Image credit:
Deep Lens Survey

Simulation and Signatures of Dark Sector Glueball Showers

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Work discussed:

arXiv: 2202.12899 (with D. Curtin, C.B. Verhaaren)
arXiv: 2211.05794 (with D. Curtin)
arXiv: 2310.13731 (with A. Batz, T. Cohen, D. Curtin, G.D. Kribs)

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UNIVERSITY OF TORONTO

Overview:

1. Dark Sector Glueballs:
   - Background and Motivation
   - Decay Portals and Production
2. Simulating Dark Glueball Hadronization
3. Phenomenology
   - Collider Signatures
   - Indirect Detection
4. Conclusions

Dark Sector Glueballs: Background and Motivation

Dark Sector Glueballs

- Consider an extension of the Standard Model, a new dark SU(N)

- In the $N_f = 0$ limit, the only hadrons that form below the confinement scale, Λ, are ‘dark sector’ glueballs

    - Similarly the case when all quark masses are above the confinement scale

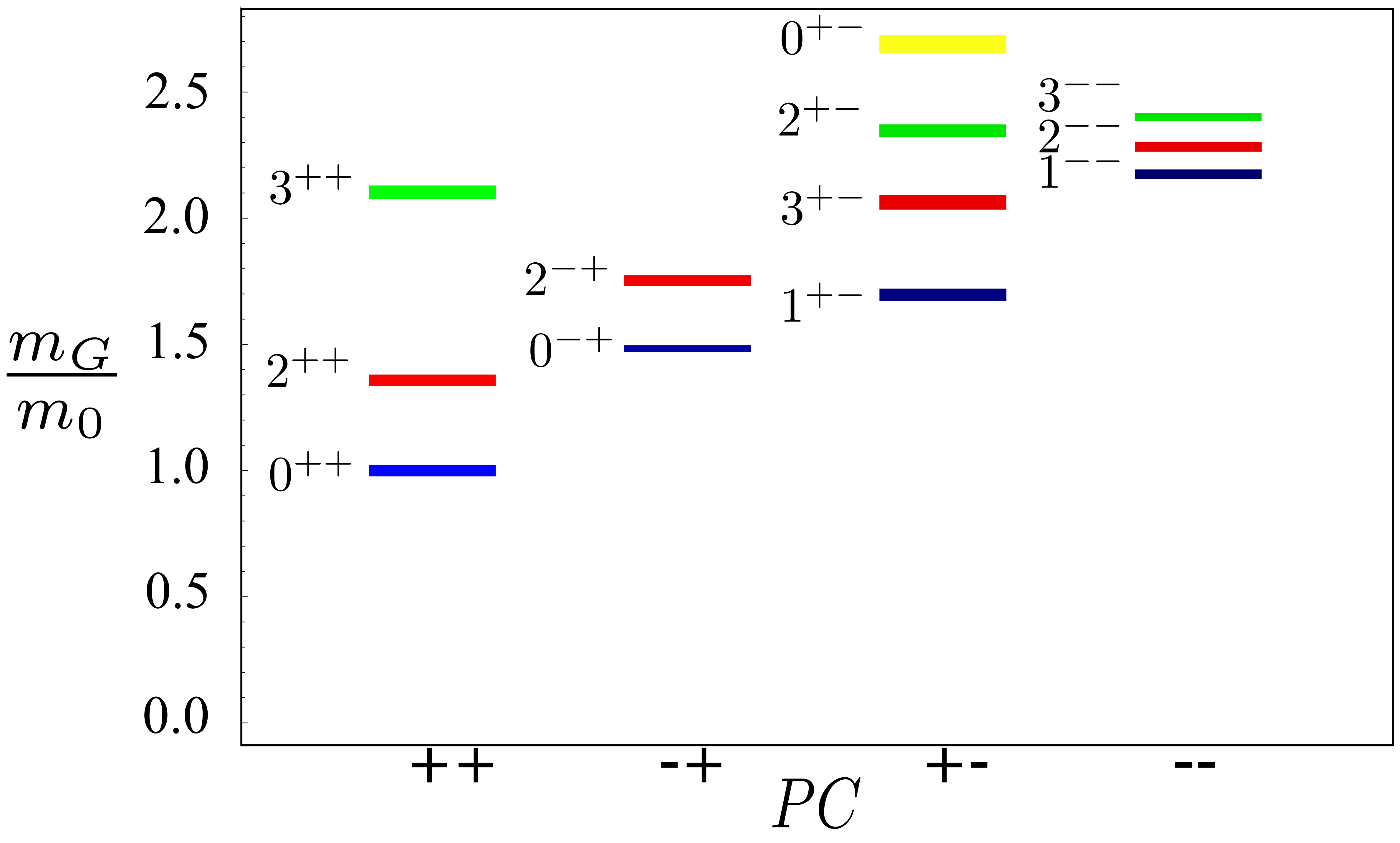
Dark Sector Glueballs

- **Majority of knowledge comes from lattice QCD studies** Morningstar, Peardon, arXiv: hep-lat/9901004
  Chen et al., arXiv: hep-lat/0510074
  Athenodorou, Teper, arXiv:2106.00364

- **Spectrum of 12 (stable) states**

- **Masses parameterised by the confinement scale,**
  $m_0 \sim 6\Lambda >> \Lambda$

Juknevich, arXiv: 0911.5616



Theory Motivation

- **Why extend the SM with a new SU(3) gauge group?**

Strassler, Zurek, arXiv: hep-ph/0604261

- **Generic example of a confining dark sector**

Burdman, Chacko, Goh, Harnik, arXiv: hep-ph/0609152

  - **Specific examples: Twin Higgs, Folded SUSY, many more…**

Chacko, Goh, Harnik, arXiv: hep-ph/0506256

- **Such theories of neutral naturalness provide solutions to the (little) Hierarchy Problem**

Poland, Thaler, arXiv: 0808.1290

Cai, Chen, Terning, arXiv: 0812.0843

Craig, Katz, Strassler, Sundrum, arXiv: 1501.05310

Cohen, Craig, Lou, Pinner, arXiv: 1508.05396

Cohen, Craig, Guidice, McCullough, arXiv: 1803.03647

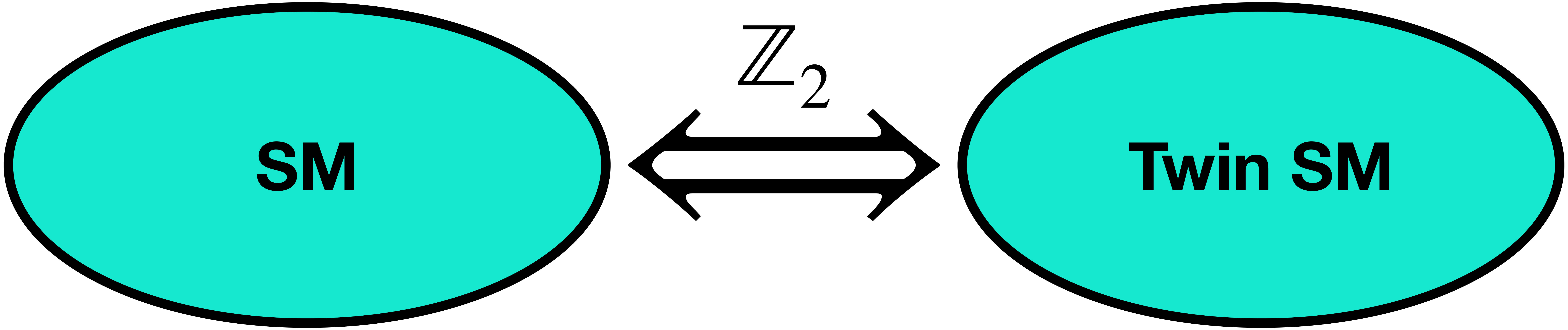
Neutral Naturalness

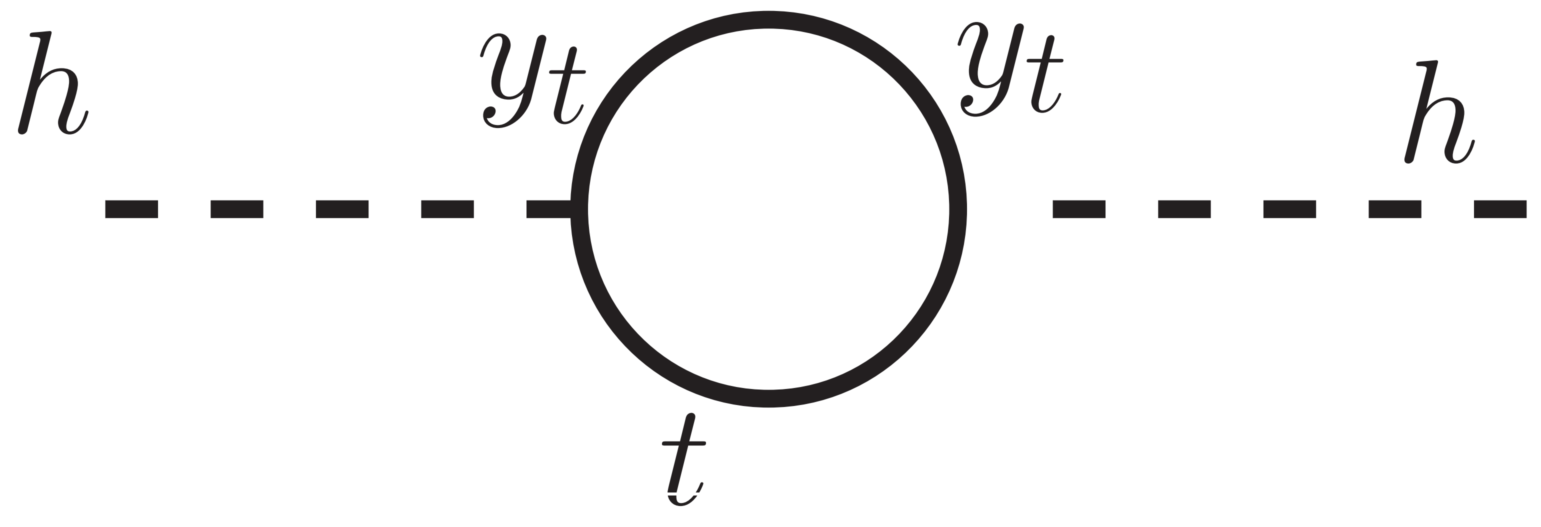
- Original solutions to the Hierarchy problem (e.g. SUSY, composite Higgs) lead to coloured states expected at the TeV scale
- Neutral naturalness theories protect the Higgs mass with a new discrete symmetry, with additional SM colour neutral (or dark/twin) fields
- Lack of evidence of coloured states at the LHC increased motivation for neutral naturalness models:

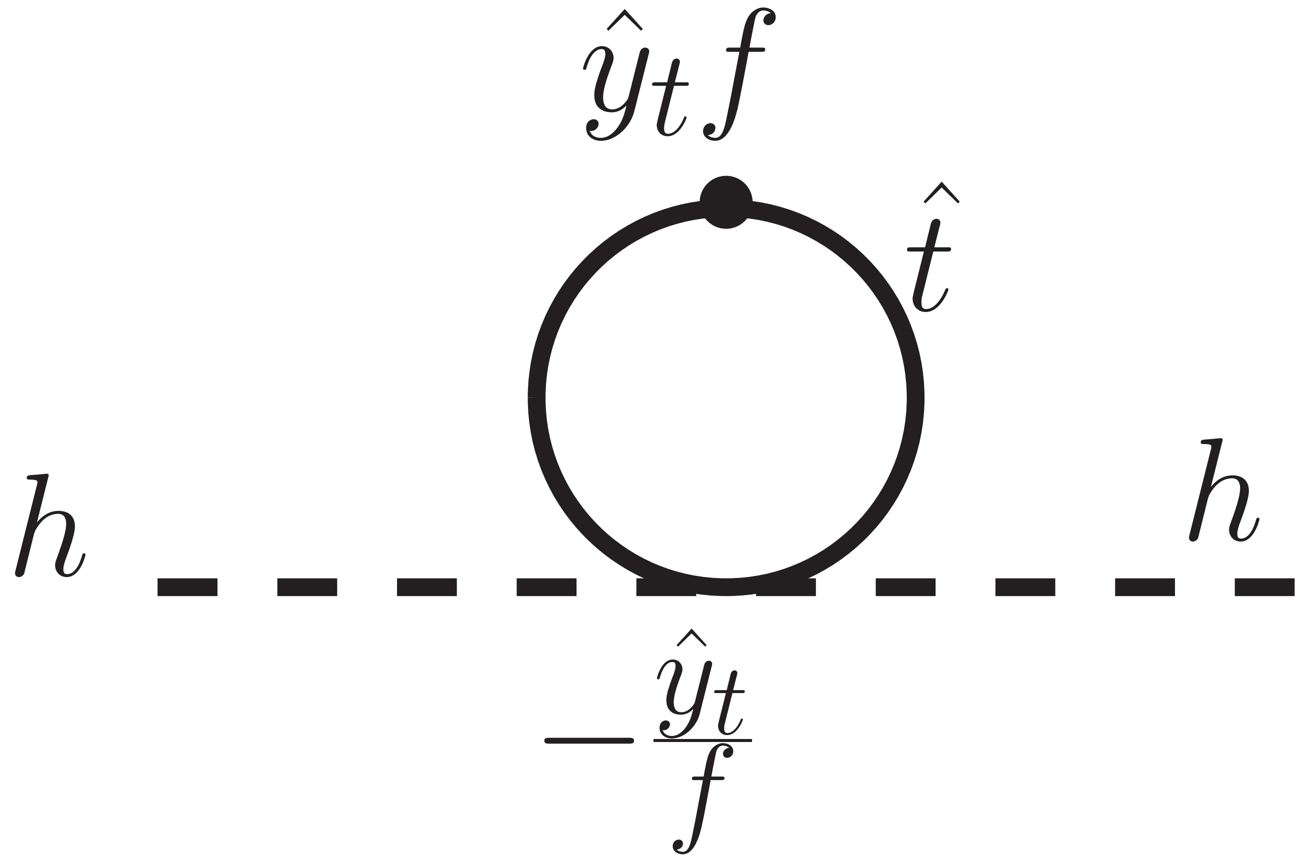
    A. Protect the Higgs mass at the TeV scale

    B. Avoided the new LHC collider constraints

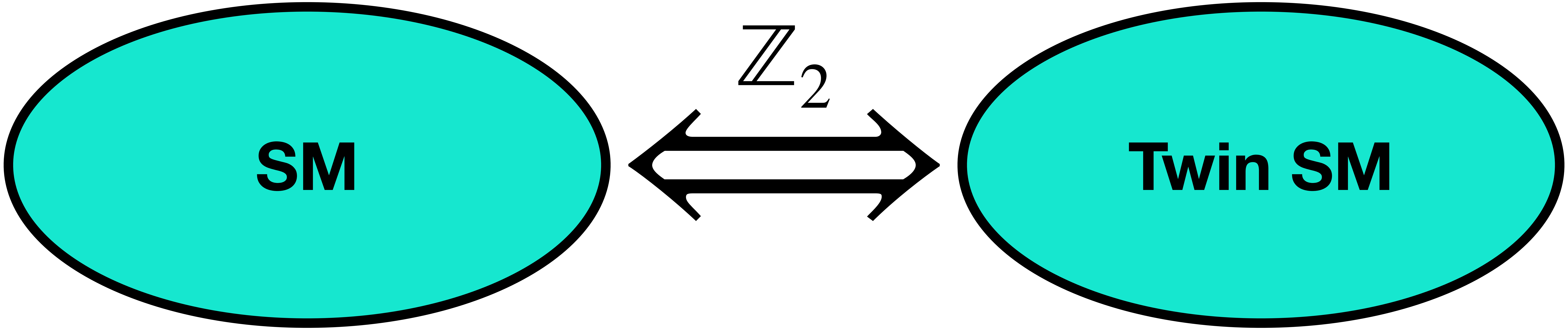
Twin Higgs



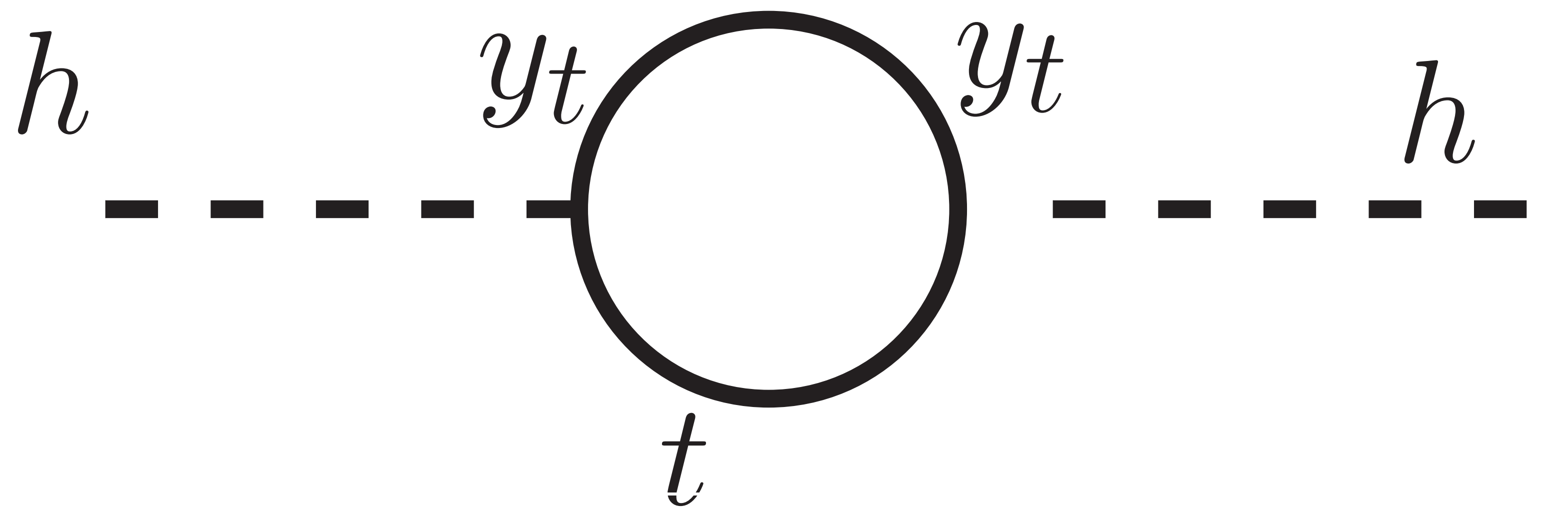


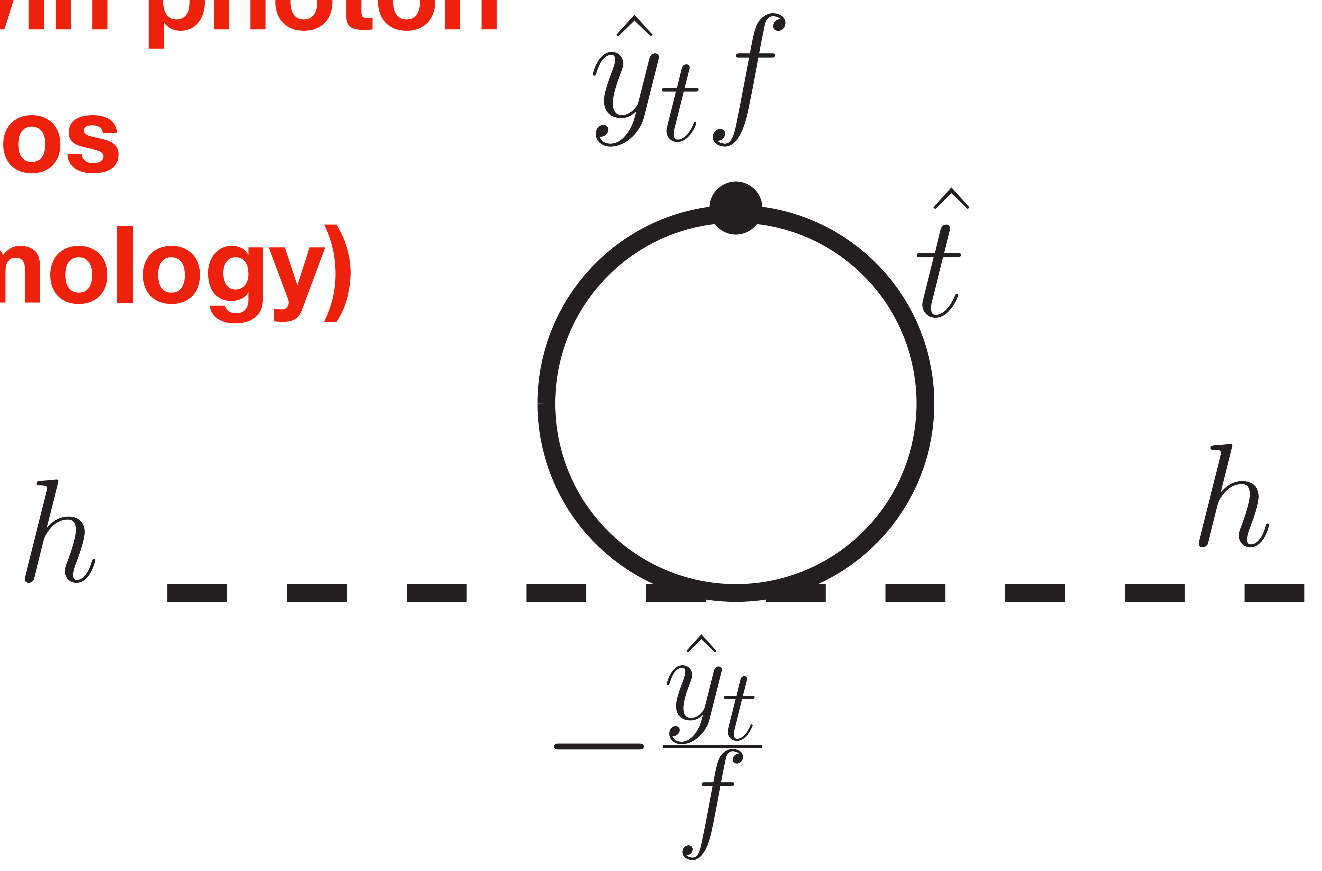


Twin Higgs

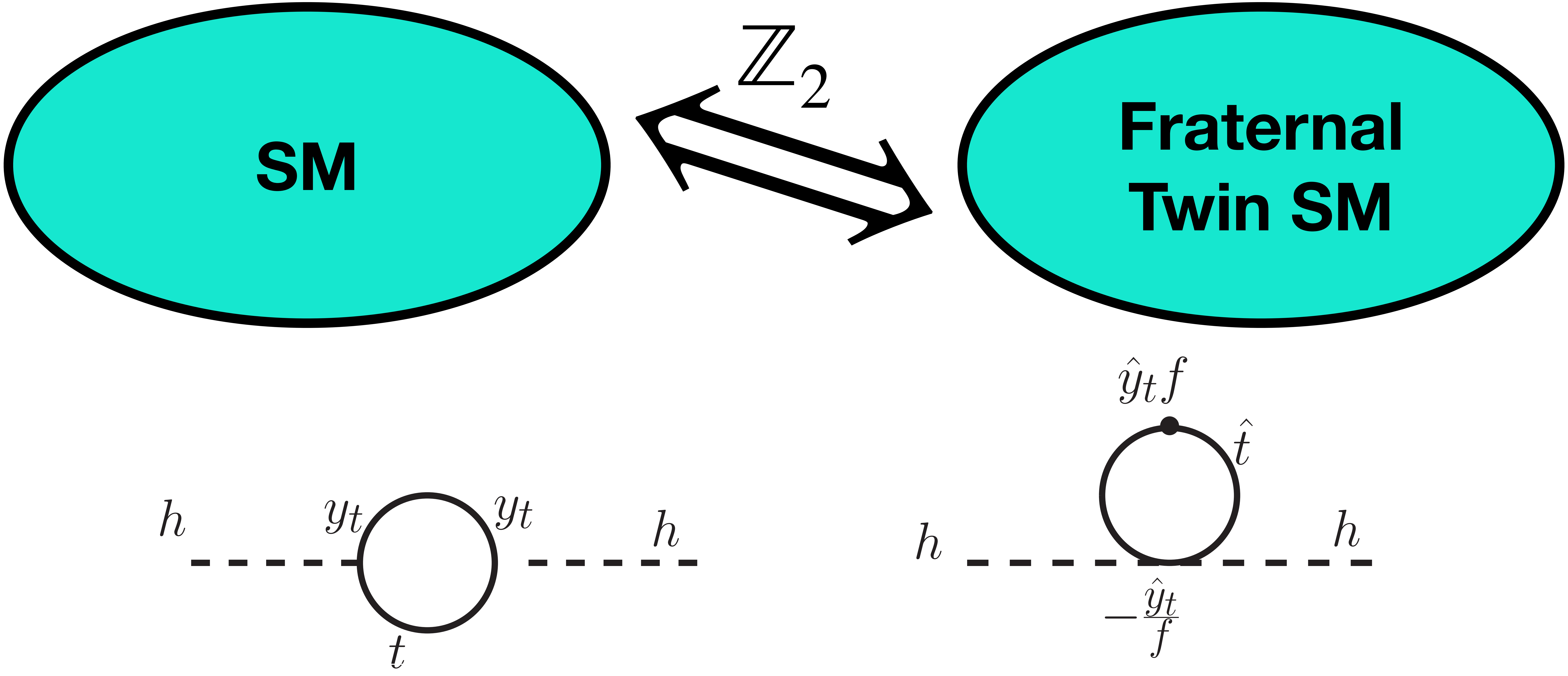


...but $\Delta N_{\text{eff}} \sim 5$ from twin photon
+ 3 twin neutrinos
(constrained by cosmology)





(Fraternal) Twin Higgs



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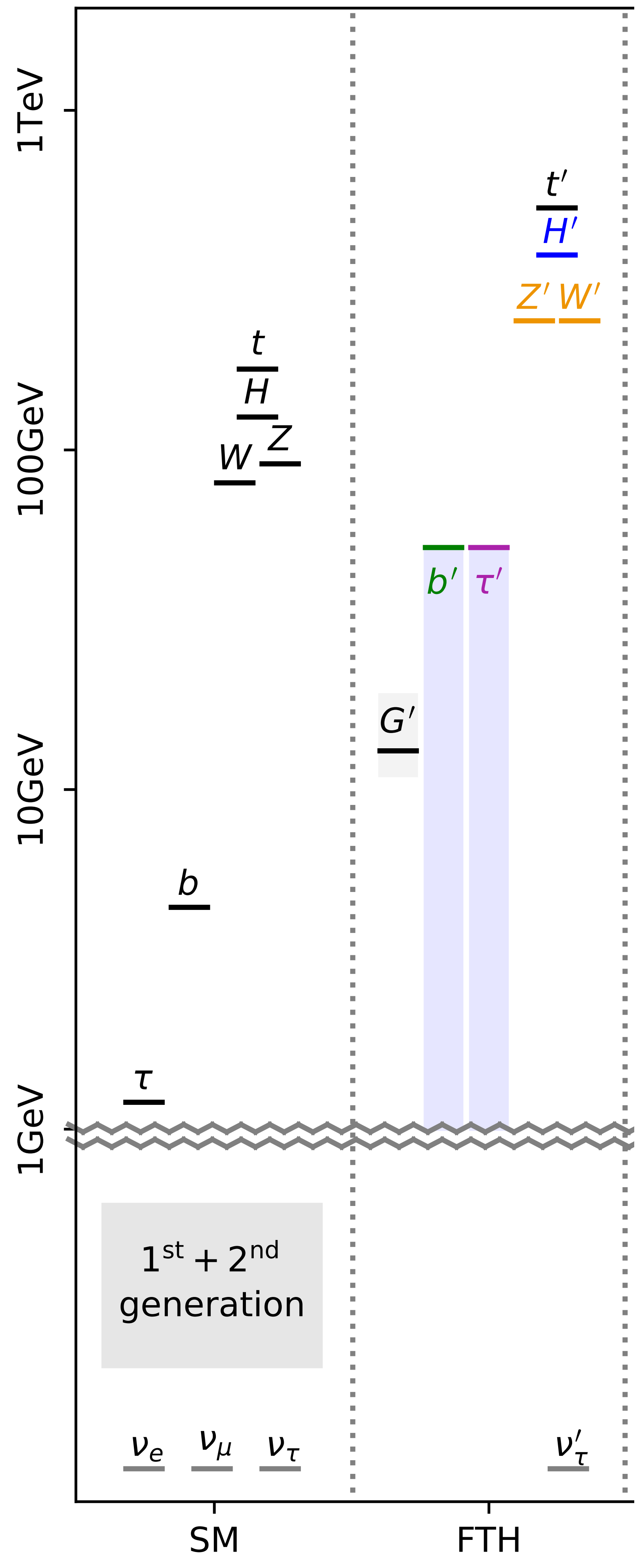

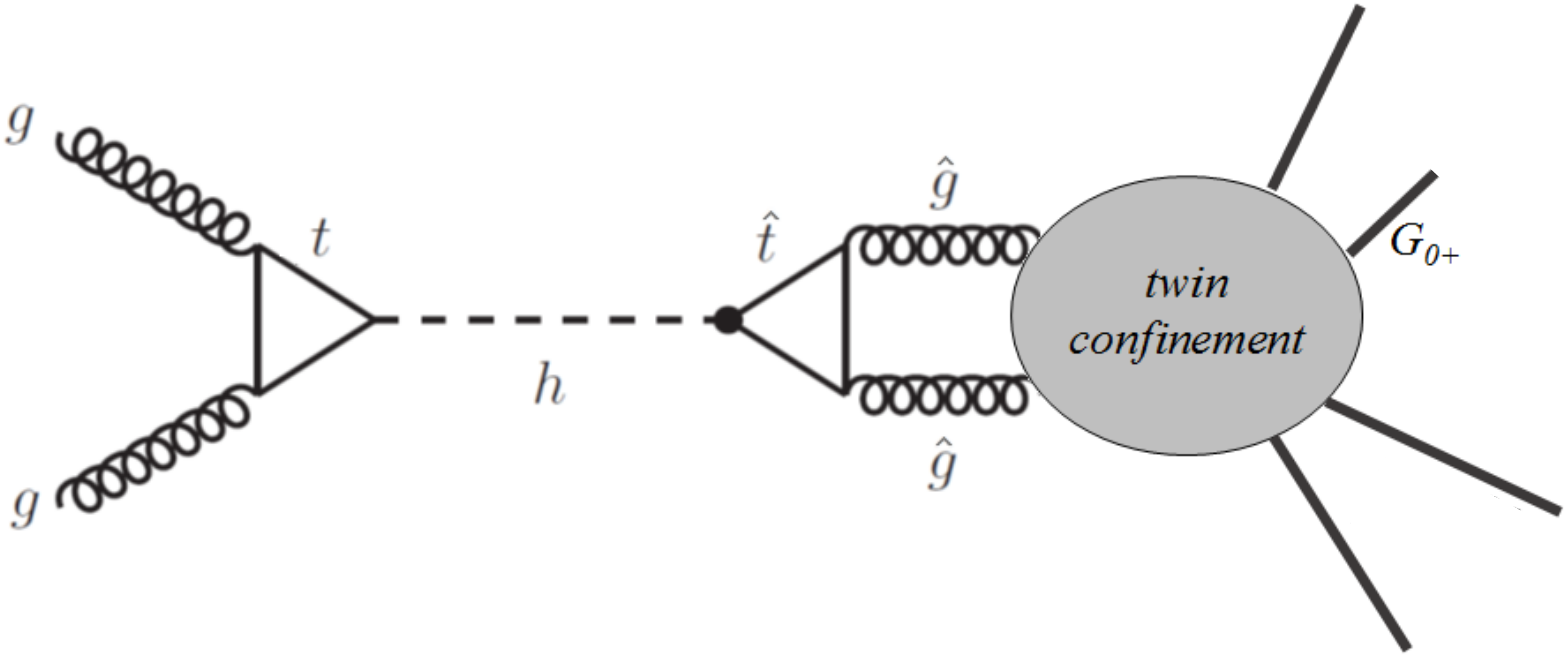

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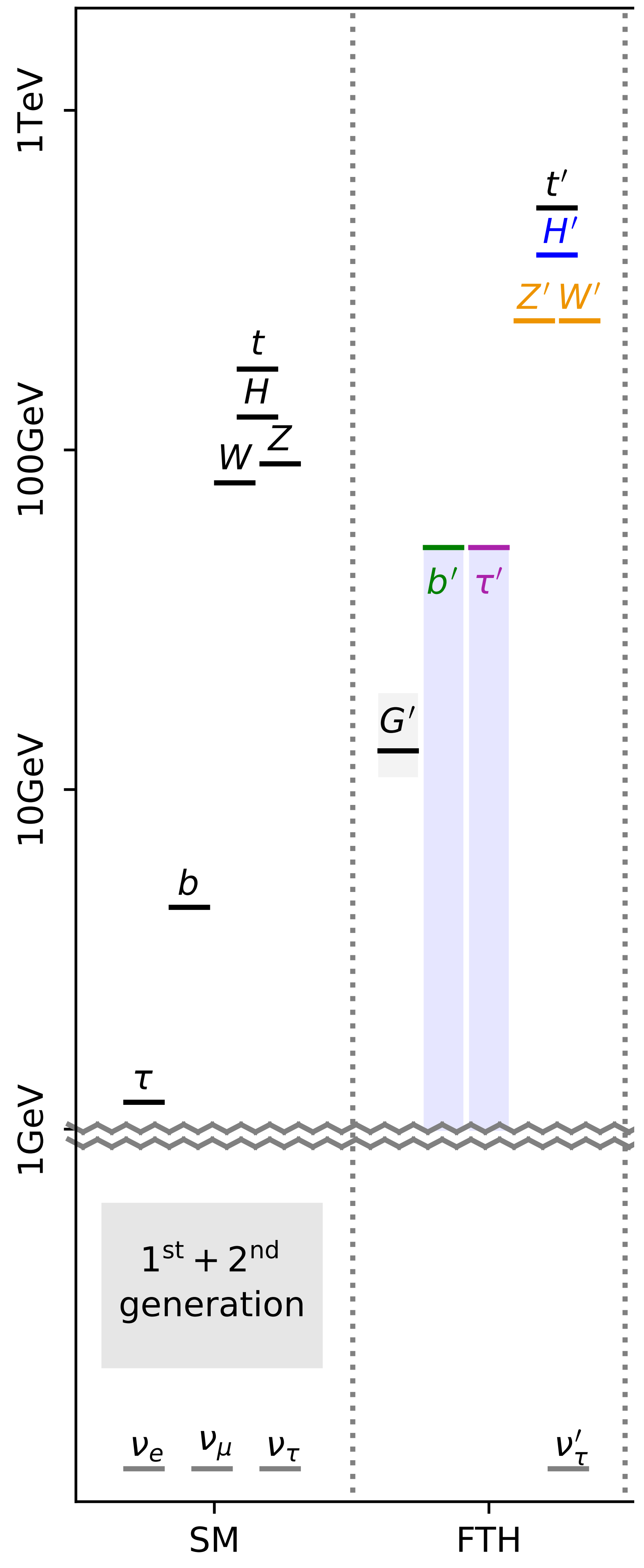
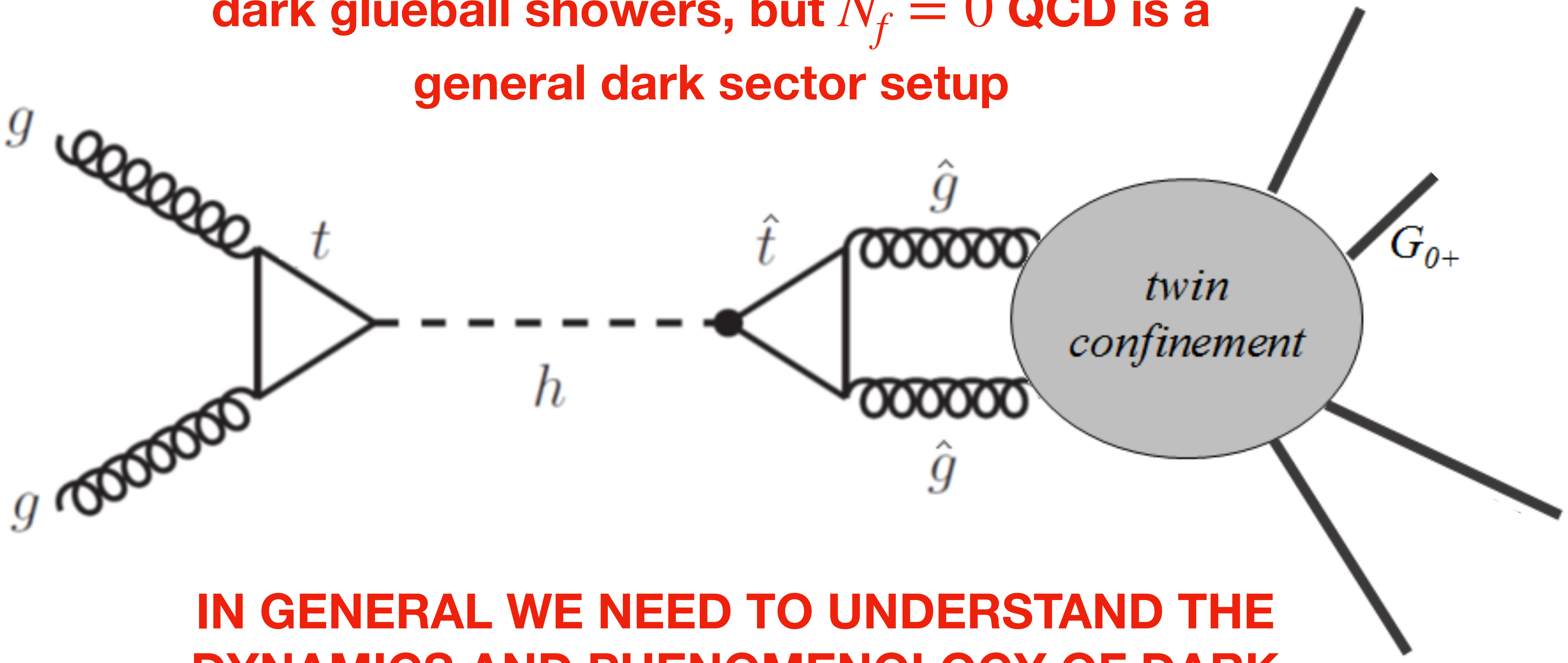


FTH is just one realisation that motivates studying dark glueball showers, but $N_f = 0$ QCD is a general dark sector setup

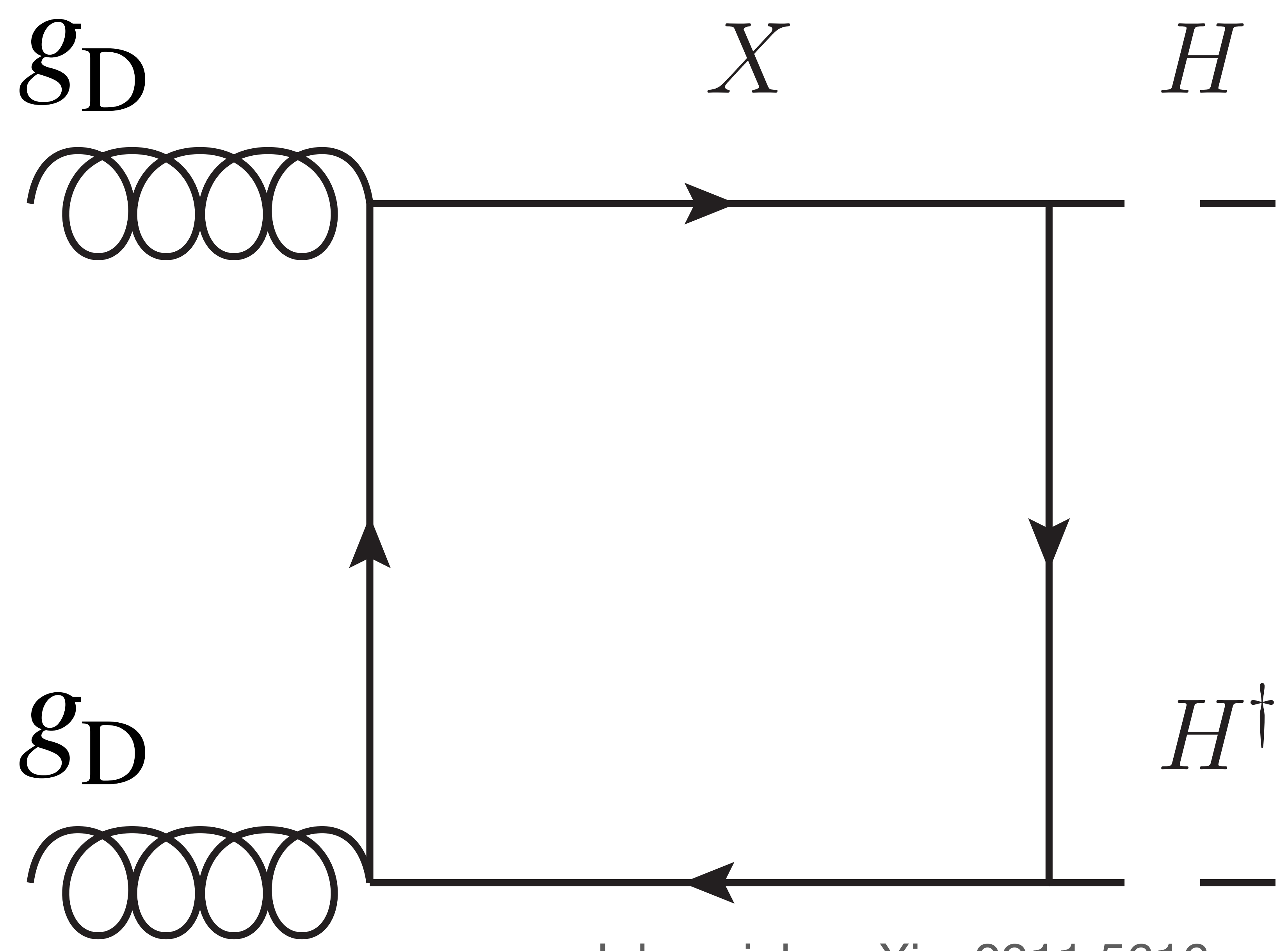


IN GENERAL WE NEED TO UNDERSTAND THE DYNAMICS AND PHENOMENOLOGY OF DARK SECTOR GLUEBALL PRODUCTION

Dark Sector Glueballs: Decay Portals and Production

Decay Portals

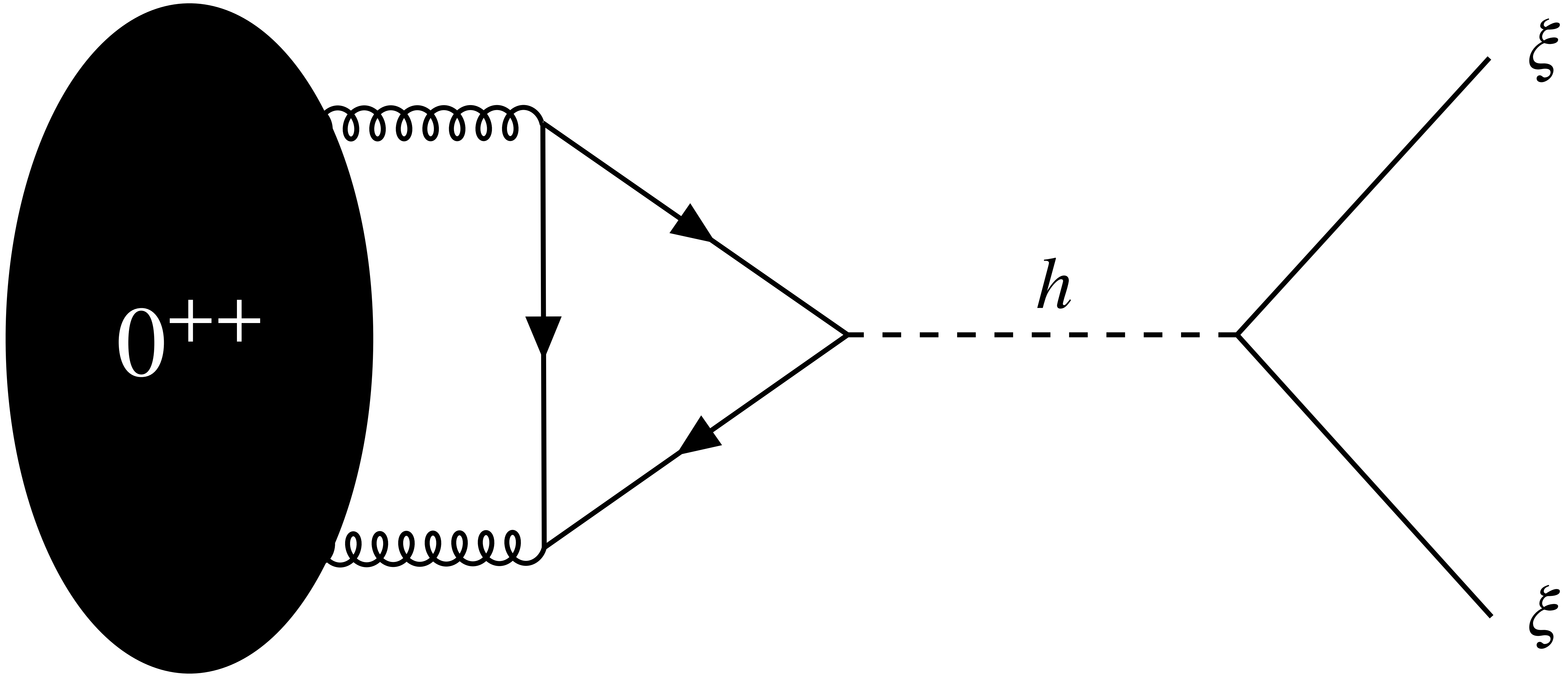
- **Assume dark quarks couple to the SM Higgs**
- **Dark sector glueballs able to decay via heavy quarks running in loop**
- **Integrate out to get an effective dimension 6 operator**



Juknevich, arXiv: 0911.5616

$$\mathscr{L}^{(6)} = \frac{\alpha_D}{3\pi}\frac{y^2}{M^2}H^\dagger H G_D^{\mu\nu} G_{D,\mu\nu}$$

Decay Portals

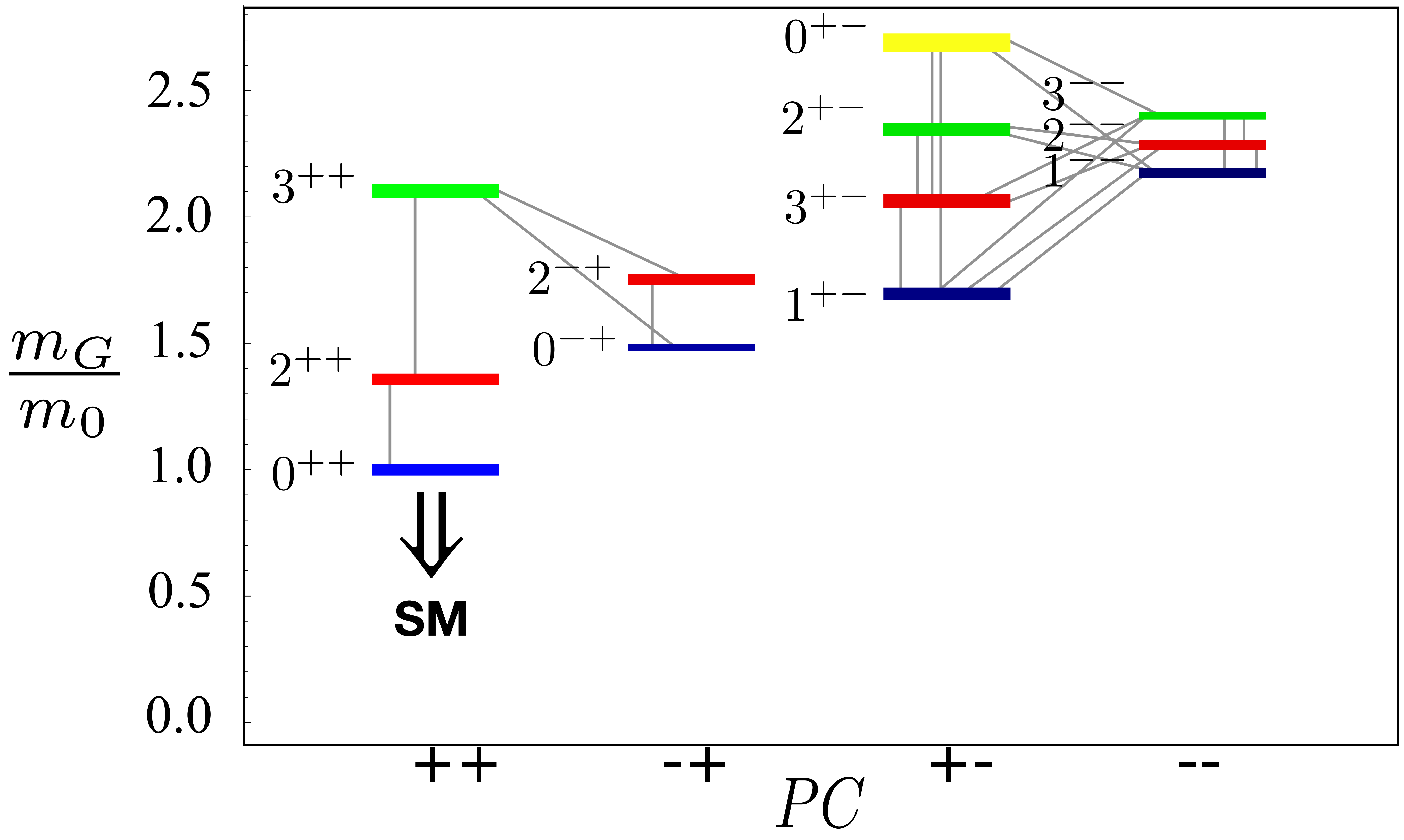


$$\Gamma_{0^{++}\to\xi\xi} = \frac{y^4}{M^4}\left(\frac{v_H \alpha_D \mathbf{F}_{\mathbf{0}^{++}}}{3\pi(m_H^2 - m_0^2)}\right)^2 \Gamma^{SM}_{h\to\xi\xi}$$

Non-perturbative decay constant
(comes from lattice studies)

$$\mathbf{F}_{\mathbf{0}^{++}} \sim m_0^3$$

Decay Portals



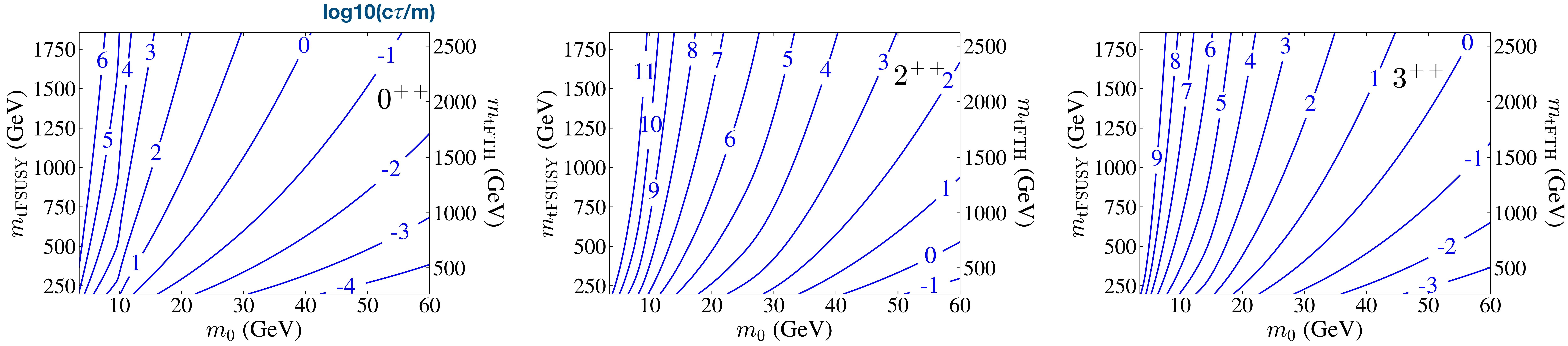
Glueball	Mass (m_0)	Higgs Portal
0^{++}	1.00	$h^* \to \mathrm{SM}, \mathrm{SM}$
2^{++}	1.40	$0^{++} + h^*$
0^{-+}	1.50	-
1^{+-}	1.75	-
2^{-+}	1.78	$0^{-+} + h^*$
3^{+-}	2.11	$1^{+-} + h^*$
3^{++}	2.15	$\{2^{++}, 0^{-+}, 2^{-+}\} + h^*$
1^{--}	2.25	$1^{+-} + h^*$
2^{--}	2.35	$\{1^{+-}, 3^{+-}, 1^{--}\} + h^*$
3^{--}	2.46	$\{1^{+-}, 3^{+-}, 1^{--}, 2^{--}\} + h^*$
2^{+-}	2.48	$\{1^{+-}, 3^{+-}, 1^{--}, 2^{--}, 3^{--}\} + h^*$
0^{+-}	2.80	$\{1^{--}, 3^{--}, 2^{+-}\} + h^*$

Decay Portals

- **Note that for most parameter space motivated by neutral naturalness, glueballs are generically long lived particles with mass 10-50 GeV**

Curtin, Verhaaren, arXiv:1506.06141

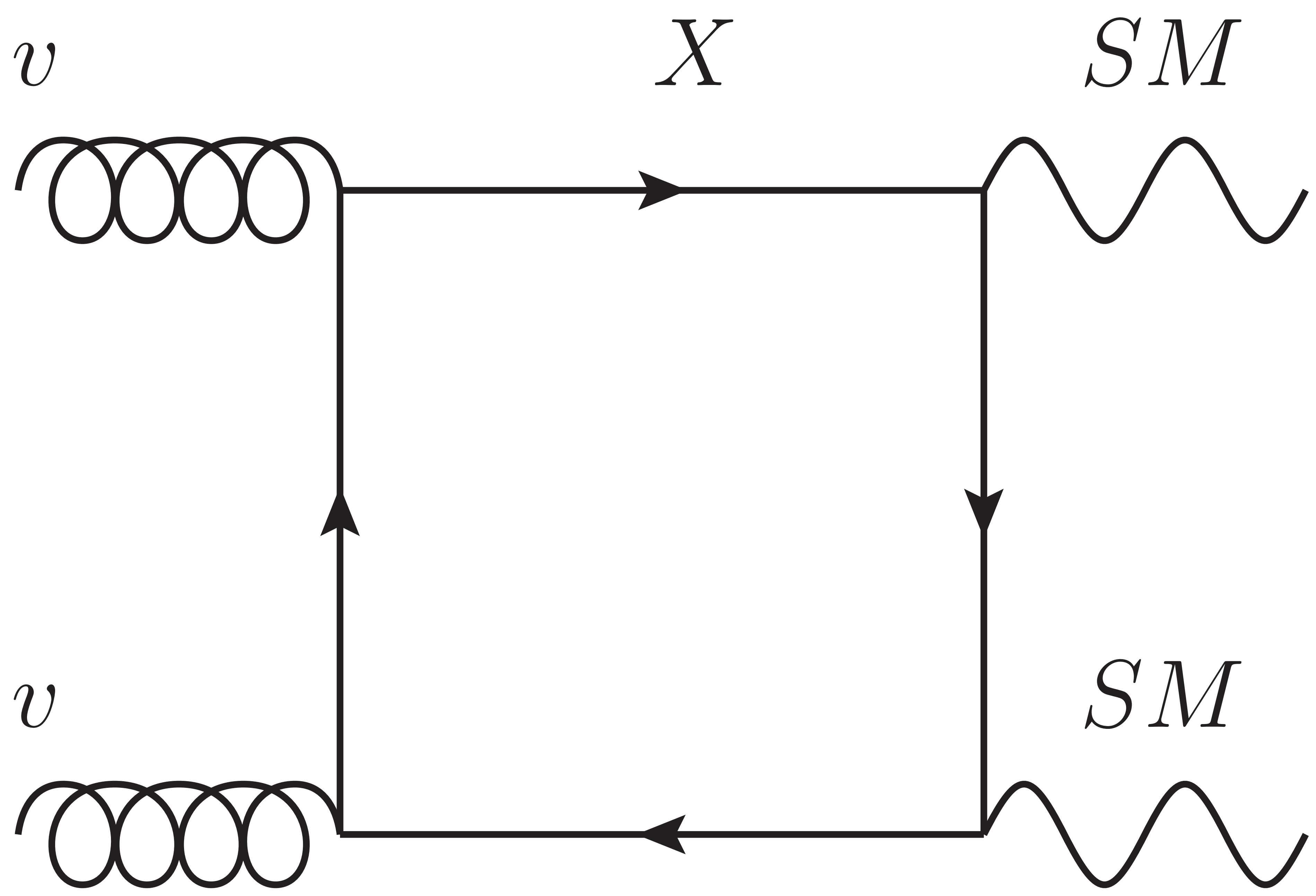
- **Additionally, across the spectrum of glueball states, lifetimes differ by orders of magnitude**



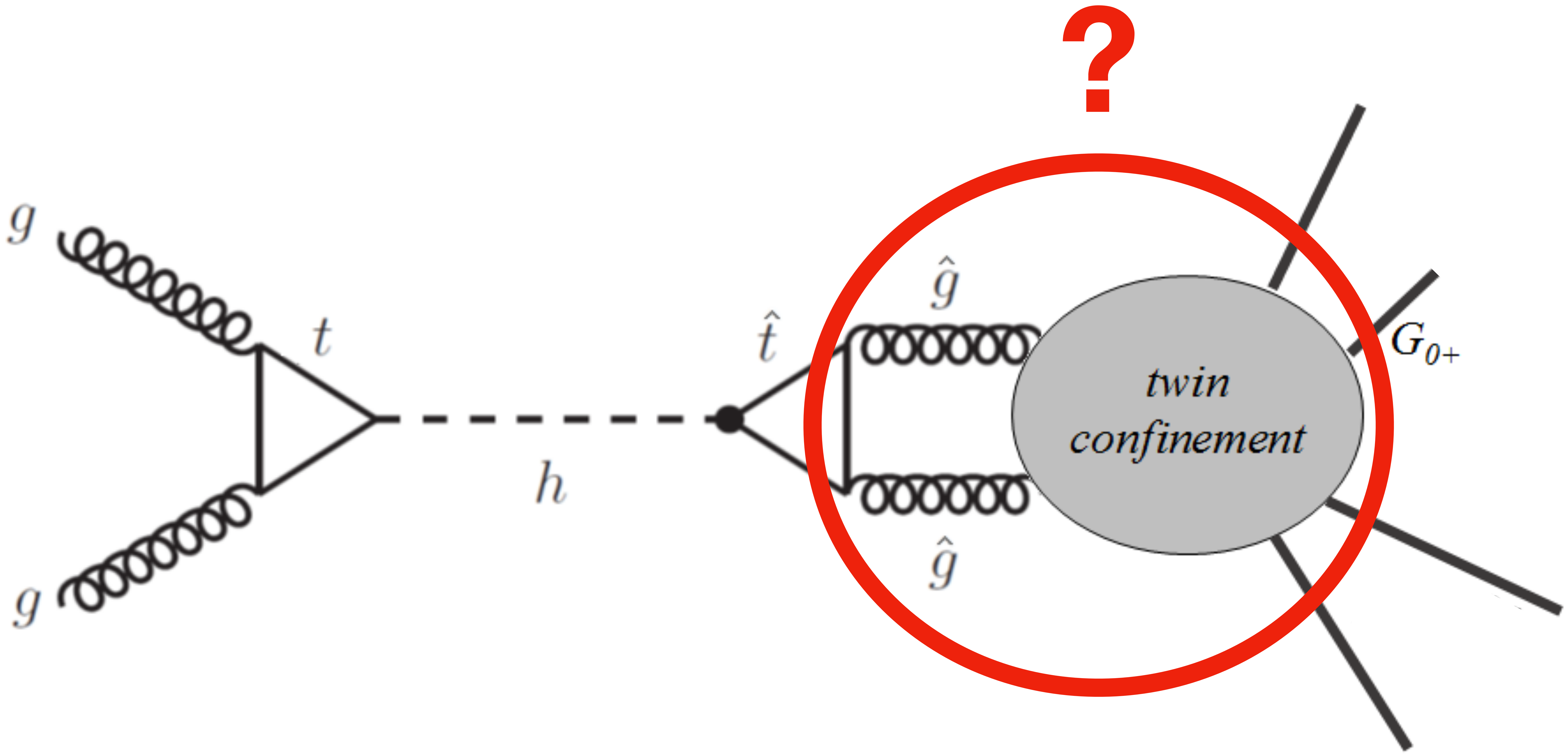
Decay Portals

- **Also possible to decay through higher dimension-8 gauge portals**
- **Requires new fields charged under SM gauge groups, stronger constraints**

Juknevich, Melnikov, Strassler, arXiv: 0903.0883
Falkowski, Juknevich, Shelton, arXiv: 0908.1790
Juknevich, arXiv: 0911.5616



Glueball production...



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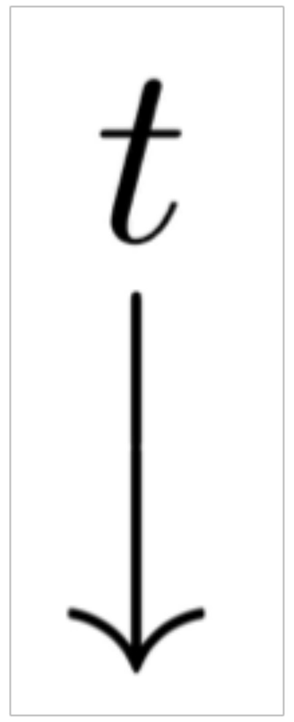
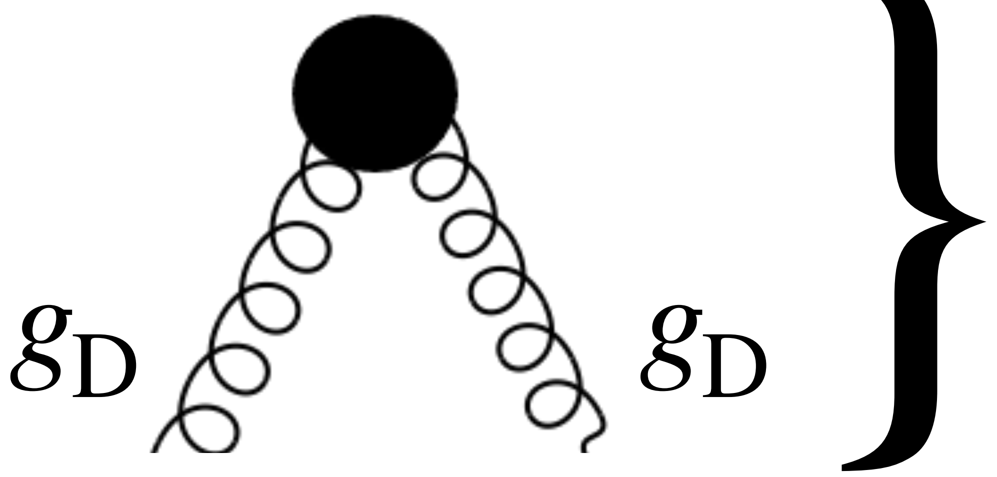
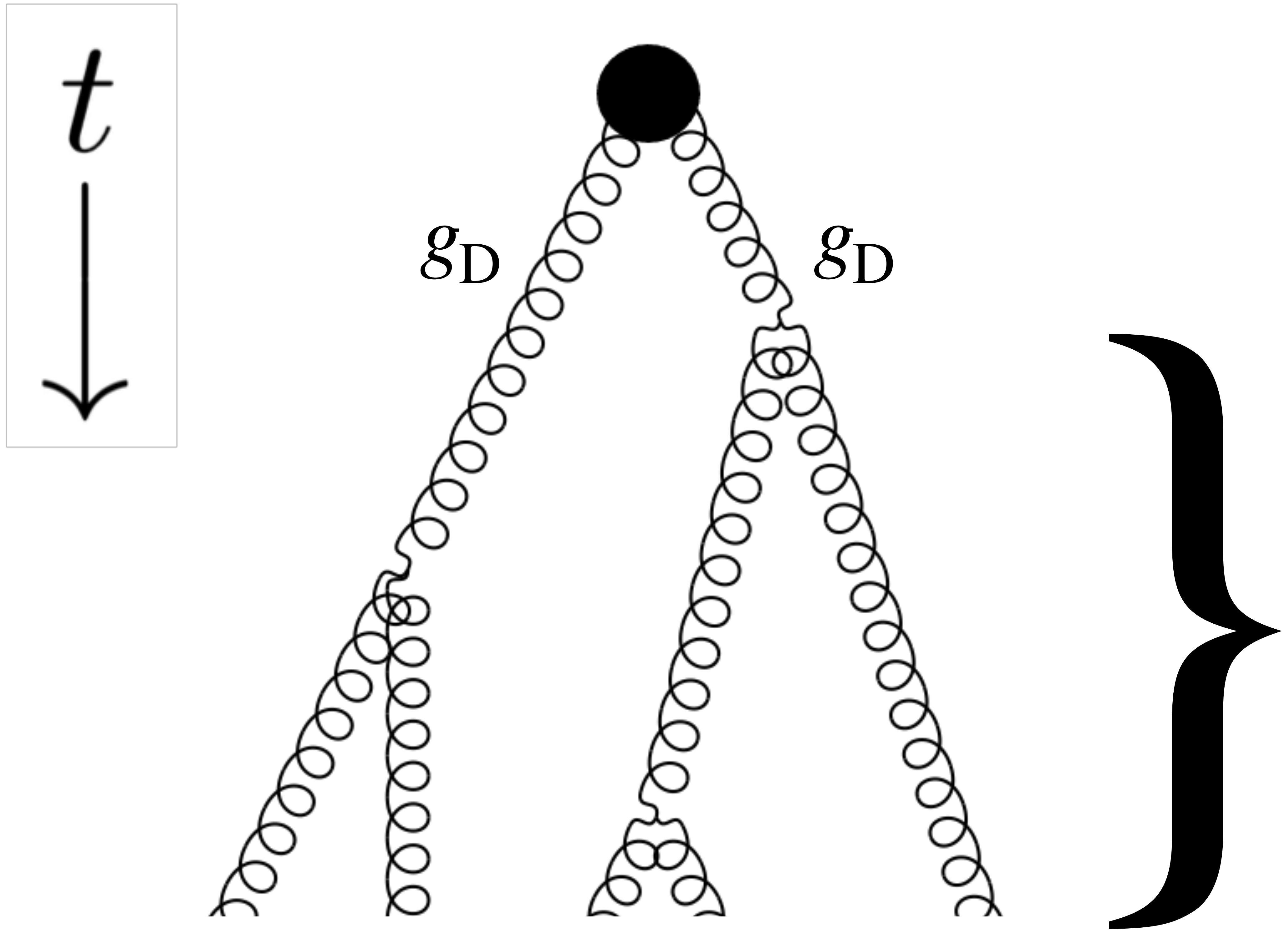




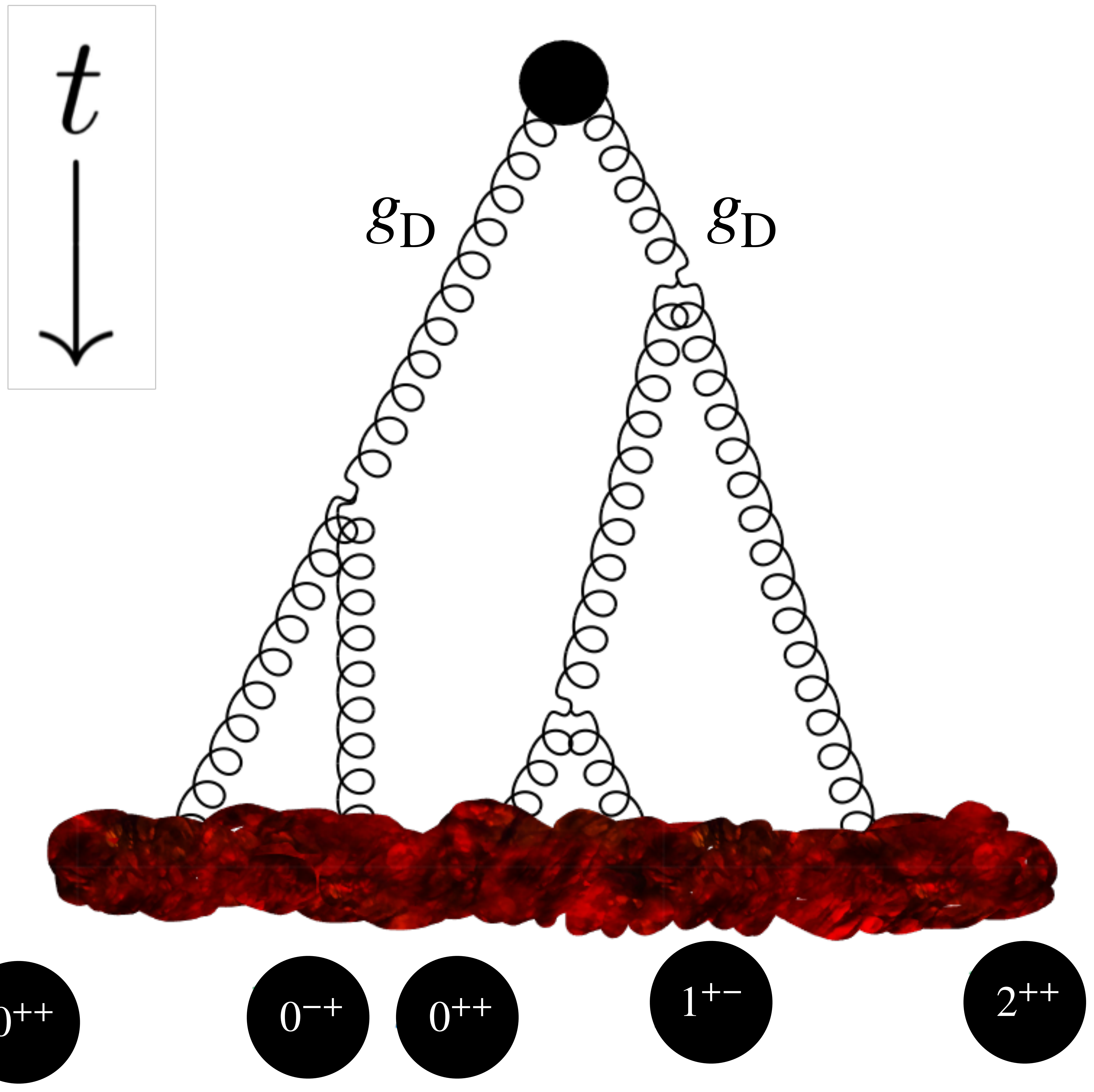
Consider some colour singlet scalar (e.g. Higgs) decaying to two dark gluons

Glueball production…



Perturbative shower

Glueball production…



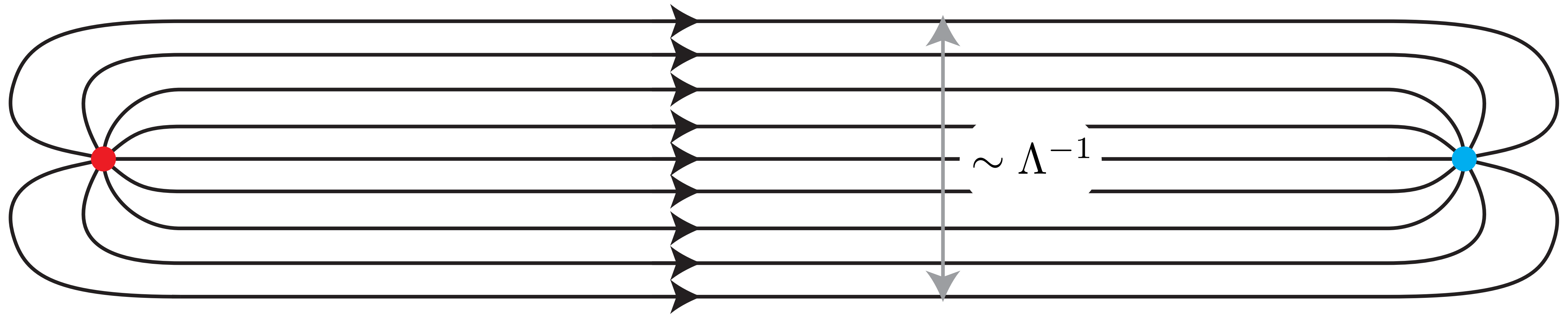
Pure Glue Hadronization ????

… then glueballs emerge

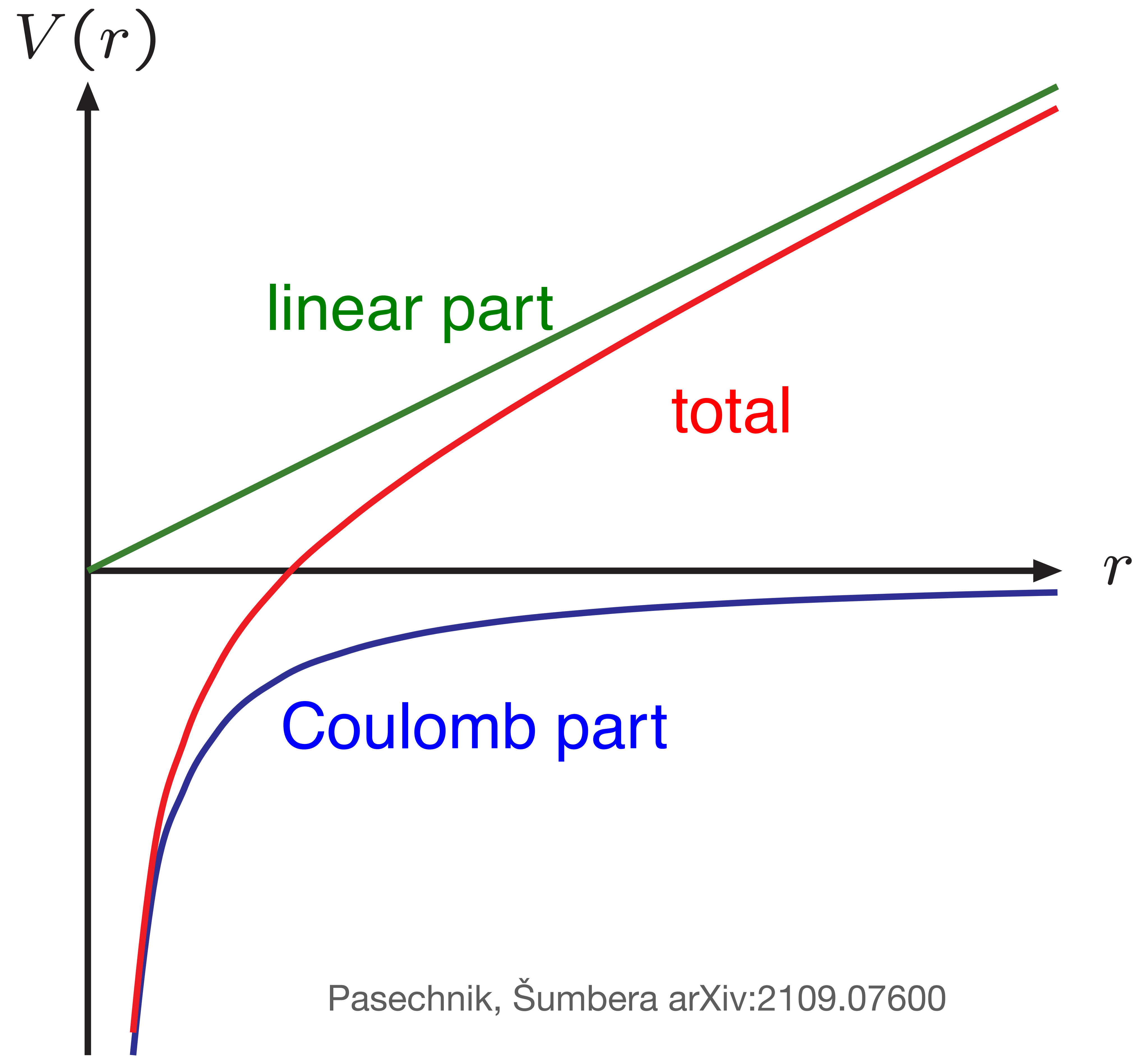
Hadronization: what do we know?

- From lattice studies we know the static inter-quark potential

- Linearly increasing potential at large distances motivates a flux tube / colour string interpretation, with some associated string tension, σ



Kang, Luty, arXiv: 0805.4642

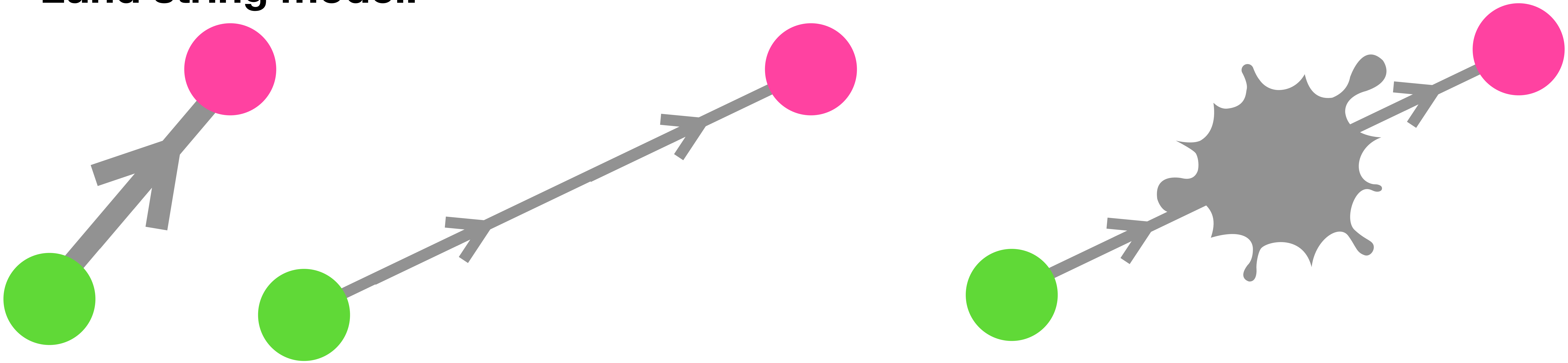


Pasechnik, Šumbera arXiv:2109.07600

Hadronization: what do we know?

Andersson, Gustafson, Ingelman, Sjöstrand, Physics Reports 97, 31 (1983)

- **Lund string model:**



- **In general, hadronization and the non-perturbative physics of confinement is a priori unknown**

- **In SM QCD, we have motivated phenomenological models, that we are able to tune to data**

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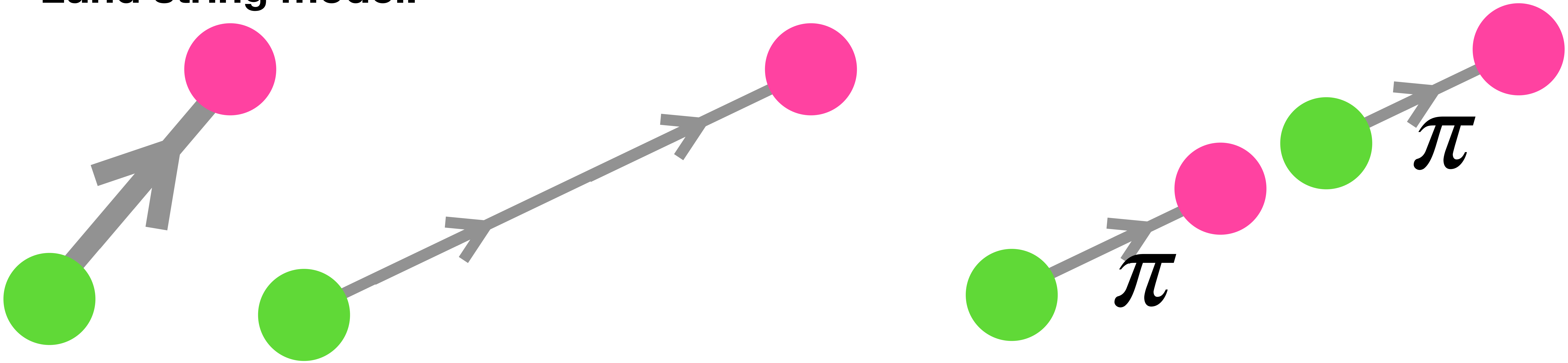

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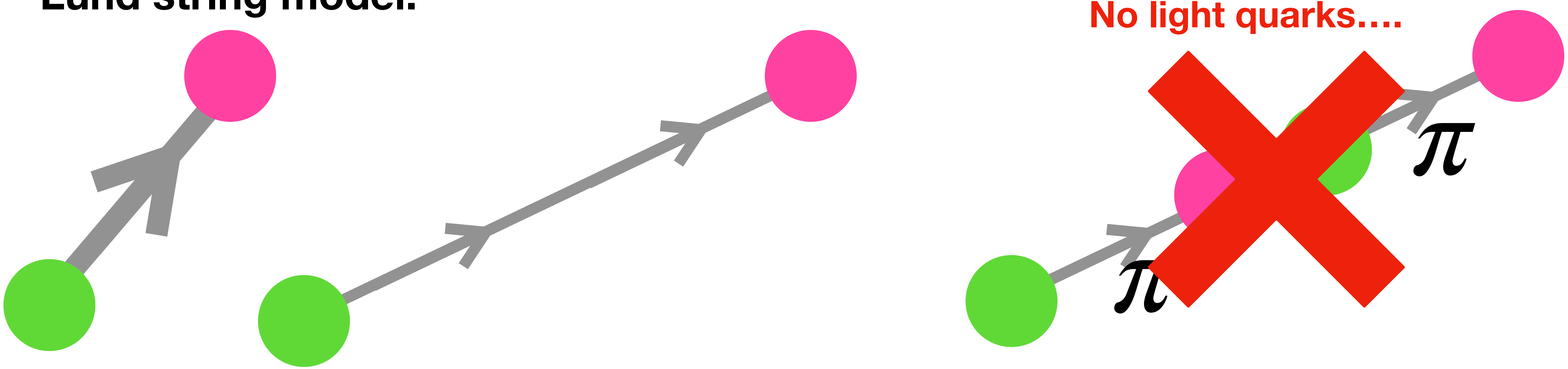
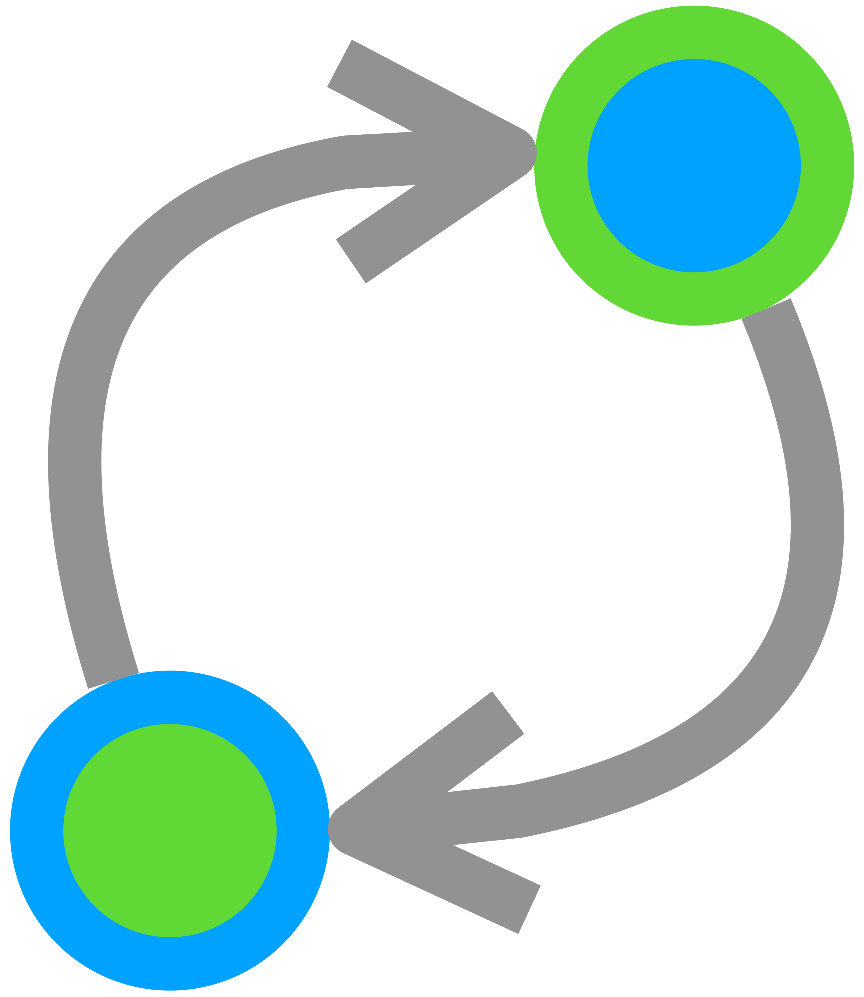


- **In general, hadronization and the non-perturbative physics of confinement is a priori unknown**

- **In SM QCD, we have motivated phenomenological models, that we are able to tu ata** No data….

Cartoon pure glue hadronization



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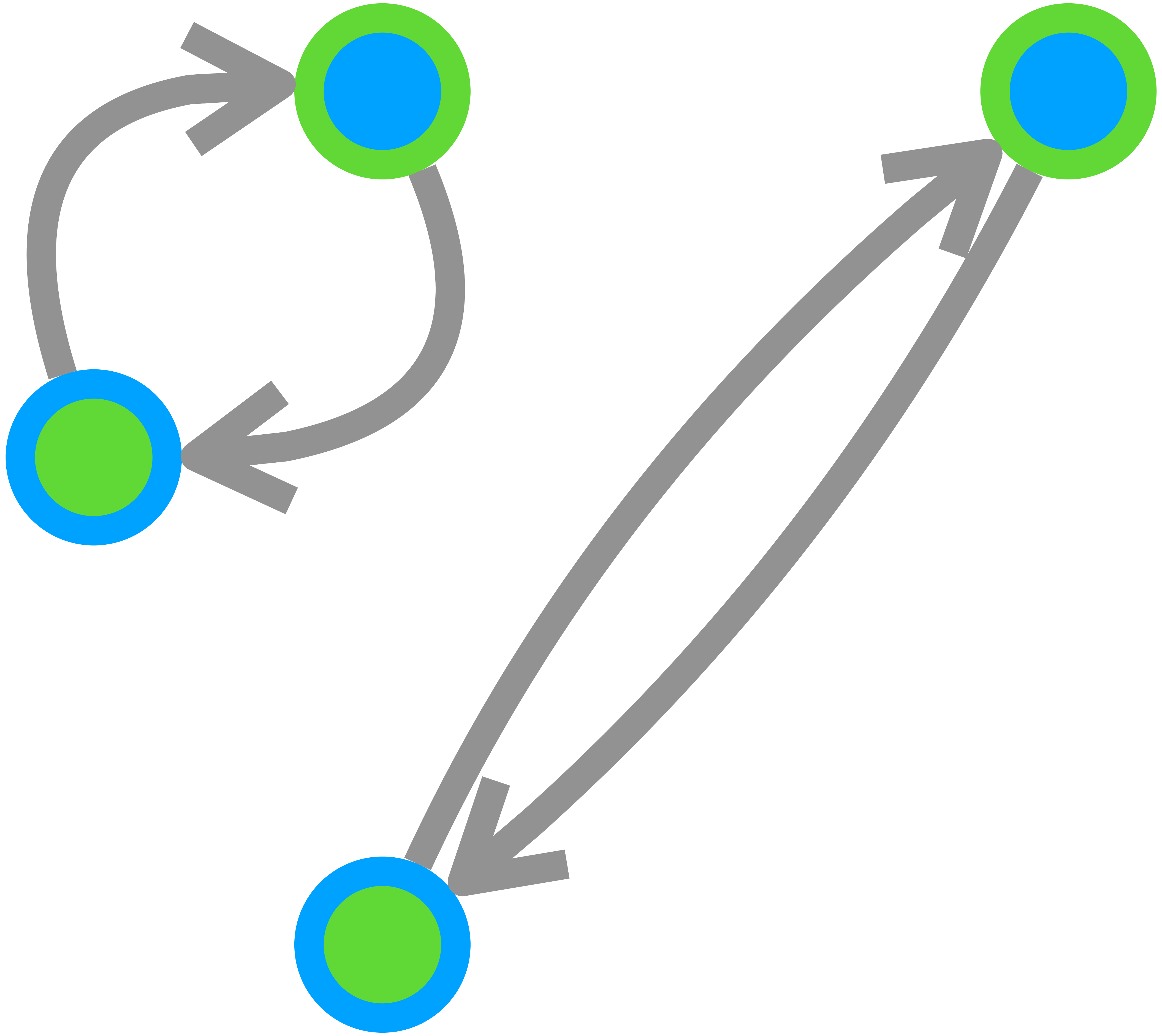

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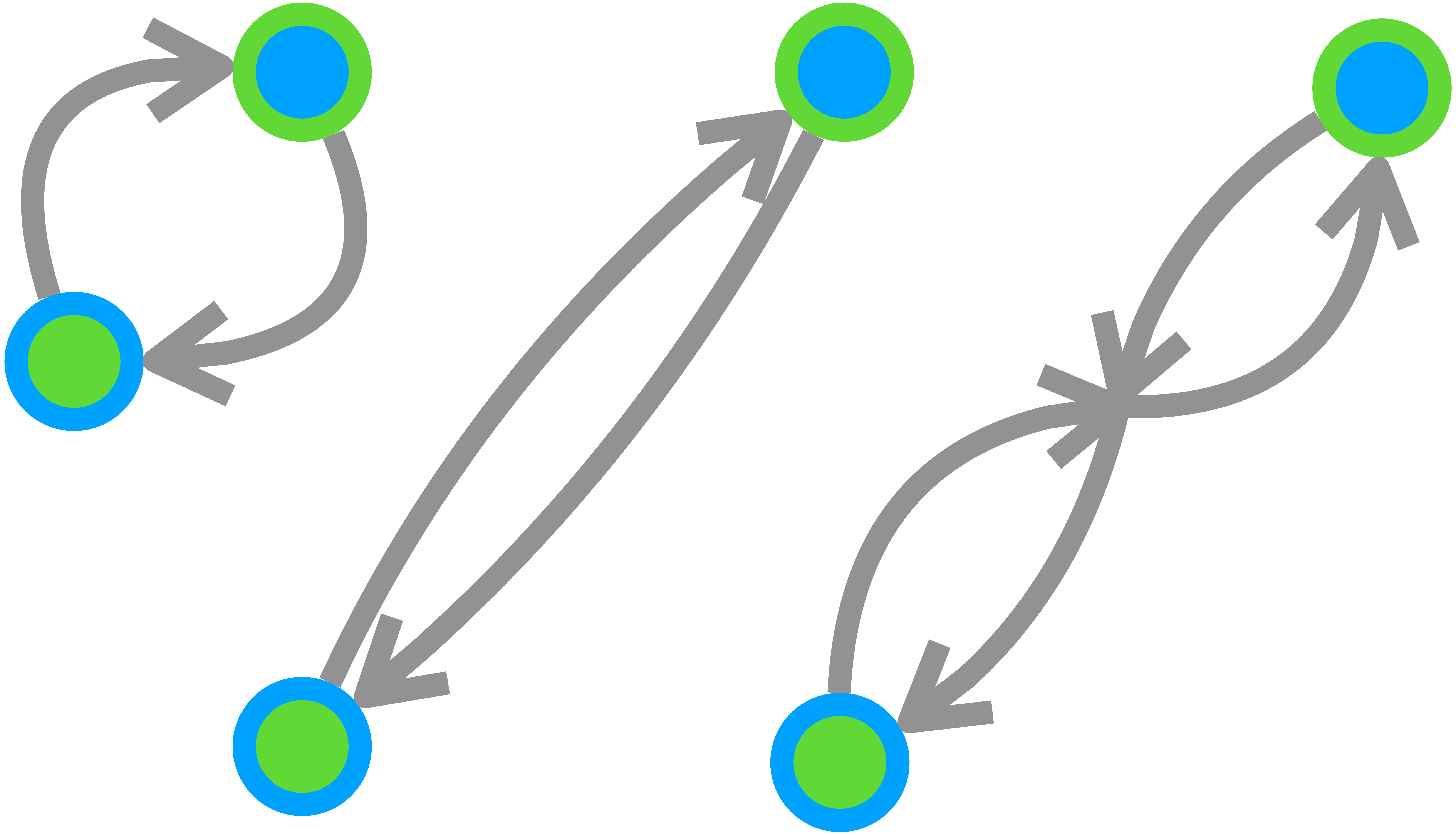

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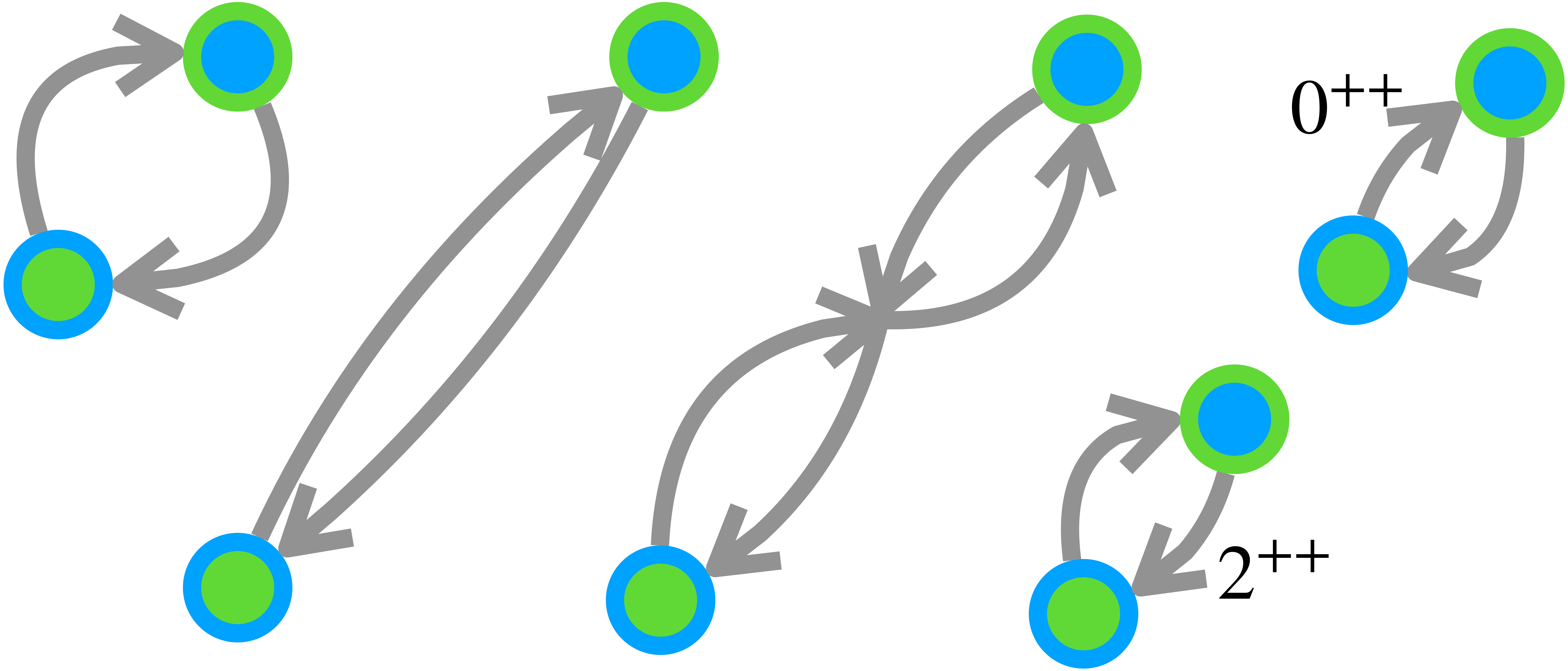

Q: How to simulate dark sector glueball hadronization?

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A: GlueShower

GlueShower

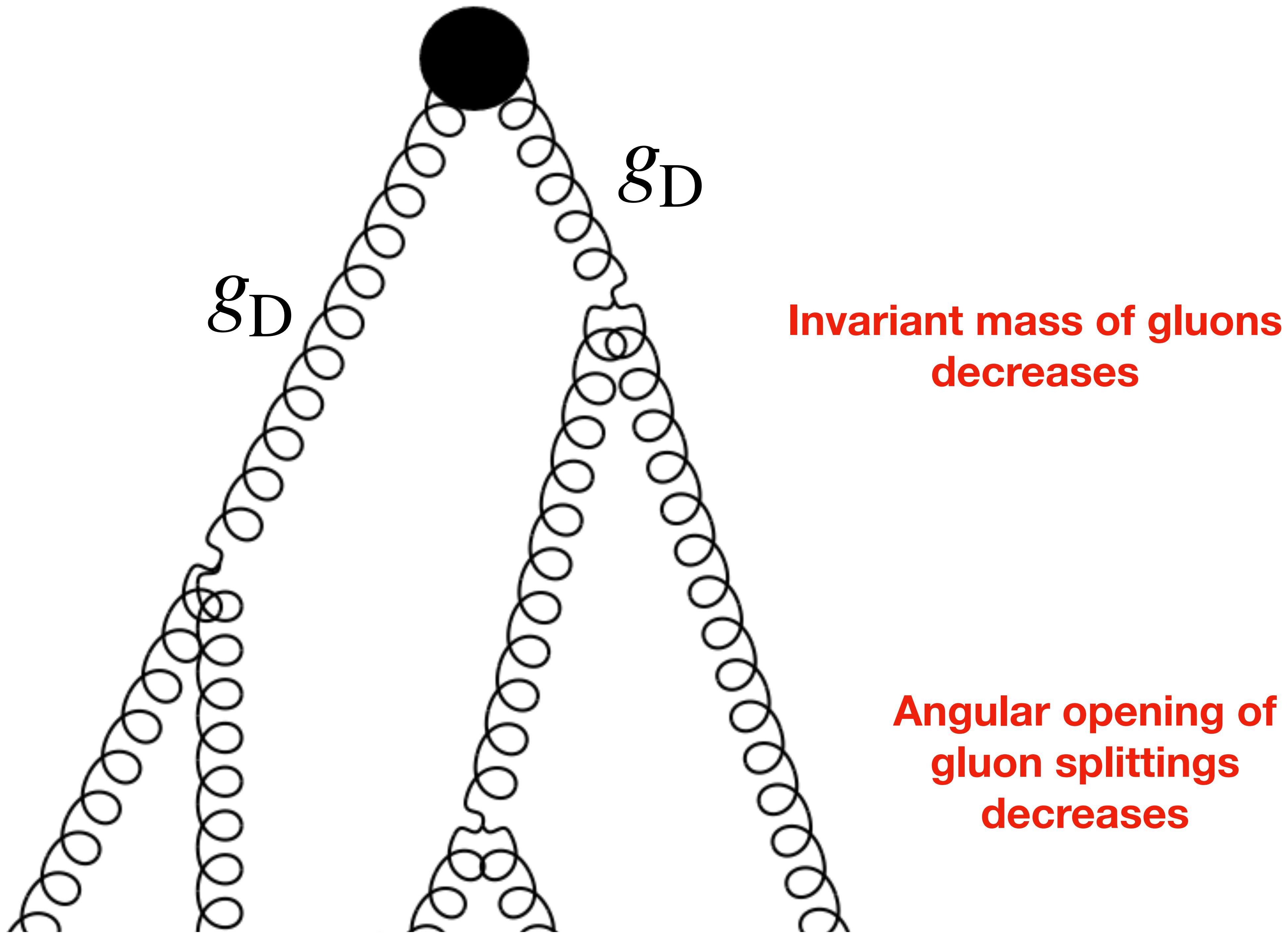
arXiv: 2202.12899 (with D. Curtin, C.B. Verhaaren)

1. Start with a standard pure glue, virtuality (invariant mass) ordered, angular ordered parton shower

   - Probability a gluon evolves from initial virtuality to a smaller virtuality without splitting is given by the Sudakov form factor,
   $$\Delta(z) = \exp\left[-\int_{t_0}^{t} \frac{dt'}{t'} \int dz \frac{\alpha_s}{2\pi} P_{gg}(z) \right]$$

   - If a gluon splits, daughter gluon energies are determined by the gluon-to-gluon splitting function, $P_{gg}(z) = 2N_c \left[\frac{z}{z-1} + \frac{z-1}{z} + z(1-z) \right]$

2. Stop perturbative splitting once gluons are unable to split with some minimum scale, t_{min}



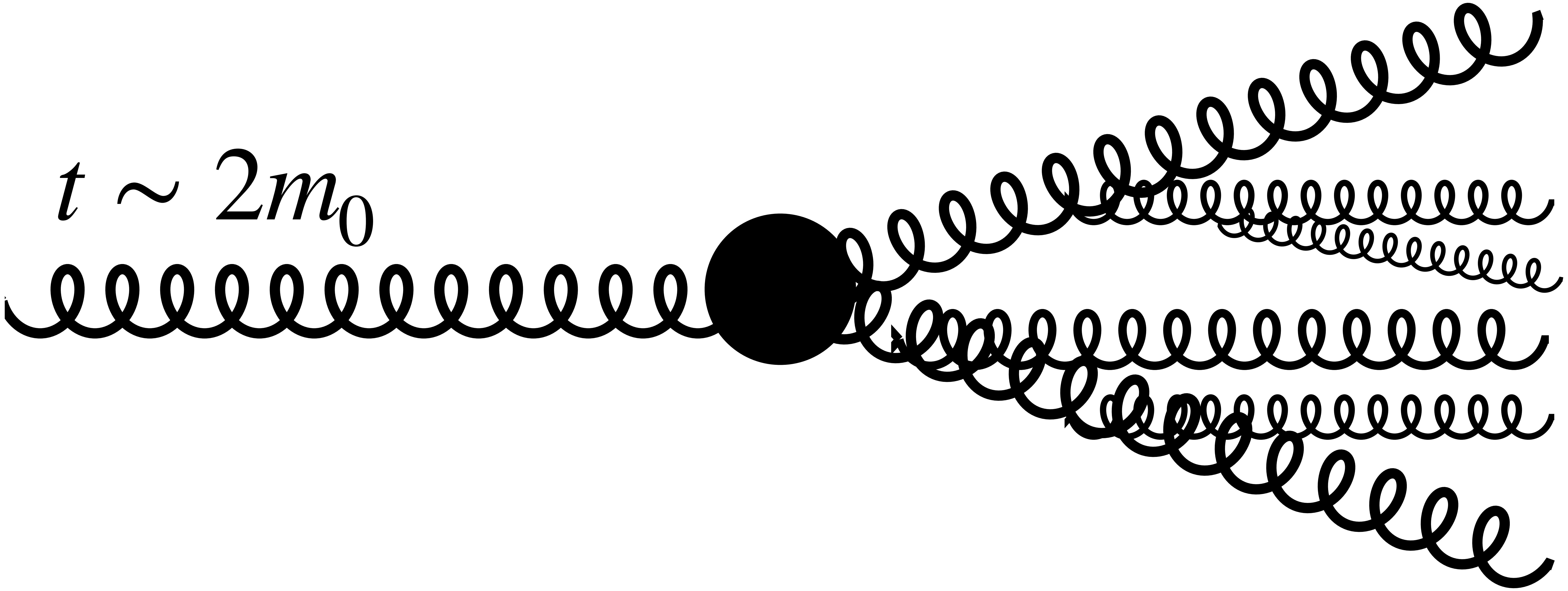
GlueShower

arXiv: 2202.12899 (with D. Curtin, C.B. Verhaaren)

3. At end of shower, exploit angular ordering and $m_0 >> \Lambda$

$t \sim \Lambda$

$t \sim 2m_0$



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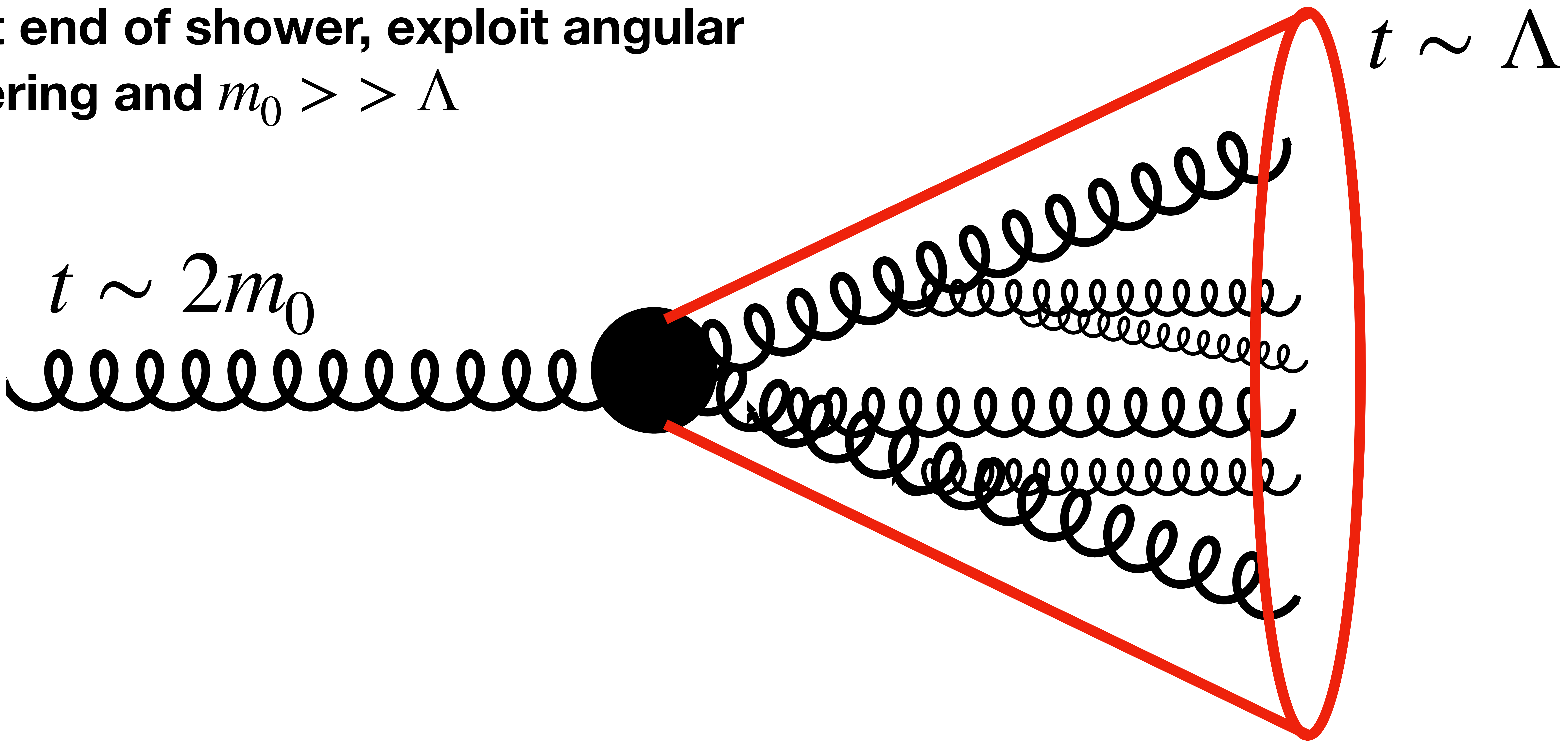


GlueShower

arXiv: 2202.12899 (with D. Curtin, C.B. Verhaaren)

$$t_{\min} \sim 2m_0$$

*Note: $t_{\min}$ sets minimum scale a gluon can reach,
the gluon usually ends with virtuality $\mathcal{O}(1)$ larger than $t_{\min}$

**BASIC IDEA:
EVOLVE GLUONS IN PERTURBATIVE SHOWER WITH $t_{\min} \sim 2m_0$, AT WHICH POINT THEY ARE PUT ONSHELL AS A GLUEBALL**

GlueShower

arXiv: 2202.12899 (with D. Curtin, C.B. Verhaaren)

$$t_{\min} \sim 2m_0$$

Also need to include entire spectrum of glueball states, so the *actual* glueball species is randomly drawn from an input distribution

Assumptions

- Since $m_0 >> \Lambda$, glueball production from flux tube energy density is extremely suppressed
- Additionally, soft gluon effects (long range interactions) between gluon branches will only lead to $p \sim \Lambda >> m_0$ momenta exchange, subdominant effect
    - Implicitly this has to occur to ensure colour singlet states can form from the perturbative gluon
- Glueball hadronization is independent on each branch
- Input distribution is thermal (motivated by SM QCD thermal production):

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

Uncertainties

- **How sensitive is our shower to the exact scale at which we terminate the shower?**
- **How sensitive is our shower to the exact hadronization temperature we assume for the Boltzmann distribution?**
- **Can we guarantee that glueball production occurs independently?**

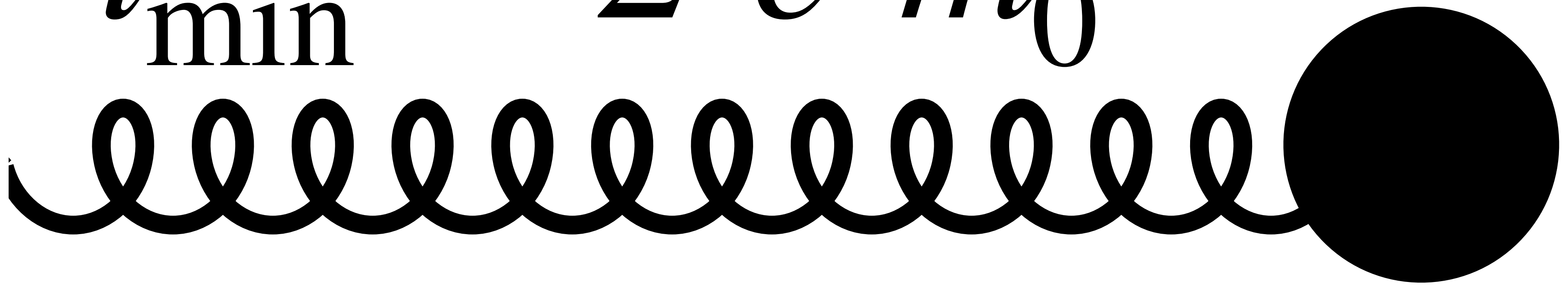
Uncertainties

- **How sensitive is our shower to the exact scale at which we terminate the shower?** $t_{\rm min} = 2\, c\, m_0\,,\, c \sim \mathcal{O}(1) > 1$
- **How sensitive is our shower to the exact hadronization temperature we assume for the Boltzmann distribution?** $T_{\rm had} = d\, \Lambda\,,\, d \sim \mathcal{O}(1) > 1$
- **Can we guarantee that glueball production occurs independently?** **Consider two possibilities… JET MODE and PLASMA MODE**

Uncertainties

JET MODE

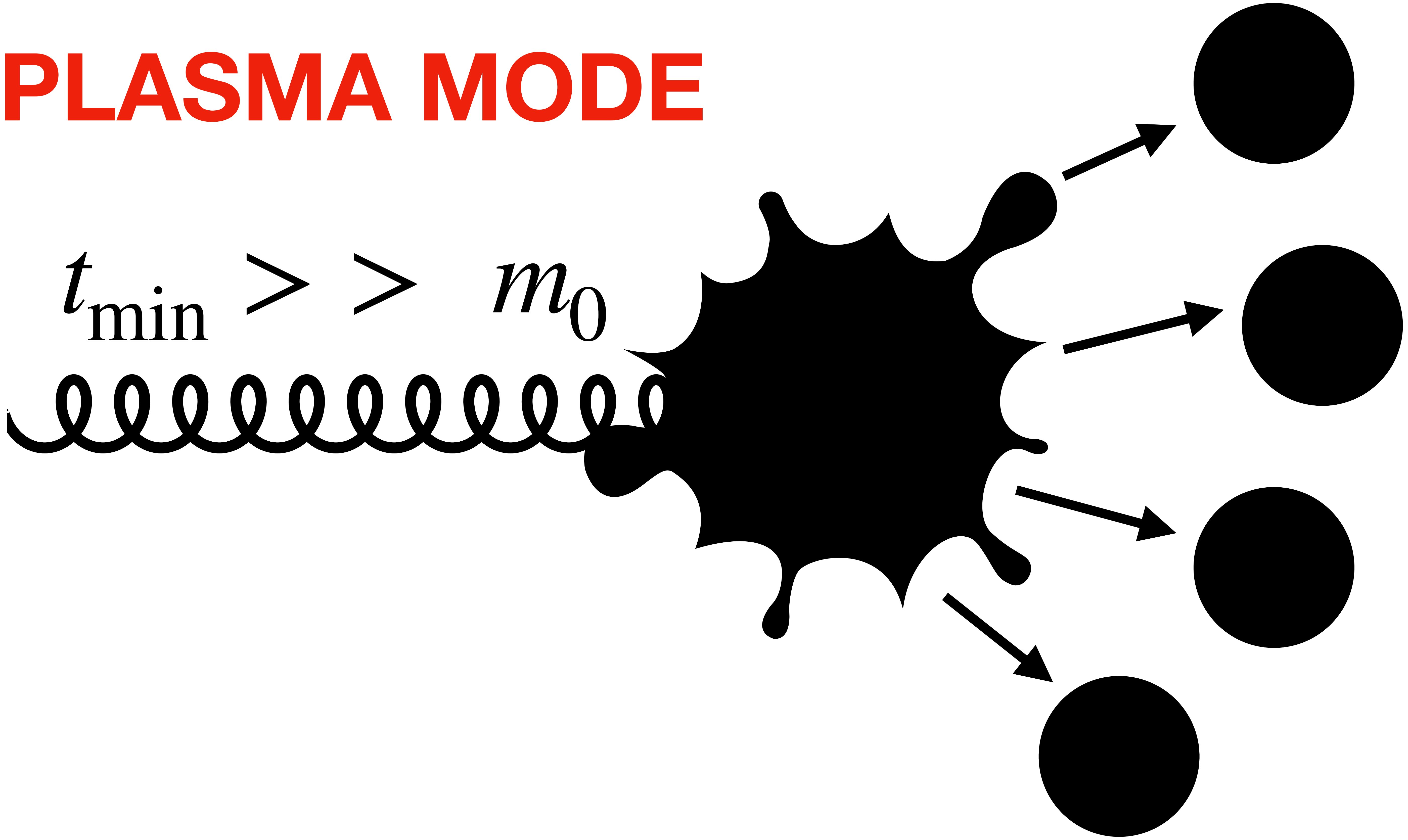
$$t_{\min} \sim 2\ c\ m_0$$



Previous we assumed $c \sim 1$, thus a single glueball can only be produced

Uncertainties

PLASMA MODE



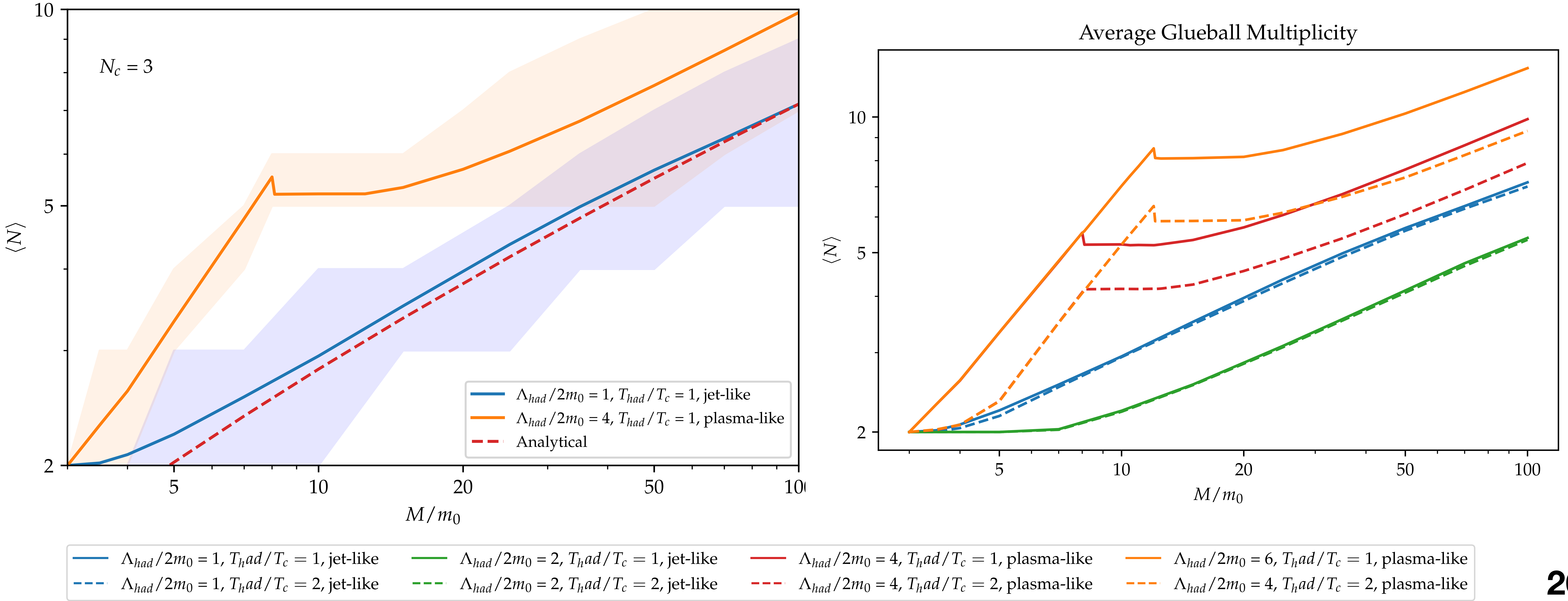
High mass pure glue fireball, evaporates via isotropic thermal emission (QGP-like)

GlueShower: Summary

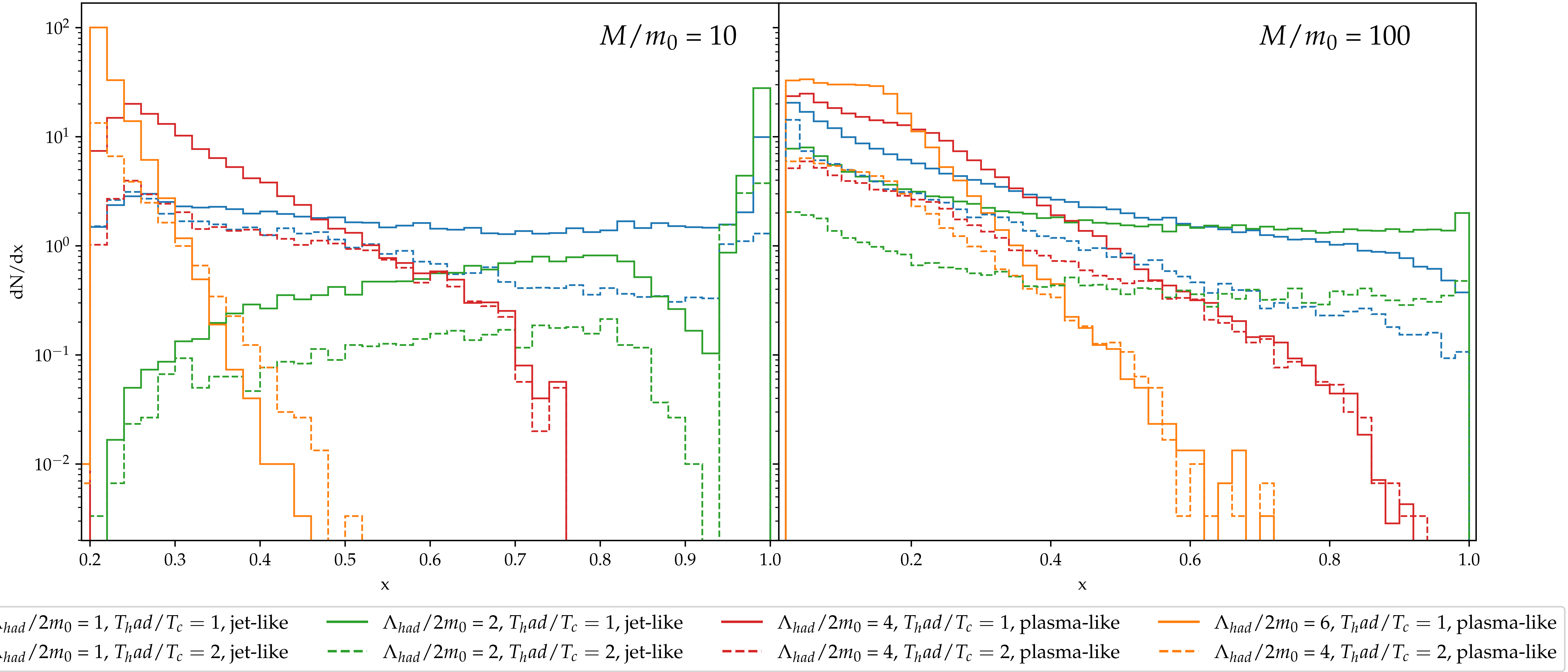
arXiv: 2202.12899 (with D. Curtin, C.B. Verhaaren)

- First version of the hadronization algorithm still very useful
  - Contains all the perturbative physics, and motivated assumptions
- Publicly available Python code, https://github.com/davidrcurtin/GlueShower
- We provide a range of benchmark parameter points, {JET/PLASMA , Λ_{had} , T_{had} }, allowing the user to bracket over hadronization possibilities
  - First attempt to quantify theory uncertainty on glueball production

GlueShower: Multiplicity scaling



GlueShower: Fragmentation Functions




Q: Can we do better?

An Updated Hadronization Methodology

arXiv: 2310.13731 (with A. Batz, T. Cohen, D. Curtin, G.D. Kribs)

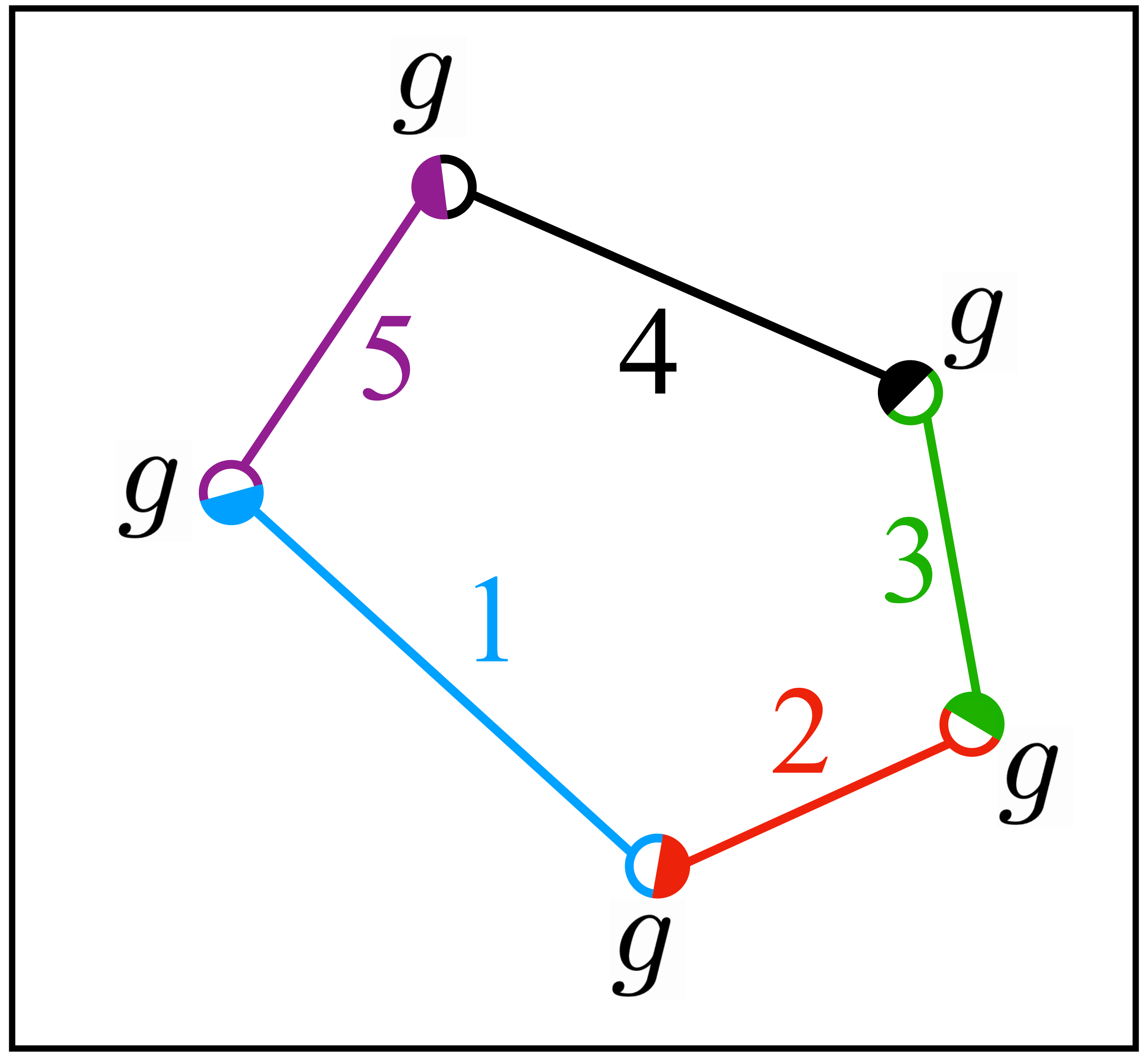
- Built from the Pythia perturbative shower code
  - Orders of magnitude faster
- Works with the colour flux rings, not just perturbative gluons
- Process:

Perturbative Shower → Color Reconnection → Glueball fragmentation

Perturbative Shower

- Builds off the standard Pythia 8 p_T -ordered shower
    - Partons evolve to reach momenta cutoff, $p_T \sim c\Lambda$
- Parton shower evolves in the $N_c \to \infty$ "leading-colour" approximation
    - Each parton is given a unique colour assignment until end of shower
    - Note that GlueShower also uses the leading-colour limit, but here the colour assignments are actually tracked

Color Reconnection



Gluons evolve in the perturbative shower in the $N_c \to \infty$ limit

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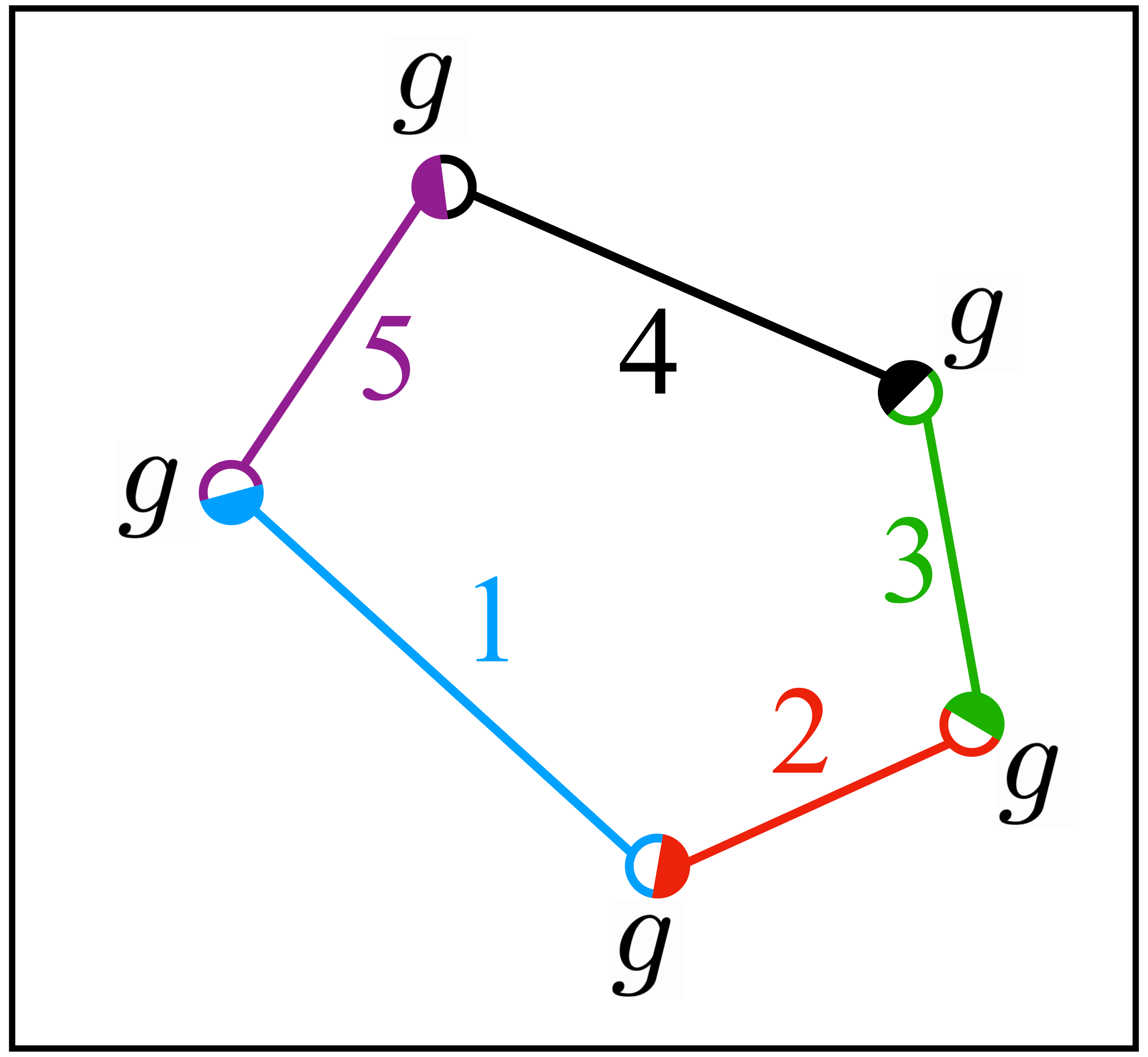

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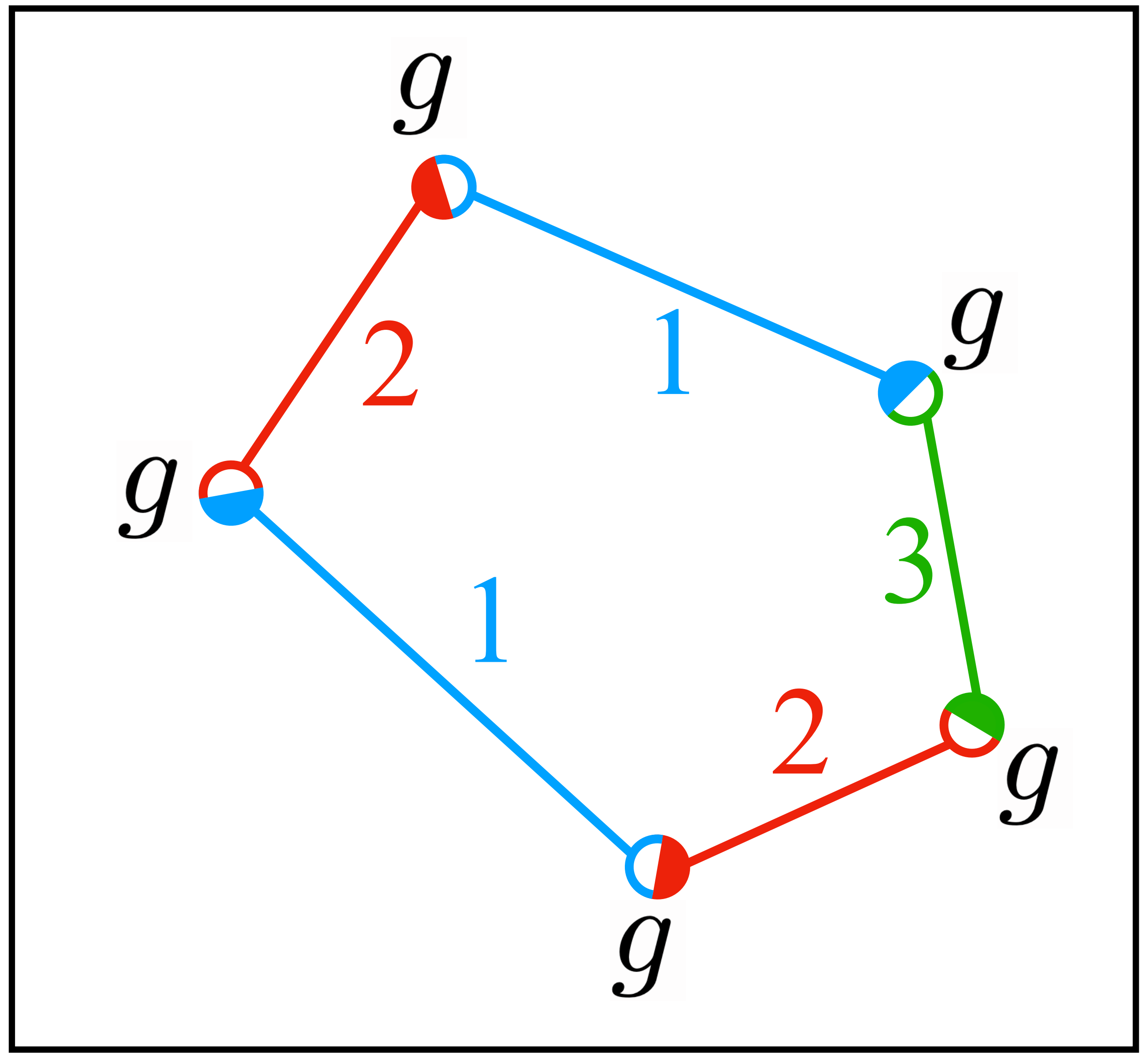
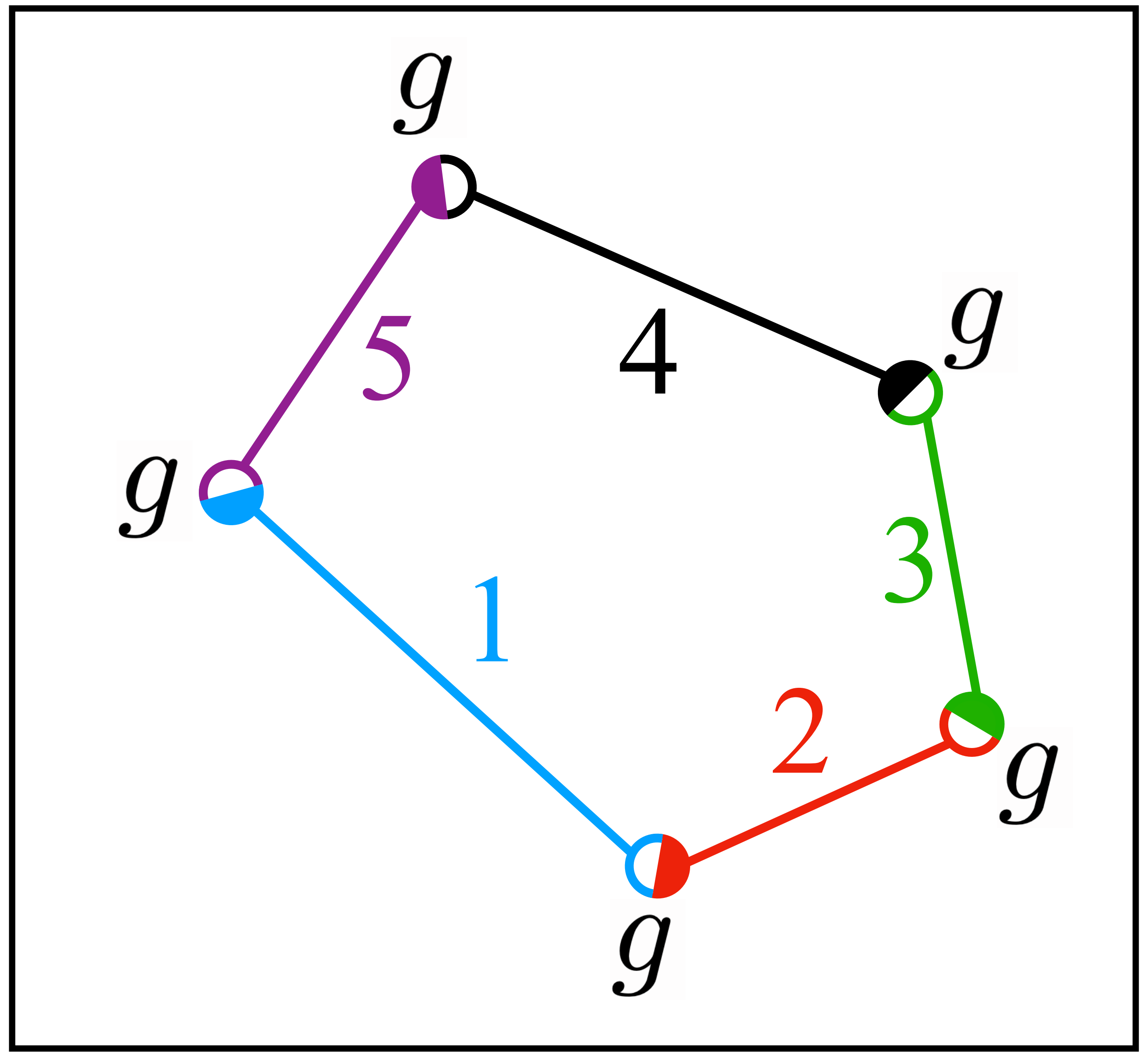


String pieces are randomly reassigned color in the $N_c = 3$ limit

Color Reconnection



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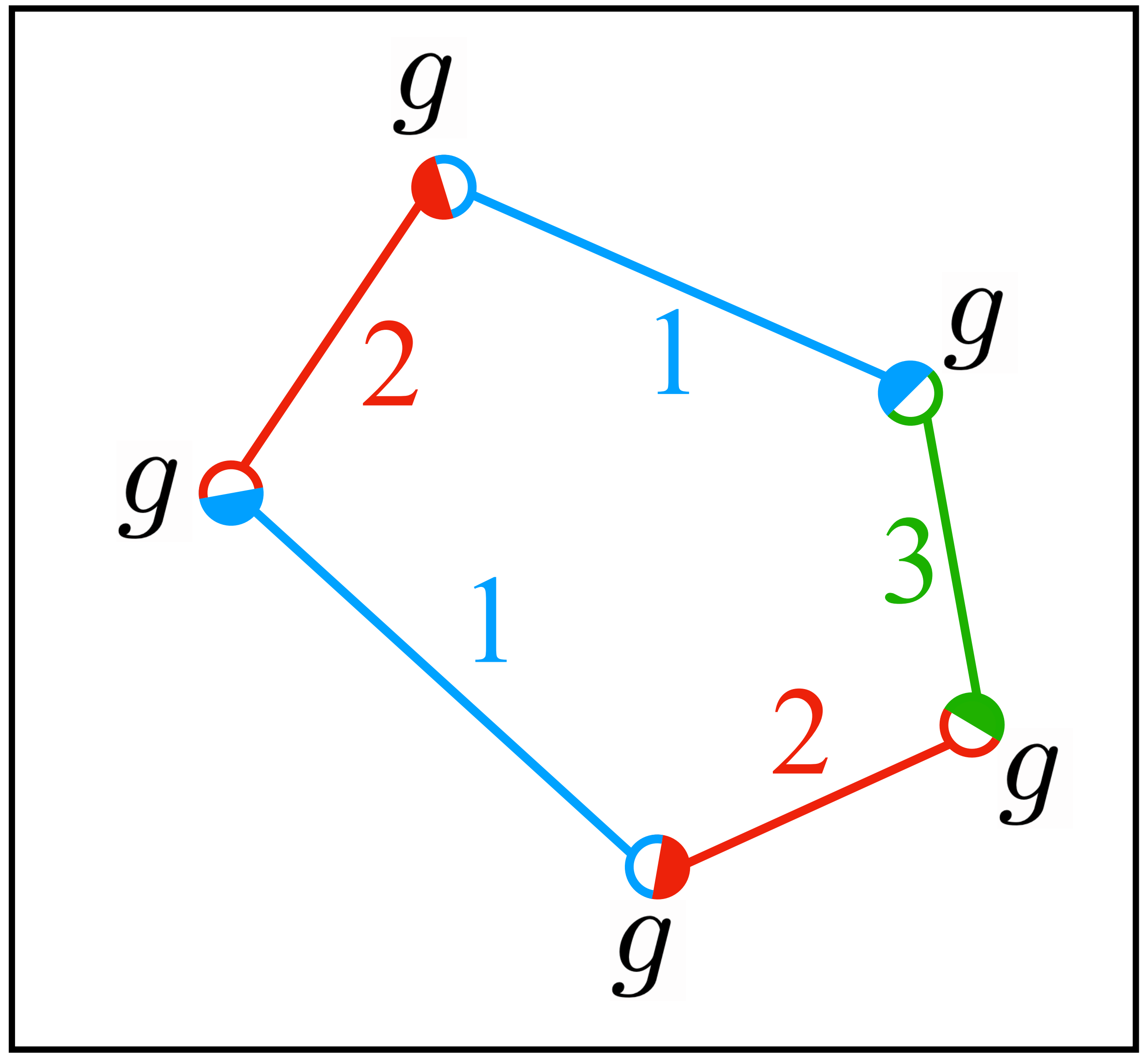
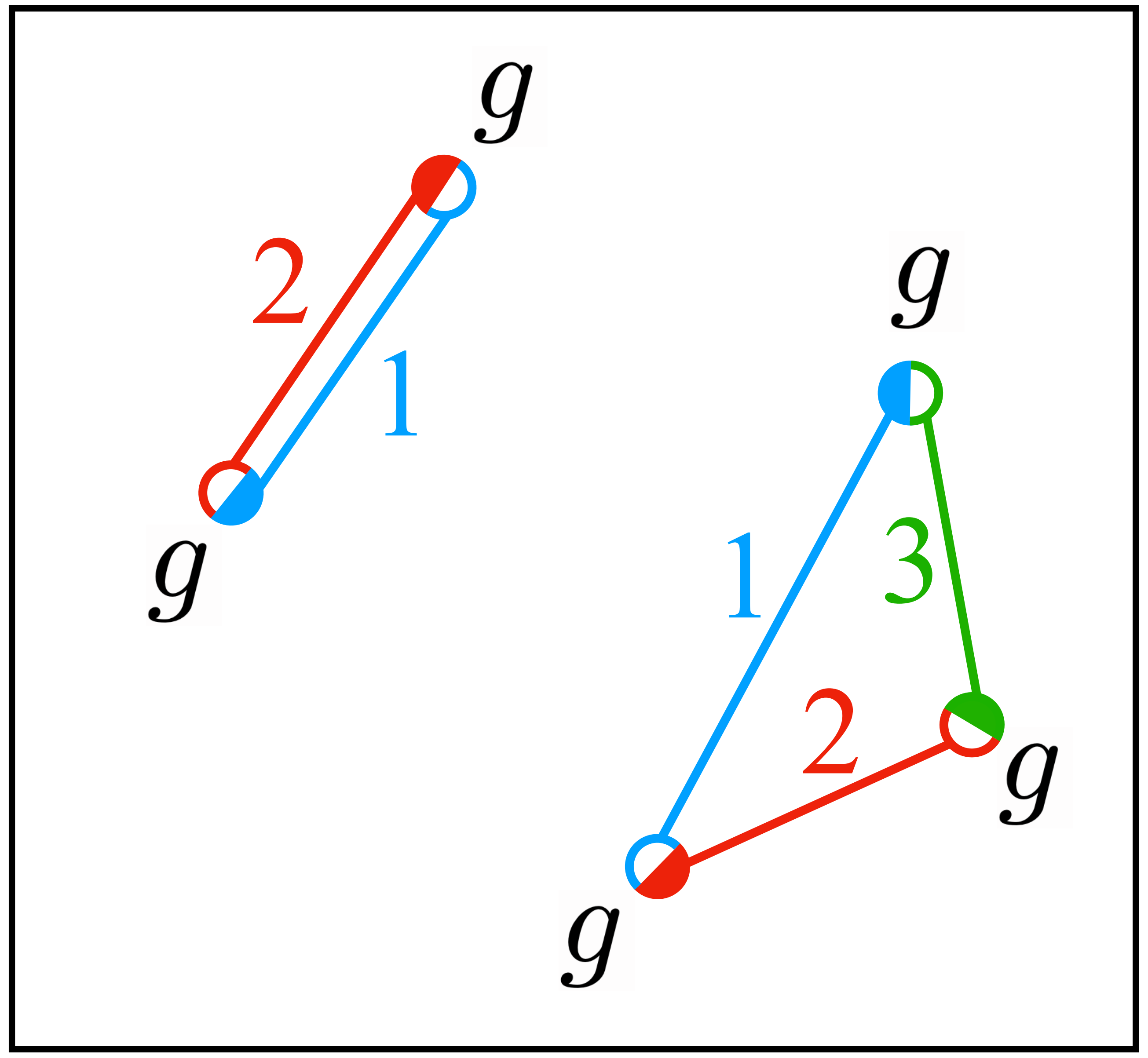


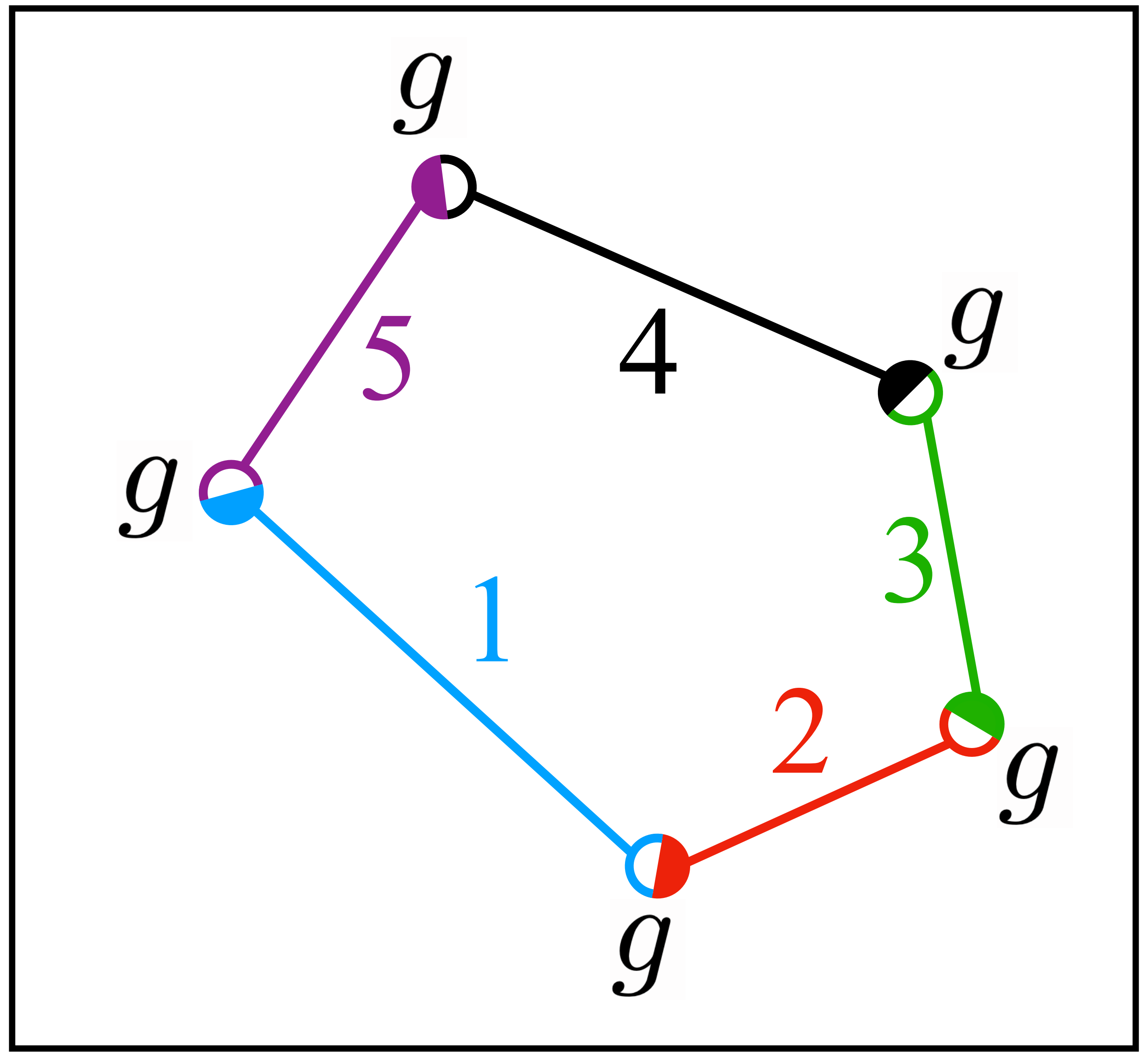
String pieces are randomly reassigned color in the $N_c = 3$ limit



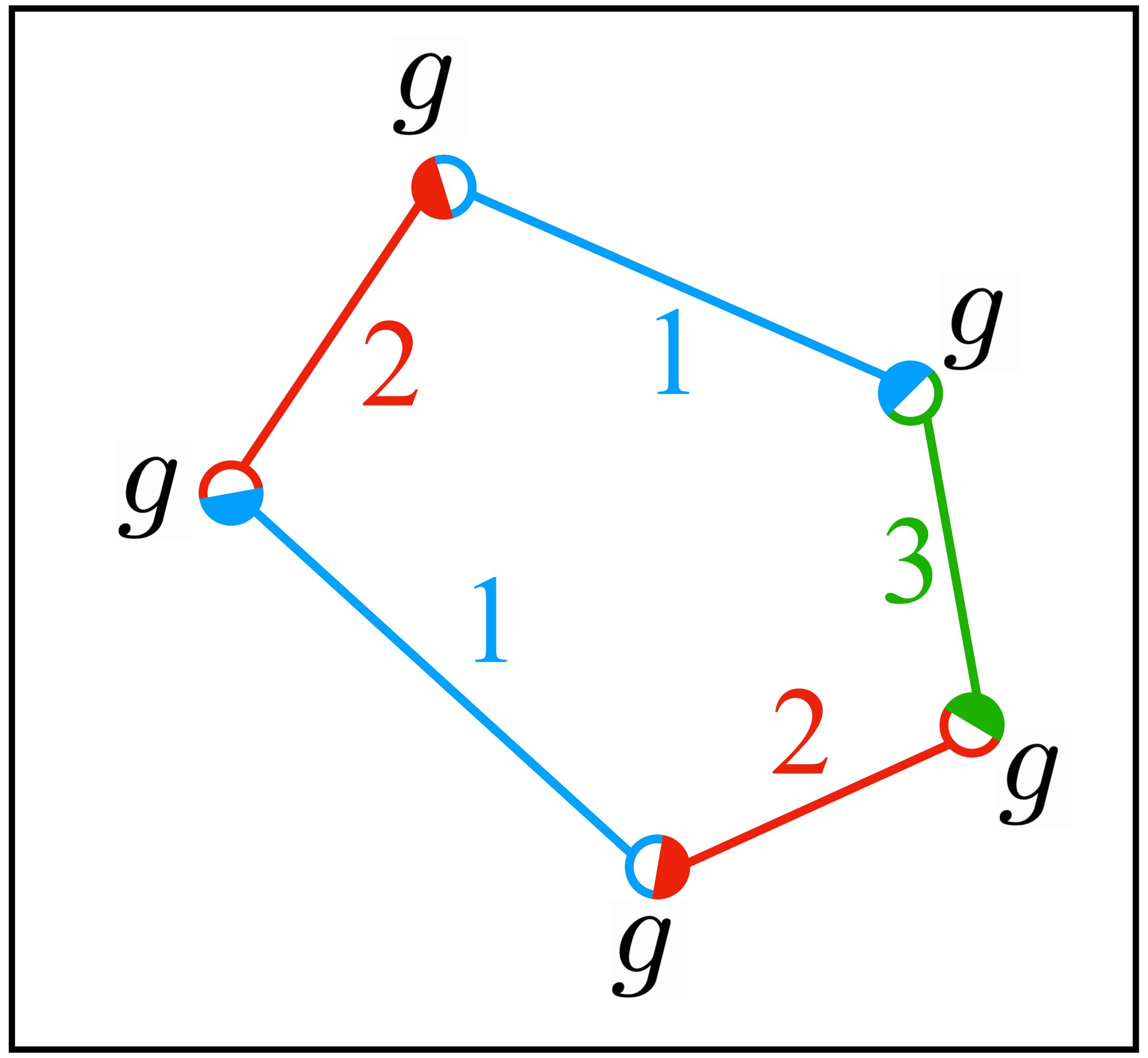
String connections are reassigned to minimise the string length quantity, λ

$$\lambda = \sum_{\text{pieces}} \ln\left(1 + \frac{\mathrm{m}^2_{\text{piece}}}{\mathrm{m}^2_0}\right)$$

Color Reconnection



Gluons evolve in the perturbative shower in the $N_c \to \infty$ limit



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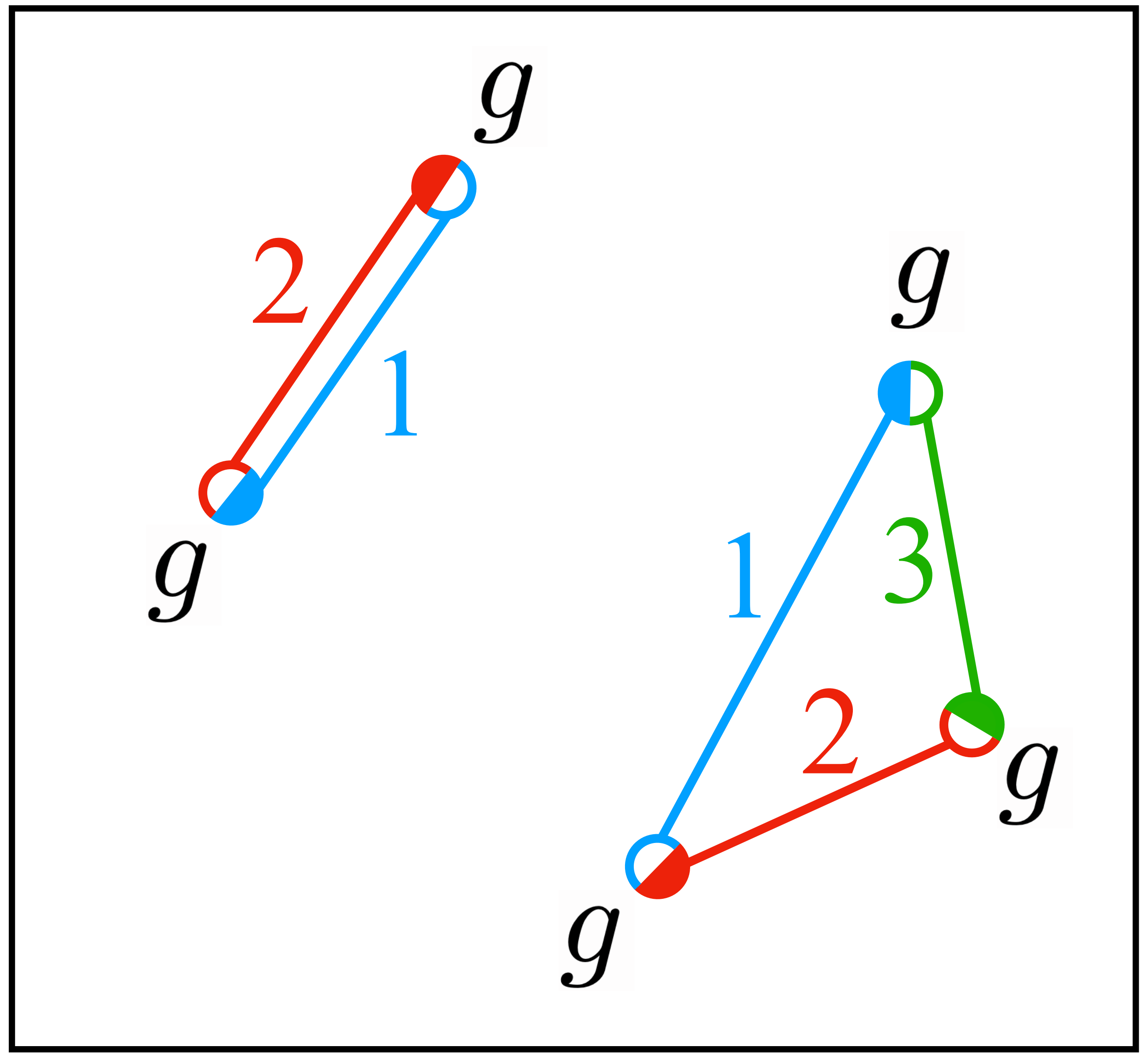
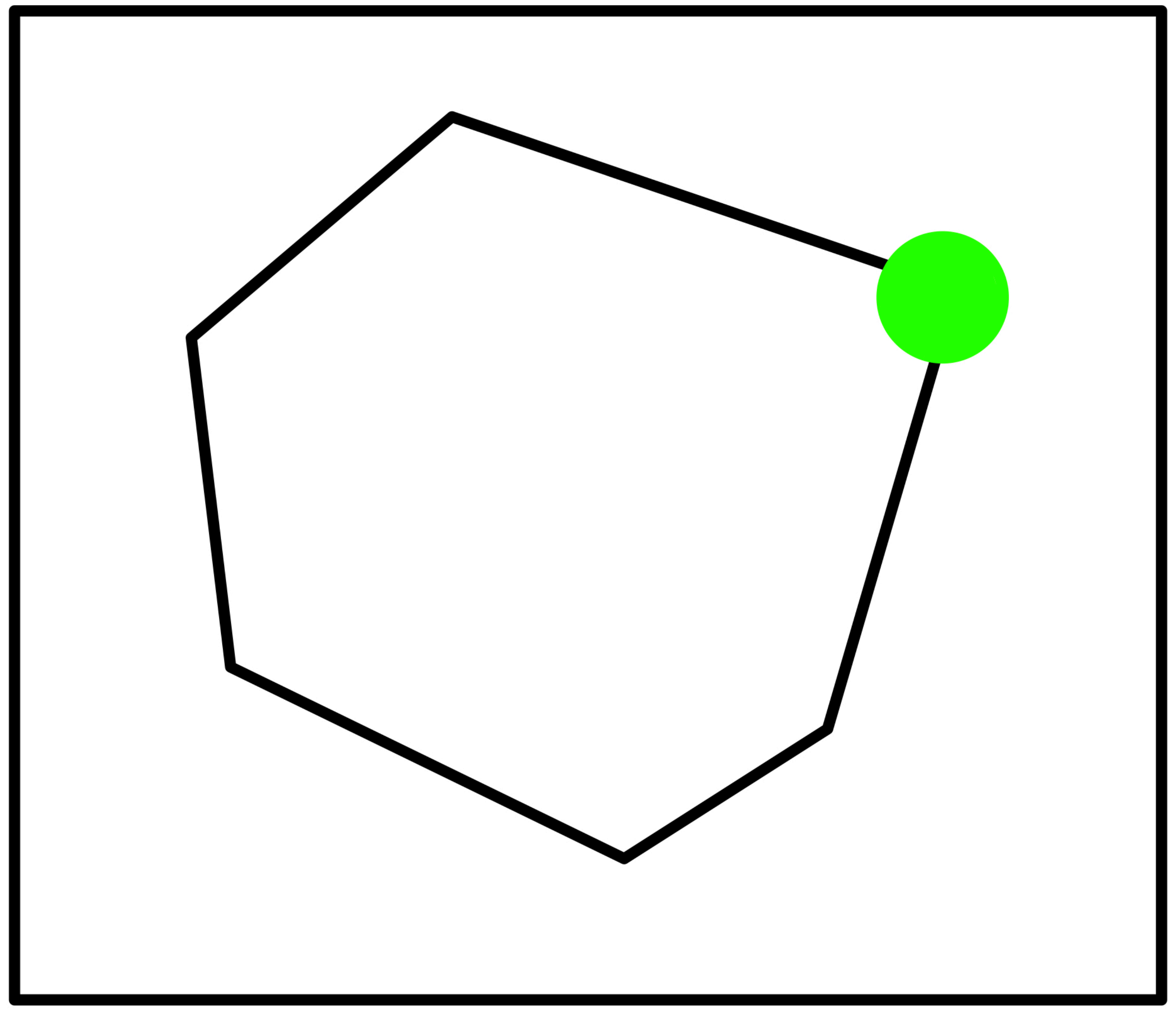


String connections are reassigned to minimise the string length quantity, λ

Defines the physical string topology at the end of the shower, same as Lund String model

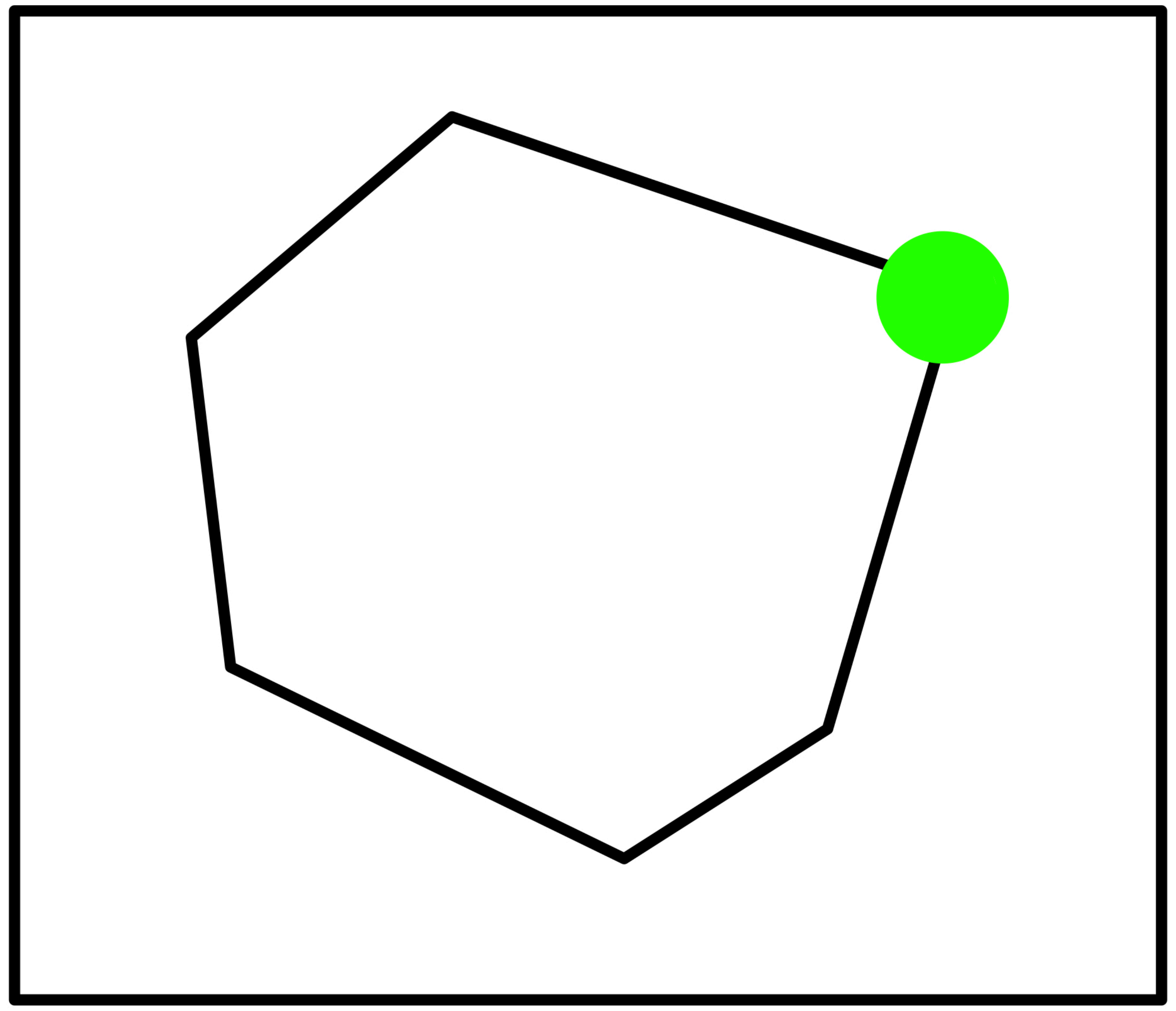
$$\lambda = \sum_{\text{pieces}} \ln\left(1 + \frac{m^2_{\text{piece}}}{m^2_0}\right)$$

Glueball Fragmentation



Vertex connecting string pieces with largest string-length is selected first for fragmentation

Glueball Fragmentation



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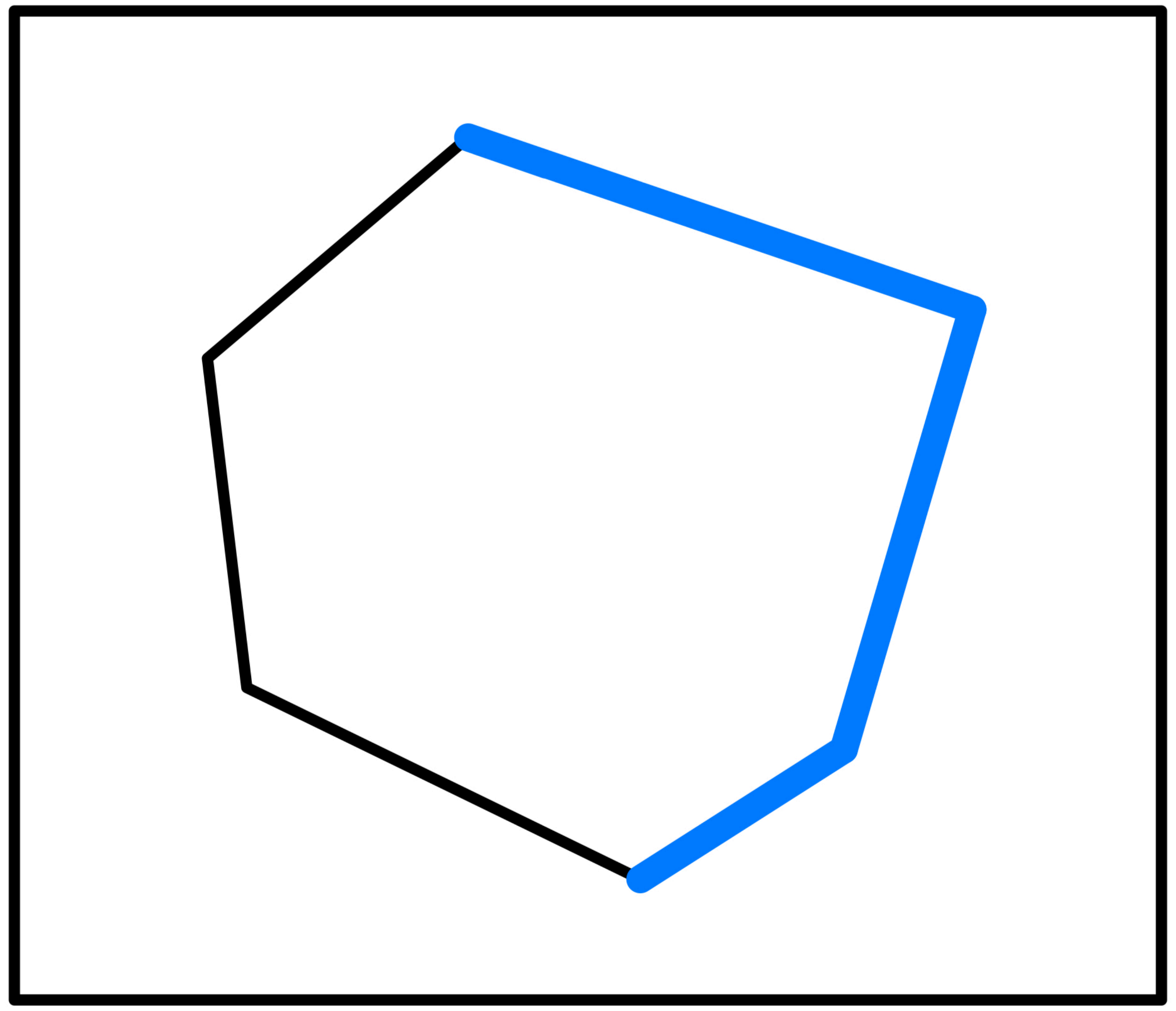
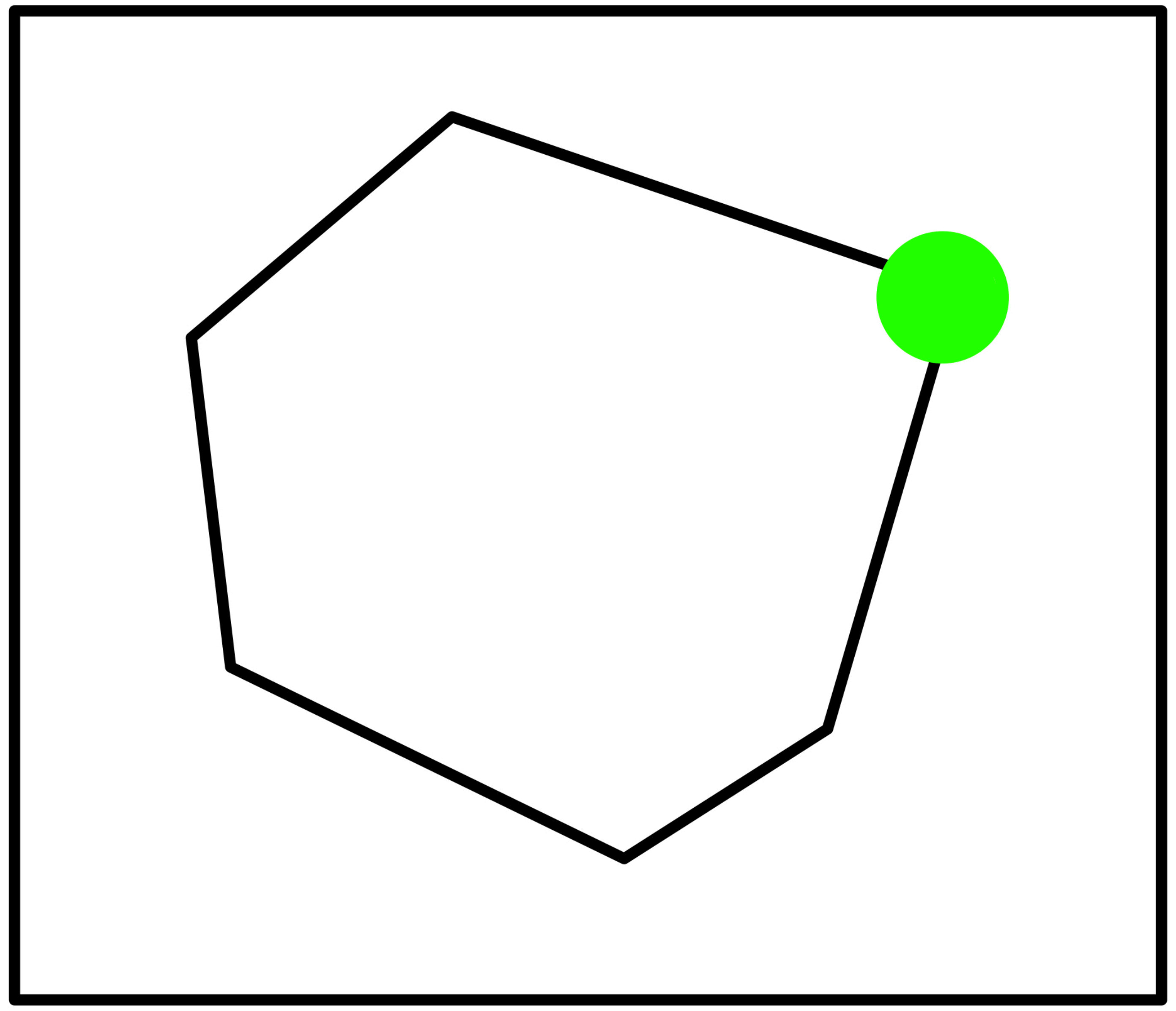


A minimal set of string pieces with total mass, $M_{\text{total}} \geq m_0$, is selected to turn into a glueball

Glueball Fragmentation



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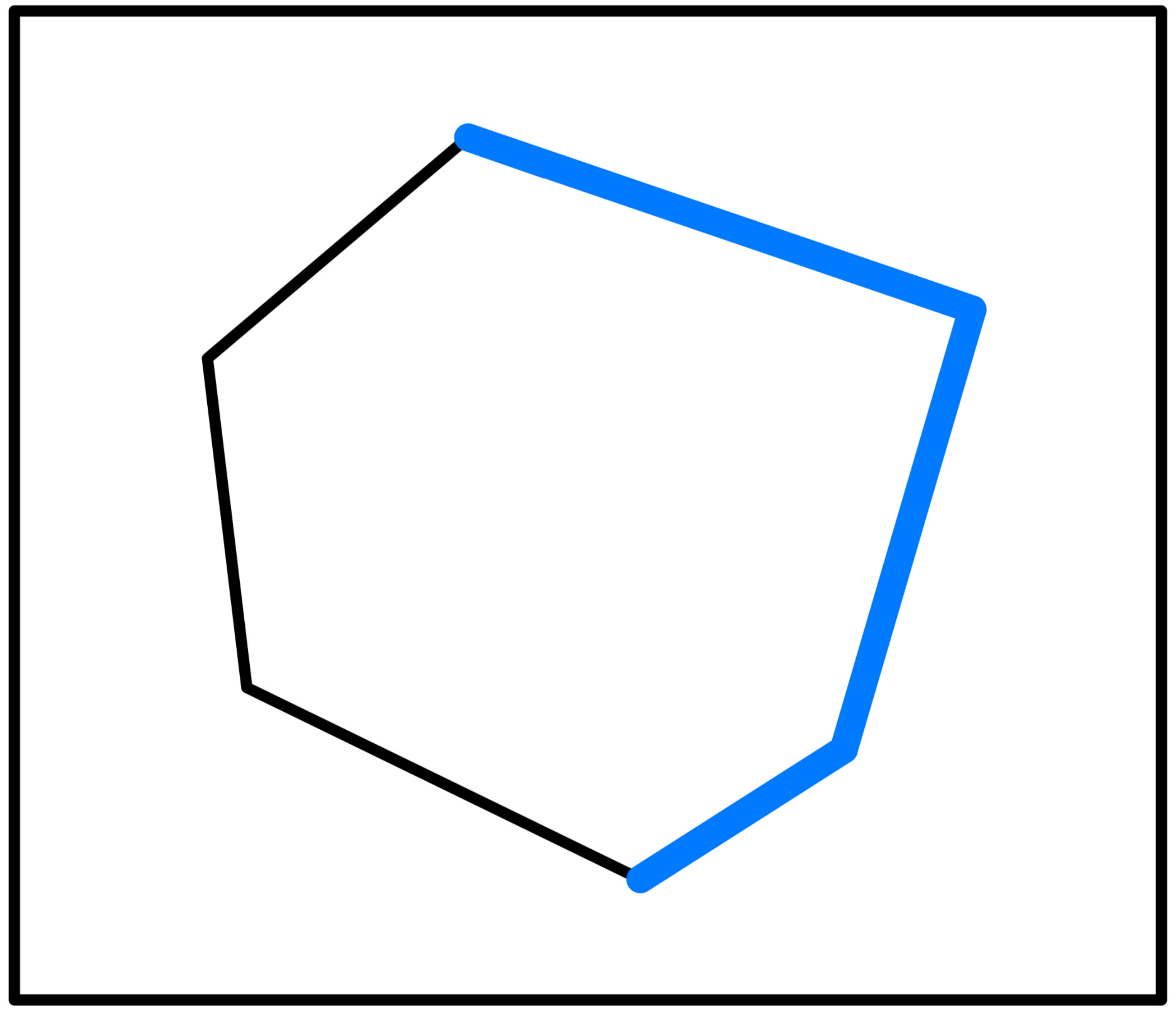

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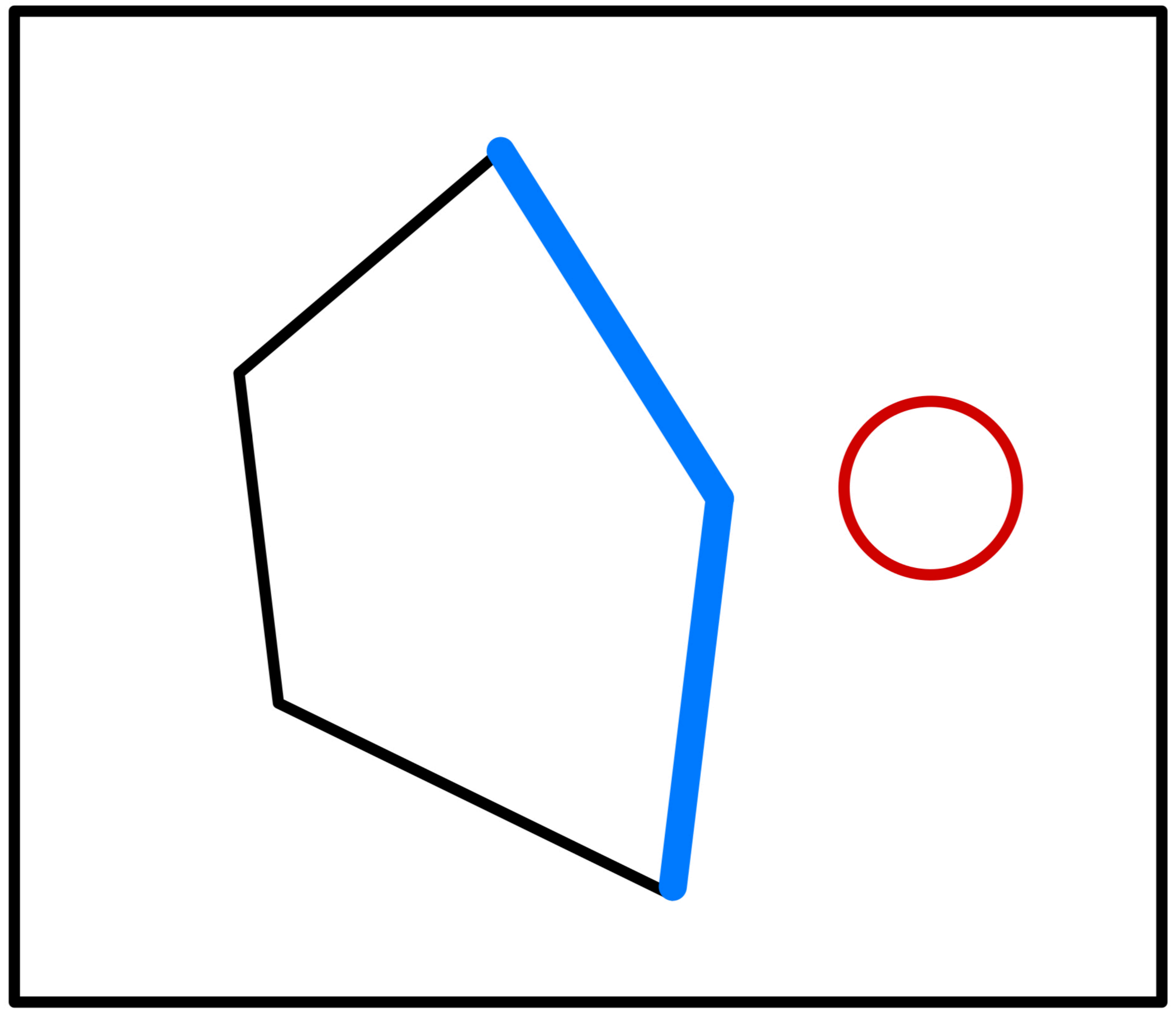


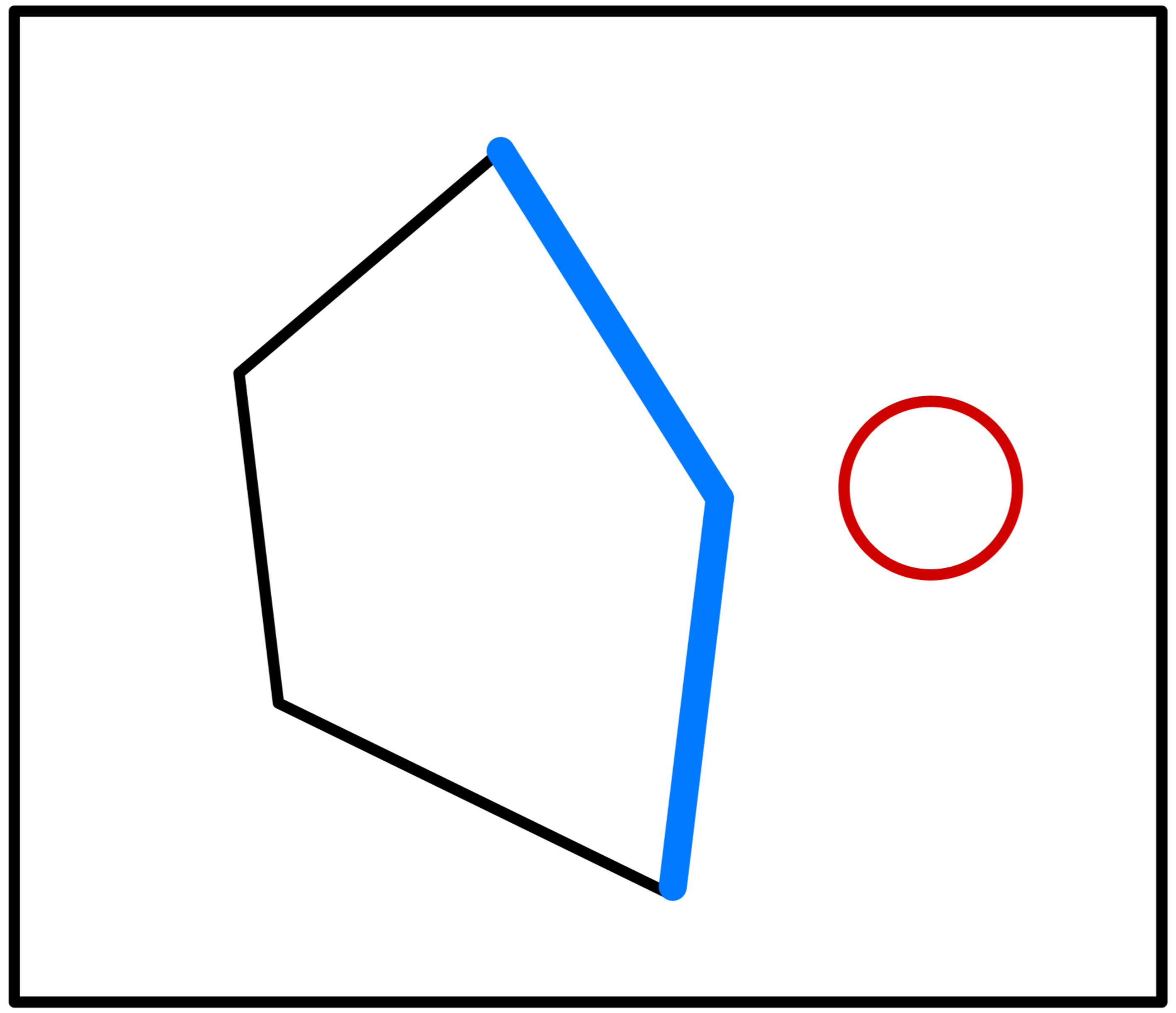
A glueball is then emitted, taking a fraction of the edge string pieces momenta. The remaining momenta is then distributed between the remaining string pieces

Glueball Fragmentation

Freedom to pick fragmentation function that determines the energy 'taken' from adjoining string pieces. General forms considering below with phenomenological parameters α and b / k_β :

$$f_{LSFF}(z) \propto \frac{(1-z)^{\alpha}}{z} e^{-bm_{\perp}^{2}/z}$$

$$f_{\beta}(z) \propto z^{\alpha-1}(1-z)^{k_{\beta}(m_0/m_G)^2}$$



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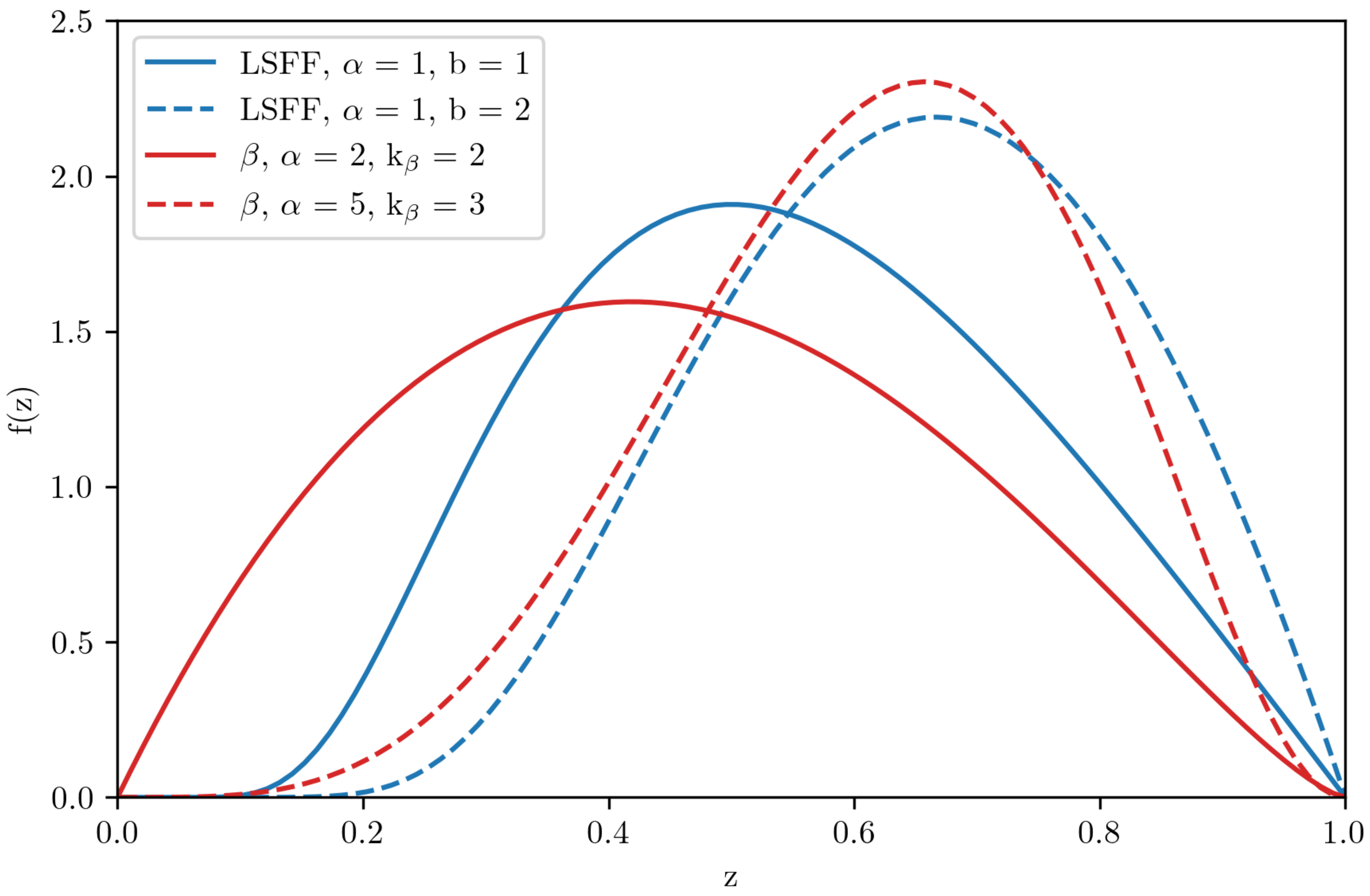

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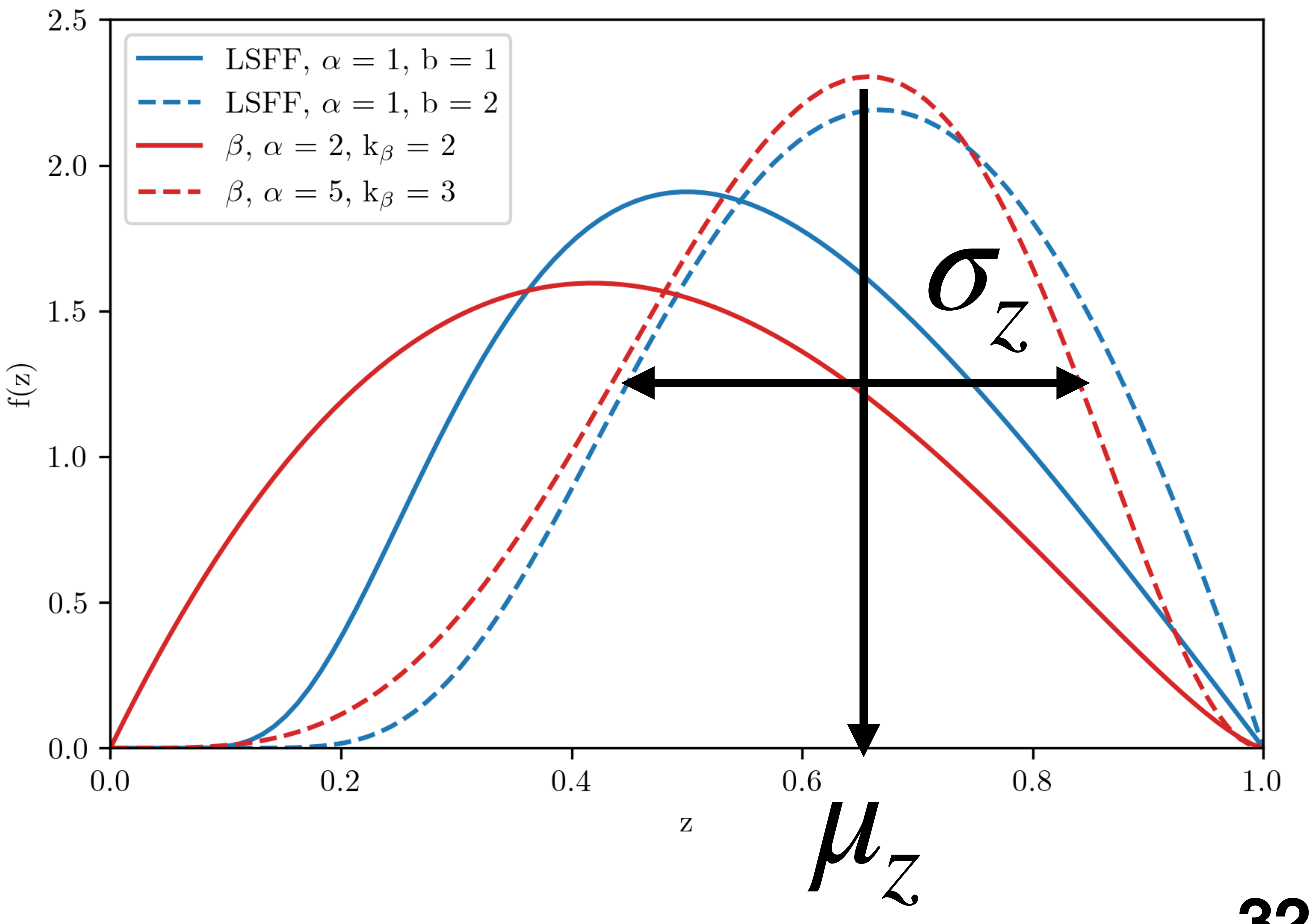
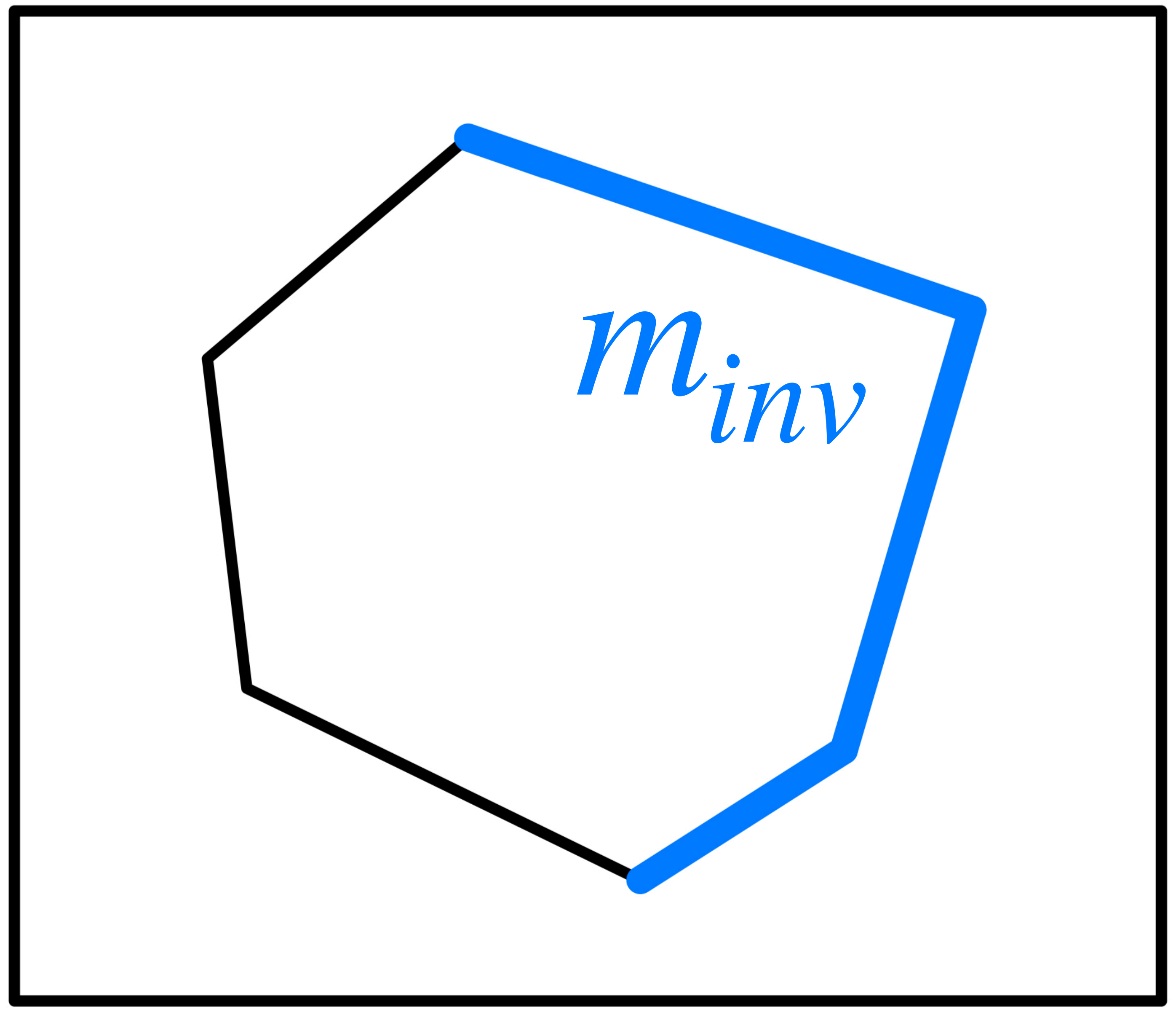


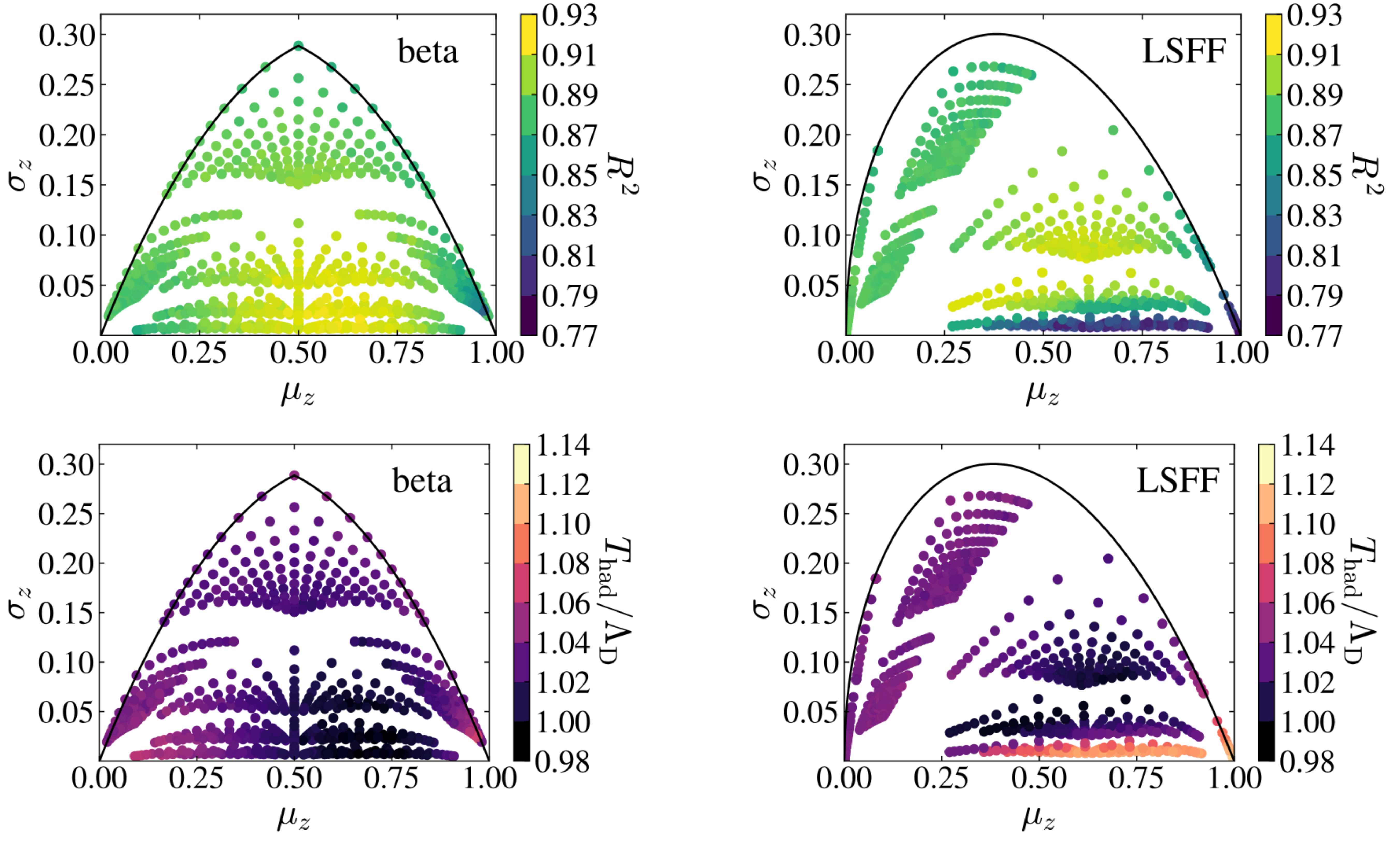
Glueball Species Distribution

- Species is chosen randomly, only including spin multiplicity weightings (assume no bias)
- However, a mass suppression does come from invariant mass of string pieces, only $m_G < m_{inv}$ glueballs accessible
    - Suppression depends on arrangement of string lengths



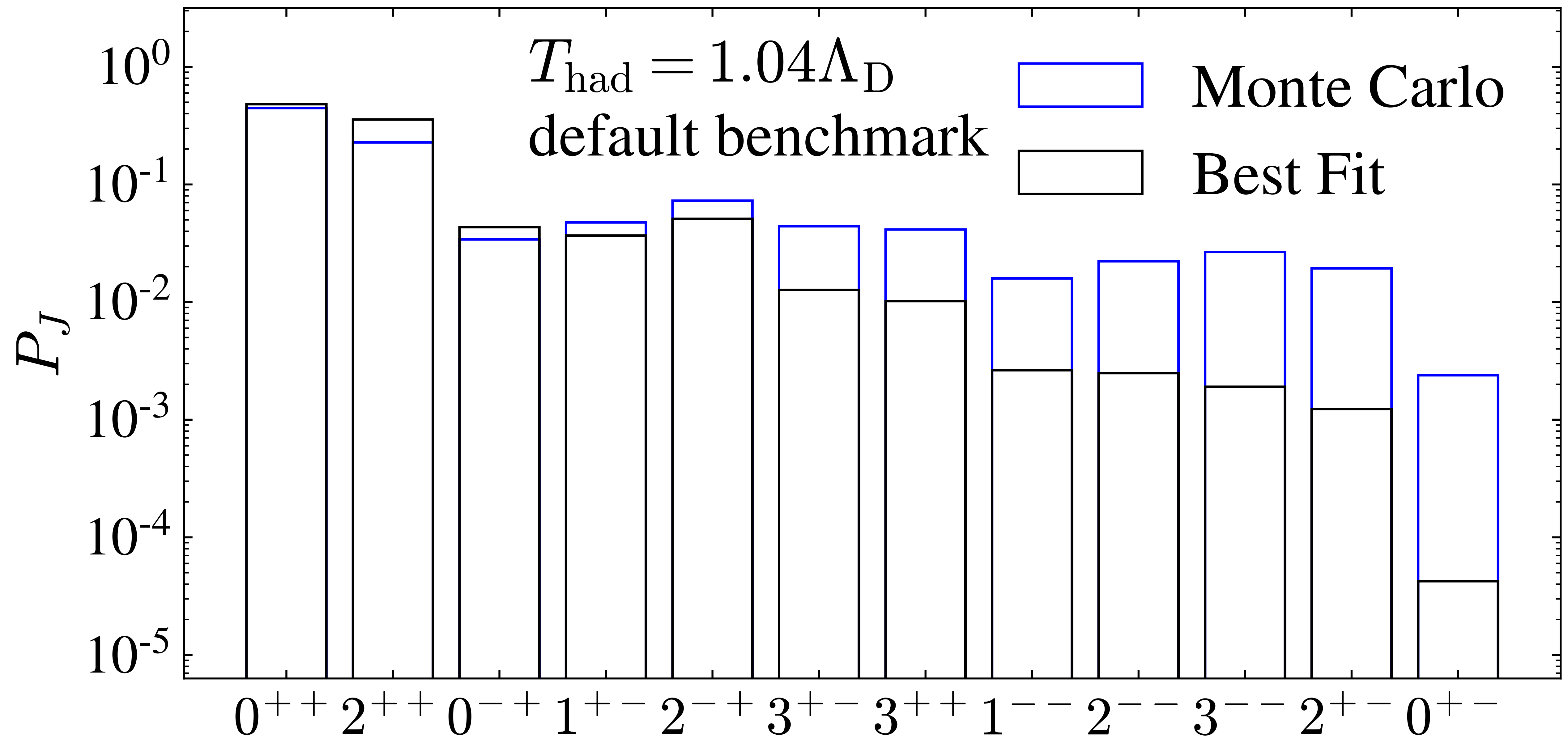
Glueball Species Distribution

- **Over wide range of fragmentation function parameterisation, good fit to thermal distribution**
- **Additionally, a thermal distribution with $T_{\text{had}} \sim \Lambda_{\text{D}}$!!!**

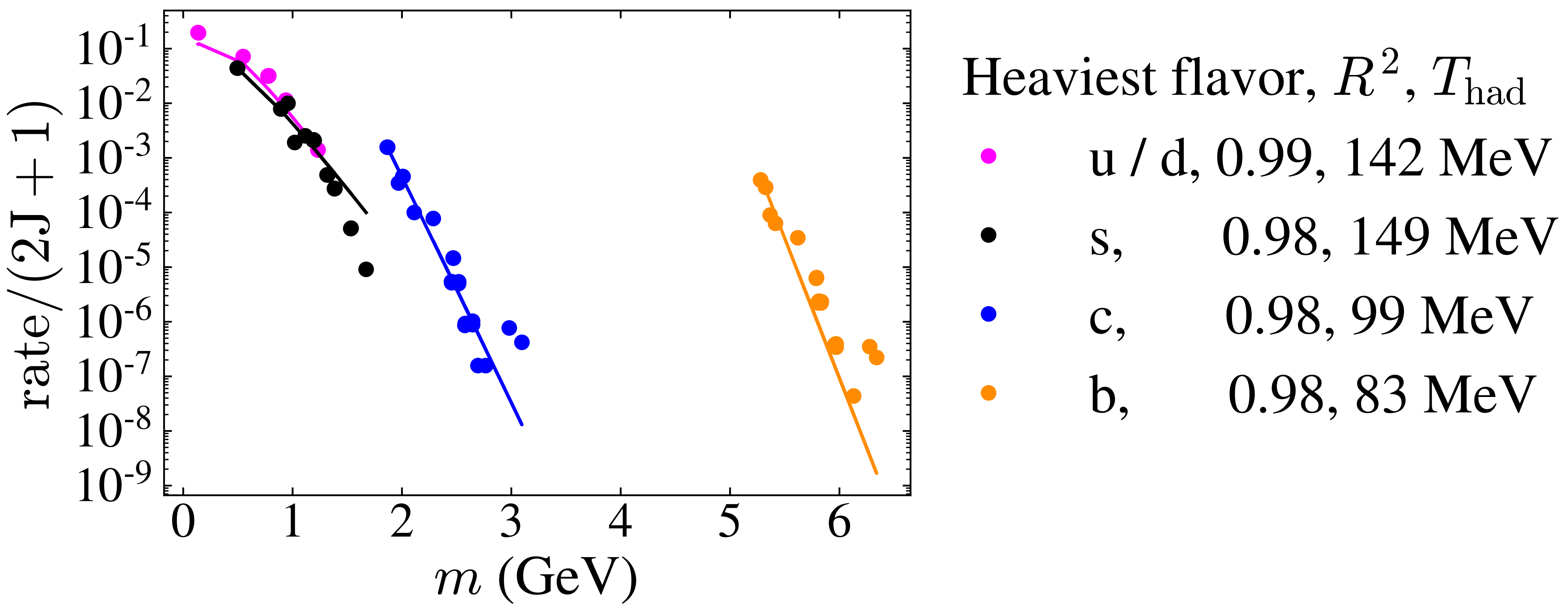


Glueball Species Distribution

Amazingly, the thermal distribution of glueball species is an OUTPUT of this model



Overproduction of heaviest states resembles thermal distribution found for heavy quarks in SM



GlueShower v2: Summary

arXiv: 2310.13731 (with A. Batz, T. Cohen, D. Curtin, G.D. Kribs)

- **Benchmark parameters provided in paper to profile over hadronization uncertainty:**

	c	function	shape parameters		$\alpha_D(p_{T\min})$	μ_z	σ_z	T_{had}/Λ_D
default	1.8	LSFF	$a = 1.9 \times 10^{-4}$	$bm_0^2 = 0.26$	1.0	0.5	0.3	1.04
soft	1.4	beta	$\alpha = 90.$	$k_\beta = 810$	1.6	0.1	0.01	0.911
hard	2.1	LSFF	$a = 82$	$bm_0^2 = 660$	0.76	0.9	0.01	1.38

- **Improves upon v1 by incorporating a more realistic handling of the flux ring fragmentation**
- **Thermal distribution of glueball species robustly emerges from the flux ring dynamics, supports this is physically reasonable**
- **Talking with Pythia authors to possibly incorporate into Hidden Valley module for public release**


Phenomenology

Collider Signatures

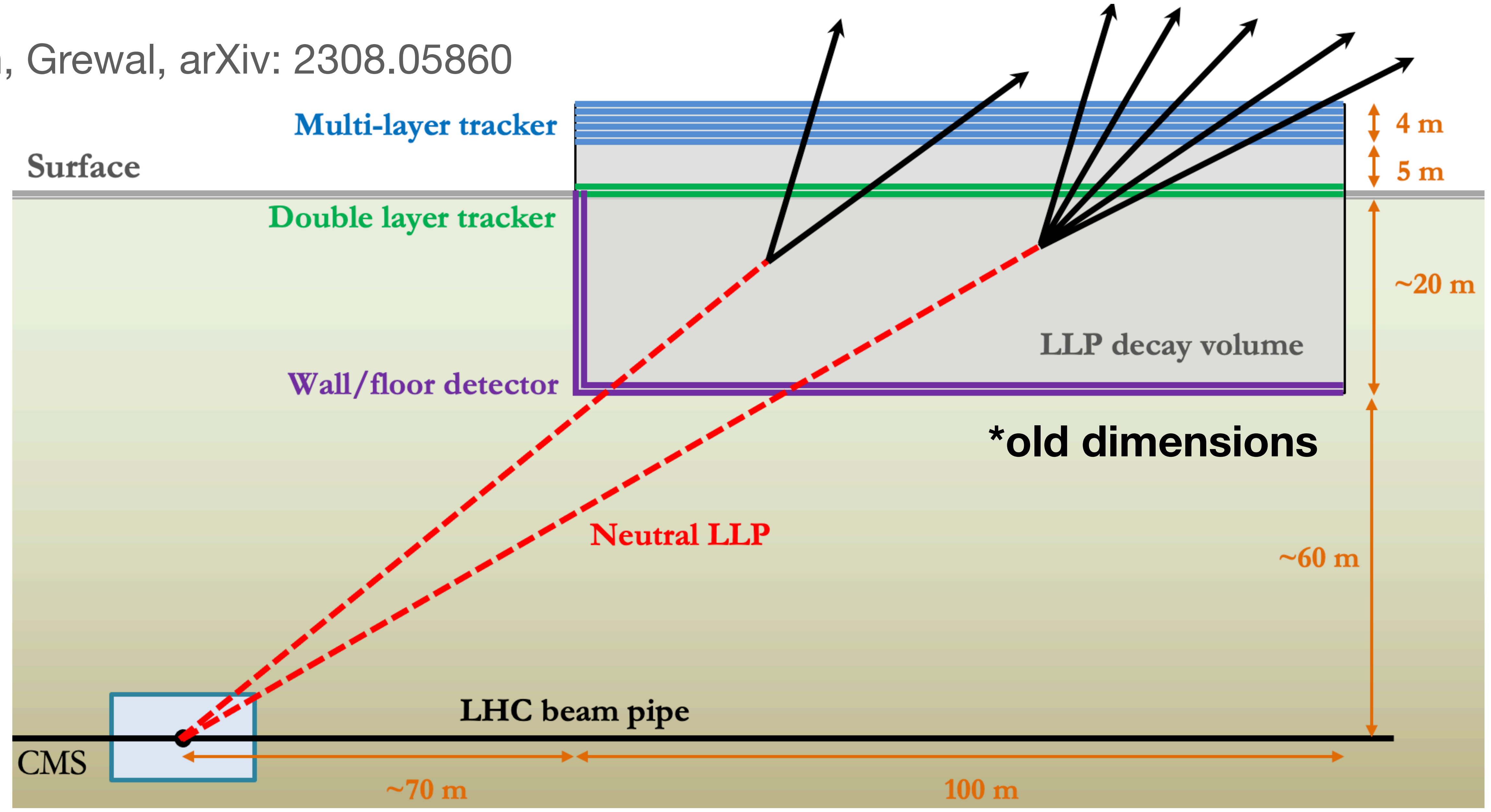
Glueballs as Long Lived Particles

- **MATHUSLA is a proposed displaced vertex detector for the HL-LHC upgrade**

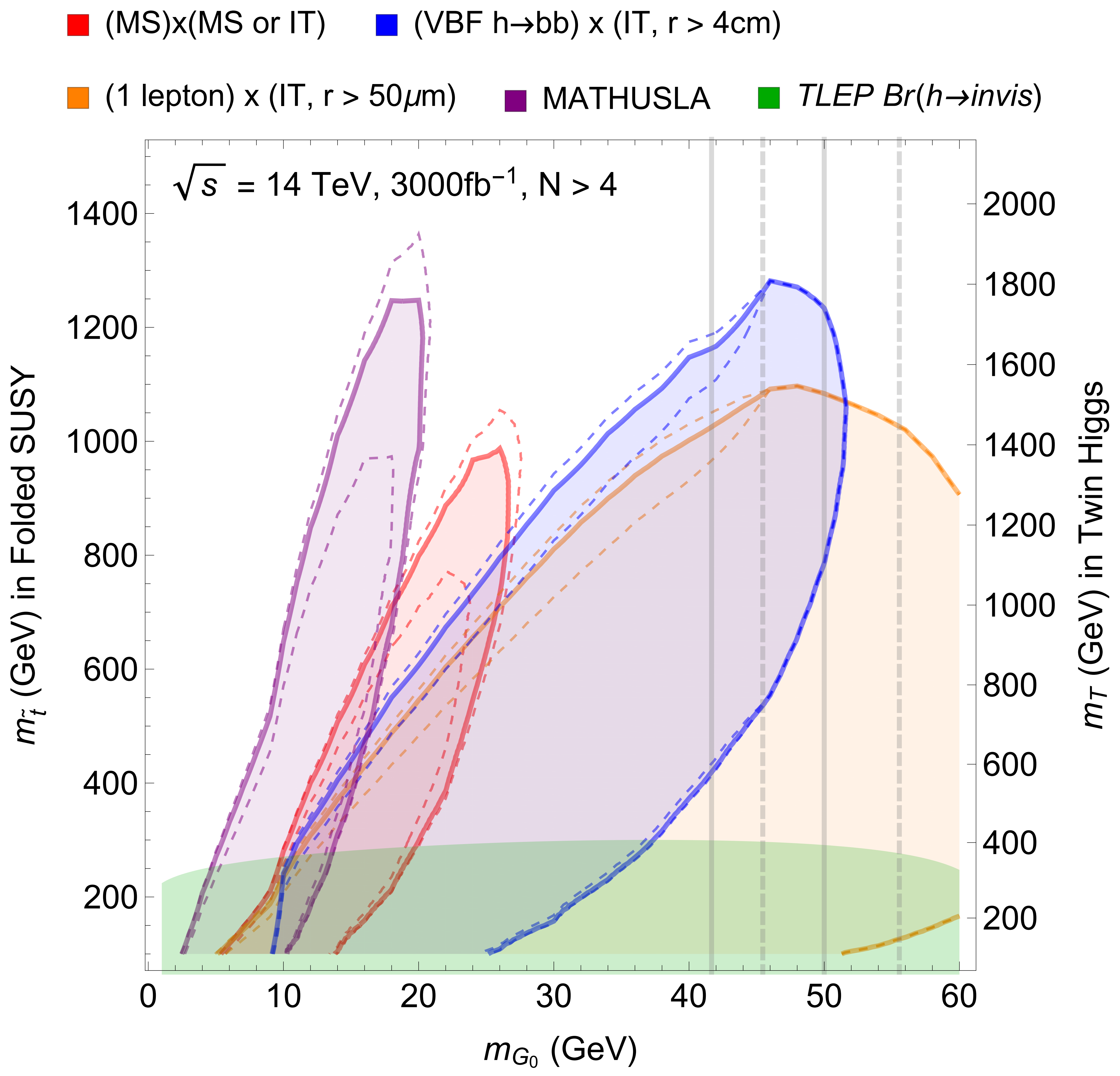
Chou, Curtin, Lubatti, arXiv:1606.06298
Alpigiani et al., arXiv:1811.00927

- **Able to probe much longer lifetimes**

Curtin, Grewal, arXiv: 2308.05860



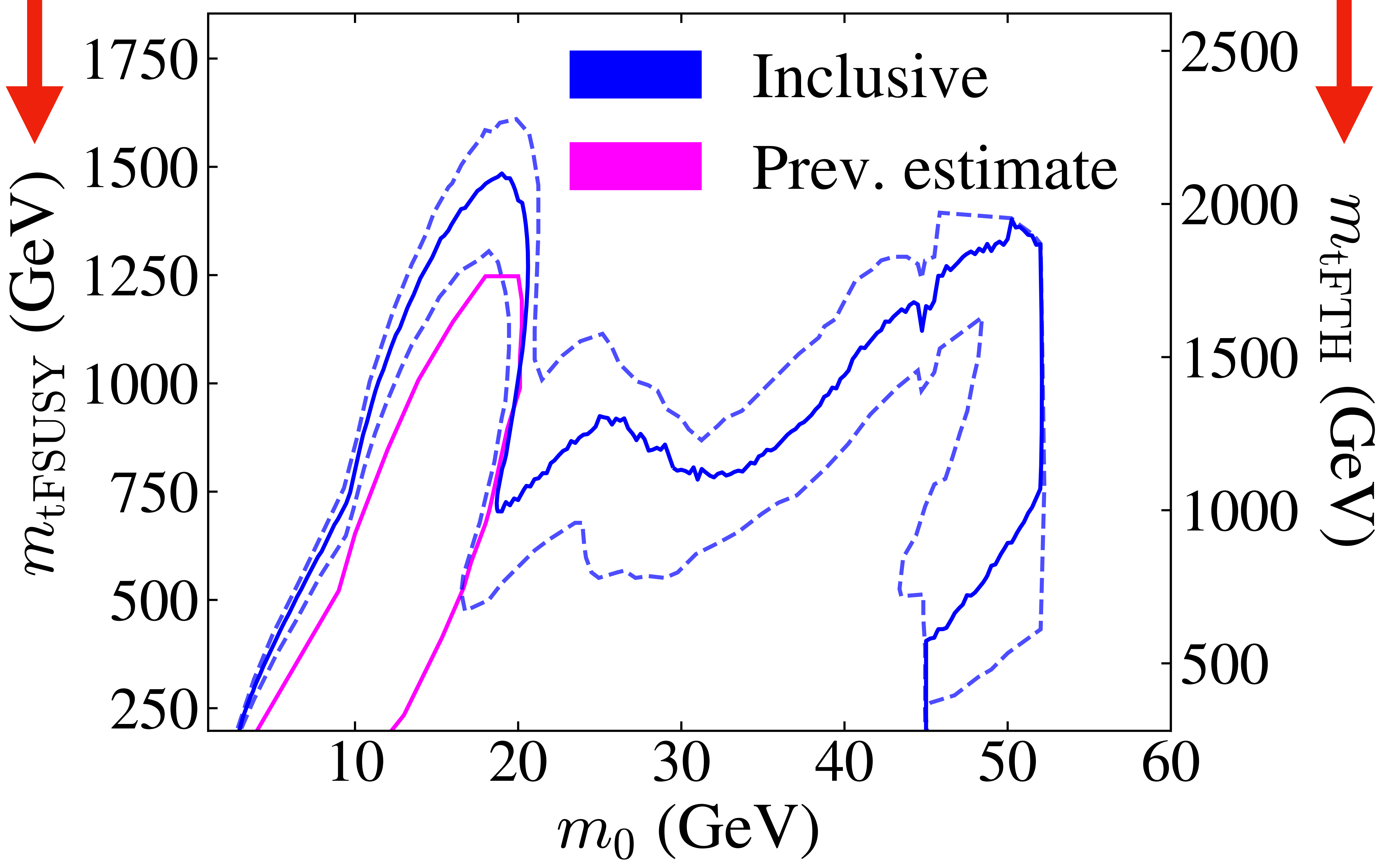
Curtin et al., arXiv: 1806.07396



Glueballs as Long Lived Particles

- Previous estimates only considered the lightest glueball (0++) and assumed Higgs only decays to two glueballs, conservative estimate
- Severely underestimated the reach, missed larger lifetimes of heavier glueball states
- Uncertainties included and don't qualitatively change the parameter space reach
- Probing the TeV scale is the goal of neutral naturalness models!

Dark top quark mass
in two different models

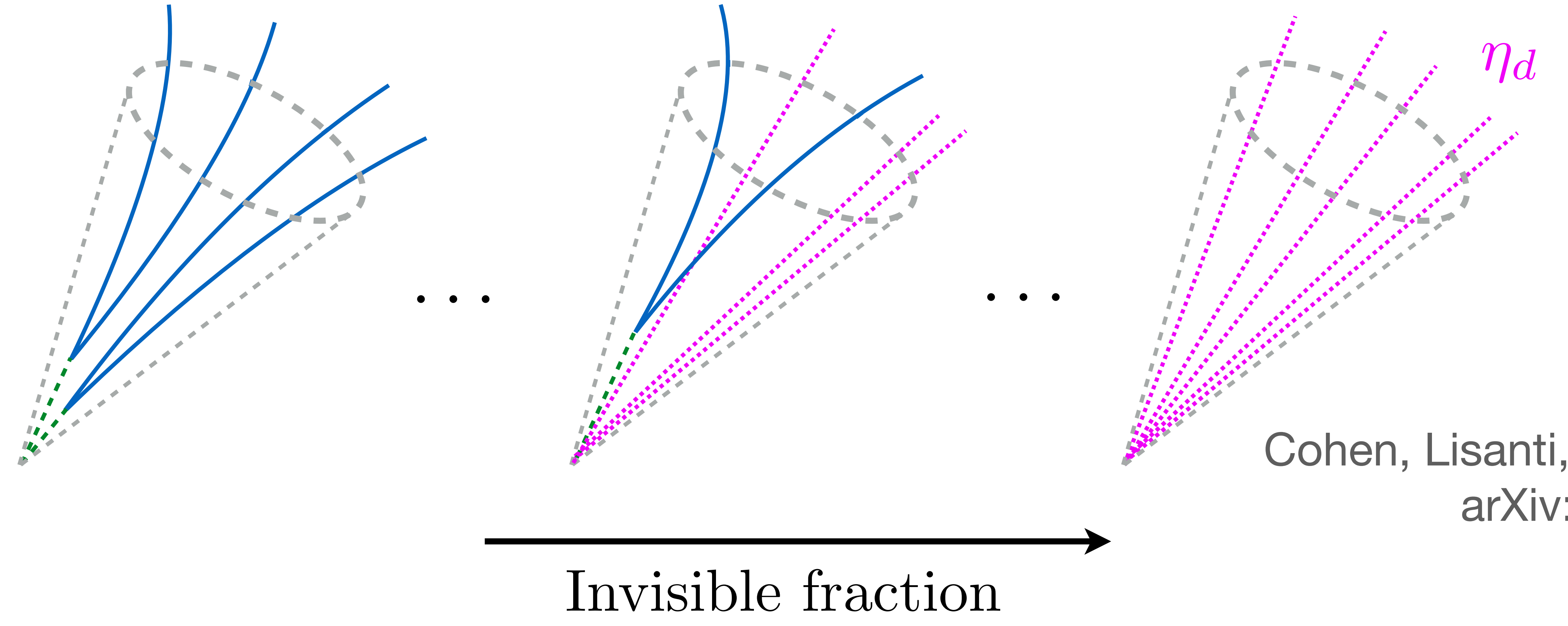


Semivisible Jets

- **Typical of dark sectors with hadrons of various lifetimes / stability**

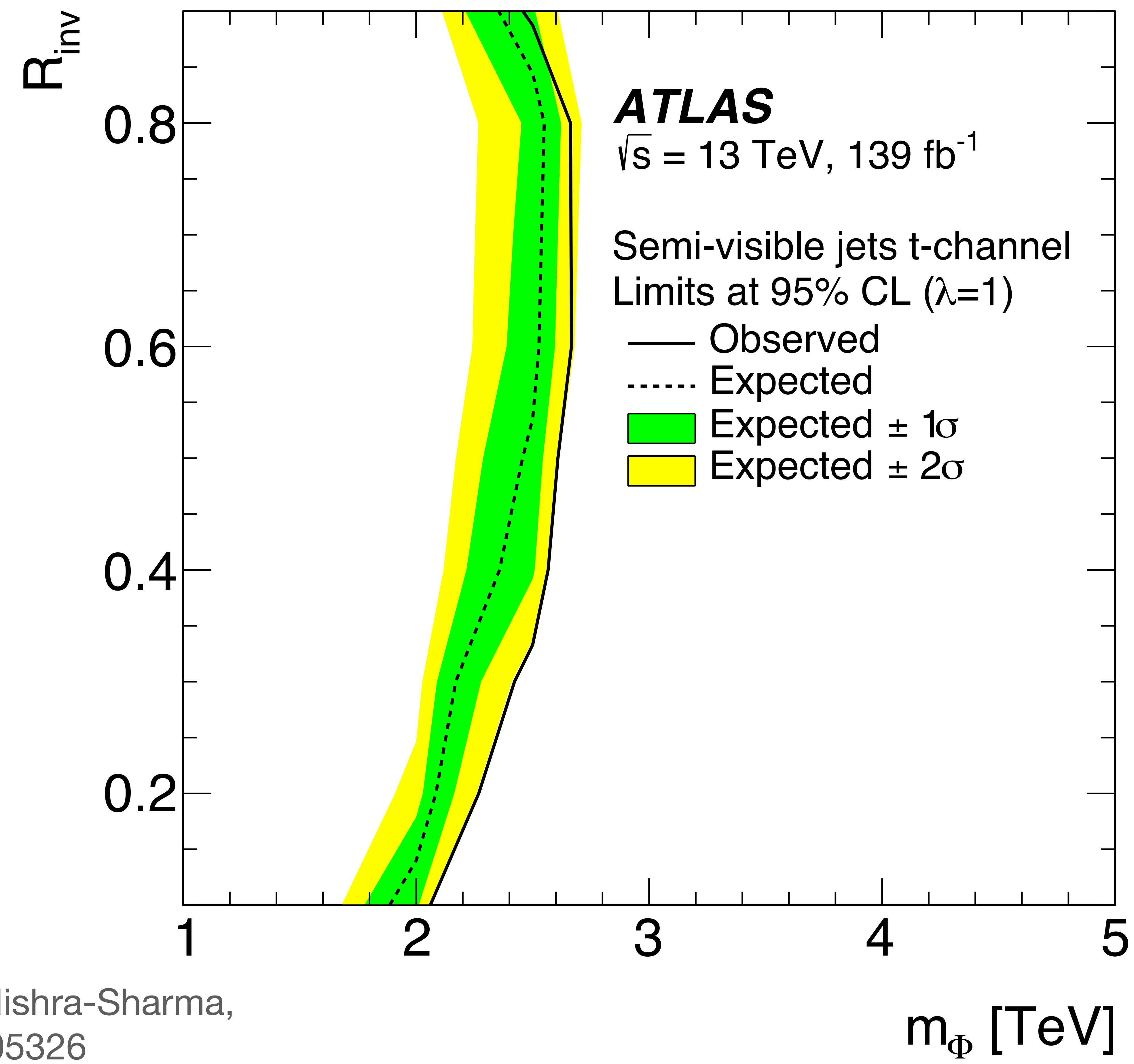
Cohen, Lisanti, Lou, arXiv: 1503.00009

- **Jet-like event coinciding with missing energy signatures**
- **Parameterised by mass of mediator and fraction of dark shower that is invisible to the LHC, R_{inv}**
- **Dark glueball showers naturally provide a benchmark for this signature due to the differing lifetimes**



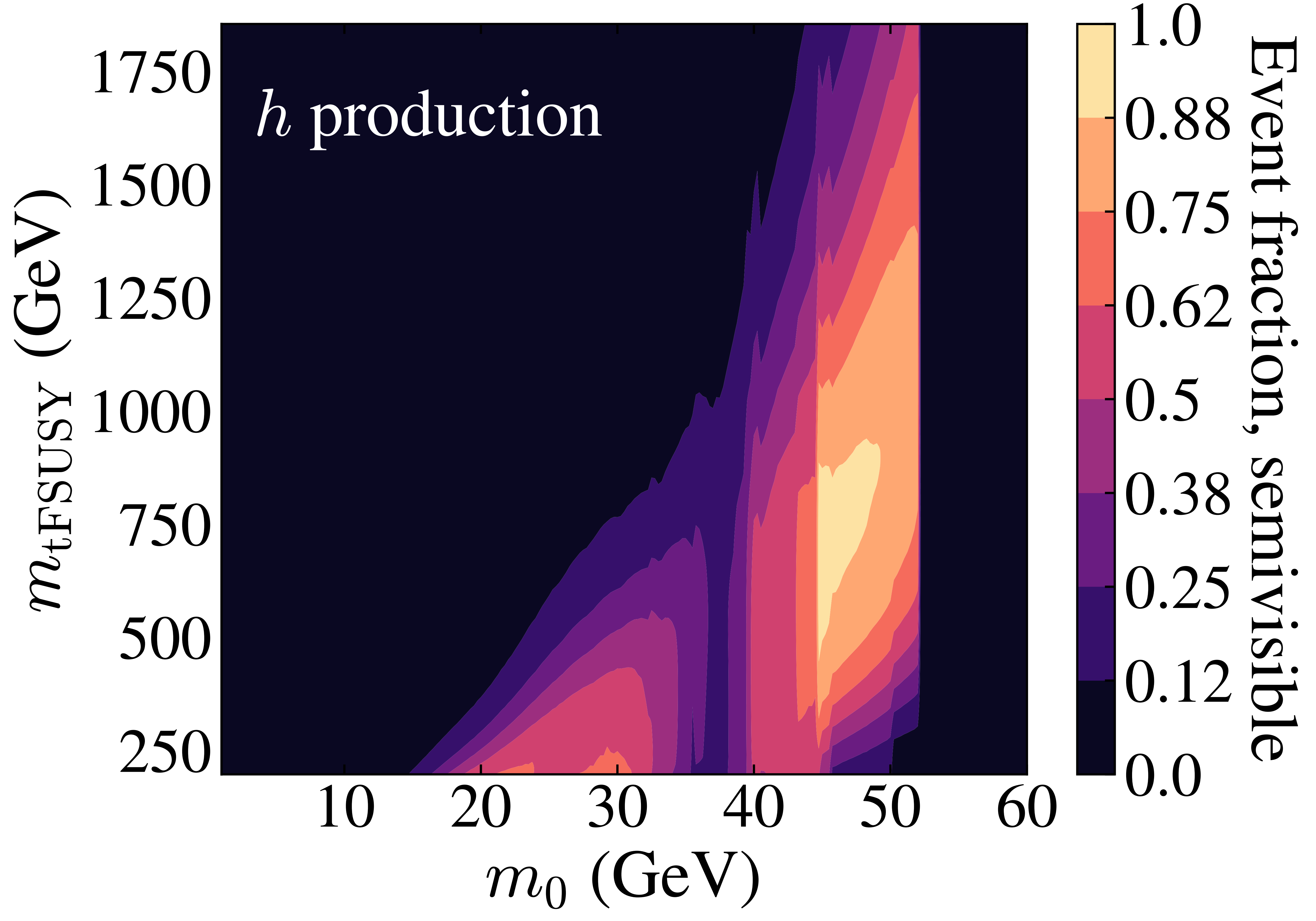
Cohen, Lisanti, Lou, Mishra-Sharma, arXiv: 1707.05326

ATLAS collab., arXiv: 2305.18037



Semivisible Jets

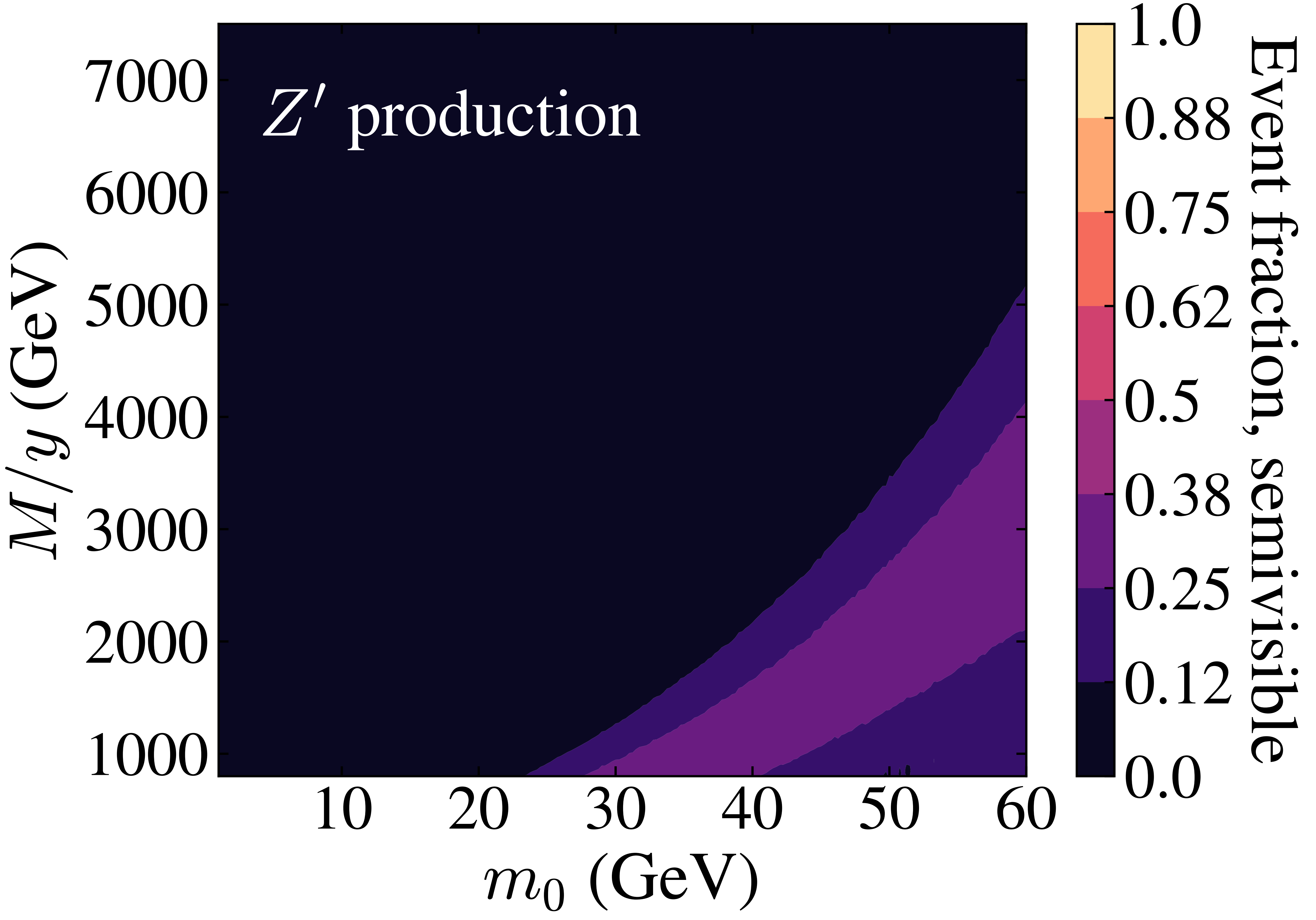
- Higg production
  - Assume gluon fusion and VBF production
  - Rescaled branching fraction to dark gluons
- Simplified analysis:
  - At least one glueball escape the tracker
  - At least one prompt glueball decay within the tracker
  - No glueball decays within the tracker with transverse displacement > 50 mm



Semivisible Jets

- Z' **production**
  - **Assume heavy mediator production,** $pp \to Z' \to Q_D\overline{Q}_D$ **, (**$m_{Z'} =$ **3 TeV)**
  - **Produces quirk-y bound state that can de-excite via dark glueball radiation**

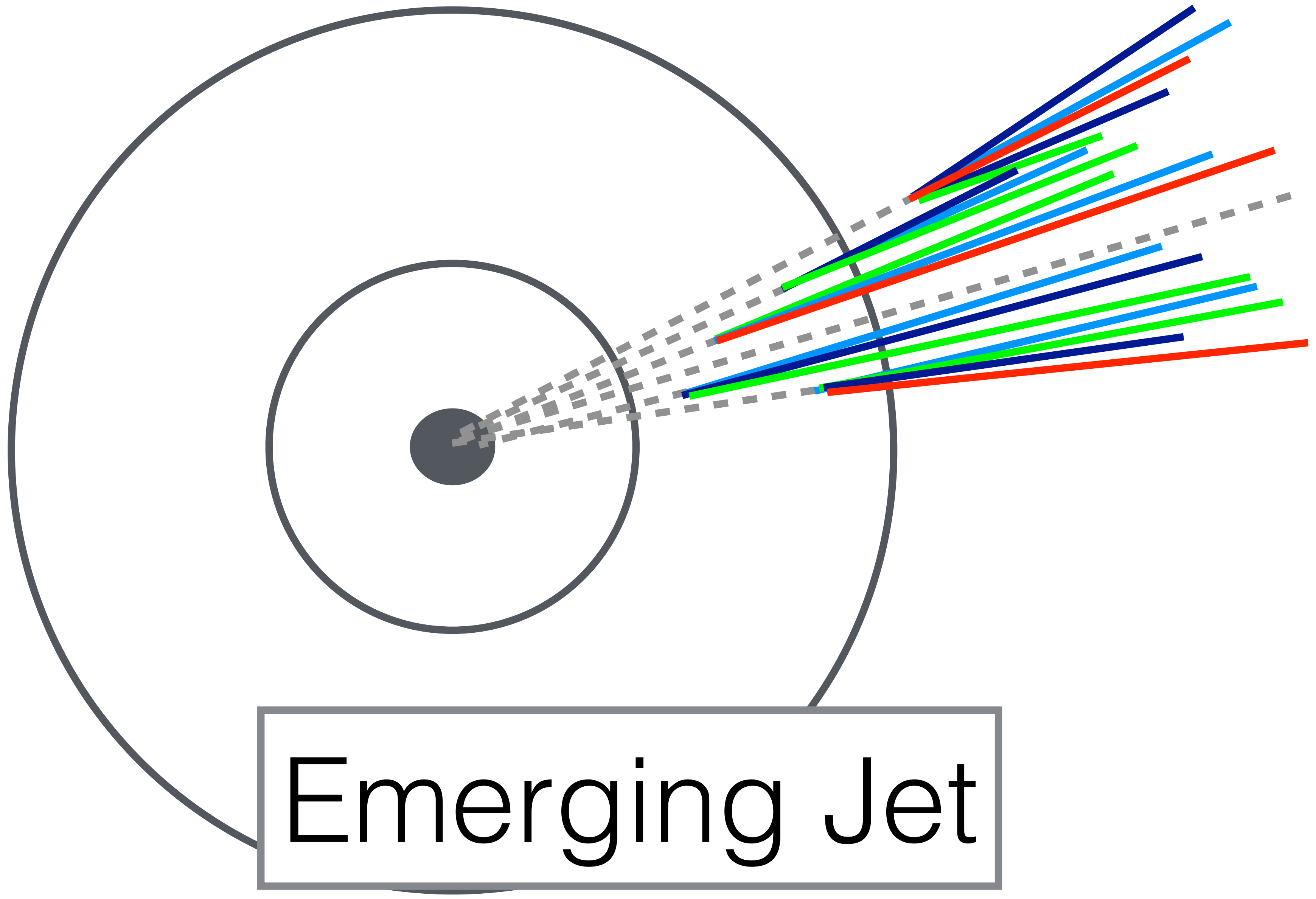
    Kang, Luty, arXiv: 0805.4642
    - **Open question, but assume** $M_Q \sim M_{Z'}/2$ **such that radiation is minimal**
  - $Q_D\overline{Q}_D$ **annihilate to dark gluons producing dark glueball shower**

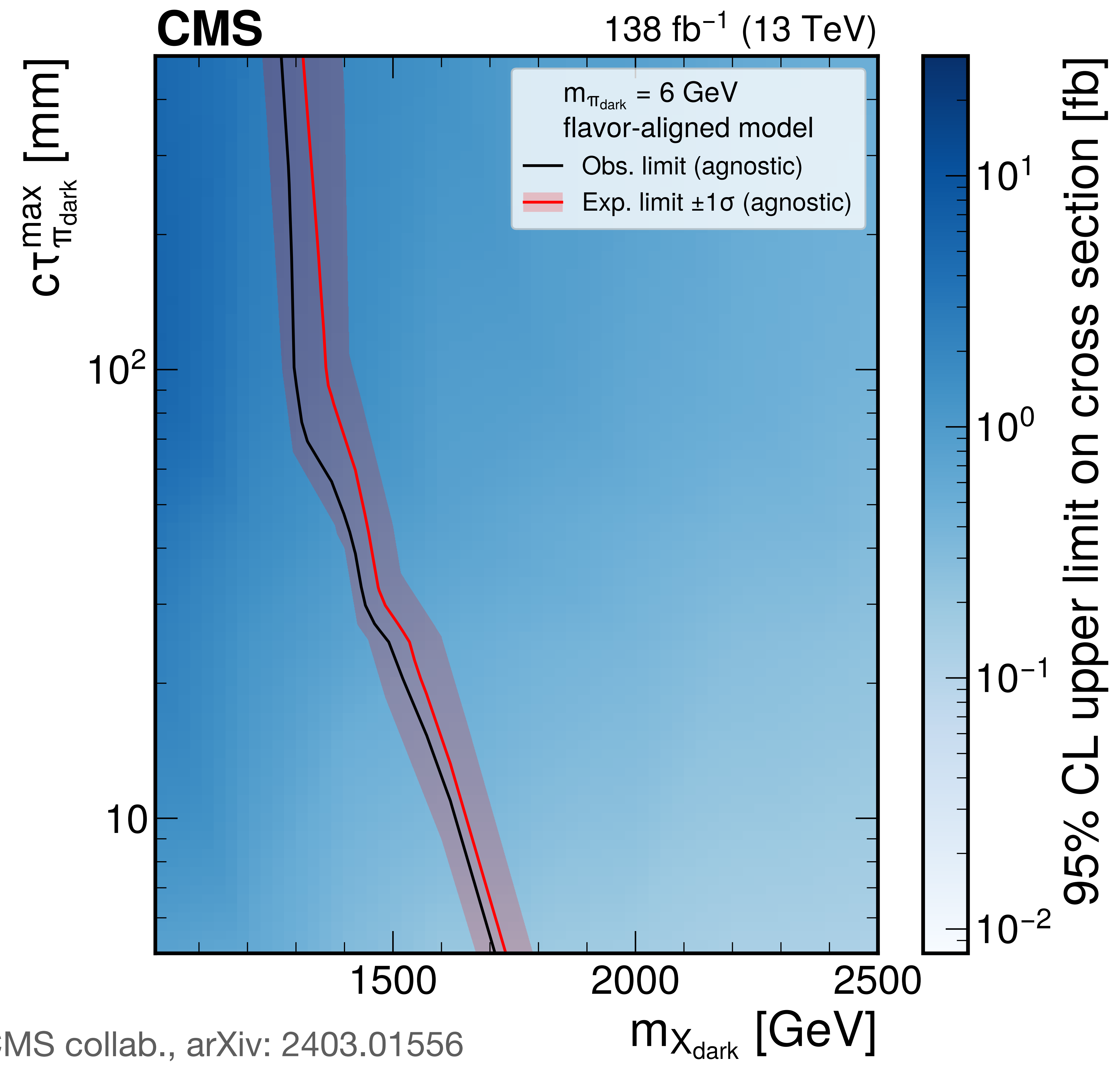


Emerging Jets

- **Similar to a semivisble jet, but requires all vertices to be displaced**

Schwaller, Stolarski, Weiler, arXiv: 1502.05409

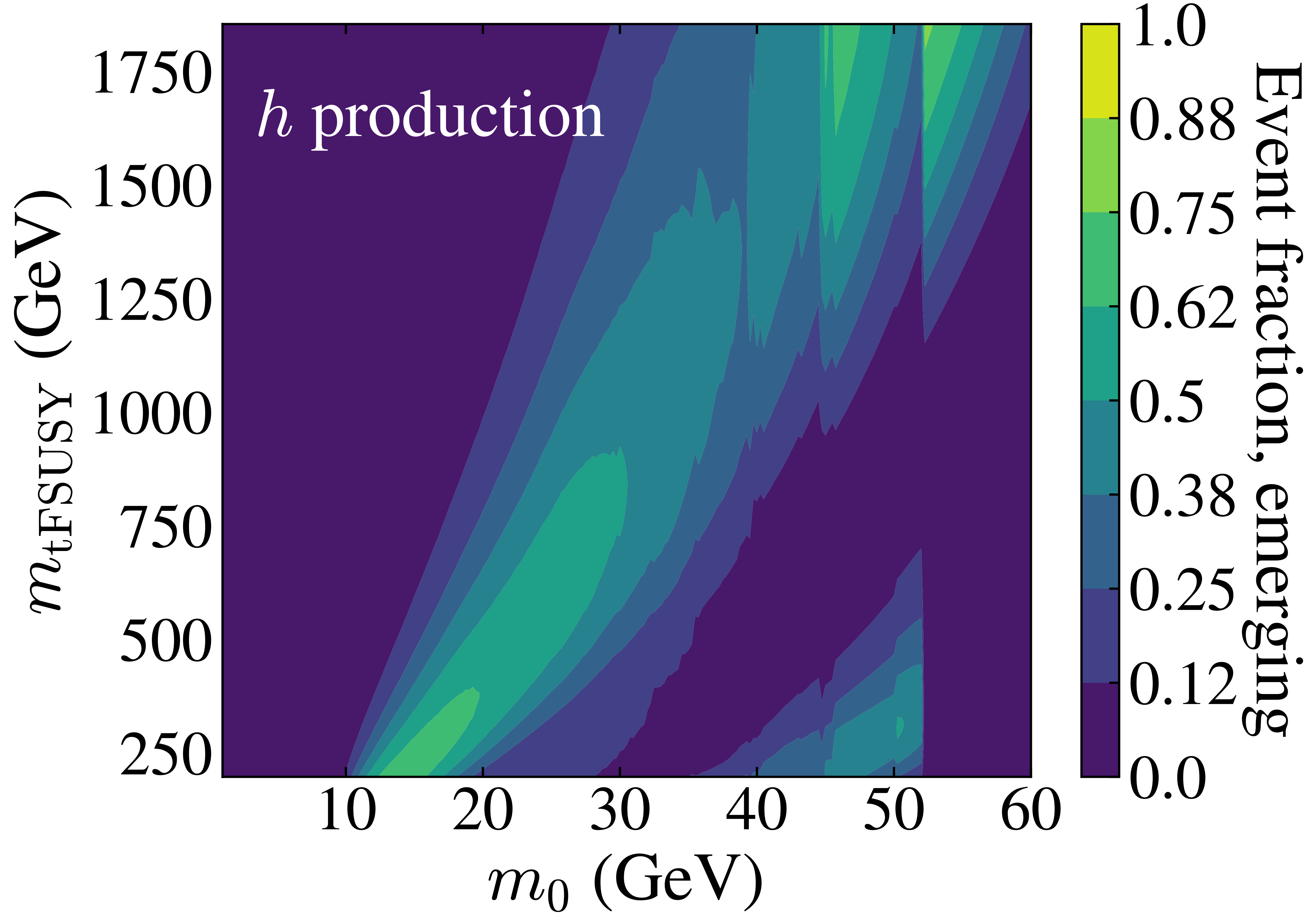




CMS collab., arXiv: 2403.01556

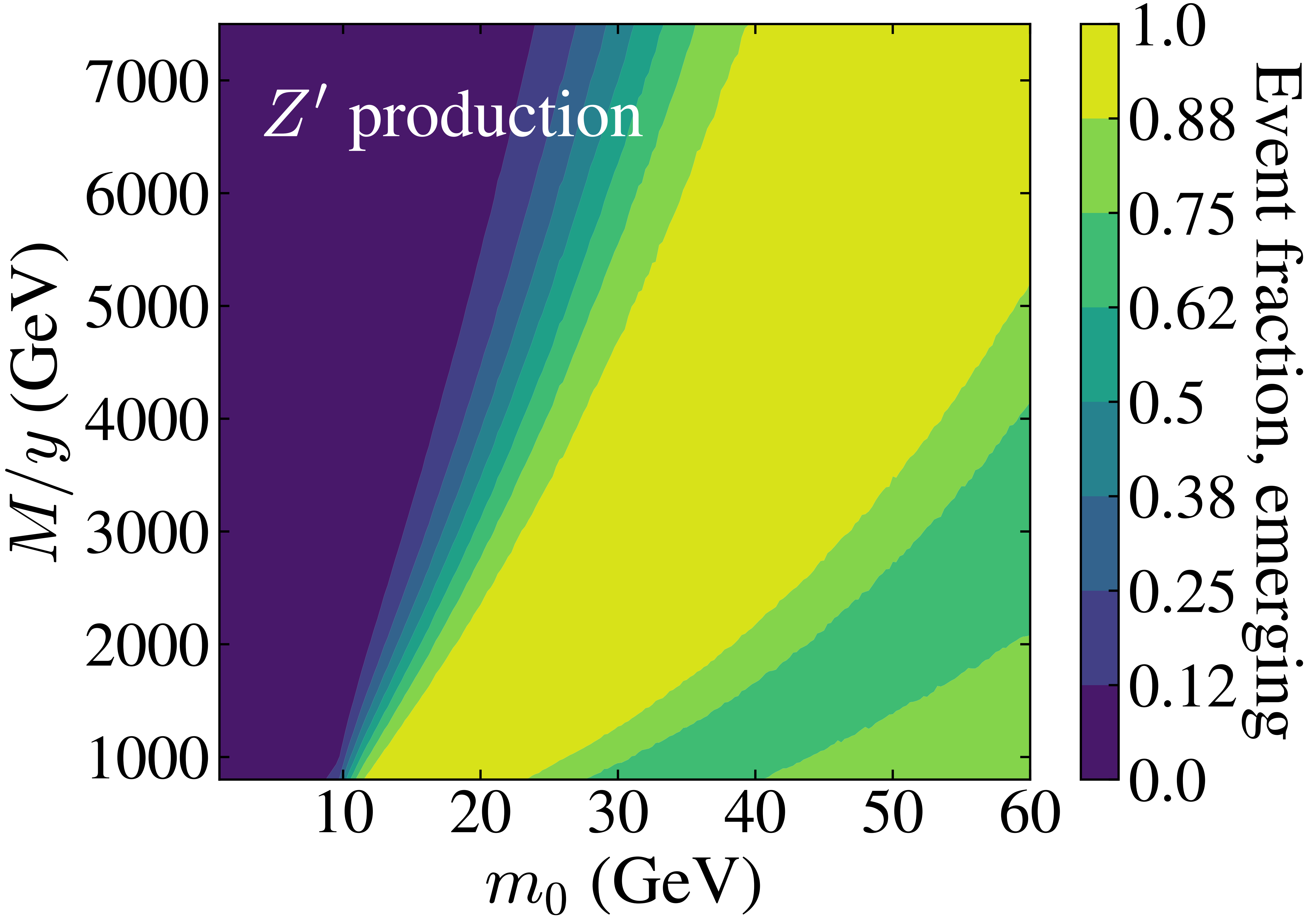
Emerging Jets

- Higgs production
- Simplified analysis:
    - At least one glueball decay within the CMS tracker with transverse displacement of at least 50 mm

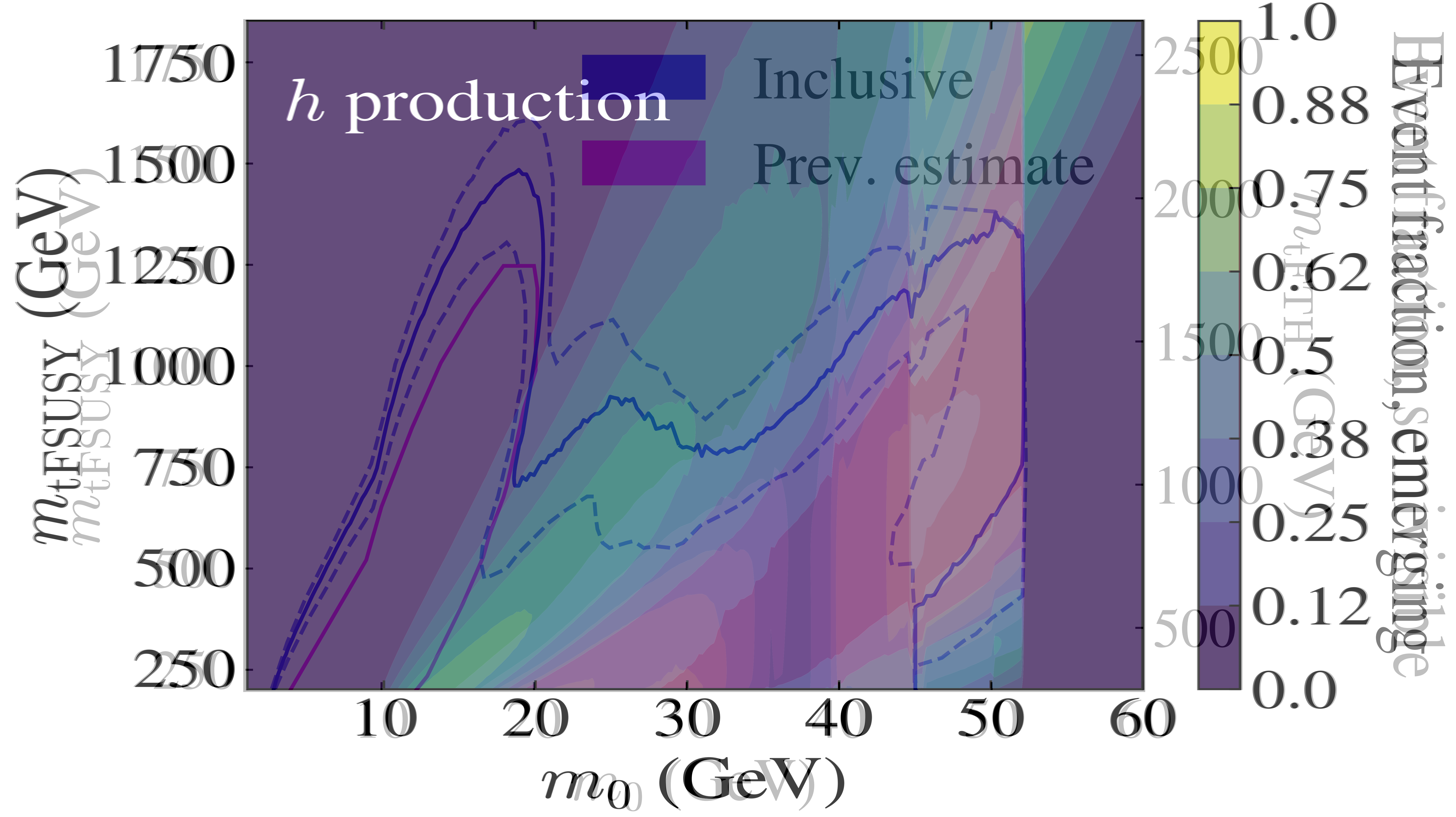


Emerging Jets

- Z' **production**
- **Simplified analysis:**
  - **At least one glueball decay within the CMS tracker with transverse displacement of at least 50 mm**



Complementarity



*Simplifed displaced jet searches

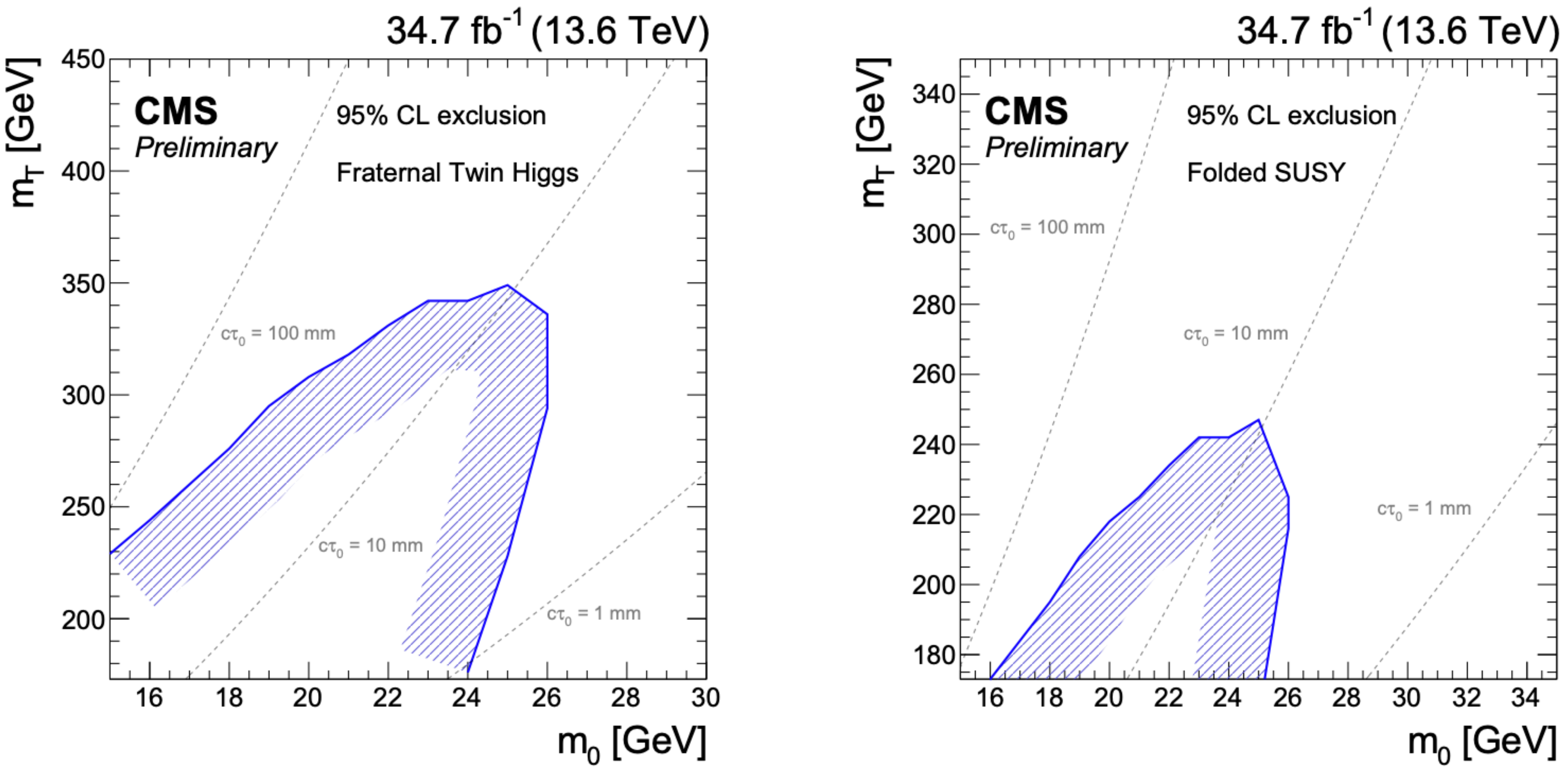
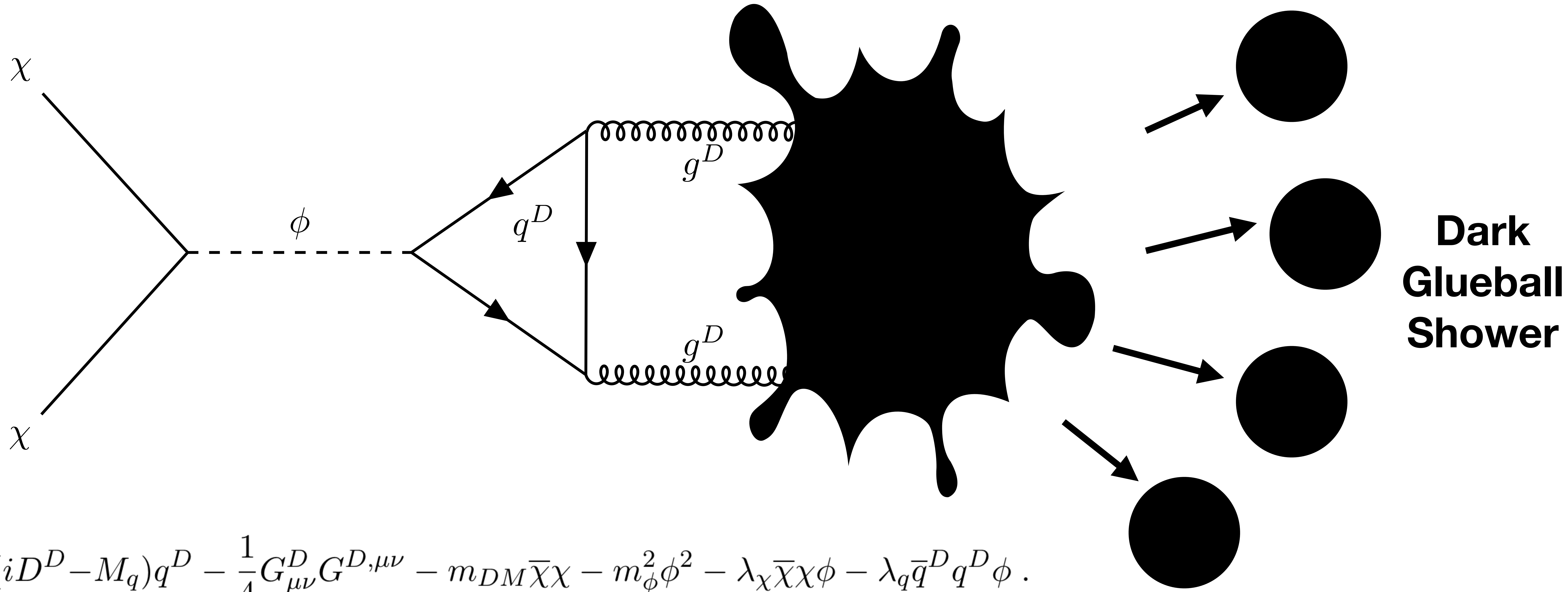


Figure 6: The 95% CL observed limits on the hidden-sector top partner mass m_T for different hidden glueball masses m_0, in the fraternal Twin Higgs model [29] (left) and the folded SUSY model [44] (right).

CMS collab., arXiv: 2409.10806

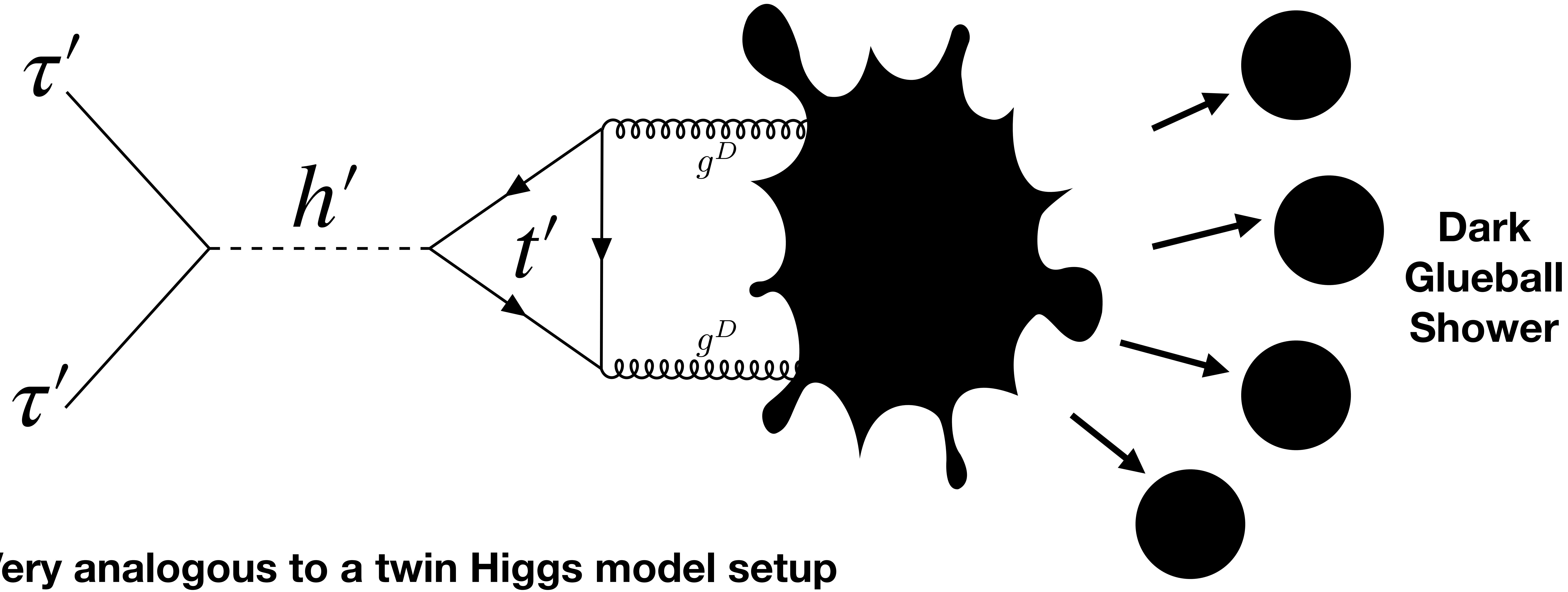

Indirect Detection

DM annihilating to glueballs



$$\mathcal{L} = \overline{q}^D(iD^D - M_q)q^D - \frac{1}{4}G^D_{\mu\nu}G^{D,\mu\nu} - m_{DM}\overline{\chi}\chi - m_\phi^2\phi^2 - \lambda_\chi\overline{\chi}\chi\phi - \lambda_q\overline{q}^D q^D\phi \ .$$

DM annihilating to glueballs



Very analogous to a twin Higgs model setup

Decay Benchmarks

Glueball	Higgs Portal
0^{++}	$h^* \to SM, hh$
2^{++}	$0^{++} + h^*$
0^{-+}	-
1^{+-}	-
2^{-+}	$0^{-+} + h^*$
3^{+-}	$1^{+-} + h^*$
3^{++}	$\{2^{++}, 0^{-+}, 2^{-+}\} + h^*$
2^{--}	$\{1^{+-}, 3^{+-}\} + h^*$
1^{--}	$1^{+-} + h^*$
2^{+-}	$\{1^{+-}, 3^{+-}, 2^{--}, 1^{--}\} + h^*$

Decay Benchmarks

Glueball	Higgs Portal	Gauge Portal
0^{++}	$h^* \to SM, hh$	$gg, \gamma\gamma, Z\gamma, ZZ, WW$
2^{++}	$0^{++} + h^*$	$gg, \gamma\gamma, Z\gamma, ZZ, WW$
0^{-+}	-	$gg, \gamma\gamma, Z\gamma, ZZ, WW$
1^{+-}	-	$\{0^{++}, 2^{++}, 0^{-+}\} + \{\gamma, Z\}$
2^{-+}	$0^{-+} + h^*$	$gg, \gamma\gamma, Z\gamma, ZZ, WW$
3^{+-}	$1^{+-} + h^*$	$\{0^{++}, 2^{++}, 0^{-+}, 2^{-+}\} + \{\gamma, Z\}$
3^{++}	$\{2^{++}, 0^{-+}, 2^{-+}\} + h^*$	$1^{+-} + \{\gamma, Z\}$
2^{--}	$\{1^{+-}, 3^{+-}\} + h^*$	$\{0^{++}, 2^{++}, 0^{-+}, 2^{-+}\} + \{\gamma, Z\}$
1^{--}	$1^{+-} + h^*$	$\{0^{++}, 2^{++}, 0^{-+}, 2^{-+}\} + \{\gamma, Z\}, ff$
2^{+-}	$\{1^{+-}, 3^{+-}, 2^{--}, 1^{--}\} + h^*$	$\{0^{++}, 2^{++}, 0^{-+}, 2^{-+}\} + \{\gamma, Z\}$

Decays to
two gauge bosons

Decays to lighter glueball
+ gauge boson

Decay Benchmarks

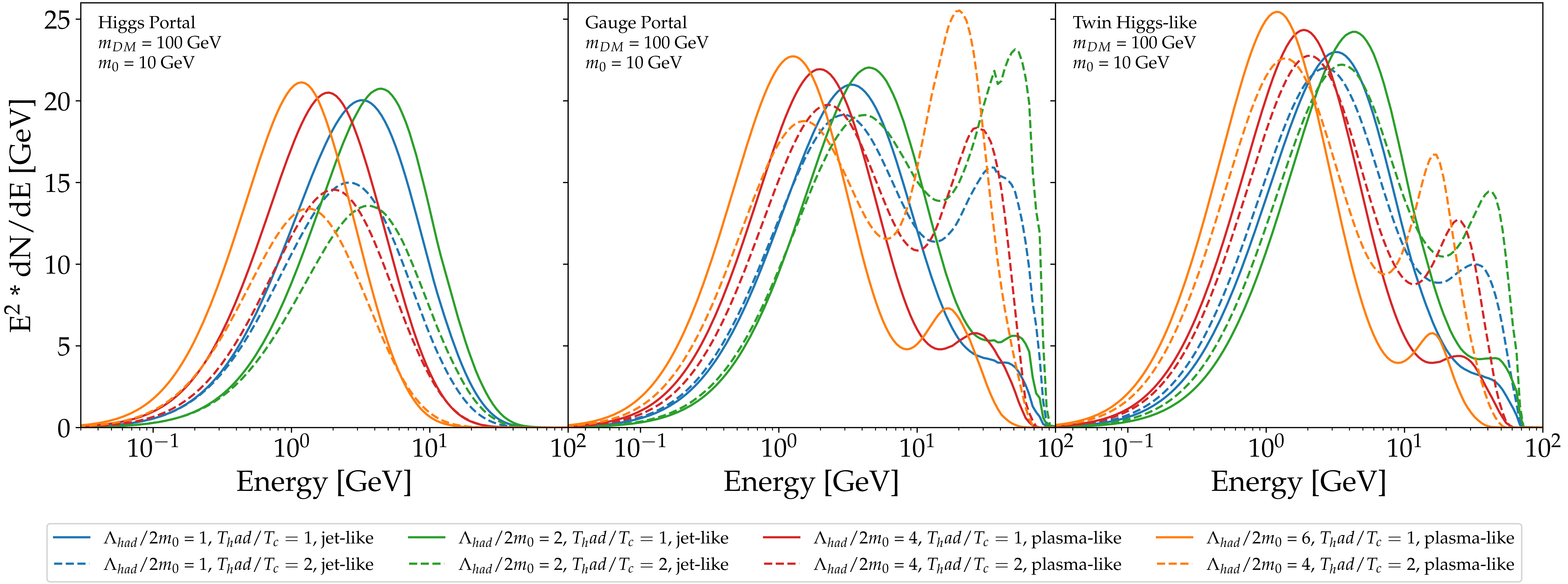
Glueball	Higgs Portal	Gauge Portal	Twin Higgs-like
0^{++}	$h^* \to SM, hh$	$gg, \gamma\gamma, Z\gamma, ZZ, WW$	h^*
2^{++}	$0^{++} + h^*$	$gg, \gamma\gamma, Z\gamma, ZZ, WW$	$0^{++} + h^*$
0^{-+}	-	$gg, \gamma\gamma, Z\gamma, ZZ, WW$	$gg, \gamma\gamma, Z\gamma, ZZ, WW$
1^{+-}	-	$\{0^{++}, 2^{++}, 0^{-+}\} + \{\gamma, Z\}$	$\{0^{++}, 2^{++}, 0^{-+}\} + \gamma$
2^{-+}	$0^{-+} + h^*$	$gg, \gamma\gamma, Z\gamma, ZZ, WW$	$0^{-+} + h^*$
3^{+-}	$1^{+-} + h^*$	$\{0^{++}, 2^{++}, 0^{-+}, 2^{-+}\} + \{\gamma, Z\}$	$1^{+-} + h^*$
3^{++}	$\{2^{++}, 0^{-+}, 2^{-+}\} + h^*$	$1^{+-} + \{\gamma, Z\}$	$\{2^{++}, 0^{-+}, 2^{-+}\} + h^*$
2^{--}	$\{1^{+-}, 3^{+-}\} + h^*$	$\{0^{++}, 2^{++}, 0^{-+}, 2^{-+}\} + \{\gamma, Z\}$	$\{1^{+-}, 3^{+-}\} + h^*$
1^{--}	$1^{+-} + h^*$	$\{0^{++}, 2^{++}, 0^{-+}, 2^{-+}\} + \{\gamma, Z\}, ff$	$1^{+-} + h^*$
2^{+-}	$\{1^{+-}, 3^{+-}, 2^{--}, 1^{--}\} + h^*$	$\{0^{++}, 2^{++}, 0^{-+}, 2^{-+}\} + \{\gamma, Z\}$	$\{1^{+-}, 3^{+-}, 2^{--}, 1^{--}\} + h^*$

Assumes both Dimension 6 (Higgs) and Dimension 8 (Gauge) operators, but Dimension 6 dominates

Indirect Detection Spectra

arXiv: 2211.05794 (with D. Curtin)

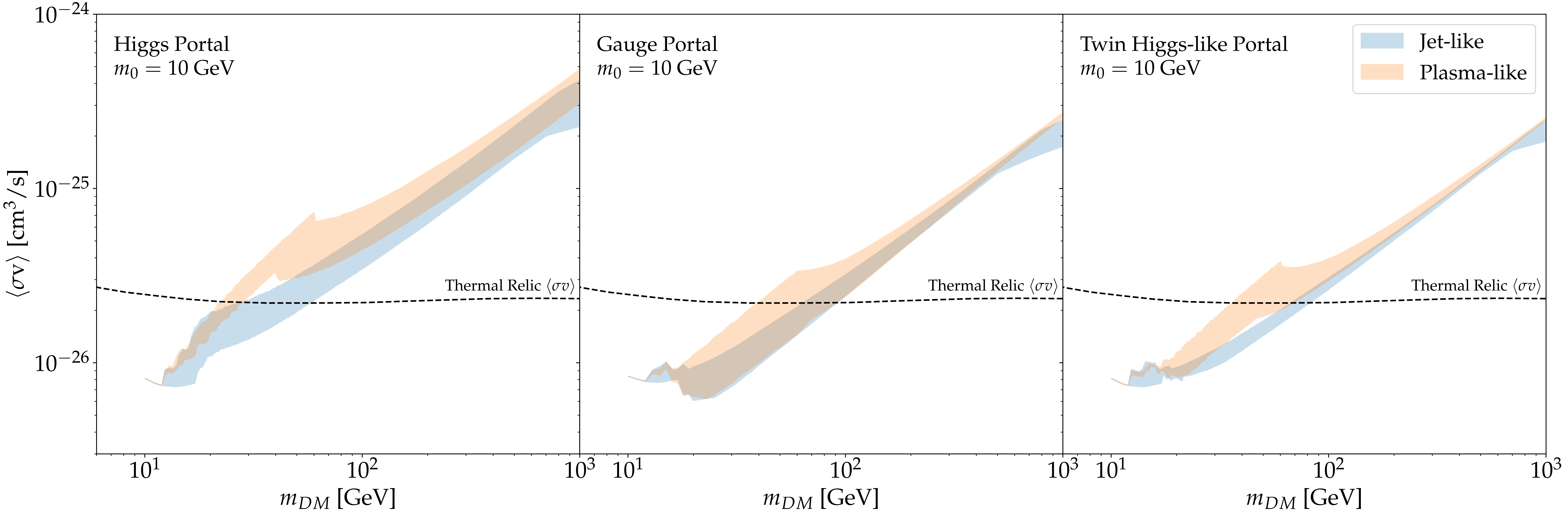
Dark glueball photon spectra computed using `GlueShower v1` and a range of decay portals



Fermi-LAT constraints

arXiv: 2211.05794 (with D. Curtin)

Utilising likelihood functions from Fermi-LAT, arXiv:1611.03184

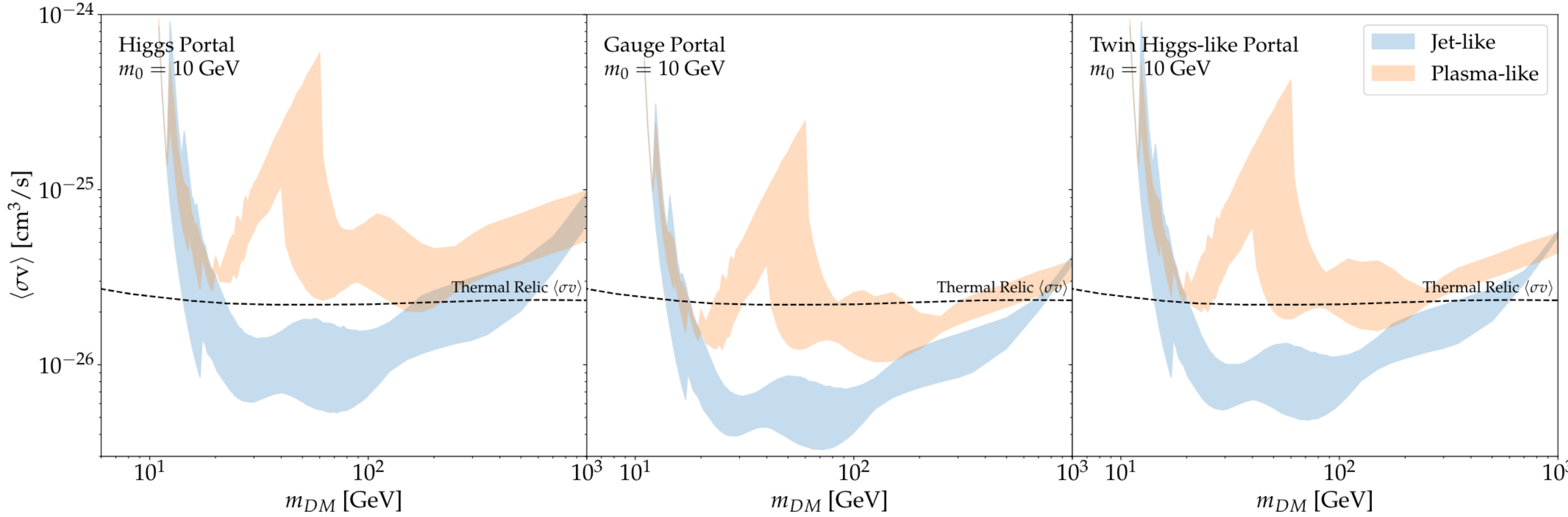


AMS-02 cosmic ray constraints

arXiv: 2211.05794 (with D. Curtin)

Evoli et al., arXiv:1607.07886

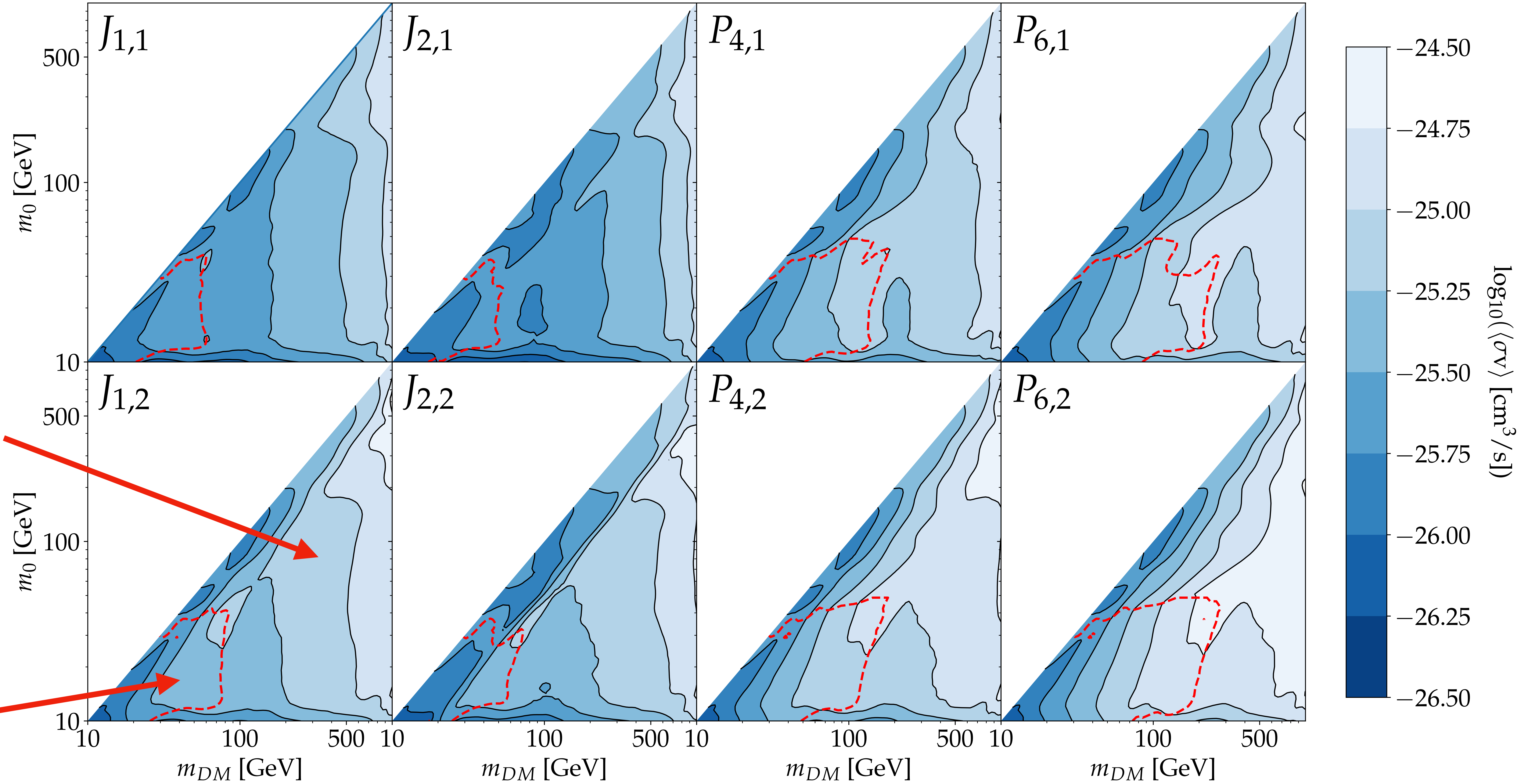
Antiproton spectra propagated using DRAGON



Combined constraints

arXiv: 2211.05794 (with D. Curtin)

Eight different hadronization benchmarks

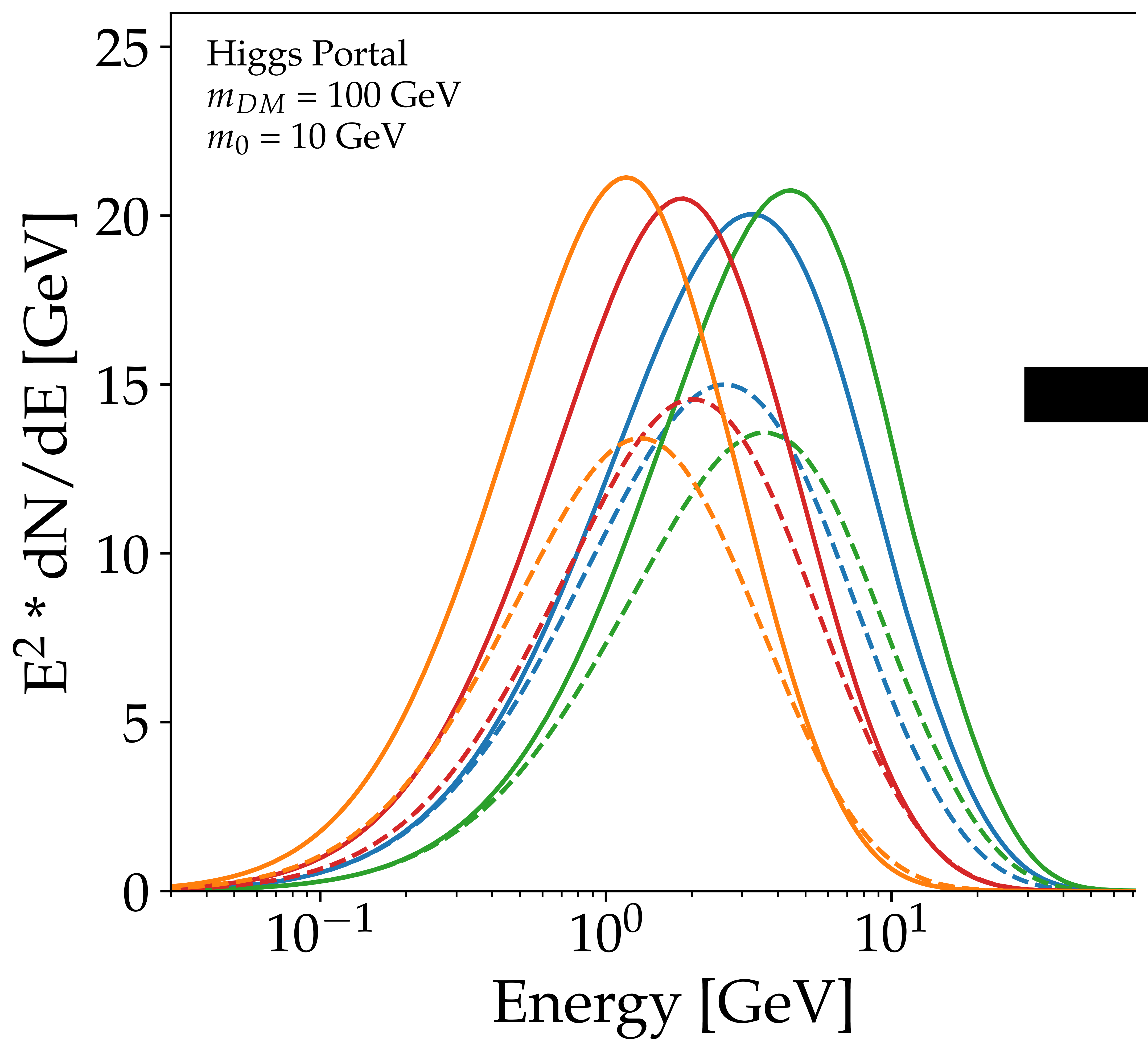


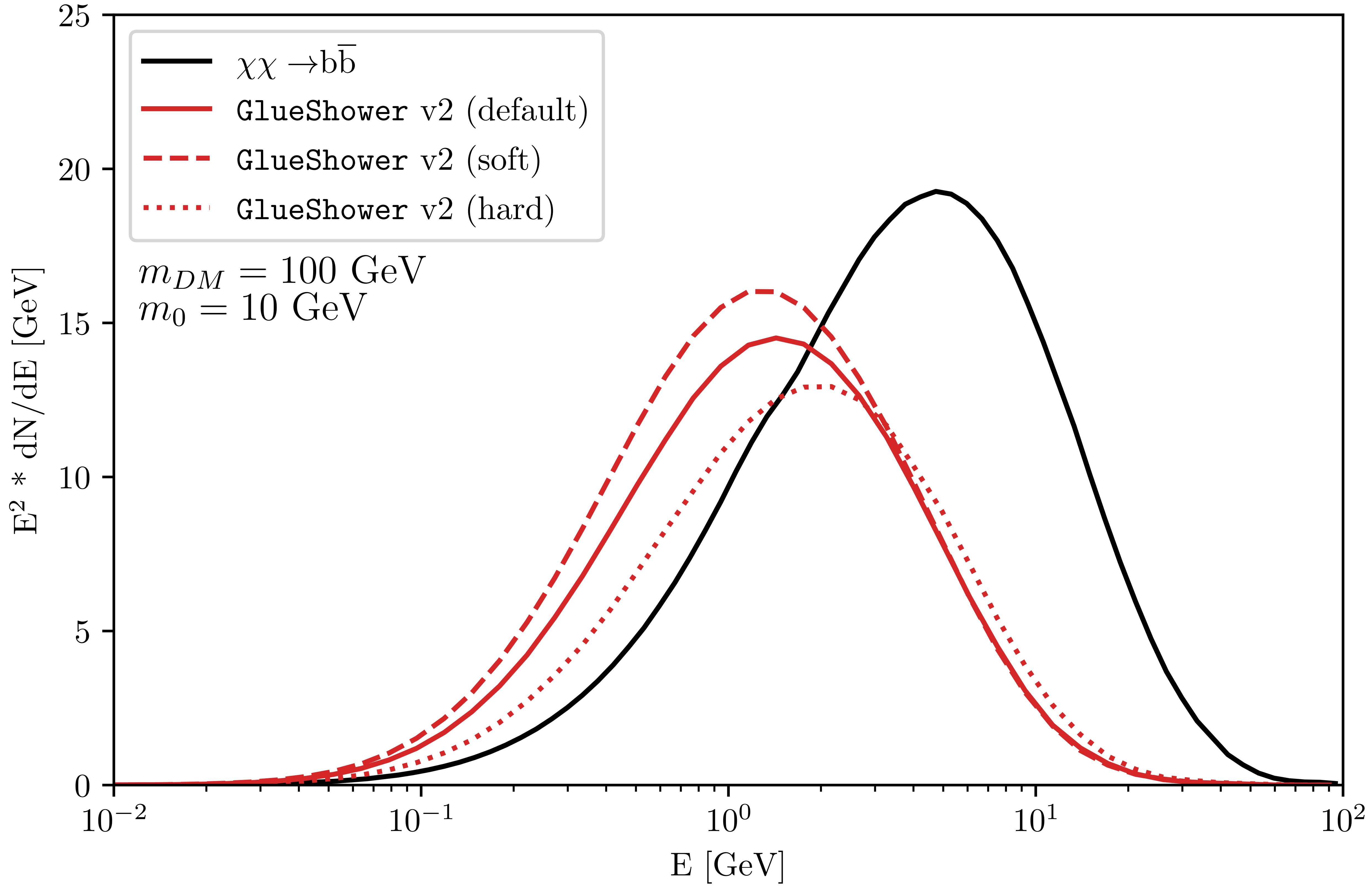
Antiproton constraints

Photon constraints

Updating results with v2

(in progress)





Updating results with v2
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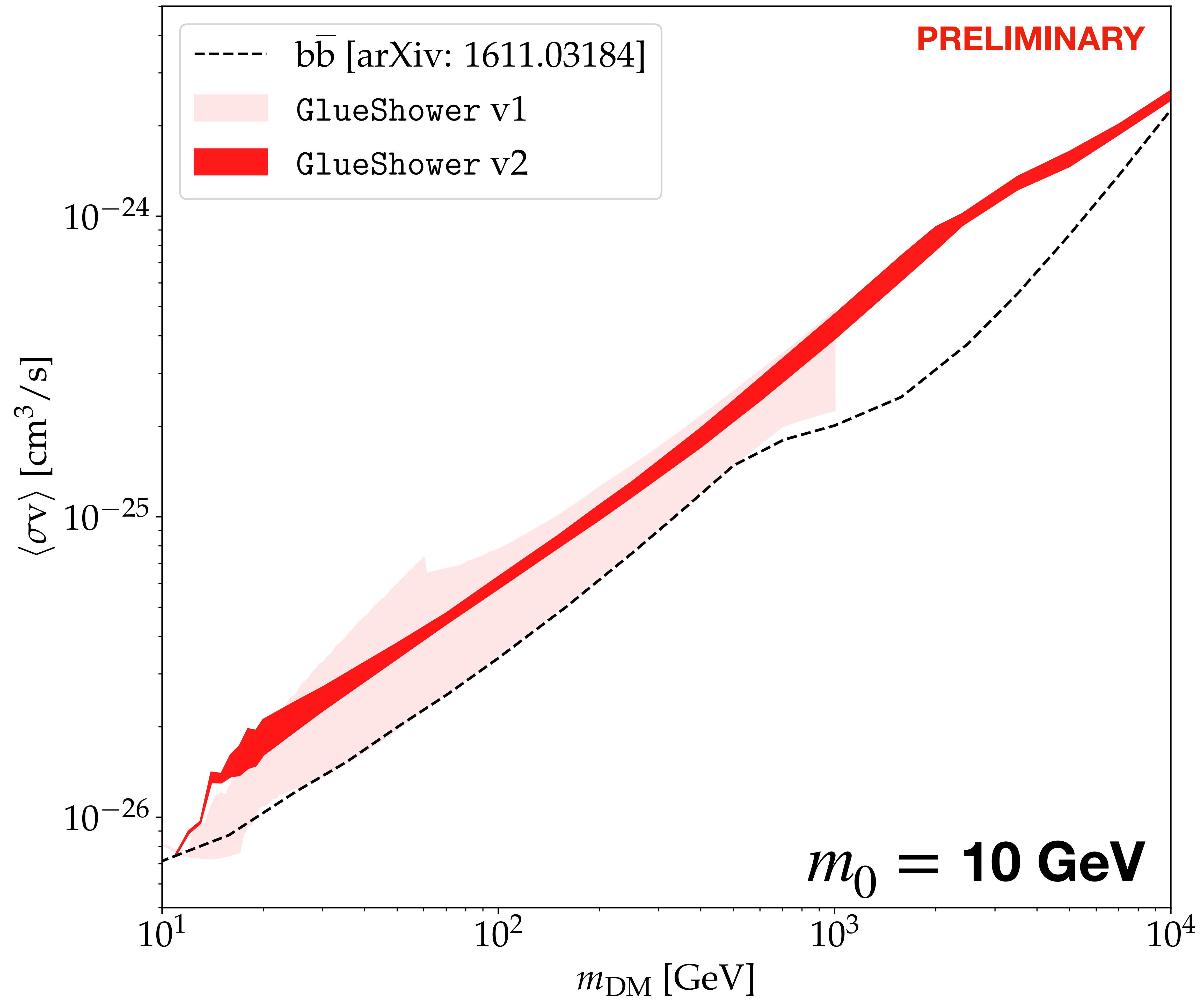
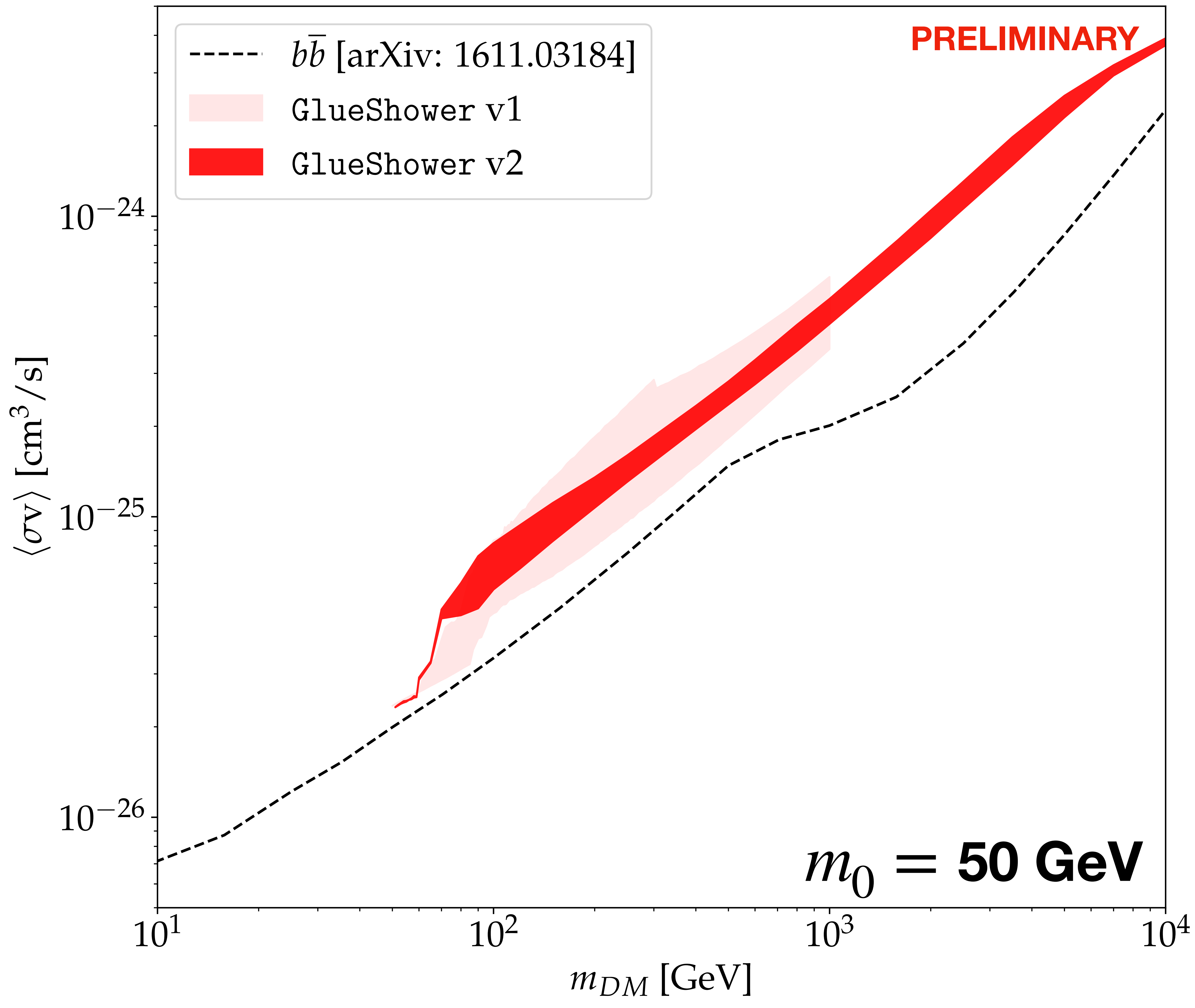
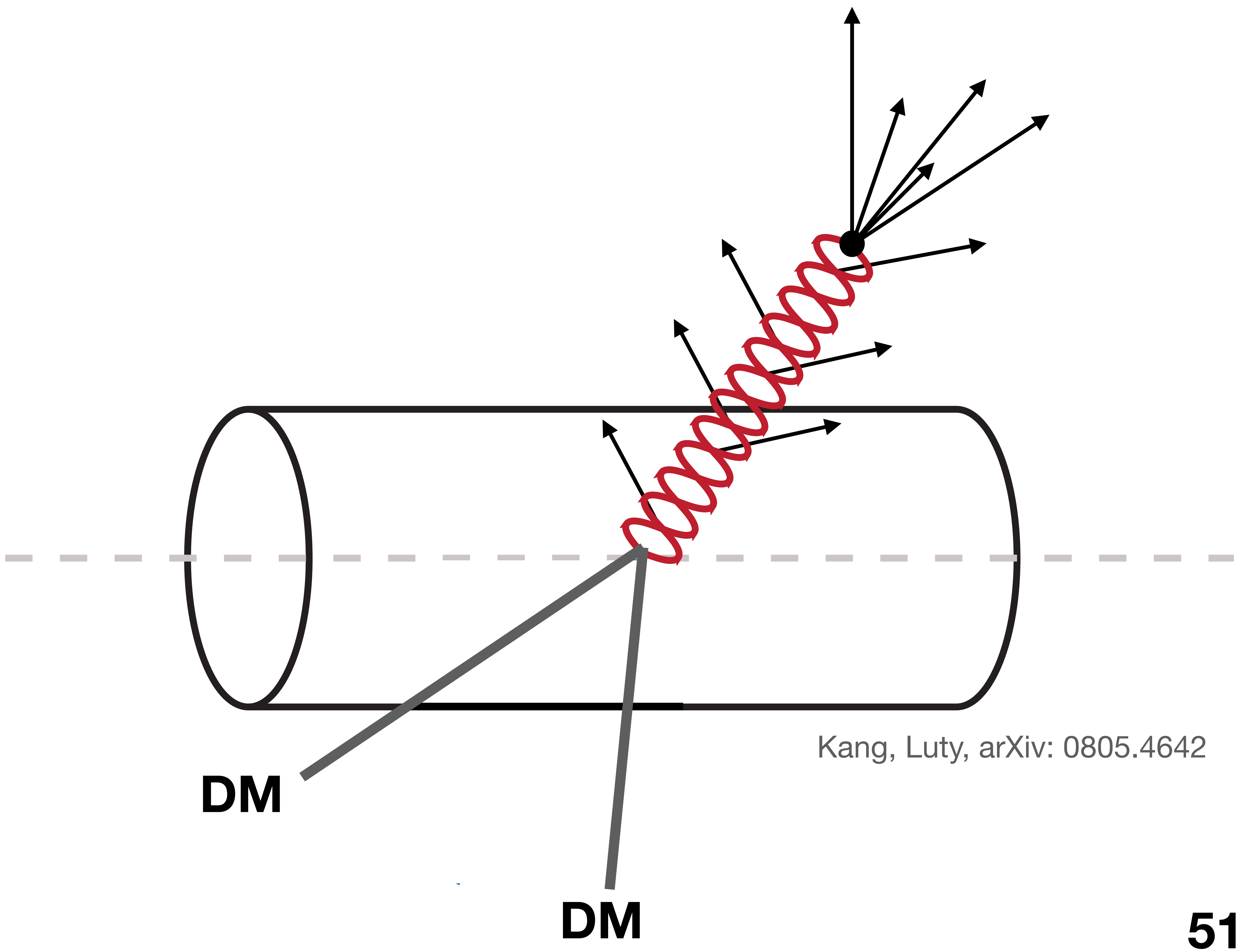




Future Work

Open Questions

- Quirkonium dynamics
    - If DM could annihilate to the heavy quarks, they would form a ‘quirky’ bound state
    - This system can only de-excite by glueball emission, once each crossing time, still unknown
    - Eventually the heavy quarks annihilate into gluons which then produces a glueball shower



Kang, Luty, arXiv: 0805.4642

Open Questions

- AMS-02 antinuclei excess
  - AMS-02 is potentially seeing comparable rates of antihelium-4 production to antihelium-3 production
  - Naively should expect $\mathcal{O}(10^3 - 10^4)$ suppression relative to each species due to phase space suppression

Winkler, De La Torre Luque, Linden, arXiv: 2211.00025

  - Other papers have hypothesised the ability of a confining dark sector to boost SM Parton multiplicity to overcome the phase space suppression
  - Dark sector glueballs are generically too long lived to achieve this, but could other dark sector implementations work? SUEP?

Summary

- A $N_f = 0$ dark QCD sector is both a theoretically motivated but also relatively generic BSM extension
- `GlueShower` and its updates provide the first MC simulations to allow quantitative studies of these model observables
  - Collider sensitivity estimates
  - Indirect detection constraints
- Lots of work still to do: further iterations on the `GlueShower` physics, addressing new astro anomalies, detailed collider searches…