Signatures of New Hidden Sectors at the LHC

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
Phenomenology of hidden valleys at hadron colliders.
Han, Si, Zurek & M.J.S., arXiv/0712.2041
Why Unparticle models with mass gaps are examples of hidden valleys.
M.J.S., arXiv/0801.0629

Several papers in preparation…
See also Ciapetti, Lubatti, Dionisi…M.J.S. ATLAS note

Matthew Strassler
Rutgers University

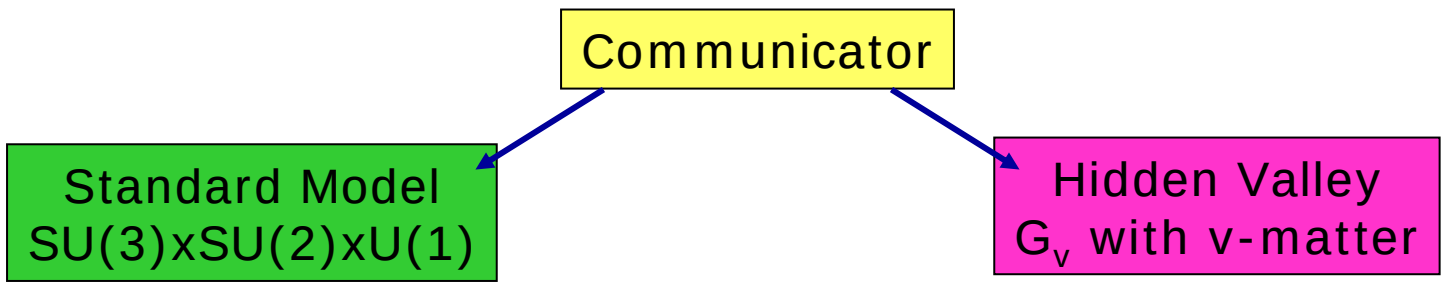
Plan of the Talk

- Basic structure and phenomenology of Hidden Valley scenario
- Relation to unparticle models with mass gaps
- Subtleties and phenomenology of such models
- If time, novel signals of hidden-sector strong dynamics

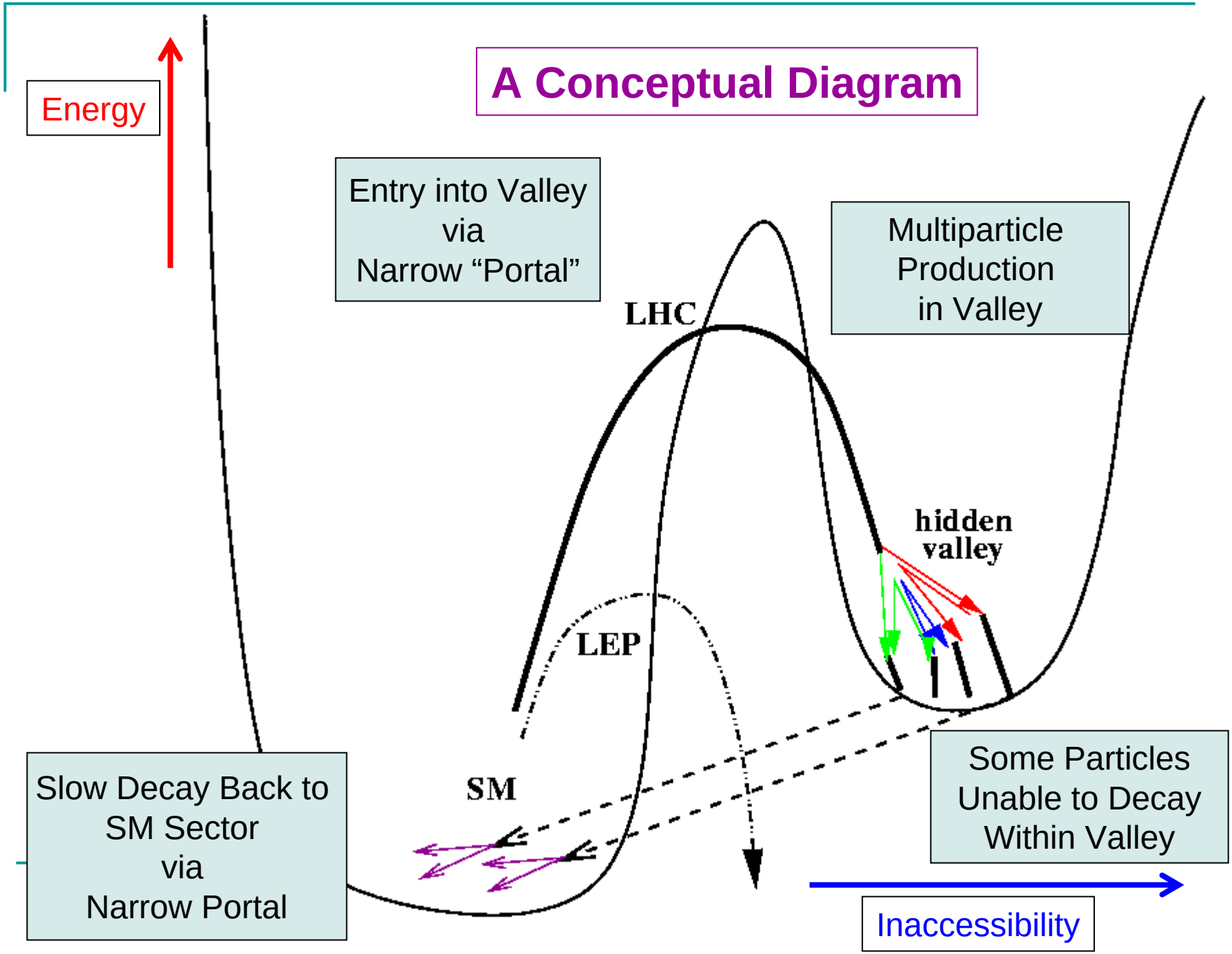
Hidden Valley Scenario (w/ K. Zurek)

hep-ph/0604261

- A scenario: **Large Meta-Class of Models**
- Motivation: in a moment
- Basic structure:

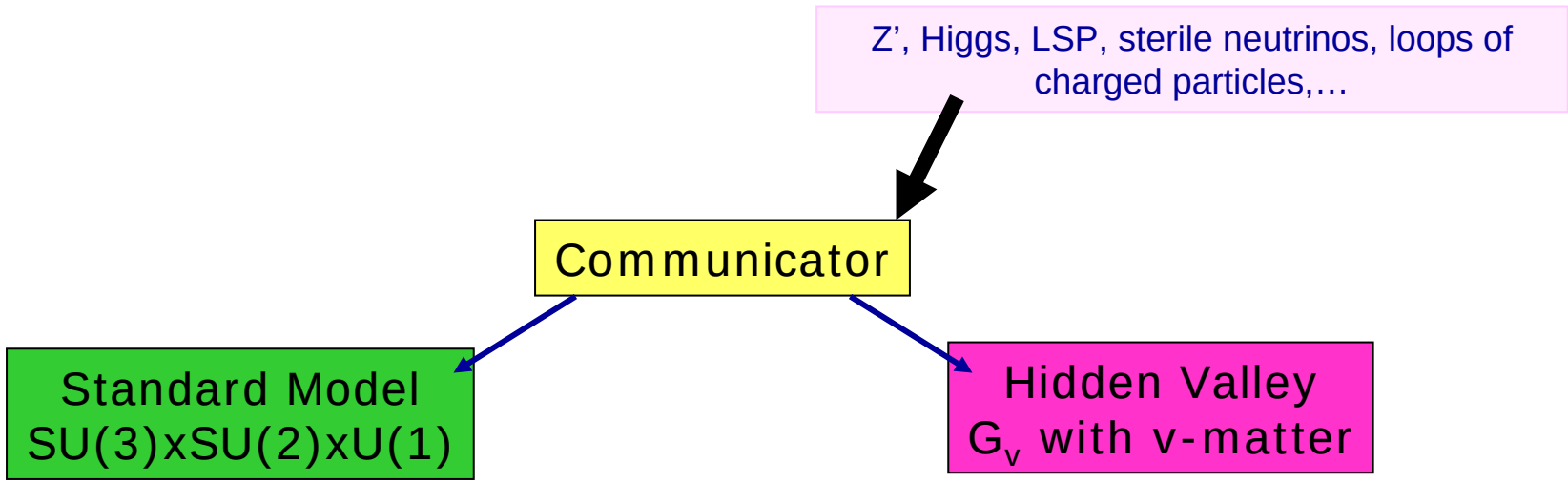


A Conceptual Diagram



Hidden Valley Models (w/ K. Zurek)

hep-ph/0604261



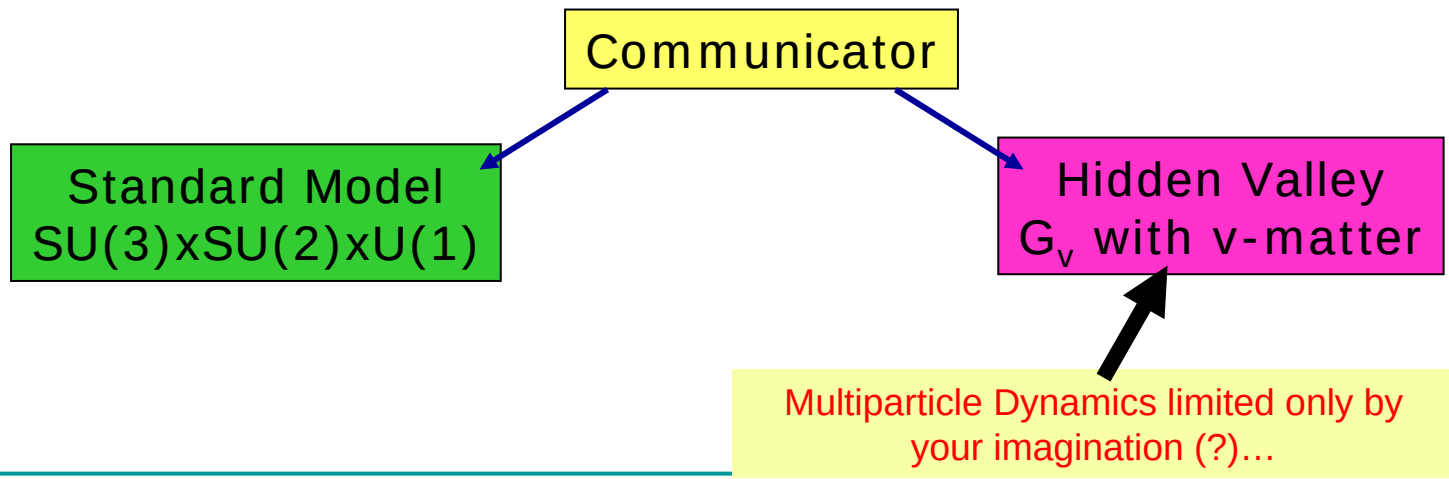
Hidden Valley Models (w/ K. Zurek)

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 very challenging for hadron colliders – urgent!!**

- Our approach:
  - Find characteristic predictions of large classes of models at once
  - Produce search strategies, Monte Carlo tools that experimentalists can use now

Common Predictions of HV Scenario

MJS + Zurek hep-ph/0604261

- "Common predictions of Supersymmetry are missing transverse momentum, high pT jets, medium pT leptons"
  - But of course not all SUSY models do this
  - And some other non-SUSY models also do this
- Common predictions of Hidden Valley models are…

Common Predictions of HV Scenario

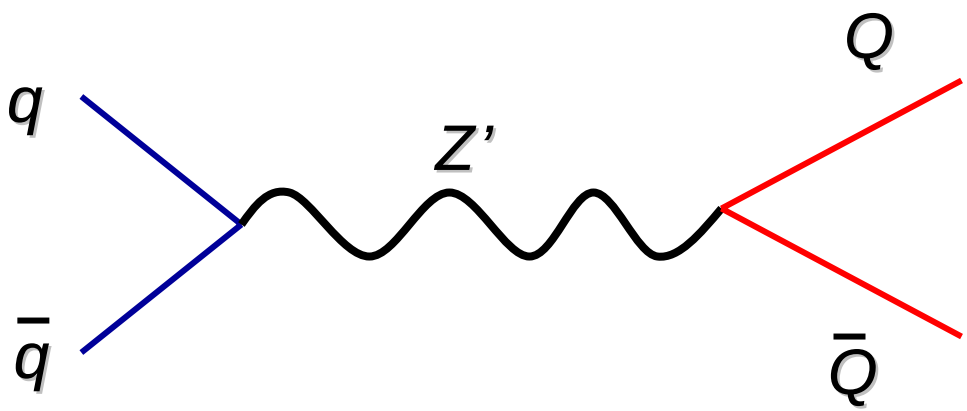
MJS + Zurek hep-ph/0604261

- New Metastable Neutral Excitations "X"
  - Typically more than one X in v-sector
  - Possibly quite light (mass < M_Z)
  - Often long-lived; displaced vertices, missing transverse energy
- Moderate- to High-Multiplicity Final States
  - Exceptionally busy final states possible
  - Unusual event shapes
  - Jets ⇔ partons breaks down
  - Very large fluctuations in appearance of events

A Confining Hidden Valley

MJS + Zurek hep-ph/0604261

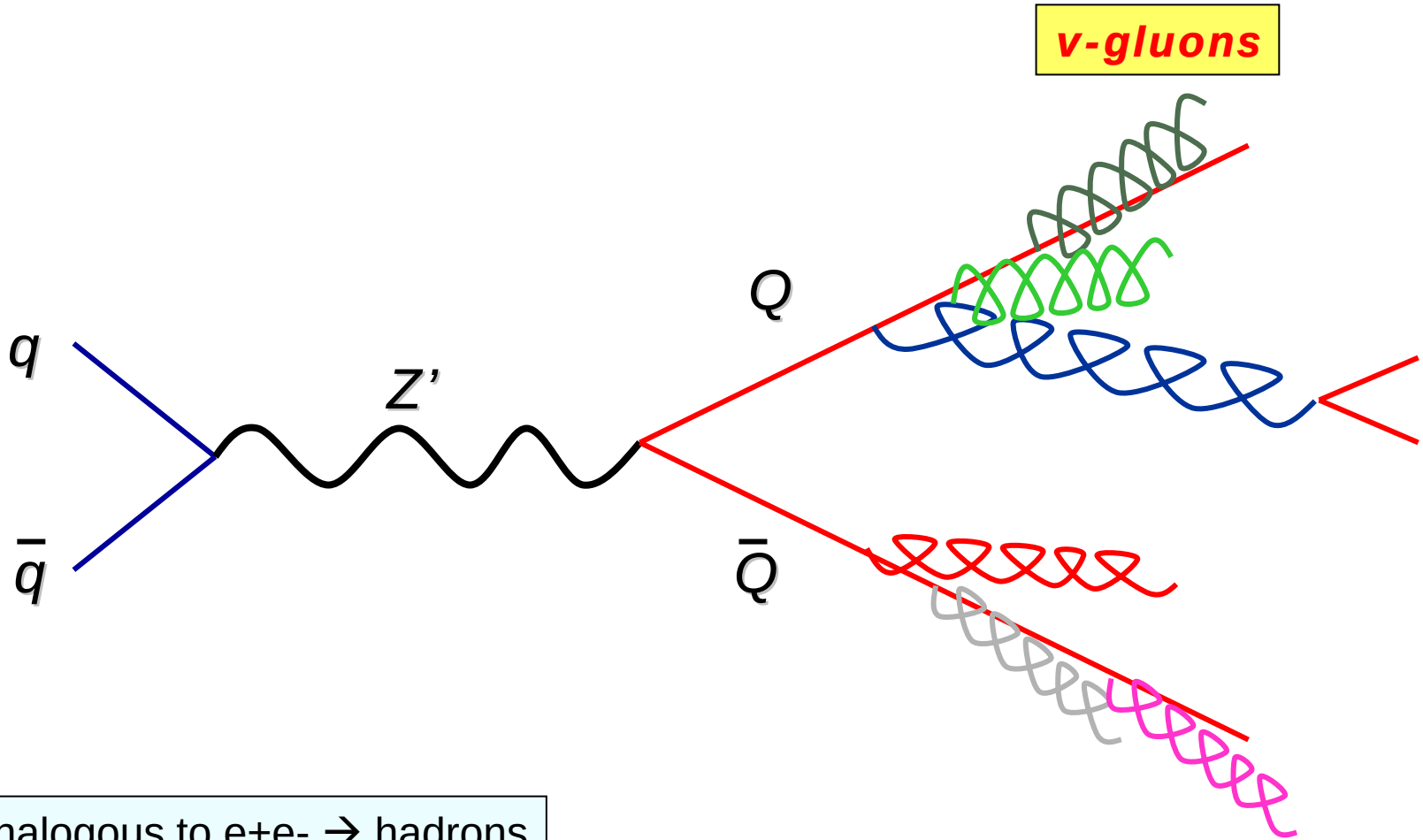
v-quarks



Analogous to e+e- → hadrons

A Confining Hidden Valley

MJS + Zurek hep-ph/0604261



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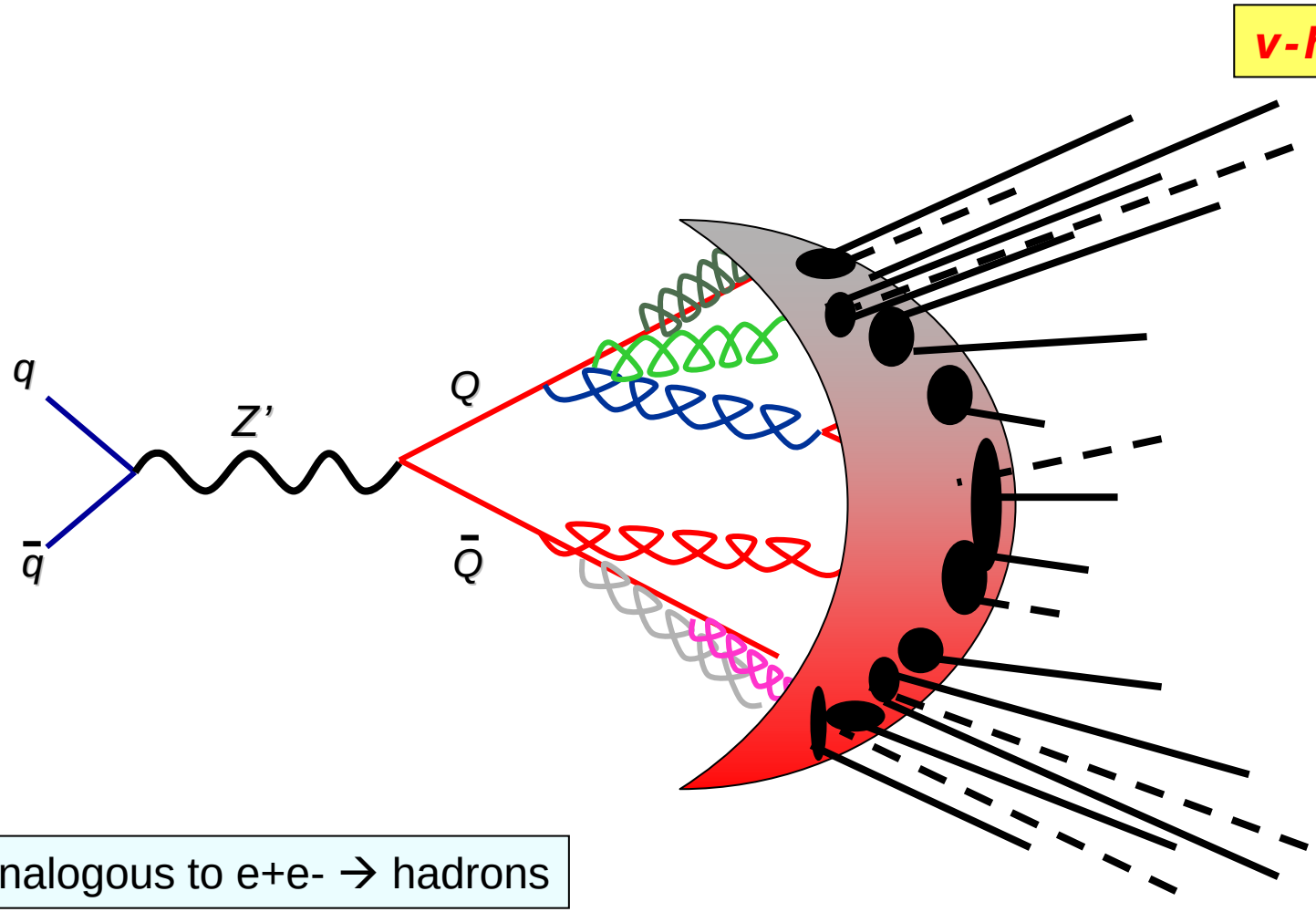
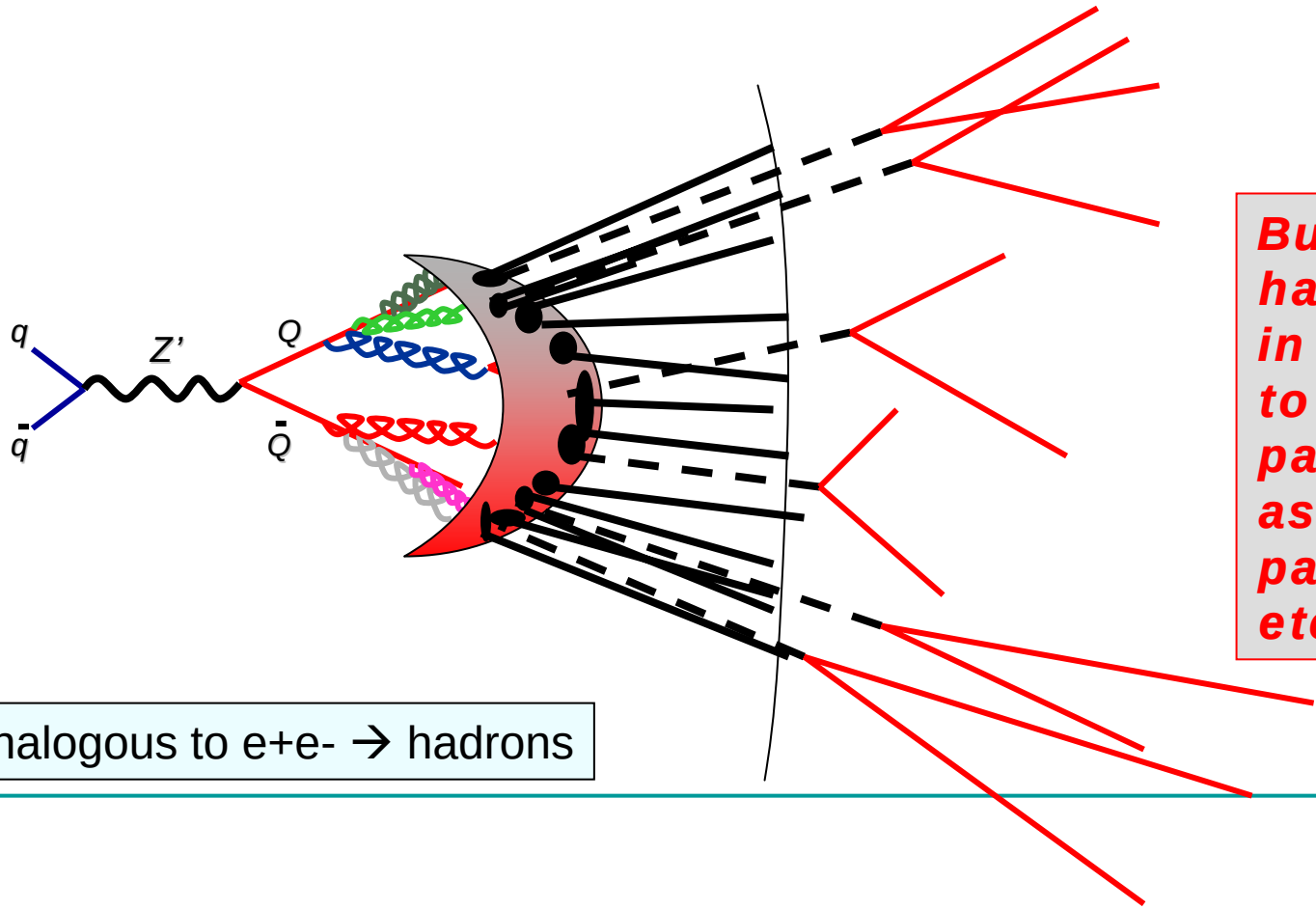


Analogous to e+e- → hadrons

A Confining Hidden Valley

MJS + Zurek hep-ph/0604261

Some v-hadrons are stable and therefore invisible

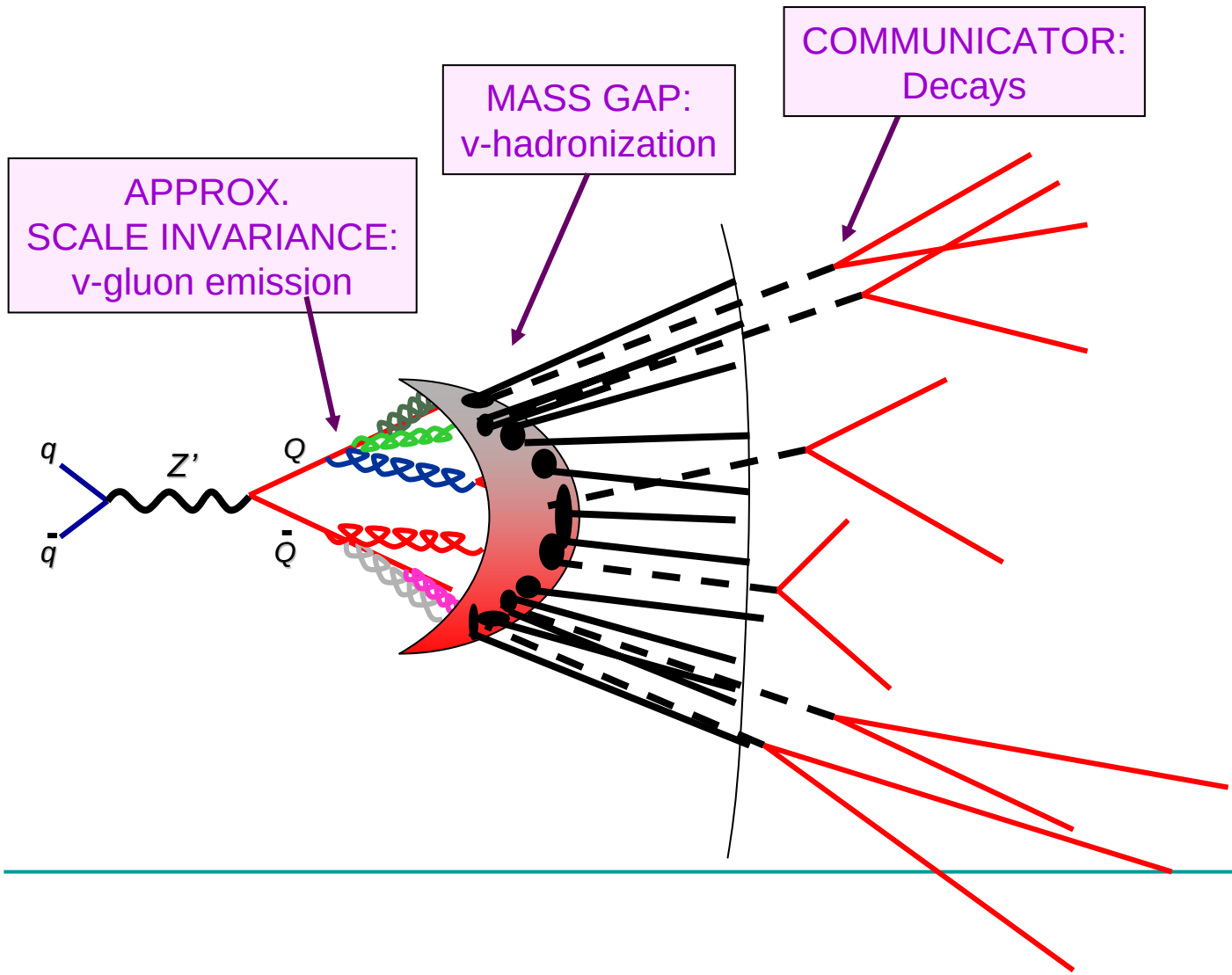


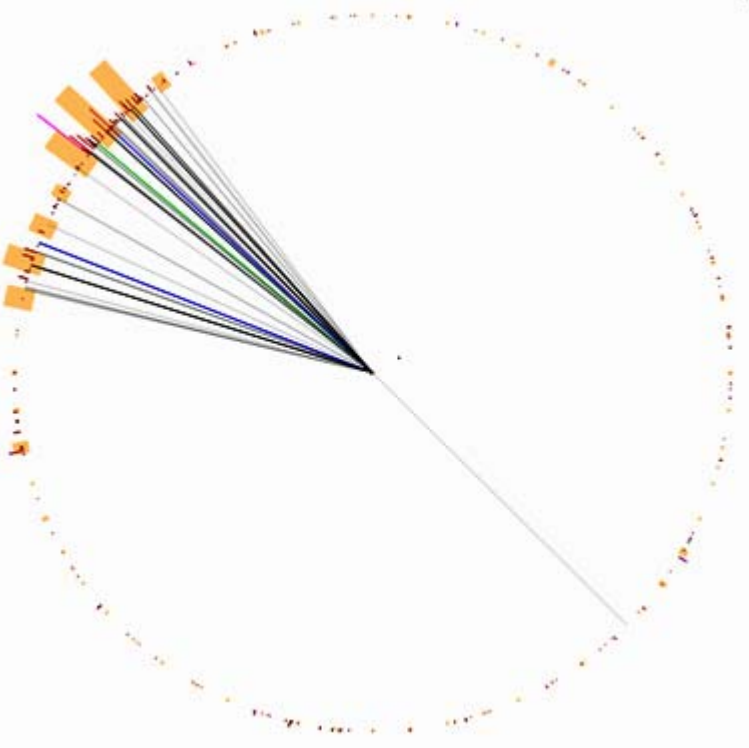
But some v-hadrons decay in the detector to visible particles, such as bb pairs, qq pairs, leptons etc.

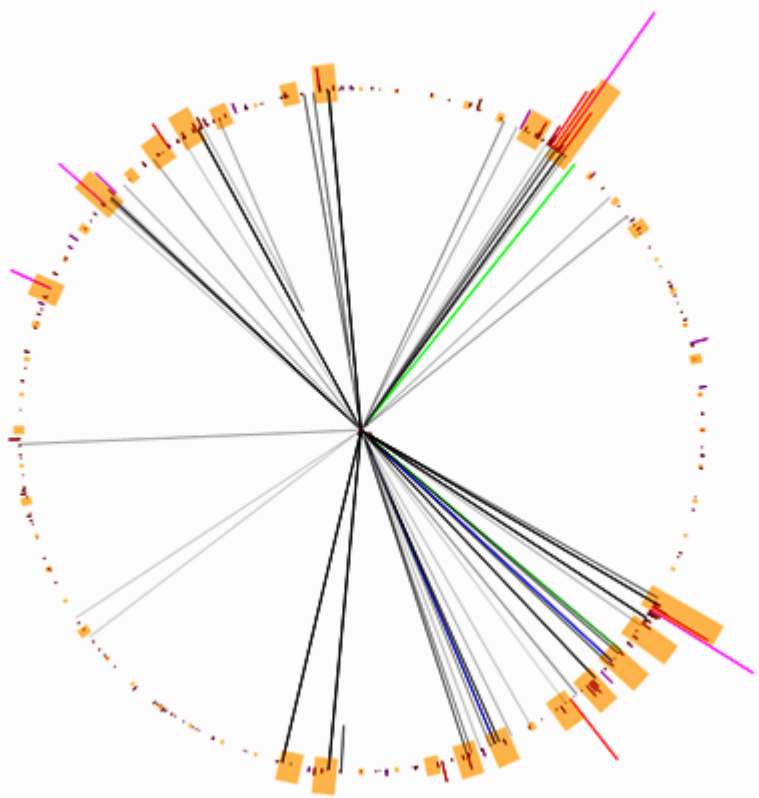
Analogous to e+e- → hadrons

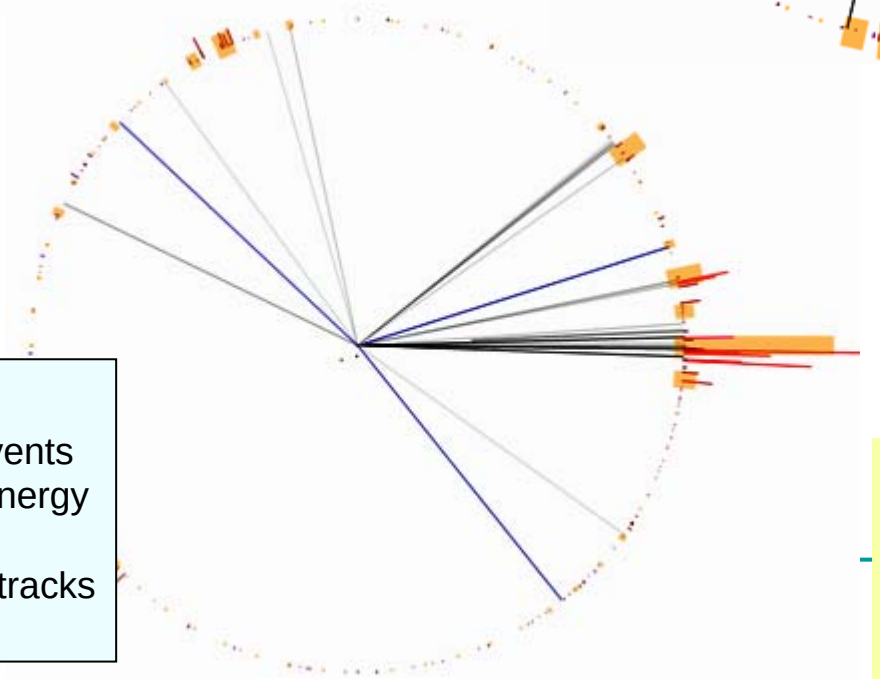
High Multiplicity?

MJS + Zurek hep-ph/0604261







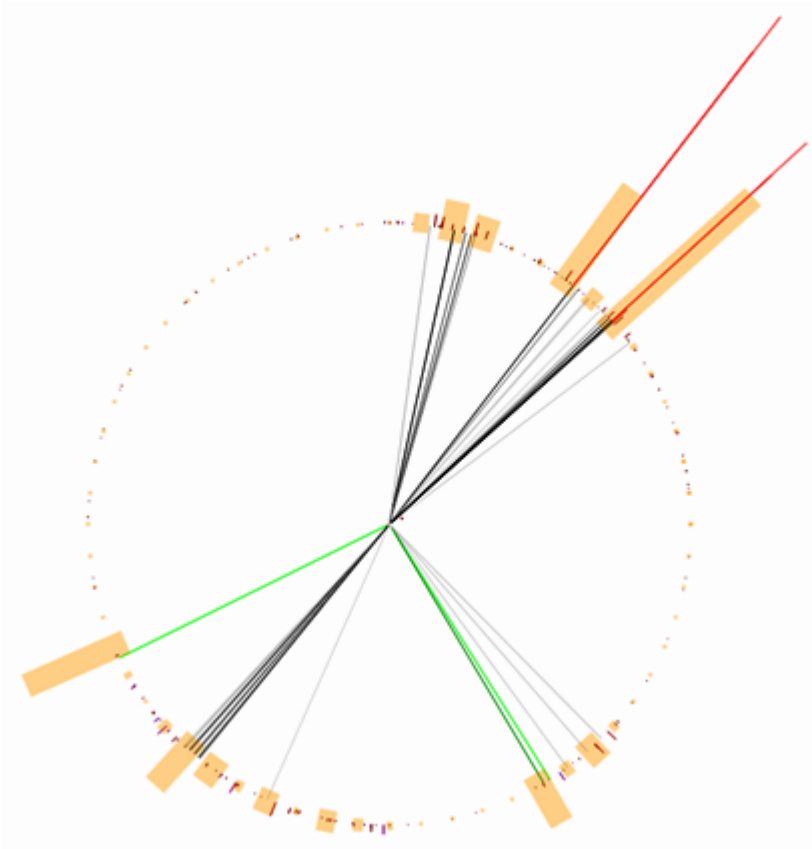


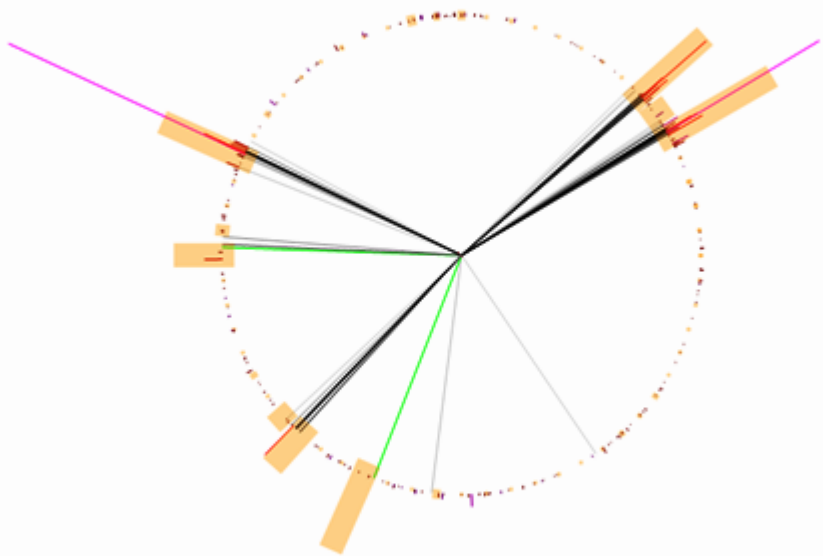
Average: 8 b's
Max: 22 b's

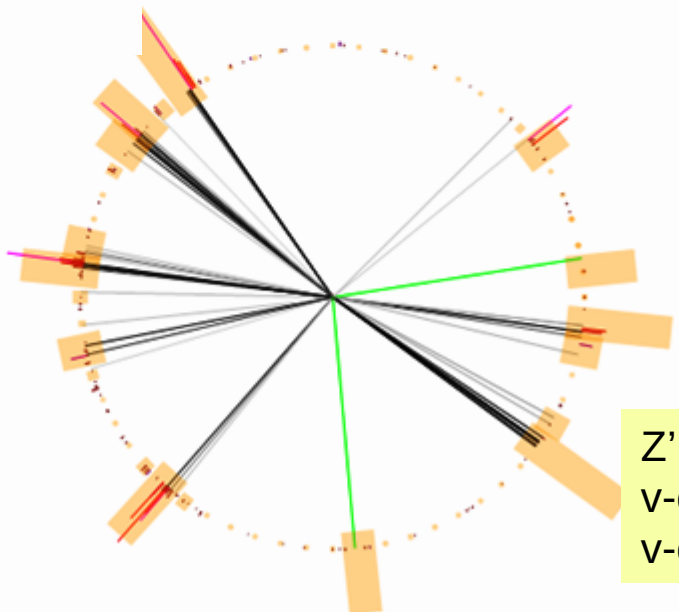
MJS, in preparation

Search Strategy:
Find di-jet resonance in busy events
- missing and total transverse energy
- # jets
- # B meson vertices/displaced tracks
- Single jet invariant mass ?

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







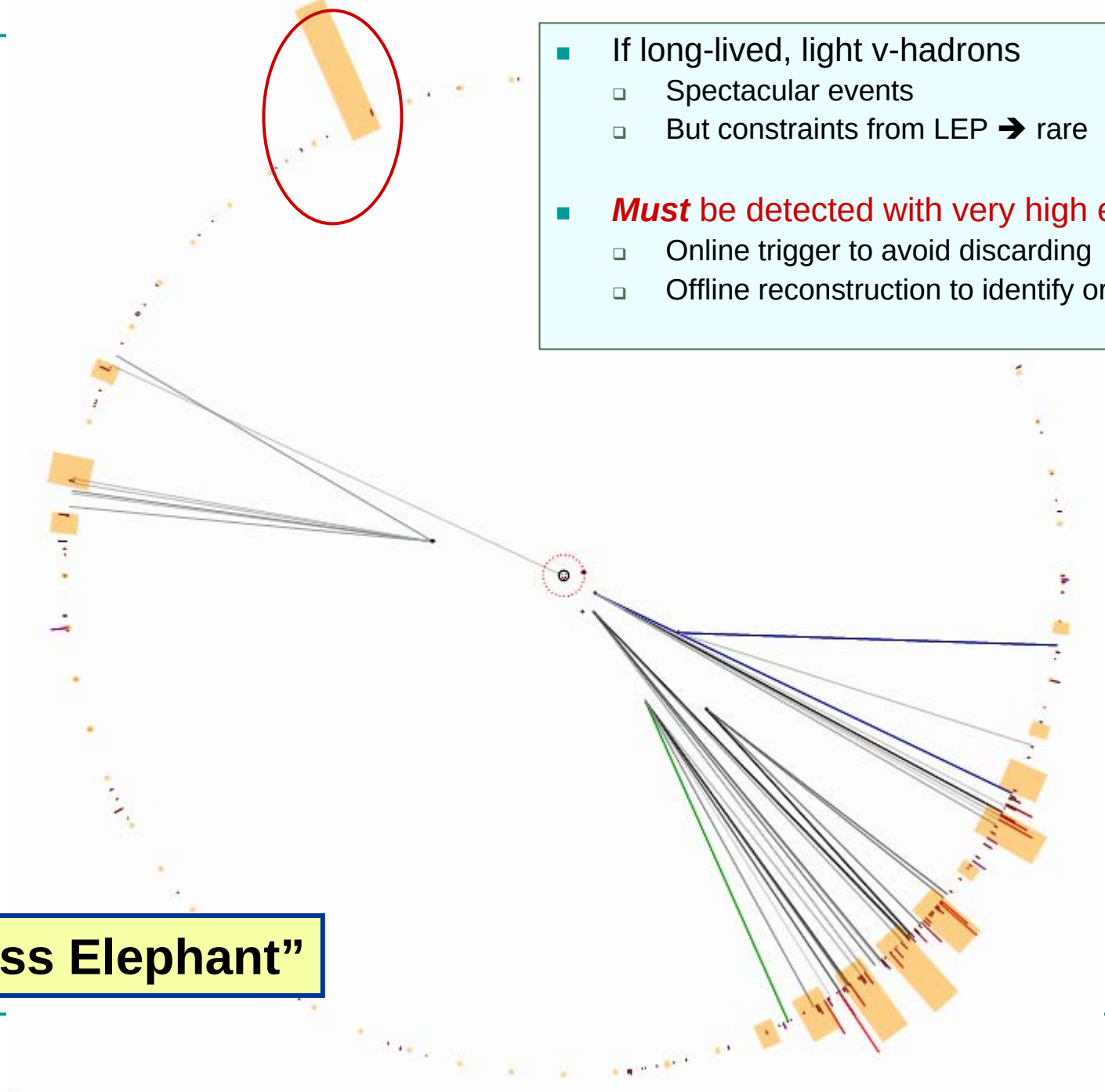
Search Strategy:

Find dilepton resonance in busy events

- Event Shapes
- Dilepton invariant mass

Han, Si, Zurek + MJS, 2007

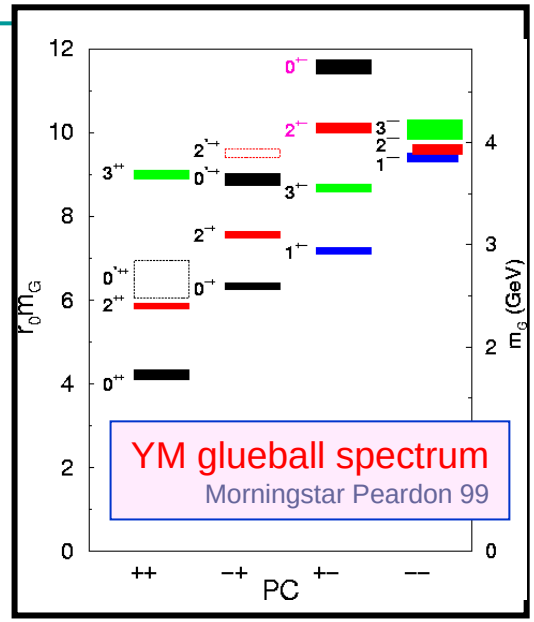
Z' mass = 3 TeV
v-eta' mass = 150 GeV
v-omega mass =210 GeV



- 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

“Glass Elephant”

v-Glueballs

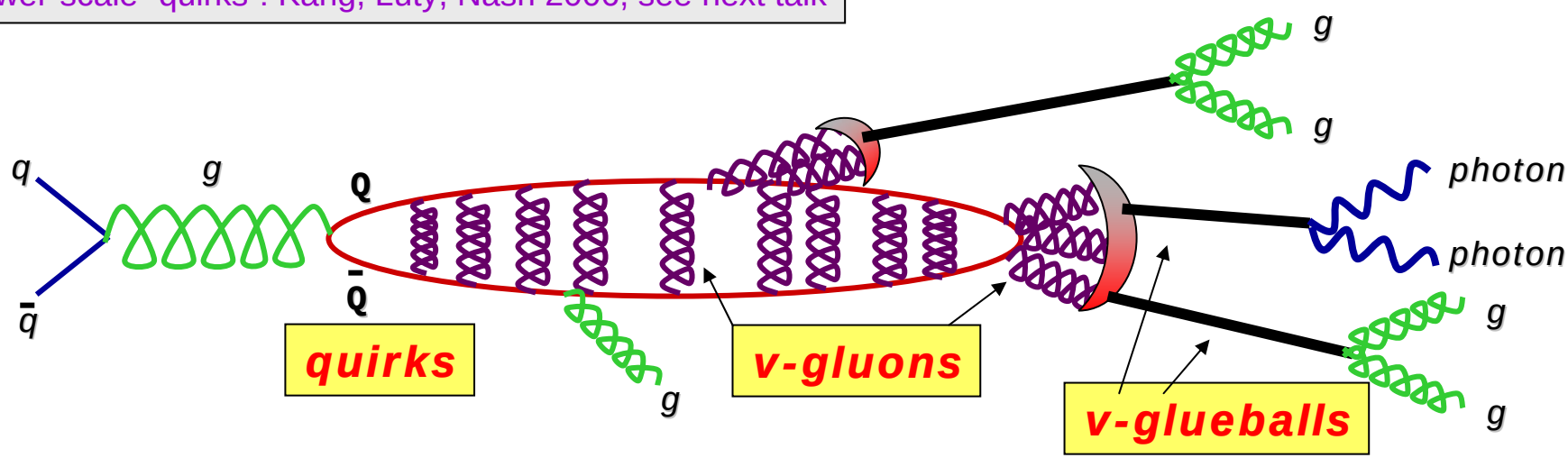


TeV–mass quirk production/annihilation

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

- Quirk: Matter charged under SM and confining group…
- …such that confining string cannot break

Lower-scale “quirks”: Kang, Luty, Nasri 2006; see next talk



Common Predictions of HV Scenario

- Higgs "Portal" allows higgs to mix into hidden sector

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

- In Hidden Valley ➔ new Higgs decays

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

  - H → XX with X decays displaced ➔ new discovery mode

See also
Carpenter Kaplan Rhee 06

  - H → XX with X → dileptons or dijets or diphotons

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

  - H → XXX, XXXX, etc

See also
Chang Fox Weiner 05

- Also true for other scalars

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  - H → XX with X → dileptons or dijets or

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CDF/D0: new searches carried out

Very difficult to trigger at ATLAS/CMS…
New ATLAS trigger strategy (internal note)

LHCb opportunity!!

Common Predictions of HV Scenario

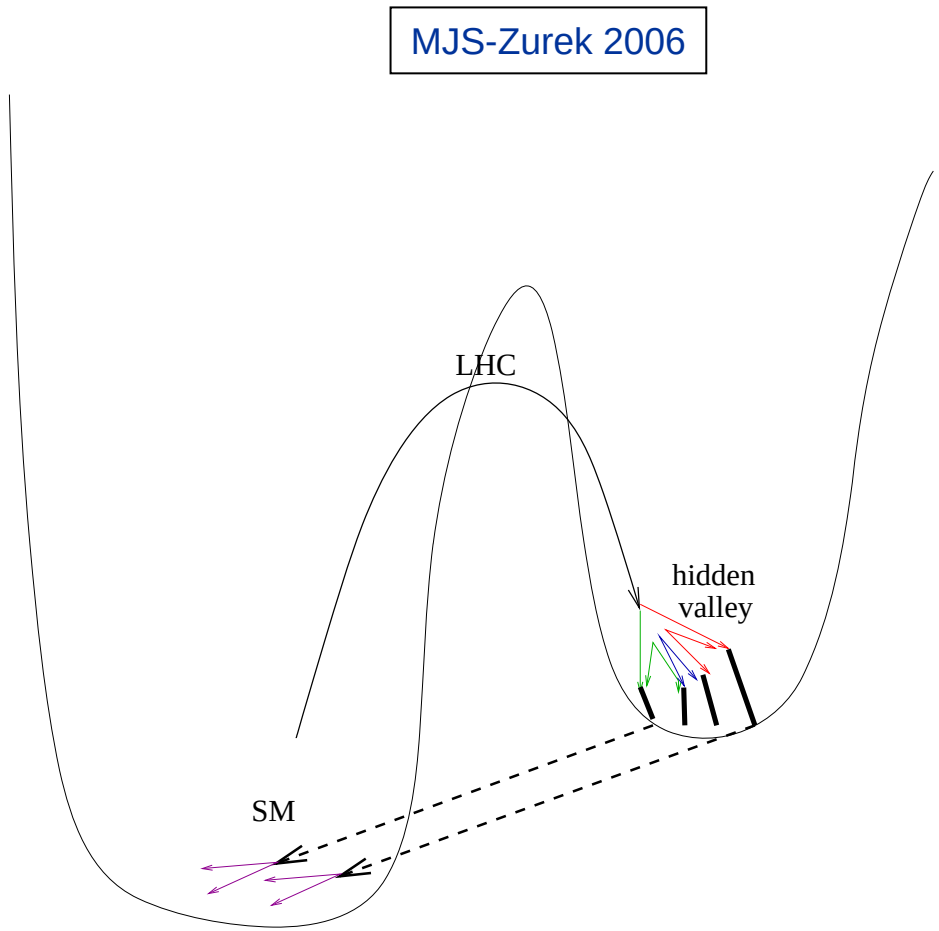
- Big effect on SUSY
  - LSP of SM sector can decay to the valley LSP…
    - … plus SM particles …
    - … and/or plus v-particles, which then decay to SM particles
  - Either v-particles or LSP may be long-lived

MJS hep-ph/0607160

- Same effect applies to any theory w/ new global charge
  - UED with KK parity
  - Little Higgs with non-anomalous T parity
  - Many other models

Generalizes SUSY phenomenology from 90s e.g. GMSB, Anomaly, etc.

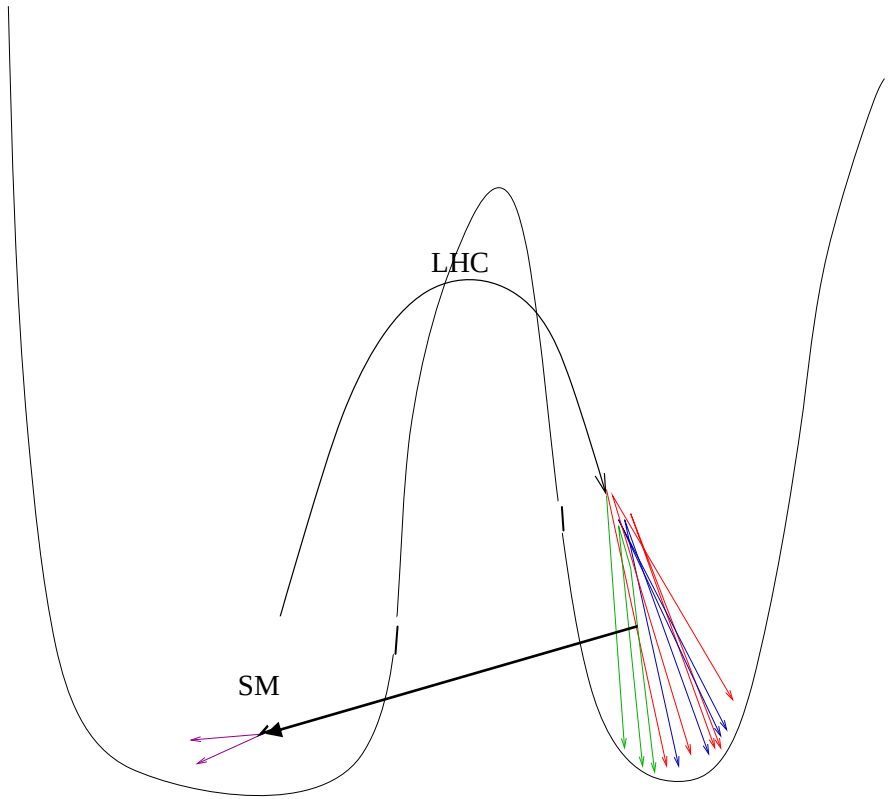
Remark on Unparticle Models



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

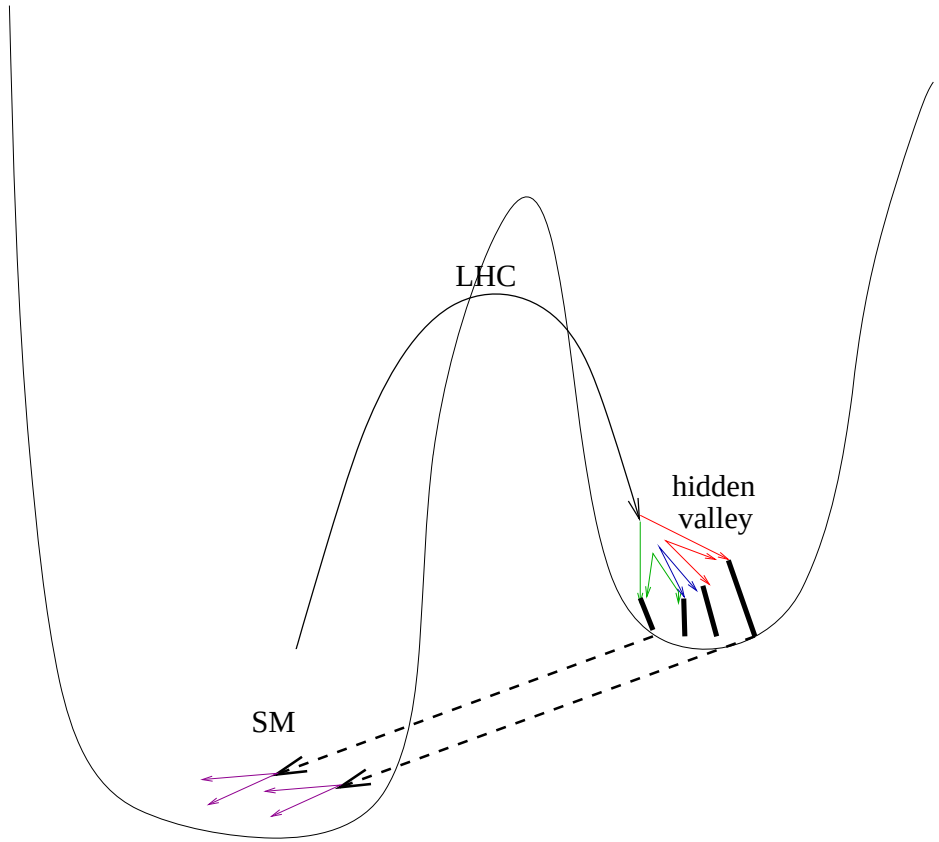


Remark on Unparticle Models

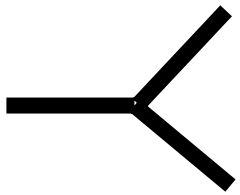
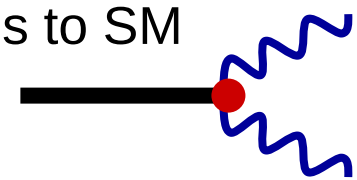
- In Unparticle models
  - a scale-invariant hidden sector generates indirect effects on observables
    - Events with MET
    - Rare virtual effects
- With large mass gap, model becomes a hidden valley
  - Scale-symmetry breaking can lead to direct, common, model-dependent, observable effects
    - Multiparticle production
    - Possible long-lived states

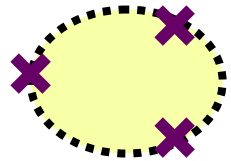
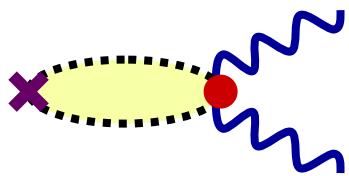
MJS 0801.

MJS-Zurek 2006



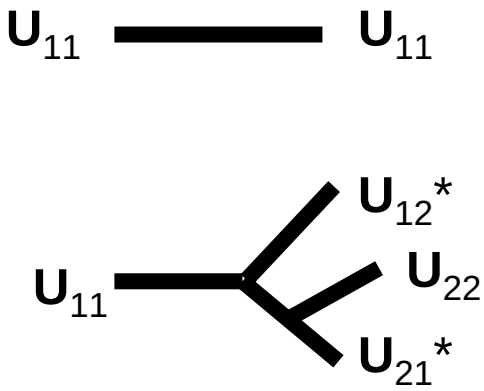
Unparticles vs. Conventional Language

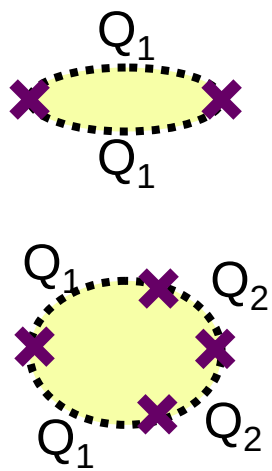
- Unparticle **U**
- Dimension D of **U**
- Propagator
- Interactions 
- Couplings to SM 

- Gauge-Invariant Local Composite Operator O(x)
- Scaling Dimension D of O(x)
- 2-pt. Func < O(x) O(y) > 
- Higher-pt. Func. < O(x) O(y) O(z) > 
- Couplings to SM 

To Illustrate: A simple unparticle model

- Supersymmetric SO(N) QCD with F flavors Q_J in hidden sector
- Conformal Fixed Point for $3(N-2) > F > {}^{3}/_{2}(N-2)$ Seiberg 1994
- Unparticles $\mathbf{U}_{JK} = Q_J Q_K$ have $D = 2 - {}^{3(F-N+2)}/_{2F}$ [thus $2 > D > 1$]





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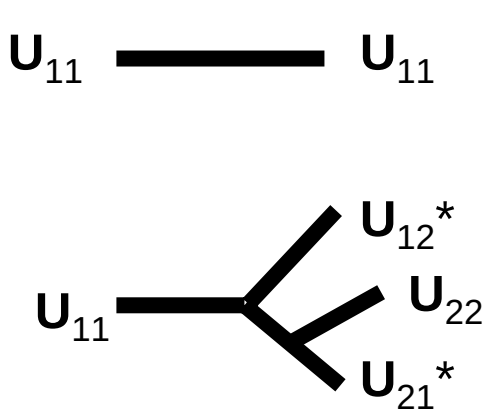
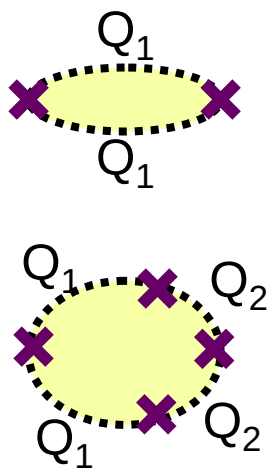


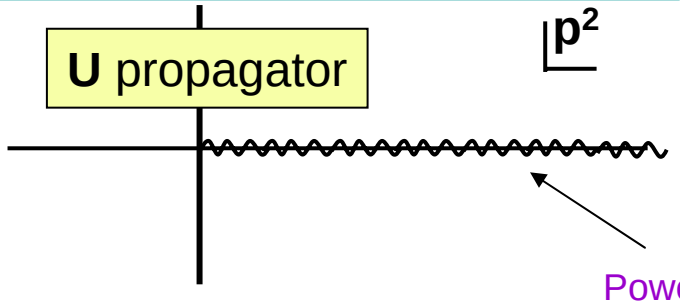
As F → 3(N-2)

Fixed pt. cplg → 0
(Banks-Zaks limit)

Q becomes free
but
U does not!



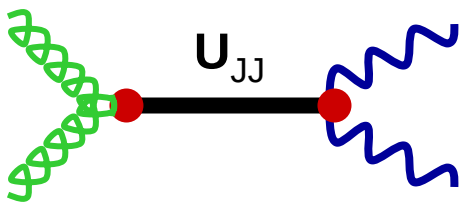
Scale-Invariant Sector

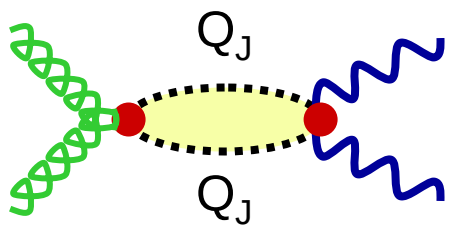


Couple to SM gauge bosons: $^{1}/_{M^{p}} \left(\Sigma\, c_{JK}\, \mathbf{U}_{JK} \right) \mathrm{Tr}\left[F^{2} \right]$

g g → 2 photons

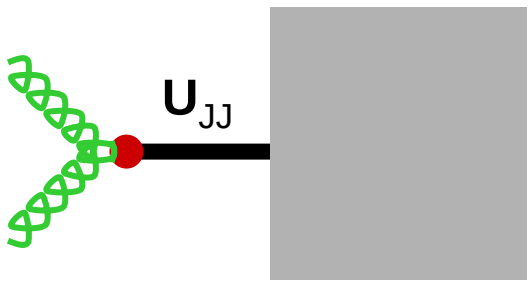
~ c^{2} M^{-2p}

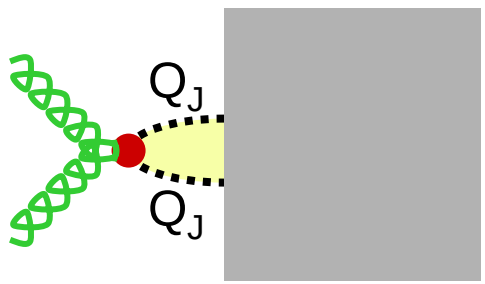




g g → nothing

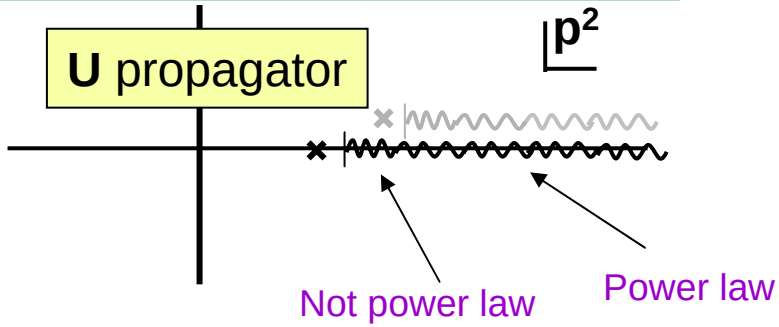
~ c^{1} M^{-p}





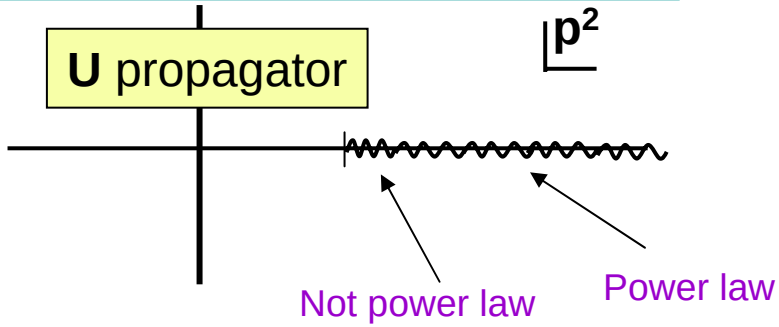
Dominant Process

Masses m_{JK} for the Q_J



- Add term $m^2_{JK}\ Q_J Q_K^* = m^2_{JK}\ \mathbf{V}_{JK}$

Masses m_{JK} for the Q_J



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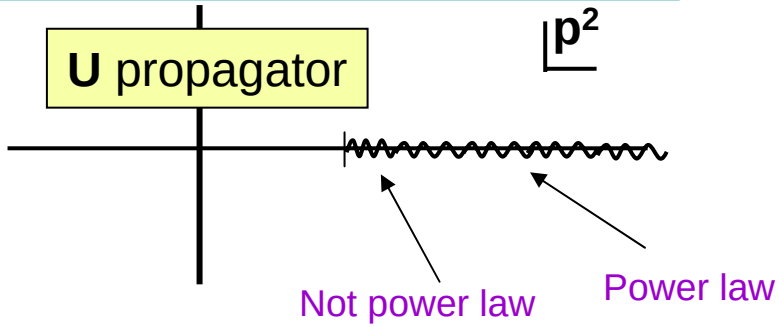
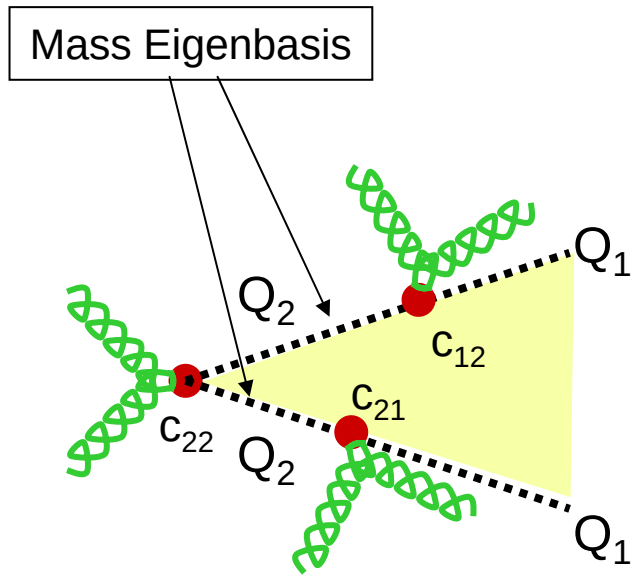


- Add term $m^2_{JK}\ Q_J Q_K^* = m^2_{JK}\ \mathbf{V}_{JK}$
- Suppose m^2_{JK} , c_{JK} not simultaneously diagonal

g g → 4 jets + MET

~ $c_{22}^{\ 1}\ M^{-p}$ [NOT $c^3\ M^{-3p}$!]



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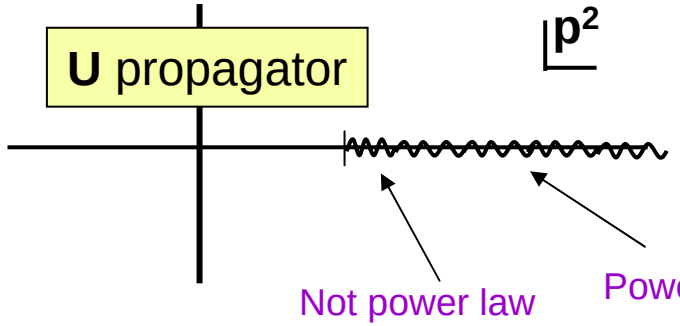

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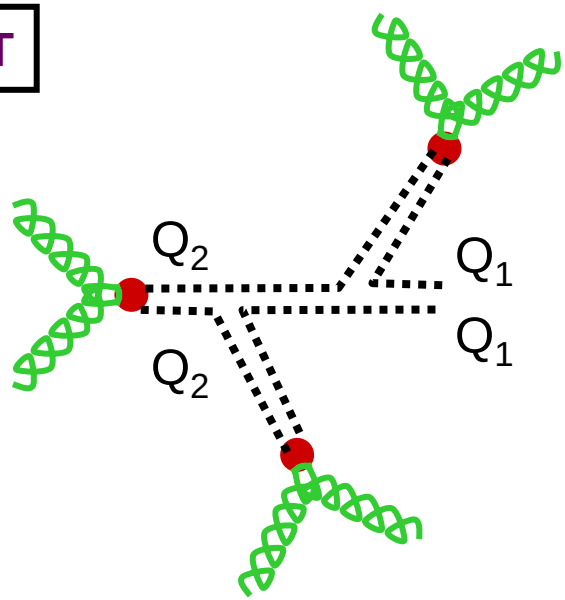
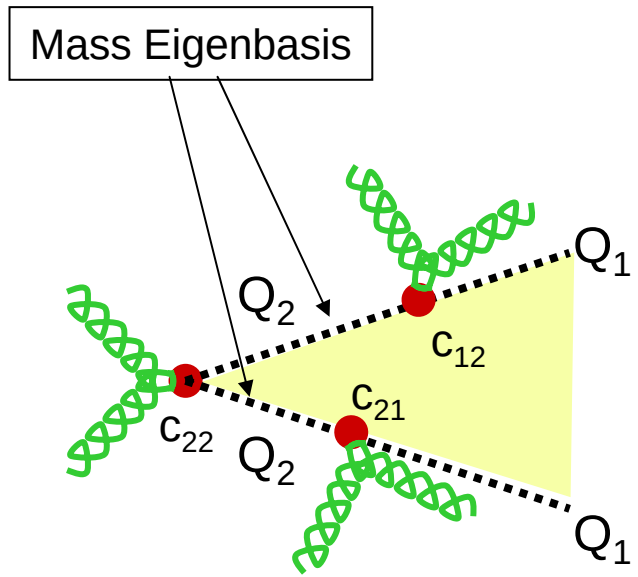
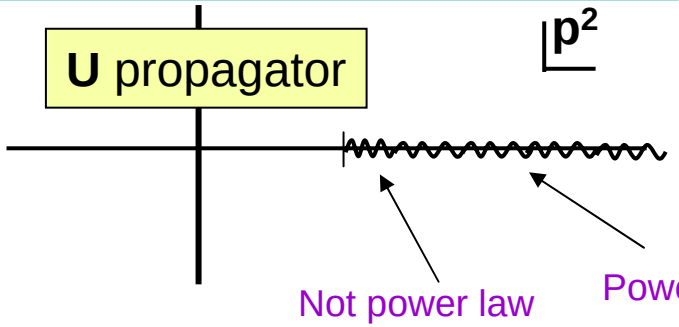
g g → 4 jets + MET

~ c_{22}^{1} M^{-p}





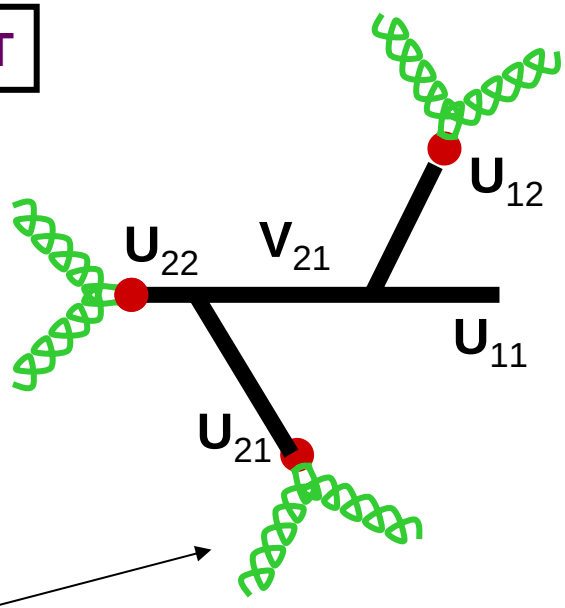
Masses m_{JK} for the Q_J



- Add term $m^2_{JK}\ Q_J Q_K^* = m^2_{JK}\ \mathbf{V}_{JK}$
- Suppose m^2_{JK} , c_{JK} not simultaneously diagonal

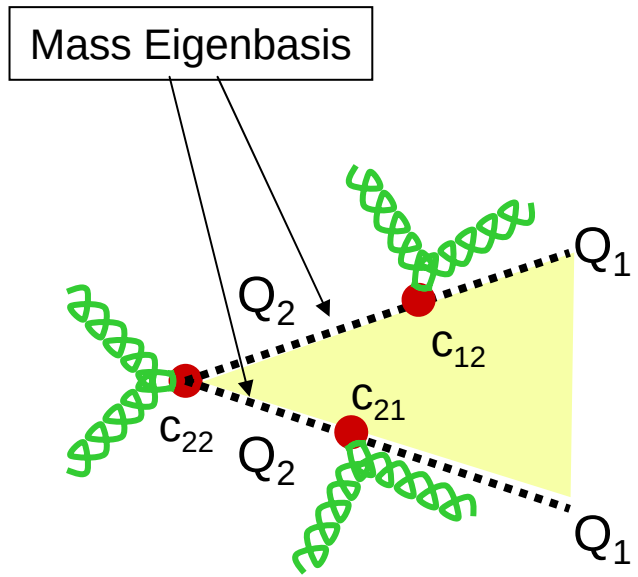
g g → 4 jets + MET

~ c_{22}^{1} M^{-p}



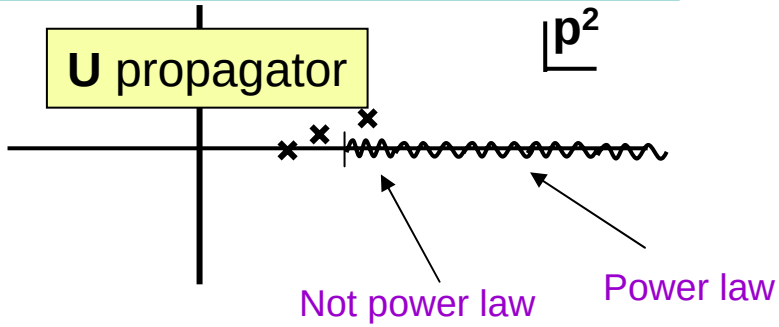
$\mathbf{V}_{21} = Q_2 Q_1^*$

Below the cut



Hidden sector is not invisible
Visible production amplitude is order(c)
Higher-multiplicity
Can't use D to predict kinematics

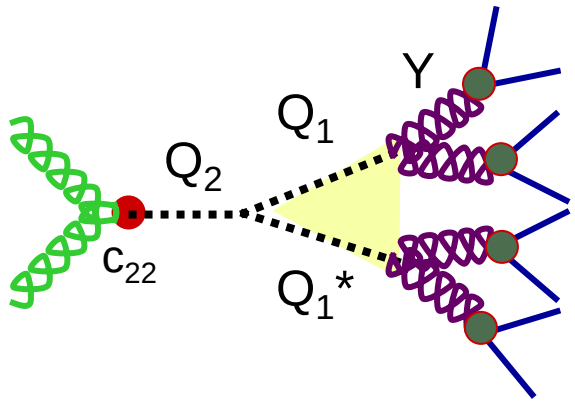
m_J and $\langle Q_J \rangle = v_J$



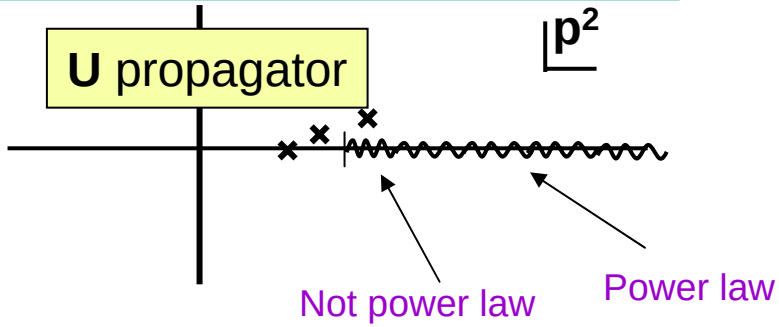
- **SUSY potential now has cubic terms: $Q_J \rightarrow Q_K\, Q_K^*$**
- **Hidden massive v-gluons Y**
- **If Y mixes with Z boson, then Y → SM fermions**

g g → 8 quarks/leptons

~ $c_{22}^{1}\, M^{-p}$



m_J and $\langle Q_J \rangle = v_J$

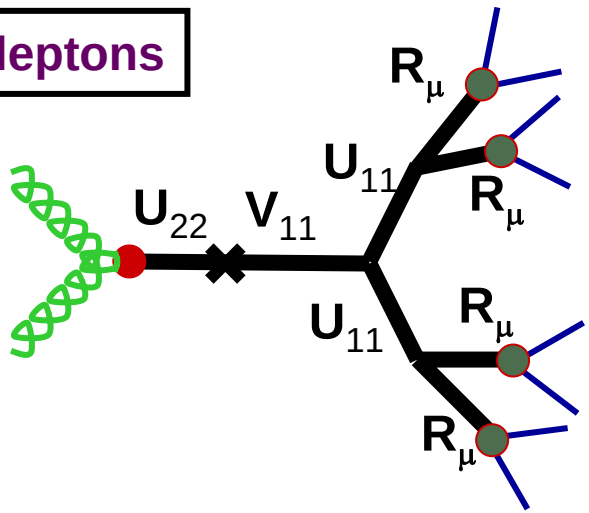


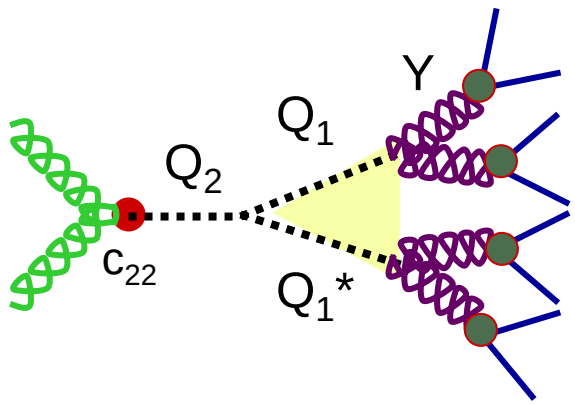
- **Shifted U: linear + quadratic in shifted Q**
- **U's interact with unparticle $R_\mu = Q^* D_\mu Q$**
- **If Z boson couples to R_μ …**

- **SUSY potential now has cubic terms: $Q_J \rightarrow Q_K Q_K^*$**
- **Hidden massive v-gluons Y**
- **If Y mixes with Z boson, then Y → SM fermions**

g g → 8 quarks/leptons

~ $c_{22}^1 M^{-p}$





Hidden sector is not invisible
Visible production amplitude is order(c)
High-multiplicity, light neutral resonances
Possible displaced vertices

Lesson

- We cannot predict production rates, final states, or observables unless we know **precisely**
  - The nature of the hidden sector and its multipoint functions
  - The couplings of SM to that sector
  - The details of the breaking of scale invariance
- With mass gap, often D of unparticle cannot be measured at LHC

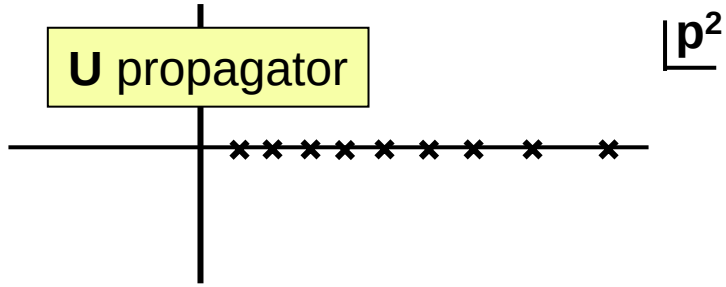
Example: t → c **U** : measure t/c relative kinematics to determine D

- Gap <<<< m_{top} : **U** invisible → Missing energy
- Gap << m_{top} : **U** → many SM particles; **U** daughters long-lived
- Gap << m_{top} : **U** → many SM particles; **U** daughters short-lived
- Gap not << m_{top} : **U** → SM particles; t/c kinematics not determined by D

Signatures

HV	Un
No	Yes
Yes	Yes
Yes	Can't Observe
Yes	No

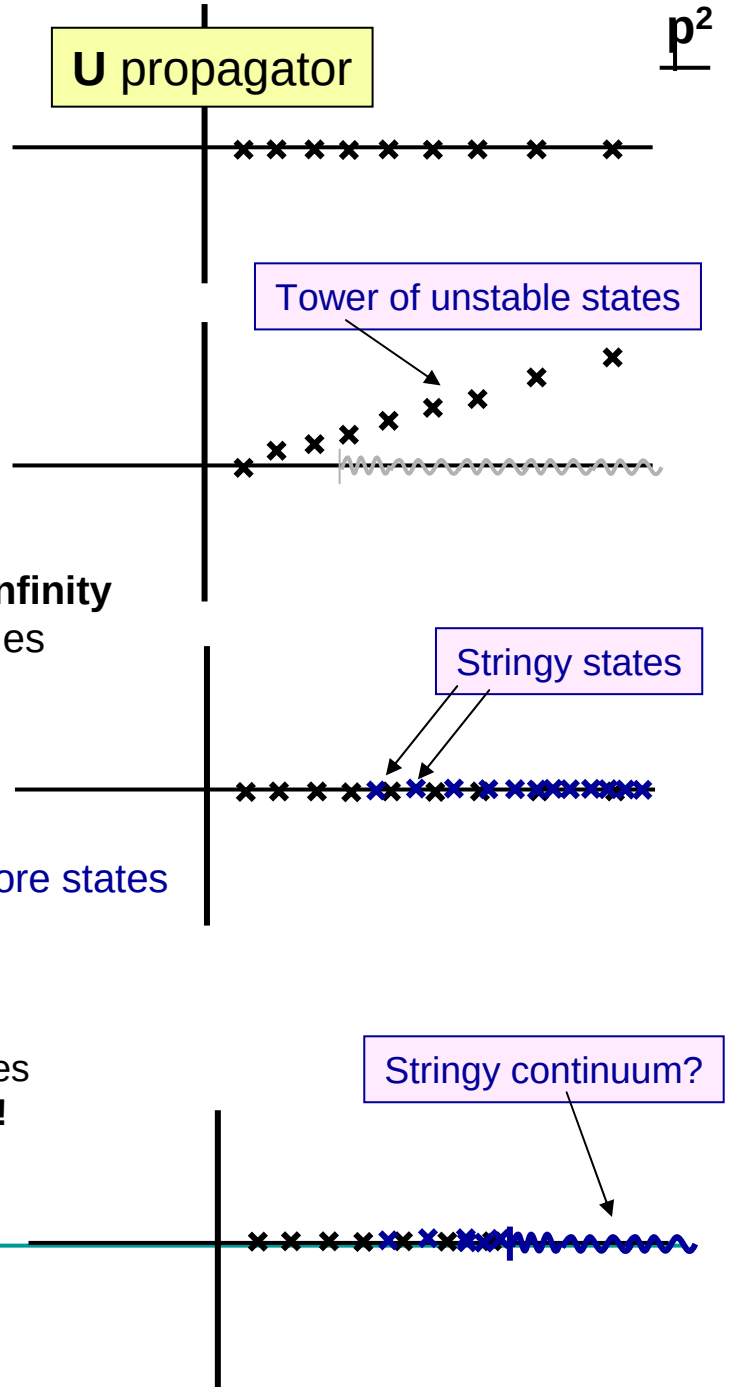
Un/HV and AdS/CFT



Stephanov Narrow-Tower Model [not “deconstruction”]

- AdS/CFT: mass gap turns < **U U** > into sum of poles
- Predicts tower of long-lived states (lifetimes ➔ D)

Un/HV and AdS/CFT



Stephanov Narrow-Tower Model [not "deconstruction"]

- AdS/CFT: mass gap turns < **U U** > into sum of poles
- Predicts tower of long-lived states (lifetimes ➔ D)

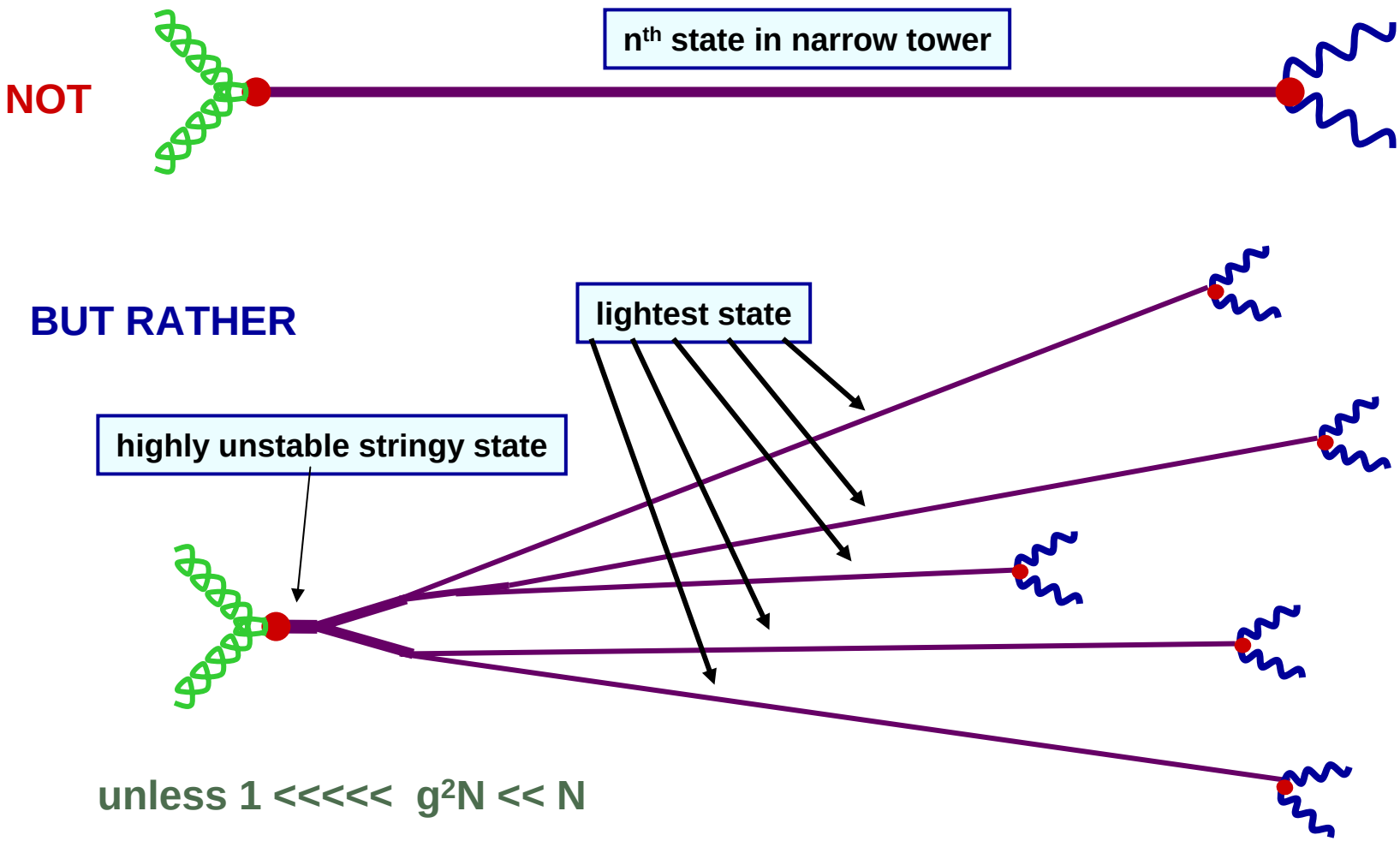
But neglects unparticle interactions…

- AdS/CFT: tower = narrow hadronic resonances at N → **infinity**
- **Finite** N: unparticle interacts with self and other unparticles
- Narrow states are wide! Also new cuts!

Also neglects strings…

- At finite 't Hooft coupling g^2N, even at infinite N, many more states
- There may even be a continuum at infinite N, finite g^2N
  - D7 brane: quarkonium states plus unconfined quark states
  - **The continuum cannot be seen without string theory!**

Un/HV and AdS/CFT



Thus AdS/CFT DOES resemble QCD, QCD-like Hidden Valley

Caution on AdS/CFT usage

Sometimes, “~” is not enough

paraphrasing Matthias Neubert

For Analytic Structure of Correlation Functions,
“=” is necessary

- In general, if one neglects
  - 1/N corrections
    (bulk interactions, D-branes, metric back-reaction,…)
  - $1/(g^2N)$ corrections
    (bulk classical string corrections, massive states, high-spin operators,…)

  one might miss subtle and crucial details of the physical amplitudes

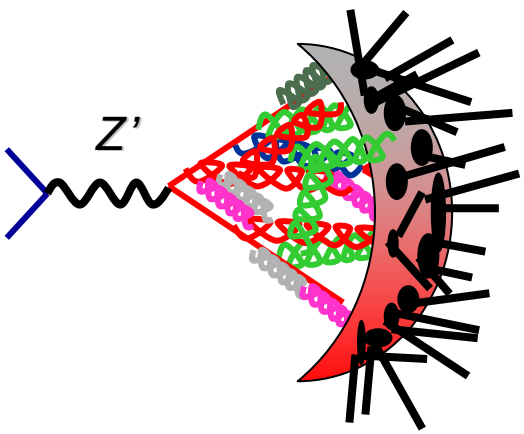
Predictions of hidden strong dynamics

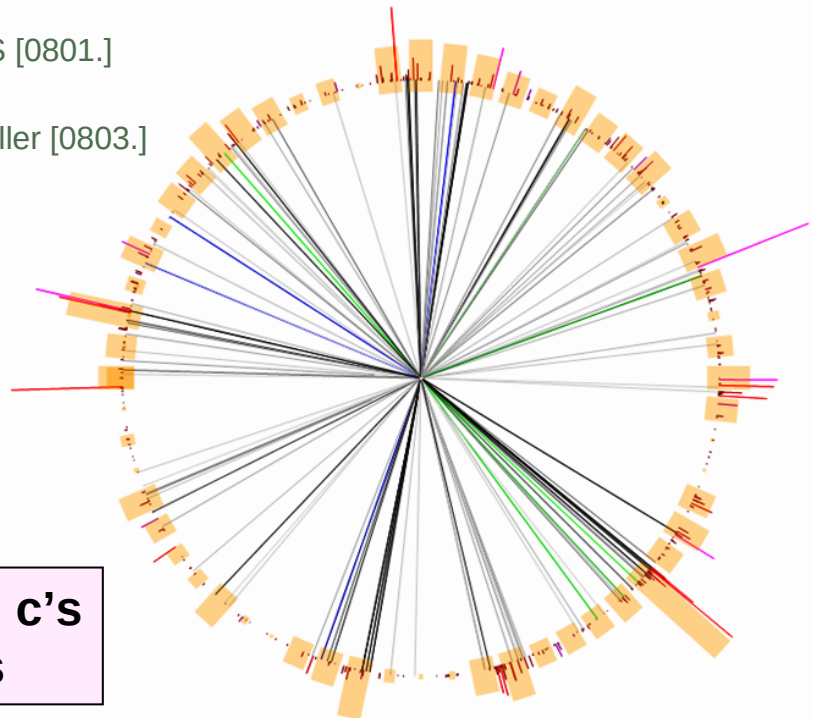
Powerful gluon emission in scale-invariant region at strong ‘t Hooft coupling –

- from large anom. dims. of **high-spin high-dimension** operators

Predicts near-spherical high-multiplicity events

- Conjecture based on AdS/CFT arguments MJS [0801.]
- Recently proven – Hoffman/Maldacena [0803.]
  see also conjecture in Hatta, Iancu, Mueller [0803.]





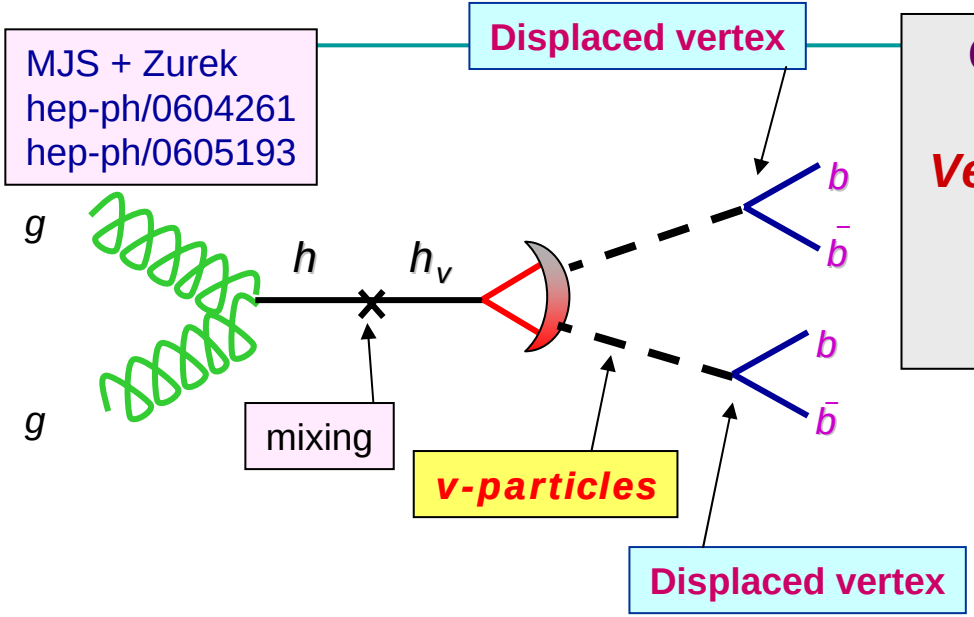
~ 54 b’s, c’s
~ 6 tau’s

Summary

- Hidden valleys ➔ rich and novel phenomena at LHC and beyond
  - High multiplicity events
  - Long-lived particles
  - Novel decays for Higgs, LSP/LTP/LKP, Z', Z, etc.
- "Unparticle" models with mass gaps become HV models
  - Hidden sector becomes visible, at leading order in coupling
  - Unparticle interactions must be included
  - Must account for multiple Unparticles in any model
  - Unparticle dimension does not determine most observables
  - Many processes give classic Hidden Valley signatures
- AdS/CFT must be used with great care when making predictions
- For large g^2N hidden valley, AdS/CFT predicts:
  - Ultra-high-multiplicity quasi-spherical events with low-pT jets/leptons

Backup Slides

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



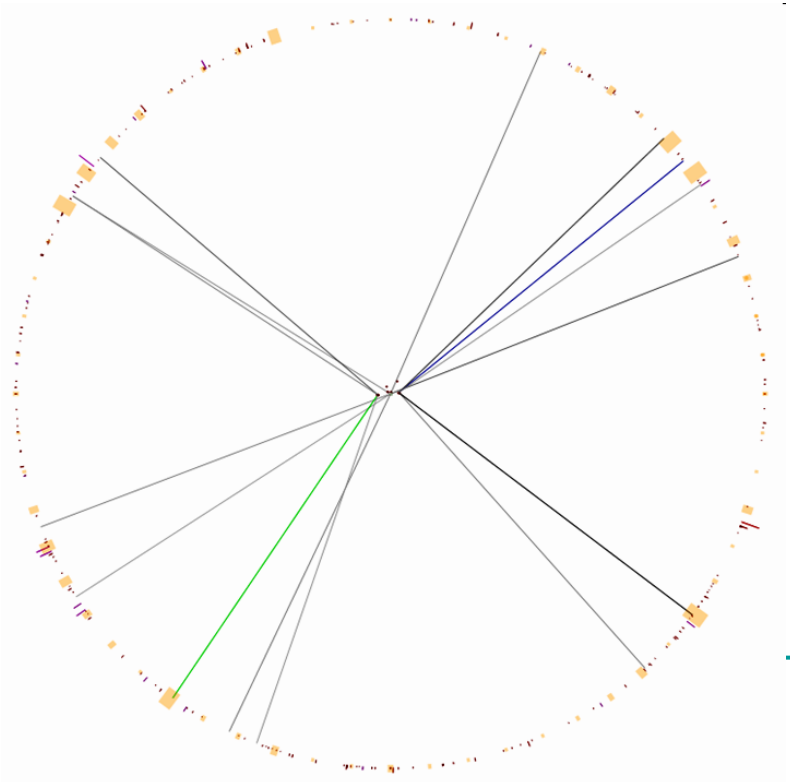
CDF/D0: new searches carried out

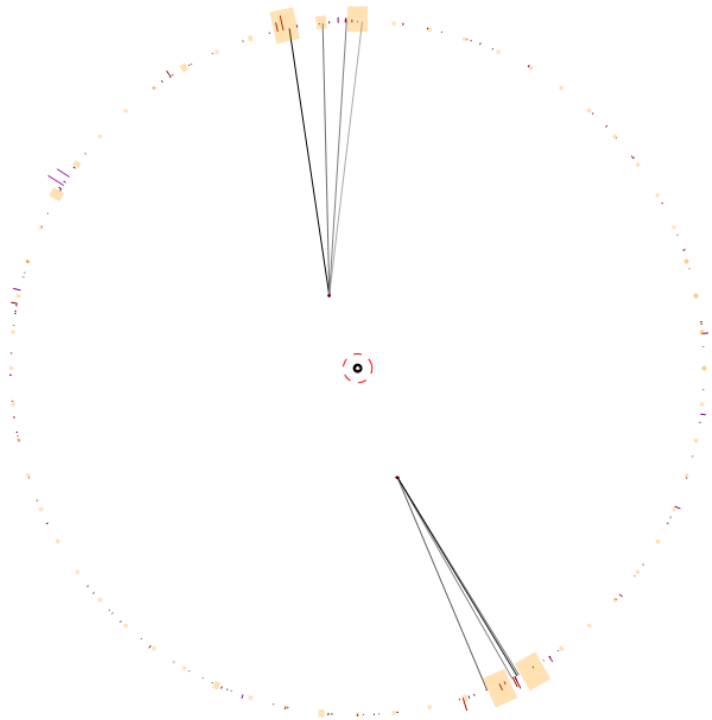
Very difficult to trigger at ATLAS/CMS…
New ATLAS trigger strategy (internal note)

LHCb opportunity!!

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

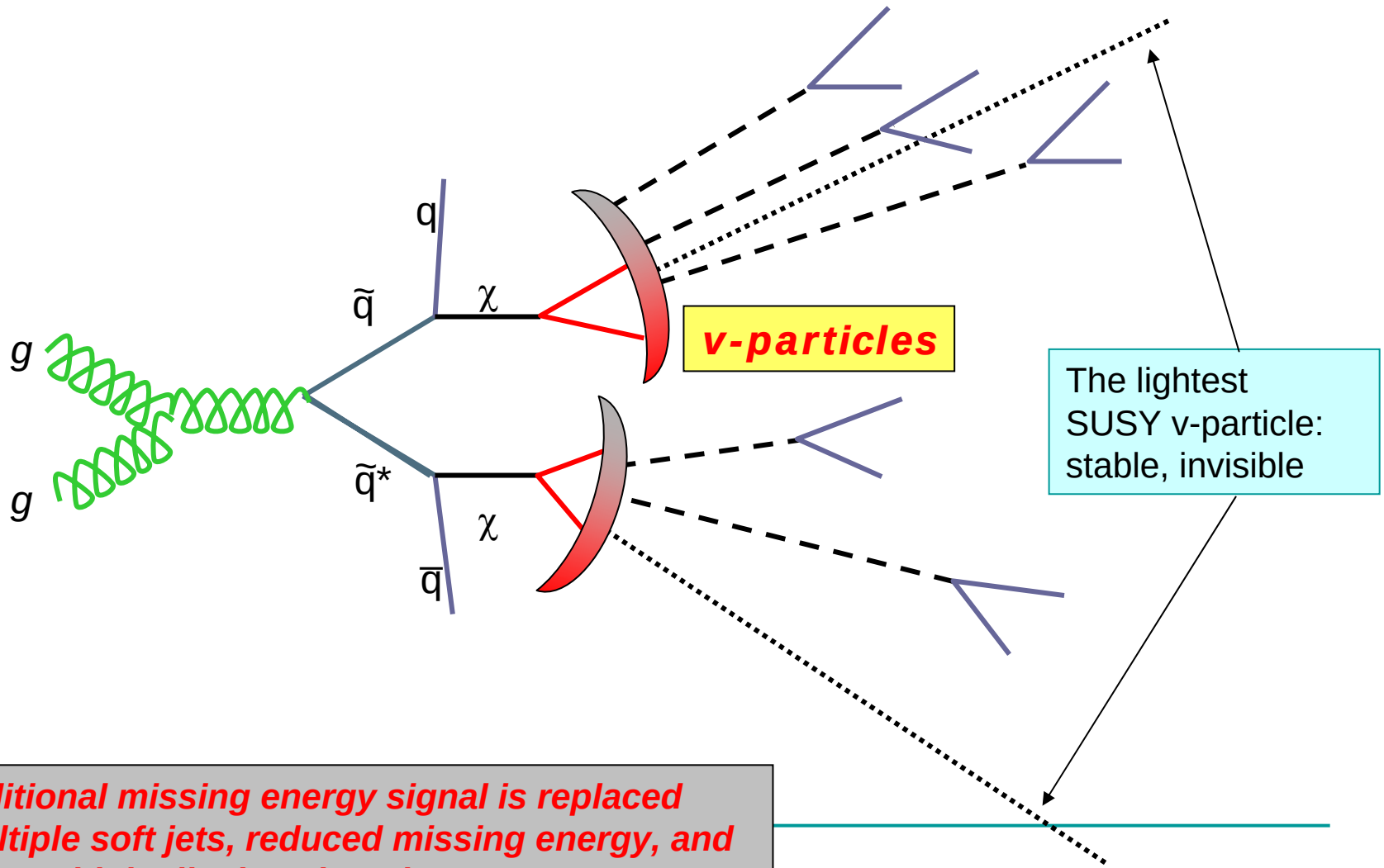
Precursor (LEP focus):
Chang, Fox, Weiner, limit of model in hep-ph/0511250





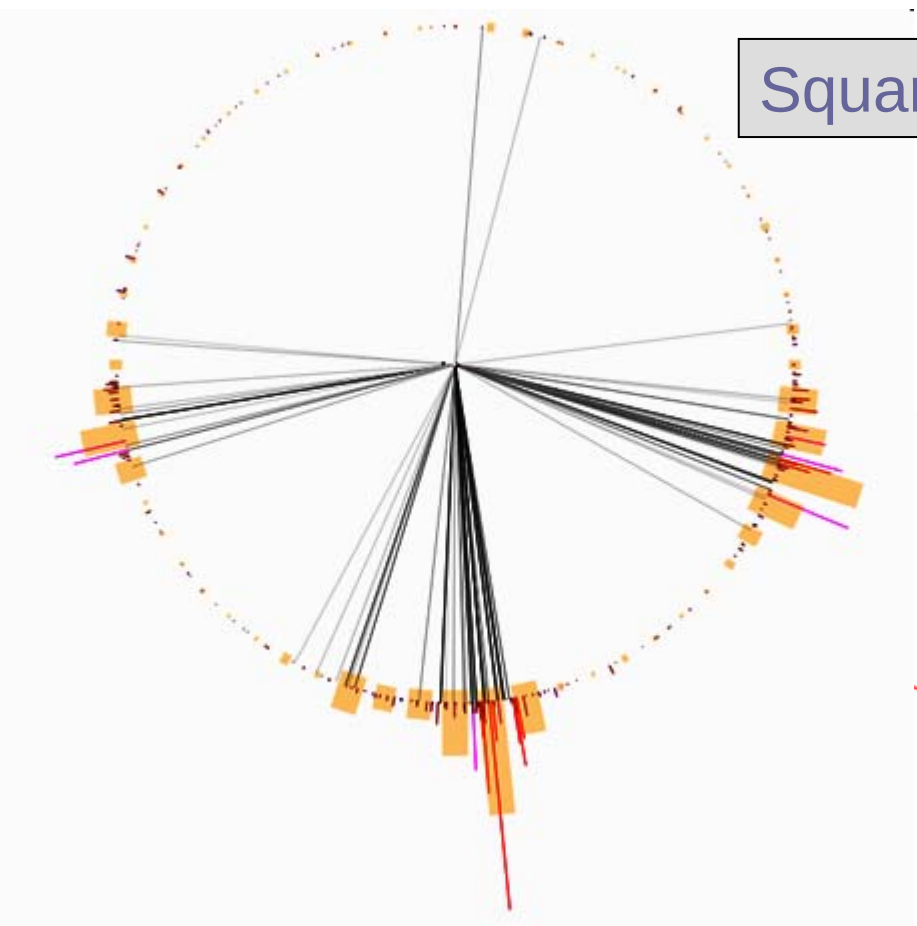
SUSY decays to the ν-sector

MJS hep-ph/0607160



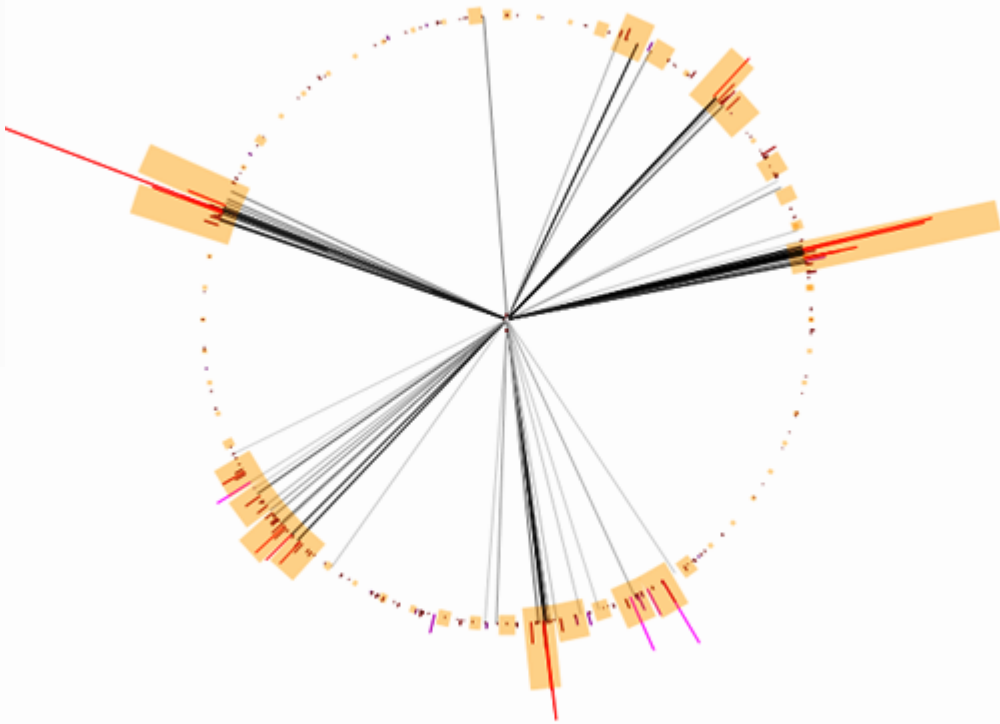
The traditional missing energy signal is replaced with multiple soft jets, reduced missing energy, and possibly multiple displaced vertices

Squark-Antisquark Production at LHC



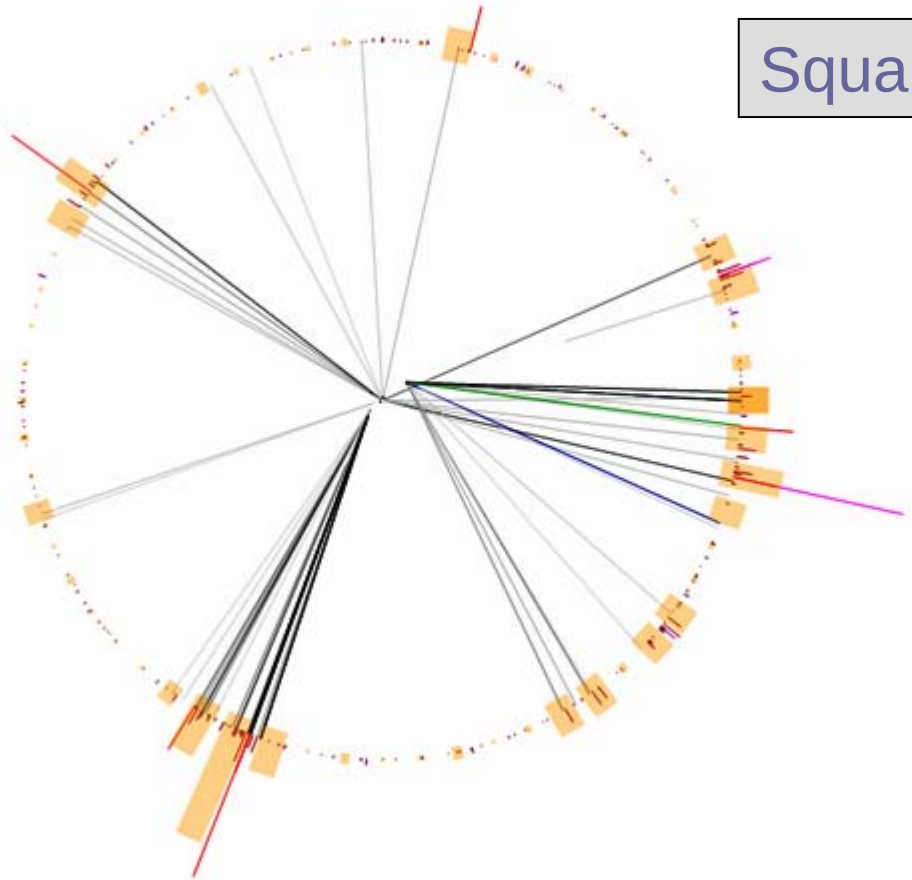
Stable Neutralino

Unstable Neutralino
Decaying to v-Sector



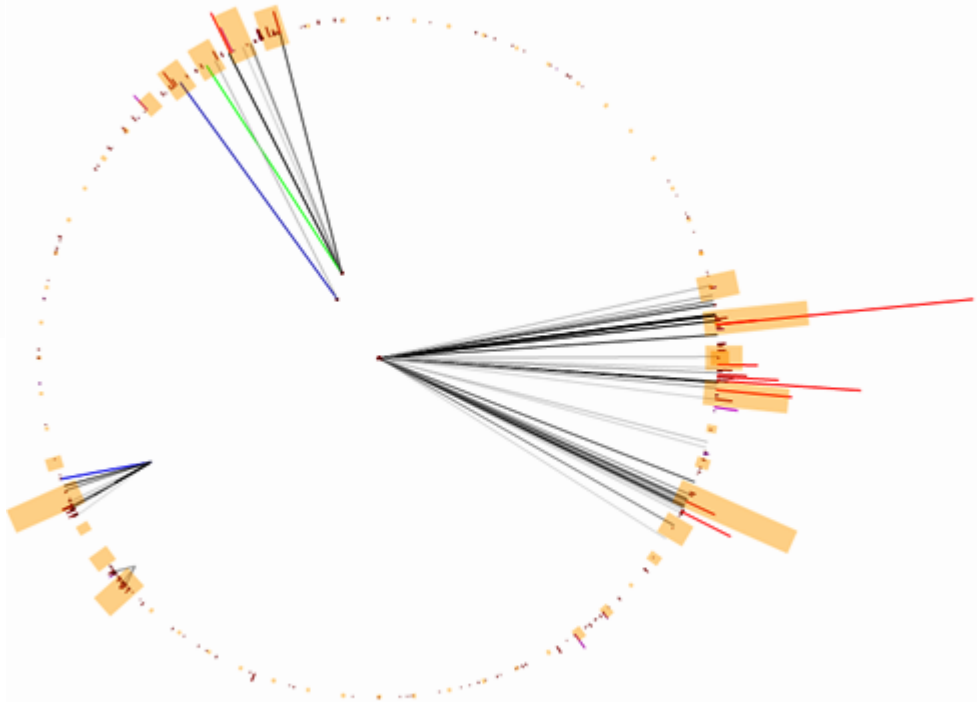
Hacked simulation using
Hidden Valley Monte Carlo 1.0
Mrenna, Skands and MJS

Squark-Antisquark Production at LHC



Long-Lived Neutralino
Prompt v-Particle Decay

Prompt Neutralino Decay
Long-Lived v-Particles

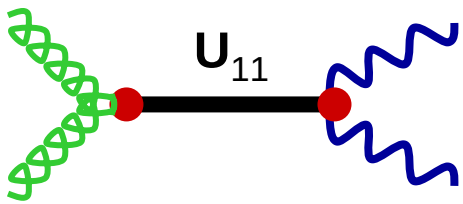


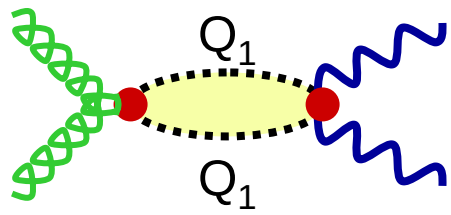
Hacked simulation using
Hidden Valley Monte Carlo 1.0
Mrenna, Skands and MJS

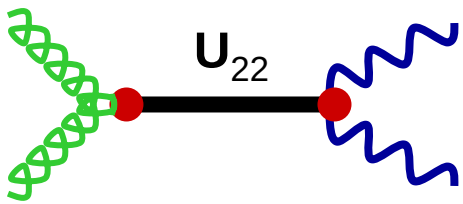
Masses m_J for the Q_J

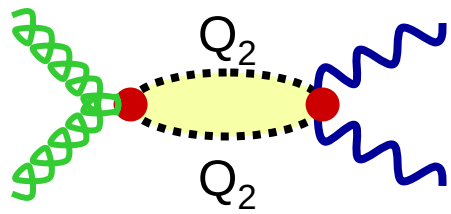
g g → 2 photons

~ c_J M^{-p}

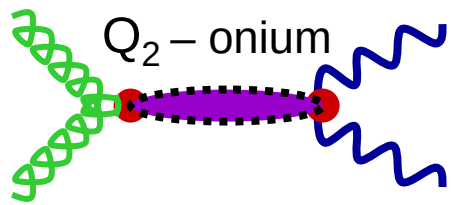








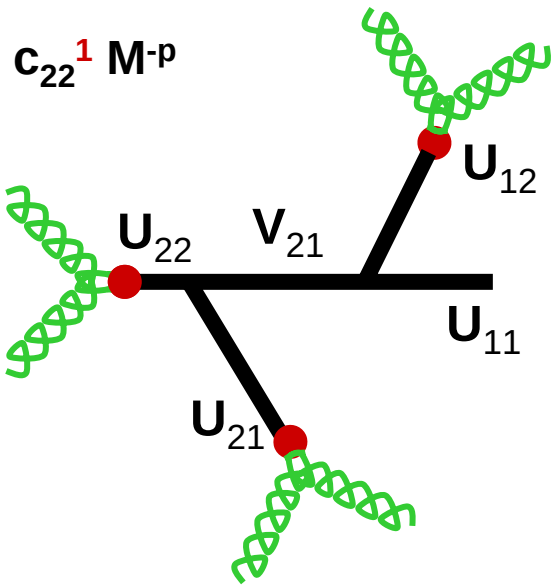
- **Thresholds at energy = 2 m_1 , 2 m_2 , …**
- **v-Quarkonium resonances below threshold**
- **Details depend on N , F , m_J**



Hidden sector effects not predictable
Order–c^2 terms dominate observables

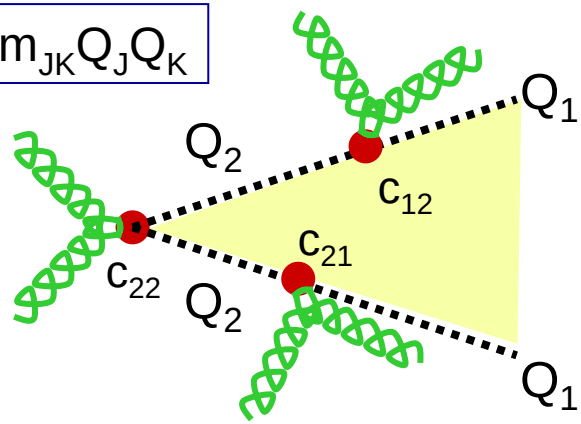
g g → 4 jets + MET

$\sim c_{22}^{1}\, M^{-p}$



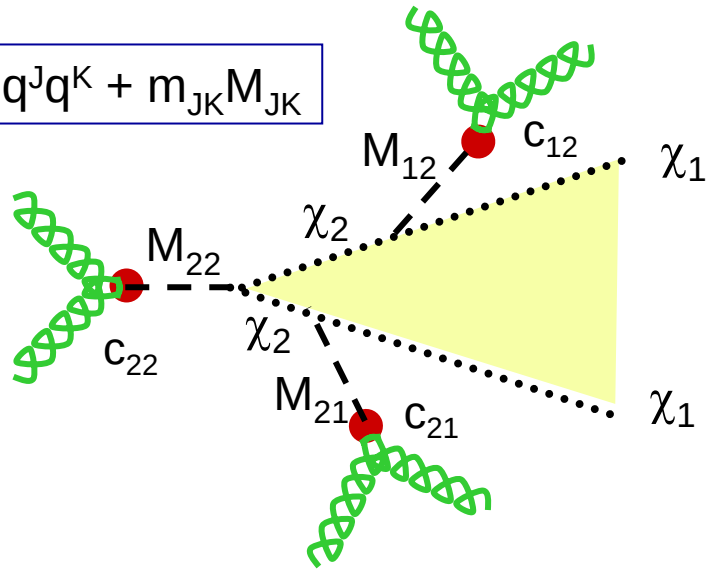
F ~ 3(N-2) (Banks-Zaks weakly coupled)

$W = m_{JK} Q_J Q_K$

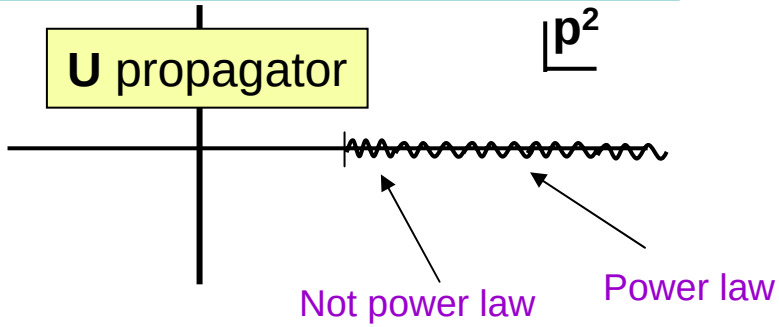


F ~ $^{3}/_{2}$(N-2) (Seiberg dual weakly coupled)

$W_{dual} = M_{JK}\, q^J q^K + m_{JK} M_{JK}$



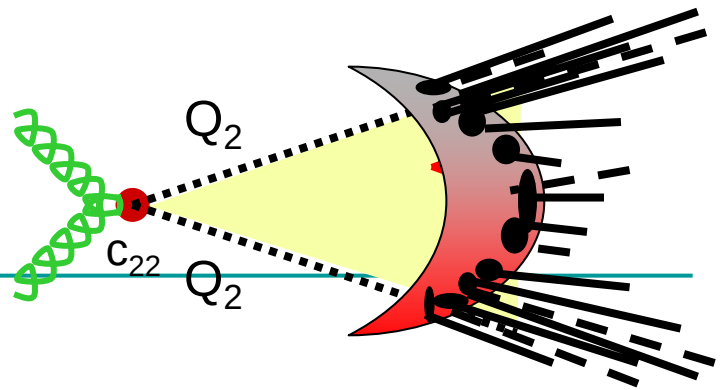
Masses m_{JK} for the Q_J



- Add term $m^2_{JK}\ Q_J Q_K^* = m^2_{JK}\ \mathbf{V}_{JK}$
- Suppose m^2_{JK} , c_{JK} simultaneously diagonal
- Mass terms from SUSY breaking ➔ too few fermions for new BZ fixed point
- This causes immediate confinement
- v-hadrons could include massless states (v-pions)
- or v-pions could be massive ➔ visible decays as in QCD-like models

g g ➔ VISIBLE STATES

Visibility at LHC depends on v-pion masses



With a mass gap, there are always poles in some two-point functions

- Put some energy into the vacuum at x = 0
- Wait a while
- The energy will eventually distribute itself widely
- There are no long-range forces
- Therefore the final state can be well approximated by a tensor product of localized states, non-interacting with each other, each of which is a stable eigenstate of the Hamiltonian
- Consider any one of these states
- Some local operators interpolate this state
- These operators have poles in their two point functions