Tagging b-jets at Colliders

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b-tagging: Why do we need it?

- **B-hadrons themselves are very interesting objects:**
  - **Many experiments and whole accelerators are specially built for their study;**
  - **Unique combination of properties: CP- violation, oscillation in B_d and B_s, lifetimes, rich spectroscopy etc.;**
  - **They have strong coupling to Higgs boson;**
  - **Can also be sensitive to new physics.**
- **Many heavy particles decay to b-quarks with large probability:**
  - $Z^0 \to b\bar{b} \ \sim 22\%$;
  - $t \to bW^- \ \sim 100\%$;
- **Many new particles predicted by different theories decay preferentially to b-quarks or t-quarks, which also produce b.**
  - $H \to b\bar{b}$ **is dominant for** $M_H < 150$ **GeV/c^2.**

b-tagging: Difficult Task

- **Like ordinary quarks, b-quarks hadronize into jets and are not directly observable;**
- **Exclusive reconstruction of B hadrons is not suitable for b-tagging as all exclusive decay rates are very small;**
- **Usually the background of ordinary quarks is much higher than the b-quark signal;**
- **As a rule, high efficiency and purity of b-tagging is required for the most interesting measurements.**

Very sophisticated analysis methods are required to efficiently select b-quarks in the background of other quark flavours.

Unique properties of b-quarks

Many properties of b's make them significantly different from other light quarks:

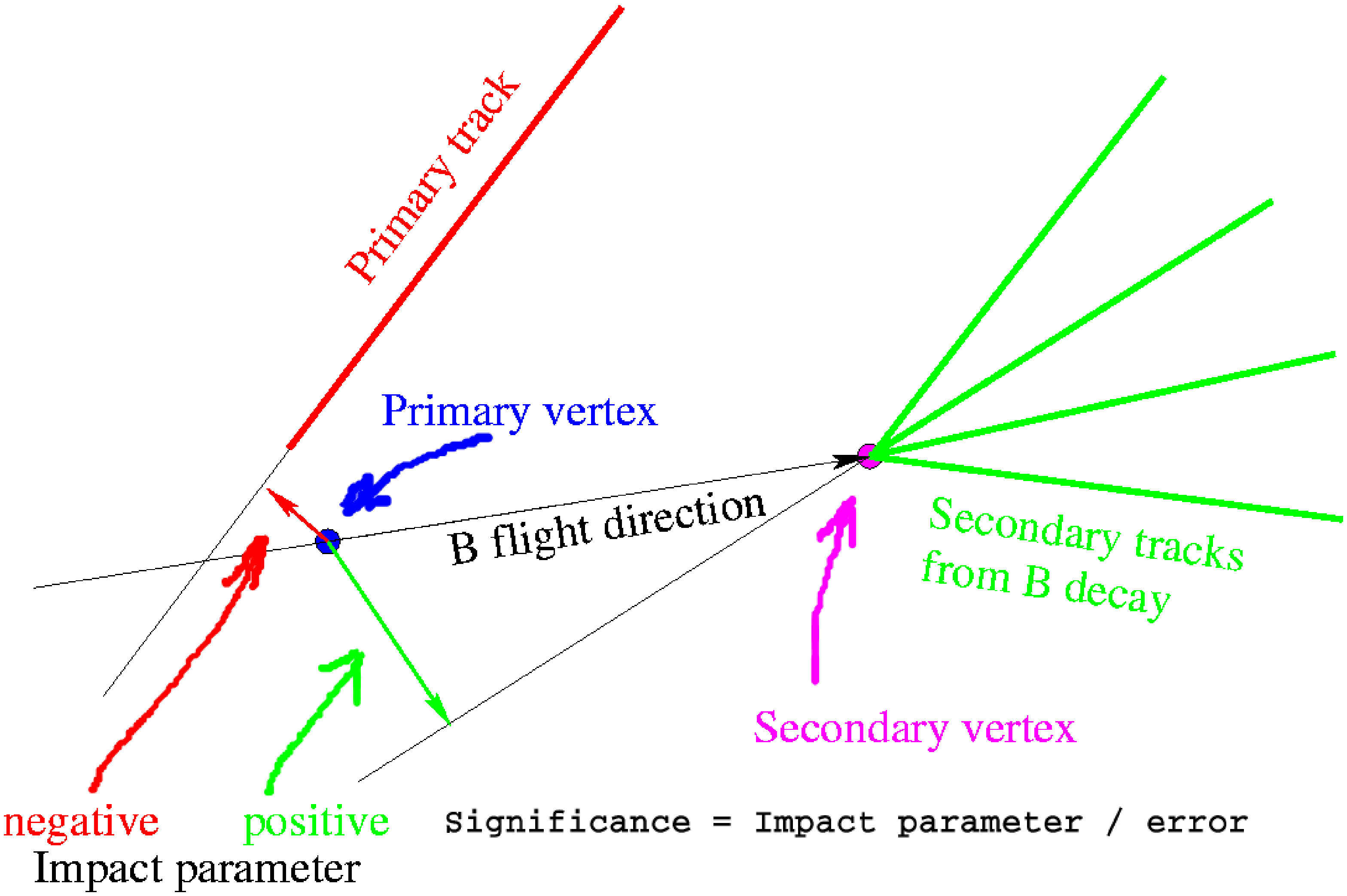
- **Long lifetime:** $c\tau \sim 500\mu$**m;**
- **Large mass of corresponding B hadrons:** $M_B \simeq 5.3$ **GeV/c^2;**
- **Large decay multiplicity: average number of charged particles in B decays is about 5;**
- **specific decay modes: semi-exclusive decays $B \to l\nu X$ have probability $\sim 10\%$;**
- **production properties: e.g. average fraction of energy taken by B hadron from b-quark is higher than for c-quark;**

Task of b-tagging is to detect all these differences and utilise them in the most optimal way to obtain pure and efficient selection of b-quark.

B-hadron Lifetime

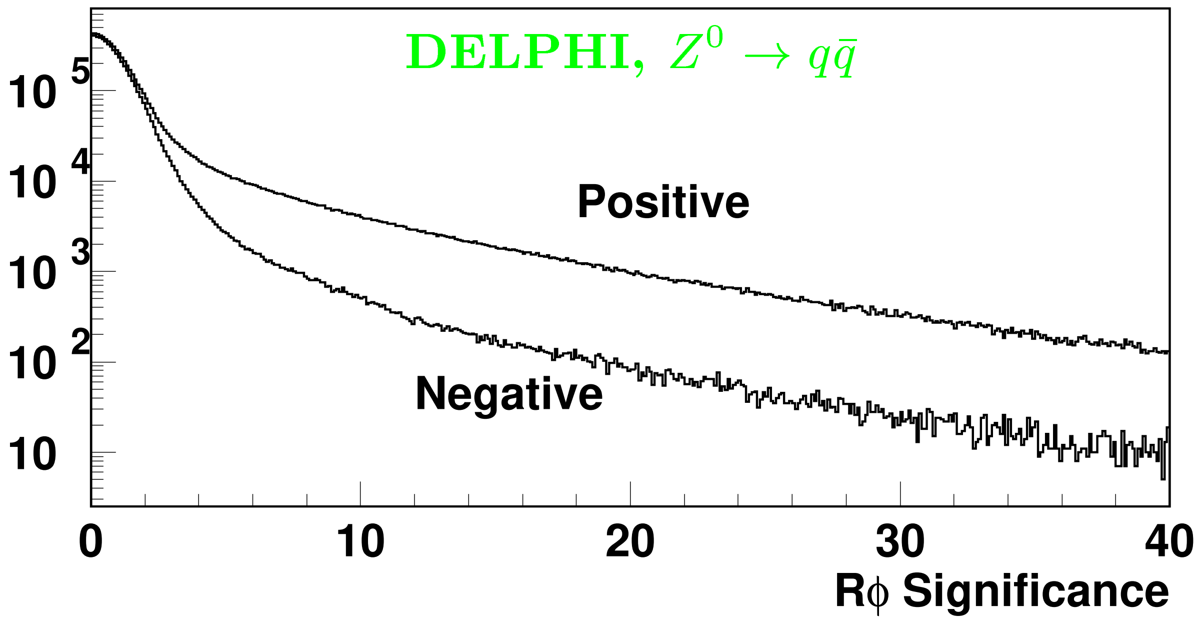
- **Due to long lifetime of B-hadron, its decay products have large impact parameter w.r.t. collision point (primary vertex);**
- **Typical value of impact parameter in B decays $\sim 500\mu$m;**
- **Precise measurement of particle trajectory is required to work with such small values;**
- **Impact parameter divided by the expected precision of its measurement is called *Significance*;**
- **This variable gives statistical significance of deviation of impact parameter from 0;**
- **Significance is the main input variable for lifetime b-tagging;**

Definition of Impact Parameter



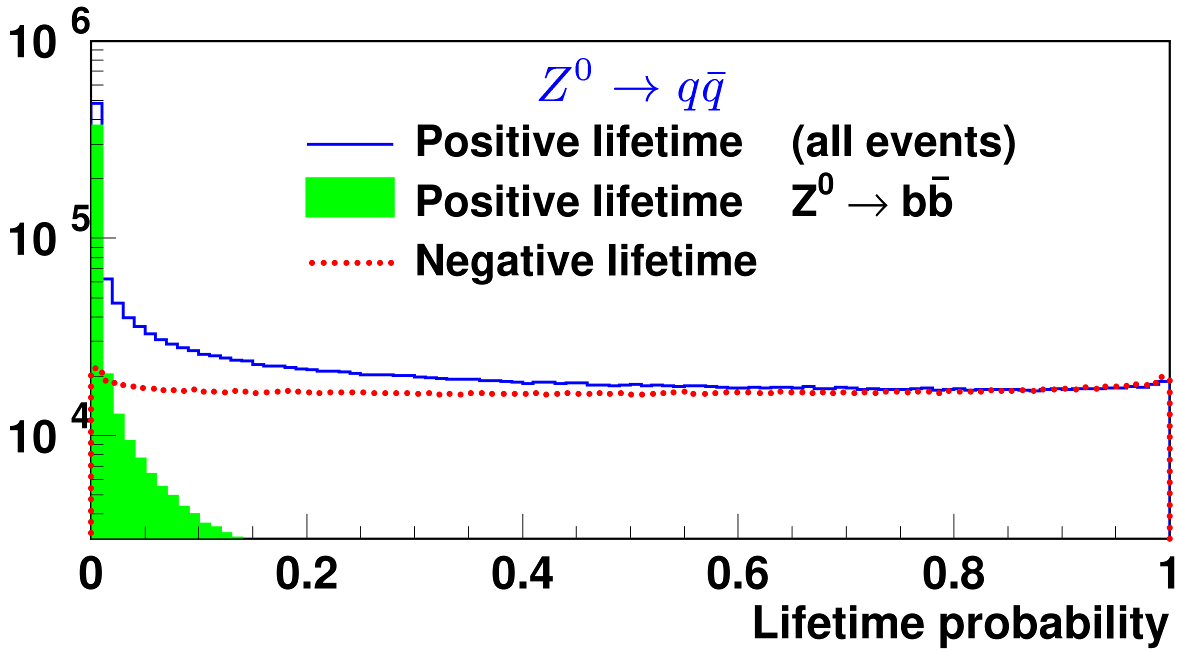
Sign of Impact Parameter

- **Sign of impact parameter is defined as positive, if the track crosses the B-hadron flight direction after the primary vertex;**
- **Sign is defined as negative, if track crosses the flight direction behind the primary vertex;**
- **Tracks from B decay always have positive impact parameter;**
- **They produce excess of tracks with large positive significance (significance = impact parameter/error).**



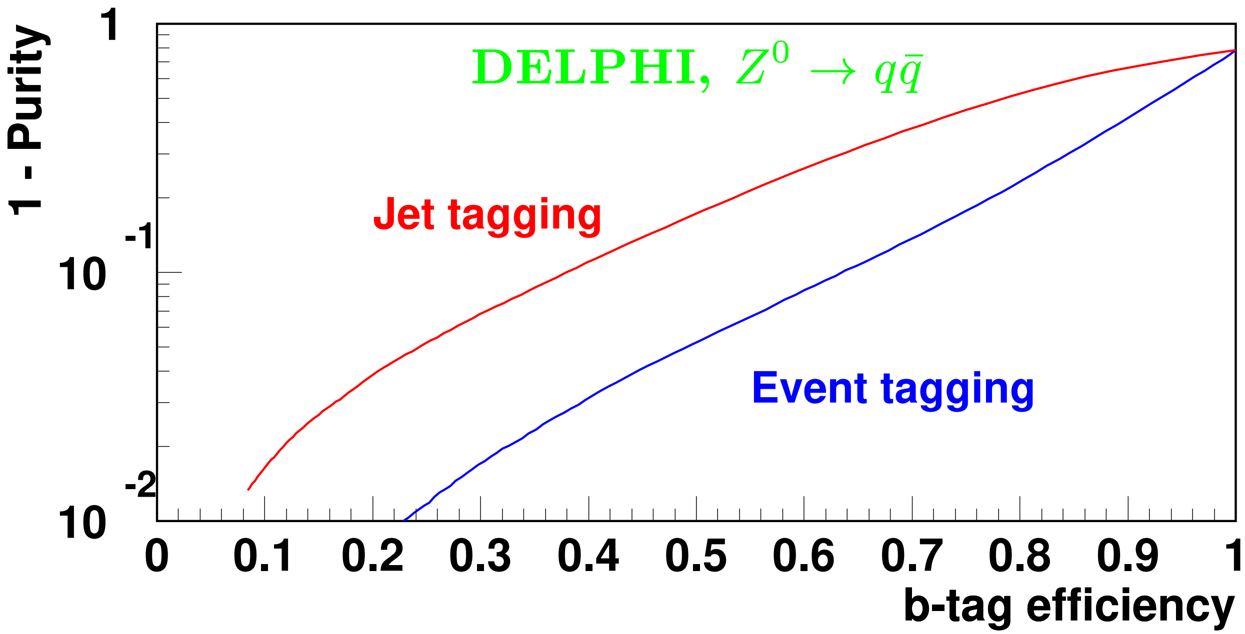
Lifetime Probability

- **B-hadron decay gives many tracks with large significance;**
- ***Lifetime Probability* (ALEPH) is an efficient and simple way of combining all significances into a single variable. It gives probability for given group of tracks to come from primary vertex.**
- **For B-hadron this probability is very small; for group of primary tracks it is evenly distributed between 0 and 1.**



Lifetime Tagging

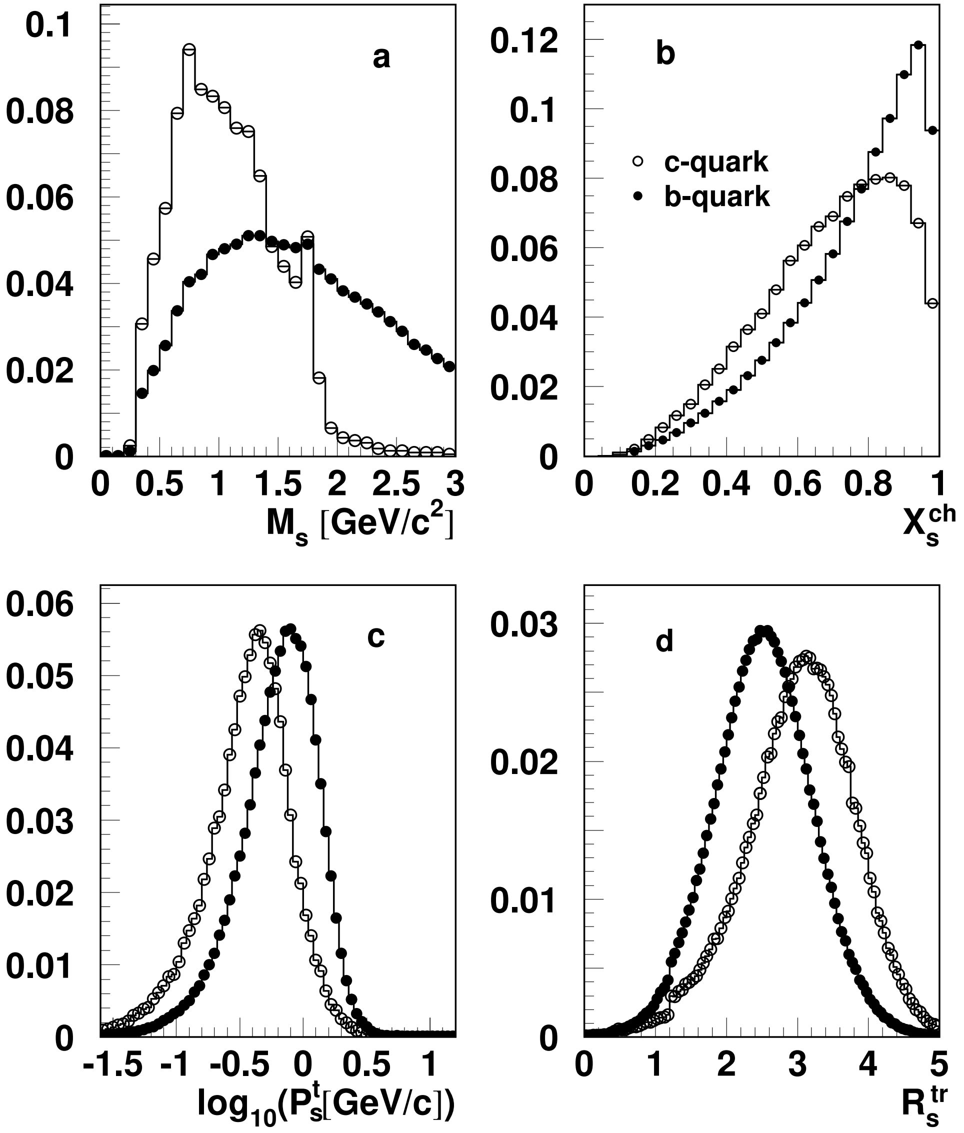
- **selecting events with small lifetime probability gives pure sample with b-quarks;**
- **Lifetime probability can be computed for any group of tracks (single jet, whole event). b-quarks are usually produced in pairs and tagging the whole events is always more efficient.**
- **Background suppression $\sim 10^{-2}$ can be achieved with reasonable selection efficiency $\sim 20-30\%$.**



Additional Variables

- **Other properties of B-hadron production and decay, which make it different from light quark flavours (u, d, s, c), can be included in the b-tagging;**
- **Many of them can be constructed with reconstructed secondary vertices;**
- **They can be:**
  - **Invariant mass of group of particles in secondary vertex (SLD);**
  - **Fraction of jet energy, taken by B-hadron (DELPHI);**
  - **Visible transverse momentum of B-hadron with respect to its flight direction (SLD);**
  - **Energetic lepton (muon or electron) from $B \to l\bar{\nu}X$ (10%);**
  - **track rapidity with respect to B flight direction (DELPHI);**
- **Each property itself has a poor b-selection power;**
- **Combined together, they give significant improvement of b-tagging performance.**

Comparison of Some Properties in b- and c-jets



$a:$ M_s **- Invariant mass of group of particles in secondary vertex;**

$b:$ X_s^{ch} **- fraction of jet energy, included in the secondary vertex;**

$c:$ P_s^t **- transverse momentum of particles, included in the secondary vertex w.r.t. the flight direction;**

$d:$ R_s^{tr} **- rapidity of track from secondary vertex.**

Combination of Discriminating Variables

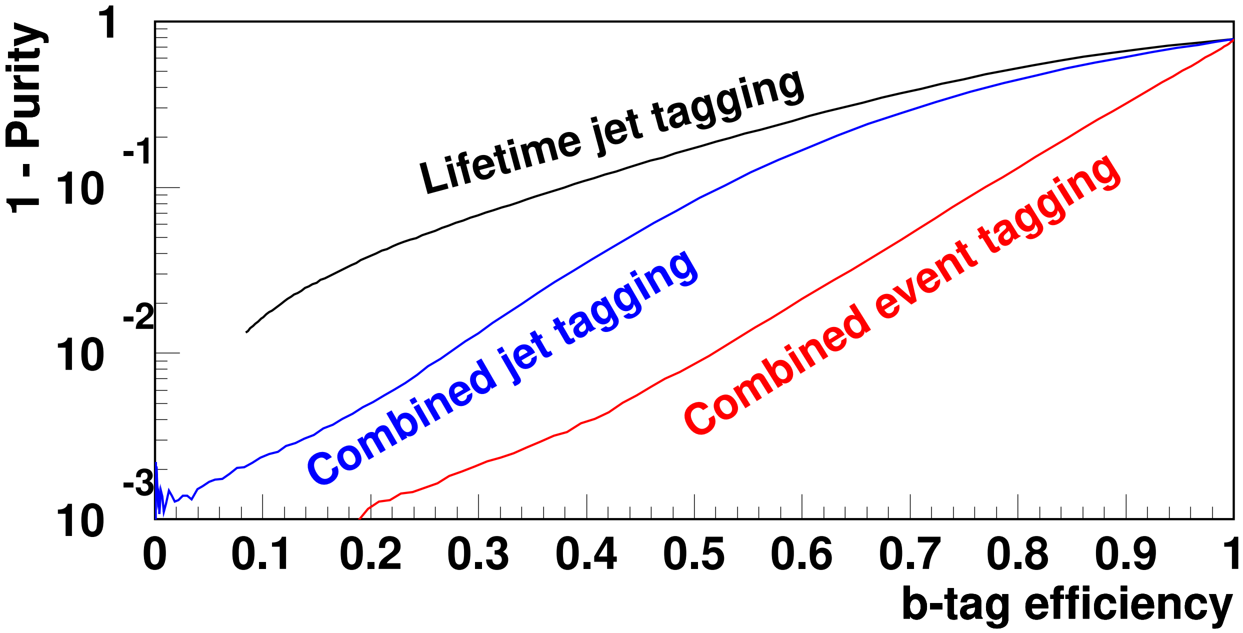
- **Additional properties can be combined with lifetime tagging in many different ways:**
  - **Apply cuts (not efficient);**
  - **Neural Network;**
  - **Likelihood ratio;**
- **Likelihood ratio - simple and performant method;**
- **For each discriminating variable x_i the ratio of probabiliity density functions for background ($f_i^{bgd}(x_i)$) and signal ($f_i^{sig}(x_i)$) is computed;**
- **The combined tagging variable is simply:**

$$y = \prod_{i=1}^{n} \frac{f_i^{bgd}(x_i)}{f_i^{sig}(x_i)}$$

Enhanced Performance with Combined Tagging

- **Including additional properties in b-tagging improves its performance by up to 10 times;**
- **Typical performance: background suppression up to 10^{-3} with 20-30% b-quark efficiency.**

DELPHI, $Z^0 \to q\bar{q}$



b-tagging at Hadron Colliders

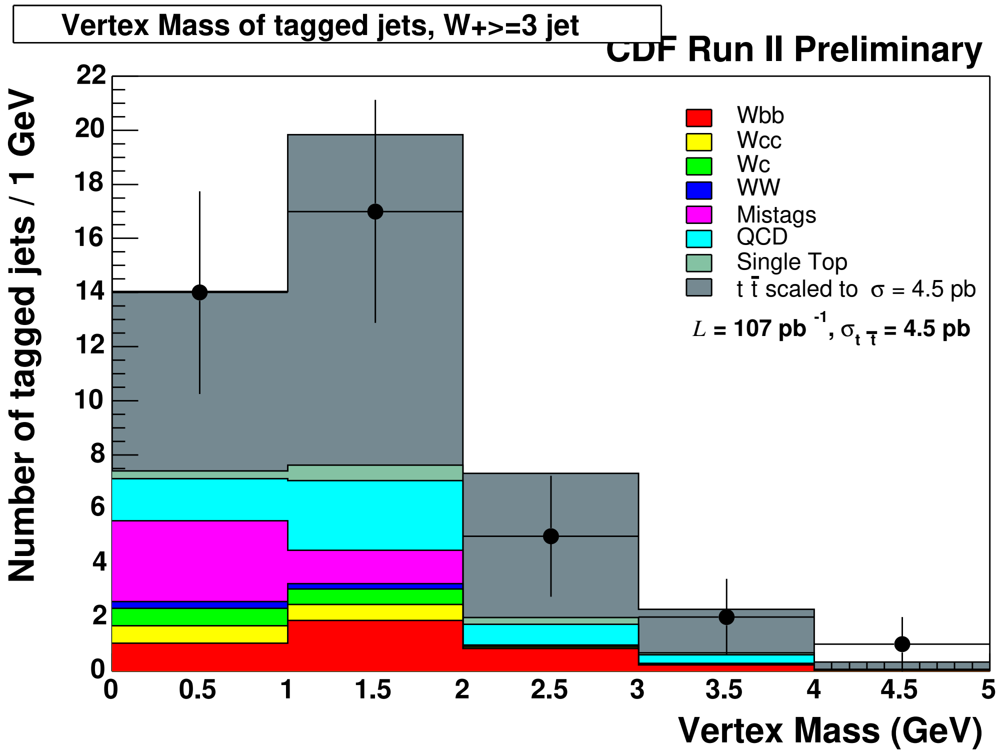
- **Both CDF and DØ experiments at Tevatron (Fermilab) use the b-tagging to select t-quark and for the Higgs boson search;**
- **Both experiments use reconstructed secondary vertices and energetic leptons to tag b-quarks;**
- **Multivariate b-tagging methods are still in development stage (especially in DØ);**
- **Applying b-tagging for the t-quark selection significantly improves results:**

CDF summer 2003

$\sigma(t\bar{t}) = 4.5 \pm 1.4(stat) \pm 0.8(syst)$ **(lepton+jet+btag)**

$\sigma(t\bar{t}) = 6.9 + 2.7 - 2.4(stat) \pm 1.2(syst)$ **(di-lepton and no btag)**

Mass of Secondary Vertex in $t\bar{t}$ Events (CDF)



Conclusions

- b-tagging is important part of any collider experiments;
- Long lifetime of B-hadrons provides powerful tagging variable;
- Additional properties significantly improve b-tagging;
- b-tagging is useful in many analyses at hadron colliders;
- b-tagging is the important for the search for the Higgs boson and other new particles.