Peeking into a Hidden Valley:

A First Look at Exotic Phenomenology

Matthew Strassler
Rutgers University

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

M.J.S., in preparation
S.Mrenna, P. Skands, M.J.S., in preparation

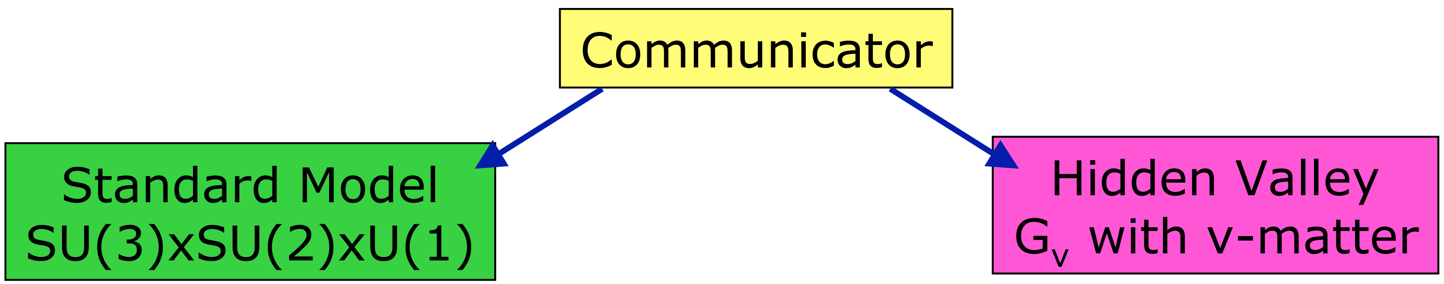
Plan of the Talk

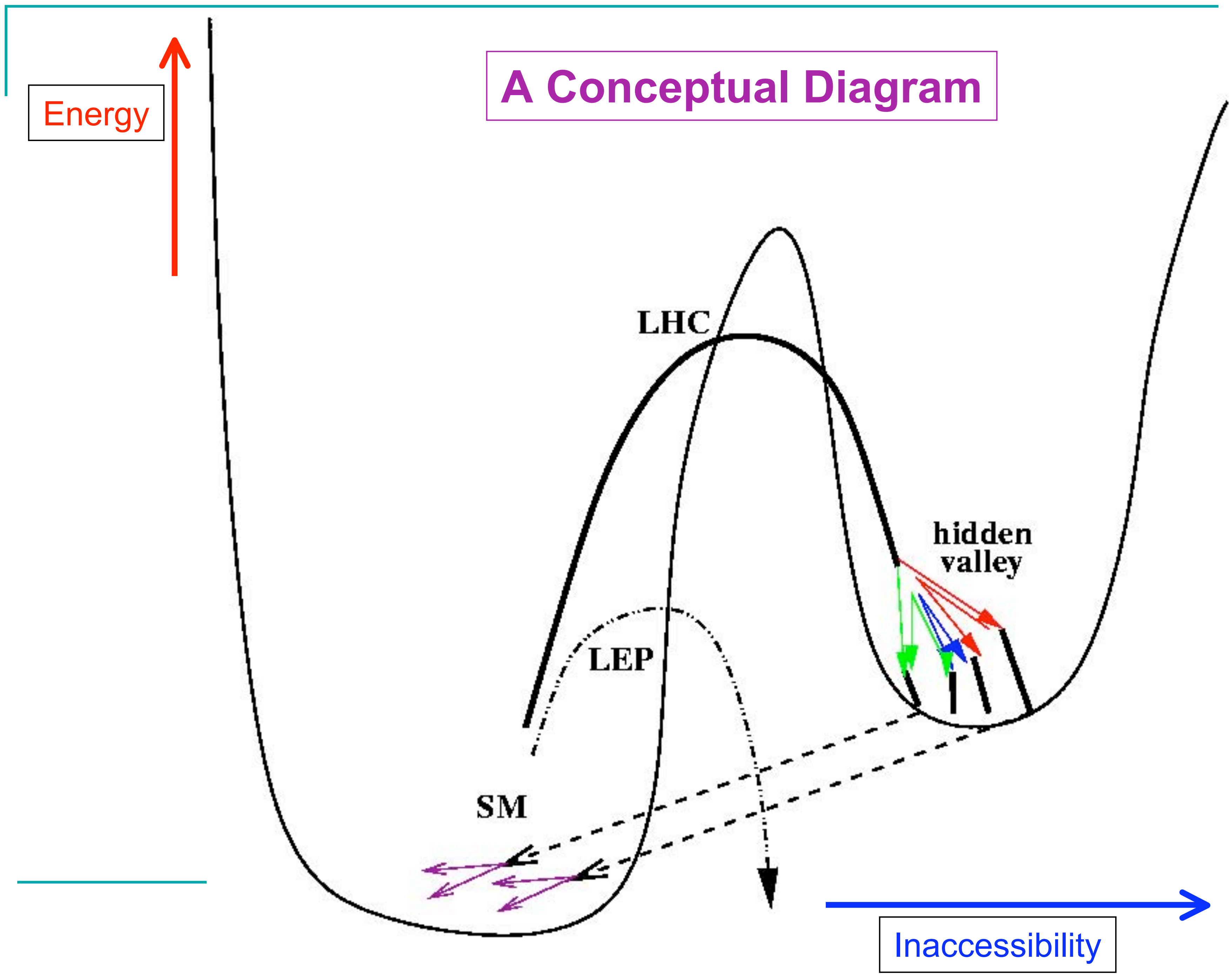
- What's a hidden valley, and why should we care?
- Basic properties of any hidden valley model
  - New neutral particles, possibly light
  - Various decay final states
  - Long lifetimes possible
- Production of HV particles in Higgs boson decay
  - New discovery channel
- Production of HV particles in SUSY processes
  - Obstructions and opportunities
- Production of HV particles in Z' models
  - Several cases with novel phenomenology
  - Hints of need for new reconstruction and analysis methods

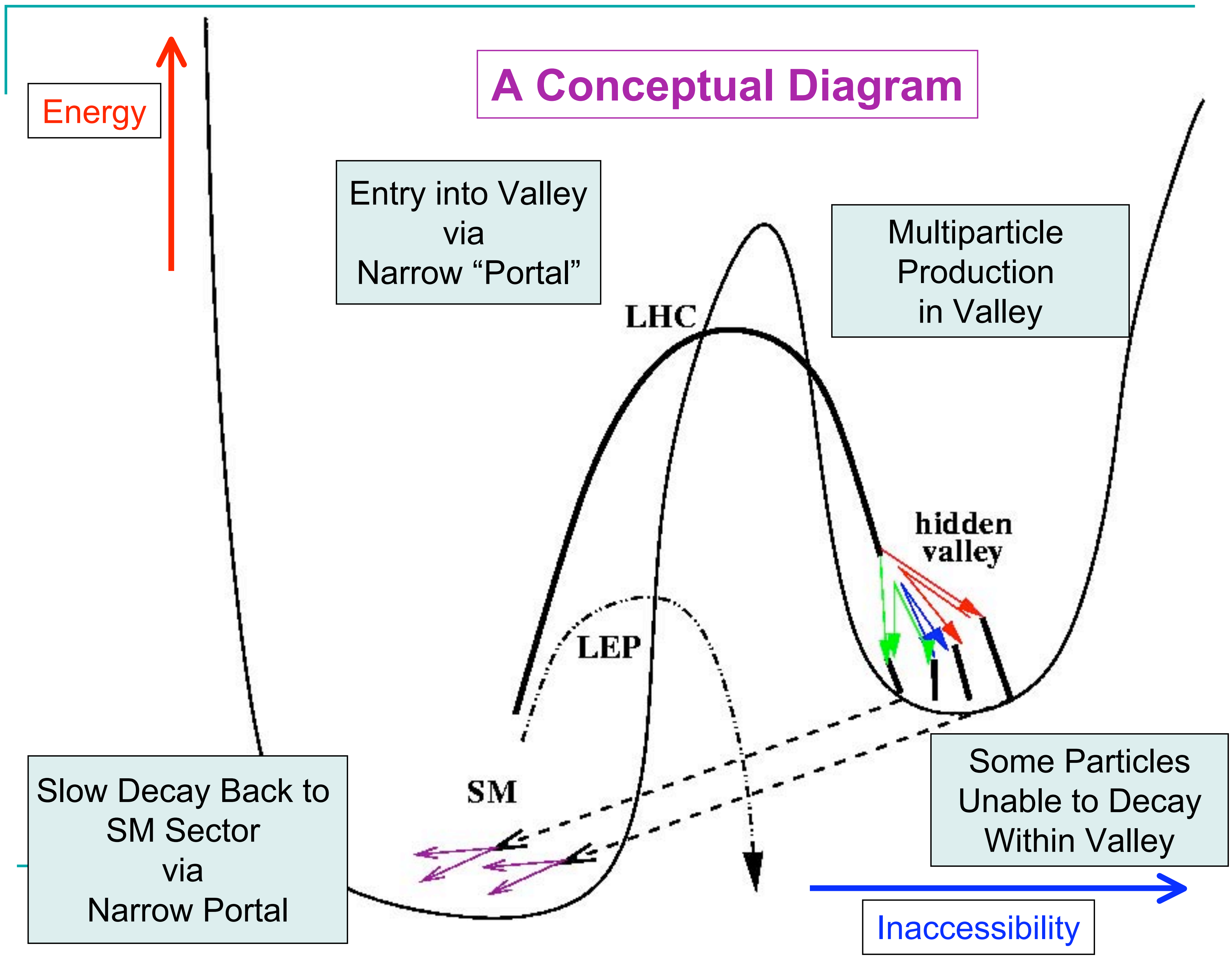
Hidden Valley Models (w/ K. Zurek)

hep-ph/0604261

- Basic minimal structure




A Conceptual Diagram
Energy
LHC
hidden
valley
LEP
SM
Inaccessibility


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

Hidden Valley Scenario

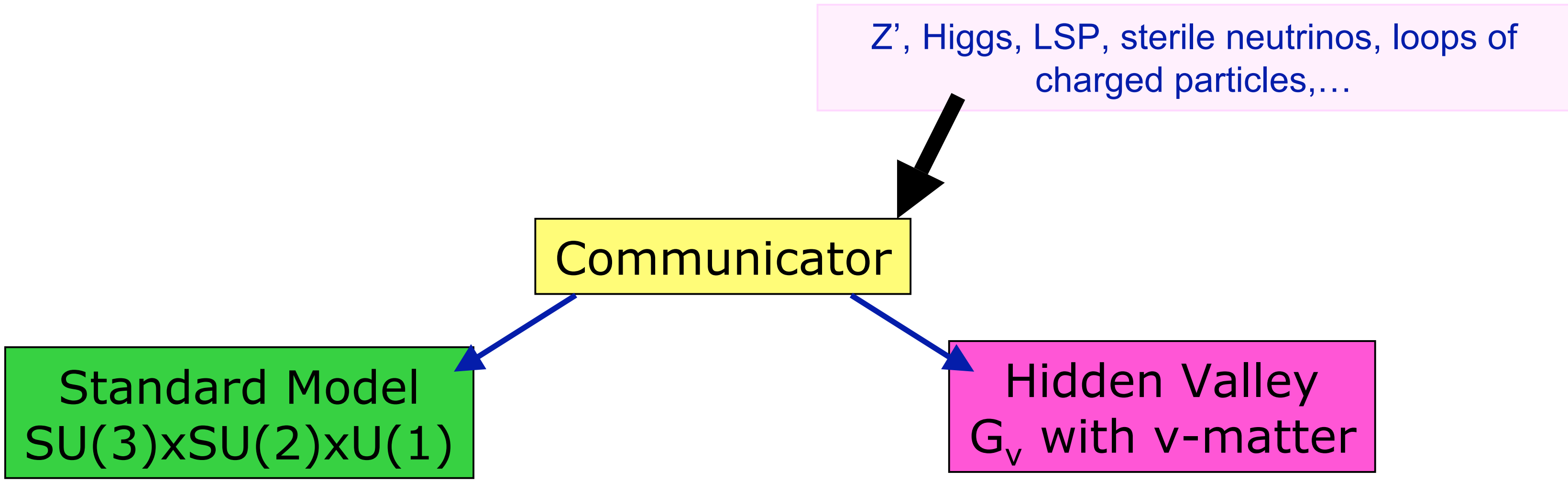
- A scenario, not a model !
  - Represents an enormously wide class of models
  - Models of this type exist in the literature [especially in string theory]

- Hidden sector is an very old concept. [Mirror matter]
  - Observable effects of Hidden Sector have been considered before

- What is new? Why a new name for old ideas?
  - A class with unnoticed fascinating and challenging collider phenomenology.
  - Emphasis on the reasonableness of these models.
  - Implications for Tevatron/LHC experiments are URGENT.

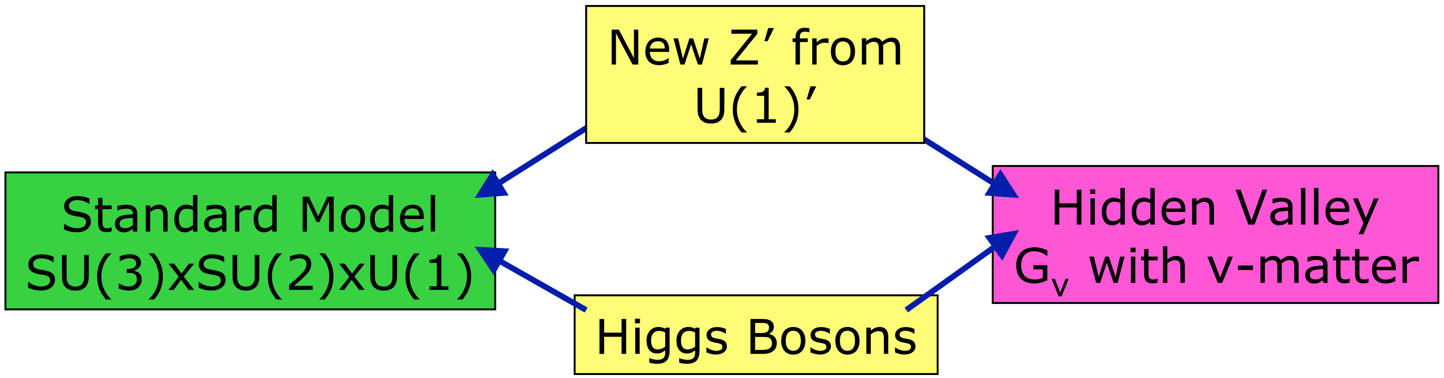
  - Can coexist with any solution to the hierarchy problem
    - SUSY, technicolor, little Higgs, RS, ADD, etc.
  - but in some cases **strongly alters** its phenomenology!

Hidden Valley Models (w/ K. Zurek)



Communicators

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

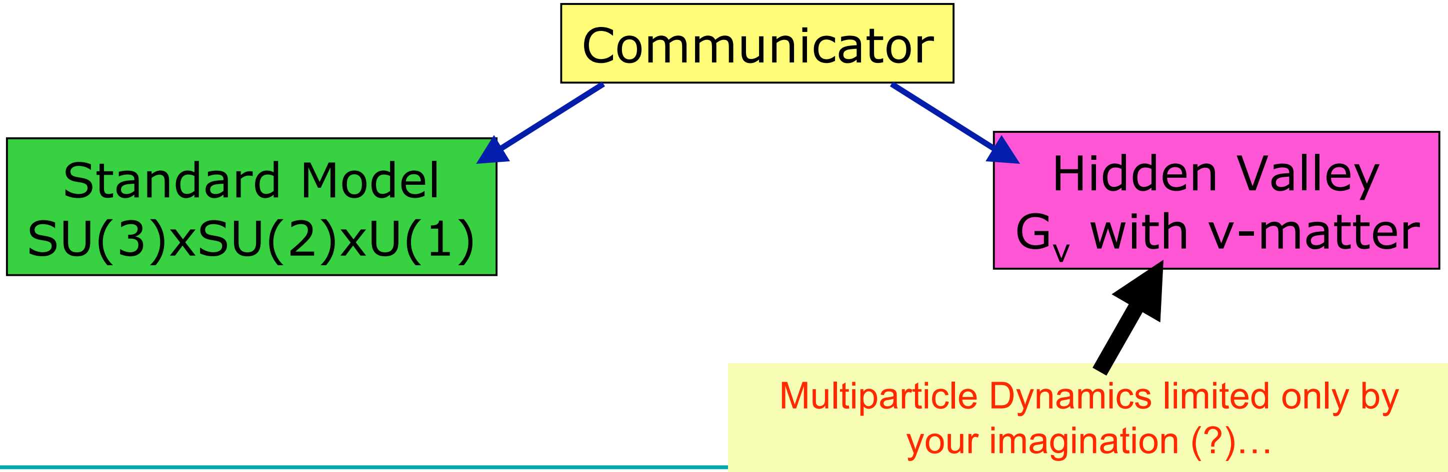


Hidden Valley Models (w/ K. Zurek)

Vast array of possible v-sectors…

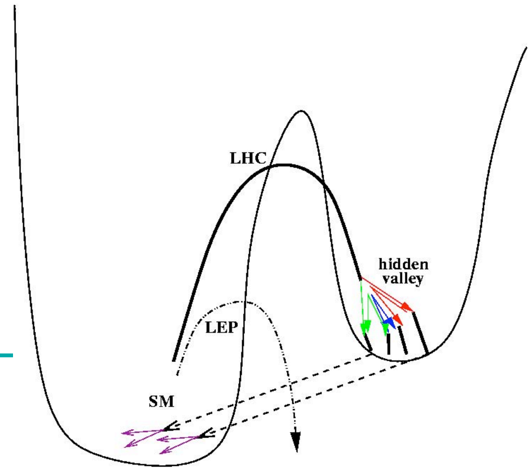
- QCD-like theory with F flavors and N colors
- QCD-like theory with only heavy quarks
- QCD-like theory with adjoint quarks
- Pure glue theory
- UV-fixed point → confining
- N=4 SUSY Conformal → N=1
- RS throat

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



Motivation: Why Hidden Valley

- One answer (my answer):
  - Top-down string models predict many hidden sectors
  - Nothing rules these models out experimentally
  - Phenomenology highly varied and unlike typical beyond-SM physics
  - Experimental implications for Tevatron and LHC are substantial and urgent
- Common Question:
  - Why should hidden sector have these properties?
    - A Z' at 1 – 5 TeV coupling us to hidden sector
    - A confinement (or symmetry-breaking) scale in 1 GeV - 1 TeV range
  - Isn't this unmotivated?
  - Aren't such models rather fine-tuned?
- Z' at 1 TeV ?
  - TeV scale Z' not ***required*** in hidden valley models
- New dynamics at 1 GeV – 1 TeV?
  - Question for you: *why is QCD scale so close to EW scale?*



Why is QCD scale so close to EW scale?

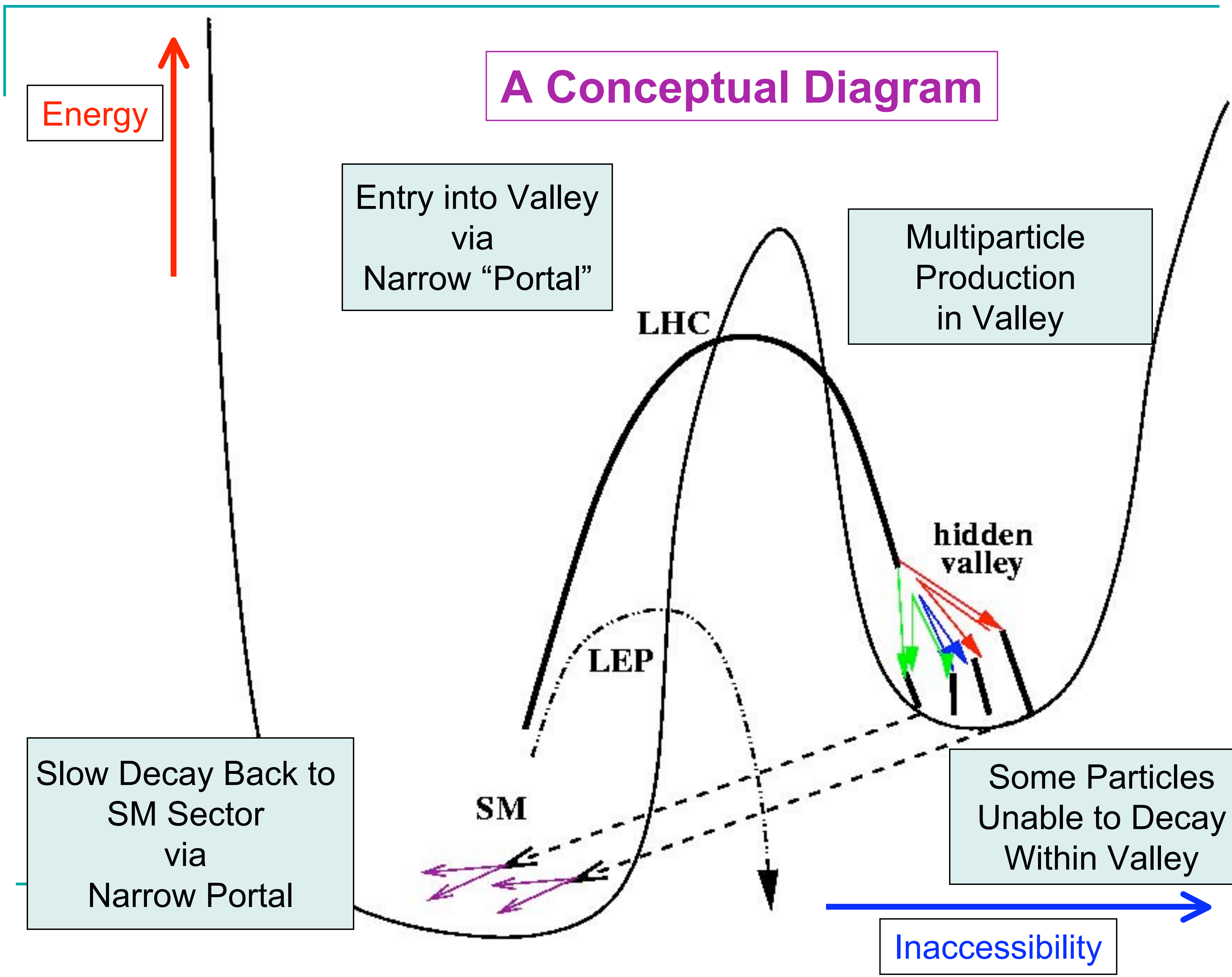
- Answer: Partly chance; Partly **Hierarchy Compression**

- Example: SUSY model
  - SUSY-breaking sector gives soft masses ~ 100 GeV-1 TeV
  - This drives EW Symmetry breaking at ~ 100 GeV
  - Together these make many particles massive (gluino, squarks, top)
  - In turn makes the SU(3) beta function more negative
    - From -3 to -7.4
  - *Increases SU(3) strong-dynamics scale from 1 keV to 100 MeV !!*

- Why EW scale at 100 GeV? soft masses at 1 TeV
- Why QCD scale close to EW scale? soft masses at 1 TeV

- SUSY breaking often feeds into valley sector as it does into ours

- Thus several dynamical scales may easily cluster below and near 1 TeV
    - In our sector
    - In some hidden sectors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Decays of v-hadrons to SM

- Imagine a confining v-sector
  - v-quarks, v-gluons → v-hadrons

- Most v-hadrons decay immediately to other v-hadrons (like r → p p)
- Those that do not
  - May be completely stable
  - May decay to SM via communicator(s)

- Several natural pathways for decays
  - Scalars and Pseudoscalars
    - Decays to heavy flavor
      - X → bb, cc, tau tau
  - Vectors and Axial Vectors
    - Decays democratically
      - 2 body decay X → f f
  - Fermions (also some others)
    - Decays democratically
      - 3 body decay X → f f Y
  - Other options (will not appear in today's examples)
    - X → pairs of photons, gluons ;
    - 4-body decays

Lifetimes Long for Many Reasons

- Many ways to have long lifetime for v-hadrons
  - Light v-hadron 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-hadrons in each model → multiple lifetimes
- v-Hadron decays may easily be anywhere
  - prompt (d < 0.1 mm)
  - displaced (0.1 mm < d < 3 cm)
  - highly displaced (3 cm < 10 m)
  - outside detector (> 10 m)
- I will discuss prompt and late decays in parallel

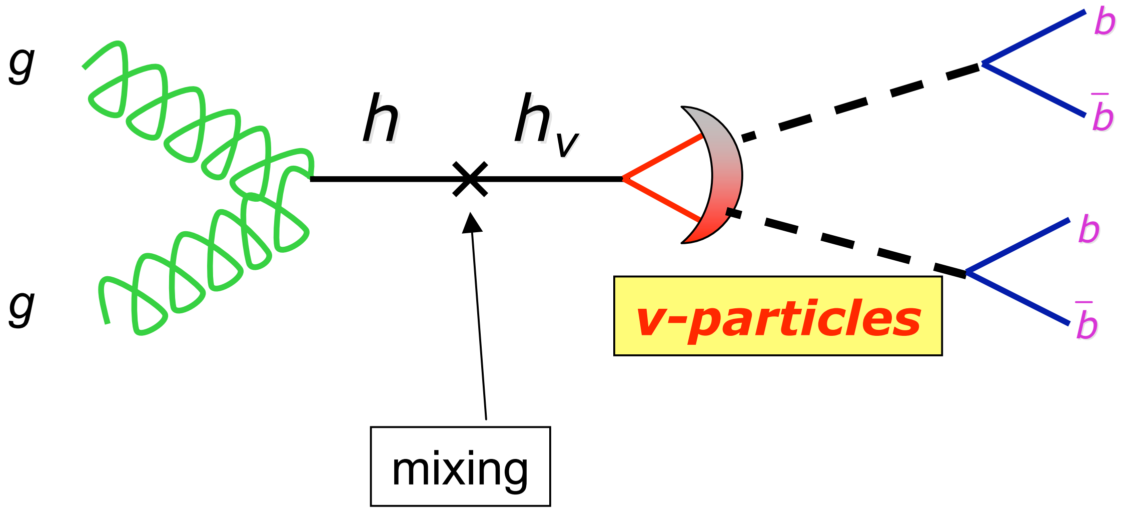
Production #1: Higgs boson decay

- 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)

Higgs decays to the v-sector

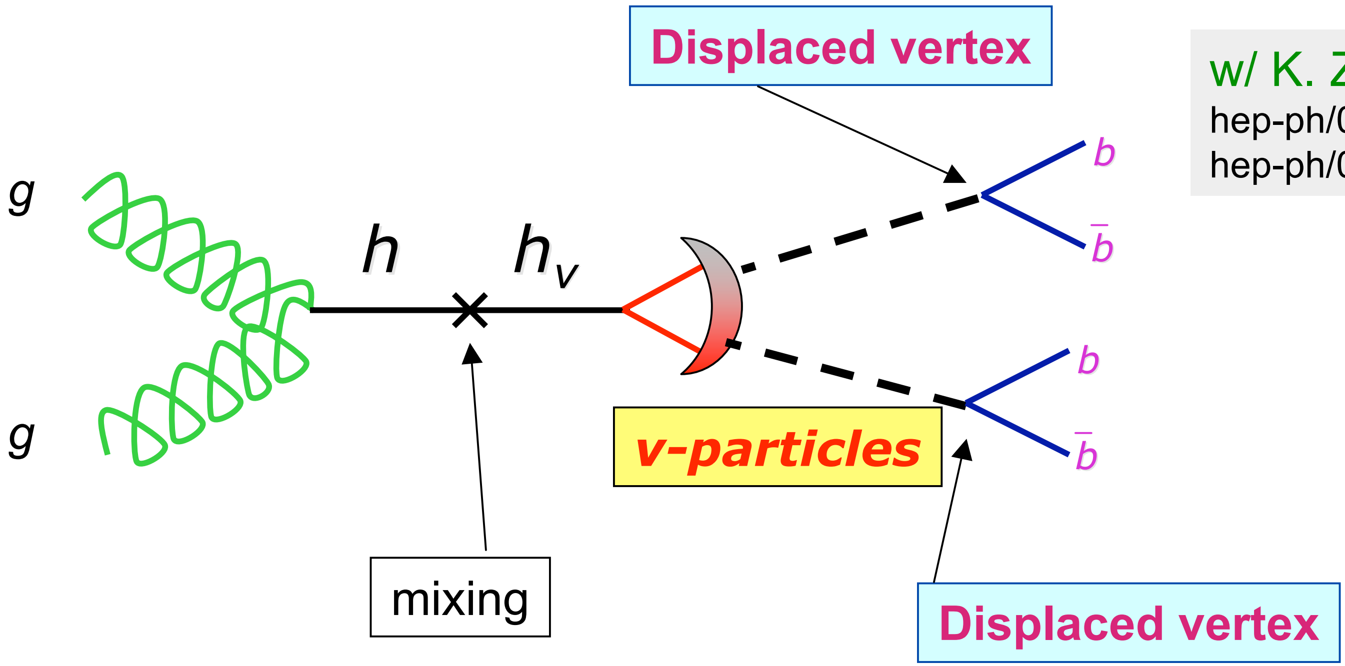
w/ K. Zurek
hep-ph/0604261
hep-ph/0605193



See Dermasek and Gunion 04-06 and many others following

h→ aa → bb bb, bb t t , t t t t , etc.

Higgs decays to the v-sector



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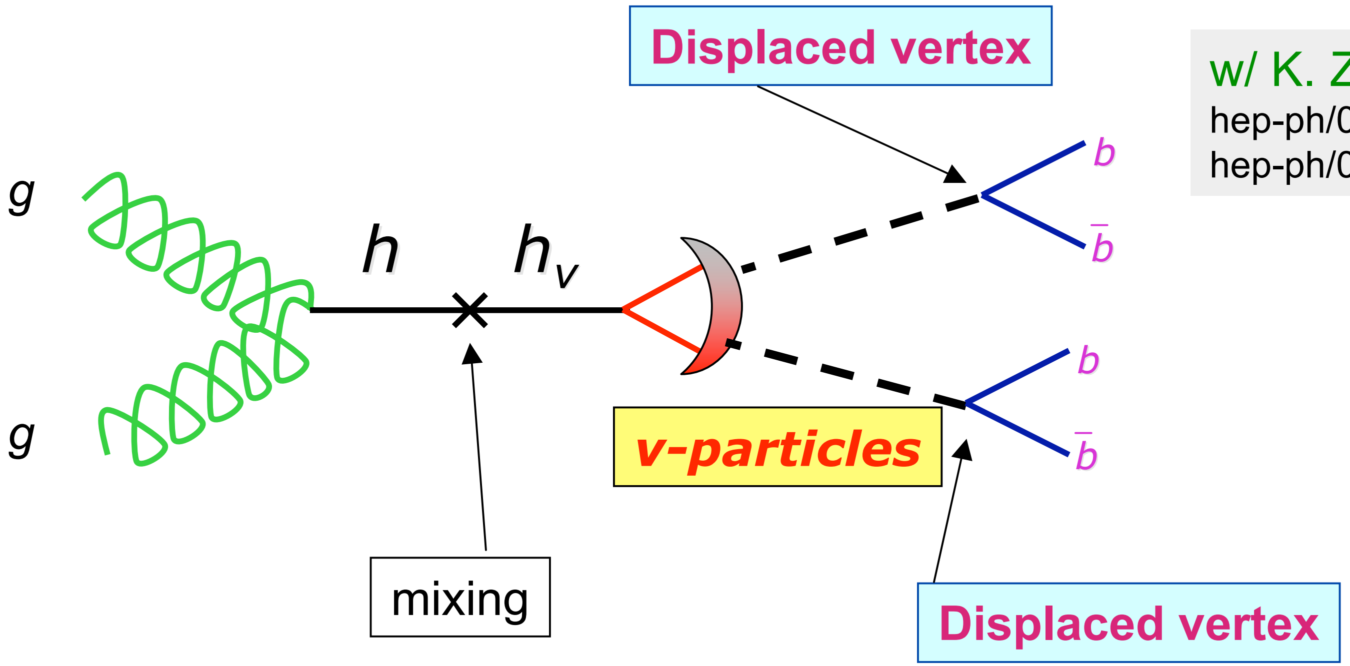
Higgs decays to the v-sector

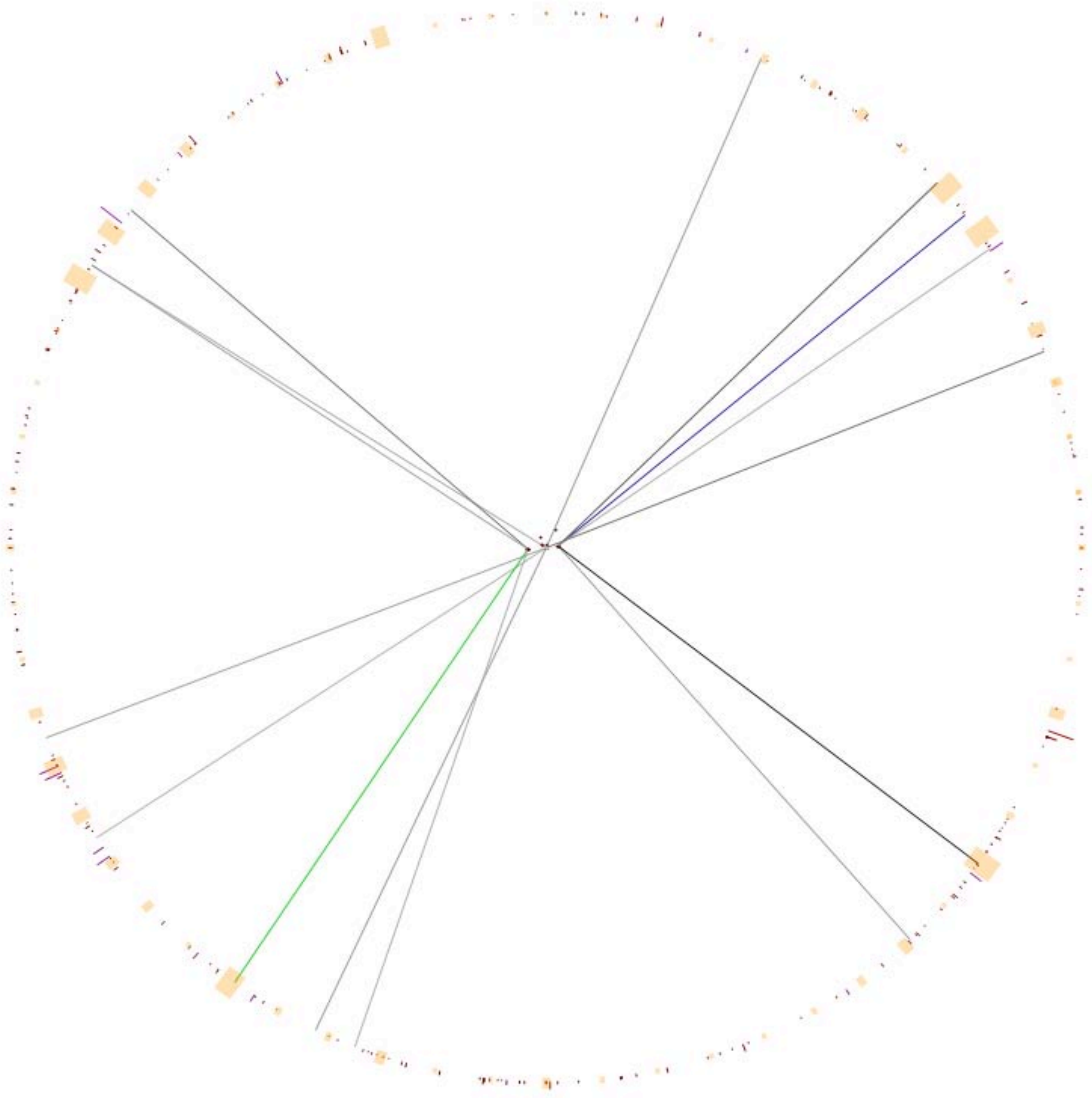
Overlooked Discovery Mode for the Higgs!!

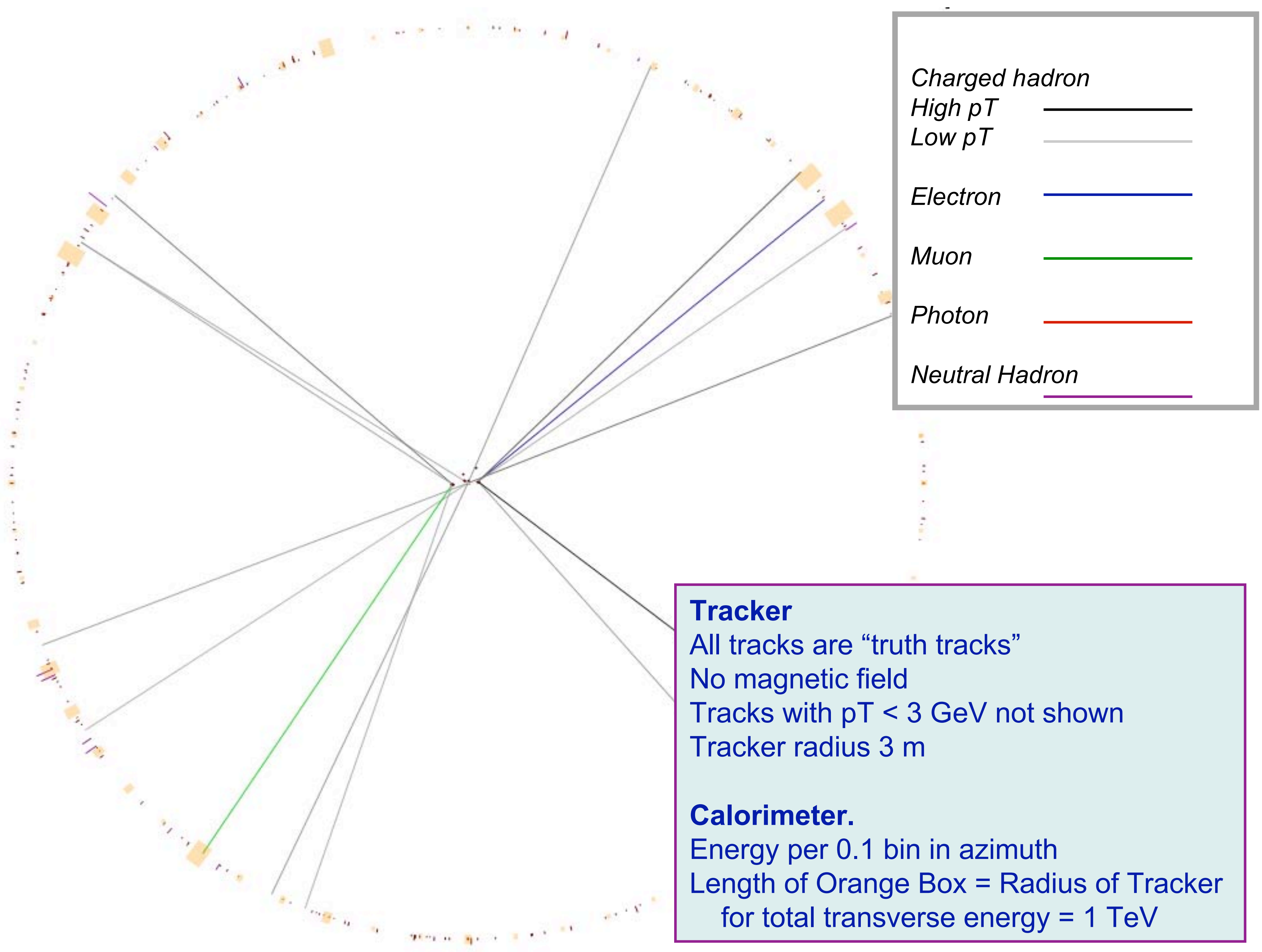


w/ K. Zurek
hep-ph/0604261
hep-ph/0605193

Precursor: Chang, Fox and Weiner, limit of model mentioned in **hep-ph/0511250, Naturalness and Higgs decays in the MSSM with a singlet.** Focus on LEP.

Similar Results: **hep-ph/0607204** : Carpenter, Kaplan and Rhee, **Reduced fine-tuning in supersymmetry with R-parity violation;** X → jjj

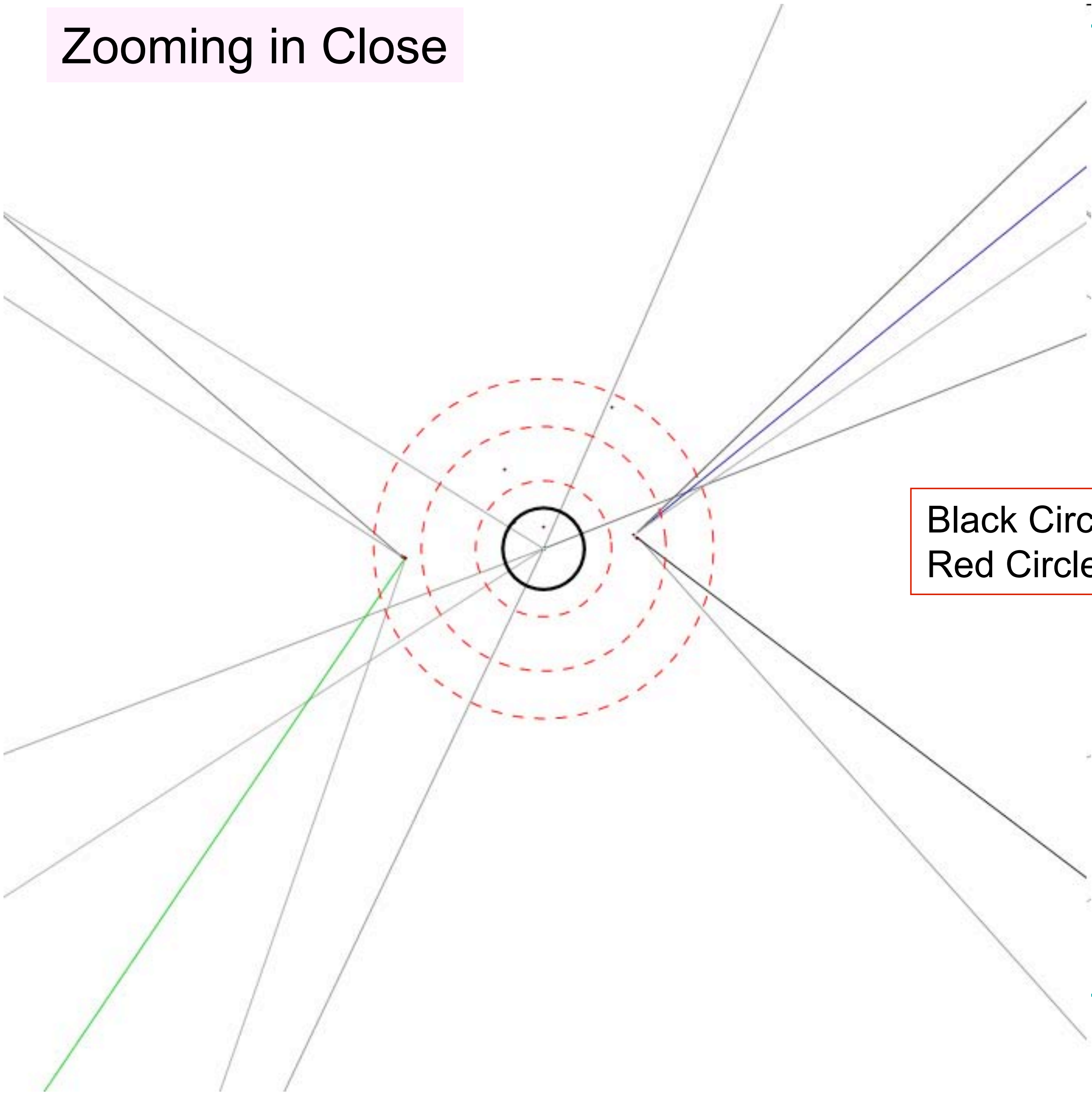




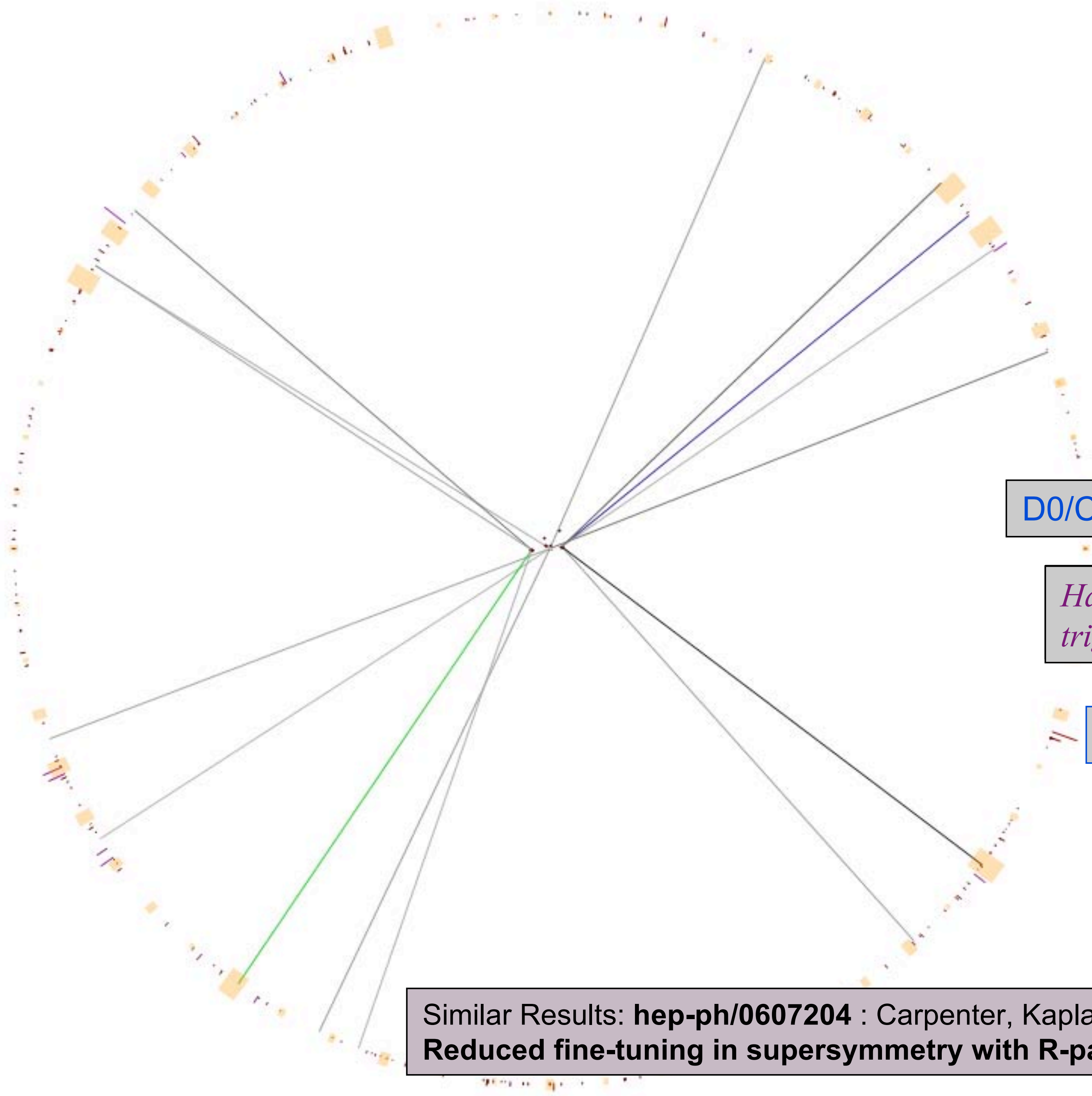
Tracker
All tracks are “truth tracks”
No magnetic field
Tracks with pT < 3 GeV not shown
Tracker radius 3 m

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



D0/CDF might see this…

Hard for ATLAS/CMS to trigger!?

LHCb might win here!

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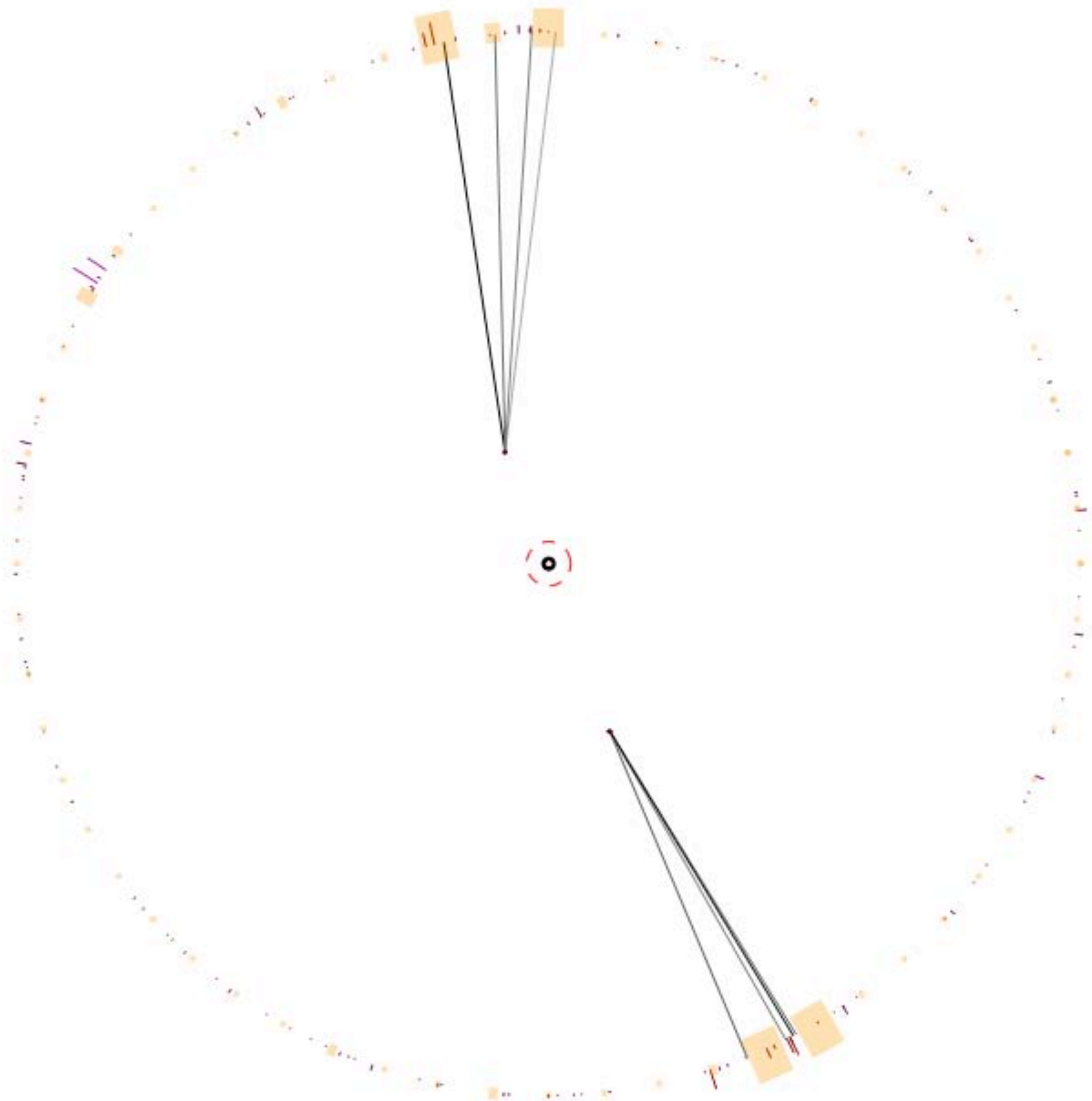


Black Circle: 3.0 cm
Red Circle: 12.5 cm

Long-Lived Neutral Weakly-Interacting X

- Spectacular signal – **if** you see it !! Serious challenges for
  - 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?

Finding the X isn't easy

- CDF/D0
  - Can look (& are now looking) for vertices in beampipe or in pixels (20 cm)
  - No simple method for finding decays further out; no attempts made
    - Events would need to be reprocessed with new tracking software
  - No special triggers for enhancing signal

- CMS/ATLAS
  - CMS/ATLAS cannot easily trigger on low pT events
    - Must study VBF, not easy; or Wh, low rate;
    - Or give up and wait for 2-photon decay (possibly reduced!)
  - Design special triggers for long-lived SM-neutral particles?
    - Studies underway
      - cf. Hidden Valley Working Group, ATLAS [UWashington, Rome 1, Genoa]
  - No reconstruction studies

- LHCb
  - For lifetime 0.1 – 30 (?) cm,
    - vertexing, low trigger threshold makes up for low luminosity, low acceptance
      - cf. S. Stone, Syracuse group
      - Also European groups working on Carpenter Kaplan Rhee model

Production #1: Higgs boson decay

- Higgs → X X
  - Two pseudoscalars X
    - X → heavy flavor
    - H → 4 b's or tau's
- MJS & Zurek 4/2006,5/2006
  - CDF/D0 mass reach extended?
  - CMS/ATLAS trigger trouble
  - LHCb discovery possibility!
- Other final states possible
  - XXXX → 8 displaced b's
  - Y Y → displaced leptons
- Precursor:
  - Chang, Fox & Weiner 11/2005
- Similar results:
  - Carpenter, Kaplan & Rhee 7/2006:
    - X → 3 jets (R-parity violating SUSY)

X decay	Comment
Prompt	Famous (and difficult) NMSSM scenario
Displaced	**New Discovery Channel?!**
Highly Displaced	**New Discovery Channel?!**
Outside Detector	Invisible Higgs

Production #2: SUSY decays

- The SM LSP is ***also*** extremely sensitive to new sectors
- IF
  - R parity conserved
  - Lightest SM superpartner heavier than the true LSP in another, hidden sector

  then SM LSP will decay to the hidden LSP
- Much more general than SUSY!
  - Applies to lightest particle in SM stabilized by
    - KK parity in extra dimensions,
    - T parity in little Higgs
    - Any new global symmetry
- All of this is well known…
  - Gauge mediated SUSY decays to gravitino
  - Neutralino decays to singlino
  - Etc.
- However, useful to review, and note new elements

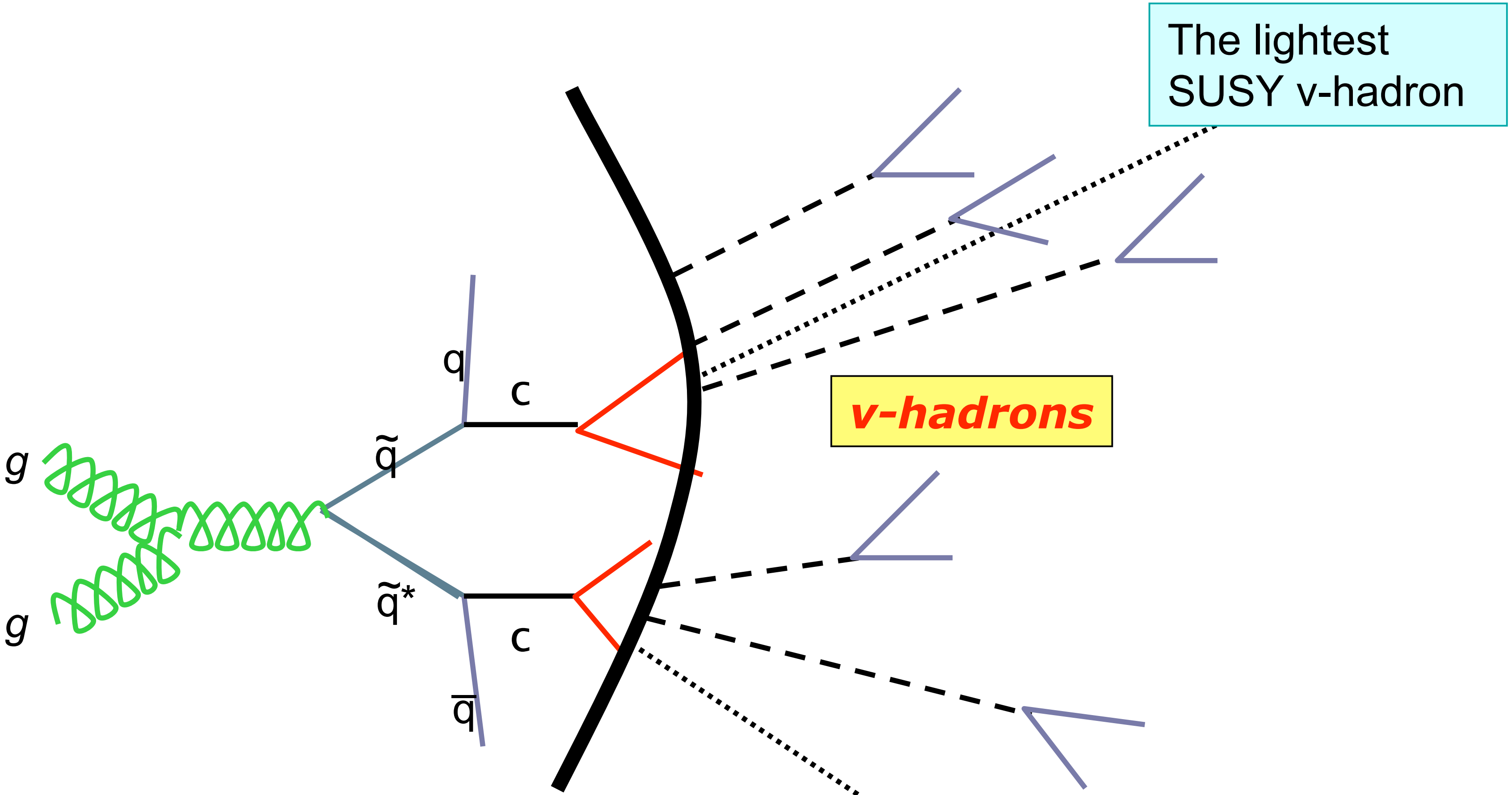
Production #2: SUSY decays

- If the SM LSP decays to hidden LSP
  - Need not be electrically neutral or color neutral!
    - Any SM superpartner can be the LSP!
  - May be long lived and may
    - Leave a track
    - Make an R-hadron
    - Decay with displaced vertex
    - Etc.

- If hidden sector has complex multiparticle dynamics,
  - Several hidden particles may be produced in SM LSP decay
  - Only one (the hidden LSP) need be stable
  - Others may decay visibly,
    - possibly with long lifetimes

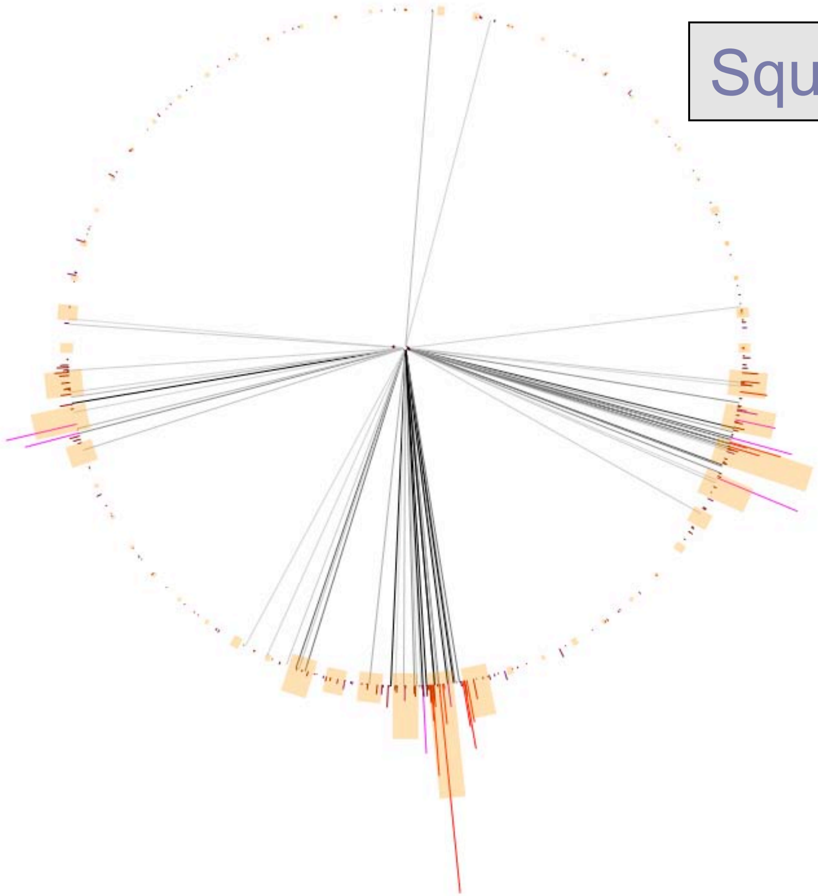
SUSY decays to the v-sector

MJS July 06



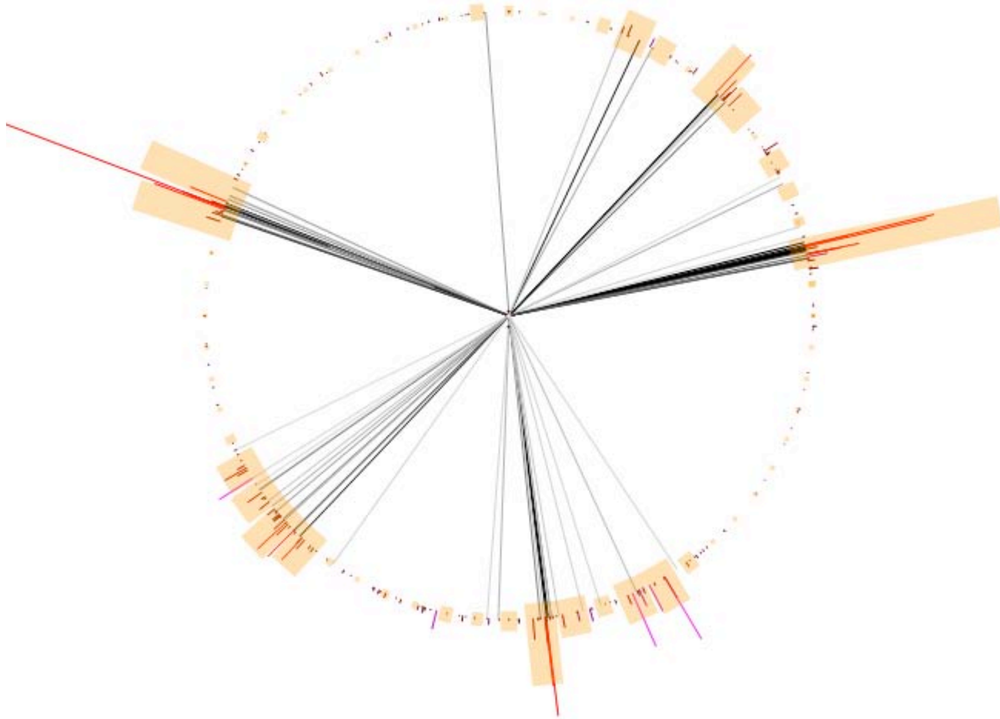
The traditional missing energy signal is replaced with multiple soft jets, reduced missing energy, and possibly multiple displaced vertices

Squark-Antisquark Production at LHC



Stable Neutralino

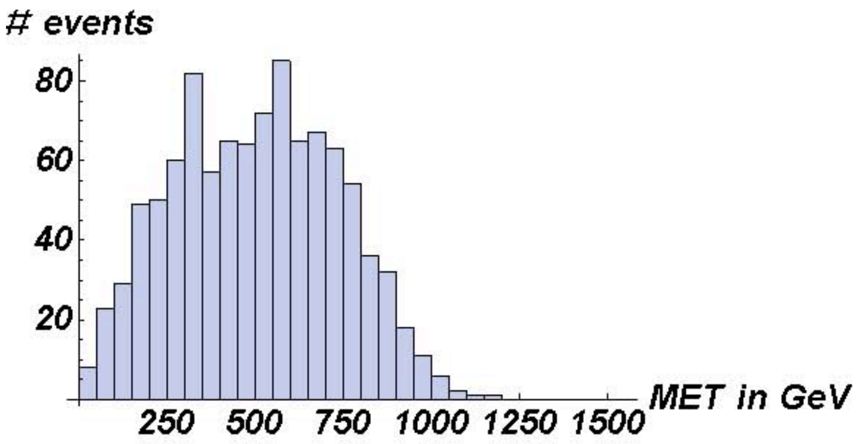
Unstable Neutralino
Decaying to v-Sector



Hacked simulation using
Hidden Valley Monte Carlo 1.0
Mrenna, Skands and MJS

Reduction of Missing Energy Signal

Distribution of Missing Transverse Energy



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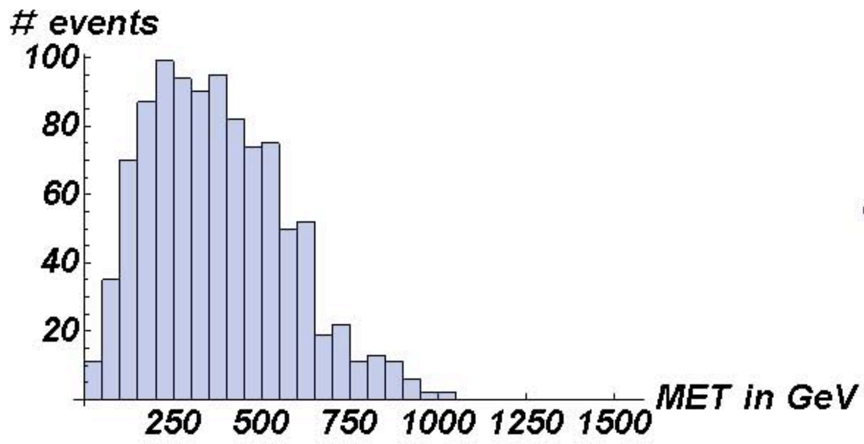

Unstable Neutralino
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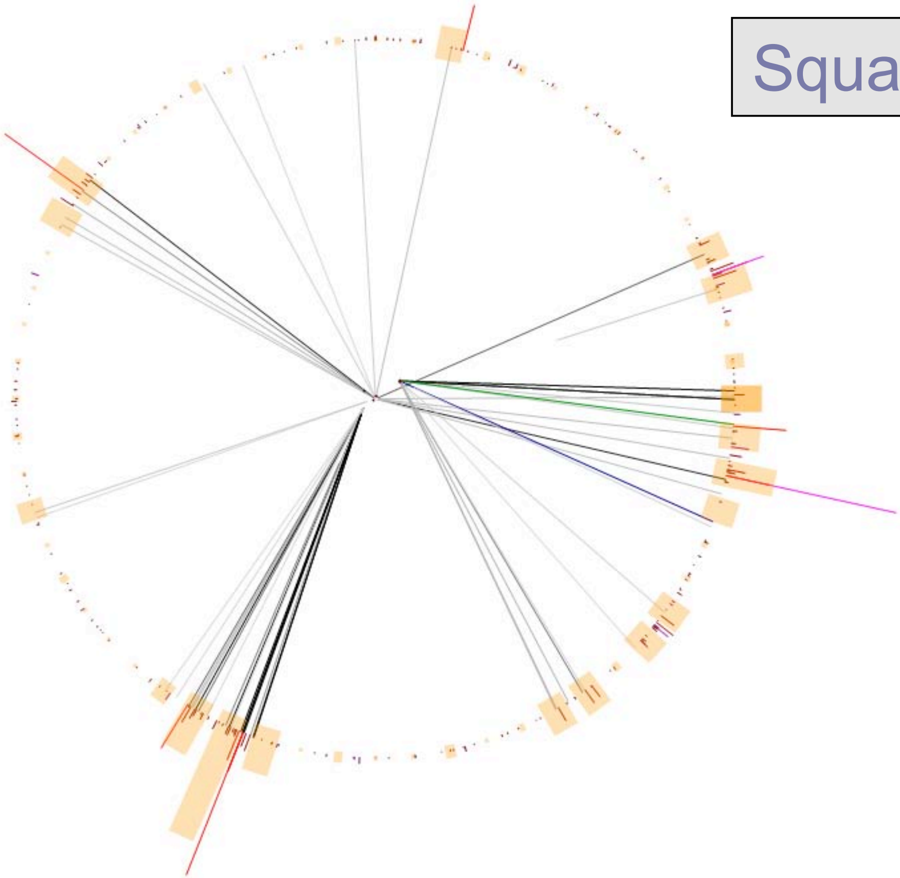
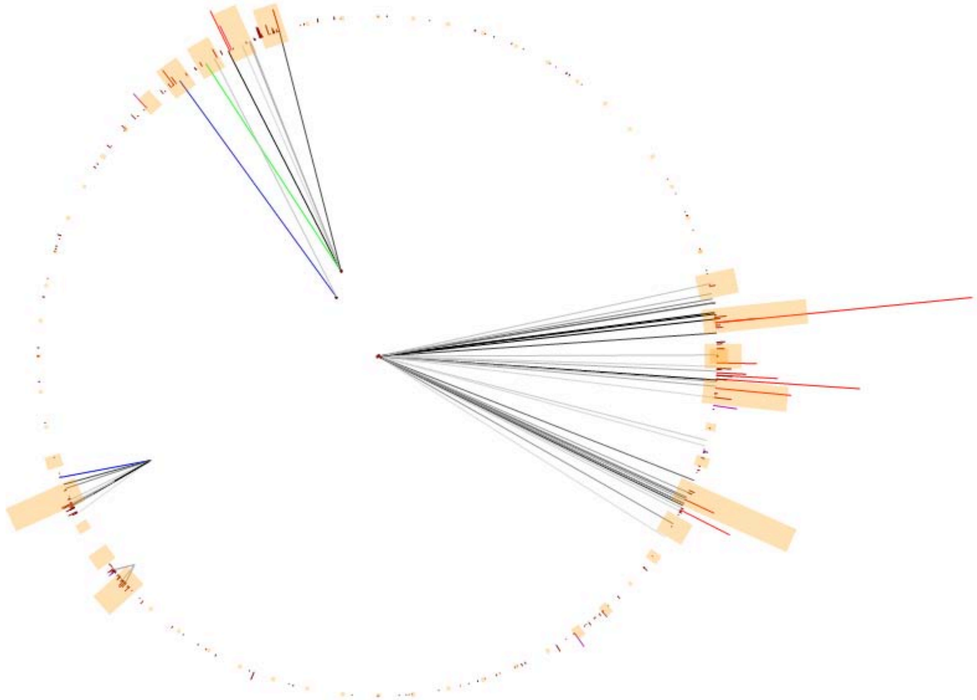


Prompt Neutralino Decay
Long-Lived v-Hadrons



Long-Lived Neutralino
Prompt v-Hadron Decay

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Production #2: SUSY decays

- Range of phenomenology enormous…

- This can be challenging for CMS/ATLAS/CDF/D0
  - Reduced missing tranverse momentum
  - Multiple soft jets/leptons likely
  - Highly displaced vertices possible
    - Maybe in cascades

- Potentially this is again great for LHCb
  - Cross section for SUSY is so large that low acceptance, luminosity doesn’t matter

- Hidden Valley Monte Carlo Simulation program not yet ready for SUSY
  - Stay tuned for updates

Production #3: Z' decays

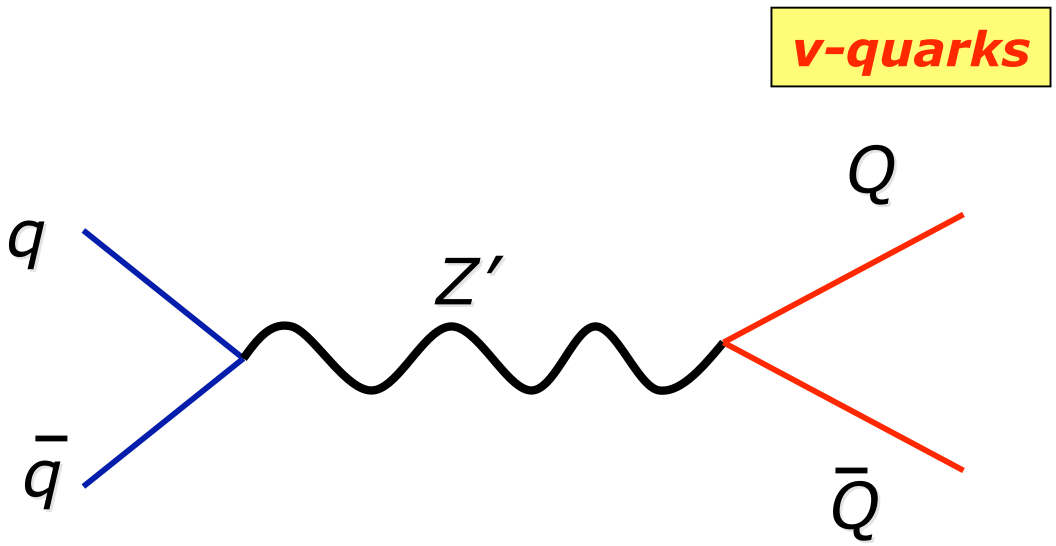
- This case is the easiest nontrivial one to simulate (after Higgs)
  - *Only one flux tube to fragment in the v-sector*

- For this reason, well-studied

- Its phenomenology is completely new (I believe)
  - High multiplicity final states
    - with uncalculable multi-jet or W/Z + multijet backgrounds
  - Low rates
    - Not so good for LHCb
  - Challenge for reconstruction and analysis more than for trigger
    - Unlike previous cases, a theorist's problem as much as an experimentalist's problem!

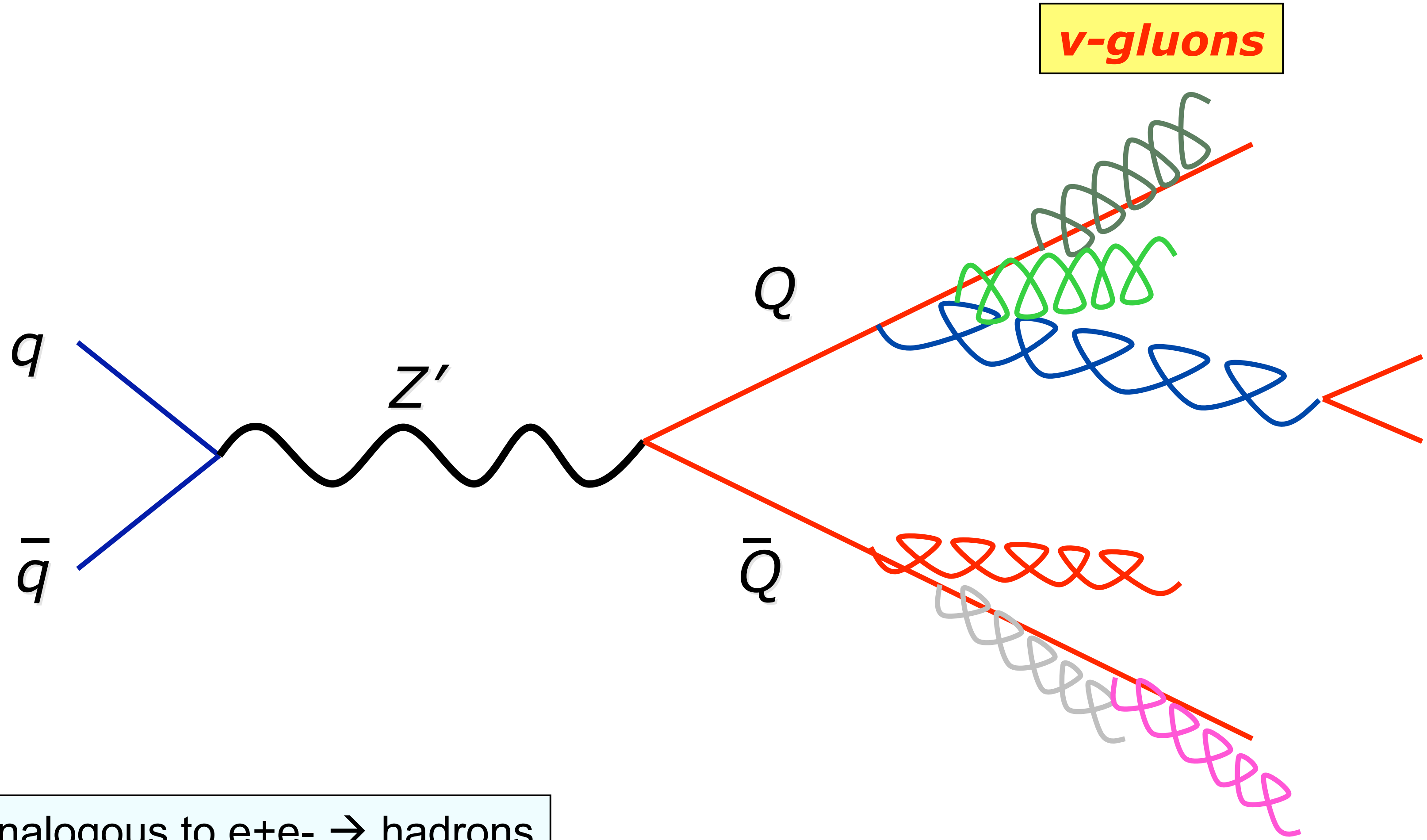
  - Only black hole studies are even vaguely similar
    - But (cf. L Randall's talk) not really

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



Analogous to e+e- → hadrons

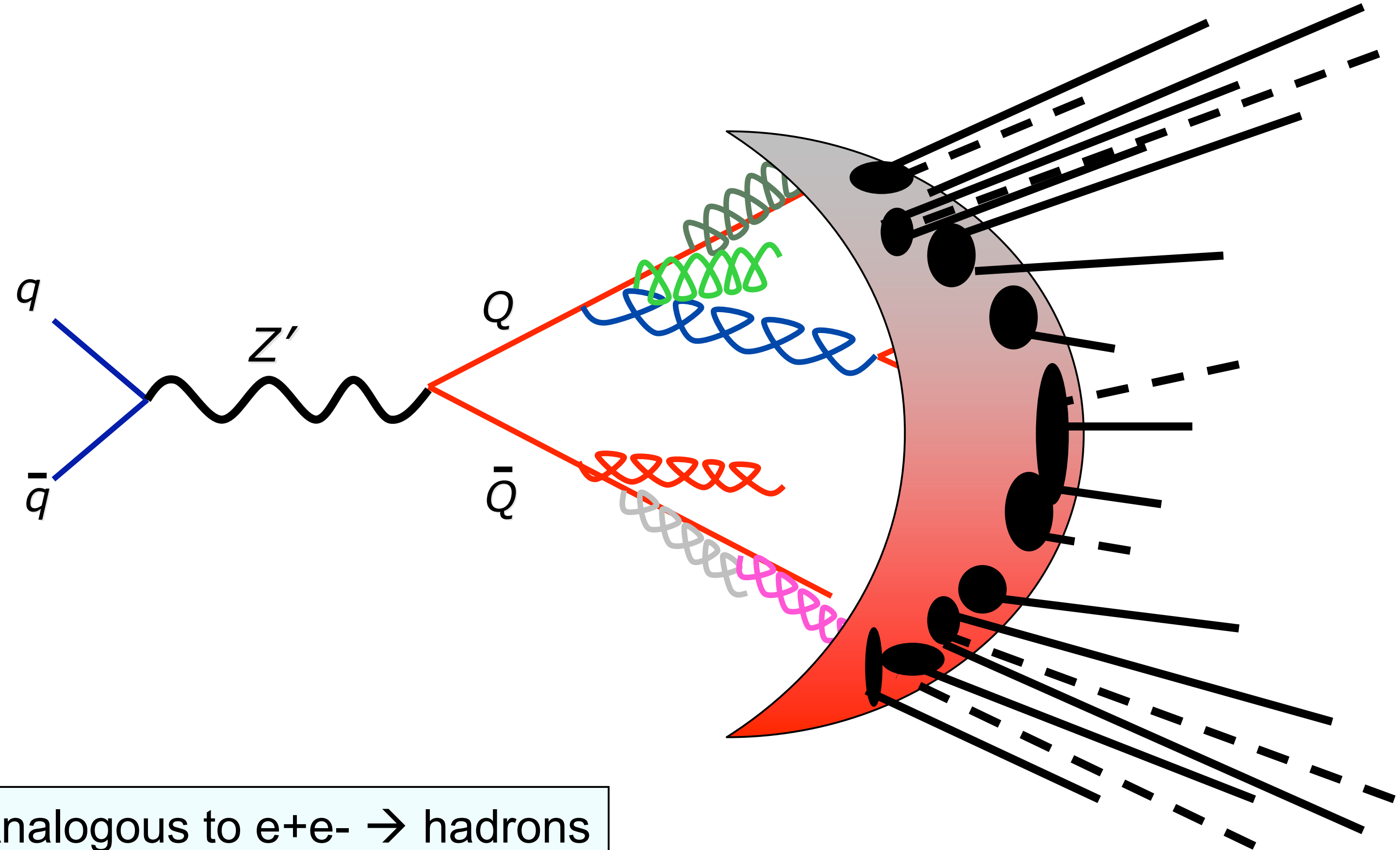
$q\,\bar{q} \rightarrow Q\,\bar{Q}$



Analogous to e+e- → hadrons

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

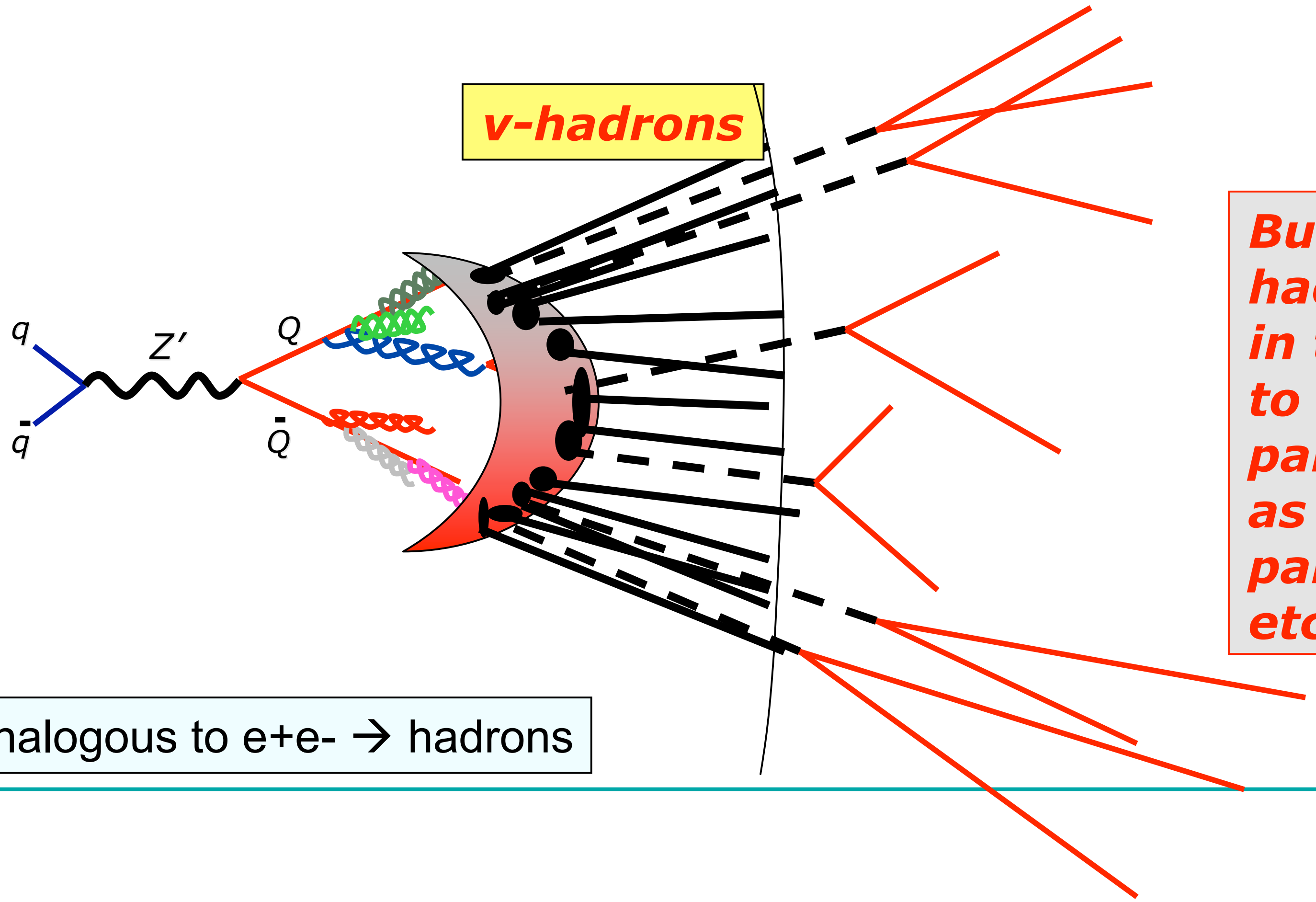
v-hadrons



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

Preliminary Studies of Z' events

Explicit studies possibly using HV Monte Carlo (version 0.5 MJS ; version 1.0 Mrenna, Skands & MJS)

- Will show Z' decays in 3 models, selected because
  - I can simulate them (more or less)
  - Each has phenomenology characteristic of large subclass of HV models
  - Each has adjustable parameters allowing different issues to be explored

    Note there are many other classes of models! Not the full range of phenomenology!

1) QCD-like theory with 2 flavors of light v-quarks
   - Without vFCNCs: High multiplicity of b's, large MET
   - With vFCNCs: VERY high multiplicity of b's
2) QCD-like theory with 1 flavor of light v-quarks **X**
   - Heavy pions, metastable rho mesons
   - Moderate multiplicity; rare lepton resonances, endpoints

   QCD-like theory with 2 flavors, moderate-mass v-quarks
3) Strongly-coupled CFT with IR confinement, many flavors
   - Dual to RS model [same as AdS/QCD sector, or as "unparticles"]
   - With and without FCNCs: Splash of b quarks (with and without much MET)

- In each case, can consider prompt or late decays

- Currently, understanding of signal incomplete
- If v-hadron decays all prompt, backgrounds clearly important! But which ones?
- Signal study suggests unusual reconstruction and analysis methods are needed.

1) QCD-like v-sector with 2 flavors

MJS, in preparation

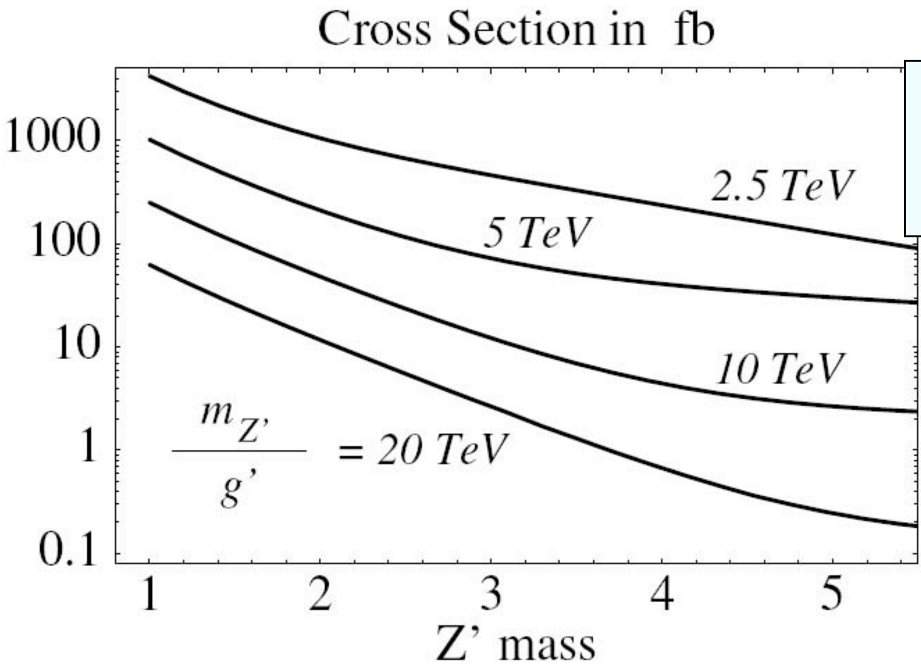
- Easy to Simulate: HV0.5 (MJS)
  - Scaled-Up 2-flavor QCD

- Z' mass of 3.2 TeV decays to v-quarks → v-hadrons

- v-Hadron States:

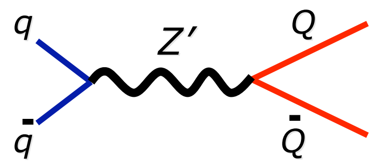
  - Triplet of light v-pions that decay to SM (or are stable)
    - Flavor diagonal pion decays to heavy flavor
    - Flavor off-diagonal pion may or may not decay
  - Triplet of heavy v-rho mesons that decay to v-pions
  - Other unstable v-mesons
  - Heavier v-baryons (stable, will not see)

Cross-sections and Decay Lifetimes



For a particular model. Others may differ by ~ factor of 10

~ 100 events/year

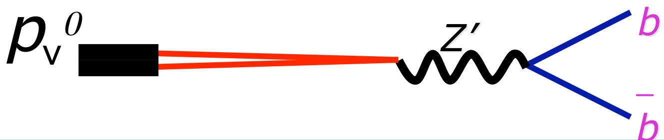


$p_v^+ \sim Q_1\bar{Q}_2 \sim$ *stable*

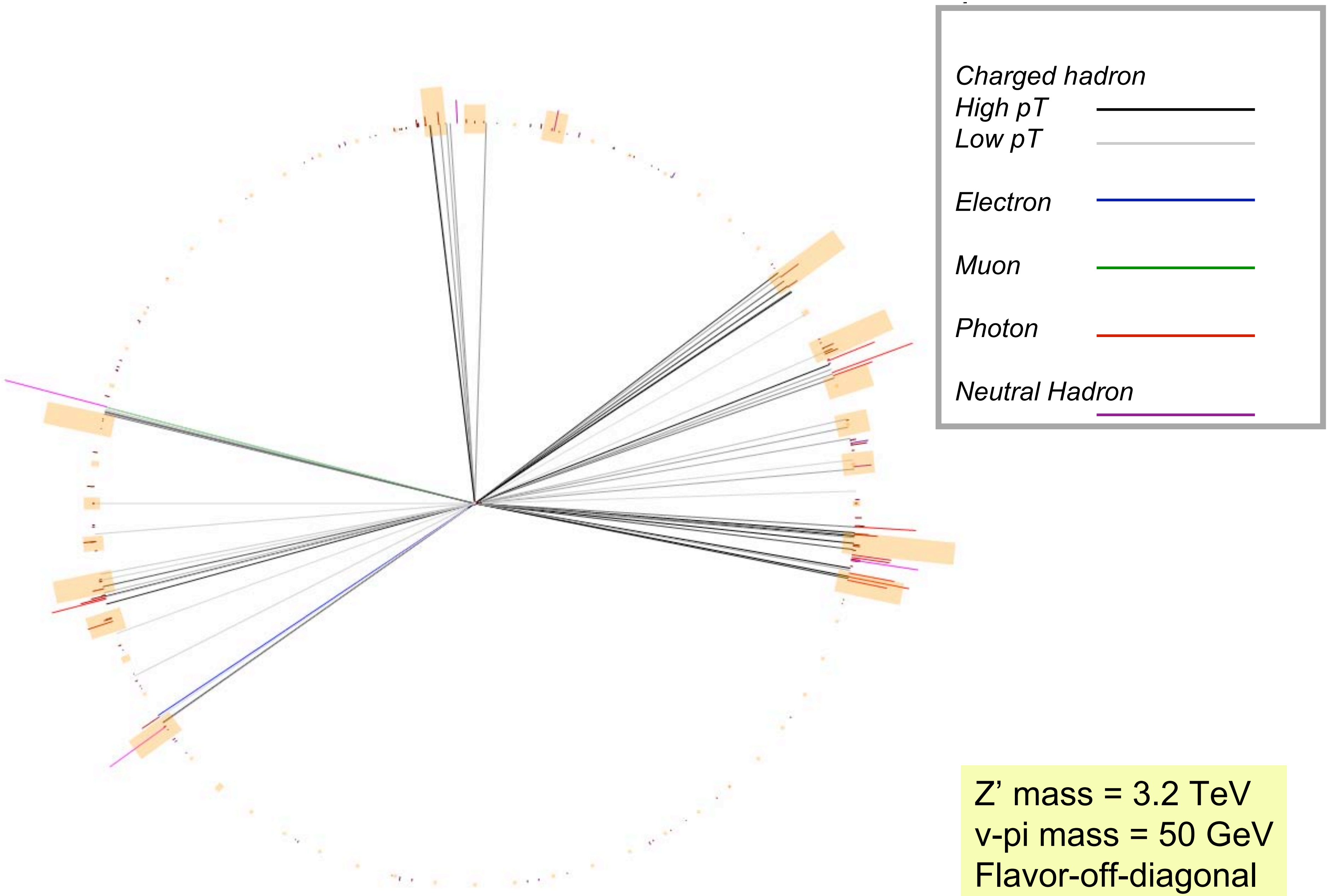
$p_v^- \sim Q_2\bar{Q}_1 \sim$ *stable*

$p_v^0 \sim Q_1\bar{Q}_1 - Q_2\bar{Q}_2 \rightarrow (Z')^* \rightarrow f\bar{f}$

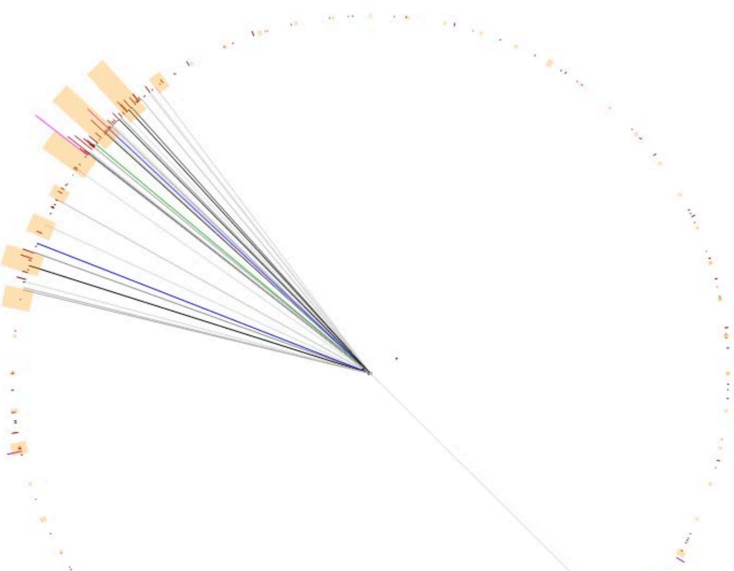
$$\Gamma_{\pi_v \to b\bar{b}} \sim 6 \times 10^9 \ \text{sec}^{-1} \frac{f_{\pi_v}^2 m_{\pi_v}^5}{(20\ \text{GeV})^7} \left(\frac{10\ \text{TeV}}{m_{Z'}/g'}\right)^4$$



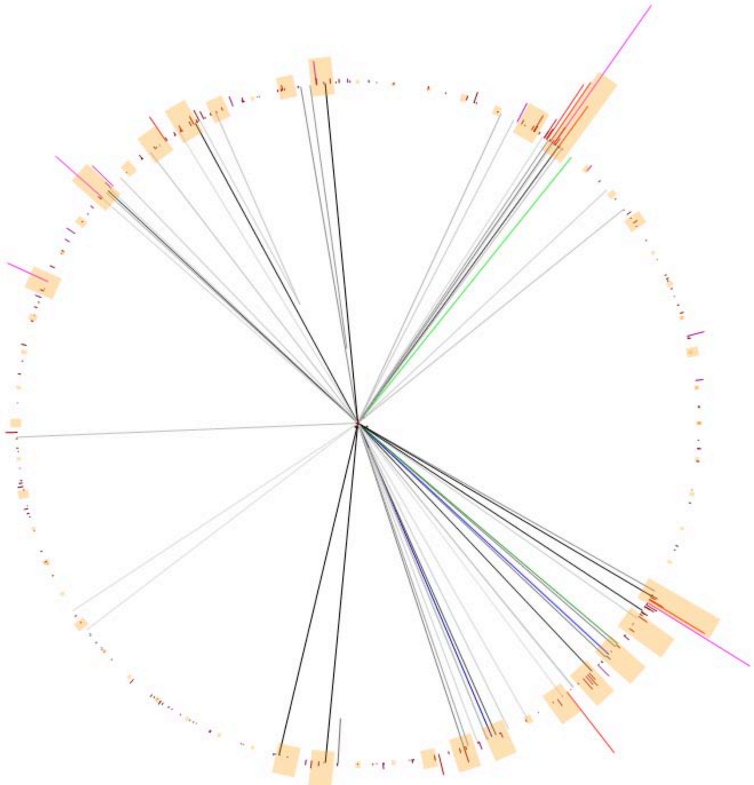
If Z' has v-flavor-changing couplings, then all three pions will decay

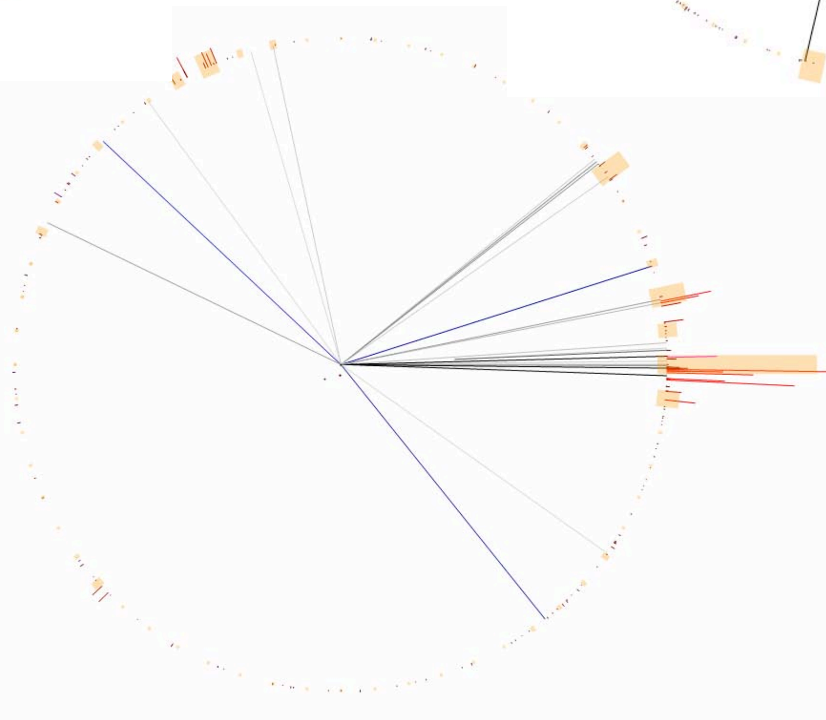


Z’ mass = 3.2 TeV
v-pi mass = 50 GeV
Flavor-off-diagonal
v-pions stable



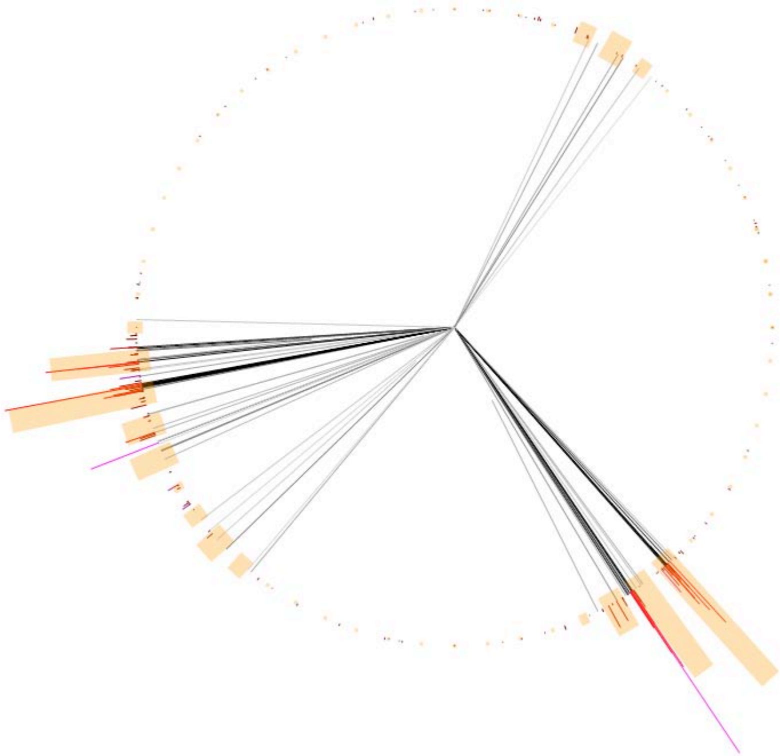
- High MET, jet energy
  - Triggering ok
- Large fluctuations
- Sometimes many b's
  - Many hard tracks
  - 2-3 muons
  - Many displaced tracks
  - Many vertices
- High pT jets are single v-hadrons
  - 2 or more b's per hard jet
  - 2 or more vertices per hard jet
- V-hadrons cluster too
  - Additional parton clustering
- Number of jets << number of b's
  - Jets do not indicate partons
  - Jets indicate *parton clusters*
- Overall event shape unusual
  - *Quantify?!*

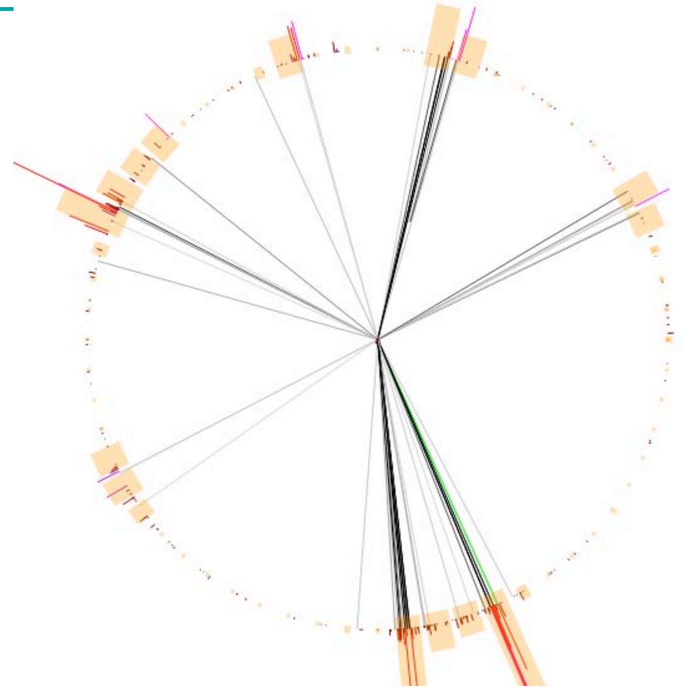


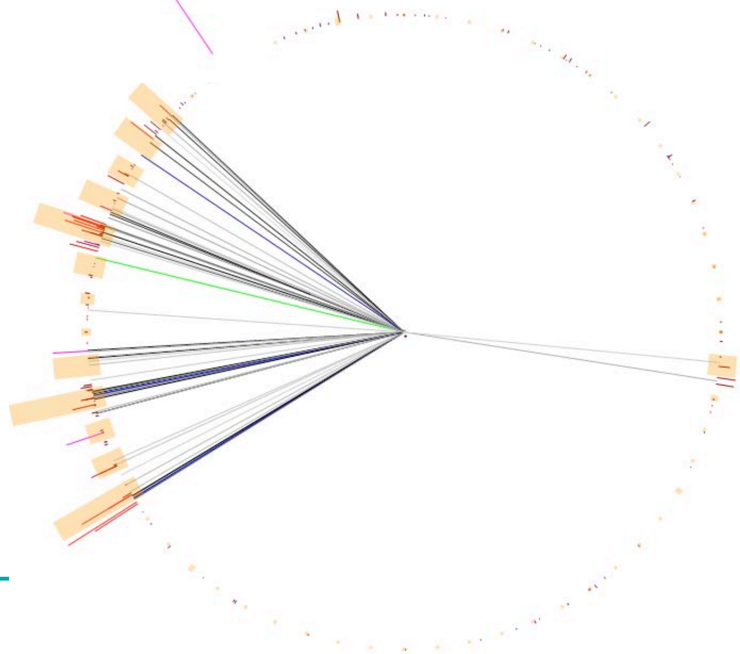


MJS, in preparation

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

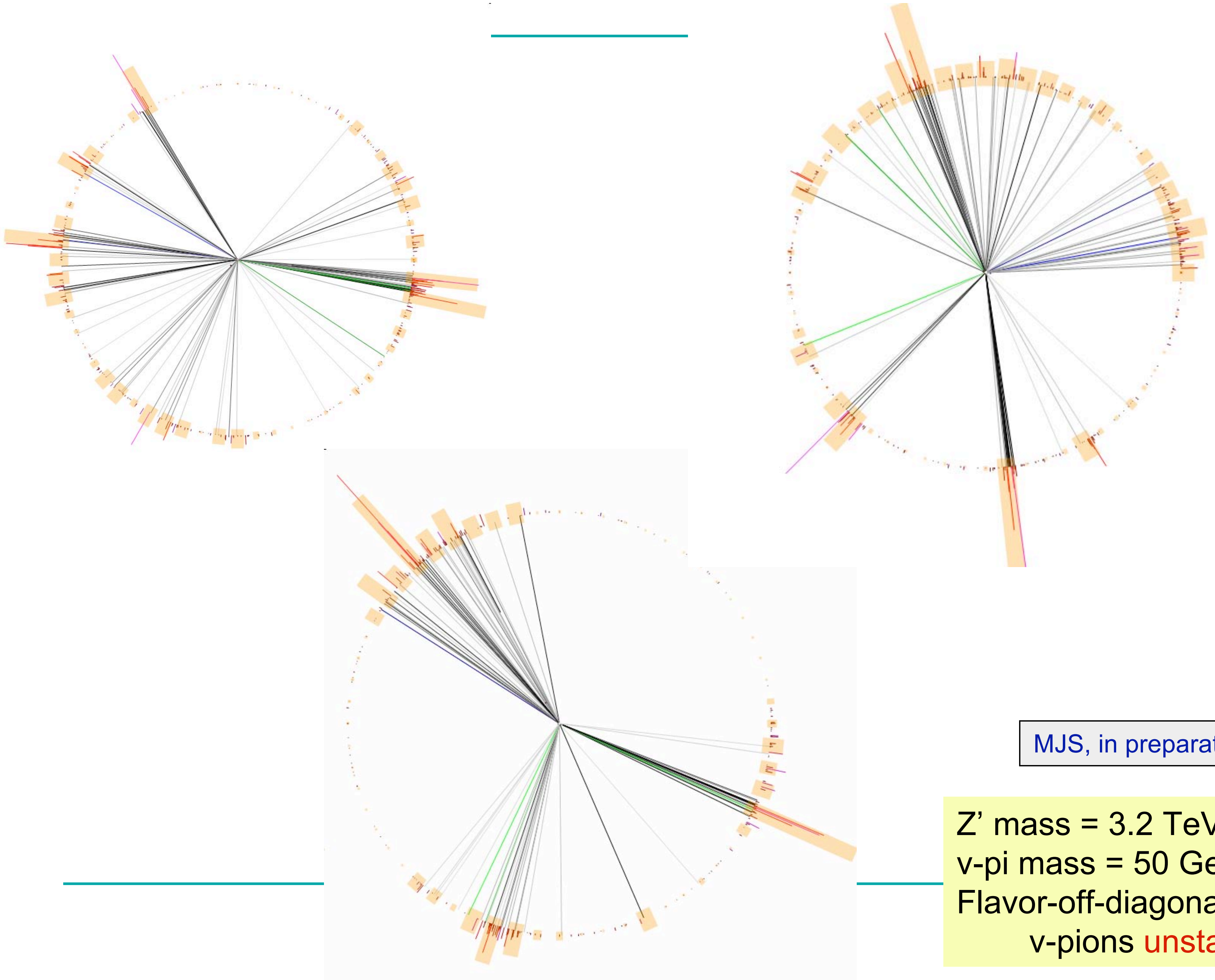






MJS, in preparation

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



MJS, in preparation

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

How many quarks/leptons per event?

Double to get number of SM quarks/leptons (mostly b's here)

m_{π_v} (GeV)	π_v^+ stable?	ave. # π_v decays/event	)	MET (GeV)
50	Yes	4.0		318
120	Yes	2.4		400
200	Yes	1.5		459
50	No	10.3		214
120	No	6.1		182
200	No	3.9		145

TABLE I: The case studies.

MJS, in preparation

Results (plots available on request)

MJS, in preparation

- Triggering not a problem here, but reconstruction and analysis are problems

- Number of hard jets < Number of hard partons
  - Jets do not correspond necessarily to hard partons
  - Jets correspond often to parton ***clusters***

➔ Too few jets ➔ too few b-tags (in many cases) for beating backgrounds

- Standard variables treating jets as **objects** are not sufficient

➔ Need to use unusual correlations among jets, vertices, tracks

- Moderate to high pT jets tend to be single boosted v-pions

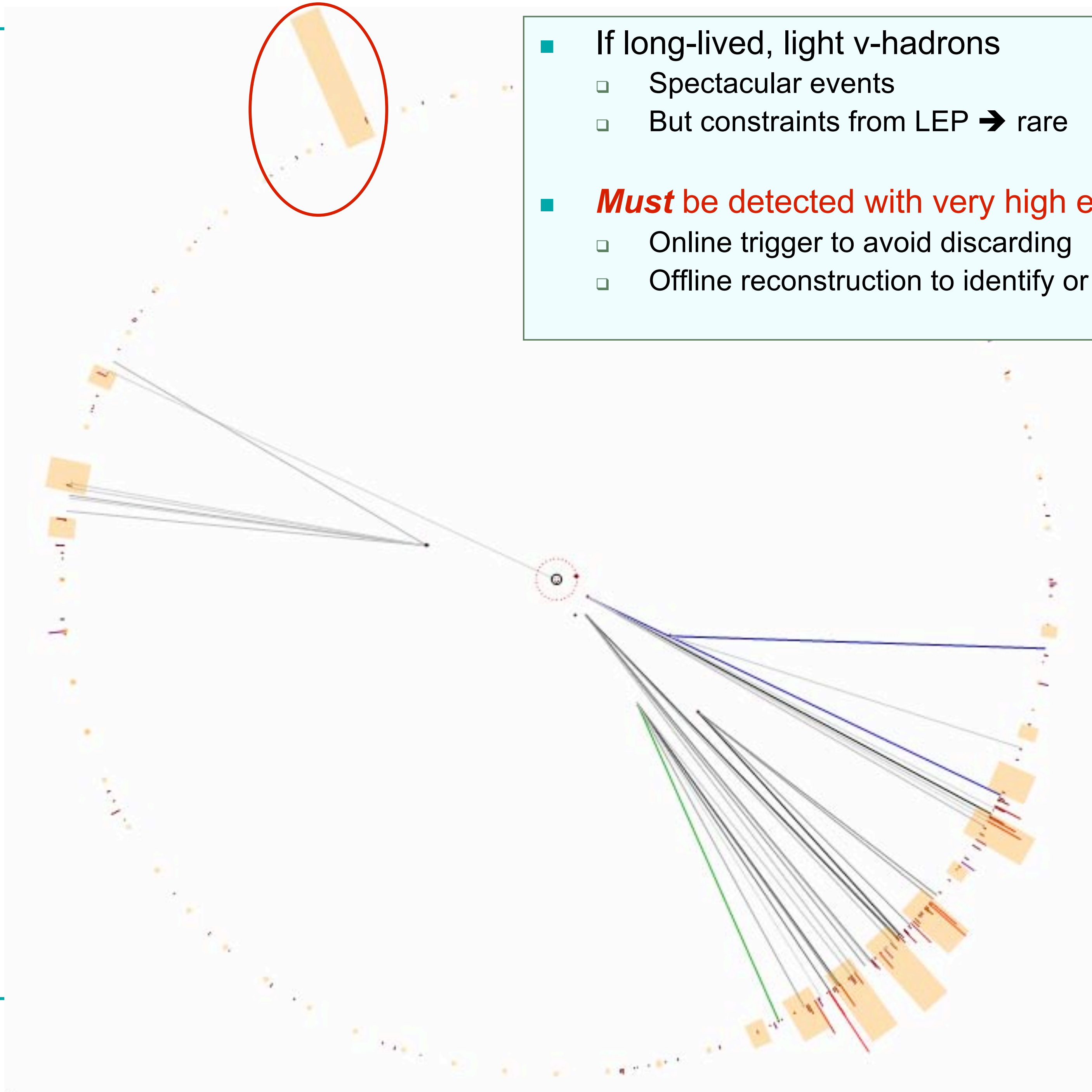
➔ Need to store sufficient information about jet substructure

- Overall event shape unusual –

➔ May need novel shape variables

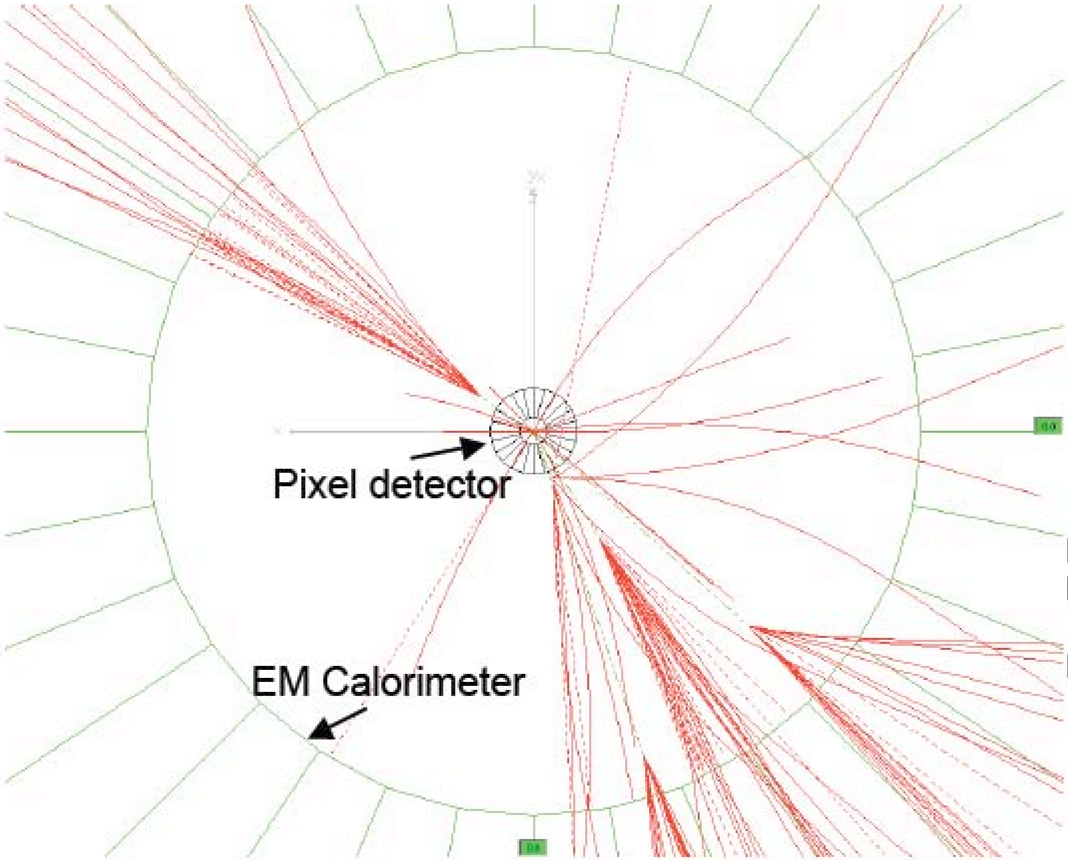
  - ➔ Working w ith S. Ellis, J. Miner, C. Vermillion, J. Walsh

Reliable strategy for extracting signal from background still not clear



- If long-lived, light v-hadrons
  - Spectacular events
  - But constraints from LEP ➔ rare
- ***Must*** be detected with very high efficiency
  - Online trigger to avoid discarding
  - Offline reconstruction to identify or at least flag

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

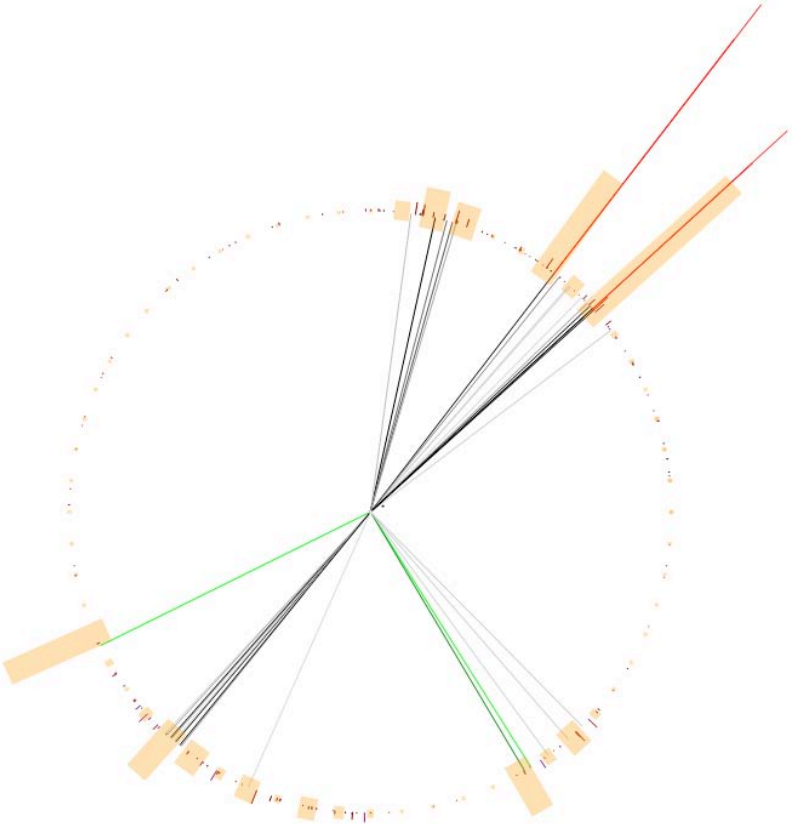
Display program: Daniele Depedis

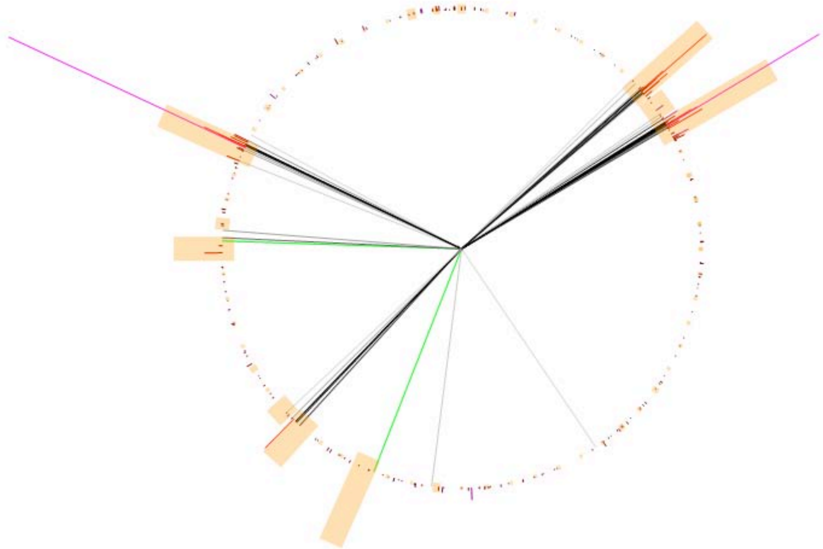
2) QCD-like v-sector with 1 flavor

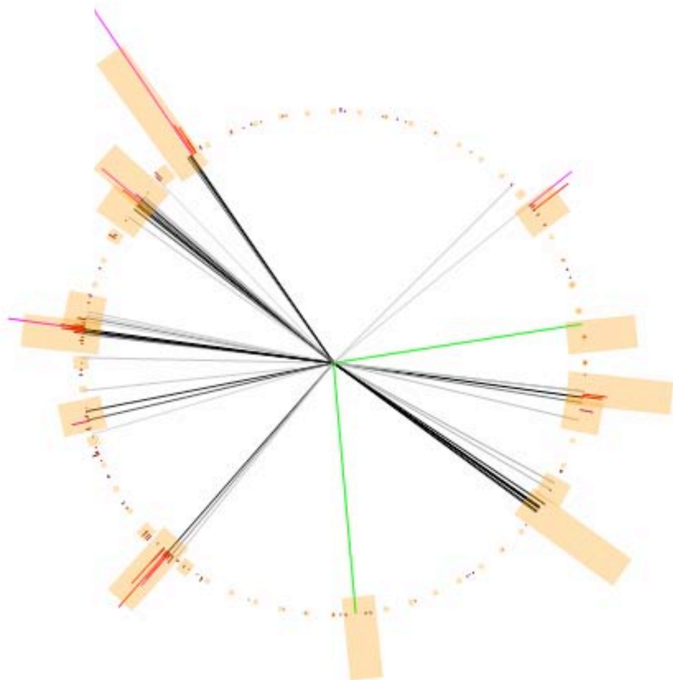
- Natural and interesting model
  - Psuedoscalar v-eta' that decays to SM ← *heavy flavor final states*
  - Vector v-omega that decays to SM ← *dilepton final states*
  - Scalar states decaying to SM plus a v-hadron ← *dilepton + invisible final states*
  - Many heavy unstable v-mesons, v-baryons
- But simulation package unavailable

- Replace this model with surrogate
  - 2-flavor QCD and heavier v-quark masses
  - Pion becomes heavier; kinematics forbids r → p p
    - A bit fine-tuned but useful
- Easy to simulate with new HV1.0 MC (Mrenna, Skands, MJS)

- Similar phenomenology to 1-flavor model
  - Triplet of pseudoscalar v-pions that decay to SM (or are stable) ← *heavy flavor*
  - Triplet of vector v-rho mesons that
    - decay to SM ← *dilepton final states*
    - decay to SM + v-pion ← *dilepton + invisible final states*
  - Other stable v-mesons decaying to SM
  - Heavier unstable v-mesons decaying to other v-mesons

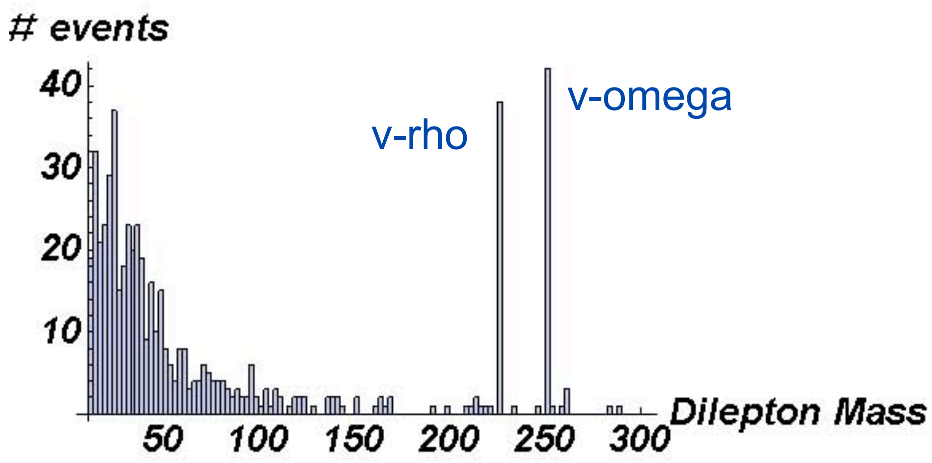




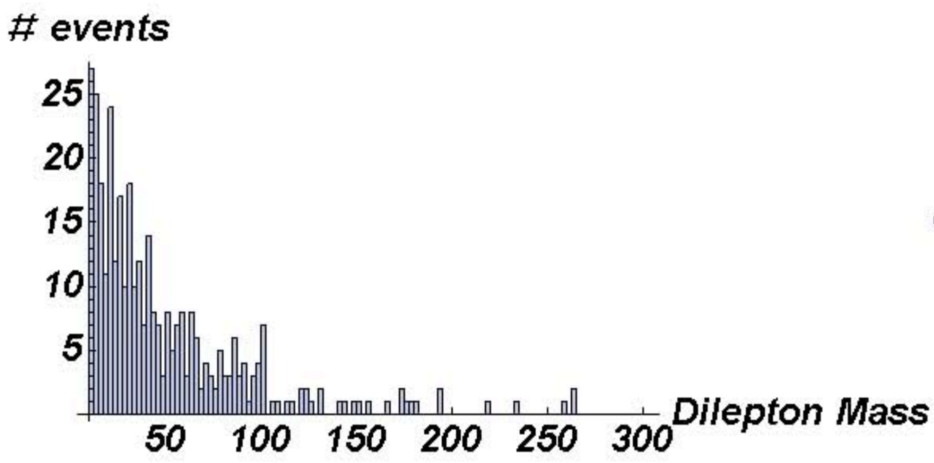


Dilepton Mass Distribution

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

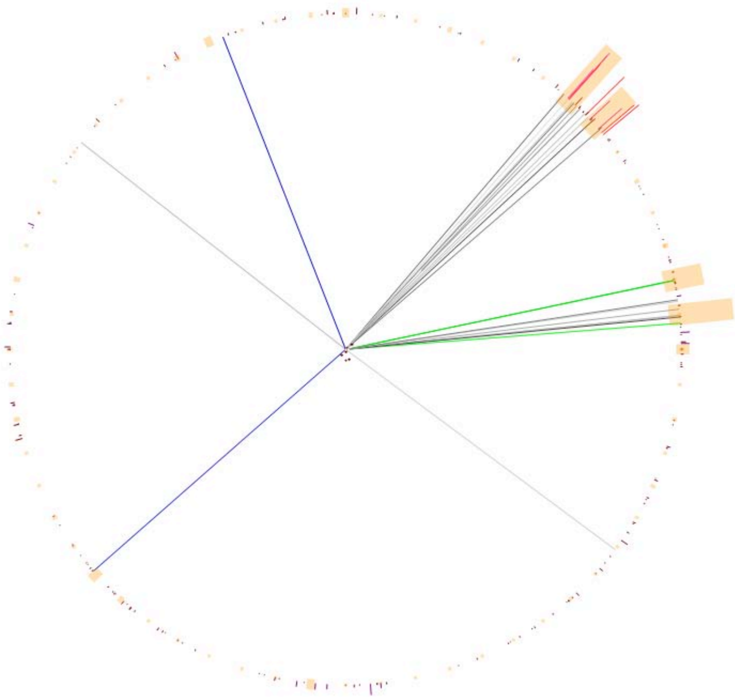


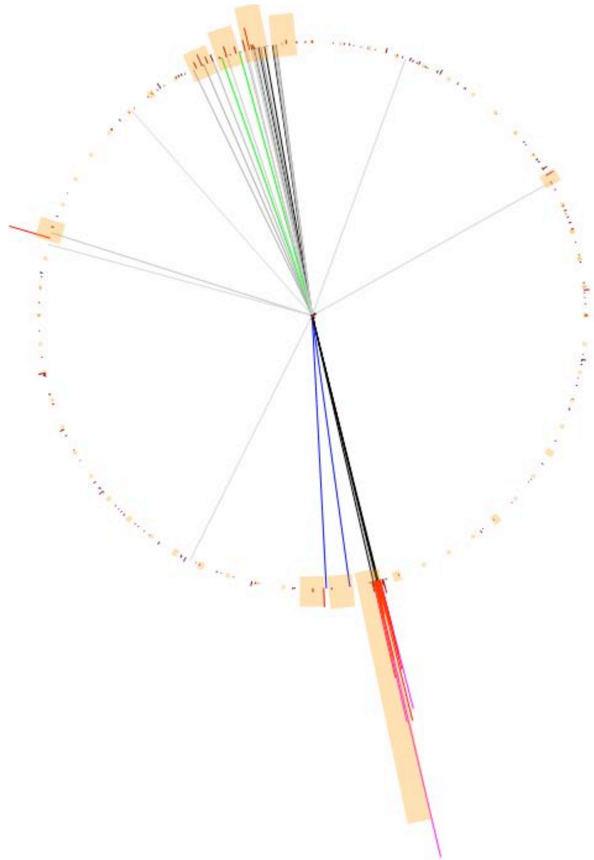
Same Flavor Opposite Sign

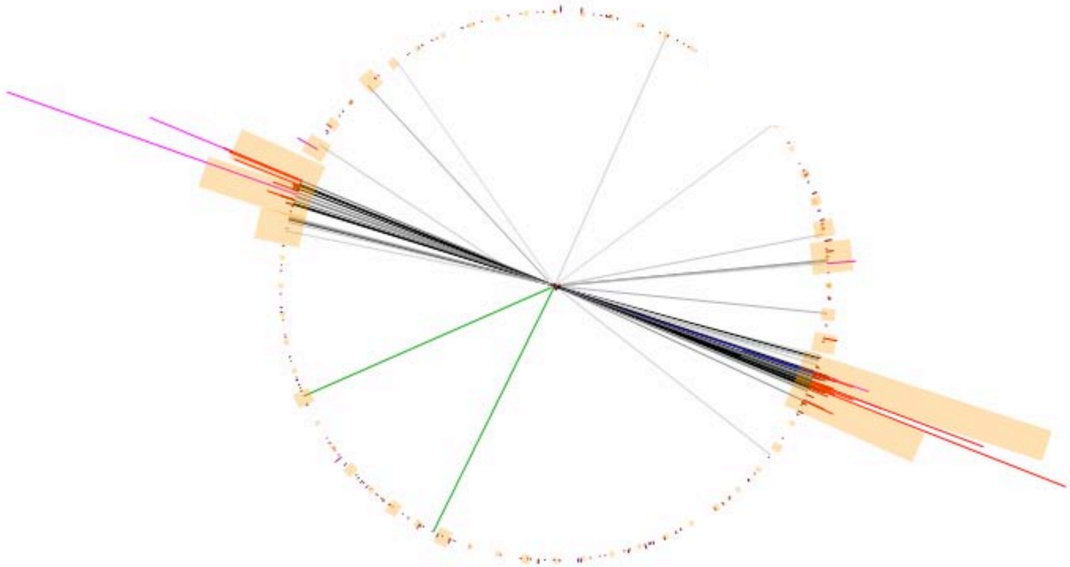


Opposite Flavor Opposite Sign

…but what should your event selection criteria be?

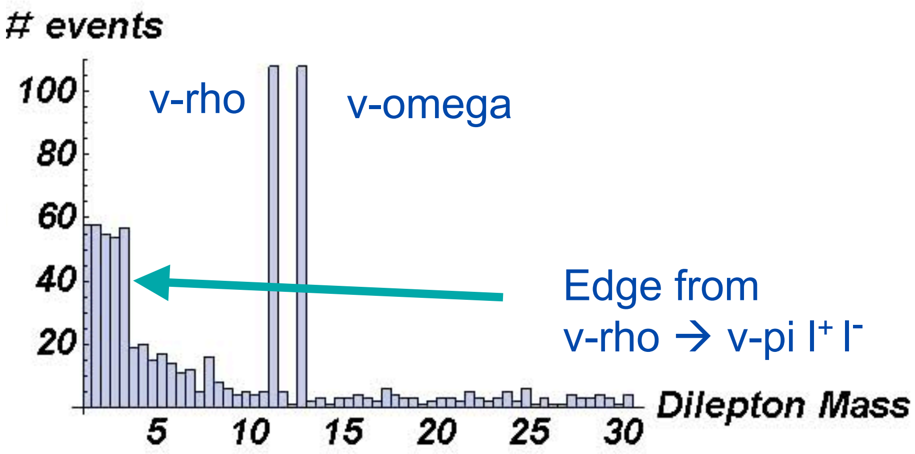




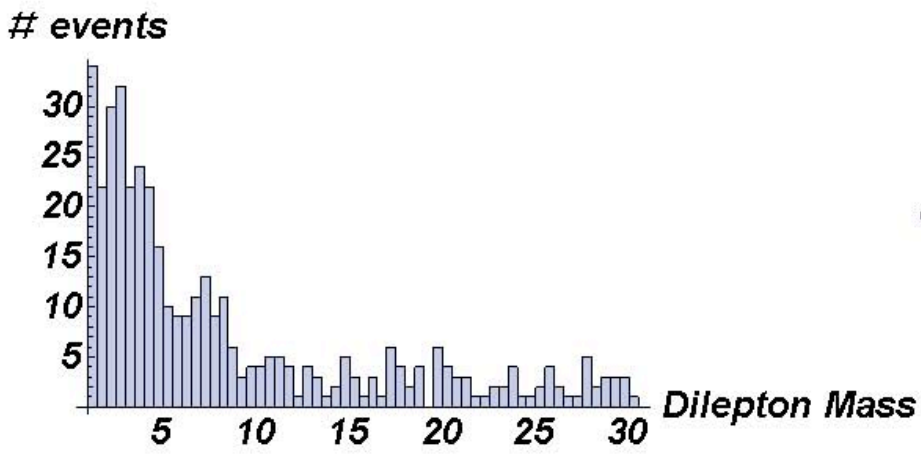


Dilepton Mass Distribution

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

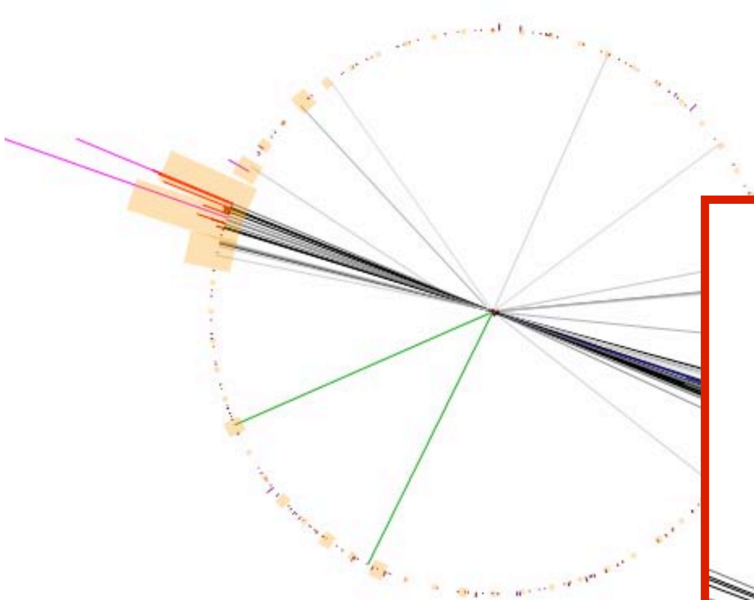


Same Flavor Opposite Sign

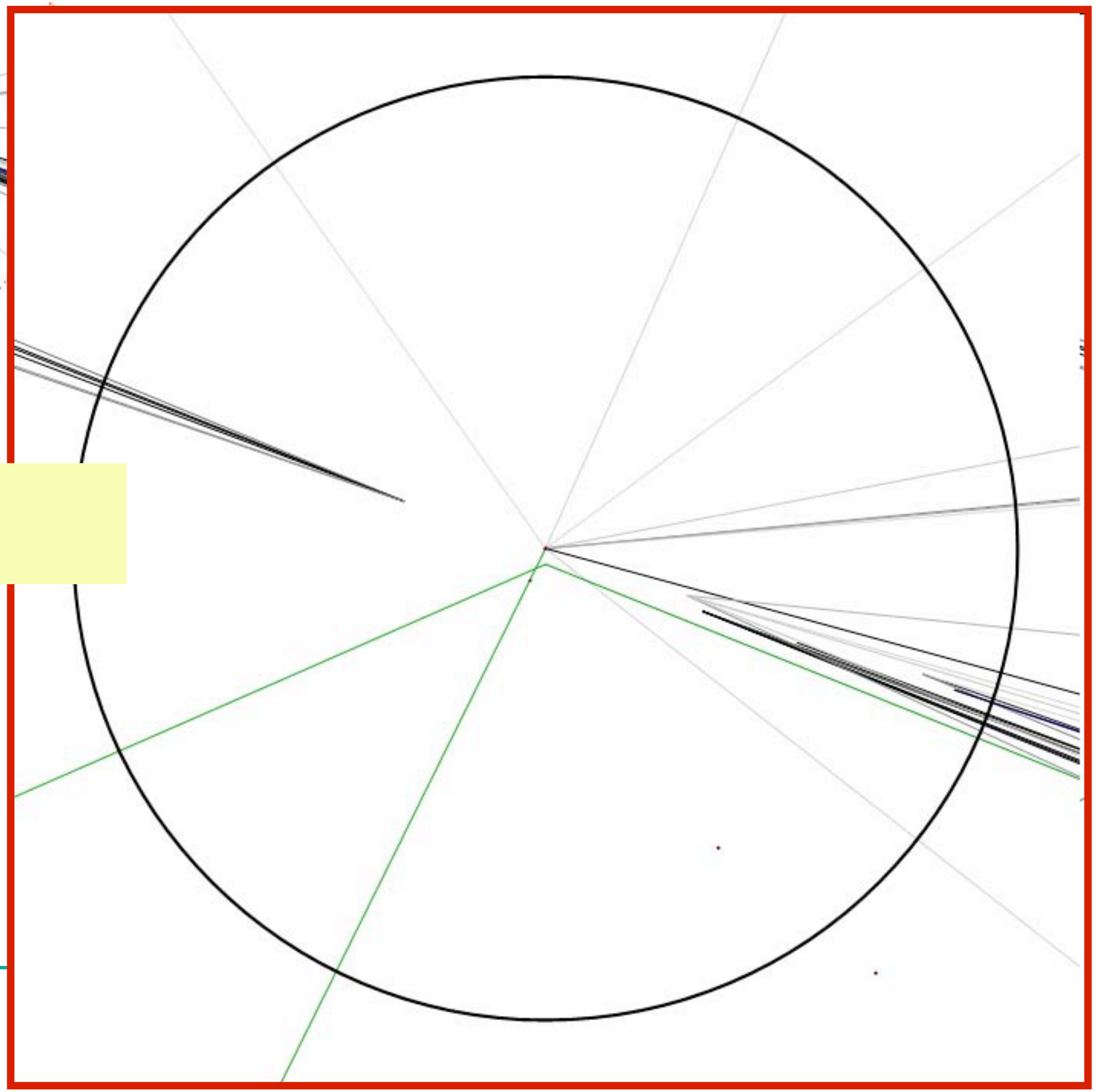


Opposite Flavor Opposite Sign

…but what should your event selection criteria be?



In a lucky case, select on displaced vertices…



3) Strongly-coupled UV-Conformal Field Theory with many light flavors

- Dynamics of Conformal Field Theory (CFT) from 60s-70s

- Many ways to have CFTs in four dimensions
  - “Banks-Zaks” fixed points (70s)
  - N=4 SUSY Yang-Mills, N=1 finite models (80s)
  - Huge class of N=1 supersymmetric models (cf. Seiberg etc. 90s)

- Many papers use destabilized fixed points for BSM model building
    - UV fixed point, IR confinement
  - At least as far back as “Walking Technicolor” (1980s)

- There are three crucial quantities to track
  - a the gauge coupling
  - b the running of the gauge coupling
  - g the deviation of operator dimensions from naïve values

a vs. b vs. g

- a *the gauge coupling*
- b *the running of the gauge coupling*
- g *the deviation of operator dimensions from naïve valu*

	Zero b (CFT)	Small b	Large b
Small aN (small g)	Banks-Zaks N=4 SUSY	Perturbed Banks-Zaks QCD UV , N=1 SUSY IR Technicolor UV Today's Model 1,2 UV	*Won't last*
Large aN (large g)	N=4 SUSY Generic Seiberg CFT N=1* UV Walking Technicolor UV	Perturbed Seiberg CFT	QCD IR, N=1 SUSY IR Technicolor IR Walking Technicolor IR Today's Model 1,2 IR Perturbed SCFT IR
Extreme aN (extreme g)	N=4 SUSY Randall-Sundrum bulk N=1* UV (PS bulk) Today's Model 3 UV	Deformed-RS bulk Duality cascade (KS bulk)	RS IR brane N=1* IR, KS IR Today's Model 3 IR ….

Models in green have an IR scale and could serve as a hidden valley sector

- Most interacting theories with light fields are “non-particle” theories
  - QCD is a non-particle model [parton shower]
  - Many Hidden Valley sectors are “non-particle”
    - ➔ multiparticle production *MJS & Zurek 06*

- *Many Hidden valley sectors are UV-CFT or UV-almost-CFT model*
  - *same phenomenology – same models -- as “unparticles” with IR scale*

Hidden Conformal Theories = *“Unparticle” models* *Georgi 07*

Hidden Walking Technicolor is an “unparticle” model in UV

Hidden QCD is an almost-“unparticle” model in UV

		Today’s Model 1,2 UV	
Large aN (large g)	N=4 SUSY Generic Seiberg CFT N=1* UV Walking Technicolor UV	Perturbed Seiberg CFT	QCD IR, N=1 SUSY IR Technicolor IR Walking Technicolor IR Today’s Model 1,2 IR Perturbed SCFT IR
Extreme aN (extreme g)	N=4 SUSY Randall-Sundrum bulk N=1* UV (PS bulk) Today’s Model 3 UV	Deformed-RS bulk Duality cascade (KS bulk)	RS IR brane N=1* IR, KS IR Today’s Model 3 IR ….

Models in green have an IR scale and could serve as a hidden valley sector

A Hidden Valley Sector
With UV-CFT Dynamics
and
Infrared Mass Gap

=

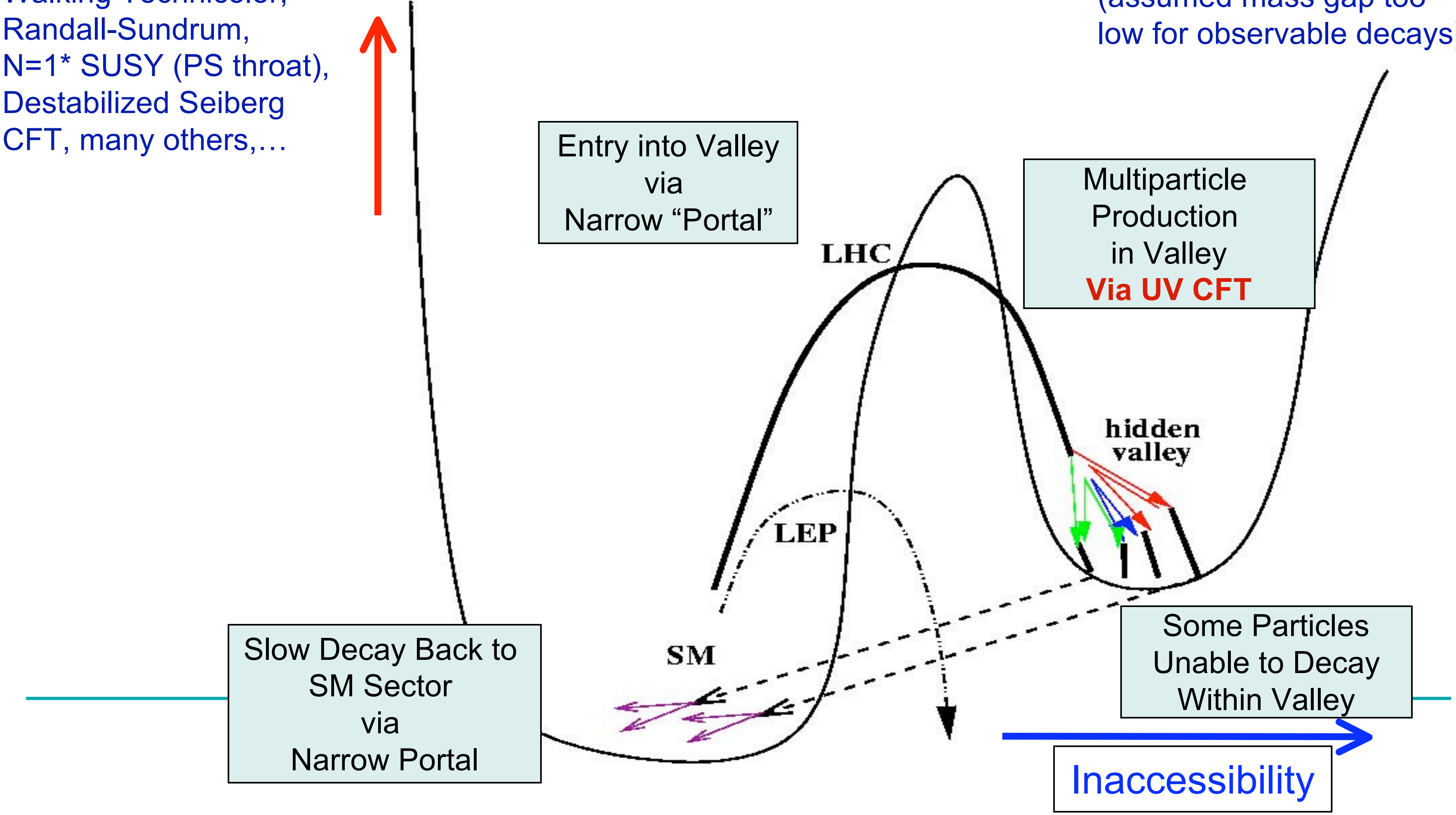
Non-particle Model
with zero UV beta function
and
Infrared Mass Gap

=

UV unparticle
Model with
Infrared Mass Gap

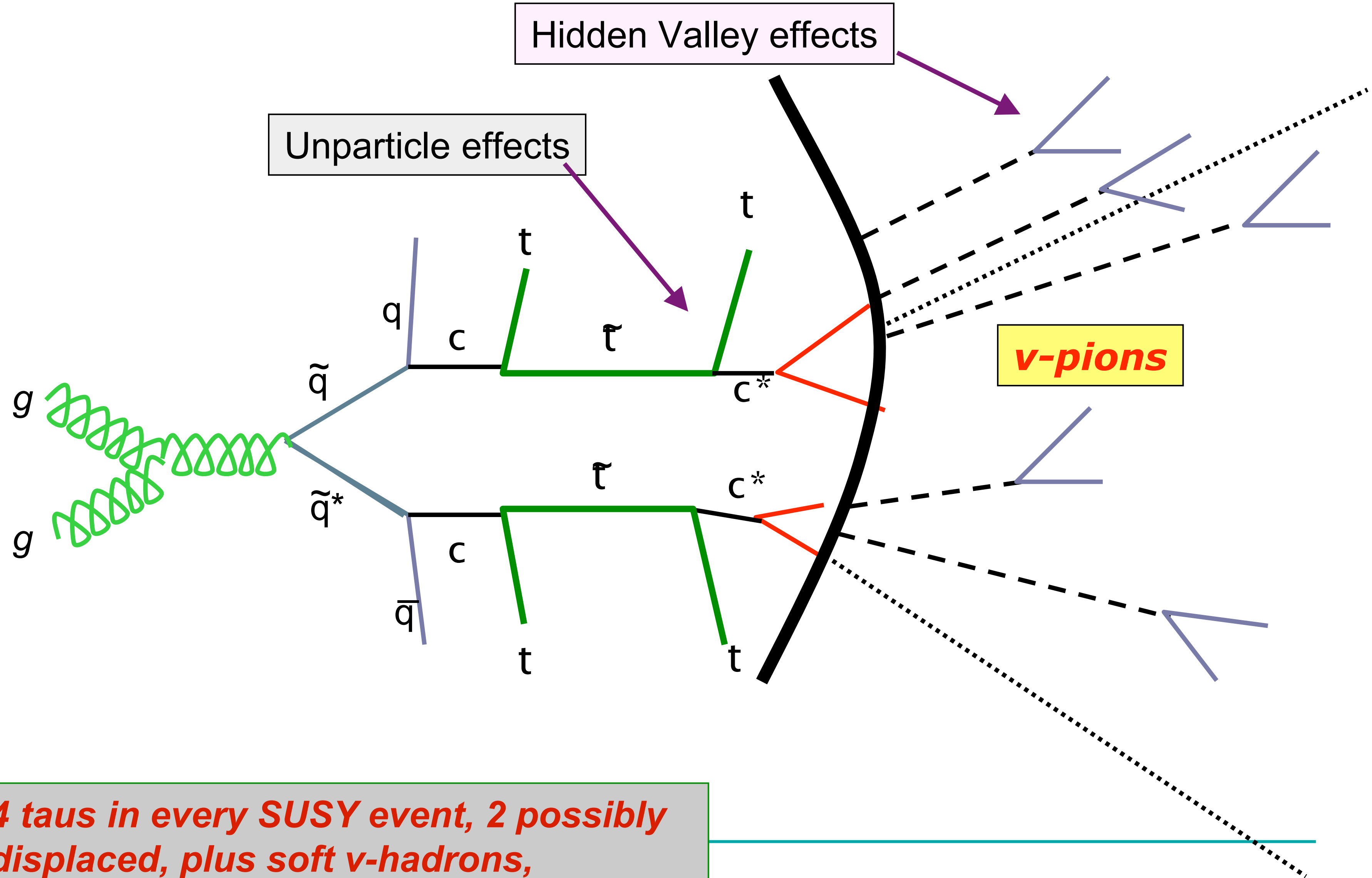
HV based on
Walking Technicolor,
Randall-Sundrum,
N=1* SUSY (PS throat),
Destabilized Seiberg
CFT, many others,…

Georgi 2007
(assumed mass gap too
low for observable decays)



SUSY decays to the v-sector

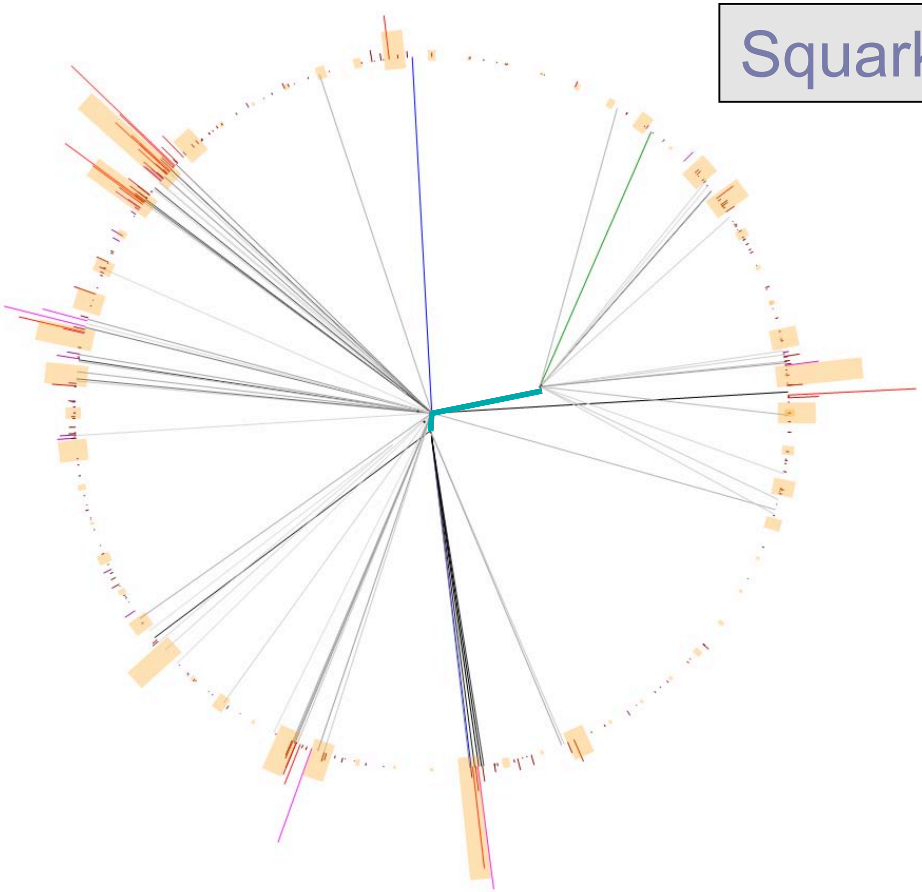
MJS July 06



4 taus in every SUSY event, 2 possibly displaced, plus soft v-hadrons, possibly with displaced decays

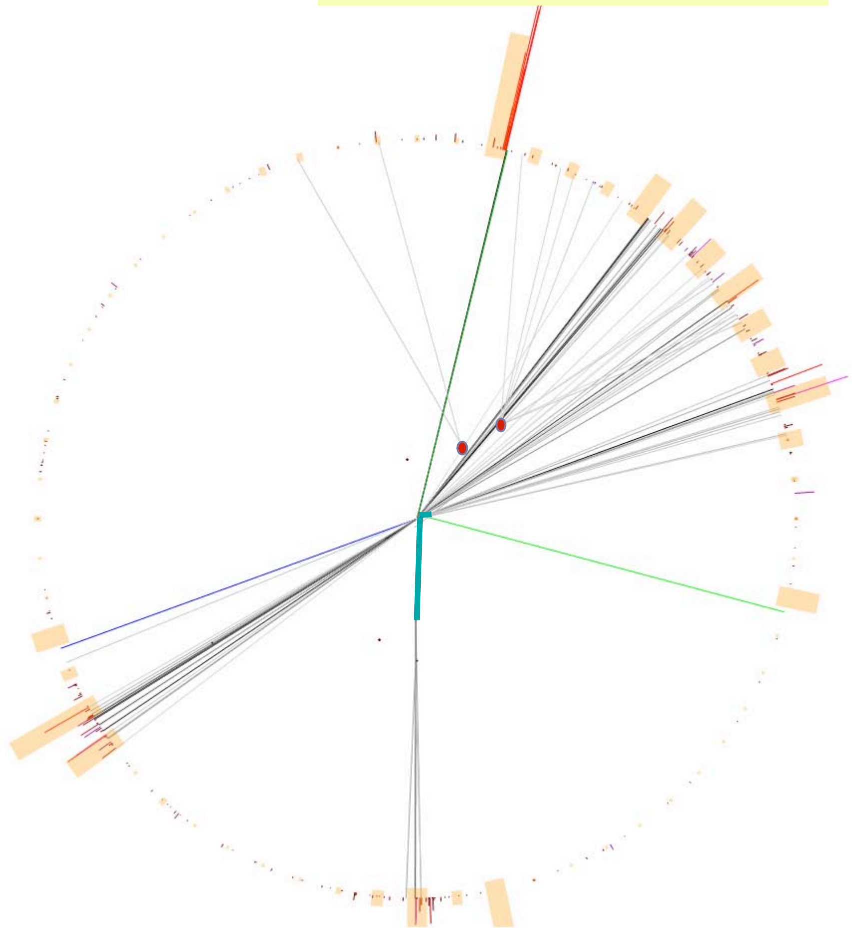
Squark-Antisquark Production at LHC

Stau tracks



Long-Lived Stau
Prompt v-Hadron Decay

Long-Lived Stau
Long-Lived v-Hadrons



Hacked simulation using
Hidden Valley Monte Carlo 1.0
Mrenna, Skands and MJS

3) Strongly coupled UV-Conformal Field Theory with many light flavors

- Many Flavors
  - Many light v-pions
    - Allow FCNCs here: all decay to SM

- I want to focus on aN >>1 (for both b = 0 and b small)

- Strong coupling
  - Enhances multiplicities,
  - Changes effects of parton shower

- *What does Z' → v-hadrons look like now?*

  - Weak coupling:
    - matrix element, parton shower almost as in QCD (until very near confinement scale)
  - Strong coupling:
    - matrix element altered strongly; parton shower is not separate process.

What happens in Conformal Field Theory

- Parton shower and deep inelastic scattering
  - Have similar collinear physics
  - Share the same splitting function at leading order

- Deep Inelastic Scattering in CFT (Kogut & Susskind 75)
  - Weak coupling: slow evolution like QCD –
    - Hard partons and soft partons like QCD
  - Strong coupling: extremely rapid evolution (Polchinski & MJS 02)
    - Collinear physics driven to small x
    - Only soft partons remain.

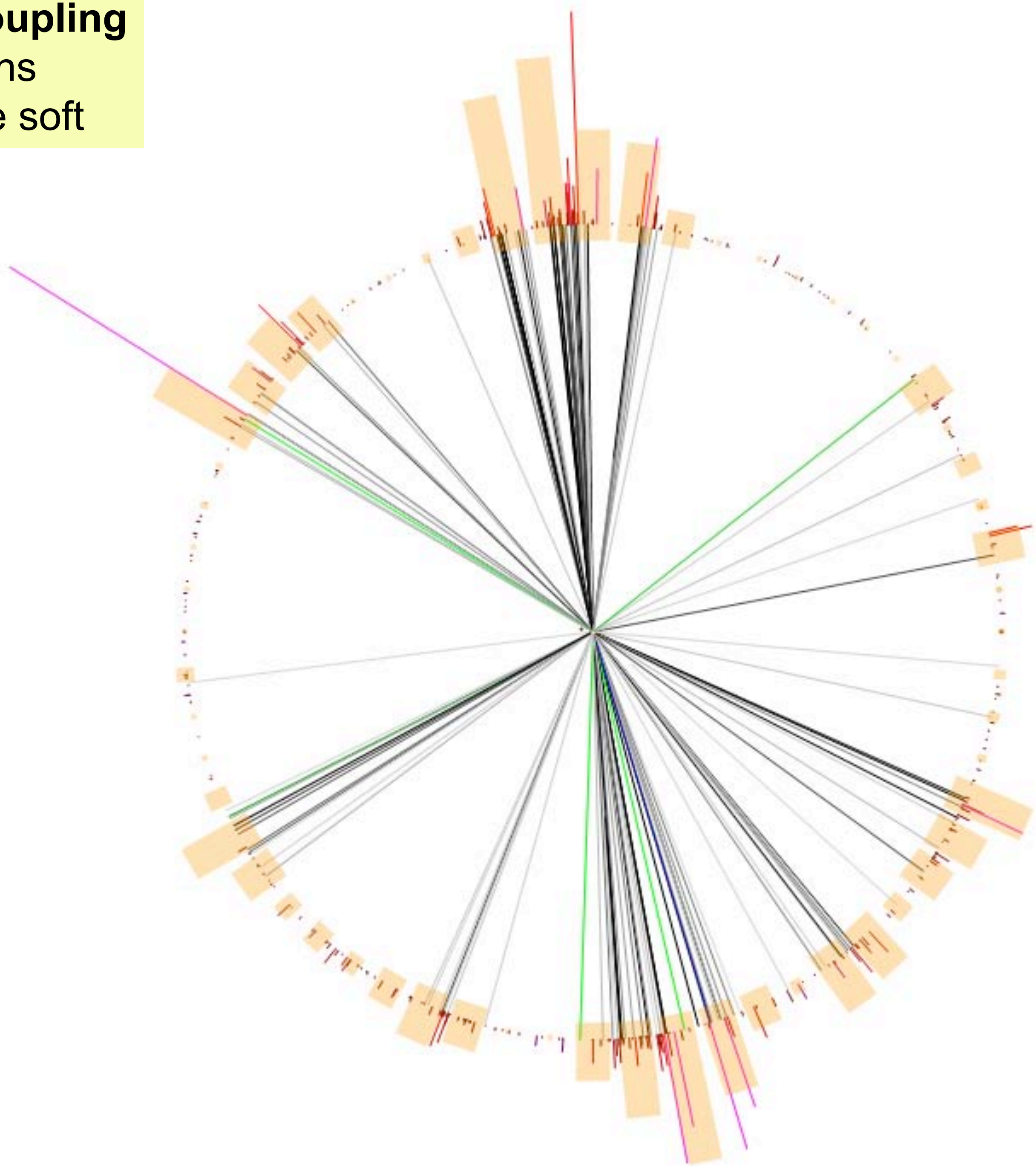
- If this is true also for parton shower
  - Then any collinear partons split until soft-collinear
  - Soft physics dominates the final state
  - Soft physics forgets its initial direction ➔ Spherical event

- I can't prove this (yet)
- If it is correct,
  - Many more v-hadrons with lower transverse momentum; huge soft multiplicity

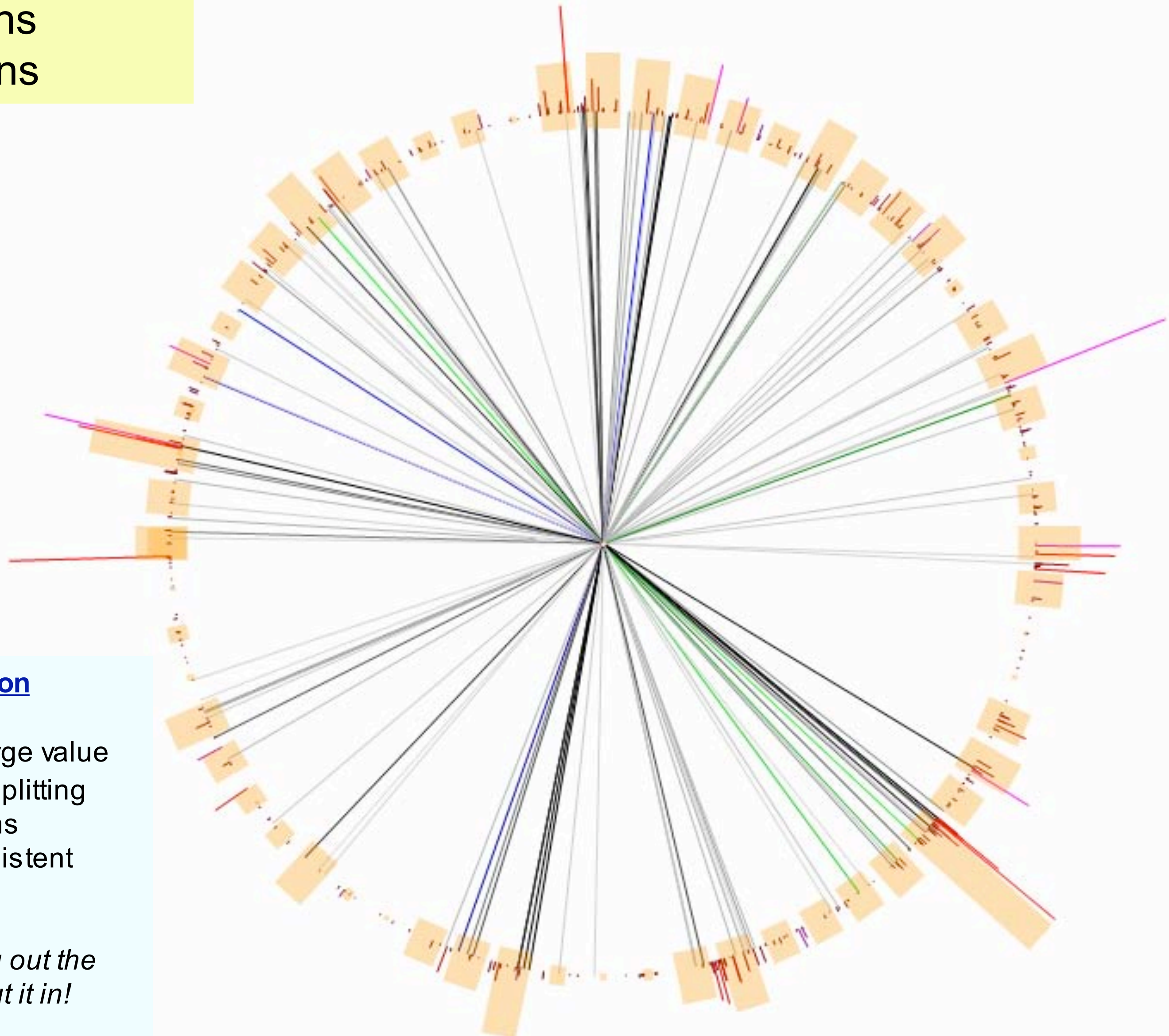
Running Weak-Coupling

Many v-hadrons

Some hard, some soft



Strong-Coupling Fixed Point
(educated guesswork!)
More v-hadrons
Softer v-hadrons



Crude and uncontrolled simulation

- Fix a 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

Do not overinterpret! I am getting out the answer that I expect because I put it in!

Conclusions

- Theoretical exploration of possible LHC phenomenology is not complete

- The Hidden Valley scenario offers a vast array of unstudied phenomena
    - High-multiplicity final states
    - Several new neutral long-lived particles with a variety of final states
    - Effects on Higgs, SUSY, (and Technicolor, Little Higgs, Extra Dimensions….)
  - Many other realizations, which often
    - Give phenomenology distinct from today's examples
    - Are typically partly or completely unpredictable due to unknown strong dynamics

  - Theoretical Challenges
    - Prediction, Simulation, Background Reduction, Signal Extraction
  - Experimental Challenges
    - Triggering, Reconstruction, Event Storage, Event Selection, Analysis

- *What other classes of phenomena have we missed?*

- We should work quickly to ensure that we do not lose crucial data!
  - New methods are needed, designed and studied in realistic contexts
  - Good cross-talk between theorists and experimentalists essential