GlueShower:
Simulating a Pure Gluon Shower for Dark Sector Searches

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Based on ongoing work with Dr. David Curtin and Dr. Chris Verhaaren

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TORONTO

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Introduction and Motivation

Strassler, Zurek, arXiv:hep-ph/0604261
Craig, Katz, Strassler, Sundrum, arXiv: 1501.05310
Curtin, Verhaaren, arXiv:1506.06141
Knapen, Shelton, Xu, arXiv:2103.01238

- Dark showers are a signature that arise from hidden valley models

- In the case where there is no light coloured states below the confinement scale, the only hadronic states that can form are 'glueballs', composite gluon states

  - Generic possibility of hidden valley models, so should be explored

- Very few quantitative studies of dark glueball showers, due to the fact all known hadronization models no longer hold Andersson, Gustafson, Ingelman, Sjöstrand (1983)

- Hidden valley models are theoretically motivated as they can solve ongoing problems such as dark matter and the hierarchy problem

- Also experimentally motivated by the fact they are largely unconstrained by current experiments

- Can be represented as a minimal HV model but also fits into specific theoretical frameworks: Twin Higgs… Folded SUSY… etc… Chacko, Goh, Harnik, arXiv:hep-ph/0506256
Burdman, Chacko, Goh, Harnik, arXiv:hep-ph/0609152

- We are currently writing a Python code, `GlueShower`, we will publicly release that will allow you to simulate $N_f = 0$ Dark QCD showers

So what is known ?

Dark Glueball Spectrum

- Majority of knowledge comes from Lattice QCD

  Morningstar, Peardon, arXiv:hep-lat/9901004

- Masses entirely parameterized by the

  Athenodorou, Teper, arXiv:2106.00364

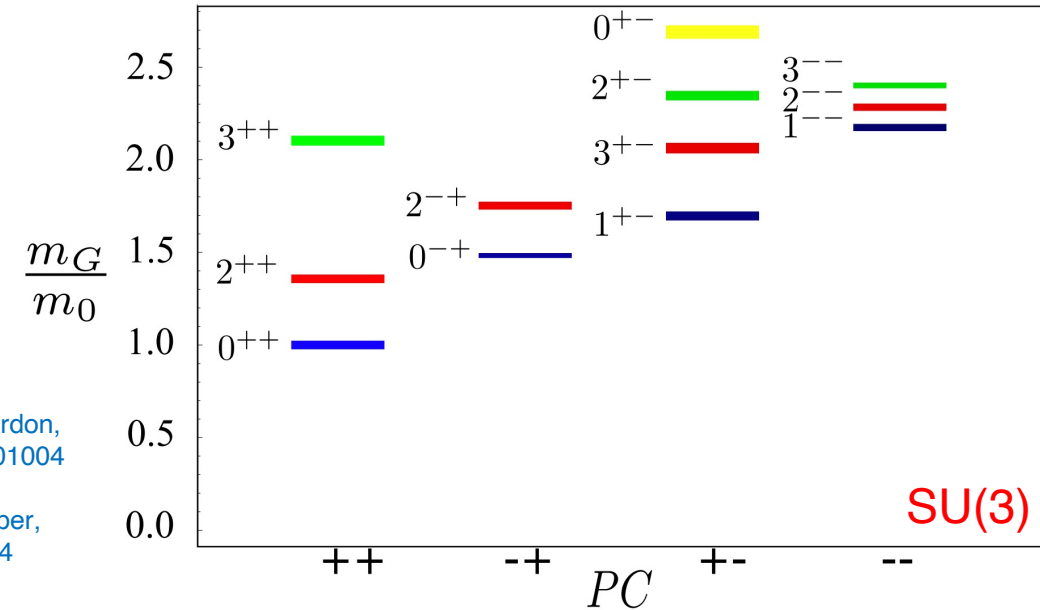 confinement scale ($m_0 \sim 7\Lambda$)

- Dark gluon production / dark glueball decay

  - Coupling to standard model via heavy quark loop:

  - Dimension 6 Higgs operator

    Juknevich, arXiv:0911.5616

  - Possible dimension 8 operator could also couple

    the dark glueballs directly to SM gauge bosons

    Juknevich, Melnikov, Strassler, arXiv:0903.0883

$$0^{++} \to (h^*) \to b\bar{b}, \tau^-\tau^+, c\bar{c}...$$

$$2^{++} \to (h^*)0^{++} \to 0^{++}(c\bar{c}, gg, \mu^-\mu^+...)$$

$$2^{-+} \to (h^*)0^{++} \to 0^{++}(b\bar{b}, c\bar{c}, gg...)$$
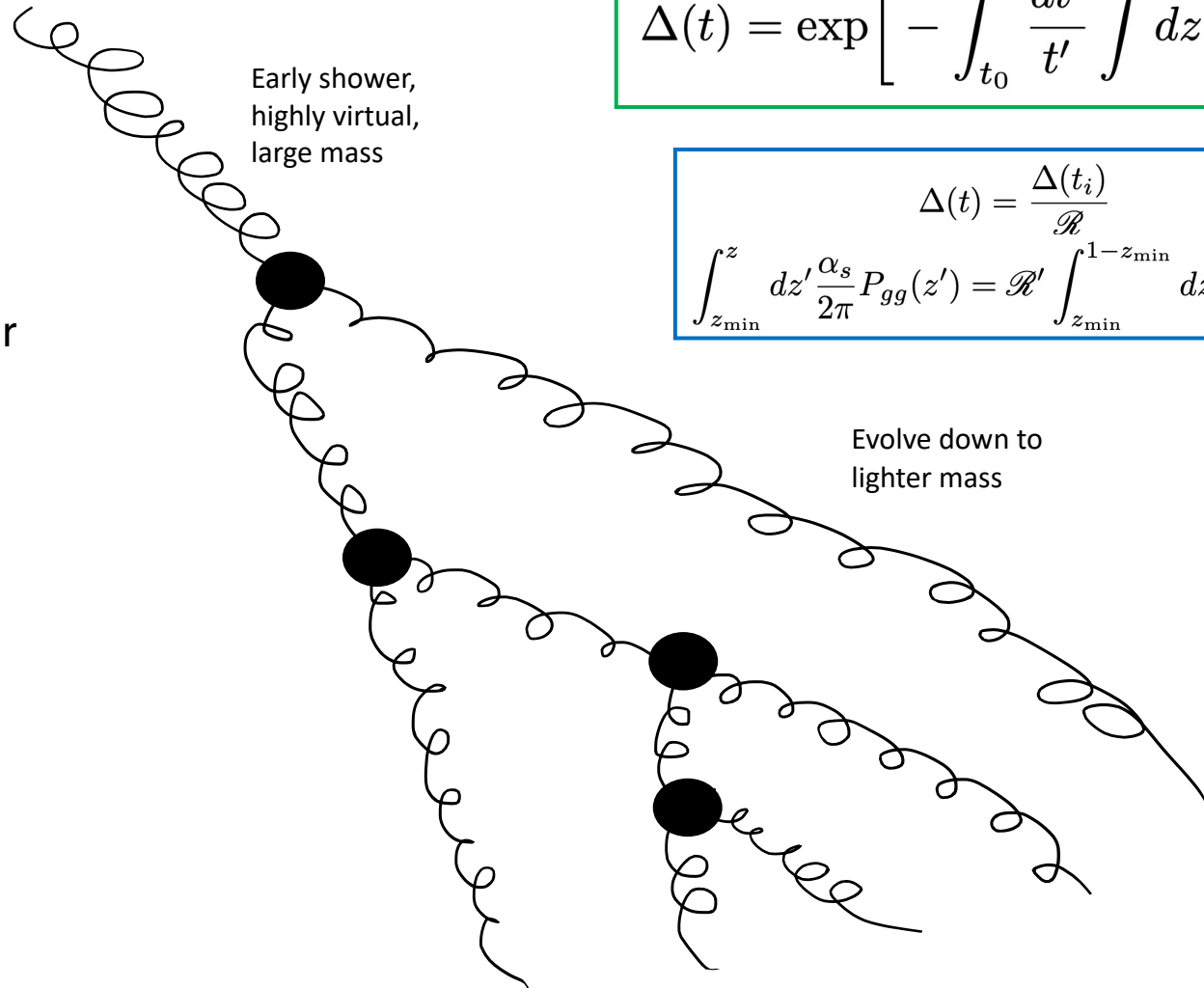
$$0^{\pm+}, 2^{\pm+} \to V_{SM}V_{SM}$$

$$1^{+-} \to \gamma\,0^{++}, \gamma\,2^{++}, \gamma\,0^{-+}$$

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The Perturbative Shower

$$P_{gg}(z) = 2C_A \left[\frac{z}{1-z} + \frac{1-z}{z} + z(1-z) \right]$$

$$\Delta(t) = \exp\left[-\int_{t_0}^{t} \frac{dt'}{t'} \int dz \frac{\alpha_s}{2\pi} P_{gg}(z) \right]$$

$$\Delta(t) = \frac{\Delta(t_i)}{\mathcal{R}}$$

$$\int_{z_{\min}}^{z} dz' \frac{\alpha_s}{2\pi} P_{gg}(z') = \mathcal{R}' \int_{z_{\min}}^{1-z_{\min}} dz' \frac{\alpha_s}{2\pi} P_{gg}(z')$$

Early shower, highly virtual, large mass

Evolve down to lighter mass

- Gluon-to-gluon splitting function
  - Determines energy of each of their daughter gluons

- Sudakov form factors
  - Determines the probability of a gluon evolving down from a high virtuality (mass) closer to the glueball mass without splitting

- Monte Carlo Method
 - How the above is practically used in our simulation

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But what isn't well known …
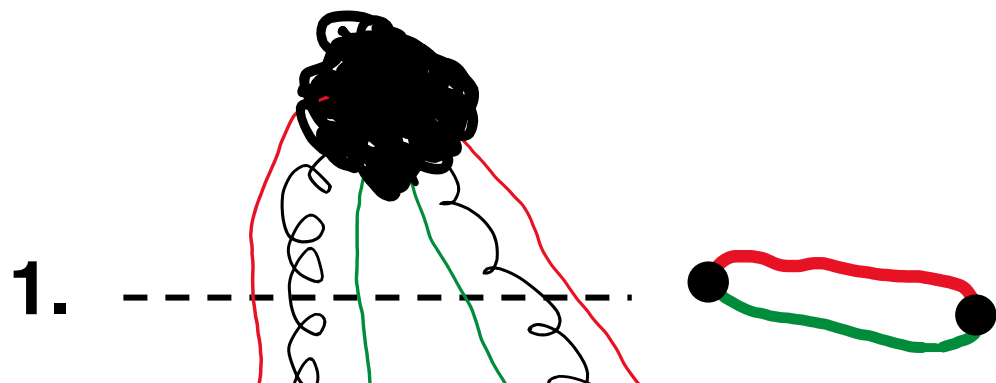
Hadronization Process

- Even in SM QCD, specifics of the non-perturbative hadronization process are not well understood

  - Models are tuned to fit data

- In the absence of data for pure glue showers, we have to come up with a physically reasonable and motivated approach, but also ideally is able to generate a representative range of possible phenomena

  - Range of phenomena controlled by internal parameters

  - Gives us an idea of theory uncertainties

  - Importantly, **how robust are output signatures to changes in the theoretical parameters**
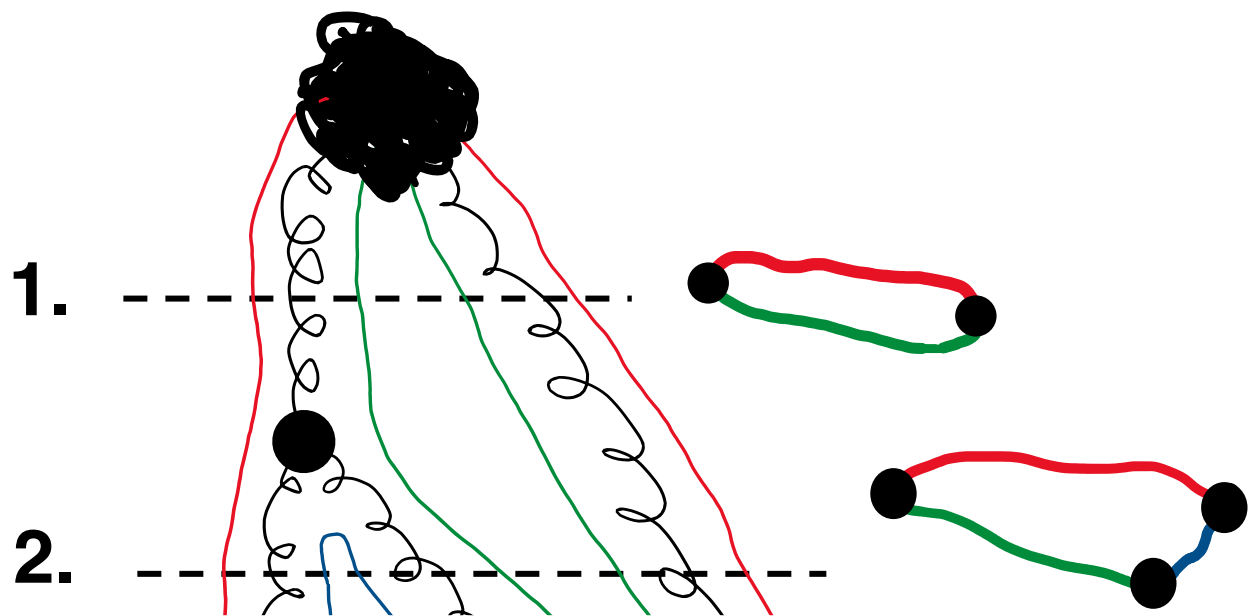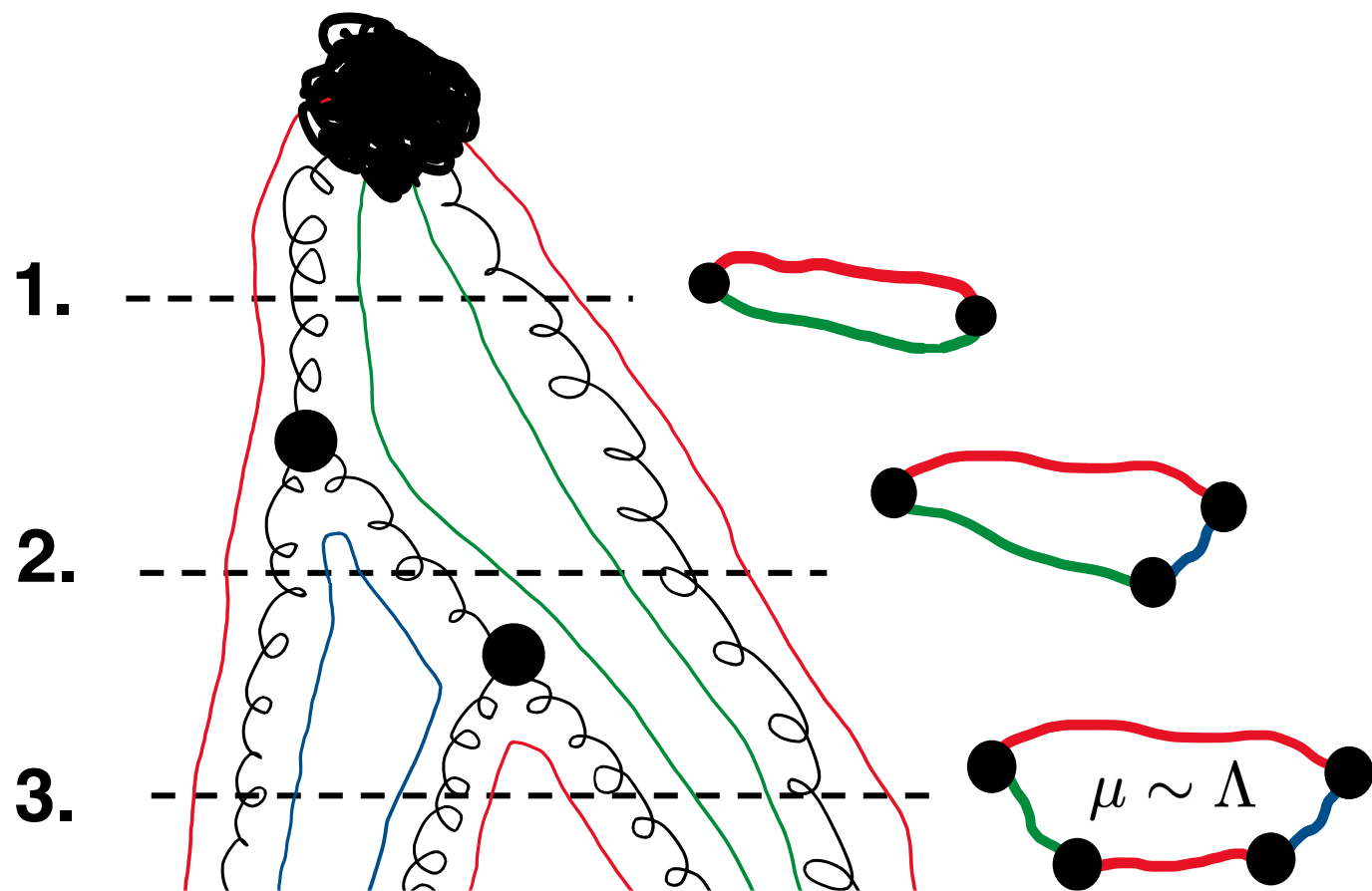
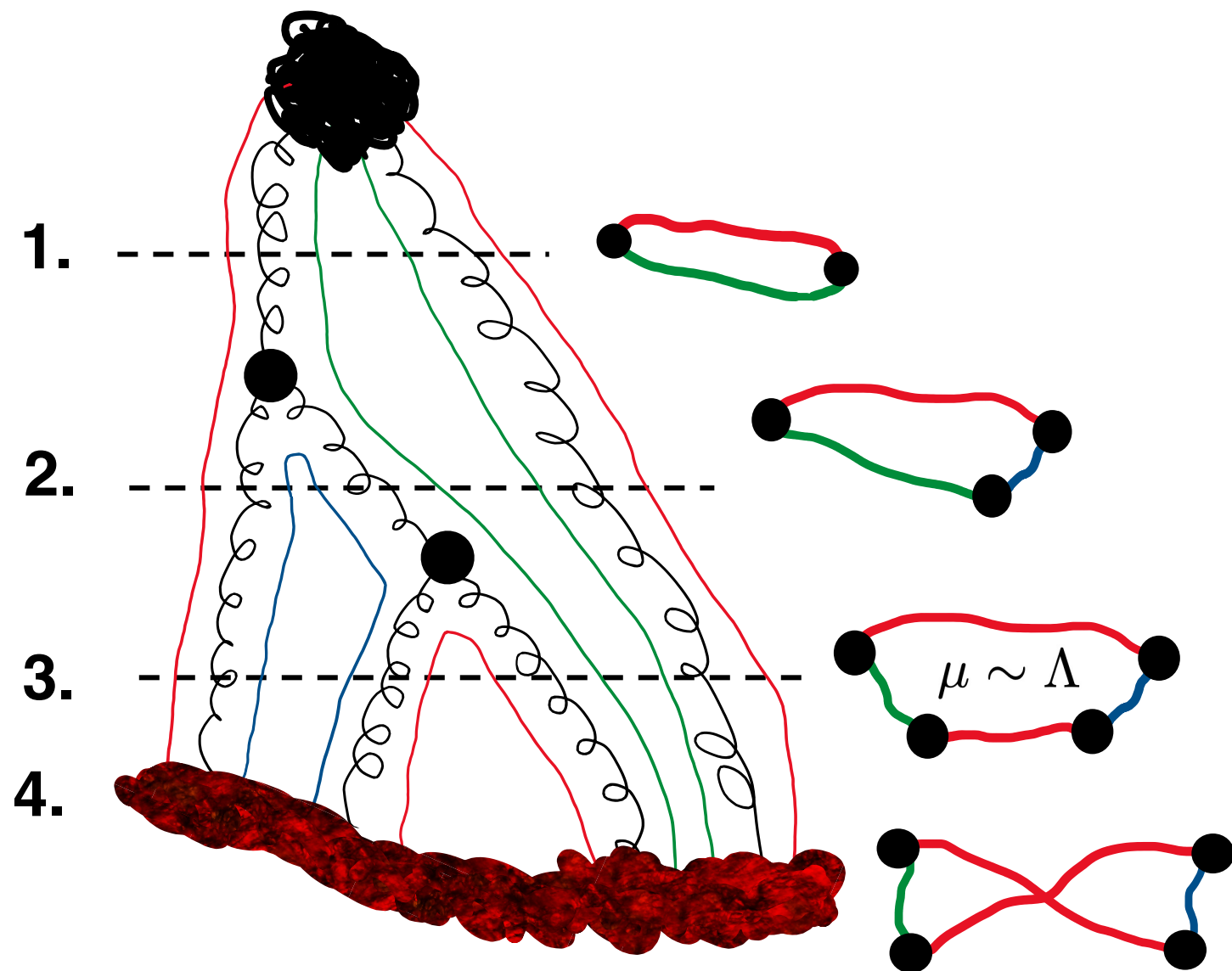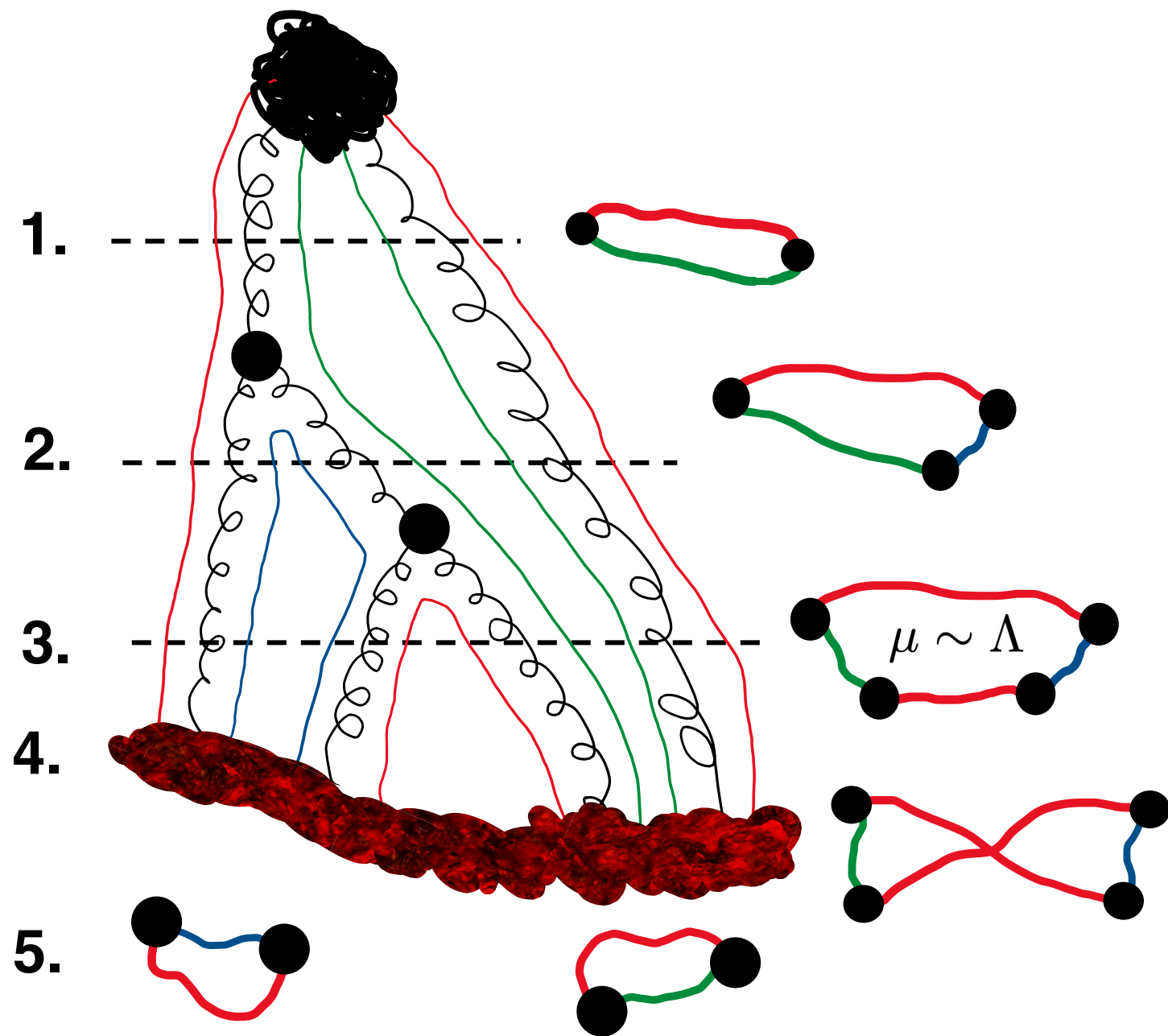**Let's start off by considering**

a single glueball species…
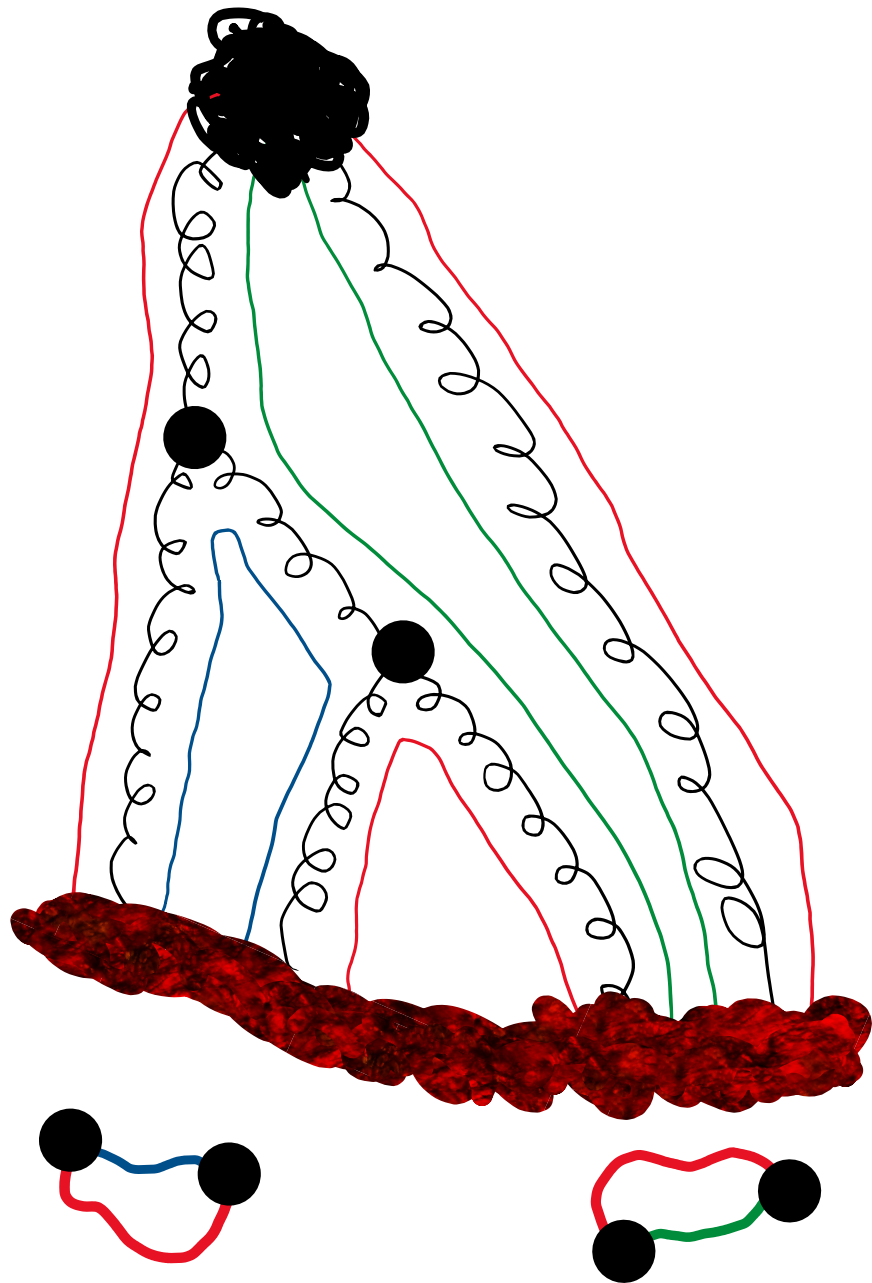
One example:
Simple case of two gluon production forming two glueballs

1.

1. - - - - - - - - - - - - - - - - -

2. - - - - - - - - - - - - - - - - -

1. -

2. -

$\mu \sim \Lambda$

3. -

13

1.

2.

3. $\mu \sim \Lambda$

4.

1.

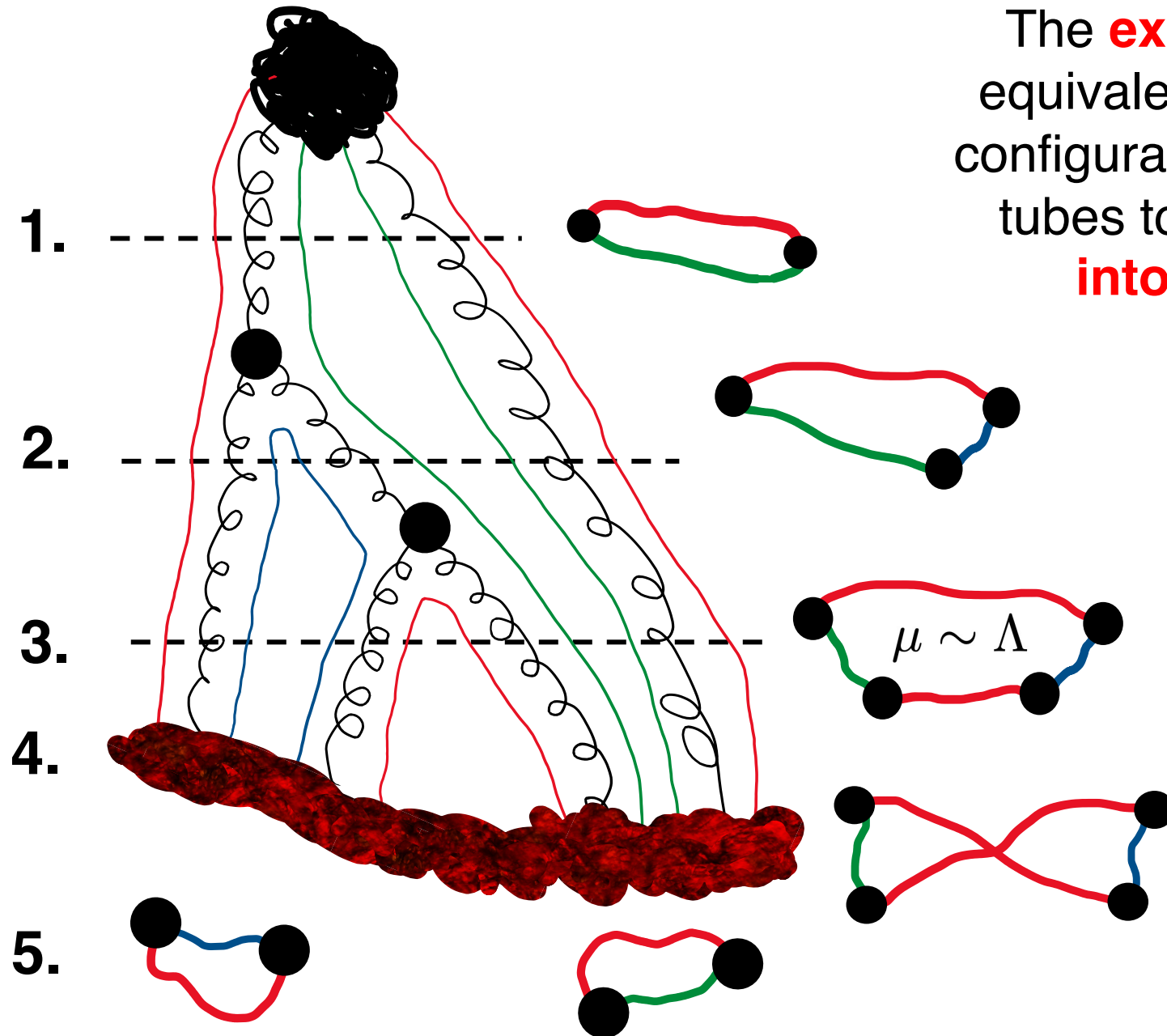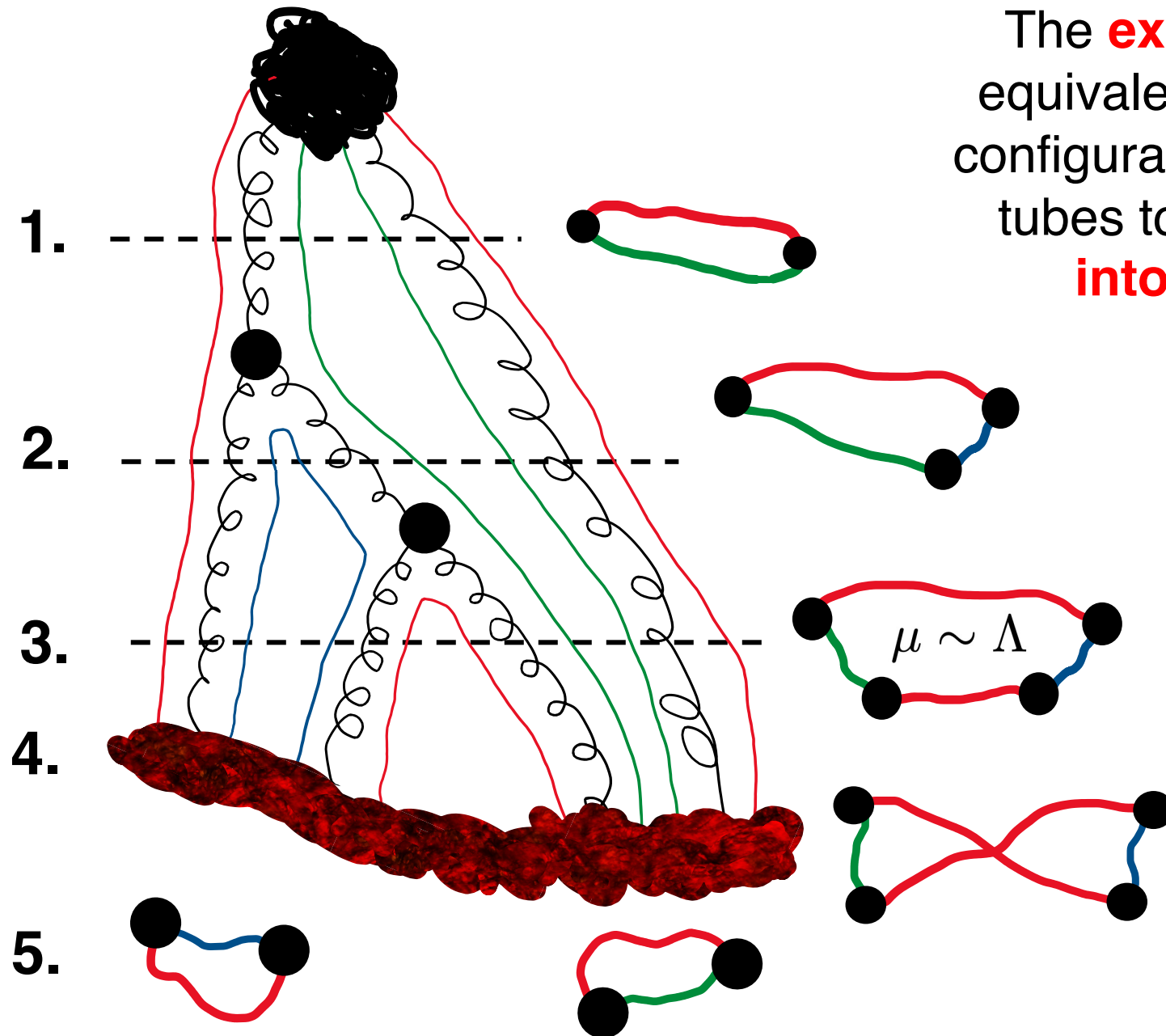2.

3. $\mu \sim \Lambda$

4.

5.

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The **exchange of an IR gluon** is equivalent to generating a flux tube configuration that allows same-colour tubes to cross and then **separate into colour singlet states**

1.

2.

3. $\mu \sim \Lambda$

4.

5.

1.

2.

**3.** $\mu \sim \Lambda$

4.

5.

The **exchange of an IR gluon** is equivalent to generating a flux tube configuration that allows same-colour tubes to cross and then **separate into colour singlet states**

Given that extended flux tubes are energetically expensive, we assume that glueball hadronization is **broadly similar to SM QCD jet intuition** (will explore more exotic possibilities shortly)

Fundamental question:

Given previous assumption and some arrangement of gluons at the confinement scale, how do we map them to an arrangement of final state glueballs?
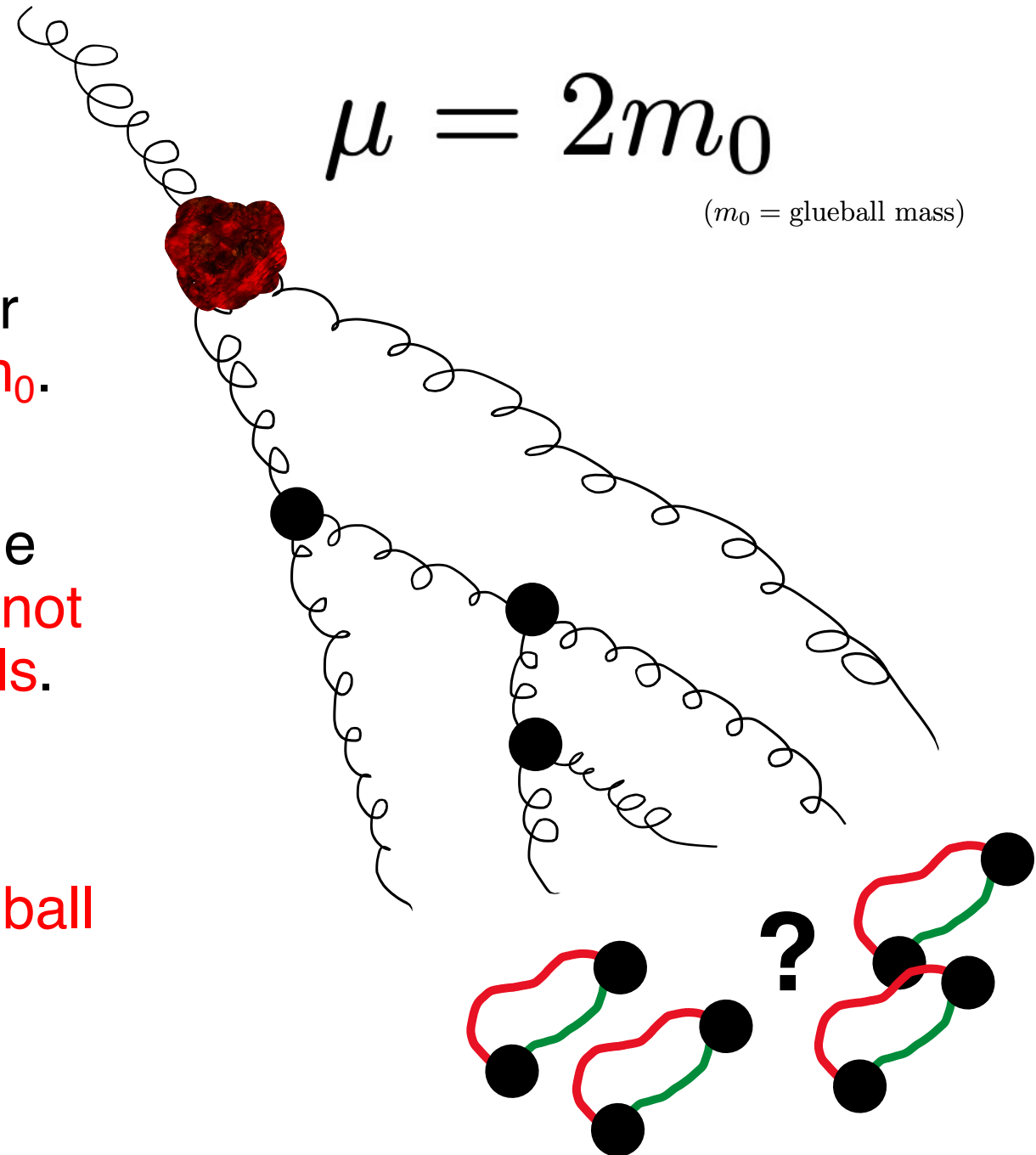
$$\mu \sim \Lambda$$
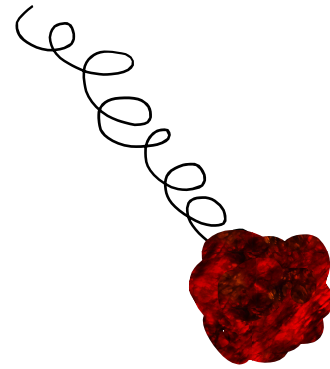
?
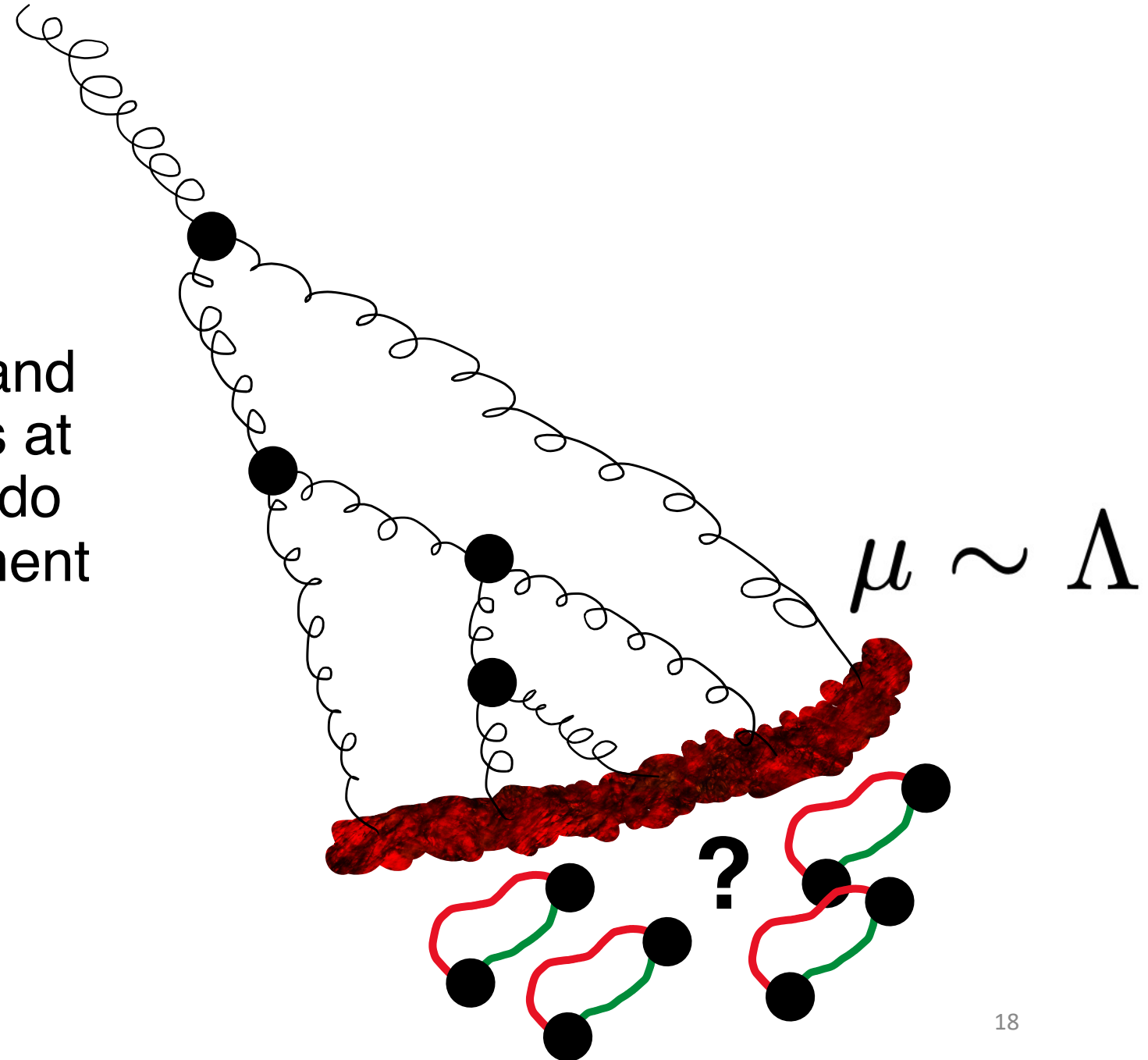
$$\mu = 2m_0$$

$(m_0 = \text{glueball mass})$

Instead consider the shower crossing the higher scale 2 m_0.

In this 'jet', the virtuality of the gluons following this point cannot produce two on-shell glueballs.

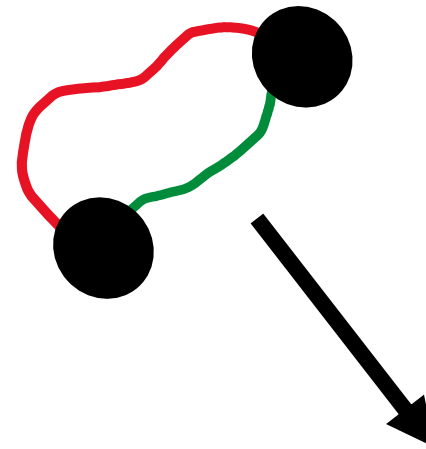The following gluons must coalesce into at most one glueball state.
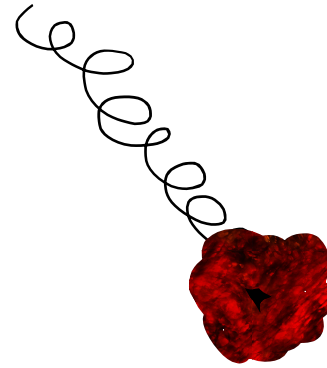
$$\mu = 2m_0$$

(m_0 = glueball mass)

SIMPLEST IDEA:

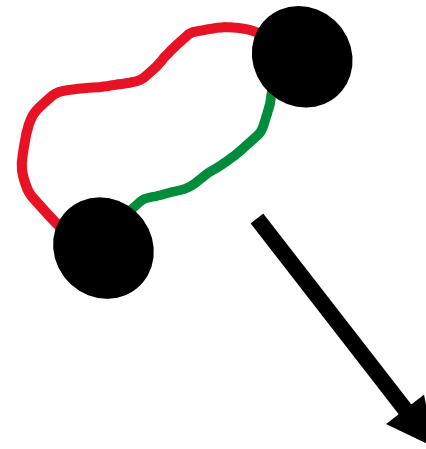**TERMINATE SHOWER AT 2m_0**

TURN GLUON INTO GLUEBALL

Comments:

$$\mu = 2m_0$$

$(m_0 = \text{glueball mass})$

- Shower is terminated far above confinement scale, perturbative QCD is still trusted

- Final gluons are still colour octet states, implicitly some IR gluons are exchanged so colour singlet glueballs form
  - Assumption: gluons are transferred around confinement scale, thus any momentum transferred will be roughly order of magnitude smaller than glueball energies
  - $\Lambda/m_0 \sim$ 15% uncertainty in final energy distribution

- 2 -> 3 processes are phase space suppressed, glueball multiplicity should be a robust upper bound

- To explore other possibilities just need to consider evolution leading to fewer glueballs

Terminating the shower earlier

- A multiplicative factor that tunes the scale at which the shower terminates, hadronization scale $= c * (2 * m_0), c > 1$

- Terminate earlier $\longrightarrow$ Fewer splittings $\longrightarrow$ Fewer glueballs
  - Internally consistent method of generating fewer glueballs, part of theory uncertainty in signal

- Physically corresponds to the possibility that gluons are exchanged above the confinement scale, colour singlets are formed earlier
  - Alternative phrasing: Due to nonperturbative physics particular to Nf = 0 SU(N), colour loop fragmentation happens at time scales shorter than perturbative showering

$c = 1$ $\implies$ $c = 2$
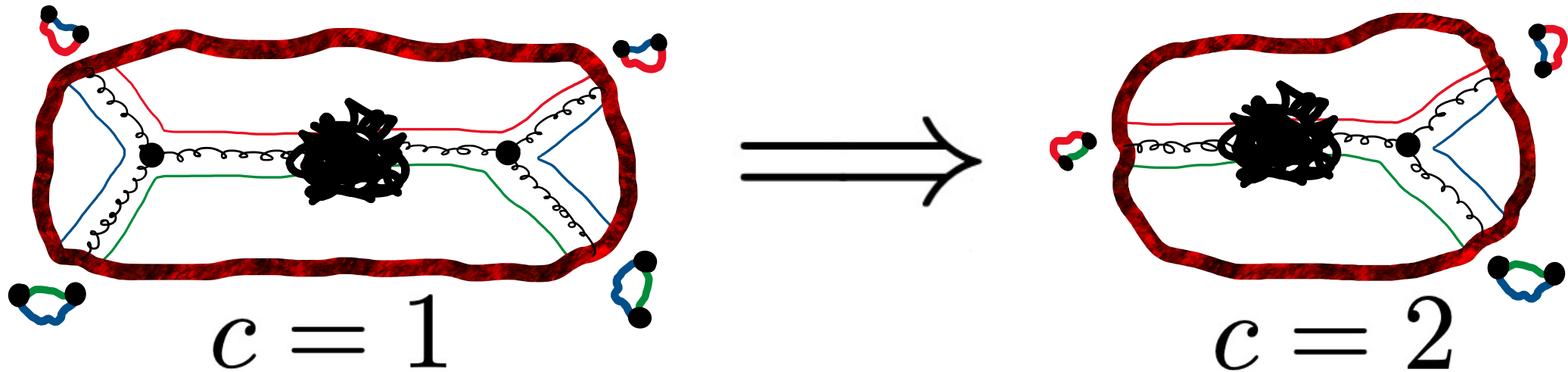
However !!!
What if QCD intuition is wrong ?

- What about the possibility of a gluon plasma ?
  - Instead of glueballs forming , a higher energy colour singlet state pinches off, forms a high mass pure-glue fireball, and then evaporates by glueball emission
  - Similar to the case for high values of c, but instead of being put on shell, forms a high mass 'plasma' state
  - Would decay isotropically by thermally emitting glueballs (SUEP-y)

Knapen, Pagan Griso, Papucci, Robinson, arXiv:1612.00850

- Currently working on incorporating this as an option in our code
  - Additional parameter that can be turned on for c values larger than 2
  - Will terminate the shower at some early point, then allow this excited state to decay in a similar matter to what is used in current SUEP simulations

Relative Glueball Multiplicity

- In reality there are multiple glueball species
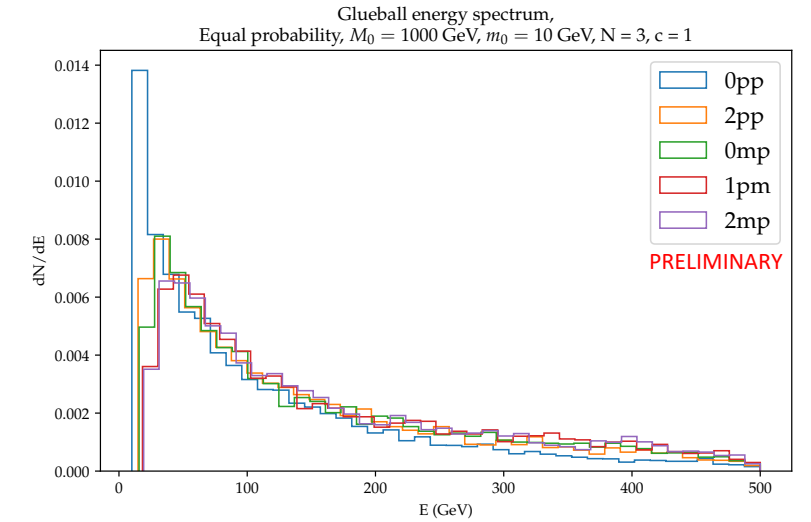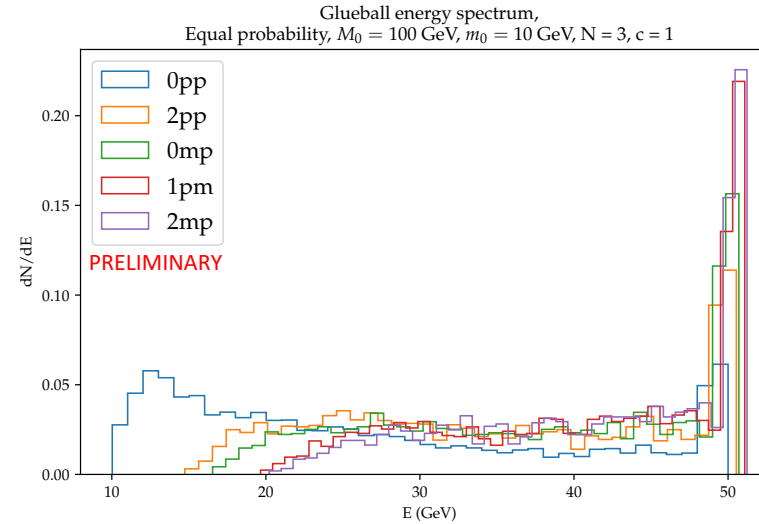- Currently use thermal model Falkowski, Juknevich, Shelton, arXiv:0908.1790

$$\frac{N_J}{N_0} = (2J + 1)\left(\frac{m_J}{m_0}\right)^{3/2} e^{-(m_J - m_0)/T_c}$$

- Reasonable zero-th order approximation
- T_c also calculated in lattice
- 5 lightest states account for 98% for glueballs
- Limitations: Non-local effects…
- Freedom to tweak in code, adjust T_c values to span probabilities.
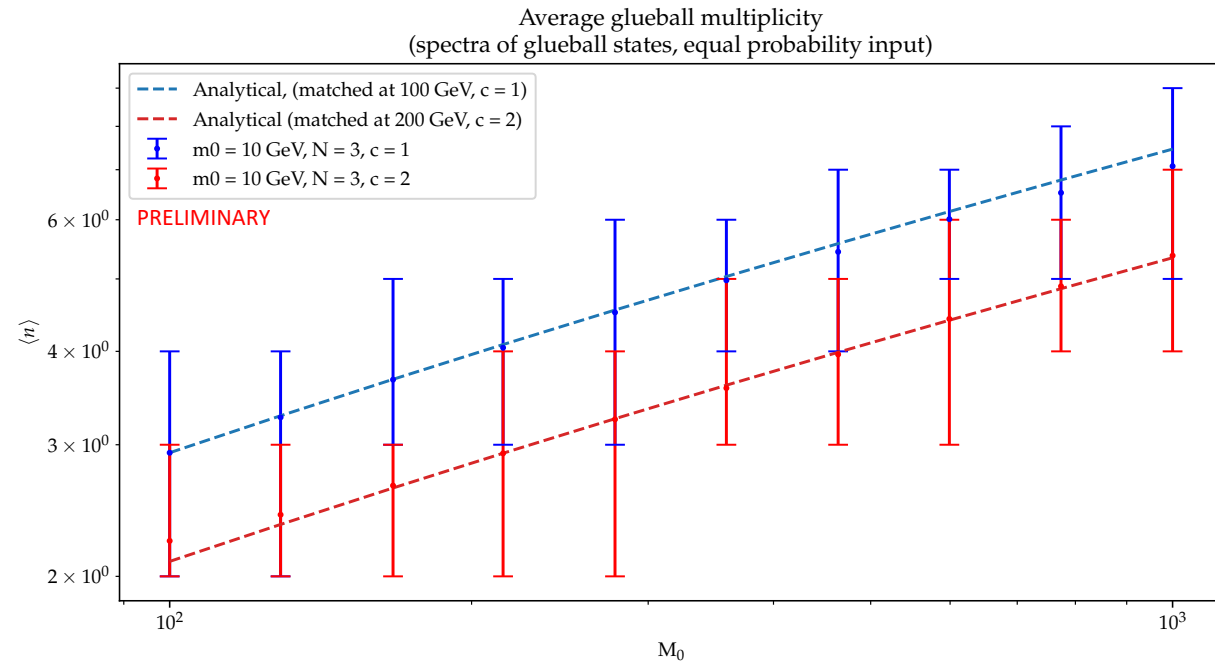
GlueShower Example Plots

- Exemplar fragmentation functions
  - Low energy case dominated by two-body decays
  - High energy case resembles a standard fragmentation function

Glueball energy spectrum,
Equal probability, $M_0 = 100$ GeV, $m_0 = 10$ GeV, $N = 3$, $c = 1$

Glueball energy spectrum,
Equal probability, $M_0 = 1000$ GeV, $m_0 = 10$ GeV, $N = 3$, $c = 1$

- Get back the correct multiplicity scaling for zero flavour QCD
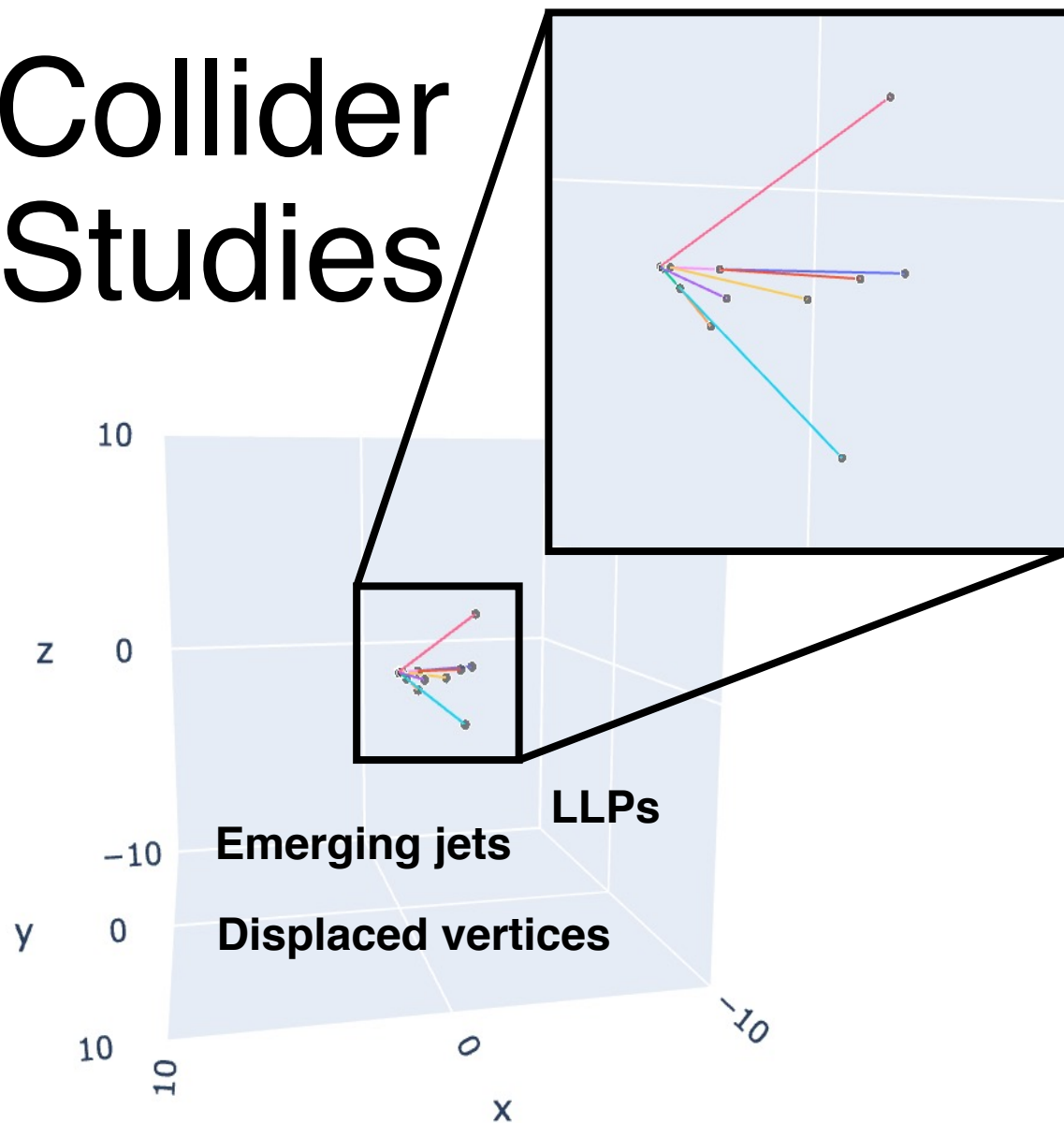- Doubling hadronization scale still leads to largely similar outputs

$$\langle n(E_{CM}^2)\rangle \propto \exp\left[\frac{12\pi}{11C_A}\sqrt{\frac{2C_A}{\pi\alpha(E_{CM}^2)}} + \frac{1}{4}\ln\left(\alpha(E_{CM}^2)\right)\right]$$

Webber, Stirling, Ellis, QCD and Collider Physics

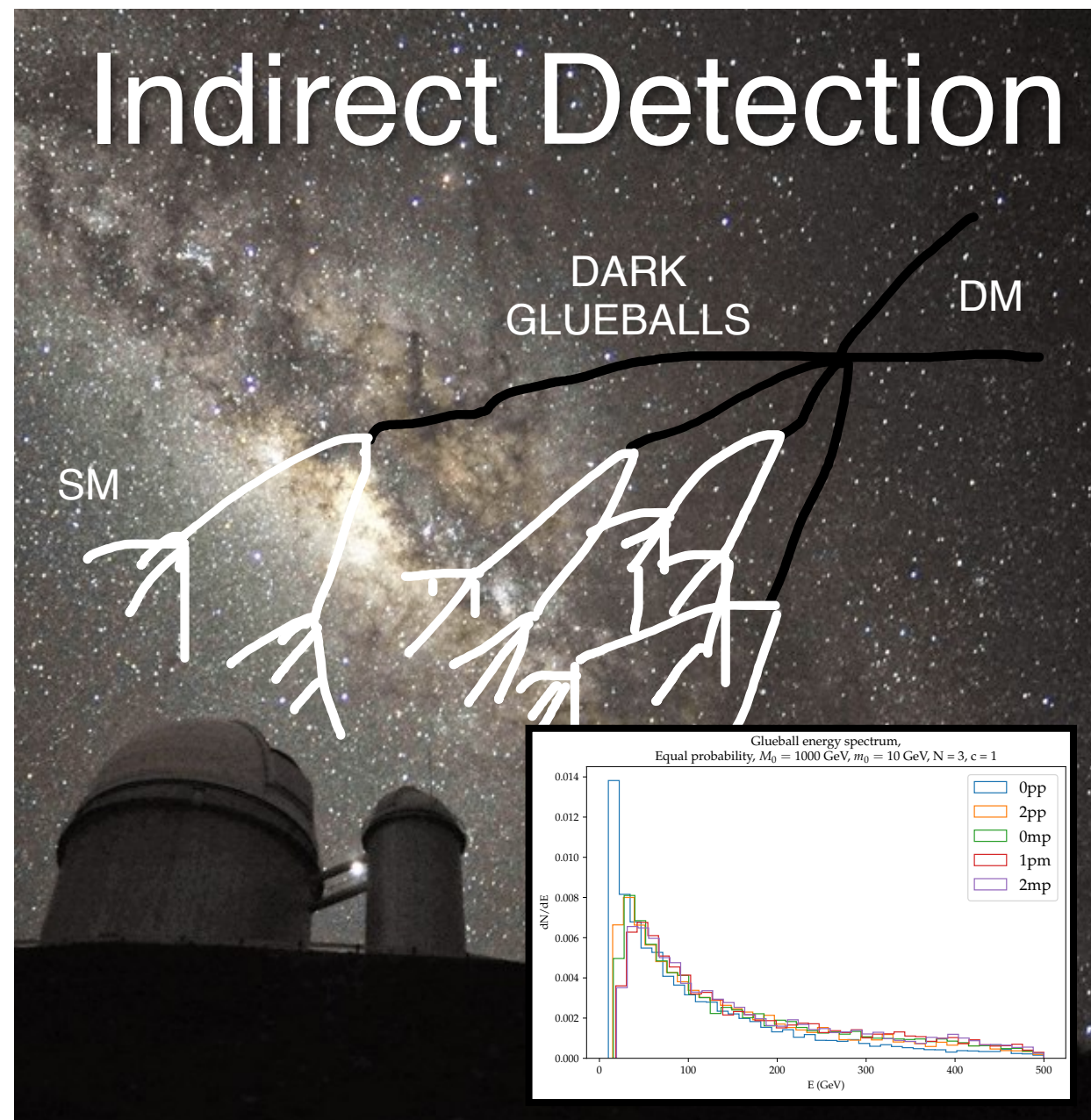Average glueball multiplicity
(spectra of glueball states, equal probability input)

Applications

Collider Studies

LLPs

Emerging jets

Displaced vertices

Indirect Detection

DARK GLUEBALLS

DM

SM

Glueball energy spectrum,
Equal probability, $M_0 = 1000$ GeV, $m_0 = 10$ GeV, $N = 3$, $c = 1$

0pp
2pp
0mp
1pm
2mp

Conclusions

- Dark showers are a general signature of hidden valley models, motivated by neutral naturalness
  - The zero flavour case being a possible version
- Still many unknowns around the pure-glue hadronisation process
- This work is an attempt at producing a physically motivated tool that can scan the possible range of phenomena, through adjusting internal parameters
  - Outputs are relatively robust to scanning the current parameters
- Intend to publicly release a Python code, `GlueShower`, for the community to use
  - Can run for SU(N), where N can be select values in the range 2 to 12

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