Hidden Valleys: A Model-Independent Overview

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See also Seattle/Rome 1/Genoa/SLAC ATLAS note in preparation

Matthew Strassler
Rutgers University

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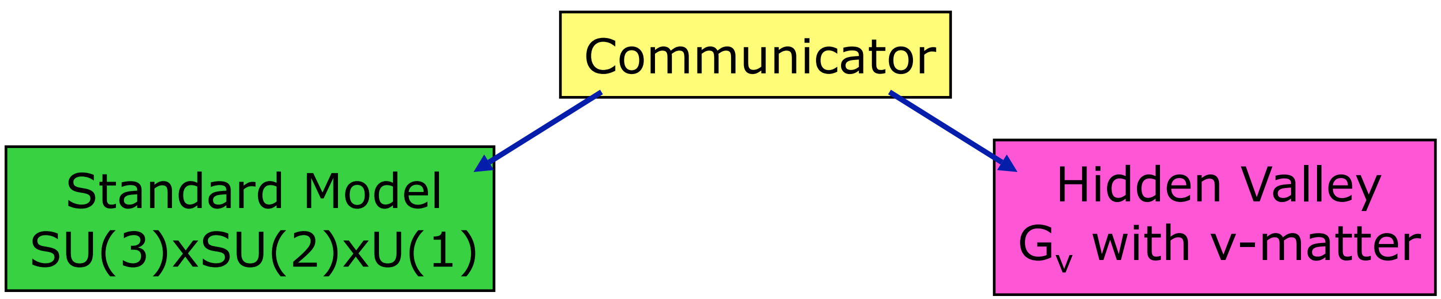
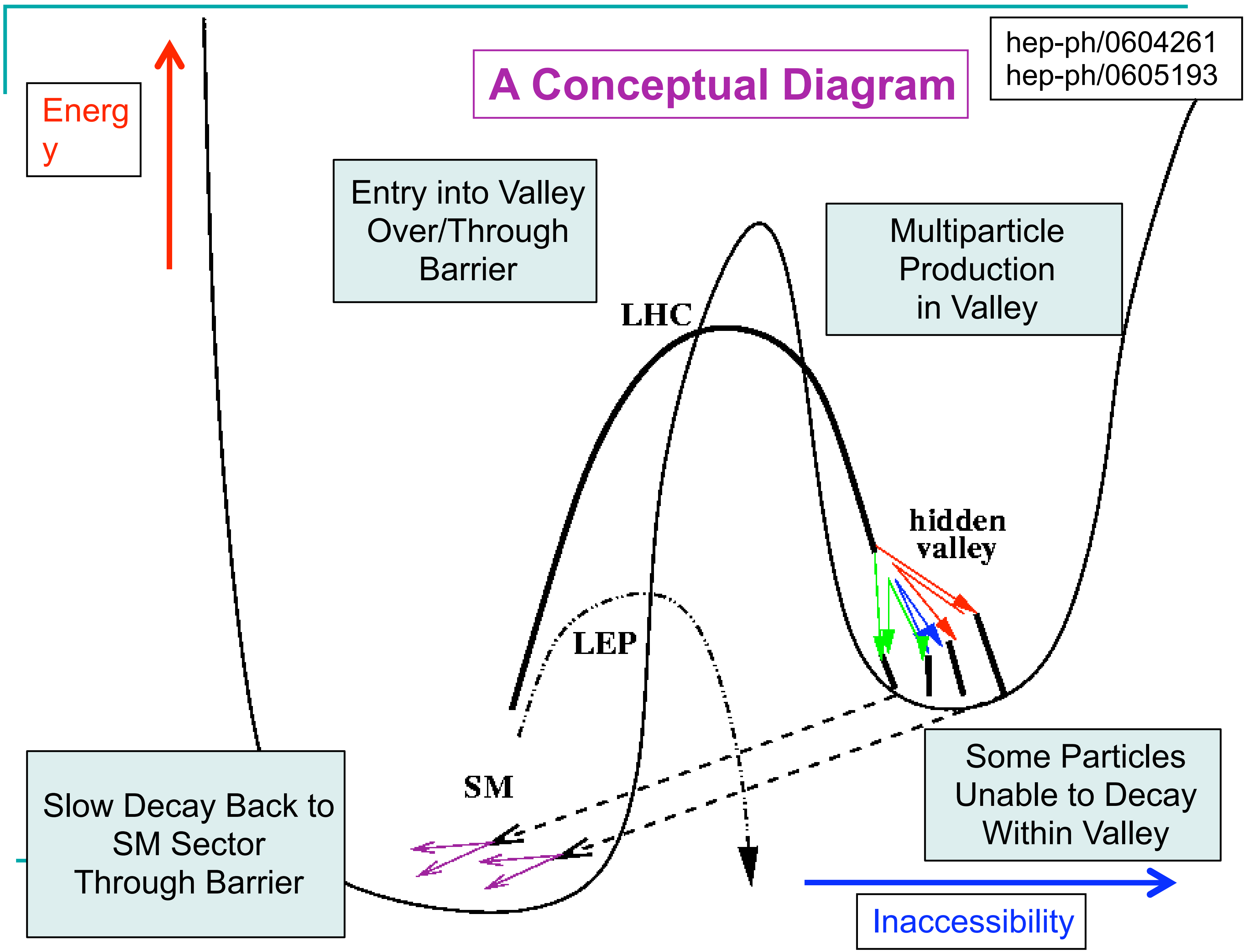
Hidden Valley Scenario (w/ K. Zurek)

hep-ph/0604261

- A scenario: **Very Large Class of Models**

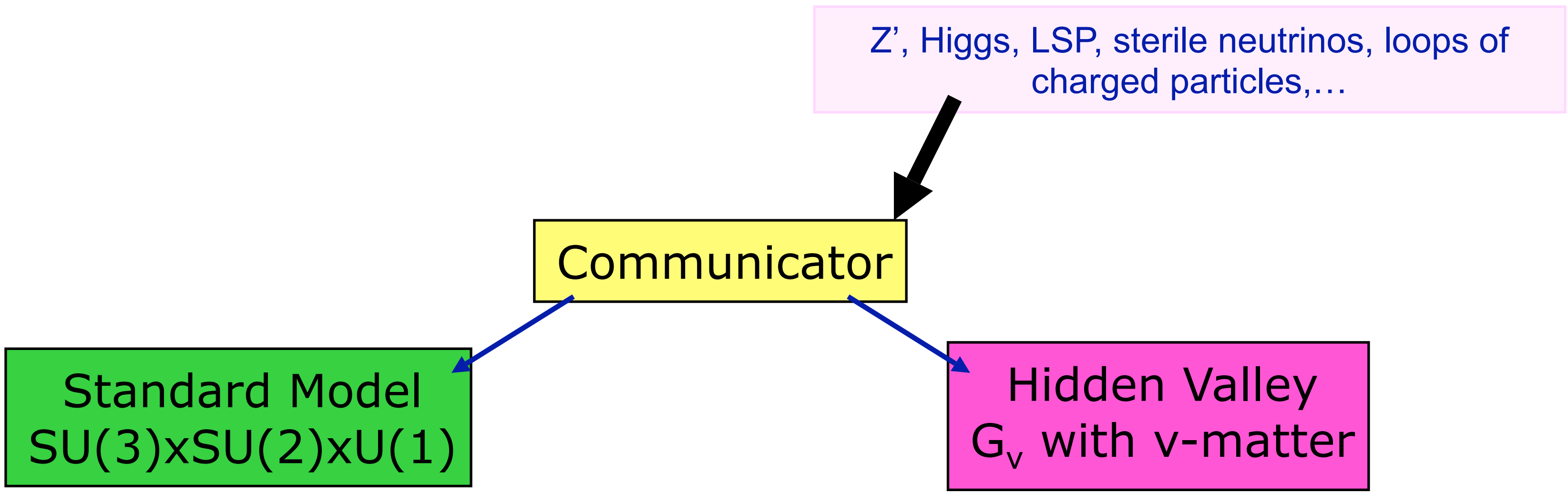
- Basic minimal structure




A Conceptual Diagram
hep-ph/0604261
hep-ph/0605193
Energy
Entry into Valley Over/Through Barrier
LHC
Multiparticle Production in Valley
hidden valley
LEP
SM
Slow Decay Back to SM Sector Through Barrier
Some Particles Unable to Decay Within Valley
Inaccessibility

Hidden Valley Scenario (w/ K. Zurek)

hep-ph/0604261



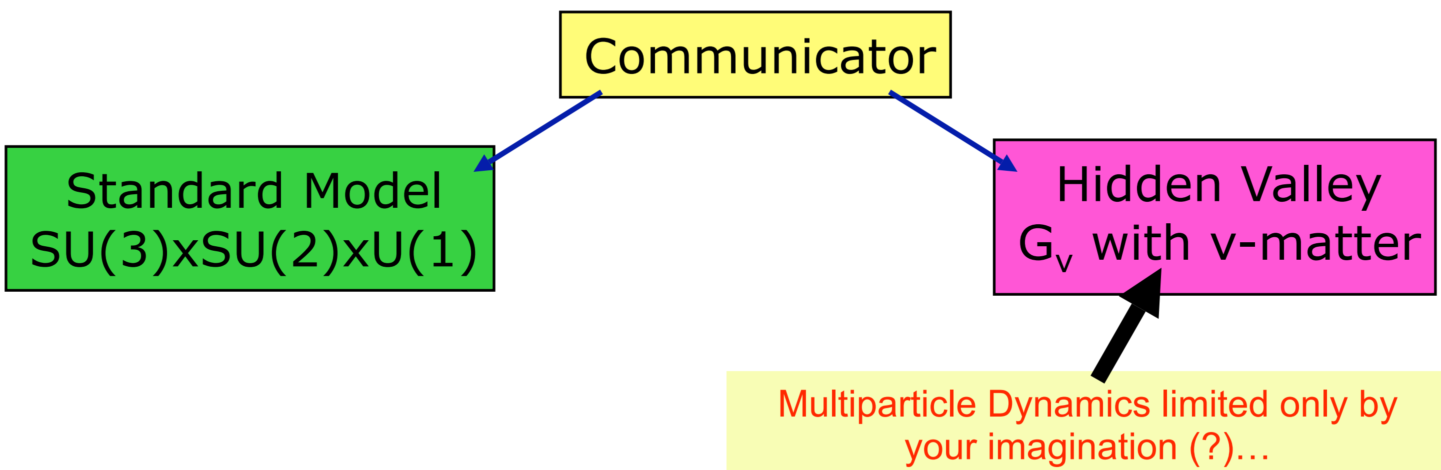
Hidden Valley Scenario (w/ K. Zurek)

hep-ph/0604261

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

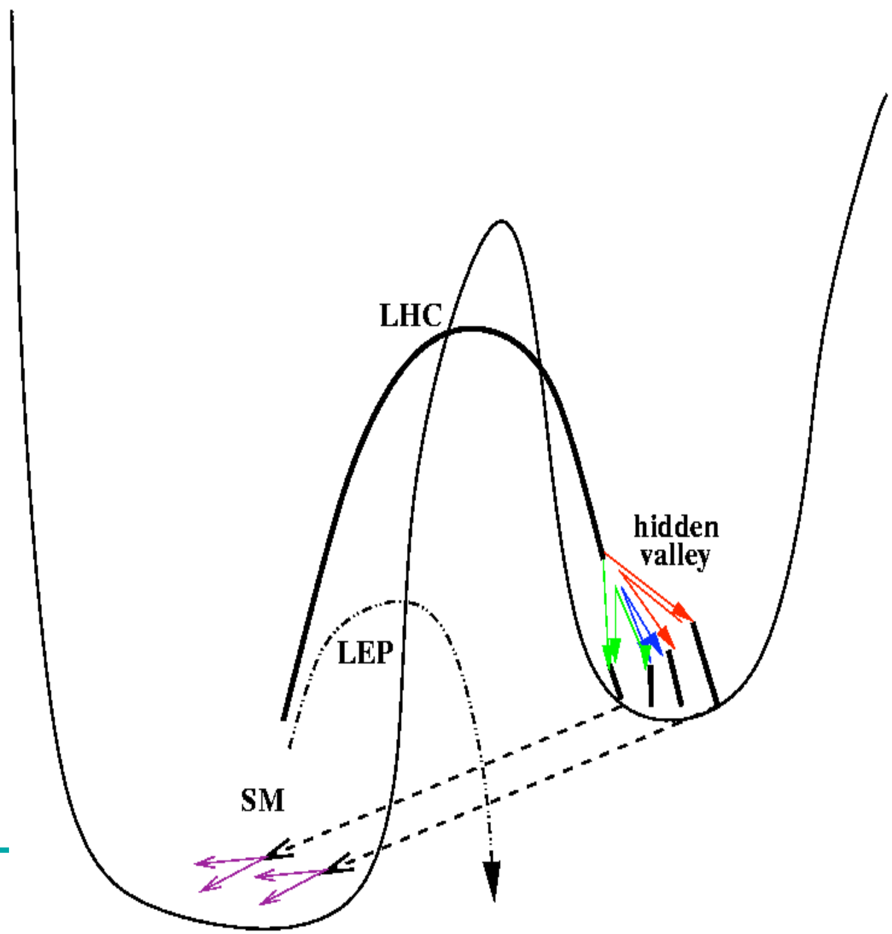
Almost-supersymmetric N=1 model
Seiberg duality cascade
KS throat
Quiver gauge theory
Remnant from SUSY breaking
Partially higgsed SU(N) theory
Multiflavor model w/ cascading decays



The Essential Ingredients:

hep-ph/0604261

- A coupling between the two sectors
  - *O_1(SM-sector)O_2(v-sector)*
  - Induced via particle exchange or loops
- Multiparticle production in the v-sector
  - Cascade of decays, or
  - [Quasi]-conformal physics
    - QCD-like parton shower
    - Walking-technicolor-like parton shower
  - Or 5d string physics (AdS/CFT,RS)
- A mass gap [or ledge] preventing some v-particles from decaying in the v-sector
  - Confinement, or
  - Higgsing, or
  - Bottom to AdS/RS throat,or
  - Explicit masses after SUSY breaking



The Challenge

- 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
  - Theoretical bias should not blind experimental searches.
- 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 challenges for theorists
- Our approach:
  - Find generic predictions of very large classes of models within HV Scenario
  - Ground our investigations in fully or largely predictive models
  - Help the experimentalists develop strategies for broad searches

General Predictions of HV Scenario

hep-ph/0604261

- New neutral resonances
  - Maybe 1, maybe 10
  - 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
  - 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

Common Predictions of HV Scenario

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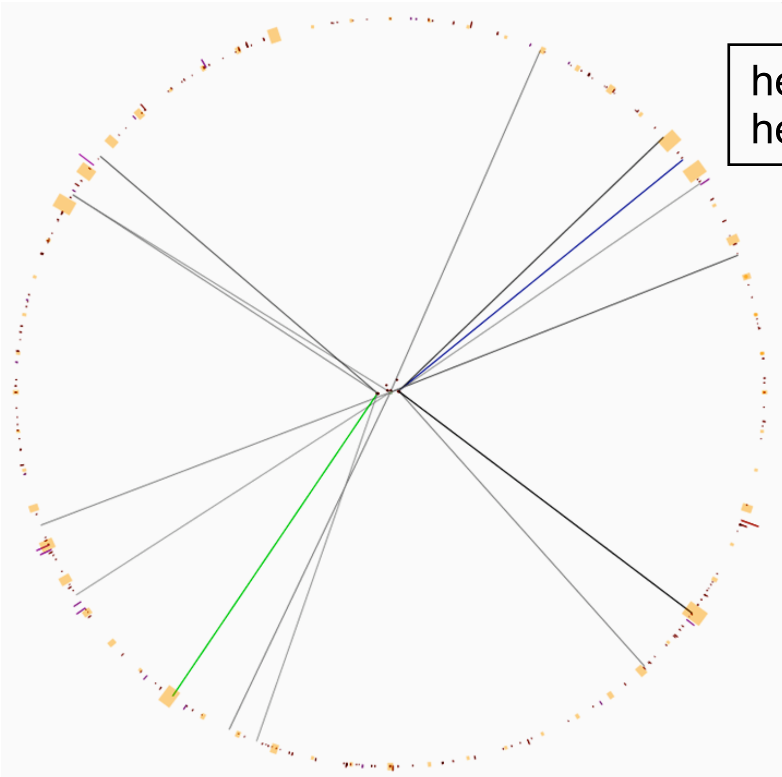
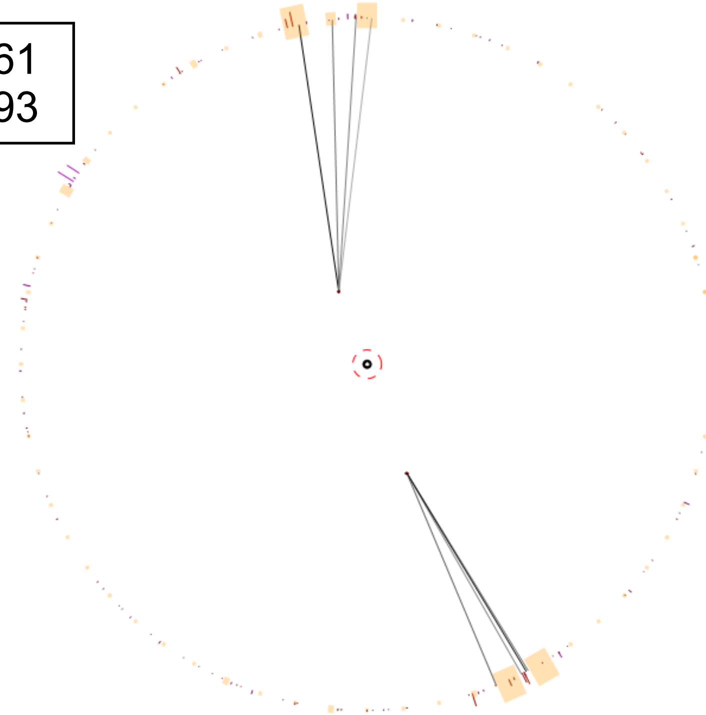
hep-ph/0605193

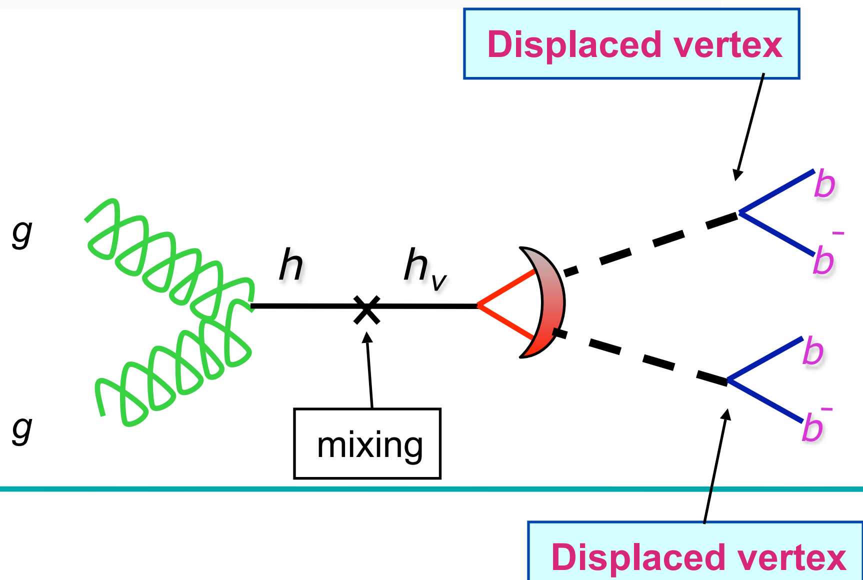
- Possible big effect on Higgs
  - H → XX, X decays displaced ➔ new discovery mode
    - *not unique to HV!!! Chang Fox Weiner 05 / Carpenter Kaplan Rhee 06*
  - H → XXX, XXXX, etc
    - *not unique to HV!!!*
- Big effect on SUSY, UED, Little Higgs – any theory w/ new global charge
  - LSP (or LKP or 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



hep-ph/0604261
hep-ph/0605193





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

Common Predictions of HV Scenario

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- Possible big effect on Higgs
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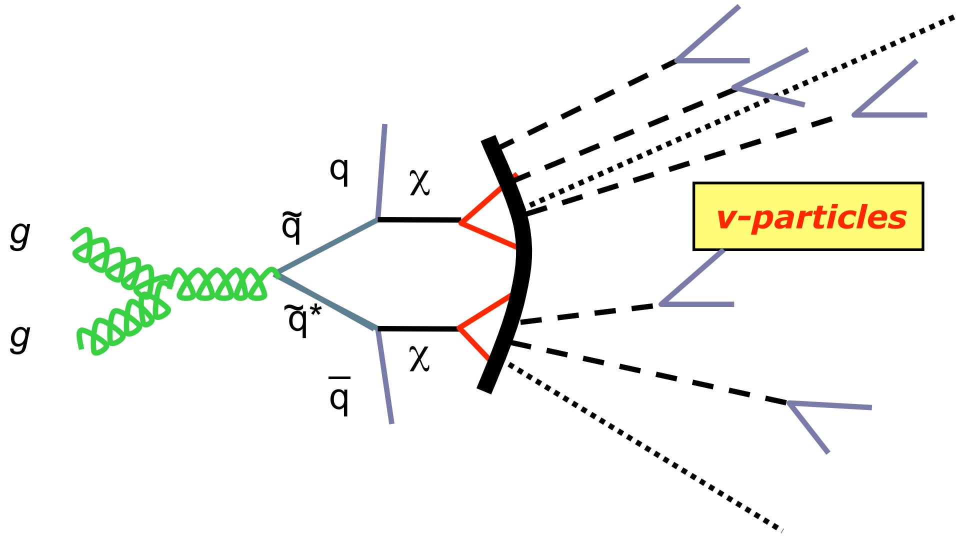
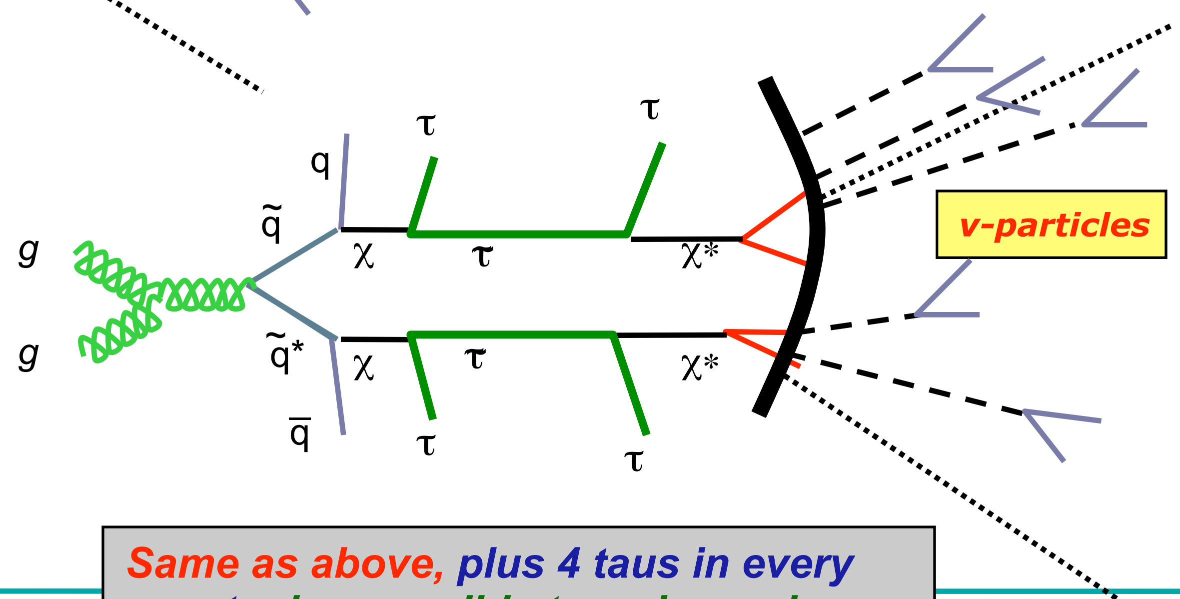
SUSY decays – two examples among many

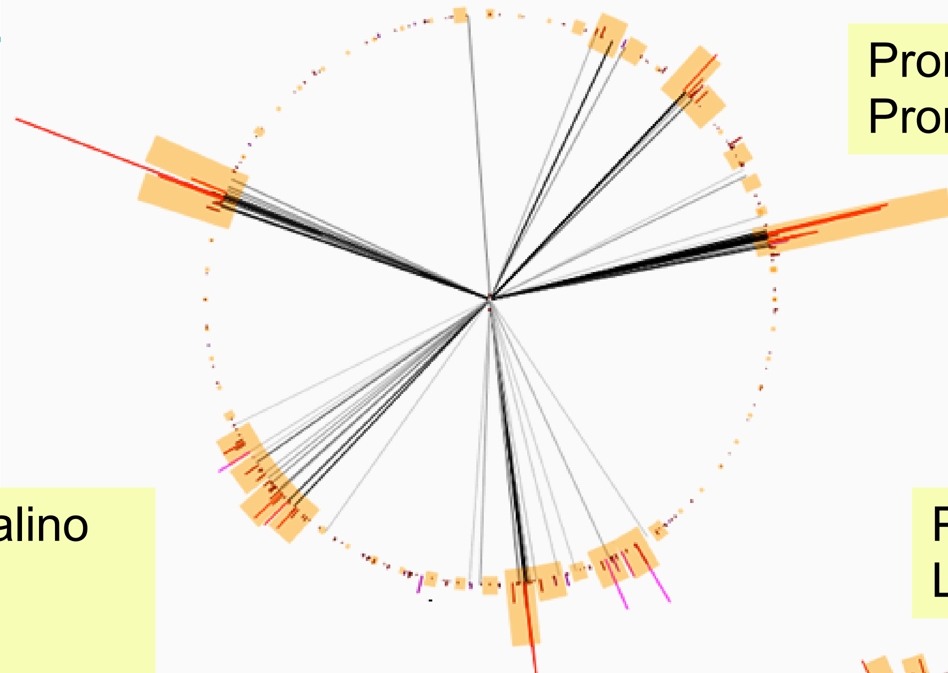


The traditional missing energy signal is replaced with multiple soft jets, reduced missing energy, and possibly multiple displaced vertices

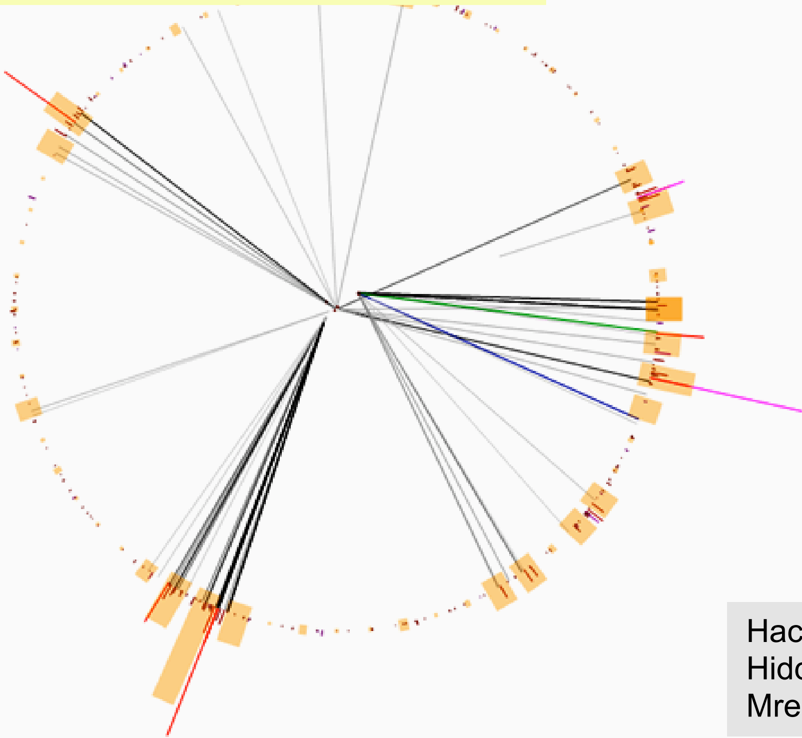


Same as above, plus 4 taus in every event, plus possibly two charged tracks for the s-tau's.

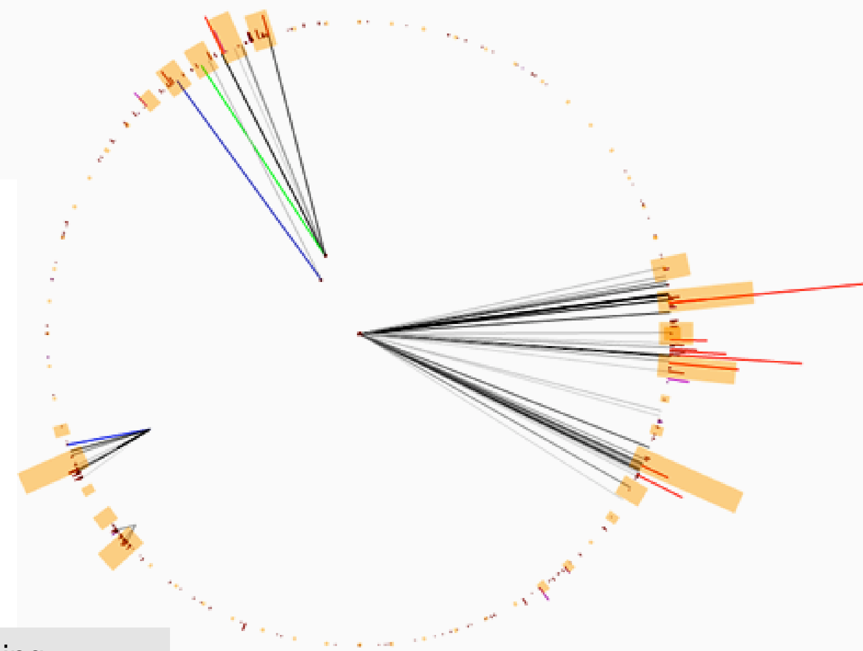
Prompt Neutralino Decay
Prompt v-Particle Decay



Long-Lived Neutralino
Prompt v-Particle
Decay



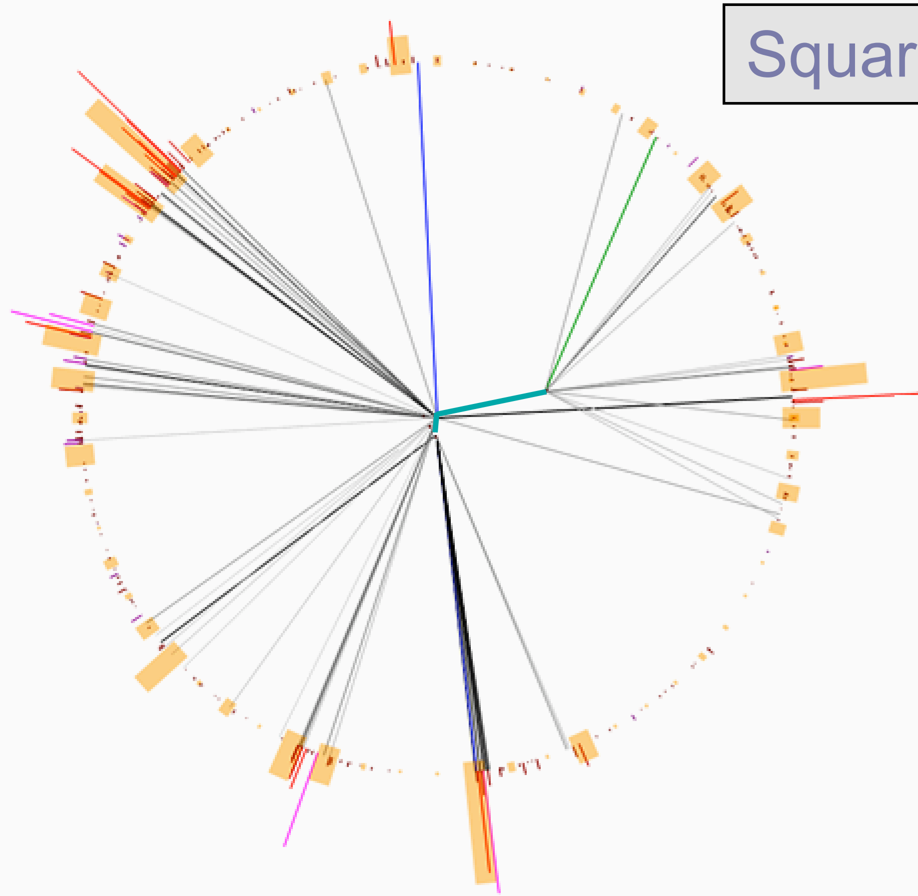
Prompt Neutralino Decay
Long-Lived v-Particles



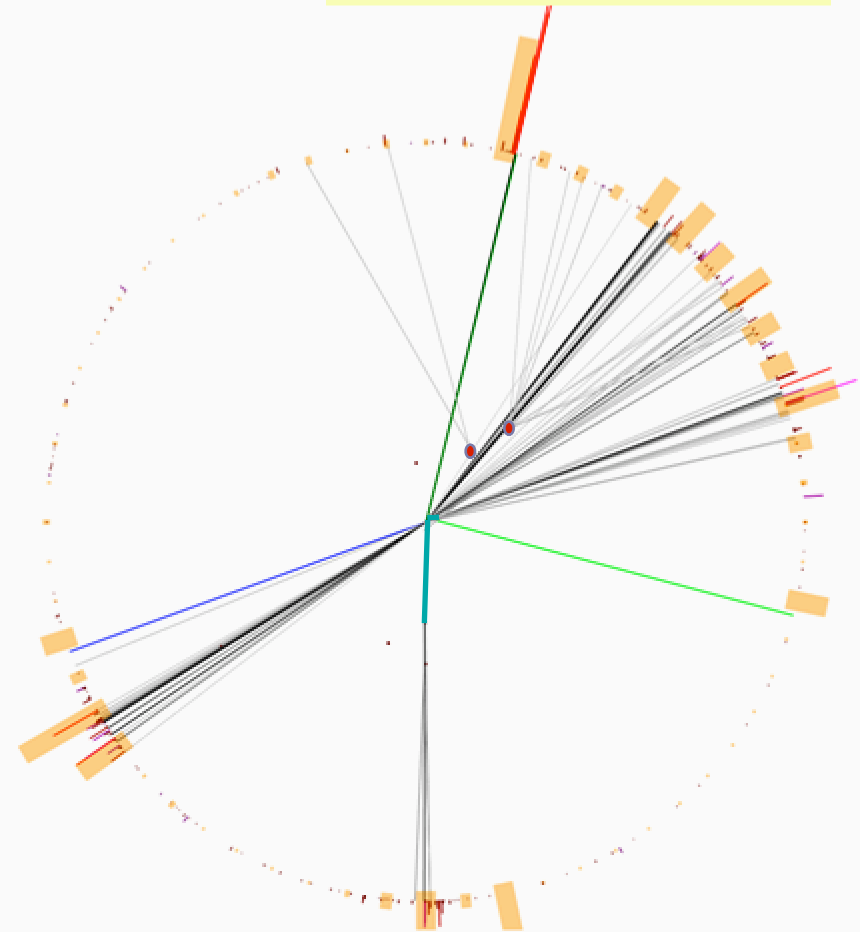
Hacked simulation using
Hidden Valley Monte Carlo 1.0
Mrenna, Skands and MJS

Squark-Antisquark Production at LHC

Stau tracks



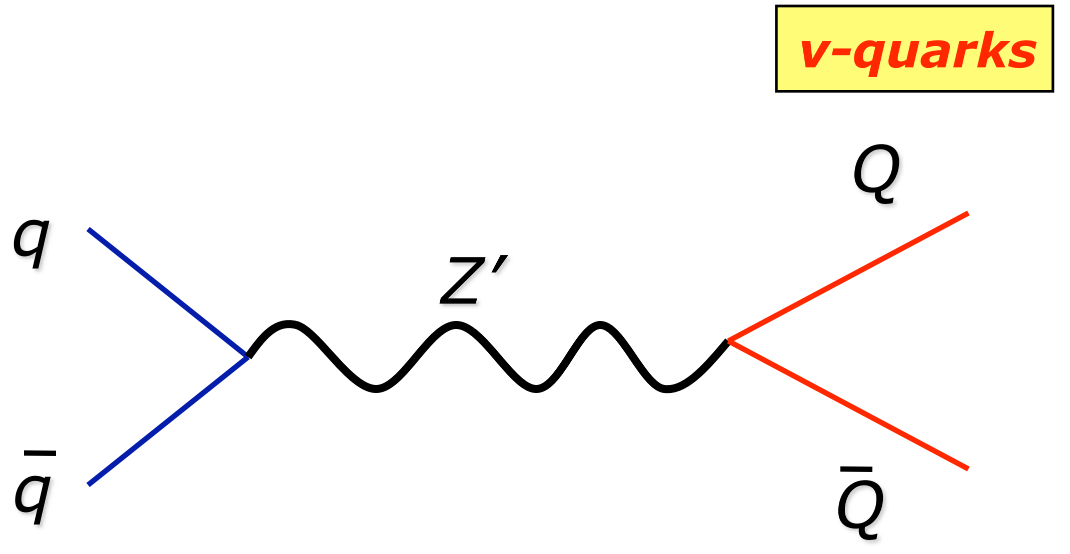
Long-Lived Stau
Prompt v-Hadron Decay



Long-Lived Stau
Long-Lived v-Hadrons

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

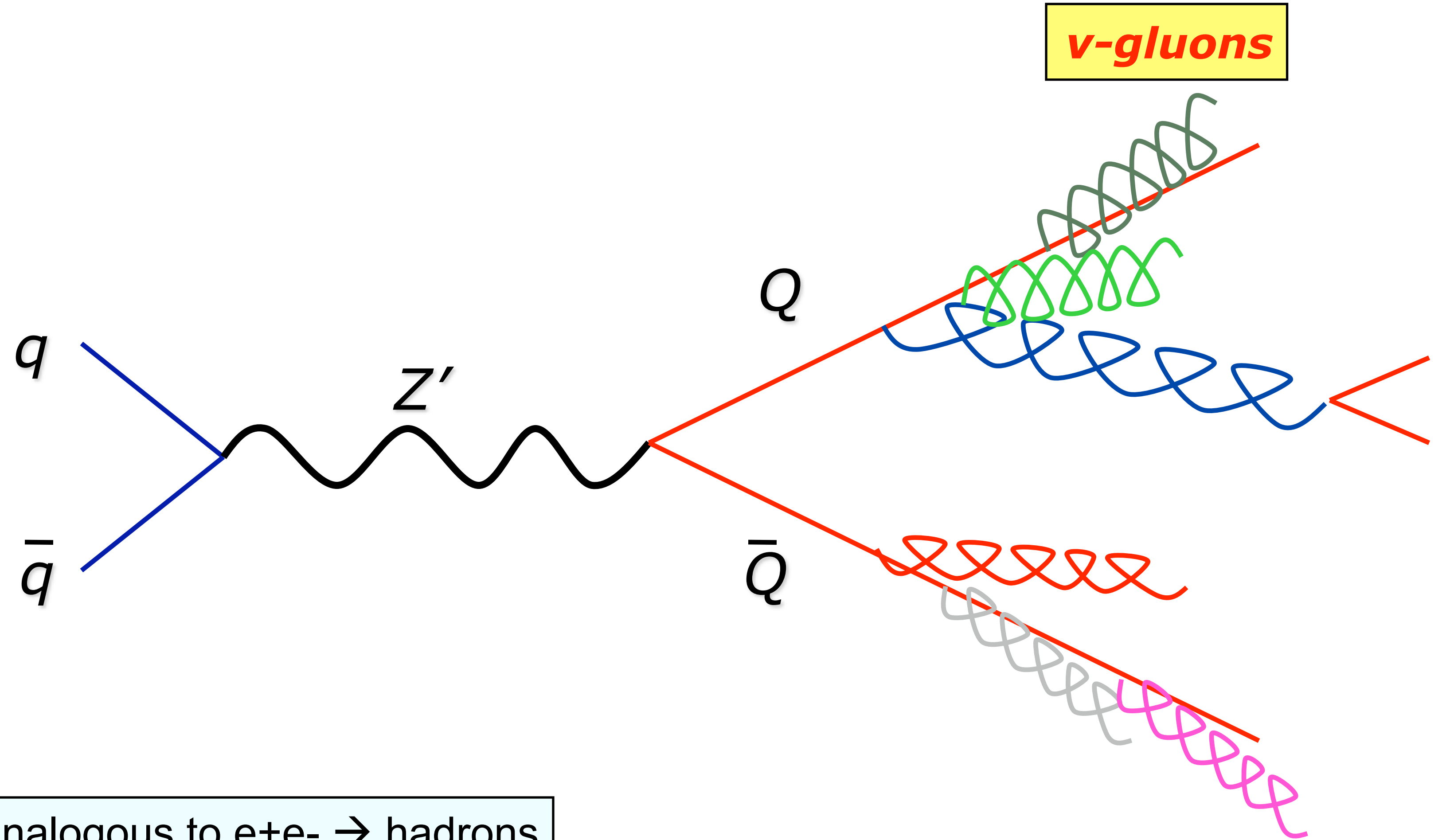
$q\bar{q} \rightarrow Q\bar{Q}$: v-quark production



Analogous to e+e- → hadrons

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

hep-ph/0604261

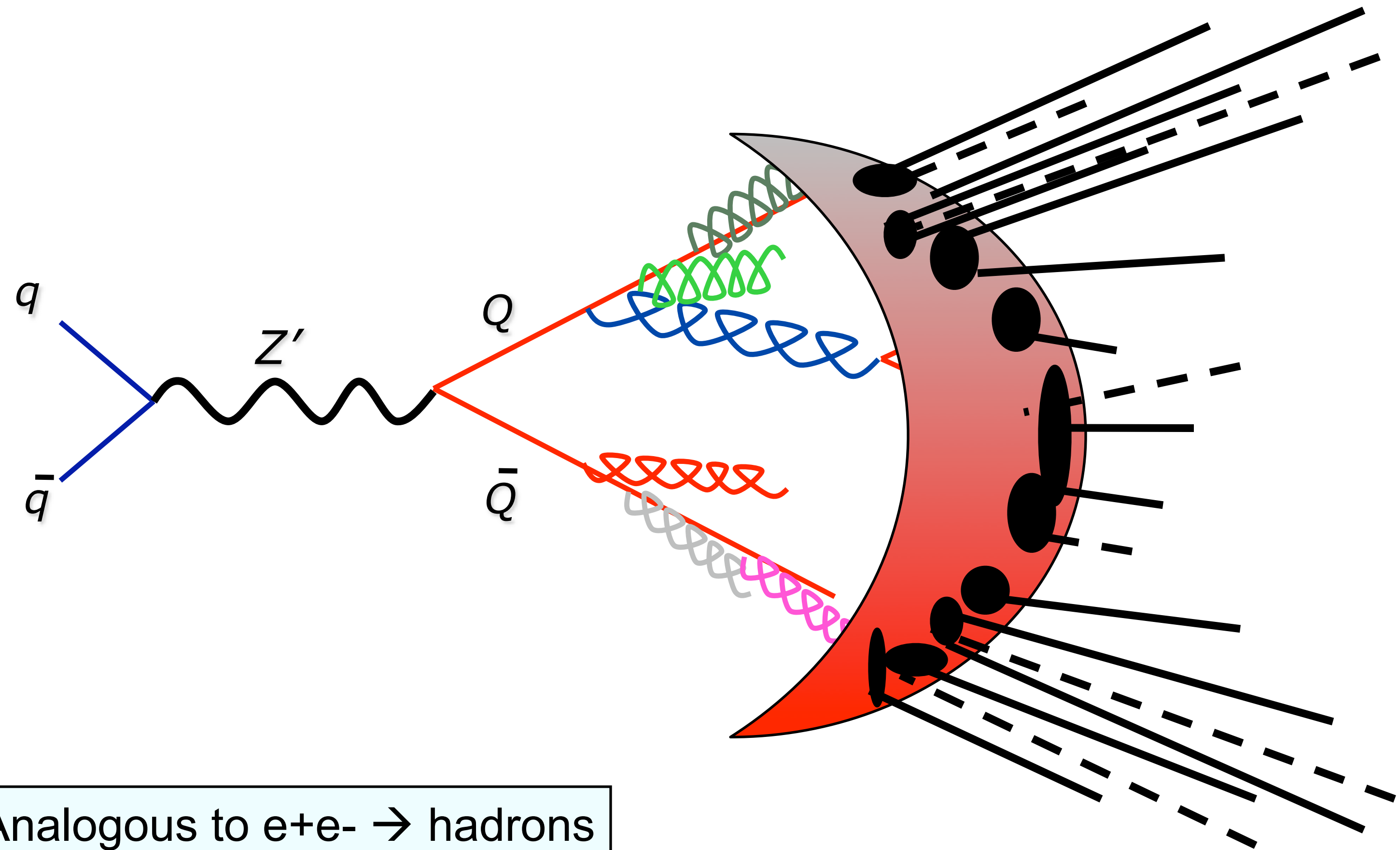


Analogous to e+e- → hadrons

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

hep-ph/0604261

v-hadrons

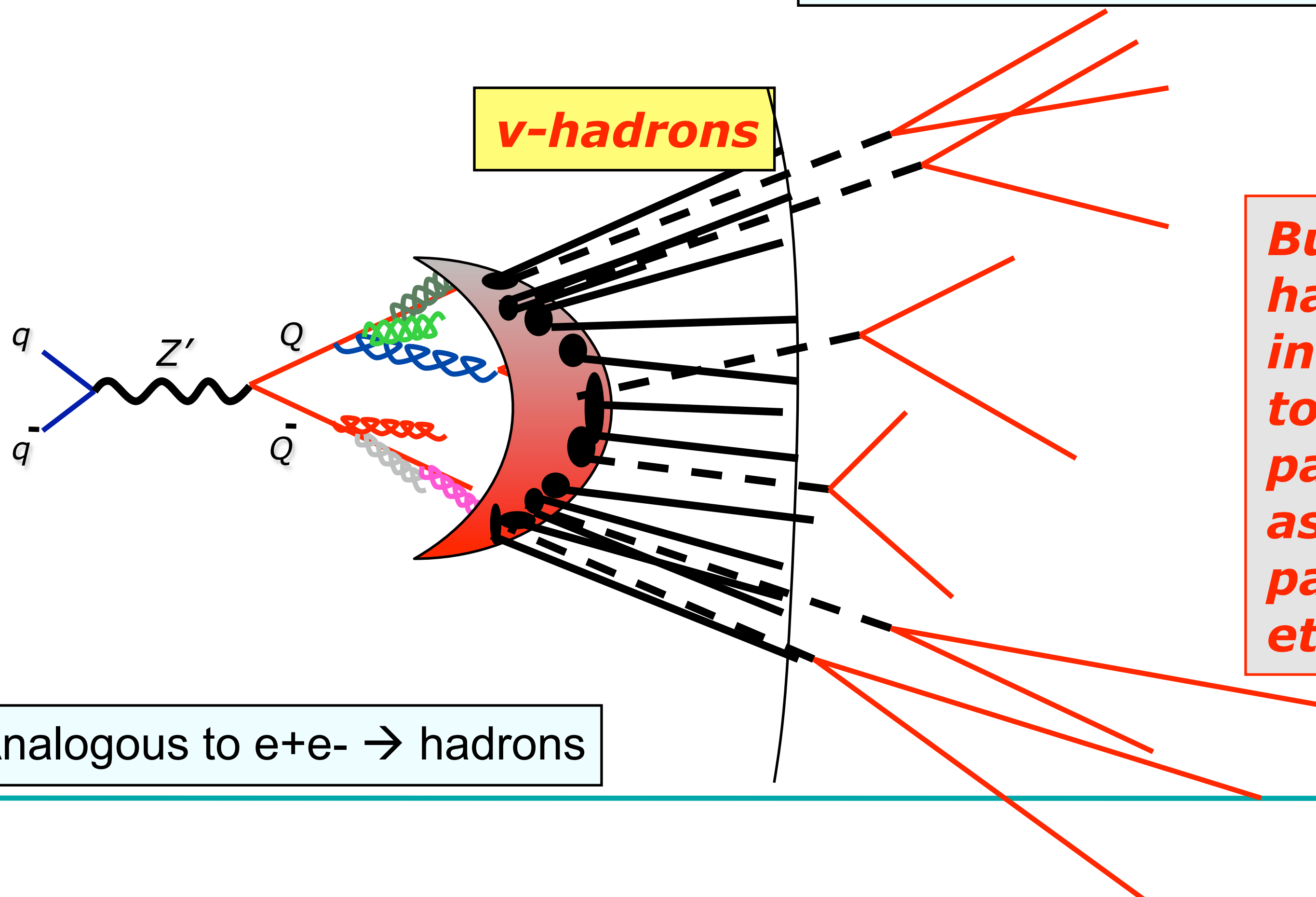


Analogous to e+e- → hadrons

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

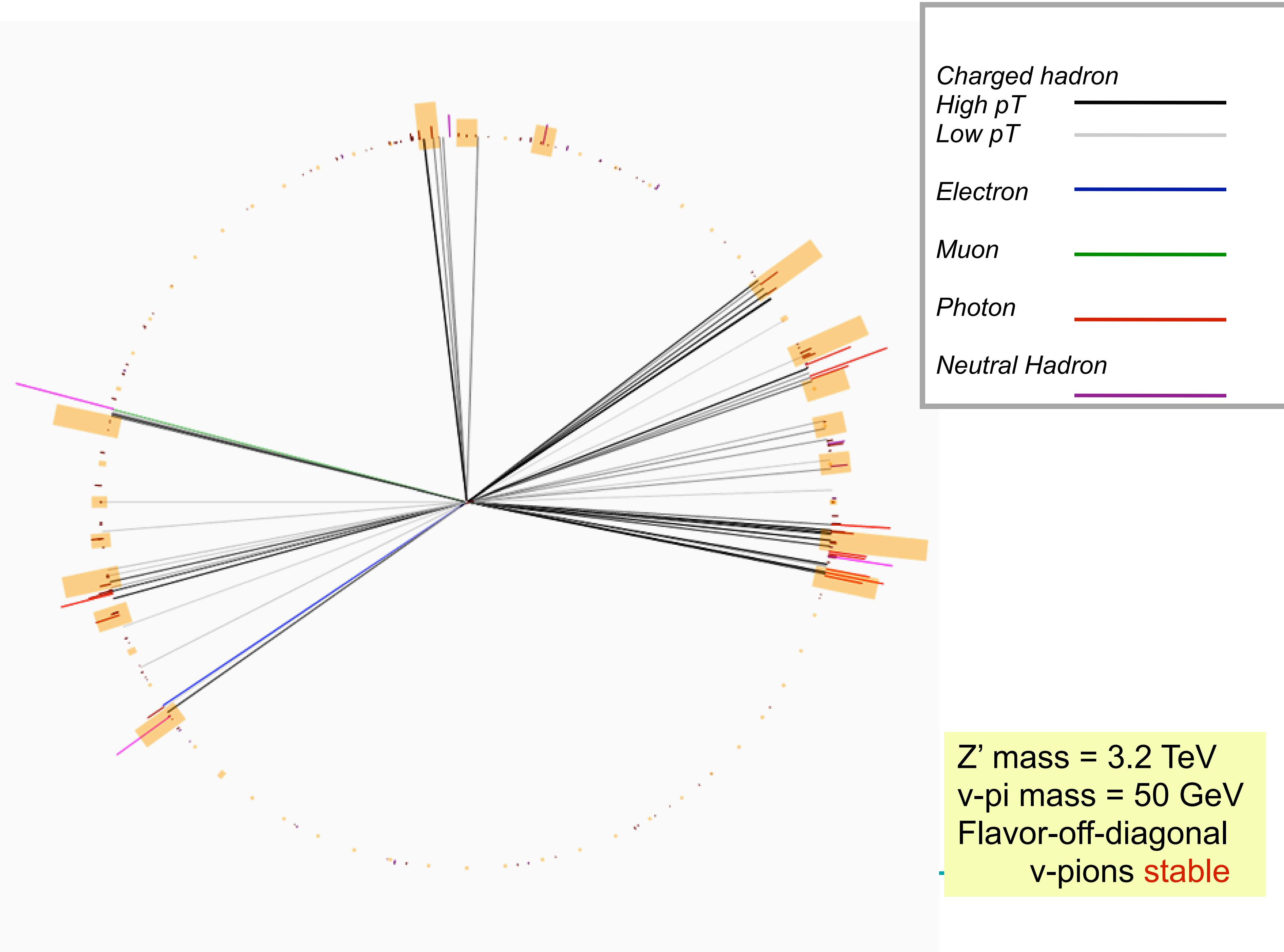
hep-ph/0604261

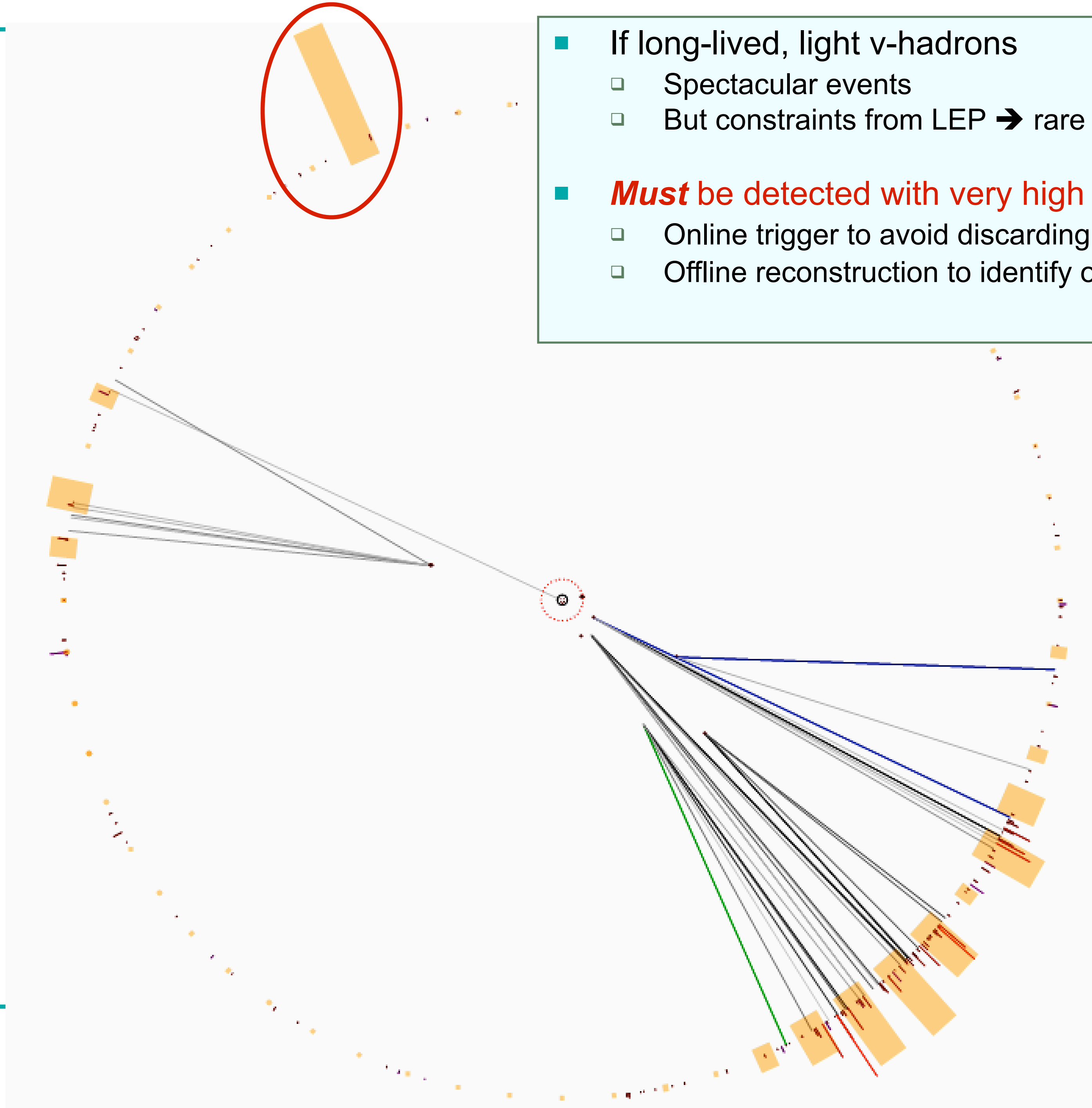
Some v-hadrons are stable and therefore invisible



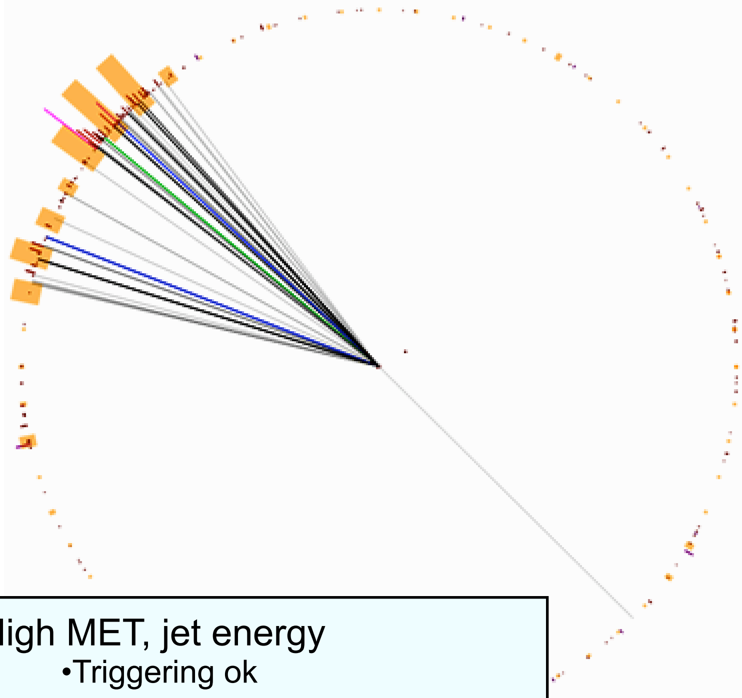
But some v-hadrons decay in the detector to visible particles, such as bb pairs, qq pairs, leptons etc.

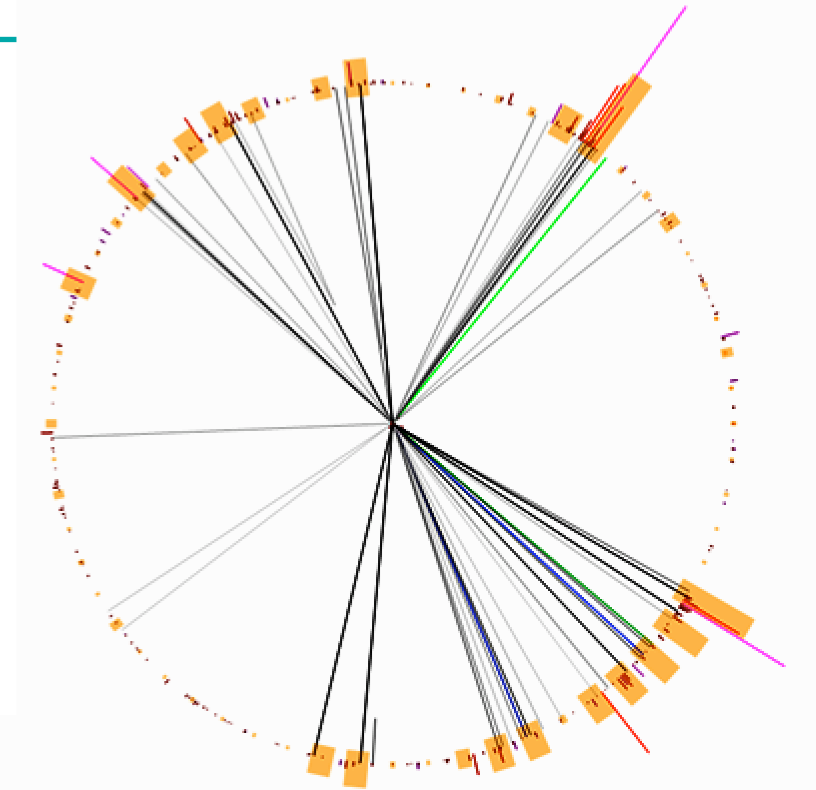
Analogous to e+e- → hadrons


Charged hadron
High pT
Low pT
Electron
Muon
Photon
Neutral Hadron
Z' mass = 3.2 TeV
v-pi mass = 50 GeV
Flavor-off-diagonal
v-pions stable

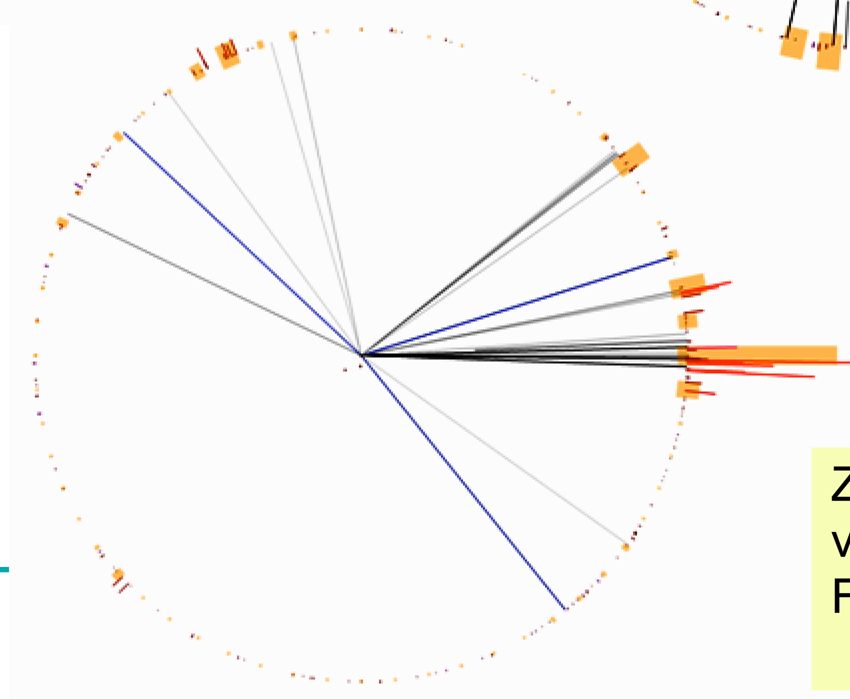


- If long-lived, light v-hadrons
  - Spectacular events
  - But constraints from LEP ➔ rare
- ***Must*** be detected with very high efficiency
  - Online trigger to avoid discarding
  - Offline reconstruction to identify or at least flag





- 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

Results of Study of Several Z' Models

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

➔ Even if many b's, too few b-tags for beating backgrounds directly

- 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-hadrons

➔ Need to store sufficient information about jet substructure

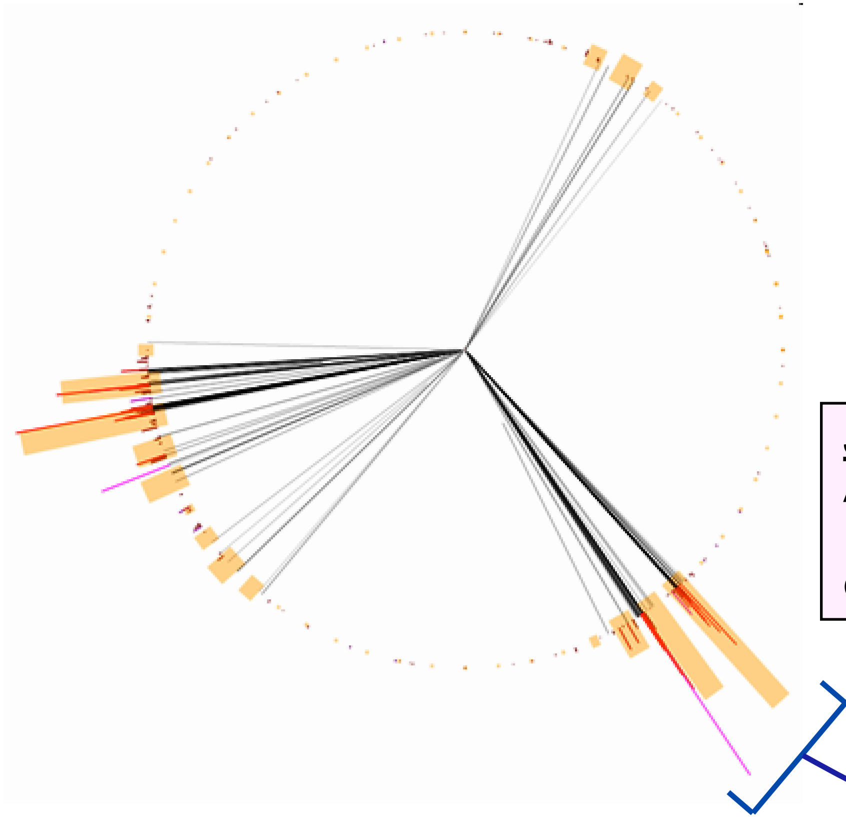
- Overall event shape unusual –

➔ May need novel shape variables

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

Reliable strategy for extracting signal from background still not clear

Jet Substructure is a Key Observable

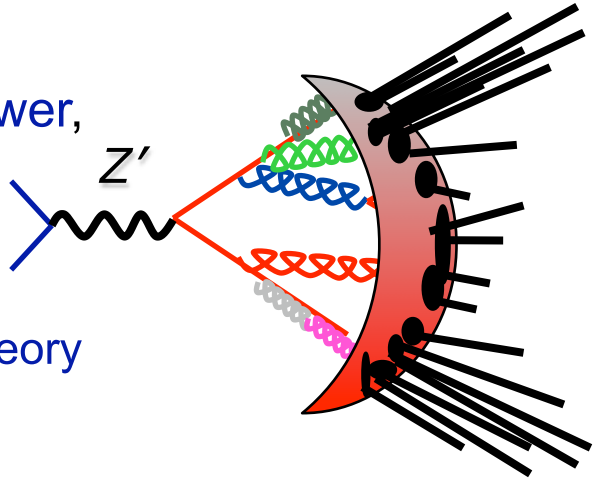


Jet Substructure
A boosted light v-hadron decaying to two quarks inside one jet

*Clearly should use the **tracker and calorimeter** together for improved resolution*

Multiparticle Production

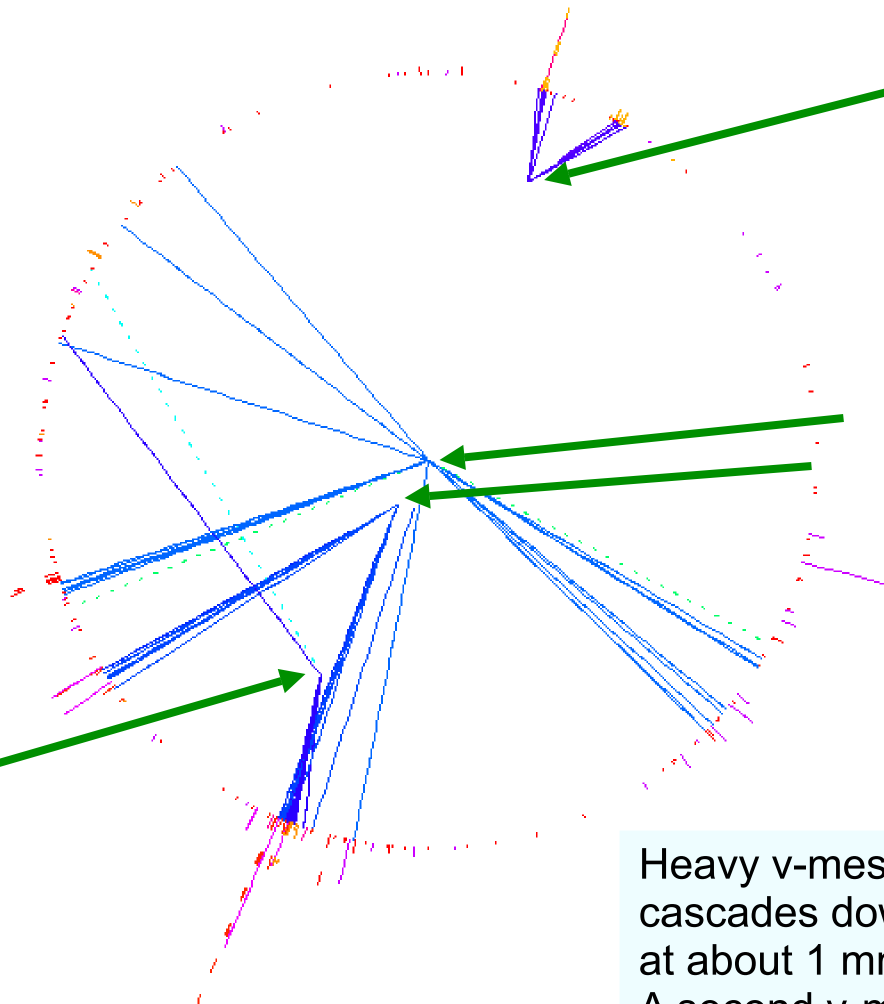
hep-ph/0604261



- Multiparticle production starts at the parton shower, not at hadronization
- Parton shower:
  - quasi-conformal dynamics of interacting gauge theory with small beta function
  - It is an *all-scales* effect, not an infrared effect
    - Cf. the physics of Z boson decays to QCD hadrons
- Above a few GeV,

  QCD is a nearly-conformal field theory:
  - Efremov & Radyushkin; Lepage & Brodsky 1979-80
  - Braun et al, The Uses of Conformal Symmetry in QCD, hep-ph/0306057
  - Stephanov 0705.3049 – Unparticles and AdS/QCD
  - Neubert 0708.0036 – Unparticles and QCD

Multi-v-flavor Cascade



In QCD, flavor-changing decays

B →D → K → pions

In v-sector, cascade decays also possible

But v-quark mass ratios will be different from those in QCD

v-hadron spectrum?
v-hadron decay modes?
v-hadron lifetimes?

Displaced Decays

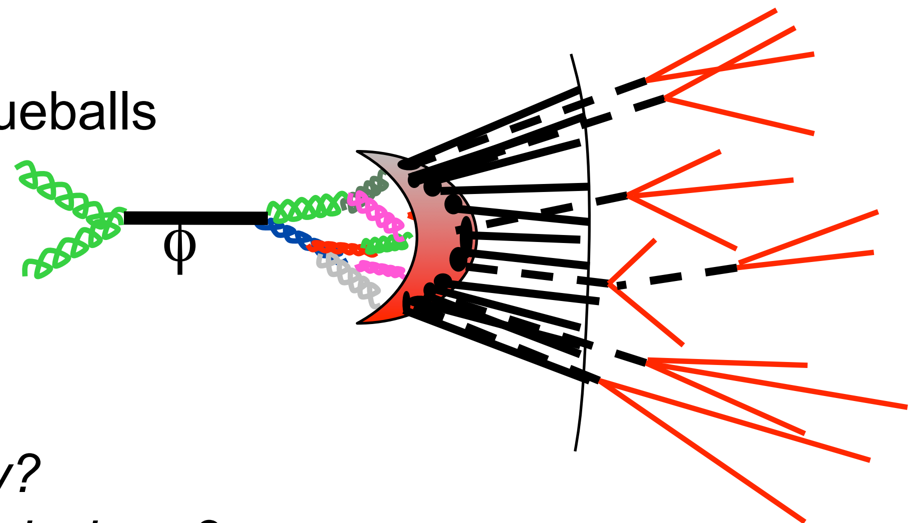
Heavy v-meson heading to the lower left cascades down in three displaced decays at about 1 mm, 10 cm and 100 cm;
A second v-meson decays at upper rght

Event generated using HVMC 1.0 (Mrenna, Skands, MJS)

A Pure Glue v-Sector

hep-ph/0604261

- Suppose v-sector is v-gluons only
- Coupling to SM via a heavy scalar ϕ
  - ϕ *(tr FF)*



- **Lattice**: Six or seven stable v-glueballs
  - Various spins. C, P
  - Various masses
  - Various decay modes to SM
  - Widely different lifetimes
- *To what do the v-glueballs decay?*
- *How many displaced vertices and where?*
- *Cosmological constraints?*

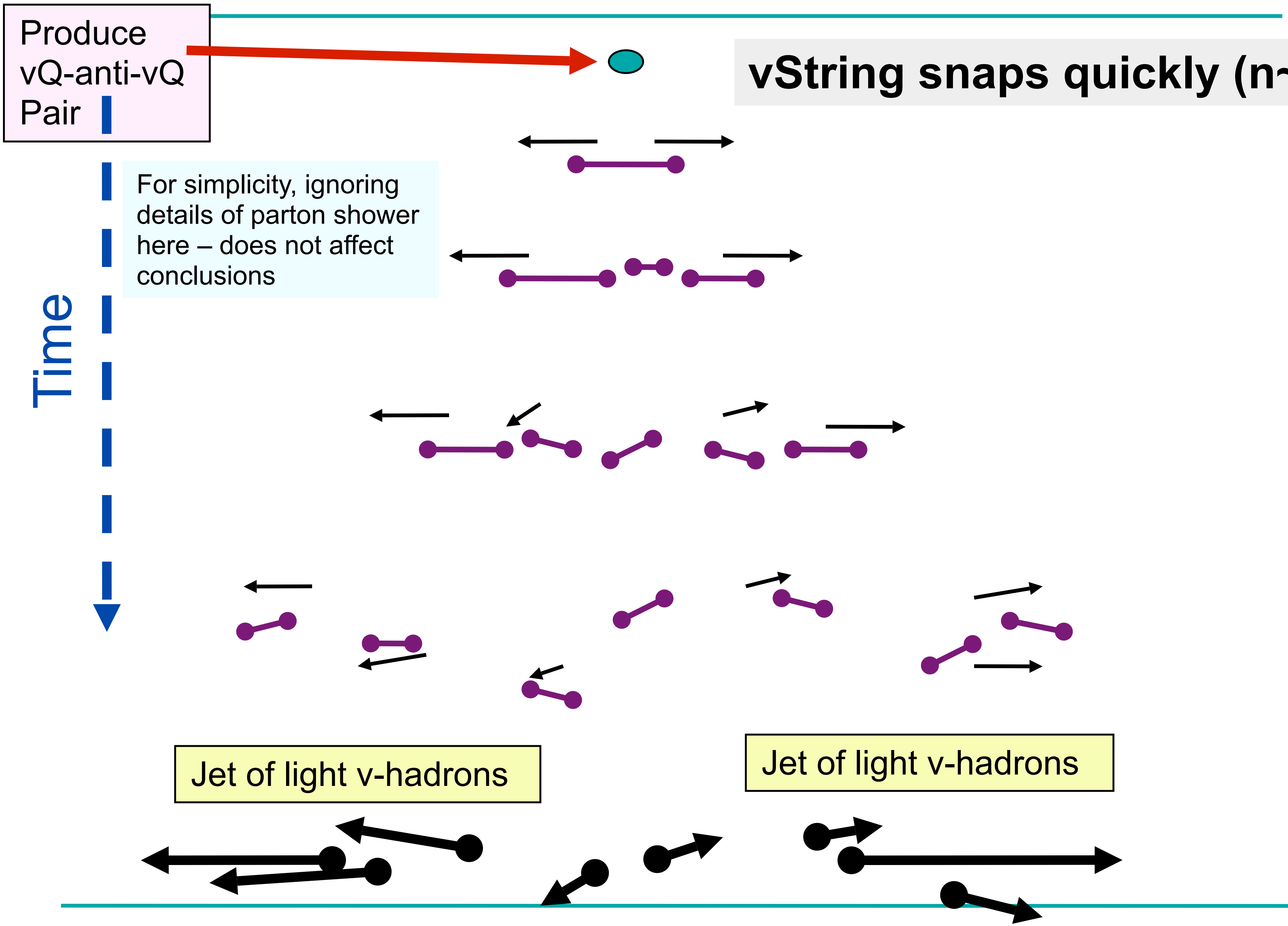
- This at least we *could* calculate…

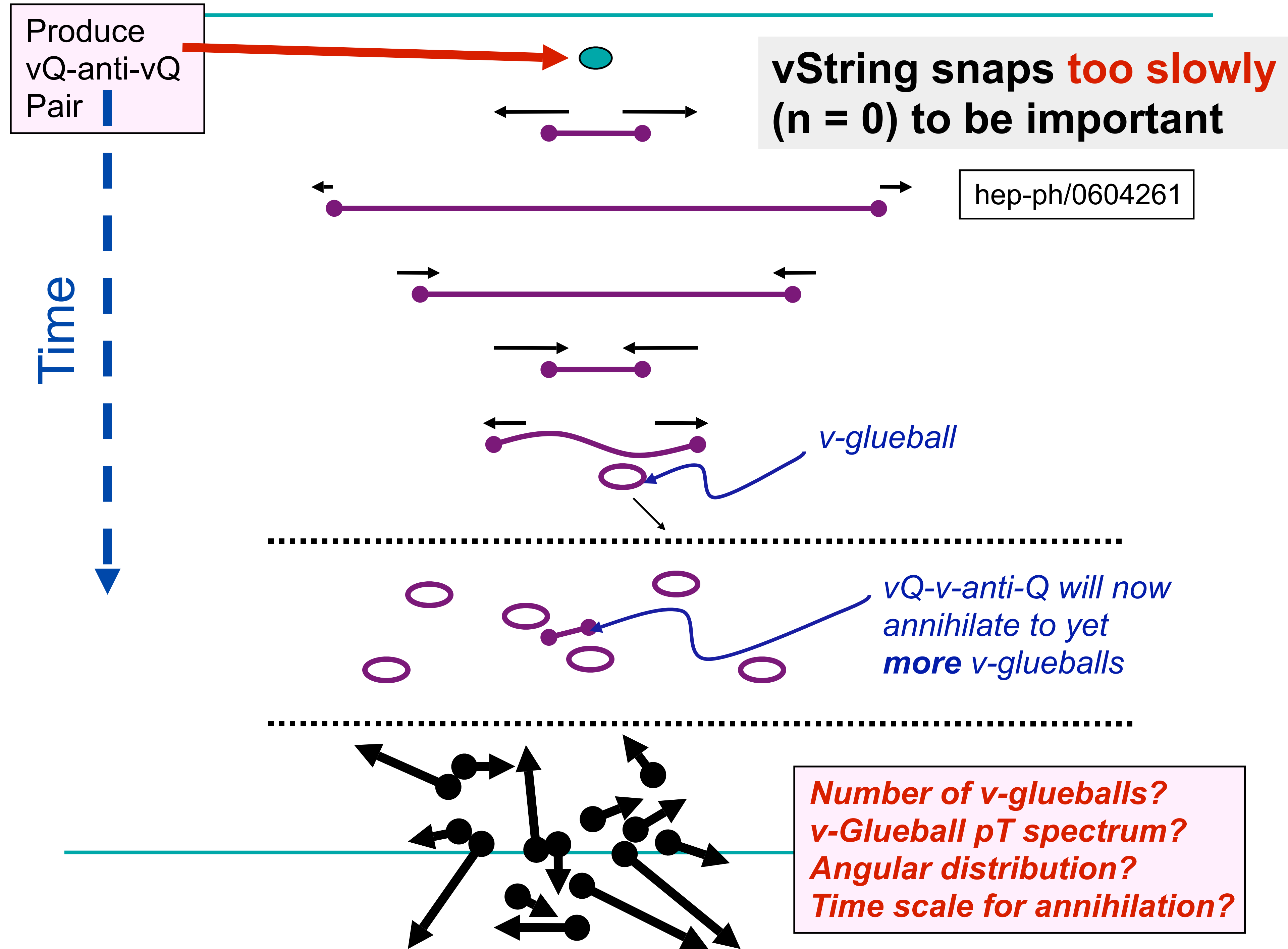
Failure of Parton/Hadron Duality

hep-ph/0604261

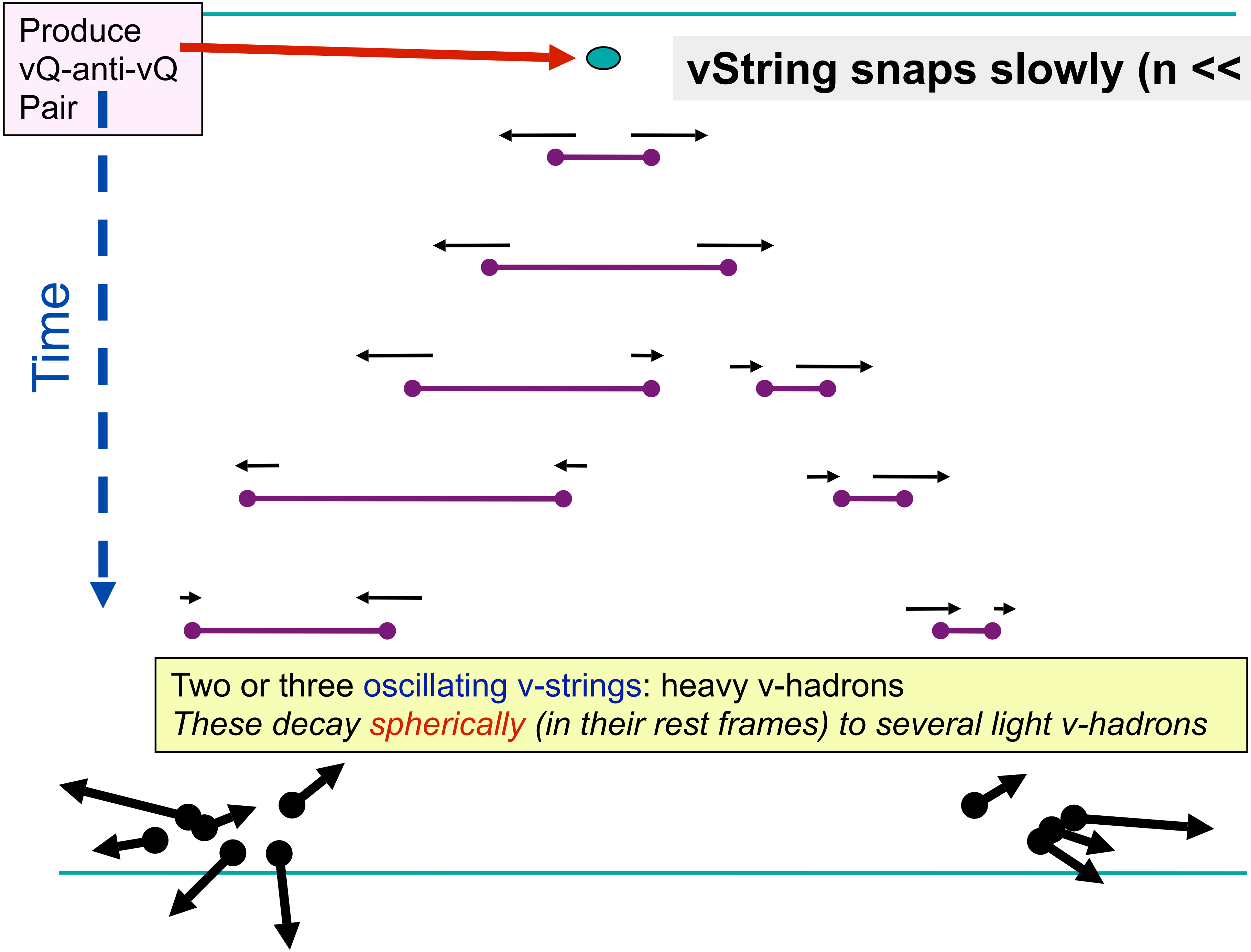
- Gauge Theory with quarks in fundamental representation
  - Number of light quarks *n* is of order
  - Number of colors *N*
- Real world QCD: *n* ~ *N* exhibits " parton-hadron duality"
  - Hard quark/gluon at short distance ➔
  - Hard jet of hadrons with roughly same 4-momentum
- *As n/N goes down, this fails.*

vString snaps quickly (n~N)




Produce vQ-anti-vQ Pair
vString snaps too slowly (n = 0) to be important
hep-ph/0604261
Time
v-glueball
vQ-v-anti-Q will now annihilate to yet more v-glueballs
Number of v-glueballs?
v-Glueball pT spectrum?
Angular distribution?
Time scale for annihilation?

vString snaps slowly (n << N)



Two or three oscillating v-strings: heavy v-hadrons
These decay spherically (in their rest frames) to several light v-hadrons

What if the ends of the string have color or electric charge?

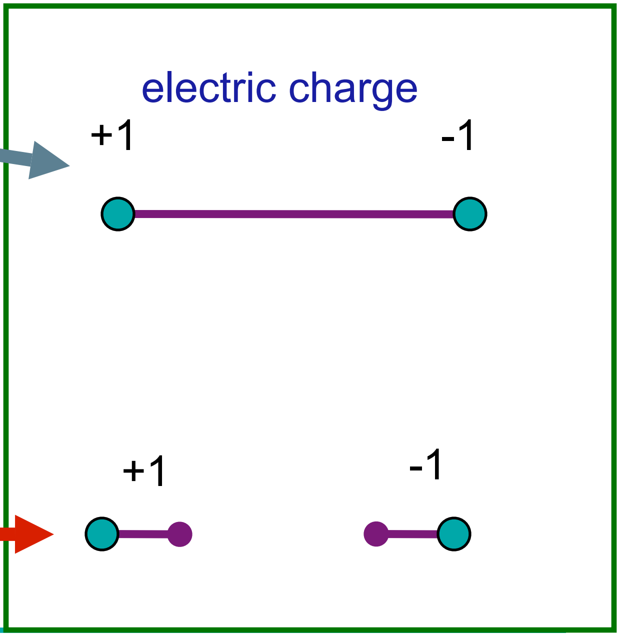
Kang and Luty

MJS and Zurek, hep-ph/0604261

- Then these are often called quirks
- …but here high confinement scale
  - (of order 100 GeV)

  so strings remain microscopic

- *How do the excited strings decay down?*
- *What electromagnetic/color interactions are observable?*
- *What other v-particles are produced along with them?*
- *If light v-quarks, then strings break:*
  - *obtain stable composite heavy-lepton-like or heavy-hadron-like states*

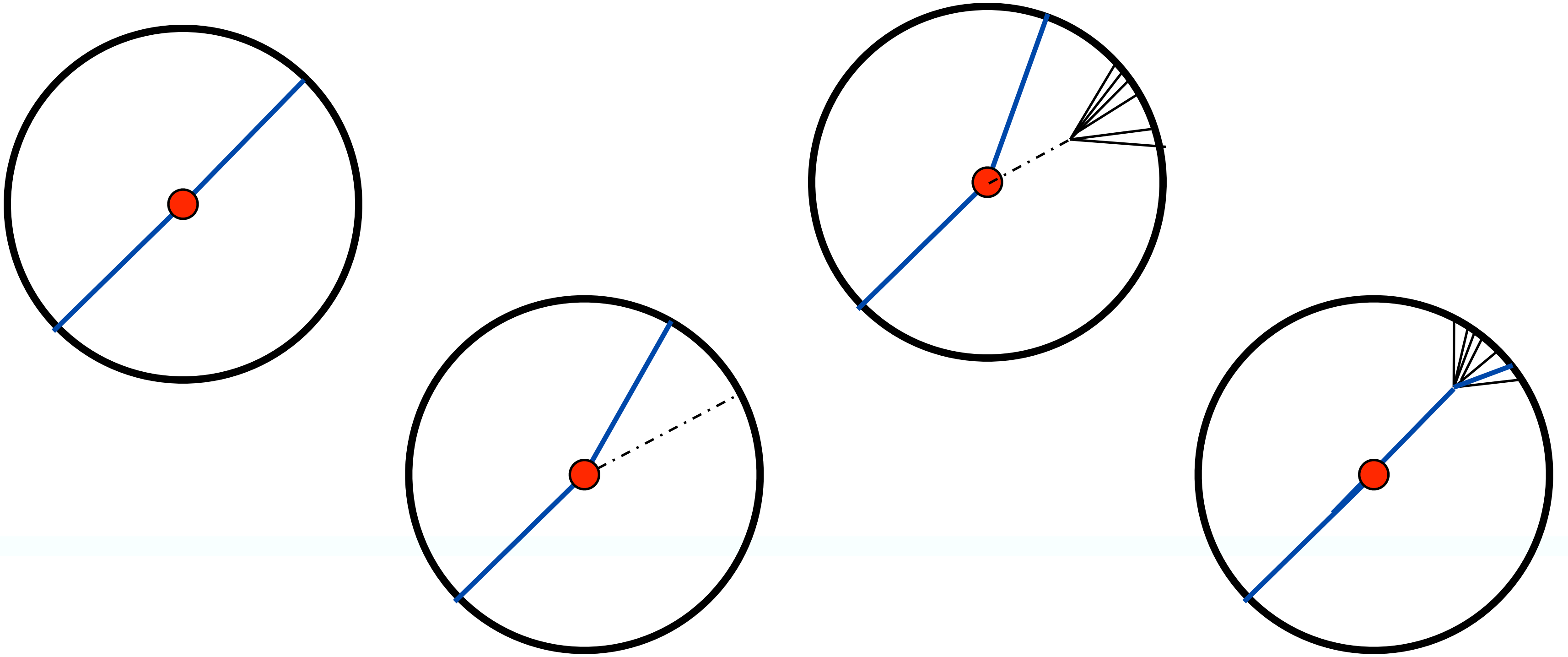


New Particle Production

hep-ph/0604261

- If the quirk is charged but the string breaks, so that if forms bound states, we can get particles that look like new heavy leptons or new heavy colored particles

- If a composite due to v-forces binding it together, then may radiate v-particles
- Signature: a (possibly long-lived) neutral particle accompanying it



Multiparticle Production in QCD

hep-ph/0604261

Note that in this example

- Multiparticle production starts at the parton shower, not at hadronization
- Parton shower:
  - quasi-conformal dynamics of QCD
    - (or of any interacting gauge theory with small beta function)
  - It is an *all-scales* effect,
  - It is **not** dominantly an infrared confinement effect
    - Cf. the physics of Z boson decays to QCD hadrons
- Above a few GeV, QCD is a nearly-conformal field theory:
  - Practically useful over 30 years
  - A few references and reviews
    - Efremov Radyushkin; Lepage Brodsky 1979-89 [and earlier]
    - Review: Braun et al, The Uses of Conformal Symmetry in QCD, hep-ph/0306057
    - Stephanov 0705.3049 – Unparticles and AdS/QCD
    - Neubert 0708.0036 – Unparticles and QCD

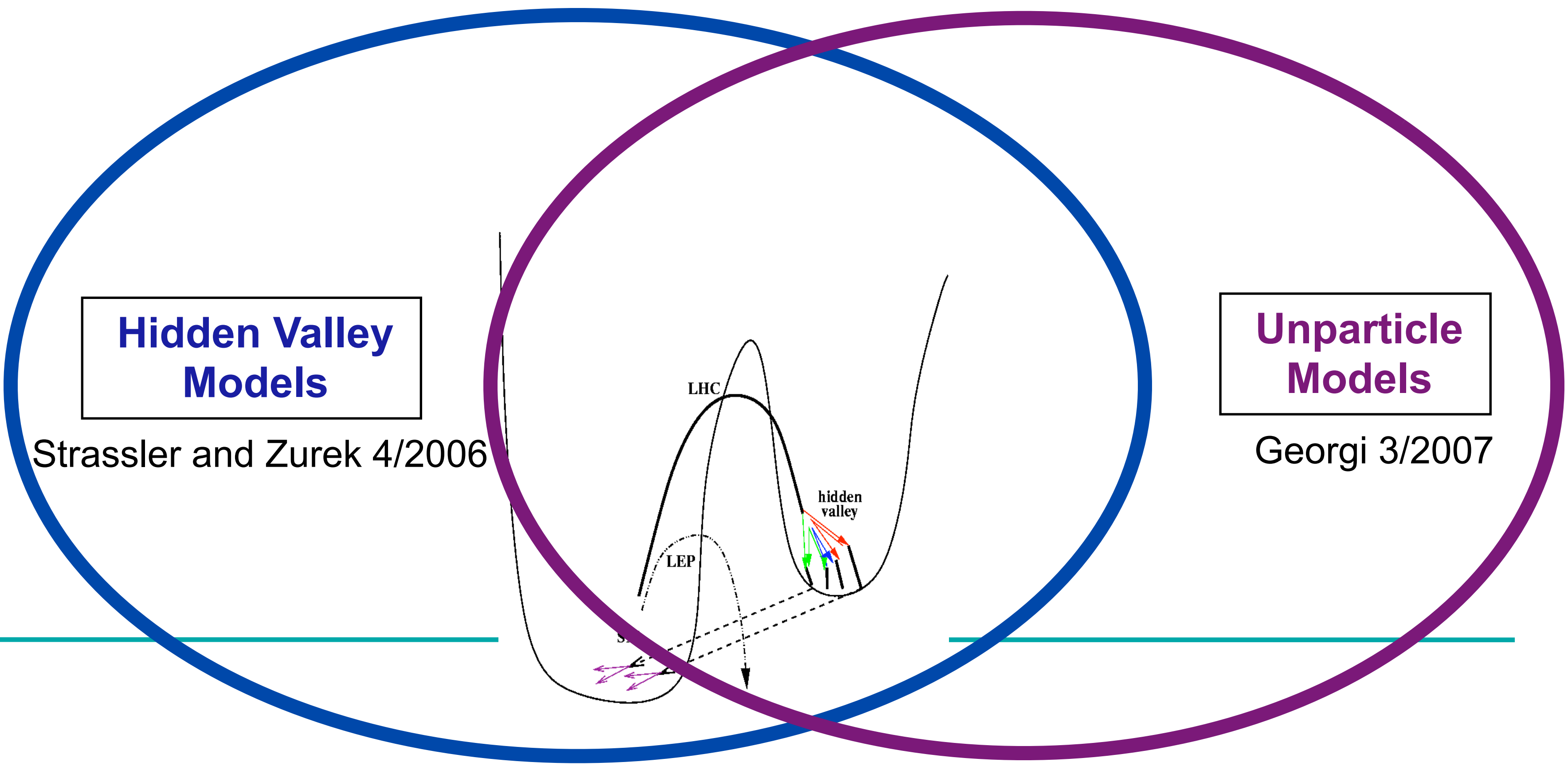
My Favorite v-Sectors

Strongly Coupled Field Theories with
- Large Anomalous Dimensions
- Mass Gap in the v-Sector (often due to confinement or its dual)

Examples:
- Walking Technicolor
  - Holdom, Georgi, Appelquist, Terning, Wijewardena, Sundrum, …
- Supersymmetric Gauge Theories
  - Seiberg, Intriligator, Leigh, MJS, Luty, Terning, Schmaltz, Poppitz, Trivedi, Shadmi, Shirman, Ratazzi, Arkani-Hamed, Csaki, Skiba, Sundrum, Nelson
  - Supersymmetry-Breaking Models
  - Flavor physics driven by large anomalous dimensions
    - Nelson and MJS; Luty, Sundrum
- Gauge Theories with String Theory Dual Descriptions
  - Csaki, Oz, Ooguri, Terning; Randall, Sundrum; Polchinski, MJS; Klebanov, MJS

UV-Conformal Hidden Valley Models

- **Conformal Field Theories with a Mass Gap in the v-Sector**
  - This is a subclass of Hidden Valley models
  - … these are also Unparticle Models with Conformal Symmetry Breaking
  - I suggest they be termed "Hidden Valley/Unparticle" Models



UV Conformal/IR Mass Gap

- Hidden Valley/Unparticle models are not predictive in detail
  - Certain technical challenges for computation in CFTs
  - But typically their dominant signals resemble what I've shown already

- Note that all known CFTs in 4d are gauge theories
  - **Caution: Gauge theories cannot be written simply in terms of *local* gauge invariant operators**
    - *Cannot easily see parton shower using local operators*
  - Must be careful with calculational methods

    - ***Try this with a free gauge theory***:
      - Write it using gauge invariant operators
      - Compute the unparticle propagators, unparticle scattering
      - 3-point, 4-point functions non-vanishing; *looks like an interacting theory*!

    - ***Then repeat for a Banks-Zaks fixed point***.
      - 3-point, 4-point functions potentially misleading, since were so in free theory;
      - Where is the parton shower?

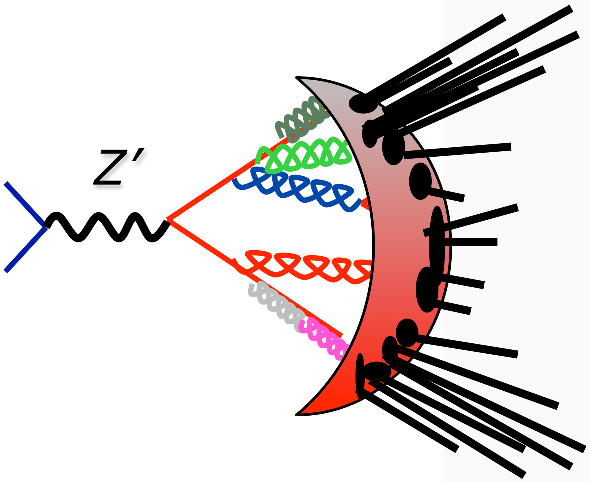
α vs. β vs. γ

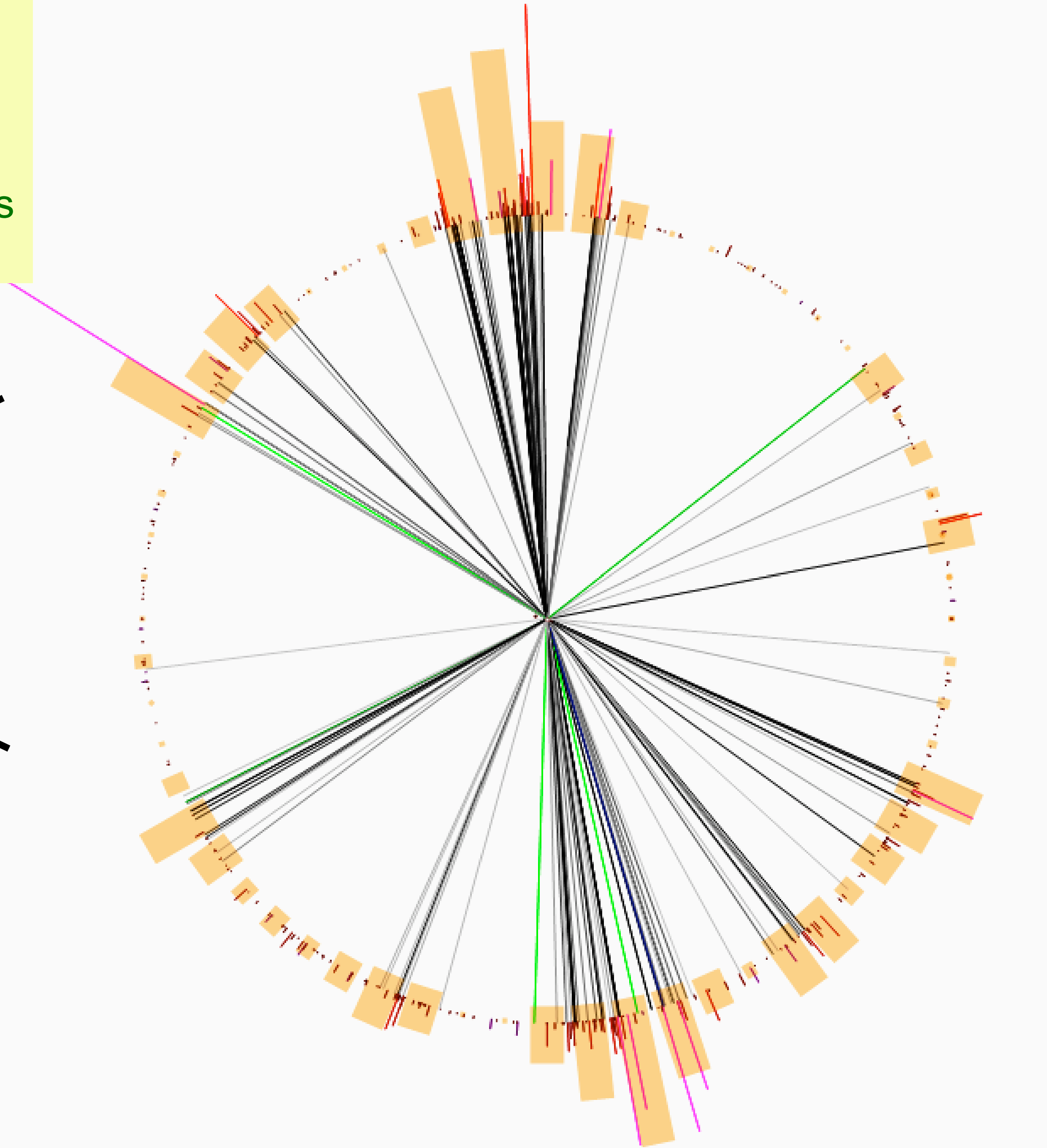
- α *the gauge coupling*
- β *the running of the gauge coupling*
- γ *the deviation of operator dimensions from naïve values*

	Zero β (CFT)	Small β	Large β
Small αN (small γ)	Banks-Zaks N=4 SUSY	Perturbed Banks-Zaks QCD UV , N=1 SUSY IR Technicolor UV	*Won't last*
Large αN (large γ)	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 Perturbed SCFT IR
Extreme αN (extreme γ)	N=4 SUSY Randall-Sundrum bulk N=1* UV (PS bulk)	Deformed-RS bulk Duality cascade (KS bulk)	RS IR brane N=1* IR, KS IR ….

Models in green have an IR mass gap/ledge and could serve as a hidden valley sector

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



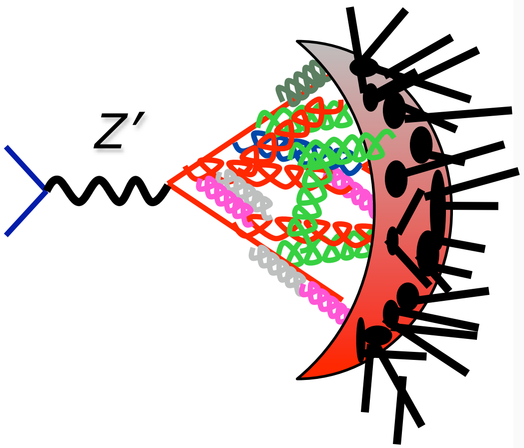


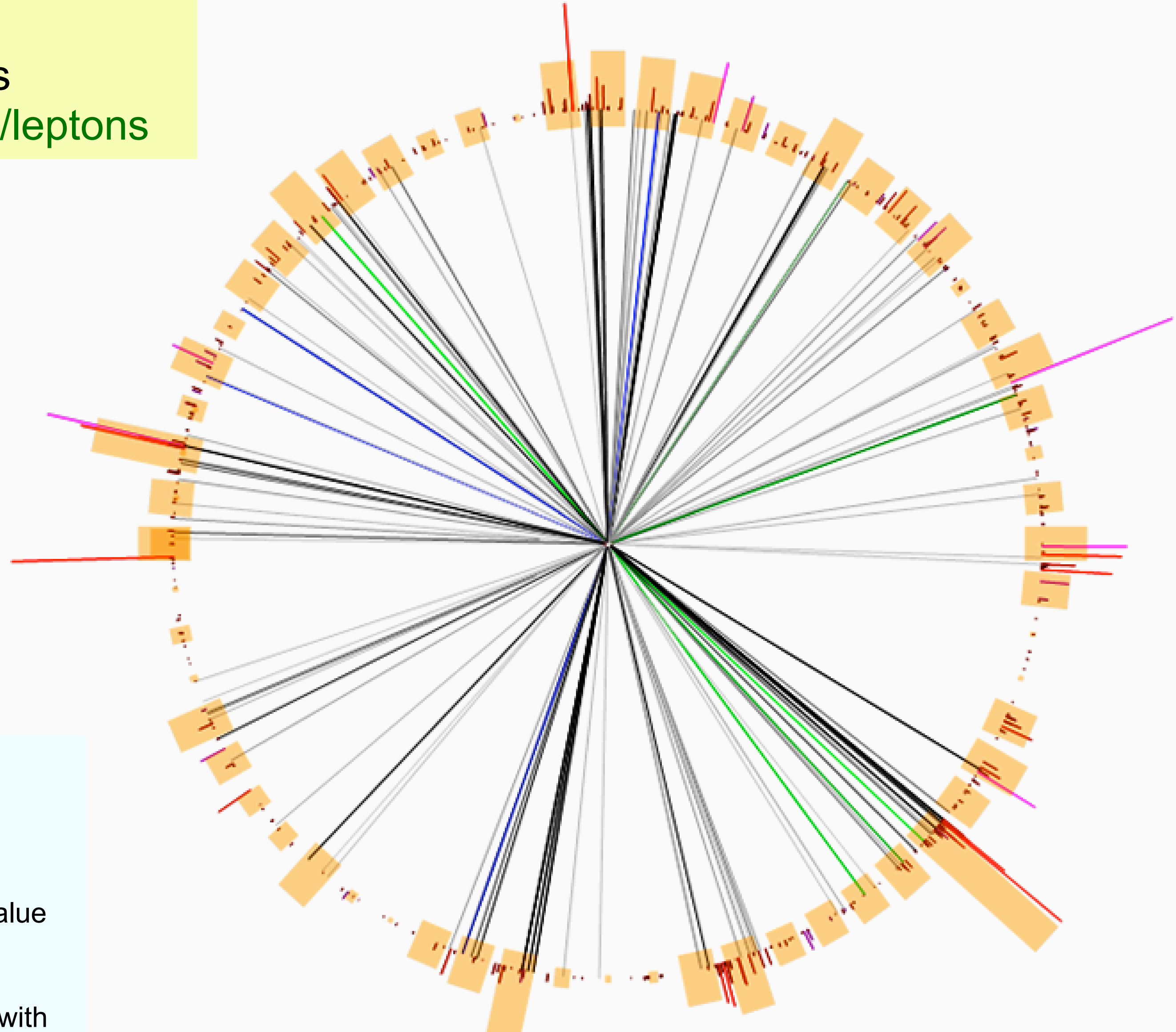
UV Strong-Coupling Fixed Point (large anom dims)

~ 30 v-hadrons

Softer v-hadrons

~ 50-60 soft SM quarks/leptons





Educated guesswork!

Crude and uncontrolled simulation

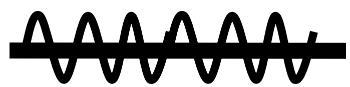
- Fix α in HV Monte Carlo 0.5 at large value
  - This increases collinear splitting
- Check that nothing awful happens
- Check answer is physically consistent with my expectation

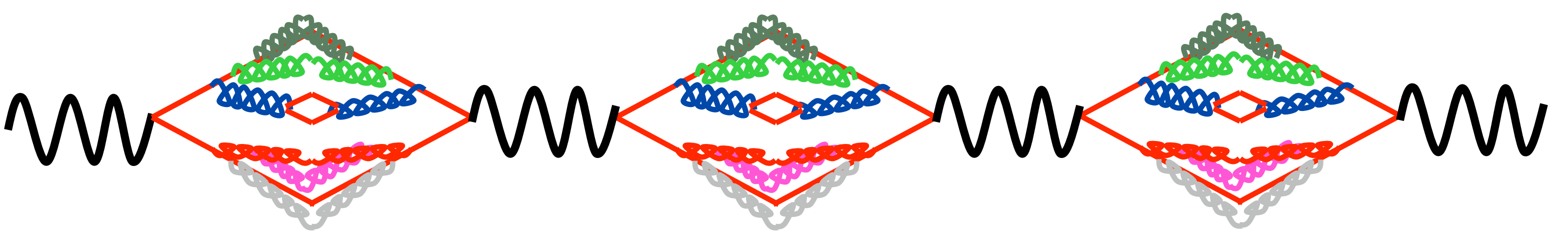
Hidden Valley/Unparticle Phenomena

Consider the Z' model outlined above as an example of a general case

- There is an $f\, O_1\, O_2$ coupling induced by Z'
  - O_1 is standard model Axial current
  - O_2 is v-sector Axial current

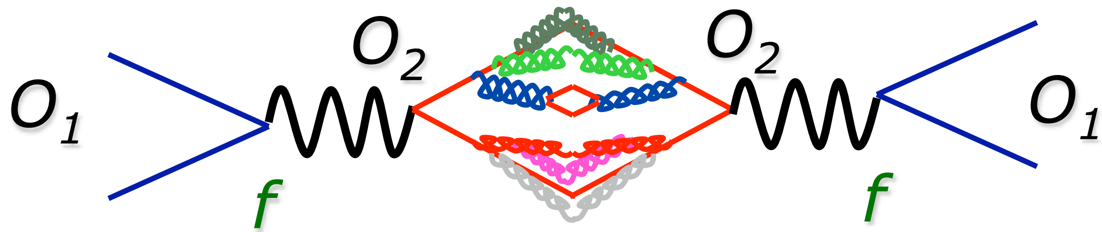
- If v-sector is UV CFT, O_2 has a fixed dim d
  - Why d > 1? Composite operator, or mixes with a composite operator
  - Why does unitarity require d>1? All composite operators spread faster than free particles

$< O_2 \quad O_2 > \; =$  $\sim \; FT\,[1/(x-y)^{2d}] \; =$

$= O_2$  O_2

Notice this two point function has a ***large imaginary part***.

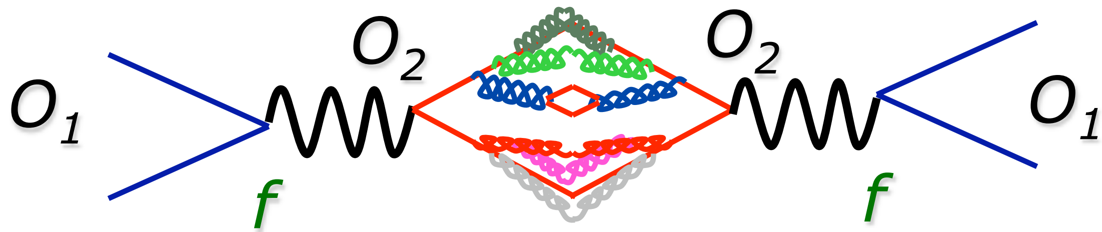
LHC Signals below the Z' resonance



Effect of order f^2

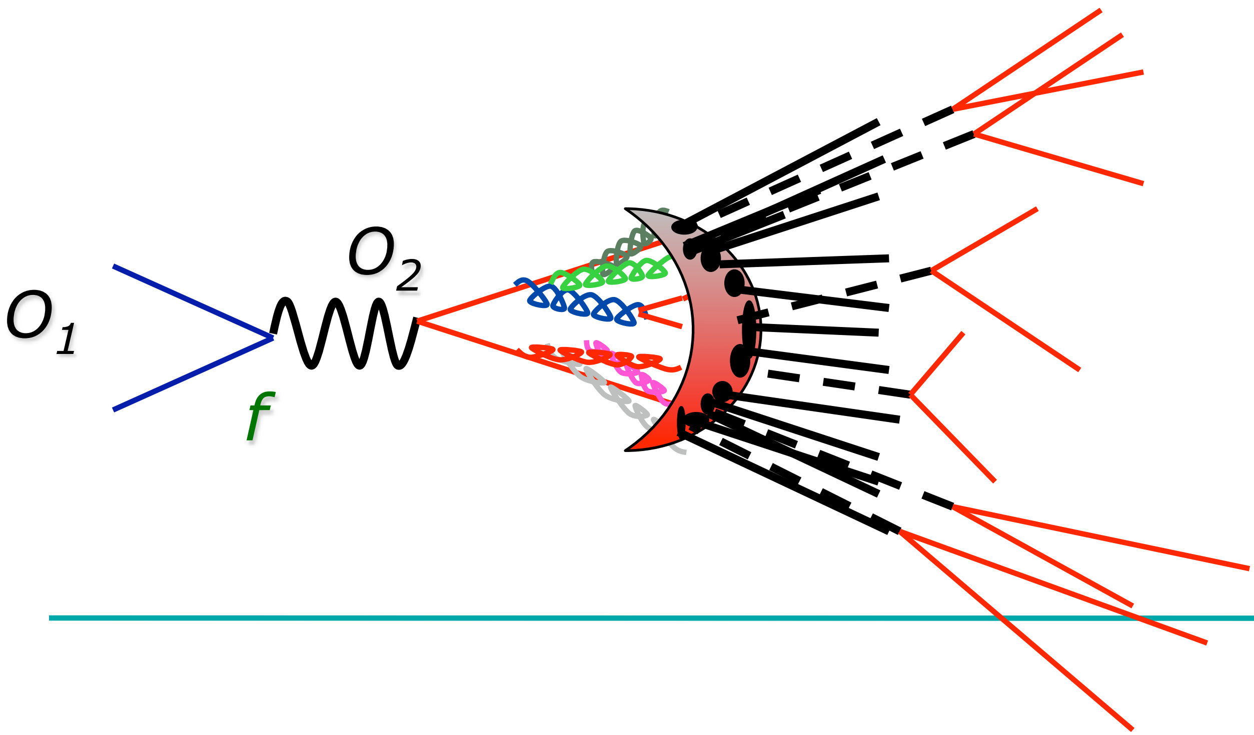
Contribution to low-energy tail of off-shell Z' boson line shape

LHC Signals below the Z’ resonance



Effect of order f^2

Contribution to low-energy tail of off-shell Z’ boson line shape



Effect of order f

Will dominate Z’ decays (even on low-energy tail) if the loop effect is big

Summary of Hidden Valley Scenario (2006)

- Hidden Sector
  - Coupled to the Standard Model at TeV-accessible energies
  - Multiparticle production mechanism
  - Mass gap/ledge to allow decays back to SM
- Predictions
  - Multiparticle final states with new resonances
  - Several possible sources of long-lived particles
  - New decay channels for Higgs, LSP/LKP/LTP/etc., Z, W, RH neutrinos
  - Many new and unusual final states for the LHC
- Importance
  - Trigger challenges
  - Reconstruction challenges
  - Analysis challenges
  - Theoretical challenges
- Hidden Valley/Unparticle Models deserve a theoretical synthesis

Backup Slides

PDF evolution

See
- Kogut Susskind 1975
- Peskin & Schroeder Chapter 18

Mellin Moments of Parton Distribution in Conformal Field Theory: $\beta = 0$

$$M_n^{(s)}(q^2) \equiv \int_0^1 dx\; x^{n-1}\; F_1(x, q^2) \approx \frac{1}{4}\; C_n\; A_n \left(\frac{\Lambda^2}{q^2}\right)^{\gamma_n/2}$$

- γ_n : the anomalous dimension of the lowest-dimension spin-n operator
- Unitarity: particles always split **to lower x**: anom dims always > 0.
- $\beta = 0$, $\alpha << 1$ ➔ $\gamma << 1$: small powers ~ written as logs in pert. theory.
- $\beta << 1$, $\alpha << 1$: additional logs
- In QCD literature, β logs and γ logs often treated as equivalent

Parton Shower

Ellis, Stirling, Webber QCD Chapter 5

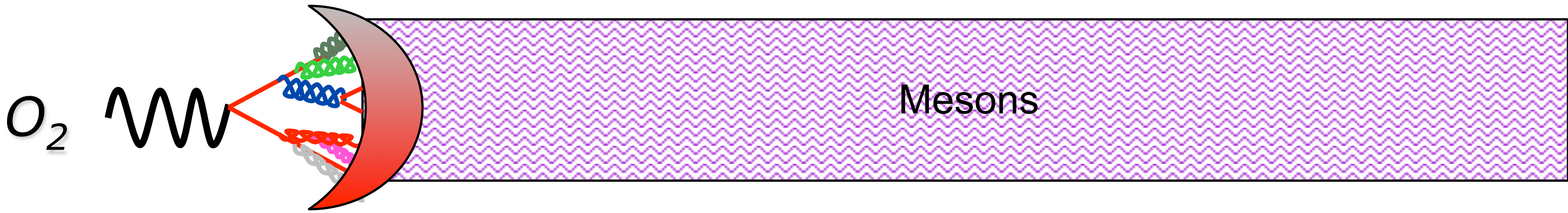
- Parton shower equations same at leading order as DGLAP pdf equations
  - Same splitting functions in perturbative CFT or quasi-CFT
- Anomalous dimensions of gauge invariant operators drive the parton shower and the ensuing multiparticle dynamics
- Unitarity: particles always shower **down**, so anom dims always > 0.
  - In theories with weak coupling, small powers ~ logs in perturbation theory.
    - Standard Monte Carlo
  - In theories at strong 't Hooft coupling, extreme anomalous dimensions!
    - Parton shower extremely efficient
    - All collinear physics lost, only soft physics remains: no jets!!

Polchinski & MJS 2002

- Prediction:
  - As anomalous dimensions become large, v-jets are worn down
  - If the v-sector is extreme-coupling CFT in the UV, no v-jets; just soft v-hadrons
  - Same if beta function is small but nonzero

V-hadrons

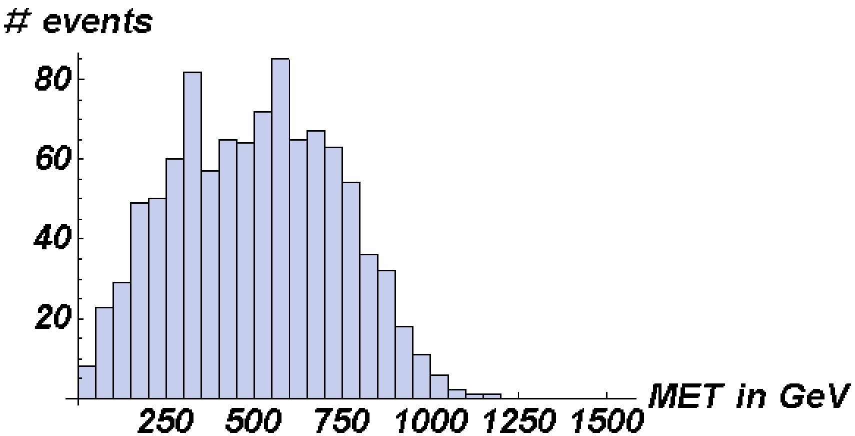
- In a confining v-model, at low momentum the operator creates a meson state with an ordinary massive-particle propagator

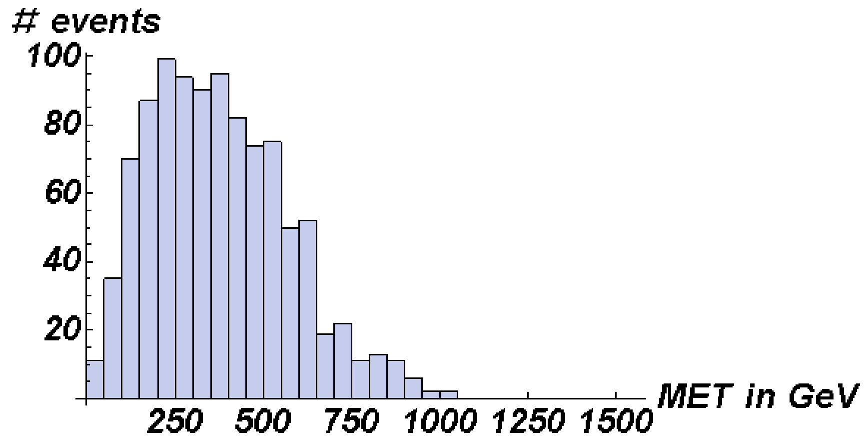


- More precisely it creates an infinite tower of such states,
- The sum over these states reproduces at high-energies the two-point function in the CFT
  - This is often used in AdS/CFT and is precisely what is done in Stephanov 07

Reduction of Missing Energy Signal

Distribution of Missing Transverse Energy





Stable Neutralino

Unstable Neutralino
Decaying to ν-Sector