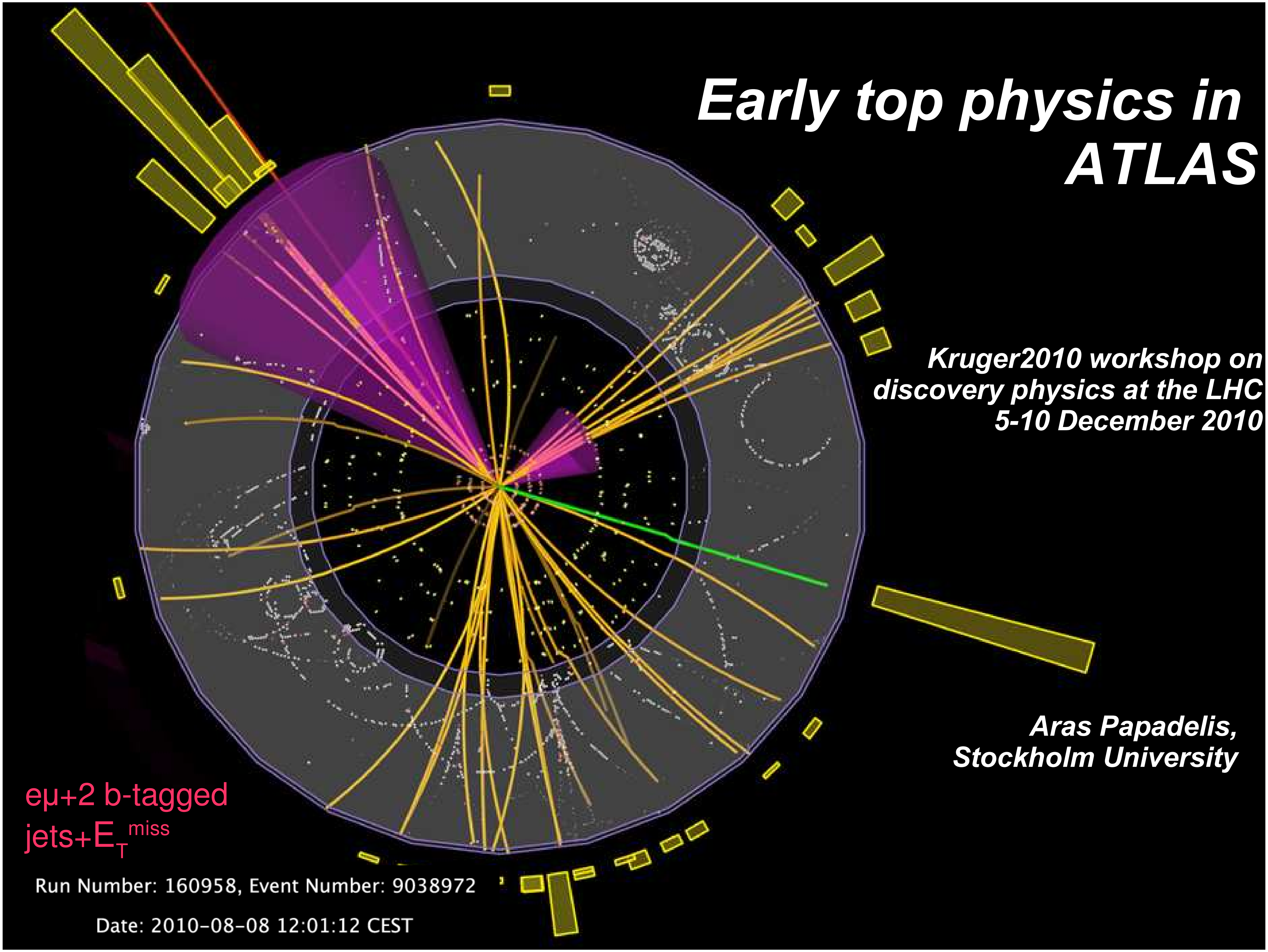
Early top physics in ATLAS

Kruger2010 workshop on discovery physics at the LHC
5-10 December 2010

Aras Papadelis,
Stockholm University

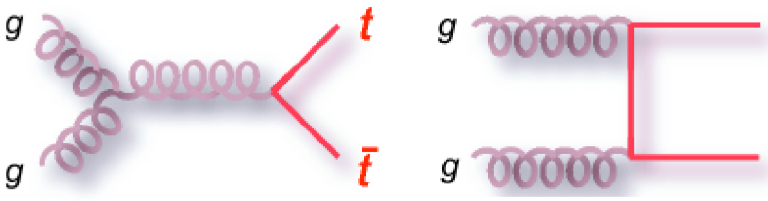


eμ+2 b-tagged jets+E_T^{miss}

Top physics at the LHC

The top quark is the heaviest known elementary particle, m = 173.3 ± 1.1 GeV

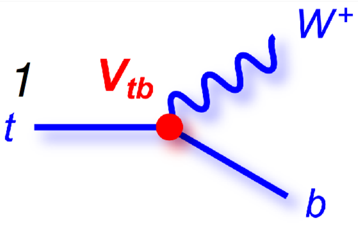
Main LHC production modes (~80-85%) are gluon fusion:

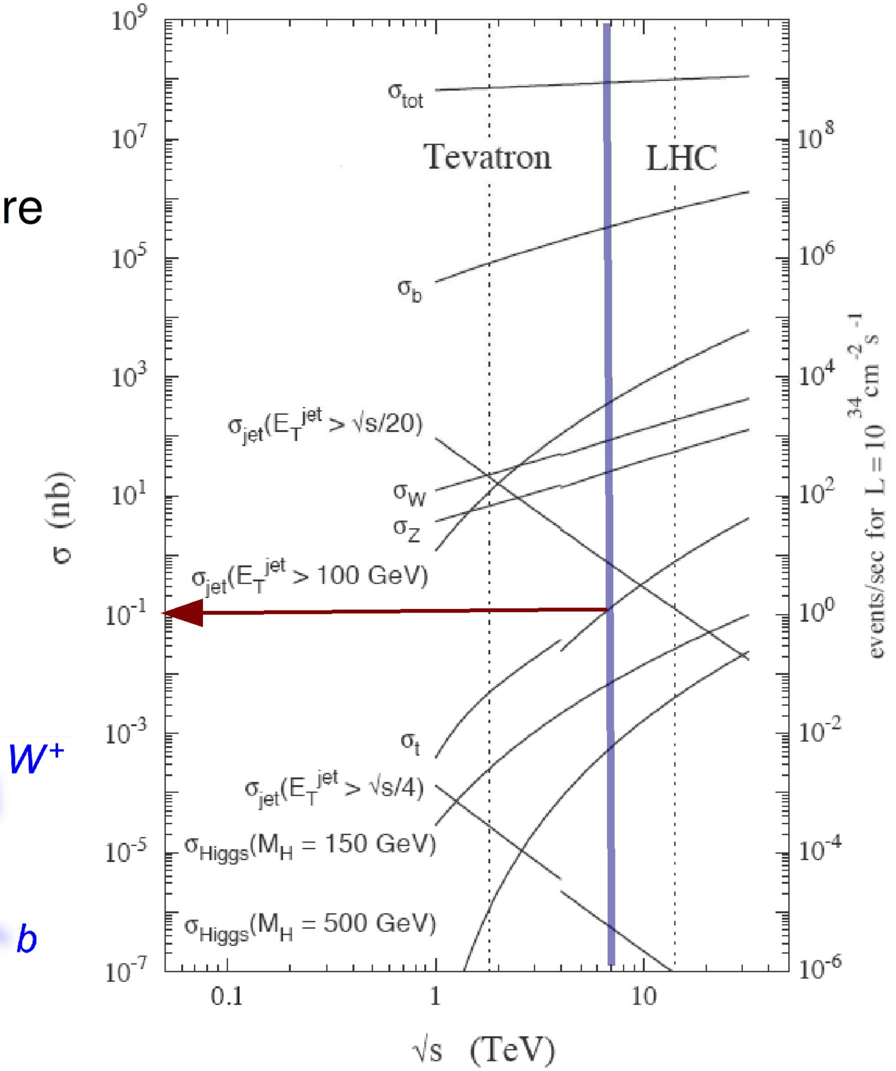


(remaining 15-20% is $q\bar{q}$-annihilation)

$\tau \sim 5 \times 10^{-25}$s (no hadronisation)

$|V_{tb}| > 0.999$: BR($t \to Wb$) ≈ 1

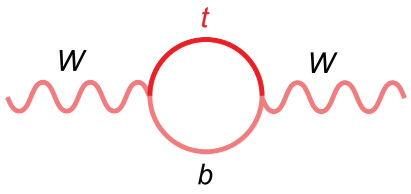




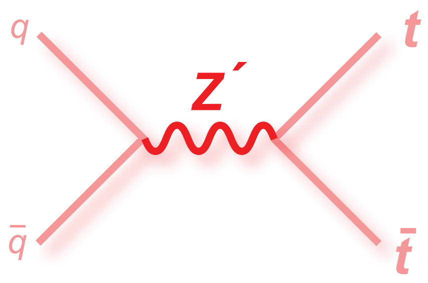
$\sigma_{tt,\text{ theory}}$ (pp, $\sqrt{s}$=7 TeV) = $164.6\,^{+11.4}_{-15.7}$ pb $\simeq$ 20 $*$ σ_{tt} ($p\bar{p}$, $\sqrt{s}$=1.96 TeV)

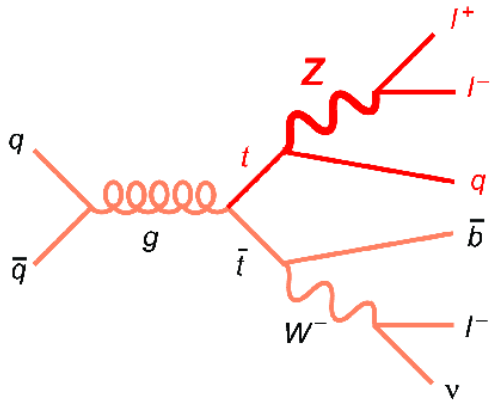
Motivation to study top quarks

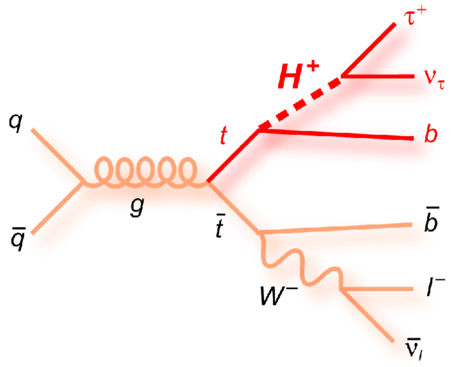
- The high mass makes the top quark unique in the SM. Precision EW+Higgs physics very sensitive to top mass.



- Top appears in many extensions to the Standard Model:
  - Heavy resonances $pp \to Z' \to t\bar{t}$
  - FCNC (highly suppressed in SM)
  - Final state of many SUSY processes
  - Background to SUSY processes
  - ...







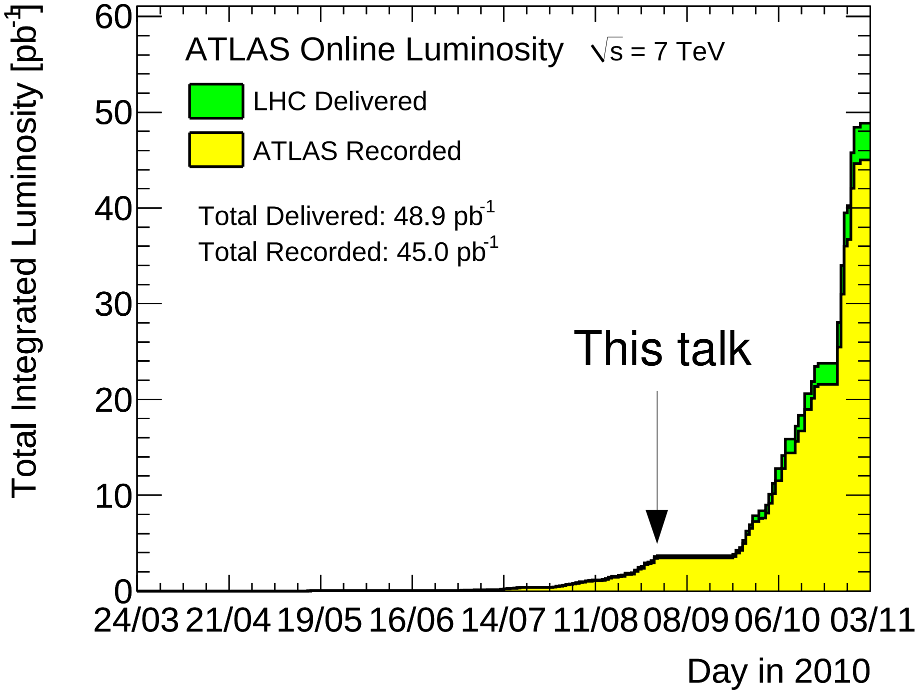
From experimentalist point of view, *top is a bridge from SM to New Physics:*
Good calibration and understanding of high p_T leptons, jets, missing E_T , b-tagging necessary.

ATLAS top programme 2010-2011

We currently have $45 pb^{-1}$ of data recorded,
hope for 1-2 fb^{-1} in 2011.

Top to-do list for 2010-2011:

- Top mass
- Single top production cross-section
- Top properties
    - Wtb vertex structure
    - top quark charge
    - spin correlations
    - FCNC
    - heavy resonances



- Top pair production cross-section **(this talk)**
The analysis in this talk uses L=2.9 pb^{-1} of collected data

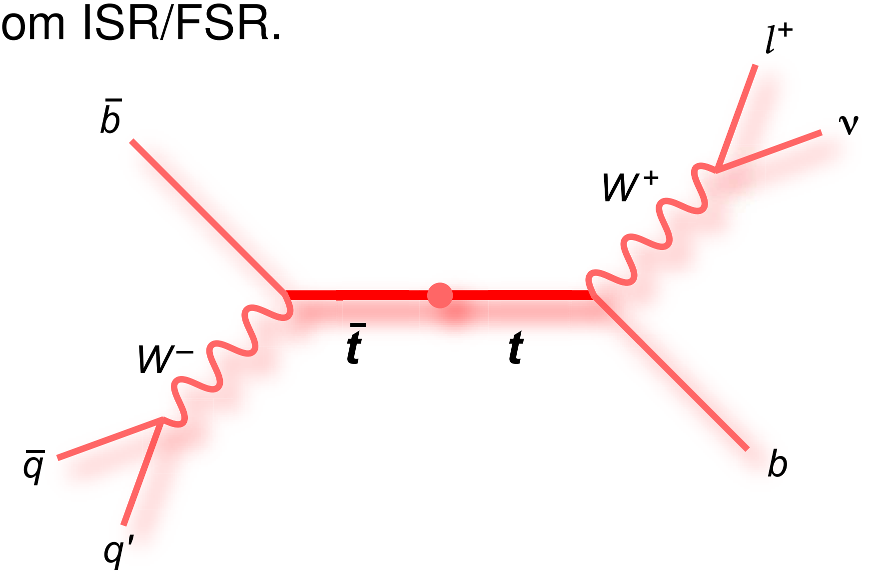
Top decays

Top quarks decay almost exclusively through *$t \rightarrow Wb$.* Depending on the decay of the *W*, the *observed final state* will be:

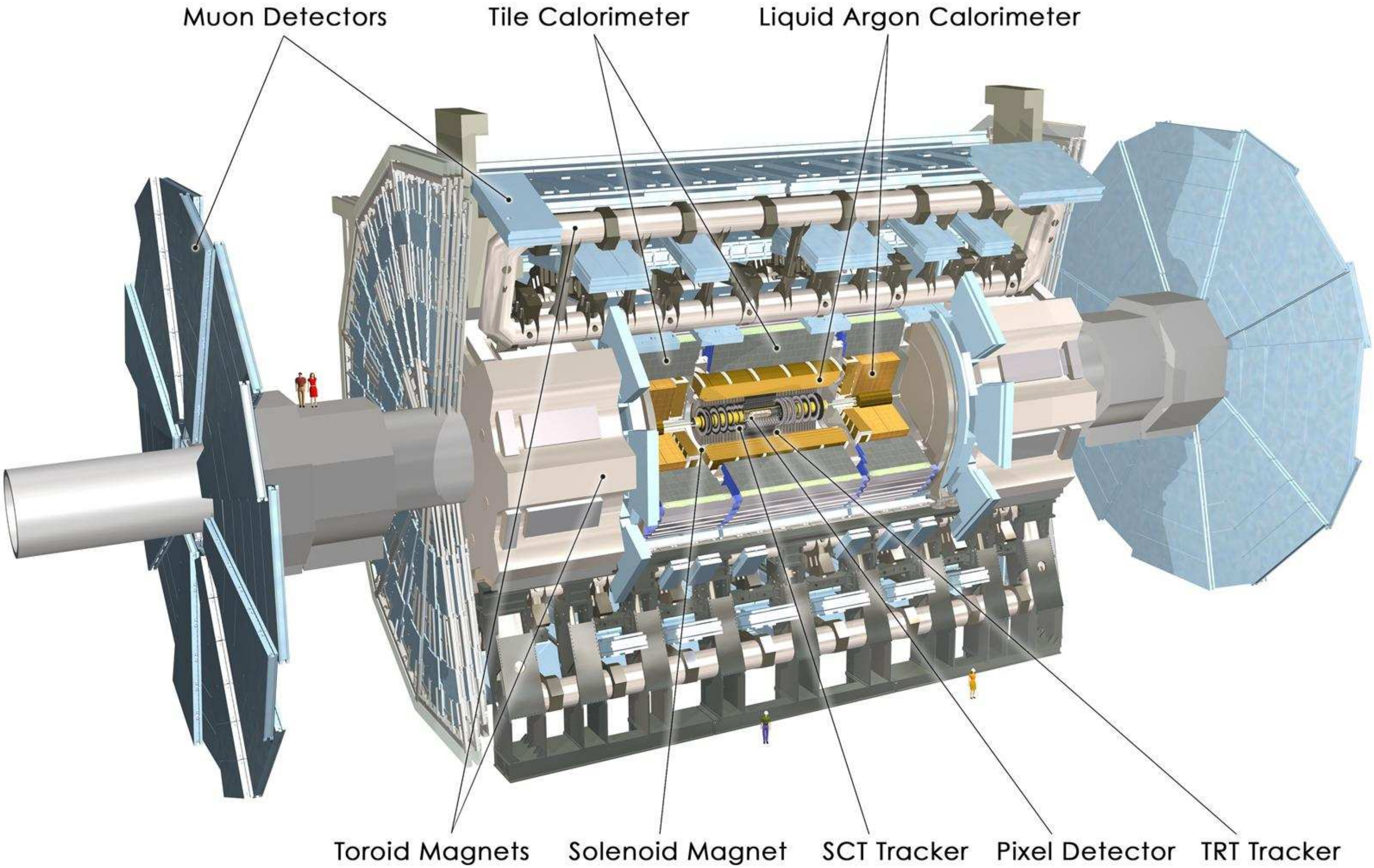
- Dilepton (6.5%): $l^+ l^- \nu\nu bb$ = 2 opposite charge leptons (e or μ), 2 jets, missing E_T
- Single lepton (38%): $l\nu qqbb$ = 1 lepton (e or μ), 4 jets, missing E_T
- All hadronic (55.5%): qqqqbb = 6 jets

(the above numbers include intermediate tau decays to leptons and hadrons)

Additional jets come from ISR/FSR.



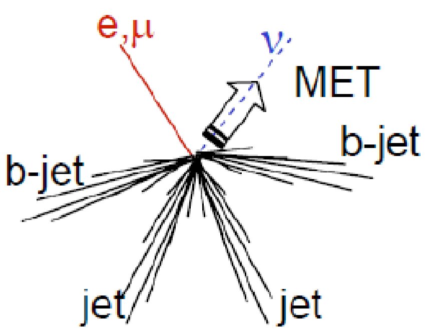
The ATLAS detector



Event selection for σ_{tt} measurement

Cosmics,pile-up rejection: ≥5 tracks from primary vertex
Trigger: Single lepton trigger, p_T>10 GeV (fully efficient at 20 GeV)
Leptons: electron or muon, p_T>20 GeV, isolated (to suppress leptons from hadrons decaying in-flight and semi-leptonic production in heavy flavor jets), $|\eta|<2.5$
Jets: anti-k_t, R=0.4, $|\eta|<2.5$

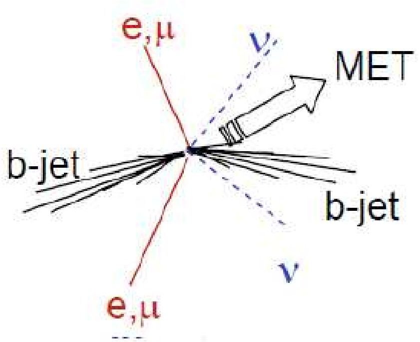
Single lepton channel



- Exactly 1 lepton (e or μ)
- ≥4 jets with p_T>25 GeV
- ≥1 with b-tag (50% efficiency working point)
- E_T^{miss}>20 GeV (reject QCD BG)
- E_T^{miss} + $m_T(W)$ > 60 GeV ("triangular cut")

$$m_{\mathrm{T}}(W) = \sqrt{2p_{\mathrm{T}}^{l}p_{\mathrm{T}}^{\nu}[1-\cos(\phi^{l}-\phi^{\nu})]}$$

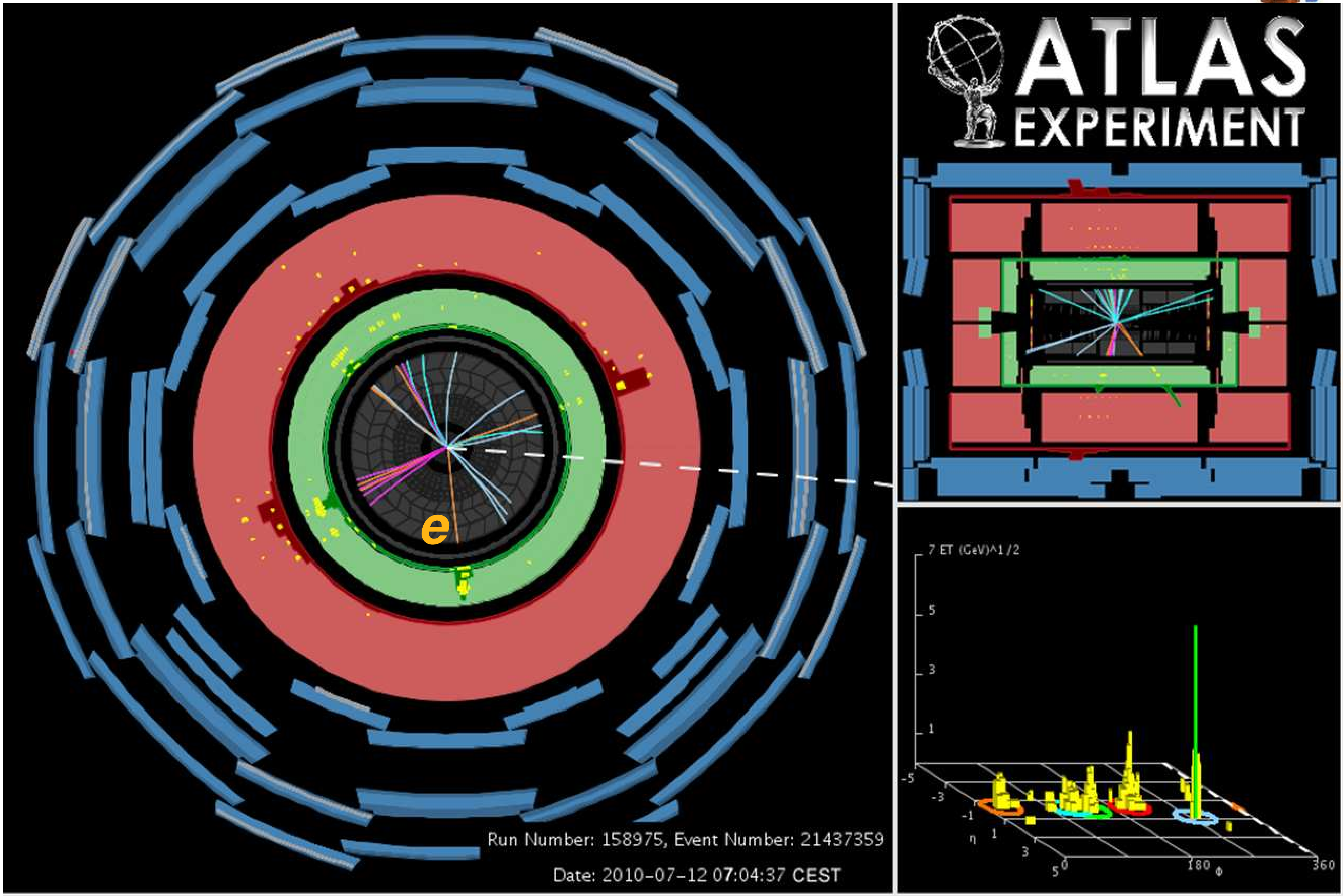
Dilepton channel



- Exactly 2 leptons(ee, μμ, eμ) with opposite charge
- ≥2 jets with p_T>20 GeV, *no b-tag*

ee: $|M_{ee} - M_Z|$ > 5 GeV , E_T^{miss}>40 GeV
μμ: $|M_{\mu\mu} - M_Z|$ > 10 GeV, E_T^{miss}>30 GeV
eμ: H_T>150 GeV (H_T is scalar sum of p_T of leptons and selected jets)

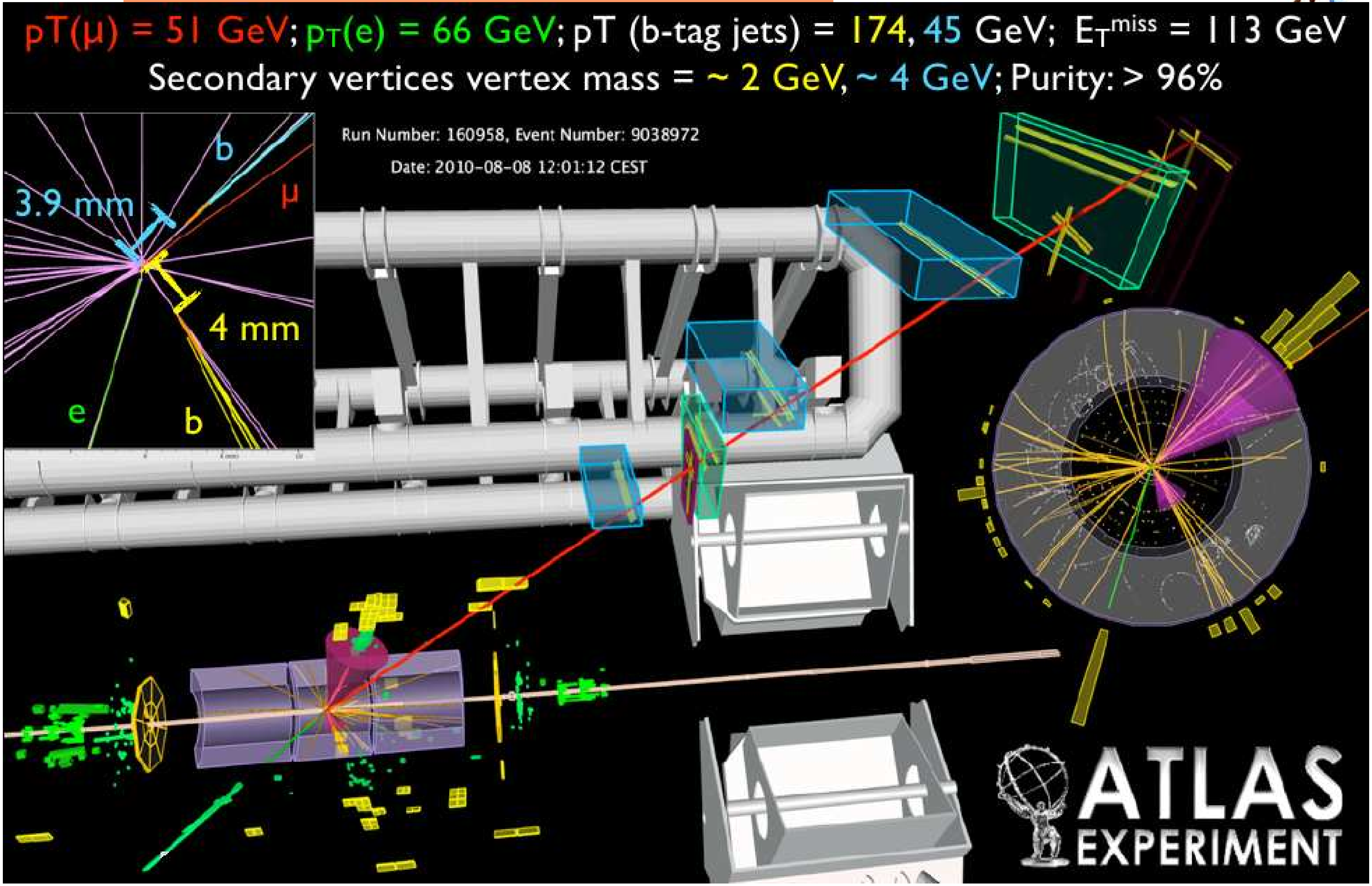
e + 4 jets top candidate



Run Number: 158975, Event Number: 21437359

Date: 2010-07-12 07:04:37 CEST

eμ + 2 b-tagged jets top candidate



$p_T(\mu) = 51$ GeV; $p_T(e) = 66$ GeV; p_T (b-tag jets) = 174, 45 GeV; $E_T^{miss} = 113$ GeV

Secondary vertices vertex mass = ~ 2 GeV, ~ 4 GeV; Purity: > 96%

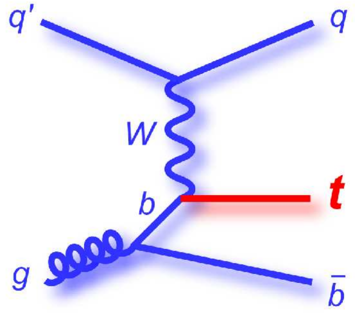
Run Number: 160958, Event Number: 9038972

Date: 2010-08-08 12:01:12 CEST

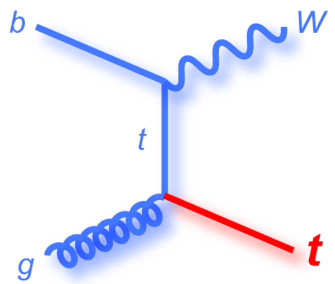
Irreducible background processes

Backgrounds can be *irreducible* or *instrumental.*
Irreducible backgrounds have the **same final state as $t\bar{t}$ decay** and can pass all cuts. Most of them give such small contribution that they can be **estimated from MC, one notable exception!**

Single top, estimated from MC

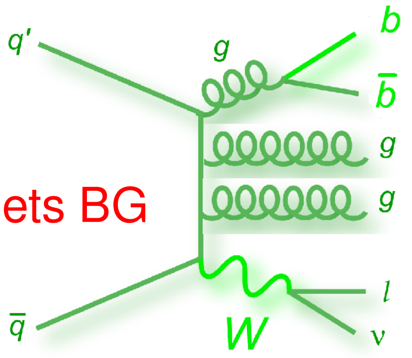


l+jets BG



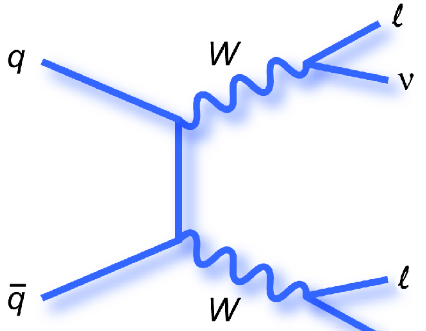
Dilepton BG

W+b$\bar{b}$+jets, data-driven



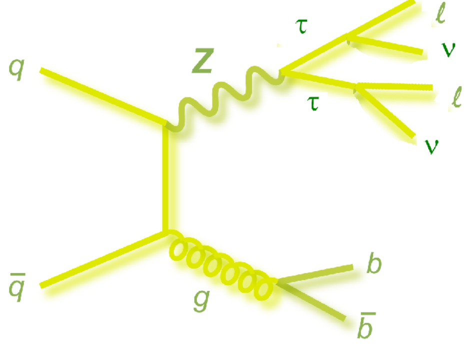
l+jets BG

Dibosons: WW, ZZ, WZ
Estimated from MC

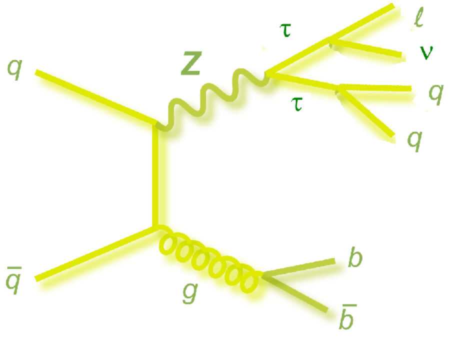


Dilepton BG

Z → ττ +jets, estimated from MC



Dilepton BG



l+jets BG

Instrumental backgrounds

Instrumental backgrounds are due to misreconstruction:
- jets, photons reconstructed as leptons
- non-prompt leptons from heavy flavour decays.
- leptons not reconstructed → fake missing E_T
- fake missing E_T due to imperfect calibration
- mistagged b-jet

Detector not perfectly modelled in MC, cross-sections are often not well known
→ **use data-driven estimates:**

Single leptons: *QCD multijets,* 1 fake/non-prompt lepton from jet

Dileptons: *W+jets,* 1 fake lepton from jet

QCD multijets – 2 fake leptons from jets

$Z \rightarrow ee/\mu\mu$+jets (Drell-Yan)
Most Z+jets events rejected by the Z mass veto. BG from events in Z-peak tail with fake missing E_T

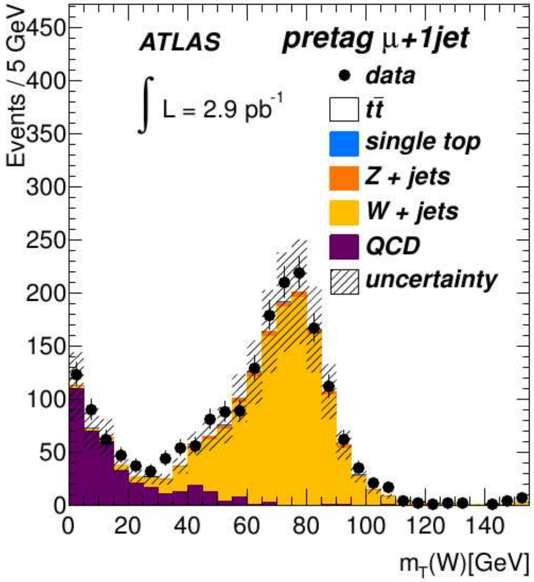
QCD multijet background – single leptons

μ+jets contrib. from heavy flavour decays

Use Matrix method: Define a loose (non-isolated muons) selection in addition to the standard used in the main event selection:

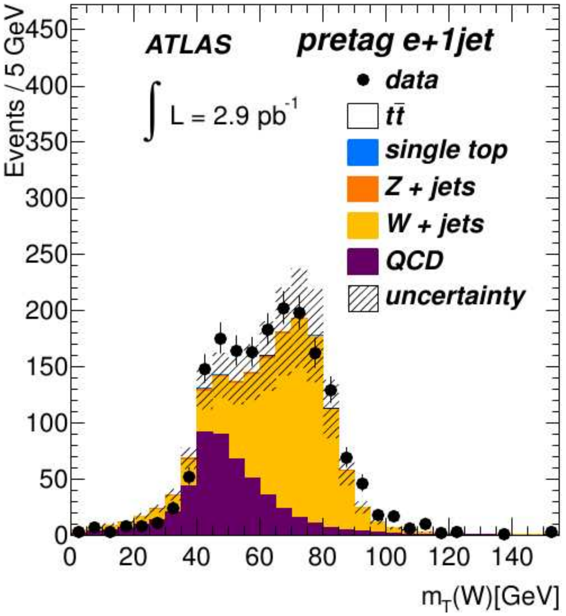
$$N^{\rm loose} = N^{\rm loose}_{\rm real} + N^{\rm loose}_{\rm fake},$$
$$N^{\rm std} = rN^{\rm loose}_{\rm real} + fN^{\rm loose}_{\rm fake}$$

- *r* measured in Z → μμ events
- *f* measured in 2 separate QCD enriched control regions



e + jets contribution from heavy flavour, $\gamma \rightarrow ee$, $\pi^{\pm}$

Use E_T^{miss} template fitting method where QCD templates are obtained from 2 separate control regions. Signal, W+jets, Z+jets templates from MC.



Control plots:
- No b-tag requirement

Left plot:
- No E_T^{miss} +m_T(W) cut

W+jets background – single leptons

To estimate W+jets BG in single lepton channel,use:

$$W^{\text{tagged}-\geq 4\text{jet}} = W^{\text{pretag}-\geq 4\text{jet}} \cdot f_{\text{tagged}}^{\geq 4-\text{jet}}$$

Extrapolated from low-jet multiplicity
control sample using
Berends-Giele scaling

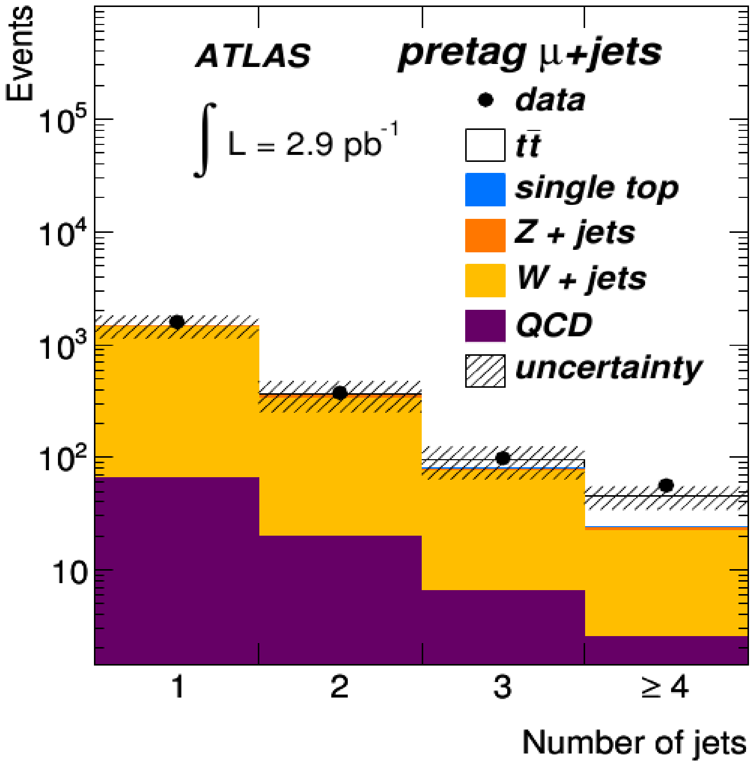
$$\frac{W + (\text{n+1})\ \text{jets}}{W + \text{n jets}} \sim \text{const}$$

$$f_{\text{tagged}}^{\geq 4-\text{jet}} = f_{\text{tagged}}^{2-\text{jet}} \cdot f_{2\to\geq 4}^{\text{corr}}$$

Tag fraction in
2-jet sample

Estimated with ALPGEN

Control region, no b-tag required



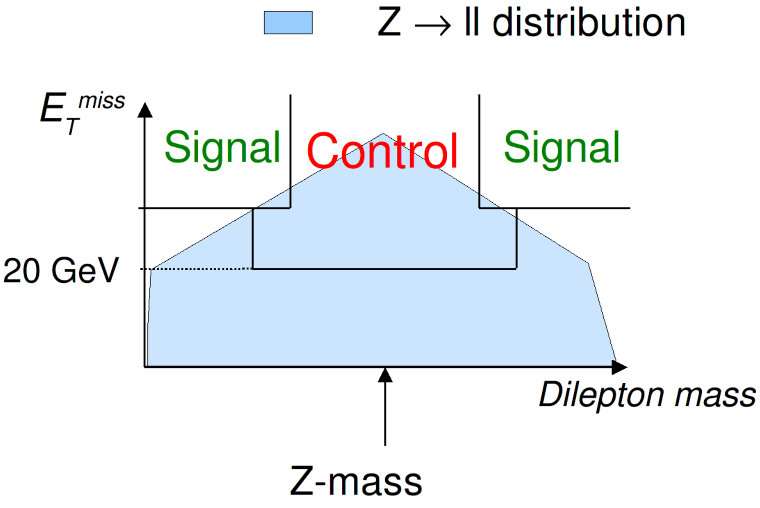
Data driven background - dileptons

Dilepton **W+jets background** is estimated using a **Matrix Method** similarly to μ+jets. Cross-checked with two independent methods.

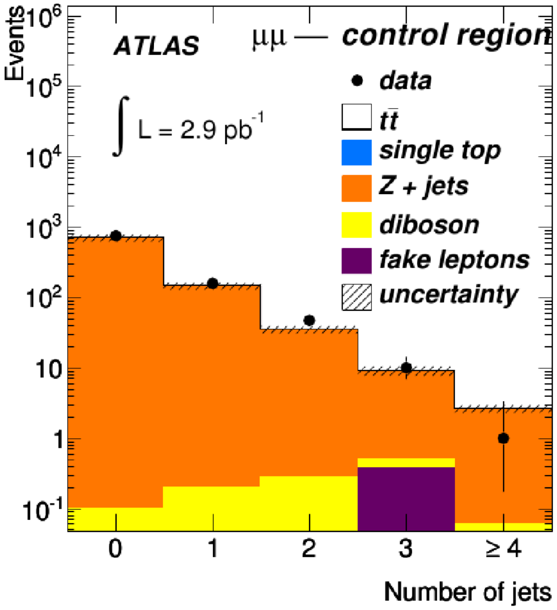
Drell-Yan background estimation

Define control region in Z-window and below the E_T^{miss}-cut

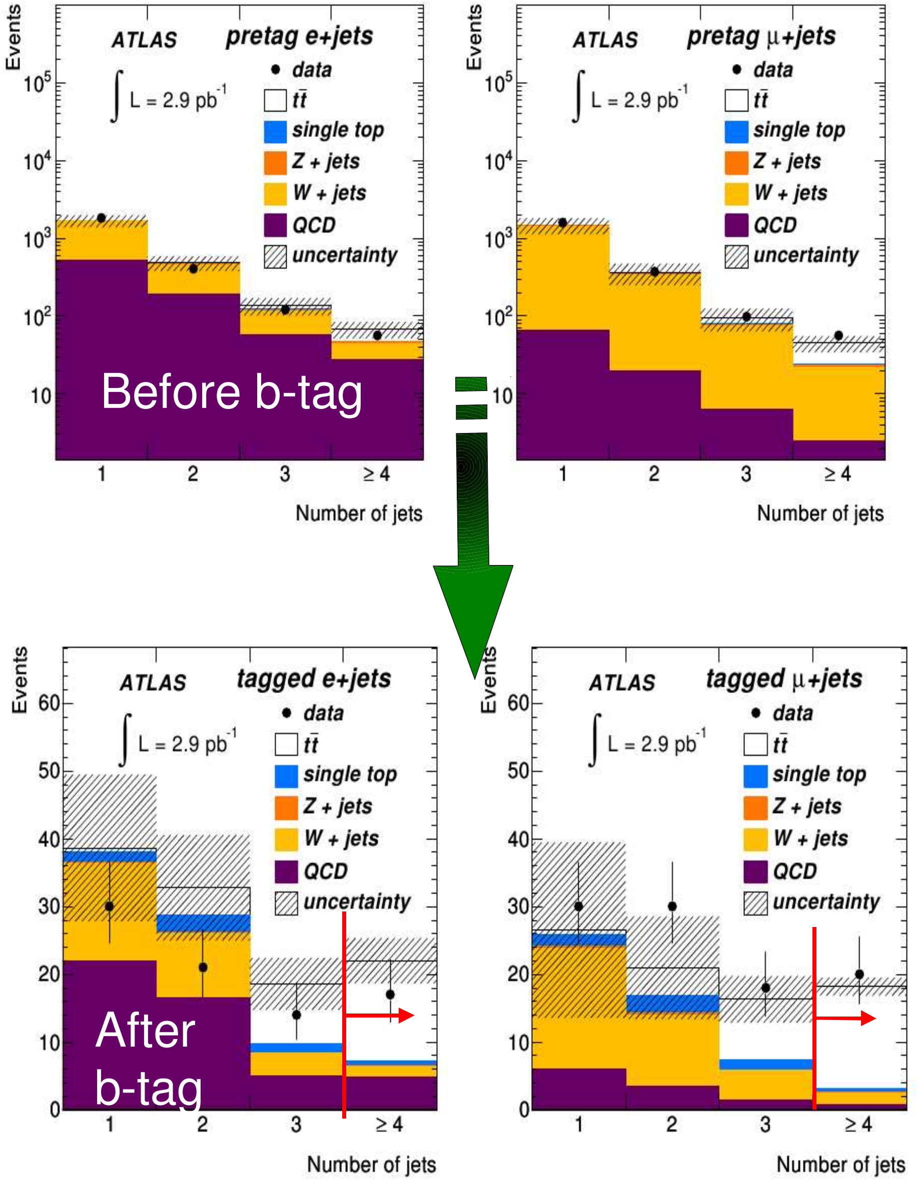
$$N_{signal,data} = N_{control,data} \times \frac{N_{signal,MC}}{N_{control,MC}}$$



No Z-veto



Event distributions – single leptons

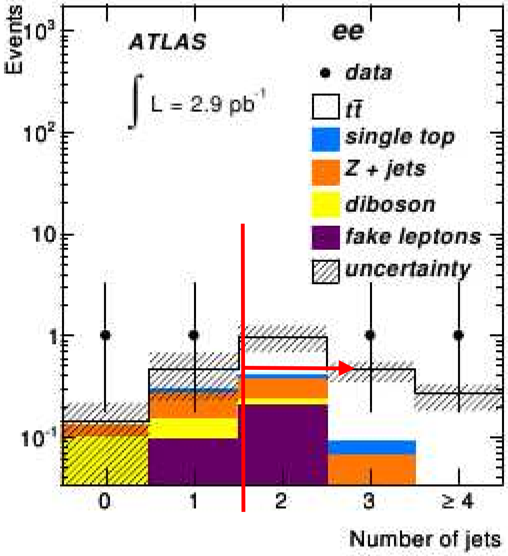


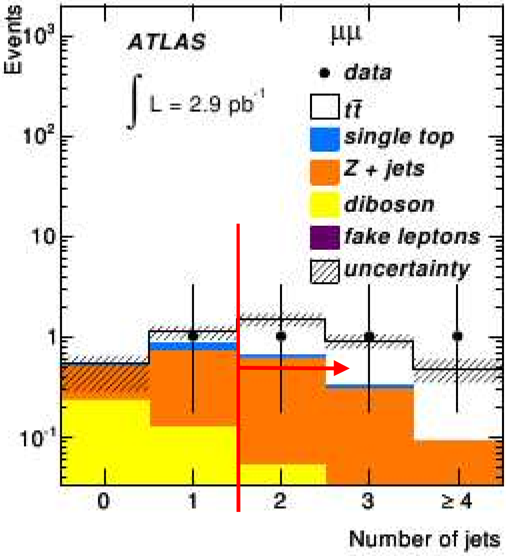
37 events pass selection in total

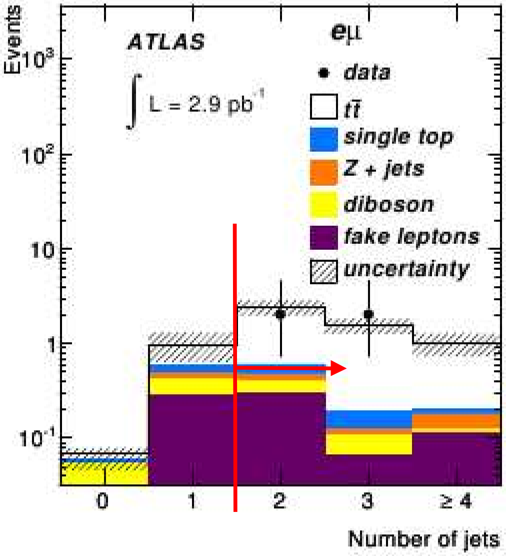
Background breakdown:

	e+jets	μ+jets
QCD (DD)	4.8 ± 3.1	0.8 ± 0.5
W+jets (DD)	1.9 ± 1.1	3.2 ± 1.7
Z+jets (MC)	0.2 ± 0.1	0.1 ± 0.1
single-t (MC)	0.7 ± 0.2	0.7 ± 0.2
Total est. BG	7.5 ± 3.1	4.7 ± 1.7
$t\bar{t}(MC)$	14.9 ± 3.5	15.0 ± 3.4
Observed	17	20

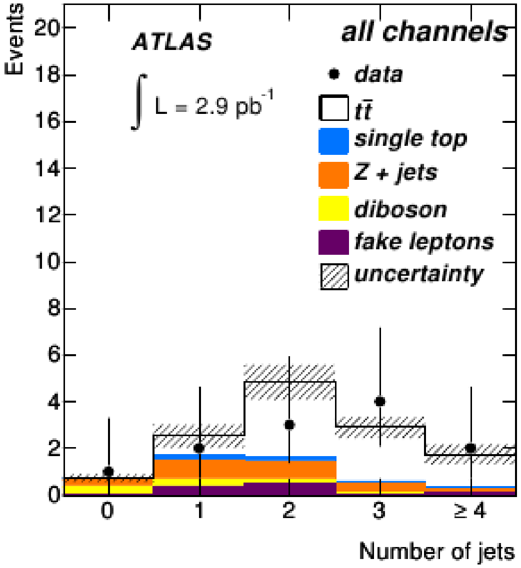
Event distributions - dileptons

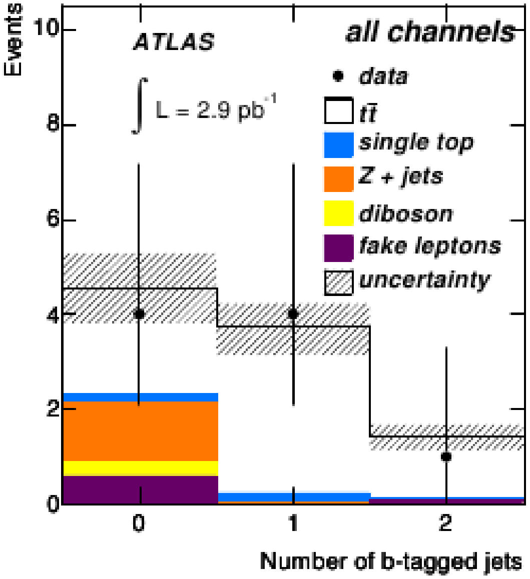






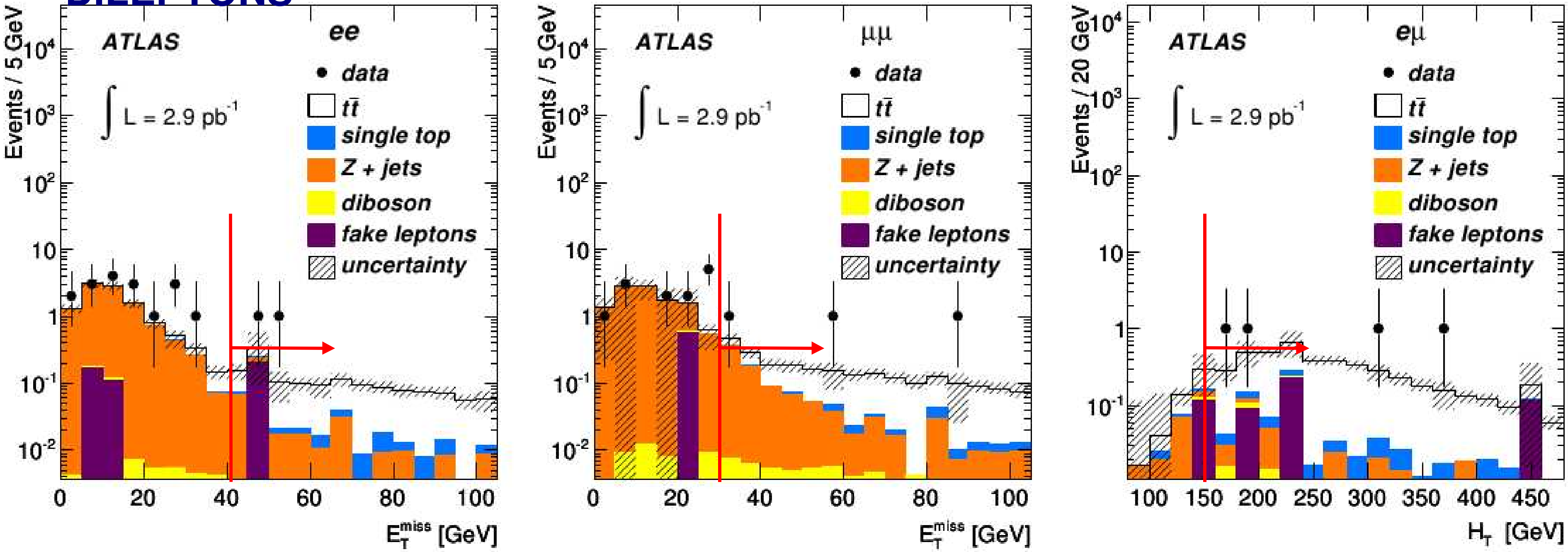
2 ee events
3 μμ events
4 eμ events





Event distributions – E_T^{miss} , H_T

DILEPTONS



Background breakdown:

Process	ee	$\mu\mu$	$e\mu$
Z+jets (DD)	0.25 ± 0.18	0.67 ± 0.38	-
$Z(\to \tau\tau)$+jets (MC)	0.07 ± 0.04	0.14 ± 0.07	0.13 ± 0.06
Non-Z leptons (DD)	0.16 ± 0.18	-0.08 ± 0.07	0.47 ± 0.28
single top (MC)	0.08 ± 0.02	0.07 ± 0.03	0.22 ± 0.04
dibosons (MC)	0.04 ± 0.02	0.07 ± 0.03	0.15 ± 0.05
Total predicted (non $t\bar{t}$)	0.60 ± 0.27	0.88 ± 0.40	0.97 ± 0.30
$t\bar{t}$	1.19 ± 0.19	1.87 ± 0.26	3.85 ± 0.51
Total predicted	1.79 ± 0.38	2.75 ± 0.55	4.82 ± 0.65
Observed	2	3	4

* H_T is scalar sum of p_T of leptons and selected jets

Cross-section measurement

A binned likelihood fit used to extract the cross-section. Express expected number of events as:

$$N^{exp}(\sigma_{t\bar{t}}, \alpha_j) = L \cdot \epsilon_{t\bar{t}}(\alpha_j) \cdot \sigma_{t\bar{t}} + \sum_{bkg} L \cdot \epsilon_{bkg}(\alpha_j) \cdot \sigma_{bkg}(\alpha_j) + N_{DD}(\alpha_j)$$

L = luminosity, ε = efficiency * acceptance , α = variation of acceptance and background due to systematic uncertainties.

For each final state, define likelihood:

$$\mathcal{L}(\sigma_{t\bar{t}}, L, \alpha_j) = \mathrm{Pois}\left(N^{obs}\,|\,N^{exp}(\sigma_{t\bar{t}}, \vec{\alpha})\right) \times G(L_0|L, \delta_L) \times \prod_{j \in \mathrm{syst}} \Gamma_j(\alpha_j)\,.$$

Counting experiment → Use Poisson to model N^{obs} given N^{exp} (contains cross-section as fit parameter)

Luminosity uncertainty is a nuisance parameter, modelled by a Gaussian.
L_0=2.9 pb^{-1}, δ_L=11%

Systematic uncertainties (JES, lepton efficiencies, uncertainties on data-driven measurements, etc) are modelled by Gamma functions (→ Gaussian at limit of small uncertainty)

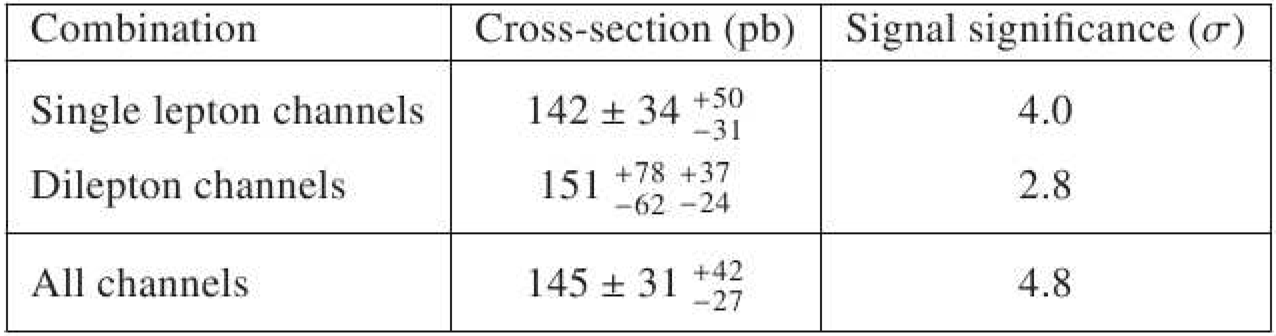
Cross-section combination

The combined cross-section is measured by a simultaneous fit of the product of the channel likelihoods:

$$\mathcal{L}_{combined}(\sigma_{combined}, \vec{\alpha}) = \prod_{i \in ee,\mu\mu\, e\mu, e+jets, \mu+jets} \mathcal{L}_i(\sigma_i, \vec{\alpha}_i)$$

Correlations accounted for:
- *in each channel* (e.g. correlated JES effect on acceptance and background) and
- *between channels* (e.g. correlated JES effect on the different acceptances)

Additionally, the significance of the observed #events under a SM-background-only hypothesis is extracted from fit.

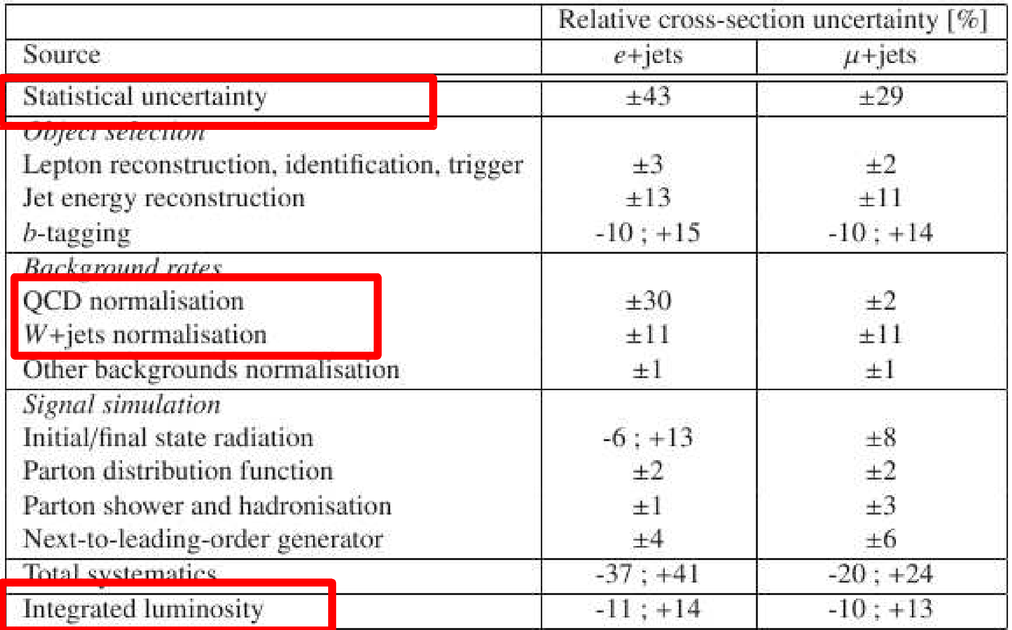


Combination	Cross-section (pb)	Signal significance (σ)
Single lepton channels	$142 \pm 34\ ^{+50}_{-31}$	4.0
Dilepton channels	$151\ ^{+78}_{-62}\ ^{+37}_{-24}$	2.8
All channels	$145 \pm 31\ ^{+42}_{-27}$	4.8

Systematic uncertainties

Effect of systematic uncertainties on cross-section

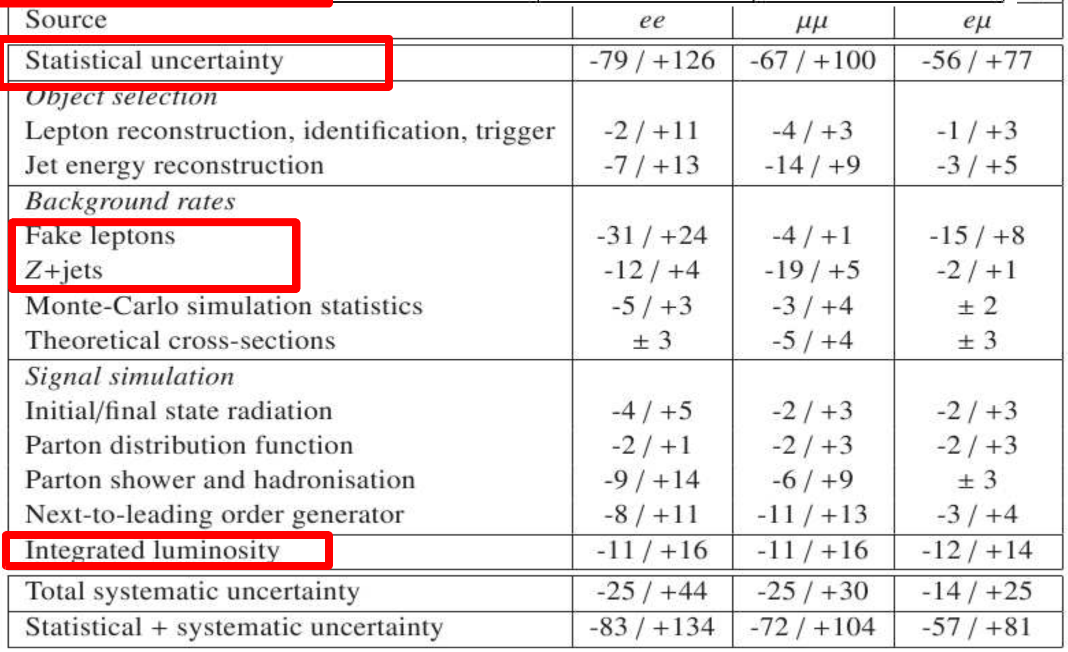
Single lepton



	Relative cross-section uncertainty [%]	
Source	e+jets	μ+jets
Statistical uncertainty	±43	±29
Object selection		
Lepton reconstruction, identification, trigger	±3	±2
Jet energy reconstruction	±13	±11
b-tagging	-10 ; +15	-10 ; +14
Background rates		
QCD normalisation	±30	±2
W+jets normalisation	±11	±11
Other backgrounds normalisation	±1	±1
Signal simulation		
Initial/final state radiation	-6 ; +13	±8
Parton distribution function	±2	±2
Parton shower and hadronisation	±1	±3
Next-to-leading-order generator	±4	±6
Total systematics	-37 ; +41	-20 ; +24
Integrated luminosity	-11 ; +14	-10 ; +13

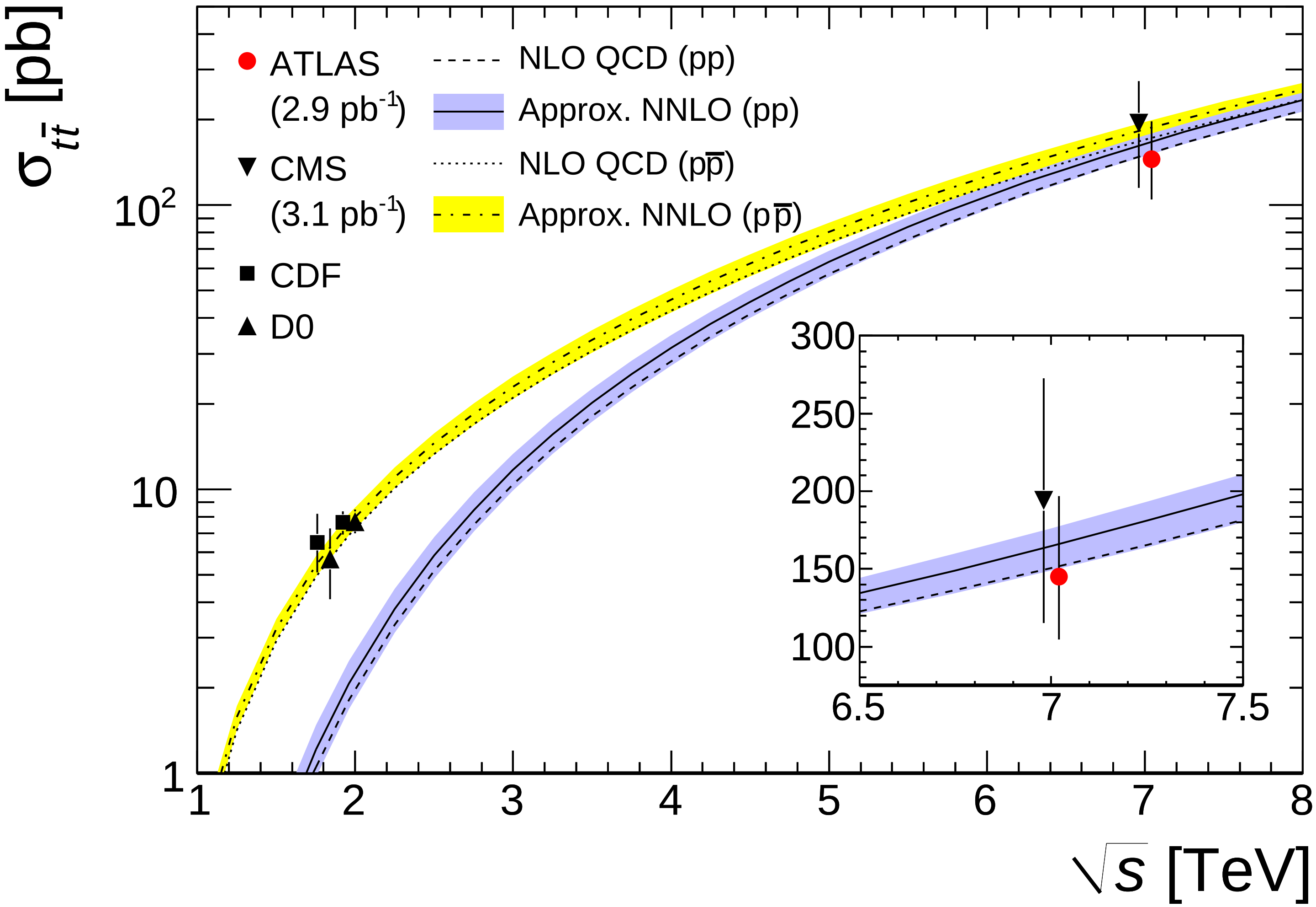
Many of the dominating systematics are due to statistical uncertainties in data-driven measurements.
Great room for improvement.

Dilepton



Source	ee	$\mu\mu$	$e\mu$
Statistical uncertainty	-79 / +126	-67 / +100	-56 / +77
Object selection			
Lepton reconstruction, identification, trigger	-2 / +11	-4 / +3	-1 / +3
Jet energy reconstruction	-7 / +13	-14 / +9	-3 / +5
Background rates			
Fake leptons	-31 / +24	-4 / +1	-15 / +8
Z+jets	-12 / +4	-19 / +5	-2 / +1
Monte-Carlo simulation statistics	-5 / +3	-3 / +4	± 2
Theoretical cross-sections	± 3	-5 / +4	± 3
Signal simulation			
Initial/final state radiation	-4 / +5	-2 / +3	-2 / +3
Parton distribution function	-2 / +1	-2 / +3	-2 / +3
Parton shower and hadronisation	-9 / +14	-6 / +9	± 3
Next-to-leading order generator	-8 / +11	-11 / +13	-3 / +4
Integrated luminosity	-11 / +16	-11 / +16	-12 / +14
Total systematic uncertainty	-25 / +44	-25 / +30	-14 / +25
Statistical + systematic uncertainty	-83 / +134	-72 / +104	-57 / +81

Cross-section comparison



* CMS measurement does not include single lepton channel.

Summary

ATLAS has measured the top pair production cross-section at the LHC in the first 2.9 pb^{-1} of data using a combination of 5 final states: e+jets, μ+jets, ee, μμ, eμ.

Dominant backgrounds have been estimated with data driven methods.

The SM background-only hypothesis is ruled out at a significance level of 4.8σ.
The cross-section is measured to be

$$\sigma_{t\bar{t}} = 145 \pm 31 \, ^{+42}_{-27} \, \text{pb}$$

Approximate NNLO QCD prediction: $164.6 \, ^{+11.4}_{-15.7} \, \text{pb}$ (HATHOR, Moch&Uwer)
at m_{top} = 172.5 GeV. Good agreement!

- We have good understanding of top events in ATLAS.
- Many more top measurements around the corner.
- With top as final state and background to many New Physics processes, exciting times are ahead!

BONUS SLIDES

Simulation samples

All samples processed with GEANT4 simulation of ATLAS, reconstructed and analysed as the data

Event generation: ttbar and single top

MC@NLO v3.41 withPDF set CTEQ66 assuming mtop= 172.5 GeV

ttbar normalized to NNLO calculation of HATHOR:165 pb

single top, s,t Wt included mormalized to MC@NLO using”diagram removal scheme” for Wt to remove overlap with ttbar

Data sample and trigger

- All data taken in DQ periods A-F passing ‘top’ GRL

  = all detectors & relevant triggers fully operational

  - ☐ **Total luminosity = 2.9 pb^{-1}**

- Triggers used (evolved with instantaneous lumi)

  single lepton trigger with threshold fully efficient for leptons with pT>20 GeV

Object definitions for event selection (I)

- **Electron** = ‘medium robust electron’ with $p_T>20$,
  E/p (as in “tight” electron)
  track with b-layer hit
  to suppress γ conversion
  $|\eta_{cluster}|<2.47$ (excluding $1.37<\eta<1.52$)
  isolation: $E_T(R=0.2)< 4 + 0.023*E_T(el)$ GeV

- **Muon** = ‘MUID tight’, pT>20 GeV, $|\eta|<2.5$
  isolation: $E_T(R=0.3)<4$ GeV, $P_T(R=0.3)<4$ GeV
  DR>0.4 w.r.t nearest jet with pT>20 GeV

to suppress bck from hadron and b,c, decays

Object definitions for event selection (II)

- **Jet** = AntiKt4 TopoCluster jets

  EM+JES (MC hadron scale p_T,η dependent)

  DR(jet-el)>0.2 (to avoid double counting el as jet).

- **B-jet** = Jet + SV0 cut at 50% MC efficiency point

  early tagger - efficiency for ttbar OK

  ~220 rejection of light jets

- **Missing E_T** = Simplified METRefFinal

  contribution from selected muons included

- Require a primary vertex with Ntracks>4.

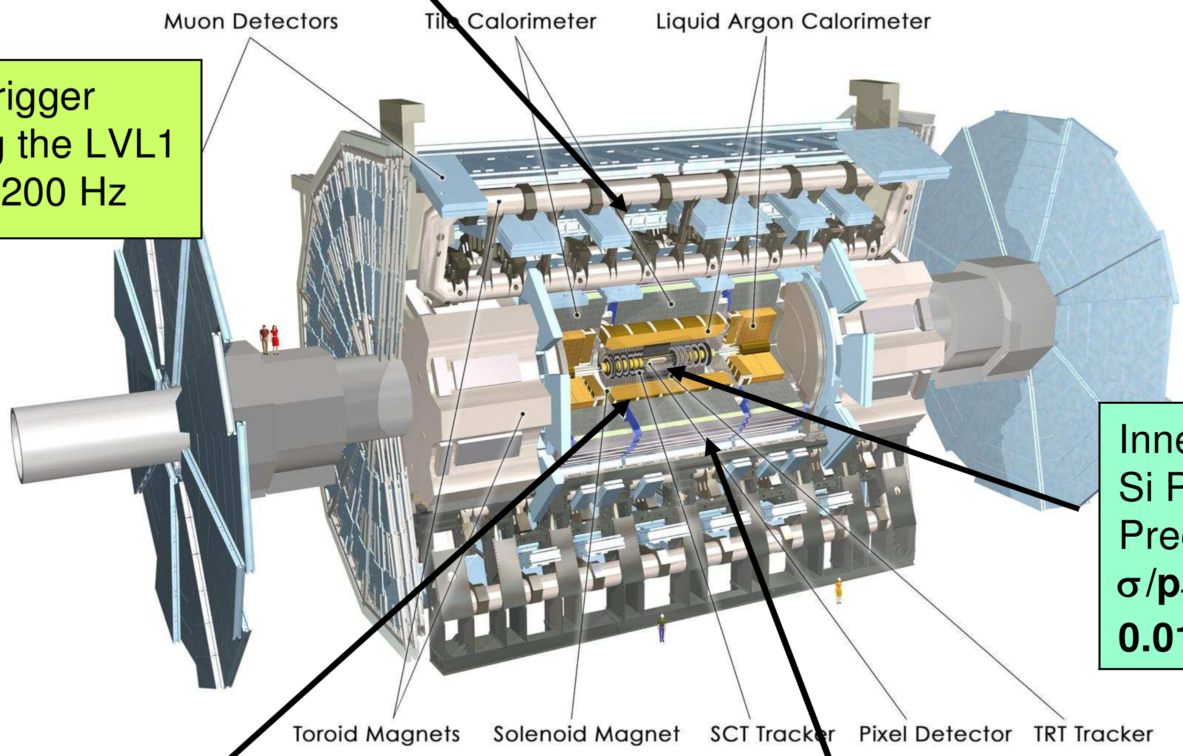
  discard events with “bad” jets pT>15 GeV

The ATLAS detector

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 LVL1 rate to ~200 Hz

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

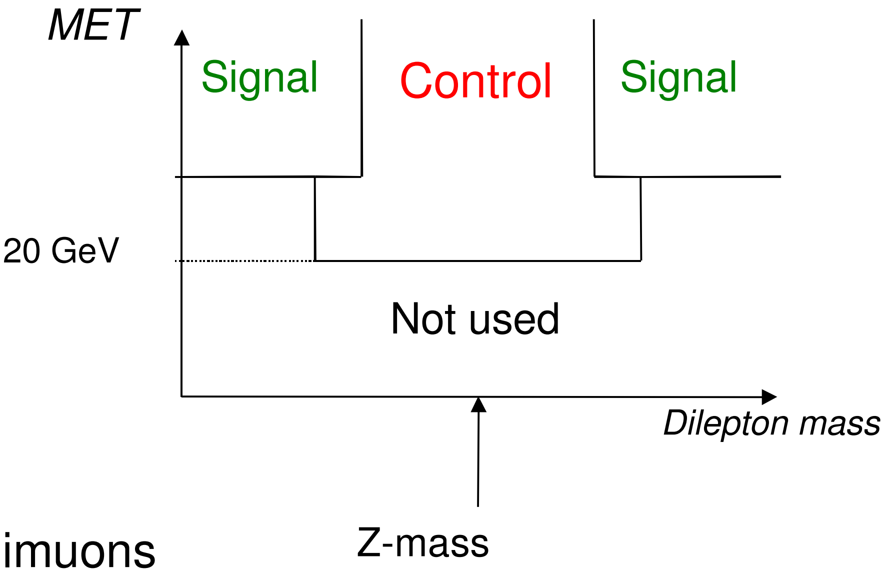


Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, TRT
Precise tracking and vertexing,
σ/p_T ~ 3.8×10^{-4} p_T (GeV) $\oplus$ 0.015

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: **σ/E ~ $10\%/\sqrt{E} \oplus 0.007$**
granularity :.025 x .025 $\oplus$ strips

HAD calorimetry ($|\eta|<3$): segmentation **0.1 x 0.1**
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
E-resolution: **σ/E ~ $50\%/\sqrt{E} \oplus 0.03$**
FWD calorimetry:W/LAr **σ/E ~ $90\%/\sqrt{E} \oplus$ 0.07**

Drell-Yan control region, details


MET
Signal
Control
Signal
20 GeV
Not used
Dilepton mass
Z-mass

Control region dimuons

20 GeV<MET<30 GeV: $|M_{\mu\mu} - Mz| < 15$ GeV ,
MET>30 GeV: $|M_{\mu\mu} - Mz| < 10$ GeV

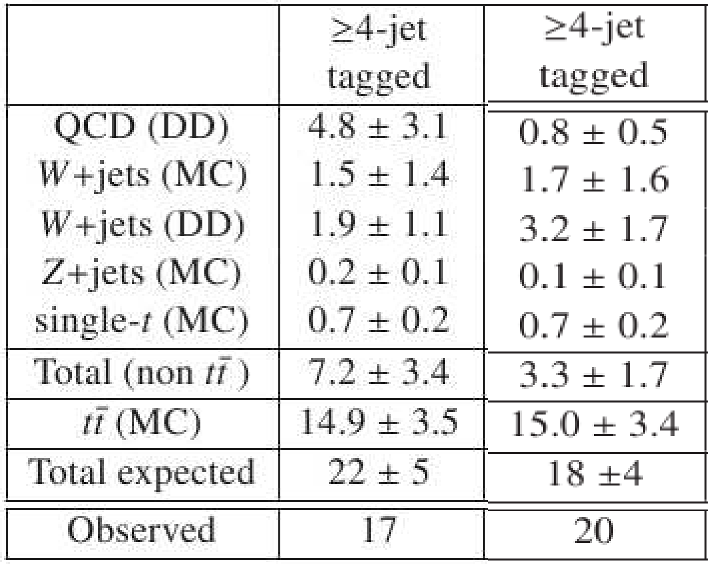
Control region dielectrons

20 GeV<MET<40 GeV: $|M_{ee} - Mz| < 15$ GeV ,
MET>40 GeV: $|M_{ee} - Mz| < 5$ GeV

Event yields, single lepton

TO BE INCLUDED IF APPROVED

e+jets mu+jets



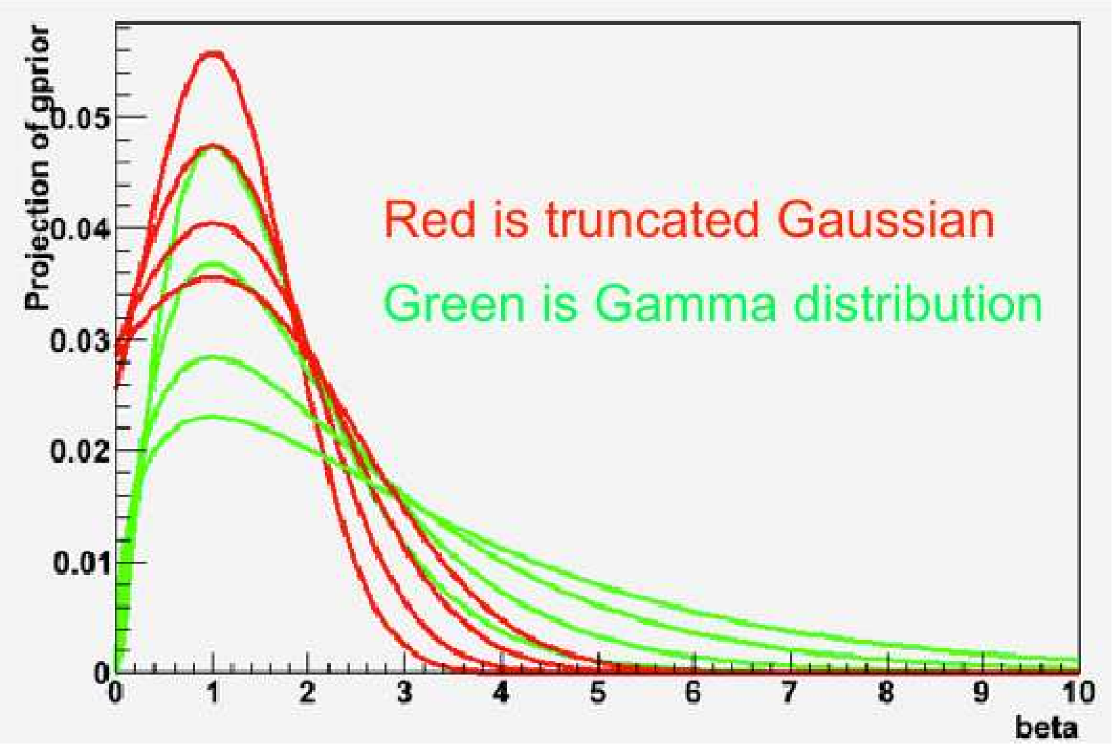
	≥4-jet tagged	≥4-jet tagged
QCD (DD)	4.8 ± 3.1	0.8 ± 0.5
W+jets (MC)	1.5 ± 1.4	1.7 ± 1.6
W+jets (DD)	1.9 ± 1.1	3.2 ± 1.7
Z+jets (MC)	0.2 ± 0.1	0.1 ± 0.1
single-t (MC)	0.7 ± 0.2	0.7 ± 0.2
Total (non $t\bar{t}$)	7.2 ± 3.4	3.3 ± 1.7
$t\bar{t}$ (MC)	14.9 ± 3.5	15.0 ± 3.4
Total expected	22 ± 5	18 ±4
Observed	17	20

37 l+jets events observed.
Uncertainties in table are systematic.

PDF for systematics terms

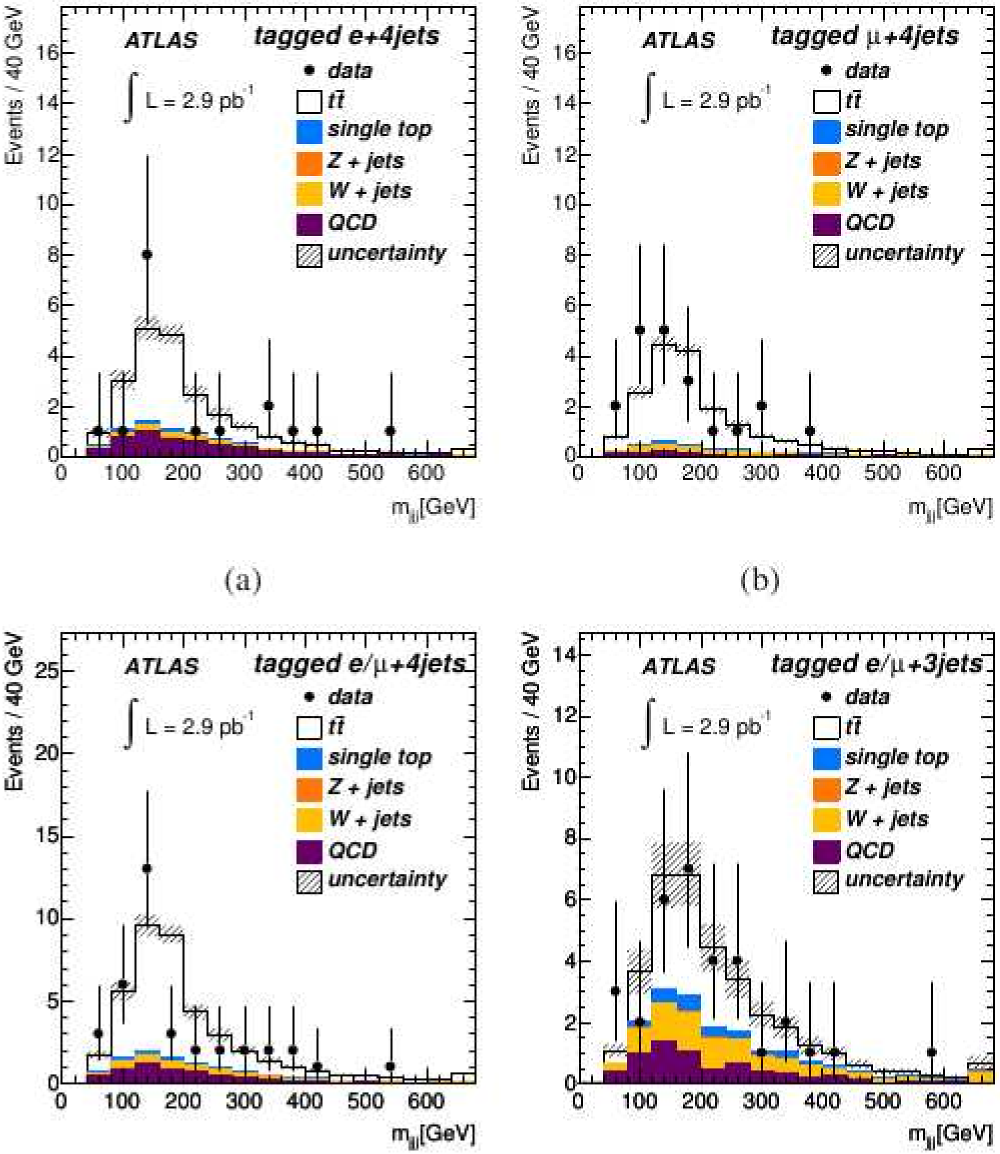
Truncated Gaussian is the classical choice for the shape of a systematic term → not suitable when relative uncertainties are large (>20%)

Instead, use a Gamma function:
+ Well behaved close to 0.
+ Long tail (more conservative than Gaussian)
+ Natural choice if auxiliary measurement is based on counting (Drell-Yan and fakes BG).



We use Gamma-functions for all systematics except for luminosity, where a Gaussian is used. Sources of systematics are allowed to have either have **no correlation** of **full correlation** between channels.

Control plots – single lepton

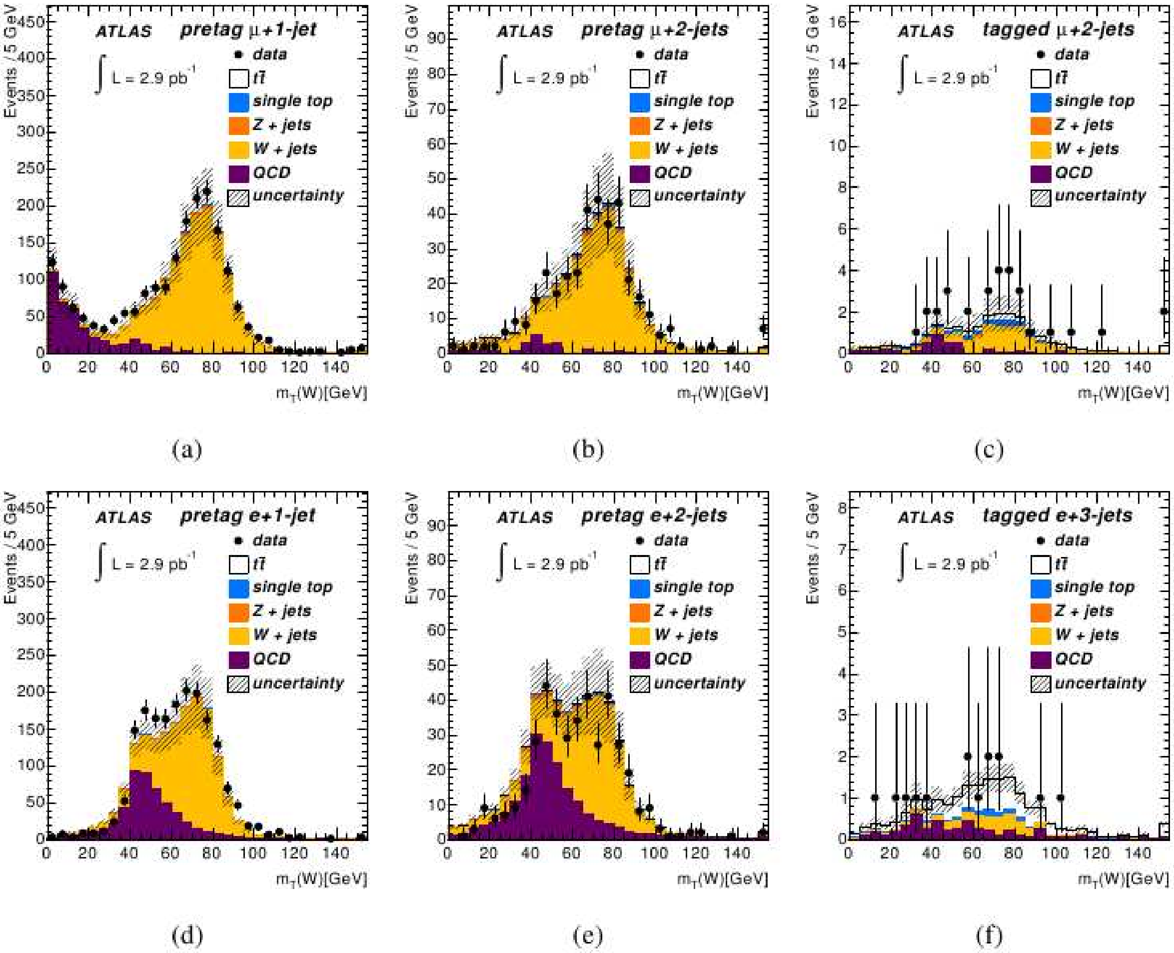


(a)

(b)

Invariant mass of 3-jet combination with the highest p_T

Control plots – single lepton

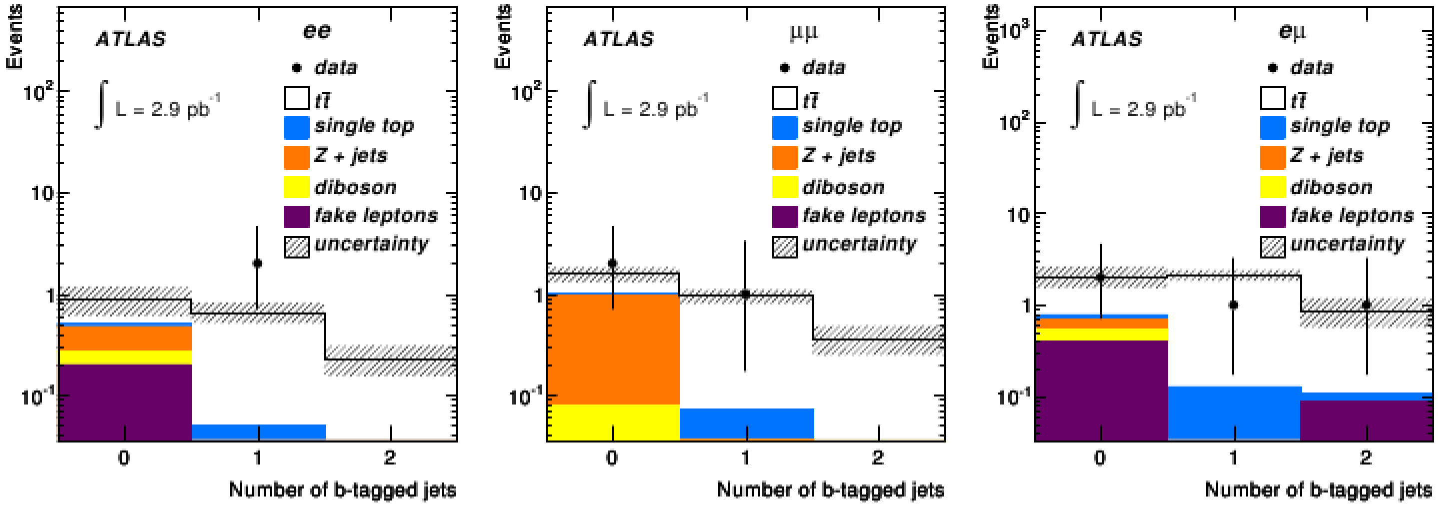


(a) (b) (c)

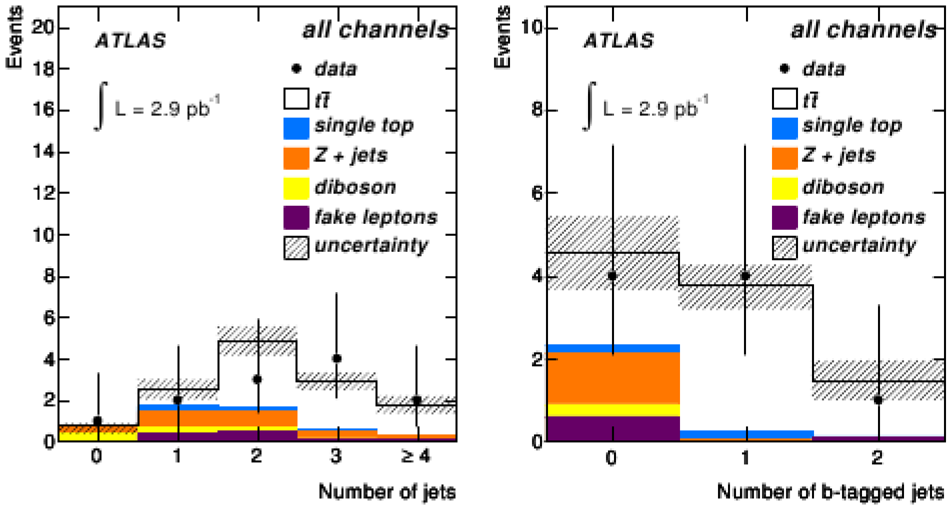
(d) (e) (f)

Figure 2: Distributions of $m_T(W)$. Top row - μ+jets channel : (a) the 1-jet pre-tag sample (where the E_T^{miss} + $m_T(W)$ requirement is not applied), (b) the 2-jet pre-tag sample and (c) the 2-jet tagged sample. Bottom row - e+jets channel: (d) the 1-jet pre-tag sample, (e) the 2-jet pre-tag sample and (f) the 3-jet tagged sample. In each plot data are compared to the sum of the data-driven QCD estimate plus the contributions from W/Z+jets and top from simulation. The background uncertainty on the total expectation is represented by the hatched area.

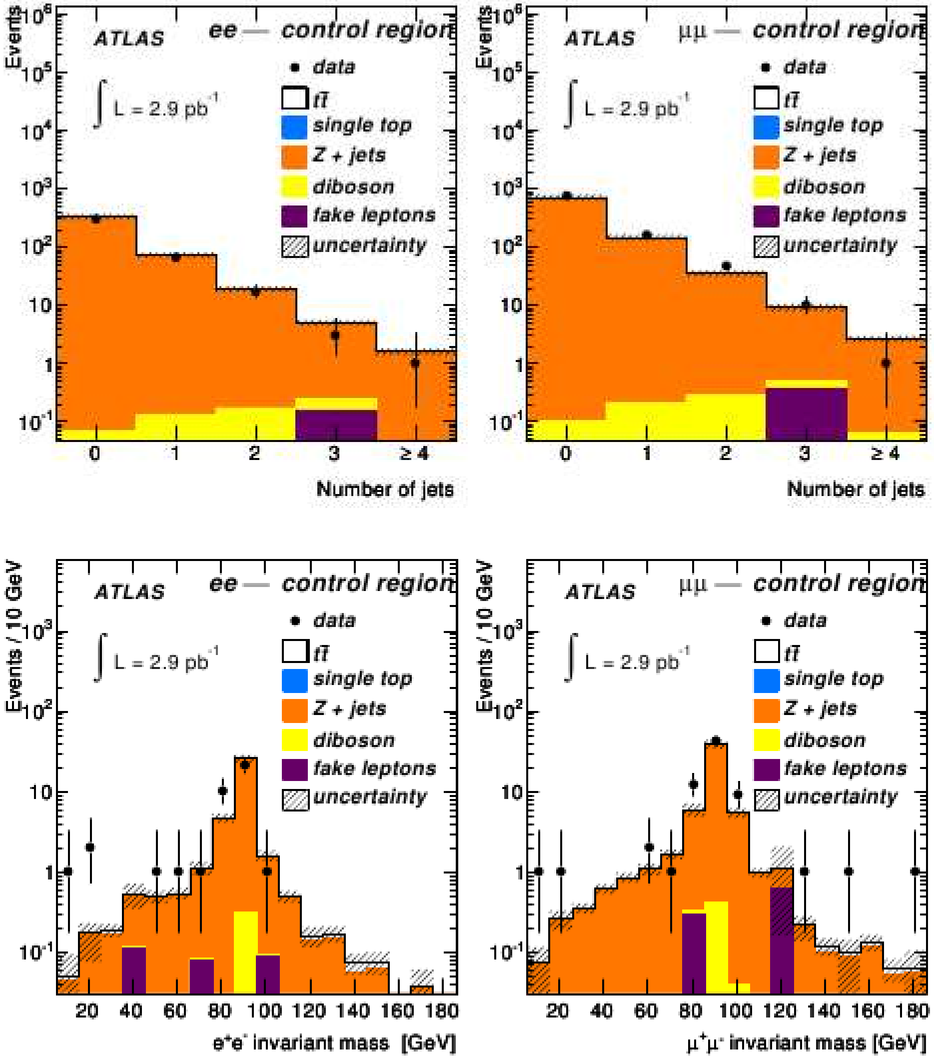
B-tagged jets – dilepton channel



NB! No b-tag requirement in the event selection.



Control samples/cross-checks



DILEPTONS

Data well modelled by signal+ background estimates in control regions orthogonal to signal region

Plots are for opposite sign ee and μμ in region
Top row:
 - inside Z-window
Bottom row:
 - No Z-veto, below E_t^{miss}-cut