

Perspectives

“LIVE LONG AND PROSPER”

Matt Strassler
ACFI Workshop on LLPs
Nov 2015

Long-Lived Discussion

Why are we doing this? How do we convince our colleagues of the importance of this work?

Run 1 was a trial run; How do we assure Run 2 searches are maximally robust and efficient?

What could be out there? Anything we haven't thought of?

What can we predict about new signals? What can't we predict, and how do we parametrize it?

Do we need searches we haven't discussed, and what are they?

Priorities: Triggers, Algorithms, Analysis Strategies, Recasting

Remembering the Pioneers

SUSY LLPs mid-to-late 90s (GMSB ,AMSB)

- I learned an enormous amount from Scott Thomas, Ann Nelson, Uri Sarid, Jonathan Feng, Lisa Randall, Shufang Su, Konstantin Matchev, ...

LEP, especially Tevatron searches for HSCPs, displaced photons, displaced vertices

Theory Homework (but experimentalists, please pay attention!)

What is our list of signatures?

Strategy: What would be a minimal, efficient, robust set of searches?

- We have already seen that we probably do not need a vast array of searches!
- Especially in Run 2! Run 3 is coming...

Which known signatures fall through the cracks in this strategy?

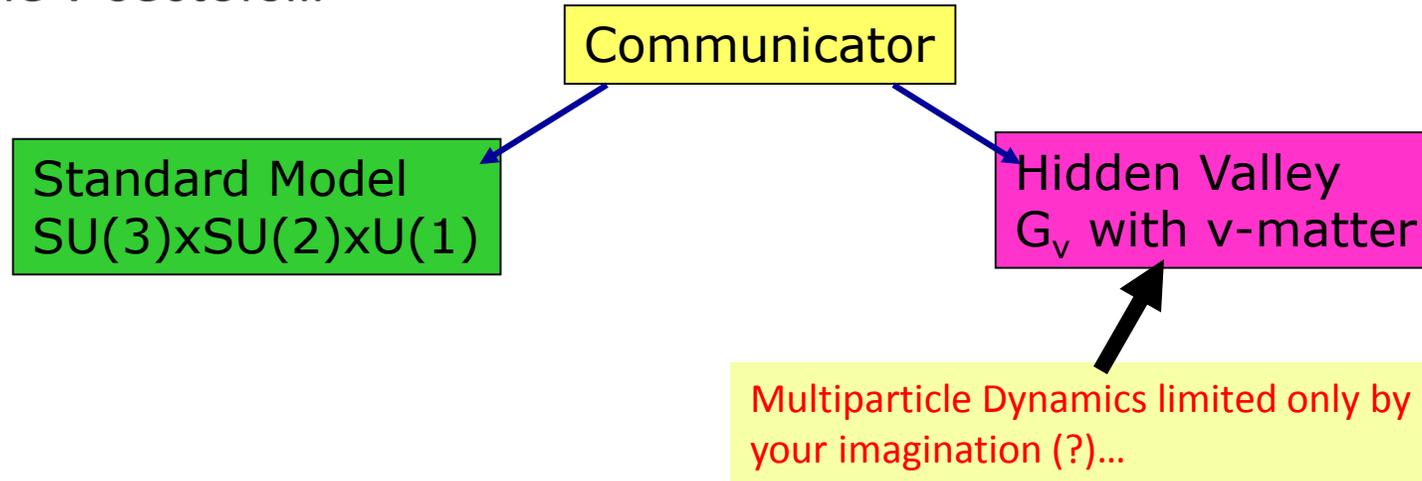
Into the unknown:

- Look for additional class of signatures that we may have missed
- Would it fall through the cracks? If so, can a robust, efficient general search be designed around it?

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-gluon theory
...

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

Why Hidden Valleys and LLPs?

Typically SUSY → Usually one potential LLP

- Need some luck for its lifetime to be in magic range

Typically Hidden Valleys → Often more than one potential LLP

- With more particles and diverse lifetimes, much more likely to find a particle in magic range
- Diversity of models, multiplicity of particles → greater variety of signatures to cover; challenge

Thought Experiment: QCD as a Hidden Valley

Turn off the photon.

Imagine we are made only from leptons and neutrinos, maybe a leptophoton, ...

We have never seen a baryon; we can't see them. We do not know quarks exist.

What now? How do we discover them?

Searching for QCD

Long-Lived Particles

- $\pi^+ \rightarrow \mu\nu$ (via W^*)
- $\pi^0 \rightarrow e^+e^-$ (via Z^*)
- $K^+ \rightarrow \mu\nu, e\nu, \pi^0, \mu\nu, \pi^0, \pi^+\pi^-$

Decaying to Hadrons (reconstruct later)

- $\eta \rightarrow \pi^+\pi^-\pi^0$
- $\rho \rightarrow \pi^+\pi^-$
- $\omega \rightarrow \pi^+\pi^-\pi^0$

π^+ DECAY MODES	Fraction (Γ_i/Γ)	Confidence
$\mu^+ \nu_\mu$	[b] (99.98770 ± 0.00004) %	99.98770 %
π^0 DECAY MODES	Fraction (Γ_i/Γ)	Confidence
2γ	(98.823 ± 0.034) %	98.823 %
$e^+e^- \gamma$	(1.174 ± 0.035) %	1.174 %
γ positronium	(1.82 ± 0.29) × 10 ⁻⁹	1.82 × 10 ⁻⁹ %
$e^+e^+e^-e^-$	(3.34 ± 0.16) × 10 ⁻⁵	3.34 × 10 ⁻⁵ %
e^+e^-	(6.46 ± 0.33) × 10 ⁻⁸	6.46 × 10 ⁻⁸ %
K^+ DECAY MODES	Fraction (Γ_i/Γ)	Confidence

Leptonic and semileptonic modes

$e^+ \nu_e$	(1.582 ± 0.007) × 10 ⁻⁵
$\mu^+ \nu_\mu$	(63.56 ± 0.11) %
$\pi^0 e^+ \nu_e$	(5.07 ± 0.04) %
Called K_{e3}^+ .	
$\pi^0 \mu^+ \nu_\mu$	(3.352 ± 0.033) %
Called $K_{\mu3}^+$.	
$\pi^0 \pi^0 e^+ \nu_e$	(2.55 ± 0.04) × 10 ⁻⁵
$\pi^+ \pi^0$	(20.67 ± 0.08) %
$\pi^+ \pi^0 \pi^0$	(1.760 ± 0.023) %
$\pi^+ \pi^+ \pi^-$	(5.583 ± 0.024) %

Searching for QCD

Long-Lived Particles

- $\pi^+ \rightarrow \mu\nu$ (via W^*)
- $\pi^0 \rightarrow e^+e^-$ (via Z^*)
- $K^+ \rightarrow \mu\nu, e\nu, \pi^0, \mu\nu, \pi^0, \pi^+\pi^-$
- $K_S \rightarrow \pi^+\pi^-$
- $K_L \rightarrow e\nu, \mu\nu, \pi^+\pi^-, 3\pi^0, \pi^+\pi^-\pi^0$
- $D \rightarrow e\nu, K, \mu\nu, K, K\pi, e\nu, K\pi \dots$

Decaying to Hadrons (reconstruct later)

- $\eta \rightarrow \pi^+\pi^-\pi^0$
- $\rho \rightarrow \pi^+\pi^-$
- $\omega \rightarrow \pi^+\pi^-\pi^0$

K_S^0 DECAY MODES	Fraction (Γ_i/Γ)	Confidence level
	Hadronic modes	
$\pi^0\pi^0$	$(30.69 \pm 0.05) \%$	
$\pi^+\pi^-$	$(69.20 \pm 0.05) \%$	
$\pi^\pm e^\mp \nu_e$	[gg] $(7.04 \pm 0.08) \times 10^{-4}$	

K_L^0 DECAY MODES	Fraction (Γ_i/Γ)	Confidence level
	Semileptonic modes	
$\pi^\pm e^\mp \nu_e$	[gg] $(40.55 \pm 0.11) \%$	S=1
Called K_{e3}^0 .		
$\pi^\pm \mu^\mp \nu_\mu$	[gg] $(27.04 \pm 0.07) \%$	S=1
$3\pi^0$	$(19.52 \pm 0.12) \%$	S=1
$\pi^+\pi^-\pi^0$	$(12.54 \pm 0.05) \%$	

D^+ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level
$\bar{K}^0 e^+ \nu_e$	$(8.83 \pm 0.22) \%$	
$\bar{K}^0 \mu^+ \nu_\mu$	$(9.3 \pm 0.7) \%$	
$K^- \pi^+ e^+ \nu_e$	$(3.91 \pm 0.11) \%$	
$K_S^0 \pi^+$	$(1.53 \pm 0.06) \%$	S=2.8
$K_L^0 \pi^+$	$(1.46 \pm 0.05) \%$	
$K^- 2\pi^+$	[ss] $(9.46 \pm 0.24) \%$	S=2.0

Searching for QCD

Long-Lived Particles

- $\pi^+ \rightarrow \mu\nu$ (via W^*)
- $\pi^0 \rightarrow e e$ (via Z^*)
- $K^+ \rightarrow \mu\nu, e\nu \pi^0, \mu\nu \pi^0, \pi \pi$
- $K_S \rightarrow \pi \pi$
- $K_L \rightarrow e\nu \pi^+, \mu\nu \pi^+, 3 \pi^0, \pi^+ \pi^- \pi^0$
- $D \rightarrow e\nu K, \mu\nu K, K \pi, e\nu K \pi \dots$

Decaying to Hadrons (reconstruct later)

- $\eta \rightarrow \pi \pi \pi$
- $\rho \rightarrow \pi \pi$
- $\omega \rightarrow \pi \pi \pi$

2 body decays, heavy-flavor-weighted

- Wide range of lifetimes

3 body decays, flavor democratic

- Easiest way to get electrons

Even 4 body decays!

Cascade decays (multiple vertices)

- Funny lifetime patterns
 - $D \rightarrow K_S \rightarrow \pi$

What if we change QCD a little?

Long-Lived Particles

- $\pi^+ \rightarrow \mu\nu$ (via W^*)
- $\pi^0 \rightarrow e e$ (via Z^*)
- $K^+ \rightarrow \mu\nu, e\nu \pi^0, \mu\nu \pi^0, \pi \pi$
- $K_S \rightarrow \pi \pi$
- $K_L \rightarrow e\nu \pi^+, \mu\nu \pi^+, 3 \pi^0, \pi^+ \pi^- \pi^0$
- $D \rightarrow e\nu K, \mu\nu K, K \pi, e\nu K \pi \dots$

Decaying to Hadrons (reconstruct later)

- $\eta \rightarrow \pi \pi \pi$
- $\rho \rightarrow \pi \pi$
- $\omega \rightarrow \pi \pi \pi$

Decrease strange quark mass?

- K_L can only decay to leptons

Increase down quark mass?

- Delta baryon decays to leptons + nucleon
- Eventually rho decays to leptons.

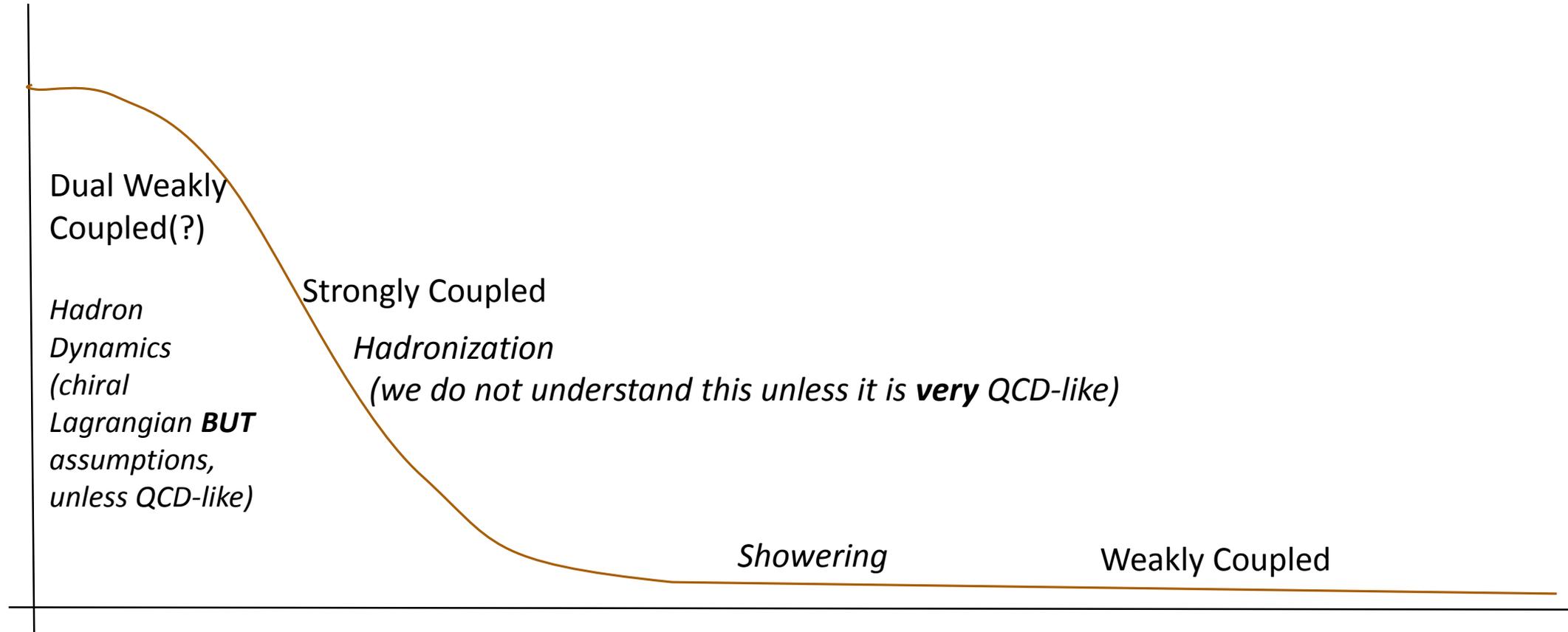
Change CKM matrix?

Allow large tree-level FCNCs?

What can we predict?

MJS + Zurek 06

QCD and other asymptotically-free confining theories



Hidden QCD with 2 flavors

MJS + Zurek 06

Z' , no W' \rightarrow

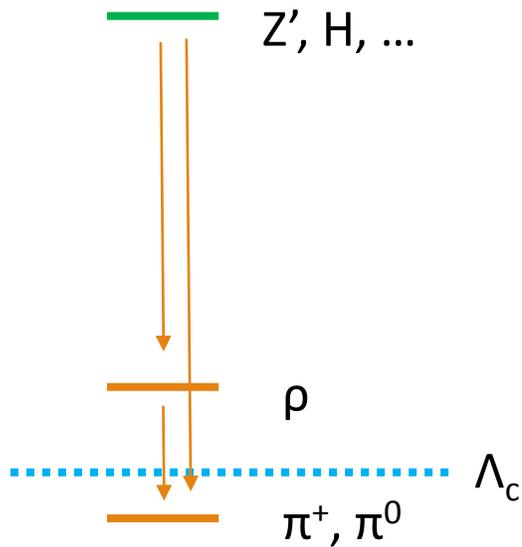
π^0 can decay

π^+ cannot decay

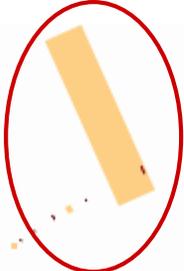
so $< \frac{1}{2}$ of pions visible [MET!]

UNLESS FCNCs

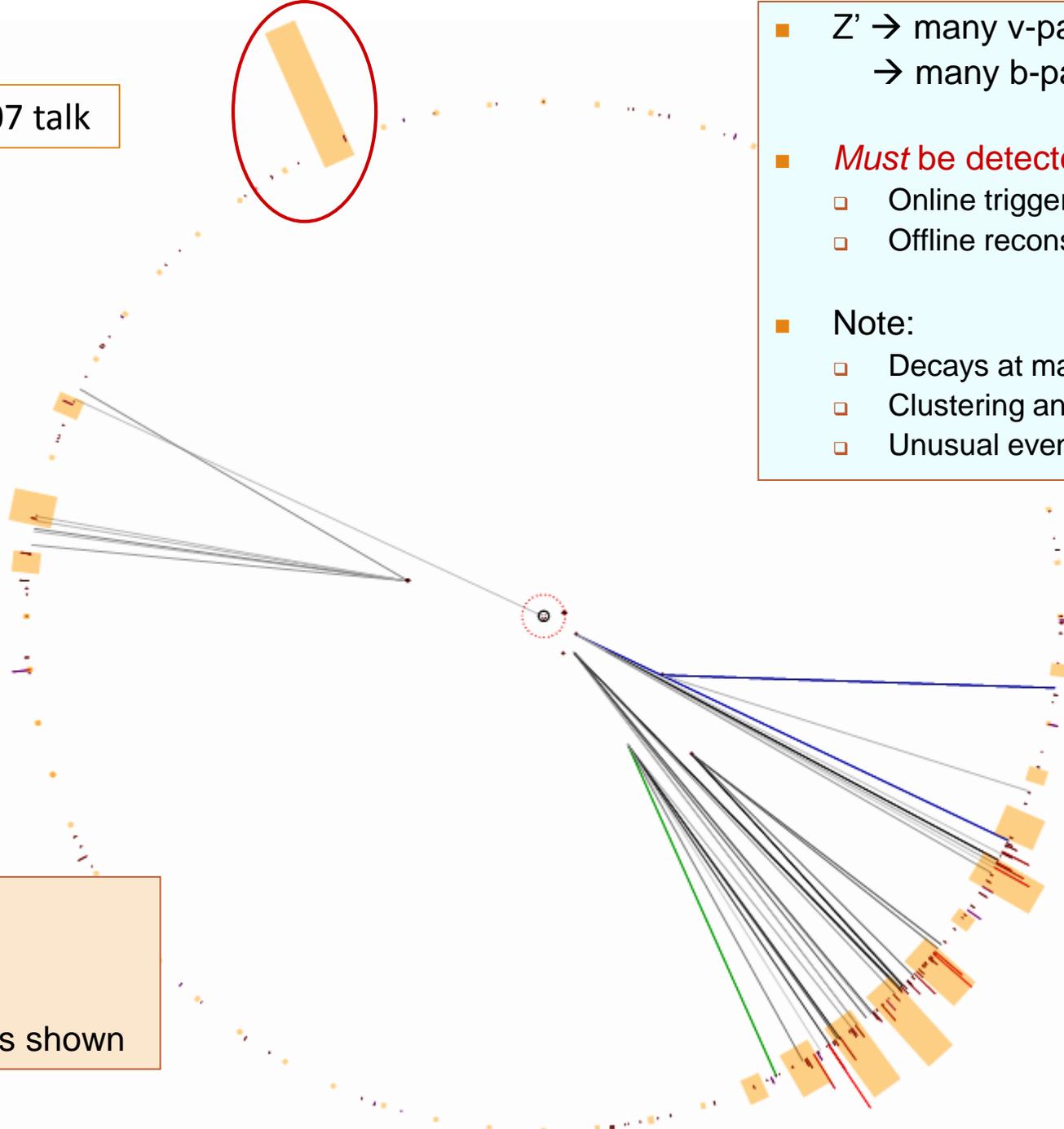
$\pi^+ \rightarrow$ SM with longer lifetime than π^0



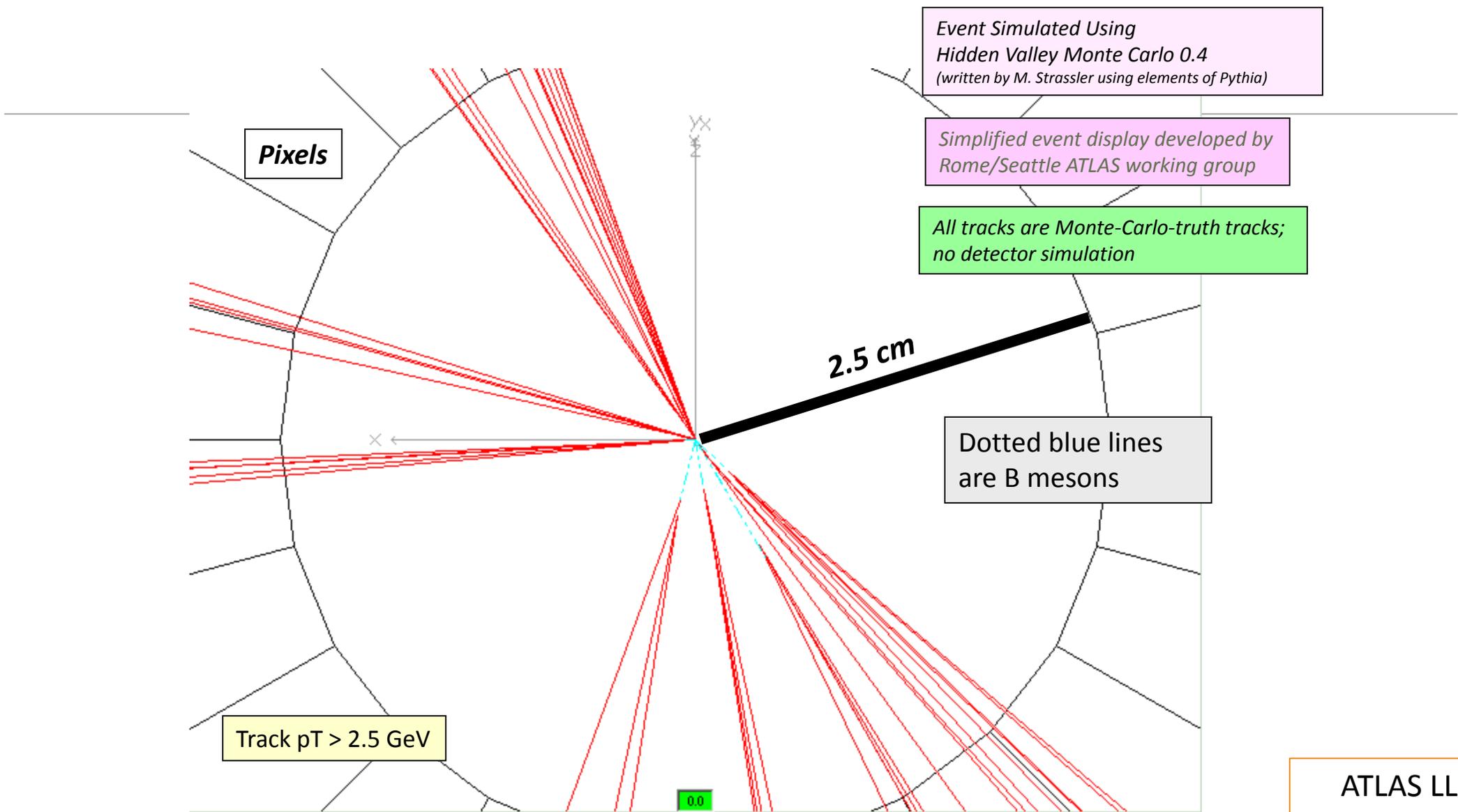
MJS 2007 talk



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



- 3 TeV Z' , 20 GeV v-pion
- Crude tracker
 - Truth level
 - 3 GeV pT cut on tracks shown



Pixels

Event Simulated Using
Hidden Valley Monte Carlo 0.4
(written by M. Strassler using elements of Pythia)

Simplified event display developed by
Rome/Seattle ATLAS working group

All tracks are Monte-Carlo-truth tracks;
no detector simulation

2.5 cm

Dotted blue lines
are B mesons

Track $p_T > 2.5$ GeV

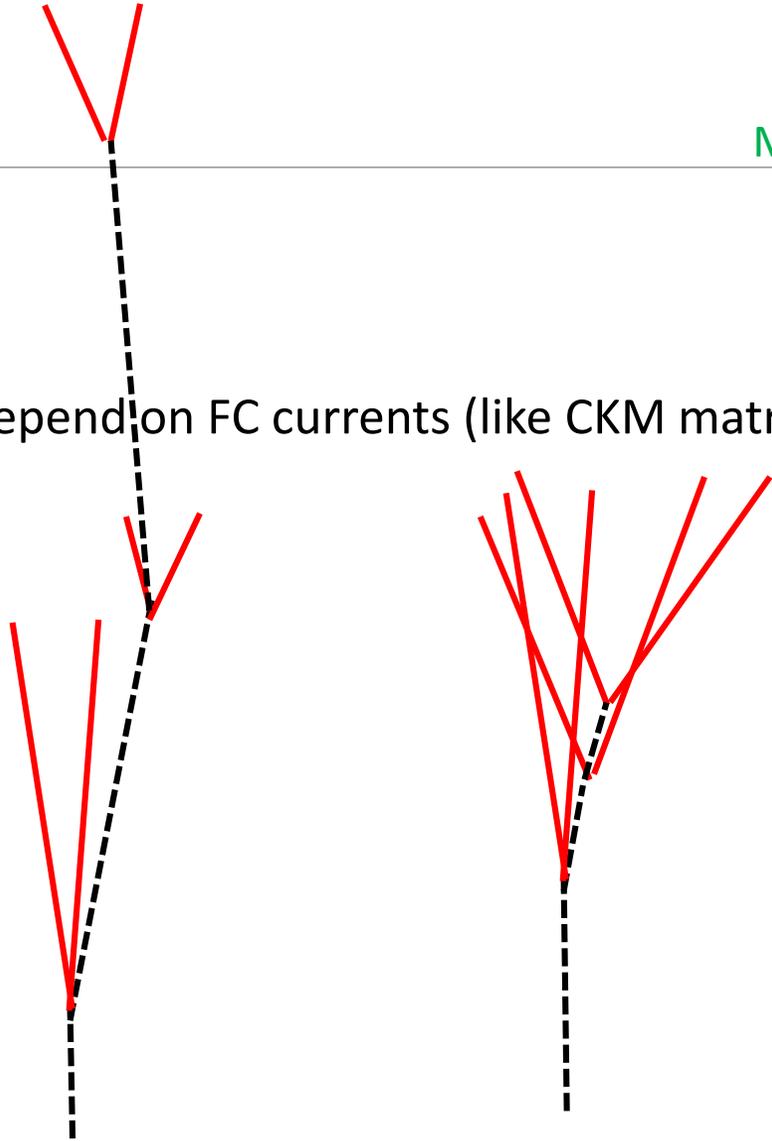
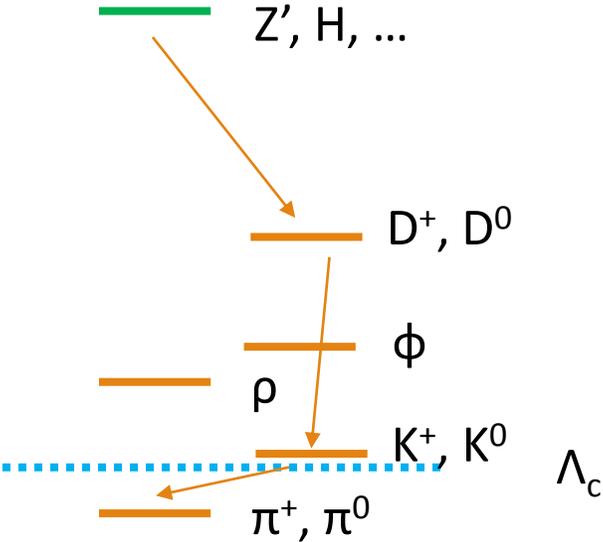
0.0

ATLAS LLP
Working Group
2007

Multiple vertices may cluster in a single jet

More flavors

Cascade decays
Lifetimes depend on FC currents (like CKM matrix and FCNCs)



Is Clustering a Problem or Not?

Should we worry about clustering of vertices?

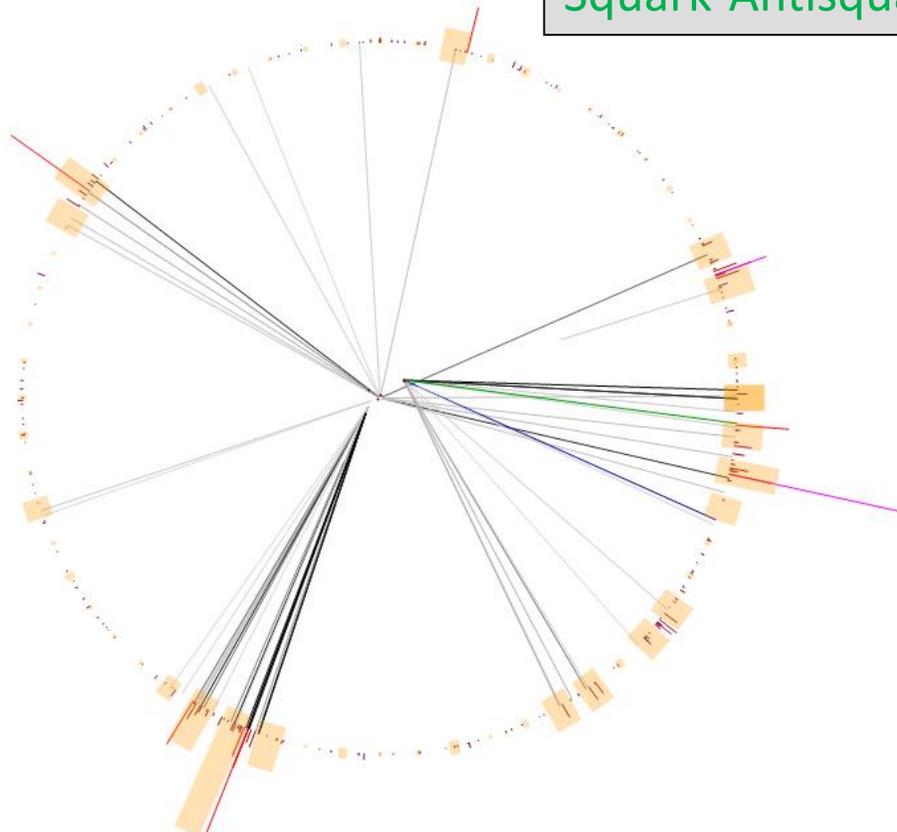
For what signatures & kinematics is this a problem?

- Maybe only for DV triggers?
- Reconstruction ok?

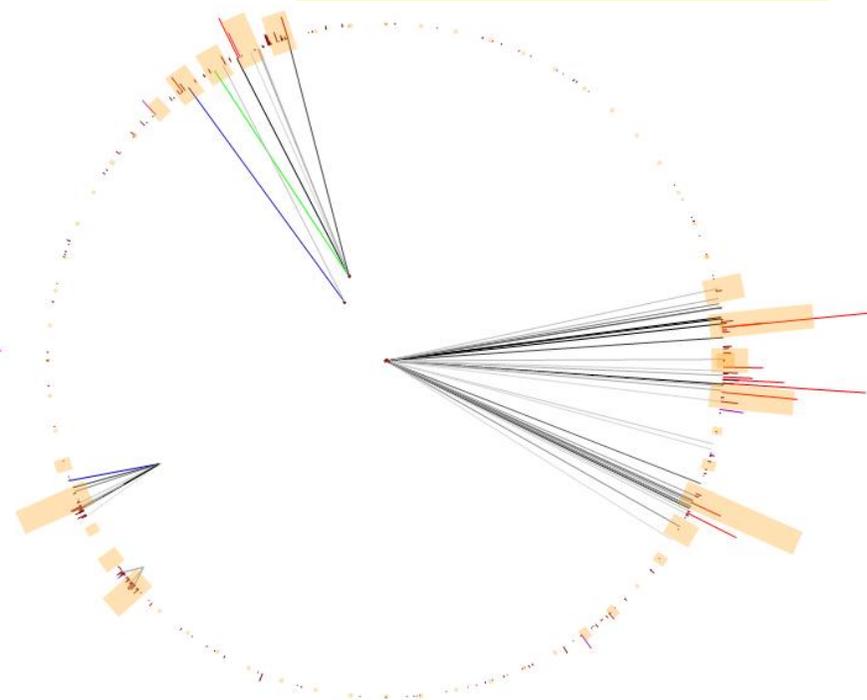
To the extent this is **not** a problem, the number of searches needed drastically decreases!!

Squark-Antisquark Production at LHC

Prompt Neutralino Decay
Long-Lived ν -Hadrons



Long-Lived Neutralino
Prompt ν -Hadron Decay



MJS 2007 talk

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

N_f Light Quarks

MJS + Zurek 06

Z' , no W' →

diagonal mesons can decay

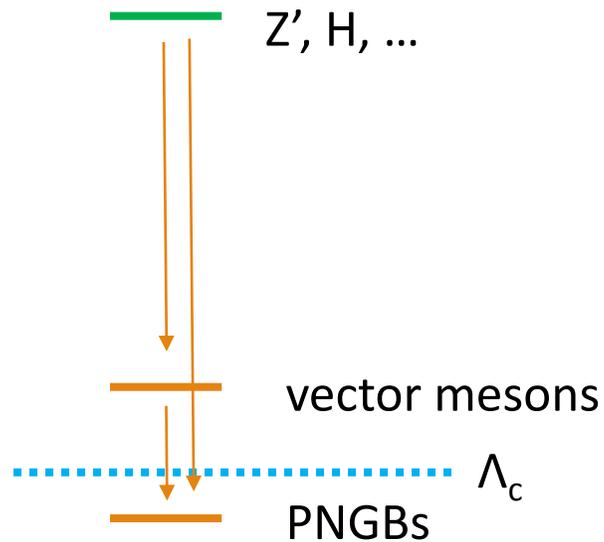
off-diagonal cannot decay

so $O(1/N_f)$ of pions visible

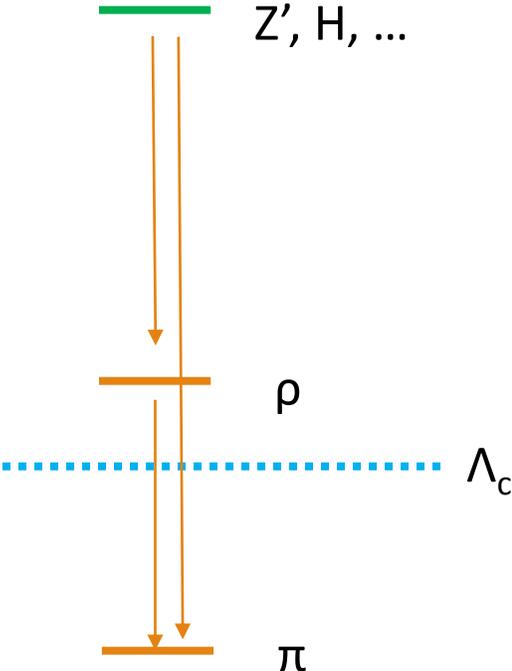
[**LESS** MET!! Need ISR + MET + DV]

UNLESS FCNCs

these → SM with various longer lifetime than diagonal



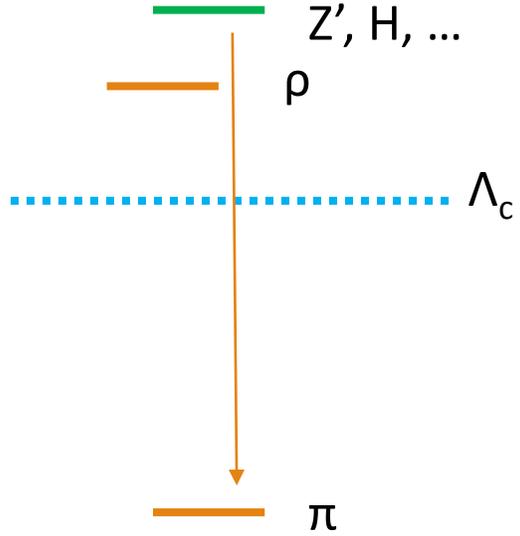
Lower Pion Mass Relative to Confinement



Lower quark masses \rightarrow lighter, much longer-lived pion
Multiplicity largely unchanged

Raising the Confinement Scale

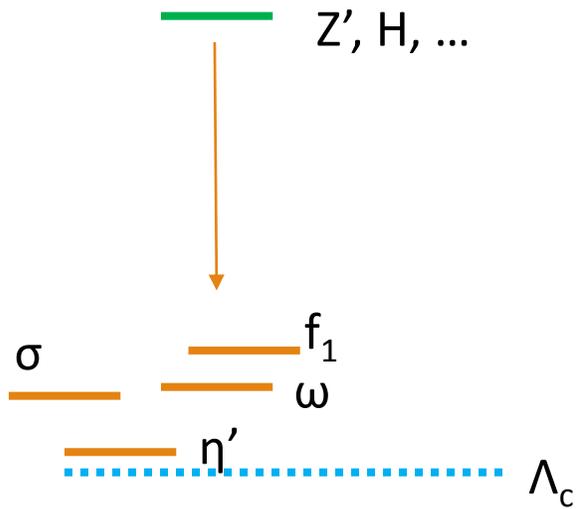
MJS + Zurek 06



Higher confinement scale, fixed pion mass \rightarrow somewhat shorter-lived pion
Multiplicity decreases to two or three pions; *no hadronization uncertainty*

Only One Light Flavor

MJS + Zurek 06



$$\Gamma_{\omega} \sim 4 \times 10^{18} \text{ sec}^{-1} \left(\frac{m_{\omega v}}{200 \text{ GeV}} \right)^5 \left(\frac{10 \text{ TeV}}{m_{Z'}/g'} \right)^4$$

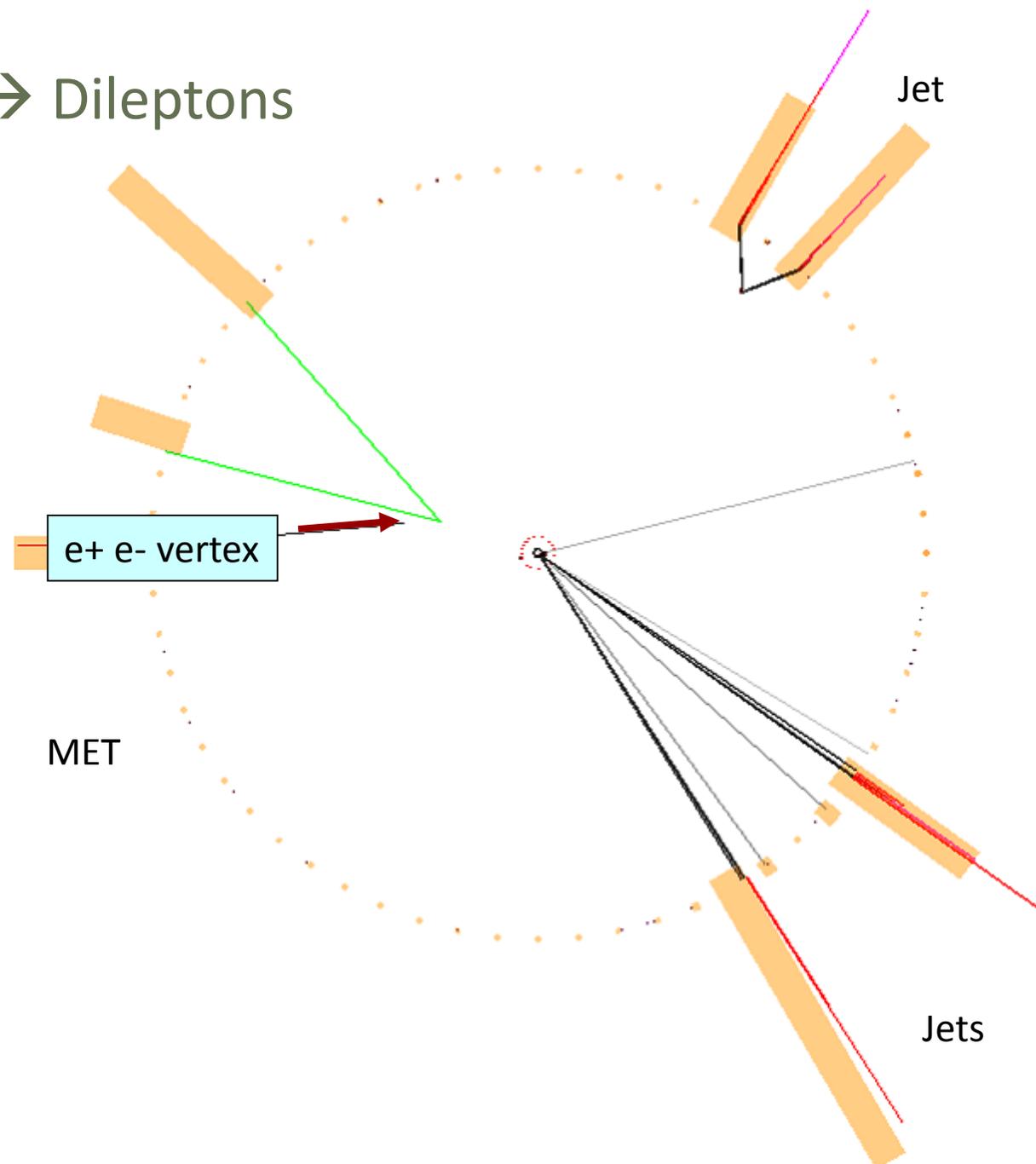
Much higher down quark mass → metastable 0- 0+ 1- 1+ ...?

Multiplicity ~ ½ of QCD-like?

Spin 0 → heavy flavor, long lifetime

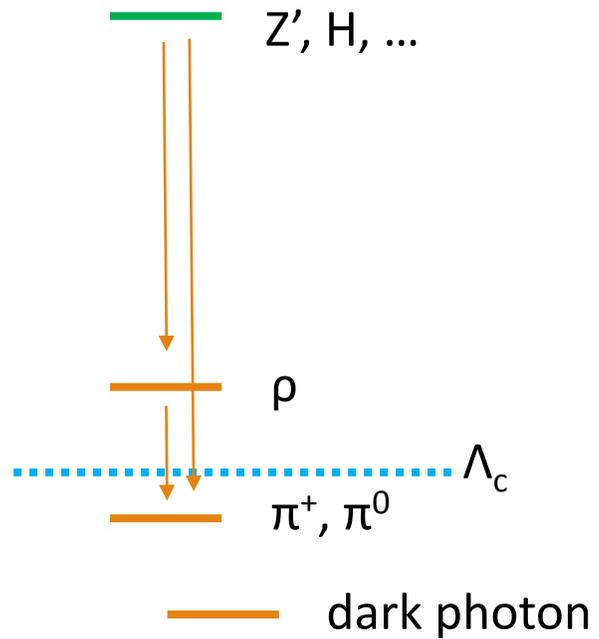
Spin 1 → democratic (including dileptons), shorter lifetime

Long-Lived Particle \rightarrow Dileptons



MJS 2009 talk

Add a Dark Photon



Add dark photon: neutral pion \rightarrow dark photons

Multiplicity $\sim 2 \times$ QCD-like?

Spin 1 \rightarrow democratic (including dileptons), shorter lifetime

Keep our minds open...

Even hidden sectors very similar to QCD can give a very, very, very wide variety of signals

Must not get locked to any given model at this stage in LHC; not enough theory guidance

- Consider broad set of variations and make sure our searches are broadly sensitive
- **Are there any signals that our current and planned searches will miss?**

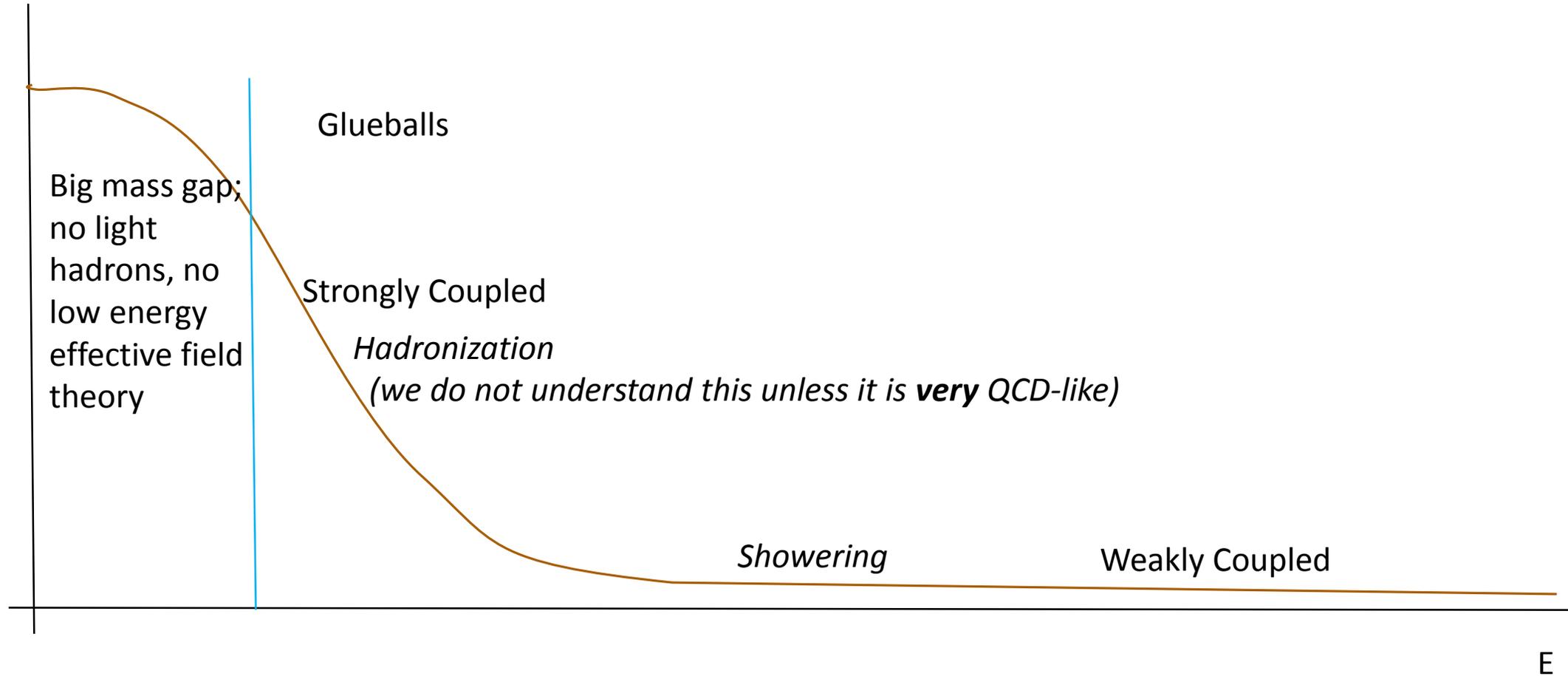
Many other models have been explored by large number of theorists.

There may not be many new phenomena yet to uncover.

Still, not clear our phenomenological coverage is sufficiently complete.

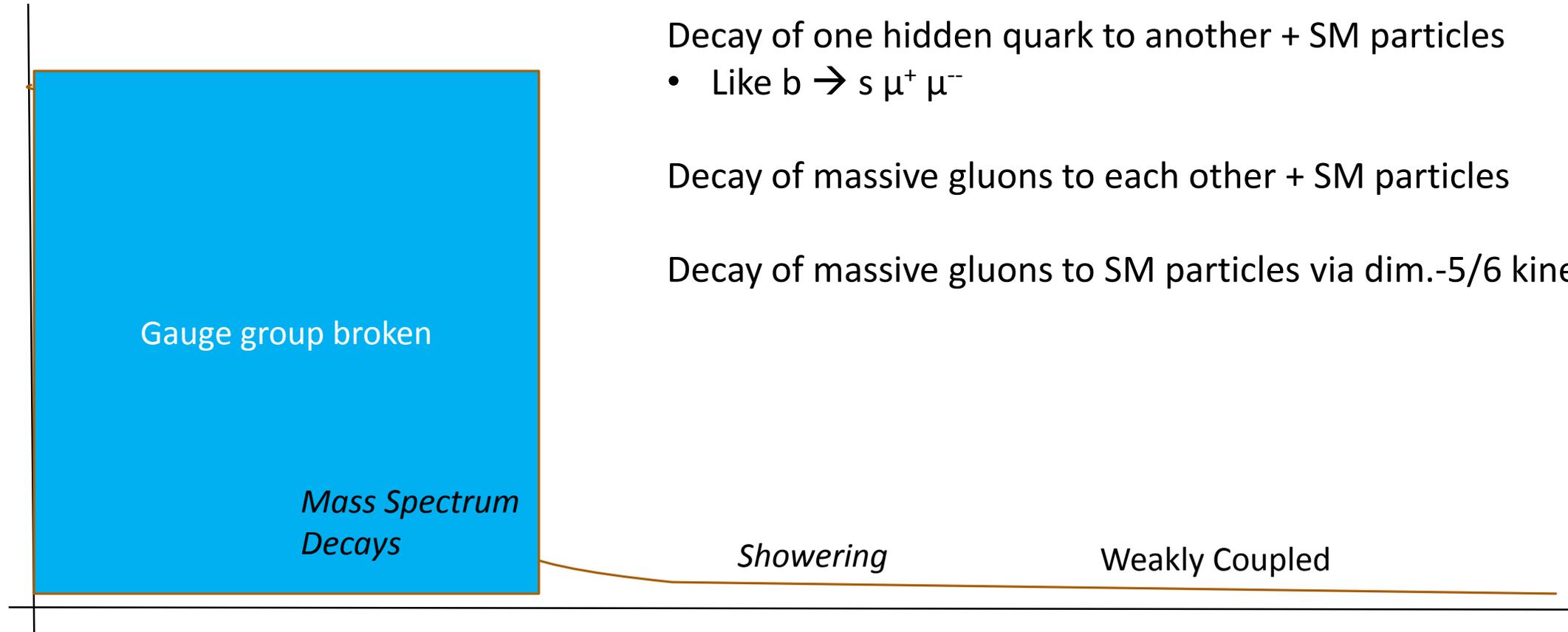
What can we predict?

Pure-Glue (“Yang-Mills”) Theory



What can we predict?

Broken QCD-like Theory – fully predictable



Decay of one hidden quark to another + SM particles

- Like $b \rightarrow s \mu^+ \mu^-$

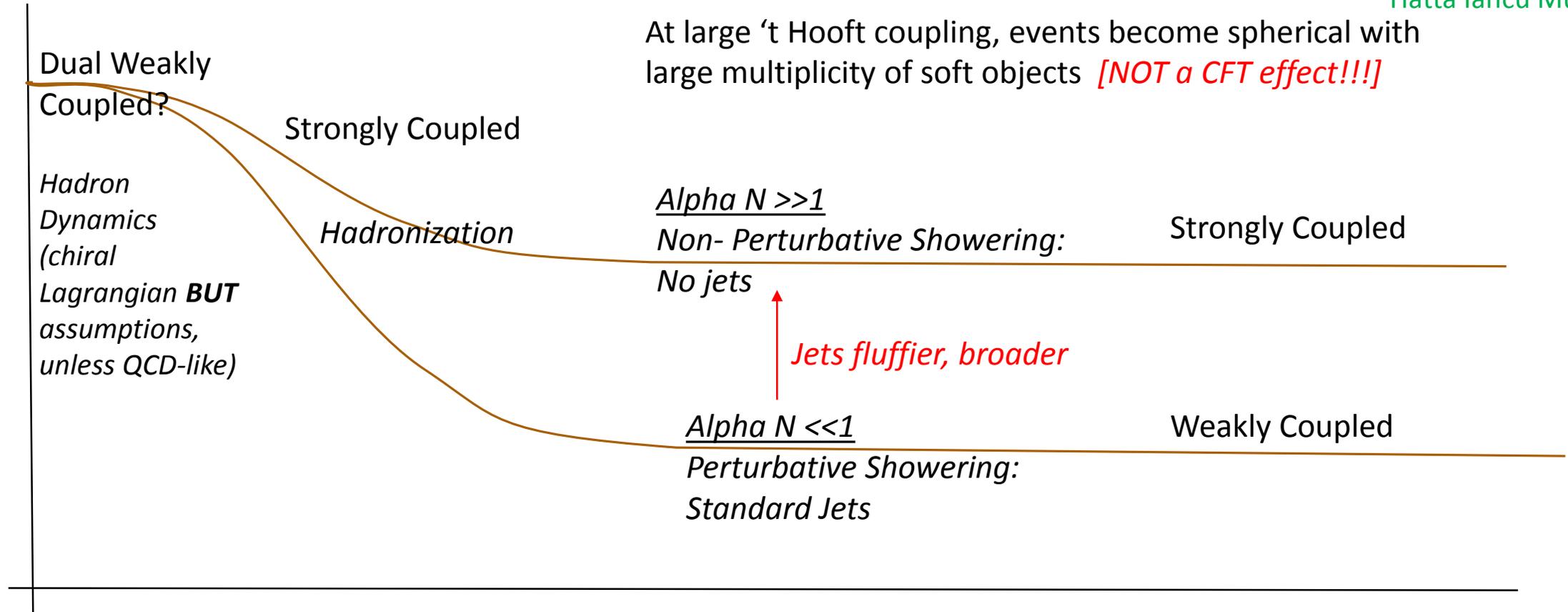
Decay of massive gluons to each other + SM particles

Decay of massive gluons to SM particles via dim.-5/6 kinetic mixing

What can we predict?

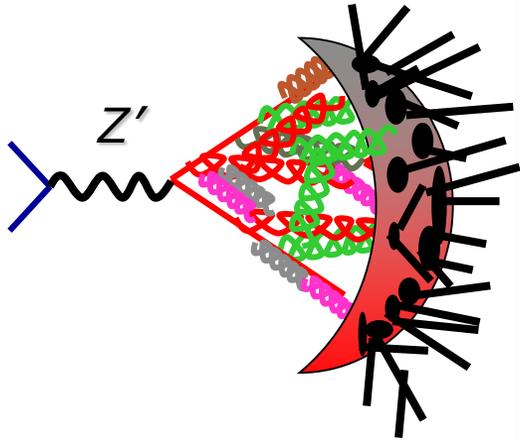
Conformal Field Theory \rightarrow Confining

MJS 08
Hoffman Maldacena 08
Hatta Iancu Mueller 08

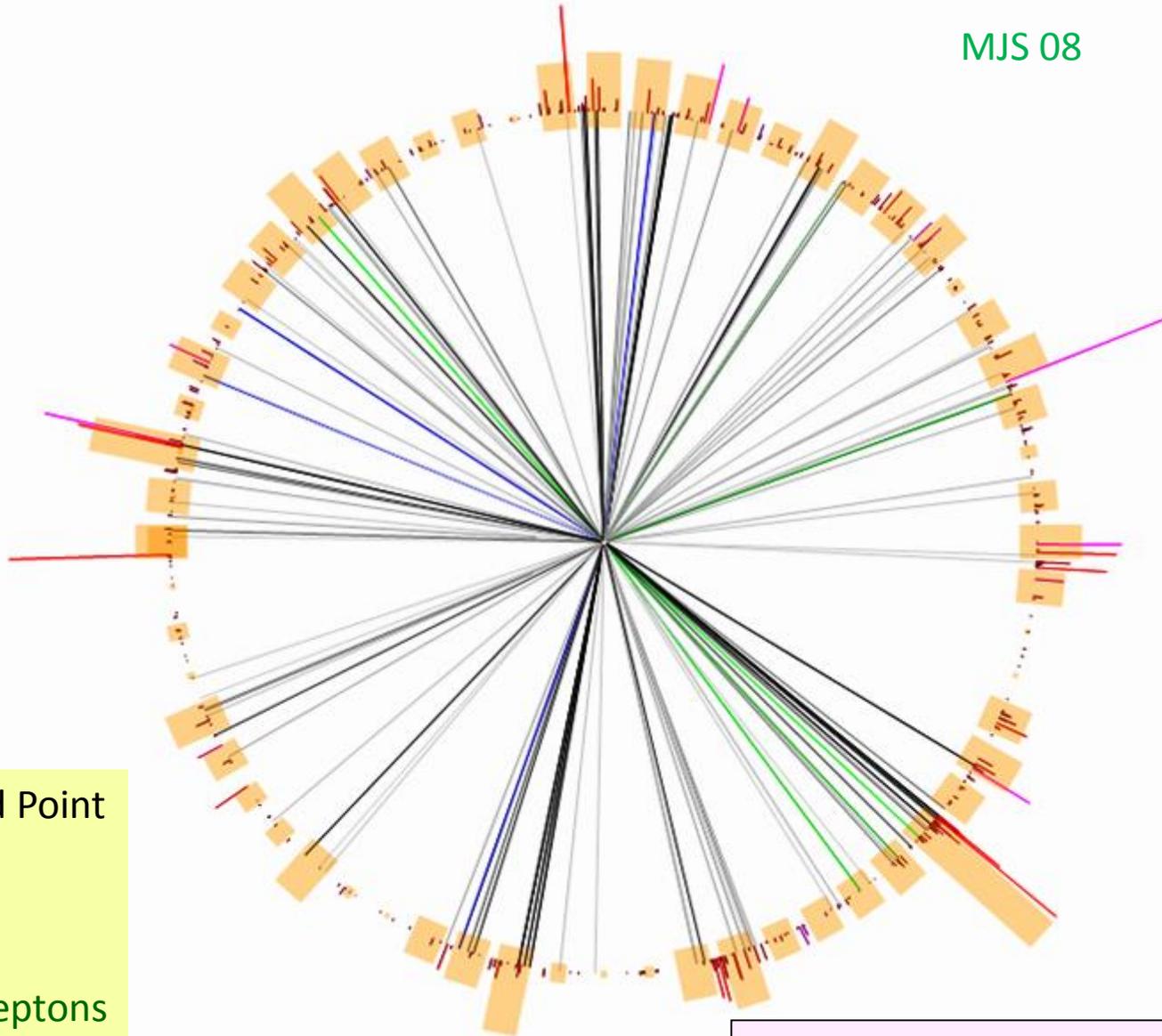


Event Display

MJS 08



UV Strong-Coupling Fixed Point
(large anom dims)
~ 30 v-hadrons
Softer v-hadrons
~ 50-60 soft SM quarks/leptons



This hidden valley is also an “unparticle theory with a mass gap”

Fireworks! Muon or Electron or Pion “Bomb”

Spherical decay with many LLPs of low mass

- possibly with prompt particles
- possibly with MET

Role for LHCb?

Taking Stock Of What We Know

Charged/Colored Particles

Stable HSCP under good control

Stopped particles under good control

Particle decaying in flight; may need to combine

- Disappearing track
- Vertex with few tracks
- Single isolated displaced muon/electron?/track??



Displaced Photons

Shouldn't be a problem, but is it falling through a crack?

- Stealth SUSY can give scalar \rightarrow displaced diphotons [but 4 photons + HT has almost no background]
- HV with glueballs coupled to SM via quirks give hidden glueballs \rightarrow displaced diphotons, digluons, WW, ZZ

Displaced Vertices

Tracker: best friend in analysis, worst enemy in trigger!

Need to get more analyses into the tracker – vertexing is worth the trouble!

- Displaced tracks without a vertex may be too common
- It seems unlikely to me that any other effort will yield more fruit than this

HCAL/Muon system triggers

- Only work for long average lifetime
- Hard to look for a single LLP (background issues)
- Displaced muon(s) always help

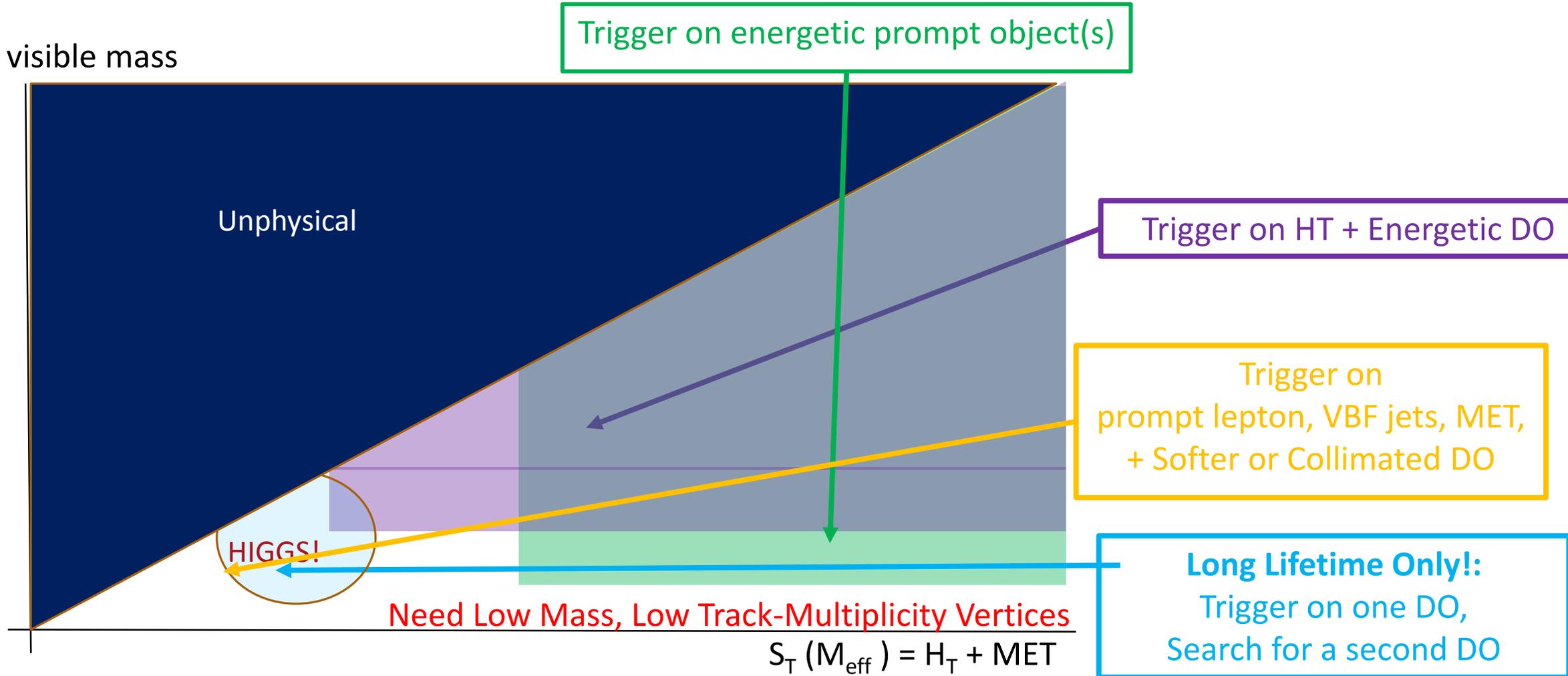
Prompt triggers + trackless jet or displaced tracks

- Work for any average lifetime [linear loss of efficiency with lifetime]
- Allow access to a single LLP where it is most easily observed

Triggering and Analyses

Short Lifetimes: Confront b,c Background
• ATLAS FTK Trigger??

LLP visible mass



ATLAS/CMS Priorities

Push Lower

- Lower LLP (visible) Mass
- Lower LLP Track Multiplicity
- Lower LLP Lifetime
- Lower Trigger Threshold on displaced objects (using associated objects)

New Trigger/Analysis Objects?

- Diphoton vertex?
- Dimuon vertex in outer tracker? In calorimeter?
- HCAL deposition with emerging muon?

Challenges of High Multiplicity/Emerging Jet/Tau-Pair/... : problems or not?

- Informal recasting BY EXPERIMENTALISTS; run theory LHE events through the data analysis simulation

Recasting

We are working in a tough (and fun!) subfield...

- Can recasting work to better than factor of 10? When do we need it to work better than factor of 10?
- ***Should*** it be easy to recast this stuff? Maybe we're just inviting novices to make errors?
- Workshop to help train young theory experts?

Clearly, most of the recasting work should go into the most general searches

- The Big Brooms: broad & deep impact (cf. Liu & Tweedie on displaced dijets)
- Makes us focus on the big holes

Back-and-forth theory \leftrightarrow experiment needs to be faster and cruder (but still accurate!)

- and this needs to be acceptable to the experimental collaborations!!
- Rough efficiency information for displaced objects AND prompt objects
- Needs to be ok for theorists to publish with factor-of-ten uncertainties! [educating referees?]

After Run 2 and into Run 3 we can try to make recasting higher precision.

- Only final results matter!

Aside: Electron-Positron H Factory

Important for our community to assure the detectors are not mis-designed!

- Must be able to detect, study wide variety of displaced decays from Higgs
 - Especially if LHC discovers something displaced
 - Especially if e^+e^- can do better in some channels than LHC
- Also need to look carefully at non-displaced exotic Higgs decays
 - Dilepton mass resolution
 - Other issues?

Conclusions

Theory Homework:

- Go explore Hidden Valleys (and other models) with an open theoretical mind
 - Vary the QFT (or dual warped xtra dimension) in the hidden sector and explore what happens
- Are there phenomena our experimental colleagues won't find with existing/planned searches?

Experimental Situation: as promising as it seems?

- Big Broom searches: spectacular!
- Higgs-specific searches: Good start, but long lifetime only (except dilepton vertex)
- To be added: Smaller Brooms: lepton + DV, jet+MET + DV, VBF + DV
- A few others?
- Trigger losses at higher energy?

Looking good for Run 2!!