Top quark reconstruction in ATLAS

V. Kostyukhin
INFN Genova

on behalf of ATLAS collaboration

General remarks

- Large production cross section for $t\bar{t}$ ~830pb $\Rightarrow$ 8.3 millions top pairs for one year of low luminosity. ~300pb for single top production.
- Statistical error of top mass measurement is <100 *MeV* after one year of ATLAS running. Systematic is ≥1 *GeV*!!!
- For many top studies statistics is not an issue. Systematic is the main problem.

Later I will give a description of ATLAS efforts on top quark reconstruction with emphasis on decreasing the systematical errors and keeping them under control.

Jet reconstruction

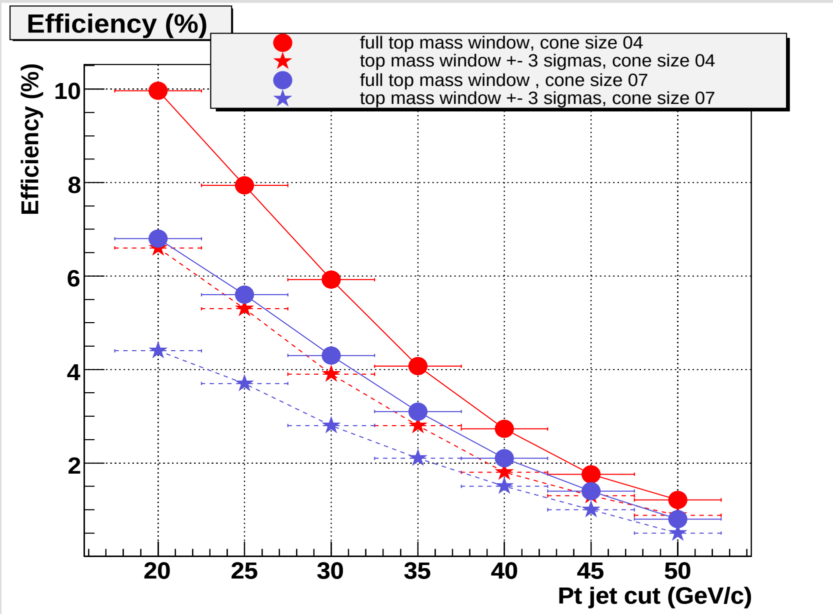
Key issue for any top studies is jet reconstruction

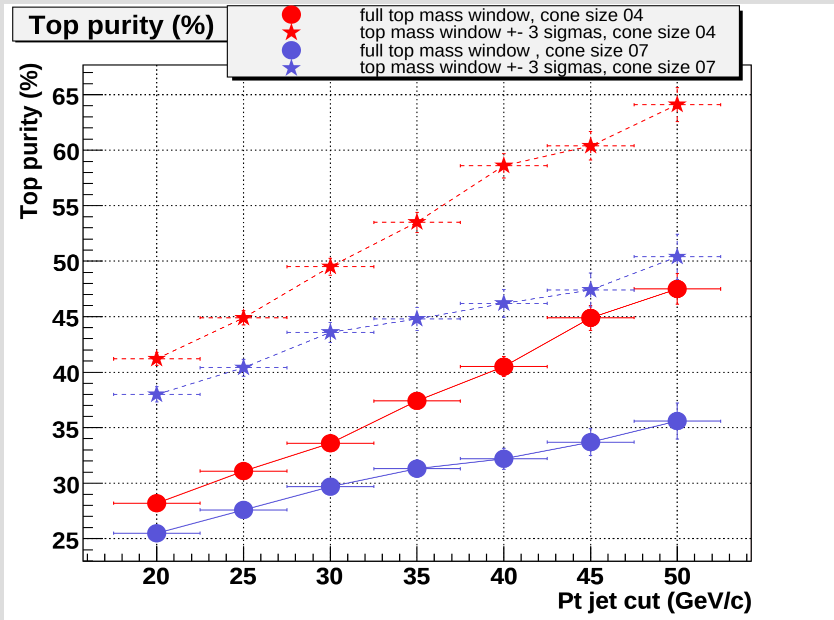
Three methods have been tested for top reconstruction:

1. Cone R=0.4
2. Cone R=0.7
3. $K_\perp$ (d=1)

Scale factor for $K_\perp$ d=1 makes it similar to cone with R=0.7.

Full simulation study of $t\bar{t} \rightarrow jjbbl\nu$

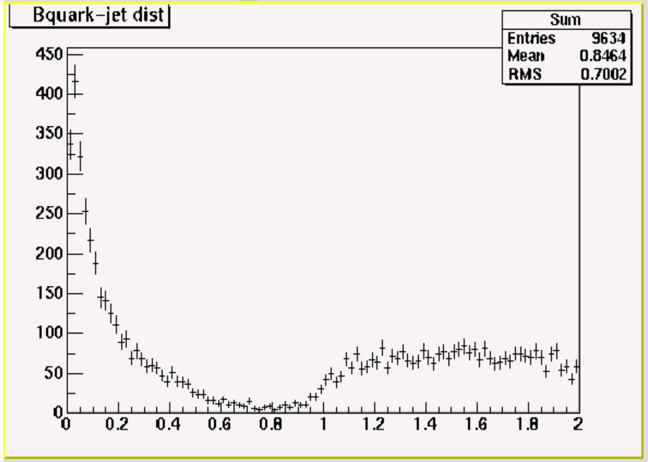




Bquark-jet distance

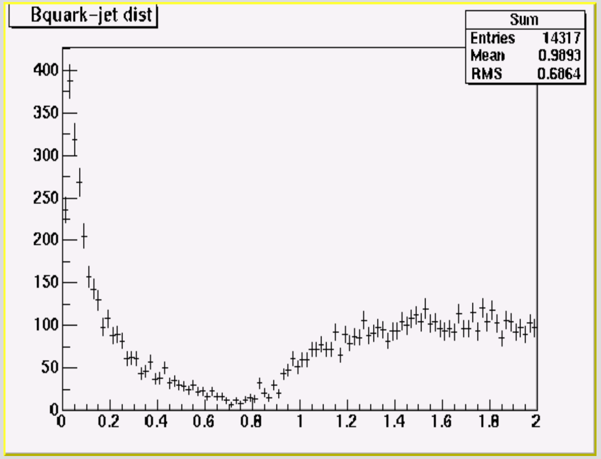
Bquark-jet distance

$K_{\perp}$(d=1)



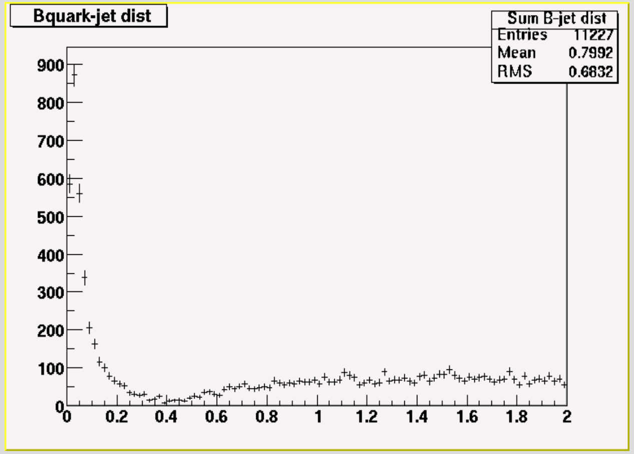
Bquark-jet distance

ConeR=0.7



Bquark-jet distance

ConeR=0.4



Cone R=0.4 provides significantly better angular resolution with respect to b-quark direction!!!

- *B-tagging performance is affected.*
- *Impact on precision of kinematical reconstruction is not clear (t-quark decays to partons)*

For the moment cone R=0.4 algorithm looks the best choice for top-quark reconstruction (in dense jet environment)

$K_{\perp}$ algorithm with d=0.5 might be studied as another option.

Jet calibration

A problem to measure the QCD object (quarks, gluons) properties based on detector response can be divided into 2 parts:

1) **Detector corrections**
(give energy of stable particles hitting detector at given region based on detector signal):
   - Calorimeter cracks, noncompensation, nonuniformity, η-dependence, dead material, noise, longitudinal energy leakage, etc…

2) **Physics corrections**
(give properties of parton which produces the jet):
   - Energy leak outside jet cone, semyleptonic decays, jet masses, pileup, etc.

Step (1) is well understood/developed

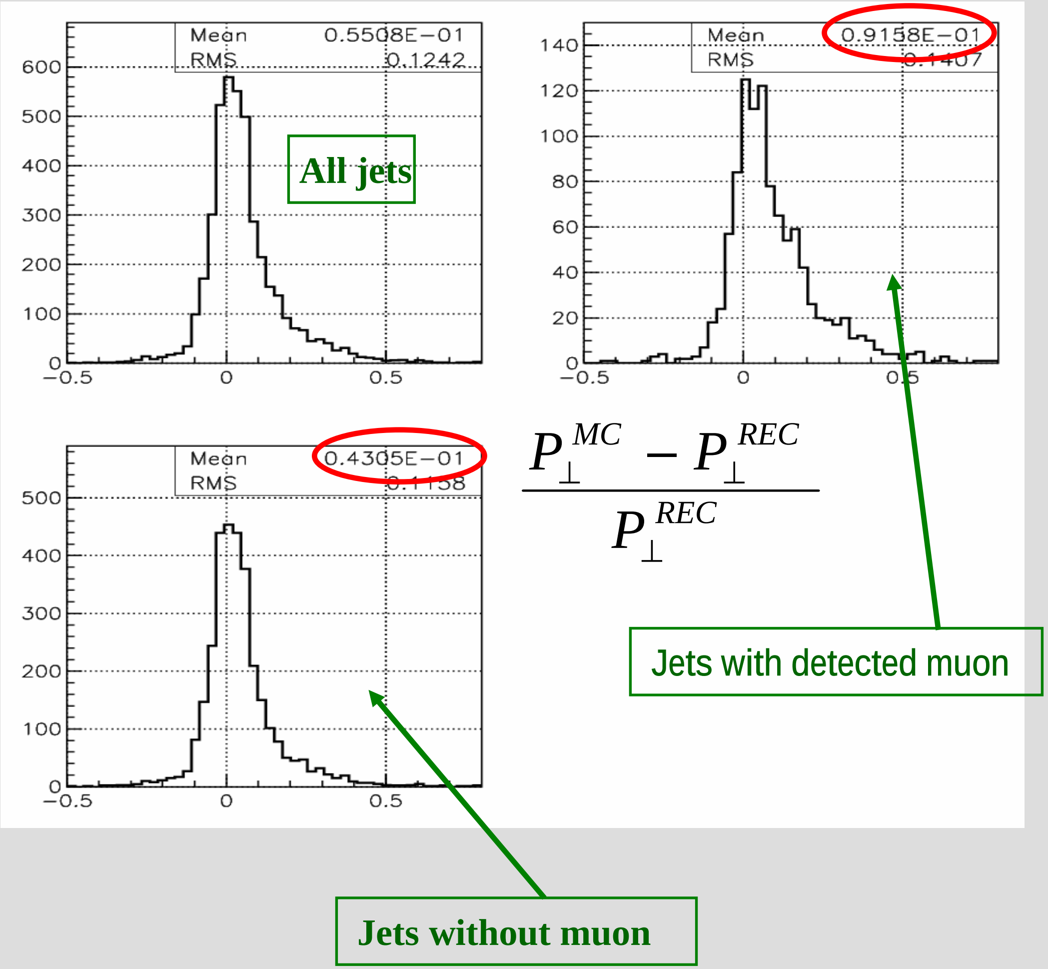
Cell weighting method, testbeam data, cosmics and Cs calibration, detector weighing for amount of material estimations, data based single particle calibrations, etc… (*a lot of information but outside the scope of current presentation*)

Step (2) is still obscure

not clear which corrections must be applied to obtain parton properties from jet properties.

B-jet calibration: lepton in jet

$P_{\perp\,b\text{-}jet}$ >100 *gev* fast simulation



$$\frac{P_\perp^{MC} - P_\perp^{REC}}{P_\perp^{REC}}$$

Leptonic decays of B(D) in jets produce a strong shift of jet energy with a long tail.

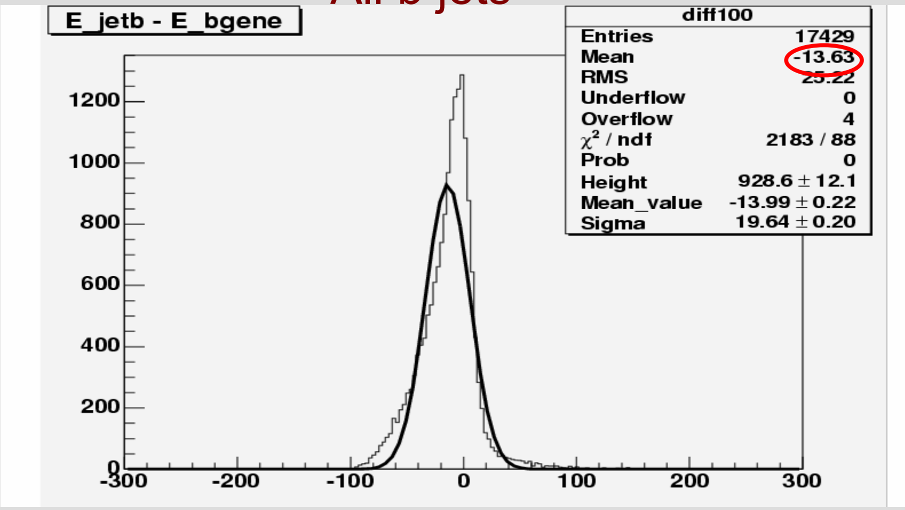
⇓

- *Worsening of b-jet energy resolution (additional to calorimeter performance)*
- *Nongaussian shapes of all kinematical distributions with b-jets*
- *Strong influence on reconstructed top kinematical parameters (χ^2 dependence…)*

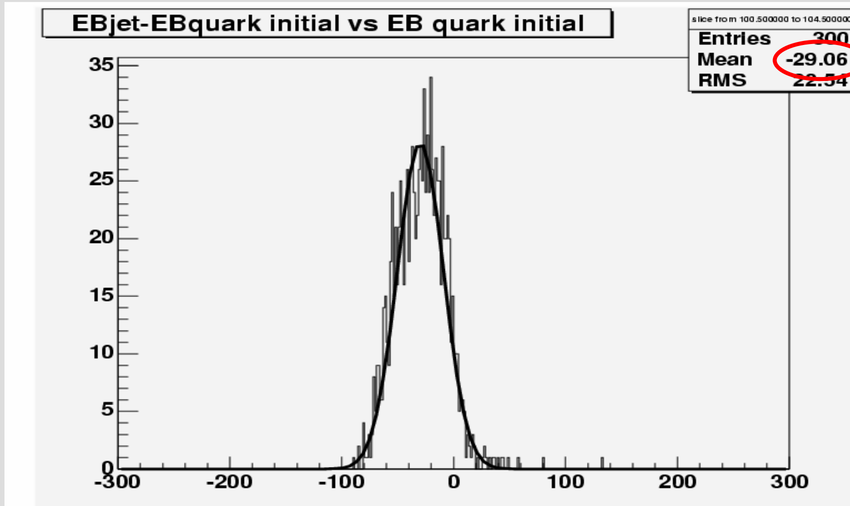
B-jet calibration: lepton in jet

$E_{b\text{-}jet} - E_{initial\ b\text{-}quark}$ *for* $100<E_{b\text{-}quark}<105$, $|\eta| < 0.6$ *full simulation*

All b jets



(b →μ) jets



Taking into account a huge produced number of t-quark it seems that the best solution for precise top physics is to remove from analysis any jet with detected lepton inside!

Up to 50% of the $t\bar{t}$ *statistics might be lost depending on lepton in jet detection efficiency (30% for single top) but systematics will be greatly reduced*

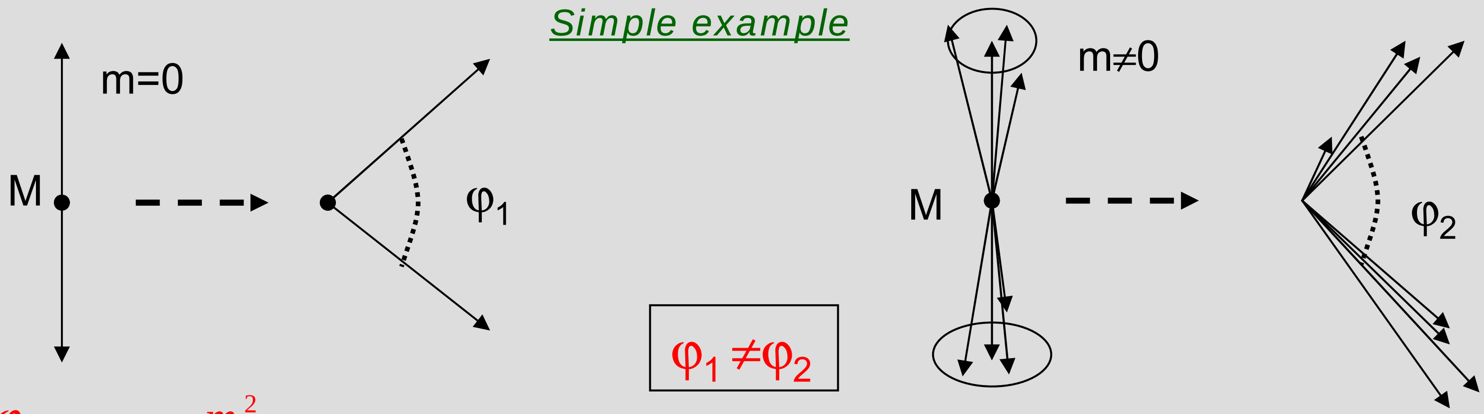
For the processes where statistics is important (e.g. "single top", FCNC) some other solutions can be used if needed (separate calibration, ν energy correction, etc…)

Jet-parton difference

Jet is a ***collection of particles***.

Lorentz boost gives different results for the collection of particles and single massless particle with the same total 3-momentum.

A simplest way to take into account a fact that jet is a collection of particles is to introduce ***jet mass***.



$$\frac{\varphi_2}{\varphi_1} \approx 1 - 2\frac{m^2}{M^2}$$

difference ~2% for m=8 GeV and M=80 GeV (W mass)

Consequences

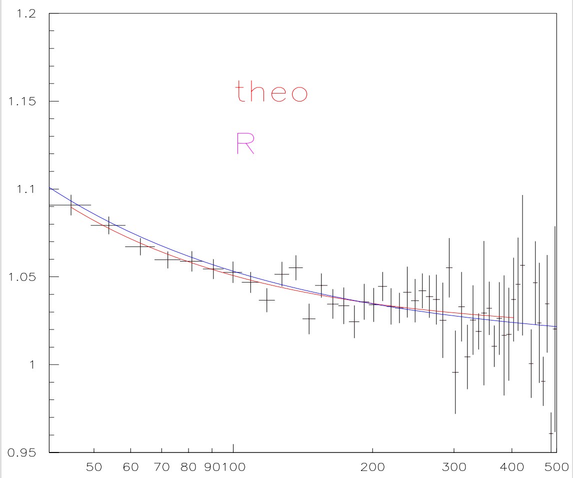
- Jet direction and parton direction never coincide (except for specially chosen reference systems).
- $P_\perp$ based jet calibration (*Z+jets*,…) doesn't coincide with mass based (*W mass*). First one calibrates 3-momentum and second calibrates jet energy.
- Jet-parton differences are at percent level but to get rid of this systematics in kinematical calculations (masses, angles) in a natural way one has to use jet mass .

Light jet calibration

A natural way to calibrate light jet energy for top physics is W peak in $t\bar{t}$ events.

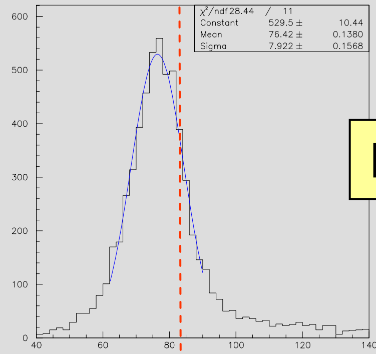
$$R \equiv M_W^{PDG} / M_W = \sqrt{\alpha_1 \alpha_2} \quad \text{with} \quad \alpha_i = \frac{E_i^{part}}{E_i^{jet}}$$

E_{Part} / E

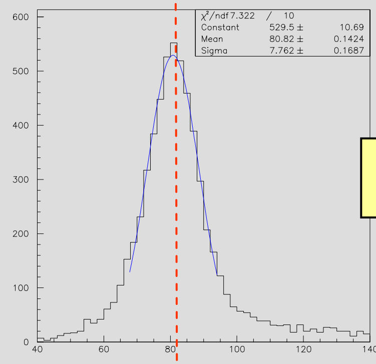


E_{part}

Jet energy (not direction!!!) is scaled based on W mass shift



before

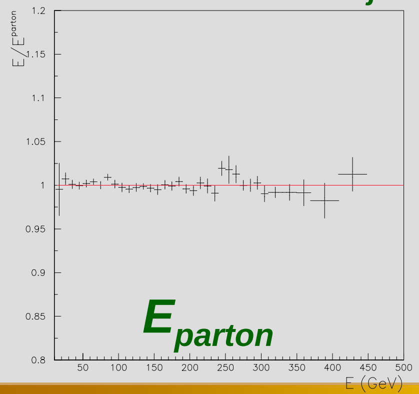


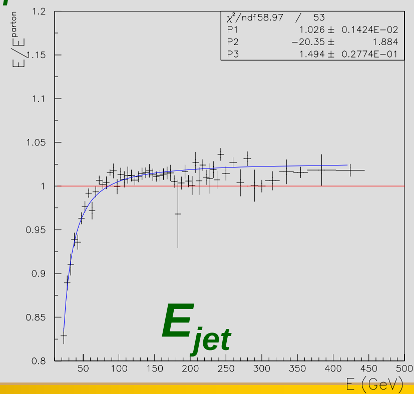
after

M_W

Due to changing jet energy resolution and non-flat jet energy spectrum one can make flat either E_{jet} or E_{parton} dependency BUT NOT BOTH TOGETHER!!!

E_{jet} / E_{parton}





E_{parton} calibration produce a $P_\perp$ dependent top mass estimation.
Better way is to flatten E_{jet} dependance.

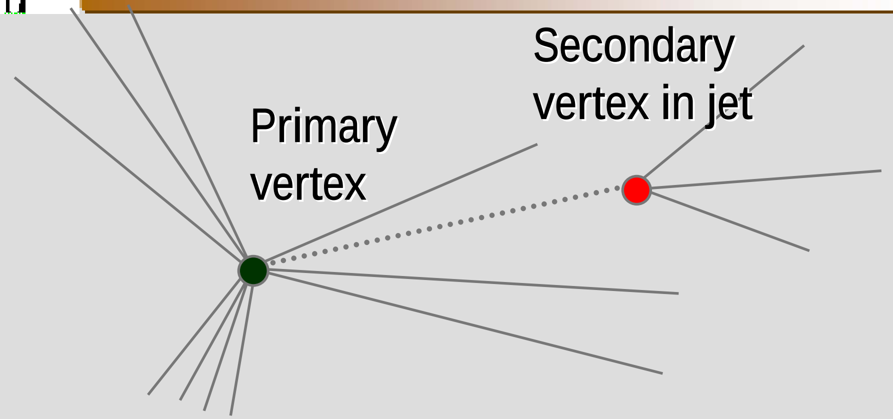
Jet calibration summary

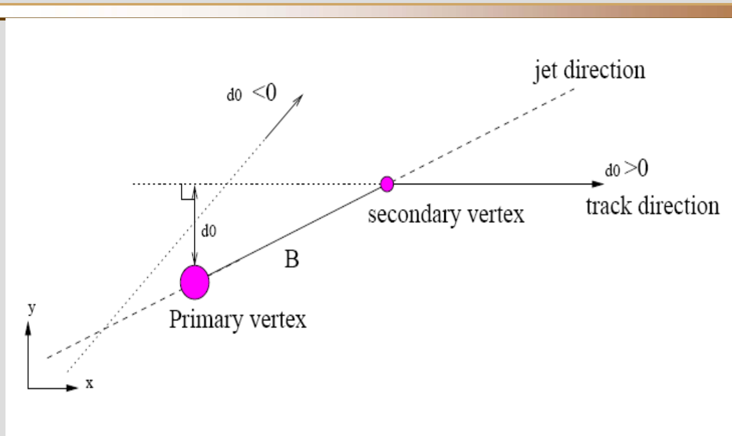
1. ATLAS has a clear strategy for detector based jet energy corrections.
2. Still not clear how to reconstruct parton energy/direction based on jet properties (physics corrections). Not a problem for QCD jet properties themselves, but a big problem if one needs to measure properties of parton system (e.g. top quark mass) with a precision <1%.

Seems important for precise top physics:

1. Special treatment for b-jets with lepton inside (removal or special correction???).
2. Using jet mass for any kinematical reconstruction.
3. Difference between $P_{\perp}$-based and mass-based (W,Z peaks) jet calibrations. It seems that $P_{\perp}$-based jet calibration always gives a shifted estimation of mass.
4. Decoupling of jet energy correction from jet energy resolution.
5. Correction for density of jet environments (leaks between jets).

B-tagging





Several algorithms based on track impact parameters and secondary vertex in jet presence are available in ATLAS.

1. **LogL** $$P_{jet} = \sum_{i=1}^{N_{tr}} \ln \frac{b(S_i)}{u(S_i)}$$
2. **ALEPH style** $$P_{jet} = \Pi \cdot \sum_{j=0}^{N_{tr-1}} \frac{(-\ln \Pi)^j}{j!}, \quad \Pi = \prod_{i=1}^{N_{tr}} P_{tr\,i}$$
3. **Simple counting (under development…)**

Currently most powerful ATLAS algorithm is based on LogL approach and is a combination of different taggers :

$2D_{impact}$ + Z_{impact}+SV+… (leptons in jet, jet shape, etc… in future)

B-tagging

For top reconstruction b-tagging is needed to remove physical (*W+jets, Z+jets*) and combinatorial background . Also it's needed to distinguish between top pair and single top production.

B-tagging performance is usually characterized by 2 numbers:

- ***b-jet tagging efficiency***
- ***Light jet rejection***

These numbers are unambiguous only when there is a ***single jet*** in event, either b-jet or light one!!!

For multijet events like top pair production these numbers strongly depends on ***definitions***:
- what is a maximal allowed distance between jet direction and b-quark for "b-jet",
- what is a minimal allowed distance between jet direction and b-quark for "light quark jet" .

Example of rejections for fully simulated tt events

	R_u (ε_b=50%) (raw)	R_u (ε_b=60%) (raw)	R_u (ε_b=50%) (purified)	R_u (ε_b=60%) (purified)
SV1+IP3D	**505 ± 14**	**184 ± 3**	**773 ± 30**	**240 ± 5**

"Raw" – minimal distance between light jet and b/c quark is 0.3
"Purified" – minimal distance between light jet and b/c quark is 0.8

B-tagging - another example

ttjj-system, final state $l\nu$4j2b (6 jets)

ATLFAST(truth) jets, 3 layers pixel detector, no pileup, ΔR(jet-jet)=0.7

ε_b=50% R_u=320 ε_b=60% R_u=160

+ no b-quark in a cone ΔR=0.6 around light quark jet

ε_b=50% R_u=2500 ε_b=60% R_u=680 **!!!**

Great sensitivity to gluon splitting and occasional coincidence between light jet direction and b-quark nearby

B-tagging performance is strongly dependent on jet density and cuts used for definition of "b" jet and "light" jets. For multijet event there is a big probability that near a "light quark jet" there is a b-quark. This decreases the "light jet rejection" of b-tagging in comparison with "single jet" event.

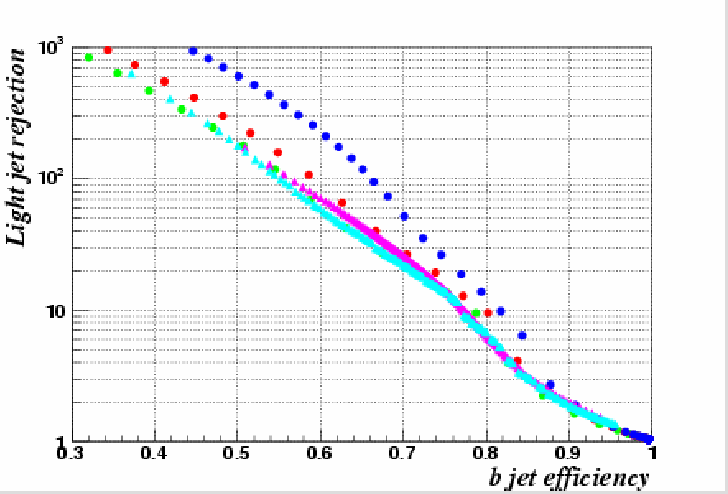
B-tagging efficiency is also affected because the angular accuracy of jet reconstruction depends on jet amount due to jet overlap.

Not a problem for MC but what about data???

It seems that b-tagging performance must be compared with data (calibrated) on well separated jets only (preferably in "single jet" events). Then one should rely on MonteCarlo to propagate this performance to multijet events to be able to estimate the "event selection efficiency" with b-tagging.

B-tagging

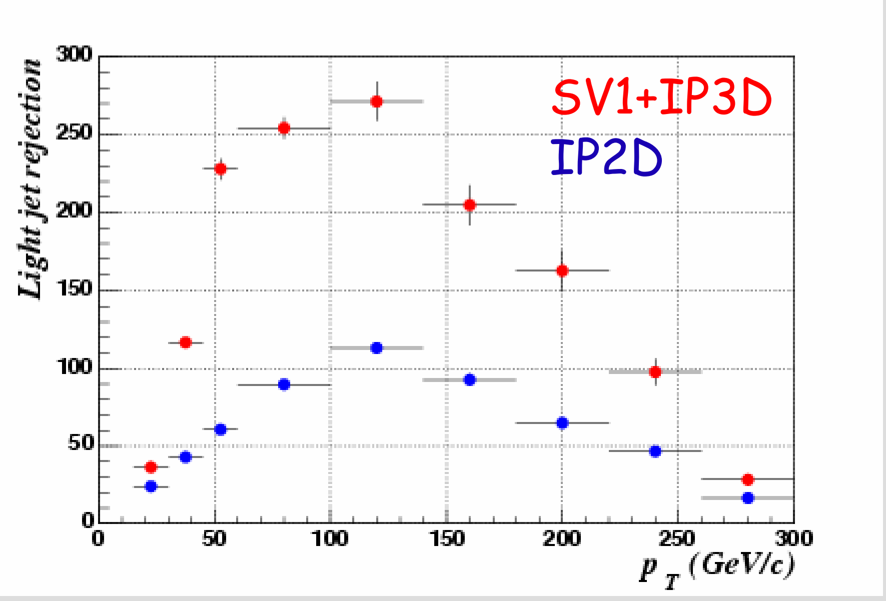
Light jet rejection vs b-tag efficiency for ttH, ttjj events (no purification of light jet)

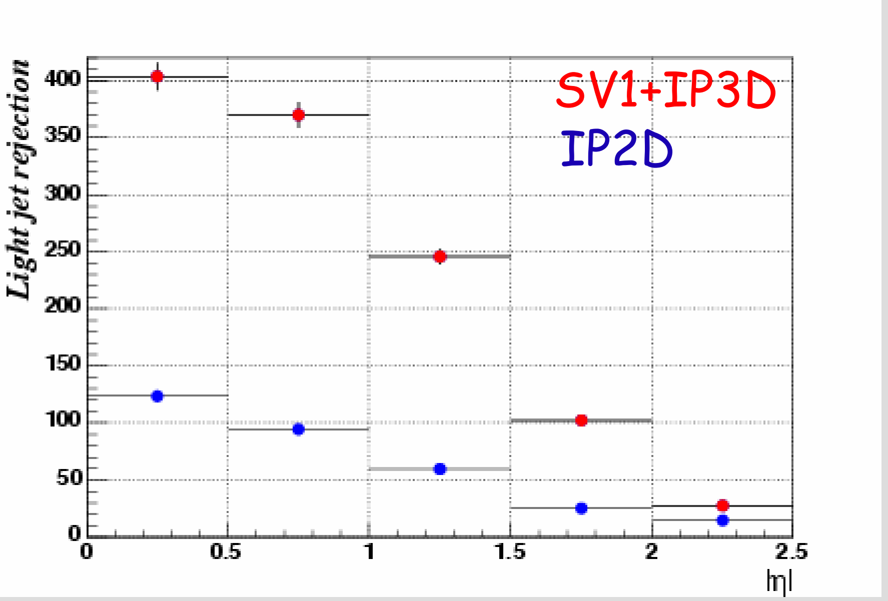


SV1+IP3D
IP3D
IP2D
Lifetime2D
lhSig

SV1+IP3D

R_u (ε_b=50%)	R_u (ε_b=60%)	R_u (ε_b=70%)
610 ± 12	**229 ± 3**	**53**





B-tagging

ATLAS b-tagging is very effective but…

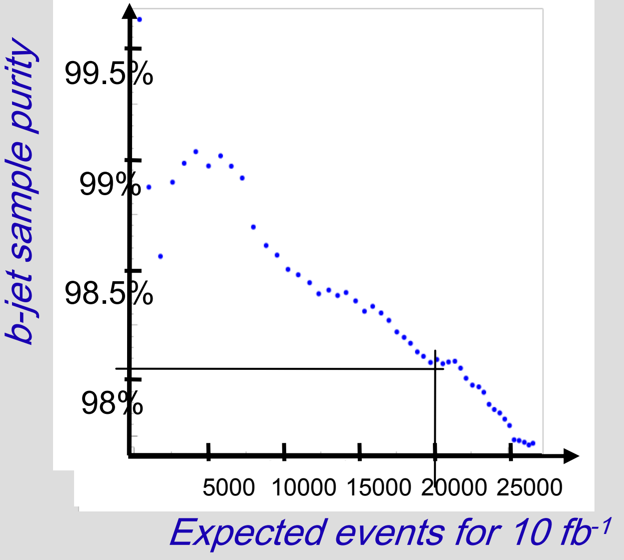
It's very difficult to predict a process (not jet!!!) selection efficiency with b-tagging because it depends on:

1. *Jet density*
2. *Jet $P_\perp$ and η , which are process selection cuts dependent*
3. *Jet algorithm*
4. *Time dependent detector and luminosity conditions*

For the moment ATLAS doesn't have a well established strategy for b-tagging performance calibration on real data and its monitoring with time.

Work just started…

First attempt of b-jet selection from tt→bbjjlν events for b-tagging calibration

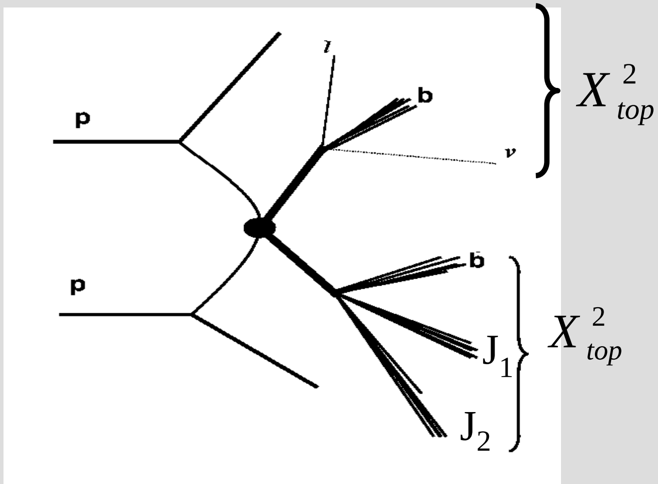


Kinematical constraint fit for tt

Kinematical fit with constraints is able to restore a complete topology of $t\bar{t} \rightarrow bbjjl\nu$ decay.

- Equal t-masses constraint: $(b+J_1+J_2)^2=(b+l+\nu)^2=X^2_{top}$
- W-masses constraints: $(J_1+J_2)^2=M^2_w=const$

  $(l+\nu)^2=M^2_w=const$



$$\begin{cases}(b+l+\nu)^2=M^2_w+2\cdot(b,l+\nu)=X^2_{top}\\ (l+\nu)^2=2\cdot(l,\nu)=M^2_w\end{cases} \Rightarrow \begin{cases}E_b\cdot E_\nu-\vec{p}_b\cdot\vec{p}_\nu=\dfrac{X^2_{top}-M^2_w}{2}-(b,l)\\ E_l\cdot E_\nu-\vec{p}_l\cdot\vec{p}_\nu=\dfrac{M^2_w}{2}\end{cases}$$

$$\Downarrow$$

$$\begin{cases}E_\nu\cdot\left(E_b-|\vec{p}_b|\cdot\cos\varphi_{b\nu}\right)=\dfrac{X^2_{top}-M^2_w}{2}-(b,l)\\ E_\nu\cdot\left(E_l-|\vec{p}_l|\cdot\cos\varphi_{l\nu}\right)=\dfrac{M^2_w}{2}\end{cases}$$

W mass constraint determines angle between lepton and neutrino $\Rightarrow$ ambiguous neutrino direction

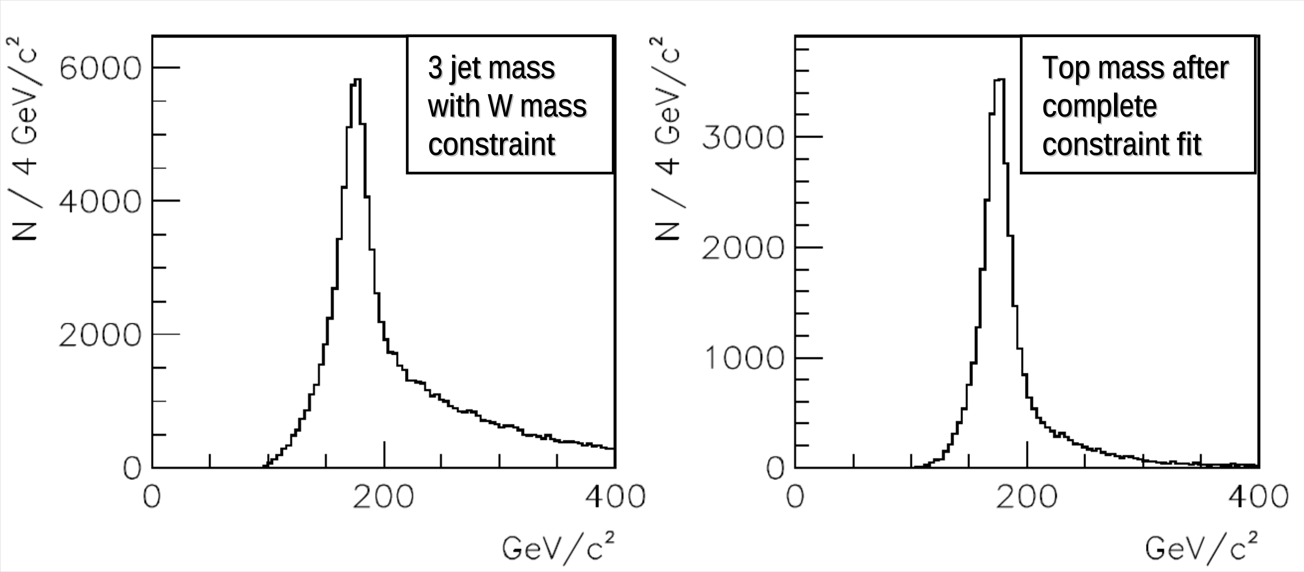
Equal top masses constraint determines second angle between neutrino and b-quark $\Rightarrow$ no ambiguity in neutrino direction

Kinematical constraint fit for tt

Fit variables are jet energies (not directions!!!) and z component of neutrino momentum.

W mass term $\chi^2 = \frac{(M_{jj} - M_W)^2}{\Gamma_W^2}$ **works well for ideal light jet calibration.**

W mass constraint $M_{jj} = M_W$ is more robust and works even for nonprecise light jet calibration!



- Reduce significantly a sensitivity to light jet calibration due to W mass constraint.
- Fit χ^2 is a powerful tool to reject combinatorial and physical background.
- Method is applicable both for "lepton+jets" and "6 jets" channels of $t\bar{t}$ decay.

ATLAS commissioning

- Can we see top signal during ATLAS startup?
- If so – what can be done with it?

“Initial” ATLAS

1) Tracking and muon systems are not well aligned.
2) Hadron calorimeter response is uniform up to 1% level (Cs source calibration and monitor system), but not correctly scaled.
3) LAr electromagnetic calorimeter response is known up to 1-2% precision.
4) Trigger thresholds are increased to reduce rate.

Top quark reconstruction related issues:

1) Jets are reconstructed with good resolution but shifted energy.
2) Leptons (e and μ) are detectable but again with incorrect energy.
3) B-tagging efficiency is significantly reduced if present at all.

Reference is $100pb^{-1}$ (a few days of accelerator work depending on initial luminosity)

"Initial" top-quark

A simplest accessible mode is $t\bar{t} \rightarrow jjbbl\nu$ (~250 *pb* production cross section)

Trigger – isolated lepton (e, μ)

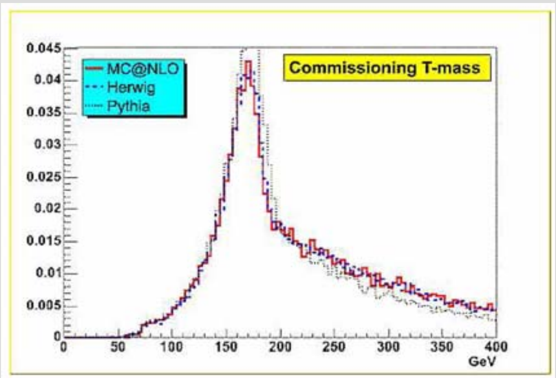
"Standard" ATLAS offline selection for this mode without b-tagging:

Missing energy	E_T > 20 GeV
1 lepton	P_T > 20 GeV
4 jets(R=0.4,|η|<2.5)	P_T > 40 GeV

Selection efficiency = ~4.5% (~11pb)

1100 *ev* for 100 pb^{-1}

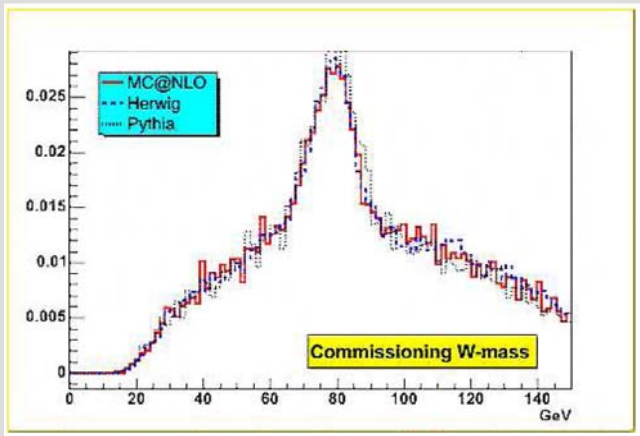
Top reconstruction is extremely simple – one needs to select 3 jets with maximal $\vec{P}_{\perp} = \sum_{i=1}^{3} \vec{P}^{\,i}_{\perp jet}$



Top reconstruction efficiency ~70%.
~750 *ev* in the peak for 100 pb^{-1}.

One may select 2 jets out 3 top quark jets again with highest $\vec{P}_{\perp} = \sum_{i=1}^{2} \vec{P}^{\,i}_{\perp jet}$

This selection gives W peak.

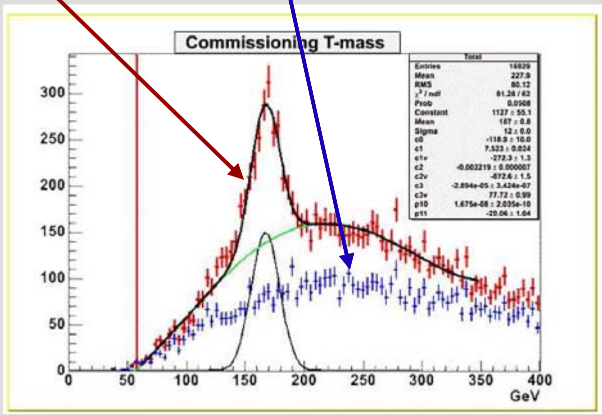


“Initial” top-quark

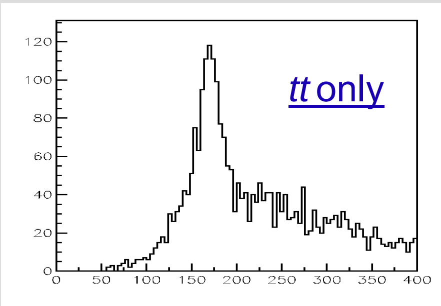
Main background for $t\bar{t} \rightarrow jjbbl\nu$ is *W+jets* process. Other background contributions are small.

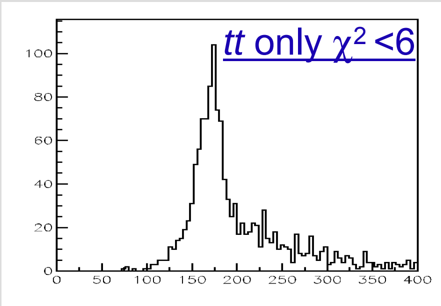
“Initial” top signal is clearly visible even with background after a few days of ATLAS running.

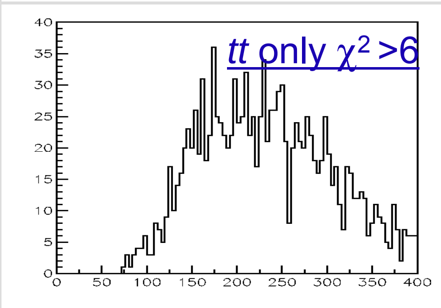
$t\bar{t}$ and *W+jets* for 150 pb^{-1}



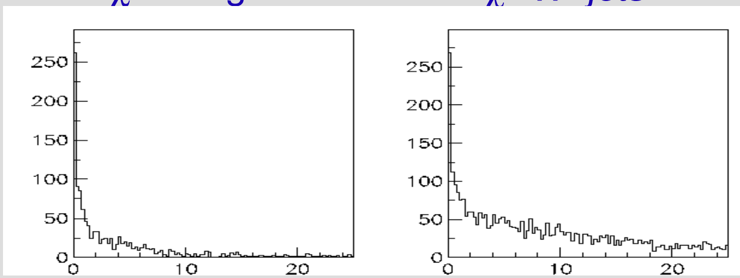
Further combinatorial and physical background reduction can be obtained with constraint fit for top pair:







χ^2 tt signal χ^2 *W+jets*



In a few weeks (trigger conditions dependent) after ATLAS startup a rather clean sample of several thousands top-quarks will be available for physics measurements and detector calibration

Summary

1. LHC is a real "top factory" and for many top related measurements the main issue is systematics.
2. Even with a limited ATLAS performance at startup it's possible to see top quark signal for preliminary physics and calibration studies.
3. The needed level of systematical accuracy requires additional efforts in understanding of basic reconstruction algorithms performance.
4. Some ideas how to decrease the systematical errors in top reconstruction have been presented.
5. Let's hope that very precise top physics measurements will be done at LHC.