Vertexing and b-tagging at the Tevatron

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Outline

Vertexing and b-tagging algorithms overview.

Kalman filter vertex fitting algorithm.

Primary vertex reconstruction.

Adaptive primary vertex fitting.

Secondary vertex reconstruction and b-tagging.

Global vertex reconstruction: multi-vertex fitting.

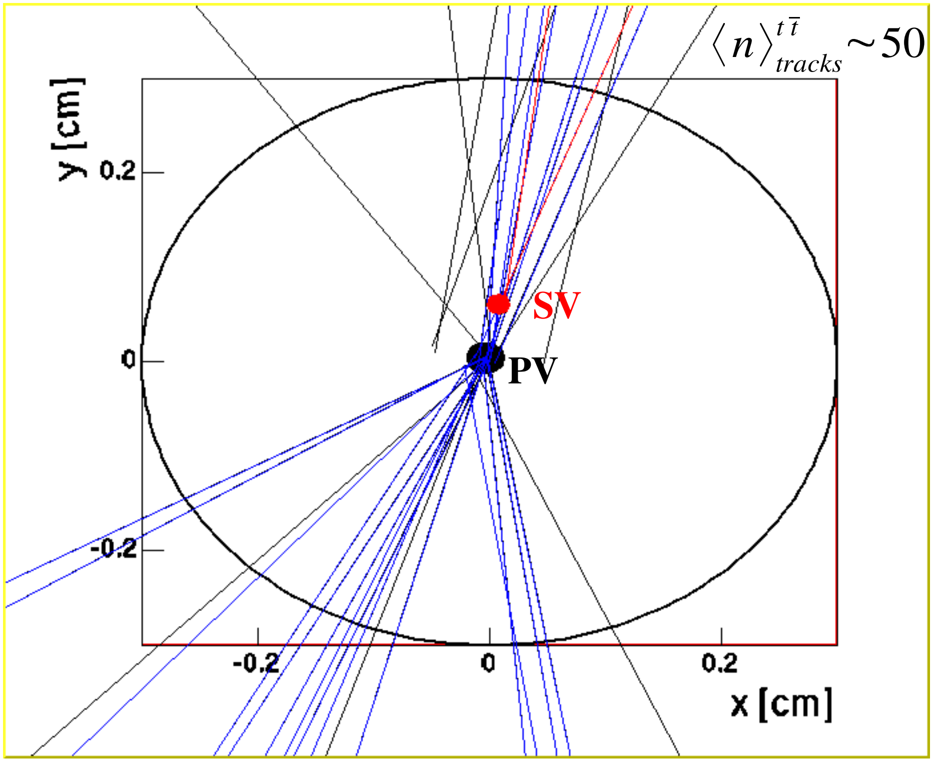
b-tagging optimization in the Top quark mass analysis.

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 a vertex, and the momentum of the tracks at the vertex.
- Secondary Vertex b-tagging:
  - Tag long lived hadrons from b decays.

Vertexing and b-tagging Algorithm



b-jets are identified by tagging long lived hadrons within jets (*<lifetime> ~ 3mm*)

1- Primary vertex reconstruction:

Hard scatter (HS) and additional minimum-bias interactions.
Adaptive Kalman Filter.

2- Primary vertex (HS) selection:

Probabilistic algorithm.

3- Secondary vertex reconstruction:

Track jet reconstruction.
Build-up vertexing algorithm

4- b-tagging

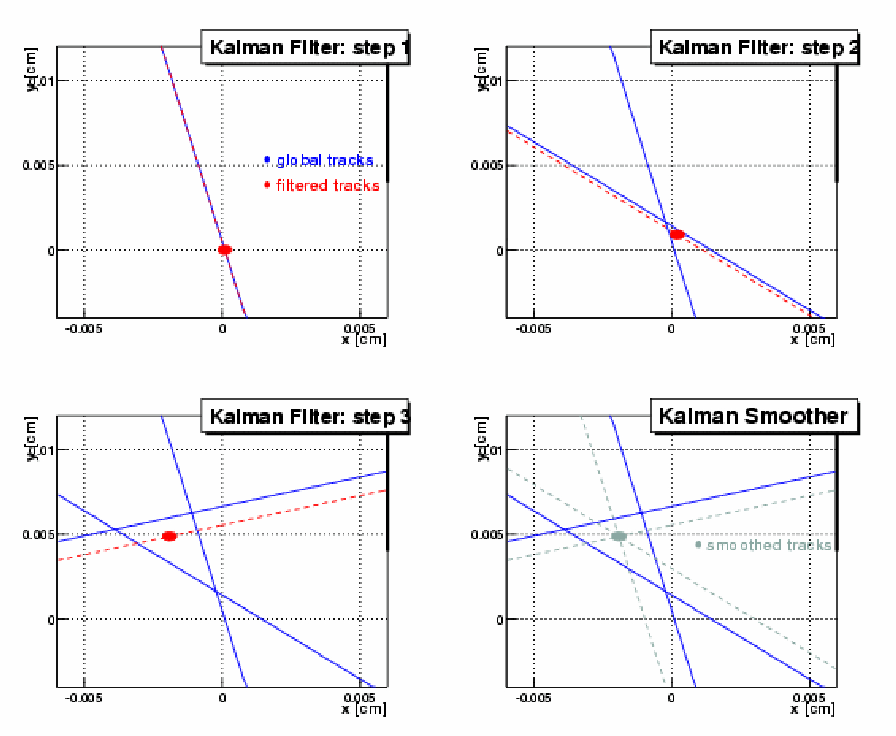
Match vertices with calorimeter jets.

Kalman Filter Vertex Fitting Technique

- Sequential minimization of a local χ^2:

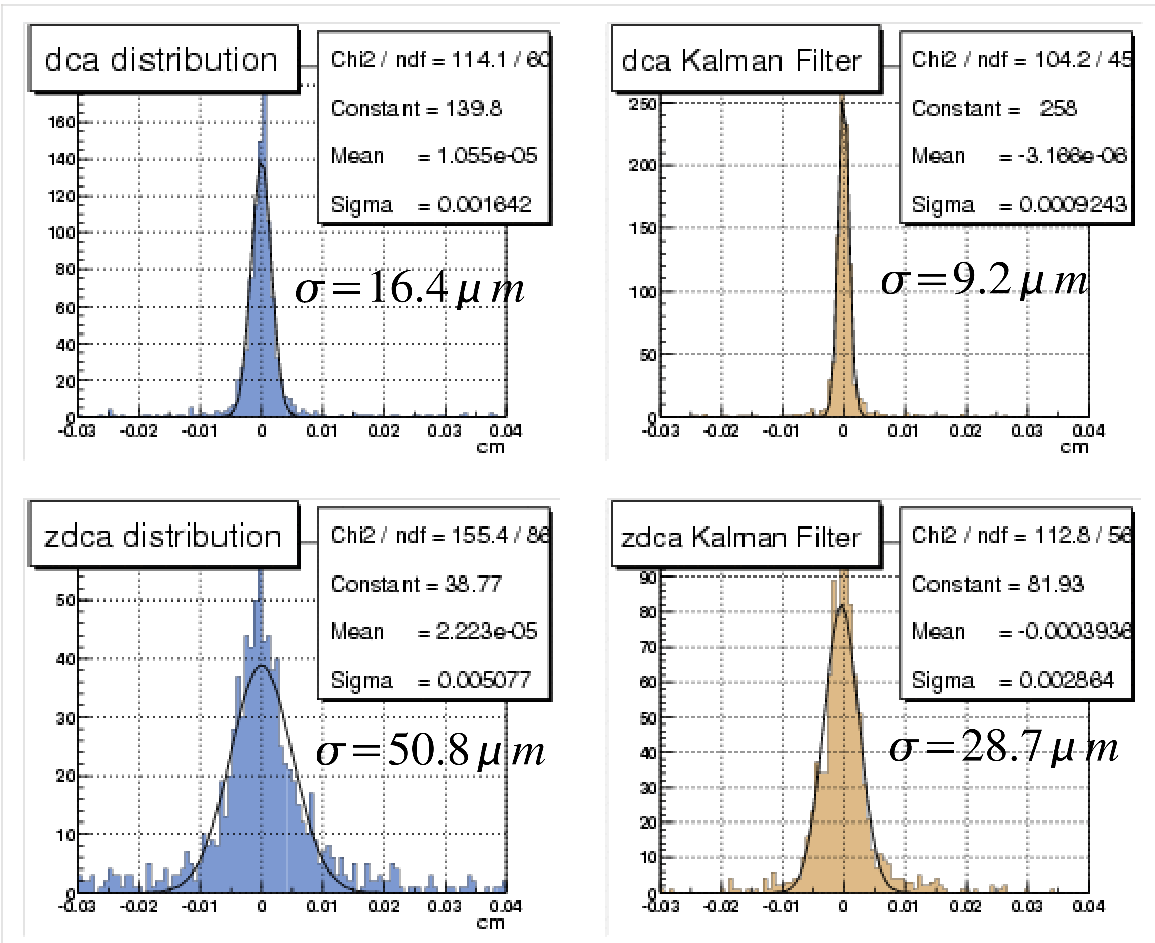
$$\chi^2(x,q)=(x-x_{k-1})^T C^{-1}(x-x_{k-1})+(m_k-h(x,q))^T V_k^{-1}(m_k-h(x,q))$$

- *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 momentum 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:

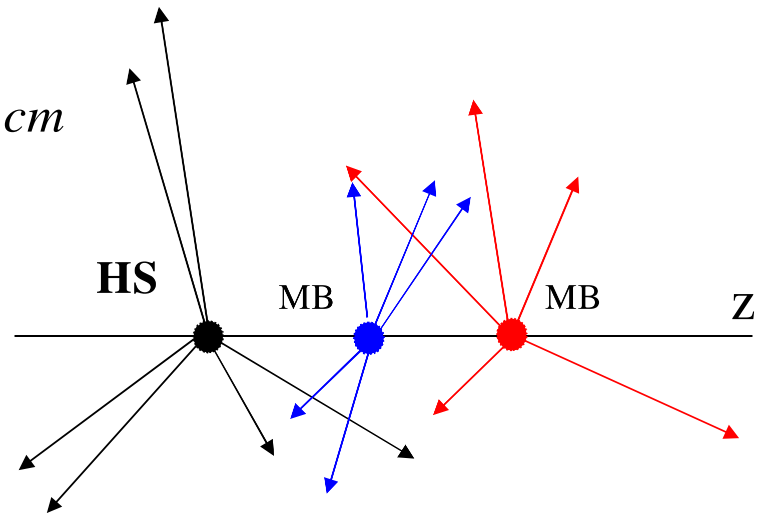
$p = (dca, zdca, phi, \tan\lambda, q/p_T)$

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

Primary Vertex Finding at DZero

- **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 point)



- **2Pass**: preselect tracks with small impact parameter with respect to the estimated beam spot position: $s/\sigma(s) < 5$

At $L=10e^{31}cm^{-1}s^{-2}$, there are ~ 3 additional min bias interactions distributed within a sigma of 25cm in z.

At the LHC, <mb> ~ 25 !

Tear-down finding algorithm:

- Vertex fit of all candidate tracks
- Reject the highest χ^2 contributing track and re-fit, until the total vertex χ^2 is smaller than 10.

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

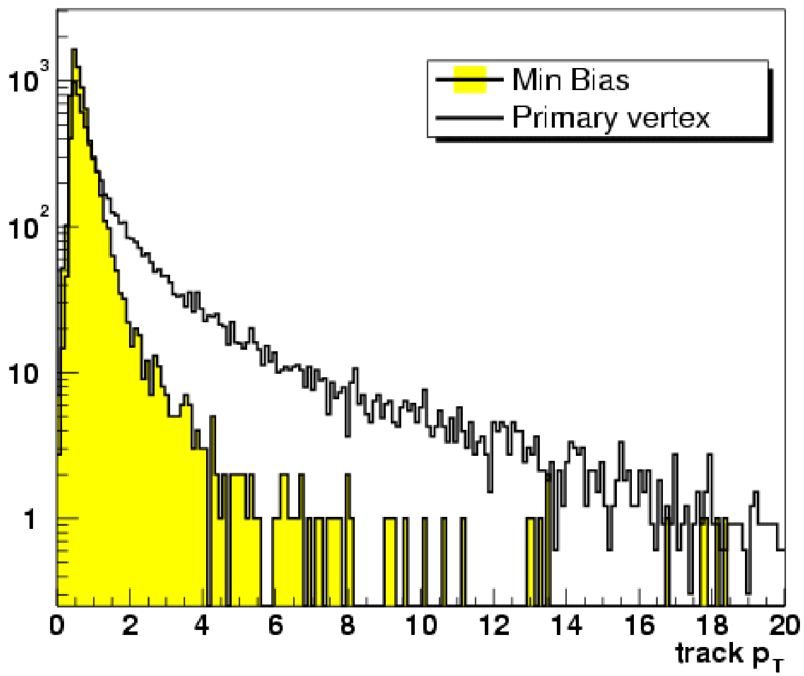
Hard-Scatter Vertex Selection

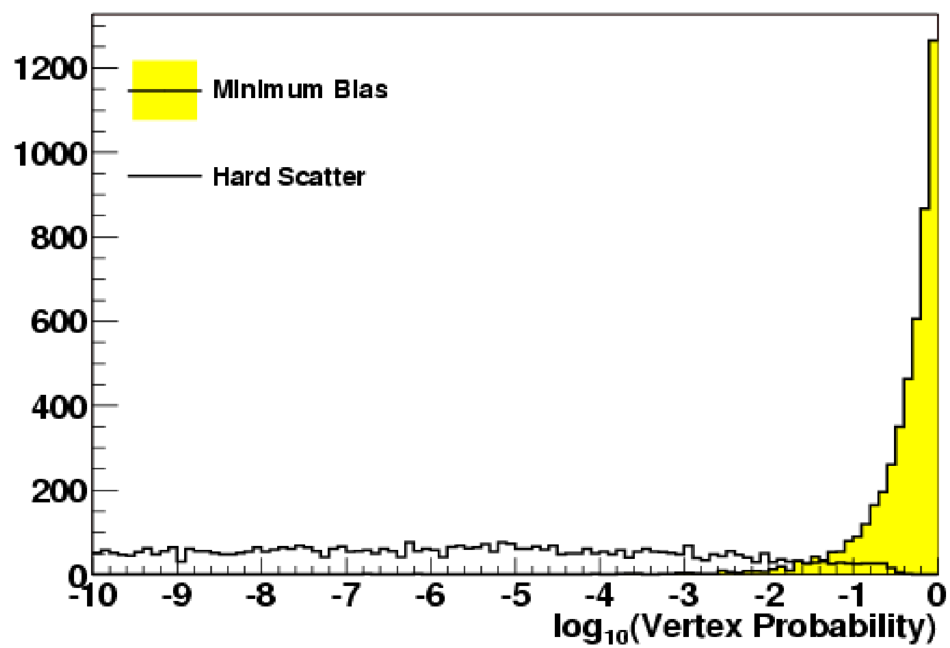
Identify the hard scatter vertex from additional min-bias interactions based on the p_T spectrum of tracks

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

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

$$P = \prod_{k=0}^{N-1} p_k(p_T)$$





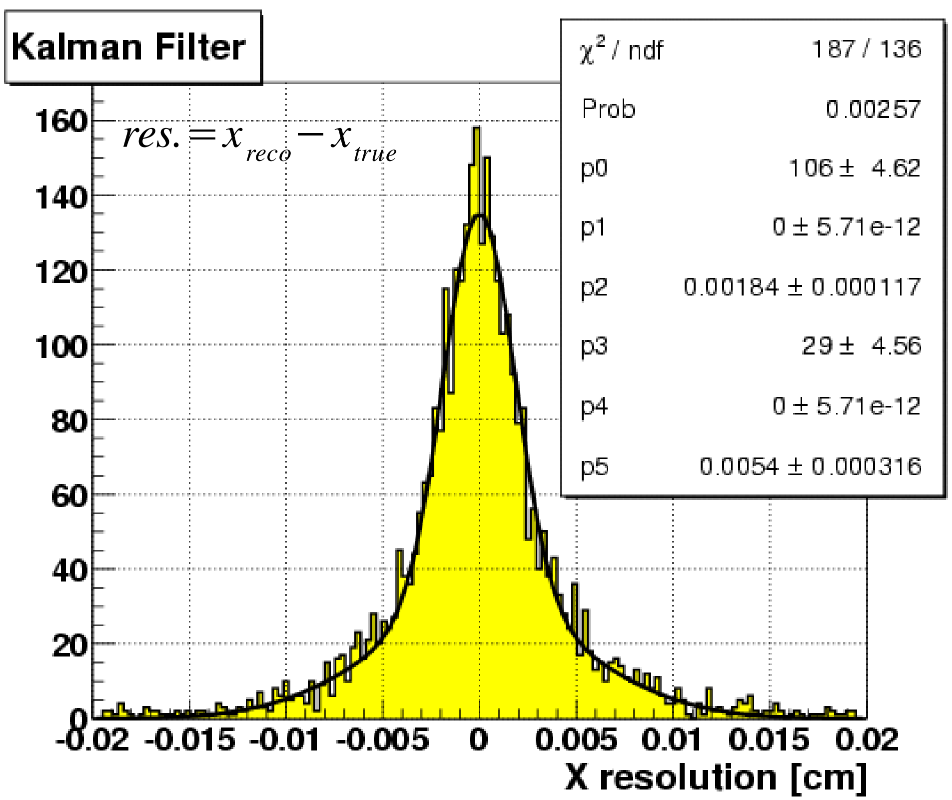
$$p(p_T) = \frac{\int_{\log_{10}(p_T)}^{\infty} F(P_T)\, dp_T}{\int_{\log_{10}(0.5)}^{\infty} F(P_T)\, dp_T}$$

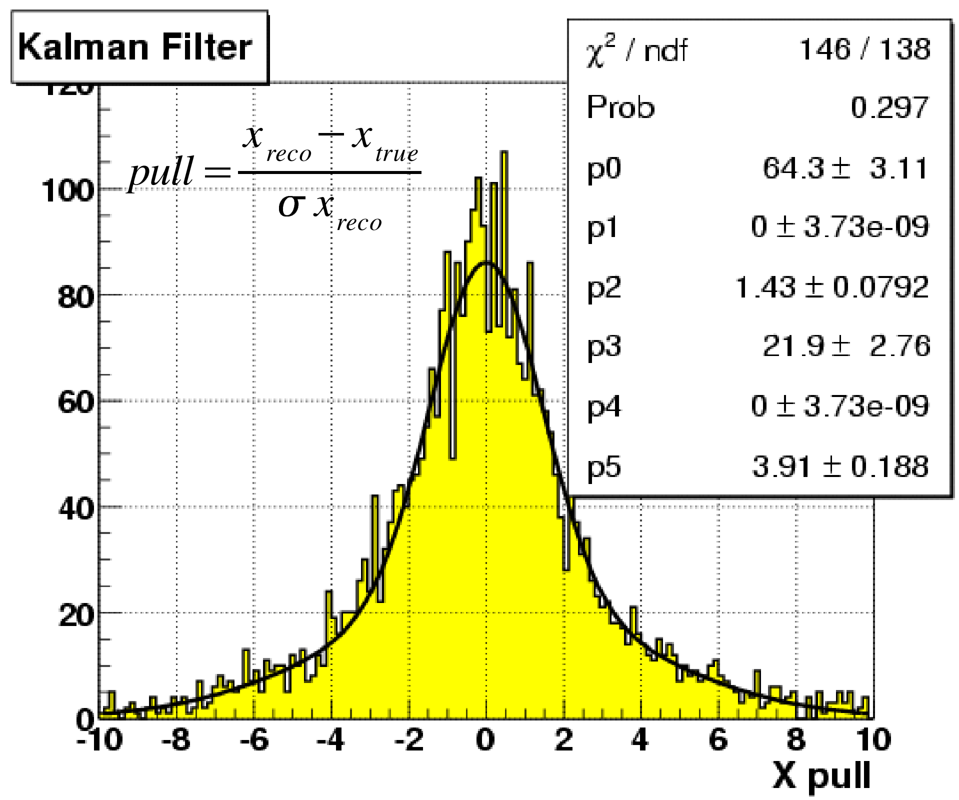
$F(p_T)$ is built using Z -> mu mu events

Challenges of Primary Vertexing

Primary vertex position is biased by the presence of tracks from secondary vertices with small decay length.

Vertex Resolution and Pull are significantly affected.

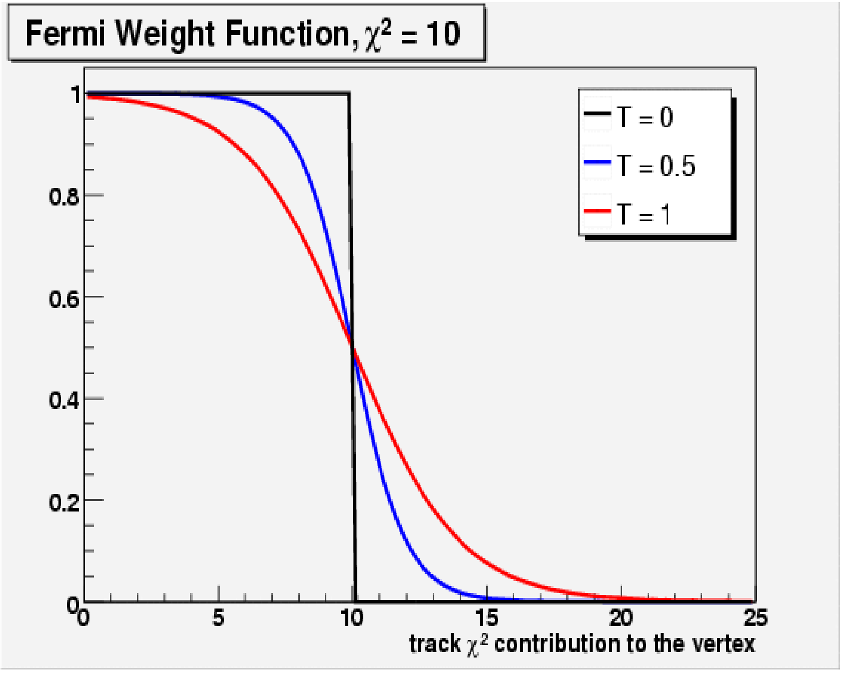




Kalman Filter fitting is very sensitive to the presence of outliers: all fitted tracks equally contribute to the result.

New Approach: Adaptive Vertex Fitting

- Improve the recognition of tracks not belonging to the primary vertex
- Reduce the bias in the final fit.
- Better separation between primary and secondary vertices.



Reweigh track errors according to their distance to the vertex

Iterative re-weighted Kalman Filter:

Kalman Fit: estimation of the vertex position.

Tracks are down-weighted by their association probabilities *w*.

Computation of the weights: *w* is calculated for all tracks with respect to the current vertex position.

The iteration is stopped when the weights have stabilized.

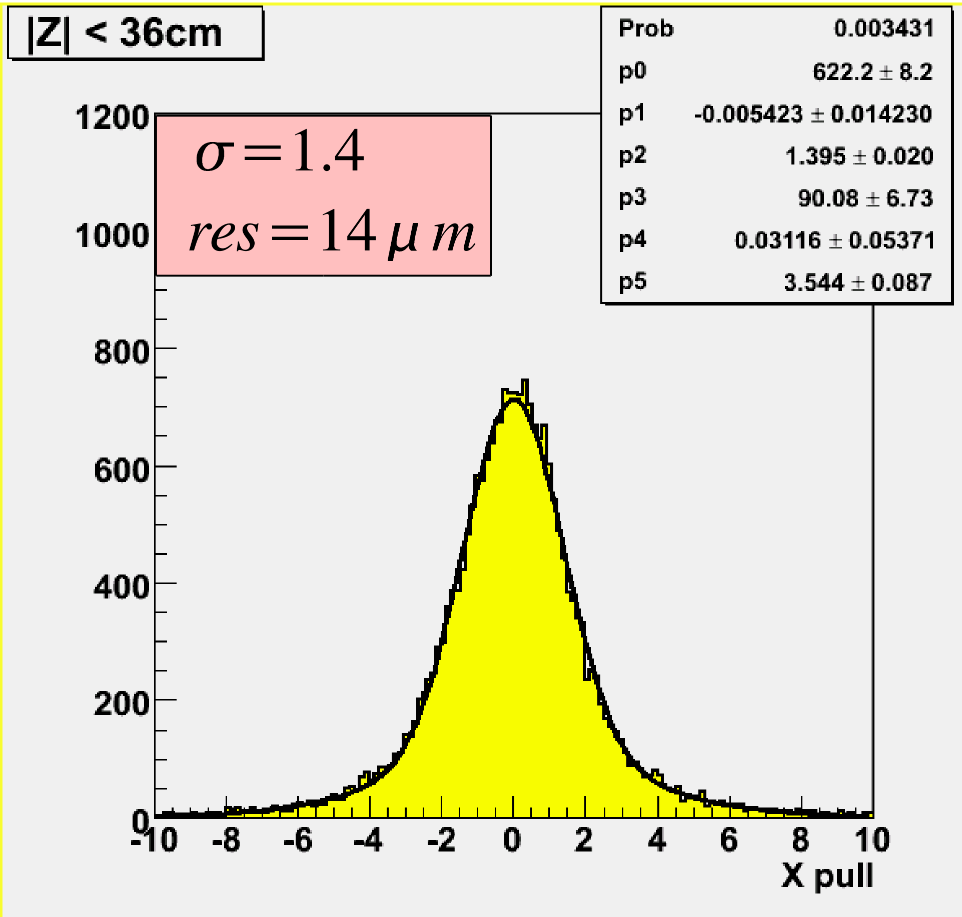
Weight w of track i at iteration k, depends on the distance to the vertex at iteration k-1.

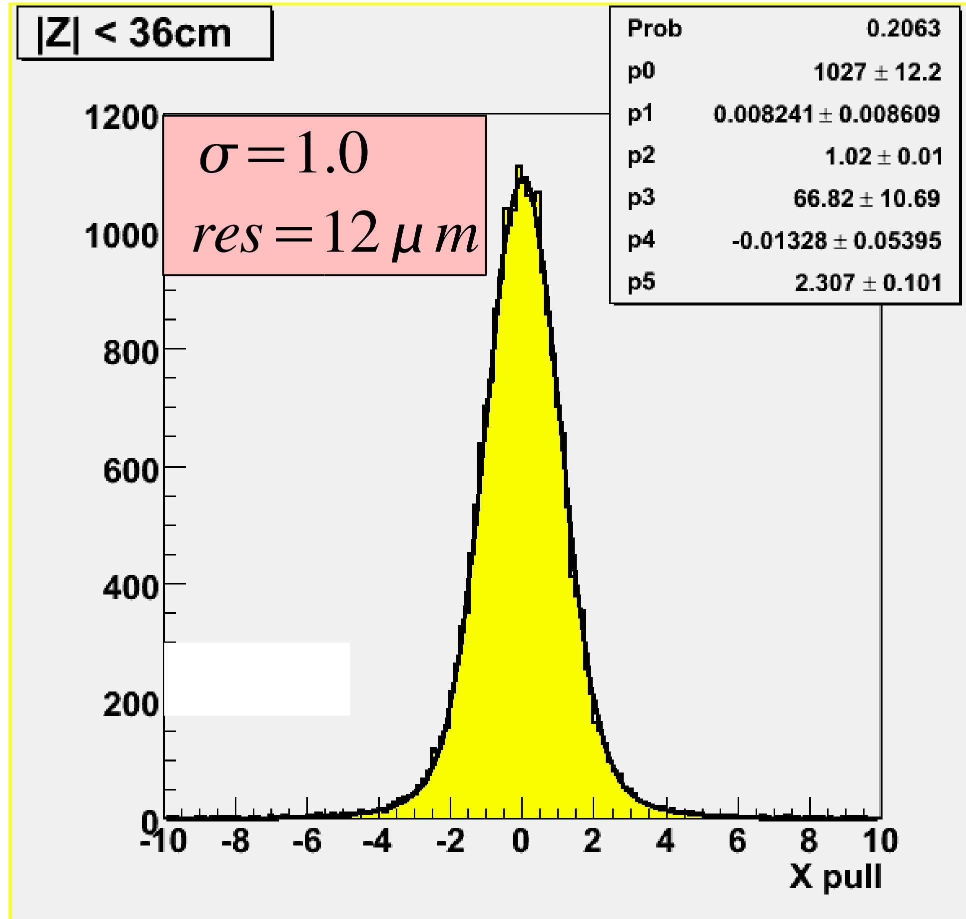
All tracks are used in the fit: No square x^2 cut!

Adaptive Primary Vertex Performance

$Z \to b\bar{b}$ Monte Carlo

Kalman **Adaptive**





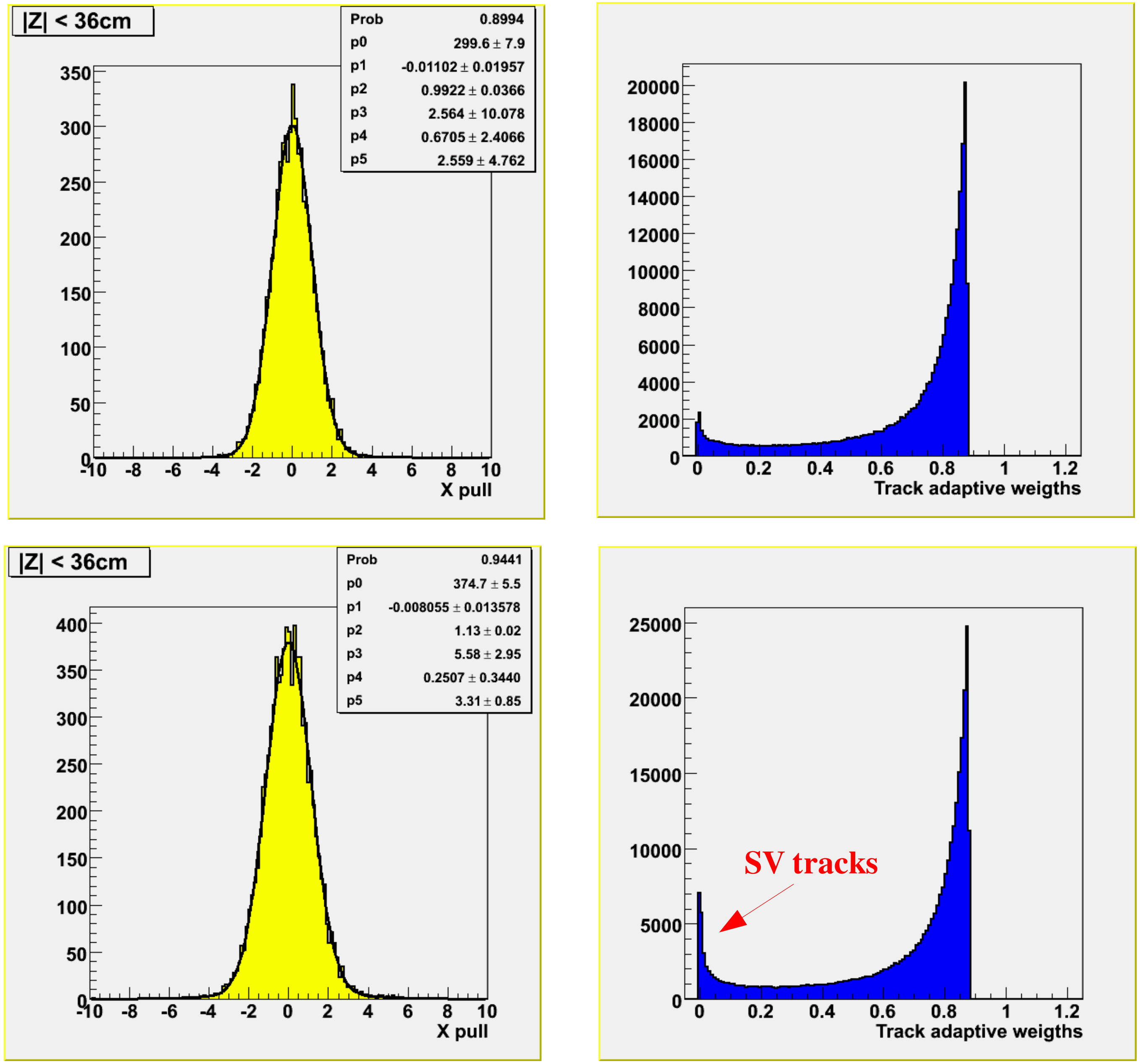
Algorithm proposed for the CMS Experiment (R. Fruhwirth, W. Waltenberg, et.al, 2003)
Implemented for the fist time at the Tevatron.

Default vertex algorithm used for all DZero measurements.

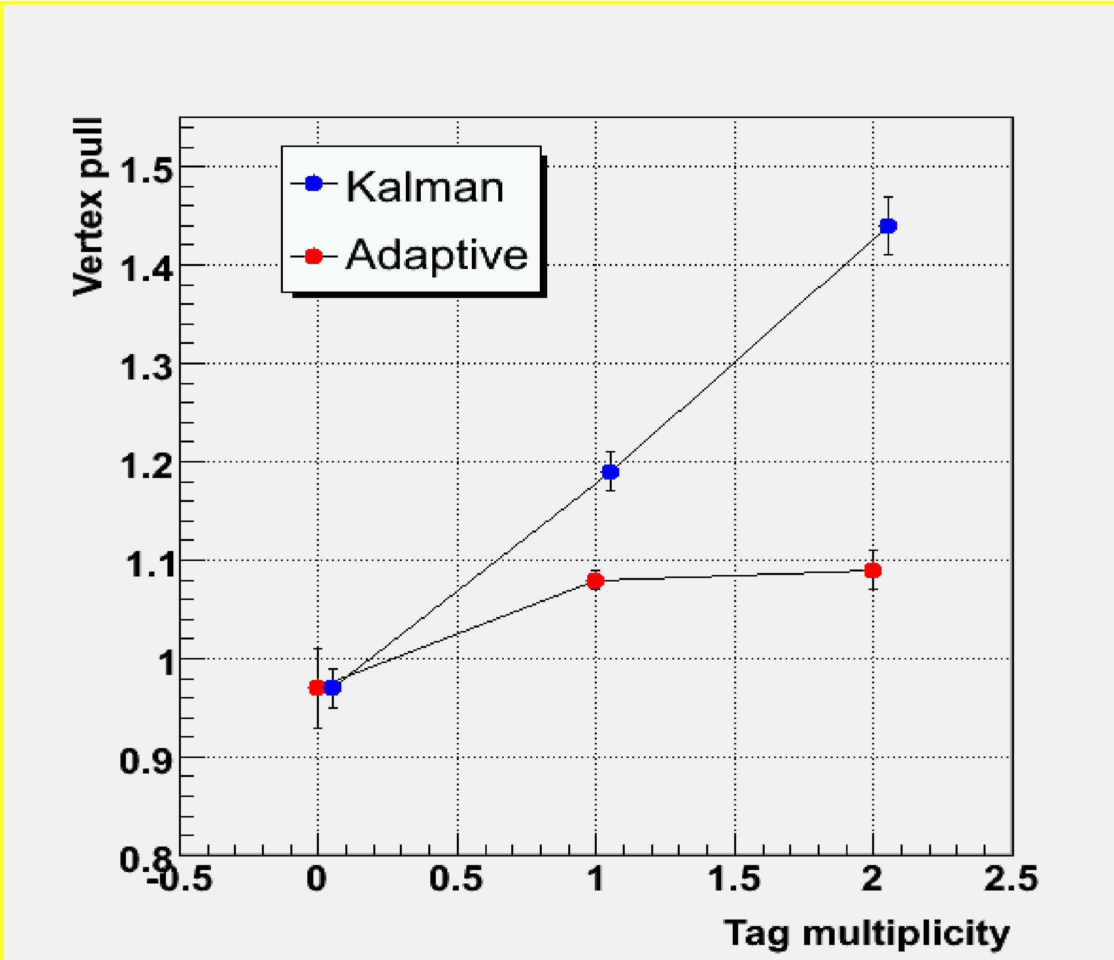
Adaptive Weights in Top/W+jets Events

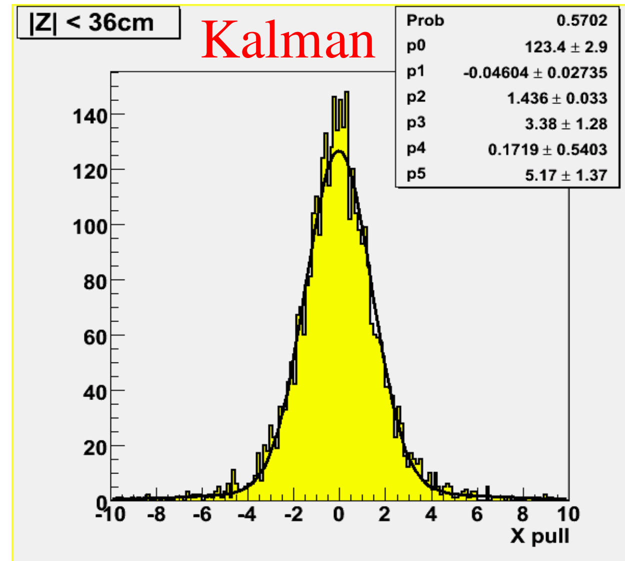
$W \rightarrow l\, \nu\, j\, j\, j\, j$

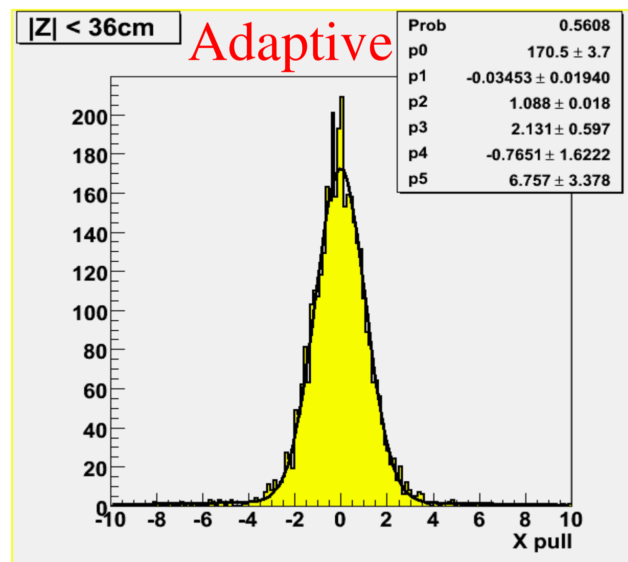
$t\, \bar{t} \rightarrow l\, \nu\, b\, b\, j\, j$



APV Performance in the Data





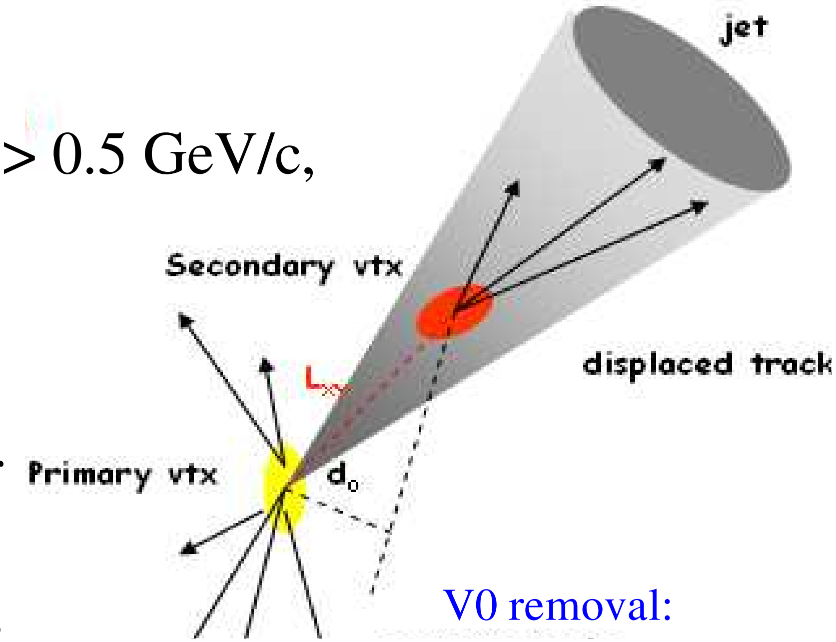


Adaptive primary vertex algorithm is less sensitive to heavy flavor tracks

5% b-tagging efficiency improvement

Secondary Vertex Reconstruction

- 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.

- Associate secondary vertices with jets:

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

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

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

V0 removal: remove tracks consistent with K_S, Lambda and conversions prior to secondary vertex reconstruction.

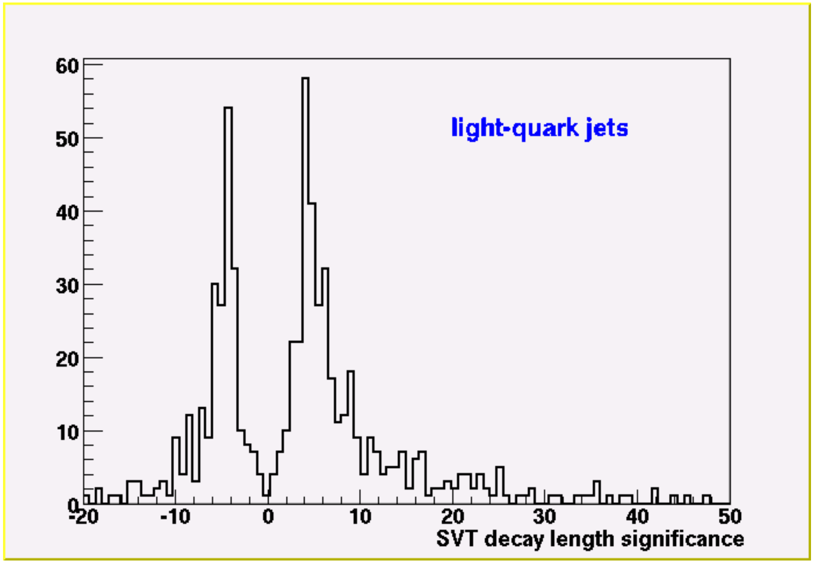
Light Quark Mistag Rate

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

- Fake tracks displaced from the primary vertex, and tracking and 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**.

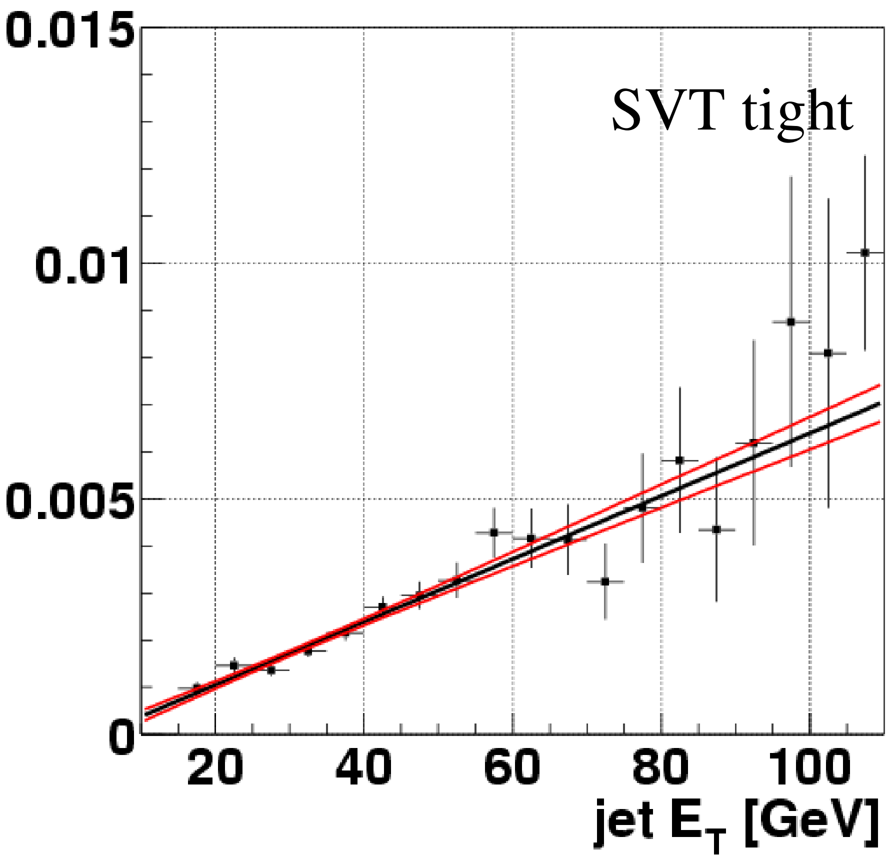
2- Convert negative tag-rate into light quark mistag using Monte Carlo: $\epsilon_l = \epsilon^n SF_{hf} SF_{long\ lived}$

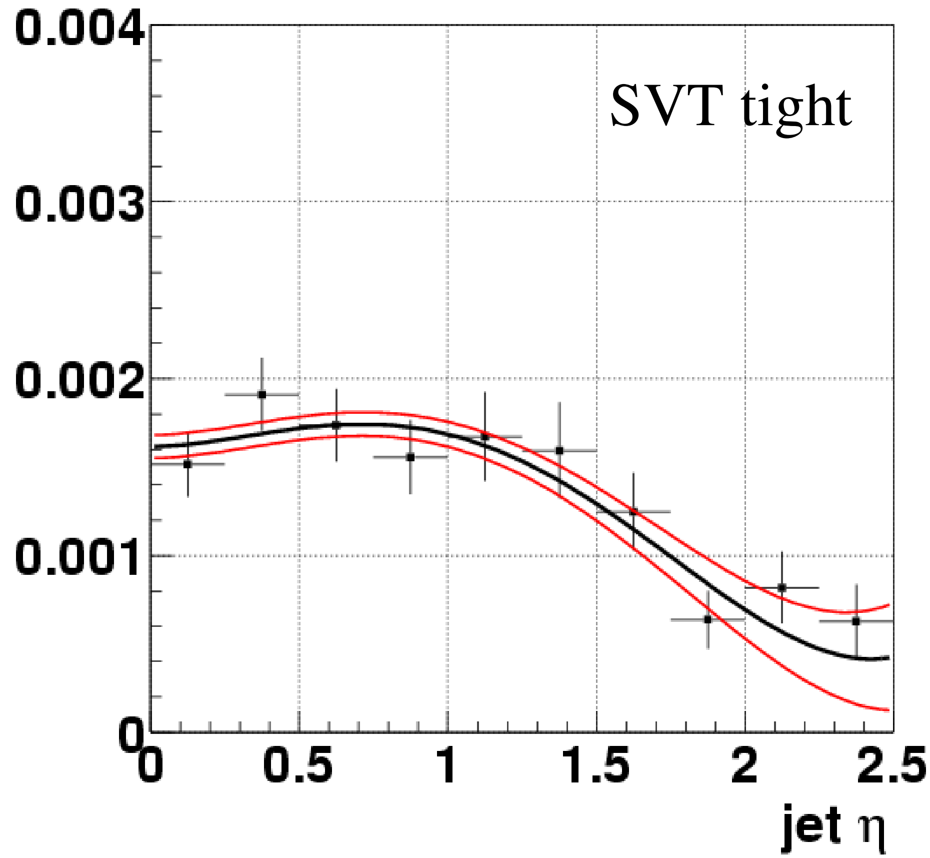


Sign of L_{2D} is given by the angle between the jet axis and the vertex momentum

Measurement of the Mistag Rate

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.

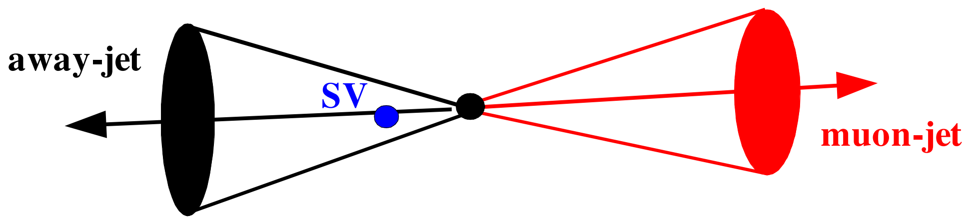
Measurement of b-tagging Efficiency

Simulation: Ratio of tagged jets to the total number of (*taggable*) jets.

Data: Mixture of light and heavy flavor jets.
Select a sample enriched in heavy flavor *(muon in jet)*
Estimate the b-content of the sample.

- Measure b-tagging efficiency in data and parameterize it as a function of Jet E_T and Eta.
- Apply parameterization to the simulation.
- Factorize taggability and efficiency.

b-tagging Efficiency: System-8 Method



- 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}

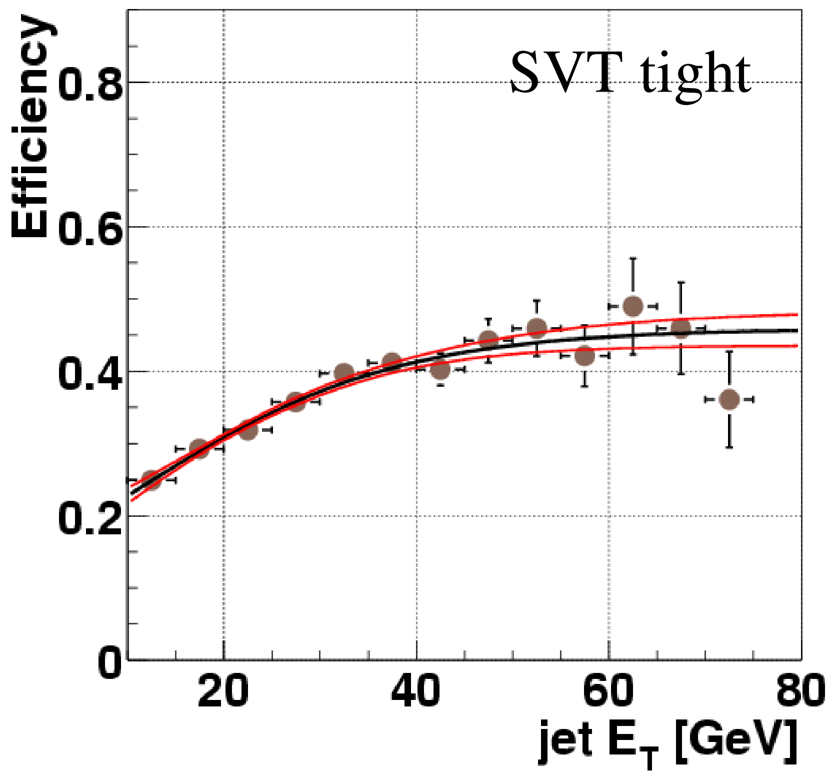
Use Monte Carlo to obtain the inclusive hadronic b-tag efficiency: $\epsilon_b^{incl} / \epsilon_b^{b \to \mu}$

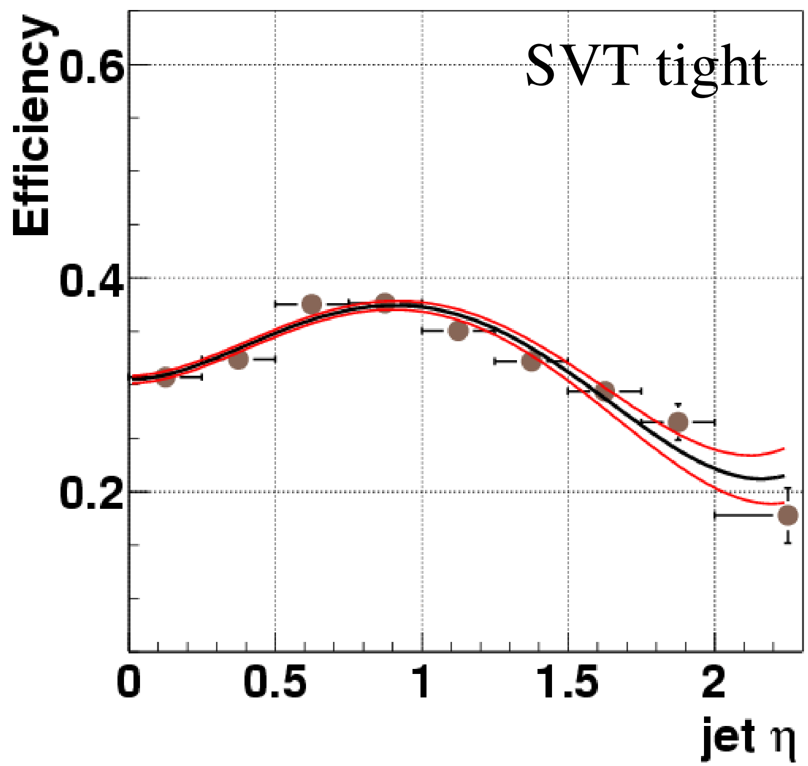
b-tagging Efficiency: System-8 Method

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: $\epsilon_{SVT+SLT} = 1.02\,\epsilon_{SVX}\,\epsilon_{SLT}$
- muon p_T^{rel} cut.

Efficiencies per taggable jet.





Multi-Vertex Reconstruction and b-tagging Optimization in Physics Analysis

- Simultaneous reconstruction of primary and secondary vertices.

- b-tagging optimization for the Top quark mass measurement.

Adaptive Multi-Vertex Finding

- Extend Adaptive fitting formalism to simultaneously find primary and secondary vertices.

- Initially, vertex candidates (PV and SVs) can share tracks.

- Each track is weighted according to its distance to each vertex (a same track has a different weight for each vertex: w_{ij})

- Iteration procedure allows to "swap" tracks between vertices.

Adaptive Multi-Vertex Reconstruction

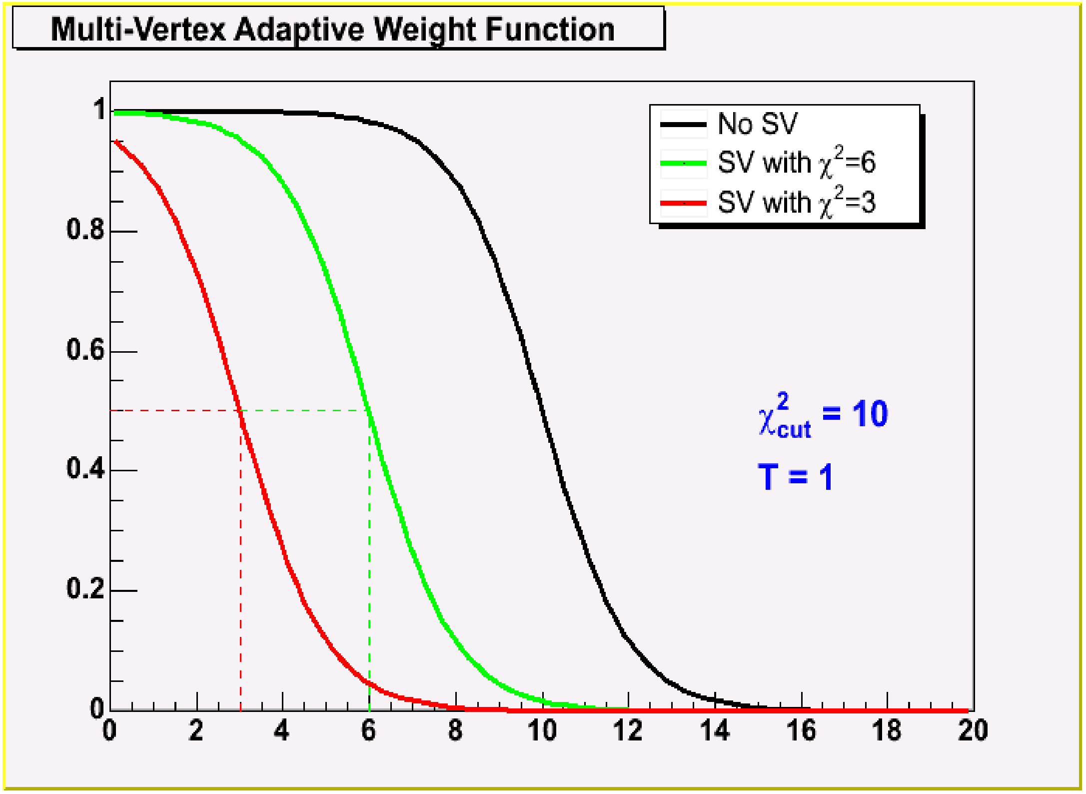
Global vertex reconstruction of primary and secondary vertices

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***.



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

Multi-Vertex b-tagging Algorithm

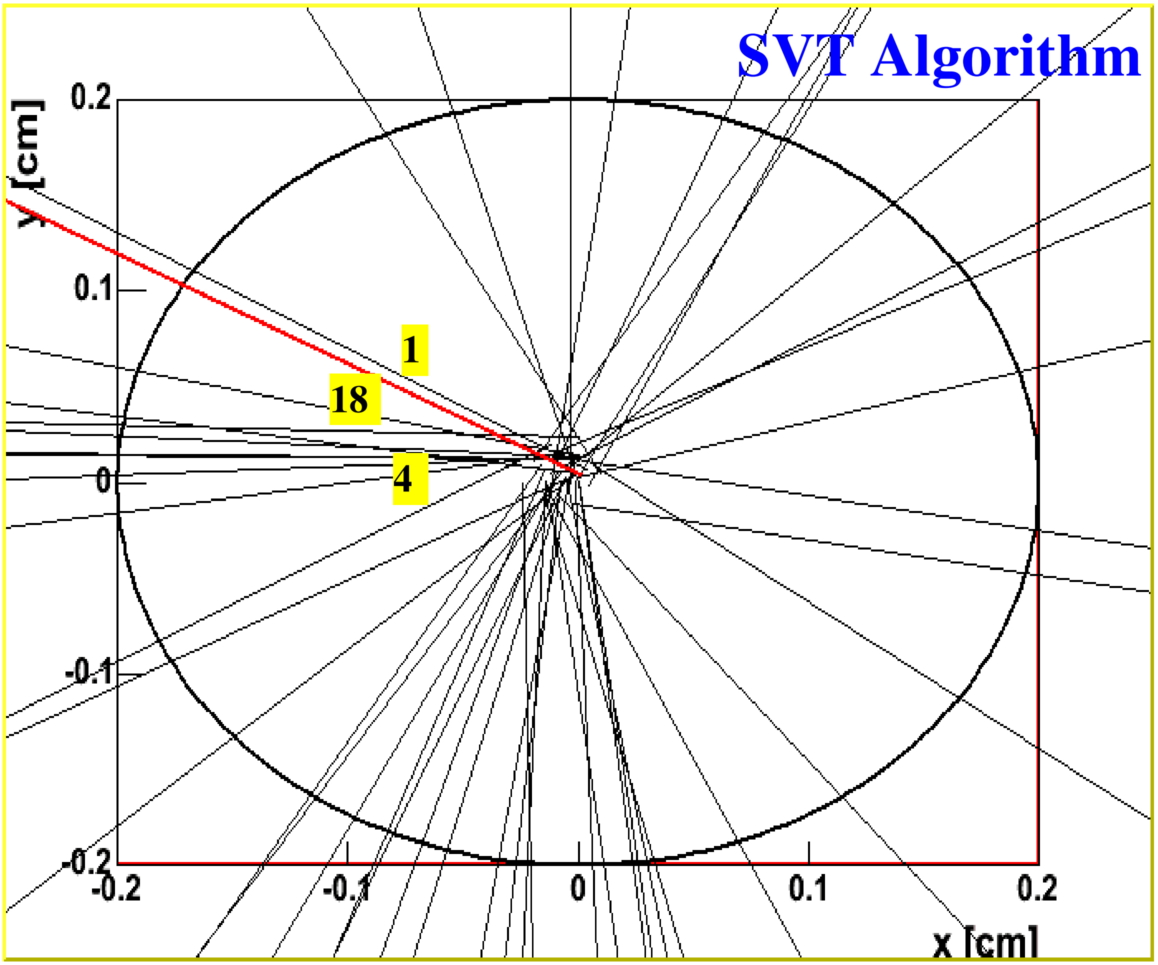
- Find Adaptive primary vertex.

- SVT extra-loose finds vertex “seeds” within jets. Most seeds will share tracks with other seeds and with the PV.

- Adaptive Multivertex fitter will resolve / merge / eliminate seeds and create a final list of vertices after convergence of weights:

  - Adaptive (Multi-vertex) primary vertex.
  - Adaptive (Multi-vertex) secondary vertices.

AMV in Top Quark Events (I)

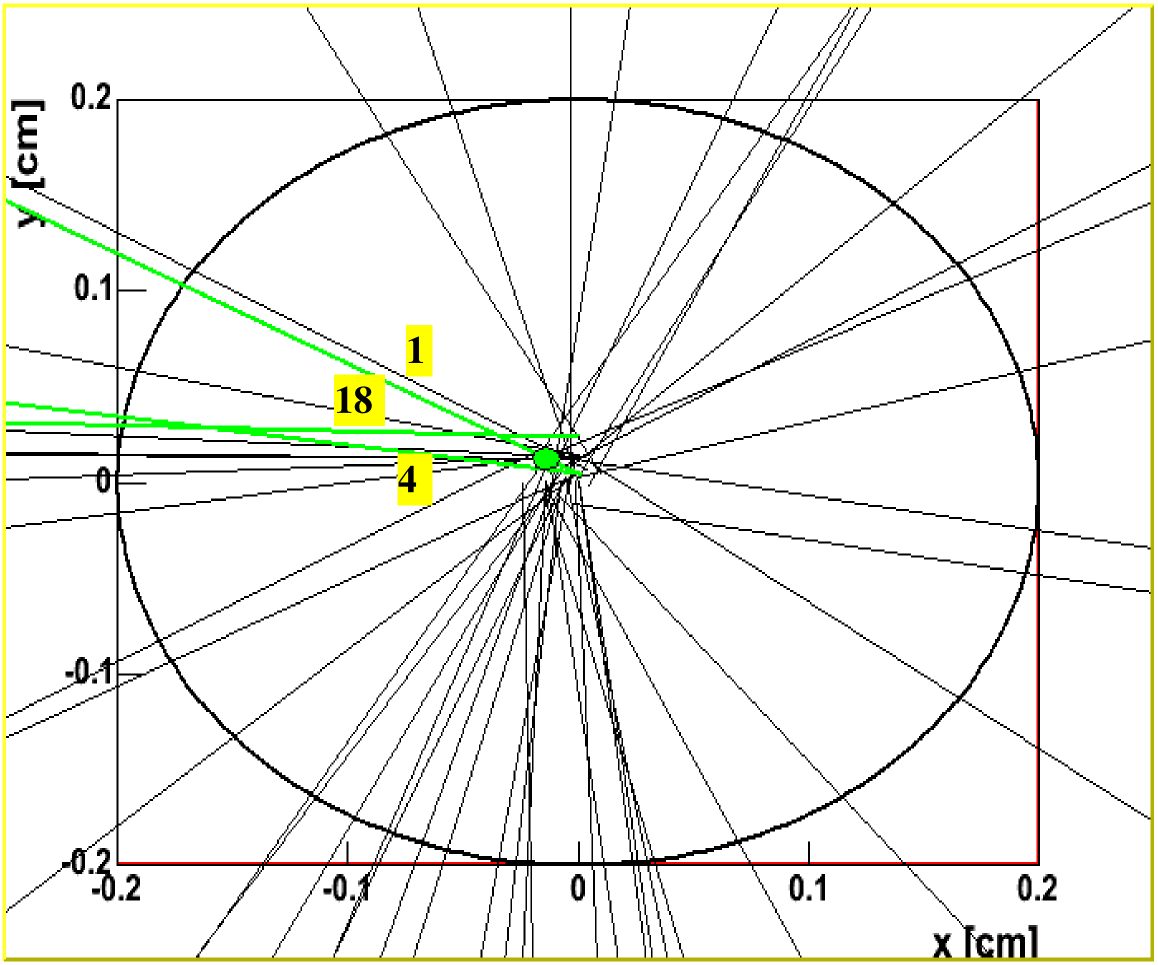


SVT extra loose finds a 3-track secondary vertex:

trk 1: dcasig = -4.6
trk 4: dcasig = -2.3
trk 18: dcasig = 2.1

Only track 1 passes dcasig>3 cut and the b-jet cannot be tagged with SVT loose algorithm.

AMV in Top Quark Events (II)



MultiVertex Fit: all 3 tracks form a SV.

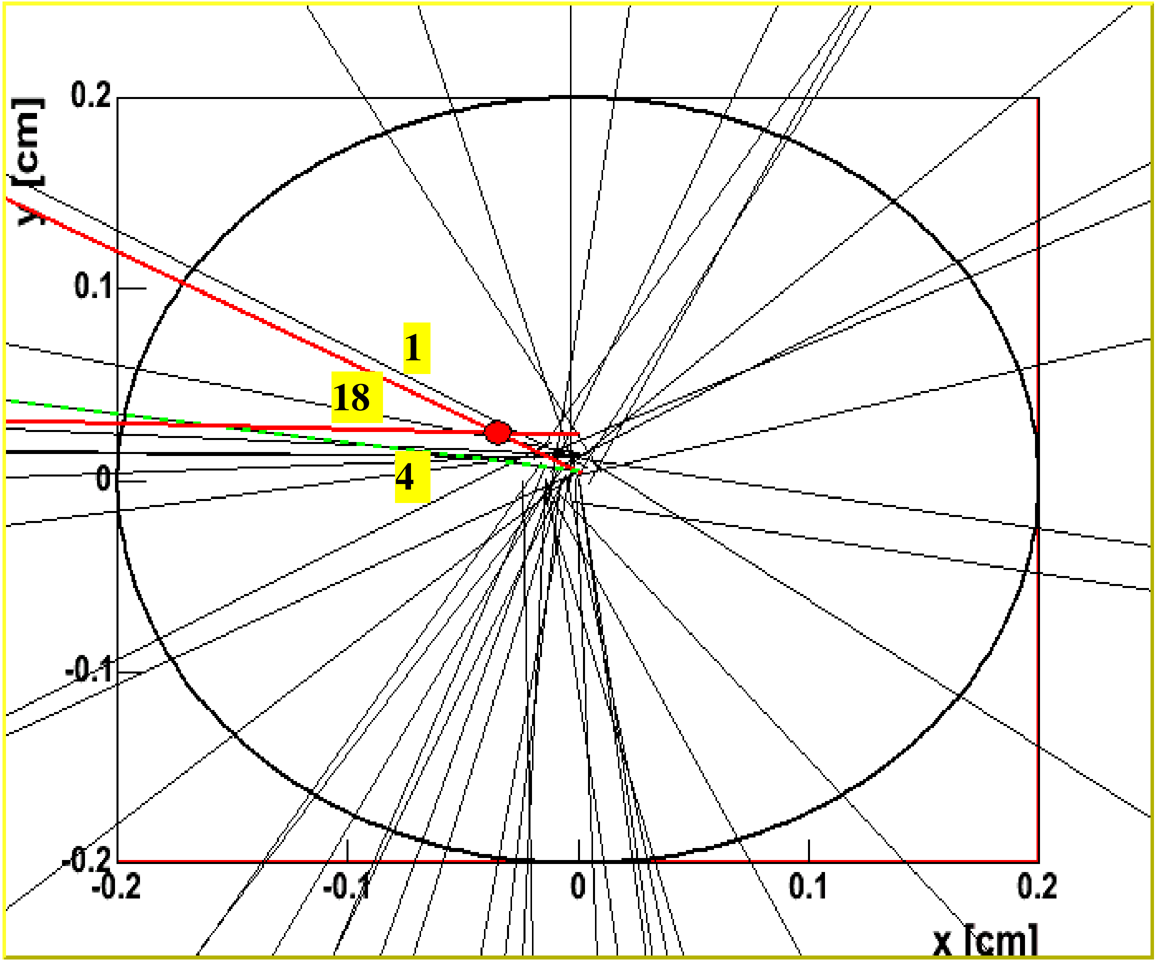
trk1:
wsv = 0.36

trk4:
Wpv=0.68 -> 0.61
Wsv=0.26 -> 0.10

trk18:
Wpv=0.66 -> 0.53
Wsv=0.42 -> 0.20

Second column shows how the weight for a track changes when there is another vertex competing for the same track.

AMV in Top Quark Events (III)



MultiVertex Fit:

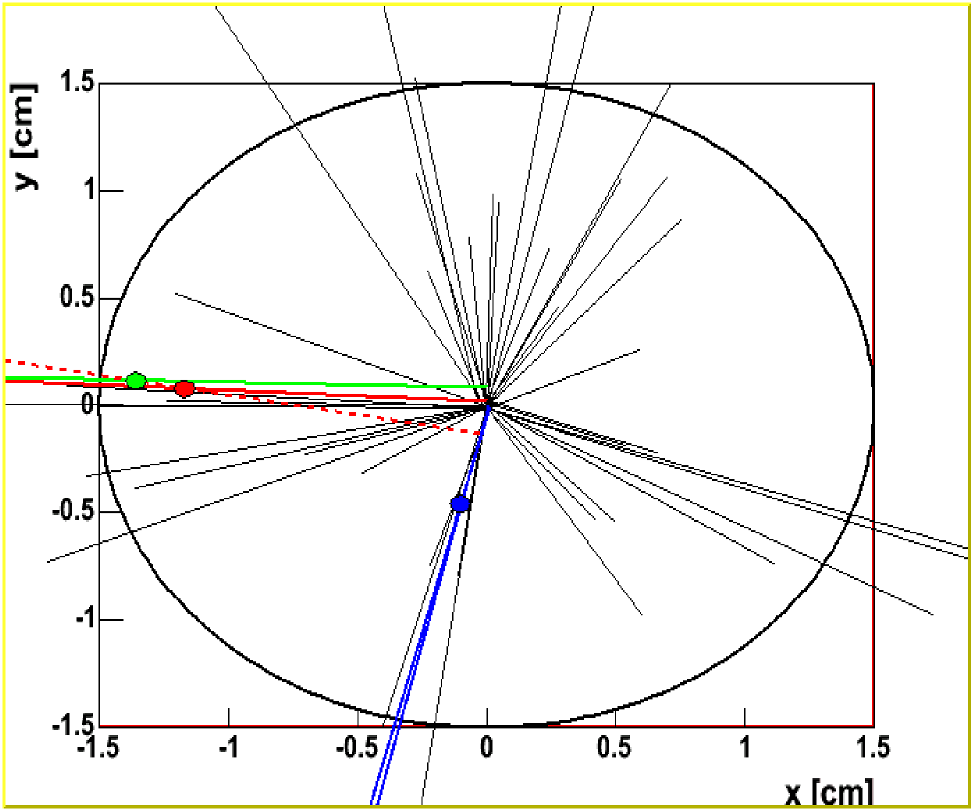
trk1:
wsv = 0.80

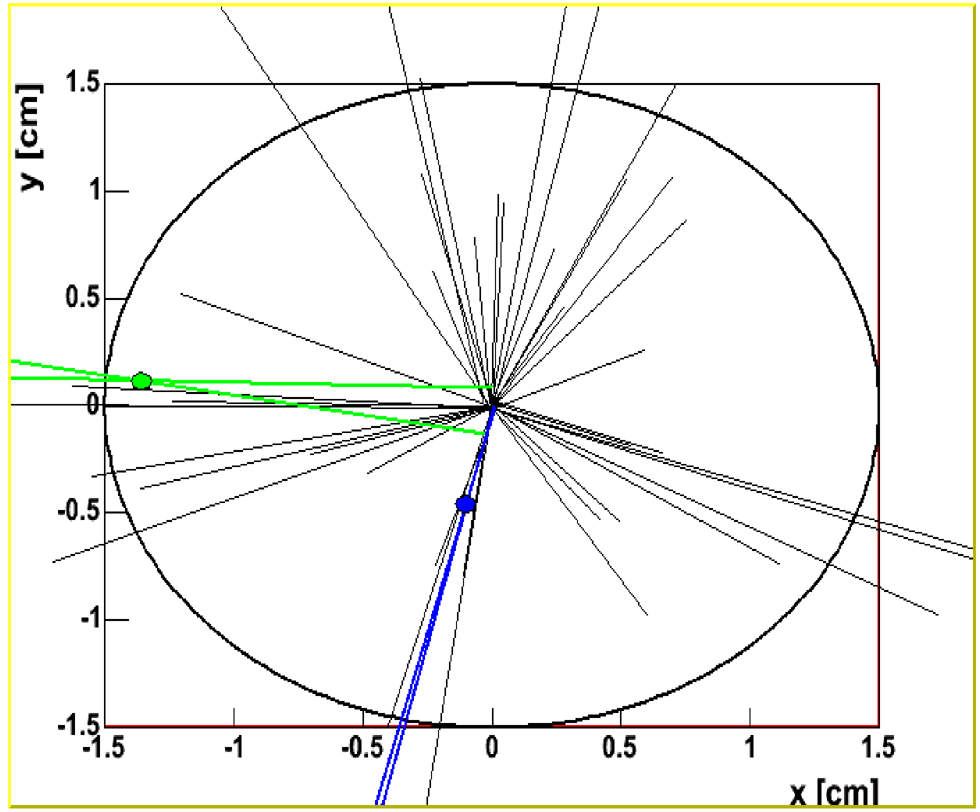
trk4:
wpv=0.40
wsv=0

trk18:
wpv=0.15
wsv=0.67

Track 4 is removed from the SV and attached to the PV.

AMV in Top Quark Events (IV)

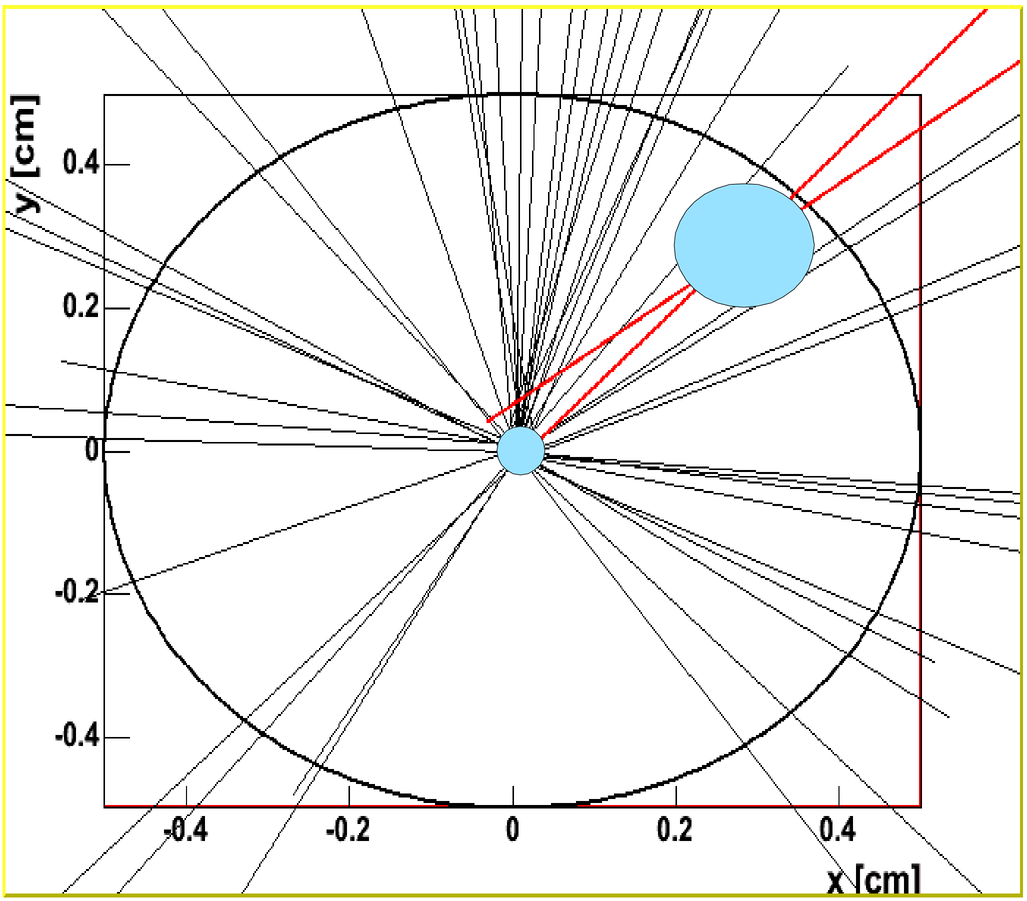




In this double-tagged event, a second SV sharing 1 track (red) is resolved by assigning one track to the PV and the second track to the 3rd (green)vertex.

Multi-Vertex Efficiency Issues

First studies have shown a lower SV Efficiency.

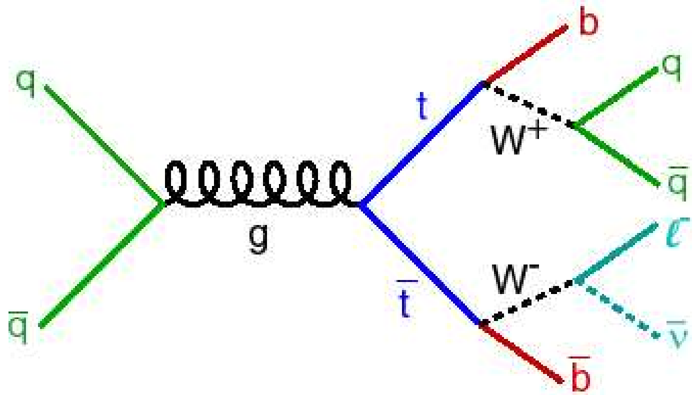


Secondary vertex resolution is worse than PV resolution (vertex multiplicity, track quality).

When a SV track can be associated to the PV, the PV is most likely to "win" the track due to the fact that the PV is a better reconstructed object.

Use Higher Temperature (Chi2) for SV tracks: account for different resolutions.

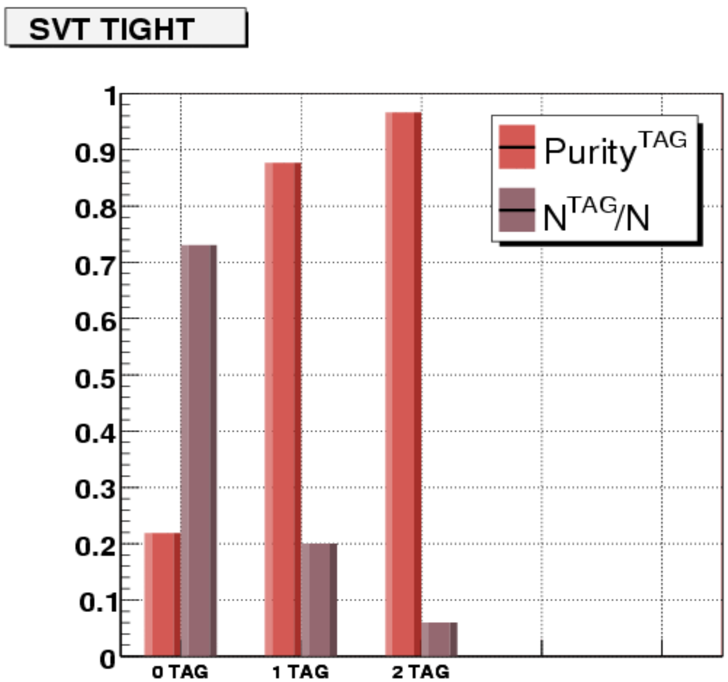
b-tagging in Top Quark Analyses



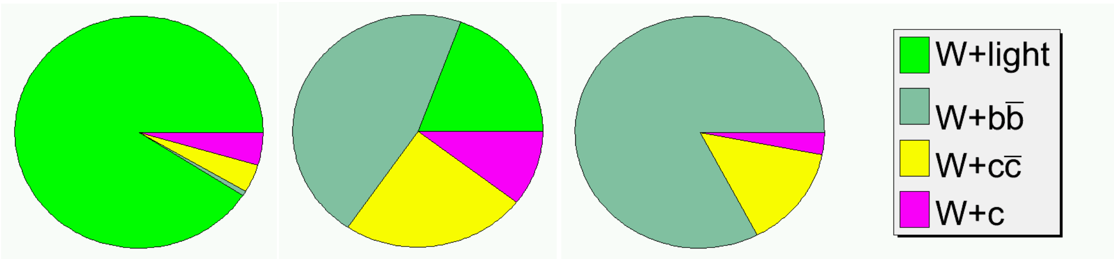
Experimental signature in the lepton+jets channel:

- 1 high p_T lepton
- 4 jets (2 b-jets)
- large E_T^{mis}

b-tagging classifies events in 3 tag categories, with different S/B.



W+jets flavor composition:



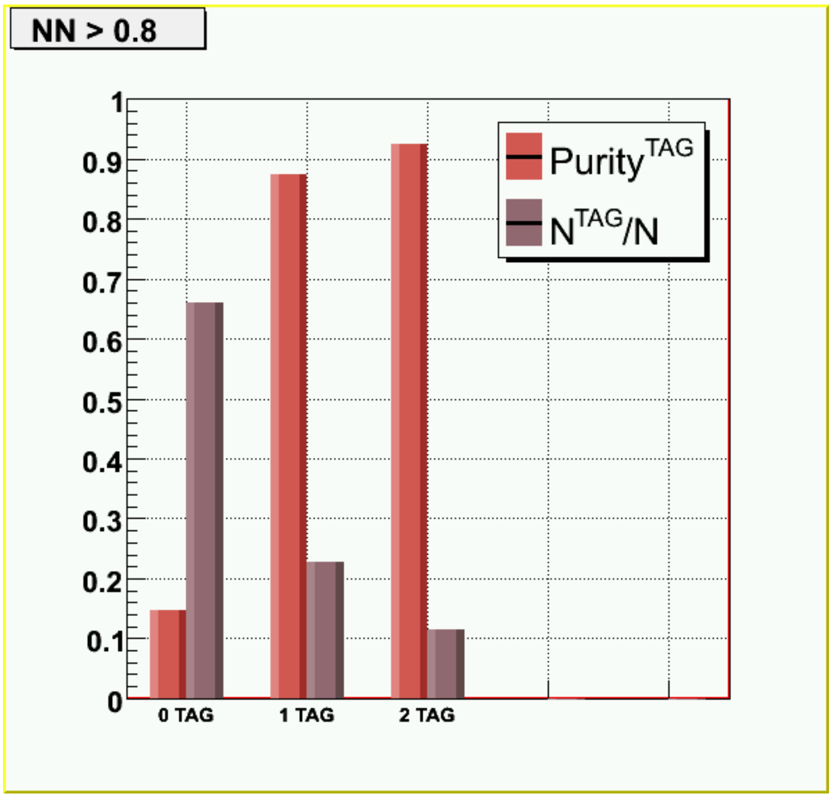
0-tag: 73%, f_{top} = 22%

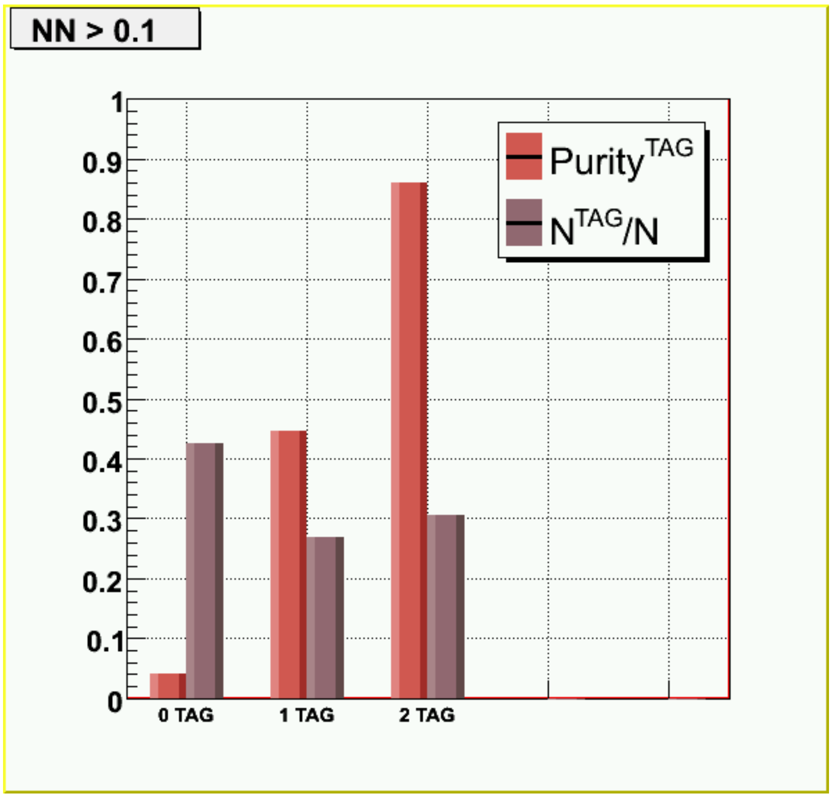
1-tag: 20%, f_{top} = 88%

2-tag: 7%, f_{top} = 97%

b-tagging Optimization in Top Analyses

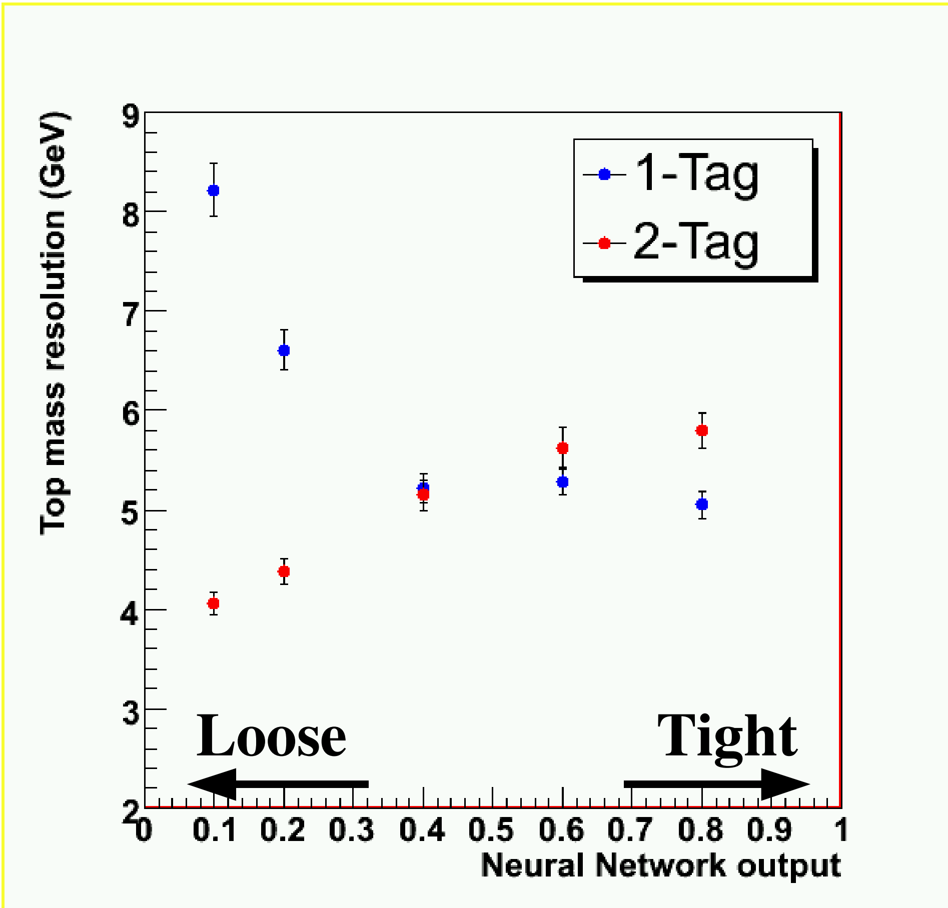
The b-tag operational point allows to change the number of events and purity in each tag-multiplicity bin: for example, increasing the number of double-tag events, where more b-tag information is available.

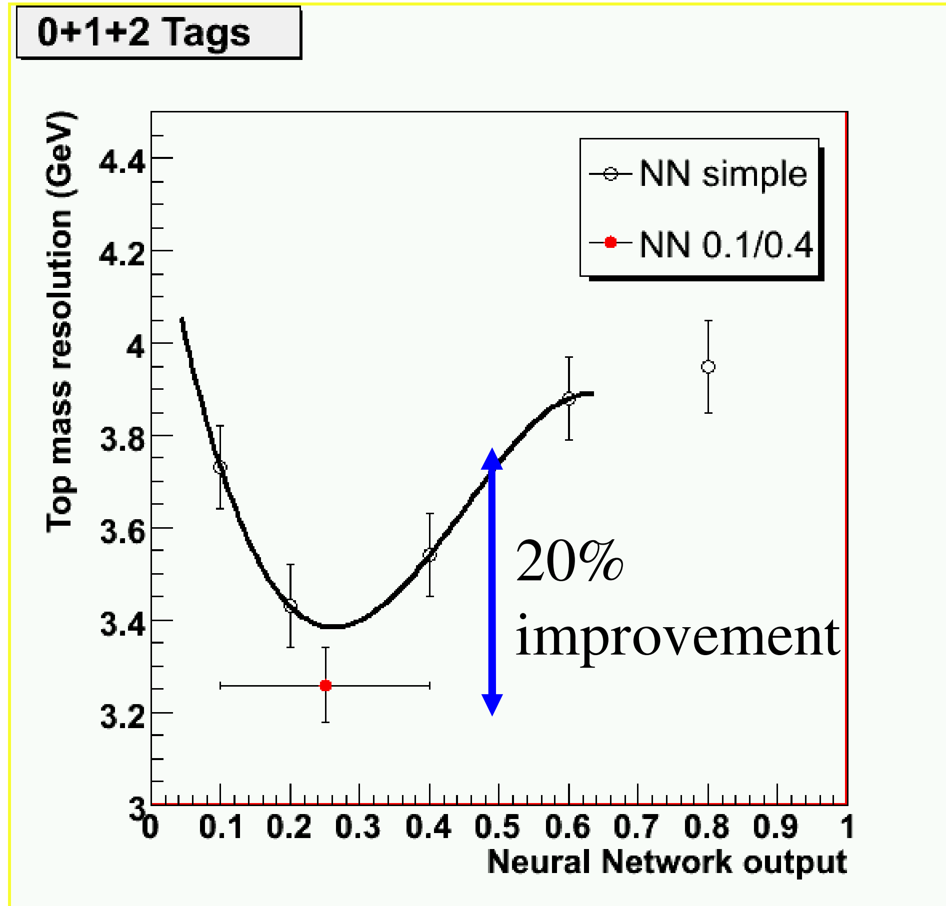




Optimize the b-tagging operational point to achieve the **best top quark mass resolution**.

b-tagging Optimization in Top Analyses





The best resolution is achieved using a multi-operational point: combination of loose/tight neural network outputs:

double Tag: NN>0.1, single Tag: NN>0.4

Summary and Conclusions (I)

Description of vertexing and b-tagging algorithms developed at DZero:

- Adaptive Kalman Filter fitter.
- 2Pass PV finder.
- MinBias PV selector.
- BuildUp SV finder.

Description of the techniques used to measure b-tagging performance in the data:

- Light quark mistag: Negative tag rate.
- b-tagging efficiency: System 8.

Summary and Conclusions (II)

The Adaptive primary vertex fitter:

- Robust, iterative Kalman Filter.
- Secondary vertex tracks are down-weighted depending on the distance to the PV.
- Significantly improved performance in heavy flavor events.

New approach for Global Multi-Vertex reconstruction.

b-tagging optimization results to improve the top quark mass resolution:

- Multi-Operational points.