UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

# Standard Model and Top Physics with ATLAS

Kruger 2012 Workshop on Discovery Physics at the LHC – 6 December 2012

K. Rosbach on behalf of the ATLAS collaboration

# outline

- **Standard Model Physics**
  - Jet physics,
  - High mass Drell-Yan differential cross-section,
  - W+b-jet measurement,
  - Di-photon production,
  - Diboson production and limits on anomalous triple gauge couplings.

- Talk by Will Buttinger on vector boson and diboson production yesterday.

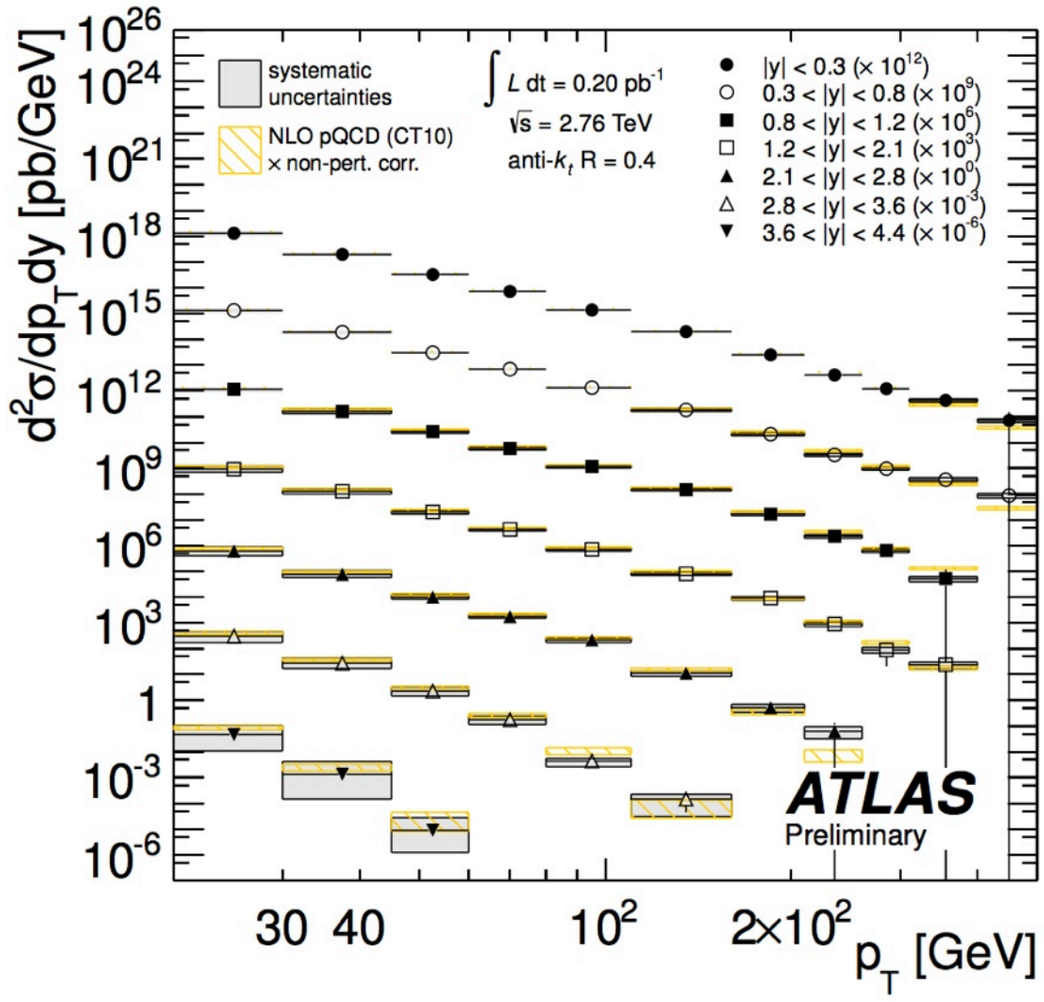
- **Top Physics**
  - Production cross-sections: top-antitop pairs, single top,
  - Differential cross-section measurements (transverse momentum, extra jets),
  - Production properties: polarization, spin correlation, charge asymmetry,
  - Intrinsic and decay properties: mass, polarization of W bosons from top decays.

- More details on top properties and production in **two dedicated talks** by Lucia Batkova and Danilo Ferreira de Lima **this afternoon (parallel session XI)**.

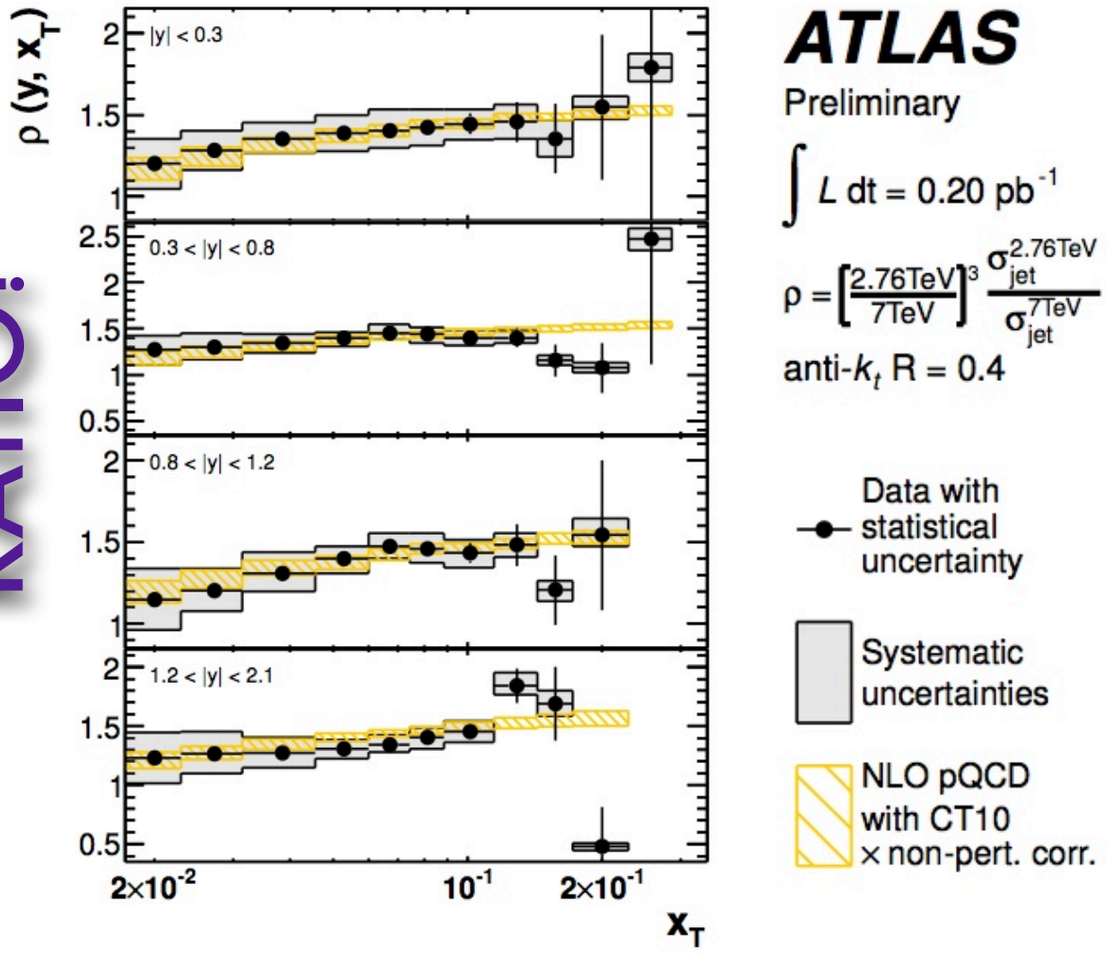
# Standard Model @ ATLAS

# inclusive jet cross-section at 2.76 TeV and 7 TeV

**ATLAS-CONF-2012-128**
0.20 pb$^{-1}$ $\sqrt{s}$=2.76 TeV




RATIO!



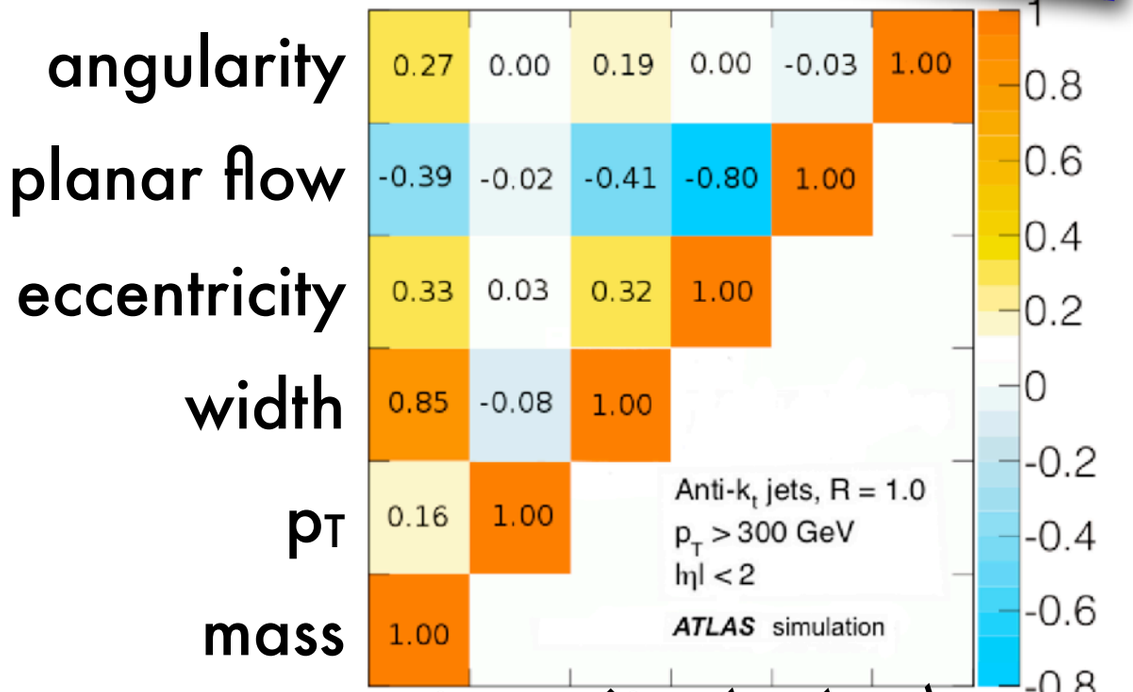

- Information on strong coupling, proton structure, and test of **perturbative QCD**.
- **Comparison to 7 TeV result** (PRD 86 (2012) 014022), cancellations of systematic uncertainties.
- Good agreement with NLO pQCD calculations.

# jet properties for boosted particle searches

**PR D 86, 072006 (2012)**
35 $pb^{-1}$ $\sqrt{s}$=7 TeV

- **Boosted particles** → collimated decays → **single jet** containing decay products.
- Expect different jet properties compared to jets from light quarks or gluons.

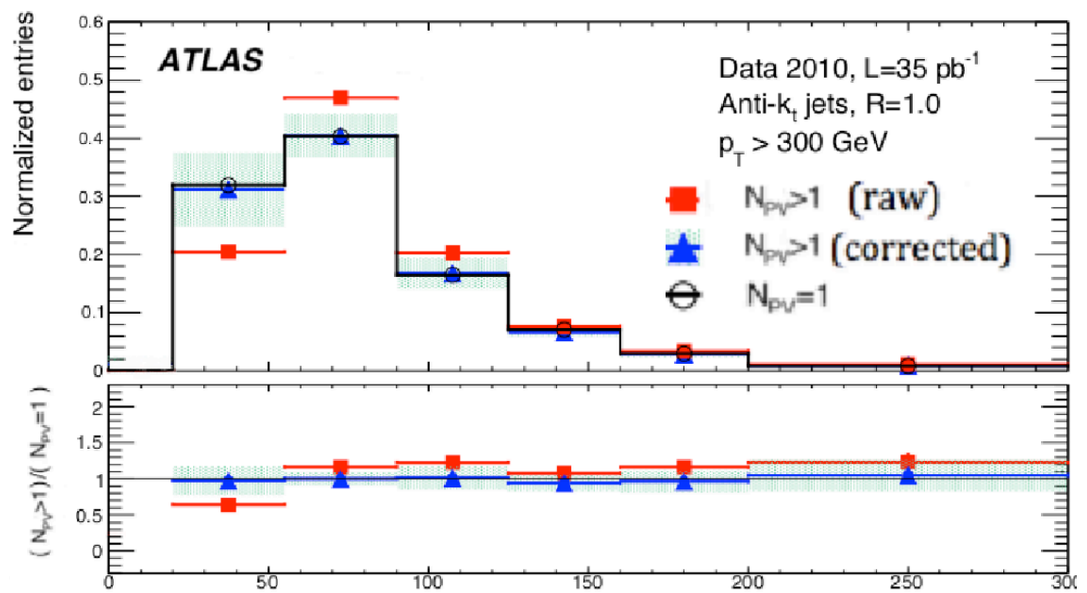
- **Observables** (computed from highest $p_T$ jet in event)**:** Angularity, planar flow, eccentricity, width, transverse momentum and mass.




- Recent result, but using 2010 data because of **lower instantaneous luminosity**.
  - 28% of events in dataset have **only one primary vertex (PV)**, $p_T$-dependent correction for $N_{PV} > 1$, was derived using complementary cone method.

- Overall good agreement with all tested MCs.

- Distributions of properties provided as plots and in tabulated form.



# Flavour composition of dijet events

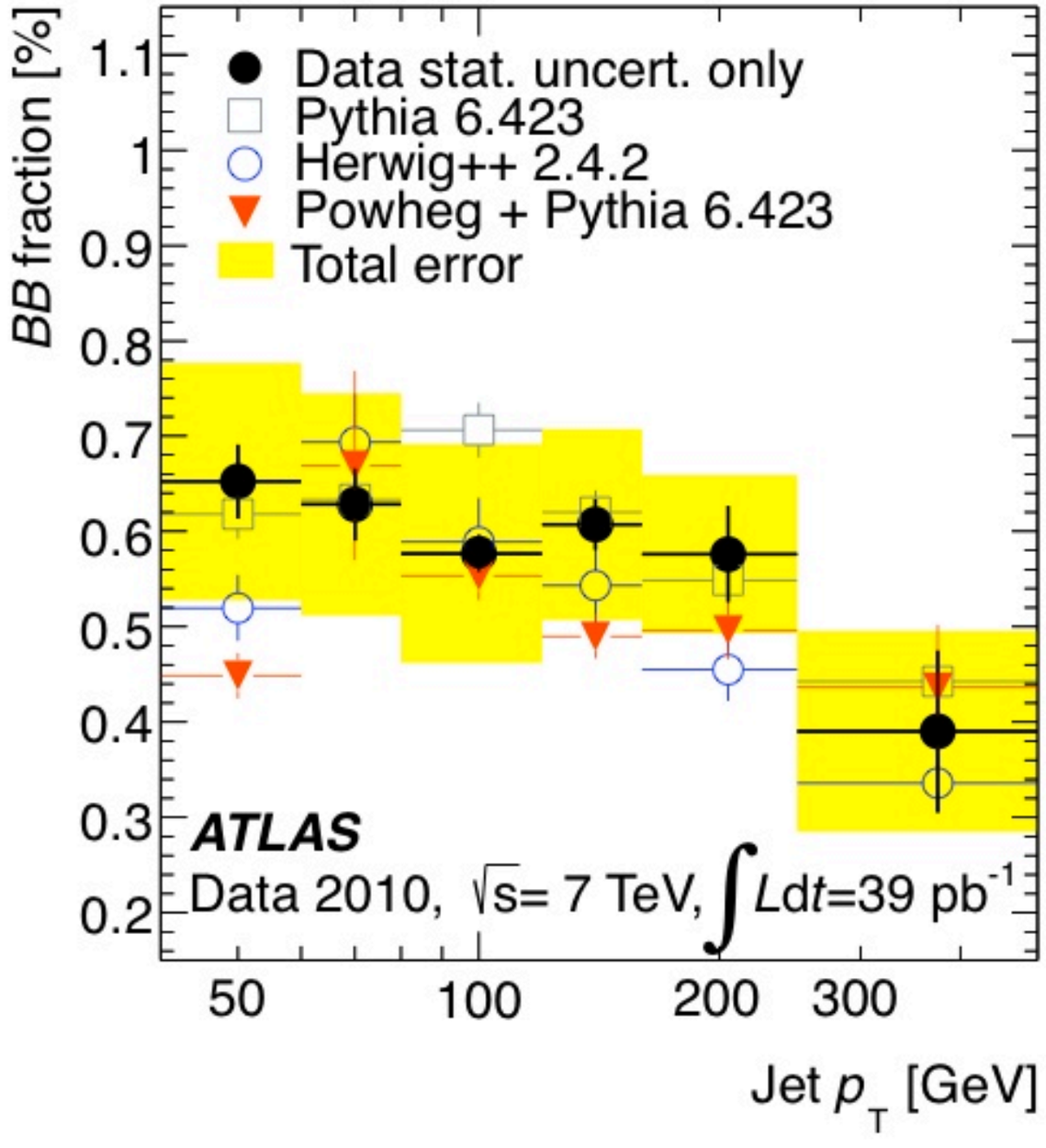
**CERN-PH-EP-2012-255**
submitted to EPJ C
39 $pb^{-1}$ $\sqrt{s}$=7 TeV

- Study of **all six combinations** of jets from **light** quarks or gluons, **charm** quarks, or **bottom** quarks.

- Extracting flavour fractions with **template fit** (no explicit b-tagging).
  - Dedicated variables based on kinematic properties of reconstructed secondary vertices inside jets.

- **Excellent separation of charm and bottom** flavoured jets in ATLAS.

- Generally good agreement with all tested MC generators; bottom-light fraction above all predictions in high $p_T$ region (not shown).



# high mass Drell-Yan differential cross-section

**ATLAS-CONF-2012-159**
4.9 fb$^{-1}$ $\sqrt{s}$=7 TeV

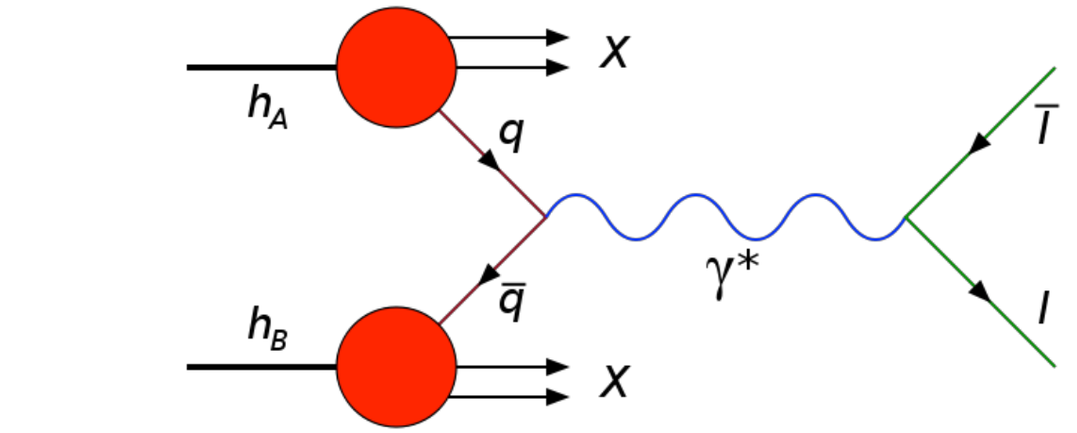
- Test of pQCD, background for other SM measurements, mass spectrum sensitive to new physics.

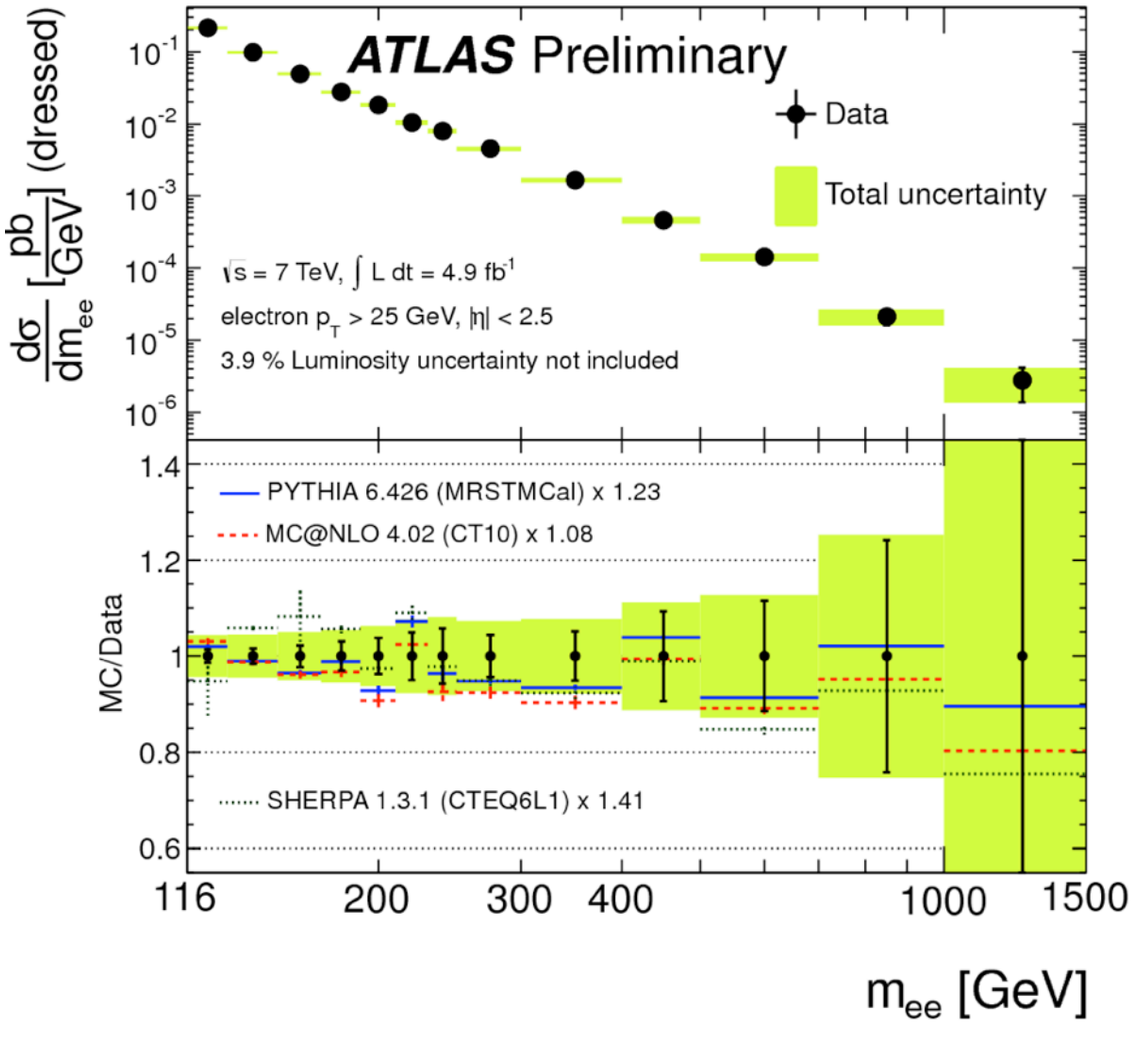
- **Differential cross section** obtained from yields in di-electron channel, accounting for selection efficiency and luminosity.

- **Background modeling** (W+jets, di-jet events) dominates **uncertainty** at low mass; statistics-limited at higher masses.

- Good shape agreement in comparisons to Pythia, MC@NLO and Sherpa MC.

- "Angular correlations of Drell-Yan lepton pairs" submitted to PLB on 30 Nov (arXiv:1211.6899).



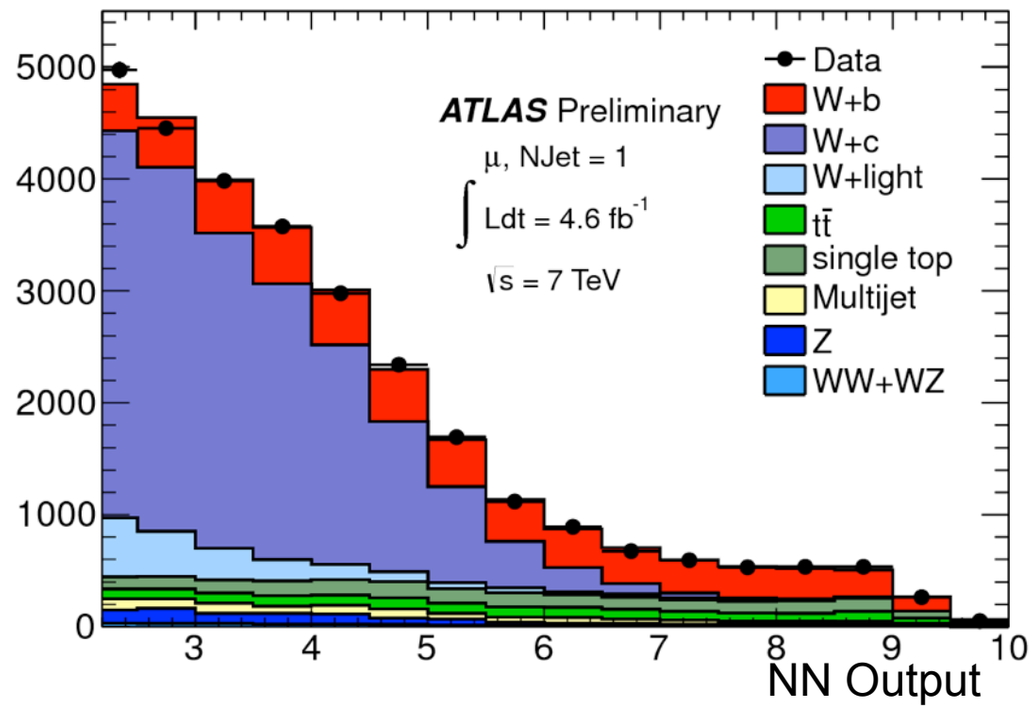
# W boson + b-jet cross-section

**ATLAS-CONF-2012-156**
4.6 fb$^{-1}$ $\sqrt{s}$=7 TeV

*recent preliminary result (14 November 2012)*

- **Motivation:** test of pQCD with heavy quarks, important background for WH (with H→b$\bar{\text{b}}$).

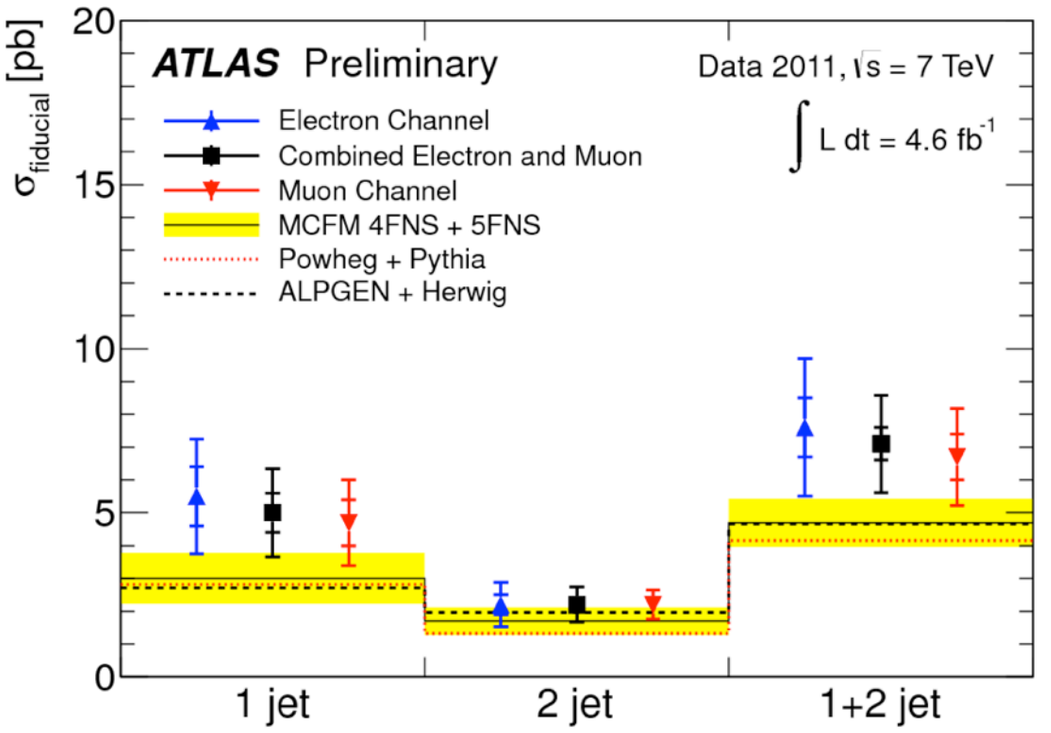
- **Selection:**
  - isolated electron or muon, 1 or 2 jets including 1 b-tag, $E_T^{miss}$>25 GeV, $m_T(W)$>60 GeV.
  - b-tagging with **neural network** (NN) algorithm, based on properties of secondary vertices.




- **Data-driven backgrounds**:
  - QCD multijets from CR with lepton isolation reversal.
  - t$\bar{\text{t}}$ from 4 jet CR, extrapolated to 1 and 2 jet bins using MC transfer factors.

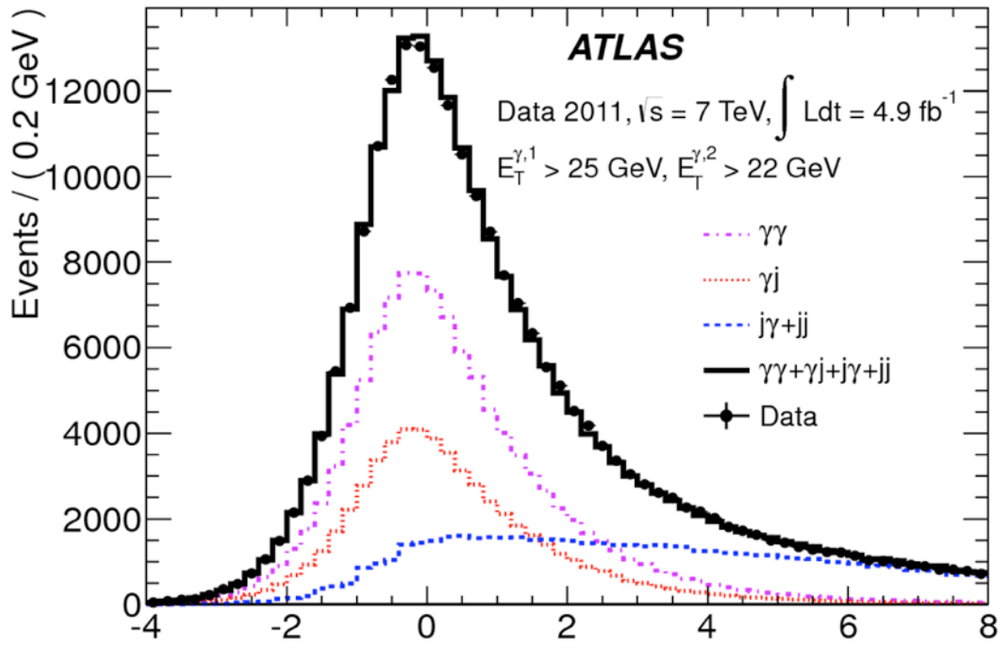
- **Cross section** for 1+2 jets from template fit to NN output, after iterative Bayesian unfolding:

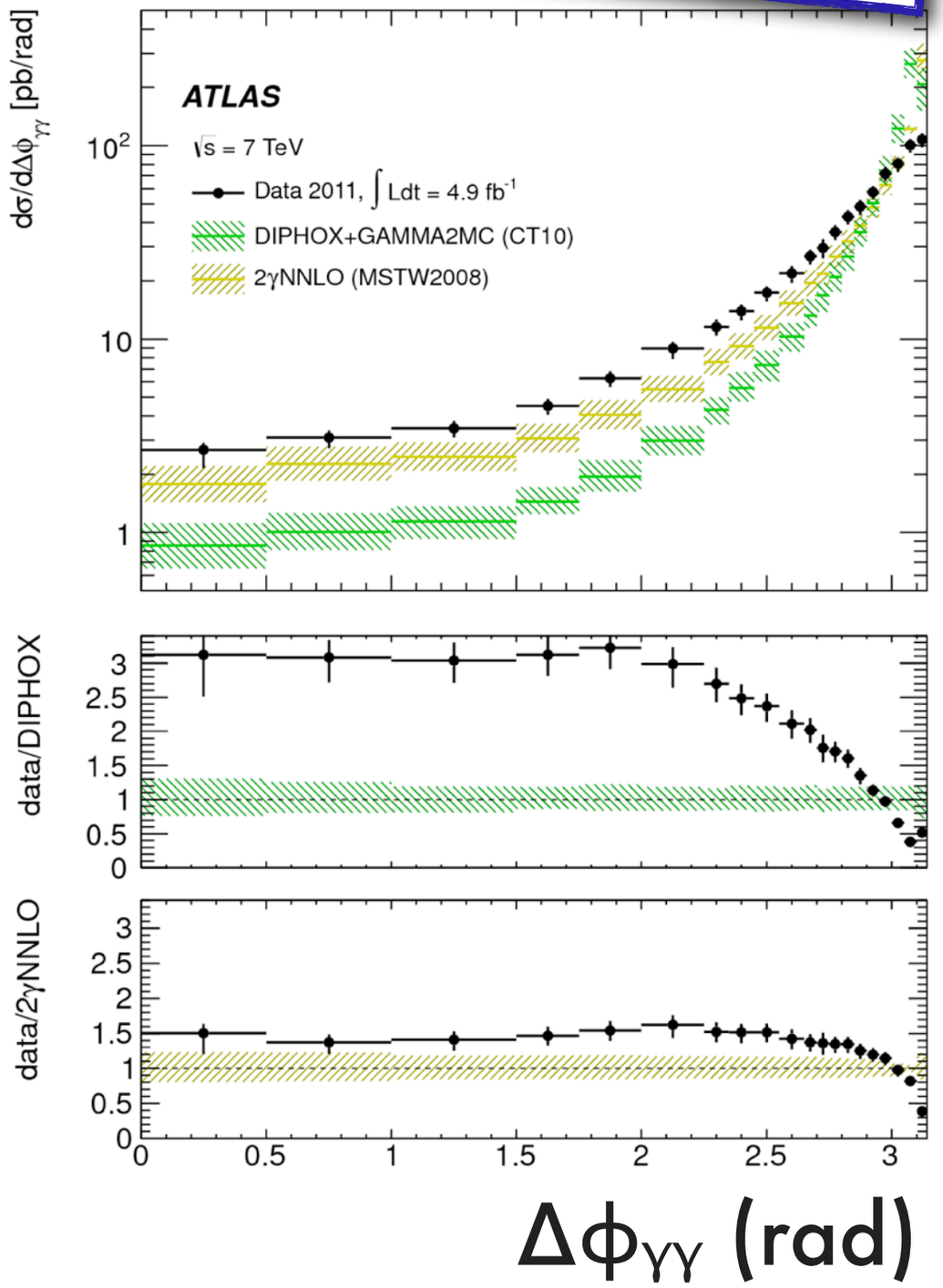
$$\sigma_{\mathrm{W+b-jet}} = 7.1 \pm 0.5(\mathrm{stat}) \pm 1.4(\mathrm{syst})\,\mathrm{pb}$$



# isolated photon pair production

**CERN-PH-EP-2012-300** (JHEP)
4.9 fb$^{-1}$ $\sqrt{s}$=7 TeV



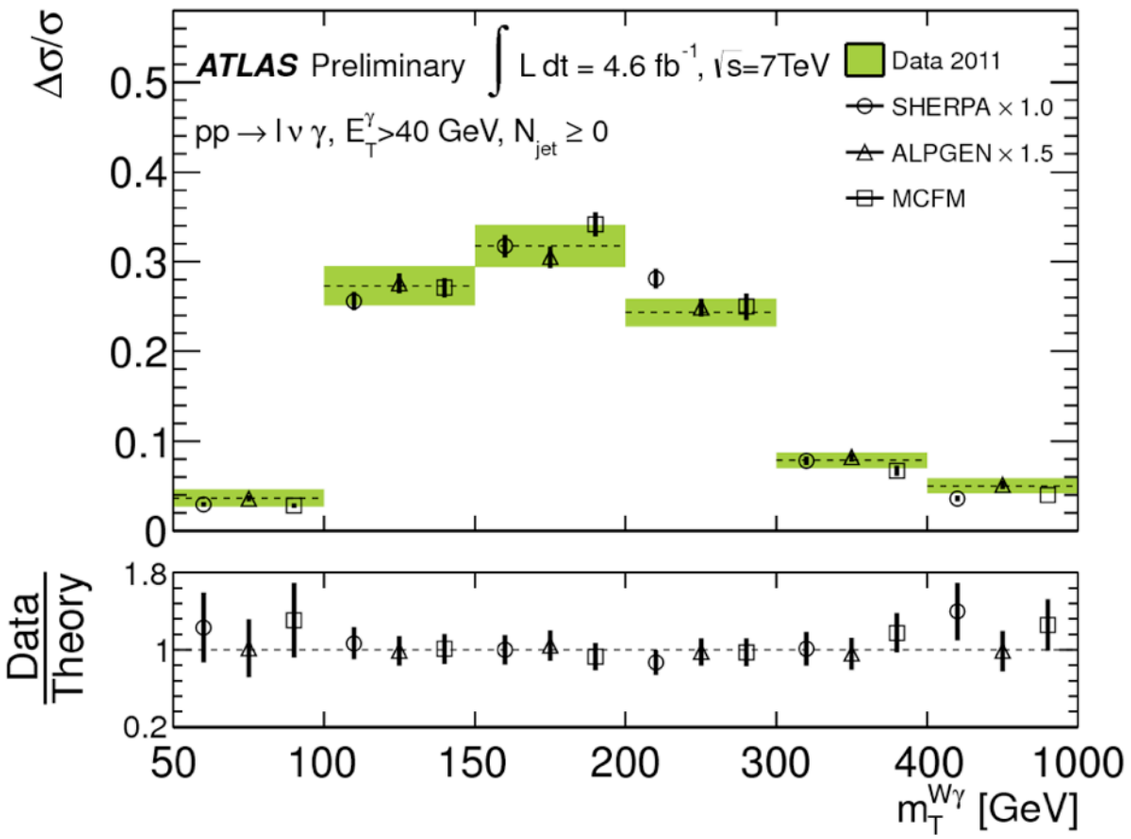




- Probe of pQCD. Irreducible background to H→γγ.
- **Event selection:** two isolated photons with $E_T$>25 and 22 GeV (di-photon trigger, ~98% efficient), separated by $\Delta R > 0.4$,
- γ+jet and di-jet backgrounds: 2-dimensional template fit of **energy deposited around photons**, fit templates from Sherpa.
- Misidentified isolated electrons: e→γ rate estimated at ~6%, counting ee and eγ pairs with invariant mass close to Z mass.
- **Total cross section** accounting for trigger, selection and luminosity:

$$\sigma = 44.0^{+3.2}_{-4.2}\,\mathrm{pb}$$

# Wγ and Zγ

**CERN-PH-EP-2012-345**
4.6 fb$^{-1}$ $\sqrt{s}$=7 TeV



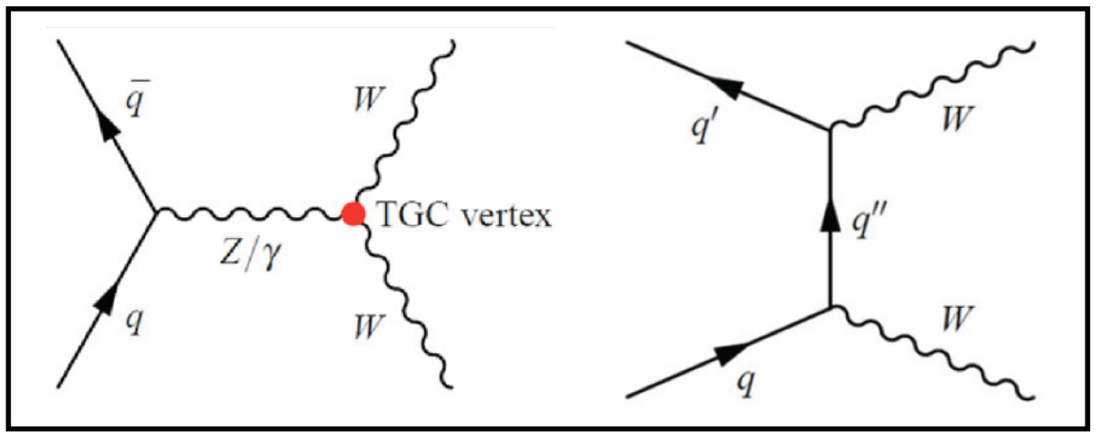

## measured fiducial cross-sections (pb)

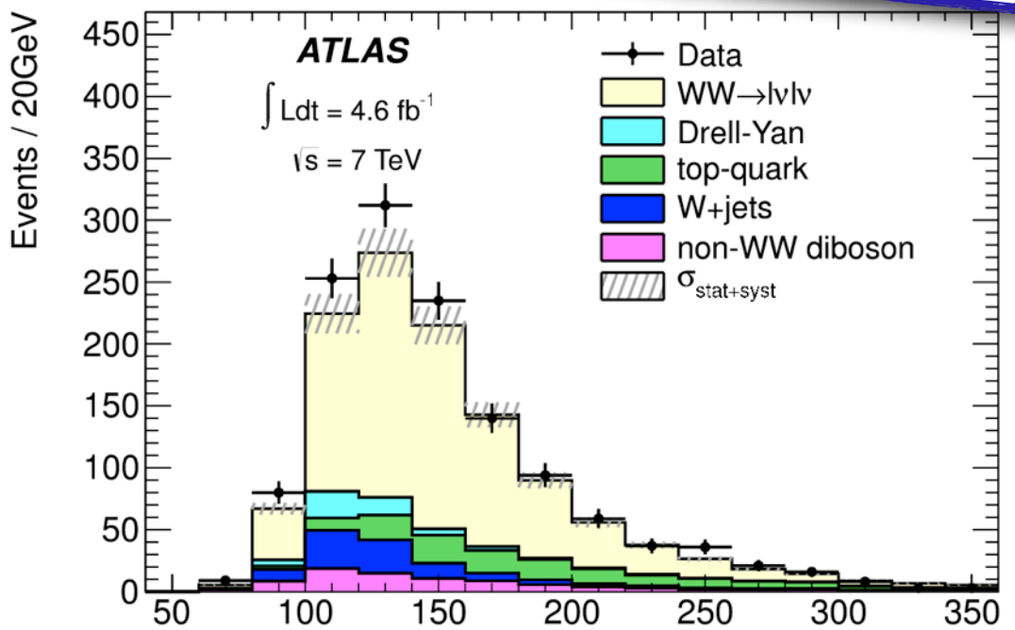
| | |
|---|---|
| $e\nu\gamma$ | $2.74 \pm 0.05$ (stat) $\pm 0.32$ (syst) $\pm 0.14$ (lumi) |
| $\mu\nu\gamma$ | $2.80 \pm 0.05$ (stat) $\pm 0.37$ (syst) $\pm 0.14$ (lumi) |
| $l\nu\gamma$ | $2.77 \pm 0.03$ (stat) $\pm 0.33$ (syst) $\pm 0.14$ (lumi) |
| $e^+e^-\gamma$ | $1.30 \pm 0.03$ (stat) $\pm 0.13$ (syst) $\pm 0.05$ (lumi) |
| $\mu^+\mu^-\gamma$ | $1.32 \pm 0.03$ (stat) $\pm 0.11$ (syst) $\pm 0.05$ (lumi) |
| $l^+l^-\gamma$ | $1.31 \pm 0.02$ (stat) $\pm 0.11$ (syst) $\pm 0.05$ (lumi) |
| $\nu\bar{\nu}\gamma$ | $0.133 \pm 0.013$ (stat) $\pm 0.020$ (syst) $\pm 0.005$ (syst) |

- Test of electroweak sector, search for new phenomena.
- Fiducial cross-section measurements for several decay modes.
- Integrated and differential cross-sections (vs Wγ transverse mass / Zγ mass).
- Dominant systematic uncertainty: photon identification efficiency (~6%).
- No deviation from SM expectations; limits on triple gauge couplings (WWγ, ZZγ, Zγγ).

# WW production cross section

**CERN-PH-EP-2012-242**
submitted to Phys. Rev. D
4.6 fb$^{-1}$ $\sqrt{s}$=7 TeV

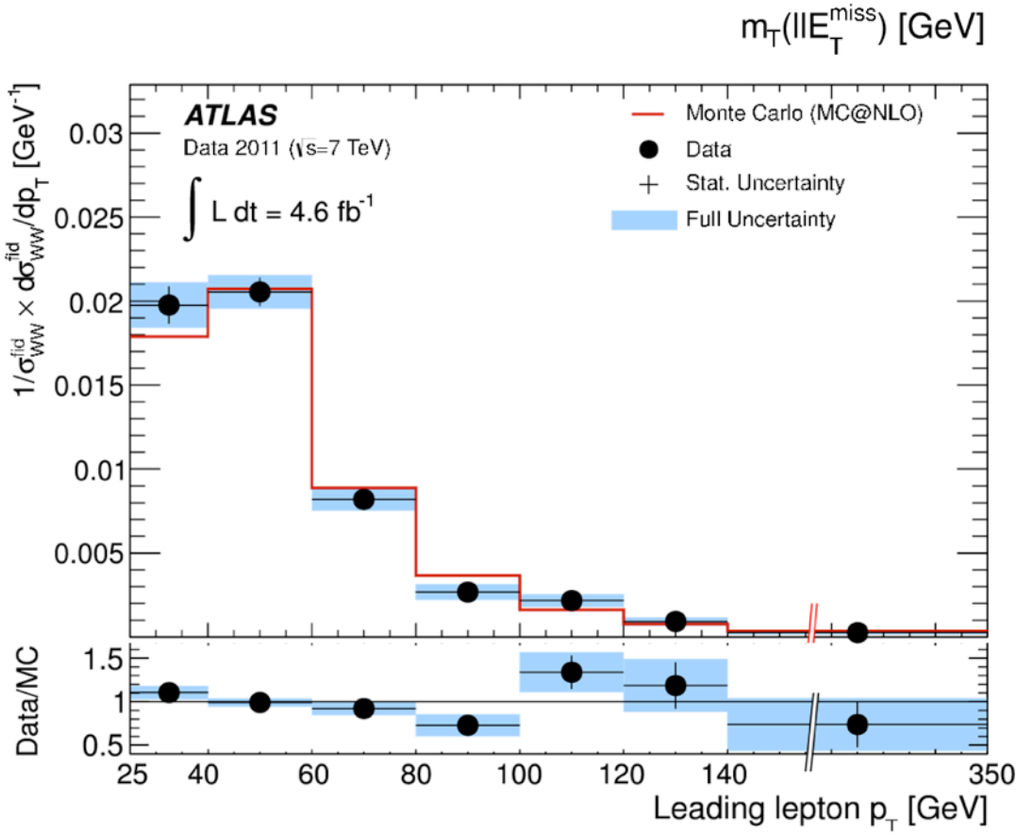



- Analysis in **di-leptonic decay channels** (ee, eμ, μμ).
- Require $E_T^{miss} >$ 45 GeV from 2 neutrinos, also suppresses Drell-Yan background.
- Veto on any jet with $p_T$>25 GeV and $|\eta|$<4.5, reduces contributions from $t\bar{t}$ and single top.

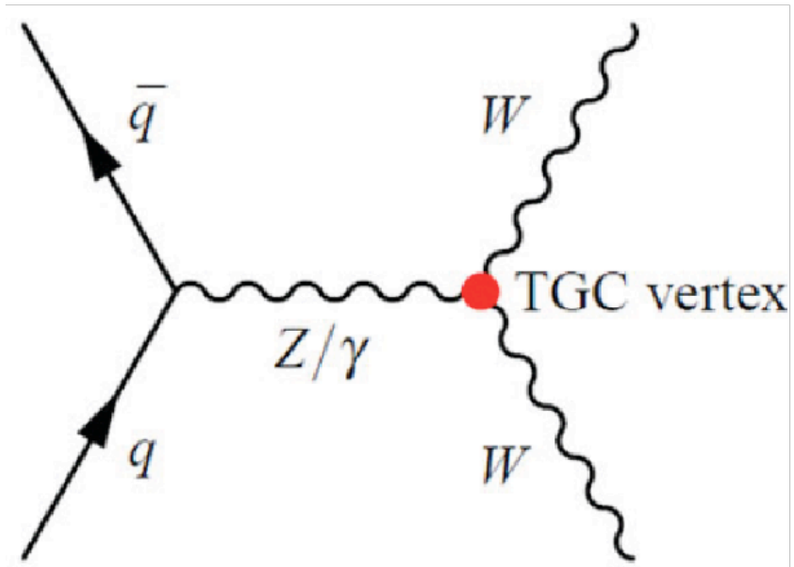
**$\sigma(pp \rightarrow W^+W^- + X)$** = 51.9 ± 2.0 (stat) ± 3.9 (syst) ± 2.0 (lumi) pb, compatible with SM prediction 44.7 ± 2.1 pb.

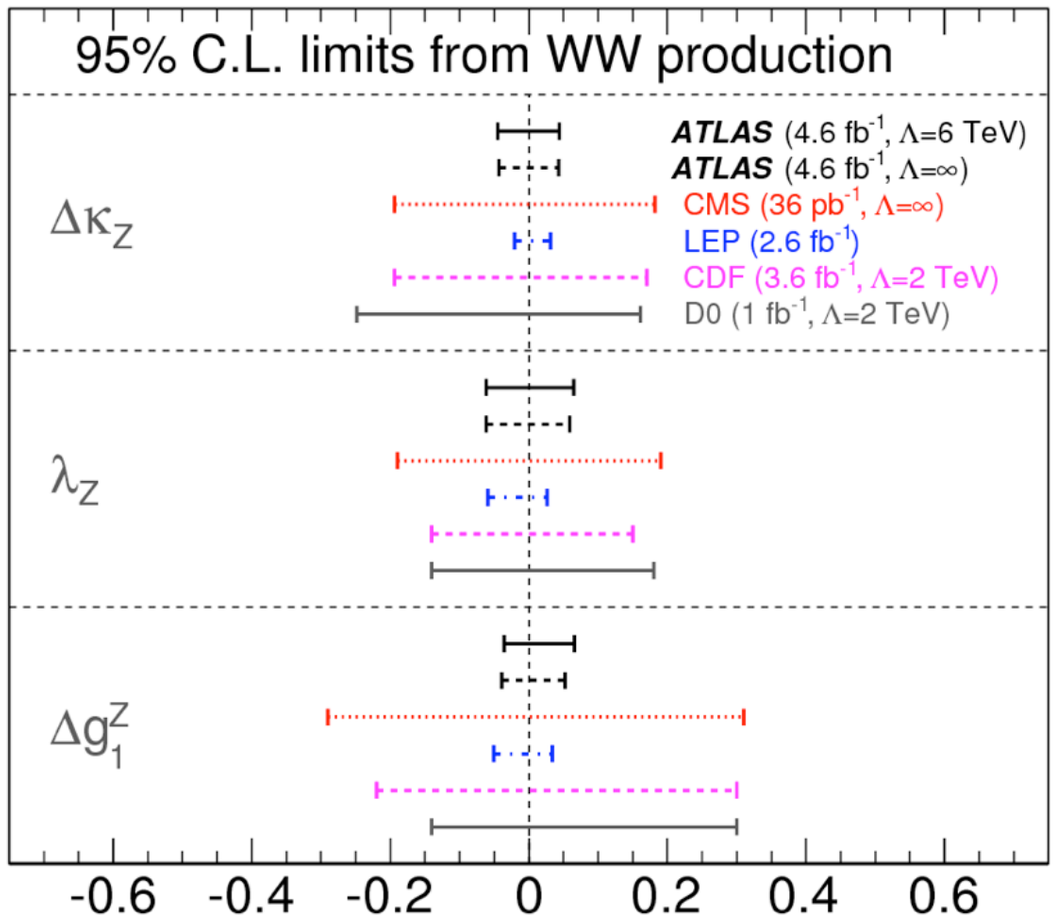
- **Fiducial differential cross-section** is obtained using iterative Bayesian unfolding.



# WWγ and WWZ triple gauge coupling (TGC) limits

**CERN-PH-EP-2012-242**
4.6 fb$^{-1}$ $\sqrt{s}$=7 TeV




- Compare leading lepton $p_T$ distribution to simulations of **varied TGC parameters**.
- WWZ and WWγ Lagrangian has **14 coupling parameters**, only 5 remain when assuming EM gauge invariance and conservation of C and P.
- Reduced to **3 parameters** by choosing "LEP scenario" (additional constraints).

# combined WW/WZ cross-section

**ATLAS-CONF-2012-157**
4.7 fb$^{-1}$ $\sqrt{s}$=7 TeV

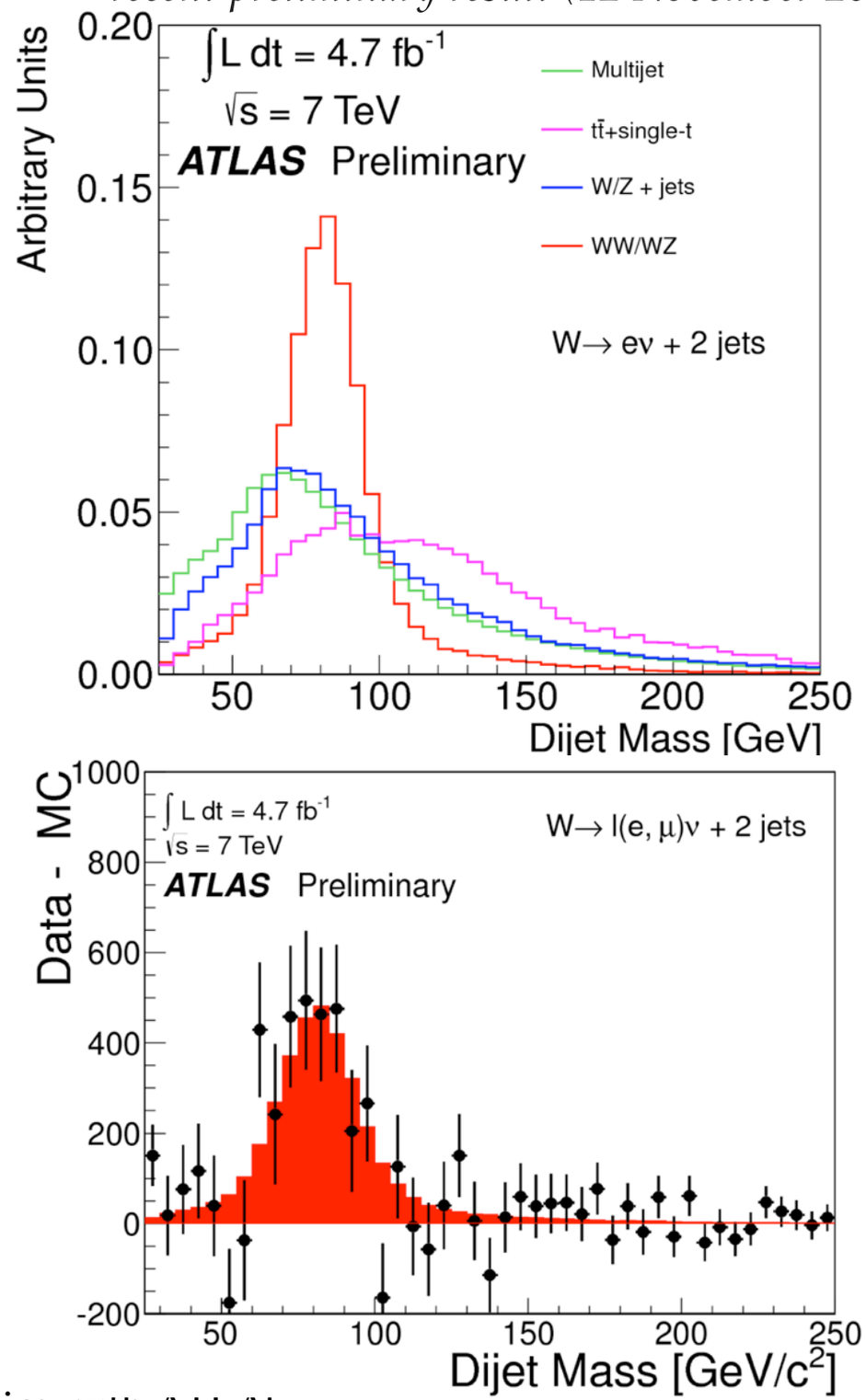
- Probing electroweak sector of SM.
- Major background for Higgs and possible new physics.

- **Semi-leptonic:** W→ $\ell\nu$ and W/Z→quarks
- **Selection:** exactly 1 lepton, exactly 2 jets, $E_T^{miss}$>30 GeV, $m_T$(W)>40 GeV.

- **Background** shapes from simulation.
  W normalization and QCD multijet rates from data-driven method.

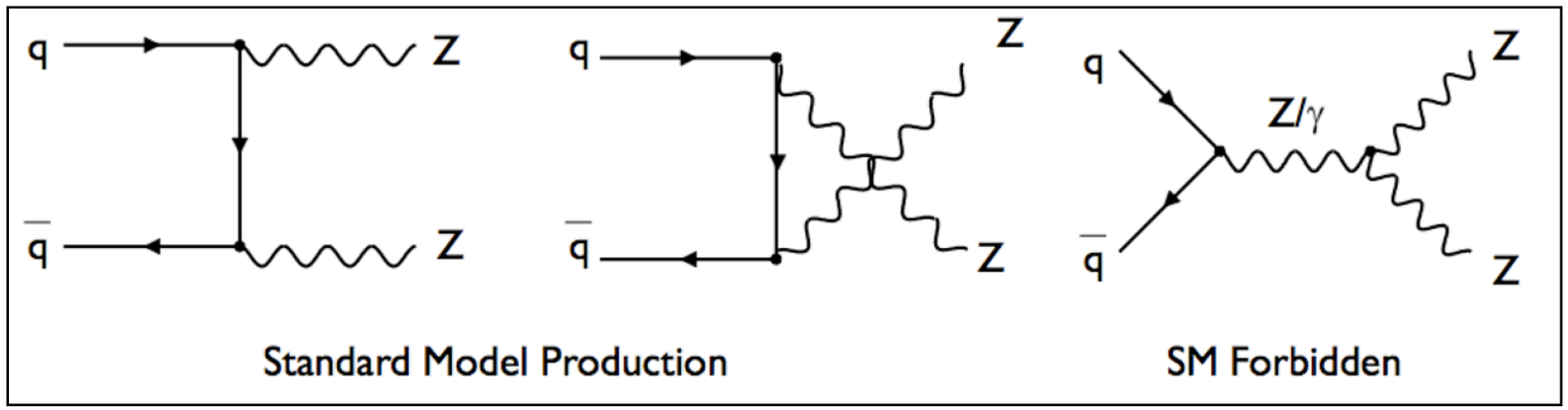
- Binned maximum likelihood fit to di-jet mass.
  **σ(WW+WZ)= 72 ±9(stat)±15(syst)±13 (MC stat) pb**
  SM expectation 63.4 ± 2.6 pb.
- Dominant systematics: JES (12%), W norm. (11%).
- Significance of resonance: 3.3 σ (3.0 σ expected).

*recent preliminary result (12 November 2012)*



# ZZ production cross-section @ 7 TeV

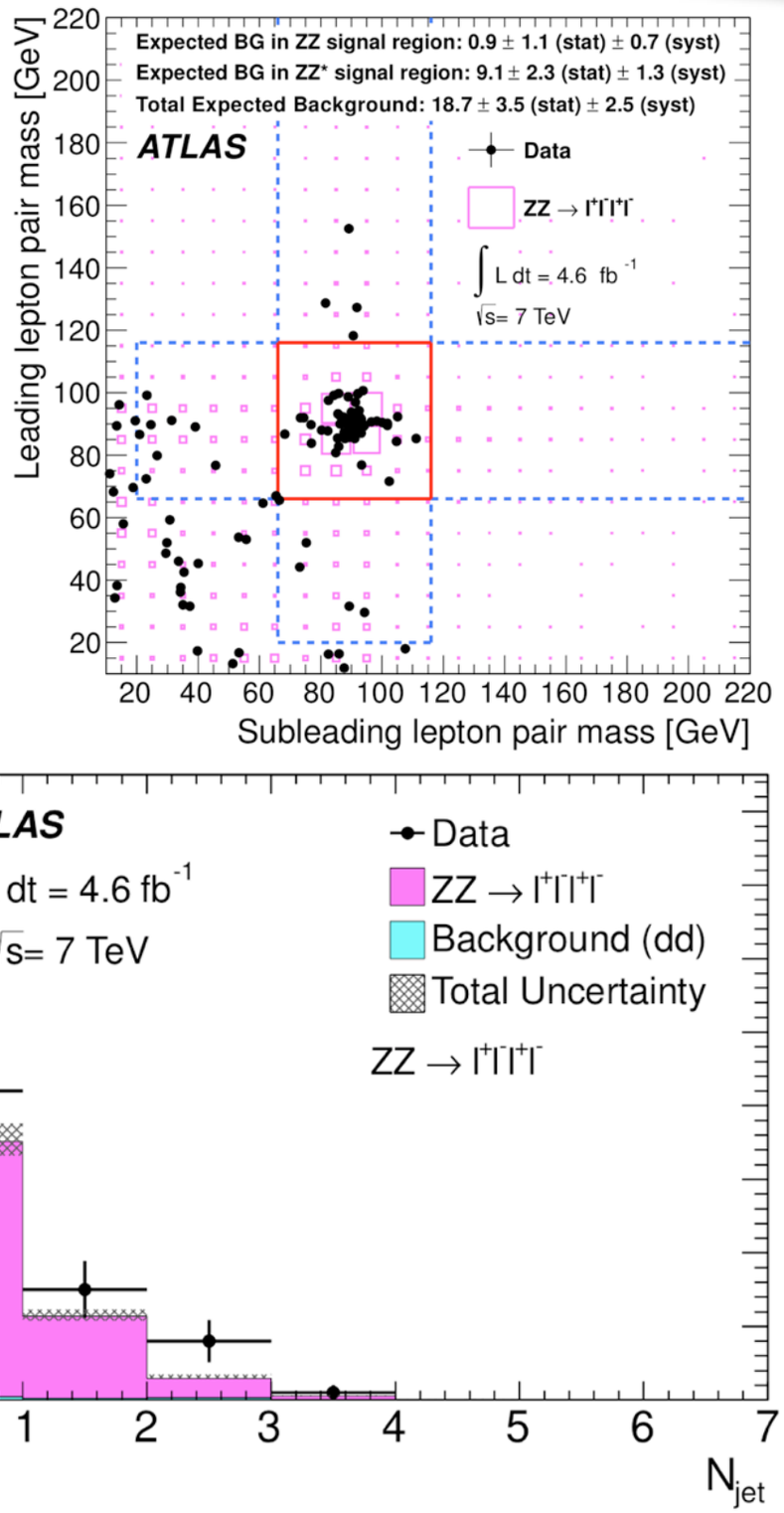
**submitted to JHEP**
4.6 fb$^{-1}$ $\sqrt{s}$=7 TeV




- Test electroweak SM predictions at TeV scale.
  Irreducible background of H→ZZ.
- ZZ→4$\ell$ (66 candidates, 1 BG expected),
  ZZ*→4$\ell$ (84 candidates, 9 BG expected) and
  ZZ→$\ell\ell\nu\nu$ (87 candidates, 47 BG expected),
  all compatible with SM expectation.
- Correcting for selection efficiency one finds:

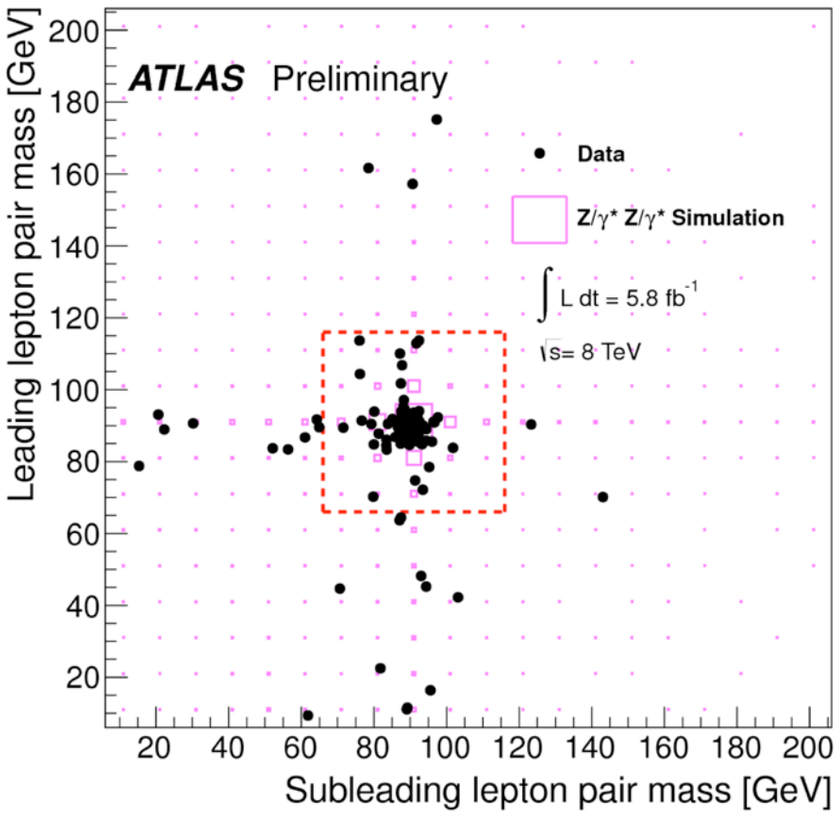
$$\sigma_{ZZ}^{\text{tot}} = 6.7 \pm 0.7\ (\text{stat.})\ ^{+0.4}_{-0.3}\ (\text{syst.}) \pm 0.3\ (\text{lumi.})\ \text{pb}.$$

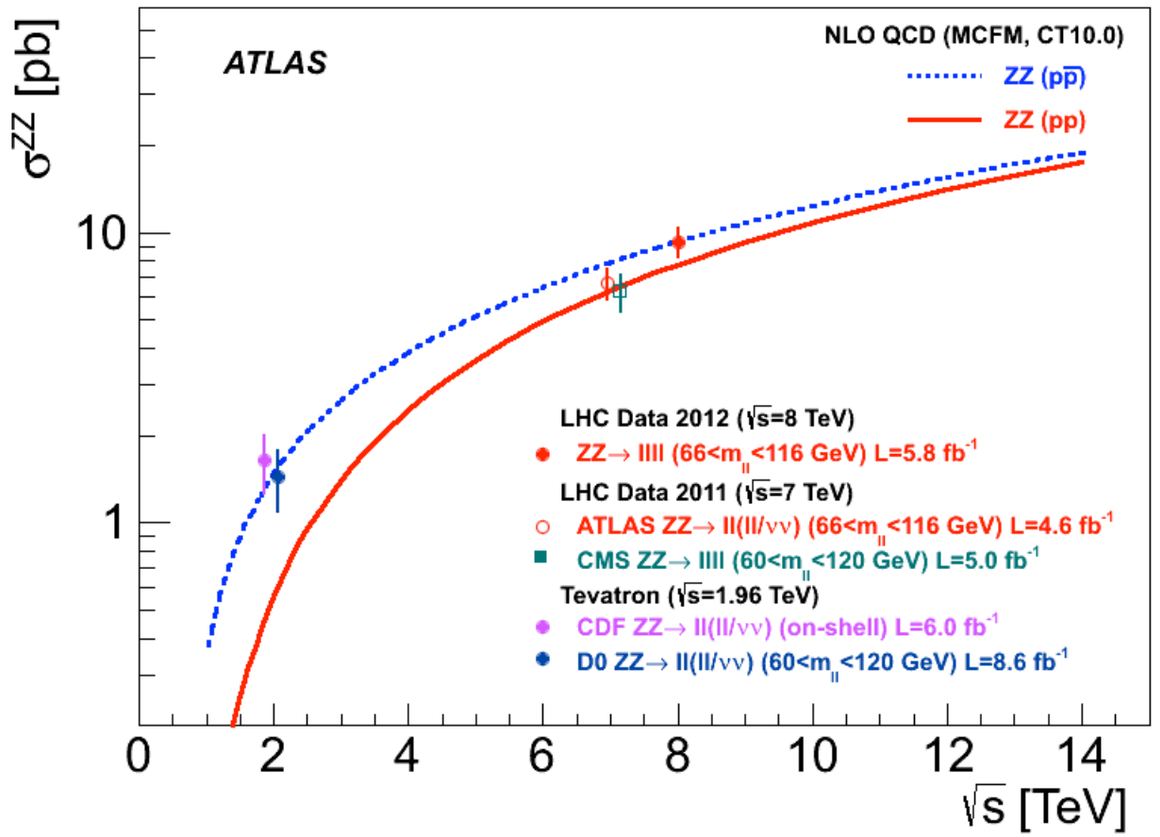
- NLO prediction: 5.9 ± 0.2 pb
- Fiducial differential cross-sections and limits on neutral triple gauge couplings are derived.



# ZZ production cross-section @ 8 TeV

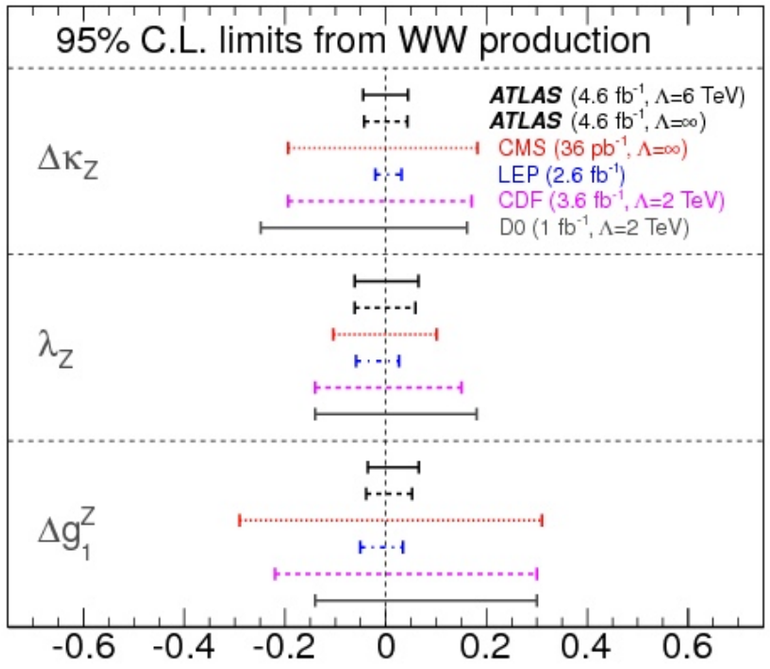
**ATLAS-CONF-2012-090**
5.8 fb$^{-1}$ $\sqrt{s}$=8 TeV



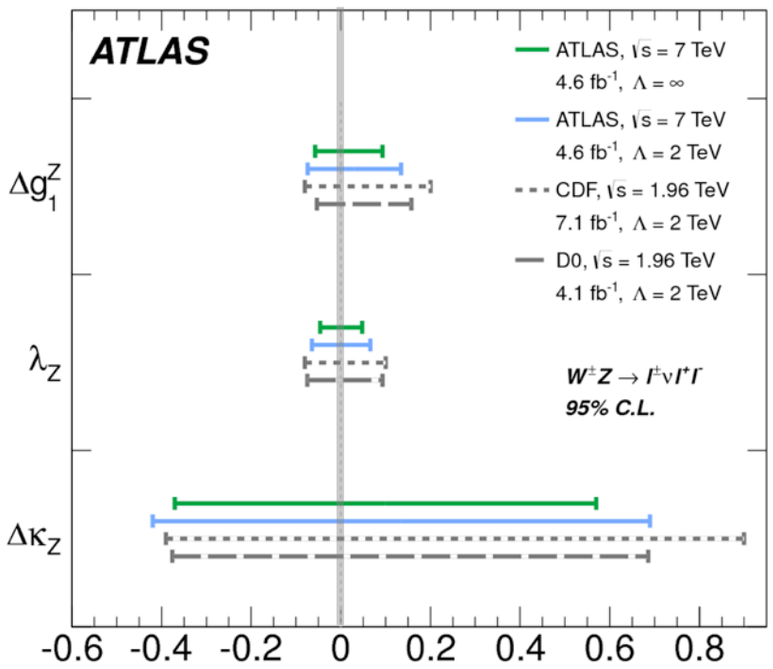




- Very similar cut and count strategy, four-lepton decay channel only.
- Select leptons with $p_T > 15$ GeV (leading lepton > 25 GeV) within η acceptance, ask for 2 pairs of opposite-sign, same-flavour leptons, consistent with $m_Z \pm 25$ GeV.
- 85 candidate events, expected background ~1.
- Total ZZ production cross section $9.3^{+1.1}_{-1.0}(\text{stat.})^{+0.4}_{-0.3}(\text{syst.}) \pm 0.3(\text{lumi.})$ pb
- Consistent with SM expectation $7.4 \pm 0.4$ pb.

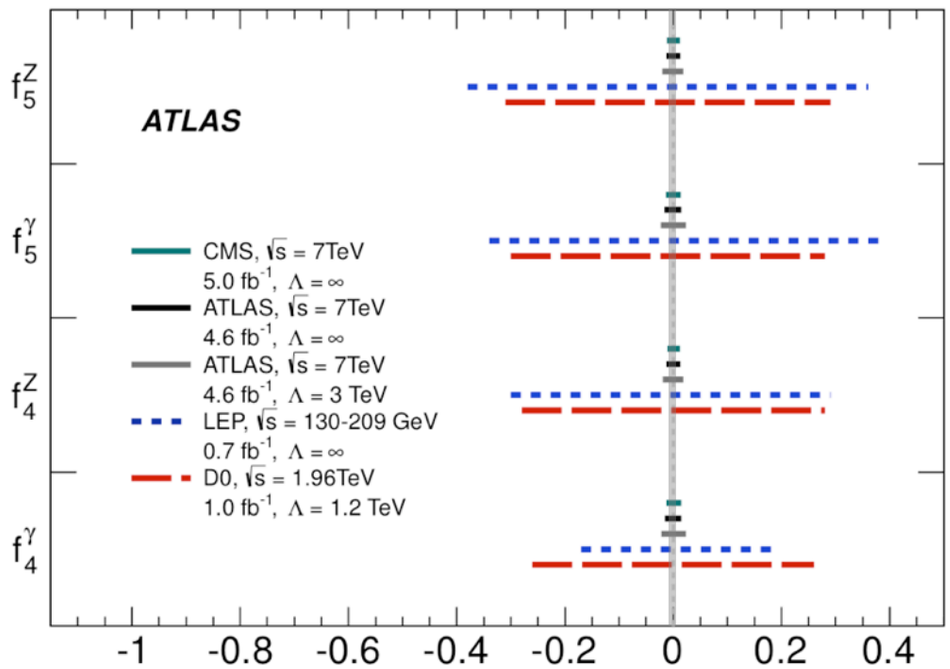
# Diboson cross-sections and TGC limits (summary)




- **WW** (submitted to Phys. Rev. D)
  51.9 ± 2.0 (stat) ± 3.9 (syst) ± 2.0 (lumi) pb
  44.7 ± 2.1 pb expected




- **WZ** (EPJ C (2012) 72:2173)
  19.0 ± 1.4 (stat) ± 0.9 (syst) ± 0.4 (lumi) pb
  17.6 ± 1.1 expected

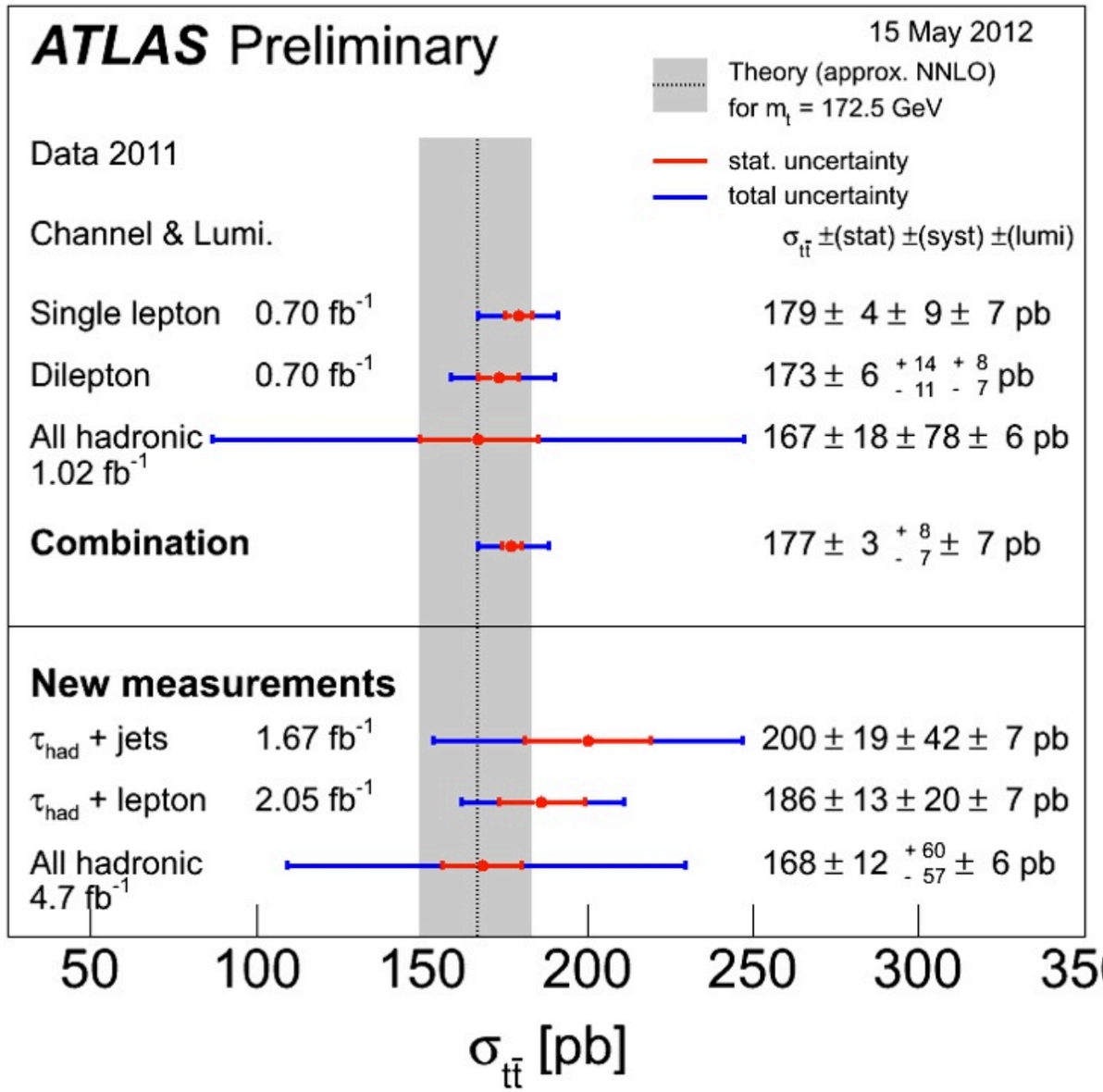



- **ZZ at 7 TeV** (submitted to JHEP)
  6.7 ± 0.7 (stat) ± 0.4 (syst) ± 0.3 (lumi) pb
  5.9 ± 0.2 pb expected

- Cross-section measurements of WW, WZ, ZZ at 7 TeV.
- ZZ at 8 TeV: $9.3^{+1.1}_{-1.0}(\text{stat.})^{+0.4}_{-0.3}(\text{syst.}) \pm 0.3(\text{lumi.})$ pb
- No deviations from SM expectation.

# Top Physics @ ATLAS

# top-antitop pair production cross-section




PLB 711 (2012) 244-263

JHEP05 (2012) 059

ATLAS-CONF-2011-140

ATLAS-CONF-2012-032

PLB 717 (2012) 89-108

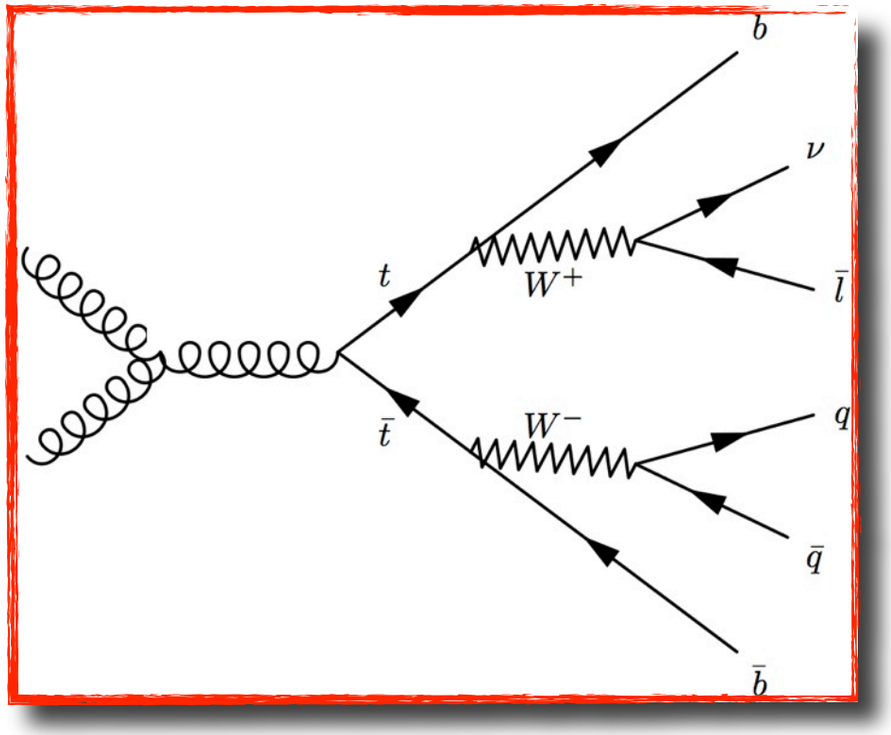
ATLAS-CONF-2012-031

**paper 30 Nov**: 194±18 (stat)±46 (syst) pb
submitted to EPJC, arXiv:1211.7205

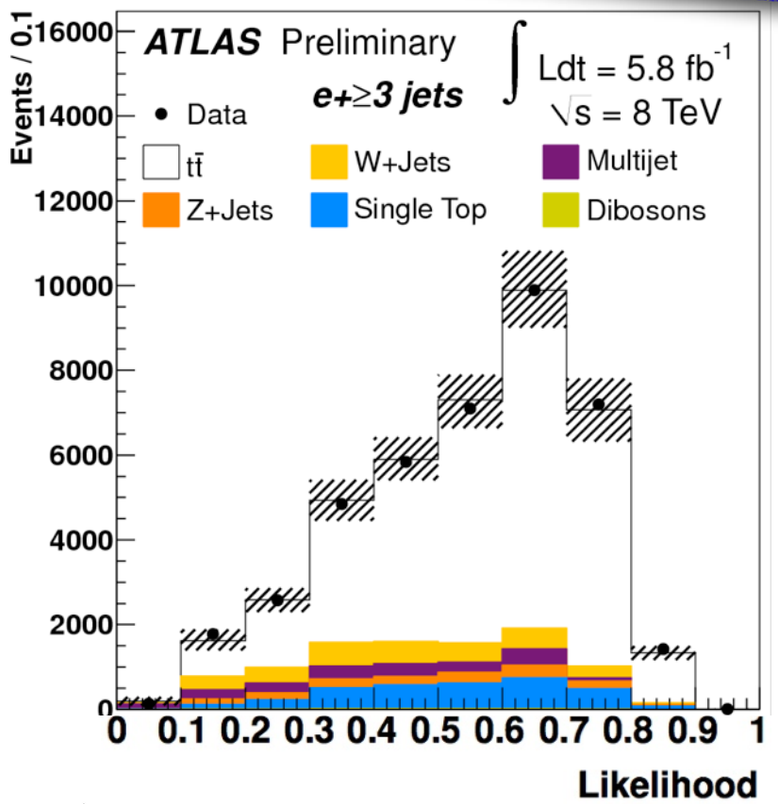
- 7 TeV single-lepton channel result with semi-leptonic b decays (4.7 fb$^{-1}$), ATLAS-CONF-2012-131
- 8 TeV single-lepton channel result released on 10 November (5.8 fb$^{-1}$). ATLAS-CONF-2012-149

# top-antitop pair production cross-section at 8 TeV

**ATLAS-CONF-2012-149**
5.8 fb$^{-1}$ $\sqrt{s}$=8 TeV



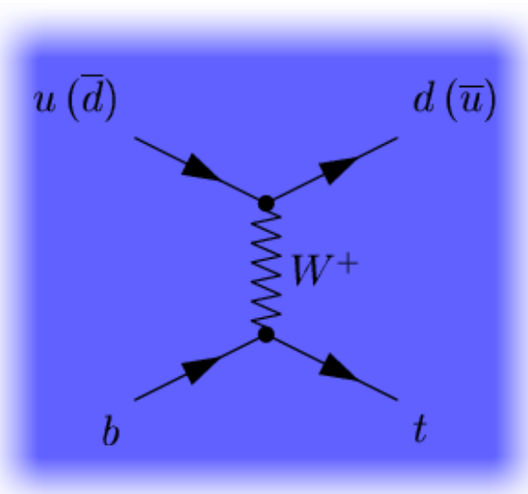

| | $e$+≥3 jets | $\mu$+≥3 jets |
|---|---|---|
| $t\bar{t}$ | $31000^{+2900}_{-3100}$ | 44000±4000 |
| $W$+jets | 5700±2400 | 9000±4000 |
| Multijet | 1900± 900 | 1100± 500 |
| $Z$+jets | 1400± 600 | 1200± 500 |
| Single top | 3260± 160 | 4610± 230 |
| Dibosons | 115± 6 | 158± 8 |
| Total Expected | 43000±4000 | 61000±6000 |
| Data | 40794 | 58872 |

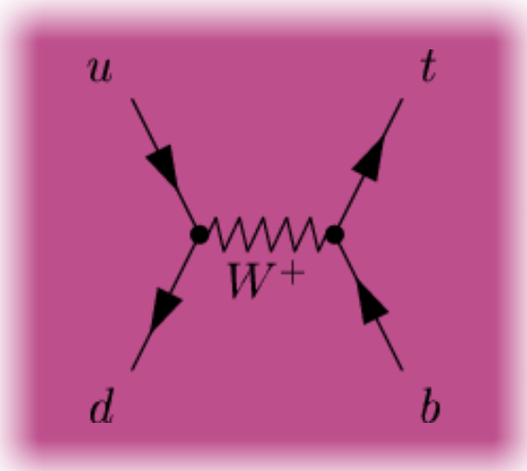


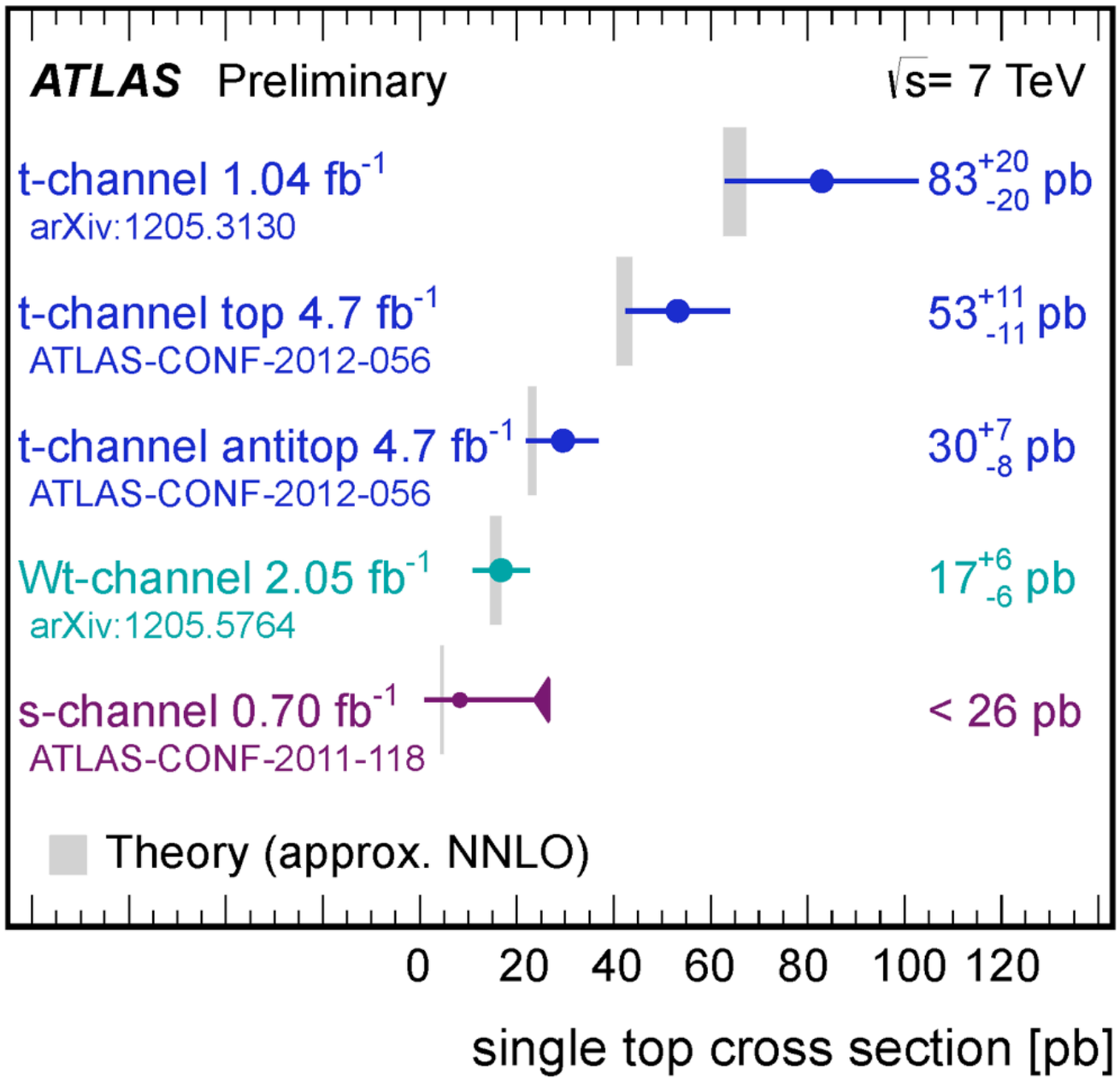

- **Signature**: 4 jets (2 b-jets), 1 lepton, missing momentum from neutrino.
- **Event Selection:**
  - At 8 TeV, jet merging more likely → require 3 jets including 1 b-tagged jet ($p_T$>25 GeV).
  - Electron or muon with $p_T$>40 GeV, no additional lepton >25 GeV.
  - $E_T^{miss}$>30 GeV (e-channel) or >20 GeV (μ-channel); $m_T(W)$>30 GeV (e-chan) or $E_T^{miss}$ +$m_T(W)$>60 GeV (μ-chan).
- Data-driven QCD multijet estimate, and W+jets normalization from data.
  Other backgrounds from MC.
- Extract top-antitop yield with multivariate likelihood discriminant template fit.

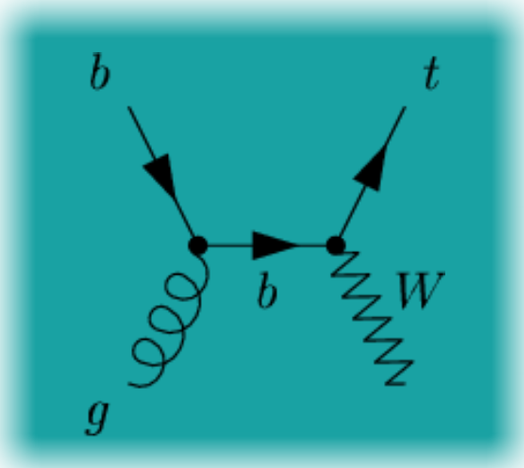
$$\sigma_{t\bar{t}} = 241 \pm 2\ (\text{stat.}) \pm 31\ (\text{syst.}) \pm 9\ (\text{lumi.})\ \text{pb.} \qquad \sigma_{t\bar{t}}^{\text{theor.}} = 238^{+22}_{-24}\ \text{pb}$$

# single top production (overview)



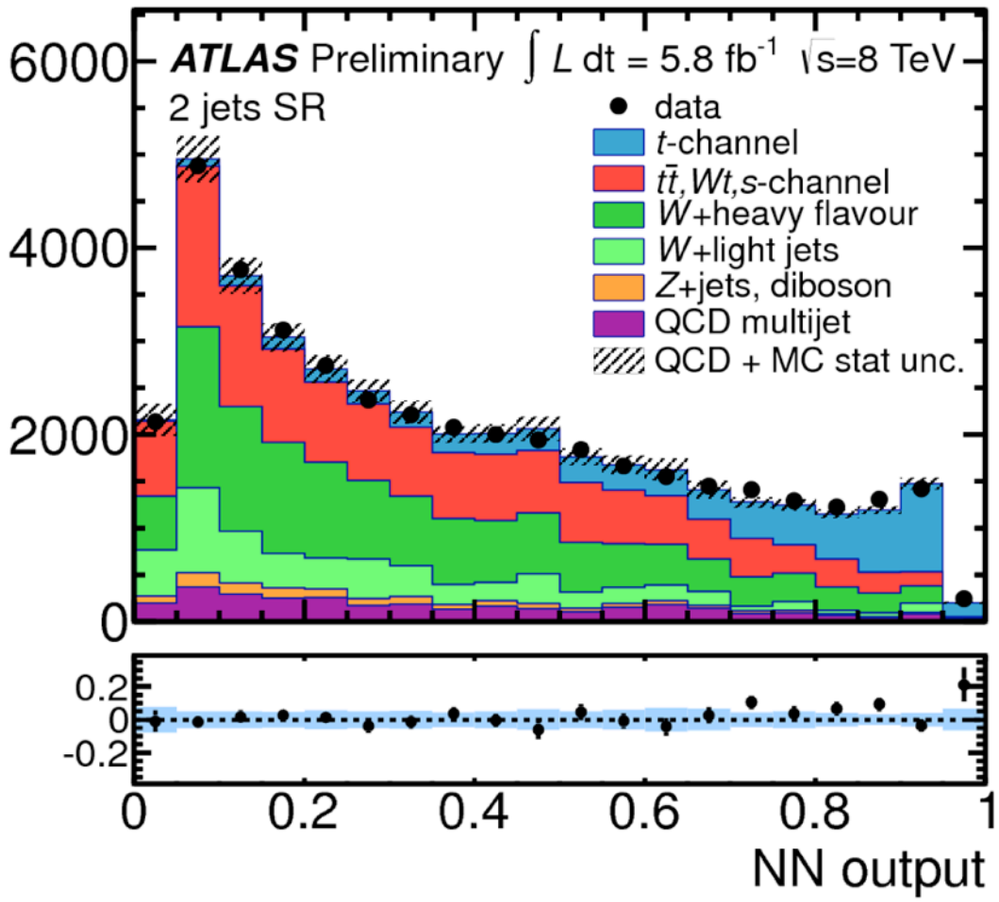



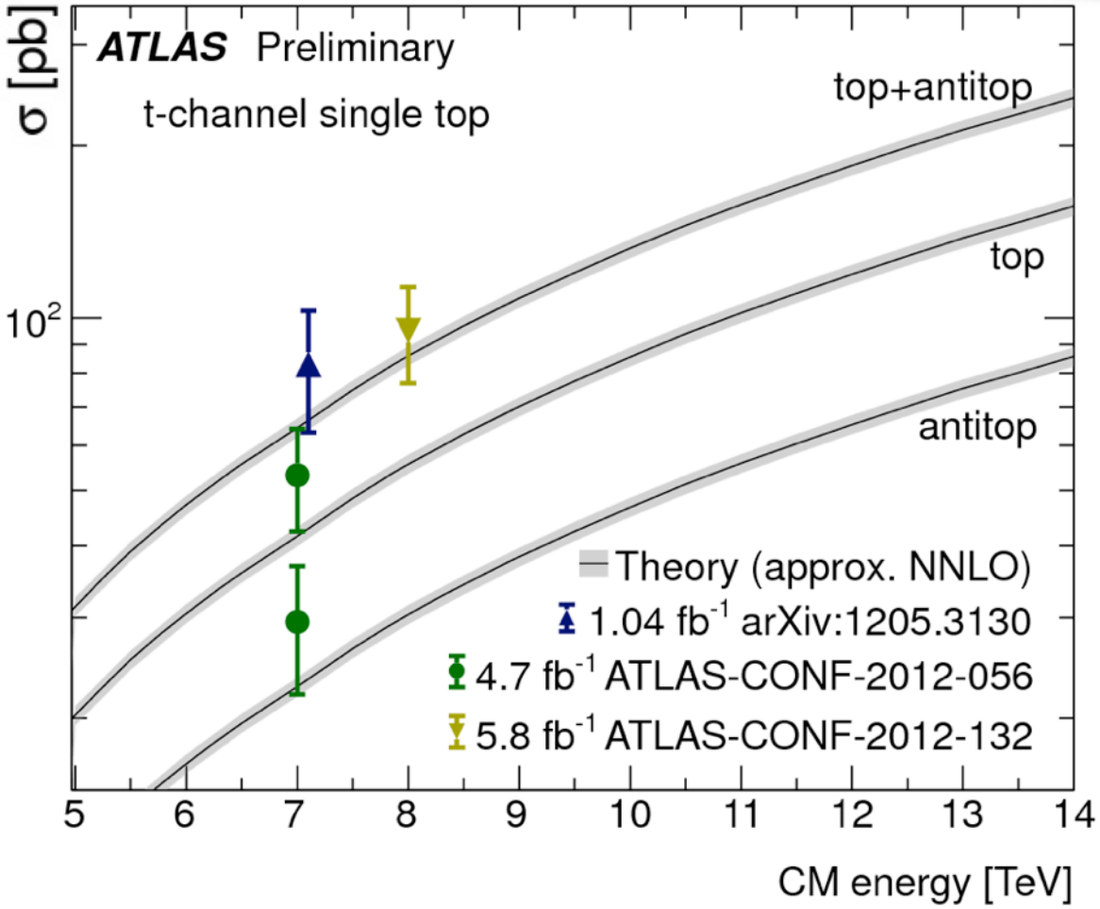




- First preliminary result for t-channel at √s=8 TeV released in September.

# single top production (t-channel)

**ATLAS-CONF-2012-132**
5.8 fb$^{-1}$ $\sqrt{s}$=8 TeV



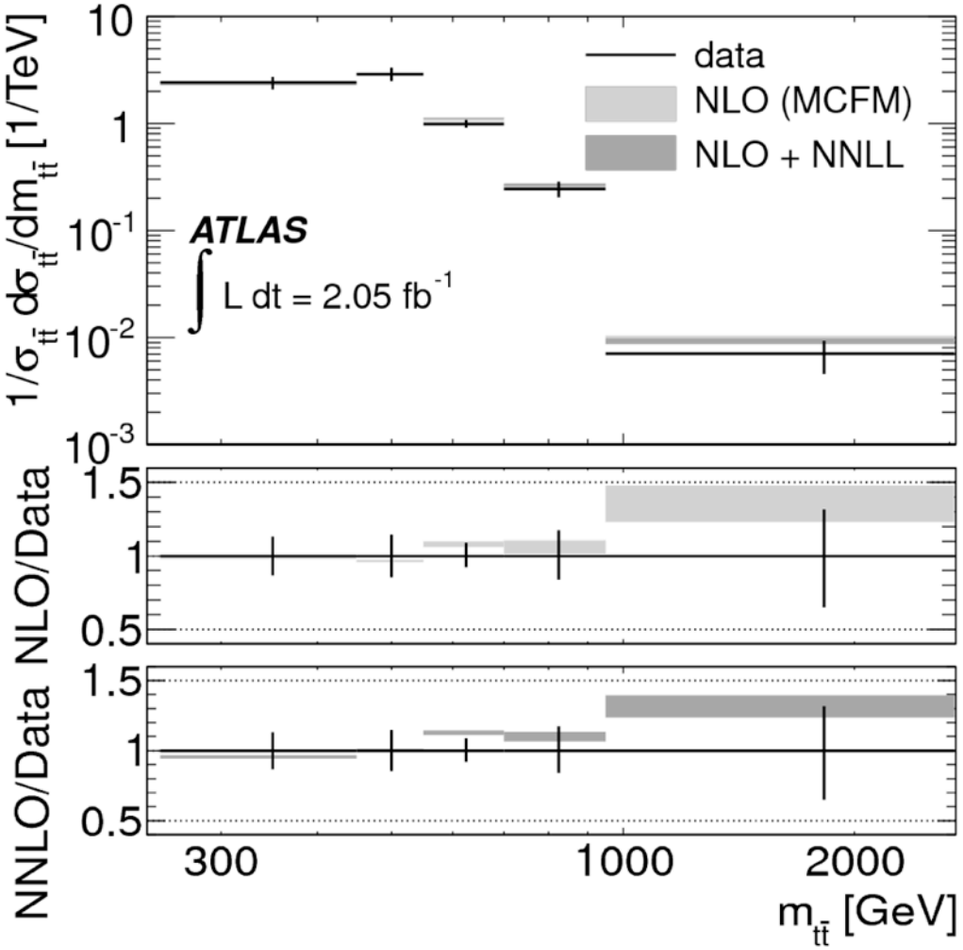

- Neural network based discriminant using kinematic properties of events with 1 lepton, significant $E_T^{miss}$, and 2-3 jets (1 b-tag).
- Combined binned maximum likelihood fit to NN output for 2+3 jets.

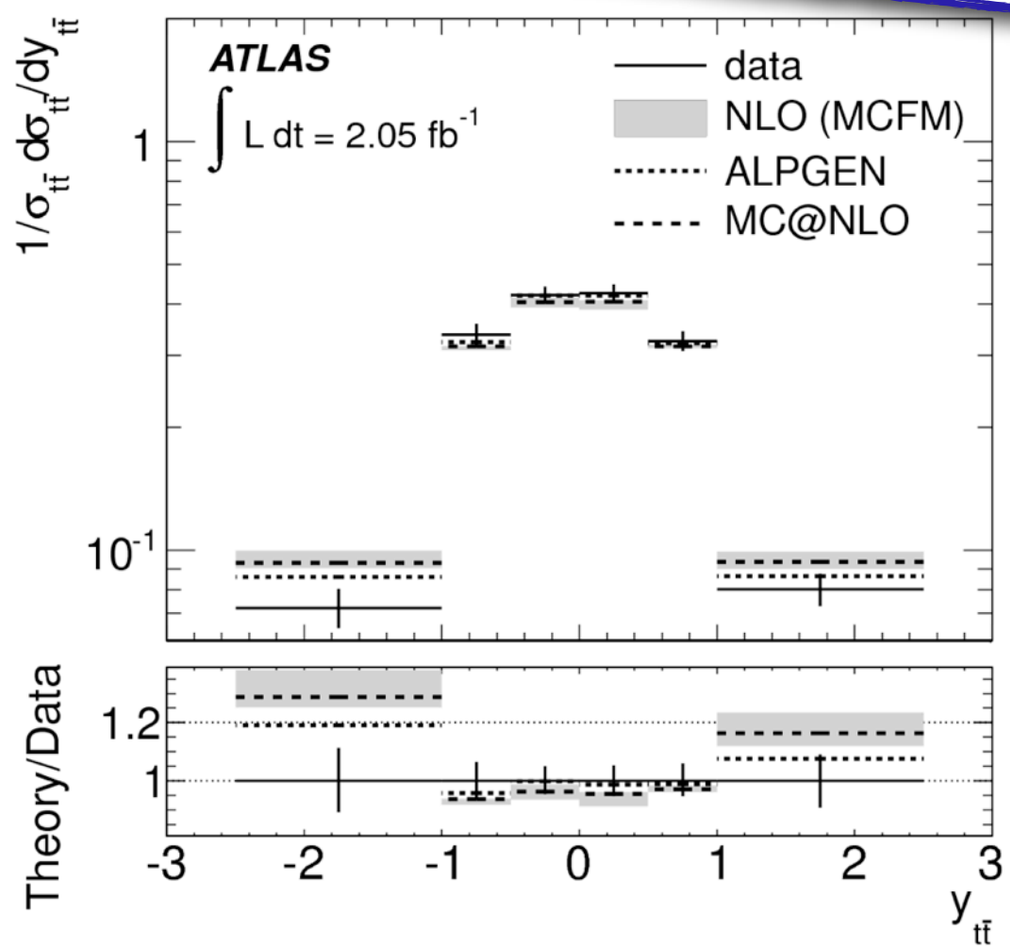
$\sigma_t$= 95 ± 2 (stat.) ± 18 (syst.) pb= **95 ± 18 pb**

- Constraints on CKM matrix: $|V_{tb}| = 1.04^{+0.10}_{-0.11}$ or $|V_{tb}| > 0.80$ at 95% CL.

# top pair differential cross-section

**CERN-PH-EP-2012-165**
submitted to EPJ C
2.05 $fb^{-1}$ $\sqrt{s}$=7 TeV



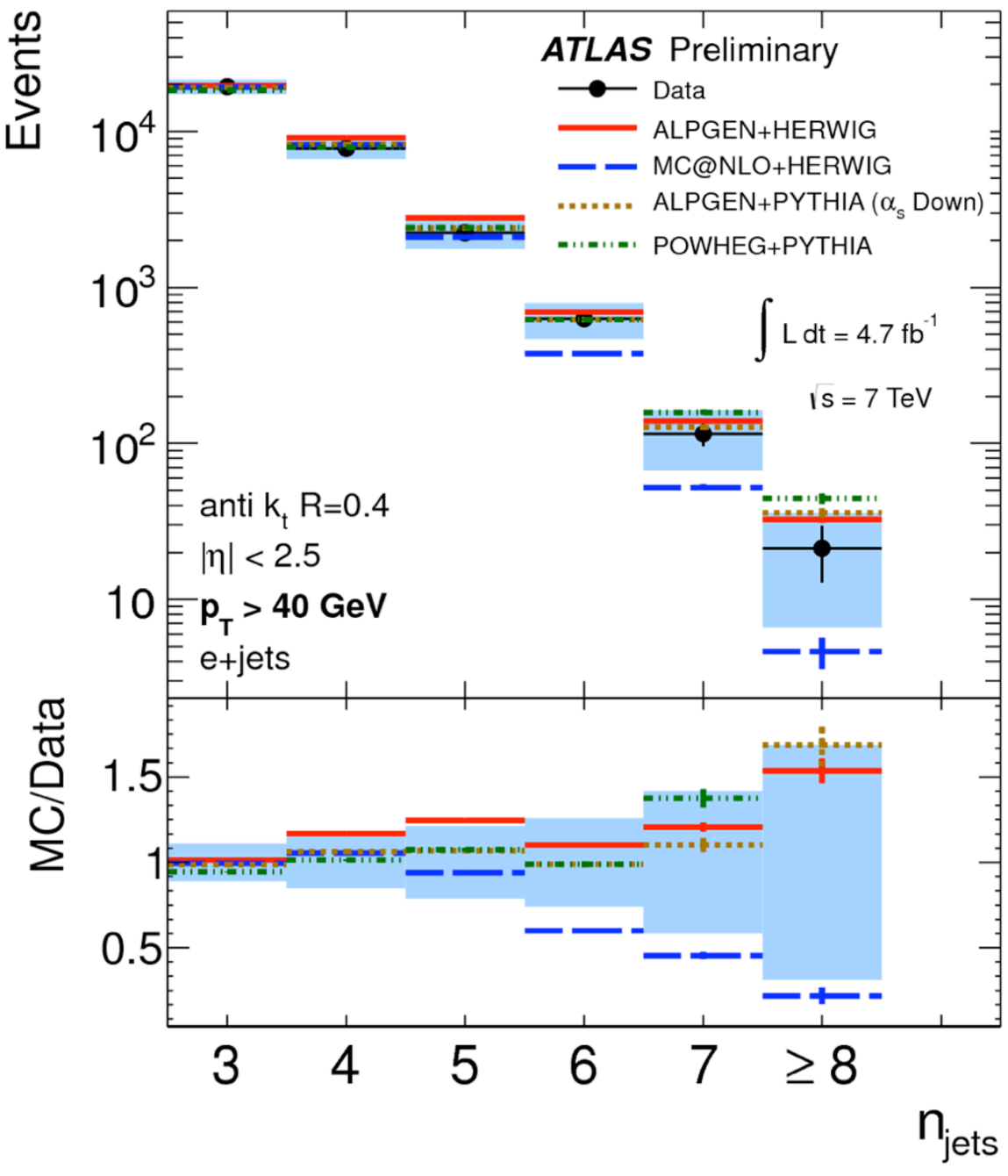

- Measurement of **$t\bar{t}$ system properties** in **single-lepton** channel.
- Reconstruction of full $t\bar{t}$ system with **kinematic likelihood fit** of lepton, neutrino and jet.
- Differential cross-sections as function of kinematic properties of top quark pair system; results relative to total inclusive $t\bar{t}$ production cross-section (systematics reduced to ~10-20%),
- No significant deviations from the SM expectations (different generators).

# top pair + extra jets cross-section

**ATLAS-CONF-2012-155**
4.7 fb$^{-1}$ $\sqrt{s}$=7 TeV

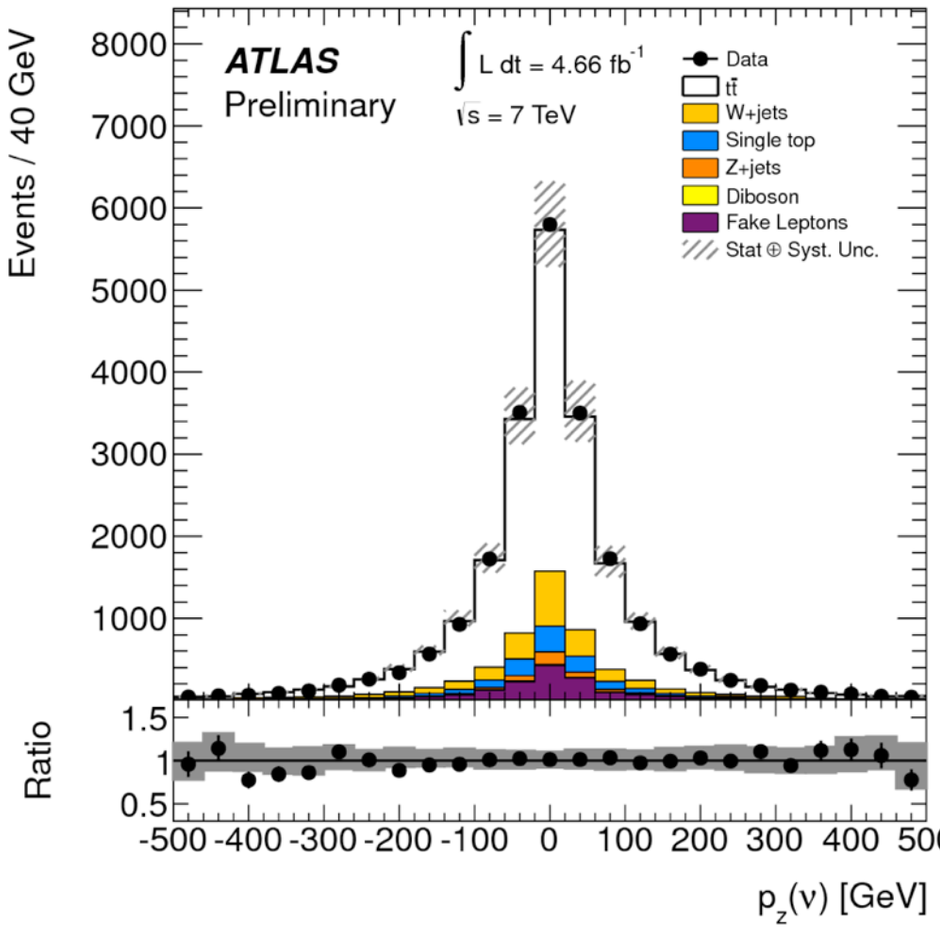
*recent preliminary result (11 November 2012)*

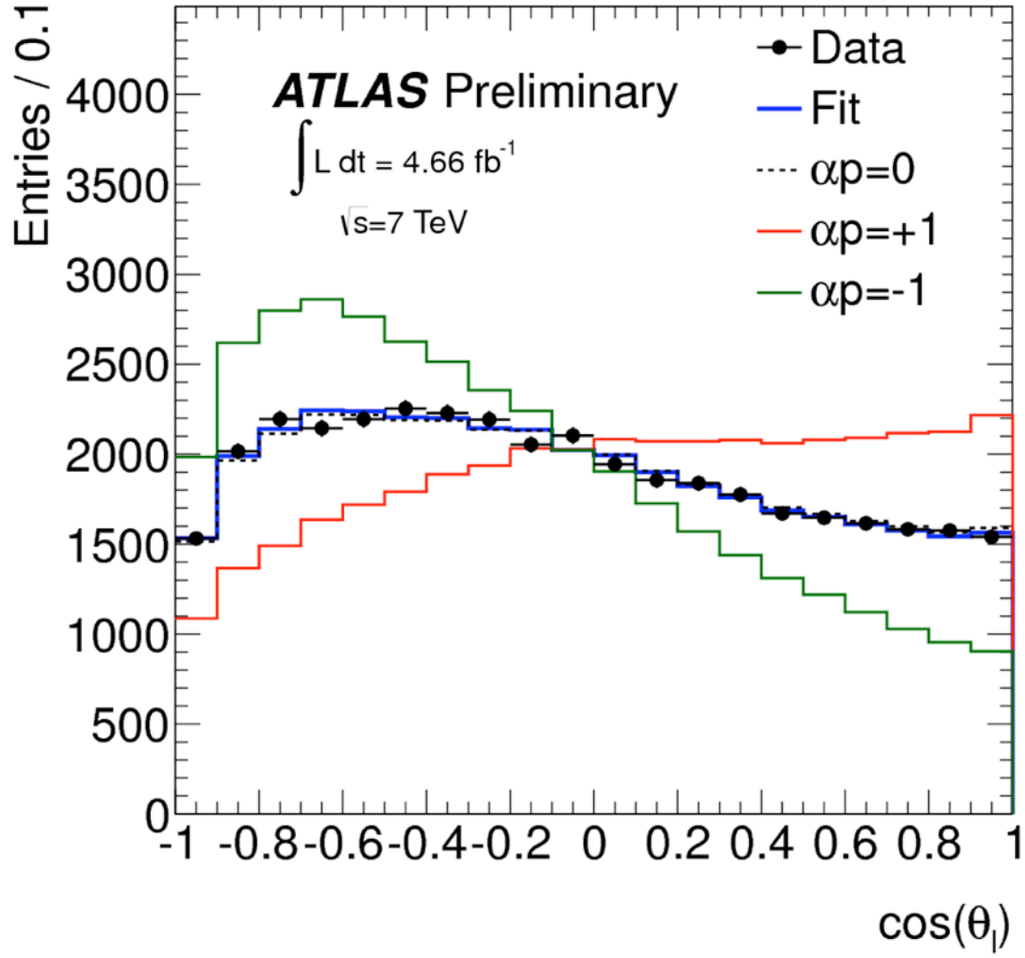
- Useful to constrain models of **initial** and **final state radiation (ISR/FSR)** at $m_t$ scale.
- Select events in **$t\bar{t}$ enhanced region**, measure reconstructed **jet multiplicity** for different $p_T$-thresholds.
- Reconstructed spectra are unfolded for detector effects.
- Systematics-limited: background modelling at low $n_{jets}$, JES at high $n_{jets}$.
- Comparison to several MC models including ME calculations and ISR/FSR variations.
- Agreement to **Alpgen+Herwig, Alpgen +Pythia** and **Powheg+Pythia**.
- **MC@NLO disfavoured** by data, as expected.



# top polarization

**ATLAS-CONF-2012-133**
4.7 fb$^{-1}$ $\sqrt{s}$=7 TeV



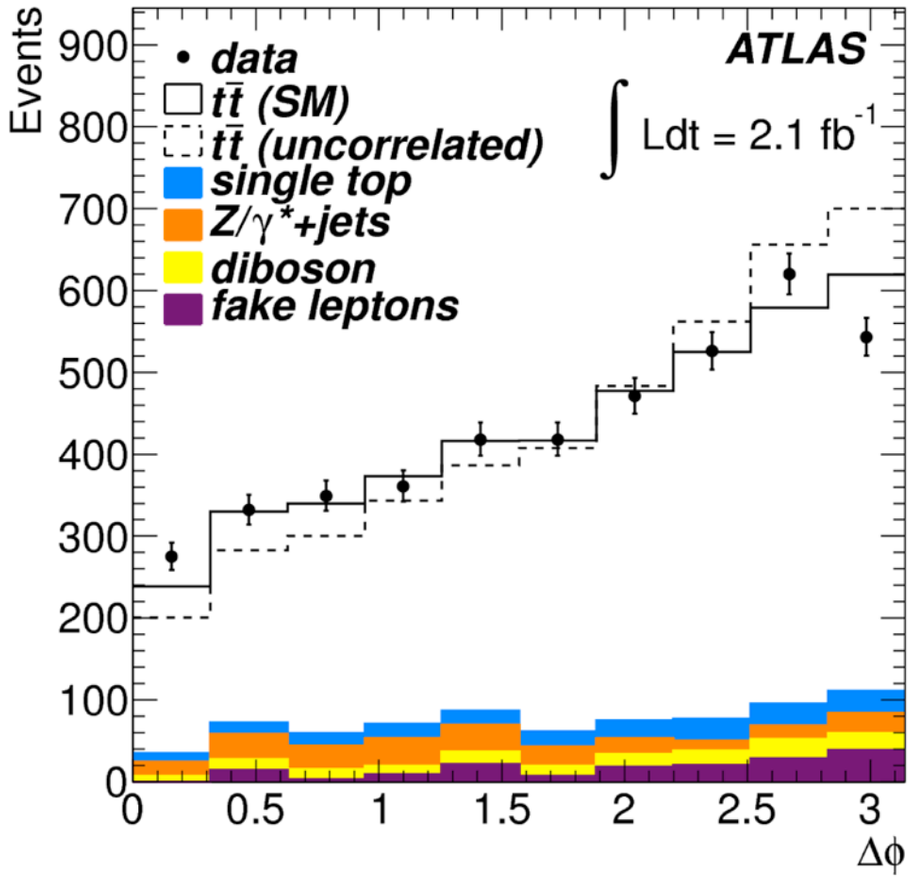



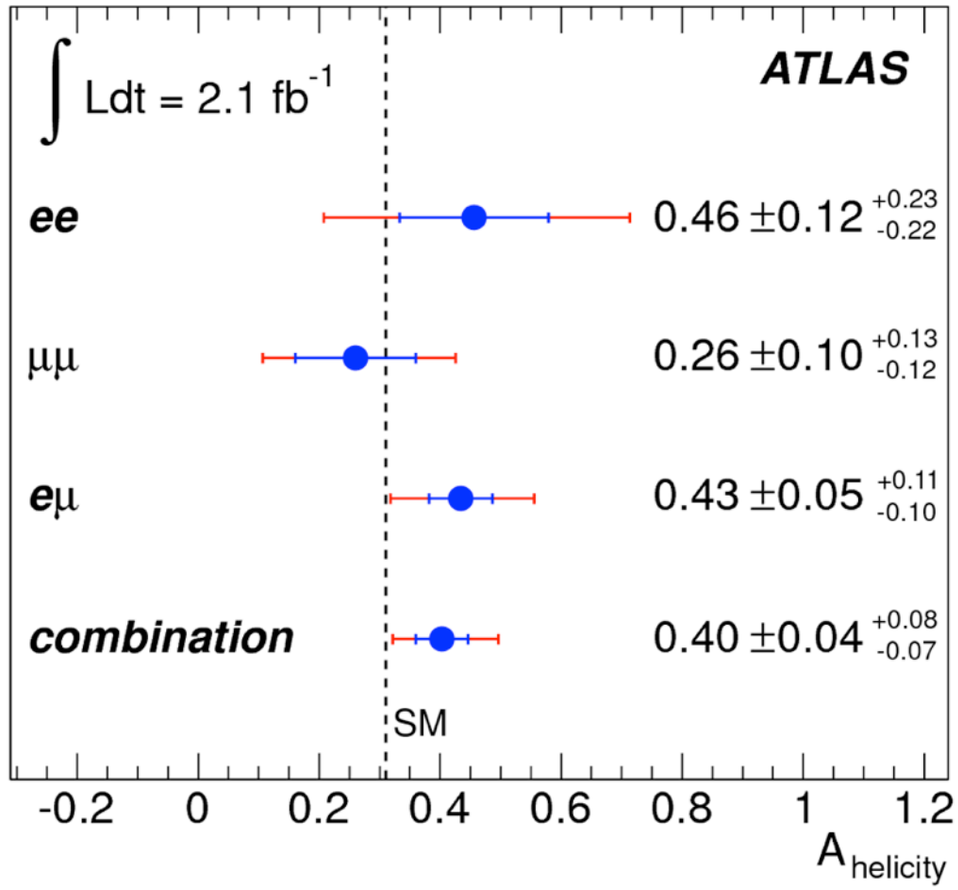

- Single lepton channel, full reconstruction of **top quark pair kinematics** with likelihood fit.
  - $\theta_l$ = polar angle of lepton, calculated in rest frame of leptonically decaying top.
- Extract polarization from template fit of polar angle of top quark decay products.
- Observation compatible with **50% positive polarization**, as expected from SM.

$$f = 0.470 \pm 0.009(\text{stat})^{+0.023}_{-0.032}(\text{syst})$$

# observation of spin correlation

**PRL 108, 212001 (2012)**
2.1 fb$^{-1}$ $\sqrt{s}$=7 TeV




- Top polarization is small, but top-antitop spins are expected to be **correlated**.
- Top quark decays before strong force can flip the spin.
- Measuring **degree of correlation** $A$ in dileptonic channel, **sensitive to new physics** in production and decay!

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

- Template fit to angular distribution of the two leptons is used to extract $A$.
- **A=0.40 (helicity basis)**, consistent with SM expectation of **0.31** at NLO.
- Zero spin correlation hypothesis rejected at 5.1 σ.

# charge asymmetry (1/3)

- **Source of asymmetry?**
  - $q\bar{q} \rightarrow t\bar{t}$ symmetric between top and anti-top at leading order, but not at NLO due to **interferences** between Born level and box diagrams.
  - $qg \rightarrow t\bar{t}q$, $q\bar{q} \rightarrow t\bar{t}g$ not symmetric as well.
  - Dominant production mode $gg \rightarrow t\bar{t}$ is symmetric, **small effect at LHC**!

- **How to observe it?**
  - Tevatron: observed as forward-backward asymmetry, 2-3 σ deviation from SM expectation,
  - LHC: initial state is symmetric, **antitop quarks produced more centrally** on average.

**Define charge asymmetry $A_C$:**

$$\Delta|y| \equiv |y_t| - |y_{\bar{t}}| \quad A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

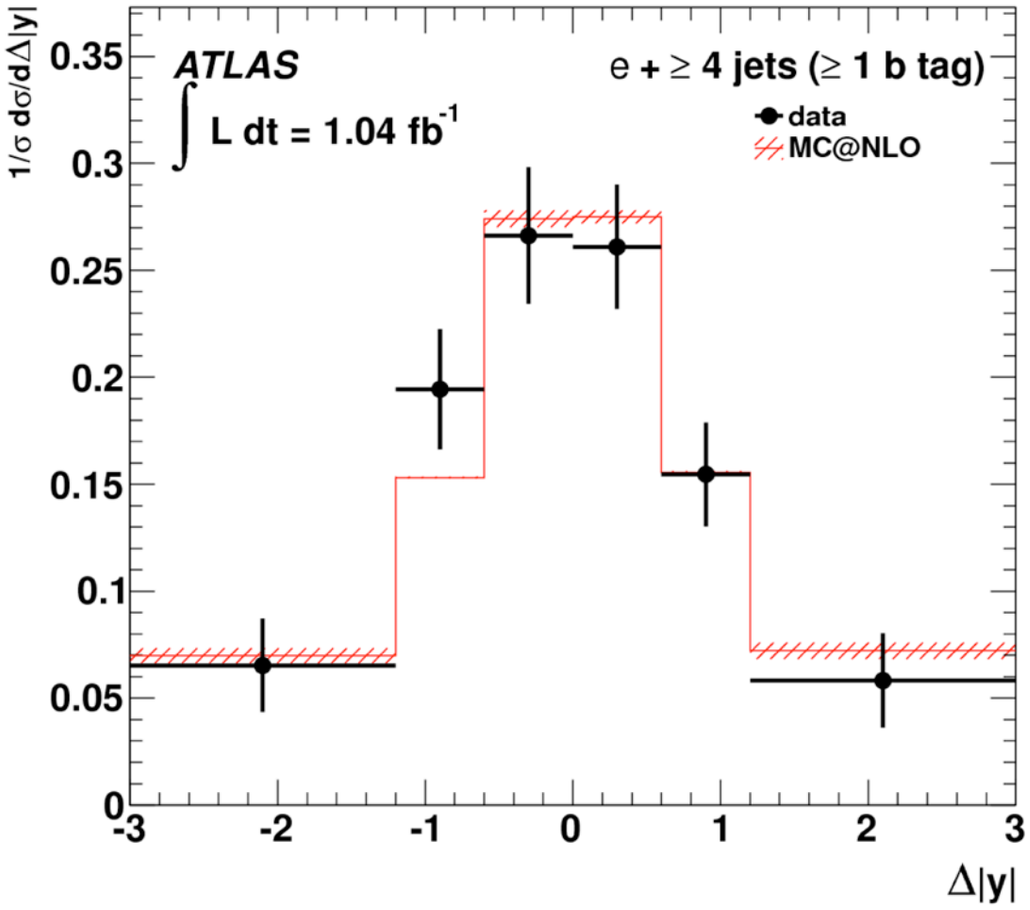
# charge asymmetry (2/3)

**EPJC (2012) 72:2039**
**ATLAS-CONF-2012-057**
1.04 $fb^{-1}$, 4.7 $fb^{-1}$, $\sqrt{s}$=7 TeV

- Results from **single-lepton** (EPJC) and **di-lepton channels** (ATLAS preliminary).

- **Single-lepton event selection:** exactly 1 lepton, 4 jets, 1 b-tag, sufficient $E_T^{miss}$ and $m_T(W)$,
- Reconstruct **$t\bar{t}$ system** with kin. likelihood fit.
- Reconstruct distribution of rapidity difference $\Delta|y|$, unfold for detector effects, and compute charge asymmetry:

$$A_C^{t\bar{t}} = -0.019 \pm 0.028(\text{stat.}) \pm 0.024(\text{syst.})$$




- Two methods used for **di-lepton channel**:
  - (a) reconstruction of $t\bar{t}$ system
  - (b) computation of lepton-based asymmetry.
- **Combination (single- and di-lepton $t\bar{t}$):**

$$A_C^{t\bar{t}} = 0.029 \pm 0.018\,(\text{stat.}) \pm 0.014\,(\text{syst.})$$

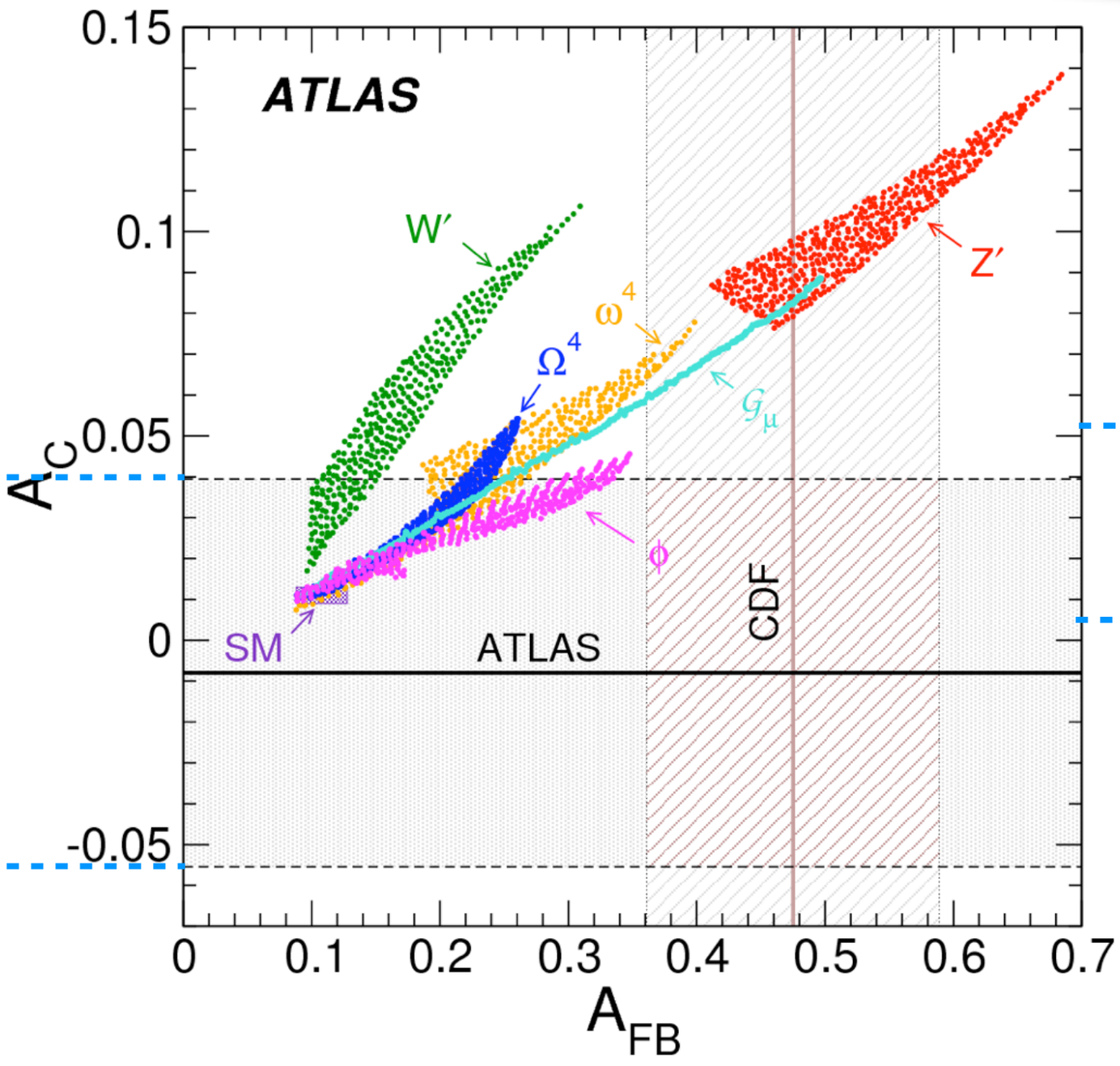
**SM expectation (MC@NLO):**
$$A_C = 0.006 \pm 0.002$$

# charge asymmetry (3/3)

EPJC (2012) 72:2039
ATLAS-CONF-2012-057
1.04 fb$^{-1}$, 4.7 fb$^{-1}$, $\sqrt{s}$=7 TeV

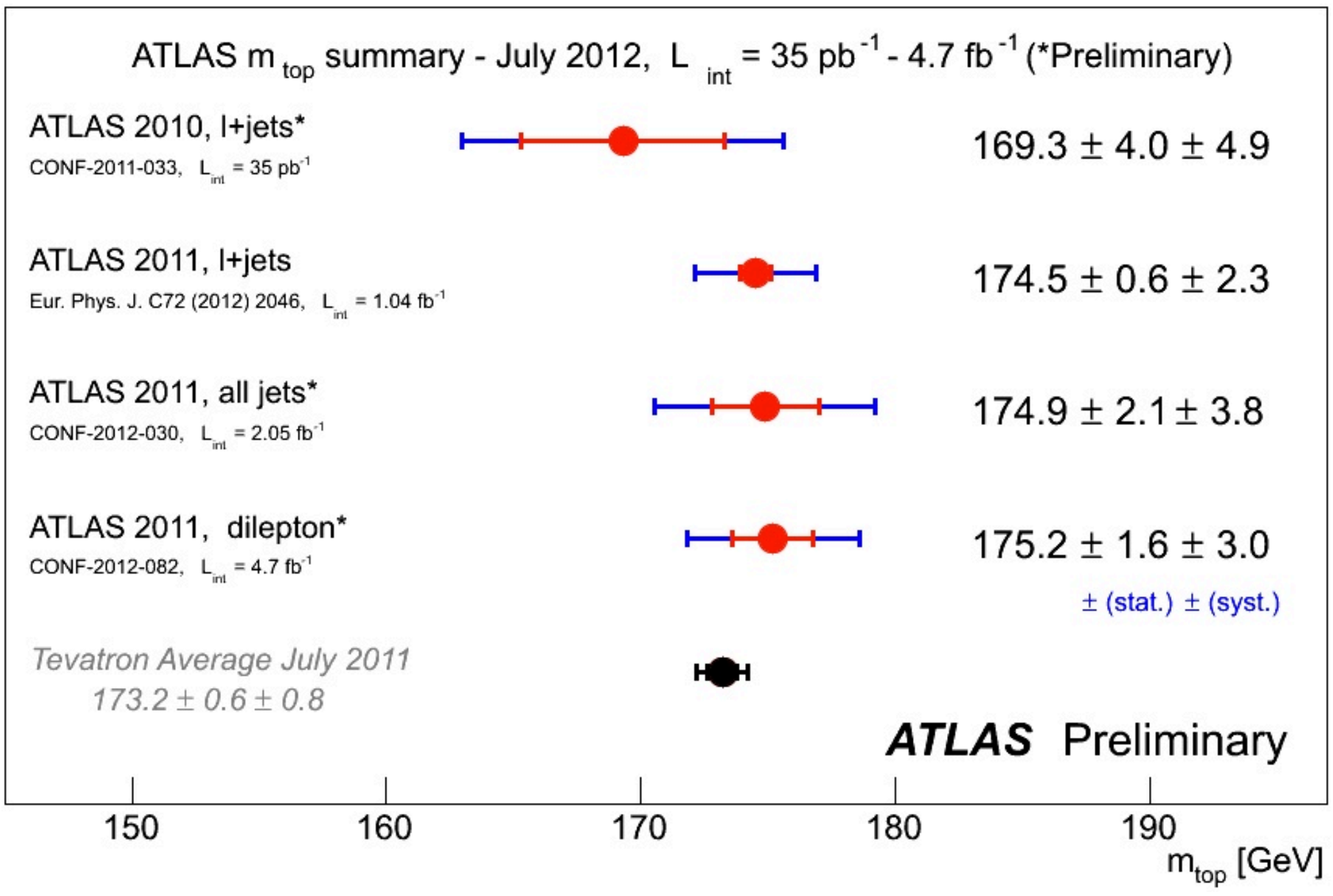
single-lepton

di-lepton




- Implications for various **new physics scenarios** from ATLAS charge asymmetry and CDF forward-backward asymmetry results.

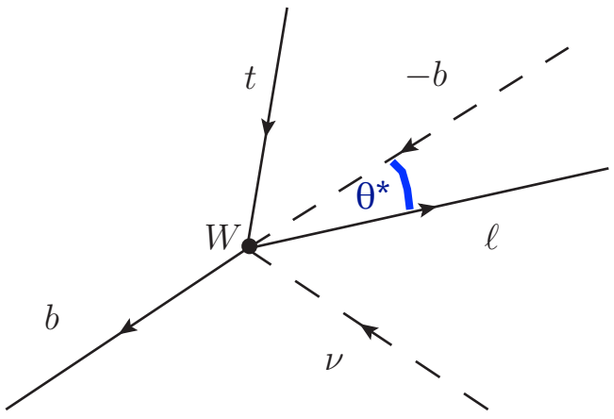
# top mass



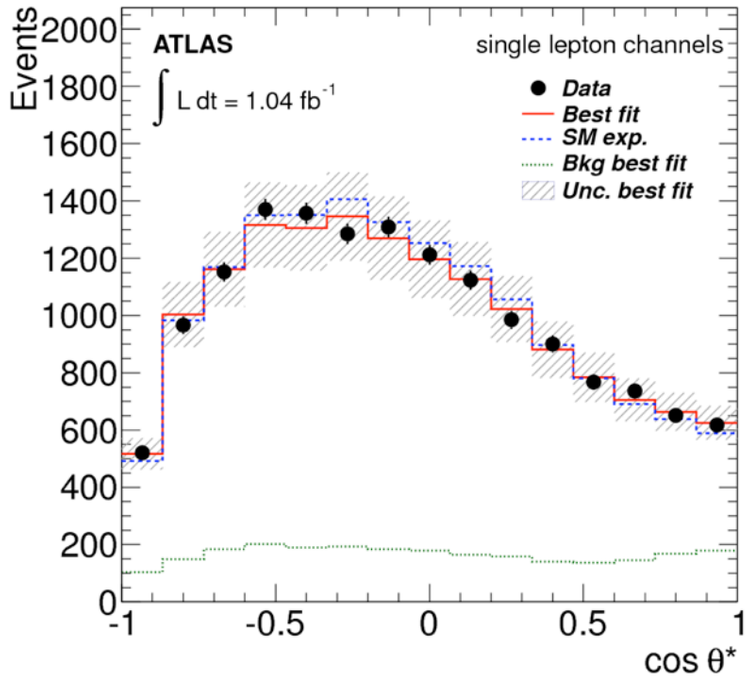

- Top mass and charge will be discussed in Lucia's talk this afternoon.

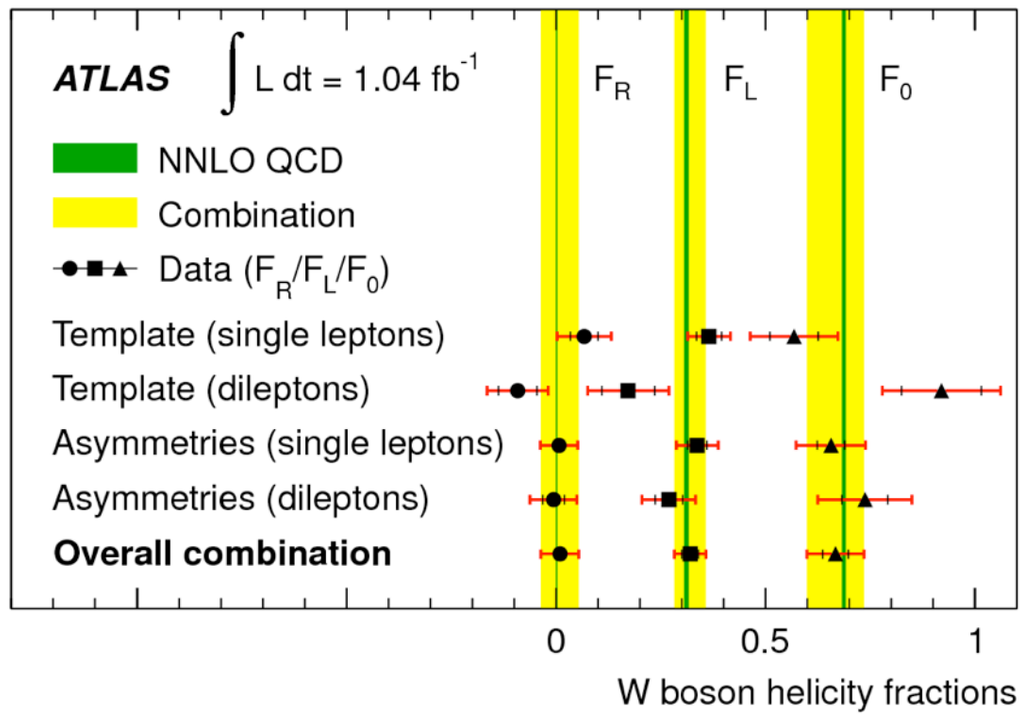
# polarization of W bosons from top decays

**JHEP06 (2012) 088**
1.04 fb$^{-1}$ $\sqrt{s}$=7 TeV




definition of θ*
in W rest frame




- Fractions of different **W helicities** are measured in single- and di-lepton channels, using (i) a template method and (ii) from unfolded angular distributions.
- Results in agreement with NNLO QCD predictions and more precise than previous Tevatron results.

- **New physics** could contribute to **Wtb vertex**. Limits on Wtb vertex anomalous couplings were extracted and are consistent with (V − A) structure of Wtb vertex.

# Summary

- An overview of **recent ATLAS SM measurements** was given ...
  - jet measurements (inclusive jet production, boosted jet properties, di-jet flavour fractions)
  - high mass Drell-Yan, W + b-jet production,
  - di-boson cross-sections from $\gamma\gamma$ to ZZ, including TGC limits.
- These measurements help us to test our understanding of **perturbative QCD** and the **electroweak sector** of the Standard Model at LHC energies.

- Recent measurements of **top production** and **top properties** were presented ...
  - including top pair and single top production,
  - measurements of top quark polarization, top pair spin correlation, charge asymmetry,
  - and W from top quark decay polarization.

- No significant deviations from SM expectations were found.

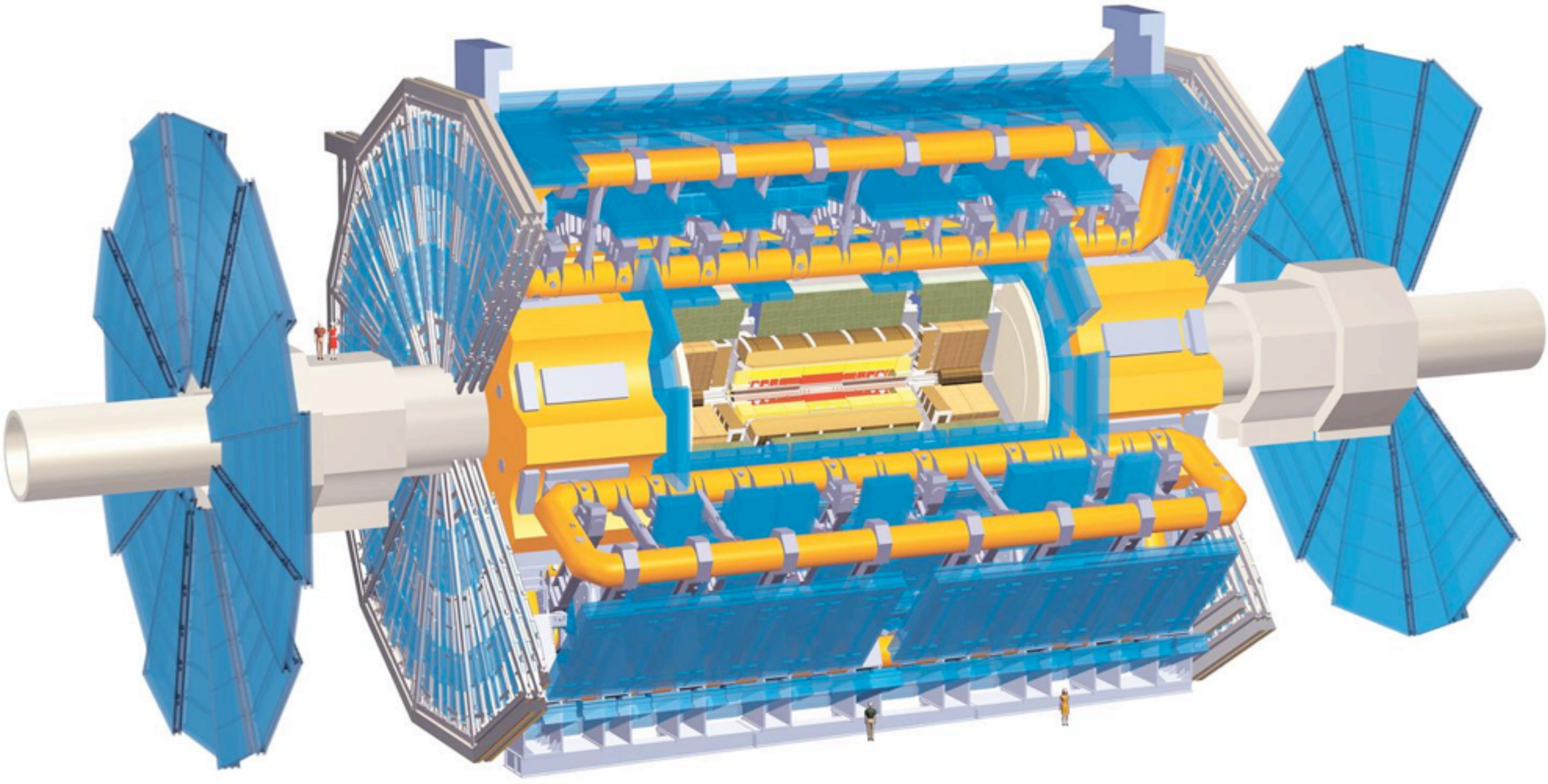
*Thank you for your attention!*

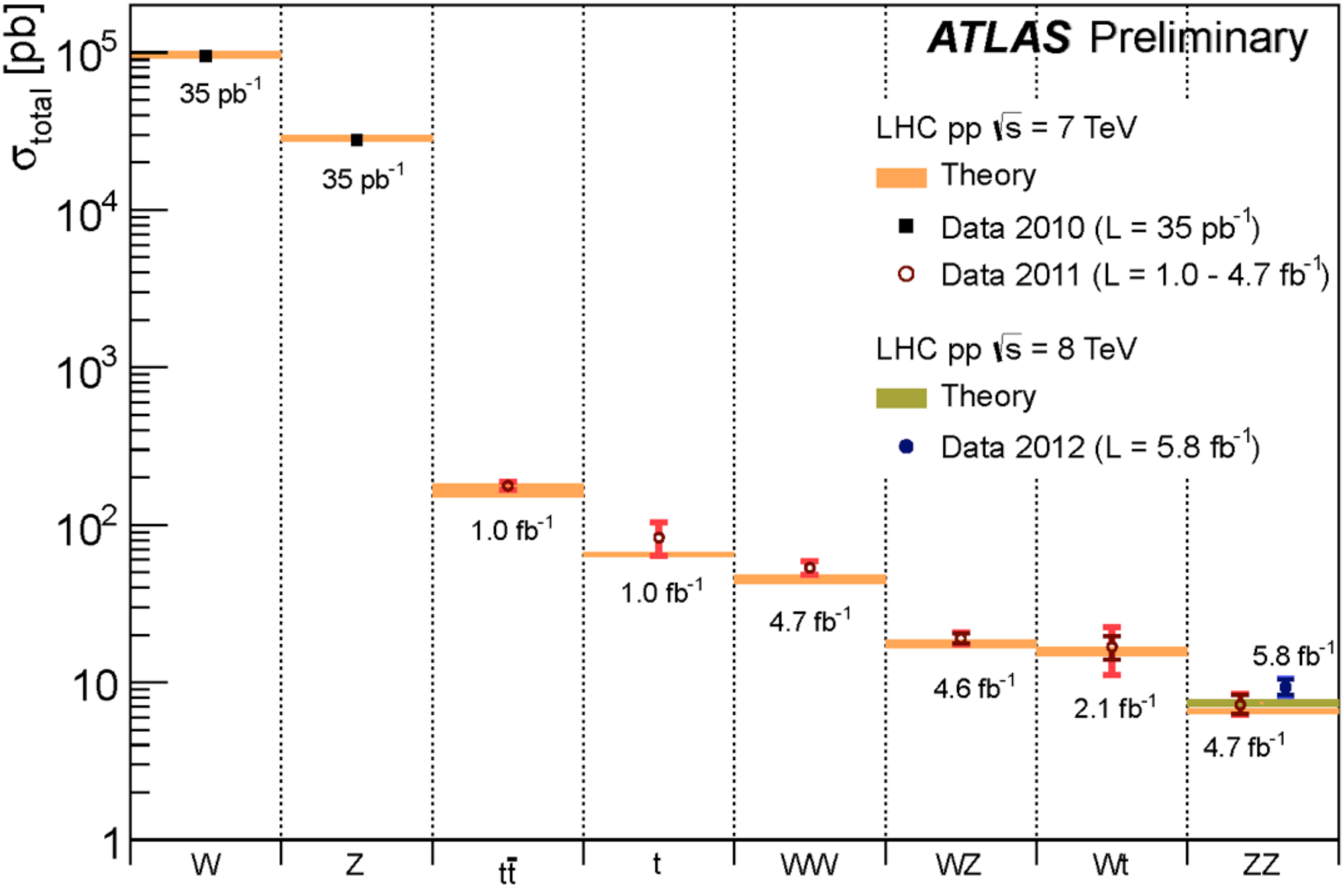
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

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

# Additional Material

# ATLAS (overview)




ATLAS Preliminary
LHC pp √s = 7 TeV
Theory
Data 2010 (L = 35 pb-1)
Data 2011 (L = 1.0 - 4.7 fb-1)
LHC pp √s = 8 TeV
Theory
Data 2012 (L = 5.8 fb-1)
σtotal [pb]
10^5
10^4
10^3
10^2
10
1
35 pb-1
35 pb-1
1.0 fb-1
1.0 fb-1
4.7 fb-1
4.6 fb-1
2.1 fb-1
5.8 fb-1
4.7 fb-1
W
Z
tt̄
t
WW
WZ
Wt
ZZ

# ATLAS measurements of the properties of jets for boosted particle searches

### A. Jet mass

The jet mass $M$ is calculated from the energies and momenta of its constituents (particles or clusters) as follows:

$$M^2 = \left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p}_i\right)^2, \quad (1)$$

where $E_i$ and $\vec{p}_i$ are the energy and three-momentum of the $i$th constituent. The sum is over all jet constituents in this and all subsequent summations. The standard ATLAS reconstruction procedure is followed: clusters have their masses set to zero, while Monte Carlo particles are assigned their correct masses.

### B. Jet width

The jet width $W$ is defined as:

$$W = \frac{\sum_i \Delta R^i p_{\mathrm{T}}^i}{\sum_i p_{\mathrm{T}}^i}, \quad (2)$$

where $\Delta R^i = \sqrt{(\Delta\phi_i)^2 + (\Delta\eta_i)^2}$ is the radial distance between the jet axis and the $i$th jet constituent and $p_{\mathrm{T}}^i$ is the constituent $p_{\mathrm{T}}$ with respect to the beam axis.

### C. Eccentricity

The jet eccentricity $\mathcal{E}$ is calculated using a principal component analysis (PCA) [12]. The PCA method provides the vector which best describes the energy-weighted geometrical distribution of the jet constituents in the $(\eta, \phi)$ plane. The eccentricity is used to characterize the deviation of the jet profile from a perfect circle in this plane, and is defined as

$$\mathcal{E} = 1 - \frac{v_{\mathrm{min}}}{v_{\mathrm{max}}}, \quad (3)$$

where $v_{\mathrm{max}}(v_{\mathrm{min}})$ is the maximum (minimum) value of variance of the jet constituents' positions with respect to the principal vector. The calculation consists of the follow-

### D. Planar flow

A variable complementary to the eccentricity is planar flow $P$ [10,46,47]. The planar flow measures the degree to which the jet's energy is evenly spread over the plane across the face of the jet (high planar flow) versus spread linearly across the face of the jet (small planar flow).

### E. Angularity

Angularities ($\tau_a$) are a family of observables that are sensitive to the degree of symmetry in the energy flow inside a jet. The general formula for angularity [10] is given by

$$\tau_a = \frac{1}{M}\sum_i E_i \sin^a\theta_i [1 - \cos\theta_i]^{1-a}. \quad (9)$$

Here $a$ is a parameter that can be chosen to emphasize radiation near the edges ($a < 0$) or core ($a > 0$) of the jet, $M$ is the jet mass, $E_i$ is the energy of the $i$th jet constituent and $\theta_i$ is its angle with respect to the jet axis. In the limit of small-angle radiation ($\theta_i \ll 1$), $\tau_a$ is approximated by

$$\tau_a \simeq \frac{2^{(a-1)}}{M}\sum_i E_i \theta_i^{(2-a)}. \quad (10)$$

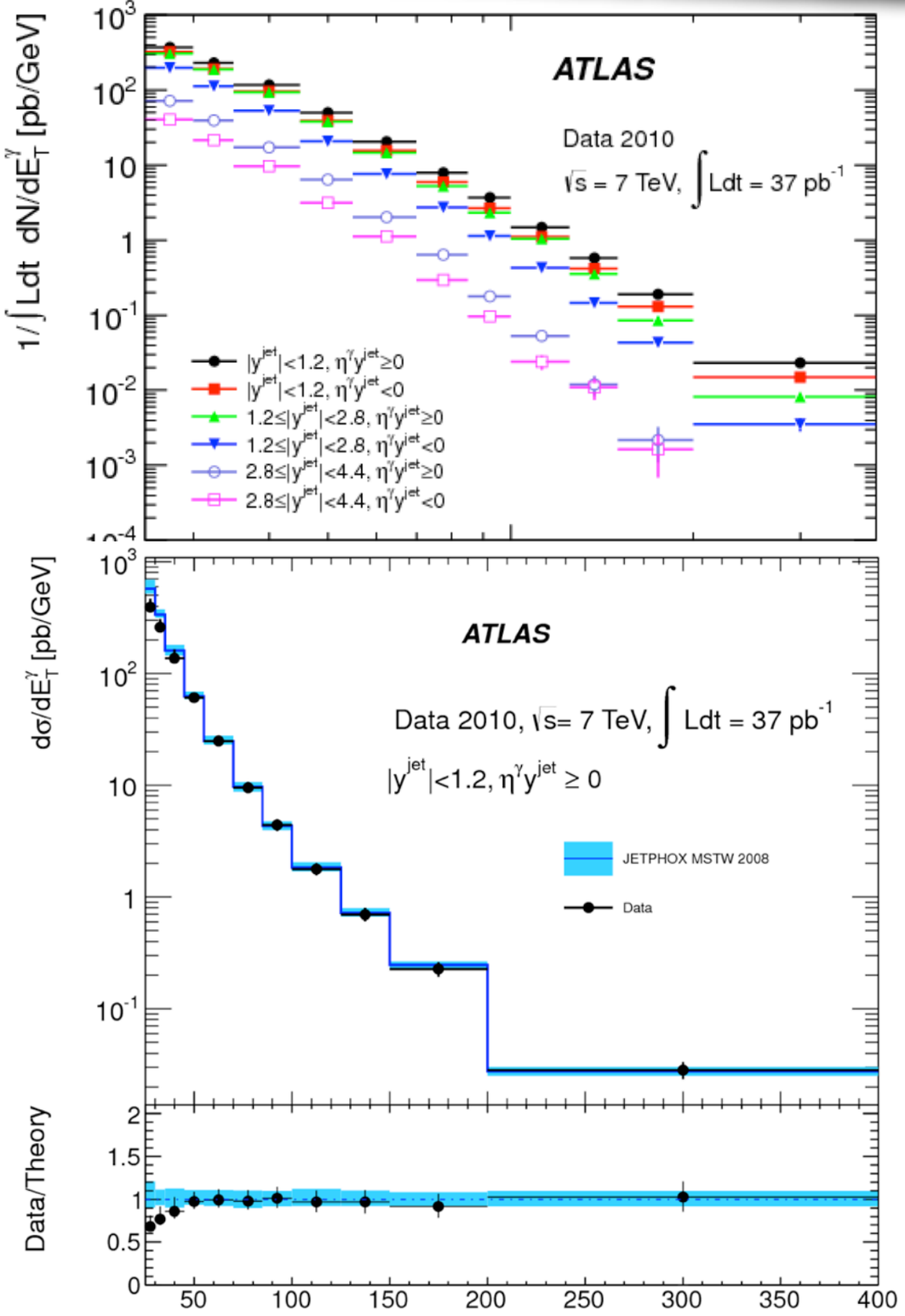
Angularities are infrared-safe for $a \leq 2$ [13]. In the analysis presented here, Eq. (9) with a value of $a = -2$ is used. The $\tau_{-2}$ observable can be used as a discriminator

just as a reminder. taken from paper, but strongly abridged.

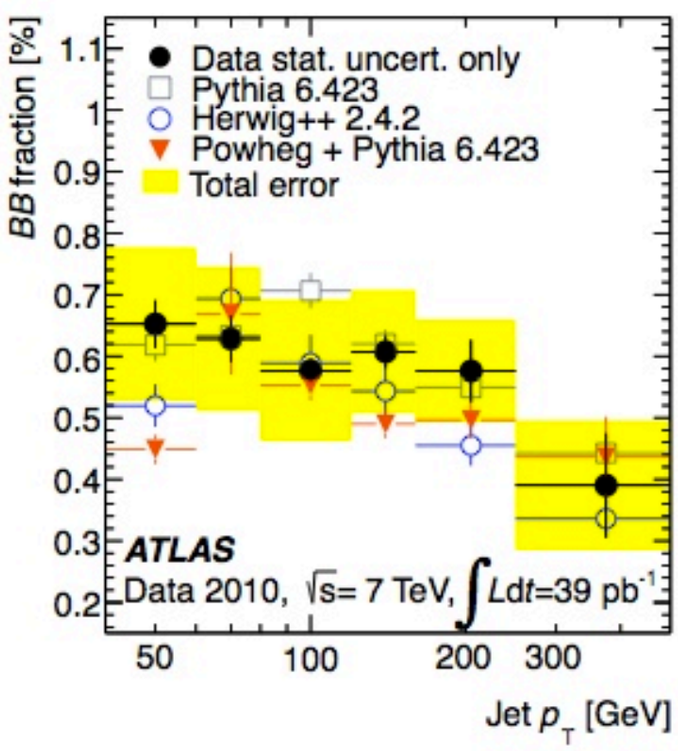
# photon+jet production

**Phys. Rev. D 85, 092014 (2012)**
37 pb$^{-1}$ $\sqrt{s}$=7 TeV

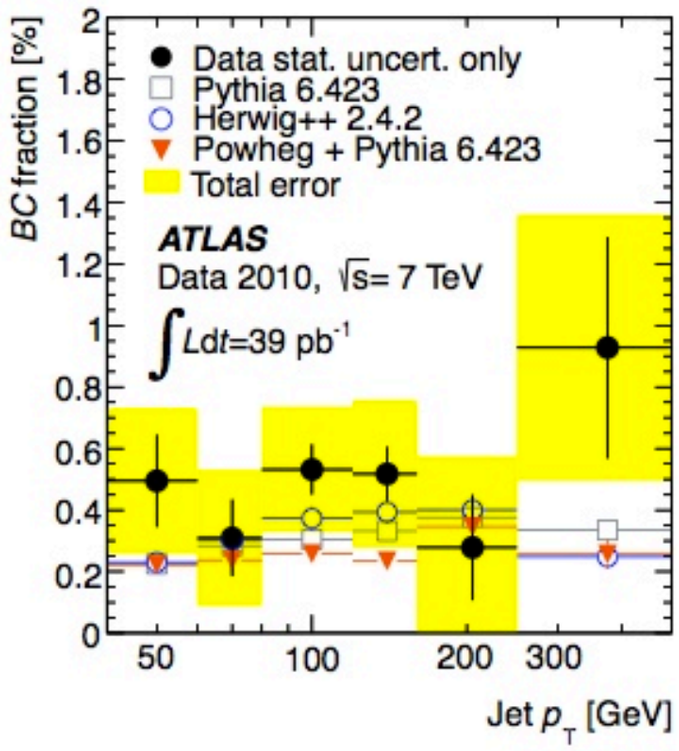
- **Prompt photons** are created in the hard interaction or the fragmentation, not in a particle decay.
- **Photon + jets production** probes perturbative QCD (pQCD) at high momentum transfer $Q^2$ over a wide range of parton momentum fraction $x$.
  - ... and it's a background for H→γγ.
- **Event selection:**
  - combination of two triggers: photon $E_T$>40 GeV, unprescaled; photon $E_T$>20 GeV, prescaled by 5.5,
  - require tight photon with transverse momentum >25 GeV, and anti-$k_T$ 0.4 jet above 20 GeV,
  - Δ R>1.0 between photon and jet.
- **Backgrounds:**
  - Mostly dijet events with one misidentified jet: jet contains light neutral meson, decaying to collimated pair of photons.
  - Less often: diphoton or W/Z+jets events with misidentification.
  - Estimated with data-driven method using several control regions, transfer factors obtained from MC.
- Signal efficiencies are estimated from MC, total cross section and differential cross sections at particle level are computed.
- NLO pQCD cross sections provided by JETPHOX (MSTW 2008) in fair agreement with measured ones. In the $E_T$ < 45 GeV region, the NLO QCD calculation consistently overestimates the measured cross section.



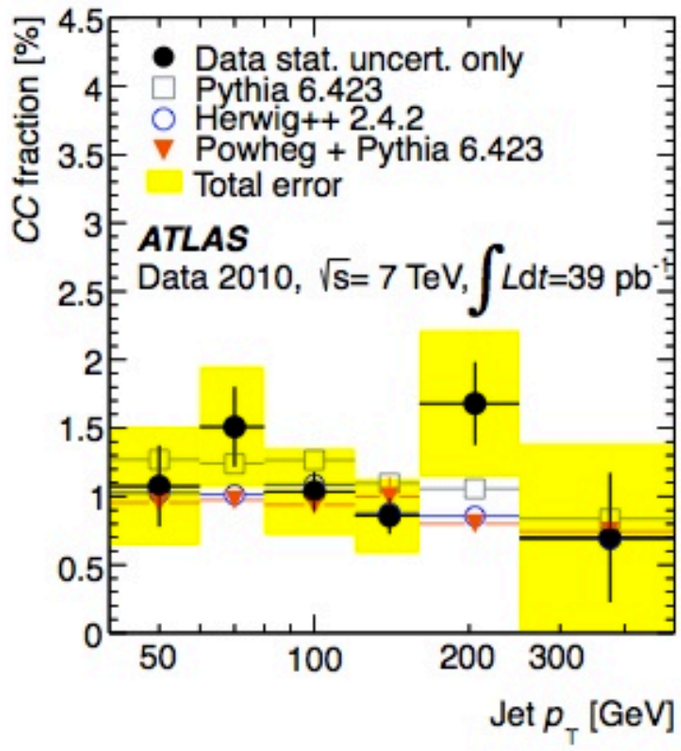
# di-jet flavour fractions




(a)




(b)




(c)