Theory and Simulation Challenges

for

Hidden Valleys / Dark Sectors

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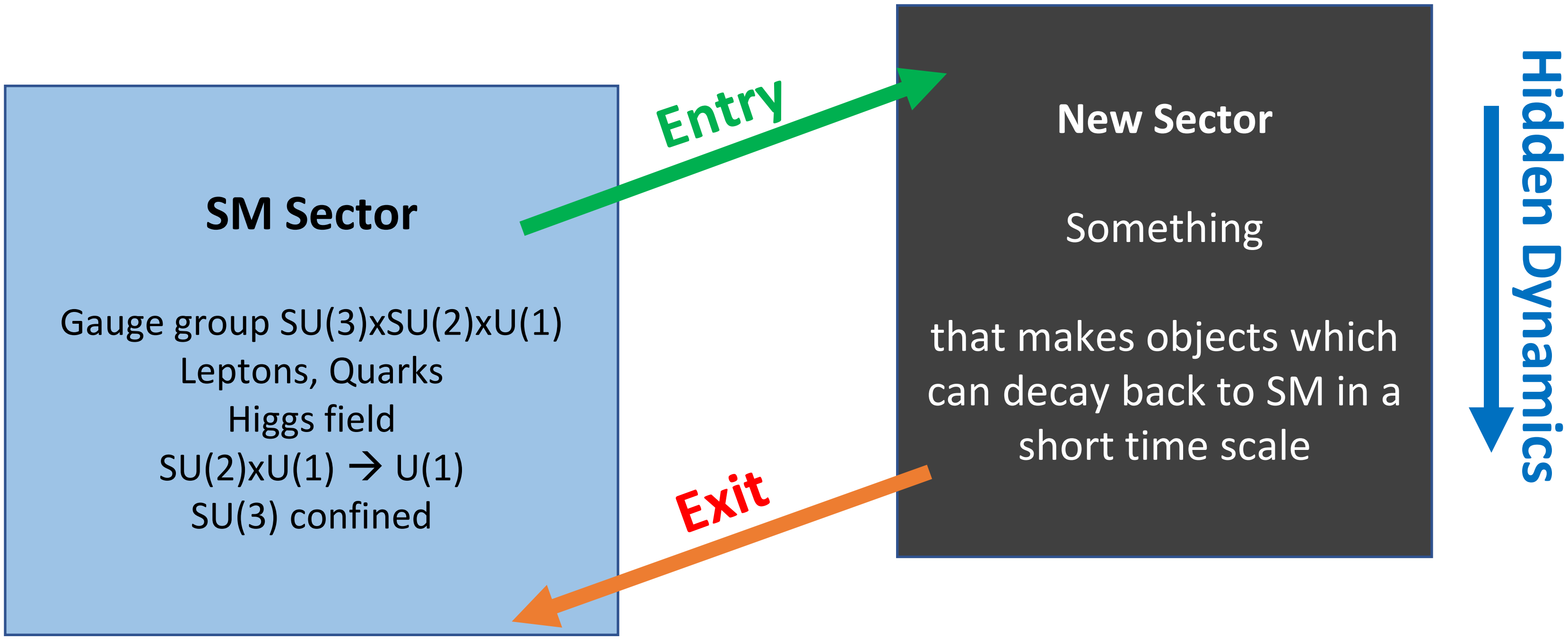
Hidden Valley / Dark Sector



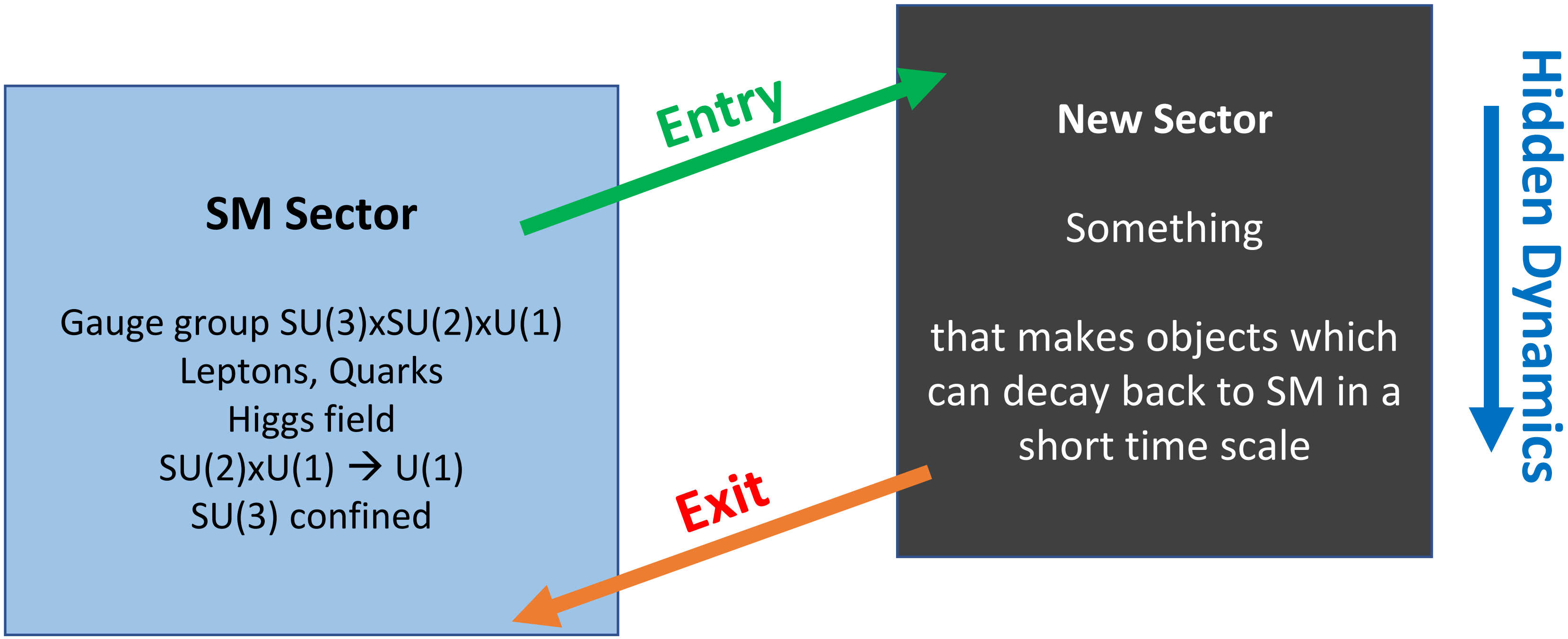
MJS & Zurek, 2006

- Entry portal and exit portal may be different or the same
- New sector may be new particles/fields, new spacetime, or both
- Rather few collider/cosmo/astro constraints on new sector or even entry/exit portals

A vast continent of theories: overwhelming!

(but that's our problem; we have to solve it)

Hidden Valley / Dark Sector



Fortunately, some generic predictions *(any one model may not have all of them)*

MJS & Zurek, 2006

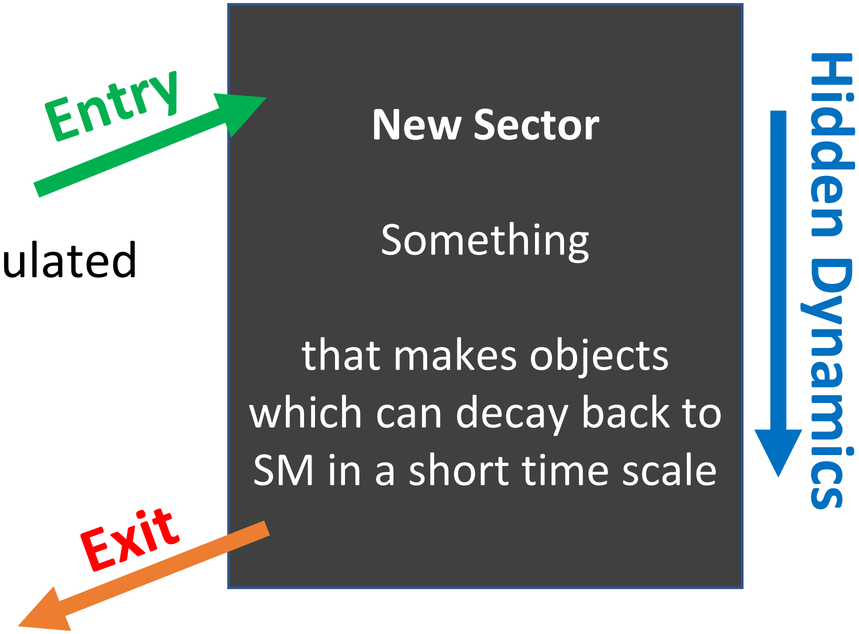
1. New neutral particles, possibly many, potentially quite light
   - decaying to neutral combinations of SM particles [resonances, endpoints]
2. Possibly high multiplicity
3. Possibly clustered
4. Possibly long-lived **[[LLP!]]**
5. Production: rare SM-particle decays or common BSM decays

Still, huge range of models
- Hard to ensure complete coverage
- Want good model simulations

A Continent of Theories: How to Search?

Entry and Exit:

- usually can be calculated/estimated and simulated
  - Production usually perturbative
  - Decay often perturbative/semi-perturbative
  - CAUTION: exceptions exist



Hidden Dynamics:

- can be anything known or unknown
  - Many known cases can't be calculated/estimated
  - Even of those that can, many cannot be simulated yet (or ever?)

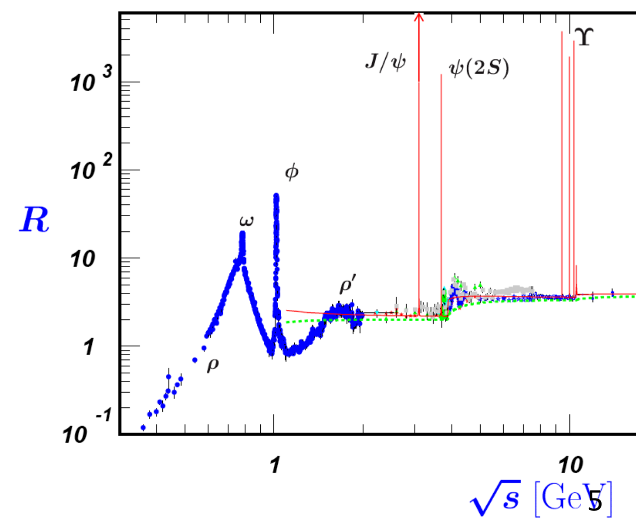
Often No Special Simulation Needed

If Feynman diagrams suffice, then Madgraph + standard Pythia (or similar) is fine

1. **Theory is weakly coupled at all scales:** calculable
   - HV/DS example: $p\, p \rightarrow H \rightarrow \gamma_D\, \gamma_D \rightarrow e^+\, e^-\, e^+\, e^-$

True for all simple LLP benchmark models

2. **Theory can be described using weakly-coupled effective theory:**
   - Analogy: $e^+\, e^- \rightarrow$ *hadrons*
     - $E > \sim 2$ GeV, many pions; need simulation: Pythia/Herwig showering/hadronization
     - $E < \sim 1$ GeV well described using pion EFT with $\rho/\omega/\varphi$ resonances
   - HV/DS example: QCD-like Sector
     - If $m_{Z'} >> \Lambda$ then $p\, p \rightarrow Z' \rightarrow$ *many* π_D (need sim.)
     - If $m_{Z'} \sim$ few Λ then $p\, p \rightarrow Z' \rightarrow \pi_D \pi_D$ (EFT sufficient)
   - HV/DS example: Fraternal Twin Higgs
     - If $m_H >> \Lambda$ then $p\, p \rightarrow H \rightarrow$ *many v-glueballs* (need sim.)
     - If $m_H \sim$ few Λ then $p\, p \rightarrow H \rightarrow G^0\, G^0$ (EFT sufficient)



Often No Special Simulation Needed

Usually best to use simple benchmark model whenever possible!

- A simple benchmark interpretation is easy to simulate, constrain, recast

- Especially if seeking LLPs via **one or two isolated LLP vertices**
  - HV/DS example: $p\ p \rightarrow Z' \rightarrow$ jets of hidden π_D with lifetimes of **100 m**;
    - will likely only observe 1 vertex per event
    - Complexities of the signature are lost to the search; no gain in including them
      - Maybe could use: $p\ p \rightarrow S \rightarrow \pi_D \pi_D$ (with long pion lifetime.)

Caution: simple benchmark models don't cover all simple signals

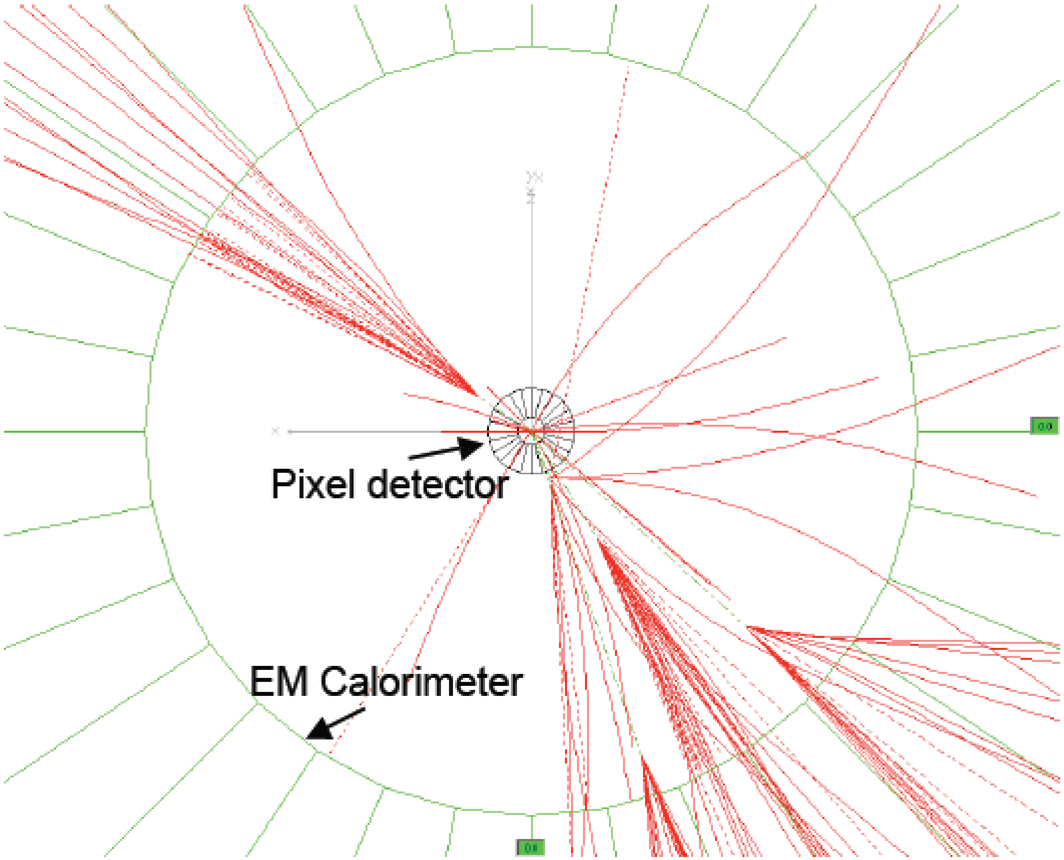
- Many models can give two qualitatively different vertices and/or MET
  - HV/DS example : p p $\rightarrow Z' \rightarrow h_D\ \gamma_D \rightarrow \pi_D \pi_D\ \gamma_D \rightarrow$
    - two different lifetimes, perhaps at most two vertices observed,
      different final states, may not be back-to-back

Need to be careful that simple benchmarks don't channel our thinking

But Sometimes Feynman Graphs Won’t Work

(A few fun examples from ancient history)

"Dark Shower" → "Emerging Jets" (archeology)



Effect of the magnetic field on HV events (circa 2007)

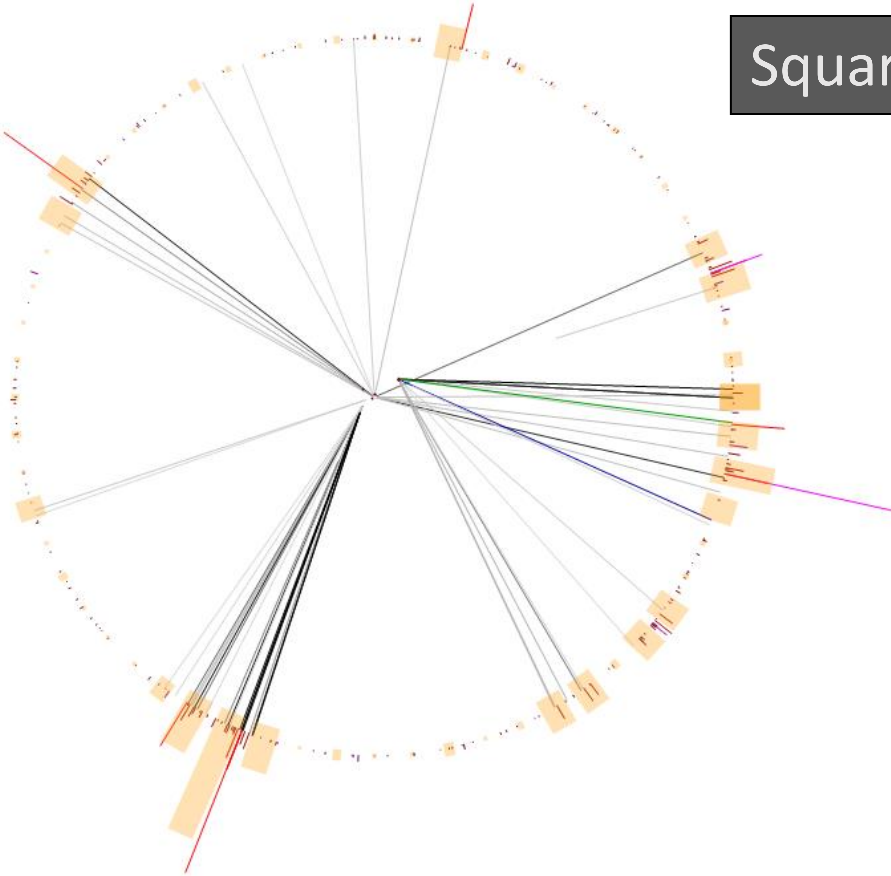
(picture courtesy of ATLAS Rome/Seattle/Genoa working group)

Event generator: Hidden Valley Monte Carlo 0.5
M. Strassler to appear

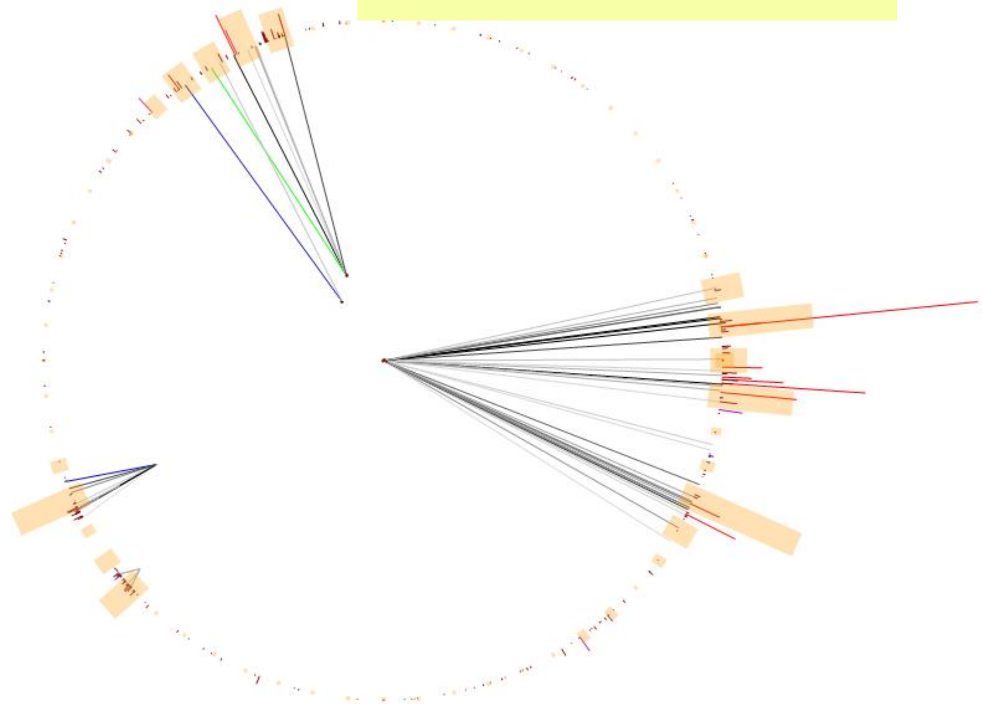
Display program: Daniele Depedis

Squark-Antisquark Production at LHC

Circa 2008



Prompt Neutralino Decay
Long-Lived v-Hadrons
>2 LLPs



Long-Lived Neutralino
Prompt v-Hadron Decay
2 LLPs

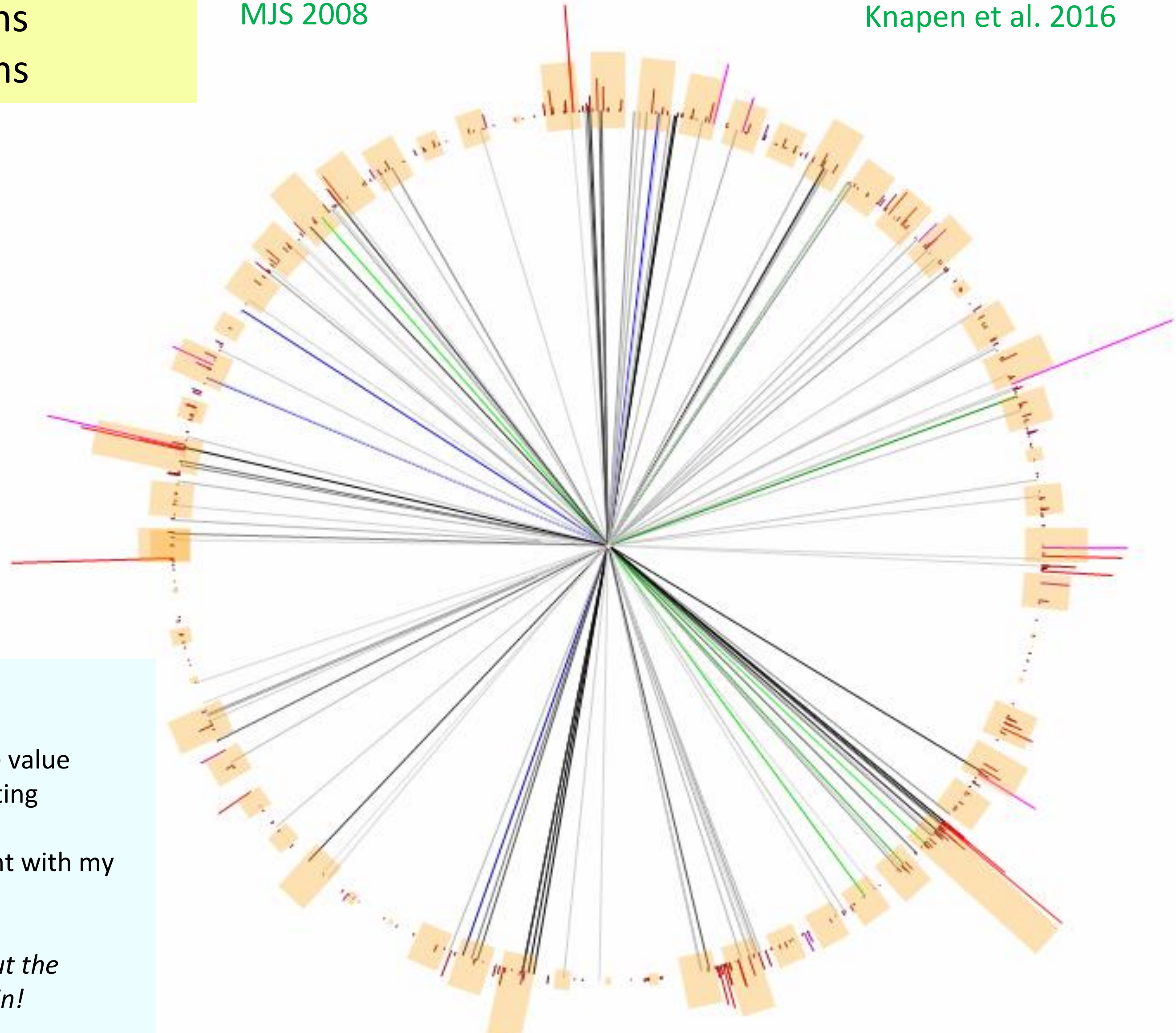
Hacked simulation using Hidden Valley Monte Carlo 1.0
Mrenna, Skands and MJS

Strong-Coupling Fixed Point
(educated guesswork!)
More v-hadrons
Softer v-hadrons

HUEPs (a bit harder than SUEPs)

MJS 2008

Knapen et al. 2016



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

Do not overinterpret! I am getting out the answer that I expect because I put it in!

SEUPs/HUEPs: soft unclustered energy pattern

When Feynman Graphs Aren't Enough

If experiment is seeking complex signature

- e.g. multiple clustered LLP vertices
- e.g. LLP vertex plus complex prompt physics

or rejects complex signature

- e.g. LLP vertex must be isolated (no nearby tracks or CAL deposits)

And hidden sector has complicated dynamics:

- Resummation (e.g. showering)
- Reorganization of Feynman graphs
  - (e.g. scale invariance, bound states)
- Strong coupling ($\alpha >> 1$ or $\alpha N >> 1$)
- Non-perturbative bound state spectrum and matrix elements (e.g. hadrons)
- Creation of multiple bound states (e.g. **hadronization/fragmentation**)
  - Dynamical, so no lattice calculation, limited theory
  - QCD Simulation based on **phenomenological models tuned to data**;

N = # colors in gauge theory
α = gauge coupling

compare/contrast Pythia (string model) vs. Herwig (pre-confinement model)

Then need advanced theoretical analysis and/or dedicated simulation

Goals of This Talk

- Focus on nearly the simplest non-trivial model, for which
  - Hidden sector has a Lagrangian similar to QCD
  - Very few parameters (2 discrete, 1 continuous dimensionless, 1 overall scale Λ)
  - Pythia 8 claims to be able to simulate it
  - An array of studies/searches have been focused on it

- Will point out
  - Limitations of Pythia 8: where it does not apply
  - Caution/advice on how to use it correctly where it should apply
  - Possible extensions to larger parameter range and to more general models
  - Implications for LLP searches in particular

Brief, Incomplete History of HV/DS Simulation

- 2007-9: Use of fragmentation models to generate events at LHC, in galaxy

Han et al. 2007 (fat jets with lepton pairs),
Meade Papucci Volansky 2009 (galactic neutrino signals)

- 2007-9: Use of Pythia 6 QCD modules to simulate QCD-like hidden sector at LHC
  (with/without strange quark)

MJS 2008 (b-rich fat jets); 2009 (conformal, unparticle)
MJS+ATLAS LLP group 2006 – 2012 (Z' → "emerging jets")

- 2010: Pythia 8 HV Module
  - New production model
  - Implements showering routine (constant coupling)
  - Calls QCD-hadronization routines (pions, rhos only)

Carloni Sjostrand 2010, with Rathsman 2011
(production of particles with color and hidden color)

Over 30 papers have used this module

- 2015: Extension to running coupling
  - Showering improved

Schwaller Solarski Weiler 2015
(emerging jets in the Carloni-Sjostrand model)

But interface to hadronization still incomplete, needs fixing

SU(N) gauge theory with F degenerate-mass quarks

- 2 discrete parameters N, F
- 2 continuous parameters **when quark masses equal**
  - α (measured at some fixed UV scale), quark mass m

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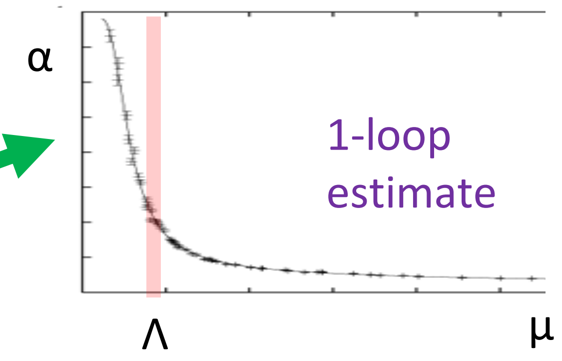
- Better to trade these for
  - 1-loop strong coupling scale Λ
    - Or confinement string tension
  - Mass of lightest hadron $m_{lightest}$
    - Pion (pseudo-NGB) in this model



$$\frac{1}{\alpha(\mu)} = -\frac{b_0}{2\pi}\log\frac{\mu}{\Lambda}$$

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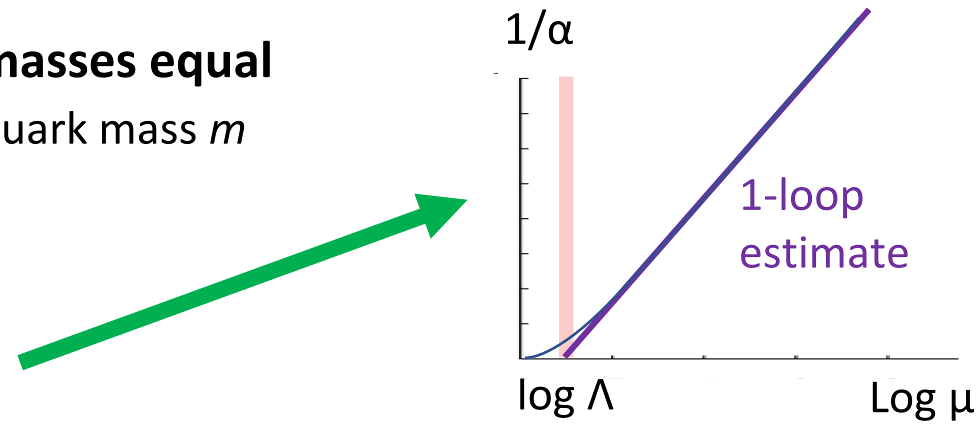

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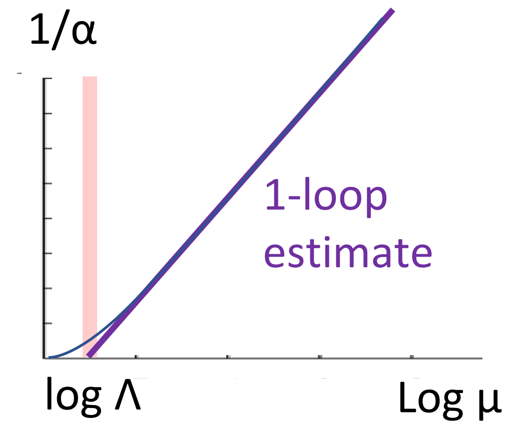

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For suitable (!!) N,F

Global Symmetries:

Anomaly ~ 1/N

SU(F)xSU(F)xU(1)$_B$xU(1)$_A$

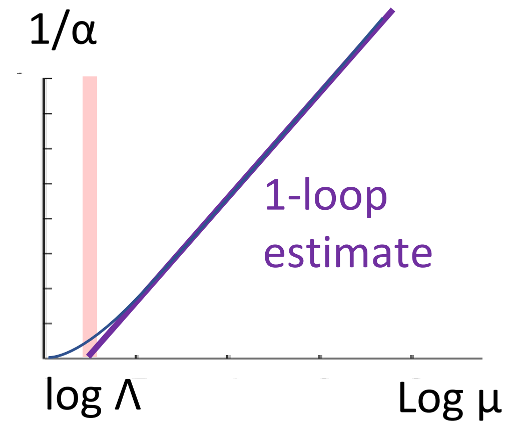
$m_\pi^2 \propto m\Lambda$
Nambu-Goldstone bosons if $m = 0$:

Spontaneous <q$\bar{q}$>
Explicit m

SU(F)xU(1)$_B$

SU(N) gauge theory with F degenerate-mass quarks

- 2 discrete parameters N, F
- 2 continuous parameters **when quark masses equal**
  - α (measured at some fixed UV scale), quark mass *m*



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Spontaneous <qq̄>
Explicit m

SU(F)xU(1)$_B$

➔ 1 dim-less continuous param $\boldsymbol{m_\pi / \Lambda}$

Summary: N, F, m_π/Λ ; overall scale Λ

- *Won't need to fix Λ*
- *Note: Additional parameters in entry/exit*

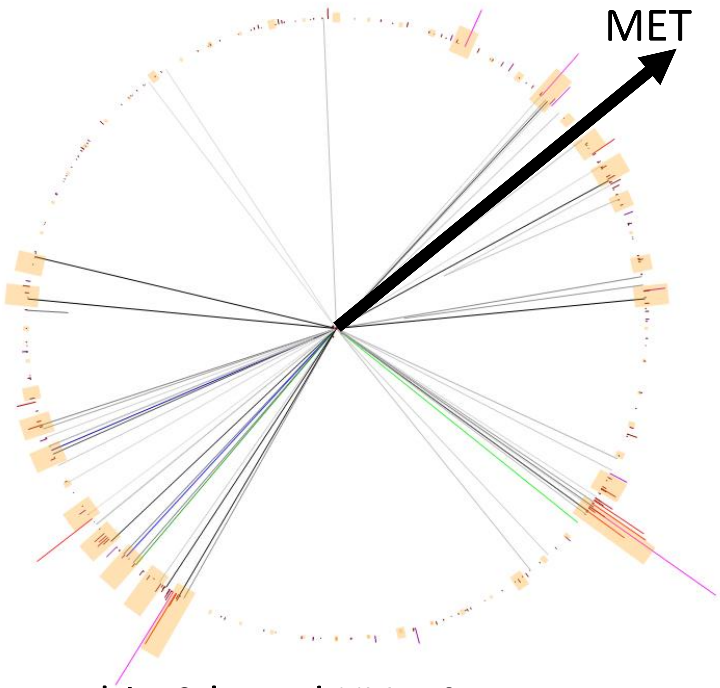
What Events May Look Like

pp→ Z' → HV/DS pions

Cohen Lisanti Lou 2015

Exploit the jet-aligned MET

Reconstruct Z' peak



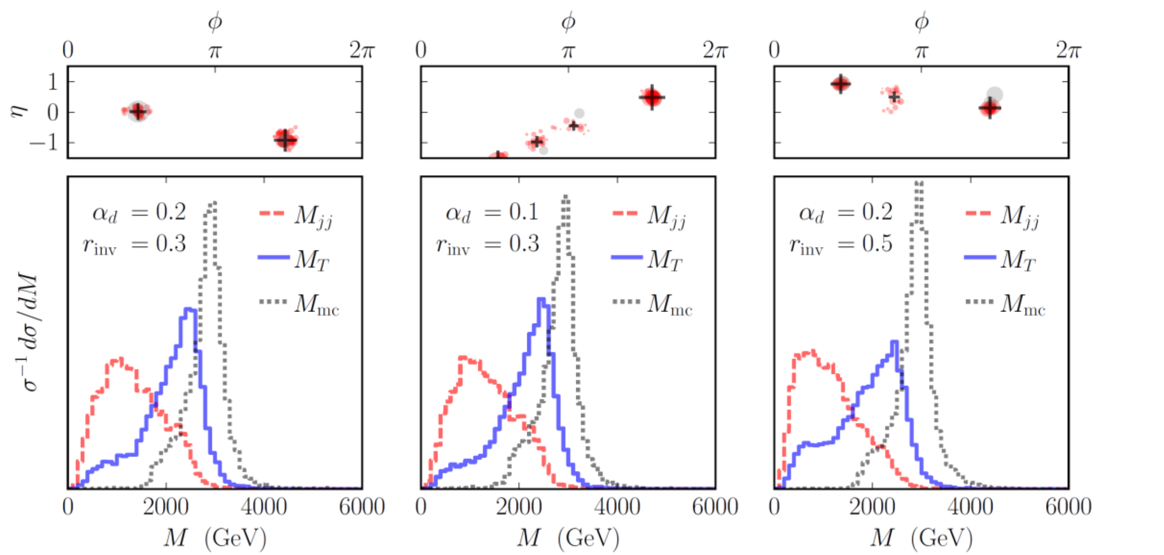


FIG. 2: Mass distributions after event selection cuts for the benchmark model in Table I, for various α_d and $r_{\rm inv}$. M_{jj} is the mass of the two large reclustered jets, M_T the transverse mass, and $M_{\rm mc}$ the reconstructed Z' mass using all the dark-matter particles in the Monte Carlo. The $\eta - \phi$ lego plots show the corresponding energy deposition in the detector. Red circles indicate visible SM hadrons, while the grey circles indicate undetected stable mesons. The crosses indicate the position of anti-k_T $R = 0.5$ jets. The relative size of each circle and cross is set by the $\sqrt{p_T}$ of the object.

Pythia 6-based HVMC

MJS 2008

Exploit the MET or HT

Exploit the heavy flavor

Reconstruct hidden pions

Pythia 8 HV Module

Carloni & Sjostrand 2010

Ideal(ish) Simulation

What SHOULD Happen in a perfect world:

- Specify N,F ; m_π/Λ ; overall scale Λ
- All other hadron masses would be known from lattice calculations: input by user
- User sets all hadron decay modes (including F^2-1 π & ρ) based on model's portals
  - Specific flavor sym breaking and couplings

$$M = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1j} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2j} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mj} & \cdots & a_{mn} \end{bmatrix}$$

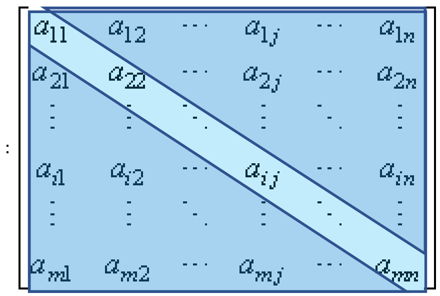
Lowest spin-0,1 hadrons in FxF matrix
- F^2 - 1 (adjoint) lightest and
- trace of matrix a heavier state.

- Production by user or Pythia or Madgraph etc.
- Pythia would
  - Do showering based on running of coupling
  - Do hadronization using a magic routine that can correctly handle any spectrum

Pythia 8 HV Module: a first attempt

Current Pythia 8 Carloni & Sjostrand 2010

- Specify N,F *[can also do U(1), separate discussion]*
- Hadron spectrum:
  - Only spin-0,1 degenerate SU(F)-adjoint hadrons (π, ρ)
    - No flavor-singlets η' , f_0; no excited states, other parities, baryons
  - Hadronization: Pythia-QCD fragmentation modules
  - Decays: adjoint splits (π, ρ) to flavor diagonal and flavor off-diagonal [hard-wired!]
    - Can specify lifetime, decay modes only for these two sets of (π, ρ)

M = 

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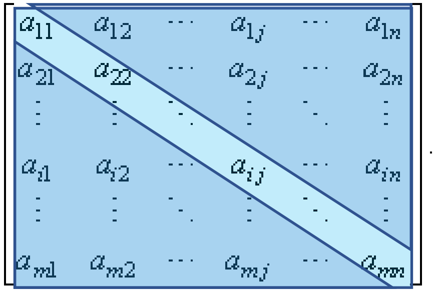

Original version: **constant-coupling *α*** showering

- Confinement scale (and dynamics) set by m_π, quark "mass" m_{qv}
- Default: $m_\pi = m_\rho = 2\, m_{qv}$

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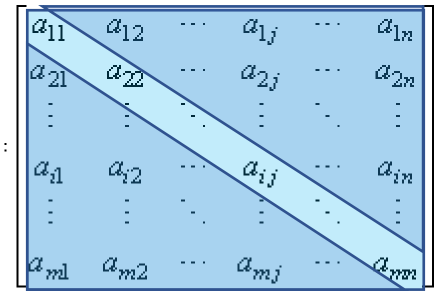

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Updated version: Schwaller Solarski Weiler 2015

- Running coupling (with dynamical confinement scale Λ) and QCD-like showering
  - Some limitations, e.g. no $g \rightarrow q\bar{q}$
- But other defaults and relations unchanged in the code

➢ ***User must impose reasonable constraints on*** m_π / Λ, m_ρ / Λ, m_{qv} / Λ
Otherwise the resulting simulation gives nonsense events!!

Pythia 8 HV Module: a firs

Known issues:

m_{qv} is **constituent** quark mass
- $m_{qv} \sim m + \#\Lambda$
- must not → 0 in chiral limit!
- NEVER take smaller than Λ

** *cf.* $\boldsymbol{m_u}$**=330 MeV** in QCD code
- used in fragmentation code
- How far can/should it increase?

Hard-wiring in code
- may fail if $\Lambda < \Lambda_{QCD}$
- may fail if $m_\pi << \Lambda$

Defaults unphysical

No warnings about validity range

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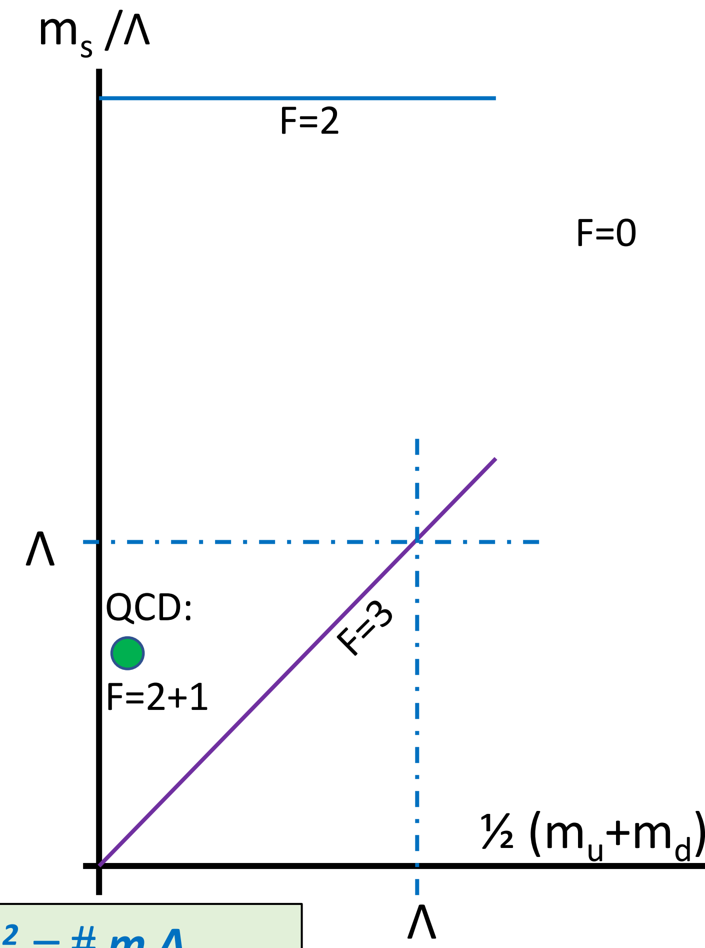
Spectrum: SU(3), F =2,3, QCD

<u>N = 3, F = 2 or 3</u>

Use QCD data to gain insight

- Compare to QCD in real world
  - N=3, F=6 but…
  - Dynamics most affected by light quarks (m < Λ)
  - So F=2+1 **dynamically relevant** quarks

Use lattice calculations to confirm, extend

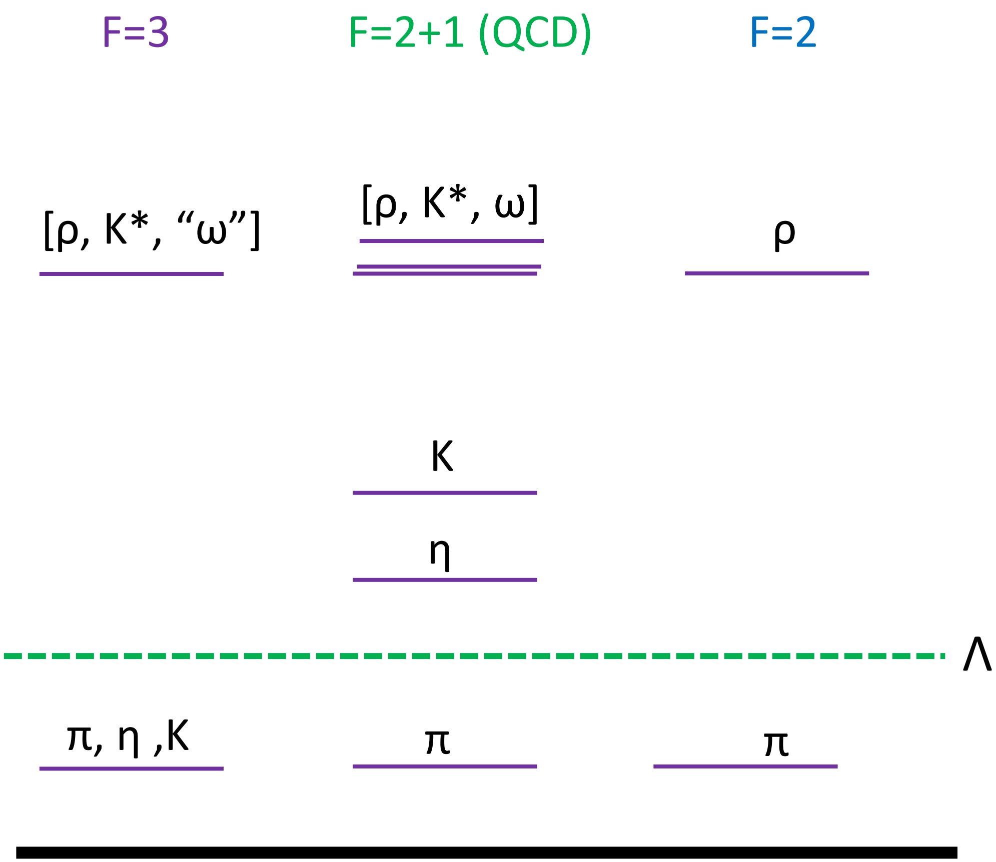


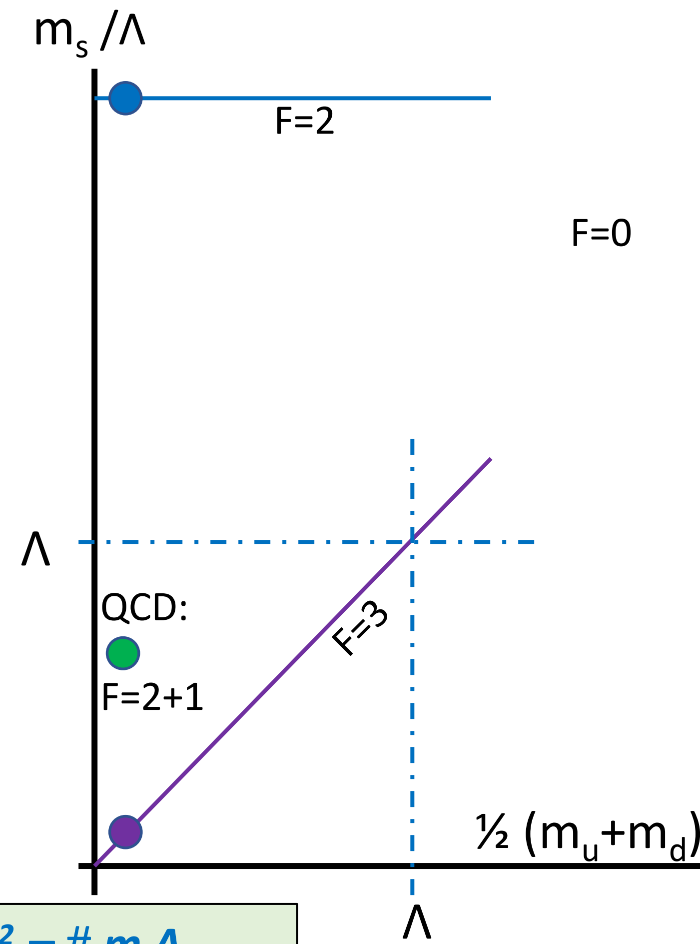
$$m_\pi^2 = \# \, m \, \Lambda$$

Spectrum: SU(3), F =2,3,QCD (at equal m_π / Λ)

Schematically: SU(F)-adjoint mesons

Not shown: many flavor-singlets: η’ , f_0 ; ϕ/ω



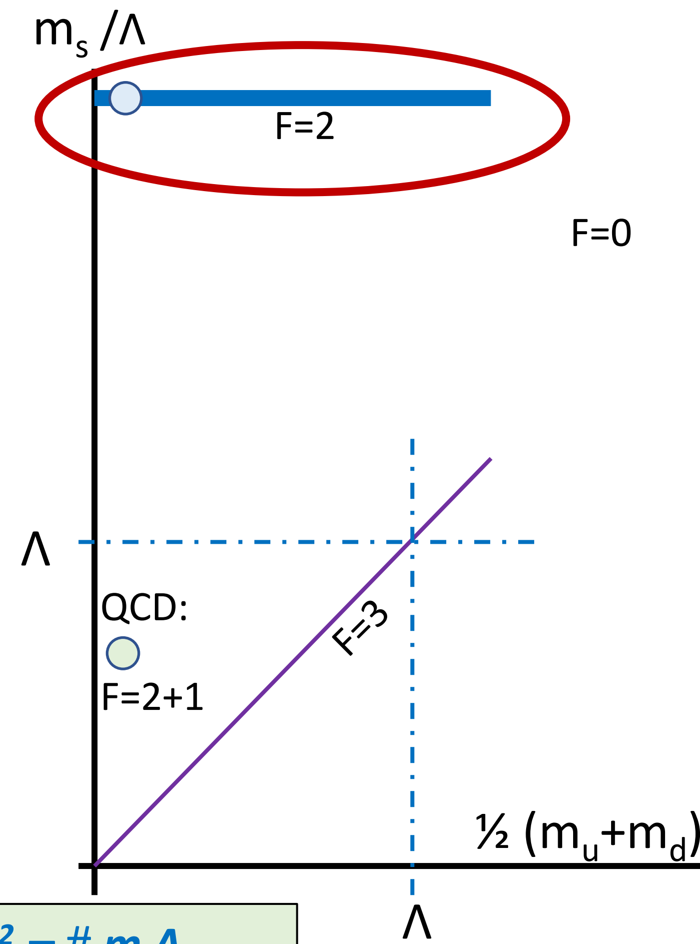


$m_\pi^2 = \# \, m \, \Lambda$

$m_\rho^2 \approx m_\rho^2(m=0) + \#' \, m_\pi^2$

This is why Δm(spin-1) << Δm(spin-0)

Spectrum: SU(3), F =2 (varying m_π)



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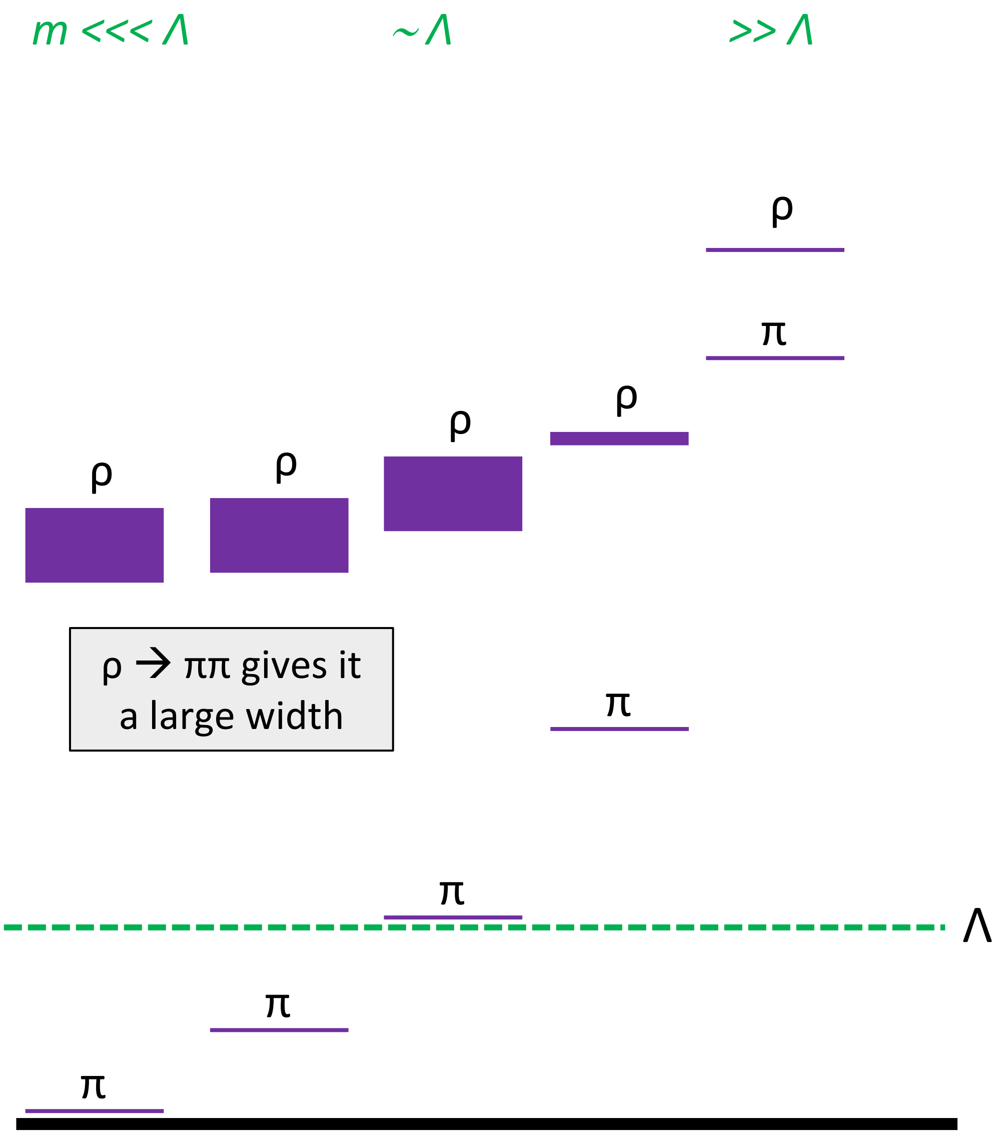
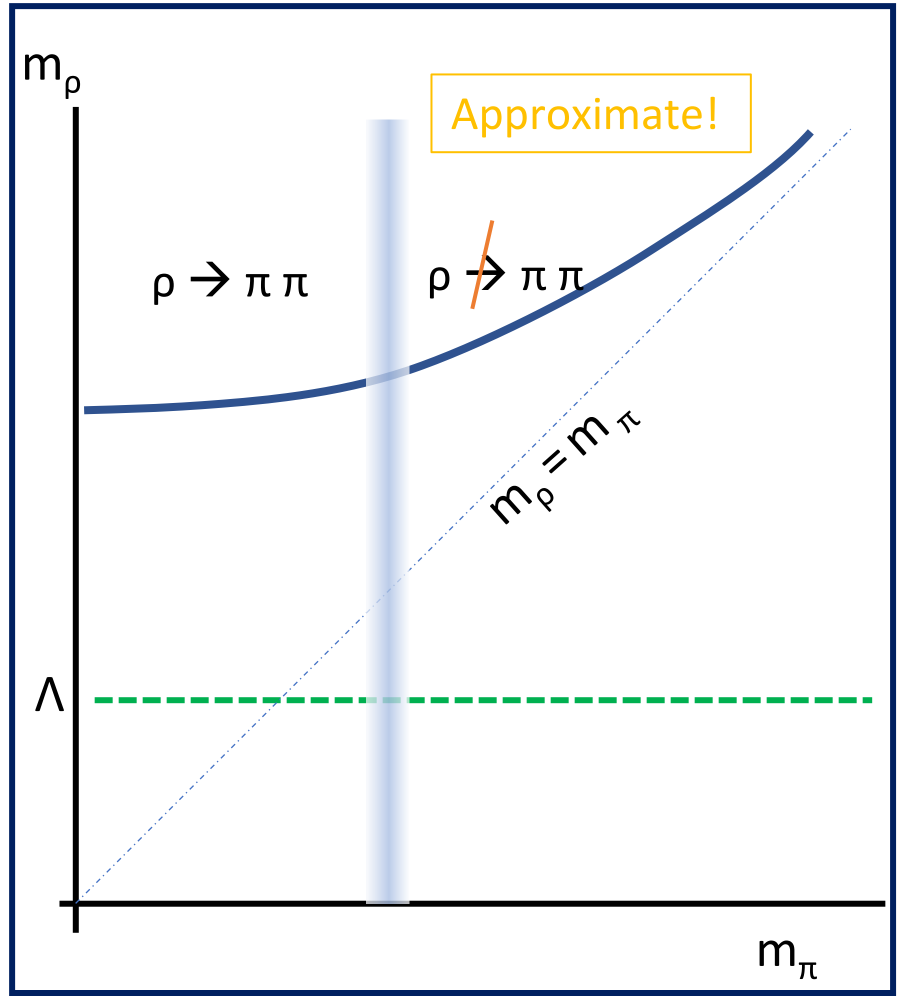
***m* = current quark mass!!** $m_{qv} \sim m + \#\Lambda$





$$m_\pi^2 = \# \, m \, \Lambda$$

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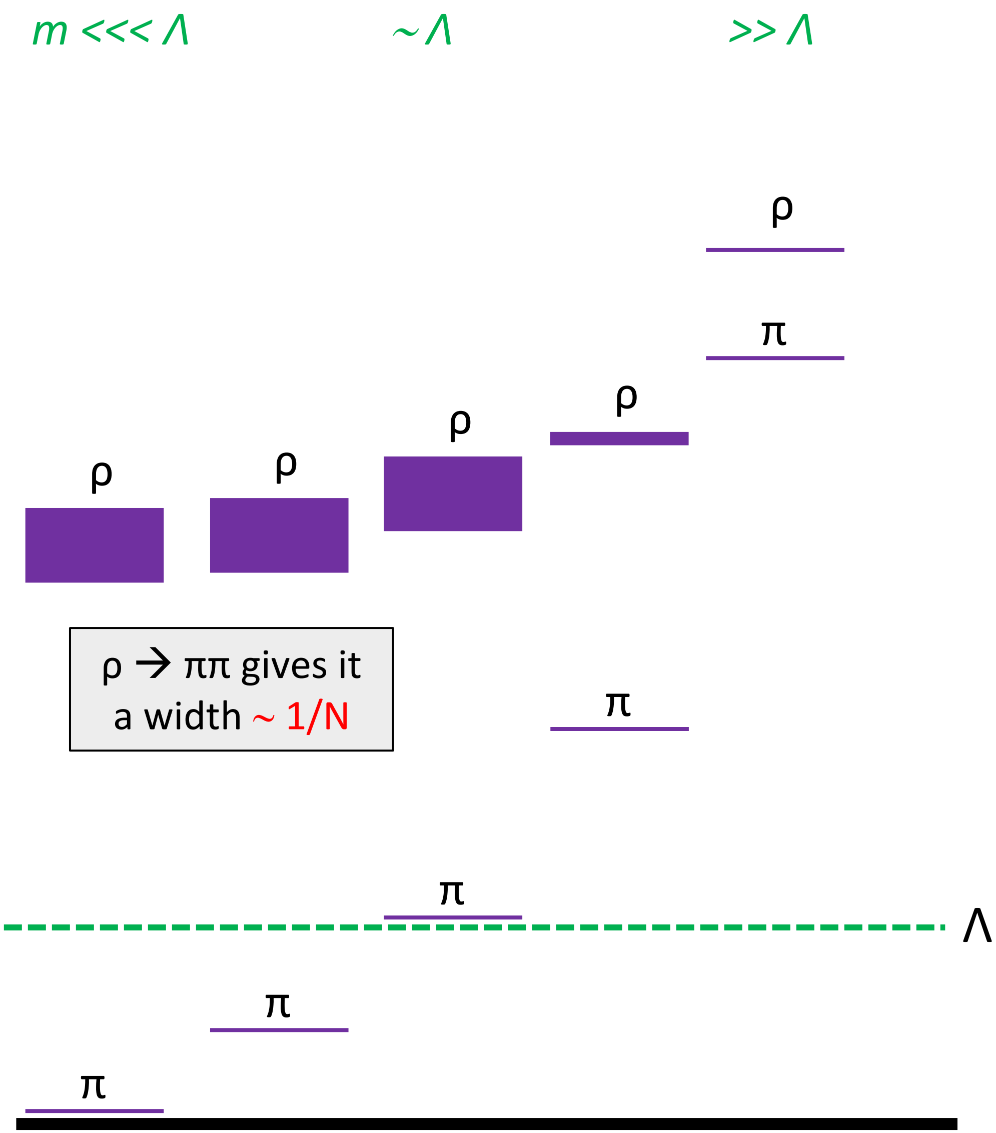
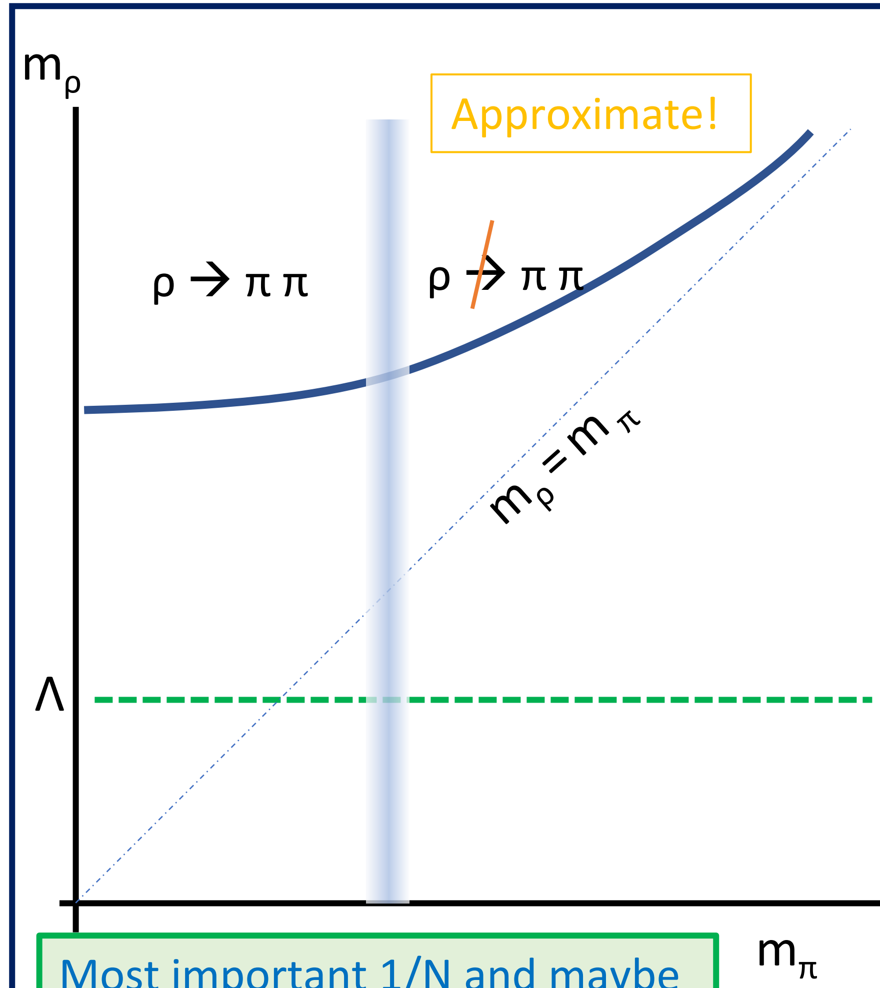
Similar Spectrum: SU(N ≥ 3) , ~ 2N(?) ≥ F ≥ 2

m = current quark mass!! *$m_{qv} \sim m + \#\Lambda$*





Most important 1/N and maybe F/N corrections to spectrum believed small to moderate

[Qualitatively yes. Quantitatively?]

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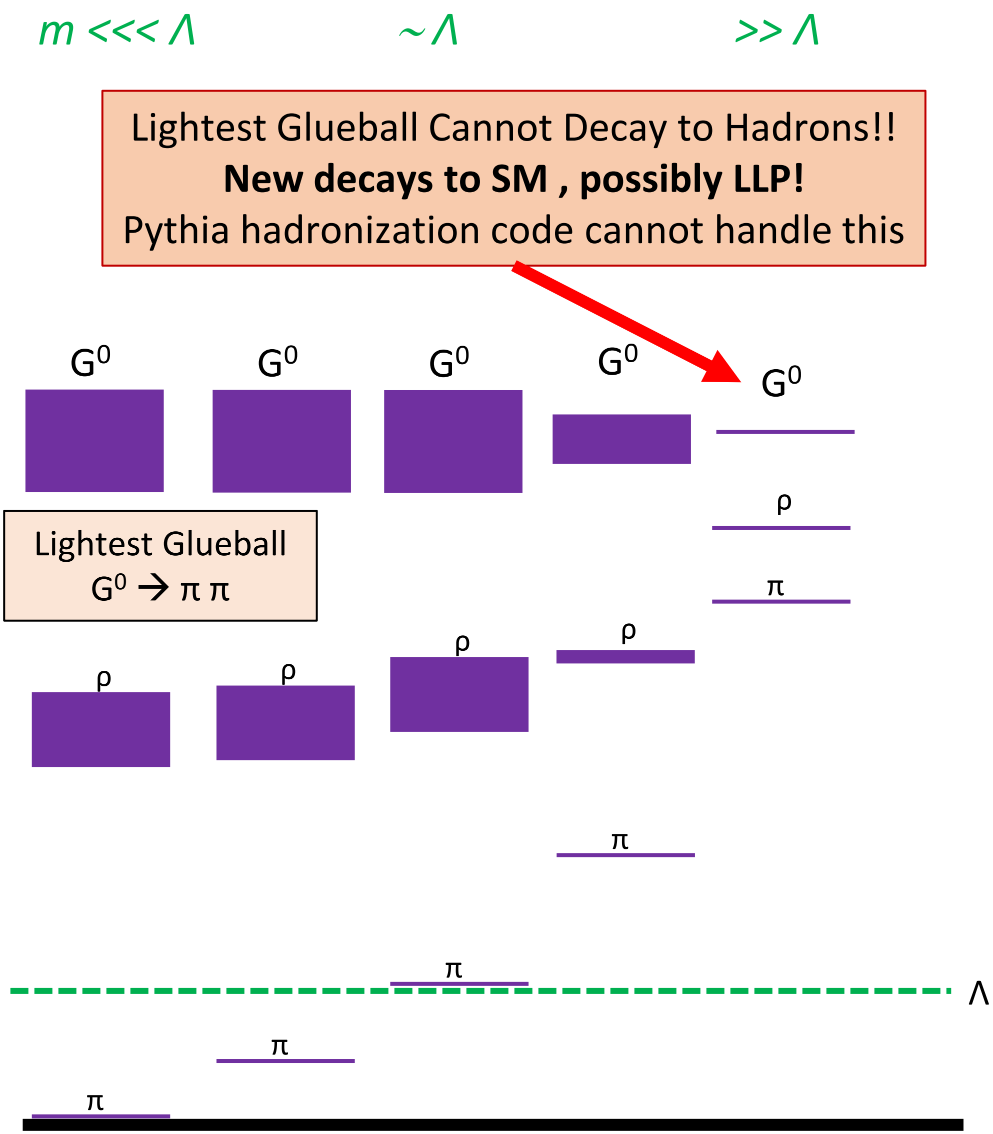
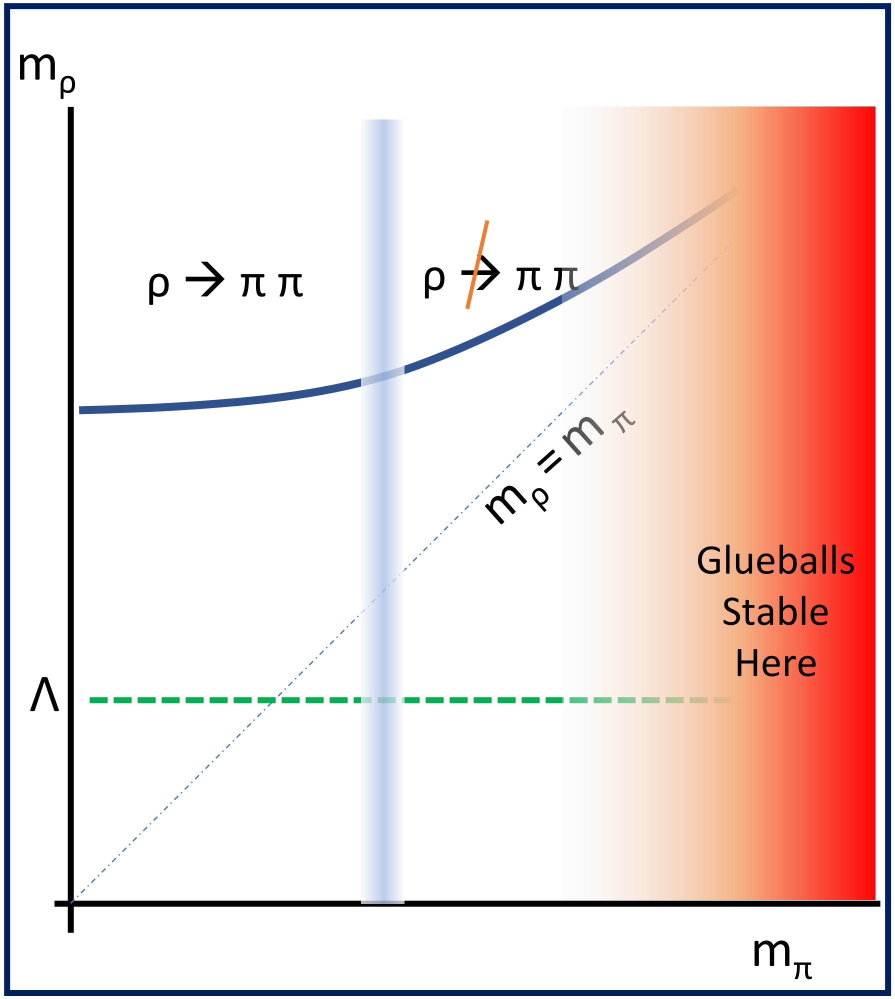




Similar Spectrum: $SU(N \geq 3)$, $\sim 2N_{(?)} \geq F \geq 2$

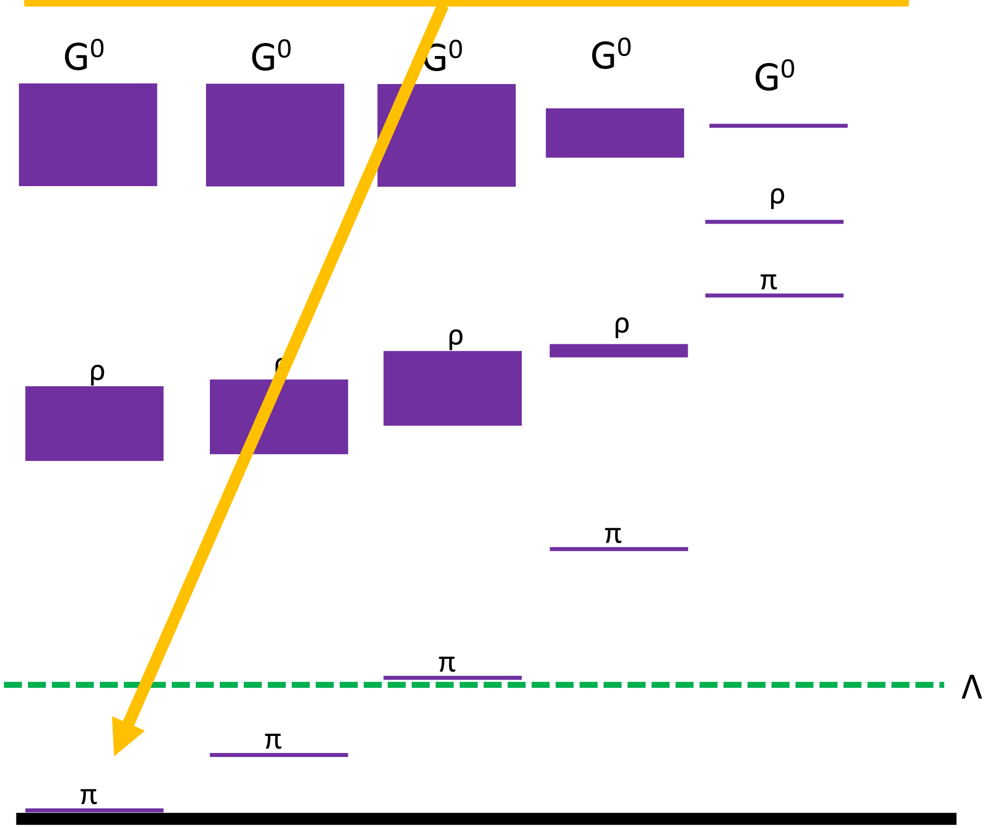
m = current quark mass!! $m_{qv} \sim m + \#\Lambda$

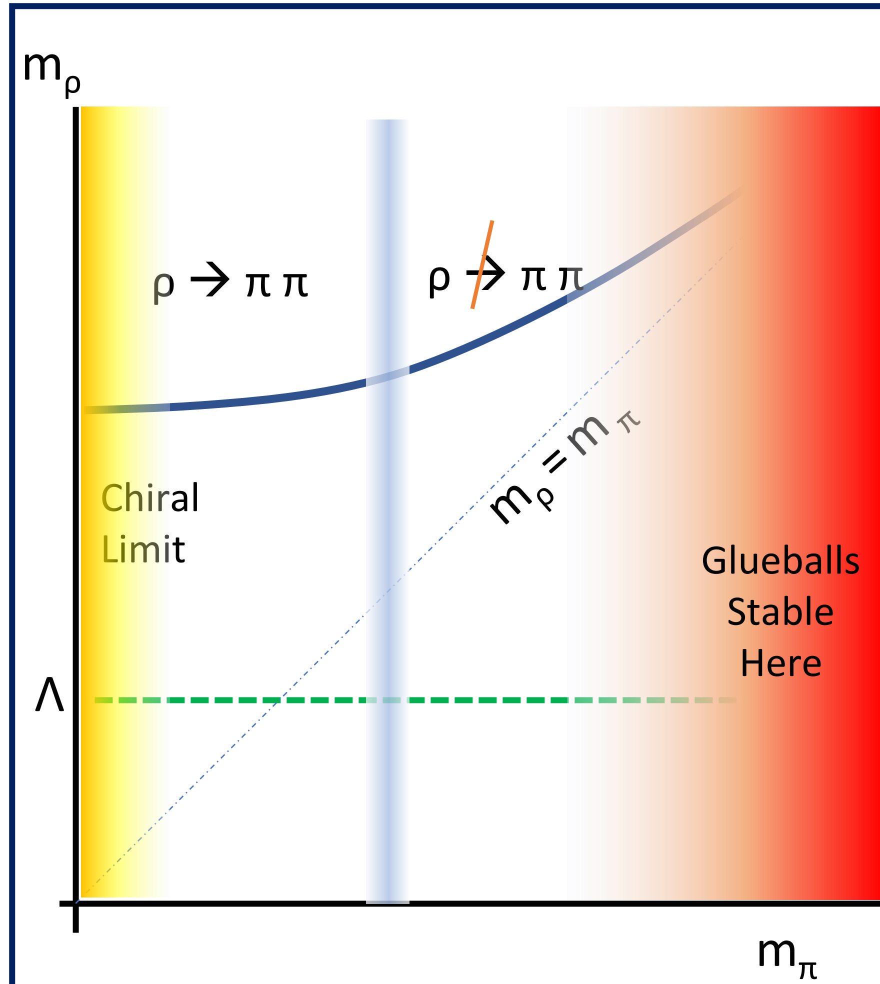
$m <<< \Lambda$ $\sim \Lambda$ $>> \Lambda$

Chiral limit: $m_\pi / \Lambda << 1$

- Big or small change in hadronization?
- Big change in kinematics and parameters ➔

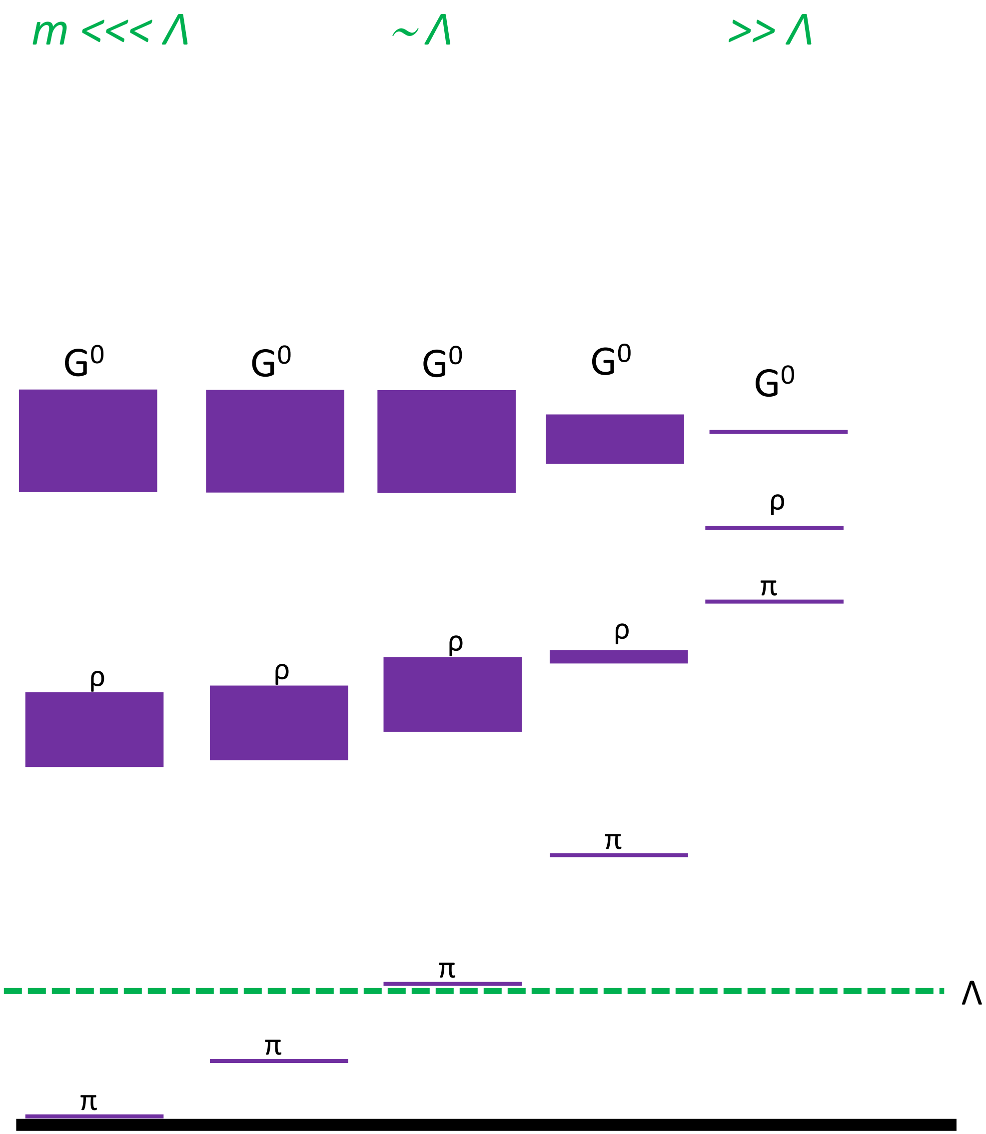
Pythia 8 HV module code may well fail here

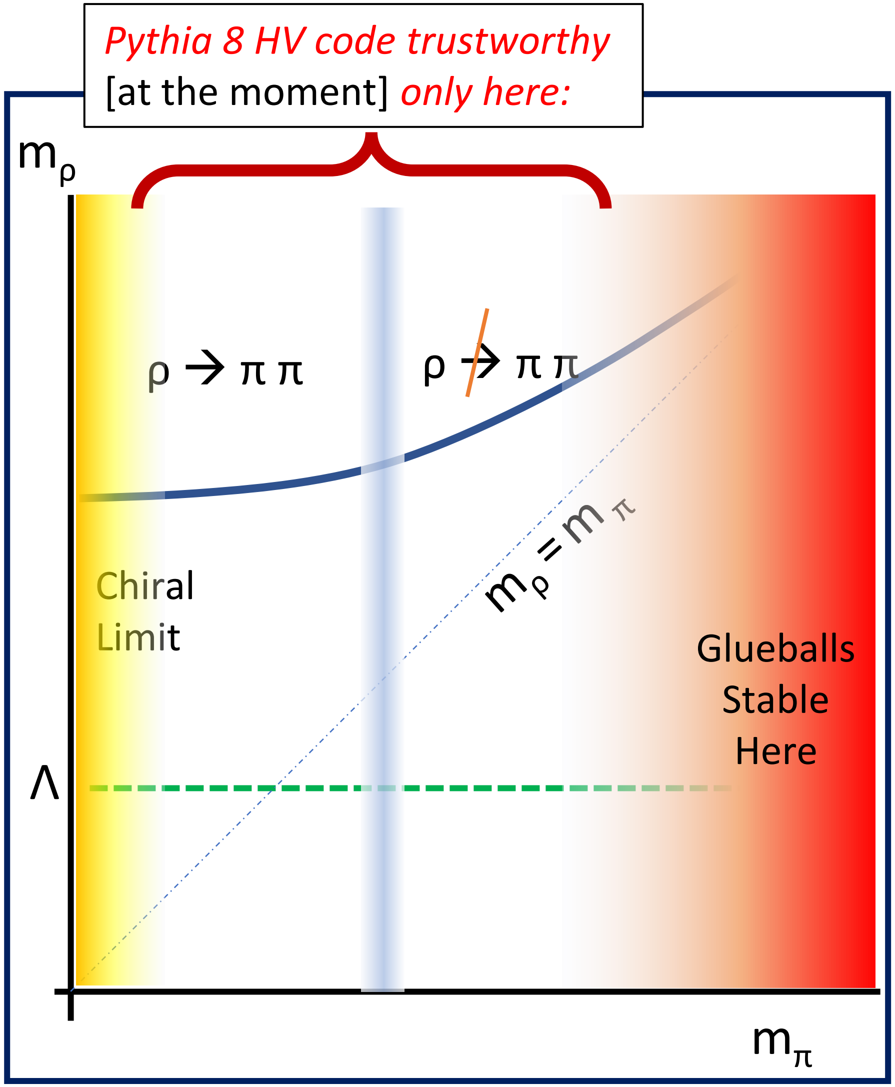




Similar Spectrum: SU(N ≥ 3) , ~ 2N(?) ≥ F ≥ 2

m = current quark mass!! *$m_{qv} \sim m + \#\Lambda$*

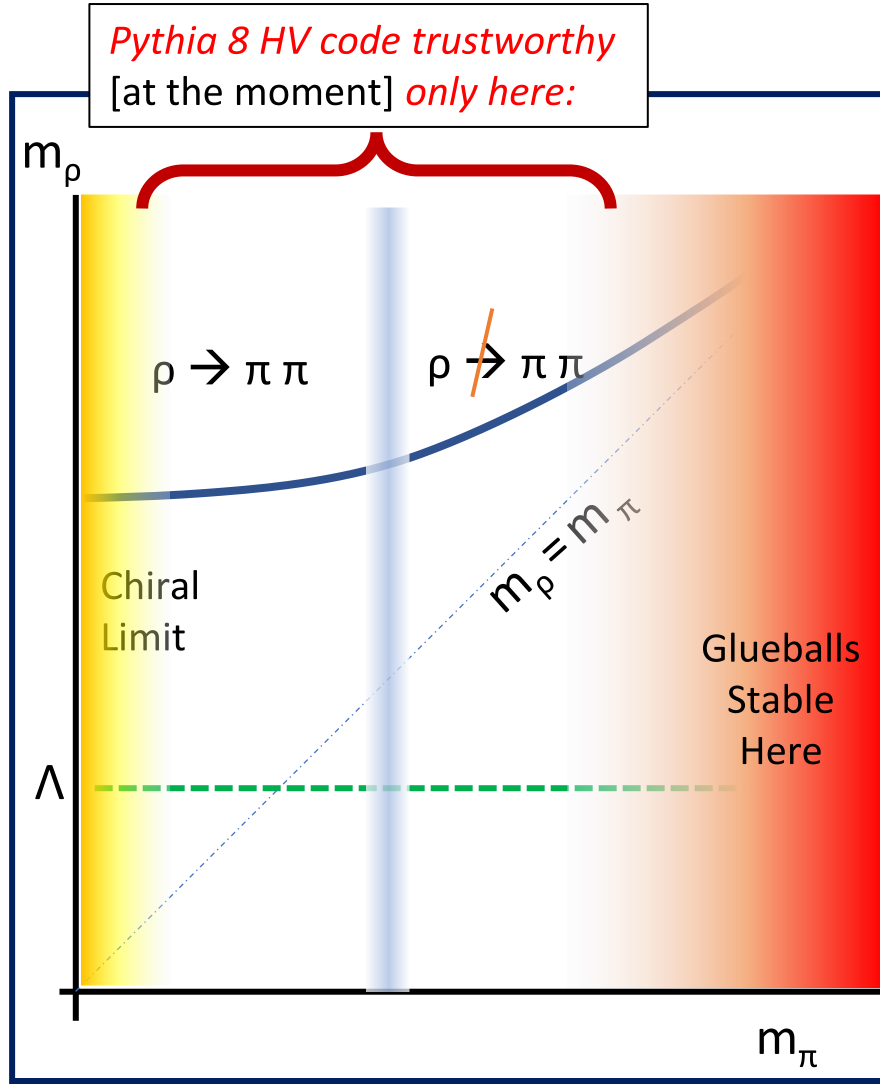




(relatively) Safe Zone for Using Pythia 8 HV Module

See also Knapen, Shelton & Xu 2021

- $N \geq 3$ *(caution: there are N-dependent effects!)*
- $F \geq 2$ *(caution: do not take F/N very large)*
- Choose Λ (*but not* [yet] *below* Λ_{QCD})
- Choose m_π/Λ in mid-range
  - Surely not > 3, maybe not even 2
  - Not << ½
    - need further code and theory studies
- Estimate m_ρ/Λ using chiral PT/lattice results
  - Never take $m_\pi \geq m_\rho$
  - If $\rho \rightarrow \pi\pi$ open, will always dominate
    - otherwise ρ may decay to SM
- Choose reasonable hadronization params.



User must also assure exit/entry portals implemented correctly!! (see backup for pitfalls)

Cases Where Pythia 8 HV Module Won’t Work

Many theories differ greatly from QCD

- “Meta-stable” hadrons
    - *(can’t decay to other hadrons)*
  - Give the main pheno signals, but
  - May differ greatly from QCD
    - Maybe no pions
    - Light baryons
    - Multiple excited hadrons
    - Glueballs

For such theories,

- ➢ Theory constraints may be limited
- ➢ Lattice studies are few
- ➢ Hadronization modeling is unclear
- ➢ Pythia 8 HV Module will not work

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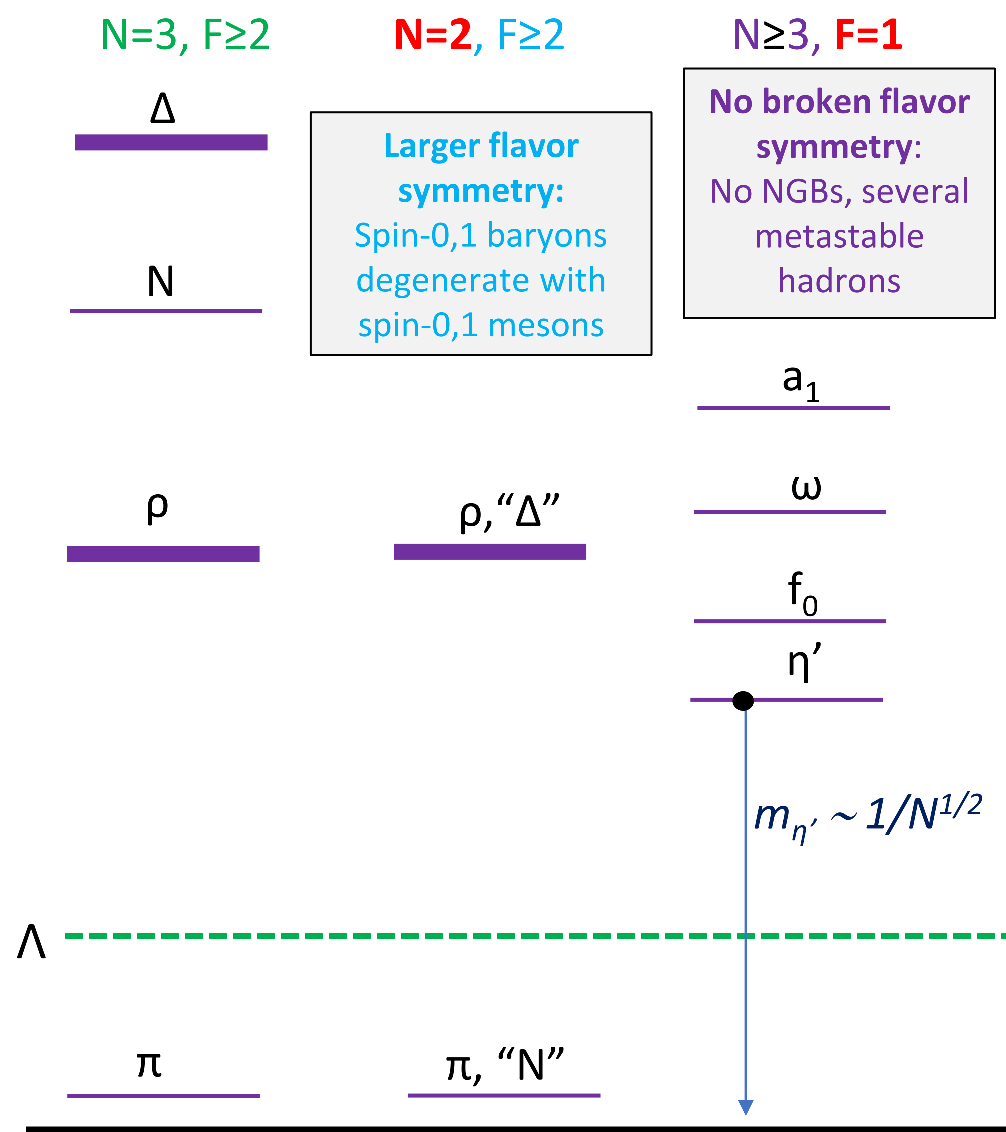

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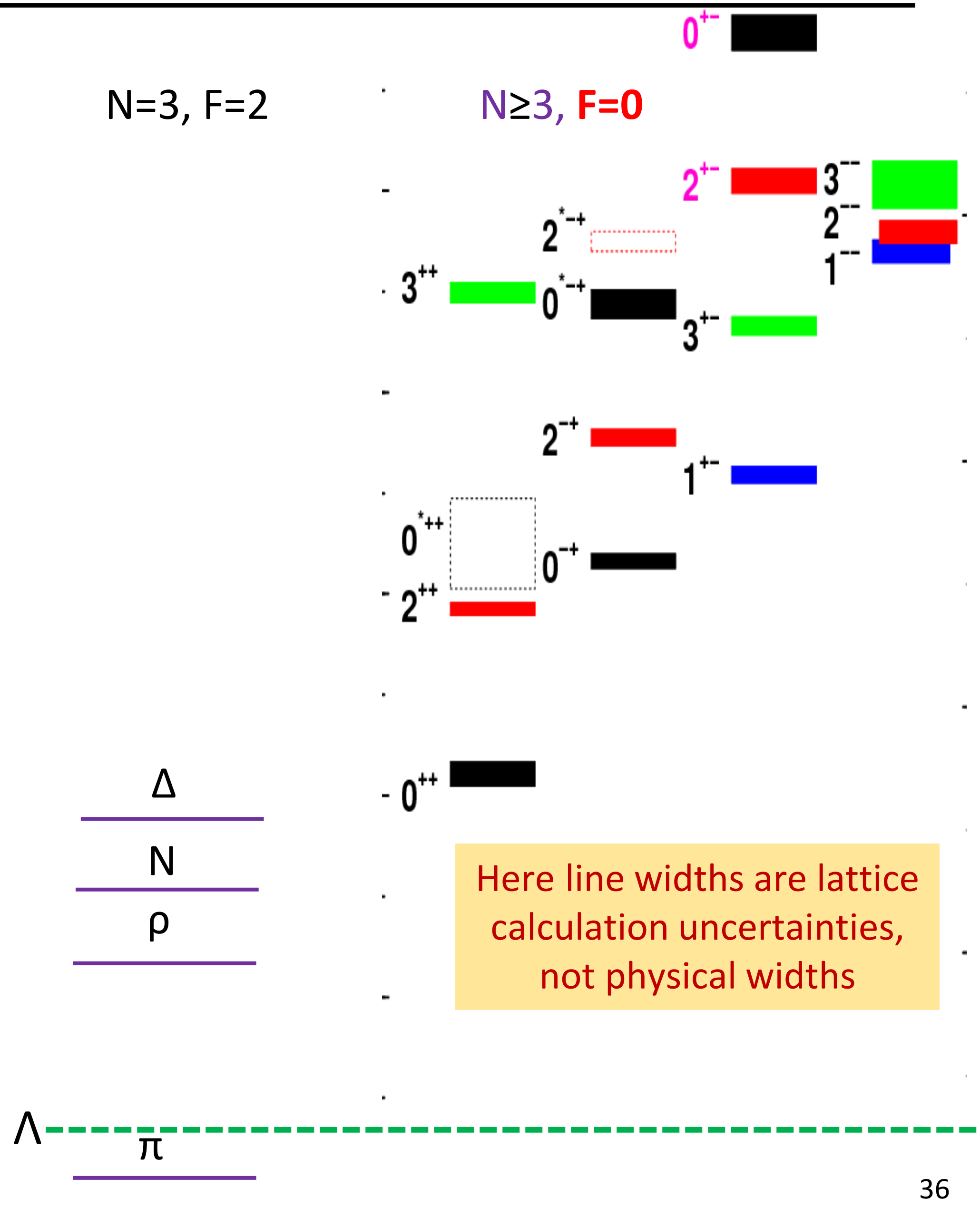

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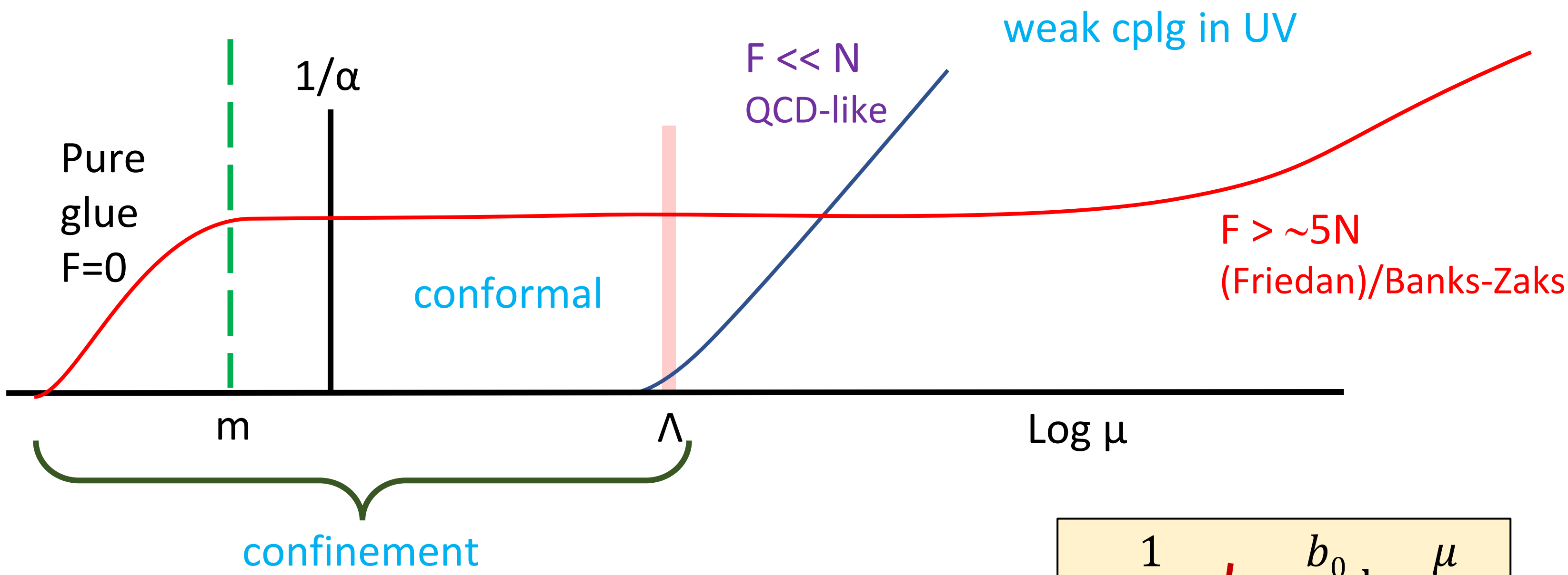

$$\frac{1}{\alpha(\mu)} \neq -\frac{b_0}{2\pi}\log\frac{\mu}{\Lambda}$$

5.5N > F >> N:

- Higher loop corrections to $\alpha(\mu)$ important!
- Conformal from m to >>Λ
- Confinement occurs
  - at Λ for small F
  - at m for large F (no confinement for massless quarks)
    - Low-E theory is pure glue (F=0), light hadrons are glueballs

F > 5.5 N: β>0, *no confinement*

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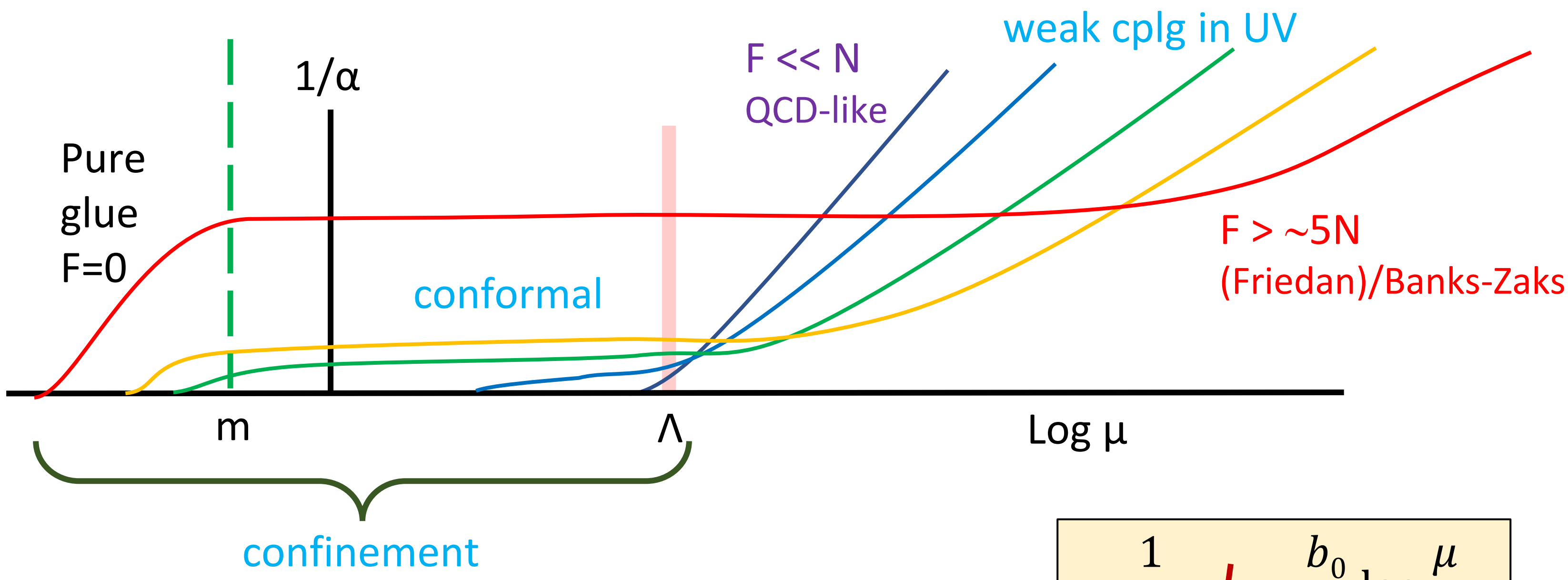

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How Could Pythia 8 HV Module Be Extended?

Probably doable:

- Chiral regime ($m_\pi/\Lambda << 1$)
  - Theory must convince us that Lund algorithm still captures the correct physics
  - Small adjustments to Pythia code -- allow existing module to work without crashing?
- Non-degenerate hidden quarks with $m_j <\sim \Lambda$ (see later slide)
  - Code needs generalization but should be able to handle this
  - User must do many calculations of meson masses, decays within & outside HV/DS
- Sp(N) and SU(2), perhaps SO(N) as well?
  - Probably not very difficult to adjust showering and hadronization codes
    - But do we really get qualitatively new phenomena?
    - Might be enough to use SU(N) code and adjust/reinterpret it
- Other color representations? Spin 0 quarks?
  - Case by case; some may be easy.
    - But easy ones may often have qualitatively similar physics, so choose wisely;
    - Maybe SU(N) code often can serve as a benchmark model

Where We Need Entirely New Approaches

- F=0 or other regimes with stable glueballs
  - Hadronization is controversial; not clear what approximations to use
    - An attempt underway by Curtin, Gemell & Verhaaren ; **see Gemell talk Friday**
    - But will we come to some consensus?

  If successful, then perhaps F >> N regime of above model can be modeled?
  - Needs revised showering calculations
  - Needs more theory of conformal-to-confinement transition

- Color/spin representations with novel bound states
  - SU(N) with quarks Q and symmetric color tensor T forms QTQ states
    - Similarly SO(N) with quarks in N and other quarks in color-spinor rep
  - SU(N) x SU(M) gauge group with matter in (M,N) forms chains of quarks

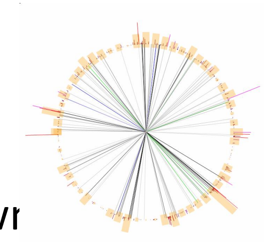
  Can we understand or guess how hadronization works?

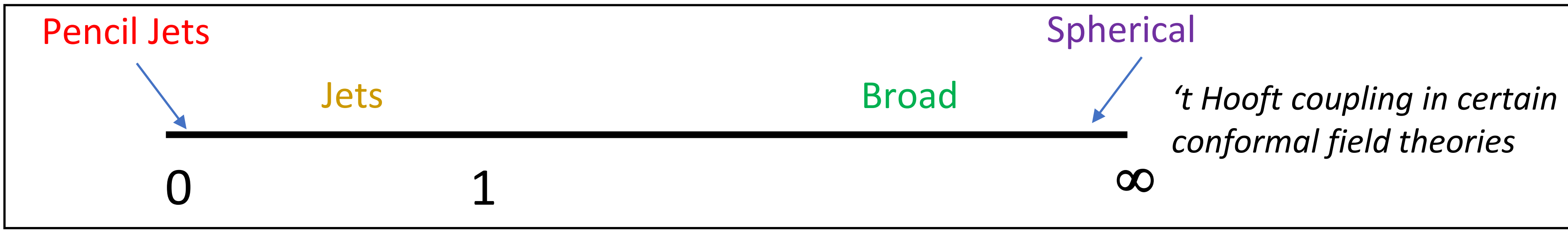
- Conformal dynamics in various regimes

Etc…

Two Cautions (details in backup slides)

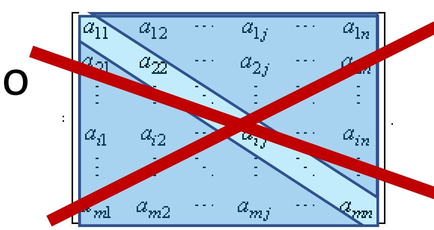
1. Conformal invariance DOES NOT imply spherical events
   - Showering shape depends on how couplings of the conformal theory
   - Only extreme theories have spherical events; corrections not fully known





2. The F x F matrix of degenerate mesons MAY NOT separate into
   - F-1 diagonal mesons
   - F^2-F off-diagonal mesons
   - 1 heavy singlet meson

Assumes portals break
SU(F)xU(1) → S_F x U(1)^F (semidirect)



- Note this is the Pythia 8 HV Module default assumption
- But true decay pattern depends in detail on the entrance and exit portals
  - Couplings may break the SU(F) flavor symmetry in many different ways

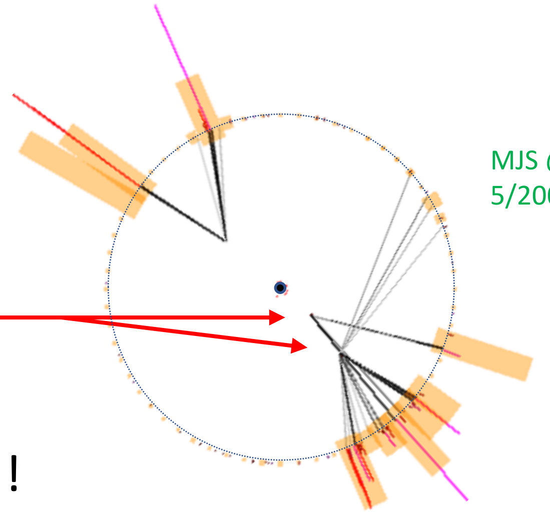
Comments on Non-Degenerate Quarks

MJS+Zurek 2006

- Profusion of parameters
- Profusion of new types of decays
  - **Many important phenomena do not happen for degenerate quarks!**
  - Lots of new pheno signatures with cascade decays
    - For instance, cascade decays among hadrons creating SM particles in chains
      - Compare QCD: $K^+ \rightarrow \pi^0 e \nu$, followed by $\pi \rightarrow \gamma \gamma$
      - Similarly in HV/DS: $X \rightarrow Y e^+ e^-$ followed by $Y \rightarrow b b$

- *Cf.* MJS+Zurek 2006 some discussion of 2-flavor and 3-flavor non-degenerate cases

- **Very important for LLPs signatures!**
  - Can give extremely complex vertex
  - Or a prompt decay followed by a displaced vertex
  - Or a chain of vertices



MJS @ UW LLP 5/2009

This is why LLP community needs Pythia 8 upgrade!!

What Haven't I Considered Today?

- Sp(N), SO(N), E_N
- Multiple gauge groups
- Multiple quark representations
- Scalar quarks
- Dark photons/neutrinos/Higgs bosons
- Partially or completely Higgsed gauge groups
- Extra dimensional sectors
  - possibly a la Maldacena/AdS-CFT/Randall-Sundrum/Unparticles
  - Motivates: $\alpha N \gg 1$ effects on showering, spectrum
  - Motivates: N >>> 1 regime
- Strong hidden dynamics in entrance/exit

- Etc…

Clearly we can't cover it all! must be smarter.
- Need to advance on theory side
- Determine what's covered with existing searches
- Propose new searches
- Advance simulation tools

Summary

- Existing Pythia 8 HV Module covers SU(N) with F degenerate quarks
  - Standard QCD-like showering [or constant-coupling showering]
  - Standard QCD-like hadronization includes only spin-0,1 flavor-adjoint mesons

- But this module does not work for all N, F
  - Many values of N,F have very different spectrum or new showering dynamics

- Even for acceptable N,F
  - not necessarily (yet) working for small quark mass (chiral limit)
  - and definitely not for large quark mass (very different spectrum)

- For LLPs: definitely want
  - The chiral limit (pion lifetimes increase; multiplicity too?)
  - Non-degenerate quarks (cascades, more lifetimes)

Needs work by theorists/tool-developers to assure Pythia 8 HV module is
- made **more robust**
- stable/accurate for **low pion mass**
- extended to **non-degenerate quarks**.

Backup Slides

Portals: Beware a Common Error

Focus on N ≥ 3, F ≥ 2, $m_\pi < ½\, m_\rho$

- F^2 pseudoscalars in matrix M
  - = $(F^2 – 1)$ π's in flavor adjoint plus *1* heavier flavor singlet η' (in *tr M*)
    - Be careful to account for heavier singlet in use of Pythia 8 HV module
- Entry/exit via on-shell/off-shell Z'
  - If same Higgs gives mass to Z' and quarks, then Z' can mediate π decay

Despite what Pythia 8 HV module implicitly suggests, it is not generally true that

- all $F – 1$ light flavor-diagonal mesons will decay the same way
- all $F^2 – 1$ flavor-off-diagonal mesons will decay the same way (or won't decay)
- For this to be meaningful, need U(F) broken by Z' couplings to $U(1)^F$
  - But even this could lead to different lifetimes for flavor-diagonal mesons, unless permutation sym
- And often this is not the breaking pattern
  - Ex: if Z' couples to half the quarks with Q=1, half with Q=-2
  - ➔ pions are in representations of $SU(F/2)xSU(F/2)xU(1)_{new}$; **only the singlets can decay**

User must ensure decay patterns correctly calculated, implemented in Pythia 8 decay table

PYTHIA 8 CODE WILL NOT DO THIS FOR YOU

Conformal Physics: Beware a Common Error

QCD-like theories generally give dijetty events

Can we get spherical events from a conformal field theory? ***Generally NO!!***

- CFTs can be at weak coupling, moderate coupling, ultra-strong coupling
- At weak coupling CFT's give dijet showering very similar to QCD
    - Showering can probably be simulated moderately well,
- Certain classes of ultra-strong theories they give quasi-spherical showering BUT
    - Even for extreme theories, only ∞-multiplicity distributions are spherical
        - With finite multiplicity or escaping particles, never actually observe spherical events
    - Away from the extreme limit, not even ∞-multiplicity distributions are spherical
    - Momenta, spin distributions of hidden hadrons aren't determined
        - *These do affect LHC observables!*
    - In some theories spherical shower may reorganize into non-spherical events!!
- We do not know how to simulate these events reliably
    - **Simply generating spherical events is a good start, but generally is not realistic**

see Knapen et al. 2016

Tool Developed for Event Shape Studies

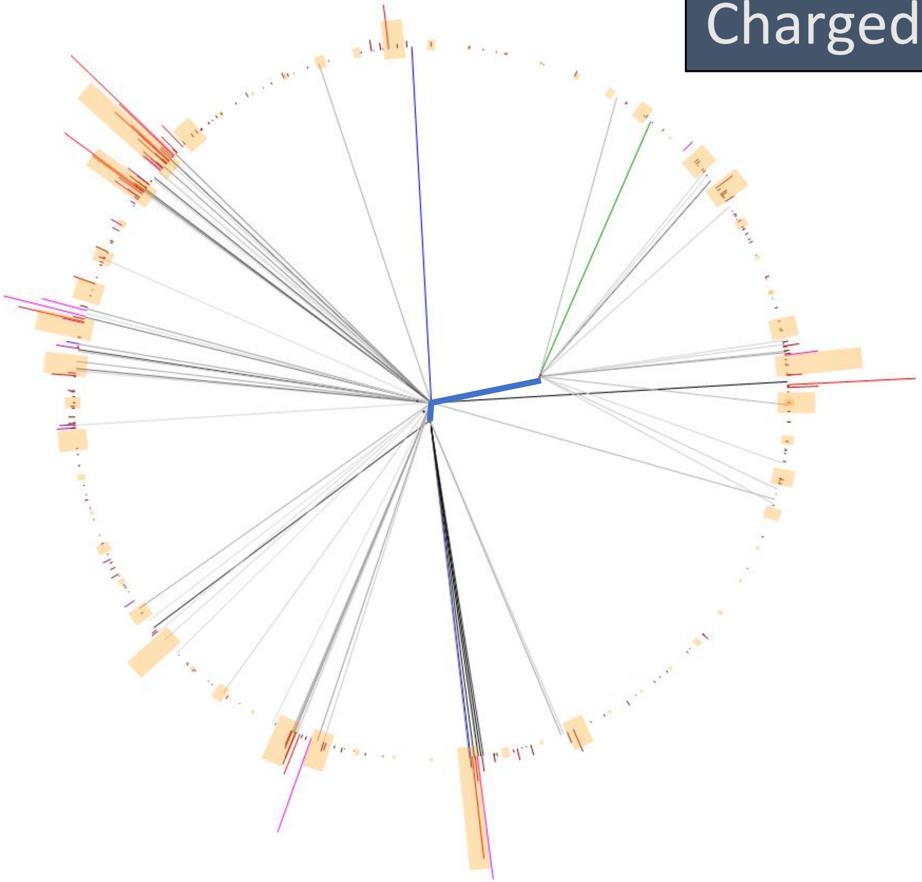
Cesarotti, Reece & MJS 2020

- Theories with very large N may have many metastable hadrons
  - e.g. Rho meson is narrow, as are many of its excited states
- Some theories with very large N *and* very strong 't Hooft coupling above the confinement scale can be calculated or estimated using string-theory methods
- Cascade decays among these hadrons may also give spherical events
  - Is this merely an alternative view of CFT spherical events? Disproved.
  - Instead this is a second means to get spherical events in strongly interacting theories
  - Different choices of hadrons can give jetty cascades or quasi-spherical cascades
- This simulation strategy was designed for event-shape studies and is not really suitable as a real-world target
- However, some modification of it may be quasi-realistic

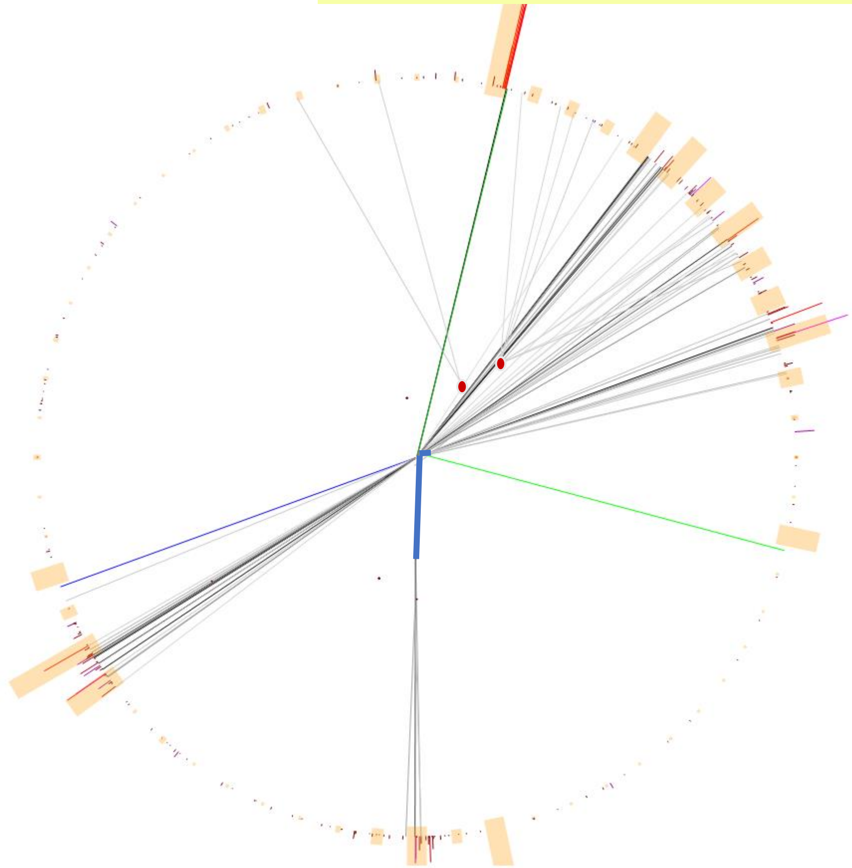
Charged slepton decaying in flight to HV/DS

Circa 2008

Stau tracks



Long-Lived Stau
Prompt v-Hadron Decay
Wide spray at end of track



Long-Lived Stau
Long-Lived v-Hadrons
Multiple clustered vertices

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