Vertex Reconstruction and b-tagging at CDF/D0

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Outline

- Introduction.

- Vertex fitting.

- Primary and secondary vertex reconstruction.

- b-tagging: overview of algorithms and performance.

New Ideas:

- Robust methods for vertex reconstruction: Adaptive fitting and global vertex reconstruction.

- Multivariate b-tagging.

Vertex Reconstruction and b-tagging

Vertex b-tagging consists of three main steps, related to each other:

- **Vertex Finding:**

  - a pattern recognition problem: identification of tracks belonging to the vertex, rejection of outliers (poorly measured tracks, tracks belonging to different vertices).

- **Vertex Fitting:**

  - estimation of the spatial position of the vertex, and the momentum of the tracks at the vertex.

- **Secondary Vertex b-tagging:**

  - Tag long lived hadrons from b decays.

Kalman Filter Vertex Fitting Technique

- Sequential minimization of a local χ^2:

$$\chi^2(x,q) = (x-x_{k-1})^T C^{-1}(x-x_{k-1}) + (m_k - h(x,q))^T V_k^{-1}(m_k - h(x,q))$$
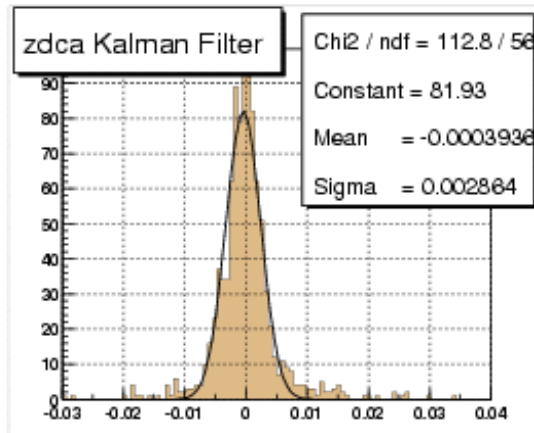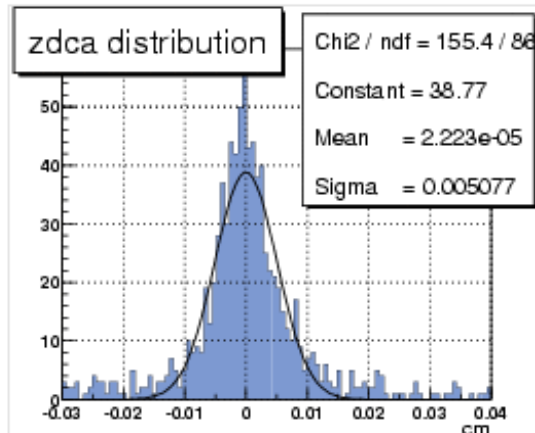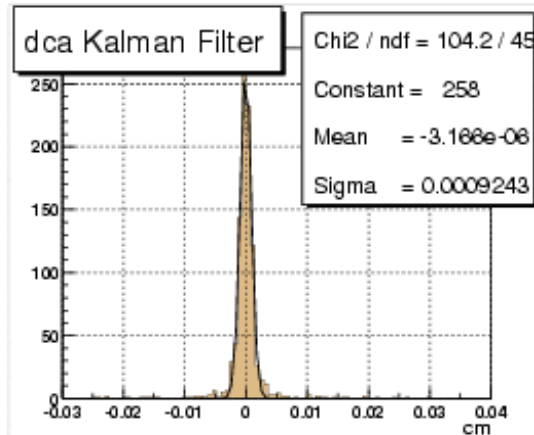
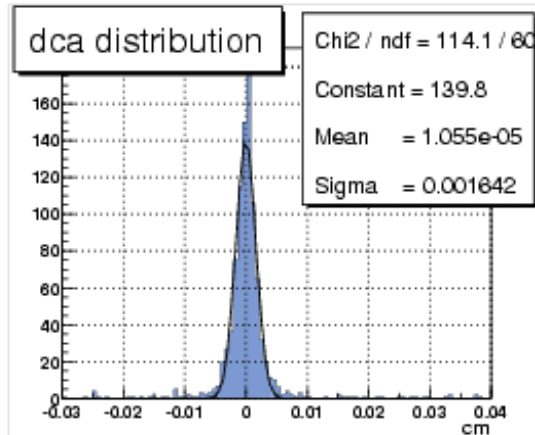- *m, V*: track parameters and errors

- *x, C*: vertex position and errors.

- *q* : track momentum at the vertex

- *h(x,q)* : "measurement equation"
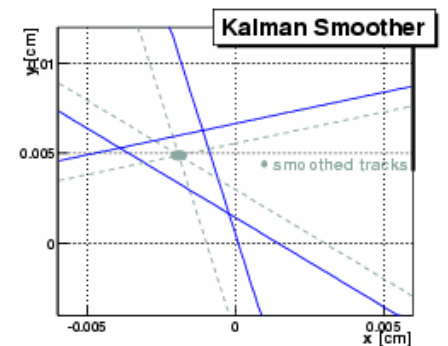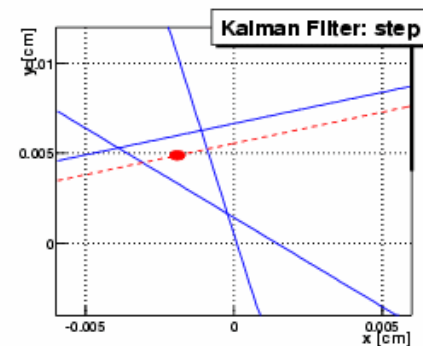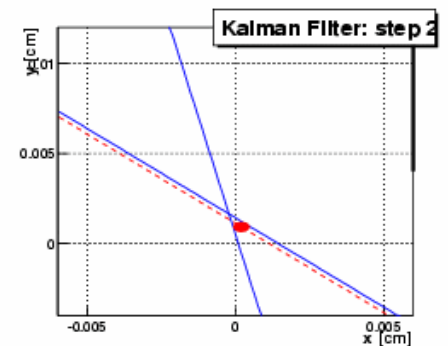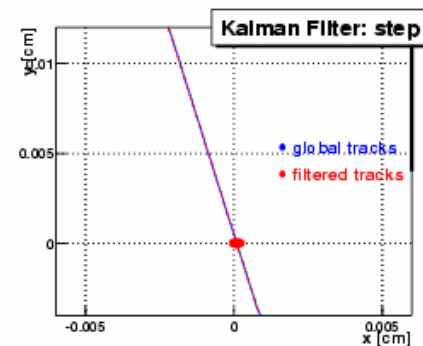
Filtering: tracks are added one at the time and the vertex position is updated.
Smoothing: recalculate track parameters at the final vertex position.

Kalman Filter Vertex Fitting Technique

Track parameters are significantly improved after smoothing.

Better vertex kinematic variables: mass, energy, etc.

track parameters:
$$p = (dca, zdca, phi, \tan\lambda, q/p_T)$$

Monte Carlo example of track-parameter resolution before/after Kalman vertexing for a 5-track displaced vertex fit.

Primary Vertex Finding at D0

- Cluster tracks along the Z direction: $\Delta Z < 2\,cm$

- 1Pass: determine beam spot at each cluster (fitting all tracks with loose selection to a common pint)

- 2Pass: preselect tracks with small impact parameter with respect to the estimated beam spot position: $s/\sigma(s) < 3$

Tear-down finding algorithm:

- Vertex fit of all candidate tracks
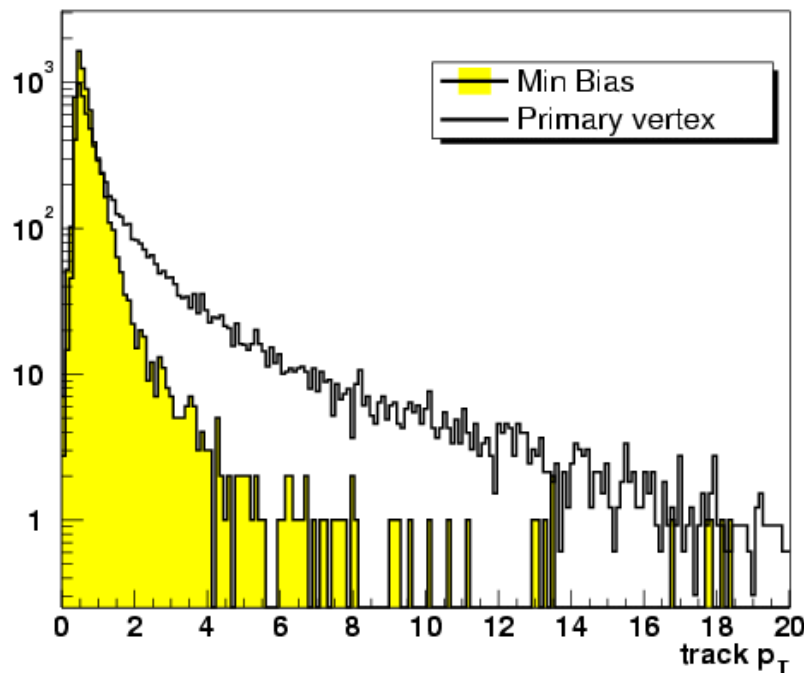- Reject the highest x^2 contributing track and re-fit, until the total vertex x^2 is smaller than 10.
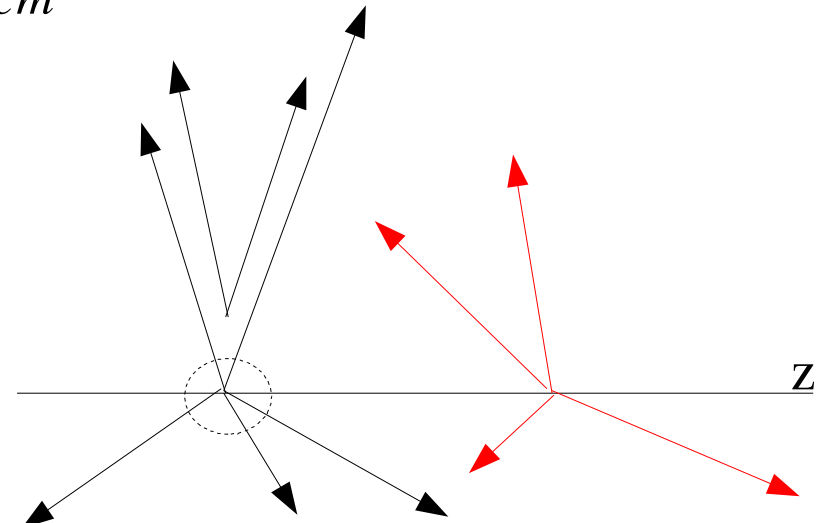
At L=10e^{31}cm/s^2, we expect 2.7 additional min bias interactions distributed within a sigma of 25cm in z:

PV algorithm finds both the hard-scatter and min-bias interaction vertices.

Primary (Hard-Scatter) Vertex Selection

Identify the hard scatter vertex from additional min-bias interactions based on the p_T spectrum of tracks

Compute the probability that a vertex is a min-bias interaction, and select the vertex with the lowest $p(MB)$.

$$p(MB) = \prod \sum_{k=0}^{N-1} \frac{(-\log P)^k}{k!}$$
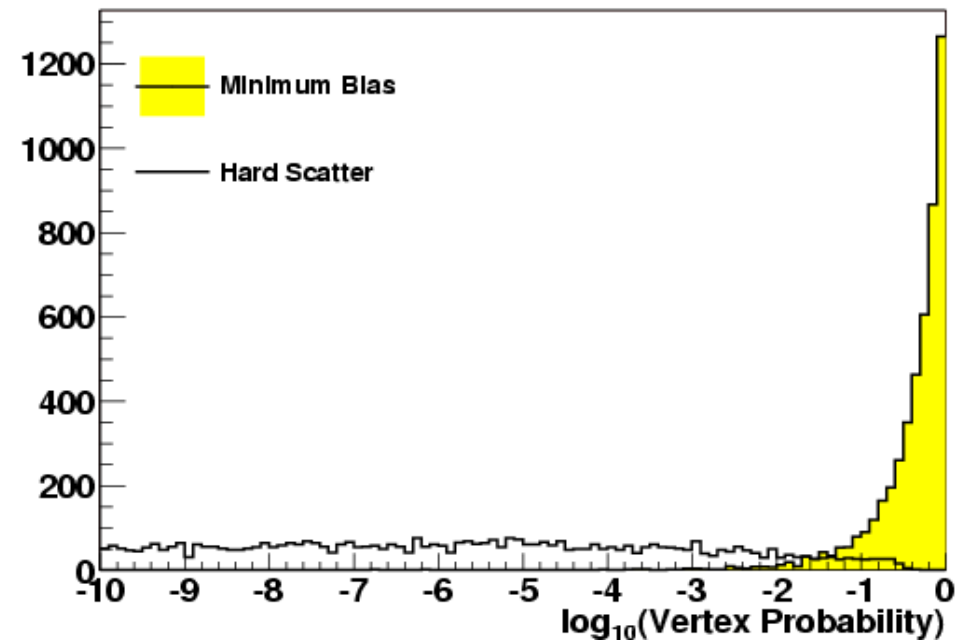
$$P = \prod_{k=0}^{N-1} p_k(p_T)$$

$$p(p_T) = \frac{\int_{\log_{10}(p_T)}^{\infty} F(P_T)\, dp_T}{\int_{\log_{10}(0.5)}^{\infty} F(P_T)\, dp_T}$$

**CDF selects the vertex with the highest Sum(E_T)**

Secondary Vertex Reconstruction (D0)

- Find track-based jets:
    - Simple cone algorithm of size R=0.5
    - Select tracks based on number of hits, $p_T > 0.5$ GeV/c,
      and $|dca| < 0.15\,cm$, $|dcaz| < 0.4\,cm$

- Build-Up vertex finding within track-jets:
    - Select tracks with large impact parameter
    - Find all 2-track seeds vertices
    - Attach additional tracks pointing to seeds
      according to the resulting chi^2 contribution to the vertex.
    - Select secondary vertices based on 2D decay length.
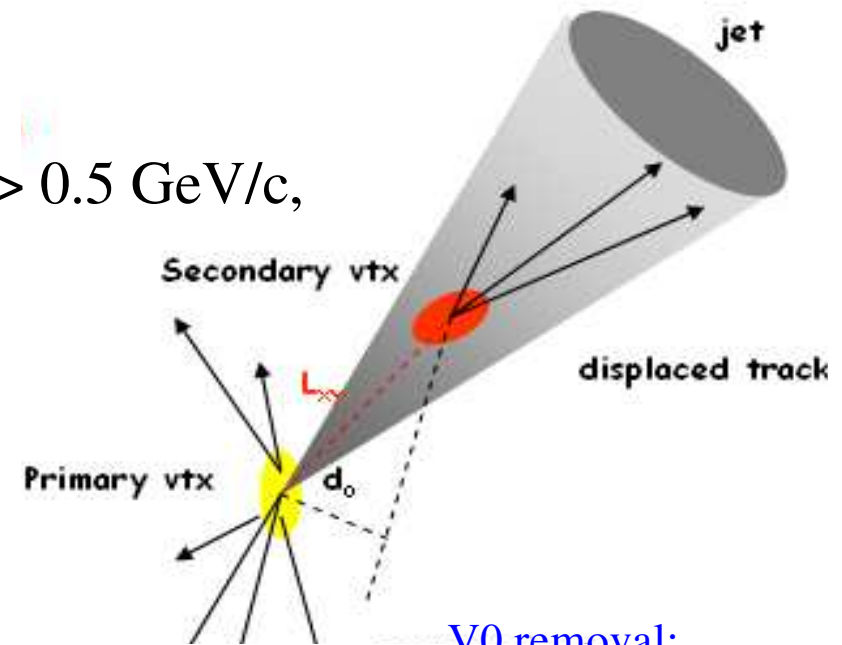
V0 removal:
remove tracks
consistent with $K_{S,}$
Lambda and
conversions prior to
secondary vertex
reconstruction.

- Associate secondary vertices with jets:

$$\Delta R(vtx, jet) < 0.5$$

$$\left| \frac{L_{2D}}{\sigma L_{2D}} \right| > S, \quad S = 5,6,7$$

$$\left| L_{2D} \right| = \left| \vec{r}_{SV} - \vec{r}_{PV} \right|$$

Secondary Vertex Reconstruction (CDF)

Select tracks within calorimeter-jet cone:
    Require at least 2 "good" tracks based on p_T, number of hits and chi^2.

Pass1: Search for a secondary vertex with at least 3 tracks:
    $p_T > 0.5$GeV/c, at least 1 track with $p_T > 1$GeV/c
    displaced tracks: $s/\sigma(s) > 2.0$

Pass2: Search for a secondary vertex with at at least 2 tracks:
    $p_T > 1$GeV/c, at least 1 track with $p_T > 1.5$GeV/c
    displaced tracks: $s/\sigma(s) > 3.5$

Select secondary vertices based on the transverse decay length significance:

$$\left| \frac{L_{2D}}{\sigma L_{2D}} \right| > 7.5 \quad \text{(tight)}$$

L_{2D} is calculated as the projection onto the
jet axis (in r-phi) of the vector $\vec{r}_{SV} - \vec{r}_{PV}$

Light Quark Mistag Rate

Mistags are non-heavy flavor jets tagged by the secondary vertex algorithm.

- Fake tracks displaced from the primary vertex, and tracking/vertexing resolution
- Long-lived particles and nuclear interactions with detector material not reconstructed by the V0-Filter algorithm.
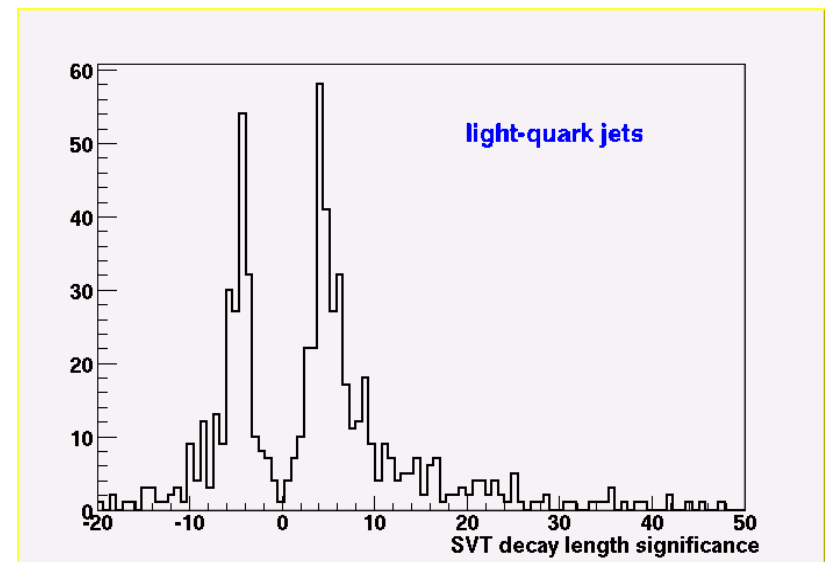
1- Use negative decay length vertices to measure the Negative tag rate.

2- Convert negative tag-rate into light quark mistag using Monte Carlo (D0): $\epsilon_l = \epsilon^n SF_{hf} SF_{ll}$

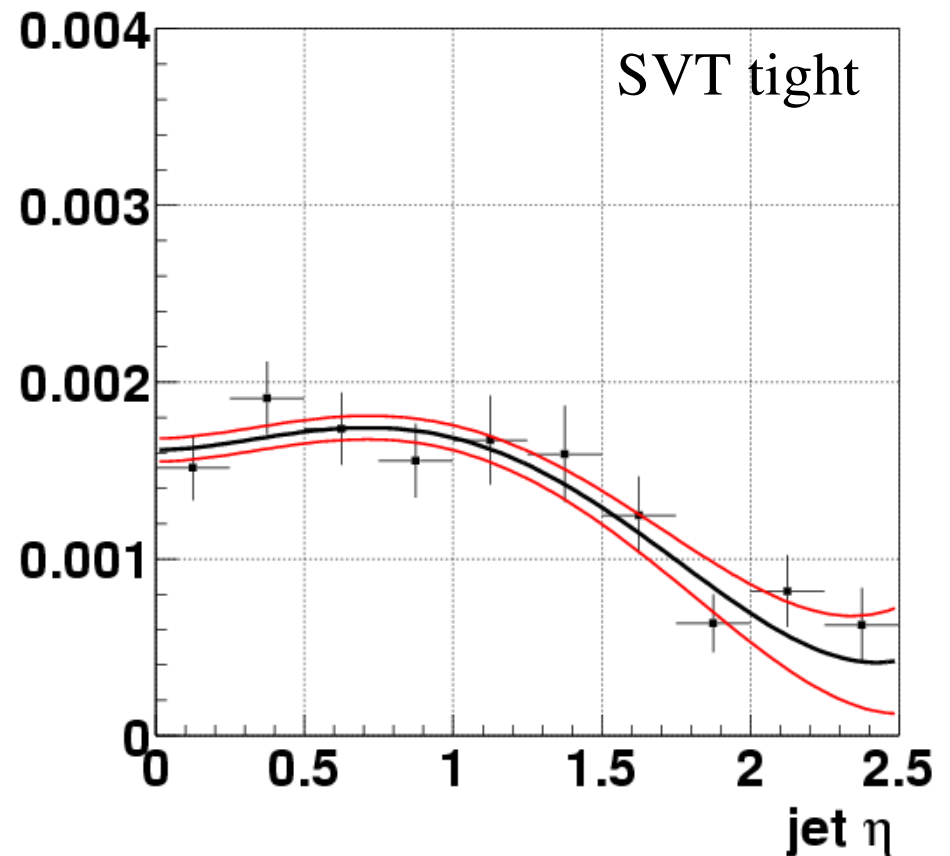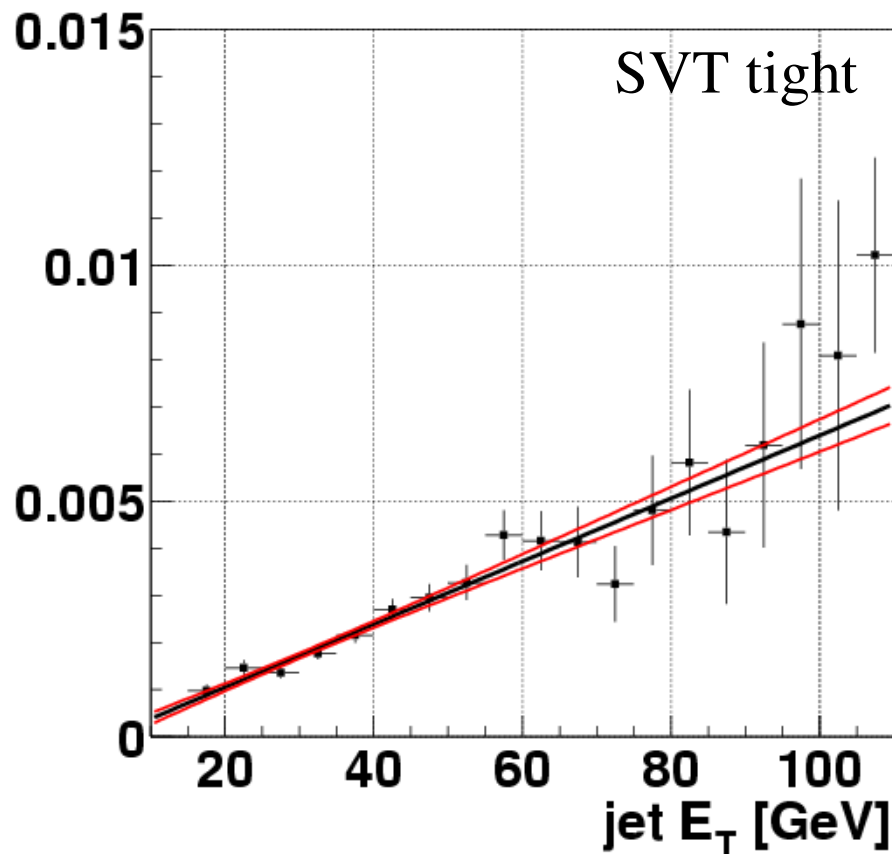$SF_{hf} = \epsilon_l^n / \epsilon^n$ Heavy flavor in negative tags

$SF_{ll} = \epsilon_l^p / \epsilon_l^n$ Long lived particles

light-quark jets

SVT decay length significance

Sign of L_{2D} is given by the angle between the jet axis and the vertex momentum
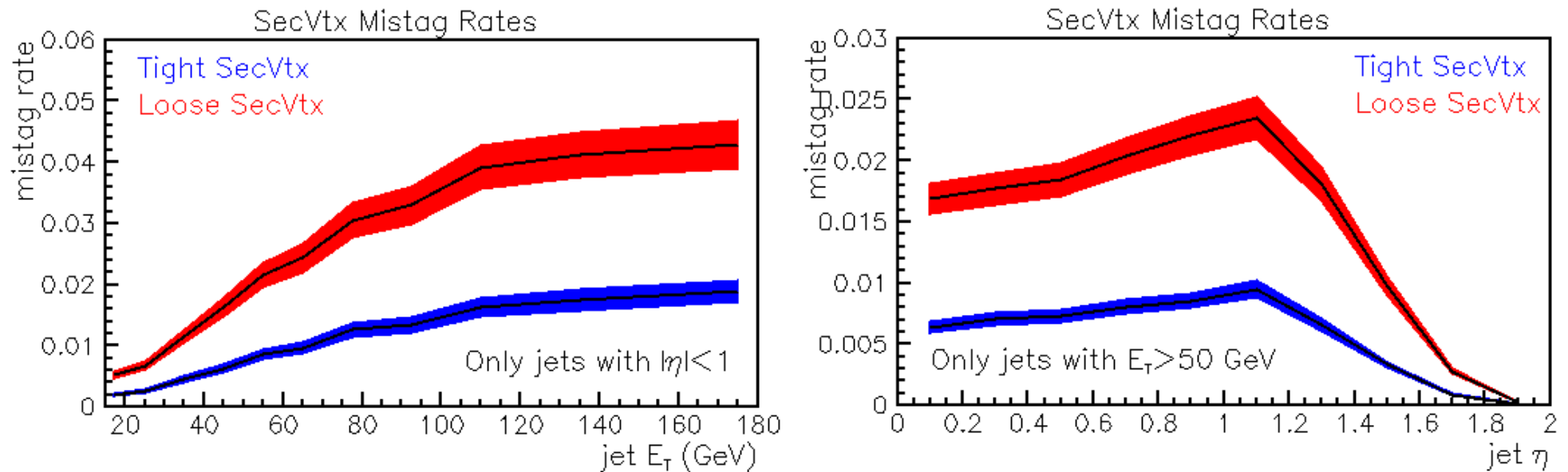
Measurement of the Mistag Rate (D0)

Both CDF and D0 use inclusive jet trigger data to measure the negative tag rate

Light quark tagging rate is parametrized as a function of jet eta and E_T.

Measurement of the Mistag Rate (CDF)

Light quark tagging rate is parametrized as a function of four jet variables and one event variable:

E_T, track-multiplicity, eta, phi, Sum(jet E_T)

Systematic errors due to trigger jet bias and sample bias.

Measurement of b-tagging Efficiency

Simulation: ratio of tagged jets the total number of (*taggable*) jets.
Data: mixture of light and heavy flavor jets.
             select a sample enriched in heavy flavor.
             estimate the b-content of the sample.

CDF:

- Measure b-tagging efficiency in data and in the simulation.
- Compute the ratio of of efficiencies between data and simulation.
- Correct the tagging efficiency in the simulation by the scale factor.

D0:

- Measure b-tagging efficiency in data and parameterize it as a function
  of jet ET and eta.
- Apply parameterization to the simulation.
- Factorize taggability and efficiency.
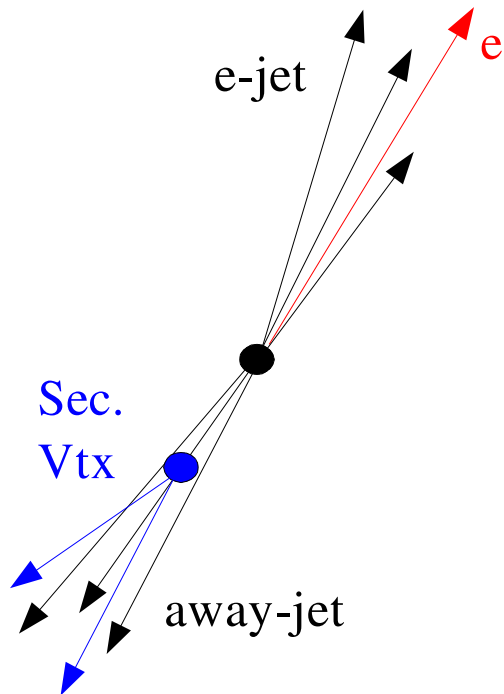
b-tagging Efficiency:
Double Tag Method (CDF)

Low p_T inclusive electron sample (enriched in semileptonic b/c decays)

non-isolated electron $E_T > 9$ GeV, track $p_T > 8$ GeV/c.

Two back-to-back jets, $E_T > 15$ GeV (electron and away jets)

Require the away jet to be tagged by the secondary vertex algorithm.

e-jet

e

Sec.
Vtx

away-jet

Large fraction of electron are from conversions or fakes in light jets
Tagged away jet can be mistagged or contain heavy flavor from gluon splitting.

Use conversions to determine the light flavor composition of the electron jets.
Use mistags to account for events with light flavor on both sides.
b/c ratio is measured on data, from invariant mass templates of positive tag tracks.

b-tagging Efficiency: Double Tag Method (CDF)

b-content F_{HF} of e-jet, estimated from $D^0 \to K\pi$ decays and secondary muons from cascade c decays using the same-sign rate to estimate background.

$$\epsilon_b = \frac{(N^{+e}_{+a} - N^{-e}_{+a}) - (N^{+e}_{-a} - N^{-e}_{-a})}{(N_{+a} - N_{-a})} \frac{1}{F^a_{HF}}$$

$F^a_{HF} < 1$ derived from identified conversions.
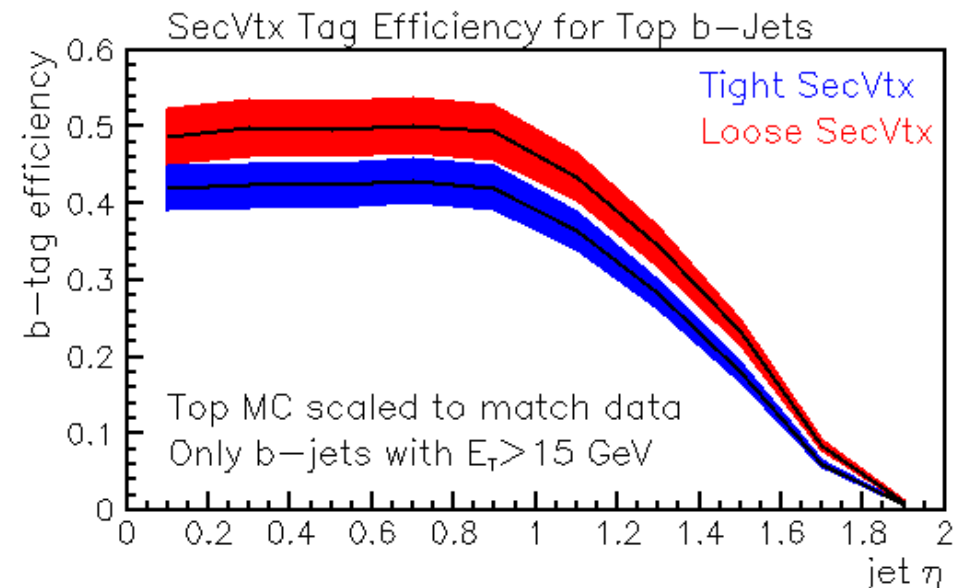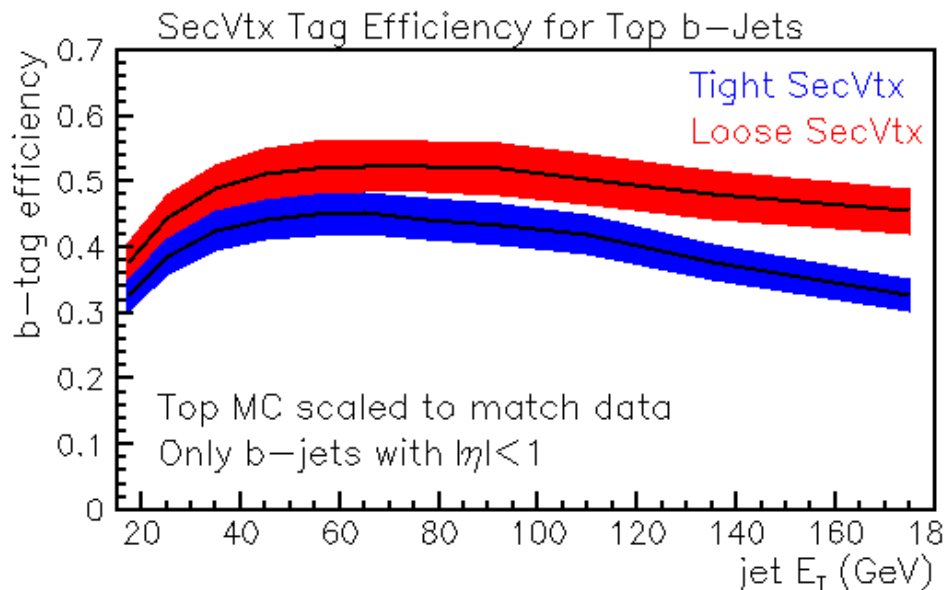
b-tagging Efficiency: System-8 Method (D0)

- Use two samples with different heavy flavor content:

  muon-in-jet sample (n)

  muon-in-jet sample with SVT tagged away jet (p)

- Use two independent (<u>uncorrelated</u>) algorithms to tag the muon-jet:
  - SVT algorithm.
  - SLT: muon $p_T^{rel} > 0.7$ GeV/c

$$n = n_b + n_l$$

$$p = p_b + p_l$$

$$n^{SVT} = n_b \epsilon_{btag}^{SVT} + n_l \epsilon_{non-b}^{SVT}$$

$$p^{SVT} = p_b \epsilon_{btag}^{SVT} + p_l \epsilon_{non-b}^{SVT}$$

$$n^{SLT} = n_b \epsilon_{btag}^{SLT} + n_l \epsilon_{non-b}^{SLT}$$

$$p^{SLT} = p_b \epsilon_{btag}^{SLT} + p_l \epsilon_{non-b}^{SLT}$$

$$n^{DT} = n_b \epsilon_{btag}^{SVT} \epsilon_{btag}^{SLT} + n_l \epsilon_{non-b}^{SVT} \epsilon_{non-b}^{SLT}$$

$$p^{DT} = p_b \epsilon_{btag}^{SVT} \epsilon_{btag}^{SLT} + p_l \epsilon_{non-b}^{SVT} \epsilon_{non-b}^{SLT}$$
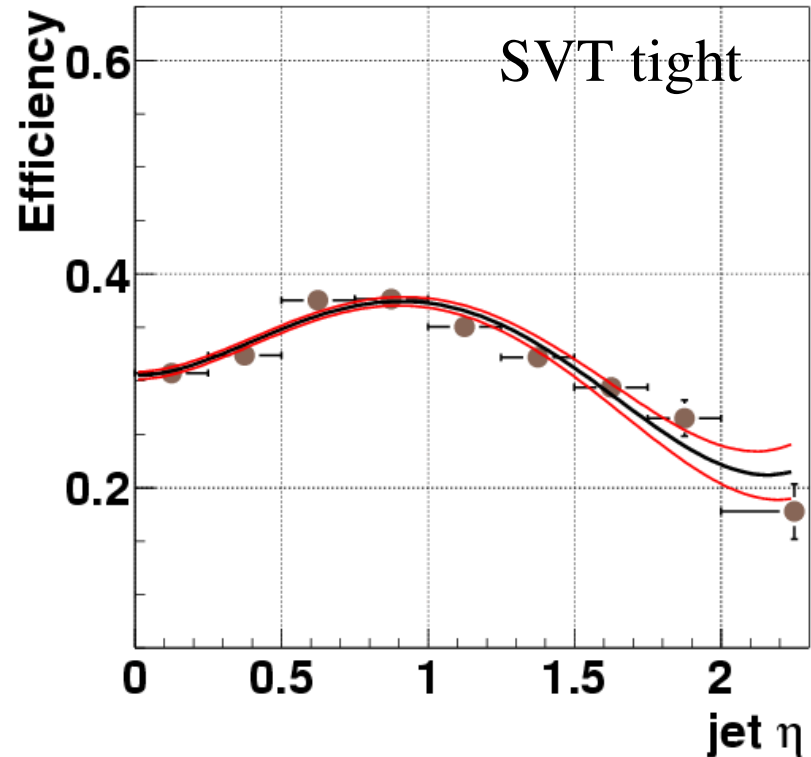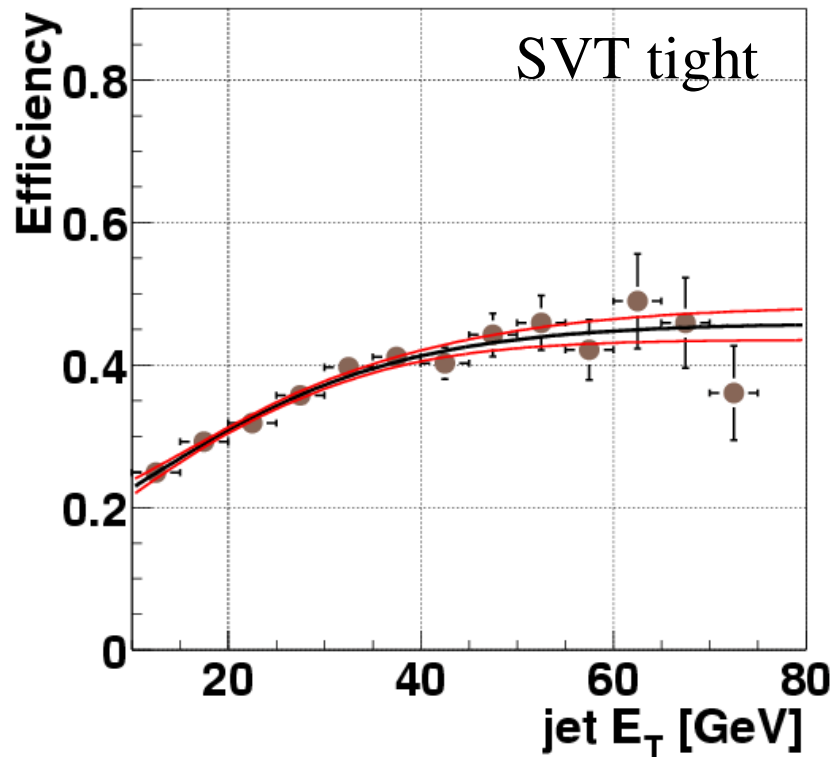
Solve system of 8 equations for ϵ_{btag}^{SVT}

Use Monte Carlo to obtain the inclusive hadronic b-tag efficiency: $\epsilon_b^{incl} / \epsilon_b^{b \to \mu}$

b-tagging Efficiency: System-8 Method (D0)

Dominant sources of systematics:
- b-tagging efficiency in the muon-jet is independent of tagging the away jet. (calculated from Monte Carlo: 1.012)
- SLT and SVT are decorrelated: $\epsilon_{SVT+SLT} = 1.02\, \epsilon_{SVX}\, \epsilon_{SLT}$

Efficiencies per taggable jet.

# b-tagging Efficiency: p_T^{rel} Method

Method used by both CDF and D0.
Select jets with muons. Tag away jet to increase the b-content
and reduce the dependence on the background model.
Use MC/Data templates of muon p_T^{rel} distribution for b and

$$\epsilon_b = \frac{N_\mu^{tag} F_{b\to\mu}^{tag}}{N_\mu F_{b\to\mu}}$$

non-b muon decays. (non-b includes charm and light quark decays)
Main limitation: low statistics at high jet E_T. Scale factor derived at low E_T.
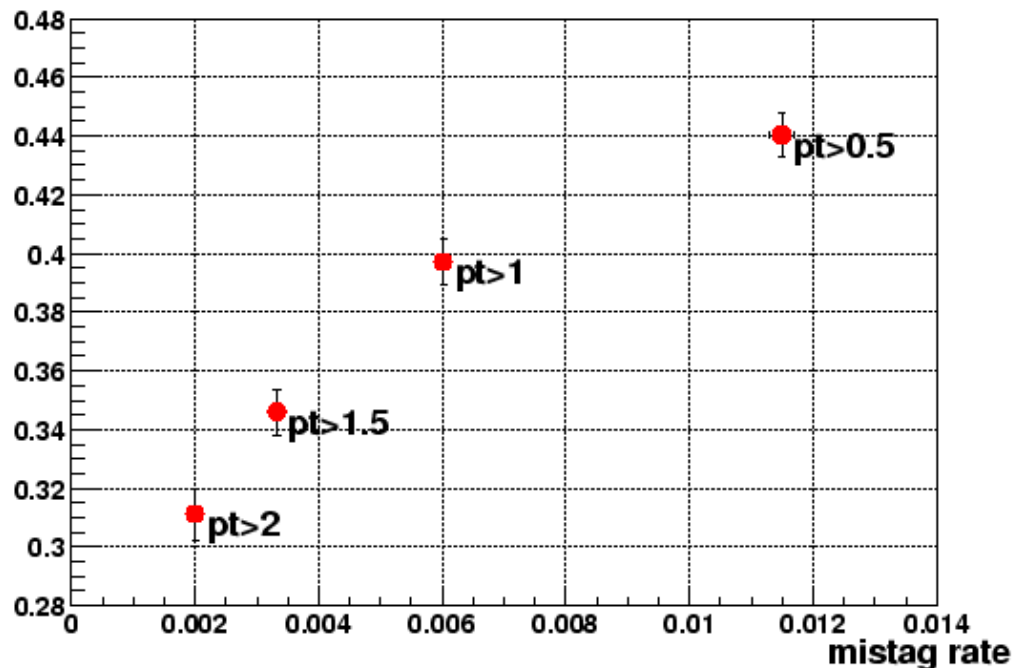
CDF results:
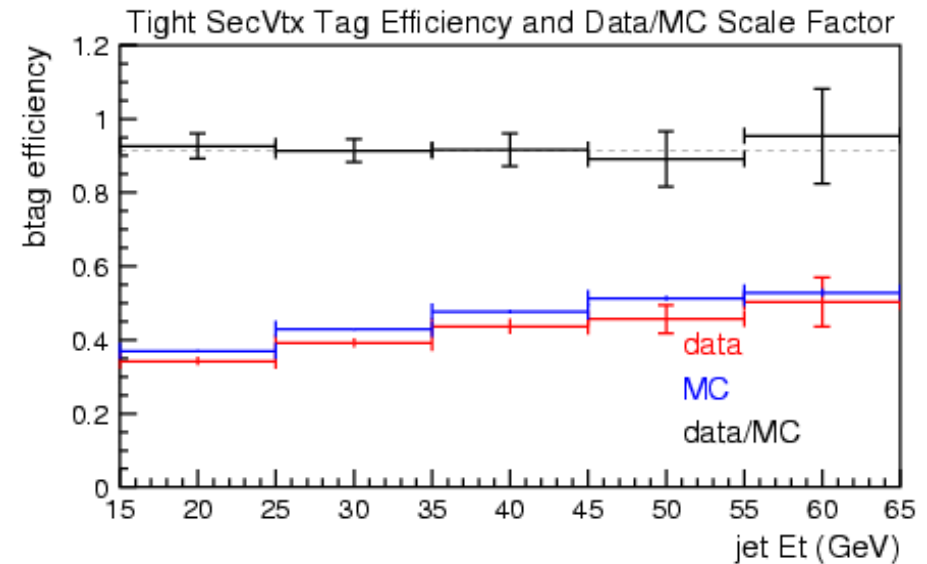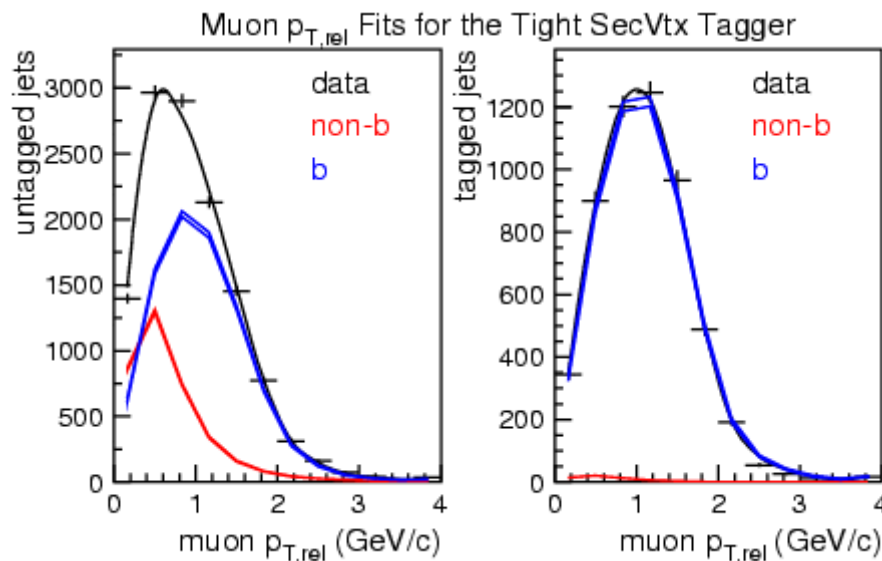
Other Lifetime Tagging Algorithms

Counting Signed Impact Parameter

Based on impact parameter significance of tracks in jets:
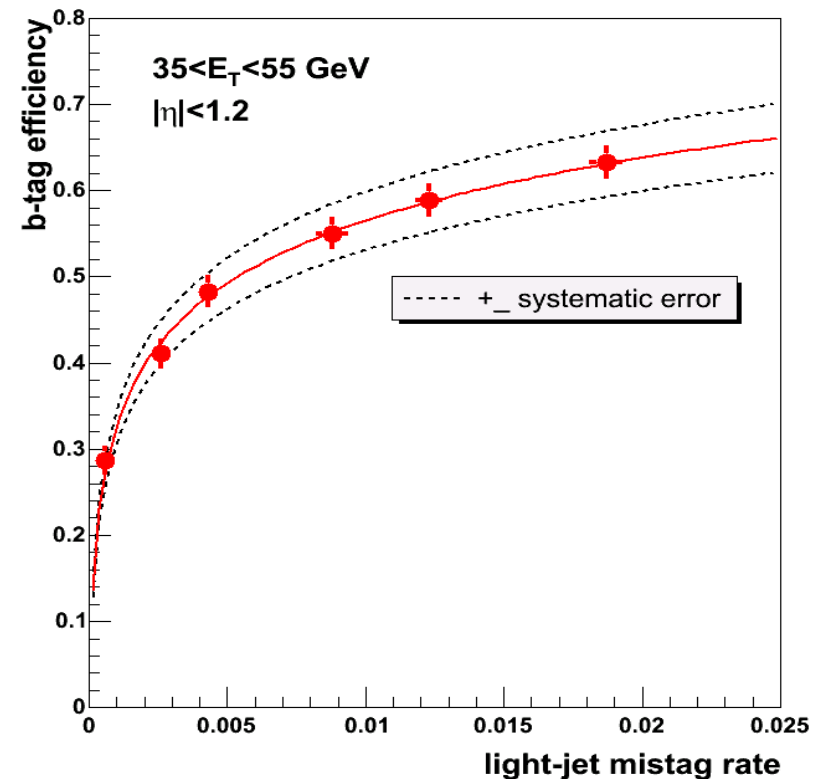- at least 2 tracks with S>3
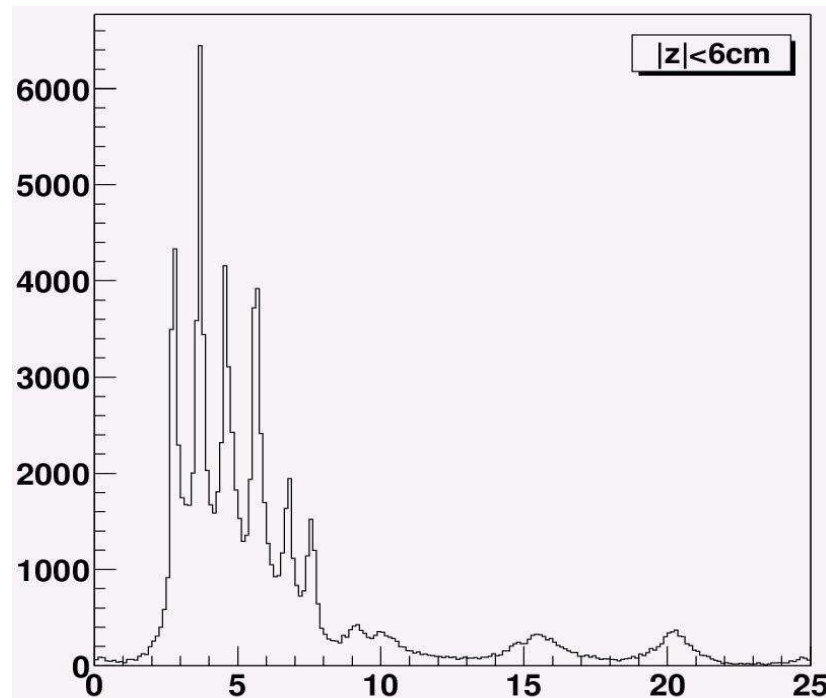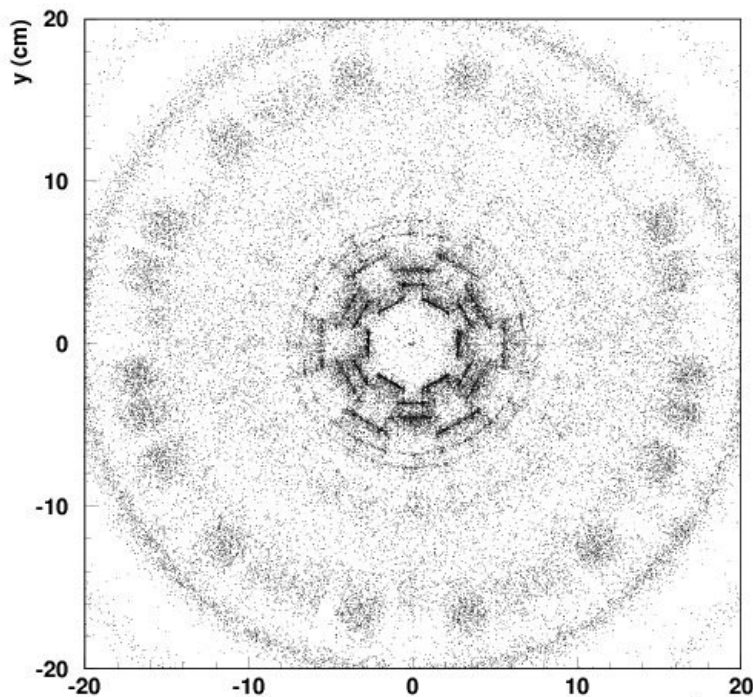- at least 3 tracks with S>2

Jet Lifetime Impact Parameter

Build probability for a track to come from the PV.

P(light-quark) is calculated for each jet.

Data / Monte Carlo Issues

Particle decays are used to fine-tune the detector geometry used in the Monte Carlo, and study material in the detector.
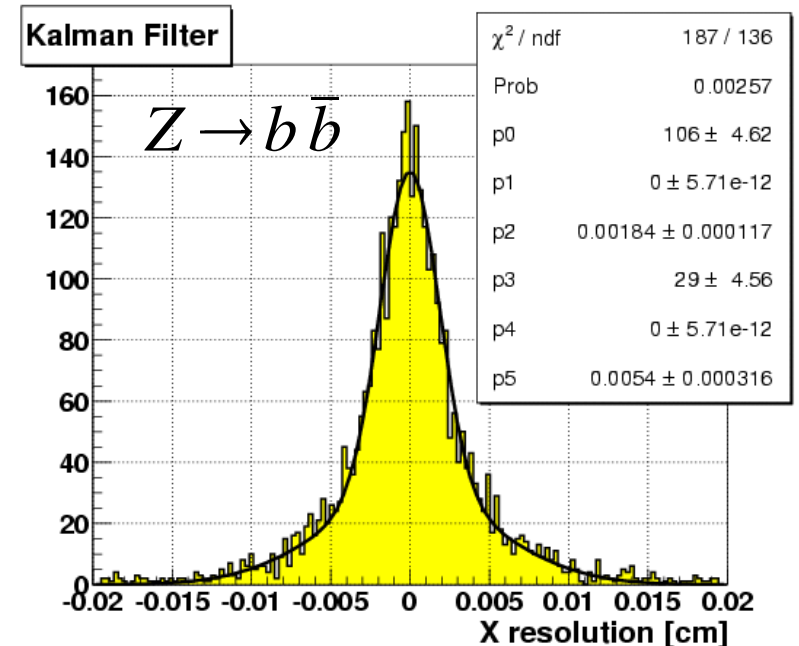

$$J/\Psi \rightarrow \mu^+ \mu^-$$
$$Z \rightarrow \mu^+ \mu^-$$
$$K_S \rightarrow \pi^+ \pi^-$$
$$\gamma \rightarrow e^+ e^-$$

Adjust magnetic field in the simulation and material description studying mass peaks.

Robust Vertex Algorithms (D0)

- **Standard vertex fitting algorithms:**

  – Position is biased if the vertex candidate

  contains tracks from secondary vertices.

- **Robust vertex algorithms:**

  – insensitive to outliers.

  – Improve recognition of tracks not

  belonging to the vertex.

  – Reduce bias in the final fit.

  – Better separation between primary and secondary vertices.

- **M-estimator** (R. Fruhwirth, P. Kubinec, et.al., 1996)

- **Adaptive fitter** (**CMS**). (R. Fruhwirth, W. Waltenberg, et.al, 2003)

Kalman Filter		
χ^2 / ndf		187 / 136
Prob		0.00257
p0		106 ± 4.62
p1		0 ± 5.71e-12
p2		0.00184 ± 0.000117
p3		29 ± 4.56
p4		0 ± 5.71e-12
p5		0.0054 ± 0.000316

$Z \to b\bar{b}$

**Tracks from B decays significantly affect PV resolution.**

Adaptive Vertex Fitting

Reweigh track errors according to their distance to the vertex

$$\chi^2(x,q) = (x - x_{k-1})^T C^{-1}(x - x_{k-1}) + (m_k - h(x,q))^T w_k V_k^{-1}(m_k - h(x,q))$$

Weights

- Iterative, re-weighted Kalman Filter fit.

- Weight w of track i at iteration k, depends

  on the distance to the vertex at iteration k-1.

- Iteration of two steps:

  – Kalman Fit.

  – Computation of the weights.

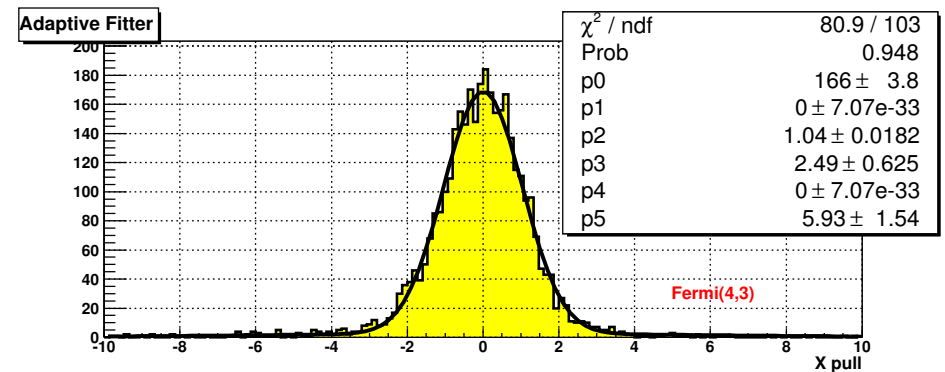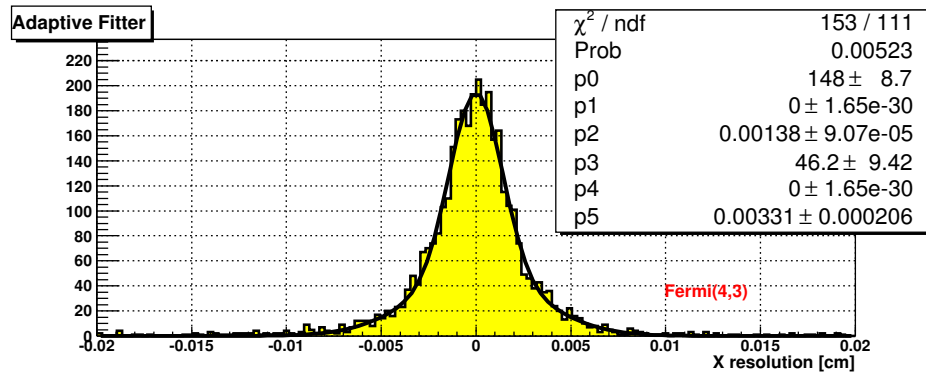- The iteration is stopped when the weights
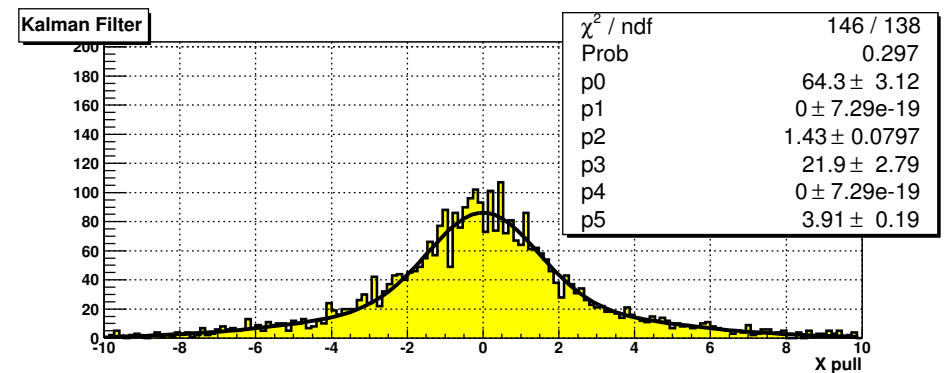
  have stabilized.

Fermi Weight function

Fermi(10,0)
Fermi(10,1)
Fermi(10,3)
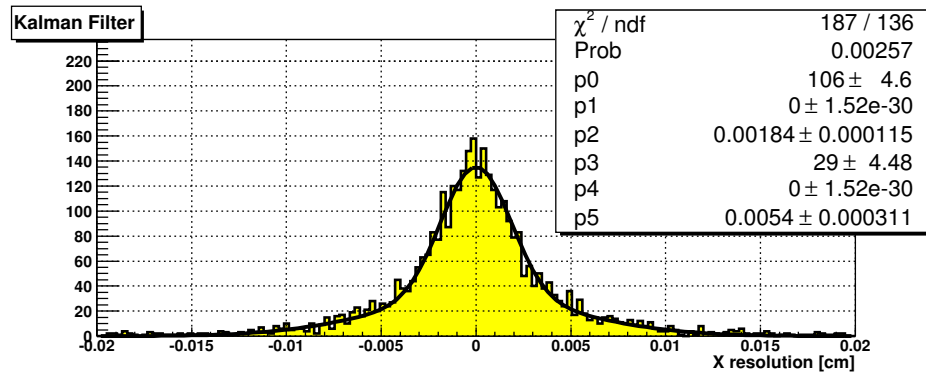Fermi(10,5)

$\chi^2_{\text{trk-to-vtx}}$
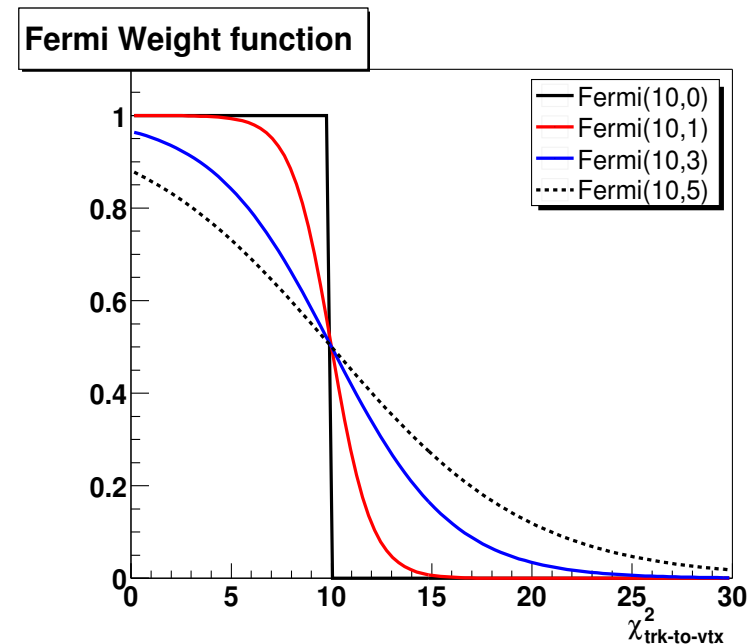
$$w_k = f(\chi_k^2, \theta)$$

x Distance between track m_k and vertex.

θ Temperature.

Adaptive Primary Vertex Performance

Significant improvement in primary vertex resolution and pull.

Adaptive Multi-Vertex Reconstruction

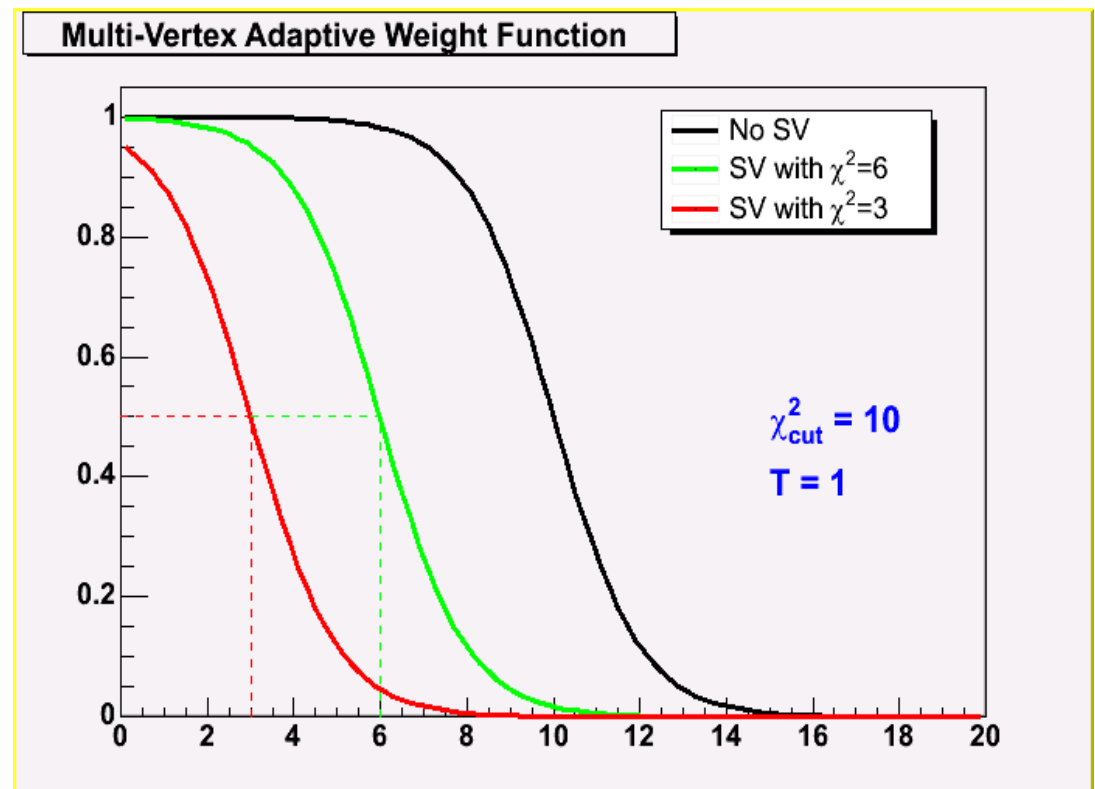Global vertex reconstruction of primary and secondary vertices

Iterative Fit of several vertices **with competition**

Weight each track i relative to all vertices k it belongs to:

$$w_{ij} = \frac{e^{-\chi^2_{ij}/T}}{\sum_k e^{-\chi^2_{ik}/T} + e^{-\chi^2_{cut}/T}}$$

w_{ij} is the weight of track i to vertex j.

CMS algorithm, implemented at D0.

Multi-Vertex Adaptive Weight Function

— No SV
— SV with $\chi^2=6$
— SV with $\chi^2=3$

$\chi^2_{cut} = 10$

$T = 1$

Adaptive track weights are modified if the track can be assigned to more than 1 vertex hypothesis.

Combining Taggers (D0)

Loosen secondary vertex reconstruction and add kinematic variables to distinguish b-jets from c, light, and gluon jets. Several implementations are being developed at D0.
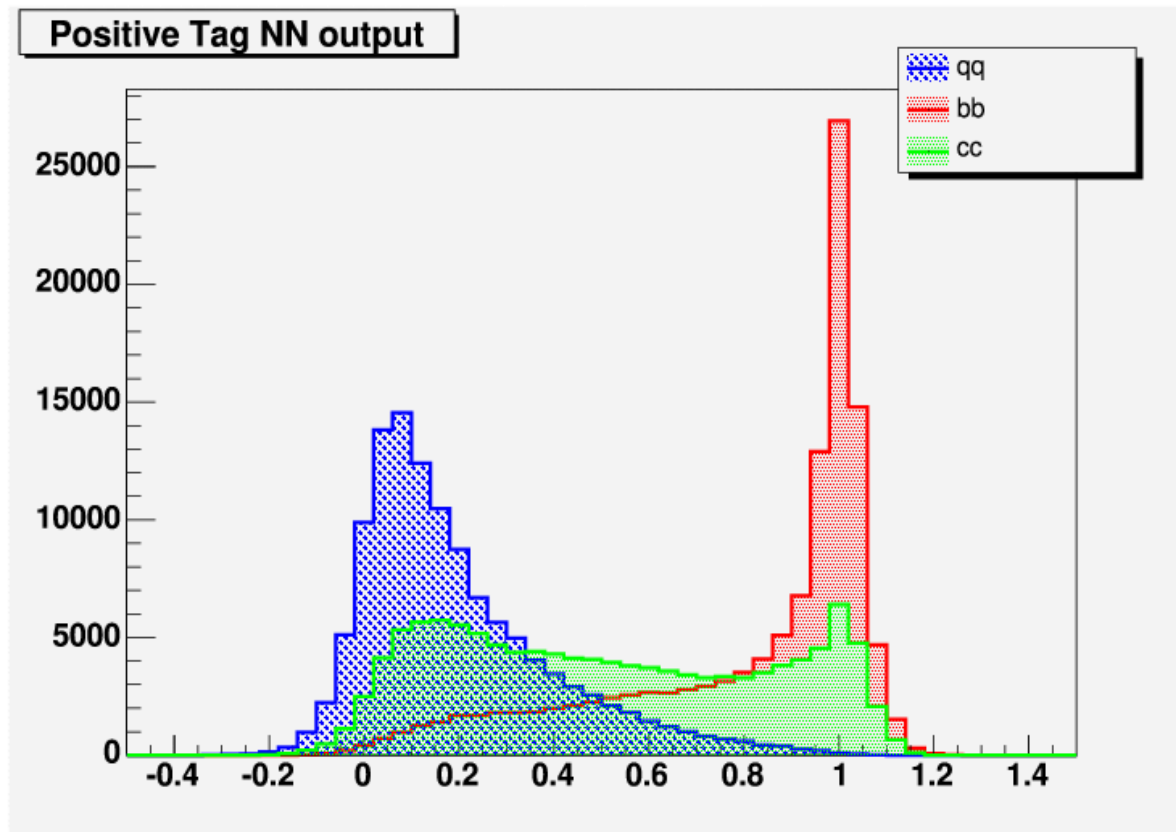
Input variables:

JLIP probability output.
CSIP output.
SV decay length significance.
SV χ^2/ndof.
SV track-multiplicity.
SV mass.
PV χ^2/ndof.

Summary and Conclusions

Description of different techniques to tag b-jets and measure b-tagging efficiency and mistag rate from data.

Different tagging algorithms (not 100% correlated) allow the possibility to combine them using multivariate techniques.

Photon conversions and long-lived particles are used to improve the material description in the simulation.

New ideas to improve b-tagging are being pursued:
- Adaptive vertex algorithms.
- Global PV-SV reconstruction.
- Multivariate b-jet tagging.