# Hidden Valley Higgs Search

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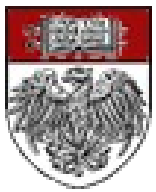


# Introduction

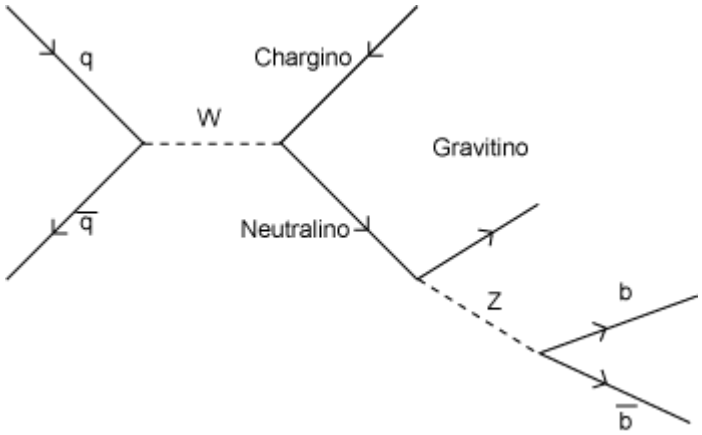
- Introduction to Displaced Vertices
  - Searching outside the SM
  - Hidden Valley Theory
- Event Selection
  - ZBB Trigger
  - Analysis Strategy
  - P.d.f. construction to model the SM, our background
- Background Estimate Algorithm Flowchart
- Discriminant Variables for our analysis
- A counting experiment

# Displaced Vertices

- Why look at displaced vertices?
  - It is an interesting signature outside of the Standard Model (SM).
  - While there are long lived particles in the SM (K, D, & B hadrons) there are few SM processes for two massive objects originating from a single common vertex.
- Some Previous Analyses:
  - Done at CDF-looking for a long-lived particle decaying into $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ by looking at the tracking information.
    - Finds the track intersection of the leptons, and looks for a large distance between this intersection and the primary vertex.
  - Done at D0-looking for a long-lived particle decaying into two b-quarks
    - Same signature and model as this analysis
- Because we can.
  - CDF employs a Silicon Vertex Trigger (SVT) that can trigger on displaced tracks.
  - This trigger allows us to enrich our signal while reducing the QCD background present at hadron colliders.
- What are we looking for:
  - In general we are searching for a long lived massive object decaying into two quarks, which then hadronize into jets in the detector.

# Phenomenology

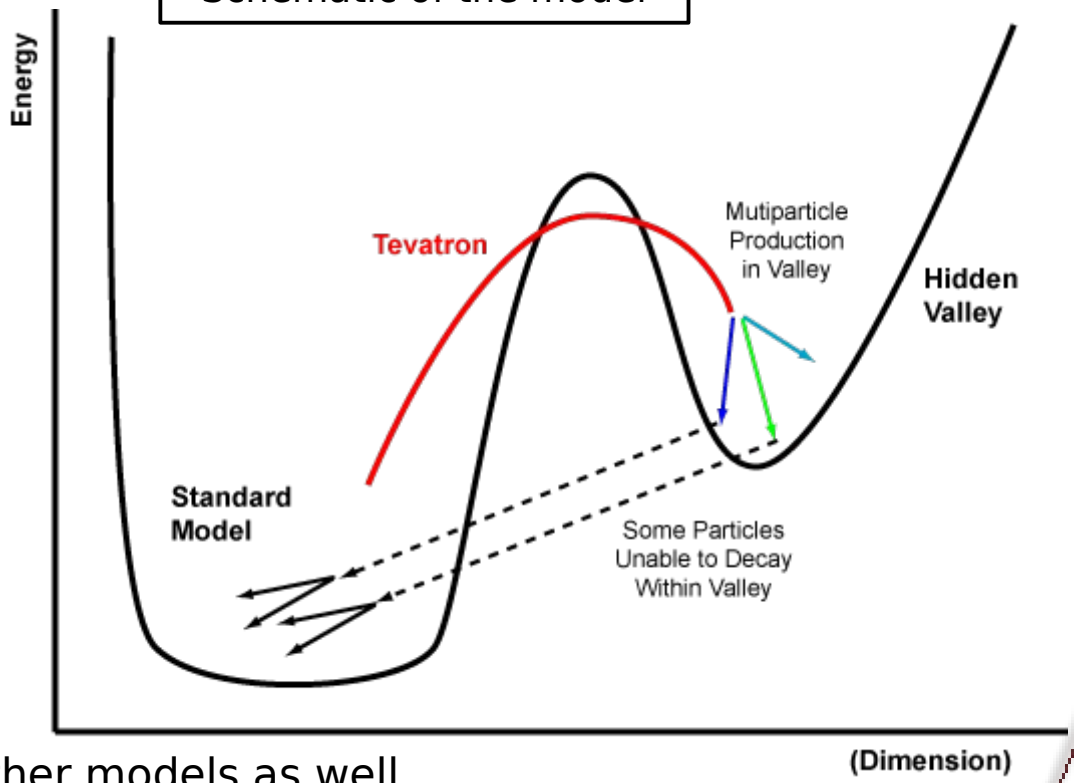
- There are a number of theories where displaced vertices play a role.
  - Hidden Valley model by Matt Strassler (Rutgers) and others.
    - The SM communicates with a Hidden Valley with valley (or v-) particles.
    - We wound up adopting this model for our search.
    - See next slide for more details.
  - Gauge-mediated SUSY models where the gravitino is the Lightest Stable Particle (LSP).
    - If the next to lightest stable particle (NLSP) has a large $\widetilde{Z}$ content, then it may decay to a $Z^0$ boson and the LSP.
    - The sparticle content of the NLSP is a free parameter in some SUSY models.



# Hidden Valley

- Energy from collisions enter into the new sector.
- It is transformed into multiple particles through the dynamics of the new sector.
  - These valley-particles (or v-particles) behave in the same way as SM particles.
  - They obey a "v-QCD,"
  - Most likely decay is a v-$\pi$.
- Some of these particles decay back into SM particles.

Schematic of the model



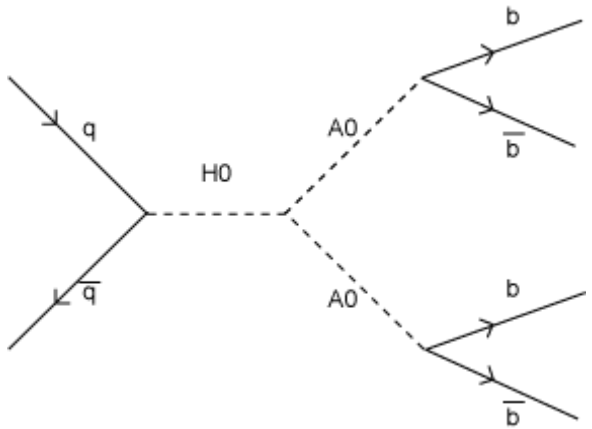

- This model can co-exist with other models as well.
  - SUSY, technicolor, etc.
- It may help in the search for the Higgs.
  - The Higgs may decays into long-lived neutral v-particles, which are heavy and meta-stable. They would decay at a displaced vertex.
  - These would then decay into the heaviest SM fermion available (b-quarks).
- Because this sector is dark, there may be Dark Matter/Astrophysics connections as well.
- In some models (see Kaplan, Luty, Zurek) $c\tau$ for the heavy metastable particle could be of order 1 cm.

# Hidden Valley

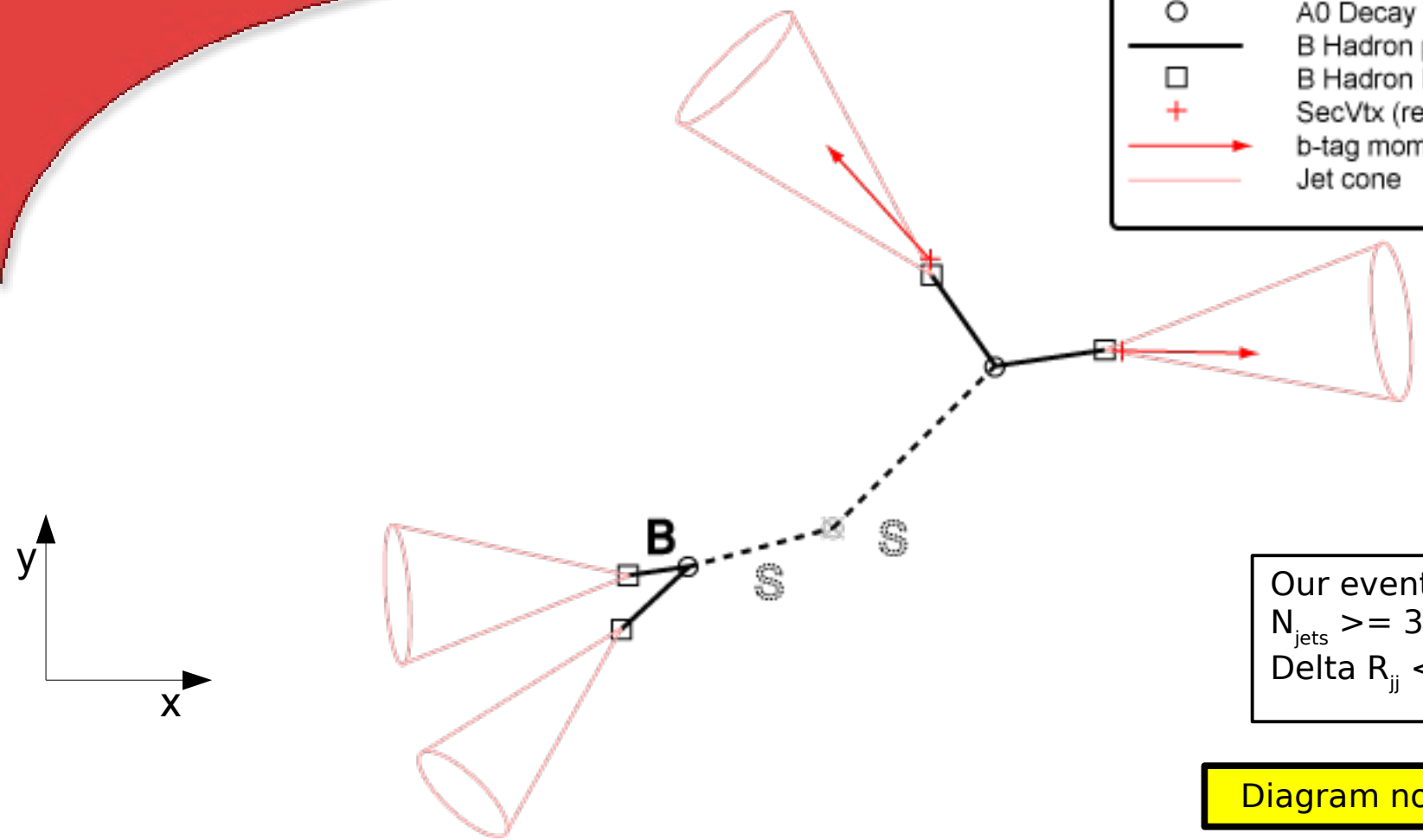
- The Hidden Valley model provides a large, and dark, sector which is weakly constrained by current experiments.
  - In general, experiments at LEP, CDF, BABAR have little or no constraints on neutral particles with small couplings to photons or Z.
  - In particular particles that have no weak, electric or color charge.
- Because this model has few constraints, there are a large number of experimental signatures that are possible.
  - We have chosen to concentrate on one signature, displaced vertices, and one model, Higgs production.
  - The signature provides sensitivity to a broad range of heavy metastable particles.
  - The model provides a benchmark result that can later be translated for other theories.
- Although we are looking for a Higgs, this search is signature based. Any particle which decays in such a fashion, with a displaced vertex into q, qbar pairs, can be the source of our signal.

# MC Studies

- First thing we did was generate some signal MC to study. This was done with Pythia w/ the CDF detector simulation and CDF "tunes."
  - The decay chain is: $H_0 \rightarrow A_0$ $A_0 \rightarrow$ b,bbar, b,bbar.
  - Here the Higgs is a MSSM Higgs.
    - The Higgs has been constrained to decay into $A_0$s.
  - The $A_0$ represents a heavy pseudo-scalar, the hidden valley particle (v-$\pi$), that has a long lifetime.
    - The proper lifetime studied so far is $c\tau$ = 1.0 cm.
  - We generate different masses of $H_0$s and $A_0$s.
    - $H_0$ = 130 GeV and 170 GeV
    - $A_0$ = 20 GeV, 40 GeV, and 65 GeV
  - The $A_0$s are constrained to decay into b, bbar quark pairs.
  - The MC also simulates an underlying event.



# Model Diagrams




Our event selection:
$N_{jets}$ >= 3
Delta $R_{jj}$ < 2.5

Diagram not to Scale

Here the Higgs decays at the primary vertex (the X). S represents the heavy pseudoscalar with a long lifetime, which decays into bbbar pairs.

The pink cones represent the hadronization of the B hadrons into jets.

The red represents reconstructed secondary vertices and their corresponding momenta.

Black is the "truth" information.

# Signal Event Selection

- We will be looking for events with central b-tagged jets, with a relatively low $E_T$ requirement: **Signal Region**
  - All jets are required to have:
    - $E_T$ > 20 GeV, corrected at Level-5
    - $|\eta|<1.0$
  - Jet multiplicity: $N_{jet} \geq 3$
  - For the dijet system, require that it be in a region that would be populated by signal.
    - $\Delta R_{jj} < 2.5$
- A **Control Region** is defined which contains events orthogonal to the Signal Region,
  - Two tight central jets ($N_{jet} = 2$)
  - A third jet with Level 5 corrected $E_T < 15$ GeV.
  - There is no $\Delta R_{jj}$ cut in this region.

# Big Picture

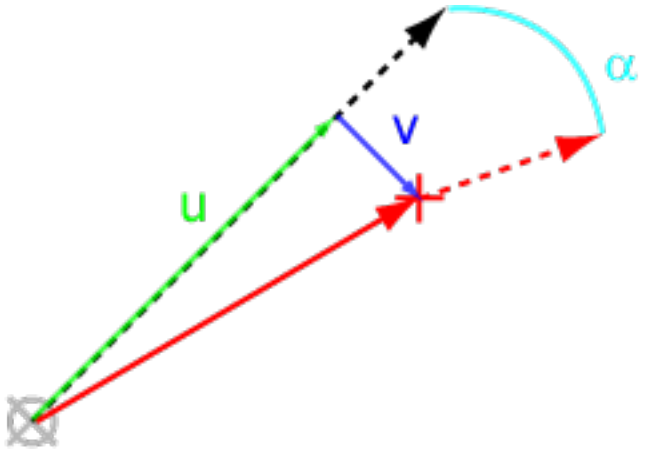
- The trigger we are using is the ZBB trigger
  - At Level-2, the trigger selects tracks w/ 160 μm < $|d_0|$ < 1000 μm.
  - This is the displaced track part of the trigger.
- Default SecVtx cuts on the $d_0$ of tracks considered for vertexing.
  - Our signal has highly displaced vertices with highly displaced tracks.
  - This cut reduces the efficiency of particles that decay with much longer lifetime than B hadrons, such as our signal's A0s.
- TStnSVF is a (T)Stntuple Secondary Vertex Finder.
  - The algorithm is the same as SecVtx, but the input data is from the Stntuple instead of Production data.
  - We run this b-tagger over 20 max $d_0$ cuts for the tracks in the jet, in order to find a $d_0$ cut which maximizes the efficiency for finding a signal.
- We are building p.d.f.s from single jet to form the background estimate.
- We use these p.d.f.s to create pseudo events from real jets in the ZBB trigger data.
  - These pseudo events use the kinematic information of ZBB trigger events.
    - $E_T$, $\Delta R$, etc.
  - While generating SM secondary vertices using the p.d.f.s based on the flavor composition of the ZBB sample

# Analysis Strategy

- We want to use real data to estimate our background.
  - SM background sources include
    - Mundane b background: QCD bb, ttbar, Z etc.
    - Mundane c background: QCD cc, Z
    - Light flavor background: QCD qq/gg
    - (Others such as tau hadronic)
  - Use data triggers when possible to build the p.d.f.s of SM sources.
    - Muon calibration data, which is rich is heavy flavor jets
    - Single Tower 5, jet data, for light-quark and gluon jets
    - Pythia QCD cc MC
  - These p.d.f. are per jet (not per event).
  - These per jet p.d.f.s can be applied to multijet QCD production, either data or MC, to estimate the final background and decide on cuts.
  - We expect the QCD SM process to dominate our background to the signal.
- What are the variables in the p.d.f.s?
  - The variables are those dealing with the secondary vertex. Specifically characterizing the secondary vertex's position and momentum.
  - More details are given on the next slide.
- Generate pseudo events to represent the SM (the background).
- Perform a counting experiment searching for an excess in the real data w.r.t. the SM.

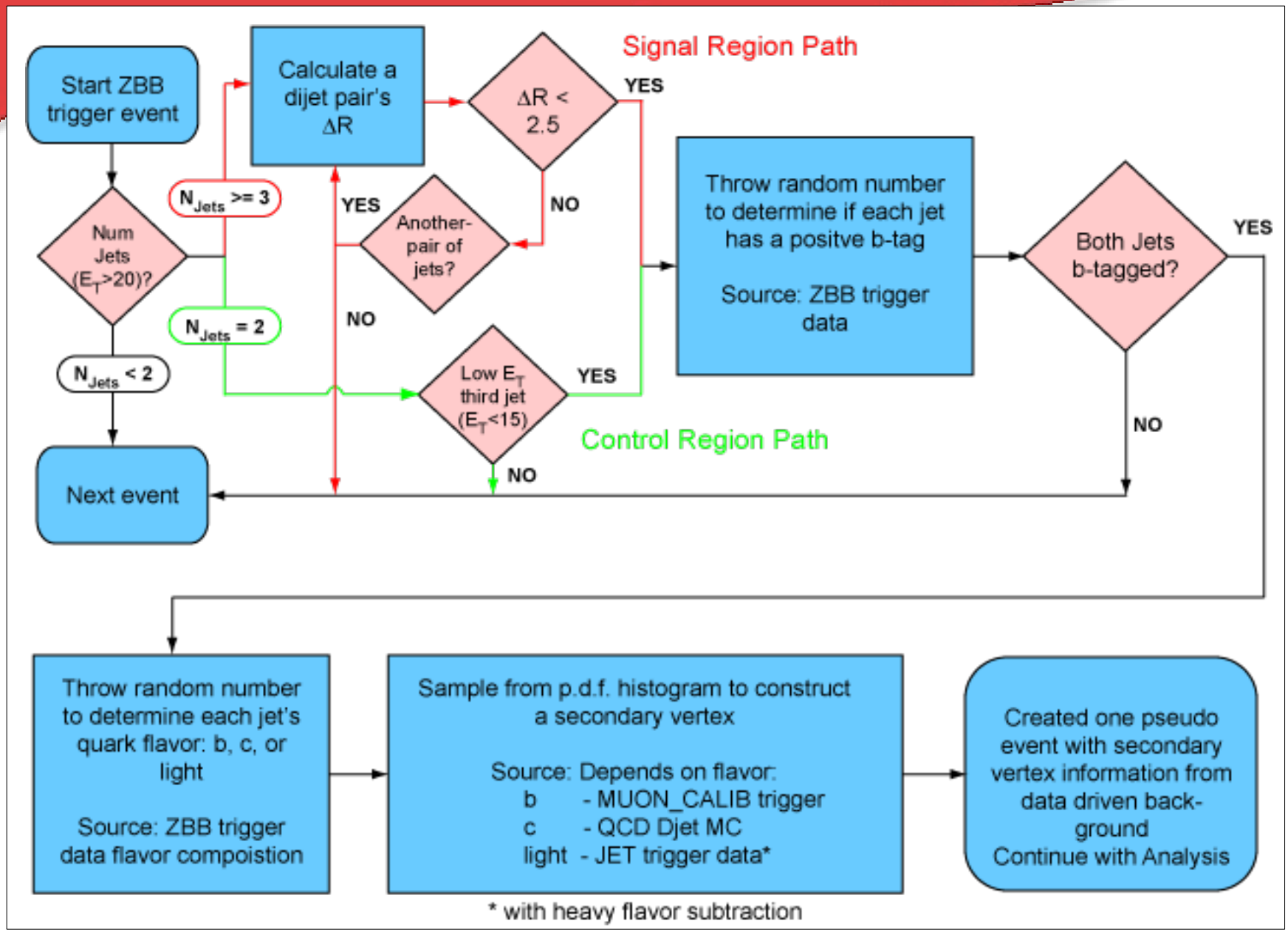
# Building p.d.f.s

- There are three p.d.f. variables
  - *u* – the $L_{xy}$ component vector parallel to the jet axis
  - *v* – the $L_{xy}$ component vector perpendicular to the jet axis
  - $\alpha$ – the angle between the secondary vertex momentum and the jet momentum
- We are working in 2 dimensions.
- These three variables encapsulate the information about a single secondary vertex.
- These are plotted in a three dimensional histogram, this preserves all correlations among these variables.




| | |
|---|---|
| Black Dashed Line | Jet Momentum |
| Red Cross | Secondary Vertex |
| Red Solid Line | Sec Vertex $L_{xy}$ |
| Red Dashed Line | Sec Vertex Momentum |
| Green Line (u) | Parallel component of $L_{xy}$ |
| Blue Line (v) | Perp. component of $L_{xy}$ |
| Cyan Arc (α) | Angle b/w the two momenta |

# Flowchart




This flowchart shows the background estimate / pseudo event generating algorithm.

# Discriminants

- Next few slides are figures of the discriminate variables.
- Afterward are a few histograms showing these discriminants in the Signal MC v. a QCD to bbbar MC.

# Diagrams ψ

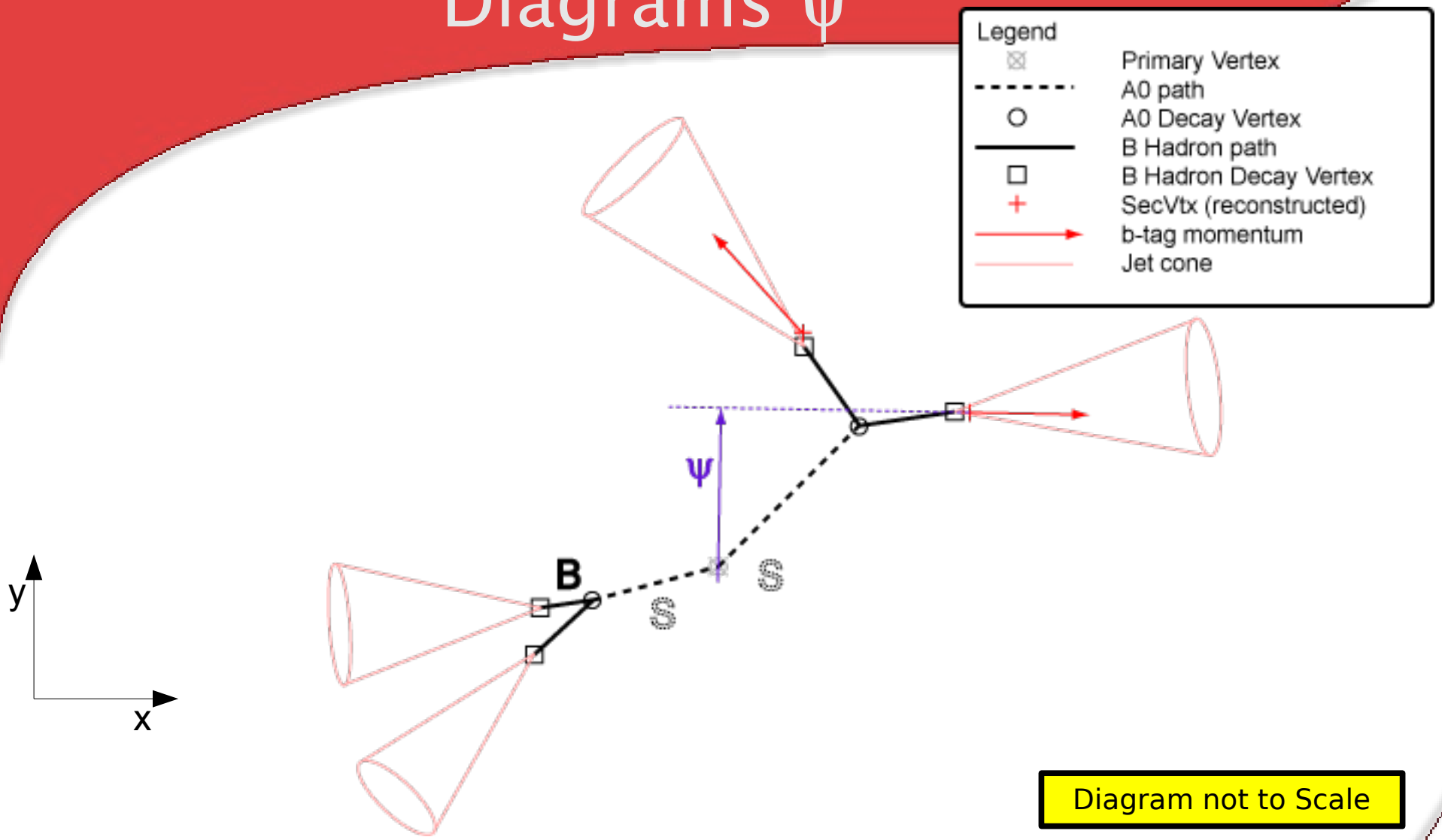



Diagram not to Scale

ψ is the impact parameter of a jet with a secondary vertex.

This is in two-dimensional space.

# Diagrams ζ

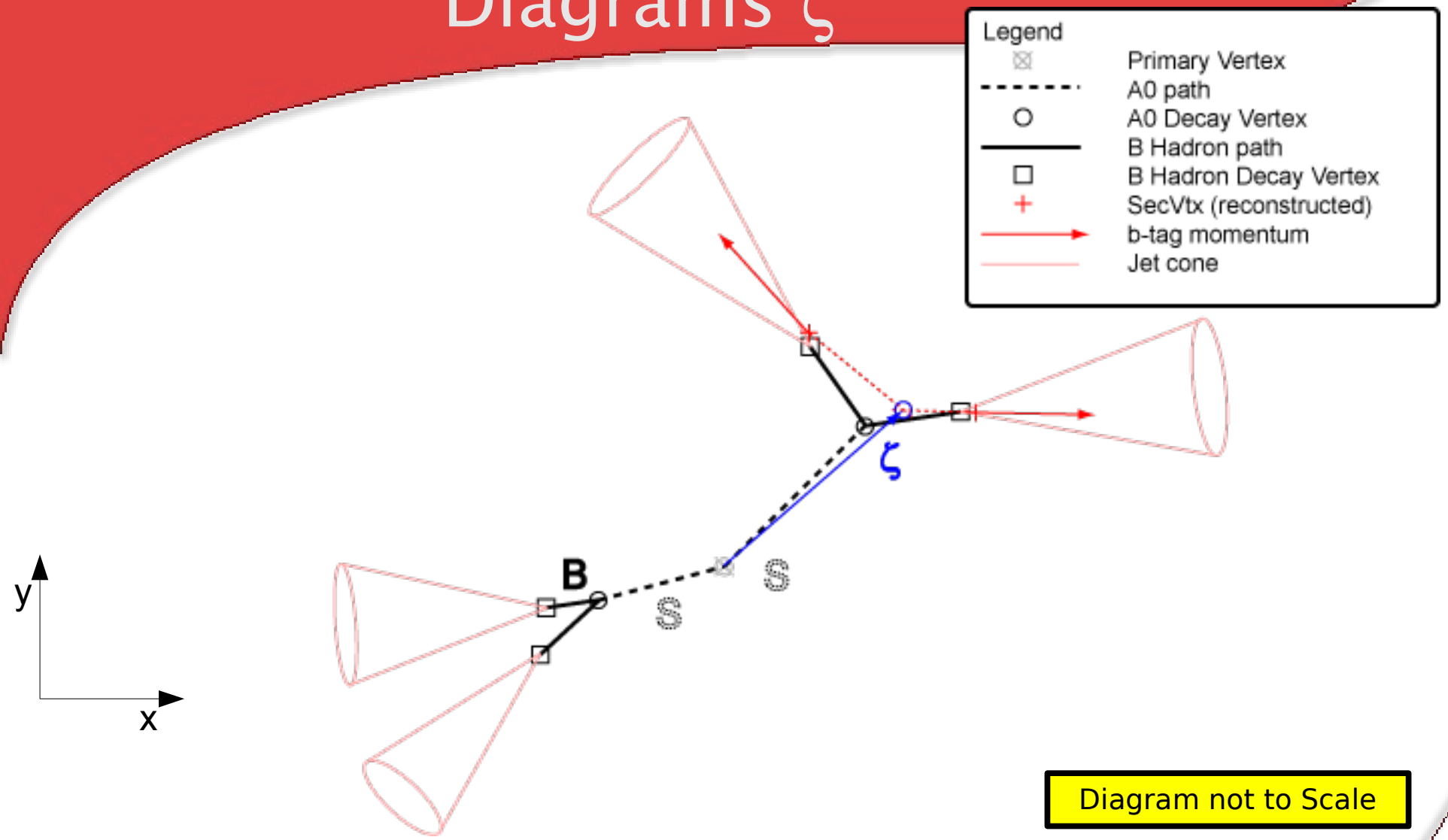



Diagram not to Scale

ζ is the reconstructed decay distance of the heavy pseudoscalar S ($A_0$). It requires two tagged jets.

This is in two-dimensional space.

# Background Diagrams

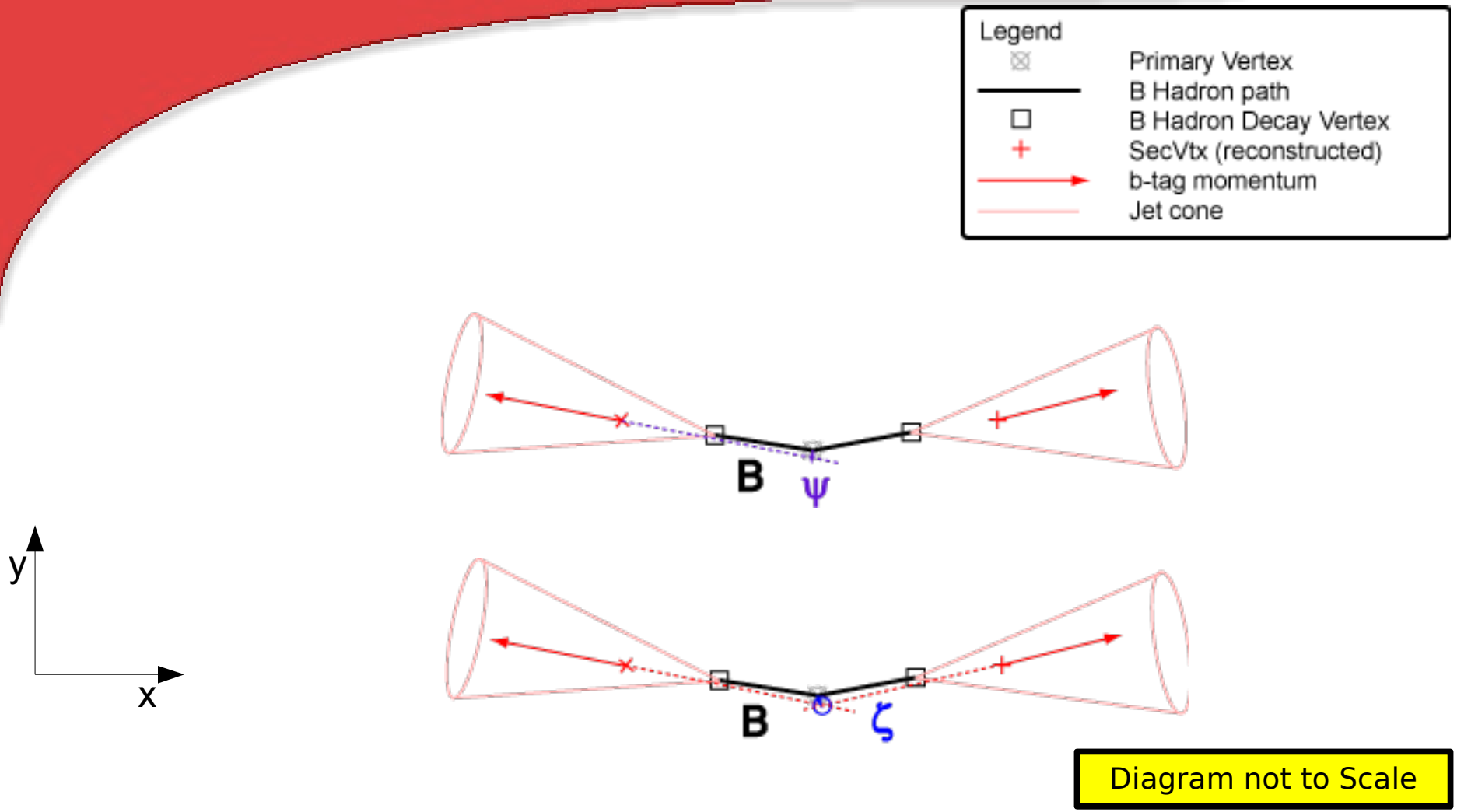



Diagram not to Scale

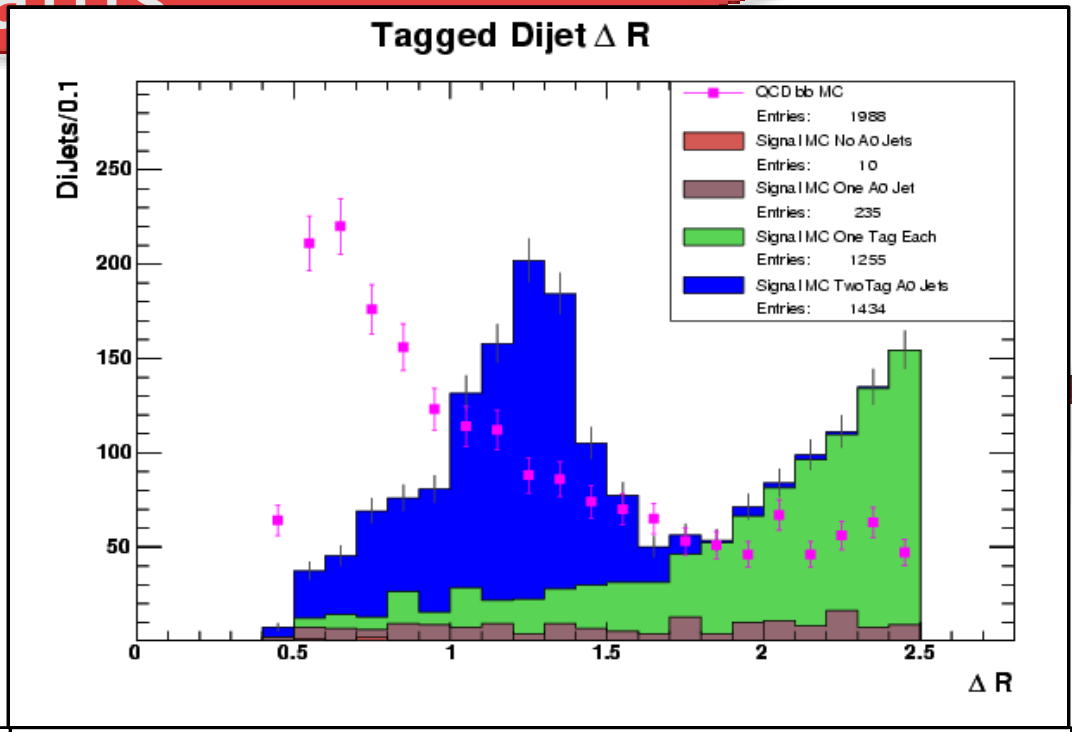
Here is a typical QCD di-jet event with two b quarks (b & bbar) decaying into two B hadrons. Each has a reconstructed secondary vertex represented by a red cross. Both ψ/ζ are very small for these background events.

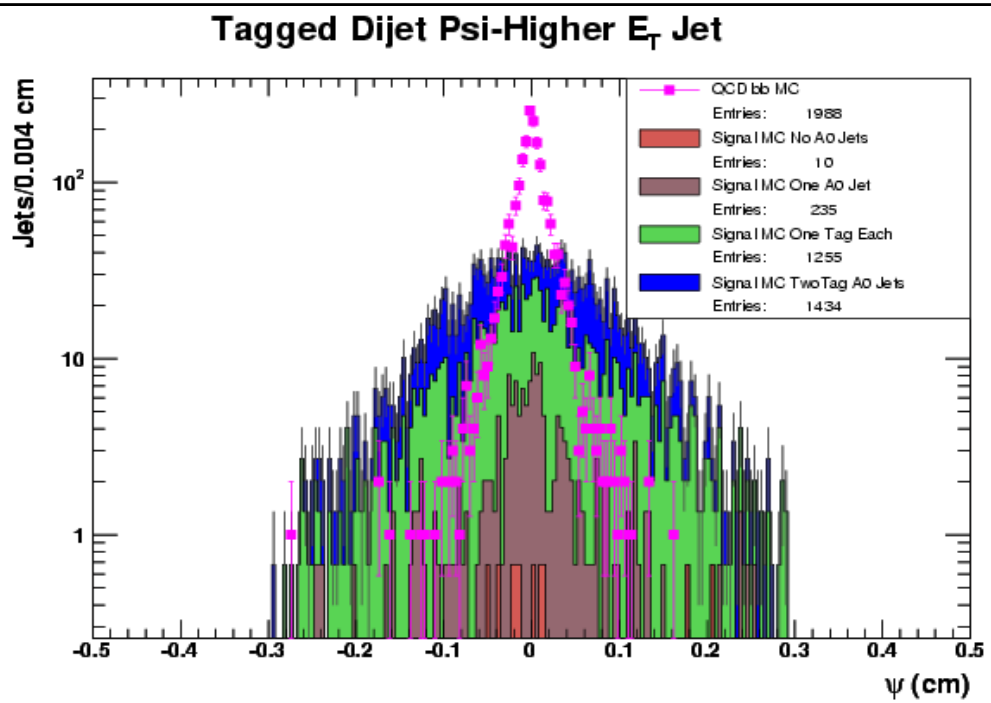
# Discriminants

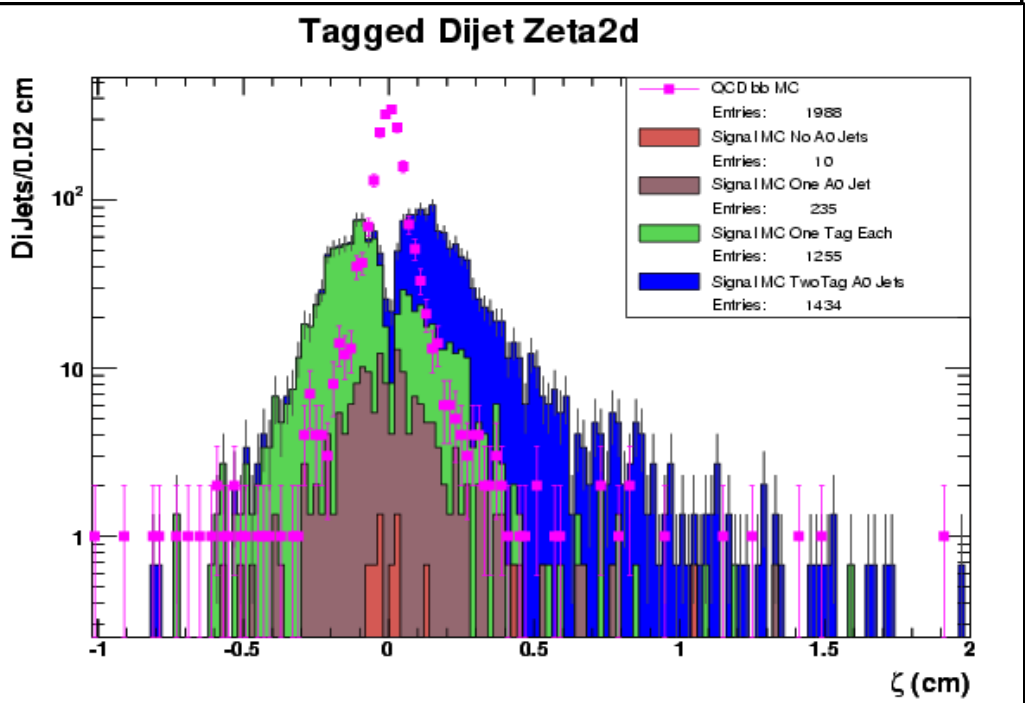
- New Variables were developed: Psi($\psi$) and Zeta($\zeta$).
- $\psi$ is the impact parameter of the jet.
  - Take the secondary vertex of a jet, it has a position and a direction (momentum), which can be traced back to the primary vertex to give a distance of closest approach (DCA) in 2-dim space.
- $\zeta$ is the distance from the primary vertex to the intersection of multiple jet directions in 2-dim space.
  - This is the reconstructed decay vertex of the $A_0$ (candidate $A_0$).
  - It can be positive or negative (like a b-tag).
- There are a few more discriminants of use.
  - Delta R between the jets.
  - Distance between the secondary vertices ($\Delta S$).
  - Average $L_{2d}$ of the secondary vertices.
    - $L_{2d}$ is the two-dimensional distance of the secondary vertex to the primary vertex, projected onto the momentum vector of the jet.
  - See backup slides for additional figures.
- As reminder, both signal MC and QCD bb background MC events must pass the ZBB trigger.

# MC Histograms

- Signal MC v. QCD bb MC (magenta)
  - The max $d_0$ cut is $|d_0| < 0.30$ cm.
  - Normalize to unit area to compare shapes.
  - $H_0 \rightarrow A_0A_0 \rightarrow$ bb, bb: the $A_0$ represents the long-lived pseudoscalar.
  - What's shown here is $H_0$=130 GeV and $A_0$=40 GeV with lifetime 1.0 cm.
  - Cut on $\Delta R < 2.5$ has been applied.

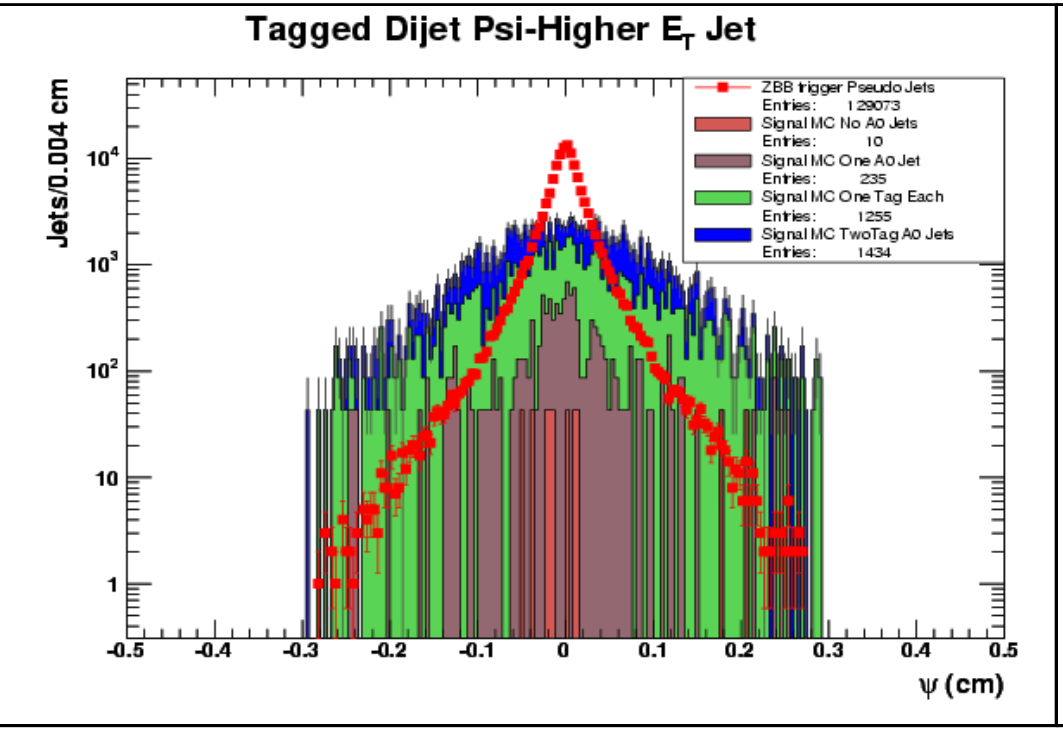


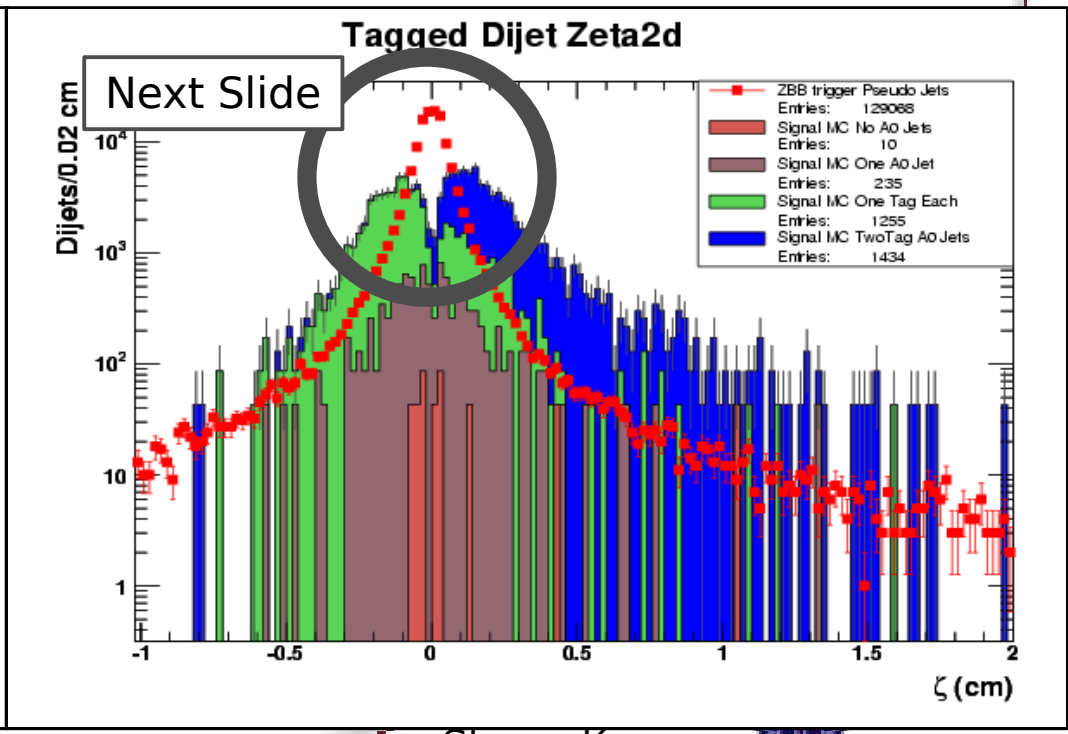



# Comparing Signal to Background

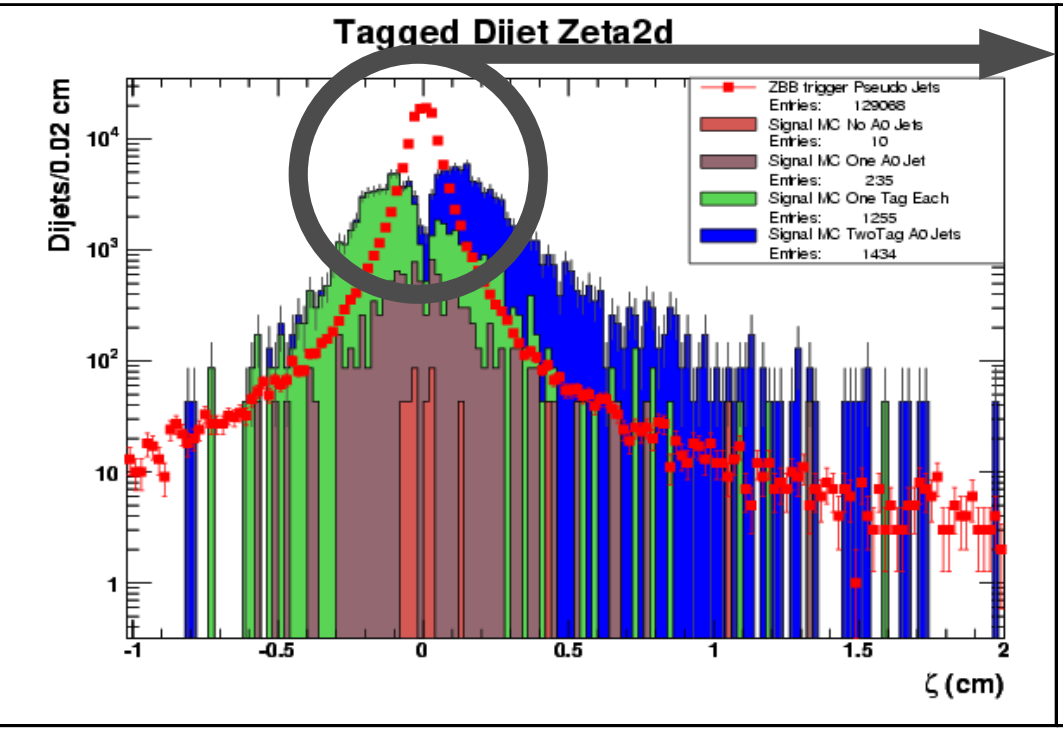
- Generate psuedo data which represents the SM background (red).
- Compare the signal MC to the pseudo events generated from the ZBB trigger data – background estimate data, 3 jet Signal region.
  - The max $d_0$ cut is $|d_0| < 0.30$ cm.
  - The signal MC area has been normalized to the pseudo data.
- Looking to make some simple cuts for a counting experiment.

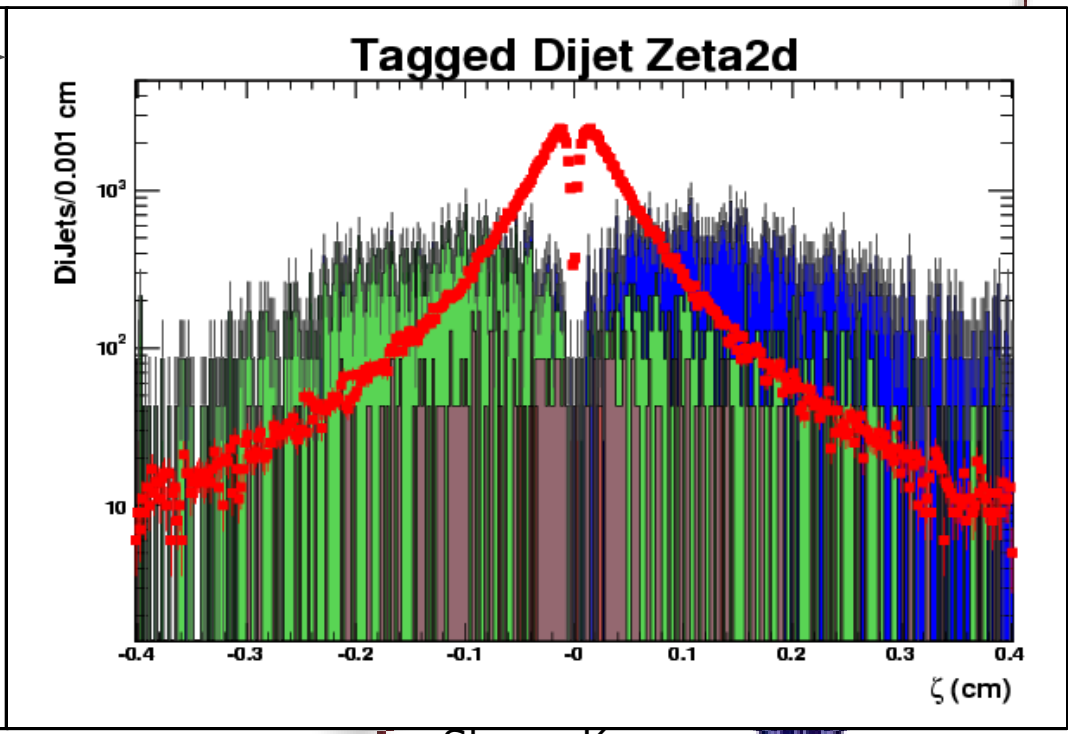


# Signal vs Background

- ζ is a 2 dimensional distance: from the primary vertex, to the intersection of the two b-tag directions.
- Left: same plot as last slide
- Right: zoomed in, with 10x more bins.
  - Phase space
  - Resolution effect
- There is more phase space for ζ to exist away from the primary vertex, and the signal MC by construction has larger ζ, the result is the “hole” you see below.



# Counting Experiment

- Shown the background pseudo events vs. Signal MC.
- The purpose is to select a series of cuts in $\psi$ and $\zeta$ to minimize the background and maximize our signal.
- Compare the real jet, with real secondary vertices, in ZBB data and make comparisons with the pseudo data where we look for an excess of events.

- Systematic Uncertainties (Future Tasks)
  - Shape uncertainties in the p.d.f.s themselves
  - Flavor uncertainties in the flavor generation of the pseudo jets
  - Other systematics, which affect the p.d.f.s.

# Conclusions

- Displaced vertices can be used to search outside of the SM.
  - The Hidden Valley theory provides us with a model to search for the Higgs boson with this signature.
  - The SVT trigger at CDF aids in this signature search.
- In order to model the background correctly we use real data.
  - P.d.f.s of SM jets with SM secondary vertices model the background.
  - Real events are used to construct pseudo events, built with SM p.d.f.s.
- Discriminants for signal were developed.
  - Perform a simple counting experiment to search for the signature of displaced vertices.
- The analysis is currently ongoing.
  - Make selection cuts for counting experiment,
  - Systematic Uncertainties need to be studied.

# Backup Slides

- ZBB Trigger
- Additional diagrams

# ZBB Trigger

- Details of the trigger in the trigger table:
  - L1 :
    - one central tower with $E_T > 5$ GeV
    - two XFT tracks, $p_T^1 > 5.48$ GeV, $p_T^2 > 2.46$ GeV
  - L2 :
    - veto events w/ clusters with $E_T > 5$ GeV, $|\eta| > 1.1$
    - requires two clusters $E_T > 5$ GeV, $|\eta|<1.1$ which have $9 < \Delta\text{Wedge} < 12$
    - two SVT tracks with $p_T > 2$ GeV, $d_0 > 160$ microns, $d_0 < 1000$ microns, $\chi^2 < 12$,
      - $150 < \Delta\phi < 180$ “Opposite Side”
      - $0 < \Delta\phi < 30$ “Same Side”
      - This triggers on displaced tracks in the event.
  - L3:
    - two R=0.7 jets with $E_T > 10$ GeV, $|\eta| < 1.1$
    - two SVT tracks with $p_T > 2$ GeV, $d_0 > 160$ microns, $d_0 < 1000$ microns, $|\eta| < 1.2$
    - two tracks with $p_T > 1.5$ GeV, $d_0 > 130$ microns, $d_0 < 1000$ microns, $|\eta| < 1.2$, IP significance $Sd_0>3$, $\Delta z < 5$ cm
  - Dynamically Prescaled Trigger
  - This is for the latest trigger “chunk,” #17. Chunks 10-16 are nearly the same, with minor changes in the cut values, but the structure is the same.

# Add. Diagrams

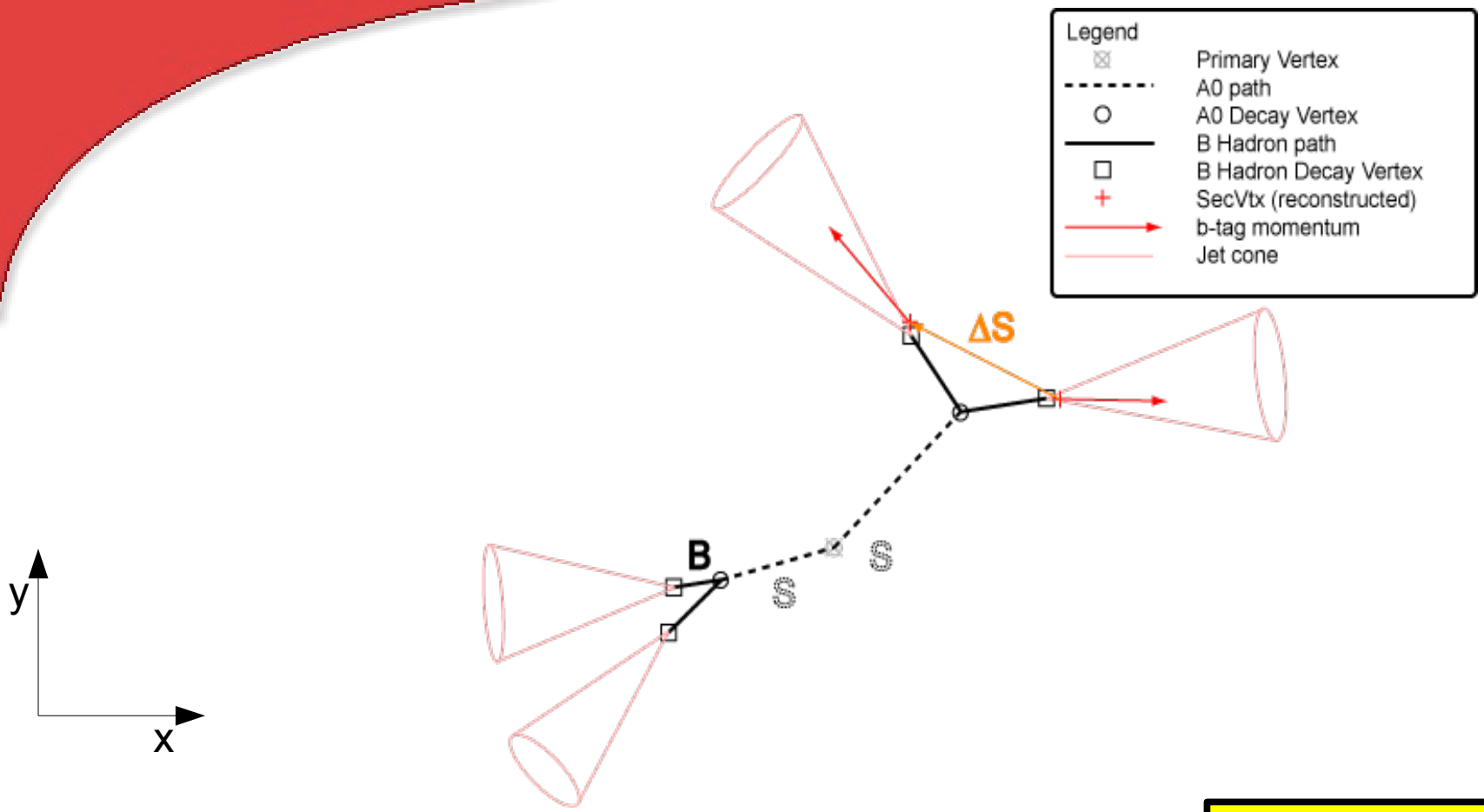



Diagram not to Scale

ΔS is the distance between two of the B hadrons decaying from a heavy pseudoscalar S ($A_0$). It requires two tagged jets.

This is in two-dimensional space.

# Add. Diagrams

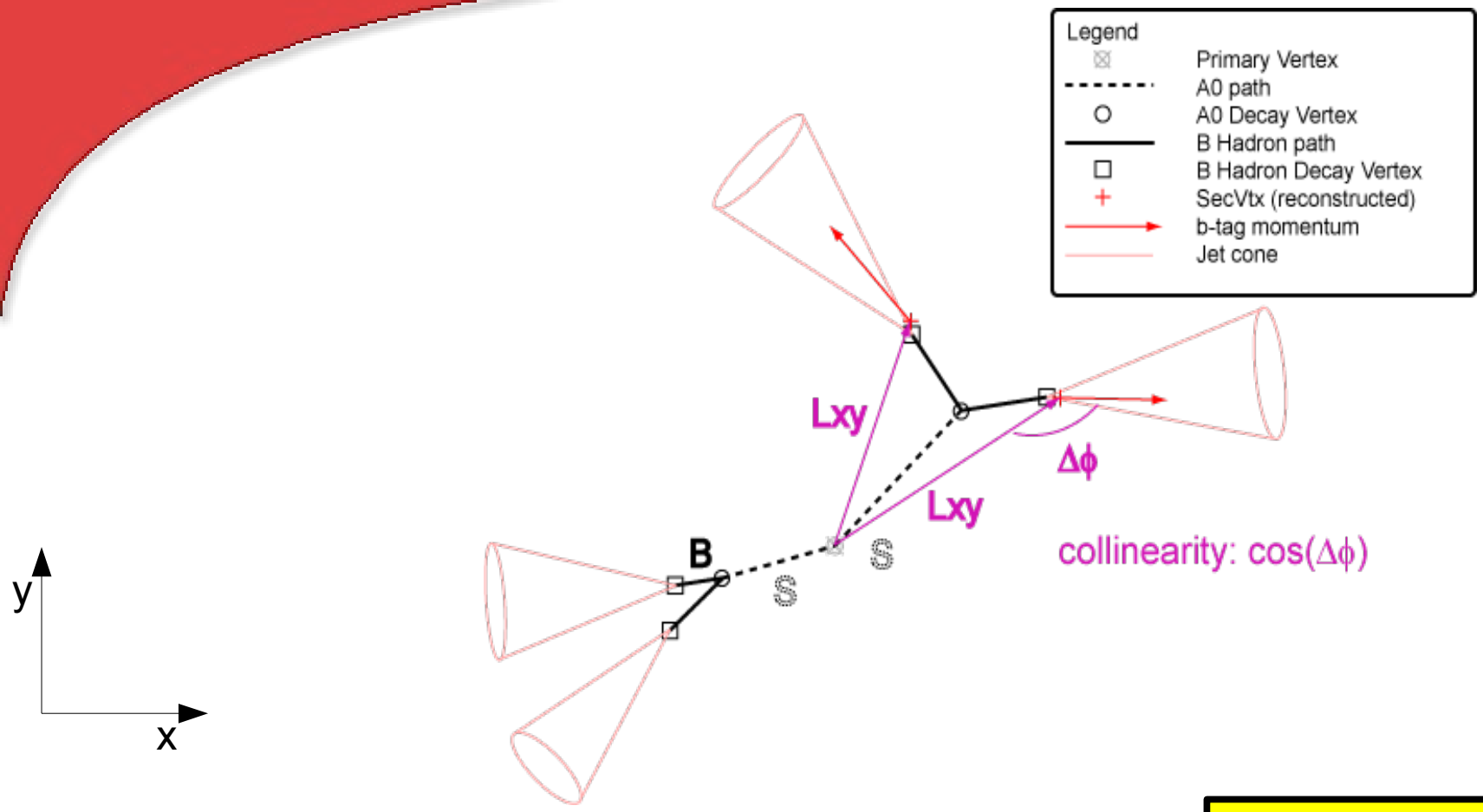



Diagram not to Scale

$L_{xy}$ is the two-dimensional distance from the primary vertex to the secondary vertex, shown here for both b-tags. $L_{2d}$ is $L_{xy}$ projected onto the jet momentum vectors (not shown). Collinearity is the cosine between the angle of the $L_{xy}$ vector and the secondary vertex's momentum vector.

This is in two-dimensional space.

# Wrong Combination

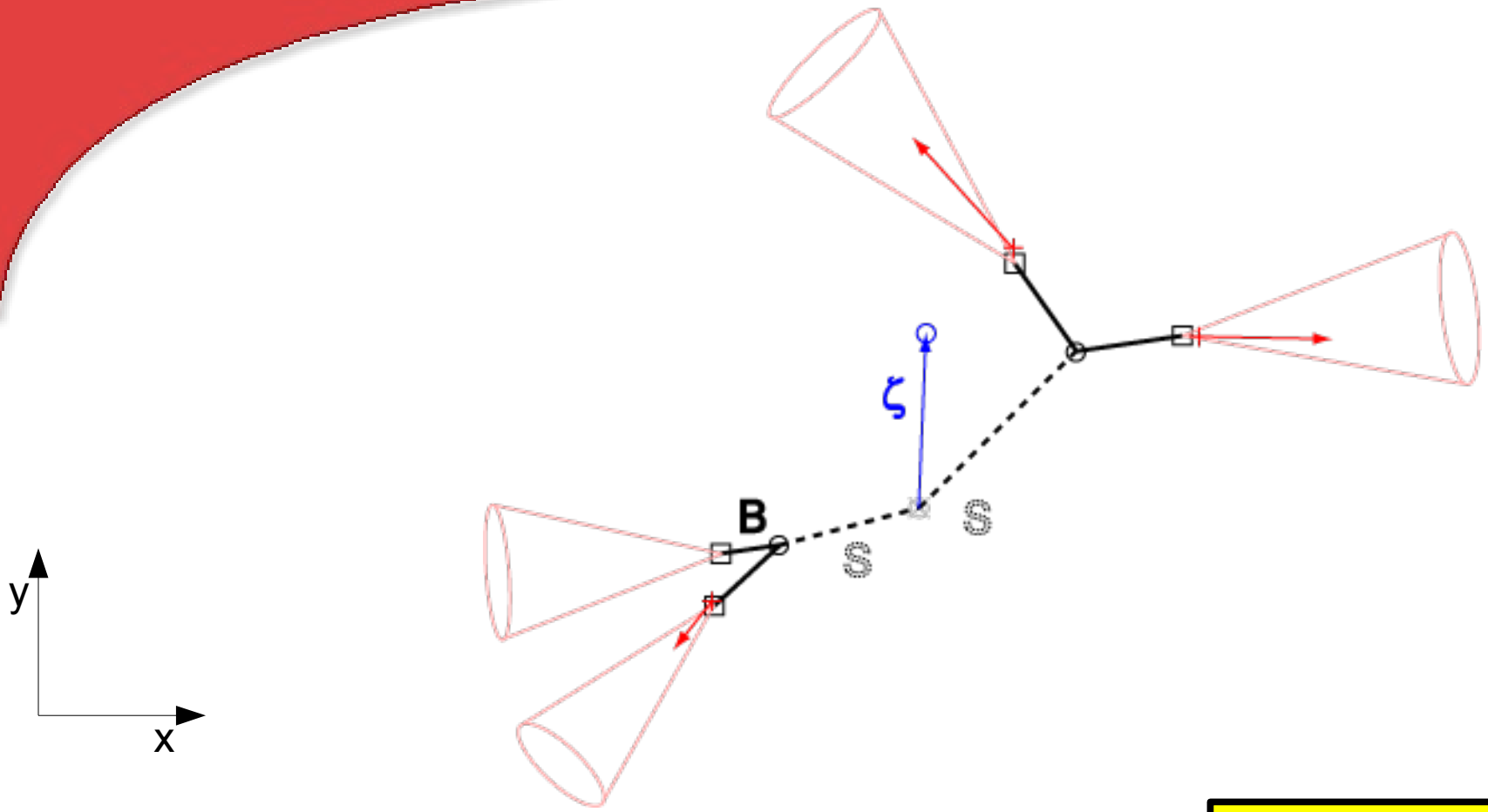



Diagram not to Scale

If two b quarks, each from a different $A_0$s, are b-tagged, then the wrong combination may be present. In this case, the B at the lower-left and the B from the upper-right has would have ζ shown above.

This is in two-dimensional space.