LPC Lecture 1
Long-Lived Particles and Other Oddities from Hidden Sectors

Echoes of a hidden valley at hadron colliders.
M.J.S. & K. M. Zurek , Phys.Lett.B651:374-379,2007, hep-ph/0604261
Discovering the Higgs through highly-displaced vertices.
M.J.S. & K. M. Zurek , hep-ph/0605193
Possible effects of a hidden valley on supersymmetric phenomenology.
M.J.S., hep-ph/0607160
Phenomenology of hidden valleys at hadron colliders.
Han, Si, Zurek & M.J.S., arXiv/0712.2041
Why Unparticle models with mass gaps are examples of hidden valleys.
M.J.S., arXiv/0801.0629
On the phenomenology of hidden valleys with heavy flavor
M.J.S. arXiv/0805….
Several papers in preparation…
See also Ciapetti, Lubatti, Dionisi…M.J.S. ATLAS note

Matthew Strassler
Rutgers University

Plan of the Talk

- What's a hidden valley, and why should we care?

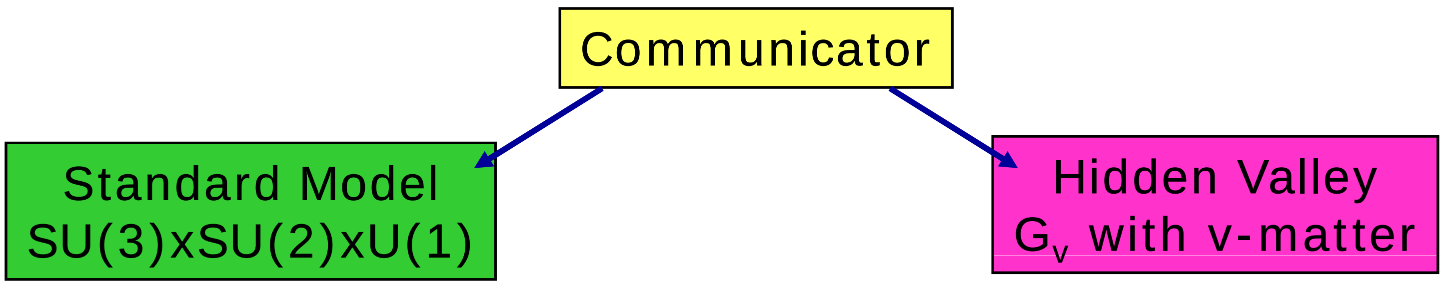
- Basic properties of any hidden valley model
  - New neutral particles, possibly light
  - Various decay final states, often high multiplicity
  - Long lifetimes possible

- Sample of experimental signals, with illustrations & commentary
  - Long-lived particles
  - Unusual signatures of various types

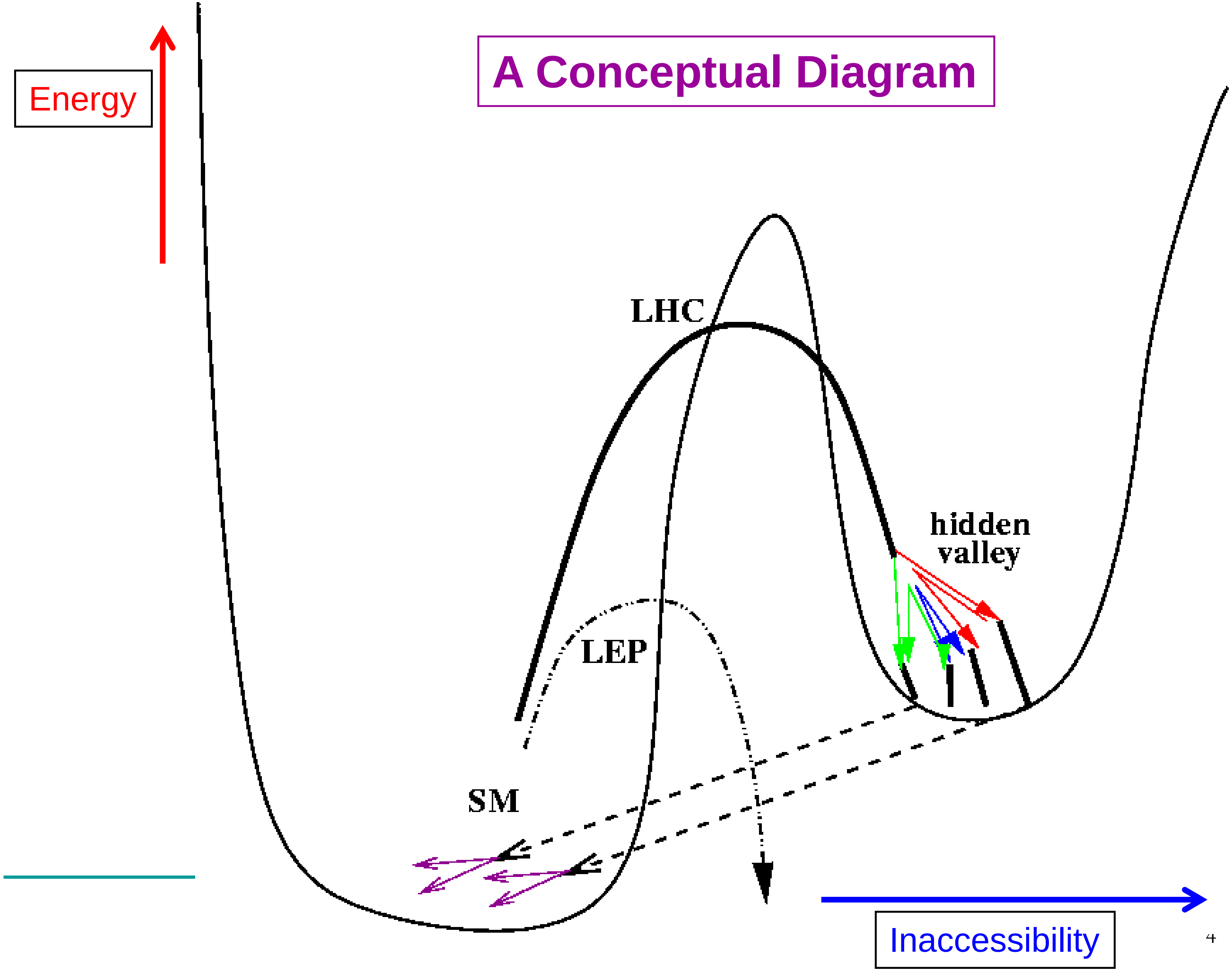
Hidden Valley Scenario (w/ K. Zurek)

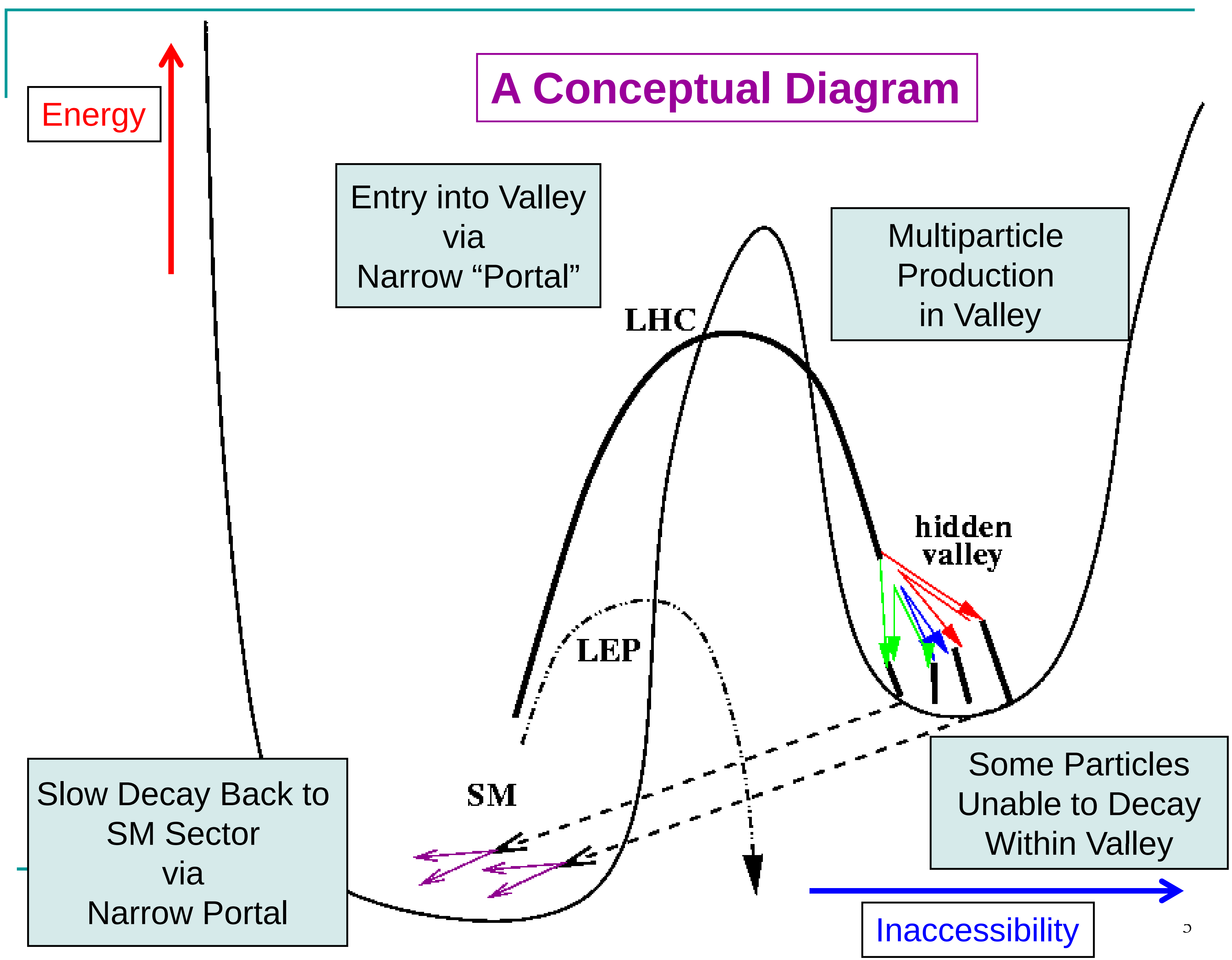
hep-ph/0604261

- A scenario:
  - **A Very Large Meta-Class of Models**
- Basic minimal structure



A Conceptual Diagram




A Conceptual Diagram
Energy
Entry into Valley via Narrow "Portal"
LHC
Multiparticle Production in Valley
hidden valley
LEP
SM
Slow Decay Back to SM Sector via Narrow Portal
Some Particles Unable to Decay Within Valley
Inaccessibility

Another way to think about it…

A hidden sector serves as a processor:
it turns energy into particles more efficiently than we are used to

- Energy from pp collision enters into new sector
- The energy is transformed into multiple particles through the dynamics of the new sector
- Some of these particles decay back to standard model particle pairs, triplets, etc…

The huge variety of hidden sectors
generates signatures unfamiliar, wildly variable, even unpredictable

These can cut against the grain of our
analysis techniques, reconstruction software, and even our triggering schemes

The Motivation

- Why the Hidden Valley Scenario?
  - Extra sectors often appear in string theory, SUSY breaking, etc.
  - Assumption that hidden sector is inaccessible is a theoretical bias
  - Dark matter is … dark!

- Not mutually exclusive
  - Can coexist with any solution to the hierarchy problem
    - SUSY, technicolor, little Higgs, RS, ADD, etc.
  - but in some cases **strongly alters** its phenomenology!

- The challenge of the Hidden Valley Scenario
  - Weak experimental constraints!
  - Vast array of possibilities to be prepared for
  - Many of the signals pose new challenges for LHC experiments
  - Many of the models pose technical challenges for theorists

Why such weak constraints?

- **What does LEP constrain?**
  - Particles below 100 GeV that carry electric charge
    - And are stable or decay with significant energy release
    - Caution regarding degenerate charged-neutral pairs
  - New light bosons that mix with the Z boson at > 10^{-3} level
  - Invisible decay modes for Z with Br > 10^{-4} (?)
  - Exotic decay modes of Z with Br > $10^{-(6–7)}$

- **But no constraints on:**
  - Neutral particles of any mass with small couplings to Z, photon
    - In particular, particles that carry no weak, electric, or color charge
  - Electrically charged particles with mass above 100 GeV
  - Colored particles with mass above 100 GeV (below?)

Why such weak constraints?

- **What does LEP constrain indirectly?**
  - Particles that appear singly and unsuppressed in one-loop diagrams
  - New heavy bosons that mix with the Z boson at > 10^{-3} level
  - Particles that get their masses mainly from the Higgs boson

- **But no constraints on:**
  - Particles that appear only in two-loop diagrams
  - Particles that appear in one-loop diagrams suppressed by small mixing
  - Particles that couple weakly to the Higgs and get their masses in some other way

Hidden sectors can easily evade all these constraints…

Why such weak constraints?

- **What do BABAR, BELLE constrain?** *(roughly!)*
  - Particles below 10 GeV that can be emitted from bottomonium
    - New vector bosons that mix with the photon, Z boson at > 10^{-3} level
    - New scalar bosons that couple with > Higgs-coupling strength
- **What do CDF, D0 constrain?**
  - Colored particles below 200 GeV that can decay to leptons/photons
  - Colored particles below 150 GeV (?) that can decay to jets only
  - Vector bosons that mix with photon/Z at > 10^{-3} level (DY)
- **But no constraints on:**
  - Neutral particles of any mass with small couplings to Z, photon
    - In particular, particles that carry no weak, electric, or color charge
  - Electrically charged particles with mass above 100 GeV
  - Colored particles with mass above 150 GeV (and below if exotic)

Cosmology and Astrophysics?

Allowed: Dark Sectors with GeV-scale, interacting, short-lived particles

- No stellar astrophysics can make particles with mass > 100 MeV

- No cosmological observable affected by particles living << 1 sec
- Particles with lifetimes >> 1 sec annihilate efficiently if they
  - Interact strongly enough, and
  - Can annihilate/convert into something with a lifetime << 1 sec

Also: Dark Sectors can easily be responsible for Dark Matter

- can easily produce dark matter remnants with reasonable abundance
  - "WIMP miracle" vs. "WIMPless miracle" J. Feng et al.
  - Recent dark matter model of Arkani-Hamed, Finkbeiner, Weiner, etc.

The Challenge

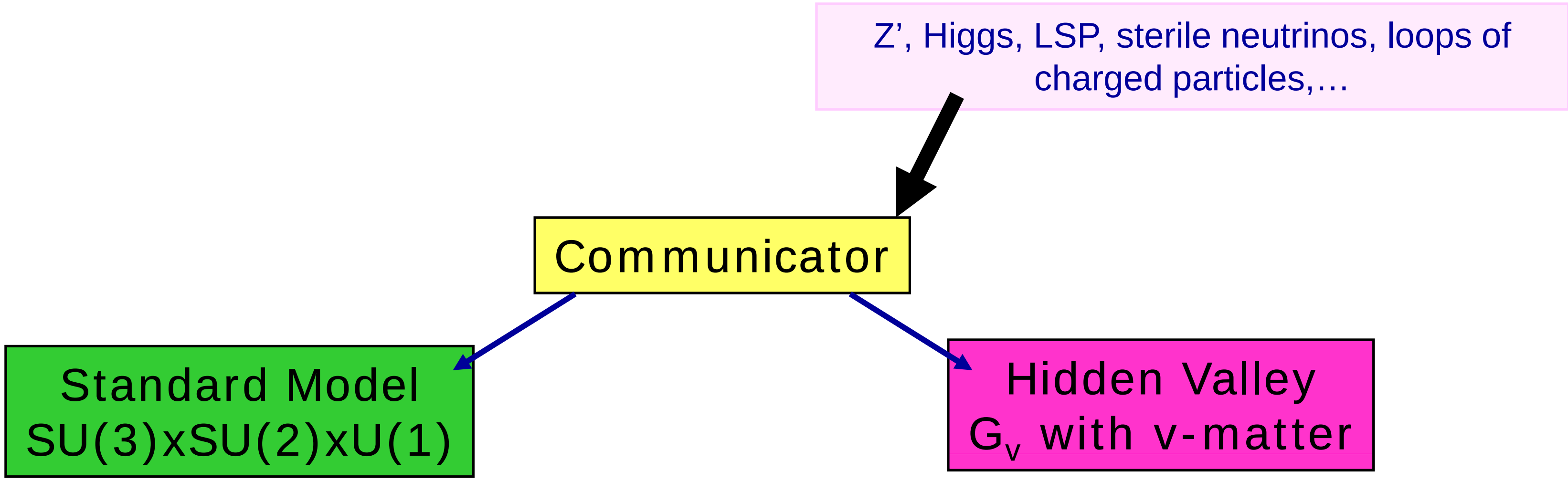
- No Constraints ➔ Vast Continent of Hidden Valleys
  ➔ Many New Experimental Signatures

- **How can we deal with this huge range of novel signatures?**

- Theoretical approach:
  - Find generic predictions of very large classes of models within HV Scenario
  - Ground our investigations in fully or largely predictive models
  - Help the experimental groups develop strategies for broad searches

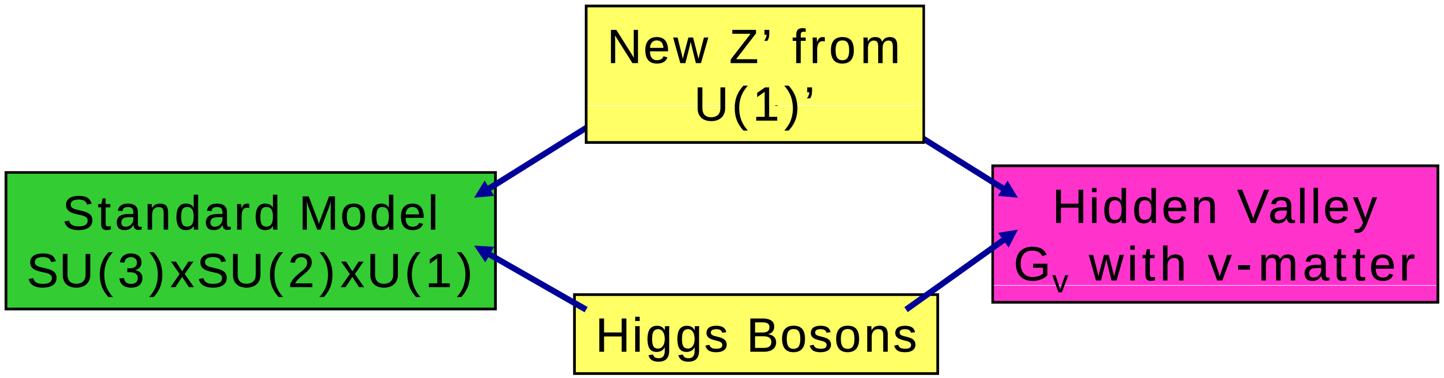
- Things to do experimentally:
  - Try to classify the rapidly expanding list of signatures
  - Improve triggering on exotic signatures
  - Carefully reconsider reconstruction techniques ←
  - Develop new, efficient, robust analysis strategies ←

Hidden Valley Models (w/ K. Zurek)



Communicators

- Note that the communicator for production need not be the communicator for the decays…

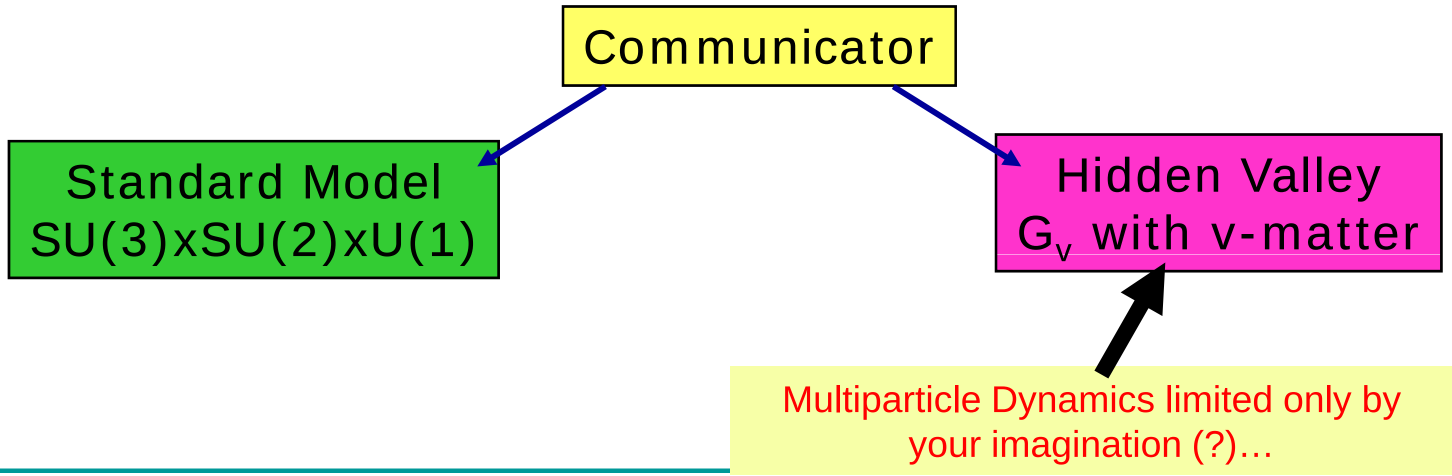


Hidden Valley Models (w/ K. Zurek)

Vast array of possible v-sectors…

QCD-like theory with F flavors and N colors
QCD-like theory with only heavy quarks
QCD-like theory with adjoint quarks
Pure glue theory
UV-fixed point → confining
N=4 SUSY Conformal → N=1
RS throat

Almost-supersymmetric N=1 model
Seiberg duality cascade
KS throat
Quiver gauge theory
Remnant from SUSY breaking
Partially higgsed SU(N) theory



General Predictions of HV Scenario

hep-ph/0604261

- New neutral resonances
  - Maybe 1, maybe 10 new resonances to find
  - Many possible decay modes
    - Pairs of SM particles (quarks, leptons, gluons all possible; b quarks common)
    - Triplets, quartets of SM particles…
  - Often boosted in production; jet substructure key observable
- Long-lived resonances
  - Often large missing energy
  - Displaced vertices common (possibly 1 or 2, possibly >10 per event)
    - … in any part of the detector
    - Great opportunity for LHCb if rates high
    - Problem for ATLAS/CMS trigger if event energy is low
- Multiparticle production with unusual clustering
  - Exceptionally busy final states possible
    - 6-20 quarks/leptons typical in certain processes
    - up to 60 quarks/leptons/gluons in some cases
  - Breakdown of correspondence of measured jets to partons
  - Very large fluctuations in appearance of events

Common Predictions of HV Scenario

hep-ph/0604261
hep-ph/0605193

- Possible big effect on Higgs
  - H → XX, X decays displaced ➔ new discovery mode
    - *not unique to HV!!! Chang Fox Weiner 05 / Carpenter Kaplan Rhee 06*
  - H → XXX, XXXX, etc
    - *not unique to HV!!!*

- Big effect on SUSY, UED, Little Higgs – any theory w/ new global charge
  - LSP (or LKP or LTP) of our sector can decay to the valley LSP/LKP/LTP
    - Plus SM particles or
    - Plus v-particles which decay back to SM particles or
    - Plus both
  - Either the v-particles or the LSP/LKP/LTP may be long-lived
  - *Generalizes well known work from 90s [GMSB, Anomaly, Hidden Sector]*

hep-ph/0607160

Various possibilities to consider today

- Long-lived particles
  - Triggering, Reconstruction, Analysis?

- New di-lepton/di-photon resonances etc.
  - High boosts
  - High multiplicity, clustering
  - Complex event structure

- New di-tau, di-jet resonances etc.
  - Muons, tracks and MET
  - Jet substructure
  - High multiplicity, clustering
  - Soft particles from soft jets

- Entirely soft signals
  - Soft jets and leptons in jets
  - Soft photons

Long-lived particles

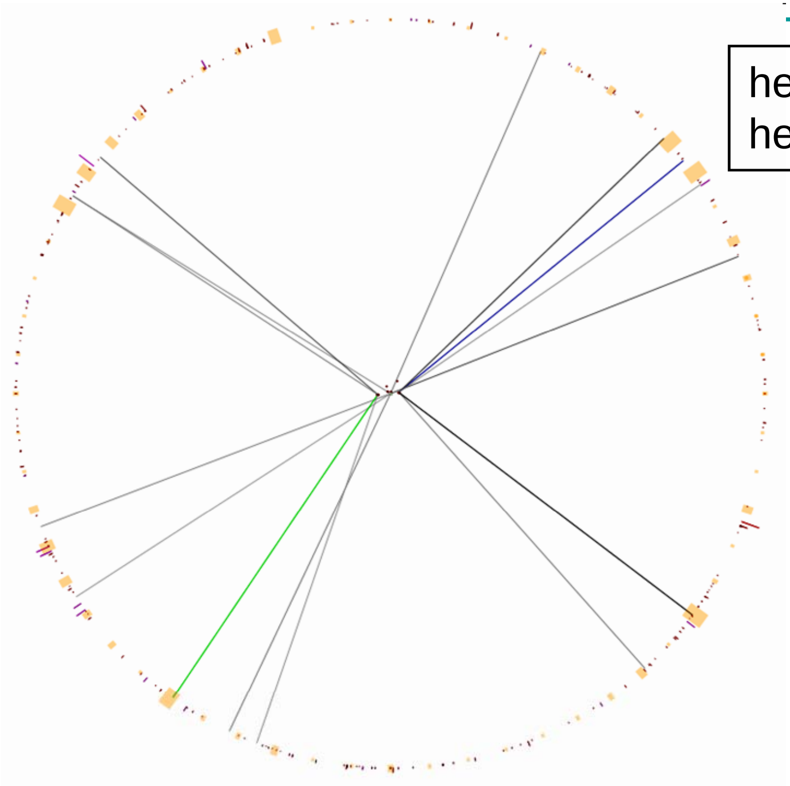
Lifetimes Long for Many Reasons

- Many ways to have long lifetime for v-particles
  - Light v-particle has little phase space
  - Heavy mass, weak coupling, or mixing of communicator
  - Loop factors in communicator mechanism
  - Approximate global symmetry in v-sector (e.g. vFCNCs)
  - Approximate global symmetry in SM sector
  - Etc.
- Multiple v-particles in each model → multiple lifetimes
- V-particle decays may easily be anywhere
  - prompt ($d < 0.1$ mm)
  - displaced ($0.1 \text{ mm} < d < 3$ cm)
  - highly displaced ($3 \text{ cm} < 10$ m)
  - outside detector (> 10 m)

Example #1: Higgs boson decay

Example #1: Higgs boson decay

- Higgs boson very sensitive to new sectors
  - True for light higgs, any CP-odd higgs
    - Weak coupling to b quarks
  - New interaction can easily generate new decay mode
    - Branching fraction can be 1, or .01, or .0001
    - Can cause substantial reduction in h → photons
  - Rare decays can be experimentally important
    - even for heavier Higgs
- Well-known in wide range of models
  - h → invisible (1980s)
  - h → 4 b's, 4 tau's (NMSSM : Dermisek and Gunion 2004)
  - Even h → 8 b's (Chang, Fox and Weiner 2005)



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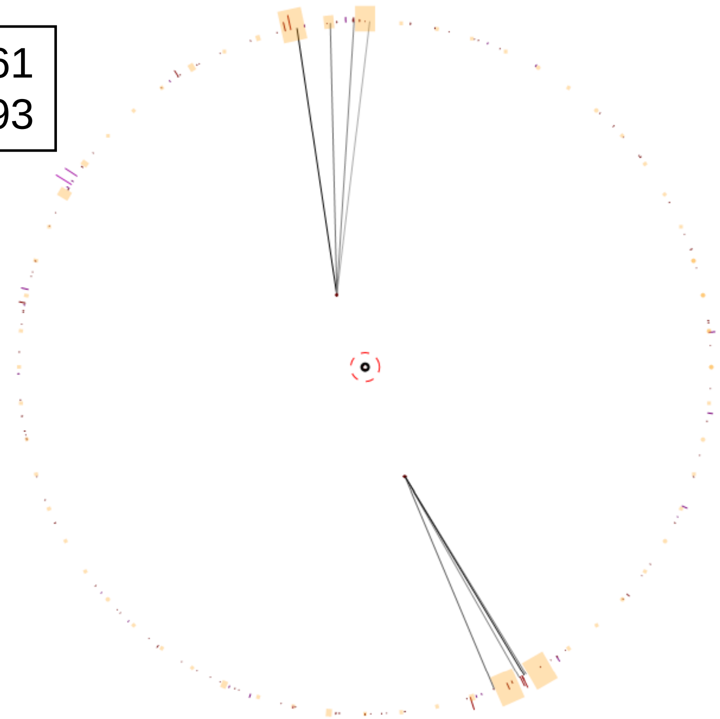
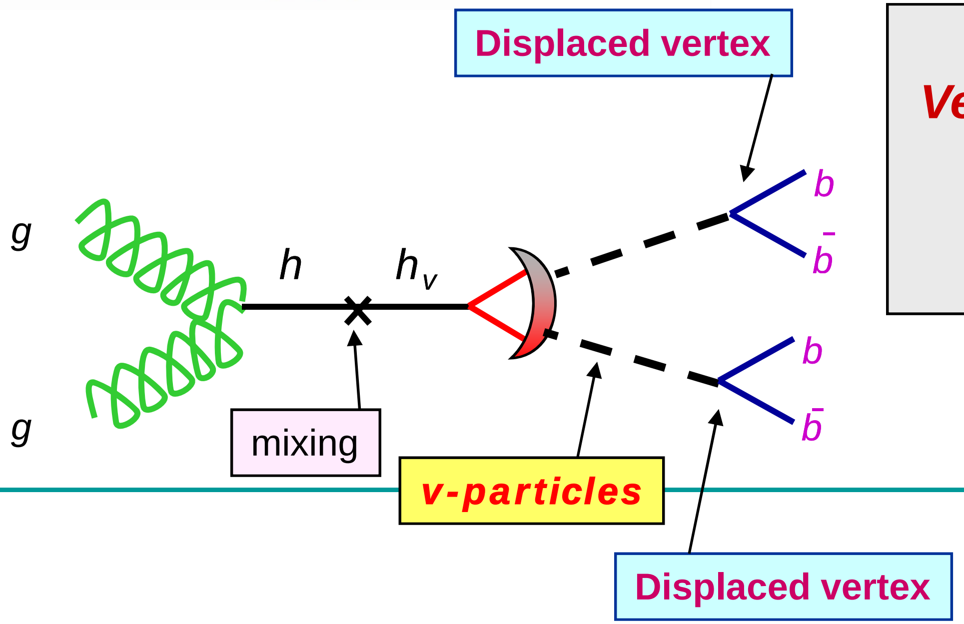
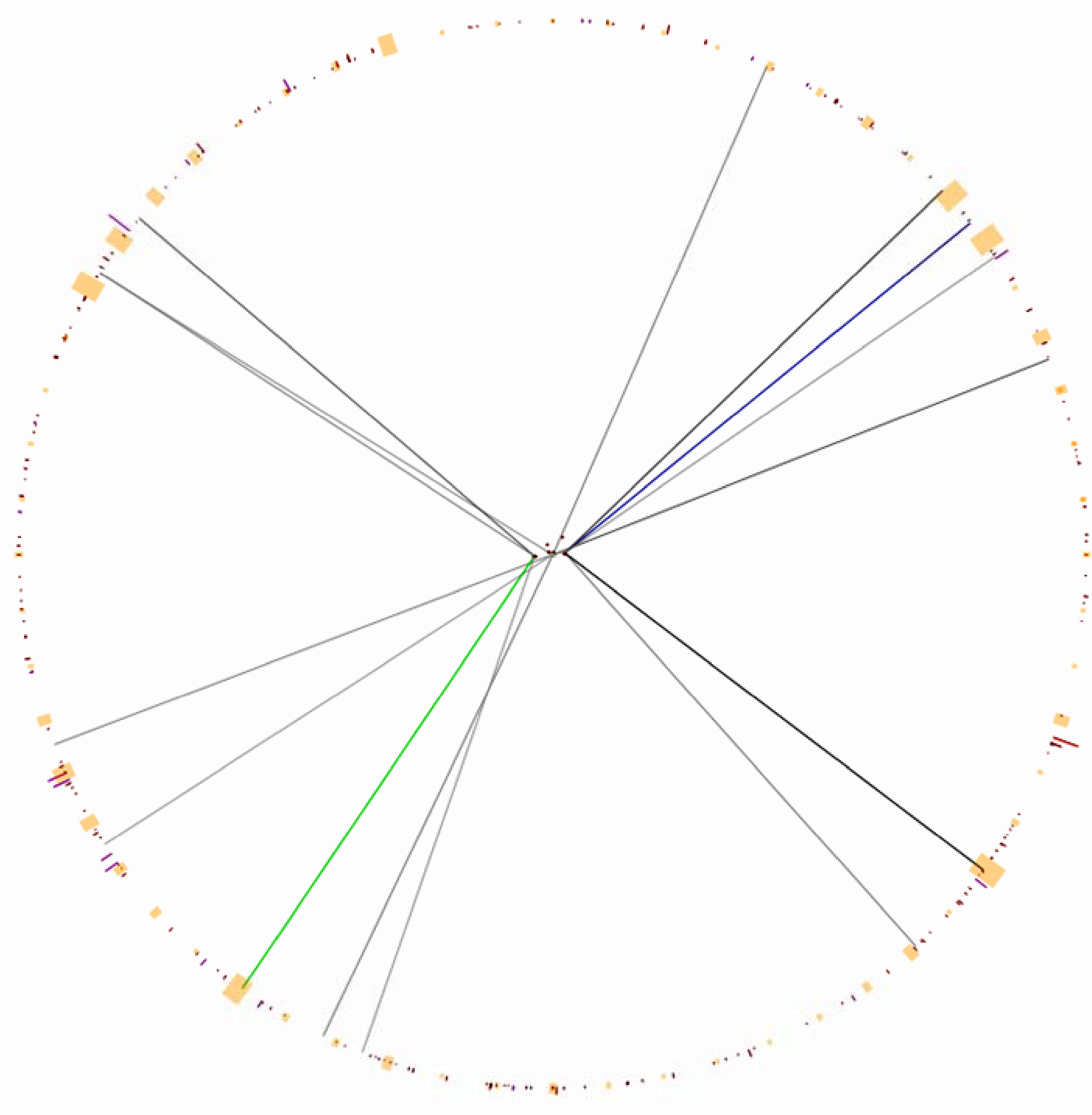


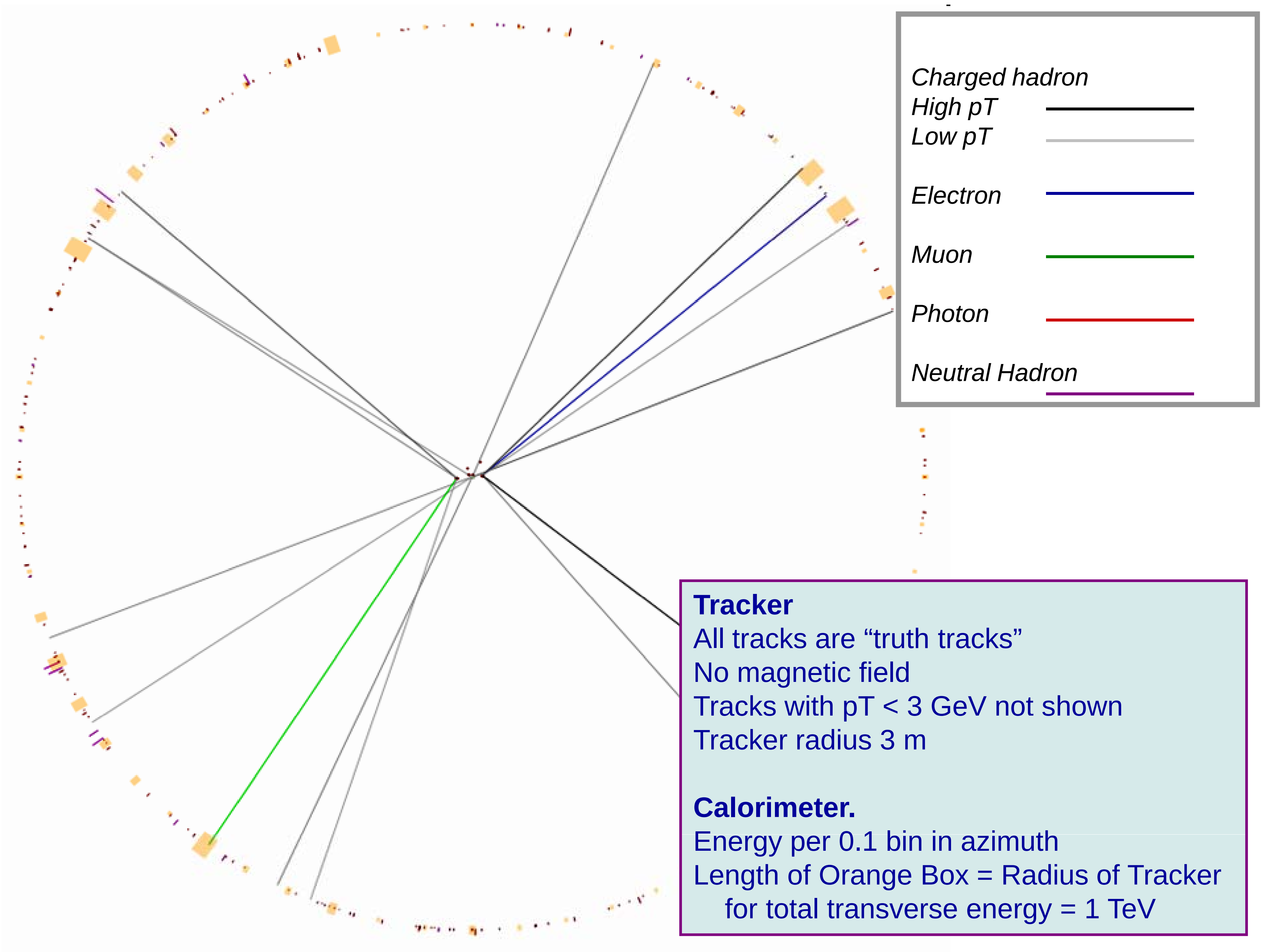


Very difficult to trigger at ATLAS/CMS…
Reconstruction challenges…
LHCb opportunity!!

Similar Observations: **hep-ph/0607204** :
Carpenter, Kaplan and Rhee

Precursor (LEP focus): Chang, Fox and Weiner, limit of model mentioned in hep-ph/0511250





Tracker

All tracks are “truth tracks”

No magnetic field

Tracks with pT < 3 GeV not shown

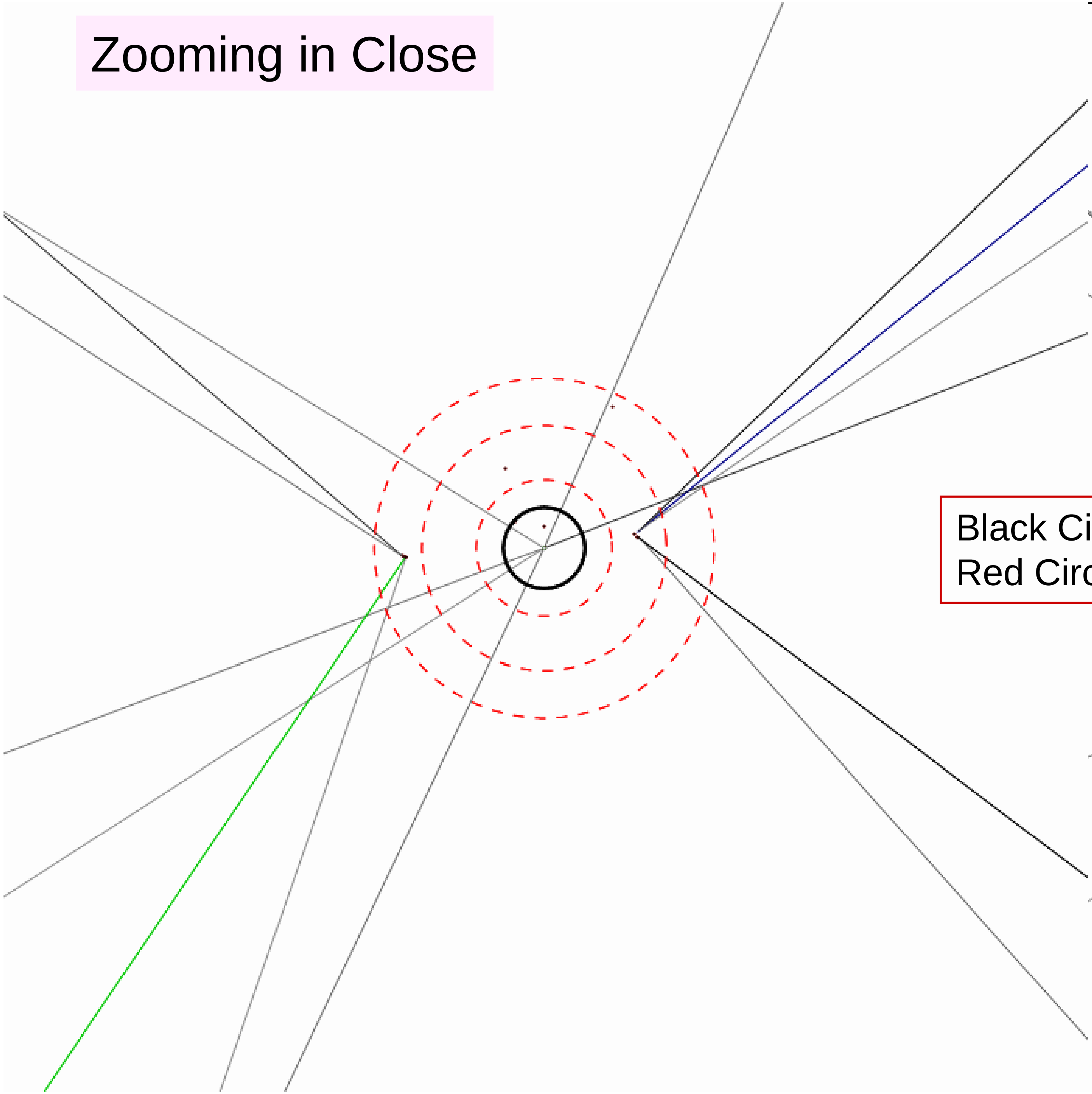
Tracker radius 3 m

Calorimeter.

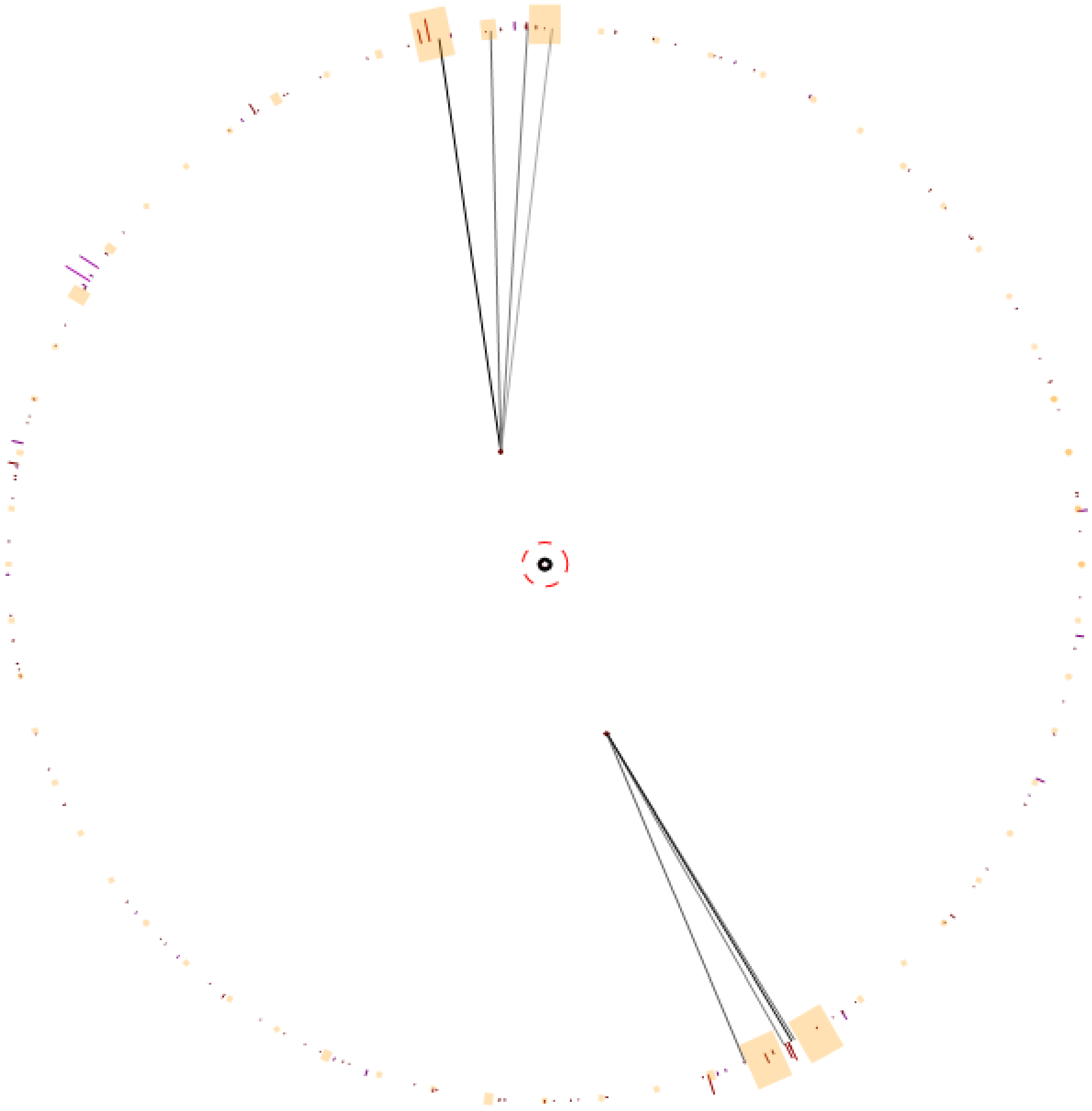
Energy per 0.1 bin in azimuth

Length of Orange Box = Radius of Tracker for total transverse energy = 1 TeV

Zooming in Close



Black Circle: 3.0 cm
Red Circles: 5.0, 9.0,12.5 cm



Black Circle: 3.0 cm
Red Circle: 12.5 cm

Long-Lived Neutral Weakly-Interacting X

- Partial List of Experimental Challenges for H → X X , X long-lived
  - Trigger
    - Muons lack pointing tracks
    - Jets are low pT, don't trigger
    - Vertex may be rejected (too far out to be a B meson)
    - Weird-looking event may fail quality control
  - Reconstruction
    - Event may be badly mis-reconstructed
    - Tracks may be missed
    - Calorimeter effects may be misconstrued as cavern background etc.
    - Event may not be flagged as interesting
    - May be thrown into bin with huge number of unrelated, uninteresting events
  - Event Selection
    - The events may be scattered in different trigger streams, reconstruction bins
    - If an event was not flagged as interesting in reconstruction, how is it to be found?
  - Analysis
    - What precisely to look for if the decays are outside the early layers of the tracker?
    - What can be done if decays are in calorimeter or muon system?

Production #1: Higgs boson decay

What can a new valley sector do?

- Higgs → X X (new [pseudo]scalars)
  - X → heavy flavor
  - H → 4 b's or tau's
- Higgs → F F (new fermions)
  - F → jets + MET, etc.
- Higgs → Y Y (new vectors)
  - Y → jets, mu pairs, e pairs, neutrinos
- Other final states possible
  - H →YY→ XXXX → 8 b's or tau's (or mu's)
  - H →FF → 4 b's, tau's plus MET
  - H → XX → YYYY → 8 soft quarks/leptons
  - …

X decay	Comment
Prompt	Difficult if all b's, tau's; easy if many muon or electron pairs
Displaced	**New Discovery Channel?!**
Highly Displaced	**New Discovery Channel?!**
Outside Detector	Invisible Higgs

Recent CDF paper and interpretation

Multi-muon study: unexplained clusters of displaced muons

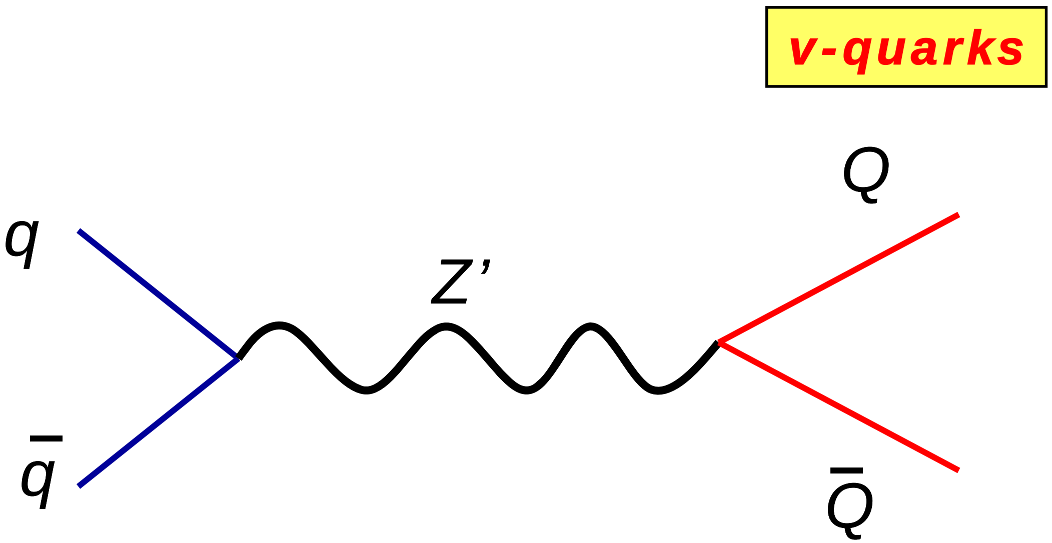
- Interpretation paper (**P. Giromini, F. Happacher, M.J. Kim, M. Kruse, K. Pitts, F. Ptohos, S. Torre**)
  - p pbar → ??? → h h → ss ss → xxxx xxxx → [8 + 8] taus
    - x → ♦✉♦📪 with lifetime of 20 ps
  - Perfectly ok as a theory (no LEP constraints, etc.)
  - Not great fit to the data
    - h, s, x masses fine tuned, x → ❍✉❍📪 should have been seen, …
  - Other variants (replace x with fermion f → ♦✉♦📪■)

- Questions: IF this theory, or a similar hidden valley, were true,
  - what could be done to improve the current analysis?
  - how could the reconstruction software have been written to make this easier to find or exclude?
  - what would have been the ideal analysis technique?

Example #2: Decays to QCD-like Sector

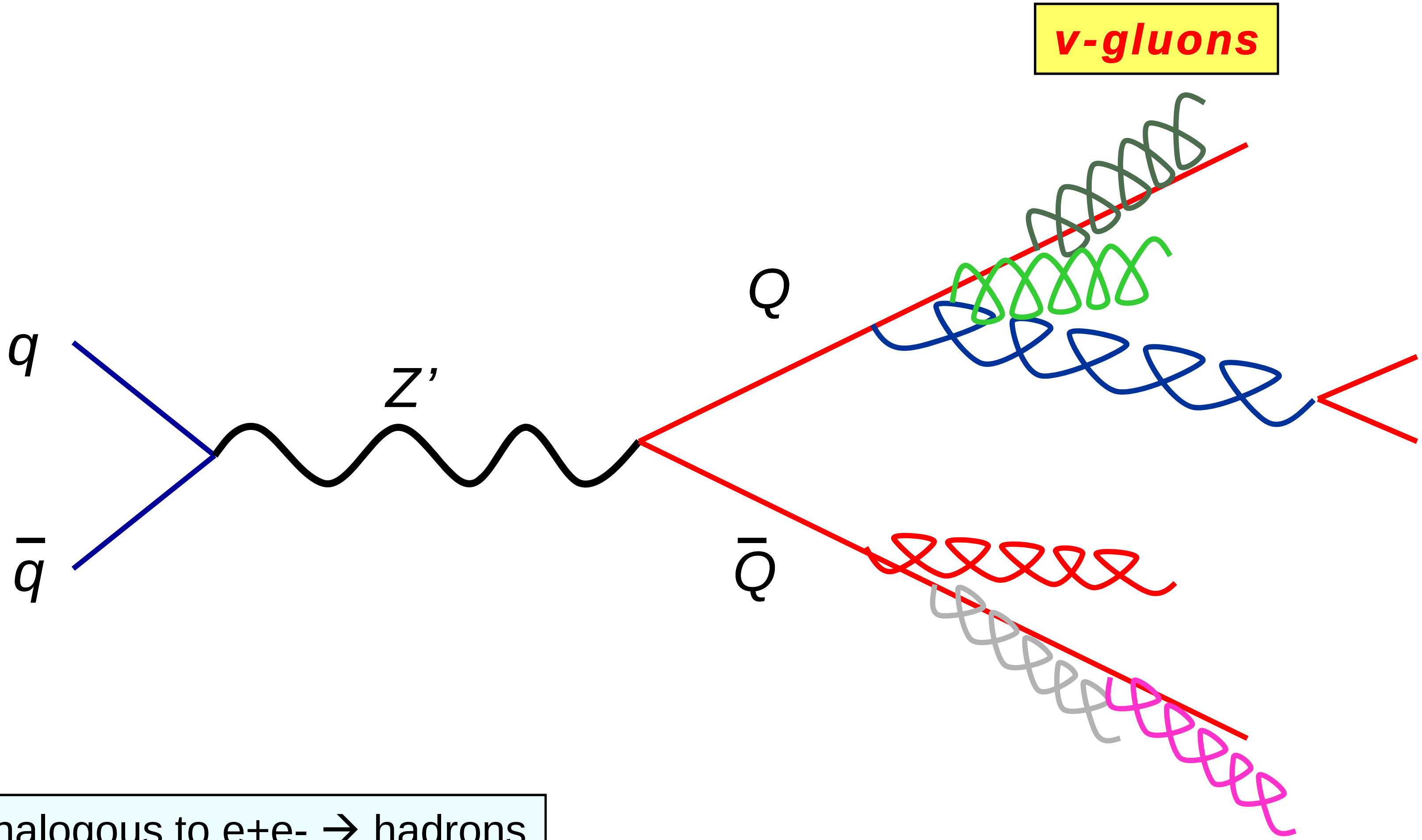
A case illustrating high multiplicity events without a corresponding Feynman diagram…

$q\bar{q} \rightarrow Q\bar{Q}$: v-quark production



Analogous to e+e- → hadrons

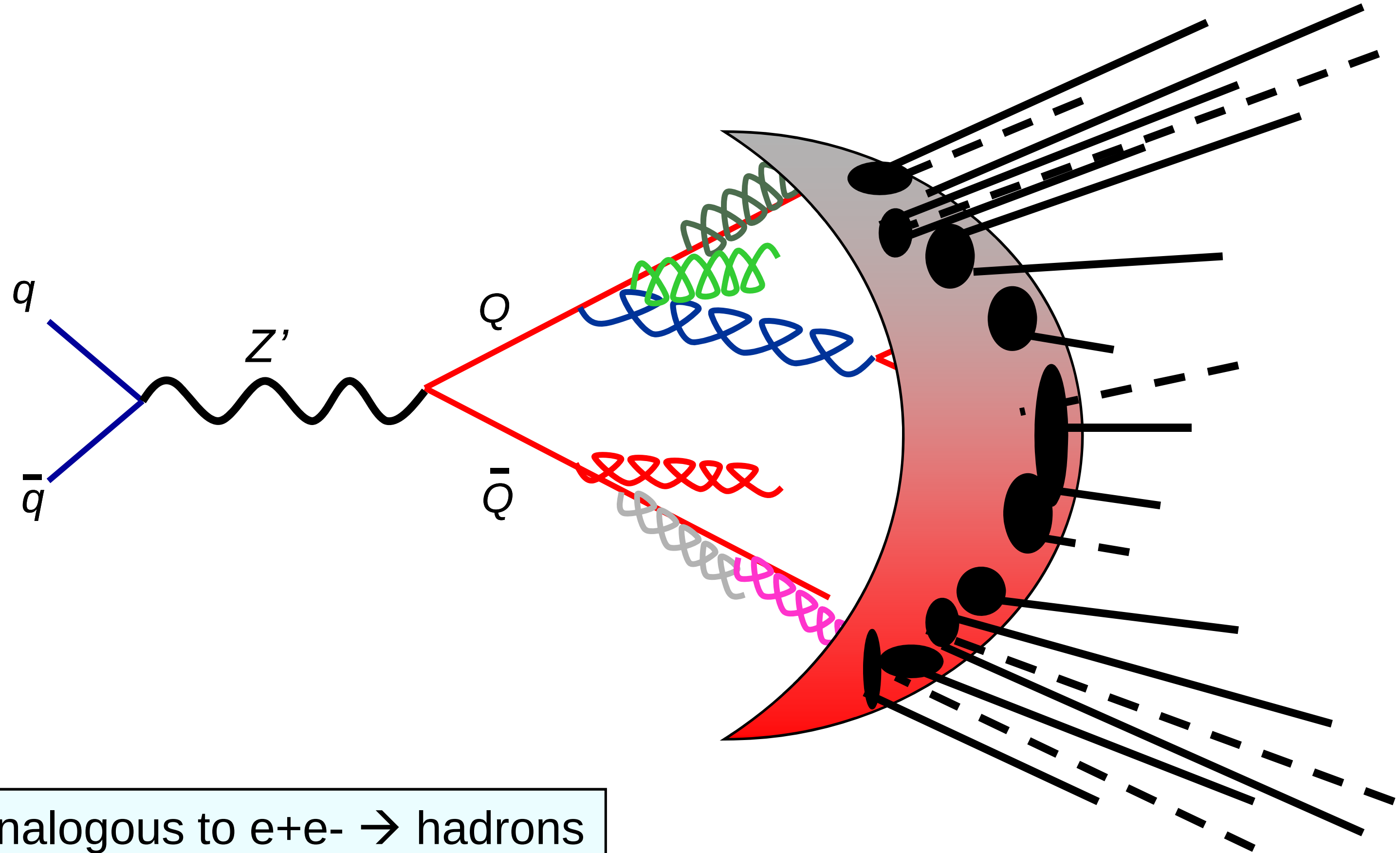
$q\,\bar{q} \rightarrow Q\,\bar{Q}$



Analogous to e+e- → hadrons

$q\bar{q} \rightarrow Q\bar{Q}$

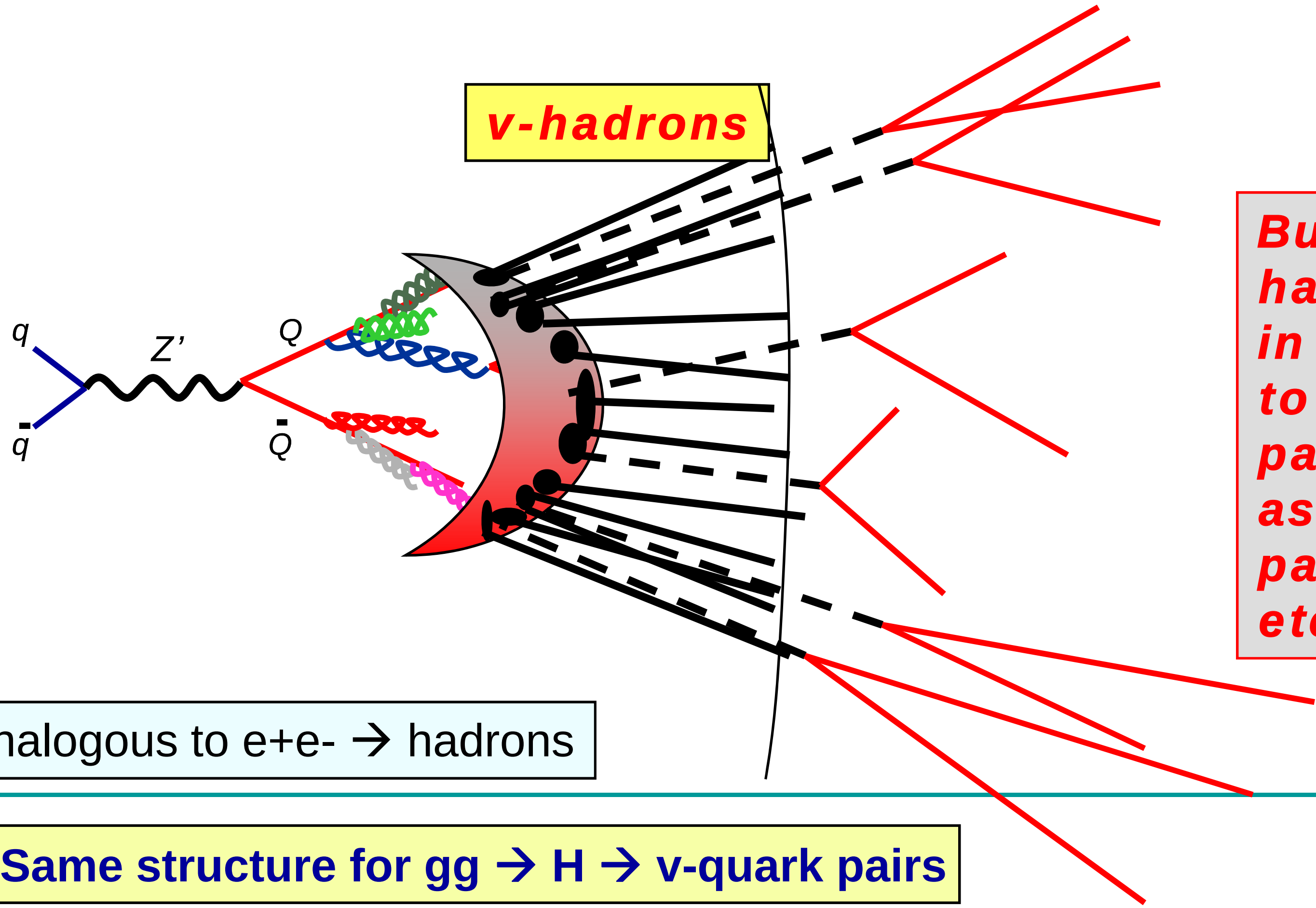
v-hadrons



Analogous to e+e- → hadrons

$q\,\bar{q} \rightarrow Q\,\bar{Q}$

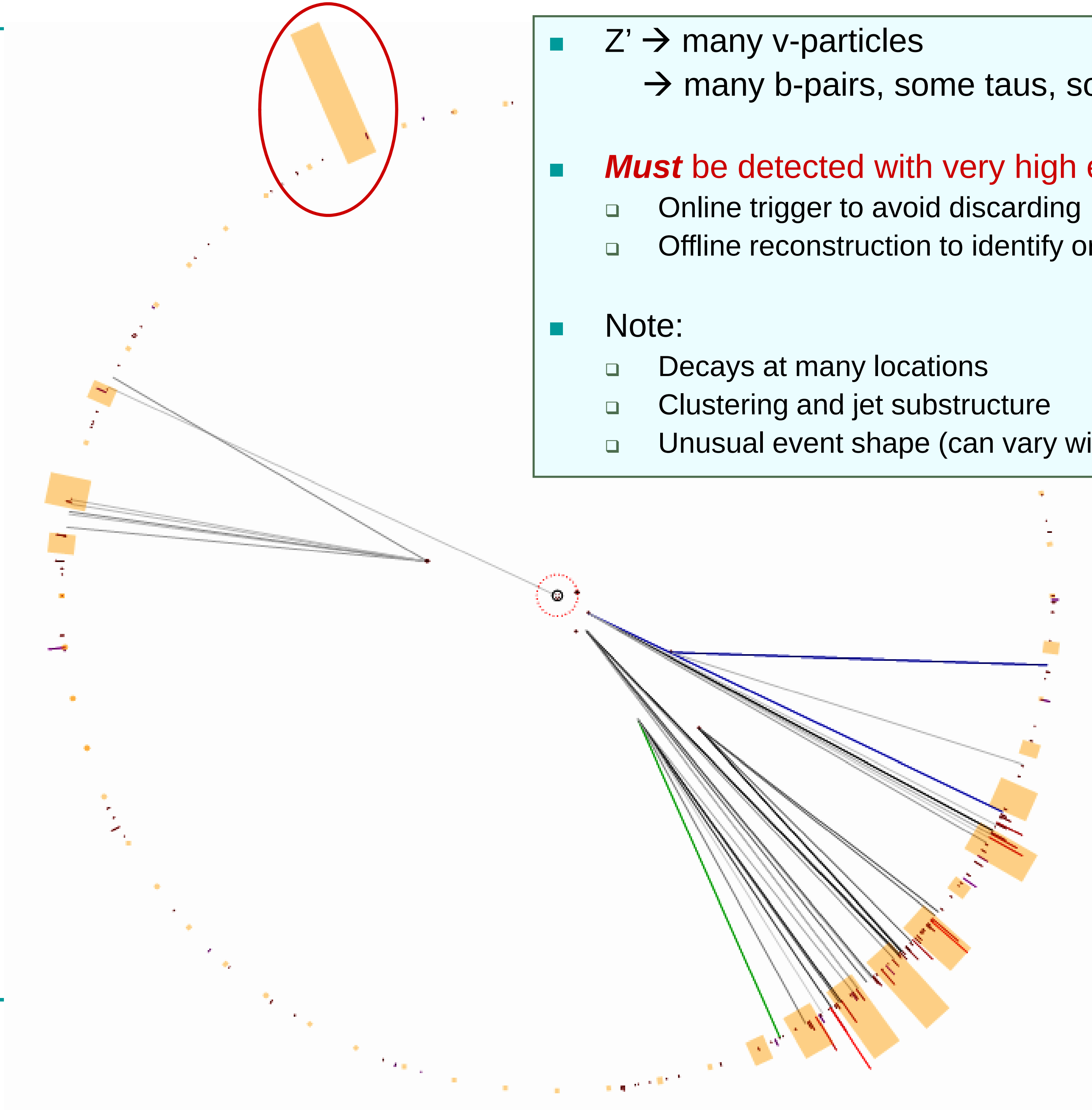
Some v-hadrons are stable and therefore invisible



But some v-hadrons decay in the detector to visible particles, such as bb pairs, qq pairs, leptons etc.

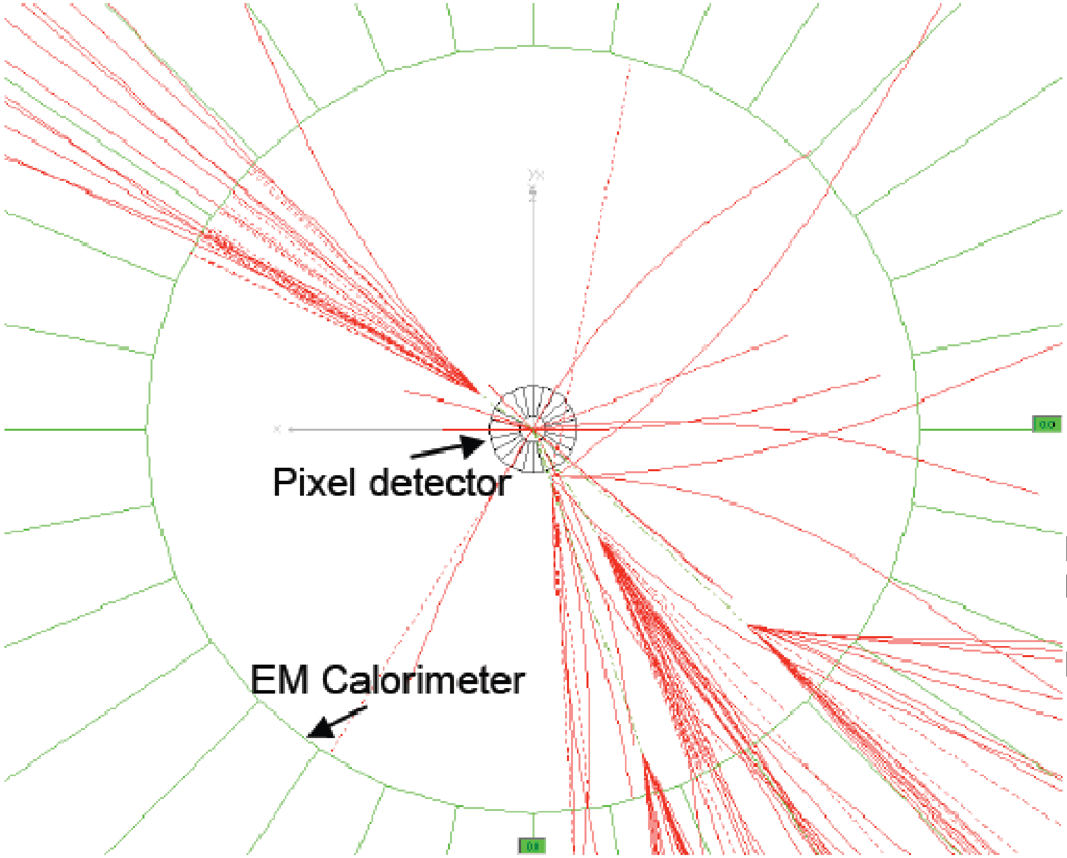
Analogous to e+e- → hadrons

Same structure for gg → H → v-quark pairs



- Z’ → many v-particles
  → many b-pairs, some taus, some MET
- ***Must*** be detected with very high efficiency
  - Online trigger to avoid discarding
  - Offline reconstruction to identify or at least flag
- Note:
  - Decays at many locations
  - Clustering and jet substructure
  - Unusual event shape (can vary widely!)

Effect of Magnetic Field

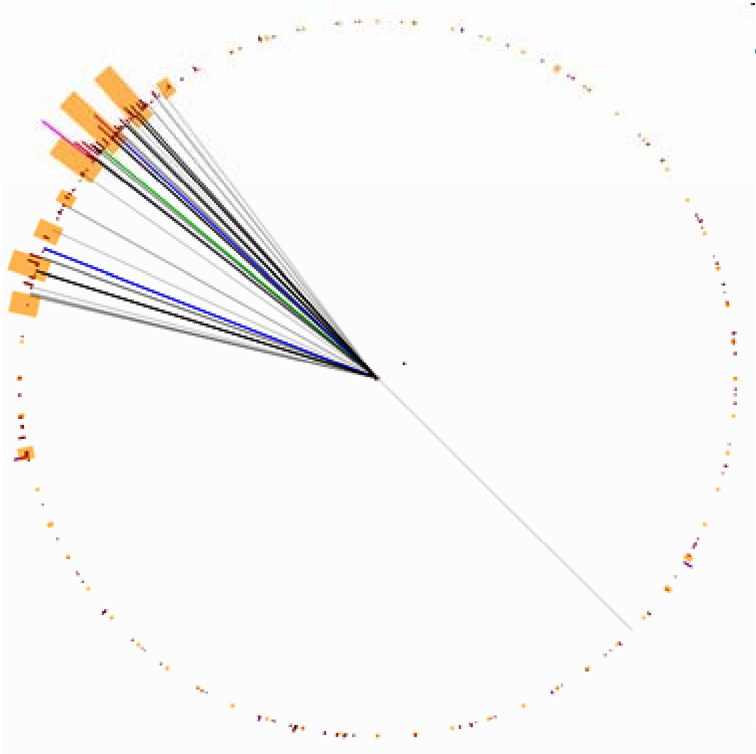


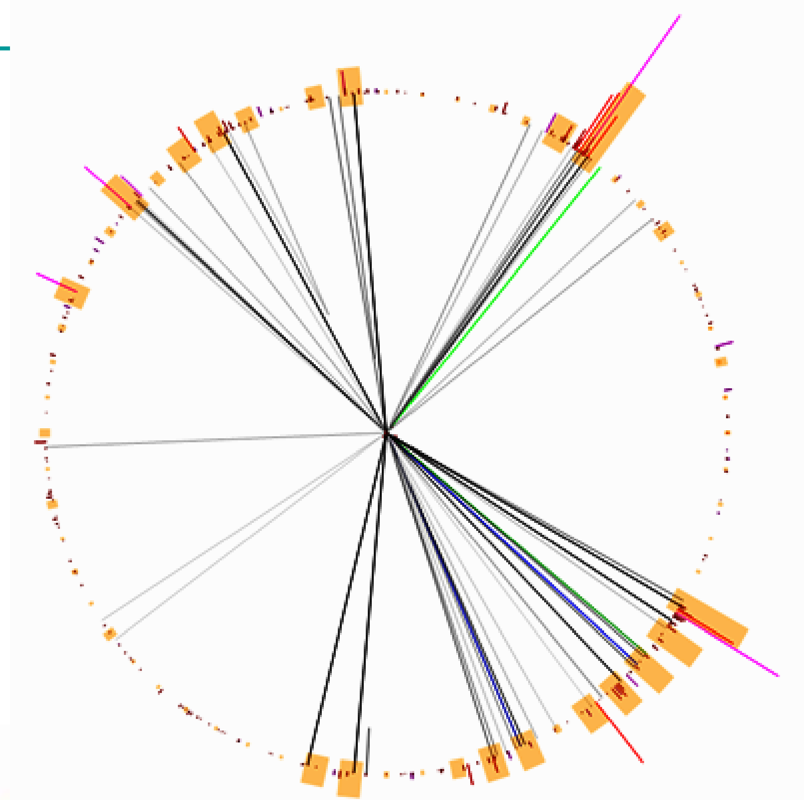
Effect of the magnetic field on HV events

(picture courtesy of ATLAS Rome/Seattle/Genoa working group)

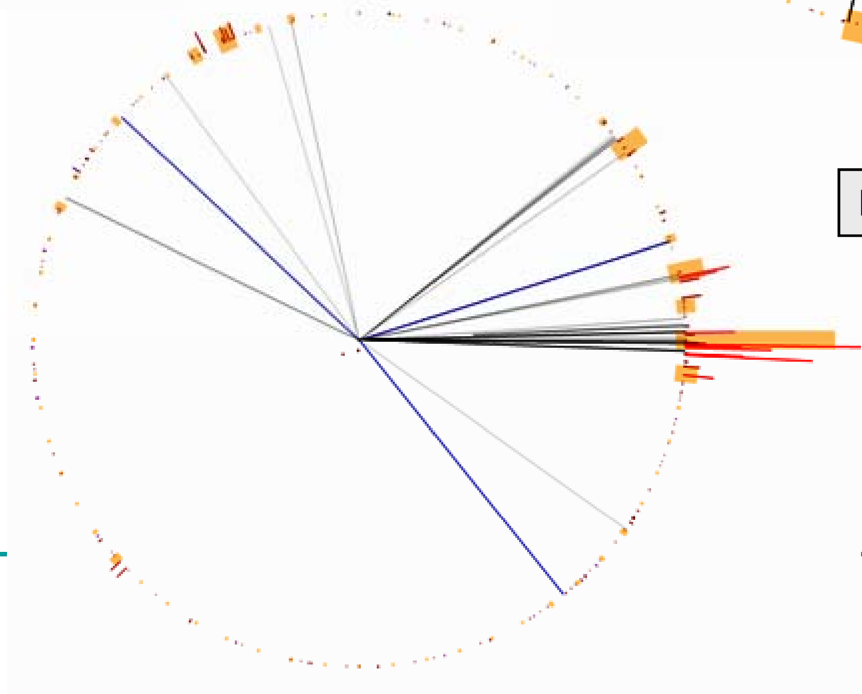
Event generator: Hidden Valley Monte Carlo 0.5
M. Strassler to appear

Display program: Daniele Depedis





Z’ → v-hadrons
Average: 8 b’s
Max: 22 b’s



Prompt decays: MJS 08

Z’ mass = 3.2 TeV
v-pi mass = 50 GeV
Flavor-off-diagonal
v-pions stable

Example #3: SUSY/UED/Little Higgs

… will address this Friday if time and interest permits…

New Resonances: di-leptons (e, mu) (di-photons similar)

- Everynone knows we should to look for resonances in leptons and photons

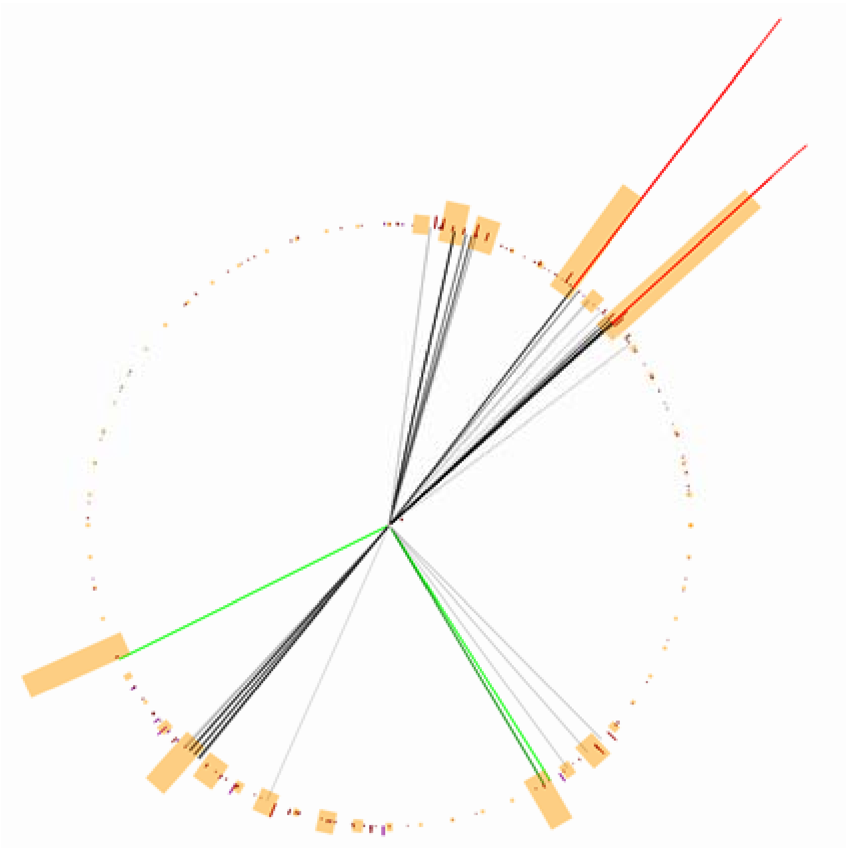
- The problem: how to find them if they appear only in rare events

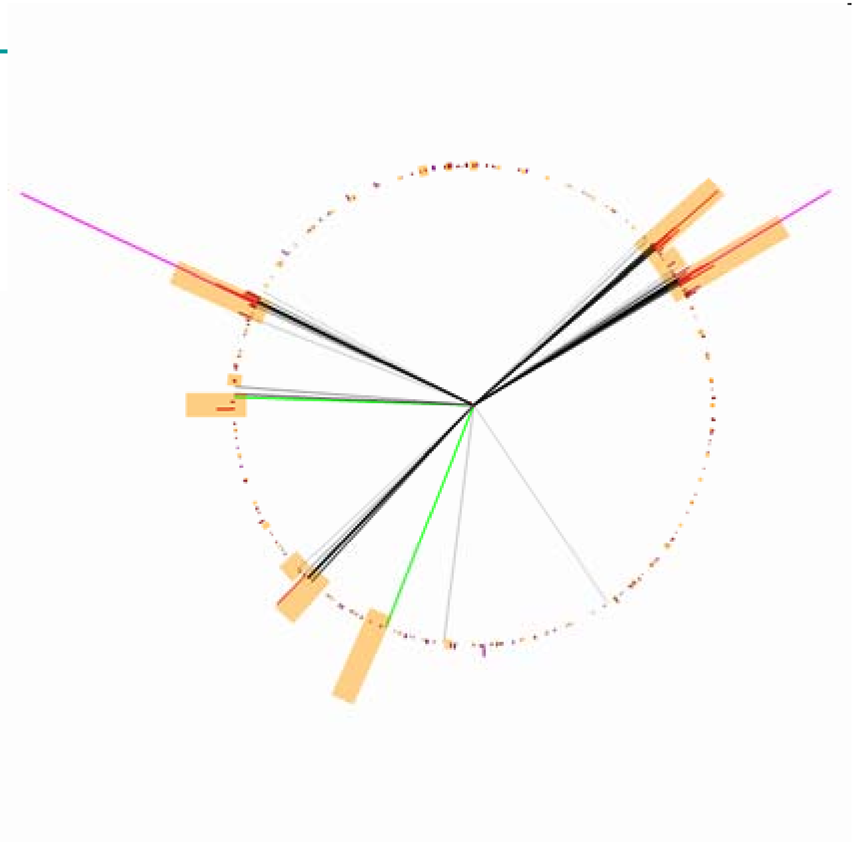
- Without correct event selection, drowned in Drell-Yan or lost altogether

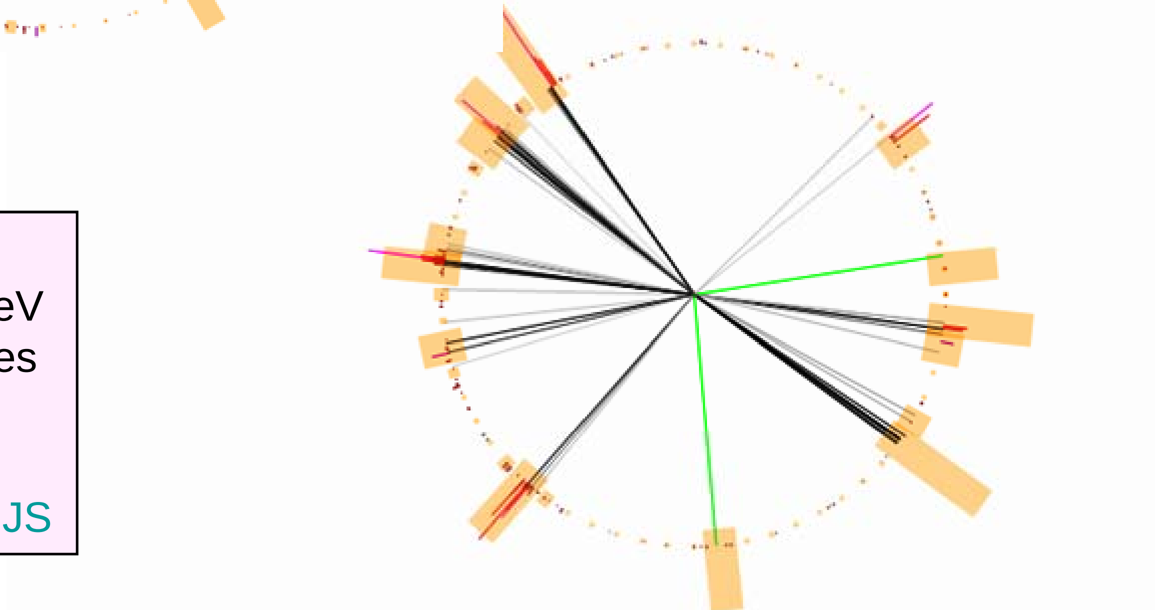
- Two step process:
  - Select events with leptons/photons (isolated?!) and some other characteristic(s)
  - Plot invariant masses of lepton or photon pairs, etc.

An Example: Han, Si, Zurek & Strassler 2007

See also unpublished Haas, Wacker





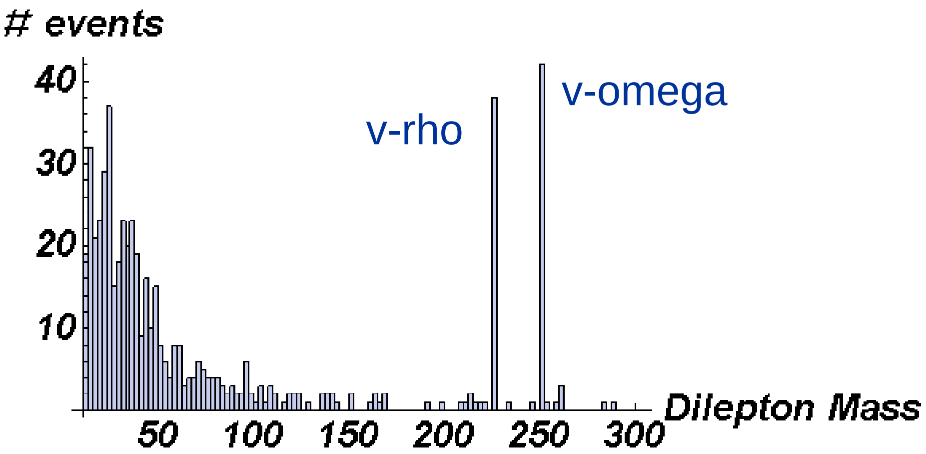


Z' → v-hadrons
Including ~ 200 GeV dilepton resonances

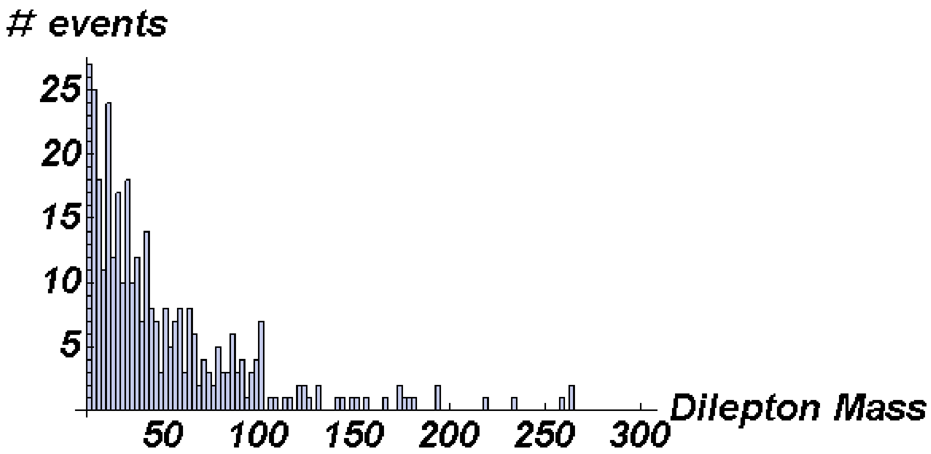
HVMC1.0
Mrenna,Skands,MJS

Dilepton Mass Distribution

If you could find enough events… in a sample with low Drell-Yan background…



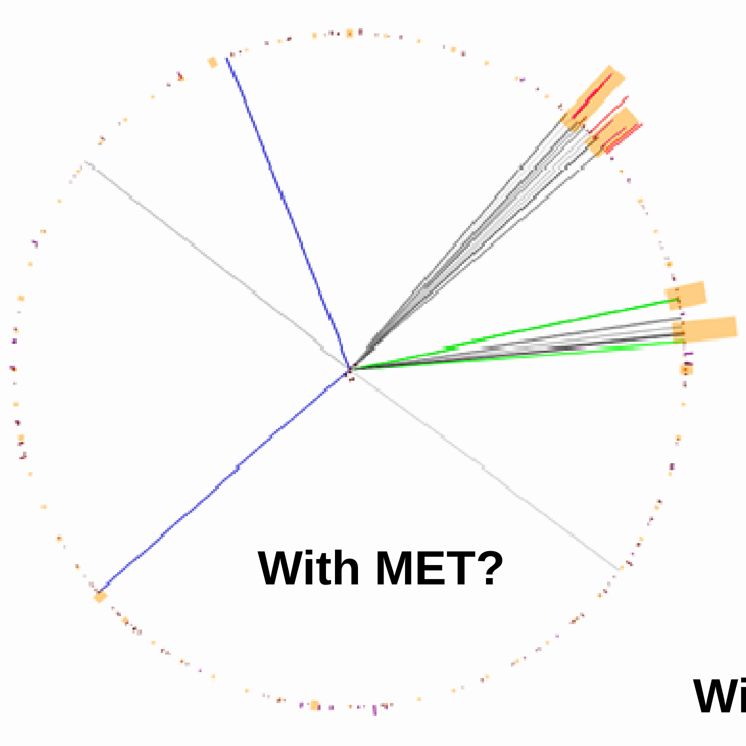
Same Flavor Opposite Sign

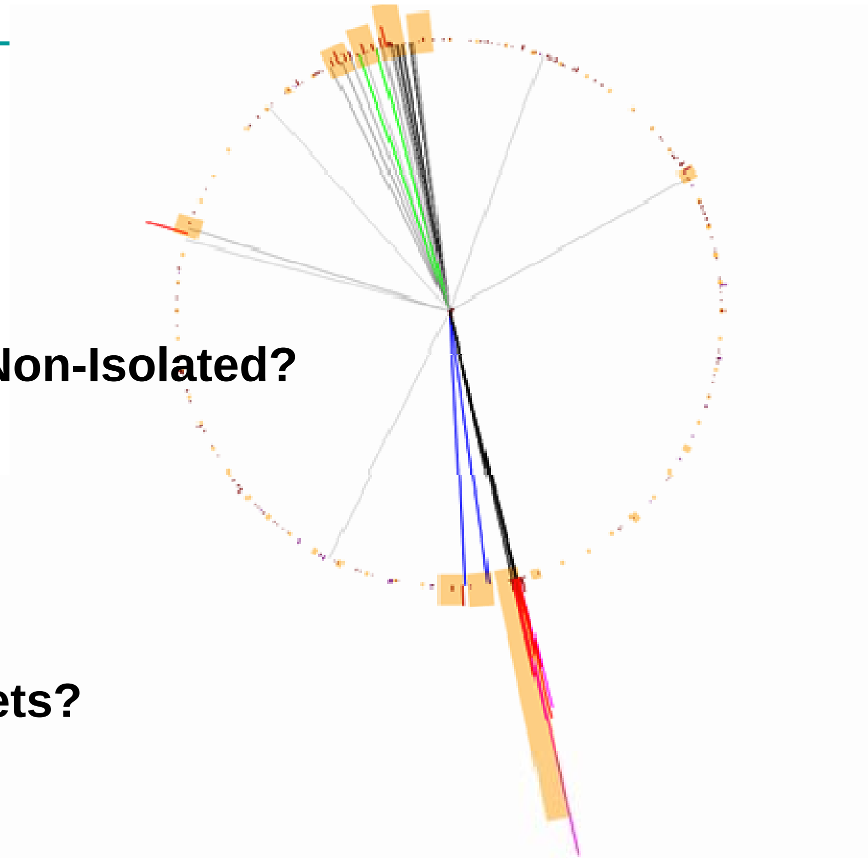


Opposite Flavor Opposite Sign

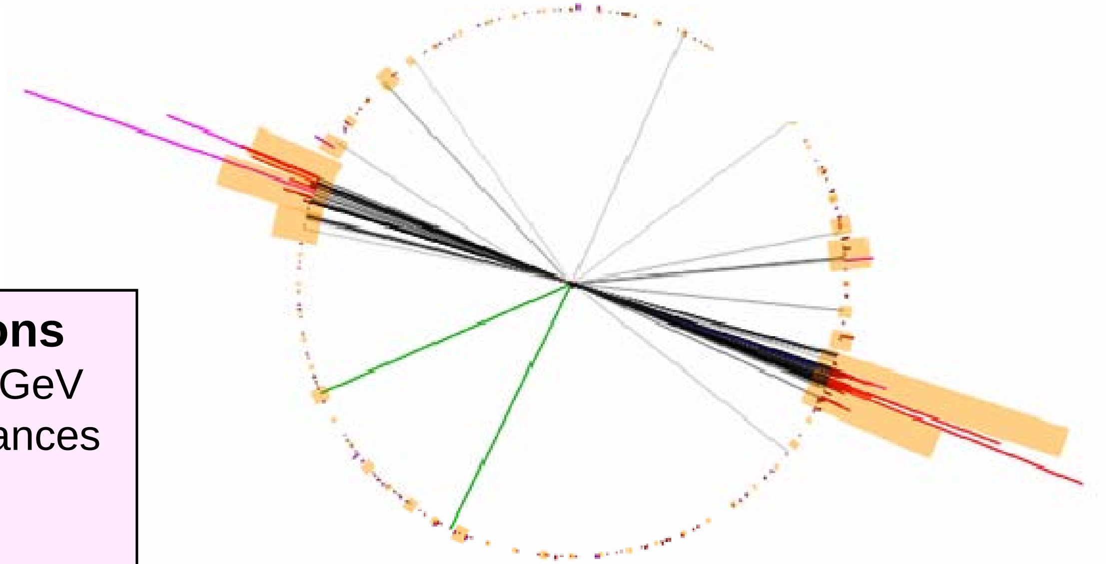
Event selection: use event shapes, object multiplicity, HT, possibly MET

Could be much lighter – 20 GeV?





With >1 Hard Jets?

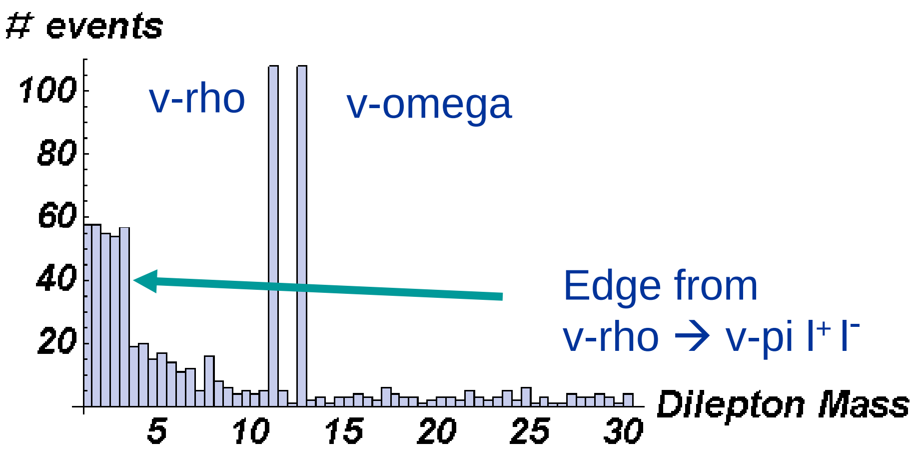


Z’ → v-hadrons
Including ~ 10 GeV dilepton resonances

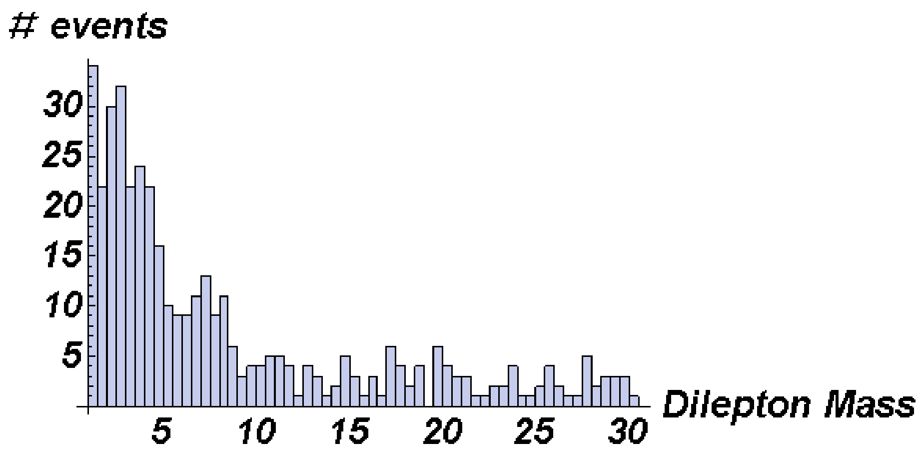
HVMC1.0
Mrenna,Skands,MJS

Dilepton Mass Distribution

If you could find enough events… in a sample with low Drell-Yan background…



Same Flavor Opposite Sign



Opposite Flavor Opposite Sign

…but what should your event selection criteria be?

See also recent paper of Arkani-Hamed and Weiner ("lepton-jets")

General Lesson

Suggests – a systematic search for dilepton resonances

- Explore a wide variety of event classes with 2 or more leptons
- Important to plan in advance;
  perhaps discuss with theorists to look for gaps in the search strategy
- Both isolated and non-isolated leptons should be used
- Displaced leptons are also of interest
- Special attention to >3-lepton events (isolated or not)
- Also want to look for dilepton edges/endpoints

Same goes for photon pairs, photon-lepton combinations, etc.

New Resonances: di-taus

- Essentially impossible to directly reconstruct di-tau resonances
- 1/36 chance to get two muons (1/9 to get two leptons)
  with known spectrum
- But typically will also see di-muon resonance!
  - New flavor structure in the hidden sector typically generates new FCNCs
  - To avoid, spin-1 resonance typically flavor blind: Br(❍❍)=Br(♦♦)
    mixes with photon, Z, Z'
  - To avoid, spin-0,2 resonance typically has Br(❍❍)/Br(♦♦) = $(m_{❍}/m_{♦})^2$ ~ 1/285
    mixes with Higgs, or helicity-suppression
    - ➔ 1/10 of di-mu decays are resonant, above bkdg from di-tau
- General lesson: when looking for tau's, look for mu's first

Taus and di-muons at 7.2 GeV

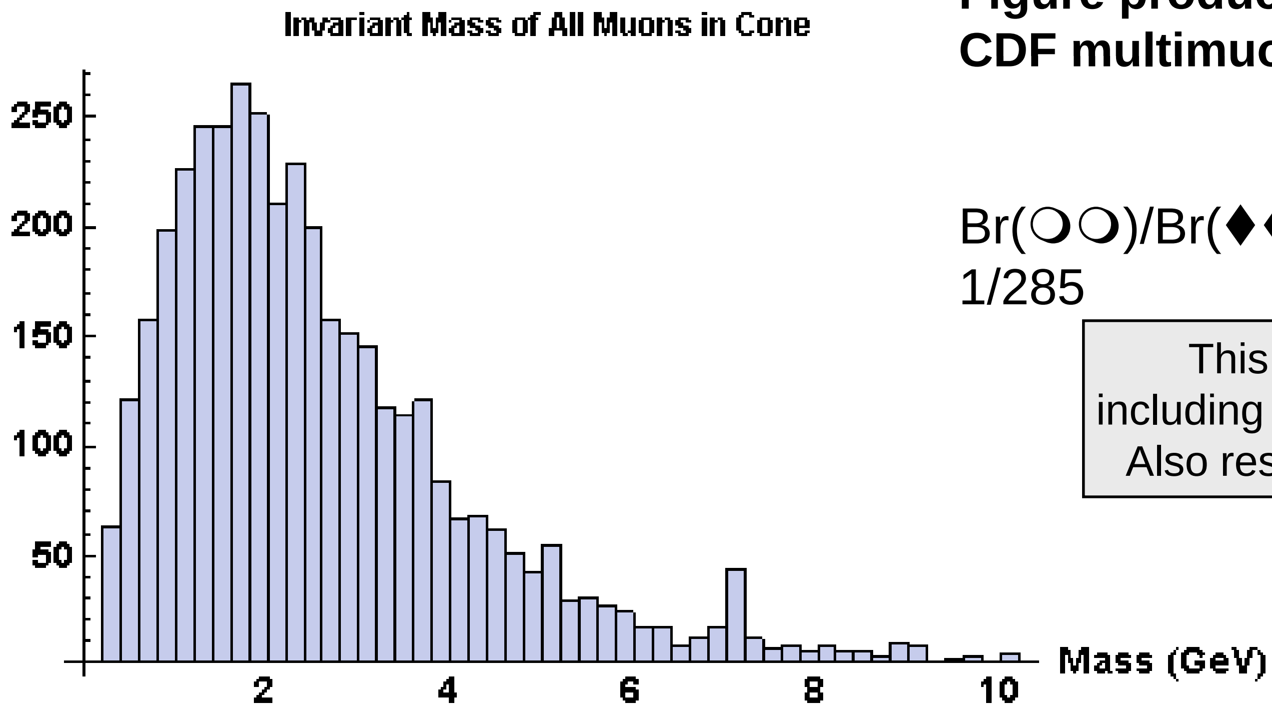


Figure produced using methods of CDF multimuon study MJS 08

Br(❍❍)/Br(♦♦) = $(m_{❍}/m_{♦})^2$ ~ 1/285

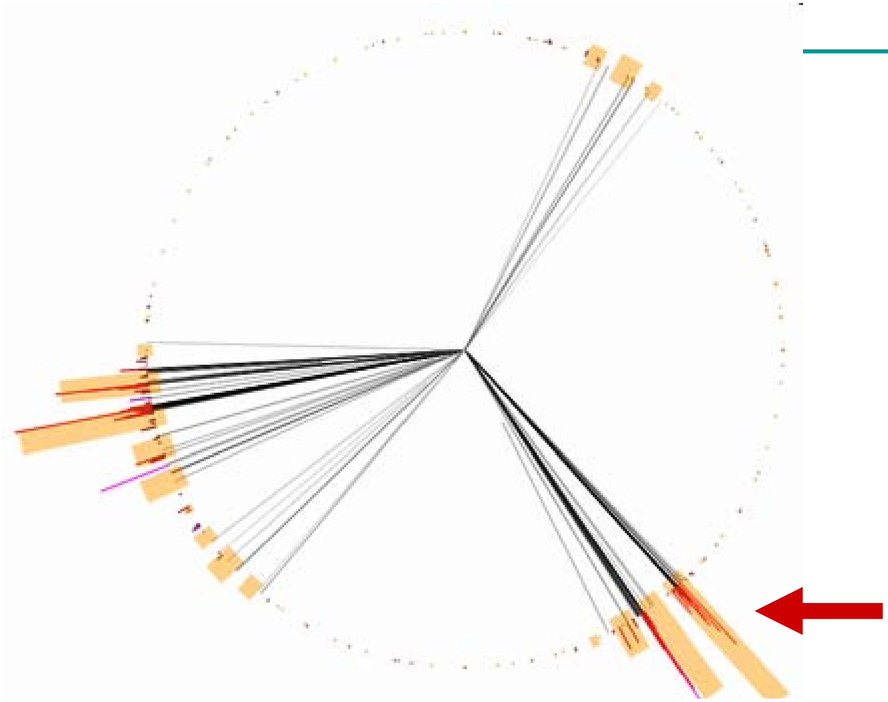
This has all muon pairs, including same- and opposite-sign
Also resolution is not optimized

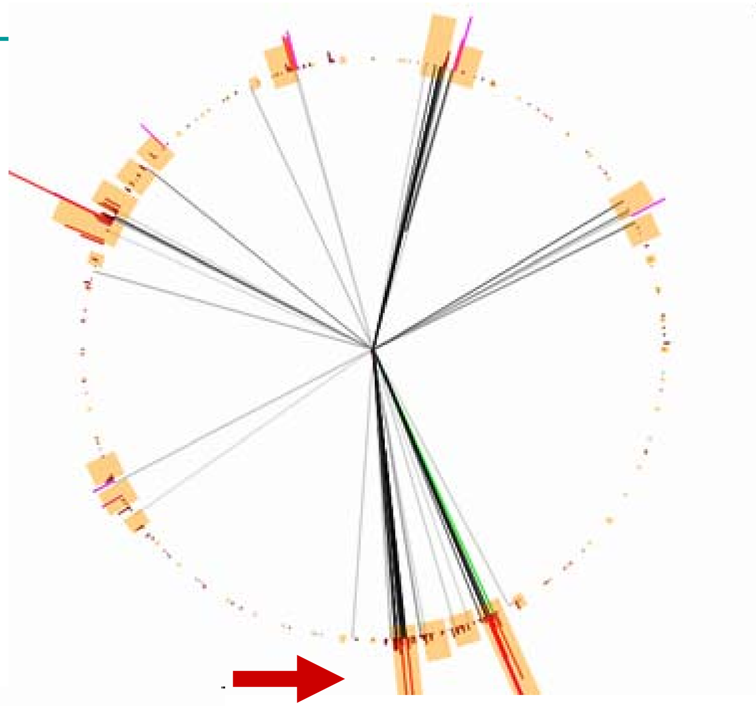
Compare figure with CDF multimuon study: Light vector boson or scalar boson decaying to ❍❍ with Br > 10^{-3} excluded by data

Note it **is** theoretically possible to eliminate the dimuon resonance; disfavored theoretically, but not excluded

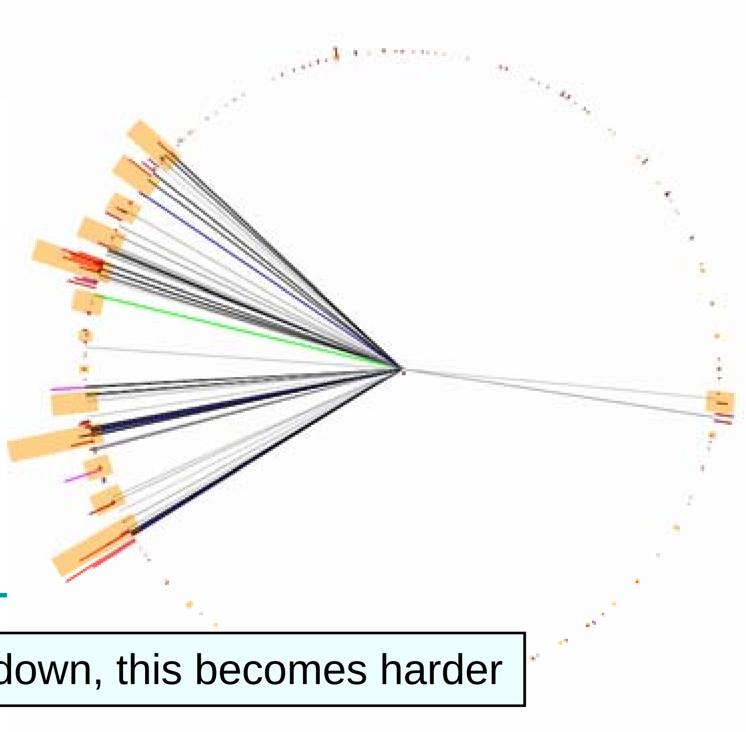
New Resonances: di-jets (including b's)

- Easiest way to find di-jet resonances is if boosted
  - boost is common in decays of Z', H, etc.
  - cf. technical advances: Butterworth, Davison, Rubin & Salam 2008
- The problem is to find them;
  without correct event selection, drowned in QCD
- So we have a three-step problem:
  - Select events that have a chance of containing a resonance
  - Study high-p_T jets, look for substructure consistent with a boosted particle
  - Look for invariant mass peak built from the substructure of the jets
- We'll start with the substructure, then turn to event selection methods





Z’ → v-hadrons
Average: 3 b’s
Max: 12 b’s



MJS 2008

Z’ mass = 3.2 TeV
v-pi mass = 200 GeV
Flavor-off-diagonal
v-pions stable

As the mass goes down, this becomes harder

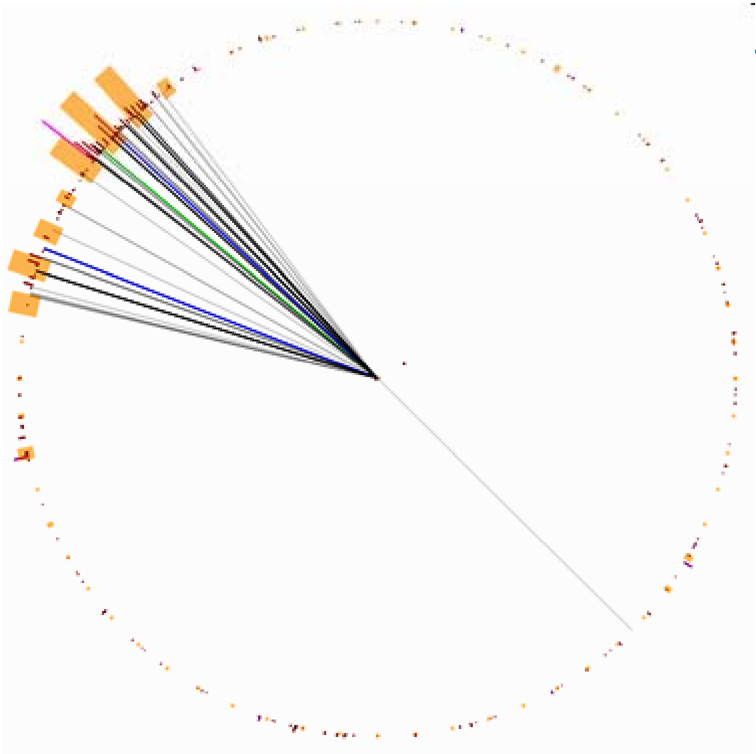
Event Selection Criteria

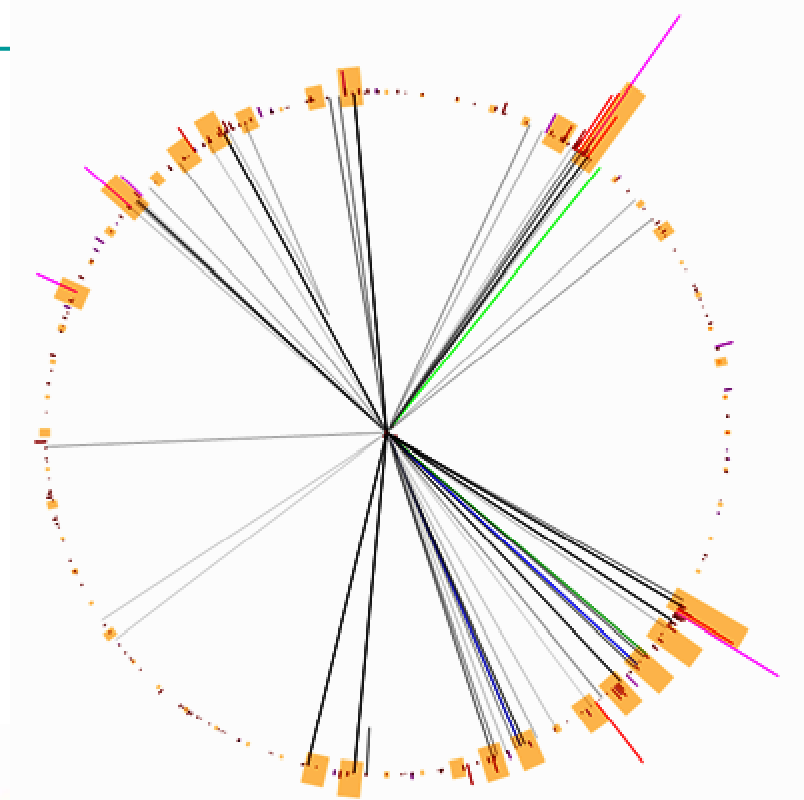
- Object-Based
- Tracks/Vertices
- H_T / MET
- Overall Event Shapes

Event Selection Criteria

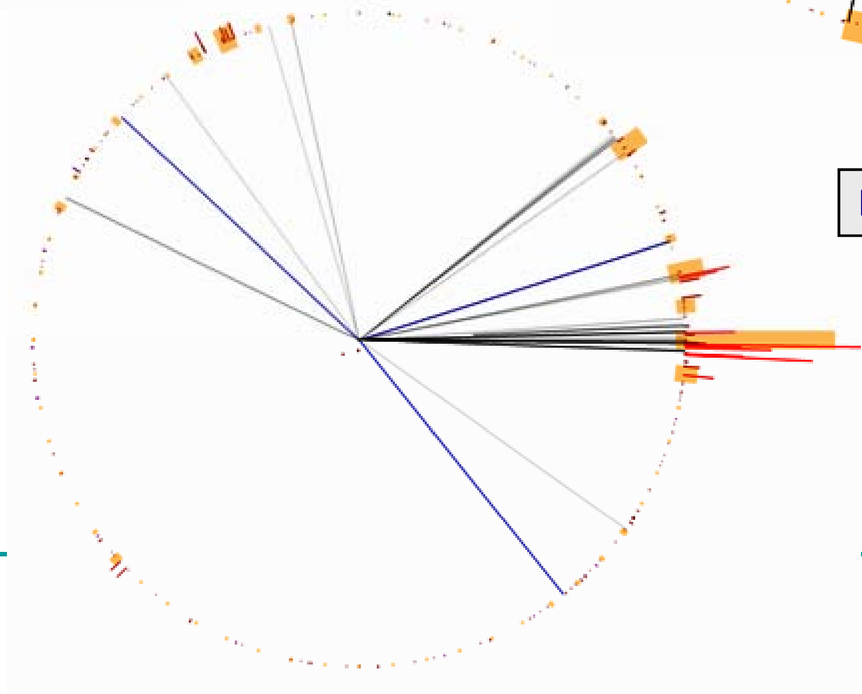
Object-Based Selection

- High multiplicity of standard objects
  - Caution: at very high quark/lepton/gluon/photon multiplicity,
    jets merge, leptons/photons fail isolation
- Multiple leptons or photons?
  - Relax or remove isolation criteria?
  - Look at clustering?





Z’ → v-hadrons
Average: 8 b’s
Max: 22 b’s

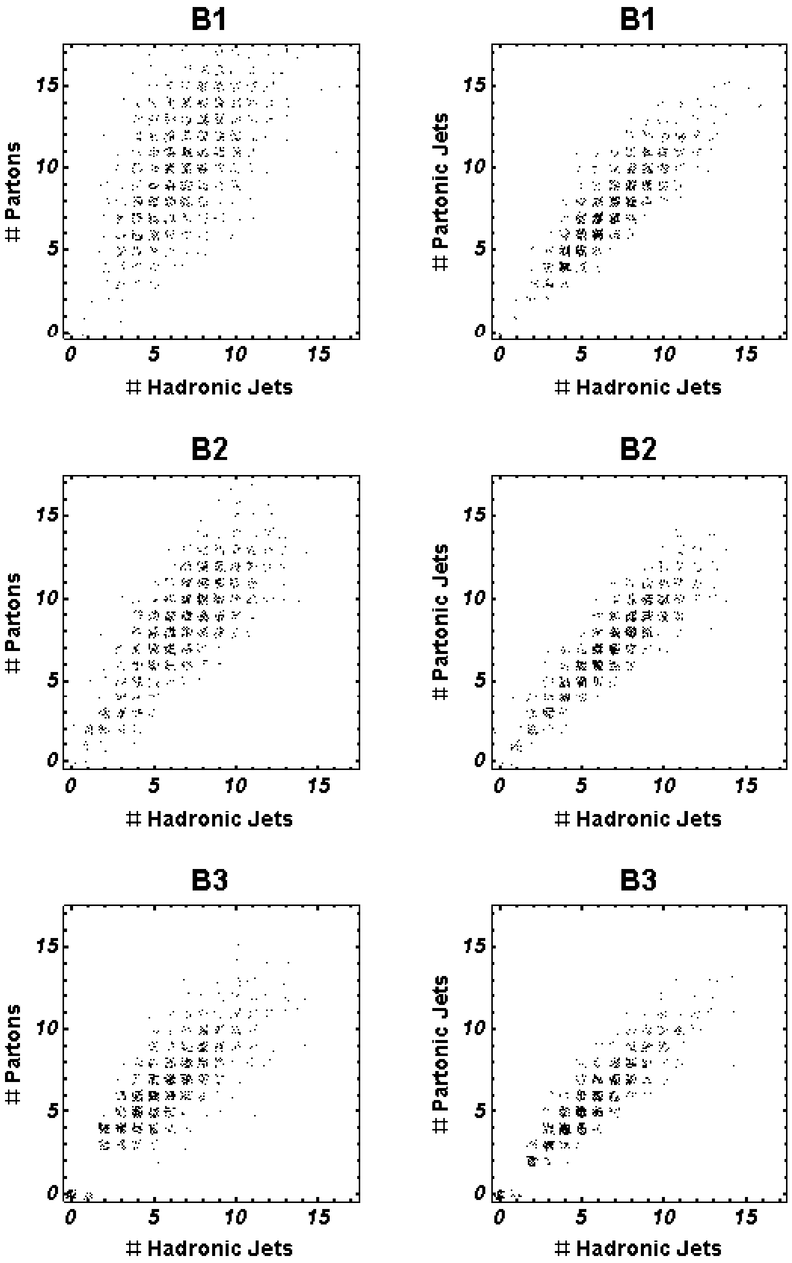


Prompt decays: MJS 08

Z’ mass = 3.2 TeV
v-pi mass = 50 GeV
Flavor-off-diagonal
v-pions stable

Quarks vs Jets

Counting objects can be inefficient



Number of Partons and Partonic Jets vs. Number of Hadronic Jets

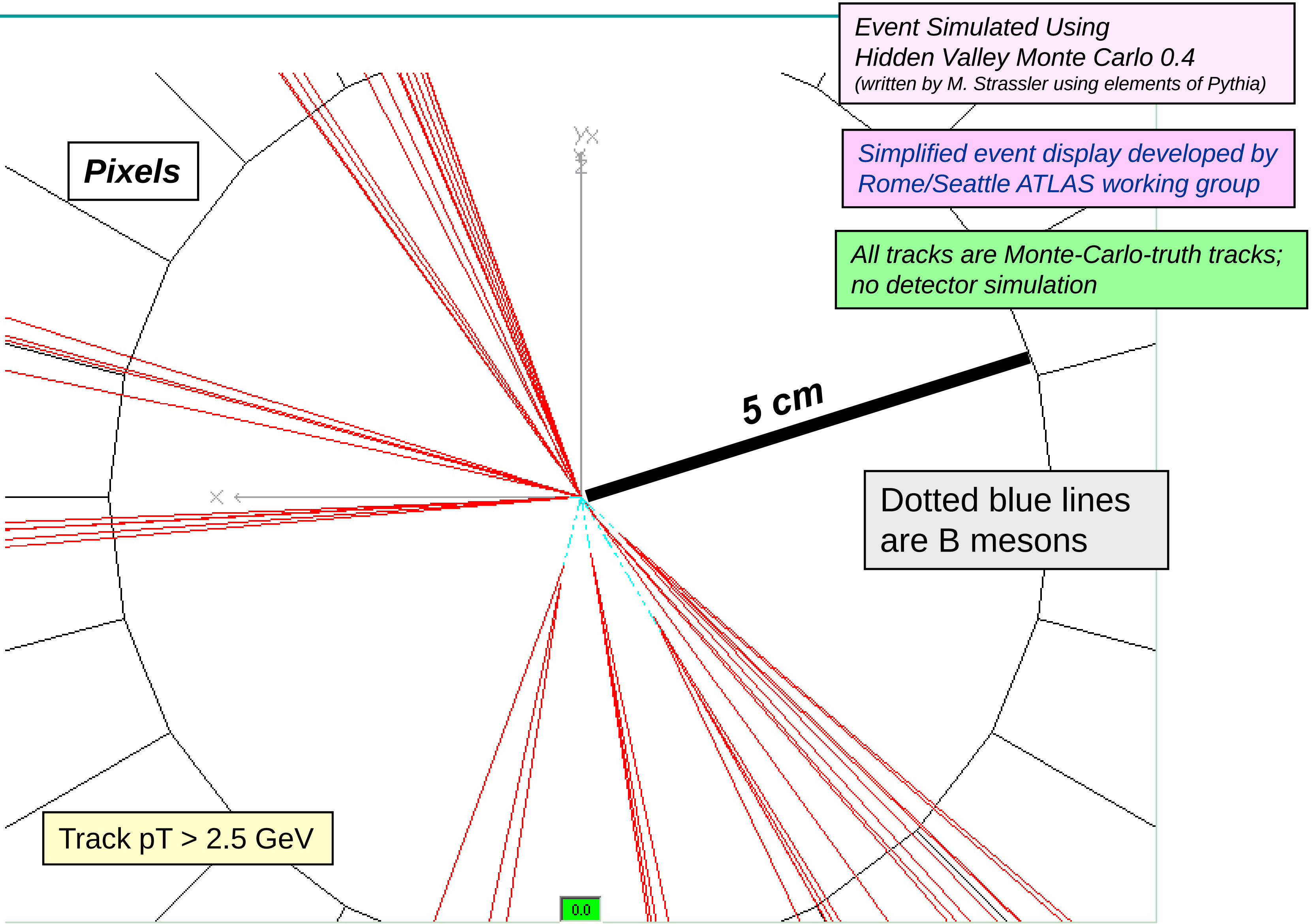
Event Selection Criteria

Tracks/Vertices

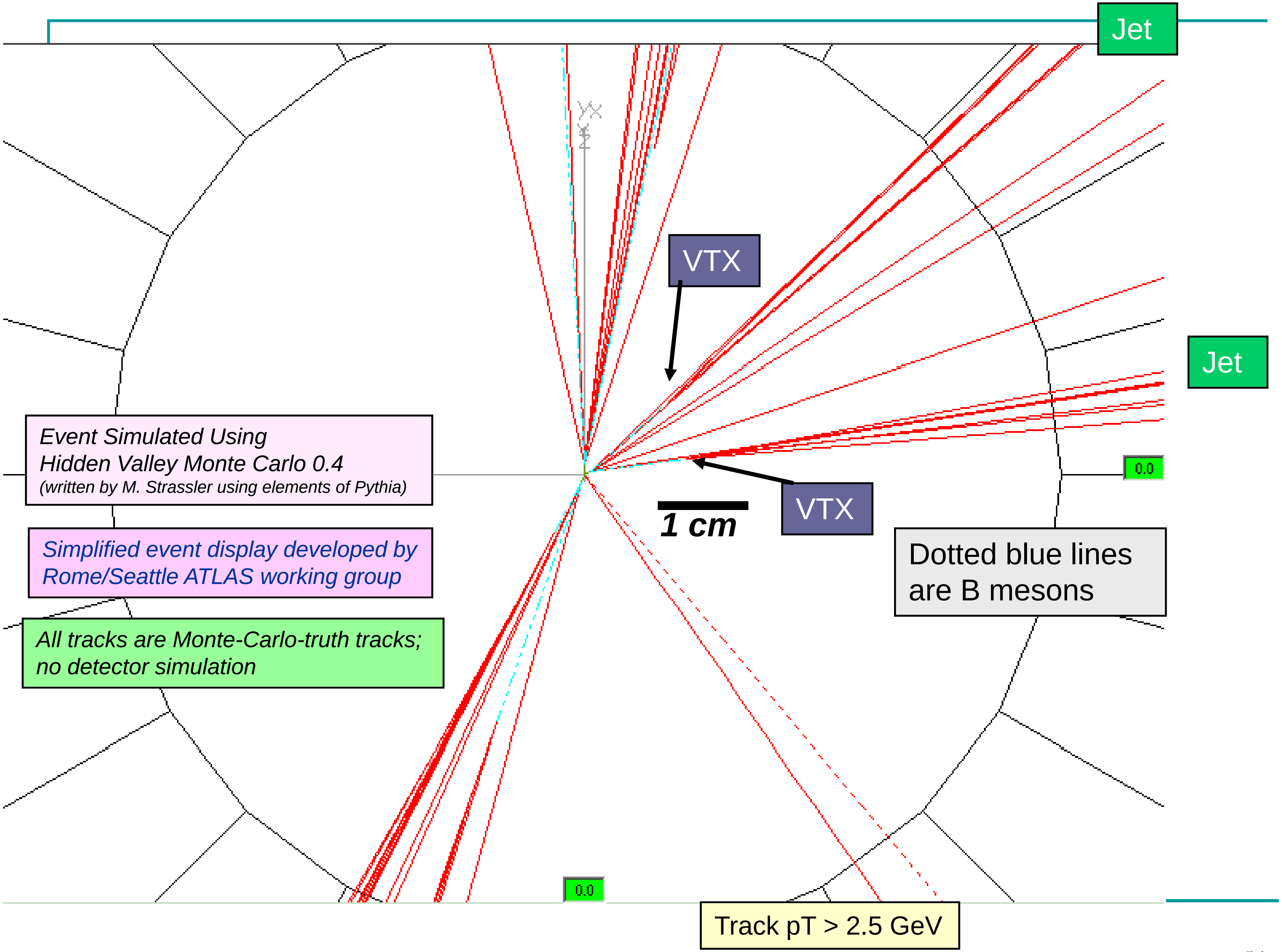
- Signal with many soft particles:
  - count tracks rather than jets/leptons
- Signal with many v-particles → b quark pairs
  - Many B-mesons – often many more B-mesons than jets
  - Don't just tag the jets –

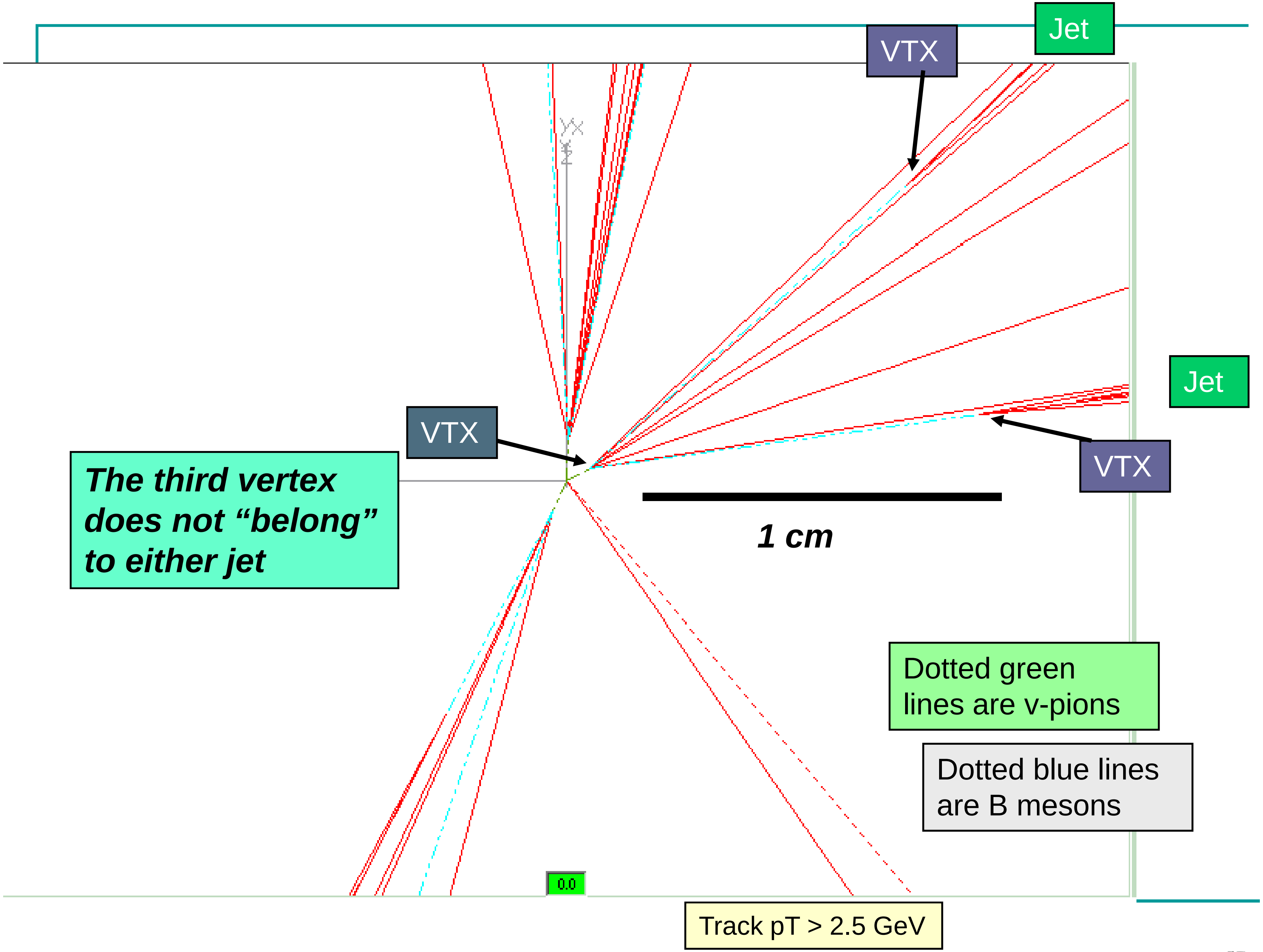
    count tracks, vertices, displaced tracks

    study clustering of tracks and vertices
- Signal with v-particles → jets with lifetime 1 ps
  - One vertex for each jet pair
  - Look for jets that share a displaced vertex with many tracks



Multiple vertices may cluster in a single jet


Jet
Jet
VTX
VTX
1 cm
Event Simulated Using
Hidden Valley Monte Carlo 0.4
(written by M. Strassler using elements of Pythia)
Simplified event display developed by
Rome/Seattle ATLAS working group
All tracks are Monte-Carlo-truth tracks;
no detector simulation
Dotted blue lines
are B mesons
Track pT > 2.5 GeV
0.0
0.0



Jet
VTX
Jet
VTX
VTX
The third vertex does not "belong" to either jet
1 cm
Dotted green lines are v-pions
Dotted blue lines are B mesons
0.0
Track pT > 2.5 GeV

Event Selection Criteria

H_T / MET

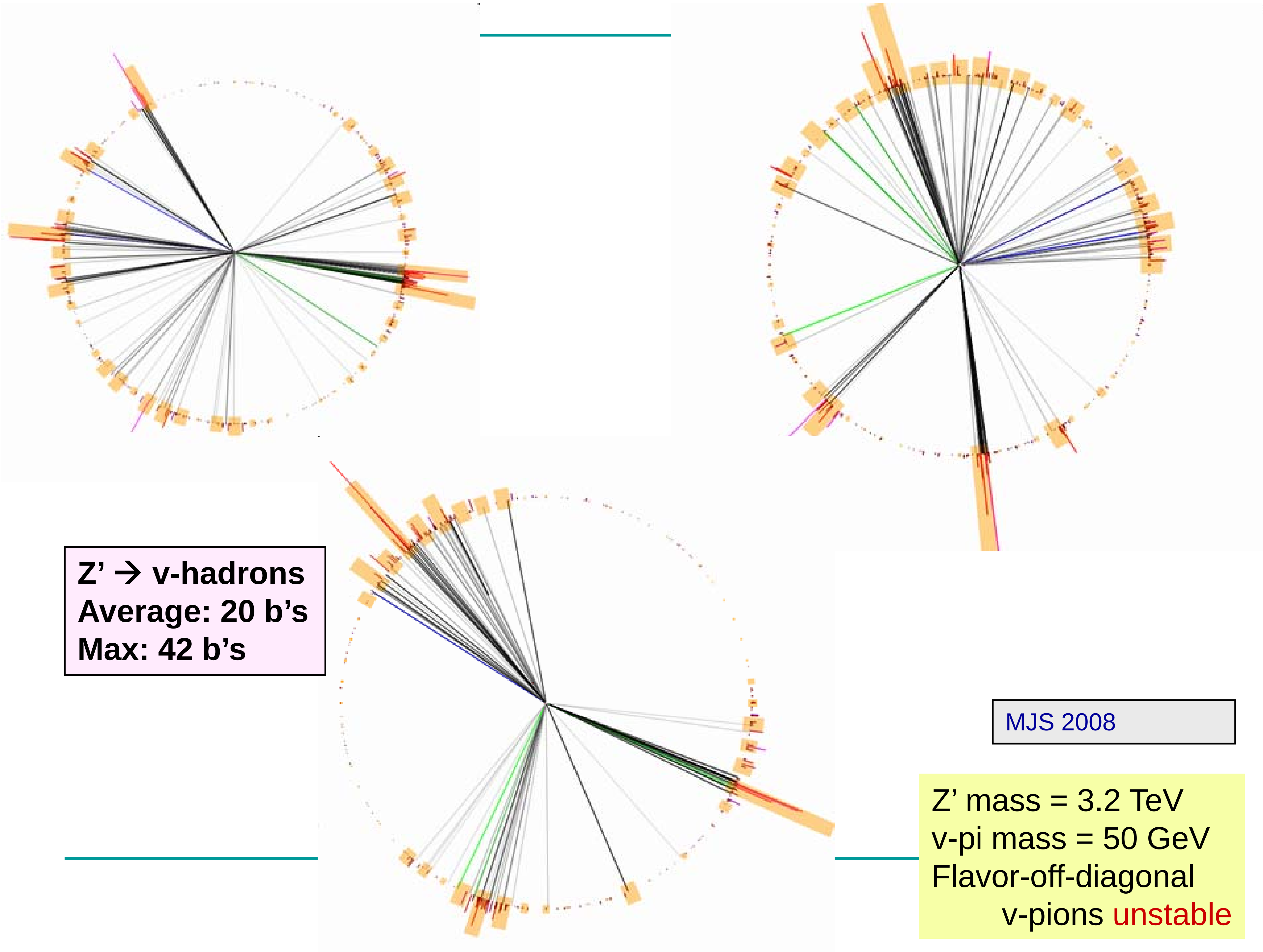
- For a process with high parton-parton invt. mass
  - Few if any v-particles decay invisibly

    ➔ large HT, low MET, high multiplicity

    ➔ Moderate QCD, tt backgrounds
  - Large fraction of v-particles decay invisibly

    ➔ medium HT, medium MET, medium multiplicity

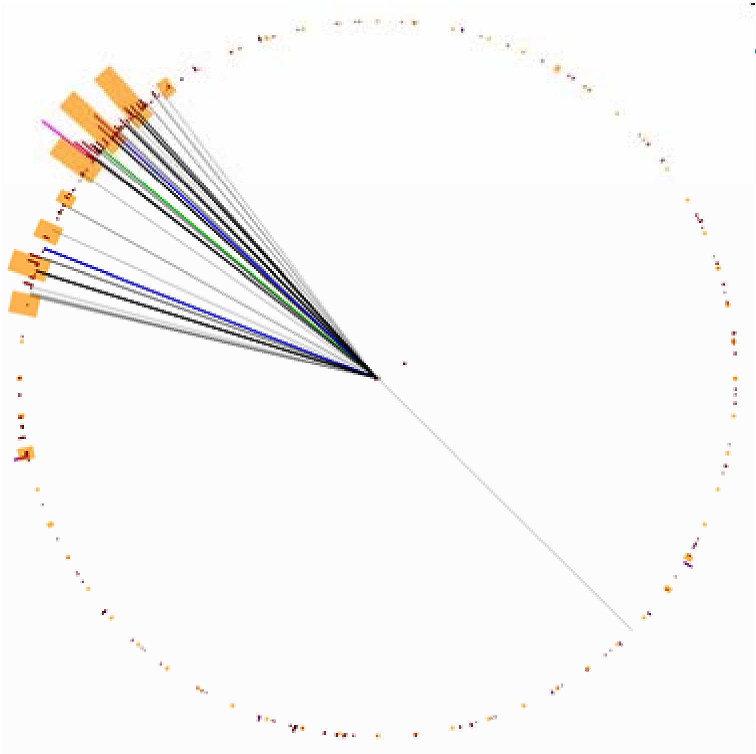
    ➔ Large Z + jets etc. backgrounds

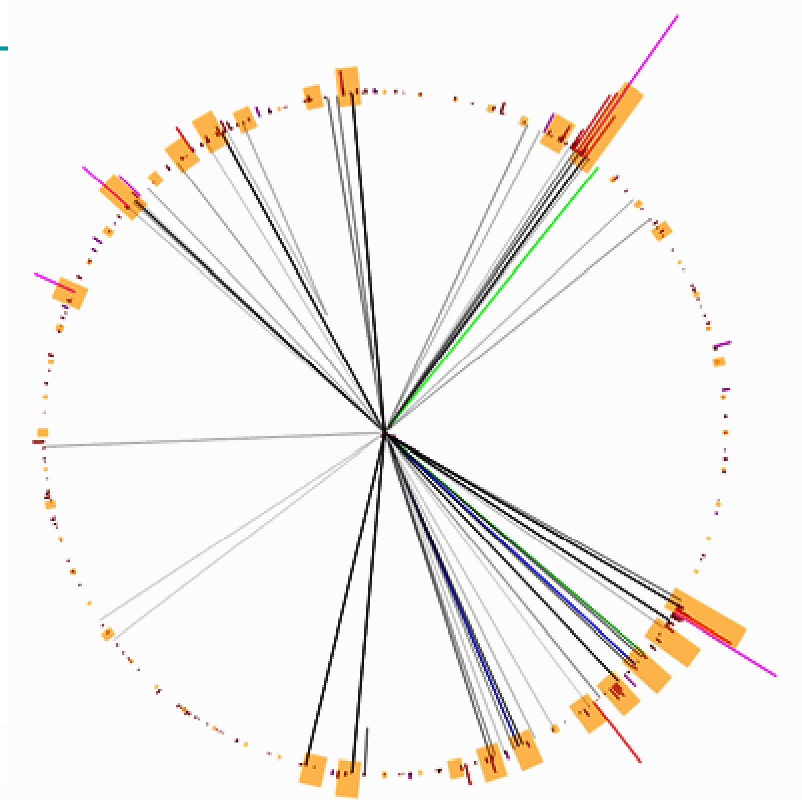


Z’ → v-hadrons
Average: 20 b’s
Max: 42 b’s

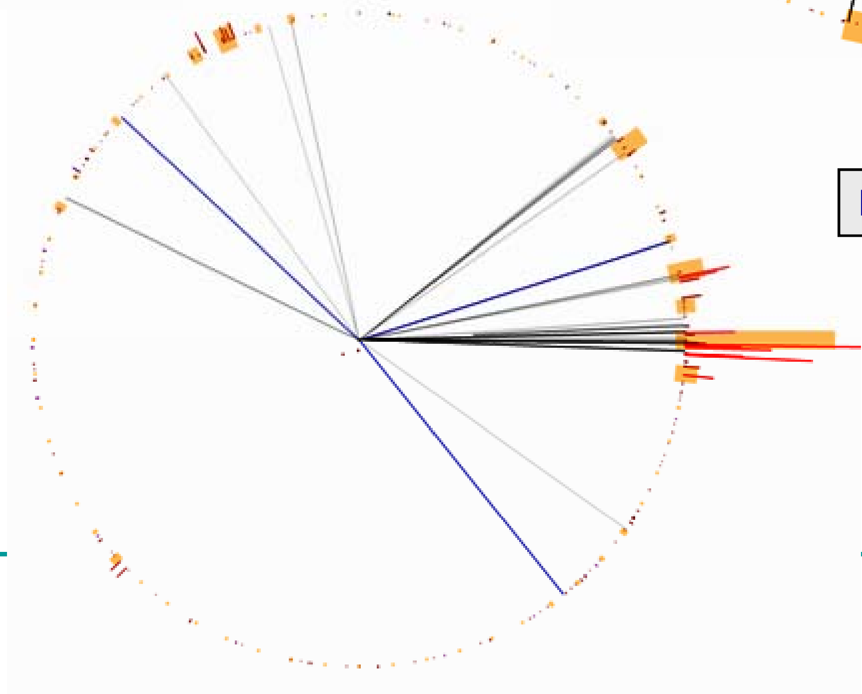
MJS 2008

Z’ mass = 3.2 TeV
v-pi mass = 50 GeV
Flavor-off-diagonal
v-pions unstable





Z’ → v-hadrons
Average: 8 b’s
Max: 22 b’s

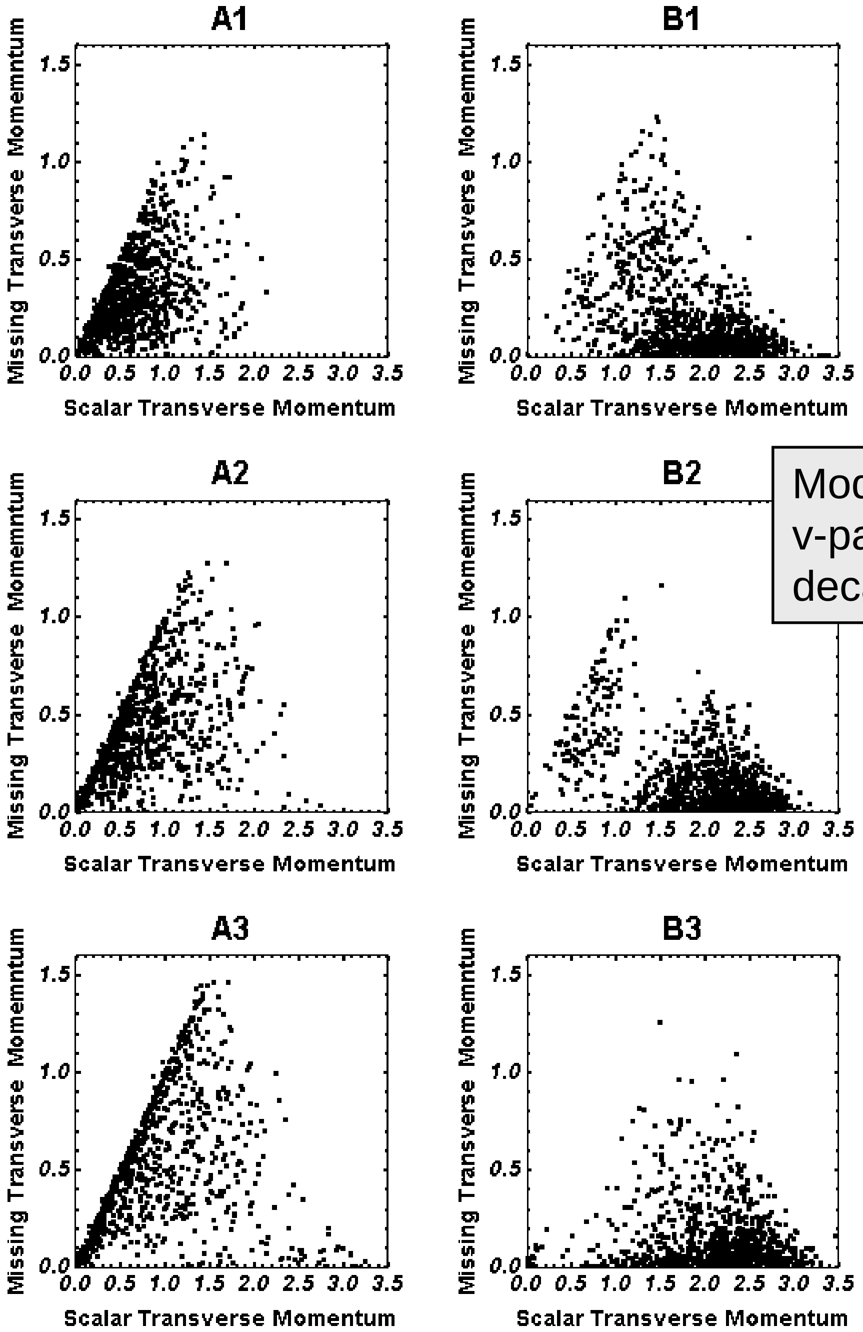


Prompt decays: MJS 08

Z’ mass = 3.2 TeV
v-pi mass = 50 GeV
Flavor-off-diagonal
v-pions stable

MET vs HT

Models with ~2/3 of v-particles stable and invisible



Models with all v-particles decaying visibly

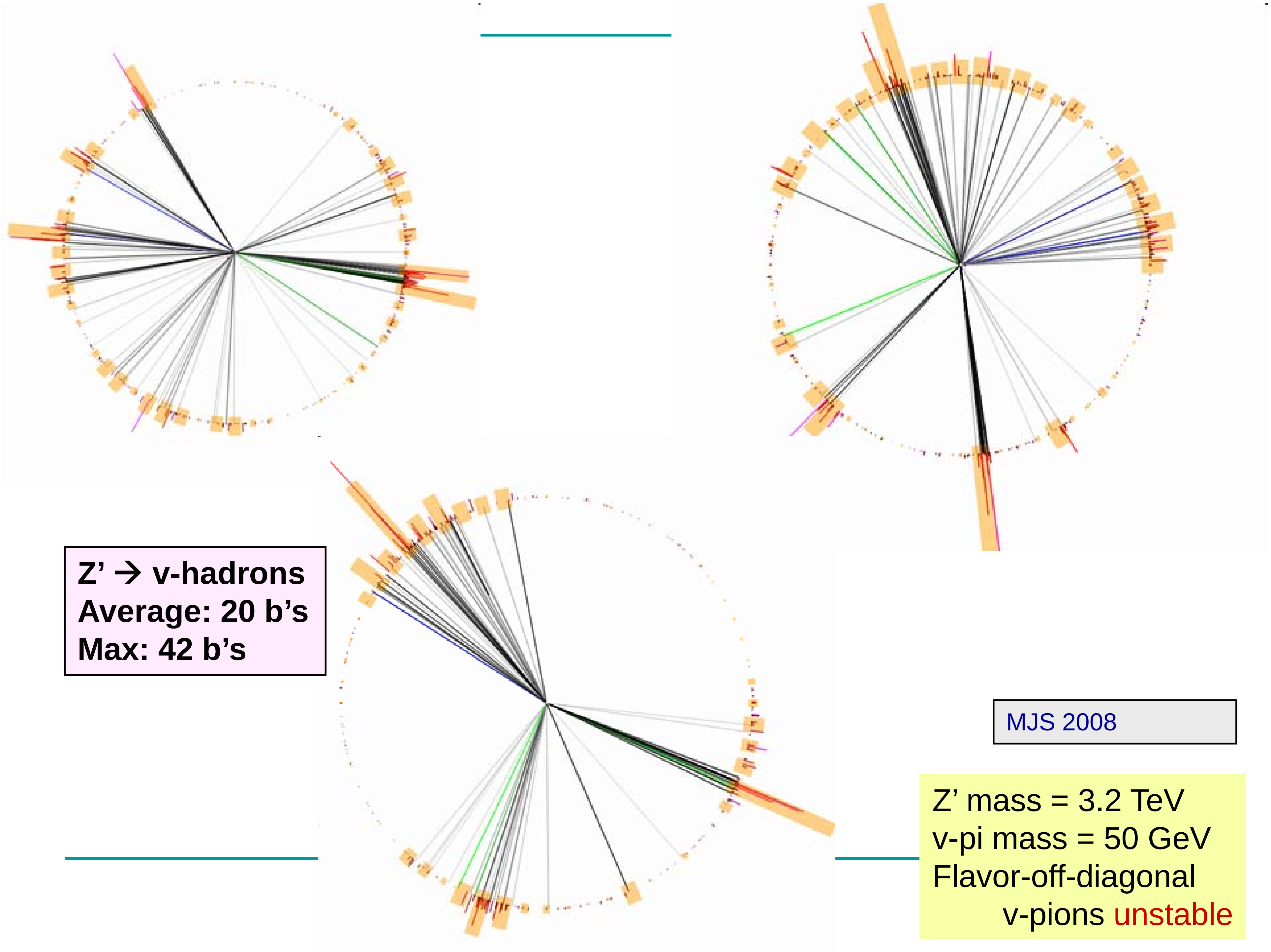
Missing Energy vs Scalar Transverse Calorimeter Energy

Event Selection Criteria

Overall Event Shapes … relatively unexplored territory

- Events with few invisible particles:
  - Tend to be oblong to spherical, not like dijets
  - Tend to be different from tri-jets (acoplanarity in some frame)
  - May be “spiky” or “mushy”

- Events with many invisible particles
  - Tend to be asymmetric (but so is Z + jets)
  - Highly variable!!!! Hard to get large sample with any one criterion
    - E.g. multiplicity of visible particles varies widely
  - May be “spiky” or “mushy” but not always so distinctive



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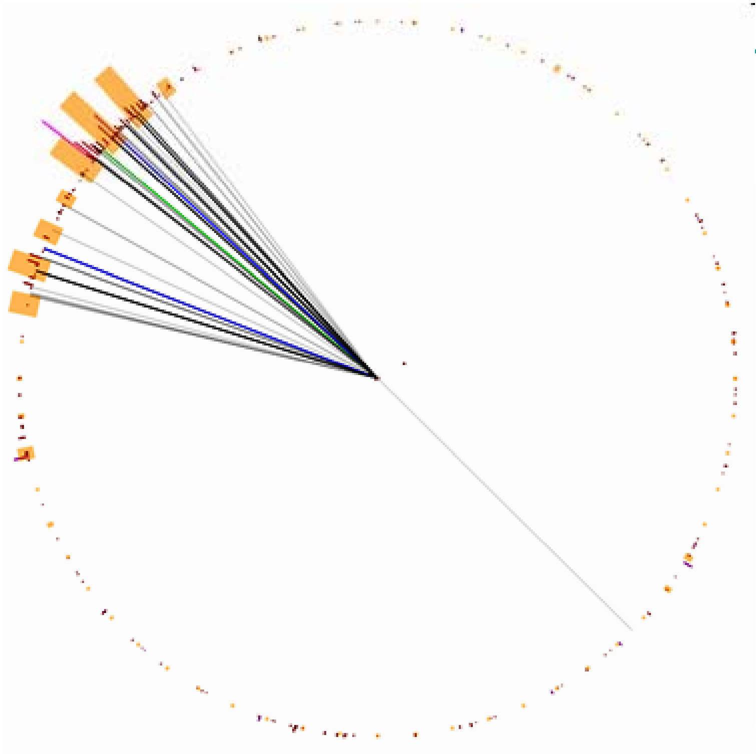

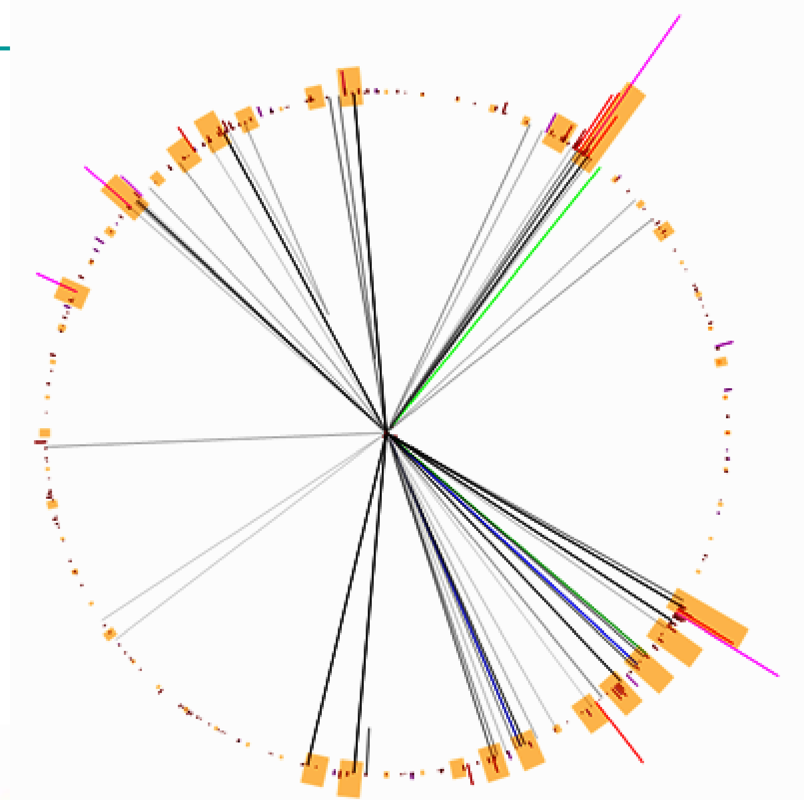

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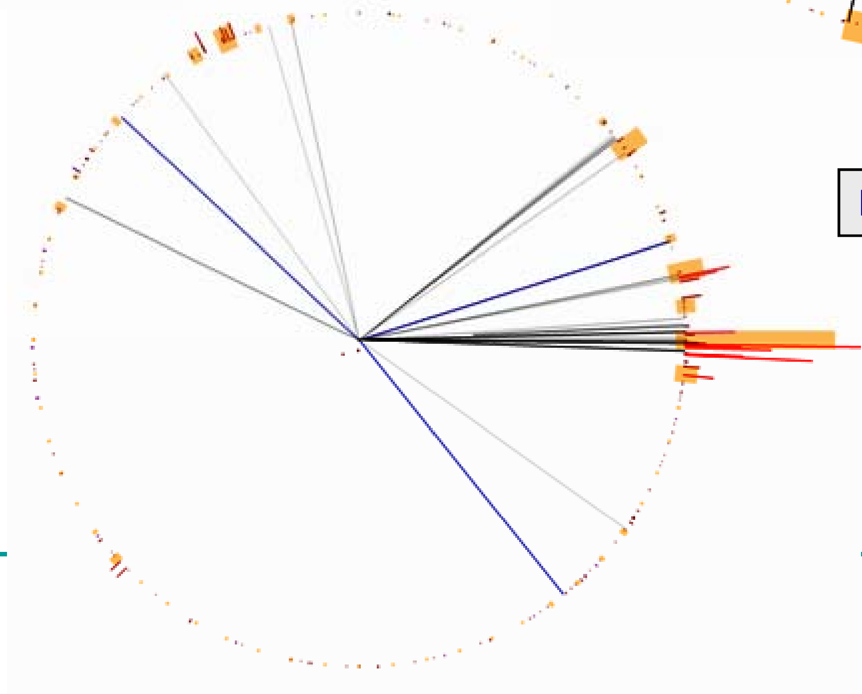
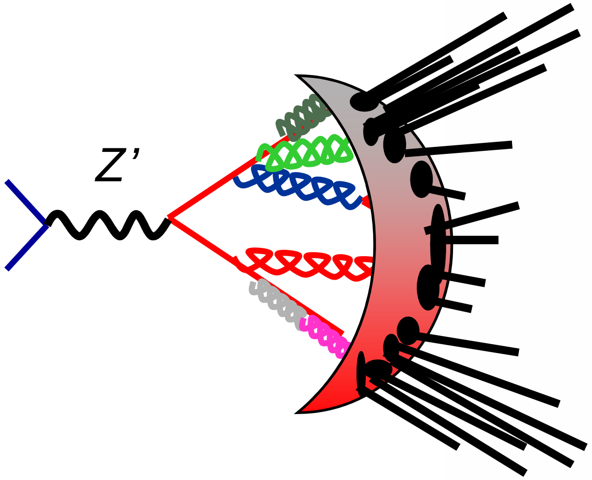
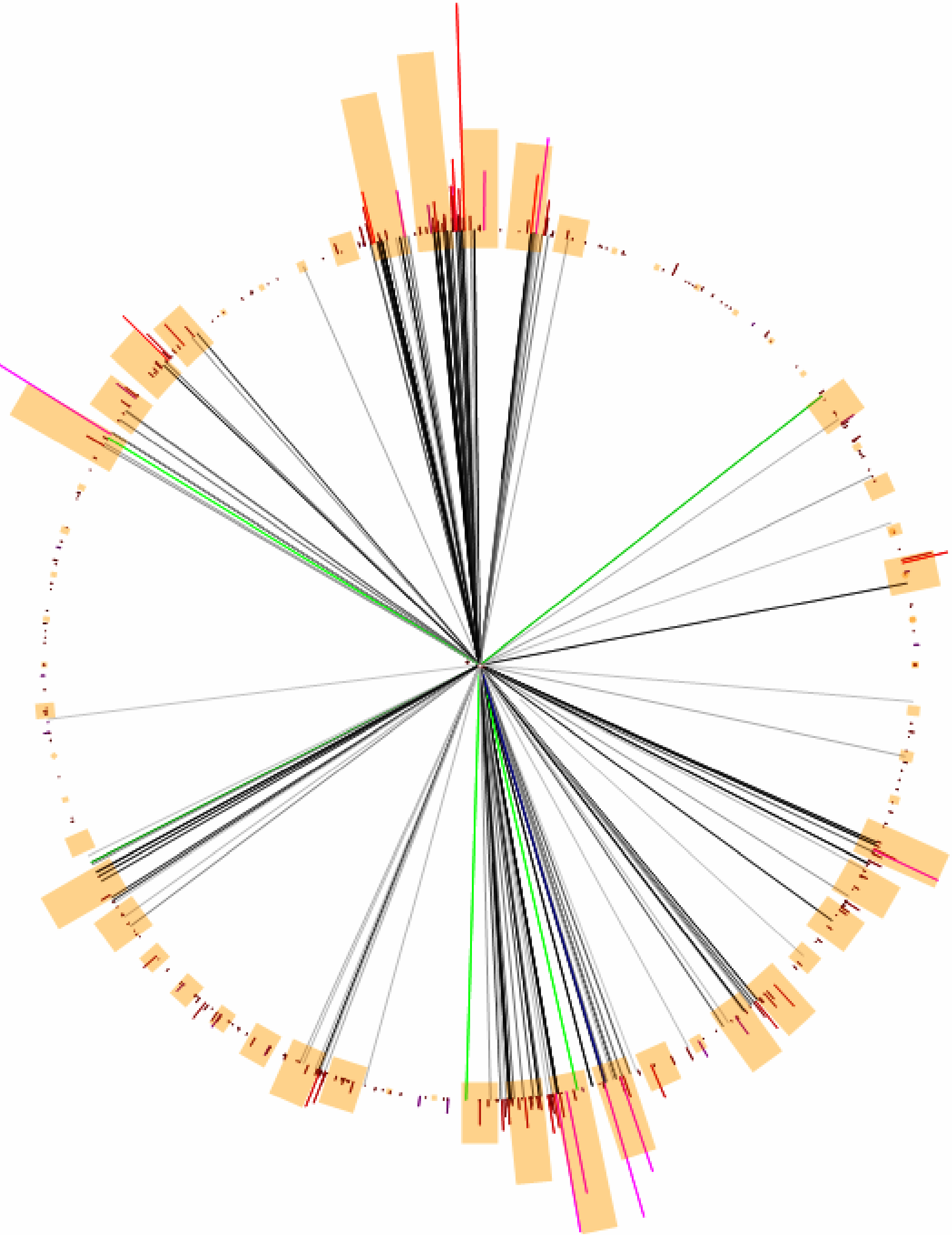


Z’ mass = 3.2 TeV
v-pi mass = 50 GeV
Flavor-off-diagonal
v-pions stable

UV Weak-Coupling
(small anom dims)
~ 10 v-hadrons
Some hard, some soft
~ of order 20 quarks/leptons
of widely varying pT





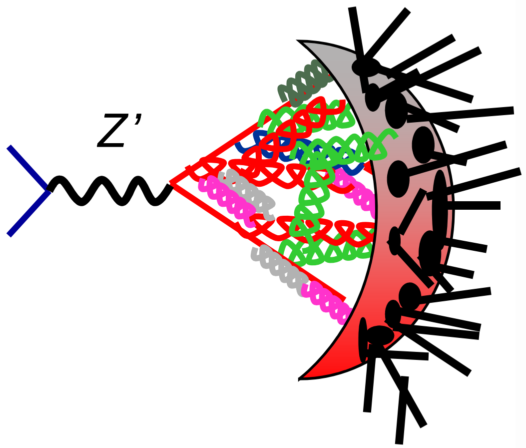
UV Strong-Coupling Fixed Point (large anom dims)

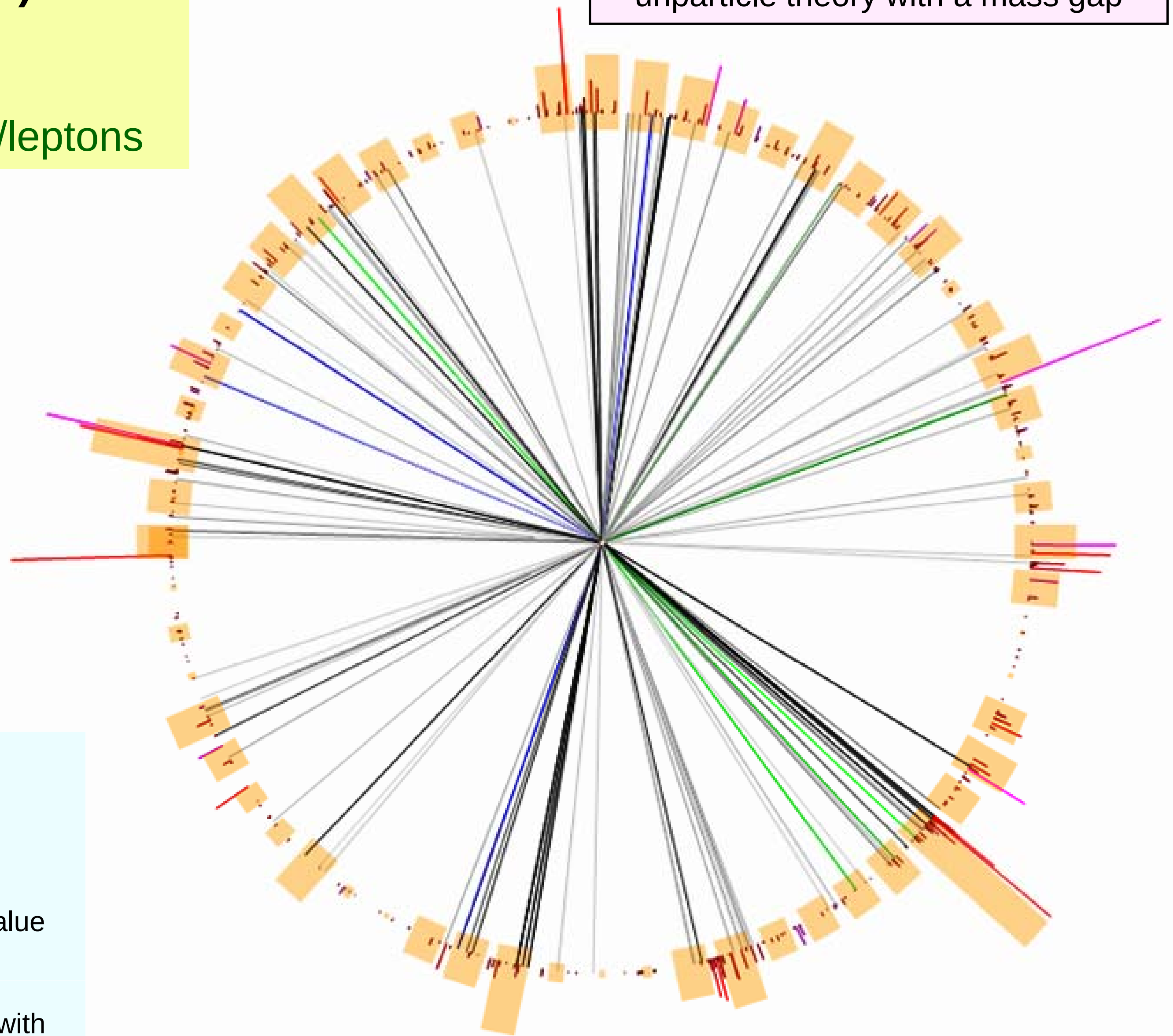
~ 30 v-hadrons

Softer v-hadrons

~ 50-60 soft SM quarks/leptons

This is sometimes called an "unparticle theory with a mass gap"





Educated guesswork!

Crude and uncontrolled simulation

- Fix α in HV Monte Carlo 0.5 at large value
    - This increases collinear splitting
- Check that nothing awful happens
- Check answer is physically consistent with my expectation

Conclusions for today…

- Hidden Valleys
  - allowed by experiment, consistent with dark matter, occur in string theory
  - urgent and important: must cover all bases at LHC!

- Long-lived particles:
  - trigger, reconstruction, analysis challenges

- High-multiplicity events and new resonances:
  - issues with reconstruction, isolation
  - event selection is key
  - standard n-tuples will often fail
  - events with invisible particles are challenging!

- Stay tuned for Friday… and feel free to bug me during the week… (except Wed.)