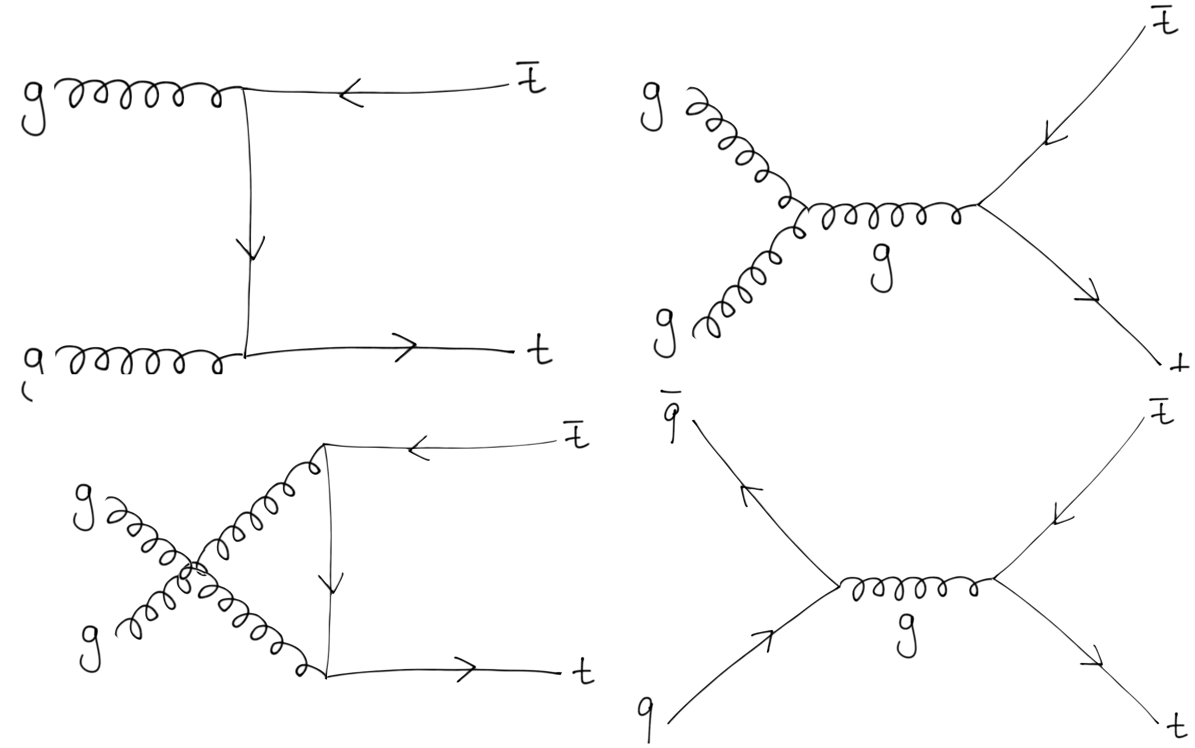
EPS-HEP Stockholm - 18.-24.07.2013

Inclusive Top Quark Pair Production Cross Section at 7 & 8 TeV

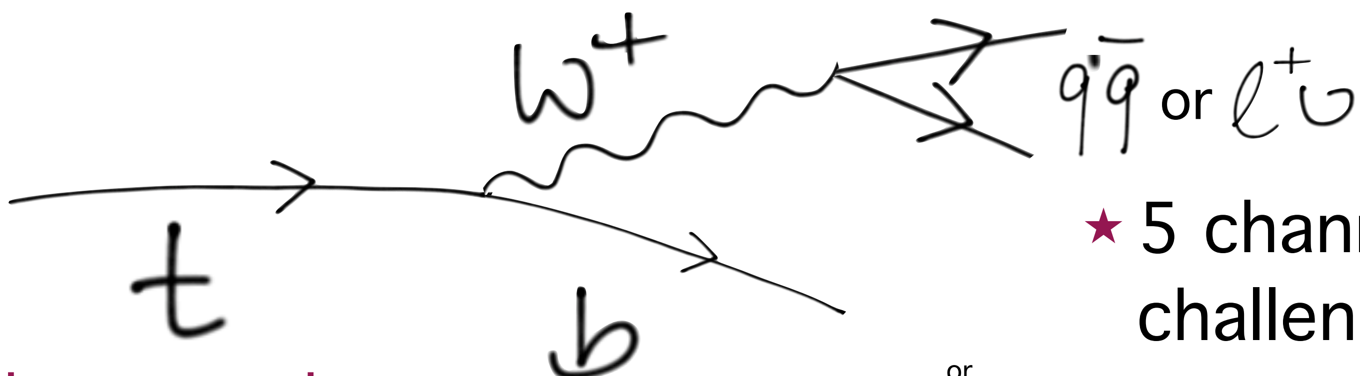
Anna Henrichs (Yale University)
on behalf of the ATLAS collaboration

Top Production and Decay

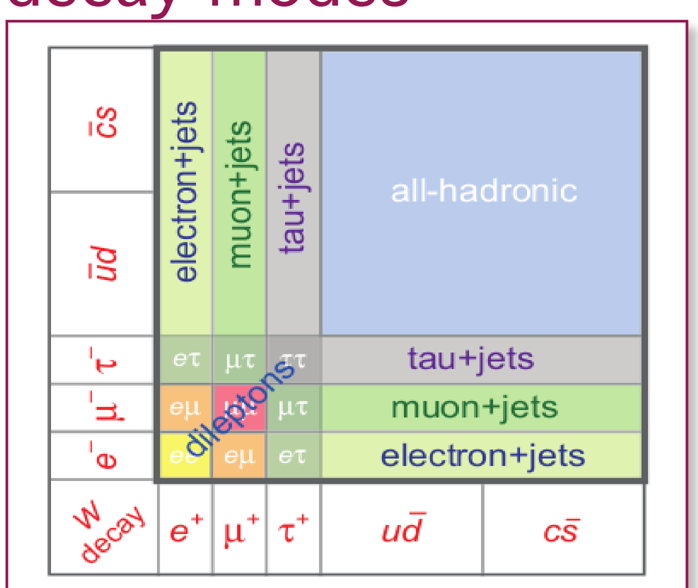
- ★ pair production through strong interaction
- ★ gluon fusion dominates at the LHC



- ★ electroweak decay t → Wb
- ★ W decay modes classify events:



decay modes



- ★ 5 channels with different advantages and challenges - all covered by ATLAS:
  - ★ 46% All hadronic (2xW→qq)
  - ★ 10% τ_{had}+Jets (W→qq, W→τ_{had} ν)
  - ★ 34 % Lepton+Jets (W→qq, W→e/μ ν)
  - ★ 4% τ_{had}+Lepton (W→τ_{had} ν,W→e/μ ν)
  - ★ 6% Dilepton (2x W→e/μ ν)

Why Top Quark Pair Production?

★ top quarks are an important handle in understanding the Standard Model and searching for physics beyond it

precision

- ★ huge data sets available at 7 & 8 TeV to measure top production
- ★ can precisely test perturbative QCD
- ★ calculations available up to NNLO+NNLL* with m_t = 172.5 GeV:

$$\sigma_{t\bar{t}}(\sqrt{s} = 7\ \text{TeV}) = 177^{+10}_{-11}\ \text{pb}$$

$$\sigma_{t\bar{t}}(\sqrt{s} = 8\ \text{TeV}) = 253^{+13}_{-15}\ \text{pb}$$

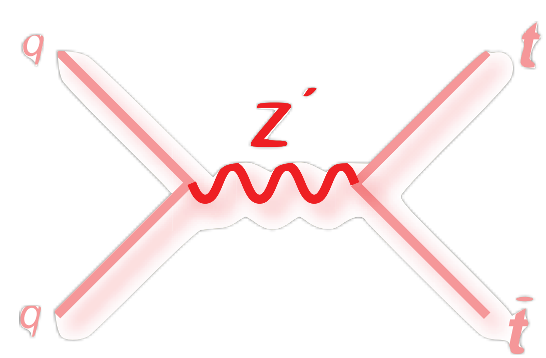
*arxiv/hep-ph: 1111.5869,1112.5675,1204.5201,1207.0236,1210.6832,1303.6254

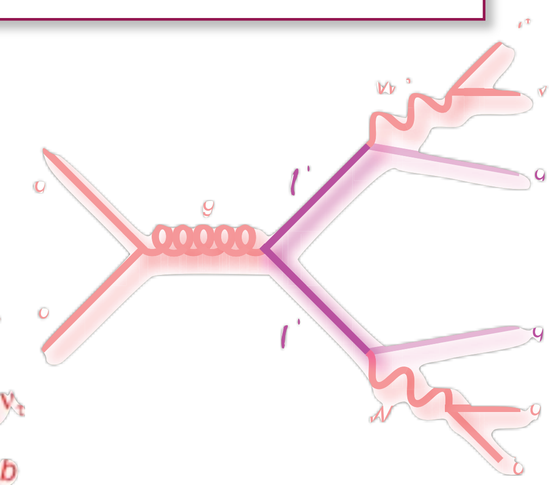
tools & methods

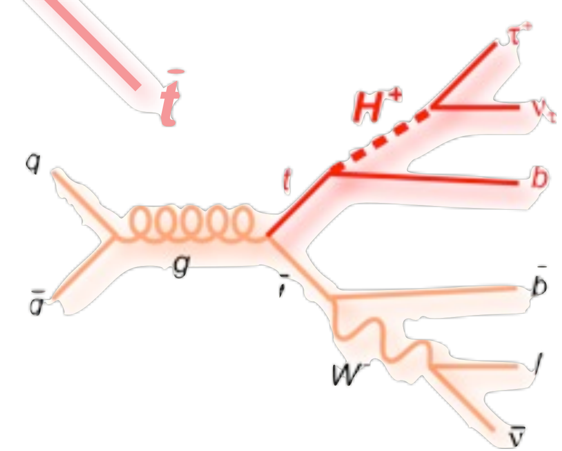
- ★ provides a well understood environment to understand the detector performance in events with high p_T objets, many jets, many b-jets
- ★ development and understanding of new techniques - soft muon tagging
- ★ measuring rare and difficult processes - measurements including τ_{had}

new physics?

- ★ dominant background to many searches for new physics (ttH, stop, heavy resonances)
- ★ also direct sensitivity to new physics
  - ★ in production (Z')
  - ★ in the decay chain (t')
  - ★ in decay itself (H^+)
- ★ comparison of different decay modes is crucial







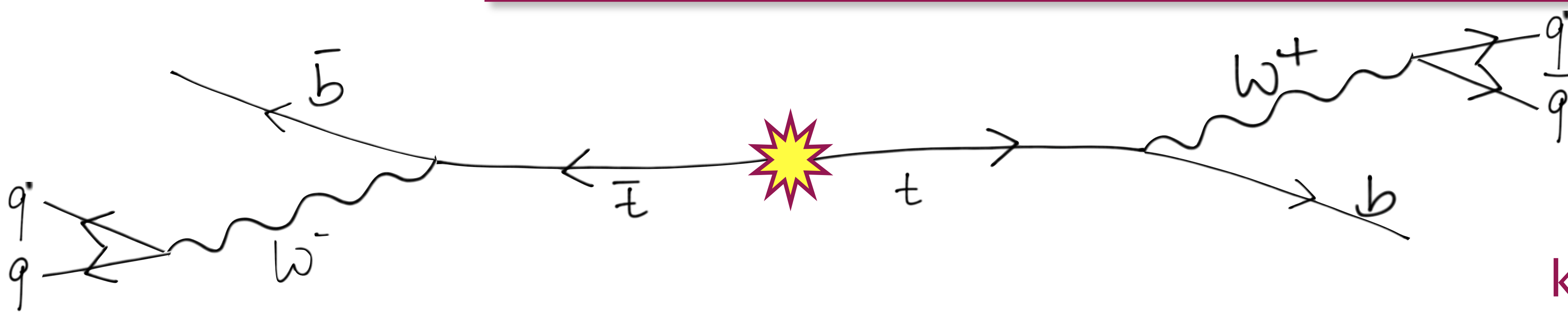
All hadronic 7 TeV, 4.7 fb^{-1}

challenge

- ★ large background from QCD multijet production
- ★ no ‘signature’ lepton

event selection

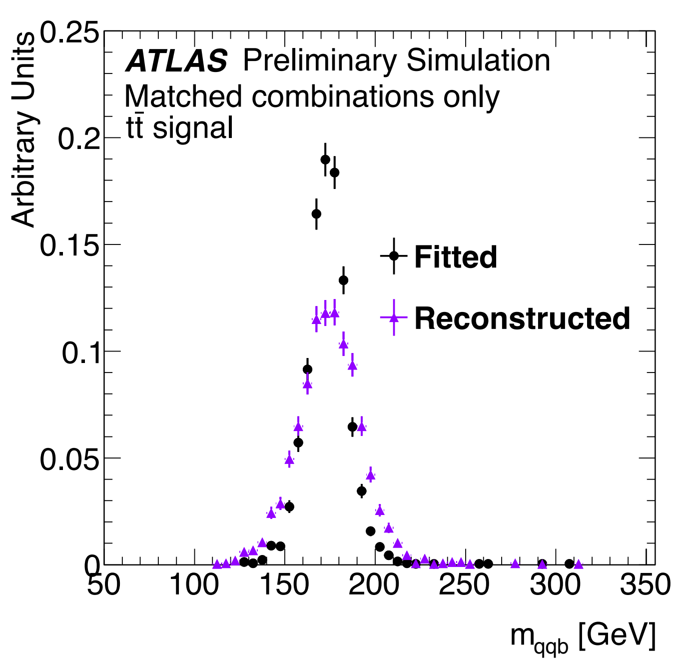
- ★ multijet trigger - 5 jets with p_T > 30 GeV at trigger level
- ★ require ≥ 5 jets with p_T > 55 GeV, 6th jet with p_T > 30 GeV within $|\eta|$ < 2.5
- ★ at least 2 b-jets with p_T > 55 GeV
- ★ veto any electron or muon with p_T > 20 GeV
- ★ veto missing transverse energy through $S(E_T^{miss}) = E_T^{miss} / (0.5 \times \sqrt{\sum E_T}) < 6$
- ★ $\Delta R(b,b) > 1.2$ (suppress gluon splitting)
- ★ AR(j,j) > 0.6 for any jet pair



kinematic fitting

- ★ reconstruct full event topology
- ★ kinematic likelihood fit to determine best assignment of jets to the top quark decays
- ★ constraints on W boson mass and m(top) = m(antitop)
- ★ allows to build top mass as discriminant with improved resolution
- ★ select events with:
  - ★ m(top) > 125 GeV with 6-10 jets
  - ★ also require high probability of best permutation
  - ★ good agreement with SM values through X^2

top mass

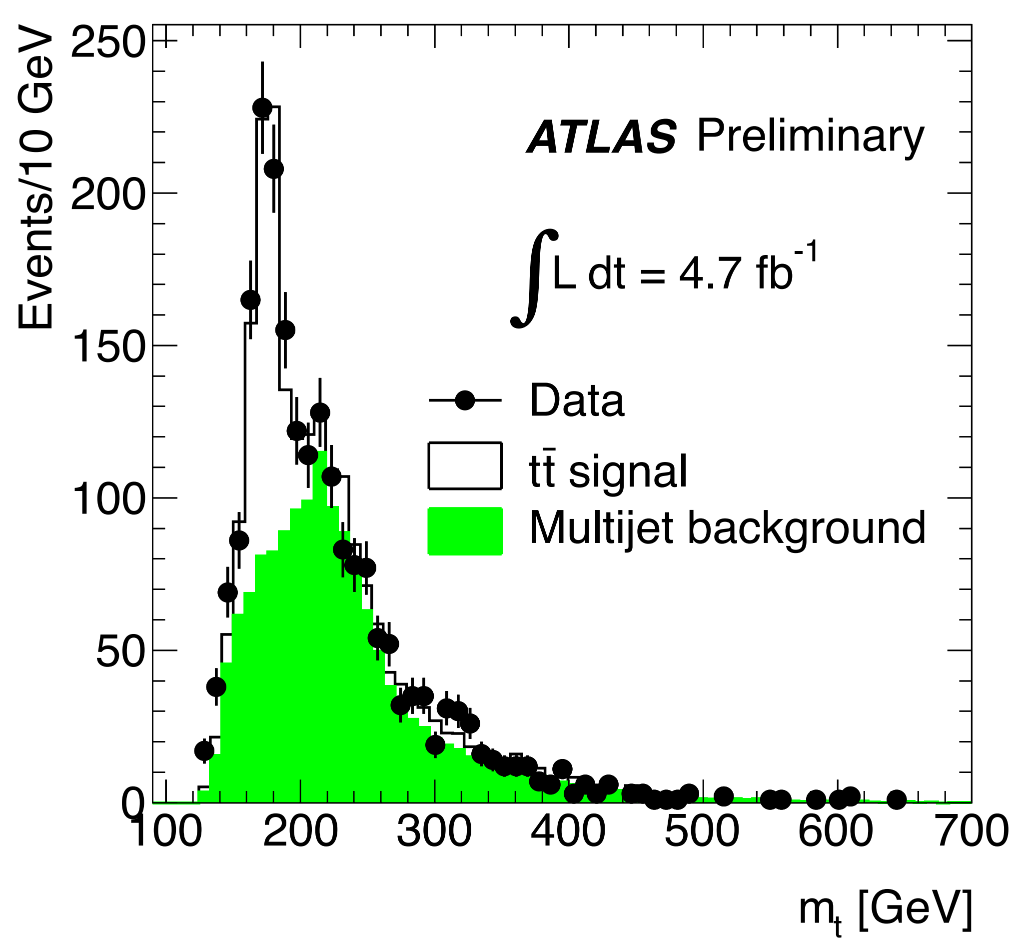


ATLAS-CONF-2012-031

All hadronic 7 TeV, 4.7 fb^{-1}

- ★ unbinned likelihood fit to extract cross section from m_t
- ★ QCD multijet background template from data, dropping b-jet requirements in event selection
- ★ correction factors to account for modeling & composition differences from MC

fit result



- ★ good agreement with Standard Model predictions
- ★ exploits full 7 TeV data set
- ★ total uncertainty 37%, dominated by systematics

dominant uncertainties

- ★ jet energy scale uncertainties
- ★ b-tagging
- ★ ISR/FSR model

- ★ 36% total systematic uncertainty

$$\sigma_{t\bar{t}} = 168 \pm 12\ (\mathrm{stat.})^{+60}_{-57}\ (\mathrm{syst.}) \pm 6(\mathrm{lumi.})\mathrm{pb}$$

ATLAS-CONF-2012-031

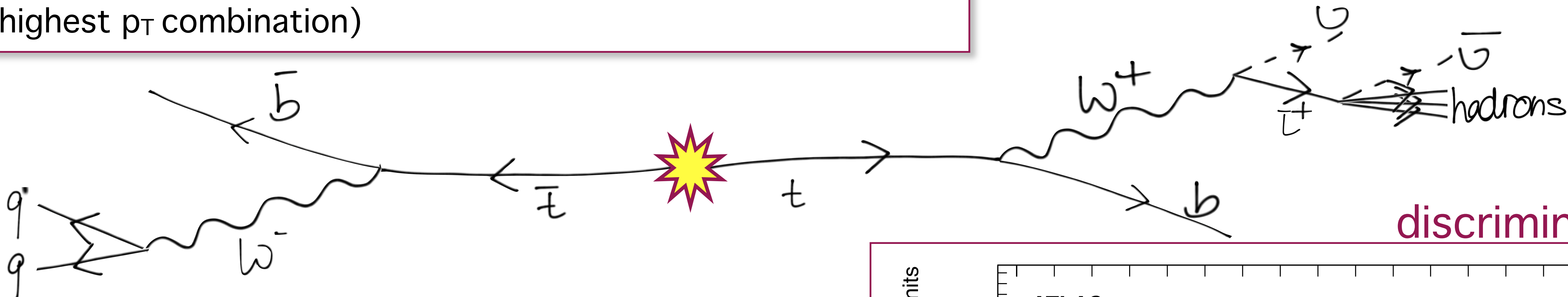
τ+Jets 7 TeV, 1.67 fb^{-1}

event selection

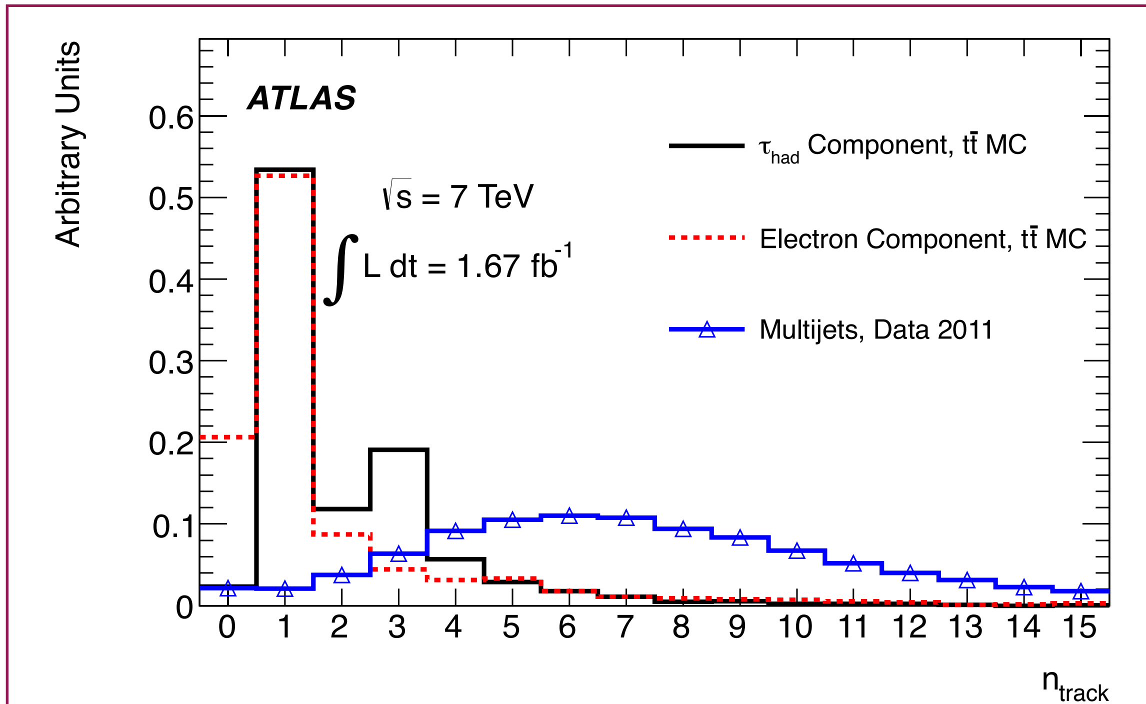
- b-jet triggered events & at least two b-jets
- at least 5 jets with $p_T > 20$ GeV & $|\eta| < 2.5$
- veto events with leptons with $p_T > 15$ GeV
- $S(E_T^{miss}) = E_T^{miss} / (0.5 \times \sqrt{\sum E_T}) > 8$
- find $\tau_{had} > 40$ GeV, as highest p_T jet that is not b-tagged and does not belong to the hadronic top decay (3 jets yielding highest p_T combination)

main backgrounds

- top pairs (l+Jets)
- QCD multijets
- W+Jets



discriminant



Eur.Phys.J.C, 73 3 (2013) 2328

strategy

- 1/3-prong decays of τ_{had} yield small number of tracks associated to τ_{had}-candidate
- count number of tracks with $p_T > 1$ GeV within $\Delta R < 0.2$ & variable p_T cut in cone $0.2 < \Delta R < 0.6$
- real electrons from tt can fail the lepton veto and give τ_{had}-candidate: consider as signal and subtract based on e/τ_{had} - MC ratio

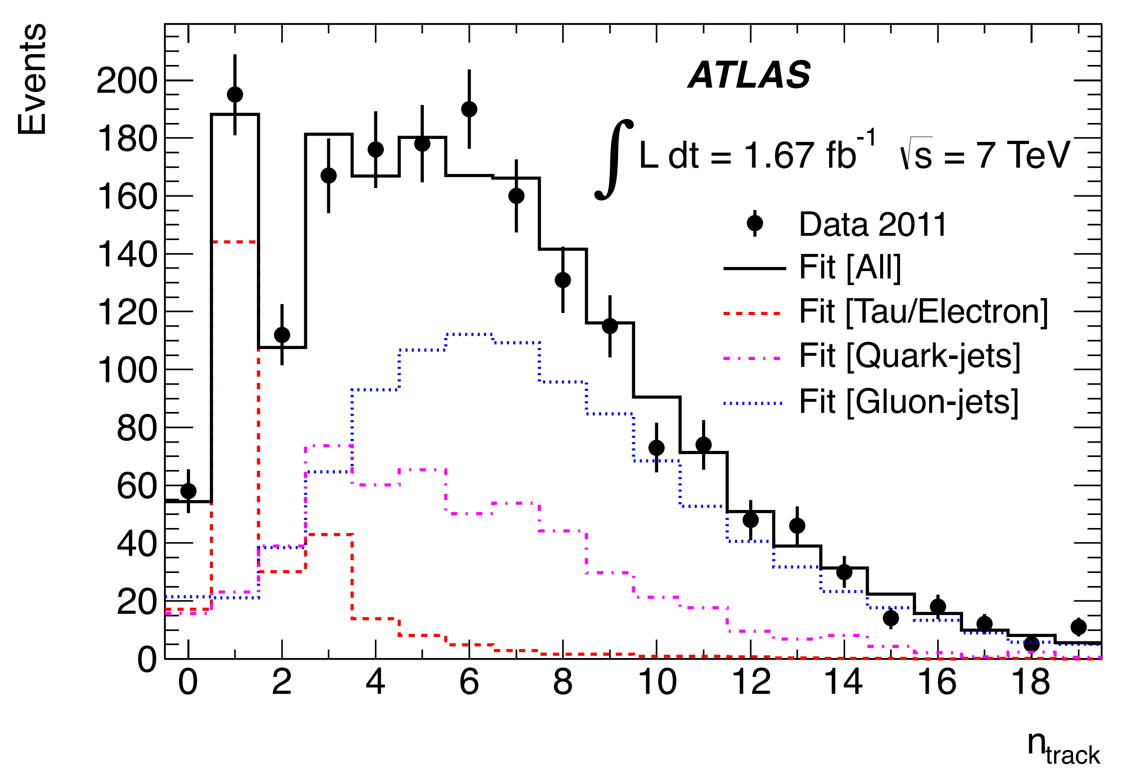
τ+Jets 7 TeV, 1.67 fb^{-1}

- ★ likelihood fit to number of track distribution with:
  - ★ combined e/τ - template (signal)
  - ★ gluon jet - template (QCD multijet from sideband)
  - ★ quark jet - template (tt from μ+Jets)

dominant uncertainties

- ★ ISR/FSR modeling
- ★ choice of generator
- ★ b-Jet tagging efficiencies
- ★ 24% total systematic uncertainty

final fit



- ★ first measurement in τ+Jets final state at LHC
- ★ reaches ~ 25% uncertainty
- ★ in good agreement with all other measurements
- ★ in good agreement with theoretical predictions

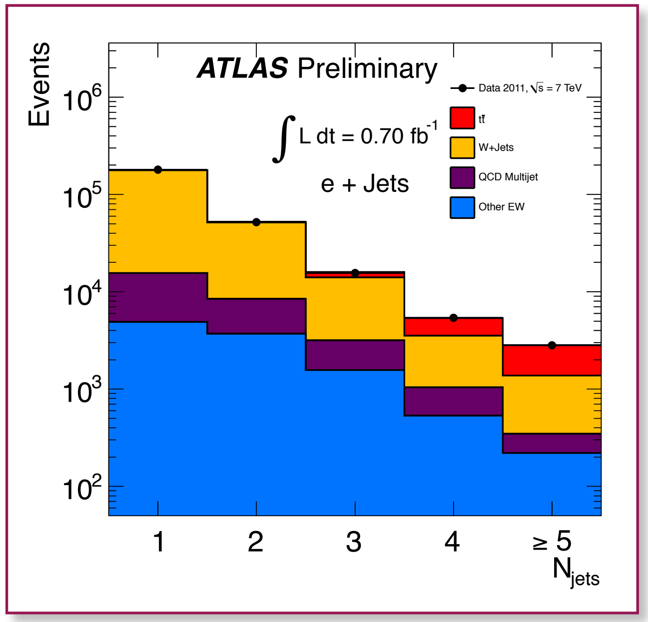
$$\sigma_{t\bar{t}} = 194 \pm 18\ (\text{stat.}) \pm 46\ (\text{syst.})\ \text{pb}$$

Eur.Phys.J.C, 73 3 (2013) 2328

Lepton + Jets 7 & 8 TeV

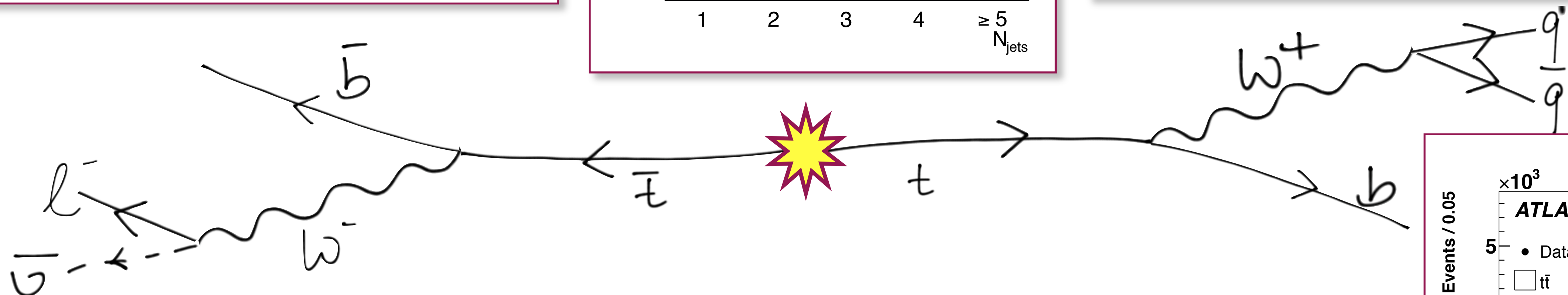
backgrounds

- W+Jets
- QCD multijet, jets faking isolated leptons
- single top production
- Z+Jets
- diboson production

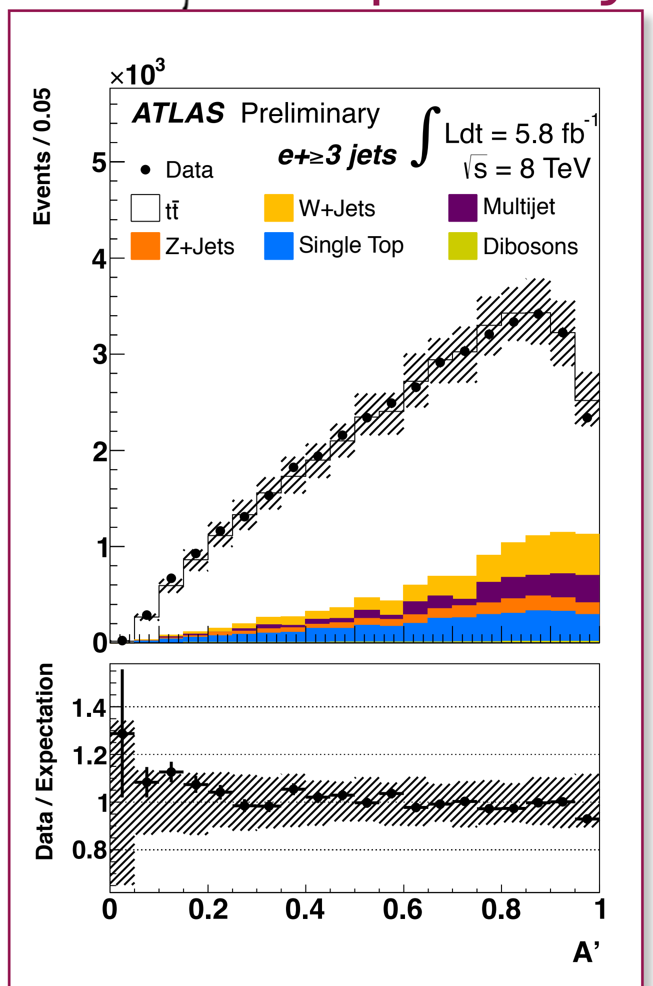


typical selection

- one isolated lepton with p_T > 20-25 GeV
- ≥3 jets with p_T > 25 GeV
- significant amount of E_T^{miss} > 20-35 GeV
- additional cut to suppress QCD multijets on m_T (> 20 GeV) or $m_T + E_T^{miss}$ (> 60 GeV)
- can require ≥1 b-tagged jet



aplanarity



background modeling

- main backgrounds need to be estimated from data
- W+Jets normalization exploiting charge asymmetry of W production at LHC
- QCD multijet fake lepton background through "matrix method"
- needs efficiencies for loosely isolated leptons passing selections

discriminators

- requiring b-tagging enhances signal purity
- η (e/μ) more central in tt compared to W+Jets
- several event shape variables, like aplanarity, energy ratios

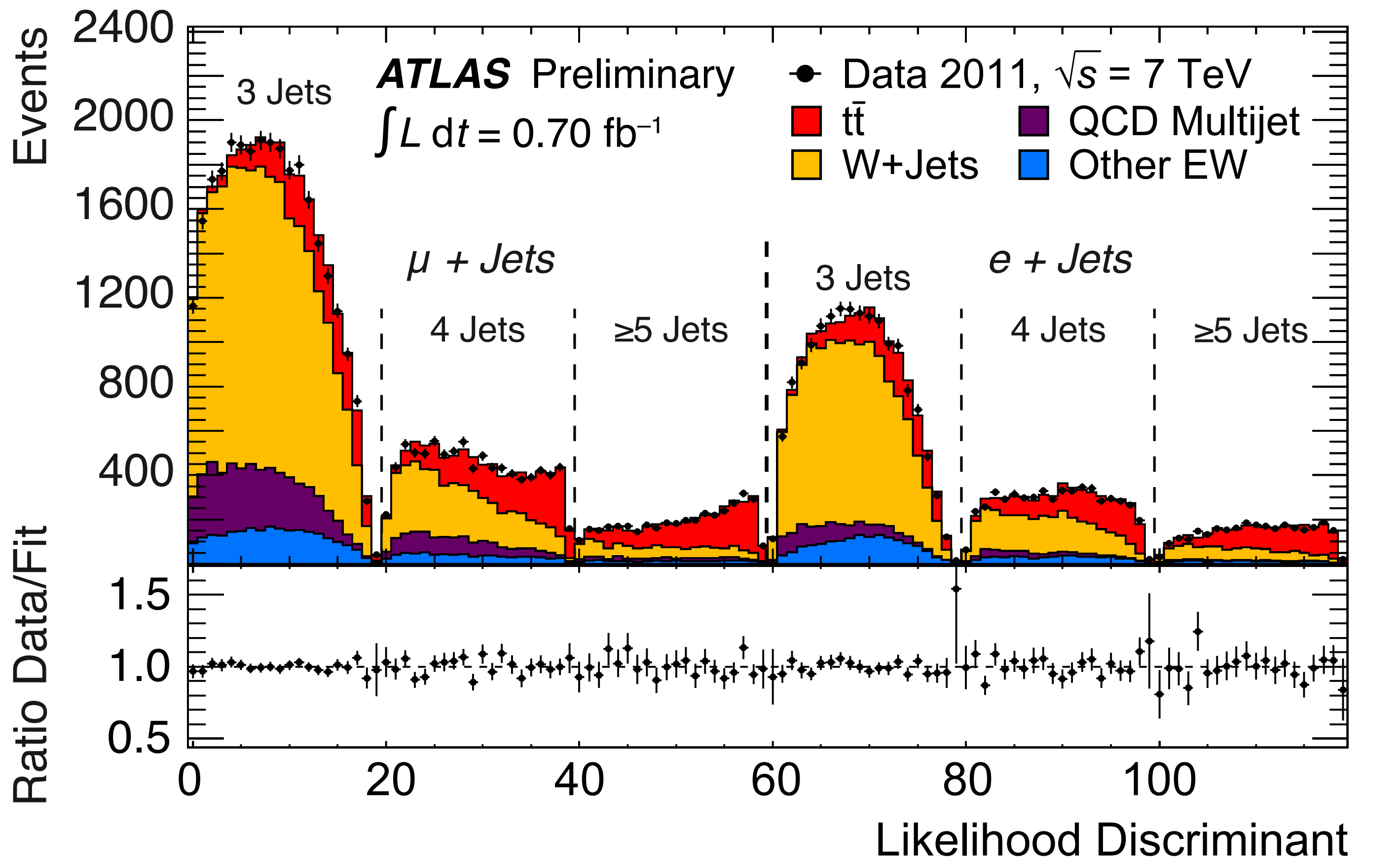
ATLAS-CONF-2011-121 ATLAS-CONF-2012-131,149

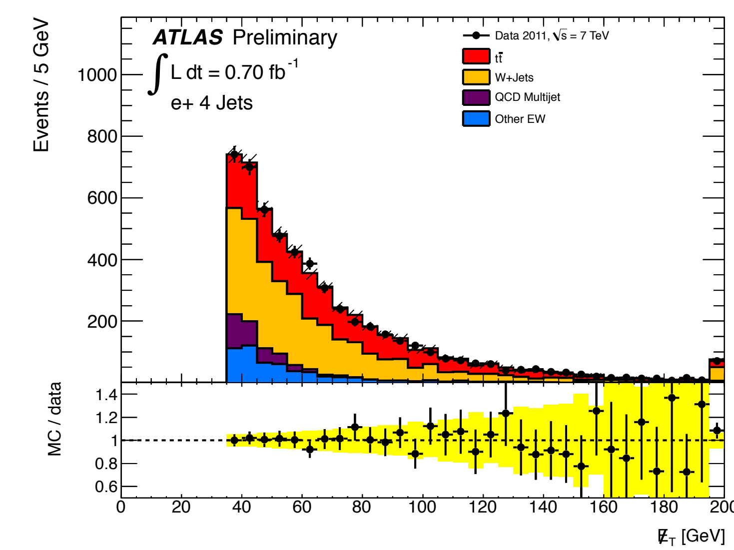
Lepton + Jets 7 TeV, 0.7 fb^{-1}

- ★ likelihood discriminant from η(e/μ), $p_T(j_1)$, aplanarity, $H_{T,3p}$
- ★ no use of b-tagging information
- ★ simultaneous fit in e/μ + 3,4,≥ 5 jet events
- ★ profile likelihood fit including systematic uncertainties as nuisance parameters

main systematics

- ★ signal modeling
- ★ jet energy scale
- ★ MC statistics





after fit

- ★ ability to constrain systematic uncertainties yields high precision
- ★ 6.6% total uncertainty - most precise ATLAS result
- ★ good agreement with SM prediction - theory uncertainty of similar size

$$\sigma_{t\bar{t}} = 179.0 \pm 3.9\ (\text{stat.}) \pm 9.0\ (\text{syst.}) \pm 6.6 (\text{lumi.}) \text{pb}$$

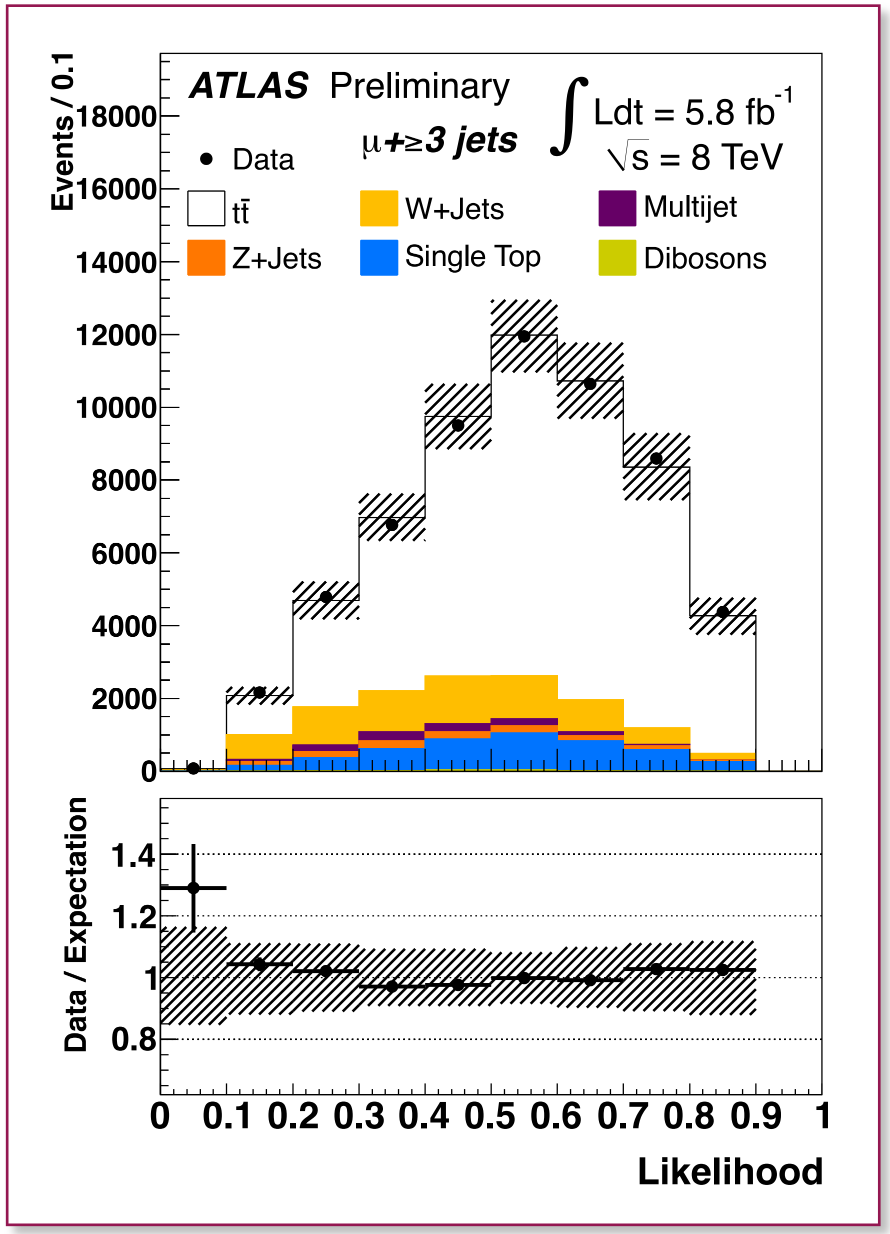
ATLAS-CONF-2011-121

Lepton + Jets 8 TeV, 5.8 fb^{-1}

★ first ATLAS measurement of σ_{tt} at 8 TeV
★ likelihood discriminant: η(e/μ), Aplanarity

background suppression

★ tight cut on lepton p_T > 40 GeV to further reject QCD multijets faking leptons



★ inclusive e/μ+ ≥ 3 jet selection for high statistics
★ ≥ 1 b-tagged jet to suppress W+jets background

★ negative log-likelihood minimization to obtain cross section
★ W+jets normalization determined by fit

★ consistent results between channels and with SM predictions

high statistics

Channel	$N_{t\bar{t}}$	$\sigma_{t\bar{t}}$ (pb)
$e+\geq3$ jets	31050±350	239±3
$\mu+\geq3$ jets	45000±400	242±2
$l+\geq3$ jets	76000±500	241±2

main uncertainties

★ signal modeling
★ jet calibrations
★ 13% systematic uncertainty

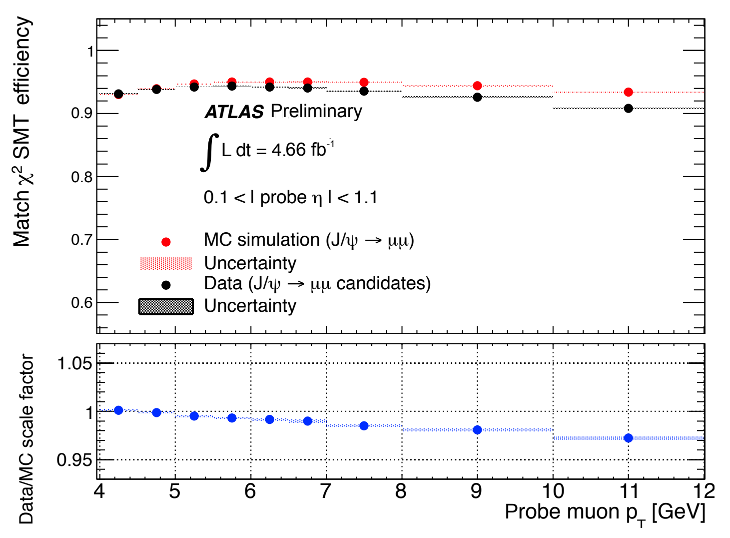
$$\sigma_{t\bar{t}} = 241 \pm 2\ (\text{stat.}) \pm 31\ (\text{syst.}) \pm 9(\text{lumi.})\text{pb}$$

ATLAS-CONF-2012-149

Lepton + Jets 7 TeV, 4.66 fb^{-1}

Soft Muon Tagging

- ★ 36% of the signal events contain semimuonic b→μX decays
- ★ uses quality of match between ID and MS hits as discriminator
- ★ 10% efficiency for b-jets



- ★ ≥ 3 jet selection, ≥ 1 SMT-b-jet
- ★ remove Z/Y resonances in μ+jets events
- ★ dominant backgrounds estimated from data
- ★ cross section extraction counting signal events after selection

- ★ good agreement with SM prediction
- ★ 10.6% total uncertainty

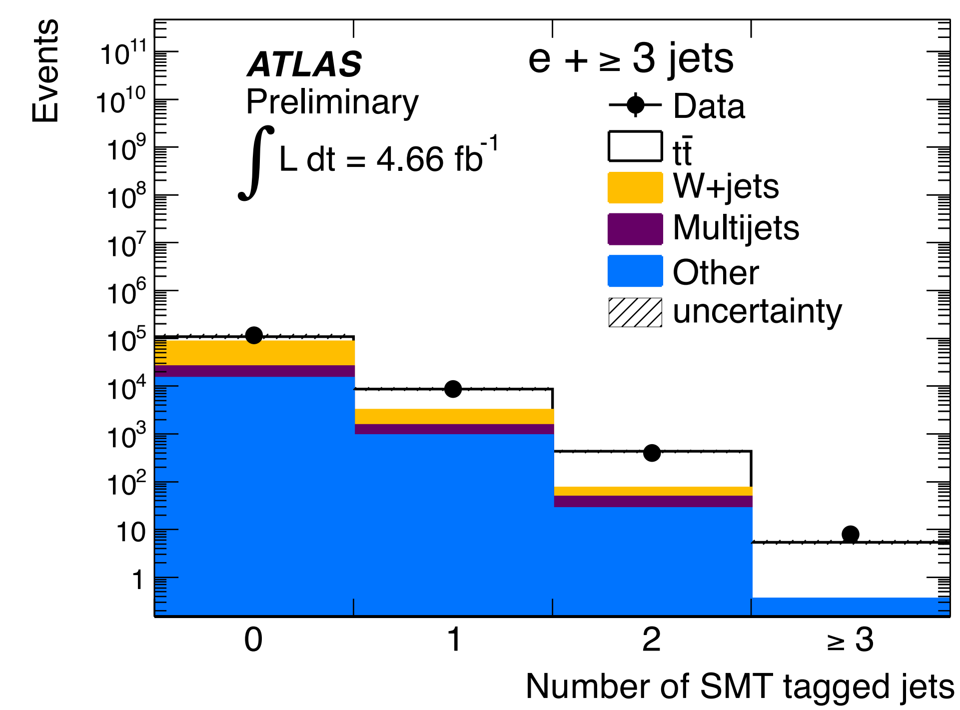
advantages

- ★ sensitive to new physics through invisible cascade decays
- ★ development of new technique
- ★ complementary in terms of systematics

systematics

- ★ ~ 10% total, dominating the result
- ★ uncertainties on background (W/QCD) normalisation
- ★ jet energy scale
- ★ simulation of b→μX

final selected events



$$\sigma_{t\bar{t}} = 165 \pm 2\ (\text{stat.}) \pm 17\ (\text{syst.}) \pm 3(\text{lumi.})\text{pb}$$

ATLAS-CONF-2012-131

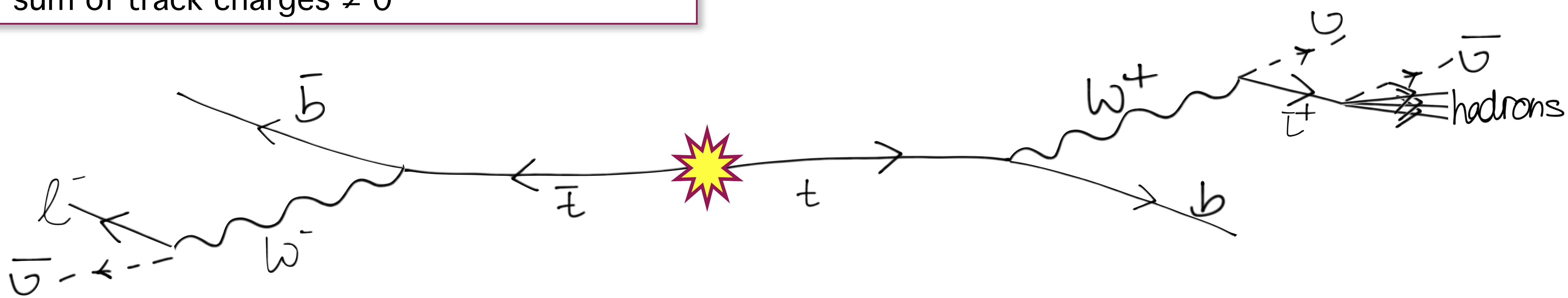
τ+lepton 7 TeV, 2.05 fb^{-1}

τ-ID

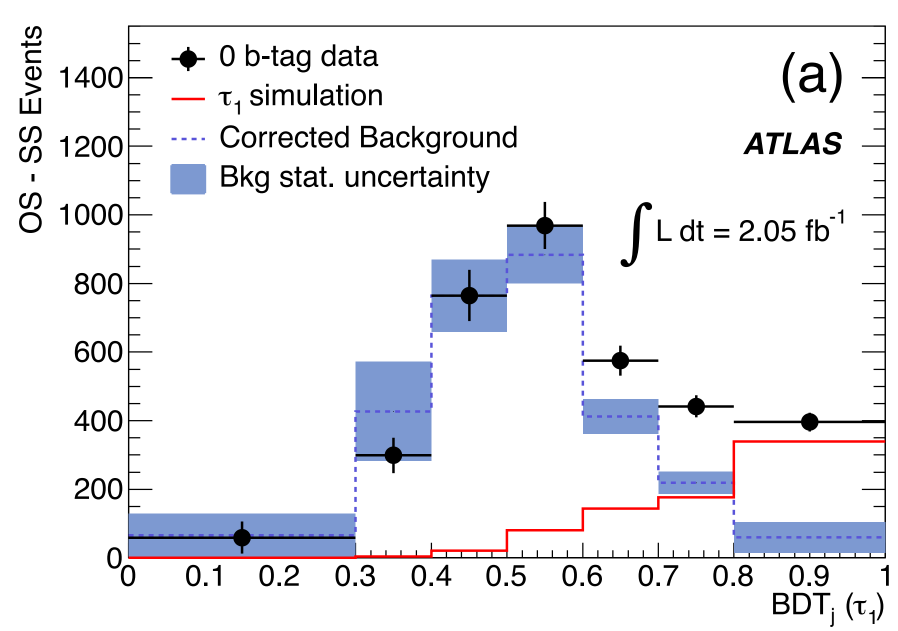
- start considering all jets as τ-candidates
- boosted decision trees (BDTs) from calorimeter- & track-based variables
- 20 GeV < E_T (τ) < 100 GeV, |η| < 2.3
- 1-3 associated tracks with p_T > 1 GeV within ΔR < 0.4
- sum of track charges ≠ 0

event selection

- one isolated lepton with p_T > 20 GeV (μ) or 25 GeV (e)
- one τ-candidate
- ≥ 2 jets with p_T > 25 GeV and ΔR(τ,j) > 0.4
- sample split in 0 b-jets and ≥ 1 b-jet events
- E_T^{miss} > 30 GeV and $\sum E_T$ > 200 GeV



BDT output



backgrounds

- electrons faking τ's: dedicated BDT_e to suppress
- jets faking τ's have two sources:
  - gluon splitting symmetric in charge - construct OS-SS distributions
  - light jets - look at 0 b-jet distributions, correct for real τ's from Z→ ττ and differences to ≥ 1 b-jet selection

Phys. Lett. B 717 (2012) 89-108

τ+lepton 7 TeV, 2.05 fb^{-1}

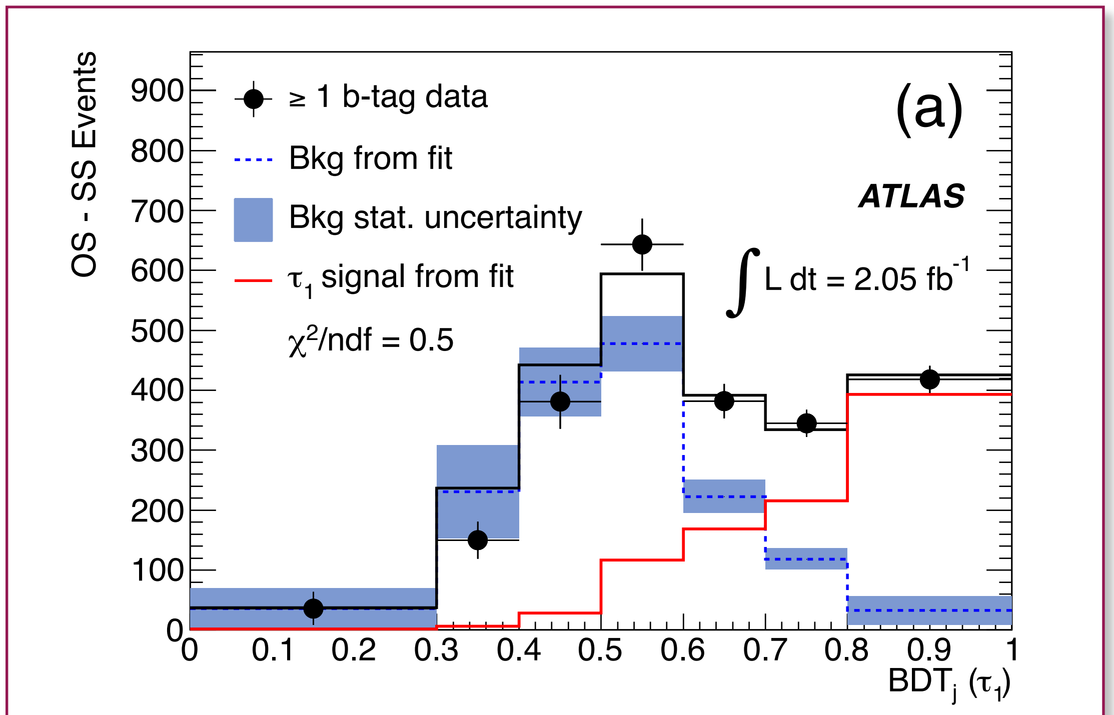
- ★ χ^2 - fits to OS-SS BDT$_j$ (τ vs. jet) distributions for ≥1 b-jet
- ★ separate BDTs for τ_1/τ_3 and different distributions in $e\tau/\mu\tau$
- ★ signal templates from MC, background from 0b events
- ★ combination of τ_1/τ_3 and $e\tau/\mu\tau$ for cross section extraction

- ★ good agreement with Standard Model & other channels

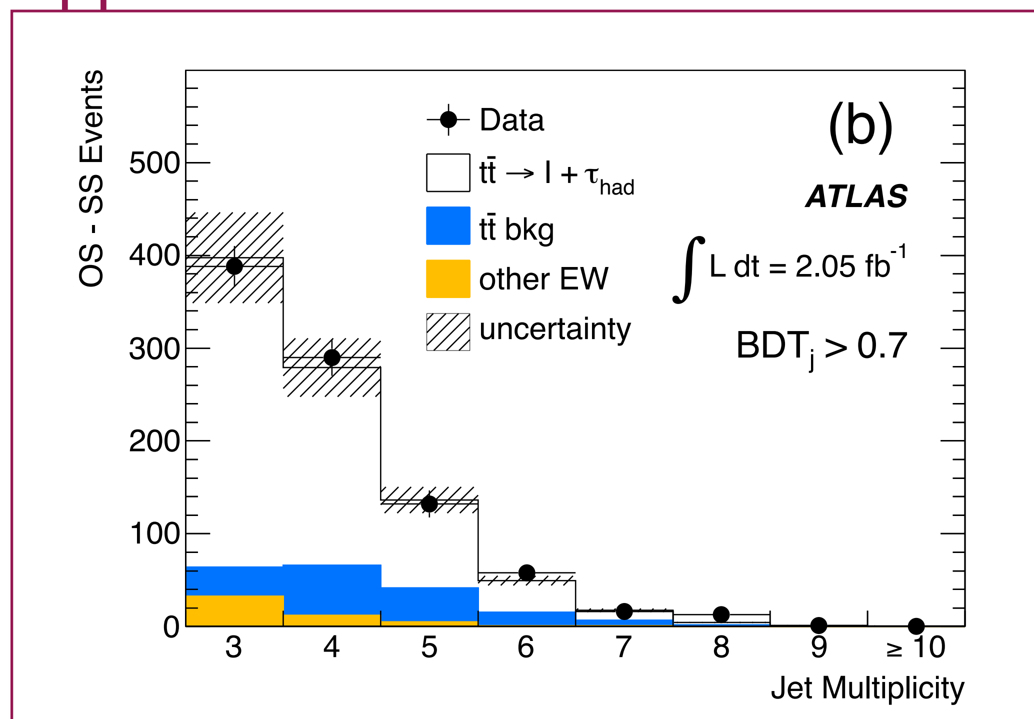
main uncertainties

- ★ b-Jet tagging
- ★ ISR & FSR models
- ★ τ-ID
- ★ total 11% systematics

final fit for τ_1



application of fit results



$$\sigma_{t\bar{t}} = 186 \pm 13 \ (\text{stat.}) \pm 20 \ (\text{syst.}) \pm 7(\text{lumi.})\text{pb}$$

Phys. Lett. B 717 (2012) 89-108

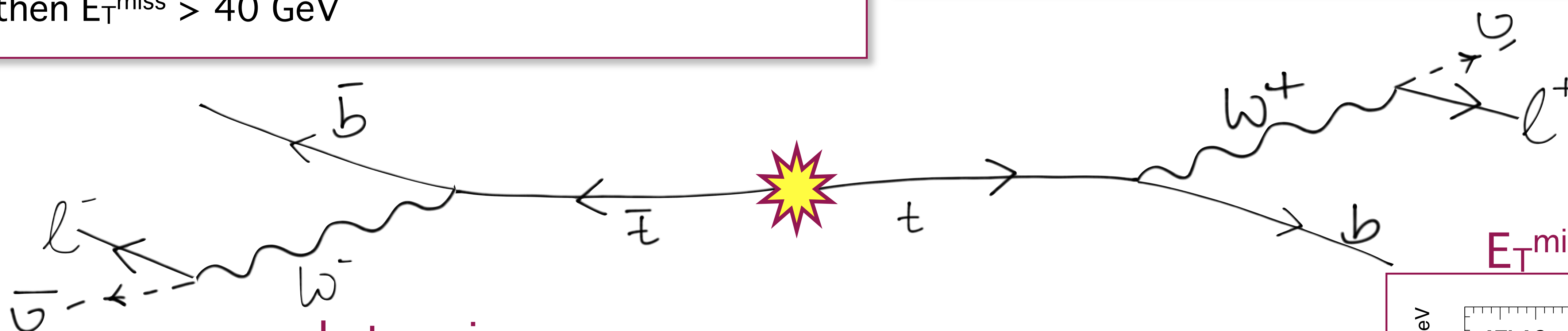
Dilepton 7 TeV, 0.7 fb^{-1}

event selection

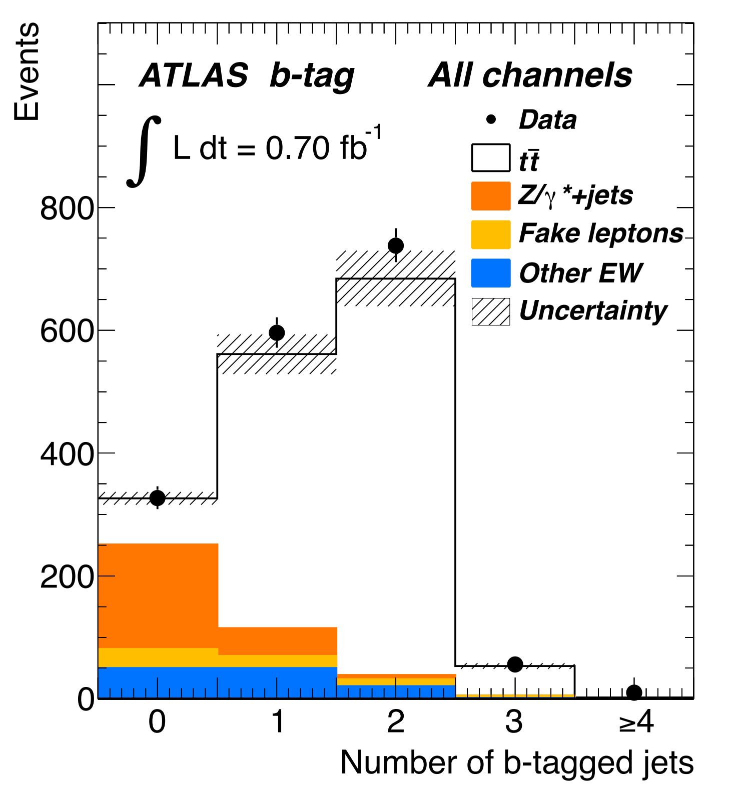
- ★ 2 OS leptons with p_T > 20-25 GeV
- ★ ≥ 2 jets with p_T > 25 GeV
- ★ m_{ll} > 15 GeV and $|m_{ll}-m_Z|$ > 10 GeV for ee, μμ
- ★ E_T^{miss} > 60 GeV for ee, μμ
- ★ H_T > 130 GeV for eμ
- ★ additional selection with ≥ 1 b-jet, then E_T^{miss} > 40 GeV

lepton+track

- ★ sensitivity can be enhanced selecting events with one isolated lepton and one isolated track
- ★ ID track with p_T > 25 GeV
- ★ track-based isolation in cone of ΔR=0.3 < 2 GeV
- ★ no additional b-tag requirement
- ★ E_T^{miss} > 45 GeV, H_T > 150 GeV



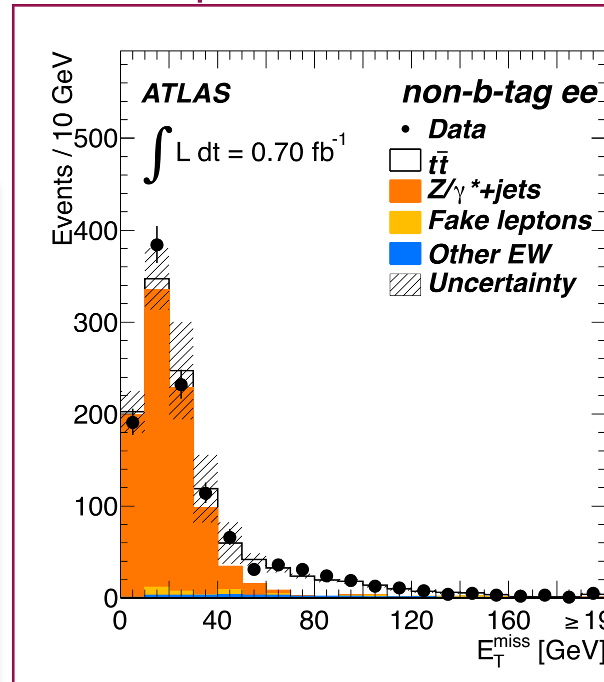
b-tagging



backgrounds

- ★ dominant background is Z/γ*+Jets
- ★ suppress by requirements on m_{ll}
- ★ estimate remaining contributions from $|m_{ll}-m_Z|$ < 10 GeV control region (E_T^{miss} > 30/45 GeV)
- ★ W+Jets, tt (Lepton+Jets), single top contribute through jets faking leptons
- ★ estimate using “matrix method” from data

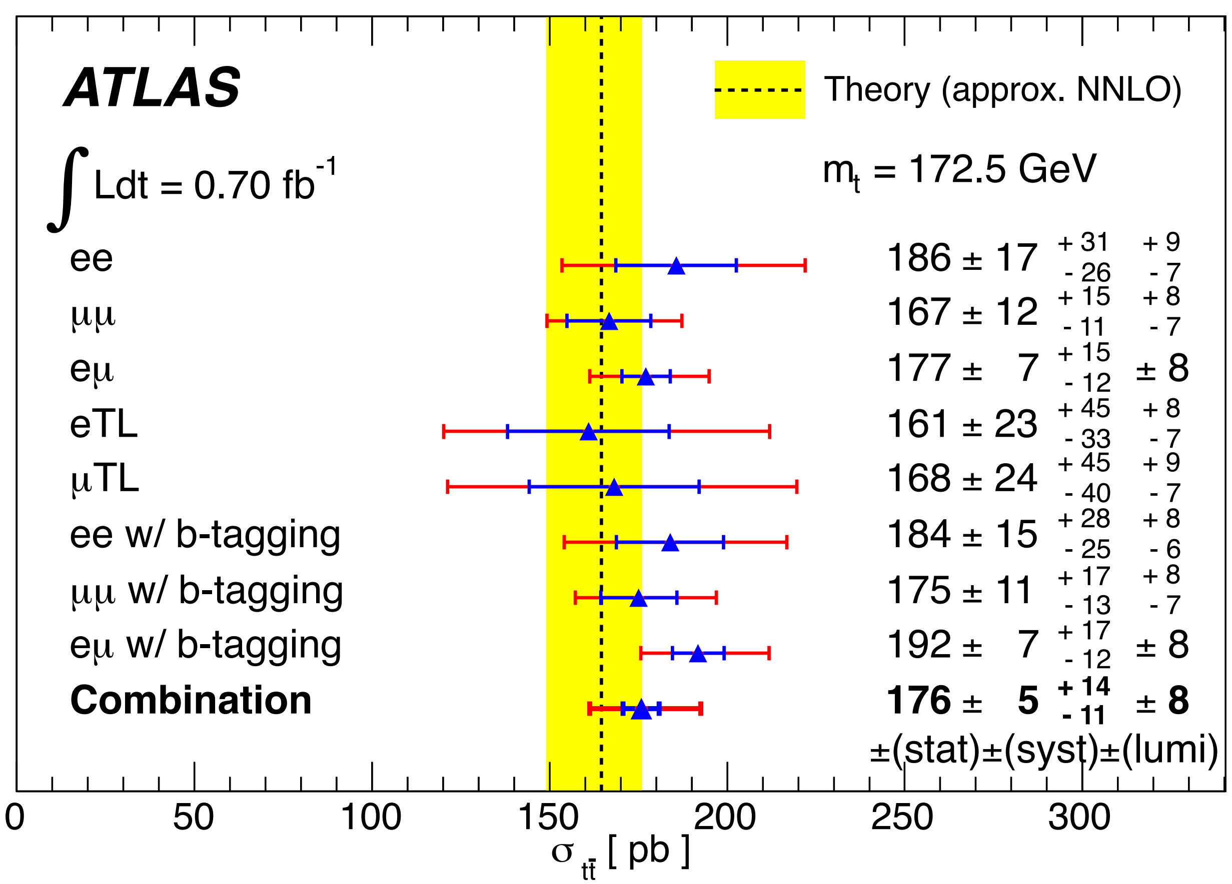
E_T^{miss} > 60 GeV



JHEP 1205 (2012) 059

Dilepton 7 TeV, 0.7 fb^{-1}

- ★ counting events in ee, μμ, eμ, μ+track, e+track without b-tagging and ee, μμ, eμ with b-tagging selections
- ★ profile likelihood fit to all 8 bins simultaneously
- ★ consistent picture between all channels
- ★ 9.5% total uncertainty in good agreement with predictions



dominant systematics

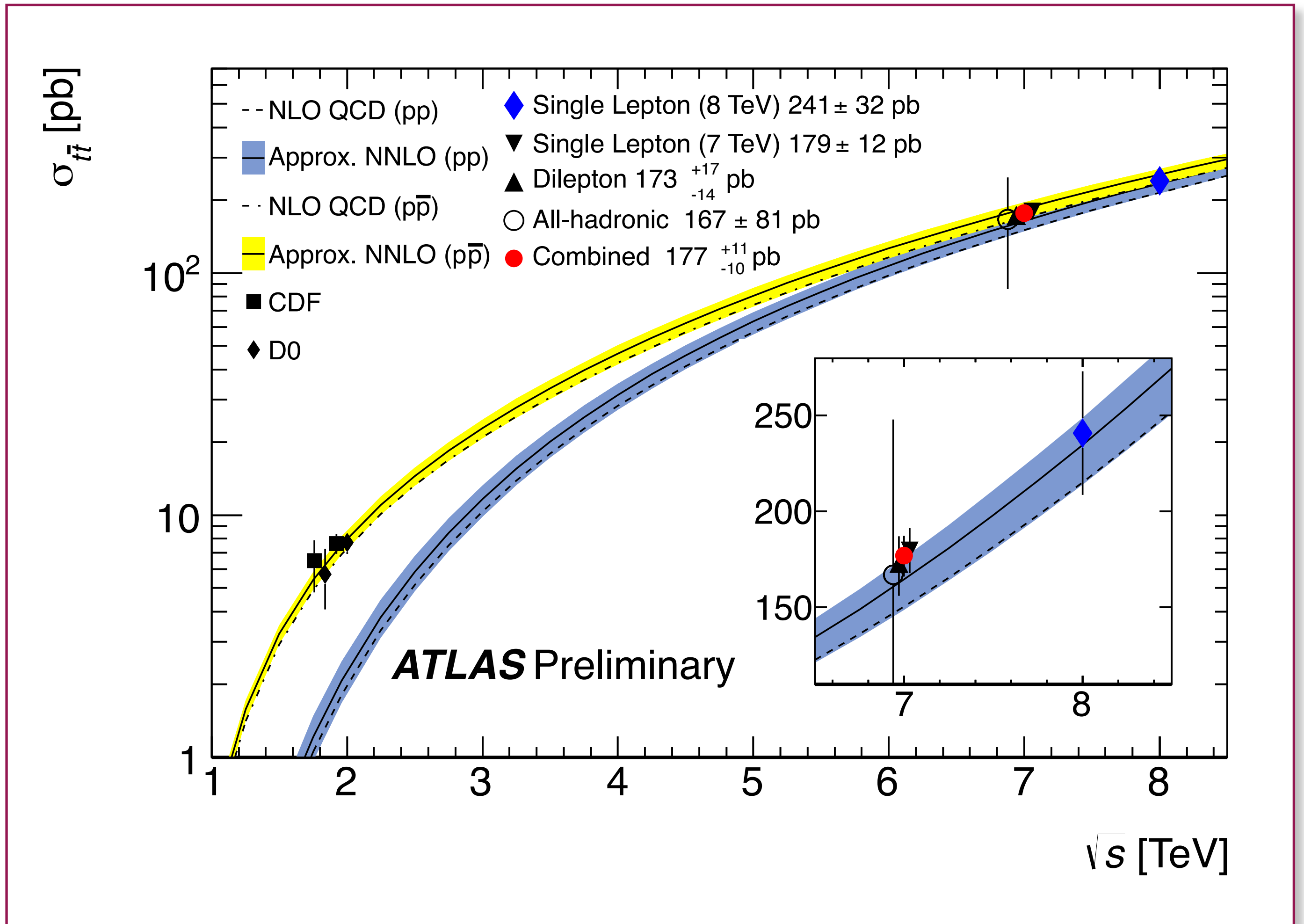
- ★ modeling of the signal process
- ★ jet related uncertainties
- ★ lepton related uncertainties
- ★ systematic uncertainties dominate measurement

$$\sigma_{t\bar{t}} = 176 \pm 5\ (\text{stat.})^{+14}_{-11}\ (\text{syst.}) \pm 8(\text{lumi.})\text{pb}$$

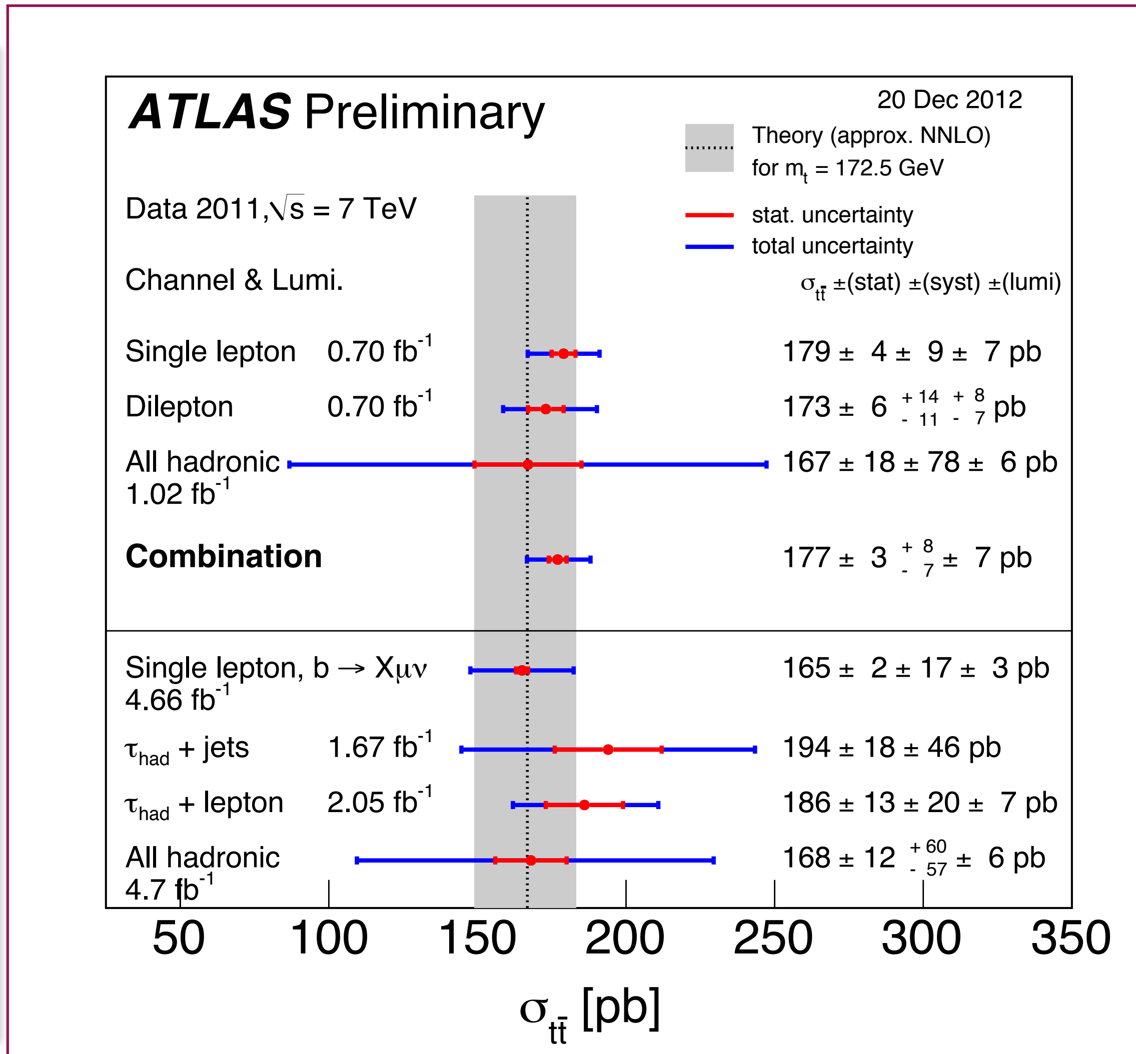
JHEP 1205 (2012) 059

Overview

7 & 8 TeV



combination, 7 TeV



- ★ results presented for all channels
- ★ precise understanding of top quark production at hand
- ★ no surprises - good agreement with each other and with SM predictions

- ★ ATLAS-CONF-2012-131 for ATLAS combination
- ★ combination driven by high precision Lepton +Jets and Dilepton results
- ★ ATLAS & CMS combination will be shown by M. Cristinziani (Saturday)

Conclusions

- broad program of inclusive top quark pair production measurements at ATLAS
- excellent understanding of 7 TeV data set in terms of
  - precision
  - development of new techniques
  - coverage of all channels
  - sensitivity to new physics in top quark pair production
  - allows to move to complicated properties measurements, differential cross sections etc.

- effort on 8 TeV just starting
- first result in Lepton+Jets channel available
- but much more to come!

BACKUP

BACKUP - systematics

- systematic uncertainties on signal modeling through:
  - ISR/FSR radiation using Pythia variations in AcerMC (typically dominant)
  - choice of generator
    - for hard process: MC@NLO vs PowHeg (Alpgen)
    - for parton showering: PowHeg can be interfaced with Herwig/Pythia
    - PDFs through varying errors/PDF sets

dilepton 7 TeV, total ~ 8% systematic uncertainties

Uncertainties $\Delta\sigma/\sigma[\%]$	ee	$\mu\mu$	$e\mu$	eTL	μTL	Combined
Data statistics	±8.1	±6.1	±3.9	±14.1	±14.2	±2.9
Luminosity	+4.4/-3.8	+4.4/-3.9	±4.2	+5.1/-4.2	+5.4/-4.4	±4.3
MC statistics	±1.6	±1.2	±0.8	±5.5	±4.6	+0.7/-0.6
Lepton uncertainties	+6.2/-5.4	+2.9/-1.3	±3.1	±4.1	+1.8/-1.6	+2.6/-2.2
Track leptons	—	—	—	±4.4	±1.9	+0.3/-0.2
Jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainties	+5.7/-5.7	+6.4/-3.5	+4.7/-3.2	+14.8/-6.4	±13.1	+4.4/-3.4
b-tagging uncertainties	+1.2/-1.0	±0.7	—	—	—	+0.4/-0.0
Z/γ^*+ jets evaluation	±0.4	+0.5/-0.0	—	±6.2	+2.4/-2.7	+0.3/-0.2
Fake lepton evaluation	±3.3	+1.5/-1.3	±3.0	±13.7	±15.1	±1.7
Generator	+12/-11	+4.5/-4.3	+4.8/-4.5	+14/-11	+14/-13	+5.1/-4.9
All syst.(except lumi.)	+16.4/-14.4	+8.8/-6.4	+8.2/-6.8	+27.9/-20.7	+26.5/-23.7	+8.0/-6.5
Stat. + syst.	+18.9/-16.9	+11.6/-9.5	+10.1/-8.8	+31.8/-25.2	+30.7/-27.8	+9.6/-8.2

JHEP 1205 (2012) 059

BACKUP - systematics

lepton+jets 8 TeV, total ~ 13% systematic uncertainties

Source	$e+\geq 3$ jets	$\mu+\geq 3\,jets$	combined
Jet/MET reconstruction, calibration	6.7, -6.3	5.4, -4.6	5.9, -5.2
Lepton trigger, identification and reconstruction	2.4, -2.7	4.7, -4.2	2.7, -2.8
Background normalization and composition	1.9, -2.2	1.6, -1.5	1.8, -1.9
b-tagging efficiency	1.7, -1.3	1.9, -1.1	1.8, -1.2
MC modelling of the signal	±12	±11	±11
Total	±14	±13	±13

l+jets SMT 7 TeV, ~ 10.5%

	Relative cross section uncertainty [%]		
Source	e+jets	μ+jets	Combined
Statistical Uncertainty	±1.5	±1.3	±1.0
Object selection			
Lepton energy resolution	+0.4 /-0.3	+0.2 /-0.1	+0.2 /-0.1
Lepton reco, ID, trigger	+2.4 /-2.5	+1.5 /-1.5	+1.7 /-1.8
Jet energy scale	+3.8 /-4.3	+3.2 /-3.6	+3.5 /-3.8
Jet energy resolution	±0.2	±0.5	±0.2
Jet reconstruction efficiency	±0.06	±0.06	±0.06
Jet vertex fraction	+1.2 /-1.4	+1.2 /-1.4	+1.2 /-1.4
E_T^{miss} uncertainty	±0.06	±0.08	±0.07
SMT muon reco, ID	±1.3	± 1.3	±1.3
SMT muon χ^2_{match} efficiency	±0.6	±0.6	±0.6
Background estimates			
Multijet normalisation	± 5.2	± 3.9	± 4.4
W+jet normalisation	± 5.2	± 5.7	± 5.5
Other bkg normalisation	± 0.2	± 0.2	± 0.1
Other bkg systematics	+1.6 /-1.5	+2.5 /-2.0	+2.2 /-1.8
Signal simulation			
$b \rightarrow \mu X$ Branching ratio	+2.9 /-3.0	+2.9 /-3.1	+2.9 /-3.1
ISR/FSR	± 2.4	± 0.9	± 1.5
PDF	± 3.2	± 3.0	± 3.1
NLO generator	± 3.2	± 3.2	± 3.2
Parton shower	± 2.2	± 2.2	± 2.2
Total systematics	±11.2	±10.2	±10.5
Integrated luminosity	± 1.8	± 1.8	± 1.8

l+jets 7 TeV, ~5%

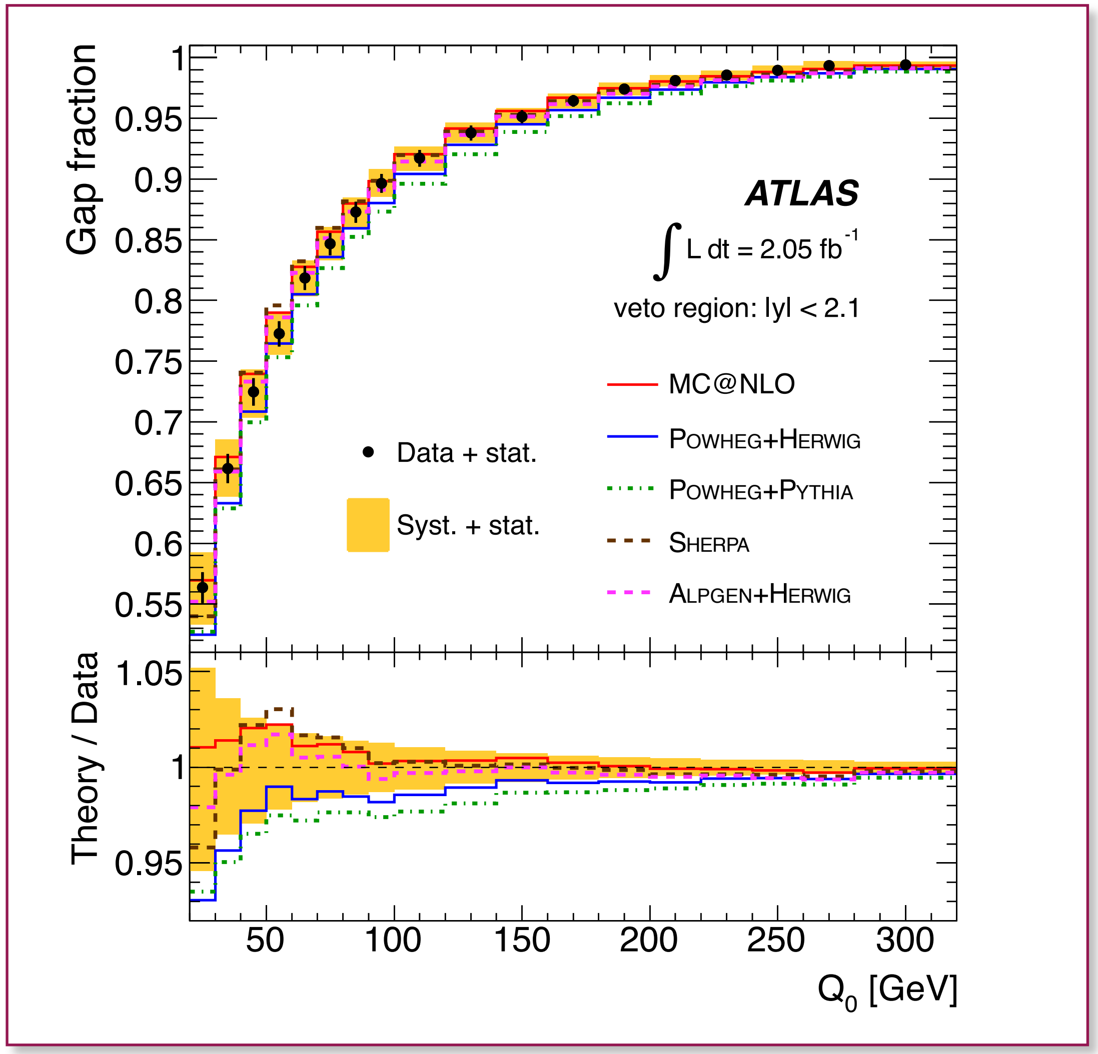
Uncertainty	up (pb)	down (pb)	up (%)	down (%)
Statistical	3.9	−3.9	2.2	−2.2
Detector simulation				
Jets	3.2	−4.3	1.8	−2.4
Muon	4.1	−4.1	2.3	−2.3
Electron	2.7	−3.0	1.5	−1.7
E_T^{miss}	2.0	−1.6	1.1	−0.9
Signal model				
Generator*)	5.4	−5.4	3.0	−3.0
Hadronization*)	0.9	−0.9	0.5	−0.5
ISR/FSR	3.0	−2.3	1.7	−1.3
PDF*)	1.8	−1.8	1.0	−1.0
Background model				
QCD shape*)	0.7	−0.7	0.4	−0.4
W shape*)	0.9	−0.9	0.5	−0.5
Monte Carlo statistics*)	3.2	−3.2	1.8	−1.8
Systematic	9.0	−9.0	5.0	−5.0
Stat. & Syst.	9.8	−9.8	5.4	−5.4
Luminosity	6.6	−6.6	3.7	−3.7
Total	11.8	−11.8	6.6	−6.6

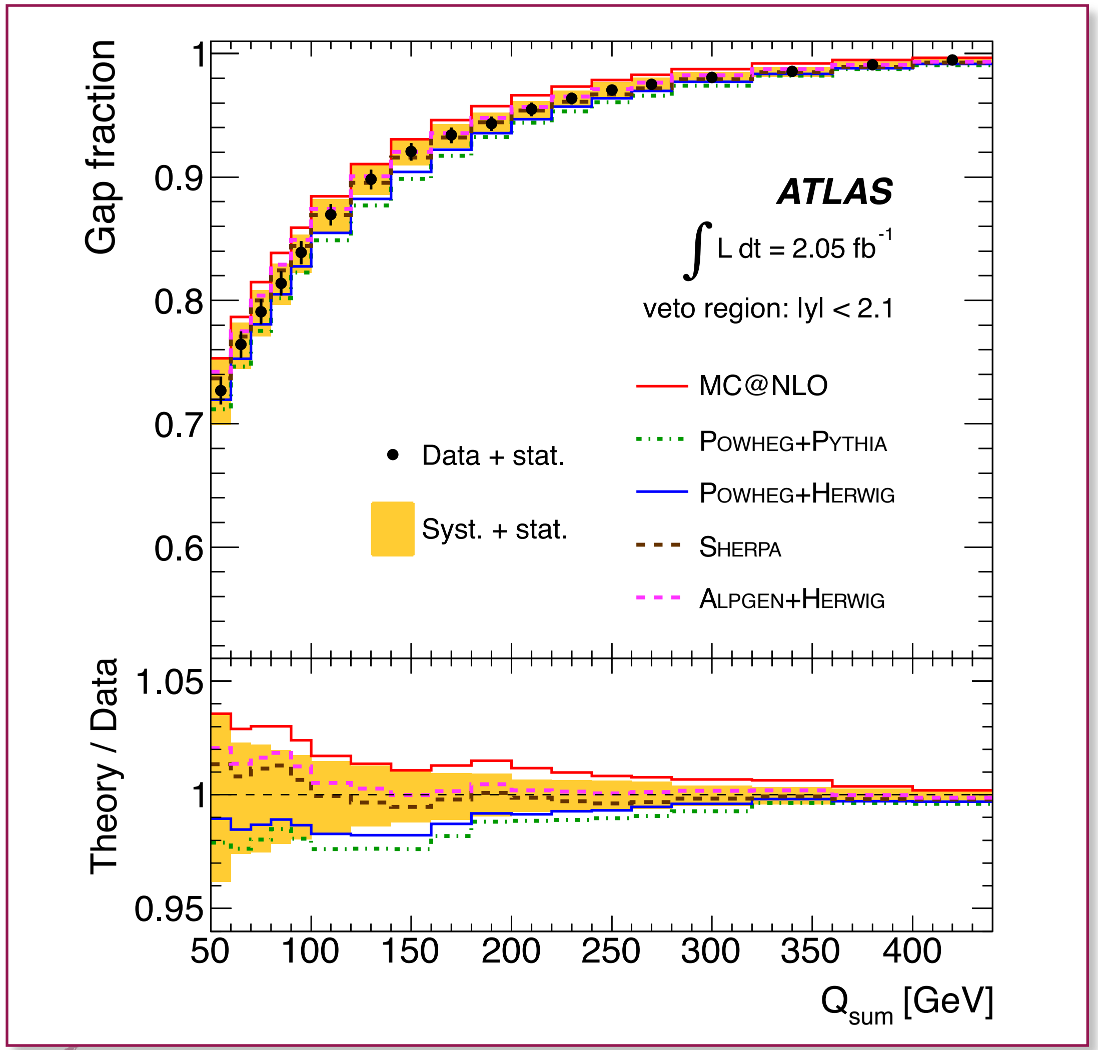
ATLAS-CONF-2011-121 ATLAS-CONF-2012-131,149

BACKUP

- ★ important to reduce systematic uncertainties through signal modeling
- ★ best handle is to provide good different measurements of the cross sections as function of the top kinematics (see talk F.Garberson) and top quark pair production with additional jets (see poster K.J.Grahn)

- ★ analysis with veto on additional central jets (7 TeV) can test generator predictions





Eur.Phys.J C72 (2012) 2043