Simulation and Indirect Detection of Dark Glueball Showers

Caleb Gemmell

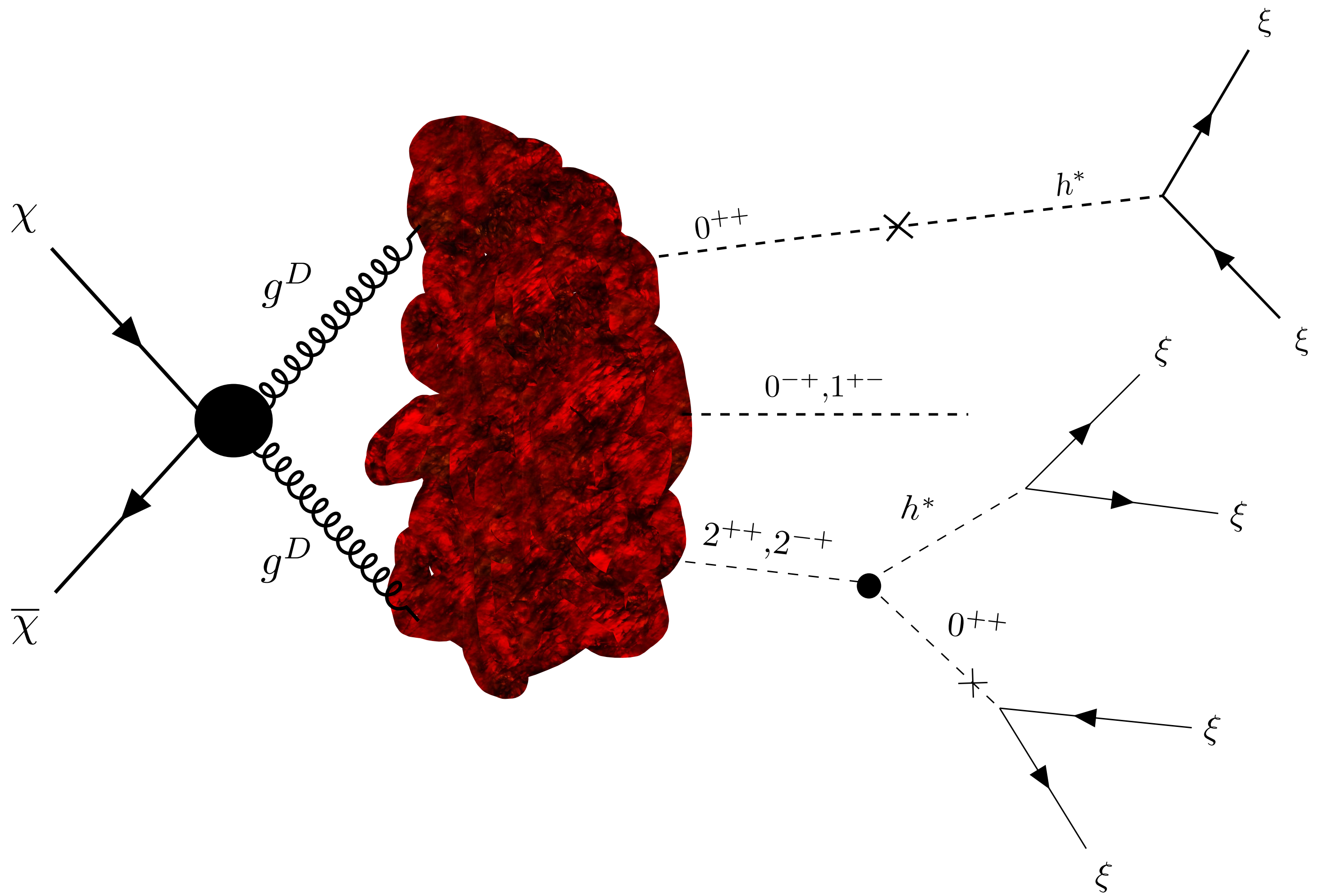
Phenomenology Symposium 2022

Based on work with David Curtin and Chris Verhaaren [arXiv: 2202.12899]

Contact: caleb.gemmell@mail.utoronto.ca

UNIVERSITY OF TORONTO

Outline:



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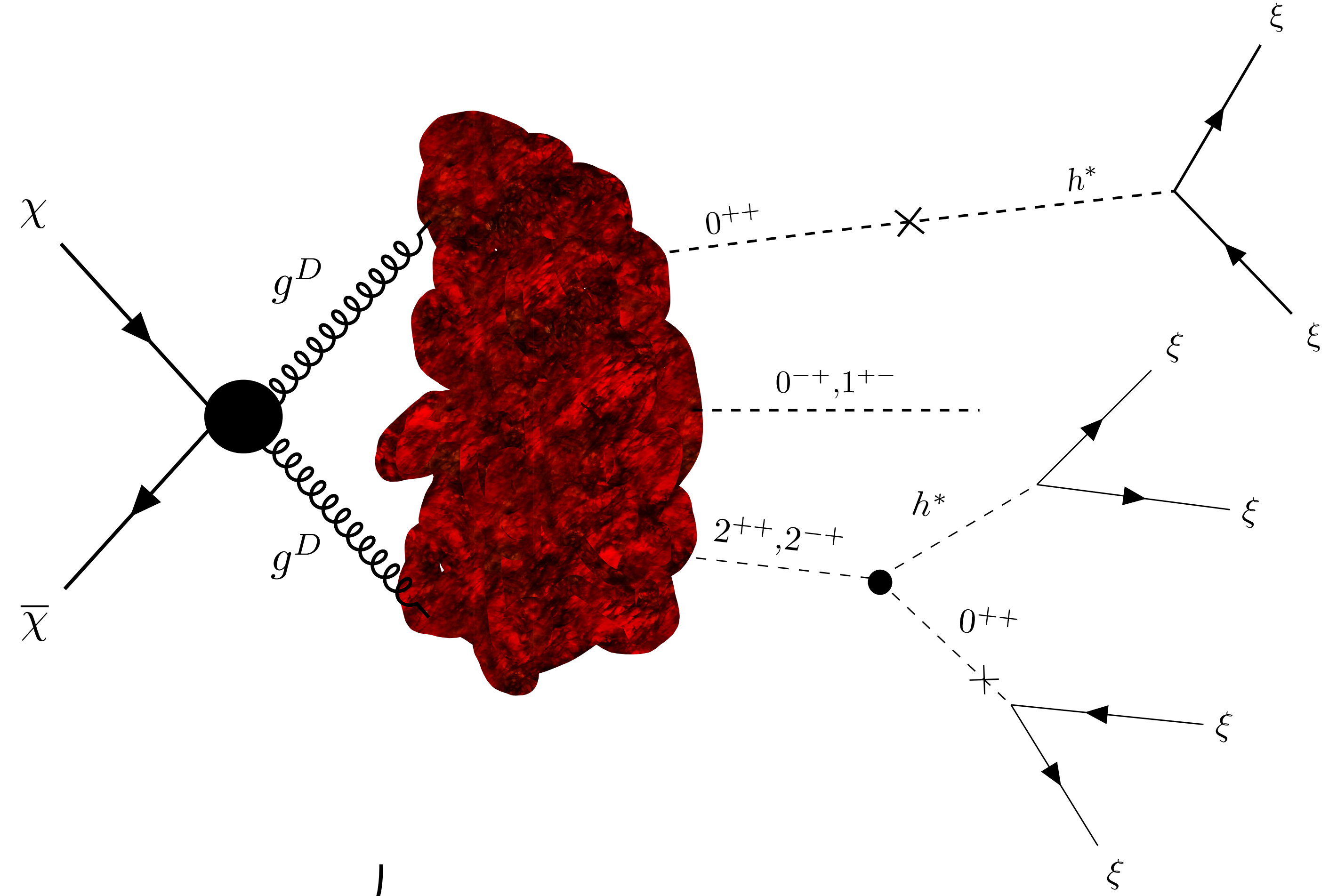
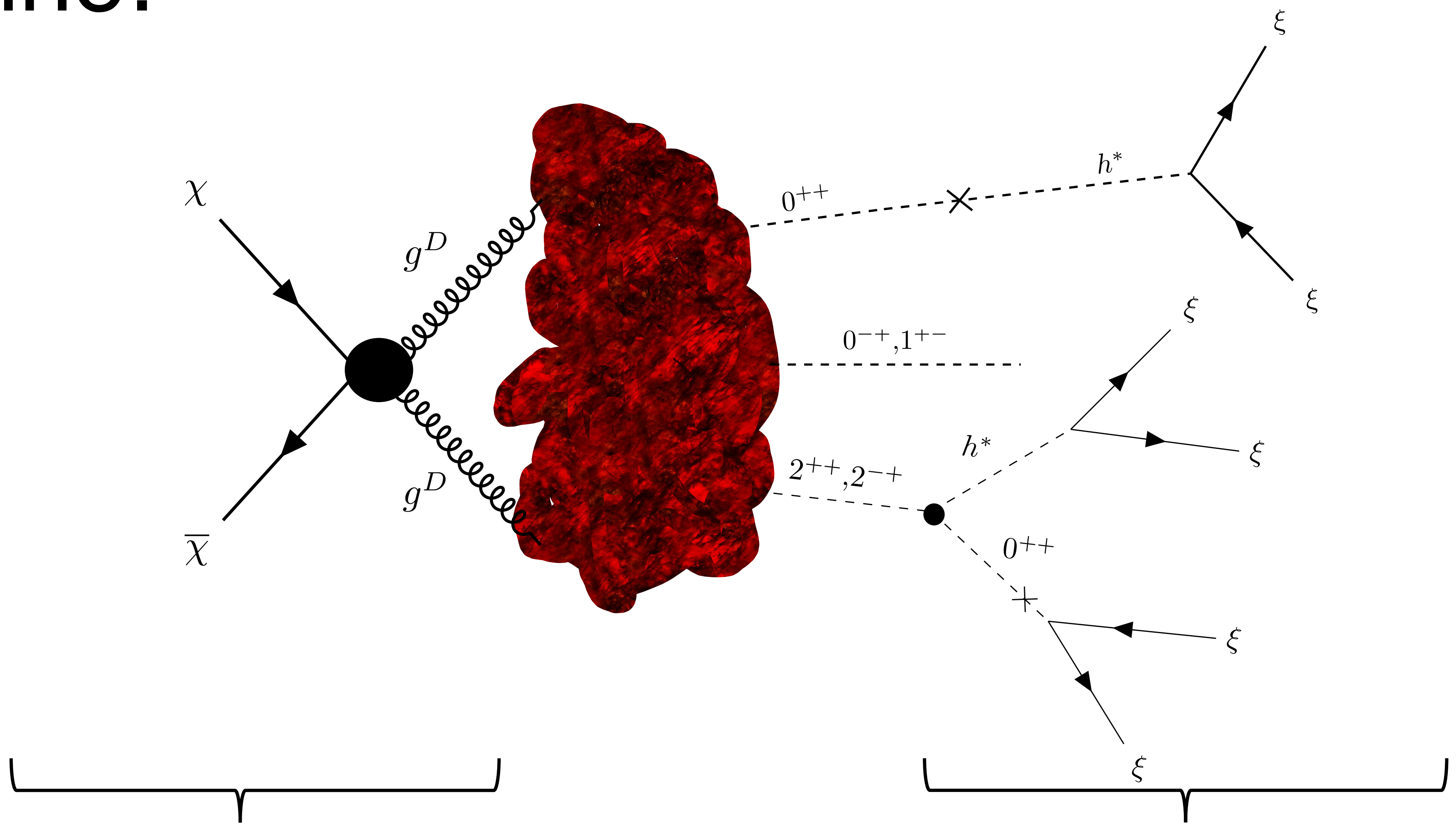


1. Why are we interested in models where DM annihilates to dark gluons ?

Outline:



1. Why are we interested in models where DM annihilates to dark gluons ?

2. How do the dark glueballs decay to the SM ?

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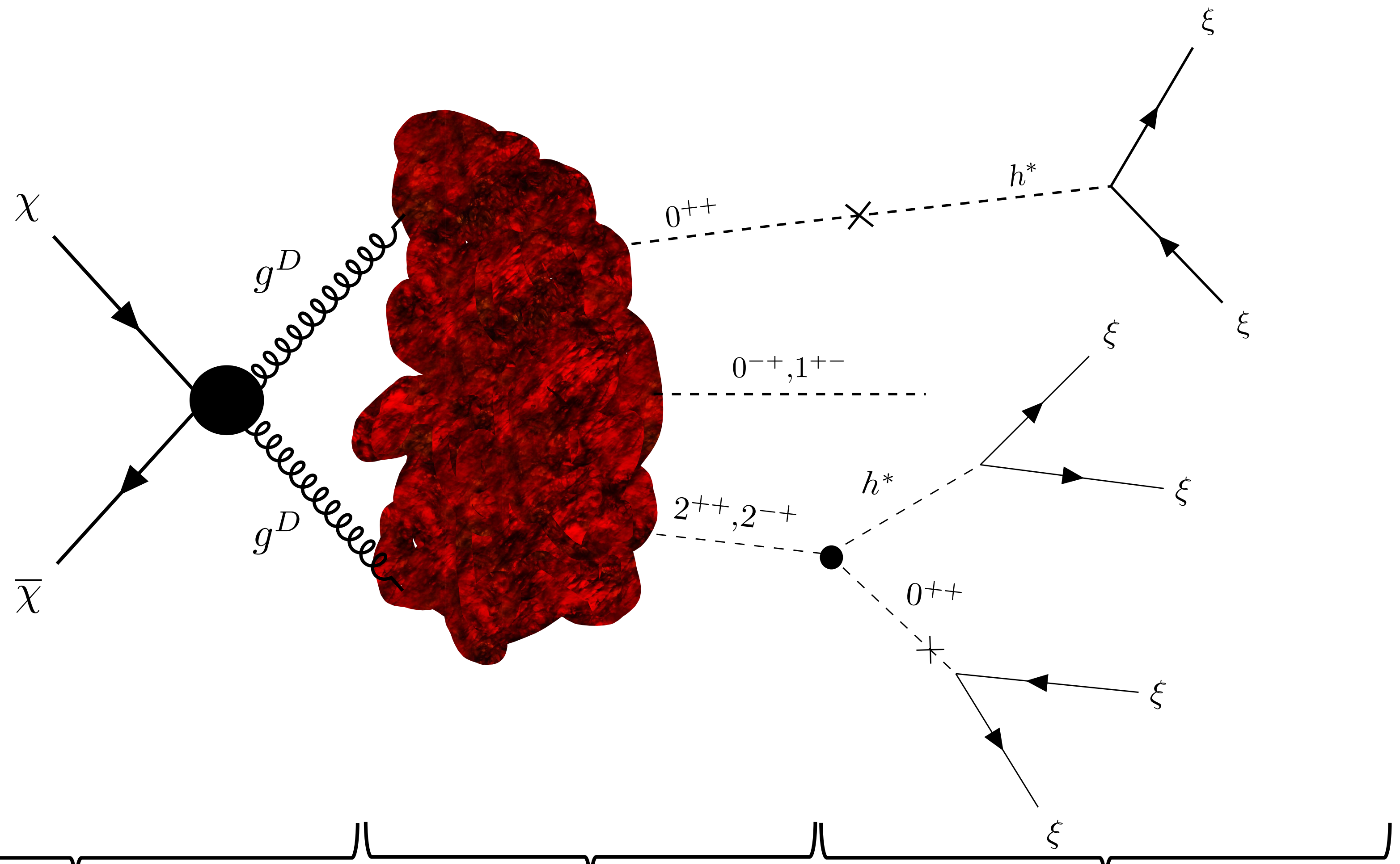
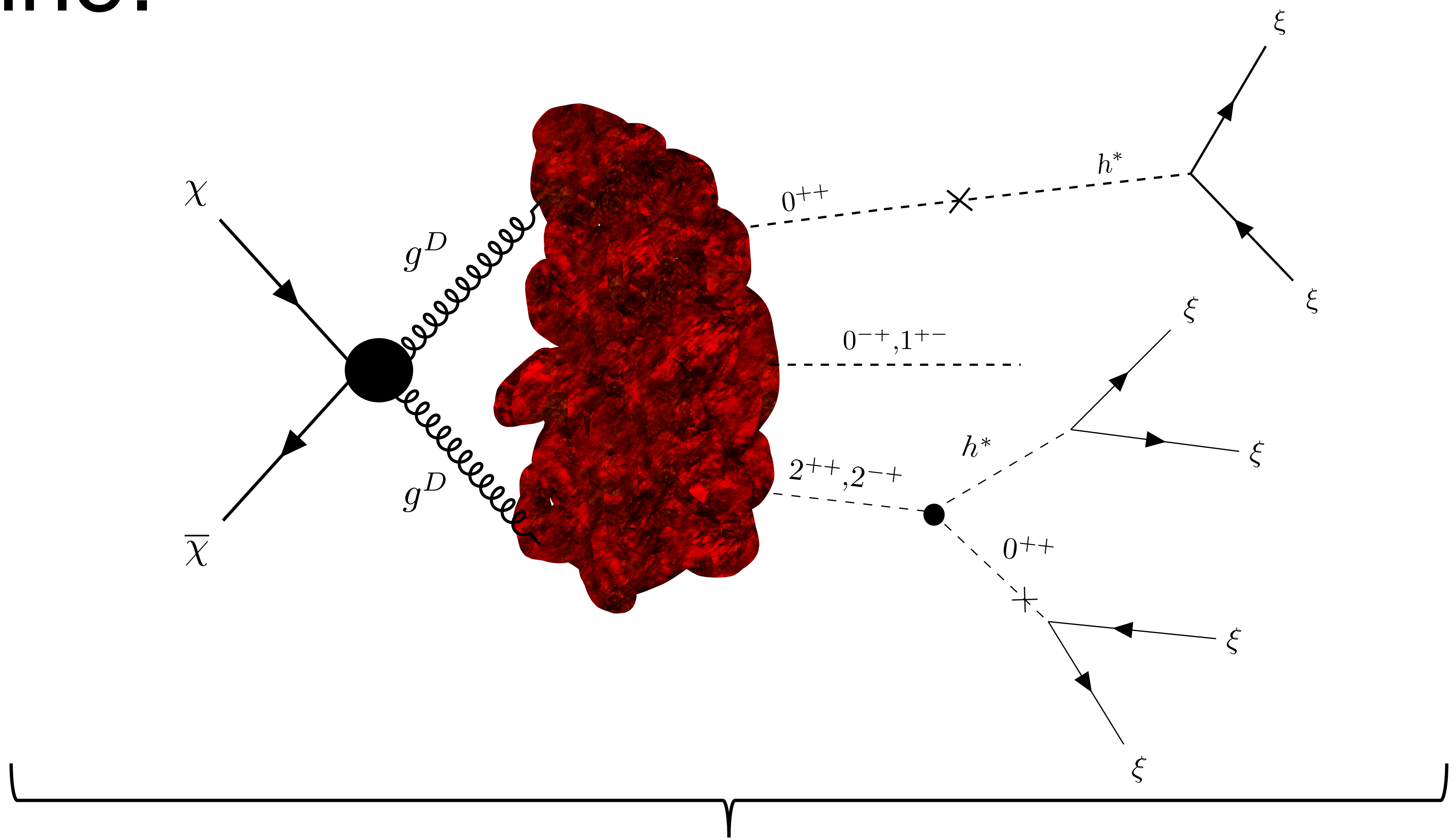


1. Why are we interested in models where DM annihilates to dark gluons ?

3. How to we simulate dark gluon hadronization to dark glueballs ?

2. How do the dark glueballs decay to the SM ?

Outline:



4. What are the indirect detection constraints on this process?

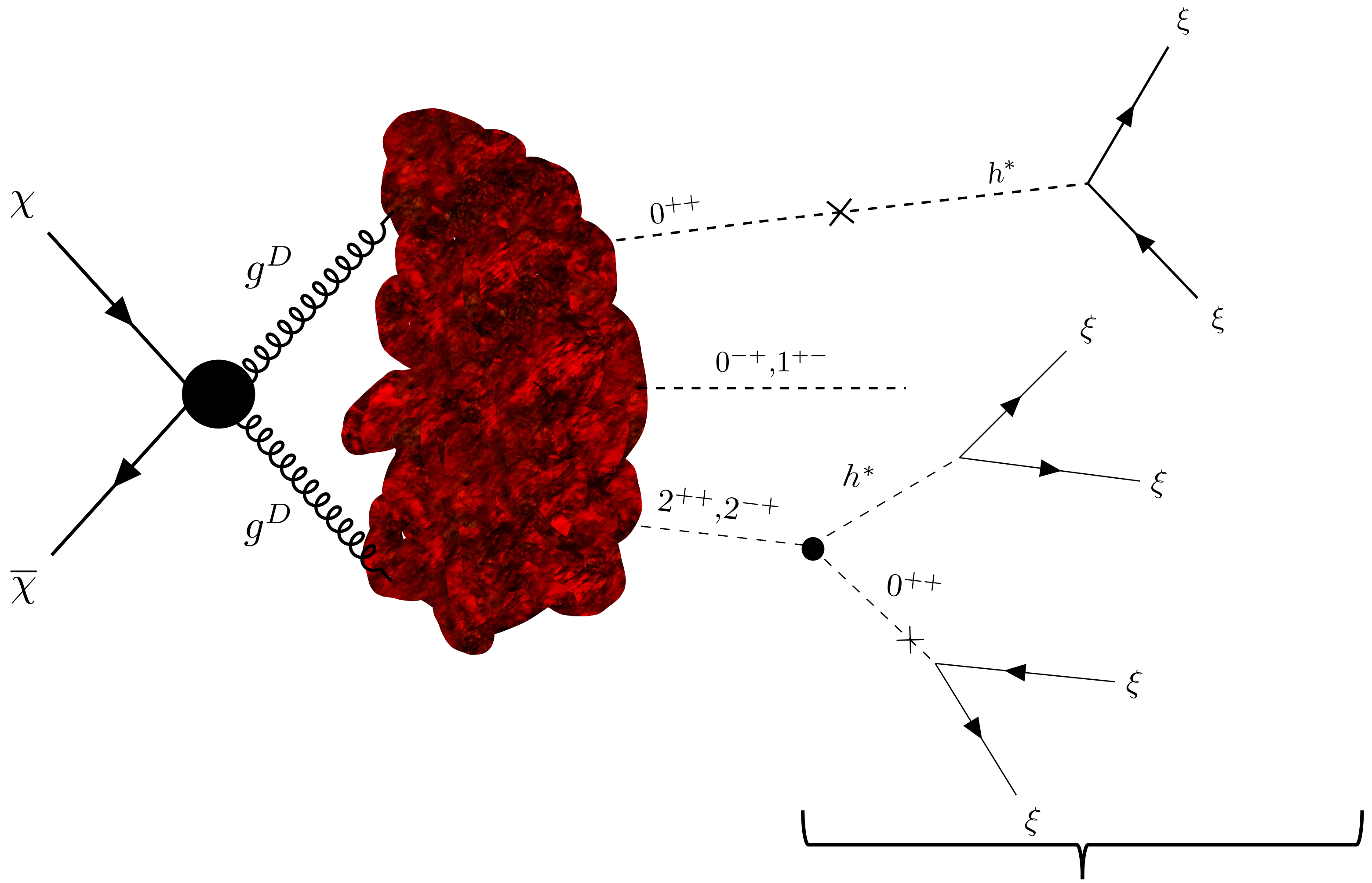
1. Motivation:

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
  - Hidden valley models are theoretically motivated as they can solve ongoing problems such as dark matter and the little hierarchy problem
  - Experimentally motivated as they are hard to detect in collider or direct detection searches
- 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
- Very few quantitative studies of dark glueball showers, due to the fact all known hadronization models no longer hold

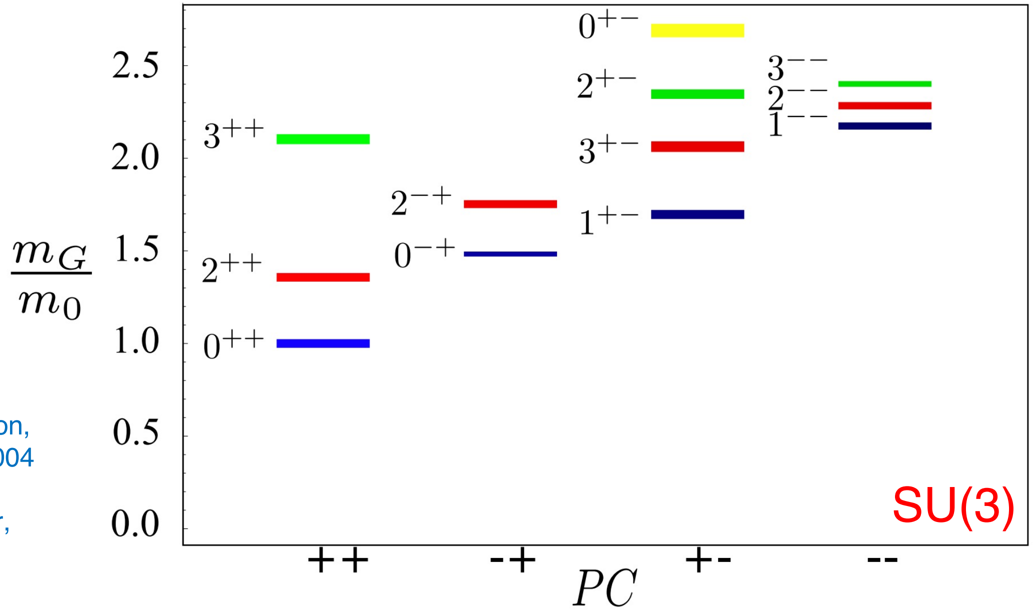
Andersson, Gustafson, Ingelman, Sjöstrand (1983)

Outline:



2. How do the dark glueballs decay to the SM ?

2. Dark Glueball Properties:



- 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 ($m_0 \sim 6\Lambda$)
- 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

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

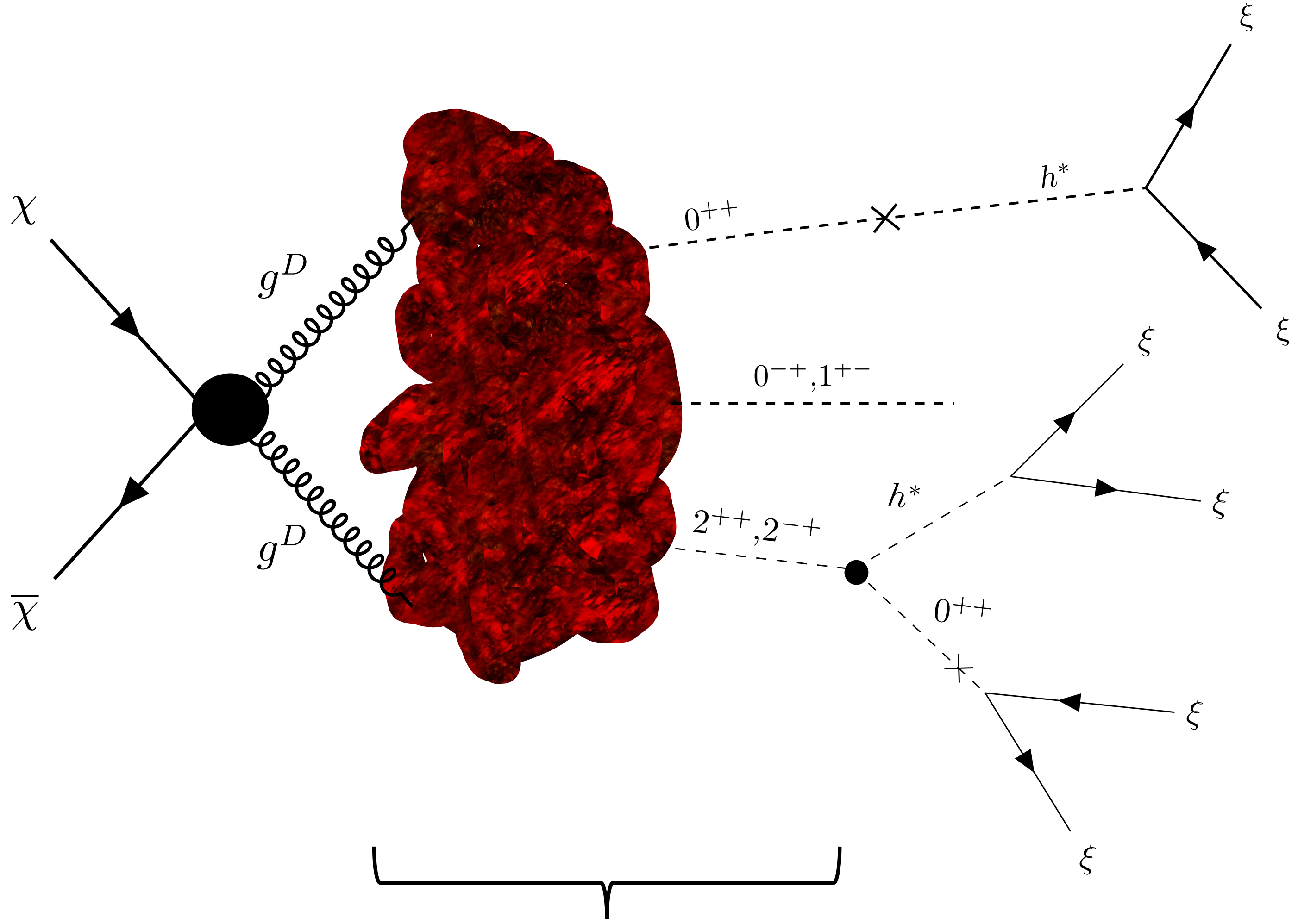
$$2^{++} \rightarrow (h^*)0^{++} \rightarrow 0^{++}(c\bar{c}, gg, \mu^-\mu^+...)$$

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

$$0^{\pm+}, 2^{\pm+} \rightarrow V_{SM}V_{SM}$$

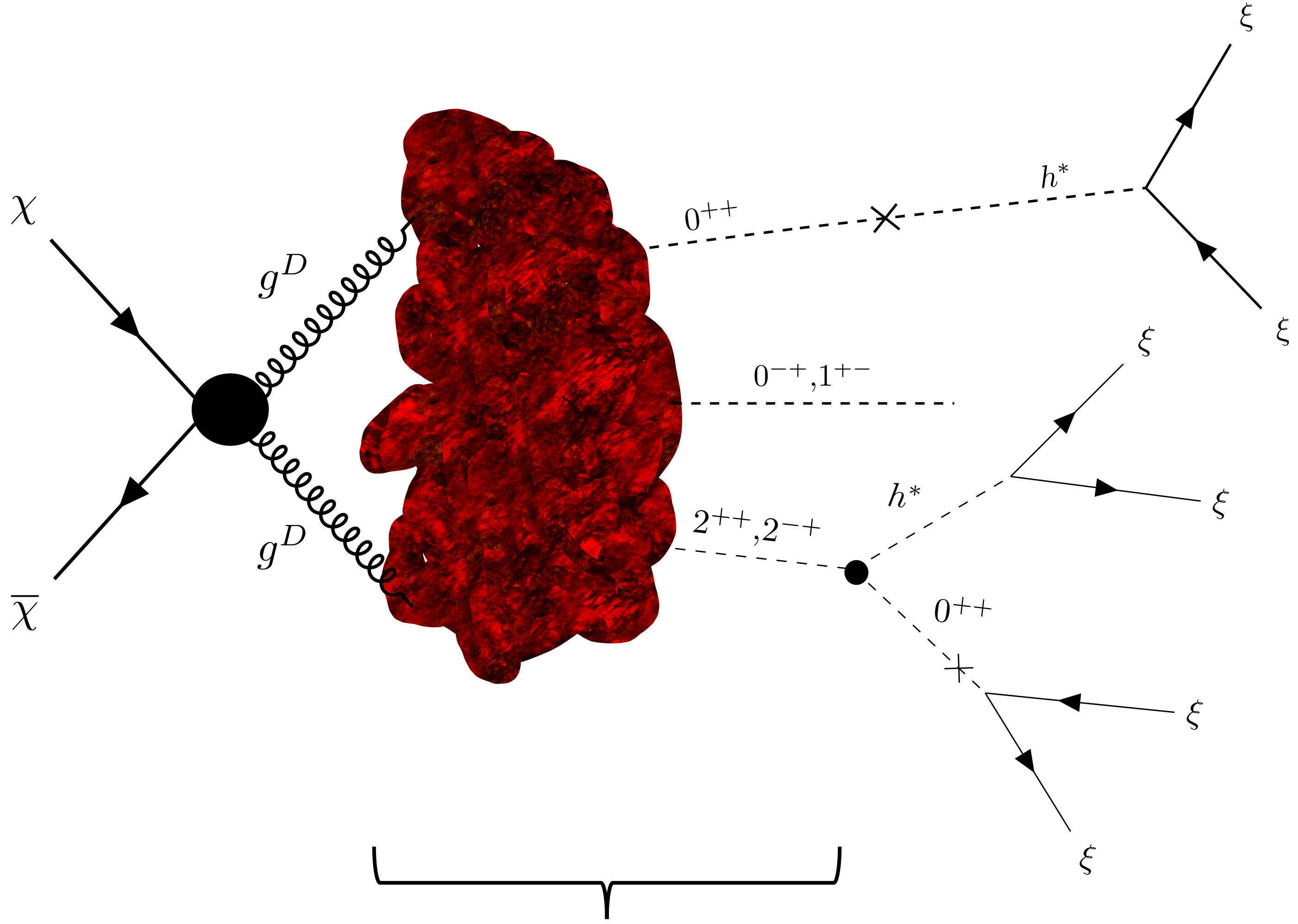
$$1^{+-} \rightarrow \gamma\, 0^{++}, \gamma\, 2^{++}, \gamma\, 0^{-+}$$

Outline:



3. How to we simulate dark gluon hadronization to dark glueballs ?

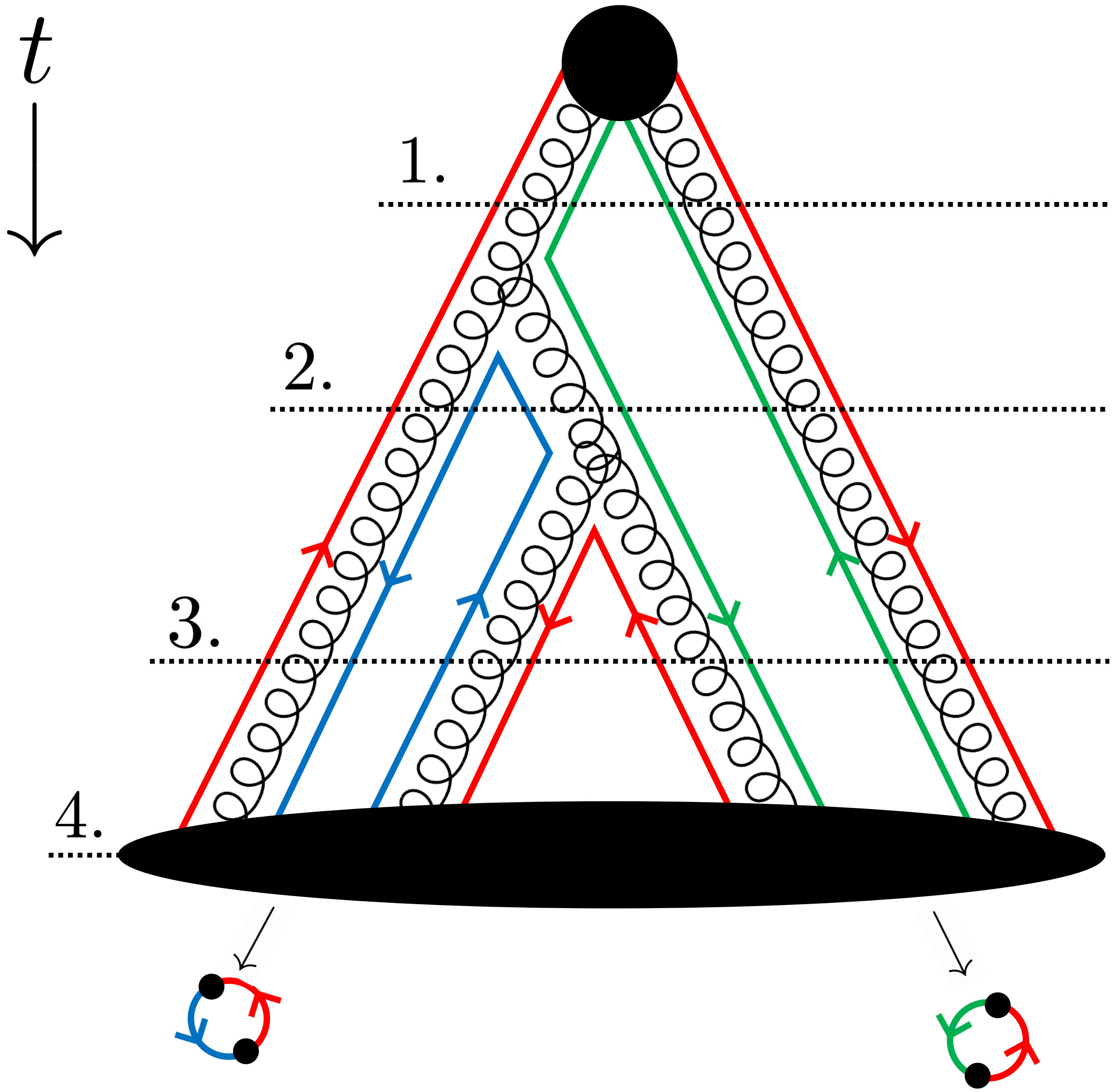
Outline:



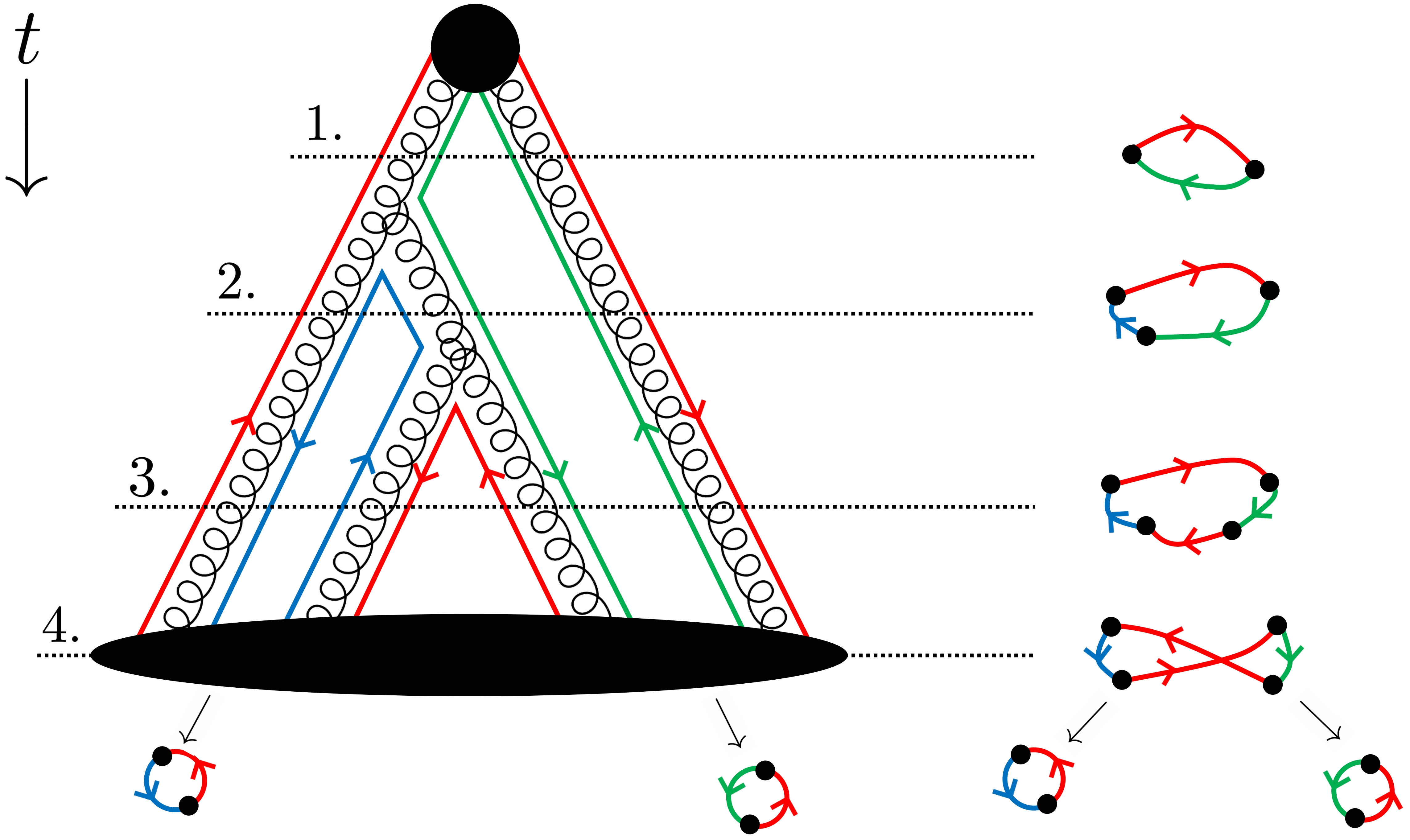
3. How to we simulate dark gluon hadronization to dark glueballs ?

GlueShower!

Let's start off by considering a single glueball species with mass m_0…

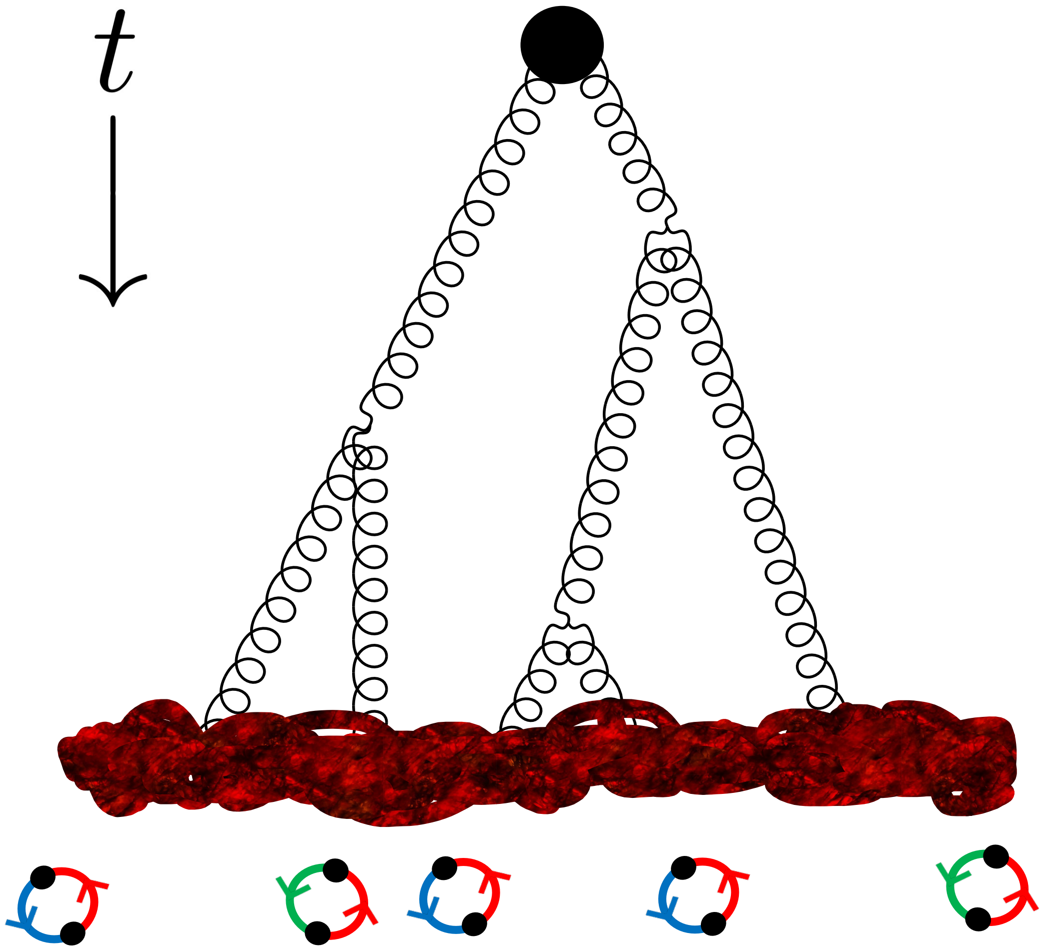


One example:
Simple case of two gluon production forming two glueballs


t
1.
2.
3.
4.

Now general shower possibilities…

Base Case:

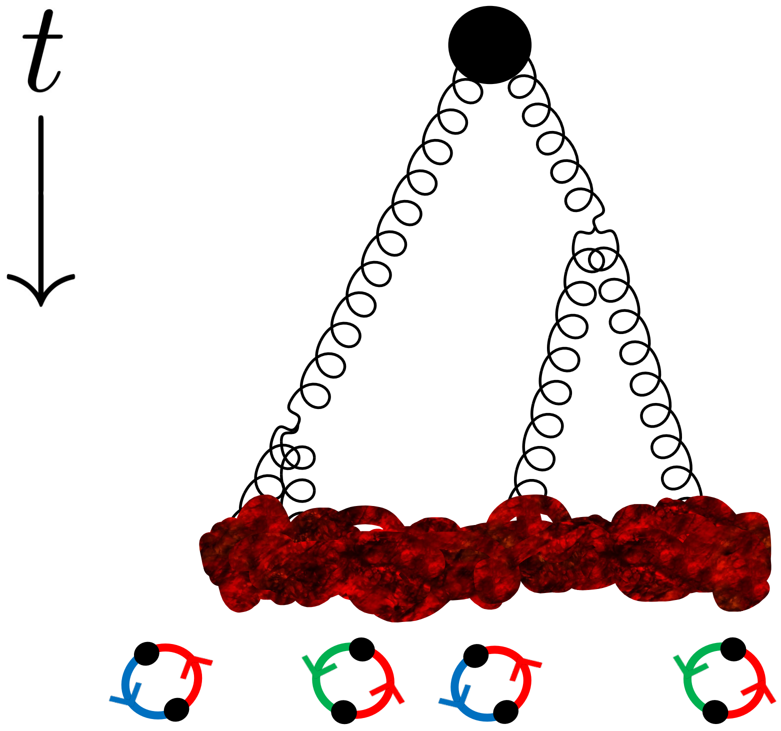


Perturbative QCD

$$\Lambda_{had} = 2m_0$$

- Shower is terminated far above confinement scale, perturbative QCD is still trusted
- 2 -> 3 processes are phase space suppressed, glueball multiplicity should be a robust upper bound

Alternatives:



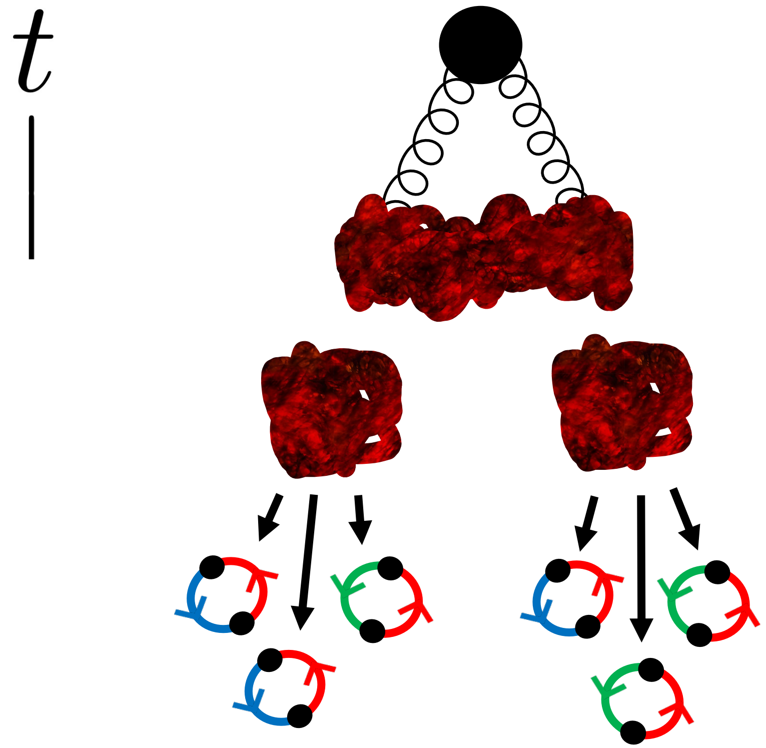
Perturbative QCD

$$\Lambda_{had} = c * (2m_0)$$

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

- Introduce multiplicative factor that tunes the scale at which the shower terminates
- Internally consistent method of generating fewer glueballs, part of theory uncertainty in signal

Alternatives:



Perturbative QCD

Dark Glue Plasma

Decays isotropically by thermally emitting glueballs

What if closed loop fragmentation is not an IR process?

- Colour singlet state arranges at high scales, forms a large mass pure glue plasma, and then evaporates by glueball emission
- Similar to the case for high values of Λ_{had}, but instead of being put on shell, forms a high mass plasma state

Relative Glueball Multiplicity

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

$$P_J \propto (2J+1)\left(\frac{m_J}{m_0}\right)^{3/2} e^{-(m_J - m_0)/T_{had}}$$

- Reasonable zero-th order approximation Manes, arXiv:hep-th/0109196
  - Closed string emission follows thermal distribution
- T_c calculated in lattice Lucini, Rago, Rinaldi, arXiv:1202.6684 [hep-lat]
- Limitations: Non-local effects…
- Freedom to tweak in code, adjust T_{had} values to span different probability distributions.

$$T_{had} = d * T_c$$

In Summary:

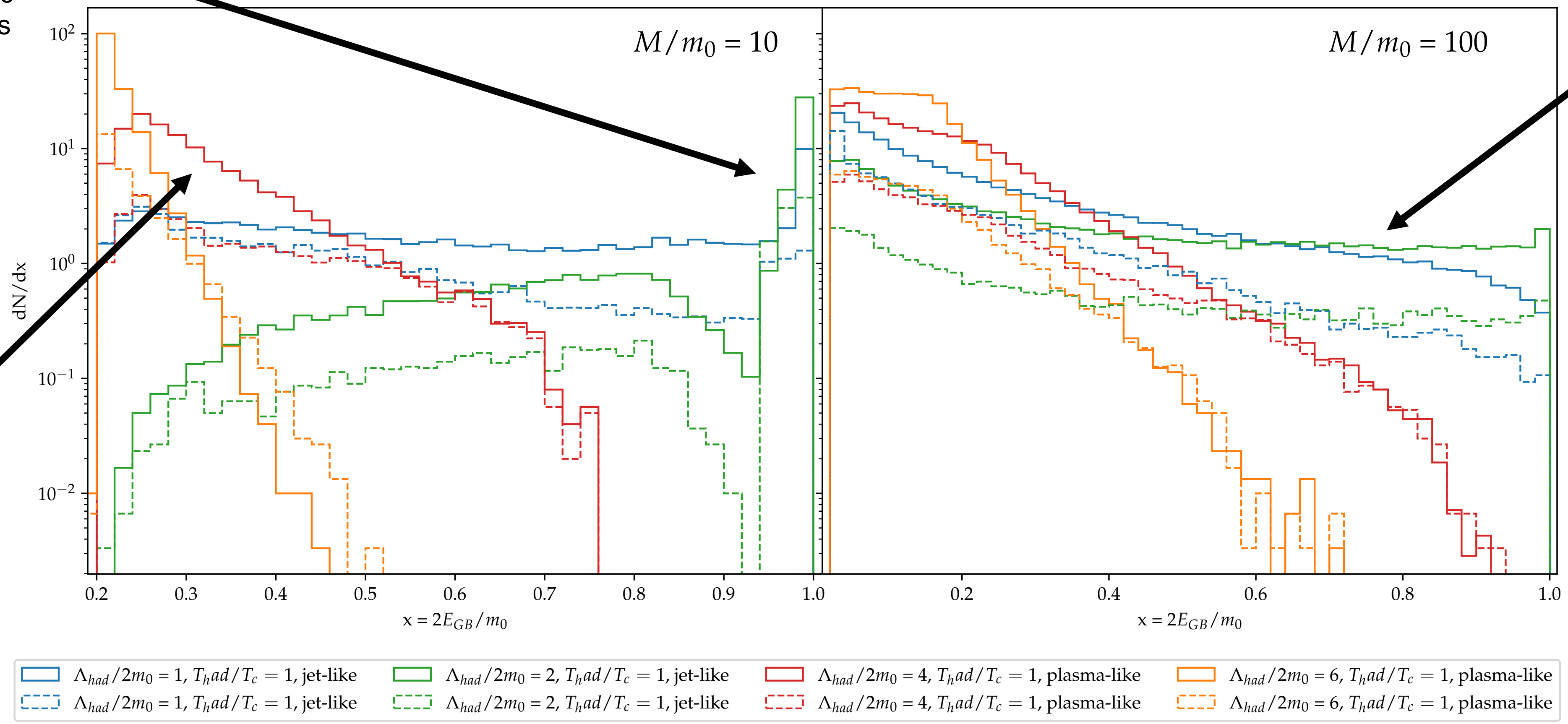
- `GlueShower` is the first Monte Carlo generator for dark sector glueballs Curtin, Gemmell, Verhaaren, arXiv:2202.12899 [hep-ph]
- Two-and-a-half nuisance parameters encode theoretical uncertainties within glueball hadronization process:
  - `plasma_mode`: Boolean parameter determines whether shower exhibits jet-like or plasma-like evolution
  - Λ_{had}: Controls scale at which the perturbative shower ends
  - T_{had}: Controls temperature that determines the relative multiplicity of various glueball states
- We provide benchmark parameters that cover a motivated extent of possible outputs

Example: Fragmentation Functions

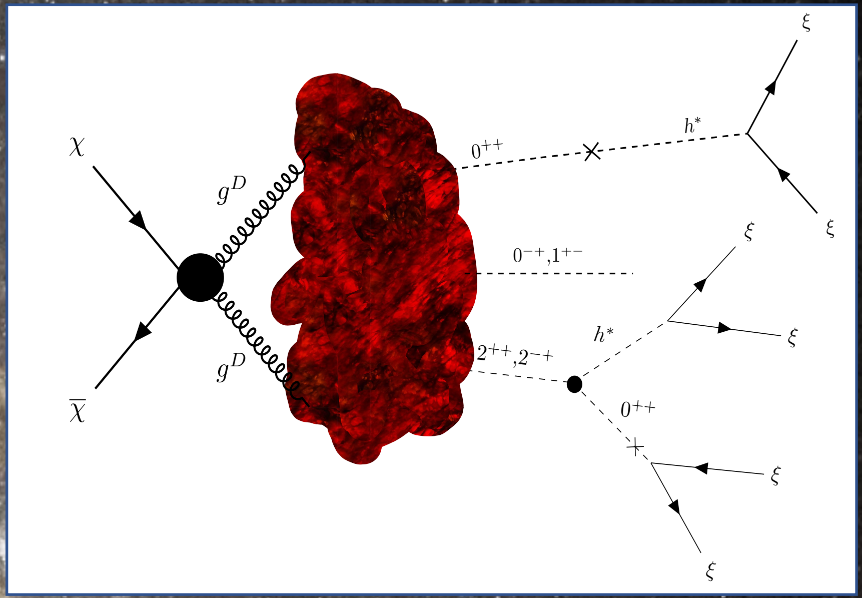
Low energy FFs dominated by two-body decays in jet-like case (captures finite mass effects)

High energy FFs resemble fragmentation functions used in SM

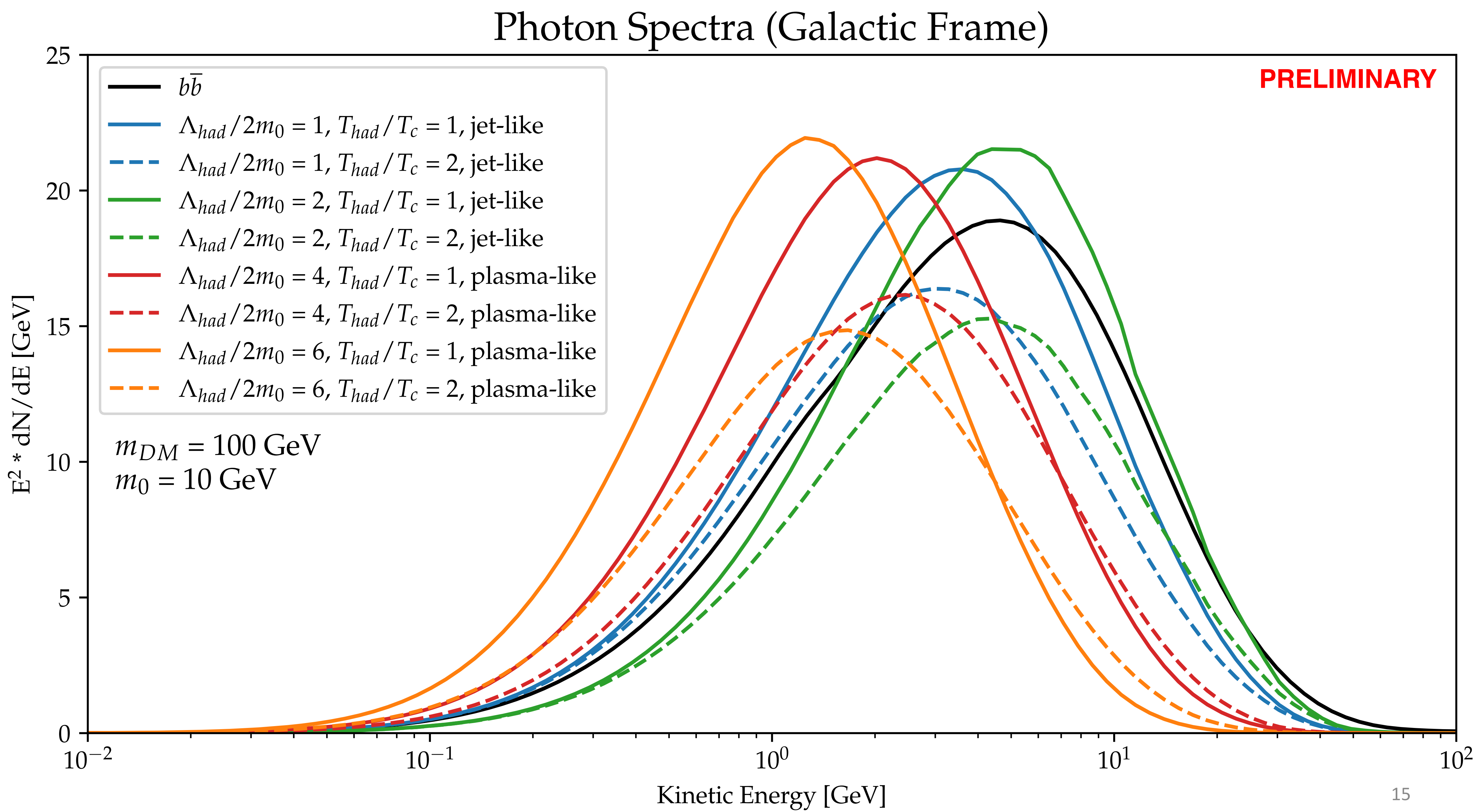
Across all C.O.M. energy ranges plasma-like case favors low energy ('soft') production of glueballs



4. Indirect Detection of Dark Glueball Showers

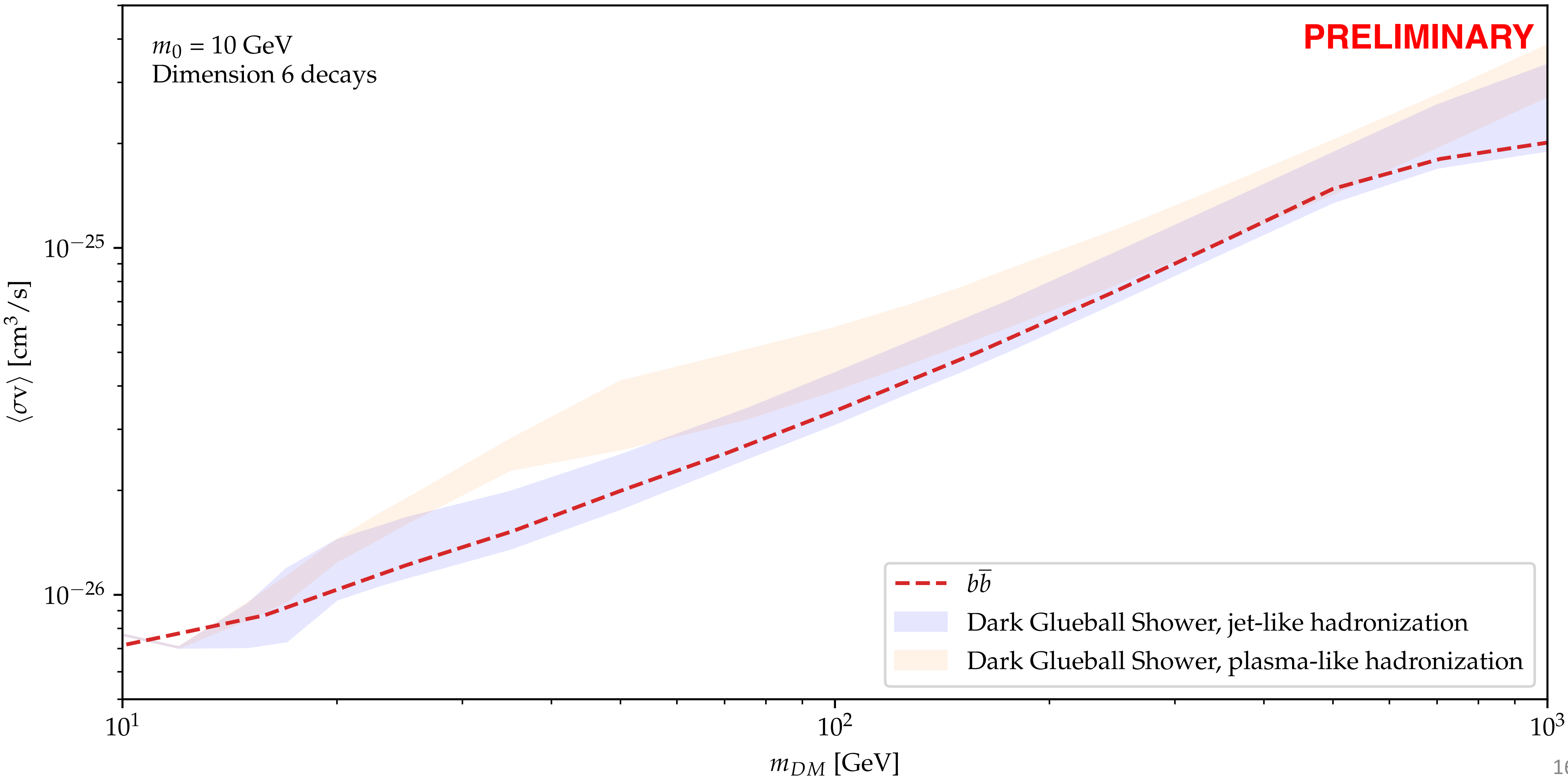


One benefit of indirect detection experiments is that they probe astrophysical length scales, possibly giving insight into more of the dark sector spectrum, not just the short living states


Photon Spectra (Galactic Frame)
PRELIMINARY
$b\bar{b}$
$\Lambda_{had}/2m_0 = 1$, $T_{had}/T_c = 1$, jet-like
$\Lambda_{had}/2m_0 = 1$, $T_{had}/T_c = 2$, jet-like
$\Lambda_{had}/2m_0 = 2$, $T_{had}/T_c = 1$, jet-like
$\Lambda_{had}/2m_0 = 2$, $T_{had}/T_c = 2$, jet-like
$\Lambda_{had}/2m_0 = 4$, $T_{had}/T_c = 1$, plasma-like
$\Lambda_{had}/2m_0 = 4$, $T_{had}/T_c = 2$, plasma-like
$\Lambda_{had}/2m_0 = 6$, $T_{had}/T_c = 1$, plasma-like
$\Lambda_{had}/2m_0 = 6$, $T_{had}/T_c = 2$, plasma-like
$m_{DM} = 100$ GeV
$m_0 = 10$ GeV
$E^2 * dN/dE$ [GeV]
Kinetic Energy [GeV]
0
5
10
15
20
25
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

Fermi-LAT Dwarf Spheroidal Constraints

(arXiv: 1611.03184)



Conclusions:

- Dark showers are a general signature of hidden valley models, motivated as solutions to the little hierarchy problem and its evasion of current constriants
- Zero flavour case is a previously unstudied parameter space due to uncertainty around pure glue hadronization process
- `GlueShower` is the first Monte Carlo glueball generator, additionally can explore various regimes of glueball production
    - Able to calculate theoretical uncertainty range on observables/constraints
    - Outputs are relatively robust to range of benchmark parameters we provide
- Indirect detection study in progress, but plenty more work to be done with dark glueball sectors !!!

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Back up Slides

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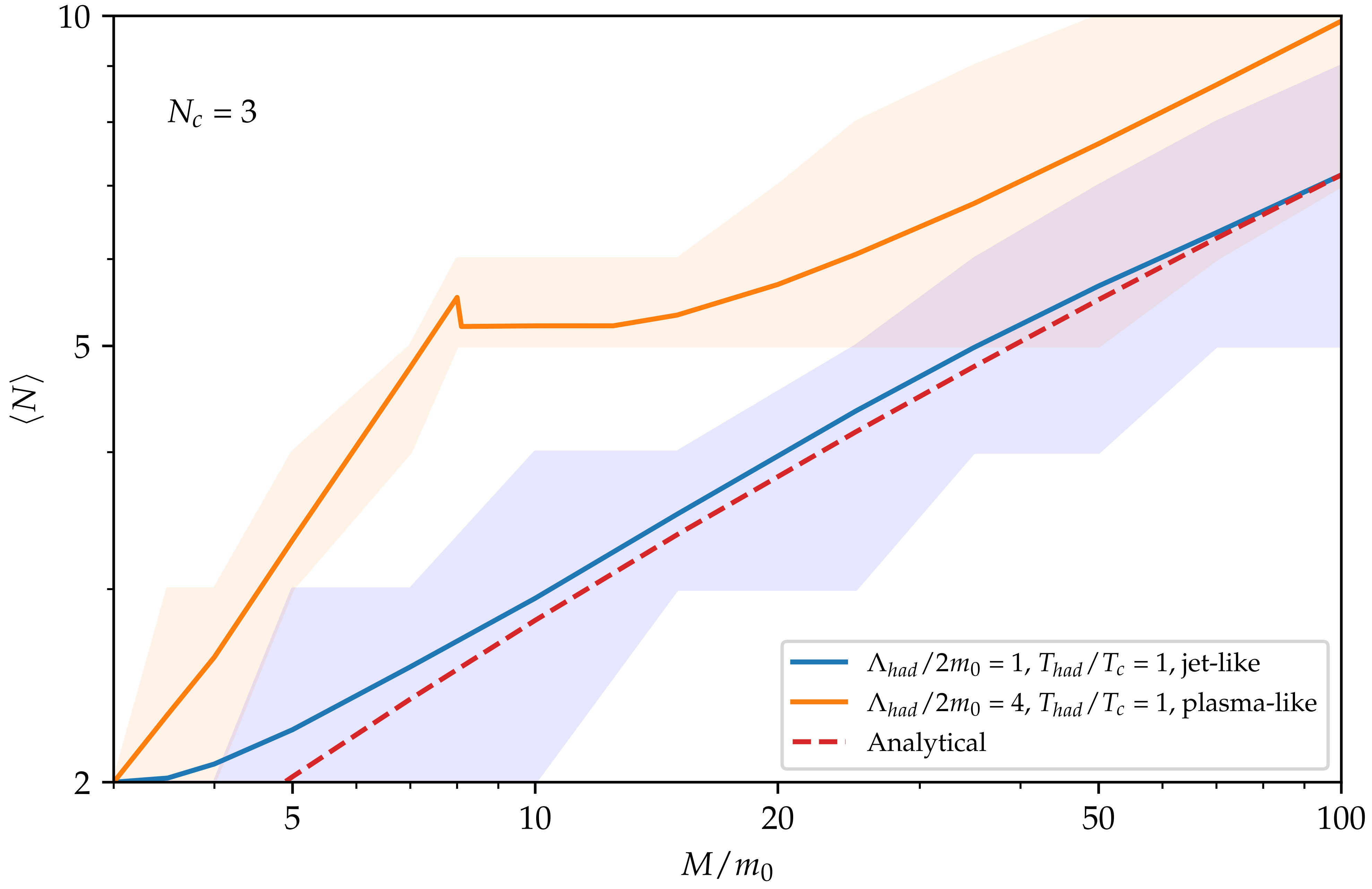
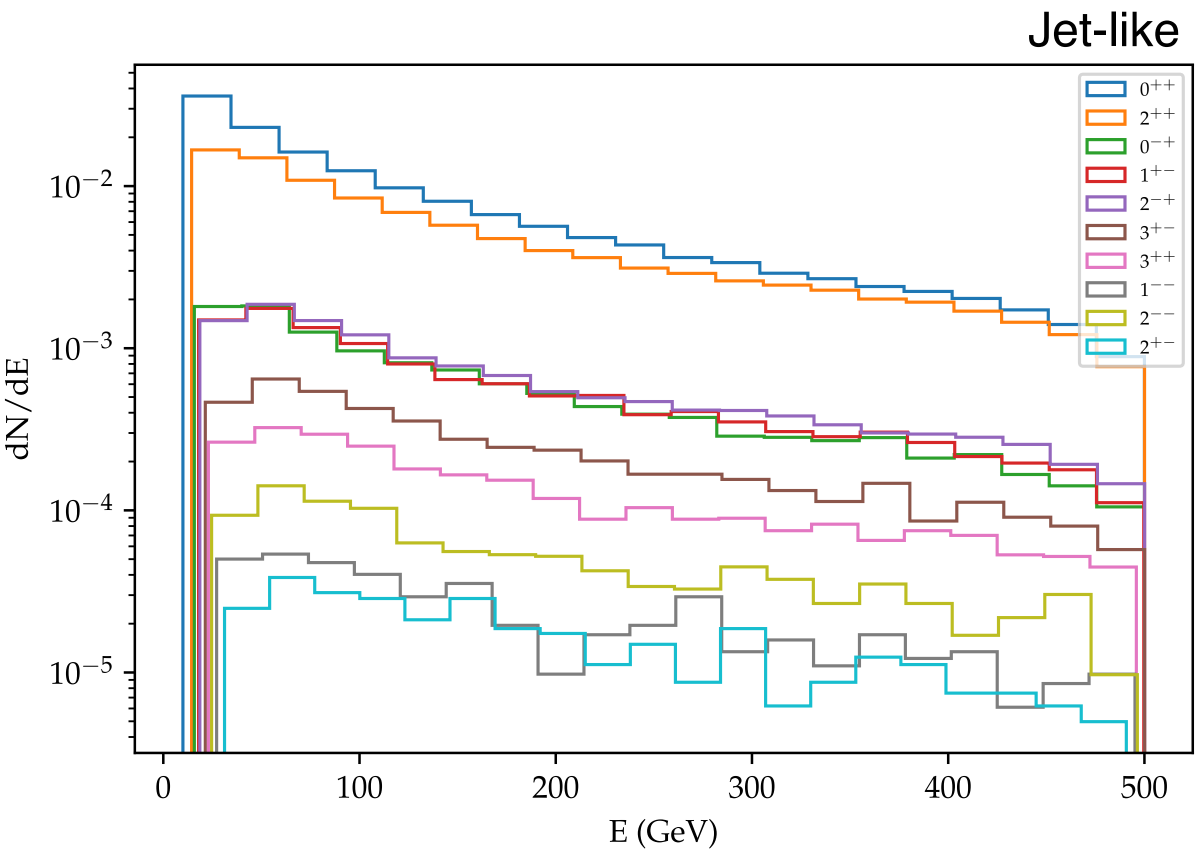
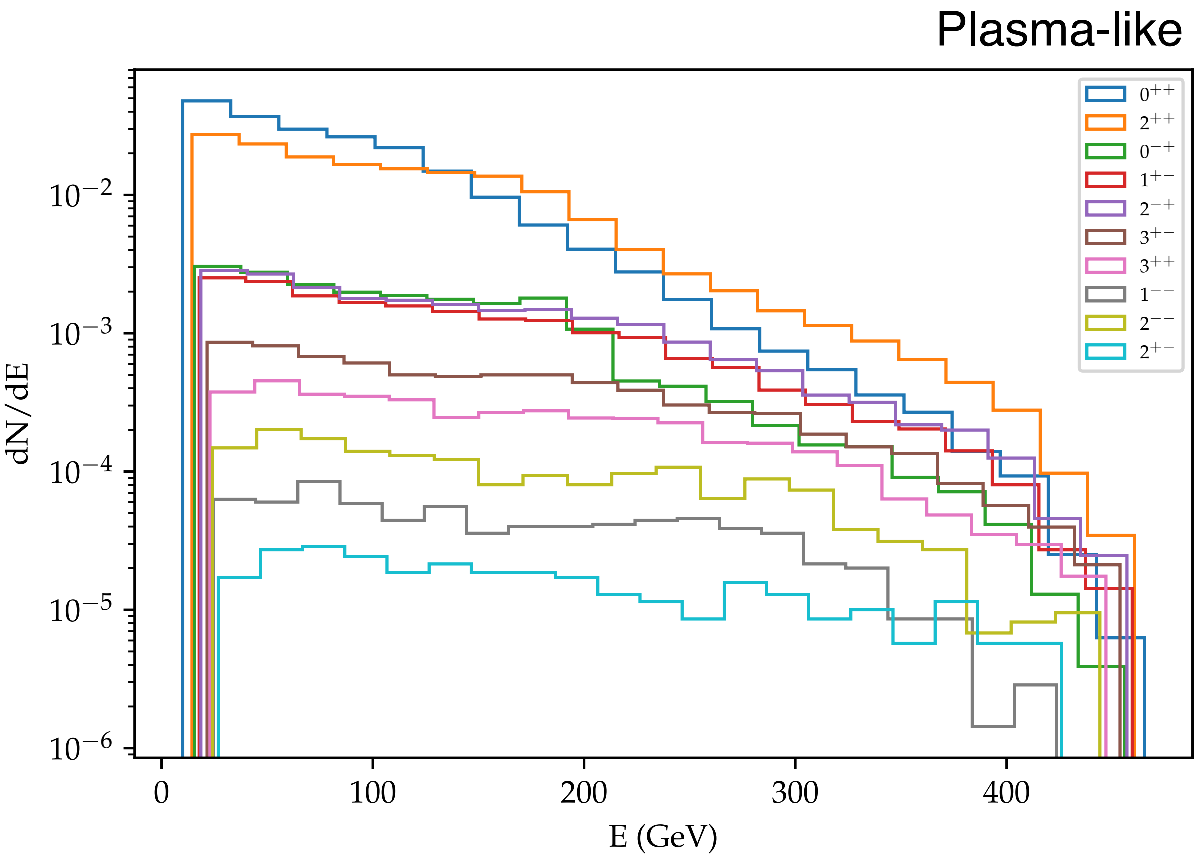
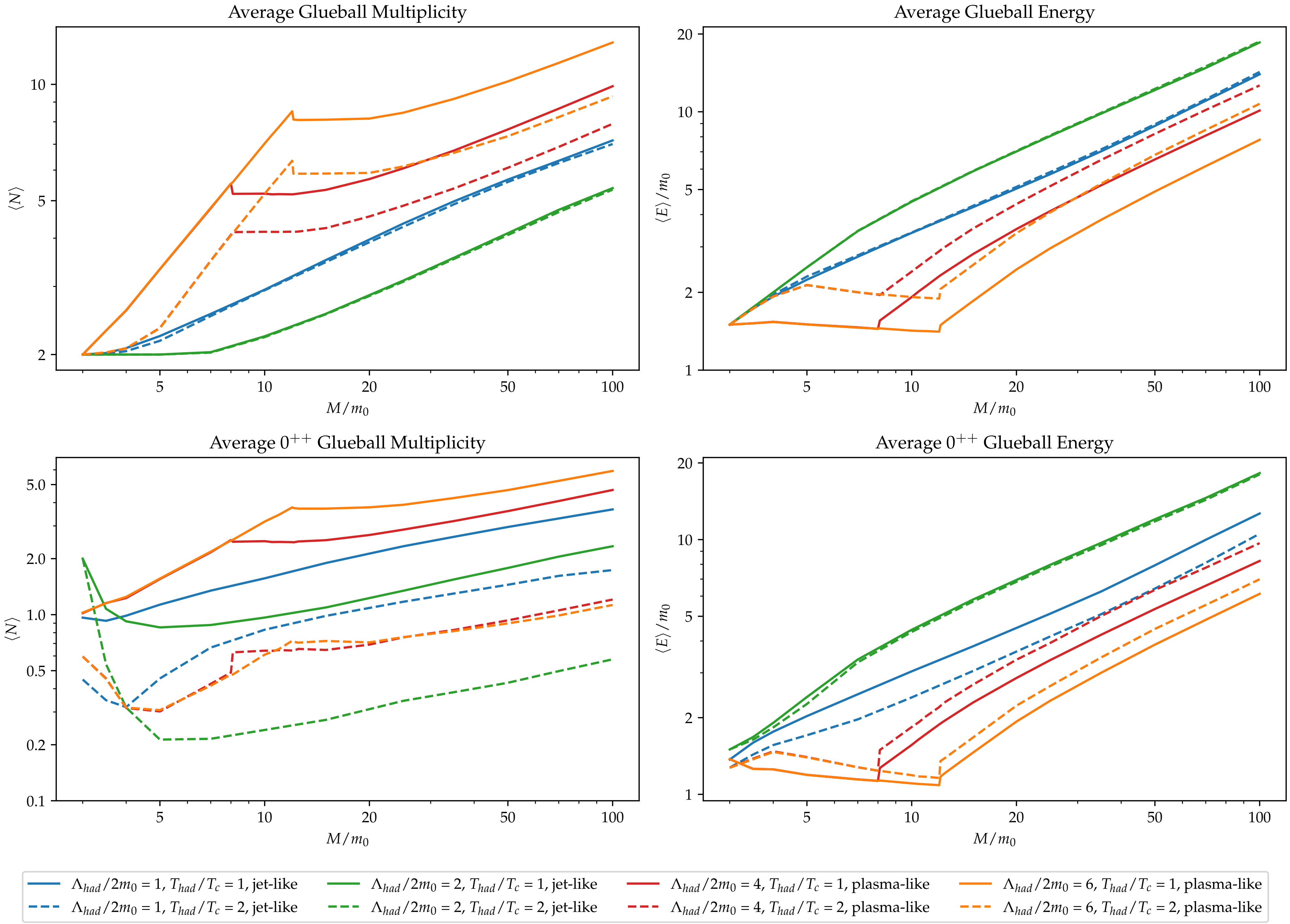


$N_c = 3$
$\langle N \rangle$
M/m_0
$\Lambda_{had}/2m_0 = 1$, $T_{had}/T_c = 1$, jet-like
$\Lambda_{had}/2m_0 = 4$, $T_{had}/T_c = 1$, plasma-like
Analytical

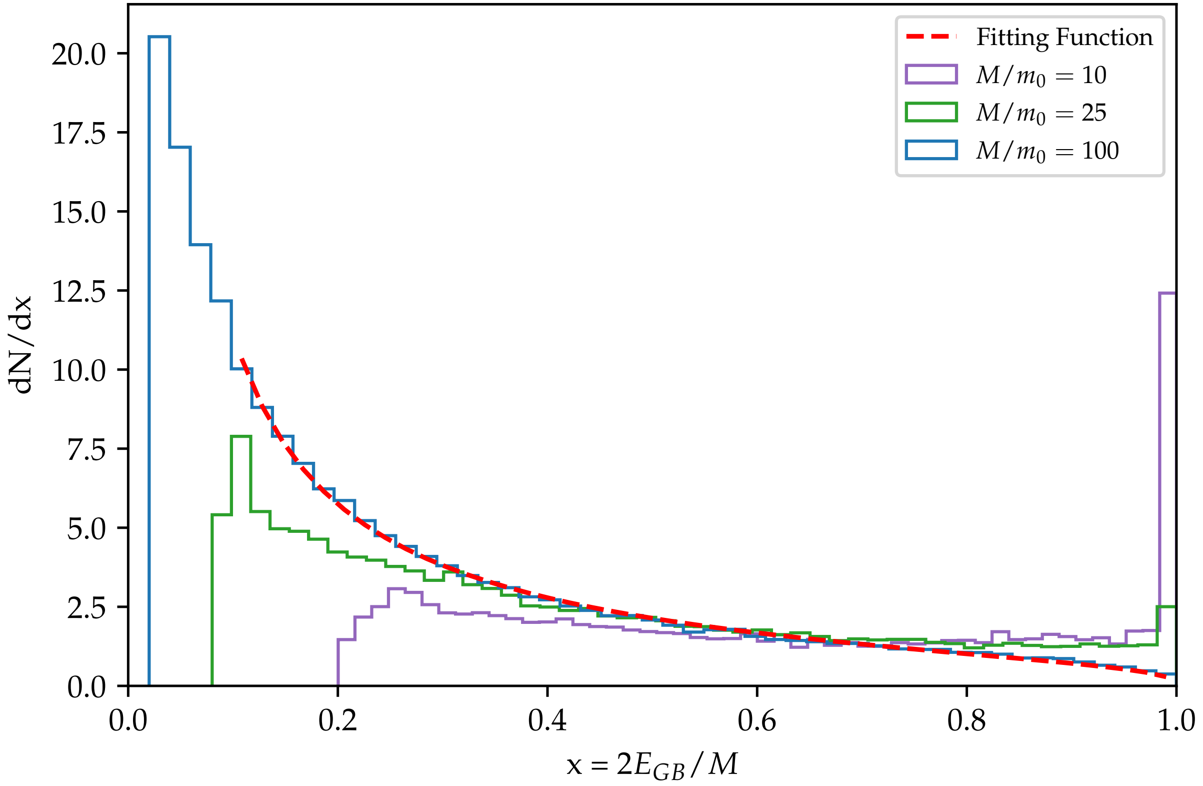

Jet-like
dN/dE
E (GeV)
0++
2++
0−+
1+−
2−+
3+−
3++
1−−
2−−
2+−


Plasma-like
dN/dE
E (GeV)
0++
2++
0−+
1+−
2−+
3+−
3++
1−−
2−−
2+−

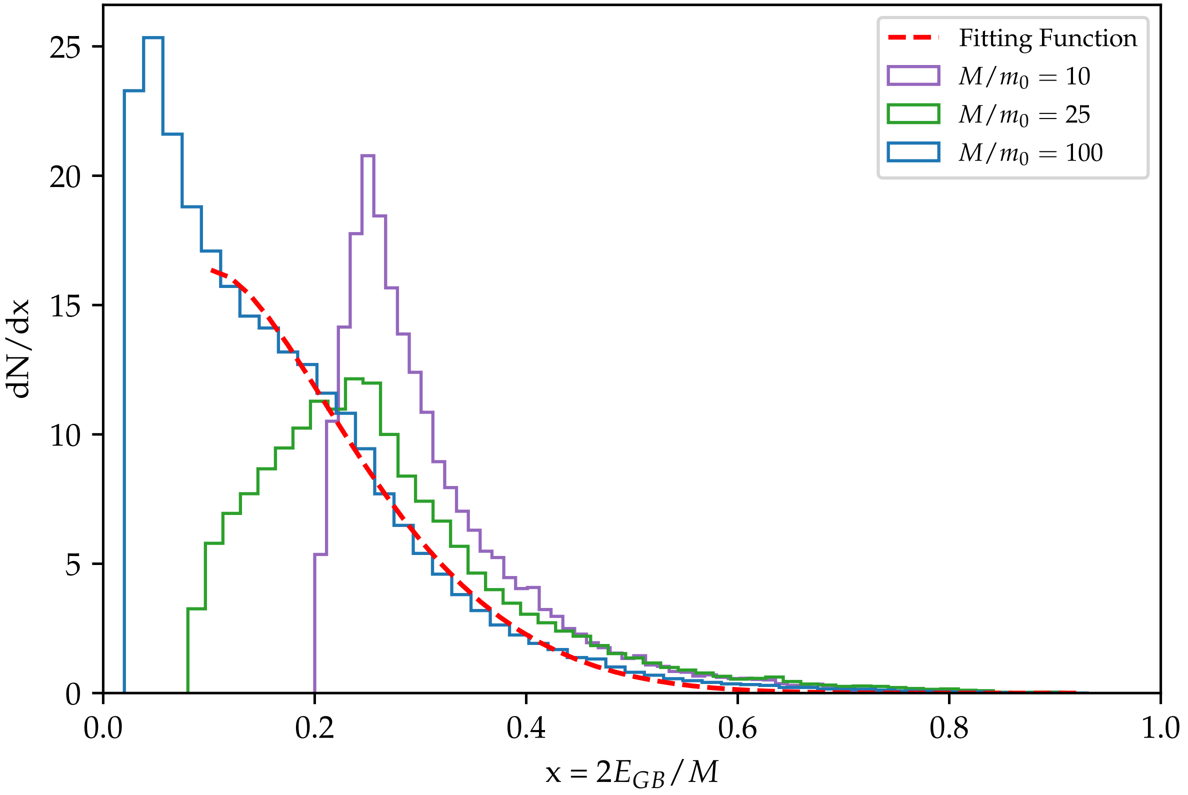


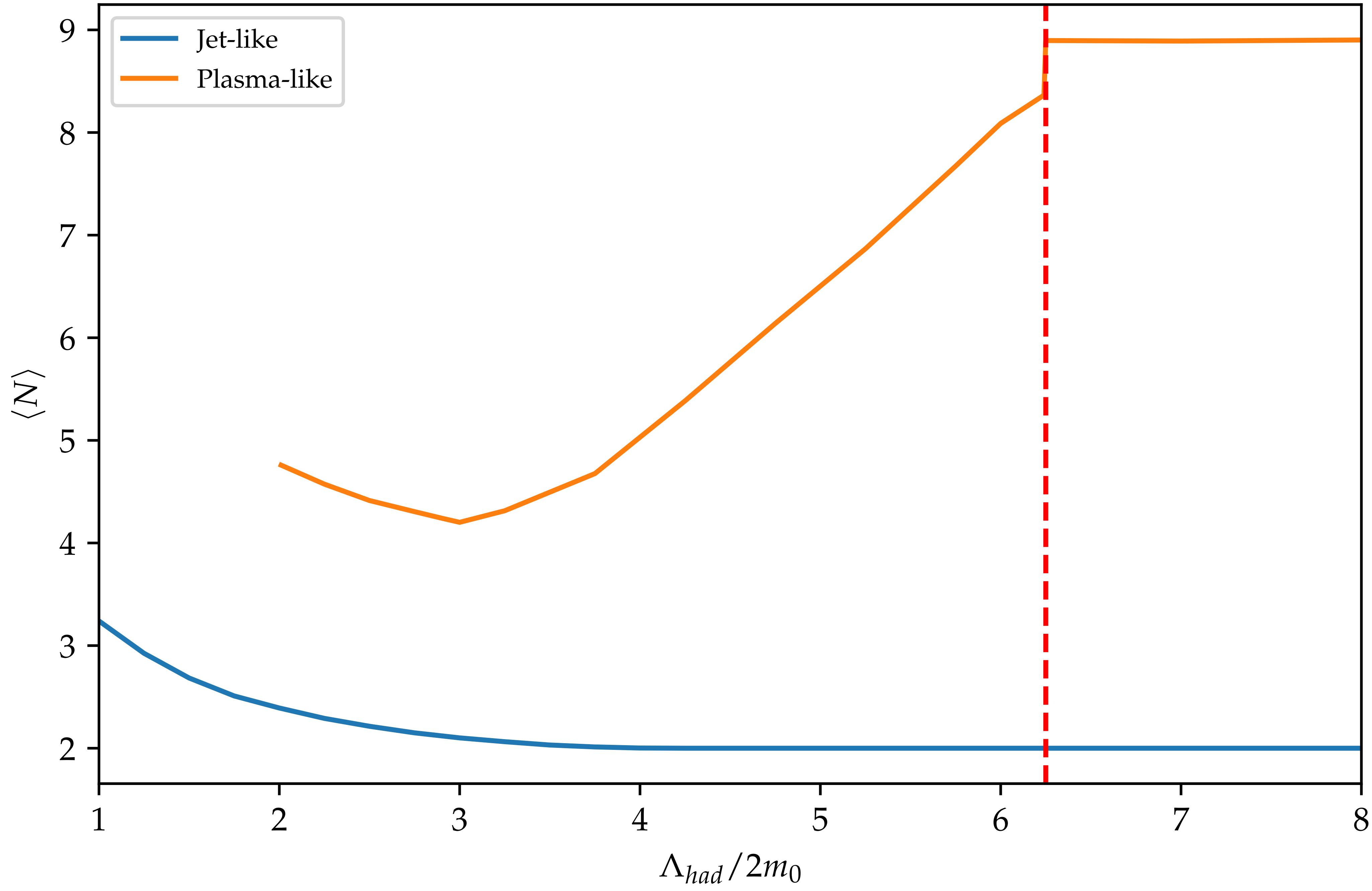
- Across wide range of benchmarks, <10 factor difference in multiplicity/energy
    - ~3 for inclusive observables
- Larger uncertainty on exclusive predictions
- In the high energy regime, correctly follows the analytical trend expected from pQCD

Jet-like

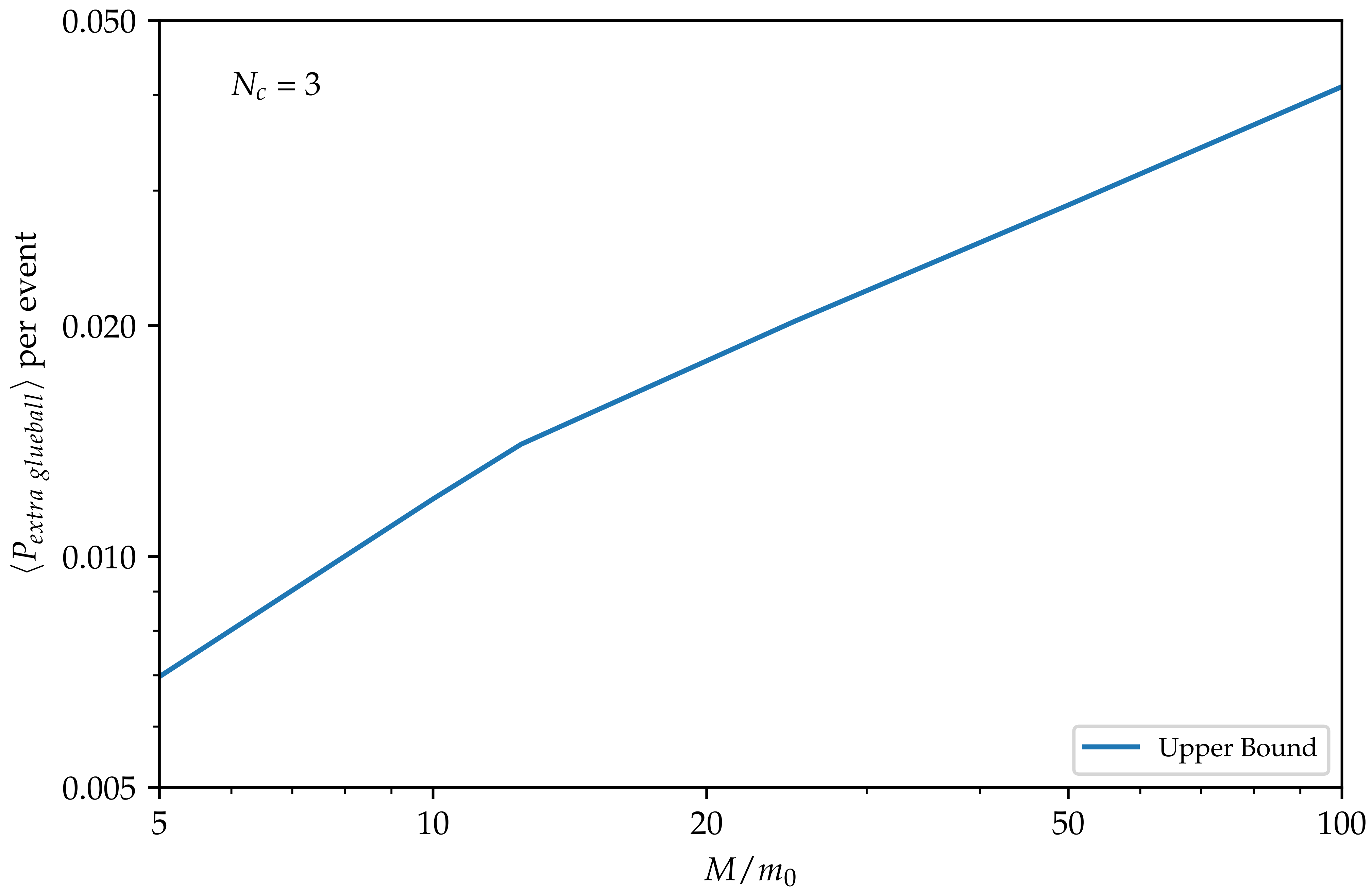


Plasma-like

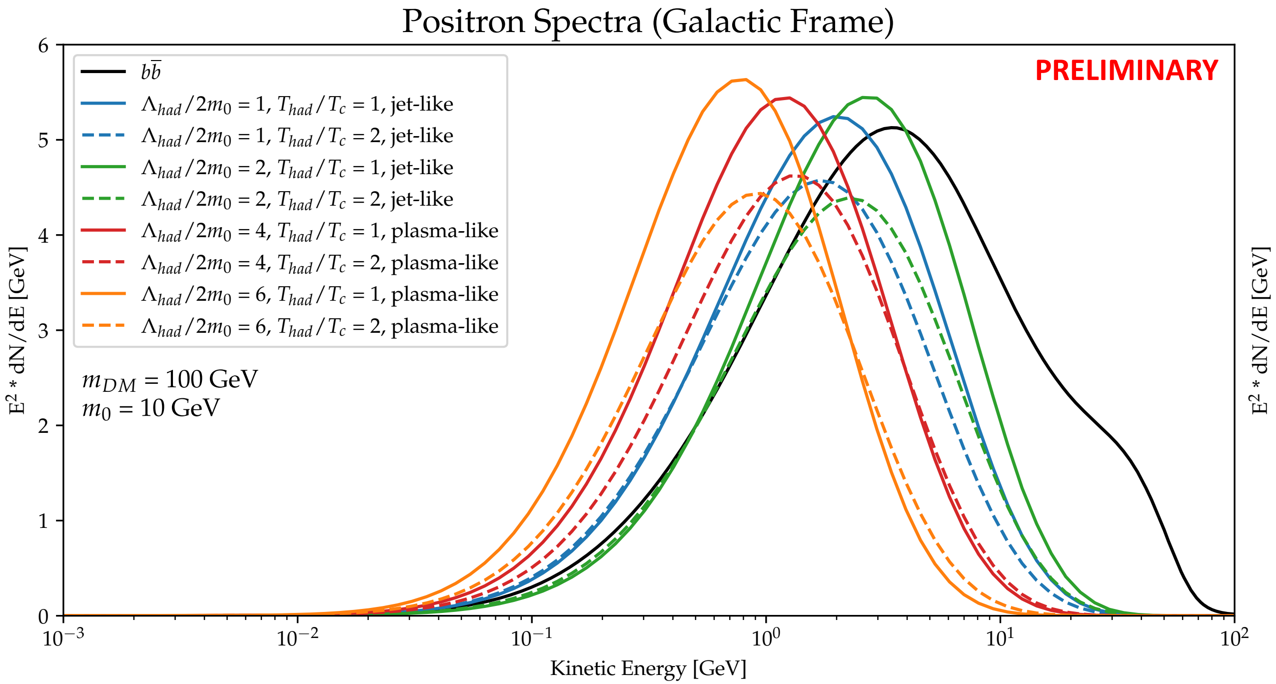


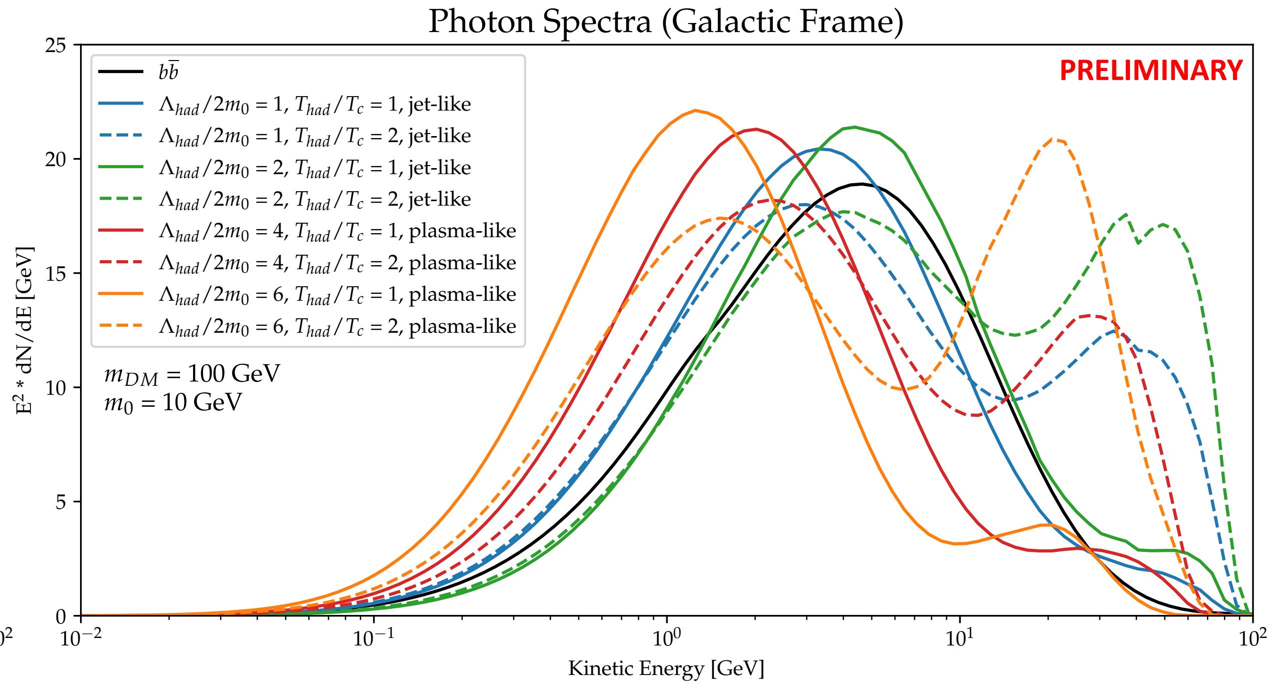


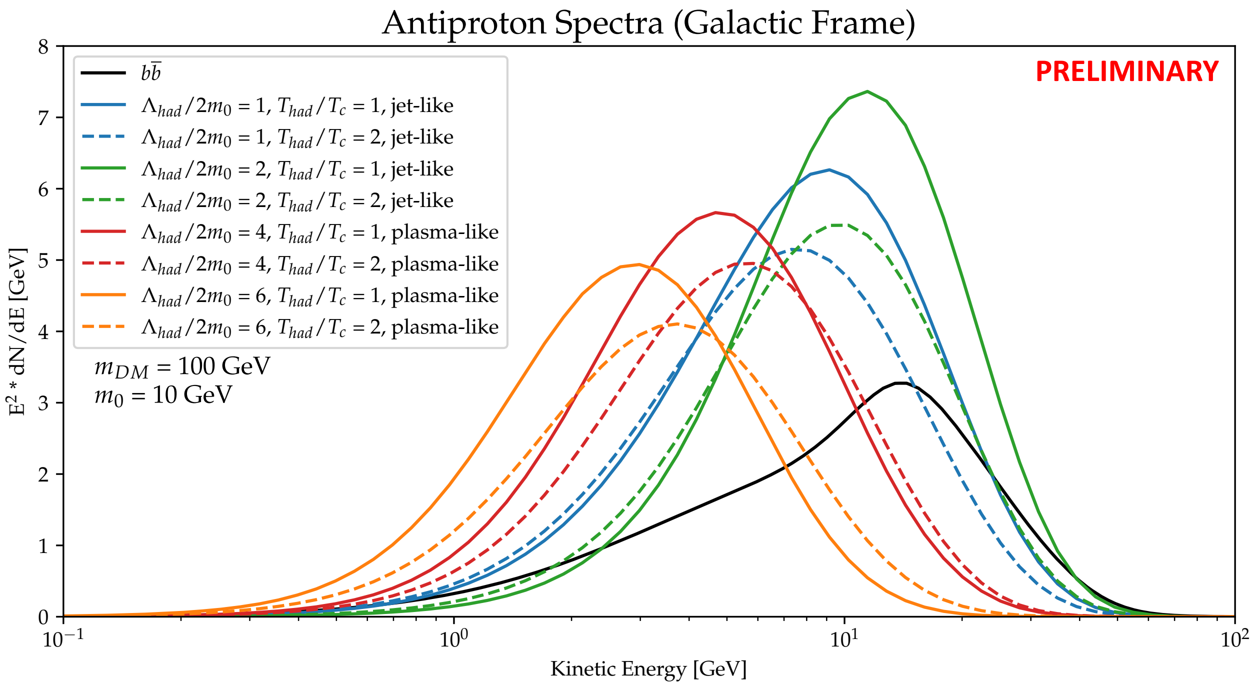
Jet-like
Plasma-like
$\langle N \rangle$
9
8
7
6
5
4
3
2
1
2
3
4
5
6
7
8
$\Lambda_{had}/2m_0$



$N_c = 3$
Upper Bound
0.050
0.020
0.010
0.005
5
10
20
50
100
M/m_0
$\langle P_{extra\ glueball} \rangle$ per event







DIMENSION 8 DECAYS ONLY

- Galactic frame, cosmic rays haven't been propagated
- Across benchmark parameters, largely same shape
  - However, variety in spectra peak position and size
  - Big difference for photon spectra
  - Overall increase in SM flux
- Spectral shape differs from WIMP-like channel in both positron and antiproton channels

Fermi-LAT Dwarf Spheroidal Constraints

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