The Challenging

Diversity

of

Hidden

Quantum Field Theories

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3rd LLP Community Workshop

What Do We Know…

- About decays of Hidden Sector particles
- About production of Hidden Sector particles

?

- Not that much! We mustn't be complacent!

- This is why Hidden Valley scenario is so challenging! MJS-Zurek 2006
  - Hidden Valley: self-interacting hidden sector with a mass gap
    - Gap: from higgsing, confinement, explicit masses, or any combination

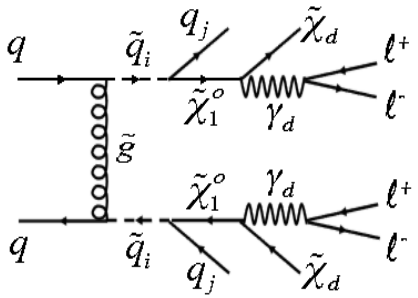
  interacting w/ SM via a "portal" (renormalizable or not)

Note:

- Numerous figures taken from talks given in 2007-2009
- Thanks to Cari Cesarotti and Matt Reece for discussions

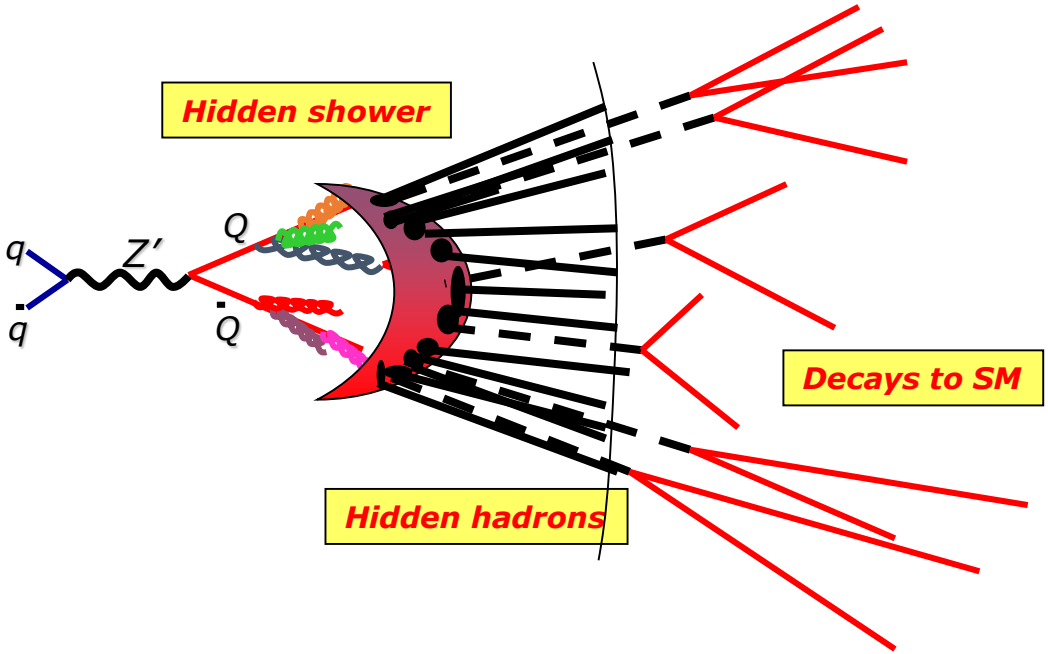
Cartoons of Hidden Sector Physics

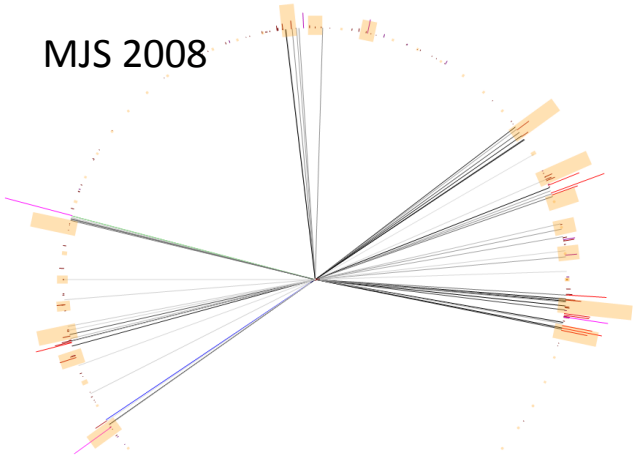
- Higgsing leads to hidden massive "dark vector bosons"



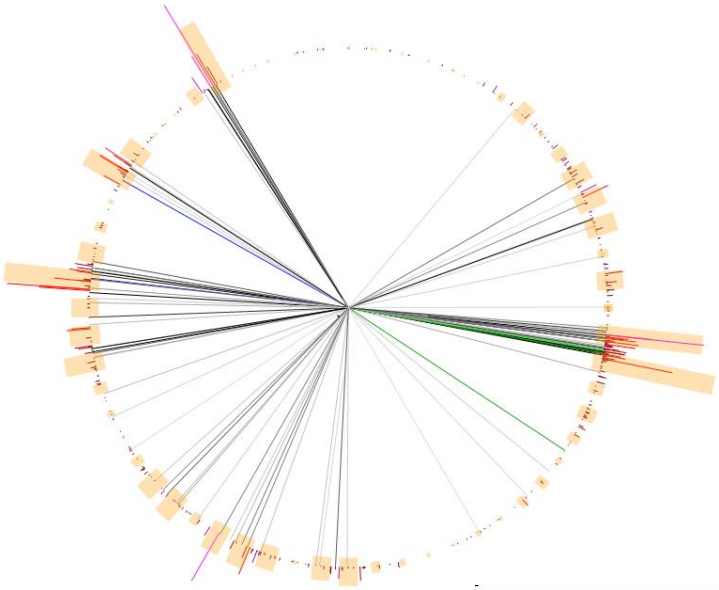
Hidden physics perturbative; easy to put into MC's

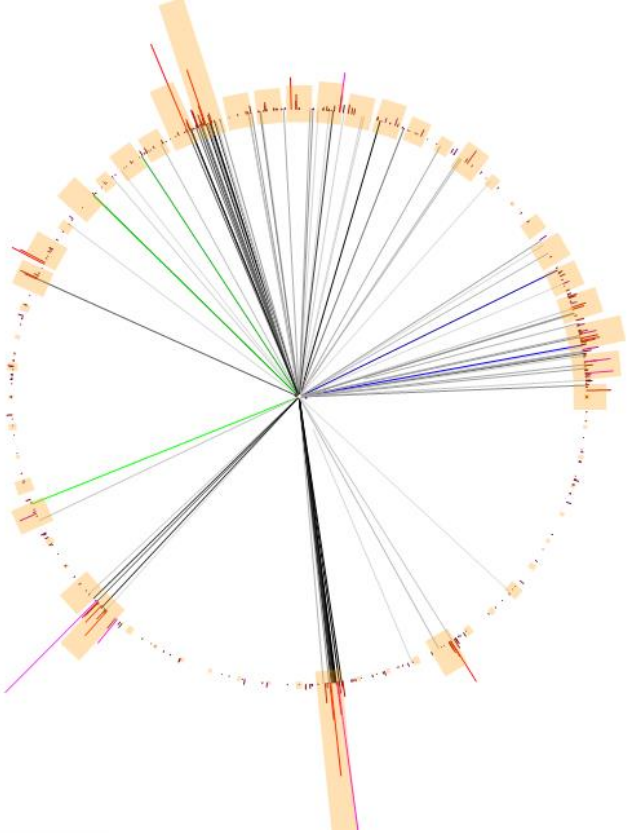
- Confinement leads to dijet of hidden hadrons

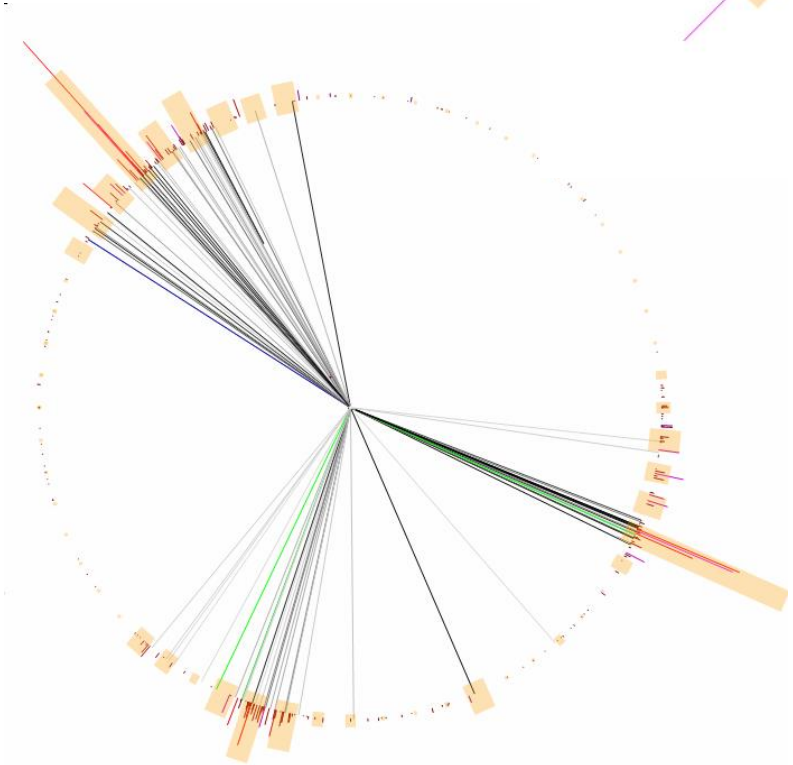




HVMC: rescaled PYTHIA; accurate for QCD-like hidden sector ONLY!







NOTE: The hidden jets are not very narrow after the hidden hadrons decay

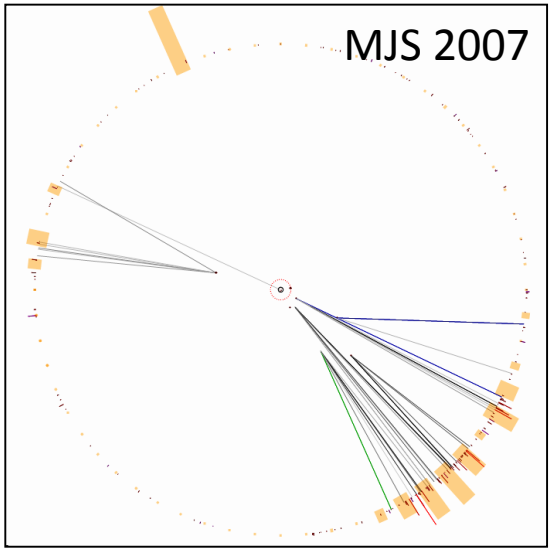
MJS 2008

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

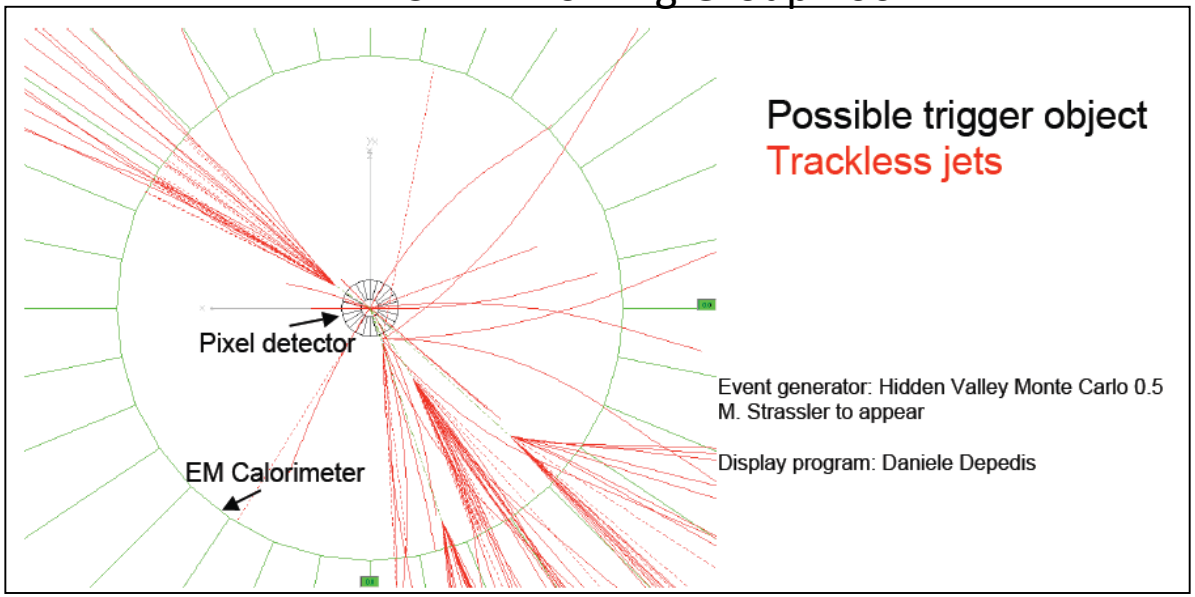
LLP Case

- The first "emerging jets"…

(cf. MJS+Zurek '06, MJS talks '07)
ATLAS studies '07-'09
Stolarski,Schwaller& Weiler '15



ATLAS LLP Working Group 2007



But Cartoons Are Just Illustrations

- These cases have been covered in talks and papers because
  - Perturbation theory is easy
  - QCD-like physics is known and easy to explain

- And in most LLP studies
  - Just one type of long-lived particle, to keep things simple

But reality is potentially very different from this… MJS-Zurek 2006

A Very Simple Example

Assumption: hidden quark → hidden jet of hidden hadrons, as in QCD

Is this justifiable? It depends.

- QCD-like theory with Z-like decay, but cascade decay before hadronization
  - The simple cartoon of Z → 2 jets implicitly assumes no cascades
  - What if Z → qq and the q decays to other quarks before hadronization

  Instead of 2 hard jets, get multiple, softer jets (as in top-quark pair production)

We know nothing about the masses and interactions in a hidden sector

- For all we know
  - there may be decay cascades in every event
  - there may be no or few events with back-to-back hidden dijets

A Less Simple Example

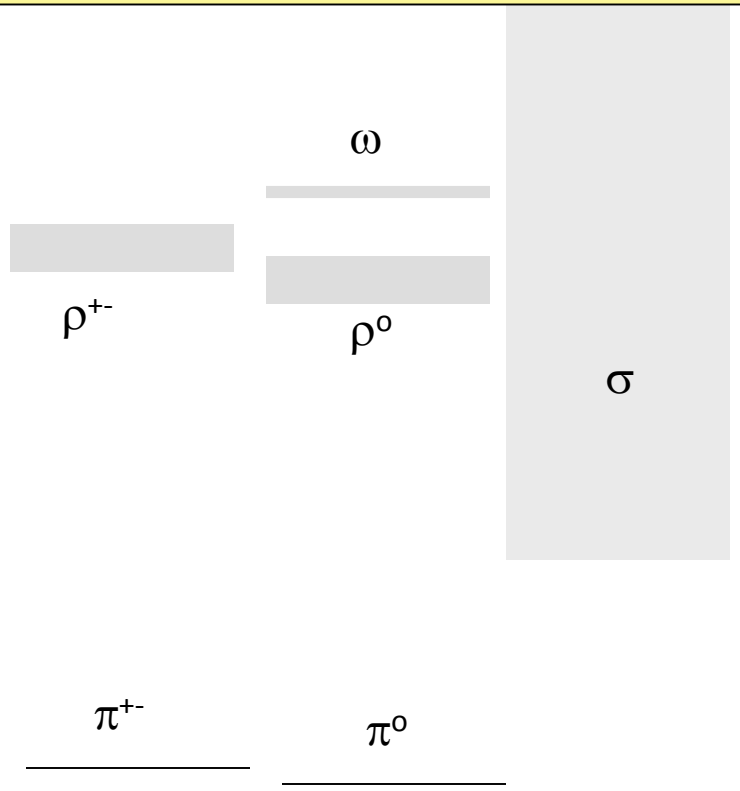
- Compare situation if QCD-like shower but
  - 3 light flavors
  - 2 light flavors
  - 1 light flavor
  - 0 light flavors
- Hidden sector resonance → hidden quark + antiquark
- In all cases, QCD-like shower forms a jet of gluons

- But now what?

HV with N colors and N_f light flavors

N_f=2

All mesons decay to pions



2 near-degenerate meta-stable particles
Completely different decays and lifetimes
Details depend on flavor violation

MJS-Zurek 2006

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

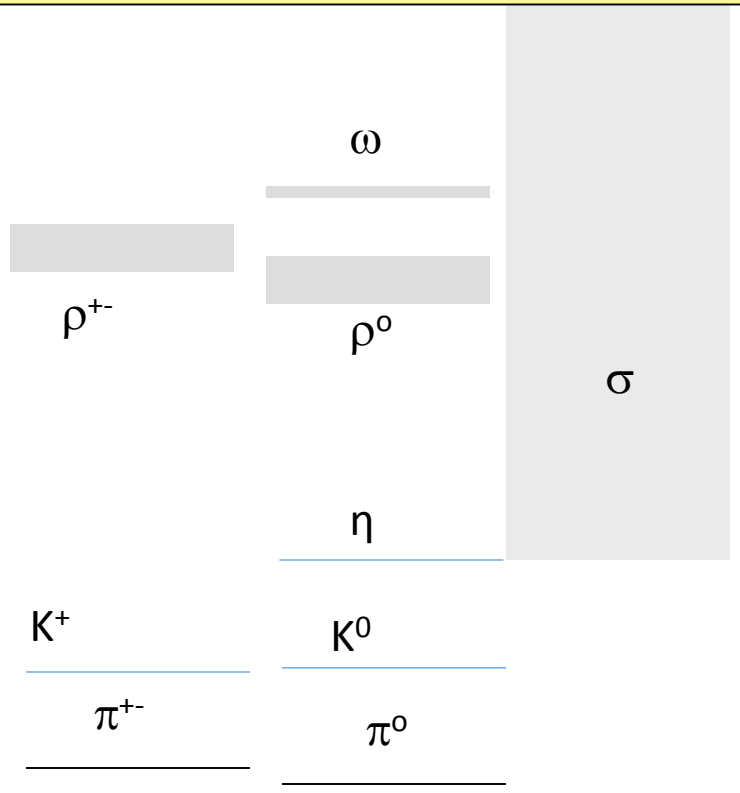
HV with N colors and N_f light flavors

More particles observable
All with different lifetimes
Cascade decays? Depends on masses, couplings

MJS-Zurek 2006

$N_f=3$

All mesons decay to pions, kaons, eta



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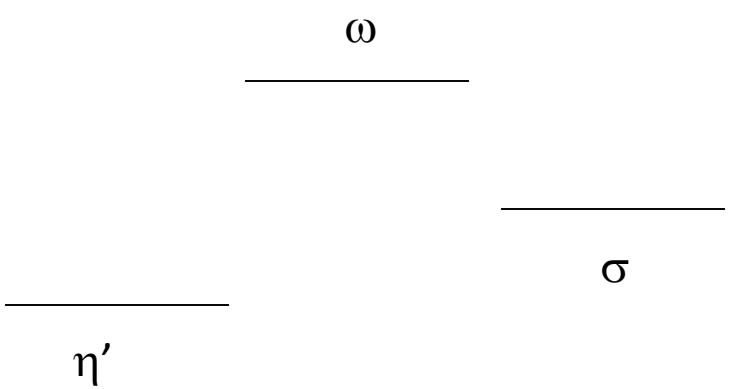
N_f=1

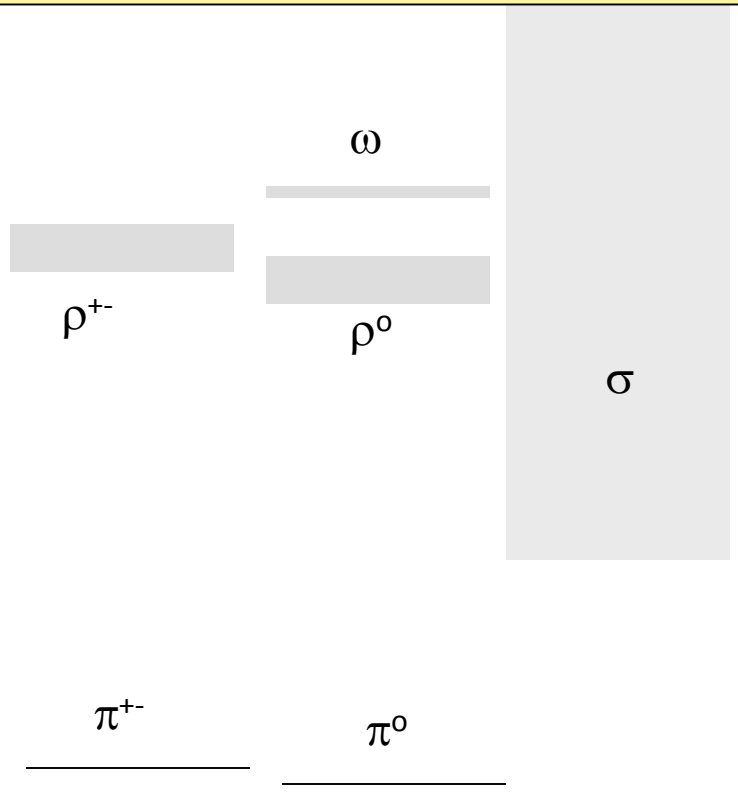
Heavy mesons decay to several stable mesons, with different J^{PC} assignments



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

N_f=2

All mesons decay to pions



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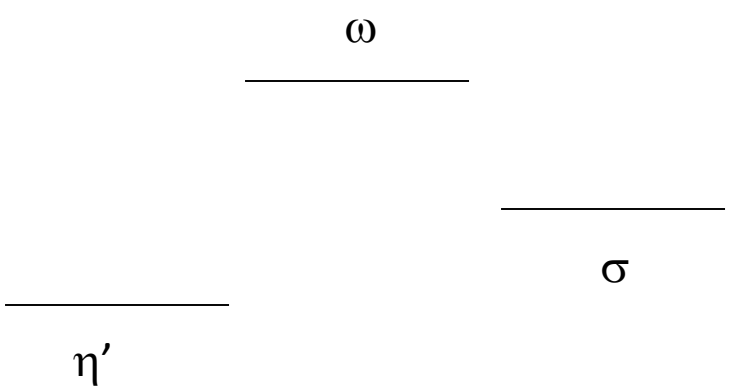

Several metastable particles including vector and scalar
Different lifetimes and different final states
Multiplicity within jets? Completely unknown.

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Spin-1 decays faster, democratic in flavor

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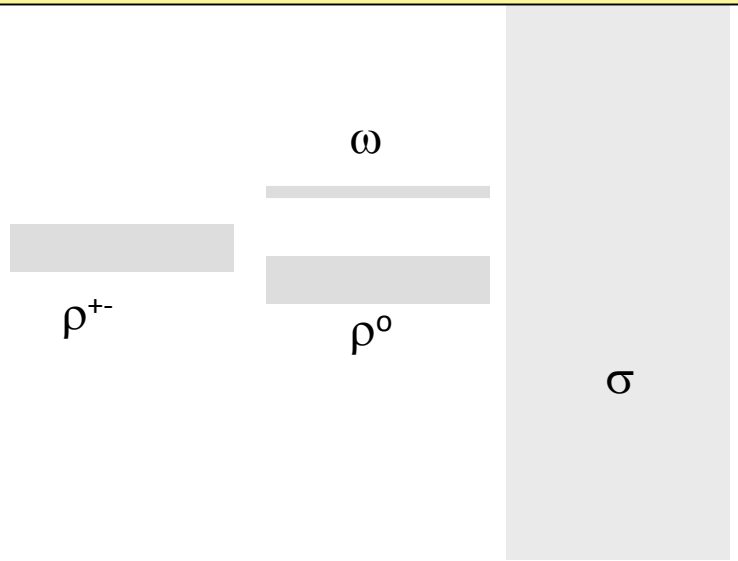
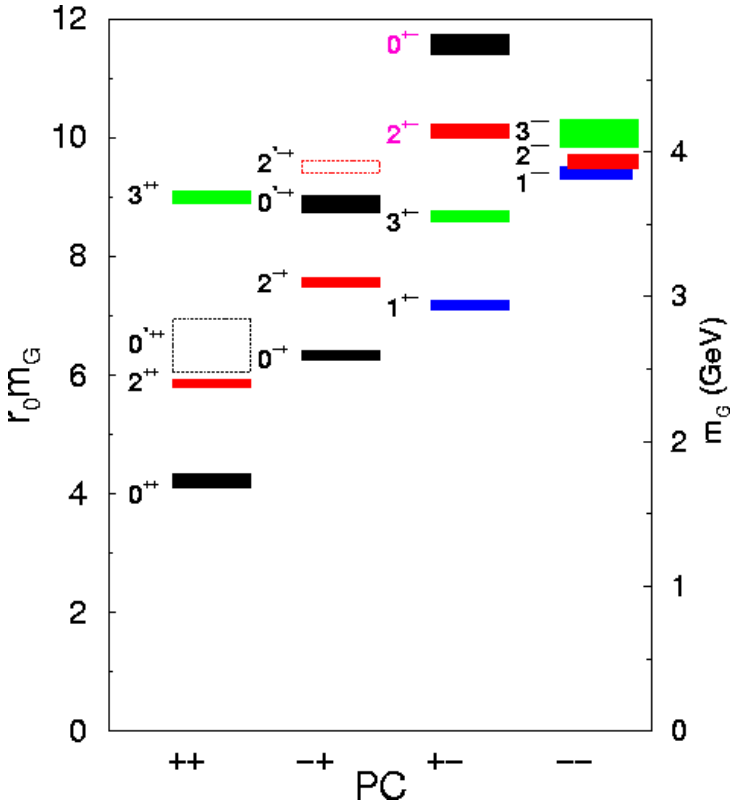


Pions are long-lived and may decay to SM particles, typically heavy flavor

HV with N colors and N_f light flavors

N_f=0

Morningstar and Peardon 99

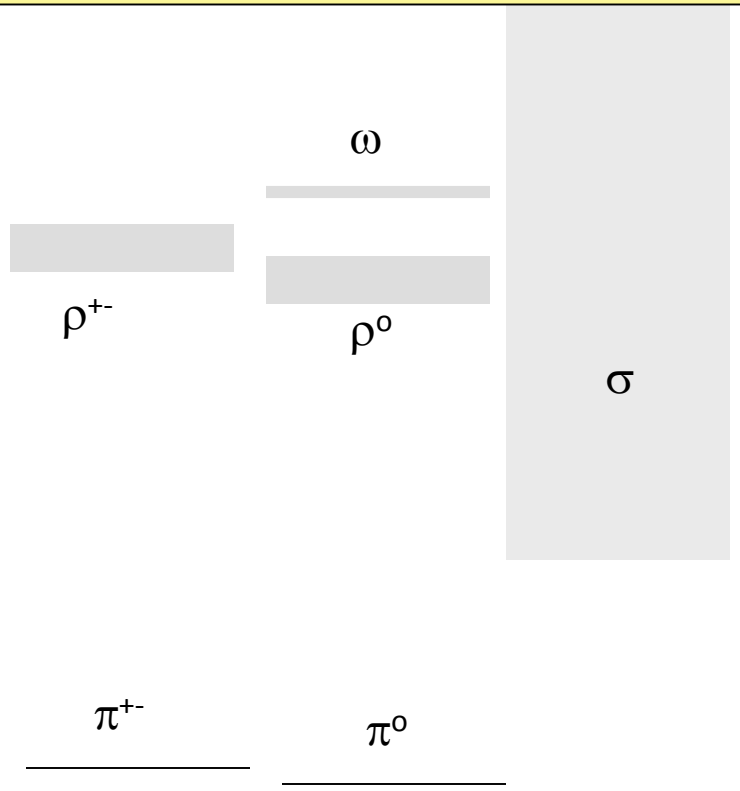


MJS & Zurek 06
Juknevich, Melnikov & MJS 09
Juknevich 10

Many meta-stable particles
Very different lifetimes
Multiplicities unknown… (and worse…)

N_f=2

All mesons decay to pions



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- In all cases, QCD-like shower forms a jet of gluons

So even with these four cases there's a huge variety…

and we've only scratched the surface…

What if I add a fermion in the sextet? In the octet?

What if we use SO(8) instead of SU(3)?

What if we have SU(3)xSU(3) with various choices of matter?

…

A Few Comments now about MCs

- If hidden physics is perturbative, MC will work
  - Feynman graphs
  - Perturbative showering
- If showering is perturbative and hadronization and hadrons are QCD-like
  - Rescaled/adapted PYTHIA/HERWIG/etc can work

That's what I did in HVMC and is what PYTHIA8 tries to do.

- But… Has anyone actually validated the PYTHIA8 Hidden Valley Module?
  - *I cannot vouch for it*
  - Does it reproduce QCD data where it should??
  - Watch out when $E / \Lambda < 25$ or so!

Meanwhile, if the hadron spectrum is quite different from QCD

- If it's just $N_f>1$ pseudoscalar mesons, can probably work out what happens,
  - but someone has to do it and then **put it into the MC**
- If it's the $N_f=1$ case, can't be precise about how hadronization makes mesons
- If it's the $N_f=0$ case, or some other case, it's much worse…

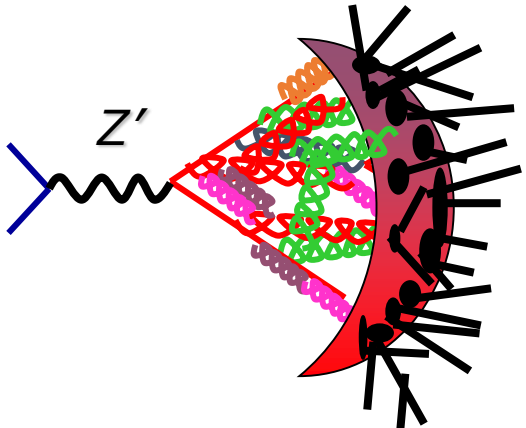
Another Cartoon

In 2002 we learned about regimes of QFT with no hard partons MJS & Polchinski '02

- Pretty clear even then that there would be no jets in such a regime
  - Instead, what we now call "suep" [soft unclustered energy pattern]
- Trend is visible even perturbatively as $\lambda = \alpha N$ ('t Hooft 73) increases

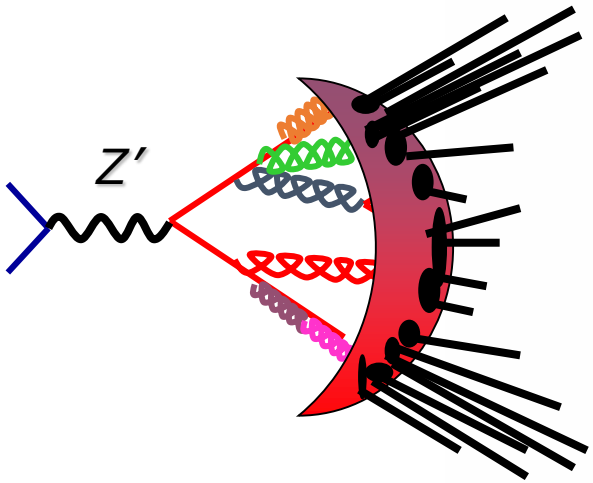
Issue became more focused in 2008

- Can argue/prove that as $N >> \lambda \to \infty$, $E \to \infty$, no jets; MJS 08; **Hoffman & Maldacena 08**; Hatta, Iancu & Mueller 08
  - **showering** is spherical in production frame
- Is the **event** spherical? Yes…
  - If there is no hadronization [no confinement, perhaps just Higgs mechanism]
  - **Or if you assume** hadronization is benign

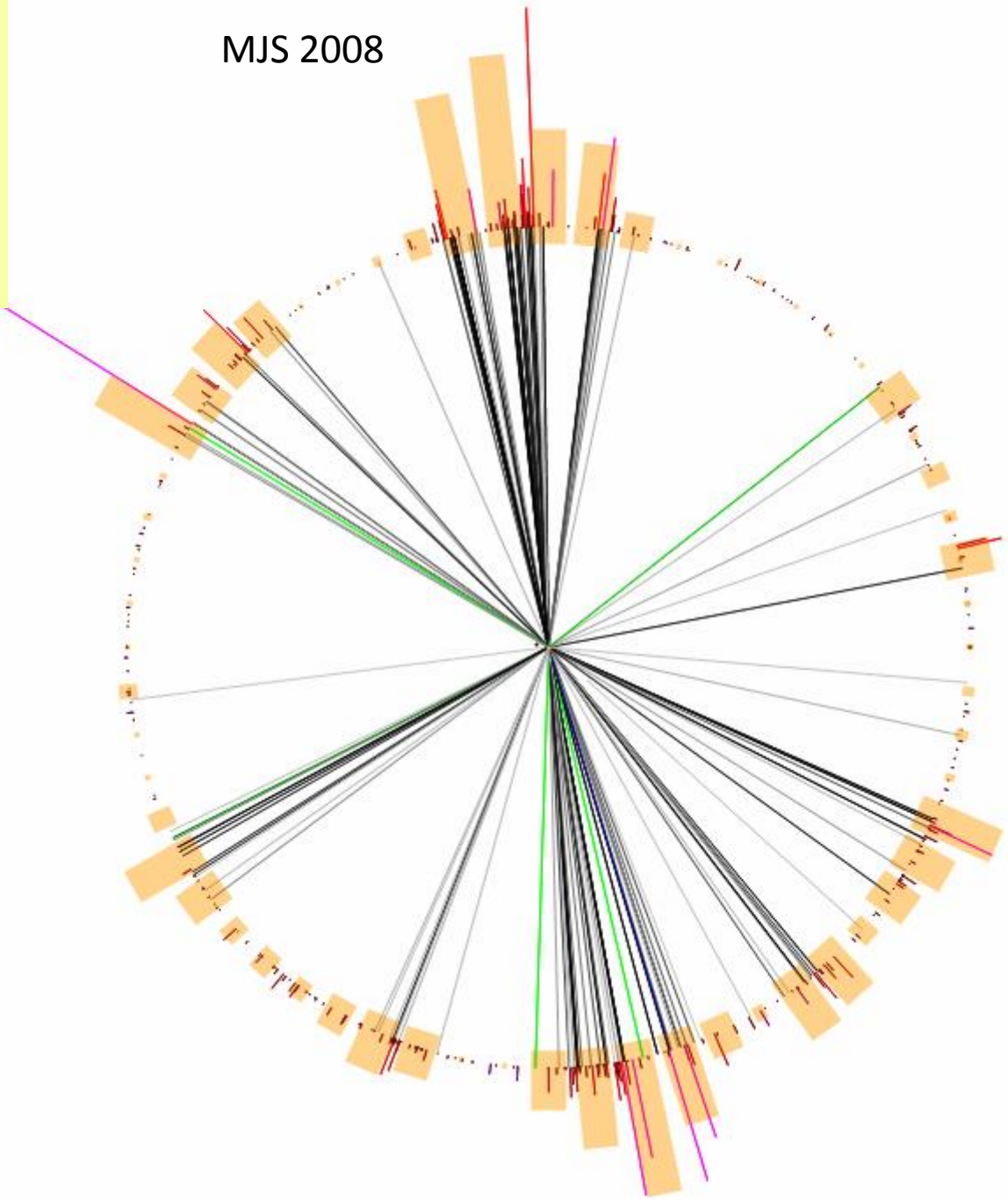


MJS '08
Slatyer [comment] '09
Knapen,Pagan, Papucci, Robinson '16

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



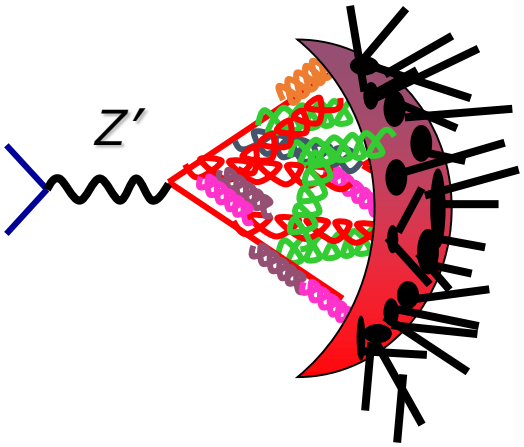
MJS 2008

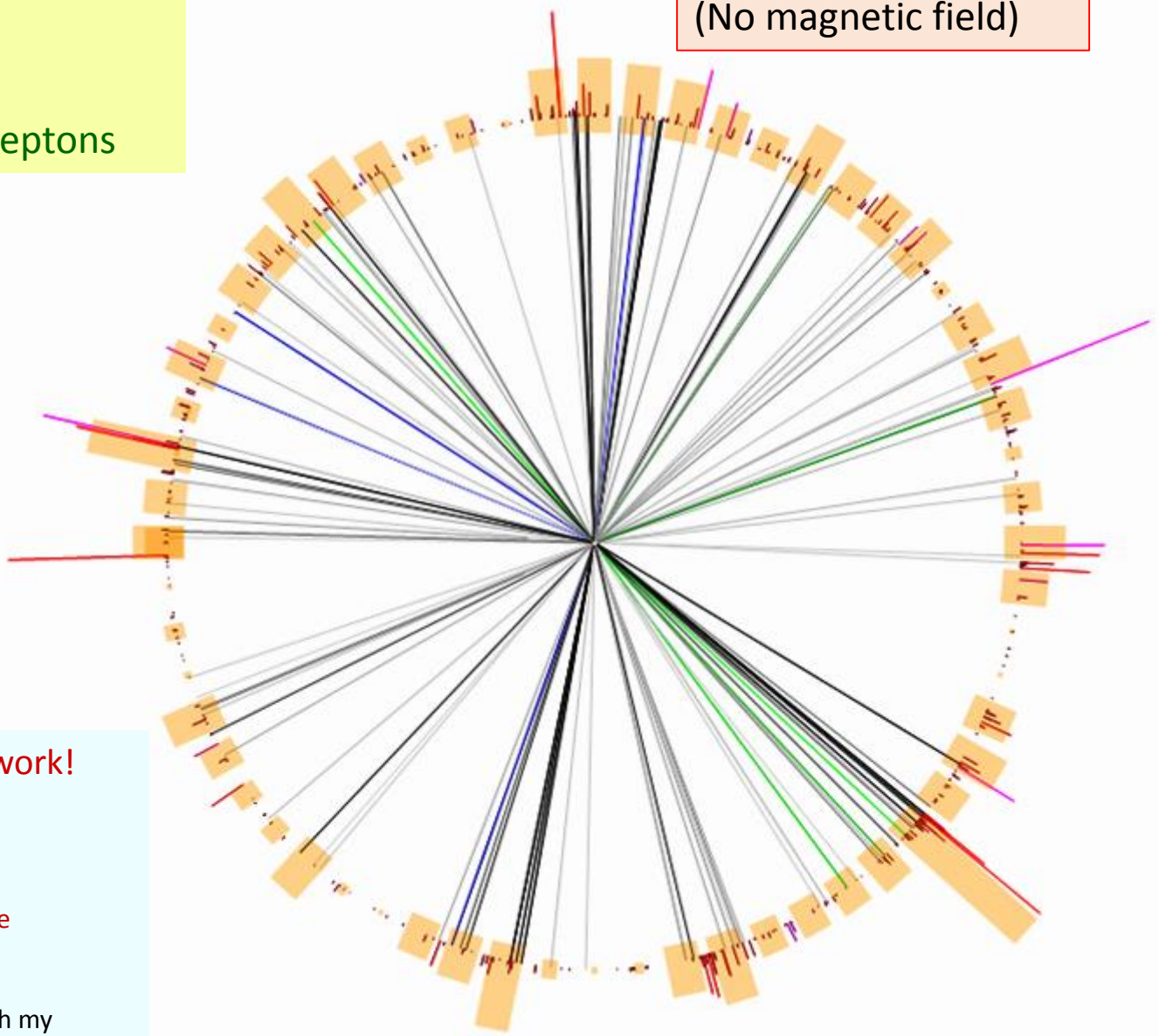


UV Strong-Coupling Fixed Point
(large anom dims)
~ 30 v-hadrons
Softer v-hadrons
~ 50-60 soft SM quarks/leptons

MJS 2008

Ancient SUEP
(No magnetic field)





Event from 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

Natural Question: SUEP to Jets

Can one interpolate from SUEP to jets?

- Wait a second… this was a cartoon suep…

- In reality there are potentially many varieties of suep
  - Some chunkier than others

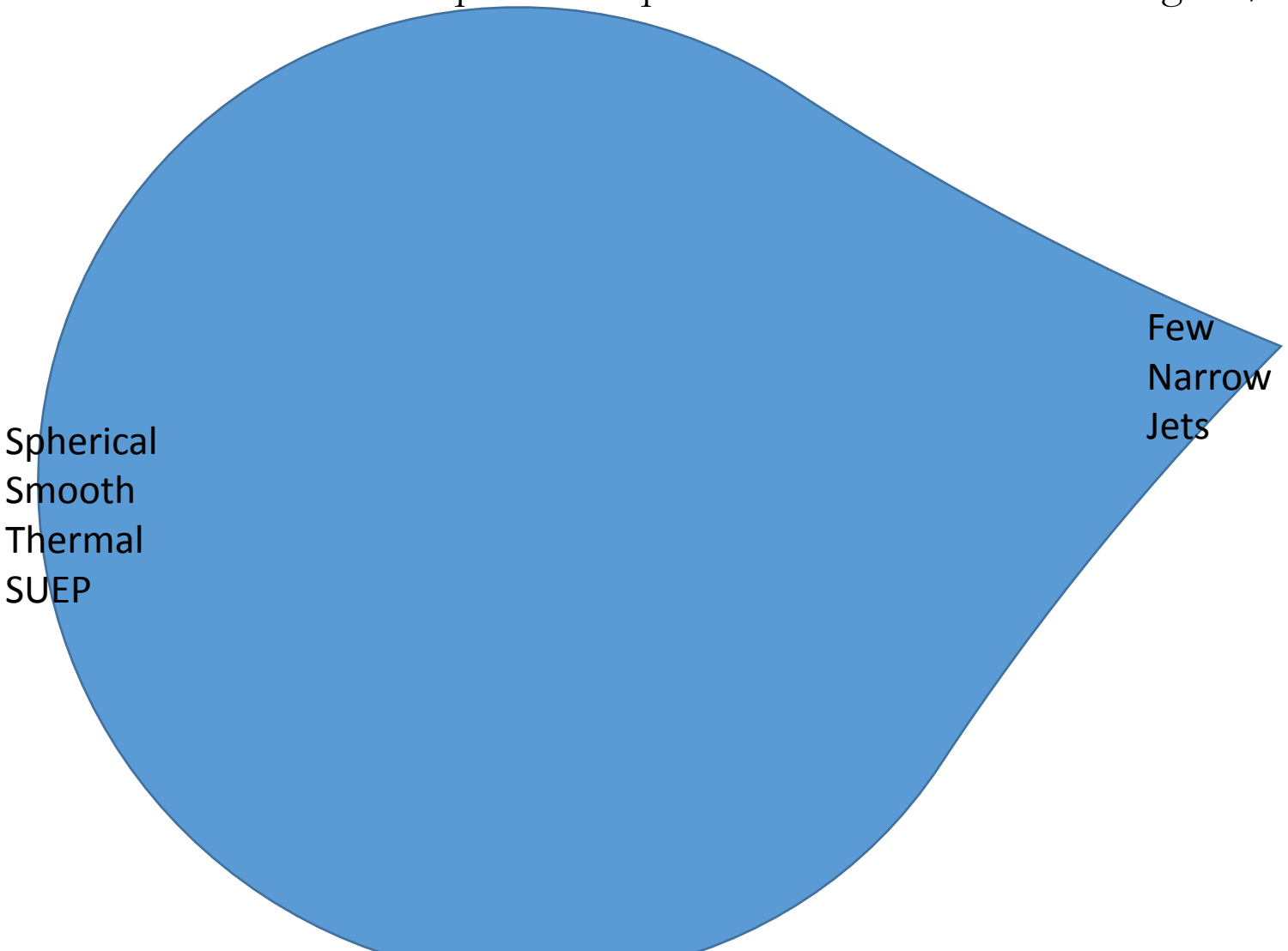
- There are even varieties of "jets" in a sense

- And important details can depends on the gauge group and matter content

So I personally do not think this is a well-posed question.

Between Jets and Suep

- The space of possibilities is almost certainly not a line
- The extreme left isn't unique and requires extreme theories and high E/m



Underappreciated Problem

- In real-world QCD, hadronization is benign
  - If E > ~10 GeV, showering pattern is preserved by hadronization
  - Quark → shower of partons → shower of hadrons

- **This is highly non-trivial!**

- We cannot assume this is the case in unfamiliar theories
- In fact it is **not** the case in some perfectly ordinary theories

- In general, hadronization may scramble what happens in the shower.
  - Showering jets may not survive hadronization [this is certain]
  - Showering suep might not survive hadronization [not proven either way]

Not an Issue if No Hadronization!

- If mass gap from Higgs mech., then no confinement and no hadronization
  - Then shower of hidden gluons freezes at Higgsing scale
  - Massive hidden gluons decay to SM if they can
  - Whatever structure is present at showering appears in SM
    - Though smeared by decays
    - And possibly very fragmentary if most gluons decay outside LHC
- So both hidden jets and hidden suep are definitely observable!

- Even then, we can ask some tough questions about suep
  - Hoffman and Maldacena: Calculation valid when $N >> \lambda >> 1 >> N_f/N$
    - Non-Gaussian fluctuations around spherical with amplitude ~ $1/\lambda^{1/2}$
      - Actually larger by 2π, but let's be generous
    - 10% corrections ➔ $\lambda = 100$ ➔ $N >> 100$?!
      - Big back-reaction on SM??
    - So fluctuations may be quite large; what do they really look like??
  - What is the momentum distribution of the particles?
    - Thermal assumption of Knapen et al. needs justification; could be wrong
      - $T < m$?? Non-relativistic?? Affects LLPs in big way (timing!!)

How to Make SUEP from Jets

- Possibly rather chunky

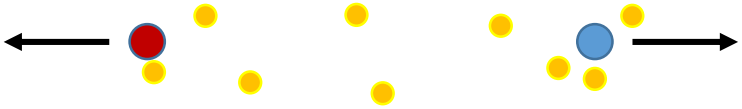
Take QCD with 3 colors and 3 flavors

1) Increase number of colors holding number of flavors fixed
2) Decrease number of flavors to zero
3) Do (1) and (2) together

Why does this matter?

How does hadronization work in QCD?

Perturbative Shower



String (flux tube) forms but immediately breaks

Rate for breaking ~ N_f/N ~ 1

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Because String Splits so Fast in Our World, Hadronization Preserves Showering Kinematics

String (flux tube) forms but immediately breaks

Rate for breaking ~ $N_f/N \sim 1$

End up with light hadrons that preserve the overall momentum distribution of the gluon-dominated shower

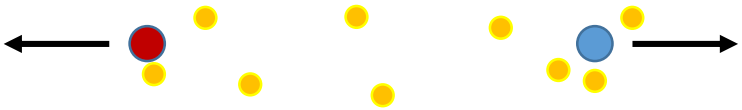
Because String Splits so Fast in Our World, Hadronization Preserves Showering Kinematics

String (flux tube) forms but immediately breaks

But what if $N_f/N \ll 1$, or 0?

Rate for breaking ~ N_f/N ~ 1

End up with light hadrons that preserve the overall momentum distribution of the gluon-dominated shower



String breaking rate becomes very slow
String slows and stops extending after time E/Λ^2
Begins to oscillate; narrow QM bound state

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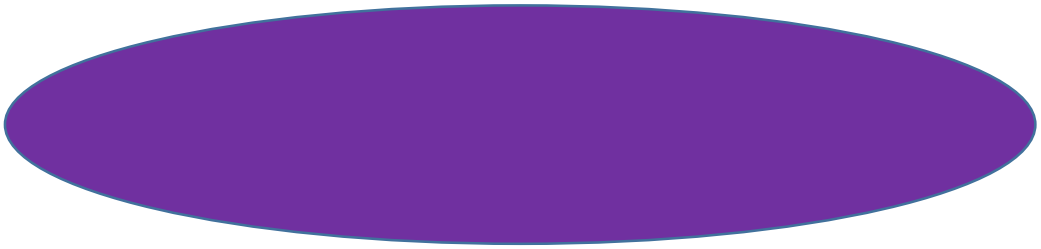
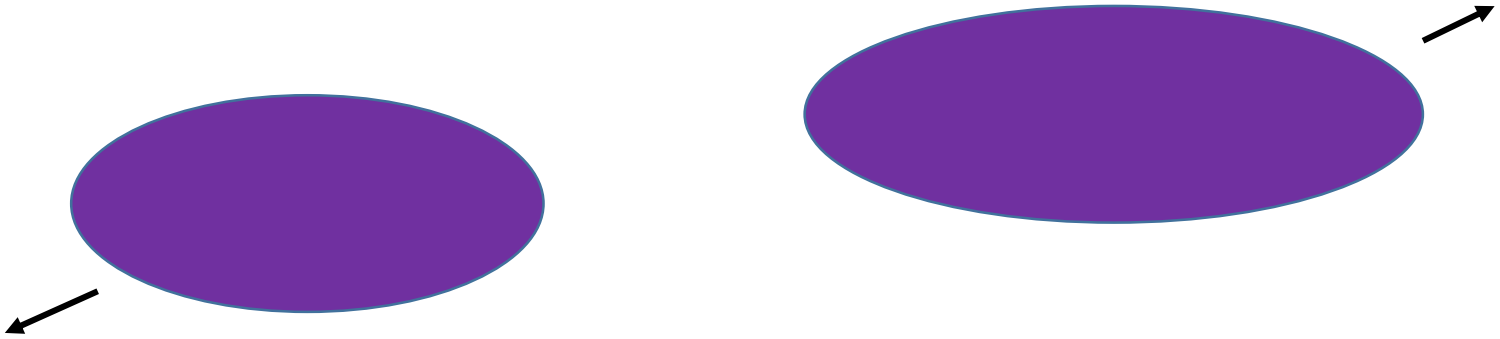
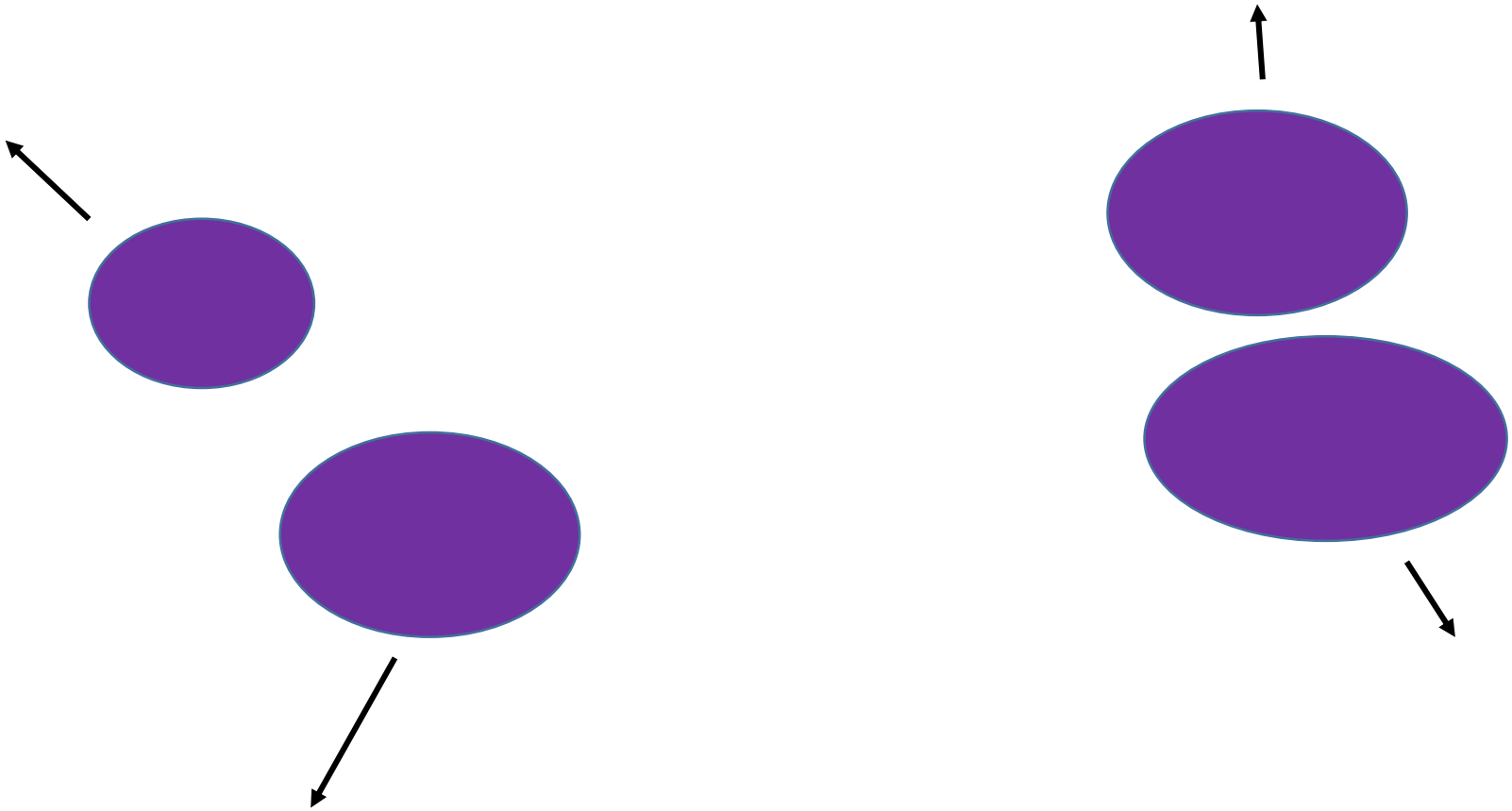
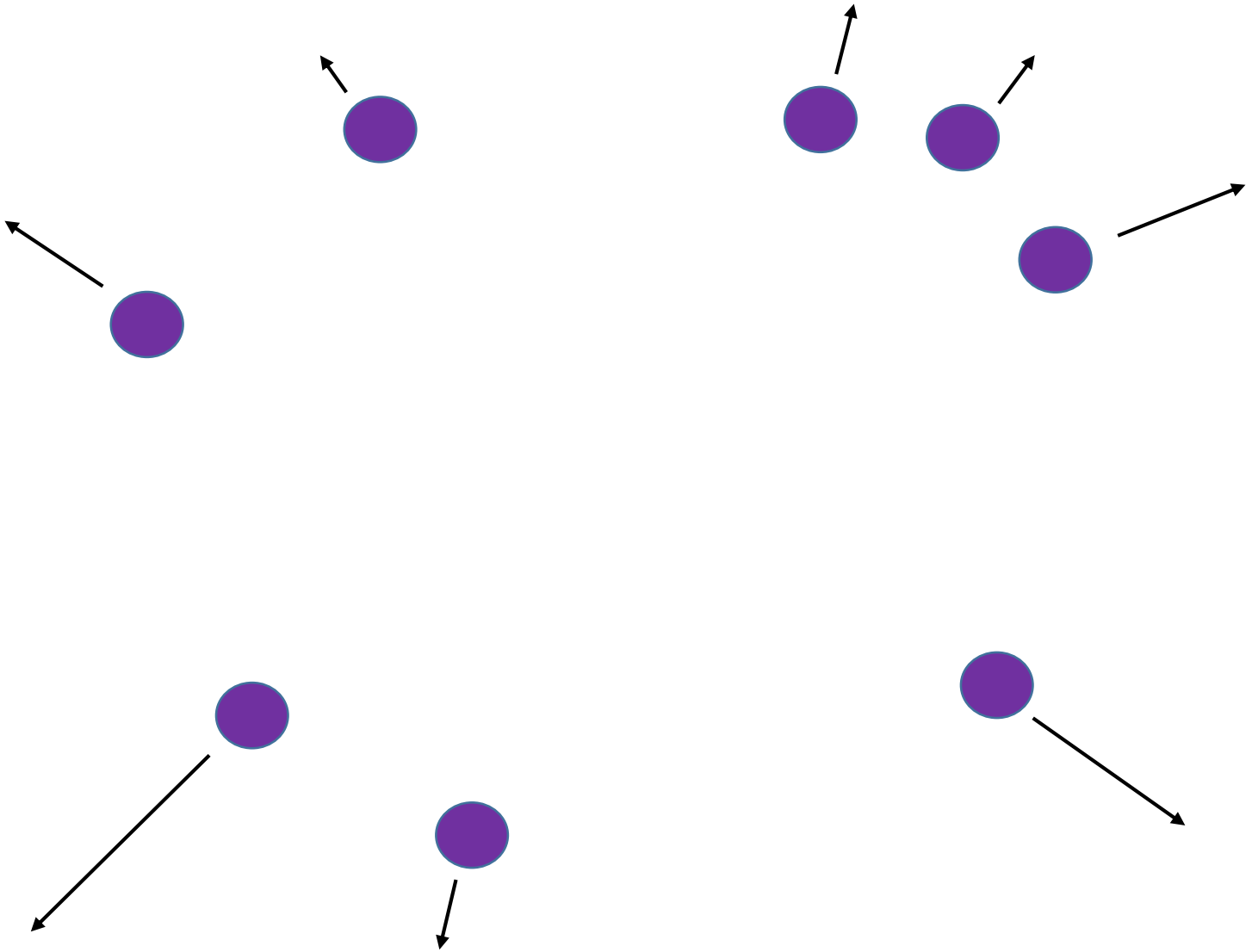


With rate ~ N_f/N (or $1/N^2$ if $N_f=0$) this heavy hadron breaks up into lighter hadrons; these, in turn, will split, and so on…

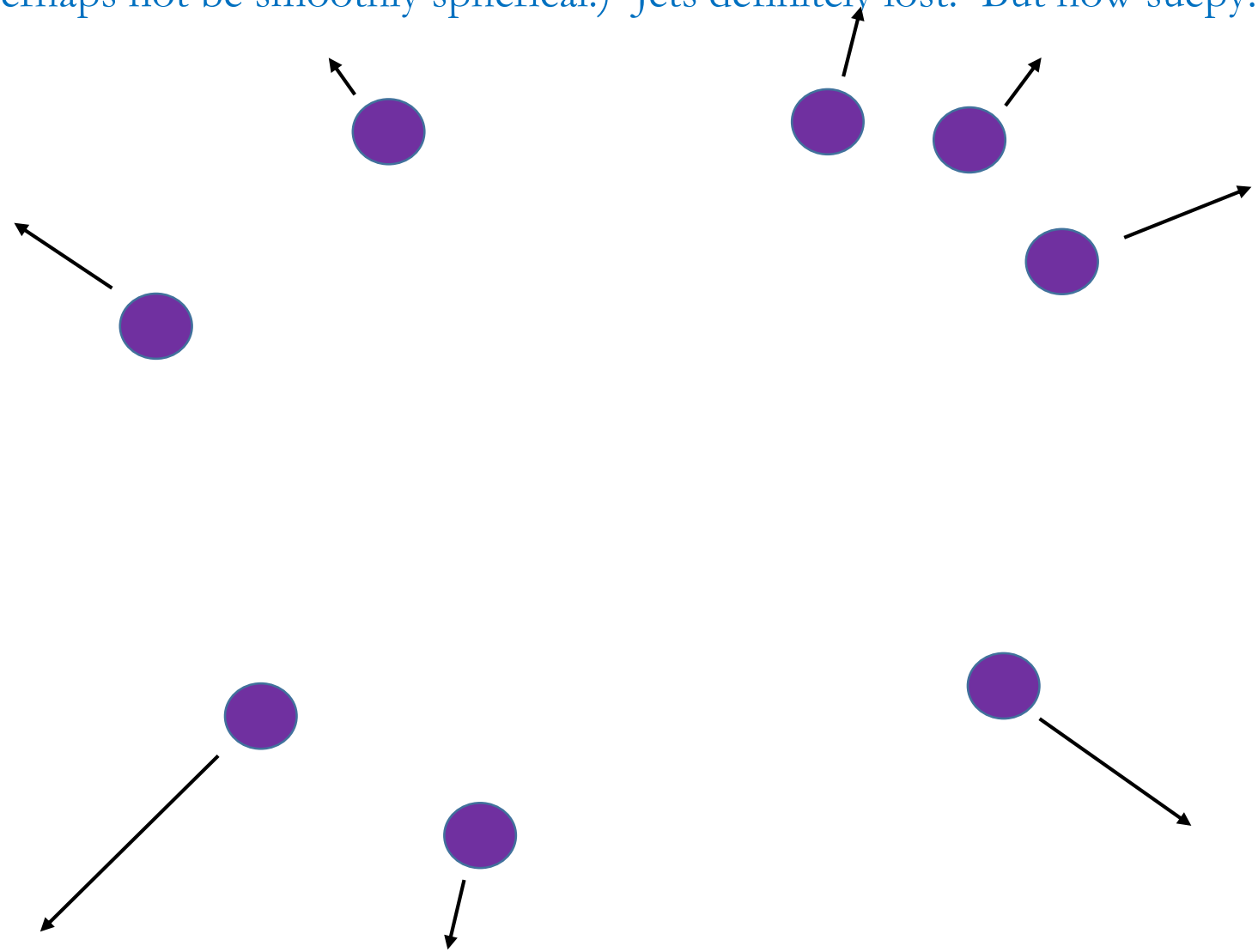




In the limit of large E/Λ, is this suep?



If the steps in the cascade decays tend to be non-relativistic – a matter of hadron splitting interactions – they tend to give events that are unoriented (though perhaps not be smoothly spherical!) Jets definitely lost! But how suepy?



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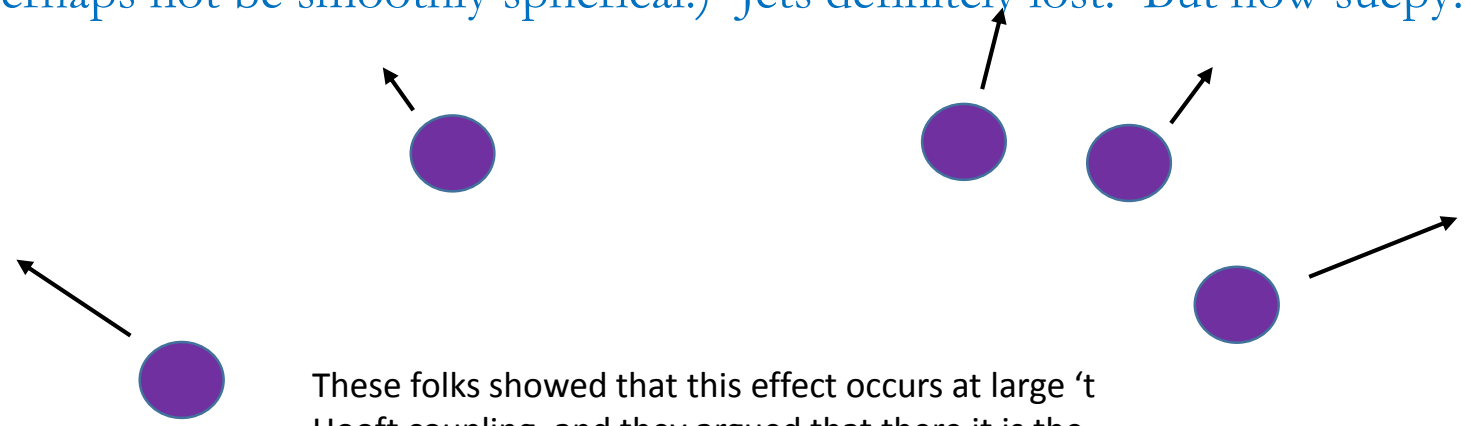


These folks showed that this effect occurs at large 't Hooft coupling, and they argued that there it is the same physics as large 't Hooft coupling suep. I don't believe it's the same. But the jury may still be out.

Cf. Csaki, Reece & Terning '08

Cesarotti, Reece & MJS ongoing study

Jets Are Fragile

In real-world QCD,

- Jets first begin to appear at 5 GeV collisions ~ 15 Λ, pretty obvious by 10 GeV

Even in pure Yang-Mills theory

- Just gluons
- Completely perturbative shower

It is far from obvious that there will be jets at E ~ 15-30 Λ

Transition from hadron resonances to continuum to jets may be markedly delayed

I do not know how this can be calculated

- No lattice gauge theory approach to this issue
- No way to design a Monte Carlo that can address this reliably
- Using QCD-like hadronization model in pure Yang-Mills would be badly wrong
- This **in addition** to the lack of knowledge re: glueball production multiplicities

Consequences: very large uncertainties in any search for high-E hidden LLP glueballs

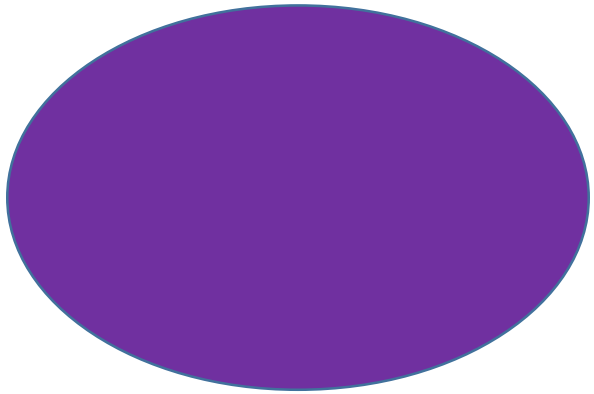
Perturbative Suep may also be Fragile

- Can hadronization make the Suep congeal? Maybe…!

Let’s assume the shower is spherical and soft suep

If string splitting rate is slow… as it is in every context where suep can be proven to exist… a single heavy metastable hadron forms.

Now what?



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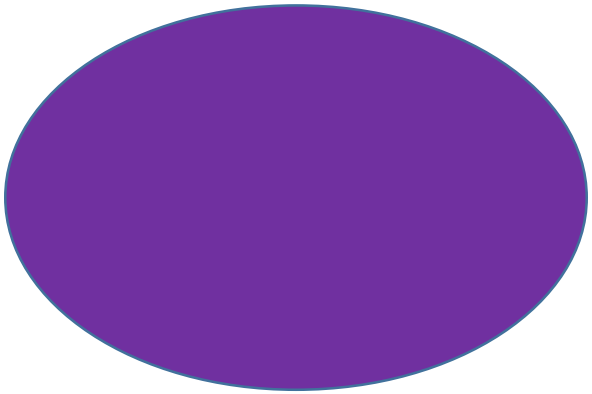
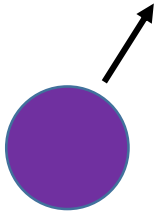
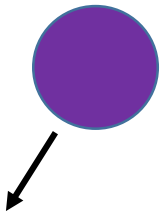


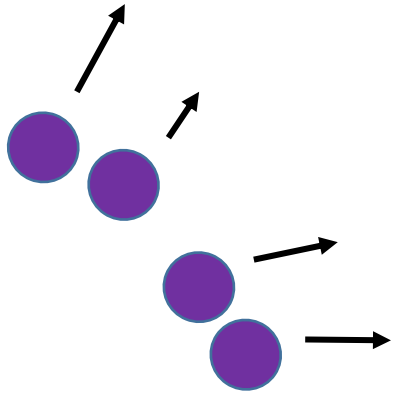
The answer depends on the hadron dynamics.
Is it universal??

What if there's a significant probability of a relativistic decay?! (an extreme but instructive case)



Hadrons with mass < ¼ parent mass.



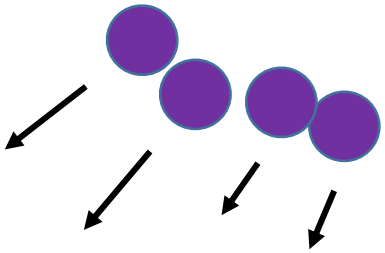


Decay products of those hadrons are collimated ---
2 kinematically-induced “jets” from a suepy shower.

Jet axis ≠ initial production axis.
But the event is not spherical or soft.

Can this happen? The jury is out.

Can it be proven to never happen? I doubt it.



Jets, Suep, and Who Knows What Else

- QFT is known to exhibit many different phenomena
- This means that there is enormous diversity in the phenomenology of hidden sectors at LHC
  - Especially since we know so little about what hidden sectors to look for
  - Any even within a model, small changes can drastically change the pheno
- In the majority of theories, we cannot calculate what will happen
  - At best we can learn a few facts that will help guide our searches
  - There are surely some phenomena that we don't yet suspect
  - There is no hope of a MC for most non-perturbative hidden sector theories

- Therefore: **we must search for LLPs in general ways,** not reliant on
  - QCD-like hidden sector dynamics
  - Unreliable and unvalidated MCs
  - Specific corners where QFT dynamics is known in an extreme limit
    - Unless all the potential implications have been worked out by theorists

Summary

Hidden Quark or Gluon → Hidden Jet of Hidden Hadrons → Visible Jet ?

- Obviously:
  - Only if the parton does not decay before hadronization
  - Only if E >> Λ (and how much larger? Not known in most theories)

- Less obviously
  - Depends on showering
    - Showering need not be narrow-jetty as in QCD
    - May even be soft and spherical in an extreme limit
      - With large corrections in most plausible situations
  - Depends on hadronization
    - Does hadronization preserve or scramble the physics of showering?
    - What is the fragmentation pattern for a particular theory at energy E?
  - Depends on how hadrons decay (varies widely) and on hadron momentum
    - Makes a jet spread out

- SUEP is observable if the theory is Higgsed;
  - but in confining theories, it probably depends

Implications for LLPs Research

- MCs will not reliably cover HV territory, and many MCs won't be reliable
  - Theoretical knowledge isn't even **close** to what we need
  - Question all claims to the contrary

- Multiplicities (total and by particle type) are often unknown
  - Low multiplicity (1!) a big issue for LLPs; need searches covering this case
- Energy distributions for non-perturbative processes are rarely known
  - Slow LLPs raise special concerns; could this dominate??
- Angular distributions are often unknown
  - This is not always a problem for LLPs
  - Except maybe (in limited cases) when typical LLP is inside prompt decay

- Soft spherical SUEP is not entirely well-defined, needs more nuance
  - Need more details, or at least more clarity on what is not known

- **LLP searches need a model-independent approach!**