Top cross section measurements at ATLAS

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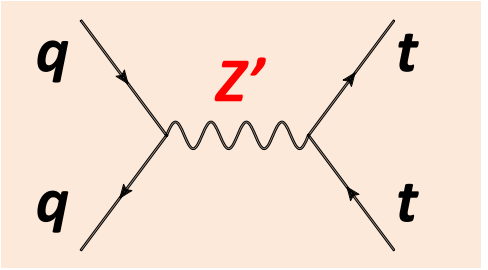
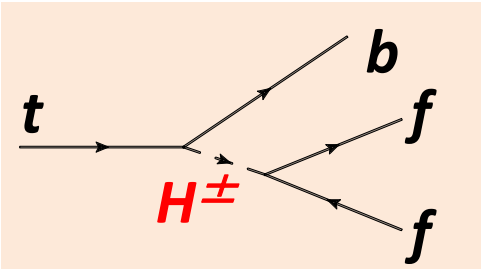
On behalf of ATLAS collaboration

The top quark

- Top quark is the heaviest quark in the SM
  - Largest coupling to Higgs boson
  - Shorter lifetime than hadronization time scale ($\tau < \Lambda_{QCD}^{-1}$)

- Top quark pair production & BR measurement have important roles
  - Good test for New Physics for example:
    - $qq \to Z' \to t\bar{t}$ production affects $\sigma_{t\bar{t}}$
    - $H^{\pm}$ production in top quark decay affects BR
  - Precise measurement of SM (p-QCD)
  - Understand $t\bar{t}$ backgrounds to new physics & Higgs boson searches

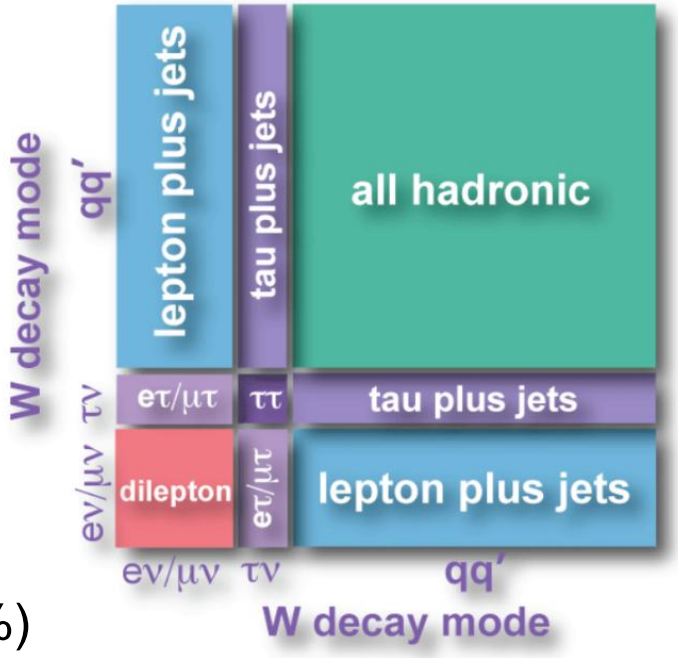




SM top quark pair production @ LHC

- $t\bar{t}$ production cross section prediction = 165pb
  - Evaluated by NNLO p-QCD calculation
    - With $\sqrt{s}$ of pp = 7 TeV, m_t= 172.5 GeV
  - Including following production modes:
    - Gluon – gluon fusion (main process at the LHC)
    - Quark – quark annihilation (main process at the Tevatron)
  - Theoretical uncertainty : $^{+11}/_{-16}$ pb
    - Relative uncertainties are $^{+7\%}/_{-10\%}$

- $t\bar{t}$ decay topology
  - BR(t→bW) ≈ 1 in SM
  - Final state is categorized by decay of 2 W bosons
    ($W \to \text{hadrons} \;/\; W \to e\nu,\ \mu\nu,\ \tau(\to e\nu\nu, \mu\nu\nu)\nu$)
    - **1-lepton (e/μ) : 34%**
    - **2-lepton ($ee/\mu\mu/e\mu$) : 6%**
    - All hadronic (46%), Tau inclusive (14%)

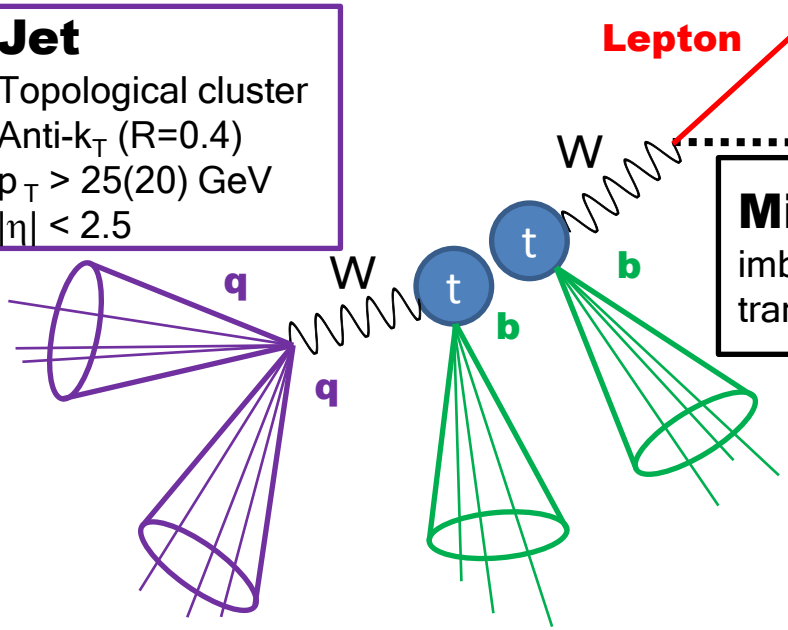


Object definition & data sample

Muon
$p_T > 20$ GeV
$|\eta| < 2.5$
Isolated muon track
Tracker & Muon detector

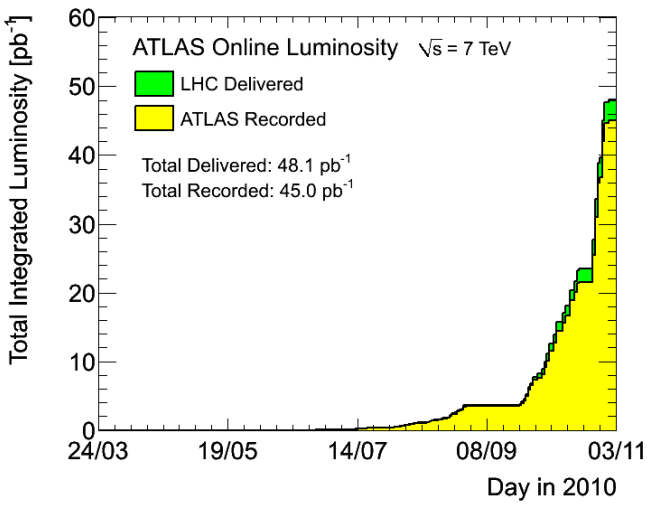
Electron
Good isolated calo object
Matching to track
$E_T > 20$ GeV
$|\eta| < 1.37$, $1.52 < |\eta| < 2.47$

Jet
Topological cluster
Anti-k_T (R=0.4)
$p_T > 25(20)$ GeV
$|\eta| < 2.5$



Missing ET
imbalance of transverse activities

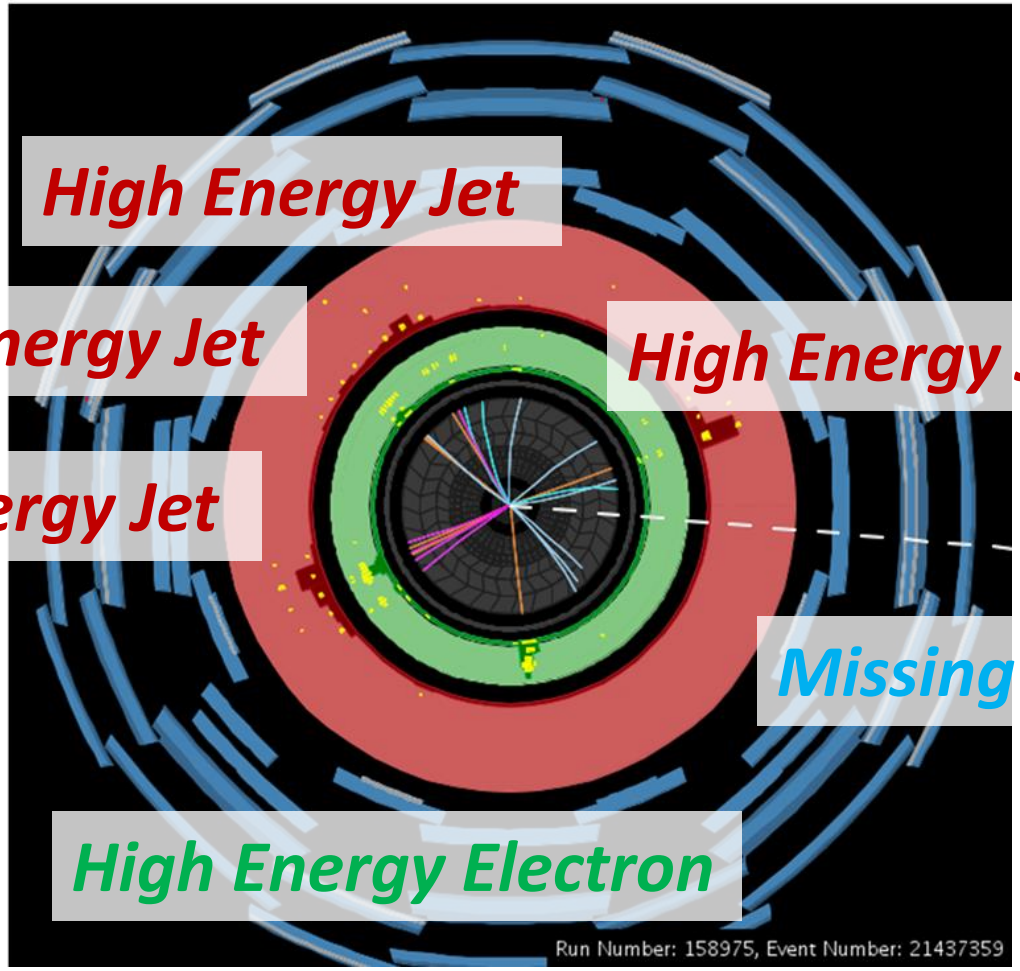
B-tagging
Based on displacement of tracks
(Transverse impact parameters or Secondary vertex)

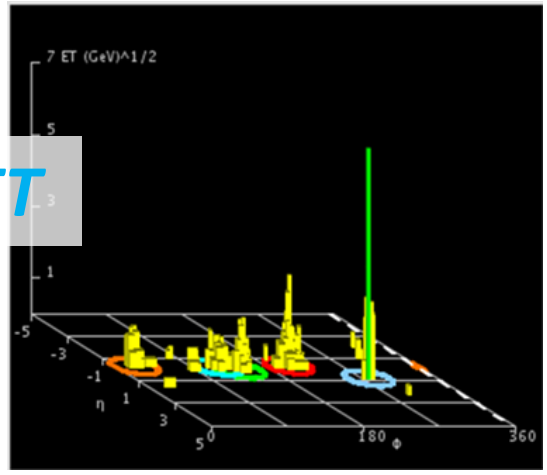


Data sample

35pb^{-1} (uncertainty = 3.4%) can be used with good data taking quality from full dataset taken in 2010

Improve measurement with **10 times more statistics** with respect to first measurement of $145 \pm 31\ ^{+42}/_{-27}$ with 2.9pb^{-1} (arXiv:1012.1792 , accepted by EPJC)



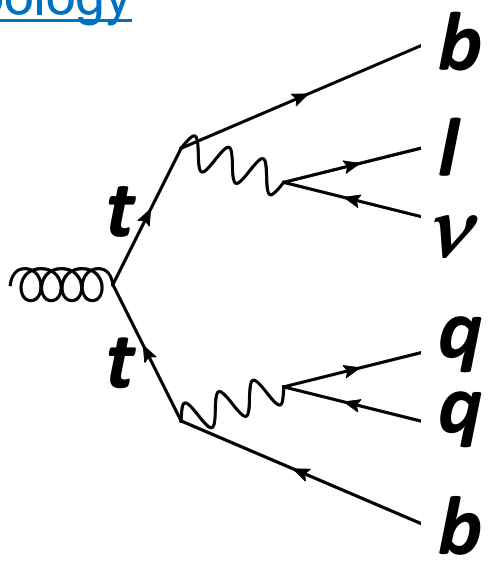


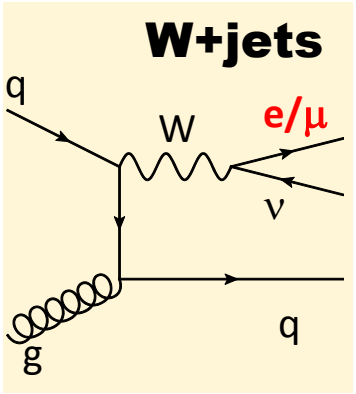
1-LEPTON MODE ANALYSIS

Analysis overview

1-lepton

- Property & selection criteria of event for 1-lepton topology
  - Single lepton trigger
  - Exactly 1 isolated lepton (e/μ) with p_T> 20GeV
  - E_T^{Miss} & $m_T(W)$
    - E_T^{Miss}> 20GeV, $E_T^{Miss} + m_T(W)$> 60GeV (*μ+jets*)
    - E_T^{Miss}> 35GeV, $m_T(W)$> 20GeV (*e+jets*)
  - 3 or more jets with p_T > 25GeV
  - Extract cross section by a fit of multivariate likelihood
- Background physics process
  - W+jets backgrounds
    - Shape is determined by MC
    - Normalization of different jet multiplicity bins are determined by a fit with constraint of ratio $\sigma_{W+njet}/\sigma_{W+(n+1)jet}$ (Berends scaling)
  - SM backgrounds (Z*/γ+jets, single top, 2-boson backgrounds)
    - Shape is estimated with MC
  - Fake lepton backgrounds (heavy/light flavor jets, γ-conversion)
    - Due to mis-ID of leptons, and not well modeled in simulation
    - (For example) **matrix method** for μ channel





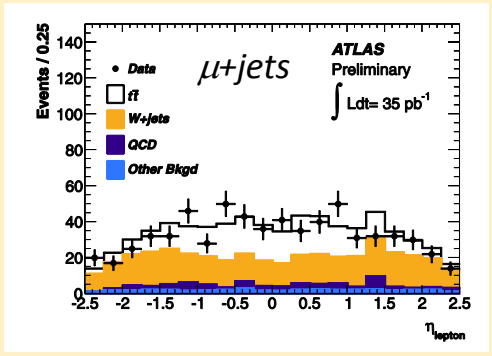
$$N_{\text{loose}} = N_{\text{fake }\mu} + N_{\text{prompt }\mu}$$

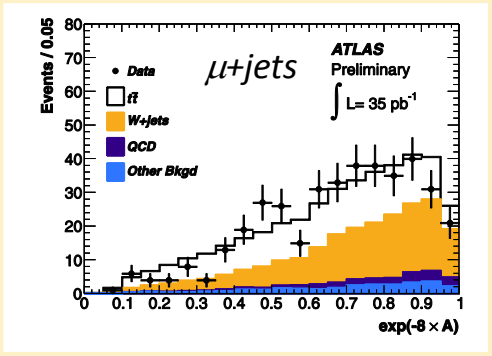
$$N_{\text{tight}} = \epsilon_{\text{tight}}^{\text{fake}} N_{\text{fake }\mu} + \epsilon_{\text{tight}}^{\text{prompt}} N_{\text{prompt }\mu}$$

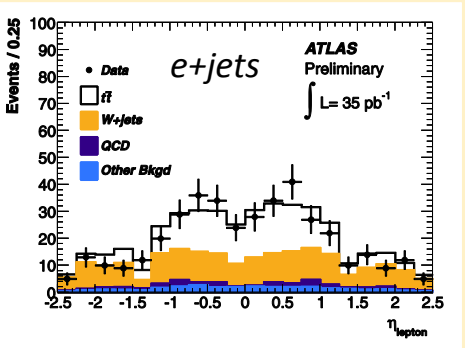
Event yield determination

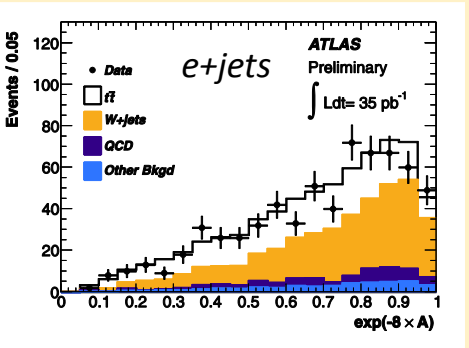
1-lepton pre b-tag

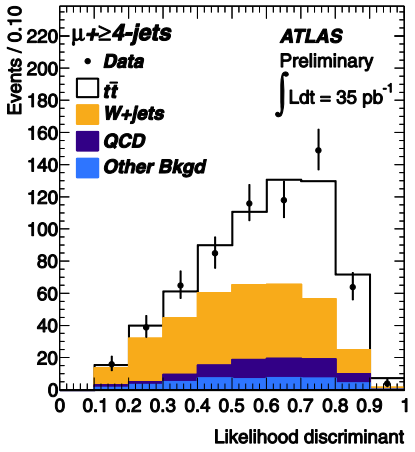
- Determination of event yields & cross section
  - Extract cross section from a fit of projective likelihood calculated with followings:
    - Lepton η, lepton charge , smallest eigen value of sphericity tensor $S^{\alpha\beta} = \sum_{\text{particles}} p_i^\alpha p_i^\beta / \sum_{\text{particles}} |\vec{p}_i|^2$ (aplanarity)

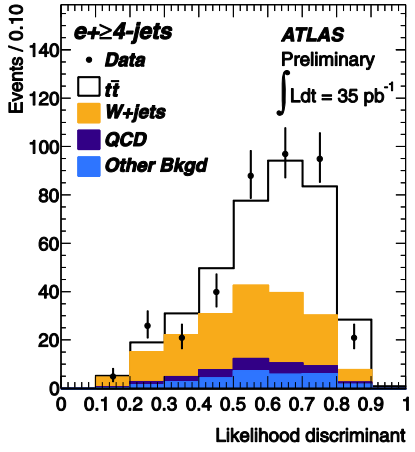












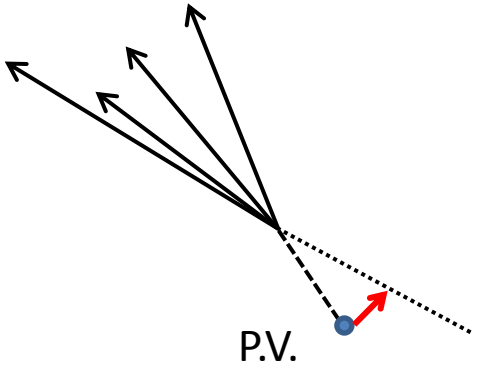
$$171 \pm 17^{+20}_{-17} \pm 6\text{pb}$$

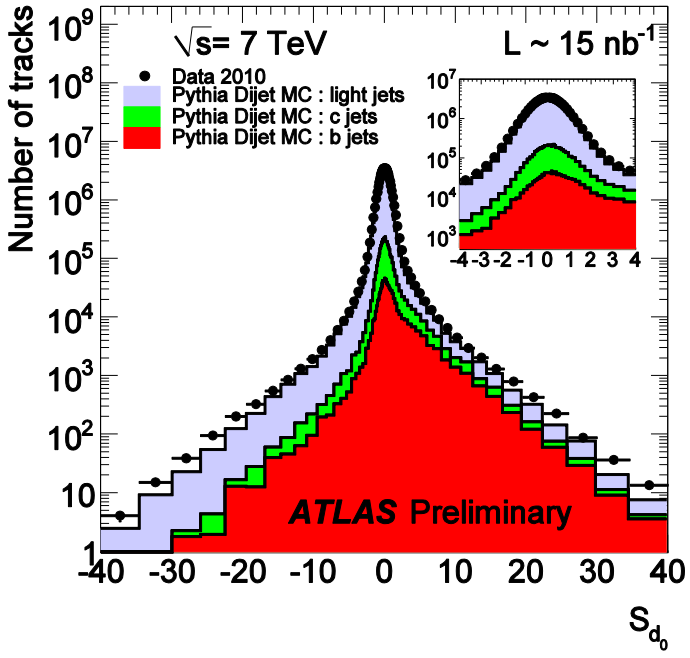
Statistical error **Systematic error**
Luminosity uncertainty

$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ **=15%**

Lifetime b-tagging

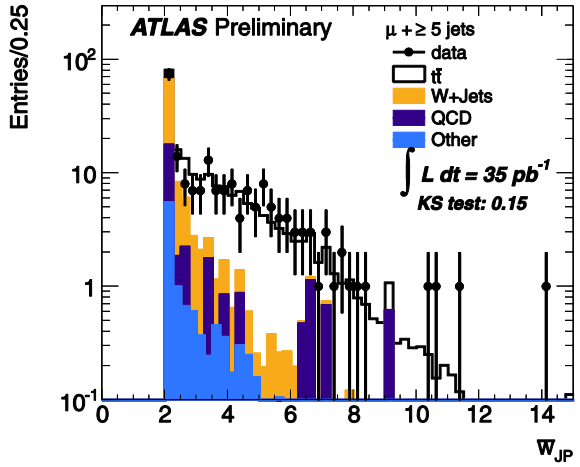
- B-tagging @ ATLAS
  - 2 b-tagging algorithms
    - Transverse impact parameters of tracks in jets (JetProb)
      - Used in main analyses
    - Displacement of vertex reconstructed with tracks in jets (SV0)
      - Used in cross-check analyses
  - Good separation performance
    - Performance of JetProb
      - Mistag rate of light jets is 5% for 70% b-tagging efficiency
    - Performance of SV0
      - Mistag rate of light jets is 0.4% for 50% b-tagging efficiency

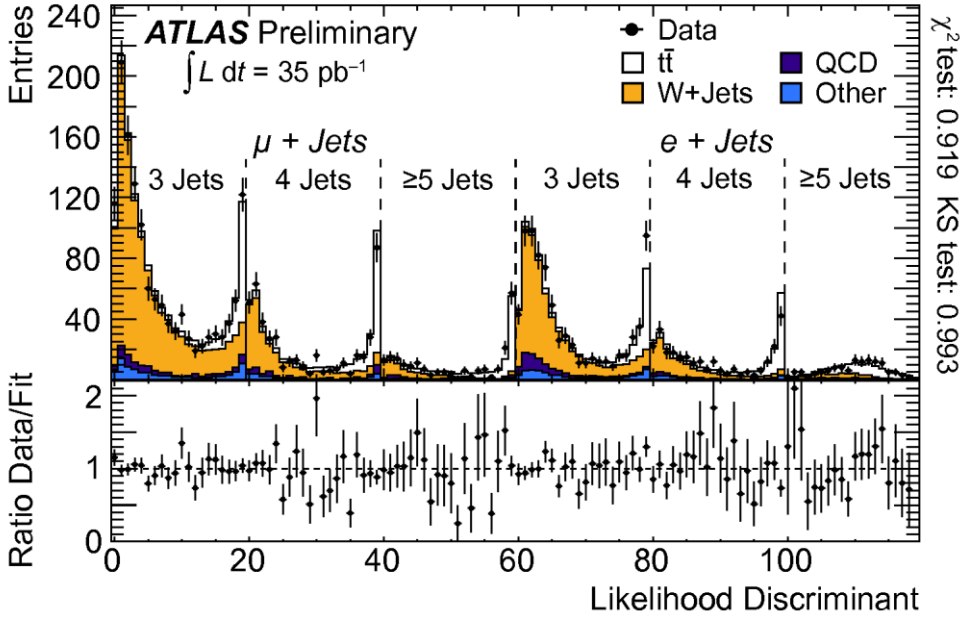




Event yield estimation 1-lepton with b-tag

- Likelihood with b-tagging
  - Lepton η, aplanarity, transverse energy sum, average of b-tagging weight of 2 jets with highest b-tagging weight
- A fit of likelihood discriminat extract:
  - Normalization parameters including $\sigma_{t\bar{t}}$
- Setup of fitting
  - Template shape are determined by MC
    - Except for QCD, determined from data
  - Many systematic uncertainties are applied as nuisance parameters in the likelihood fit





Cross section estimation **1-lepton with b-tag**

- Systematic uncertainties: Total=**11%**
  - Jet reconstruction (Energy Scale) : 6%
  - Heavy flavor fraction in W+jets : 7%
  - B-tagging efficiency : 7%
  - Initial & Final state radiation : 4%

- Cross section estimation

$$186 \pm 10\ ^{+21}/_{-20} \pm 6\ \text{pb}$$

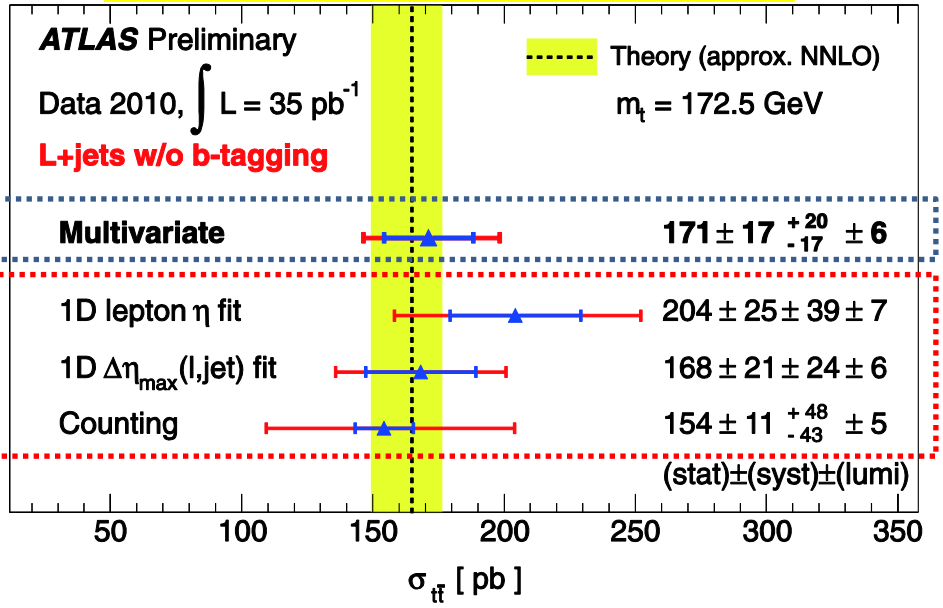
*** Statistical error, * Systematic error, * Luminosity uncertainty**

  - $\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ =**13%**

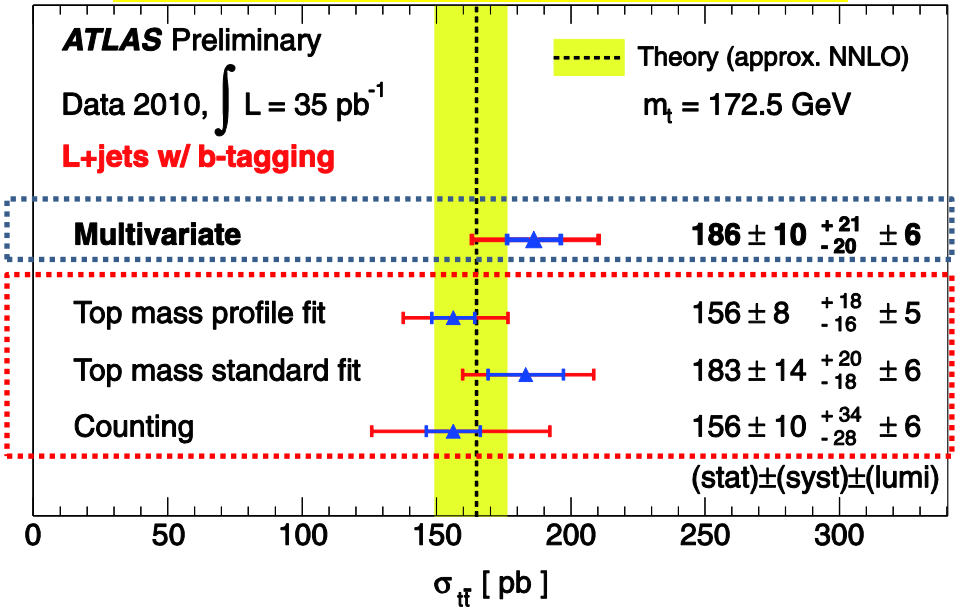
1-lepton analysis summary

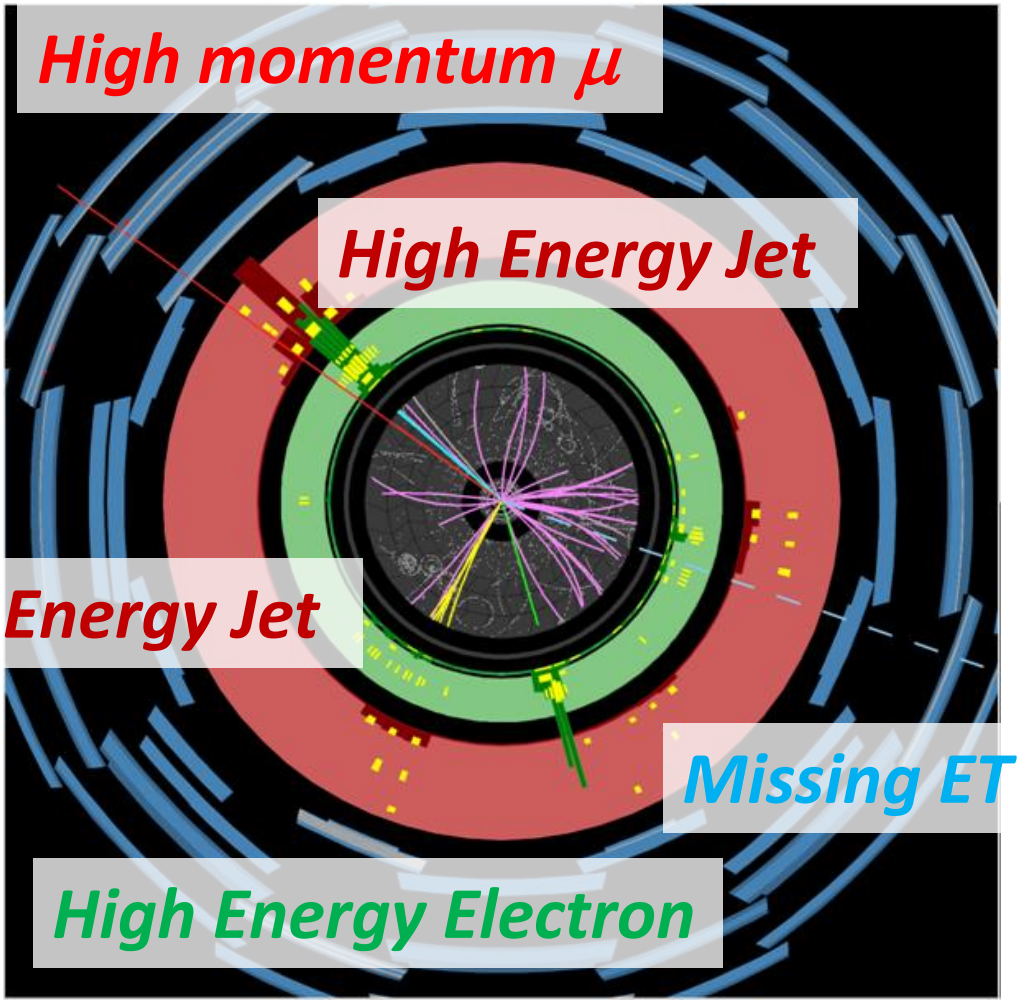
- 8 independent analyses are performed.
  - 2 main analyses & 6 cross check analyses
    - In agreement within uncertainties
    - Consistent with the theoretical prediction (165pb)

1-lepton pre b-tag



1-lepton with b-tag



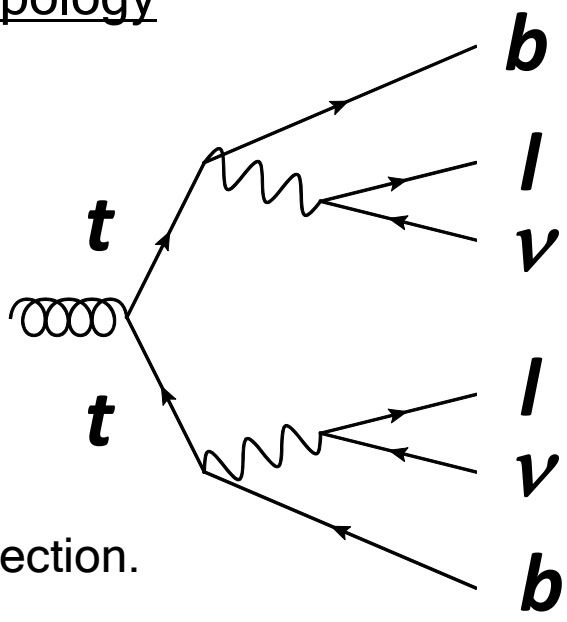


2-LEPTON MODE ANALYSIS

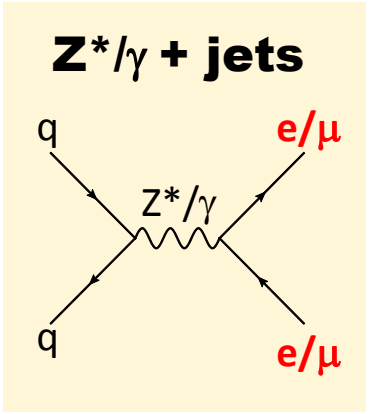
Analysis overview

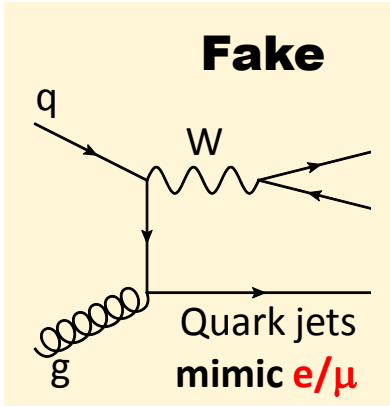
2-lepton

- Property & selection criteria of event for 2-lepton topology
  - Single lepton trigger
  - Exactly 2 isolated leptons (e/μ) with p_T >20GeV
    (3 event topologies: ee $\mu\mu$ $e\mu$)
  - E_T^{Miss} > 40GeV ($ee/\mu\mu$), H_T > 130GeV ($e\mu$)
  - 2 or more jets with p_T>20GeV
  - Z mass veto ($ee/\mu\mu$) with $|M_{ll} - M_Z|$> 10GeV
  - (b-tagging is not required by default)
  - Count number of selected events to estimate cross section.



- Background physics process
  - Z*/γ (→ $ee/\mu\mu$) + jets
    (Estimated w/ data & assistance of MC)
  - Fake from QCD, W+jets (w/ Data)
    - Matrix method (similar one for QCD determination in 1-lepton analysis.)
  - Other SM backgrounds (w/ MC)
    - Single top, 2-boson, Z */γ (→ττ)+jets backgrounds



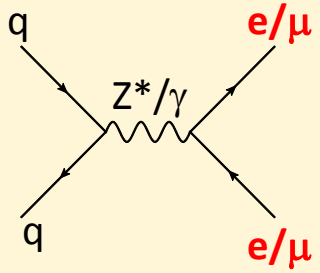


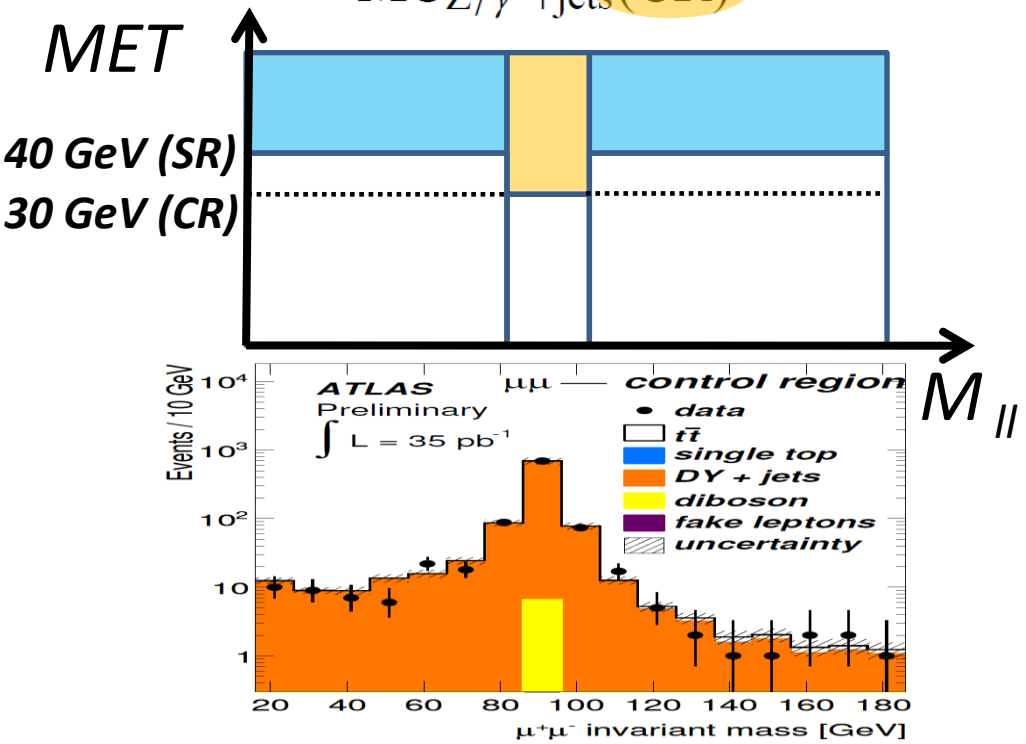
Z*/γ (→ee/μμ)+jets backgrounds **2-lepton**

- Count the Z*/γ contribution in sideband region, where fraction of Z*/γ is about 90%
- Extrapolate it to signal region

$$N_{Z/\gamma^*+\text{jets}} = \frac{MC_{Z/\gamma^*+\text{jets}}(SR)}{MC_{Z/\gamma^*+\text{jets}}(CR)} \times (\text{Data}(CR) - MC_{\text{other}}(CR))$$

Drell-Yan





Definition of control region

(1) Inside of Z mass resonance

81GeV <|M ll|< 101GeV

(2) High MET region

MET > 30GeV

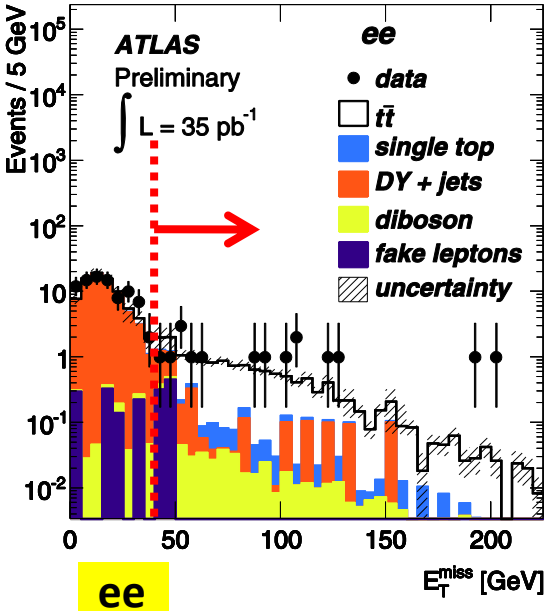
(3) High jet multiplicity events

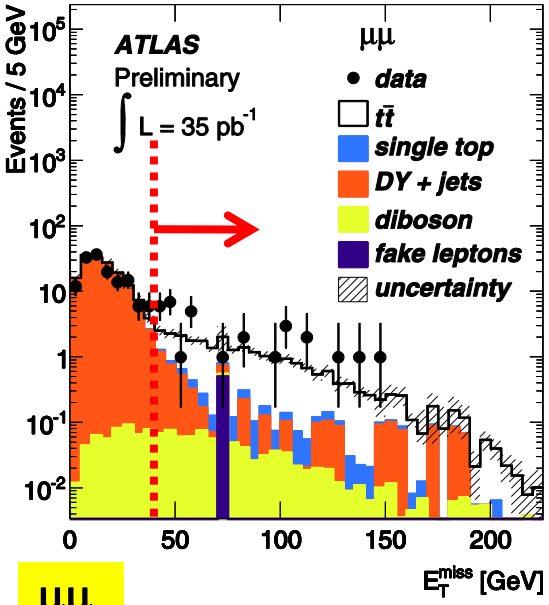
#jets≥2

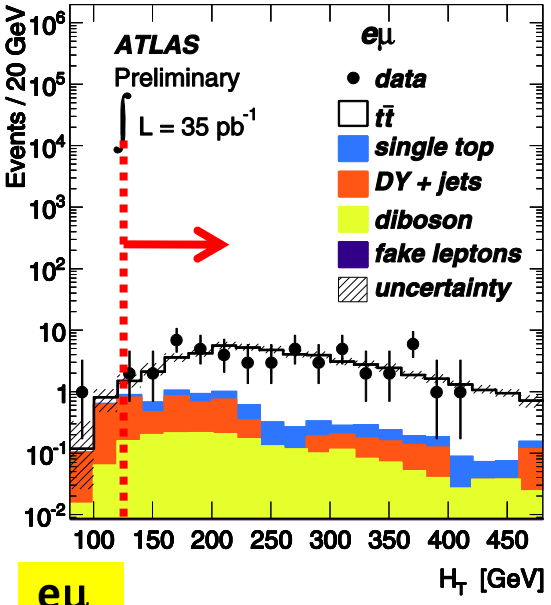
Channel	Estimation
ee	$1.2\ ^{+0.5}/_{-0.6}$
μμ	$3.4\ ^{+1.9}/_{-1.4}$

Event counting

2-lepton







ee	
Z*/γ	1.2
Fake lepton	0.8
Z→ττ	0.4
Single-top	0.7
Diboson	0.5
BG total	**3.5±1.1**
tt (σ_{theory})	**11.5±1.3**
Data	**16**

μμ	
Z*/γ	3.4
Fake lepton	0.5
Z→ττ	1.2
Single-top	1.3
Diboson	0.9
BG total	**$7.3^{+1.8}/_{-1.5}$**
tt (σ_{theory})	**20.1±1.7**
Data	**31**

eμ	
Z*/γ	-
Fake lepton	3.0
Z→ττ	3.2
Single-top	2.5
Diboson	2.1
BG total	**10.8±3.4**
tt (σ_{theory})	**47.4±4.0**
Data	**58**

Cross section estimation **2-lepton**

- Systematic uncertainties: Total=**10%**
  - Jet reconstruction : 5%
  - Lepton reconstruction : 4%
  - Fake background : 4%
  - Parton shower modeling : 4%

- Cross section estimation
  - ee channel : **178** $^{+67}/_{-57}$ $^{+37}/_{-27}$ $^{+9}/_{-5}$ **pb**
  - $\mu\mu$ channel : **194** $^{+57}/_{-51}$ $^{+20}/_{-15}$ $^{+12}/_{-5}$ **pb**
  - $e\mu$ channel : **164** ± 22 $^{+18}/_{-16}$ $^{+7}/_{-6}$ **pb**

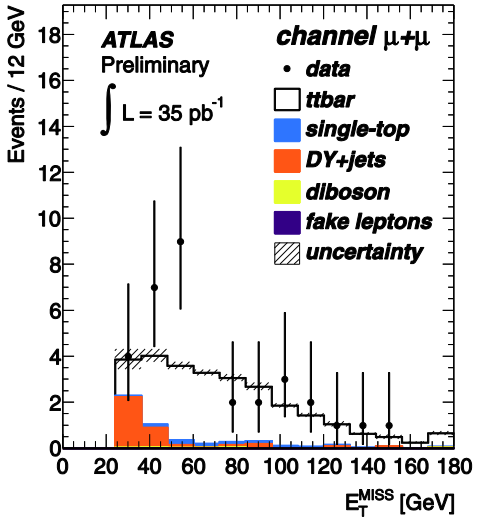
173 ± 22 $^{+18}/_{-16}$ $^{+8}/_{-7}$ pb

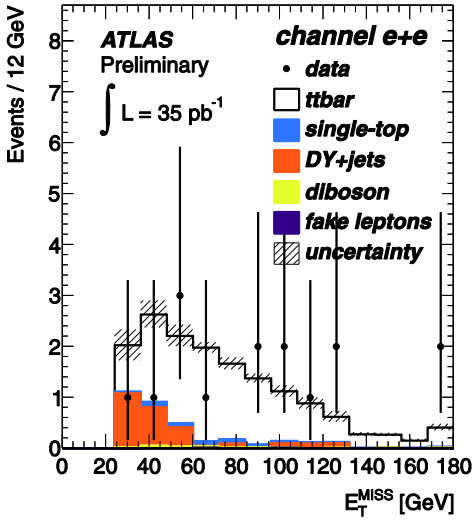
*** Statistical error, * Systematic error, * Luminosity uncertainty**

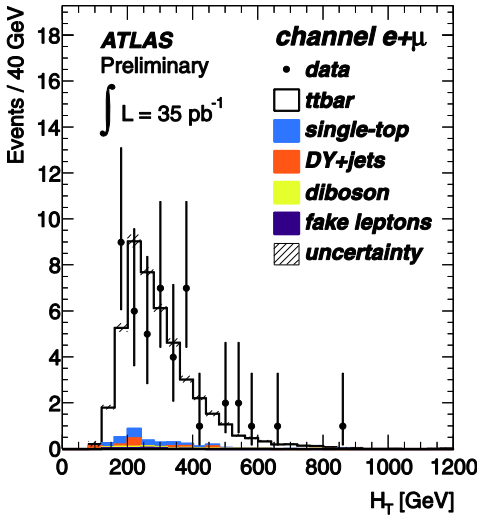
$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ **=17%**

Cross section estimation 2-lepton with b-tag

- Selection criteria
  - Require at least 1 b-jet loosen other selections
    - B-tagging algorithm with respect to transverse impact parameter are used.
- Systematic Uncertainty
  - B-tagging efficiency 7%
  - Jet reconstruction 5%







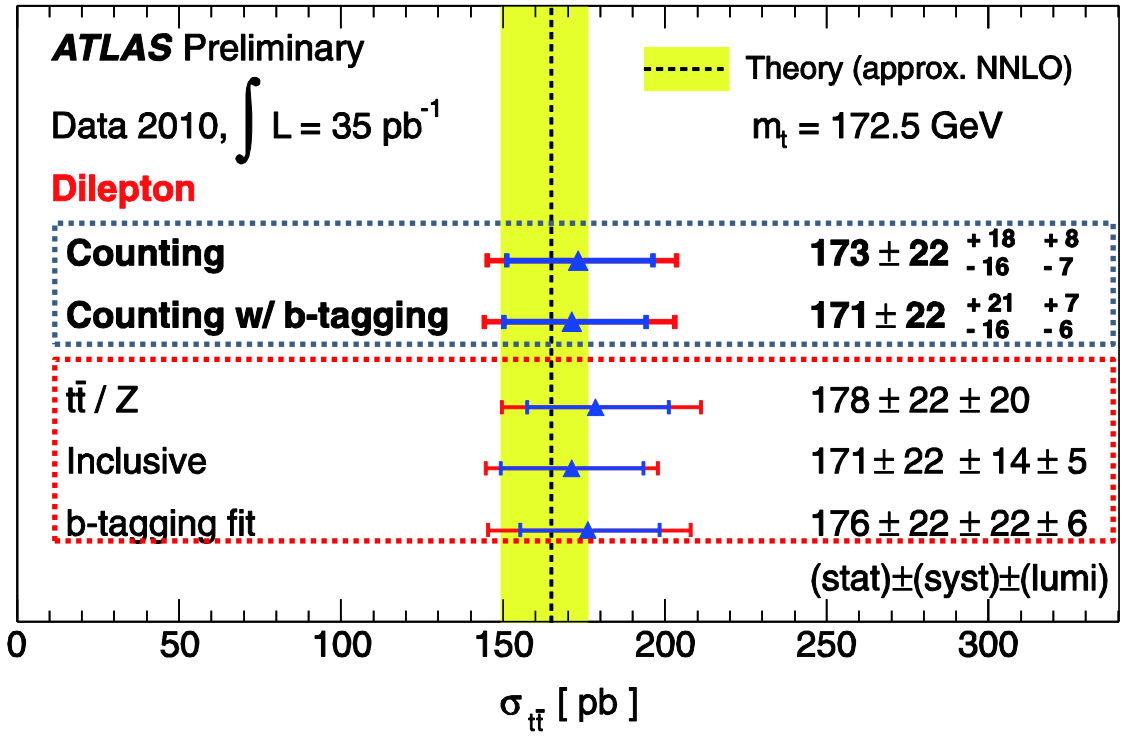
$171 \pm 22\ ^{+21}/_{-16}\ ^{+7}/_{-6}$ pb

Statistical error, **Systematic error**, **Luminosity uncertainty**

$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ **=17%**

- In agreement with pre-tag results
- Large fraction of $t\bar{t}$ signal

2-lepton analysis summary



- 5 independent analyses are performed
  - 2 main analyses & 3 extended analyses
    - In agreement within uncertainties
    - Consistent with theoretical prediction

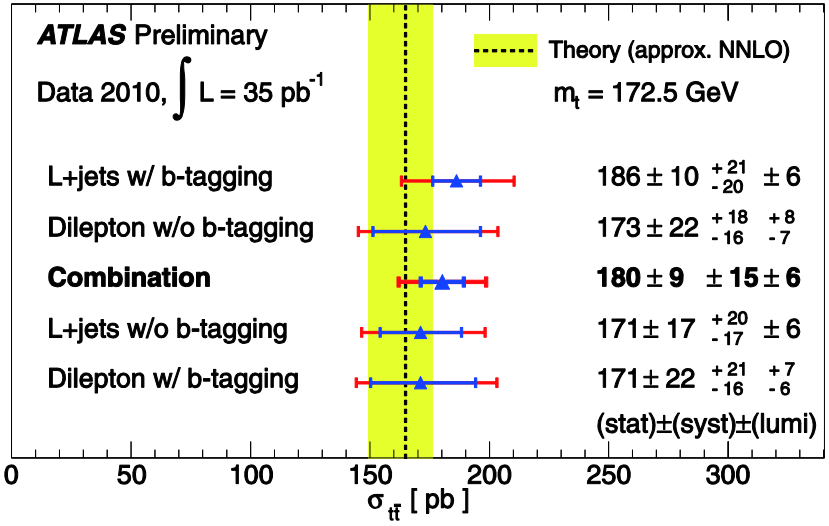
Results of combination of 1- & 2-lepton analysis

$180 \pm 9 \pm 15 \pm 6$ pb

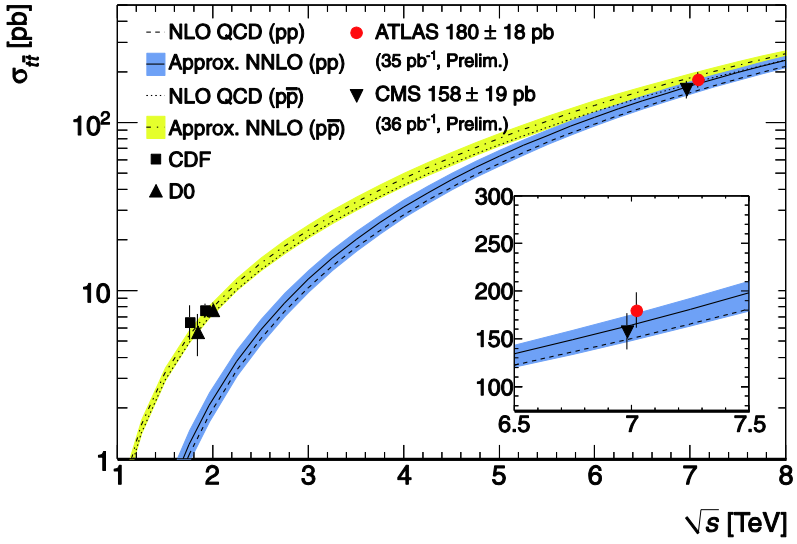
Statistical error, **Systematic error**, **Luminosity uncertainty**

$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ **=10%**

All analysis results are consistent within the uncertainties



The result agrees on the SM prediction (165pb@√s=7TeV)



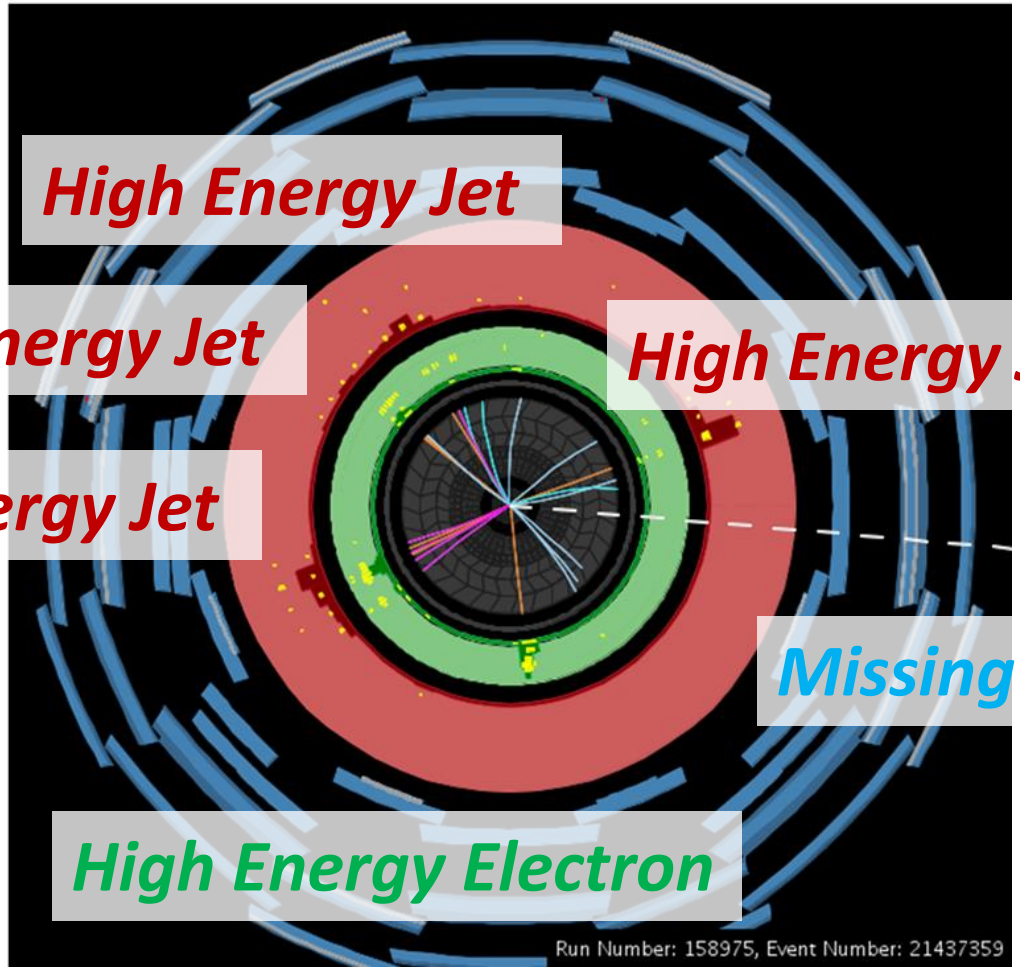
Summary

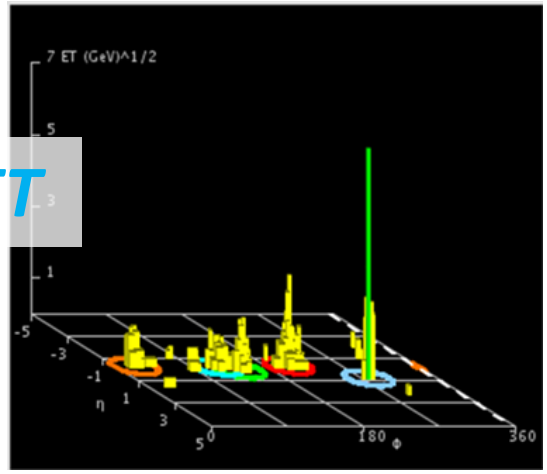
- **Big progress has been made within a year of the start of data taking**
  - ATLAS measured top pair production cross section at 7TeV proton-proton collision using **full dataset taken in 2010** in
    - 1-lepton final state
    - 2-lepton final state
  - The cross section is measured to be 180pb with **10% precision** by combining 1-lepton & 2-lepton results
    - Improve the precision by a factor of 3 with respect to the first measurement
    - Consistent with theoretical prediction ($165\ ^{+11}/_{-16}$ pb)
    - Experimental precision gets compatible to theoretical uncertainties
- **Further studies will be performed with data taken in 2011**
  - Precise top cross section measurements
  - Precise top properties measurements

ADDITIONAL SLIDES

Event display μ+jets topology

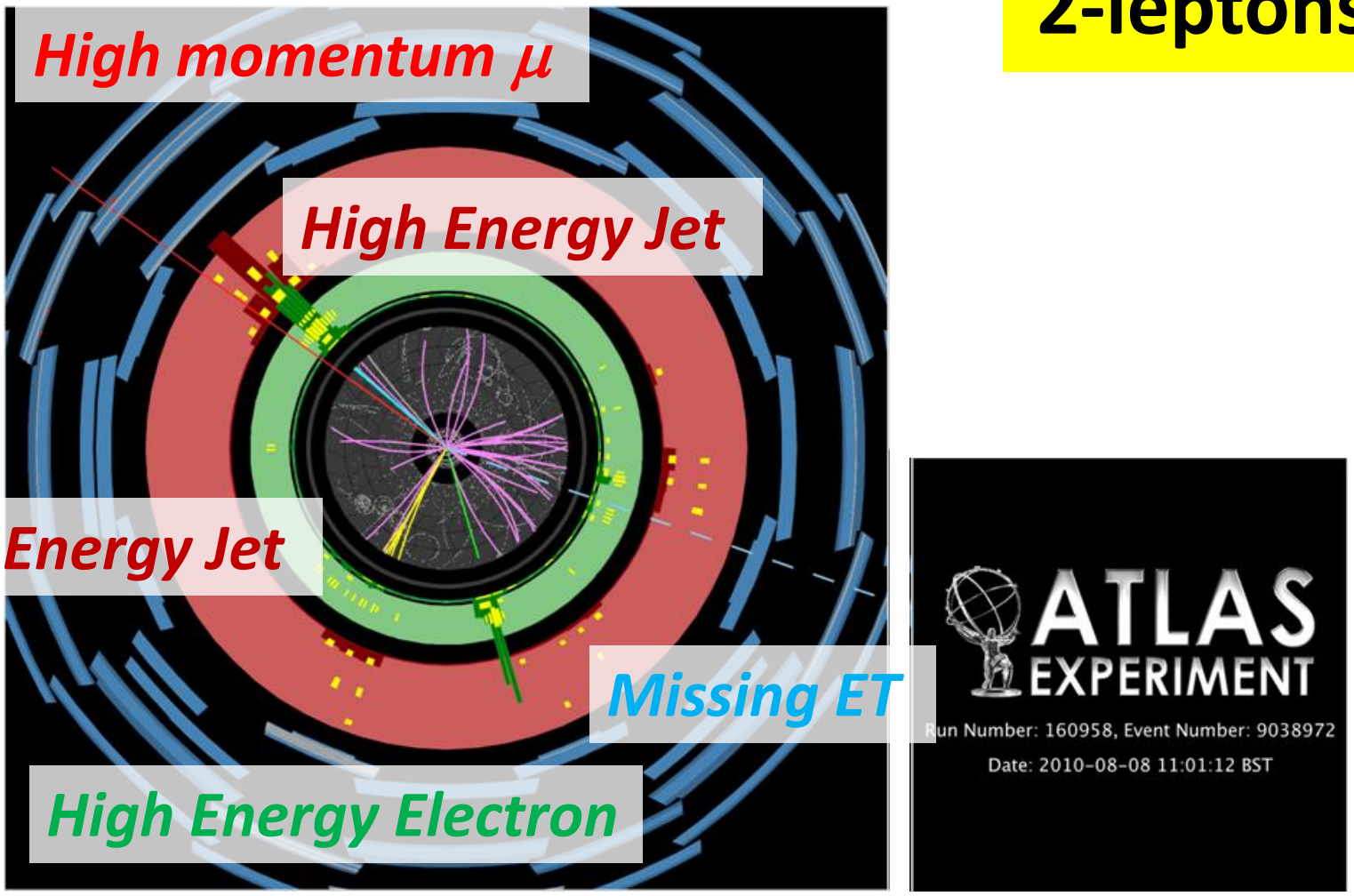
1-lepton





Event display eμ+*jets topology*

2-leptons



Definition of aplanarity

- Event shape variables
  - $A = \frac{3}{2}\lambda_3$
    - the λ_3 is minimum eigen value of sphericity tensor, which is defined as $S^{\alpha\beta} = \sum_{\text{particles}} p_i^\alpha p_i^\beta / \sum_{\text{particles}} |\vec{p_i}|^2$
  - $0 < A < \frac{1}{2}$
    - Planar events has : $A \sim 0$
    - Isotropic events has : $A \sim \frac{1}{2}$

1-lepton with b-tag

Statistical Error (%)	**+5.3**	**-5.2**
Object selection (%)		
Jet energy scale	+3.8	-2.8
Jet reconstruction efficiency	+4.2	-4.2
Jet energy resolution	+0.8	-0.2
Electron scale factor	+1.2	-0.8
Muon scale factor	+0.5	-0.6
Electron smearing	+0.3	-0.2
Muon smearing	+0.6	-0.4
Background modeling (%)		
Wjets HF content	+7.2	-6.3
Wjets shape	+1.5	-1.5
QCD shape	+1.0	-1.0
$t\bar{t}$ signal modeling (%)		
ISR/FSR	+4.0	-4.0
NLO generator	+0.5	-0.7
Hadronisation	+0.0	-0.6
PDF	+1.7	-1.7
Others (%)		
b-tagging calibration	+7.5	-6.3
Simulation of pile-up	+1.5	-0.6
Templates statistics	+1.6	-1.5
Total Systematic (%)	**+11.5**	**-10.5**

2-lepton pre b-tag

Uncertainty (%)	ee	$\mu\mu$	$e\mu$	combined	tt Z
Data Stat	-32 / 38	-26 / 29	-15 / 17	-13 / 13	-12 / 13
Lumi	-3 / 5	-3 / 6	-4 / 4	-4 / 5	N/A
MC Stat	-3 / 4	-2 / 5	-2 / 2	-2 / 2	-2 / 2
El/Mu ES	0 / 0	0 / 1	0 / 0	0 / 1	-1 / 1
El/Mu ER	0 / 0	0 / 2	0 / 0	0 / 0	-1 / 1
El/Mu SF	0 / 10	0 / 2	-4 / 5	-4 / 4	-1 / 1
JES	-10 / 13	0 / 3	-6 / 4	-5 / 4	-5 / 4
JER	0 / 2	0 / 1	0 / 0	0 / 0	-1 / 1
JEF	0 / 3	-1 / 4	-2 / 2	-2 / 2	-2 / 2
DY Method	-4 / 5	-5 / 4	0 / 0	-2 / 1	-2 / 1
Fake	-7 / 7	-2 / 4	-6 / 5	-4 / 3	-4 / 3
Generator	0 / 3	0 / 1	-2 / 2	-1 / 2	-2 / 1
P.Shower	-4 / 8	0 / 4	-4 / 5	-4 / 5	-4 / 4
ISR	-3 / 2	0 / 3	0 / -3	-1 / 0	-2 / 1
FSR	-3 / 3	-7 / 0	-2 / 0	-2 / 2	-2 / 2
PDF	-1 / 4	0 / 4	-2 / 3	-2 / 3	-2 / 2
Pile-up	-1 / 3	0 / 2	-1 / 0	0 / 1	-1 / 1
MC x-sec	0 / 4	-1 / 4	-3 / 2	-2 / 2	-2 / 2
Z-Theory	N/A	N/A	N/A	N/A	-7 / 8
All Syst. but Lumi.	-15 / 21	-8 / 10	-10 / 11	-9 / 10	-11 / 12
All Systematics	-15 / 21	-9 / 11	-11 / 12	-10 / 12	-11 / 12
Stat + Syst	-35 / 43	-28 / 31	-19 / 21	-16 / 18	-16 / 17

1-lepton event yield

Electron Channel	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
$t\bar{t}$	14.3 ± 2.9	61 ± 9	116 ± 13	111 ± 16	82 ± 12
W+jets	9000 ± 1900	2300 ± 700	580 ± 250	140 ± 90	41 ± 26
QCD multijets	290 ± 140	123 ± 62	62 ± 31	13 ± 7	8 ± 4
Single Top	36 ± 4	42 ± 5	22 ± 4	7.8 ± 1.8	3.1± 0.7
Z+jets	65 ± 14	62 ± 20	32 ± 14	12 ± 8	6 ± 4
Diboson	35.3 ± 2.8	30.1 ± 2.4	9.3 ± 1.5	2.2 ± 0.5	0.4± 1
Total Predicted	9400 ± 1900	2700 ± 800	830 ± 250	290 ± 90	141 ± 29
Data Observed	9481	2552	781	273	127

Muon Channel	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
$t\bar{t}$	19 ± 4	81 ± 12	161 ± 18	158 ± 22	115 ± 16
W+jets	19000 ± 4000	4600 ± 1500	1100 ± 500	250 ± 150	70 ± 40
QCD multijets	520 ± 160	287 ± 86	121 ± 36	30 ± 10	20 ± 6
Single Top	57 ± 7	64 ± 8	32 ± 6	11.1± 2.5	4.0± 0.9
Z+jets	770 ± 160	250 ± 80	69 ± 30	19 ± 12	6 ± 4
Diboson	63 ± 5	55 ± 4	16.1 ± 2.6	3.4± 0.7	0.6± 0.1
Total Predicted	20000 ± 4000	5300 ± 1500	1500 ± 500	470 ± 160	210 ± 50
Data Observed	20583	5228	1356	448	205

2-lepton event yield

	ee	$\mu\mu$	$e\mu$
Z+jets (DD)	$1.2^{+0.5}_{-0.6}$	$3.4^{+1.9}_{-1.1}$	-
$Z(\rightarrow \tau\tau)$+jets (MC)	$0.4^{+0.4}_{-0.3}$	$1.2^{+0.7}_{-0.6}$	$3.2^{+1.6}_{-1.3}$
Non-Z leptons (DD)	0.8 ± 0.8	0.5 ± 0.6	3.0 ± 2.6
Single top (MC)	0.7 ± 0.1	1.3 ± 0.2	2.5 ± 0.4
Dibosons (MC)	0.5 ± 0.1	0.9 ± 0.2	$2.1^{+0.5}_{-0.3}$
Total (non $t\bar{t}$)	3.5 ± 1.0	$7.3^{+1.8}_{-1.5}$	10.8 ± 3.4
$t\bar{t}$ (MC)	11.5 ± 1.3	20.1 ± 1.7	47.4 ± 4.0
Total expected events	15.0 ± 1.7	27.4 ± 2.4	58.2 ± 5.2
Observed events	16	31	58

Goal of ATLAS detector performance

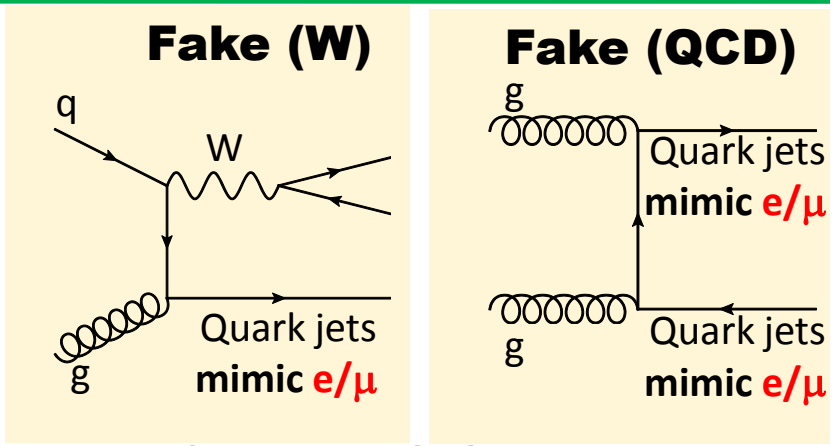
Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \lvert\eta\rvert < 4.9$	$3.1 < \lvert\eta\rvert < 4.9$
Muon spectrometer	σ_{p_T}/p_T=10% at p_T = 1 TeV	± 2.7	± 2.4

5 channels & combination

Channel	$\sigma_{t\bar{t}}$ (pb)
ee	$178 \pm {}^{67}_{57}(\text{stat.}) \pm {}^{36}_{26}(\text{syst.}) \pm {}^{9}_{5}(\text{lumi.})$
$\mu\mu$	$194 \pm {}^{57}_{51}(\text{stat.}) \pm 20(\text{syst.}) \pm {}^{12}_{5}(\text{lumi.})$
$e\mu$	$164 \pm 26(\text{stat.}) \pm 18(\text{syst.}) \pm {}^{7}_{6}(\text{lumi.})$
di-lepton combined	$173 \pm 22(\text{stat.}) \pm 18(\text{syst.}) \pm {}^{8}_{7}(\text{lumi.})$
e+jets	$223 \pm 17(\text{stat.}) \pm 27(\text{syst.}) \pm 8(\text{lumi.})$
μ+jets	$168 \pm 12(\text{stat.}) \pm {}^{20}_{18}(\text{syst.}) \pm 6(\text{lumi.})$
l+jets combined	$186 \pm 10(\text{stat.}) \pm {}^{21}_{20}(\text{syst.}) \pm 6(\text{lumi.})$
five-channel combined	$180 \pm 9(\text{stat.}) \pm 15(\text{syst.}) \pm 6(\text{lumi})$

Fake background estimation **2-lepton**

- Fake processes
  - W+jets (1 real & 1 fake)
  - QCD (both fakes)



- Matrix method
  - Use a method similar to the one for the QCD background estimation in l+jets
    - Efficiency for prompt & non-prompt e/μ are measured
    - Count N_{LL}, N_{LT}, N_{TL} as well as N_{TT} by loosening isolation selection and extract N_{RR}, N_{RF}, N_{FR}, and N_{FF}

$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} rr & rf & fr & ff \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)(1-r) & (1-r)(1-f) & (1-f)(1-r) & (1-f)(1-f) \end{bmatrix} \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}$$

The ATLAS detectors

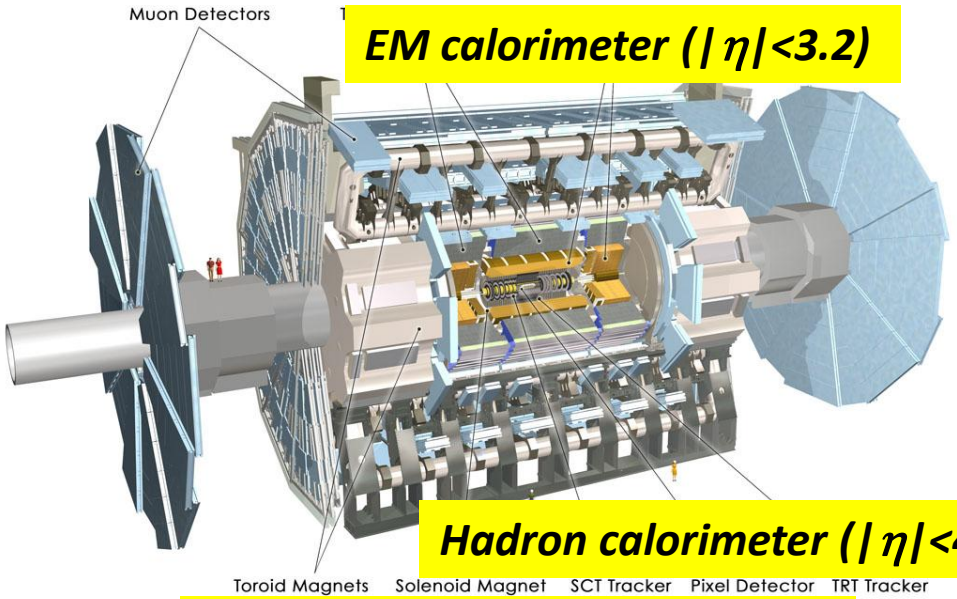
General-purpose detectors located @ LHC

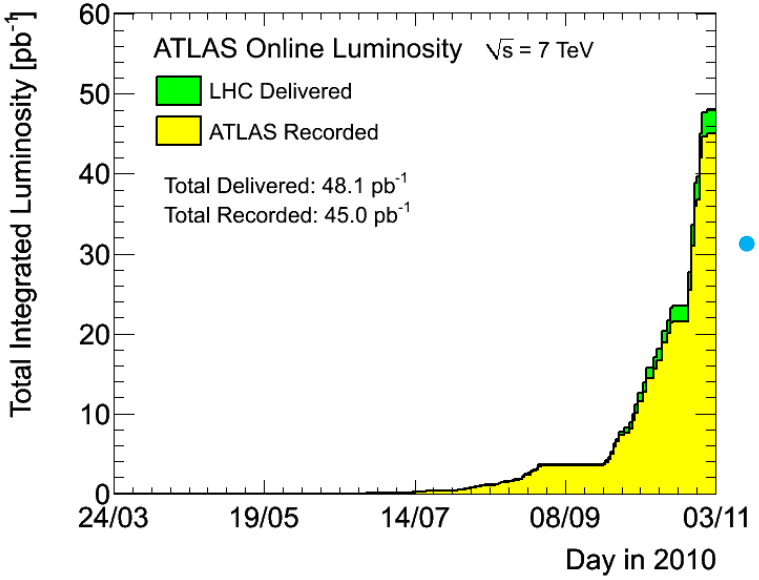
- ***lepton PID (e/μ)***
- ***Parton ID as hadron jet***

  AntiKt algorithm with R=0.4
- ***b-parton ID***

  lifetime b-tagging with secondary vertex, impact parameter
- ***Missing ET measurement***

Precise tracker & vertex detector (|η|<2.5)





- ***Luminosity***

  This measurement uses **35pb^{-1} (2010 data)**, (**updating** the first cross section measurement @ LHC-ATLAS of $145 \pm 31\ ^{+42}/_{-27}$ with 2.9pb^{-1})