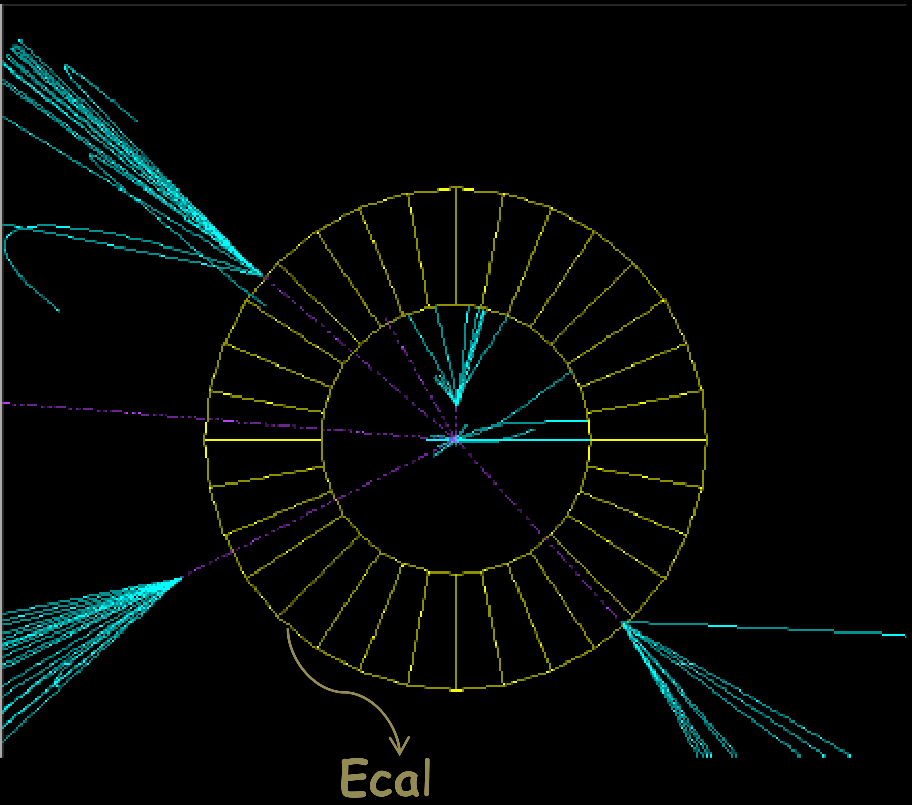
Observing Jets with Displaced Vertices in ATLAS

Hidden Valley Scenarios



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On behalf of the Hidden Valley Working Group: Genova, RomeI, Seattle, SLAC

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Long Lived Neutral Particles

- Several extensions of SM have neutral, weakly-coupled unstable particles with macroscopic decay lengths, for example
  - **gauge-mediated SUSY extensions of the MSSM, MSSM with R-parity violation, split SUSY, inelastic dark matter and the Hidden Valley (HV) Scenario in which a new sector is weakly coupled to the SM**
  - **The long-lived neutral states can appear in Higgs Boson, Z' and SUSY processes and decay to quark pairs and lepton pairs throughout the detector volume, which are challenges for the trigger and reconstruction capabilities of ATLAS**
- The Hidden Valley scenario* provides a range of models where we can study and perfect triggers to insure that if such states do exist we will be able to detect them in ATLAS

*M. Strassler, K. Zurek, Phys. Lett. B651 (2007) 374
*M. Strassler, K. Zurek, Phys. Lett. B661 (2008) 263

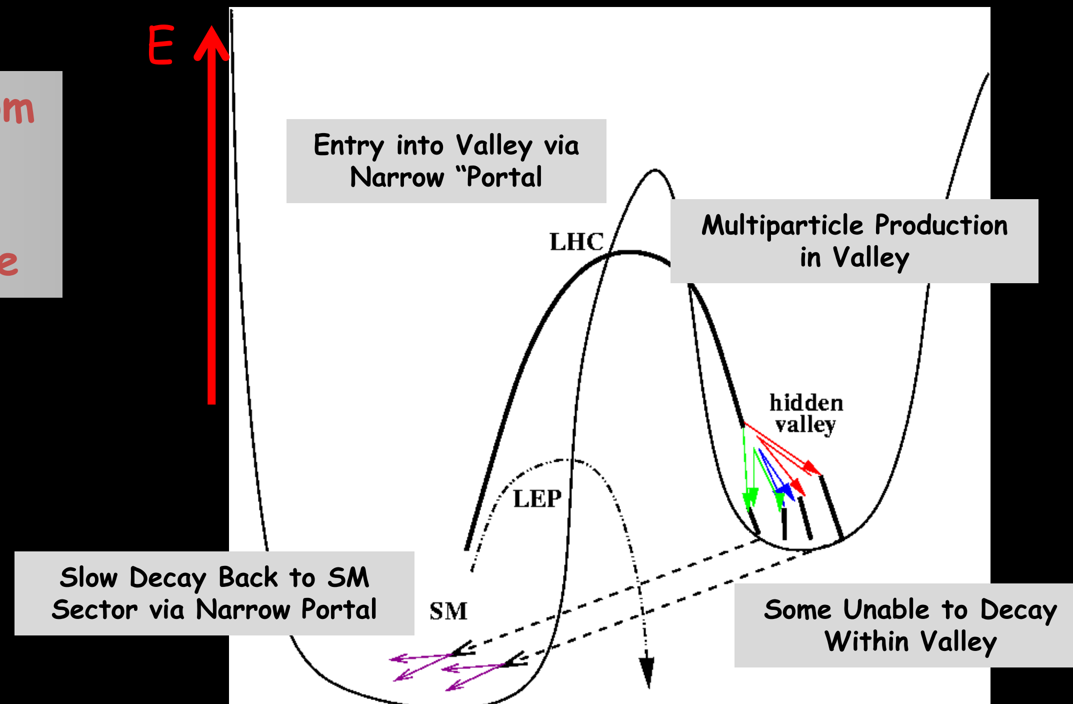
- *M. Strassler "Possible Effects of a Hidden valley on Supersymmetric Phenomenology arXiv:hep ph/0607160

Hidden Valley Scenario

- A “hidden sector” (v-sector) and communicators that weakly couple the v-sector to the standard model

A barrier separates the SM from the Hidden Sector but at LHC energies production of v-sector particles can be observably large

Some HV particles cannot decay in hidden sector but can decay in SM sector via interactions with the communicator



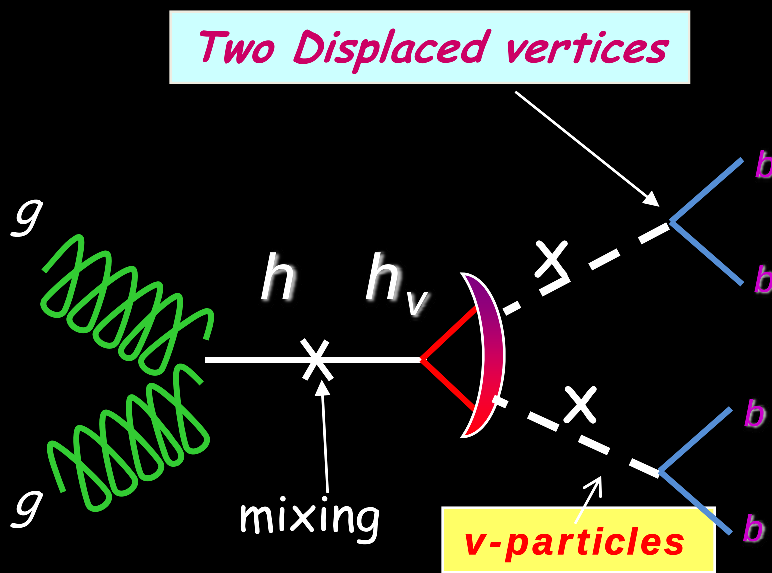
  - Communicators include Higgs Boson, Z’ Bosons, neutralinos ......
  - Hidden Valley particle are all singlets under the Standard Model

Hidden Valley Processes

- To study detection of long lived states we chose two processes to simulate: Higgs Boson and Z' decays to HV particles, which in turn decay to heavy flavor pairs
    - h → XX, where X is neutral, weakly interacting & long lived and X → bb (mostly)
    - Z' → XX…XYY…Y, where Y is stable and invisible
  - Challenge to ATLAS triggers: high multiplicity final states, lots of multi-leptons decays, displaced multi track vertices, large missing E_T
  - Displaced vertex can introduce high rejection factors at Level1 and Level2 triggers
  - The goal of our study is to optimize trigger performance for long lived neutral particles
- This choice addresses problems common to many other processes with long-lived particles

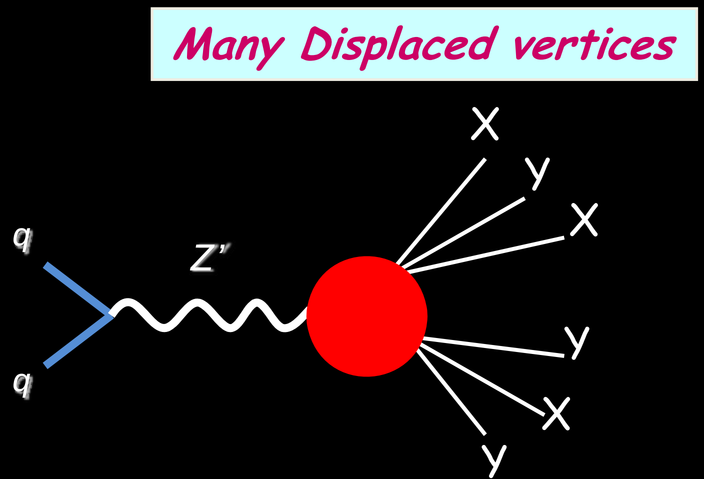
Hidden Valley Processes

- **Higgs**



Four b decays

- **Z'**



- N(X) ~ 3 - 6 **(X → bb)**
- N(Y) ~ 6-12 **(Y → MET)**

Many b decays

See also **L. Carpenter et al.** arXiv:hep-ph/0607204
S. Chang et al. arXiv:hep-ph/0511250

Hidden Valley ATHENA Samples

- Samples of Higgs and Z′ generated using ATHENA 12.0.6.4
  - For Higgs used a standard PYTHIA card
    - gg-fusion, vector boson fusion and W-higgs channels
  - Z′ special HVMC PYTHIA based MC routine provided by Matt Strassler (implemented in 13.0.30)
- Parameters:

Masses

- m_h = 140 GeV
- m_x = 40 GeV
- $m_{z'}$ = 2 TeV

Lifetimes

- Higgs: $c\tau$ = 1500 mm
- Z′: $c\tau$ = 300 mm

Current data sets

Higgs: 50K/channel

Z′: 50K

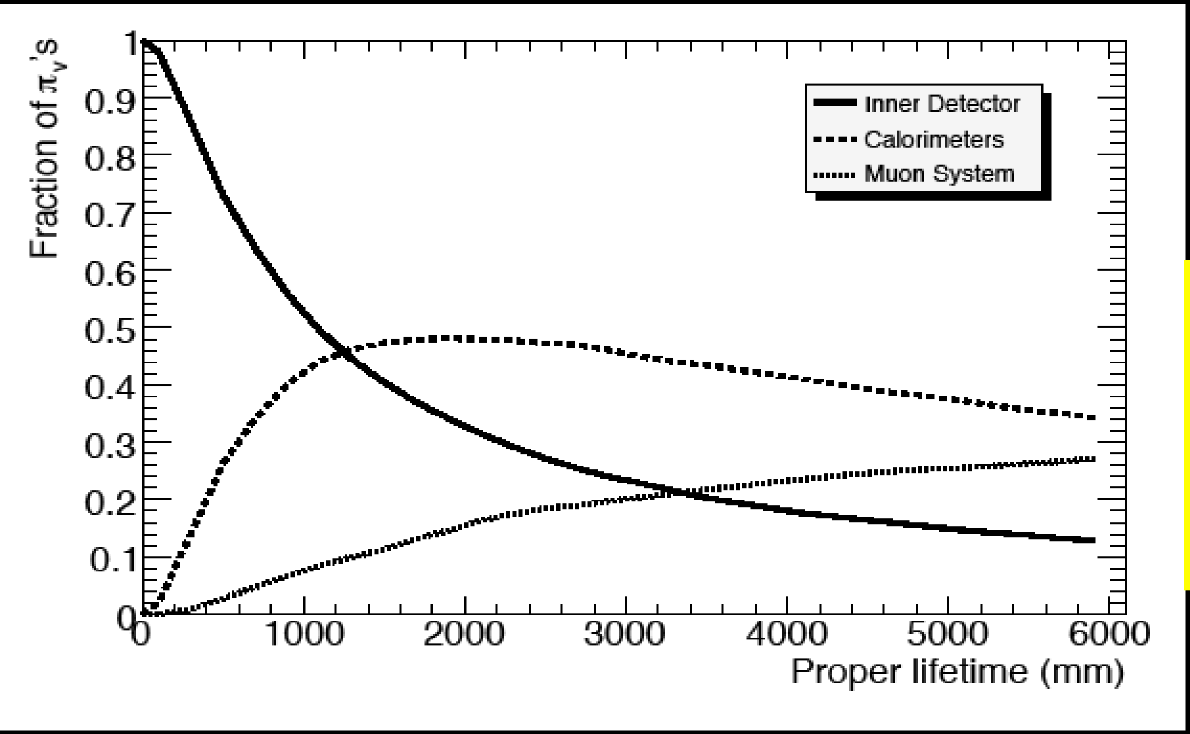
Detection in ATLAS

- **Current ATLAS trigger paths have not been optimized for picking up decays of neutral particles that decay to di-jets throughout the detector**
  - Muons from vertices that are far from the pp interaction point do not have inner detector tracks and fail Level2 muon trigger (muComb)
  - Jets from late decays will not have normal energy deposition in Calorimeter and may punch through
  - Depending on where the decay occurs (inner tracker, calorimeter or muon system) different approaches are required.

– *Signature Driven Triggers*

Detector Signatures

- **Hidden Valley particles (π_v's) can have a range of lifetimes with displaced bbar vertices occurring throughout the detector volume**



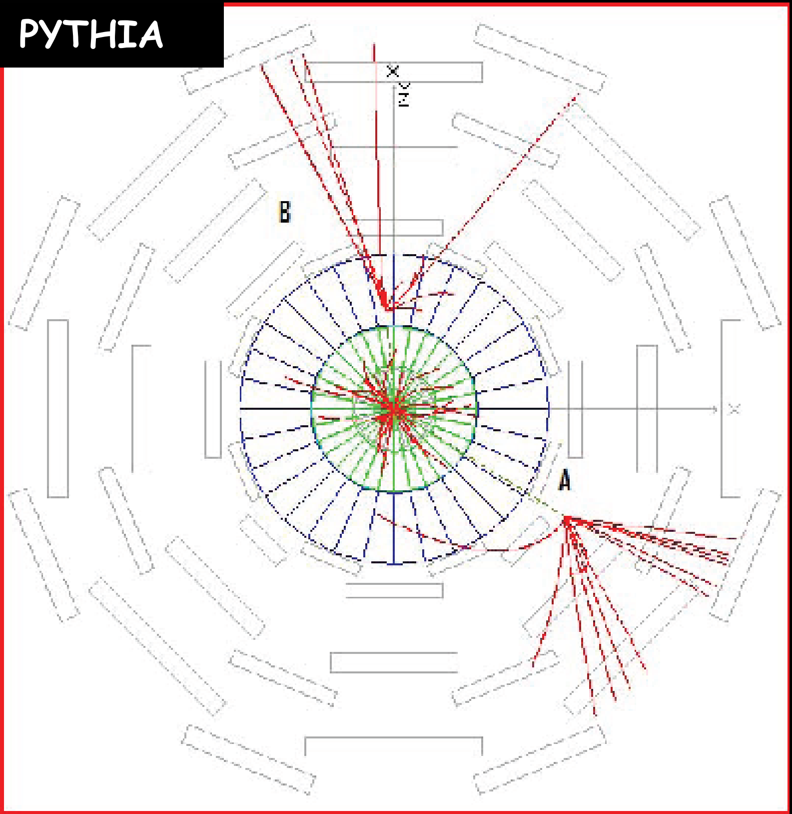
Probability of decay vs. $c\tau$ for ATLAS detector ($|\eta| \le 2.5$).(barrel plus endcap)

Different signatures observed for *decays* in different parts of detector – Three regions

- **End HCAL to 1st μ trig plane**
- **In Calorimeters**
- **Inner Tracker**

Detector Signatures

PYTHIA



Decays in or beyond ECAL gives E_{HAD}/E_{EM} ratio larger than observed for jets originating at IP – **Possible L2 Trigger Object**

Decays near end of HCAL & before 1st μ trigger plane give hadron clusters in small $\Delta R(\eta,\phi)$ region of muon spectrometer and L1 muon trigger returns multiple RoIs in this small ΔR region – **Possible L2 Trigger Object**

Detector Signatures

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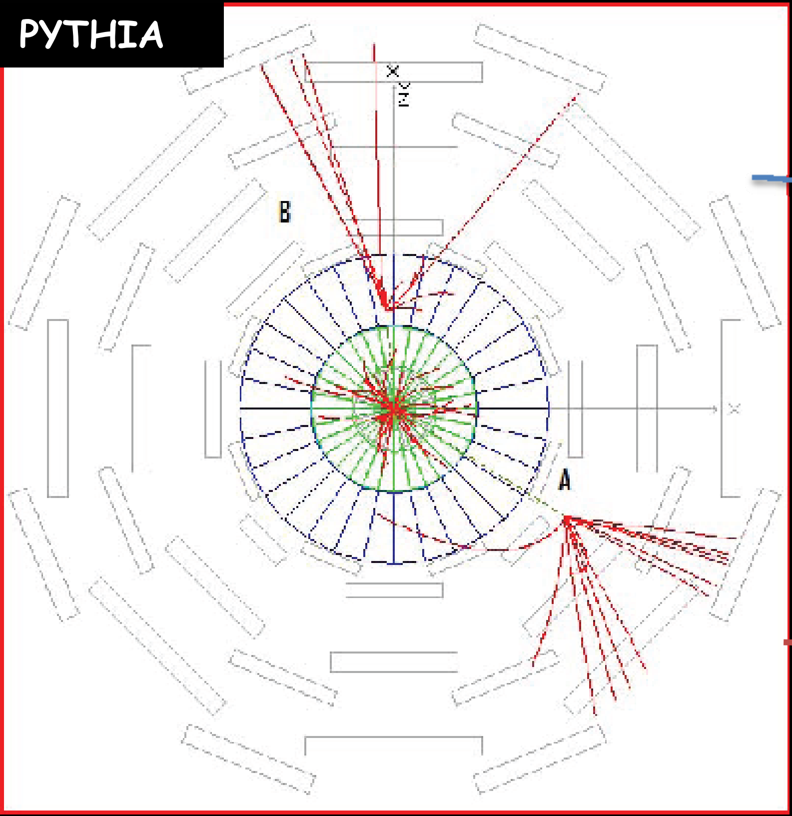

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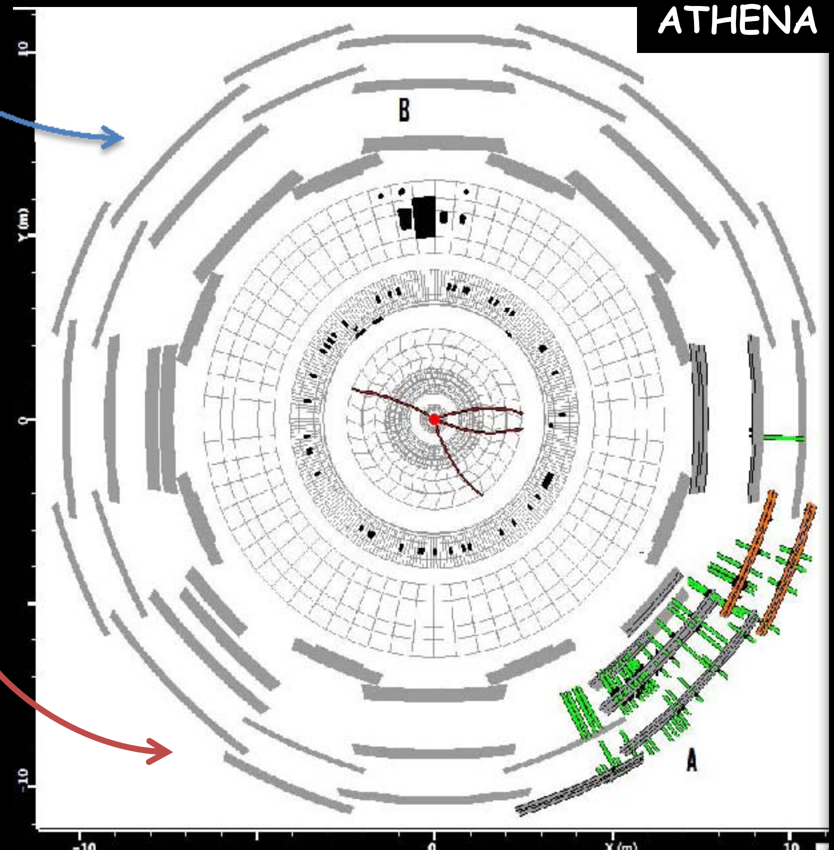
ATHENA



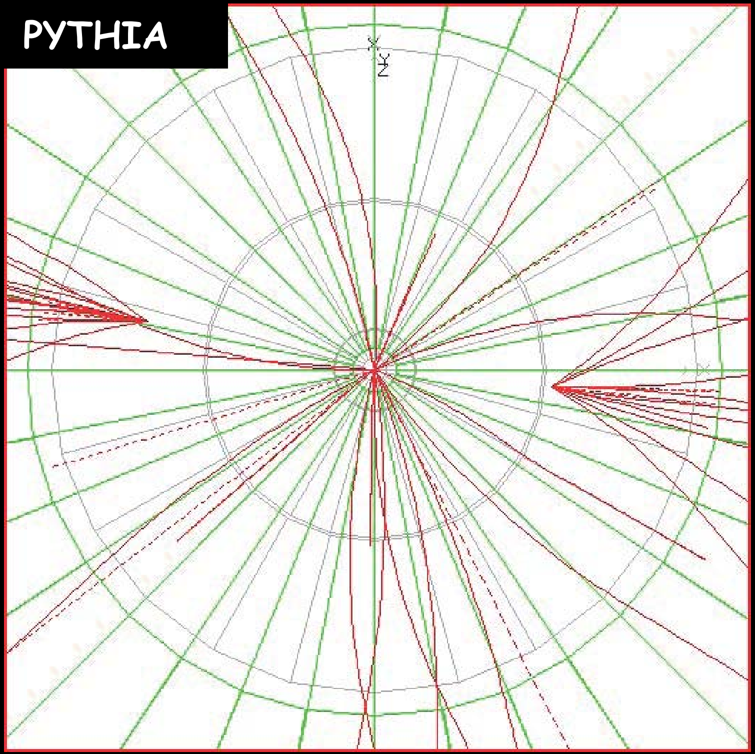
Decays near end of HCAL & before 1st m trigger plane give hadron clusters in small $\Delta R(\eta,\phi)$ region of muon spectrometer and L1 muon trigger returns multiple RoIs in this small ΔR region – **Possible L2 Trigger Object**

Detector Signatures

- π_v Decay in TRT gives ***trackless-jets***, jets with no connection to IP

Need a fast, robust L2 vertex finding algorithm to have high efficiency for finding such events

PYTHIA



TRT has lots of background that complicates pattern recognition, especially at the trigger level

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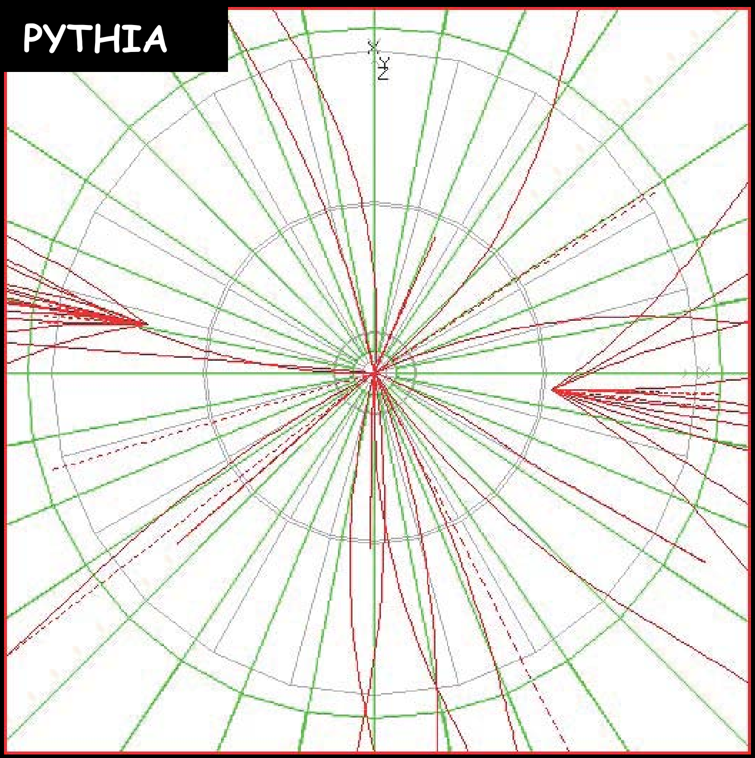
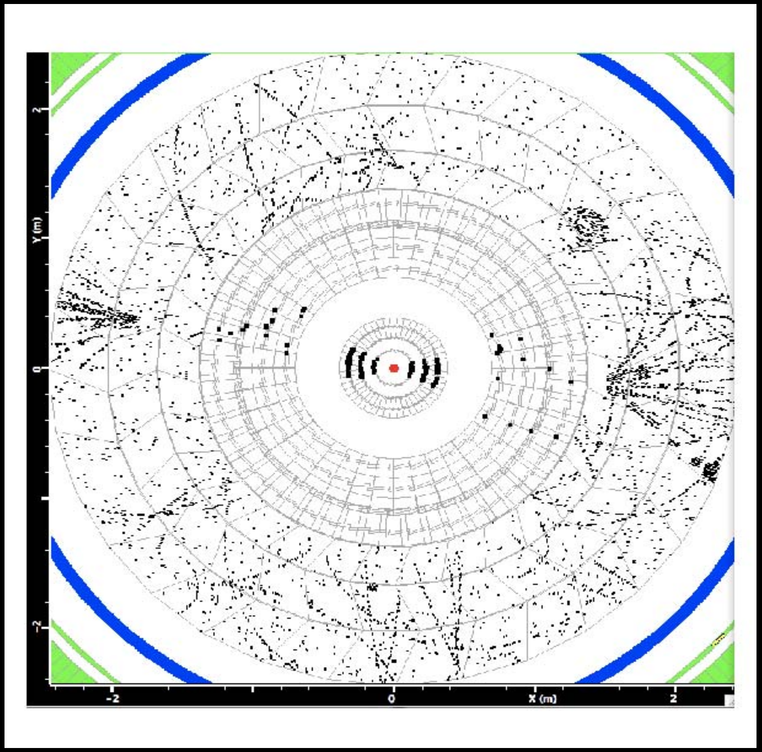


ATHENA output for this event



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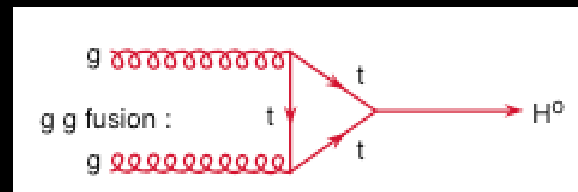
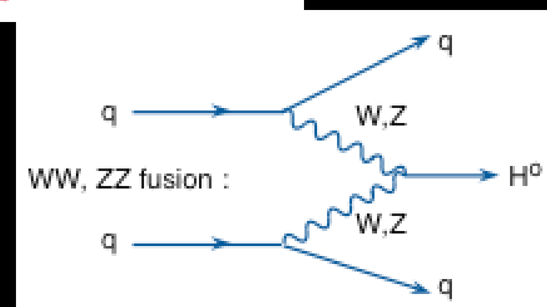
MC Production Channels

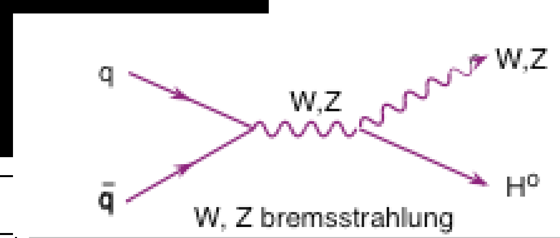
- **Higgs production mechanisms (PYTHIA)**
  - **Gluon fusion**



  - **Vector Boson Production**



  - **WH Production**



Production Channel	Cross Section (nb)
Gluon Fusion	1.537
Vector Boson Fusion	$1.08\ 10^{-1}$
W Higgs	$7.79\ 10^{-3}$

Cross Sections calculated by PYTHIA

Muon Triggers

- Level 1 muon triggers result from semileptonic decay of one of the b's or the π_v decays between end of HCal and before first muon trigger plane
- Level 2 muon trigger has two algorithms: muFast and muComb and both reject m's from displaced vertices
- Triggers are MU06, MU20 and 2MU06 (CSC-06 trigger menu)

	Level 1		
	MU06	MU20	2MU06
Gluon Fusion	30.3±0.3%	16.7±0.2%	16.5±0.2%
Vector Boson Fusion	36.7±0.3%	22.9±0.2%	22.0±0.2%
W Higgs	39.1±0.3%	26.5±0.2%	20.8±0.2%
Z′	60.0±0.3%	41.0±0.3%	36.8±0.3%

	Combined Level 1 and 2		
	mu6l	mu6	mu20
Gluon Fusion	2.21±0.07%	1.34±0.05%	0.30±0.03%
Vector Boson Fusion	3.96±0.09%	2.77±0.07%	0.70±0.04%
W Higgs	13.3±0.2%	11.7±0.2%	7.7±0.1%
Z′	4.4±0.1%	3.10±0.07%	0.84±0.04%

Level 1 efficiencies are reasonable but the Level 2 triggers requirement of a connection to the IP reduces the efficiency to an impossibly small value

$W \rightarrow \mu$ Branching Fraction is ~10% which accounts for the higher Level2 acceptance for W-higgs production

Jet Triggers

- For level 1 we require events pass logical OR of J80, 2J55 and 3J35 as defined in CSC-06 menu
  - Here Jnn refers to Jet with energy greater than nn GeV, which is convention used in release 13
  - Trigger tables for 10^{33} $cm^{-2}s^{-1}$ still being refined
- Level 1 efficiency will depend on the production mechanism and the event final states
  - gg events have no extra jets, while VB and WH both have other jets

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	Level 1			
	J80	2J55	3J35	Total
Gluon Fusion	13.1±0.2%	8.3±0.1%	5.0±0.1%	16.4±0.2%
Vector Boson Fusion	43.7±0.3%	29.0±0.2%	18.7±0.2%	51.1±0.3%
W Higgs	33.5±0.3%	22.5±0.2%	20.0±0.2%	41.1±0.3%
Z'	72.1±0.4%	49.3±0.3%	33.9±0.3%	85.3±0.4%

Total has overlap removed

Jet Triggers

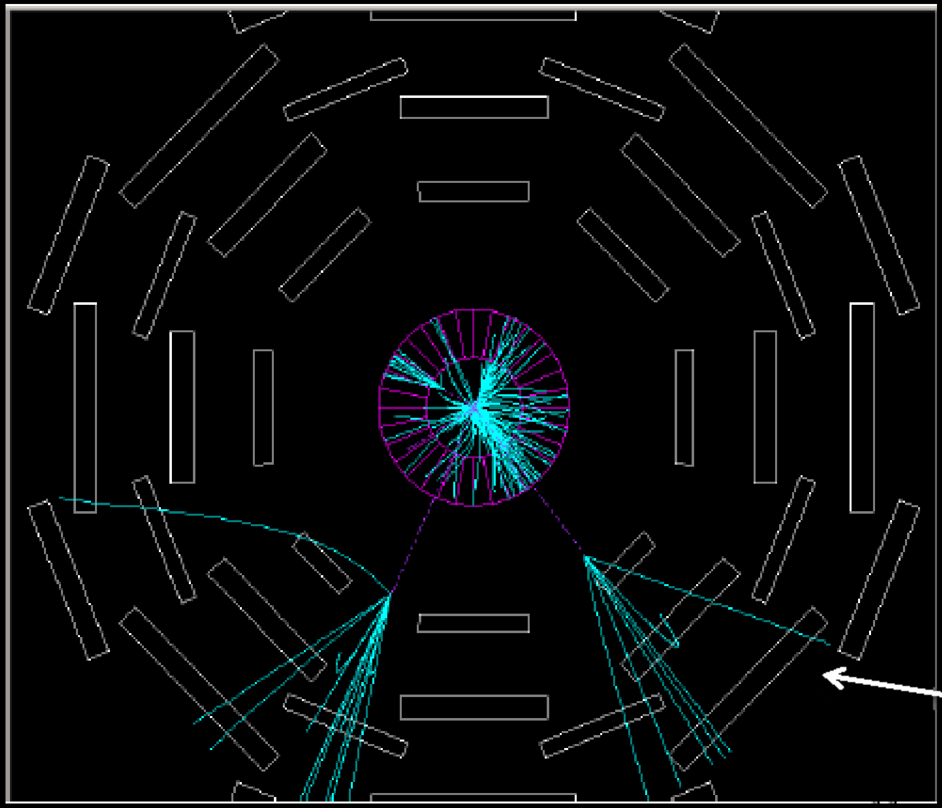
- **Level 2 events must pass Level 1 trigger and the logical OR of: J160, 2J120 and 3J65**
  - Triggers chosen because for 10^{32} running they were not pre-scaled and full table not available when analysis was done
- **The combined Level one and two triggers for Level 1 and 2 muon and jet triggers**

	Level 1 Triggers			Combined Level 1 and 2 Triggers		
	Jet	Muon	Total	Jet	Muon	Total
Gluon Fusion	16.4±0.2%	30.3±0.3%	35.8±0.3%	4.4±0.1%	2.21±0.07%	4.7±0.1%
Vector Boson Fusion	51.1±0.3%	36.7±0.3%	66.2±0.4%	17.4±0.2%	3.96±0.09%	17.9±0.2%
W Higgs	41.1±0.3%	39.1±0.3%	59.8±0.3%	13.1±0.2%	13.3±0.2%	20.0±0.2%
Z'	85.3±0.4%	60.0±0.3%	85.3±0.4%	53.6±0.3%	4.4±0.1%	53.9±0.3%

From these results it is clear that other trigger paths are needed for the Higgs

The Z' which has many jets with higher average energy has an acceptable Level2 pass rate

Decay's in the Muon System



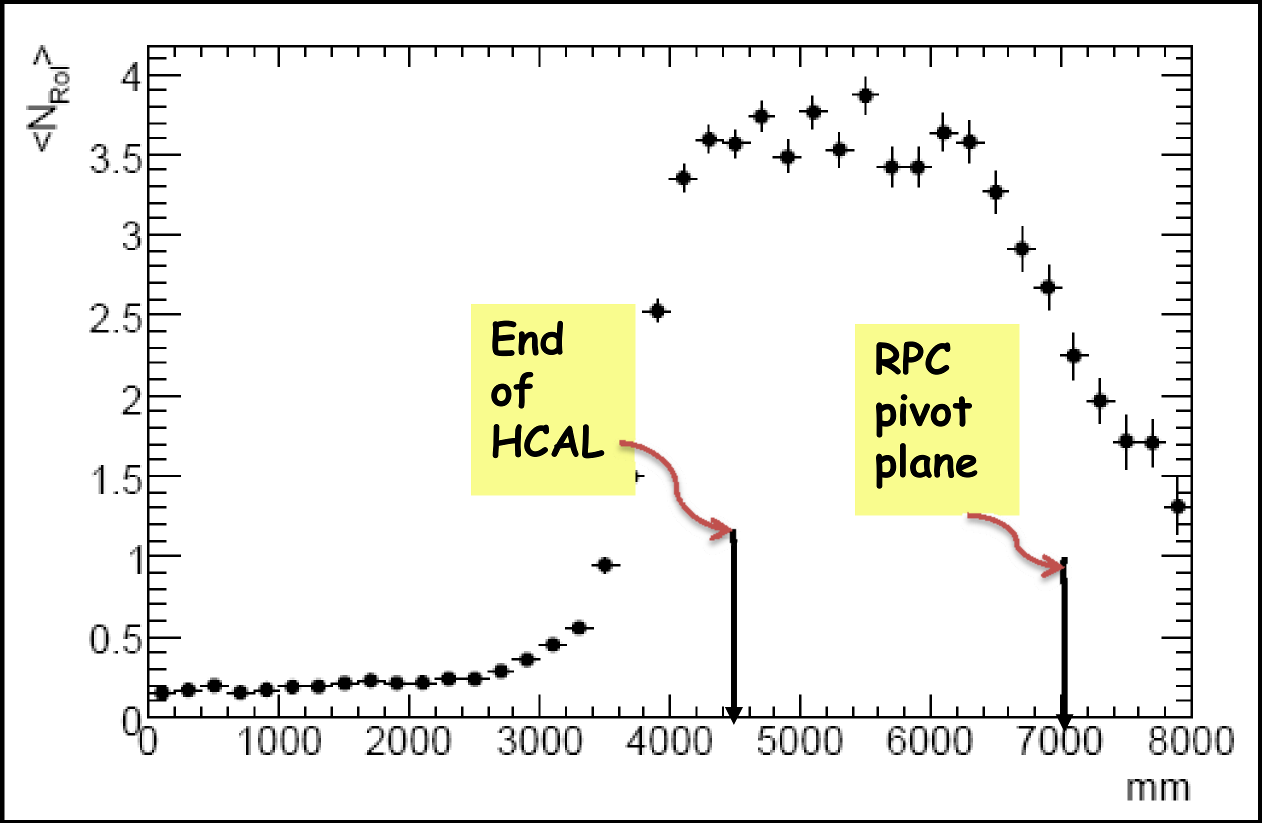
Trigger object

muROI clusters

Get muon ROI clusters in a narrow ηϕ cone

HVMC Z' event shown in event display we use to study characteristics of HV event

Average μROI's vs. X-decay point

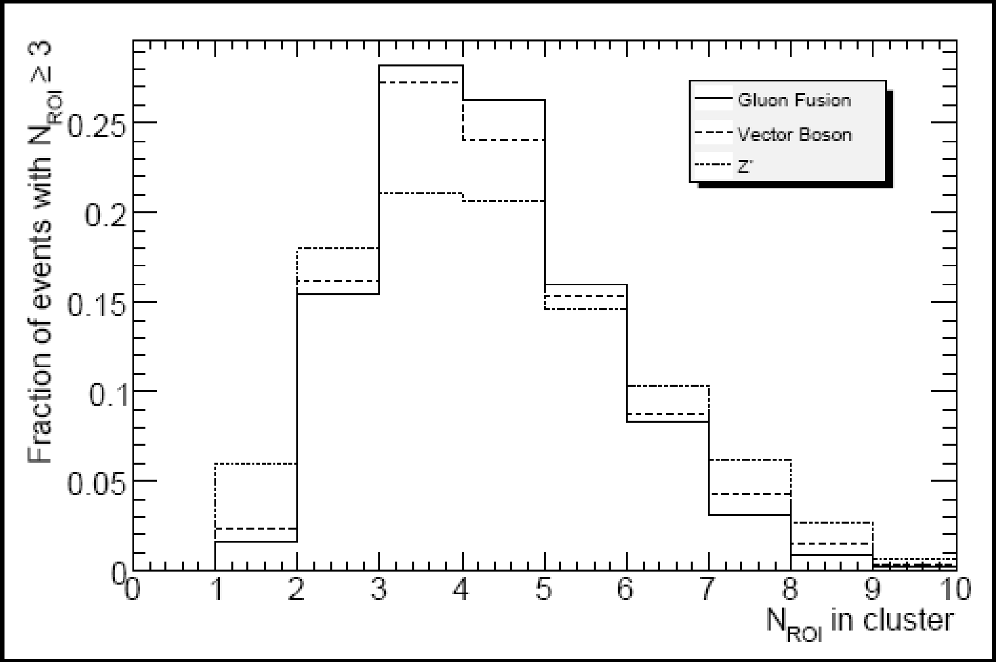


Average number of Level1 μ ROI's with $P_T > 6$ GeV in a $\Delta R=0.4$ cone centered around the π_v direction

Higgs gg
Barrel only

Muon RoI Trigger

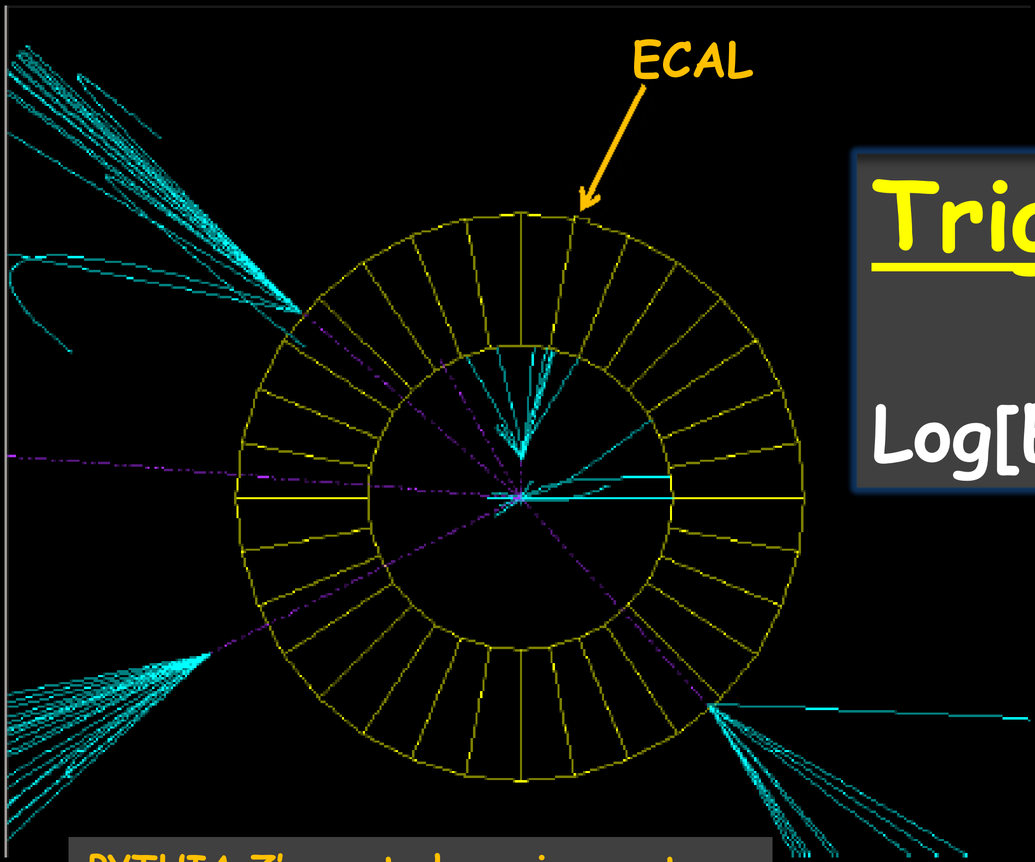
- About 80% of events with $N_{RoI} \geq 3$ have those RoI's in a cone of $\Delta R = 0.4$ about direction of the π_v line of flight



This makes it *possible to trigger at Level 2 on* a cluster of 3 or more muon RoI's with no further processing (muFast/muComb)

- The potential problem with this trigger is the QCD di-jet background, which has very large cross section and we will return to this issue

Decay's in Calorimeter



PYTHIA Z' event shown in event display used to study characteristics of HV event

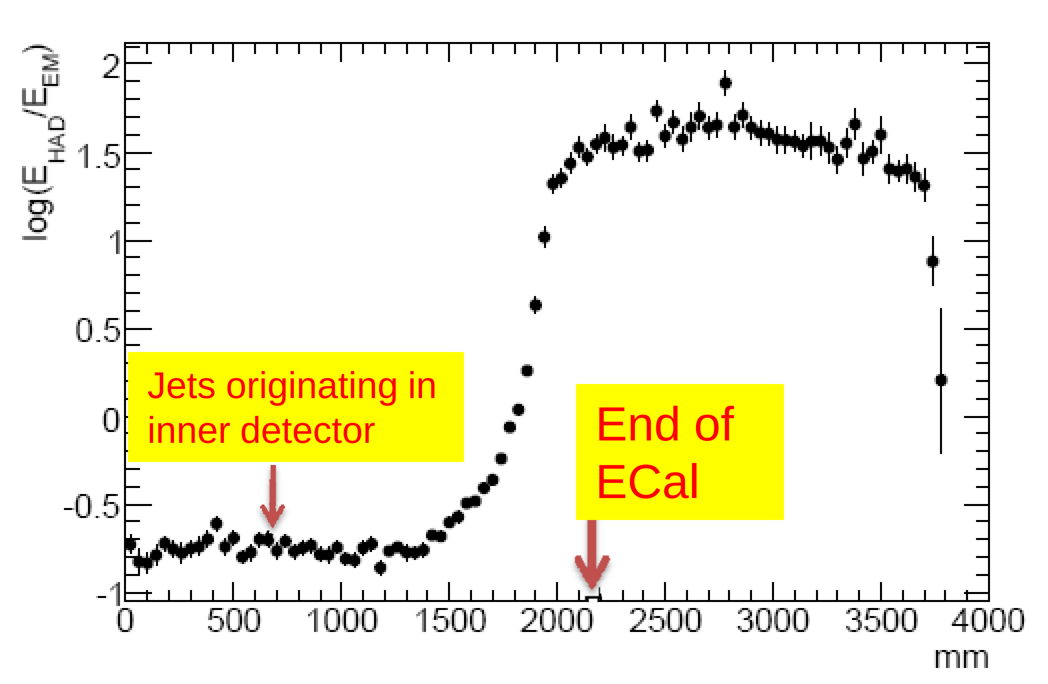
Trigger object

$\text{Log}[E_{HAD}/E_{EM}]$ for jets

Decays at end of ECAL result in non standard sharing of jet energy between HCAL and ECAL

Decays in the Calorimeters

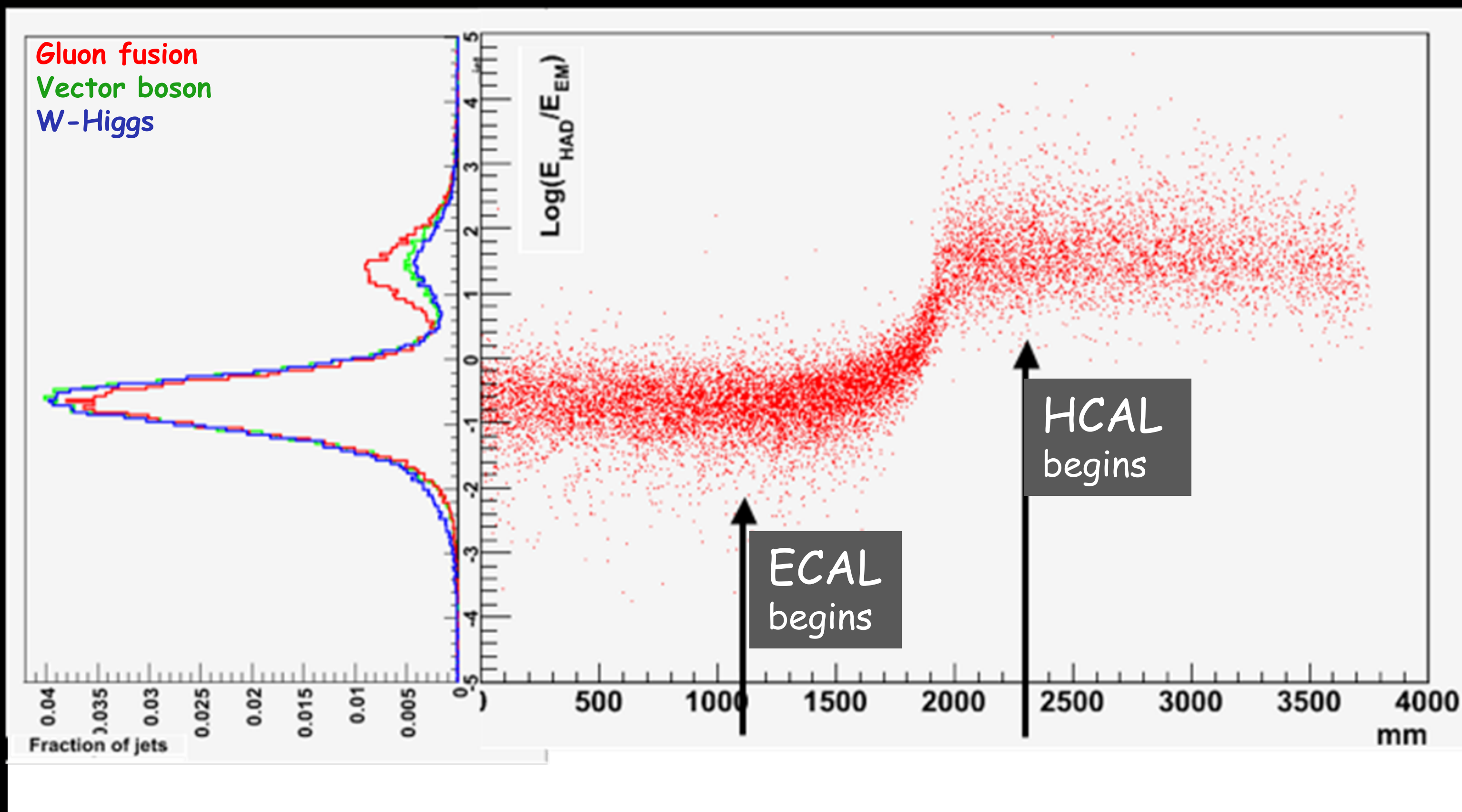
- Decays in the Calorimeters characterized by jets with few or no tracks and a non-usual energy distribution in the calorimeters
  - Decays at end of Ecal or beginning of Hcal will have very large ration of E_{HAD}/E_{EM} as shown below



The log(E_{HAD}/E_{EM}) changes from the usual negative to positive value

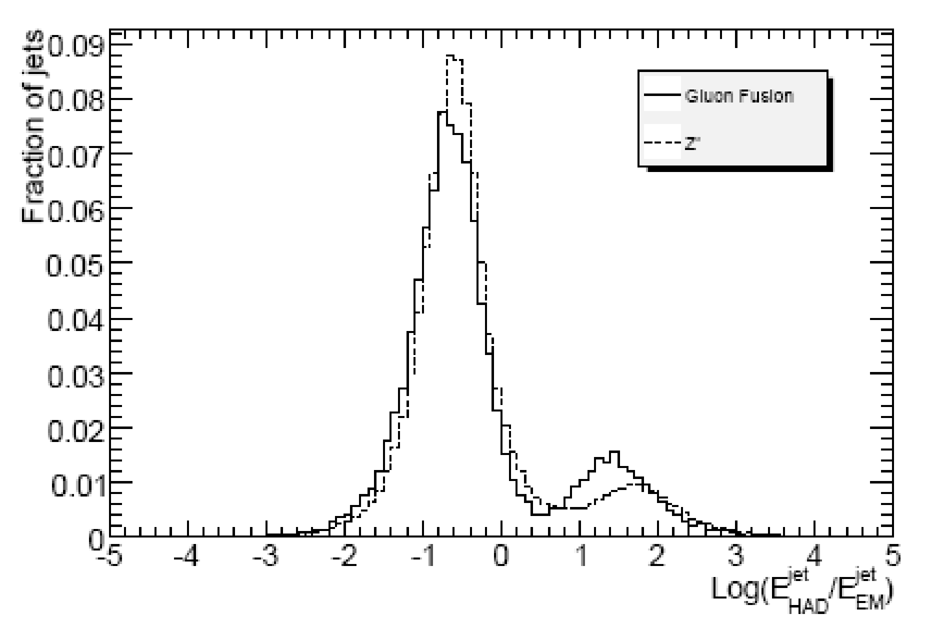
Π_v decay point

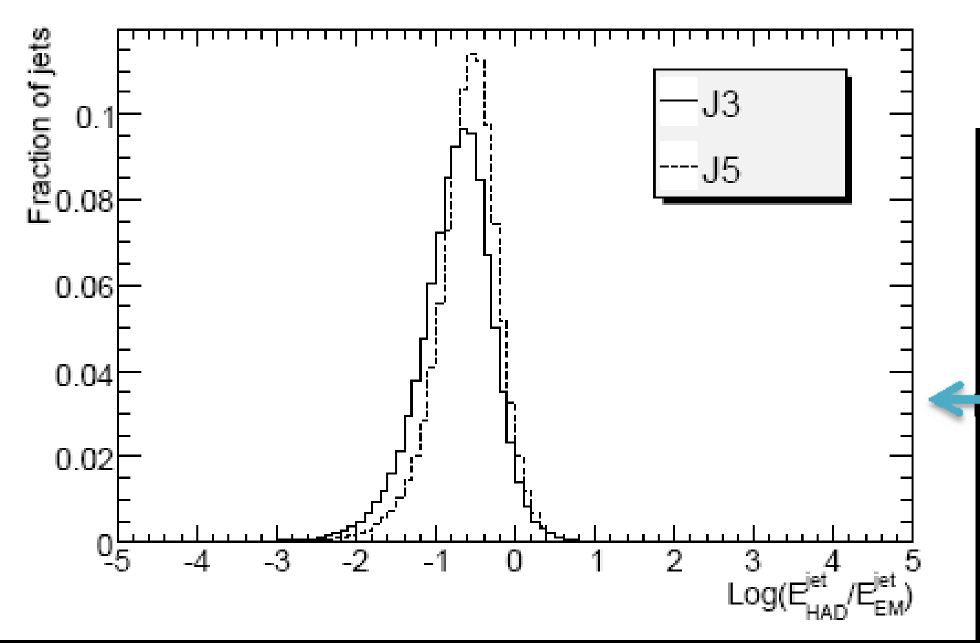
E_{HAD}/E_{EM} verses π_v decay point



Decays in the Calorimeter

Events with π_v decays two nearly distinct distributions
- peak at ~ -0.5 from IP jets
- Peak at about + 1.5 from π_v's

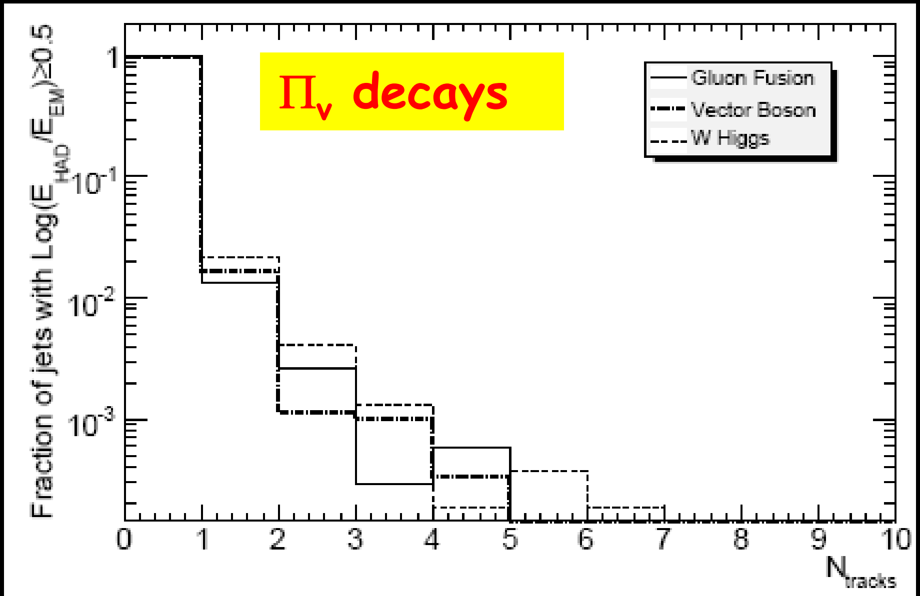


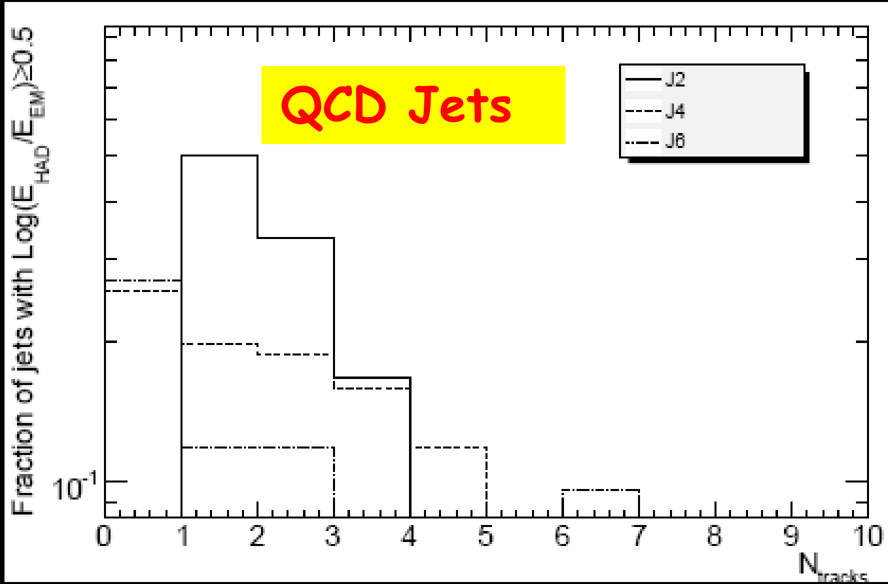


Distribution QCD di-Jets with origin at the IP

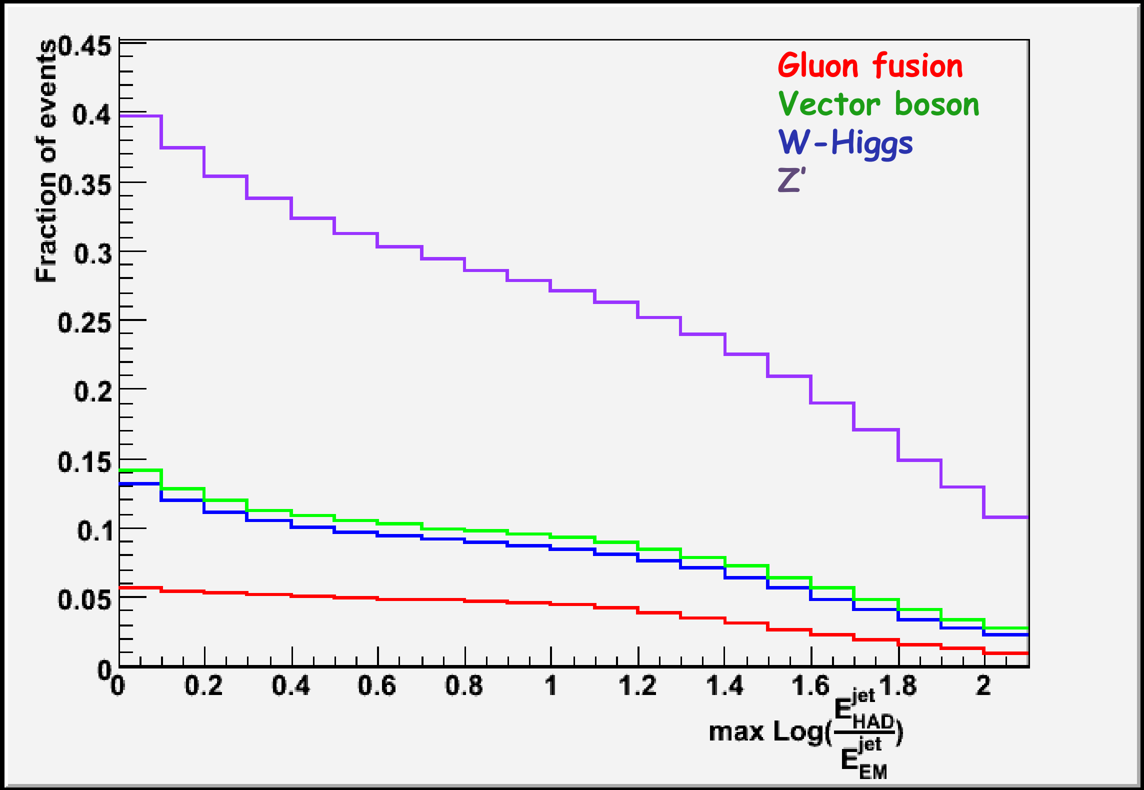
Decays in the Calorimeter

- Jets with $\log_{10}(E_{HAD}/E_{EM}) \geq 0.5$ and $-2.5 < \eta < 2.5$ (inner tracker coverage) have 95% of jets with no tracks in a 0.2 x 0.2 region of $(\delta\eta \,\xi\, \delta\phi)$ centered on the jet RoI
- For the same criteria less than 25% of SM QCD jets have 0 reconstructed tracks





Fraction of Events vs. Log[E_{HAD}/E_{EM}]

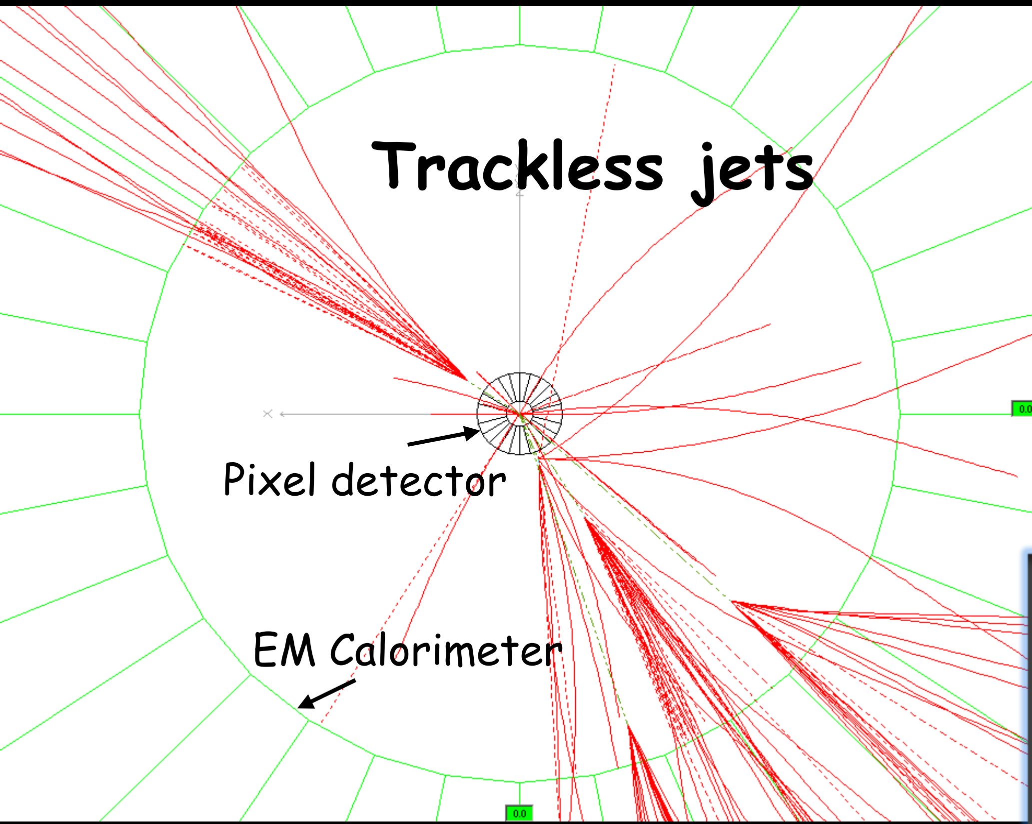


Fraction of Events that survive cut on max Log[E_{HAD}/E_{EM}] and have no L2 track

max Log[E_{HAD}/E_{EM}] is the largest obtained for any jet in each event

The distribution is relatively flat in the region 0.4 < Log[E_{HAD}/E_{EM}] < 1

Decays in the Inner Detector



Std L2 tracking algorithms are not optimized for decays beyond the pixel layers resulting in low efficiency vertex reconstruction for these events

Trigger object

Jets with no charged track connecting to IP; a possibility especially in combination with another trigger object

HVMC Z' event shown in event display used to study characteristics of HV event

Inner Tracker

- Very low efficiency for finding displaced vertices beyond the pixel layers because current tracking strategies forms track seeds requiring at least three hits in the pixel layers
  - Suggests using trackless jet may be a way to proceed
  - SM jets are prompt so have hits in pixel layers
- We find the QCD di-jet SM background for events with trackless jets to be of order 200 nb after Level 1
  - To suppress this background we require at Level 2 that our trackless jets contain at least one charged particle identified as a muon RoI at Level 1
  - In SM jets muons will leave track in inner tracker, but in the displaced decays the muon misses the innermost tracking elements and has no reconstruct able track

Performance of New Trigger Objects

- The performance of the dedicated triggers (Muon RoI, E_{HAD}/E_{EM} and Trackless jets with a muon) significantly improve our acceptance for detecting displaced vertices

	$\log_{10}(E^{jet}_{HAD}/E^{jet}_{EM})$ trigger	Trackless Jet with a muon	Muon RoI cluster	Total pass HV triggers[11)]	Total pass all triggers[12)]
Gluon Fusion	5.0±0.1%	3.8±0.1%	9.0±0.1%	15.7±0.2%	18.5±0.2%
Vector Boson Fusion	8.5±0.1%	6.3±0.1%	12.8±0.1%	24.3±0.2%	35.2±0.3%
W Higgs	7.3±0.1%	5.1±0.1%	10.7±0.1%	20.6±0.2%	34.2±0.3%
Z'	19.3±0.2%	32.2±0.3%	13.8±0.2%	46.4±0.3%	67.3±0.4%

- The total pass rate is the sum of all triggers with overlap removed

SM Backgrounds

- **OCD di-jets**

SM dijet sample	N(Events)	Energy Range (GeV)	cross section (nb)
J2	152000	35 - 70	96,300
J3	121500	70 - 140	6135
J4	160000	140 - 280	316.8
J5	112000	280 - 560	12.47
J6	208000	560 - 1120	0.3445

- **SM muon enriched di-jets**

SM muon enhanced dijet sample	N(Events)	Energy Range (GeV)	cross section (nb)
$J2\mu$	90000	35 - 70	1510
$J3\mu$	95000	70 - 140	156
$J4\mu$	181000	140 - 280	11.7

Very large cross sections require significant rejection factors

Background Acceptances

- **Jn cross sections accepted at Level 2 using signature based triggers**

	$\log_{10}(E^{jet}_{HAD}/E^{jet}_{EM})$ trigger	Trackless Jet with a muon	Muon RoI cluster	Total σ [13)] (nb)
J2	$0^{+1.9}_{-0}$	1.3 ± 0.9	3.2 ± 1.4	$4.4^{+2.5}_{-1.7}$
J3	0.15 ± 0.9	0.8 ± 0.2	0.2 ± 0.1	1.1 ± 0.2
J4	0.012 ± 0.005	0.09 ± 0.01	0.05 ± 0.01	0.15 ± 0.02
J5	$(2.2\pm1.6)\ 10^{-4}$	$(3.7\pm0.7)\ 10^{-3}$	$(9\pm1)\ 10^{-3}$	0.013 ± 0.001
J6	$(3.3\pm0.7)\ 10^{-5}$	$(1.8\pm0.2)\ 10^{-4}$	$(8.0\pm0.4)\ 10^{-4}$	$(1.02\pm0.04)\ 10^{-3}$
J2μ	$0^{+0.05}_{-0}$	1.2 ± 0.1	0.41 ± 0.08	1.6 ± 0.1
J3μ	$0^{+0.005}_{-0}$	0.44 ± 0.03	0.07 ± 0.01	0.51 ± 0.03
J4μ	$(2.5\pm1.3)\ 10^{-4}$	0.032 ± 0.002	$(8.5\pm0.8)\ 10^{-3}$	0.041 ± 0.002

One nb corresponds to 1 Hz 10^{33} cm^{-2}s^{-2}

Implementation of L2 Triggers

- We have developed Level 2 trigger algorithms in frame work of the ATLAS on line trigger system to implement these signature based triggers
  - Have evaluated these using RDO (Raw Data Objects) output of ATHENA for Z' and Higgs simulations
  - Acceptance rates agree well with those discussed using AOD output
- RoI Triggers

SM backgrounds consistent with results obtained with AOD data

	Level 1 (%)	Level 2 (%)	
	$2MU06$	Cluster $N_{RoI} \geq 3$	Isolation
Gluon Fusion	16.4 ± 0.3	8.11 ± 0.2	8.0 ± 0.2
W Higgs	20.6 ± 0.3	9.9 ± 0.3	9.3 ± 0.3
Z'	35.9 ± 0.4	15.2 ± 0.3	13.4 ± 0.3

- Jet energy trigger

Process	Events	acceptance@10^{31}	acceptance@10^{33}
Gluon Fusion	12500	$(5.27 \pm 0.2)\%$	$(6.00 \pm 0.2)\%$
W Higgs	15000	$(8.21 \pm 0.2)\%$	$(8.35 \pm 0.23)\%$
Z'	180000	$(20.96 \pm 0.30)\%$	$(20.97 \pm 0.30)\%$

Implementation of L2 Triggers

- **Goal is to implement the muon RoI and Calorimeter energy ratio trigger in release 14**
- **Currently beginning an official MC run in release 13.0.40 or possible release 14 (the MC bosses will decide)**
- **We will use this official MC to validate these triggers and request inclusion in the trigger table for this years running (how's that for optimism)**

Summary and Future Work

- We have shown that long-lived particles from decays of neural particles in the detector volume to jet-pairs can be selected using a combination of signature driven trigger objects
- We have a preliminary study of QCD di-jet backgrounds with encouraging results
- An ATLAS note is currents in the ATLAS referee black hole
- Future work planned
  - Improve L2 triggers to optimize signal and SM background rejection
  - Implement and test the new L2 trigger algorithms
  - Work on L2 tracking for decays beyond pixel layers
  - Develop and test an Event Filter
  - Off line analysis to isolate events
  - We have begun an effort to include SUSY LSP and other states as portals to Hidden Valley – many of these decays are well covered by the current signature driven triggers