Top quark properties at the LHC

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Introduction

Why studying top properties?

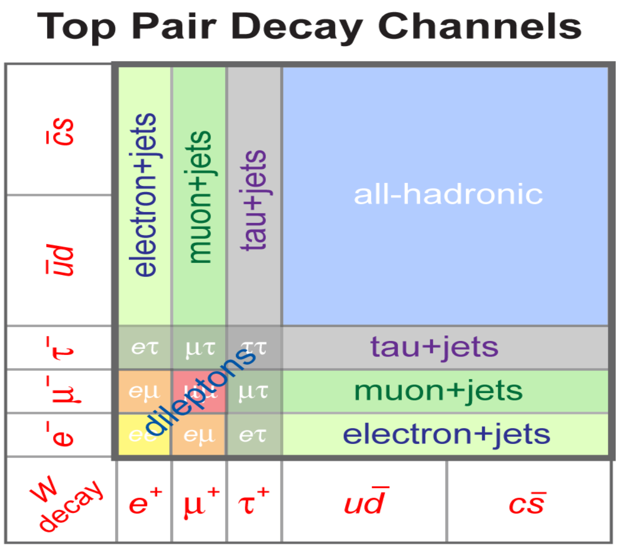
- Test Standard Model (SM) predictions
- Search for new Physics

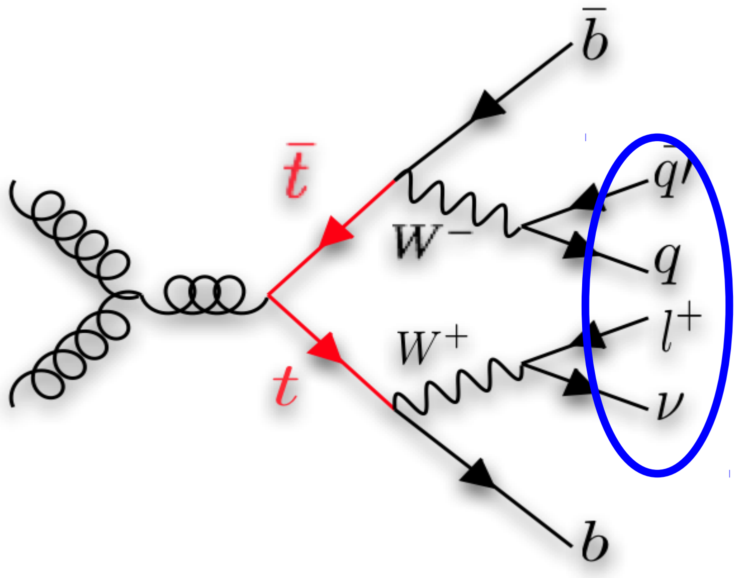
Special properties:

- Yukawa Coupling ~ 1
- Decay before hadronization
- Dominant decay in SM $t \rightarrow Wb$
- Heaviest SM particle m_{top} ~ 173 GeV

Top pair decay channels:

- Dilepton
- Lepton+jets
- All-hadronic





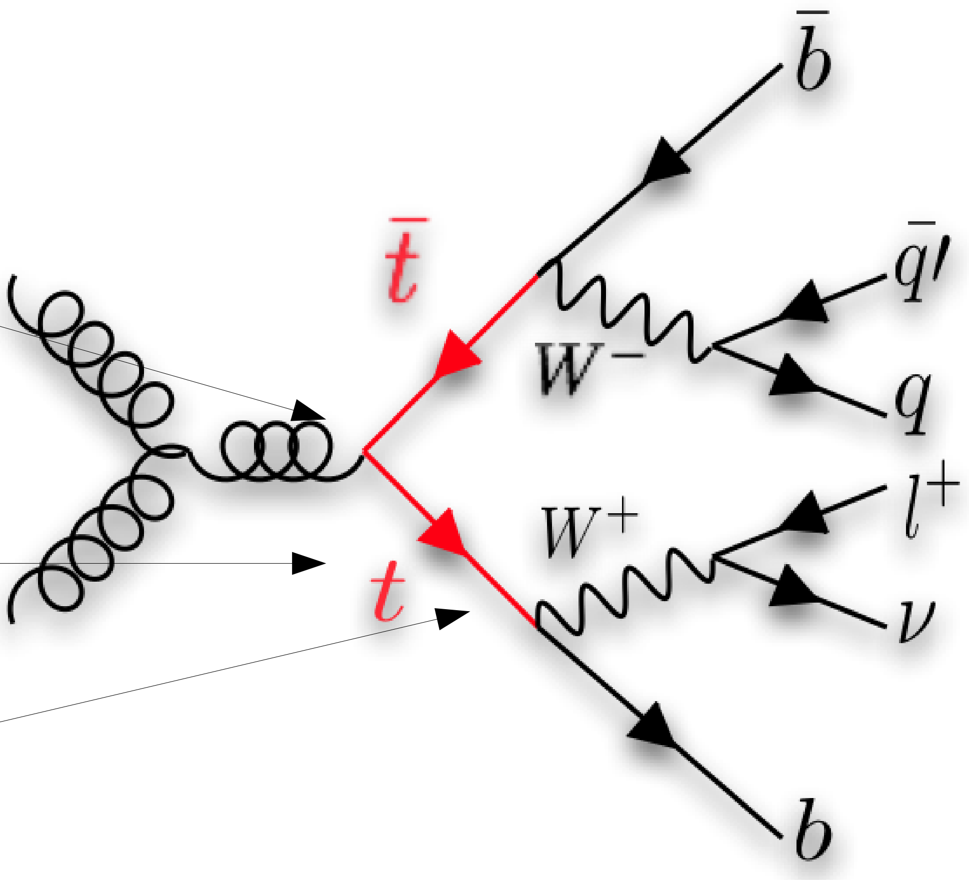
Outline

MEASUREMENTS OF TOP QUARK PROPERTIES

Top production:
- Cross section
- Spin correlation
- Resonances
- Top polarization
- Top charge asymmetry
- $t\bar{t}X$ (X=γ,Z,W,H)

Top properties:
- Top charge
- Top mass

Top decays:
- W polarization
- FCNC



**red – topics not included

Top mass results

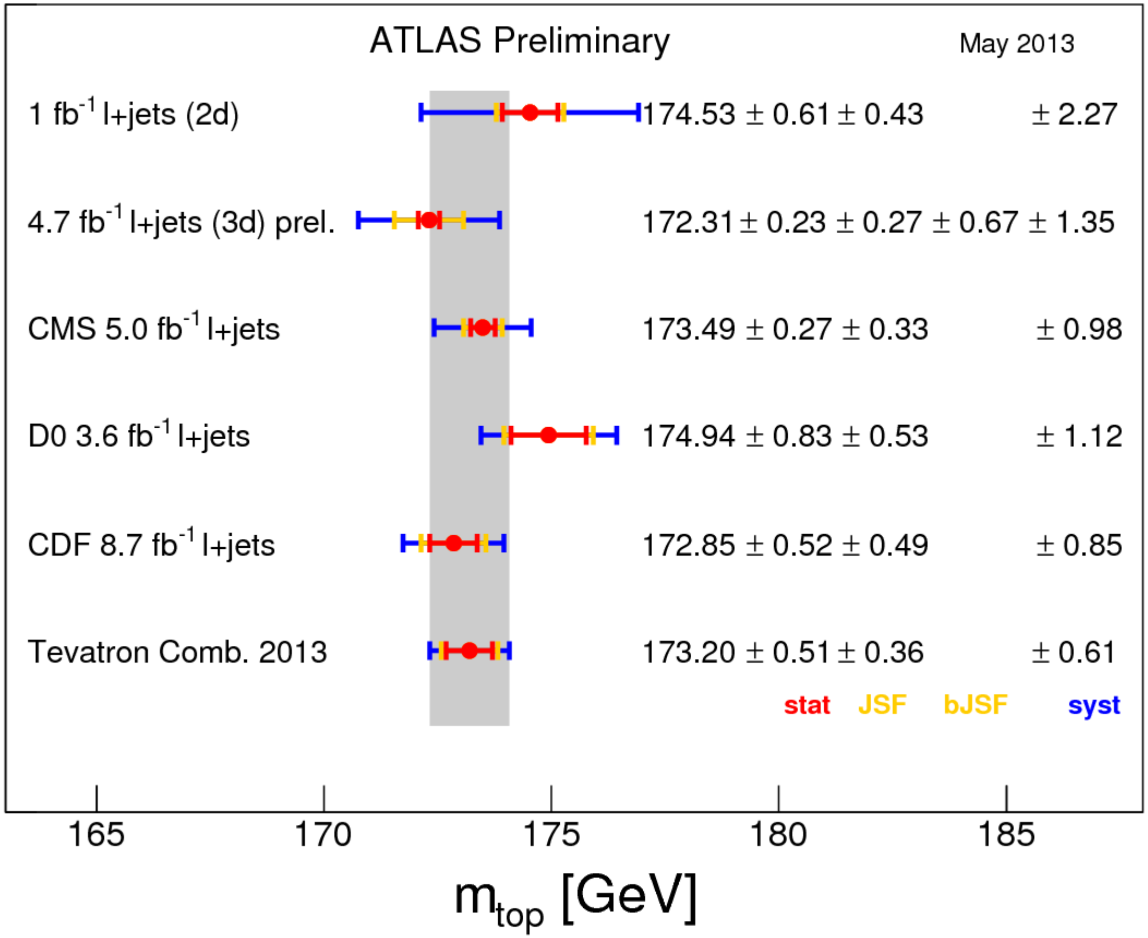
Lepton + jets

$\sqrt{s}=7\,TeV, \int Ldt=4.7\,fb^{-1}$

$\sqrt{s}=7\,TeV, \int Ldt=5.0\,fb^{-1}$

New result: ATLAS uses a **3D template** technique which determines the top quark mass together with a global jet energy scale factor (JSF),and a relative b-jet to light-jet energy scale factor (bJSF).

This measurement supersedes the previous ATLAS result - the total **systematic uncertainty has been reduced by about 40%**. The single largest systematic uncertainty - the residual relative b-jet to light jet energy scale, has been significantly reduced.



$$m_{top} = 172.31 \pm 0.75\,(\text{stat} + \text{JSF} + \text{bJSF}) \pm 1.35\,(\text{syst})\ \text{GeV}$$

ATLAS-CONF-2013-046

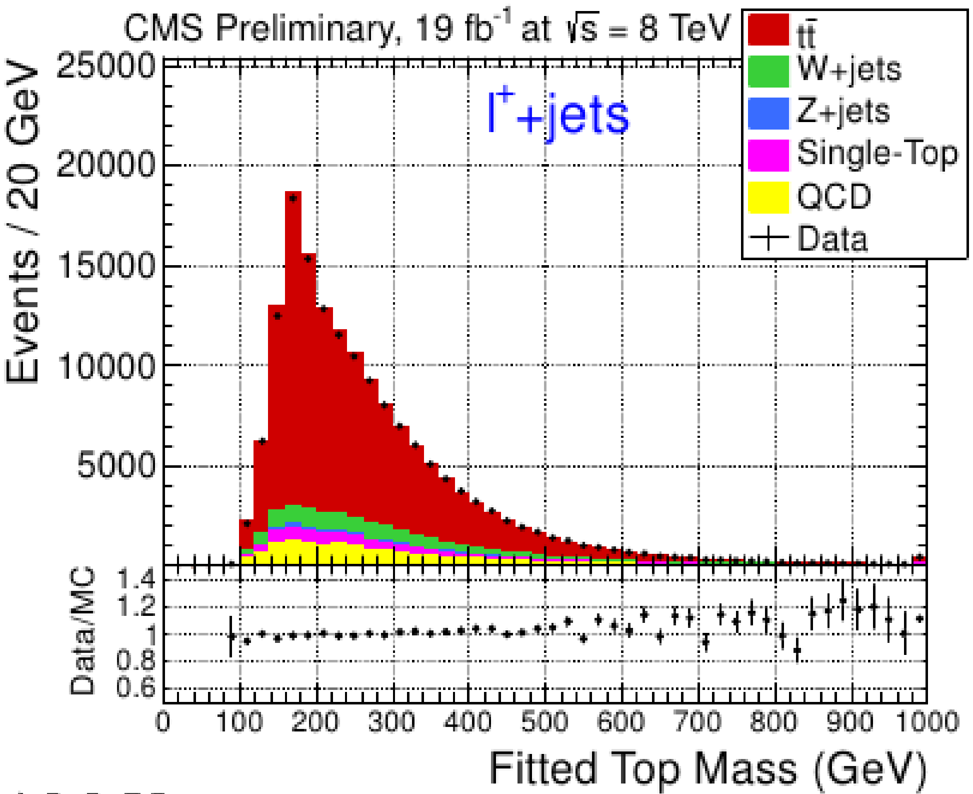
CMS-PAS-TOP-11-015

Top - anti-top mass difference

$\sqrt{s}=8\,TeV\,,\int Ldt=18.9\,fb^{-1}$

Lepton + jets

- The data are split into ℓ^- and ℓ^+ samples
- Kinematic fit - reconstruct the mass of the hadronically decaying top quark by varying the momenta of the two jets that are assigned to the W boson, using m_W = 80.4 GeV as a constraint and keeping the E/p of each jet fixed
- Ideogram method - an event-by-event likelihood is used to measure the mass of the top quark m_t or anti-top quark $m_{\bar{t}}$



$$\Delta m_t \equiv m_t - m_{\bar{t}}.$$

$$\Delta m_t = -272 \pm 196\ (\text{stat.}) \pm 122\ (\text{syst.})\,\text{MeV}.$$

The measured value is in agreement with CPT invariance, which requires no mass difference between the top and antitop quarks.

CMS-PAS-TOP-12-031

Top charge

$\sqrt{s}=7\,TeV, \int Ldt=0.7\,fb^{-1}$

$\sqrt{s}=7\,TeV, \int Ldt=4.6\,fb^{-1}$

Two scenarios:

- Standard model: $t^{2/3} \rightarrow b^{-1/3} + W^{+1}$
- Exotic Model: $\hat{t}^{-4/3} \rightarrow b^{-1/3} + W^{-1}$

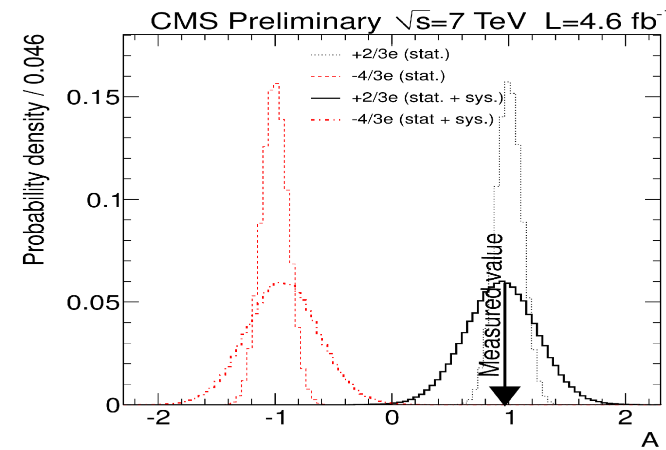
Methods:

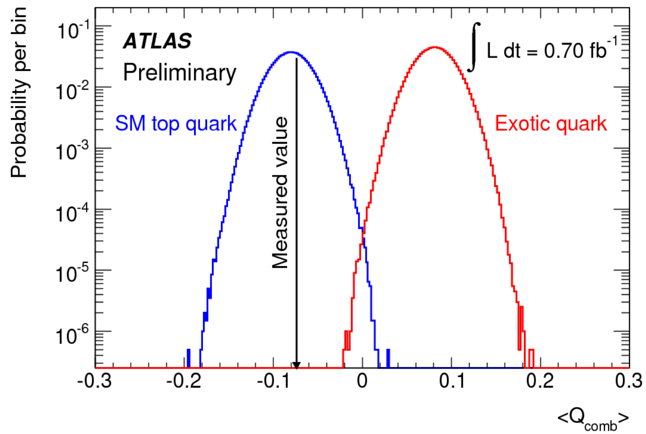
- Charge of W boson → from its leptonic decay.
- Charge of b-jet:
  - The effective b-jet charge → found through b-jet tracks charges:

$$Q_{bjet} = \frac{\sum_i q_i |\vec{j} \cdot \vec{p}_i|^{\kappa}}{\sum_i |\vec{j} \cdot \vec{p}_i|^{\kappa}} \qquad Q_{comb} = Q_{bjet} \cdot Q_l$$

<0: SM
>0: XM

  - Soft lepton technique (Semi-leptonic b-decay)
- A correct pairing of lepton and b-jet





Exotic model excluded at > 5σ

ATLAS-CONF-2011-141

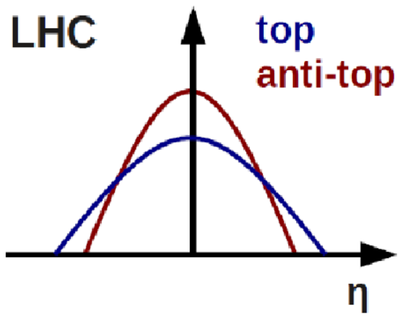
CMS-PAS-TOP-11-031

Top charge asymmetry (1/2)

Lepton + jets

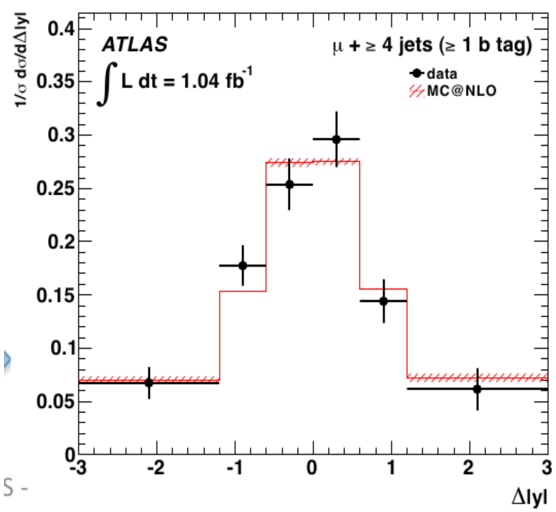
$\sqrt{s}=7\,TeV,\int L\,dt=1.04\,fb^{-1}$

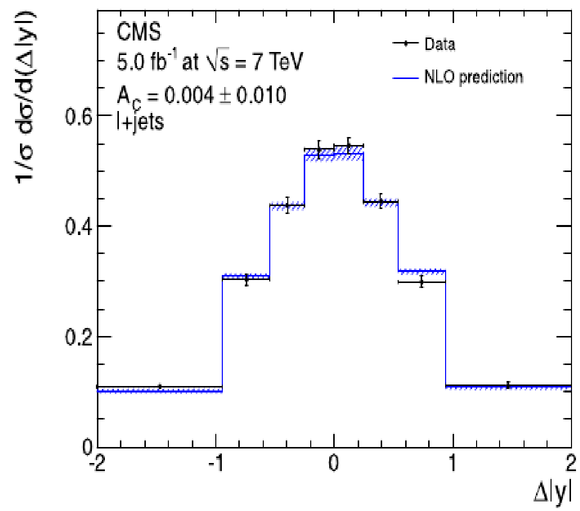
$\sqrt{s}=7\,TeV,\int L\,dt=5.0\,fb^{-1}$

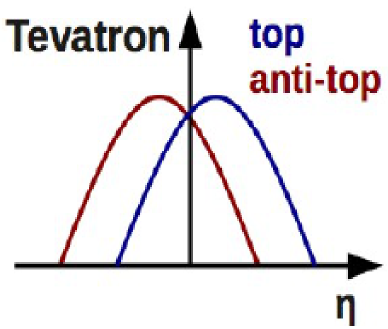


Charge asymmetry:

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







Tevatron: forward-backward asymmetry deviates more than 2σ from SM prediction

SM: 0.006 ± 0.002 (MC@NLO)

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

ATLAS: $A_C^{t\bar{t}} = -0.019 \pm 0.028(\text{stat.}) \pm 0.024(\text{syst.})$

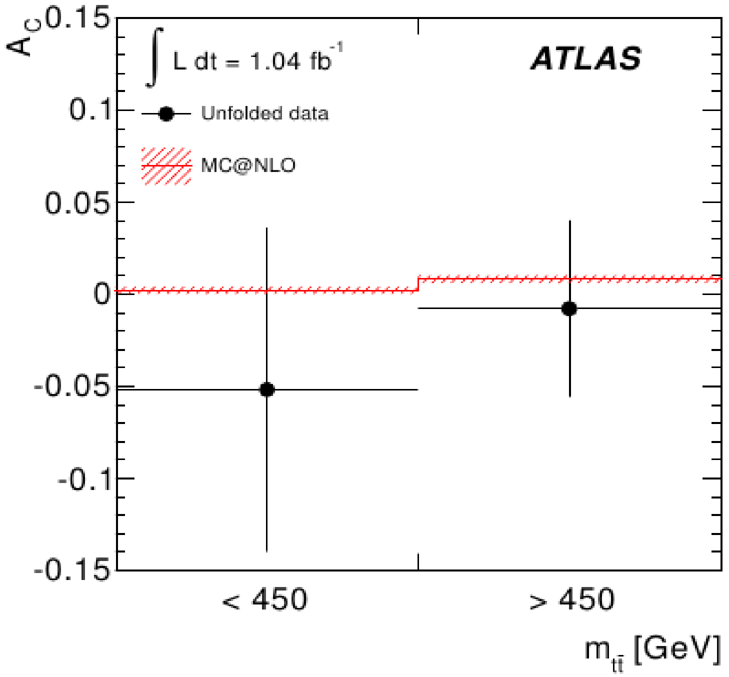
CMS: $A_C = 0.004 \pm 0.010\ (\text{stat.}) \pm 0.011\ (\text{syst.})$

Both experiments results consistent with SM predictions.

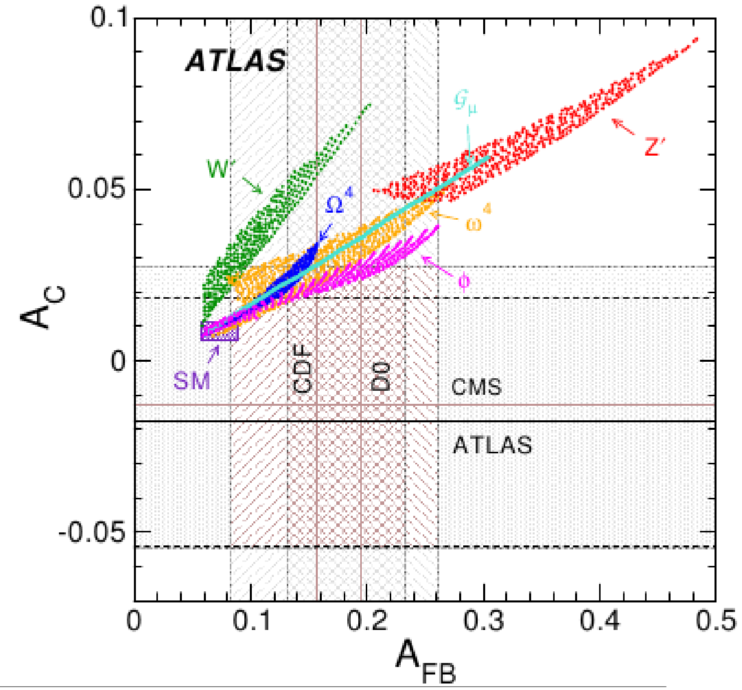
Eur. Phys. J. C (2012) 72:2039

CMS-PAS-TOP-11-030

Top charge asymmetry (2/2)



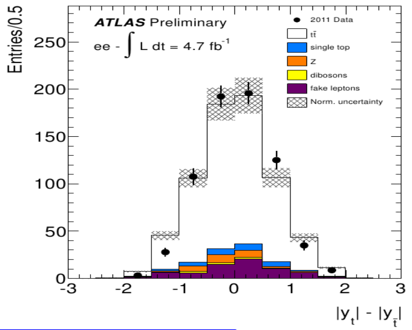
Consistent with SM, Z' is disfavored.



Dilepton

$$\sqrt{s}=7\,TeV\,,\int Ldt=4.7\,fb^{-1}$$

ATLAS: $A_C^{t\bar{t}} = 0.057 \pm 0.024\,(\text{stat.}) \pm 0.015\,(\text{syst.})$



Lepton+jet and dilepton combined:

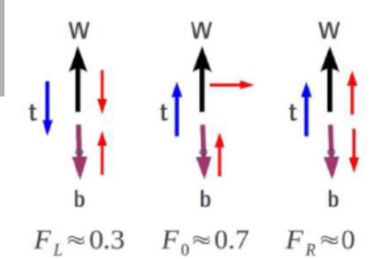
$$A_C^{t\bar{t}} = 0.029 \pm 0.018\,(\text{stat.}) \pm 0.014\,(\text{syst.})$$

ATLAS-CONF-2012-057

W polarization

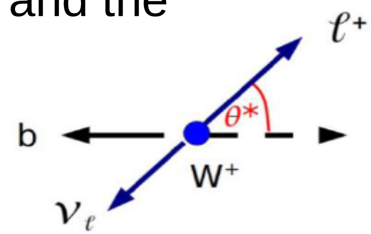
$\sqrt{s} = 7\ TeV,\ \int Ldt = 35\ pb^{-1} - 2.2\ fb^{-1}$

SM prediction - 3 helicity states:



Observable: cos (θ*) - θ* angle between the direction of the charged lepton and the reversed direction of the top quark. The differential decay rate:

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



Helicity fractions measured by:

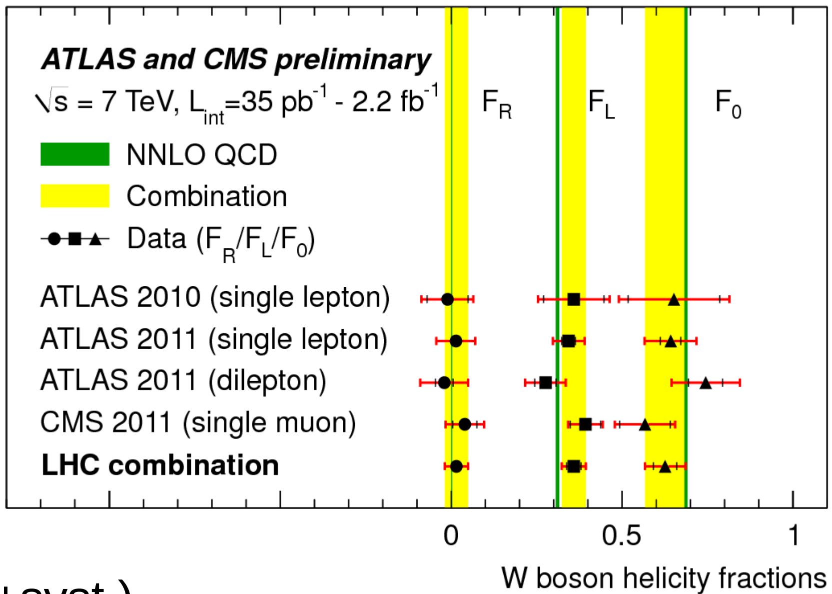
- helicity fractions (template fit)
- angular assymmetries (count events)

ATLAS+CMS combination is performed using the Best Linear Unbiased Estimator (BLUE) method:

$$F_0 = 0.626 \pm 0.034\ (\text{stat.}) \pm 0.048\ (\text{syst.})$$

$$F_L = 0.359 \pm 0.021\ (\text{stat.}) \pm 0.028\ (\text{syst.})$$

$F_R = 1 - F_0 - F_L$ => $F_R = 0.015 \pm 0.034$ (stat.+syst.)



Agreement with predictions NNLO QCD.

ATLAS-CONF-2013-033

CMS-PAS-TOP-12-025

Anomalous Wtb

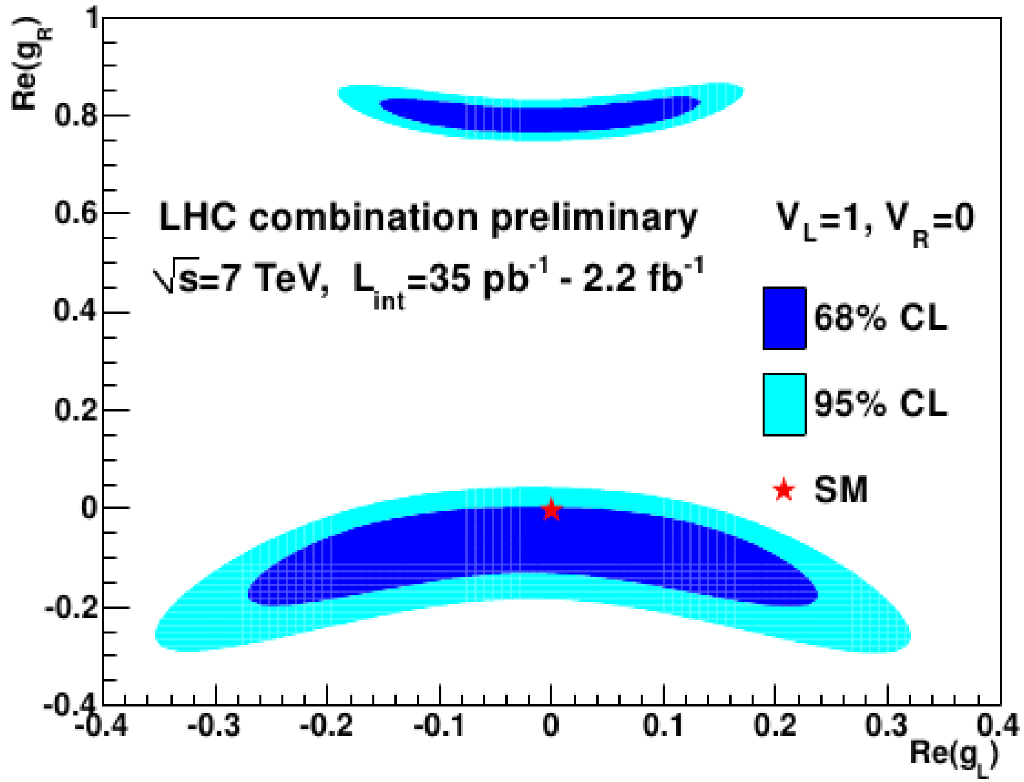
Exclusion limits on anomalous Wtb couplings are derived from W polarization results.

The polarization of the W bosons in top quark decays is sensitive to the W tb vertex. New physics parametrised as effective Lagrangian:

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

V_R, g_L, g_R: dimensionless constants (related to couplings and scale of new physics)

Assumming $V_R=0$, $V_L=1$
→ derived limits on g_L, g_R



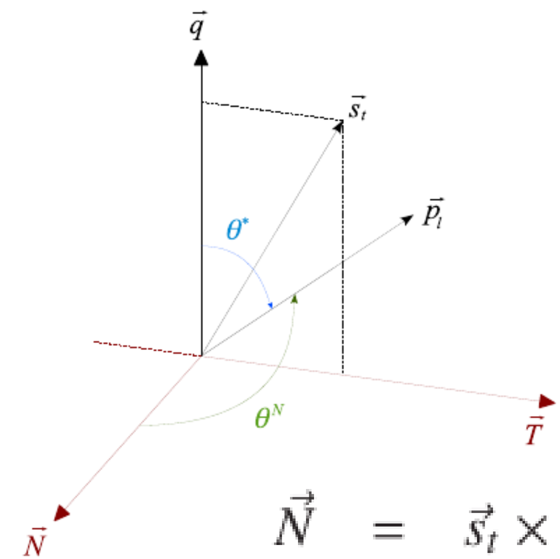
If assumming $V_R=g_L=0$, $V_L=1$:

$$\mathrm{Re}(g_R) = -0.10 \pm 0.06\,(\mathrm{stat.})\,^{+0.07}_{-0.08}\,(\mathrm{syst.})$$

CP violation in single top

$\sqrt{s} = 7\,TeV, \int L dt = 4.7\,fb^{-1}$

Helicity fractions derived with **θ* are not sensitive to all anomalous couplings**, especially to their complex phases that would imply that the top quark decay has a CP-violating component.



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

Angular asymmetries are defined as

$$A_z \equiv \frac{N_{\text{evt}}(\cos\theta > z) - N_{\text{evt}}(\cos\theta < z)}{N_{\text{evt}}(\cos\theta > z) + N_{\text{evt}}(\cos\theta < z)}$$

If z = 0 the asymmetry is called the forward-backward (A_{FB})

t-channel - top quarks are predicted to be highly polarised - predicted degree of polarisation of P ~ 0.9

Assumming $V_R = g_L = 0$, $V_L = 1$: $A_{\text{FB}}^{\text{N}} = 0.64\, P\, \mathbb{I}(g_{\text{R}})$

Forward-backward asymmetry measured is:

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

Measurement is consistent with CP invariance in top quark decays ($A_{FB}^{N} = 0$).

Assuming P = 0.9, set a first experimental limit of [-0.20, 0.30] on I(g_R) at 95% CL. - consistent with SM LO predictions and including one loop electroweak corrections.

ATLAS-CONF-2013-032

FCNC Top pair

$\sqrt{s}=8\,TeV, \int Ldt = 19.5\,fb^{-1}$

Topology: $t\bar{t} \rightarrow Wb + Zq \rightarrow \ell\nu b + \ell\ell q$

- highly suppressed in SM
- SM predicted branching fraction of $\mathcal{B}(t \rightarrow Zq)$ is O(10^{-14})

Selection:

- 3 leptons (2 from Z)
- use b-tagging
- large missing energy

Selection	data-driven estimation	SM MC prediction
$t \rightarrow Zq$ ($\mathcal{B} = 0.1\%$)	—	$6.36 \pm 0.08 \pm 1.27$
WZ	$1.54 \pm 0.12 \pm 0.74$	$0.87 \pm 0.10 \pm 0.62$
ZZ		$0.07 \pm 0.01 \pm 0.05$
Drell-Yan		$0.00 \pm 0.03 \pm 0.02$
$t\bar{t}$	$1.60 \pm 4.96 \pm 0.44$	$0.74 \pm 0.70 \pm 0.52$
$Zt\bar{t}$		$1.09 \pm 0.13 \pm 0.77$
$Wt\bar{t}$		$0.09 \pm 0.05 \pm 0.06$
tbZ		$0.33 \pm 0.02 \pm 0.23$
Total background	$3.14 \pm 4.97 \pm 1.17$	$3.19 \pm 0.72 \pm 2.26$
Observed events	1	—
Expected limit	$\mathcal{B}(t \rightarrow Zq) < 0.10\%$	—
Observed limit	$\mathcal{B}(t \rightarrow Zq) < 0.07\%$	

Major systematics:

- the parton distribution function
- the generator parameters of the signal MC simulation

CMS: $\mathcal{B}(t \rightarrow Zq)$ **< 0.07%** at 95% C.L.

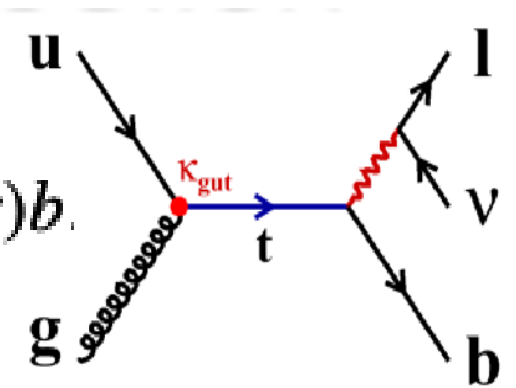
ATLAS-CONF-2011-154

CMS-PAS-TOP-11-028

FCNC **Single top**

$$\sqrt{s}=7\,TeV\,,\int Ldt=2.05\,fb^{-1}$$

$$qg \to t \to W(\to \ell\nu)b.$$
$$q=\{u,c\}$$

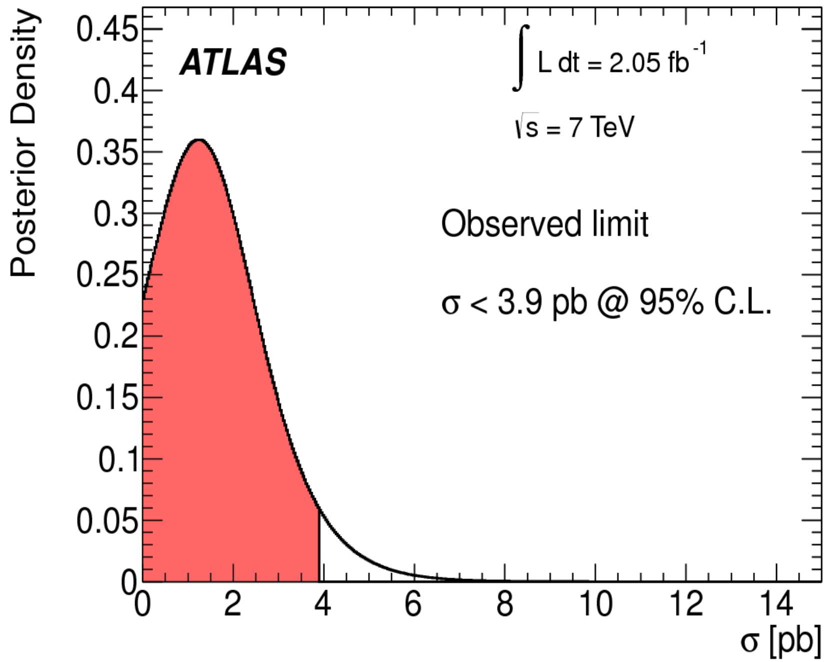


Selection:

- 1 lepton
- use b-tagging
- large missing energy

Major systematics:

- jet energy scale
- ISR/FSR
- b-tagging efficiencies and mis-tag rates.



Llimits set on the coupling constant:

$$\mathcal{B}(t \to ug) < 5.7 \cdot 10^{-5} \text{ assuming } \mathcal{B}(t \to cg) = 0$$
$$\mathcal{B}(t \to cg) < 2.7 \cdot 10^{-4} \text{ assuming } \mathcal{B}(t \to ug) = 0$$

$$\sigma_{qg\to t} \times \mathcal{B}(t \to Wb) < 3.9\text{ pb}$$

at 95% C.L.

Physics Letters B 712 (2012) 351-369

Top polarization

Lepton + jets

$\sqrt{s}=7\,TeV, \int Ldt=4.7\,fb^{-1}$

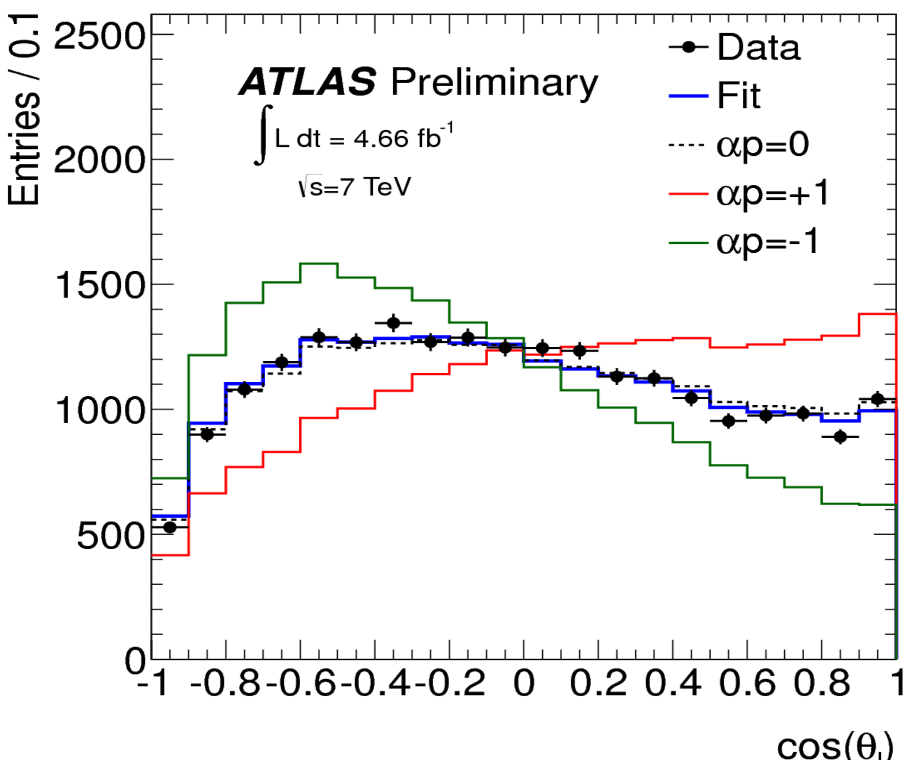
A template fit to the distribution of lepton polar angles θ in the parent top quark's rest frame is used to extract the fraction of positively polarised top quarks. Spin of the top quark is conserved -> extract it from the decay products of the W boson:

$$W(\cos\theta_i) \propto 1 + \alpha_i p \cos\theta_i,$$

where p is degree of polarisation, α_i is the spin analysing power (charged leptons = 1)

$$f = \frac{1}{2} + \frac{N(\cos\theta_l > 0) - N(\cos\theta_l < 0)}{N(\cos\theta_l > 0) + N(\cos\theta_l < 0)}$$

$$\alpha_\ell p = 2f - 1$$



Major systematics:

- jet energy scale
- the effect of the top quark mass on the signal modelling

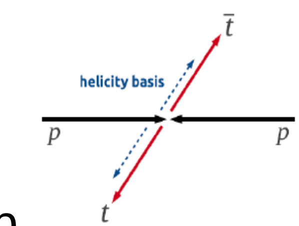
The result, fraction of positively polarised top quarks:

ATLAS-CONF-2012-133

$$f = 0.470 \pm 0.009(\mathrm{stat})^{+0.023}_{-0.032}(\mathrm{syst})$$

$$f_{SM} = 0.5$$

$t\bar{t}$ spin correlation



$\sqrt{s}=7\ TeV, \int Ldt = 2.1\ fb^{-1}$

Lifetime ~5x10^{-25}s, spin don't have time to flip
Correlation between top and anti-top spin is defined by coefficient:

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

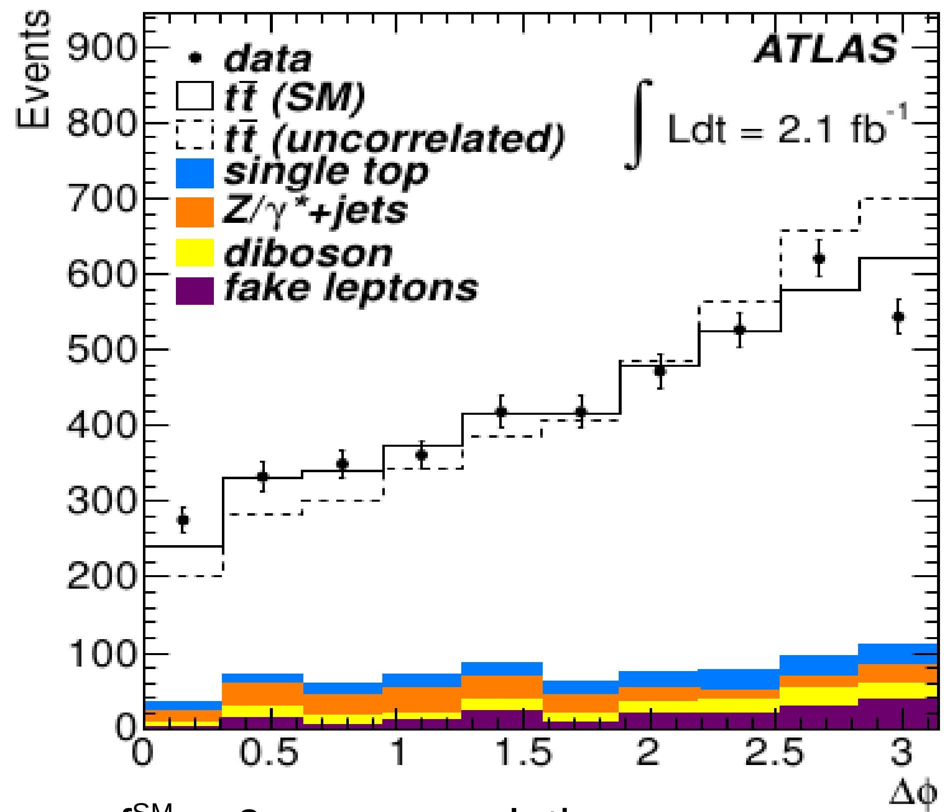
Measure in dilepton topology:

- two opositively-charged leptons
- fraction of SM-like events (f^{SM})
- Binned likelihood fit to two templates

Basis helicity: $A^{measured} = A^{SM} . f^{SM}, A^{SM} = 0.31$

$$f^{SM} = 1.30 \pm 0.14\ (\mathrm{stat})\ ^{+0.27}_{-0.22}\ (\mathrm{syst})$$

$$A_{\mathrm{helicity}} = 0.40 \pm 0.04\ (\mathrm{stat})\ ^{+0.08}_{-0.07}\ (\mathrm{syst})$$



f^{SM} = 0 -> no correlation
f^{SM} = 1 -> correlation -> SM prediction

Phys. Rev. Lett. 108 (2012) 212001

First observation of spin correlation: 5.1 σ

Summary

- Since the beginning of LHC era many precision measurements of top quark properties have been done, most of them constrain the phase-space of new physics.
- More results are coming with data collected in 2012 at 8 TeV, as well as the results at 7 TeV.

Top quark results can be found at

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

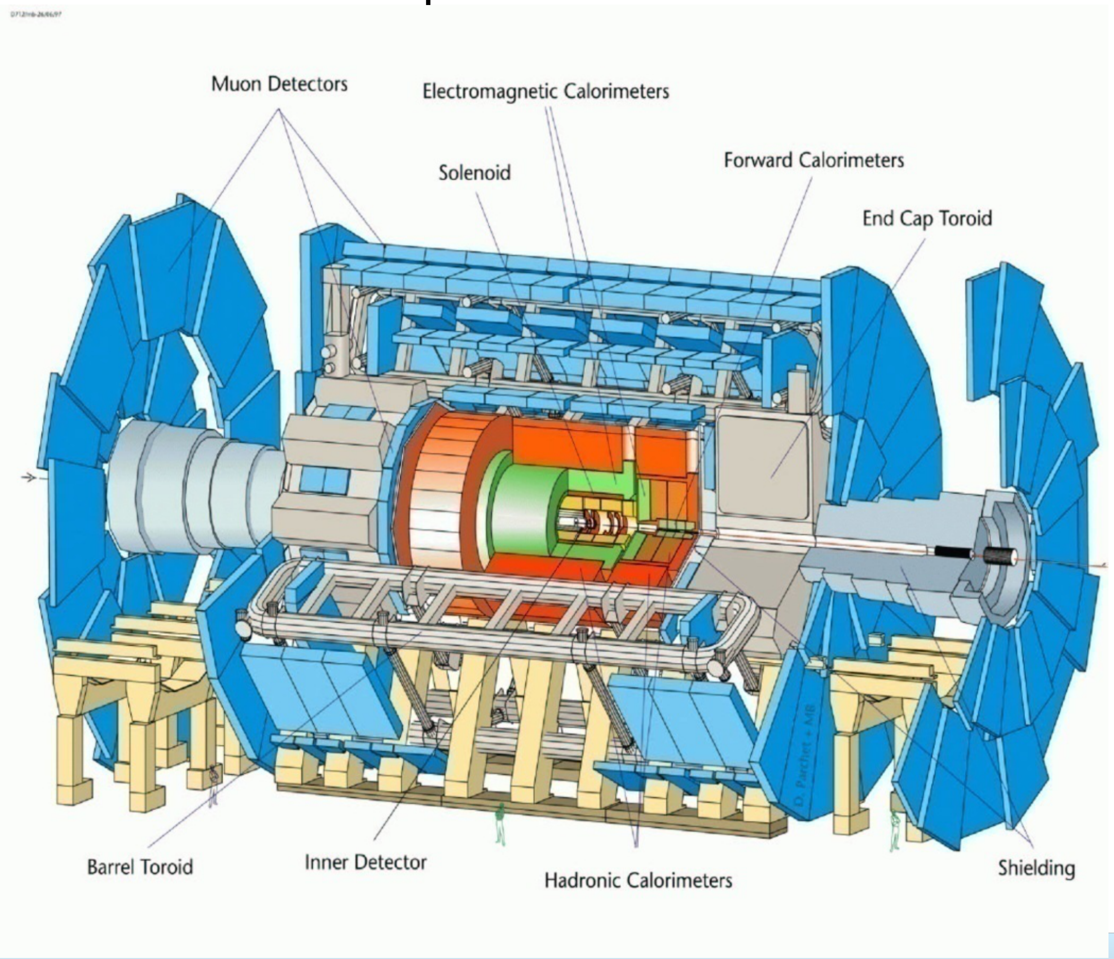
Thank you!

Backup slides

ATLAS

ATLAS is one of two general-purpose detectors at the LHC.
A wide range of physics to be studied:

- precision test of Standard model, including search for the Higgs boson
- look for a new physics as e.g. SUSY effects, extra dimensions, particles that could make up dark matter etc.



ATLAS detector:

- **Size:** 46 m long, 25 m high and 25 m wide.
- **Inner Detector:**
  $$\sigma/p_T \approx 0.05\% \times p_T(GeV) \oplus 0.1\%$$
  Tracking range $|\eta| < 2.5$
- **EM Calorimetry:**
  $$\sigma/E \approx 10\%/\sqrt{E(GeV)} \oplus 1\%$$
  Fine granularity up to $|\eta| < 2.5$
- **Hadronic Calorimetry:**
  $$\sigma/E \approx 50\%/\sqrt{E(GeV)} \oplus 3\%$$
  Range: $|\eta| < 4.9$
- **Muon System:**
  $$\sigma/p_T \approx 2-7\%, \quad \text{range: } |\eta| < 2.7$$