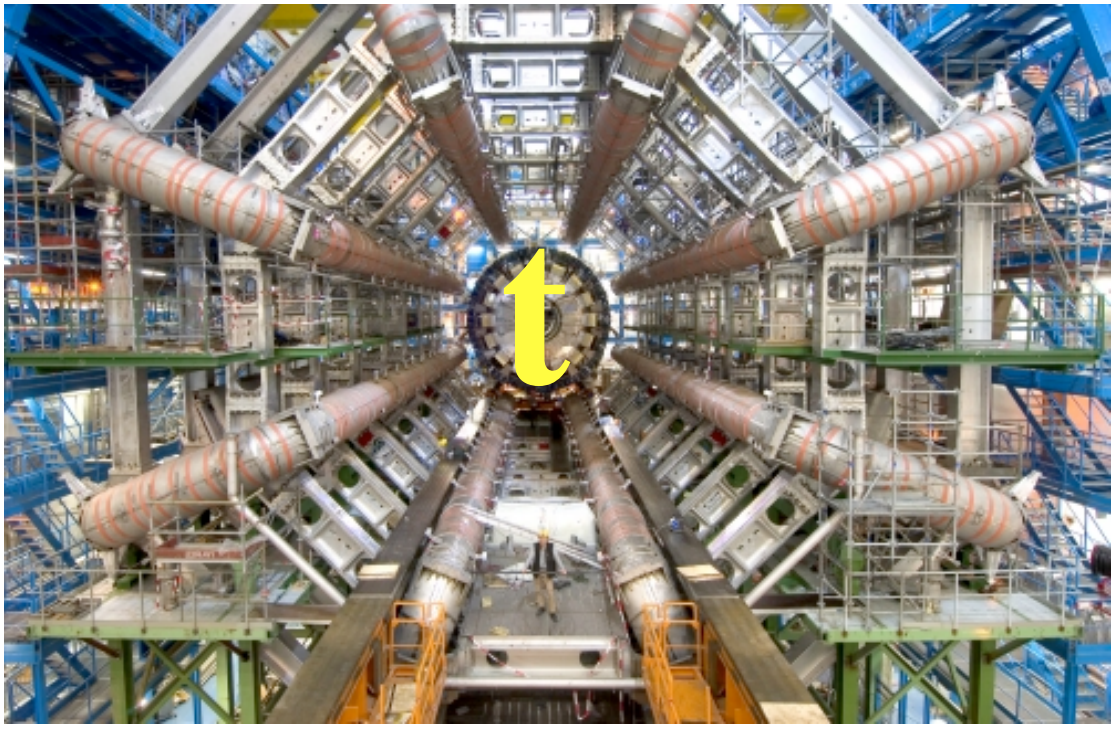
Top Quark Physics with ATLAS



Lucio Cerrito
Queen Mary, University of London
on behalf of the ATLAS Collaboration

Queen Mary University of London

The Leverhulme Trust

ATLAS

International Conference on New Frontiers in Physics (ICFP)
Kolymbari, Crete, 10-16 June 2012

Introduction to top quark physics

Physics Highlights

➢Test of SM (production, decay, coupling....etc)

➢ Top quark does not hadronize: momentum and spin transferred to decay products

➢ Search for processes with similar signature (t', Z'...)

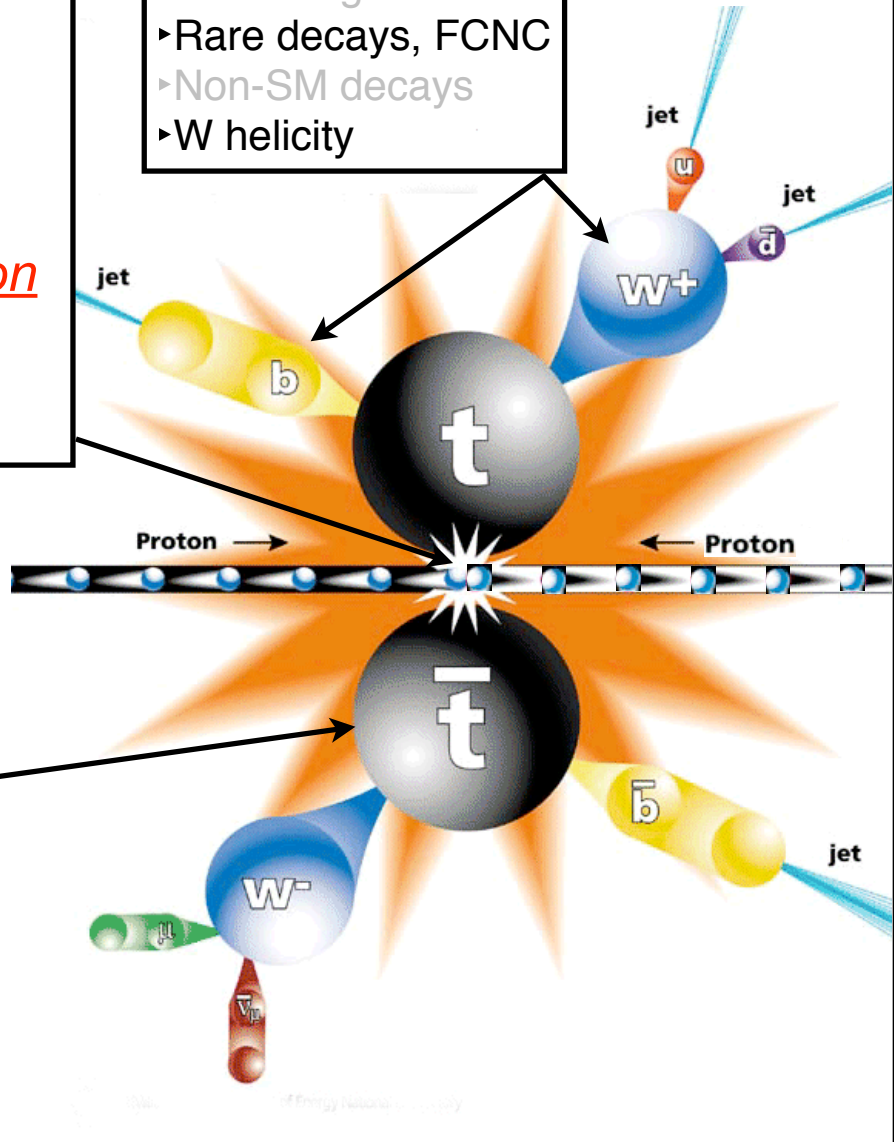
➢ Measuring the top quark mass allows the prediction of the SM Higgs boson mass.

Production Rate
- Pair Production cross section
- Single (EWK) production, $|V_{tb}|$
- FCNC, anomalous couplings
- Differential cross sections
- Production mechanism (gg,qq)

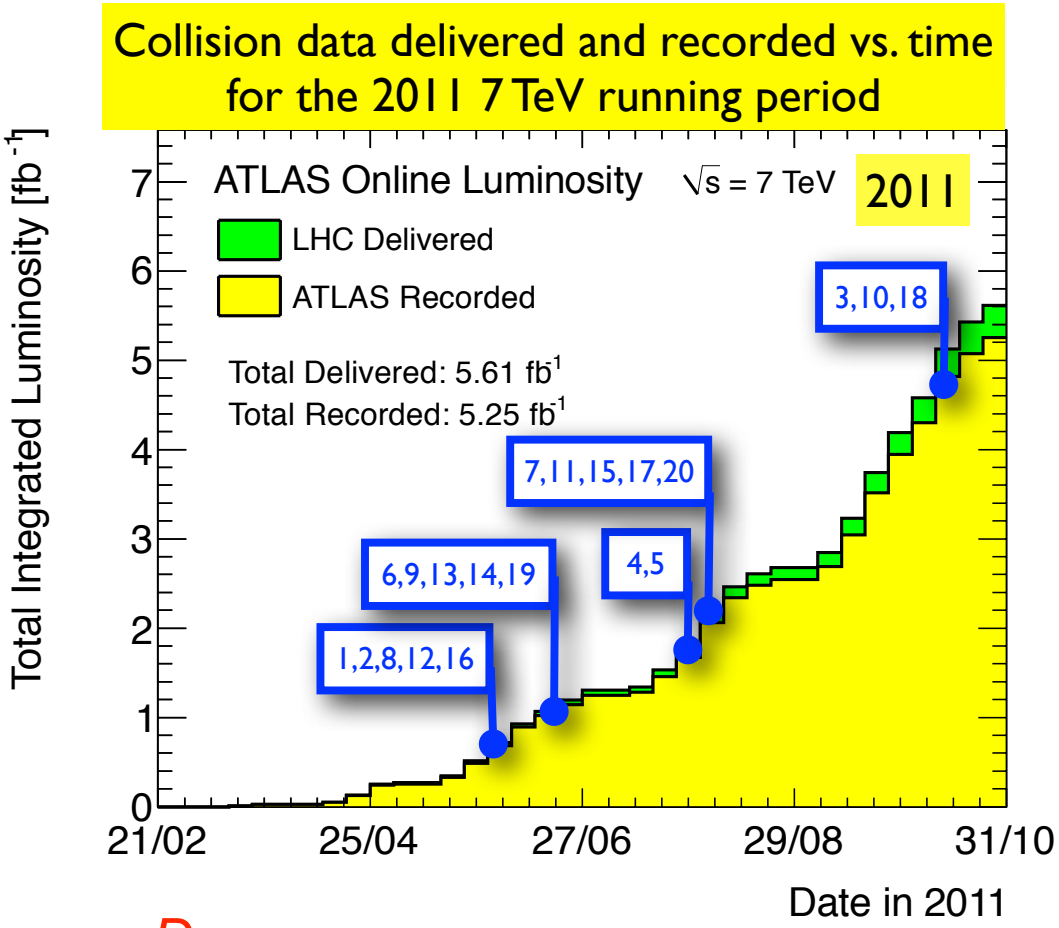
New Physics in production
- Resonant production?
- HQ production?
- ...

Decay
- Branching ratios
- Rare decays, FCNC
- Non-SM decays
- W helicity

Properties
- Top mass
- Top charge
- Top width
- Spin correlation
- Charge Asymmetry



Outline of this talk



Production Rate

1 σ_{tt} (dilepton channel).....
2 σ_{tt} (single lepton channel).....
3 σ_{tt} (hadronic channel).....
4 σ_{tt} (τ+jets).....
5 σ_{tt} (e,μ+τ).....
6 σ_{tt} ($tt\gamma$).....
σ_{tt} combined.....
7 Differential σ_{tt}, jet veto.....
8 Differential σ_{tt}, N_{jets}.....
9 $\sigma_{t,\ t\text{-channel}}$, $|V_{tb}|$.....
10 $R=\sigma_{t,}/\sigma_{tbar,\ t\text{-channel}}$.....
11 $\sigma_{t,\ Wt\text{-channel}}$.....
12 $\sigma_{t,\ s\text{-channel}}$.....
13 $\sigma_{t,\ FCNC} \times B(W\rightarrow l\nu)$.....

Decay

19 Helicity of W bosons.....
20 FCNC in decay ($t\rightarrow Zq$).....

New Physics in production

21 $tt+E_{Tmiss}$, ...
22 Resonant tt, ...
23 Resonant tb, ...

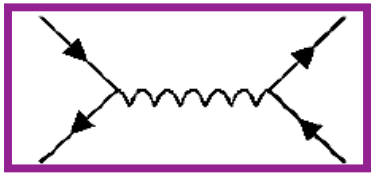
Properties

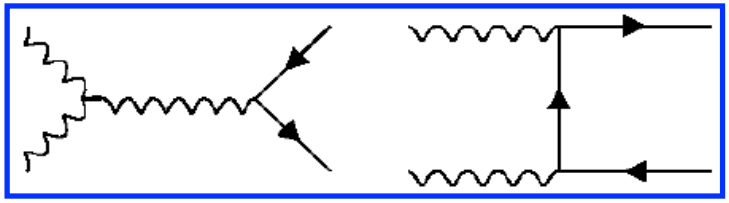
14 m_{top} (precision).....
15 m_{top} (additional methods).....
16 Q_{top}.....
17 Correlation of t-tbar spins.....
18 tt charge asymmetry.....

Production of top in hadronic collisions

Pair:

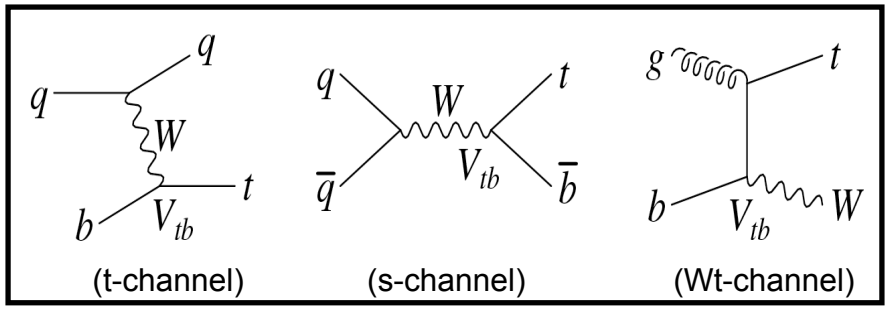
- *qq* annihilation via strong interaction (~15% at the LHC)
- *gg* fusion (dominant, ~85% at LHC)





NOTE: Production through virtual Z and γ are much smaller

Single (EWK production):



Theoretical Predictions

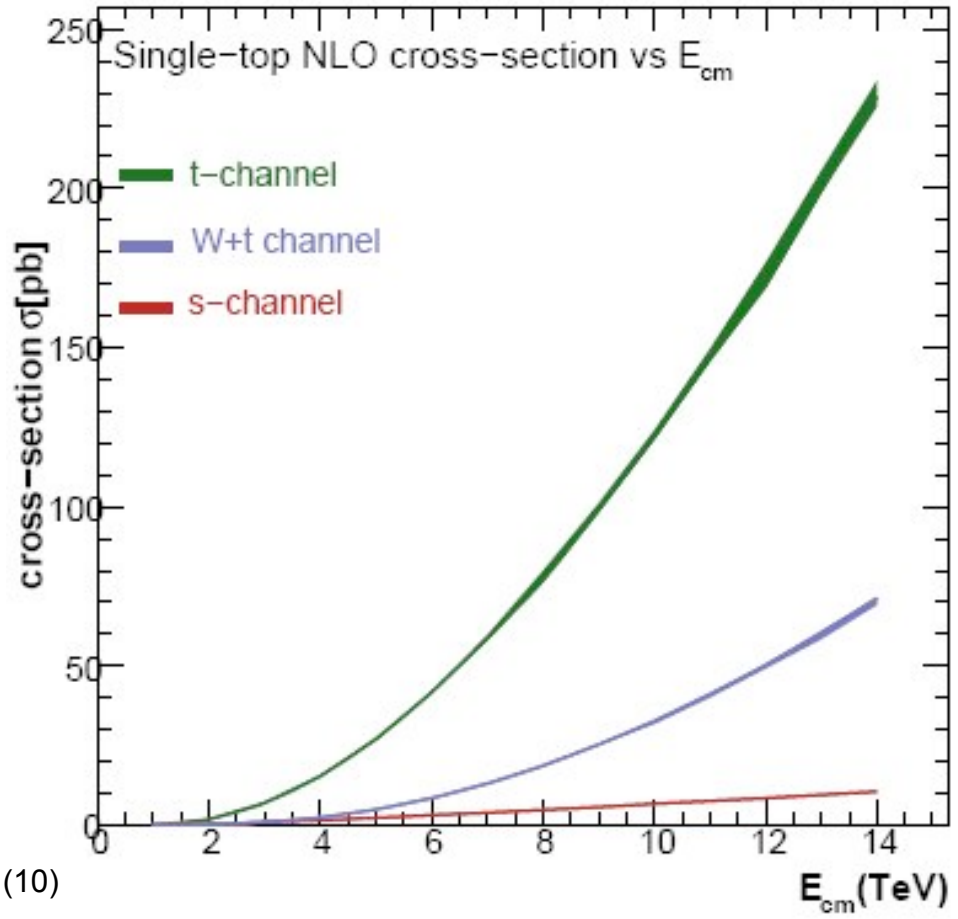
pp@7 TeV, approx. NNLO, (m_t=172.5 GeV/c^2)

$\sigma_{t\bar{t}} = 167^{+17}_{-18}$ pb (1)

$\sigma_t = 64.6^{+2.7}_{-2.0}$ pb (2)

$\sigma_{Wt} = 15.7 \pm 1.1$ pb (2)

$\sigma_s = 4.6 \pm 0.2$ pb (2)



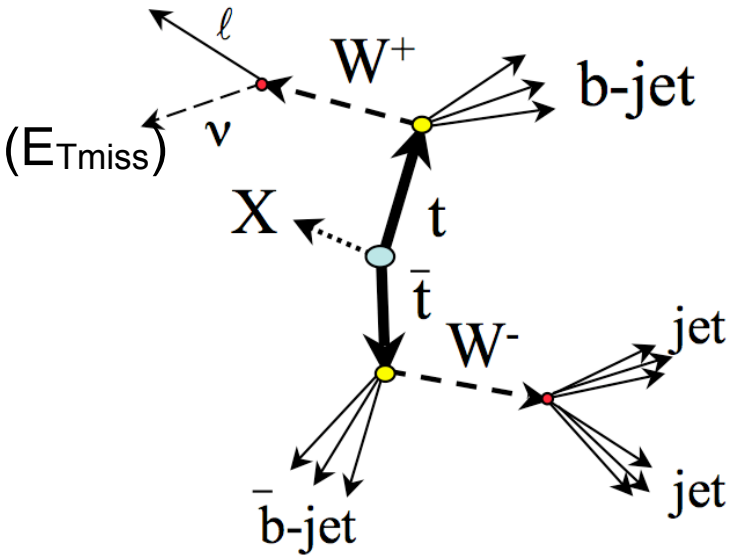
(1) Computed with: Aliev et. al., HATHOR, arXiv:1007:1327 (2011)

(2) Kidonakis, PRD 83, 091503 (11); PRD 82, 054018 (10), PRD 81, 054028 (10)

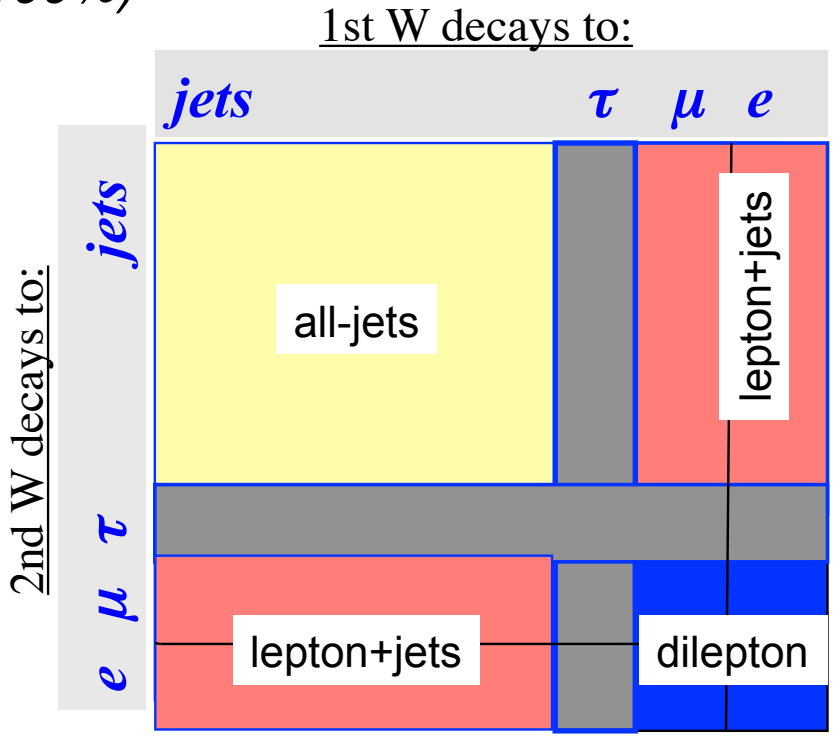
Decay of top quarks and event classification

Decay:

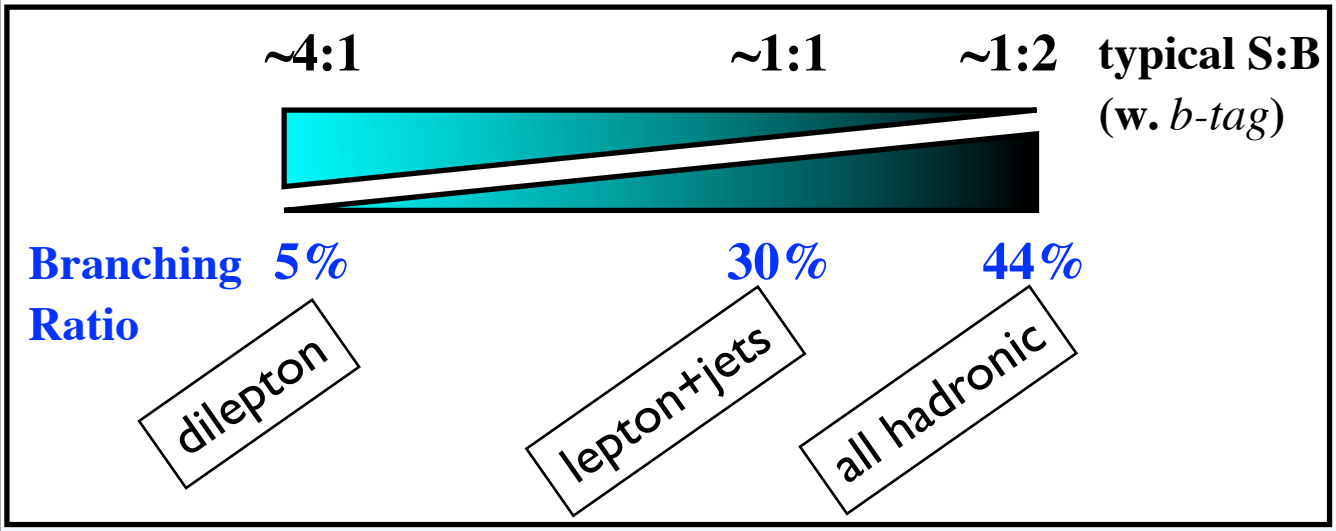
$|V_{tb}|\sim 1$, and $M_t > M_W + M_b \Rightarrow t \rightarrow Wb$ (~100%)



tt event classification:



Backgrounds to top pair events:



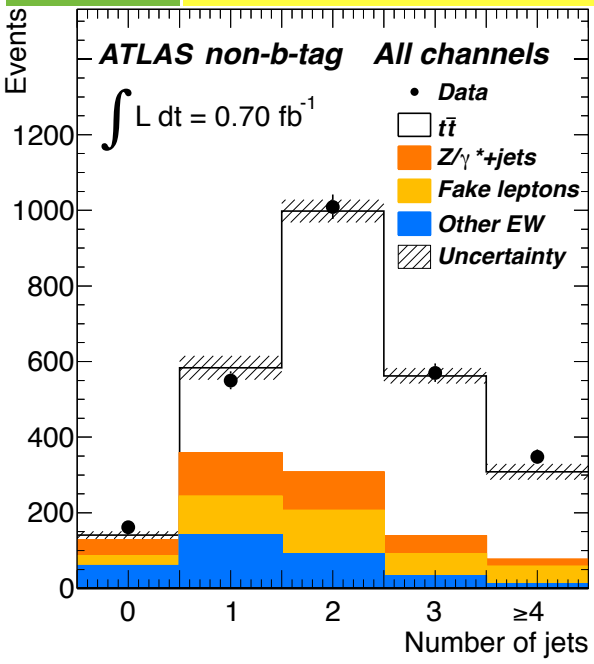
Backgrounds topology

- No neutrinos or less E_{Tmiss}
- No (or less) b-jets
- Leptons could be fakes (less isolated)
- Less central

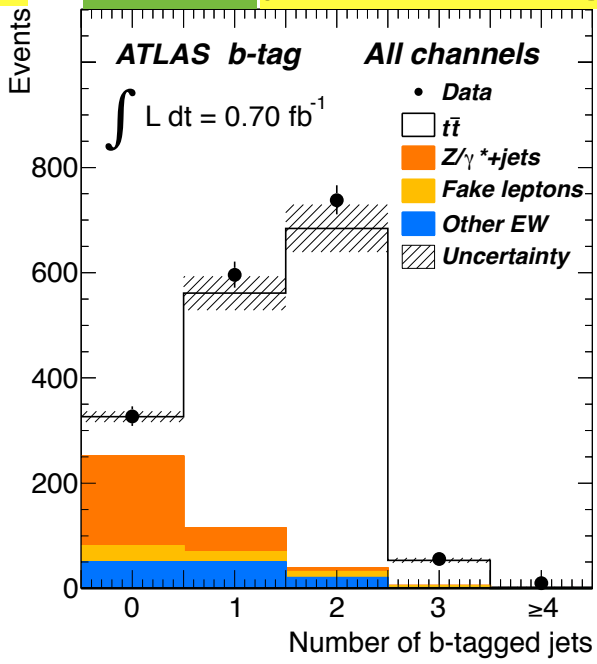
Pair production with 2 leptons+jets

Signature: 2 isolated e/μ +E_{Tmiss}+jets **new** ◀ results post March 2012

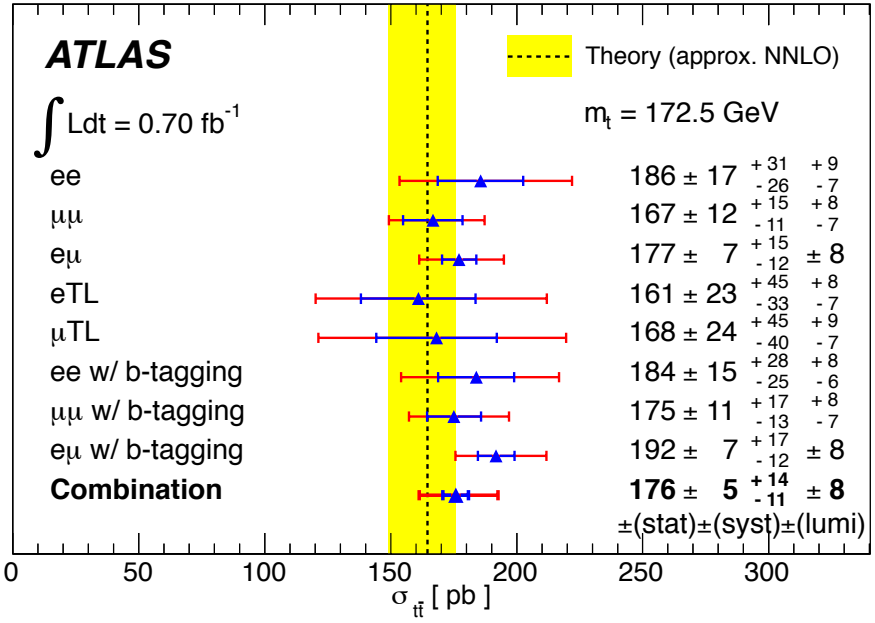
0.7 fb^{-1} Jet count: untagged



0.7 fb^{-1} Jet count: b-tagged



0.7 fb^{-1} Cross checks: subsamples



$$\sigma_{t\bar{t}} = 176 \pm 5(\text{stat})^{+14}_{-11}(\text{syst}) \pm 8(\text{lum})\ \text{pb}$$

Overall precision: ~9%

Limited by systematic uncertainties

[arXiv:1202.4892 (2012), JHEP1205 (2012) 059]

Pair production with lepton+jets

Signature: 1 isolated e/μ +E_{Tmiss}+jets.

Method: multivariate discriminant based on: η_l,$p_{T,lead\ jet}$,Apl.,$H_{T,3p}$

0.7 fb^{-1} Multivariate Discriminant output; multisample

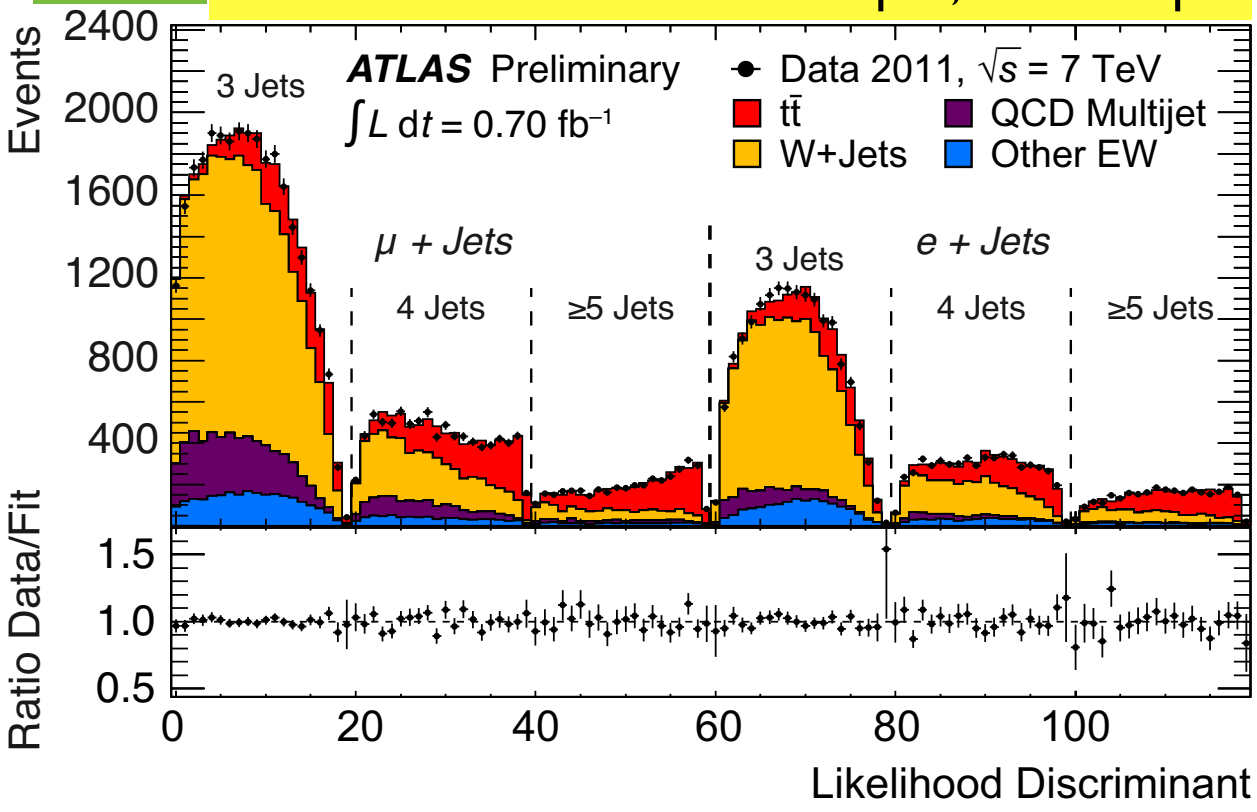


Table of Systematic Uncertainties

Uncertainty	up (%)	down (%)
Statistical	2.2	−2.2
Detector simulation		
Jets	1.8	−2.4
Muon	2.3	−2.3
Electron	1.5	−1.7
E_T^{miss}	1.1	−0.9
Signal model		
Generator*)	3.0	−3.0
Hadronization*)	0.5	−0.5
ISR/FSR	1.7	−1.3
PDF*)	1.0	−1.0
Background model		
QCD shape*)	0.4	−0.4
W shape*)	0.5	−0.5
Monte Carlo statistics*)	1.8	−1.8
Systematic	5.0	−5.0
Stat. & Syst.	5.4	−5.4
Luminosity	3.7	−3.7
Total	6.6	−6.6

$$\sigma_{t\bar{t}} = 179 \pm 4(\text{stat}) \pm 9(\text{syst}) \pm 7(\text{lum})\ \text{pb}$$

Overall precision: ~7%

Limited by systematic uncertainties

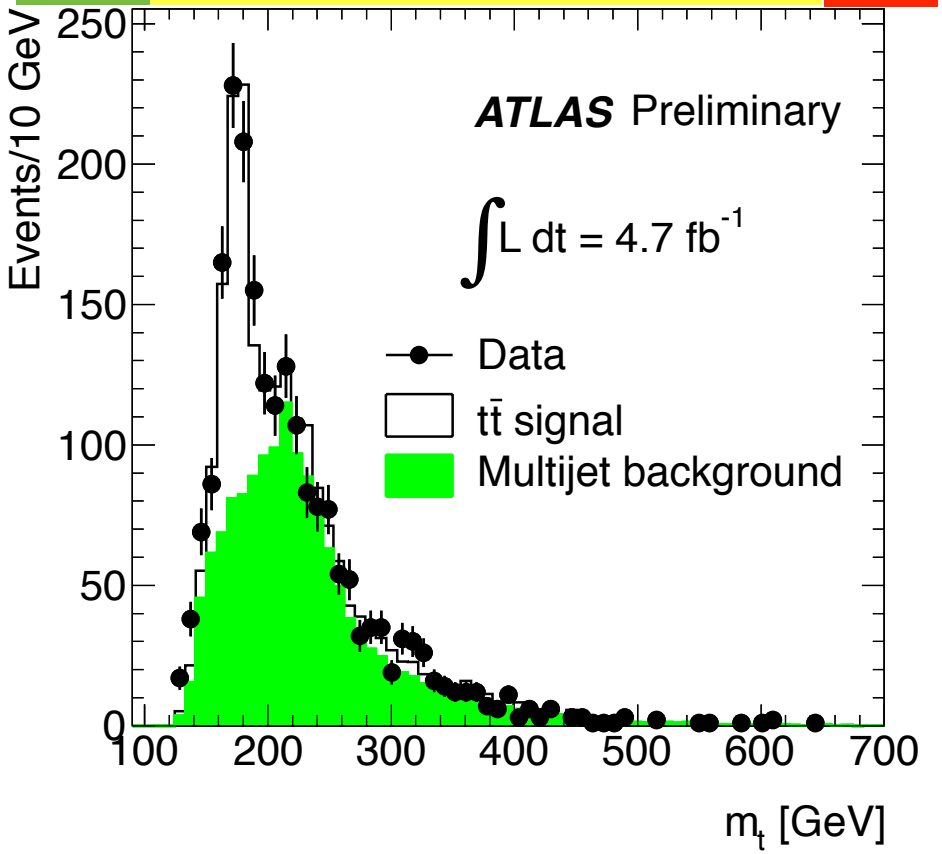
[ATLAS-CONF-2011-121]

Pair production with hadronic events

All-hadronic channel

Signature: Multijets (2*b*)
Method: Fit to m_t distribution

5 fb^{-1} top candidates invariant mass **new**



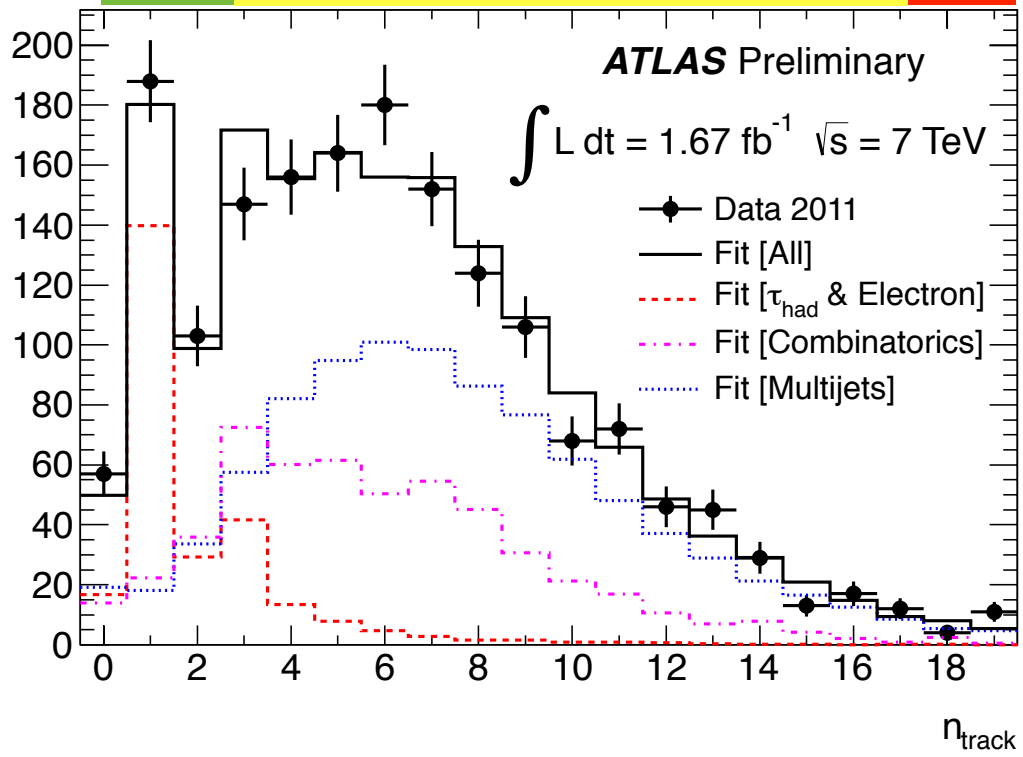
$\sigma_{t\bar{t}} = 168 \pm 12(\text{stat}) \pm 59(\text{syst}) \pm 7(\text{lum})$ pb

[ATLAS-CONF-2012-031]

Hadronic τ+jets

Signature: Multijets (2*b*)
Method: Fit to n_{track} distribution

2 fb^{-1} number of tracks for τ-jets **new**



$\sigma_{t\bar{t}} = 200 \pm 19(\text{stat}) \pm 42(\text{syst}) \pm 8(\text{lum})$ pb

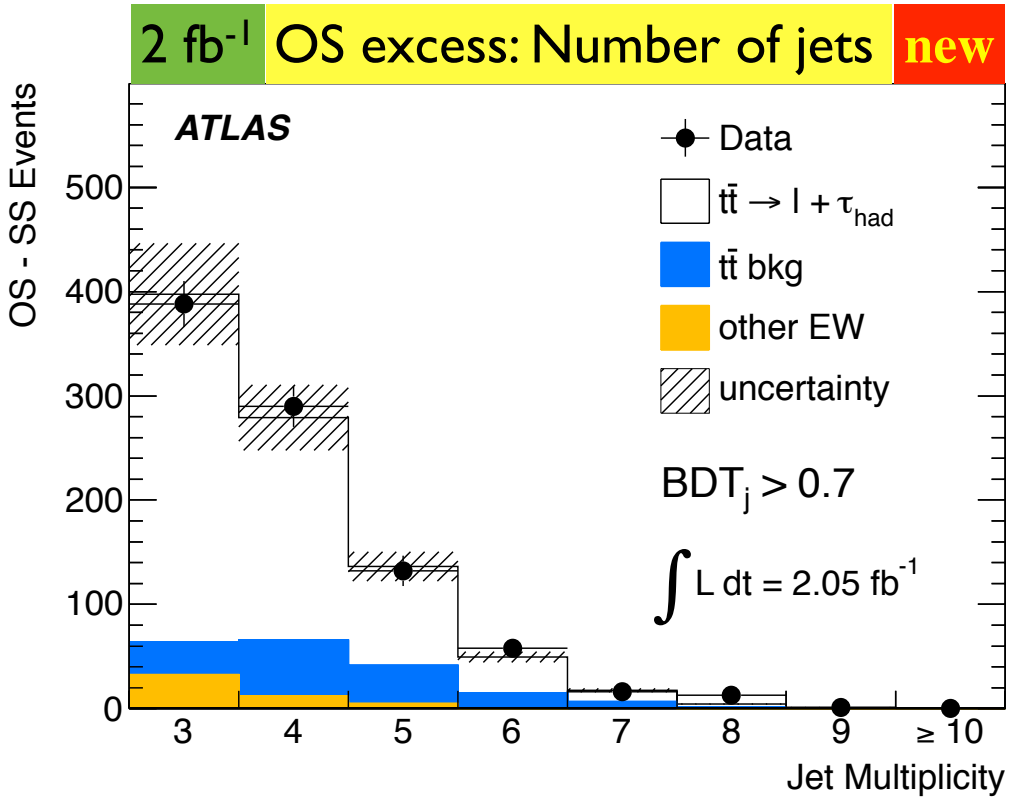
[ATLAS-CONF-2012-032]

Additional top pair production

Pair production with (e,μ)+τ+jets

Signature: (e,μ)+τ+E_{Tmiss}+jets (1*b*)

Method: MV τ identification from tracking and calorimeters



$\sigma_{t\bar{t}} = 186 \pm 13(\text{stat}) \pm 20(\text{syst}) \pm 7(\text{lum})$ pb

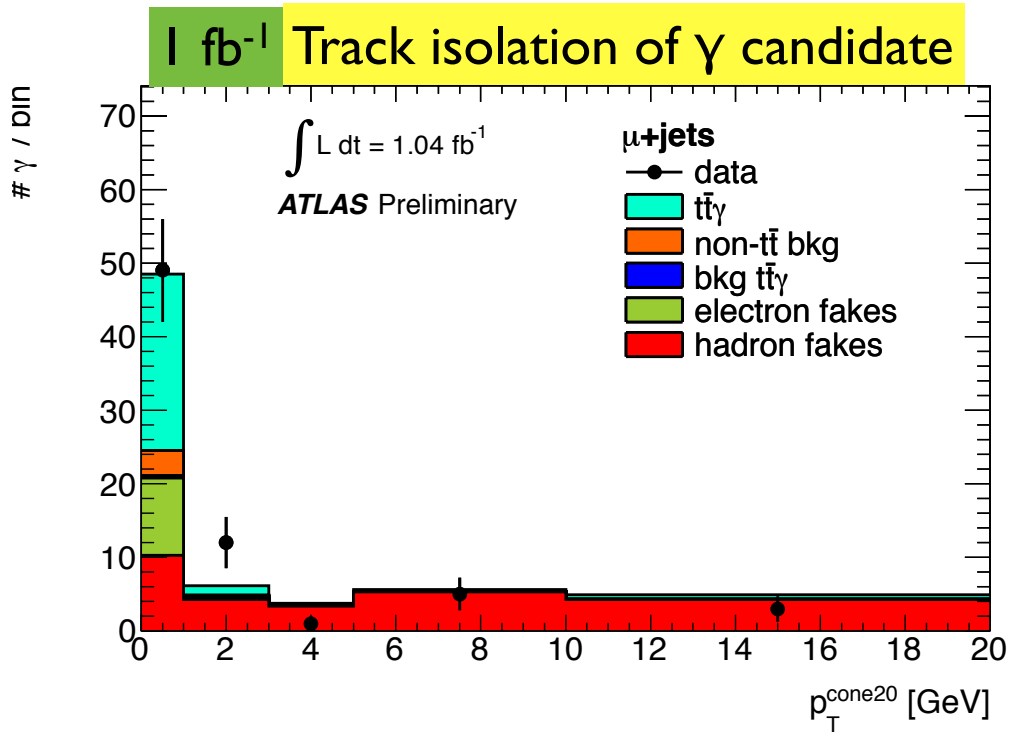
[arXiv: 1205.2067 (2012)]

tt+Photon

Signature: 1 isolated e/μ+E_{Tmiss}+ 4 jets(≥1*b*)+γ

Method: Fit to track isolation of γ

Expected: $\sigma^{NLO}_{t\bar{t}\gamma}(p_{T,\gamma} > 8\text{GeV}) \times BR(LJ, DIL) = 2.1 \pm 0.4$ pb

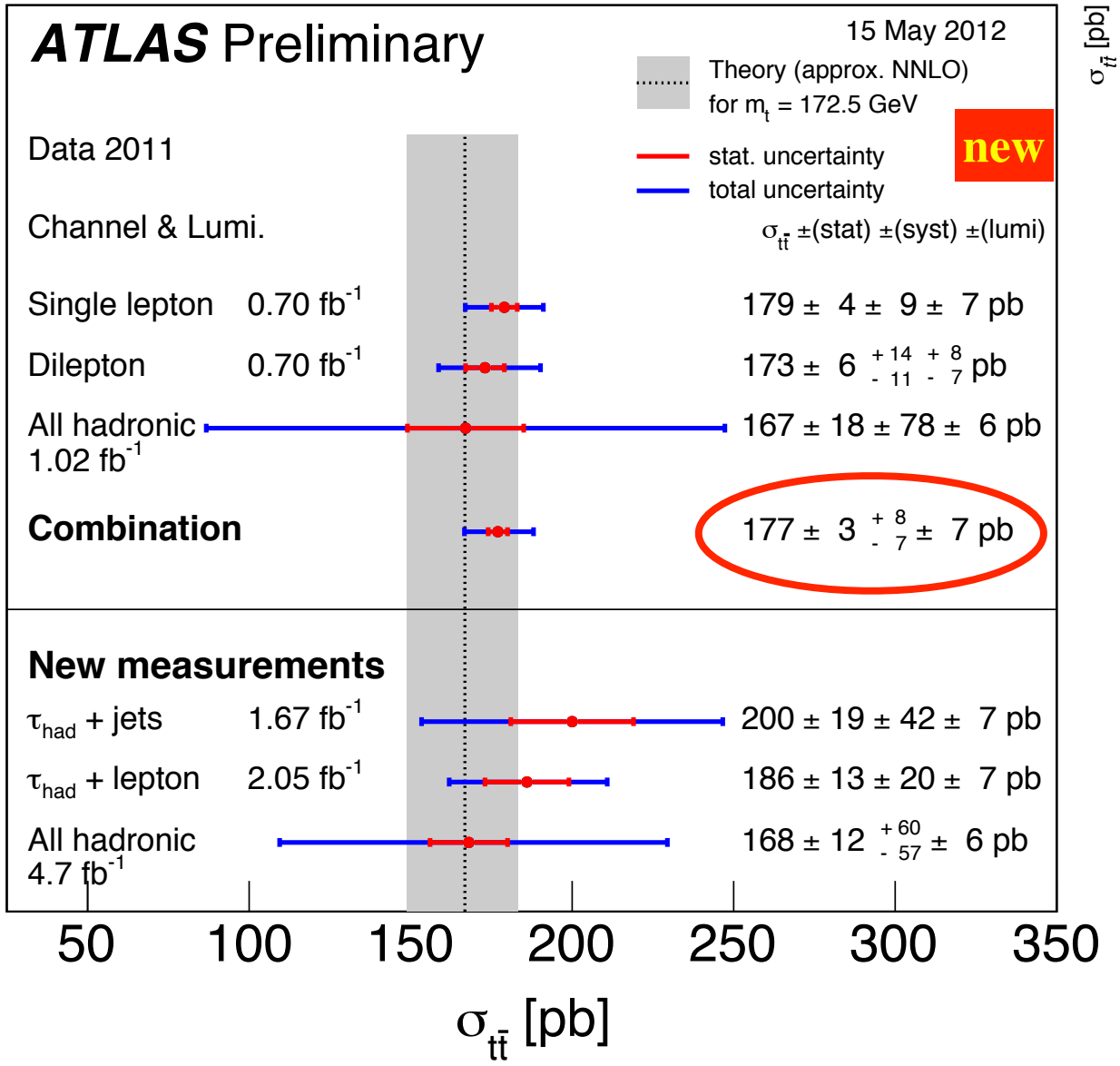


$\sigma_{t\bar{t}\gamma}(p_{T,\gamma} > 8\text{GeV}) \times BR(LJ, DIL) = 2.0 \pm 0.5(\text{stat}) \pm 0.7(\text{syst}) \pm 0.1(\text{lum})$ pb

[ATLAS-CONF-2011-153 (2011)]

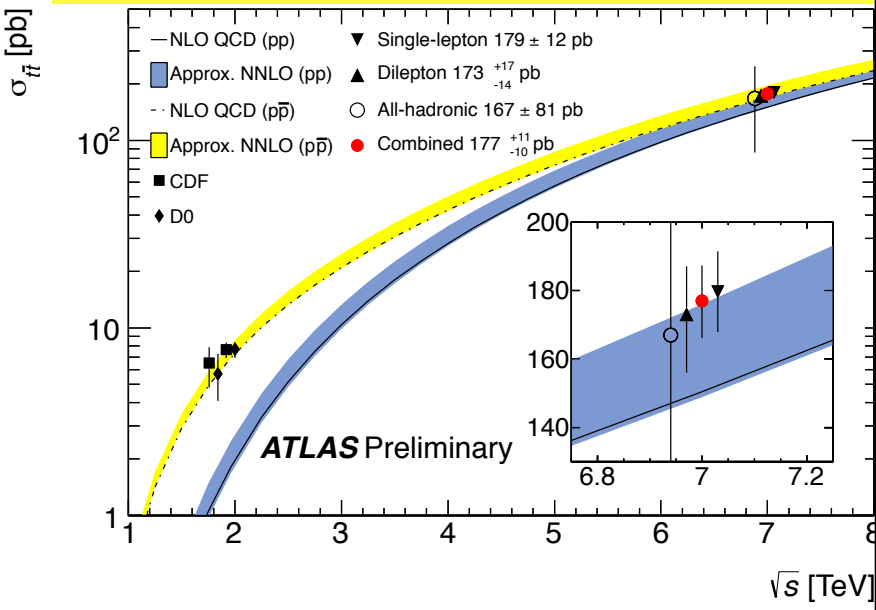
Combination of σ_{tt} measurements

Main σ_{tt} measurements and Combination of channels



[ATLAS-CONF-2012-024]

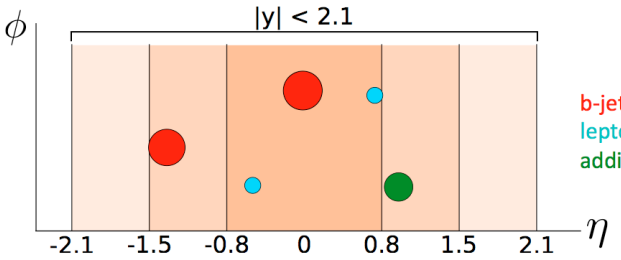
σ_{tt} vs $\sqrt{s}$ from ATLAS and Tevatron



- Precision of ~6%, 1/2 Theory uncertainty.
- Agreement between channels within uncertainties.

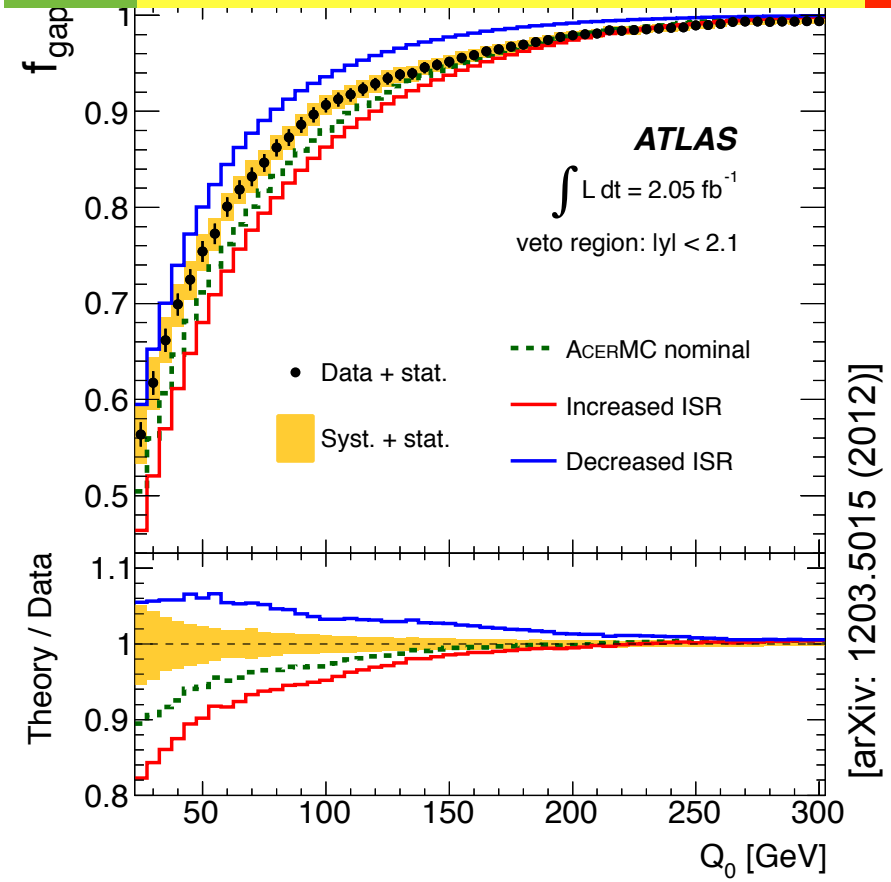
Differential *tt* measurements

Gap fraction in dileptonic events



$$f_{gap}(Q_0) = \frac{n_{gap}(Q_0)}{N_{ttbar}}$$

2 fb^{-1} f_{gap} vs. Q_0 shown with ISR tunes **new**

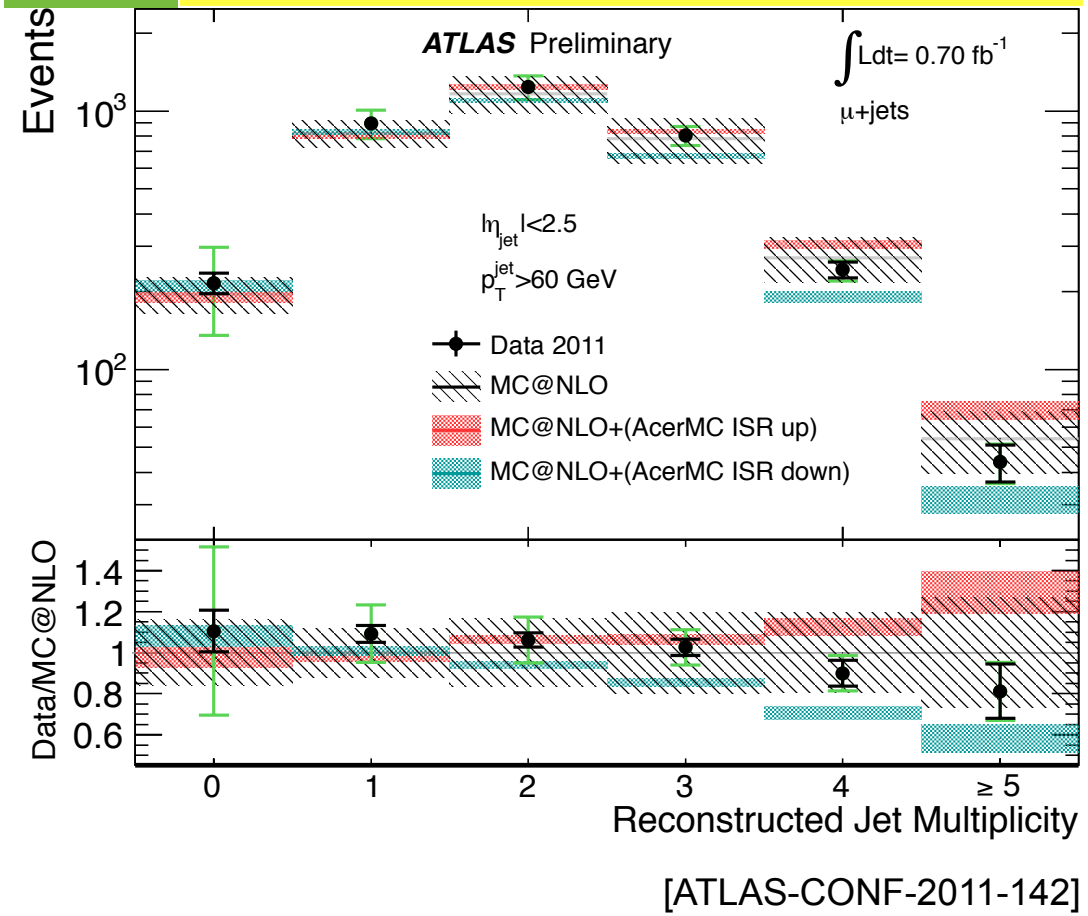


Observed jet multiplicity in *tt* events

Signature: 1 isolated e/μ+E_{Tmiss}+jets(*b*)

Method: Jet multiplicity for $E_{T,jets}$>25,40,60 GeV

0.7 fb^{-1} Reconstructed jet (60 GeV) multiplicity

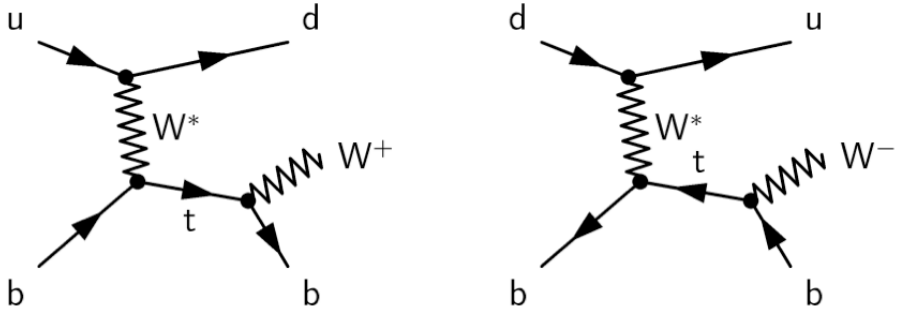


[ATLAS-CONF-2011-142]

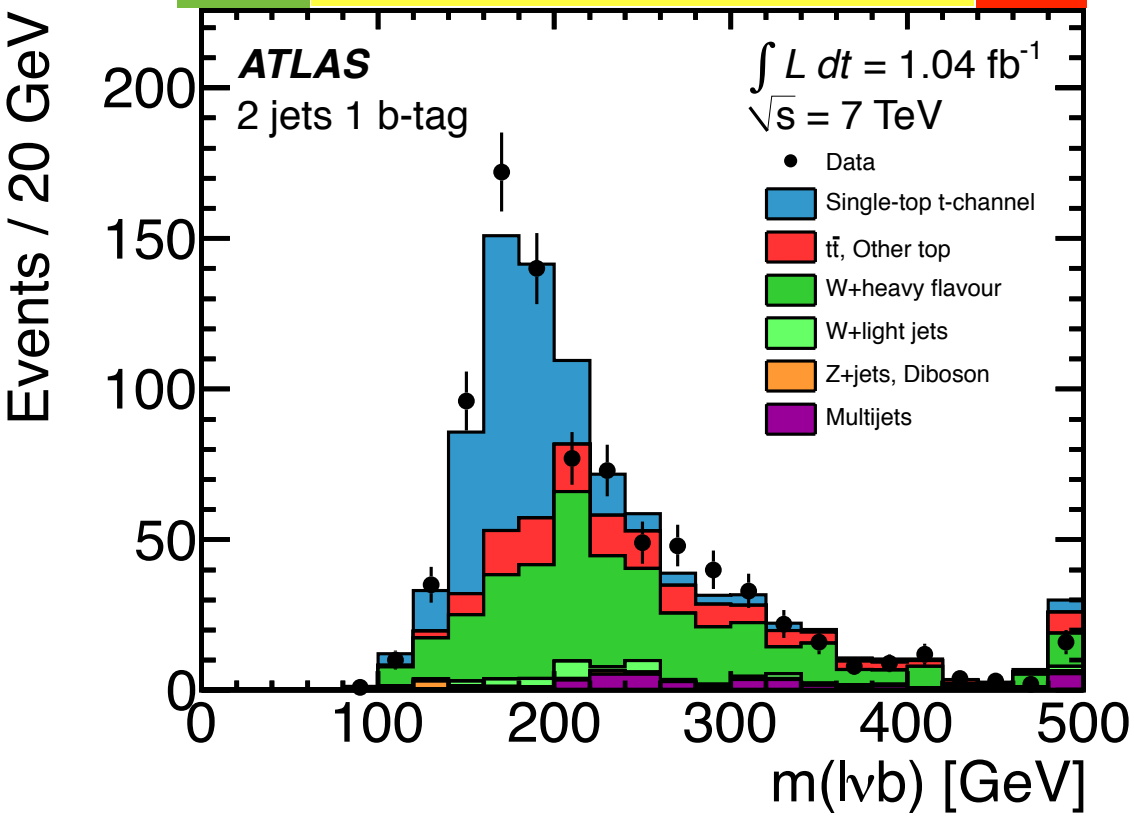
Electroweak top production: t-channel

Signature: 1 isolated e/μ +E_{Tmiss}+ 2 or 3J(==1 b-tag)

Method: Likelihood fit on NN discriminant



1 fb^{-1} Invariant mass of lνb system **new**



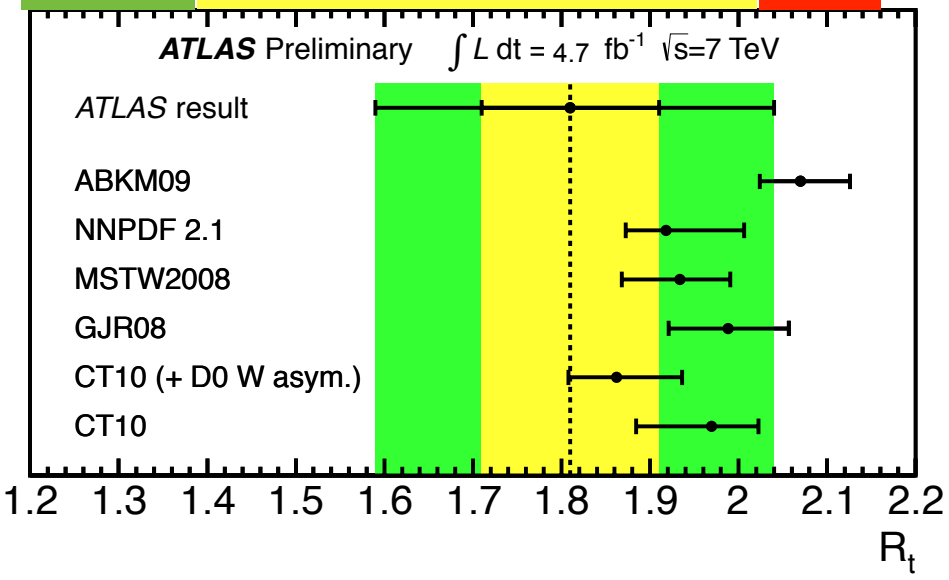
$$\sigma_t = 83 \pm 4(\text{stat})^{+20}_{-19}(\text{syst})\ \text{pb}$$

Observed significance: 7.2 σ

$|V_{tb}| > 0.75$ @95%C.L.

[arXiv:1205.3130 (2012)]

4.7 fb^{-1} Ratio of top to anti-top **new**



$$\sigma_t = 53.2 \pm 10.8\ \text{pb}$$
$$\sigma_{\bar{t}} = 29.5 \pm 7.5\ \text{pb}$$

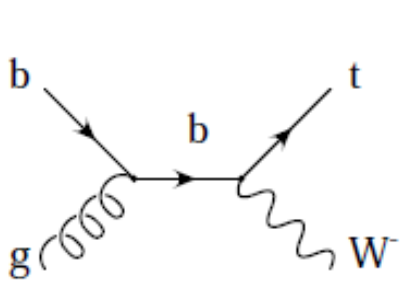
$$R_t = 1.81^{+0.23}_{-0.22}$$

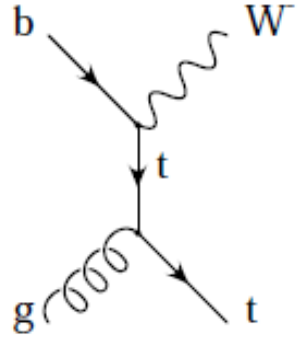
[ATLAS-CONF-2012-056]

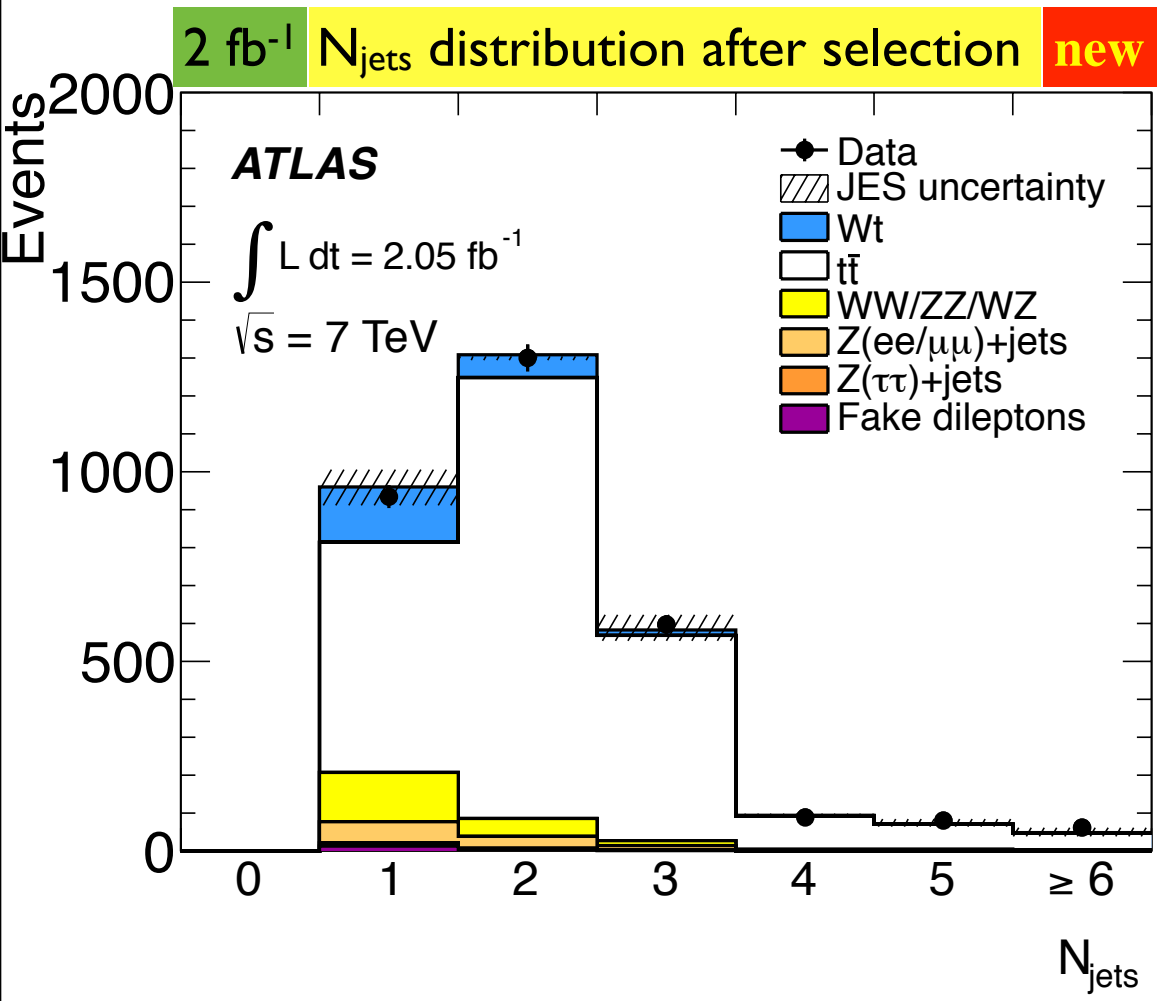
Electroweak production: Wt-channel

Signature: 2 isolated e/μ +E_{Tmiss}+ 1J

Method: BDT output fit.







[arXiv:1205.5764 (2012)]

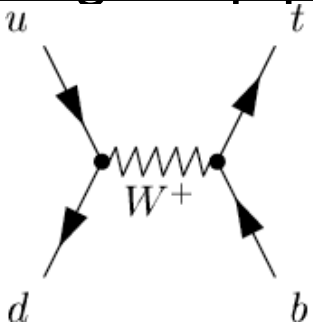
$$\sigma_{Wt} = 16.8 \pm 2.9(\text{stat}) \pm 4.9(\text{syst})\ \text{pb}$$

Observed significance: ~3.3 σ

$$|V_{tb}| = 1.03^{+0.16}_{-0.19}$$

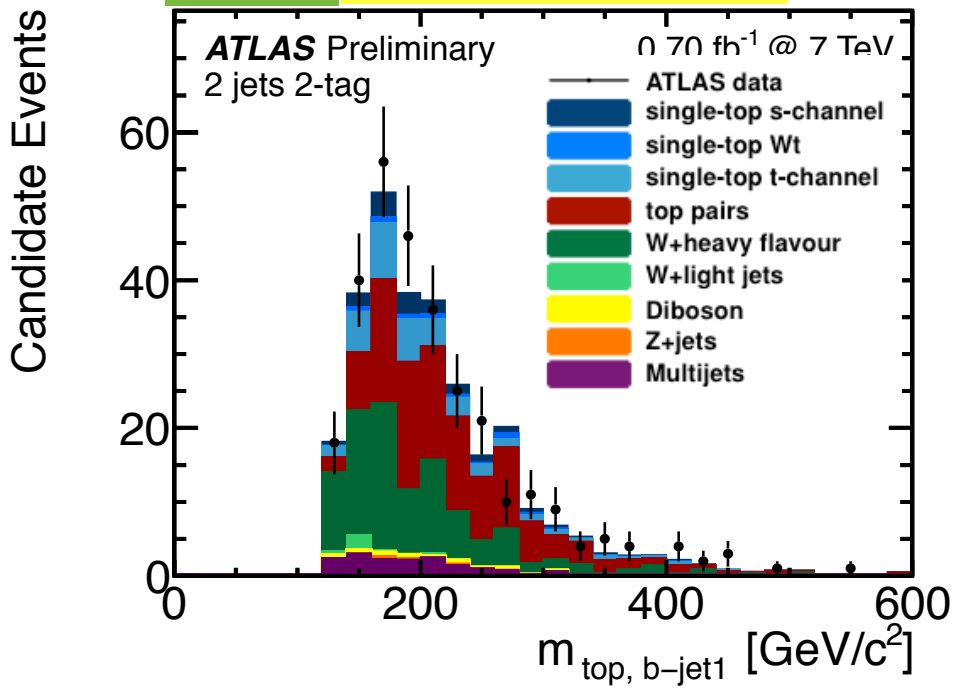
Single top production: searches

Single top production: s-channel



Signature: 1 isolated e/μ +E_{Tmiss}+ 2*b*

0.7 fb^{-1} $l\nu b_l$ invariant mass



$\sigma_{t-sch} < 26.5$ pb @95% C.L.

[ATLAS-CONF-2011-118 (2011)]

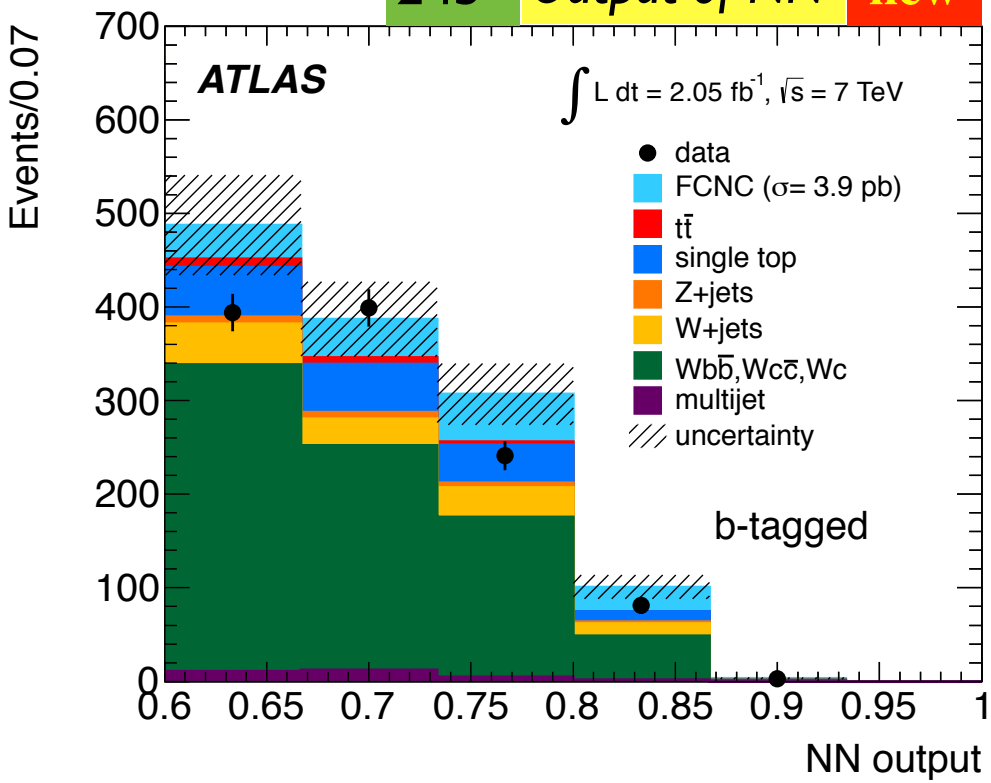
Single top production: FCNC

qg→*t*→*Wb* (2→1)

Signature: 1 isolated e/μ +E_{Tmiss}+1*b*

Method: Fit to NN distribution

2 fb^{-1} *Output of NN* **new**



$\sigma_{qg\to t} \times B(t \to Wb) < 3.9$ pb @95% C.L.

Stringent limits on *t*→*ug* and *t*→*cg*, and coupling constants

[arXiv 1203.0529 (2012)]

top quark mass: single lepton events

Mass in l+jets with template method (1D and 2D)

Signature: 1 isolated e/μ +E_{Tmiss}+ ≥4J (≥1b-tag).

Likelihood fit to event topology to improve purity

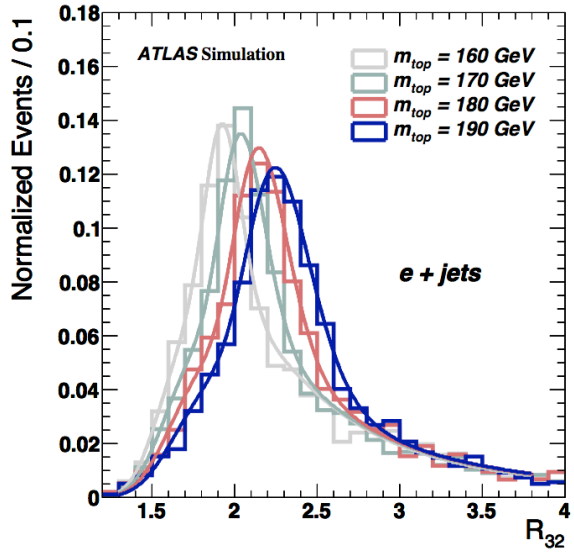
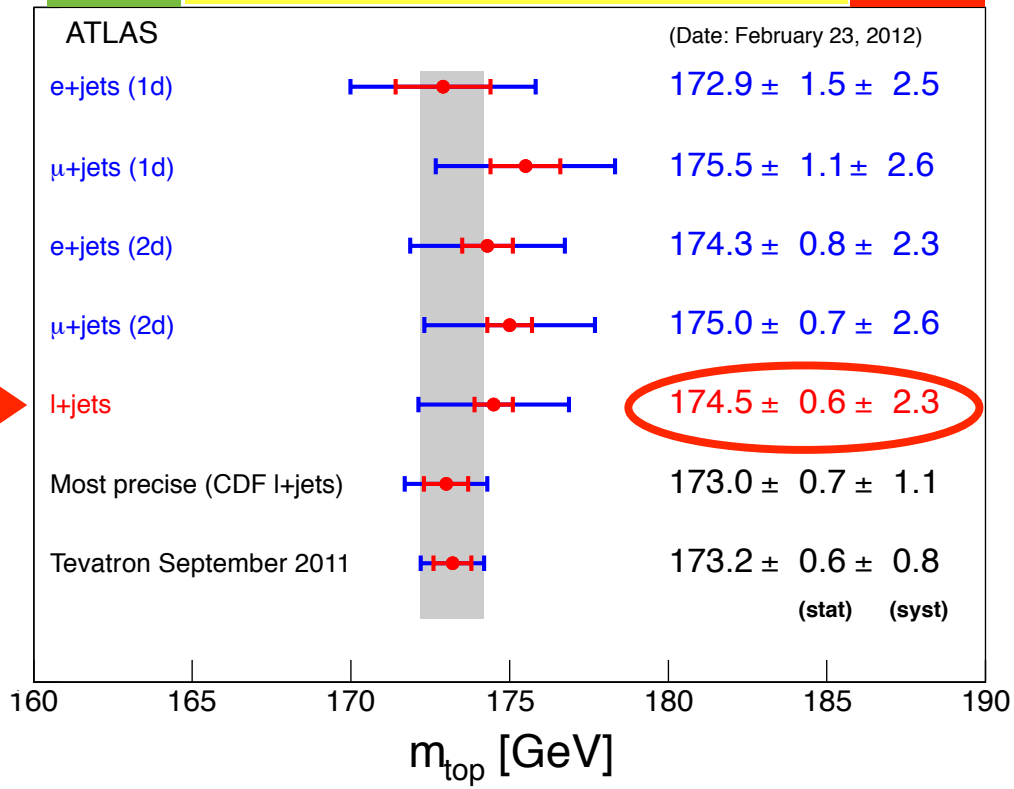


Table of uncertainties

	1d	2d
Measured value of m_{top}	174.35	174.53
Data statistics	0.91	0.61
Jet energy scale factor	na	0.43
Method calibration	< 0.05	0.07
Signal MC generator	0.74	0.33
Hadronisation	0.43	0.15
Pileup	< 0.05	< 0.05
Underlying event	0.08	0.59
Colour reconnection	0.62	0.55
ISR and FSR (signal only)	1.42	1.01
Proton PDF	0.15	0.10
W+jets background normalisation	0.18	0.37
W+jets background shape	0.15	0.12
QCD multijet background normalisation	< 0.05	0.20
QCD multijet background shape	0.09	0.27
Jet energy scale	1.23	0.66
b-jet energy scale	1.16	1.58
b-tagging efficiency and mistag rate	0.17	0.29
Jet energy resolution	0.36	0.07
Jet reconstruction efficiency	0.10	< 0.05
Missing transverse momentum	< 0.05	0.13
Total systematic uncertainty	2.50	2.31
Total uncertainty	2.66	2.39

[arXiv:1203.5755v1 (2012)]

1 fb^{-1} Combination and final result **new**



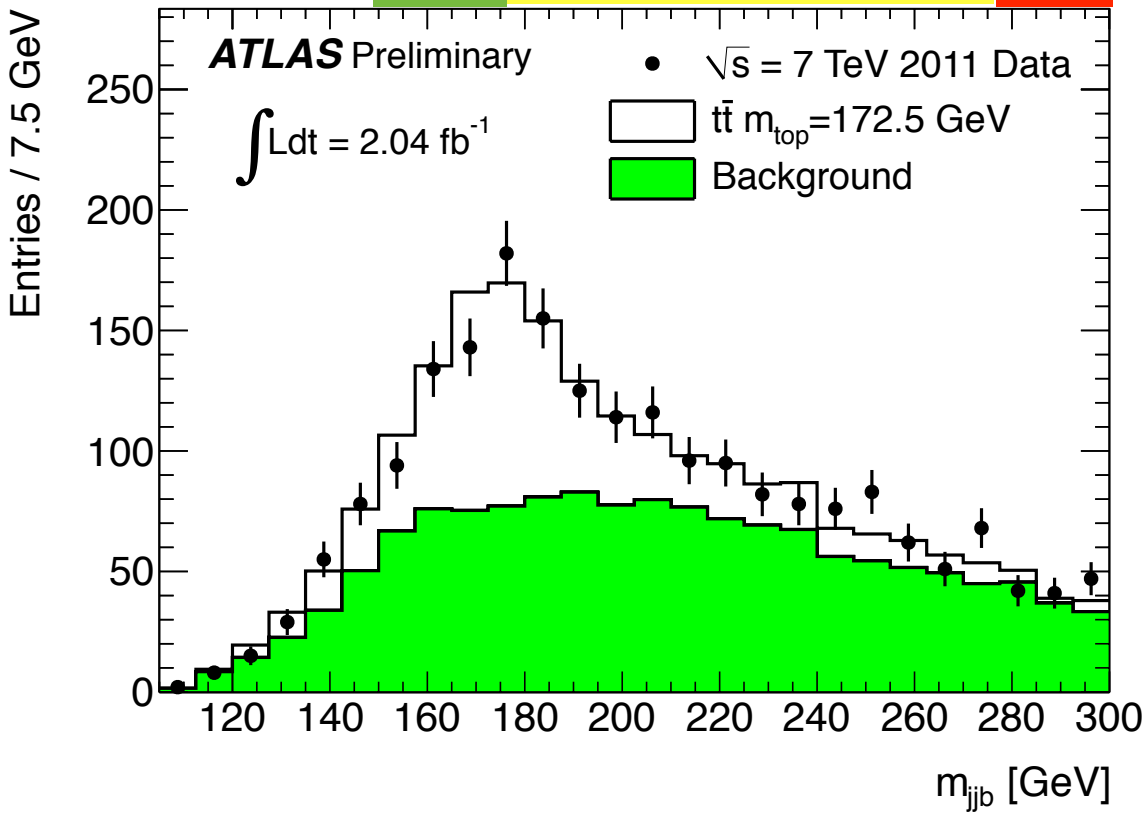
top quark mass: other

Mass in all-hadronic top decays: fit to m_{jjb}

Signature: Multijets (6, ≥2*b*-tag).

Likelihood fit to improve signal purity

2 fb^{-1} | Tri-jet invariant mass | new

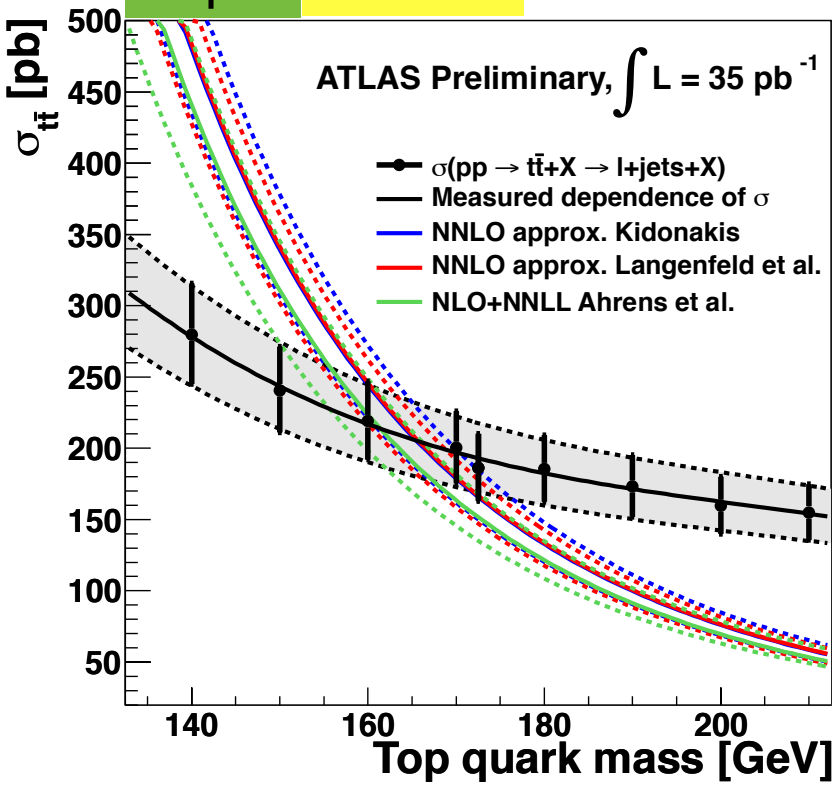


$m_t = 174.9 \pm 2.1\ (\text{stat.}) \pm 3.8\ (\text{syst.})\ \text{GeV}$

[ATLAS-CONF-2012-130]

Top mass from σ_{tt}

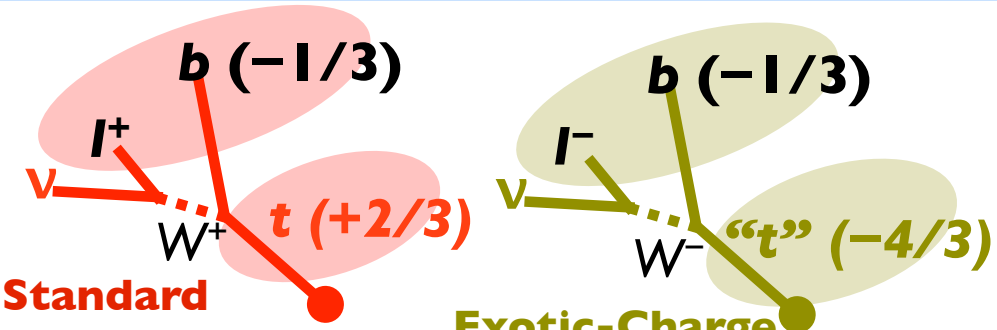
35 pb^{-1} | σ_{tt} vs. m_t



$m_{\text{top}}^{\text{pole}} = (166.4\,^{+7.8}_{-7.3})\ \text{GeV}.$

[ATLAS-CONF-2011-054]

Top quark electric charge

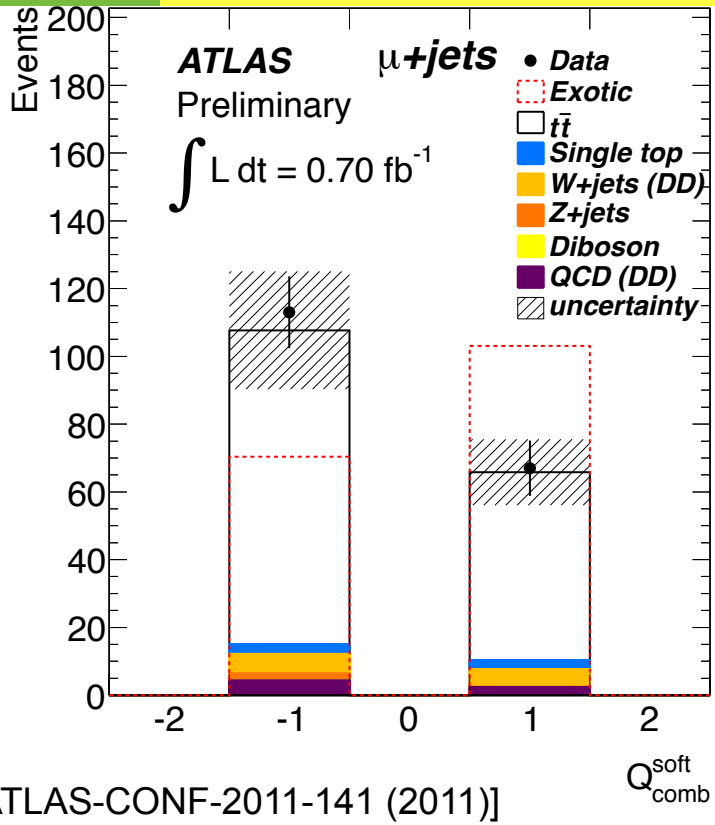


See [D. Chang et al., PRD59 (1999) 091503] for details

Signature: Lepton+jets events

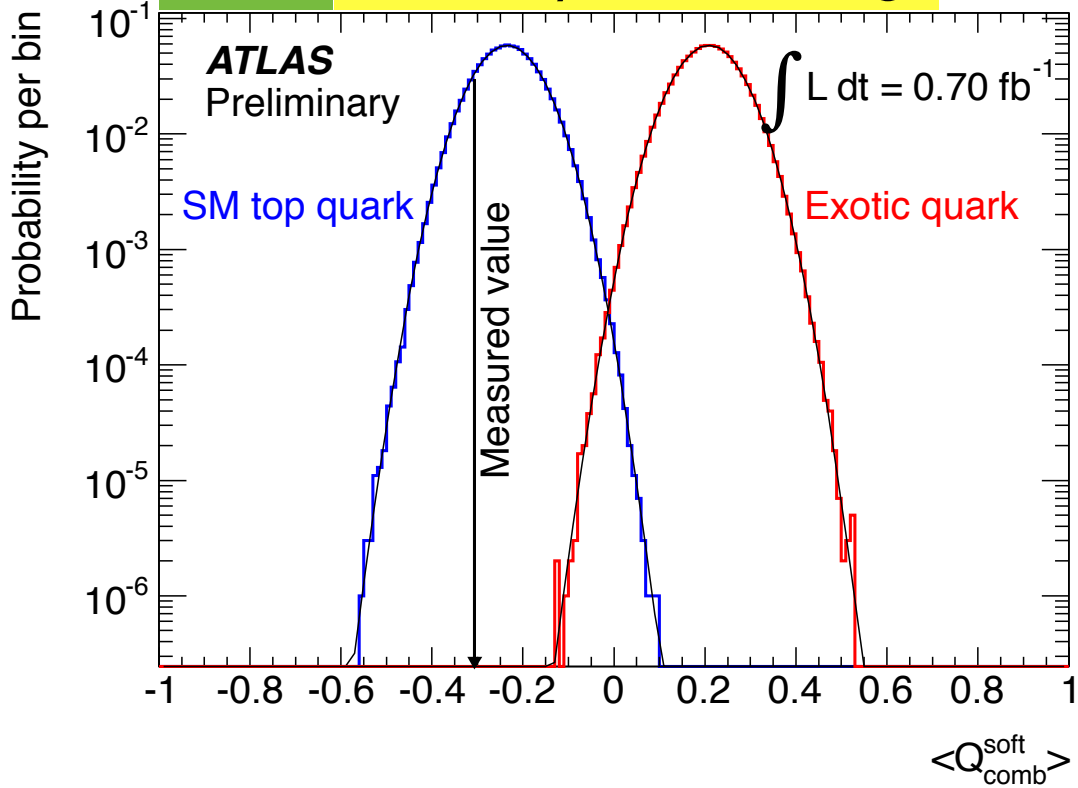
Method: jet charge and semileptonic B→μX decays

0.7 fb^{-1} Observed charge combination



[ATLAS-CONF-2011-141 (2011)]

0.7 fb^{-1} Probability for obs. charge



-4/3e excluded with >5σ

Spin correlations in top production

Signature: dilepton events

Method: leptonic angular opening, converted into *A* in the helicity and maximal bases.

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

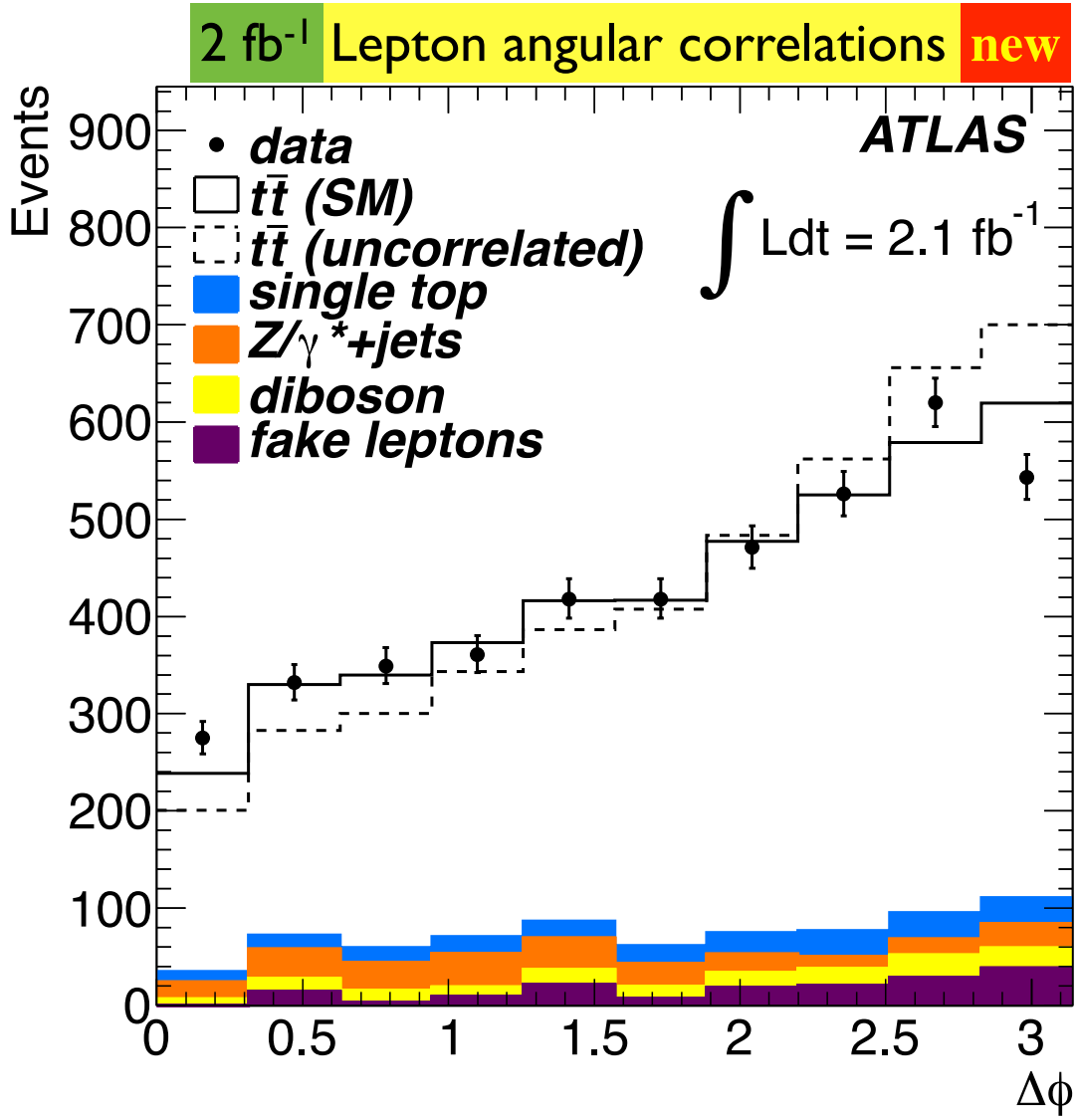
SM expectation

$$A^{\mathrm{SM}}_{\mathrm{helicity}} = 0.31 \qquad A^{\mathrm{SM}}_{\mathrm{maximal}} = 0.44$$

Measurement:

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

$$A^{ATLAS}_{\mathrm{maximal}} = 0.57 \pm 0.06(\mathrm{stat})^{+0.12}_{-0.10}(\mathrm{syst})$$



Observed significance (correlation of spins): 5.1σ

[arXiv:1203.4081v2 (2012), PRL108,212001(2012)]

Charge Asymmetry in top pairs

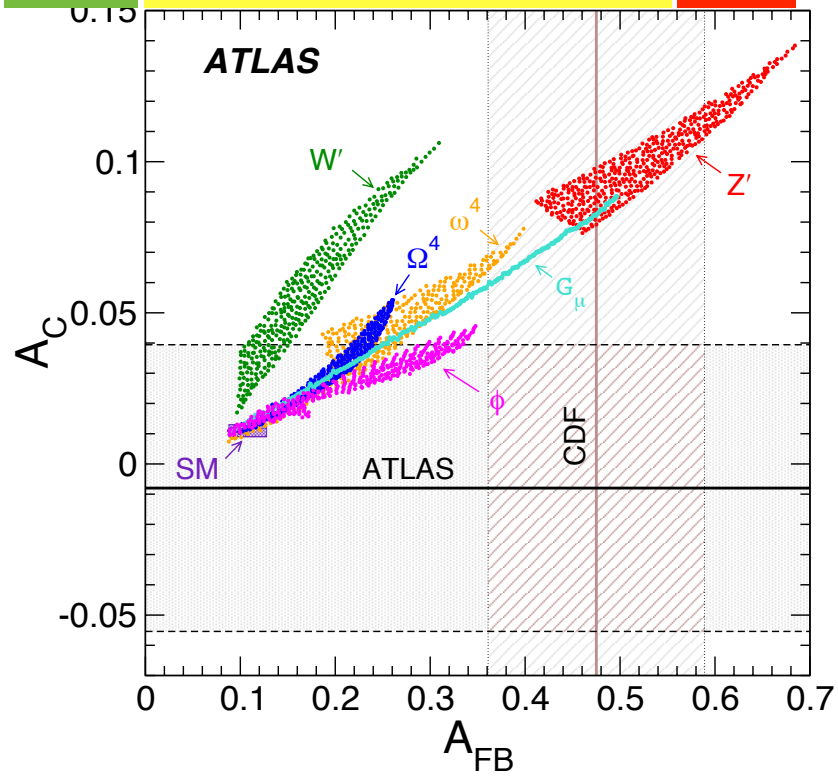
Small excess of centrally produced anti-top quarks, A_C=0.006±0.002 (MC@NLO)

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

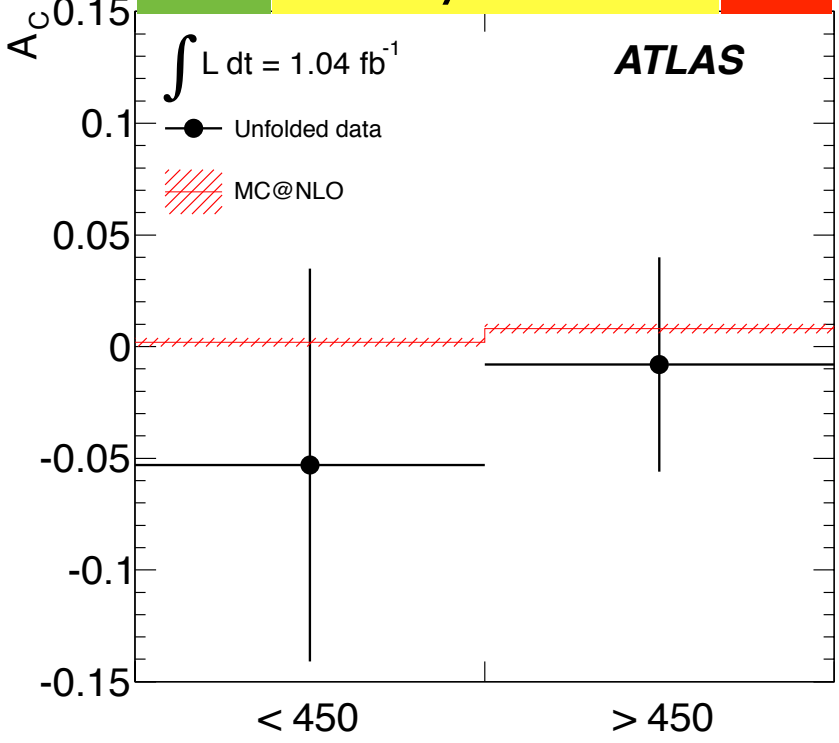
$$\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$

Signature: Lepton+jets 1 fb^{-1}
and dilepton events 4.7 fb^{-1} new
Method: Unfolding for A_C

1 fb^{-1} New Physics Scenarios new



1 fb^{-1} A_C vs system mass new



$$A_C^{t\bar{t}} = -0.018 \pm 0.028(\text{stat}) \pm 0.023(\text{syst}) \ [\text{l} + \text{jets}]$$
$$A_C^{t\bar{t}} = 0.057 \pm 0.024(\text{stat}) \pm 0.015(\text{syst}) \ [\text{dilep.}]$$
$$A_C^{t\bar{t}} = 0.029 \pm 0.018(\text{stat}) \pm 0.014(\text{syst}) \ [Comb.]$$

[arXiv:1203.4211 (2012)]
[ATLAS-CONF-2012-057]

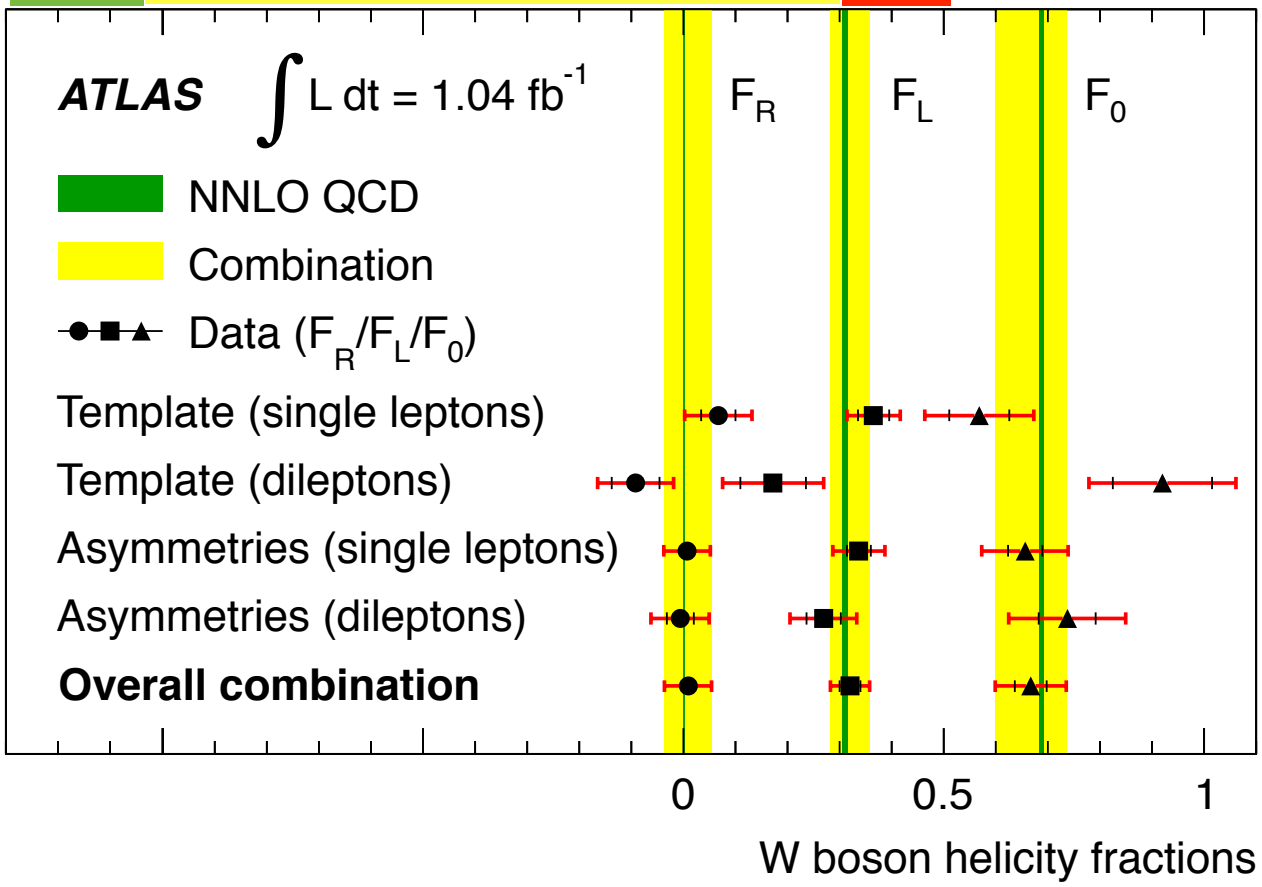
Helicity of W bosons in top decays

Two methods: $\cos\theta^*$ Template fit and Asymmetries from $\cos\theta^*$

Signature: Single lepton and dileptons channels

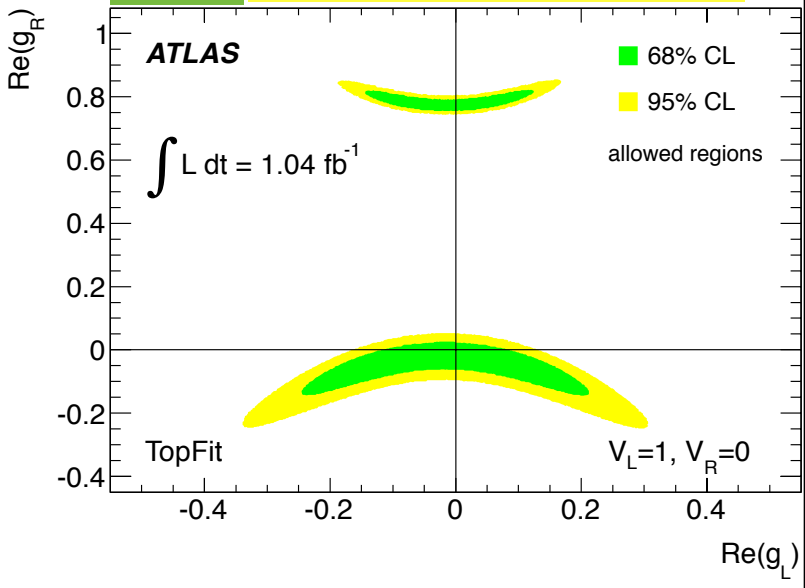
Likelihood fit for event topology

1 fb^{-1} Measured W helicity fractions **new**



[arXiv:1205.2484(2012)]

1 fb^{-1} Anomalous couplings



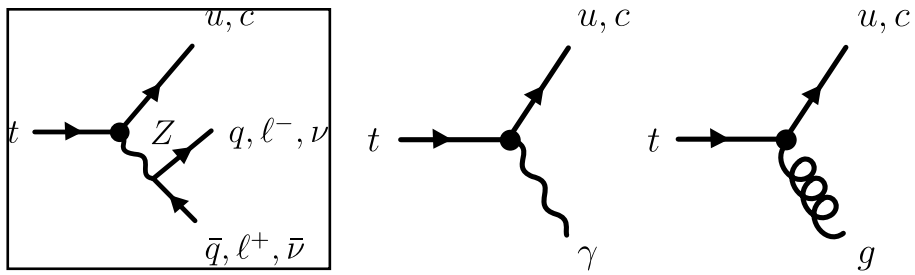
~±10%

$$F_0 = 0.67 \pm 0.03\ (\text{stat.}) \pm 0.06\ (\text{syst.}),$$
$$F_L = 0.32 \pm 0.02\ (\text{stat.}) \pm 0.03\ (\text{syst.}),$$
$$F_R = 0.01 \pm 0.01\ (\text{stat.}) \pm 0.04\ (\text{syst.}).$$

Anomalies in tt production and decays

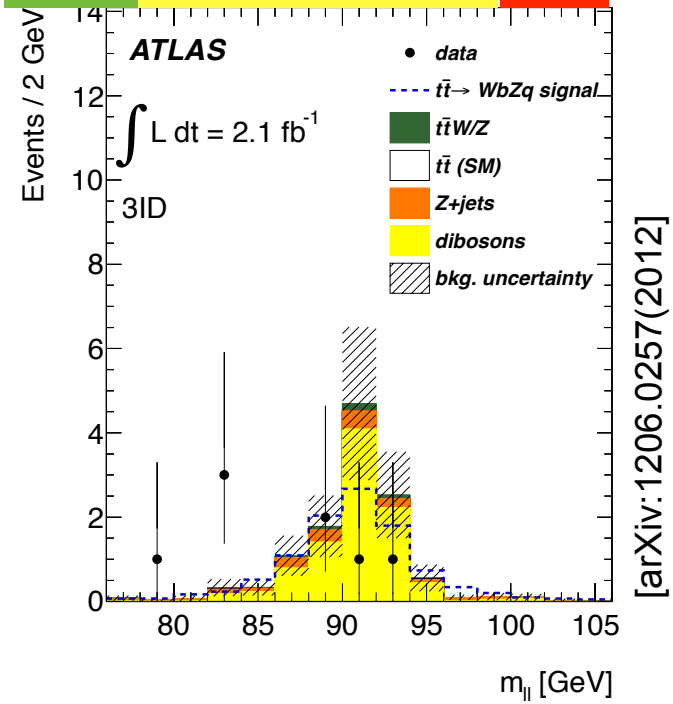
FCNC in top pair decays

Expected O(10^{-4})



Signature: 3 isolated leptons+2j+E_{Tmiss}

2 fb^{-1} FCNC in ttbar **new**



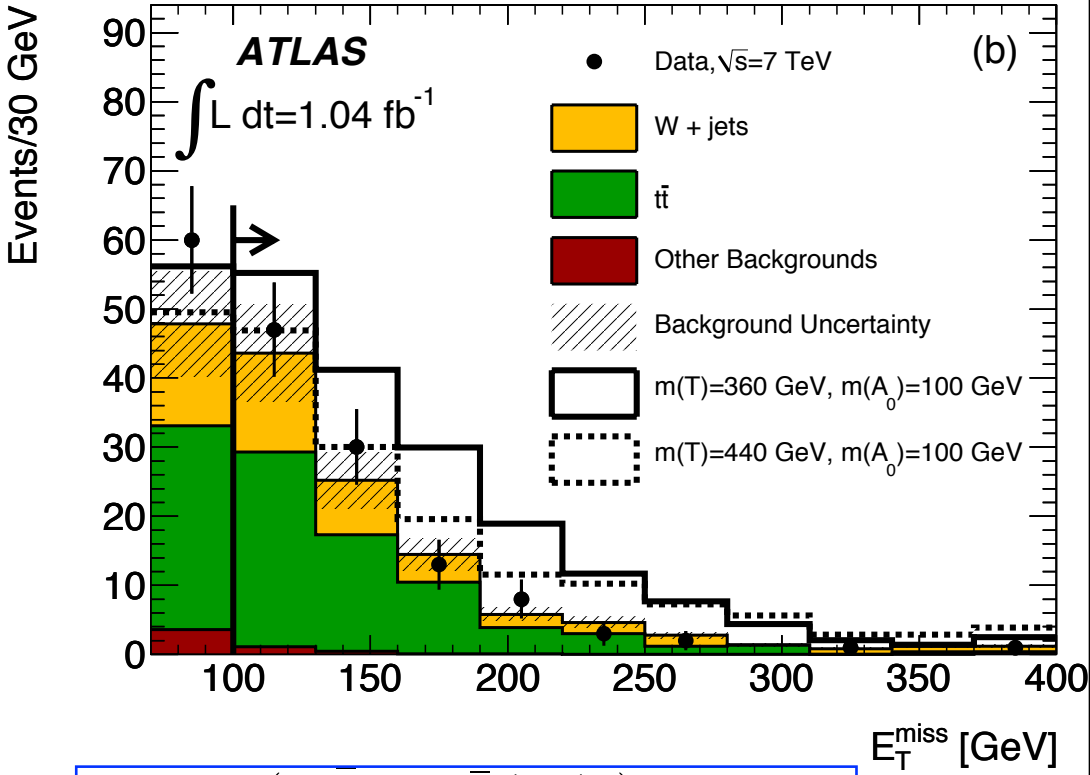
$BR(t \rightarrow Zq) < 0.73\%$ @95%(C.L.)

Large Missing Energy in top pairs

Signature: Lepton+jets events w. large E_{Tmiss}

Hypotheses: $TT \rightarrow ttA_0A_0$

1 fb^{-1} large ME_T in tt events



$\sigma \times BR(T\bar{T} \rightarrow t\bar{t}A_0A_0) < 1.1$ pb

@95%C.L. for $m_T = 420$ GeV, $m_{A_0} = 10$ GeV

Search for resonant top production

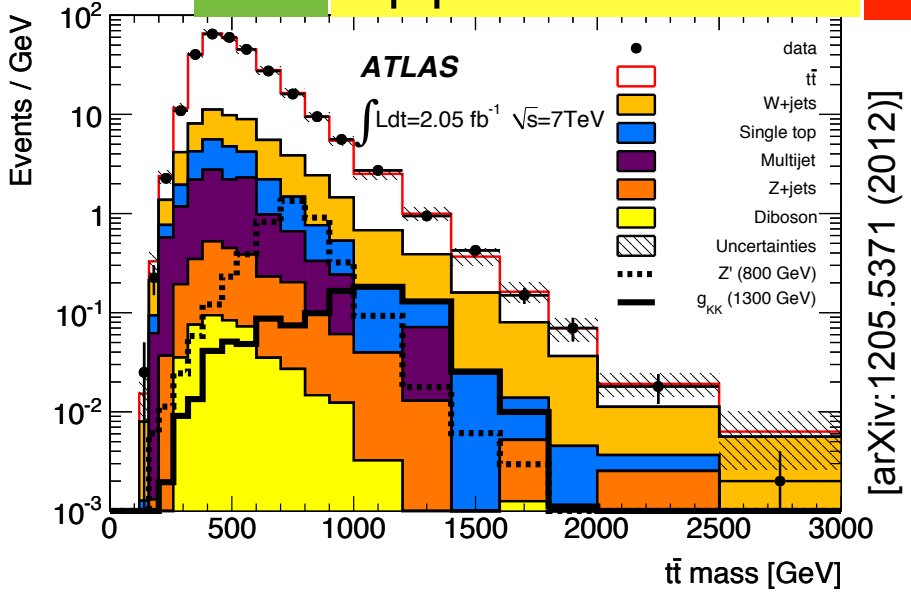
Resonant top pair production

Signature: Lepton+jets and dilepton events

analysis #1: mass reco.(L+J) and total tranverse energy (DIL).

analysis #2: dedicated "fat-jet" search (boosted top, L+J)

2 fb^{-1} top pair invariant mass new



$m_{Z'}, m_{gKK} < 500\ GeV/c^2$

$m_{Z'} > 1.2\ TeV/c^2$ leptophobic topcolor, narrow

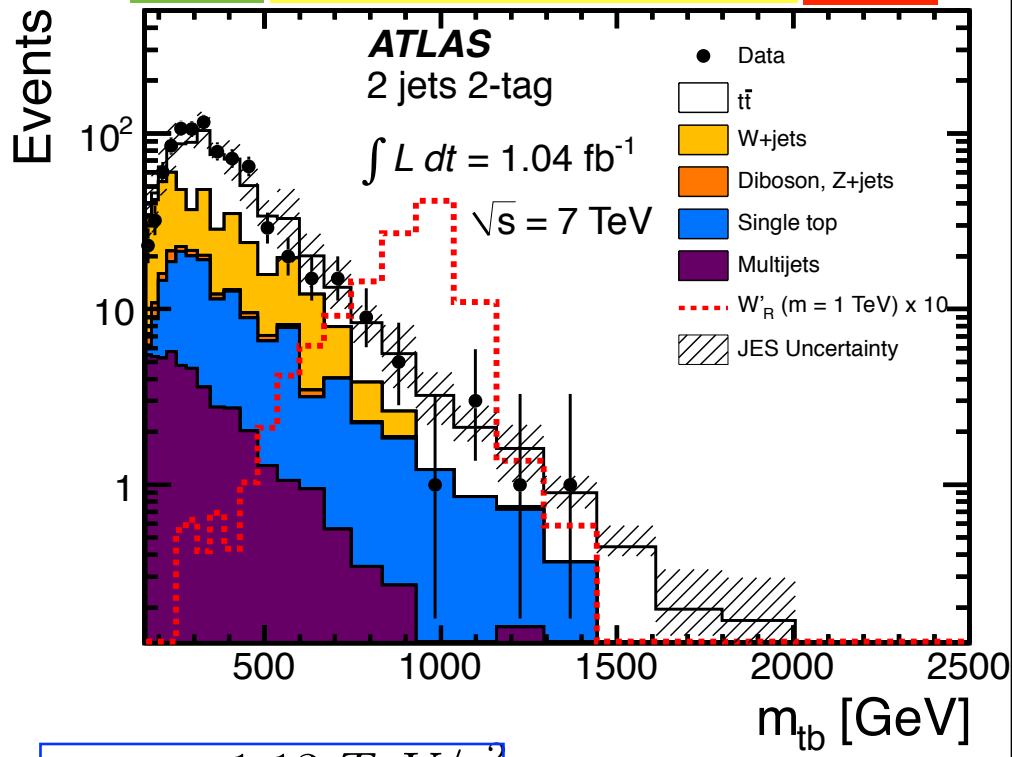
$m_{gKK} > 1.5\ TeV/c^2$ KK guon, broad

Resonant *tb* production

Signature: $tb \rightarrow lvbb$

Method: *lv-W* reconstruction and double b-tag

1 fb^{-1} tb (W') invariant mass new

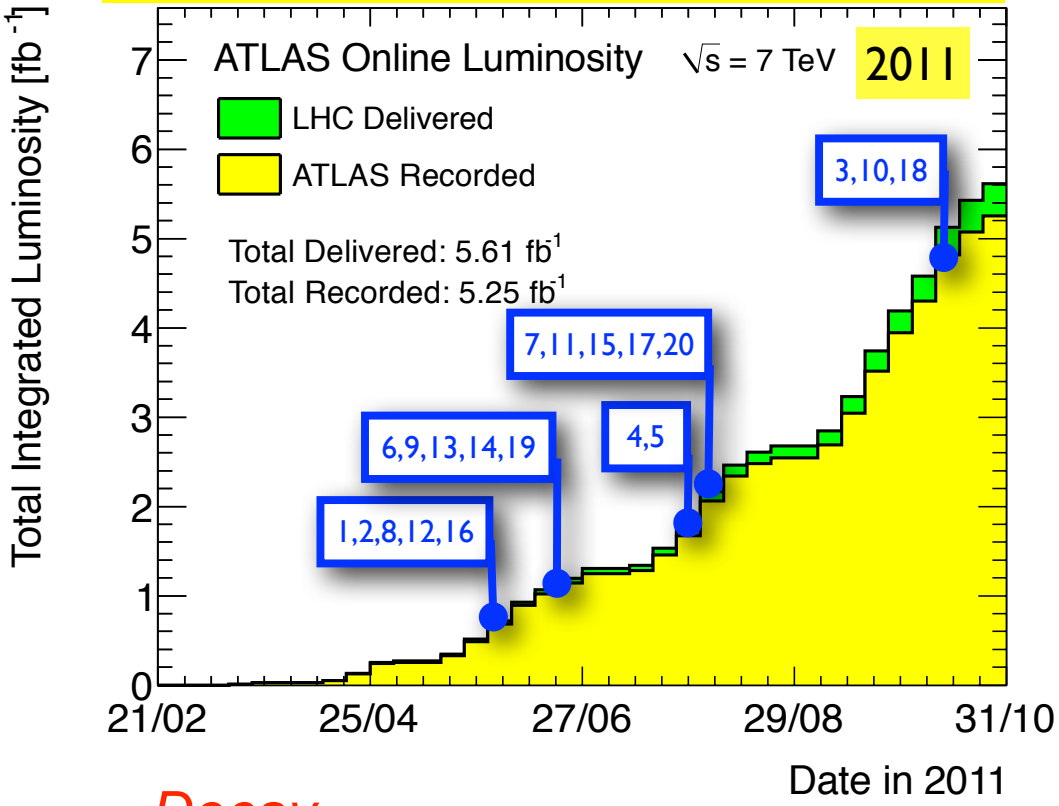


$m_{W'_R} > 1.13\ TeV/c^2$ W' boson, Right-handed

[arXiv:1205.1016 (2012)]

Summary of ATLAS top physics

Collision data delivered and recorded vs. time for the 2011 7 TeV running period



Production Rate

1	σ_{tt} (dilepton channel)	±9%
2	σ_{tt} (single lepton channel)	±7%
3	σ_{tt} (hadronic channel)	±36%
4	σ_{tt} (τ+jets)	±27%
5	σ_{tt} (e,μ+τ)	±15%
6	σ_{tt} (ttγ)	±41%
	σ_{tt} combined	±6%
7	Differential σ_{tt}, jet veto	obs.
8	Differential σ_{tt}, N_{jets}	up to 5
9	$\sigma_{t,\ t\text{-channel}}$, $\lvert V_{tb}\rvert$	~7.2σ
10	$R=\sigma_{t,}/\sigma_{tbar,\ t\text{-channel}}$	±12%
11	$\sigma_{t,\ Wt\text{-channel}}$	~3.3σ
12	$\sigma_{t,\ s\text{-channel}}$	<26 pb
13	$\sigma_{t,\ FCNC}$ x B(W→lν)	<3.9 pb

Decay

19	Helicity of W bosons	~±10%
20	FCNC in decay (t→Zq)	<0.73%

Properties

14	m_{top} (precision)	±1.4%
15	m_{top} (additional methods)	obs.
16	Q_{top}	not 4/3e
17	Correlation of t-tbar spins	~5.1σ
18	tt charge asymmetry	±2.3%

New Physics in production

21	$tt+E_{Tmiss}$,	m_T>0.42 TeV
22	Resonant tt,	$m_{Z'}$>1.2 TeV
23	Resonant tb,	$m_{W'}$>1.1 TeV

Summary of ATLAS top physics

Decay

Helicity of W bosons	~±10%
FCNC in decay (t→Zq)	<0.73%

New Physics in production

$tt+E_{Tmiss}$,	m_T>0.42 TeV
Resonant tt,	$m_{Z'}$>1.2 TeV
Resonant tb,	$m_{W'}$>1.1 TeV

For more information visit:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

Production Rate

σ_{tt} (dilepton channel)	±9%
σ_{tt} (single lepton channel)	±7%
σ_{tt} (hadronic channel)	±36%
σ_{tt} (τ+jets)	±27%
σ_{tt} (e,μ+τ)	±15%
σ_{tt} (ttγ)	±41%
σ_{tt} combined	±6%
Differential σ_{tt}, jet veto	obs.
Differential σ_{tt}, N_{jets}	up to 5
$\sigma_{t,\ t\text{-channel}}$, $\lvert V_{tb}\rvert$	~7.2σ
$R=\sigma_{t,}/\sigma_{tbar,\ t\text{-channel}}$	±12%
$\sigma_{t,\ Wt\text{-channel}}$	~3.3σ
$\sigma_{t,\ s\text{-channel}}$	<26 pb
$\sigma_{t,\ FCNC}$ x B(W→lν)	<3.9 pb

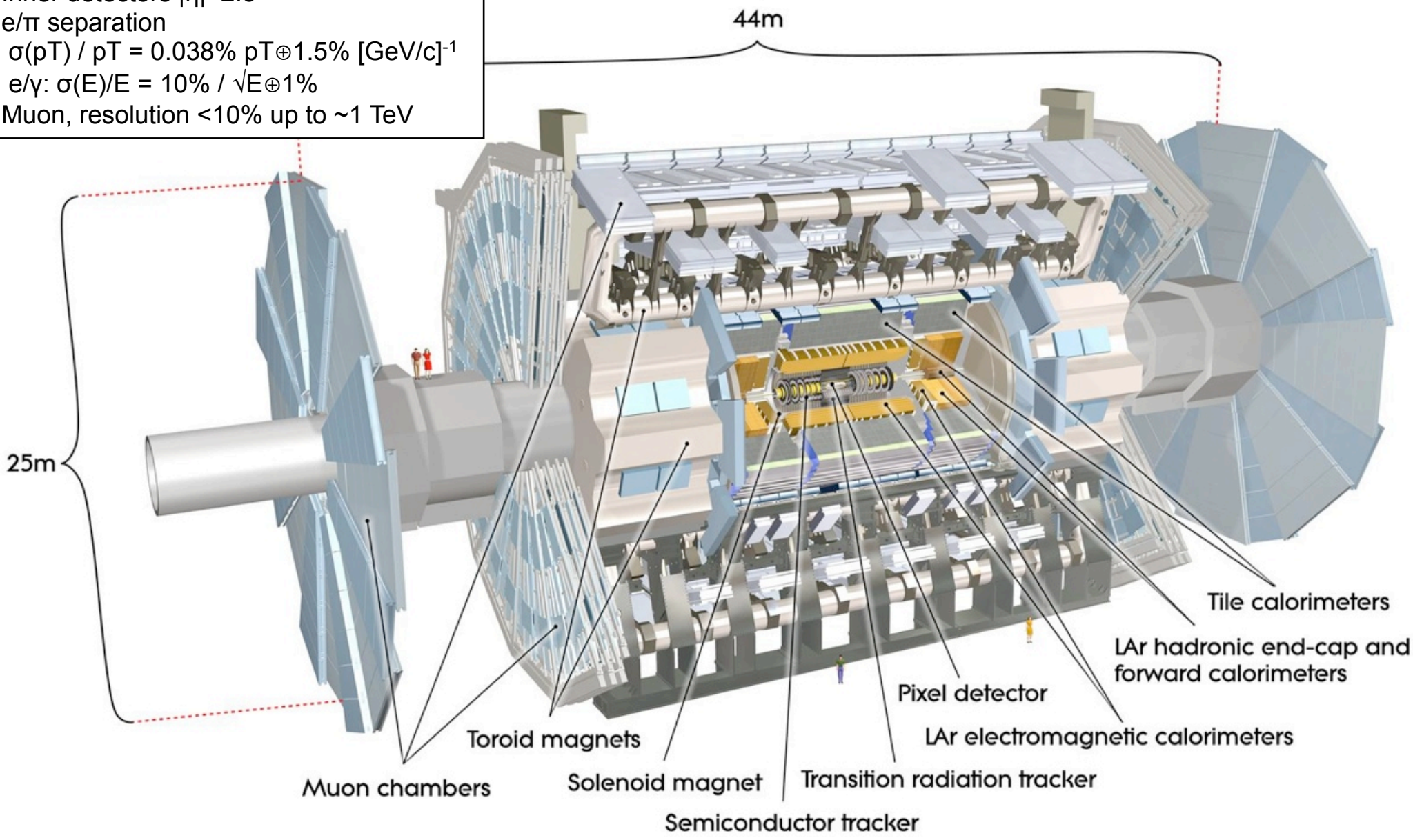
Properties

m_{top} (precision)	±1.4%
m_{top} (additional methods)	obs.
Q_{top}	not 4/3e
Correlation of t-tbar spins	~5.1σ
tt charge asymmetry	±2.3%

Additional Info

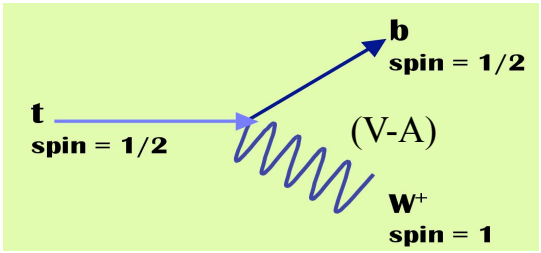
The ATLAS detector

- 2 T magnetic field for ID
- Inner detectors |η|<2.5
- e/π separation
- σ(pT) / pT = 0.038% pT⊕1.5% [GeV/c]$^{-1}$
- e/γ: σ(E)/E = 10% / √E⊕1%
- Muon, resolution <10% up to ~1 TeV



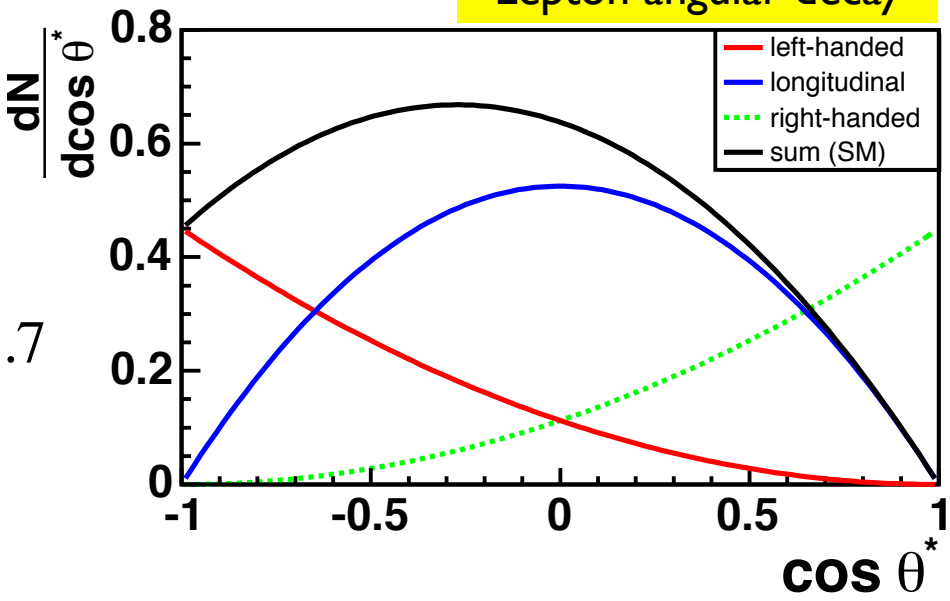
Helicity of W bosons in top decay

- Positive W helicity f_+ suppressed by chiral factors ~ M_b^2 / M_W^2
- Relative fraction of f_0 to f_- is:

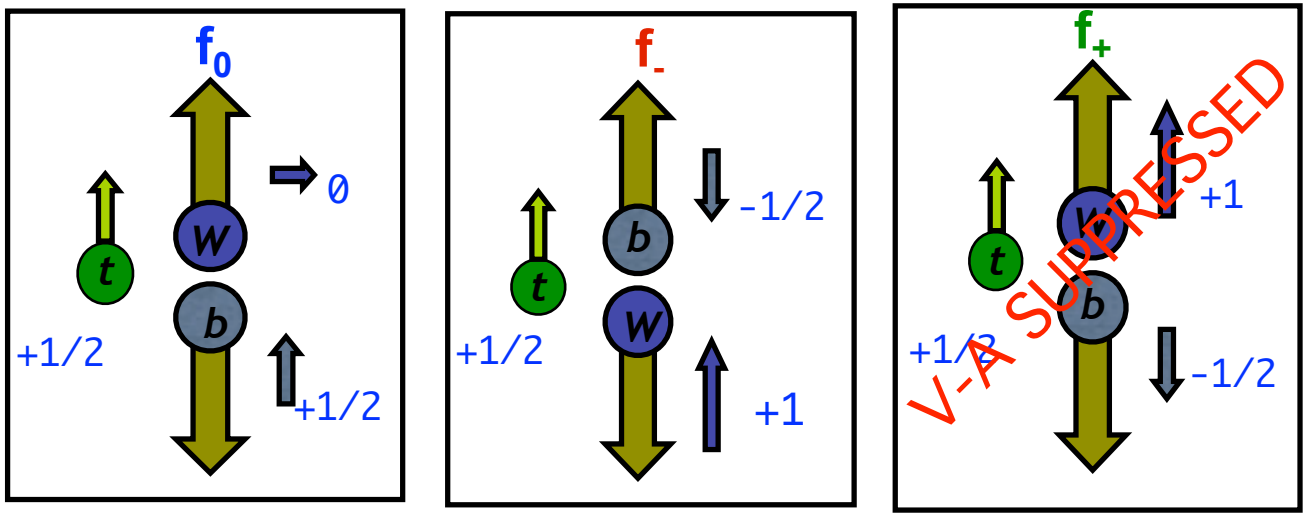


$$f_0 = \frac{M_t^2 / 2M_W^2}{1 + M_t^2 / 2M_W^2} \cong 0.7$$

Lepton angular decay



Longitudinal fraction | Left-Handed fraction | Right-Handed fraction



cos θ* is the angle between the *d*-type fermion in the *W* rest frame and the *W* flight-direction in the top rest frame