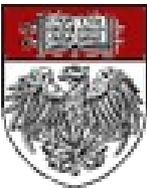


Search for Heavy Metastable Particles Decaying to quark pairs at CDF

Shawn Kwang
Advisor: Mel Shochet

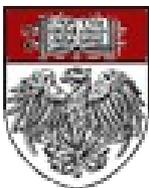
University of Chicago



Outline

- ▶ Introduction
 - ▶ Standard Model and Displaced Vertices
 - ▶ Hidden Valley Phenomenology
 - ▶ FermiLab and the CDF II detector
- ▶ Overview of the analysis
 - ▶ Monte Carlo simulation and searching for discriminants
 - ▶ Event selection
 - ▶ Data-driven background
 - ▶ Constructing a background estimate
- ▶ Results of the search
 - ▶ Systematic uncertainties
- ▶ Conclusion

2011-01-27



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Standard Model

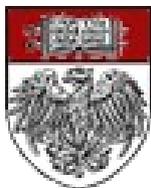
- ▶ The Standard Model (SM) of particle physics describes elementary particles and their interactions through mediating particles.

	I	II	III	
Quarks	u	c	t	γ
	d	s	b	g
Leptons	ν_e	ν_μ	ν_τ	Z
	e	μ	τ	W

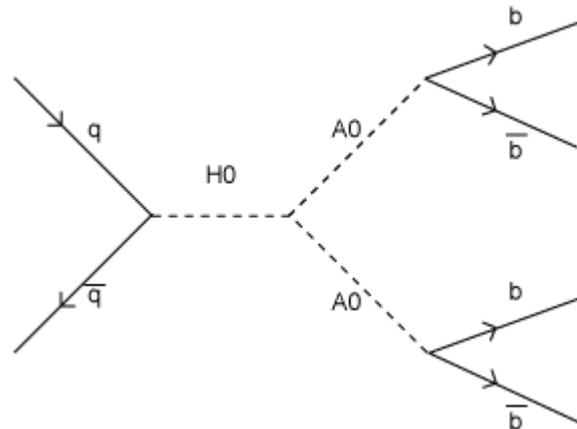
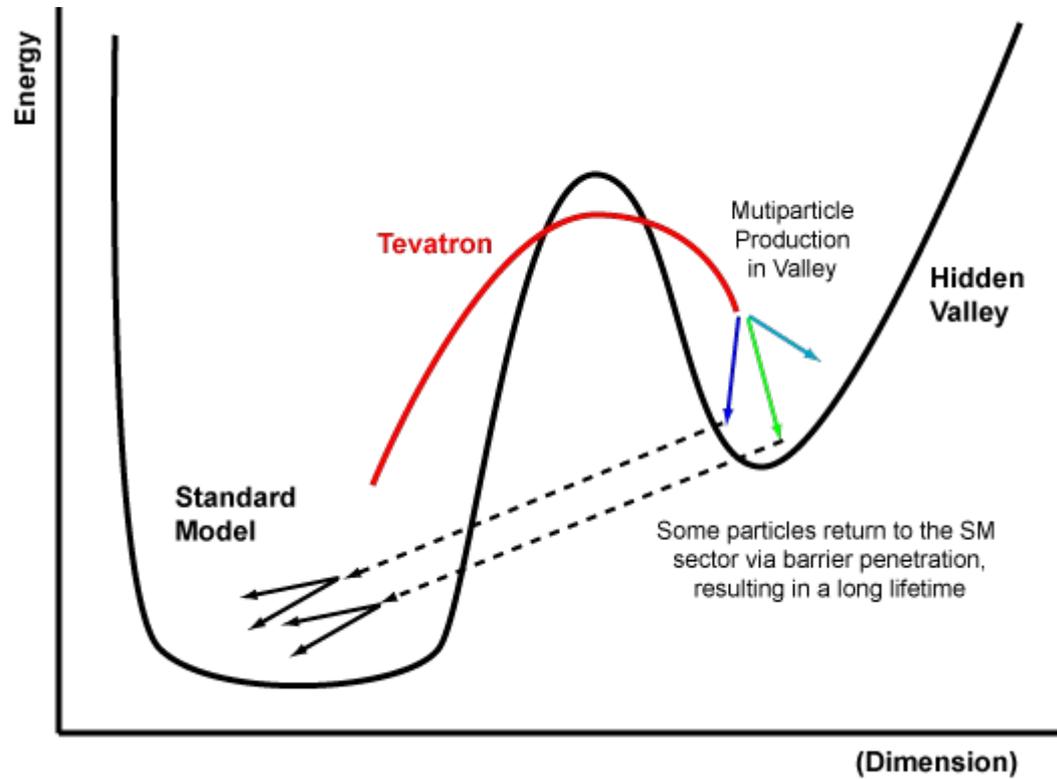
Three Generations of Matter

- ▶ One way to test the SM is to search for a unique signature, such as displaced vertices.
 - ▶ While there are long lived particles in the SM (K, D, & B hadrons) there are few (if any) SM processes for a massive metastable particle.
- ▶ 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 (metastable) object decaying into two quarks, which then hadronize into jets in the detector at a displaced vertex.

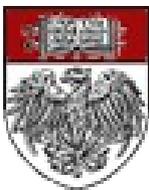
2011-01-27

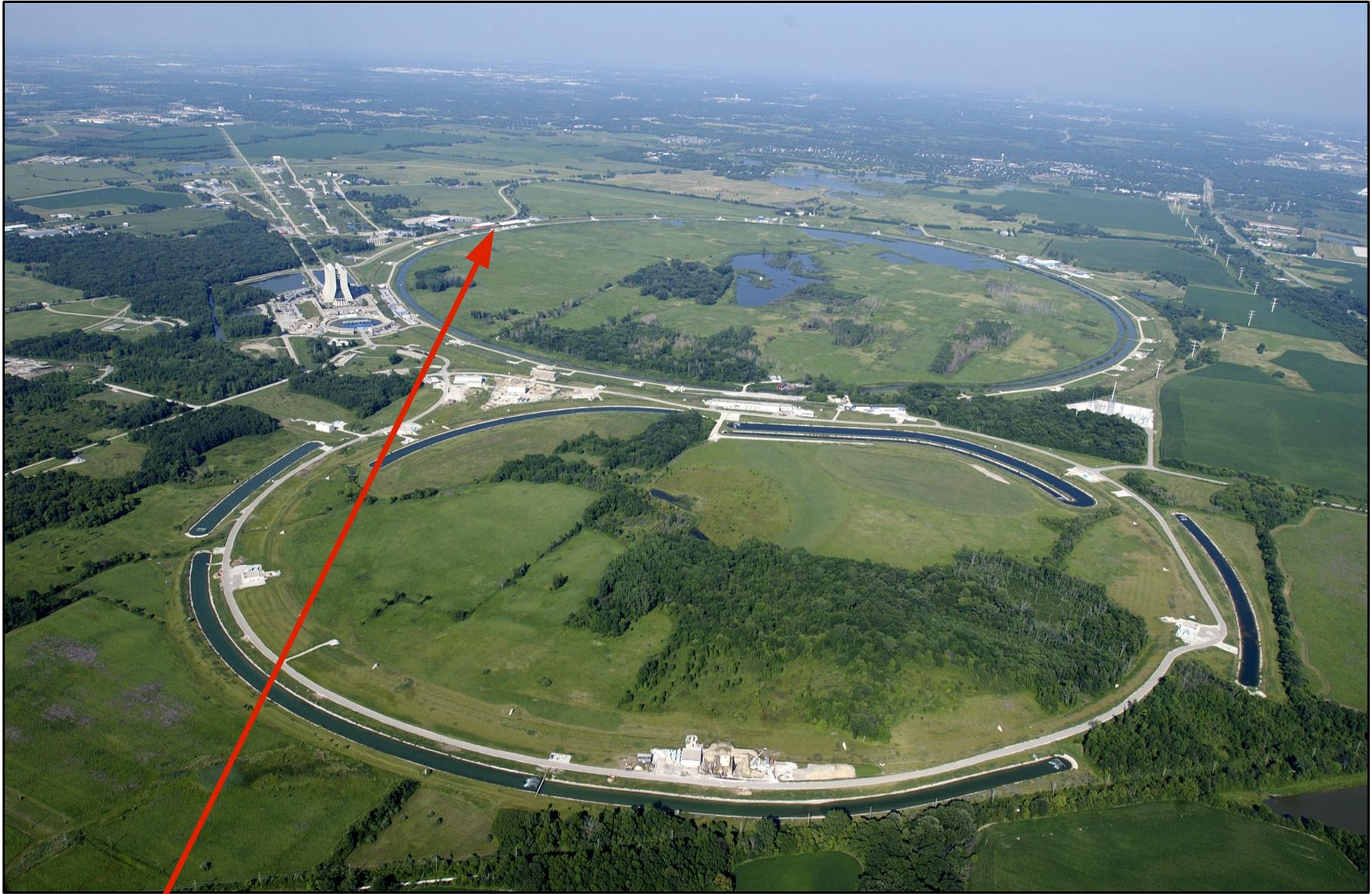


Hidden Valley Phenomenology



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CDF

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CDF II Detector

Muon Detectors

HAD Cal

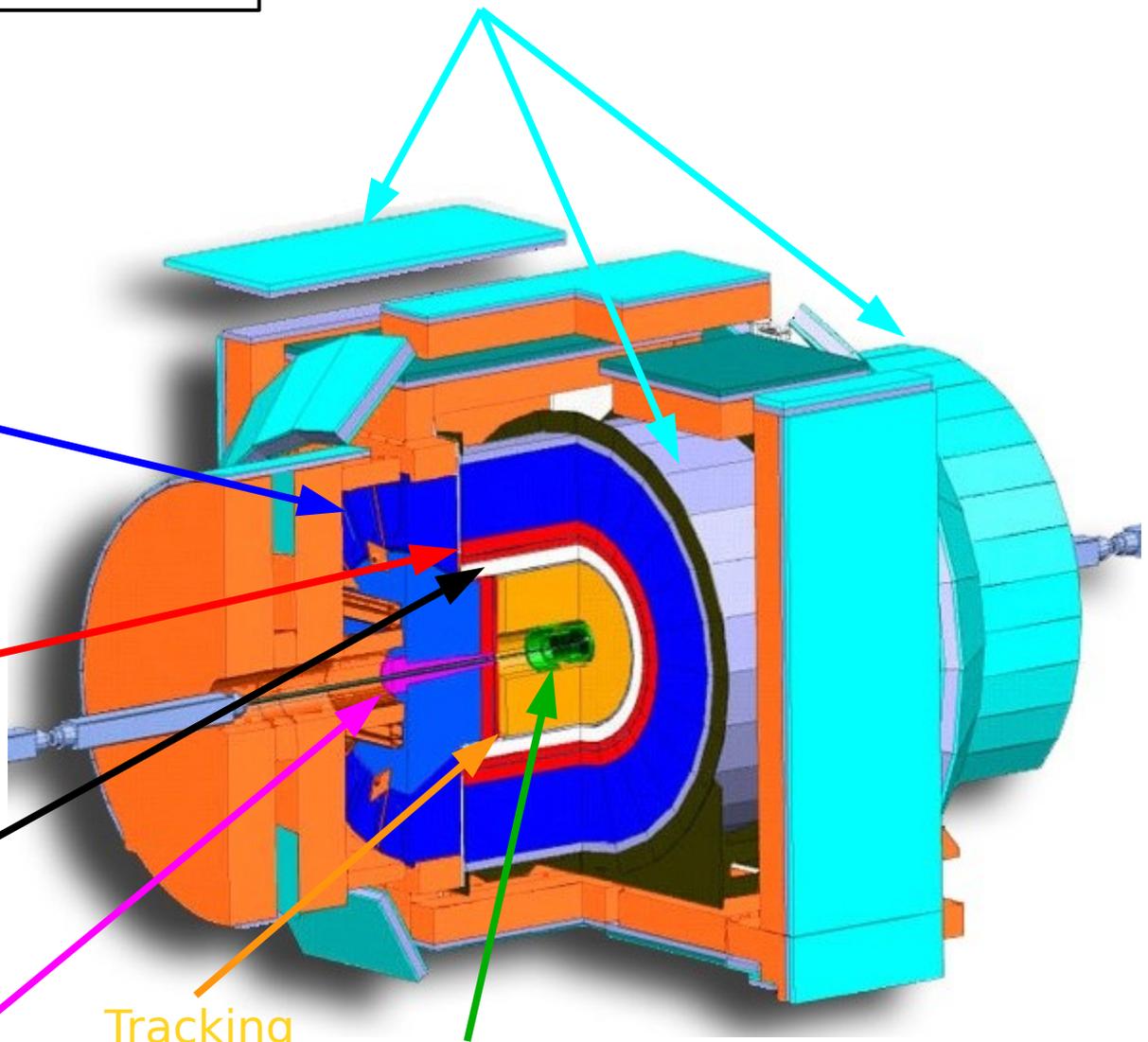
EM Cal

Solenoid

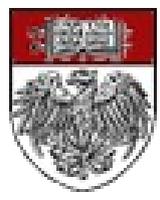
Luminosity Detector

Tracking Chamber

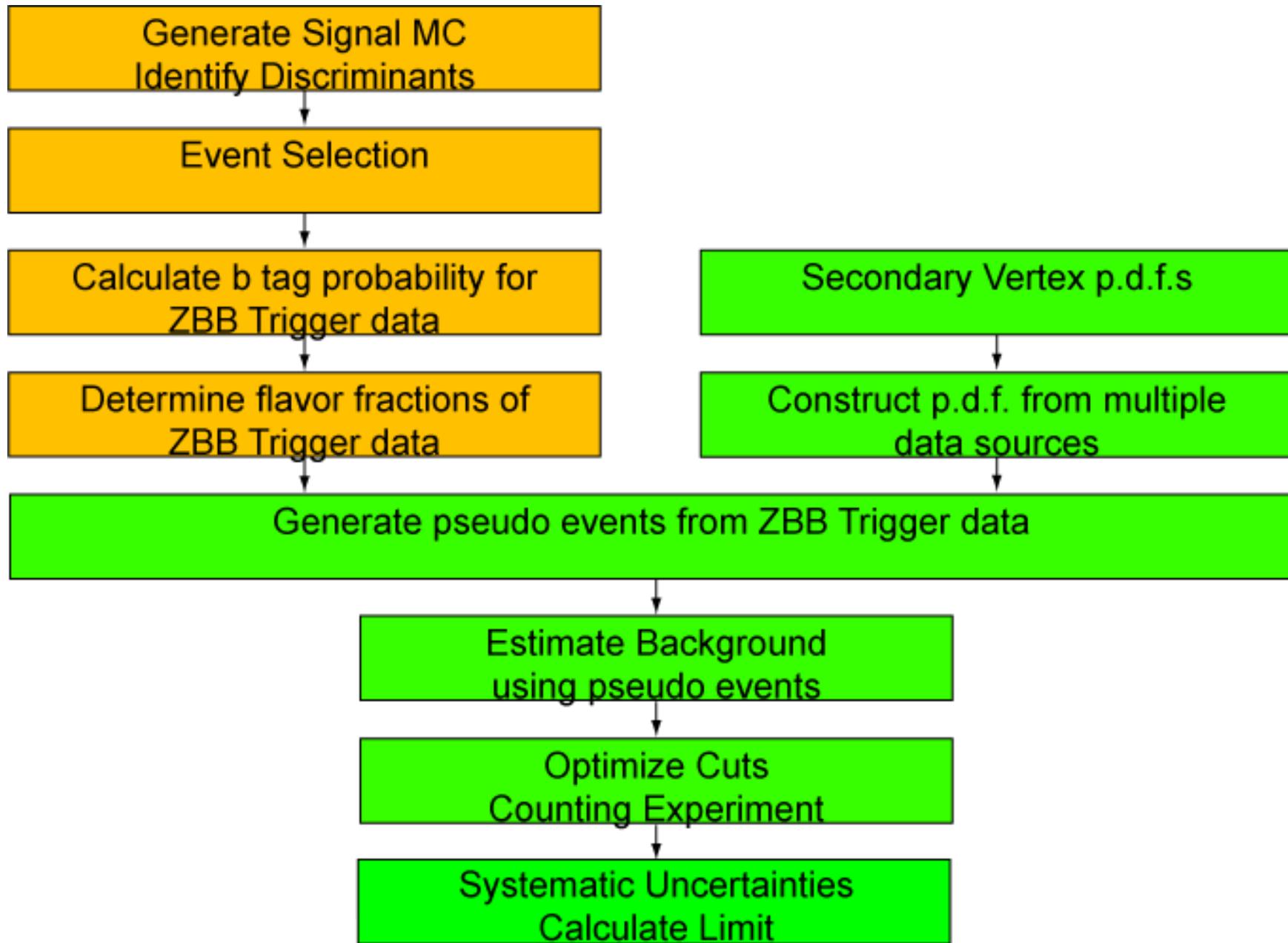
Silicon Detectors



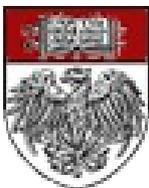
2011-01-27

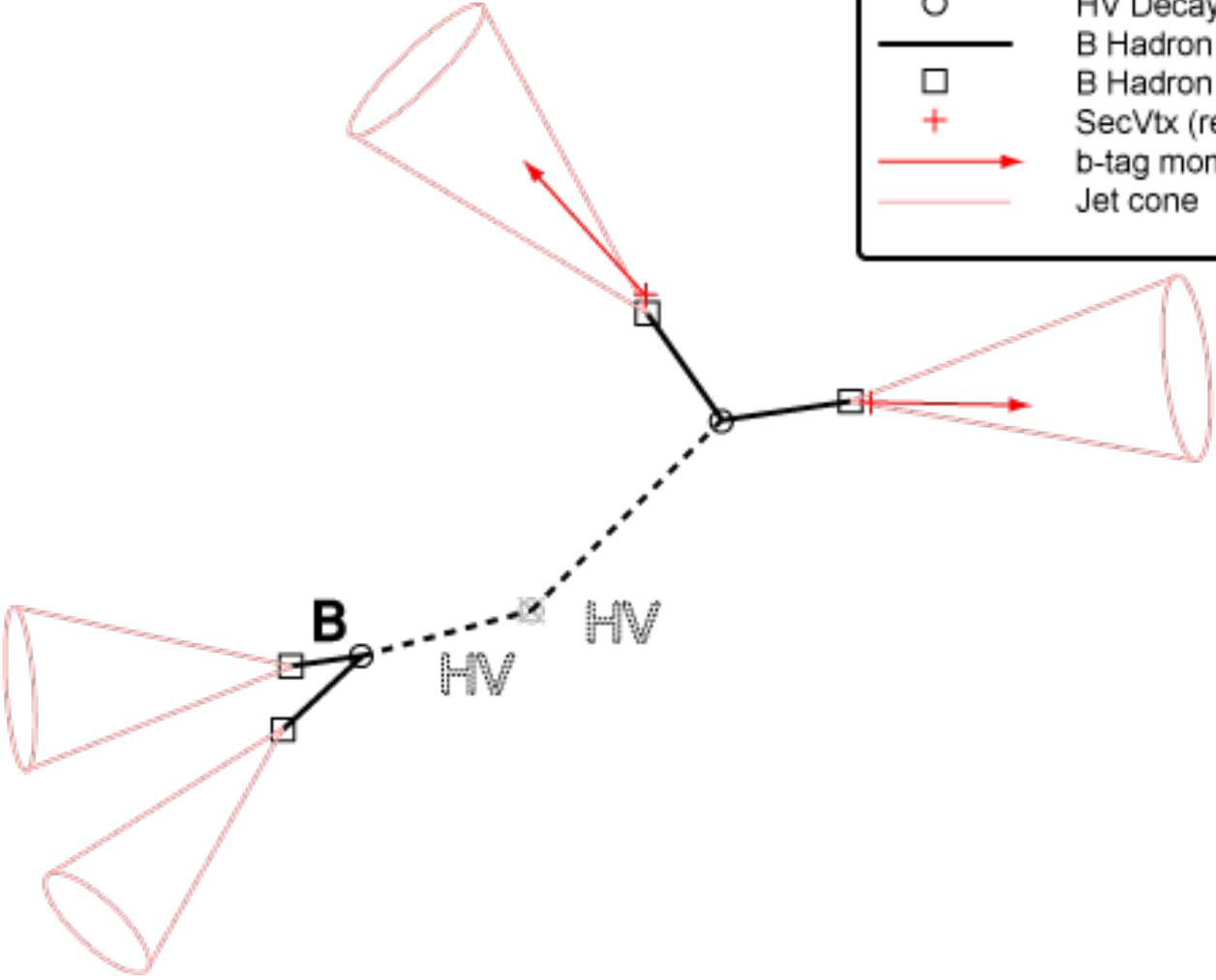
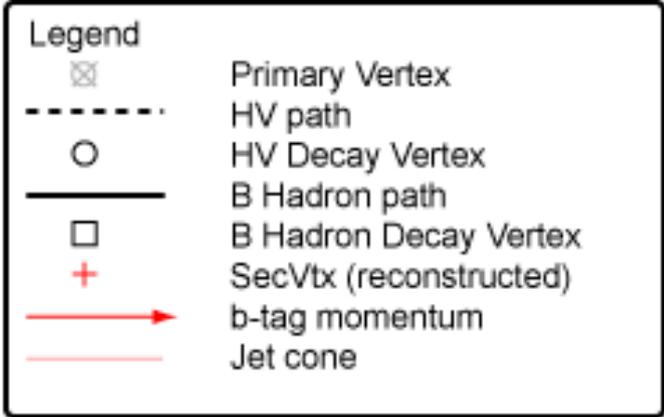


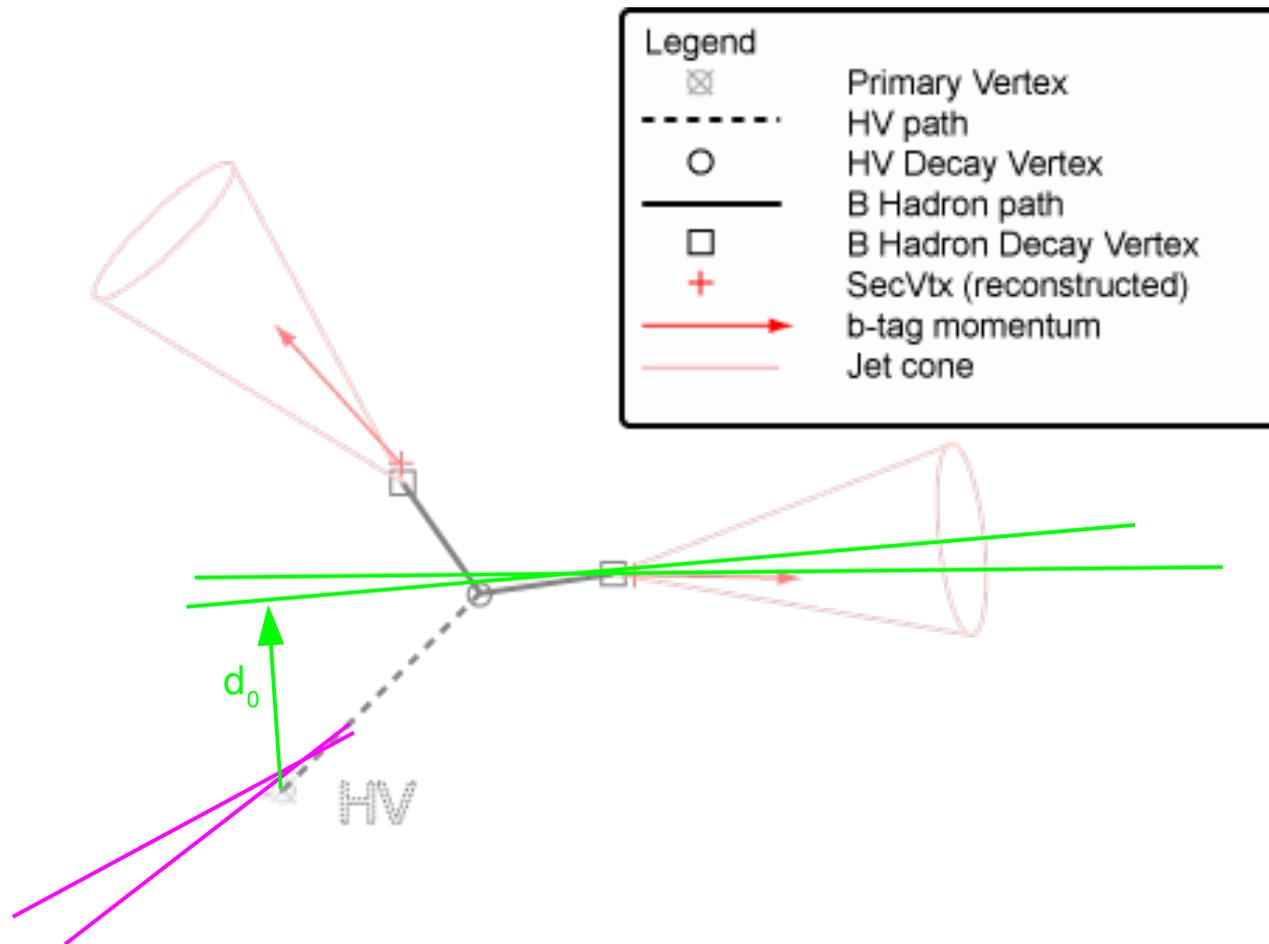
Overview of the Analysis



2011-01-27



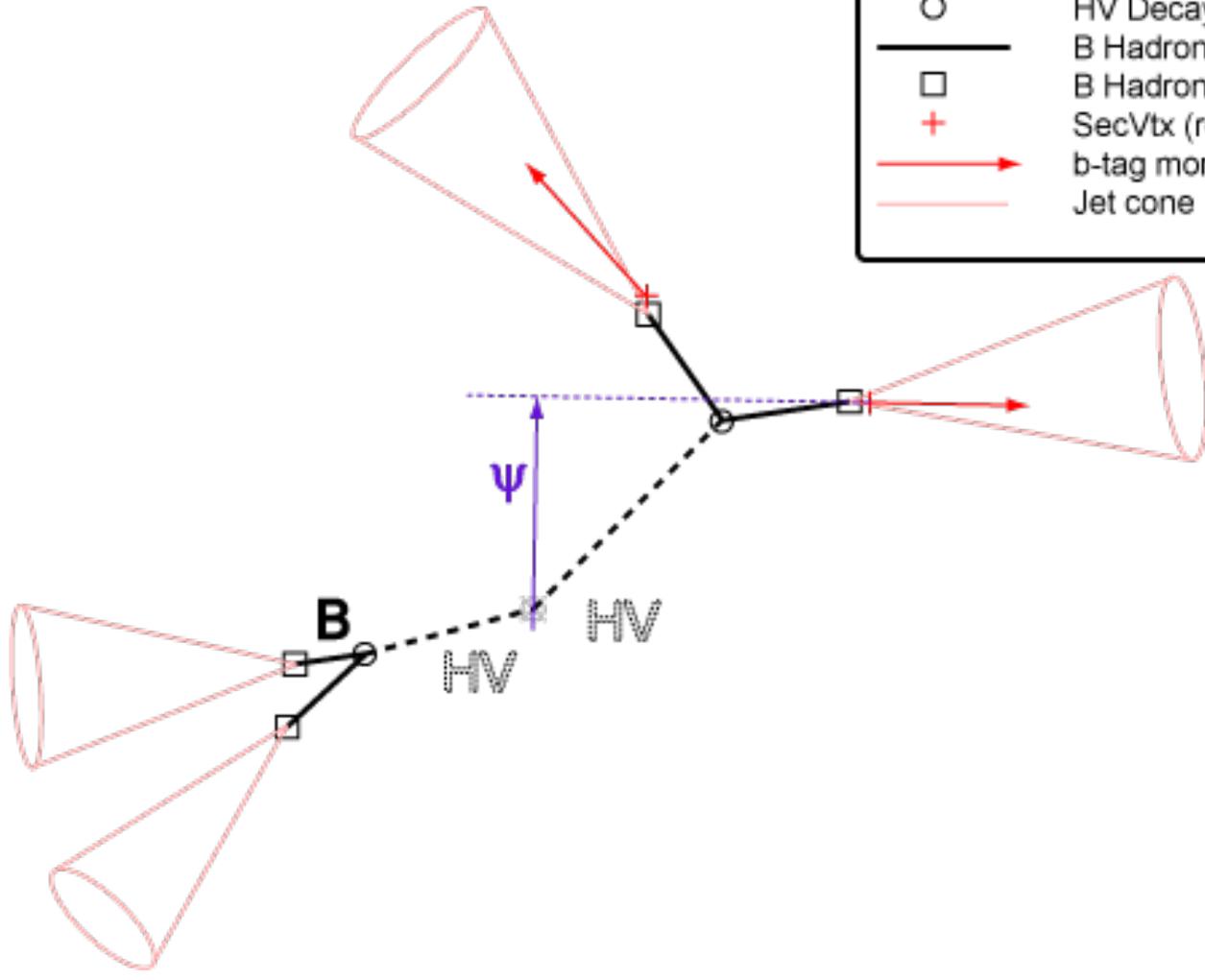
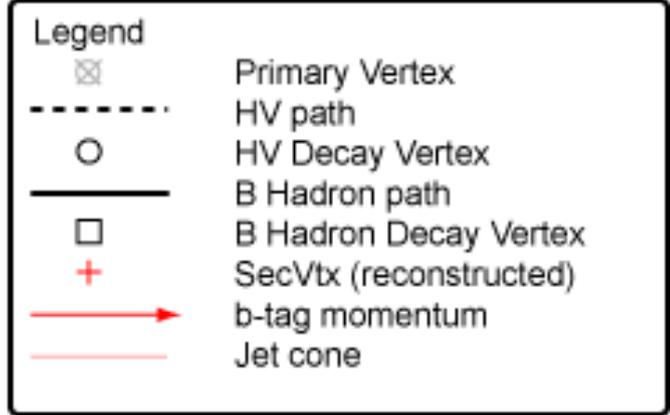


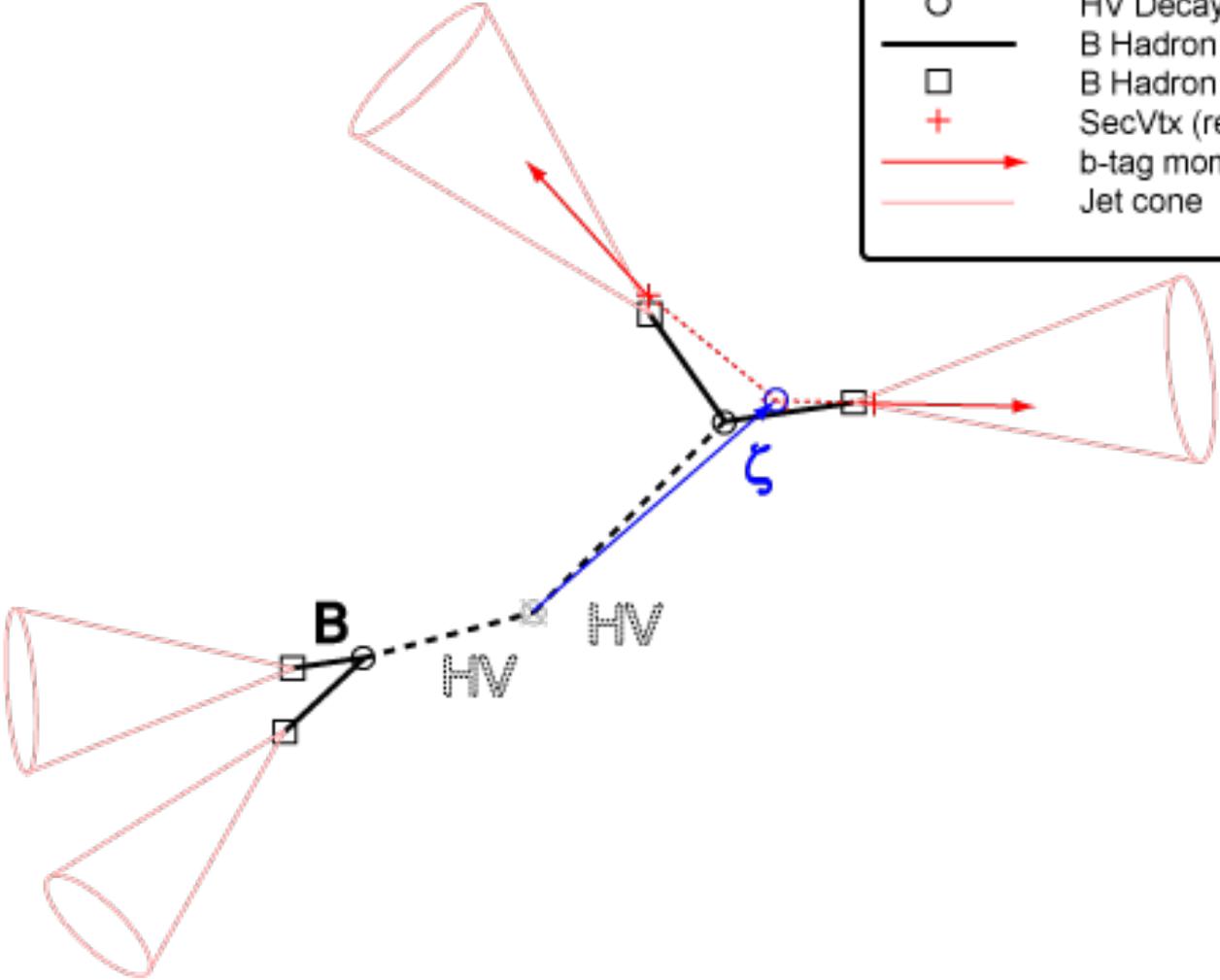
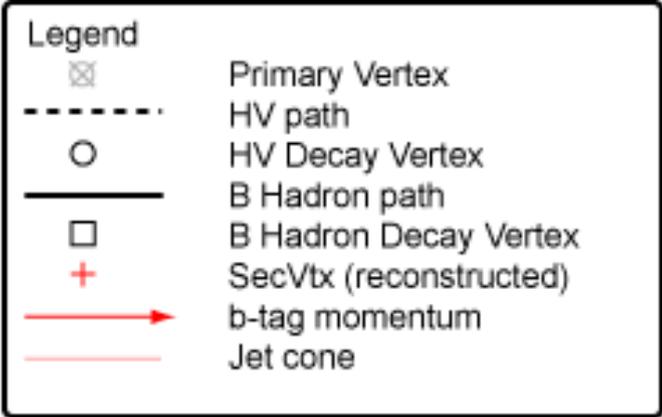


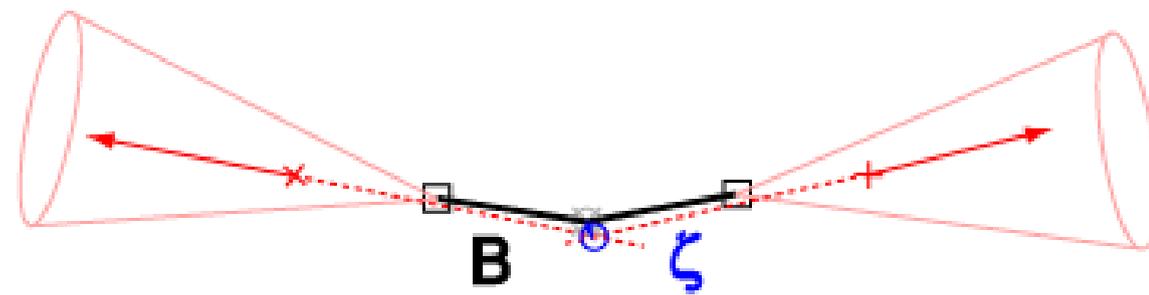
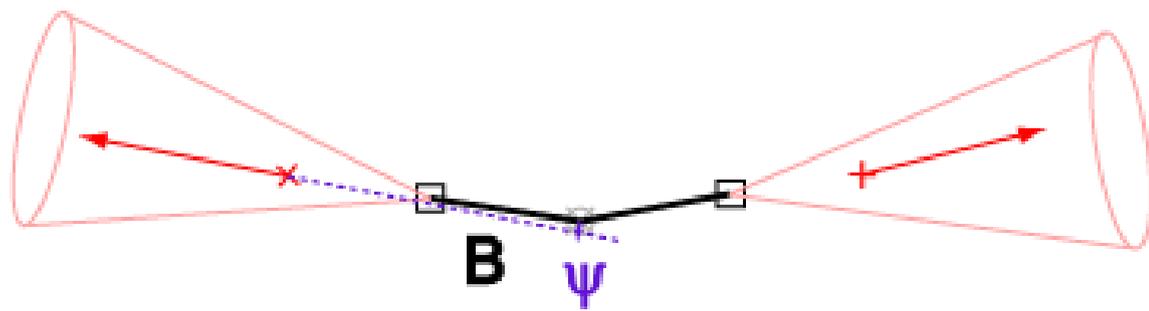
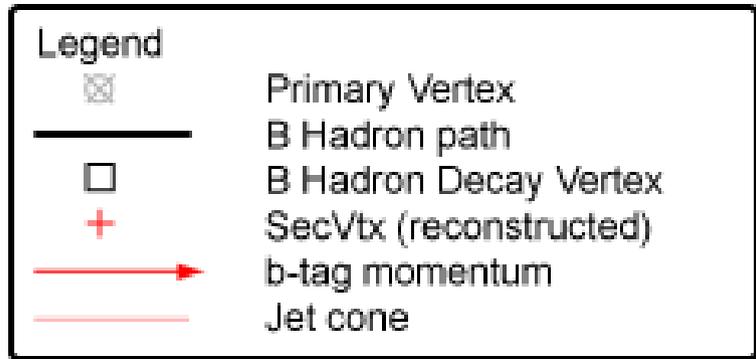
Tracks from Hidden Valley (HV) particles (green) have larger impact parameter (d_0) than typical tracks (magenta)

2011-01-27

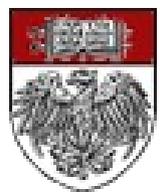
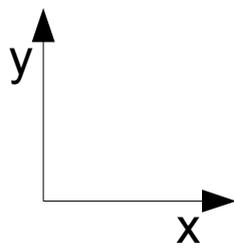








Both diagrams represent a SM background



Event Selection

▶ Discriminants

- ▶ ψ and ζ
- ▶ ΔR : Opening angle between the jets
- ▶ ΔS : Distance between the two secondary vertices

▶ Trigger Path

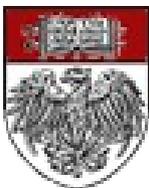
- ▶ ZBB Trigger Path – triggers on displaced tracks

▶ Secondary Vertex Reconstruction

▶ Signal and Control Region Selection

- ▶ Control Region : Two Jets, low E_T third jet
- ▶ Signal Region : Three Jets, two of which must have $\Delta R < 2.5$

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ZBB Trigger Data

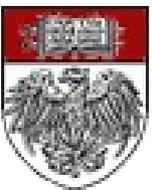
Tagged dijet	ET30-70, SVT0	SVT1	SVT2
ET20-30, SVT0	1252	4303	9727
SVT1	3220	7385	9857
SVT2	5119	6717	6637

All dijets	ET30-70, SVT0	SVT1	SVT2
ET20-30, SVT0	840880	665335	403921
SVT1	317183	168691	69302
SVT2	130013	40258	19826

Probability	ET30-70, SVT0	SVT1	SVT2
ET20-30, SVT0	0.0015	0.0065	0.024
SVT1	0.010	0.044	0.14
SVT2	0.039	0.17	0.33

- ▶ B-tag probability – probability that both jets have a b tag
 - ▶ Split into bins of E_T and number of SVT tracks
- ▶ Flavor composition – quark flavors of both jets
 - ▶ Perform simultaneous fit to the vertex mass: sum of tracks in secondary vertex, and take the invariant mass.

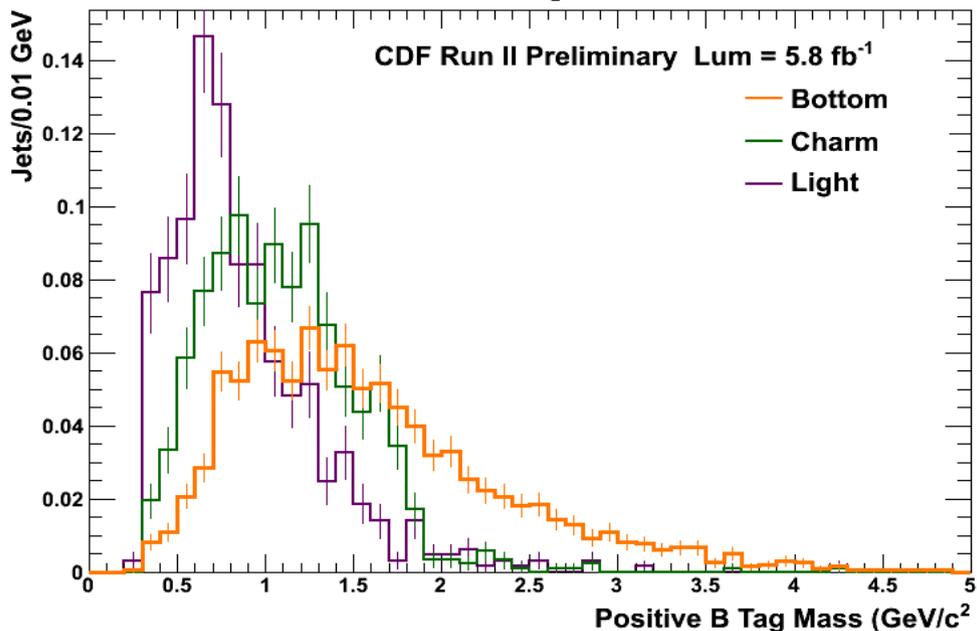
2011-01-27



Flavor Composition

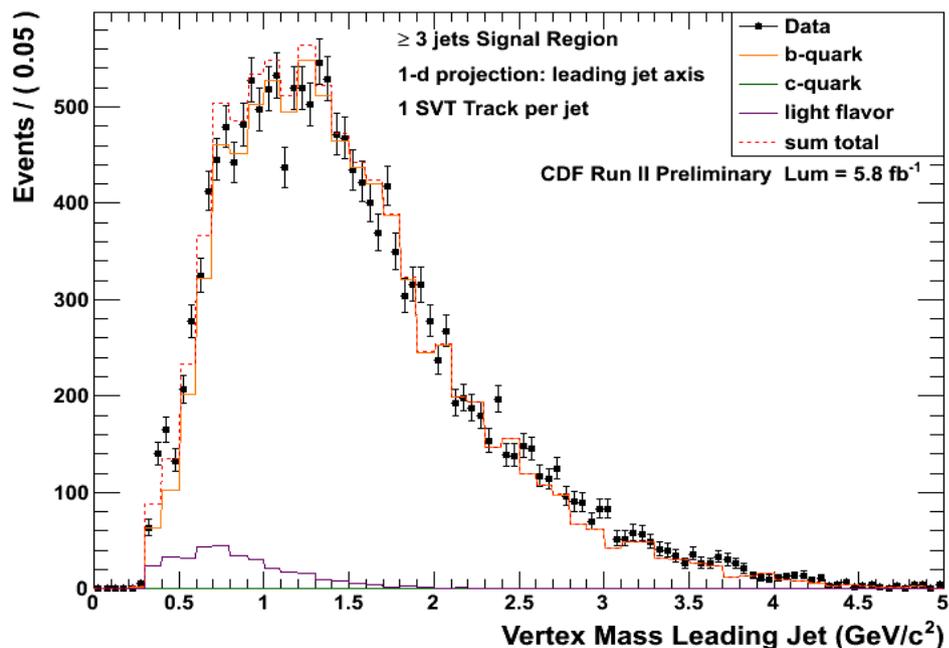
Fit MC Templates simultaneously to both jets, keeping the leading and sub-leading jet, in E_T , separate.

Fit Templates

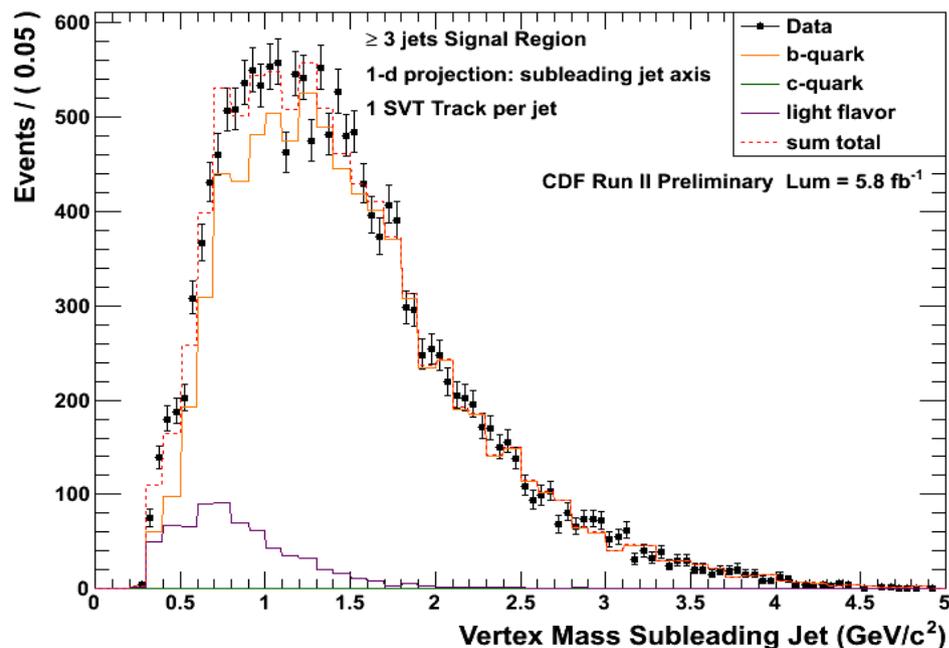


flavor	Value	Error
BB	90.9	0.95
BC	0	0.34
BL	5.09	0.82
CB	0	0.34
CC	0	0.19
CL	0	0.29
LB	1.14	0.5
LC	0	0.18
LL	2.86	0.81

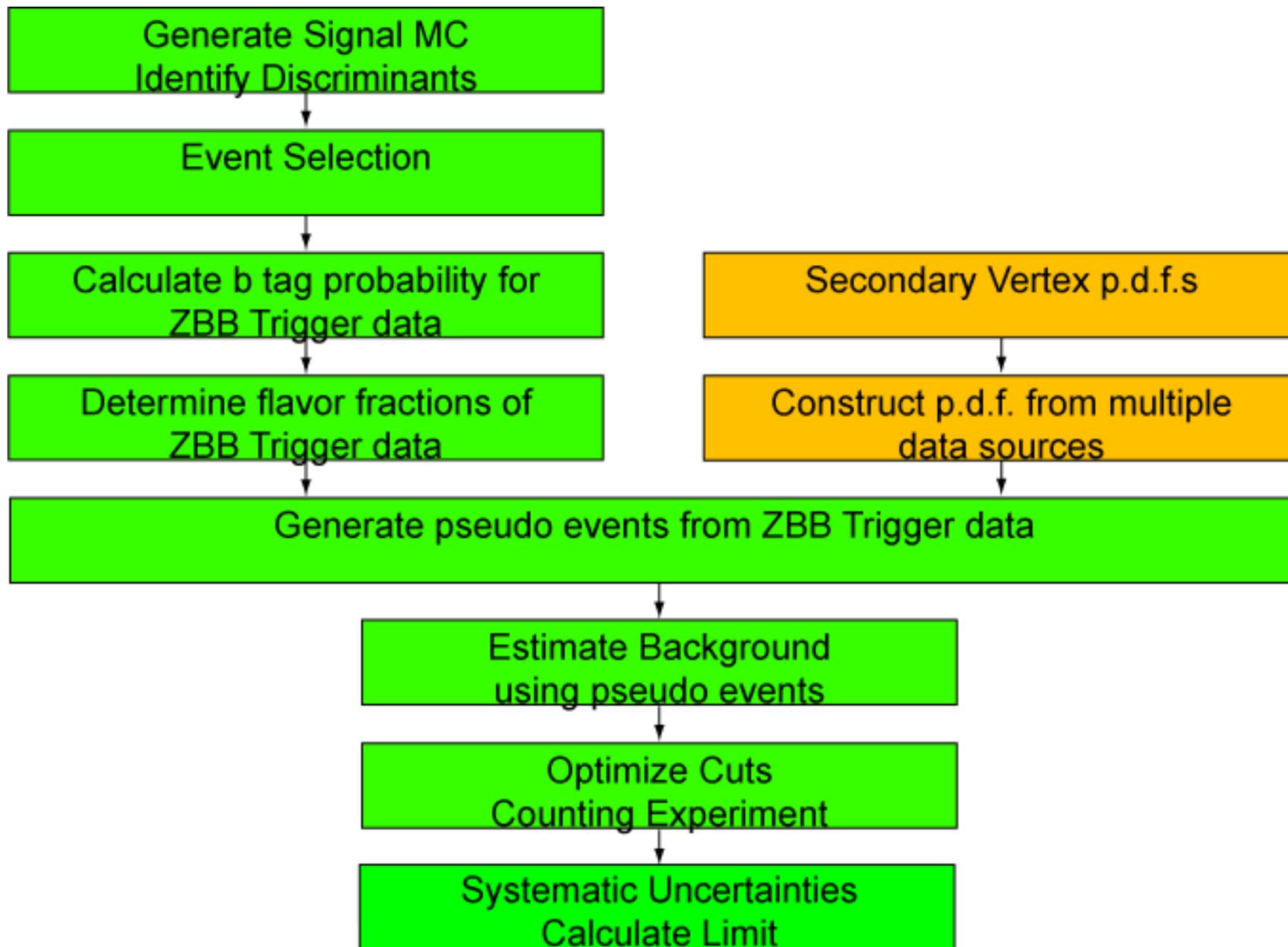
Fit of Both Jets' Vertex Masses



Fit of Both Jets' Vertex Masses



Overview of the Analysis



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Probability Density Functions

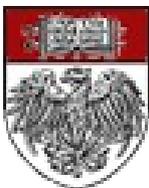
▶ PDF Sources

- ▶ 8 GeV Muon trigger : heavy flavor (b-quark) jets which decay semi-leptonically
- ▶ QCD multijet triggers : light-flavor jets
- ▶ QCD MC : c-quark jets, as there is no dedicated charm trigger

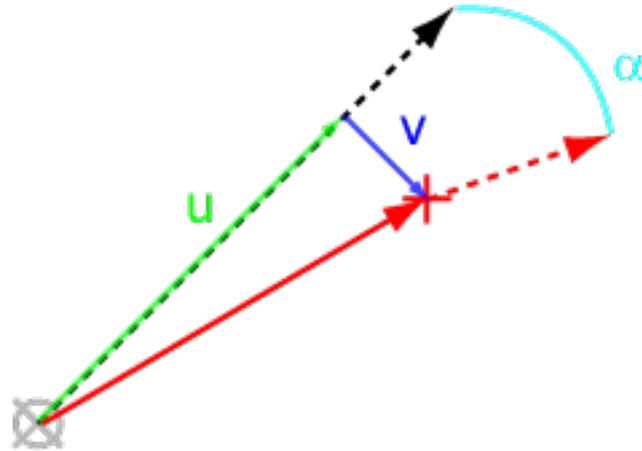
▶ PDF Construction

- ▶ Secondary vertex (b tag) in jet is found

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Black Dashed Line

Red Cross

Red Solid Line

Red Dashed Line

Green Line (u)

Blue Line (v)

Cyan Arc (α)

Jet Momentum

Secondary Vertex

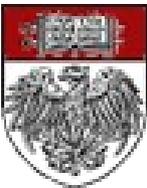
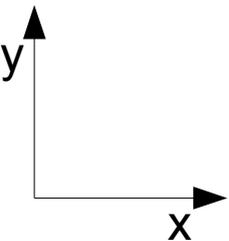
Sec Vertex L_{xy}

Sec Vertex Momentum

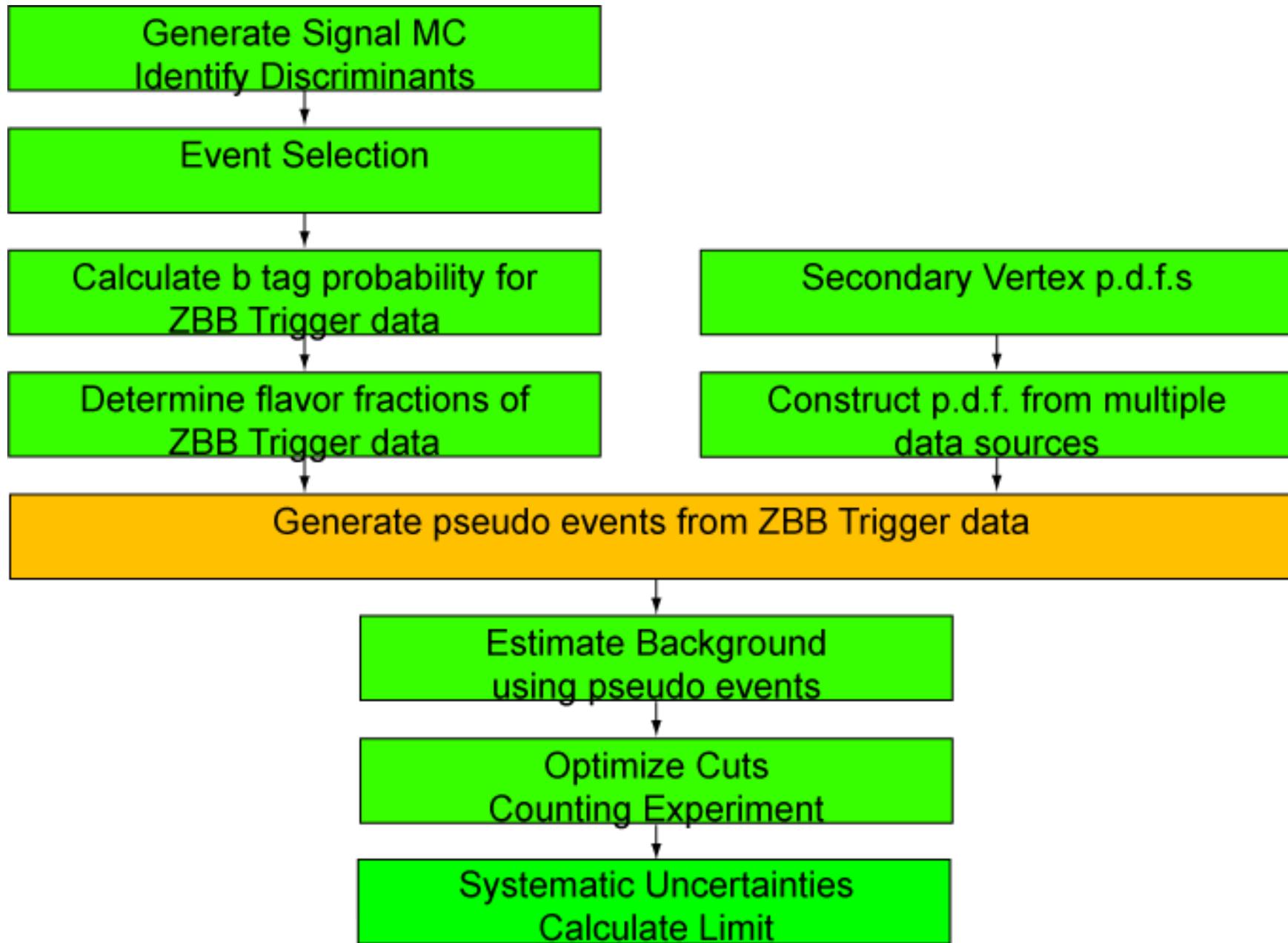
Parallel component of L_{xy}

Perp. component of L_{xy}

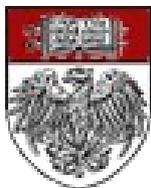
Angle b/w the two momenta



Overview of the Analysis



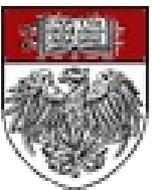
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Pseudo Event Algorithm

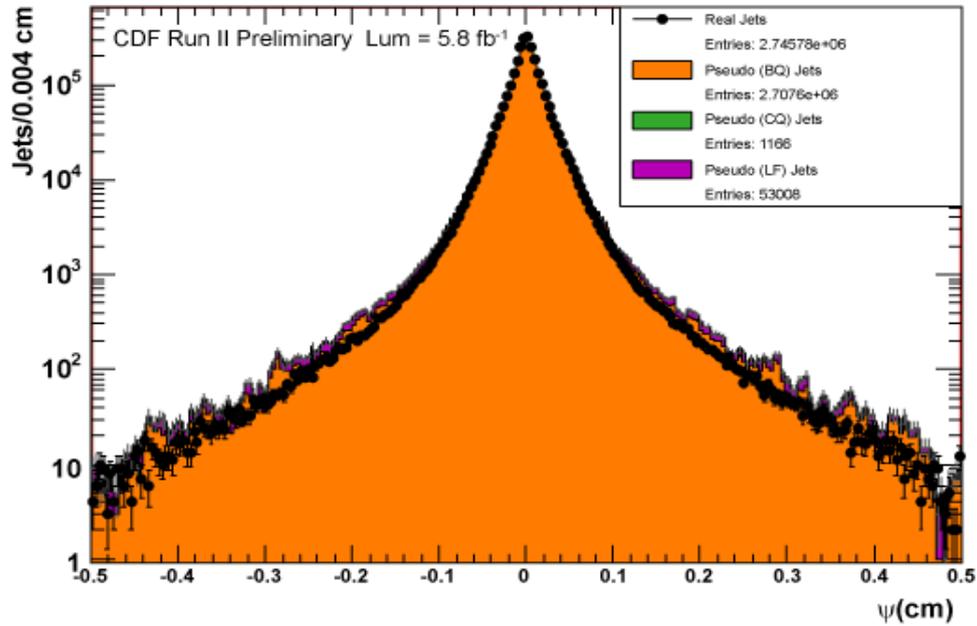
- ▶ Kinematic Selection
 - ▶ Selects events with Control and Signal region dijets
- ▶ Pseudo Event Generation
 - ▶ Use b-tag probability to assign pseudo b tags to dijets
 - ▶ Use flavor composition to assign pseudo flavor to dijets
- ▶ PDF Sampling
 - ▶ Sample from the p.d.f.s for the secondary vertex information
- ▶ **The original event's kinematics are unchanged. The secondary vertex information of the jets is sampled from the p.d.f.s**

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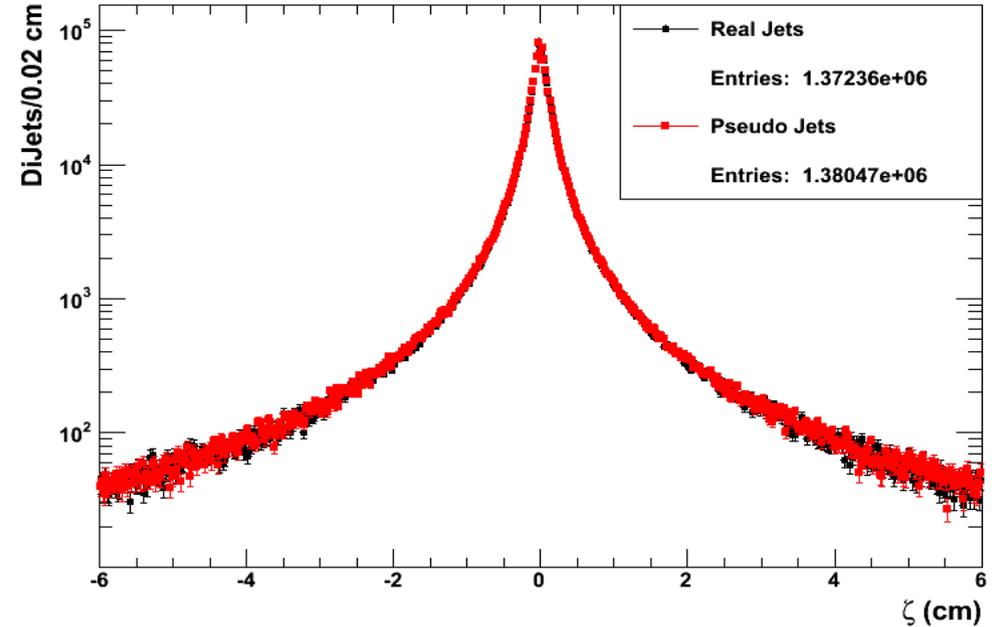


Pseudo Event Validation

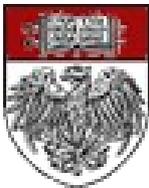
Tagged Jets Psi2d



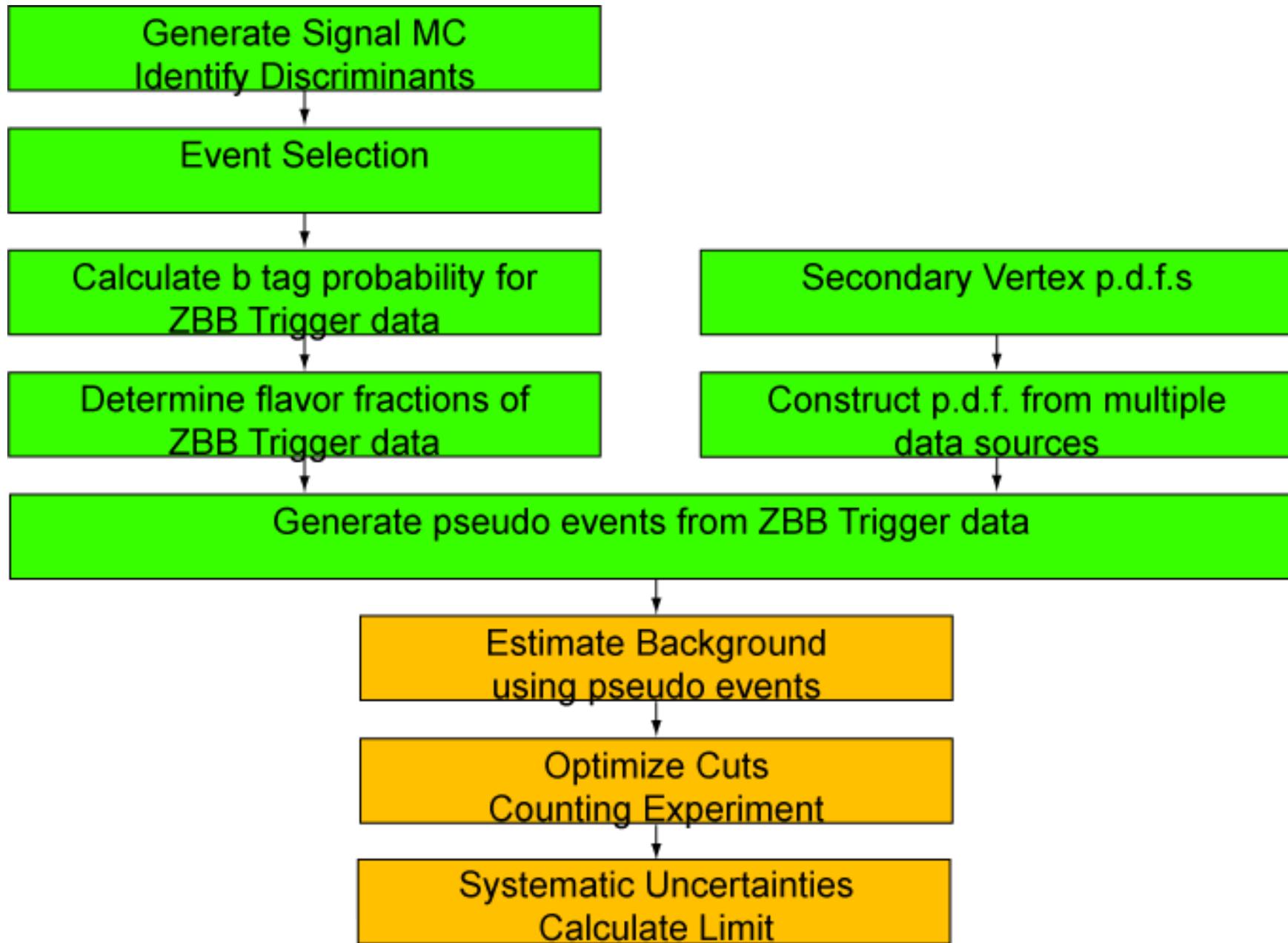
Tagged Dijet ζ CDF Run II Preliminary Lum = 5.8 fb⁻¹



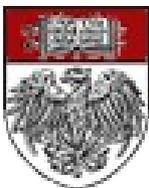
2011-01-27



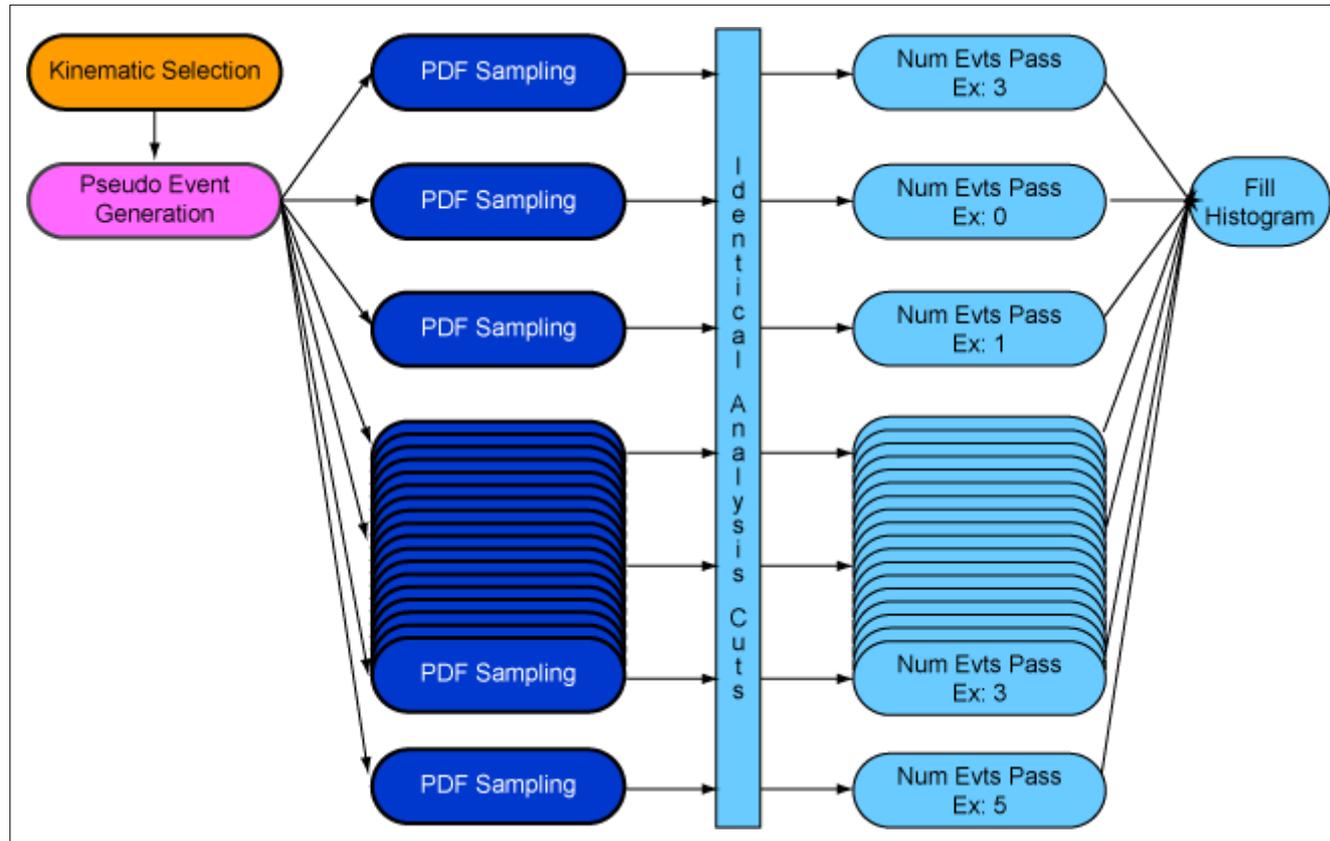
Overview of the Analysis



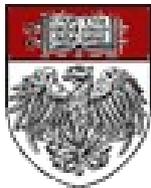
2011-01-27



Background Estimate Algorithm



2011-01-27



Analysis Cuts

▶ After Optimization the cuts for the [High Mass HV Search](#) are:

▶ $|d_0|_{\max} < 1.0 \text{ cm}$

▶ $0.75 < \Delta R < 2.0$

▶ $|\psi| > 0.11 \text{ cm}$

▶ $\zeta > 0.8 \text{ cm}$

▶ After Optimization the cuts for the [Low Mass HV Search](#) are:

▶ $|d_0|_{\max} < 1.0 \text{ cm}$

▶ $\Delta R < 0.75$

▶ $|\psi| > 0.12 \text{ cm}$

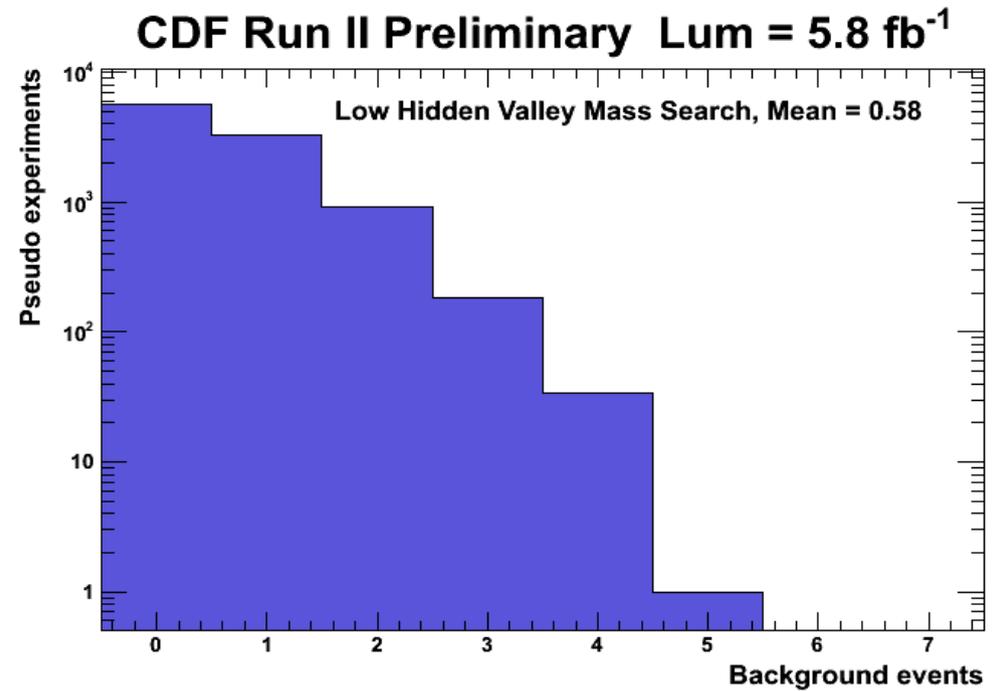
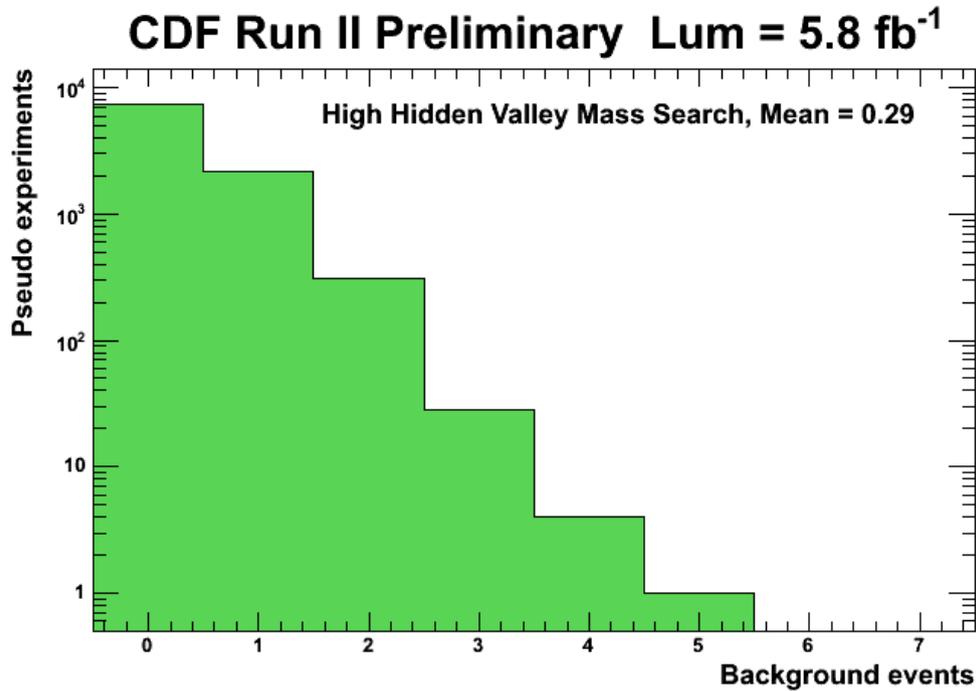
▶ $\zeta > 0.7 \text{ cm}$

▶ In addition, ζ was required to be less than the distance from the primary to closest secondary vertex (L_{xy}), i.e. it has to be between the secondary vertices and the beamline.

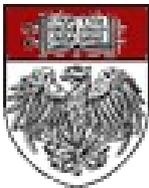
2011-01-27



Background Estimate Result



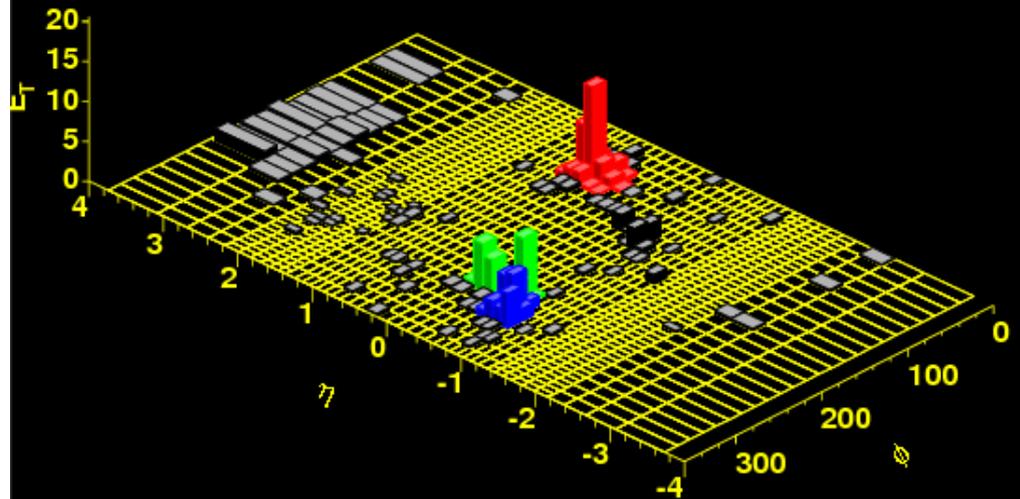
2011-01-27



Low Mass HV Search

Run 186306 Event 4192804

- ▶ Narrow cone reconstructs two jets
- ▶ Two secondary vertices reconstructed
- ▶ Vertices are coincident
- ▶ Sum of tracks in both vertices, invariant mass is less than b-quark mass.



```
Missing Et
Et=11.4 phi=1.8
Jet Collection:
JetClnModule-cone0.4

Particles: first 5
pdg   pt   phi   eta
22    9.0  4.3  -0.0
22    3.3  2.2  -0.0
11    1.8  2.1  -0.0
11    1.0  3.3  -0.0
11    1.0  4.9  -0.0

Jets(R = 0.4): first 5
Em/Tot  et   phi   eta
0.6     34.4  1.1  -0.0
0.9     25.3  4.5  -0.0
0.7     21.2  4.9  -0.0
```

Event : 4192804 Run : 186306 EventType : DATA | Unpres: 1,33,34,4,7,40,43,13,14,15,17,19,20,21,

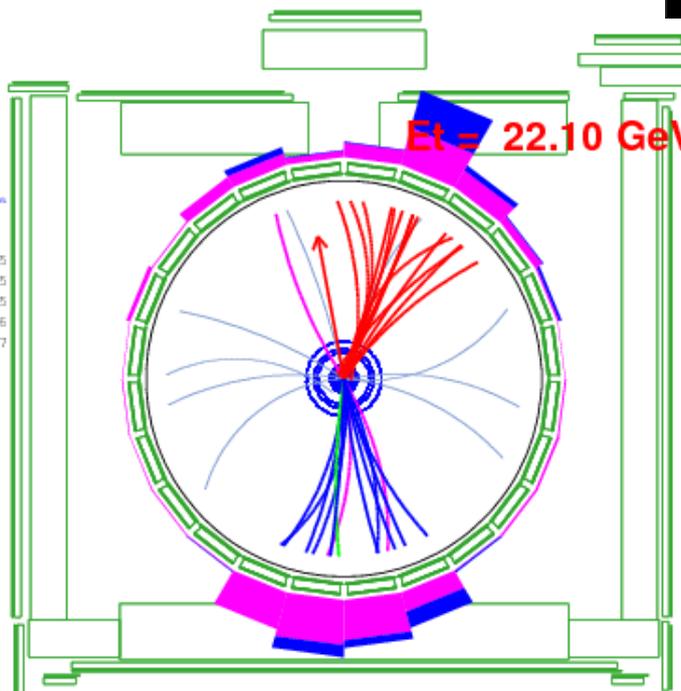
```
Missing Et
Et=11.4 phi=1.8

List of Tracks
Id   pt   phi   eta
Cdf Tracks: first 5
257  14.4  1.2  0.5
245  -10.7  1.2  0.5
225   5.6  1.2  0.5
226   4.5  1.1  0.6
227  -4.5  -1.6  -0.7

To select track type
SelectCdfTrack[Id]

Svt Tracks: first 5
1    6.0  1.2
4    -4.5  4.7
0    4.2  1.1
2    -3.1  0.9
3    2.5  1.8

To select track type
SelectSvtTrack[Id]
```



```
Et = 22.10 GeV

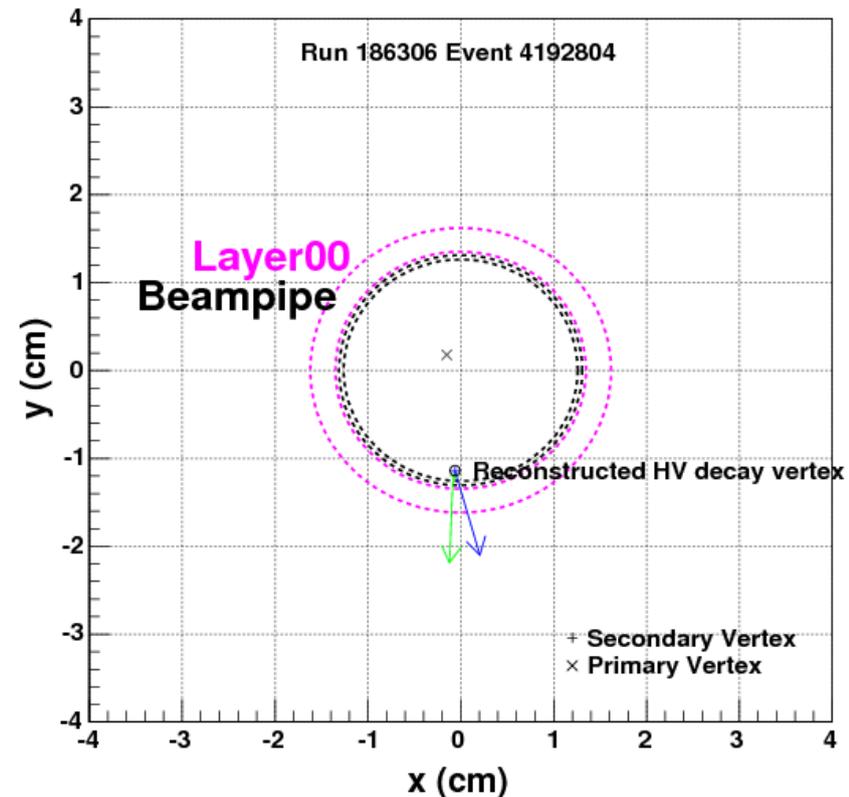
Particles: first 5
pdg   pt   phi   eta
22    9.0  4.3  -0.0
22    3.3  2.2  -0.0
11    1.8  2.1  -0.0
11    1.0  3.3  -0.0
11    1.0  4.9  -0.0

To list all particles
ListCdfParticles()

Jets(R = 0.4): first 5
Em/Tot  et   phi   eta
0.6     34.4  1.1  -0.0
0.9     25.3  4.5  -0.0
0.7     21.2  4.9  -0.0

To list all jets
ListCdfJets()
```

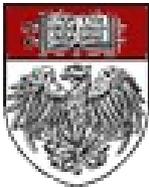
Inner Detector



Unanticipated Background

- ▶ Additional cuts are included in the [Low Mass HV Search](#).
 - ▶ $\Delta S_{2d} < 0.06$ cm
 - ▶ $\text{SumVertex4Momenta} \rightarrow \text{Mass}() < 5.0$ GeV
 - ▶ If both conditions are fulfilled, the event is removed

2010-12-03



Shawn Kwang

Signal MC

▶ Unanticipated Background

- ▶ Applied to the [Low Mass HV Search](#)

▶ Signal MC: Re-weighting

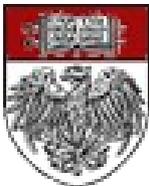
- ▶ Weighted to ZBB data number of primary vertices (luminosity profile)
- ▶ Weighting to ZBB data to account for differences in trigger efficiency

▶ Signal MC: Scale Factors

- ▶ B-tagging scale factor ($SF_{\text{BTSF}} = 0.9$) is applied twice (0.81)
- ▶ Trigger Simulation scale factor ($SF_{\text{trigger}} = 1.12$)

Search Name	M_{h_0} (GeV)	M_{HV} (GeV)	$c\tau_{\text{HV}}$ (cm)
Low Mass HV Search	130	20	1.0
Low Mass HV Search	170	20	1.0
High Mass HV Search	130	40	1.0
High Mass HV Search	170	40	1.0
High Mass HV Search	170	65	1.0
High Mass HV Search	130	40	0.3
High Mass HV Search	130	40	2.5
High Mass HV Search	130	40	5.0

2010-12-03



Results

- ▶ N_{signalMC} is the number of expected signal MC events.
- ▶ N_{bkgrnd} is the expected number of background events from the SM, derived from the background estimate algorithm.
- ▶ N_{obs} is the number of events found in the ZBB trigger data.
 - ▶ There are two events, one in the [Low Mass HV Search](#) and one in the [High Mass HV Search](#)

M_{h_0} (GeV)	M_{HV} (GeV)	$c\tau_{\text{HV}}$ (cm)	N_{signalMC}	N_{bkgrnd}	N_{obs}
130	20	1	0.64	0.58	1
170	20	1	0.074	0.58	1
130	40	1	0.26	0.29	1
170	40	1	0.38	0.29	1
170	65	1	0.14	0.29	1
130	40	0.3	0.24	0.29	1
130	40	2.5	0.101	0.29	1
130	40	5	0.043	0.29	1

- ▶ The uncertainties on N_{signalMC} and N_{bkgrnd} are discussed next.

2011-01-27



Systematic Uncertainties

Uncertainty	Down (%)	Up (%)
Background Estimate – low HV mass search		
Data statistics	± 0.039	
B-tag prob. statistics	-7.74	3.42
Flavor composition	-0.5	2.75
Background Estimate – high HV mass search		
Data statistics	± 0.046	
B-tag prob. statistics	± 3.92	
Flavor composition	-0.5	8.91
Signal MC		
Jet Energy Scale	-15.6 to -6.3	4.0 to 25.5
Trigger Uncertainty	± 8.9	
B-tagging scale factor	± 10	
P.d.f	± 2.5	
Luminosity	± 6	



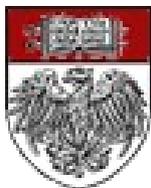
p-values

- ▶ p-values were calculated for each set of masses.

M_{h_0} (GeV)	M_{H_V} (GeV)	$c\tau_{H_V}$ (cm)	p-value
130	20	1.0	0.44
170	20	1.0	0.43
130	40	1.0	0.27
170	40	1.0	0.26
170	65	1.0	0.26
130	40	0.3	0.27
130	40	2.5	0.27
130	40	5.0	0.27

- ▶ We conclude that there is no statistically significant excess.

2011-01-27

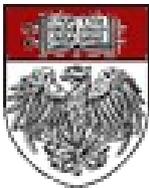


Limit Calculation

- ▶ Use a Bayesian limit calculator to calculate limits

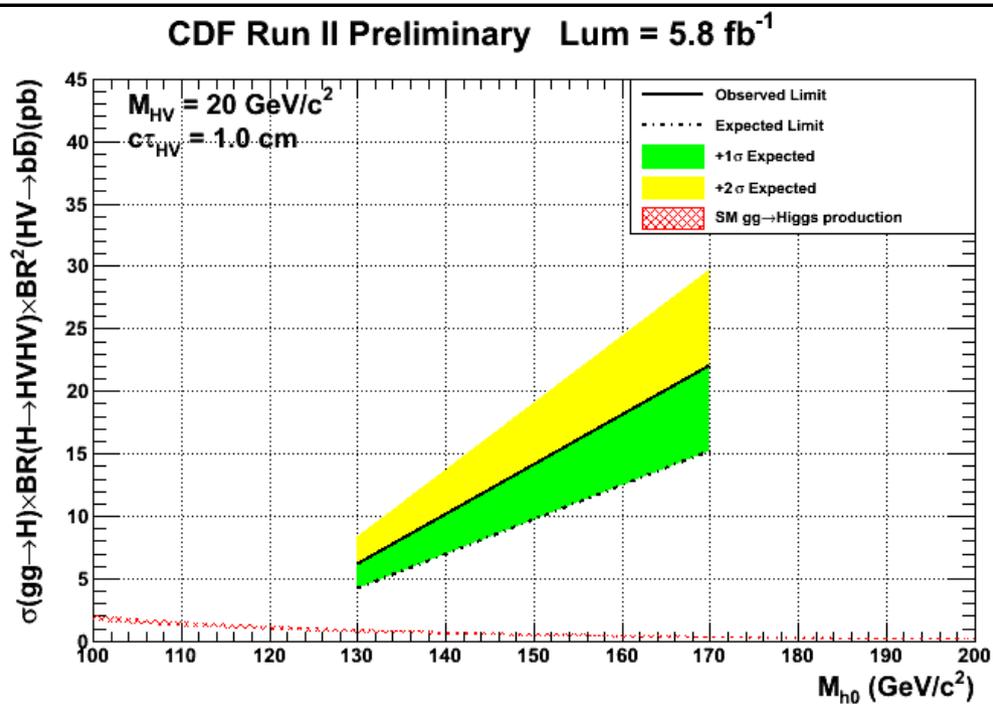
M_{h_0} (GeV)	M_{H_V} (GeV)	$c\tau_{H_V}$ (cm)	Ob Limit (pb)	-2σ Exp	-1σ Exp	Med Exp	$+1\sigma$ Exp	$+2\sigma$ Exp
130	20	1.0	6.2	4.3	4.3	4.3	6.2	8.4
170	20	1.0	22.1	15.2	15.2	15.2	22.1	29.9
130	40	1.0	15.9	10.5	10.5	10.5	15.9	21.5
170	40	1.0	4.4	2.9	2.9	2.9	4.4	6.0
170	65	1.0	11.7	7.7	7.7	7.7	11.7	15.7
130	40	0.3	17.8	11.7	11.7	11.7	17.8	24.2
130	40	2.5	40.7	26.8	26.8	26.8	40.7	55.1
130	40	5.0	94.3	62.0	62.0	62.0	94.3	127.9

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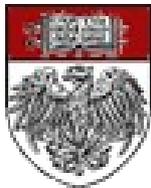


Limit Calculation

- ▶ Limit graph for the [Low Mass HV Search](#).
- ▶ x-axis is Higgs mass.
- ▶ Held constant are the HV mass and lifetime.
 - ▶ $M_{HV} = 40 \text{ GeV}$
 - ▶ $c\tau_{HV} = 1.0 \text{ cm}$



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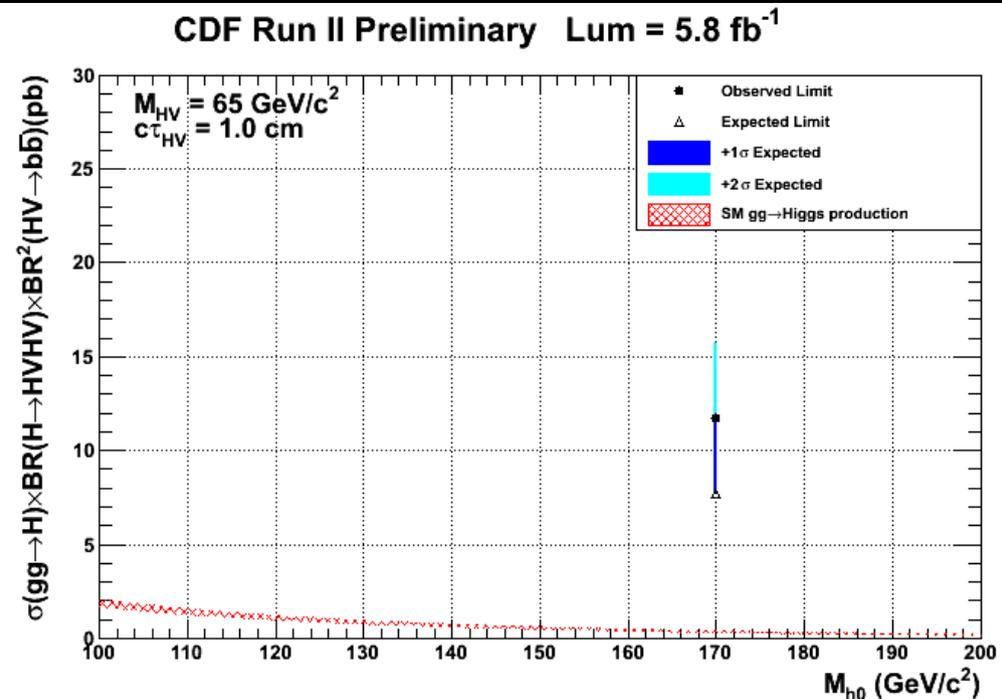
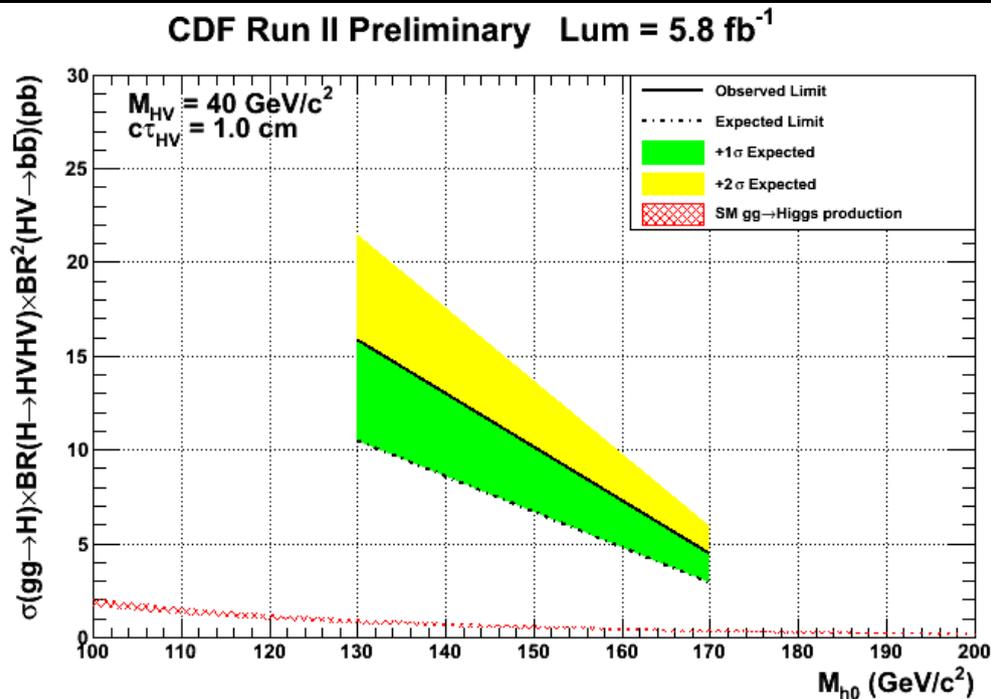
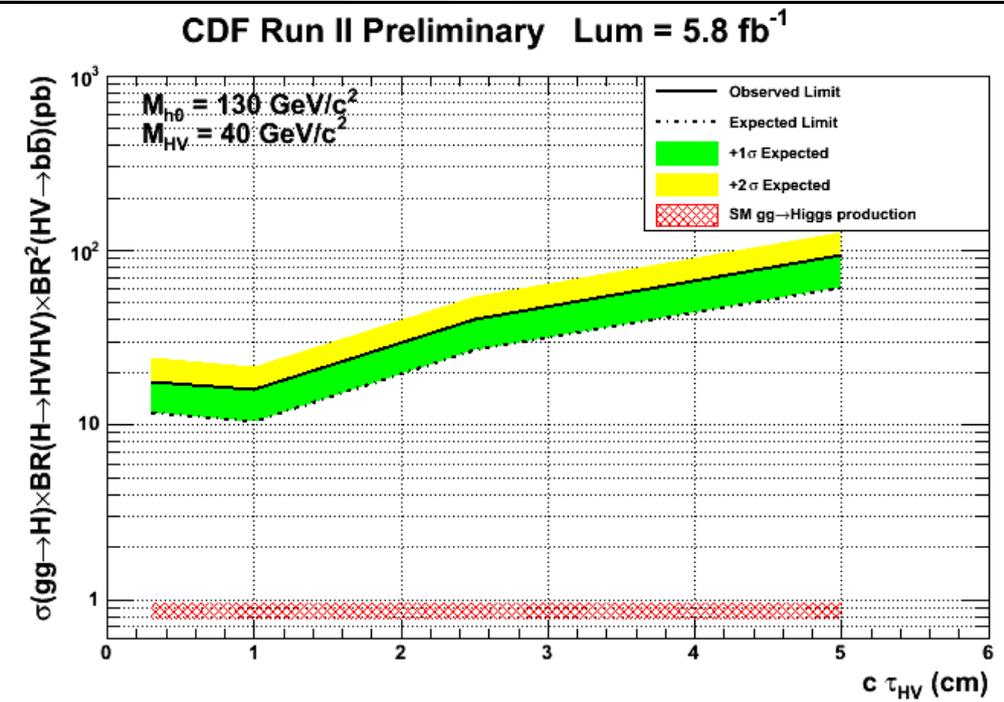
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Limit Calculation

▶ Limit graphs for the [High Mass HV Search](#)

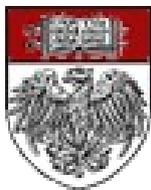
- ▶ $c\tau_{HV}$: 0.3, 1.0, 2.5, and 5.0 cm (right)
- ▶ M_{HV} : 40 and 65 GeV (below)



Conclusion

- ▶ We searched for displaced vertices at CDF, with the model of Higgs decaying into the Hidden Valley phenomenology.
- ▶ No statistically significant excess is observed.
- ▶ Limits are placed on the cross-section times branching ratio of HV production.

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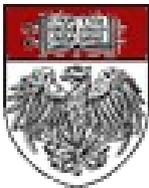


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Acknowledgments

- ▶ Thanks to the people who helped in this analysis
- ▶ Mel Shochet, Florencia Canelli, Dan Krop and Erik Brubaker
- ▶ CDF physicists, including but not limited to Ben K., Eric James, and Tom Junk
- ▶ Committee Members: Ed Blucher, Jon Rosner, Woowon Kang

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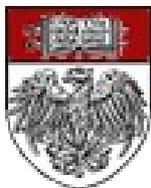
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Appendix

- ▶ Event Displays of N_{obs}

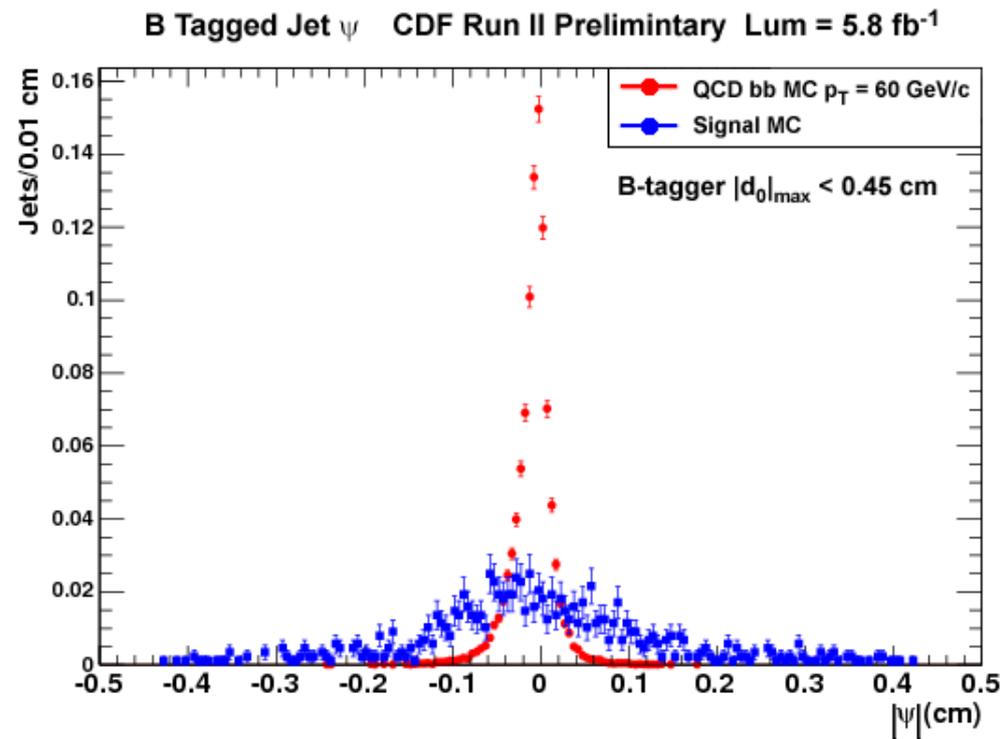
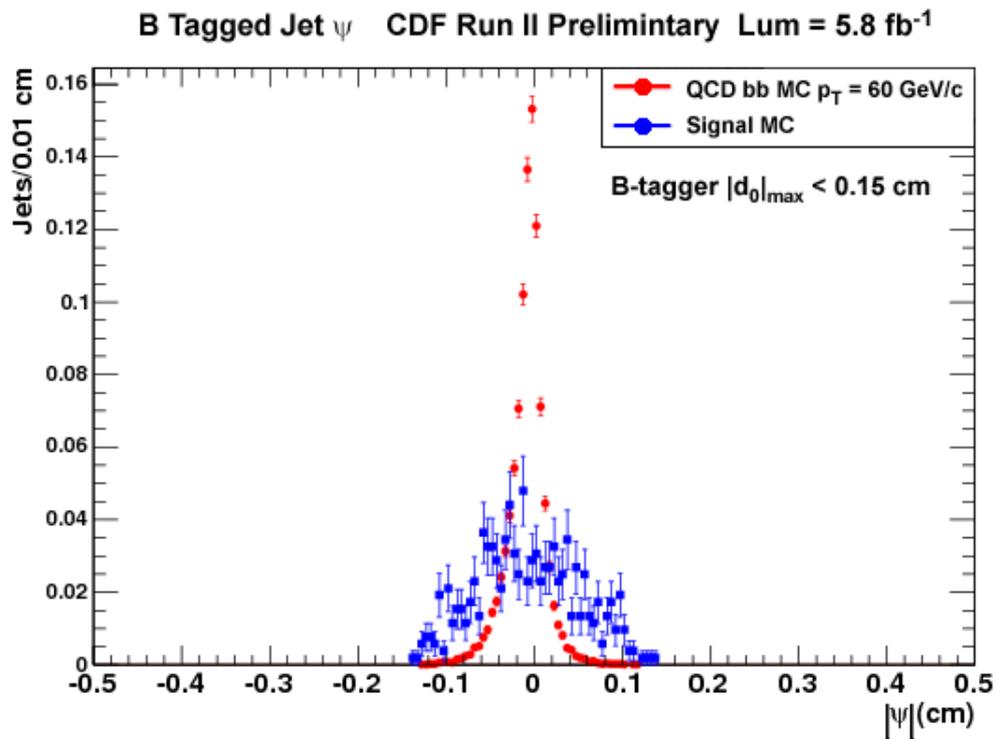
- ▶ <http://www-cdf.fnal.gov/htbin/twiki/bin/view/ZtoBBbar/ObservedEventDisplaysLowE0>
- ▶ <http://www-cdf.fnal.gov/htbin/twiki/bin/view/ZtoBBbar/ObservedEventDisplaysHighE0>

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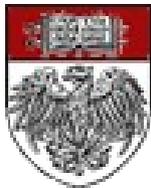


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MC Studies, $|d_0|_{\max}$ cut

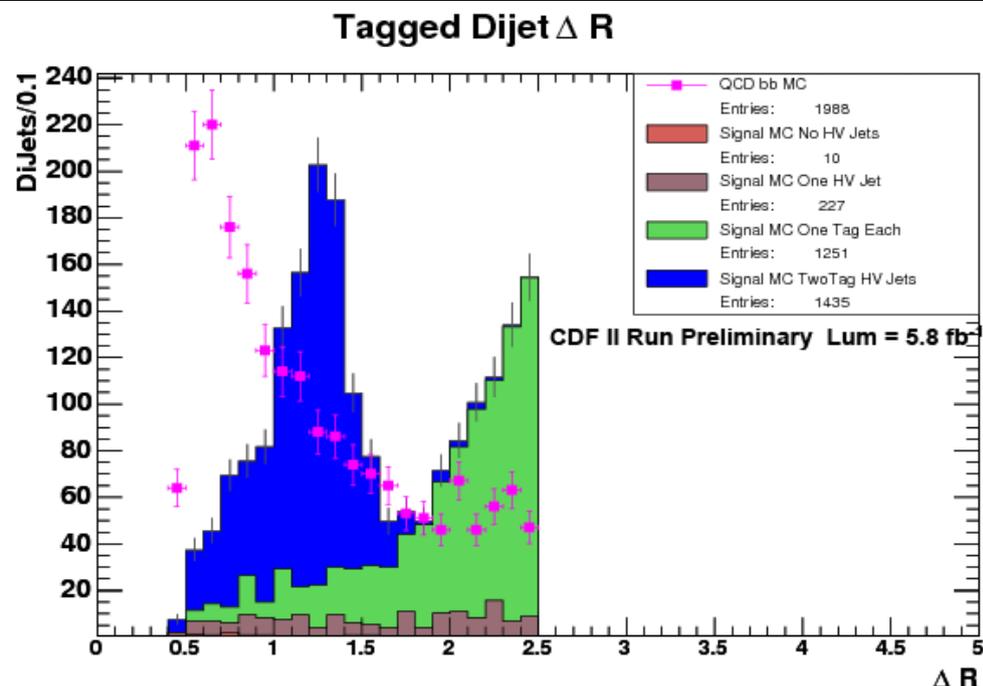


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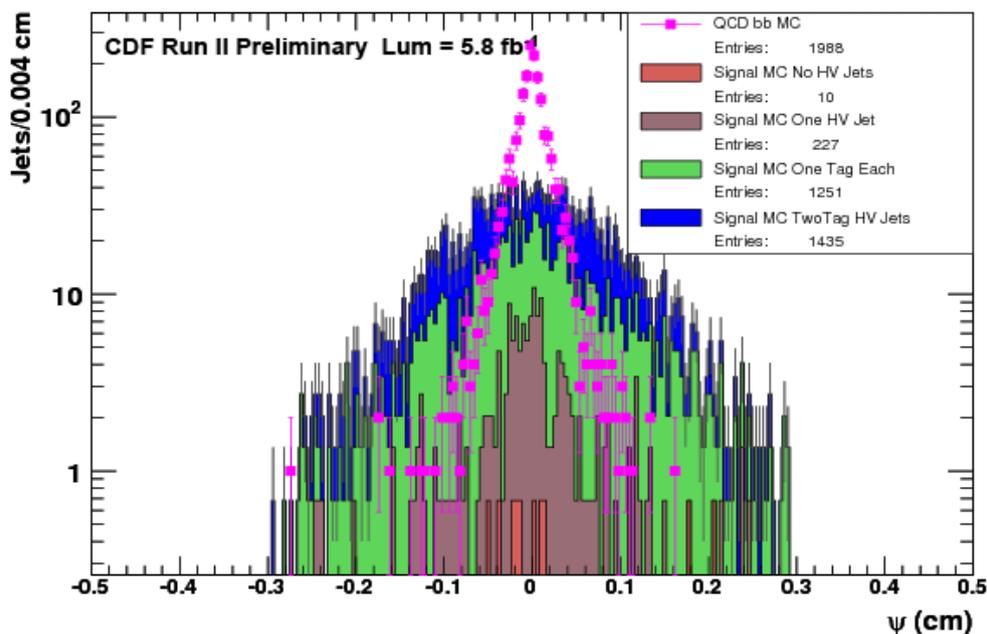


MC Studies, Discriminants

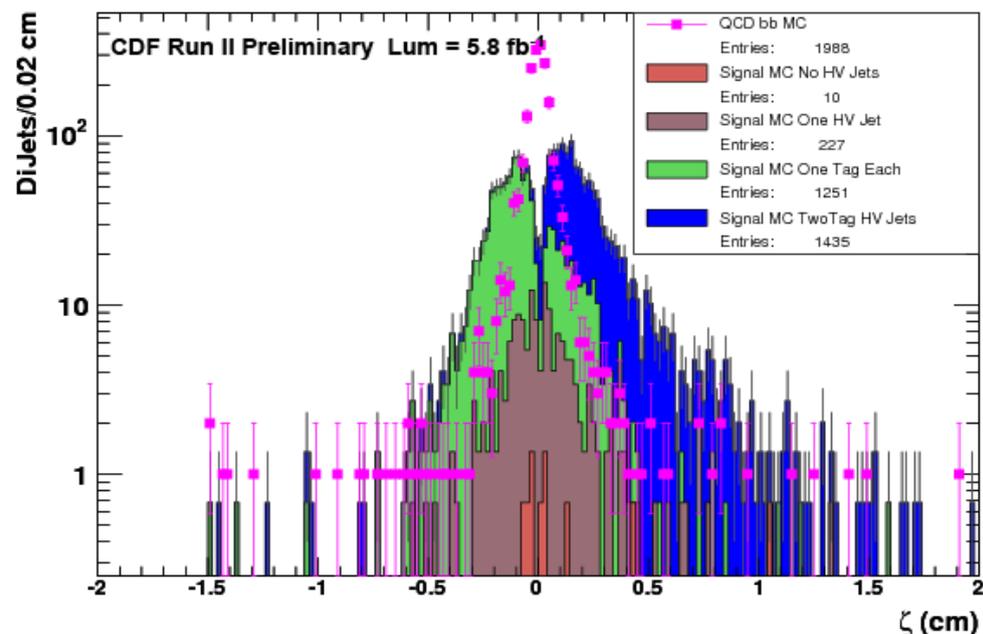
- ▶ Blue: Signal MC, the jets originates from a single HV particle.
- ▶ Green: The case where each jet originates from a different HV particle
- ▶ Brown (2): cases where a jet does not originate from a HV particle.



Tagged Dijet Psi-Higher E_T Jet

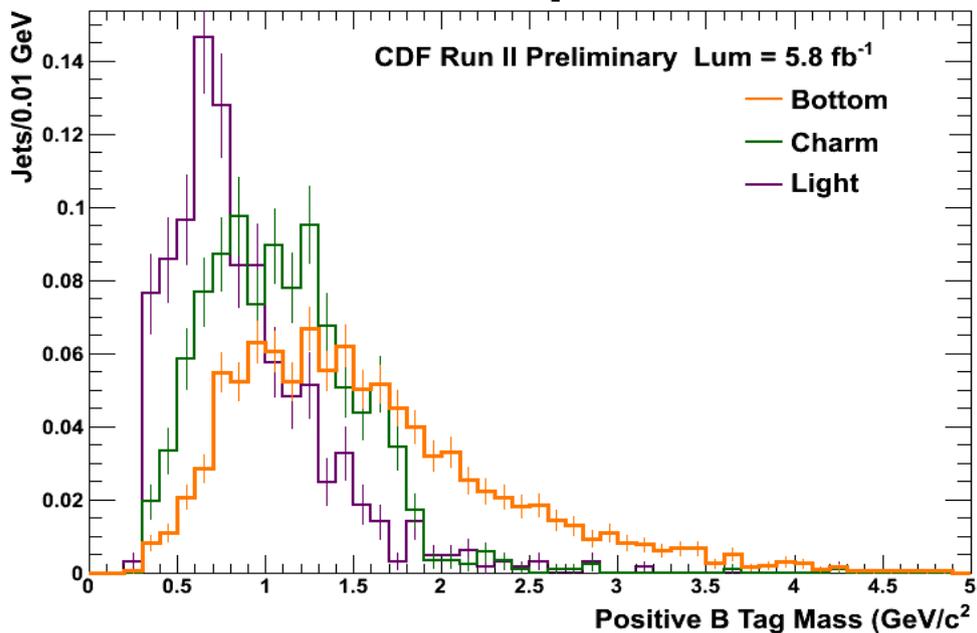


Tagged Dijet Zeta2d

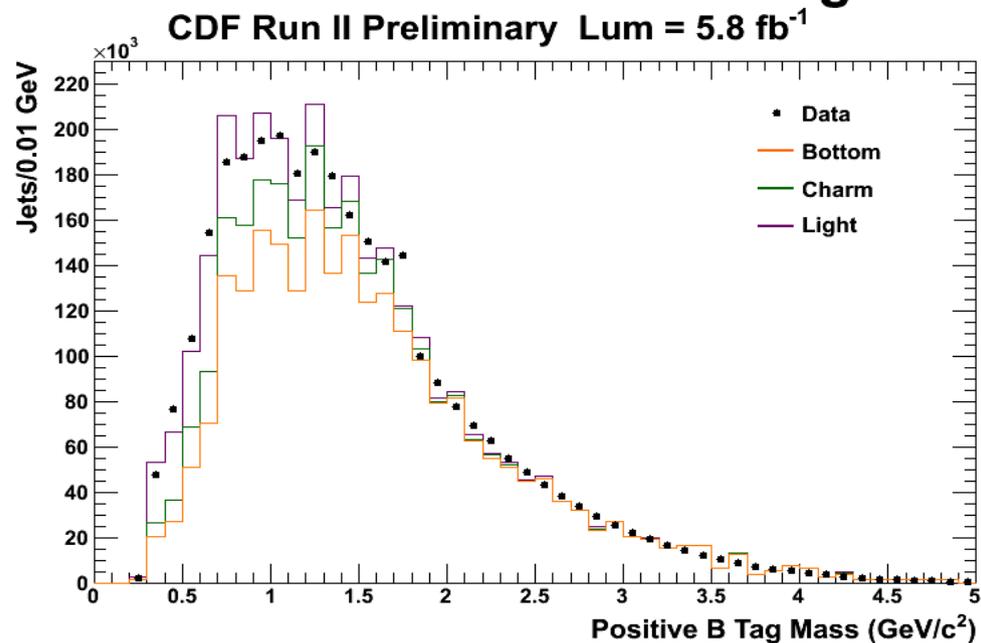


Heavy Flavor Subtraction

Fit Templates



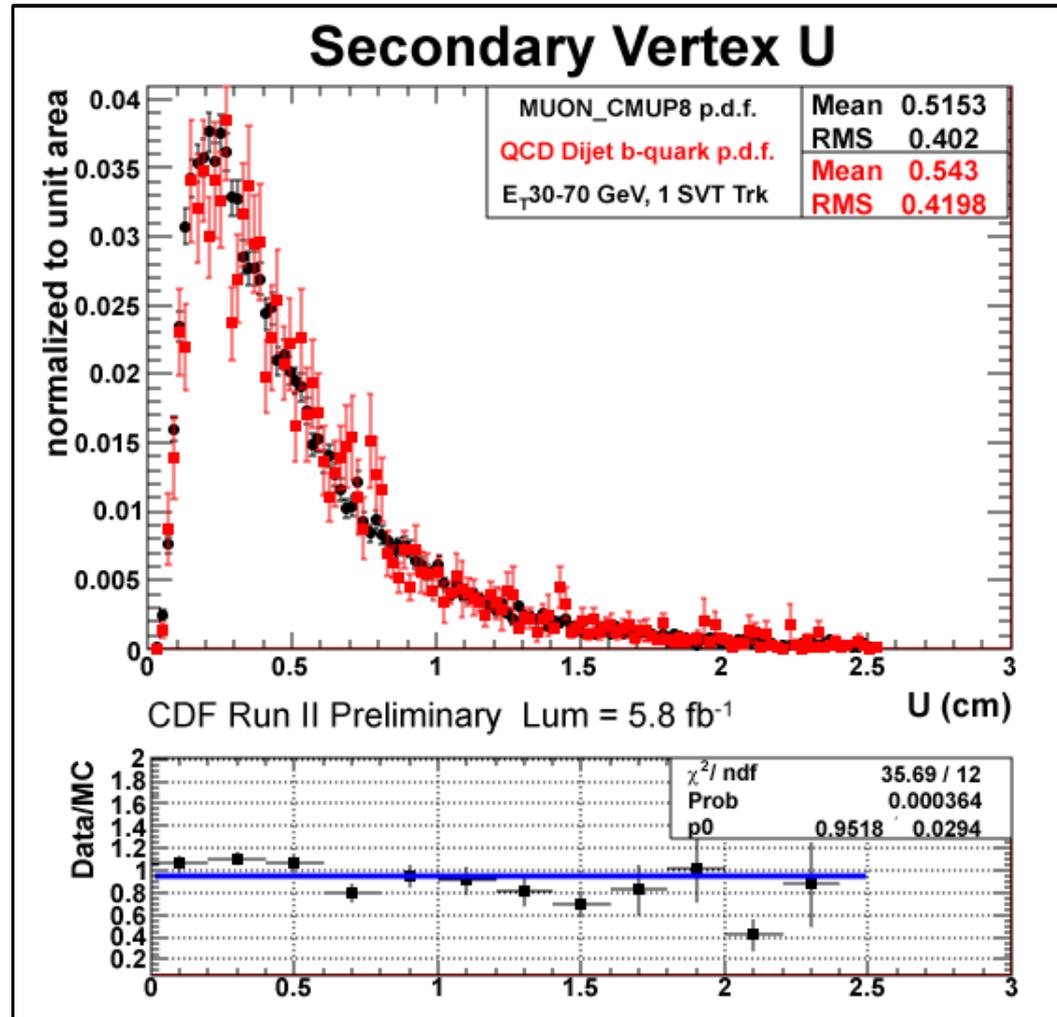
Vertex Mass Positive B Tag Fit



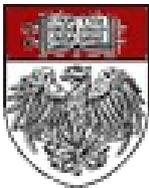
2011-01-27



PDF Scale Factor

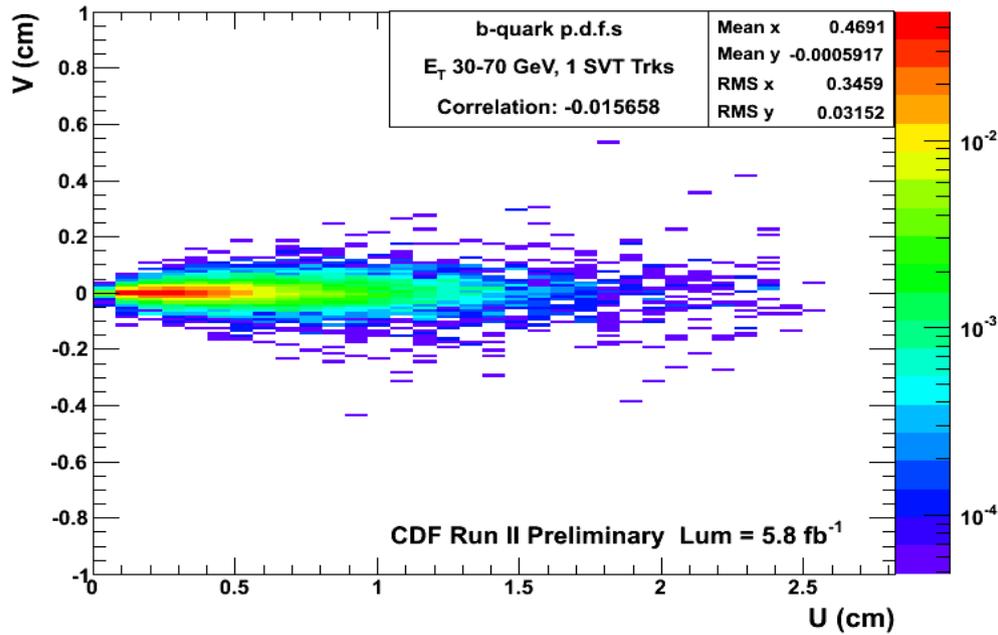


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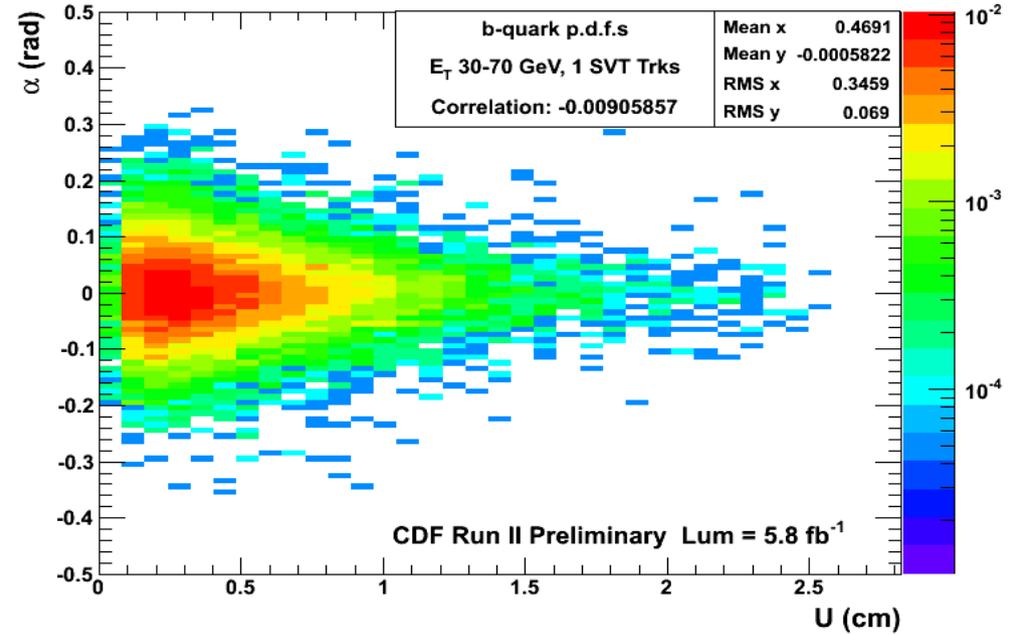


PDF Examples

Secondary Vertex V vs U

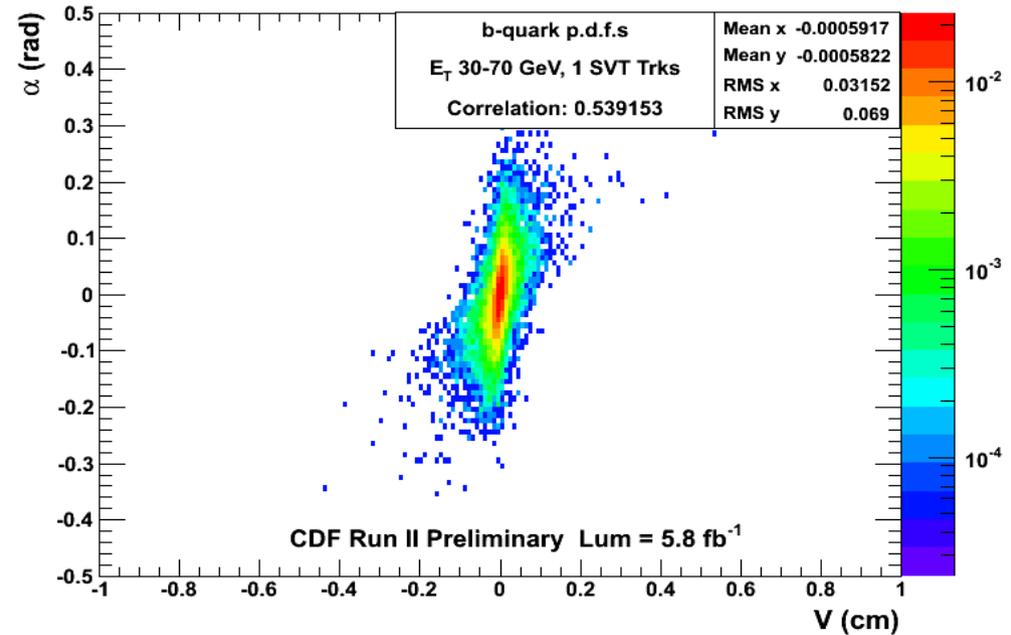


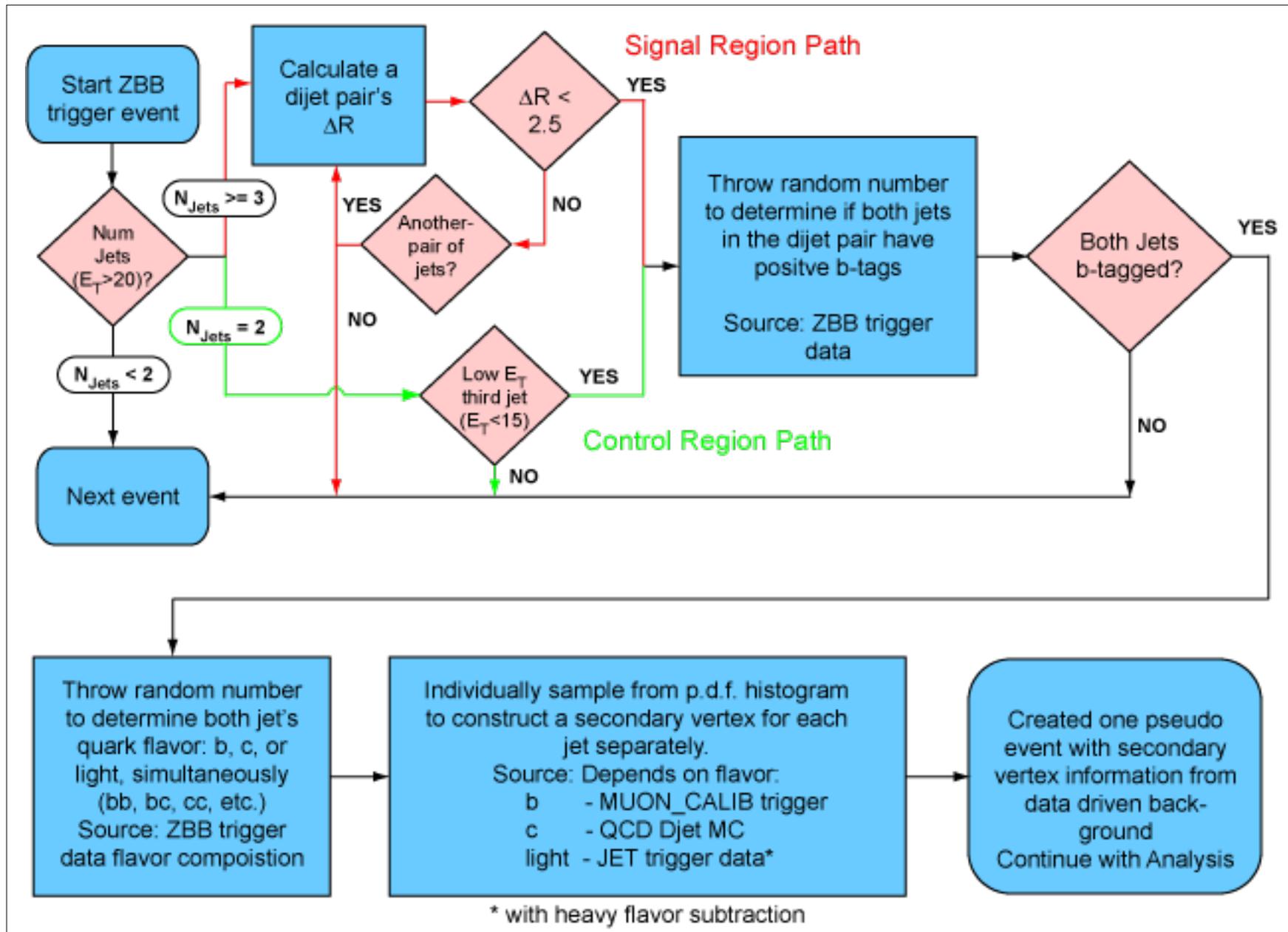
Secondary Vertex Alpha vs U



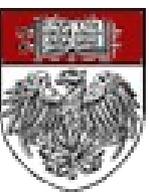
Jets w/ E_T [30,70) GeV, 1 SVT Track

Secondary Vertex Alpha vs V





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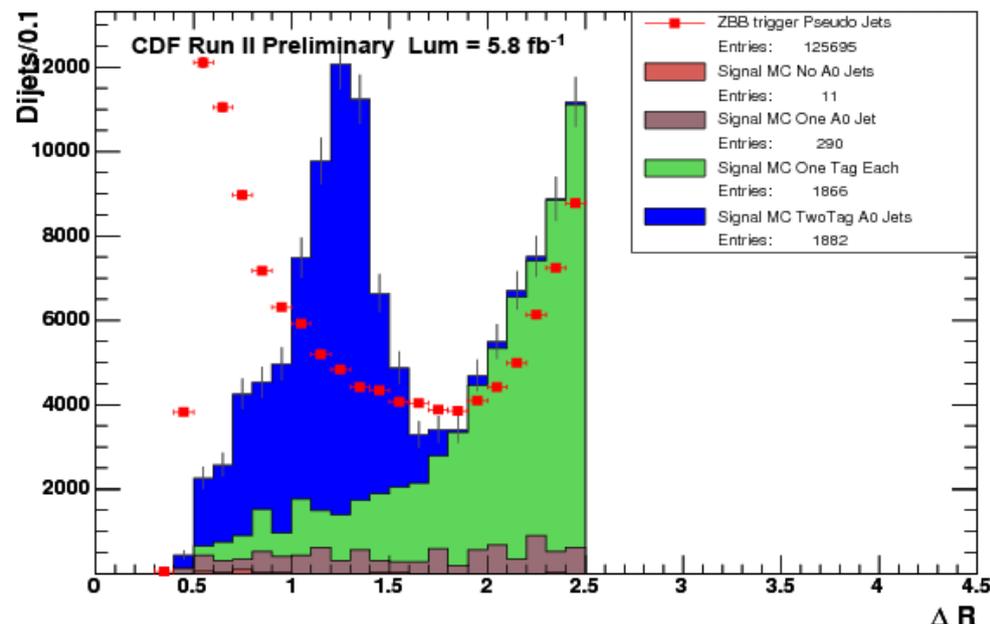


Pseudo Event Algorithm

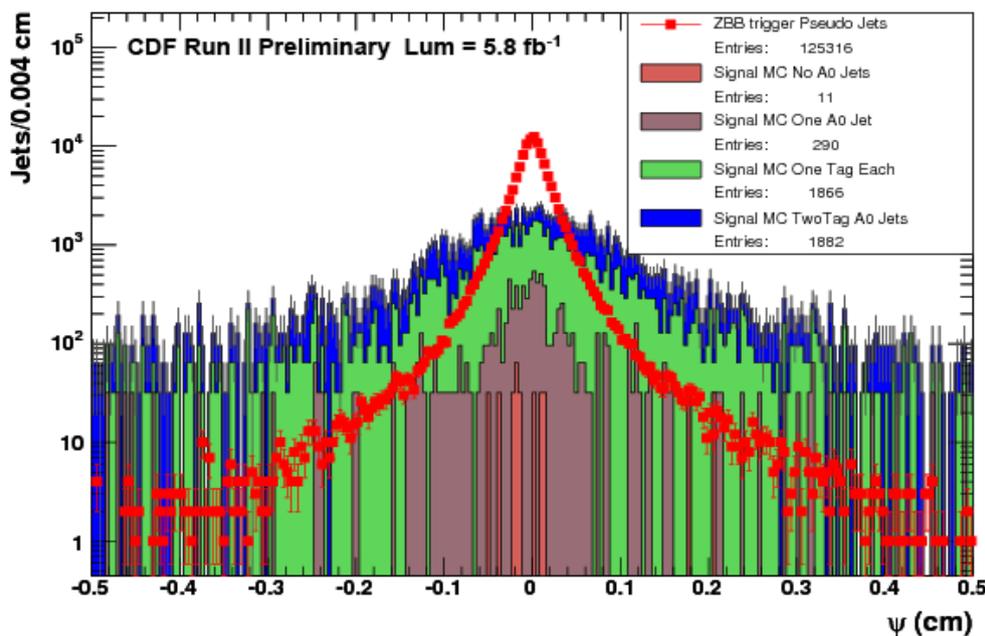
Analysis Variables

- ▶ Blue: Signal MC, the jets originates from a single HV particle.
- ▶ Green: The case where each jet originates from a different HV particle
- ▶ Brown (2): cases where a jet does not originate from a HV particle.

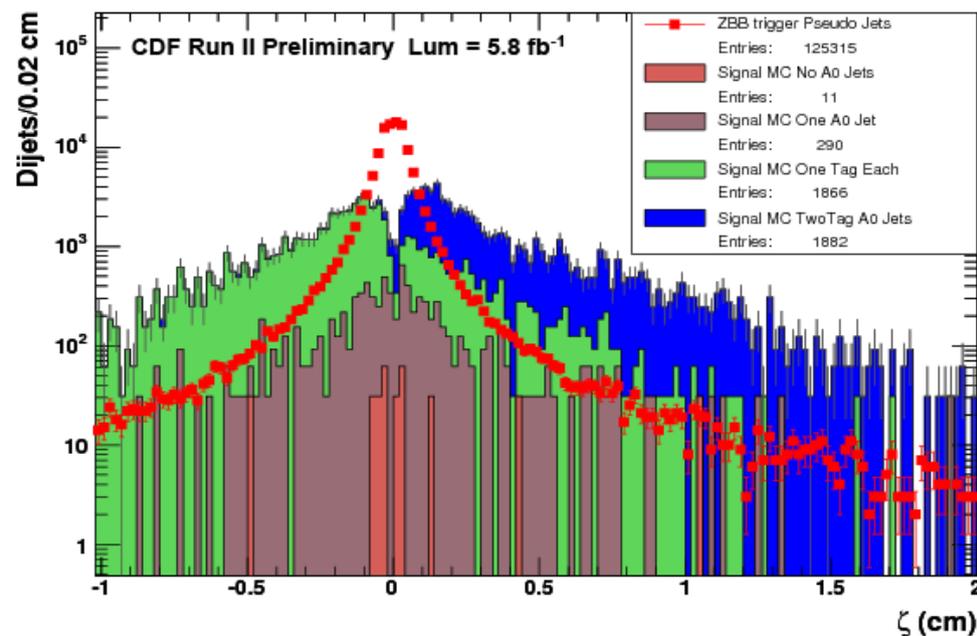
Tagged Dijet ΔR



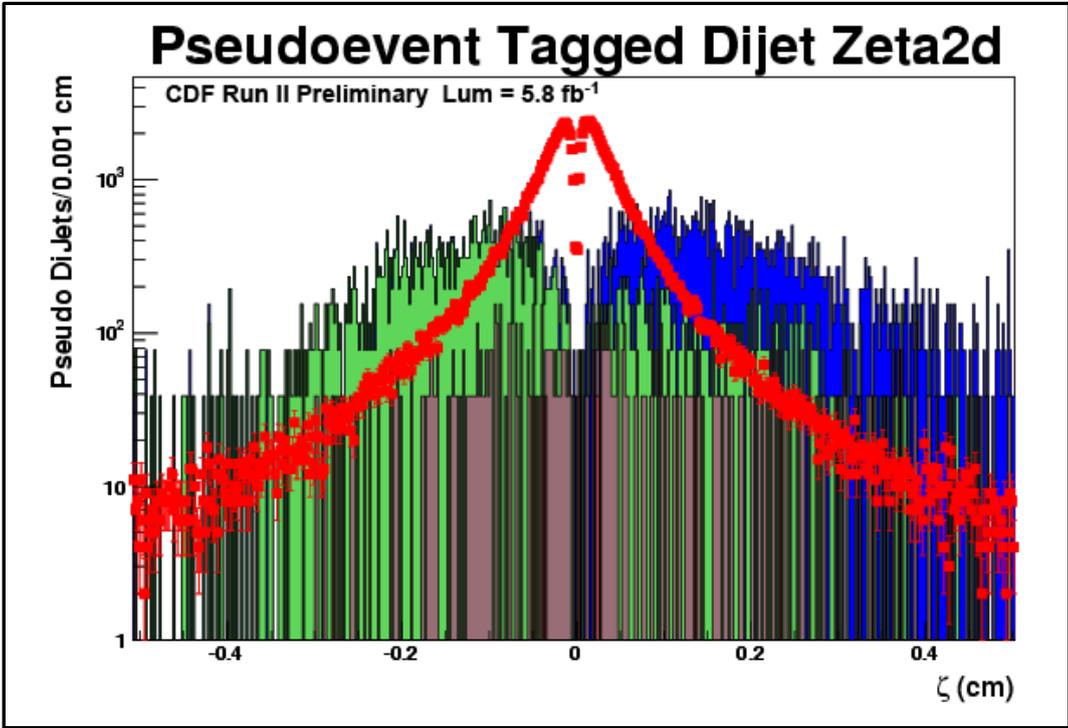
Tagged Dijet Psi-Higher E_T Jet



Tagged Dijet Zeta2d



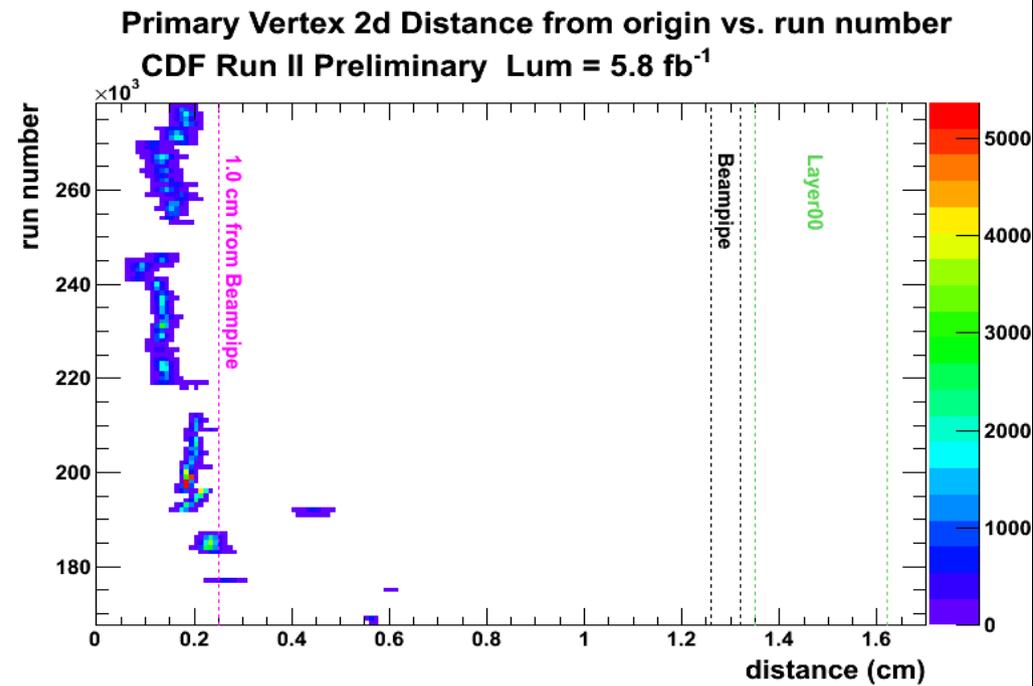
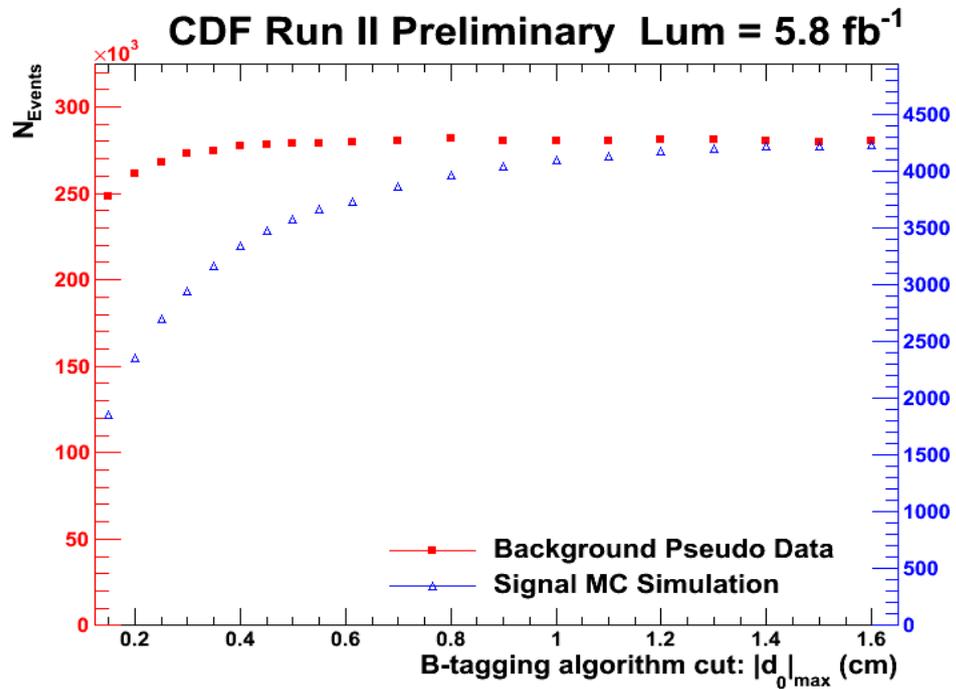
Zeta Resolution



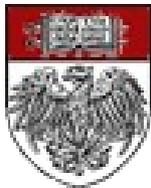
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$|d_0|_{\max}$ cut Selection

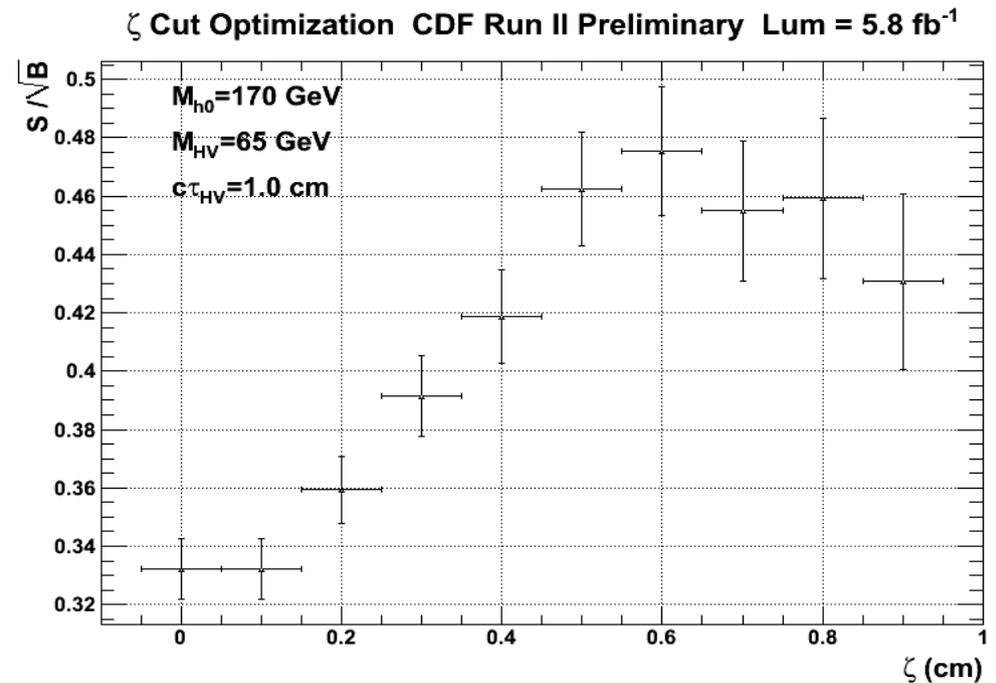
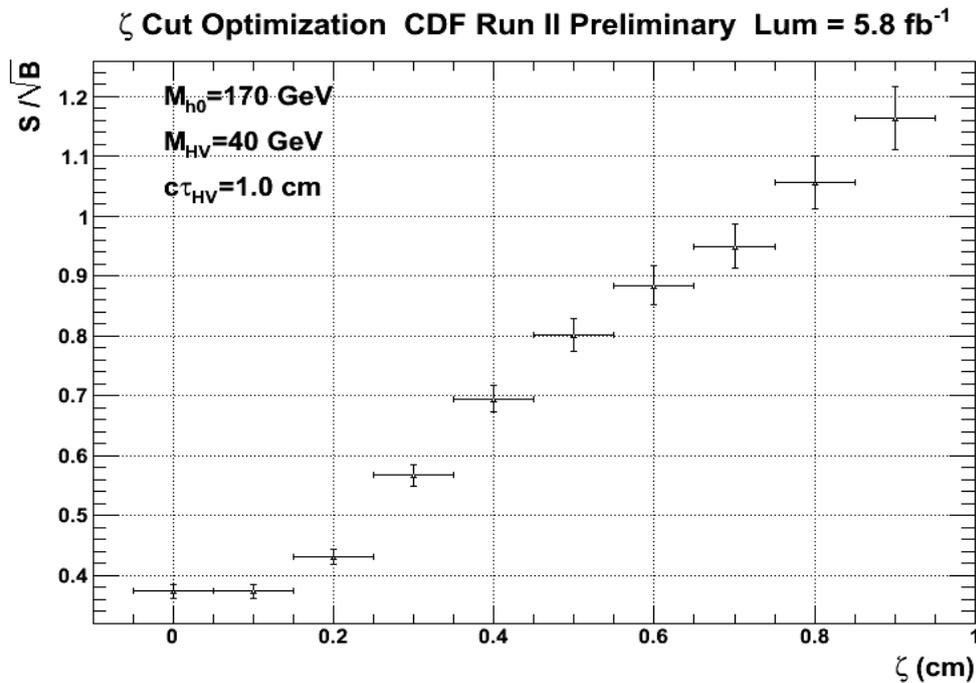
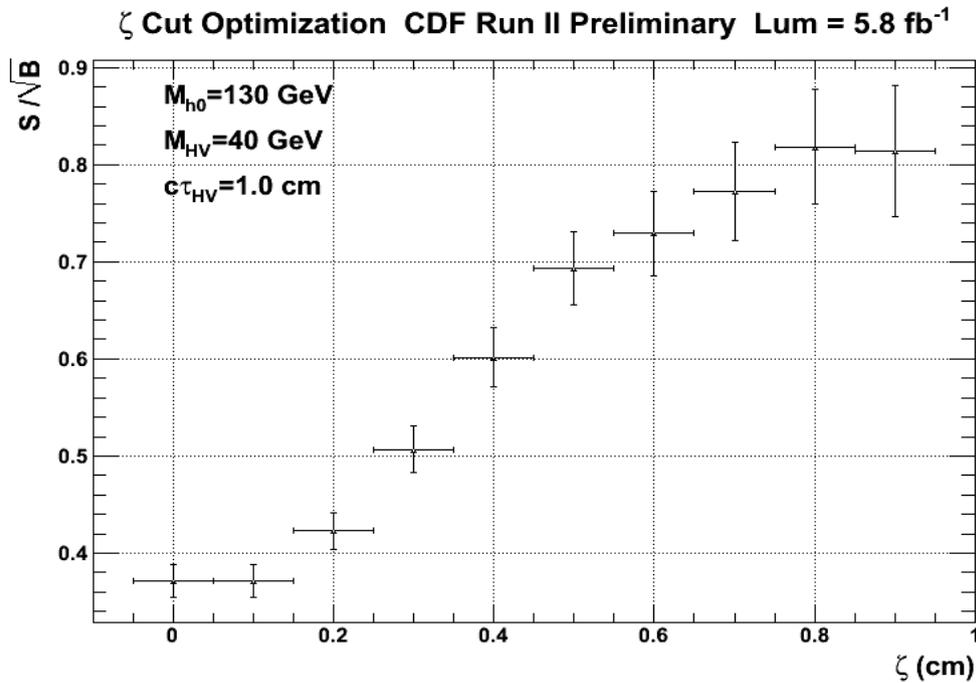


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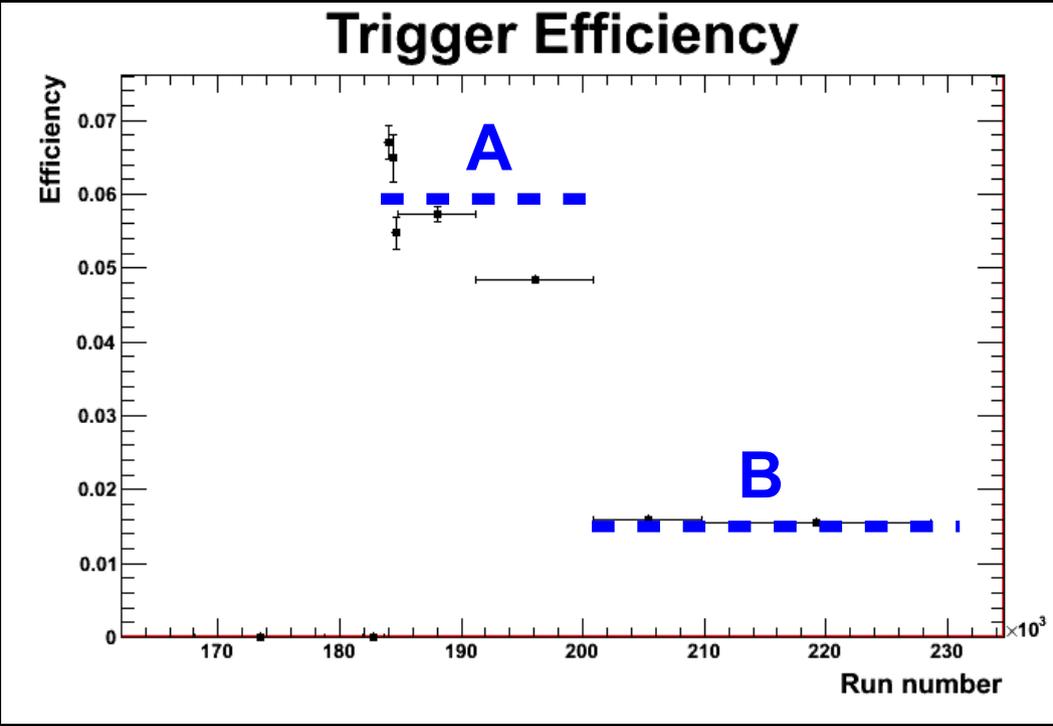
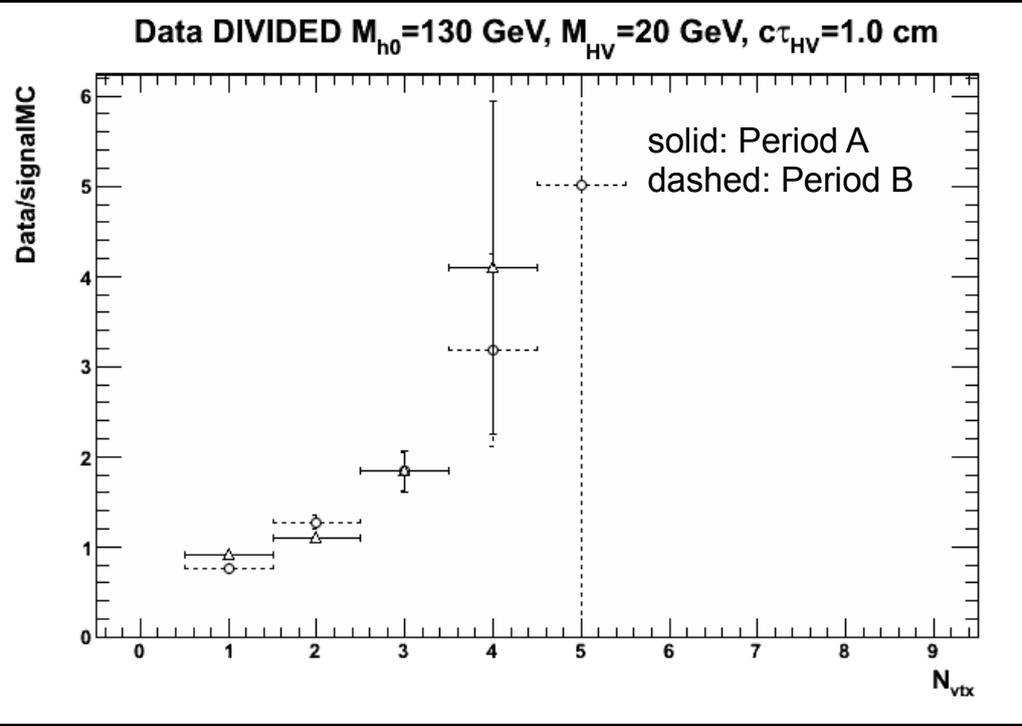


Variable Optimization

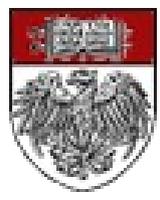
High Mass HV Search



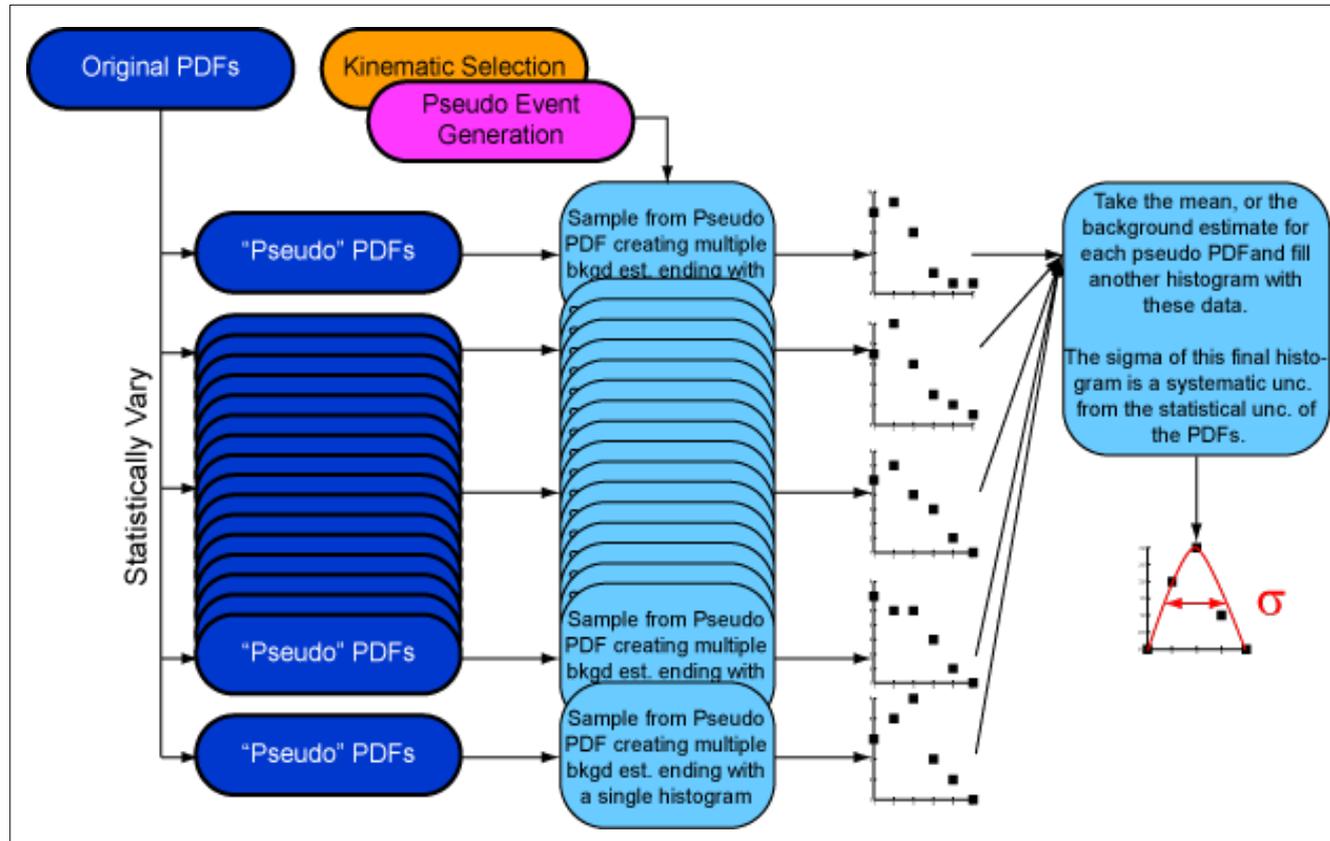
Signal MC Reweighting



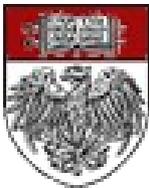
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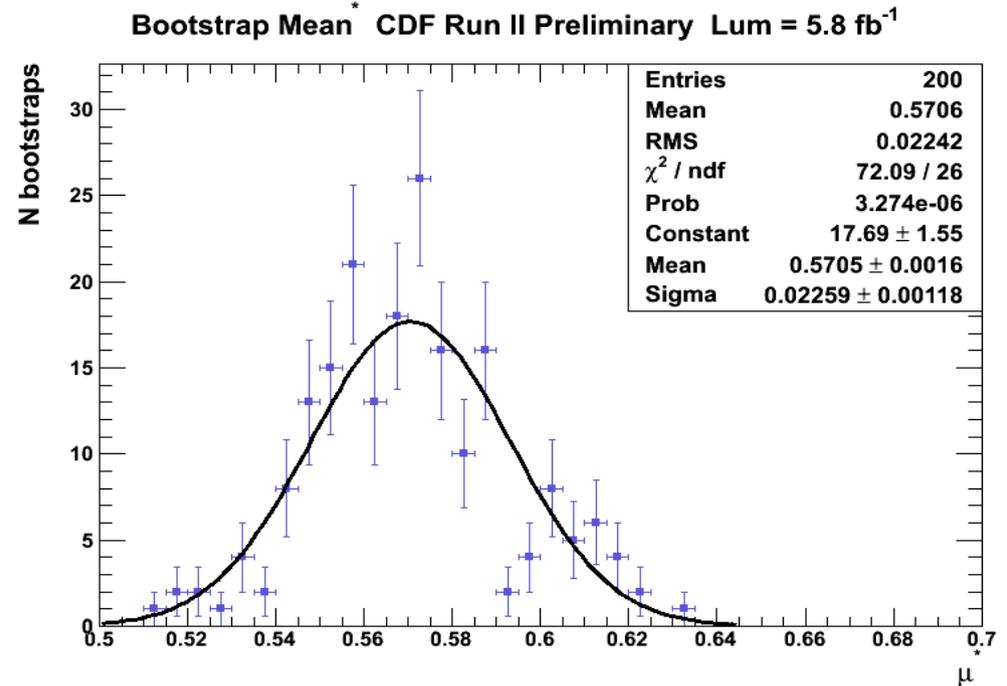
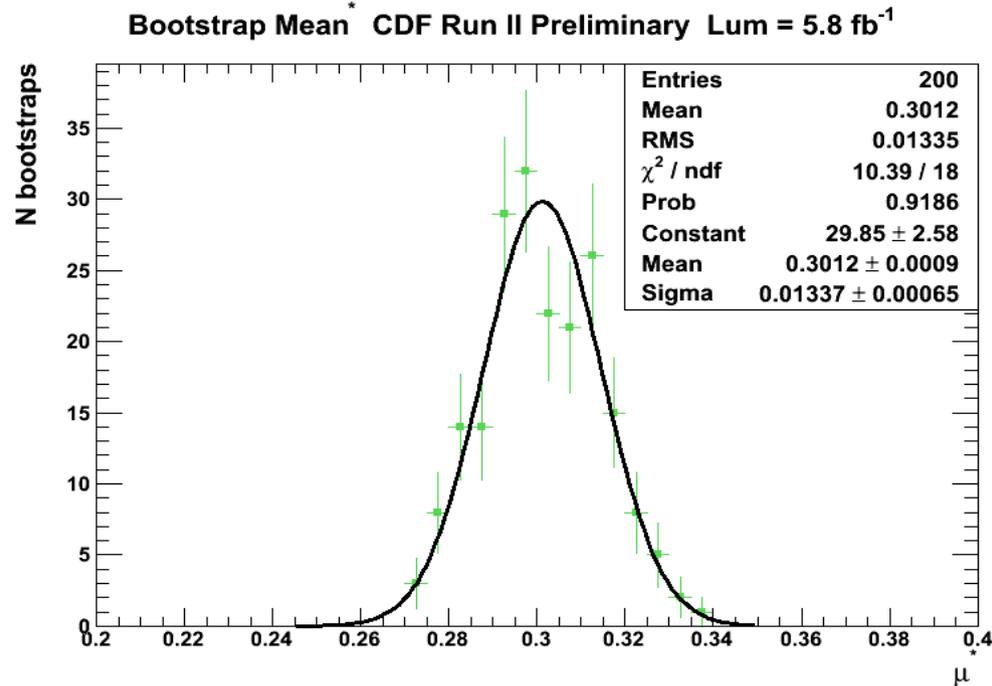
Bootstrap Algorithm



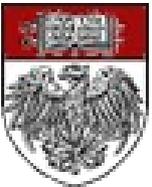
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Bootstrap Results



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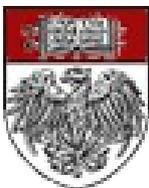
Comparison with D0

- ▶ D0 performed a similar analysis with the same Hidden Valley Model.
 - ▶ [hep-ex/0906.1787v2](https://arxiv.org/abs/hep-ex/0906.1787v2)
- ▶ $M_{h_0} = 100, 120, \& 200$ GeV
- ▶ $M_{HV} = 15 \& 40$ GeV
- ▶ $c\tau_{HV} = 5.0$ cm for the above six mass points

- ▶ $c\tau_{HV} = 2.5, 5.0, \& 10.0$ cm for one mass point:
 - ▶ $M_{h_0} = 120$ GeV, $M_{HV} = 15$ GeV

- ▶ Our lifetime is shorter because of the SVT.
- ▶ A direct comparison is not possible because the Higgs masses are slightly different, $M_{h_0} = 120$ GeV vs. $M_{h_0} = 130$ GeV.

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