Single top: prospects at LHC

Markus Cristinziani (Uni Bonn) for ATLAS,
Giovanni Petrucciani (SNS & INFN Pisa) for CMS

Outline

- What changes between Tevatron and LHC
- Overview of single top quark at LHC
- Searches at CMS, mostly $O(10fb^{-1})$ and early searches at ATLAS, mostly $O(1fb^{-1})$
- Conclusions

LHC is good for searches

- High luminosity: gathering $O(10fb^{-1})$ should be easy, once we start.
- High energy: larger signal cross sections (and not so larger background ones)

	σ(Tevatron)	σ(LHC)	
ttbar pairs	$6.70^{+0.71}_{-0.88}$ pb	825±150 pb	(x120)
single top, s-ch.	0.88±0.12 pb	10±1 pb	(x10)
single top, t-ch.	1.98±0.22 pb	245±17 pb	(x120)
tW production	0.15±0.04 pb	60±10 pb	(x400)
Wjj (*)	~1200 pb	~7500 pb	(x6)
bb+jets (*)	~2.4x10^5 pb	~5x10^5 pb	(x2)

(*) hep-ph/9806332: after selection cuts to mimic top signals

LHC is bad for systematics

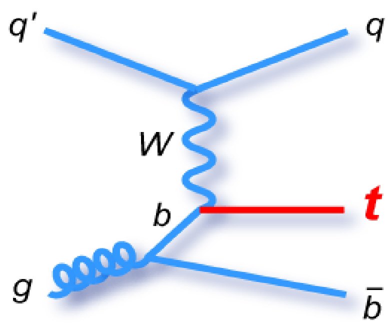
- Rejection of backgrounds depends on observables not easy to control at startup:
  - **jet counting:** uncertainties on JES knowledge, extra jets from radiation, pile up or detector noise
  - **b-tagging:** knowledge of its performance with a misaligned detector
  - **MET:** controlling the detector resolution for a small true missing energy (~40GeV) in multi-jet events

(none of these comes for free from Z->μμ/ee)

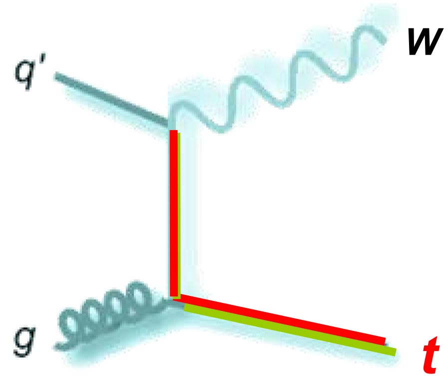
- Because of this, single top can be easy to see but very hard to measure accurately

Overview at LHC

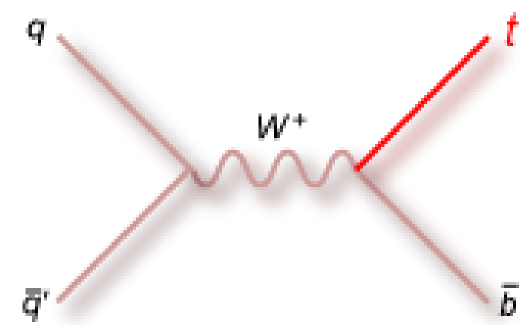
- The cross section hierarchy is different at LHC



t-channel
σ = 240pb



tW production
σ = 60pb



s-channel
σ = 10pb

- Only decays with at least one **e/μ** in the final state will be usable at the beginning

Overview at LHC

- Taking into account the BR, not summing on flavours the cross sections become
  - t-ch (qt → qbW → qbℓν) σ·BR = 26pb (x2)
  - tW/1ℓ (tW → bWW → bqq'ℓν) σ·BR = 4pb (x2)
  - tW/2ℓ (tW → bWW → bℓνℓ'ν') σ·BR = 0.74pb (x4)
  - s-ch (bt → bbW → bbℓν) σ·BR = 1.1pb (x2)

Studies at CMS

- All the four possible final states have been studied for the Physics TDR *[CERN/LHCC-2006-021]*
- The basic assumptions were:
  - 10fb^{-1} integrated luminosity, with the "$2 \cdot 10^{33}$" pileup
  - Ideal alignment, calibrations with 10fb^{-1} of data
  - Keeping the analysis simple: extract only σ, as a counting experiment, no multivariate methods
  - Generators: SingleTop and TopRex for signal, TopRex, Alpgen and Pythia for the backgrounds.
  - Use of full GEANT4 simulation when possible, or the fast but fairly accurate FAMOS simulation

Studies at ATLAS

- CSC notes will be public ~July, all results shown here are thus preliminary
- The three channels are considered in the final states with exactly one lepton (electron or muon)
- Studies based on:
  - 1fb^{-1} integrated luminosity, with no pileup
  - Realistic detector and misalignment
  - Cut-and-count analysis as a baseline; multivariate methods in addition for better background rejection
  - Generators: AcerMC for signal, MC@NLO, AlpGen and Pythia for backgrounds
  - Use of full GEANT4 simulation

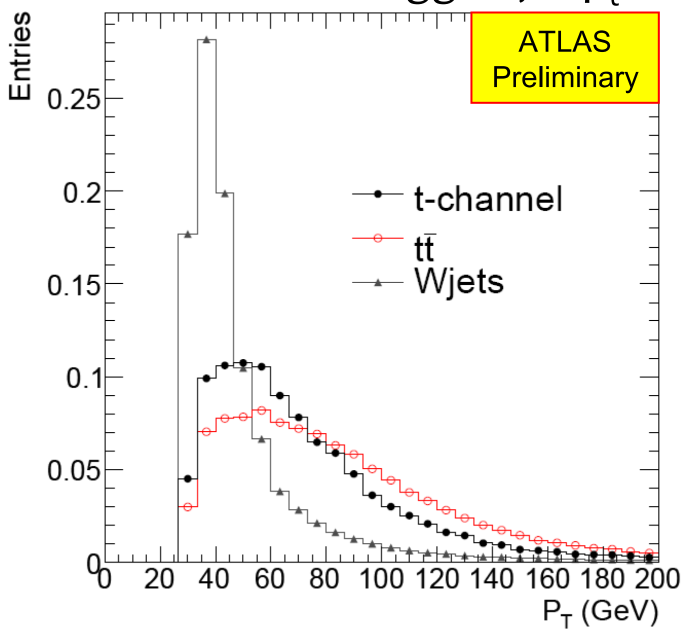
ATLAS common preselection

- Similar features in the three channels → common preselection to reduce backgrounds (ttbar, W+jets and QCD)
  - Exactly one isolated high p_T lepton
  - 2-4 jets, one of which is tagged as a b-jet
  - MET > 20 GeV
- Single-top efficiency
  - 9-10% (electrons)
  - 10-12% (muons)
- Rejection of W+jets $O(10^4)$, ttbar O(20)

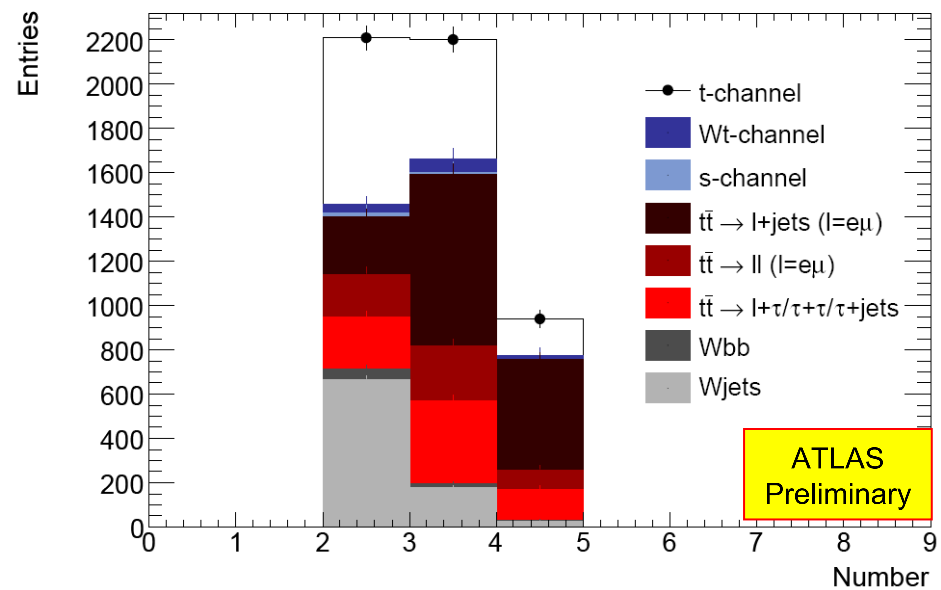
ATLAS: t-channel

- Cut-and-count analysis with simple kinematic cuts
  - p_t (b-jet) > 50 GeV (against W+jets)
  - Hardest light jet $|\eta|$ > 2.5 (against ttbar)

b-tagged jet p_t



number of jets after selection



ATLAS: t-channel sensitivity

- Results for sequential cut analysis
- Significant reduction wrt to ATLAS TDR (1999)
- Difference understood in terms of
  - Pythia new parton shower algorithm
  - ME: Pythia→AcerMC
  - W+jets: Herwig→Alpgen
  - tt dileptonic and tt with τ were neglected

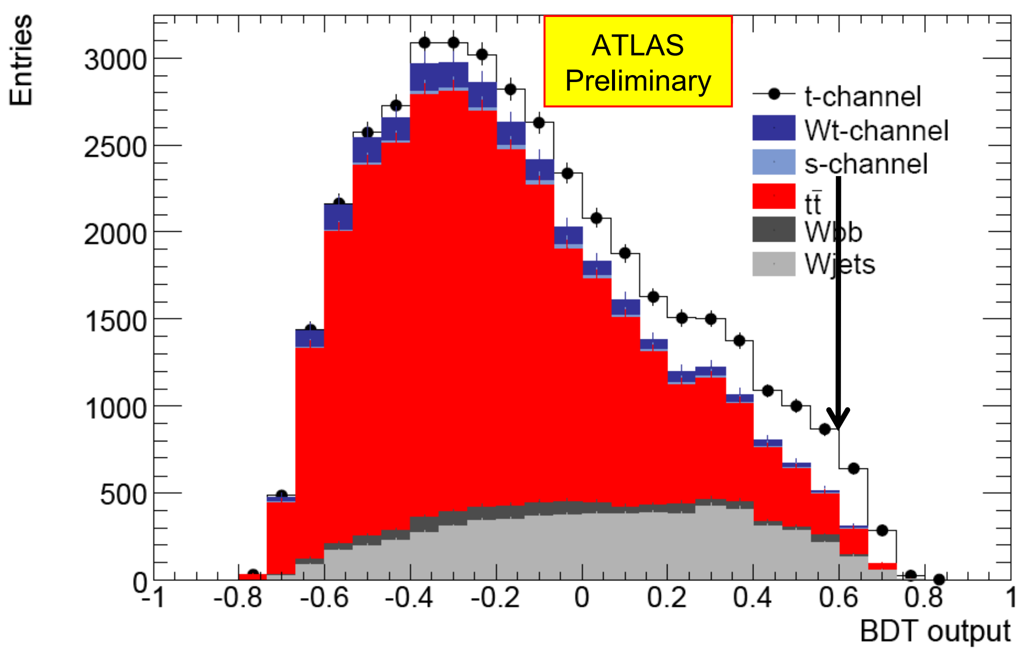
Process	Efficiency	N (1 fb^{-1})
t-channel (μ or e)	1.8%	1460
tt (l+jets)	0.6%	1560
tt with τ	0.4%	740
tt (dilepton)	1.3%	520
W+jets	0.0017%	870
Wbb+jets	0.4%	70
S/B		**0.37**

ATLAS: t-channel BDT

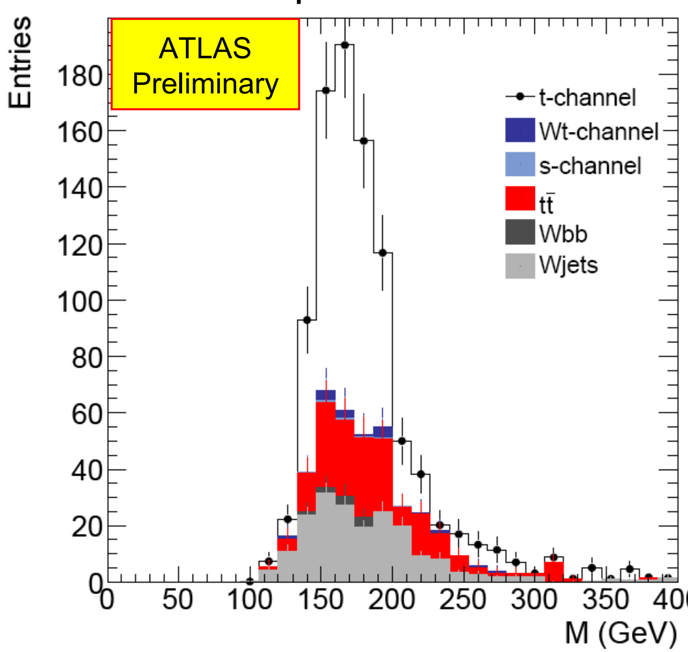
- MV analysis to suppress ttbar background
- Boosted Decision Trees (BDT) applied after selection (except η cut)
- 40 object/event level variables considered
- Reduce to sets that are less sensitive to JES,e.g.
  - p_T and $\cos(\theta^*)$ of leading jet
  - p_T and η of leading non-b jets
  - centrality(j_1,j_2) , $H_T(j_1,j_2,MET,\ell)$, $M_T(W)$
  - $\Delta R(j_1,j_2)$, $\Delta R(j_1,lep)$, $\Delta R(j_1 non\text{-}b,\ell)$
  - η (max), #jets

ATLAS: t-channel BDT result

- BDT cut optimised for cross-section uncertainty including systematic effects
  - S/B = 1.3 (542 events)
  - 5.7% (stat), 22.4% (total uncert.)



Reco'd top mass after D cut



ATLAS: t-channel systematics

- Experimental: b-tagging, jet energy scale
- Theoretical/MC: ISR/FSR, PDF, MC model

source	Cuts $\Delta\sigma/\sigma$	BDT $\Delta\sigma/\sigma$	source	Cuts $\Delta\sigma/\sigma$	BDT $\Delta\sigma/\sigma$
MC stat	6.5%	7.9%	Bckgnd normal.	22.9%	8.2%
lumi 5%	18.3%	8.8%	PDF	12.3%	2.6%
b-tag 5%	18.1%	6.6%	Lepton ID	1.5%	0.7%
JES 5%	21.6%	9.9%	MC model	4.2%	4.2%
ISR/FSR	9.8%	9.4%	**Total systematic**	**44.7%**	**22.4%**
			Data stat	**5.0%**	**5.7%**

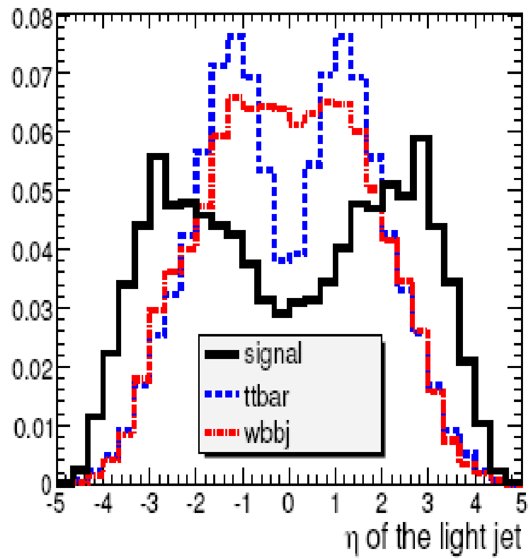
CMS, t-channel

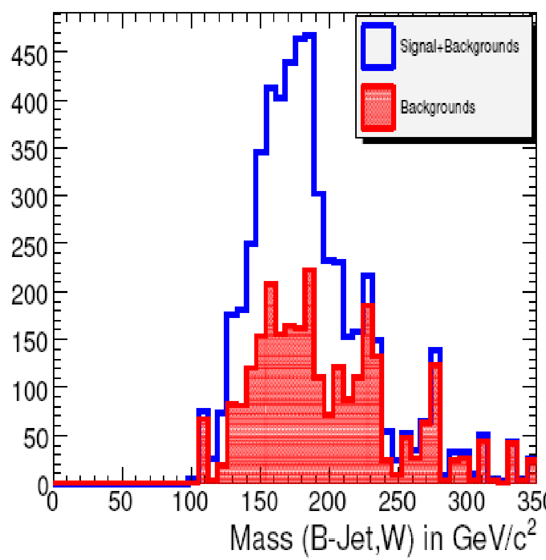
- Analysis performed only in the W→μν channel
- 1 muon, 1 b-tagged jet, 1 forward jet, E_T^{miss}
- Cuts on $M_T(W)$, M(top), $|\Sigma_T| = E_T(\mu+b+j+E_T^{miss})$

Expected events

Process	$N/10fb^{-1}$
Signal	2389
t tbar	1189
Wbb+jet	195
W+jet	102

S/B ~ 1.4





[CMS NOTE 2006-084; CMS Physics TDR II, sect. 8.4.2]

CMS: t-channel, results

Uncertainties on S and B for 10fb^{-1}, and their impact on the cross section measurement

	signal	ttbar	Wbbj	Wjj	Δσ/σ
Statistics	2.0%	2.9%	7.2%	4.9%	**2.7%**
Theory	4.0%	5.0%	17.0%	5.0%	**5.0%**
JES (5-2.5%)	3.0%	6.1%	3.1%	<1%	**4.3%**
B-tagging	4.0%	4.0%	4.0%	4.0%	**4.5%**
Luminosity	5.0%	5.0%	5.0%	5.0%	**8.7%**

("theory" includes PDFs, m_t, m_b, Λ_{QCD}, $\sigma_{background}$)

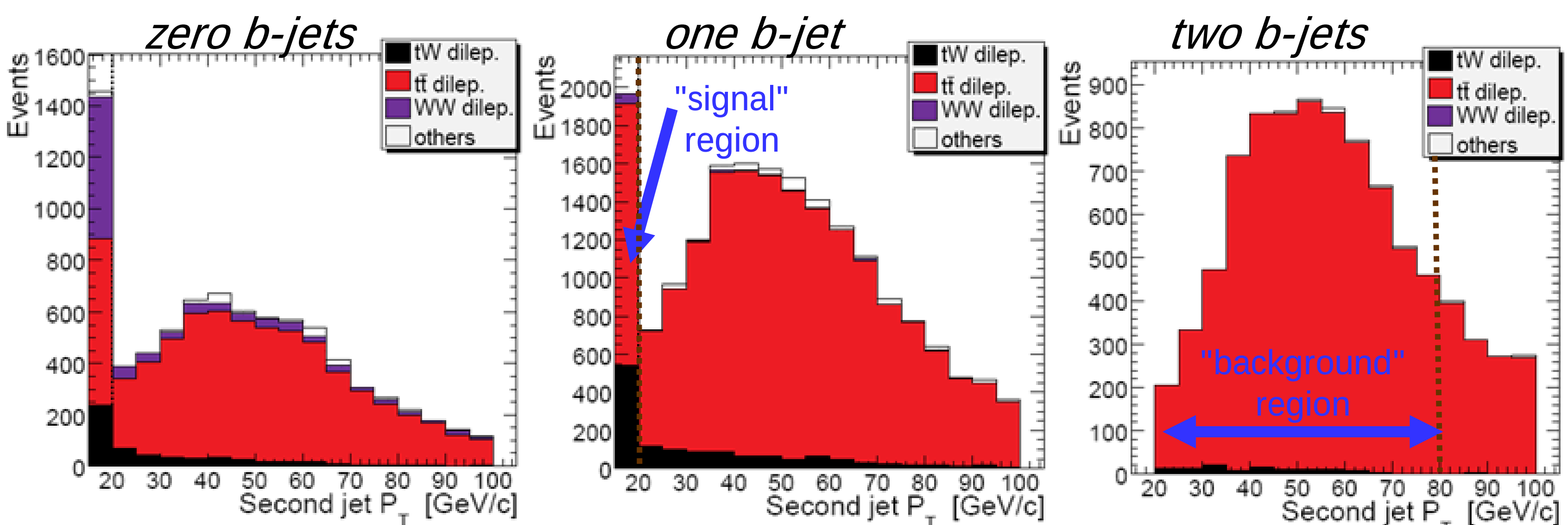
$\Delta\sigma/\sigma$ = 2.7%$^{(stat)}$ + 8%$^{(syst)}$ + 8.7%$^{(lumi)}$

tW production

- The final state is very similar to ttbar production, except for one less b-jet: jet counting is critical
  - CMS: Jets from calorimeter noise were vetoed by using information from tracks and calo tower distribution
  - ATLAS: b-tag veto, analysis adapted according to #jets
- Can't achieve a good S/B, so background normalization from data important to avoid large systematic uncertainties
  - Background-like sample dominated by ttbar selected with cuts very similar to the ones for signal, to cancel out systematics on background subtraction

CMS: tW dileptonic

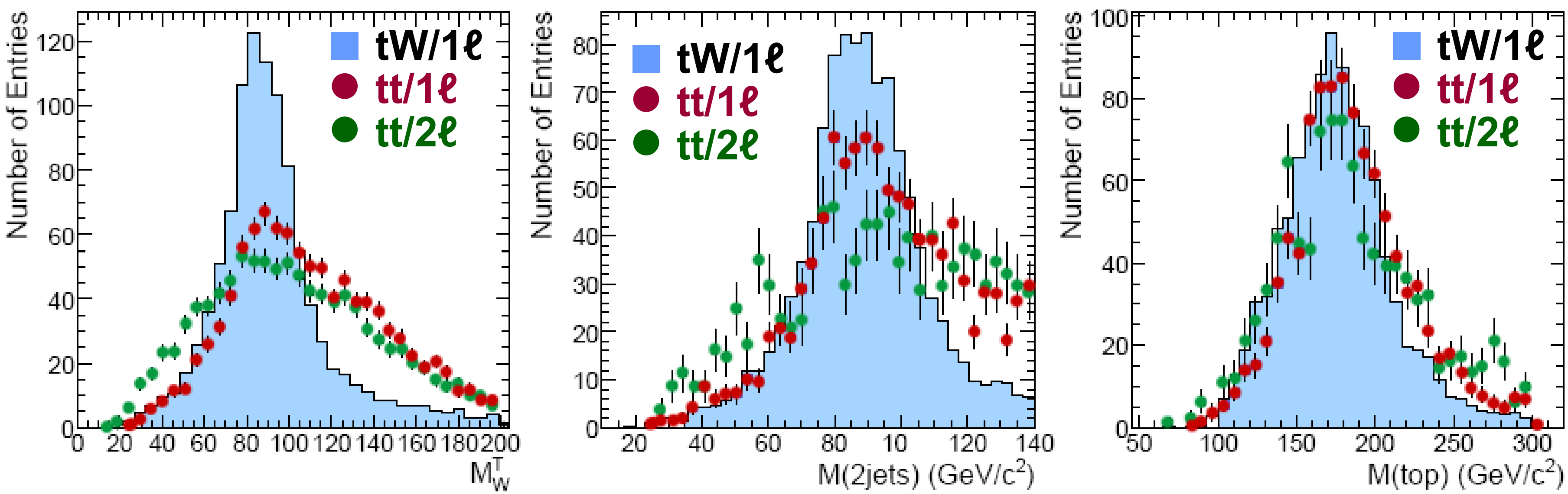
- In the e+μ channel, to avoid Z background
- Select events with 1 or 2 jets, classify by the P_T of the second jet (if any) and the number of b-tags.
- Signal selected as 1 b-jet, background control as 2 b-jet



(note: first bin in all three plots are single jet events)

CMS: tW semi-leptonic

- Events are selected requiring exactly one lepton (e,μ), 1 b-jet and two light quark jets, and some MET (to control QCD background)
- (W,b) pairing from a Fisher discriminant using P_T(b+W), ΔR(W,b) and q(b)·q(W) from jet charge



CMS: tW summary

Expected events [$10fb^{-1}$]

- **Semi-leptonic** (S/B~0.2)
  signal: 1700
  ttbar: 7624
  W+jets: 759
  t-ch top: 351
- **Di-leptonic** (S/B~0.37)
  signal: 562
  ttbar: 1433
  WW+jets: 55

$\Delta\sigma/\sigma$ expected $10fb^{-1}$

	1L	2L
Statistics	7.5%	8.8%
Luminosity	7.8%	5.4%
Jet E.S.	**9.4%**	**20%**
b-tagging	3.6%	**8.7%**
PDF	1.6%	6.0%
Pileup	**10%**	6.1%
TOTAL	**19%**	**25%**

[CMS NOTE 2006-086; CMS Physics TDR II, sect. 8.4.2]

ATLAS: tW cut-and-count

- Only semi-leptonic final state considered
- Analysis divided according to #jets in final state
- 1 b-tagged jet with p_T>50GeV, veto second b-jet to optimally reject ttbar (main concern)
- W window cut for events with >3 jets

Events in 1 fb^{-1}	1b+1jet	1b+2jets	1b+3jets
tW channel	435	164	40
other single top	1260	99	58
ttbar	1980	770	274
W(bb)+jets	3075	220	44
S/B	6.8%	15%	10.6%

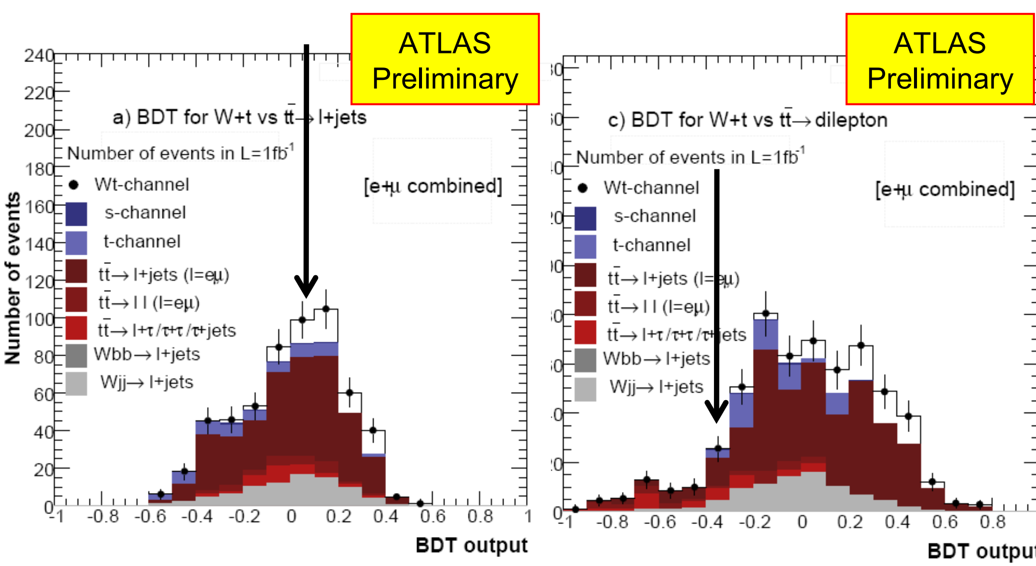
ATLAS: tW BDT

- for each background
  - ttbar 1l, 2l, W(bb)+jets, t-channel
- and each jet multiplicity a boosted decision tree function is defined →12 BDTs (e and μ together)
- pool of 25 discriminating variables identified
  - Opening angles(6), p_T(3), η(2), $\cos\Delta\varphi$
  - Invariant (transverse) masses (6), f(MET), H_T(2)
  - p_z(neutrino)
  - sphericity, aplanarity, centrality
- minimize uncertainty on σ including syst. uncert.

ATLAS: tW results

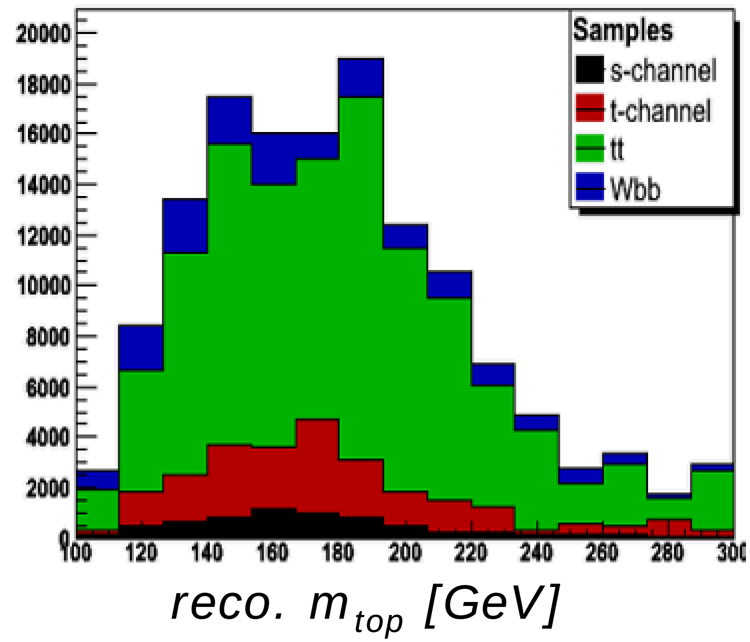
- S/B ratios in the 3 classes
  - 35%,45%,16% (86ev. sel.)
- 3σ evidence with few fb^{-1}
- 20% uncertainty with 10 fb^{-1}

Source	1 fb^{-1}		10 fb^{-1}	
	Var	Δσ/σ	Var	Δσ/σ
MC stat		15.6%		
Lumi	5%	20%	3%	7.9%
b-tagging	5%	16%	3%	6.6%
JES	5%	11%	1%	1.5%
lepton ID	1%	2.6%	1%	2.6%
Bckgnd σ	10%	23.4%	3%	9.6%
ISR/FSR	9%	24.0%	3%	7.8%
PDF	2%	5.2%	2%	5.2%
b-fragm.	3.6%	9.4%	3.6%	9.4%
data stat.		20.6%		6.6%
Total uncert.		52%		20.5%



CMS: s-channel

- Much harder at LHC than at Tevatron as the relative cross section is much smaller.
- Selection requirements:
  - one isolated lepton (e,μ)
  - exactly two jets, both b-tagged
  - missing E_T
  - cuts on $M_T(W)$, $M(t)$, $P_T(t)$, Σ_T, H_T



[CMS NOTE 2006-084; CMS Physics TDR II, sect. 8.4.4]

CMS: s-channel

- Two control samples selected to constraint ttbar background (semi-leptonic and di-leptonic)
- **Expected events** [10fb^{-1}] (S/B ~ 0.13)

signal:	273
ttbar:	1260
t-channel:	630
Wbb:	155

- **Uncertainty on σ** [10fb−1]

Δσ/σ = 18%(stat) + 31%(syst) + 19%(lumi)

dominated by the systematics on the ttbar semi-leptonic background normalization from JES

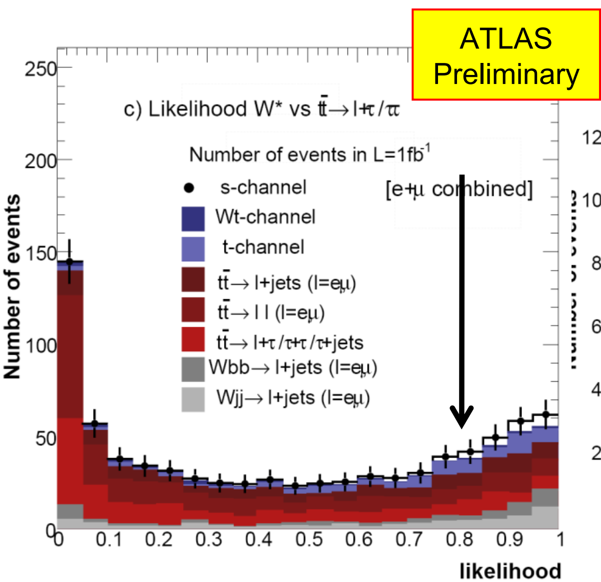
[CMS NOTE 2006-084; CMS Physics TDR II, sect. 8.4.4]

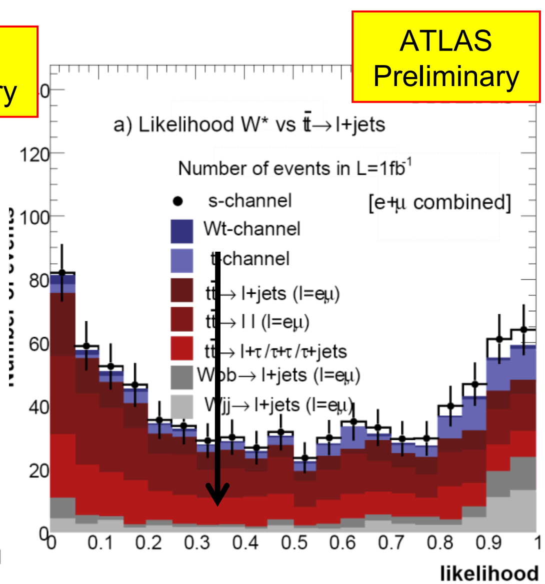
ATLAS: s-channel

- Require exactly two b jets, veto any further jet
- Pure cut-and-count analysis not possible
  - S/B 10%, 25 selected events
- Define 5 likelihood functions for background categories (3 ttbar, W+jets, t-channel)
- Discriminating variables
  - see tW channel
  - $\Delta\eta$, p_T(top)
  - choose only most significant

ATLAS: s-channel likelihood

- S/B improves to 19% (15ev)
- ISR/FSR radiation and b-tagging critical

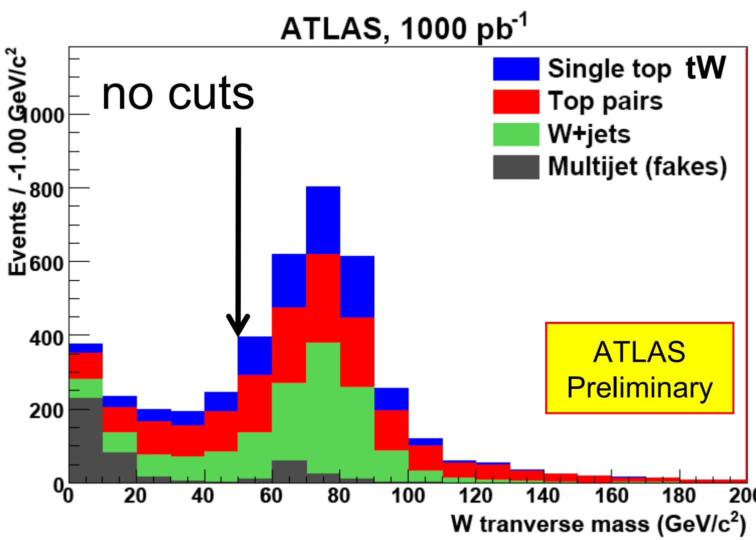


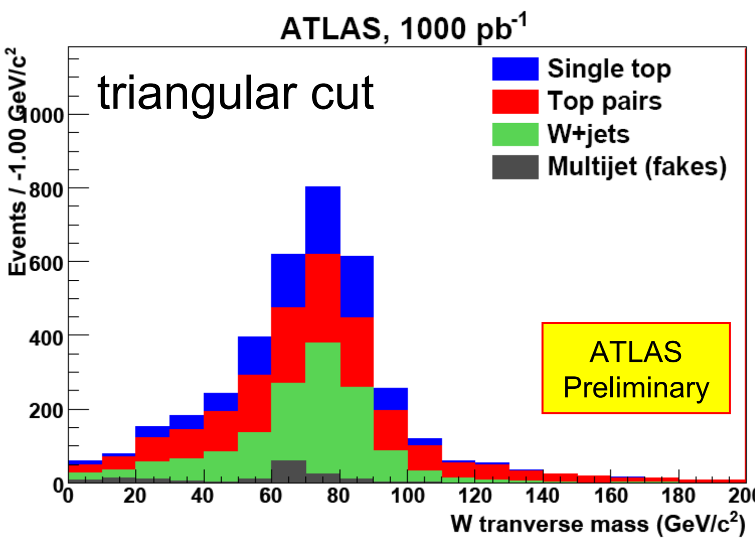


Source	1 fb^{-1}		10 fb^{-1}	
	Var	Δσ/σ	Var	Δσ/σ
MC stat		29%		
Lumi	5%	31%	3%	18%
b-tagging	5%	44%	3%	25%
JES	5%	25%	1%	5%
lepton ID	1%	6%	1%	6%
Bckgnd σ	10%	47%	3%	16%
ISR/FSR	9%	52%	3%	17%
PDF	2%	16%	2%	16%
b-fragm.	3.6%	19%	3.6%	19%
data stat.		64%		20%
Total		115%		52%

ATLAS: QCD rejection

- Observation (e.g. D0): fake MET aligned with lepton → triangular cut in Δφ vs. MET plane
- Fake lepton rate will be determined from data
  - e.g. $m_T(W) < 50$GeV extrapolated to signal region
  - assume QCD background fully under control





CMS: QCD background estimation

- Due to the huge cross section, the background from QCD multi-jet could only be estimated indirectly, using the **cut factorization** method:
  - The first steps of the selection were grouped into some sets of approximately independent cut sets, for which the efficiency was extracted from QCD simulations
  - The combined efficiency was taken as product of the efficiencies of all the cut sets
  - An upper limit to the efficiency of the later steps of the selection on QCD was taken using the signal efficiency
- The estimated background is very small except for tW semi-leptonic analysis, for which $B_{QCD}/S \sim 30\%$.

Conclusions

- All channels with leptons have been studied
- t-channel
  - CMS: PhysTDR study gives >5σ observation for $10fb^{-1}$ (naïve rescaling of statistical and systematic uncertainties hints that even $1fb^{-1}$ might be ok)
  - ATLAS: two studies shown for $1fb^{-1}$
- tW channel should be visible with $O(10fb^{-1})$
- s-channel might be visible with $O(10fb^{-1})$, but it will be hard due to poor S/B ratio

Backup

ATLAS: Effect of pile-up

- With a luminosity of 10^{32} $cm^{-2}s^{-1}$ we estimate the relative efficiency for signal and bckgnd
- Pile-up modeling will be tuned with data

Channel	rel. ε(signal)	rel. ε(ttbar)
t	75%	66%
tW (2jets)	82%	84%
tW (3jets)	53%	61%
tW (4jets)	74%	80%
s	91%	85%

- Uncertainty is expected to become negligible wrt to other sources
- No systematic uncertainty considered here

ATLAS: Results summary

Analysis	Stat $1fb^{-1}$	Syst $1fb^{-1}$	Stat $10fb^{-1}$	Syst $10fb^{-1}$
t-channel C&C	5.0%	44.4%	1.6%	22.3%
t-channel BDT	5.7%	21.7%	1.8%	9.8%
tW-channel BDT	20.6%	48%	6.6%	19.4%
s-channel LH	64%	95%	20%	48%

ATLAS: triggering on single top

- Inclusive isolated electron and muon triggers
- Overall top quark efficiency 84%
- Preselection requires 30 GeV leptons, well on the trigger efficiency plateau

CMS: triggering on single top

- Single lepton triggers used.
- Full L1 and HLT simulation included in the analysis.
- Combined L1*HLT efficiency
  - ~50% for channels with a single lepton
  - ~70% for tW di-leptonic

(note: W→ tau nu are included)

CMS, t-channel: selection

- Selection cuts ($W \rightarrow \mu\nu$ only):
  - 1 muon, $P_T > 19$ GeV, $|\eta| < 2.1$
  - 1 b-jet, $P_T > 35$ GeV, $|\eta| < 2.5$, b-discr > 2.4
    (b-tag cut giving $\varepsilon_\mathbf{b} \sim 50\%$, $\varepsilon_\mathbf{uds} \sim 0.3\%$)
  - 1 forward jet ($P_T >$ GeV, $|\eta| < 2.5$)
  - $E_T^{miss} > 40$ GeV
  - $|\Sigma_T| < 43.5$ GeV ($\vec{\Sigma}_T = \vec{p}_T(\mu) + \vec{E}_T(b) + \vec{E}_T(j) + \vec{E}_T^{miss}$)
  - $m_T(W)$ within [50, 120] GeV
  - m(t) within [50, 120] GeV

CMS: t-channel, plots

Process	$N^{expected}$ /$10fb^{-1}$
Signal	2389
t tbar	1189
Wbb+jet	195
W+jet	102