# Some New Issues in the Phenomenology of Hidden Valleys


Echoes of a hidden valley at hadron colliders.
M.J.S. & K. M. Zurek , hep-ph/0604261 , Phys.Lett.B651:374-379
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

Han, Si, Zurek & M.J.S., arXiv/0712.2041
M.J.S., arXiv/0801.0629
M.J.S. (some with J. Juknevich and D. Melnikov) in preparation

See also Ciapetti, Lubatti, Dionisi…M.J.S. ATLAS note



Matthew Strassler
Rutgers University

KITP Conference 6/08

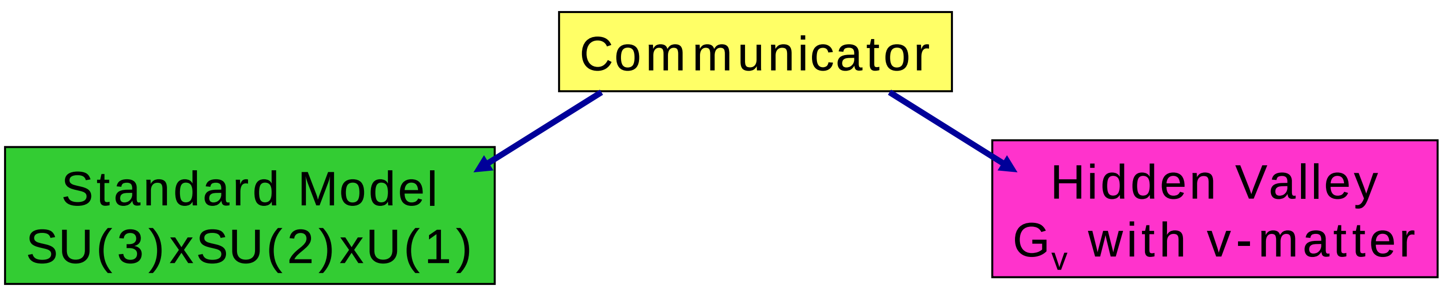
# Anticipating Physics

# at the LHC…

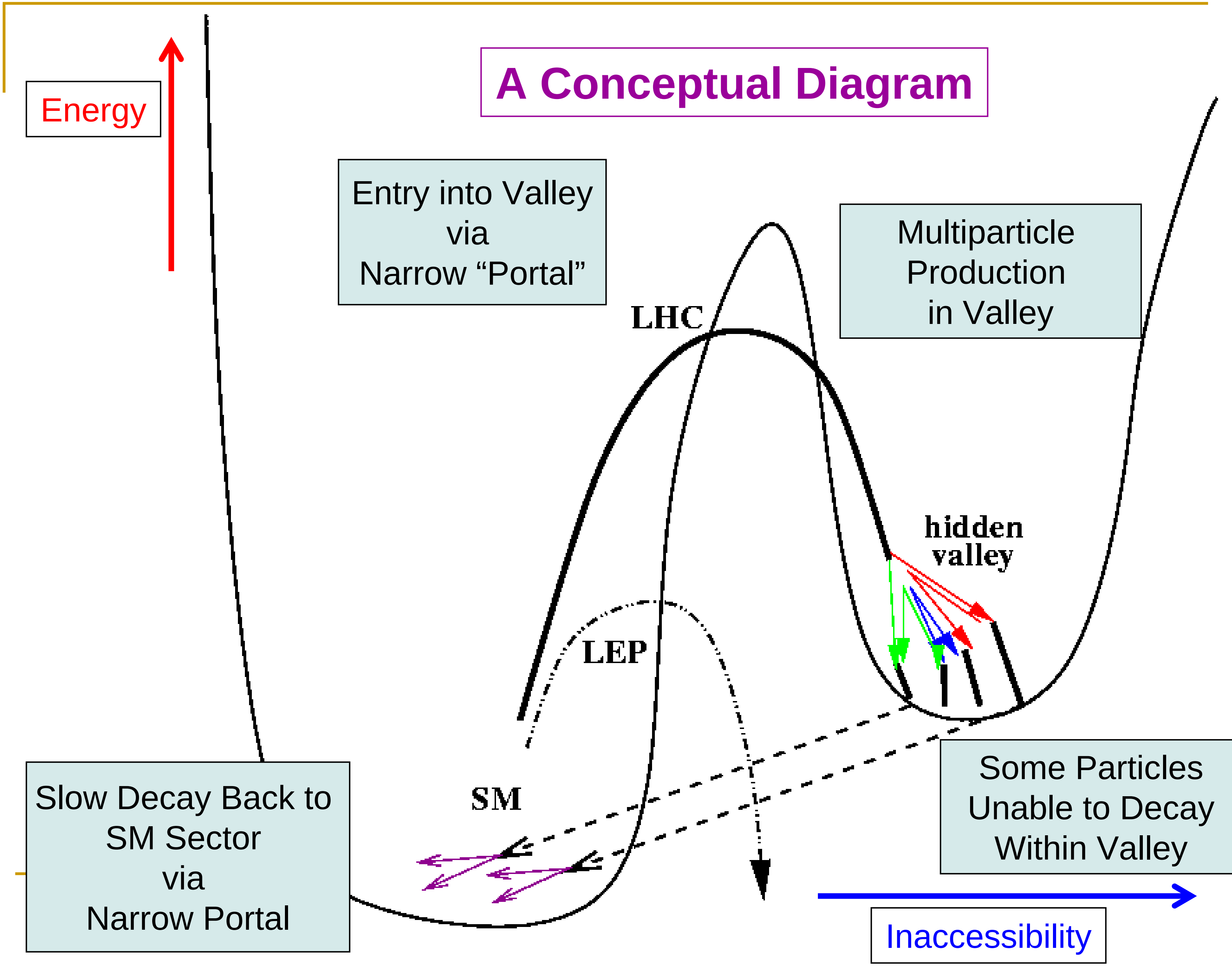

ARE WE THERE YET !?!
MATT GROENING

# Hidden Valley Scenario (w/ K. Zurek)

hep-ph/0604261

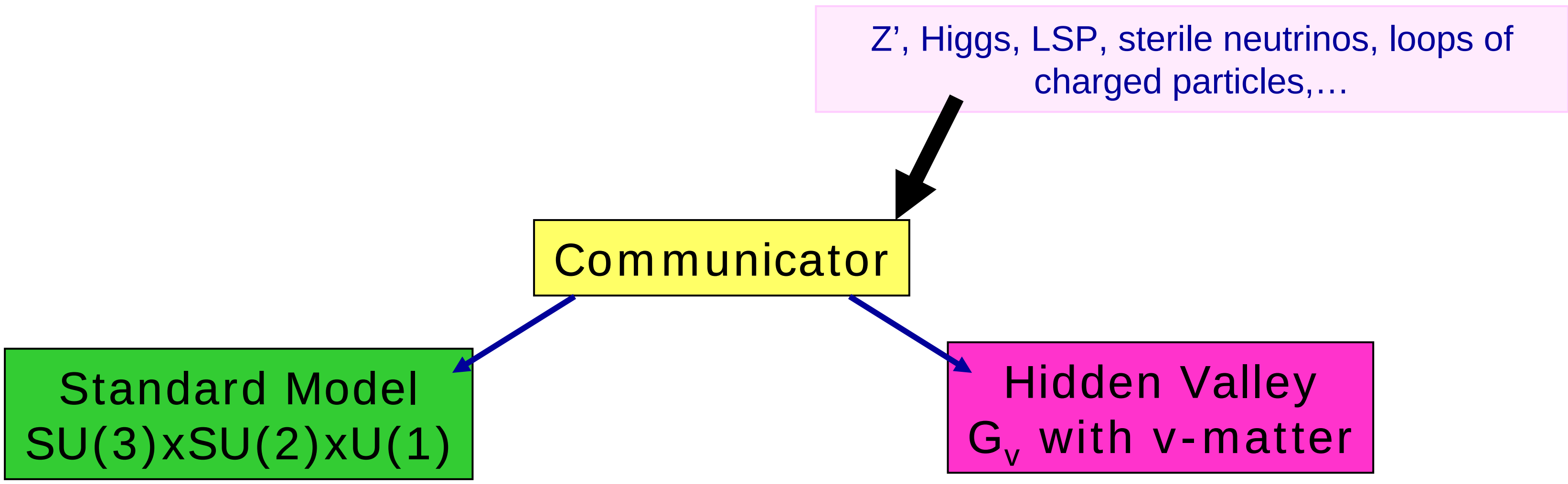


# A Conceptual Diagram



# Hidden Valley Models (w/ K. Zurek)

hep-ph/0604261



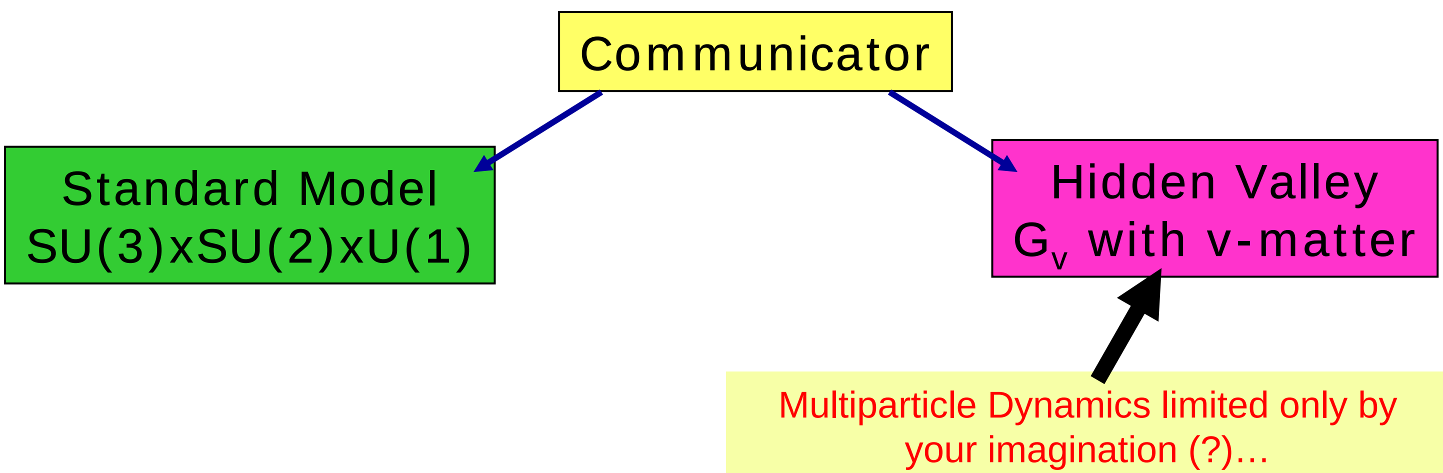
# Hidden Valley Models (w/ K. Zurek)

hep-ph/0604261

## Vast array of possible v-sectors…

QCD-like theory : F flavors and N colors
QCD-like theory : only heavy quarks
QCD-like theory : adjoint quarks
Walking-Technicolor-like theory
Pure-glue theory
…

N=4 SUSY → N=1 (N=1*)
RS or KS throat
Almost-supersymmetric N=1 model
Moose/Quiver model
Broken/Tumbling SU(N) theory
…



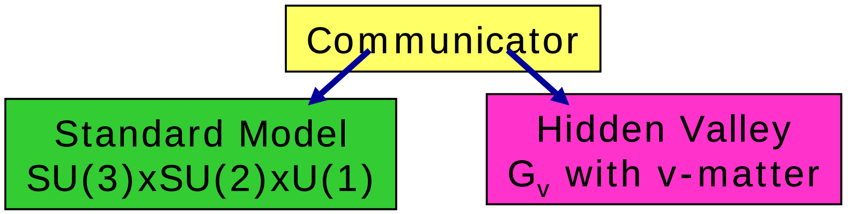
# Motivation and Approach

- Why the Hidden Valley Scenario?
  - Extra sectors common in string theory, SUSY breaking, Extra dims, etc.
  - Incredibly exciting if found: new particles, forces, dynamics [possibly strong]
  - Can drastically change phenomenology of SUSY/Extra Dims/etc.
  - Dark matter, early universe cosmology, astrophysics ?
- The challenge of the Hidden Valley Scenario
  - Weak experimental constraints!
  - Vast array of possibilities
  - **Phenomenology can be very challenging for hadron colliders – urgent!!**
    - Moderate to extreme multiplicities
    - Long-lived particles
    - Often different from standard theories
- Our approach: Divide and Conquer
  - Find characteristic predictions of large classes of models at once
  - Produce search strategies, Monte Carlo tools that experimentalists can use now

# Outline

- Some v-sectors: spectrum and decays
- Low-energy production: Higgs decays
  - Multiparticle decays
  - Displaced vertices
    - Triggering issues
- High-energy production: Z’ decays, Quirk annihilation
  - Easy channels – lepton or photon resonances
  - Harder channels – high multiplicity heavy flavor
  - Very hard channels – medium multiplicity heavy flavor

# Classification of models




- v-particle spectrum
- v-particle decays to standard model: lifetimes
- v-particle decays to standard model: final states
- v-particle production mechanism

# Some simple v-sectors

Hidden Valley
$G_v$ with v-matter

- Confining v-sector with confinement scale $\Lambda_v$
  - N colors, f flavors with $m < \Lambda_v$
  - Perhaps other flavors with $m > \Lambda_v$
- Weakly coupled dual description
  - Chiral Lagrangian or its generalization
  - A Higgs model
- Stringy extra-dimensional dual
  - A known stringy-throat model
  - Any RS-inspired 5d model
- Spectrum
  - $f > 1$ ➔ light metastable PNGBs
  - $f = 1$ ➔ no PNGBs, several metastable spin 0,1 mesons
  - $f = 0$ ➔ no PNGBs, many metastable spin 0,1,2,3 glueballs
- Approximate-supersymmetry optional

# V-sector with N colors, f > 1 light flavors

Hidden Valley
$G_v$ with v-matter

f > 1
- ➔ chiral symmetry breaking
- ➔ light v-pions

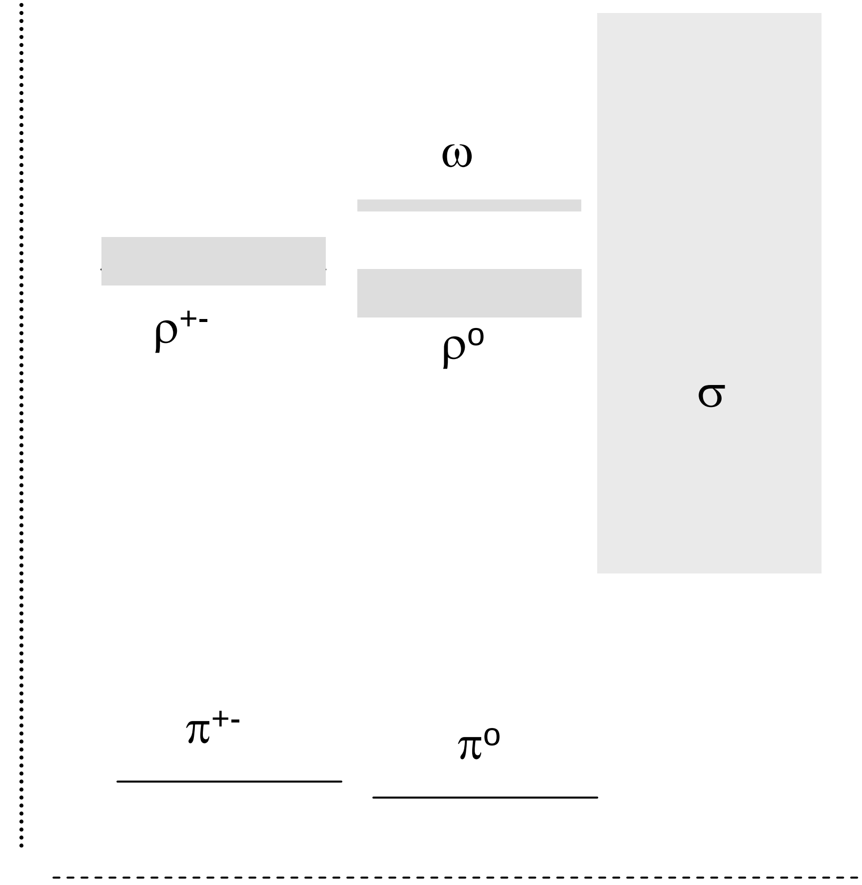
Z' or Higgs Communicator:

- v-pions → SM heavy flavor
  - b pairs, tau pairs, c pairs, g pairs
  - t pairs if heavy

**No easy-to-see resonances**

Standard Model
SU(3)xSU(2)xU(1)

All v-mesons decay to v-pions




v-pions are long-lived and may decay to SM particles, typically heavy flavor

# V-sector with N colors, f = 1 light flavors

Hidden Valley
$G_v$ with v-matter

f = 1

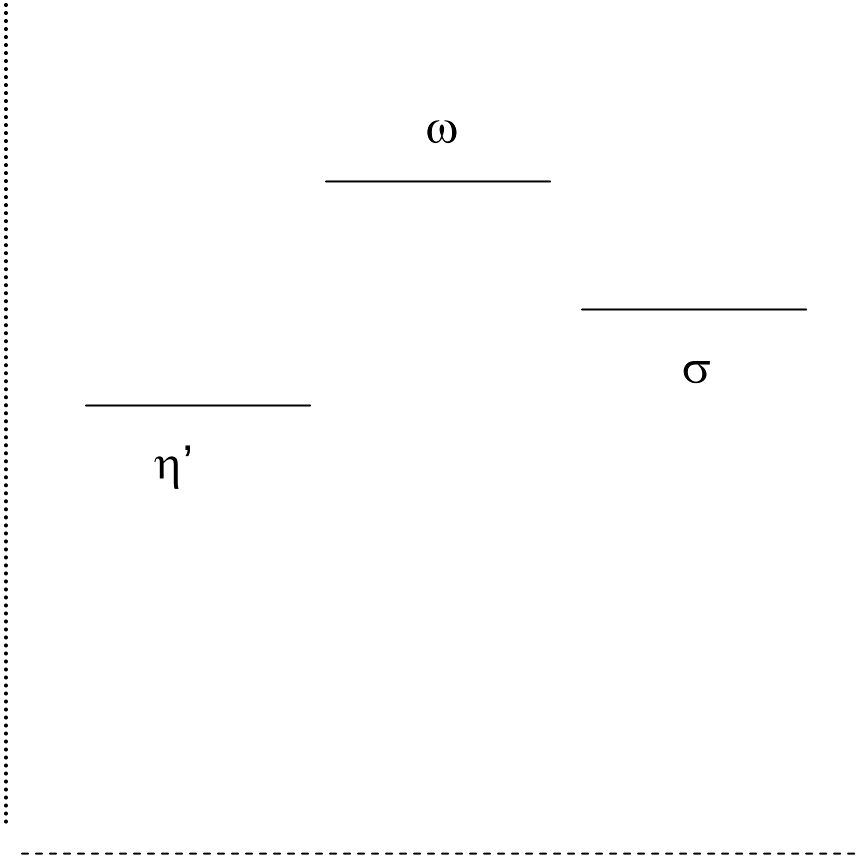
➔ no chiral symmetry breaking
➔ several metastable mesons

Z’ or Z Communicator :

- Spin-0:
  typically decay to heavy flavor
- Spin-1:
  typically decays democratically
  - Reasonable rate for **e/μ pairs**
- **Easy dilepton resonance**

Standard Model
SU(3)xSU(2)xU(1)

Heavy v-mesons decay to several stable mesons, with different $J^{PC}$ assignments




Spin-0 decays slowly, to heavy flavor
Spin-1 decays faster, democratic in flavor

# V-sector with N colors, f = 0 light flavors

Hidden Valley
$G_v$ with v-matter

f = 0

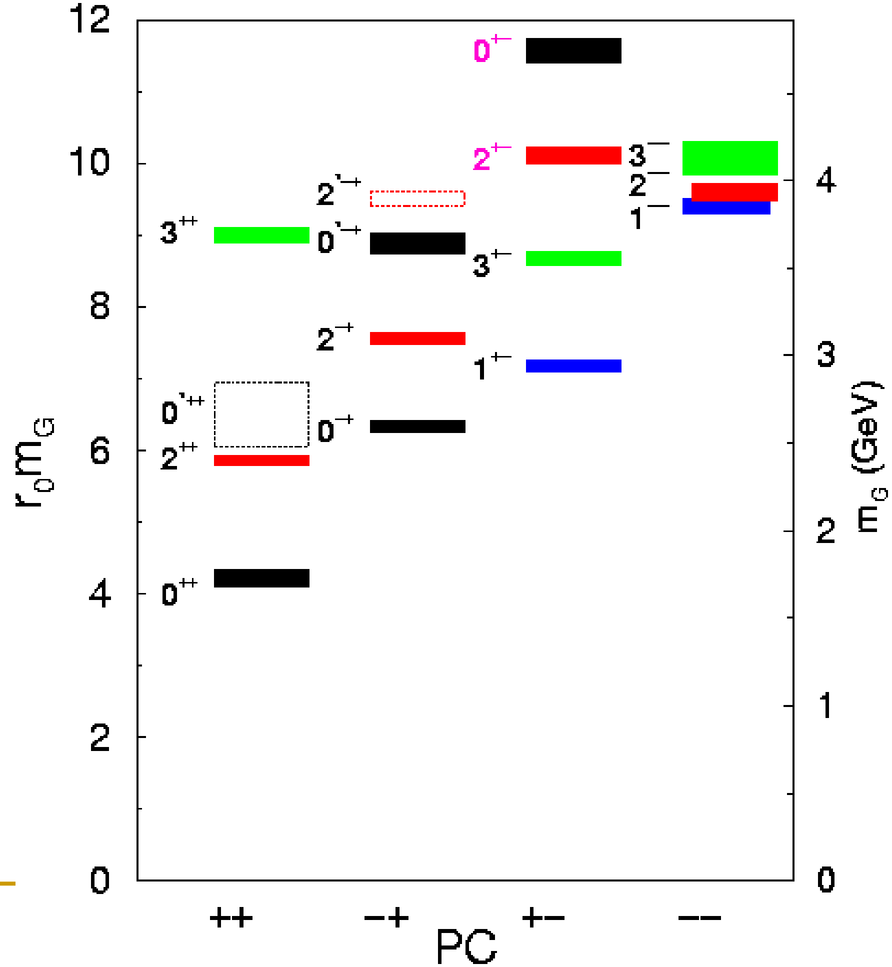
➔ v-glueballs

"Quirk" Communicator

- Low-lying v-glueballs decay to SM gauge bosons
  - Mostly gluon pairs
  - Some photon pairs (> 0.4 %)
  - Also some radiative decays
- **Easy diphoton resonance**

Standard Model
SU(3)xSU(2)xU(1)

Morningstar and Peardon 99



# Summary so far

Hidden Valley
$G_v$ with v-matter

Some v-Sector Spectra

- Typically multiple stable particles with various $J^{PC}$ charges

- May get
  - Dilepton resonances - easy
  - Diphoton resonances - easy
  - Heavy flavor resonances – hard
  - Cascade decays – still to be studied

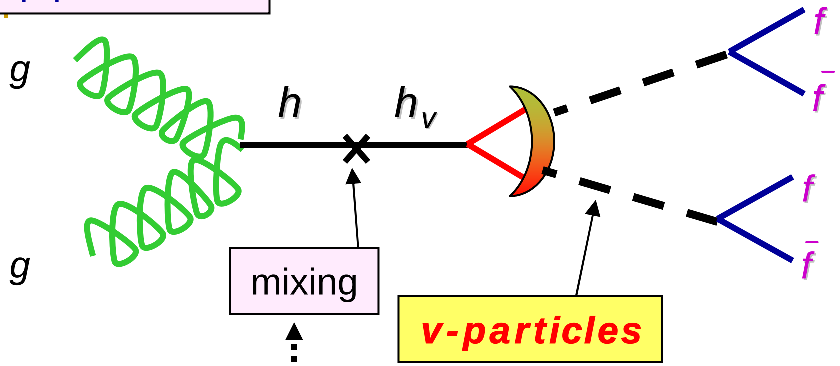
Standard Model
SU(3)xSU(2)xU(1)

- Lifetimes are often very long ➔ may have highly-displaced vertices

- Other signals still to explore

# Higgs Decays to v-Sector

MJS + Zurek
hep-ph/0604261
hep-ph/0605193




See also
Dermisek Gunion 04
Schabinger Wells 05
Chang Fox Weiner 06
Bowen Cui Wells 07
Gopalakrishna et al. 08

Recent work
Schabinger Wells **hep-ph/0509209**
MJS + Zurek **hep-ph/0604261**
Patt Wilczek **hep-ph/0605188**

# Higgs → new promptly-decaying particles

If H → X X and X → e/μ-pair or γ-pair

See also
Gopalakrisha et al. 08

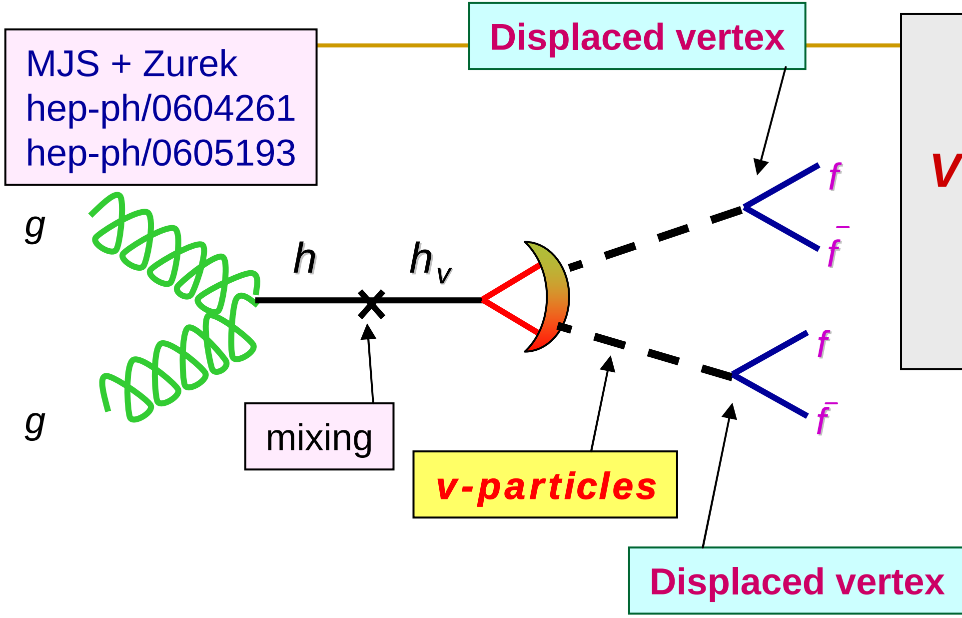
See also
Chang Fox Weiner 06

- Search events with e/μ-pair or γ-pair plus jet pair or MET
  - Discover the X resonance, infer the H
- A few events with four leptons or four photons
  - Measure the X and H mass together
- Trouble can arise if H → XXX, XXXX, ….
  - Same strategy probably needed, but much harder

See also
Chang Fox Weiner 05

Really big trouble if predominantly X → b's, tau's, c's, …

See also NMSSM
Dermisek Gunion 04
……………..




## CDF/D0: new searches carried out

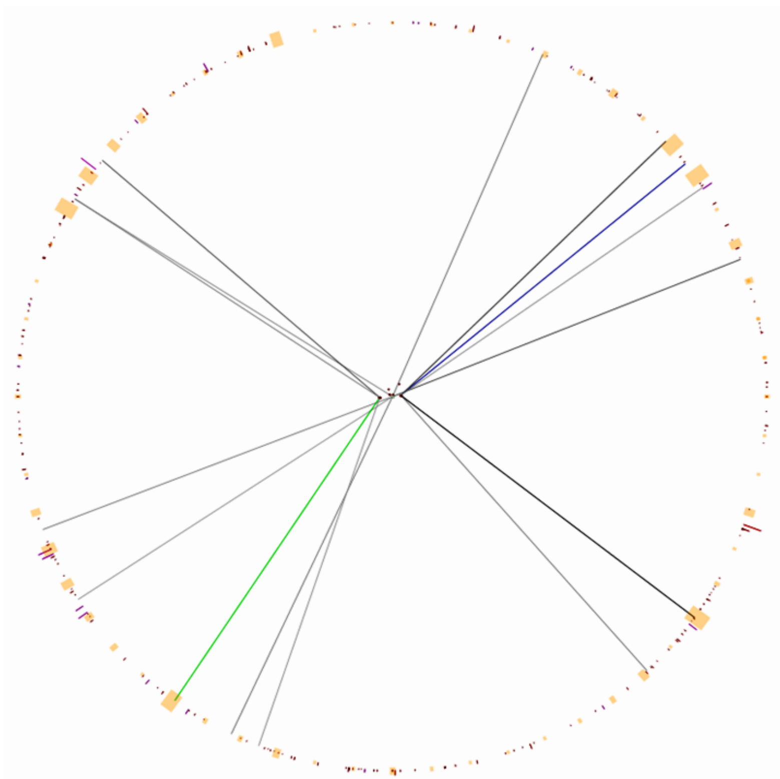
***Very*** difficult to trigger at ATLAS/CMS…

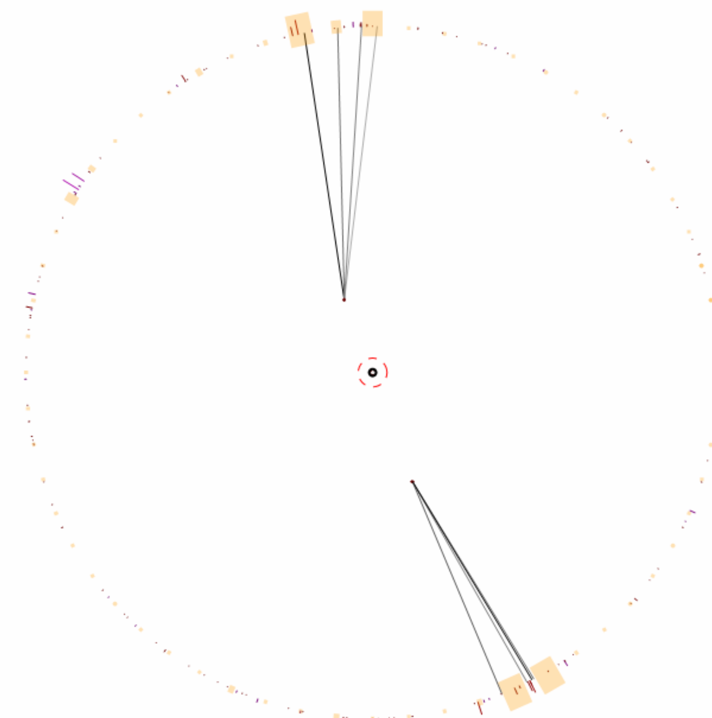
*New ATLAS trigger strategy* (internal note)

***LHCb opportunity!!***

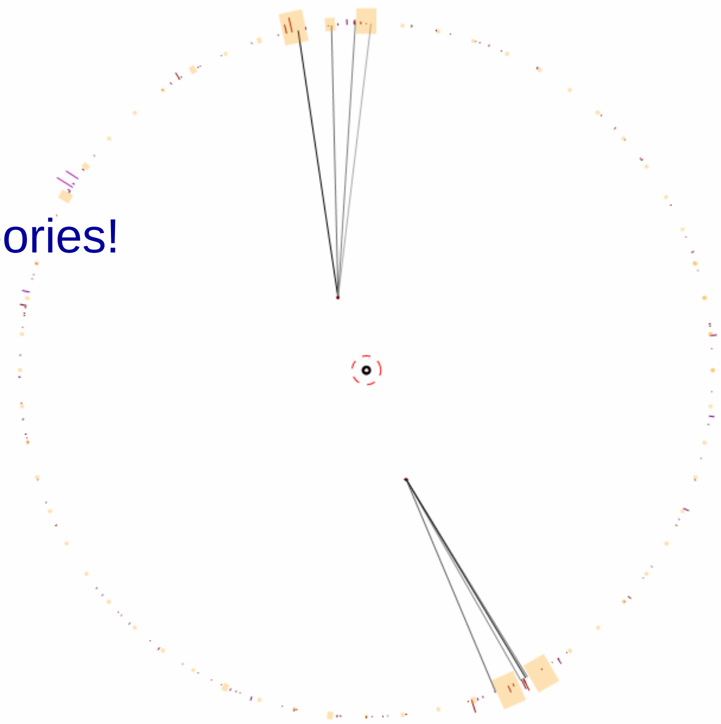
Similar Observations:
**hep-ph/0607204** : **Carpenter, Kaplan and Rhee**

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





# Displaced Vertices



Much more natural in HV than in most BSM theories!

- Several new v-resonances (can exceed 10)
- Lifetimes vary over orders of magnitude
  - f = 0 ➔ v-glueballs ➔ 2 – 3 orders
  - f = 1 ➔ v-mesons ➔ 2 – 6 orders
  - f > 1 ➔ multiple v-PNGBs ➔ unpredictable

**But experimental challenges:**

- Offline: Reconstruction
  - Every jet will have hadron collisions with detector material
  - Every jet will have pi-zero → photons → conversions
  - Beam halo collisions with detector
- Online: Trigger
  - If a low-energy process, might be serious problem

# Light Higgs (or other scalar) decays

Suppose Higgs (or other scalar) with mass 10 – 300 GeV decays to X X and X decays to standard model particles with displaced vertex 1 mm – 10 m

No SM background, so easily observed if triggering efficiency ok

**But ATLAS/CMS trigger may have dangerously low efficiency**

- The energy is too low for jet triggers
- Vertex beyond ~ 10 cm ➔ lepton tracks will be lost
- Low [ rate x efficiency ] to trigger on associated objects
- Photon trigger works (for electrons too) but low [ rate x efficiency ]

Meanwhile most models have jets as majority branching fraction for X

# Displaced Jets

Reconstruction challenging due to detector background

- Nearly every jet will have pion collisions with detector material

No trigger aimed at this signal

- Can try to depend on other triggers, but risky for low-energy processes

New trigger approaches under consideration – internal ATLAS note
(public note in review process)

- Decay in muon system creates many hits
- Decay in hadronic calorimeter creates unusual jet
- Decays in tracker: jets without tracks, possibly with embedded muon hit -- ???

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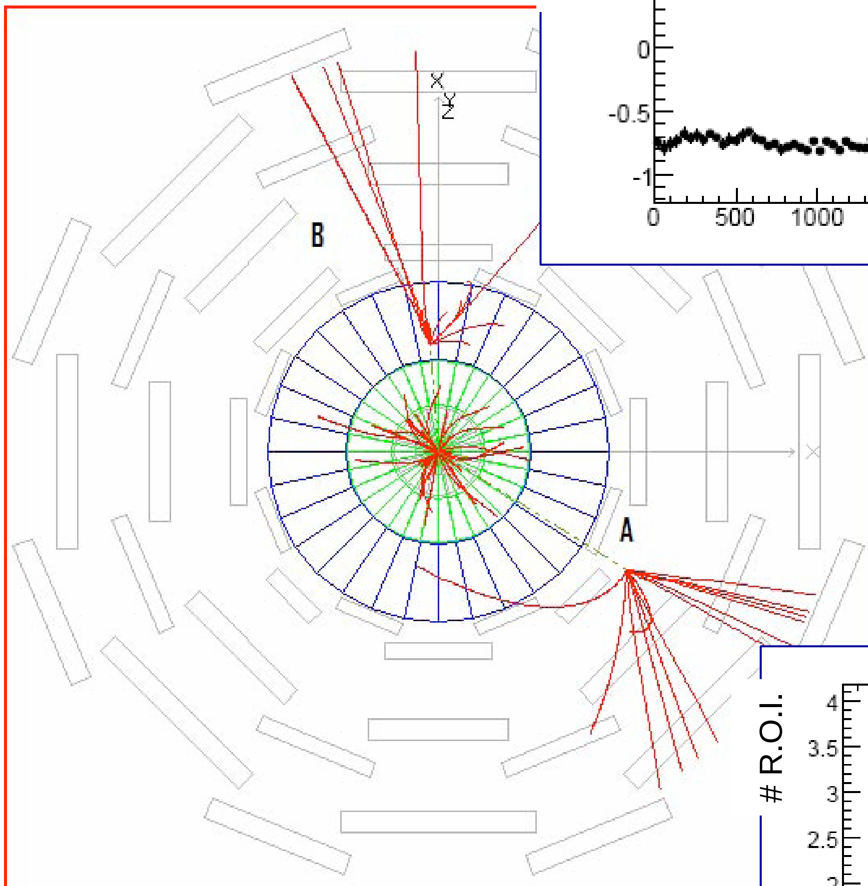
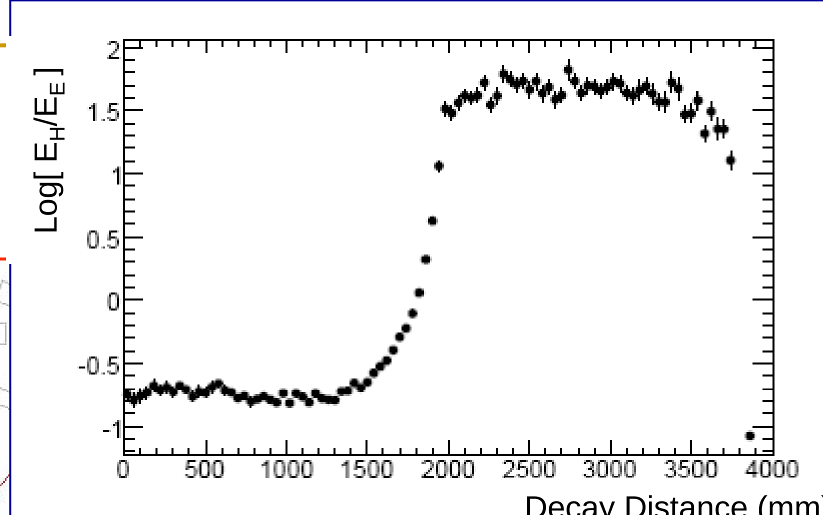
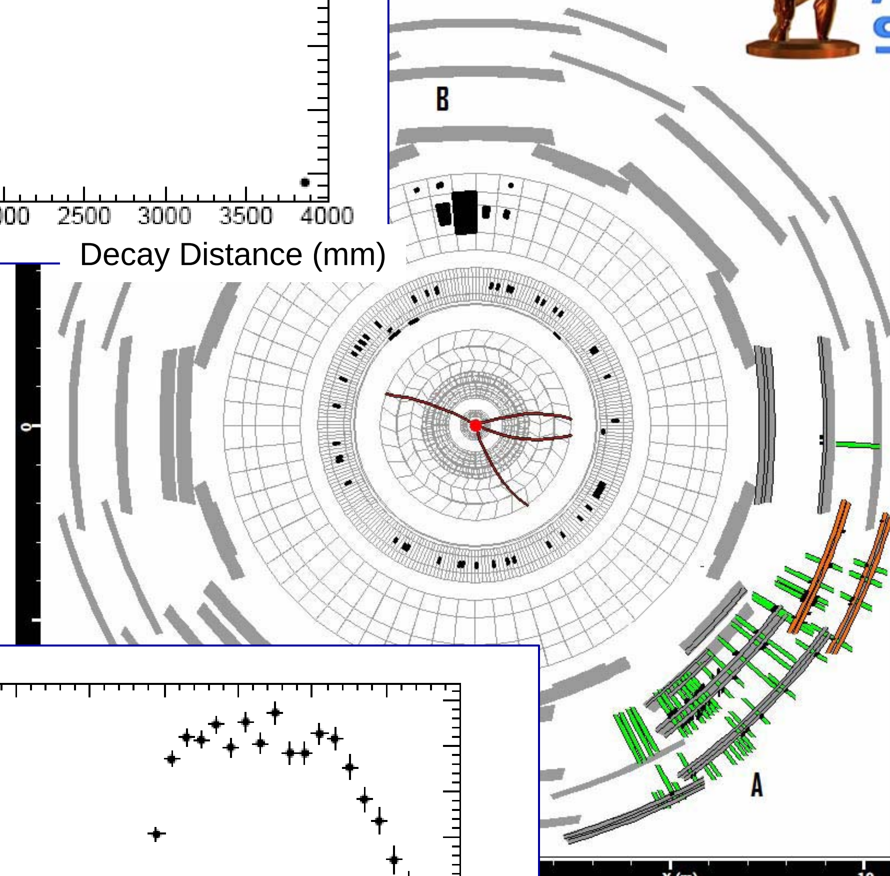
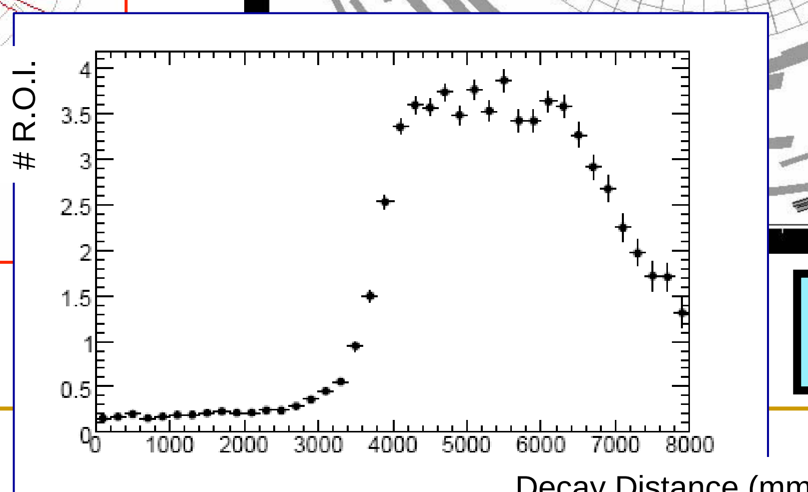
MJS
(non-member of ATLAS)




Shown by permission of ATLAS collaboration; do not reproduce

ATLAS Simulation, Preliminary

# Displaced Jets

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**Can ATLAS/CMS do better on jet triggers for vertices in 3 – 300 cm range?**

LHCb might well do better than ATLAS/CMS for vertices in the 1 – 30 cm range

- Low-pT-muon trigger, less material, no luminosity cost in early running


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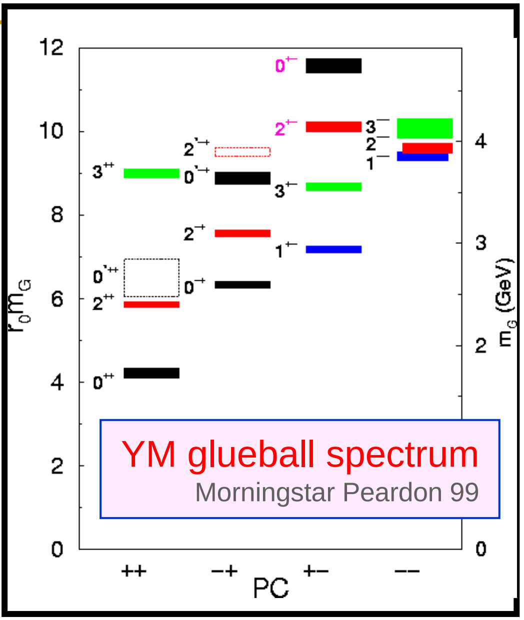
(non-member of ATLAS)

# Quirks as Communicators

# v-Glueballs via Quirks



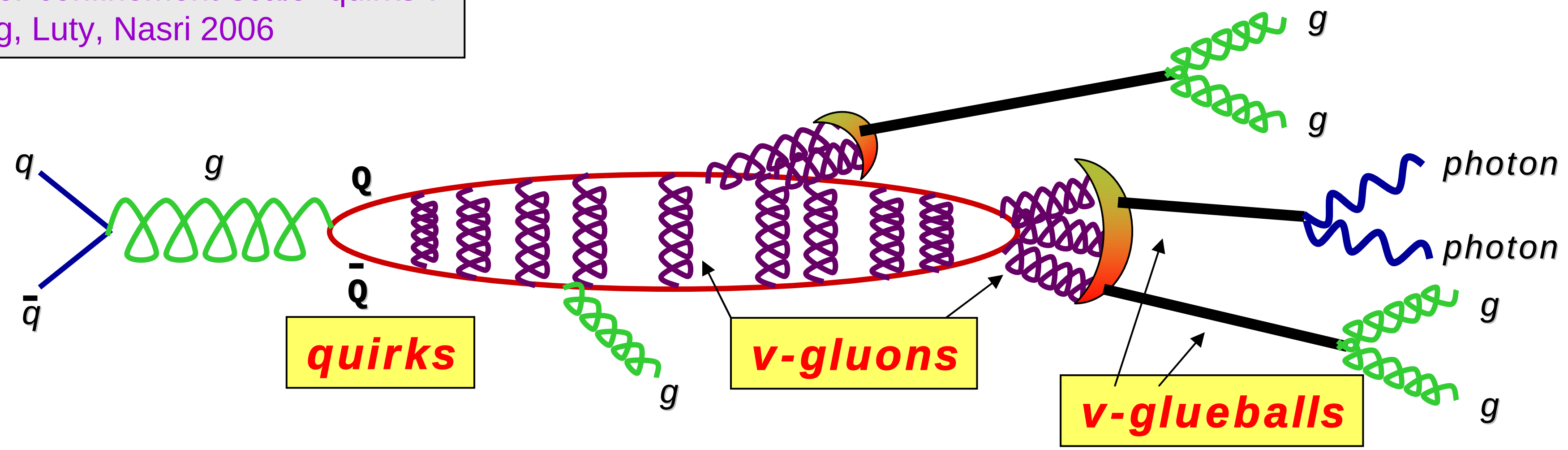

TeV–scale quirk production/annihilation

MJS + Zurek hep-ph/0604261
Juknevich, Melnikov, MJS in prep

Quirk: Matter charged under SM and hidden confining group…

- Hidden confining string cannot break ➔ Quirkonium
- Quirk loops induce couplings of SM and hidden gauge bosons

Lower-confinement-scale "quirks":
Kang, Luty, Nasri 2006



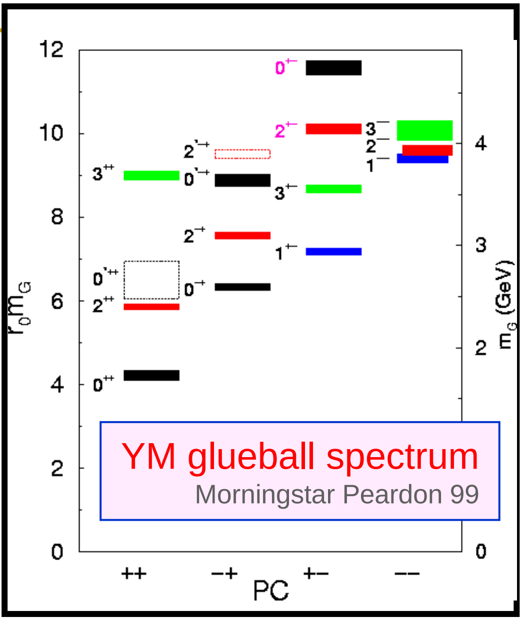
# v-Glueballs via Quirks

Signal? Can’t simulate reliably, but can make very rough estimate:

- Expect jets + 2 photons, with $\gamma\gamma$ mass = v-glueball mass
- If “Quirks” colored, mass < 1 TeV,
  - Cross-section > 500 fb
    - Assume typically ~ 2 v-glueballs/event
    - Lowest 3 – 4 v-glueball states produced with probabilities of same order
    - Each state has 0.4% branching fraction to photon pairs
  - Detector acceptance ~ 25% – 50% [isolation?]
    - ➔ >0.5 fb in each resonant peak
- Backgrounds from jets + 2 photons (real and fake)
  - ~ 100-200 fb continuum background with $p_T$>100 on jets/photons

# v-Glueballs via Quirks

**PRELIMINARY!**

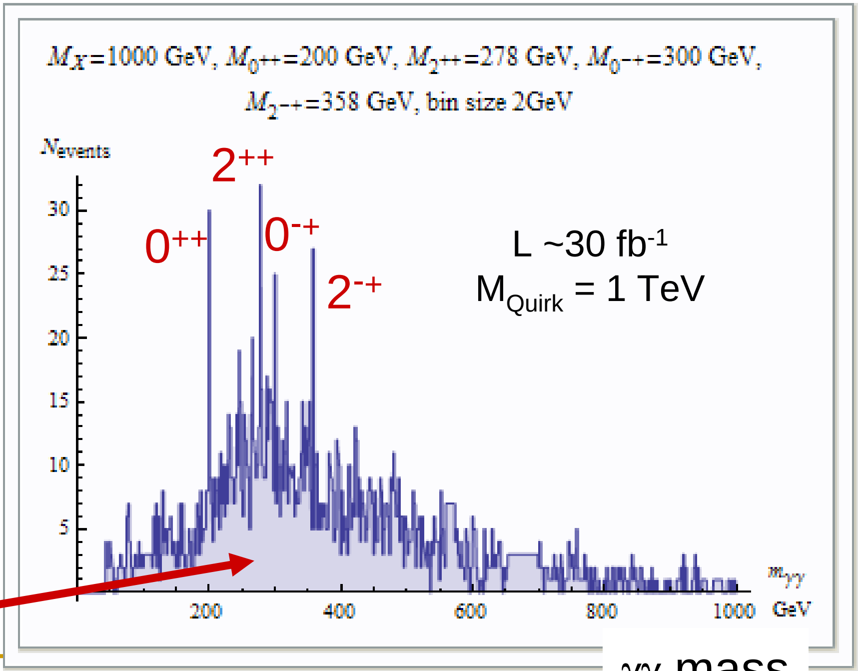



Select events with

- 2 photons pT > 100 GeV (or 150, 200)
- 2 jets pT > 100 GeV
  - (or 1 jet, pT > 200 GeV)

Plot invariant mass of photon pairs

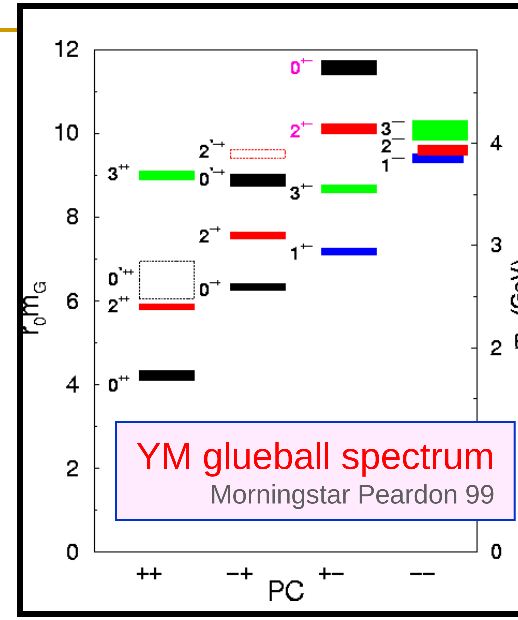
Also can look for $1^{+-} \rightarrow 0^{++} + \gamma$




SM: 2 jets + 2 real photons, $p_T$ > 100 Gev

# v-Glueballs via Quirks

INARY!




Spectrum of v-glueballs tests v-sector

- Check spin 2 of $2^{++}$ state
- Presence $2^{-+}$ state ➔ weak 't Hooft coupling
- Presence $1^{+-}$ state ➔ **SU**(N>**2**) gauge group

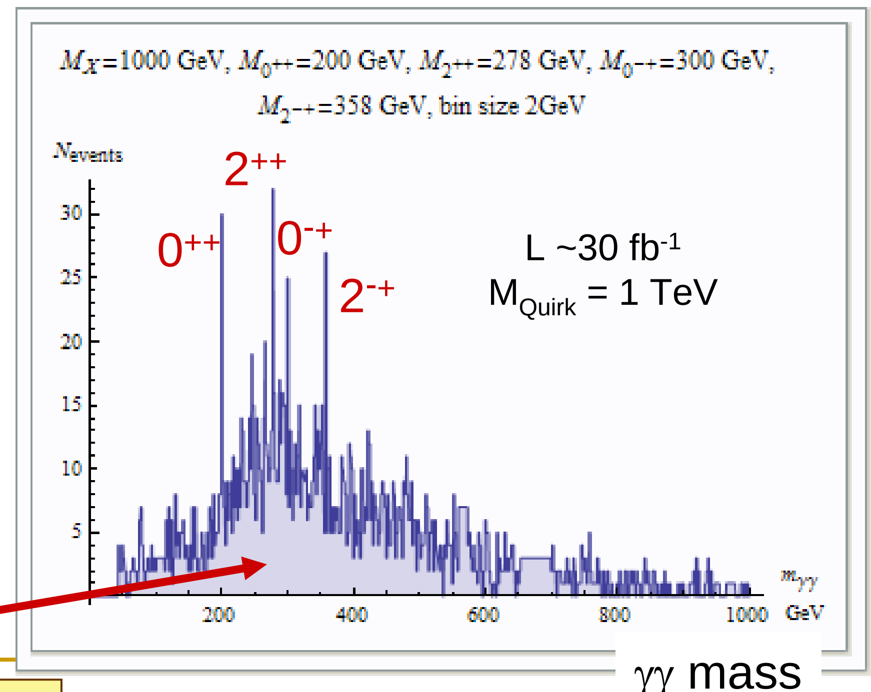
2 photons pT > 100 GeV (or 150, 200)

2 jets pT > 100 GeV

(or 1 jet, pT > 200 GeV)

Plot invariant mass of photon pairs

Also can look for $1^{+-}$ ➔ $0^{++} + \gamma$

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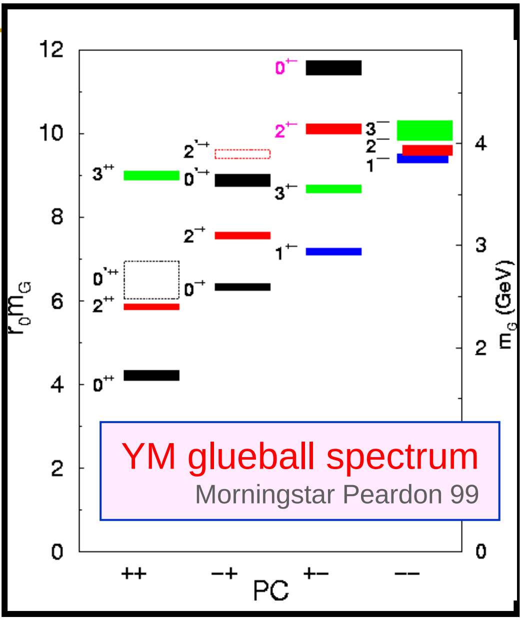
# v-Glueballs via Quirks

INARY!

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2 photons pT > 100 GeV (or 150, 200)

2 jets pT > 100 GeV

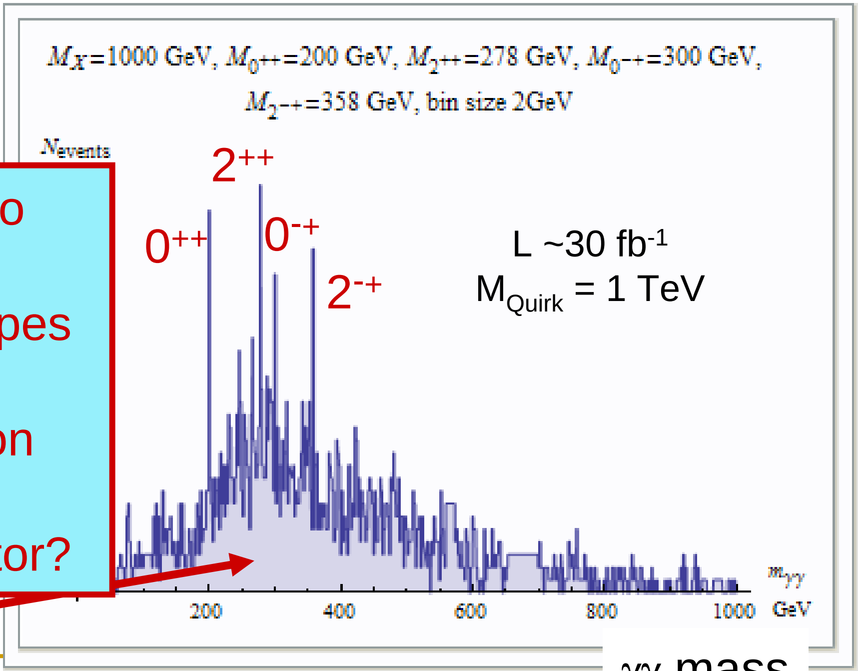
(or 1 jet, pT > 200 GeV)

We cannot simulate production process, so

We don't know numbers of jets or event shapes

Also do not know effects on photon isolation

Can we develop a reasonable event generator?




γγ mass

SM: 2 jets + 2 real photons, $p_T$ > 100 Gev

# v-Glueballs via Quirks

Signal? Can't simulate reliably, but can make very rough estimate:

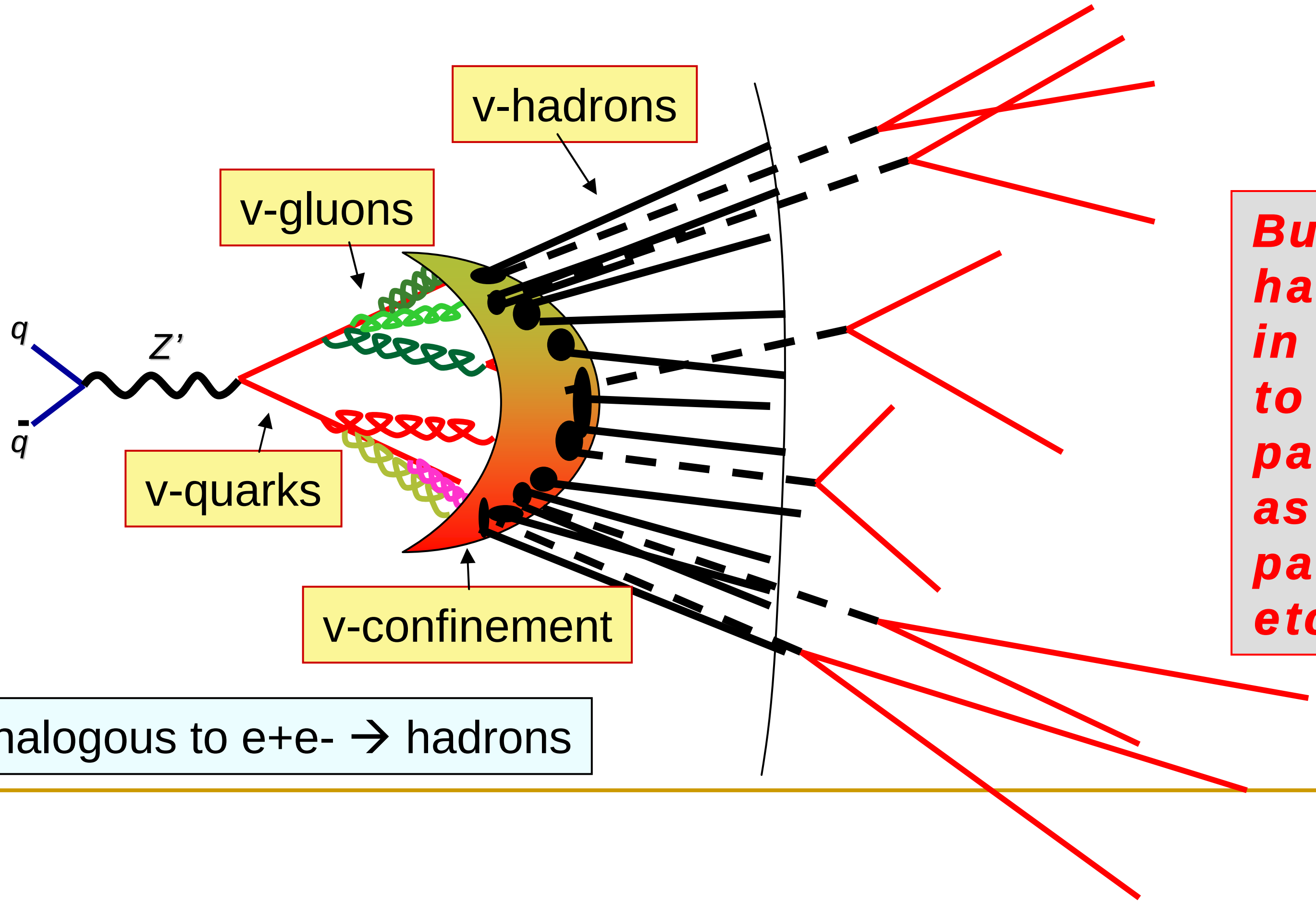
- Expect jets + 2 photons, with $\gamma\gamma$ mass = v-glueball mass
- If "Quirks" uncolored, mass < 500 GeV,
  - Cross-section 1000 times smaller than colored case but
    - v-glueball mass << 150 GeV ➔ 100% branching fraction to $\gamma\gamma$
    - v-glueball mass >> 200 GeV ➔ 10% branching fraction to $\gamma\gamma$ (remainder to WW, ZZ, Z$\gamma$)
  - Signatures:
    - Events with 2 pairs of photons; may be highly displaced
    - Events with 2 photons + displaced jets
    - Events with 2 photons + jets and/or lepton and/or MET

# Z' Decays to v-Sector

# A Confining Hidden Valley

MJS + Zurek hep-ph/0604261

***Some v-hadrons are stable and therefore invisible***

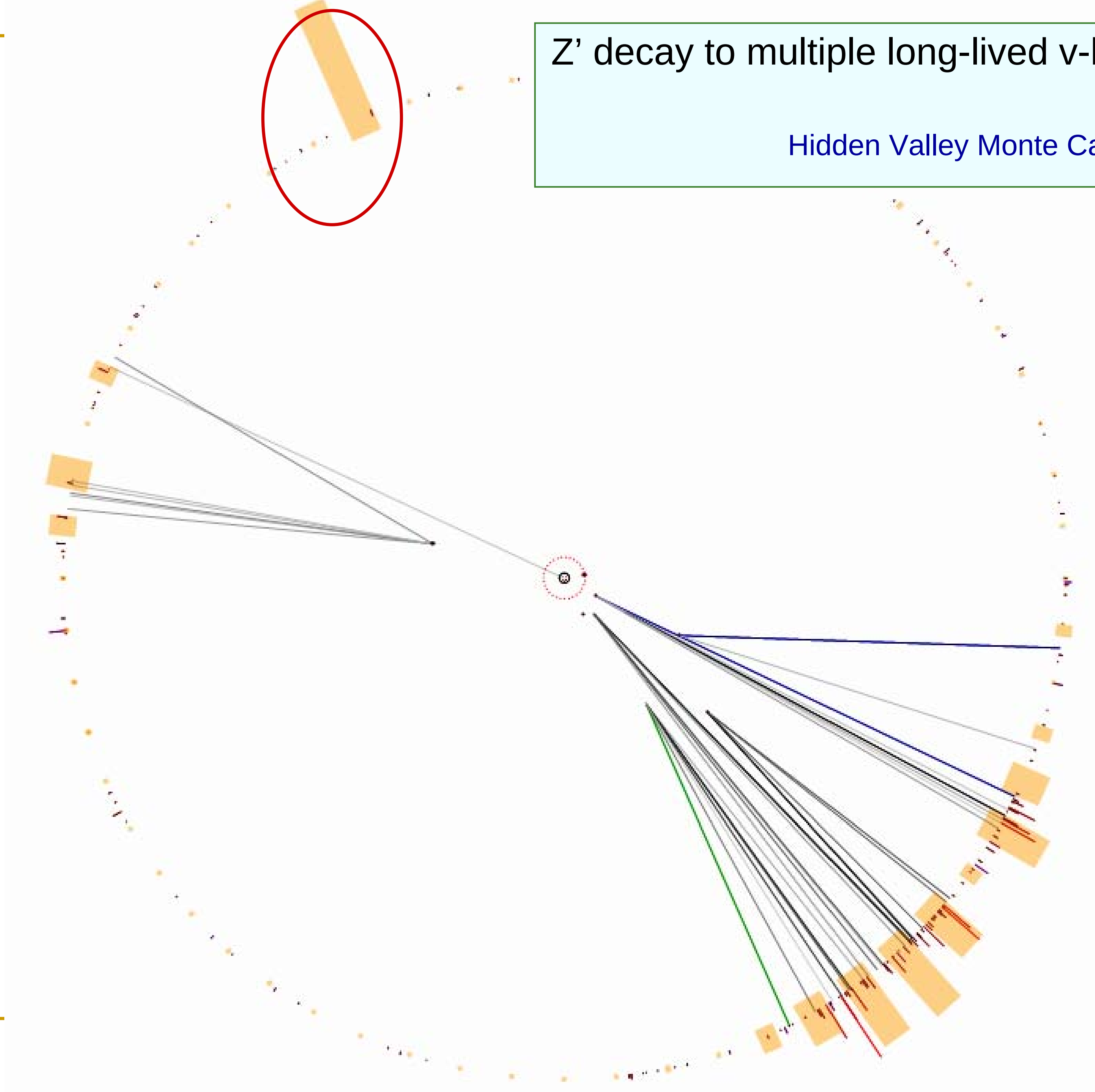



***But some v-hadrons decay in the detector to visible particles, such as bb pairs, qq pairs, leptons etc.***

Analogous to e+e- → hadrons

# Z’ decay to multiple long-lived v-hadrons

Hidden Valley Monte Carlo 0.5 (MJS)



# Z' → new <u>promptly</u>-decaying particles

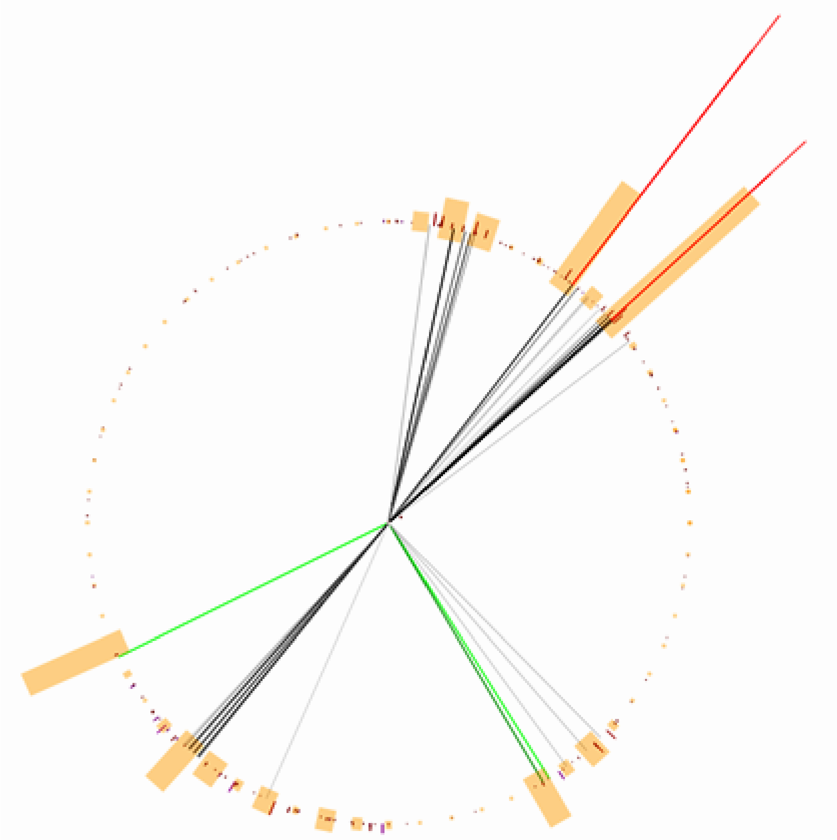
<u>Strategy:</u>

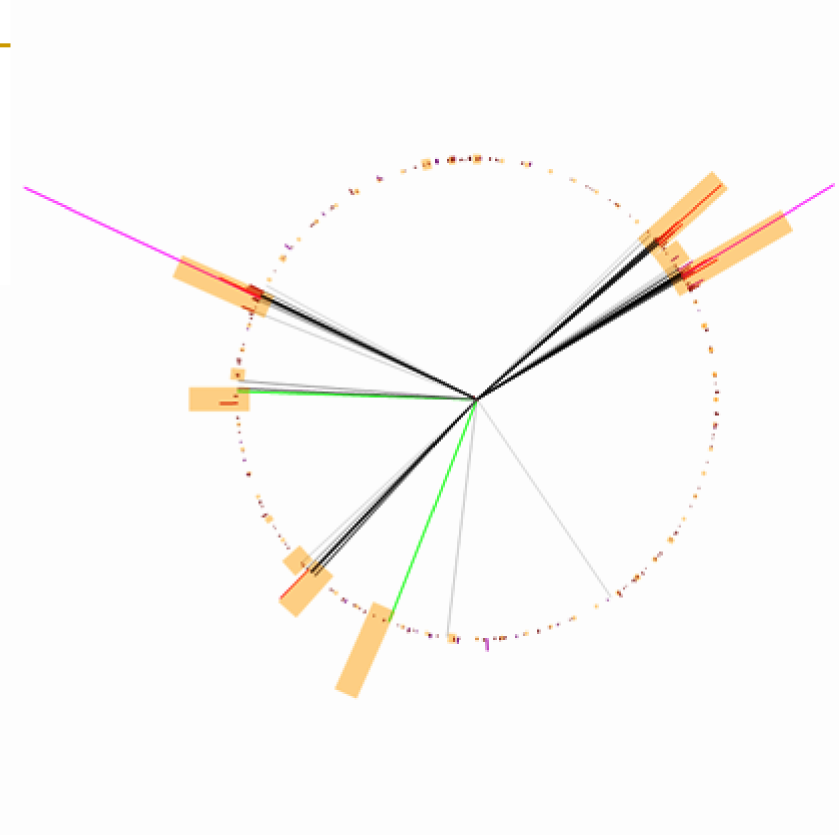
Depends on multiplicity of final state

- Low multiplicity → several high-pT jets, large backgrounds
- High multiplicity → many jets, harder to reconstruct, unusual event shape

Depends on presence of an easy sub-signature

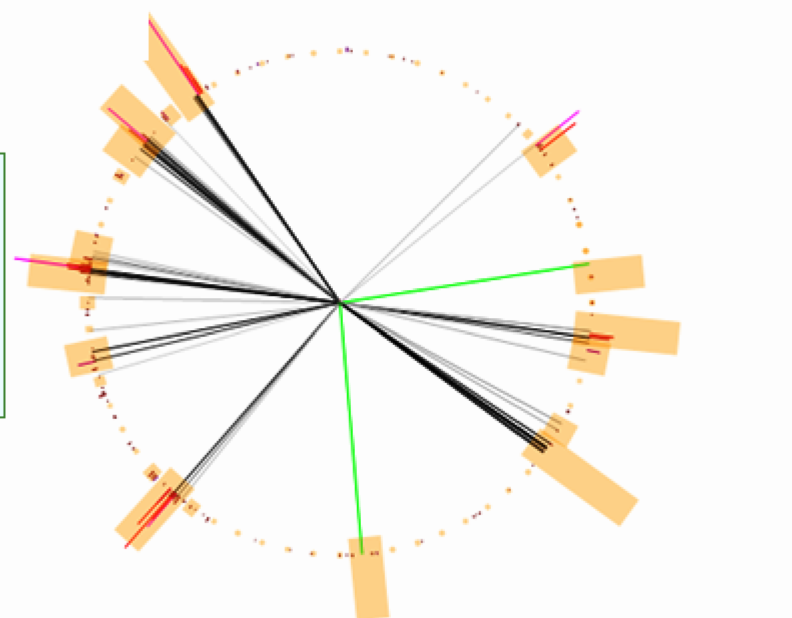
- If e/$\mu$-pair or $\gamma$-pair resonance, backgrounds potentially very low
  - Select events with special characteristics and e/$\mu$/$\gamma$-pair
  - Plot invariant mass of e/$\mu$/$\gamma$-pair in this sample
  - Also look for events with two e/$\mu$/$\gamma$-pairs
- If not – potentially challenging





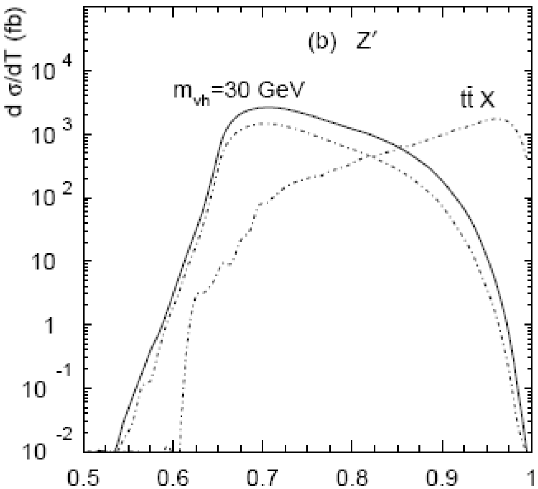
Z' decay to multiple v-hadrons

Hidden Valley Monte Carlo 0.99
(MJS, Mrenna, Skands)



$m_{Z'}$ =1 TeV
$m_\omega$ = 30 GeV

Han, Si, Zurek + MJS, 2007

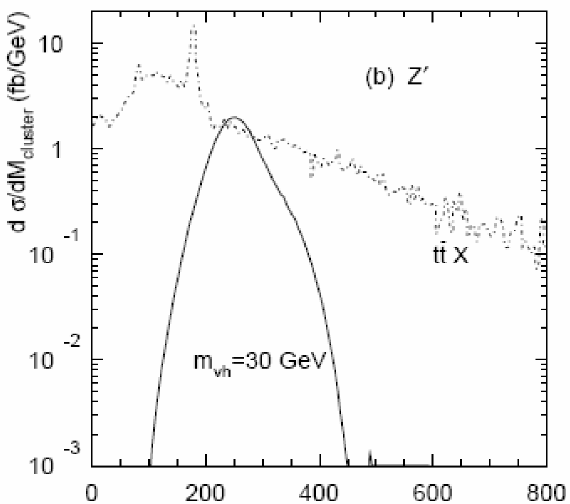



Transverse Thrust

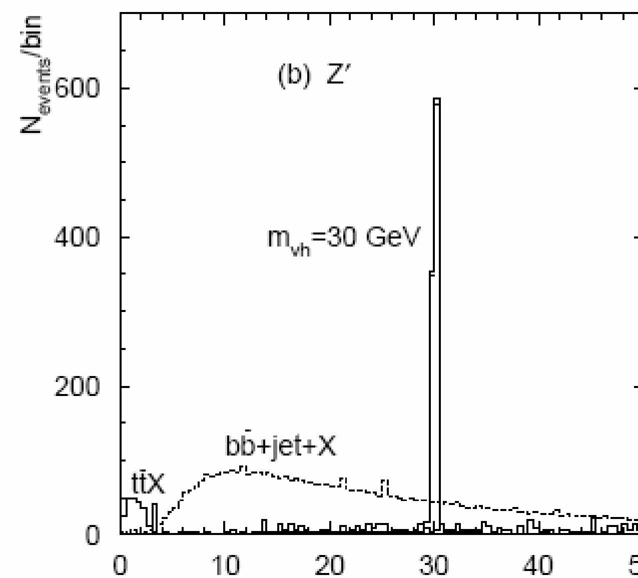
**Basic Search Strategy:**

Find dilepton resonance in busy events

- Event Shapes
- Dilepton invariant mass




Cluster Mass




Di-Muon mass (GeV)

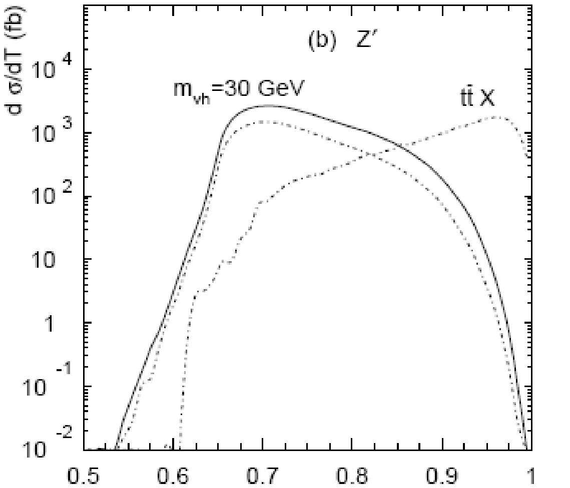
Are transverse-thrust, cluster mass the best event shape vars.?

- Theoretical stability (ISR? QCD backgrounds?)
- Experimental stability (UE, multiple collisions?)
- Experimental calibration (how to measure in backgrounds)?

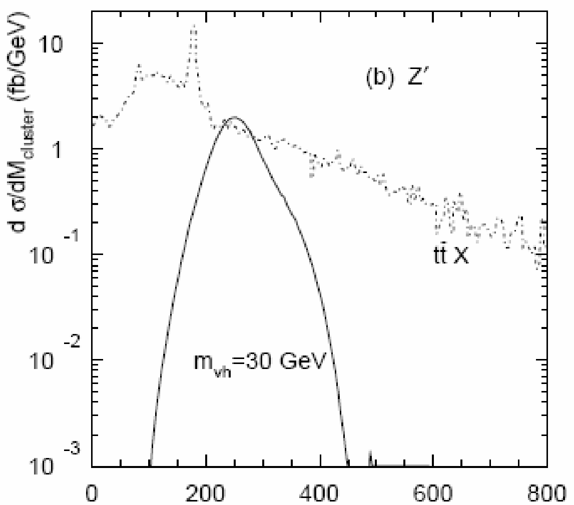
Are there alternative strategies for analysis?

- cut on number of jets? MET?
- 4-lepton events?

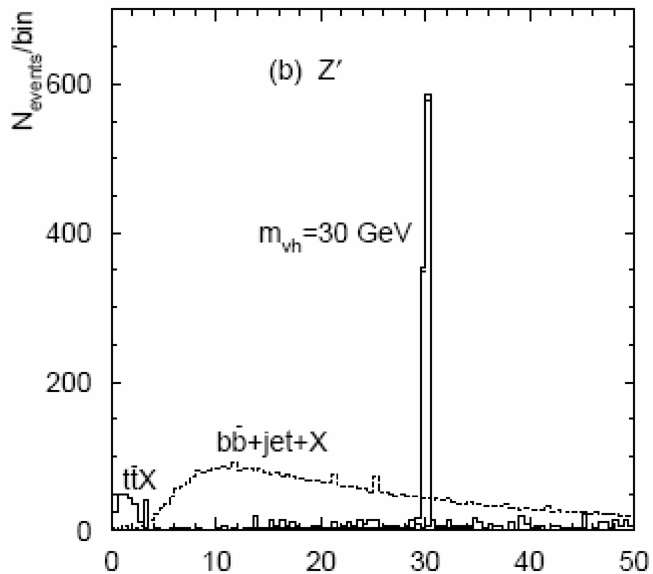
What if event rates are low? How to increase sensitivity?




Transverse Thrust




Cluster Mass



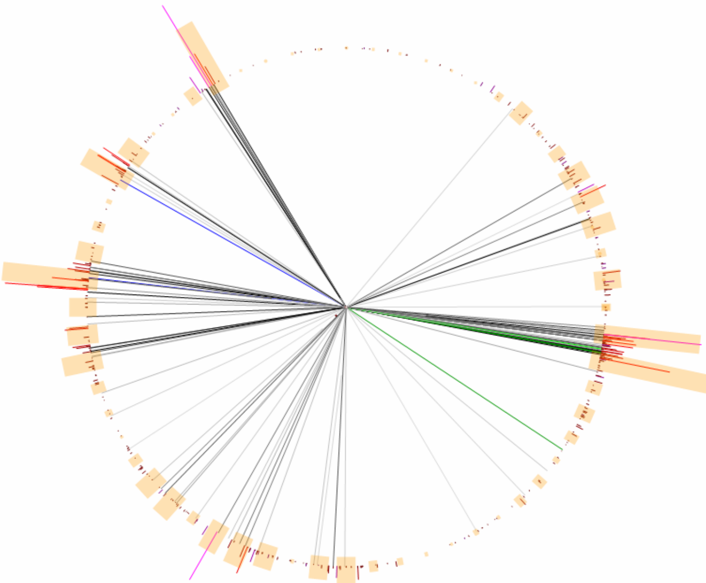

Di-Muon mass (GeV)

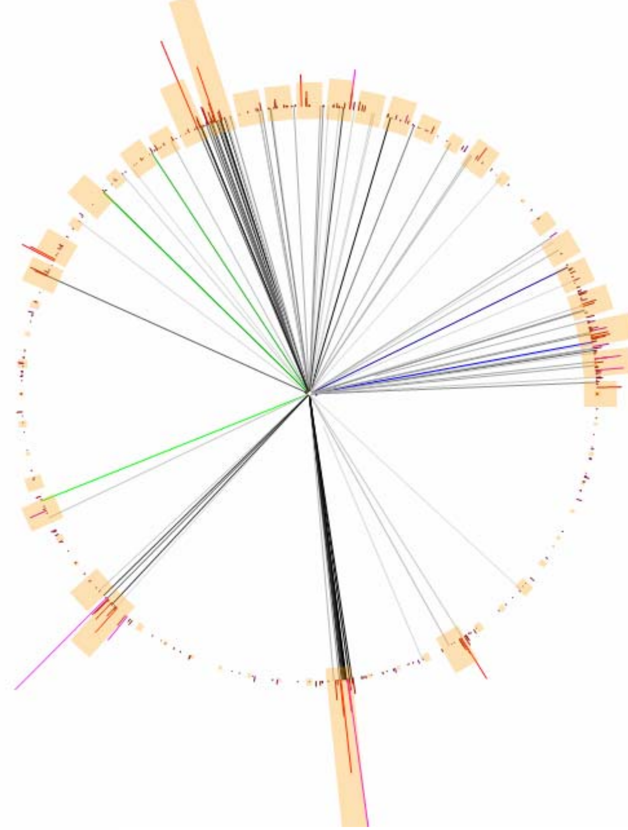
# If no $e/\mu/\gamma$-pair resonance?

If all light v-particles are spin-0, may have only heavy flavor

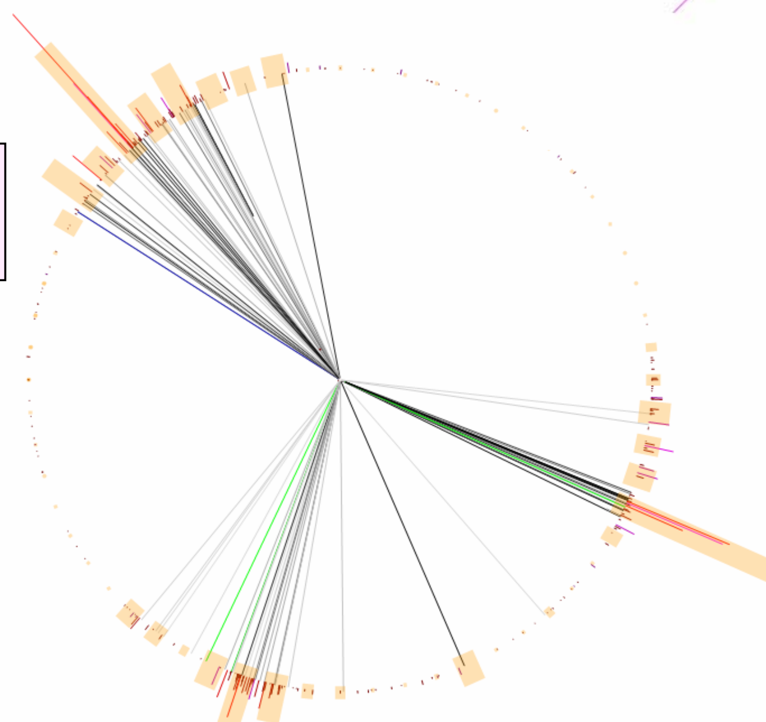
(b's, some tau's; no $e/\mu/\gamma$ pairs)

This is much harder!





**Average: 20 b's**
**Max: 42 b's**



MJS, in preparation

Z' ➔ v-hadrons

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

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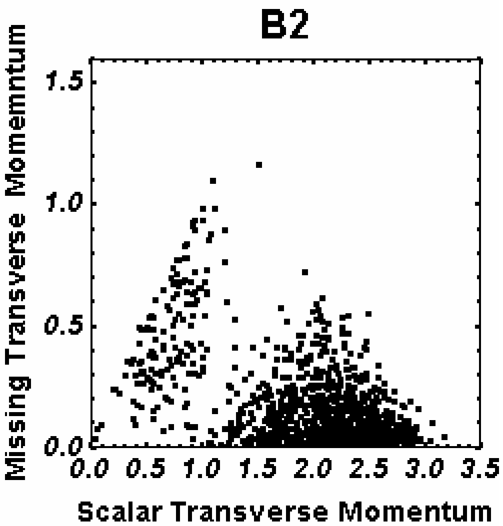
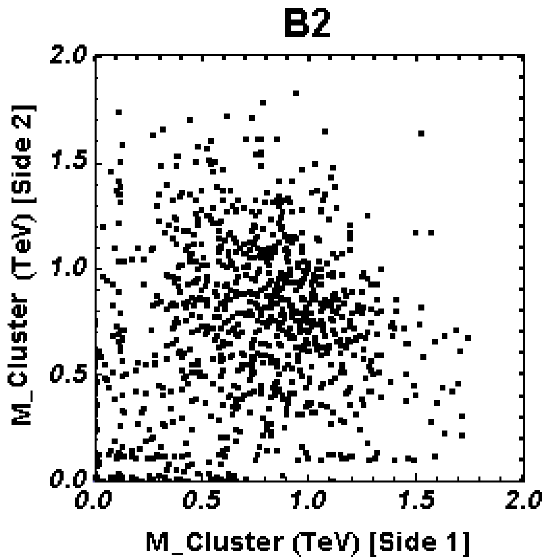
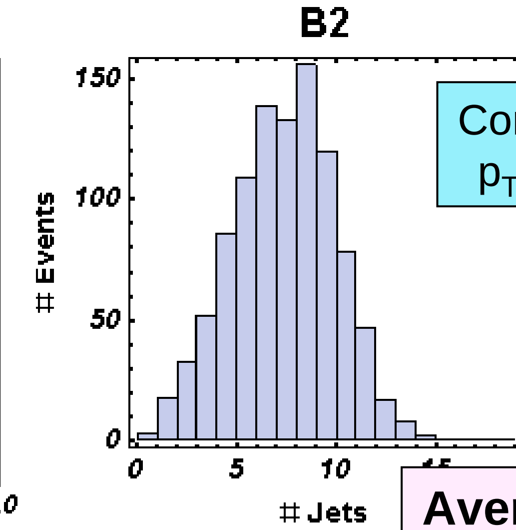
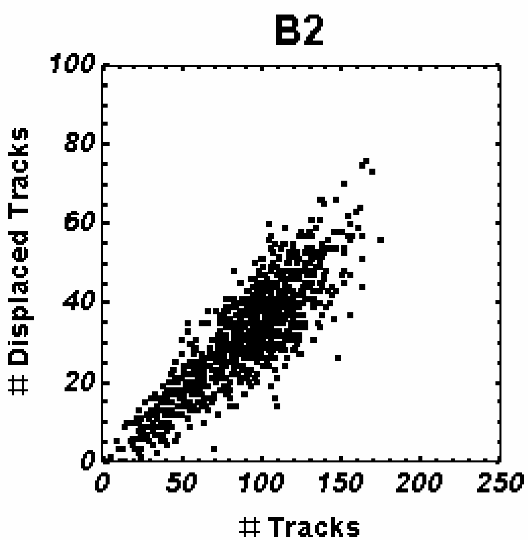


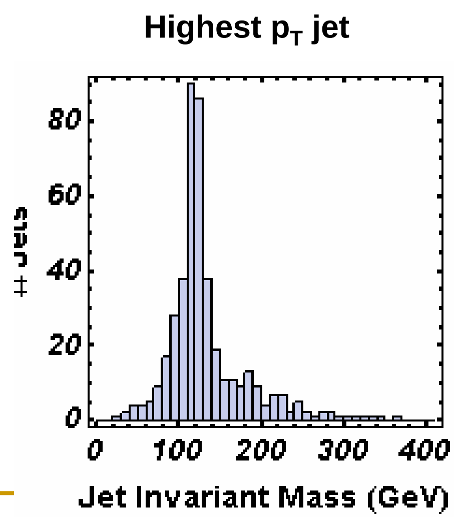



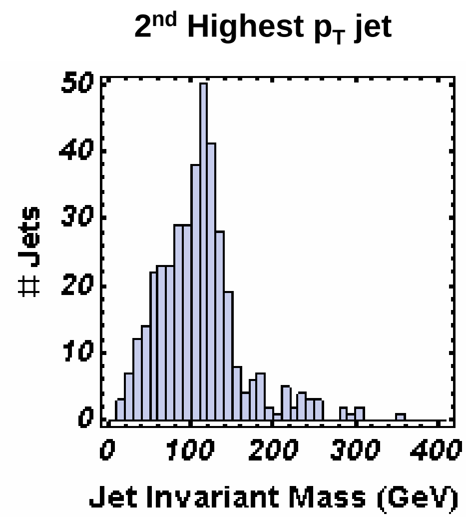




Cone jets 0.4
$p_T$>50 GeV

**Average: 12 b's**
**Max: 30 b's**




Cone jets 0.7, $m_{jet}$ > .15 $p_T$

Decays, showering, hadronization, calorimeter-cell granularity included ... l. Signal only

# Is Single-Jet Invariant Mass a good variable?

What is the appropriate resolution?

Can it be improved?

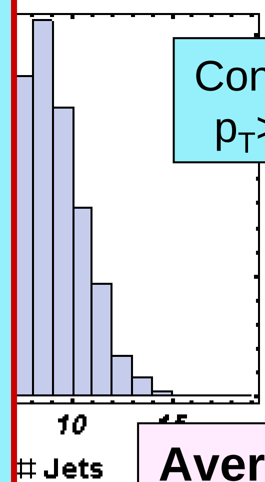
If Not, how to convincingly establish a signal?

How to estimate/measure backgrounds to multi-jet signals?

Can theorists really help?

What experimental strategy could work?

B2

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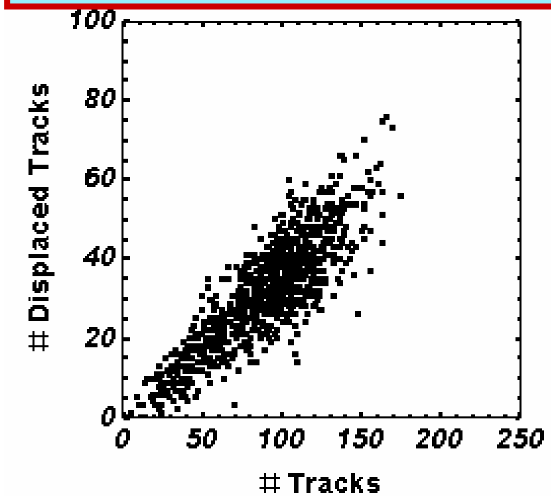
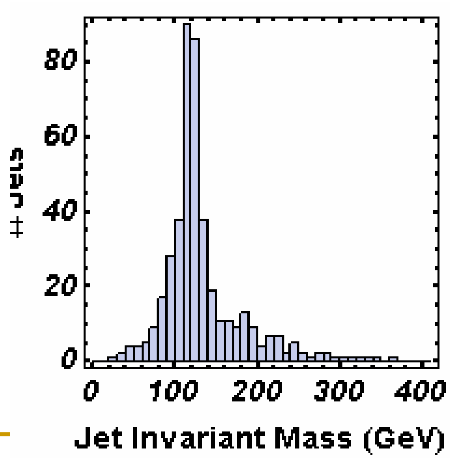
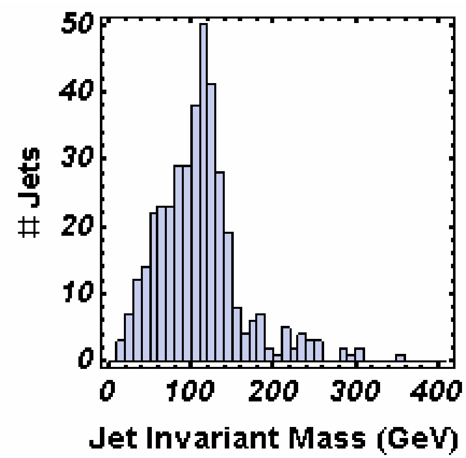



Highest $p_T$ jet




2nd Highest $p_T$ jet




Cone jets 0.7, $m_{jet}$ > .15 $p_T$

# AdS/CFT → spherical events

If v-sector is gauge theory with nice string dual description

i.e. gauge theory at large ‘t Hooft coupling

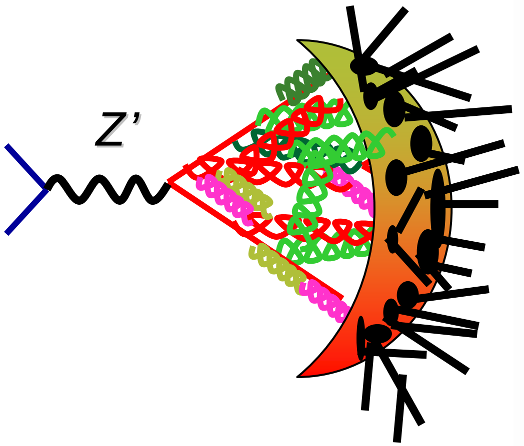
this can have substantial effects on observables

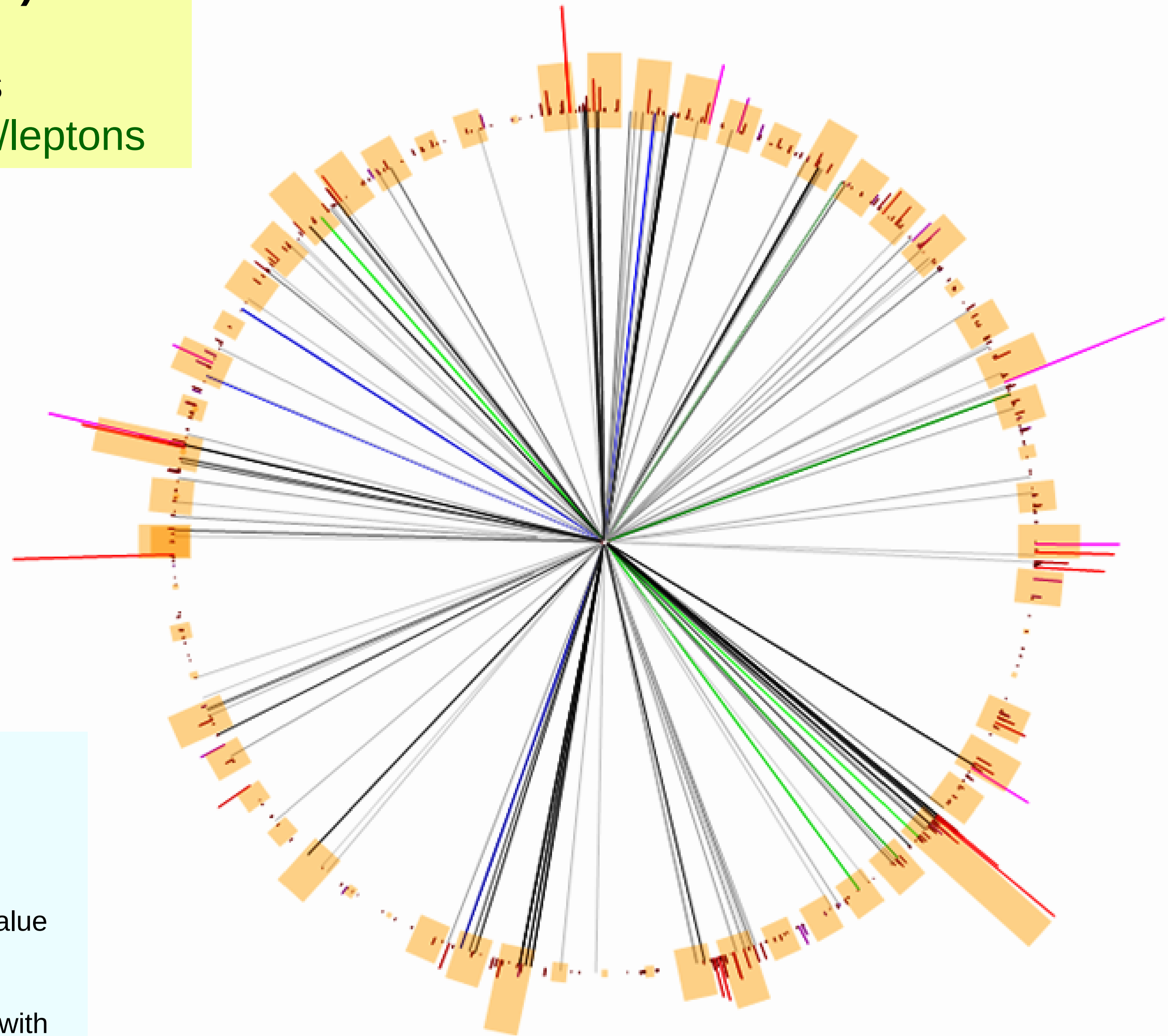
- At weak coupling, Z’ decays give two jets of v-hadrons
- At large ‘t Hooft coupling, there are no jets –
  instead events are quasi-spherical with extreme multiplicity

no jets, spherical event:

MJS conjecture [0801.]
proof Hoffman-Maldacena [0803.]
see also conjecture Hatta, Iancu, Mueller [0803.]

**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 $\alpha$ 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

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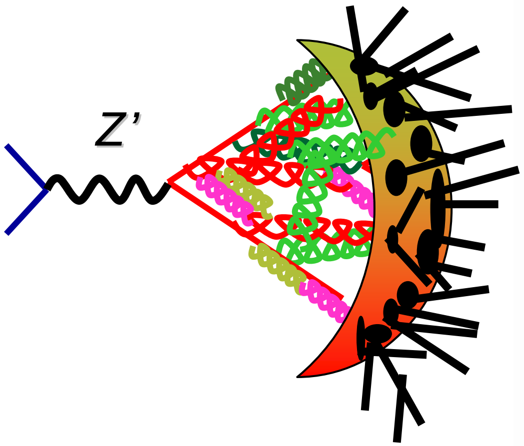


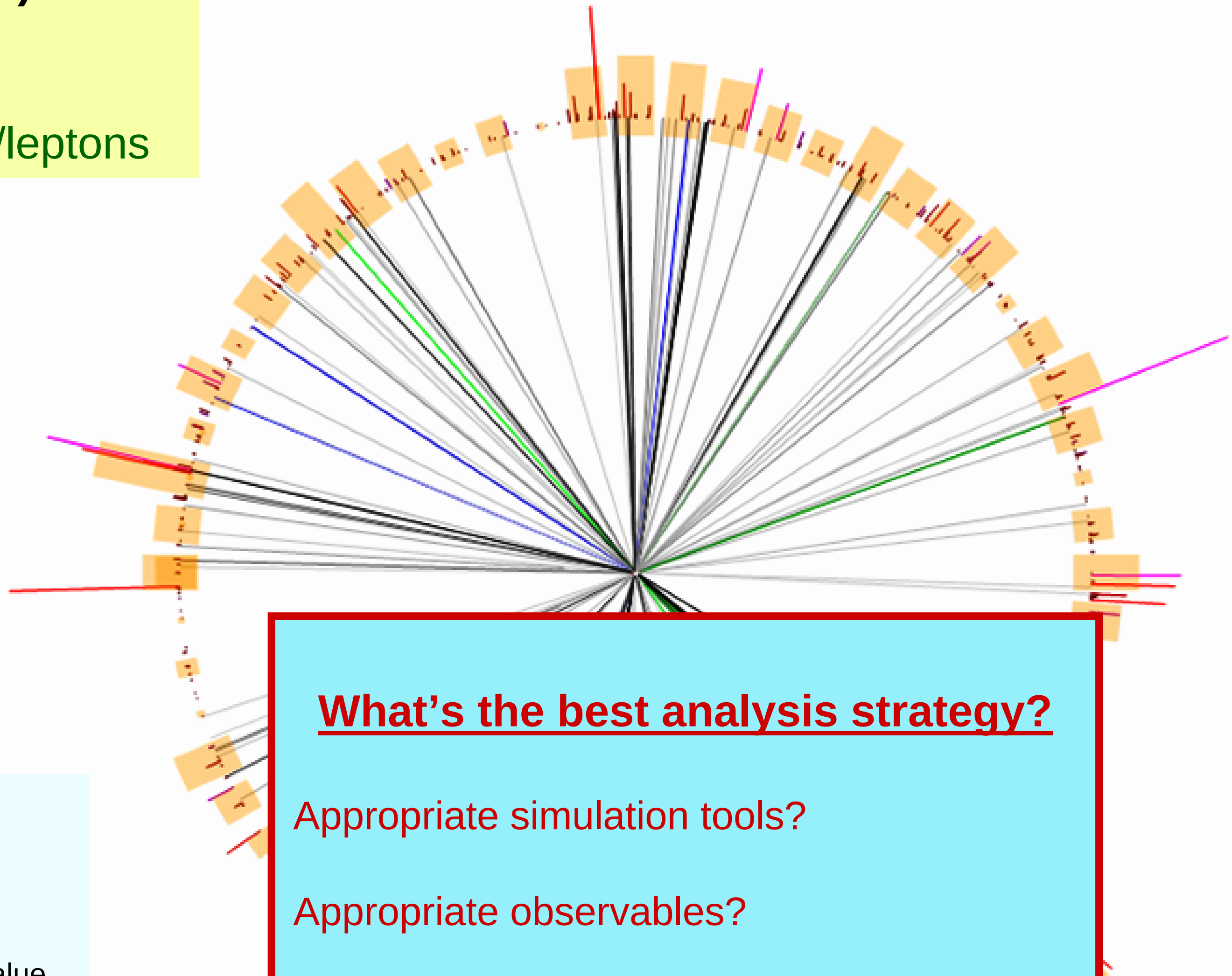

**What's the best analysis strategy?**

Appropriate simulation tools?

Appropriate observables?

Background determination?

**Educated guesswork!**

**Crude and uncontrolled simulation**

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    - This increases collinear splitting
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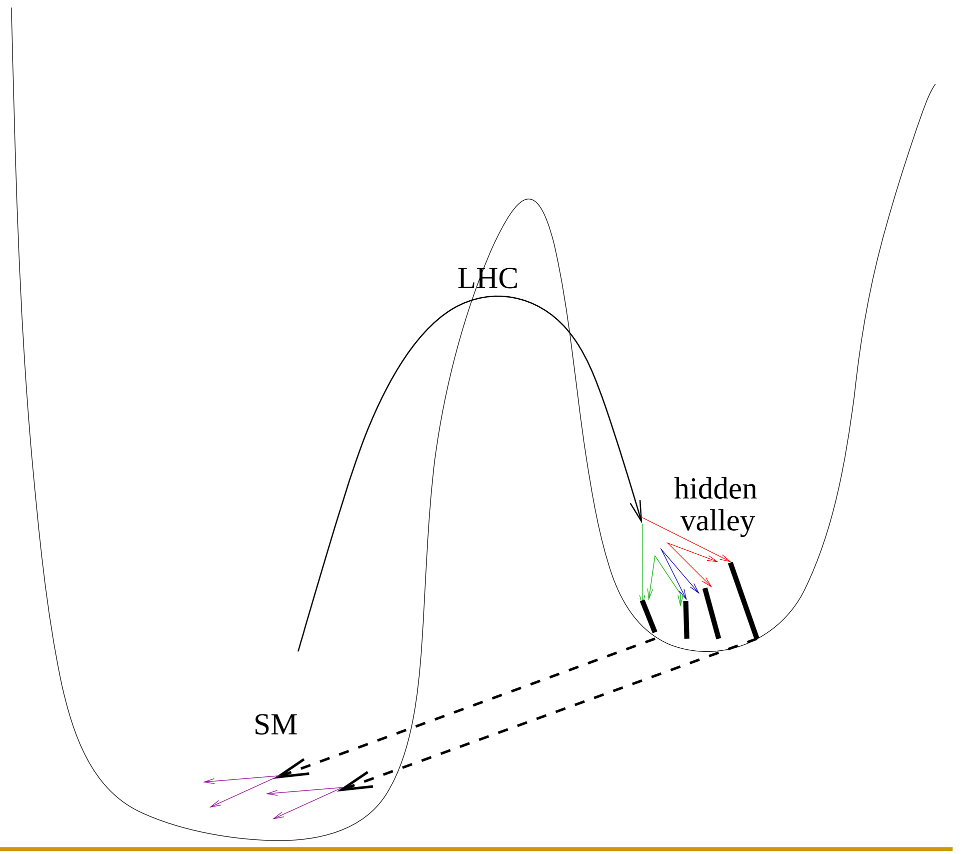
# Remark on Unparticle Models

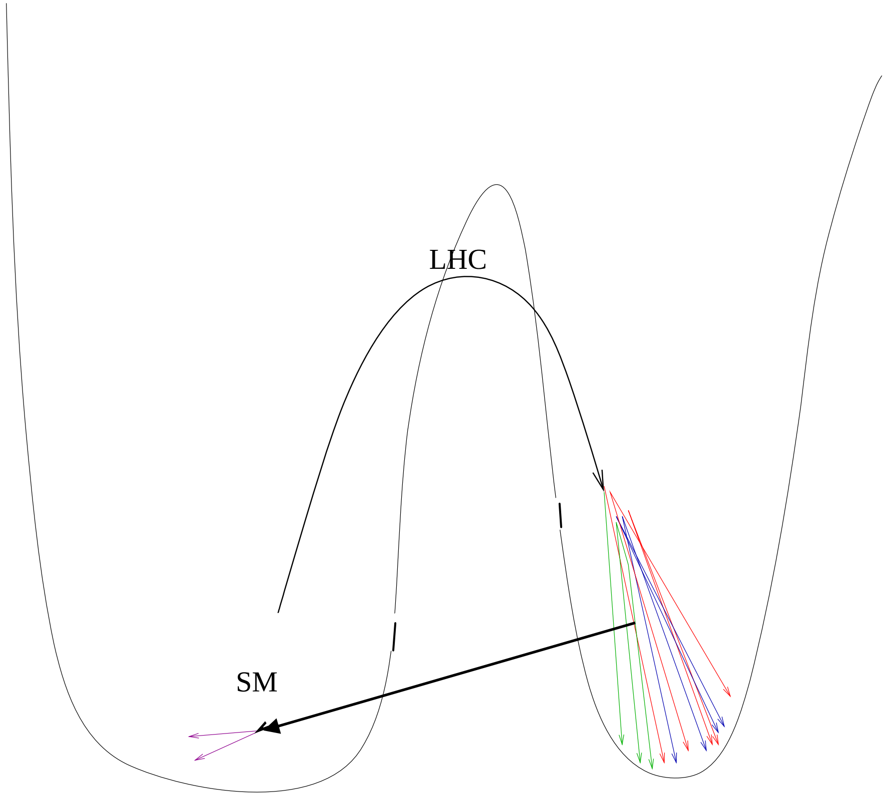
MJS-Zurek 2006



# Remark on Unparticle Models

- In Unparticle models
  - a scale-invariant hidden sector generates indirect effects on observables
    - Events with MET
    - Rare virtual effects

Georgi 2007



# Remark on Unparticle Models

- In Unparticle models
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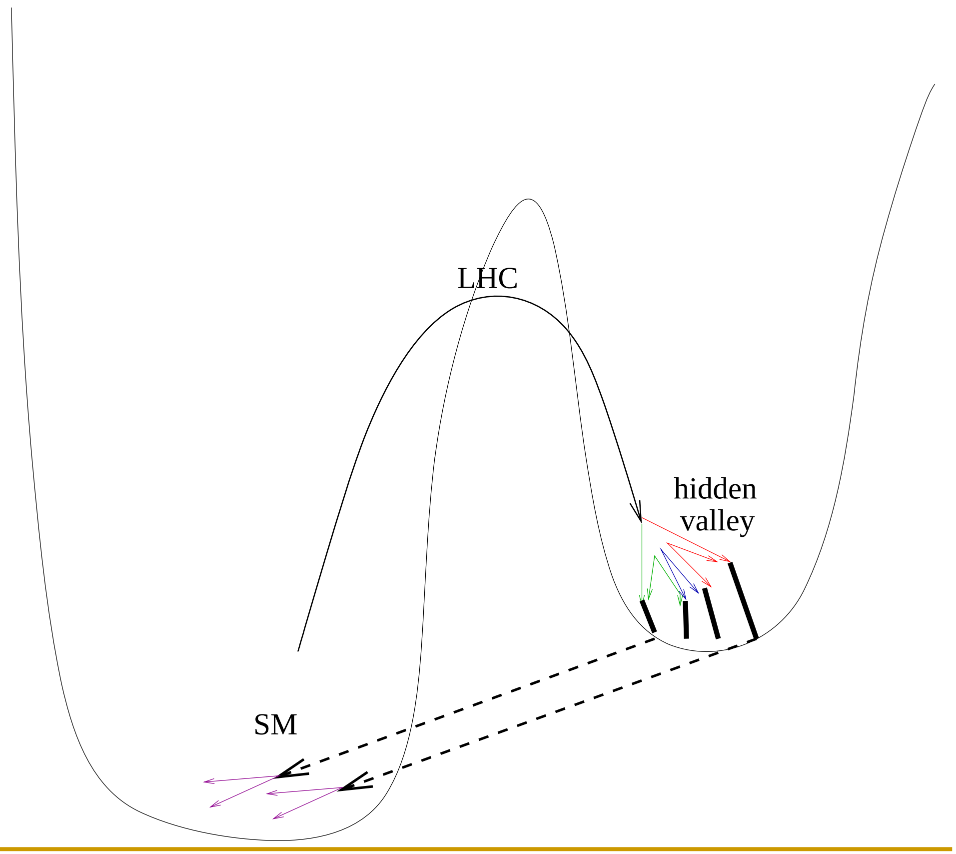
- With large mass gap, model becomes a hidden valley
  - Scale-symmetry breaking can lead to direct, common, model-dependent, observable effects
    - Multiparticle production
    - Possible long-lived states

MJS 0801.

MJS-Zurek 2006



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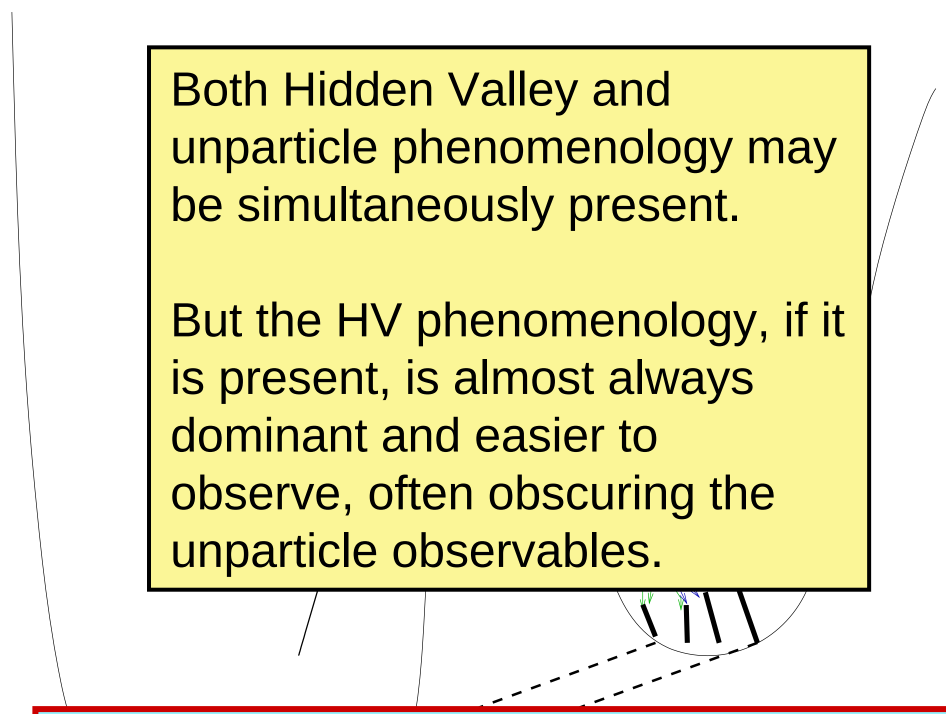
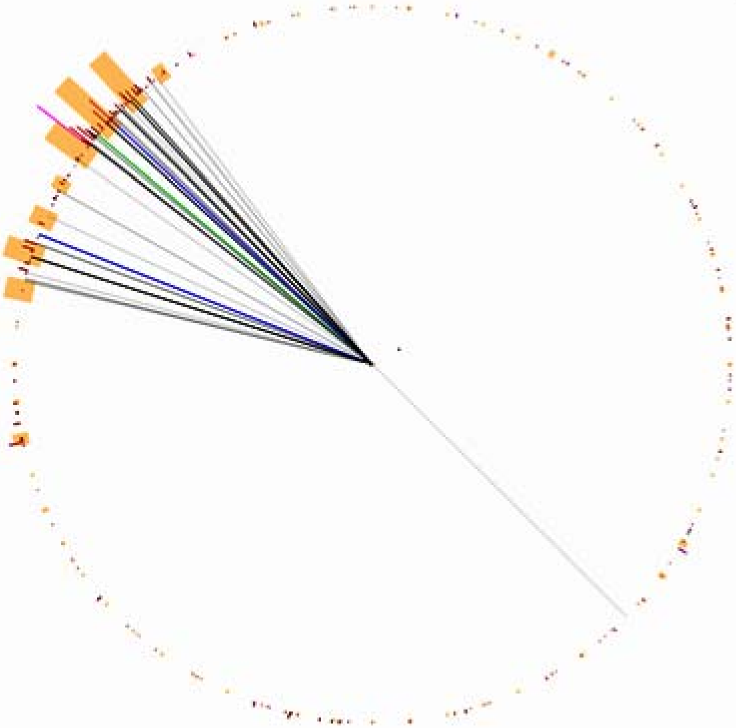


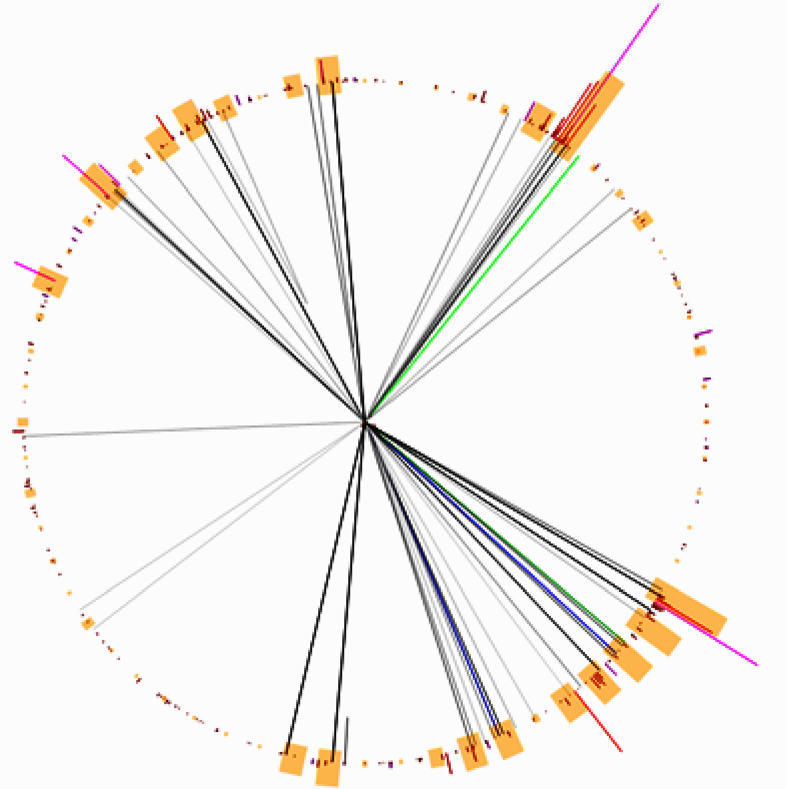
Both Hidden Valley and unparticle phenomenology may be simultaneously present.

But the HV phenomenology, if it is present, is almost always dominant and easier to observe, often obscuring the unparticle observables.

When Scale Invariance plays important role
but is badly broken,
what theoretical tools are available?
what are best observables?

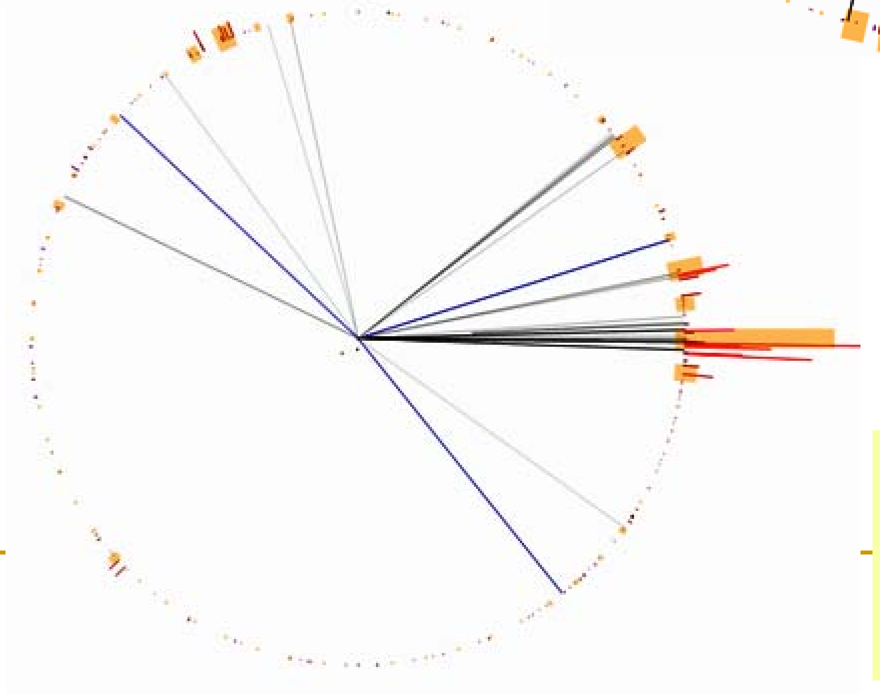
# What if some v-particles are invisible?





**Average: 8 b's**
**Max: 22 b's**

MJS, in preparation



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Flavor-off-diagonal
v-pions stable

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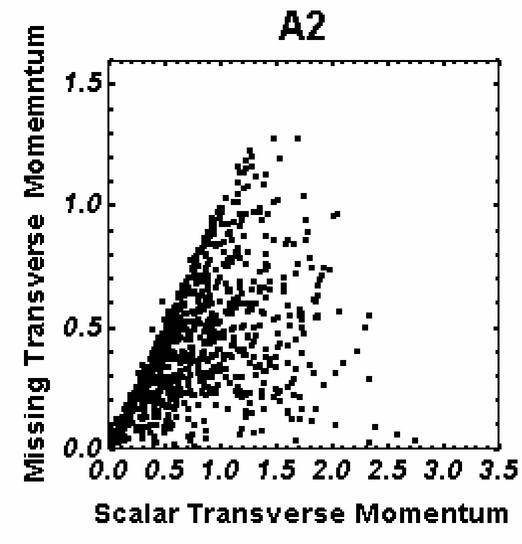
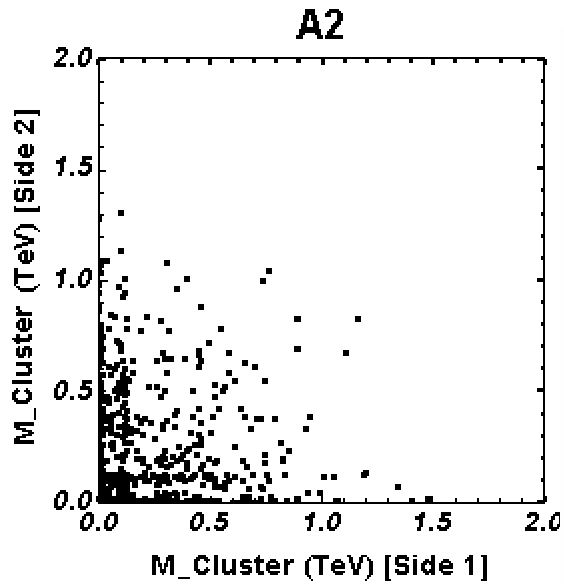
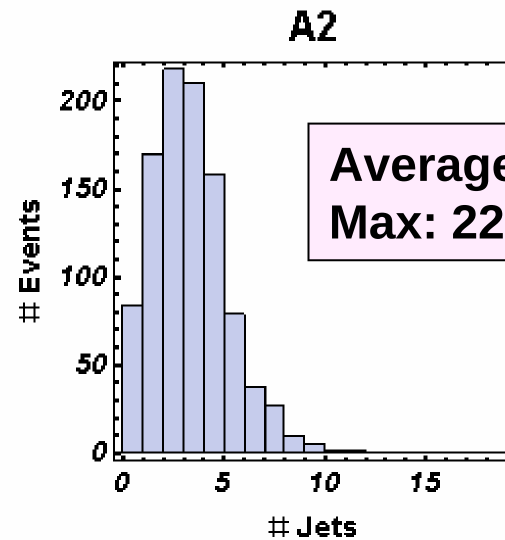
No magnetic field. Signal only

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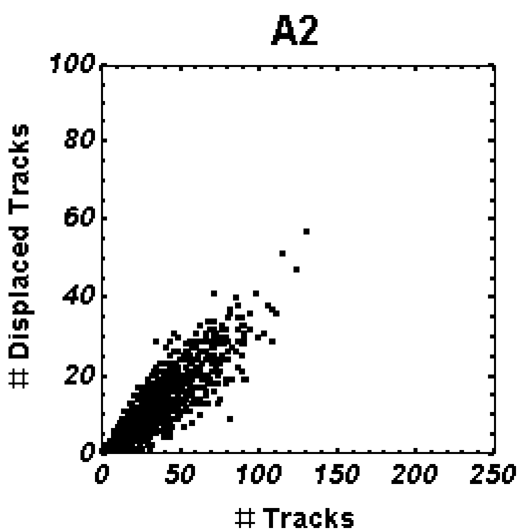


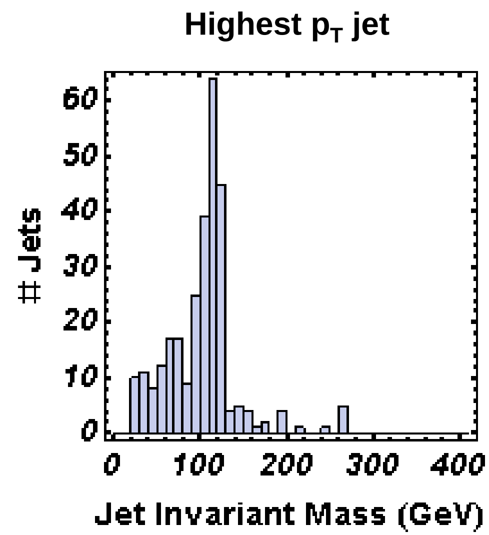


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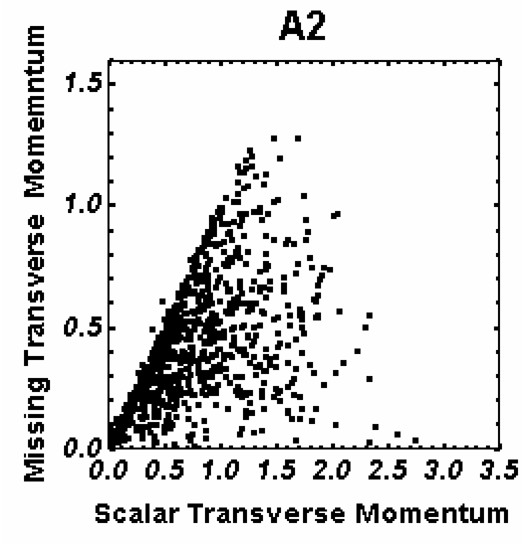


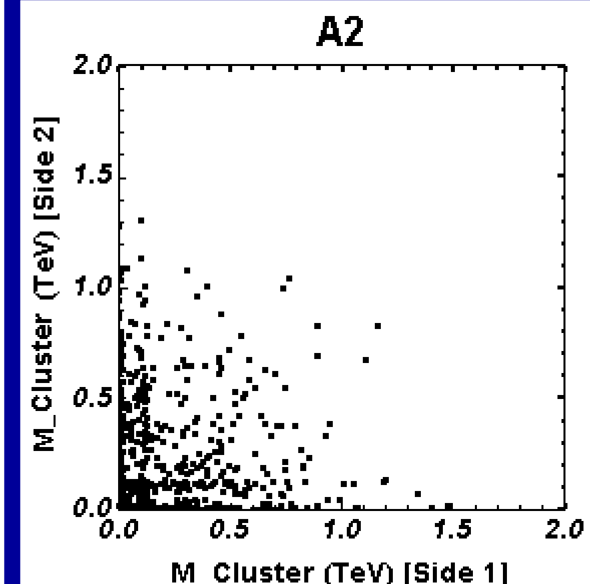


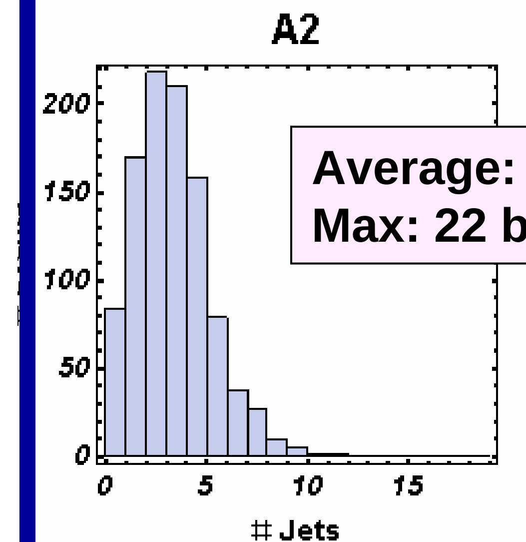


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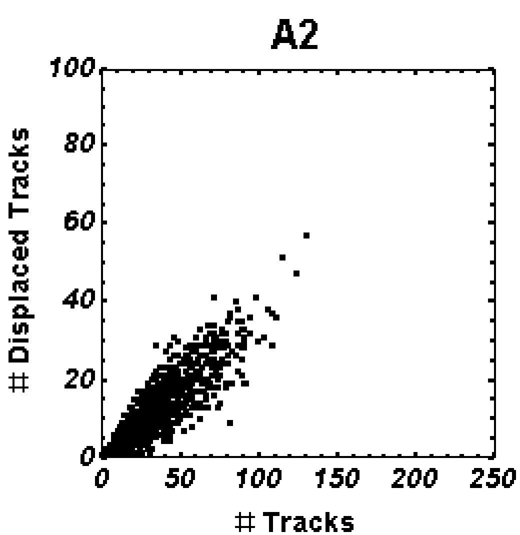
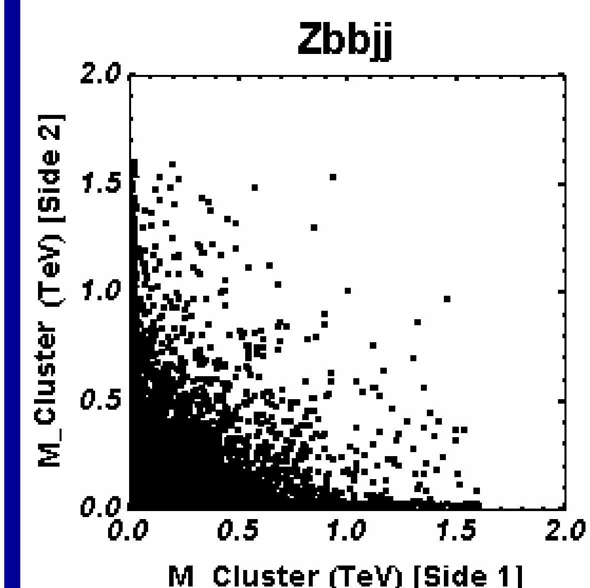
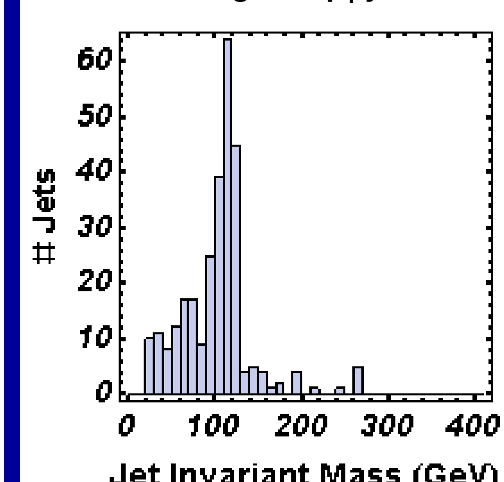



Highest $p_T$ jet

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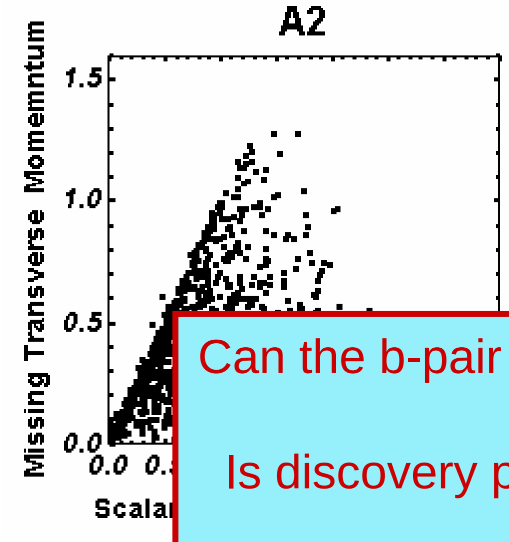
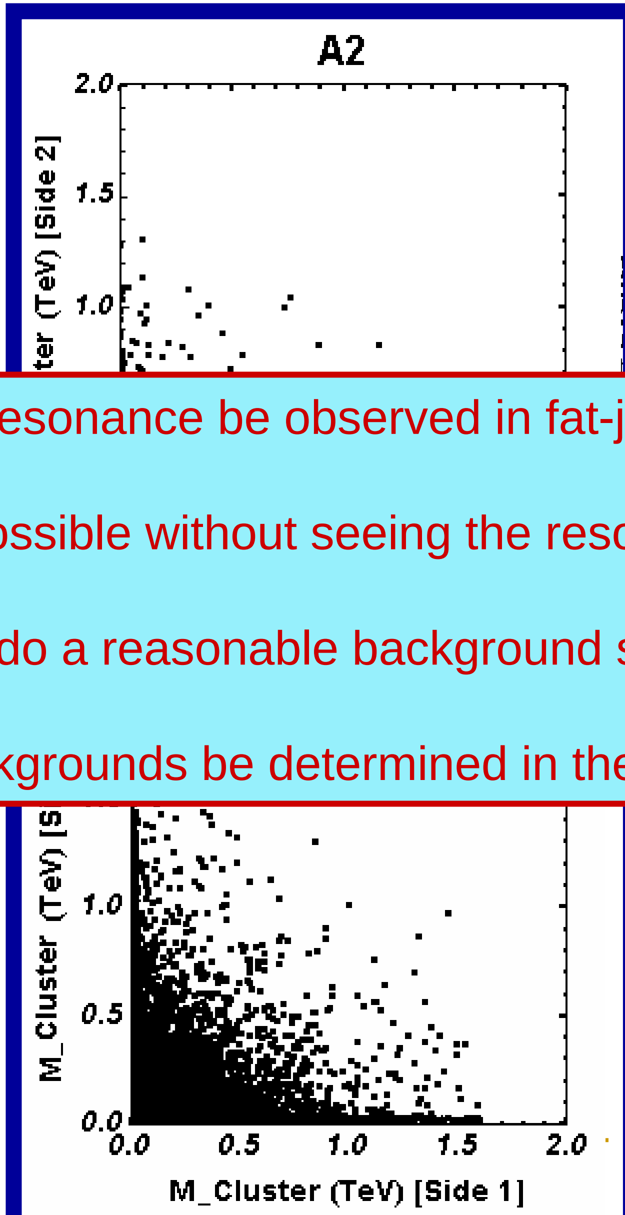
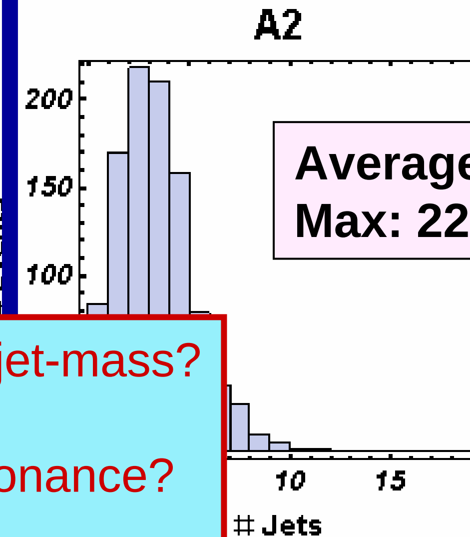


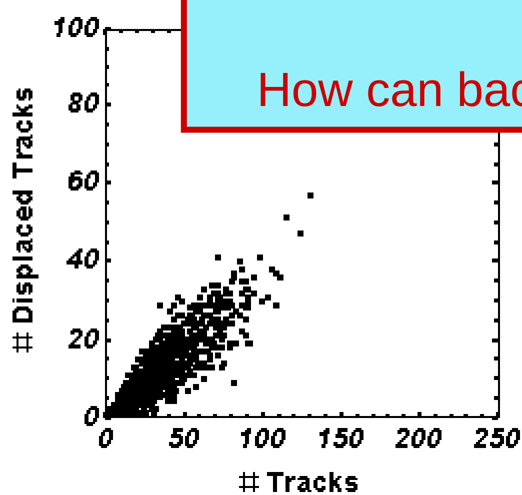

Average: 8 b's
Max: 22 b's

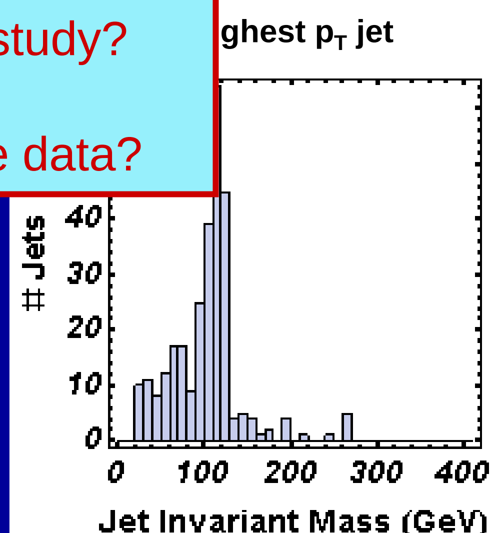
Can the b-pair resonance be observed in fat-jet-mass?

Is discovery possible without seeing the resonance?

How best to do a reasonable background study?

How can backgrounds be determined in the data?




Cone jets 0.7, $m_{jet} > .15\ p_T$

# SUSY Studies -- still to be done

Perhaps most likely scenario for v-particle production

- LSP of SM sector decays to LSP of v-sector

Enormous range of phenomenology possible

- Some familiar, some not

Possible new features

- Extra soft jets from v-particle decays, reducing MET, confusing reconstruction, isolation
- 2 displaced vertices with wide opening angle, many tracks, a bit out of time
- >> 2 displaced vertices, a bit out of time
- Vertices may come from stable charged track or R-hadron

Impact on SUSY searches not yet clear

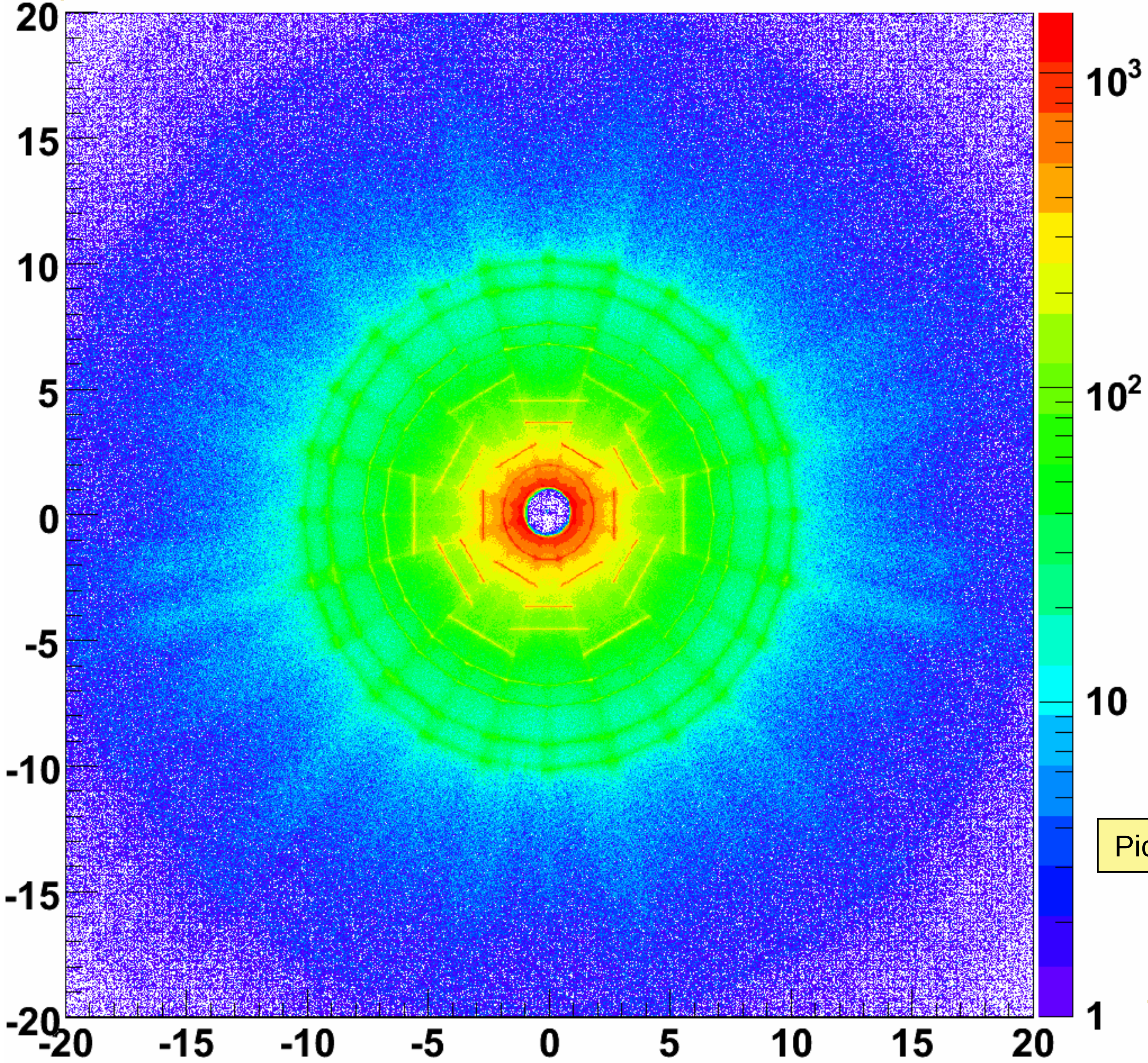
- Problem of sifting through soft jets
- Perhaps like R-parity violation searches
- Are there fundamentally new issues here?

# Summary

- Vast continent of v-sectors and communicators
- Implies a large but probably manageable array of searches
  - Easy searches for dilepton or diphoton resonances
  - Experimentally challenging searches for long-lived particles
  - Difficult searches for dijet resonances
  - Events with moderate to extreme multiplicities
  - Odd event shapes: fat jets, or quasi-spherical

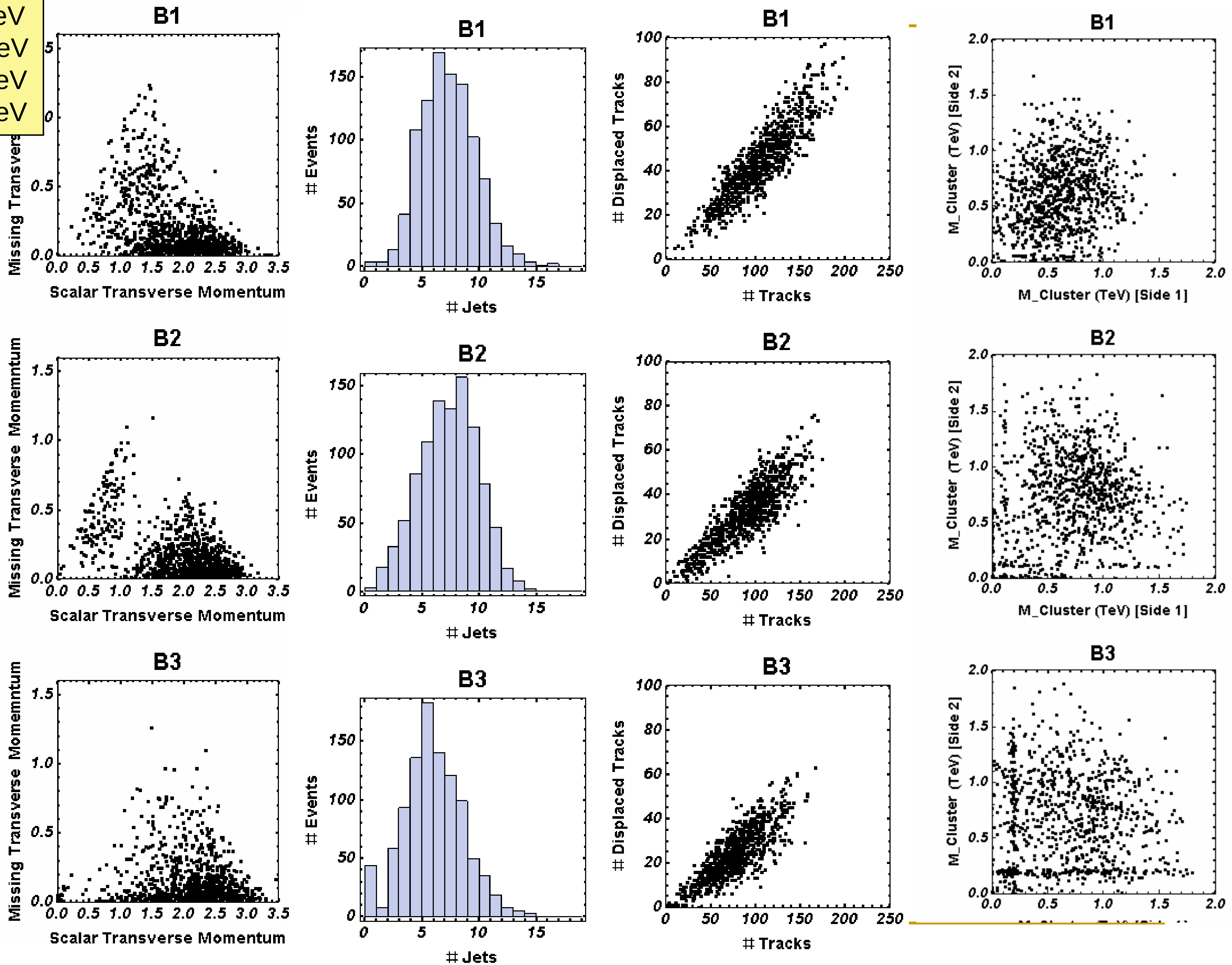
- Many questions remain
  - SUSY (and similar) models with LSP/LTP/LKP decay – can it be hard to discover?
  - Are we able to completely close the trigger loopholes with long-lived particles?
  - What are the right variables to deal with high-multiplicity events?
  - How do we improve our sensitivity to jet resonances?

# Backup Slides

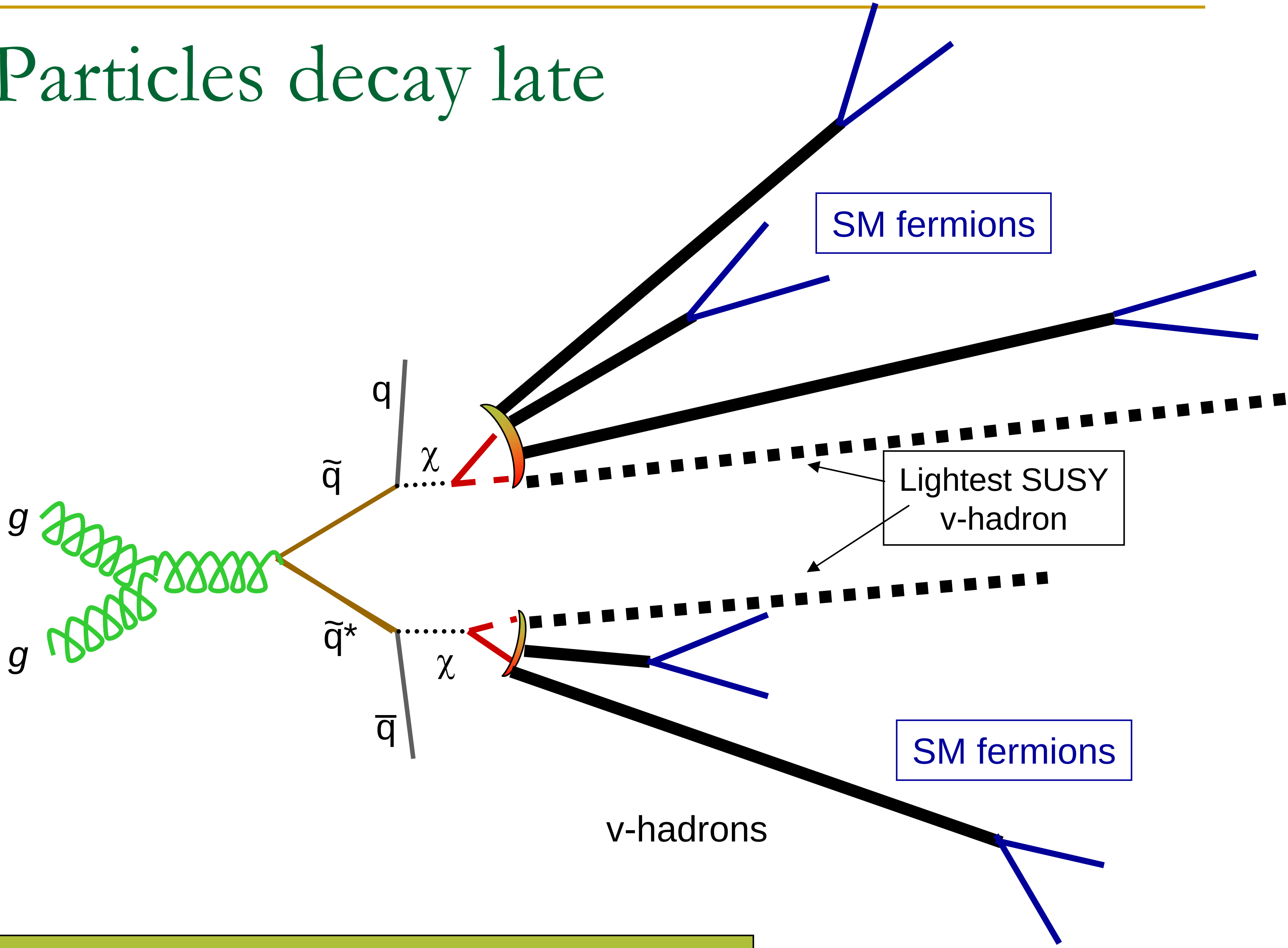



Picture courtesy of Andy Haas

$m_{Z'}$ =3.2 TeV
$m_\pi$ = 50 GeV
120 GeV
200 GeV

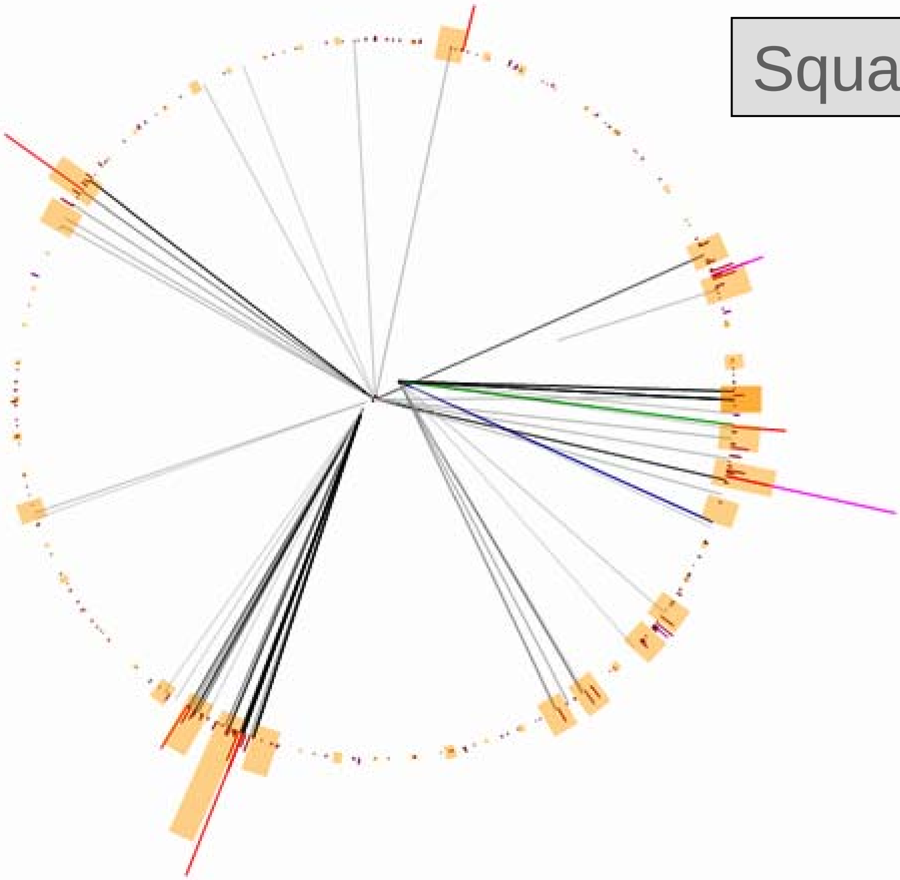


# ν-Particles decay late



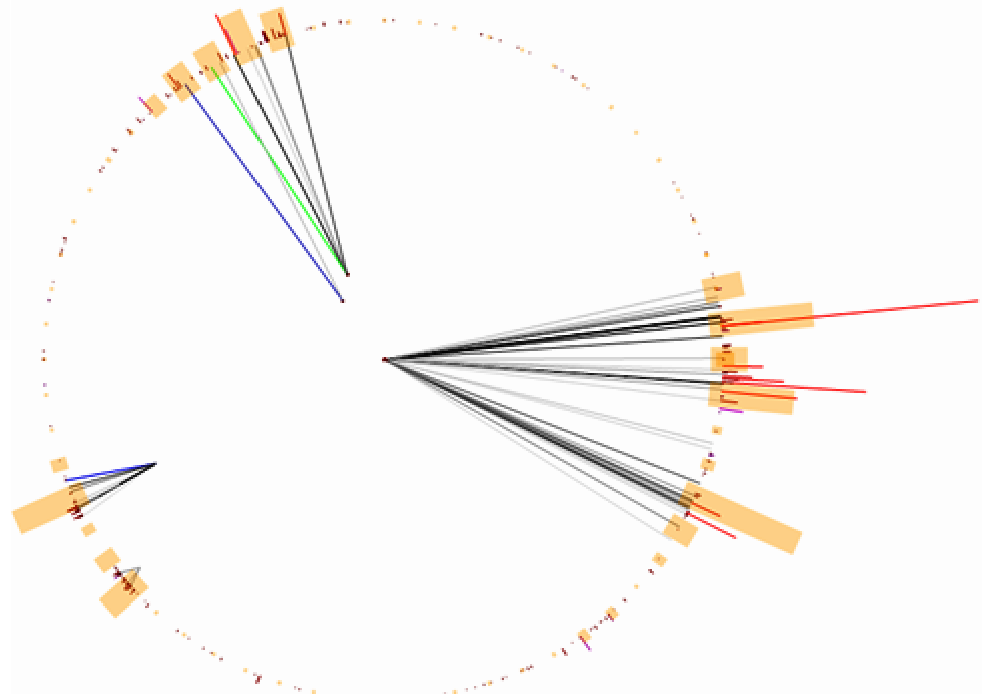

2 high-pT jets + multiple displaced jet/lepton pairs
+ MET from 2 v-SUSY-hadrons

# Squark-Antisquark Production at LHC



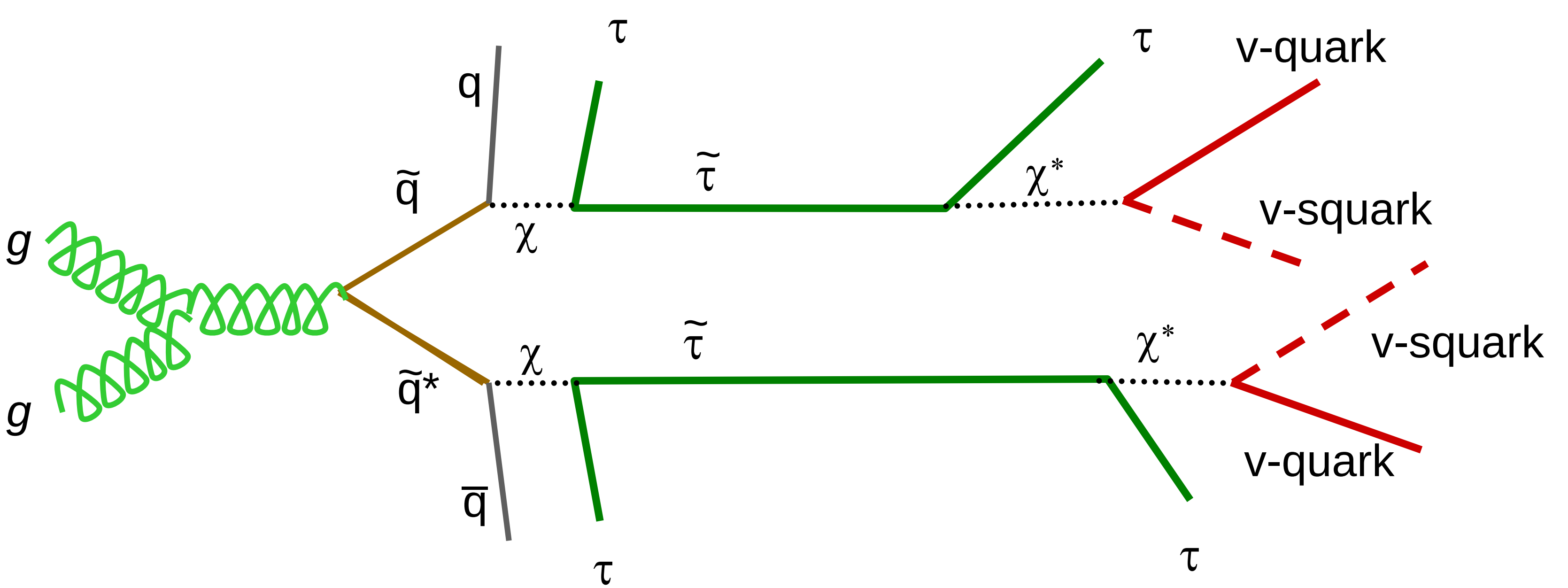
Long-Lived Neutralino
Prompt v-Particle Decay

Prompt Neutralino Decay
Long-Lived v-Particles



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

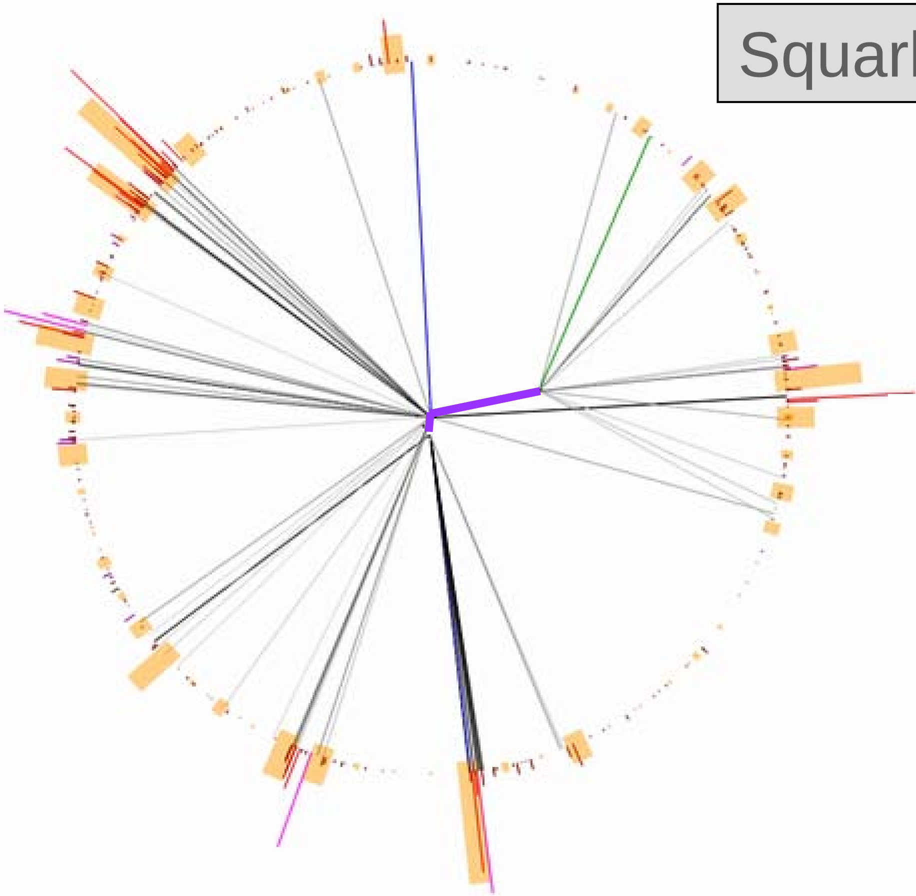
# Off-shell communicator ➔ Long lifetime likely




2 high-pT jets + 2 prompt taus + 2 possibly-displaced taus
+ v-quarks and v-squarks ➔ possibly-displaced v-hadron decays

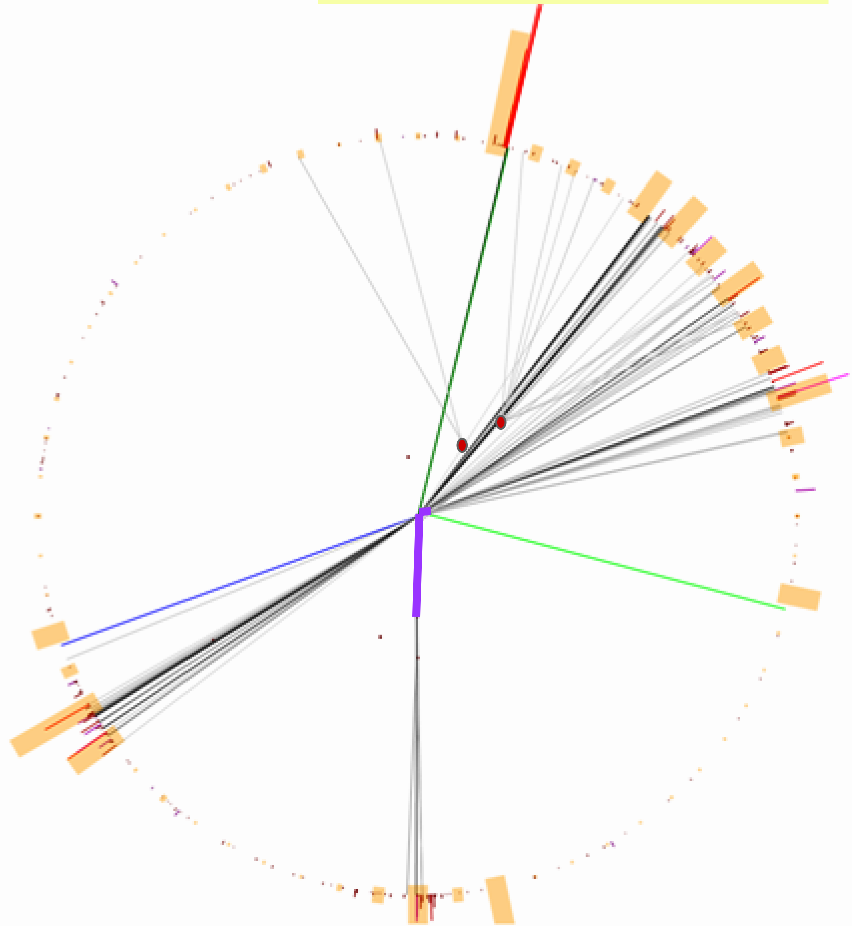
# Squark-Antisquark Production at LHC

Stau tracks



Long-Lived Stau
Prompt v-Hadron Decay

Long-Lived Stau
Long-Lived v-Hadrons



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