Measurement of Top Quark Pairs Production Cross-Section in the Lepton+Jets Channel at $\sqrt{s}$=7 TeV at the LHC with the ATLAS Experiment

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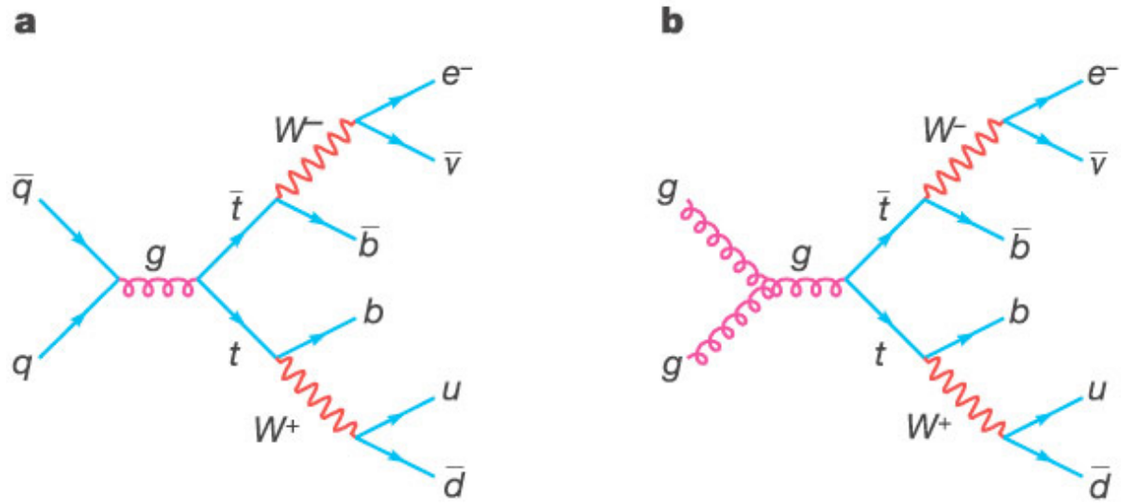
Outline

- Introduction
- The ATLAS detector
- Signal and backgrounds
- Event Selection
- Cross-section measurements by ATLAS
  - Multivariate, Cut and count
- Results
- Conclusions

Introduction

- Important test for both pQCD and the ATLAS detector!
- All parts of the detector must be understood
- Major background in BSM (*e.g.* SUSY) and Higgs searches
- Deviations in *ttbar xs* could be hints of New Physics (e.g. *Z'→ttbar*)



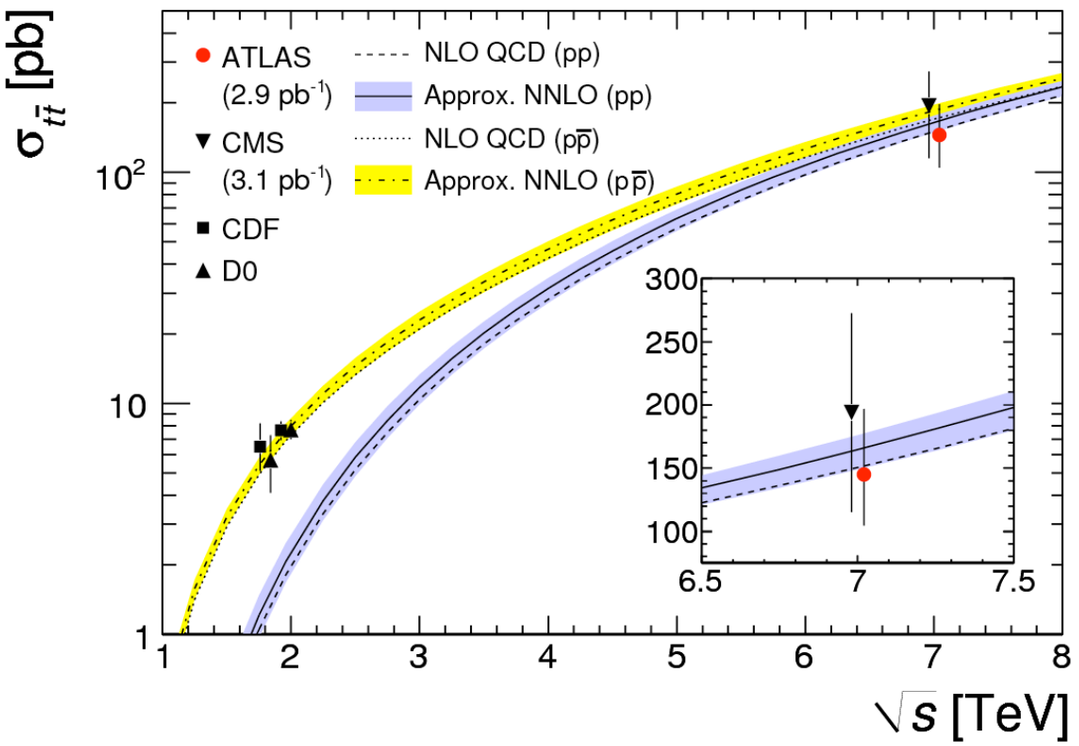
- NNLO prediction:

$$\sigma_{t\bar{t}}^{NLO} = 165^{+11}_{-16}\ pb$$

- Previous measurement with 2.9 pb^{-1}:

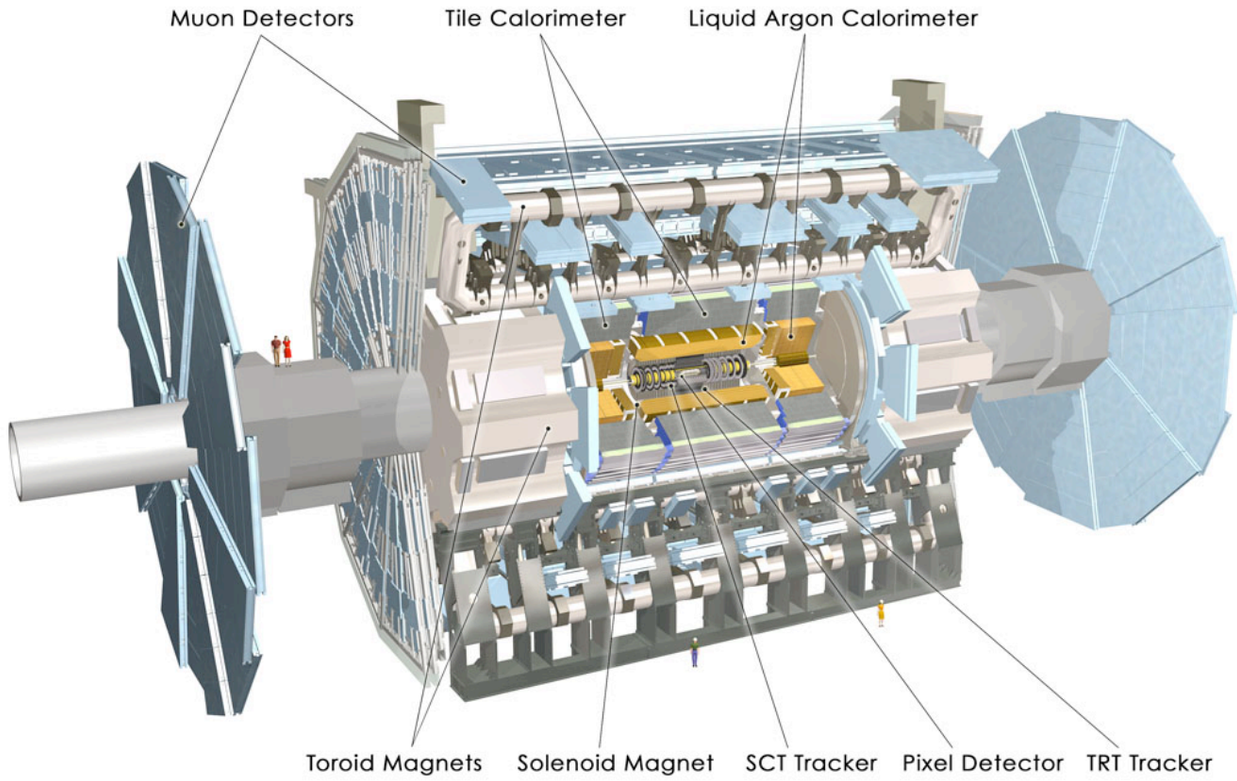
$$\sigma_{t\bar{t}} = 145 \pm 31(stat)^{+42}_{-27}(syst)\ pb$$

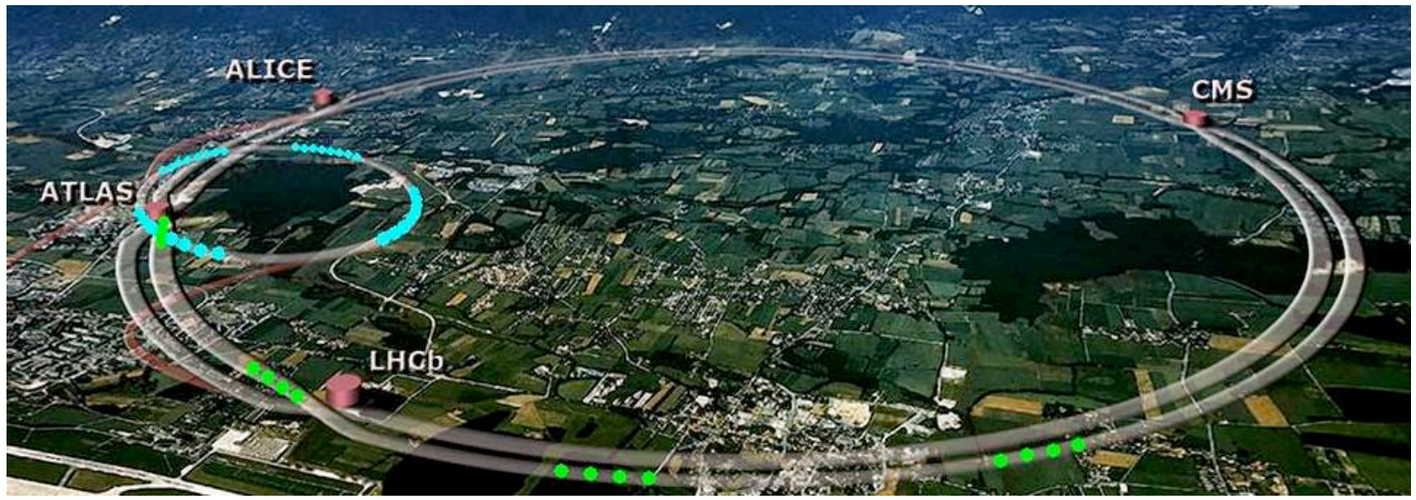
[CERN-PH-EP-2010-064]



The ATLAS detector

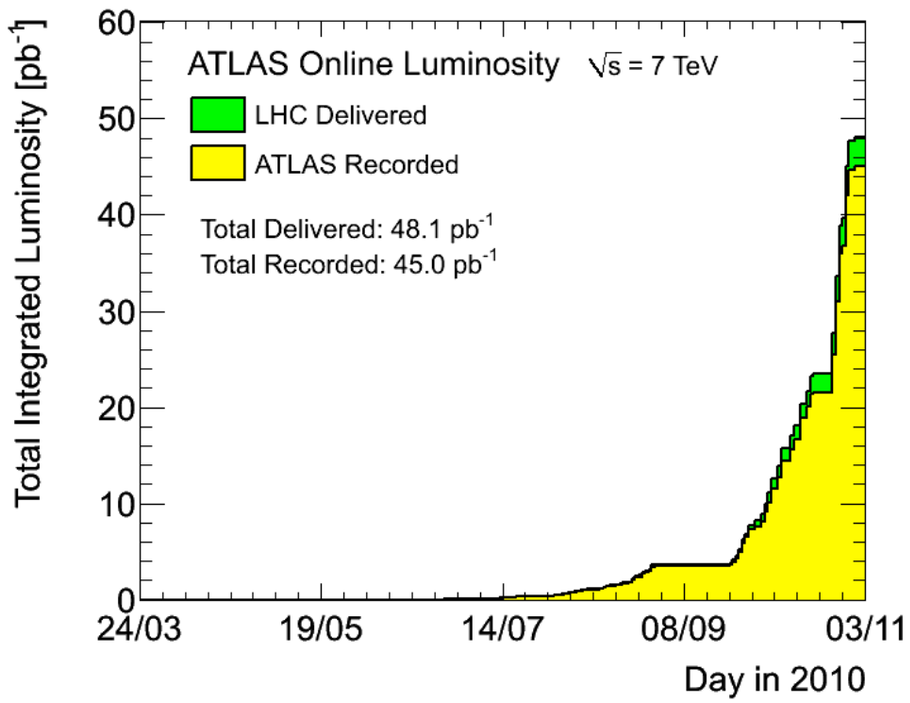
- Multi-purpose detector for *pp* and *AA* physics at the LHC
- ID: pixel + strips + straw tubes (TRT), 2T solenoidal *B* field
- Cal: LAr sampling accordion geometry (ECAL) + Tile (HCAL)
- Air-core toroids, low multiple scattering for muons
- Muon spectrometer: 3 layers of tracking chambers + trigger

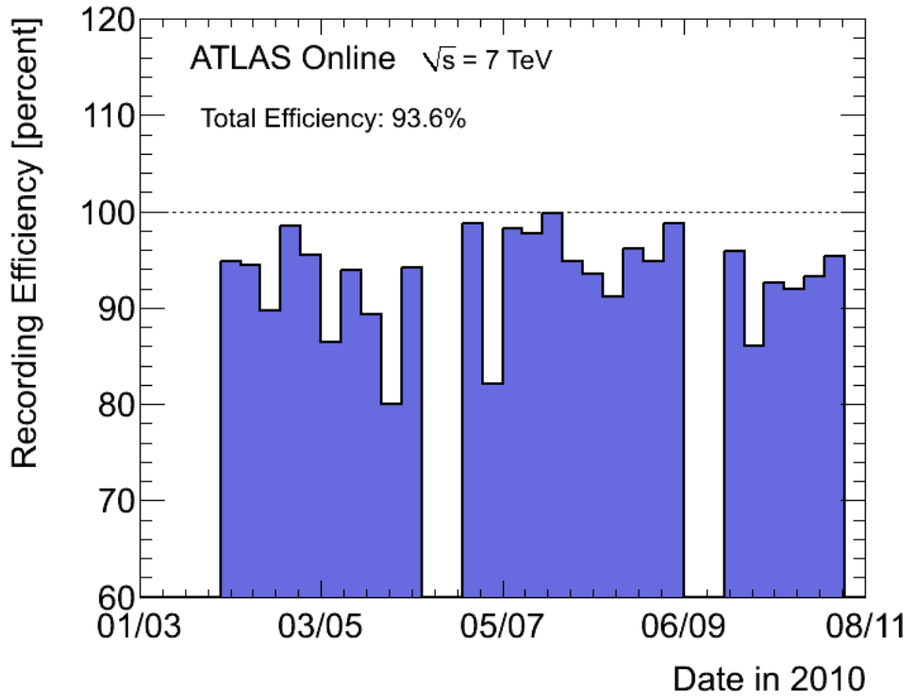




Data Samples in 2010

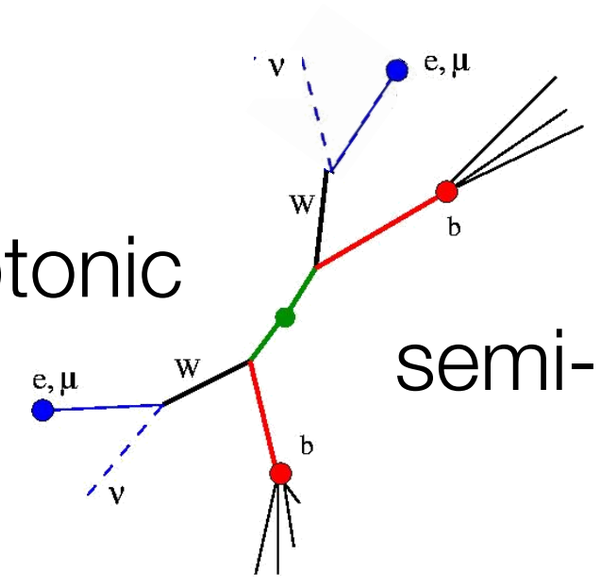
- $\sqrt{s}$ = 7 TeV *pp* runs
  - Peak luminosity 2×10^{32} $cm^{-2}s^{-1}$
  - <pileup>=3
  - δL = 3.4%
- Total delivered 48.1 pb^{-1}
- Total recorded 45.0 pb^{-1}
- ATLAS efficiency 93.6%
- *Good run list* for top quark studies 35.5 pb^{-1}



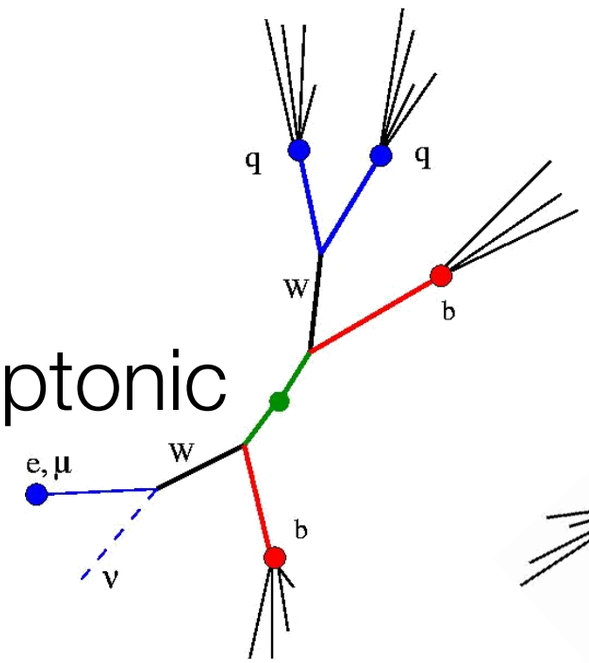


Event topology

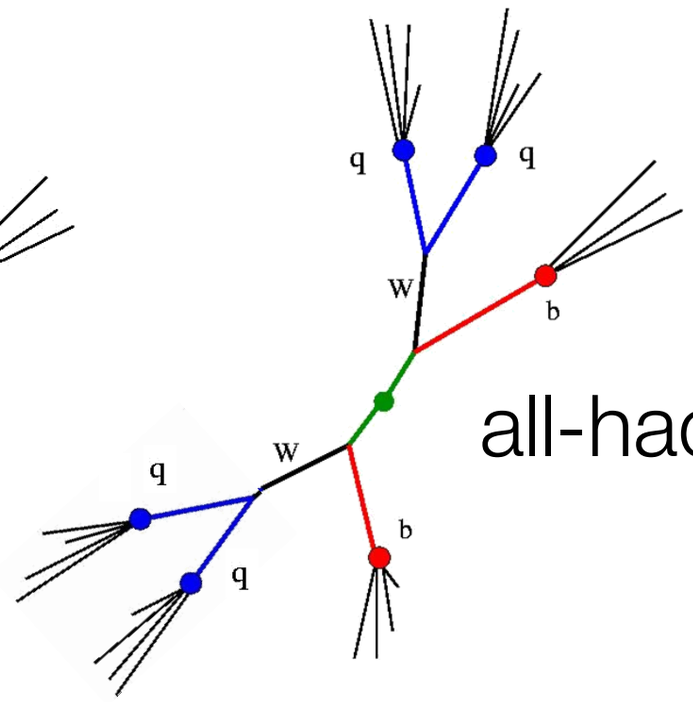
di-leptonic



semi-leptonic

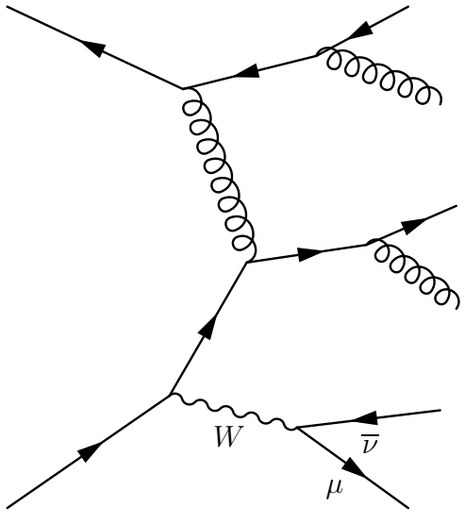


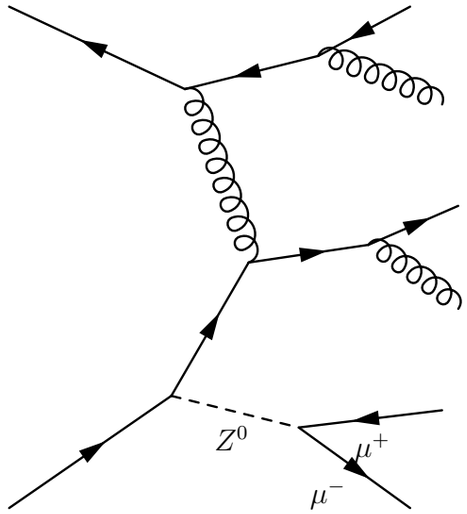
all-hadronic

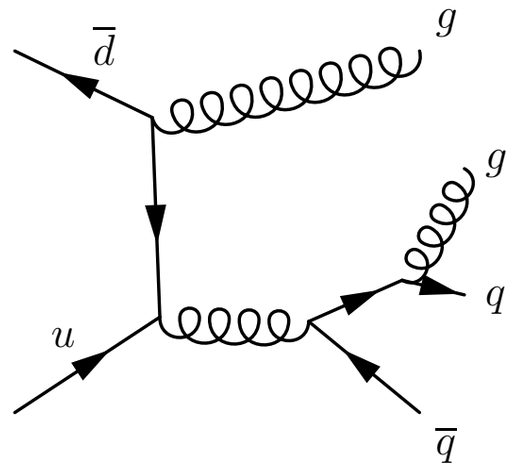


	Br	Backgrounds	Trigger	Reco
di-leptonic	1/9	Clean	✓	Mass issues
semi-leptonic	4/9	W+jets, QCD	✓	Complete!
all-hadronic	4/9	QCD	✗	Combinations

Backgrounds







- QCD and W backgrounds estimated from data
- Z+jets, Single top, WW/ZZ/WZ from MC simulations
  - Pile-up effects taken into account

Analysis Objects

kin cut on leptons and jets: pT>20 GeV, $|\eta| < 2.5$

Electrons

- Medium PID cuts
- No "crack" region $1.37 < |\eta| < 1.52$
- Isolation $\Sigma E_T(r \leq 0.2) < (4 + 0.023\, E_T)$ GeV

Muons

- Combined tracks ID + MS
- Isolation
  - $\Sigma E_T(r \leq 0.4) < 4$ GeV
  - $\Sigma p_T(r \leq 0.4) < 4$ GeV
- $\Delta R(\text{jet, muon}) > 0.4$

Jets

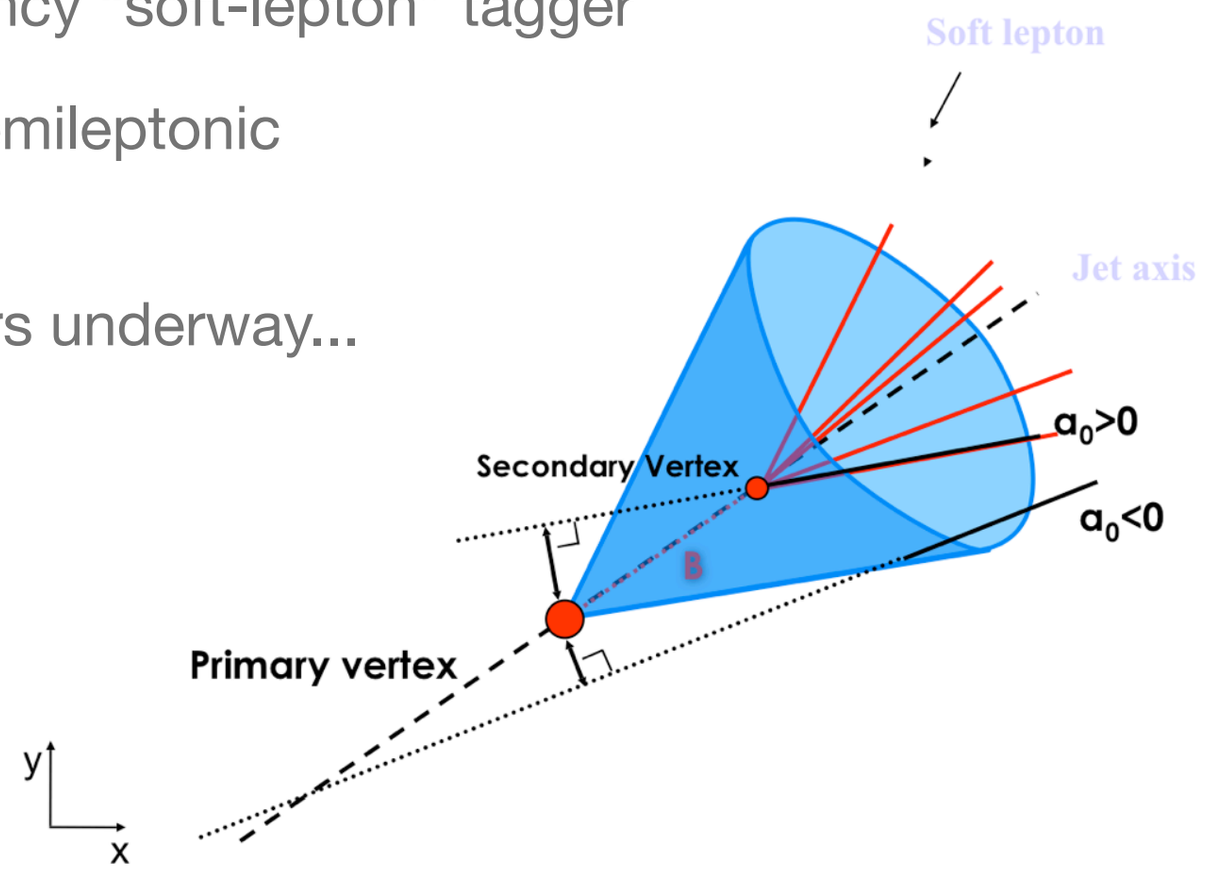
- Anti-k_T, R=0.4 from topological clusters
- Energy calibrated to hadronic scale (p_T, η)
- $\Delta R(\text{ele, jet}) > 0.2$
- b-tagged SV0 $w > 5.85$

Missing Energy

- From topological clusters.
- "Jet" cells calibrated had scale
- "Electron" and "muon" cells replaced by reco object E_T

b-Tagging

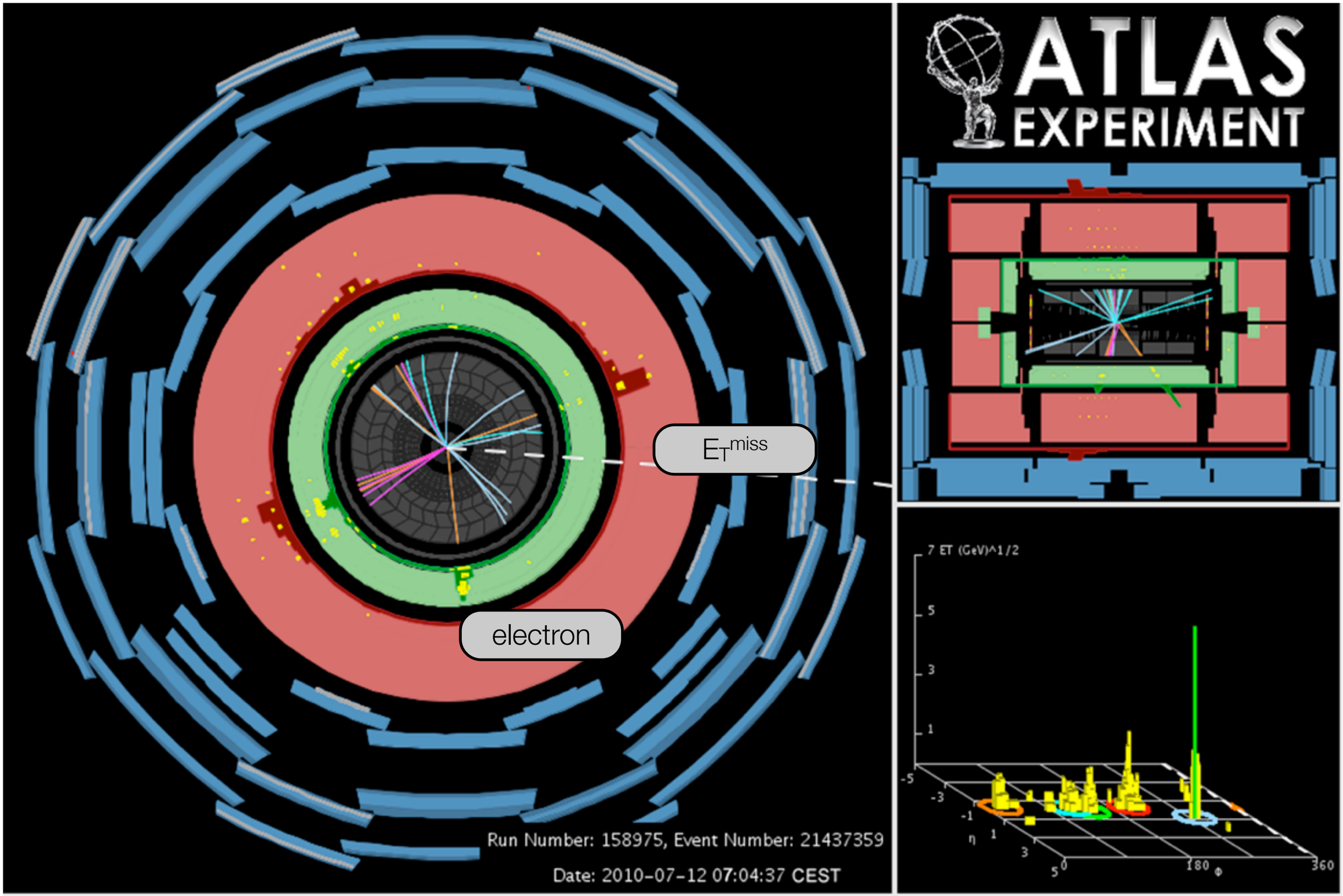
- 2010 choice: SV0 tagger
  - Long B hadrons lifetime ⇒ identification of secondary vertex
    - b-Tag = Sec vtx ⊕ L/σ(L) resulting in ε_{btag} = 50% in MC ttbar events
  - Calibrated using a lower efficiency “soft-lepton” tagger
    - Soft muon inside jet from semileptonic decays of *B* hadrons
- Calibration of more efficient taggers underway...



Event Selection

e+jets	mu+jets
Single lepton trigger	Single lepton trigger
Single electron, no muons	Single muon, no electrons
$E_T^{miss} > 20$ GeV	$E_T^{miss} > 20$ GeV
E_T^{miss} + mT(W) > 60 GeV	mT(W) > 35 GeV
3, ≥4 jets pT > 25 GeV	3, ≥4 jets pT > 25 GeV
(≥ 1 b-tagged jet)	(≥ 1 b-tagged jet)

- Depending on the analysis, one asks 3, 4, ≥4, ≥5 jets and the presence of a *b*-tagged jet
- *e.g.* ≥4 & 1 *b*-tag results in ~ 6% efficiency on signal


ATLAS
EXPERIMENT
E_T^{miss}
electron
Run Number: 158975, Event Number: 21437359
Date: 2010-07-12 07:04:37 CEST
7 ET (GeV)^1/2
5
3
1
-5
-3
-1
η
1
3
5
0
180
Φ
360

ttbar l+jets Cross-section Measurements by ATLAS

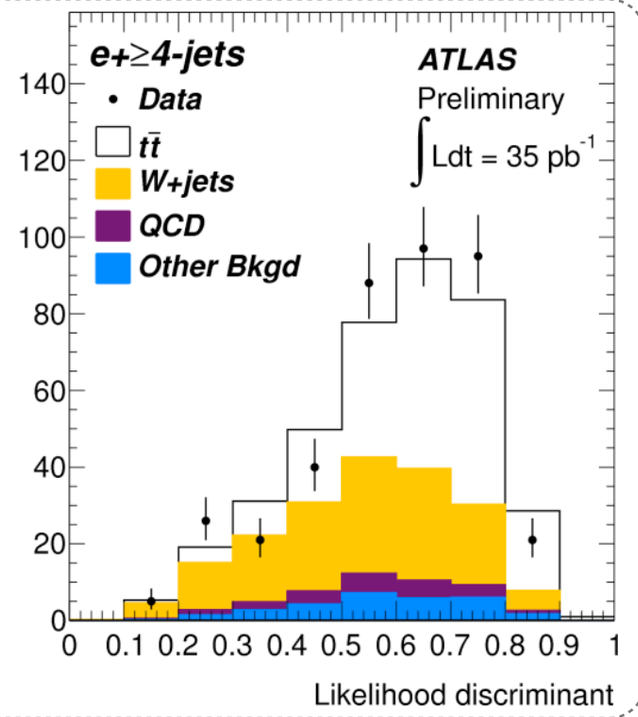
- Pre-tag analyses:
  - Multivariate with 3 variables (baseline)
  - 1D lepton η fit
  - 1D $\Delta\eta_{max}(l,\text{jet})$ fit
  - Cut and count
- Tagged analyses:
  - Multivariate with 4 variables (baseline)
  - Top mass fit in the 3- and ≥4-jets samples (16 parameters)
  - Top mass profile fit in the 3-, 4- and ≥5-jets samples (profile likelihood)
  - Cut and count
- Measurements performed in the di-lepton and full-hadronic channel as well

Baseline Multivariate Analyses

~~b-tagging~~

- Projective likelihood based on η_l, Q_l and aplanarity
- 4 channels (e/μ + 3-, ≥4-jets)
- Independent of b-tagging
  - Less systematics but worse S/B ratio
- δσ ~ 15%

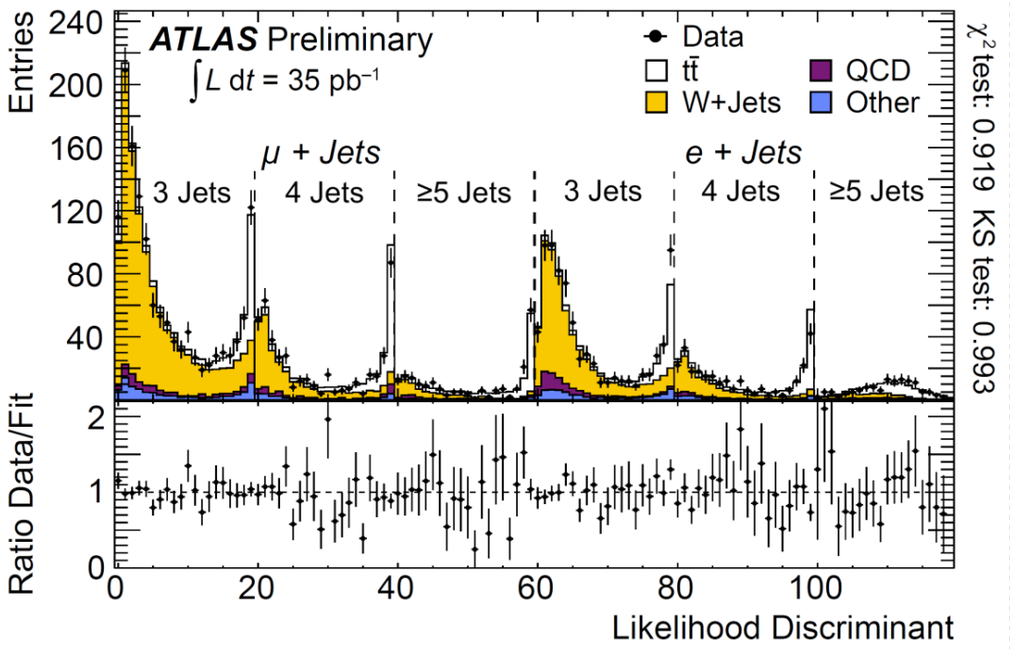
$$\sigma_{t\bar{t}} = 171 \pm 17(stat)^{+20}_{-17}(stat) \pm 6(lumi)$$



w/ b-tagging

- Profile likelihood based on η_l, $H_{T,3p}$, *b*-tag weight and aplanarity
- 6 channels (e/μ + 3-, 4-, ≥5-jets)
- Fit extracts σ_{tt} and 15 parameters
- δσ ~ 13%

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



Cut and Count Analysis

- Simplest approach: just count events and apply the cross-section formula:

$$\sigma_{t\bar{t}} = \frac{N_{sig}}{\epsilon \cdot \mathcal{B} \cdot \mathcal{L}} = \frac{N_{obs} - N_{bkg}}{\epsilon \cdot \mathcal{B} \cdot \mathcal{L}}$$

- Common ground for other top-related studies (*e.g. ttbar* resonances)

- Largest uncertainty: δσ~20%

- Statistical error ~10%

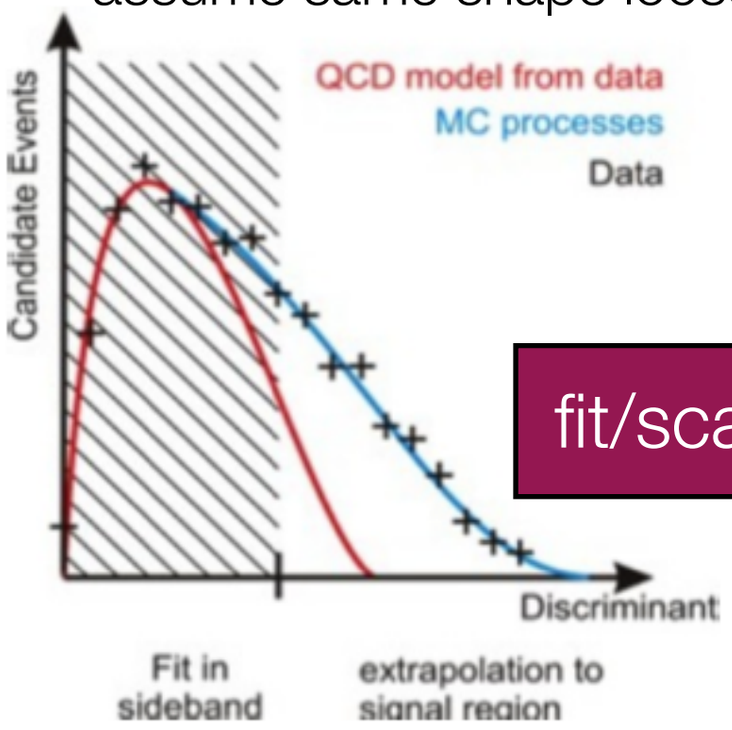
- Main systematics: ISR/FSR, Jet energy scale, *W*+jets normalization

QCD background

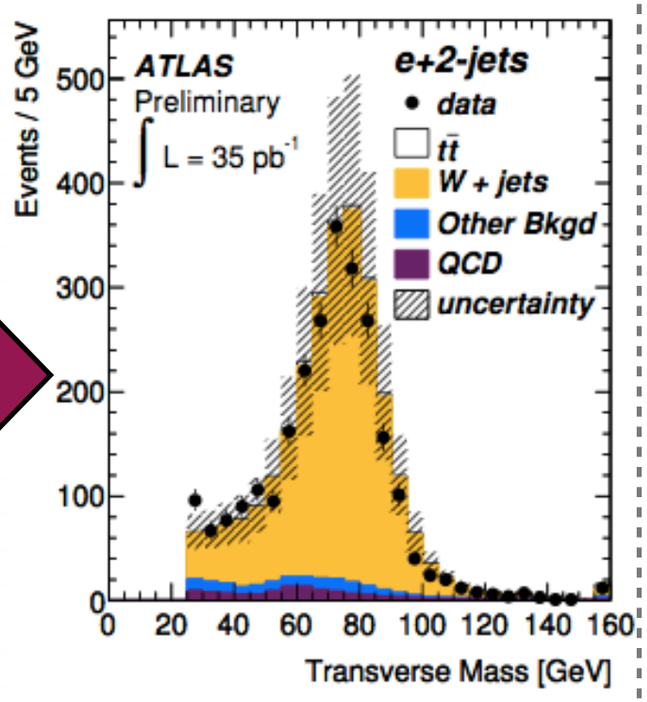
- Isolated *e*/μ from h.f. semileptonic decays
- γ→*ee* conversion
- Jets identified as electrons
- π/K punch-through

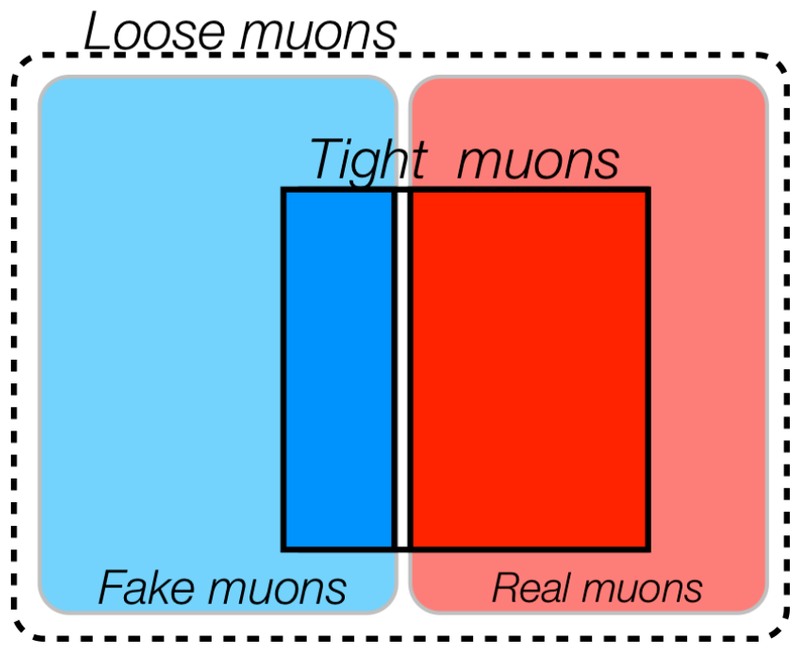
Extract shape from *loose* selection

assume same shape loose / tight electrons



fit/scale





$$N^{loose} = N^{loose}_{real} + N^{loose}_{fake}$$

$$N^{tight} = N^{tight}_{real} + N^{tight}_{fake}$$

$$= \epsilon_{real} N^{loose}_{real} + \epsilon_{fake} N^{loose}_{fake}$$

$Z \rightarrow \mu\mu$

fake-enhanced samples

W+jets background

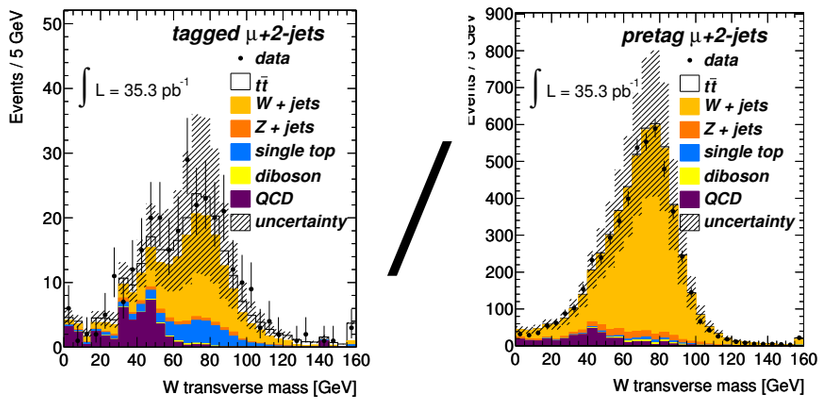
- Same final state as signal, dominated by W + *bb/cc* + jets
- MC prediction has large uncertainty
- W/Z ratio method in the *pre-tag* sample:

$$W_{data}^{\geq 4jets} = W_{data}^{1jet} \left(\frac{Z^{\geq 4jets}}{Z^{1jet}} \right)_{data} \cdot C_{MC} \qquad C_{MC} = \frac{\left(W^{\geq 4jets} / W^{1jet} \right)_{MC}}{\left(Z^{\geq 4jets} / Z^{1jet} \right)_{MC}}$$

- Extrapolation to tagged sample applying MC-driven correction factor:

$$W_{\text{tagged}}^{\geq 4\text{jet}} = W_{\text{pretag}}^{\geq 4\text{jet}} \cdot f_{\text{tagged}}^{\geq 4-\text{jet}} \qquad f_{\text{tagged}}^{\geq 4-\text{jet}} = f_{\text{tagged}}^{2-\text{jet}} \cdot f_{2\to\geq 4}^{\text{corr}}$$

$$f_{tagged}^{2-jet} = \frac{\text{tagged } \mu\text{+2-jets}}{\text{pretag } \mu\text{+2-jets}}$$



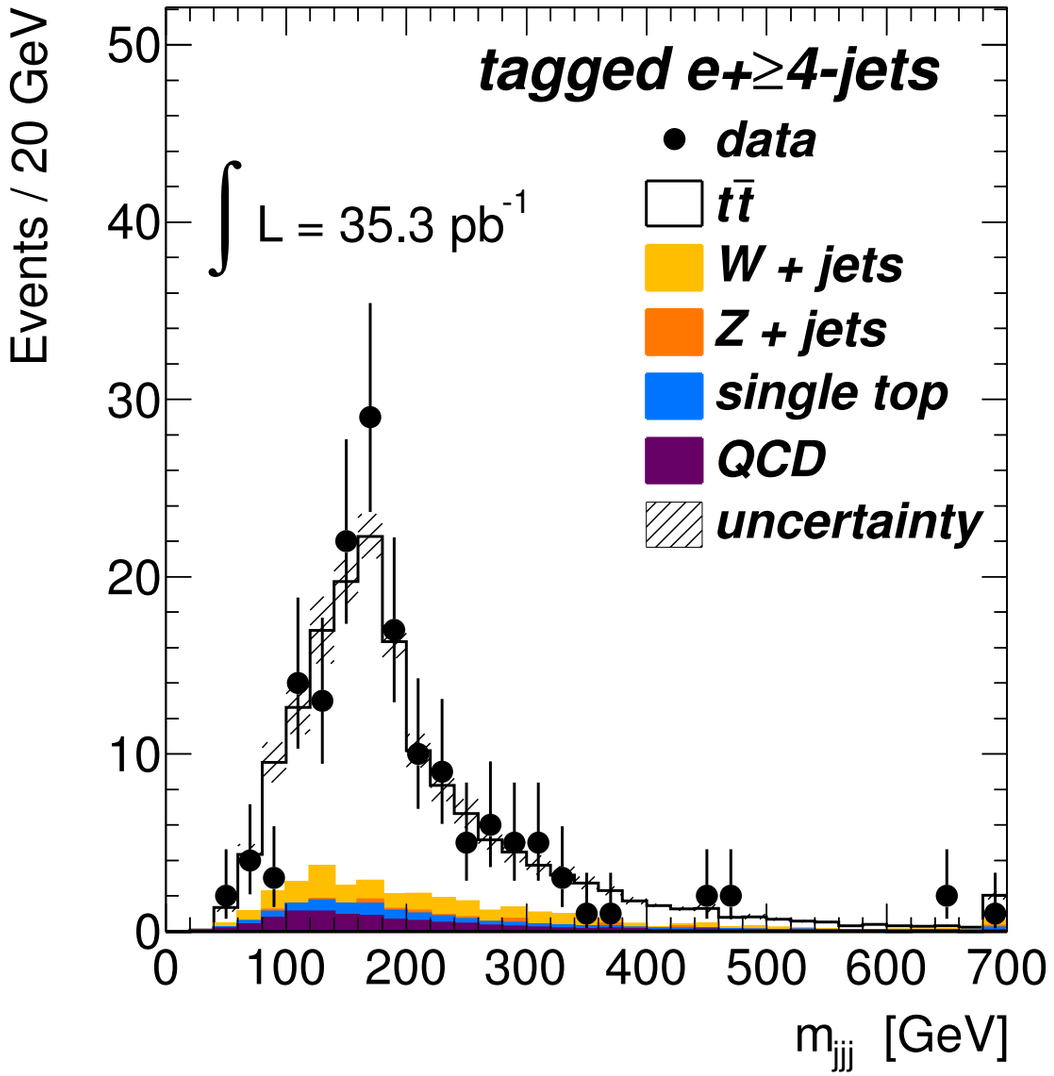
flavours in 2- and 4-jets sample not the same

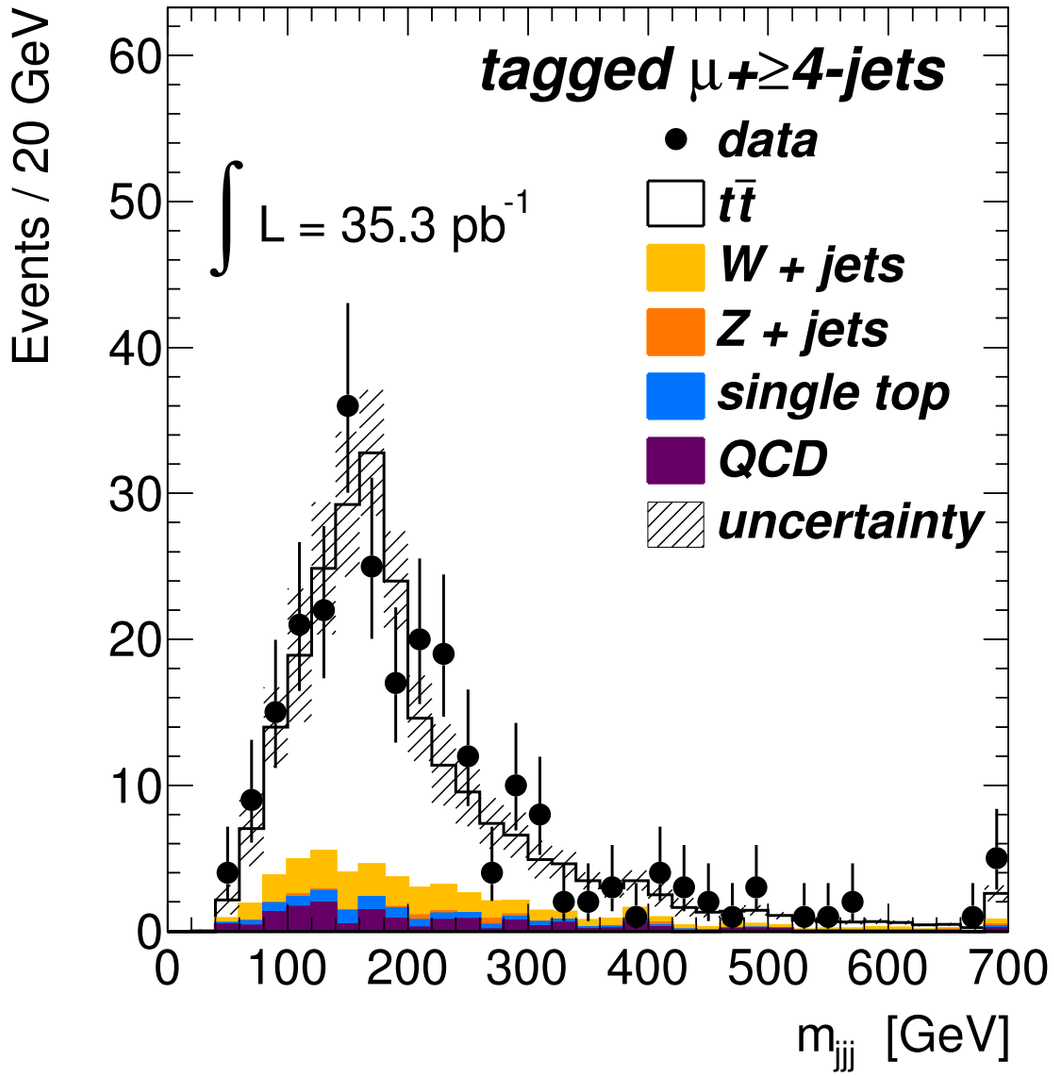
$$f_{2\to\geq 4}^{corr}$$ from MC

- Other approaches (larger uncertainty): Berends-Giele scaling, *W* charge asymmetry

Reconstruction of the Hadronic Top Quark

- Are we really reconstructing top quarks?
- Simplest method: choose 3 jet combination with maximum pT





Calculation of the cross-section

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bkg}}{\epsilon \cdot \mathcal{B} \cdot \mathcal{L}}$$

- Top mass m_t=172.5 GeV
- Acceptance ε estimated from MC
- Luminosity uncertainty 3.4%

Pretag	***e+jets***	***μ+jets***
ttbar (MC)	189.7±45.9	247.8±69.9
W+jets (DD)	156.7±38.1	309.6±61.1
QCD (DD)	22.0±11.0	51.3±15.4
Total bkg	210.3±41.3	405.2±65.1
Observed	400	653

Tagged	***e+jets***	***μ+jets***
ttbar (MC)	126.8±16.6	182.0±21.8
W+jets (DD)	12.2±5.3	39.5±14.4
QCD (DD)	8.6±9.4	13.0±3.9
Total bkg	29.2±10.9	64.0±15.2
Observed	156	246

Combination of the the two channels (*c&c* only)

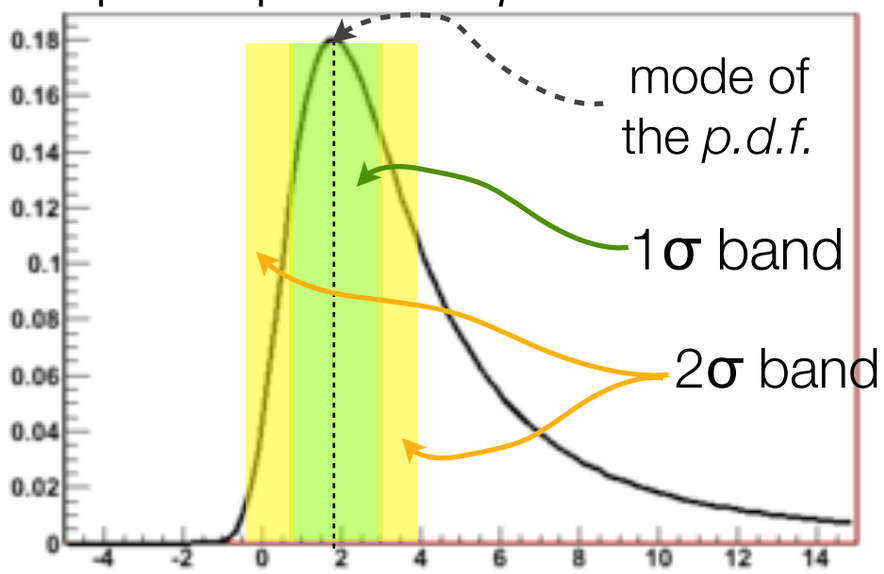
- Method based on Bayes' theorem
- Joint posterior calculated from likelihood of each channel ⊗ priors
  - Likelihood takes into account the dependence of the *xs* on the systematics (*nuisance parameters*)
- Marginalization performed with a Markov Chain Monte Carlo
- Results agree with frequentist method

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

$$p_1(\theta|D_1) \propto L(D_1|\theta)p_0(\theta)$$

$$p_2(\theta|D_2) \propto L(D_2|\theta)p_1(\theta) = L(D_2|\theta)L(D_1|\theta)p_0(\theta)$$

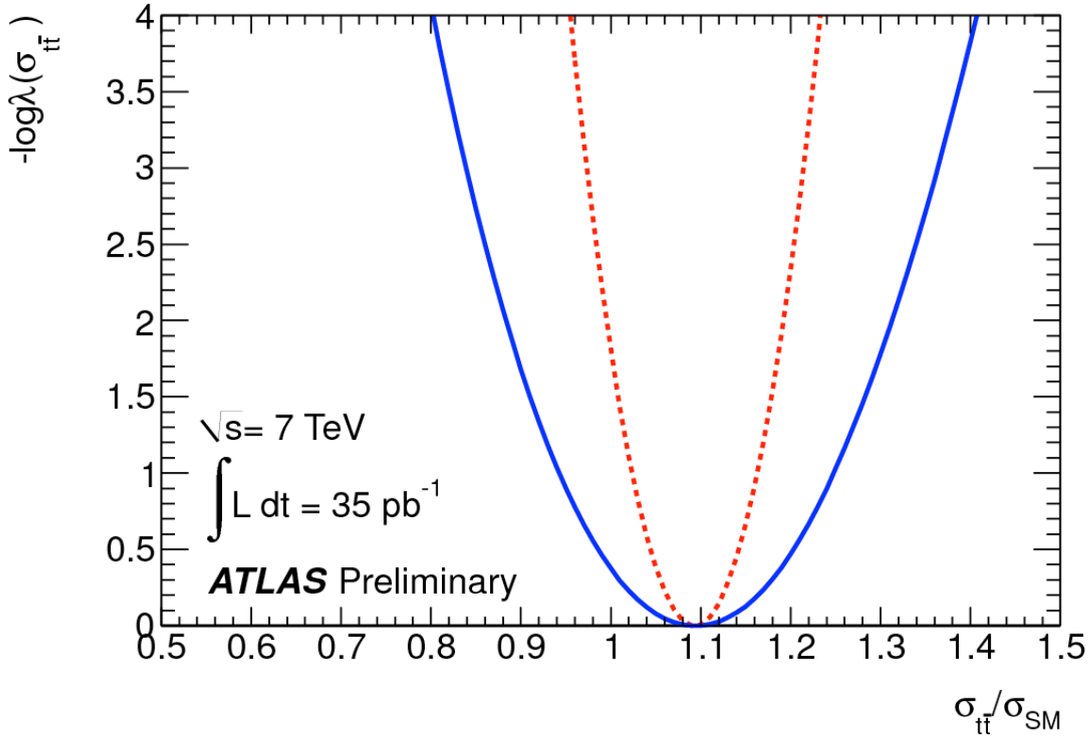
example of posterior *p.d.f.*

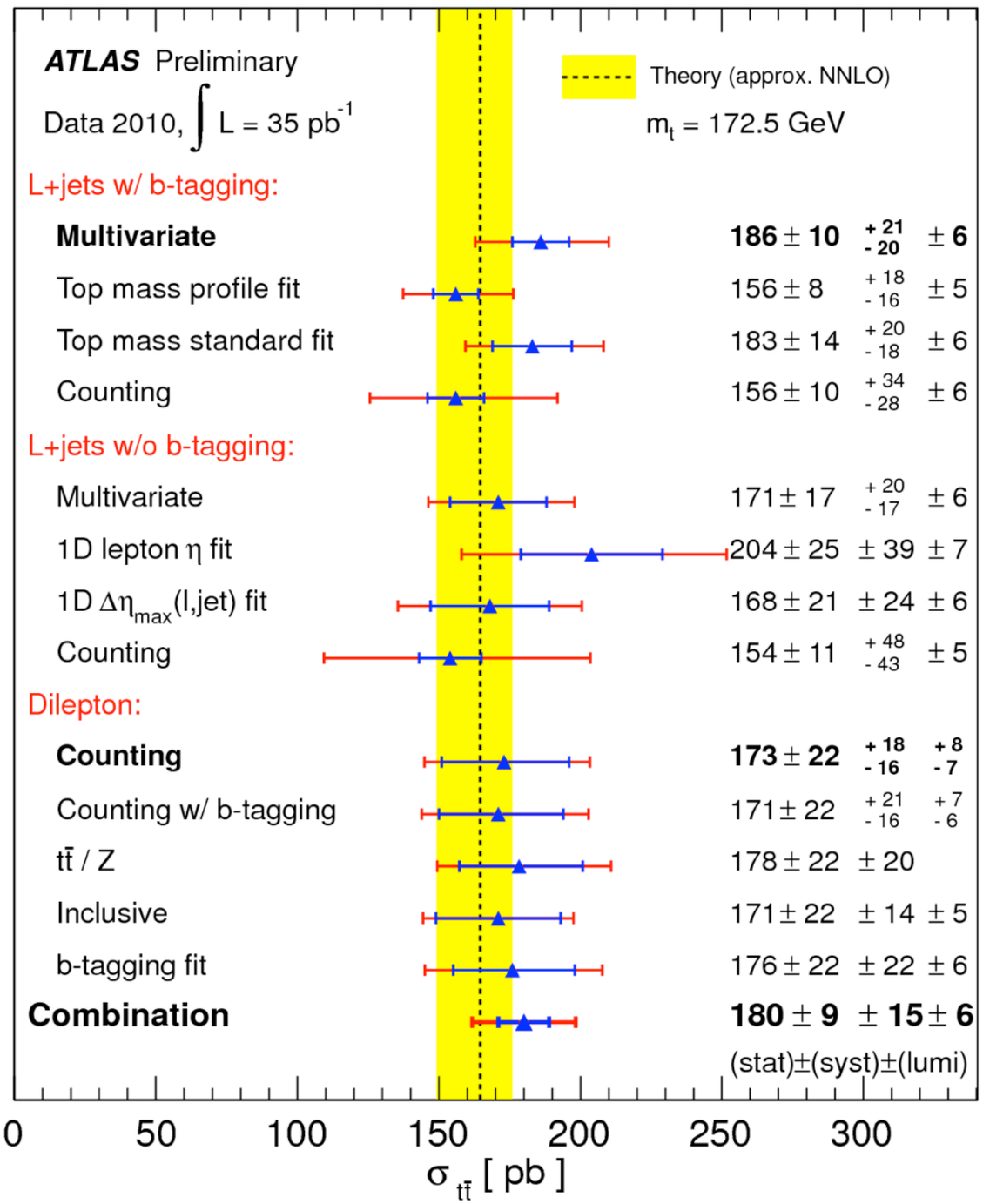


Channel	XS [pb]
e + jets pre-tag	$159 \pm 17\ ^{+50}_{-44} \pm 7$
μ + jets pre-tag	$148 \pm 16\ ^{+47}_{-47} \pm 7$
pre-tag combined	$154 \pm 11\ ^{+48}_{-43} \pm 7$
e + jets tagged	$153 \pm 16\ ^{+41}_{-27} \pm 6$
μ + jets tagged	$159 \pm 14\ ^{+35}_{-27} \pm 6$
tagged combined	$156 \pm 10\ ^{+34}_{-28} \pm 6$

Results

- Multivariate analysis has the smallest uncertainty δσ ~ 13%
- Cut and count method δσ ~ 20%
- Combination of the measurements based on frequentist method
- 5-channels combination (*l*+jets & di-leptonic)
  δσ ~ 10% !



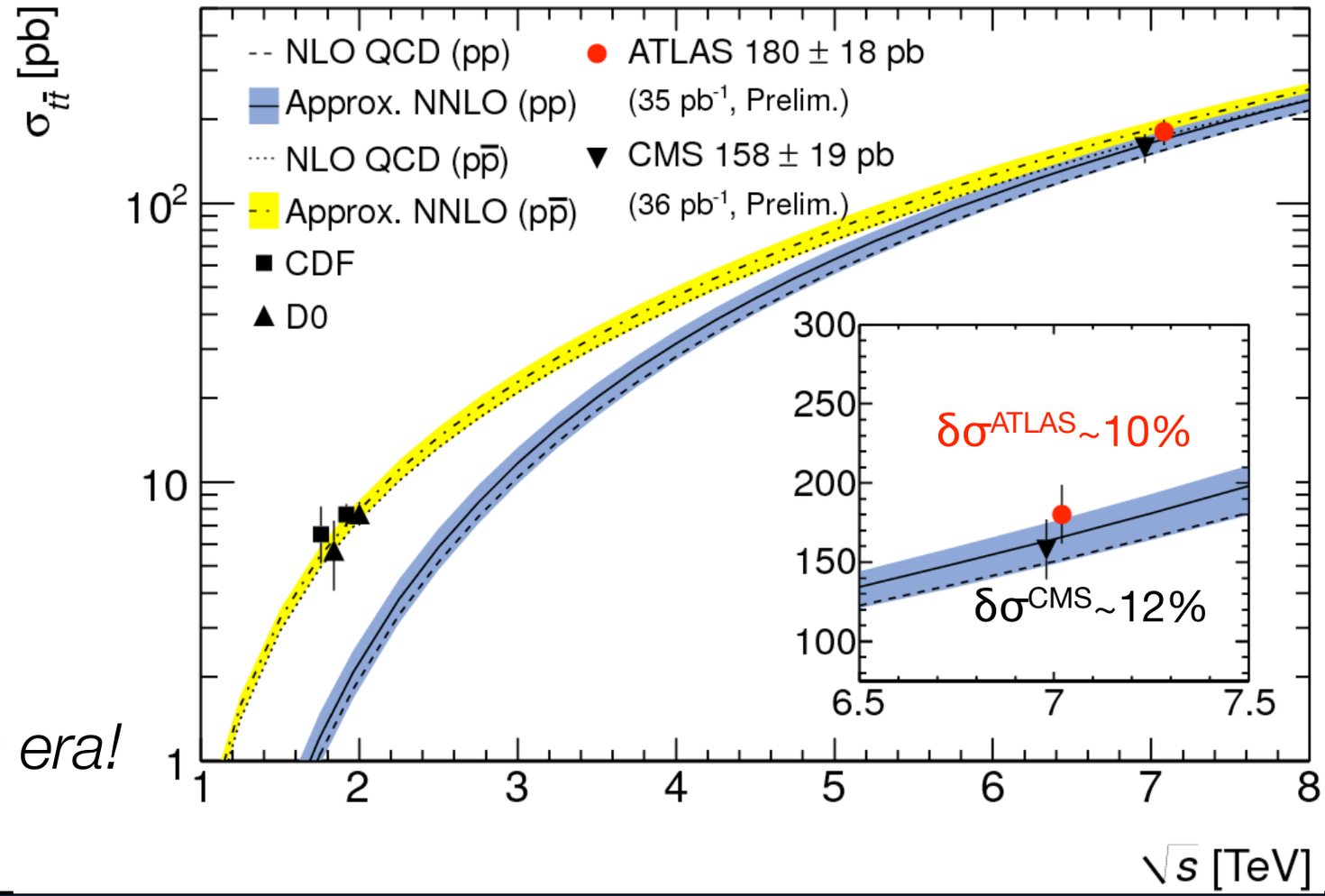


Conclusions

- Top quark production cross-section measurement performed by the ATLAS experiment with the full 2010 statistics of 35.5 pb^{-1}
- Agrees with the Standard Model pQCD prediction
- Already in the systematics-dominated regime
  - lepton+jets δσ~13%
  - Combination with di-leptonic channels δσ~10%
  - δσ~theory, Tevatron

Expected >1 fb^{-1} in 2011

Now entering top quark precision era!



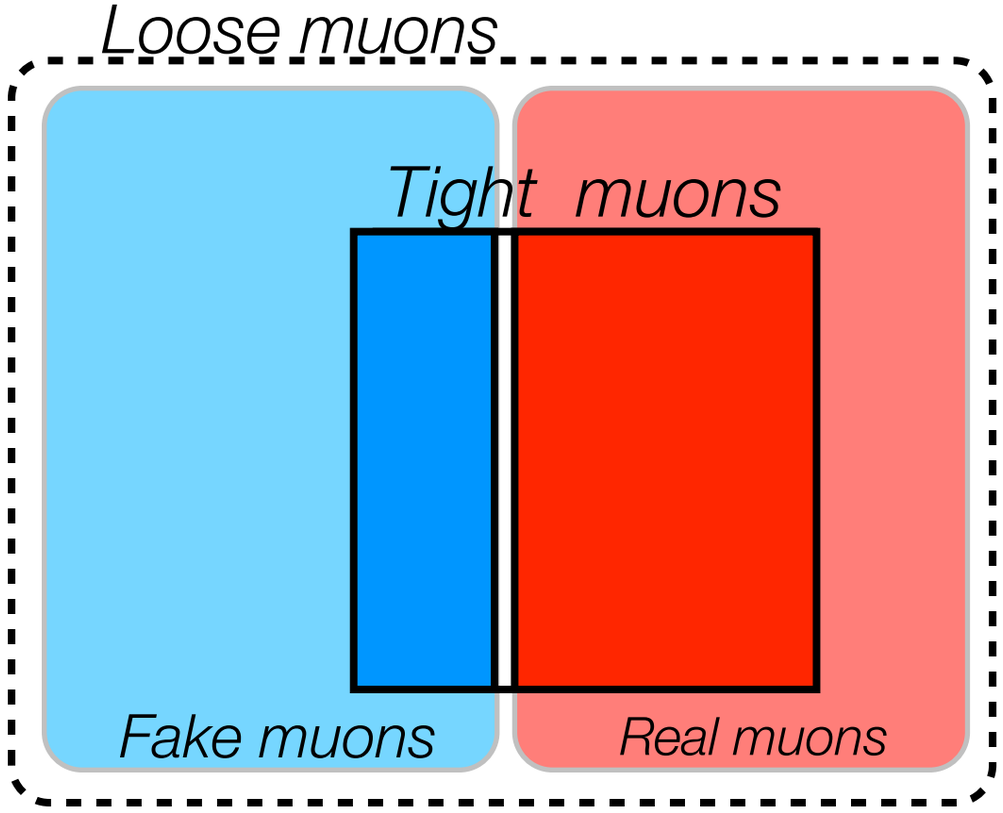
Backup slides

References for ATLAS ttbar cross-section measurements

- Top quark pair cross-section (2.9 pb^{-1}) arXiv:1012.1792
- Single lepton pre-tag ATLAS-CONF-2011-023
- Single lepton b-tag ATLAS-CONF-2011-035
- Di-lepton ATLAS-CONF-2011-034
- Combination ATLAS-CONF-2011-040

QCD background - μ Channel

- Semileptonically decaying quarks with sufficiently isolated lepton (non-prompt)
- Fake (π/K punch-through)



$$N^{loose} = N^{loose}_{real} + N^{loose}_{fake}$$

$$N^{tight} = N^{tight}_{real} + N^{tight}_{fake}$$
$$= \epsilon_{real} N^{loose}_{real} + \epsilon_{fake} N^{loose}_{fake}$$

- Solve for N^{tight}_{fake}
- ε_{real} from $Z \rightarrow \mu\mu$
- ε_{fake} from control samples enhanced in fake leptons

Systematic uncertainties for the cross-section

Source	$\Delta\sigma(e)/\sigma$[%] pre-tag	$\Delta\sigma(\mu)/\sigma$[%] pre-tag	$\Delta\sigma(e)/\sigma$[%] tagged	$\Delta\sigma(\mu)/\sigma$[%] tagged
Statistical error	10.4	10.2	9.9	8.6
Object selection				
Lepton Reco,ID,Trigger	+3.8/-3.5	+1.0/-0.9	+3.8/-3.5	+1.0/-0.9
Jet energy Reco	+14.1/-11.8	+14.5/-12.3	+11.4/-9.6	+9.9/-8.5
b-tagging	-	-	+11.7/-8.4	+11.7/-8.4
Background rate				
QCD norm	4.4	6.1	6.2	0.7
W+jets norm	19.5	23.4	4.1	7.7
Other bkg norm	5.7	6.1	0.7	0.7
Signal simulation				
ISR/FSR	+10.6/-6.5	+10.3/-4.6	+8.9/-6.7	+8.3/-5.9
PDF	1.7	1.4	1.9	1.6
Parton Shower	+4.8/-4.4	+4.0/-3.7	+4.8/-4.4	+4.0/-3.7
NLO generator	+7.1/-6.2	+5.3/-4.8	+7.0/-6.1	+2.8/-2.6
Pile-up	1.2	1.2	0.6	0.8
Sum systematics	+28.9/-26.2	+31.4/-28.9	+22.2/-18.4	+19.8/-16.2
Integrated Luminosity	+3.8/-3.6	+3.8/-3.6	+3.5/-3.3	+3.5/-3.3

Projective and profile likelihoods

$$L(D|\theta) = \frac{p(D|S,\theta_i)}{p(D|S,\theta_i) + \sum_k p(D|B_k,\theta_i)}$$ Projective likelihood

$$L_p(\theta) = L(\theta, \hat{\nu}_\theta) = \sup_{\nu} L(\theta, \nu)$$ Profile likelihood

$\hat{\nu}_\theta$ = maximum likelihood of *nuisance* parameter **ν**
for a fixed *model* parameter **θ**

Aplanarity

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |p_i|^2}$$ sphericity tensor $\Rightarrow$ eigenvalues

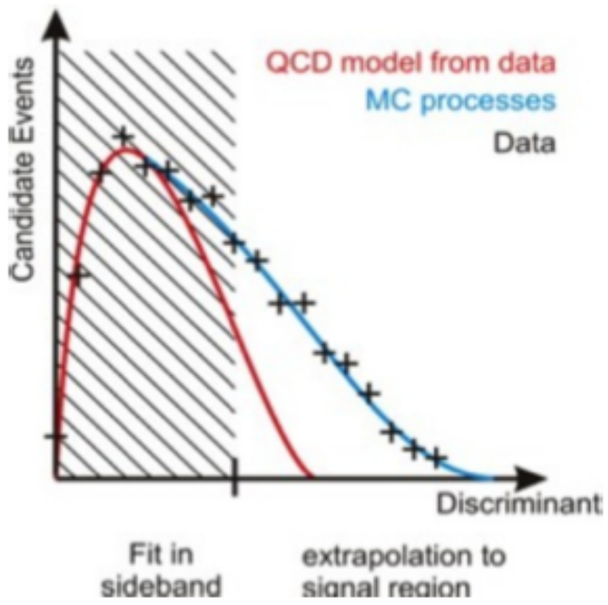
$$A = \frac{3}{2}\lambda_3$$ isotropic A=1/2, planar A=0

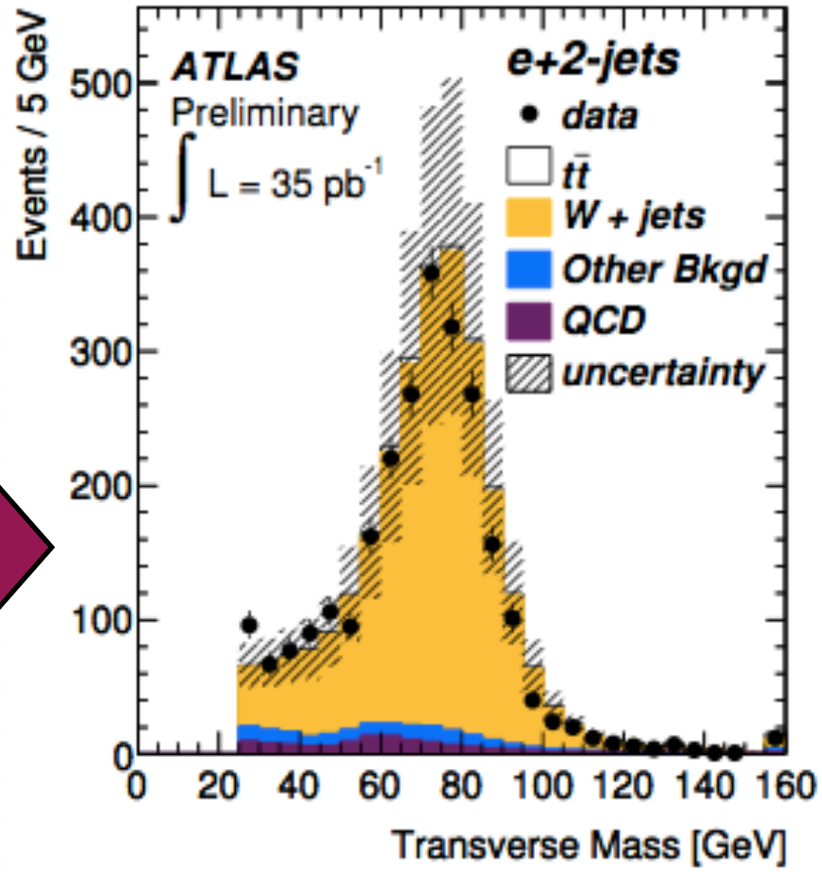
$$S_T = 2\frac{\lambda_2}{\lambda_1 + \lambda_2}$$

$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

QCD background - *e* Channel

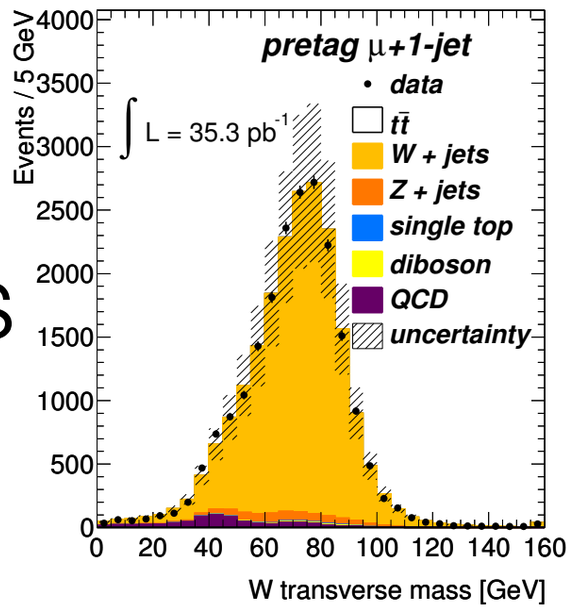
- Jets with high EM fraction (fake electrons)
- Semileptonically decaying quarks with sufficiently isolated lepton (non-prompt)
- Fitting method with “anti-electrons”:
  - *Loose electrons* failing track quality cuts
  - Fill template histograms
  - Fit E_T^{miss} template in sideband (e.g. $E_T^{miss} < 20$ GeV)

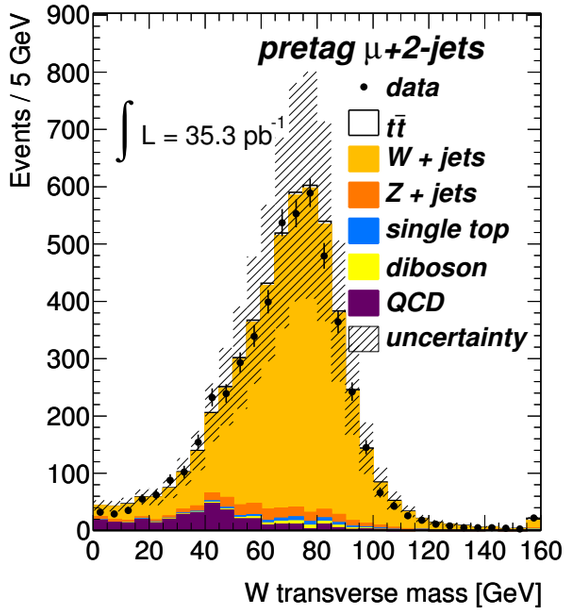


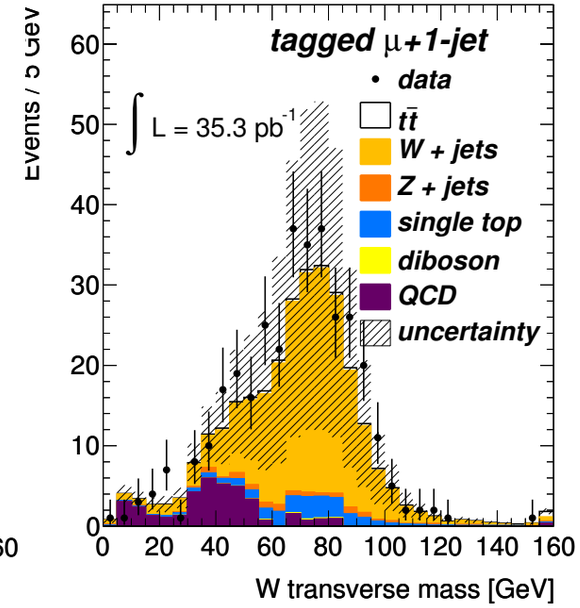


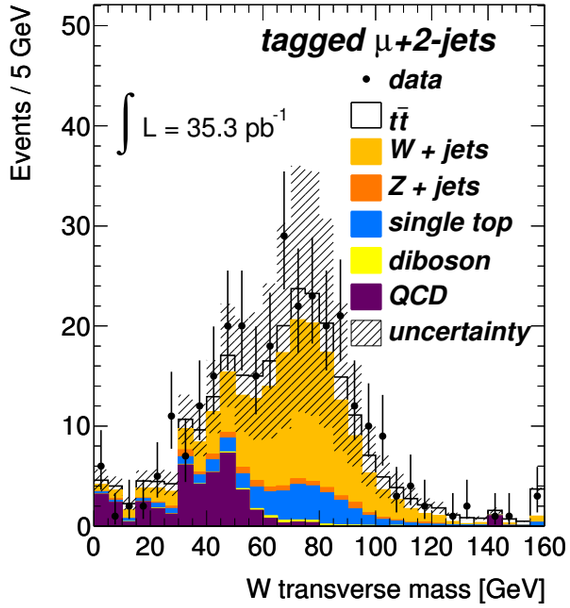
QCD Background

μ+jets

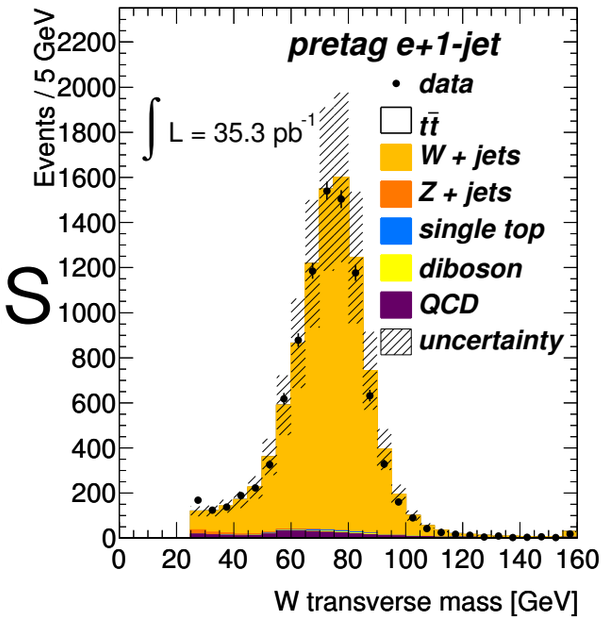


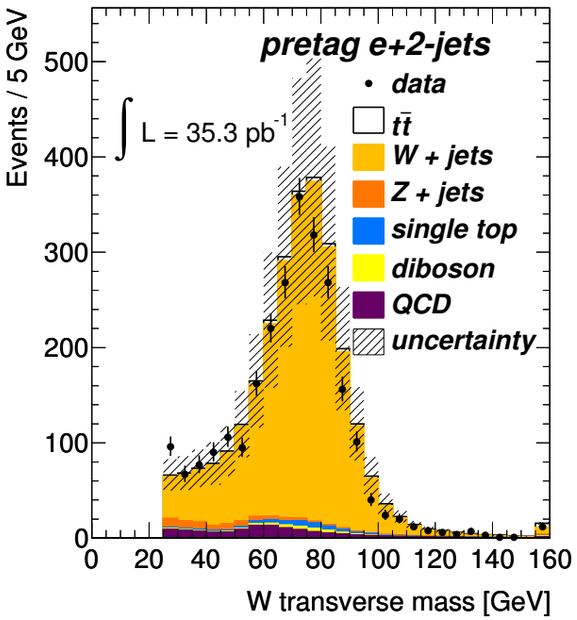


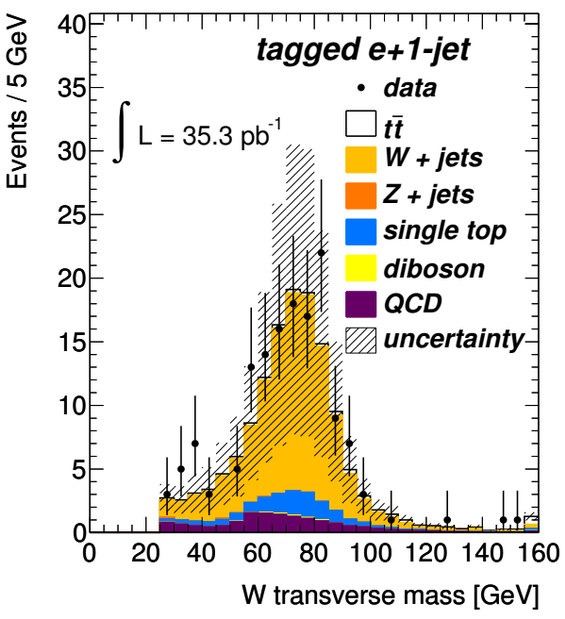


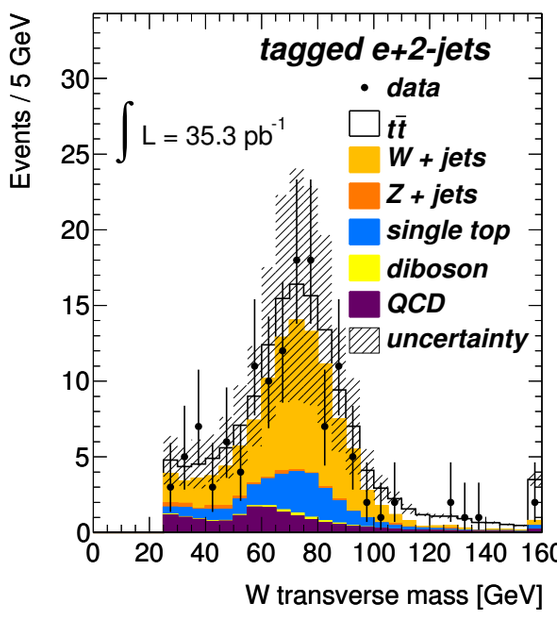


e+jets









W + jets factors

$$W^{\geq 4\text{jet}}_{\text{tagged}} = W^{\geq 4\text{jet}}_{\text{pretag}} \cdot f^{\geq 4-\text{jet}}_{\text{tagged}} \qquad f^{\geq 4-\text{jet}}_{\text{tagged}} = f^{2-\text{jet}}_{\text{tagged}} \cdot f^{\text{corr}}_{2\to\geq 4}$$

$f_{\text{tagged}^{e+2-\text{jet}}} = 0.028 \pm 0.005(\text{stat.}) \pm 0.004(\text{syst.})$

$f_{\text{tagged}^{\mu+2-\text{jet}}} = 0.040 \pm 0.004(\text{stat.}) \pm 0.003(\text{syst.}).$

$f^{\text{corr}}_{2\to 4} = 2.8 \pm 0.8(\text{syst.}), \quad e \text{ channel},$

$f^{\text{corr}}_{2\to 4} = 3.2 \pm 0.9(\text{syst.}), \quad \mu \text{ channel}.$

Channel	**Electron**	**Muon**
sample	C_{MC}	
default	1.20 ± 0.10	1.03 ± 0.07
δR	$1.04 - 1.05 \pm 0.06$	$0.96 - 0.99 \pm 0.05$
p_T	$0.98 - 1.14 \pm 0.08$	$0.92 - 1.07 \pm 0.07$
ktfac	$0.99 - 1.02 \pm 0.06$	$0.95 - 0.99 \pm 0.06$
iqopt	1.02 ± 0.05	0.98 ± 0.04

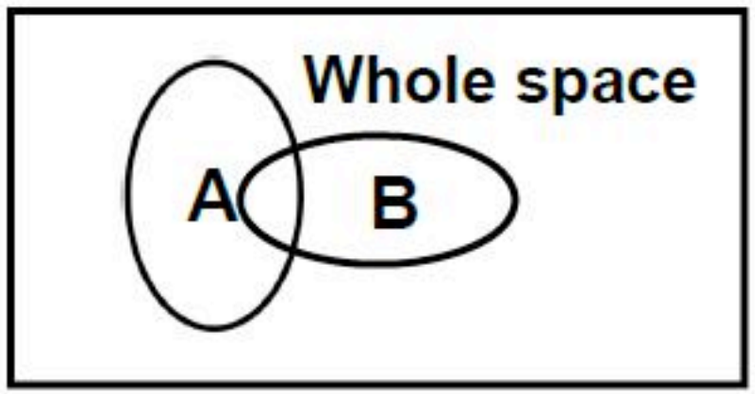
Table 7: Variation of the parameter C_{MC} in Eq. 6 from varying various parameters of Alpgen Monte Carlo: the δR and p_T of the matching between the parton shower and matrix element calculations, and the renormalization scale parameters. For each parameter variation, the range of values obtained is shown.

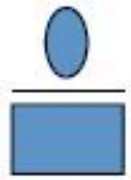
Uncertainty on signal acceptance

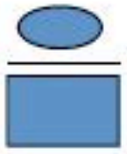
rel.uncertainty(%)	e+jets pre-tag	μ+jets pre-tag	e+jets tagged	μ+jets tagged
b/c-tagging efficiency	0	0	+9.1/-10.4	+9.2/-10.5
light jets tagging efficiency	0	0	±0.2	±0.2
lepton trigger, reconstruction and selection	±3.6	±0.9	±3.6	±0.9
jet energy scale	+9.0/-9.1	+7.8/-8.7	+8.9/-9.0	+7.6/-8.5
jet energy resolution	±0.2	±0.2	±0.4	±0.4
jet reconstruction efficiency	±2	±2	±3	±3
electron energy scale	+0.2/-0.6	0	+0.2/-0.6	0
electron energy resolution	±0.2	0	±0.2	0
muon momentum scale	0	±0.3	0	±0.3
muon momentum resolution	0	±0.1	0	±0.1
ISR/FSR	+7.0/-9.6	+4.8/-9.3	+7.2/-8.2	+6.3/-7.7
NLO generator (MC@NLO *v.s.* POWHEG)	±6.6	±5.0	±6.5	±2.7
Parton Shower generator (HERWIG *v.s.* PYTHIA)	±4.6	±3.8	±4.6	±3.8
PDFs	±1.7	±1.4	±1.9	±1.6
Pile up	-1.2	-1.2	-0.6	-0.8
TOT	+19.2 -15.3	+15.0 -15.3	+14.4 -19.9	+16.1 -15.5

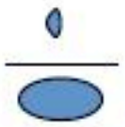
Table 15: Contributions to the uncertainty on the estimated $t\bar{t}$ signal acceptance ϵ, for electron and muon channels separately, before and after b-tagging, expressed as relative percent uncertainty.

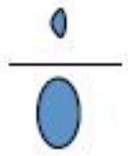
P, Conditional P, and Derivation of Bayes' Theorem in Pictures

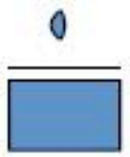


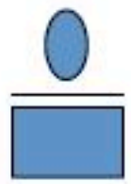
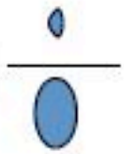
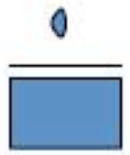
$P(A) =$ 

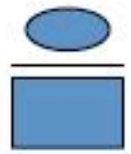
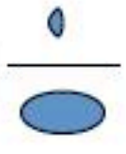
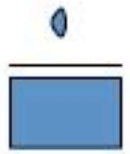
$P(B) =$ 

$P(A|B) =$ 

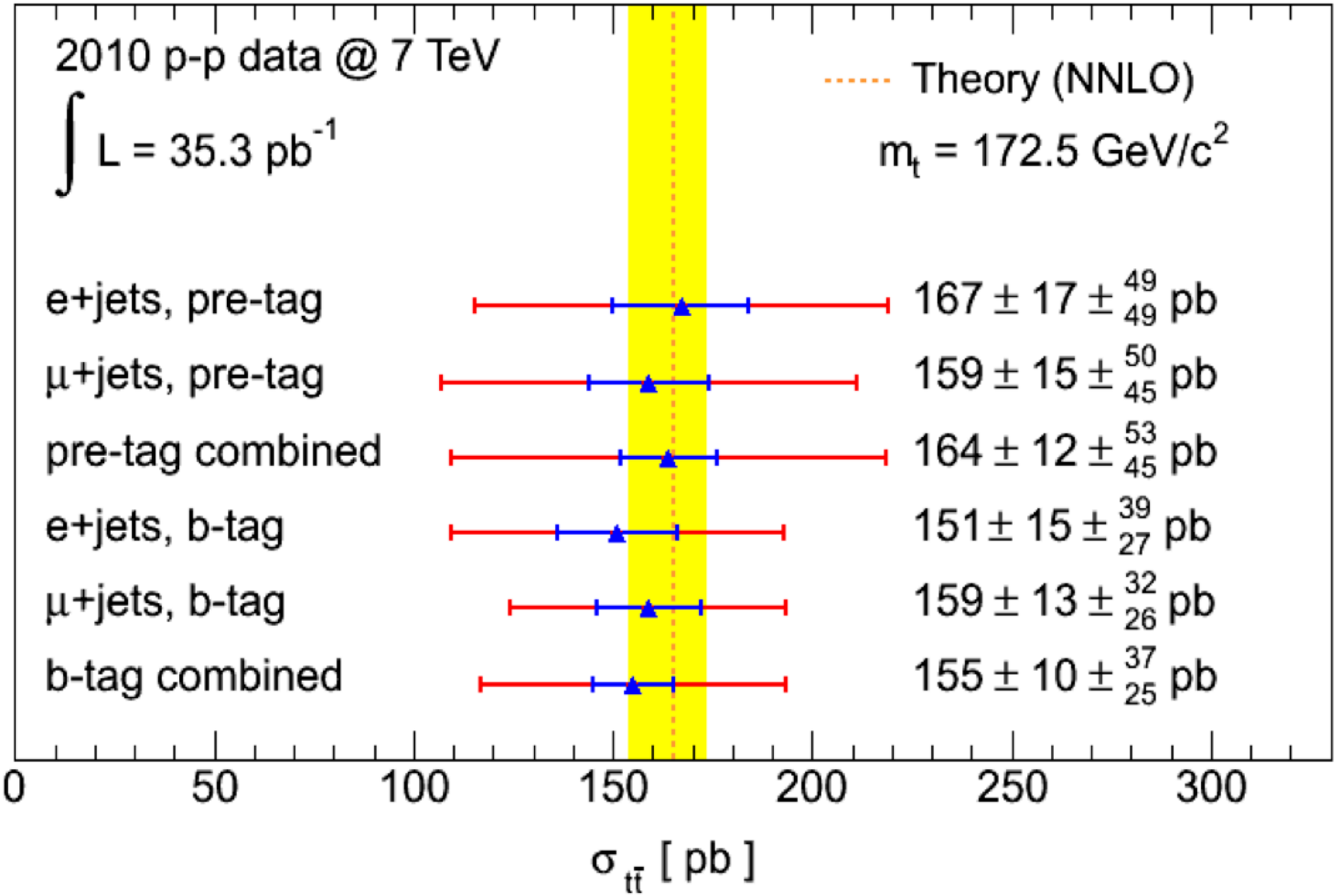
$P(B|A) =$ 

$P(A \cap B) =$ 

$P(A) \times P(B|A) =$  $\times$  $=$  $= P(A \cap B)$

$P(B) \times P(A|B) =$  $\times$  $=$  $= P(A \cap B)$

$\Rightarrow P(B|A) = P(A|B) \times P(B) / P(A)$



$$\sigma_{t\bar{t}}^{pretag} = 154^{+52}_{-47}\ pb$$

$$\sigma_{t\bar{t}}^{tagged} = 156^{+37}_{-29}\ pb$$

$$\sigma_{t\bar{t}}^{pretag} = 154 \pm 11^{+48}_{-43} \pm 7\ pb$$

$$\sigma_{t\bar{t}}^{tagged} = 156 \pm 10^{+34}_{-28} \pm 6\ pb$$