B-tagging at LEP and SLC

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Introduction

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- Flavour physics, which studies both the production and properties of quark flavours in various processes, is an essential part of a physics program of all past and future collider experiments
- Experiments at LEP and SLC pioneered the development of a special tool generically called *b*-tagging, which aimed to separate heavy (*b* and *c*) and light (*u*,*d*,*s*) quarks
- The main principle behind this development is providing a universal, efficient, and reliable method of flavour separation, which can be used in various applications

Introduction

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- Several important ideas and technical solutions in b-tagging were put forward and implemented by the dedicated work of many people in five collaborations ALEPH, DELPHI, L3, OPAL, and SLD (will be called ADLOS in the following)
- The experience gained at e^+e^- colliders provides a solid basis for the development of *b*-tagging at LHC. It can also be useful for the future experiments at FCC

Introduction

- The aim of this talk is
  - to summarise the achievements of *b*-tagging at LEP and SLD
  - to underline the main ideas of *b*-tagging developed at LEP and SLC
  - to draw some conclusions, which can be important for the design of flavour tagging algorithms at FCC

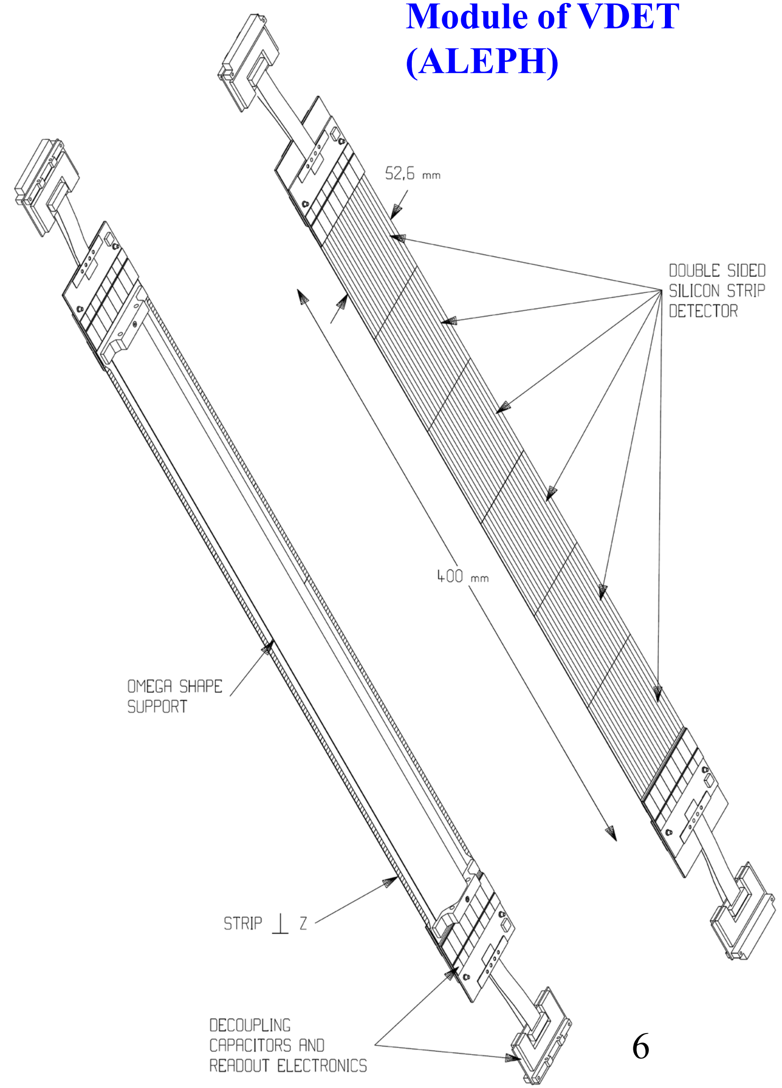
Instrumental ingredients

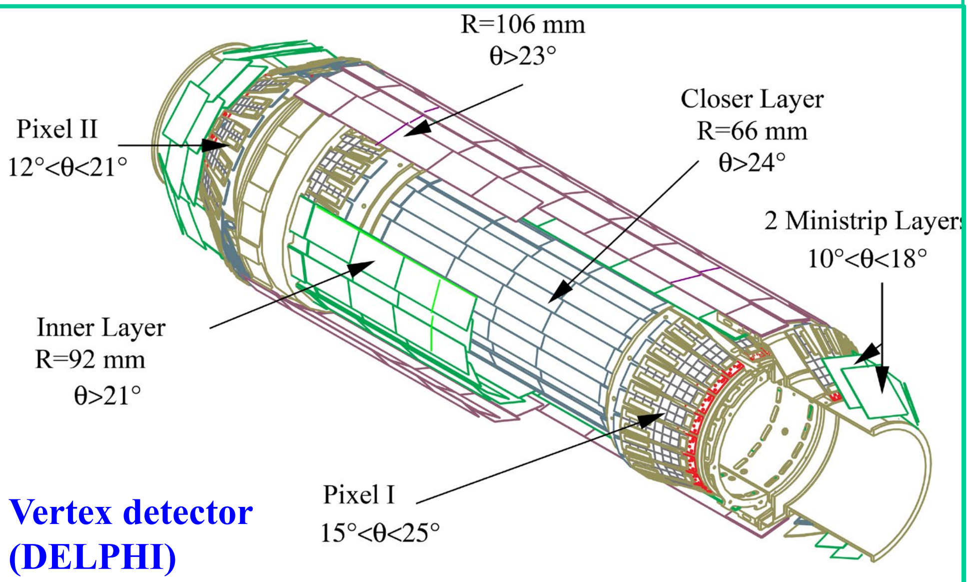
- Essential instrumental ingredients for *b*-tagging, which largely determine its performance, are
  - Vertex detector
  - Beam interaction point (beam spot)

Vertex detectors

- At LEP, vertex detectors were based on (double sided) silicon micro-strip detectors
  - 2 layers in ALEPH, L3, OPAL
  - 3 layers in DELPHI
- SLD used CCD detectors which measure space points

Module of VDET (ALEPH)

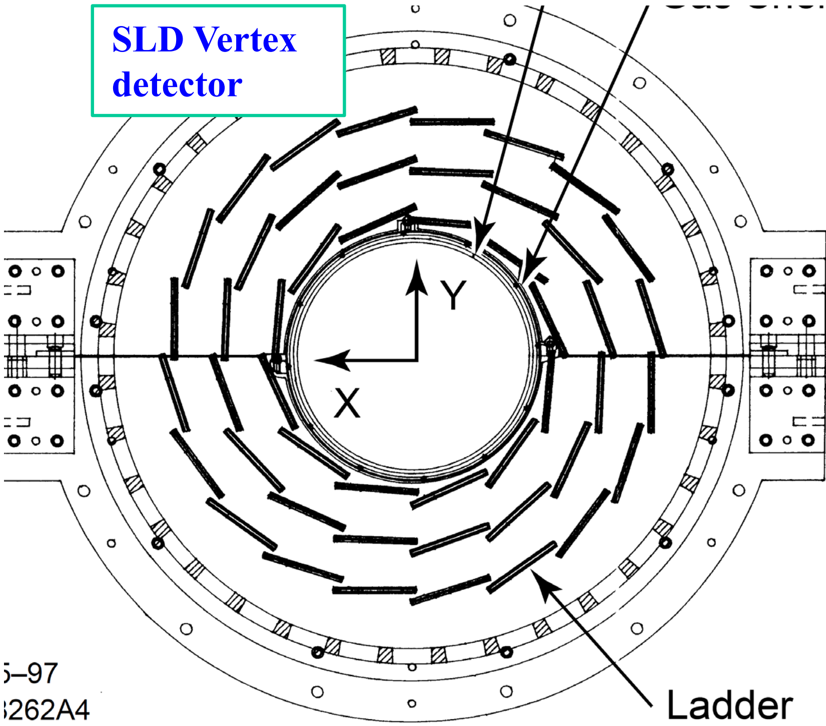




Vertex detector (DELPHI)

Essential parameters

- The quality of *b*-tagging depends on
  - Number of layers of vertex detector
  - Distance to the interaction point of the first layer
    - Especially important for the impact parameter (IP) resolution
  - Distance between the first and last layers
  - Detector resolution
    - Determines the IP resolution



Essential parameters

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- The properties of vertex detectors at LEP were similar
  - Rϕ resolution was better because of the properties of vertex detectors
- The IP resolution in SLD was superior because of a better hit resolution of CCD and smaller radius of the first layer

Table taken from: ADLOS Coll., hep-ex/0509008

Parameter	ALEPH	DELPHI	L3	OPAL	SLD
Number of layers	2	3	2	2	3
Radius of layers (cm)	6.5/11.3	6.3/9/11	6.2/7.7	6.1/7.5	2.7 – 4.8
Rϕ IP resolution (μm)	25	20	30	16	8
Rz IP resolution (μm)		30	100	35	10

  - note: the IP resolution is given for 45 GeV muons

Beam Spot

- The size of the beam spot (beam crossing area) is essential for *b*-tagging
- At LEP, the typical beam-spot size was

$$\sigma_x \approx 150\ \mu m, \sigma_y \approx 10\ \mu m$$

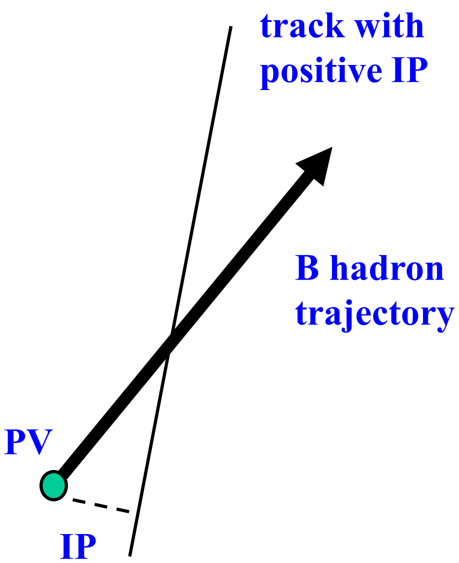
- At SLC, the beam-spot size was

$$\sigma_x \approx 4\ \mu m, \sigma_y \approx 4\ \mu m$$

- These parameters and the precision of the tracking detector determine the precision of the primary vertex (PV) reconstruction
  - LEP: $\sigma_x \approx 60 - 80\ \mu m,\ \sigma_y \approx 10\ \mu m, \sigma_z \approx 60 - 100\ \mu m$
  - SLD: $\sigma_x \approx 4\ \mu m,\ \sigma_y \approx 4\ \mu m, \sigma_z \approx 17\ \mu m$

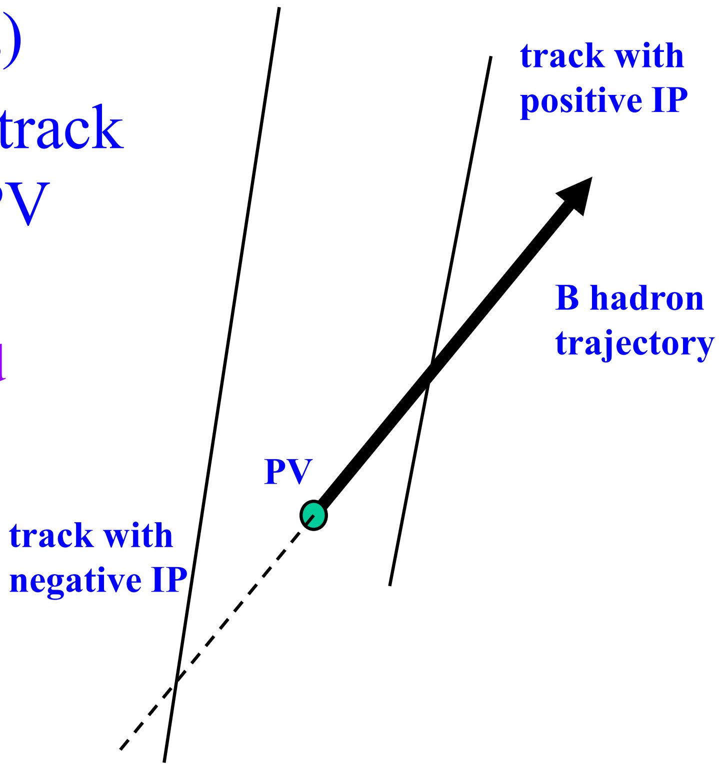
Impact parameter

- The main properties of *B* hadrons allowing their separation from light hadrons are
  - the displaced decay vertex
  - large mass
  - large decay multiplicity
- Because of these properties *B*-hadron decays produce many charged tracks with large impact parameter (IP)
  - IP is defined as the distance of closest approach of the track to PV
  - typical value of IP for *B*-decay products is ~300 μm to be compared to the IP resolution ~8-30 μm (in Rϕ plane)



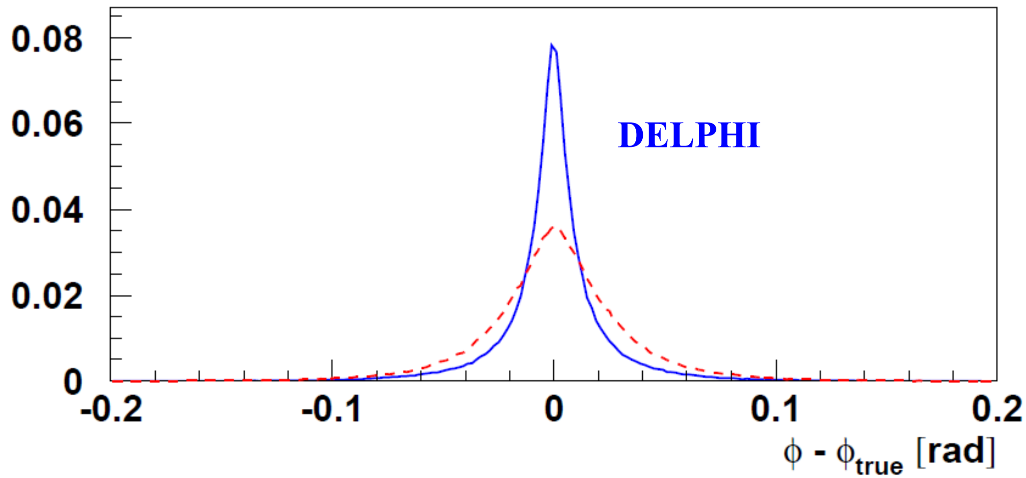
Track significance

- Typical quantity used for b-tagging is the lifetime-signed track significance (IP/σ_{IP})
- Lifetime sign of IP is positive if the track crosses the trajectory of *B* hadron after PV
  - Many tracks from *B* decay have positive IP
  - Tracks with negative IP are mainly produced in PV and their IP is due to detector resolution



Direction of *B* hadron

- To determine the lifetime sign, the direction of the decaying *B* hadron should be known
- Usually, it is approximated by the direction of the jet
- If the position of the decay vertex (SV) is known, the direction from PV to SV is used

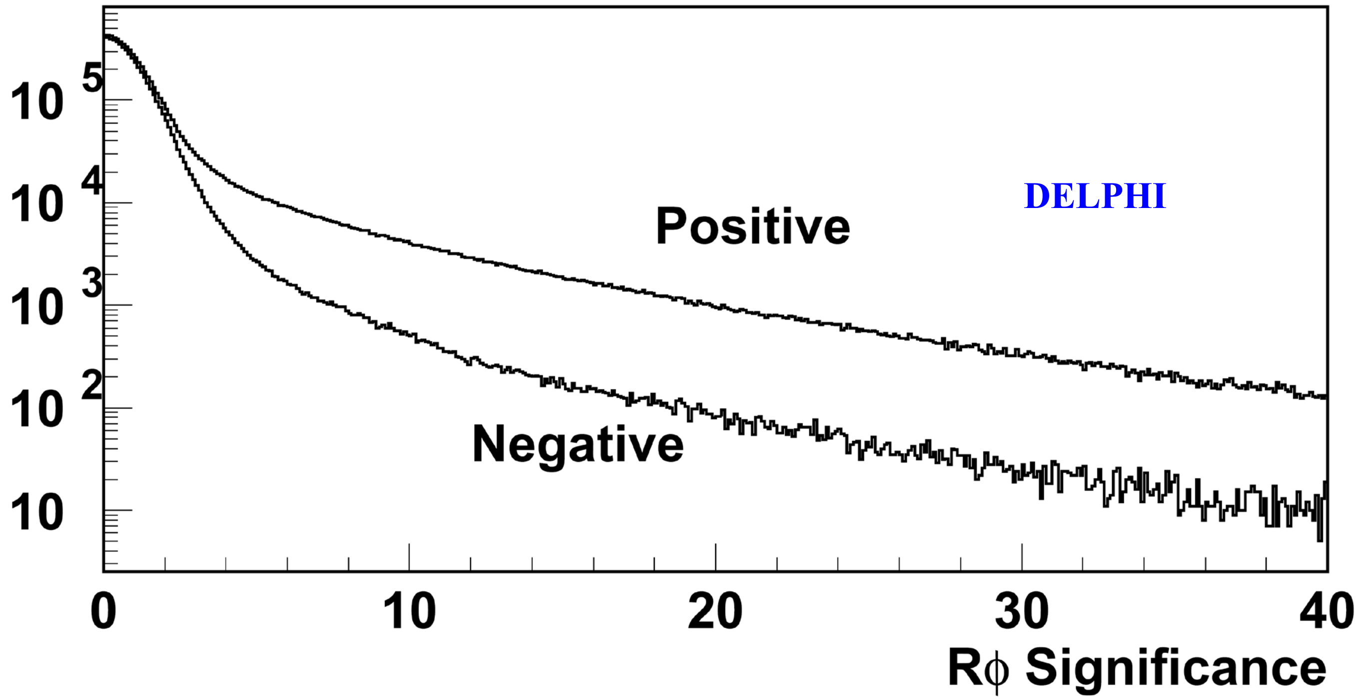


Solid line – direction from PV to SV is used as the direction of B hadron

Dashed line – direction of jet is used as the direction of B hadron

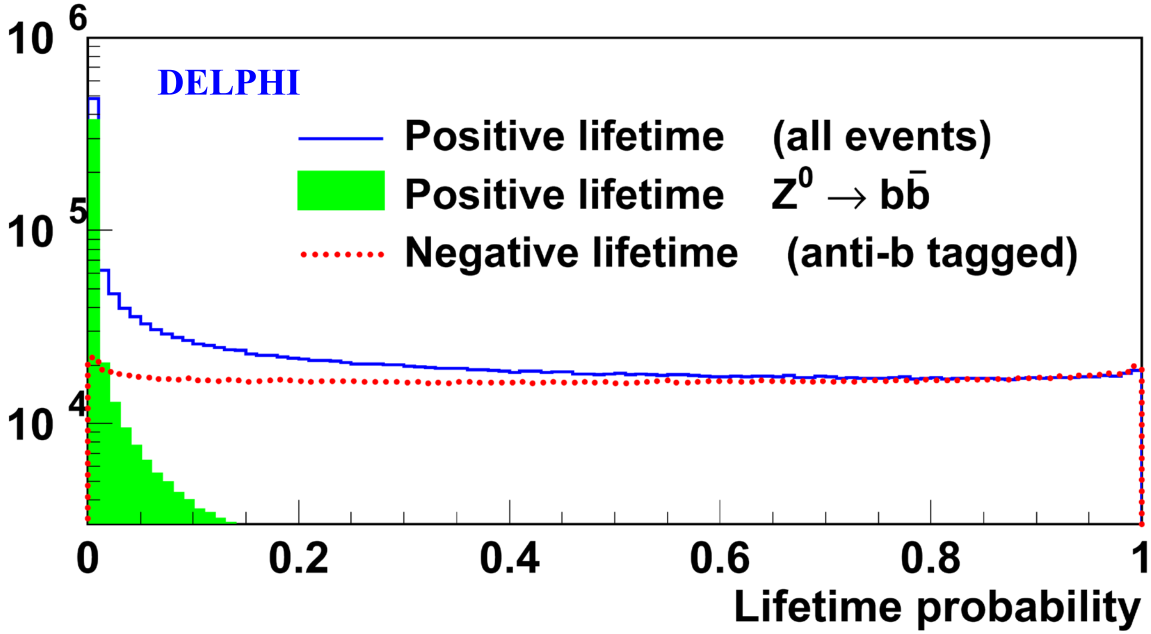
Lifetime sign

- Lifetime sign provides a clear discrimination between the tracks from *B* hadrons and from background
  - Significance of tracks with negative IP is mainly determined by the resolution and can be used for the calibration of *b*-tagging



Lifetime probability

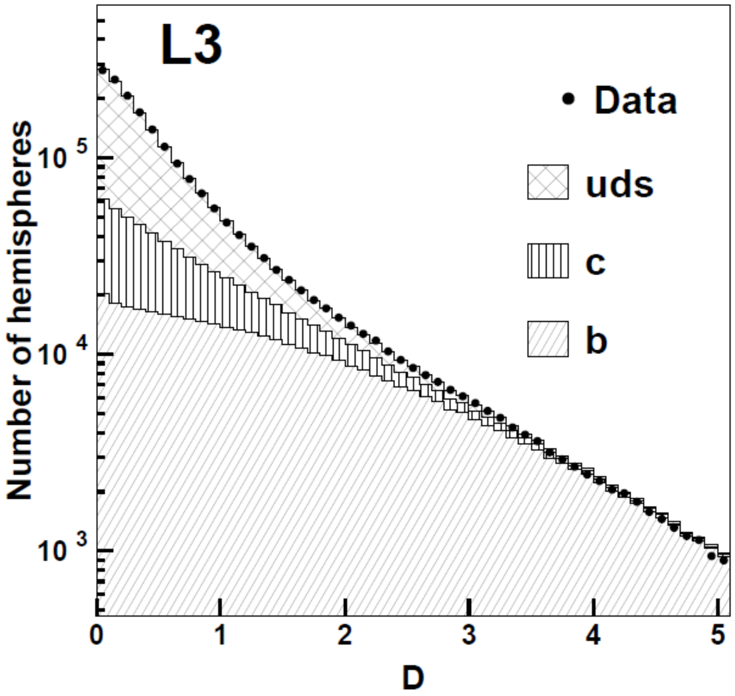
- *B* hadrons produce many tracks with large positive IP
- An original idea to combine all available information into a single variable was proposed by ALEPH (Phys. Lett., B313 (1993) 535)
- They build a single variable *P*, which gives the probability for a group of tracks to come from the primary interaction
  - flat distribution between 0 and 1 if all tracks in the group come from the PV
  - If some tracks come from *B* decays the distribution peaks at zero



Lifetime probability

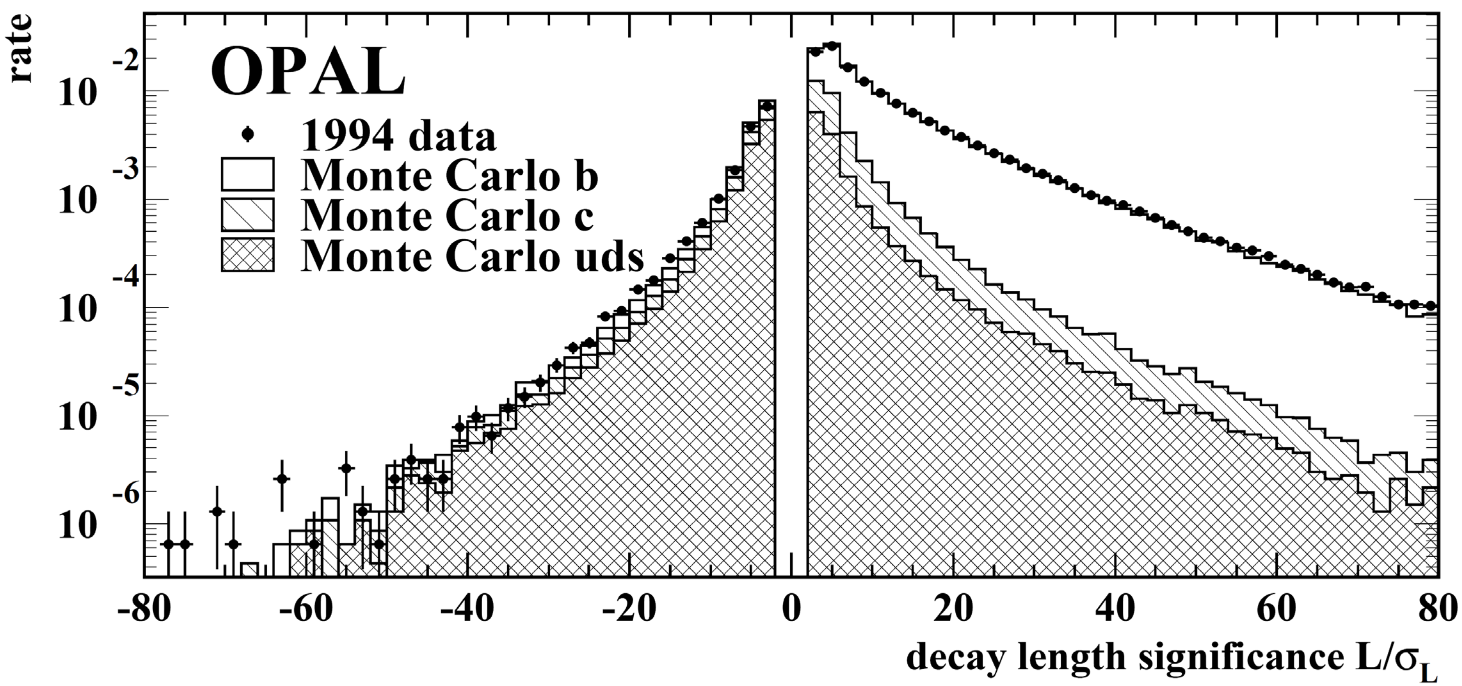
- Lifetime probability
  - Has simple and transparent meaning
  - Can be defined for any group of tracks (jet, hemisphere, event)
  - Very powerful and robust: no other combination of IP information gives a better separation between B and light hadrons
- Lifetime probability was a core variable of *b*-tagging in ALEPH, DELPHI, and L3

$-\log(P)$ in $\Gamma(Z^0 \to b\bar{b})/\Gamma(Z^0 \to had)$ measurement



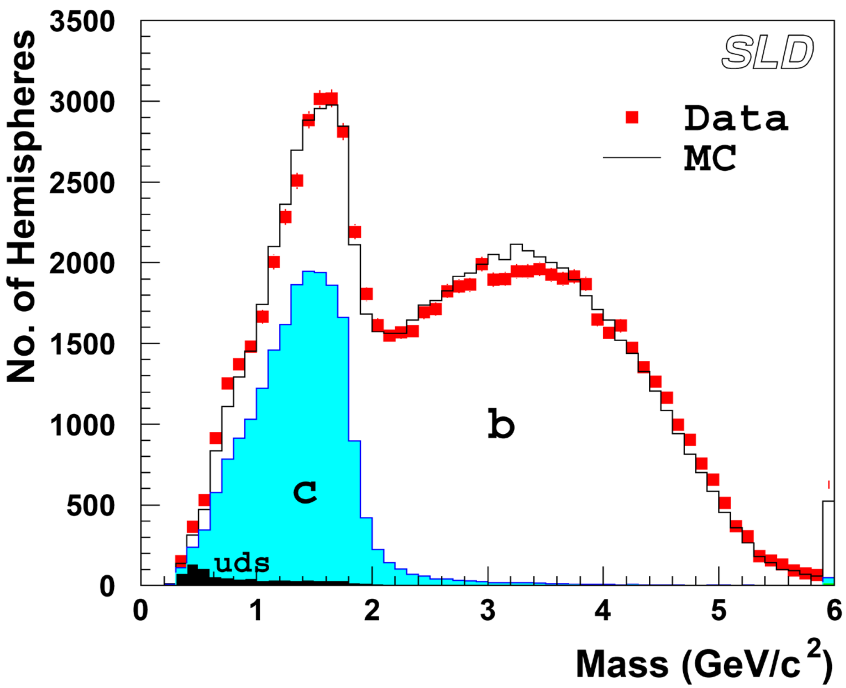
Secondary vertex

- OPAL based *b*-tagging on the secondary vertex (SV) reconstruction
  - Reconstruct SV using all track in a jet and progressively remove outliers
  - Use L/σ_L as a discriminating variable
  - Sign L/σ_L according to the relative positions of primary and secondary vertices



Secondary vertex

- *b*-tagging of SLD was also based on SV reconstruction
- Because of high quality of vertex detector and small beam-spot size, the reconstruction of SV in SLD was especially clean and efficient
- They used the mass of SV as the tagging variable
- They also included the neutral decay product in the computation of the mass



Combined *b*-tagging

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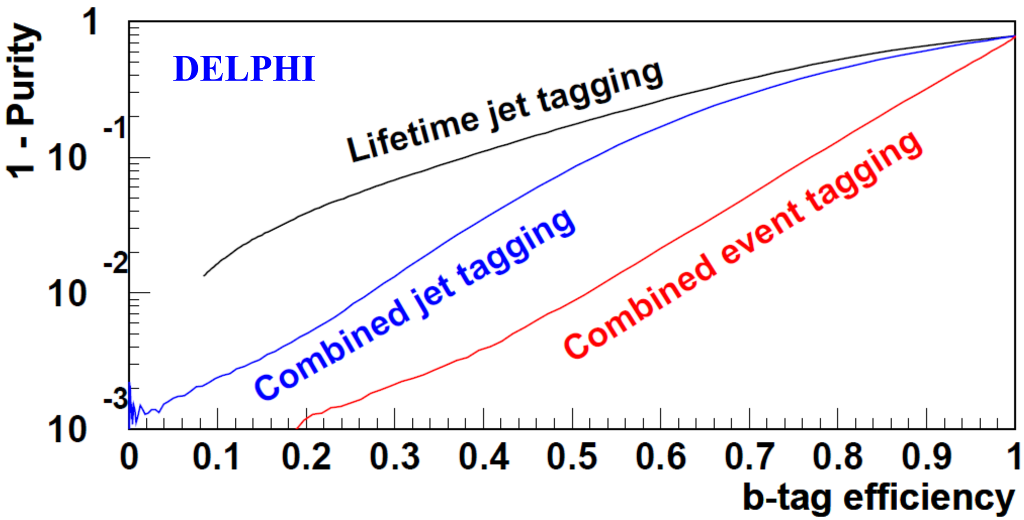
- *b*-tagging based on IP is efficient in suppressing light quarks
- However, c-hadrons also have lifetime. Hence, the separation of c- and b-quarks is less clean
- To overcome this difficulty, the experiments at LEP and SLC used additional variables, which have different distributions for *c*- and *b*-quarks
  - mass and multiplicity of SV
  - momentums of tracks

Combined *b*-tagging

- Different methods of combination of discriminating variables were used
  - SLD and OPAL used neural networks
  - DELPHI combined variables using the likelihood ratio technique
  - ALEPH used a linear sum of the lifetime probability and the second mass-sensitive variable
  - L3 used just the lifetime probability
- Combined *b*-tagging always demonstrated a much better performance



Performance of *b*-tagging

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- The benchmark process to compare the performance of *b*-tagging is the measurement of $\Gamma(Z^0 \to b\bar{b})/\Gamma(Z^0 \to had)$
- At LEP the best performance was in DELPHI
- Still, the performance of SLD is much better

Table taken from: ADLOS Coll., hep-ex/0509008

	ALEPH	DELPHI	L3	OPAL	SLD
b purity (%)	97.8	98.6	84.3	96.7	98.3
b efficiency (%)	22.7	29.6	23.7	25.5	61.8

  – All numbers are given for the tagging of a single *b*-quark

- Many other measurements used the *b*-tagging

Some lessons to learn

- SLD collaboration achieved the best b-tagging performance because of several ingredients
  - Pixels instead of strips in the vertex detector
  - Position the first layer was as close as possible to the interaction point
  - Small size of the beam spot
  - These ingredients are essential for a successful b-tagging in future experiments
- Lifetime probability developed at LEP is a very robust and transparent discriminating variable. It can be used as the basis of b-tagging in future experiments

Some lessons to learn

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- To improve the quality of *b*-tagging, and in particular, the separation between *c*- and *b*-quarks, the discriminating variables based on the properties of secondary vertex (mass, multiplicity) should be used
- The combination of all discriminating variables is a matter of taste
  - neural network is the most straightforward approach
  - other possibilities can be tried