

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

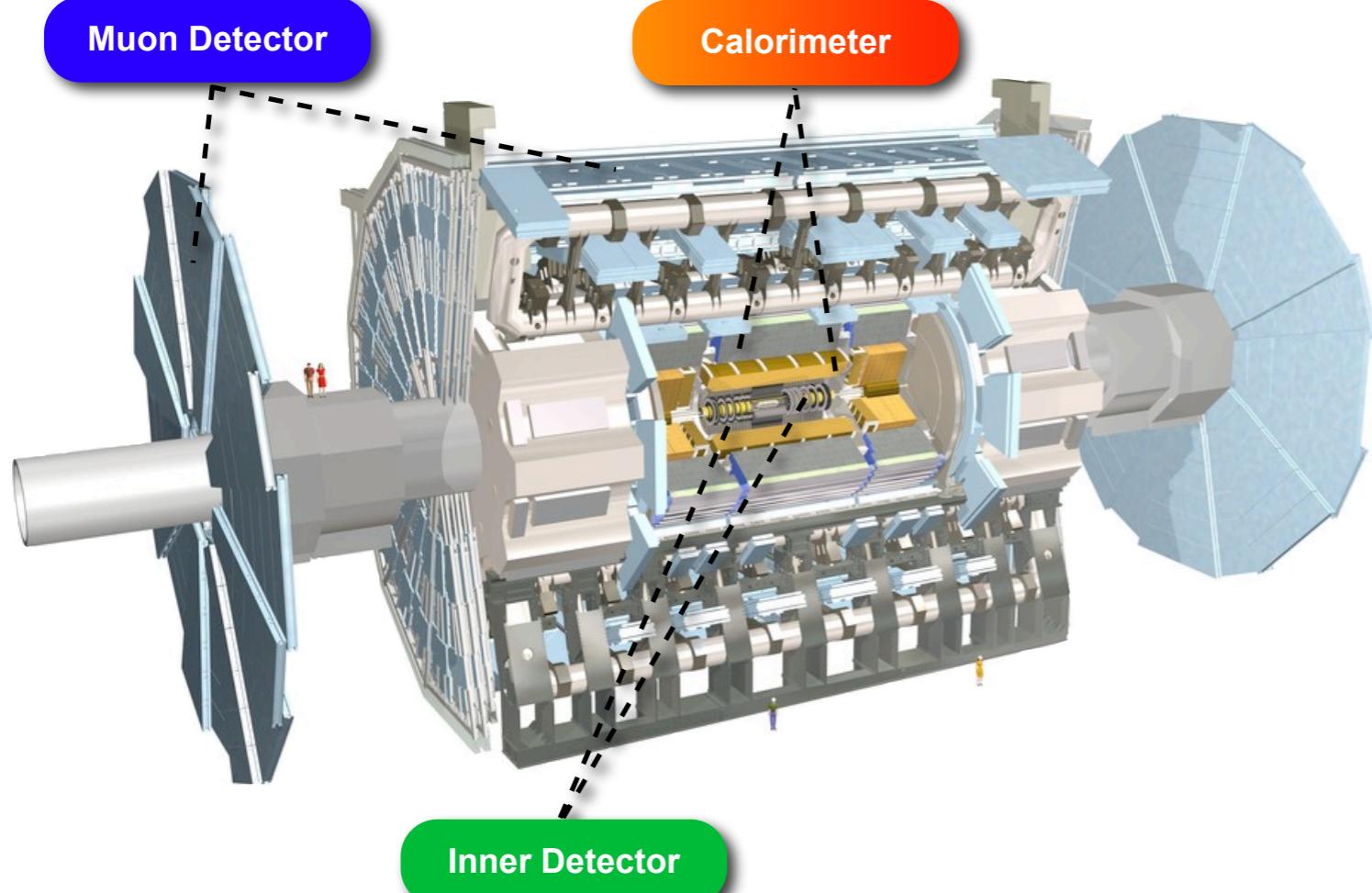
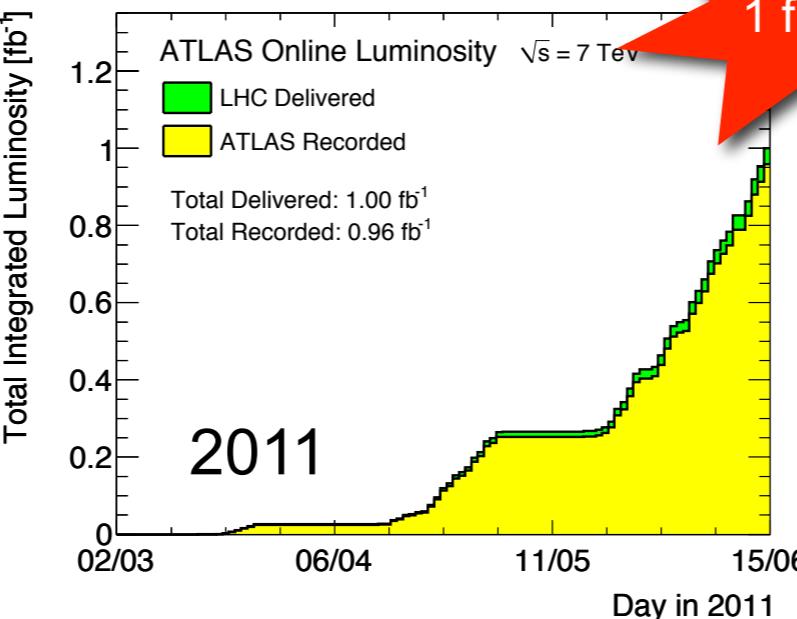
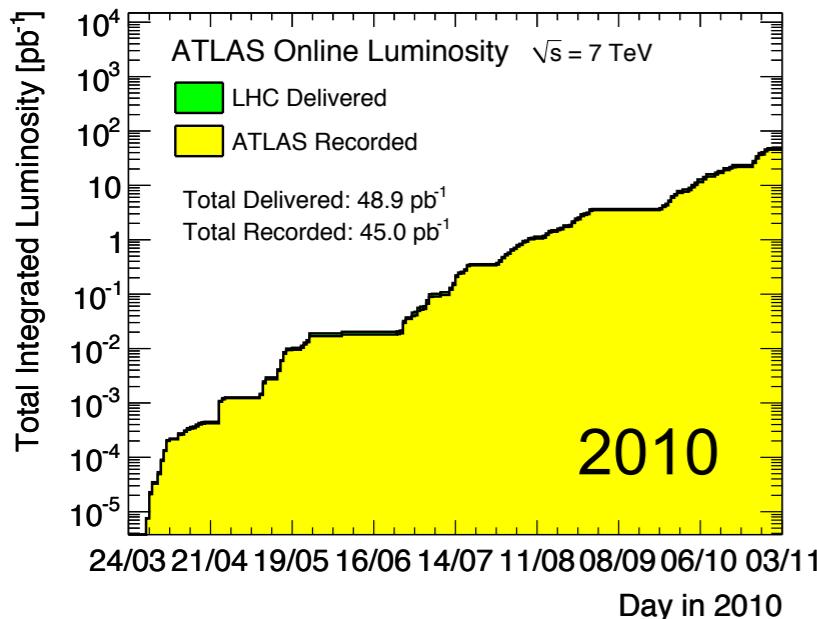
Top Pair Production and Top Properties at ATLAS



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



The LHC and the ATLAS Experiment



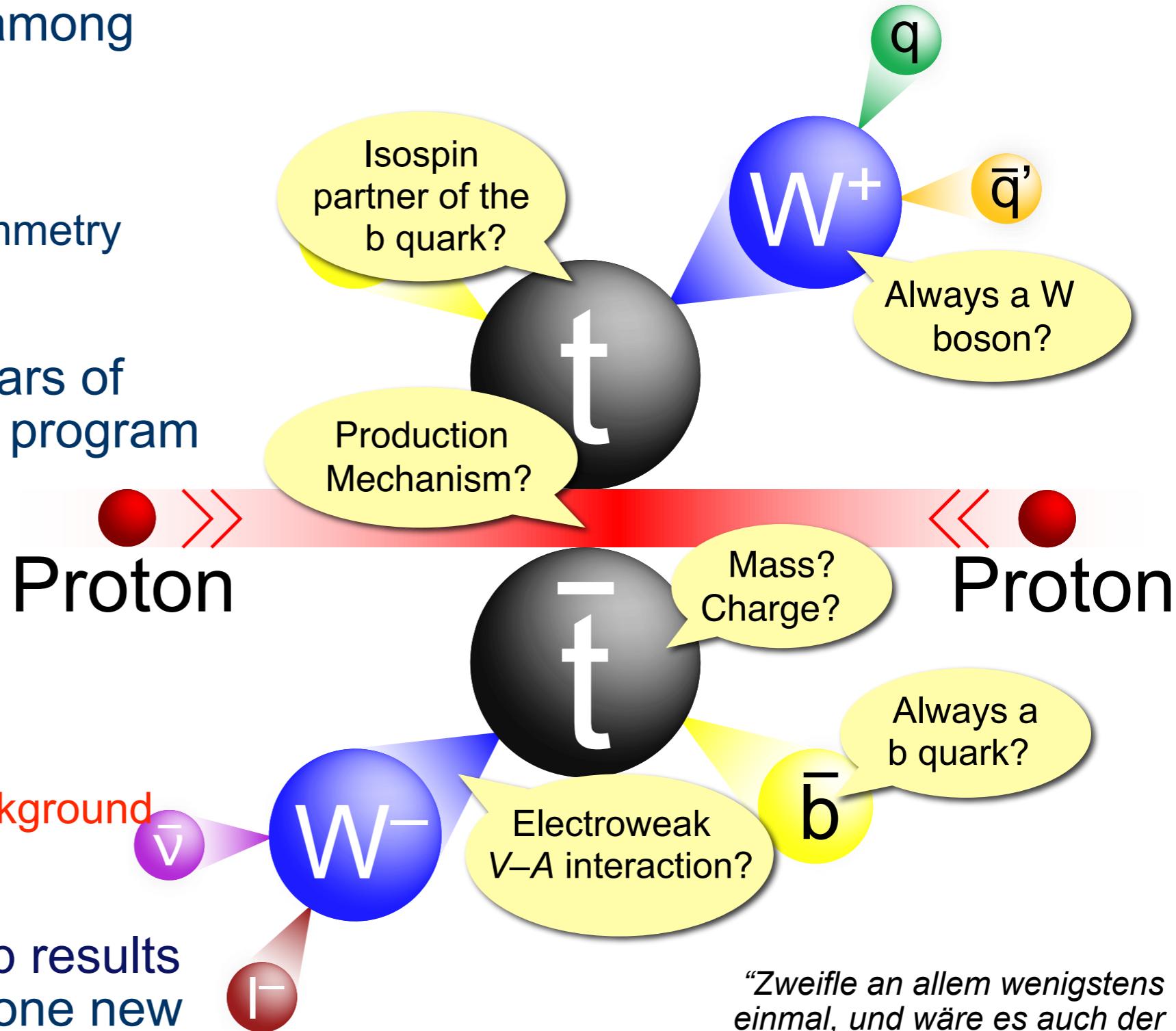
Large Hadron Collider

- 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

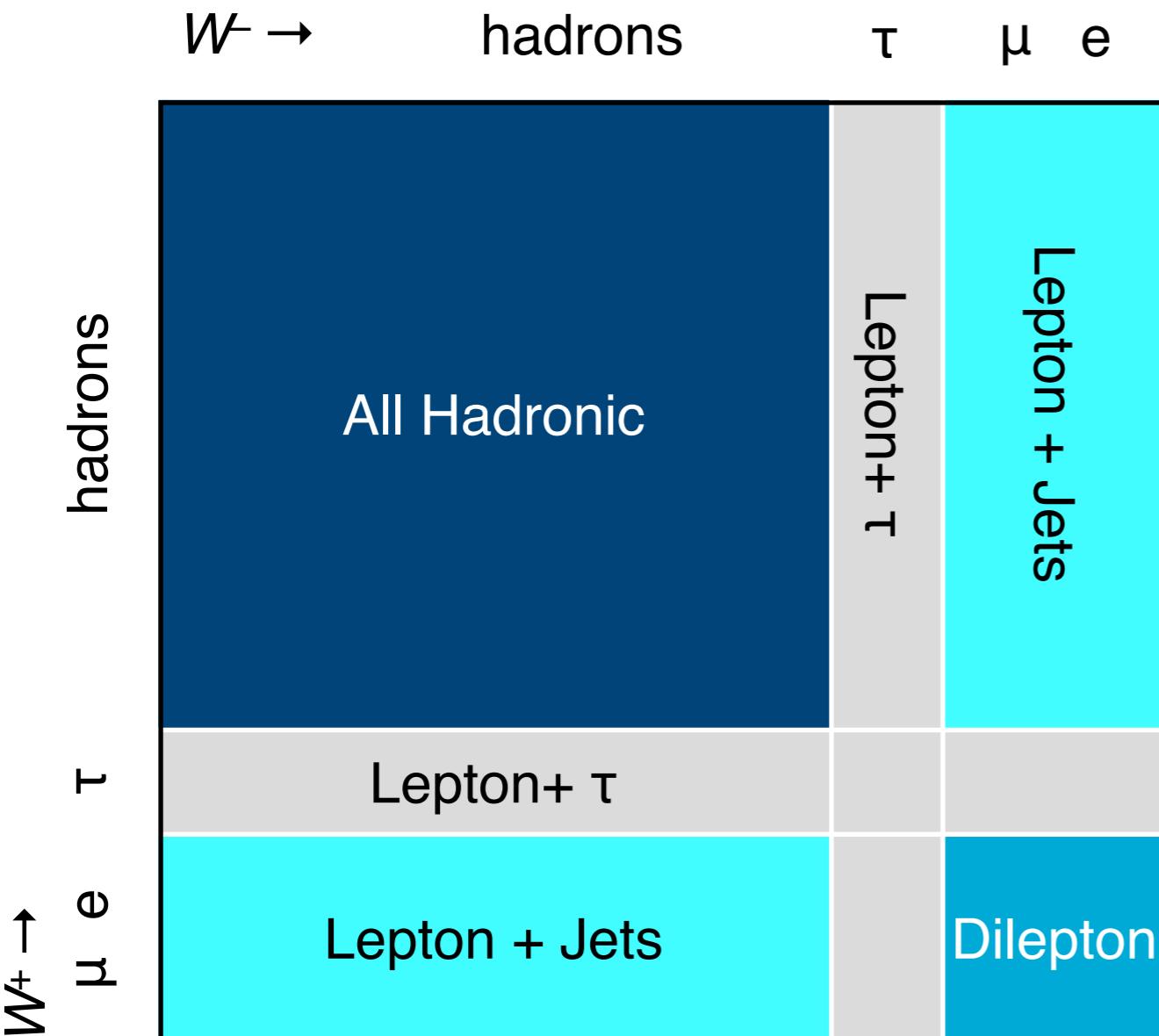
- Multi-purpose HEP detector: tracking/vertexing, calorimetry, muon detectors
- Excellent performance 2010/2011

- Top – 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 $> 20 \times$ 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)

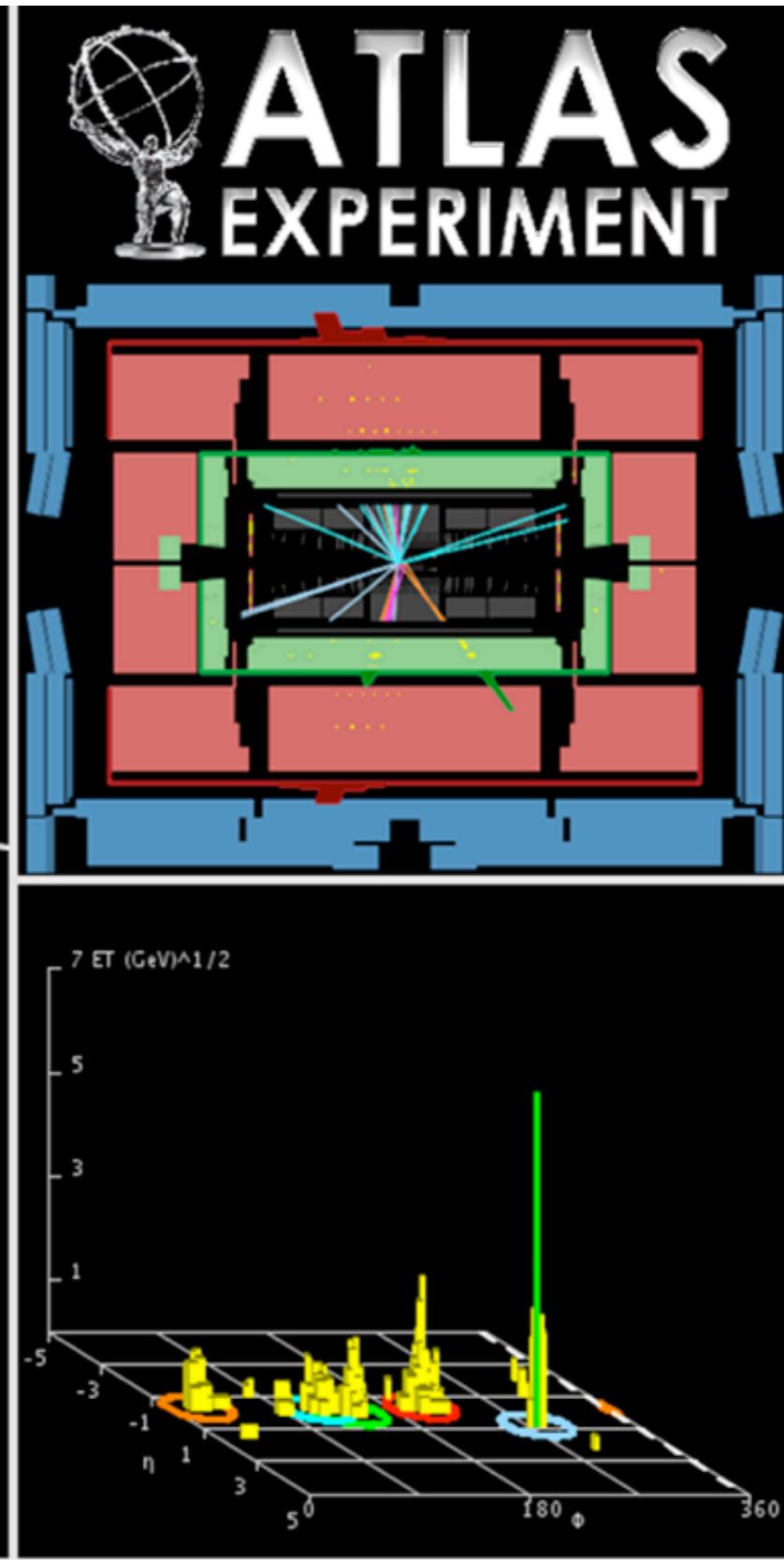
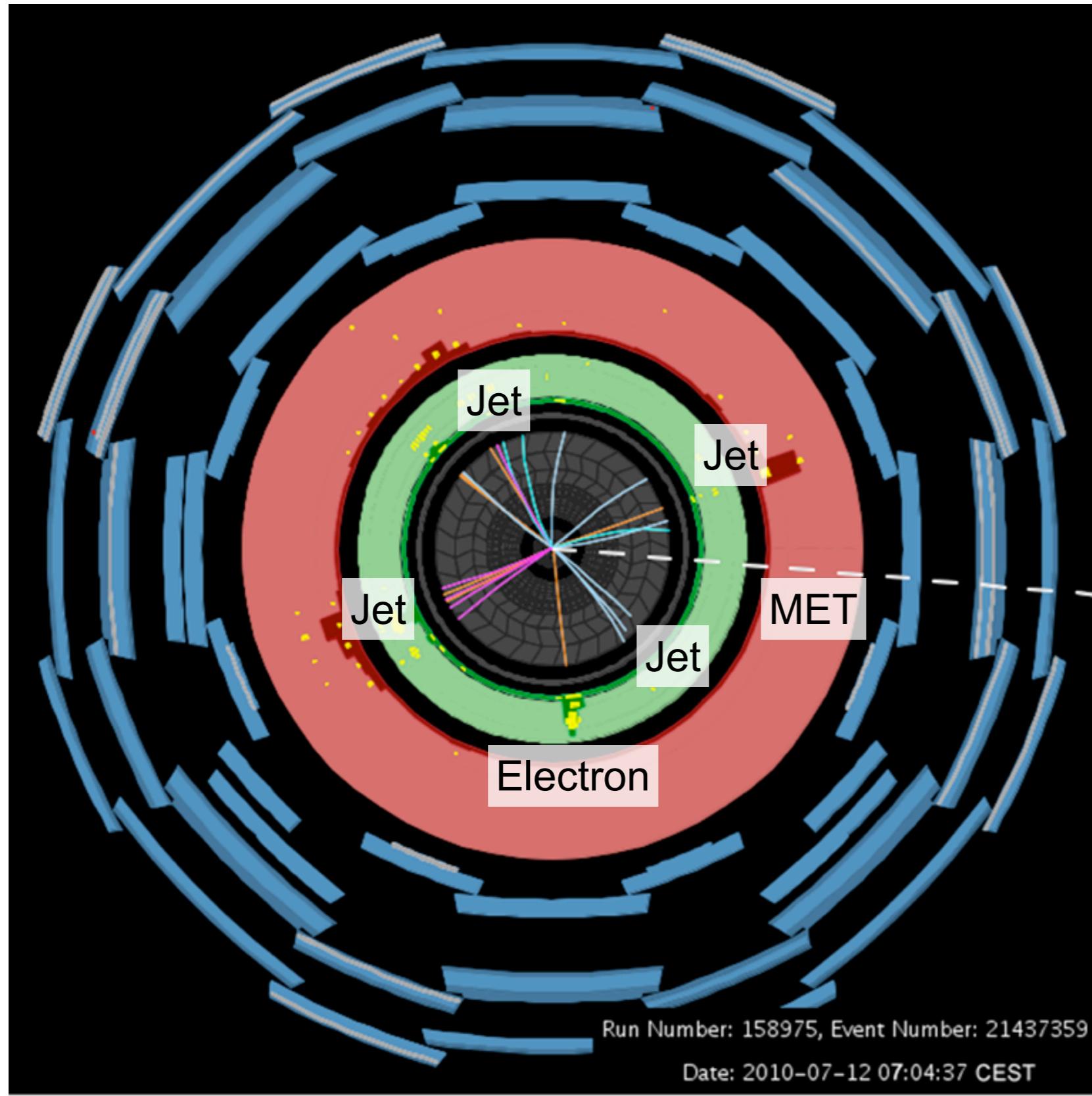
Analyzing Top Quark Events



- Top decay in the standard model:
 $B(t \rightarrow W b) \approx 100\%$
- 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



Top Pair Production Cross Section

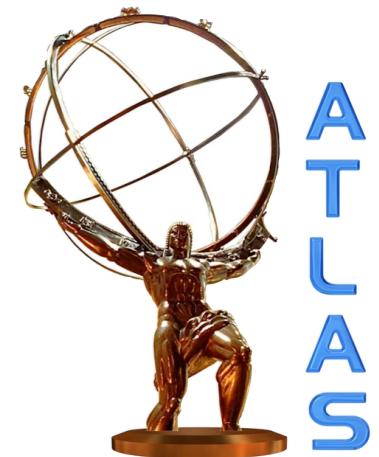
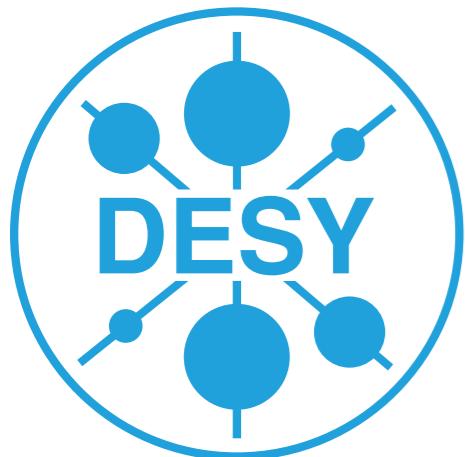
- Lepton+jets and dilepton channel, with and without b-tagging
- Cross section combination
- First look at the all-hadronic channel

Top Mass and further Properties

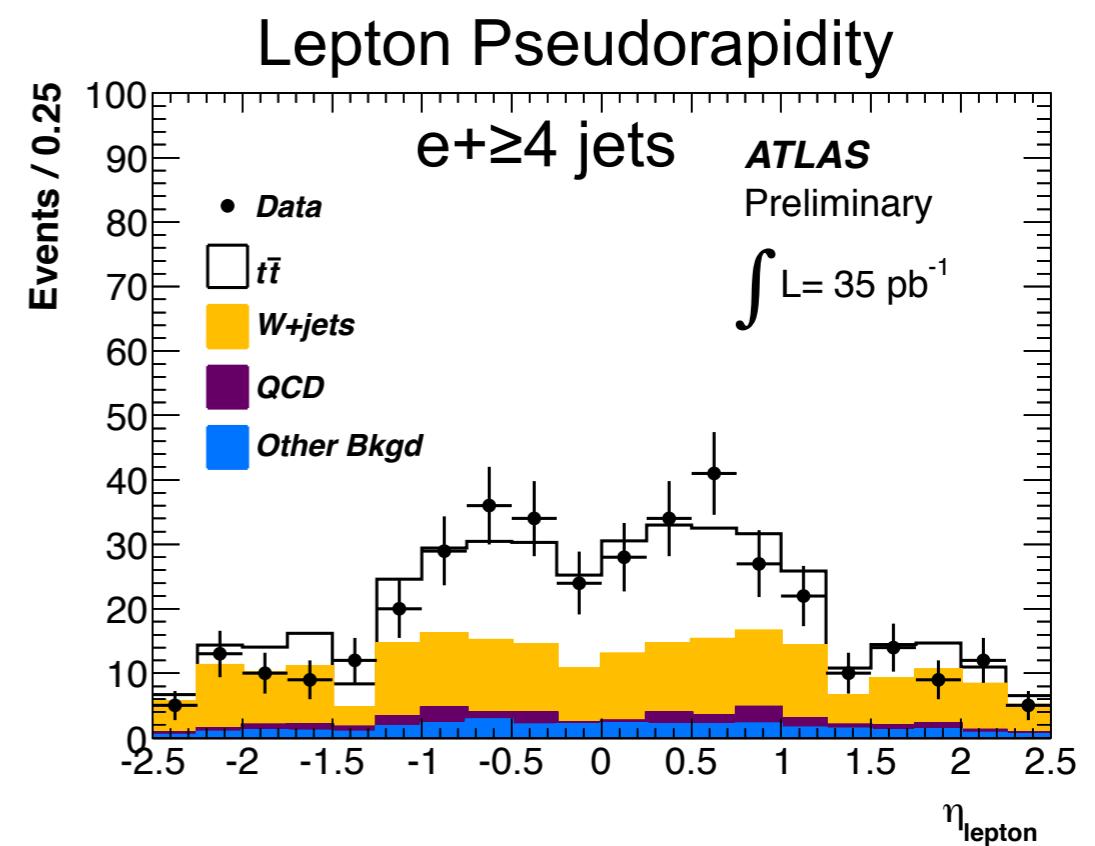
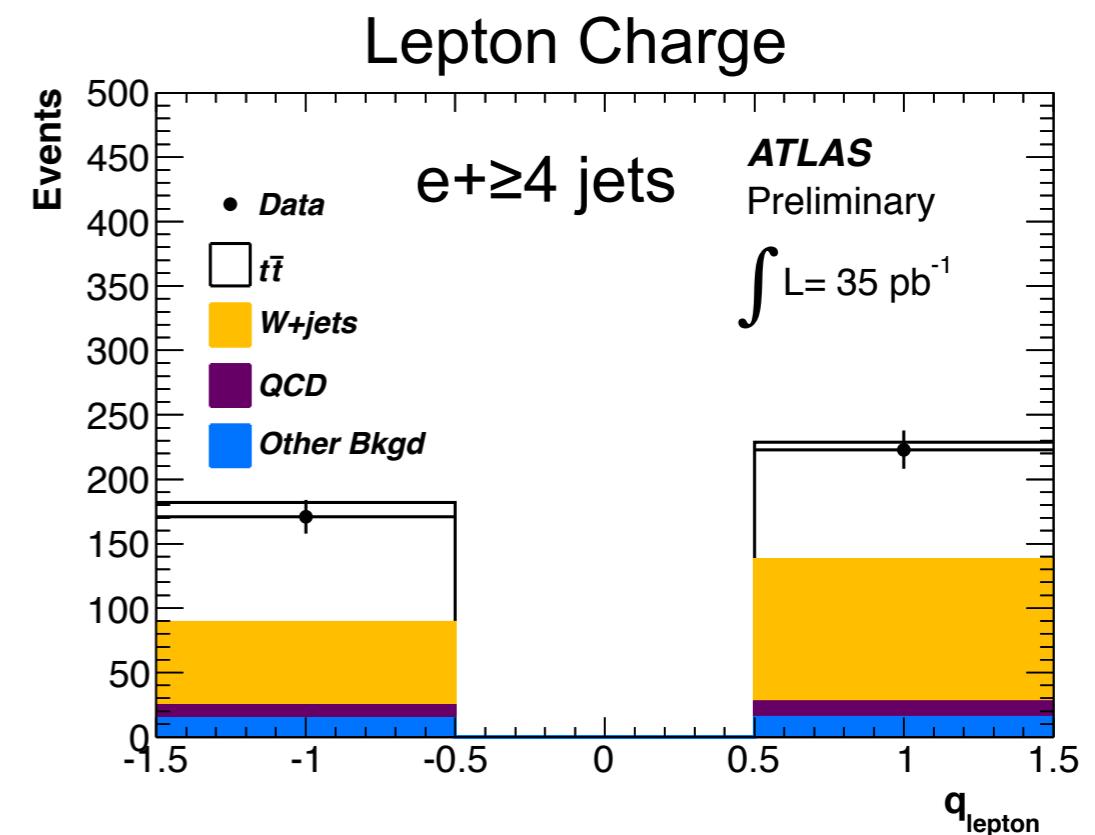
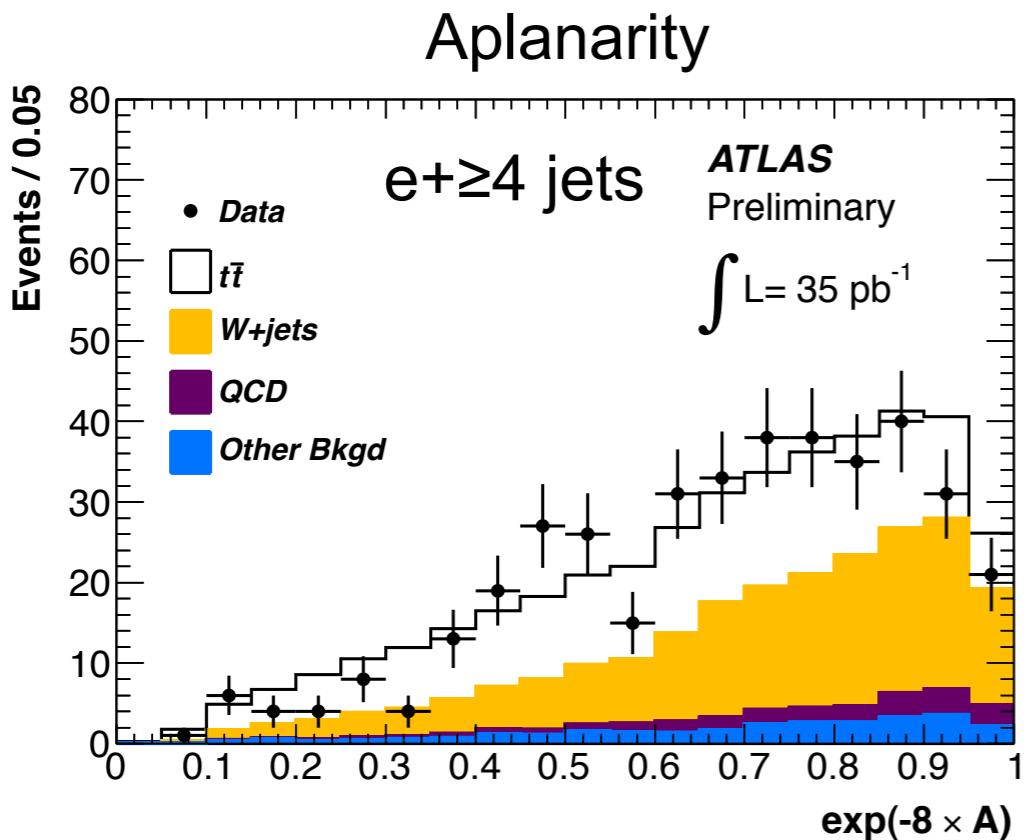
- Direct mass measurement
- Indirect mass determination via the cross section
- W polarization in top decays
- Search for FCNC in top production and decay
- Search for high-mass phenomena decaying into top

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

Top Quark Pair Production Cross Section

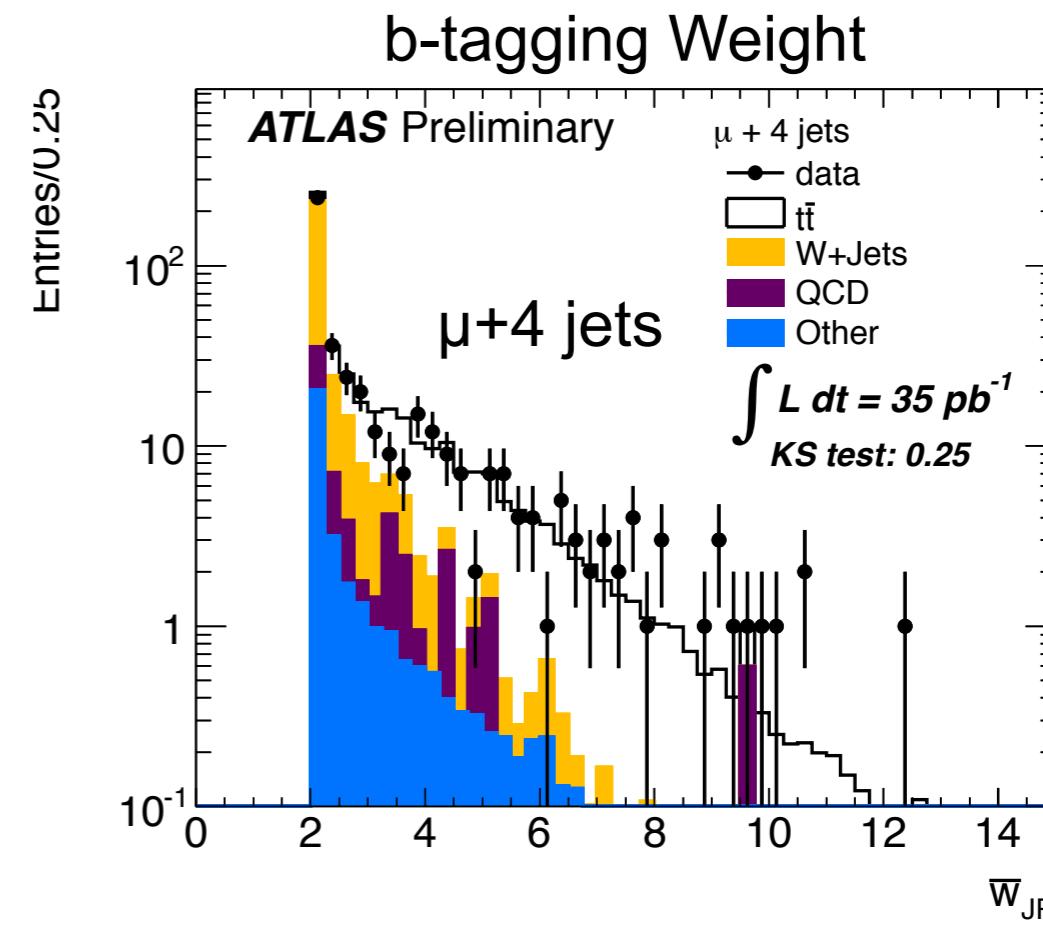
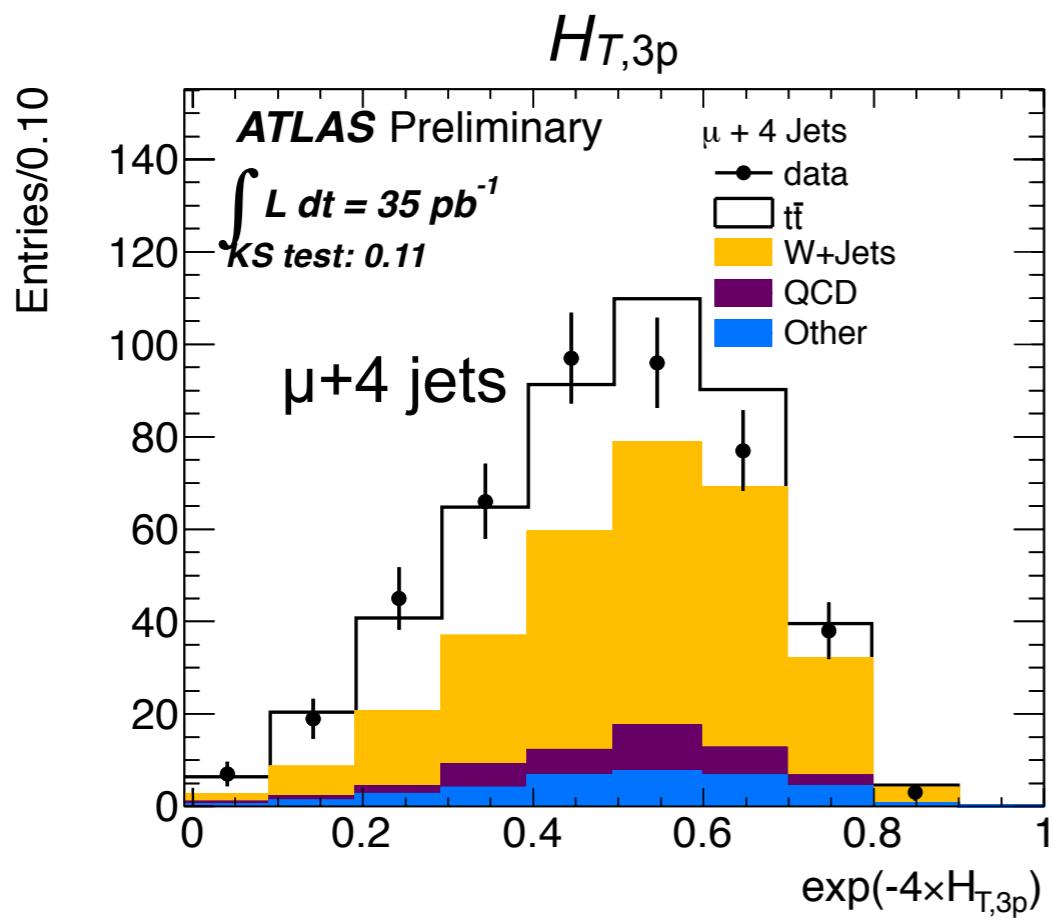


- Analysis I: without b-tagging
 - Lepton+jets selection: high- p_T e/ μ , ≥ 3 jets, missing E_T , transverse mass
 - Template fit to projective likelihood discriminant based on well-modeled event kinematics
 - Lepton charge: $t\bar{t}$ symmetric, W asymmetric
 - Pseudorapidity: $t\bar{t}$ more central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



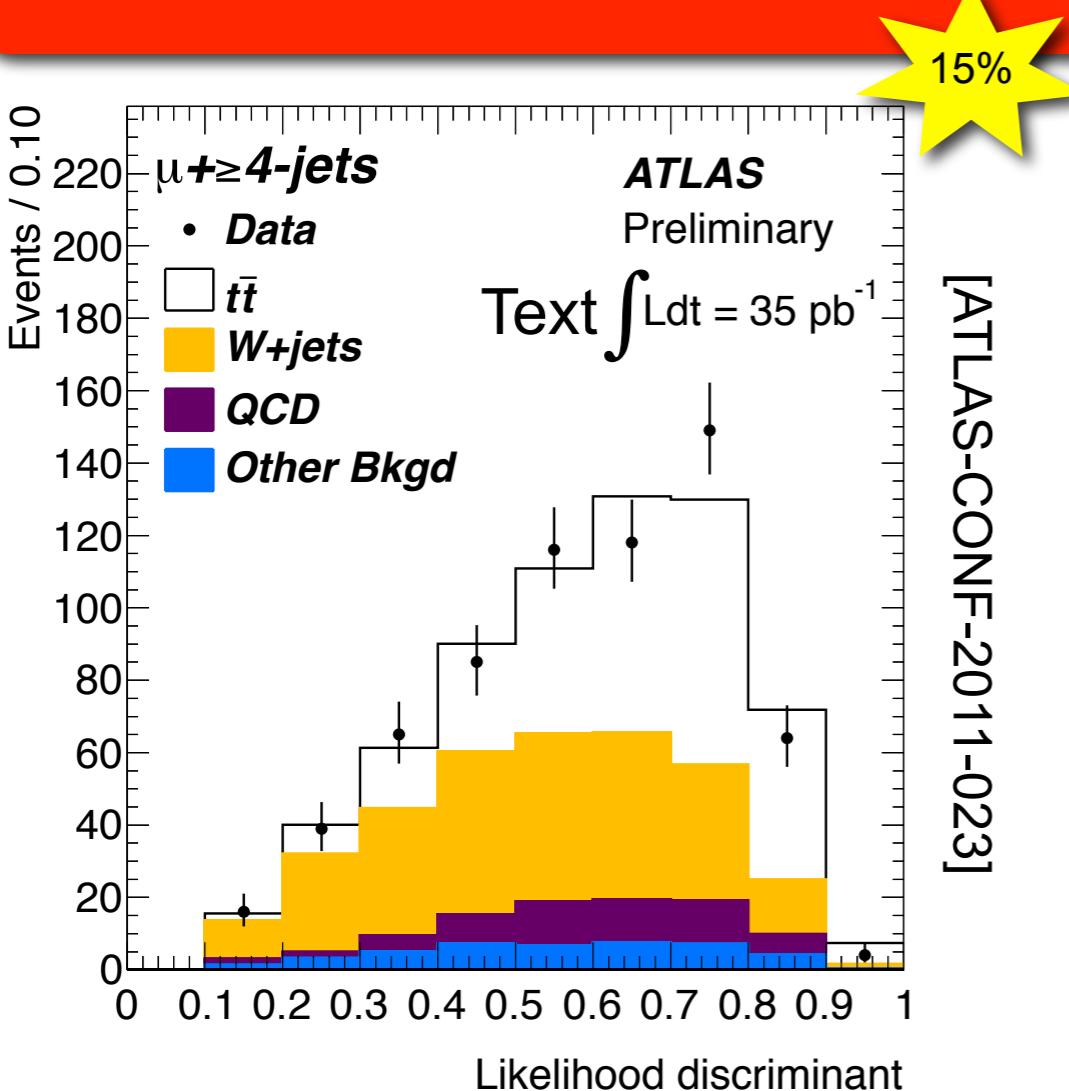
[ATLAS-CONF-2011-023]

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



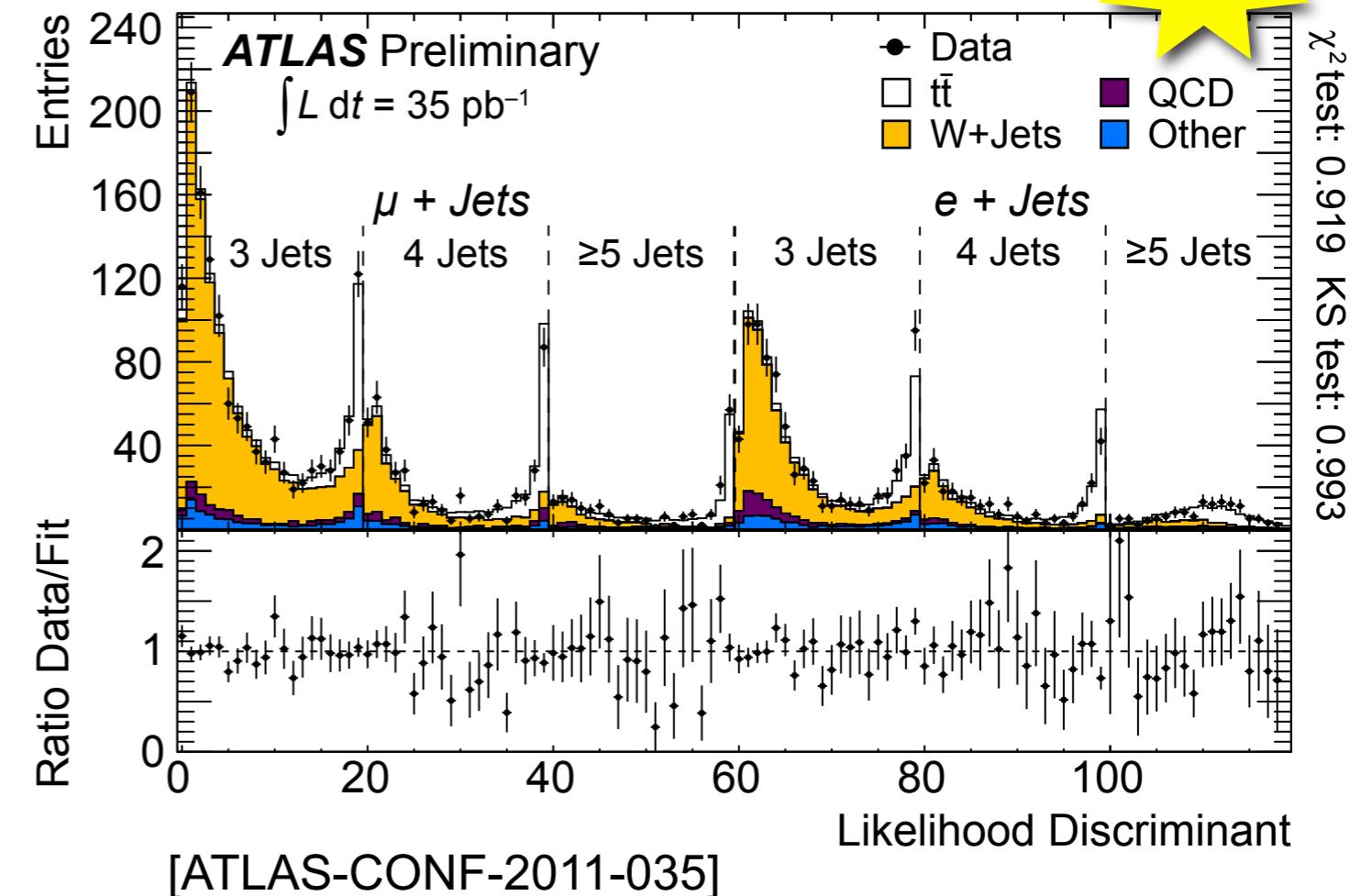
Without b-tagging:

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



Continuous b-tagging:

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



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

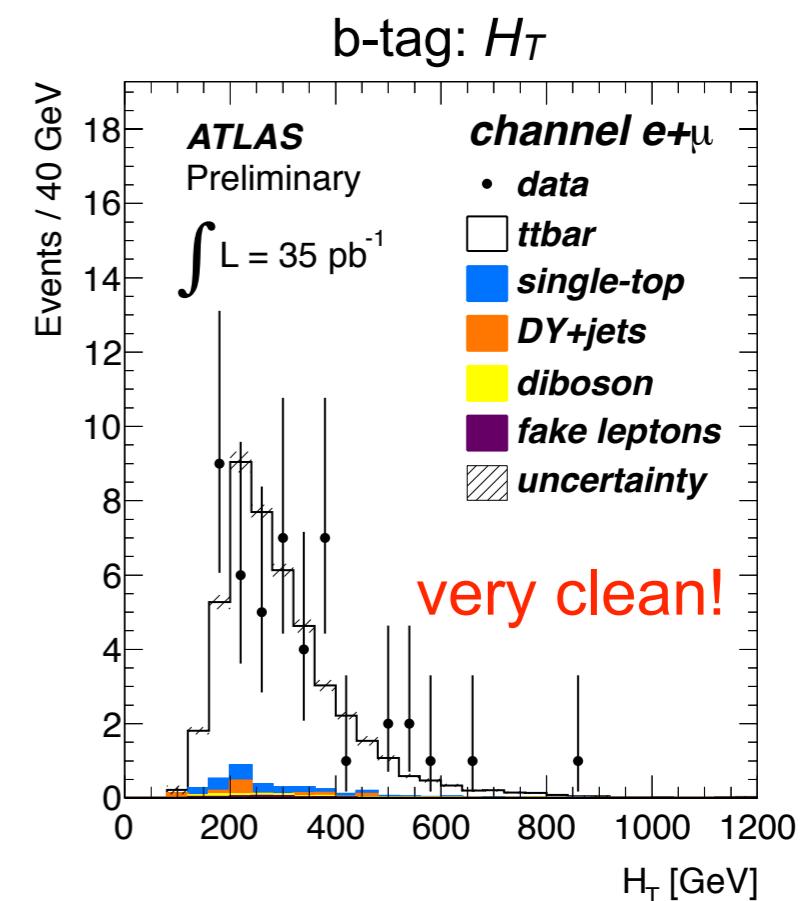
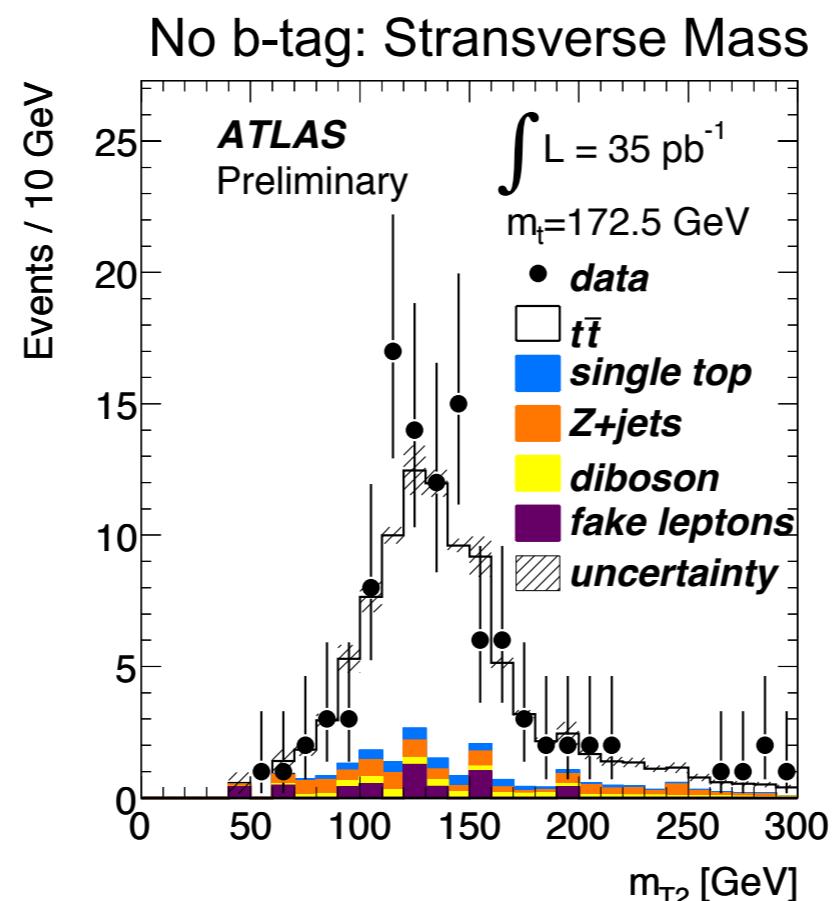
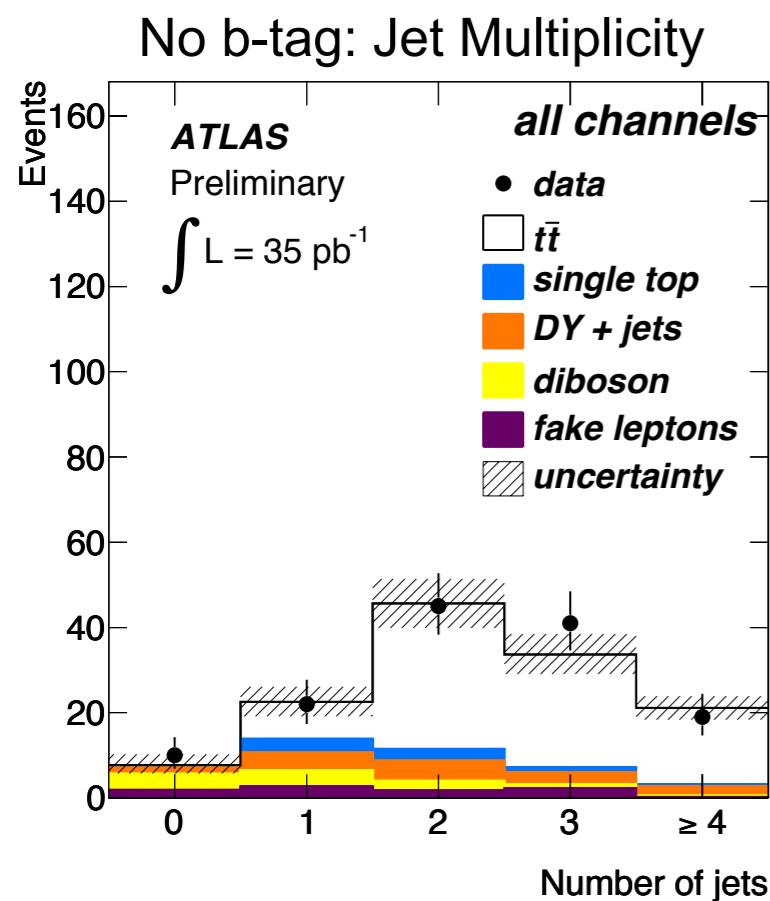
- Already with 2010 dataset: measurements precision limited by systematic uncertainties, dominant sources:
 - Both analyses: jet energy scale & resolution, ISR/FSR
 - Additionally for analysis with b-tag: b-tagging calibration, W+jets heavy flavor content
- Expect improvements of systematic uncertainties
 - 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

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

Additional Measurements

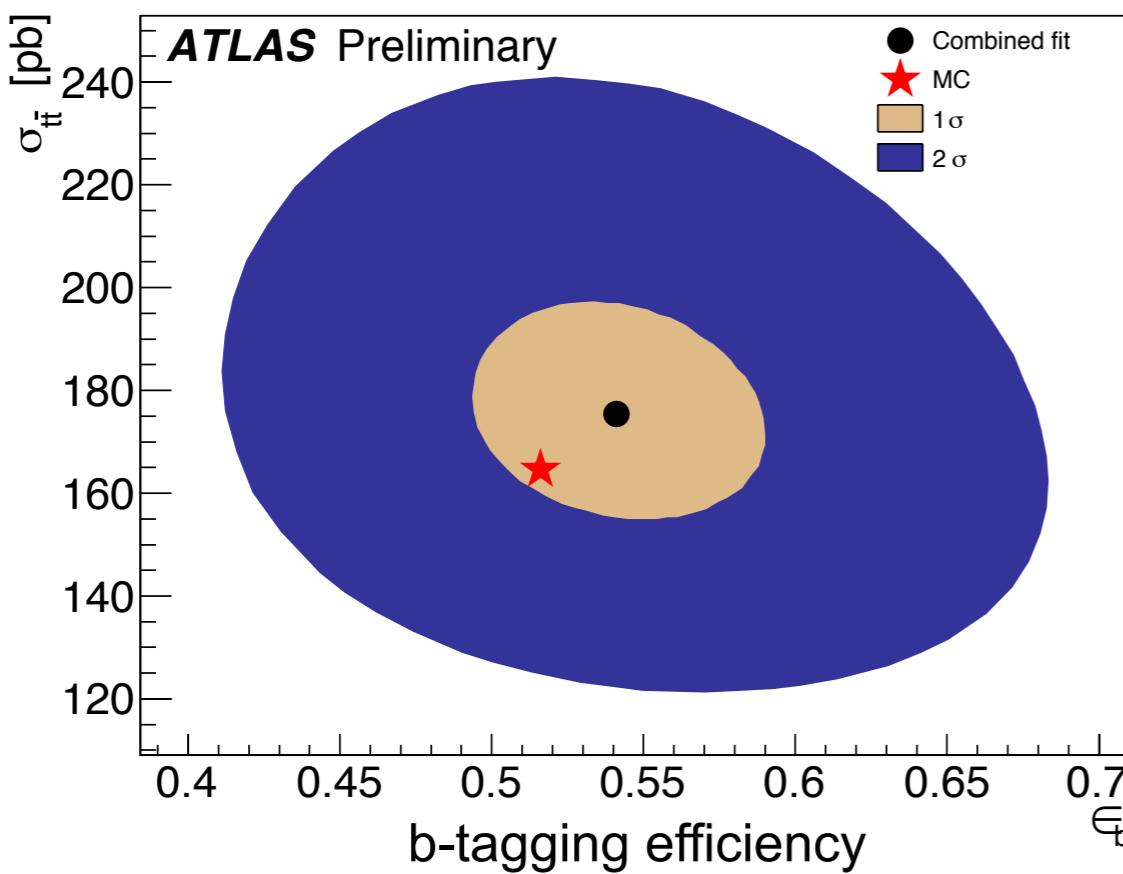
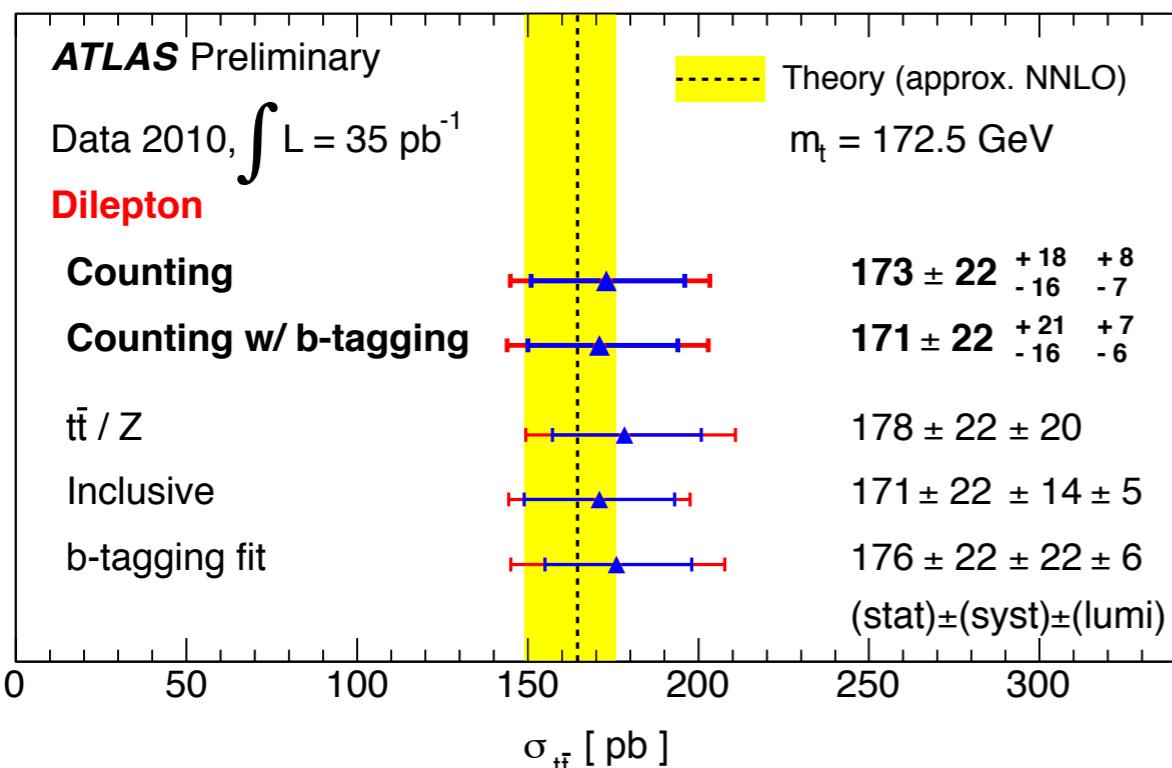
- $\sigma_{t\bar{t}}$ normalized to σ_Z
- Inclusive dilepton analysis (extract $\sigma_{t\bar{t}}$, σ_{WW} , and $\sigma_{Z \rightarrow T\bar{T}}$)
- $\sigma_{t\bar{t}}$ and b-tagging efficiency



Stransverse mass: $m_{T2}^2 = \min_{\vec{p}_{T,1} + \vec{p}_{T,2} = \vec{p}_T} \{ \max [m_T^2(\vec{p}_{T,\ell^+}, \vec{p}_{T,1}, \dots), m_T^2(\vec{p}_{T,\ell^-}, \vec{p}_{T,2}, \dots)] \}$

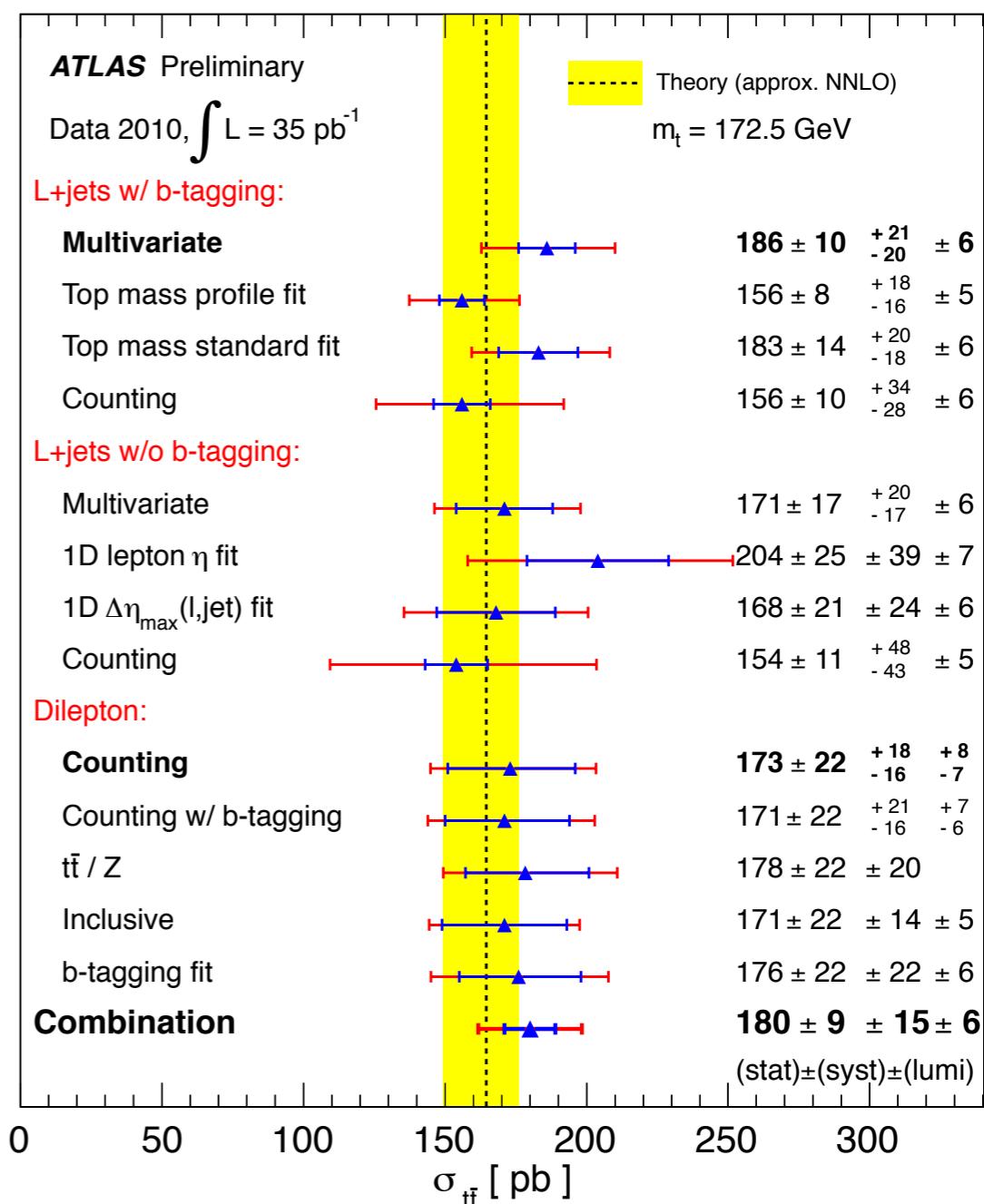
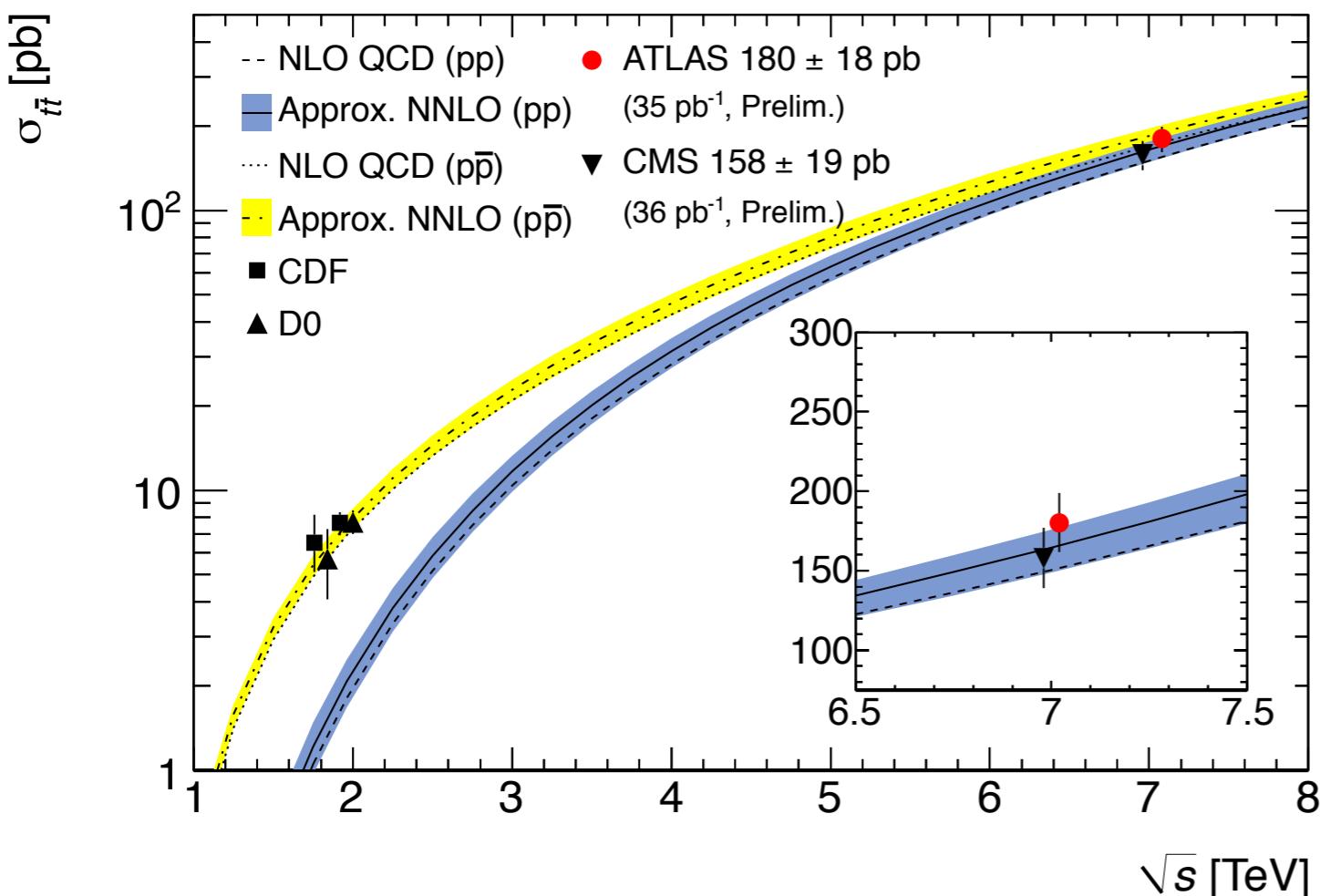
Top Cross Section: Dilepton

[ATLAS-CONF-2011-034]



- Combination of all dilepton channels: profile likelihood
- Results:
 - No b-tagging:
 $\sigma_{t\bar{t}} = 173 \pm 22(\text{stat.}) \pm 18(\text{syst.}) \pm 7(\text{lumi.}) \text{ pb}$
 - b-tagging:
 $\sigma_{t\bar{t}} = 171 \pm 22(\text{stat.}) \pm 21(\text{syst.}) \pm 7(\text{lumi.}) \text{ pb}$
- 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

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

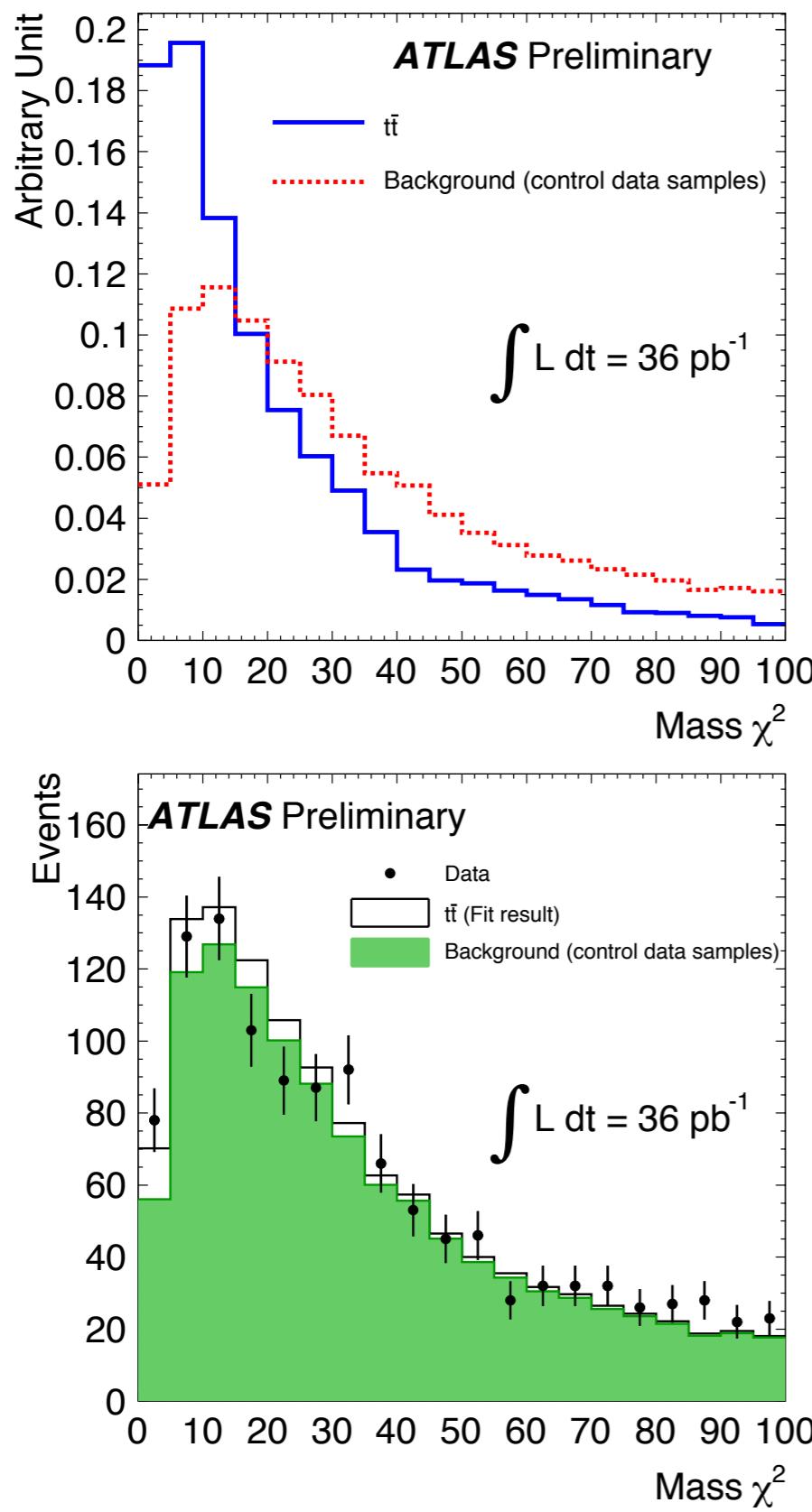


$$\sigma_{t\bar{t}} = 180 \pm 9(\text{stat.}) \pm 15(\text{syst.}) \pm 6(\text{lumi.}) \text{ pb}$$

[ATLAS-CONF-2011-040]

10%

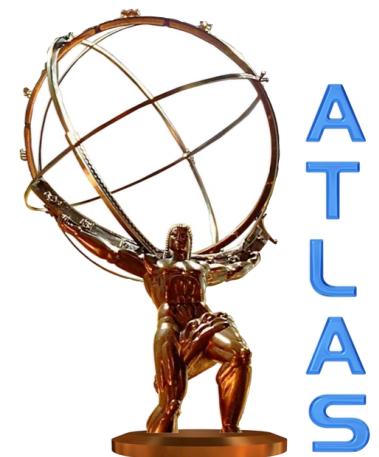
[ATLAS-CONF-2011-066]



- 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 χ^2** discriminant:

$$\chi^2 = \sum_{i=1}^2 \left(\frac{m_{jjb}^i - m_t}{\sigma_t} \right)^2 + \left(\frac{m_{jj}^i - m_W}{\sigma_W} \right)^2$$
 → 6 combinations, take lowest χ^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: $\sigma_{t\bar{t}} < 261 \text{ pb}$

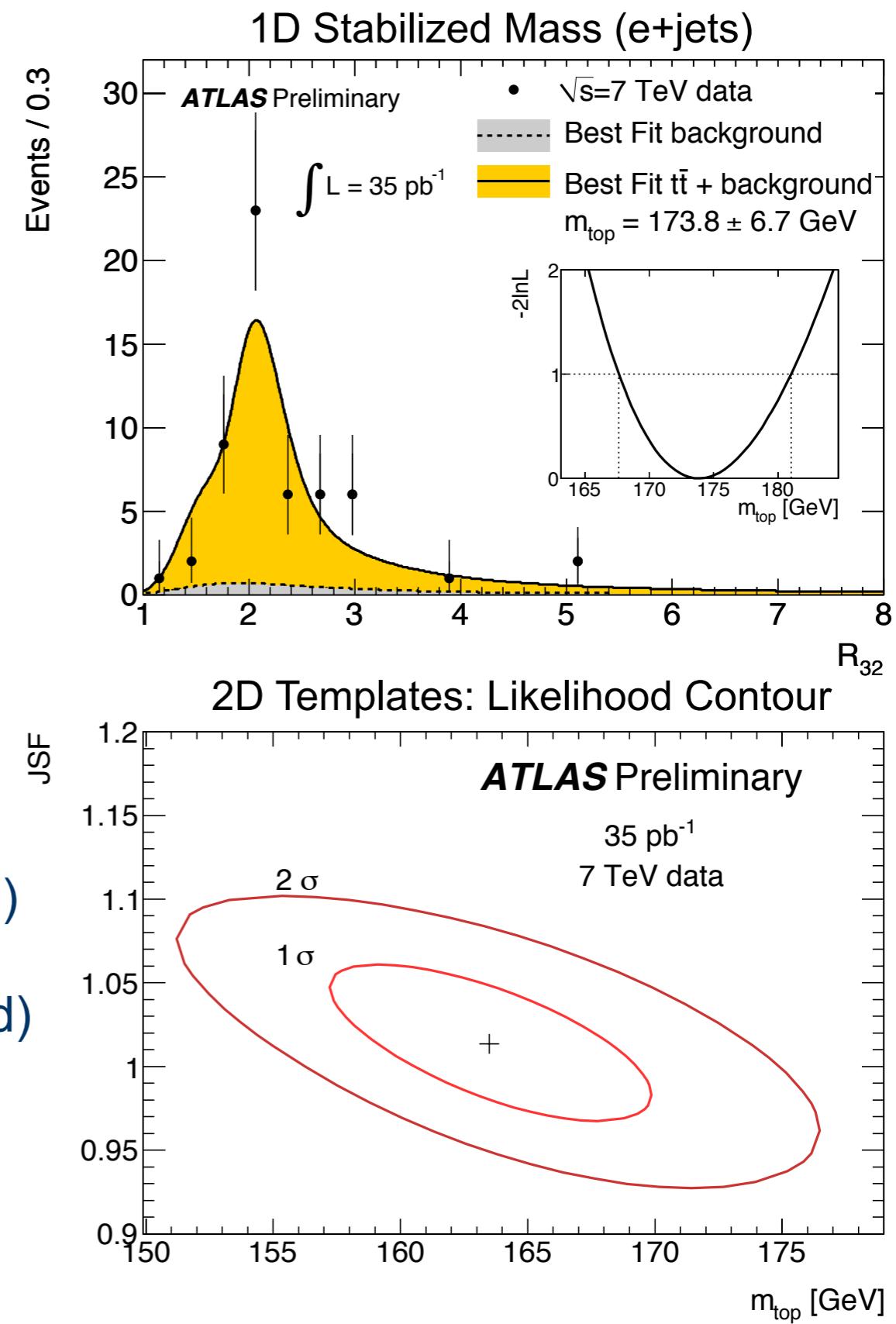
Top Mass and Properties



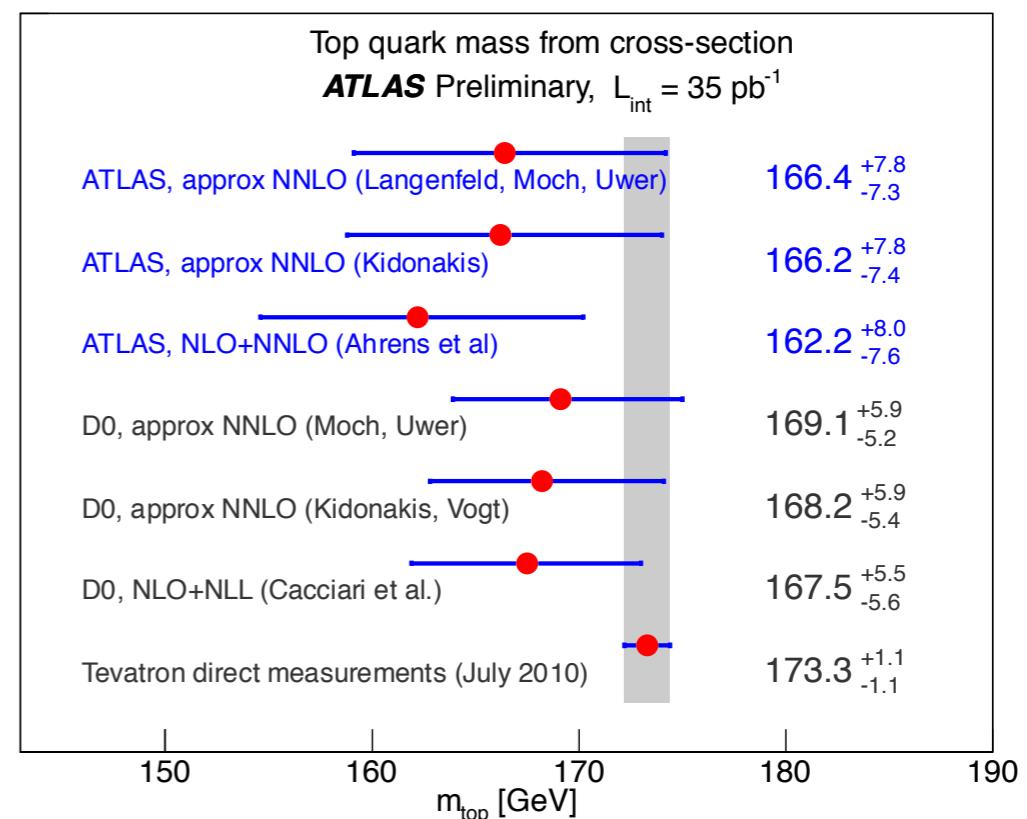
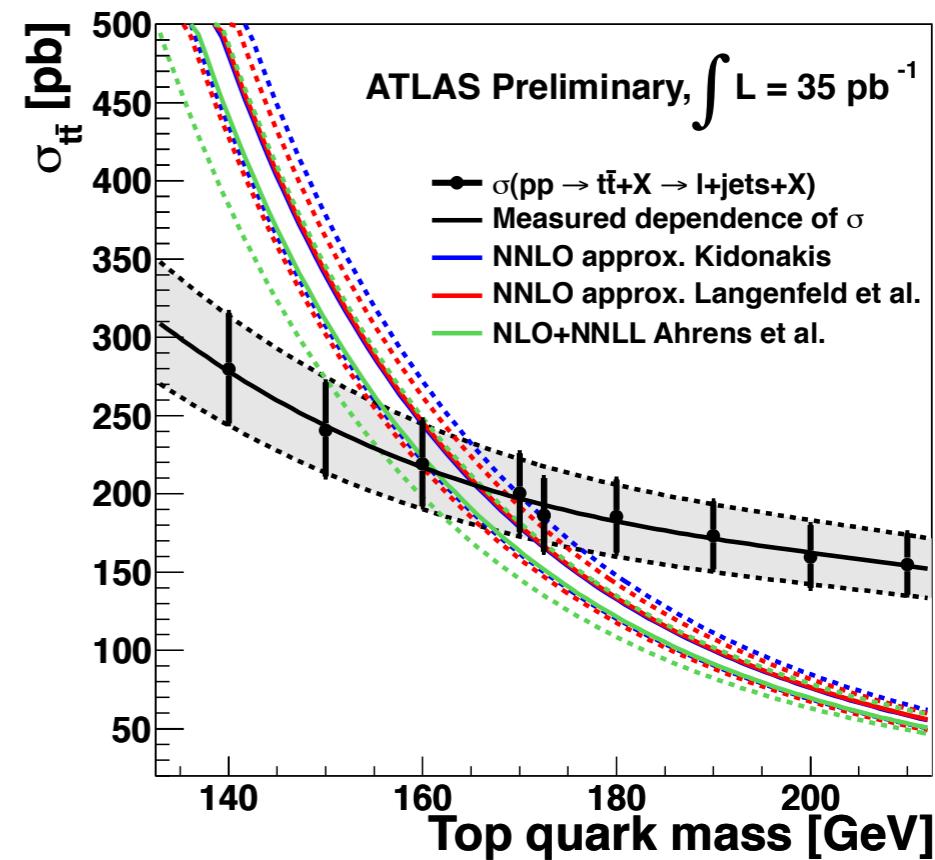
- Top quark mass:
 - Standard model: **key parameter** (relation to W and Higgs mass)
 - Known to high precision from Tevatron: uncertainty only 1.1 GeV (=0.6%) from single experiment (CDF Note 10444)
- 2010 data: **template-based** analyses
 - Lepton+jets selection
 - 1D “stabilized mass” $R_{32} =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

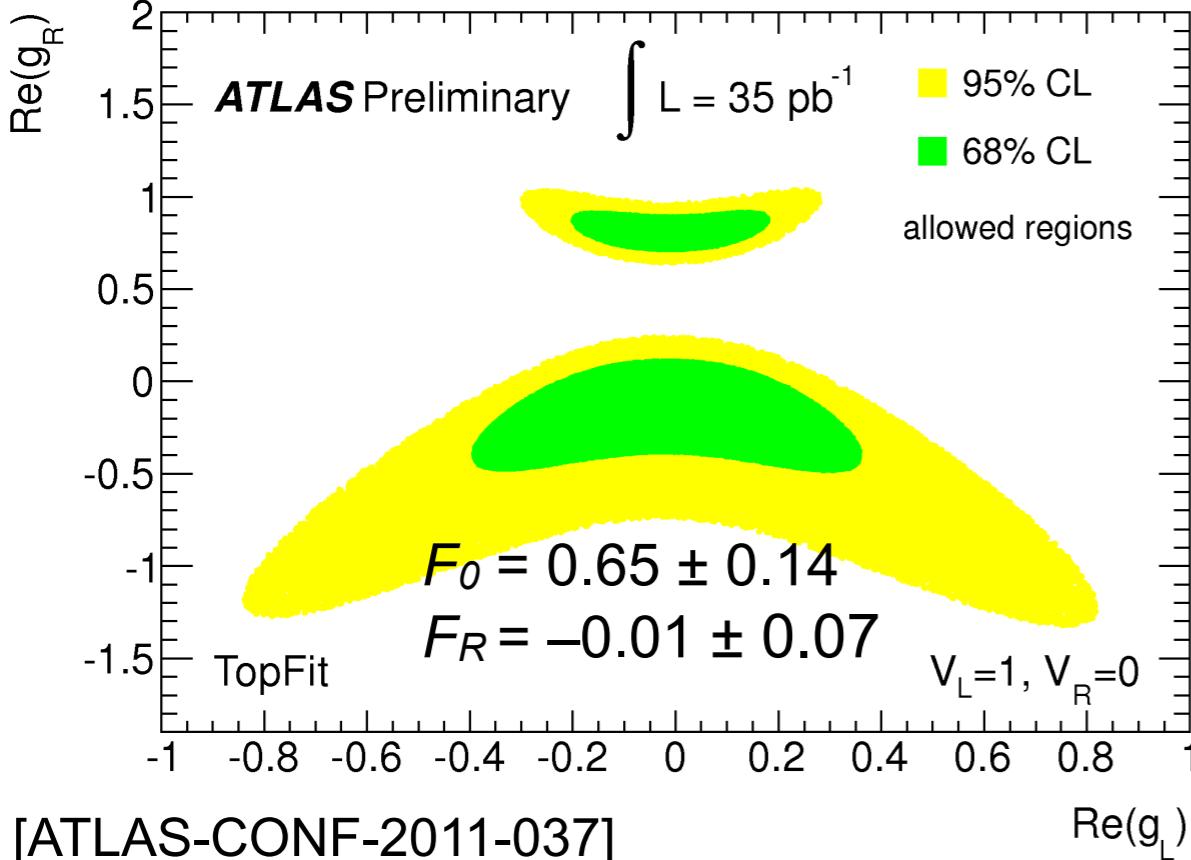
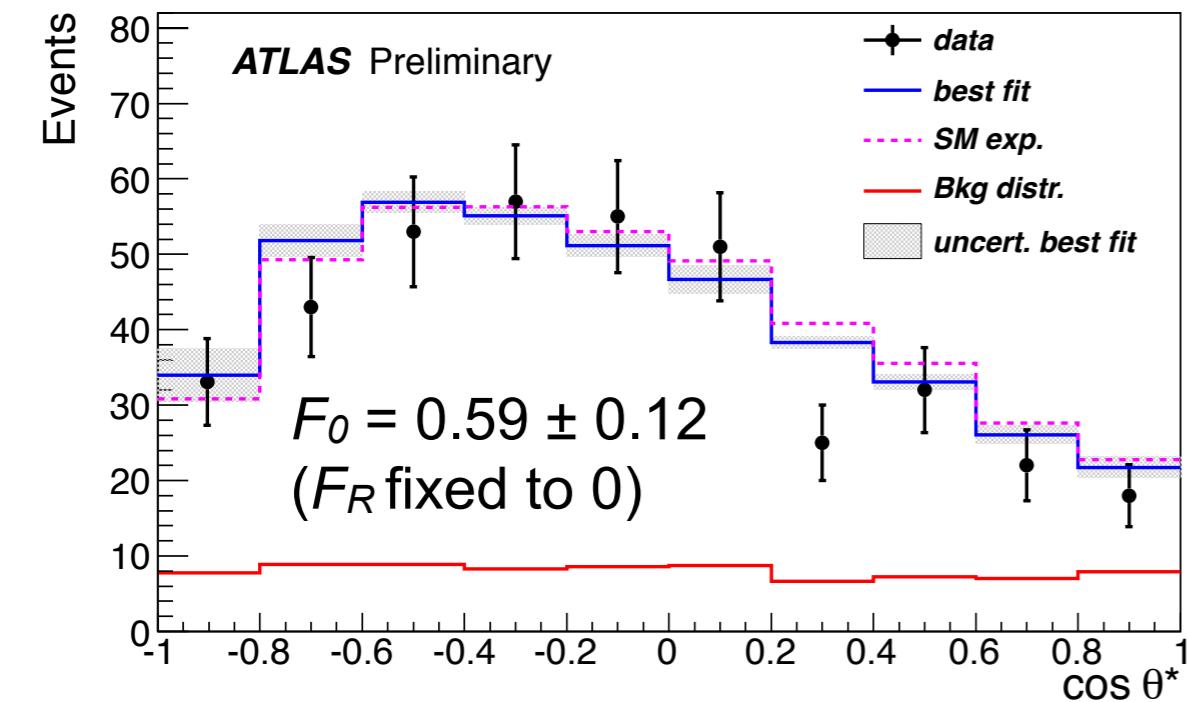
$m_t = 169.3 \pm 4.0(\text{stat.}) \pm 4.9(\text{syst.}) \text{ GeV}$

(3.7% total uncertainty)



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





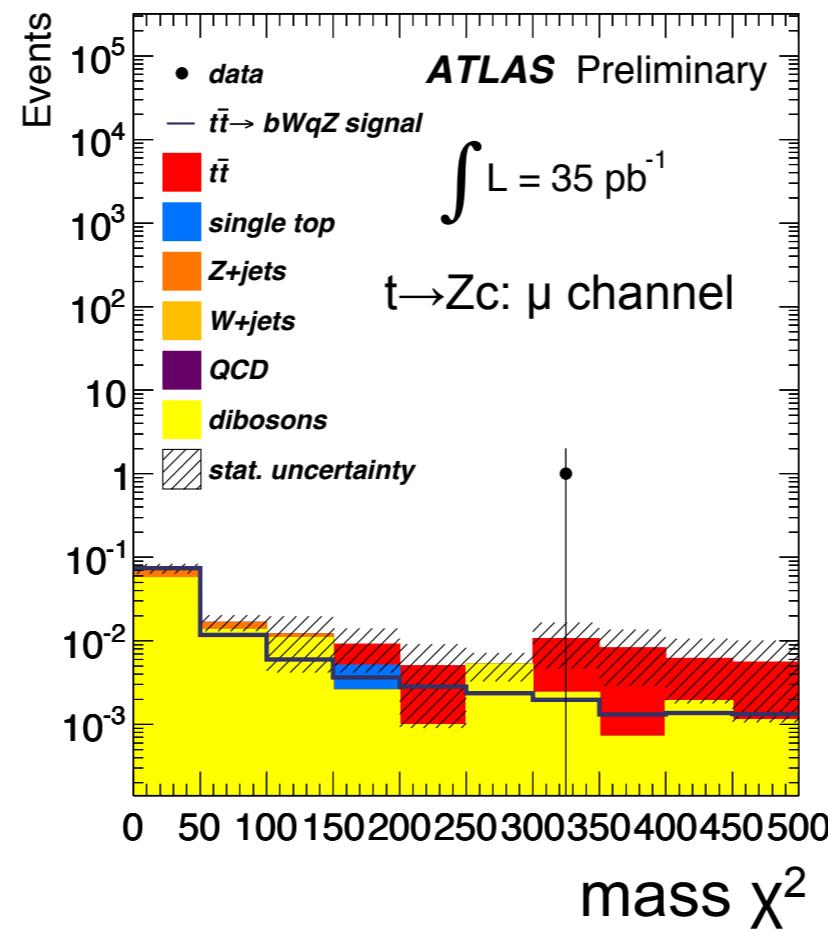
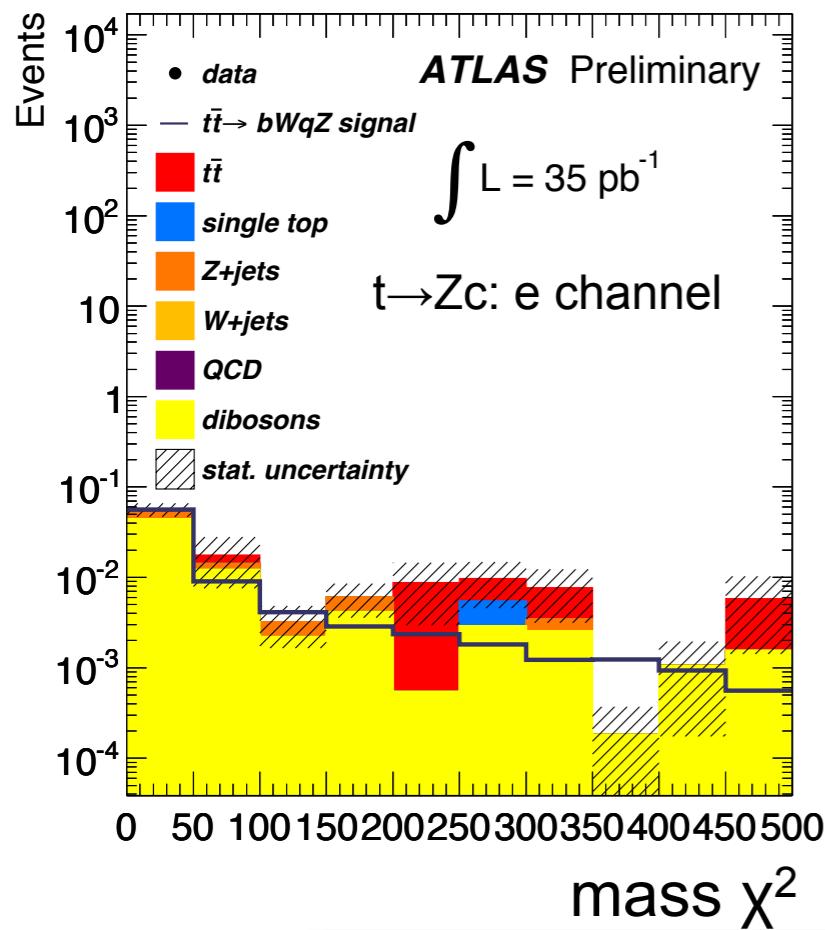
[ATLAS-CONF-2011-037]

- 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 “ $\cos \theta^*$ ”: 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 $\cos \theta^*$
 - Extract **asymmetries** (e.g. A^{FB}) from $\cos \theta^* \rightarrow$ correct back to parton level
- Interpretation: limits on **anomalous couplings** g_L, g_R

- Top flavor-changing neutral currents (FCNC)

[ATLAS-CONF-2011-061]

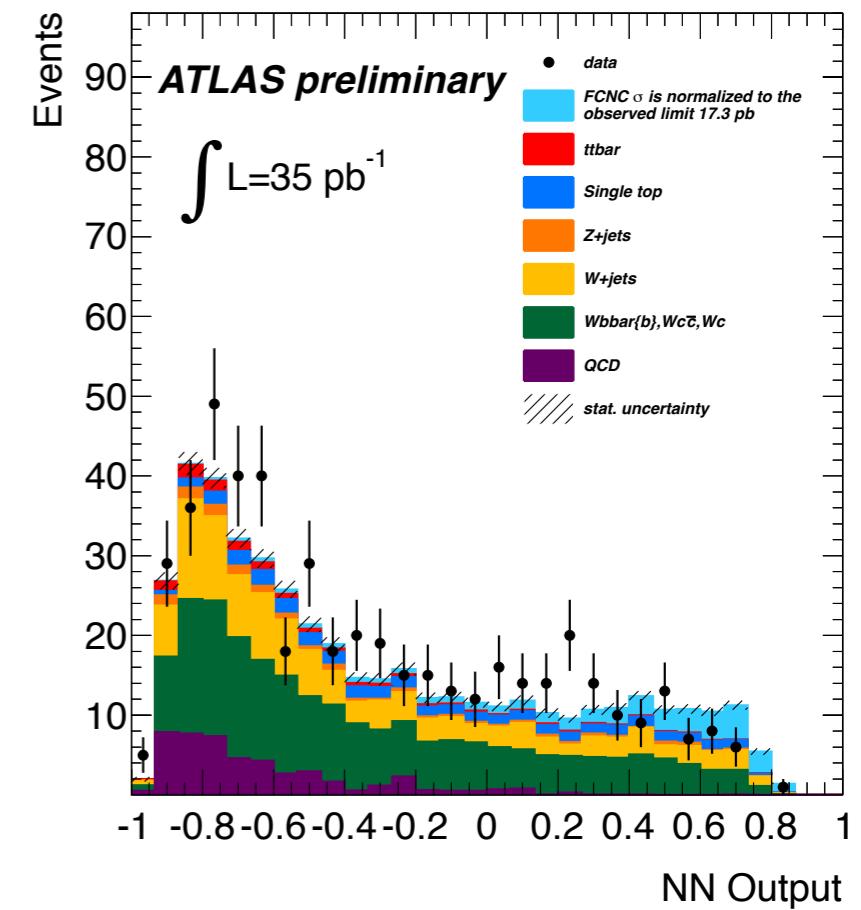
- Extremely rare in standard model ($\text{BR} < 10^{-12}$)
- Current experimental limits much weaker, e.g.
 $B(t \rightarrow Zq) < 3.2\%$ at 95% C.L.
(DØ, arXiv:1103.4574 [hep-ex])



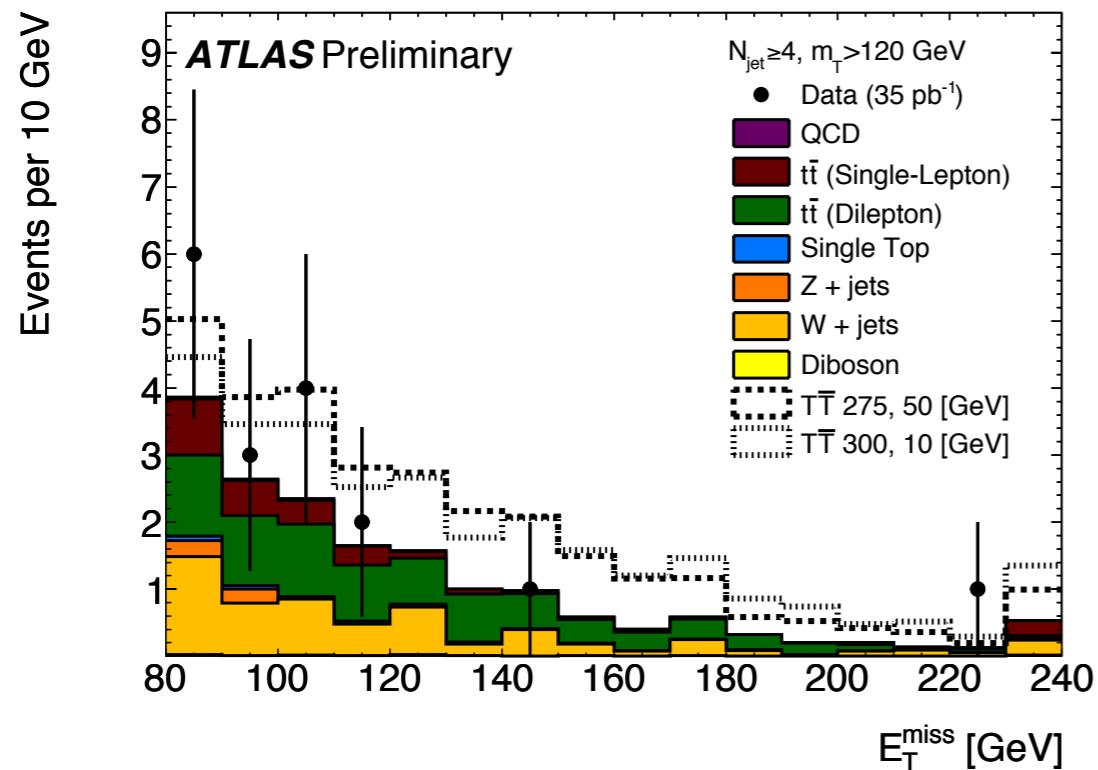
Decay $tt \rightarrow Zq Wb$

Signature: three leptons + jets + missing E_T
 $\rightarrow \text{Limit: } B(t \rightarrow Zq) < 17\% \text{ (95\% C.L.)}$

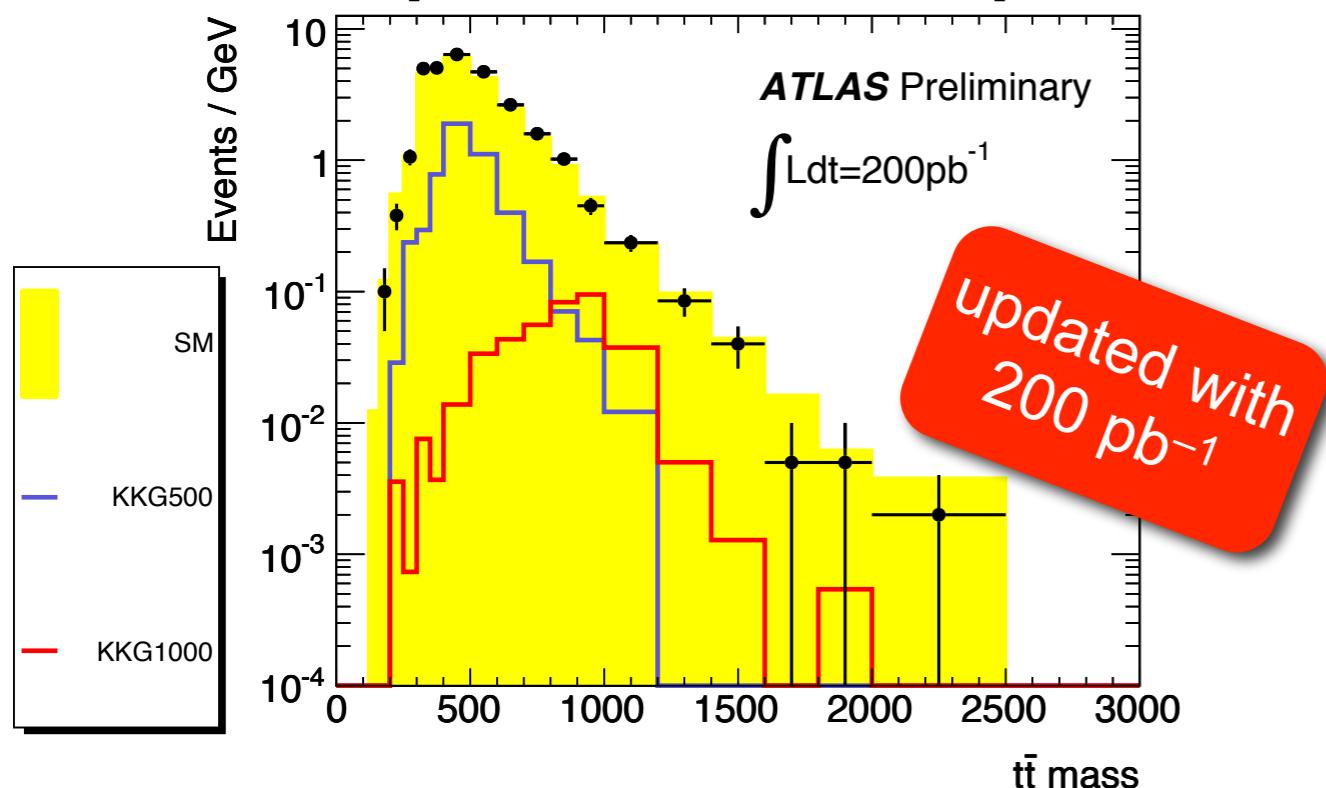
Single top: $qg \rightarrow t \rightarrow Wb$
Signature: $W + b\text{-jet} + \text{MET}$
 $\rightarrow \text{Limit: } \sigma(qg \rightarrow t) \times B(t \rightarrow Wb) < 17 \text{ pb (95\% C.L.)}$



[ATLAS-CONF-2011-036]



[ATLAS-CONF-2011-087]



- 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 $\text{MET} > 80 \text{ GeV}$ and $m_T > 120 \text{ GeV}$
 - Exclude T with 300 GeV (275 GeV) for A^0 mass $< 10 \text{ GeV}$ (50 GeV) at 95% C.L.
- 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: $\sigma(Z') \times B(Z' \rightarrow t\bar{t}) < 38 \text{ pb}$ (3.2 pb) for $M_{Z'} = 500 \text{ GeV}$ (1300 GeV) at 95% C.L.
 - Exclude Kaluza-Klein gluons with $m < 650 \text{ GeV}$ at 95% C.L.

- 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

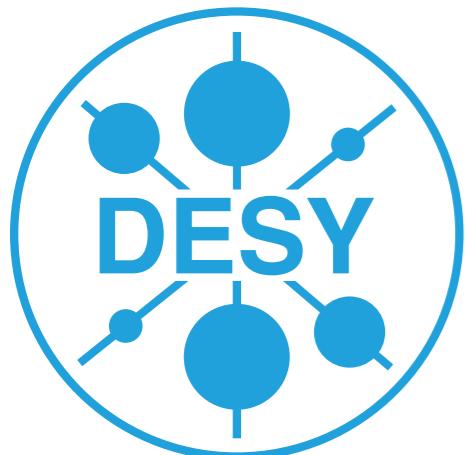


Topics for Discussion



- 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? a_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 $\sqrt{s} = 7 \text{ TeV}$	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 $\sqrt{s} = 7 \text{ TeV}$ 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 $\sqrt{s} = 7 \text{ TeV}$ 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 $\sqrt{s} = 7 \text{ TeV}$ 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>]