Top quark physics at ATLAS and CMS

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- Introduction: top physics environment at LHC
  - What can we expect in the first years..?
- Top-pair cross-section measurements
  - Using top to commission the detectors - in particular b-tagging
- Single top cross-section measurements
- Top properties: spin correlations
- Rare top decays: FCNC
- Conclusions

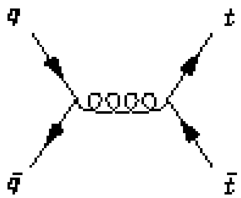
  - Showing some representative expectations/results - but only a ‘snapshot’ of activities in ATLAS and CMS … many unknowns at this stage!
  - Top mass covered in talk of Nathalie Besson

Why top quark physics?

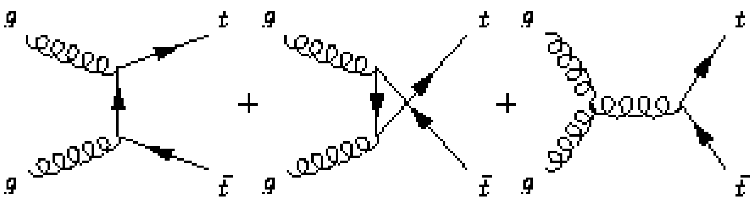
- Top quark within Standard Model:
  - It exists! Measure its fundamental parameters (production cross-section, mass, couplings, etc.)
    - Electroweak corrections typically α m_t^2 – interesting for model builders
  - Heaviest known quark, least studied, some peculiar properties
    - Decays involve real rather than virtual W
    - Decays before hadronises – spin/polarisation information is preserved
- Top quark beyond the Standard Model:
  - Top may be produced in new particle decays (t-tbar resonances, heavy H …)
  - Top quarks may decay in peculiar ways, e.g. $t \to H^+ b$
- Top is a 'template' for many new physics topologies
  - Complex decay signatures involving leptons, missing energy, multi-jets, b-jets
    - Understand the detectors, develop the tools needed for hunting for exotic things
  - Top production will be a **background** to many new physics processes
    - $H \to$leptons, SUSY, more exotic things
  - $\Rightarrow$ Understanding top physics is essential in many searches

Top physics at LHC

strong t-tbar pair production

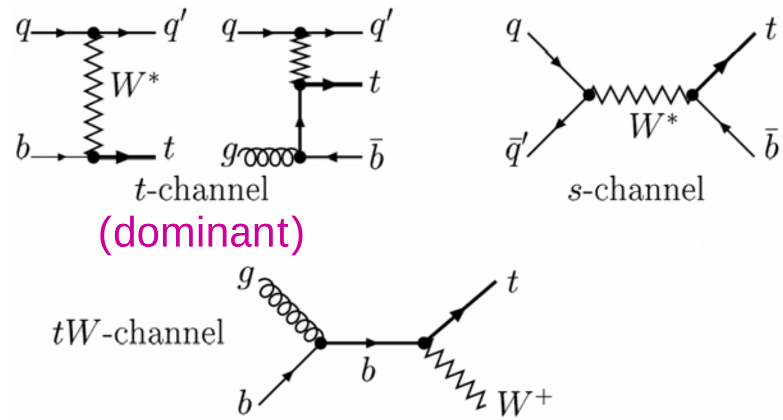


$q\bar{q} \rightarrow t\bar{t}$
(13%)



$gg \rightarrow t\bar{t}$
(87%)

electroweak single top production



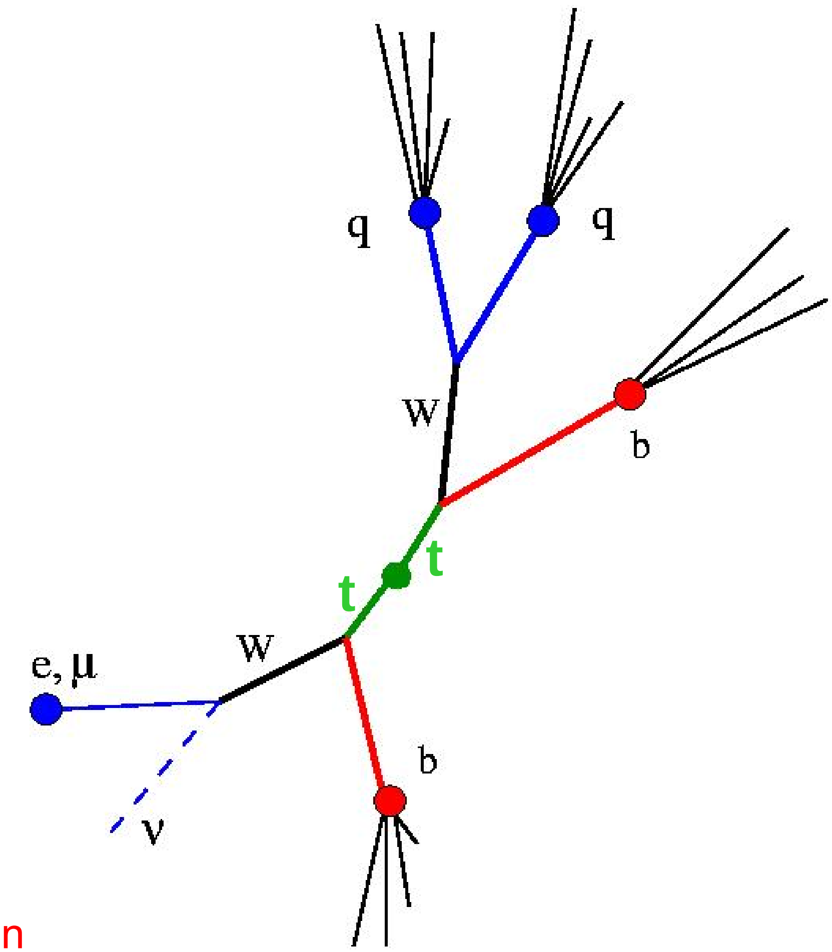
σ_{tt}(th)=830±100 pb @ 14 TeV

σ_{t}(th) ≈ 320 pb @ 14 TeV

- At 10^{33} $cm^{-2}s^{-1}$ ('nominal' low luminosity), get 1 top pair/second, or 8M/year
  - 30% of these decay to **{e/μ}νb jjb** or **{e/μ}νb{e/μ}νb** final states, good trigger efi
  - Initial data samples in 2008: 10-100 pb^{-1} ≡ few 1000 or 10000s of such events not including experimental acceptance and reconstruction efficiencies
    - Note will start LHC in summer 2008 with reduced beam energy (√s≈10TeV) - top pair cross-section reduced by factor ~2

Accessing top physics at LHC

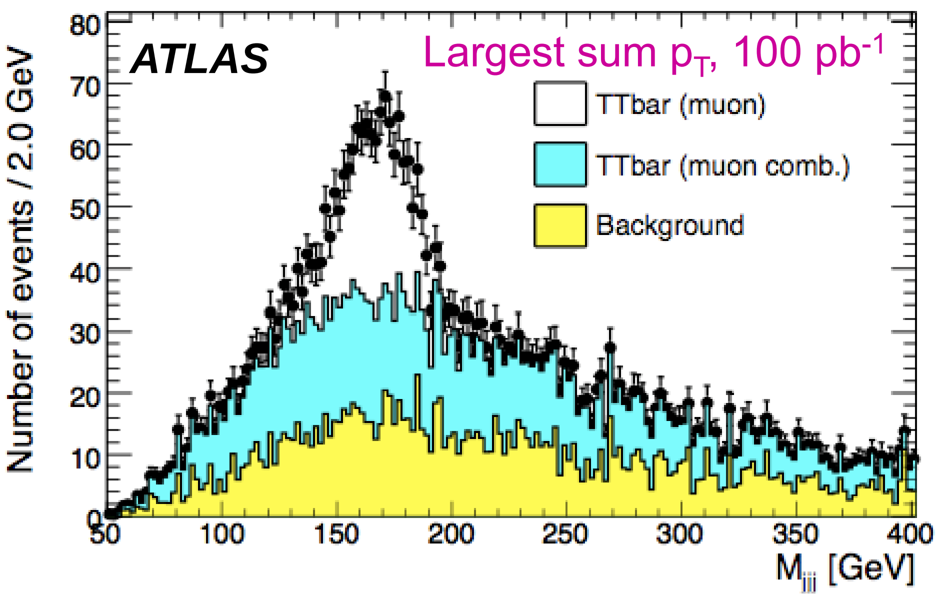
- Typical analysis - semileptonic top decay
  - Hard (E_T> ~20 GeV) isolated lepton
    - Electron and/or muon identification
  - Missing energy E_T>~20 GeV
    - Both lepton and E_T miss similar to W production
  - Hadronic W-decay:
  - 2 hard (E_T>20-40 GeV) light quark jets
    - Known $m_{jj}=m_w$ – calibration of jet energy scale
  - 2 hard (E_T>20-40 GeV) b quark jets
    - b-tagging **essential tool** in top identification
    - Some opportunities for b-tag **calibration**
  - Explore/commission full range of detector capabilities (leptons, E_T miss, jets, b-tagging)
- Main background is W+multijet production
  - Multijet with fake lepton will also be important
    - Both difficult to simulate, need data normalisation
  - In dilepton channel, Z+jets and diboson prod^n

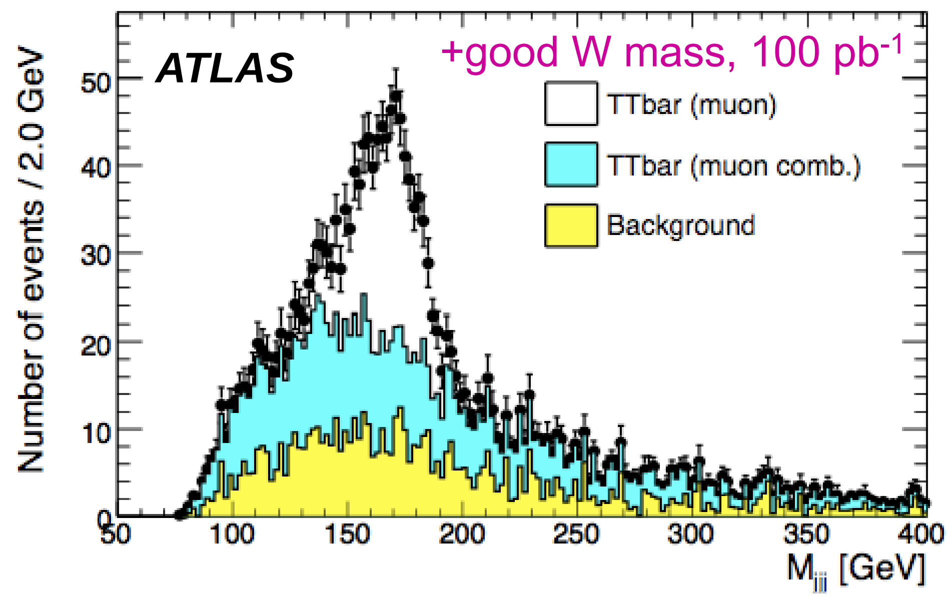


- Single top: similar ingredients, typically study semileptonic decay (**{e/μ}**ν **b)**

Top-pair cross-section: semileptonic channel

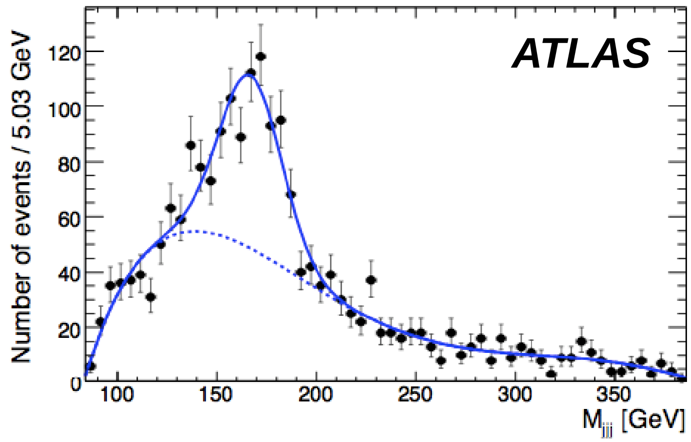
- Select events with high E_T lepton, missing E_T and 4 jets (E_T>20-40 GeV)
  - Backgrounds from W+jets events, QCD multi-jet with fake lepton, single top
    - W+jet and multijet events can be reduced by requiring 1 or 2 b-tagged jets (ε_b~ 50-70%)
    - But also interesting to look at 'commissioning' analyses **without** b-tagging
  - Find combination of 3 jets which represents the hadronic top decay
    - Criteria such as largest sum p_T, good W mass between 2 of the jets
    - … can extract a reasonable hadronic top mass peak without b-tagging information

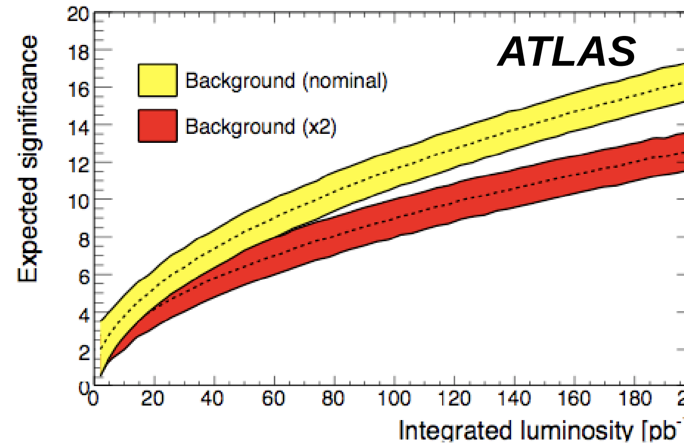




Top-pair cross-section: semileptonic channel

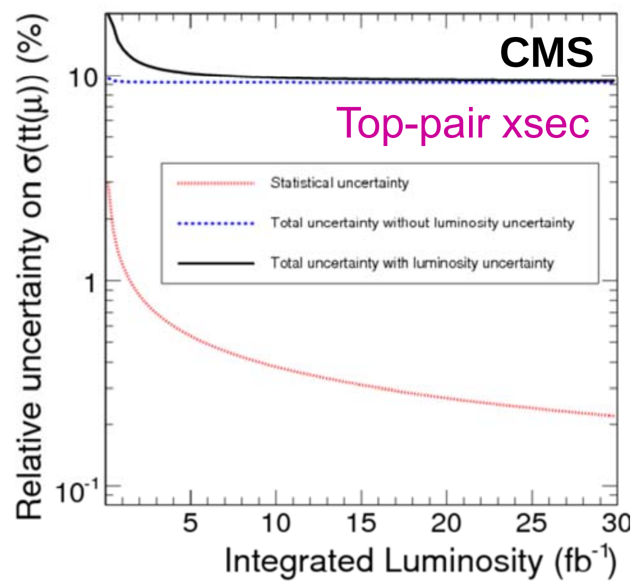
- Extract signal using event counting or fit to M_{jjj} distribution
  - Can establish signal for 100 pb^{-1} even with pessimistic background





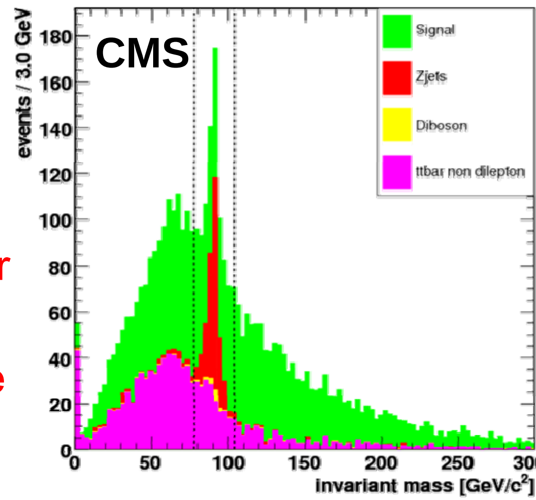
- With 100 pb^{-1} expect to commission b-tagging and understand efficiency to ~5% - use in selection
  - Require 1 or 2 b-tagged jets, reduces non-tt b/g and helps select correct combination
- For O(fb^{-1}), b-tagging, PDFs & luminosity become important

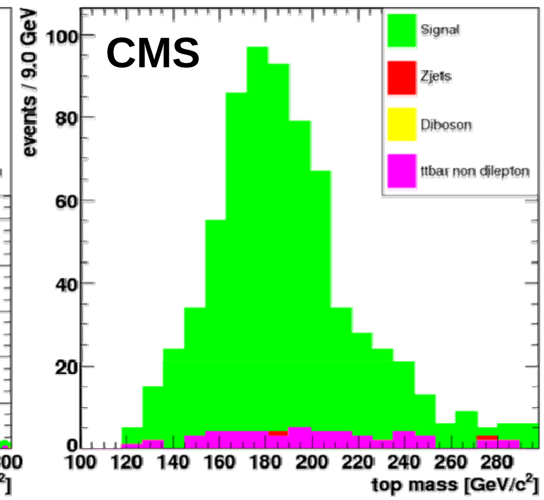
Expt	Int.L	Method	Stat (%)	Syst (%)	Lumi (%)
ATLAS	100 pb^{-1}	count ($W\rightarrow e$)	2.5	14	5
ATLAS	100 pb^{-1}	likelihood	7.4	15	5
CMS	1 fb^{-1}	count	1.2	9.2	10
CMS	10 fb^{-1}	count	0.4	9.2	3



Top-pair cross-section: dileptonic channel

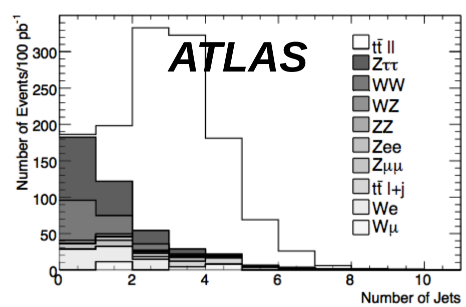
- Require two isolated leptons (e/μ)…
  - Then >=2 high E_T (b) jets, missing E_T
    - Main backgrounds from W/Z+jets, WW/ZZ+jets and semileptonic tt
    - Remove background around Z peak for ee and μμ channels
    - Possible to reconstruct an approximate top mass by imposing m_W (CMS)



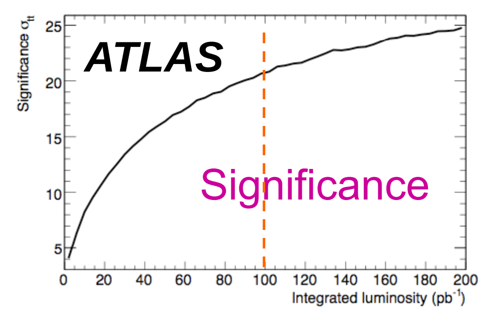


- Simple kinematic selections … establish signal early with small int L
  - Methods based on simple counting, N_{jet} vs missing E_T, likelihood fit to event distrib^{n}s
  - Then measure cross-section, limited by jet energy scale, b-tagging, PDFs, lumi

Expt	Int.L	Method	Stat(%)	Syst(%)	Lumi (%)
ATLAS	100 pb^{-1}	count	3.6	3.6	5
ATLAS	100 pb^{-1}	template	3.8	4.2	5
ATLAS	100 pb^{-1}	likelihood	5.2	6.7	5
CMS	10 fb^{-1}	count	0.9	11	3

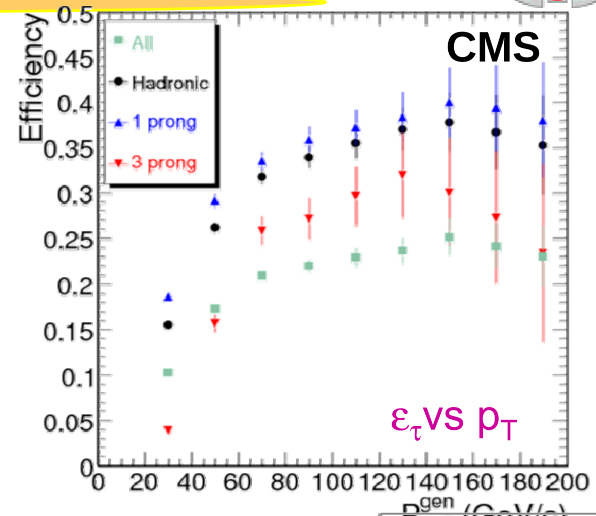


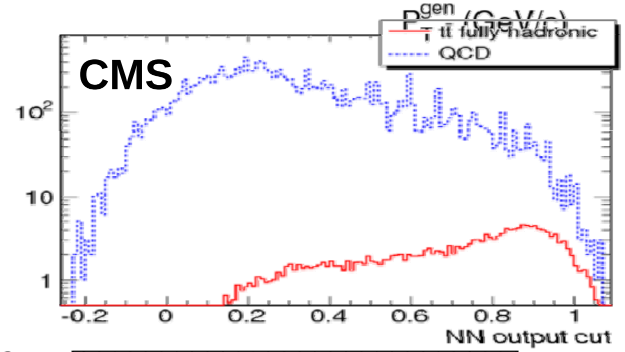
Number of jets

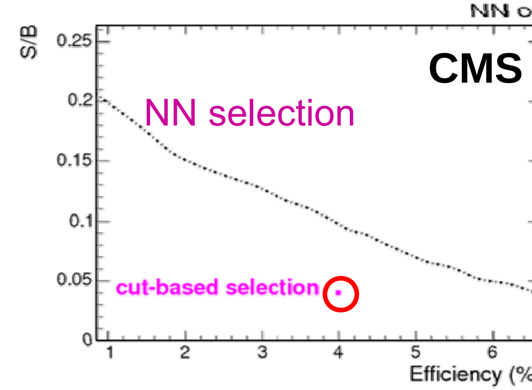


Top-pair cross-section: other channels

- Dilepton channel with tau: $tt \rightarrow bb\ l\nu_l \tau\nu_\tau$, $\tau \rightarrow$ hadrons
  - Sensitive to non-SM physics in top decays
  - Important background for SUSY/H searches
  - Identify 1/3 prong hadronic tau candidates, analysis otehrwise similar to dilepton channel
    - S:B ~ 1:1, main background from semileptonic tt decays
  - CMS: $\Delta\sigma/\sigma$=16%(syst) ±1.3%(stat) ±3% (lumi) / 10 fb^{-1}
- Fully hadronic channel: $tt \rightarrow bbqqqq$ (CMS)
  - 46% of tt decays, complex final state, huge QCD b/g
  - Need multi-jet triggers including b-tagging information
    - S/B only 1/300 after trigger selection (23 Hz)
    - Neural net selection based on jet E_T and event shape variables, applied to events with 6-8 jets
  - Few % signal efficiency, samples of ~10k tt events with S/B~0.1 in both 1- and 2-b tag selections
  - CMS: $\Delta\sigma/\sigma$=~20%(syst) ±2%(stat) ±5% (lumi) / 1 fb^{-1}
    - Sytematics: jet energy scale, ISR/FSR, pileup

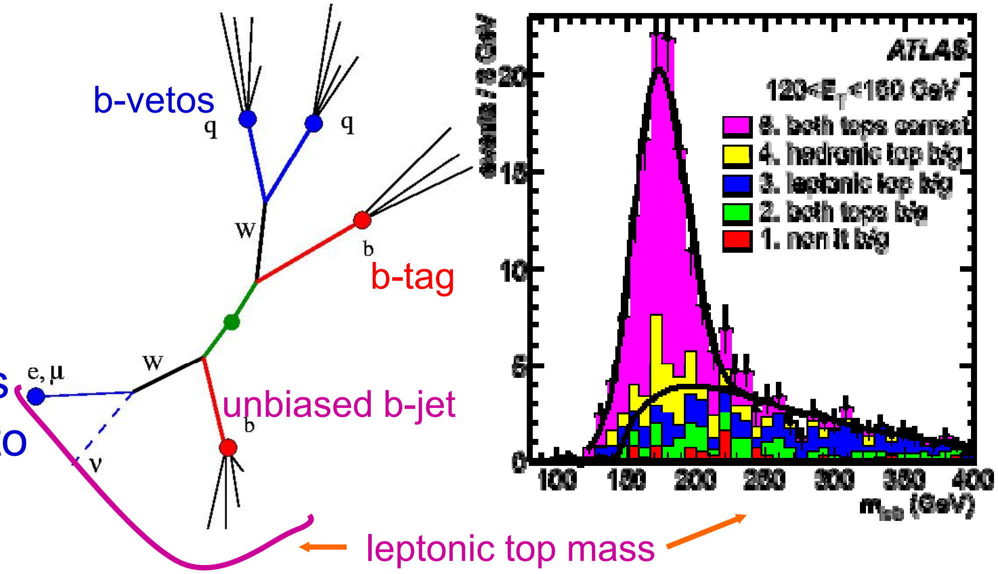


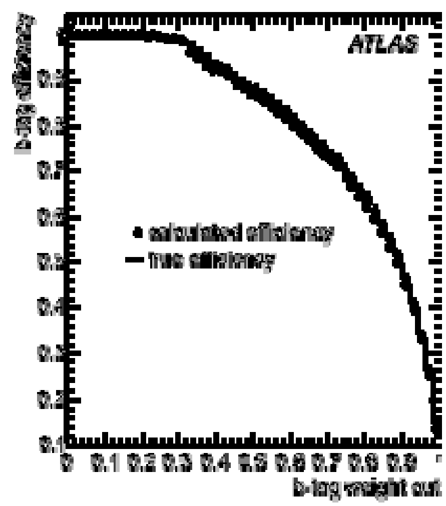


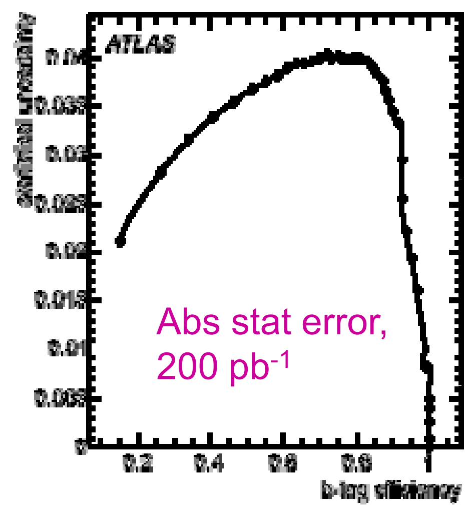


Calibration of b-tagging using top-pair events

- Top-pair events offer source of b-jets for use in b-tagging efficiency calibration
  - Method I: Count number of events with 0,1,2,3 b-tagged jets in cross-section sel^n
    - Can determine ε_b and ε_c along with σ_{tt}
    - ATLAS: get ε_b to ~5% (incl. syst) in 100 pb^{-1}
  - Method II: Exploit the topology / kinematics of the top-pair event to select the leptonic to b-jet, **without** using its b-tag info
    - Selection methods exploiting mass info, kinematic fit or jet/lepton kinematics
    - Jet samples ~70-90% pure in b flavour, have to estimate and subtract background
  - Can then study distributions of b-tagging input and output variables, calculate ε_b
    - Get ε_b to 5-10% in 200 pb^{-1}, can also look at distributions (e.g. ε_b vs jet E_T and η)
    - ε_b determined in-situ, complementary to dijet-based methods also used at Tevatron





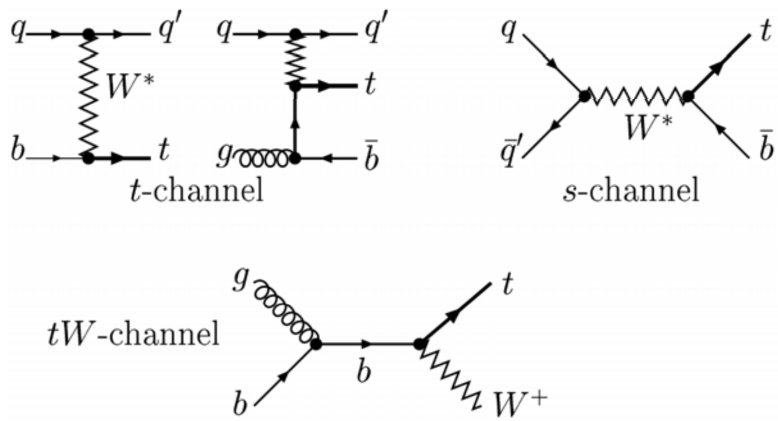


Single top production at LHC

- Electroweak top quark production - contrast to pair production
  - Sensitive to new particles (e.g. H^+, W') and flavour changing neutral currents
    - Important background to many new physics searches (lepton, missing energy)
- Overall cross section is large (c.f Tevatron), can distinguish contributions:

t-channel: σ_t=247±12 pb

s-channel: σ_t=11±1 pb



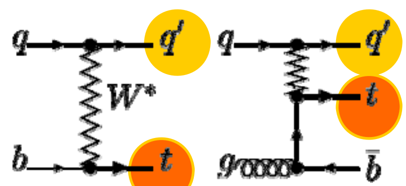
Wt-channel: σ_t=66±2 pb

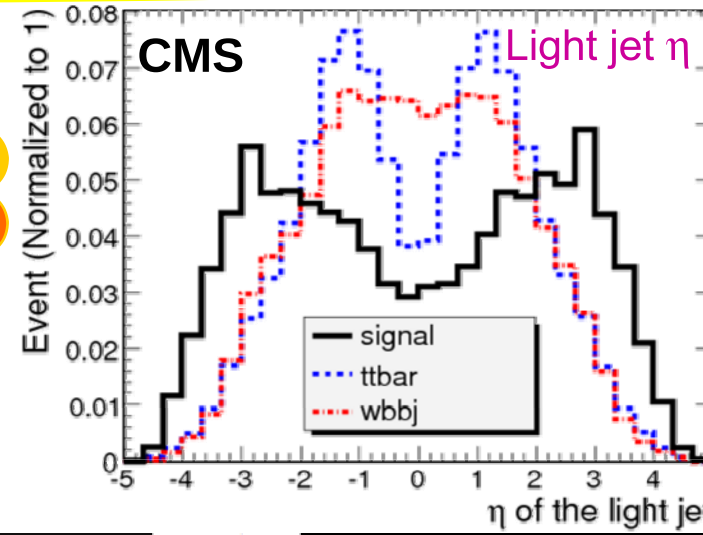
(c.f. top-pair σ_{tt}=830±50 pb)

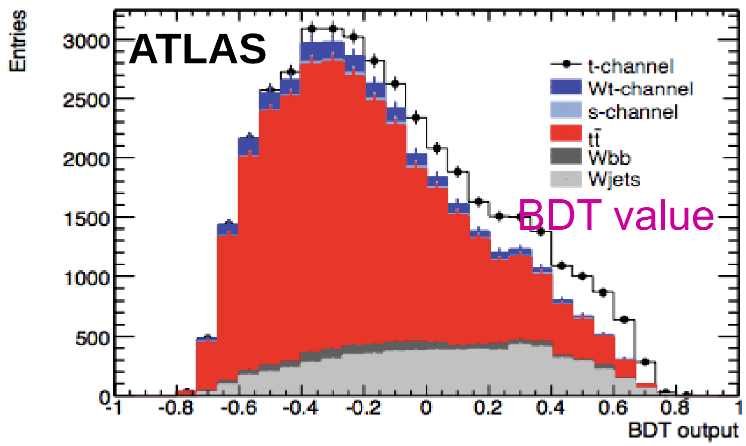
  - Large backgrounds from top pair production, also W+multijet and QCD jet events
- At LHC - attempt to measure all production modes (s-chan & Wt challenging)
  - Can then extract $|V_{tb}|$ and study polarisation, charge asymmetries, searches …
  - Basic event signatures: high E_T lepton, missing E_T, restricted number of jets
    - Fighting large backgrounds which will have to be understood from data

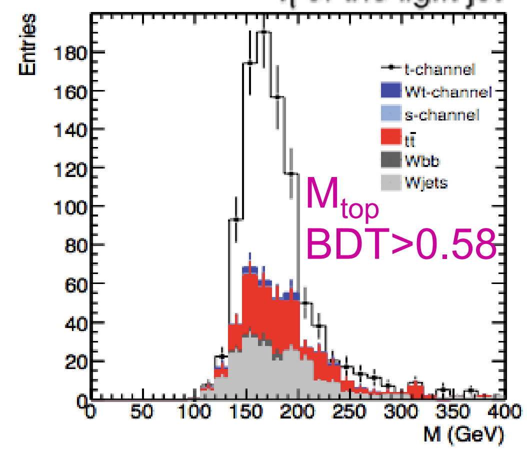
Single top production: t-channel cross-section

- Require lepton, missing E_T and one b-jet from the top quark decay
  - Infer neutrino to get top-quark mass
- Jet from light quark is **forward,** can require this jet and/or veto additional central jets
  - Second b-jet is usually soft - below E_T cut
- O(1k) events per fb^{-1}, similar size tt background ⇒ large systematics (jet E scale,ε_b)
- Can be reduced by multivariate techniques - e.g. Boosted Decision Tree with event shape variables
- Measurement to ~10% precision possible with 10 fb^{-1}
  - Then get $|V_{tb}|$ to ~5%





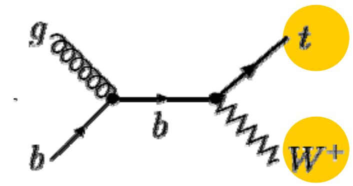


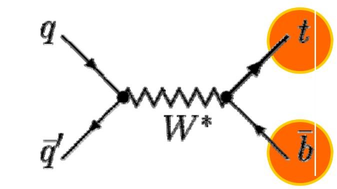


Expt	Int.L	Method	Stat(%)	Syst(%)	Lumi (%)
CMS	10 fb^{-1}	count	2.7	8	5

Single top production: W-t and s-channel

- Much smaller signal cross-sections, very large background
  - Especially from top-pair events where some particles are missed
- W-t: channel: Single b-jet; look for two light jets consistent with W decay (l-j channel), or second lepton from leptonic W decay
  - Can use control region with similar kinematics but rich in top-pairs (e.g. require extra b-jet) to estimate background, cancel systematics
- s-channel: Two b-jets, lepton + missing E_T, no other high E_T jets
- In both cases, multivariate techniques can be used to enhance signal significance





- Some representative analysis results - note small S/B and large systematics
  - Mainly from background - b-tagging/vetos, jet energy scales, PDFs, ..

Expt	Channel	Int.L	Nsignal	S/B	Stat(%)	Syst(%)	Lumi (%)
CMS	W-t (l-j)	10 fb^{-1}	1700	0.18	7.5	17	8
CMS	W-t (l-l)	10 fb^{-1}	570	0.37	8.8	24	5
CMS	s-chan	10 fb^{-1}	270	0.13	18	31	5

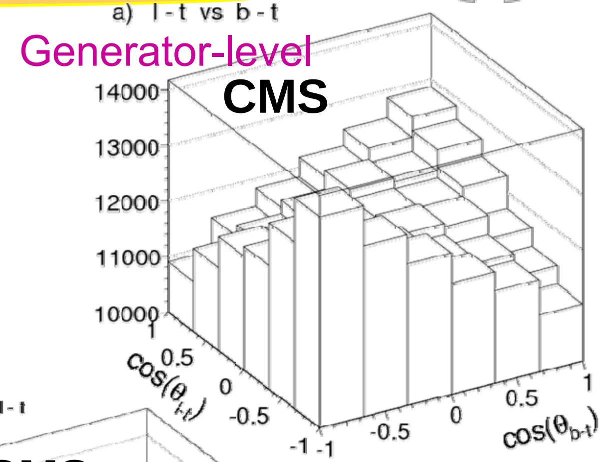
- Need O(10) fb^{-1} of data and careful background studies to establish 5σ signals

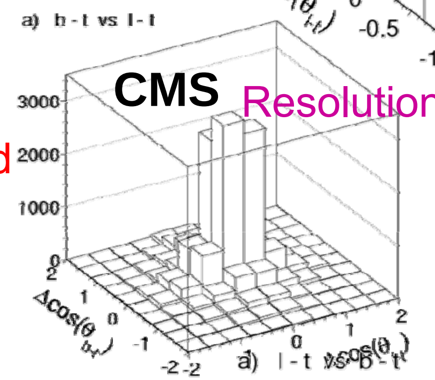
Top-pair spin correlations

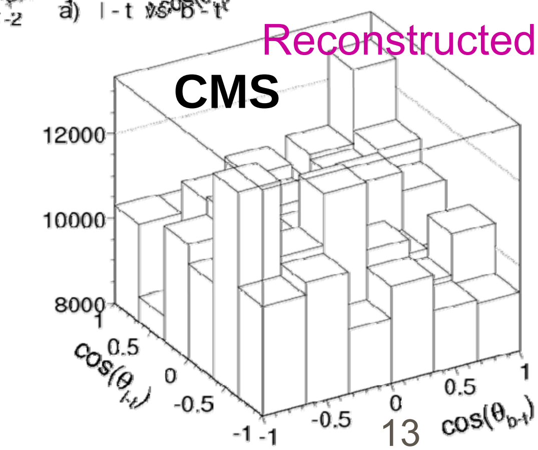
- Top decays before hadronisation or depolarisation
  - Decay products give info on top quark spin
  - Look for correlations between top/anti-top (↑↑ vs ↑↓)
    - Different for qq and gg production, in SM A≈0.32
- Measure decay angle distribution in semileptonic events

$$\frac{1}{N}\frac{d^2N}{d\cos\theta_l\, d\cos\theta_q} = \frac{1}{4}(1 - \mathcal{A}\kappa_l\kappa_q\cos\theta_l\cos\theta_q)$$; $A=(N_{\uparrow\uparrow} - N_{\uparrow\downarrow})/(N_{\uparrow\uparrow}+N_{\uparrow\downarrow})$

    - $\theta_l(\theta_q)$ angle between lepton (quark) in top quark frame and top momentum in top pair rest frame
    - Can use b-quark or lower energy light quark
  - Fully reconstruct events - distribution distorted by resl^n
  - ATLAS/CMS expect 5σ observation of spin correlation with O(10 fb^{-1}) data, in both semileptonic and dileptonic decays
    - Systematics dominate (jet energies, b-tagging, PDFs, …)
- Various related obvservables - e.g. W polarisation
  - Also look for anomalies in t→Wb vertex structure
    - Can give hints for new physics in top decay

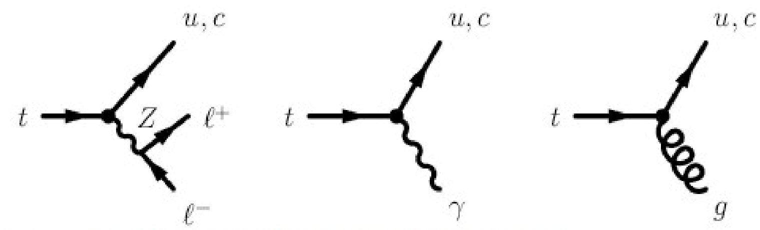




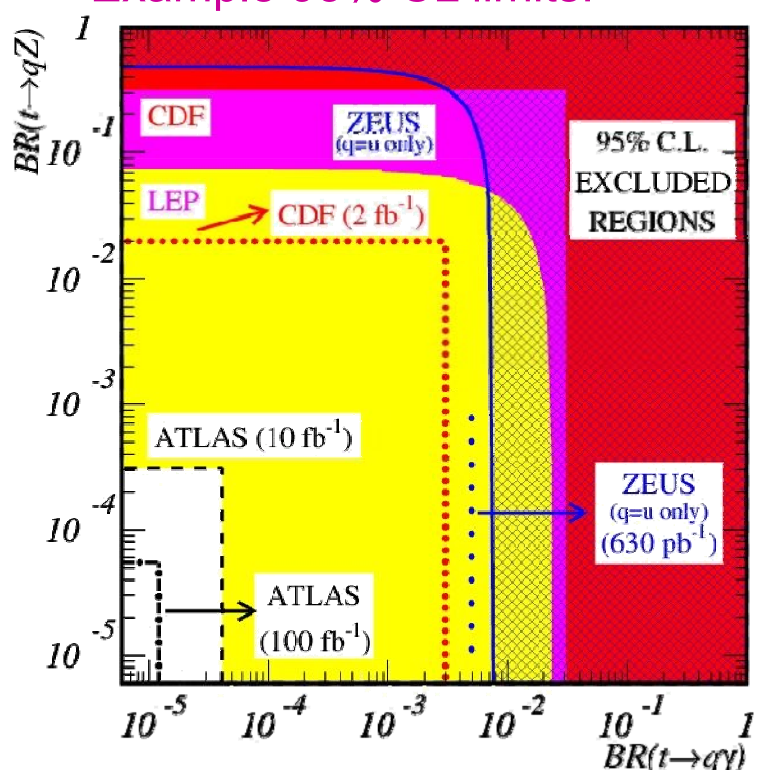


Rare top decays - flavour changing neutral currents

- FCNC decays $t \rightarrow \{Z,\gamma,g\}q$, suppressed in SM ($10^{-10}$)
  - Allowed at tree-level in SUSY, multi-H, exotic quarks
    - Could conceivably get BR 10^{-3} - 10^{-6} …
  - Typical search strategies in top-pair production
    - Assume one quark decays $t \rightarrow Wb$ with leptonic W
    - Look for leptonic Z decay, photon, high E_T gluon jet
  - Backgrounds typically dominated by mis-ID top-pair
    - Remove some contributions using likelihood selection with event shape and top mass reconstruction (ATLAS)



Example 95% CL limits:



Decay	Expt	Method	BR (5σ sens @ $100 fb^{-1}$)
$t \rightarrow Zq$	ATLAS	Cut ($Z \rightarrow qq$)	5×10^{-4}
	ATLAS	Likelihood ($Z \rightarrow ll$)	1.4×10^{-4}
	CMS	Cut ($Z \rightarrow ll$)	3×10^{-4}
$t \rightarrow \gamma q$	ATLAS	Likelihood	3×10^{-5}
	CMS	Cut	2.5×10^{-4}
$t \rightarrow gq$	ATLAS	Likelihood (3-jet)	1.4×10^{-3}
	ATLAS	Likelihood (>3 jet)	2.2×10^{-3}

Conclusions

- ATLAS and CMS are eagarly awaiting the first data …
  - Detectors/software/analysis strategies are 'almost' ready …
- Useful measurements can already be performed with ~ 100 pb^{-1}
  - … that we might hope to get in 2008 or soon after
  - Top-pair cross-section: 10-20% with O(100 pb^{-1}), then work on systematics …
    - E.g. detailed understanding of b-tagging algorithm performance
- Single top: need O(fb^{-1}) to make 10-20% measurement of t-channel
  - And O(10 fb^{-1}) to unambiguously establish the s-channel and W-t contributions
- Top properties: need O(10 fb^{-1}) to establish the top-pair spin correlations
  - Many other top-properties can be measured (e.g. top charge)
    - Some can start with much lower integrated luminosity
- Searches for non-SM physics in top prod^{n}/decay can start immediately…
  - Consistency of cross-section in different channels; top-pair vs single top
  - Searches for rare decays can use 100s fb^{-1}, continue to high luminosity LHC phase
- The era of 'top-factory' physics is approaching!