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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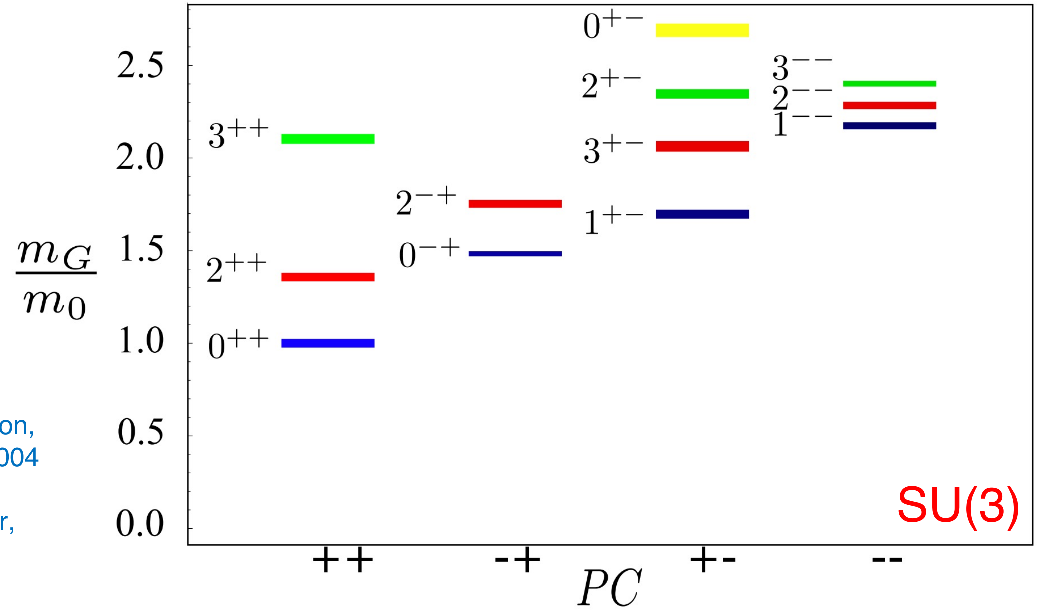
Introduction and Motivation

Strassler, Zurek, arXiv:hep-ph/0604261
Craig, Katz, Strassler, Sundrum, arXiv: 1501.053
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
- 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

Athenodorou, Teper, arXiv:2106.00364

- Masses entirely parameterized by the 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

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

  - Possible dimension 8 operator could also couple the dark glueballs directly to SM gauge bosons

Juknevich, Melnikov, Strassler, arXiv:0903.0883

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

The Perturbative Shower

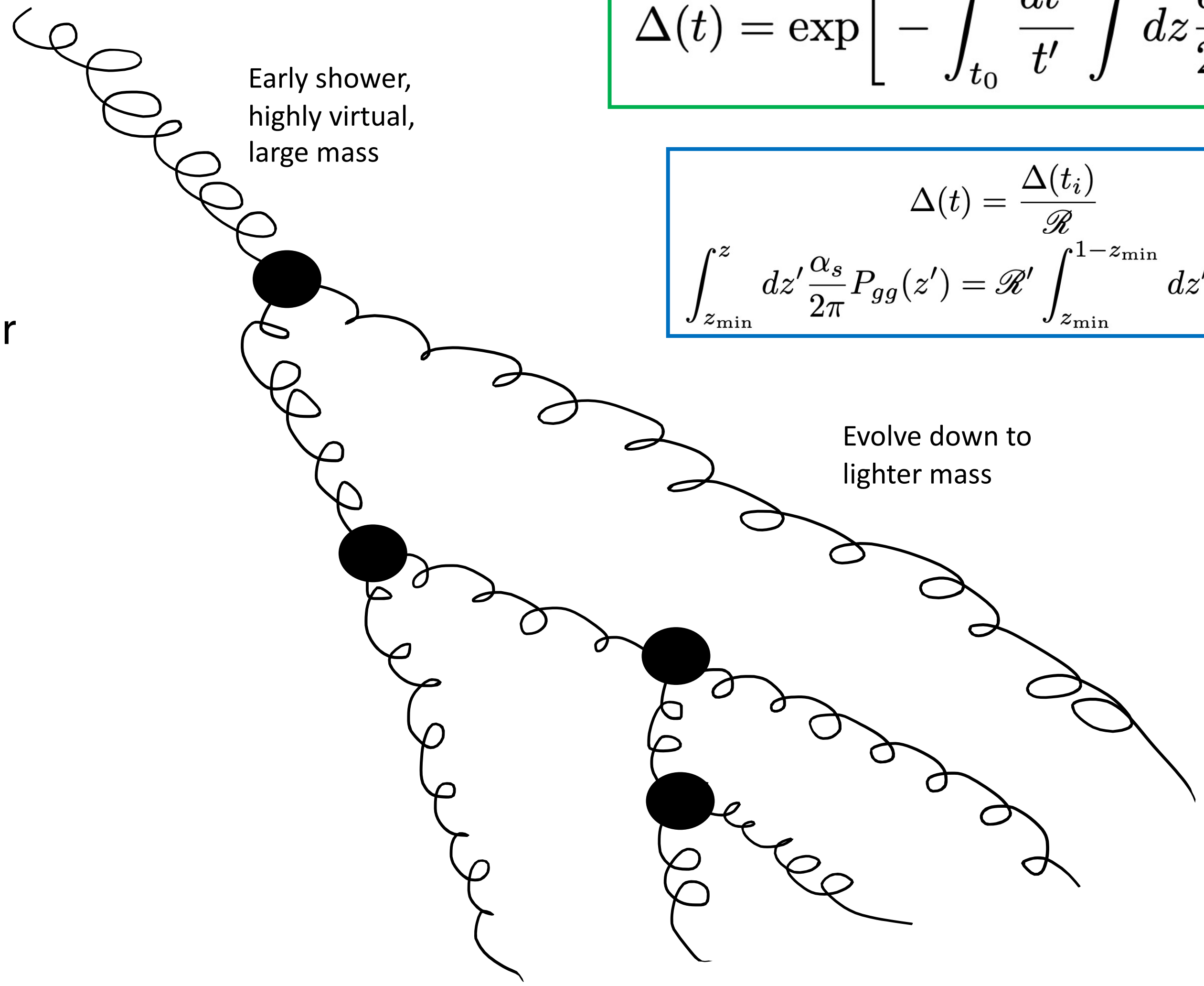
Sjostrand, Mrenna, Skands, arXiv:hep-ph/0603175
Webber, Stirling, Ellis, QCD and Collider Physics

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

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

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

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



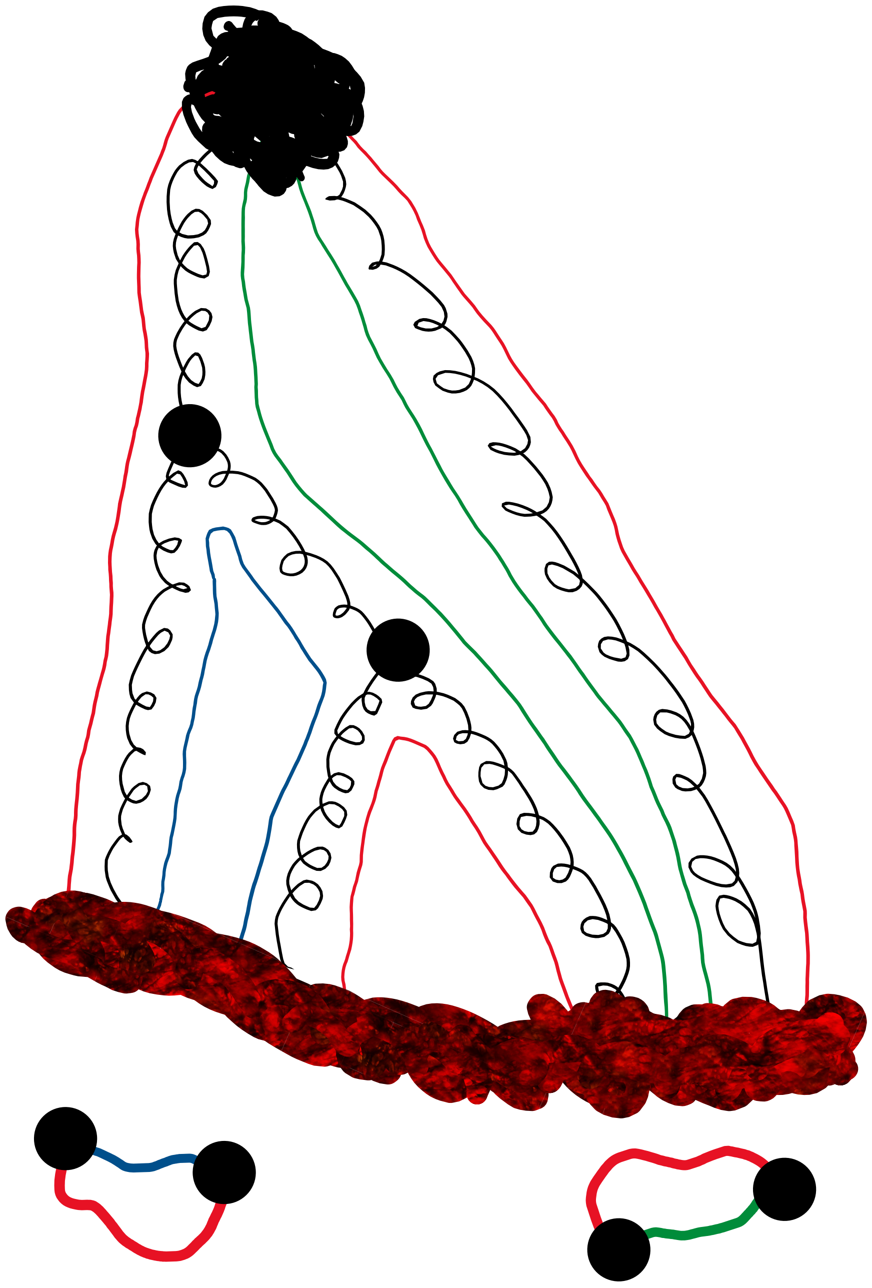
- Gluon-to-gluon splitting function
  - Determines energy of each of their daughter gluons
- Sudakov form factors
  - Determines the probability of a gluon evolving down from a high virtuality (mass) closer to the glueball mass without splitting
- Monte Carlo Method
  - How the above is practically used in our simulation

But what isn’t well known …

Hadronization Process

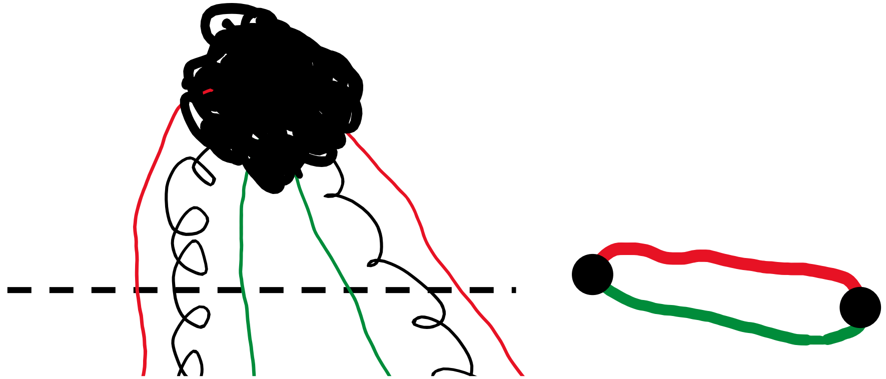
- Even in SM QCD, specifics of the non-perturbative hadronization process are not well understood
  - Models are tuned to fit data
- In the absence of data for pure glue showers, we have to come up with a physically reasonable and motivated approach, but also ideally is able to generate a representative 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**

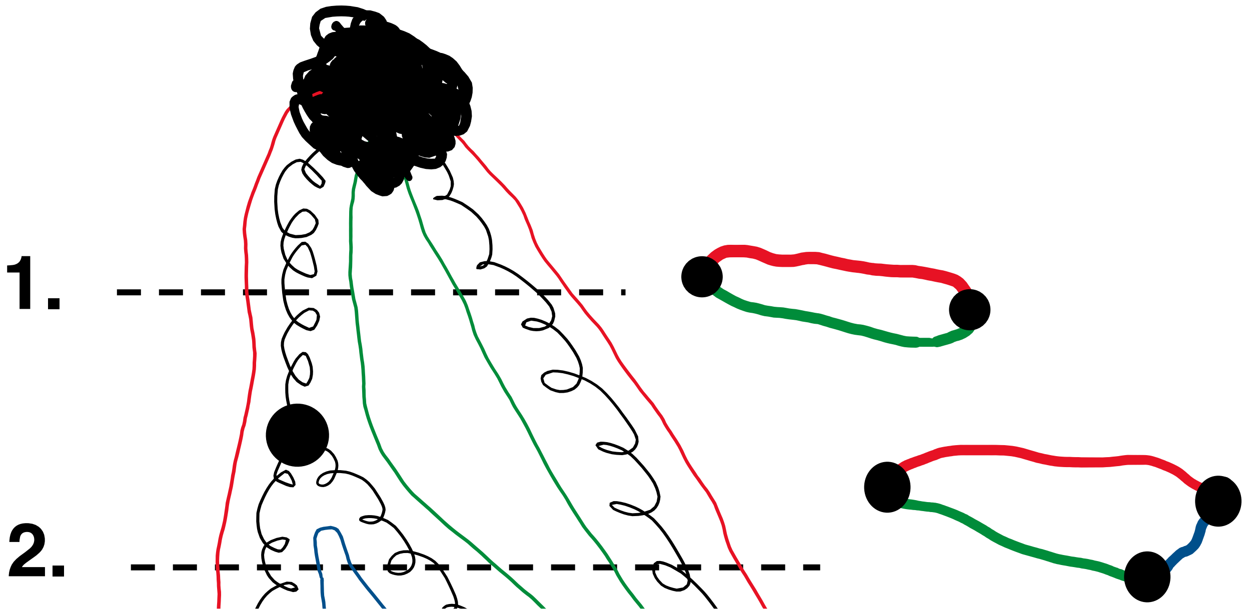
Let’s start off by considering a single glueball species…



One example:
Simple case of two gluon production forming two glueballs

1.

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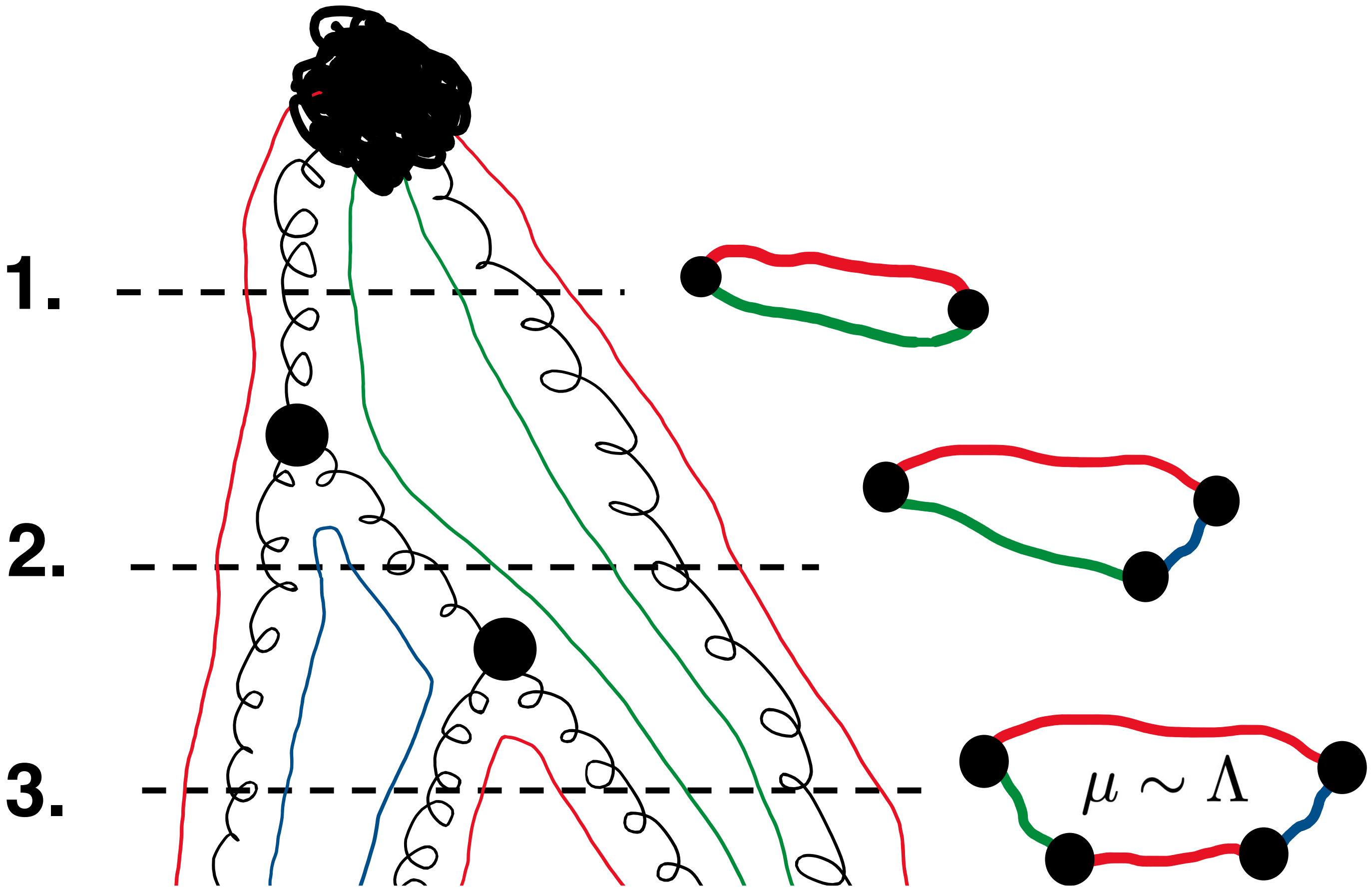
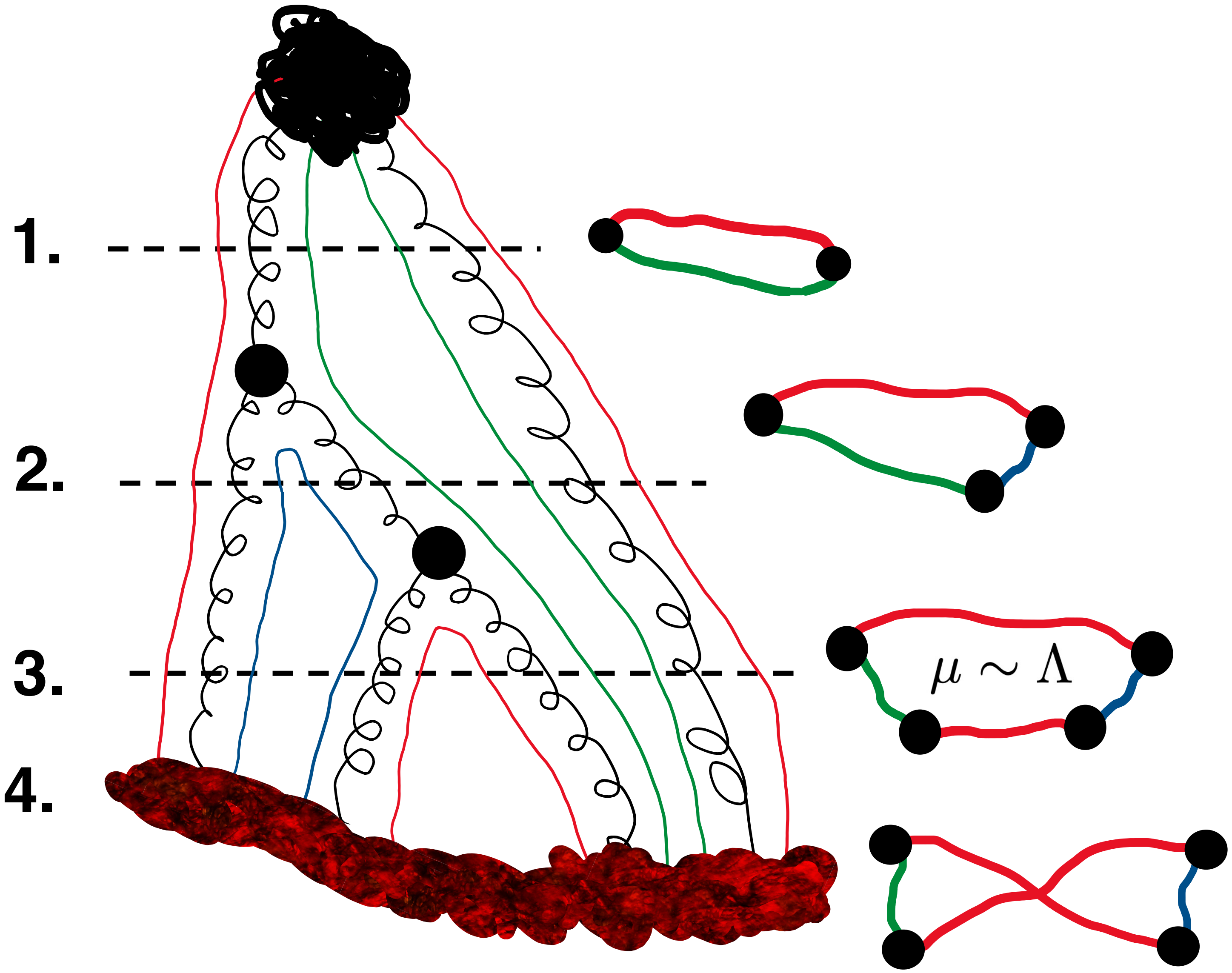
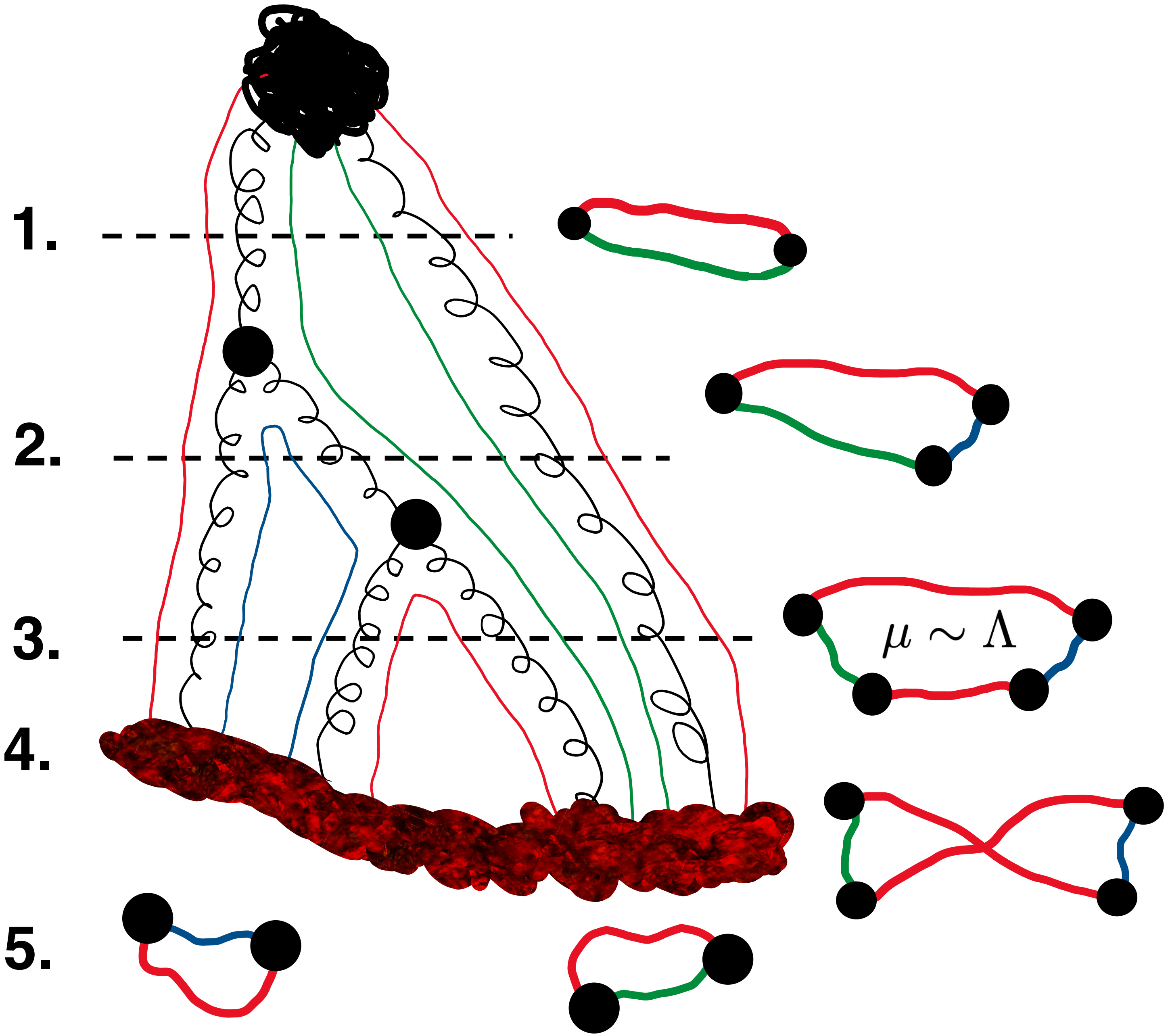

1.
2.
3.
$\mu \sim \Lambda$


1.
2.
3.
4.
$\mu \sim \Lambda$


1.
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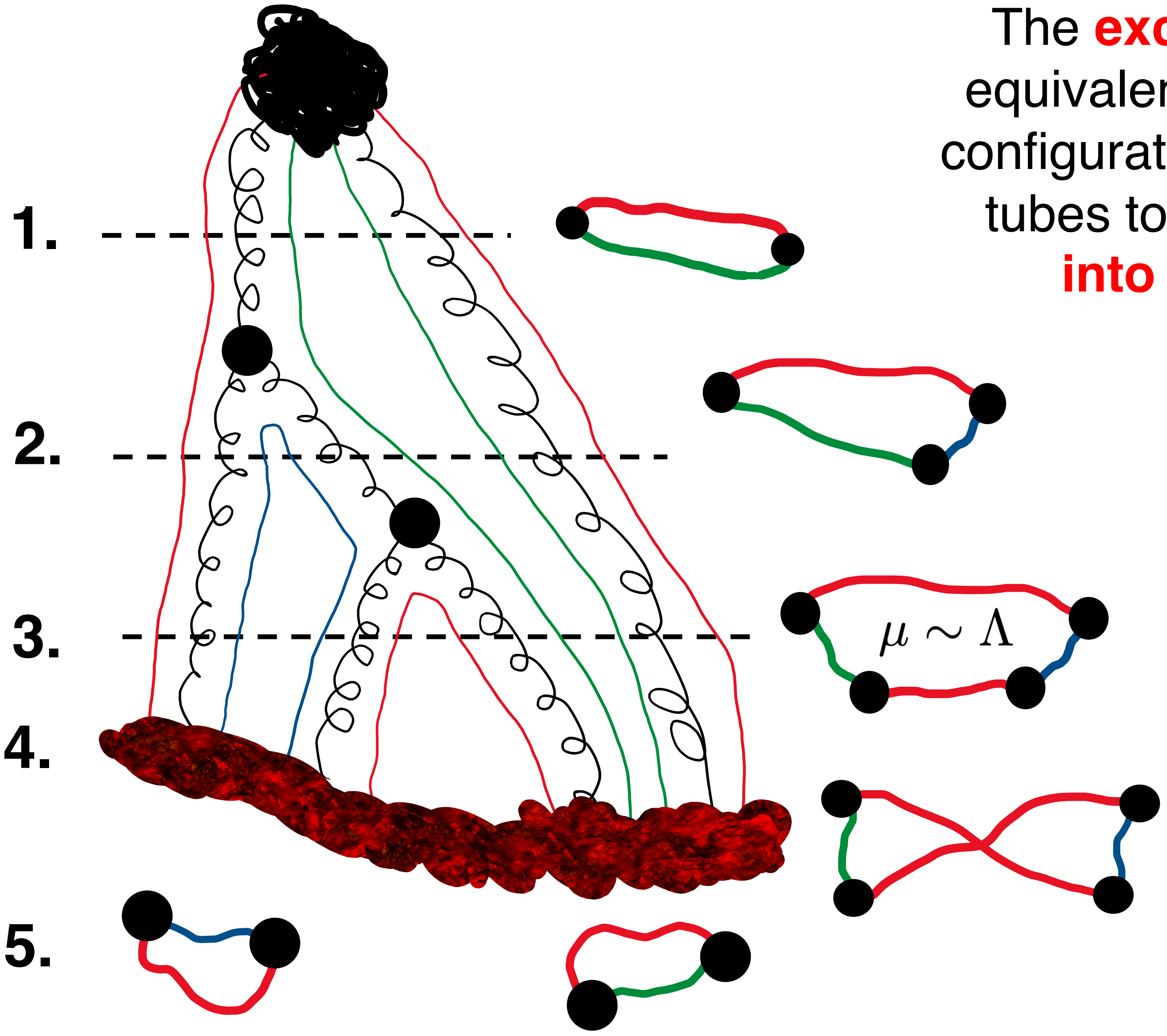
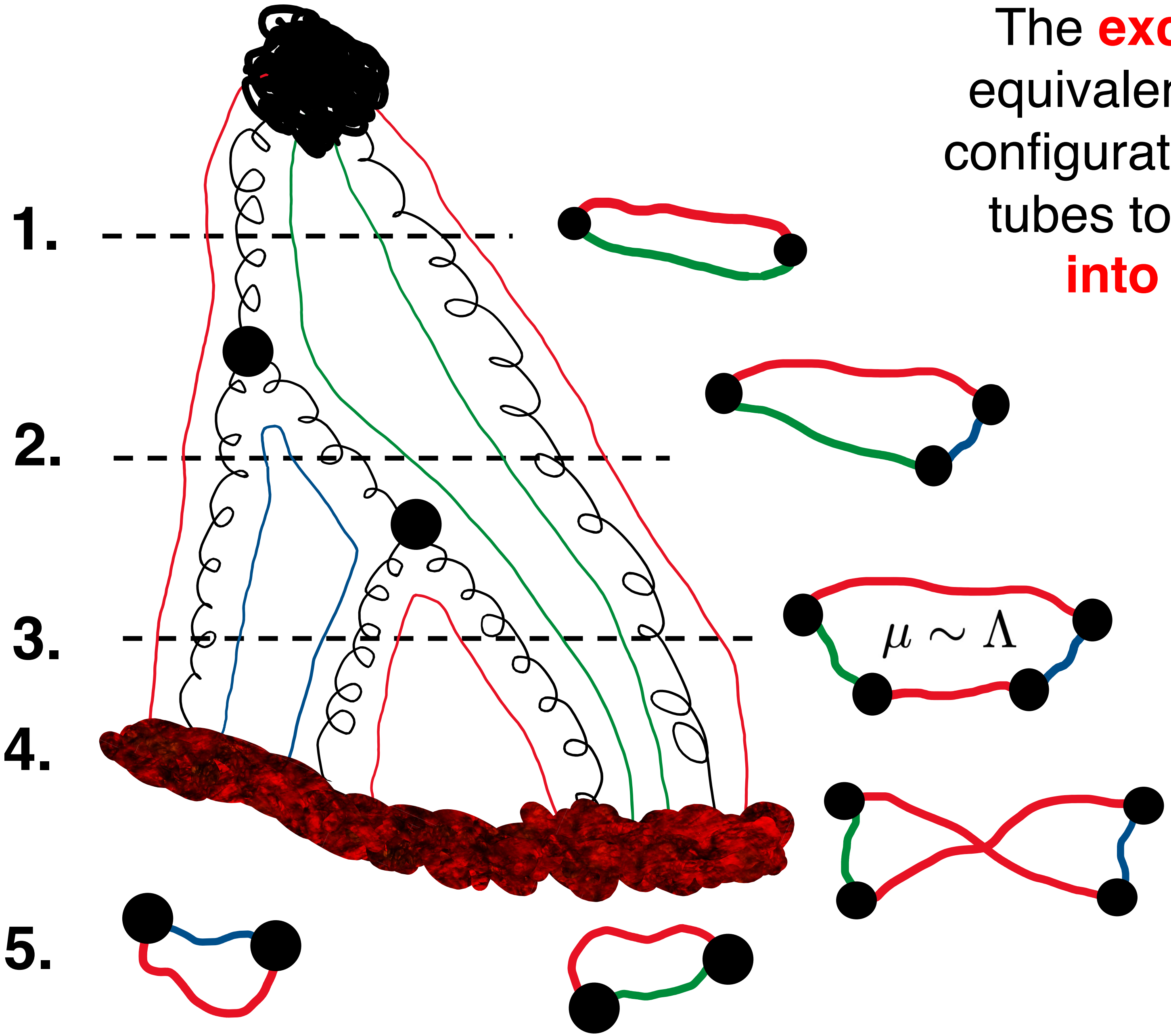
$\mu \sim \Lambda$
4.
5.



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**

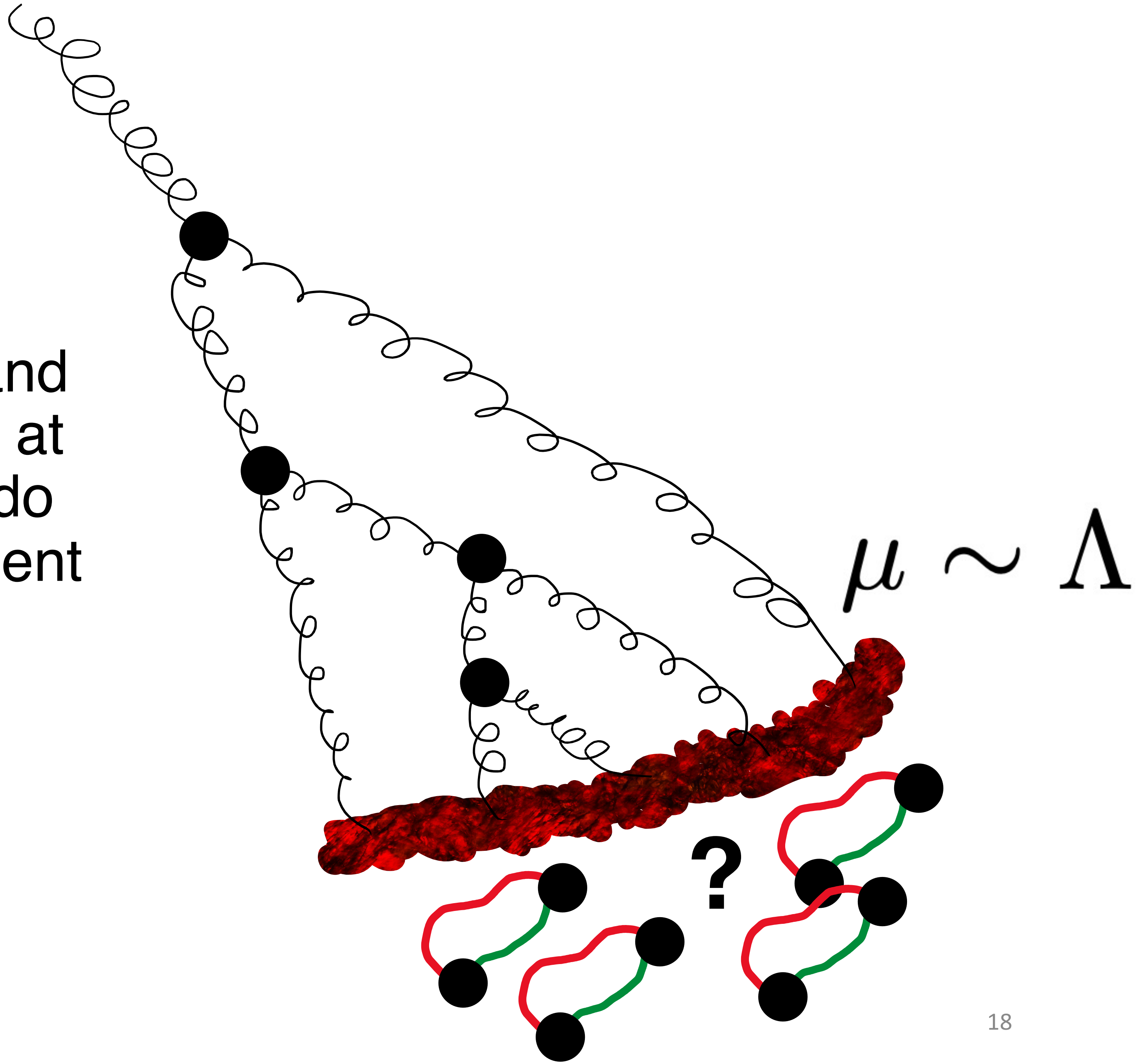


The **exchange of an IR gluon** is equivalent to generating a flux tube configuration that allows same-colour tubes to cross and then **separate into colour singlet states**

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:

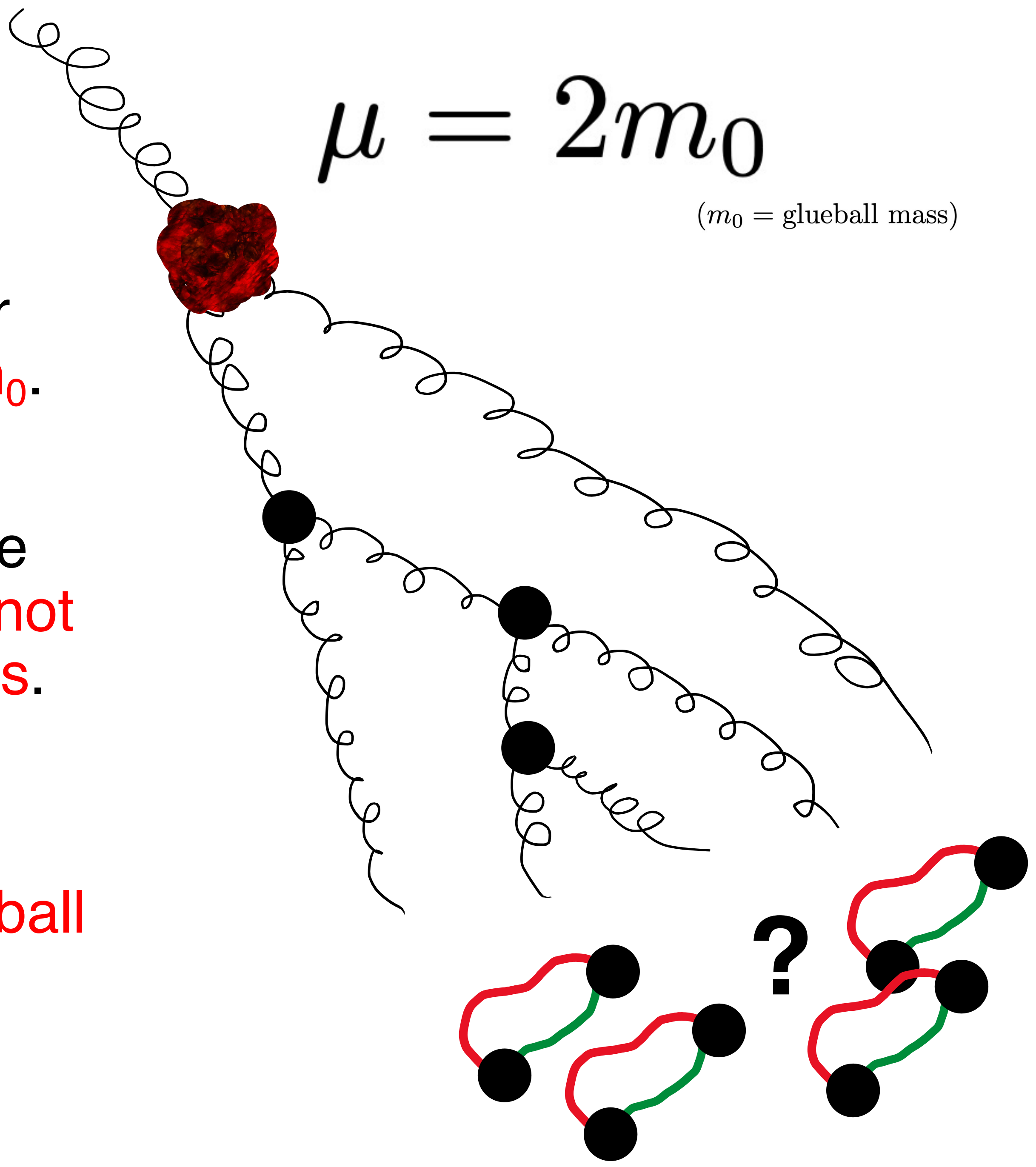
Given previous assumption and some arrangement of gluons at the confinement scale, how do we map them to an arrangement of final state glueballs?

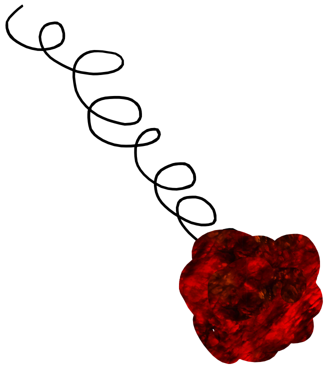


Instead consider the shower crossing the higher scale 2 m_0.

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.





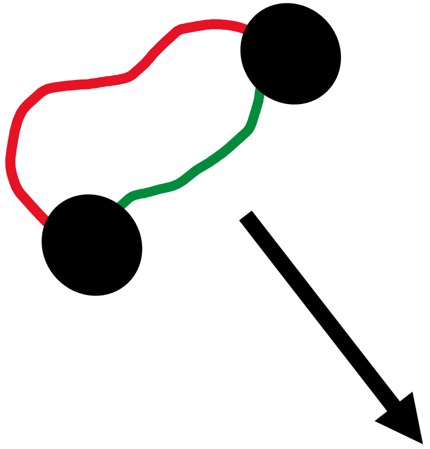
$$\mu = 2m_0$$

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

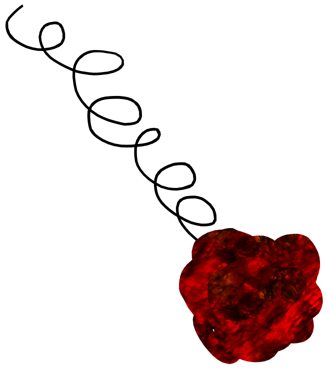
SIMPLEST IDEA:

TERMINATE SHOWER AT $2m_0$

TURN GLUON INTO GLUEBALL



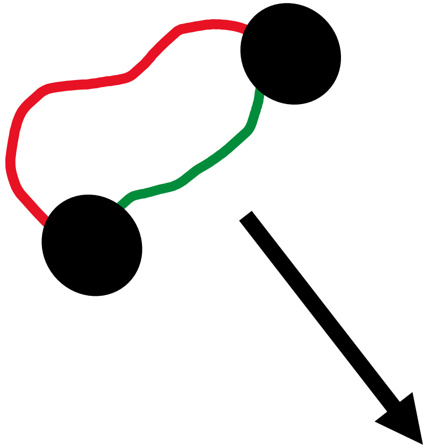
Comments:



$$\mu = 2m_0$$

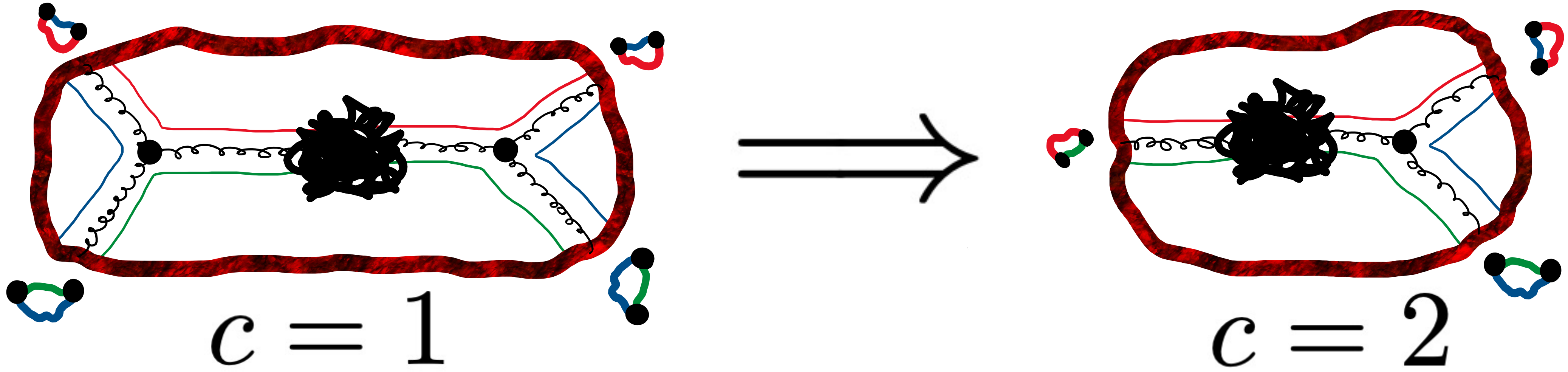
$(m_0 = \text{glueball mass})$

- 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
  - Λ/m_0 ~ 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 ⟶ Fewer splittings ⟶ 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



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
- Incorporated this as extra parameter in code
  - Natural extension of previous hadronization scale parameter to large value

Relative Glueball Multiplicity

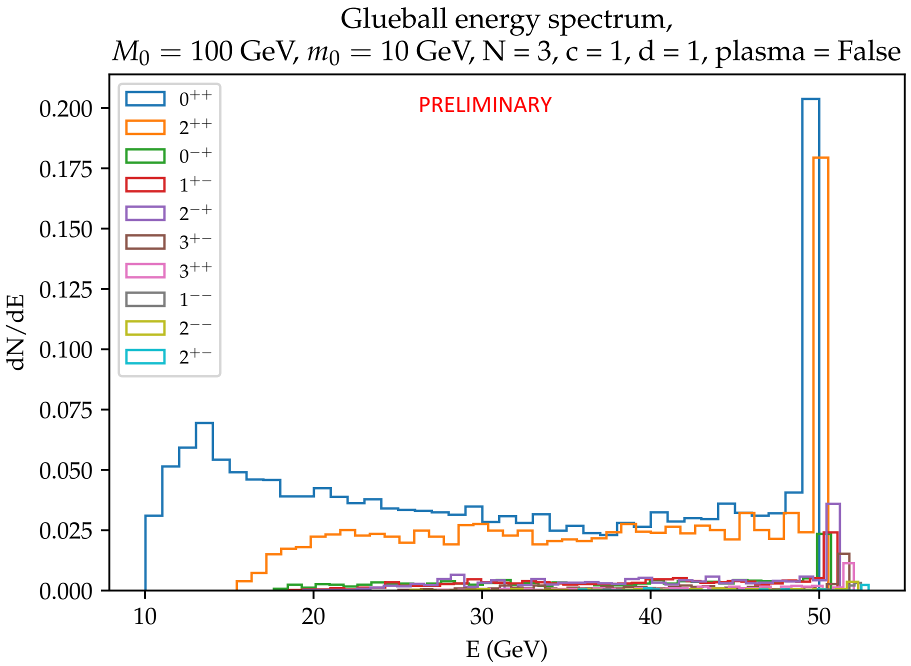
- In reality there are multiple glueball species
- Currently use thermal model Falkowski, Juknevich, Shelton, arXiv:0908.1790

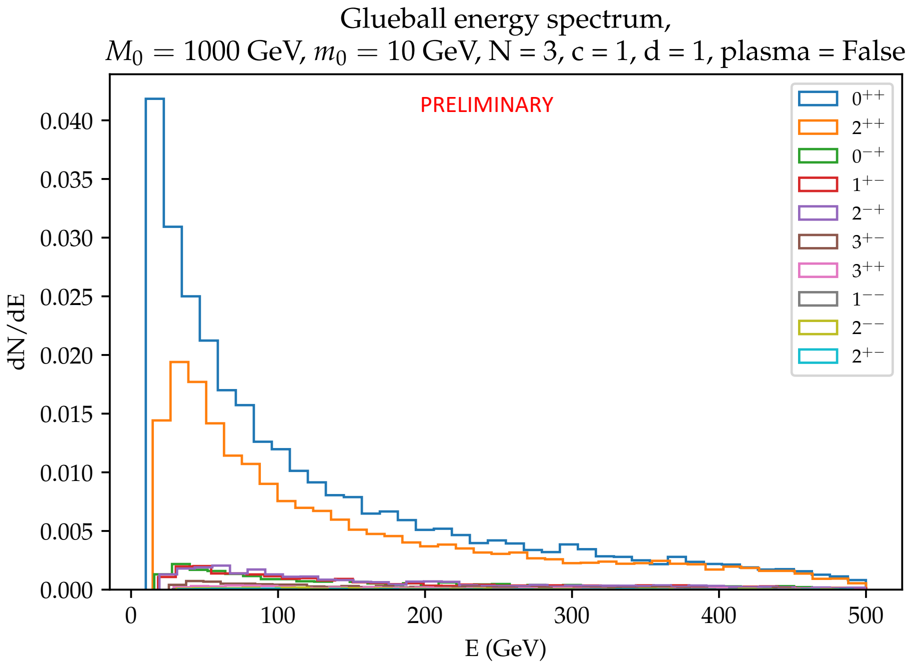
$$\frac{N_J}{N_0} = (2J+1)\left(\frac{m_J}{m_0}\right)^{3/2} e^{-(m_J - m_0)/T_c}$$

  - 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

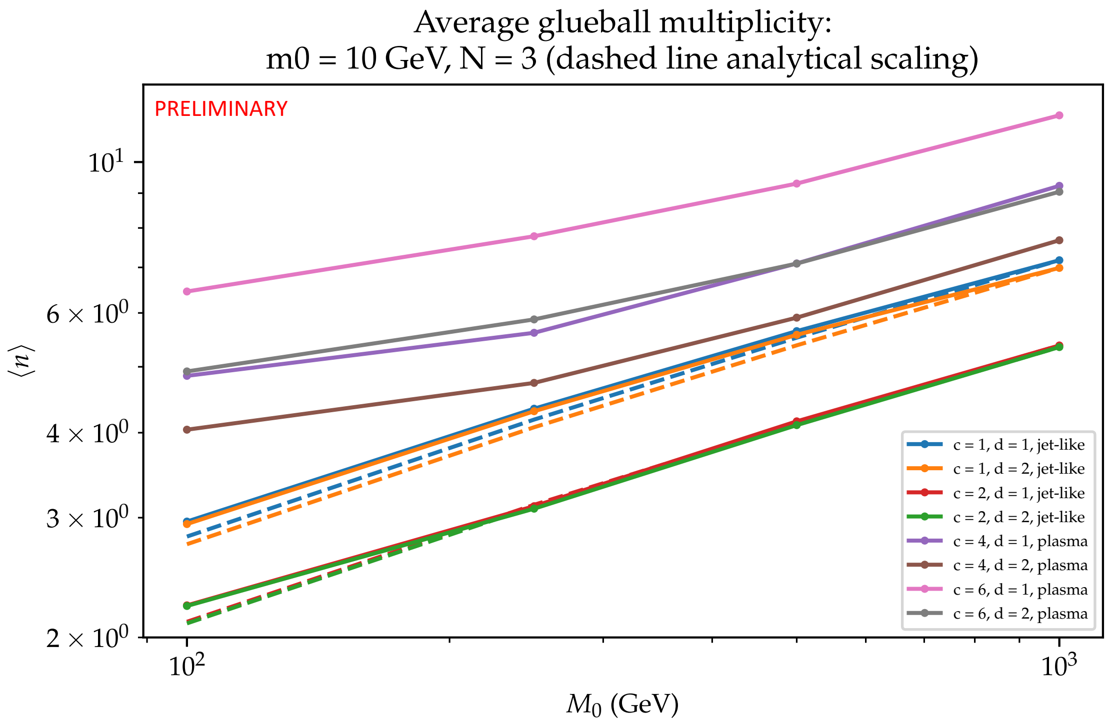




- Get back the correct multiplicity scaling for zero flavour QCD
- Various parameter benchmarks still lead to largely similar outputs

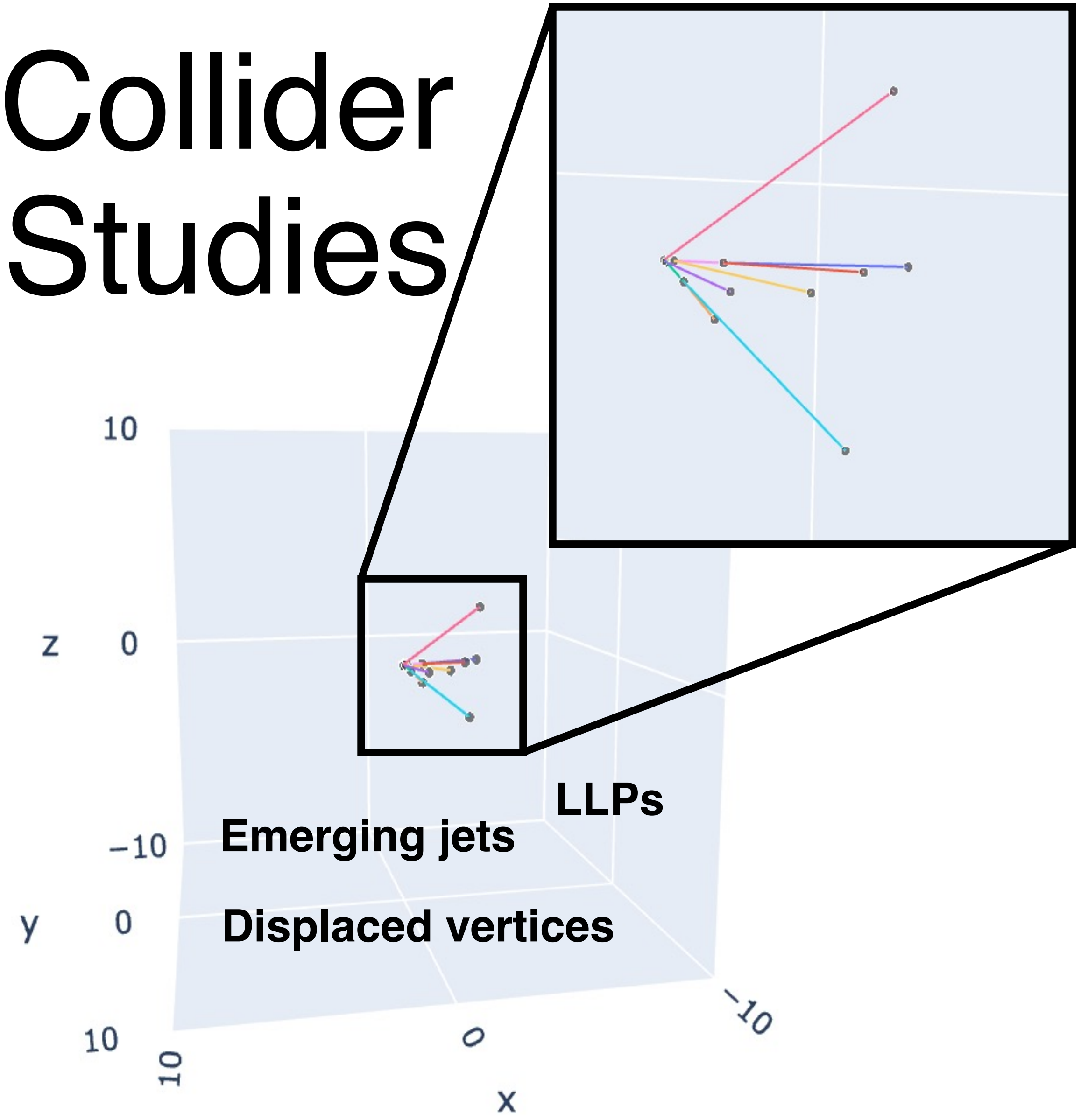
$$\langle n(E_{CM}^2)\rangle \propto \exp\left[\frac{12\pi}{11C_A}\sqrt{\frac{2C_A}{\pi\alpha(E_{CM}^2)}}+\frac{1}{4}\ln\left(\alpha(E_{CM}^2)\right)\right]$$

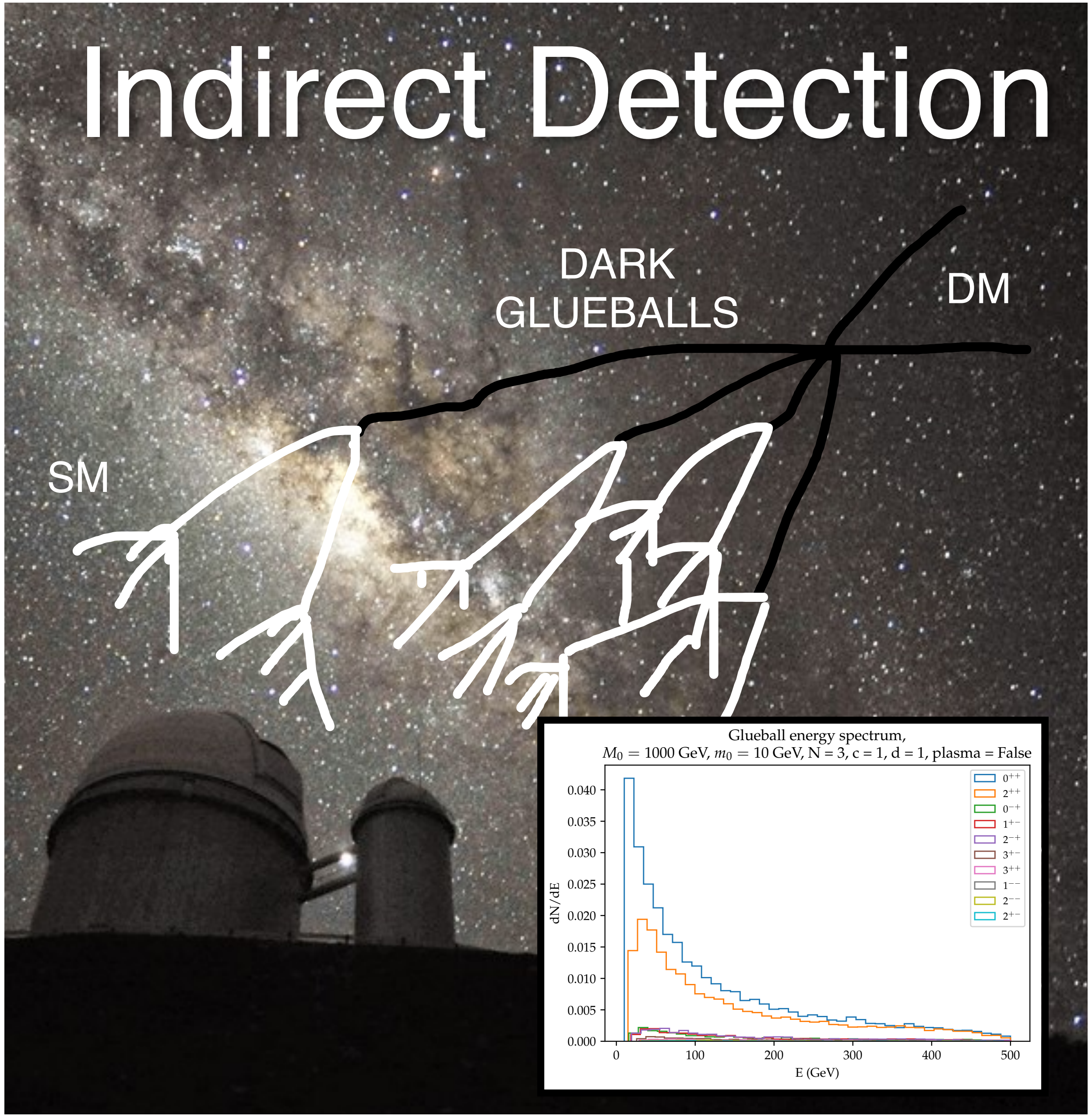
Webber, Stirling, Ellis, QCD and Collider Physics



Applications

Collider Studies

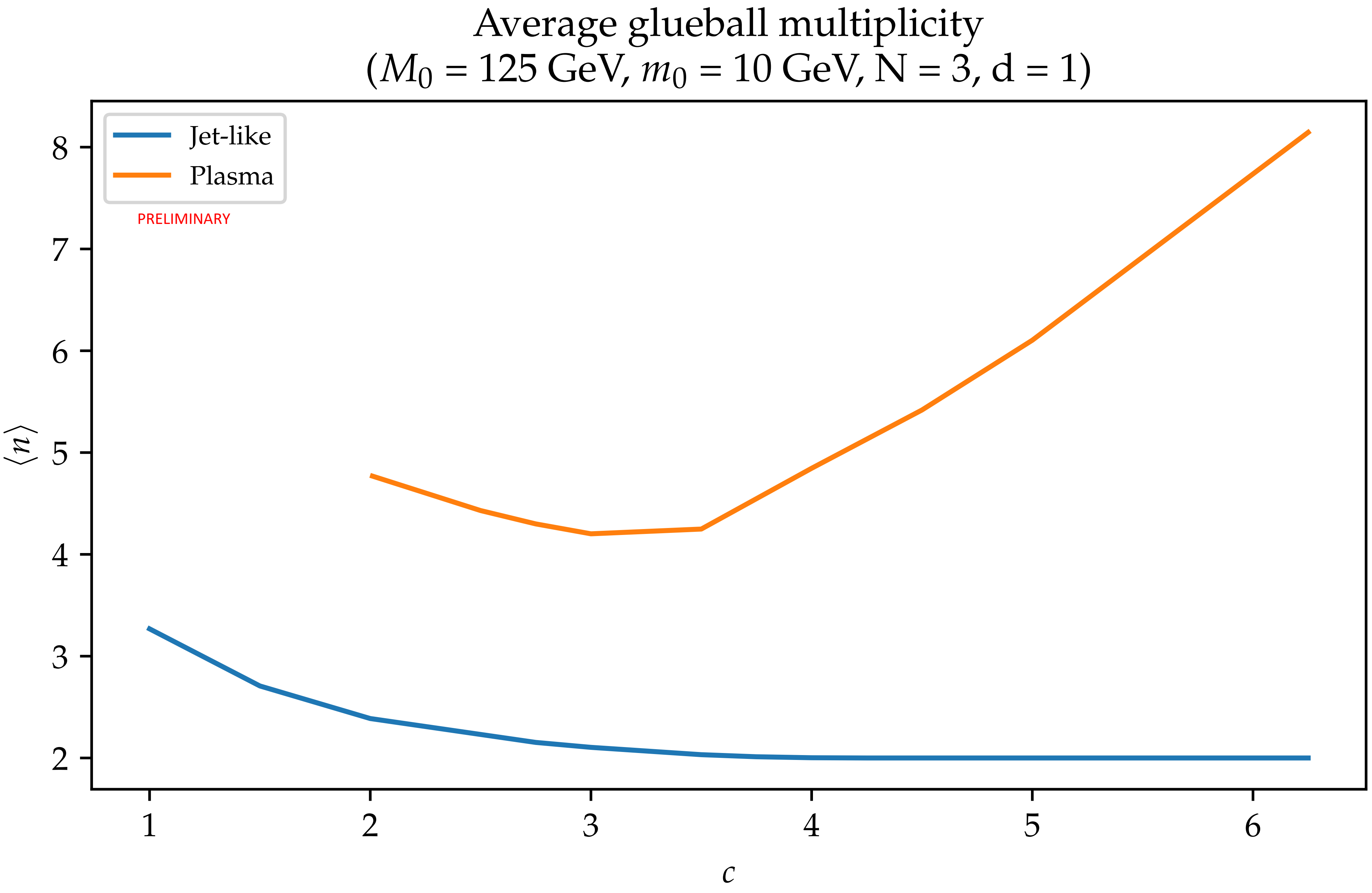




Conclusions

- 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
  - Choose benchmark parameters to cover range
- 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
  - Interested to hear ways we could improve functionality, please reach out and contact!

Contact: caleb.gemmell@mail.utoronto.ca



Average glueball multiplicity
(M_0 = 125 GeV, m_0 = 10 GeV, N = 3, d = 1)
Jet-like
Plasma
PRELIMINARY
$\langle n \rangle$
8
7
6
5
4
3
2
1
2
3
4
5
6
c

Average Glueball Energy
(m0 = 10 GeV, N = 3)