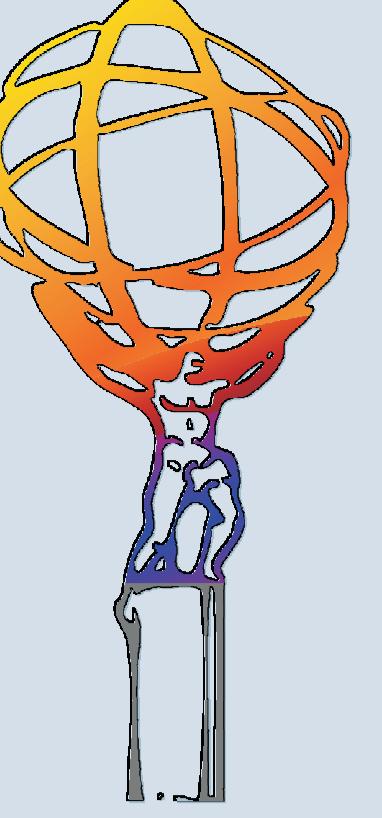




# Jet Fitter: a New Vertexing Algorithm for B-Tagging in ATLAS

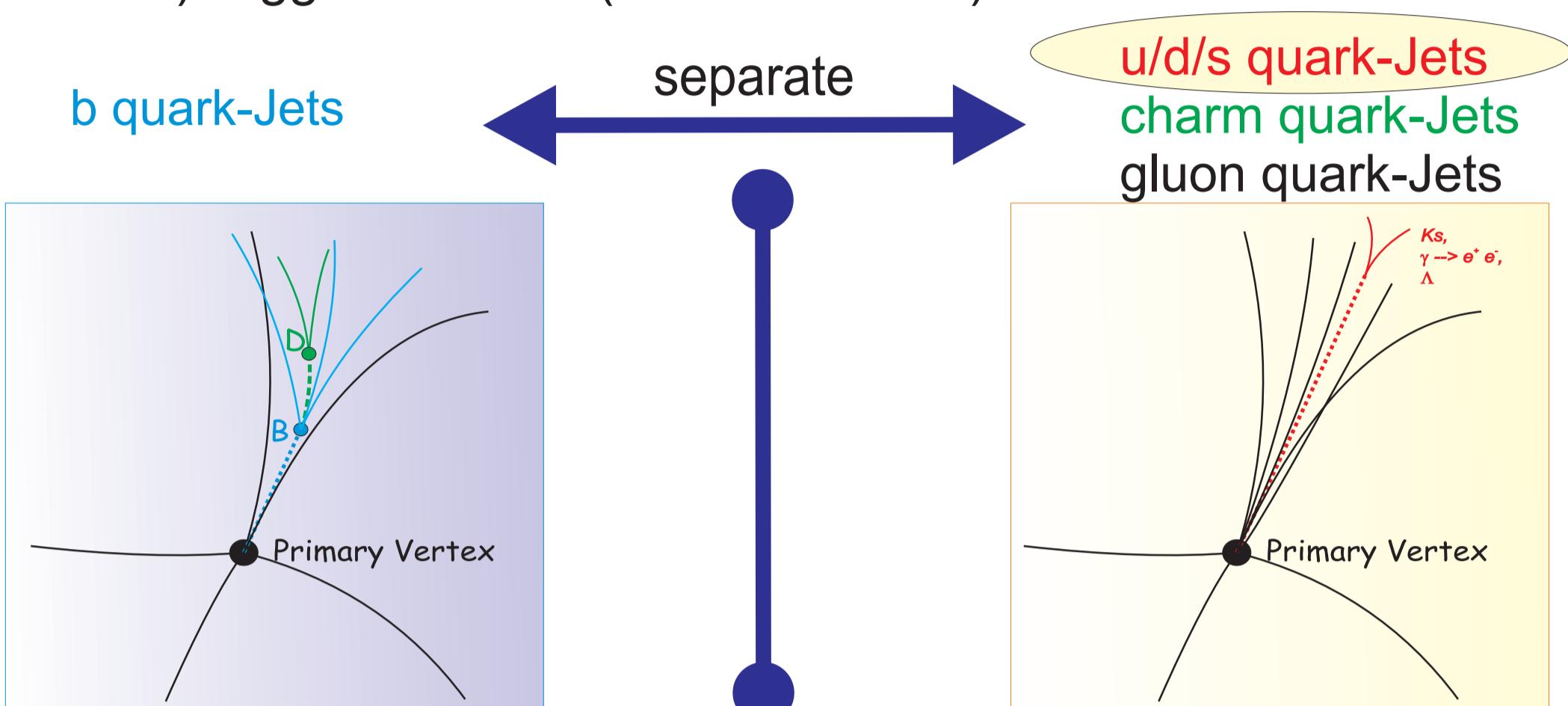
Giacinto Piacquadio - Dr. Christian Weiser  
Albert-Ludwigs-Universität Freiburg  
CHEP 2007, Victoria, 2-7 September 2007



## Motivation

### B-Tagging in ATLAS

Plays a crucial role in many analyses, for example:  
1) Reconstruction of top events ( $BR(t \Rightarrow Wb) \approx 1$ )  
2) Higgs searches (like  $t\bar{t}H \Rightarrow t\bar{t}b\bar{b}$ )



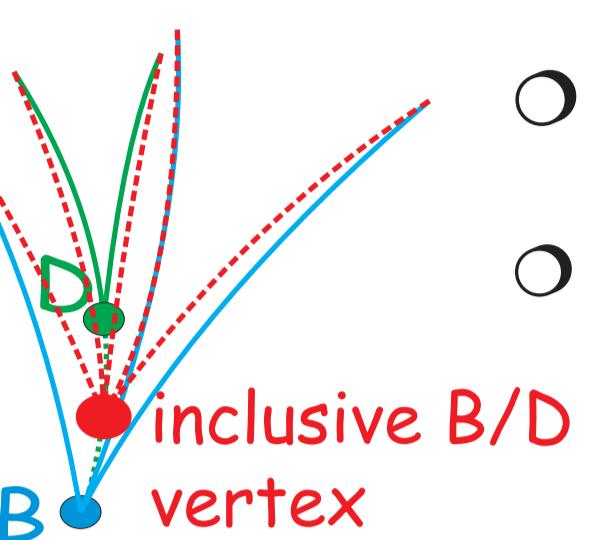
A displaced vertex provides a signature for a b-quark jet. Three tagging methods in ATLAS, based on:

- 1) Impact Parameter significance of Tracks
- 2) Reconstruction of a displaced vertex and its properties
- 3) Reconstruction of a lepton from semileptonic b-hadron decays

The default b-tagging algorithm in ATLAS uses the combination of the first two tagging algorithms.

## Vertexing inside b-jets

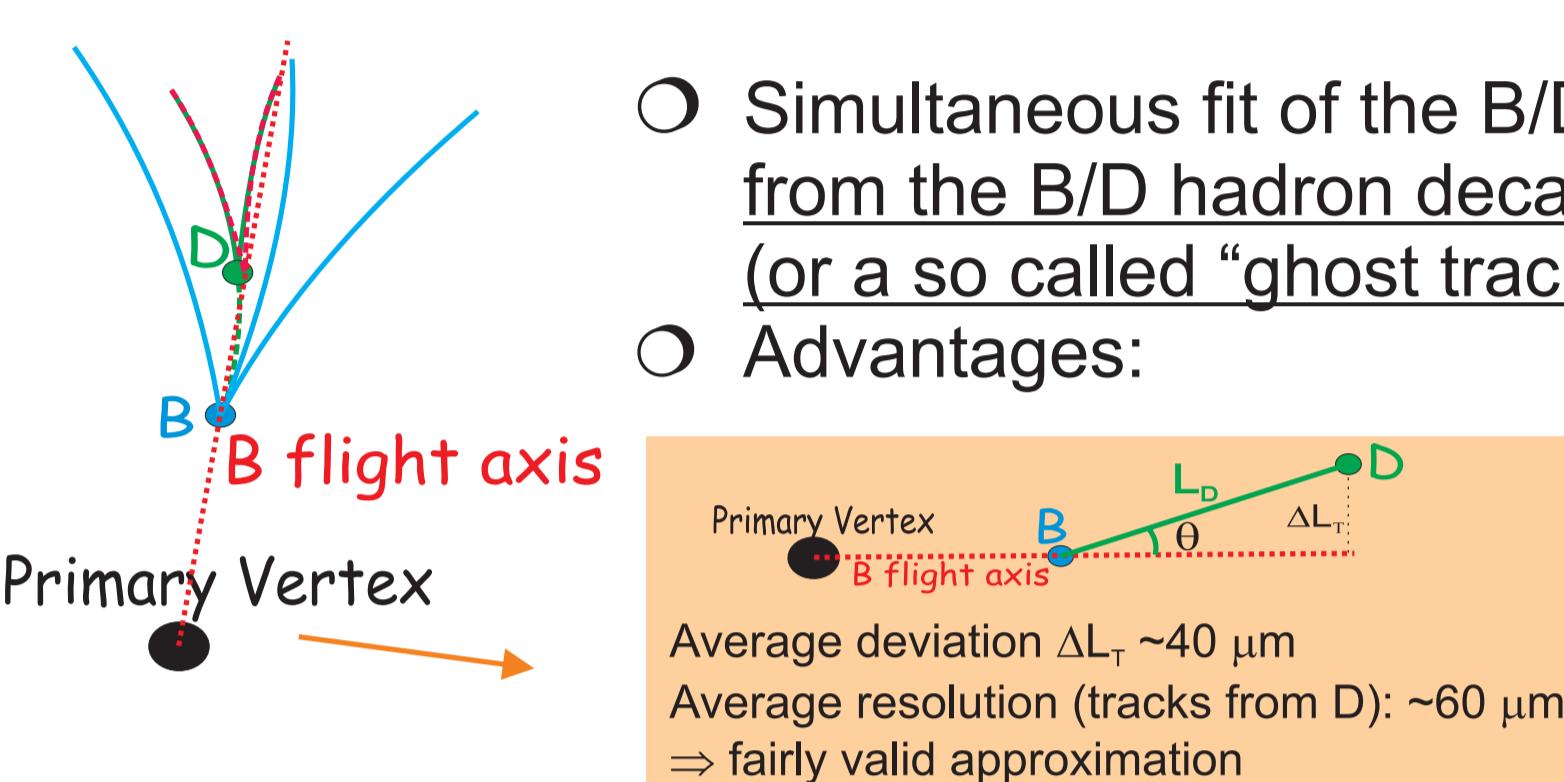
### Classical vertexing algorithm



- Displaced tracks are selected and a single inclusive vertex is obtained with a least  $\chi^2$  fit
- Drawbacks:
  - Underlying hypothesis of a single geometrical vertex is not correct
  - Incomplete topologies (like 1 track from B / 1 from D) are hard to reconstruct

Track resolutions make a simultaneous "fit" to the B/D-hadron vertices very difficult.

### "Jet Fitter"

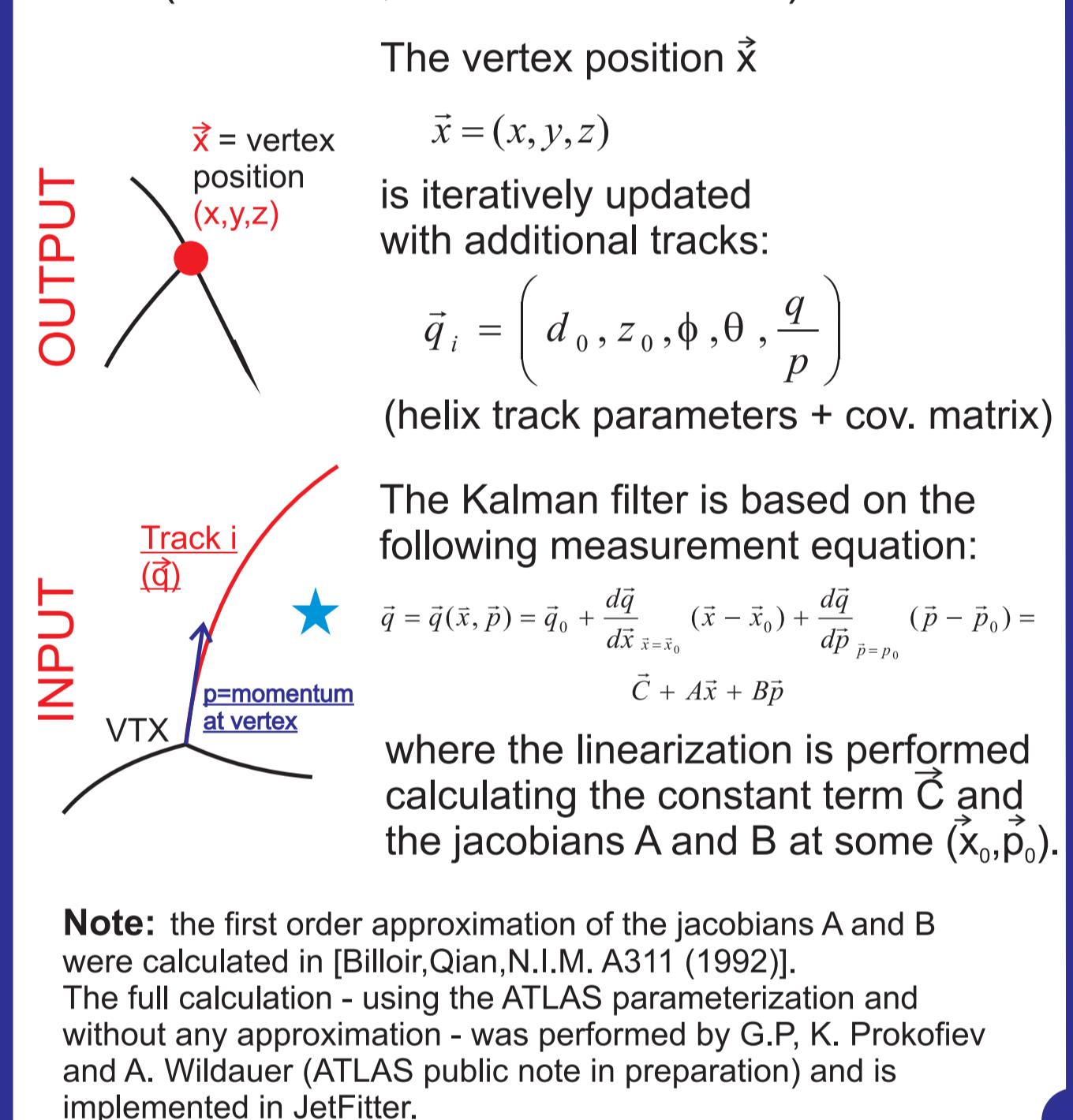


This hypothesis was explored for the first time by the "ghost track" algorithm by SLD [SLAC-PUB-8225 (1999)]

## JetFitter

### A new Kalman Filter for Vertexing

#### Standard Kalman Filter (Frühwirth, N.I.M. A262 1987)



#### JetFitter

In JetFitter the variables to fit are:

$\vec{d} = (x_{pv}, y_{pv}, z_{pv}, \phi, \theta, d_1, d_2, \dots)$   
where:  
A)  $(x_{pv}, y_{pv}, z_{pv})$ : primary vertex position  
B)  $(\phi, \theta)$ : direction of "B" flight axis  
C)  $(d_1, d_2, d_3, \dots)$ : distance from primary vertex of fitted vertices along the flight axis.

To initialize the fit,

- 1) primary vertex position (+ cov. matrix)
- 2) jet axis from calorimeter (+ error estimated from MC as convolution of jet direction resolution with average displacement of jet axis with respect to "B" flight axis)
- 3) tracks (for track i  $\vec{q}_i = (d_0, z_0, \phi, \theta, \frac{q}{p})$  +cov.)

are added to the fit through the Kalman update step specifying the vertex number to update.

#### New Kalman formalism

The measurement equation becomes:

$$\vec{q} = \vec{q}(\vec{d}, \vec{p}) = \vec{q}_0 + \frac{d\vec{q}}{dd} (\vec{d} - \vec{d}_0) + \frac{d\vec{q}}{dp} (\vec{p} - \vec{p}_0) = \tilde{\vec{C}} + \tilde{\vec{A}}\vec{d} + \vec{B}\vec{p}$$

where the new jacobian  $\tilde{\vec{A}}$  can be arranged in such a way to be obtained from the standard Kalman Filter formalism by:

$$\vec{q} = \vec{q}(\vec{d}, \vec{p}) = \vec{q}_0 + \frac{d\vec{q}}{dx} \frac{d\vec{x}}{dx} \vec{x}_{x_0} \frac{d\vec{d}}{dd} \vec{d}_{d=d_0} (\vec{d} - \vec{d}_0) + \frac{d\vec{q}}{dp} (\vec{p} - \vec{p}_0)$$

Comparing with  $\star$ , obtain the new jacobian from the standard one:

$$\text{where: } \begin{aligned} x &= x_{pv} + d_i \sin \theta \cos \phi \\ y &= y_{pv} + d_i \sin \theta \sin \phi \\ z &= z_{pv} + d_i \cos \theta \end{aligned}$$

$$\text{and: } \frac{d\vec{x}}{dd} \frac{d\vec{d}}{dd} = \frac{d(x, y, z)}{d(x_{pv}, y_{pv}, z_{pv}, \phi, \theta, d_i)} = \begin{pmatrix} 1 & 0 & 0 & -d_i \sin \theta \cos \phi & d_i \cos \theta \cos \phi & \sin \theta \cos \phi \\ 0 & 1 & 0 & d_i \sin \theta \cos \phi & d_i \cos \theta \sin \phi & \sin \theta \sin \phi \\ 0 & 0 & 1 & 0 & -d_i \sin \theta & \cos \theta \end{pmatrix}$$

Note: this jacobian is quite non linear in  $\vec{d}$ , so a trick is needed to do a fast relinearization at each additional needed Kalman iteration step.

#### Fast relinearization

Before each new fit iteration the measurement equation needs to be relinearized, but using a trick only part of it needs to be recalculated.

Before starting the fit, the "standard" measurement equation  $\star$  is linearized in the approximate vertex position  $\vec{x}_i$  and the constant  $C$  and the Jacobians  $A$  and  $B$  are calculated.

At each new Kalman iteration, only the Jacobian  $\frac{d\vec{x}}{dd}$  is recomputed, at the new position  $\vec{d} = \vec{d}_i$ , so that:

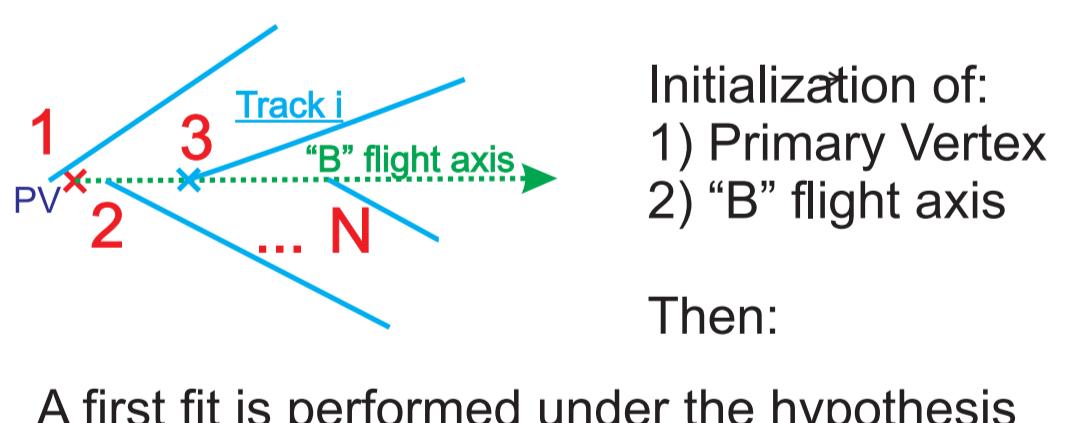
$$\begin{aligned} \tilde{\vec{A}} &= A \frac{d\vec{x}}{d\vec{d}} \Big|_{d=\vec{d}_i} \\ \tilde{\vec{C}} &= \vec{C} + A \left[ \vec{x}_i - \frac{d\vec{x}}{dd} \Big|_{d=\vec{d}_i} \vec{d}_i \right] \end{aligned}$$

#### Vertex probability estimation

For estimating the probability of  $\chi^2$  of a subset of tracks to be compatible with the vertex  $i$ , a new "smoothing" procedure has been designed, where the related tracks are iteratively removed from vertex  $i$  and the resulting "jet candidate" is compared to the old one to get the probability of the tracks to form a vertex AND to be compatible with the remaining decay chain.

## Finding algorithm

### Strategy for finding



A first fit is performed under the hypothesis that each track represents a single vertex along the "B" flight axis.

→ optimal ( $\phi_{axis}, \theta_{axis}, d_1, d_2, d_3, d_4, \dots, d_n$ )

Clustering  
All combinations of two vertexes (picked up from the vertexes on the "B" flight axis + the primary vertex) are considered.

| Table of compatibilities between vertexes |     |          |          |     |             |   |
|---|-----|----------|----------|-----|-------------|---|
| Prob.                                     | 1   | 2        | 3        | ... | Primary Vtx |   |
| 1   | X   | $P_{12}$ | $P_{13}$ | ... | $P_{1p}$    |   |
| 2   | ... | X        | $P_{23}$ | ... | $P_{2p}$    |   |
| 3   | ... | ...      | X        | ... | $P_{3p}$    |   |
| ...                                       | ... | ...      | ...      | X   | ...         |   |
| P.Vtx                                     | ... | ...      | ...      | ... | ...         | X |

The probability of having a common vertex is evaluated for each of these combinations by means of imposing a Kalman internal constraint on top of the previous "full fit":

$d_i = d_j$  (hypothesis: vertex  $i$  is merged with vertex  $j$ )  
 $d_i = 0$  (hypothesis: vertex  $i$  is merged with primary vtx)

[see W. Hulsbergen, N.I.M. A552 (2005)].

Then:  
1) merge pairs of vertexes with highest probability  
2) perform a new "full fit" and go back to 1.

Stop the iterative procedure when no pairs of vertexes can be merged anymore.

A clear topology for the "decay cascade" will then come out from the fit.

### Definition of the likelihood

In order to separate b-jets from c- and light-quark jets, a likelihood is defined, separately for each of these flavours.

$$L(x) = \sum_{cat} coeff(cat) P_{cat}(\text{mass}) \cdot P_{cat}(\text{en.Frac}) \cdot P_{cat}(\frac{\sigma(d)}{d})$$

The information about the topology of the jet as reconstructed by JetFitter is provided by the coefficient, while the vertex information is contained in the PDFs.

In order to reduce the correlations between vertex information and topology, the PDFs are split and made category dependent whenever this is strictly needed.

### Negative flight lengths

Applying the fit to a real b-jet, in few cases the "B flight axis" converges to an unphysical direction, on which most/all of the vertexes have a "negative flight length".

To avoid this, the following procedure is used  
1) A first fit is performed until convergence is reached

2) A second fit is done, where:  
- the relinearization of the track is performed as if the track would have had "opposite flight length" (a)

In this way a kink towards the correct direction is provided to all the affected tracks, resulting in a global attempt to get the fit out of the wrong minimum (b)

3) Fit is iterated until  $\chi^2$  convergence is reached (no more tracks swap between positive and negative flight lengths)

4) Default fit is performed until convergence is reached

### Topology information

The topology is described by:

- (1) number of vertexes with at least 2 tracks
- (2) number of tracks at found vertexes
- (3) number of additional single-track vertexes on "B flight axis"

To minimize correlations, they are combined in the following way:

| # vtx (1) | 0 | 1                   | 2                        | ≥ 3                      |
|-----------|---|---------------------|--------------------------|--------------------------|
| 0         | 0 | # single tracks (3) |                          |                          |
| 1         | 0 | 1                   | # tracks at vertices (2) |                          |
| ≥ 2       | 2 | 3                   | 4                        | # tracks at vertices (2) |

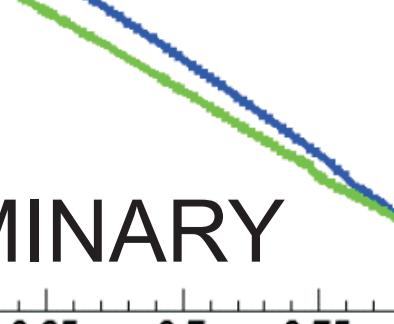
where the symbol  $\times$  indicates a simple multiplication among coefficients.

This results in 12 coefficients which have to be determined on the training samples separately for the three different jet flavours.

### Rejection against light-quark jets

- JetFitter
- ATLAS
- default

ATLAS PRELIMINARY

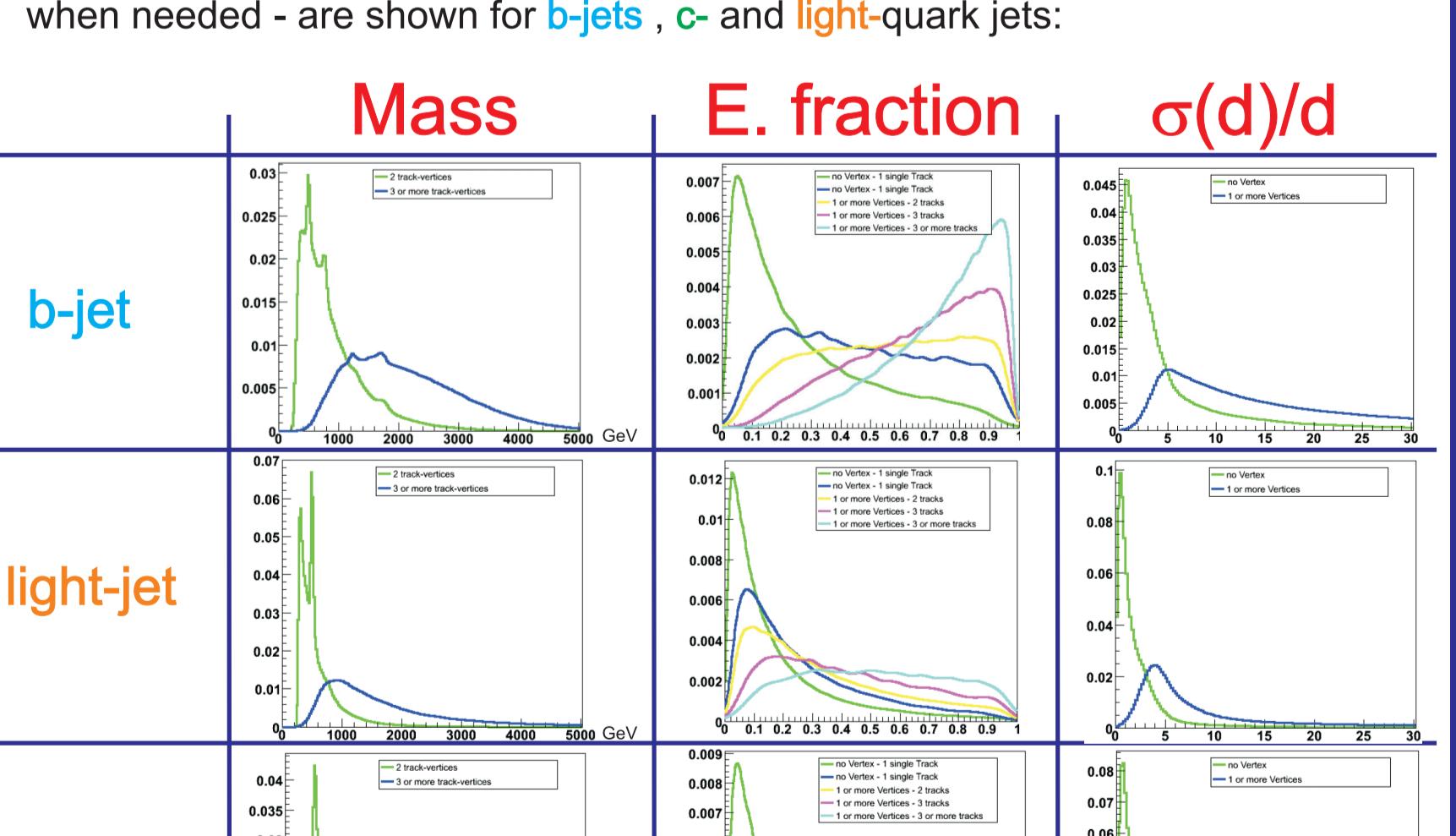


### Vertex information

The vertex information is condensed in the PDFs for the following variables:  
mass (invariant mass of all displaced tracks)  
energy Fraction (fraction of energy of displaced tracks divided by sum of energies of all tracks in jet)

flight length significance ( $\sigma(d)/d$ ) of the average displaced vertex position

The templates for these variables - in a category dependent fashion when needed - are shown for b-jets, c- and light-quark jets:



### Performance

The "JetFitter" based b-tagging algorithm (combined with the Impact Parameter based one) was compared with the ATLAS default algorithm.  
The performance was tested on a sample of 550k p p →  $t\bar{t}$  Monte Carlo events passed through the full simulation of the ATLAS Detector.

The increase in rejection power against light quark jets in these preliminary results looks very promising!

Very similar rejection rates against charm-quark jets for the two algorithms.  
Please note: these are not yet ATLAS officially approved results.