The top quark and the search for new physics at the LHC

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Outline

- Introduction
  - The top quark in the Standard Model of particle physics (and beyond)
  - The ATLAS detector
- Measurement of the top quark properties (using $t\bar{t}$ events)
  - Precision measurements
  - New physics in top production or decay?
- Searches for top-like BSM signatures

All results available in:

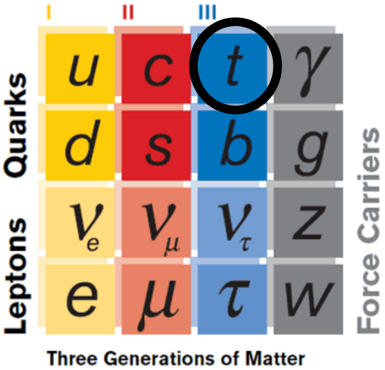
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

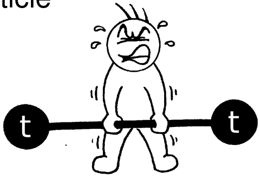
The top quark



- Top quark completes the 3 family structure of the SM
  - top is the weak-isospin partner of the *b*-quark
  - spin = $1/2$
  - charge = $+2/3\ |e|$

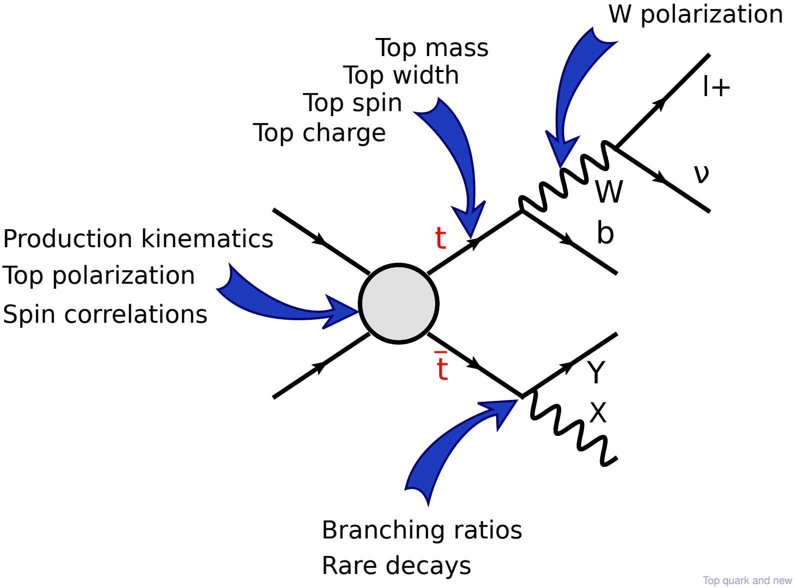
The top quark

- Top is the heaviest known fundamental particle
  $\lambda_t = \sqrt{2} m_t / v \sim 1$
  ☞ special role in EWSB?



- Top quark is short lived
  ☞ decays before hadronization
  - $\Lambda_{\mathrm{QCD}}^{-1} \sim (100\ \mathrm{MeV})^{-1} \sim 10^{-23}$s
  - $\Gamma_t^{NLO} = 1.42$ GeV
    $\tau_t \sim 10^{-25}$ s $\ll 10^{-23}$ s
- Top decays (almost exclusively) through $t \to bW$
  $BR(t \to sW) \leq 0.18\%$, $BR(t \to dW) \leq 0.02\%$
- The measurement of the top quark properties provides a powerful test of the SM

The top quark as a probe of the SM...

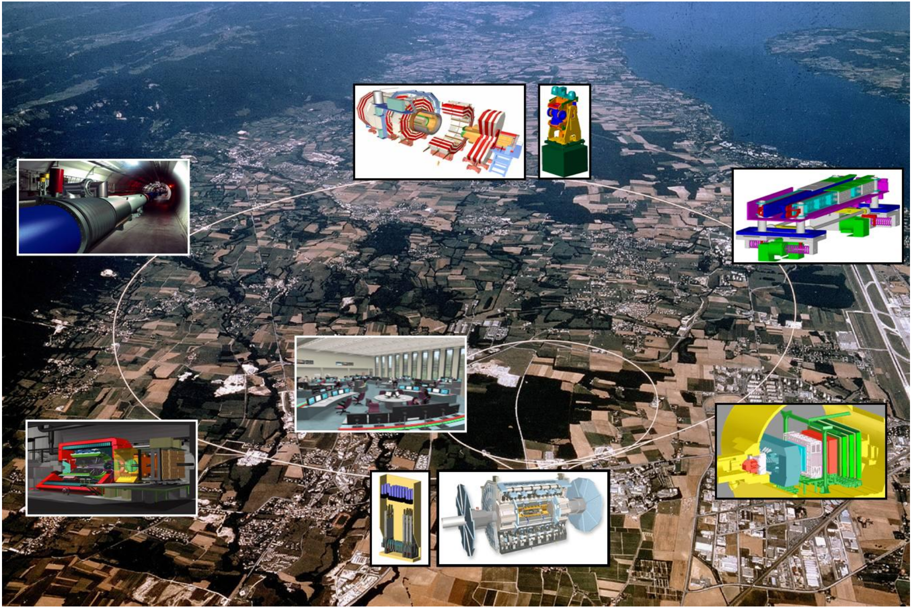


...but also as a window to new physics

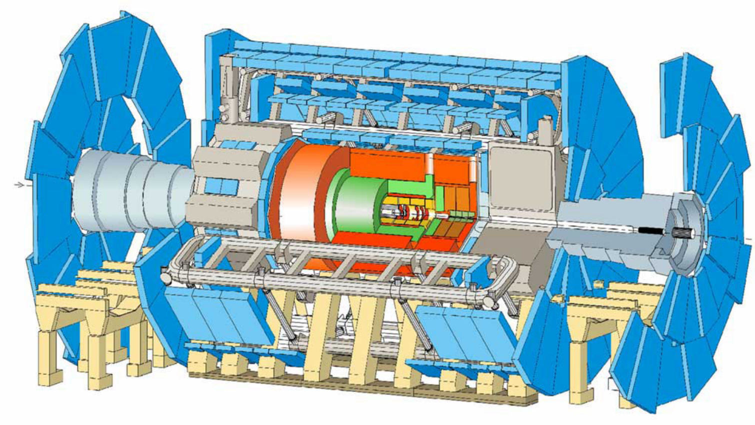
☞ Beyond-SM physics often has consequences in the top sector:

- $t\bar{t}$ and single top production can be affected by BSM models
- Wtb vertex: can have a BSM structure
- rare top decays: BSM models can increase the BR of t-quark decays via FCNC
- Exotic Higgs Bosons: large coupling to the top
- Incorporate Gravity using Extra Dimensions: many models predict new states with strong coupling to the top
- New heavy quarks: often decay to t-quarks or look like a heavy t
- ...

The Large Hadron Collider (LHC)

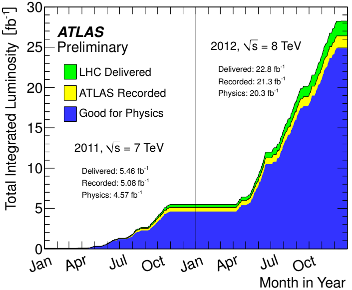


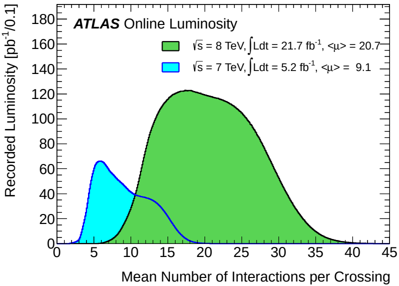
The ATLAS detector



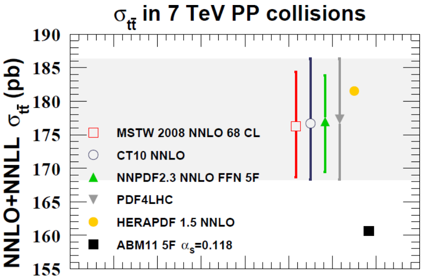
- length: $\sim$ 46 m
- diameter: $\sim$ 24 m
- weight: $\sim$ 7000 tons
- 10^8 electronic channels
- $\sim$ 3000 km of cables

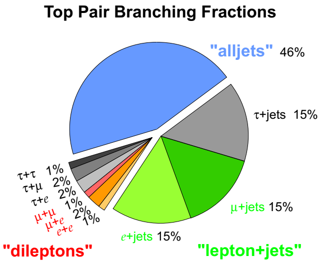
2011/2012 data ($\sqrt{s} = 7/8$ TeV)



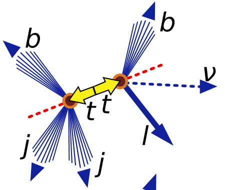


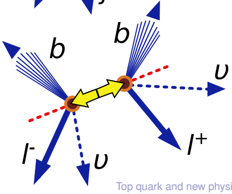
$t\bar{t}$ production at the LHC



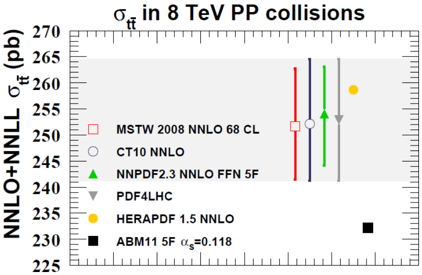


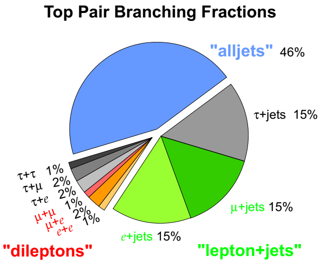
- $\sigma(t\bar{t})$ calculated at NNLO+NNLL
  [PRL 110(2013)252004]
- lepton+jets topology:
  $BR(t\bar{t} \to bq\bar{q}'\bar{b}\ell\nu;\ \ell = e^{\pm}, \mu^{\pm}, \tau^{\pm}) \sim 44\%$
- dileptonic topology:
  $BR(t\bar{t} \to b\bar{b}\ell\nu\ell\nu;\ \ell = e^{\pm}, \mu^{\pm}, \tau^{\pm}) \sim 10\%$





$t\bar{t}$ production at the LHC





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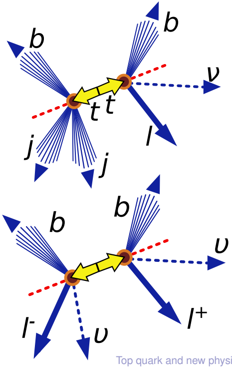


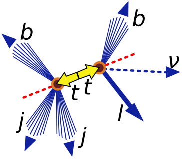
Standard $t\bar{t}$ selection

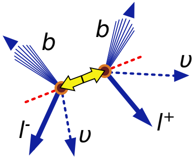
single lepton channel

- 1 isolated lepton (e or μ)
- missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$)
- 4 or more jets (anti-k_T, $\Delta R = 0.4$)
- at least 1 b-tagged jet

dilepton channel

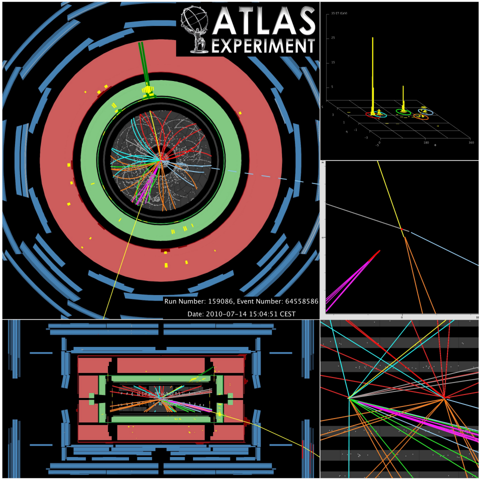
- 2 isolated leptons (ee, $\mu\mu$ or $e\mu$)
- ee, $\mu\mu$: $m_{\ell\ell}$ outside m_Z window
- $e\mu$: large scalar sum of p_T of all hard objects in the event (H_T)
- $E_{\mathrm{T}}^{\mathrm{miss}}$
- 2 or more jets



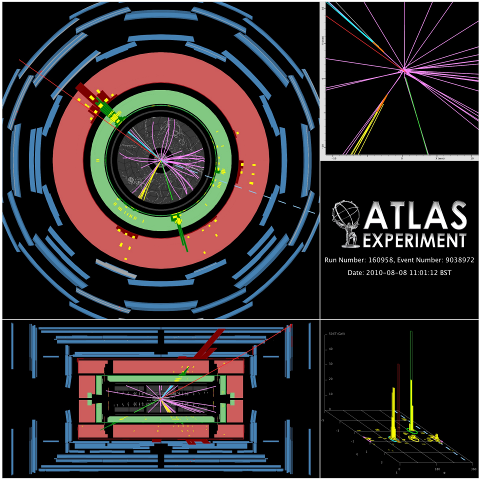


$t\bar{t}$ candidates recorded by ATLAS

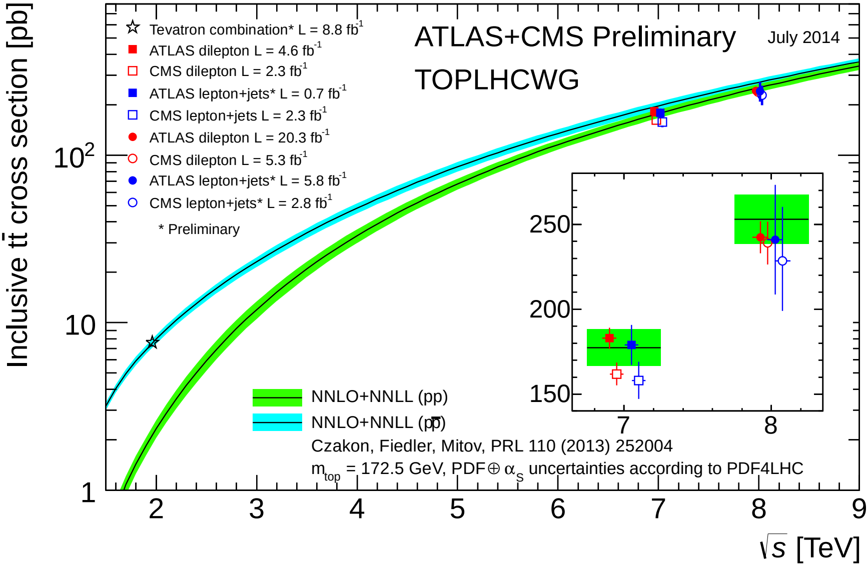
single lepton (e+jets w/btag)



dilepton ($e\mu$+jets w/2 btag)

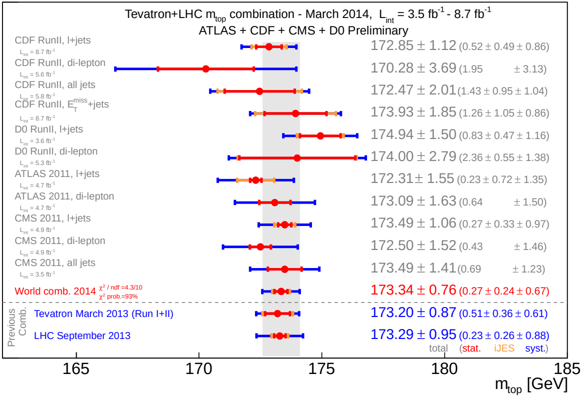


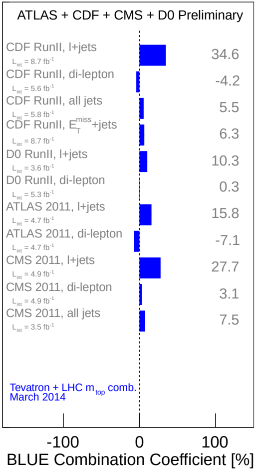
$t\bar{t}$ production cross-section



Top mass: LHC/Tevatron combination

- Combination done with BLUE ($\chi^2/\mathrm{ndf} = 4.3/10$)
- Stability checks performed

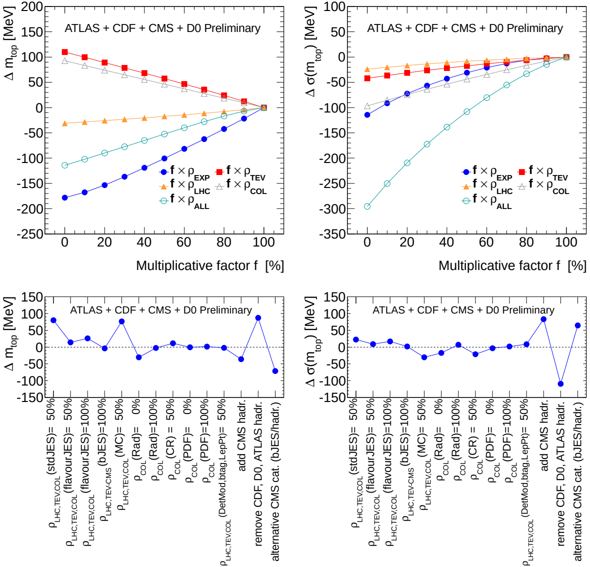




☞ Ongoing efforts to harmonise the treatment of the systematic uncertainties

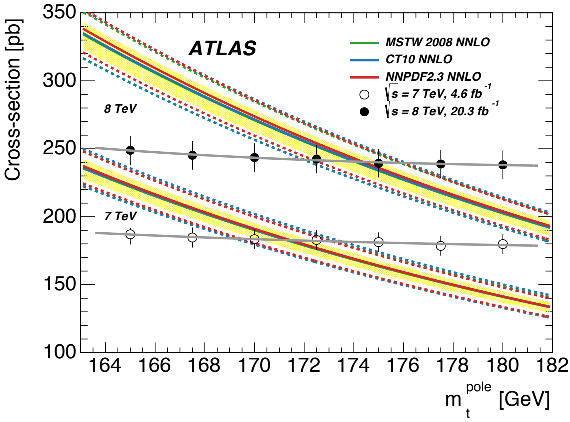
Top mass: LHC/Tevatron combination

[ATLAS-CONF-2014-008 / CDF note 11071 / CMS PAS TOP-13-014 / D0 note 6416]



Top mass from the $t\bar{t}$ production cross-section

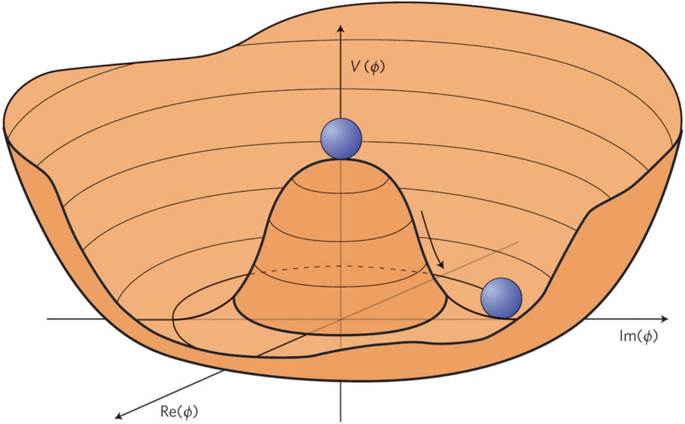
- The mass dependence of the QCD prediction for $\sigma_{t\bar{t}}$ can be used to determine the pole mass
- NNLO+NNLL prediction for $\sigma_{t\bar{t}}$ from `top++`



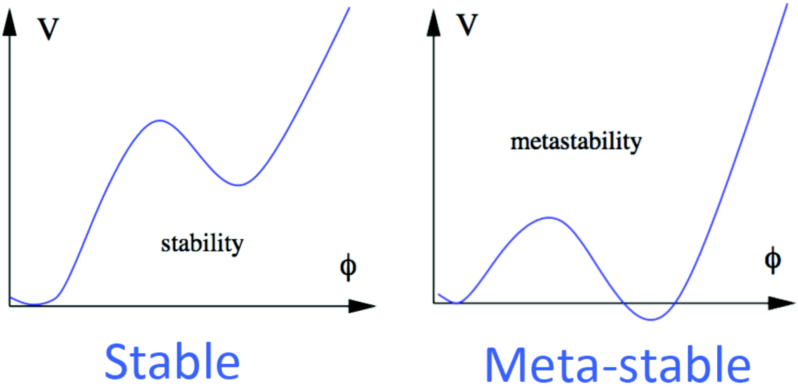
$$m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}\ \text{GeV}$$

The role of the top quark in the stability of the SM Brout-Englert-Higgs potential

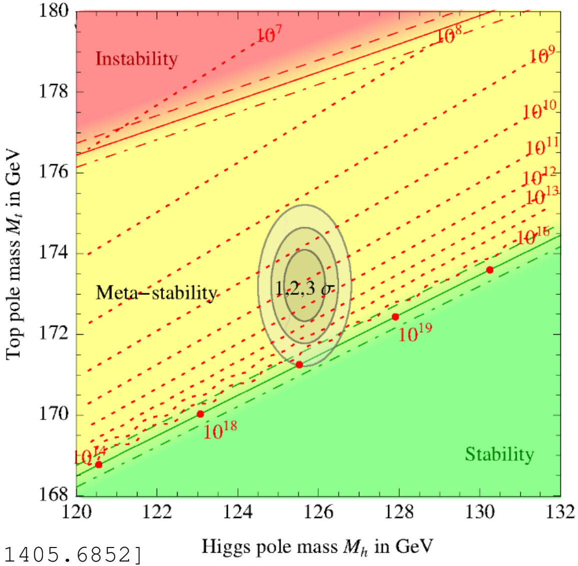
Brout-Englert-Higgs potential: $V(\phi) = -\frac{1}{2}\mu^2|\phi|^2 + \frac{\lambda^2}{4}|\phi|^4$



The role of the top quark in the stability of the SM Brout-Englert-Higgs potential



The role of the top quark in the stability of the SM Brout-Englert-Higgs potential



[arXiv:1405.6852]

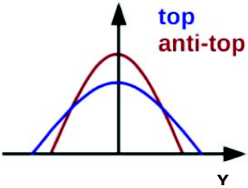
$t\bar{t}$ charge asymmetry

- In the SM at LO $t\bar{t}$ production is symmetric under charge conjugation

  ☞ at NLO (for $q\bar{q}$ and qg modes) there is a small preference to produce the t ($\bar{t}$) in the direction of the incoming q ($\bar{q}$)

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

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



- Lepton asymmetry can also be defined. In dilepton events:

  ☞ $A_C^{\ell\ell} = \frac{N(\Delta|\eta|>0)-N(\Delta|\eta|<0)}{N(\Delta|\eta|>0)+N(\Delta|\eta|<0)}$

  $\Delta|\eta| = |\eta_{\ell+}| - |\eta_{\ell-}|$

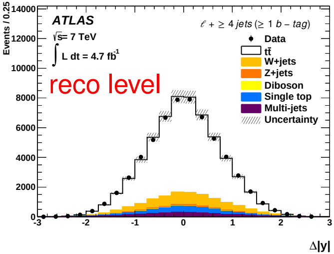
	$\sqrt{s}$	topology	reference
ATLAS	7 TeV	ℓ+jets	JHEP02(2014)107
CMS	7 TeV	ℓ+jets	PLB717(2012)129
ATLAS	7 TeV	dileptonic	ATLAS-CONF-2012-057
CMS	7 TeV	dileptonic	JHEP04(2014)191
CMS	8 TeV	ℓ+jets	CMS PAS TOP-12-033

$t\bar{t}$ charge asymmetry

- Full reconstruction of the $t\bar{t}$ system
- Unfolding of the $\Delta|y|$ distribution

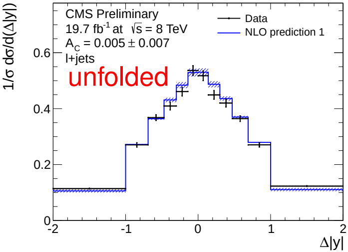
- ATLAS ($\sqrt{s} = 7$ TeV):

A_C	Data	Theory
Unfolded	0.006±0.010	0.0123±0.0005
Unfolded with $m_{t\bar{t}} > 600$ GeV	0.018±0.022	$0.0175^{+0.005}_{-0.004}$
Unfolded with $\beta_{z,t\bar{t}} > 0.6$	0.011±0.018	$0.0202^{+0.006}_{-0.007}$

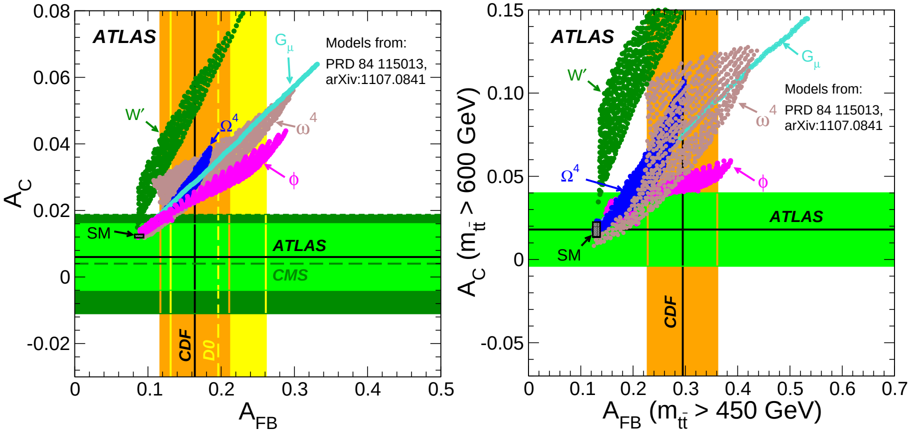


- CMS ($\sqrt{s} = 8$ TeV):

Asymmetry	A_C
Reconstructed	0.003 ± 0.002 (stat.)
BG-subtracted	0.002 ± 0.002 (stat.)
Unfolded	0.005 ± 0.007 (stat.) ± 0.006 (syst.)

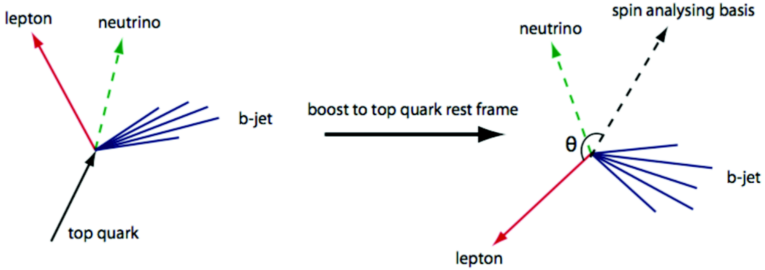


$t\bar{t}$ charge asymmetry and new physics



$t\bar{t}$ spin correlation

- t-quarks in $t\bar{t}$ events are produced (almost) unpolarized but their spins are correlated
- Different BSM scenarios predict different production and decay dynamics of the top quark, i.e. a different $t\bar{t}$ spin correlation

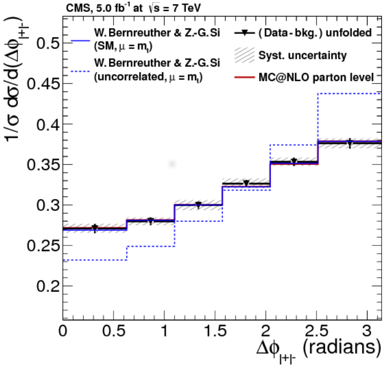


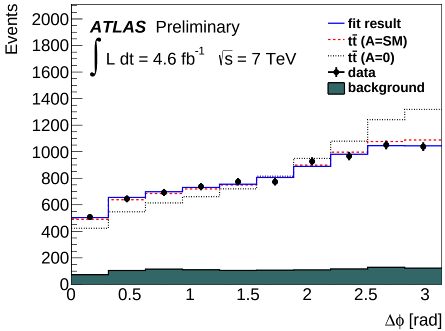
$$\boxed{\frac{1}{\sigma}\frac{d^2\sigma}{d[\cos(\theta_i)]d[\cos(\theta_j)]} = \frac{1}{4}[1 + P\alpha_i\cos(\theta_i) + P\alpha_j\cos(\theta_j) + A\alpha_i\alpha_j\cos(\theta_i)\cos(\theta_j)]}$$

	b	ℓ	d	u
α (NLO)	-0.39	0.998	0.93	-0.31

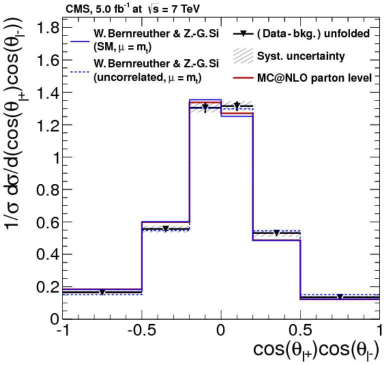
$$A = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}}$$

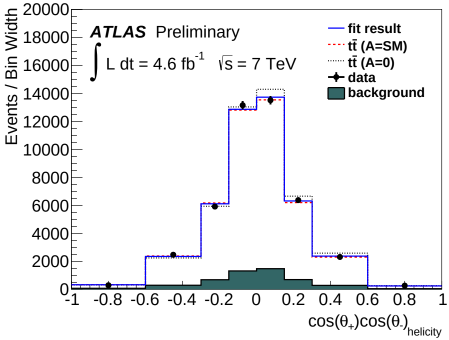
- ☞ ATLAS fits MC templates
- ☞ CMS unfolds the relevant distributions to parton level
  - $\Delta\phi$ between two spin analysers in lab frame is sensitive to spin correlations (*gg* production)





- ATLAS fits MC templates
- CMS unfolds the relevant distributions to parton level
  - $\cos(\theta_i)\cos(\theta_j)$ probes A directly: $\alpha_i\alpha_j A = -9\langle\cos(\theta_i)\cos(\theta_j)\rangle$



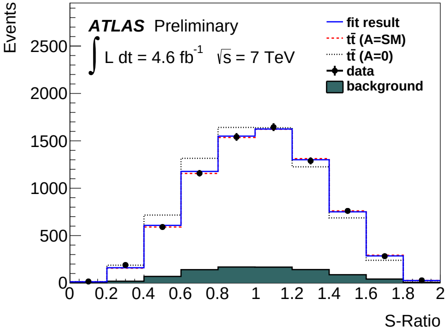


$t\bar{t}$ spin correlation

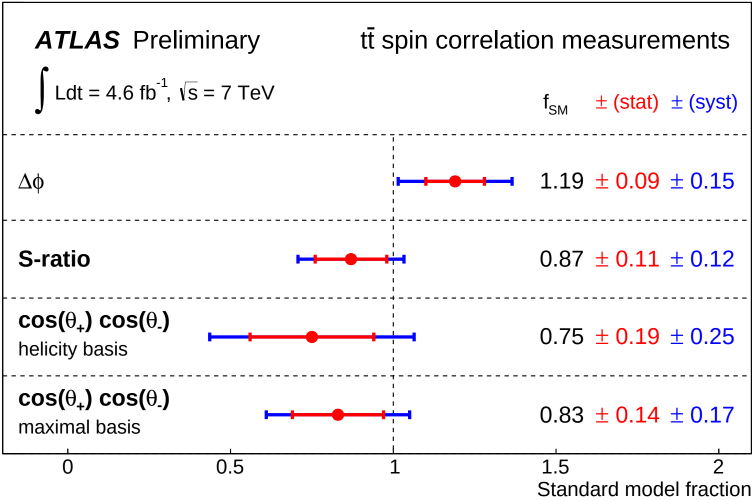
☞ ATLAS fits MC templates

- S-ratio of ME from the fusion of like-helicity gluons with and without spin correlation (at LO, built from measured 4-momenta)

$$S = \frac{(|\mathcal{M}|^2_{RR} + |\mathcal{M}|^2_{LL})_{\text{corr}}}{(|\mathcal{M}|^2_{RR} + |\mathcal{M}|^2_{LL})_{\text{uncorr}}} = \frac{m_t^2\{(t \cdot l^+)(t \cdot l^-) + (\bar{t} \cdot l^+)(\bar{t} \cdot l^-) - m_t^2(l^+ \cdot l^-)\}}{(t \cdot l^+)(\bar{t} \cdot l^-)(t \cdot \bar{t})}$$



$t\bar{t}$ spin correlation

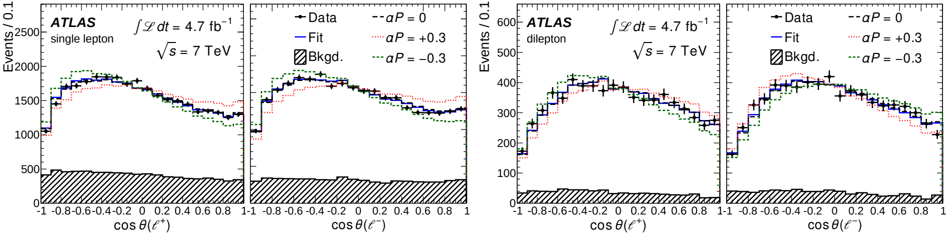


Top polarization in $t\bar{t}$ events

$$\frac{1}{\sigma}\frac{d^2\sigma}{d[\cos(\theta_i)]d[\cos(\theta_j)]} = \frac{1}{4}[1 + P\alpha_i\cos(\theta_i) + P\alpha_j\cos(\theta_j) + A\alpha_i\alpha_j\cos(\theta_i)\cos(\theta_j)]$$

$$P_{\mathrm{SM}} = 0.003 \pm 0.001$$

- Two hypotheses tested:
  - CP conserving (CPC): top and anti-top have the same P
  - CP violating (CPV): top and anti-top have opposite P



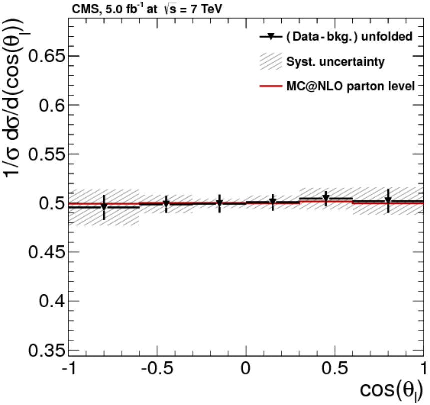
- $\alpha_\ell P_{\mathrm{CPC}} = -0.035 \pm 0.014\ (\mathrm{stat}) \pm 0.037\ (\mathrm{syst})$
  $\alpha_\ell P_{\mathrm{CPV}} = +0.020 \pm 0.016\ (\mathrm{stat})^{+0.013}_{-0.017}\ (\mathrm{syst})$

Top polarization in $t\bar{t}$ events

$$\frac{1}{\sigma}\frac{d^2\sigma}{d[\cos(\theta_i)]d[cos(\theta_j)]} = \frac{1}{4}[1 + P\alpha_i\cos(\theta_i) + P\alpha_j\cos(\theta_j) + A\alpha_i\alpha_j\cos(\theta_i)\cos(\theta_j)]$$

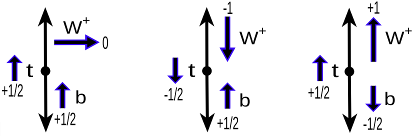
- Dilepton $t\bar{t}$ events
- $\cos\theta_\ell$ distribution unfolded to parton level
- $P = 2A_P$

  $$A_P = \frac{N(\cos\theta_\ell)>0 - N(\cos\theta_\ell)<0}{N(\cos\theta_\ell)>0 + N(\cos\theta_\ell)<0}$$

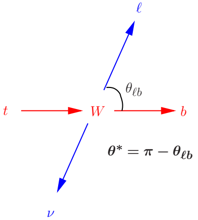


- $A_P = 0.005 \pm 0.013\,(\text{stat.}) \pm 0.020\,(\text{syst.}) \pm 0.008(p_T^t\ \text{reweig.})$

W polarization in $t \to bW$ decays



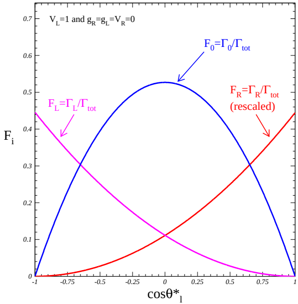
[PRD81 (2010) 111503]



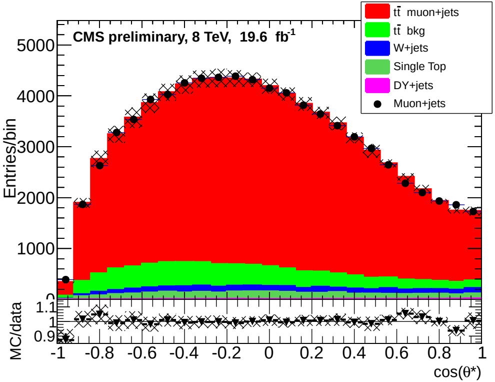
	longitudinal W	left-handed W	right-handed W
SM (NNLO):	$F_0 = 0.687$	$F_L = 0.311$	$F_R = 0.0017$

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

- ☞ fit of the $\cos\theta^*$ using templates
- ☞ BSM structure of the *Wtb* vertex changes W helicity fractions and angular asymmetries



W polarization in $t \to bW$ decays



	CMS	ATLAS]
F_0	$0.659 \pm 0.015(\text{stat}) \pm 0.023(\text{syst})$	$0.67 \pm 0.03(\text{stat}) \pm 0.06(\text{syst})$
F_L	$0.350 \pm 0.010(\text{stat}) \pm 0.024(\text{syst})$	$0.32 \pm 0.02(\text{stat}) \pm 0.03(\text{syst})$
F_R	$-0.009 \pm 0.006(\text{stat}) \pm 0.020(\text{syst})$	$0.01 \pm 0.01(\text{stat}) \pm 0.04(\text{syst})$

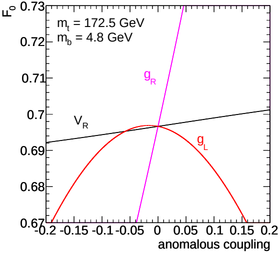
dominant uncertainties: $t\bar{t}$ modelling (ATLAS+CMS), JES and template stat. (ATLAS)

New physics in the *Wtb* vertex

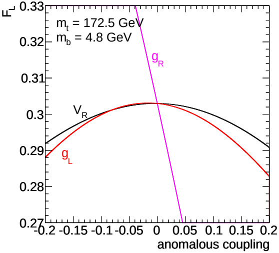
Effective *Wtb* vertex from dim-6 operators

$$
\begin{aligned}
\mathcal{L} \quad = \quad & -\frac{g}{\sqrt{2}} \bar{b}\, \gamma^{\mu} \left(V_L P_L + V_R P_R \right) t\, W_{\mu}^{-} \\
& -\frac{g}{\sqrt{2}} \bar{b}\, \frac{i\sigma^{\mu\nu} q_{\nu}}{M_W} \left(g_L P_L + g_R P_R \right) t\, W_{\mu}^{-} + \mathrm{h.c.}
\end{aligned}
$$

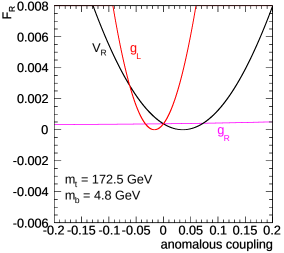
F_0



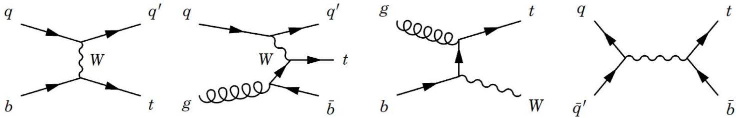
F_L



F_R



New physics in the *Wtb* vertex: single top production cross-section

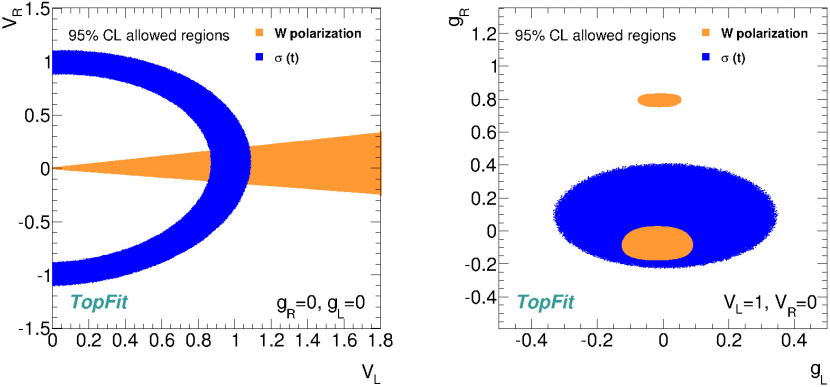


$$\sigma = \sigma_{\mathrm{SM}} \left(V_L^2 + \kappa^{V_R} V_R^2 + \kappa^{V_L V_R} V_L V_R + \kappa^{g_L} g_L^2 + \kappa^{g_R} g_R^2 + \kappa^{g_L g_R} g_L g_R + \dots \right)$$

- the κ factors determine the dependence on anomalous couplings
- the κ factors are, in general, different for t and $\bar{t}$ production
- the measurement of the single top production cross-section allows to obtain a measurement of V_L ($\equiv V_{tb}$) and bounds on anomalous couplings

New physics in the *Wtb* vertex

☞ 2 anomalous couplings $\neq$ SM at the time



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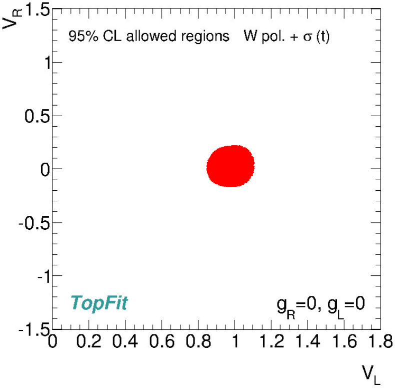
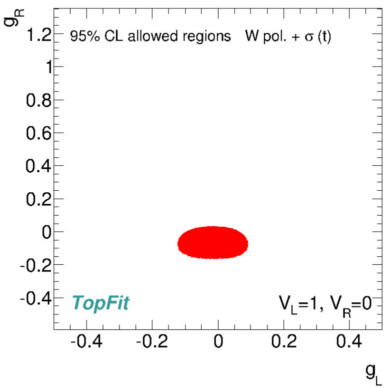
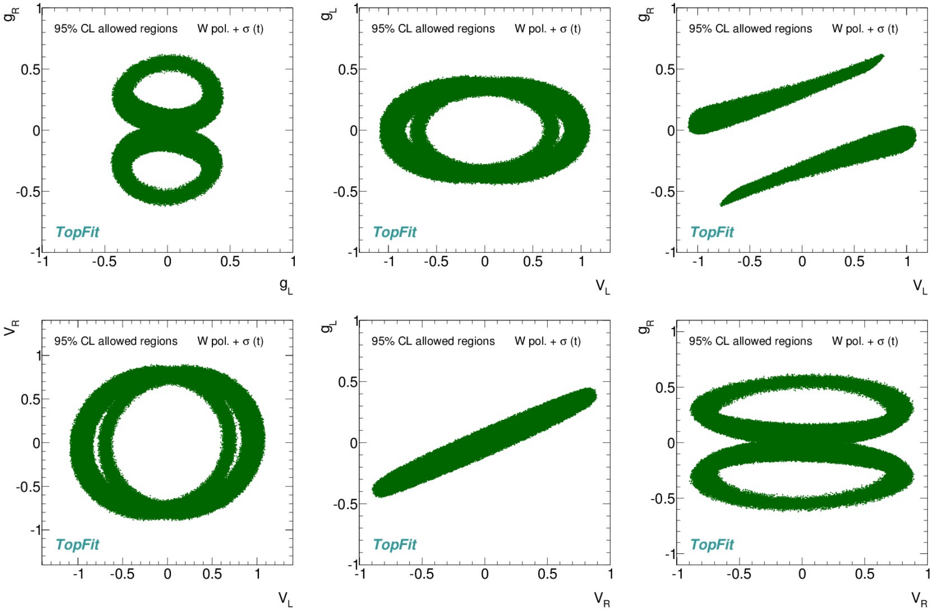
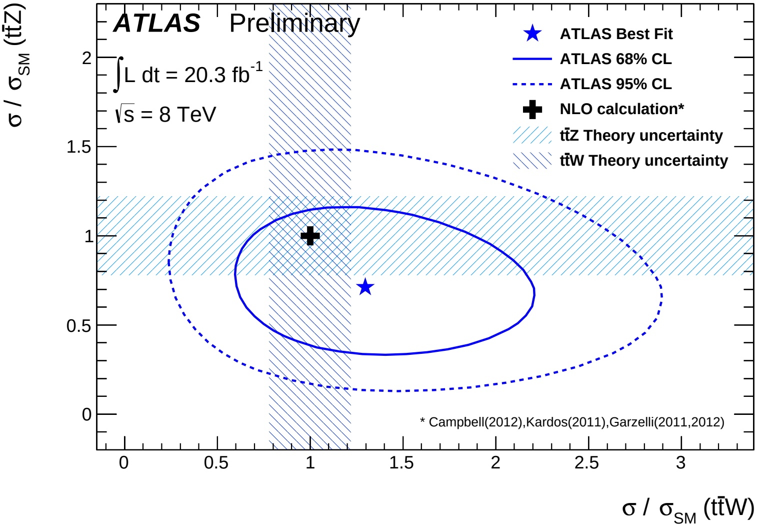




New physics in the *Wtb* vertex



$t\bar{t}V$ $(V = W, Z)$ production



New heavy quarks at the LHC

- Even if the SM has been repeatedly confirmed experimentally there are still many open questions:
  - Number of fermion generations and their mass hierarchy
  - How to stabilize the Higgs mass ($\sim$ 125 GeV)?
  - (. . .)
- BSM models (extra dimensions, top color, little Higgs, composite Higgs, . . .) trying to address some of these open points often predict new heavy quarks, which frequently couple mainly to the 3rd generation
- Sequential 4th generation of quarks disfavoured by the observed Higgs production rate via *gg* fusion
- New quarks could be vector-like

☞ L,R chiralities transform the same way under $SU(2) \otimes U(1)$

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Vector-like quarks

- VLQ's coupling to SM quarks can appear in 7 possible multiplets (assuming the scalar sector only contains doublets):

charge 2/3

charge -1/3

Singlets $T_{L,R}$ $B_{L,R}$

charge 5/3

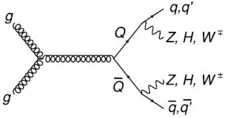
Doublets $\begin{pmatrix} X \\ T \end{pmatrix}_{L,R}$ $\begin{pmatrix} T \\ B \end{pmatrix}_{L,R}$ $\begin{pmatrix} B \\ Y \end{pmatrix}_{L,R}$

charge -4/3

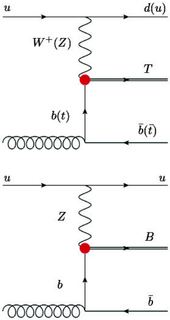
Triplets $\begin{pmatrix} X \\ T \\ B \end{pmatrix}_{L,R}$ $\begin{pmatrix} T \\ B \\ Y \end{pmatrix}_{L,R}$

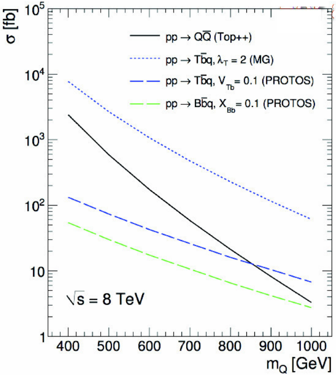
Vector-like quark production at the LHC

Pair production



Single production

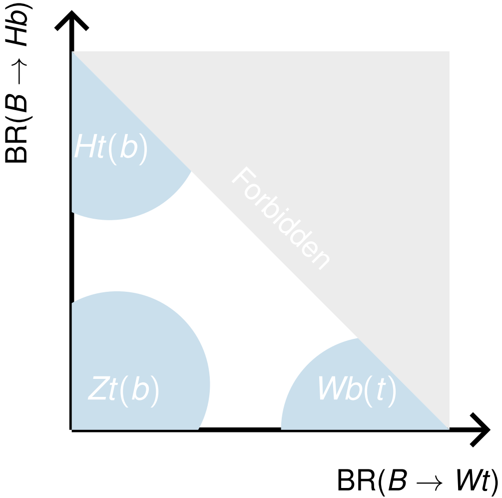




- Single production mechanism might dominate at high masses depending on the coupling strength.
- Composite-Higgs model (CHM) has been used as benchmark model for VLT.
- Singlet hypothesis has been used as benchmark for VLB.

Search strategy

- (almost) model independent search strategy
  ☞ use different final states to cover different decay modes



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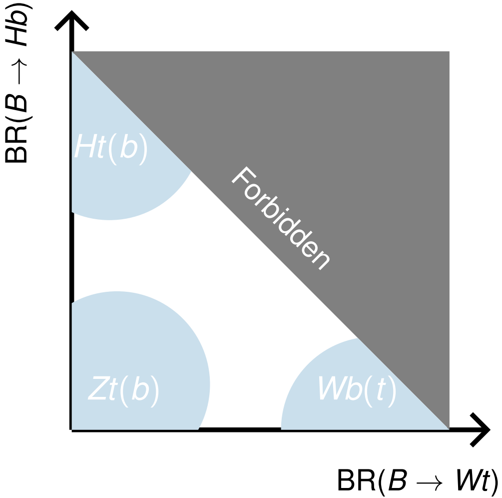

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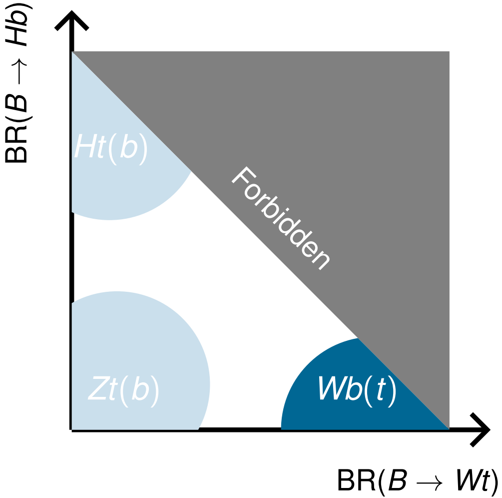

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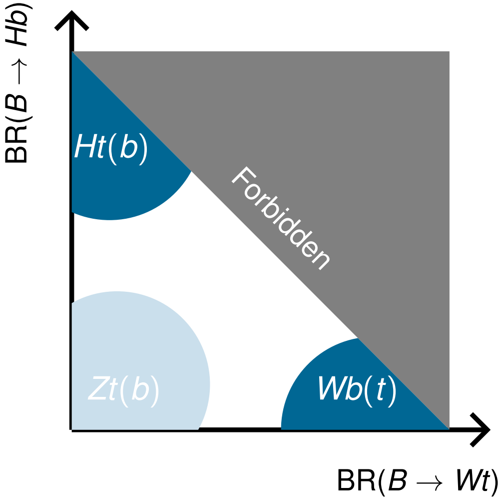

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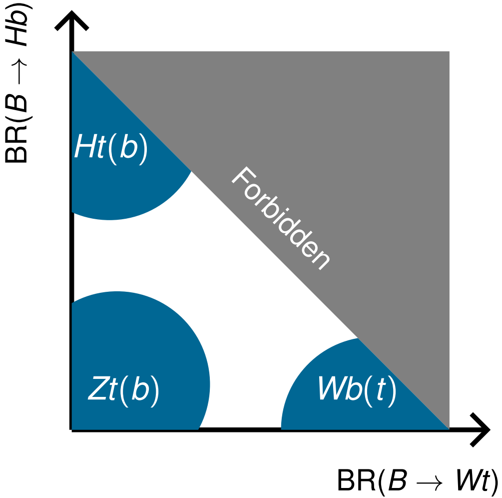
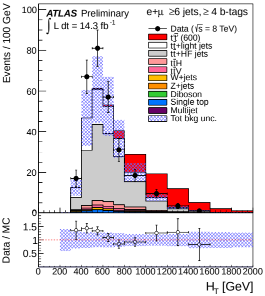
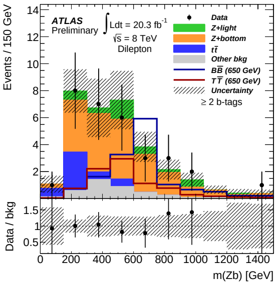


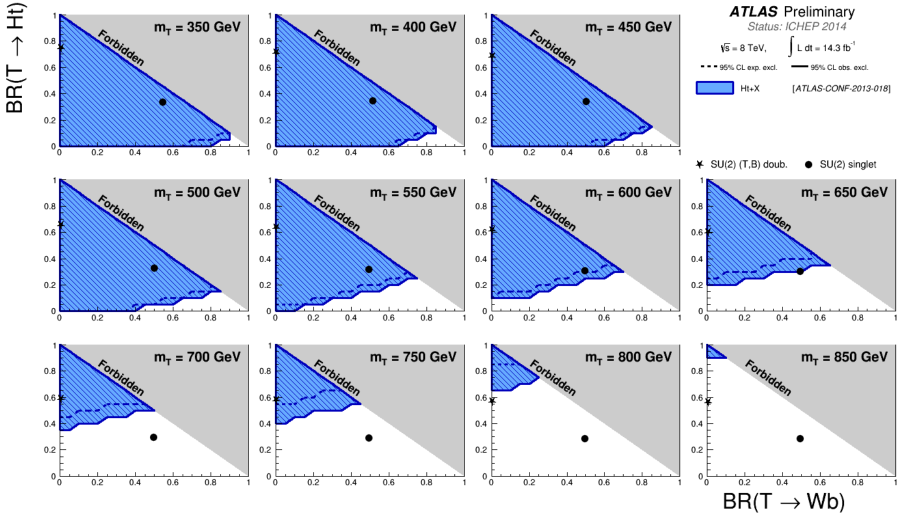
Search strategy: considered topologies

- Different topologies used to be sensitive to different corners of the BR plane:
  - $Ht + X$: T quark pair production with at least one of them decaying to a Higgs boson ($H \to b\bar{b}$)
  - $Wb + X$: both T quarks decaying to Wb (one leptonically and other hadronically)
  - Same-sign leptons: events with 2 same-sign leptons
  - $Zb/t + X$: at least one of the vector-like quarks decaying to a Z boson





95% CL limits for T



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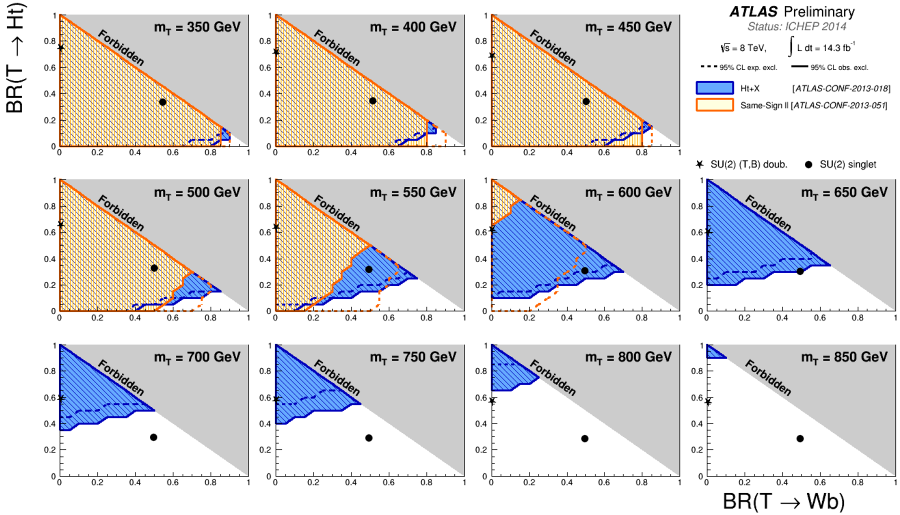

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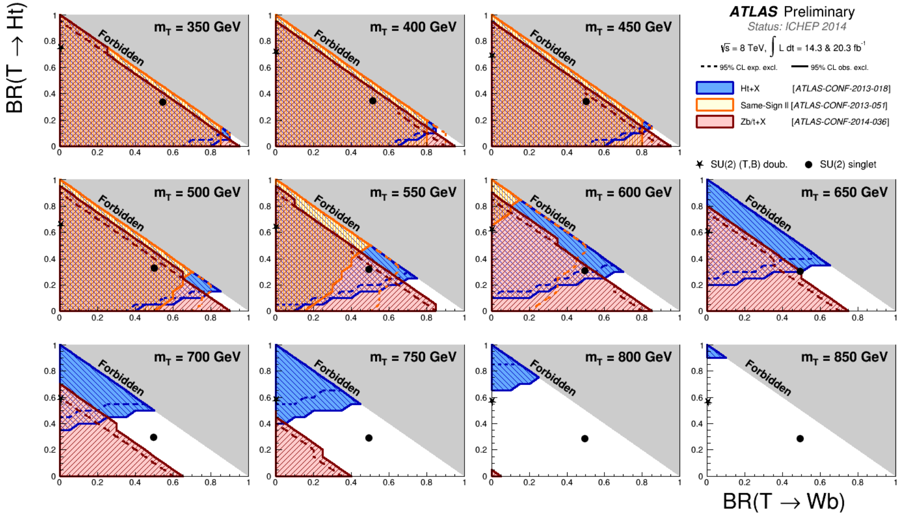

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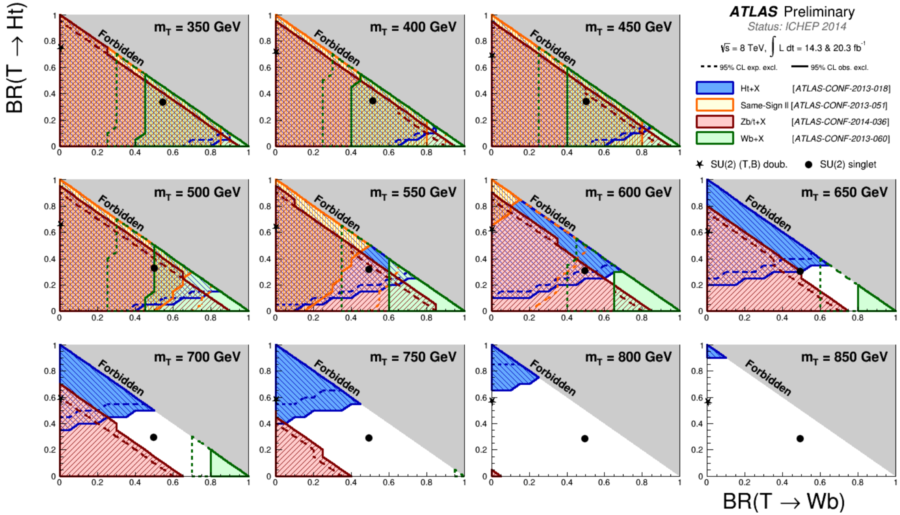
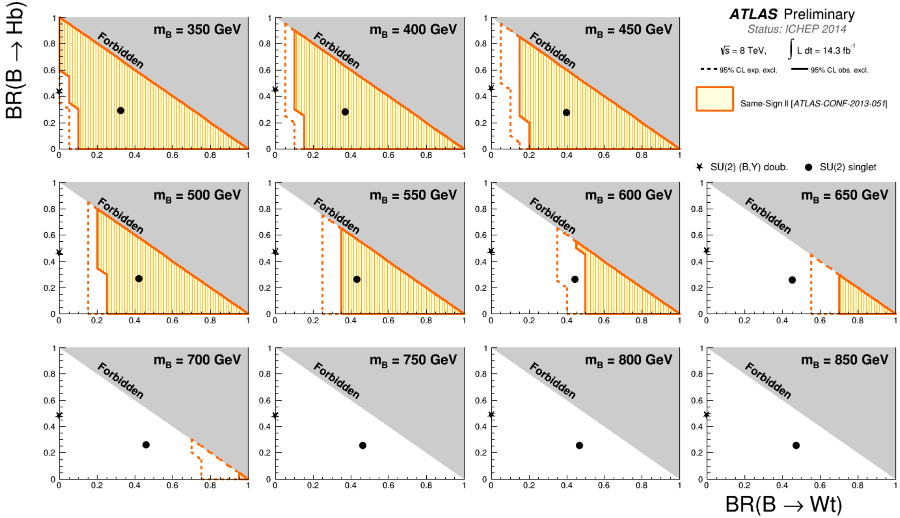
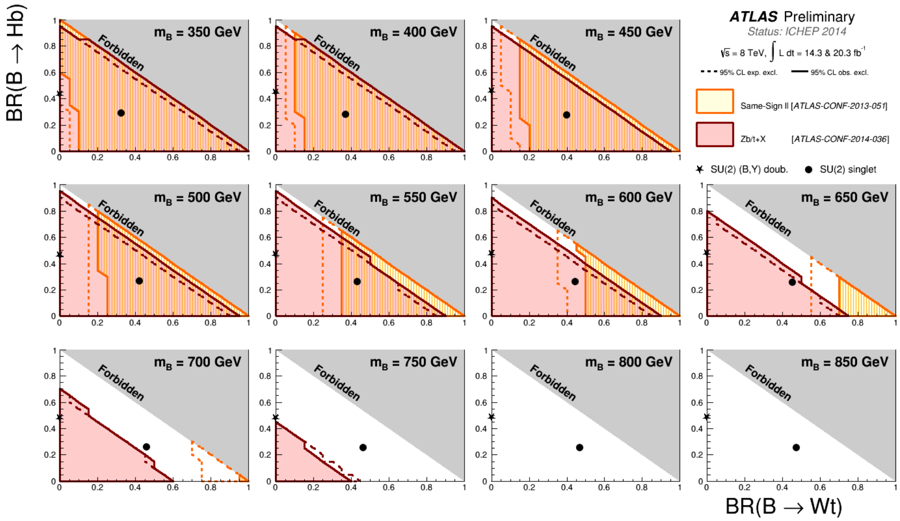


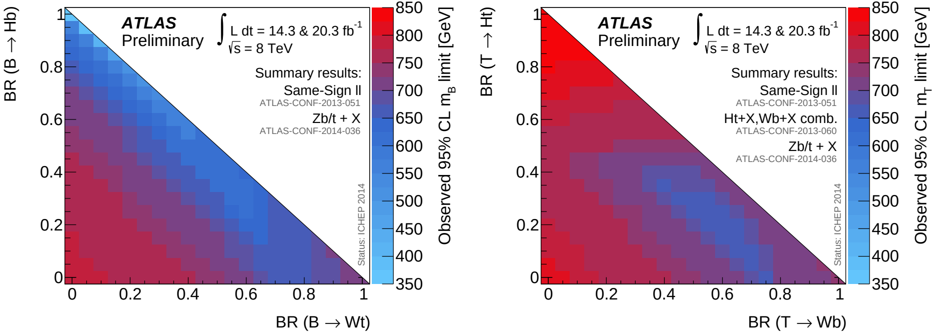
95% CL limits for B



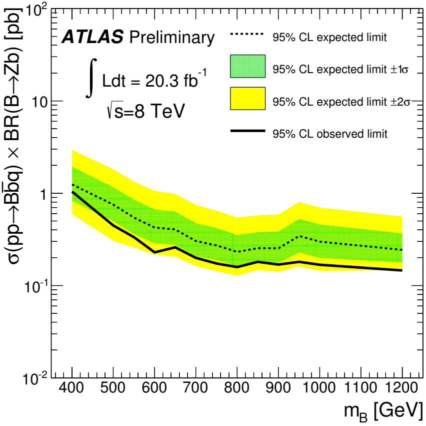
95% CL limits for B

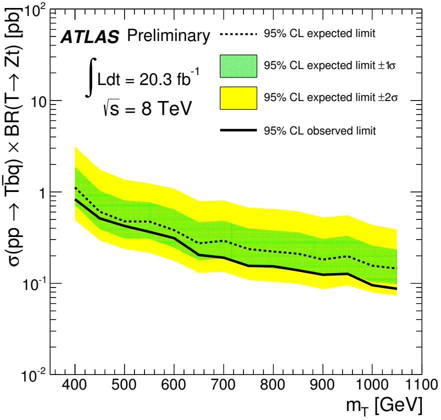


Summary of the 95% upper limits on the VLQ's mass

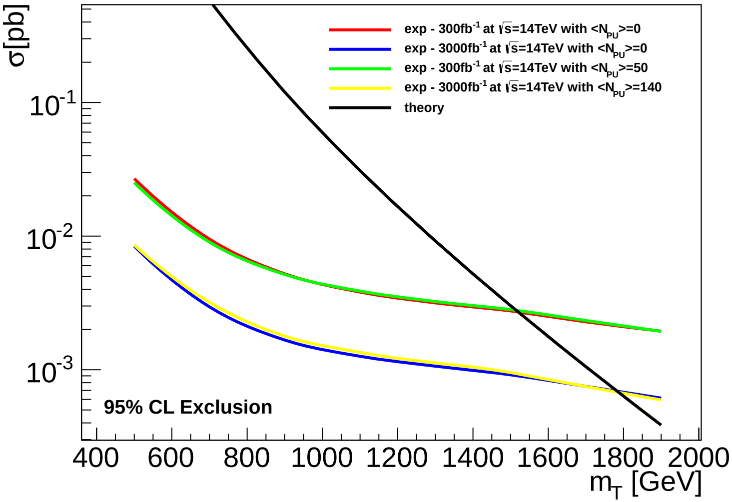


Single production





LHC upgrade projections



arXiv:1309.0026

Do we need a global fit in the top sector?

[arXiv:1302.5634]

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t W_{\mu}^{-} + \text{h.c.}\,.$$

$$\mathcal{L}_{Ztt} = -\frac{g}{2c_W}\bar{t}\gamma^{\mu}\left(X_L^t P_L + X_R^t P_R - 2s_W^2 Q_t\right) t Z_{\mu} - \frac{g}{2c_W}\bar{t}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_Z}\left(d_V^{tZ} + i d_A^{tZ}\gamma_5\right) t Z_{\mu}.$$

$$\mathcal{L}_{Htt} = -\frac{1}{\sqrt{2}}\bar{t}\left(Y_V + iY_A\gamma_5\right) t H.$$

	T	B	$\begin{pmatrix} T \\ B \end{pmatrix}$	$\begin{pmatrix} X \\ T \end{pmatrix}$	$\begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
V_L	$\downarrow$	$\downarrow$	—	—	—	$\uparrow$	$\uparrow$
V_R	—	—	$\updownarrow$	—	—	—	—
X_L^t	$\downarrow$	—	—	—	—	$\downarrow$	$\uparrow$
X_R^t	—	—	$\uparrow$	$\uparrow$	—	—	—
X_L^b	—	$\downarrow$	—	—	—	$\uparrow$	$\downarrow$
X_R^b	—	—	$\uparrow$	—	$\uparrow$	—	—
Y_V^t	$\downarrow$	—	$\downarrow$	$\downarrow$	—	$\downarrow$	$\downarrow$

Summary

- Top quark physics has entered the precision era, testing many different properties
  - Several measurements dominated by the systematic uncertainties:
    - $t\bar{t}$ modelling
    - jet energy measurement
- Differential measurements starting
  - Still limited by statistical uncertainty
- No hint for physics beyond the SM observed so far
- Plenty of new results from run-1 in preparation and run-2 is around the corner ☞ Stay tuned for news!

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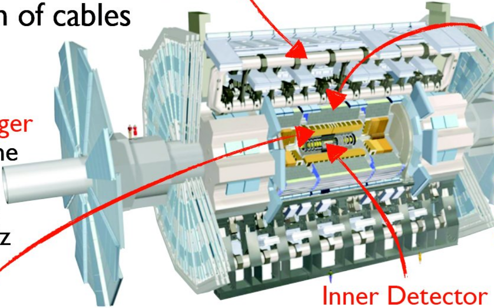
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

Backup Slides

The ATLAS detector

Length : ~ 46 m
Diameter : ~ 24 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers; Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV



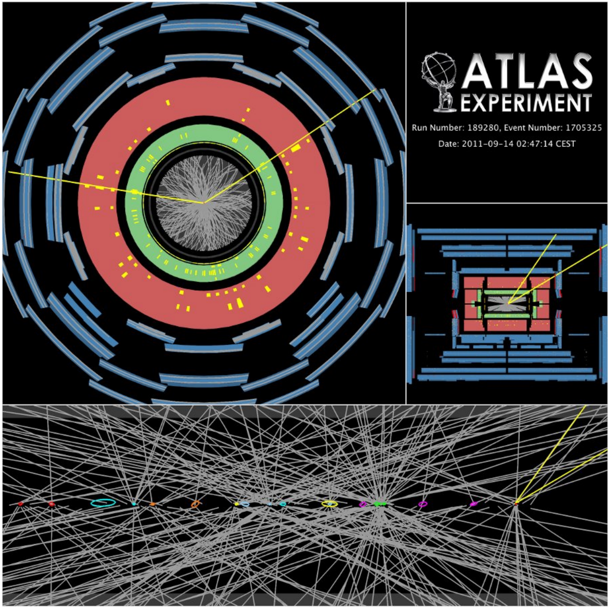
3-level trigger reducing the rate from 40 MHz to 200-300 Hz

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity Fe/scintillator Tiles (central), Cu/W-LAr (fwd) Trigger and measurement of jets and missing E_T
E-resolution:
$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

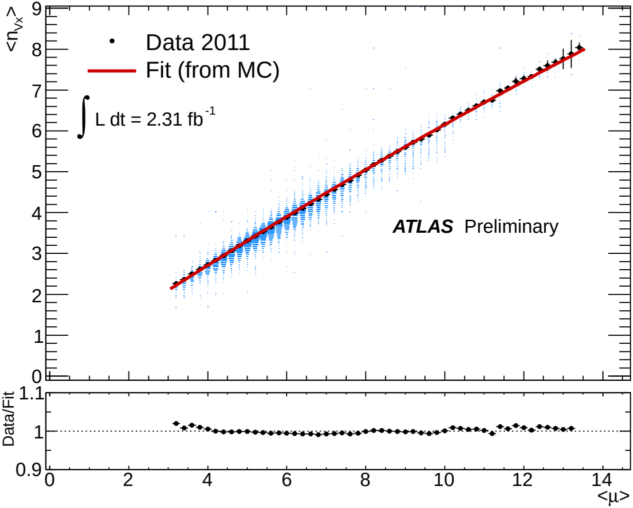
EM calorimeter ($|\eta|<3.2$): Pb-LAr Accordion; e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

Inner Detector ($|\eta|<2.5$, B=2T): Si Pixels, Si strips, Transition Radiation detector (straws); Precise tracking and vertexing, e/π separation Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\ p_T\ (\mathrm{GeV}) \oplus 0.015$
i.e. σ/p_T <2% for p_T < 35 GeV

Effect of pile-up



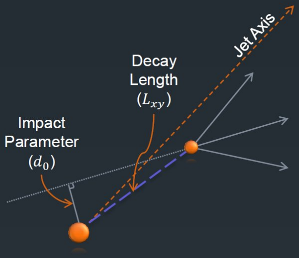
Effect of pile-up



b-tagging

Algorithm Types at ATLAS

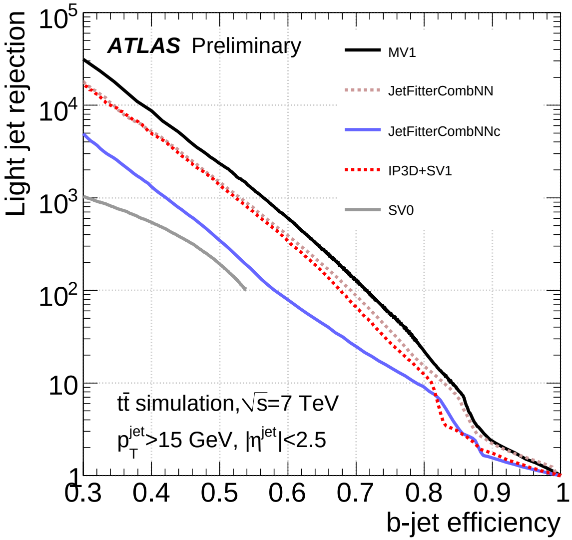
- Impact Parameter Type
- Secondary Vertex Reconstruction Type
- Combined



High Mass: $m_B \sim 5$ GeV
Long Lifetime:
$c\tau \sim 470\mu m$ (B^+, B^0, B_s)
$\sim 390\mu m$ (Λ_b)
For 50 GeV Bottom
$L_{xy} \sim 5$mm, $d_0 \sim 500\mu m$

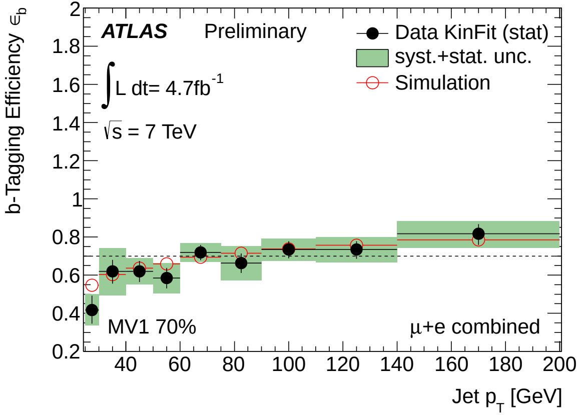
[slide from G. Watts' talk at DPF 2011]

b-tagging


ATLAS Preliminary
MV1
JetFitterCombNN
JetFitterCombNNc
IP3D+SV1
SV0
tt̄ simulation, √s=7 TeV
p_T^jet>15 GeV, |η^jet|<2.5
Light jet rejection
b-jet efficiency
10^5
10^4
10^3
10^2
10
1
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

b-tagging efficiency measurement with $t\bar{t}$ events

- Jets' flavour composition in $t\bar{t}$ events allow the measurement of b-tagging efficiency (tag & count, kin. selection and kin. fit methods studied)



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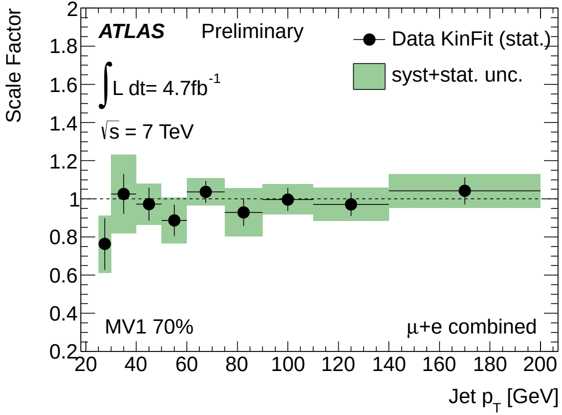
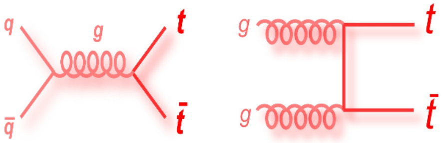


$t\bar{t}$ production at the LHC

Example diagrams:



	σ_{gg}/σ_{tot}
Tevatron	$\approx 15\%$
LHC 7 TeV	$\approx 85\%$
LHC 14 TeV	$\approx 90\%$

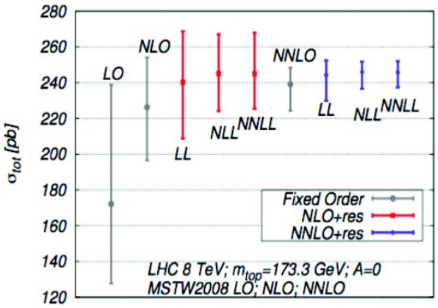
Long standing theoretical effort on fixed order QCD calculations
1989 NLO
1998 NLO+NLL
2008 NLO+NNLL
2013 NNLO+NNLL

Cross-Section rises by about 10%
from NLO to NNLO+NNLL QCD

Precision improves from ~12% to ~3% (scale)
~ 8% to 5% (PDF)

Uncertainty on parton density function dominate

Electroweak corrections also sizeable $\alpha_s^2 \sim \alpha_{ew}$



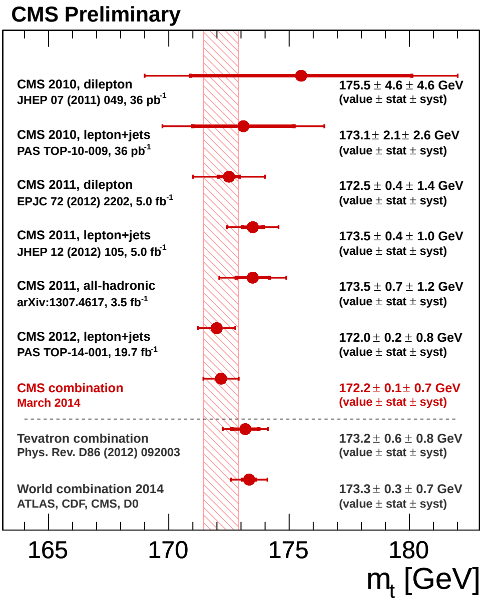
NNLO QCD calculation mandatory for precision analysis

Figures and numbers from:

Czakon, Mitov arXiv:1303.6254

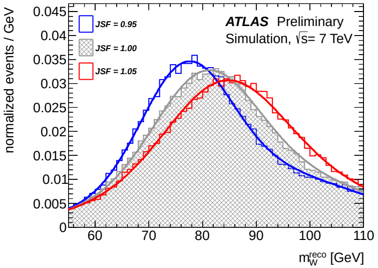
Czakon, Mangano, Mitov, Rojo: arXiv:1303.7215

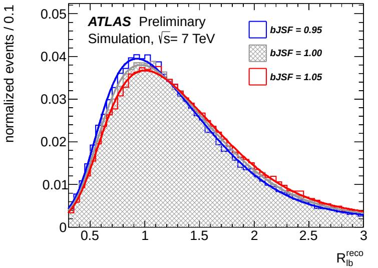
CMS results on the top quark mass

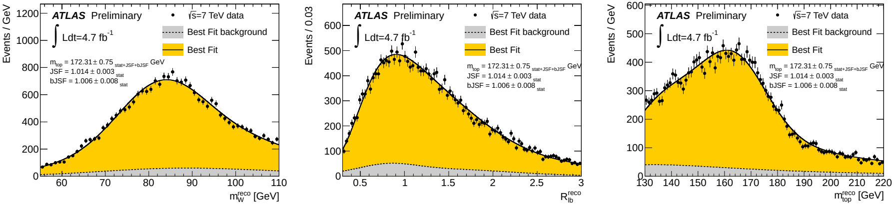


Measurement of the top quark mass (ℓ+jets channel)

- $\sqrt{s} = 7$ TeV data ($\int Ldt = 4.7\ \mathrm{fb}^{-1}$)
- Kinematic fit used to reconstruct $t\bar{t}$
- first m_t measurement with *in-situ* b-quark JES calibration
- Fit simultaneously m_t, m_W^{had} and
  $$R_{\ell b}^{\mathrm{reco}} = \frac{p_T^{b_{\mathrm{had}}} + p_T^{b_{\mathrm{lep}}}}{p_T^{W_{\mathrm{jet1}}} + p_T^{W_{\mathrm{jet2}}}}$$
- m_W^{had} used to constrain the overall jet scale factor (JSF)
- $R_{\ell b}^{\mathrm{reco}}$ used to constrain the overall ratio of b to light-parton jet energy scale factor (bJSF)







$$m_t = 172.31 \pm 0.75\,(\mathrm{stat}+\mathrm{JSF}+\mathrm{bJSF}) \pm 1.35\,(\mathrm{syst})\ \mathrm{GeV}$$

dominant systematics: bJSF (stat), residual JES, *b*-tagging, $t\bar{t}$ modelling

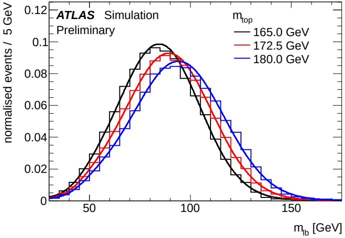
- CMS [JHEP 12 (2012) 105]:
  $\sqrt{s} = 7$ TeV data ($\int Ldt = 5\ \mathrm{fb}^{-1}$)

  $$m_t = 172.22 \pm 0.19\,(\mathrm{stat.}+\mathrm{JSF}) \pm 0.75\,(\mathrm{syst.})\ \mathrm{GeV}$$

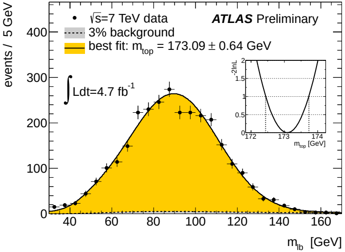
  dominant systematics: bJES, JSF, $t\bar{t}$ modelling

Top mass: dilepton channel

- [ATLAS-CONF-2013-077]
  - 1D template method:
    $m_{\ell b}$ as estimator for m_t
    ☞ lowest average $m_{\ell b}$ used
  - ≥ 2 b-tagged jets
    almost background free sample
    ($< 3\%$ single top)



$m_t = 173.09 \pm 0.64\ (\mathrm{stat}) \pm 1.50\ (\mathrm{syst})$ GeV
dominant systematics: bJES, JES,
$t\bar{t}$ modelling, b-tag



- CMS [EPJ C72 (2012) 2202]

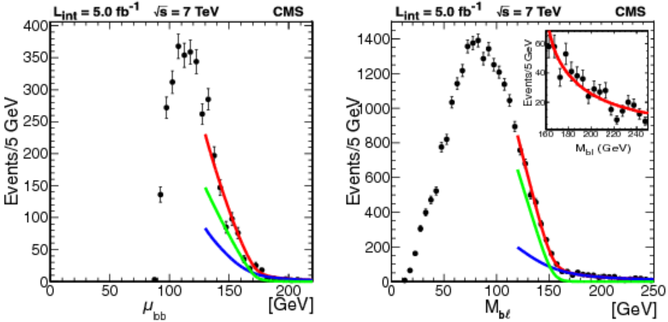
  $m_t = 172.5 \pm 0.4\ (\mathrm{stat}) \pm 1.5\ (\mathrm{syst})$ GeV

  dominant systematics: bJES, JES, renor./fact. scales

Top mass from kinematic endpoints

[EPJ C73 (2013) 2494]

- Dilepton events ($e^+e^-, \mu^+\mu^-$) with ≥ 2 b-tagged jets
- m_t sensitive to the kinematic endpoints (transverse masses)
  $M_{\mathrm{T}}^2 = m_a^2 + M_a^2 + 2(E_{\mathrm{T}}^a E_{\mathrm{T}}^b - \boldsymbol{p}_{\mathrm{T}}^a \boldsymbol{p}_{\mathrm{T}}^b), \quad M_{\mathrm{T2}} = \min_{\boldsymbol{p}_{\mathrm{T}}^a + \boldsymbol{p}_{\mathrm{T}}^b} \left(\max(M_{\mathrm{T}}^a, M_{\mathrm{T}}^b) \right)$



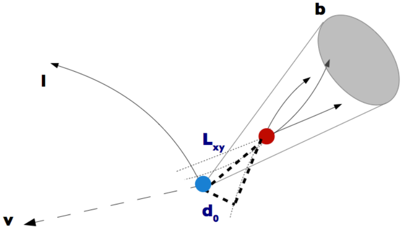
$m_t = 173.9 \pm 0.9\ (\mathrm{stat})^{+1.7}_{-2.1}\ \mathrm{syst}$

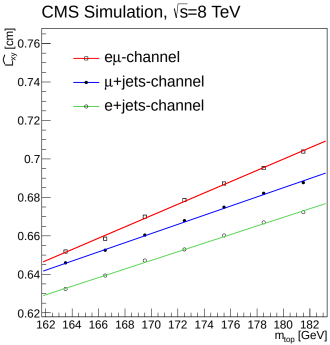
dominant systematics: JES, fit range, modelling

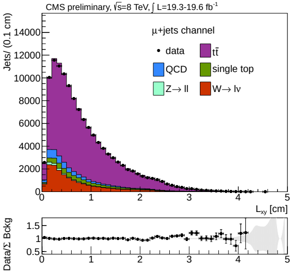
Top mass from the B-hadron lifetime

[CMS PAS TOP-12-030]

- transverse decay length (L_{xy}) of B-hadrons in $t\bar{t}$ events has a linear dependence with m_t:



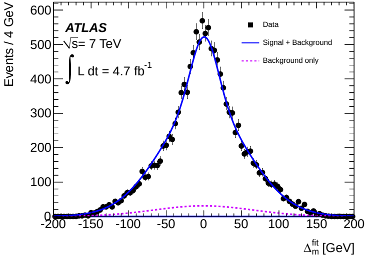


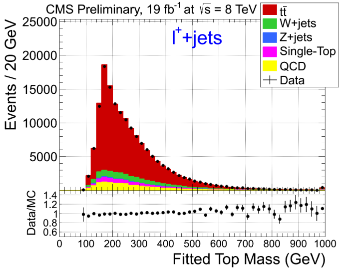


Channel	m_t [GeV]
muon+jets	$173.2 \pm 1.0_{\text{stat}} \pm 1.6_{\text{syst}} \pm 3.3_{p_T(t)}$
electron+jets	$172.8 \pm 1.0_{\text{stat}} \pm 1.7_{\text{syst}} \pm 3.1_{p_T(t)}$
electron-muon	$173.7 \pm 2.0_{\text{stat}} \pm 1.4_{\text{syst}} \pm 2.4_{p_T(t)}$

$t/\bar{t}$ mass difference

- ℓ+jets topology w/ $\geq$1 (CMS) or $\geq$2 (ATLAS) *b*-tagged jets
- Kinematic χ^2 (ATLAS) and a likelihood fit (CMS) used to determine *t* and $\bar{t}$ masses





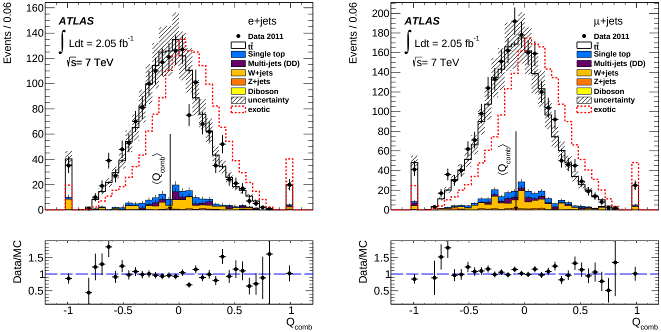
$$\text{ATLAS: } m_t - m_{\bar{t}} = 0.67 \pm 0.61 \text{ (stat)} \pm 0.41 \text{ (syst) GeV}$$
$$\text{CMS: } m_t - m_{\bar{t}} = 0.272 \pm 0.196 \text{ (stat)} \pm 0.122 \text{ (syst) GeV}$$

dominant uncertainties: choice of *b* fragmentation model (ATLAS: 0.34 GeV) and $b/\bar{b}$-jet response (CMS: 0.06 GeV; ATLAS: 0.08 GeV)

Top charge

[JHEP 11 (2013) 031]

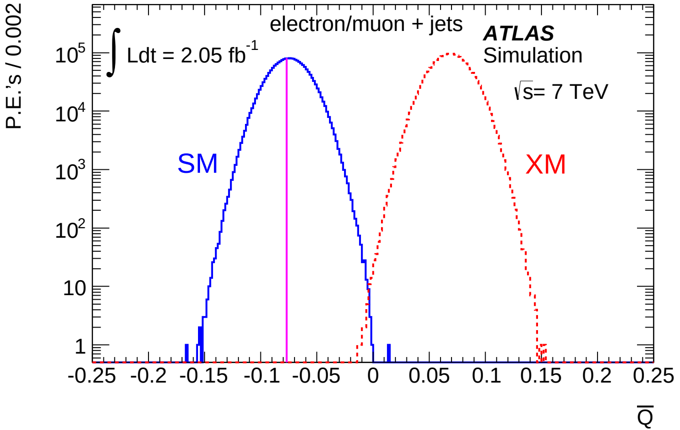
- ℓ+jets channel
- distinguish $t^{(+2/3)} \to b^{(-1/3)}\ W^{(+1)} \to b^{(-1/3)}\ \ell^{(+1)}\ \nu_\ell$
  $\tilde{t}^{(-4/3)} \to b^{(-1/3)}\ W^{(-1)} \to b^{(-1/3)}\ \ell^{(-1)}\ \bar{\nu}_\ell$
- lepton/b-tagged jet association using $m_{\ell b}$ / kin. fit
- charge of the b-jet from charge weighting / semilep. B decays



☞ $\tilde{t}^{(-4/3)}$ scenario excluded at 8 σ

Top charge

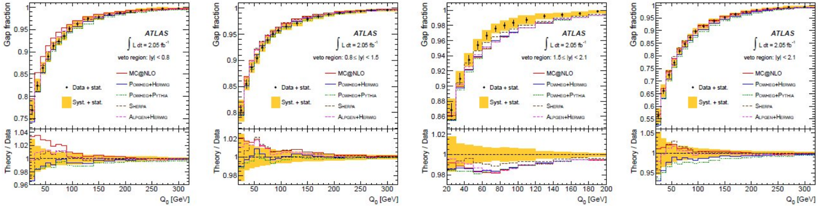
[JHEP 11 (2013) 031]



☞ $\tilde{t}^{(-4/3)}$ scenario excluded at 8 σ

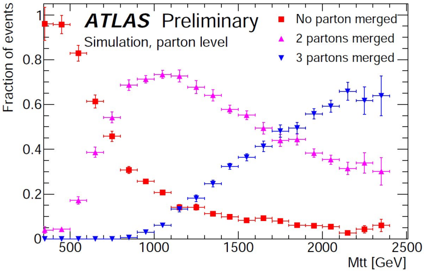
Constraining q/g radiation: central jet veto

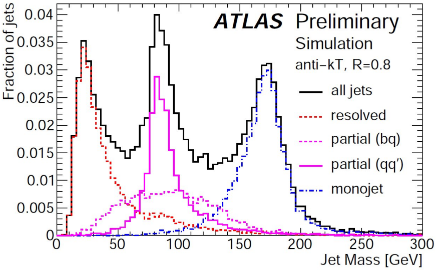
- measurement in dilepton channel of the fraction of events without an additional jet with transverse momentum above a threshold in a central rapidity interval
- comparison to 4 MC generators (MC@NLO, Powheg, Alpgen and Sherpa)



- $|y| < 2.1$: reasonable description of the data
- $1.5 \leq |y| < 2.1$: too much jet activity predicted
- $|y| < 0.8$: MC@NLO produces too little activity
- results constrain ISR uncertainties in other ATLAS measurements
- alternate measurement: veto on events where scalar sum of p_T of additional jets is above threshold in central region (gives similar conclusions)

$t\bar{t}$ resonances: boosted objects



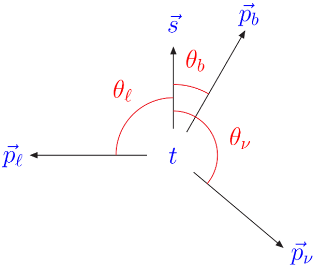


Probing the *Wtb* vertex: spin asymmetries

- polarised top decays

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_X} = \frac{1+\alpha_X \cos\theta_X}{2}$$

☞ α_X depends on the anomalous couplings



X = top decay product ➡ $\vec{p}_X$ = momentum in t rest frame

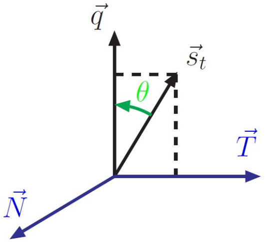
$\vec{p}_j$ = jet momentum in t rest frame

$$Q = \cos(\vec{p}_X, \vec{p}_j) \quad \rightarrow \quad A_X \equiv \frac{N(Q>0)-N(Q<0)}{N(Q>0)+N(Q<0)} = \frac{1}{2} P\,\alpha_X \quad [P = 0.95\ (t) \quad P = -0.93\ (\bar{t})]$$

[PLB 476 (2000) 323]

W polarisation beyond helicity fractions

- New idea to study top decays: [NPB840 (2010) 349]
  ☞ consider transverse and normal directions



$\vec{q}$ ➜ W mom in t rest frame
$\vec{s}_t$ ➜ top spin

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

meaningful for polarised t decays
(e.g. in single top production)

θ_ℓ^* ➜ angle between ℓ, $\vec{q}$
determine F_+, F_0, F_-

θ_ℓ^T ➜ angle between ℓ, $\vec{T}$
determine F_+^T, F_0^T, F_-^T

θ_ℓ^N ➜ angle between ℓ, $\vec{N}$
determine F_+^N, F_0^N, F_-^N

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

$$A_{\mathrm{FB}}^N = \frac{3}{4}\left[F_+^N - F_-^N\right]$$

$$\boxed{A_{\mathrm{FB}}^N \simeq 0.64\, P\, \mathrm{Im}\, g_R}$$

Branching ratios for VLQ decays