3rd Top Workshop @ Grenoble:
From the Tevatron to ATLAS

Strategies for top mass measurement with the early data in ATLAS

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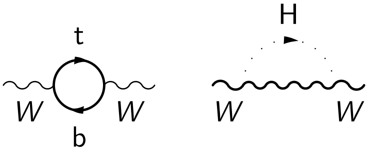
Why do we measure the top quark mass?

The top quark is very special in the Standard Model:

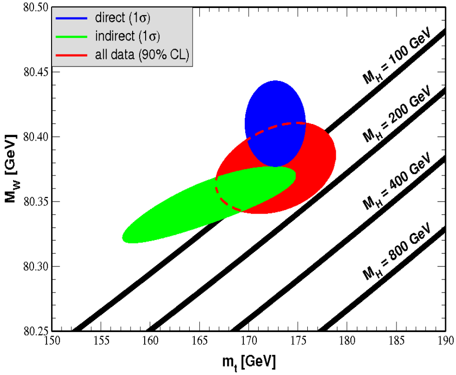
- $M_{top} \backsim \frac{v}{\sqrt{2}}$ (Higgs vev) $\Longrightarrow$ Yukawa coupling $\backsim 1$

  it is the only fermion near the EW scale

- M_{top} constrains the SM Higgs boson mass via W boson radiative corrections:



$\Longrightarrow$ Correction $\propto \log M_H,\ M_{top}^2$



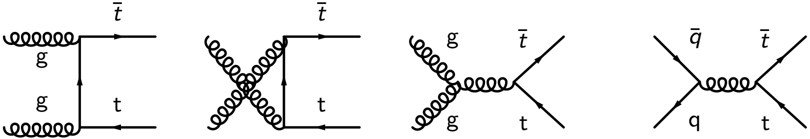
Why a new measurement with ATLAS

The last world average mass of the top quark is (Tevatron, july 08 with 2.8 fb^{-1}):

$$M_{top} = 172.4 \pm 0.7\ (\text{stat.}) \pm 1\ (\text{syst.})\ \text{GeV}$$

$\Longrightarrow$ It will be a challenge for the LHC to achieve a better precision!

But the LHC will be a top factory with the main production modes:



gg $\rightarrow$ t $\bar{t}$ (90 %)

q $\bar{q}$ $\rightarrow$ t $\bar{t}$ (10 %)

$$\sigma_{t\bar{t}}^{LHC} = 833 \pm 100 \text{ pb (NLO + NLL) } (\backsim 10 \text{ Hz})$$

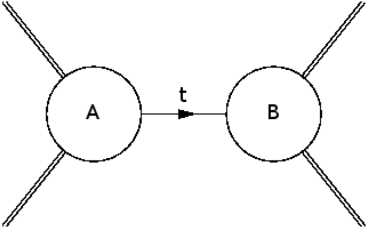
$\Longrightarrow \simeq$ 80 000 000 $t\bar{t}$ per year (100 days) at high luminosity (10^{34} cm^{-2} s^{-1})

By comparaison: $\sigma_{t\bar{t}}^{Tevatron} = 7$ pb ($\simeq 0.1$ Hz)

The statistical uncertainty will be quickly negligible in ATLAS, the main error on M_{top} will be the systematic uncertainty

Top quark pole mass

At the Tevatron, the measured mass is the input parameter of the Monte Carlo which is the pole mass.



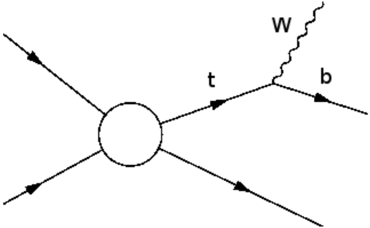
Consider a scattering process with a quark propagator connecting 2 free particles :
$\Rrightarrow$ the pole in the quark propagator would correspond to the pole mass of a stable quark.

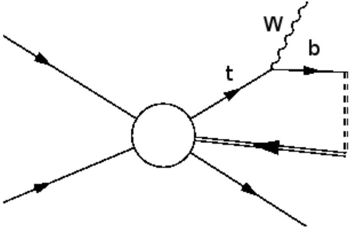
Because of confinement colour hypothesis, only colour singlet states ("colourless") exist as free particle
$\Longrightarrow$ the asymptotic states have to be color singlets.
But the quark carries colour charge $\Longrightarrow$ it is a color triplet.

The color is not conserved in such a process! There cannot be a pole in the amplitude corresponding to the pole quark mass and there is a theoretical uncertainty of the order of $\frac{\Lambda_{QCD}}{3}$ due to non-perturbative effects.

Colour reconnection

With the high statistics available in ATLAS, we will be able to measure the invariant mass of the products of the top quark decay which is also the pole mass.





The top quark decays almost exclusively into $t \rightarrow Wb$.
Experimentally, the b-quark is reconstructed as a jet of colorless hadrons.

$\Longrightarrow$ at least one of the reconstructed hadrons does not arise from the $t\bar{t}$ decay.

There is an irreducible uncertainty in the Wb invariant mass of the order of Λ_{QCD}.

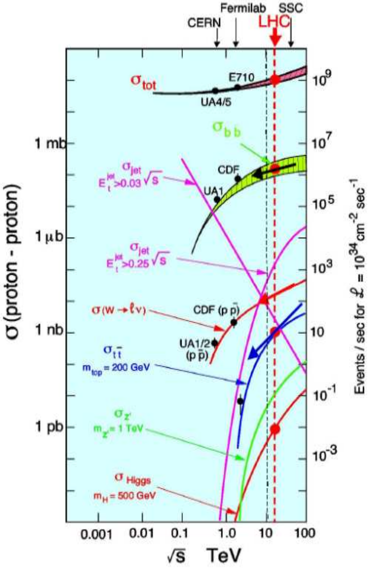
What we can expect in 2009 with a run at 10 TeV

Process	10 TeV σ_{NNLO}	14 TeV σ_{NNLO}
$t\bar{t}$ ($M_{top} = 172.5$ GeV)	401.6 pb	883.9 pb
W + jets	665 pb	948 pb

Signal reduced by ∽ 50 %
Background reduced by ∽ 33 %
$\Longrightarrow$ We will still have a good S/B ratio

As a general rule, the background scales less than signal:

- SM Higgs (200 GeV) reduced to ∽ 50 %
- Z' (2 TeV) reduced to ∽ 30 %
- Sensitivity to new Physics above 4 TeV reduced by one order of magnitude



Fully hadronic channel

No analysis foreseen with early data

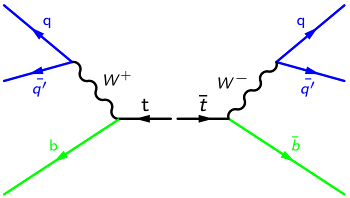
Advantages:

- High statistics
- Event fully reconstructed
- In-situ rescaling of light jets using the W boson mass

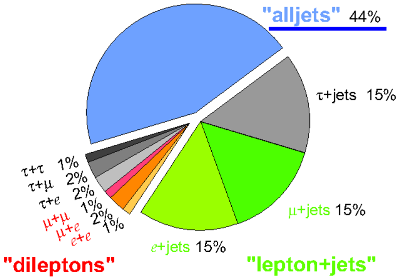
Disadvantages:

- Huge physical background
- Huge combinatorial background

Main background: QCD



Top Pair Branching Fractions



Dileptons channel

2 analyses planned with early data:

1. Matrix elements method
2. Templates method with Neutrino Weighting Algorithm

Advantages:

- Clean signature
  $\Longrightarrow$ low background
- Low combinatorics
- b-tagging less mandatory

Disadvantages:

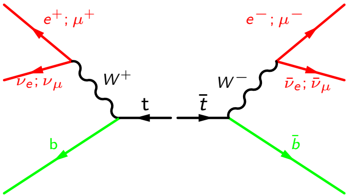
- 2 ν escape

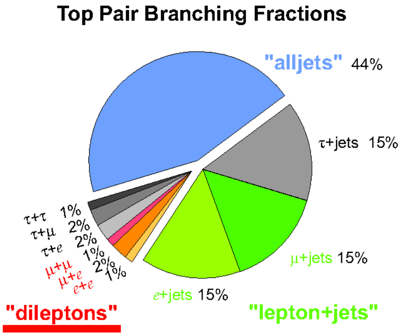
$\Longrightarrow$ kinematically underconstrained

- Low statistics

Main backgrounds:

di-bosons, $t\bar{t}$ lepton+jets





Semi-leptonic channel

Most promising analysis with early data

The golden channel

Advantages:

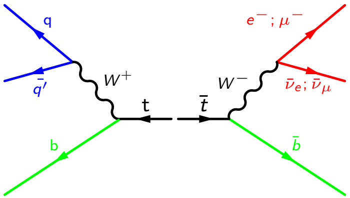
- 1 lepton
  $\Longrightarrow$ good rejection of QCD background
- BR = 30 %
  $\Longrightarrow$ good statistics
- *In-situ* rescaling of light jets using the W boson mass M_W^{PDG}

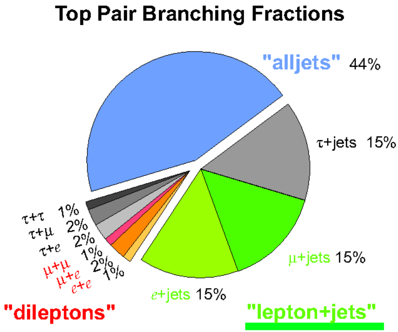
Disadvantages:

- 1 ν escapes
  $\Longrightarrow$ 2 solutions for P_z^ν
- b-tagging required to decrease the combinatorics

Main backgrounds:

single top, $t\bar{t}$ dileptons, W+jets





Top mass measurement in the lepton (e,μ) + jets channel

analysis detailed in the ATLAS Collaboration note:
Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics, CERN-OPEN-2008-020, Geneva, 2008, to appear.

All the results presented here are obtained with Monte Carlo sample at 14 TeV and scaled at 1 fb^{-1}

Event selection

Objective: Maximize the S/B ratio which is very unfavorable before any selection

Standard selection:
(all particules have $|\eta| \leqslant 2.5$)

1. $\not{E}_T \geqslant 20$ GeV
   $\Longrightarrow$ rejects QCD background
2. $= 1$ isolated ℓ (e,μ), $p_T \geqslant 20$ GeV
   $\Longrightarrow$ rejects $t\bar{t}$ fully hadronic

   Jets with cone 04 algorithm:
3. $= 2$ b-tagged jets, $p_T \geqslant 40$ GeV
   $\Longrightarrow$ rejects W,Z + jets
4. $\geqslant 2$ light jets, $p_T \geqslant 40$ GeV
   $\Longrightarrow$ rejects $t\bar{t}$ dileptons

Number of events before and after the selection cuts ($\mathcal{L}$ = 1 fb^{-1}).

Process	Before selection	After selection
$t\bar{t}$ ℓ(e,μ)+jets	313 200	15 780
$t\bar{t}$ di-leptons	52 500	720
$t\bar{t}$ all-jets	466 480	160
W background	9.5×10^5	200
single top, t channel	81 500	330
single top, Wt channel	9 590	170
single top, s channel	720	5
Z + *partons*	$1.2\ 10^6$	20
WW, WZ, ZZ	29 700	2

After the kinematic cuts: $S/B \simeq 10$

Hadronic W mass reconstruction 1: χ^2 minimization

Strategy:

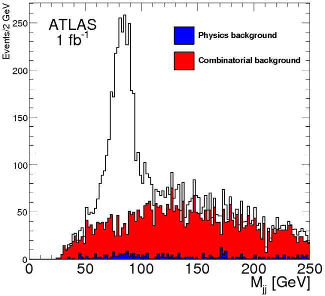
1. Select the W candidate within a mass window of $\pm$ 3 $\sigma_{M_{jj}}$ (30 GeV) around the peak of the dijets mass distribution (82 GeV)
2. Perform a χ^2 minimization for each remaining light jets pair to determine the rescaling factors α_{E_j}:

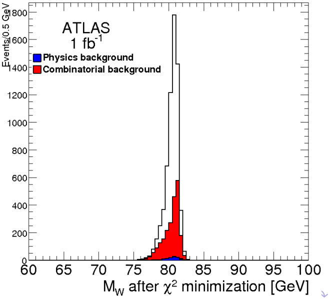
$$\chi^2 = \frac{(M_{\mathrm{jj}}(\alpha_{E_{\mathrm{j}1}}, \alpha_{E_{\mathrm{j}2}}) - M_{\mathrm{W}}^{\mathrm{PDG}})^2}{(\Gamma_{\mathrm{W}}^{\mathrm{PDG}})^2} + \frac{(E_{\mathrm{j}1}(1 - \alpha_{E_{\mathrm{j}1}}))^2}{\sigma^2_{E_{\mathrm{j}1}}} + \frac{(E_{\mathrm{j}2}(1 - \alpha_{E_{\mathrm{j}2}}))^2}{\sigma^2_{E_{\mathrm{j}2}}}$$

3. For each event, the pair with the smallest χ^2 is kept as the hadronic W boson candidate
4. Only events with $|M_{jj} - M_{\mathrm{W}}^{\mathrm{PDG}}| \leqslant 2\Gamma_{\mathrm{W}}^{\mathrm{PDG}}$ are kept

Advantage of this method:

Perform an event per event *in-situ rescaling* of the light jet energy scale in order to reduce the systematic uncertainty due to the JES





Top quark reconstruction (with χ^2 minimization)

To reconstruct the hadronic top quark, we have to select among the 2 *b*-tagged jets the right one to associate to the *W* boson.

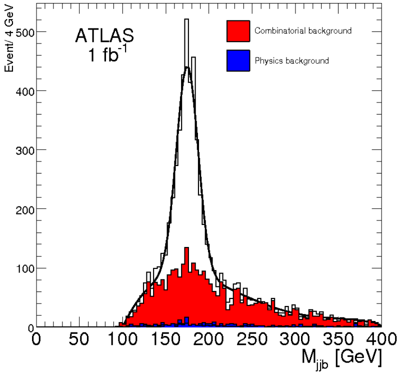
Strategy: Choose the *b*-tagged jet closest to the hadronic *W* boson.

For a generated top quark mass of 175 GeV and an integrated luminosity $\mathcal{L} = 1\ \mathrm{fb}^{-1}$ at 14 TeV:
6946 signal events are reconstructed.

Efficiency of the reconstruction = 2.22 ± 0.03% (with respect to $\ell(e,\mu)$+jets events)

- ▲ $M_{\rm top} = 175.0 \pm 0.2$ GeV
- ▲ $\sigma_{\rm top} = 11.6 \pm 0.2$ GeV

$$\frac{\chi^2_{fit}}{dof} = \frac{137}{67}$$

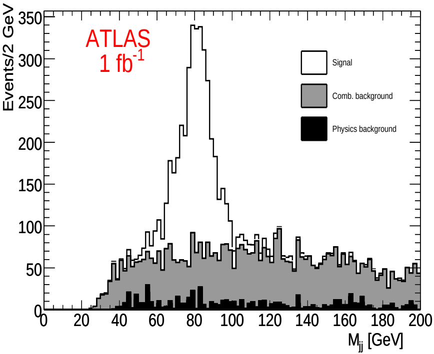


The hadronic top quark mass

Hadronic W mass reconstruction 2: Geometric method

Strategy:

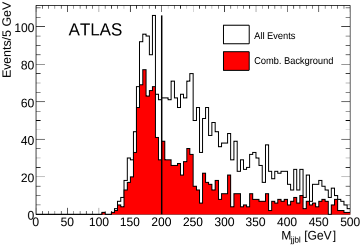
1. Choose the light jet pair with the smallest angular distance ($\Delta R = \sqrt{\Delta\Phi^2 + \Delta\eta^2}$) as the hadronic W boson candidate.
2. Only candidates within a mass window of $\pm\ 2\ \sigma_{M_{jj}}$ ($20\ \mathrm{GeV}$) around the peak of the dijets mass distribution



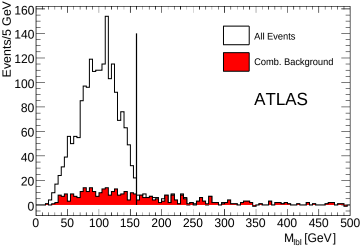
Additional cuts 1 (for high integrated luminosity)

With a large amount of $t\bar{t}$ events available, we can apply additional cuts in order to increase the final top purity:

C1 Invariant mass of the hadronic W and the leptonic b-tagged jet $\geqslant 200\ \mathrm{GeV}$



C2 Invariant mass of the lepton and the leptonic b-tagged jet $\leqslant 160\ \mathrm{GeV}$



Additional cuts 2

If we define the new variables
(* means the top rest frame)

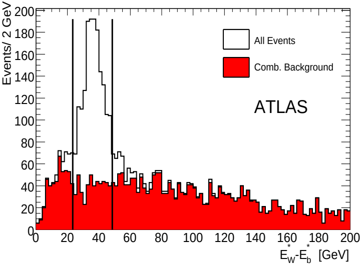
$$X_1 = E^*_{\mathrm{W}} - E^*_{\mathrm{b}} = \frac{M^2_{\mathrm{W}} - M^2_{\mathrm{b}}}{M_{\mathrm{top}}},$$

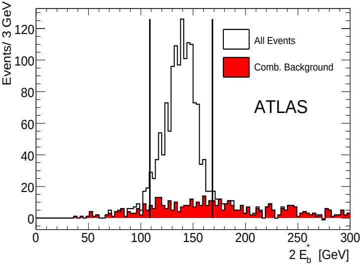
$$X_2 = 2E^*_{\mathrm{b}} = \frac{M^2_{\mathrm{top}} - M^2_{\mathrm{W}} + M^2_{\mathrm{b}}}{M_{\mathrm{top}}}.$$

We can add 2 additional cuts:
(μ is the peak and σ the width of the distributions)

C3 $|X_1 - \mu_1| < 1.5\,\sigma_1$

C4 $|X_2 - \mu_2| < 2\,\sigma_2$





Top quark reconstruction (with geometric method)

Strategy:

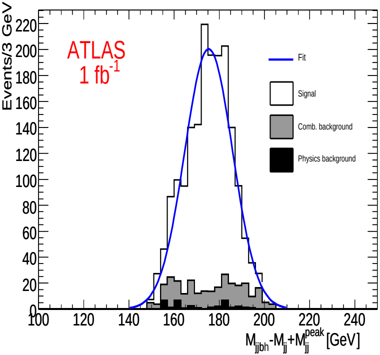
- Choose the b-tagged jet closest to the hadronic W boson.
- Compute the top quark mass as $M_{\rm top} = M_{\rm jjb} - M_{\rm jj} + M_{\rm W}^{\rm peak}$ where $M_{\rm W}^{\rm peak}$ is the peak value of dijets mass distribution

For a generated top quark mass of 175 GeV and for $\mathcal{L} = 1\ \text{fb}^{-1}$ at 14 TeV:
3949 signal events are reconstructed.
Efficiency of the reconstruction $= 1.26 \pm 0.03\%$

After C1+C2+C3+C4
1785 signal events are conserved.
Efficiency of the reconstruction $= 0.57 \pm 0.05\%$
(with respect to ℓ(e,μ)+jets events)

▲ $M_{\rm top} = 175.3 \pm 0.3$ GeV
▲ $\sigma_{\rm top} = 10.6 \pm 0.2$ GeV

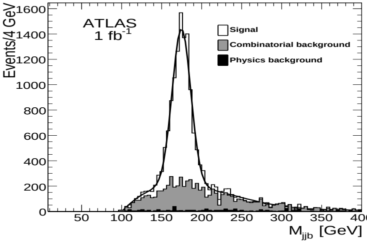
$$\frac{\chi^2_{fit}}{dof} = \frac{43}{16}$$



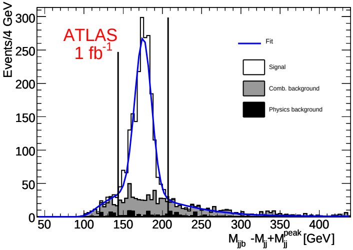
M_{top} *after C1+C2+C4+C4*

Impact of the additional cuts

cuts applied	efficiency (%)	efficiency loss	top purity gain
χ^2 minimization method	2.22 ± 0.03		
+ cuts C1 + C2	1.25 ± 0.04	1.76 ± 0.08	1.45 ± 0.05
+ cuts C1 + C2 + C3 + C4	0.91 ± 0.05	2.44 ± 0.17	1.92 ± 0.06
geometric method	1.26 ± 0.03		
+ cuts C1 + C2	0.85 ± 0.03	1.48 ± 0.09	1.23 ± 0.04
+ cuts C1 + C2 + C3 + C4	0.57 ± 0.05	2.21 ± 0.25	1.61 ± 0.03



χ^2 minimization method after C1 and C2:
$m_{\rm top} = 174.8 \pm 0.3$ *GeV and*
$\sigma_{top} = 11.7 \pm 0.4$ *GeV ($\chi^2/dof = 82/67$)*

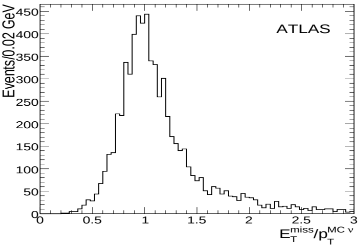


Geometric method after C1 and C2:
$m_{\rm top} = 175.4 \pm 0.4$ *GeV and*
$\sigma_{top} = 10.6 \pm 0.4$ *GeV ($\chi^2/dof = 109/73$)*

Leptonic W boson reconstruction 1

Since the neutrino escapes from the detector without having been detected, we can not reconstruct the leptonic W boson as the hadronic one.

Hypothesis: The missing transverse energy $\not\!\!E_T$ is an estimator of the neutrino transverse momentum P_T^ν.



Ratio of $\not\!\!E_T$ to the generated neutrino transverse momentum

It is only an approximation since there can be other soft neutrinos arising from the leptonic b quark decay in the $t\bar{t}$ final state.

$\Longrightarrow$ P_T^ν is underestimated by more than 2%

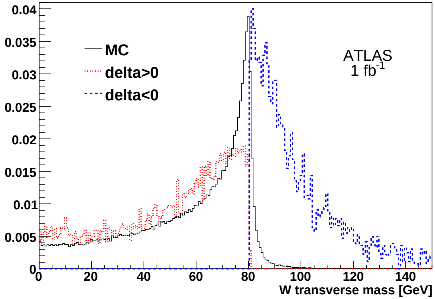
Leptonic W boson reconstruction 2

Since P_z^ν isn't measured in the detector, we have to calculate it solving the equation $M_W^{PDG} = M_{l\nu}$ with the assumption $E_T^{Miss} = P_T^\nu$.
We obtain the quadratic equation $aP_z^{\nu\,2} + bP_z^\nu + c = 0$ with:

$$a = E_l^2 - P_z^{l\,2}$$

$$b = -2P_z^l\left(\frac{M_W^2 - M_{lept}^2}{2} + P_x^l.P_x^\nu + P_y^l.P_y^\nu\right)$$

$$c = E_l^2.P_T^{\nu\,2} - \left(\frac{M_W^2 - M_{lept}^2}{2} + P_x^l.P_x^\nu + P_y^l.P_y^\nu\right)^2$$



The discriminant is $\Delta = b^2 - 4ac$.

Transverse mass of the W boson for:

- $\Delta \geq 0$
- $\Delta < 0$

Leptonic W boson reconstruction 3

Case 1: $\Delta \geq 0$ (70% of the events) we have 2 solutions for P_z^ν

Case 2: $\Delta < 0$ (30%) due to $\not{E}_T$ mismeasurement.
$\Longrightarrow$ To recover these events, we decrease P_T^ν by step of 0.001 until we obtain $\Delta \geq 0$ with the limit condition $|P_{T\,after}^\nu - EtMiss| < \sigma_{E_T^{Miss}}$

$\Longrightarrow$ 13 % of the events (that represent 40% of those with $\Delta < 0$) are recovered and lead to a b purity identical to the case $\Delta \geq 0$.

we can now perform a kinematic fit to take into account all the kinematics of the event and reduce the systematics:

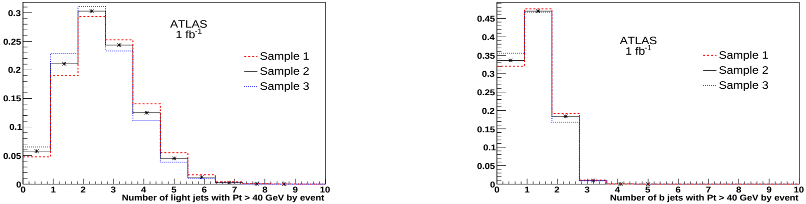
$$\chi^2 = \sum_{4jets+lepton} \left(\frac{E^{mes} - E^{fit}}{\sigma_E}\right)^2 + \left(\frac{M_{jj} - M_W^{PDG}}{\Gamma_W^{PDG}}\right)^2 + \left(\frac{M_{l\nu} - M_W^{PDG}}{\Gamma_W^{PDG}}\right)^2 + \left(\frac{M_{jjb_{had}} - M_{top}^{fit}}{\sigma_{top_{had}}}\right)^2 + \left(\frac{M_{l\nu b_{lept}} - M_{top}^{fit}}{\sigma_{top_{lept}}}\right)^2$$

For each event, we select simultaneously the jets assignement and the P_z^ν solution which give the lowest χ^2 value.

Initial and final state radiation (ISR and FSR)

Several samples have been simulated for this study (AcerMC $t\bar{t}$), corresponding to different sets of parameters:

- Sample 1: $\Lambda(QCD)_{ISR} * 2$, $\Lambda(QCD)_{FSR} * 0.5$: max reco 3 jets invariant mass
- Sample 2: with default ISR and FSR parameters.
- Sample 3: $\Lambda(QCD)_{ISR} * 0.5$, $\Lambda(QCD)_{FSR} * 2$: min reco 3 jets invariant mass



We obtain a systematic uncertainty of 0.3 GeV which corresponds to the maximum shift observed between the sample 2 and the 2 others samples.

The ISR and FSR parameters will be determined with the data in order to decrease the systematic uncertainty.

Systematic uncertainties

The statistical uncertainty will be negligible with a few fb^{-1} of collected data:

$\Longrightarrow$ the total error will quickly be dominated by the systematic uncertainties in 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	$\leq$ 0.1 GeV	$\leq$ 0.1 GeV
Background	negligible	negligible
Method	0.1 to 0.2 GeV	0.1 to 0.2 GeV

- The JES is the main source of systematic uncertainty
- Light JES systematic reduced thanks to the *in-situ* rescaling

A precision of the order of 1 to 3.5 GeV on the top quark mass measurement should be achievable with 1 fb^{-1} of collected data, assuming a jet energy scale uncertainty of 1 to 5 %.

Top quark mass measurement without *b*-tagging

In order to cope with an unefficient *b*-tagging procedure and increase the statistics for a commissioning analysis, the geometric method has been performed with no use of *b*-tagging information.

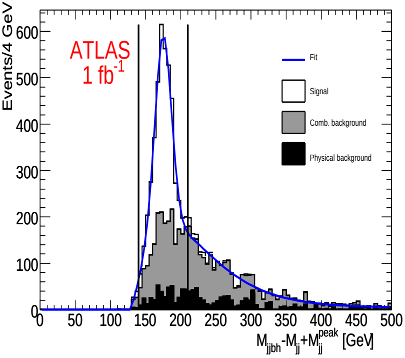
The two cuts applied here are:

1. $|M_W^{\mathrm{rec}} - M_W^{peak}| < 2\,\sigma_{\mathrm{M_W}}$
2. $M(\mathrm{lepton}, b_{\mathrm{lep}}) < 160\ \mathrm{GeV}$

For a generated top quark mass of 175 GeV 3115 signal events are reconstructed. (with $1\mathrm{fb}^{-1}$ at 14 TeV)

Efficiency $= 1.59 \pm 0.03\%$
(with respect to ℓ(e,μ)+jets events)

- ▲ $M_{\mathrm{top}} = 175.0 \pm 0.4\ \mathrm{GeV}$
- ▲ $\sigma_{\mathrm{top}} = 11.7 \pm 0.5\ \mathrm{GeV}$



The hadronic top quark mass

Top as a tool:

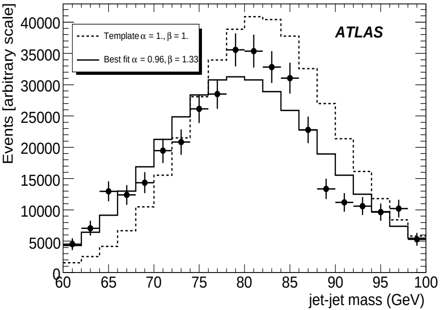
Light jet calibration with M_W

2 methods:

1. Iterative rescaling method
2. Template method

Light jets calibration with M_W: Template method

1. Generate template histograms from $t\bar{t}$ events at generator-level (Pythia) with various energy scales α and relative energy resolution β by smearing the quark energies, the jet angles and adding a correlation between the 2 jet energies.
2. Compute a χ^2 between each template histogram and the data leading to a set of triplets (χ^2, α, β).
3. Find the minimum $\chi^2(\alpha, \beta)$ in the (α, β) plane



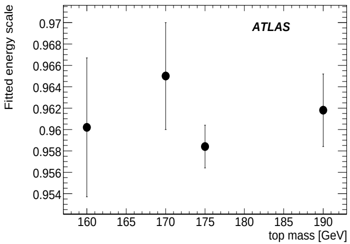
Di-jets invariant mass in "data" (dots) superimposed on the template histogram (α=1,β=1) and the best fit histogram

Light jets calibration with M_W: Template method

- The results are obtained for jets with $P_T \geq 40$ GeV
- Combinatorics doesn't affect α (less than 0.6 %) but degrades β by 30-40 %

	α	β
2 jets, good combinations	0.9693 ± 0.0045	1.145 ± 0.054
2 jets, all combinations	0.9638 ± 0.0049	1.434 ± 0.064
$\geq$ 2 jets, good combinations	0.9696 ± 0.0033	1.089 ± 0.035
$\geq$ 2 jets, all combinations	0.9660 ± 0.0036	1.308 ± 0.041

$\Longrightarrow$ the fitted α are in good agreement with the expected value from MC: $\alpha = 0.961 \pm 0.003$ (due to out of cone energy)



The error on JES is 1 %
with $\mathcal{L} = 1$ fb^{-1} at 14 TEV

Fitted jet energy scale as a function of M_{top}

Conclusion

- The LHC will be a top factory with about 80 000 000 $t\bar{t}$ pairs per year at high luminosity.
- The most promising channel is the lepton (ℓ=e,μ) + jets channel. A precision of the order of 1 to 3.5 GeV on the top quark mass measurement should be achievable with 1 fb^{-1} of collected data, assuming a jet energy scale uncertainty of 1 to 5 %.
- $t\bar{t}$ events will be useful to measure the light jet energy scale. A precision of 1 % on the light JES can be obtained with 1 fb^{-1} of collected data.