Top quark pair properties (spin correlations, charge asymmetry and complex final states) with the ATLAS detector

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HEP 2013
Stockholm
18-24 July 2013
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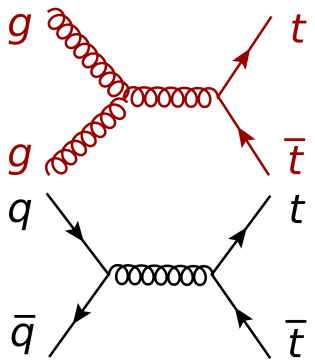
Outline

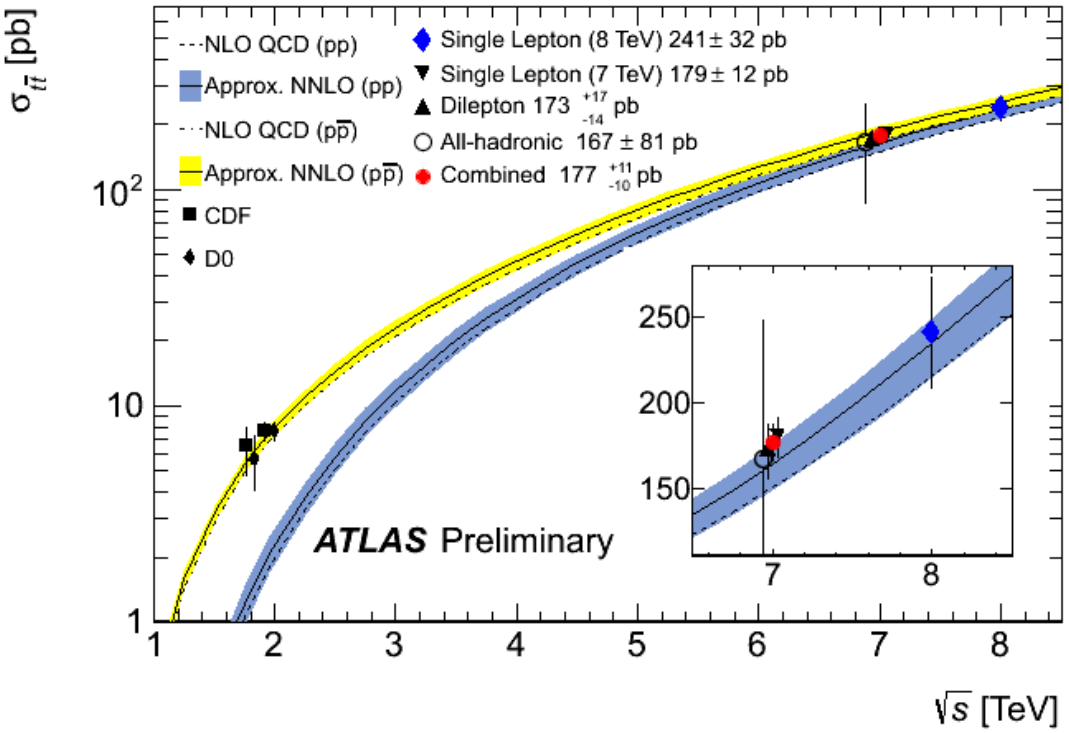
Discuss ATLAS measurements of top quark pair properties:

- **Spin correlation**
- **Charge asymmetry**
- $t\bar{t}$ + boson production : $t\bar{t}Z$ and $t\bar{t}\gamma$



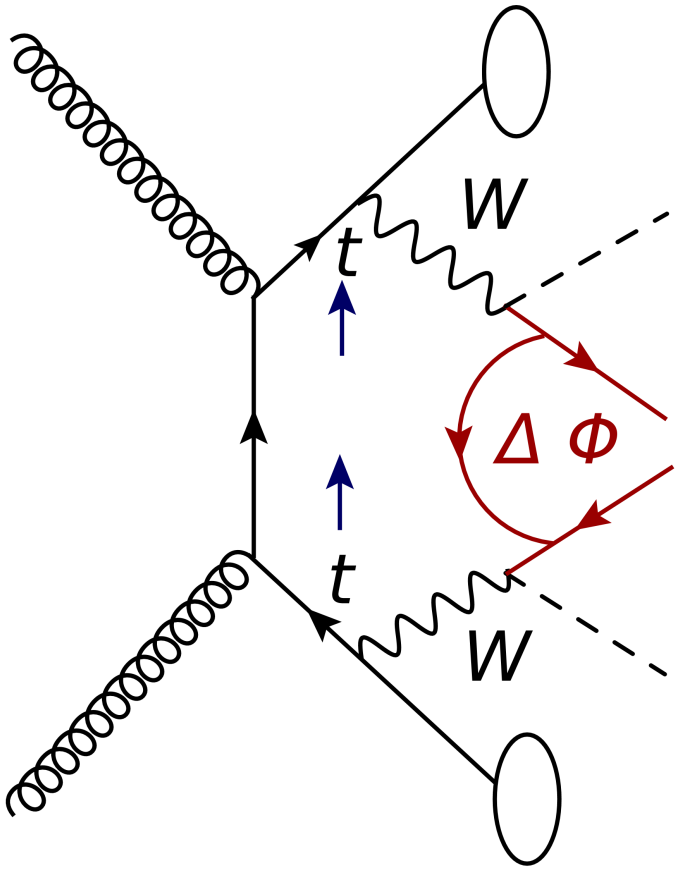
LHC vs Tevatron:
differences most relevant for these results:

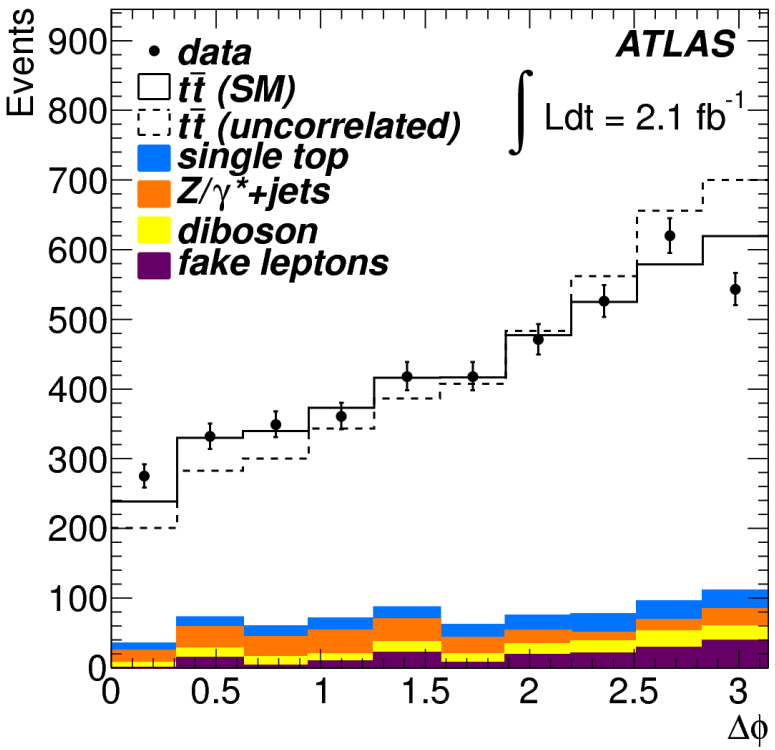
- dominant production mechanism: gg vs $q\bar{q}$
- larger cross-section (and statistics)
- symmetric $(p-p)$ vs asymmetric $(p-\bar{p})$ collisions



Spin correlation in $t\bar{t}$ events

- Phys. Rev. Lett. 108, 212001 (2012), 7 TeV, $\mathcal{L}_{\rm int}$ =2.1 fb^{-1}
- $t\bar{t}$ dilepton final state
- use the fact that for top $\tau(decay) < \tau(hadronization)$;
  $\Rightarrow$ can infer t and $\bar{t}$ spin correlation from lepton $\Delta\phi$





Spin correlation in $t\bar{t}$ events

Analysis strategy:

- select events with $t\bar{t}$ dilepton signature
- backgrounds : use DD estimates when necessary
- f_{SM} = fraction of events with SM-like spin correlation;
- extract f_{SM} from lepton $\Delta\phi$;
- binned template fit to samples with different f_{SM}

Observed and expected event yields:

$Z/\gamma^*(\rightarrow e^+e^-/\mu^+\mu^-)$ + jets (MC + DD)	64^{+11}_{-16}
$Z/\gamma^*(\rightarrow \tau\tau)$ + jets (MC)	175 ± 29
Fake leptons (DD)	160^{+140}_{-70}
Single top (MC)	197 ± 21
Diboson (MC)	148 ± 20
Total (non-$t\bar{t}$)	740^{+150}_{-80}
$t\bar{t}$ (MC)	3530^{+280}_{-340}
Total expected	4270^{+320}_{-350}
Observed	4313

Results:

- $f_{SM} = 1.30 \pm 0.14$ **stat.**$^{+0.27}_{-0.22}$ **syst.**
- interpret as degree of correlation A:

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

- helicity basis: $A = 0.40 \pm 0.04$ stat.$^{+0.08}_{-0.07}$ syst.
- maximal basis: $A = 0.57 \pm 0.06$ stat.$^{+0.12}_{-0.10}$ syst.
- **+ exclude no-correlation hypothesis with 5.1 σ significance**
- **Largest systematics: jet energy scale, resolution $\oplus$ fake leptons >70% total**

$t\bar{t}$ charge asymmetry

qg and $q\bar{q}$ $t\bar{t}$ production : t emitted in direction of q, $\bar{t}$ in direction of $\bar{q}$

Tevatron :

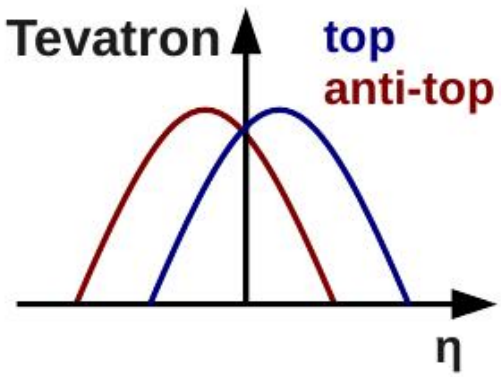
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

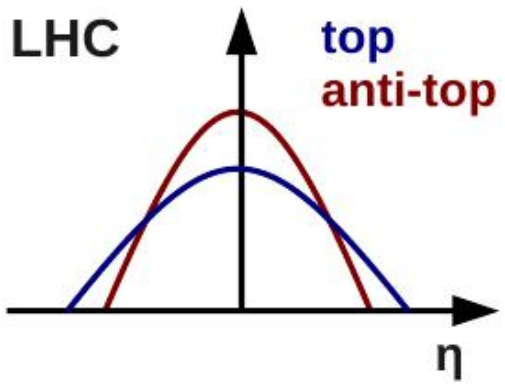
$$\Delta y = y_t - y_{\bar{t}}$$

LHC:

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

$t\bar{t}$ asymmetry: $\Delta|y| = |y_t| - |y_{\bar{t}}|$
(lepton asymmetry: $\Delta|y| = |y_{l^+}| - |y_{l^-}|$)





- A_{FB} measurements significantly **larger than SM predictions,**
- excess observed both for inclusive and **differential** $m(t\bar{t})$, $|y(t\bar{t})|$ asymmetry.

- So far: A_C **consistent with SM**
- **new ATLAS measurements** with full 7 TeV dataset and **differential asymmetry.**

NEW: $t\bar{t}$ charge asymmetry: single lepton channel

- ATLAS-CONF-2013-078, 7 TeV, $\mathcal{L}_{\rm int}$ =4.7 $\rm fb^{-1}$
- **measure top quark based asymmetry**
- correct for detector effects using Fully Bayesian unfolding
- use kinematic fit based on a likelihood approach to reconstruct t and $\bar{t}$ 4-momenta

Inclusive result:
$A_c^{t\bar{t}} = 0.006 \pm 0.010(\text{ stat. } + \text{ syst.})$,
SM: $A_c^{t\bar{t}} = 0.0123 \pm 0.0005$

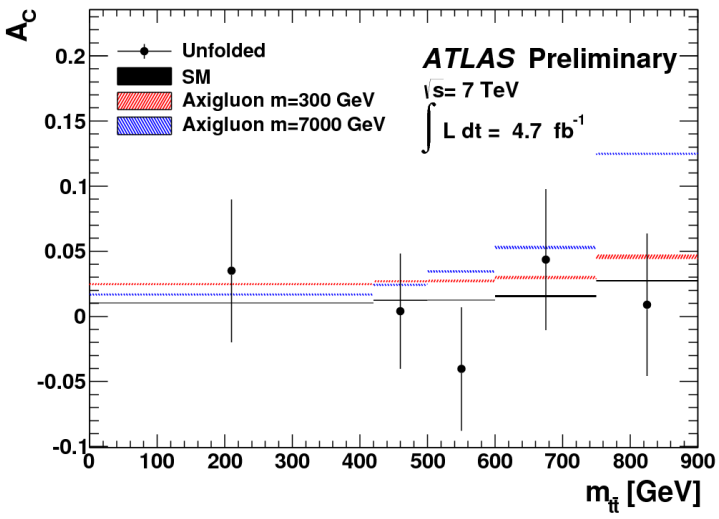
Differential measurements:

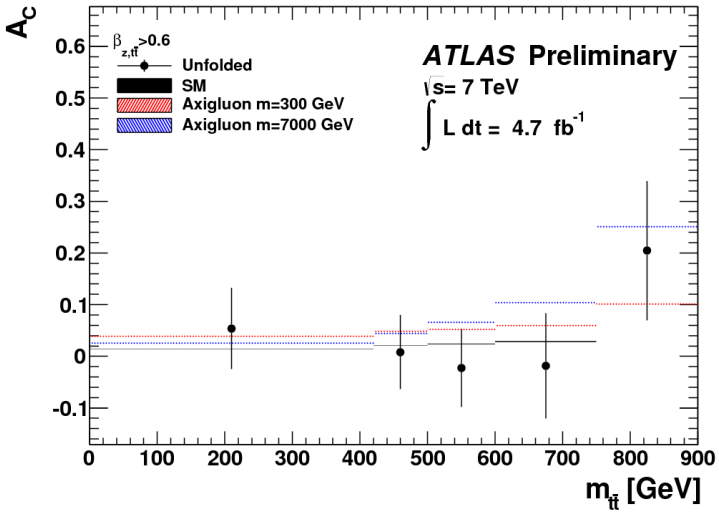
- $m(t\bar{t}), \mathrm{p_T}(t\bar{t}), y(t\bar{t})$

BSM-sensitive measurement

- z-component of $t\bar{t}$ velocity: βz
- measure asymm. for $\beta z > 0.6$

All measurements consistent with SM.





$t\bar{t}$ charge asymmetry : dilepton channel

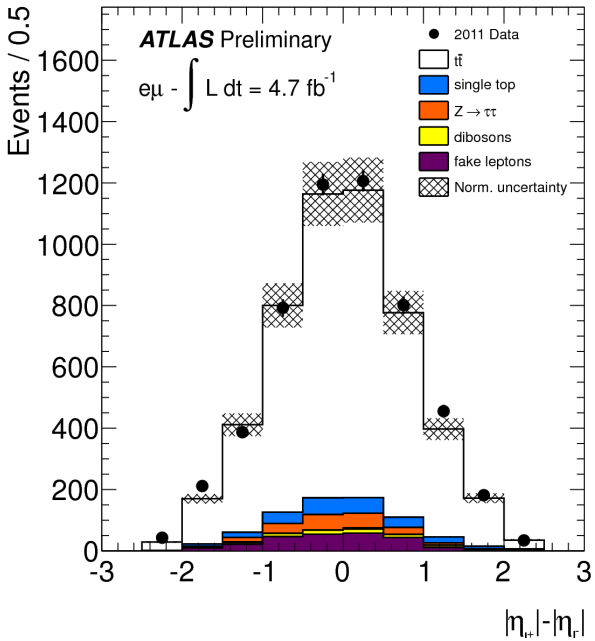
- ATLAS-CONF-2012-057, 7 TeV, $\mathcal{L}_{\rm int}$ =4.7 fb^{-1}
- **measure lepton and top quark based asymmetry**
- correct for detector effects using calibration
- use ME method to reconstruct t and $\bar{t}$ 4-momenta

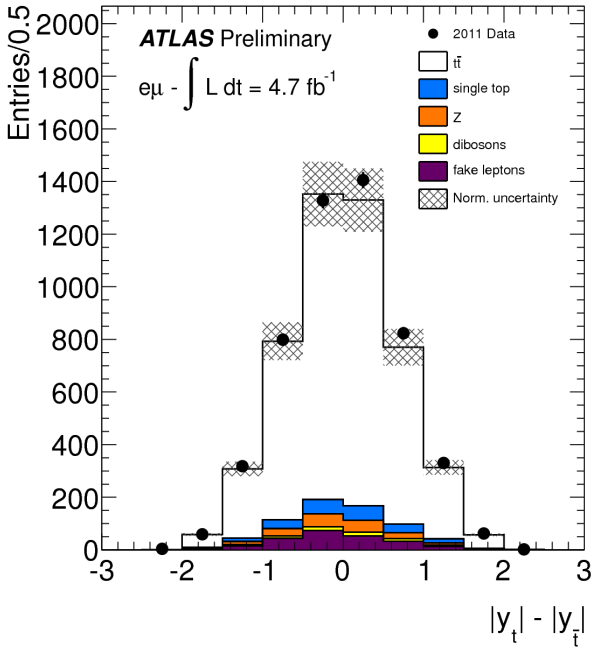
Inclusive asymmetry results:

- $A_c^{ll} = 0.023 \pm 0.012$ stat. ± 0.008 syst. , SM : $A_c^{ll} = 0.004 \pm 0.001$
- $A_c^{t\bar{t}} = 0.057 \pm 0.024$ stat. ± 0.015 syst. , SM : $A_c^{t\bar{t}} = 0.0123 \pm 0.0005$

Largest systematics (more in Extra):

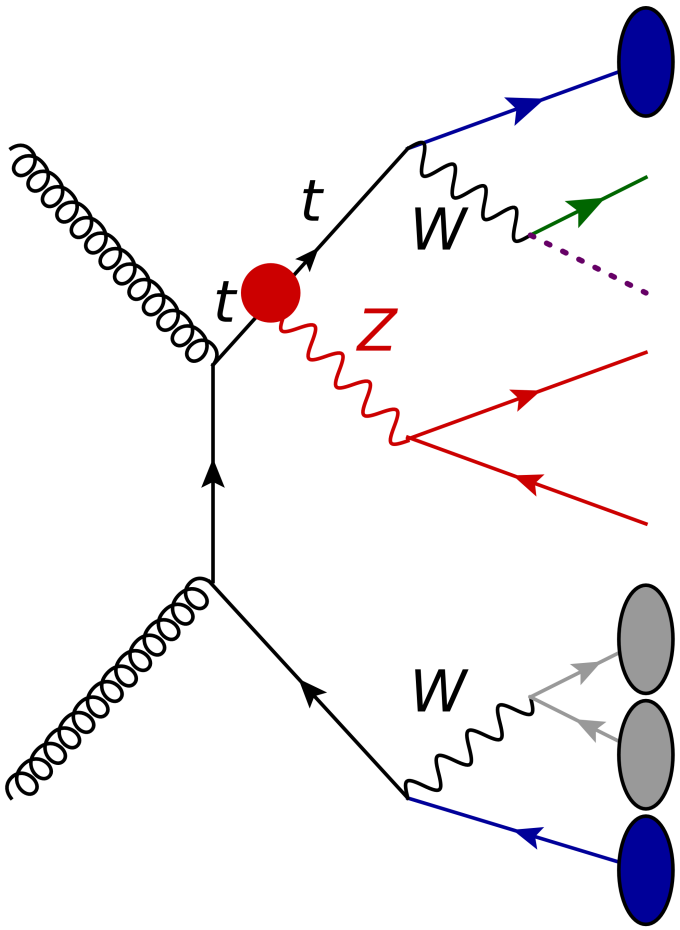
- dilepton channel:
  - A_c^{ll}: QCD, calibration (ee), $t\bar{t}$ modelling ($e\mu$, $\mu\mu$)
  - $A_c^{t\bar{t}}$: varying, QCD and $t\bar{t}$ modelling
- single lepton channel:
  - syst.< stat., main contributions to syst.:
  - **jet energy scale and resolution**
  - followed by lepton energy scale and resolution, $\not{E}_{\rm T}$ uncertainty and pile-up





$t\bar{t}Z$ production: event selection

- ATLAS-CONF-2012-126, 7 TeV, $\mathcal{L}_{\mathrm{int}}$ =4.7 fb^{-1}
- LHC : QCD production
- analysis uses 3-lepton final state



b-tagged jet

lepton from W

MET (>30 GeV)

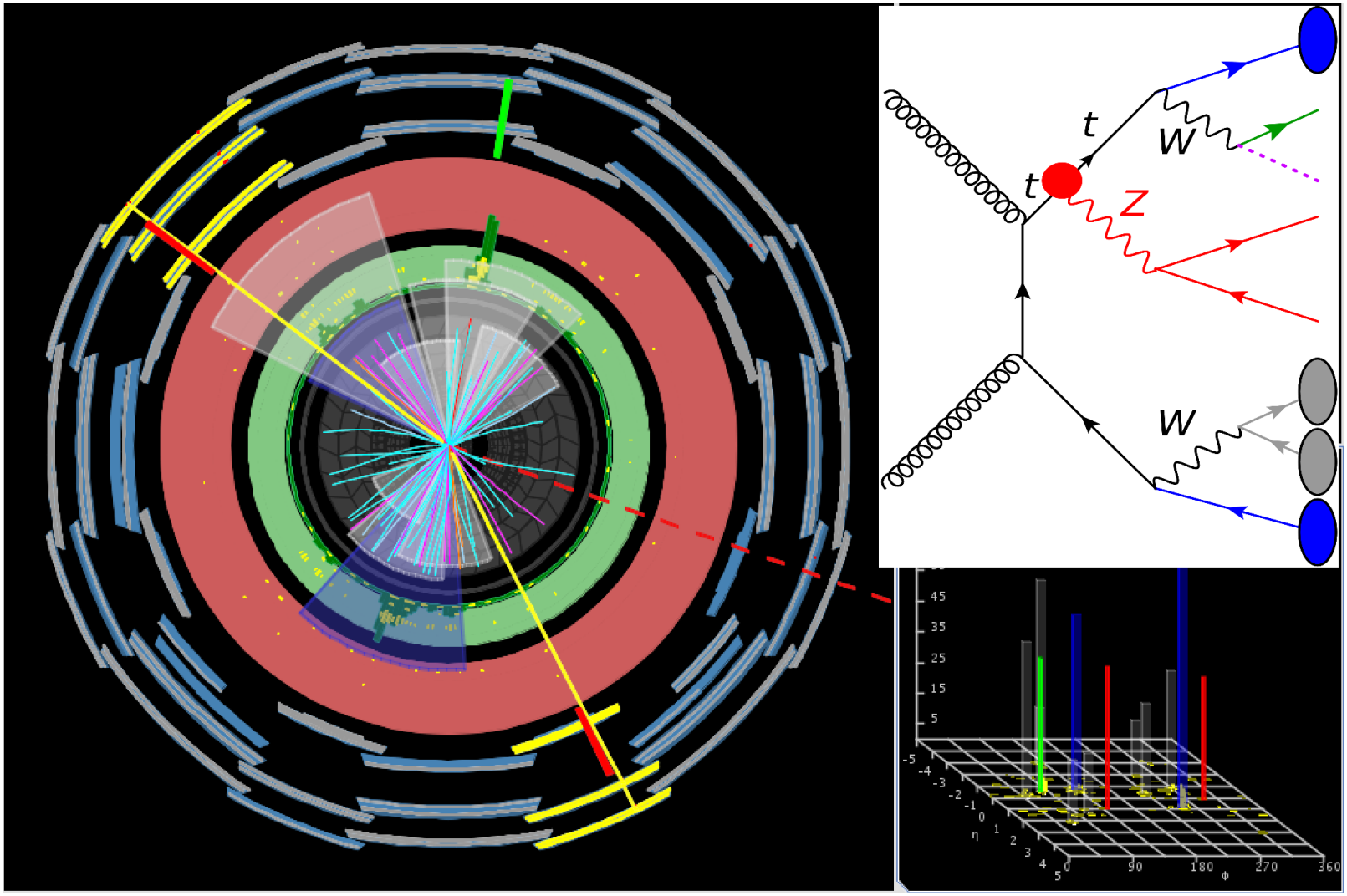
lepton pair from Z:
opposite sign, same flavour
|m(Z)-m(ll)|<10 GeV
(e(μ) : pt>25(20) GeV)

>= 4 jets with pt>30 GeV
>= 2 light jet from W->qq
>= 1 b-tagged jet

$t\bar{t}Z$ production: yields

Cut and count

- one event observed in the signal region

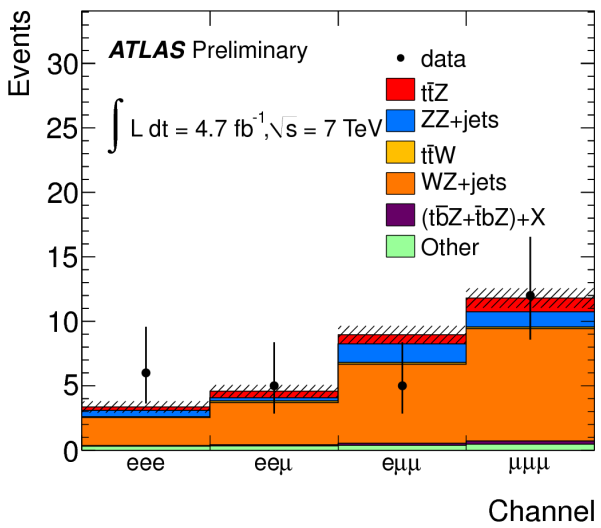


$t\bar{t}Z$ production: results

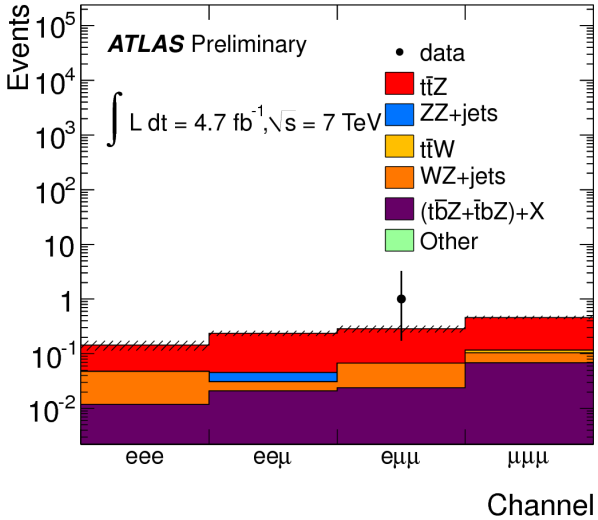
Background : real : MC, fake : DD

	SR
$t\bar{t}Z$	0.85 ± 0.04
WZ+jets	0.06 ± 0.04
ZZ+jets	0.014 ± 0.014
$t\bar{t}W$	0.011 ± 0.008
$(t\bar{b}Z + \bar{t}bZ) + X(= jj, l\nu)$	0.125 ± 0.013
$WZbbjj$	0.065 ± 0.016
MC Total	1.13 ± 0.06
Fake lepton background	$0.0^{+1.6}_{-0.0}$
Observed	1

x-check : CRs with looser jet, $m(ll)$ cuts



Signal region

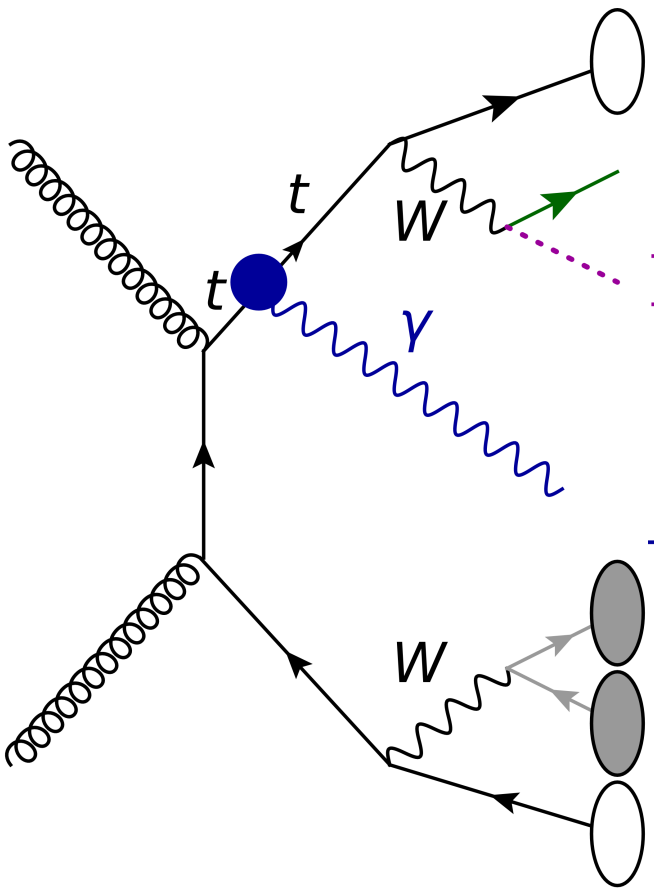


One event observed in data:

- expected signal:
  0.85 ± 0.04 stat. ± 0.14 syst.
- expected background:
  0.28 ± 0.05 stat. ± 0.14 syst.
- $\Rightarrow \sigma(t\bar{t}Z) < 0.71$ pb @ 95% CL
- consistent with SM,
  $\sigma(t\bar{t}Z) = 0.14$ pb @ NLO
- Dominant systematics: background normalization

$t\bar{t}\gamma$ production : event selection

- ATLAS-CONF-2011-153, 7 TeV, $\mathcal{L}_{\mathrm{int}}$ =1.04 fb^{-1}
- LHC : QCD production
- analysis uses single lepton final state with high-$\mathrm{p_T}$ γ



b-tagged jet

e(mu) from W, pT>25 (20) GeV

MET>35(20) GeV for e(μ)-chan
+ MET +MTW > 60 GeV in μ-chan
+ MTW>20 GeV

converted or unconverted
|m(Z)-m(eγ)|<5 GeV
pT>15 GeV
+ shower shape, had. leakage cuts

>= 4 jets with pt>25 GeV
>= 2 light jet from W->$q\bar{q}$
>= 1 b-tagged jet

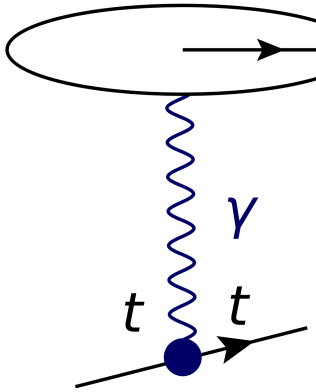
$t\bar{t}\gamma$ production : analysis strategy

Signal region yields:

- **52(70) events in $e(\mu)$ channel**
- contributions from **prompt** and **fake photons**
- and contributions from multiple processes
- $\sigma(t\bar{t}\gamma)$ estimated from a template fit to γ track isolation observable:

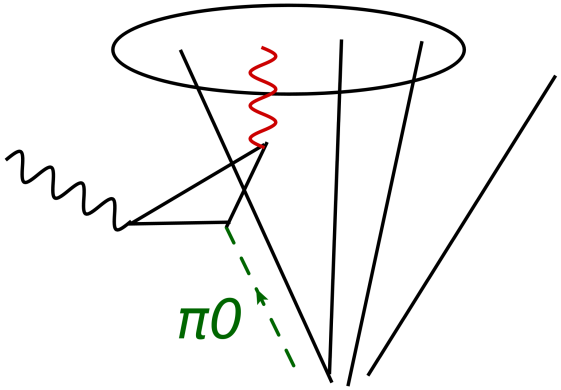
$$ptcone20 = \Sigma pt(track),$$
$$\text{for } dR(\gamma, track) < 0.20,$$

prompt γ : small ptcone20



[template from Zee]

fake γ : large ptcone20



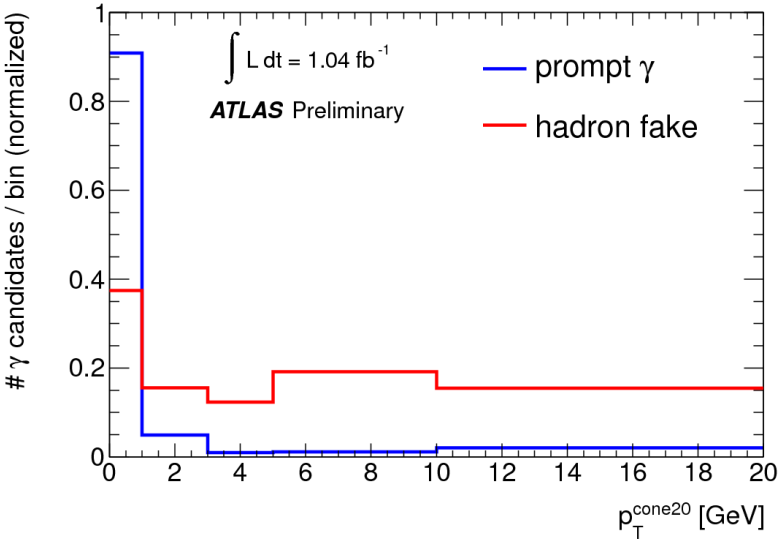
[template from QCD jet events]

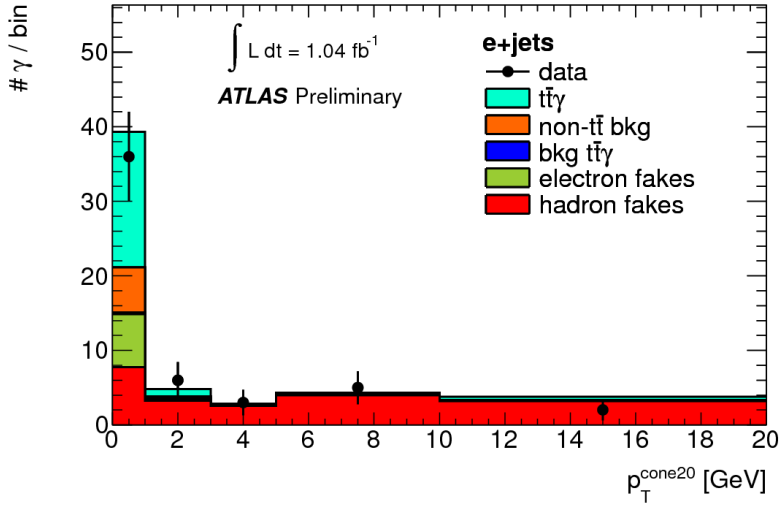
$t\bar{t}\gamma$ production : results

- **use DD estimates for main sources of background**
- pass result for branching ratio BR accounting for :
  - $t\bar{t}\gamma$, $t\bar{t} \longrightarrow$ dilepton and single lepton final states
  - $\mathrm{p_T}(\gamma) > 8$ GeV
- **template fit to γ track isolation observable** *ptcone*20 **yields**:

$$\sigma(t\bar{t}\gamma) = 2.0 \pm 0.5 \text{ stat.} \pm 0.7 \text{ syst.} \pm 0.08 \text{ lumi. pb}$$

- **consistent with SM** prediction of $\sigma(t\bar{t}\gamma) = 2.1 \pm 0.4$ pb
- Largest systematics: jet energy scale, pile-up and signal modelling





Conclusions

ATLAS measurements of top quark pair properties:

7 TeV results summary and [(statistical^2)/(systematics uncertainty^2) ratio]:

- **Spin correlation:**
  - fraction of events with SM-like spin correlation [$\sim$ 0.25]
  - consistent with SM prediction, exclude no spin correlation hypothesys with $> 5\sigma$
- **Charge asymmetry:**
  - single lepton channel: inclusive [$\geq$ 2] and differential measurements
  - dilepton channel: inclusive measurements [$\geq$ 2]
  - measurements consistent with SM predictions
- **$t\bar{t}Z$ production:**
  - upper limit on production cross-section [$\sim$ 0.1]
  - consistent with SM prediction
- **$t\bar{t}\gamma$ production:**
  - measured production cross-section [$\sim$ 0.5]
  - consistent with SM prediction

In many cases systematics improvements needed for 8 TeV measurements in order to notably improve precision.

ATLAS top group public results available at:
`https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults`

Extra

Spin correlation in $t\bar{t}$ events : systematics

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

$t\bar{t}$ charge asymmetry : single lepton channel, systematics

Source of systematic uncertainty	δA_C	
	Inclusive	$m_{t\bar{t}} > 600$ GeV
Lepton reconstruction/identification	< 0.001	0.001
Lepton energy scale and resolution	0.003	0.003
Jet energy scale and resolution	0.003	0.003
Missing transverse momentum and pile-up modelling	0.002	0.002
Multijet background normalisation	< 0.001	0.001
b-tagging/mis-tag efficiency	< 0.001	0.001
Signal modelling	< 0.001	< 0.001
Parton shower/hadronisation	< 0.001	< 0.001
Monte Carlo statistics	0.002	< 0.001
PDF	0.001	< 0.001
W+jets normalisation and shape	0.002	< 0.001
Statistical uncertainty	0.010	0.021

$t\bar{t}$ charge asymmetry : dilepton channel, systematics 1

Systematics for lepton based asymmetry:

	ee	$e\mu$	$\mu\mu$
Signal and background modeling			
Signal generator	0.011	0.003	0.002
ISR and FSR	0.004	0.004	0.006
Parton shower/fragmentation	0.001	0.004	0.003
PDF	<0.001	<0.001	<0.001
Z+jets	0.005	0.004	0.001
Diboson	<0.001	<0.001	<0.001
Single top	<0.001	<0.001	<0.001
Multijet background	0.014	0.002	<0.001
Detector modeling			
Jet efficiency and resolution	0.008	0.001	0.003
Jet energy scale	0.006	0.001	0.002
Muon efficiency and resolution	<0.001	0.001	0.002
Electron efficiency and resolution	0.005	0.003	<0.001
Calibration	0.019	0.002	0.004
Luminosity	0.002	<0.001	<0.001
Total	0.029	0.009	0.009

$t\bar{t}$ charge asymmetry : dilepton channel, systematics 2

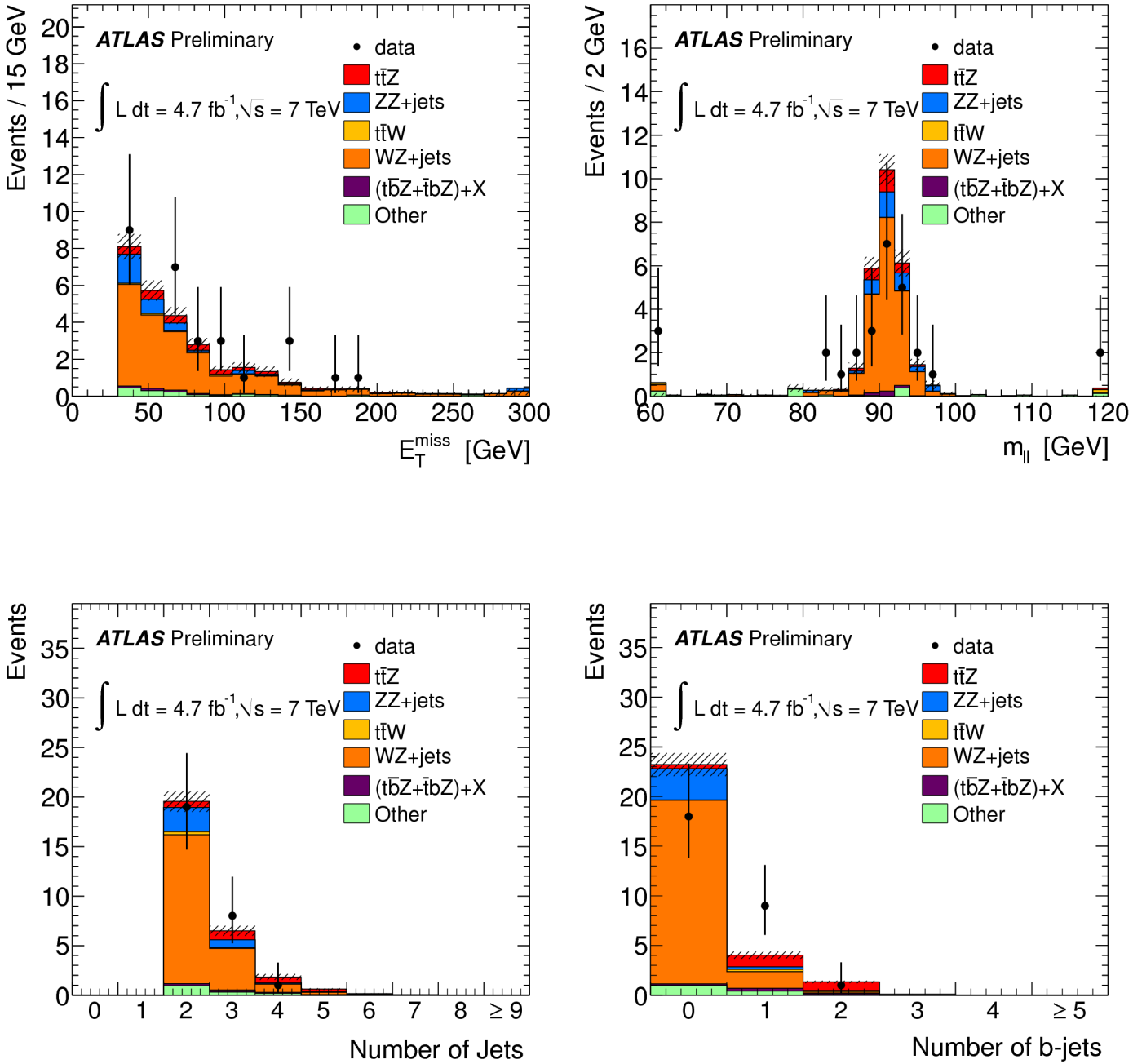
Systematics for $t\bar{t}$ based asymmetry:

	ee	$e\mu$	$\mu\mu$
Signal and background modeling			
Signal generator	0.014	0.009	0.002
ISR and FSR	0.008	0.002	0.018
Parton shower/fragmentation	0.001	0.001	0.001
PDF	0.001	<0.001	<0.001
Z+jets	0.001	0.006	0.002
Diboson	<0.001	<0.001	<0.001
Single top	<0.001	<0.001	<0.001
Multijet background	0.012	0.010	0.001
Detector modeling			
Jet efficiency and resolution	0.007	0.001	0.005
Jet energy scale	0.003	0.002	0.006
Muon efficiency and resolution	0.004	0.003	0.005
Electron efficiency and resolution	0.013	0.006	0.002
Calibration	0.004	0.001	0.002
Luminosity	<0.001	0.001	<0.001
Total	0.028	0.017	0.021

$t\bar{t}Z$ production : systematics

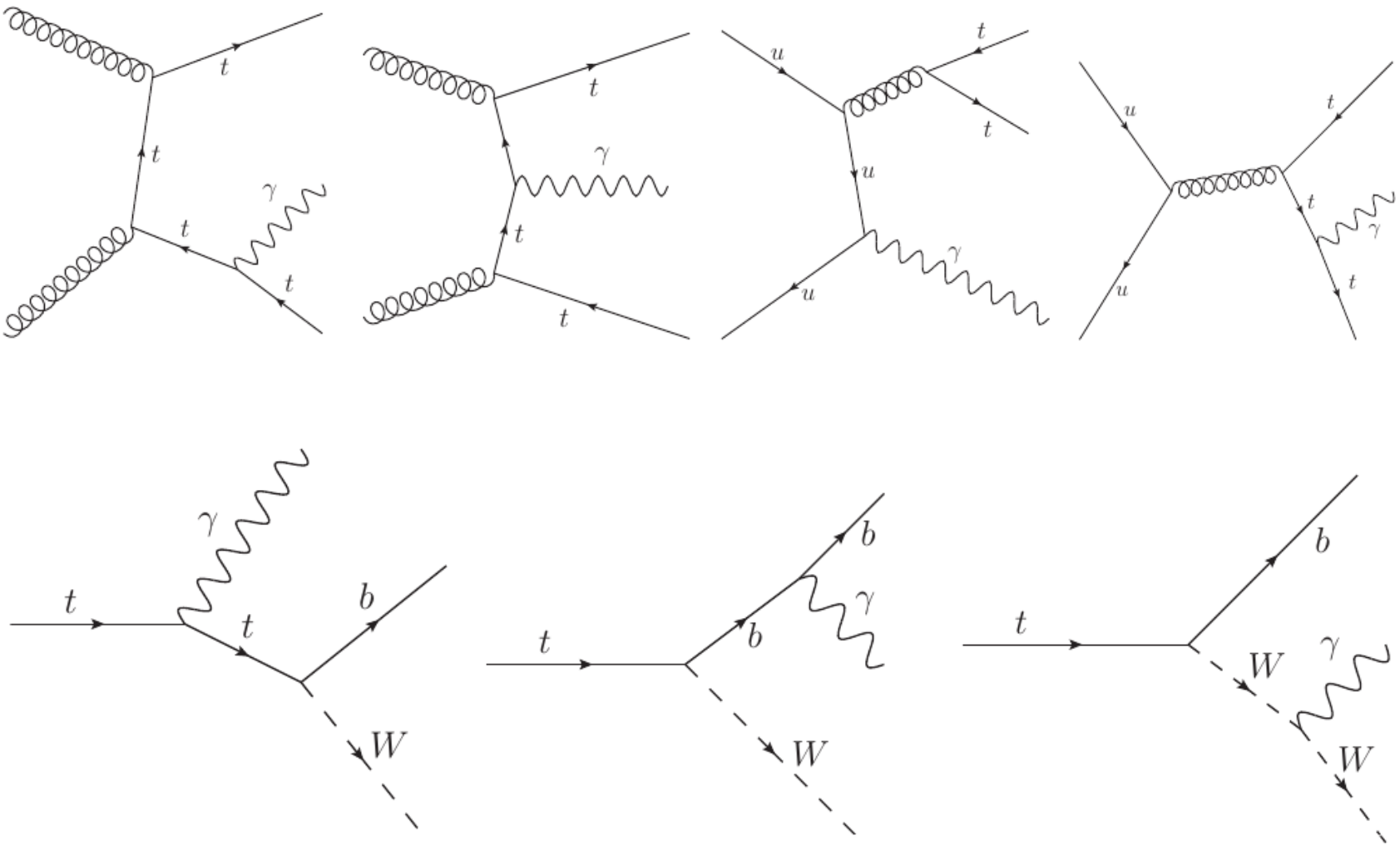
Systematic uncertainty	Background	Signal
Luminosity	4%	4%
b-tagging	5%	5%
e trigger efficiency	2%	<1%
e reco. and identification efficiency	5%	5%
e energy scale	<1%	<1%
e energy resolution	<1%	<1%
μ trigger efficiency	2%	<1%
μ reco. efficiency	2%	2%
μ momentum scale	<1%	<1%
μ momentum resolution	<1%	<1%
Jet energy scale	5%	7%
Jet reco efficiency	<1%	<1%
$E_{\mathrm{T}}^{\mathrm{miss}}$ unassociated cells and soft jet	1%	<1%
$E_{\mathrm{T}}^{\mathrm{miss}}$ pileup	1%	<1%
Jet vertex fraction	5%	6%
Renormalisation & factorisation scale	-	10%
ISR/FSR	-	6%
MC driven background normalisation	50%	-
Total	51%	17%

$t\bar{t}Z$ production : CR with $\geq$ 2 jets, no *mll* cut



$t\bar{t}\gamma$ production: example diagrams

Analysis does not separate between radiative production (top) and decay (bottom).



$t\bar{t}\gamma$ production: yields

fit parameter	fit value with statistical uncertainty		
hadron fakes in the e+jets channel	21	± 6	events
hadron fakes in the μ+jets channel	28	± 8	events
electrons faking photons from $t\bar{t}$ in the e+jets channel	7.4	± 1.7	events
electrons faking photons from $t\bar{t}$ in the μ+jets channel	10.9	± 2.2	events
$t\bar{t}\gamma$ background in the e+jets channel	0.2		events
$t\bar{t}\gamma$ background in the μ+jets channel	0.4		events
non-$t\bar{t}$ background in the e+jets channel	6.7		events
non-$t\bar{t}$ background in the μ+jets channel	3.8		events
total number of background events	78	± 14	events
total number of signal events	46	± 12	events
$t\bar{t}\gamma$ signal (before selection and acceptance cuts)	2100	± 500	events

$t\bar{t}\gamma$ production: systematics 1

Description	Uncertainty on the cross section [pb]
Modelling	± 0.18
Initial and final state radiation	± 0.31
Electron related	± 0.05
Muon related	± 0.08
Jet energy scale	± 0.24
Jet energy scale (pile-up uncertainty)	± 0.28
b-jet energy scale	± 0.06
Jet reconstruction and resolution	± 0.06
$E_{\mathrm{T}}^{\mathrm{miss}}$ related	± 0.03
b-tagging performance	± 0.18
Treatment of dead region in LAr calorimeter read-out	± 0.05
Luminosity	± 0.08

$t\bar{t}\gamma$ production: systematics 2

Photon identification efficiency	± 0.33
Photon energy scale	± 0.02
Photon resolution	± 0.01
$t\bar{t}\gamma$ background yield	± 0.03
non-$t\bar{t}$ background yield	± 0.11
Electron to photon extrapolation	± 0.22
Fraction of converted prompt photons	± 0.03
Fraction of converted hadron fakes	± 0.16
Reweighting of the background templates (p_{T})	± 0.11
Reweighting of the background templates (η)	± 0.06
Pile-up dependence of the signal templates	± 0.01
Pile-up dependence of the background templates	± 0.05
Sum	± 0.7