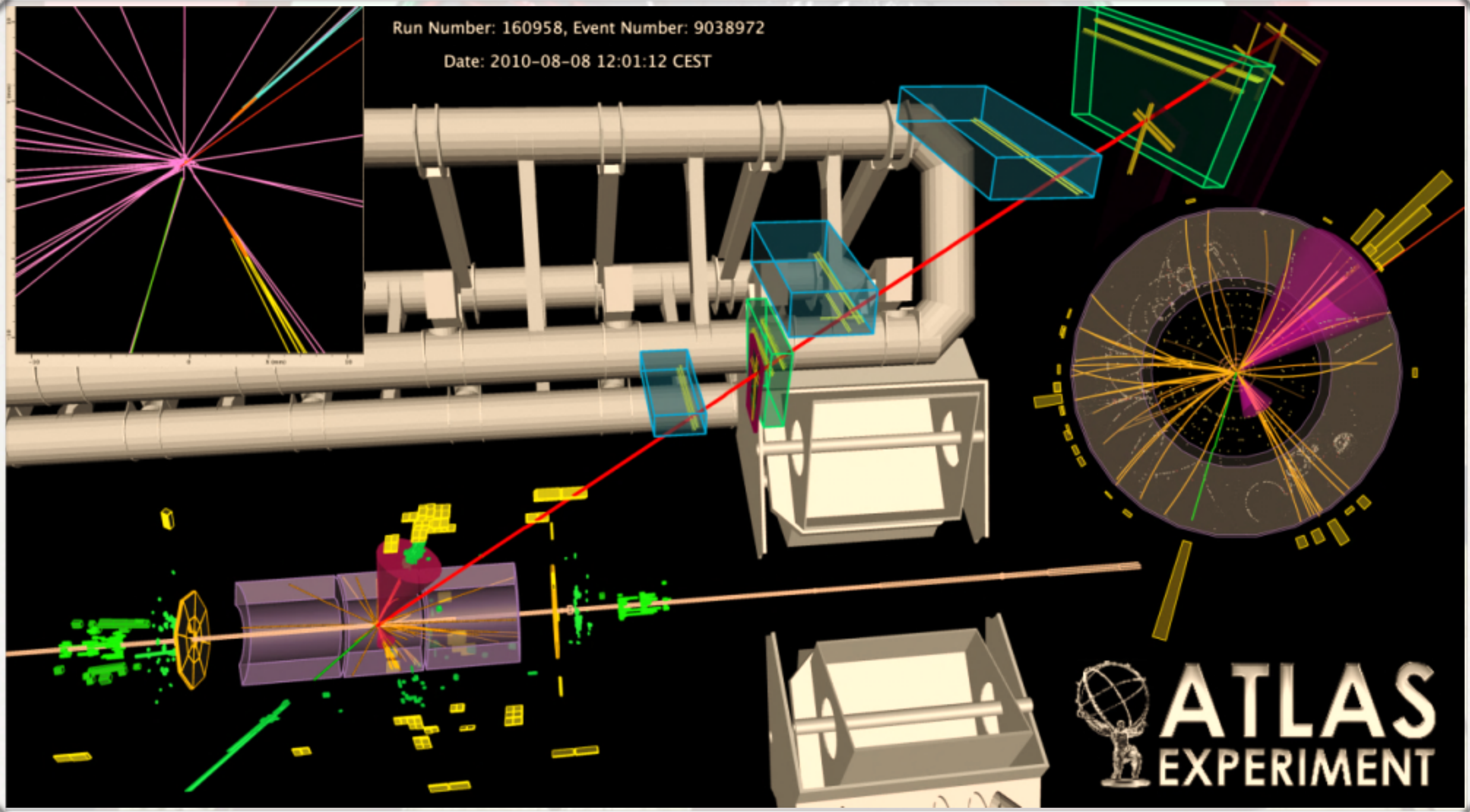
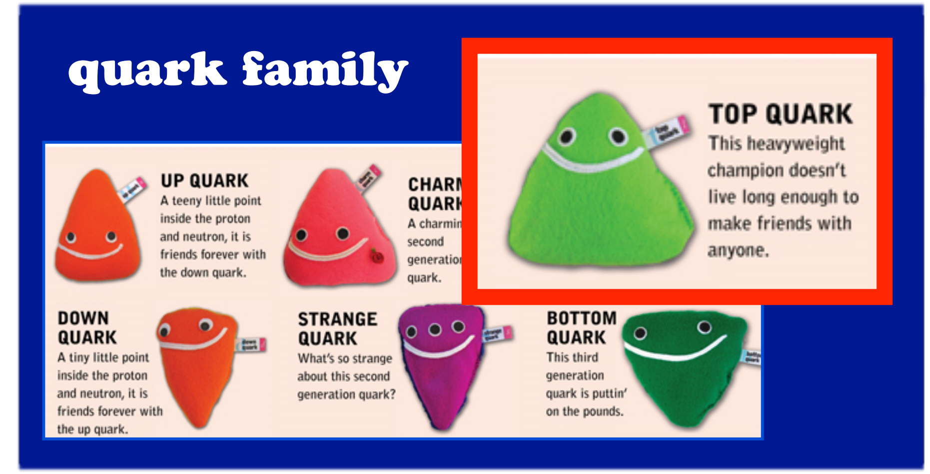
Measurement of Top Quark Production and Properties with the ATLAS Detector



IPPP, Durham
Standard Model @ LHC 2011
April 11th, 2011

Kirika Uchida, University of Bonn
on behalf of
the ATLAS Collaboration

Why top physics?



Heaviest yet fundamental particle

Decays as a free quark

New physics might affect its properties

- **Examples of interesting top measurement.**
  - **Pair-production cross-section (QCD)**
    Study different decay channels
  - **Single top production (EWK)**
    t-channel, Wt-channel, s-channel
  - **Properties: mass**, width, charge, spin
  - **Wtb vertex**
    W helicity, anomalous coupling
  - **Anomalous production**
    Resonances, **modified final state**

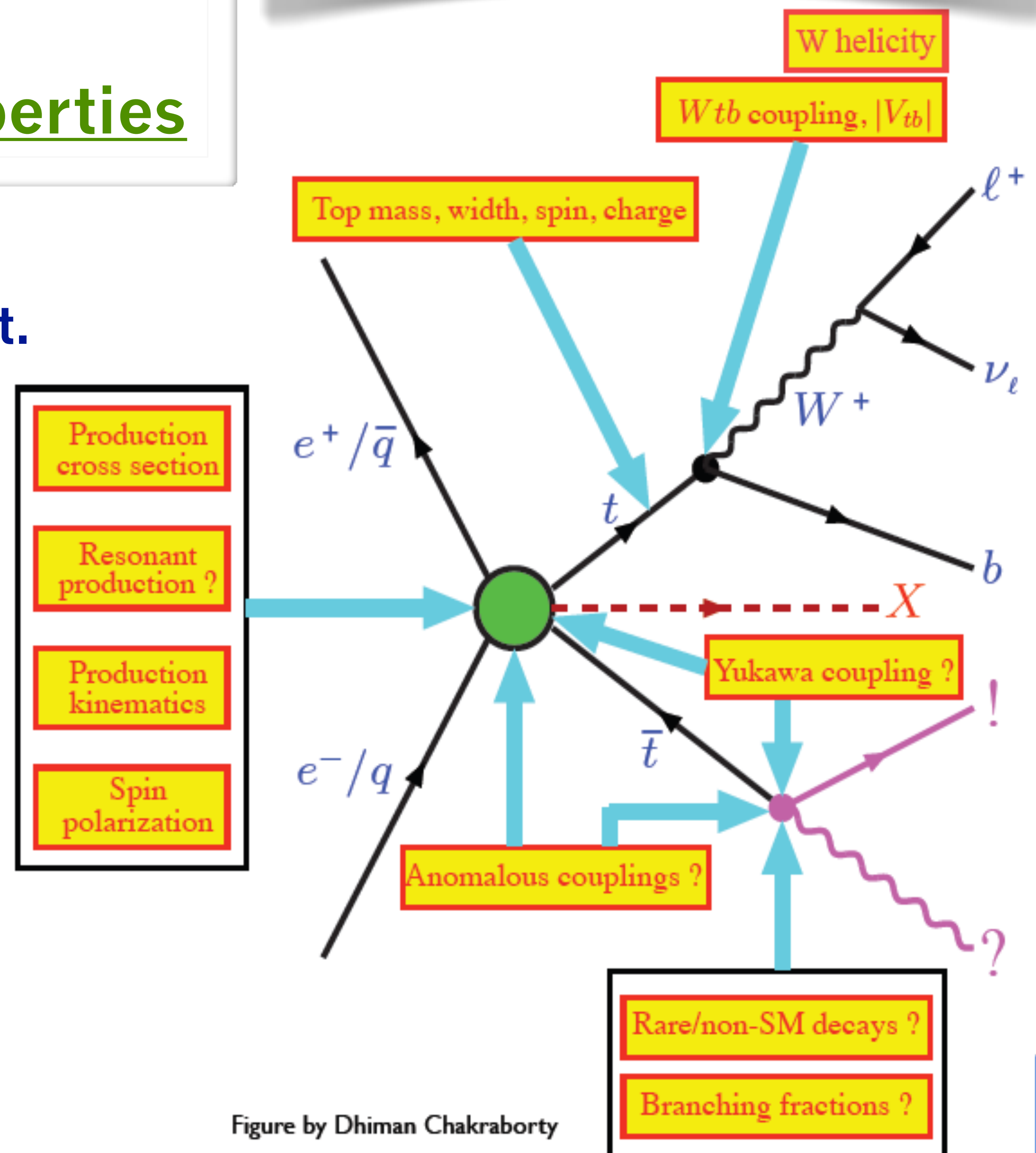


Figure by Dhiman Chakraborty

ATLAS detector and data

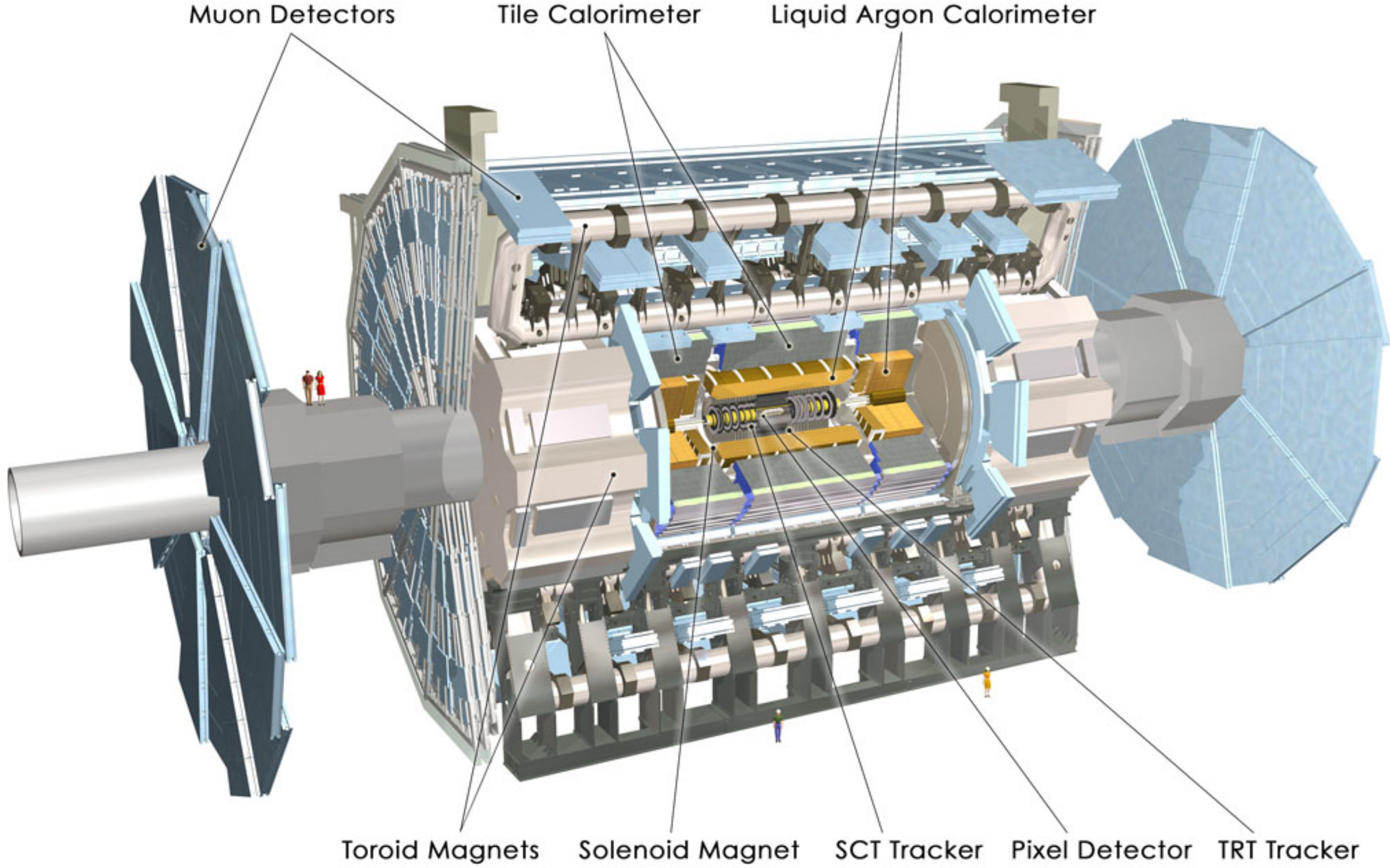
ATLAS EXPERIMENT

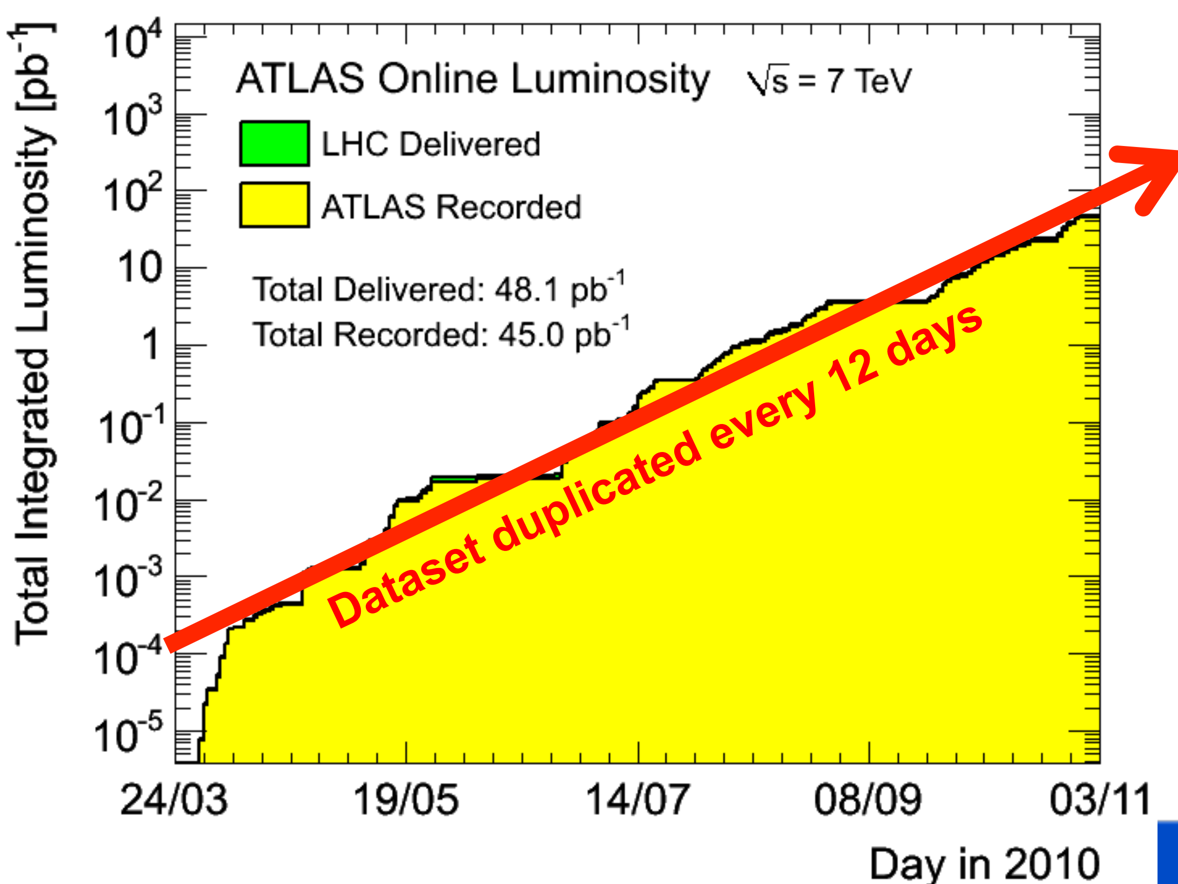
▸ Data collected in 2010 (pp collisions at $\sqrt{s}$ = 7 TeV)

- Pile-up now up to $\langle n_{vtx} \rangle = 4$
- Peak lumi $2.1 \times 10^{32}\ cm^{-2}\ s^{-1}$
- Single lepton triggers ~35 pb^{-1}
- Lumi. uncertainty down to 3.4%

Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.1	99.9	100	90.7	96.6	97.8	100	99.9	99.8	96.2	99.8

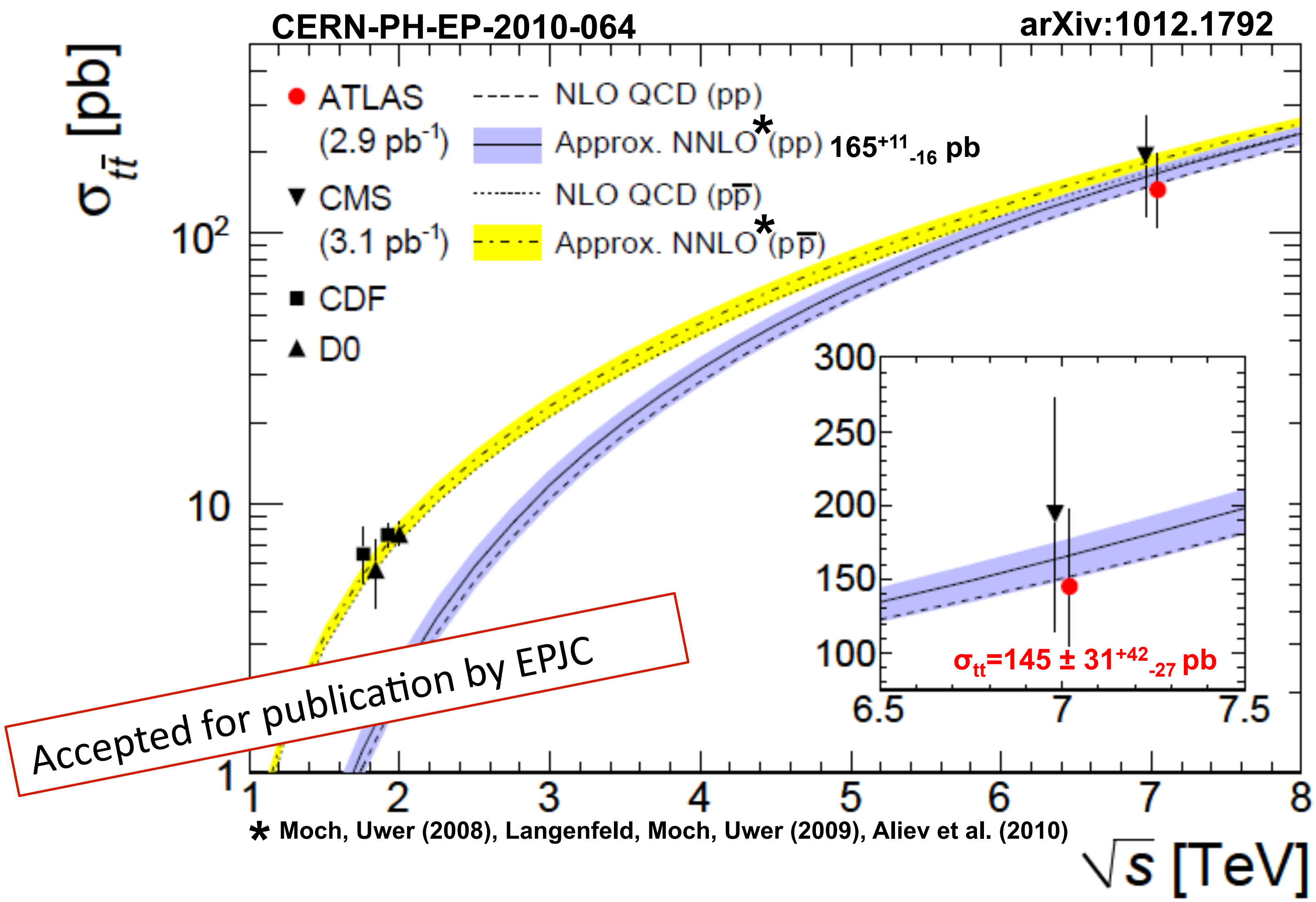
Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in pp collisions at √s=7 TeV between March 30th and October 31st (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future.





First top quarks at LHC

- **ATLAS (single, di-lepton) and CMS (di-lepton) measure σ_{tt}**



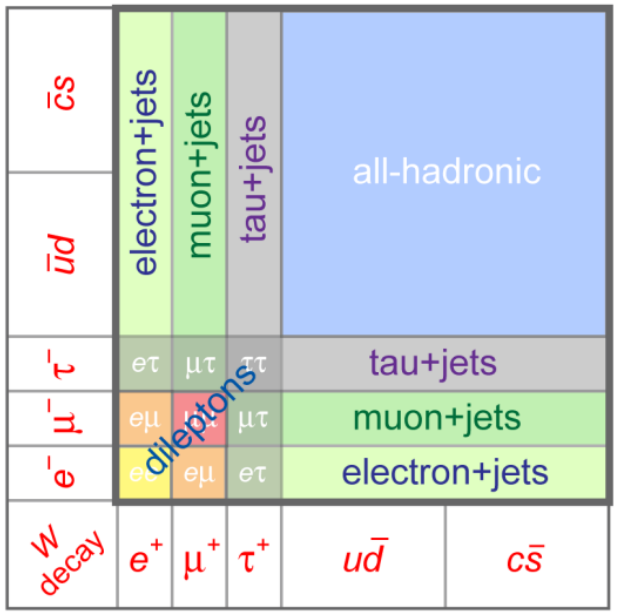
- **Essential ingredients:**

  QCD multijet background; W,Z+jets; b-tagging calibration

History of top quark measurements at ATLAS

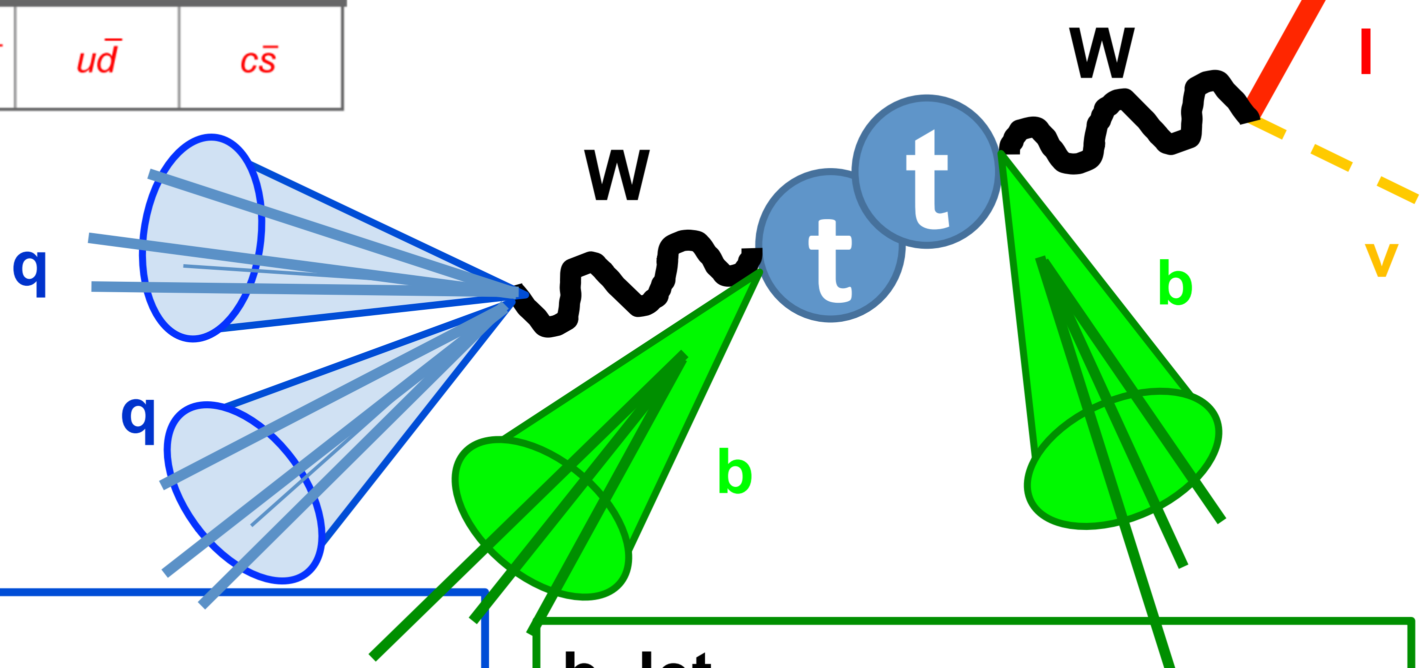
- **$280\ nb^{-1}$**
  - First event display (ATLAS-CONF-2010-063)
  - Background distributions (ATLAS-CONF-2010-087)
- **$2.9\ pb^{-1}$**
  - Cross section measurement publication on EPJC (arXiv:1012.1792)
- **Production cross section ($35\ pb^{-1}$)**
  - Single lepton pre-tag (ATLAS-CONF-2011-023)
  - Single lepton b-tag (ATLAS-CONF-2011-035)
  - Dilepton (ATLAS-CONF-2011-034)
  - Combination (ATLAS-CONF-2011-040)
  - Single top (ATLAS-CONF-2011-027)
- **Properties ($35\ pb^{-1}$)**
  - Mass (ATLAS-CONF-2011-033)
  - W helicity (ATLAS-CONF-2011-037)
  - tt + anomalous E_T^{miss} (ATLAS-CONF-2011-036)

Selecton of Top Quarks



Electron
- Good isolated calo object
- Matched to track
- E_T>20 GeV
- |η|∈[0;1.37][1.52;2.47]

Muon
- Segments in tracker and muon detector
- Isolated track
- p_T > 20 GeV
- |η| < 2.5



E_T^{miss}
- Vector sum of calo energy deposits
- Corrected for identified objects

Jet
- Topological clusters
- Anti-k_T (R=0.4)
- MC-based calibration
- p_T > 25 (20) GeV
- |η| < 2.5

b-Jet
- Displaced tracks or secondary lepton
- SV0: reconstruct sec.vertex
- JetProb: track/jet compatibility with primary vertex

Event cleaning
- Good run conditions
- PV at least 5 tracks
- Bad jet veto
- Cosmic veto (μμ)

data driven estimation of W+jets, fake(QCD), Z+jets

W+jets in single lepton channel

W / Z

- making use of clean Z+jets
- SR: ≥ 4 jets, CR: 1 jet

$$W^{\geq 4\text{jets}} = W^{1\text{jet}}_{data}(Z^{\geq 4\text{jets}}/Z^{1\text{jet}}) \cdot C_{\text{MC}}$$

$$C_{\text{MC}} = \frac{(W^{\geq 4\text{jets}}/W^{1\text{jet}})_{MC}}{(Z^{\geq 4\text{jets}}/Z^{1\text{jet}})_{MC}}$$

W^+/W^-, W charge asymmetry

- top pairs, QCD multi-jets, and Z+jets are charge symmetric but $W^+ > W^-$ due to PDF effect.

$$N_{W^+} + N_{W^-} = \left(\frac{r_{MC}+1}{r_{MC}-1}\right)(D^+ - D^-)$$

$$r_{MC} \equiv \frac{\sigma(pp \to W^+)}{\sigma(pp \to W^-)}$$

Channel	W/Z ratio **Electron**	W/Z ratio **Muon**	W^+/W^- **Electron**	W^+/W^- **Muon**
Estimated $W \to l\nu$	150	290	n.a.	n.a.
Estimated $W \to \tau\nu$	6	19	n.a.	n.a.
Statistical uncertainty	21%	17%	33%	27%
Purity of control samples	3%	2%		
Theoretical uncertainties	12%	9.4%	8.2%	7.0%
Jet energy scale	3%	3%	3.6%	3.6%
Total W+jets background	160 ± 40	310 ± 60	240 ± 80	380 ± 110

fake (QCD) & Z+jets

- **fake:**
  - **Matrix method**

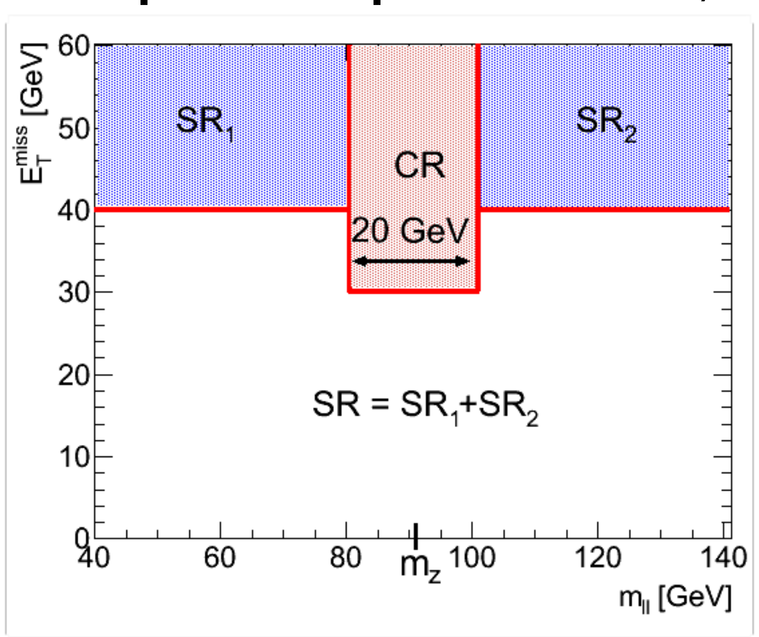
$$N^{\text{loose}} = N^{\text{loose}}_{\text{prompt}} + N^{\text{loose}}_{\text{non-prompt}},$$
$$N^{\text{tight}} = \epsilon_{\text{prompt}} N^{\text{loose}}_{\text{prompt}} + \epsilon_{\text{non-prompt}} N^{\text{loose}}_{\text{non-prompt}}$$

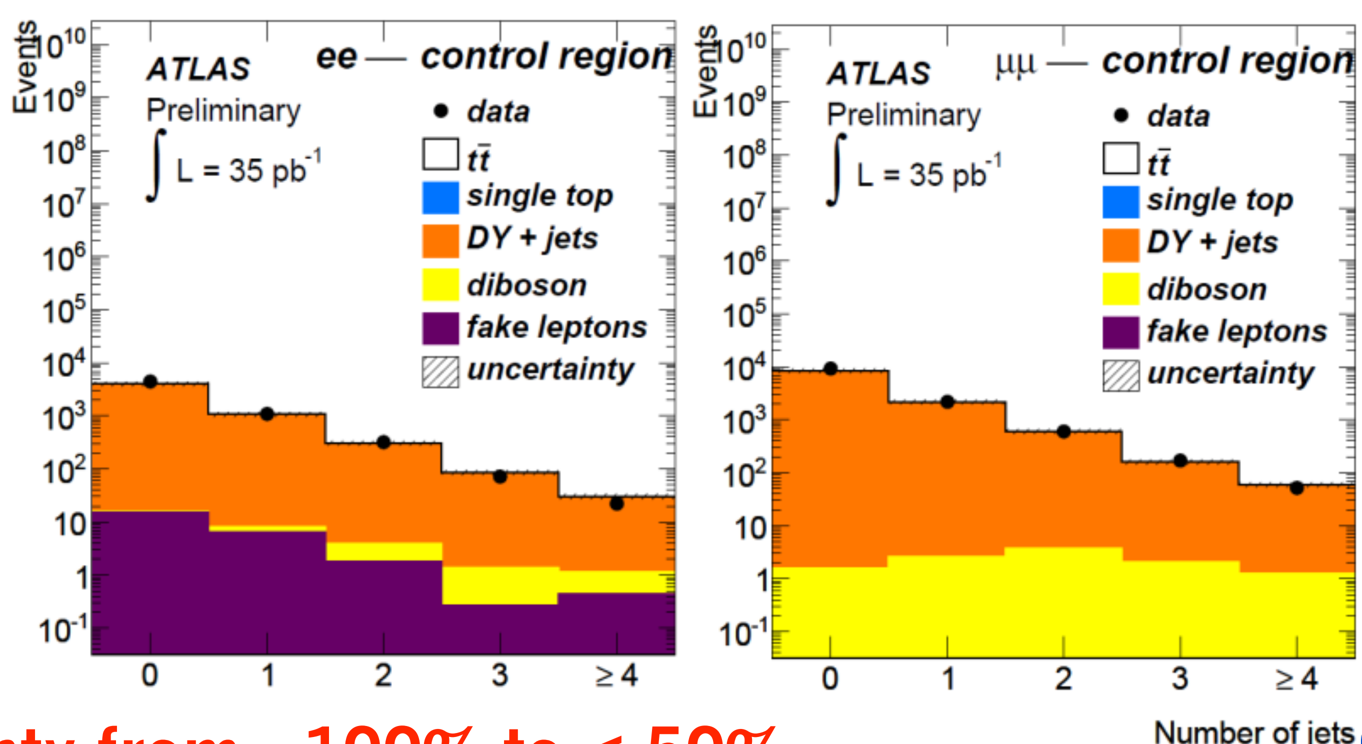
  - **AntiElectron fitting method**
    - Fit with fake template; AntiElectron: some electron ID is inverted.

- **Z/γ^*+jets : MC-assisted data-driven estimation**

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

SR: $|m_{ll}-m_Z|$ > 10 GeV, high E_T^{miss}





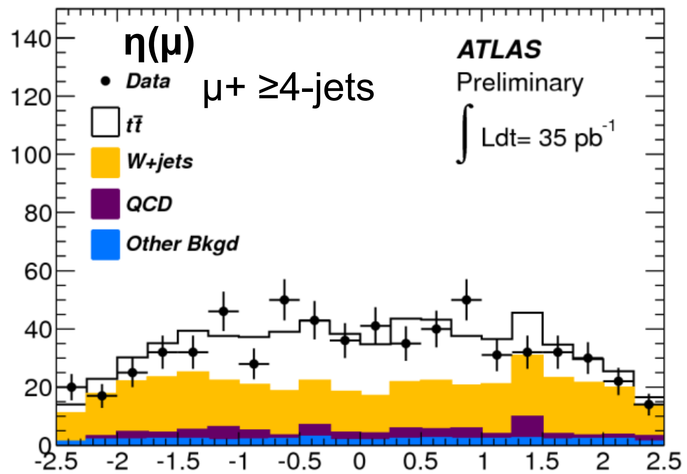
Uncertainty from ~100% to < 50%

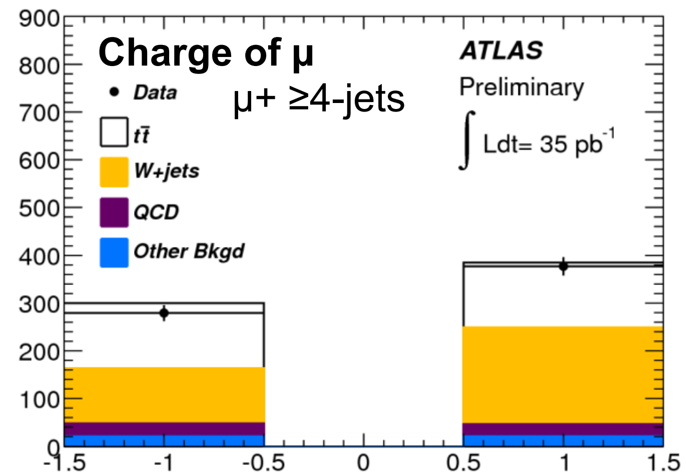
σ_{tt} measurement

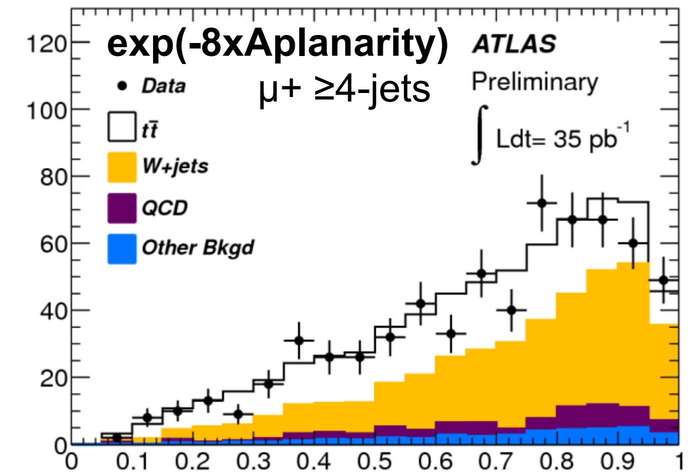
σ_{tt} single lepton (no b-tagging)

ATLAS-CONF-2011-023

- **Projective likelihood based on uncorrelated discriminating variables**
  - Three variables chosen:

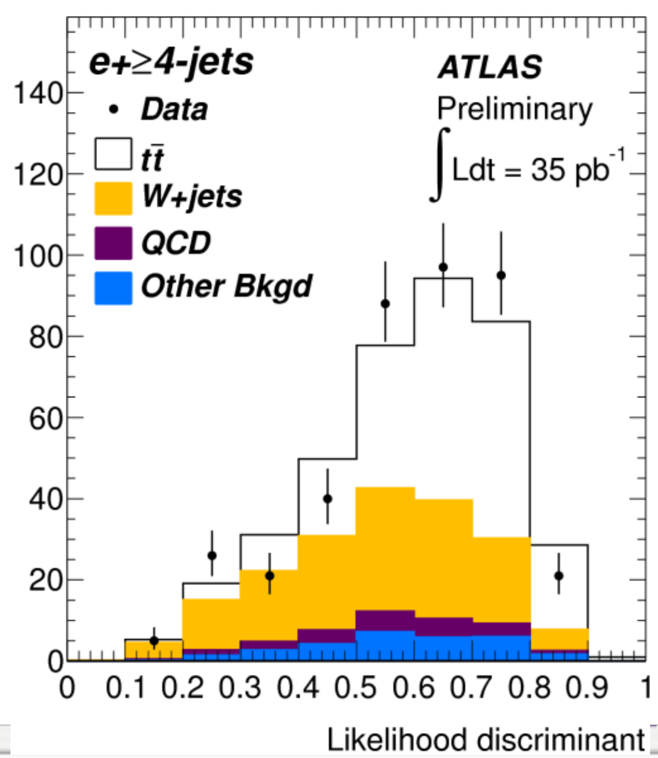






  - Binned maximum likelihood to 4 channels (3-jets, ≥ 4-jets; e, μ)

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



Syst. source	Rel. unc. %
Jet en. scale & Reconstruction	-6.1 / +5.7
ISR/FSR	-2.1 / +6.1
QCD norm.	3.9
QCD shape	3.4
Parton shower & hadronisation	3.3
Total syst.	**-10.2 / +11.6**

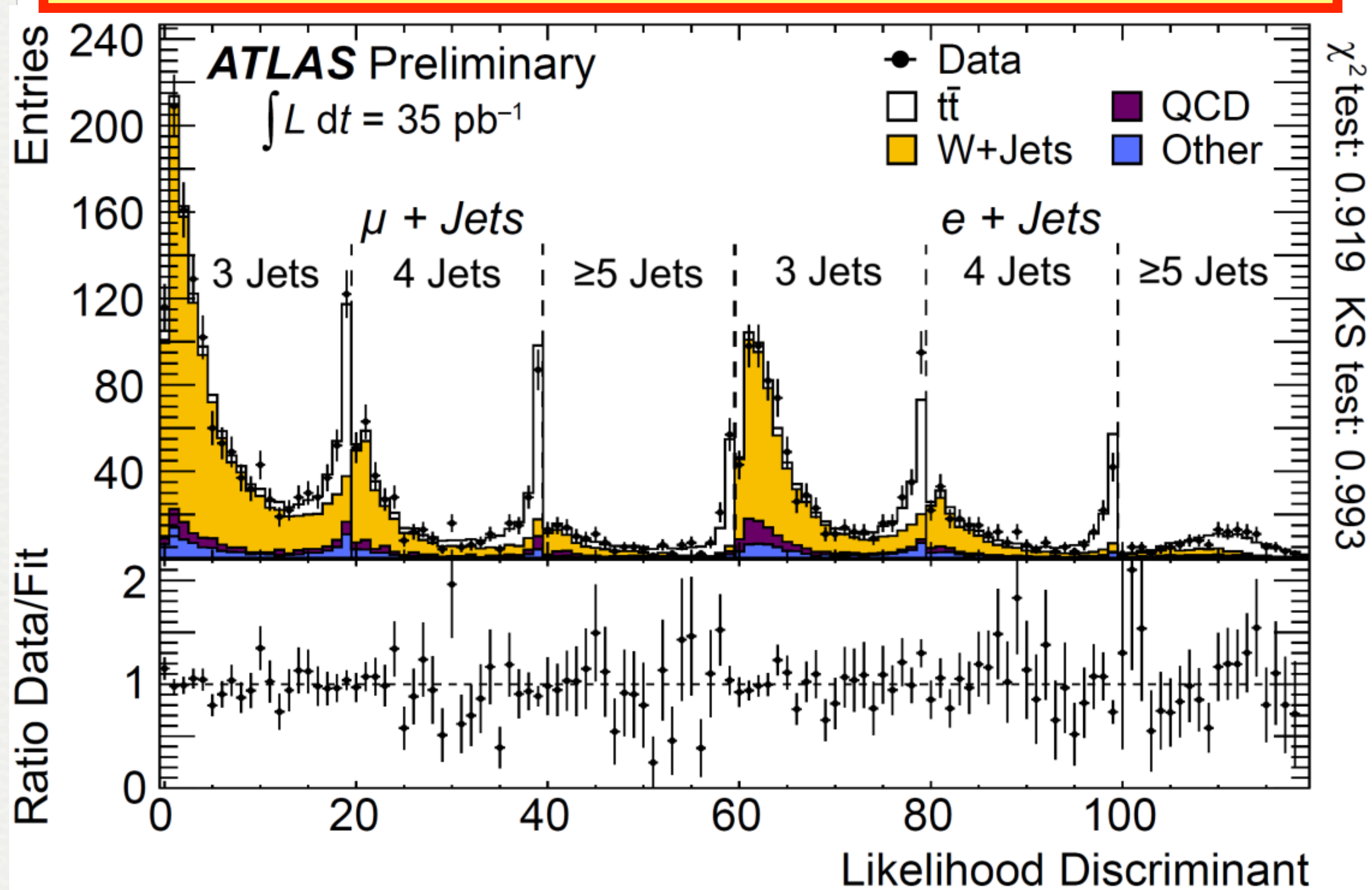
- **Independent of b-tagging**
  - avoids related systematic uncertainty at the price of a worse S/B ratio
  - Relative uncertainty ~15%
  - cross-checked by cut-and-count and 1d χ^2 and likelihood fits

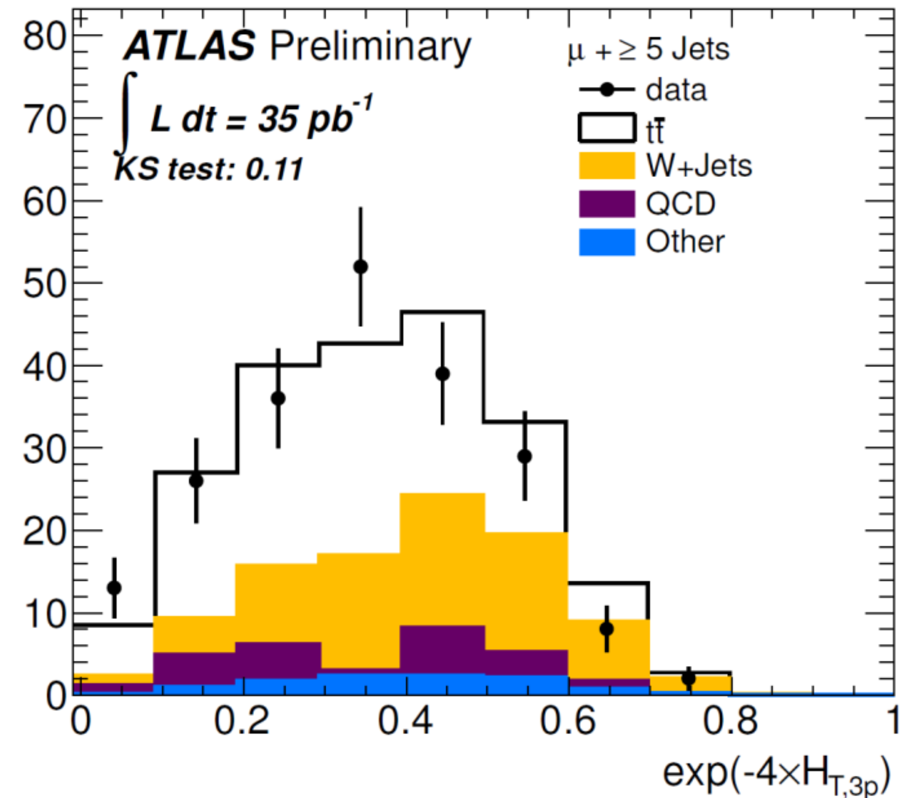
σ_{tt} single lepton with b-tags

ATLAS-CONF-2011-035

- **Multivariate method**
  - split up to six channels (3, 4, ≥5 jets, e, μ)
- **Input variables**
  - lepton η, aplanarity, $H_{T,3p}$, b-tag weight
- **Profile likelihood fit extracts**
  - 16 norm. parameters, including σ_{tt}

σ_{tt} = 186 ± 10(stat) $^{+21}_{-20}$(syst) ± 6(lumi) pb





- **Fit is set up with**
  - 17 nuisance parameters
  - constrained from data
- **Main systematics**
  - W+jets HF content (7%)
  - Tagger calibration (7%)
- **Cross-check analysis**
  - Cut-and-count, fit to m(jjj)

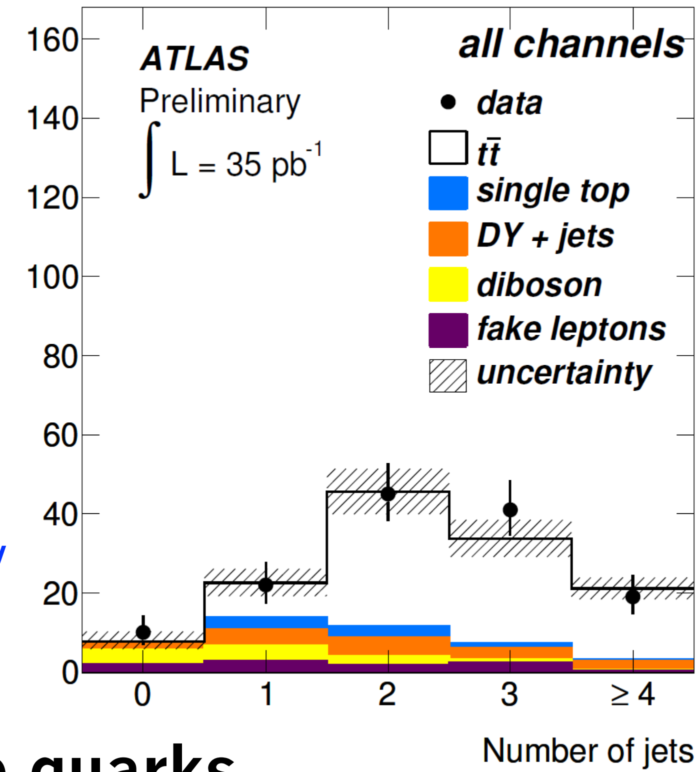
uncert. ~13%

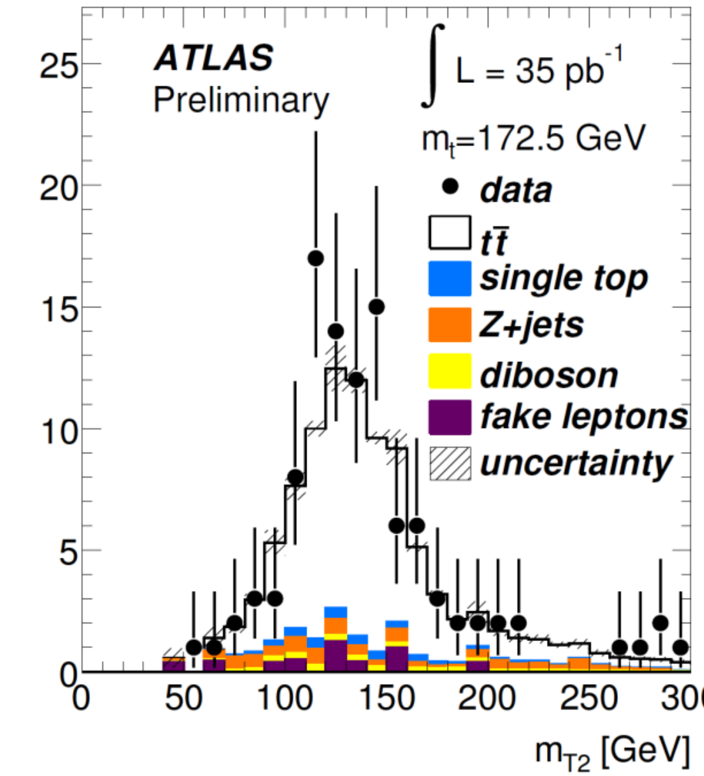
σ_{tt} dilepton

ATLAS-CONF-2011-034

Cut-based method

- require 2 OS hard leptons (e, μ), 20 GeV
- two energetic jets, 20 GeV
- Z+jets is dominating background
  - ee/μμ: $E_T^{miss} > 40$ GeV and $|m_{ll}-m_Z| > 10$ GeV
  - eμ: $H_T > 130$ GeV





- Events in SR are compatible with top quarks

Profile likelihood method to combine channels

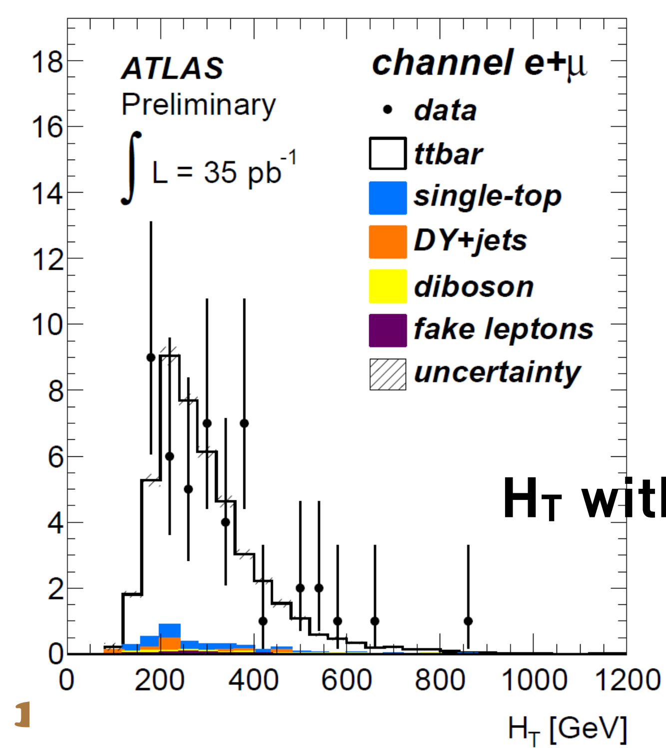
- 105 events selected, 101 ± 9 expected. Data well modeled by MC+DD.

$$\sigma_{tt} = 173 \pm 22(\text{stat})\ ^{+18}_{-16}(\text{syst})\ ^{+8}_{-7}(\text{lumi})\ \text{pb}$$

Main systematics

- Jet energy scale (5%)
- Parton shower model (5%)
- Fakes (4%)

Additional b-tagging requirement improves S/B but the systematics is large.



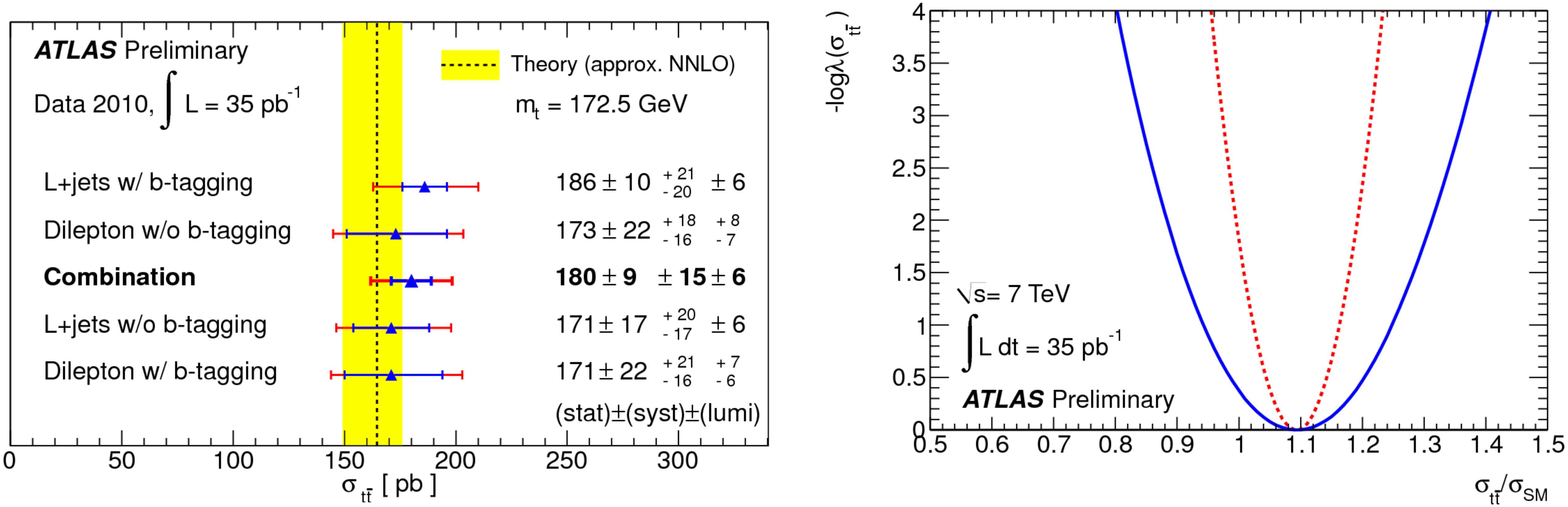
H_T with 1 b-tag

$t\bar{t}$ cross-section combination

‣ Combine single lepton and dilepton channels

- choose most precise: single lepton with b-tag & dilepton w/o b-tag

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



- Statistical uncertainty ~4%
- Systematic uncertainty ~8%
- Luminosity uncertainty ~3%
- Agrees with QCD prediction

$\delta\sigma = 10\ \%$

ATLAS-CONF-2011-040

σ_t measurements

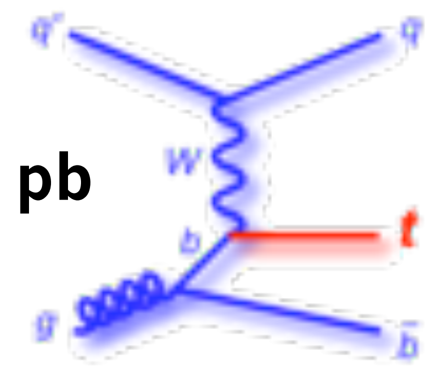
Single top: t-channels

ATLAS-CONF-2011-027

‣ cut-based (likelihood cross-check)

- 1 lepton, 1 b-jet, 1 light-jet, E_T^{miss}
- bkg: QCD multi-jets, W+jets
- final cut $m_{top} \in (130;210)$GeV; $|\eta_{light\text{-}jet}|>2.5$

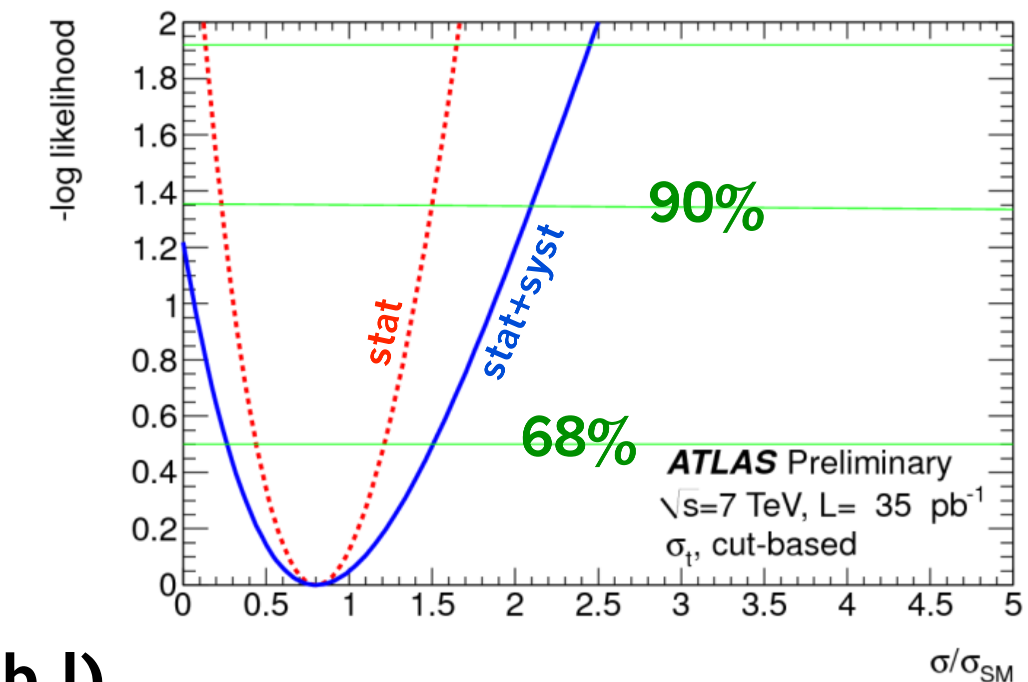
66 pb



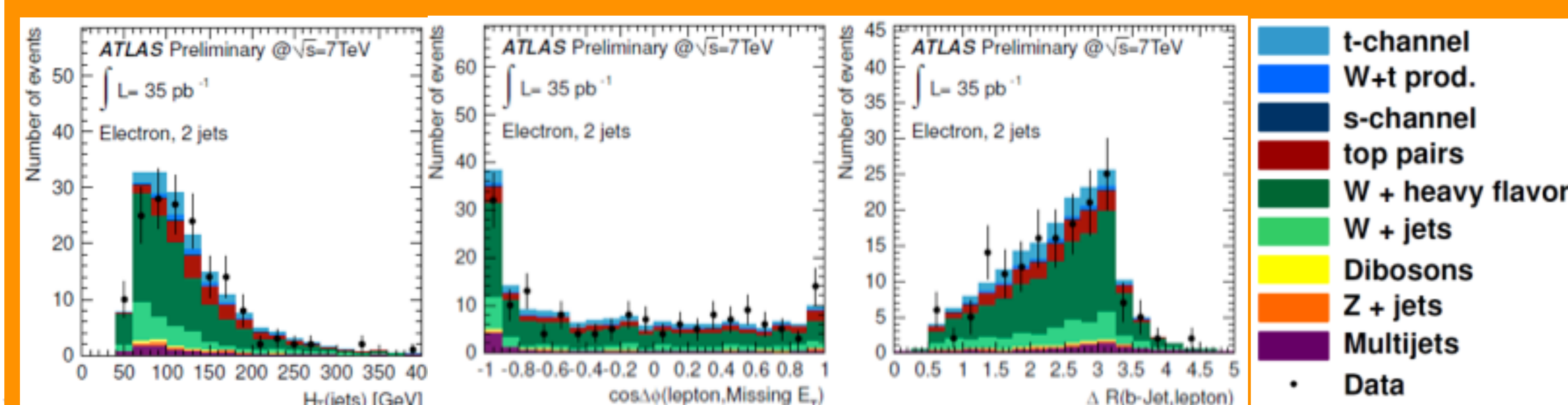
$\sigma_t = 53\ ^{+27}_{-24}(stat)\ ^{+38}_{-27}(syst) = 53^{+46}_{-36}$ pb

significance:1.6σ

	Cut-based		Likelihood	
	Lepton +	Lepton −	Lepton +	Lepton −
t-channel	10.3 ± 1.8	4.4 ± 0.8	8.0 ± 1.8	3.4 ± 0.8
TOTAL Exp	22.7 ± 3.8	13.2 ± 2.8	15.4 ± 3.0	8.8 ± 2.0
S/B	0.83	0.50	1.08	0.62
DATA	21	11	16	11



- likelihood ratio adding $H_T(j)$, $\cos\Delta\Phi(l.E_T^{miss})$, $\Delta R(b.l)$

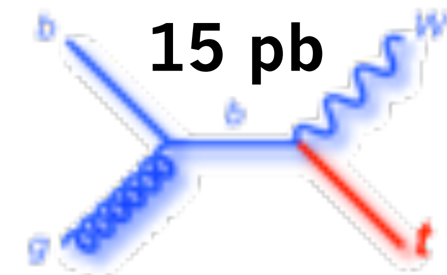


Single top: Wt-channels

ATLAS-CONF-2011-027

- cut-based

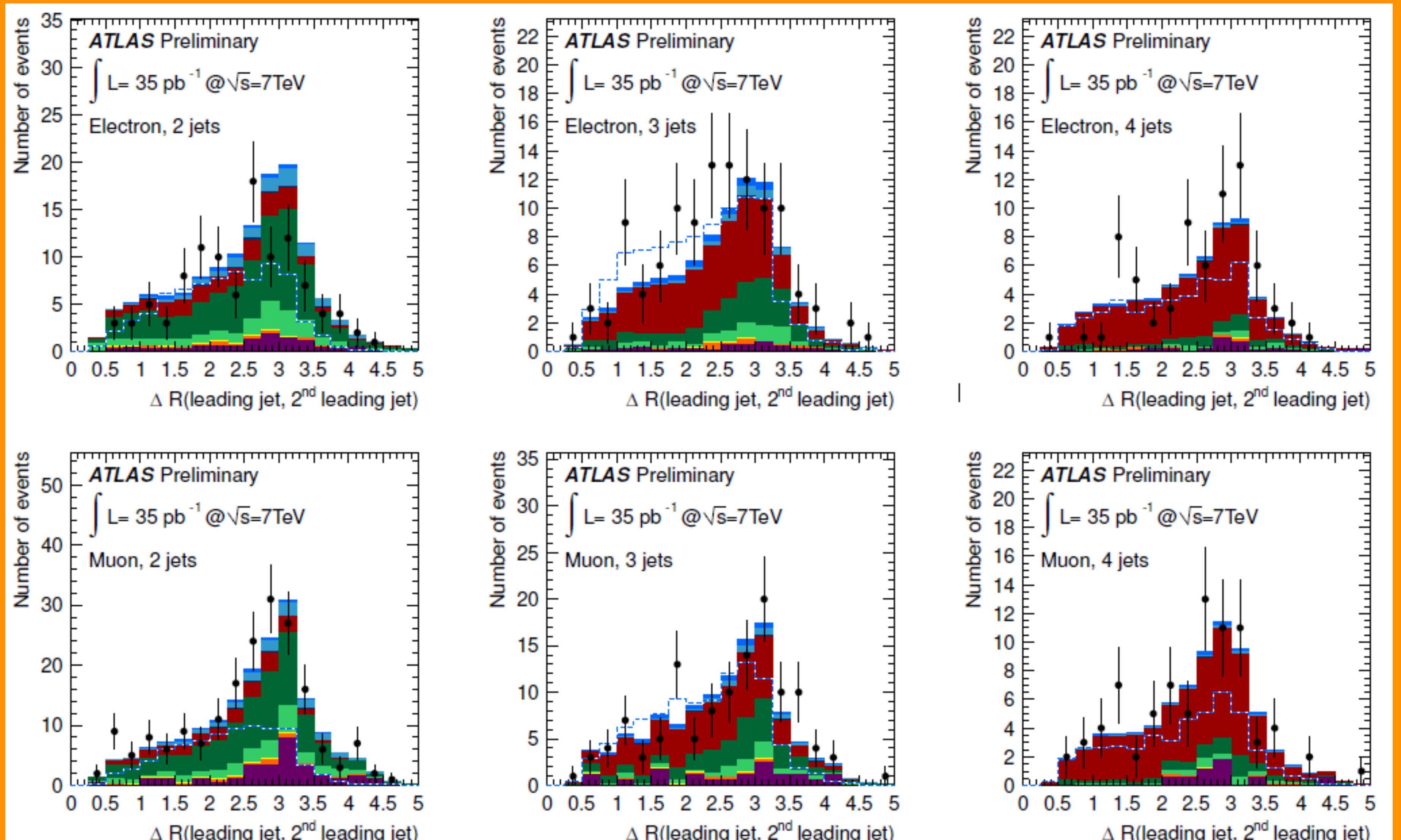
New channel!



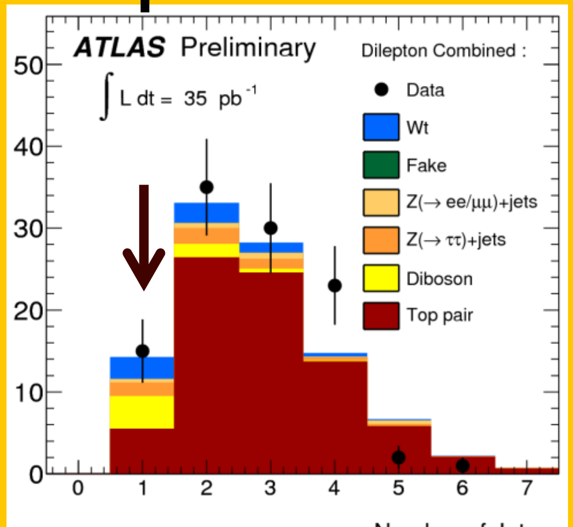
- l+jets:
  2-4 jets, exactly 1b-jet (against tt), ΔR(j1,j2)<2.5 (W+jets)
- dilepton:
  data driven Z+jets, fakes, tt (from Njets>1)
- combine channels, expect σ_{Wt} < 94 pb

σ_{Wt} < 158 pb at 95%

l+jets



dilepton



Top mass,
W helicity,
$T \rightarrow tA0$,

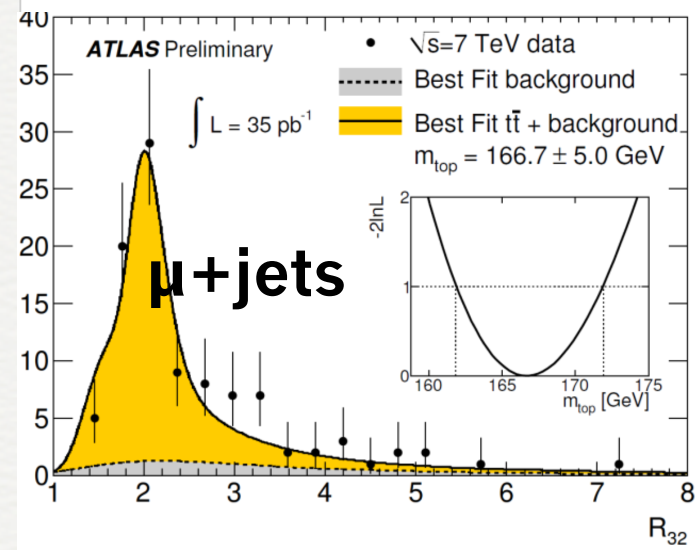
Top quark mass

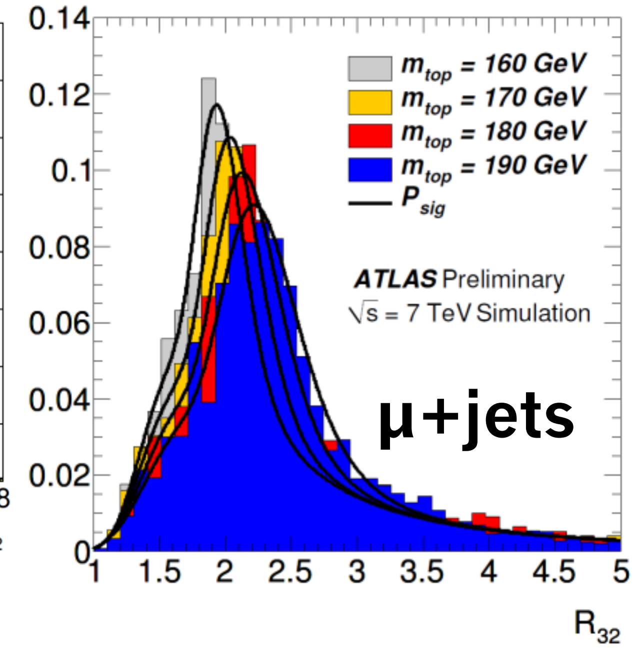
ATLAS-CONF-2011-033

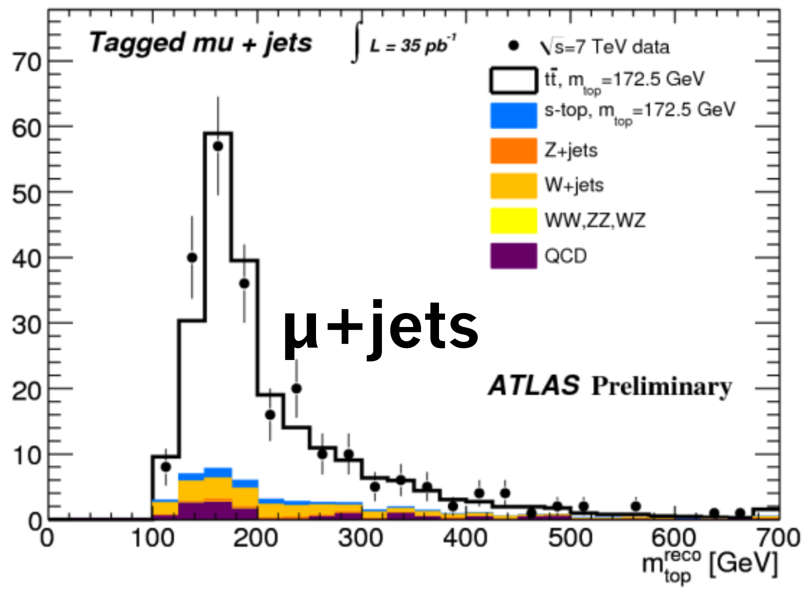
- First ATLAS measurement
  - Main aim: reduce JES uncertainty
- Template in $R_{32} = m_{jjb}(t)/m_{jj}(W)$
- Systematics (b-)JES, ISR/FSR

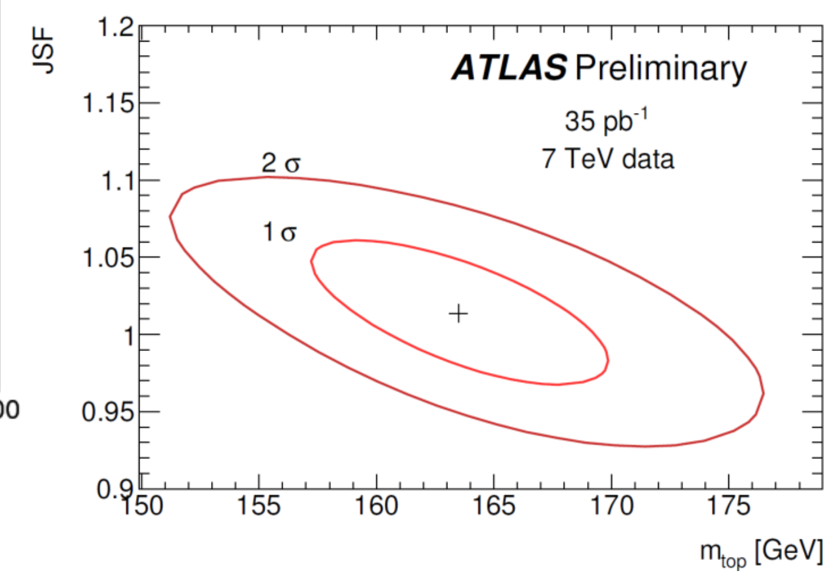
- Cross-checked by
  - kinematic fit templates
  - 2d templates with Jet Scaling Factor

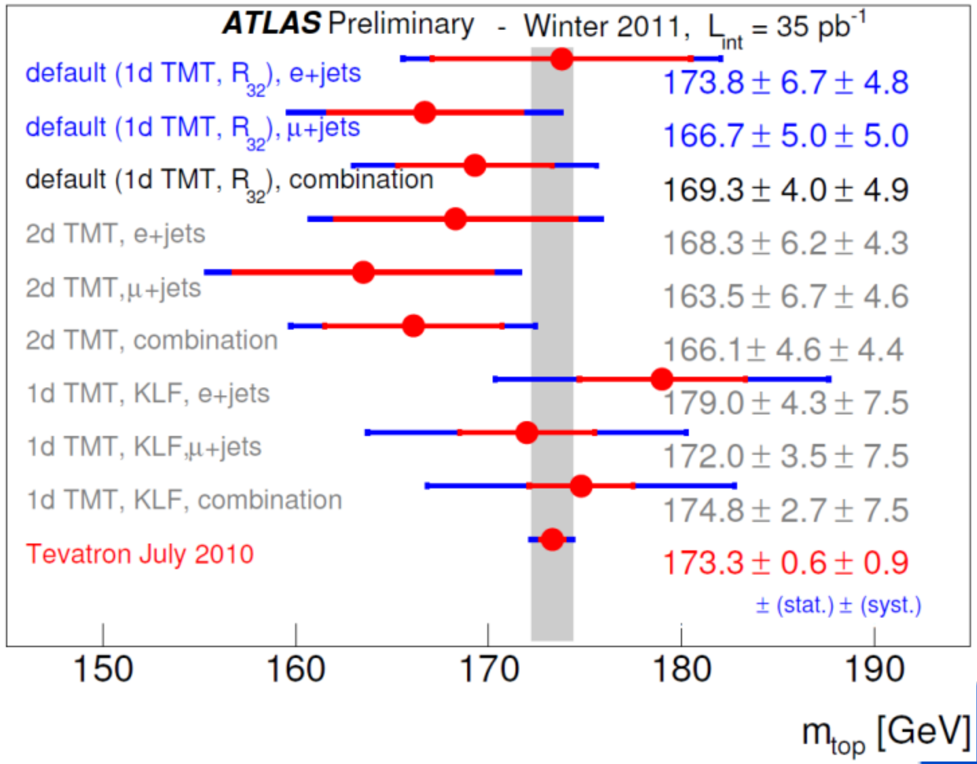
m_{top} = 169.3 ± 4.0(stat) ± 4.9(syst) GeV







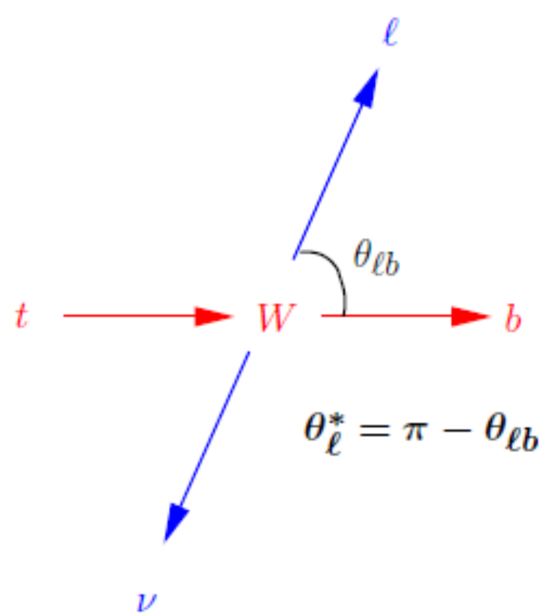


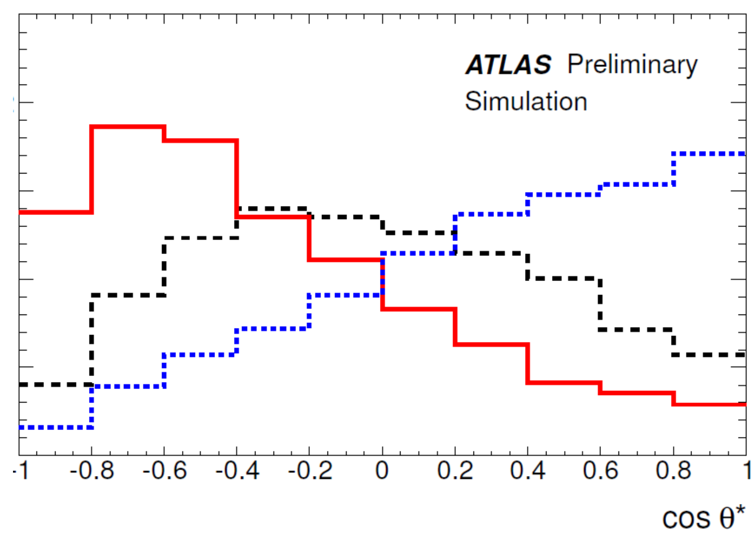


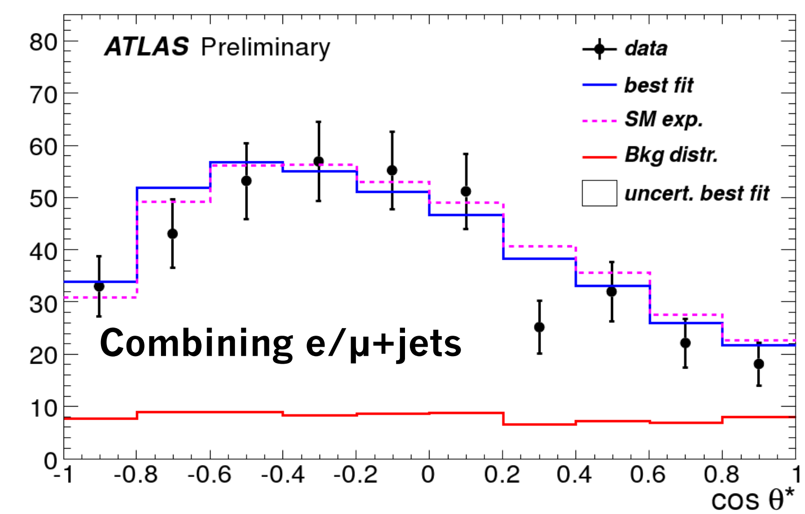
W helicity in top decays

- **The Standard Model predicts helicity fractions of W from top**
  - $F_L = 0.301$, $F_0 = 0.698$, $F_R = 4.1 \cdot 10^{-4}$
  - Wtb structure probed by verifying this; set limits on new physics
  - Can extract directly from cos θ* or unfold and calculate asymmetry
  - Use e+jets and μ+jets channels

	Asymmetry method	Template method
F_L	0.41±0.12	0.36±0.10
F_0	0.59±0.12	0.65±0.15
F_R	Fixed 0	-0.01±0.07





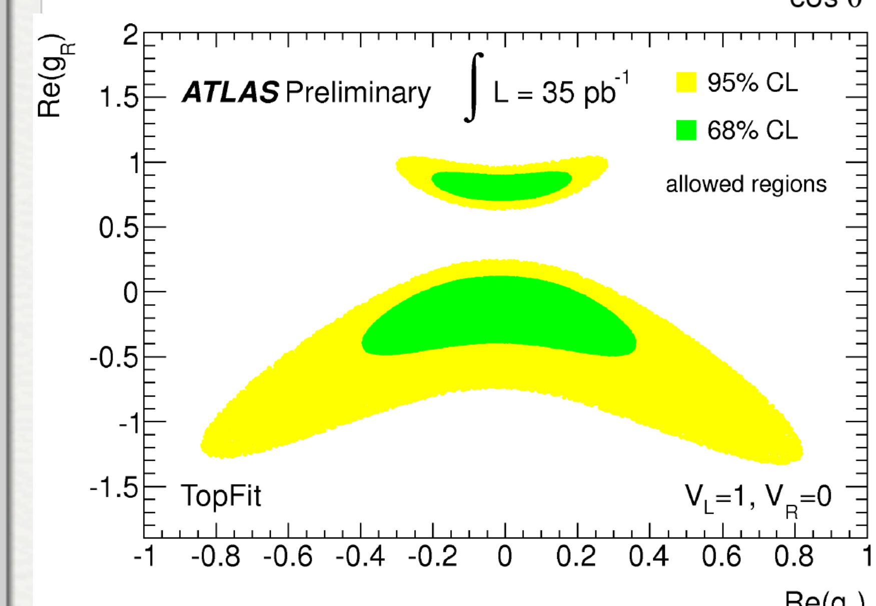


$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu\left(V_L P_L + V_R P_R\right) t\, W_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_\mu^-$$

$$\mathrm{Re}\, V_R \in [-0.44, 0.48]$$

$$\mathrm{Re}\, g_L \in [-0.24, 0.21]$$

$$\mathrm{Re}\, g_R \in [-0.49, 0.15]$$



Aguilar-Saavedra, Carvalho, Castro, Veloso, Onofre (07), Aguilar-Saavedra , Bernabeu, (2010)

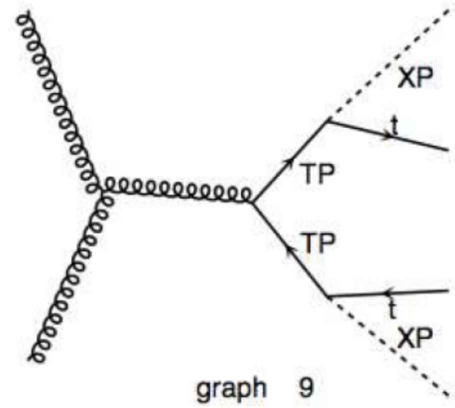
ATLAS-CONF-2011-037

tt + anomalous E_T^{miss}

ATLAS-CONF-2011-036

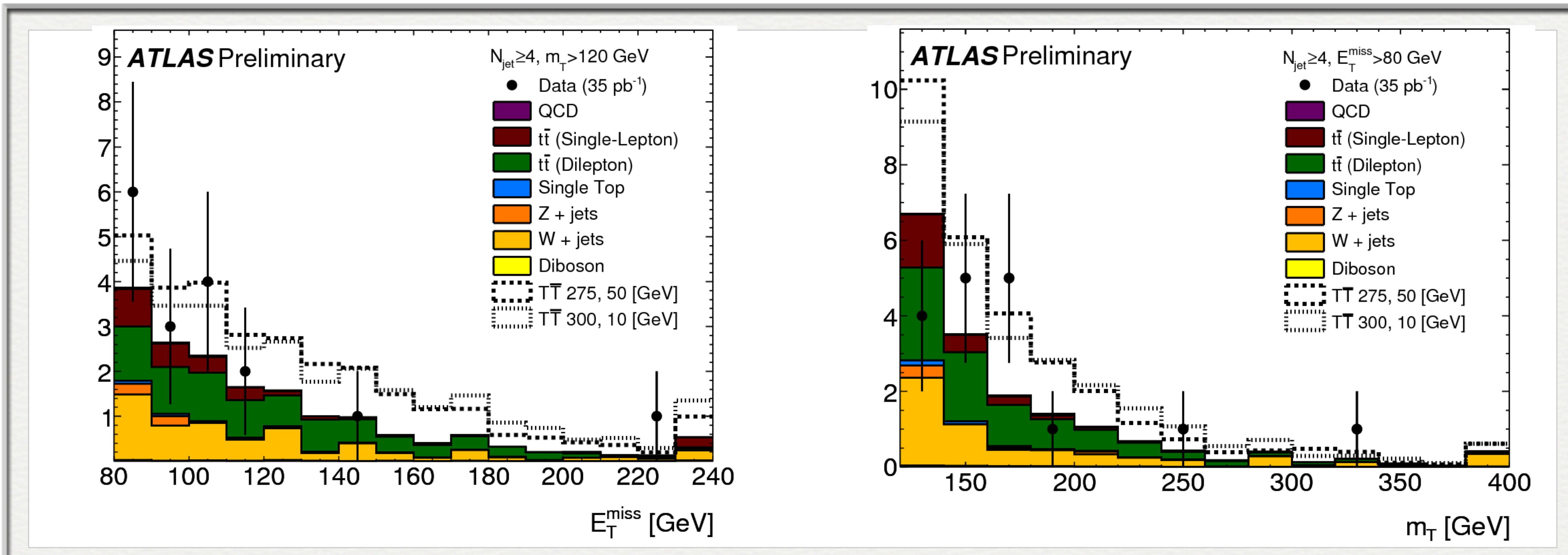
Search for anomalous E_T^{miss} in tt(l+jets) events

- **benchmark: TT pair, $T \rightarrow tA_0$**
  - A_0 dark matter candidate
  - Enhanced cross-section due to spin states



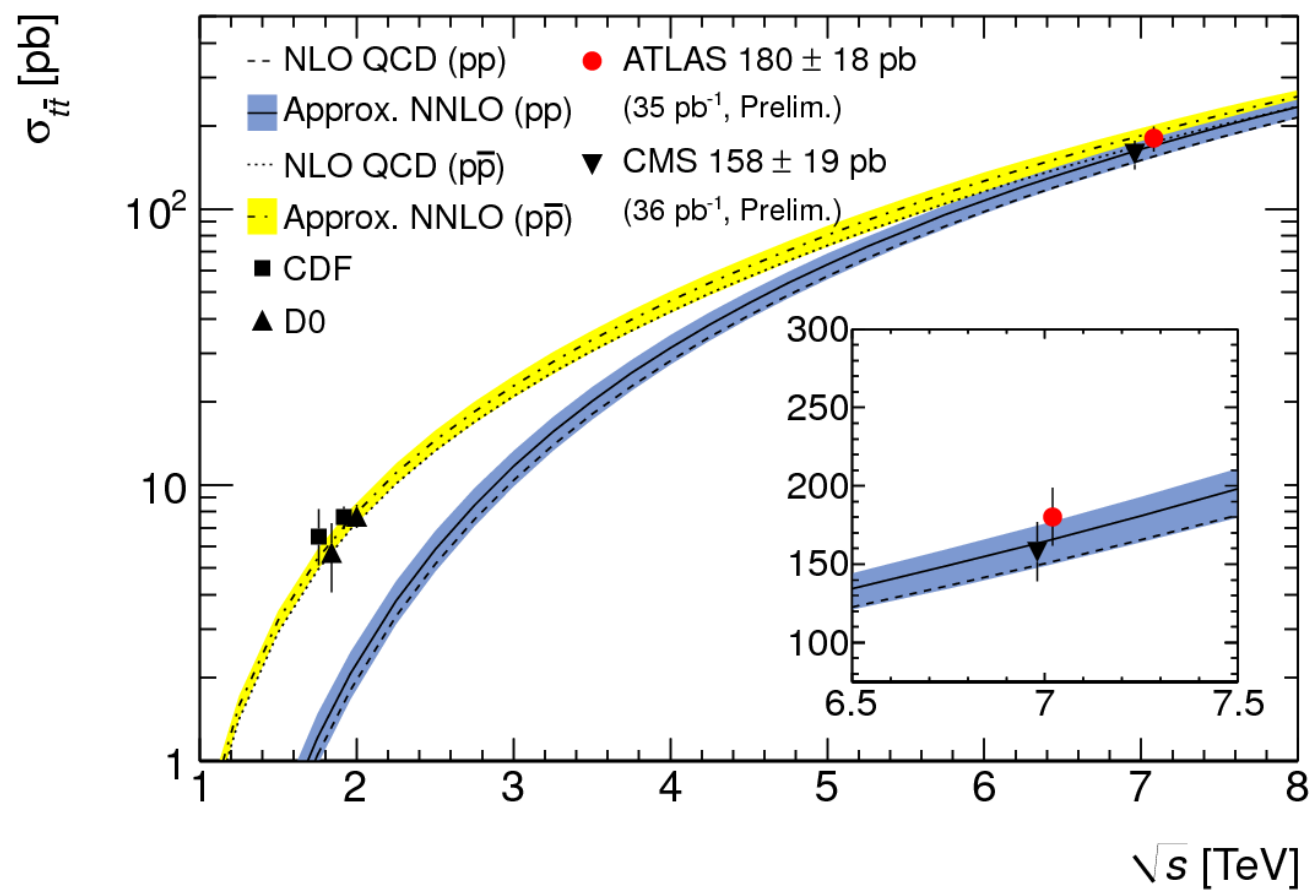
Alwall, Feng, Kumar *et al.* (2010)
Berger, Cao (2009)

- **Signal region:**
  - E_T^{miss} >80 GeV, m_T>120 GeV; dilepton veto: p_T > 15 GeV, tracks, loose electrons
- **Exclude m(T) < 275GeV, m(A_0) < 50 GeV and m(T) < 300 GeV, m(A_0) <10 GeV**



Conclusion and Outlook

- **The era of top physics at the LHC has just started**
  - with only 35 pb^{-1} can already look into production cross-section, mass, single-top and several properties
  - competitive measurements are emerging: cross-section at 10%
- **Statistics limited analysis will become attractive this year**
  - anticipate ~0.7 fb^{-1} by Summer and ~2 fb^{-1} by the end of the year
- **Focus to reduce systematics**
  - improve detector understanding; use advanced analysis techniques



- **2011: the year of precision top measurements at LHC**

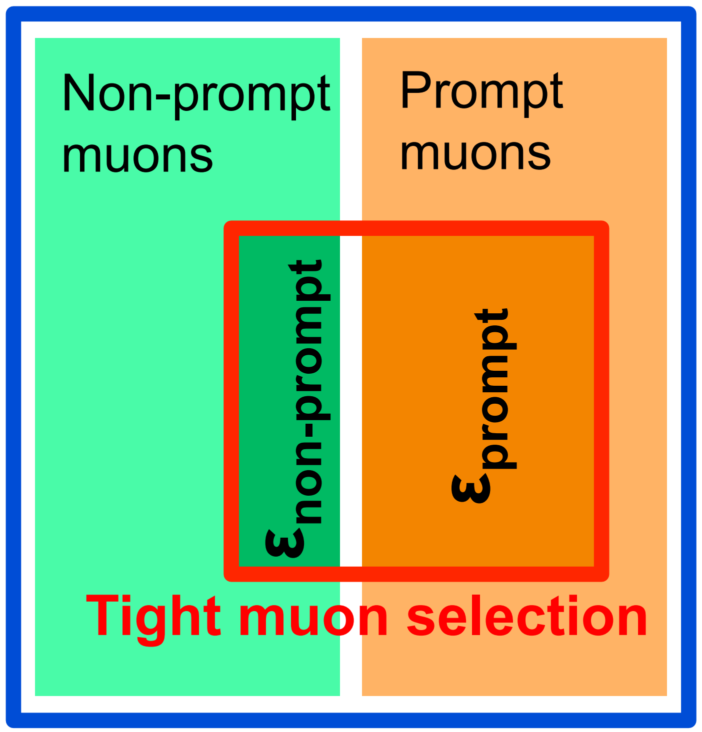
backup

QCD in single lepton channel

Matrix method (muon)

non prompt : QCD muon from jet
prompt : Isolated muon from W decay

Loose muon selection



$\varepsilon_{\text{prompt}}$: Z decay
$\varepsilon_{\text{non-prompt}}$: control region

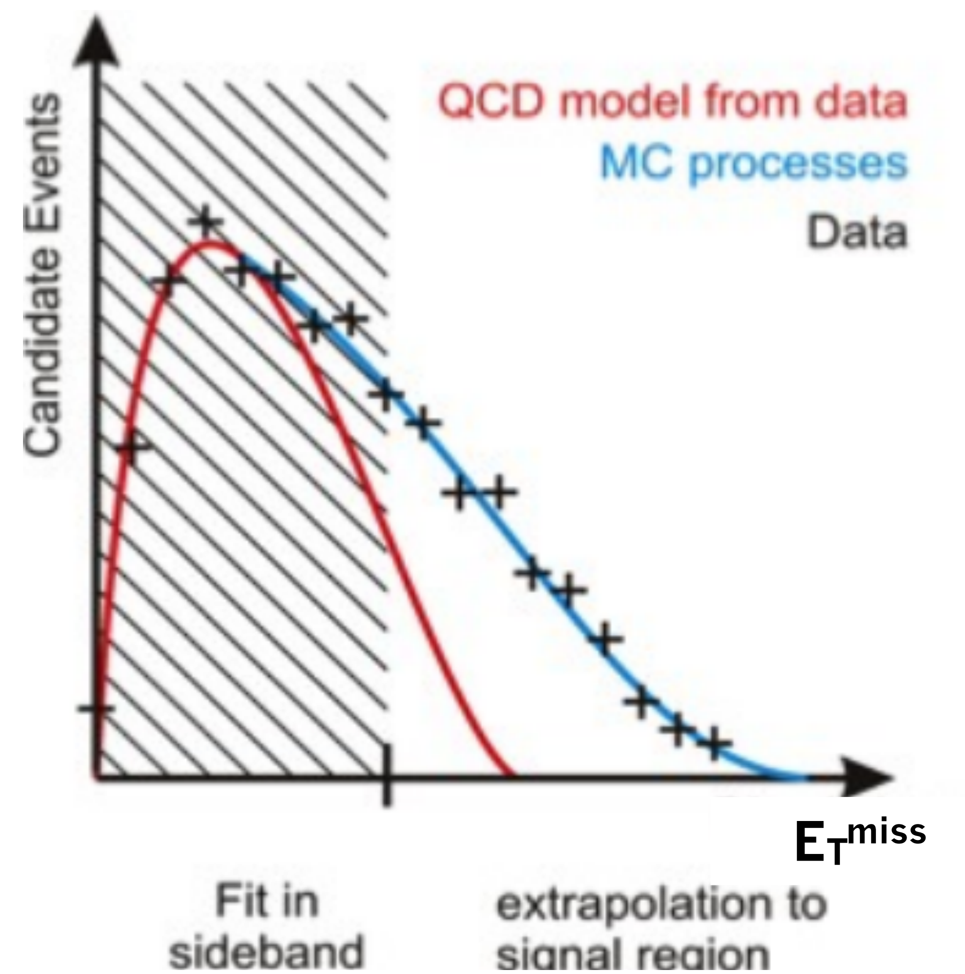
$$N^{\text{loose}} = N^{\text{loose}}_{\text{prompt}} + N^{\text{loose}}_{\text{non-prompt}},$$
$$N^{\text{tight}} = \epsilon_{\text{prompt}} N^{\text{loose}}_{\text{prompt}} + \epsilon_{\text{non-prompt}} N^{\text{loose}}_{\text{non-prompt}}$$

Uncertainty ~30%

Fitting method (electron)

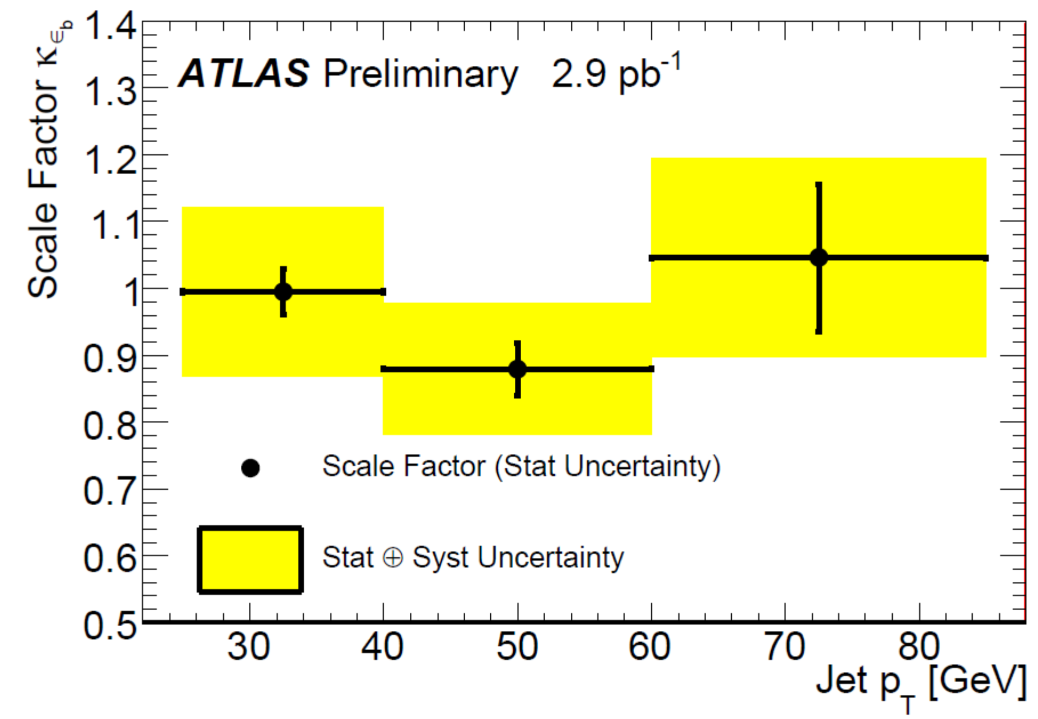
- QCD template built from electron sample with ID cut inversion.

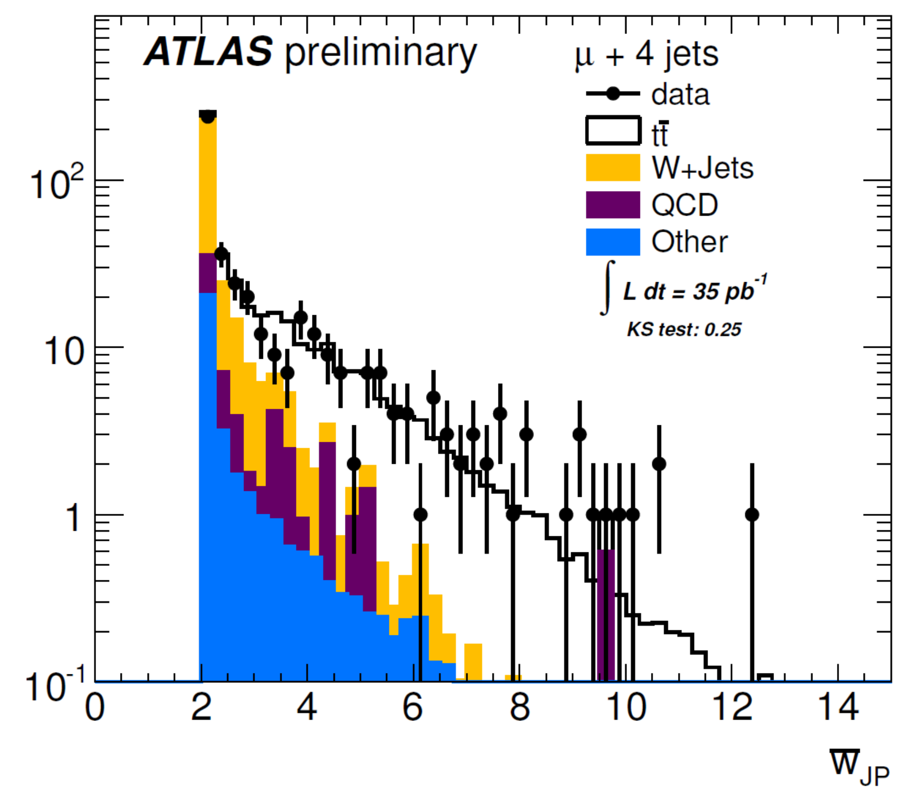
Uncertainty ~50%



b-tagging

- **Performance of b-tagging depends on details of detector performance**
- **Data-driven estimates of b-tag efficiency and mistag rate**
  - 'p_T^{rel}' : the p_T wrt jet axis of associated μ to calibrate b-tagging.
- **Study repeated for full 2010 data sample**
  - Efficiency data-to-MC scale factors $\kappa_{\varepsilon b}$ are unity within ~10%
  - D*μ and tt for cross-check
  - Mis-tag rate affects cross-section extraction less
- **JetProb calibrated for ε_b= 50%, 70%**
  - Average JetProb weight of two most b-like jets, w_{JP} is used as a continuous variable in the single lepton analysis





M_{T2}

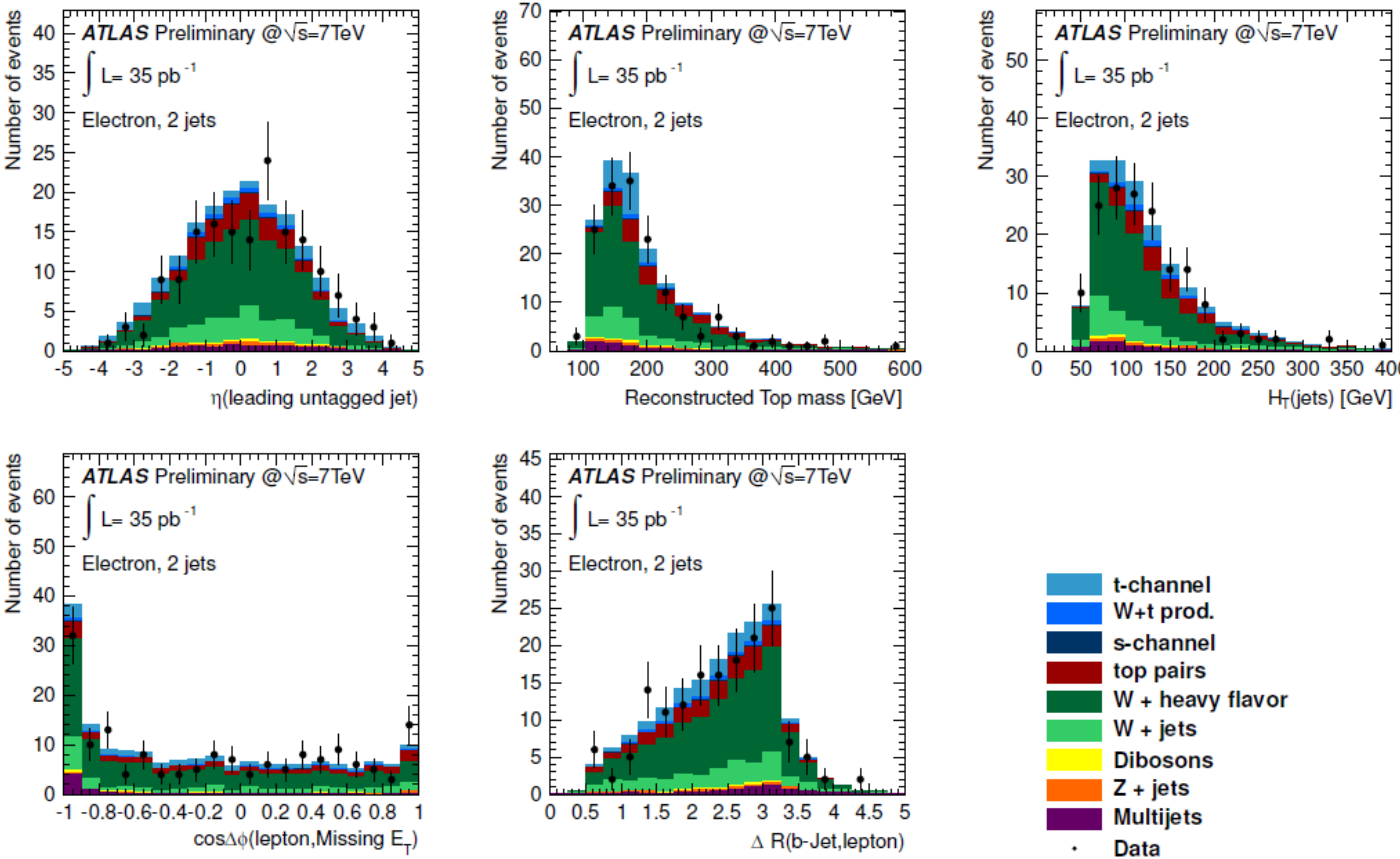
ATLAS EXPERIMENT

$$m_{\mathrm{T2}}^2 = \min_{\not{p}_{(1)}+\not{p}_{(2)}=E_{\mathrm{T}}^{\mathrm{miss}}} \left[\max\{m_{\mathrm{T}}^2(p_{\mathrm{T}}^{lj(1)}, \not{p}_{(1)}), m_{\mathrm{T}}^2(p_{\mathrm{T}}^{lj(2)}, \not{p}_{(2)})\}\right]$$

$$m_{\mathrm{T}}^2(p_{\mathrm{T}}^{lj(i)}, \not{p}_{(i)}) = m_{lj(i)}^2 + m_{\not{p}_{(i)}}^2 + 2[E_{\mathrm{T}}^{lj(i)} E_{\mathrm{T}}^{\not{p}_{(i)}} - \vec{p}_{\mathrm{T}}^{\,lj(i)} \vec{p}_{\mathrm{T}}^{\,\not{p}_{(i)}}]$$

with the transverse momentum of the composite object of one lepton and one jet $p_{\mathrm{T}}^{lj(i)}$, of the trial neutrino $\not{p}_{(i)}$ and their transverse energy E_{T} and masses m. The minimization uses trial momenta for the neutrinos which only have to satisfy the measured $E_{\mathrm{T}}^{\mathrm{miss}}$. From the two possible combinations of leptons and highest-p_{T} jets the combination with the smallest m_{T2} is chosen.

C.G. Lester, D.J.Summers (1999)


ATLAS Preliminary @√s=7TeV
∫ L= 35 pb -1
Electron, 2 jets
Number of events
η(leading untagged jet)
Reconstructed Top mass [GeV]
H_T(jets) [GeV]
cosΔφ(lepton,Missing E_T)
Δ R(b-Jet,lepton)
t-channel
W+t prod.
s-channel
top pairs
W + heavy flavor
W + jets
Dibosons
Z + jets
Multijets
Data