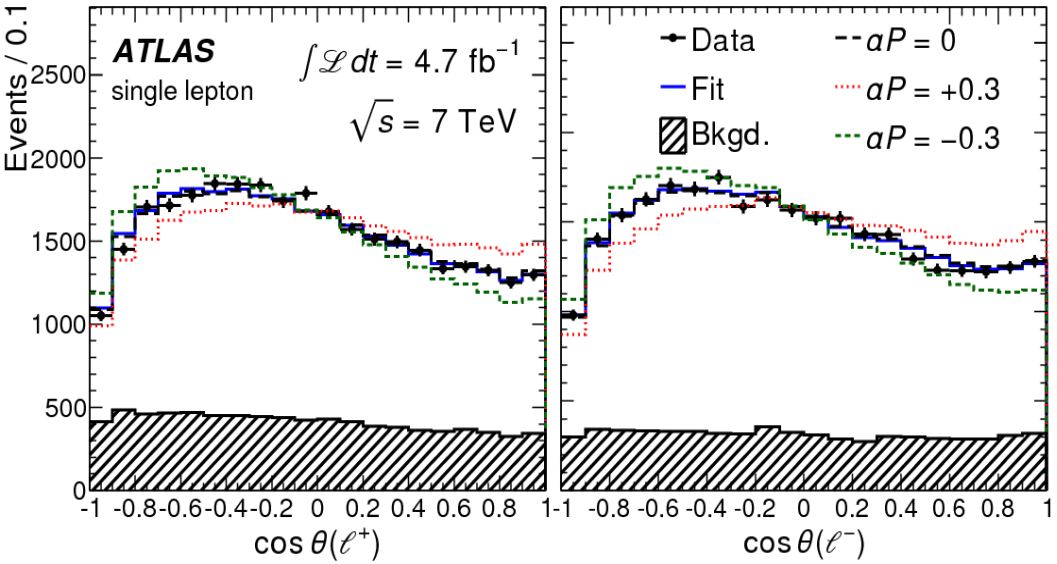
Top Quark Polarization

- $t\bar{t}$ pairs from strong production have **no** longitudinal **polarization**
- many **BSM** models trying to explain A_{FB} couple to **right-handed tops** only
  → additional terms with polarization p≠0

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 - C\cos\theta_1\cos\theta_2 + B_1\cos\theta_1 + B_2\cos\theta_2\right)$$
$$where\, C = A\,\alpha_1\alpha_2,\; B_i = \alpha_i P$$

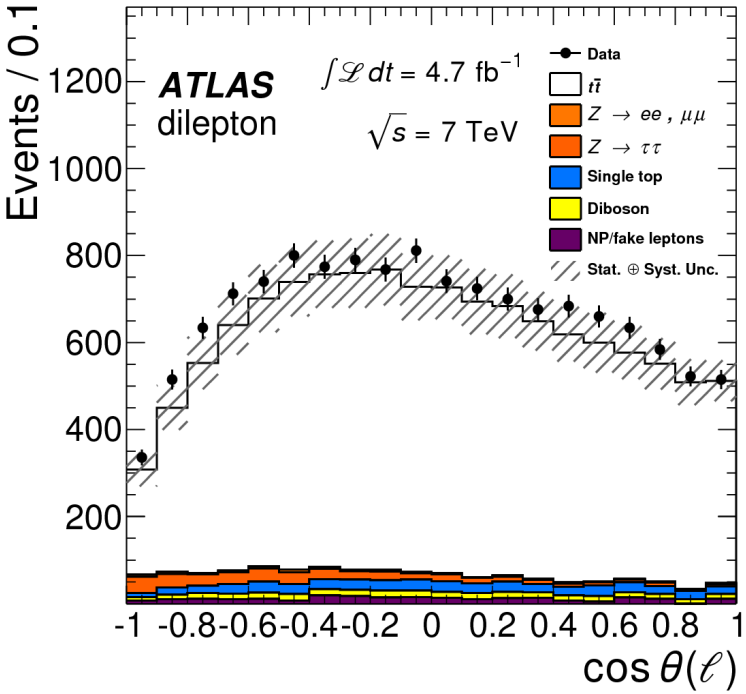


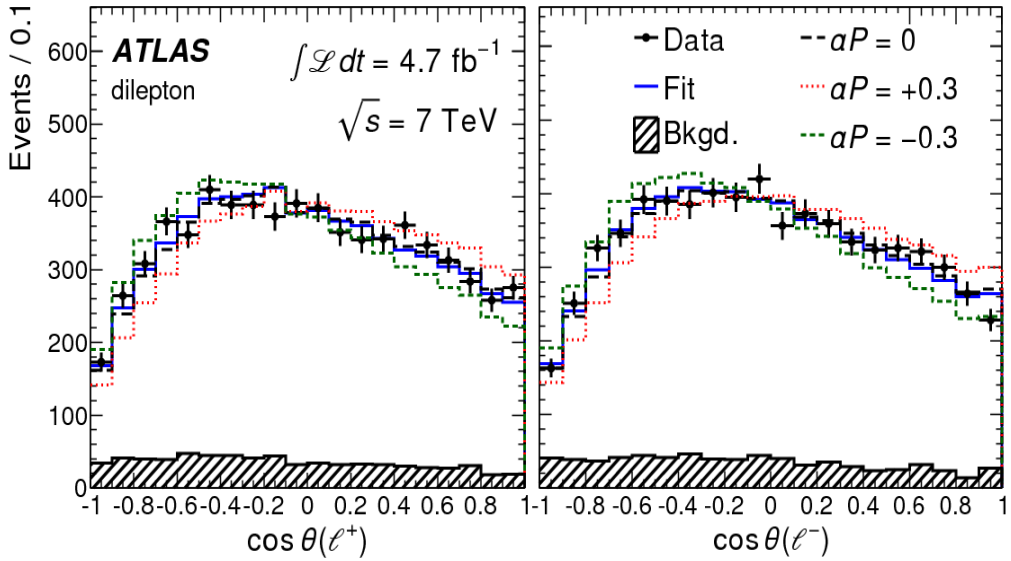
- polarization comparing templates with **pos./neg.** polarization to data:
  - **1+0.3 cos(θ_l)** and **1-0.3 cos(θ_l)**



First Measurement of Top Polarization

- measurement based on 4.7 fb^{-1} of 7 TeV single-lepton/dilepton events
- full event reconstruction to derive $\cos(\theta_l)$ based on kinematic fit
- leptons only to avoid complication of identifying down-type quark

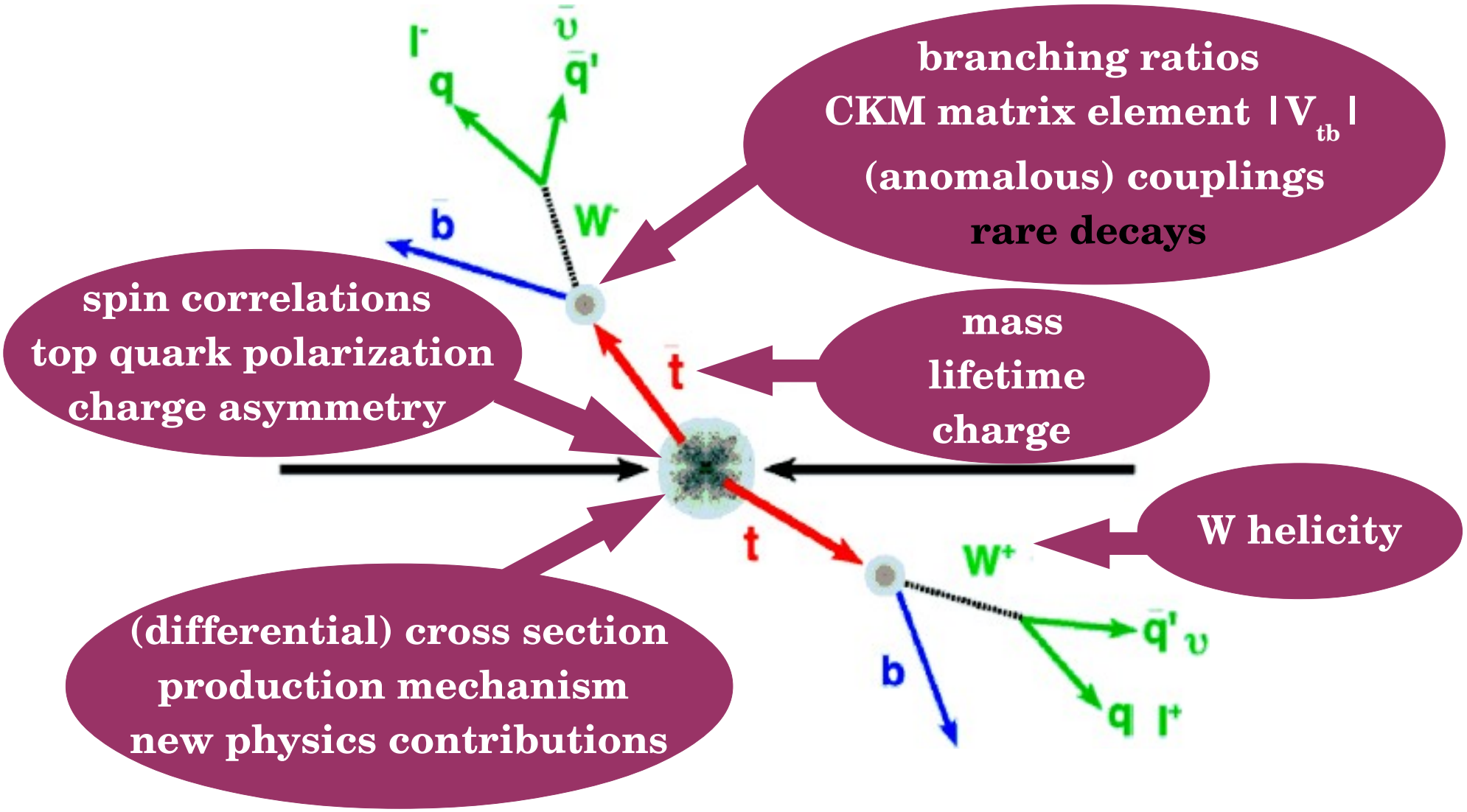




αP= -0.035 ± 0.014 (stat) ± 0.037 (syst)

- excellet agreement with SM
- largest systematic effect from jet energy scale (0.029) and top quark mass (0.012)
- PRL 111 (2013) 232002

Top Quark Physics – An Overview

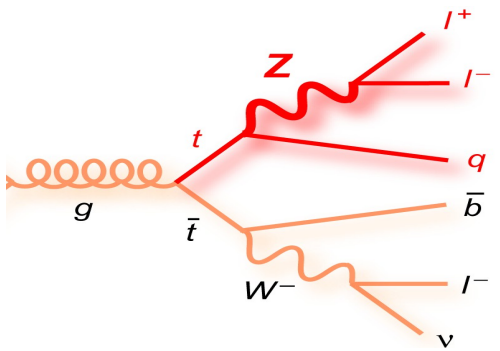


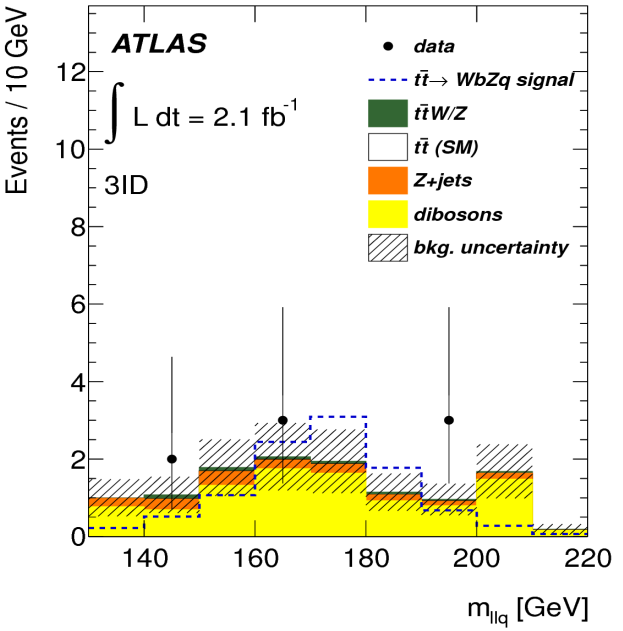
FCNC in $t\bar{t}$ Decays

- **FCNC in SM highly suppressed: O(10^{-14})**
  - **higher rate (up to 10^{-3}) in many BSM models**
- **t→Zq (q=u,c)**
  - **final state with 3 isolated, charged leptons**
  - **inclusion of high quality tracker leptons → acceptance increase by 22%**
  - **kinematic reconstruction requires matching to top/W/Z mass hypotheses**

    BR (t→Zq) < 0.73% @ 95% CL
  - **JHEP 1209 (2012) 139**
- **t→Hc**
  - **final states with hadronic and leptonic W**
  - **reconstruction of Higgs mass peak**

    BR (t→Hc) < 0.83% @ 95% CL
  - **ATLAS-CONF-2013-081**





Summary and Conclusion

- large variety of top quark properties measured at ATLAS
  - many new aspects explored
  - all results consistent with SM
  - most analyses limited by systematic uncertainties:
    - top quark modeling
    - jet energy measurements
- top quark physics is an excellent window to new physics (see talk of A. Boveia)
- more info and all details can be found here
- plenty of new results from 8 TeV run in preparation