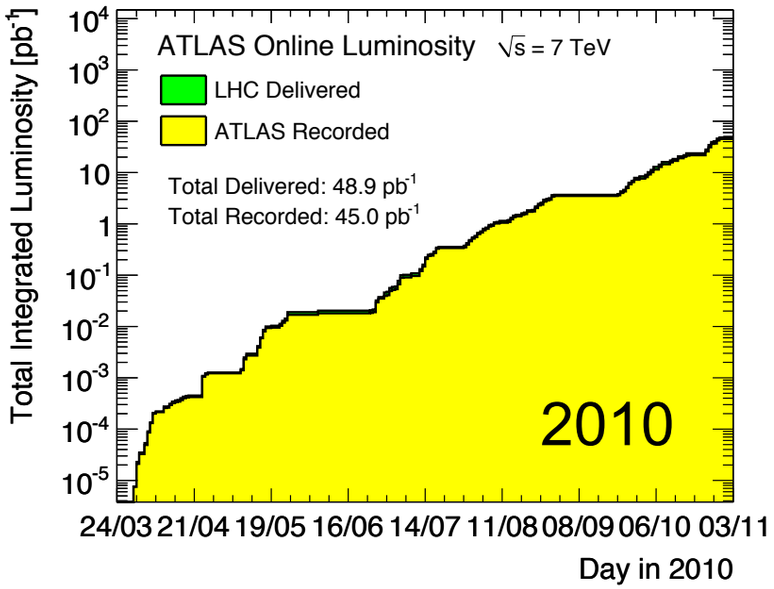
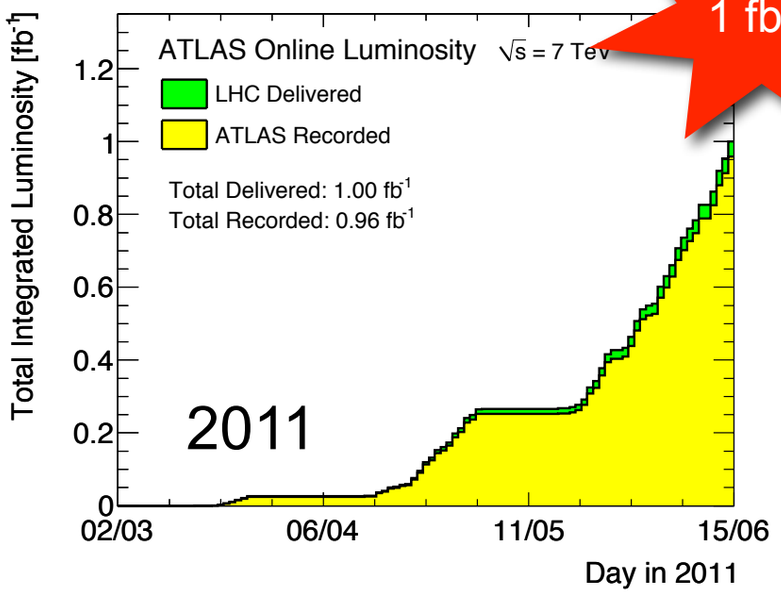
*2nd Workshop on Standard Model Benchmarks at High-Energy Hadron Colliders*
*Zeuthen, Germany, June 15–17, 2011*

# Top Pair Production and Top Properties at ATLAS

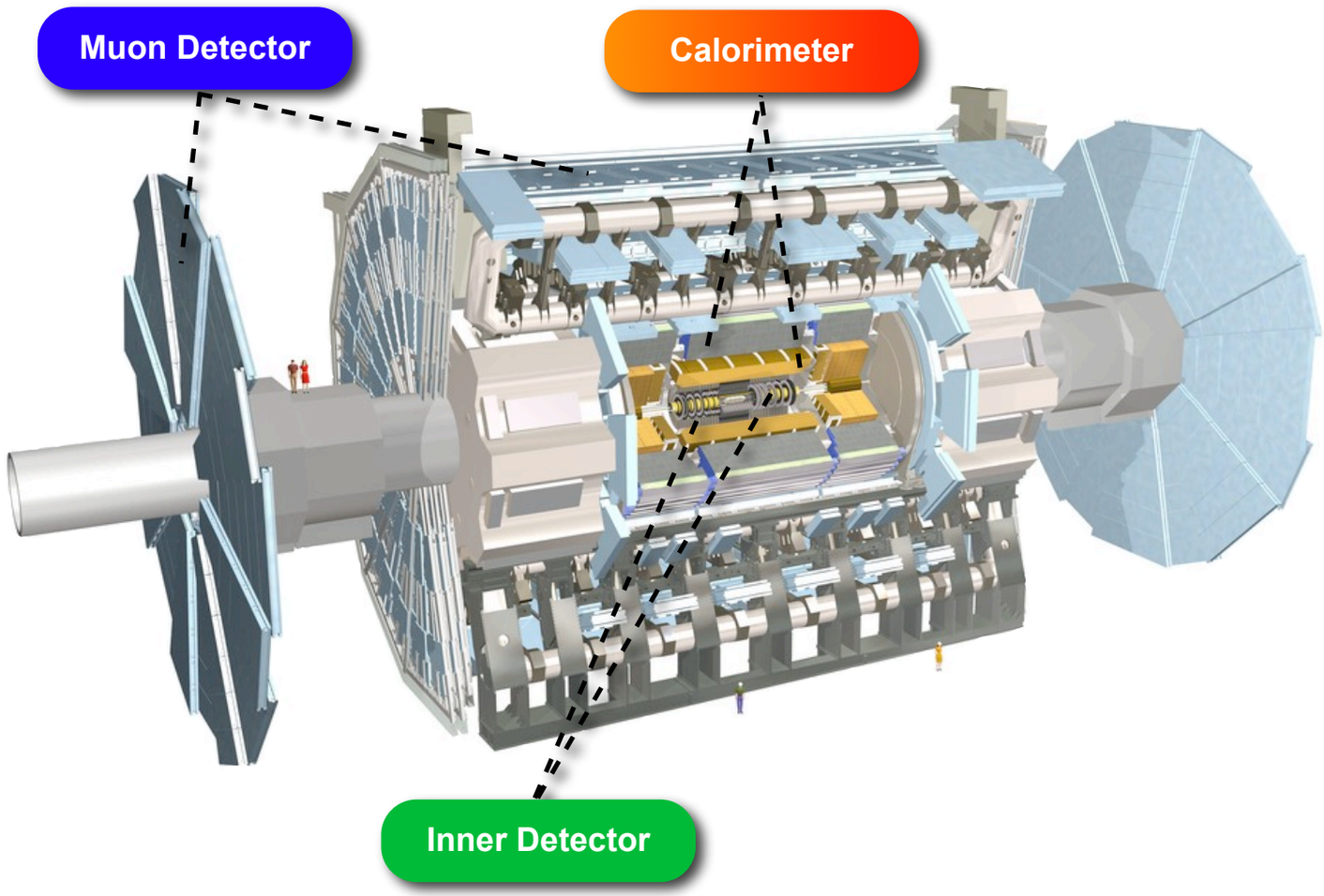
*Ulrich Husemann, DESY*
*on behalf of the ATLAS Collaboration*

# The LHC and the ATLAS Experiment



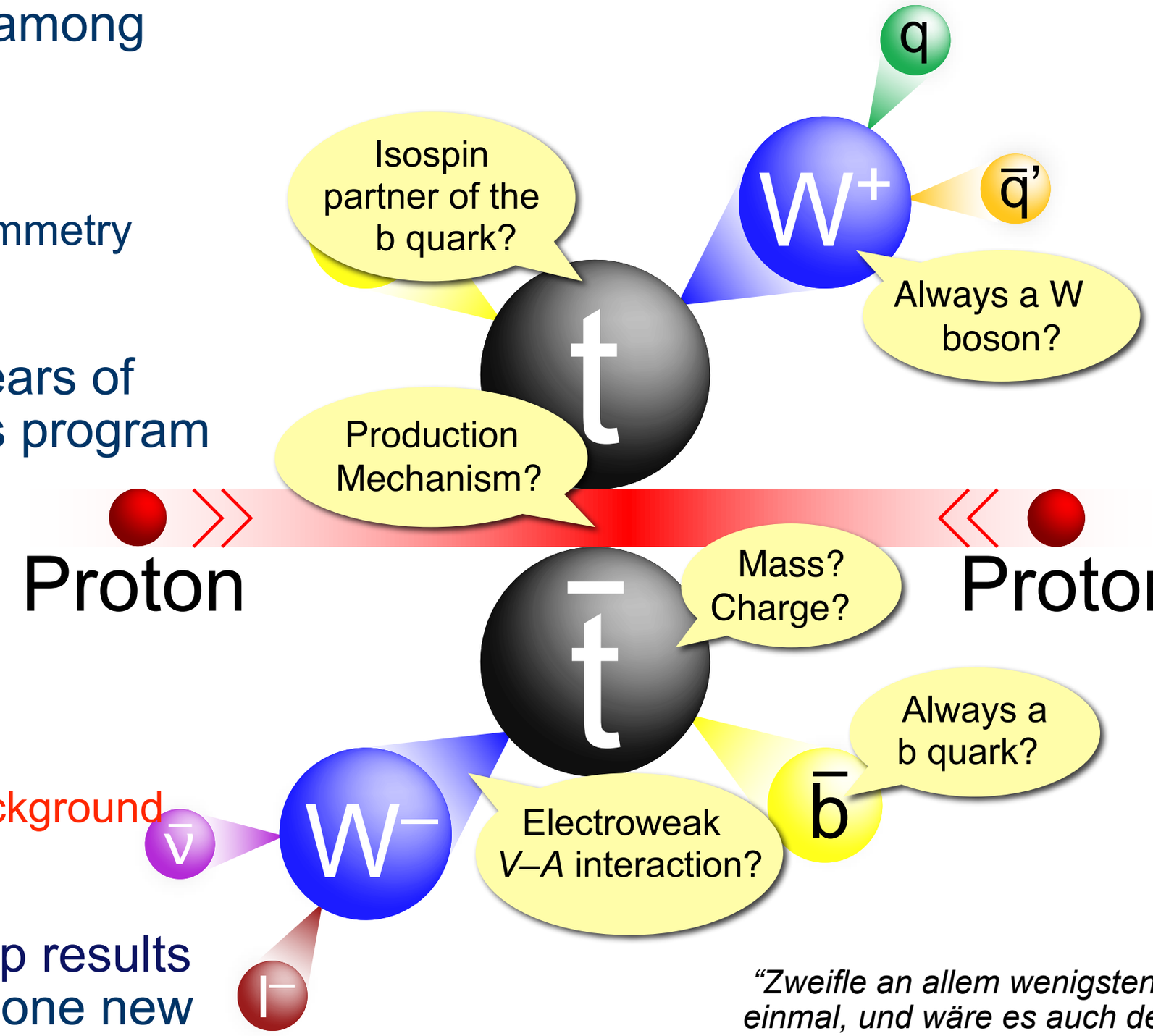

1 fb$^{-1}$




- Large Hadron Collider
  - Proton-proton collisions at 7 TeV center-of-mass energy
  - 2010: delivered about 50 pb$^{-1}$ of integrated luminosity
  - 2011: breaking luminosity records daily, more than 1 fb$^{-1}$ already delivered
- ATLAS
  - Multi-purpose HEP detector: tracking/ vertexing, calorimetry, muon detectors
  - Excellent performance 2010/2011

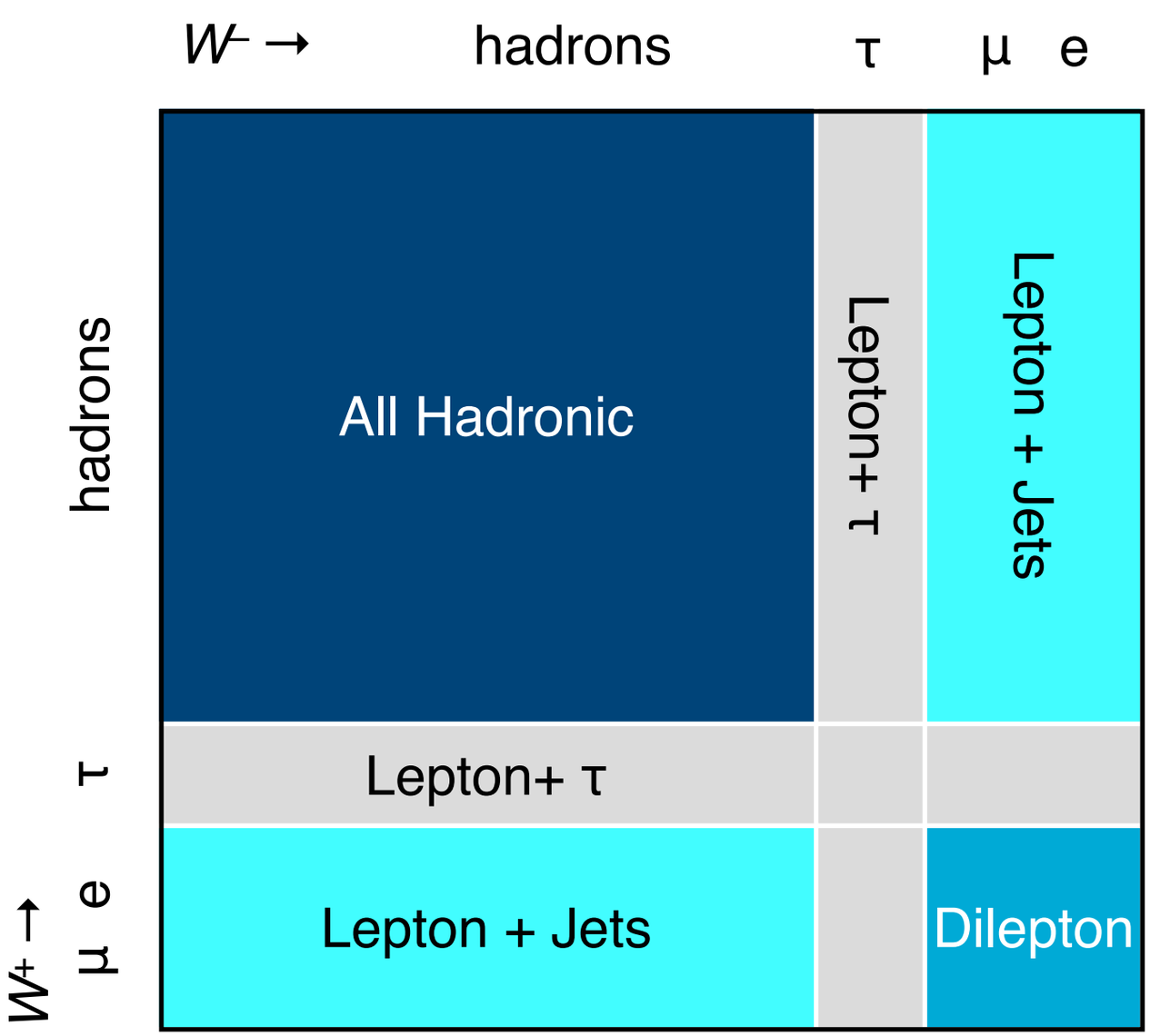
# Top Quarks Physics

- Top – a heavy-weight among the quarks:
  - The only “bare” quark
  - Role in electroweak symmetry breaking?
- Tevatron: almost 20 years of impressive top physics program
- LHC = top factory
  - LHC $t\bar{t}$ cross section at 7 TeV > 20×Tevatron
  - Today: top as a signal
  - Very soon: top as a background and calibration source
- Today’s talk: ATLAS top results with full 2010 dataset, one new result using 2011 data



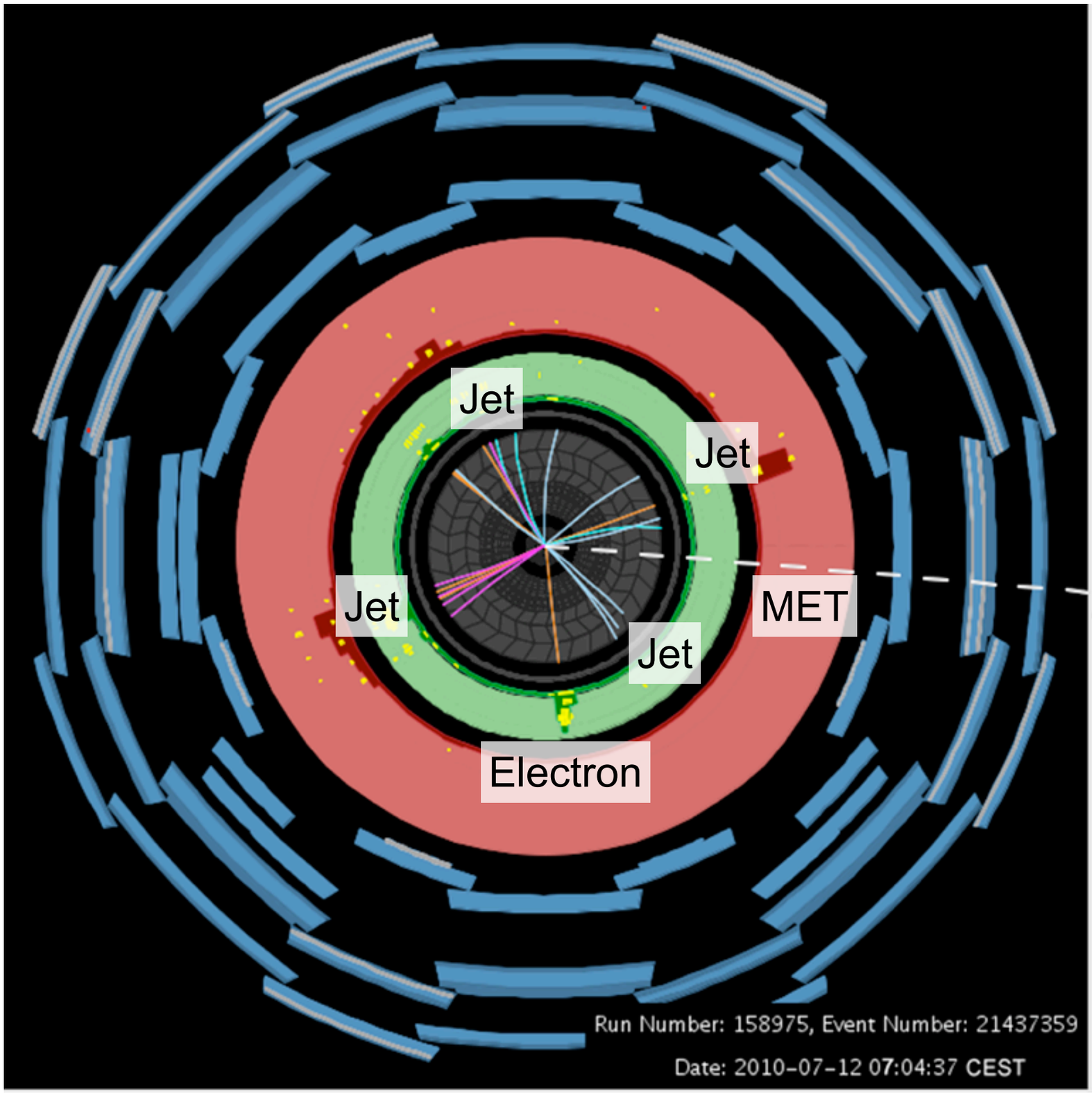

*“Zweifle an allem wenigstens einmal, und wäre es auch der Satz: zwei mal zwei ist vier” (G. F. Lichtenberg)*

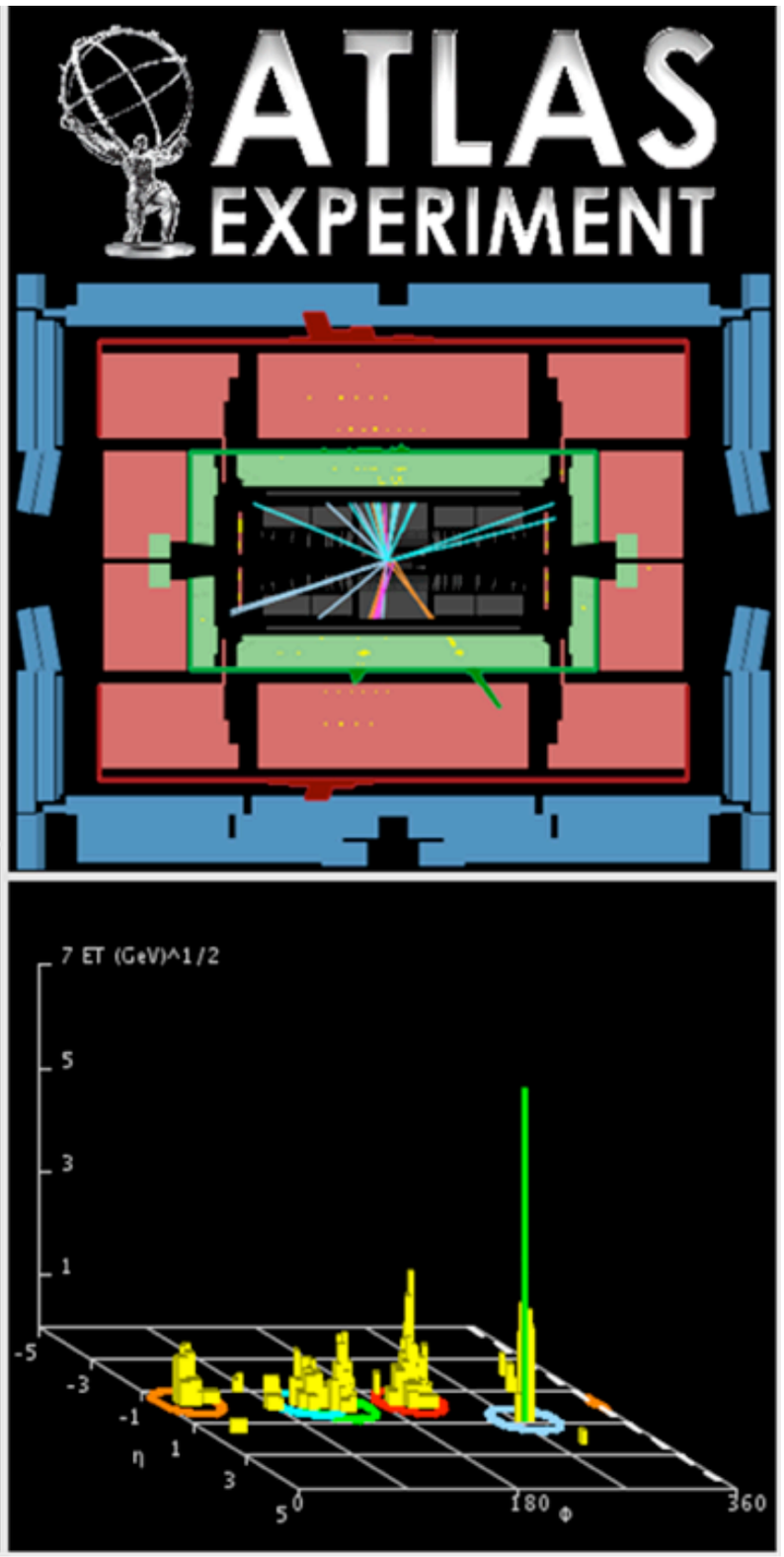
# Analyzing Top Quark Events




- Top decay in the standard model: B(t → Wb) ≈ 100%
- Challenging signature: multiple leptons & jets, missing $E_T$ (MET)
- $t\bar{t}$ decay signatures characterized by W decays:
  - All-Hadronic: 45% of all decays, large QCD background
  - Lepton+Jets: 30% of all decays, moderate backgrounds
  - Dilepton: 5% of all decays, very clean, but small branching fraction
- Dominant backgrounds for leptonic channels
  - W/Z bosons + jets (similar signature)
  - QCD jets (misidentified as leptons)

# ATLAS Event Display: e + Jets + MET



# Outline

**Top Pair Production Cross Section**

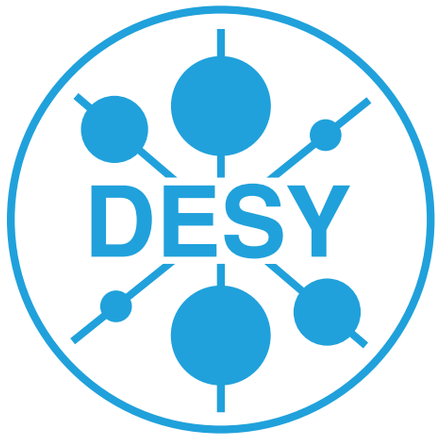
- Lepton+jets and dilepton channel, with and without b-tagging
- Cross section combination
- First look at the all-hadronic channel

**Top Mass and further Properties**

- Direct mass measurement
- Indirect mass determination via the cross section
- W polarization in top decays
- Search for FCNC in top production and decay
- Search for high-mass phenomena decaying into top

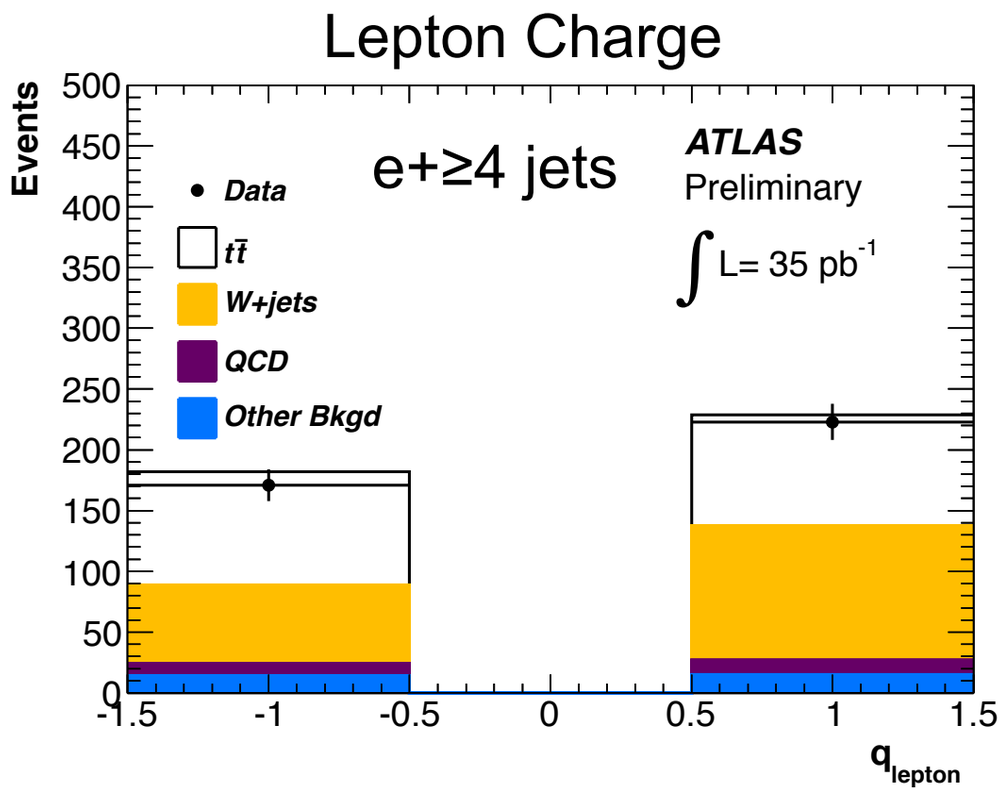
**Most results based on full 2010 dataset: 35 $pb^{-1}$**

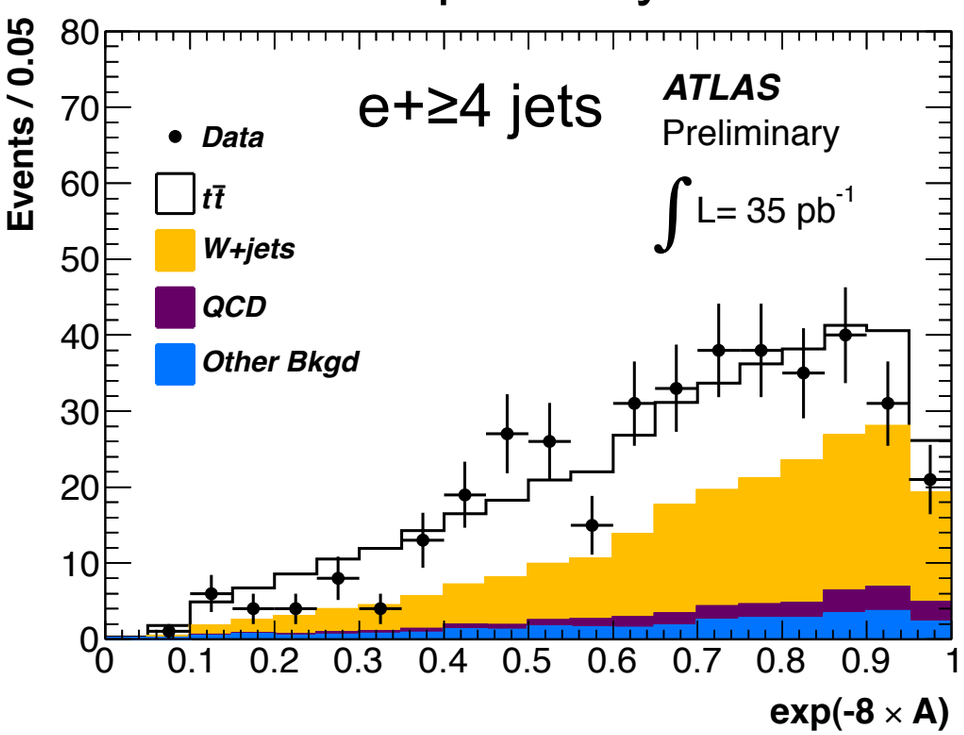
# Top Quark Pair Production Cross Section

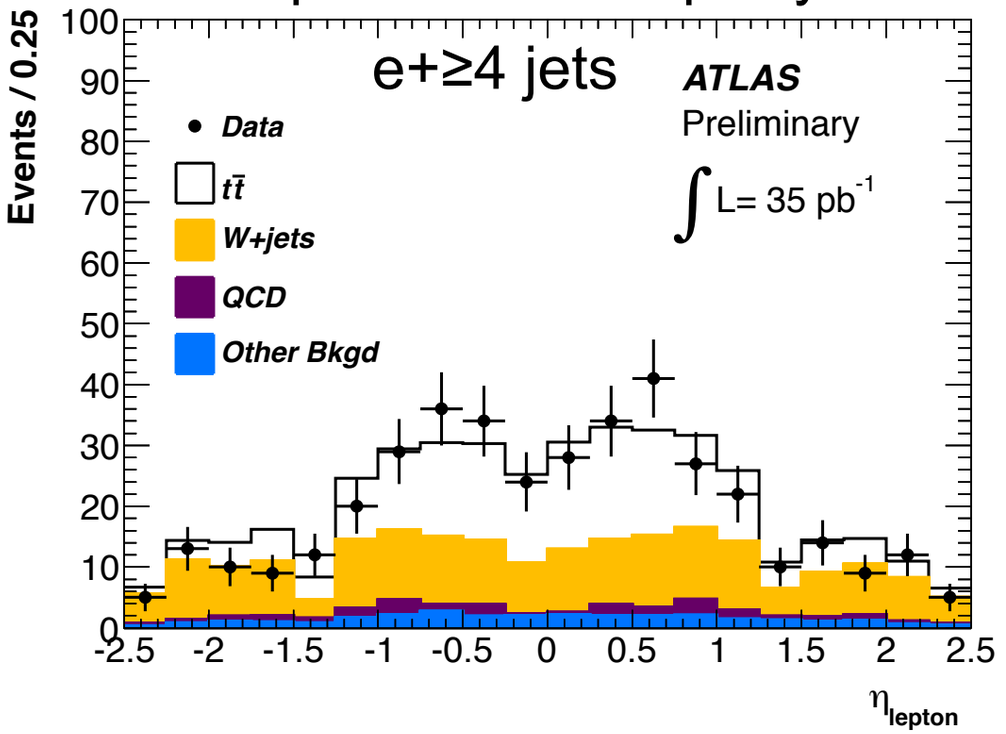



# Top Cross Section: Lepton + Jets

- Analysis I: without b-tagging
  - Lepton+jets selection: high-$p_T$ e/μ, ≥3 jets, missing $E_T$, transverse mass
- Template fit to projective likelihood discriminant based on well-modeled event kinematics
  - Lepton charge: $t\bar{t}$ symmetric, W asymmetric
  - Pseudorapidity: $t\bar{t}$ more central
  - Aplanarity: $t\bar{t}$ more spherical
  - Four-channel fit: e, μ + 3, ≥4 jets

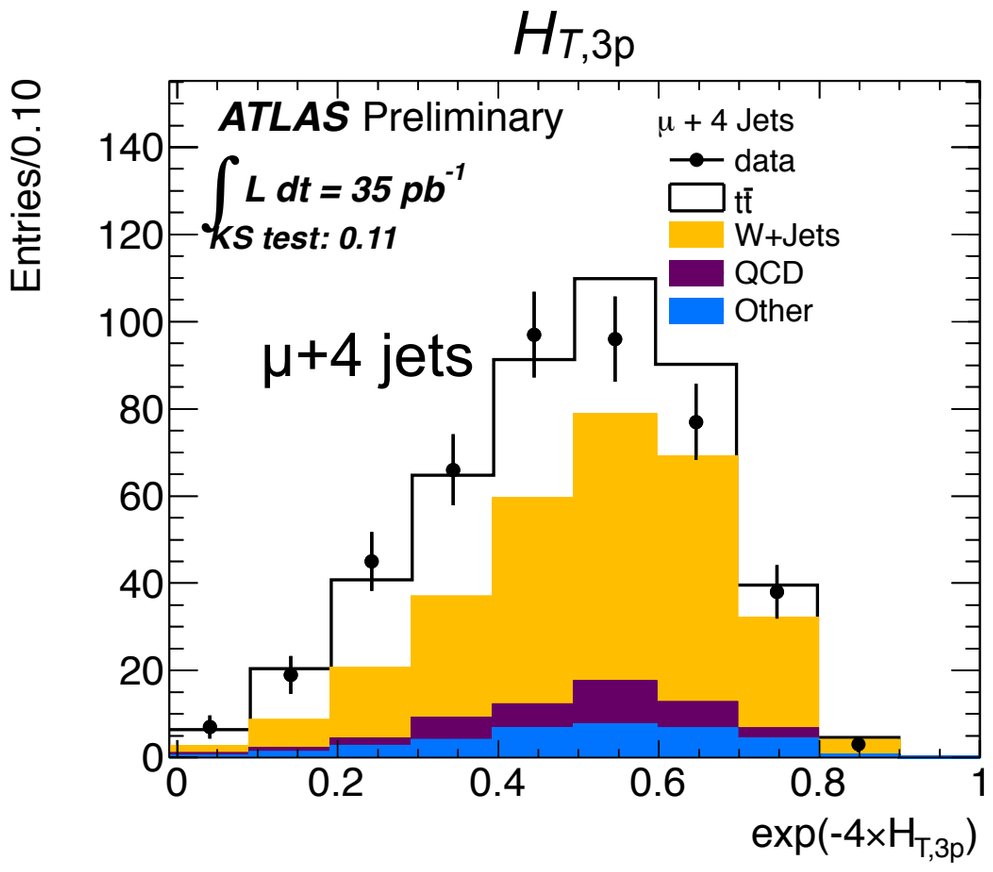


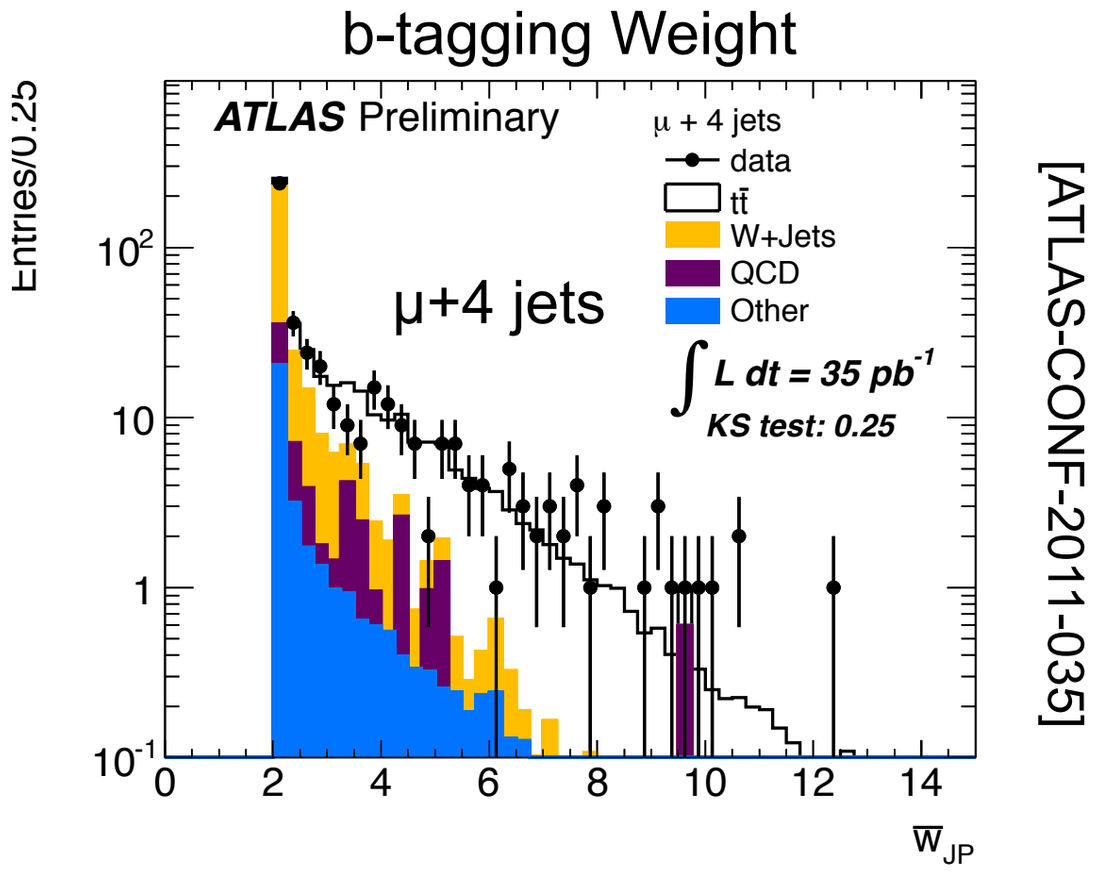



# Top Cross Section: Lepton + Jets

- Analysis II: "continuous" b-tagging (same event selection as before)
  - Input variables (as before): lepton pseudorapidity, aplanarity
  - New variable: $H_{T,3p} = \frac{\sum_{i=3}^{N_{\text{jets}}} |p_{\text{T},i}^2|}{\sum_{j=1}^{N_{\text{objects}}} |p_{z,j}|}$,
  - New variable: average *b*-tagging weight for two most b-like jets ("JetProb" tagger)
  - Six-channel fit (e, μ + 3, 4, ≥5 jets) using sophisticated profile likelihood technique: systematic uncertainties included as nuisance parameters → constrained by data



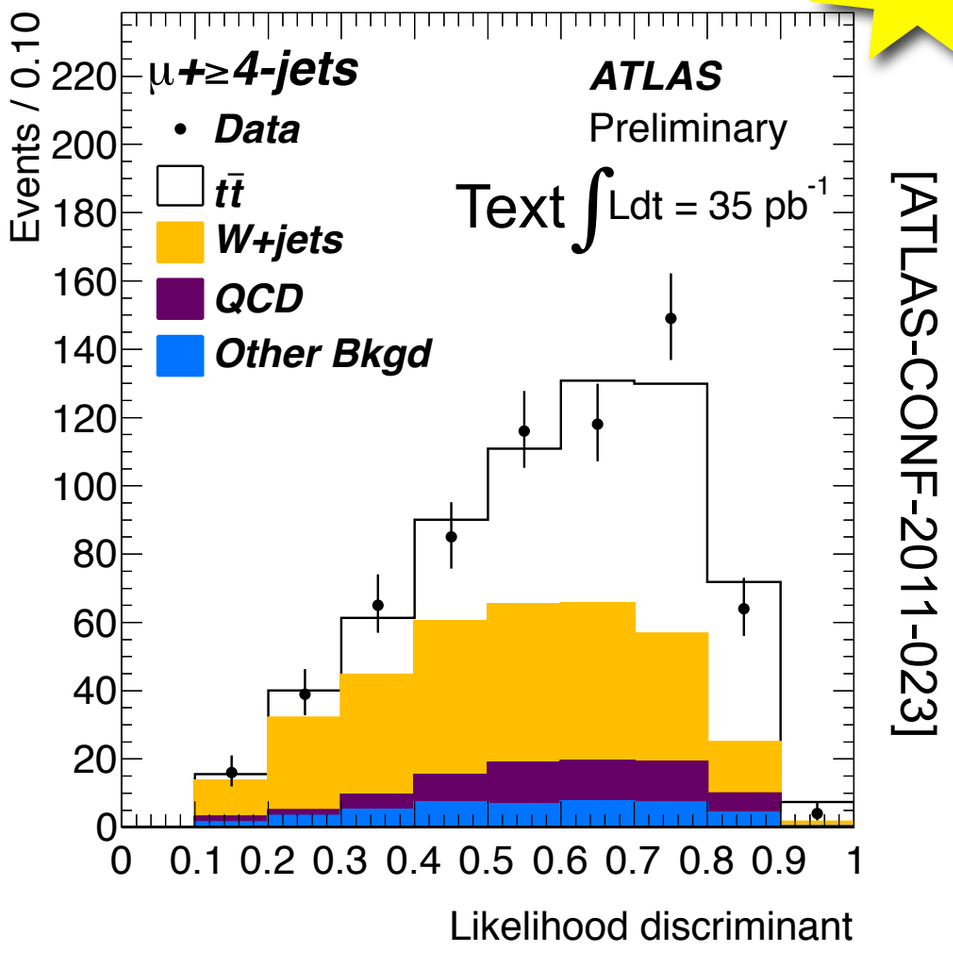

[ATLAS-CONF-2011-035]

# Top Cross Section: Lepton + Jets

## Without b-tagging:

$\sigma_{t\bar{t}} = 171 \pm 17(\text{stat.})\ ^{+20}_{-17}(\text{syst.}) \pm 6(\text{lumi.})\ \text{pb}$

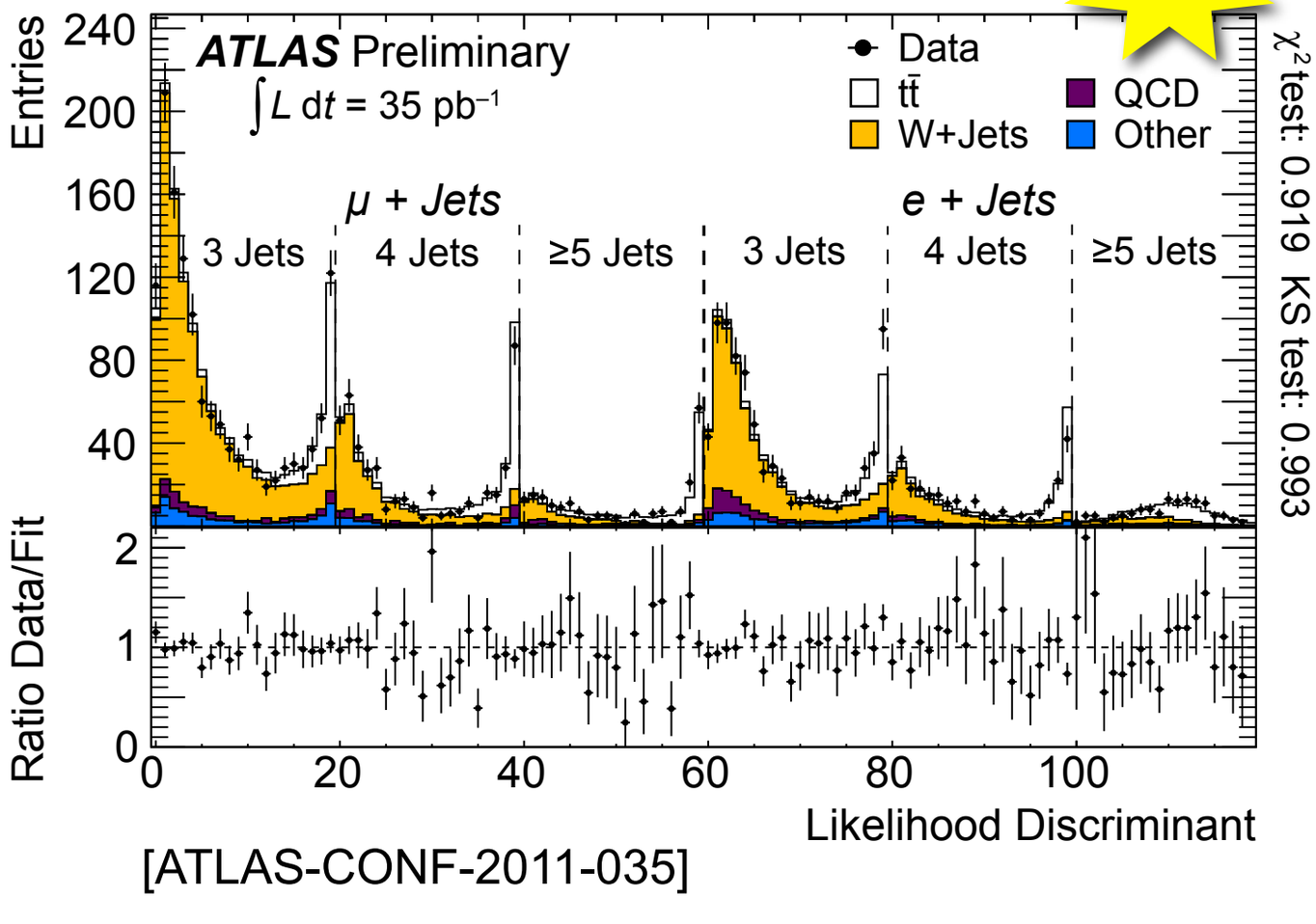
15%




## Continuous b-tagging:

$\sigma_{t\bar{t}} = 186 \pm 10(\text{stat.})\ ^{+21}_{-20}(\text{syst.}) \pm 6(\text{lumi.})\ \text{pb}$

13%




- Comparison with state-of-the-art theory prediction: $\sigma_{t\bar{t}} = 165^{+11}_{-16}\ \text{pb}$ (using Hathor, approx. NNLO, CTEQ6.6) → consistent
- Various cross check analyses (cut & count, multivariate) → consistent

# Top Cross Section: Lepton + Jets

- Already with 2010 dataset: measurements precision limited by systematic uncertainties, dominant sources:
  - Both analyses: jet energy scale & resolution, ISR/FSR
  - Additionally for analysis with b-tag: b-tagging calibration, W+jets heavy flavor content
- Expect improvements of systematic uncertainties
  - Data-driven backgrounds and profile likelihood technique: improve with more data
  - Working on improved MC-based and theory-based uncertainties

| Uncertainty (%) | No b-tag | b-tag |
|---|---|---|
| Statistical | 9.7 | –5.2 / +5.3 |
| Jet energy scale & reconstruction | –6.1 / +5.7 | –5.0 / +5.7 |
| QCD normalization & shape | 5.2 | 1.0 |
| Initial/final state radiation | –2.1 / +6.1 | 4.0 |
| b-tagging calibration | – | –6.3 / +7.2 |
| W+jets heavy flavor content | – | –6.3 / +7.5 |

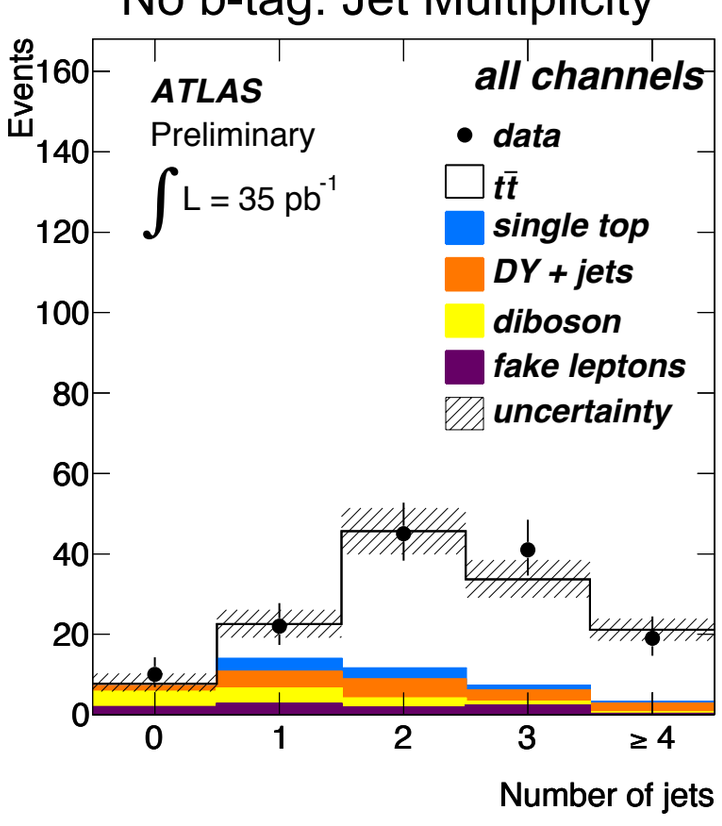
# Top Cross Section: Dilepton

- Two cut-based analysis: without & with b-tag
  - 2 high-$p_T$ leptons (ee/μμ/eμ), ≥2 jets
  - ee/μμ + jets: large missing $E_T$ and Z→ll veto
  - eμ + jets: large $H_T$ (sum of jet and lepton $p_T$)
  - Major backgrounds: Z/γ*+jets, "fake" leptons → (MC-assisted) data-driven estimates

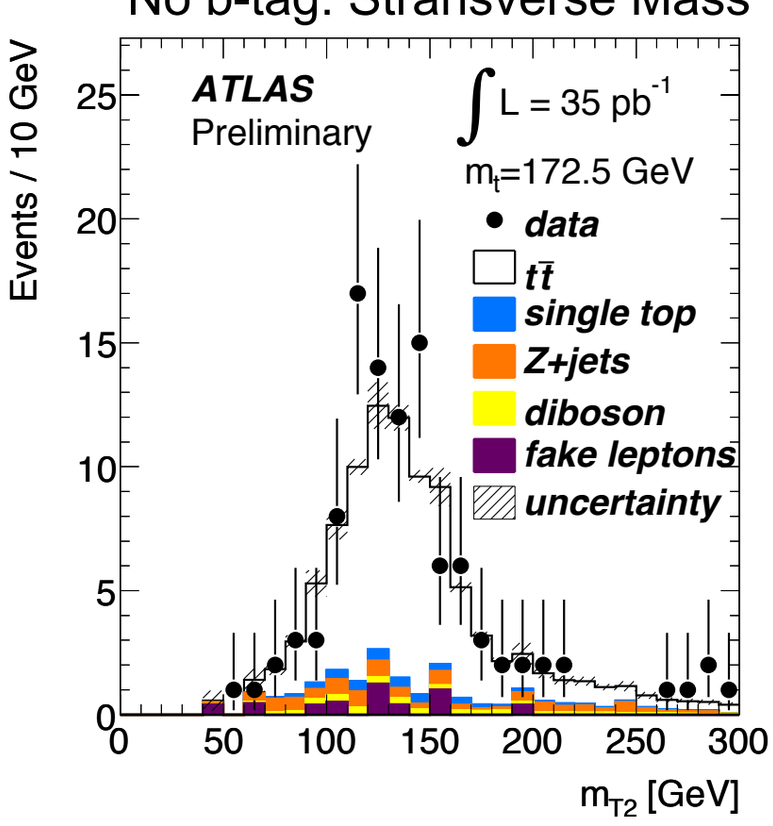
**Additional Measurements**

- $\sigma_{t\bar{t}}$ normalized to $\sigma_Z$
- Inclusive dilepton analysis (extract $\sigma_{t\bar{t}}$, $\sigma_{WW}$, and $\sigma_{Z\to\tau\tau}$)
- $\sigma_{t\bar{t}}$ and b-tagging efficiency

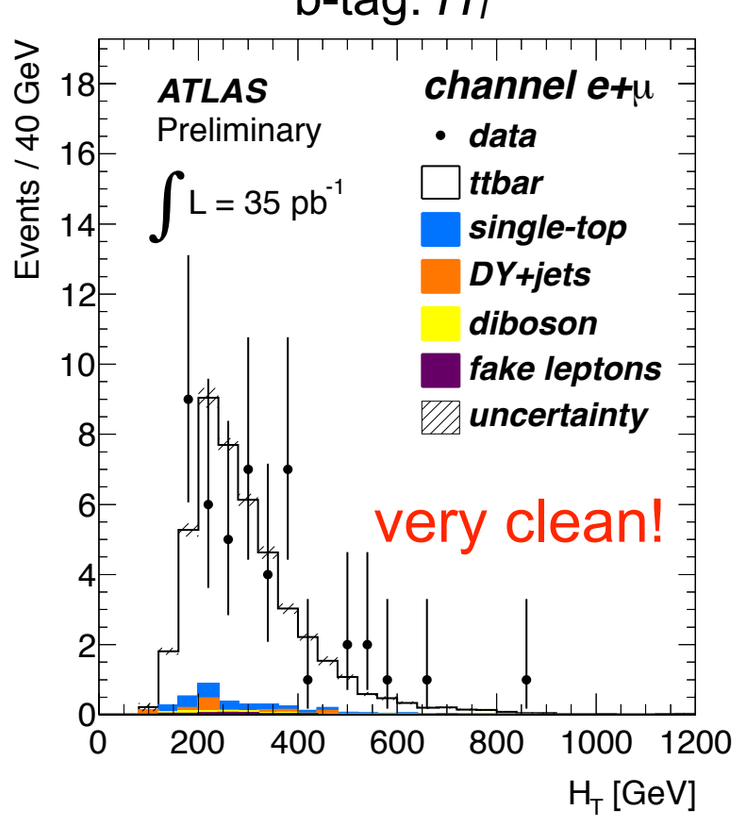
No b-tag: Jet Multiplicity




No b-tag: Stransverse Mass



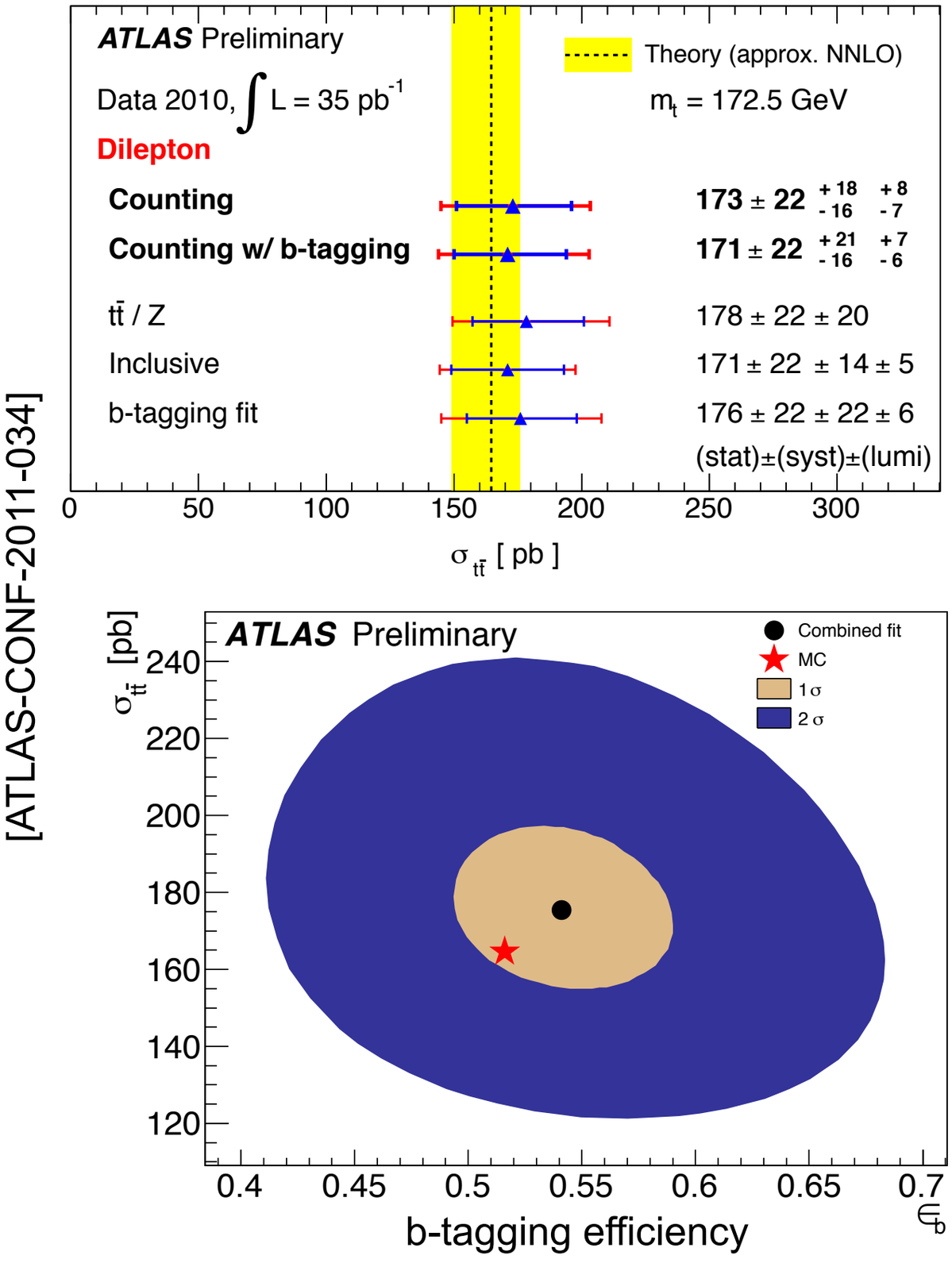

b-tag: $H_T$




[ATLAS-CONF-2011-034]

Stransverse mass: $m_{T2}^2 = \min_{\vec{p}_{T,1}+\vec{p}_{T,2}=\vec{\not{p}}_T} \left\{ \max \left[ m_T^2(\vec{p}_{T,\ell^+}, \vec{p}_{T,1}, \dots), m_T^2(\vec{p}_{T,\ell^-}, \vec{p}_{T,2}, \dots) \right] \right\}$

# Top Cross Section: Dilepton




- Combination of all dilepton channels: profile likelihood
- Results:

No b-tagging:
$\sigma_{t\bar{t}} = 173 \pm 22(\text{stat.})\ ^{+18}_{-16}(\text{syst.})^{+8}_{-7}(\text{lumi.})$ pb

17%

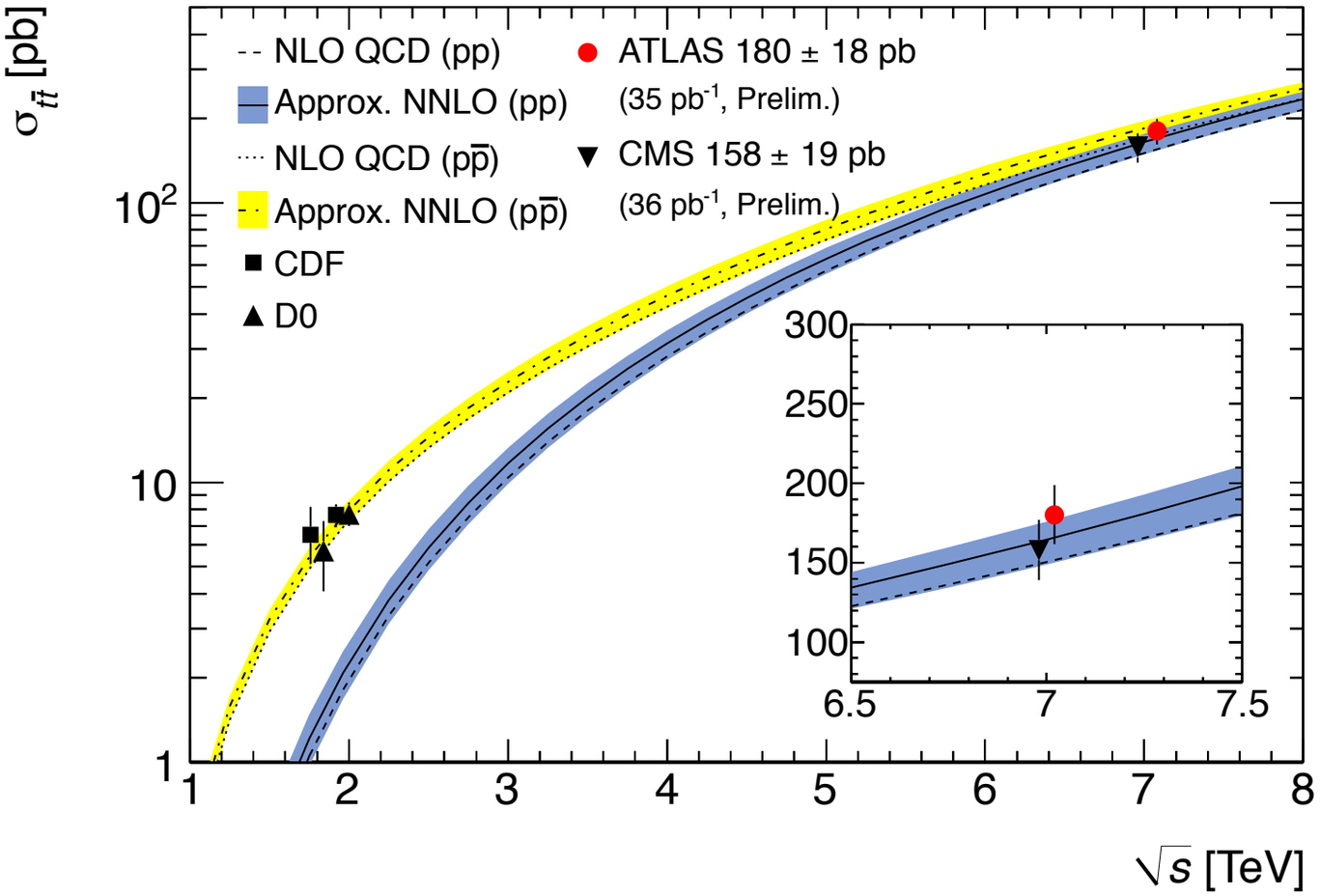
b-tagging:
$\sigma_{t\bar{t}} = 171 \pm 22(\text{stat.})\ ^{+21}_{-16}(\text{syst.})^{+7}_{-6}(\text{lumi.})$ pb

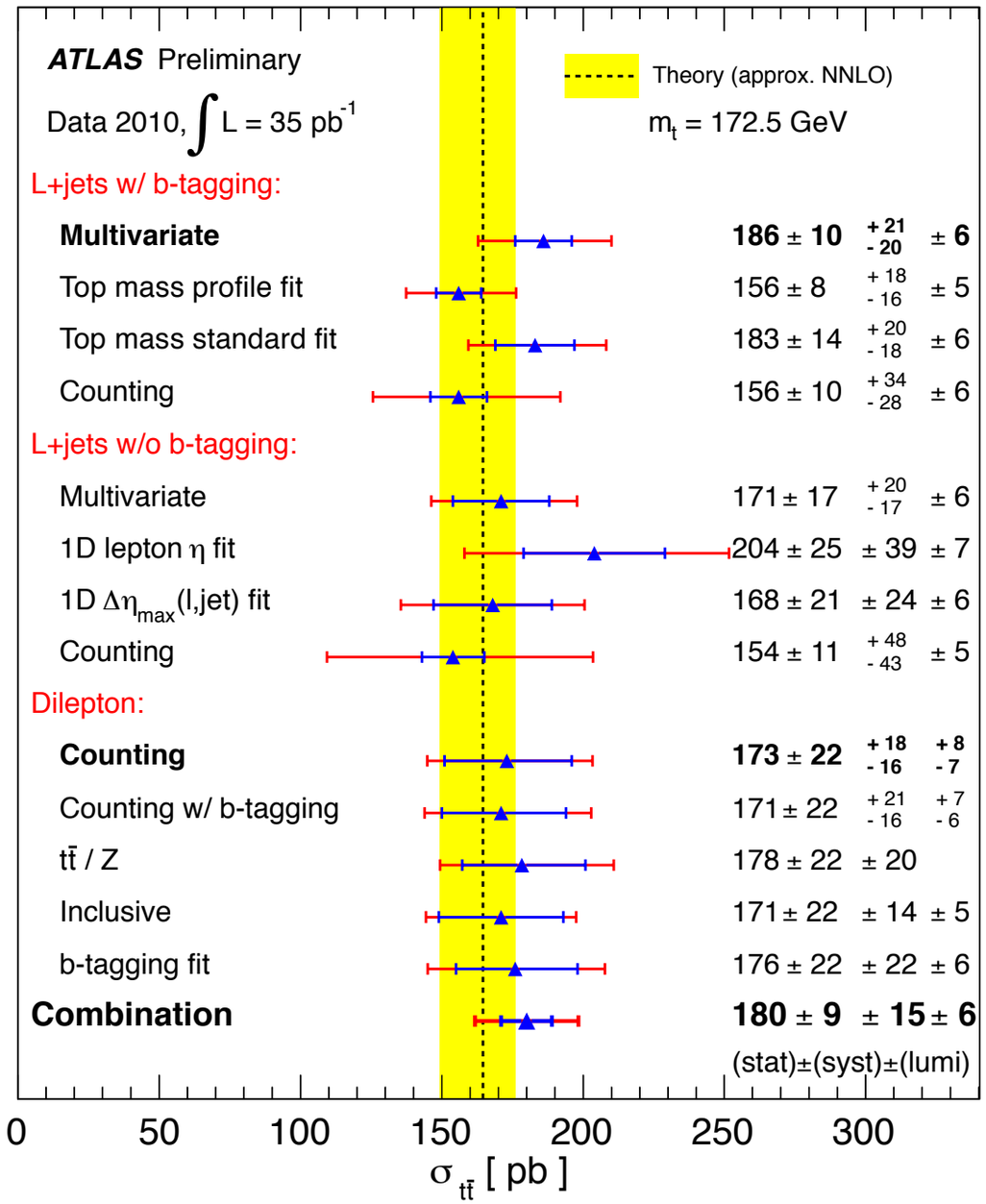
18%

- Dominant uncertainties
  - Jet energy scale: 5%
  - Parton shower model: –5%/+4%
  - Fake leptons: –4%/+3%
- Simultaneous measurement of b-tagging efficiency: fit to number of b-tags
  → consistent results

# Top Cross Section: Combined Result

- Combination of lepton+jets and dilepton analyses on the level of likelihood functions
- Uncertainty of combined result: 10% → competitive with Tevatron



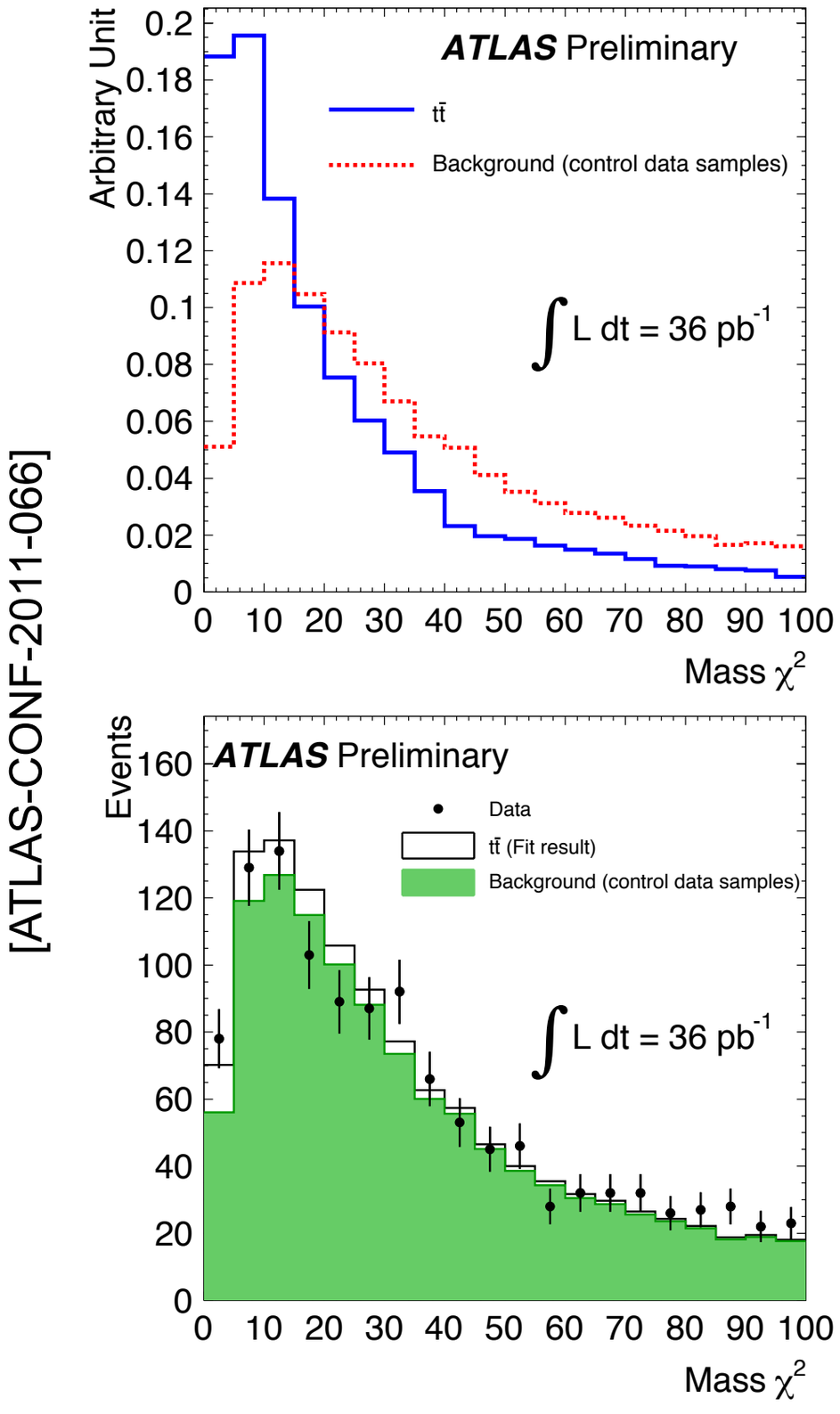




$\sigma_{t\bar{t}} = 180 \pm 9(\text{stat.}) \pm 15(\text{syst.}) \pm 6(\text{lumi.})$ pb

[ATLAS-CONF-2011-040]

10%

# Top Cross Section: All-Hadronic




- Measure cross section in all possible channels → important cross check
- All-hadronic channel:
  - Signature: ≥6 jets, 2 b-tags
  - Very challenging: QCD overwhelming
  - Construct mass $\chi^2$ discriminant:

$$\chi^2 = \sum_{i=1}^{2} \left( \frac{m^i_{jjb} - m_t}{\sigma_t} \right)^2 + \left( \frac{m^i_{jj} - m_W}{\sigma_W} \right)^2$$

→ 6 combinations, take lowest $\chi^2$

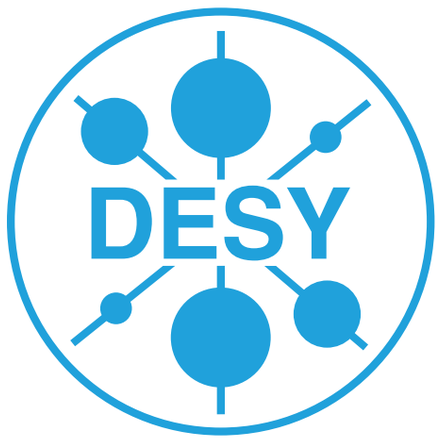
- Results with limited 2010 dataset:
  - Fitted $t\bar{t}$ production cross section:

$$\sigma_{t\bar{t}} = 118 \pm 73(\text{stat.}) \pm 48(\text{syst.}) \pm 4(\text{lumi.})\ \text{pb}$$

→ 1.6σ significance (2.2σ expected)

  - 95% C.L. upper limit: $\sigma_{t\bar{t}} < 261$ pb

# Top Mass and Properties

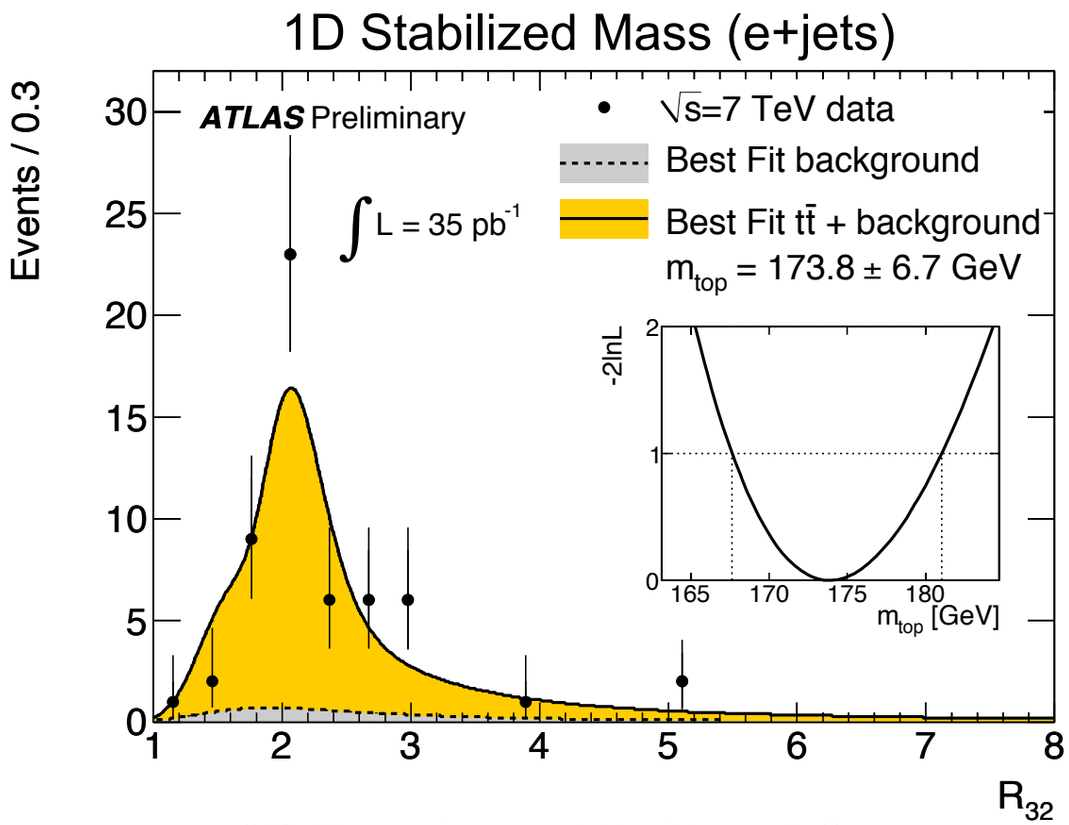



# Top Mass: Direct Measurements

- Top quark mass:
  - Standard model: key parameter (relation to W and Higgs mass)
  - Known to high precision from Tevatron: uncertainty only 1.1 GeV (=0.6%) from single experiment (CDF Note 10444)
- 2010 data: template-based analyses
  - Lepton+jets selection
  - 1D "stabilized mass" $R_{32} = m_t^{reco} / m_W^{reco}$
  - 1D kinematic fit
  - 2D: mass vs. jet energy scale factor (JSF)
- Main result (stabilized mass, e/μ combined)

$m_t = 169.3 \pm 4.0(\text{stat.}) \pm 4.9(\text{syst.})\ \text{GeV}$

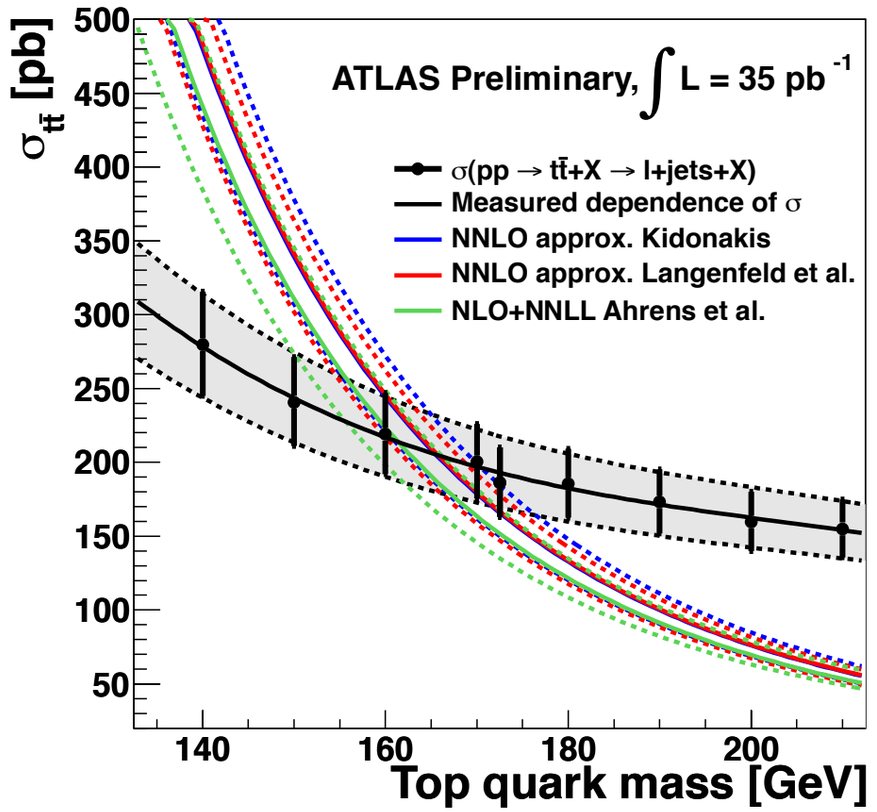
(3.7% total uncertainty)

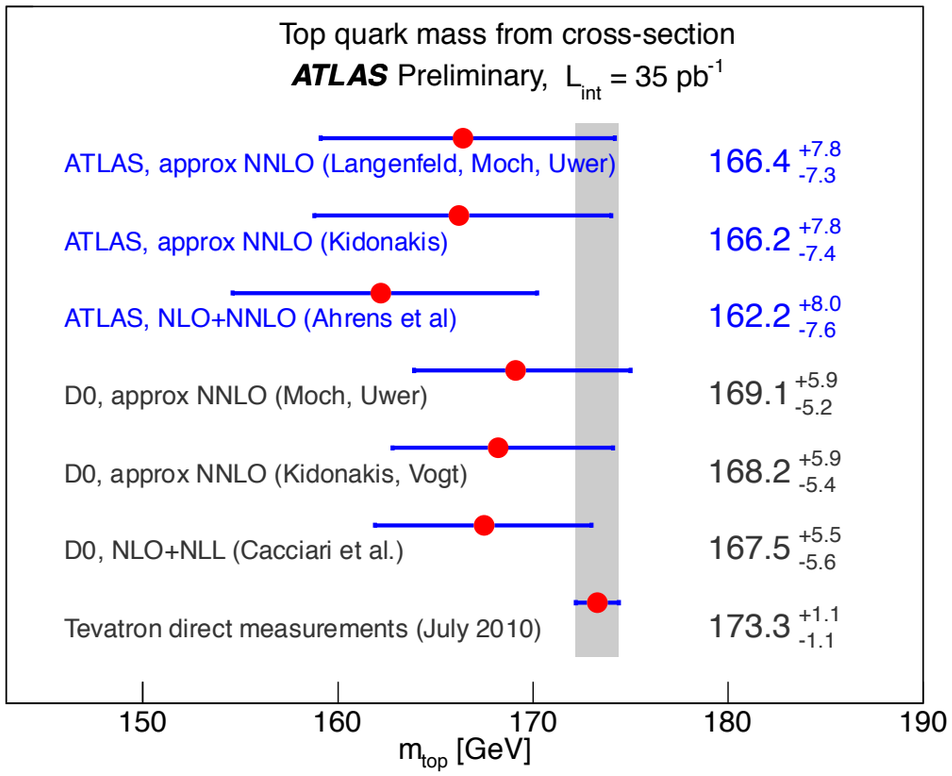


# Mass from Cross Section

- Guiding idea: experimental dependence on MC mass parameter (acceptance) weaker than theoretical dependence on pole mass ($1/m_t^4$)
- Analysis technique:
  - Lepton+jets cross section with b-tagging: repeat for nine mass hypotheses between 140 and 210 GeV
  - Assumption: relative systematic uncertainties independent of mass (verified for 140 GeV and 210 GeV)
  - Pole mass value and uncertainty extracted from overlap of experimental and theoretical likelihoods
- **Result** (for approx. NNLO calculation, Langenfeld, Moch, Uwer):

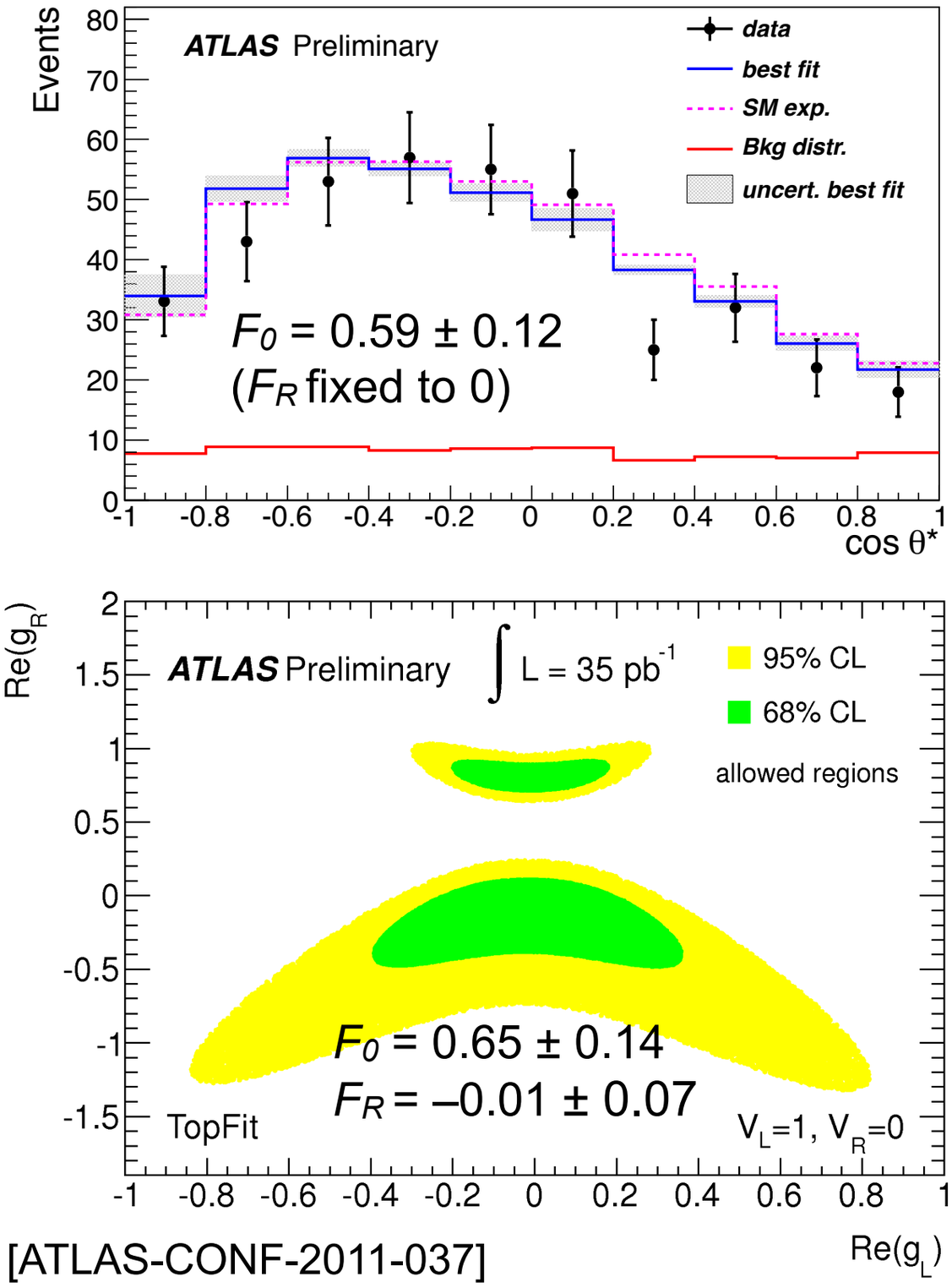
$$m_t = 166.4\ ^{+7.8}_{-7.3}(\text{stat.} + \text{syst.})\ \text{GeV}$$



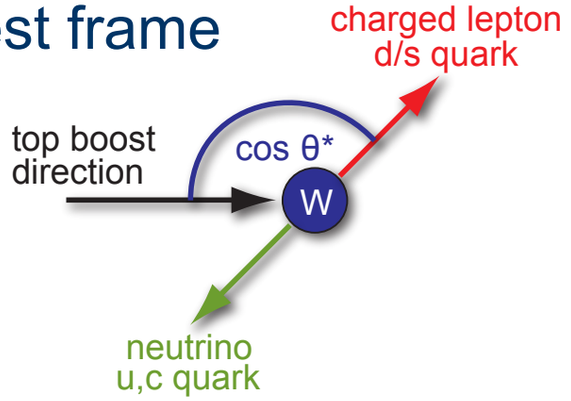

[ATLAS-CONF-2011-054]

# W Polarization in Top Decays




[ATLAS-CONF-2011-037]

- Probe *V–A* structure of Wtb vertex:
  - SM expectation for polarization fractions: left-handed $F_L \approx 0.3$ – longitudinal $F_0 \approx 0.7$ – right-handed $F_R \approx 0$
  - Observable "cos θ*": decay angle of charged lepton w.r.t. top boost direction in W rest frame

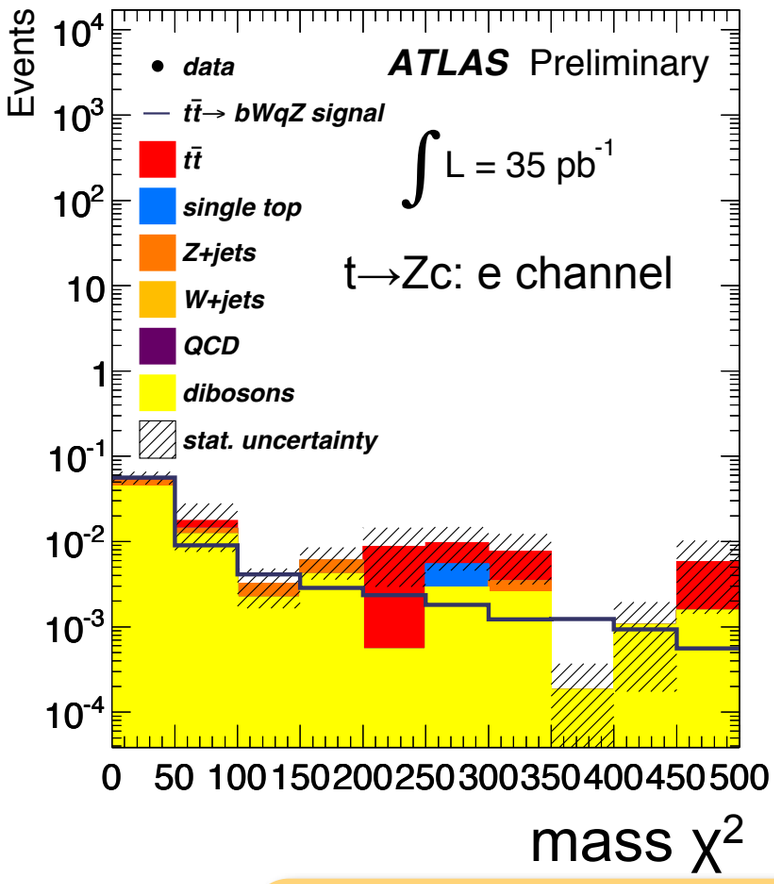


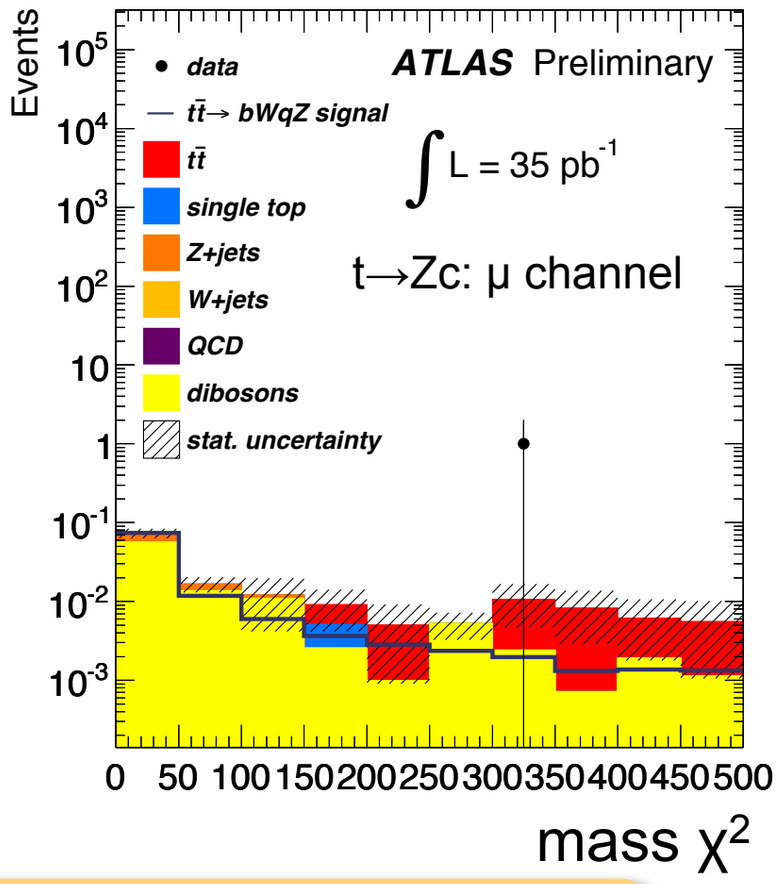

- Two analysis techniques:
  - Fit left-handed, longitudinal, right-handed templates to measured cos θ*
  - Extract asymmetries (e.g. $A^{FB}$) from cos θ* → correct back to parton level
- Interpretation: limits on anomalous couplings $g_L$, $g_R$

# Flavor-Changing Neutral Currents

- Top flavor-changing neutral currents (FCNC)
  - Extremely rare in standard model (BR<$10^{-12}$)
  - Current experimental limits much weaker, e.g. B(t→Zq) < 3.2% at 95% C.L. (DØ, arXiv:1103.4574 [hep-ex])

[ATLAS-CONF-2011-061]

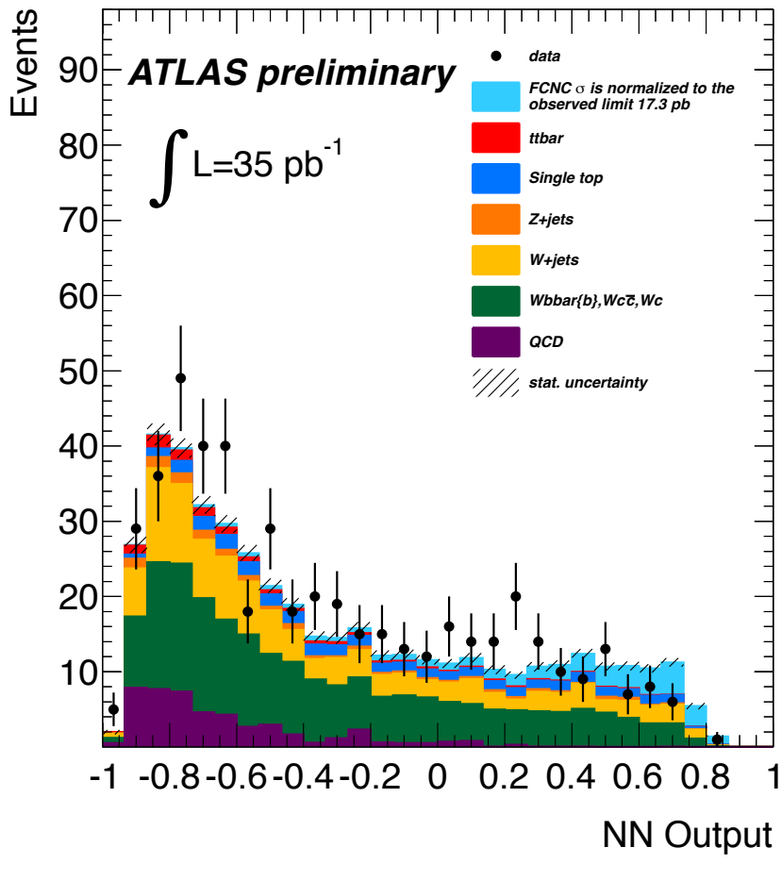



**Single top: qg → t → Wb**

Signature: W + b-jet + MET

→ Limit: σ(qg→t)×B(t→Wb) < 17 pb (95% C.L.)



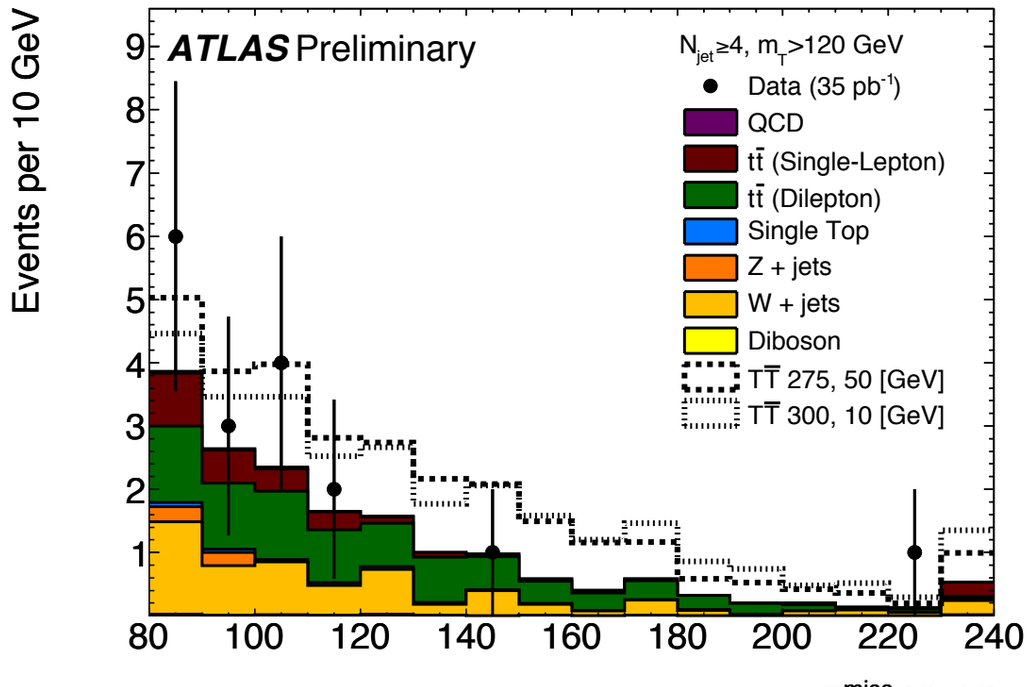

**Decay tt → Zq Wb**

Signature: three leptons + jets + missing $E_T$

→ Limit: B(t→Zq) < 17% (95% C.L.)

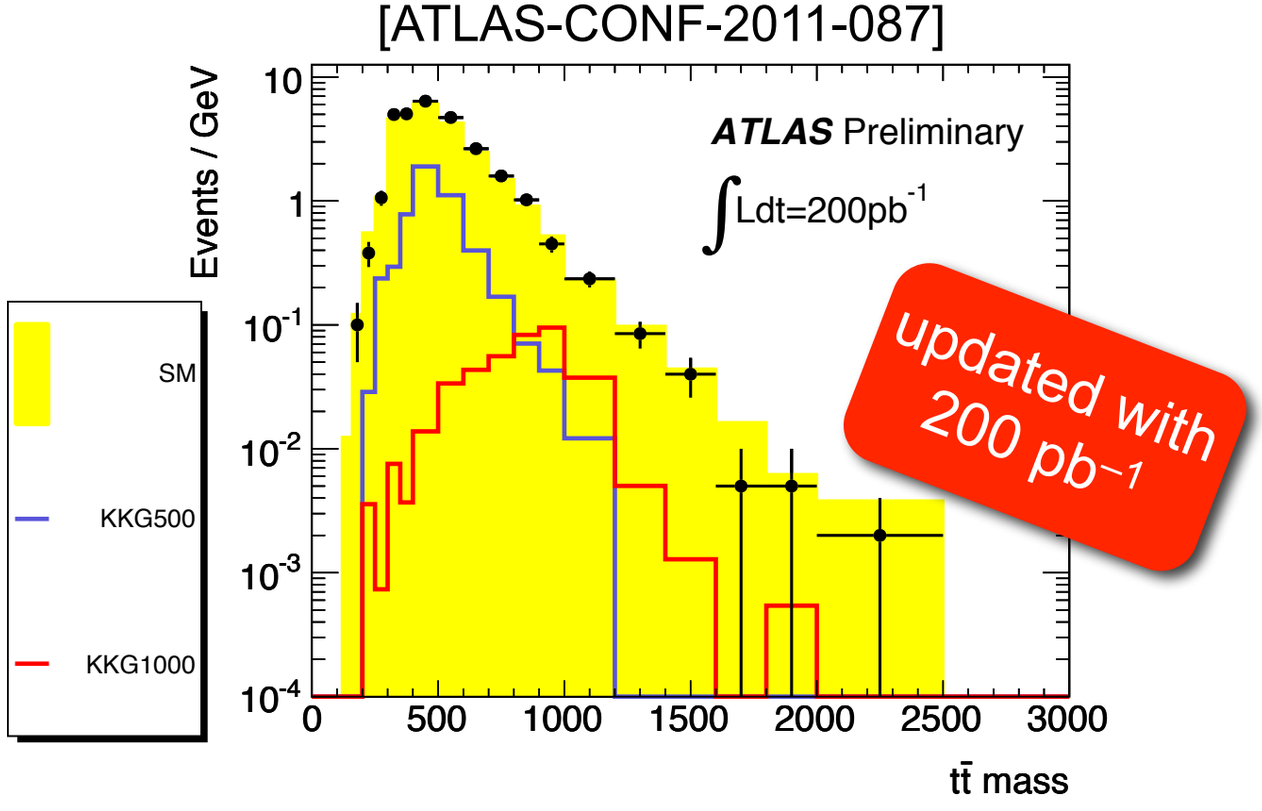
# High-Mass Phenomena Producing Top

[ATLAS-CONF-2011-036]




- Anomalous missing $E_T$ in top events
  - Benchmark: heavy $T\bar{T} \rightarrow tA^0\,\bar{t}\bar{A}^0$ ($A^0$ dark matter candidate)
  - Signature: lepton+jets with MET > 80 GeV and $m_T$ > 120 GeV
  - Exclude T with 300 GeV (275 GeV) for $A^0$ mass < 10 GeV (50 GeV) at 95% C.L.

[ATLAS-CONF-2011-087]




- Search for high-mass "resonances"
  - Reconstruct $t\bar{t}$ mass with $dR_{min}$ method (remove jets "far away" from rest of activity in event)
  - Interpretation in leptophobic Z' model: $\sigma(Z') \times B(Z' \rightarrow t\bar{t}) < 38$ pb (3.2 pb) for $M_{Z'} = 500$ GeV (1300 GeV) at 95% C.L.
  - Exclude Kaluza-Klein gluons with m < 650 GeV at 95% C.L.

# Summary & Outlook

- Analysis of 2010 LHC data: many ATLAS top results, some already competitive with Tevatron
  - Pair production cross section
  - Top mass & properties
- LHC and ATLAS performing extremely well in 2011
  - ATLAS has recorded 1 $fb^{-1}$ of data in 2010/2011
  - Expect more sensitive searches
  - Expect precision measurements

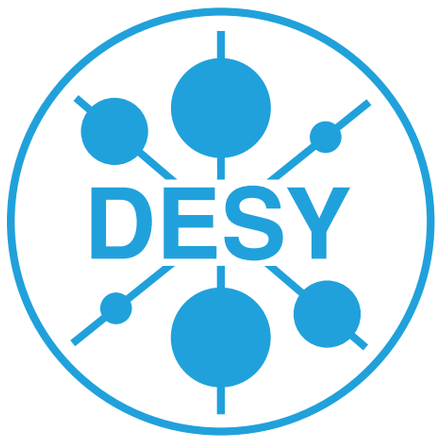
**Top: The New Standard Candle at the LHC**

# Topics for Discussion


- Making top the new standard candle
  - Cross section measurements with fiducial cuts? → reduce extrapolation uncertainty
  - Which differential cross sections are the most interesting?
  - Next step in precision: reduce systematic uncertainties

- Precision measurements: improve uncertainties related to theory
  - Vector boson + jets production: rates, kinematic shapes, heavy flavor content?
  - Additional jets in top production: hard process at (N)NLO? ISR and FSR?
  - MC generator uncertainties: LO $2 \rightarrow n$ vs. NLO (vs. MENLOPS)? $Q^2$ scales? $\alpha_S$?
  - Current PDF uncertainty prescription extremely heavy for all but the simplest analysis technique
  - … and experimenters will do their homework, too

# Backup Slides




# ATLAS Public: Top Cross Section

| Title | Reference |
|---|---|
| Measurement of the Top Quark-Pair Production Cross Section with ATLAS in pp Collisions at $\sqrt{s}$ = 7 TeV | Eur. Phys. J. **C71** (2011) 1577 |
| Top Quark Pair Production Cross-Section Measurement in ATLAS in the Single Lepton+Jets Channel without b-tagging | ATLAS-CONF-2011-023 |
| Measurement of the Top Quark Pair Cross-Section with ATLAS in pp Collisions at $\sqrt{s}$ = 7 TeV in the Single-Lepton Channel using b-tagging | ATLAS-CONF-2011-035 |
| Measurement of the Top Quark Pair Production Cross Section with ATLAS in pp Collisions at $\sqrt{s}$ = 7 TeV in Dilepton Final States | ATLAS-CONF-2011-034 |
| A Combined Measurement of the Top Quark Pair Production Cross-Section using Dilepton and Single-Lepton Final States | ATLAS-CONF-2011-040 |
| Search for tt Production in the All-Hadronic in ATLAS with $\sqrt{s}$ = 7 TeV Data | ATLAS-CONF-2011-066 |

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

# ATLAS Public: Mass, Properties, Searches

| Title | Reference |
|---|---|
| Measurement of the Top-Quark Mass using the Template Method in pp Collisions at $\sqrt{s}$ = 7 TeV with the ATLAS Detector | ATLAS-CONF-2011-033 |
| Determination of the Top-Quark Mass from the $t\bar{t}$ Cross Section Measurement at $\sqrt{s}$ = 7 TeV with the ATLAS Detector | ATLAS-CONF-2011-054 |
| Measurement of the W-boson Polarisation in Top-Quark Decays in pp Collision Data at $\sqrt{s}$ = 7 TeV using the ATLAS Detector | ATLAS-CONF-2011-037 |
| Search for Anomalous Missing $E_T$ in $t\bar{t}$ Events | ATLAS-CONF-2011-036 |
| Search for FCNC Top Quark Processes at $\sqrt{s}$ = 7 TeV with the ATLAS Detector | ATLAS-CONF-2011-061 |
| A Search for New High-Mass Phenomena Producing Top Quarks with the ATLAS Experiment | ATLAS-CONF-2011-070 |
| A Search for $t\bar{t}$ Resonances in the Lepton Plus Jets Channel using 200 $pb^{-1}$ of *pp* Collisions at $\sqrt{s}$ = 7 TeV | ATLAS-CONF-2011-087 |

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