Top Quark Physics at LHC

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On behalf of the ATLAS and CMS Collaborations

DIS 2009

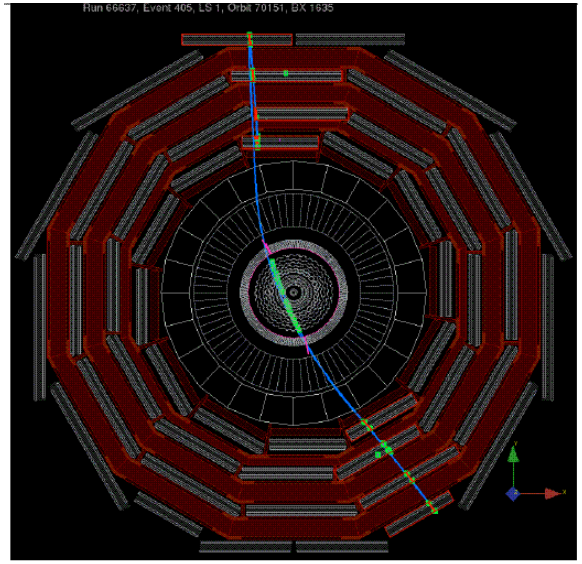
ATLAS and CMS at LHC

Multipurpose complexe detectors dedicated to particles properties measurements : good muon identification and momentum resolution, good electromagnetic identification and γ/e energy resolution, performant calorimetry for hadrons, precise and efficient inner tracking (inc. vertex capabilities), good jet and MissE_T resolution

pp collisions at LHC. Goal: $\sqrt{s}$ = 14 TeV, L = 10^{34} $cm^{-2}s^{-1}$

2009-2010: $\sqrt{s}$ = 10 TeV, L = 10^{31} - 10^{32} $cm^{-2}s^{-1}$, $\int Ldt \approx 200\ pb^{-1}$

Detector comissionning with cosmics events O(100M) events ->
Tests of reco/analysis chain, tracker operation and alignement, muon detector resolution and efficiency



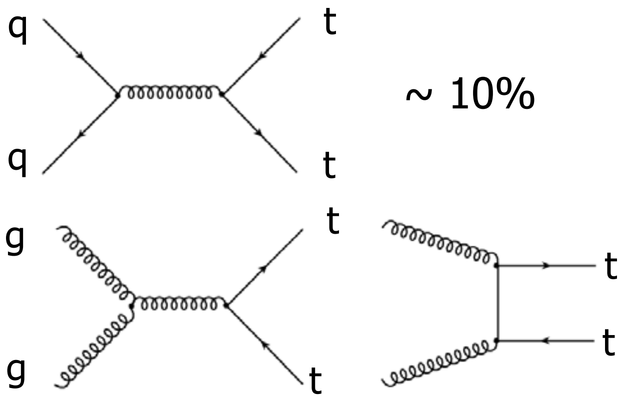
≥ 95% pixel detector operational

CMS

ALL results presented from simulations at $\sqrt{s}$ = 14 TeV

Top Quark production and decay at LHC

Strong interaction: tt pair



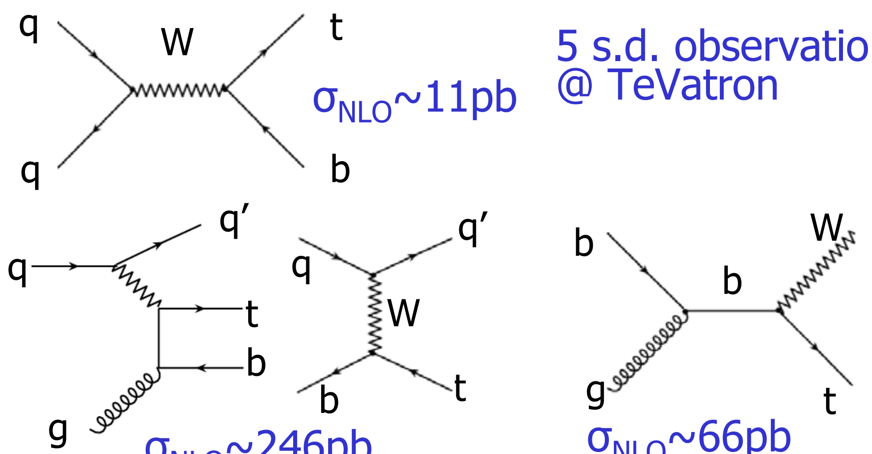
~ 10%

~ 90%

σ_{NLO}~ 900pb

ΔTh/Th : ~6-9%

Weak interaction: single t / $\bar{t}$



σ_{NLO}~11pb

5 s.d. observation @ TeVatron

σ_{NLO}~246pb

σ_{NLO}~66pb

ΔTh/Th : ~5-10%

σ(t) ≠ σ($\bar{t}$)

BR(t->Wb)~100%, no top hadronization(SM)

W->e/μν,qq

tt final states (produced,1fb^{-1}) :
Full hadronic: 6jets (2b) ~ 400K events
Semileptonic: lν+4jets (2b) ~ 270K events
Dileptonic:2l2ν+ 2b ~ 68K events

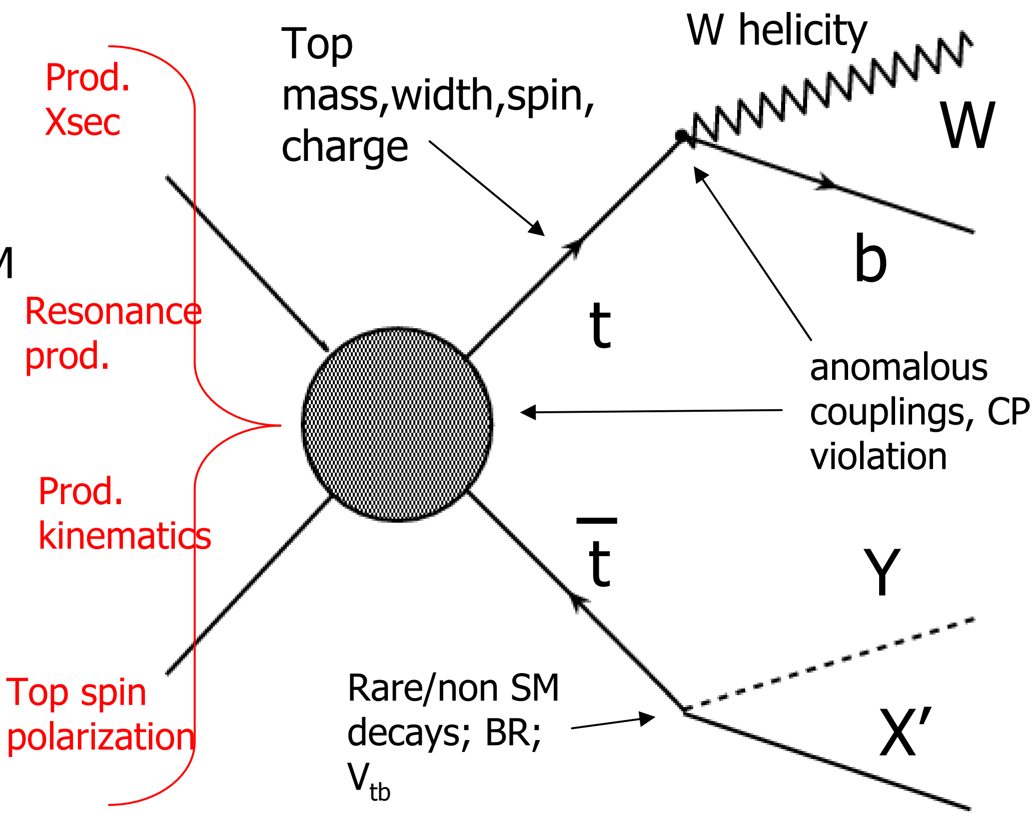
Single top final states (produced,1fb^{-1}) :
t-channel: lν +2jets (1b) ~ 50K events
tW: lν +3jets (1b) ~ 20K events
s-channel: lν + 2jets (2b) ~ 2K events

LHC=Top factory : High P_T lepton(s)+MissE_T+multijets (with≥1b)

Motivations for top quark physics at the LHC

1/ Measurements

- Xsections
  - Rediscovering (O(10pb^{-1}), basic (O(100pb^{-1}), precise (≥1fb^{-1})
  - Main bckg for searches beyond SM
- Top mass determination
  - fundamental parameter (highest mass in SM)
  - Higgs mass constraint
- Top properties
  - charge,spin pol., decays, couplings, rare/FCNC decays



2/ Top=Tool for undertstanding/calibration of the detector

- Jet energy scale, B-tagging

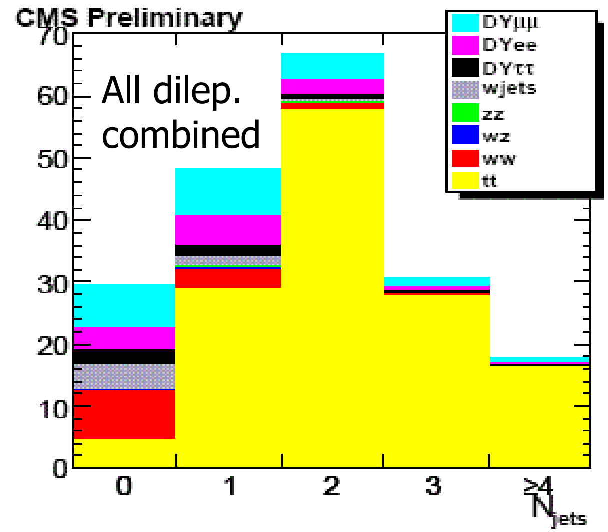
Start at √s = 10 TeV instead of √s = 14 TeV

-> tt Xsec reduced by a factor ~ 2

-> Z/W+jets down by ~ 25%, (Higgs(200GeV)~50%)

Top pairs production (rediscovering $O(10pb^{-1})$)

Remarkable topology: t and t central, back to back in transverse plane



N_{sig}=128

S/B=7

ε=10.3%

Dilepton selection (ee,μμ,eμ incl. τ ->lepton):

2 isolated high P_T (>20GeV) leptons, loose elId

2 central jets (E_T>30GeV)

MissE_T>20GeV (eμ) , 30GeV (ee,μμ)

Bckgd = Z+jets, tt semil(+fake), W+jets

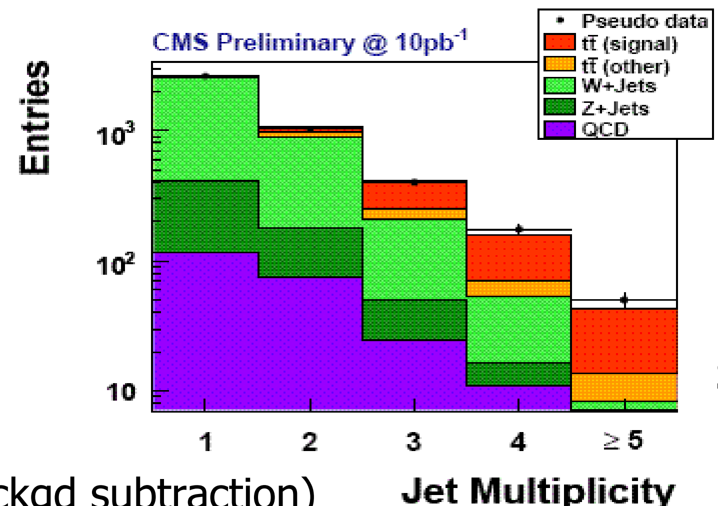
Semileptonic (μ) selection:

1 central isolated high P_T (>30GeV) μ

≥ 4 central high P_T jets (>40GeV, $E_T^{lead.jet}$(>65GeV)

Isolation cuts ($E_{cone}^{Calo/Tracker}$, ΔR(μ,closest jet))

Bckgd = W+jets, tt(other decay channels), QCD



Δσ/σ (stat) = 9%

S/B=1.7

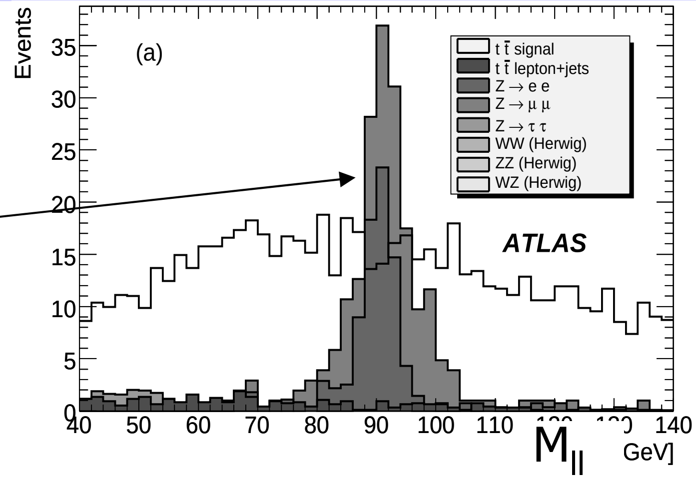
NO B-tagging, Data-driven methods to control bckgd being investigated

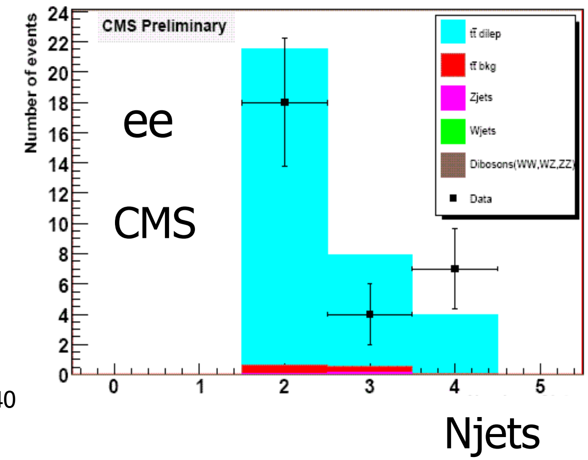
Robust counting method: σ.BR=(N_{data}-N_{bckgd})/ε∫L (bckgd subtraction)

Top pairs (measurement with ≥100pb^{-1}-1fb^{-1})

Dilepton final states

Selection similar to O(10pb^{-1}): 2 isolated high P_T l^+l^- (l=e,μ), elId, MissE$_T$, M_Z veto





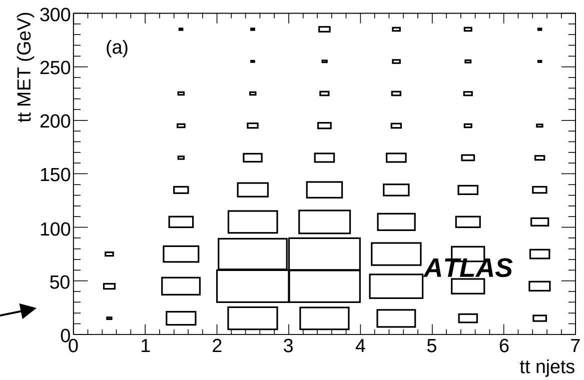
Xsection extraction from:

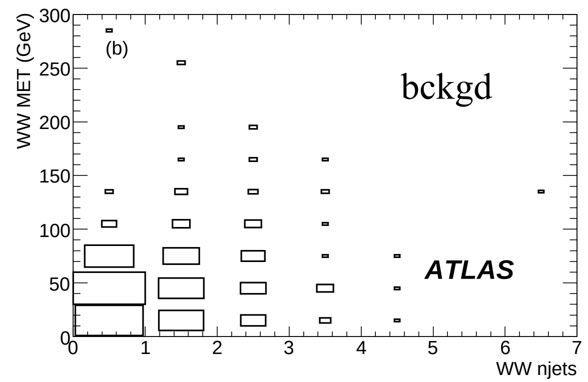
- Robust counting method:

ATLAS: Δσ/σ(100pb^{-1})= 4(stat) -2+5 (sys)±2(pdf)%

CMS(+B-tag): 8(stat)%, Bckgd~0

CMS(+B-tag, M_W constraint, 10fb^{-1}): 0.9(stat)±11%)





- 2D binned llhood fit in (MissE$_T$,N$_{jet}$) space (ATLAS): Δσ/σ(100pb^{-1}) = 4(stat)±4(sys)±2(pdf)%

- Llhood fit to angular variables (|Δφ(lepton1, MissE$_T$)|) (ATLAS): Δσ/σ(100pb^{-1}) = 5(stat)-5+8 (sys)±0.2(pdf)%

+ Lumi error = 5%

Top pairs (measurement with ≥100pb^{-1}-1fb^{-1})

Semileptonic final states

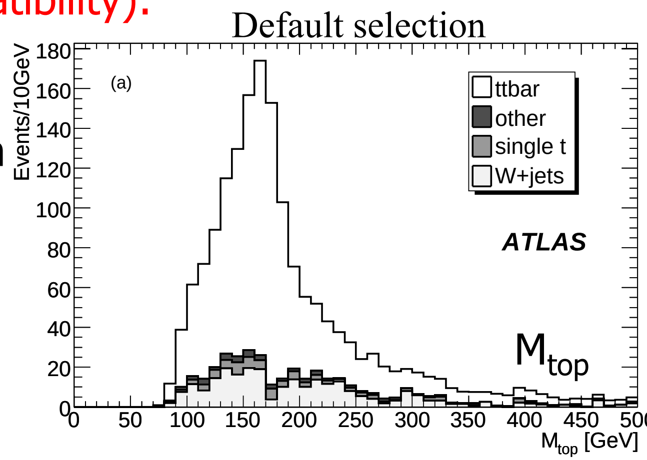
• 1 isolated high P_T (>20GeV) e/μ, ≥4 jets (P_T>20-40GeV), hadronic top mass reconstruction

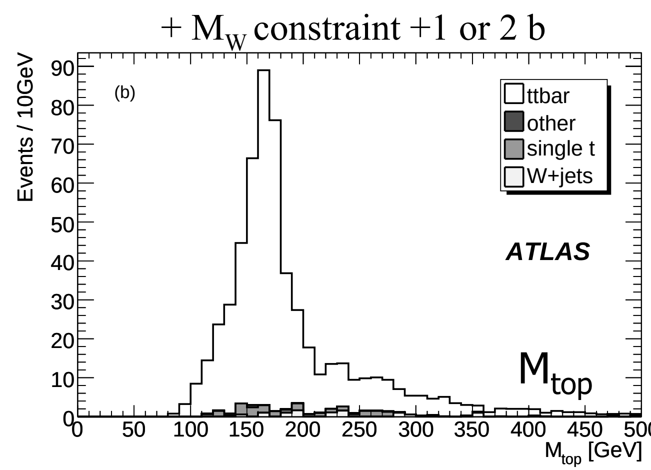
Event reconstruction (tt compatibility):

• ATLAS: = MissE_T>20GeV, purification with M_{jjj}=M_{TopHad}, {jjj}= 3 jets combinaison with highest transverse sum.

Additional constraint: at least one M_{jj}=consistent with M_W

(1 or 2 additional b-tags possible)





• CMS: 2 b-tagged jets, convergence requirement of a kine fit with M_{jj} = M_W constraint

Xsection determination: Counting method, llhood fit to M_{jjj} shape

ATLAS: Δσ/σ(100pb^{-1},no b-tag)=3(stat)±16(sys)±3(pdf)% (counting) 7±15±3(llhood), +lumi=5%
main sys=JES

CMS: Δσ/σ(1000pb^{-1}, b-tag, μ channel)=1.2(stat)±13.6(sys+lumi)% (counting)
main sys = B-tagging

Single top production (1)

σ(t)~300pb~1/3 σ(tt), important bckgd ->more complexe to select/reconstruct/extract -> Multivariate statistical analyses (boosted decision trees, genetic algorithm, multiple llhood)

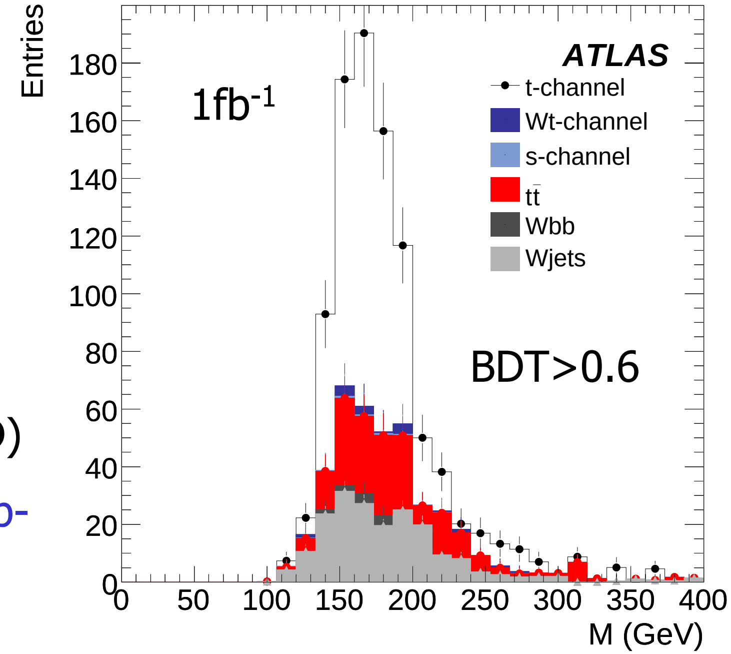
t-channel

=qlνb(b), 1light jet in forward/backward direction, low P_T additional b

Selection with sequential cuts on lepton, b-jet, $MissE_T$, forward jet and top mass

CMS (μ, optimization with genetic algo. + counting method):
$\Delta\sigma/\sigma(10fb^{-1})$=2.7(stat)±9.4(sys)%

ATLAS(e+ μ): Additional rejection of bckgd (tt,W+jets) by applying BDT (10 kinematic variables not too sensitive to JES) -> reduce sys. by a half :
$\Delta\sigma/\sigma(10fb^{-1})$=1.8(stat)±10(sys)%



Need bckgd control (data-driven methods for tt, W+jets, QCD)

AND excellent knowledge of detector performance (JES and b-tagging ≤5% uncertainty level)

Single top production (2)

tW-channel

=qqlνb, lνlνb (close to tt with only 1 b-jet)

Selection with sequential cuts on kinematic variables (lepton P_T,…, b-tagging)

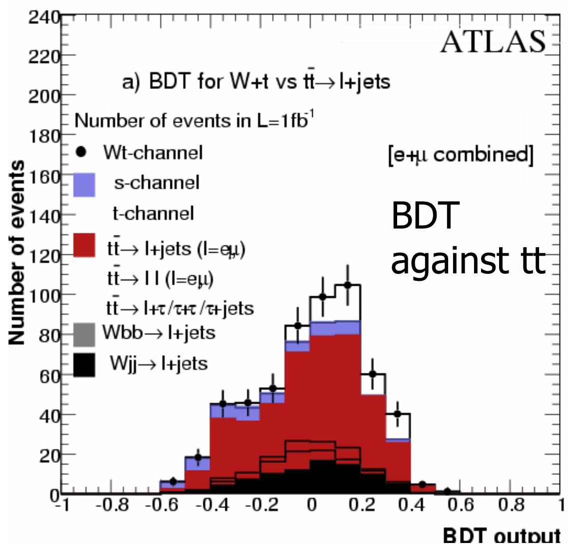
CMS:Additionnal sophisticated bW pairing (Fisher discriminant)

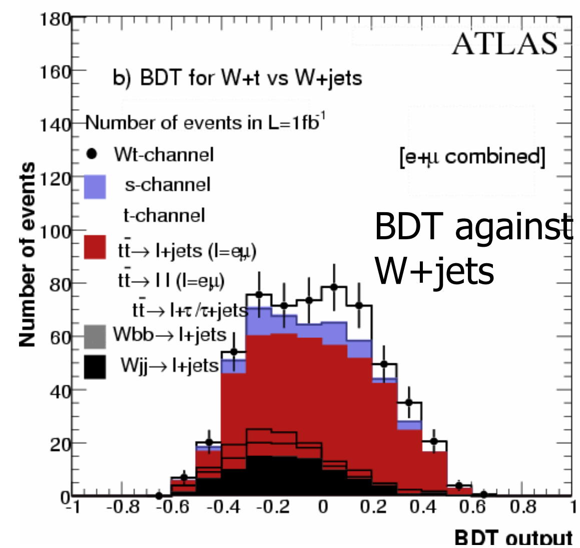
-> S/B= 0.37 (0.18) for dileptonic (semileptonic) channel ($10fb^{-1}$) => Significance = $S/(S+B)^{1/2}$ = 6 (dilep.+semil.), tt dominant bkg

ATLAS: Several Boosted Decision Trees built from 25 variables -> reduce sys. by a half :

3σ evidence with O($1fb^{-1}$), Δσ/σ($10fb^{-1}$) ~ 20%

Main sys. = JES, B-tagging





s-channel

= lνbb The most difficult, a challenge

CMS: Δσ/σ($10fb^{-1}$)= 18(stat)±31(sys)%   ,   ATLAS: 3σ evidence with 30 fb^{-1}

Top mass measurements (1)

M_{Top} = 173.1± 1.2 GeV (CDF+D0, arXiv:0903.2503)

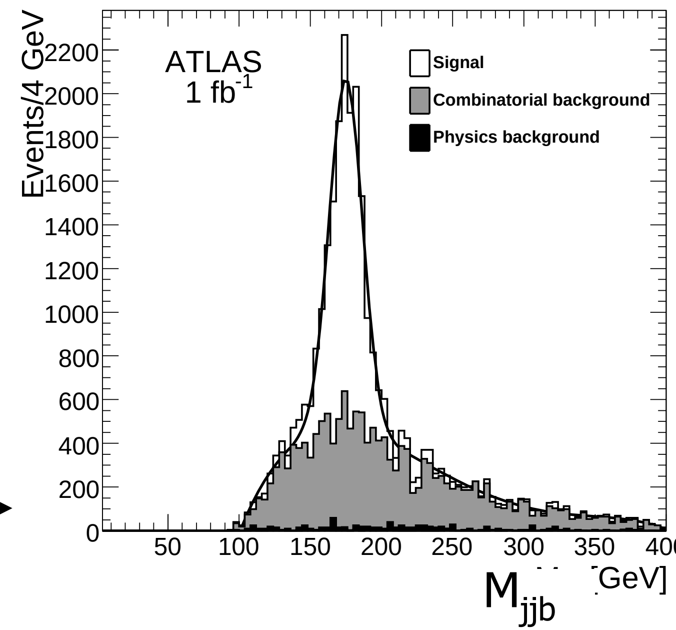
Direct measurement: the Lepton+jet "golden" channel

Event selection: mainly semil. selection for Xsec (e+μ for ATLAS, μ forCMS) with 2 b-tagged jets (optional relaxed procedure studied (0/1 b-tagged jet for ATLAS)), then

Several steps (ATLAS≠CMS):

ATLAS

- Hadronic W mass reconstruction M_{jj} (j=light) from 2 methods:
  - with χ^2 minimization event by event (M_W constraint + in-situ jet energy calibration)
  - geometric method : closest jet pair in space
- Top quark reconstruction
  - choose the closest b to {jj} →



- Top quark mass measurement from χ^2 kinematic fit (incl. {lν} reconstruction)

-> ΔM_{Top}(stat)≤0.4GeV for 1 fb^{-1}

dominated by systematics (mostly (b)JES): 1-3.5 GeV if ΔJES/JES~1-5%

Top mass measurements (2)

CMS

- Hadronic Top quark reconstruction

  - Pair of anti b-tagged jets combined with b-tagged jets according to largest llhood -> purity ~ 82%

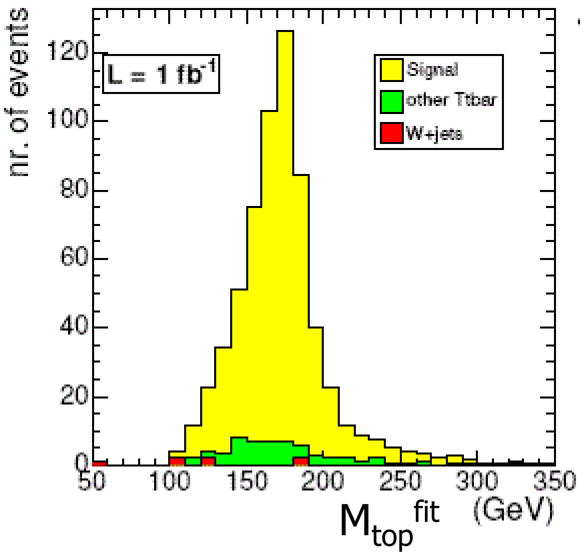
- 3 Top quark mass estimator investigated :

  - Simple gaussian fit on reconstructed mass spectrum →

  - Convolution of the theoretical expected pdf $P(M_t|M_T^{true})$ with gaussian resolution function :

$$R \sim exp\left(-\frac{1}{2}\left(\frac{M_t - M_t^{fit}}{\sigma_{M_t^{fit}}}\right)^2 \right)$$

  - Convolution with a full parametrization (incl. Breit-Wigner shape, combinatorial, residual bckgd)



=> A llhood variable L is reconstructed reflecting the signal probability: Max(L) = M_{Top}

ΔM_{Top} (GeV)

Total Systematical uncertainty	3.21	1.27	1.13
Statistical Uncertainty (10 fb^{-1})	0.32	0.36	0.21
Total Uncertainty	3.23	1.32	1.15

<1.2GeV if ΔJES/JES~1.5%

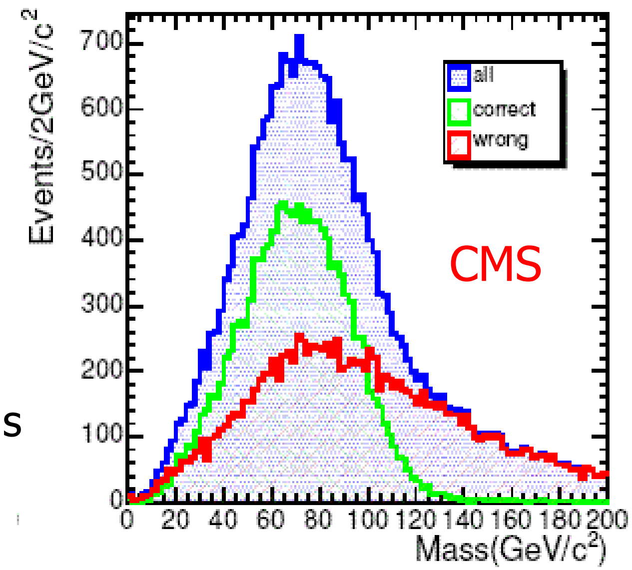
Top mass measurements (3)

Other methods

- Other W decay channels:
  - Dilepton: ΔM_{Top} ~2.9GeV for $\leq 10 fb^{-1}$ CMS, (b-JES dominates)
  - Fully hadronic: challenging! ΔM_{Top} ~ 4.2GeV ($1fb^{-1}$) limited by QCD, JES
- From t -> lepton+J/ψ + X decays, with J/ψ -> $\mu^+\mu^-$

Easy to identify (clean samples) but BR(overall in tt)~5.3 10^{-5} -> O(1000) signal events for $100fb^{-1}$ after selection

3-leptons mass:



Systematics dominated by theoritical modeling of the events, negligeable JES

ΔM_{Top} < 2 GeV for $20fb^{-1}$

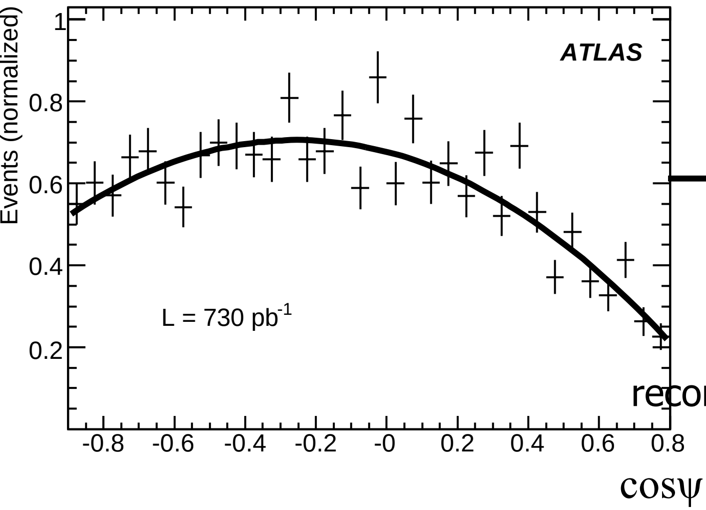
Top properties

Top : Large mass, large width => unique to top quark properties: tests of the V-A structure of top decays; top spin; $|V_{tb}|$; charge; couplings; rare decays

Semileptonic W decay -> distribution of ψ = angle(lepton/W-restframe, $W_{top\text{-}restframe}$)

$$\frac{1}{N}\frac{dN}{dcos\psi} = \frac{3}{2}\left(F_0\left(\frac{sin\psi}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-cos\psi}{2}\right)^2 + F_R\left(\frac{1+cos\psi}{2}\right)^2 \right)$$

polarized W -> longitudinal lefthanded righthanded



	F_L	F_0	F_R
	0.29±0.02±0.03	0.70±0.04±0.02	0.01±0.02±0.02
SM:	0.304	0.695	0.001

Top spin correlations in tt decays: accessible via an asymmetry measurement

$$A = \frac{N(t\bar{t}, same\ helicity) - N(t\bar{t}, opp.\ helicity)}{N(t\bar{t}, same\ helicity) + N(t\bar{t}, opp.\ helicity)}$$

→ ATLAS precision ~O(50%) ($730 pb^{-1}$)
CMS precision ~O(20%) ($10 fb^{-1}$)

Anomalous top production and rare top decays

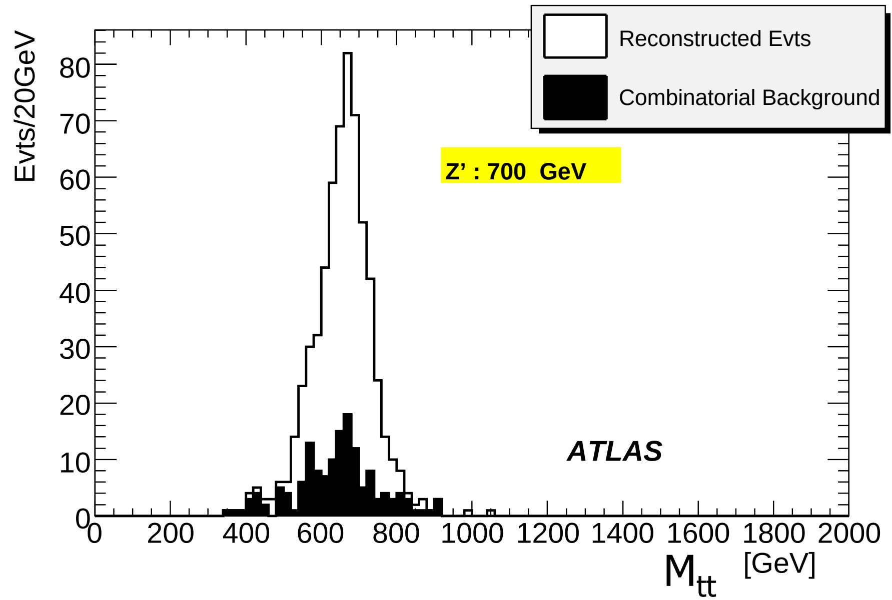
Large Yukawa coupling (~1) => Significant potential to discover new physics (top resonances, Z′,Kaluza-Klein modes, Susy)

Resonance Z′ -> tt
-> lνqqbb

ATLAS: 5σ discovery with $1fb^{-1}$ for 700GeV Z′ →

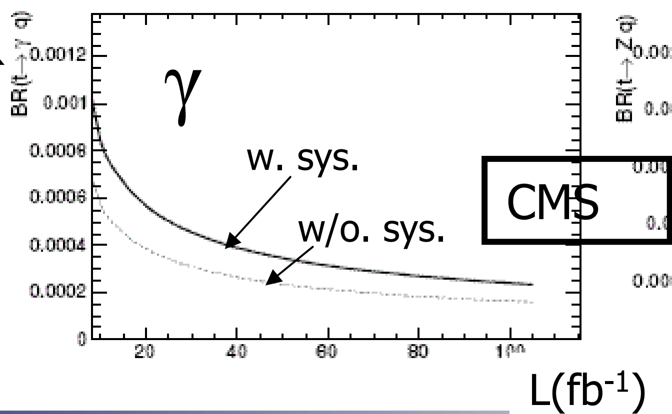
(σ.BR(Z′->tt) = 11pb)

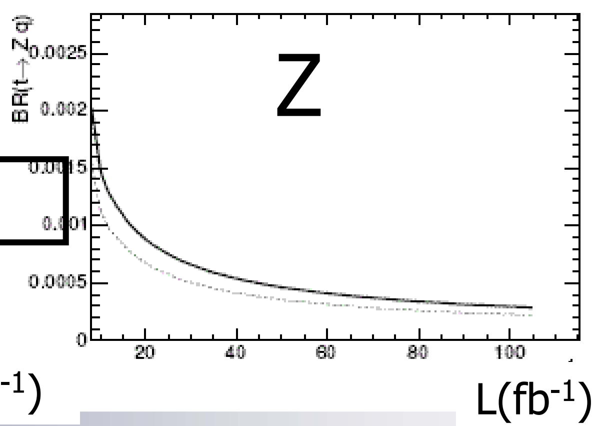
tt mass spectrum →



FCNC rare decays (t->(Z,γ,g)q) can be investigated

tt -> γqlνb or Zqlνb





5σ significance level ($10fb^{-1}$):

BR(t->γq)=5.7 10^{-4} (w/o sys.)
BR(t->Zq)=11.4 10^{-4}

Top as calibration tool (1)

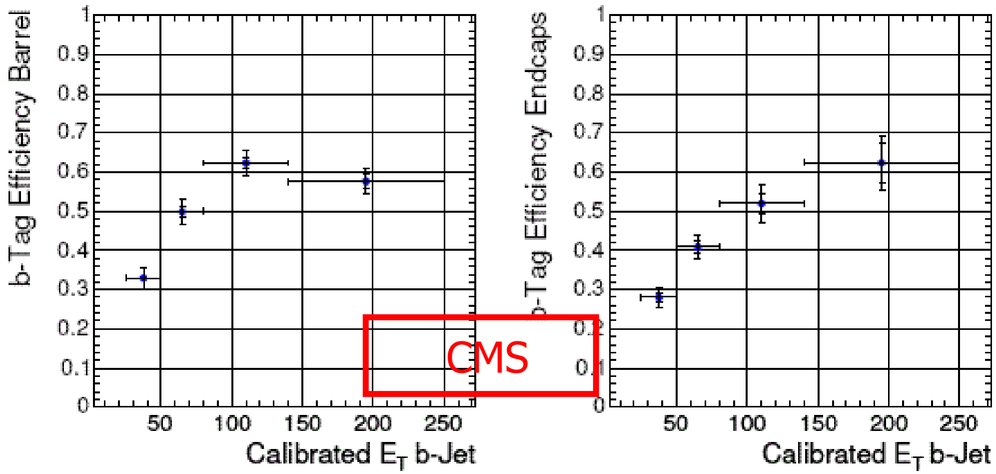
B-tagging

tt events used to isolate a highly enriched b-jet sample -> exploited to calibrate jet algorithm and extract b-tagging effficiency ε_b for energetic jet

Selection of lepton+jets or dileptons final states :

- Counting method (0,1,≥2 b-tagged jets) -> $\Delta \varepsilon_b / \varepsilon_b \sim$ 4-5% (semil. - dilep. resp., ATLAS, 100pb^{-1})

- From an enriched sample (topological/kinematic selection) , $\varepsilon_b = (Ftag - \varepsilon_b (1-P_b))/P_b$, Ftag = measured fraction of jet tagged, P_b = b purity -> get ε_b versus E_T and η of the jet



-> CMS: $\Delta\varepsilon_b/\varepsilon_b \sim$ 6/10% (barrel/endcap) for 1fb^{-1}

Main sys = ISR/FSR, event selection and purity

-> ATLAS: $\Delta\varepsilon_b/\varepsilon_b \sim$ 8% for 200pb^{-1} of semil. events

Top as calibration tool (2)

Jet Energy Scale (JES)

Selection of tt-> lνbjjb final states and identification of hadronic top system {jjb}; Use of the B-tagging

- ATLAS: 2 complementary methods

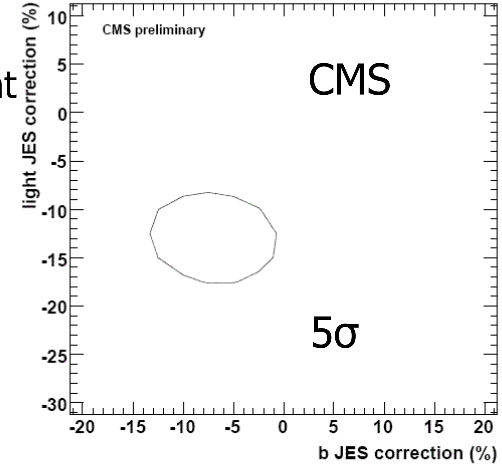
  - χ^2 fit of M_{jj} mass with template distributions(light JES,JEResolution) -> Precision of 2% for bare JES (all P_T) with 50pb^{-1}, no sys. error source > 0.5% identified

  - Iterative rescaling of M_{jj} with scale factor derived from $M^{PDG}_W / M_{jj}^{FITTED}$ constraint in bins of E_{Tjet}, η_{jet} (for the selected sample , P_{Tjet} >40GeV) -> 2% on light JES (E,η) with 1fb^{-1}

- CMS:

  -Rescale each jet with relative shifts {ΔE(light-jet),ΔE(b-jet)}, remake/refit W had. Mass and had. top (bW) mass spectra, solve the equation M(top,W;{ΔE})=M(top,W)^{PDG} -> best estimate of {ΔE}

  -> ~1% on b-JES and light-JES with 100pb^{-1}



Conclusion

Top quark physics plays an essential role in the LHC program:

• unique laboratory : large amount of quark top production (for both $\sqrt{s}$ = 14 TeV and 10 TeV) => measurement limitations from systematics. Complete tool for testing lepton, jet (incl. B), $MissE_T$.

At $\sqrt{s}$ = 14 TeV and low integrated luminosity, ATLAS and CMS can:

• Rediscover the top at the start-up (~ O(10 pb^{-1}))

• Provide basic measurements with O(100 pb^{-1}): tt pair production via strong interaction (~ 10-20%); B-tagging efficiency (~ 5-10%);

Need to develop data-driven methods to calibrate, control backgrounds

Beyond (O(1- 10 fb^{-1})),

• access to precise measurements: M_{TOP} (~1-3 GeV), single top production (10-20%) , Jet Energy Scale

Hint for new physics can be found through top signature (rare decays, resonances, backgrounds for SUSY searches …)

Backup slides

Acknowledgments

To people of ATLAS & CMS Top Groups (and others) for their help/comments

Main references:

- ATLAS: "Expected performance of the ATLAS Experiment, Detector, Trigger and physics" in CERN-OPEN_2008-20 and public results in https://twiki.cern.ch/twiki/bin/view/Atlas/TopPublicResults

- CMS: Physics TDR, Vol.2, CERN/LHCC 2006-021 and public results in http://cms.cern.ch/iCMS/

- Others (not exhaustive!):

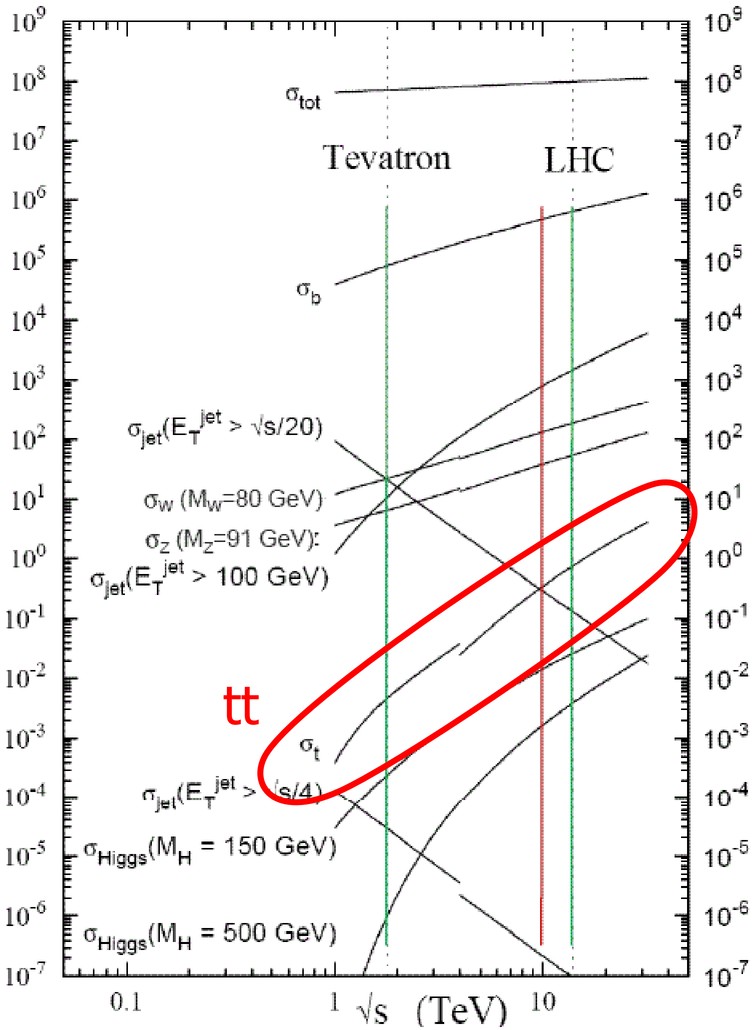
Observation of electroweak single-top production, CDF/D0: arXiv:0903.0850, arXiv:0903.0885

tt and single top theoretical Xsections: Cacciari&all (arXiv:0804.2800), Kidonakis&all (arXiv:0805.3844), Harris &all (hep-ph/0207055), Sullivan (Phys.Rev D70,114012), Campbell&all (Phys.Rev D70,094012)

ATLAS/CMS

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels+ strips TRD $\rightarrow$ particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air $\rightarrow$ σ/p_T < 10 % at 1 TeV standalone; larger acceptance	Fe $\rightarrow$ $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

LHC statiistics



SM parameter measurements will be dominated by systematics errors :

-from instrumental effects, luminosity

- from MonteCarlo :ISR/FSR, PDF, ….

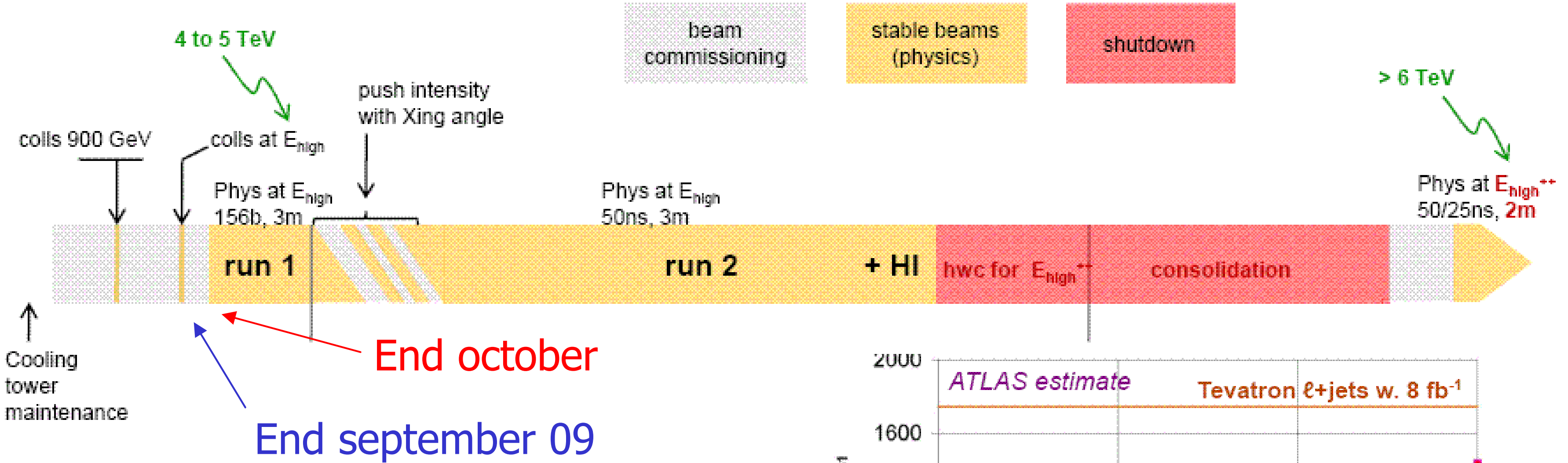
SM Process	σ(pb)		Evts/$1fb^{-1}$ for 14TeV
Minimum biais		10^{11}	~10^{14}
bb		$5\ 10^{8}$	~10^{12}
tt	414	908	~$9\ 10^{5}$
single t	164	323	~$3\ 10^{5}$
W->lν	$46\ 10^{3}$	$68\ 10^{3}$	~$70\ 10^{6}$
Z->ll	4200	8000	~$8\ 10^{6}$
	10TeV	14TeV	

LHC schedule

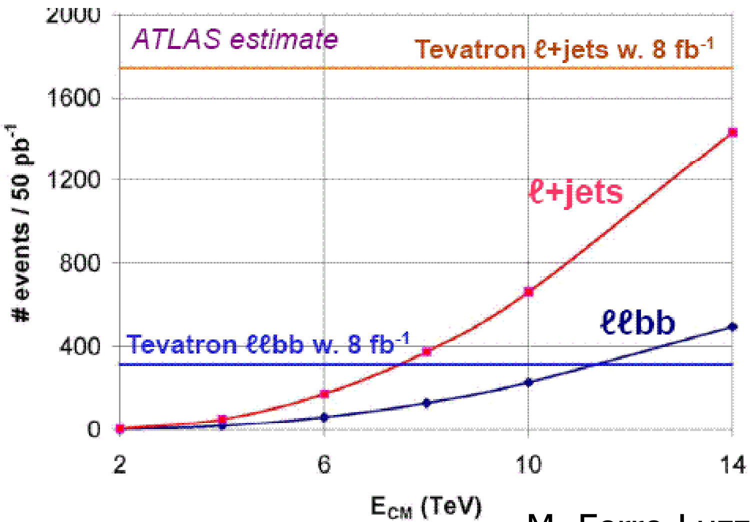
The prefered scenario:

From Chamonix '09 Workshop

Start the LHC as soon as possible and run for one year



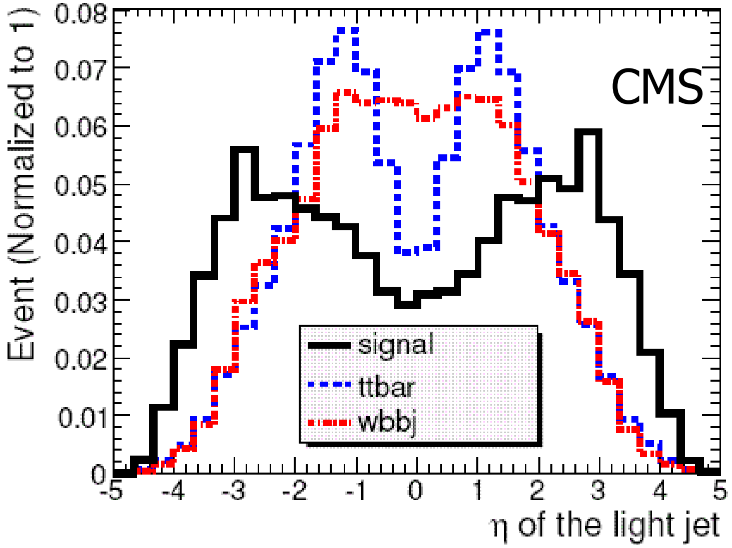
tt: Competing with Tevatron with ~ $100pb^{-1}$ @ $\sqrt{s}$ = 10 TeV



M. Ferro-Luzzi, Chamonix09

Single top (details)

t-channel



Details of sys. errors for singletop t-channel →

Source	Analysis of 10 fb^{-1} Variation	Cut-based	BDT
Data Statistics		1.6%	1.8 %
MC Statistics		2.0 %	2.5%
Luminosity	3%	10.9 %	5.2%
b-tagging	3%	10.9%	3.9%
JES	1%	4.4 %	2.0%
Lepton ID	0.2%	0.6 %	0.3%
Trigger	1.0%	3.6 %	1.7%
Bkg x-section		6.9 %	2.5%
ISR/FSR	+2.2 -3.2%	2.7 %	2.5%
PDF	+1.38 -1.07%	12.3 %	3.2%
MC Model	4.2%	4.2 %	4.2%
Total		22%	10%

Top mass reconstruction, systematics

Semileptonic channel (for 1-10fb^{-1})

ATLAS :

Systematic uncertainty	χ^2 minimization method	geometric method
Light jet energy scale	0.2 GeV/%	0.2 GeV/%
b jet energy scale	0.7 GeV/%	0.7 GeV/%
ISR/FSR	$\simeq$ 0.3 GeV	$\simeq$ 0.4 GeV
b quark fragmentation	$\lesssim$ 0.1 GeV	$\lesssim$ 0.1 GeV
Background	negligible	negligible
Method	0.1 to 0.2 GeV	0.1 to 0.2 GeV

CMS :

	Standard Selection		
	Gaussian Fit Δm_t (GeV/c^2)	Gaussian Ideogram Δm_t (GeV/c^2)	Full Scan Ideogram Δm_t (GeV/c^2)
Pile-Up (5%)	0.32	0.23	0.21
Underlying Event	0.50	0.35	0.25
Jet Energy Scale (1.5%)	2.90	1.05	0.96
Radiation (Λ_{QCD}, Q_0^2)	0.80	0.27	0.22
Fragmentation (Lund b, σ_q)	0.40	0.40	0.30
b-tagging (2%)	0.80	0.20	0.18
Background	0.30	0.25	0.25
Parton Density Functions	0.12	0.10	0.08
Total Systematical uncertainty	3.21	1.27	1.13
Statistical Uncertainty (10 fb^{-1})	0.32	0.36	0.21
Total Uncertainty	3.23	1.32	1.15

General effective Lagrangian for the tbW vertex:

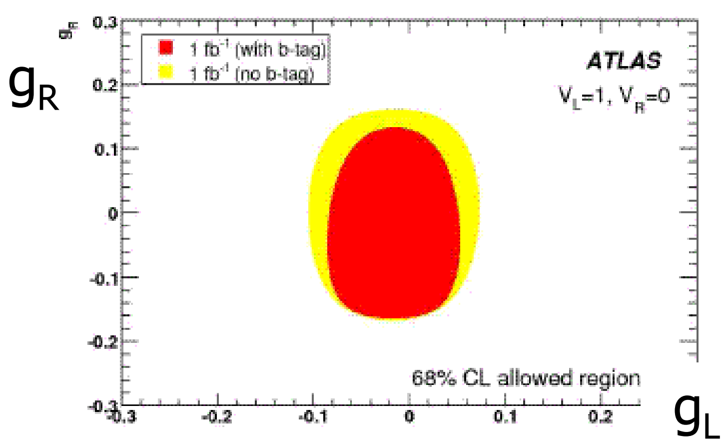
$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)tW_{\mu}^{-}(+h.c.)$$

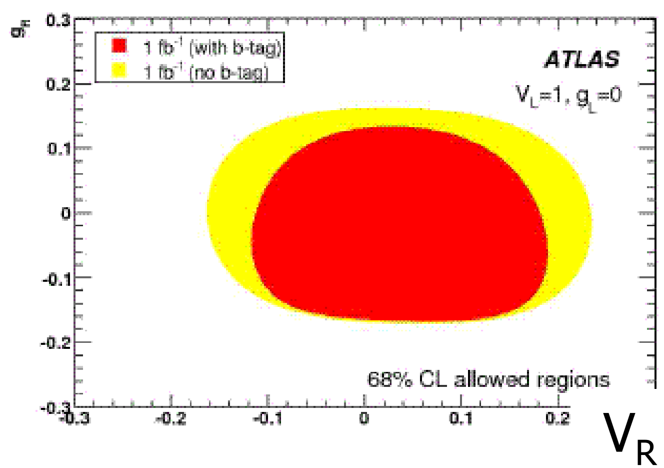
where $P_{R/L} = (1\pm\gamma^5)/2$: usual right and left handed projector, vector-like $V_{R/L}$ and tensor-like $g_{R/L}$ are top couplings. In SM: $V_L = V_{tb}$, others are anomalous.

The W polarization is sensitive to V and g couplings associated to tbW vertex => helicity fractions (F_L, F_0 , F_R) as well as helicity ratios $F_{R,L}/ F_0$ are sensitive to them

Can extract tbW vertex info from angular asymetries involving angle ψ (between charged lepton in W rest-frame and W direction in the top rest frame), ex: forward-backward asymetry $A_{FB} = ¾(F_R - F_L)$ (=-0.223 in SM). (No need to fit an angular distribution)

ATLAS ($1fb^{-1}$)

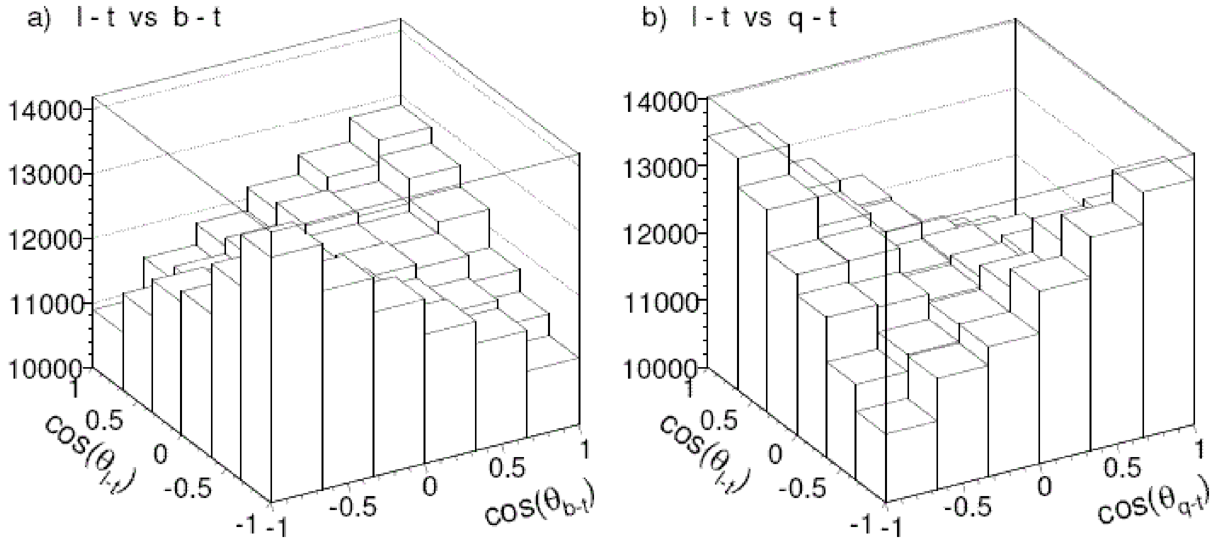




Spin correlations

Top itself is expected to be produced essentially unpolarized but there are correlations between the spins of the 2 tops in the same events (close to the threshold, in gluon gluon fusion , top pairs are produced in a $^1S_0$ state

Spin correlations accessible via double differential angular distributions : angle θ_1 between t decay product 1 in the t rest frame and the t in the tt rest frame, same θ_2 for $\bar{t}$



$\Theta_1 = \theta_{l\text{-}t}\,,\ \Theta_2 = \theta_{b\text{-}t}$ $\qquad$ $\Theta_1 = \theta_{l\text{-}t}\,,\ \Theta_2 = \theta_{q\text{-}t}$

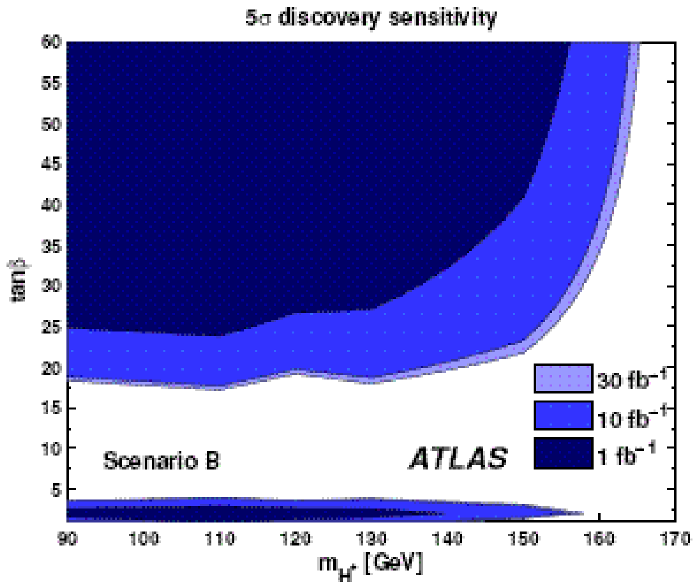
Top beyond SM (Susy)

Appears in $H^{\pm}$ searches (H± boson in MSSM, non-minimal Higgs models):

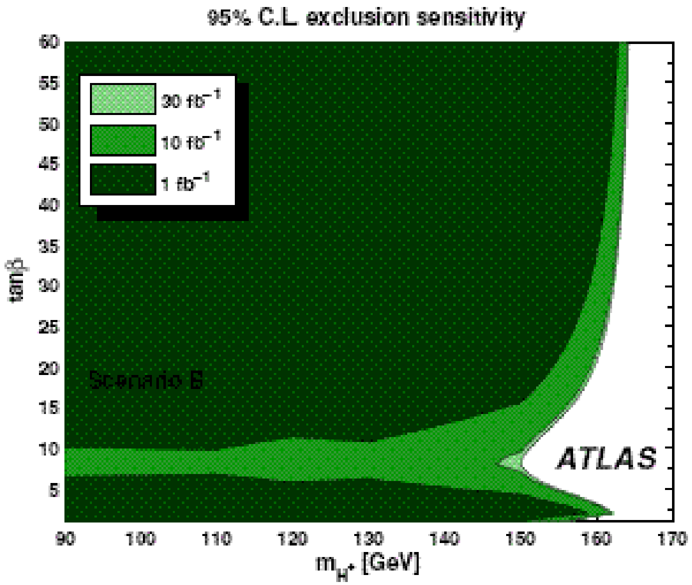
In MSSM: if $M_H<M_{top}$: t-> $H^{\pm}b$, $H^{\pm}$ ->τν (dominant decay) => signature = (Hb)(Wb)

For example (τ->had.)νWbb decays that can be directly searched (or indirectly (decrease of the number of SM tt decays)):

High P_T isolated leptons vetoed



5σ significance discovery contour

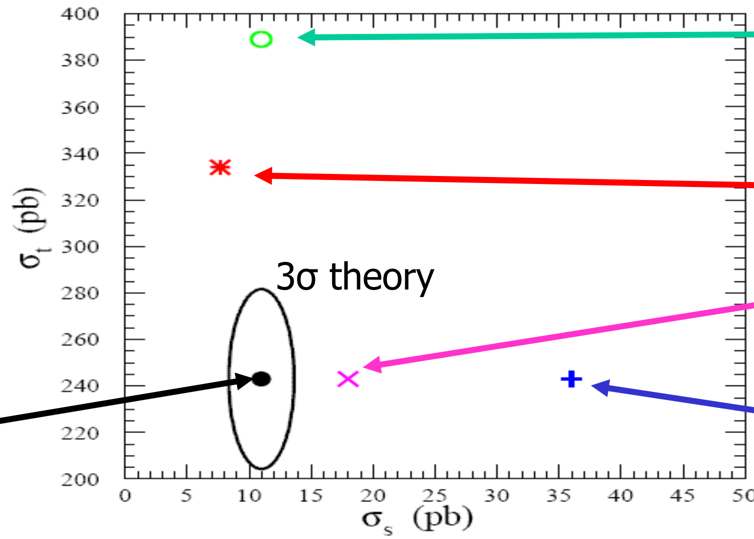


95% CL exclusion contour

if $M_H>M_{top}$: gb -> $tH^{\pm}$, $H^{\pm}$ ->tb (dominant decay)

Top beyond SM (single top & heavy top)

hep-ph/0007298 (2000)



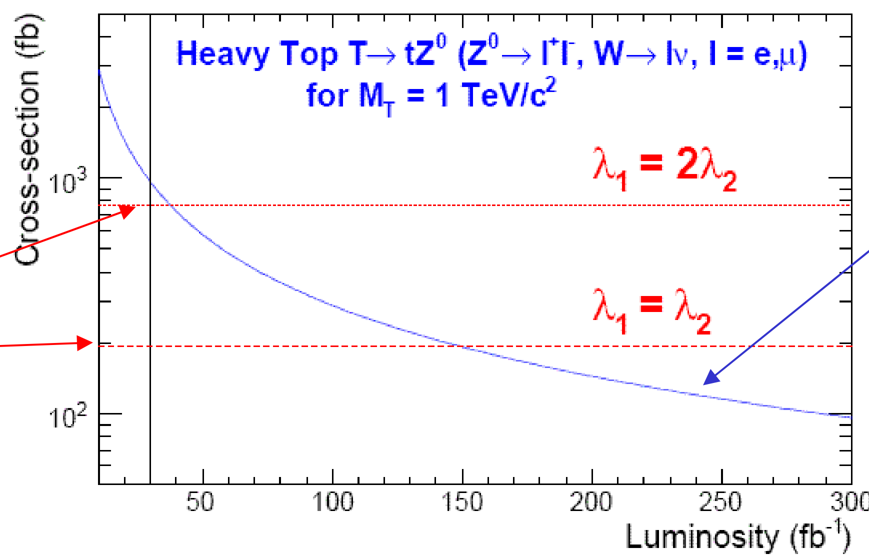
LHC SM

FCNC Z-t-c

4^{th} quark $V_{ts} = 0.55$

Top-flavor $M_{Z'} = 1$ TeV

Top-pion $M_{\pi} = 450$GeV



Xsection values for 2 cases, λ=Yukawa couplings/gauge groups

CMS, minimum Xsection required for a 5σ discovery