B-Tagging in ATLAS: expected performance and and its calibration in data

Giacinto Piacquadio (University of Freiburg)

on behalf of the ATLAS Collaboration

Charged Higgs 2008 Conference

(Uppsala: 15-19 September 2008)

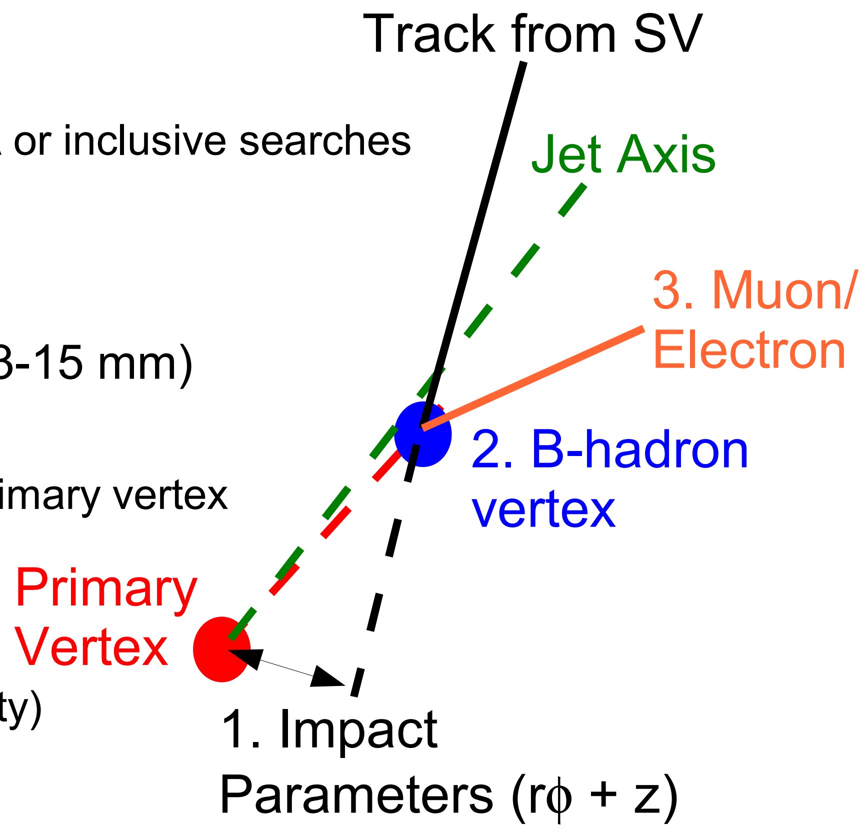
Physikalisches Institut
Albert-Ludwigs-Universität Freiburg

Outline

- Why b-Tagging?
- Review of “spatial” algorithms
- Soft-lepton Taggers
- Misalignment studies
- Calibration on data
- Conclusion
- Outlook

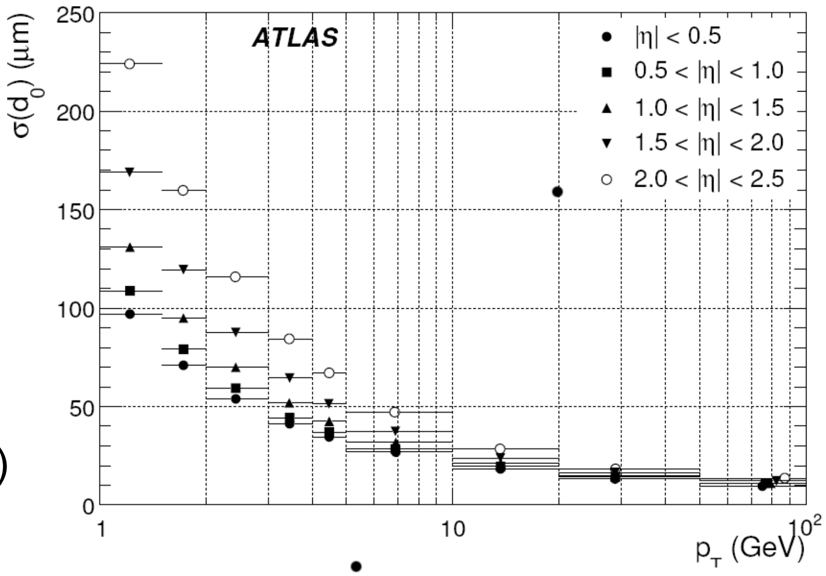
Why b-Tagging?

- Vital ingredient for the high pT physics program at the LHC, e.g.:
  - to obtain a very pure top quark sample
  - for Higgs analyses: e.g. ttH → ttbb (4 b-jets to tag!)
  - SUSY Higgses, like in charged Higgs (2-4 b-Jets) or bbH/A or inclusive searches
  - Many exotic scenarios
- Two available signatures:
  - spatial (lifetime of b-hadrons: $c\tau \sim 450\mu m \rightarrow \beta\gamma c\tau \sim$ 3-15 mm)
    - <u>*1. Impact Parameter* based algorithms</u>
relies on the (in)compatibility of single tracks with the primary vertex
    - <u>*2. Secondary vertex* based algorithms</u>
explicit determination of the weak B hadron decay vertex → use its production and decay properties (mass, fragmentation function,track multiplicity)
  - **lepton based**
    - <u>*3. Lepton-ID* based algorithms</u>
identify muon or electron from semileptonic B or B→D decay (e and μ ~20% each)



B-Tagging ingredients

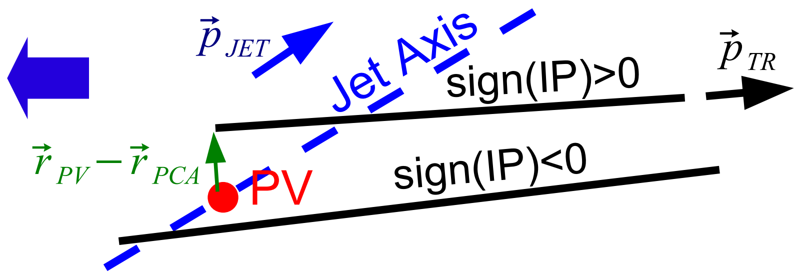
- Jets
  - Jets typically from calorimeter information are considered as b-jet candidates (need direction!)
- Tracks
  - Tracks are assigned to the jet if ΔR(Track,Jet)<0.4
  - Tracks must satisfy quality criteria (pT>1GeV, loose IP cuts, b-Layer hit requirement,...)
- Impact parameter resolution essential for “spatial” tagging
  - Resolution of the (innermost) 3 barrel pixel layers is around 10 μm in rϕ and 115 μm in z.
  - Transverse resolution of tracks goes from ~100 μm (pT=1 GeV) to ~10 μm (pT=100 GeV)
- Displacement is computed wrt. Primary Vertex (PV)
  - Transverse plane: PV well constrained by beam spot (~15 μm)
  - PV reconstruction essential to get PV z coordinate (σ ~ 50μm)



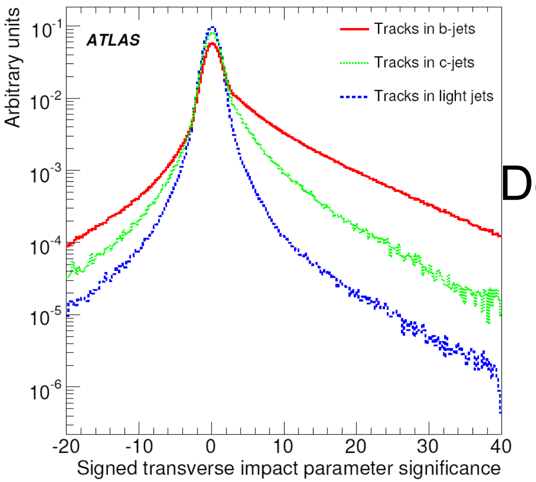
Impact Parameter based b-Tagging algorithm

Determine Lifetime Sign of Impact Parameters: in 3d

$$sign(IP) = sign\left((\vec{p}_{JET} \times \vec{p}_{TR}) \cdot (\vec{p}_{TR} \times (\vec{r}_{PV} - \vec{r}_{PCA}))\right)$$



Consider signed IP significances



$$S_i = \frac{d^\blacksquare}{\sigma(d^\blacksquare)}$$

Define PDFs:

$P_b(S_i)$

$P_{light}(S_i)$

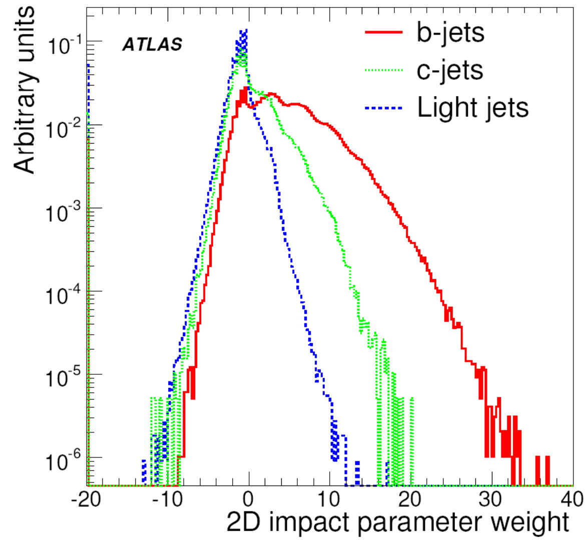
Define Jet weight:

$$W_{JET}^{IP} = \sum_{Tracks} \log\left(\frac{P_b(S_i)}{P_{light}(S_i)}\right)$$

IP2D: only transverse IPs

IP3D: also longitudinal IPs (2-dim PDFs)

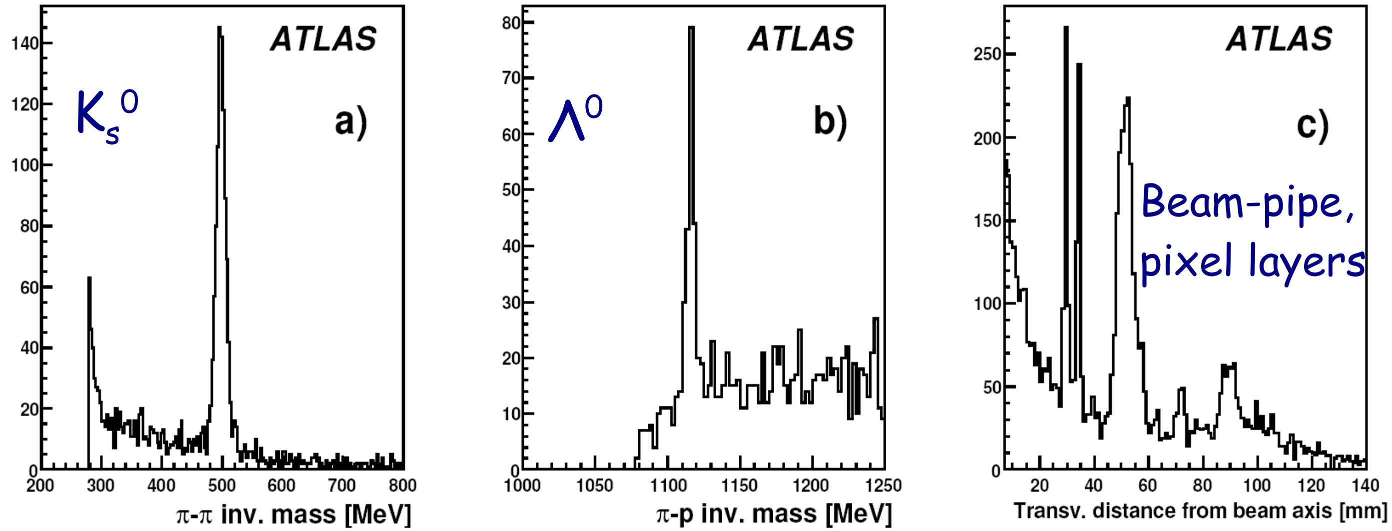
IP2D Jet Weight

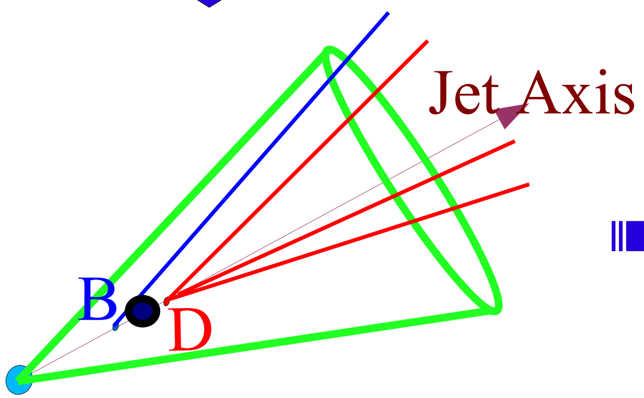


- Likelihood ratio formalism adopted for both IP based algorithms
- Simpler algorithms based only on background hypothesis (JetProb, à la Aleph) or on counting high IP tracks also available → important for commisioning!

Inclusive secondary vertex reconstruction in Jet (I)

Find all displaced two-track vertices
→ remove V^0 decays, material interactions



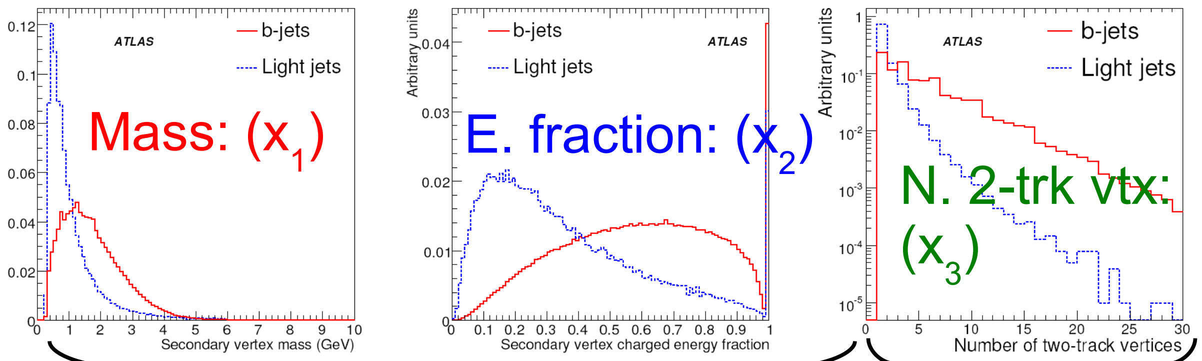


- Fit surviving tracks from two-track vertices into one inclusive geometrical vertex
- Remove iteratively most incompatible ones

Inclusive secondary vertex reconstruction in Jet (II)

Define templates based on:

- Invariant mass at vertex
- $\frac{\text{energy of charged particles at vertex}}{\text{energy of charged particles in jet}}$
- Number of good two-track vertices



$P(x_1,x_2,x_3) = P(x_1,x_2) \times P(x_3)$

- Add probability to find vertex ε:

$$PDF = \begin{cases} 1-\epsilon & \text{[no vertex]} \\ \epsilon \cdot P(x_1, x_2, x_3) & \text{[vertex found]} \end{cases}$$

- Define Jet weight based on likelihood ratio:

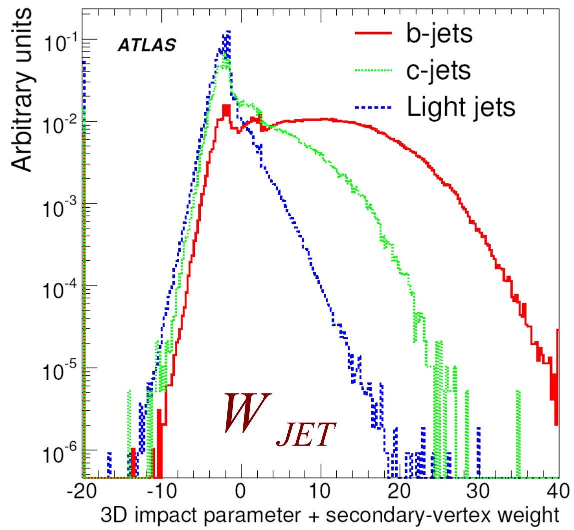
$$W^{SV}_{JET} = \log\left(\frac{PDF_b}{PDF_{light}}\right)$$

SV1

Combine IP and SV based weights:

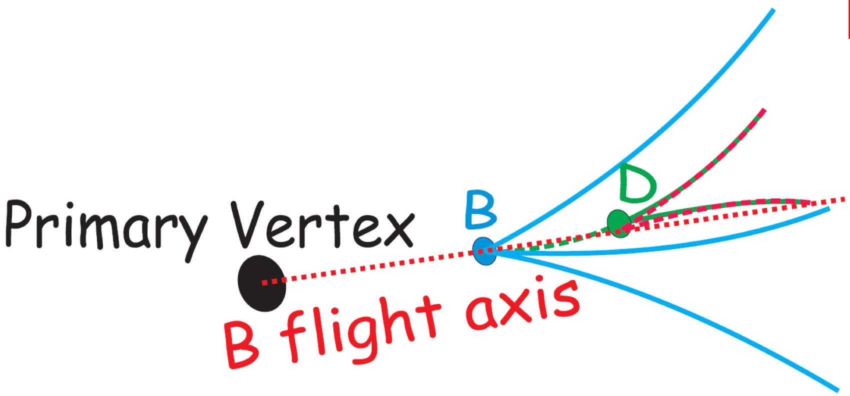
$$W_{JET} = W^{IP}_{JET} + W^{SV}_{JET}$$

COMB



Topological reconstruction of the PV → B → D decay chain (I)

The “JetFitter” algorithm tries to disentangle the weakly decaying B and D vertices.

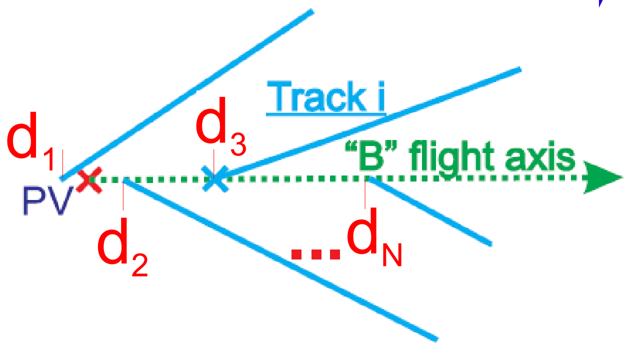


b and c vertices approx. on same line of flight
→ intersect b-hadron flight direction with tracks

Principle used by SLD in “ghost track” algorithm [SLAC-PUB-8225 (1999)]

JetFitter is based on an original extension of the Kalman Filter formalism commonly used for vertexing [J. Phys.: Conf. Ser. **119** 032032]

Finding strategy



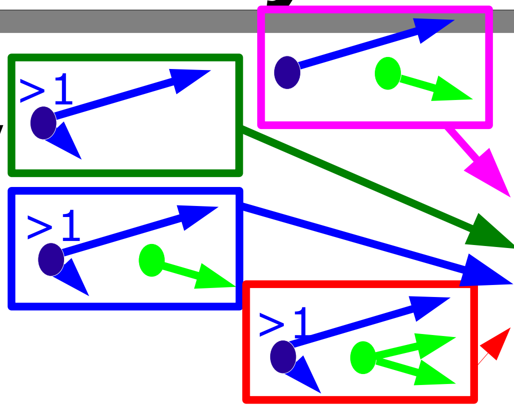
- Initialization of:
  1) Primary Vertex
  2) “B” flight axis (from calorimeter jet direction)
- First fit under the hypothesis that each track represents a single vertex along the “B” flight axis

→ optimal $(\phi_{AXIS},\theta_{AXIS},d_1,d_2,\ldots,d_N)$

Giacinto Piacquadio
University of Freiburg

Topological reconstruction of the $PV \rightarrow B \rightarrow D$ decay chain (II)

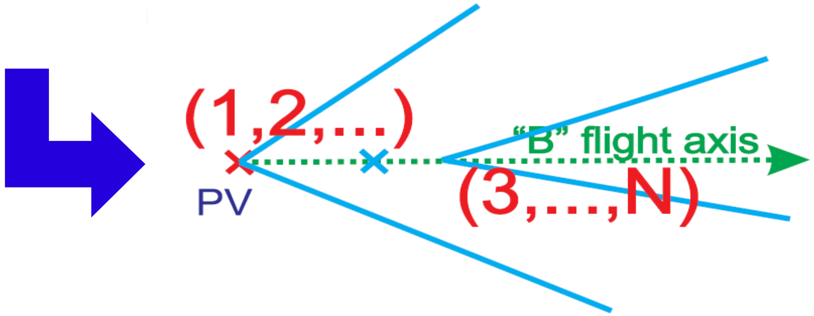
- For all combinations of two vertices (including the Primary Vertex) the probability of having a common vertex is evaluated.
  1. Merge pair of vertices with highest probability
  2. Perform a new "full fit" and repeat from 1



Flavour	b	c	l
Nothing	13.7	51.3	79.7
1 Single Track	9.9	17.4	13.6
2 Single Tracks	4.5	2.6	1.0
1 Single Vertex	49.6	25.1	5.2
1 Vertex + 1 Track	15.9	3.1	0.4
2 Vertices	6.3	0.5	0.04

Population (%) according to topology

- Stop when no pair of vertices needs to be merged anymore (P_{xy} < cut value)



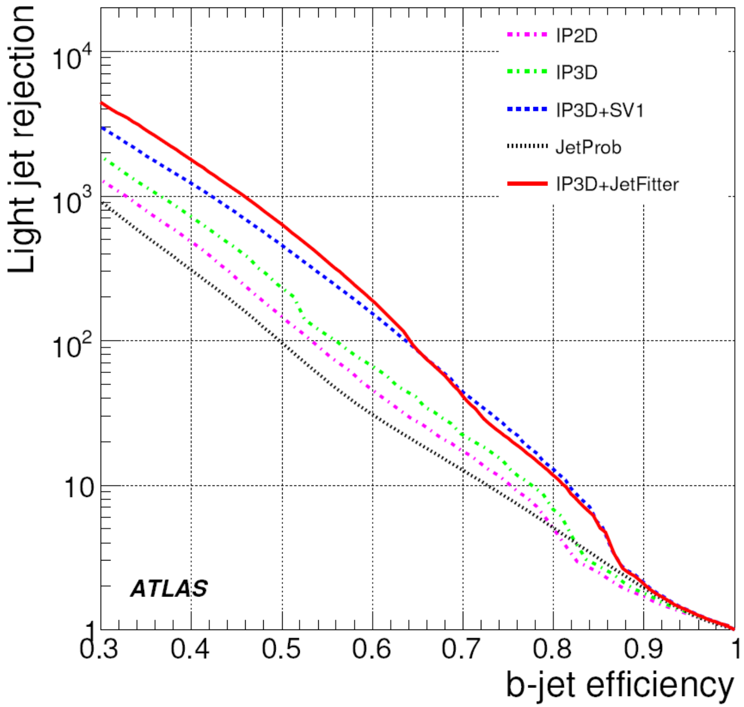
- Variables used for B-Tagging:
  - Decay topology (number of vertices, tracks at vertices, additional single tracks on flight axis)
  - Invariant mass of charged particles of decay chain
  - Fractional charged tracks energy
  - Decay length significance d/σ(d)
- Likelihood function:

$$L^{b,l,c}(x) = \sum_{cat} coeff(cat) \cdot PDF_{cat}(mass) \cdot PDF_{cat}(energyFraction) \cdot PDF_{cat}\left(\frac{d}{\sigma(d)}\right)$$

- Jet weight is again defined according to likelihood ratio. Analogously combined with IP3D.

Performance of spatial algorithms

- B-Tagging performance tested on a sample of >1M of fully simulated pp → tt and pp→ttjj events.
- Tagging efficiency: $\epsilon_q = \frac{Number\ of\ jets\ of\ flavour\ q\ tagged\ as\ b}{Number\ of\ jets\ of\ flavour\ q}$
- Rejection: $r_u=1/\varepsilon_u$, $r_c=1/\varepsilon_c$



Light jet rejections

ε(b-jet)	JetProb	IP2D	IP3D	IP3D+SV1	IP3D+JetFItter
50%	83±1	116±2	190±3	458±13	555±17
60%	30±0	42±0	59±1	117±2	134±2

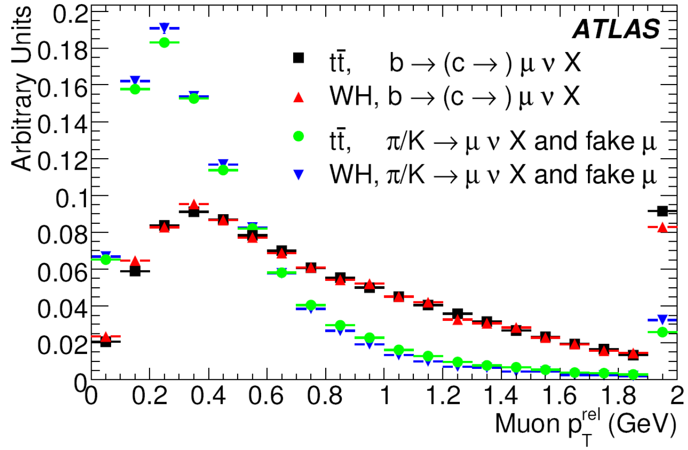
Charm jet rejections

ε(b-jet)	JetProb	IP2D	IP3D	IP3D+SV1	IP3D+JetFItter
50%	8.4±0	9.5±0	10.6±0	12.4±0.1	12.3±0.1
60%	5.1±0	5.8±0	6.5±0	7.4±0	7.4±0

- Ideal geometry and 5 % pixel inefficiency (3 % pixel inefficiency expected at the end of 2008) assumed in the simulation
- No specific charm rejection implemented

Soft Lepton based Tagging algorithms

- Efficiency is a-priori limited by semi-leptonic branching ratios:
  - BR($b \rightarrow l\,X$) ~ 11%, BR($b \rightarrow c \rightarrow l\,X$) ~ 10 % ($l=e,\mu$)
- Correlation with "spatial" algorithms is very low:
  → perfect for obtaining b-Tagging efficiency from data
- Both algorithms make use of the relative pT (pT rel) of the lepton with respect to the Jet axis



Soft Muon Tagging algorithm

- Background given by fake muons (e.g. punch-throughs) and from decay of light hadrons
- IP significance of lepton not used (avoid correlations with spatial)
- Rejection: ~300 for 10% b-Tagging efficiency

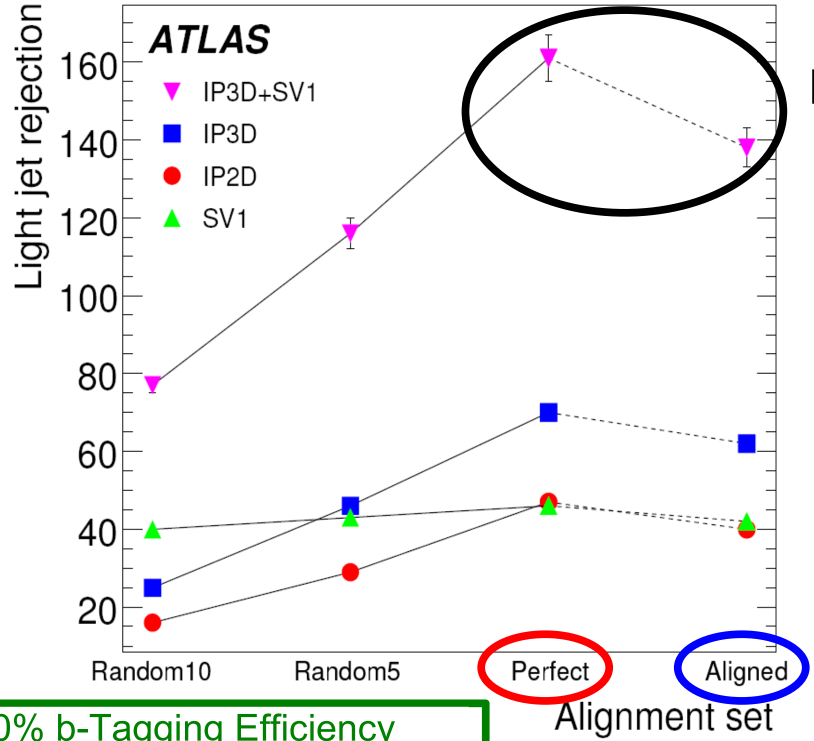
Soft Electron Tagging algorithm

- Low pT Electron-ID in dense Jet environment very challenging: use dedicated likelihood discriminator which at 80 % electron efficiency gives:
  - rejection of ~200 against charged pions
  - rejection of ~2-3 against conv./π^0 Dalitz decays
- IP significance of lepton used in addition
- Rejection: ~100 for 7% b-Tagging efficiency

Giacinto Piacquadio
University of Freiburg

Effect of detector misalignment

- Detector misalignment affects tracking efficiency and IP resolutions, thus B-Tagging.
- Dedicated study:
  - Simulation with randomly misaligned detector (~10-100 µm, including <u>some</u> global deformations)



60% b-Tagging Efficiency
IP and SV Tagging algorithms

Reconstruction with 2 alignement sets:

- **Perfectly aligned:** equivalent to no misalignment
- **Aligned:** residual misalignment after realistic track based alignment procedure

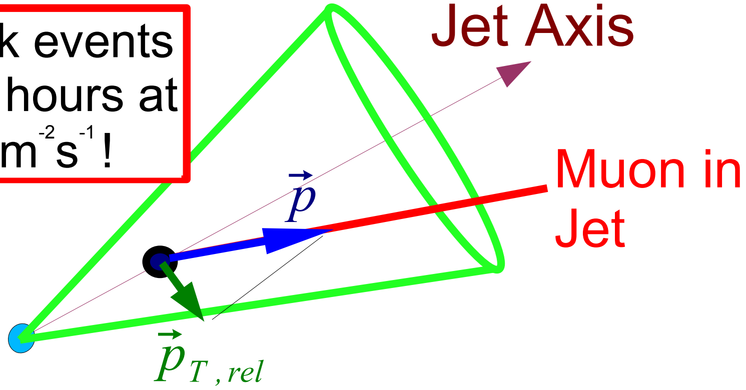
- Error scaling procedure on the track hits used to deal with residual misalignment

- On real data, **after alignement**, a **degradation of less than 25 %** in light-Jet rejection with respect to the ideal case seems feasable.

Calibration on data

- The b-Tagging efficiency can be extracted using:

~100k events in 30 hours at 10^{31} cm^{-2}s^{-1}!

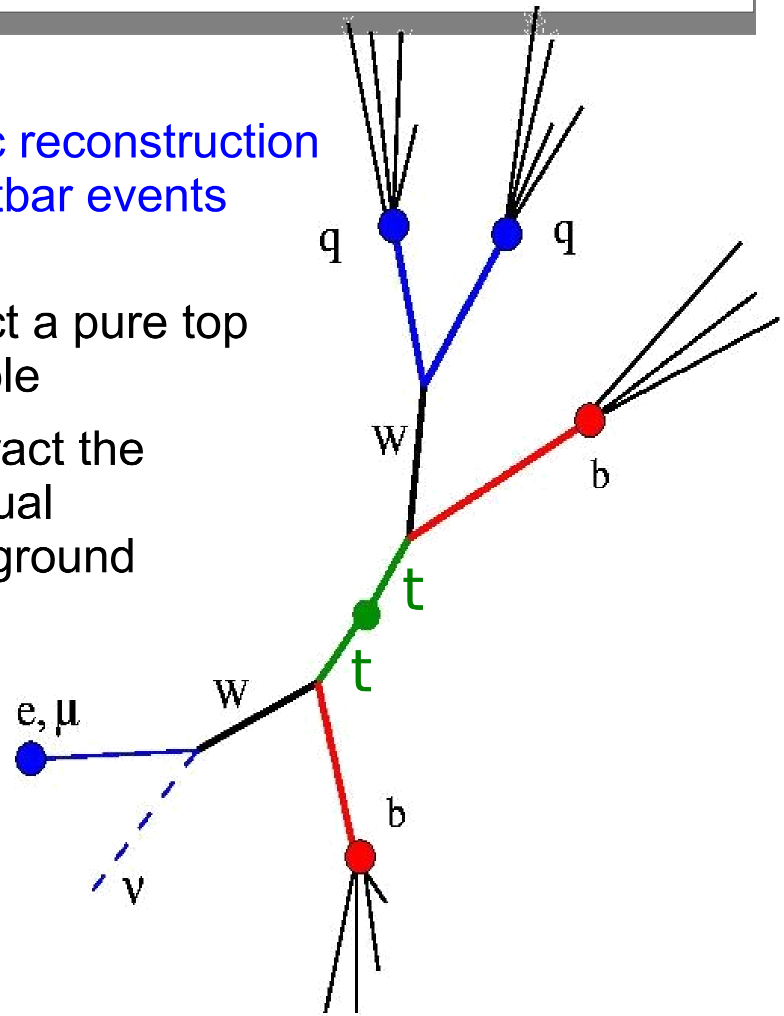


Two uncorrelated b-Tagging algorithms
(“spatial” and Soft Muon)

- use QCD dijet Events
- b-flavour enriched by Muon+Jet signature (dedicated Trigger)

Kinematic reconstruction of pp → ttbar events

- Select a pure top sample
- Subtract the residual background



- Extraction of light-Jet mistagging rates still under study...

Calibration on data using QCD dijet events (System 8 Method)

- Based on:
  - 2 samples with different flavour composition
    - 1. Jet+Muon [n]
    - 2. Jet+Muon + additional back to back b-Tagged Jet [p]

2 uncorrelated Taggers (muon, ”spatial”)
→ 4 combinations [no tag], [μ tag], [“spatial tag”], [both tags] to be applied on 2 samples

→ 8 equations with 8 unknowns

- Solve equation: obtain flavour composition of samples and b-tagging efficiency

$$n = n_b + n_{cl}$$
$$p = p_b + p_c$$
$$n_\mu = \varepsilon^\mu n_b + r^\mu n_{cl}$$
$$p_\mu = \varepsilon^\mu p_b + r^\mu p_{cl}$$
$$n_{Tr} = \varepsilon^{Tr} n_b + r^{Tr} n_{cl}$$
$$p_{Tr} = \beta \varepsilon^{Tr} p_b + \alpha r^{Tr} p_{cl}$$
$$n_{all} = \mathbf{k_b} \varepsilon^\mu \varepsilon^{Tr} n_b + \mathbf{k_{cl}} r^\mu r^{Tr} n_{cl}$$
$$p_{all} = \mathbf{k_b} \beta \varepsilon^\mu \varepsilon^{Tr} p_b + \mathbf{k_{cl}} \alpha r^\mu r^{Tr} p_{cl}$$

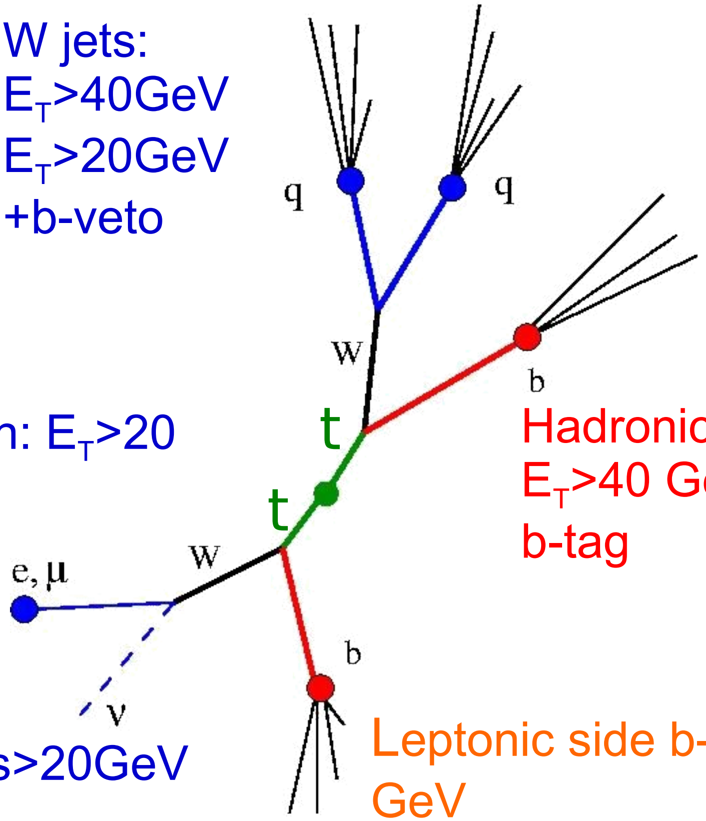
- Method is dominated by systematic uncertainties with more than 50 pb^{-1} of data
- A pT and η dependent measurement of the b-Tagging efficiency with a precision of 6 % up to 150 GeV Jet pT seems feasible.

Calibration on data using ttbar events
Topological selection (I)

W jets:
E_T>40GeV
E_T>20GeV
+b-veto

Lepton: E_T>20 GeV

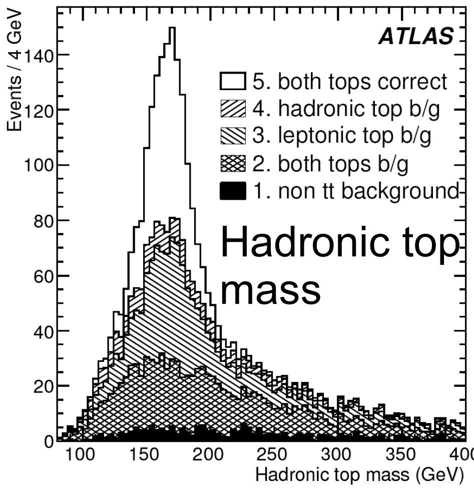
$E_T$miss>20GeV

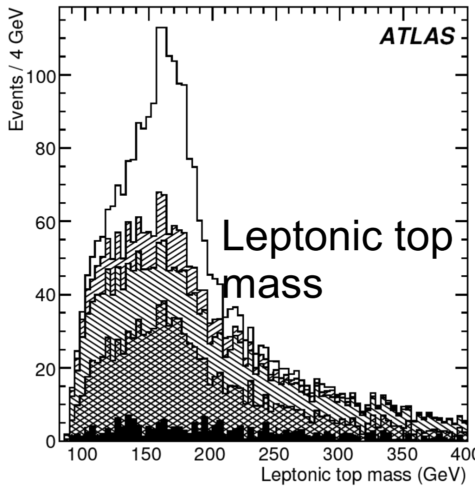


Hadronic side b-jet:
E_T>40 GeV
b-tag

Leptonic side b-jet: E_T>20 GeV
No tag requirement

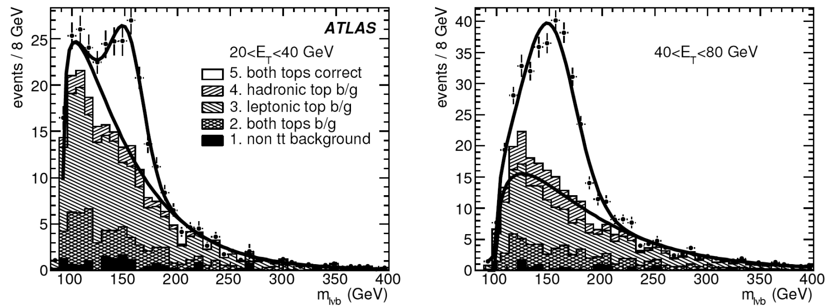
- Basic preselection of one hadronic top and one leptonic top
- Use b-Tagging on the hadronic side
  - leptonic top left unbiased
- Solve equation for missing p_z of the neutrino, take smallest solution
- More combinations? Take the one with largest ∑pT of the two tops



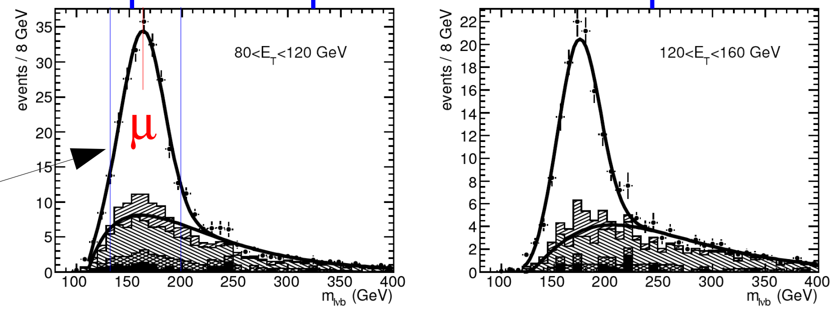


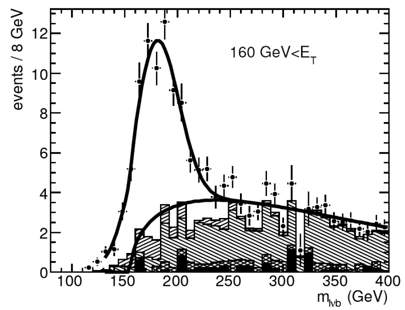
Calibration on data using ttbar events
Topological selection (II)

- Reachable b-Jet purity: 54-86 % depending on pT
- Shape for background obtained from a signal depleted control sample
- Simultaneous fit on selection + control sample
- b-Tagging weight distribution from signal region after background subtraction (gives efficiency as a function of discriminator cut)



Leptonic top mass in b-Jet pT bins





➡ With 200pb^{-1} and E_T>40GeV get a relative precision on the b-Tag. efficiency of <u>±7.7%(stat) ± 3.2%(syst.)</u>

Permits to get any distribution/property of the b-Jets on a statistical basis!
(~1 fb^{-1} needed)

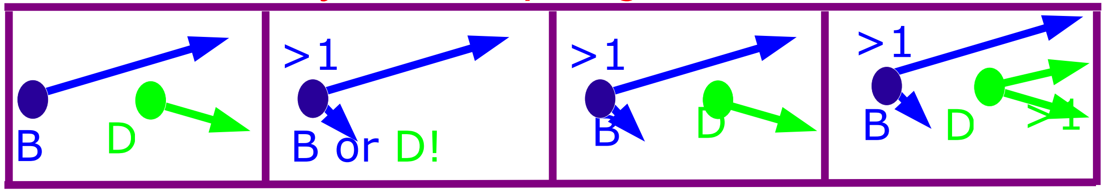
Outlook

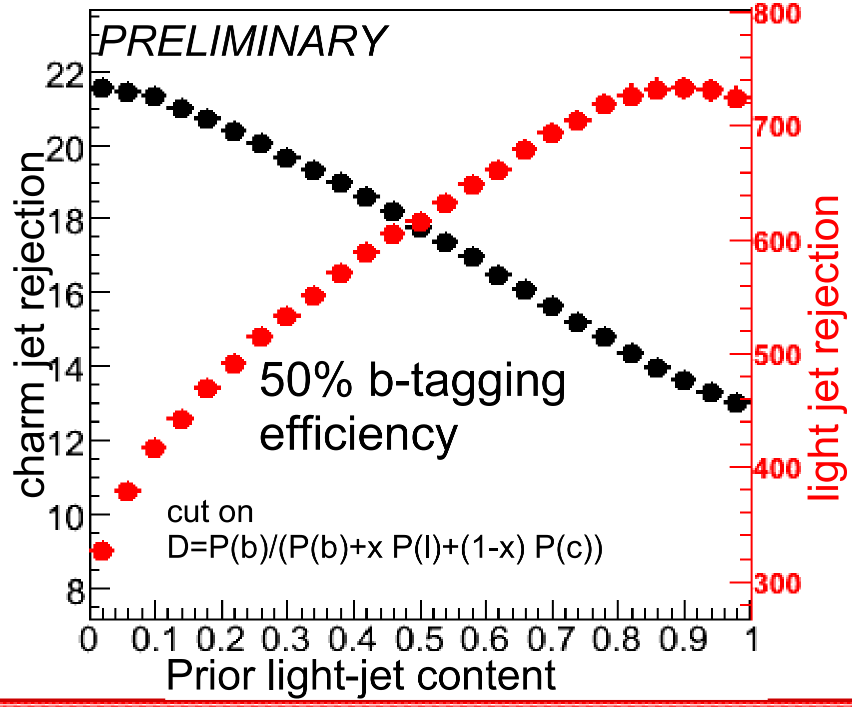
- Many algorithmic improvements to increase B-Tagging performance still on the way.

E.g. one interesting development:

- Use JetFitter's different decay chain topologies to improve the charm-Quark rejection

Possible decay chain topologies:





- Neural Network to discriminate b-Jets against light and charm-Jets
- A consistent increase in charm-Quark rejection is possible at the cost of a lower light-Quark rejection
- The method is being applied to the recent analysis of:
  - $pp \rightarrow W(\rightarrow\mu\nu)H(\rightarrow bb)$ with $p_T(H)>200GeV$ [Butterworth et al., arXiv:0802.2470]

where the bottom/charm-Jets from the top are a severe background for the Higgs→bb

Conclusions

- The LHC has started!
- Performance achievable by b-Tagging algorithms in ATLAS at 60 % b-Tagging efficiency, in order of expected commissioning:
  - JetProb → light Jet rejection of ~30 (only input: resolution function for prompt tracks in data)
  - IP3D → light Jet rejection of ~60
  - Sec Vtx based algorithms → light-Jet rejection of ~120-140
- The effect of residual misalignment is expected to degrade these rejections by less than 25 %
- A 8-15 % discrepancy in the detector material description in the Monte Carlo simulation would impact these rejections by ~10%
- Methods established to measure the b-Tagging efficiency on data to 5 % accuracy with 100 pb^{-1} of data
- Mistagging rate determination under study: 10 % precision expected from Tevatron experience.
- Many improvements still on the way !