Simulation and Indirect Detection of Dark Glueball Showers

Caleb Gemmell

TeVPA, Queen's University, 10/08/2022

Partially based on work with David Curtin and Chris Verhaaren

[arXiv: 2202.12899]

Contact: caleb.gemmell@mail.utoronto.ca

UNIVERSITY OF TORONTO

Model 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 the little hierarchy problem (Twin Higgs etc…)
- In the case where there is no light states with dark colour below the dark confinement scale, the only hadronic states that can form are 'dark glueballs', composite dark 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)
- Interested in the case that DM is uncharged under dark colour, but annihilates through the dark sector
  - DM + DM --> dark glueballs --> SM

Zero-th order Q: How does this annihilation channel change DM constraints / excesses?

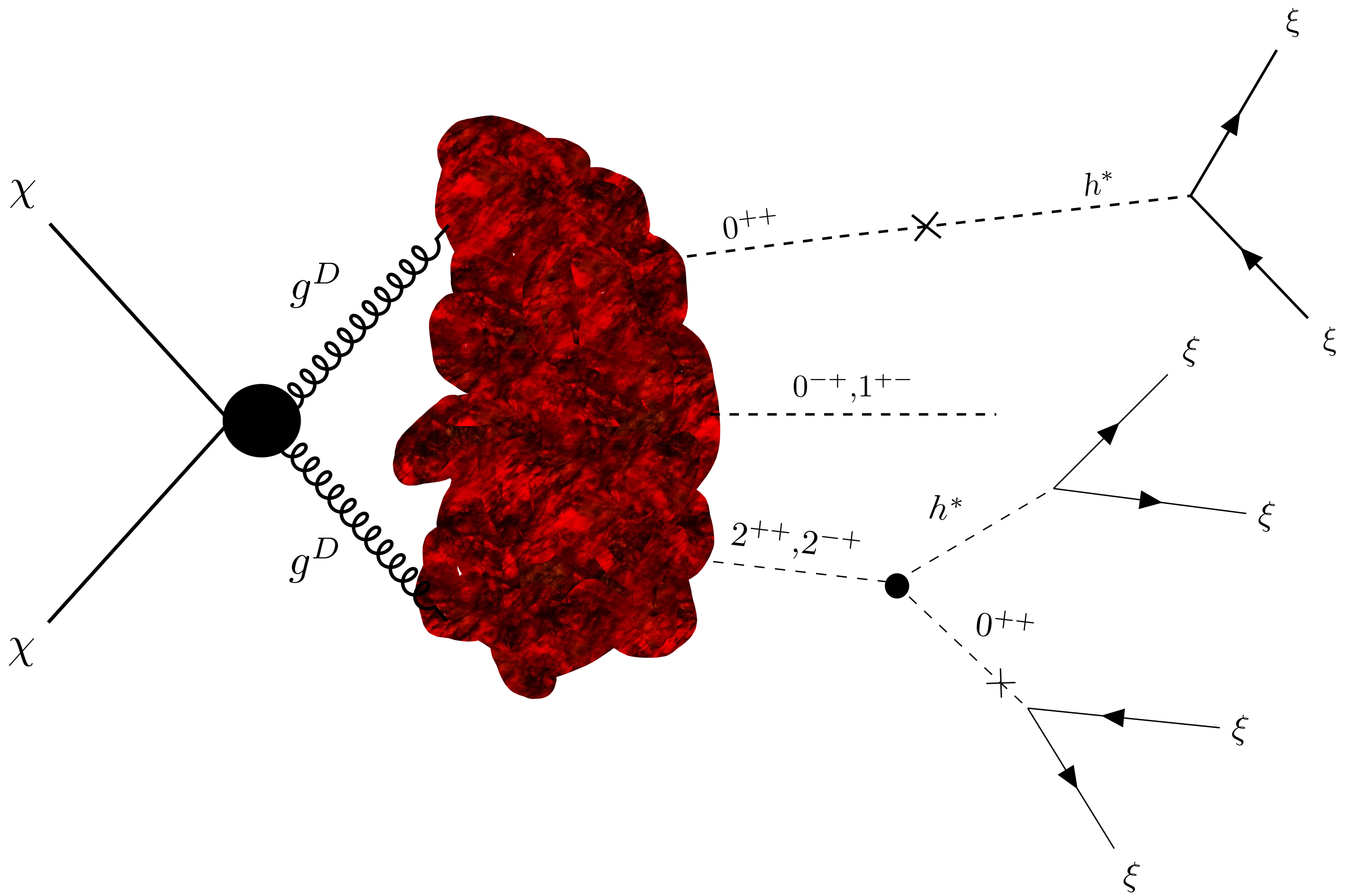
More interesting Q: Can we probe the dark sector itself through this process???

Indirect Detection Motivation

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

Simulating a Dark Glueball Shower

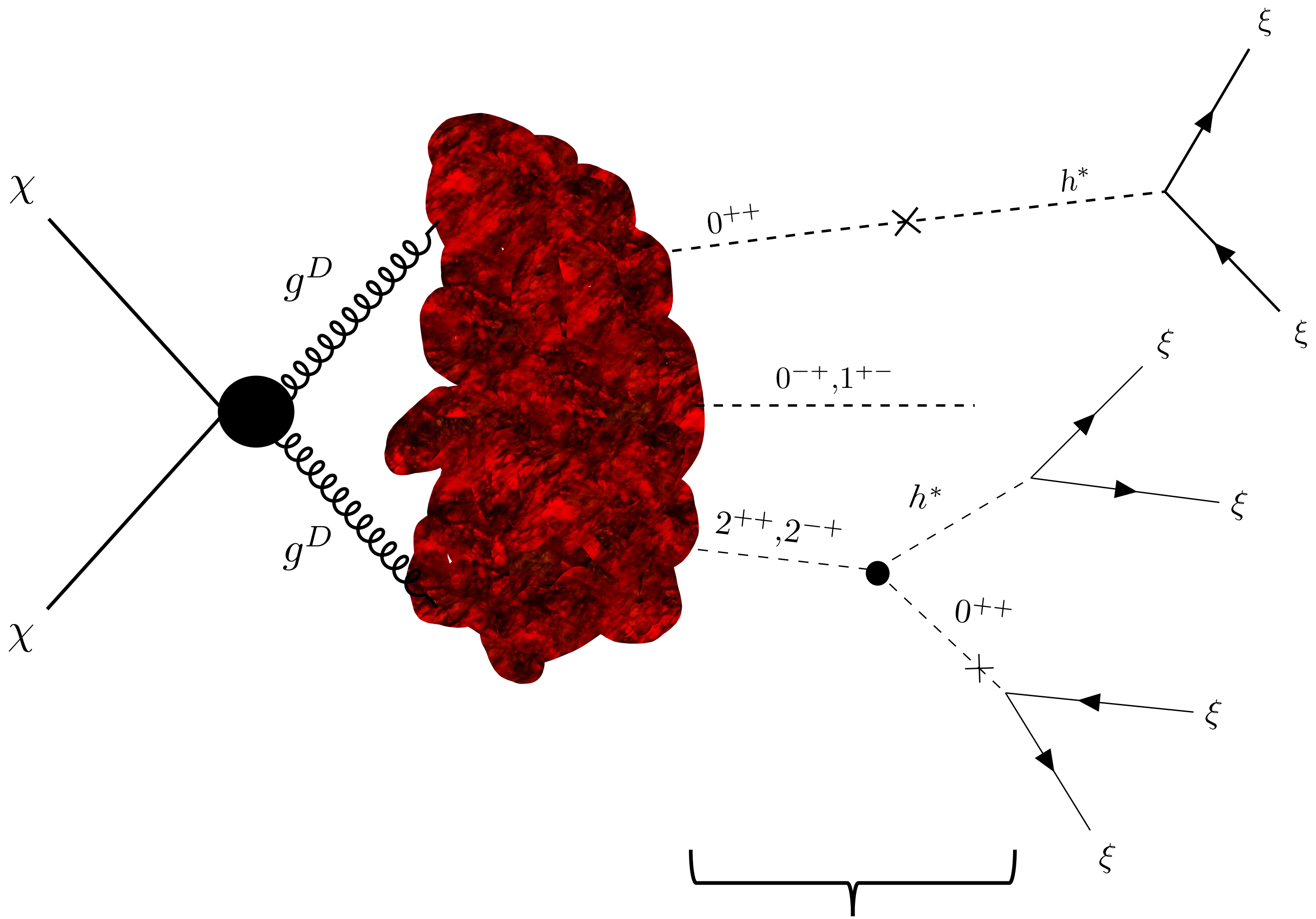
Dark Matter



SM Particles: photons, antiprotons….

Simulating a Dark Glueball Shower

Dark Matter

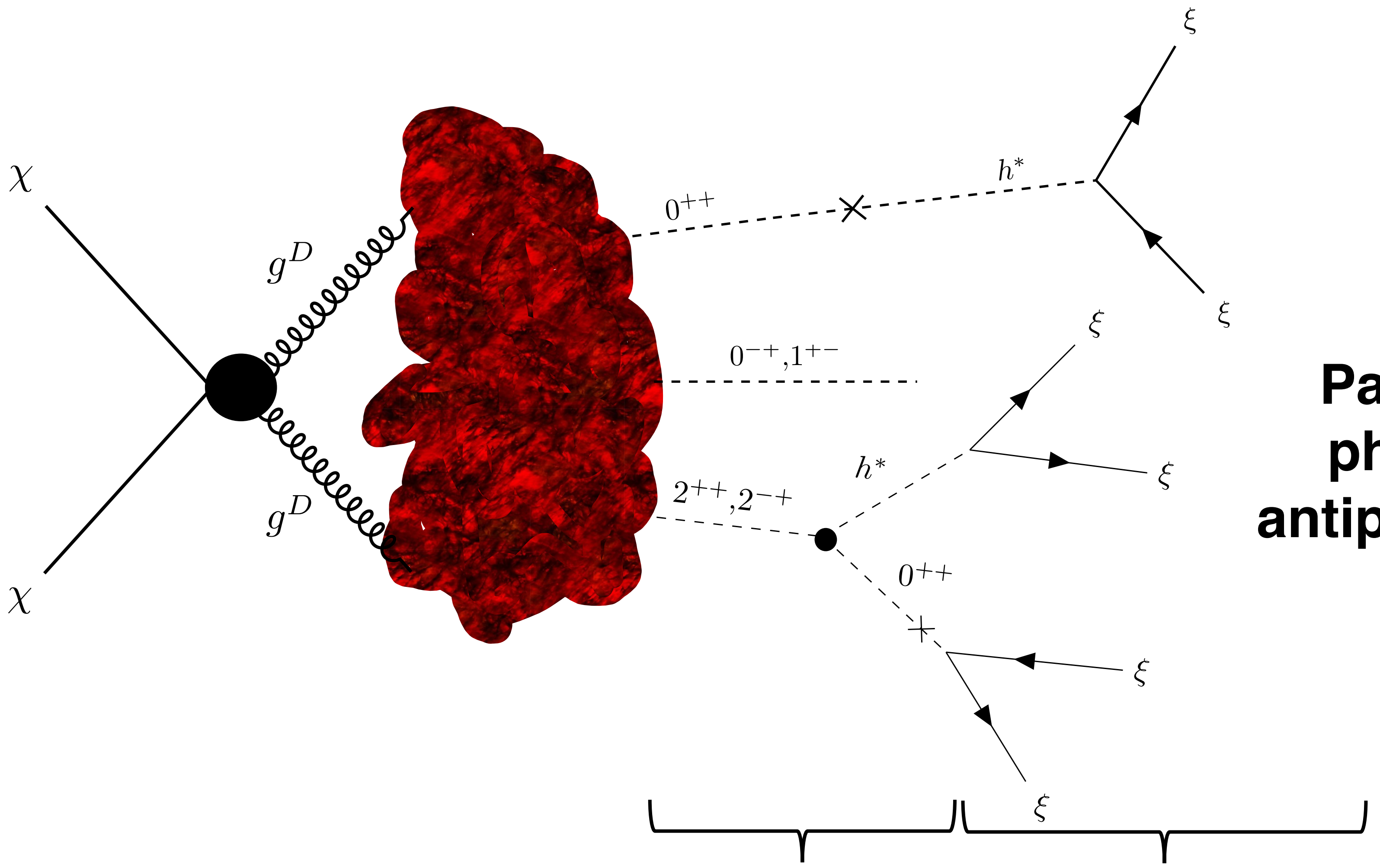


What are the dark glueball properties?

SM Particles: photons, antiprotons….

Simulating a Dark Glueball Shower

Dark Matter



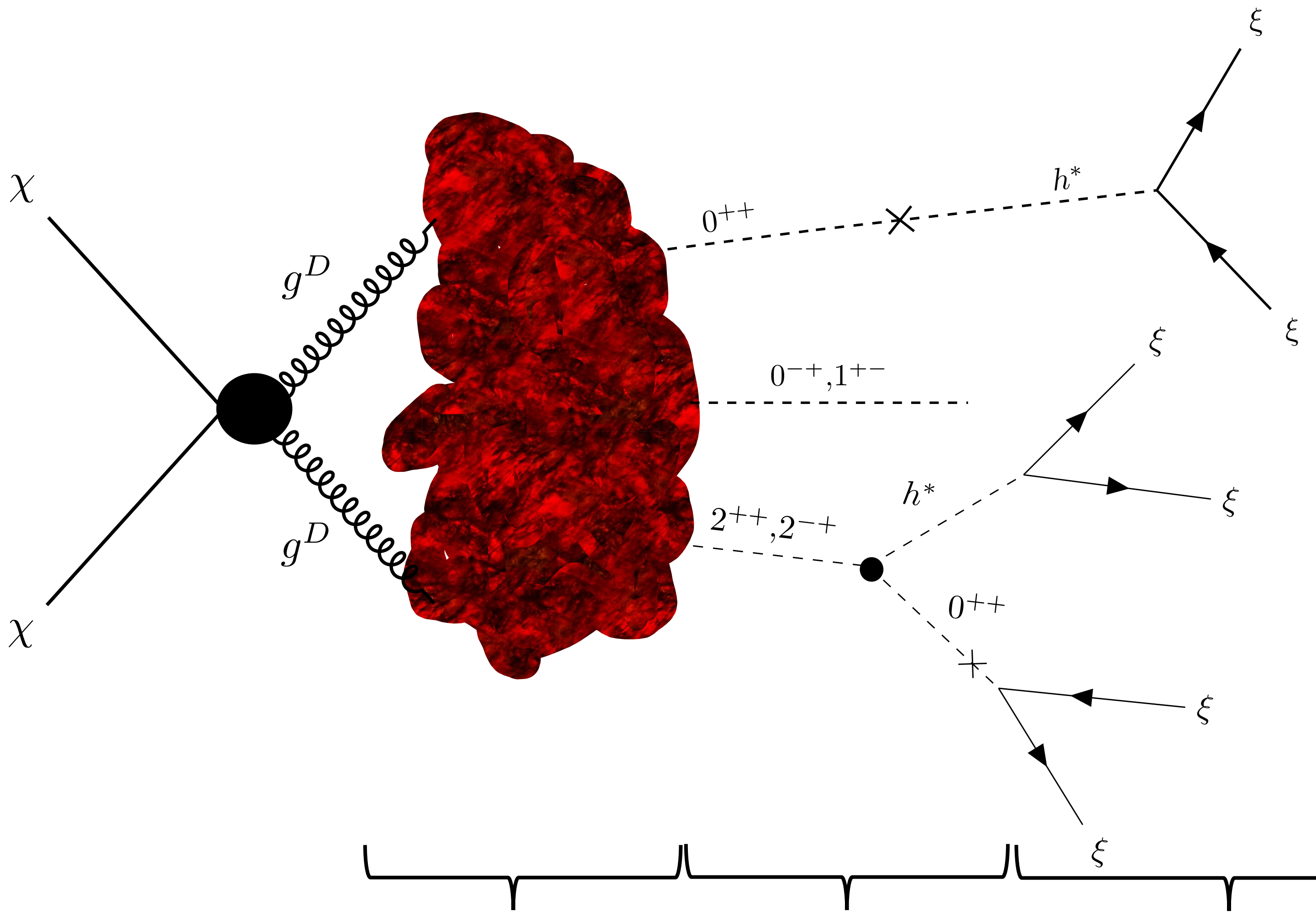
SM Particles: photons, antiprotons….

What are the dark glueball properties?

How do the dark glueballs decay to the SM?

Simulating a Dark Glueball Shower

Dark Matter



SM Particles: photons, antiprotons….

How to we simulate dark gluon hadronization to dark glueballs ?

What are the dark glueball properties?

How do the dark glueballs decay to the SM?

Dark Glueball Properties:

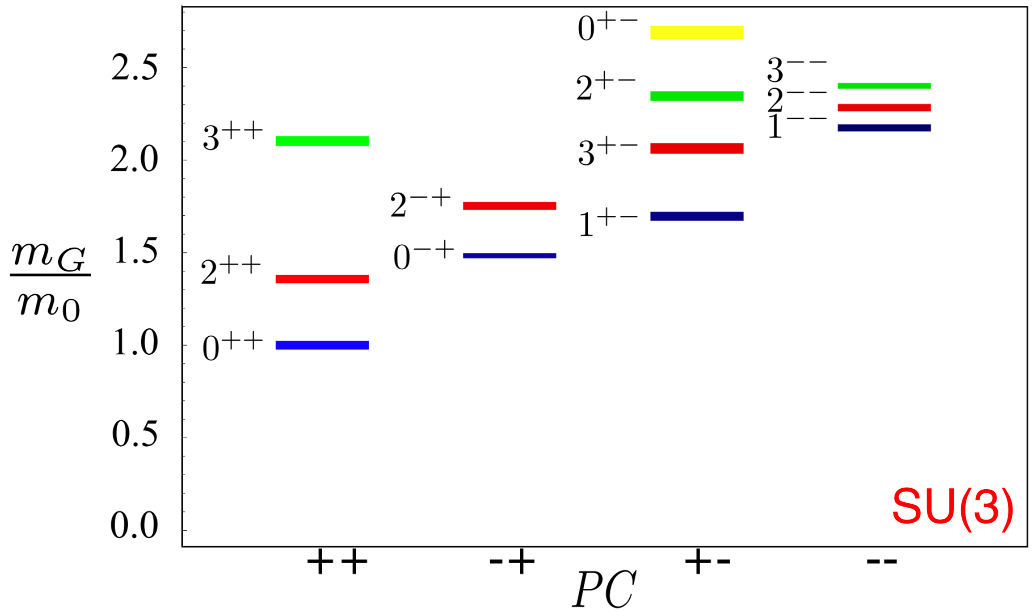
- Confined state of only dark gluons
- Majority of knowledge comes from Lattice QCD studies

Morningstar, Peardon, arXiv:hep-lat/9901004

Athenodorou, Teper, arXiv:2106.00364

- Spectrum of 12 stable states (in absence external couplings)
- Masses entirely parameterized by the confinement scale ($m_0 \sim 6\Lambda$)

Juknevich, arXiv:0911.5616



Dark Glueball Decay Modes

- Couples to standard model via heavy quark loop:
  - Dimension 6 Higgs operator

$$\mathcal{O}^{(6)} \sim \frac{1}{M^2} H^\dagger H \, tr(XX)$$

  - Dimension 8 Gauge operator

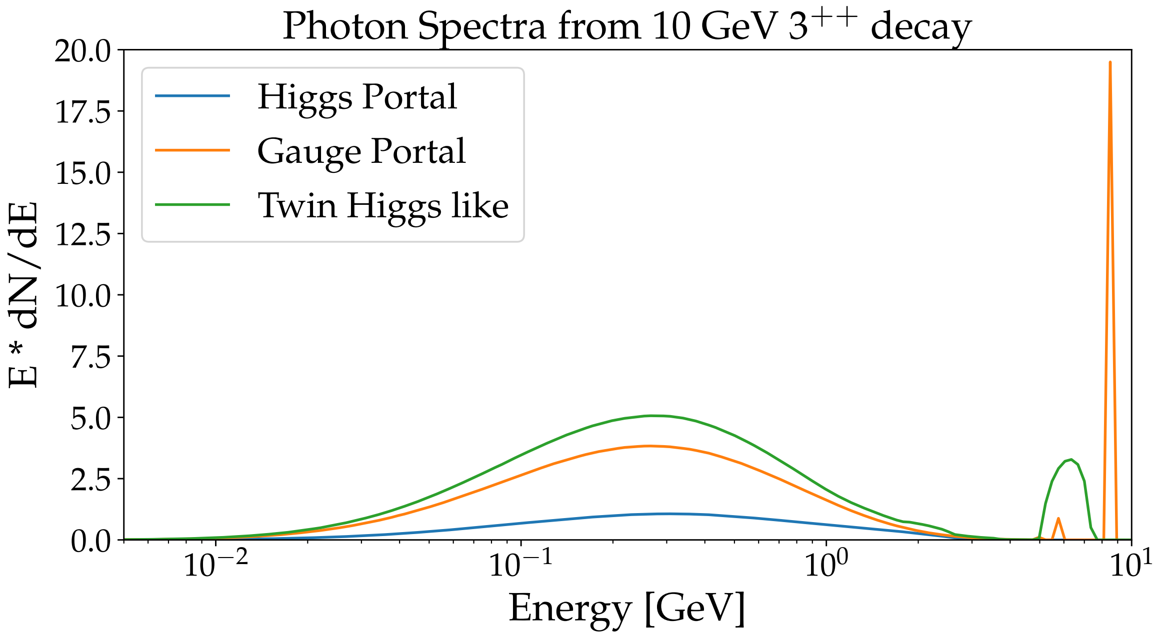
$$\mathcal{O}^{(8a)} \sim \frac{1}{M^4} tr(F_{SM} F_{SM}) \, tr(XX)$$

$$\mathcal{O}^{(8b)} \sim \frac{1}{M^4} B_{\mu\nu} \, tr(XXX)^{\mu\nu}$$

- We consider three cases:
  - Purely Dim 6 (Higgs Portal)
  - Purely Dim 8 (Gauge Portal)
  - Dim 6 and Dim 8, but Dim 8 suppressed by higher scale (Twin Higgs like)

Juknevich, arXiv:09z11.5616

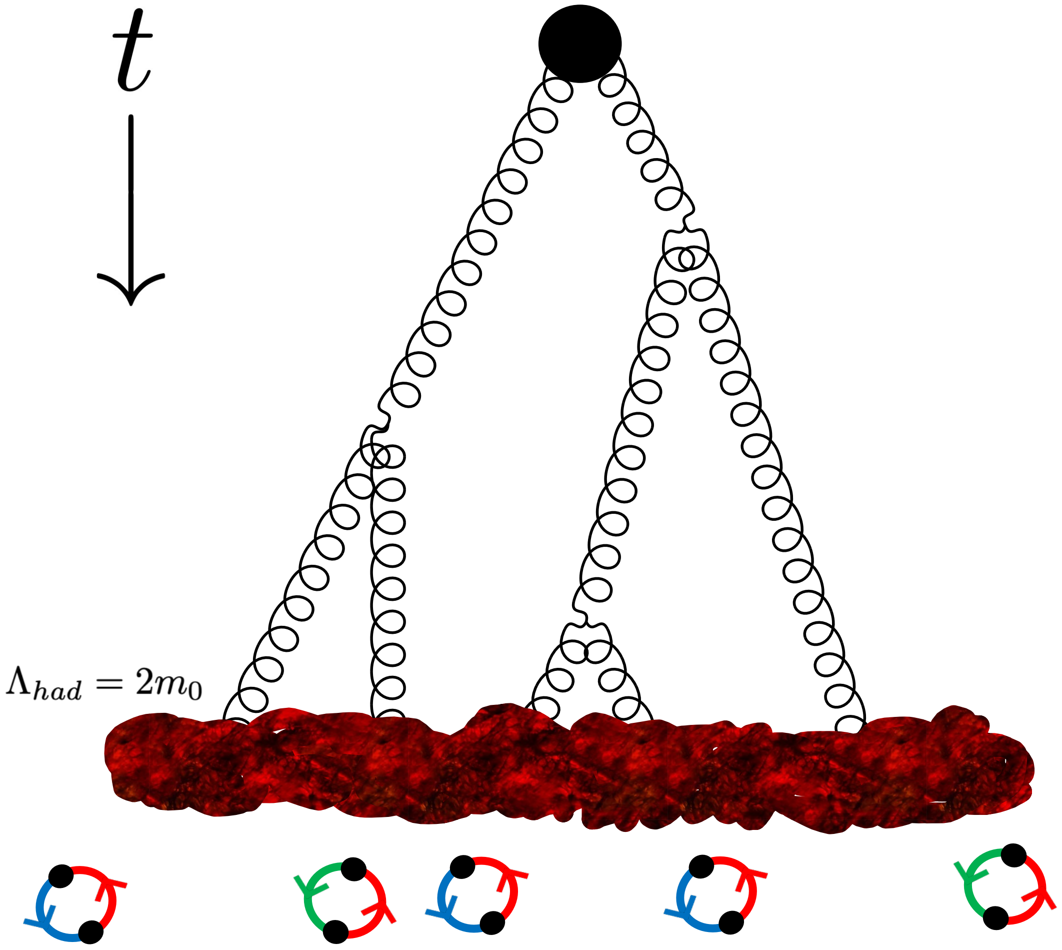
State	$D = 6$ operators	$D = 8$ operators
0^{++}	bb, W^+W^-, ZZ, hh	gg, WW, ZZ, $Z\gamma$, $\gamma\gamma$
$2^{\pm+}$	$0^{\pm+}h(h^*)$	gg, WW, ZZ, $Z\gamma$, $\gamma\gamma$
0^{-+}	-	gg, WW, ZZ, $Z\gamma$, $\gamma\gamma$
3^{++}	$0^{-+}h$, $2^{\pm+}h(h^*)$	$0^{-+}gg$ $2^{++}gg$, $1^{+-}\gamma$
1^{+-}	-	$0^{\pm+}\gamma$, $2^{-+}\gamma$
1^{--}	$1^{+-}h(h^*)$	$0^{\pm+}\gamma$, $2^{\pm+}\gamma$, ff
0^{+-}, 2^{+-}, 3^{+-} 2^{--}, 3^{--}	$J^{P-}h(h^*)$	$0^{\pm+}\gamma$, $2^{\pm+}\gamma$



Pure Glue Hadronization

Curtin, **Gemmell**, Verhaaren, arXiv:2202.12899

- We use `GlueShower`, publicly available $N_f = 0$ QCD Monte Carlo event generator
- Implement pQCD to calculate gluon splittings
- Non-perturbative production of glueballs suppressed due to large mass hierarchy
- Gives upper bound on final state multiplicity
- Jet-like shower, similar to SM

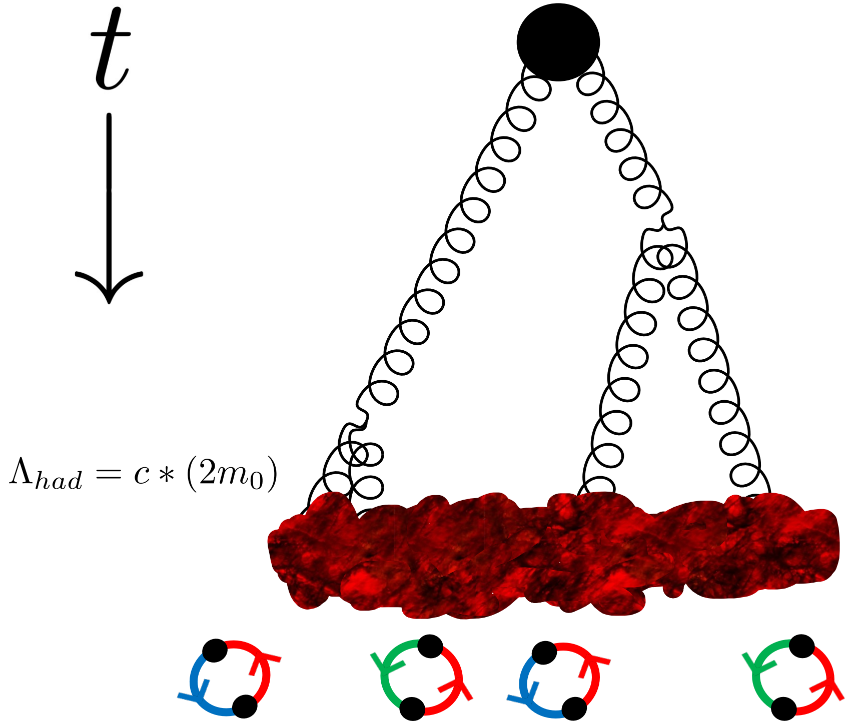


Pure Glue Hadronization

- Nuisance parameters
  - Hadronization scale multiplier
    - Scales upwards, reduces final state multiplicity
  - Hadronization temperature multiplier
    - Explores different relative multiplicities of dark glueball species

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

  - Plasma-like shower
    - Large virtuality gluons form excited states at the end of perturbative shower
    - Plasma decays isotropically by thermal glueball emission
- Define 8 benchmark points that bracket the range of possible hadronization phenomena

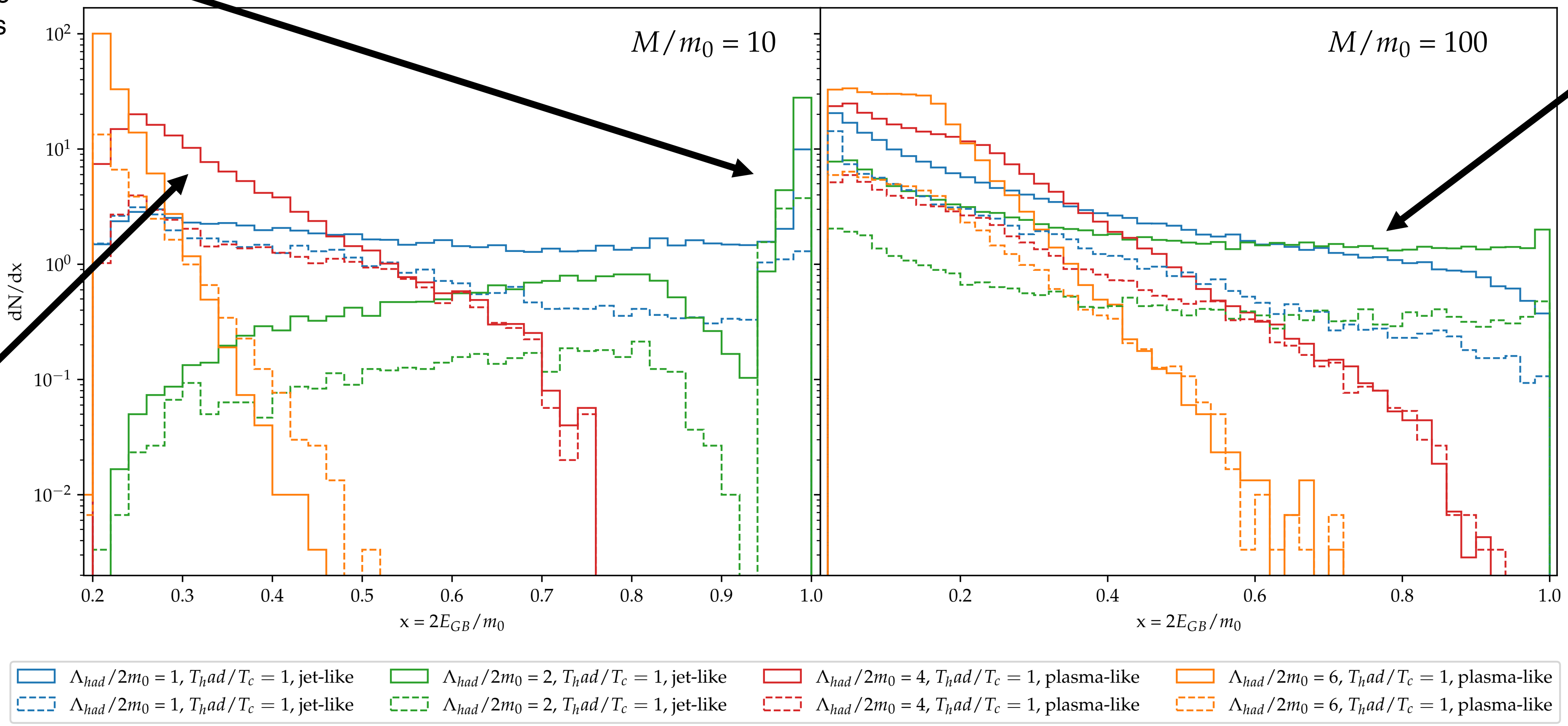


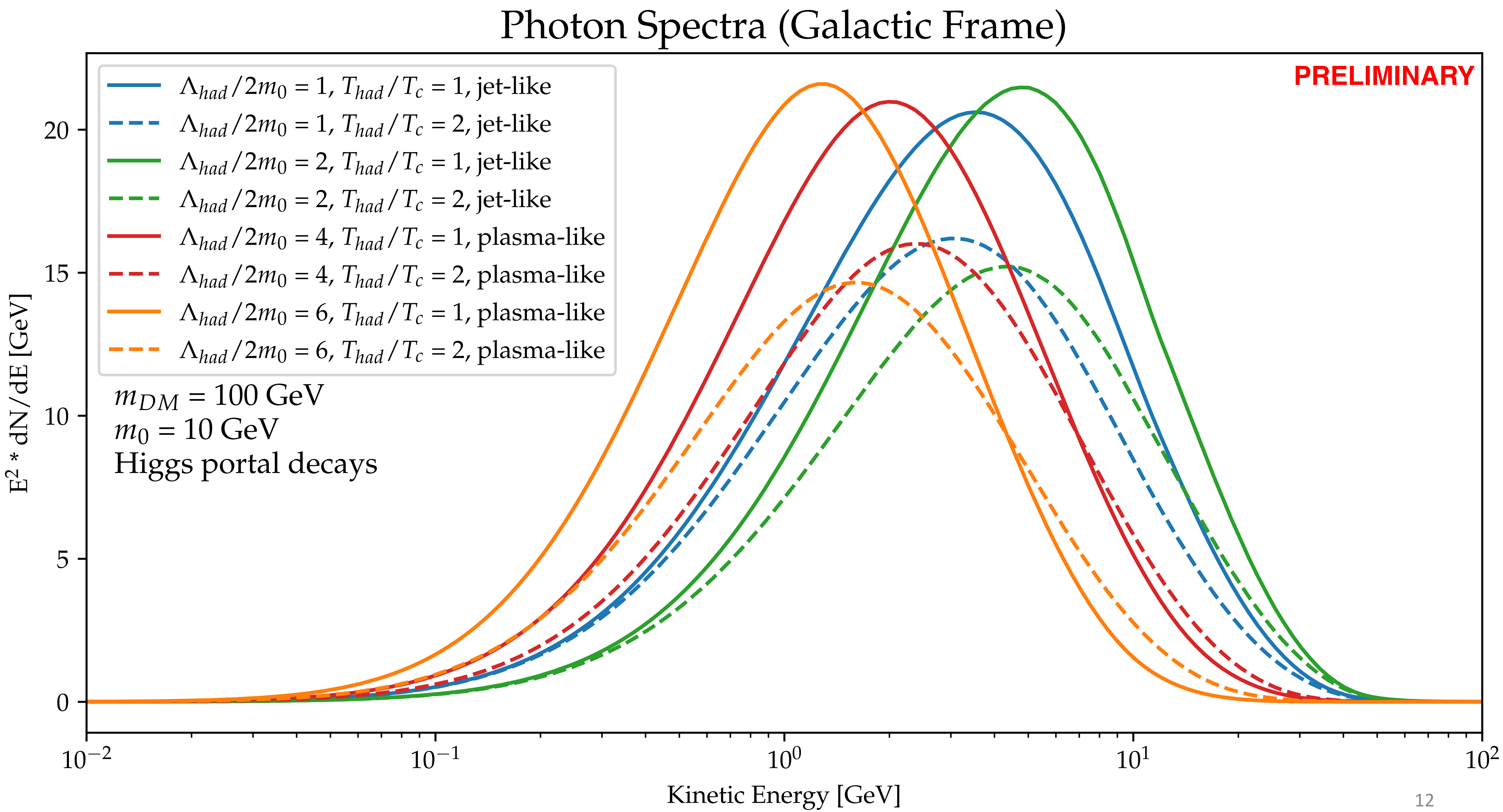
Fragmentation Functions

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, higher multiplicity events




Photon Spectra (Galactic Frame)
PRELIMINARY
$\Lambda_{had}/2m_0 = 1$, $T_{had}/T_c = 1$, jet-like
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$\Lambda_{had}/2m_0 = 2$, $T_{had}/T_c = 2$, 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
Higgs portal decays
$E^2 * dN/dE$ [GeV]
0
5
10
15
20
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Kinetic Energy [GeV]

Indirect Detection methodology

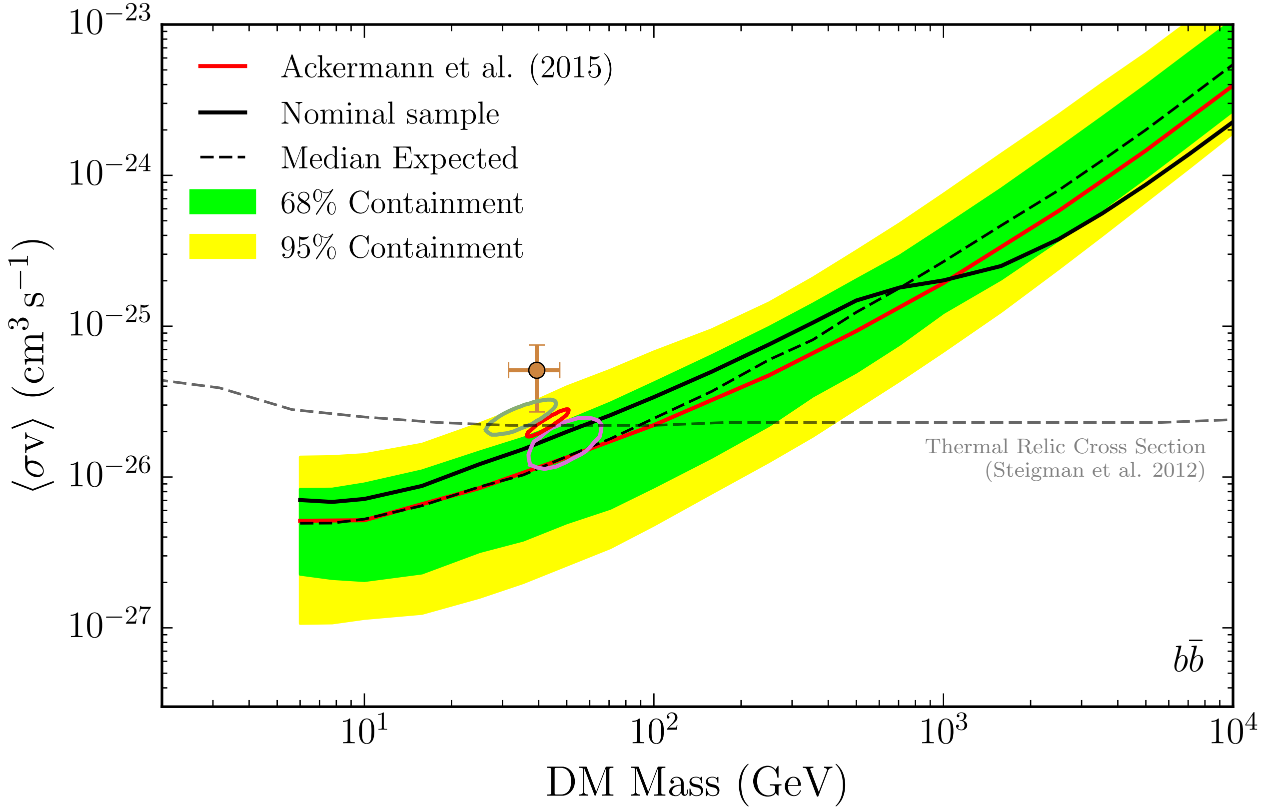
Fermi-LAT Dwarf Spheroidal Constraints

- Calculate energy flux for each bin from photon spectra

$$\Phi_E = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \left[\int_{E_{\rm min}}^{E_{\rm max}} E \frac{dN}{dE} dE \right] J_i$$

- Use publicly released likelihood profiles for each of the dwarf galaxies
- Follow Fermi-LAT methodology, profile over J-factor uncertainty

(arXiv: 1611.03184)

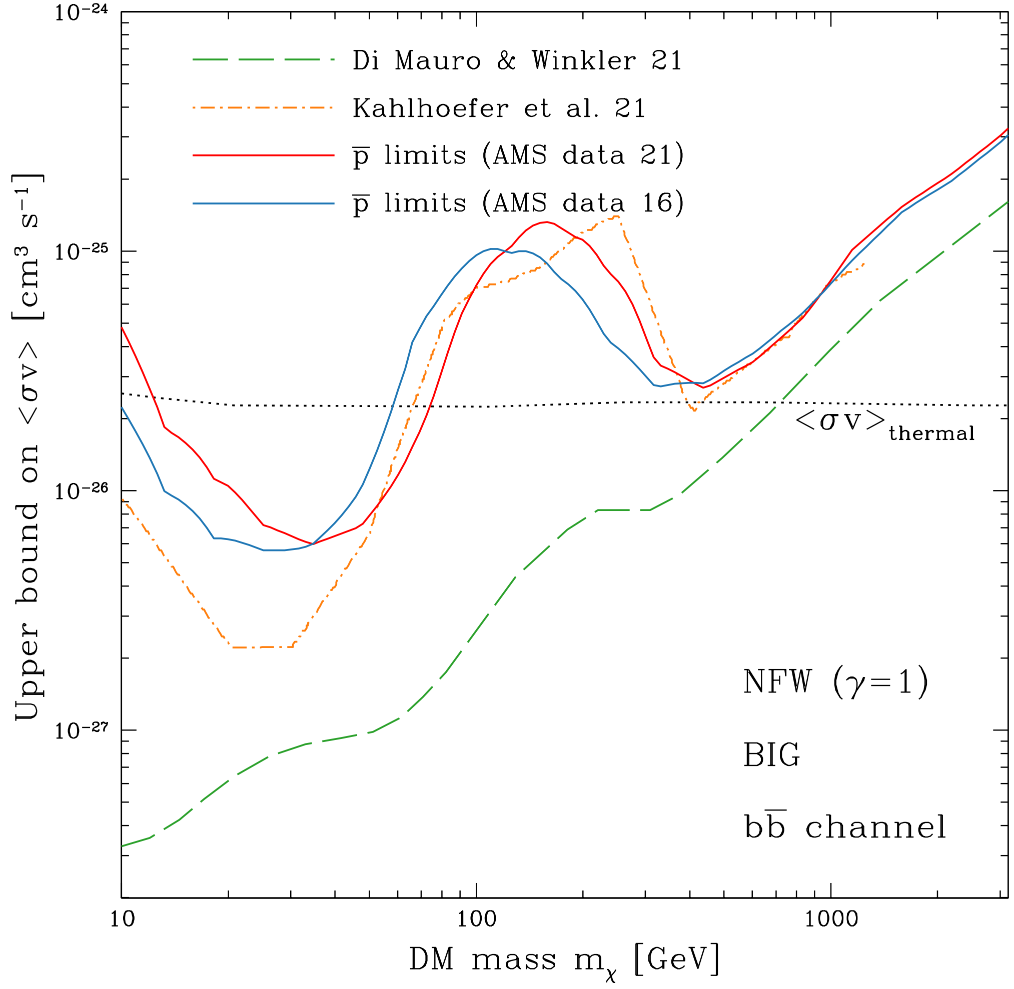


AMS-02 Antiproton Constraints

(Evoli et al., arXiv: 1607.07886)

- We use DRAGON2 to propagate cosmic rays from SM background and DM signal
- Propagation parameters taken from De La Torre Luque, arXiv:2107.06863
- To account for solar modulation due to the heliosphere we use the force field approximation with charge-dependent potential
- Keep propagation parameters fixed but vary solar modulation parameters and antiproton flux normalization in fit
  - Fit only above 5 GeV to minimize influence of solar modulation assumptions

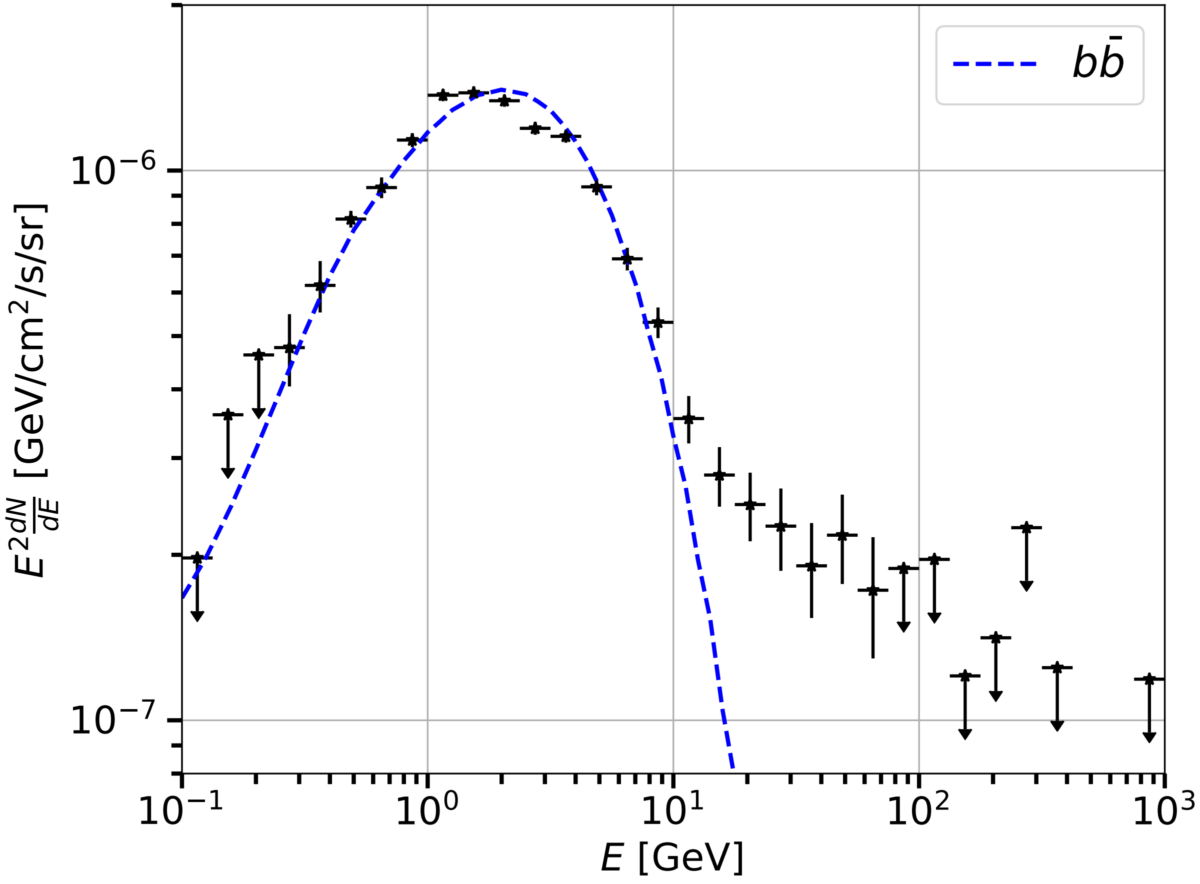
(Calore et al., arXiv: 2202.03076)



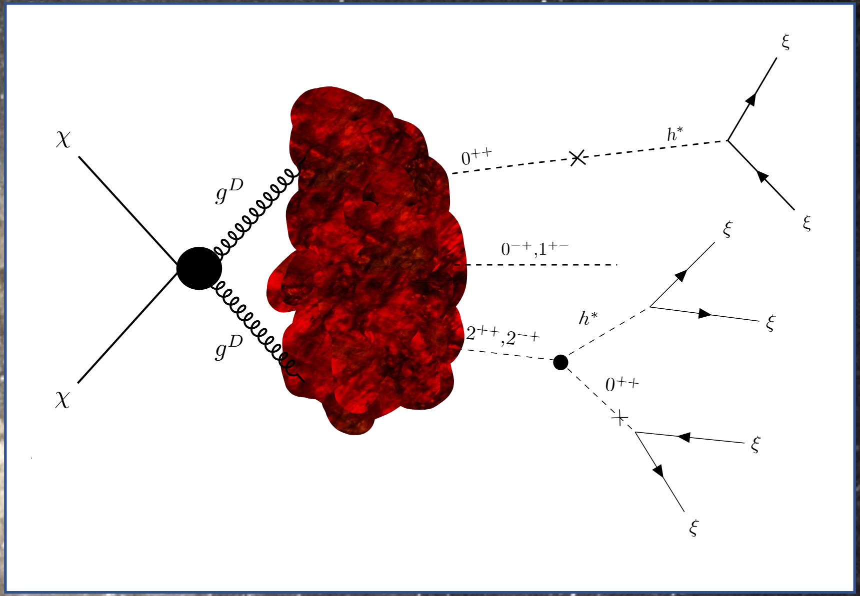
Galactic Centre Excess

- Take excess as recently calculated in arXiv:2101.11027
- Get best fit from chi-squared test using statistical errors from the base model
- Different interpretations exist of the excess (DM, millisecond pulsars) but the existence of an excess is agreed upon

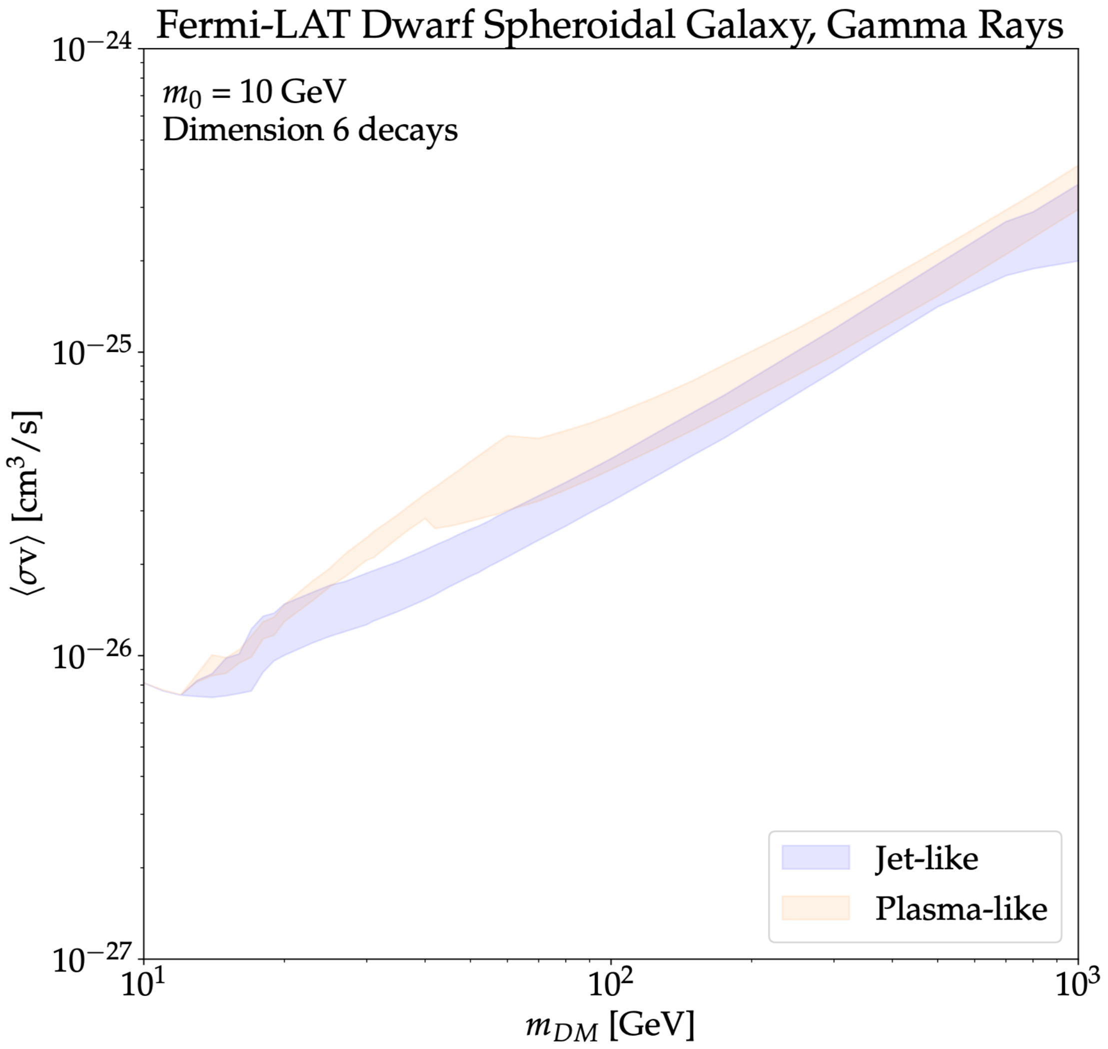
(Di Mauro, Winkler, arXiv: 2101.11027)

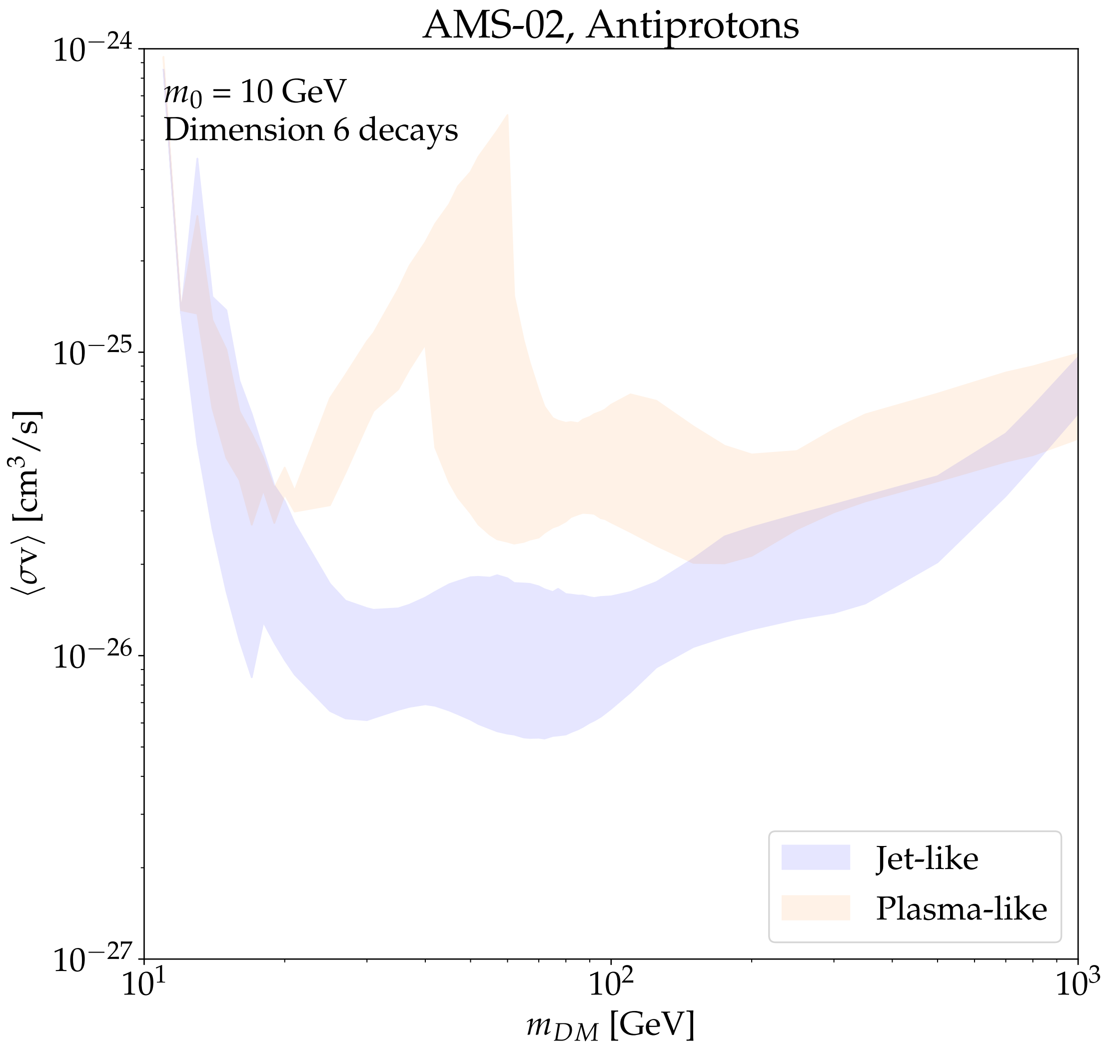


Preliminary results

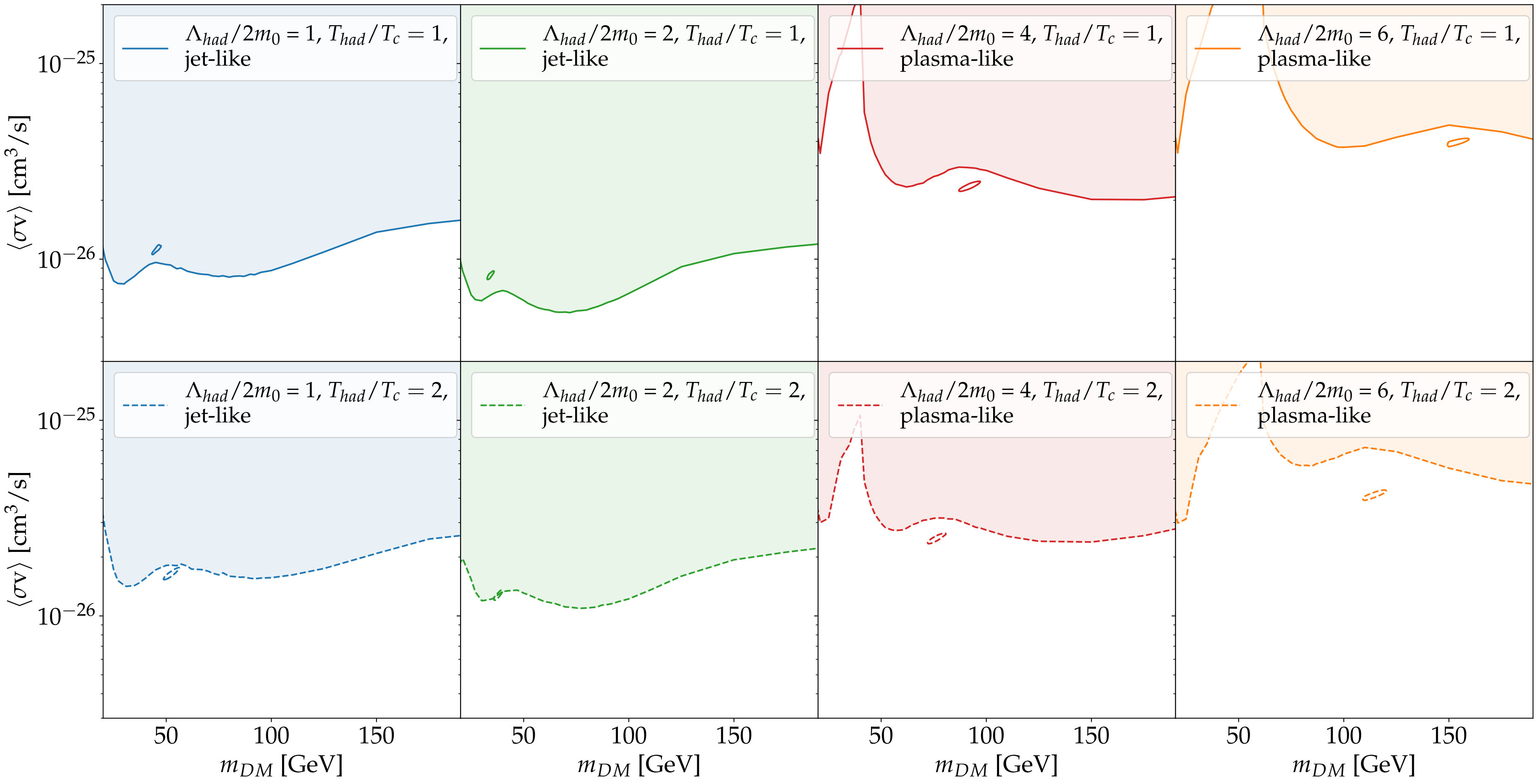


Dark Matter Constraints





Dark Glueball Sector Constraints (Higgs Portal)



- We fit the GCE and find antiproton constraints across the eight benchmark points
- We find that some hadronization models are inconsistent with current era astrophysical observations

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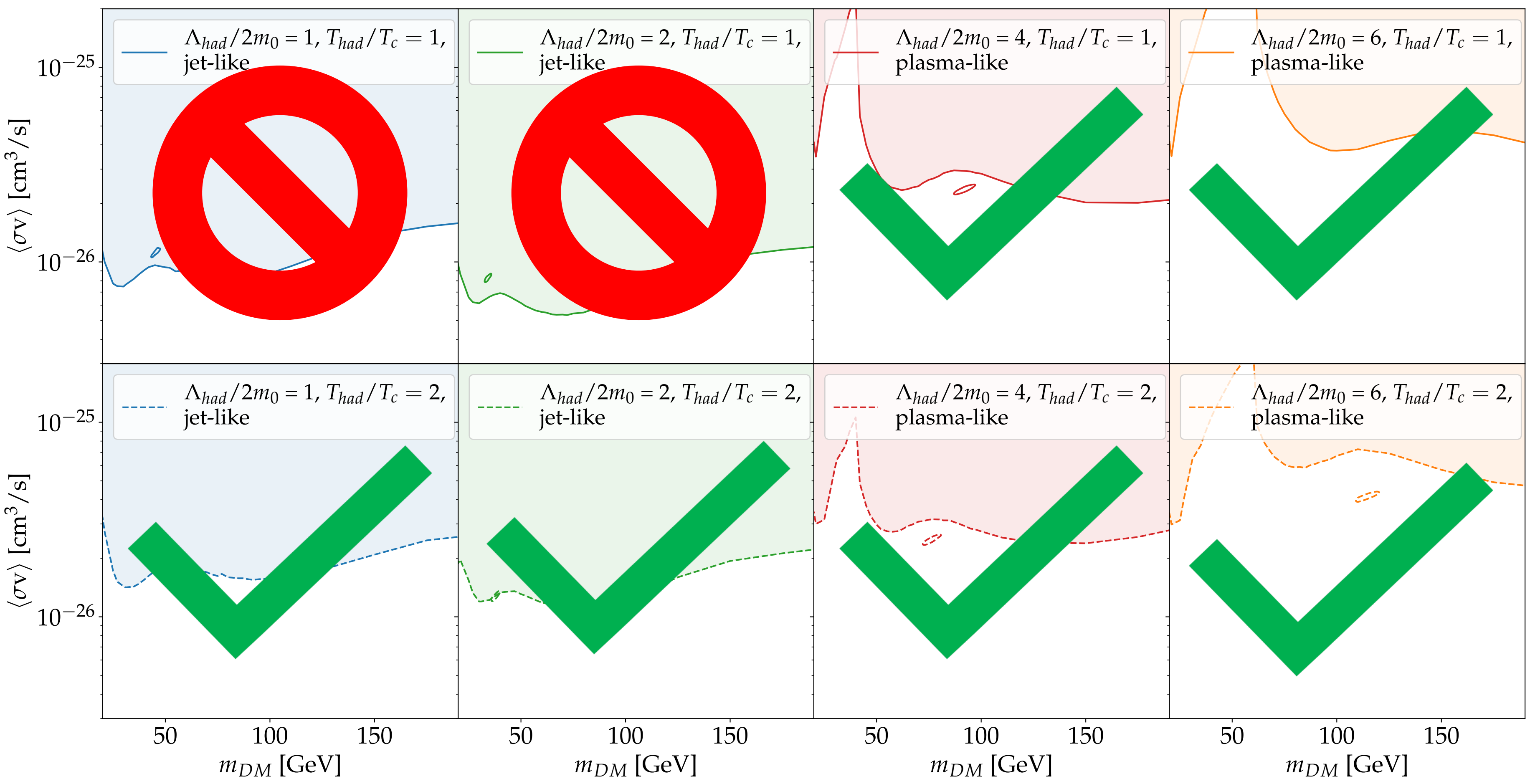

- We fit the GCE and find antiproton constraints across the eight benchmark points
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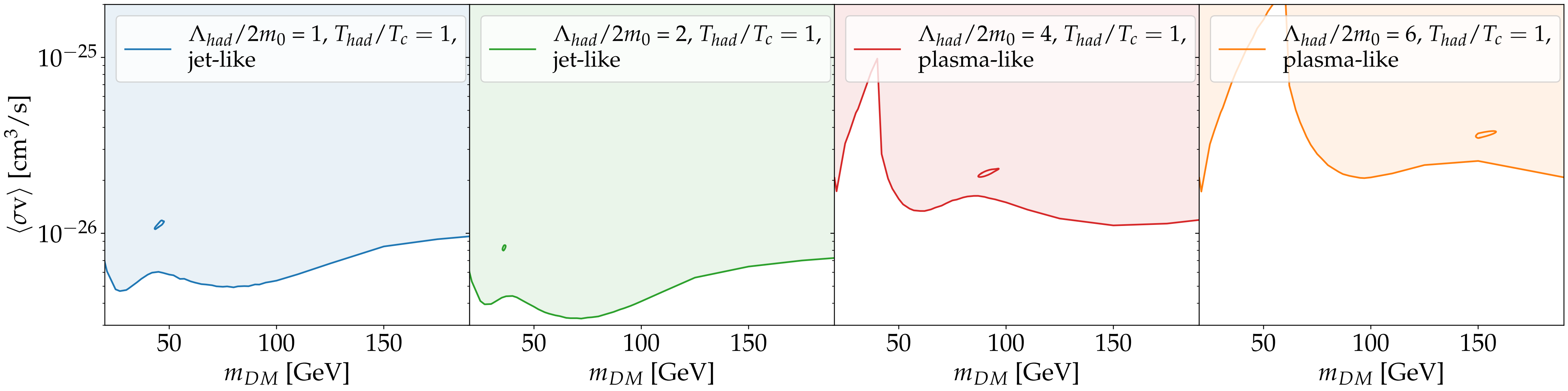
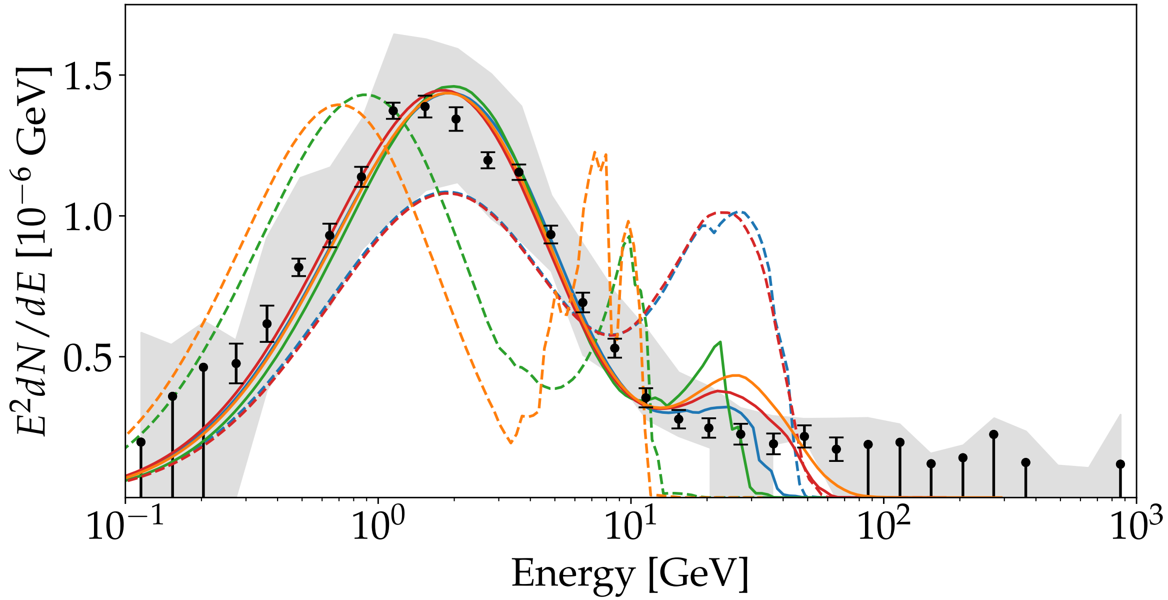
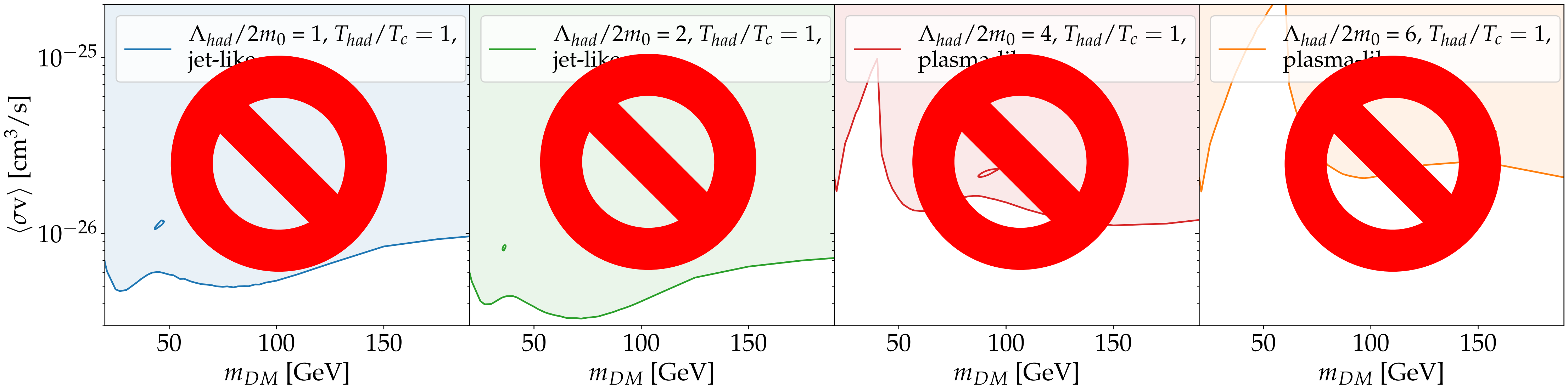
Dark Glueball Sector Constraints (Gauge Portal)

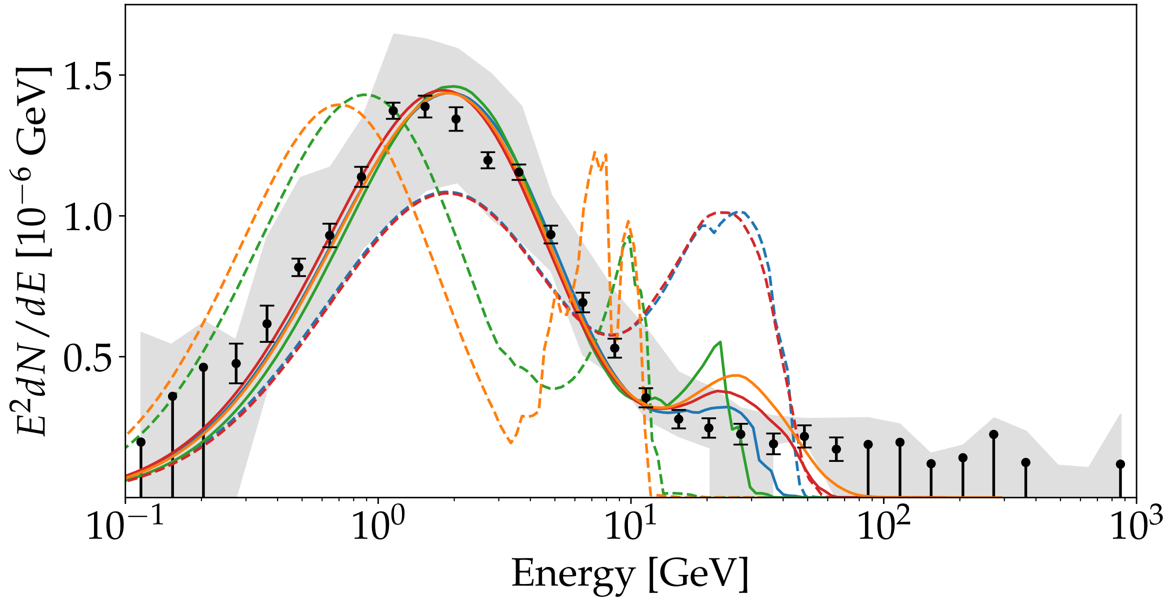




- Repeat for different higher dimension operators
- We use the GCE fits to exclude the higher hadronization temperature benchmark points (shown left)
- Antiproton constraints rule out the remaining benchmark points

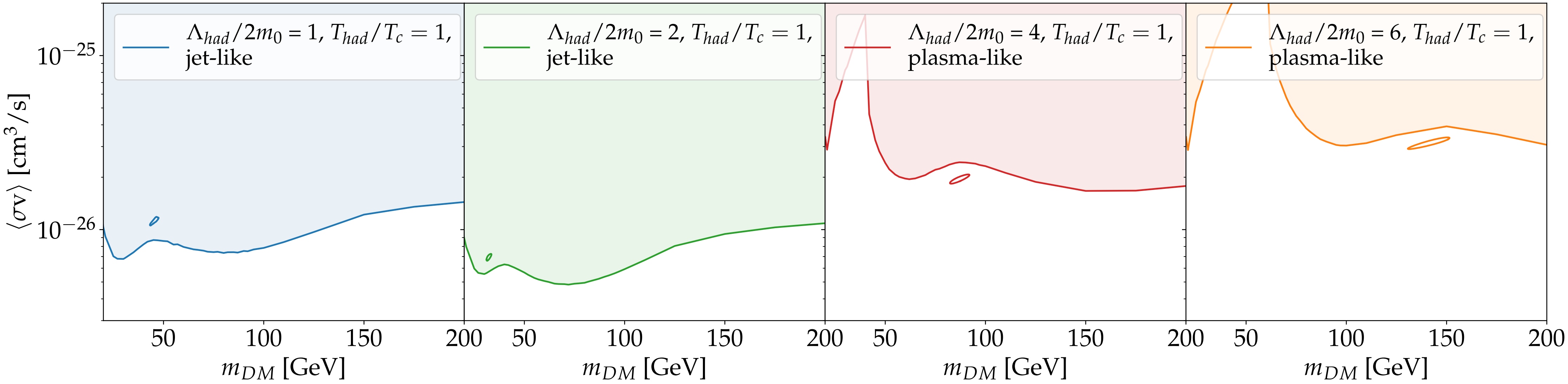
Dark Glueball Sector Constraints (Gauge Portal)

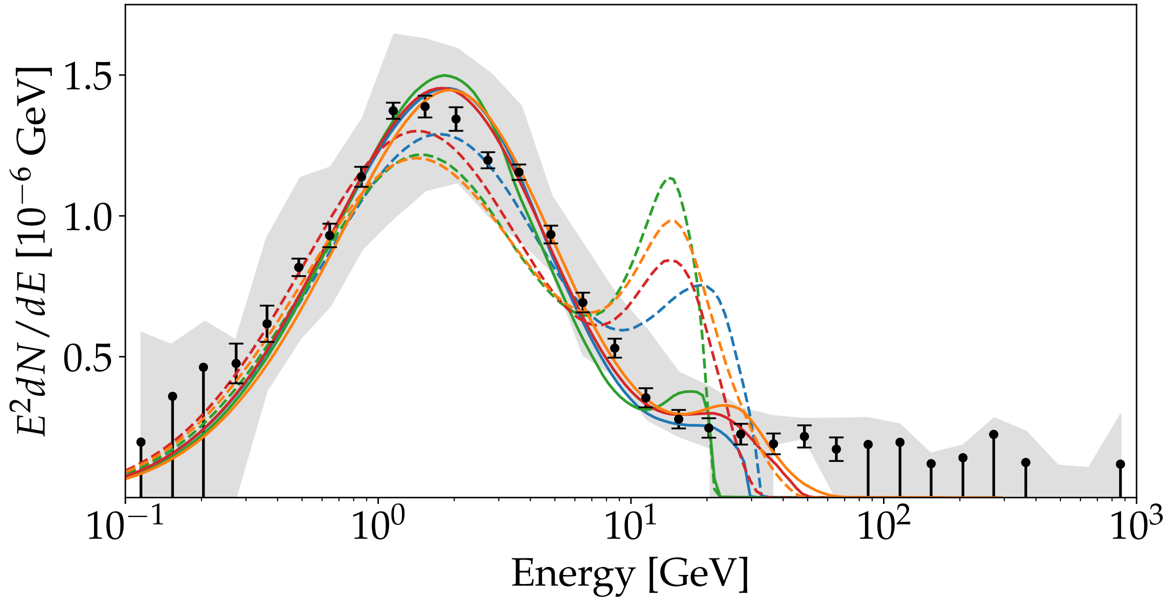




- Repeat for different higher dimension operators
- We use the GCE fits to exclude the higher hadronization temperature benchmark points (shown left)
- Antiproton constraints rule out the remaining benchmark points

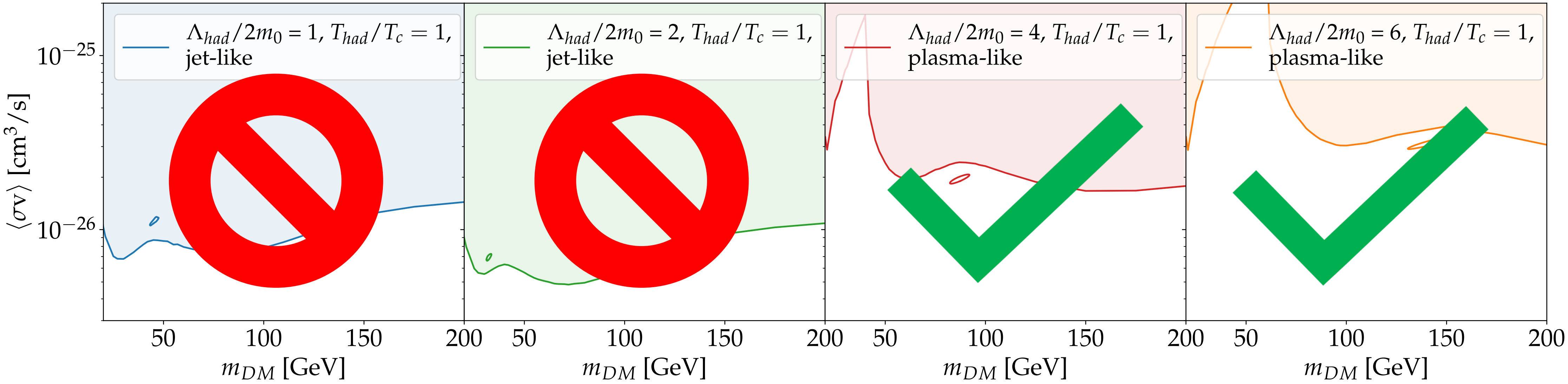
Dark Glueball Sector Constraints (Twin Higgs like)

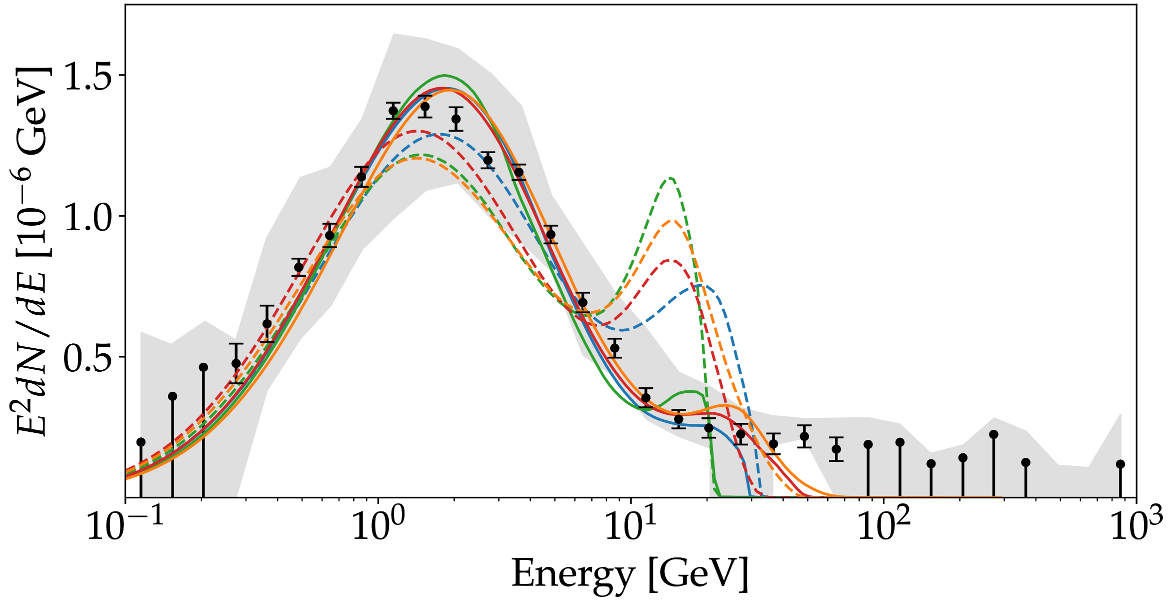




- Repeat for different higher dimension operators
- We use the GCE fits to exclude the higher hadronization temperature benchmark points (shown left)
- Antiproton constraints rule out only. The jete-like benchmark points

Dark Glueball Sector Constraints (Twin Higgs like)





- Repeat for different higher dimension operators
- We use the GCE fits to exclude the higher hadronization temperature benchmark points (shown left)
- Antiproton constraints rule out only the jet-like benchmark points

Conclusions:

- Dark showers are a general signature of hidden valley models, motivated as solutions to the little hierarchy problem and its evasion of current constraints
- 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
- **Multimessenger analysis allows us to probe the physics of the dark sector**
  - Already with current era indirect detection data we can begin to constrain the pure glue dark sector

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Thank you!

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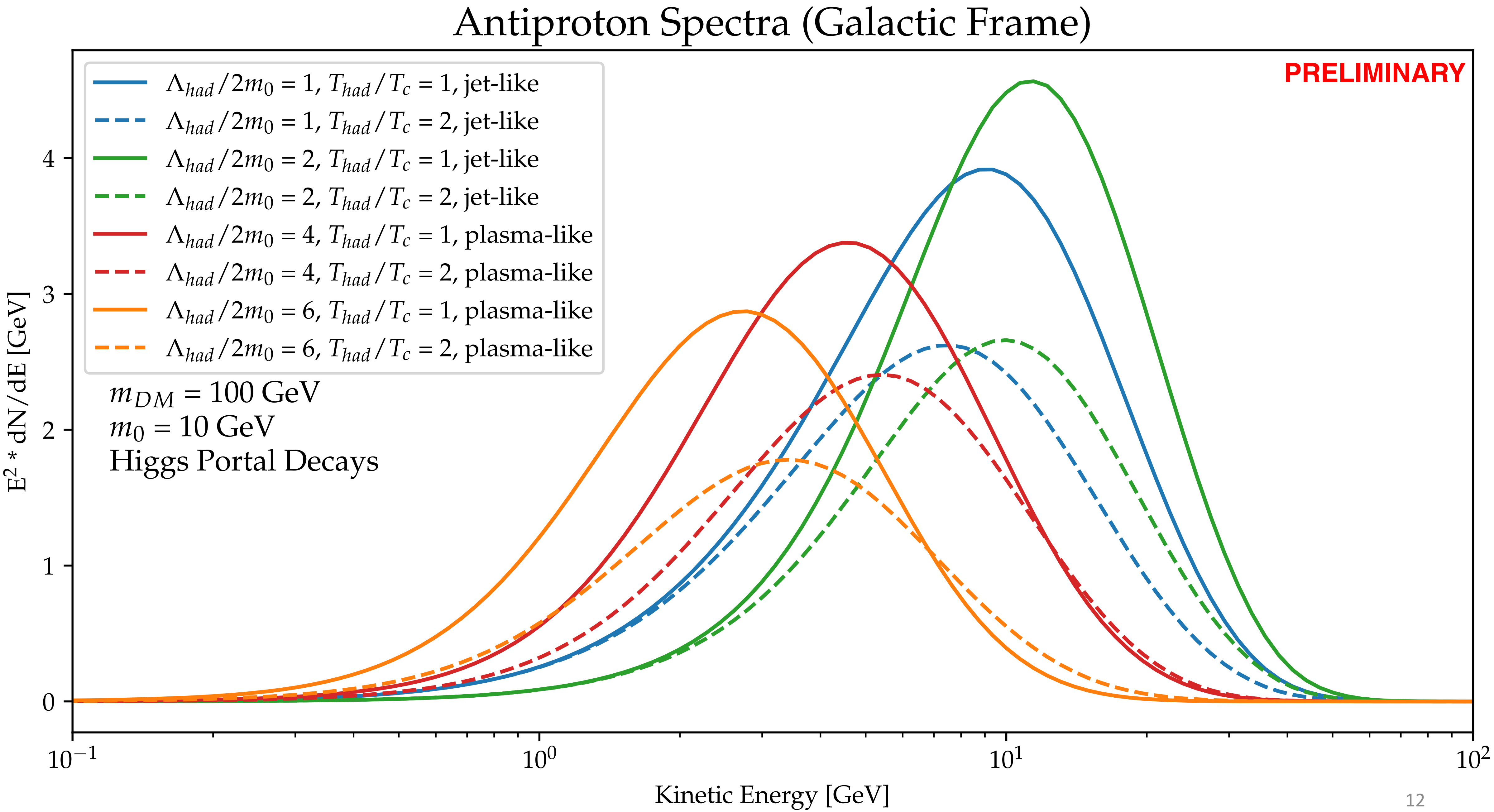

Antiproton Spectra (Galactic Frame)
PRELIMINARY
$\Lambda_{had}/2m_0 = 1$, $T_{had}/T_c = 1$, jet-like
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$\Lambda_{had}/2m_0 = 2$, $T_{had}/T_c = 1$, jet-like
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$\Lambda_{had}/2m_0 = 4$, $T_{had}/T_c = 1$, plasma-like
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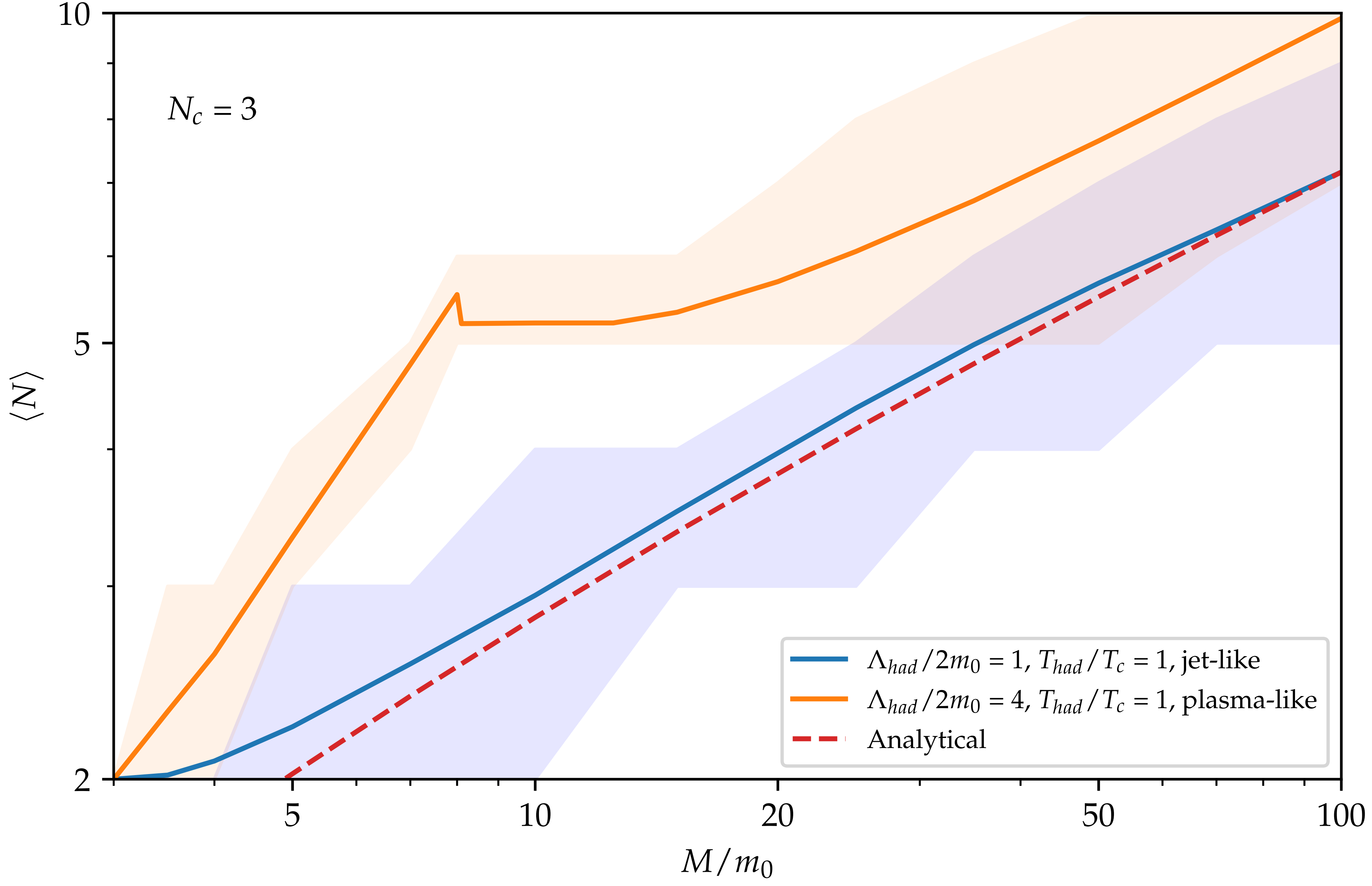
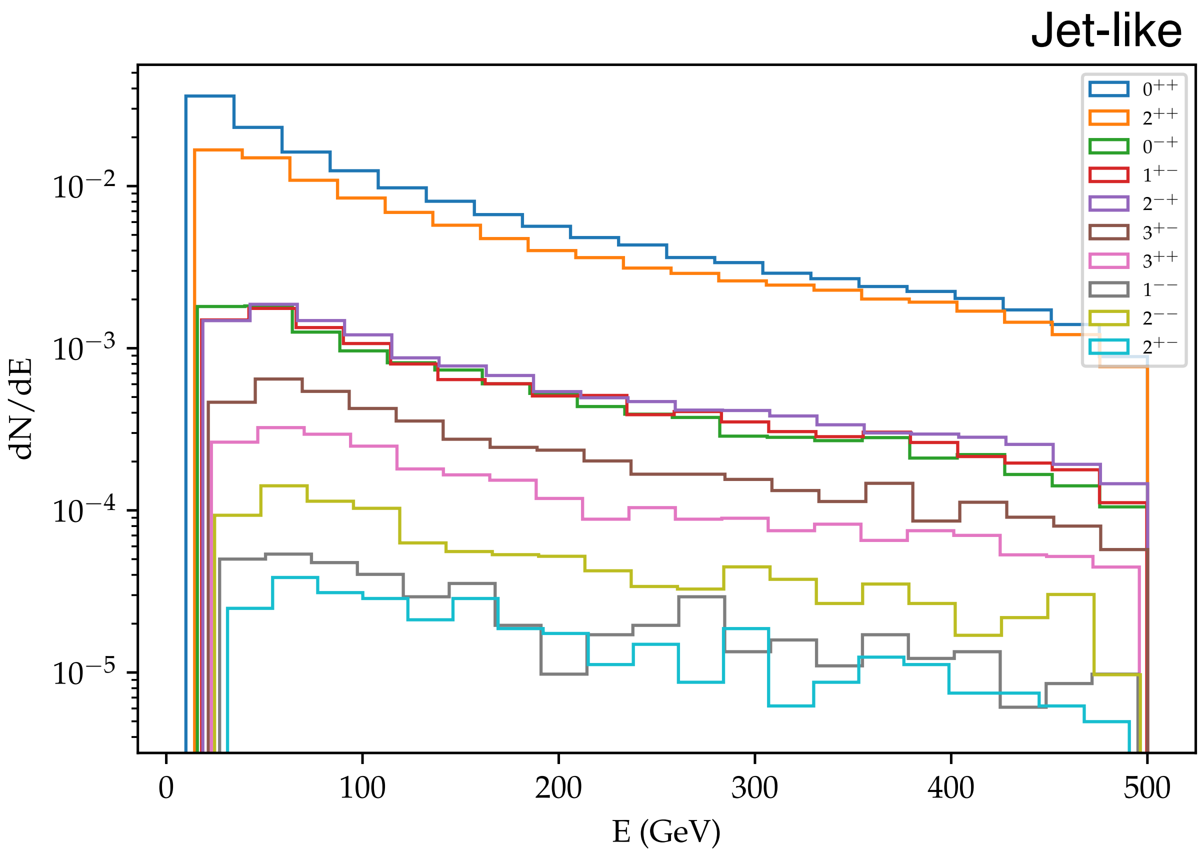
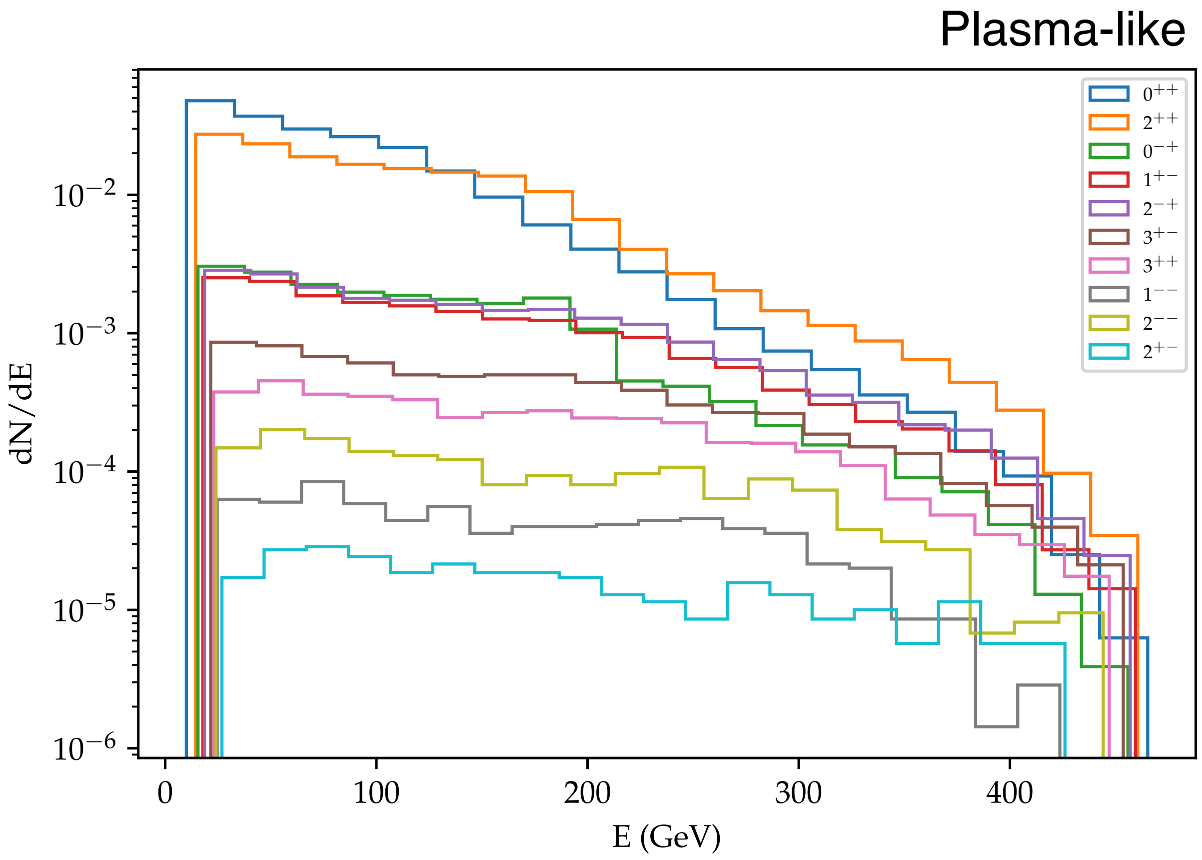
$m_{DM} = 100$ GeV
$m_0 = 10$ GeV
Higgs Portal Decays
E^2 * dN/dE [GeV]
Kinetic Energy [GeV]
0
1
2
3
4
10^{-1}
10^0
10^1
10^2



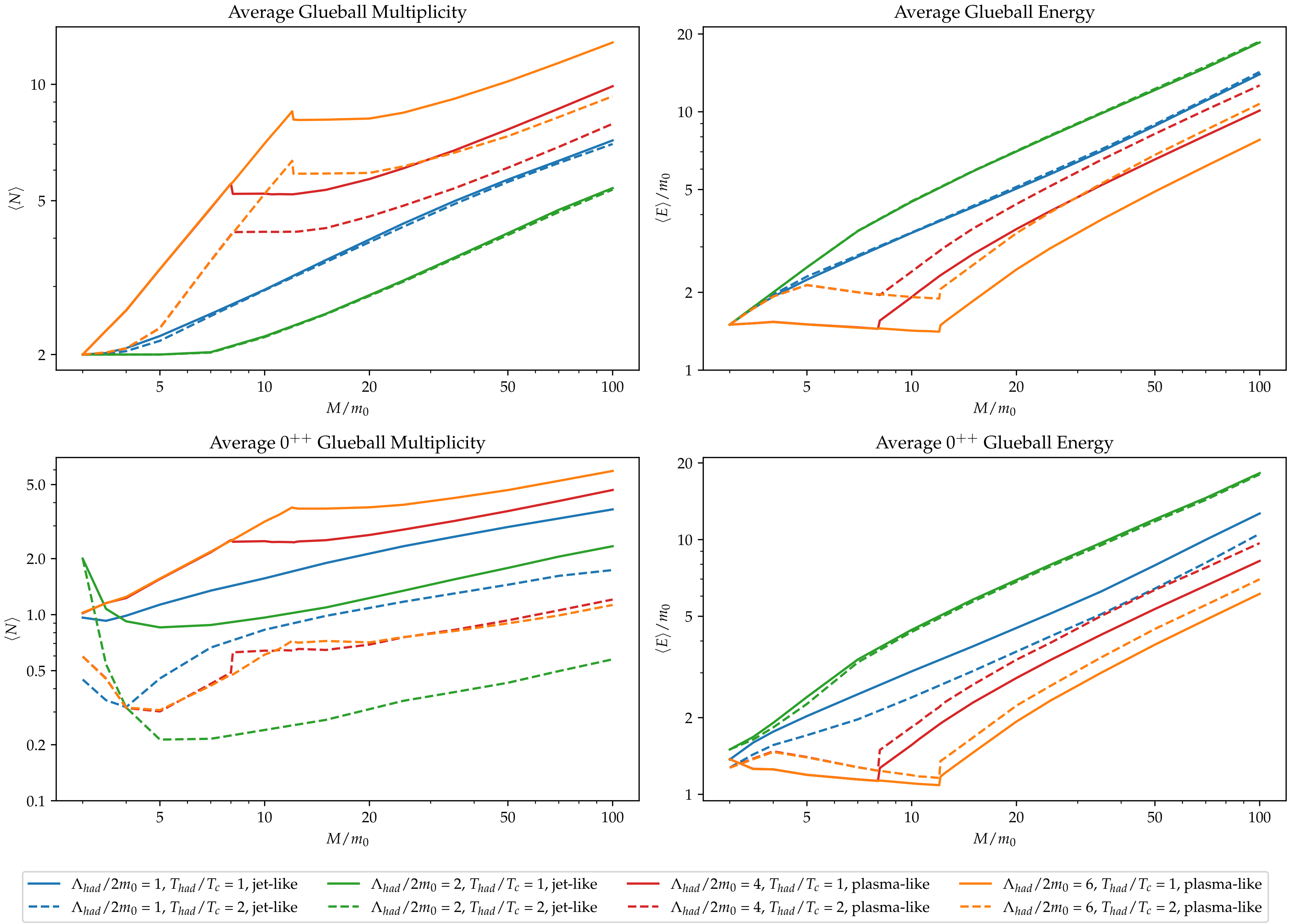
$N_c = 3$
$\langle N \rangle$
M/m_0
10
5
2
5
10
20
50
100
$\Lambda_{had}/2m_0 = 1$, $T_{had}/T_c = 1$, jet-like
$\Lambda_{had}/2m_0 = 4$, $T_{had}/T_c = 1$, plasma-like
Analytical



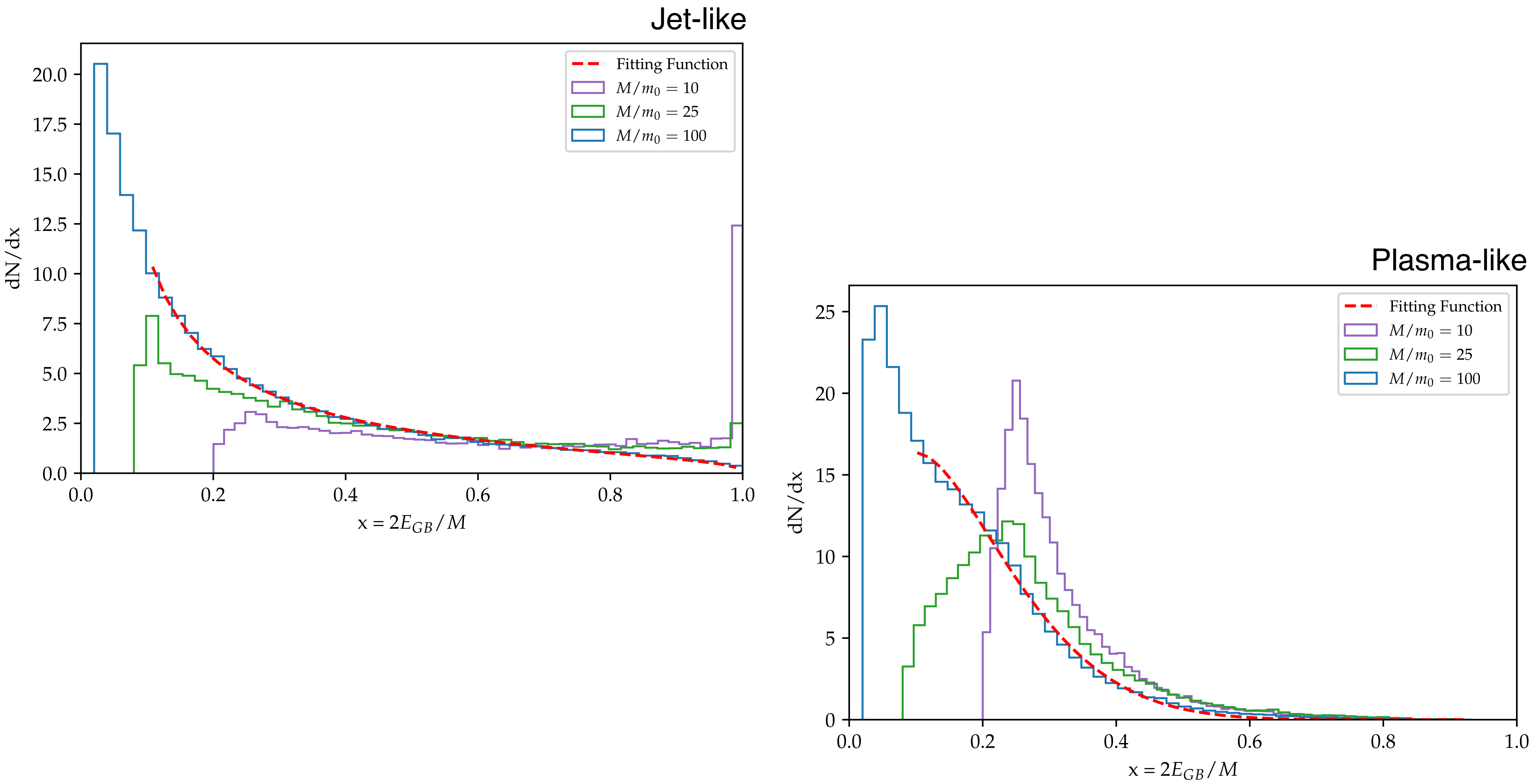
Jet-like
dN/dE
E (GeV)
0^{++}
2^{++}
0^{-+}
1^{+-}
2^{-+}
3^{+-}
3^{++}
1^{--}
2^{--}
2^{+-}

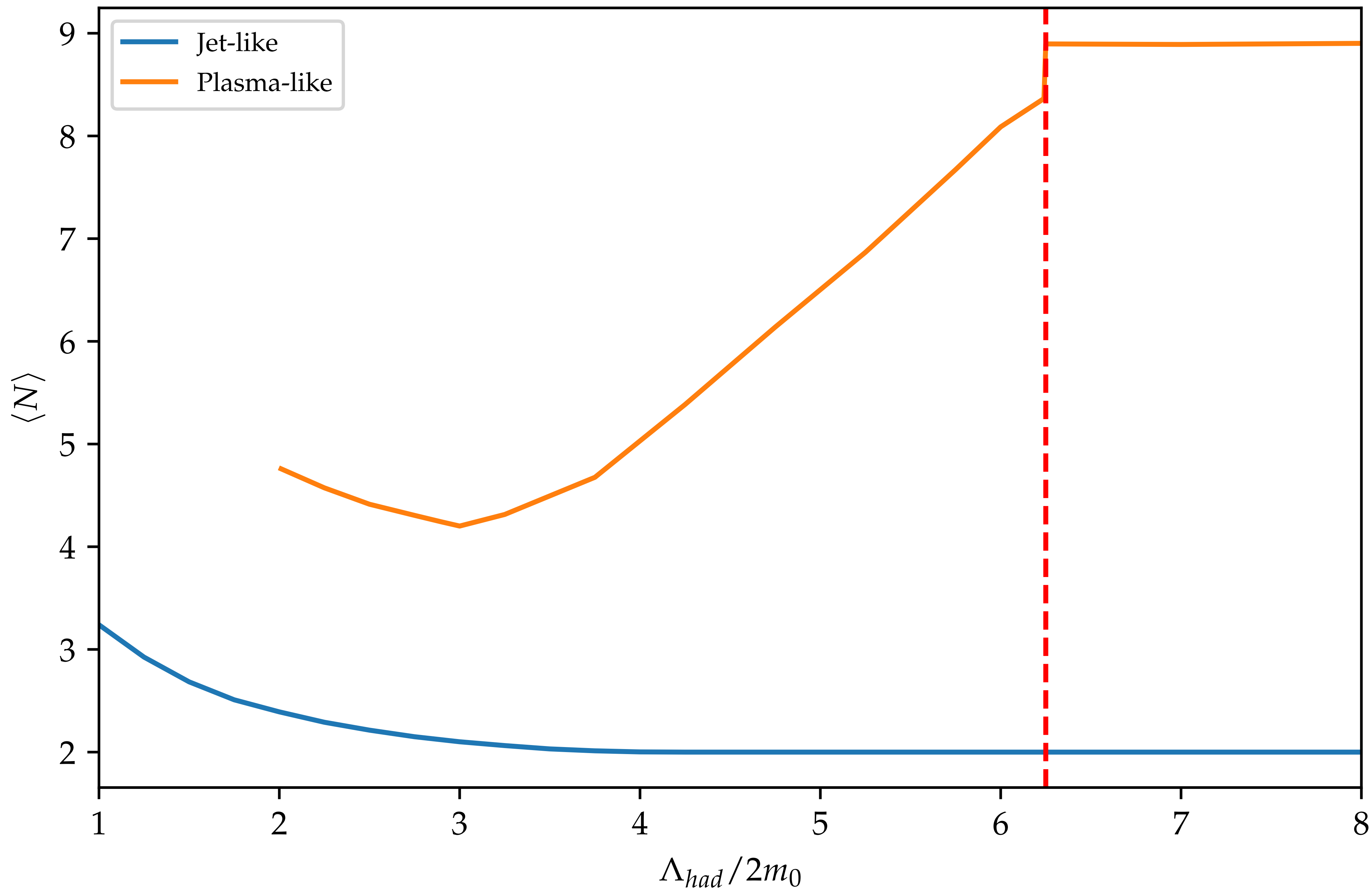


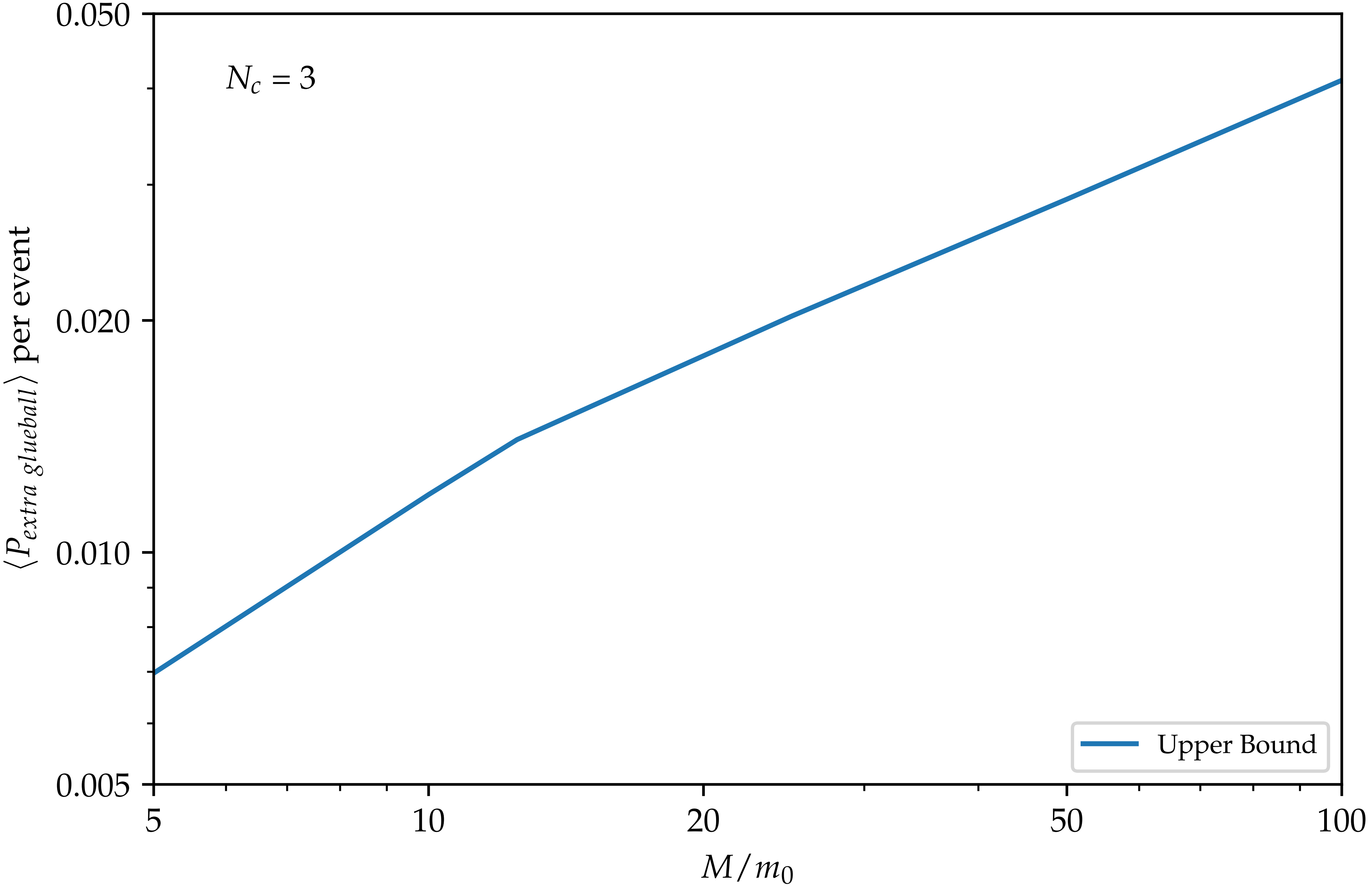
Plasma-like
dN/dE
E (GeV)
0^{++}
2^{++}
0^{-+}
1^{+-}
2^{-+}
3^{+-}
3^{++}
1^{--}
2^{--}
2^{+-}



- 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
Fitting Function
$M/m_0 = 10$
$M/m_0 = 25$
$M/m_0 = 100$
dN/dx
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
0.0
0.2
0.4
0.6
0.8
1.0
$x = 2E_{GB}/M$
Plasma-like
Fitting Function
$M/m_0 = 10$
$M/m_0 = 25$
$M/m_0 = 100$
dN/dx
0
5
10
15
20
25
0.0
0.2
0.4
0.6
0.8
1.0
$x = 2E_{GB}/M$


Jet-like
Plasma-like
9
8
7
6
5
4
3
2
$\langle N \rangle$
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