Image credit:
Deep Lens Survey

Simulation and Collider Signatures of Dark Glueball Showers

Caleb Gemmell
University of Toronto

Roadmap of Dark Matter Models for Run 3
CERN
May 2024

UNIVERSITY OF TORONTO

Overview:

1. Motivation and background
2. How to simulate dark glueball hadronization?
3. Collider Signatures
4. Conclusions

Motivation and background

Theory motivation

- **Dark showers are a generic signature that arise from confining dark sectors**

  Strassler, Zurek, hep-ph/0604261

- **Complex dark sectors are theoretically motivated as they can address naturalness issues, e.g. Little Hierarchy Problem (Twin Higgs etc…)**

  Chacko, Goh, Harnik, arXiv: hep-ph/0506256
  Burdman, Chacko, Goh, Harnik, arXiv: hep-ph/0609152
  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

- **In the $N_f = 0$ limit, the only hadronic states that can form are 'dark glueballs', composite dark gluon states (no light quarks < Λ)**

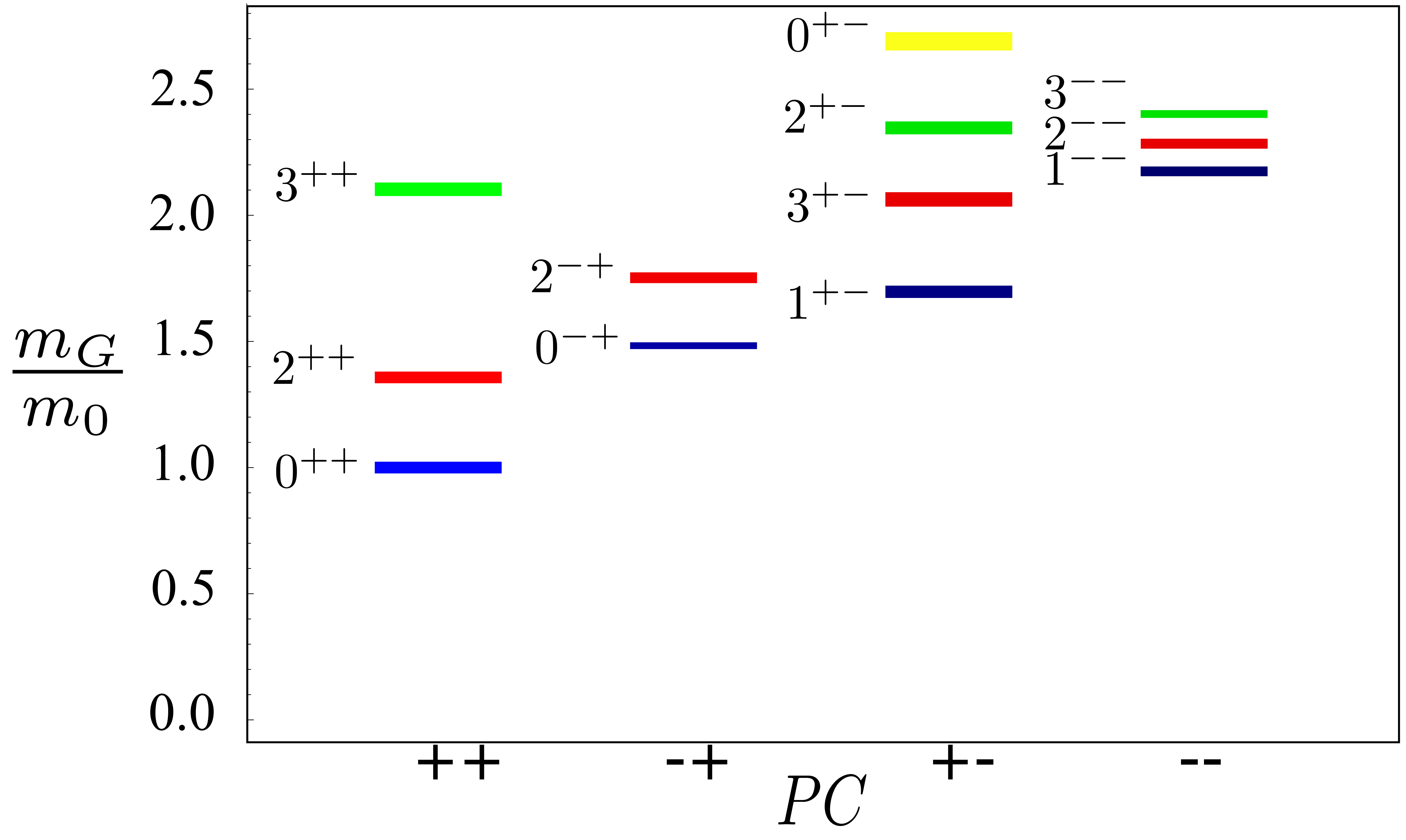
- **So far very few quantitative studies of dark glueball showers, due to the fact all known hadronization models (e.g. Lund string model) no longer hold**

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

Dark Sector Glueballs

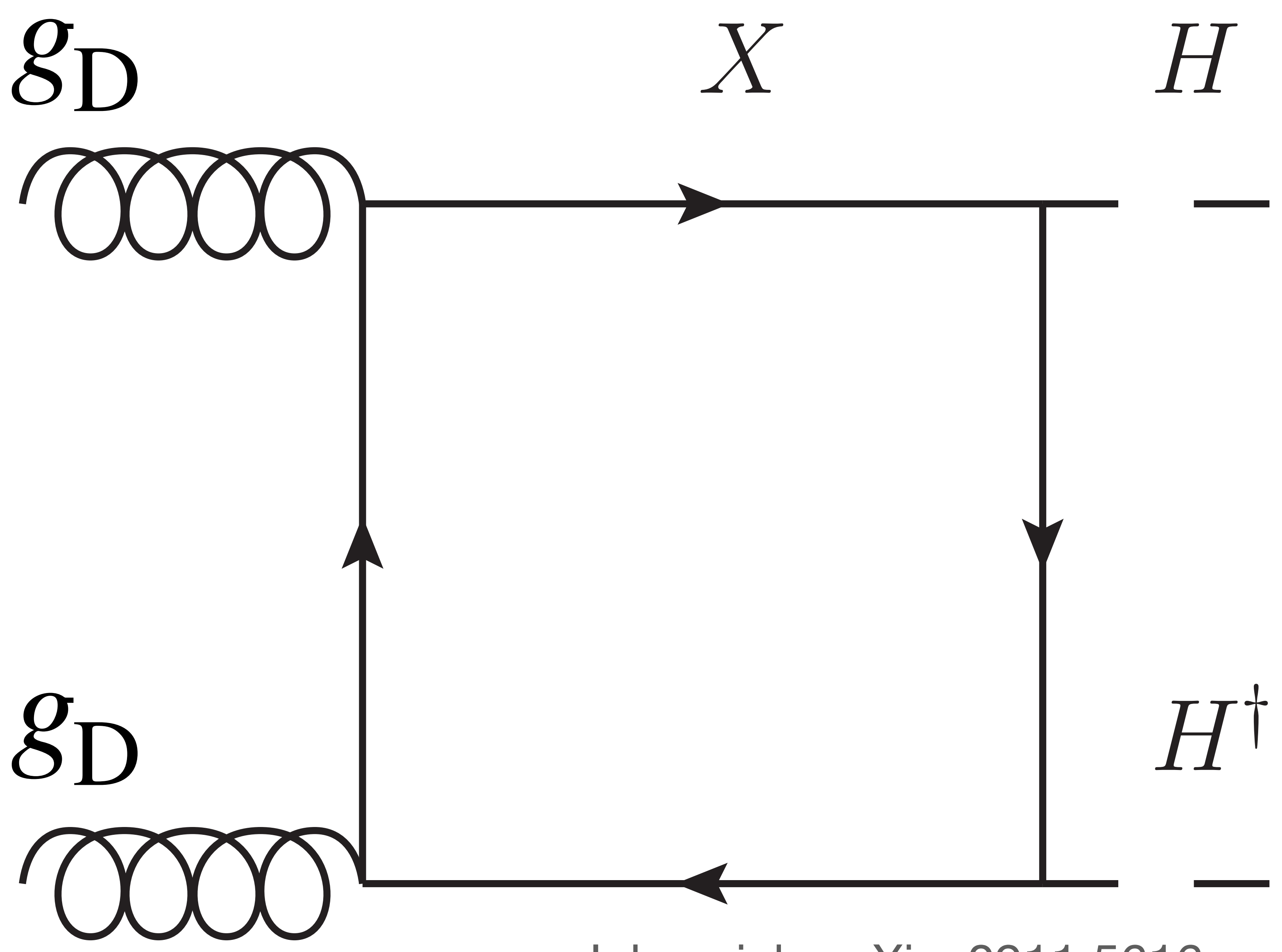
- **Majority of knowledge comes from lattice QCD studies** Morningstar, Peardon, arXiv: hep-lat/9901004
  Chen et al., arXiv: hep-lat/0510074
  Athenodorou, Teper, arXiv:2106.00364
- **Spectrum of 12 (stable) states**
- **Masses parameterised by the confinement scale,**
  $m_0 \sim 6\Lambda >> \Lambda$

Juknevich, arXiv: 0911.5616



Decay Portals

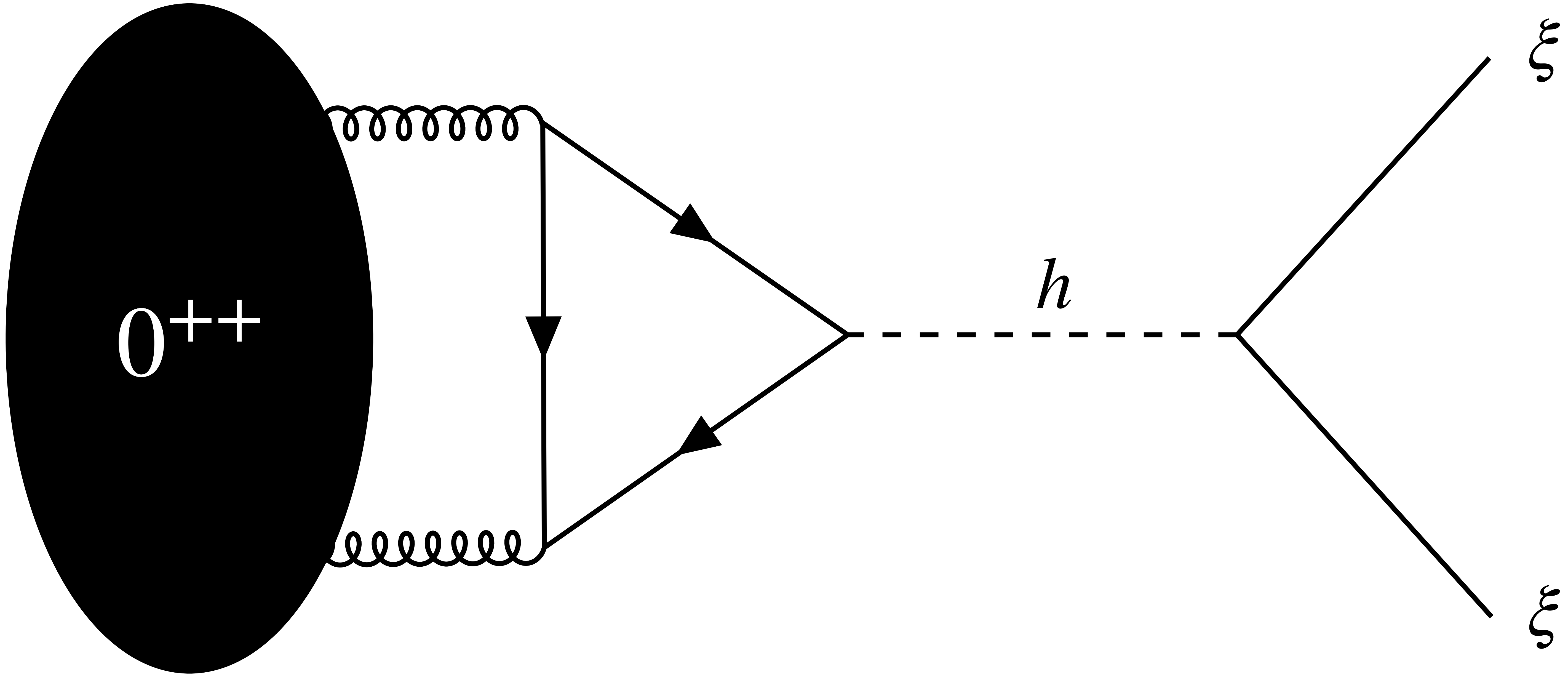
- **Assume dark quarks couple to the SM Higgs**
- **Dark sector glueballs able to decay via heavy quarks running in loop**
- **Integrate out to get an effective dimension 6 operator**



Juknevich, arXiv: 0911.5616

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

Decay Portals

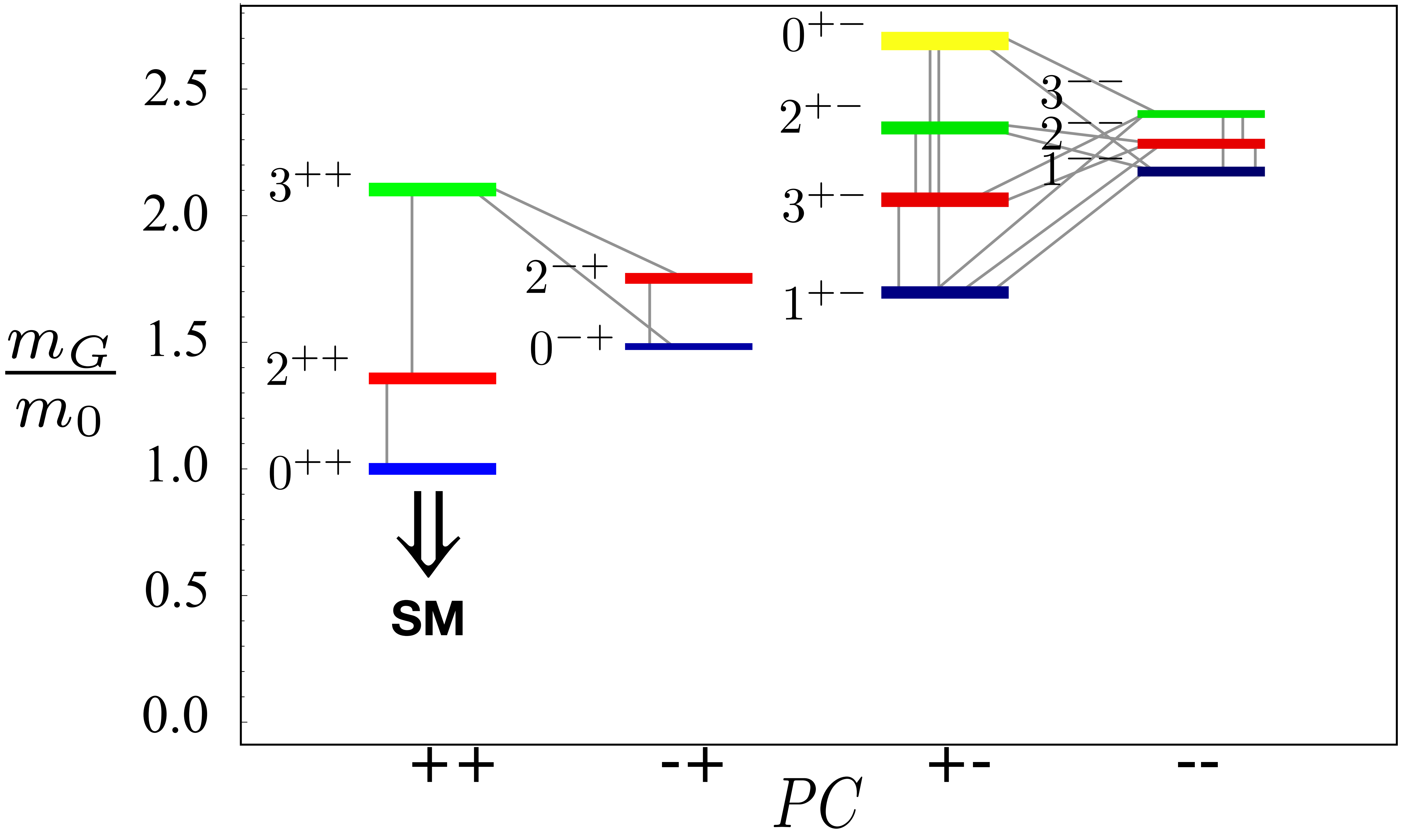


$$\Gamma_{0^{++}\to\xi\xi} = \frac{y^4}{M^4}\left(\frac{v_H \alpha_D \mathbf{F}_{0^{++}}}{3\pi(m_H^2 - m_0^2)}\right)^2 \Gamma^{\mathrm{SM}}_{h\to\xi\xi}(m_0)$$

Non-perturbative decay constant (comes from lattice studies)

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

Decay Portals



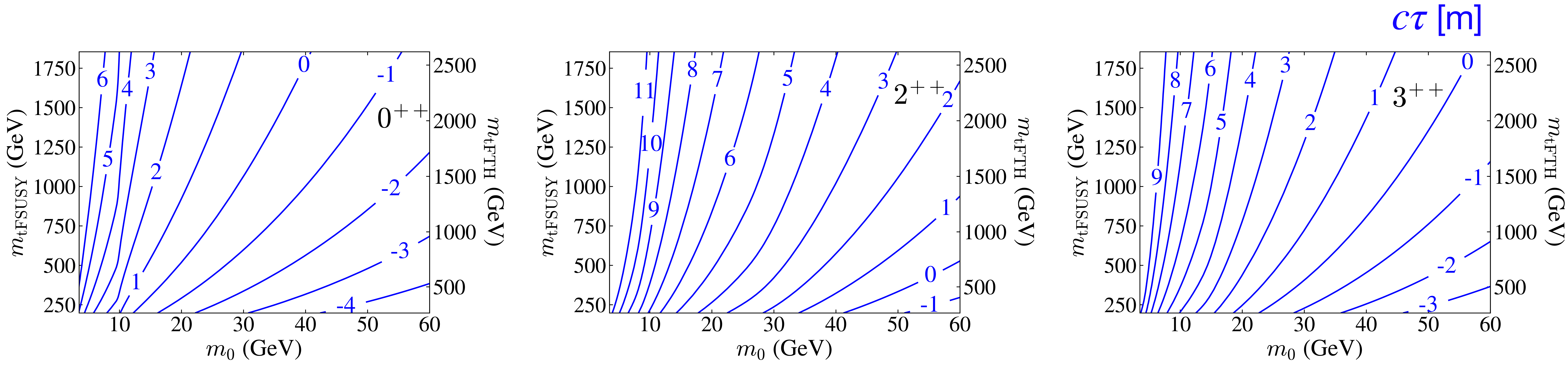
Glueball	Mass (m_0)	Higgs Portal
0^{++}	1.00	$h^* \to \mathrm{SM}, \mathrm{SM}$
2^{++}	1.40	$0^{++} + h^*$
0^{-+}	1.50	-
1^{+-}	1.75	-
2^{-+}	1.78	$0^{-+} + h^*$
3^{+-}	2.11	$1^{+-} + h^*$
3^{++}	2.15	$\{2^{++}, 0^{-+}, 2^{-+}\} + h^*$
1^{--}	2.25	$1^{+-} + h^*$
2^{--}	2.35	$\{1^{+-}, 3^{+-}, 1^{--}\}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

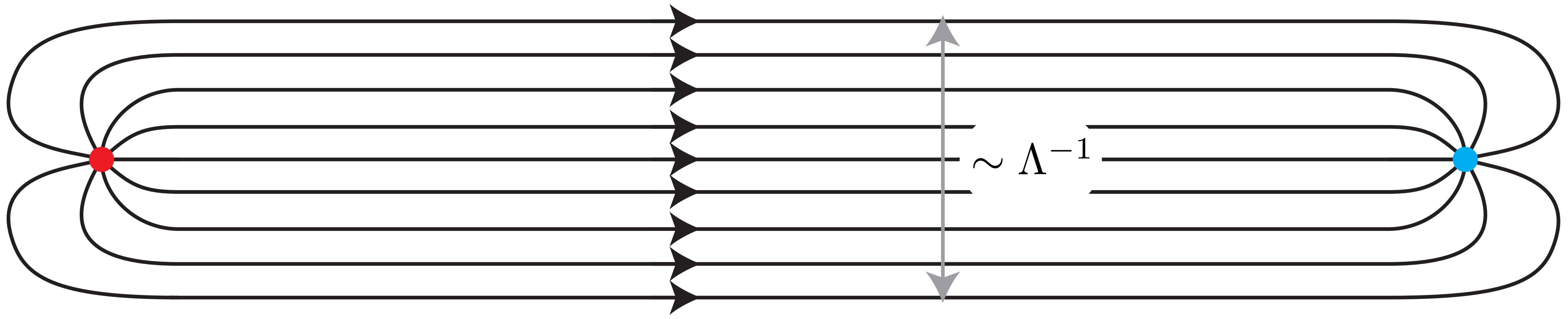
- **Additionally, across the spectrum of glueball states, lifetimes differ by orders of magnitude**



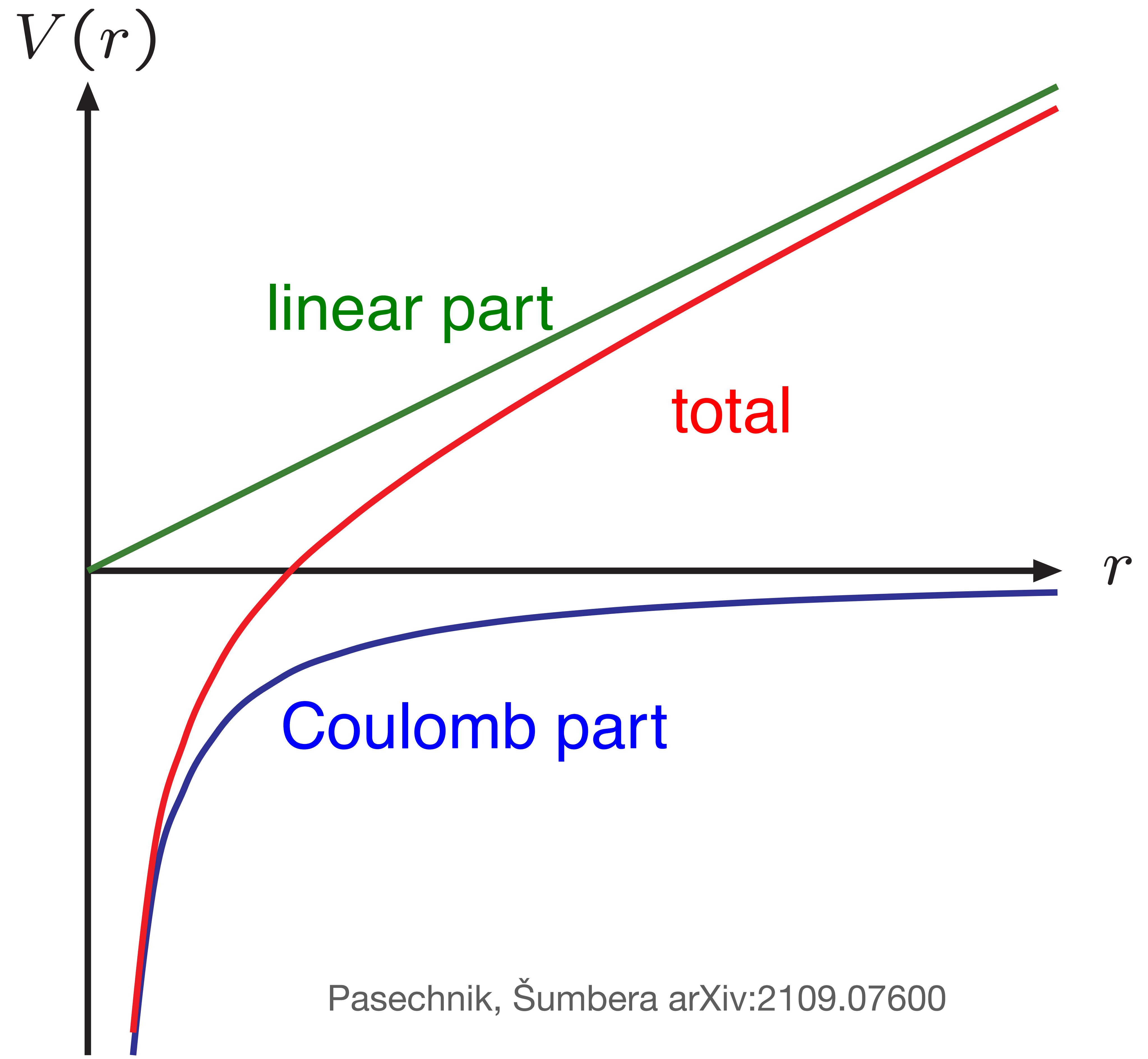
Q: How to simulate dark glueball hadronization?

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
- Motivates Lund string model in SM, still has to be tuned to data

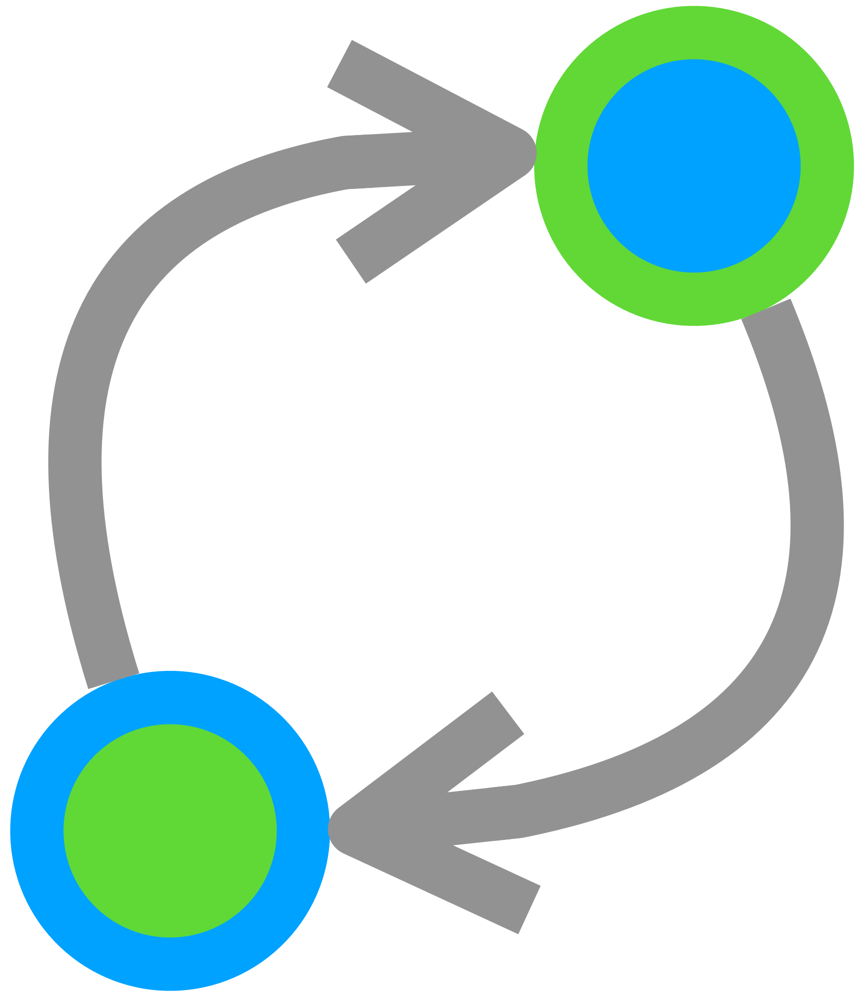


Kang, Luty, arXiv: 0805.4642

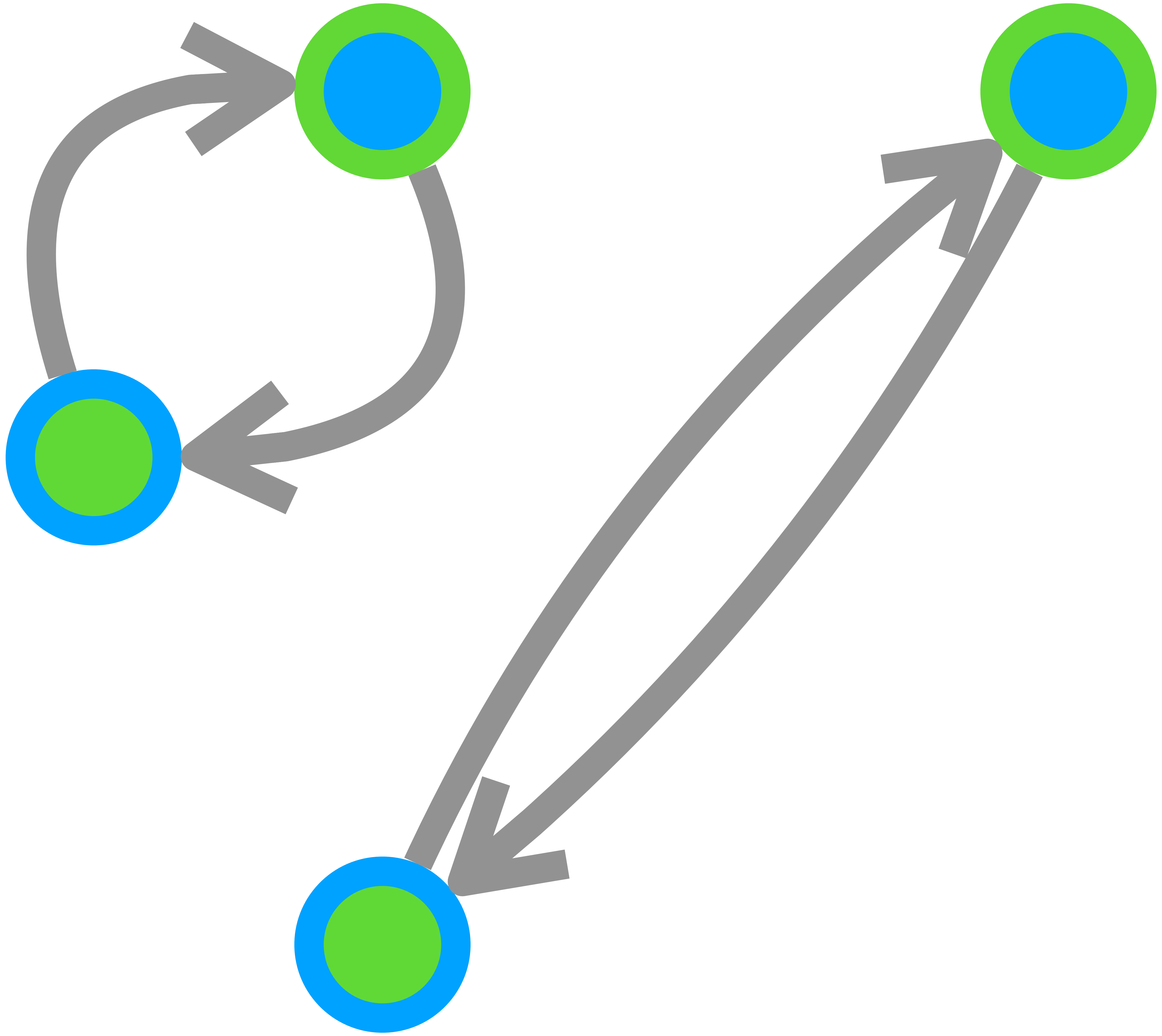


Pasechnik, Šumbera arXiv:2109.07600

Cartoon pure glue hadronization



Cartoon pure glue hadronization



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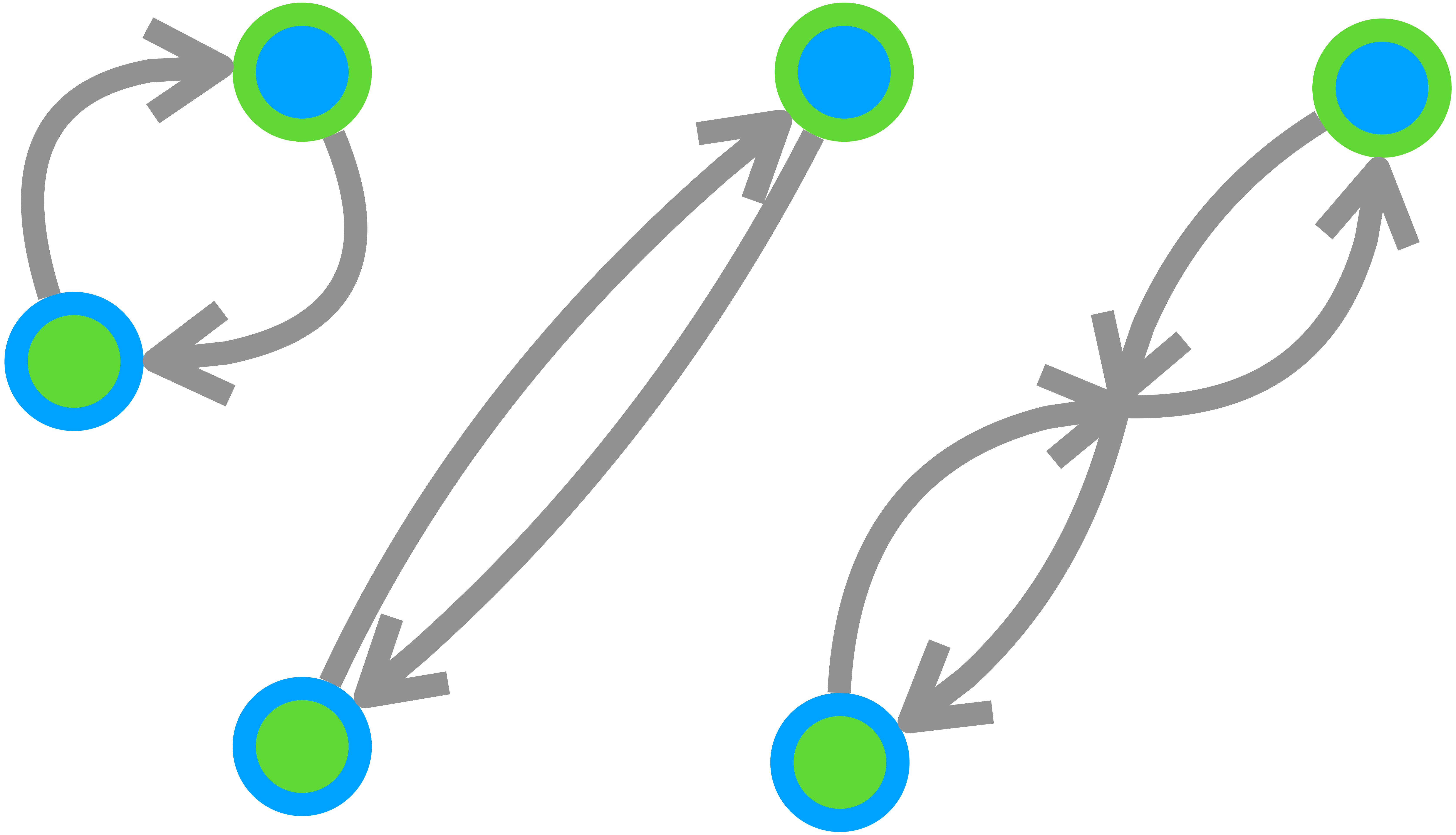

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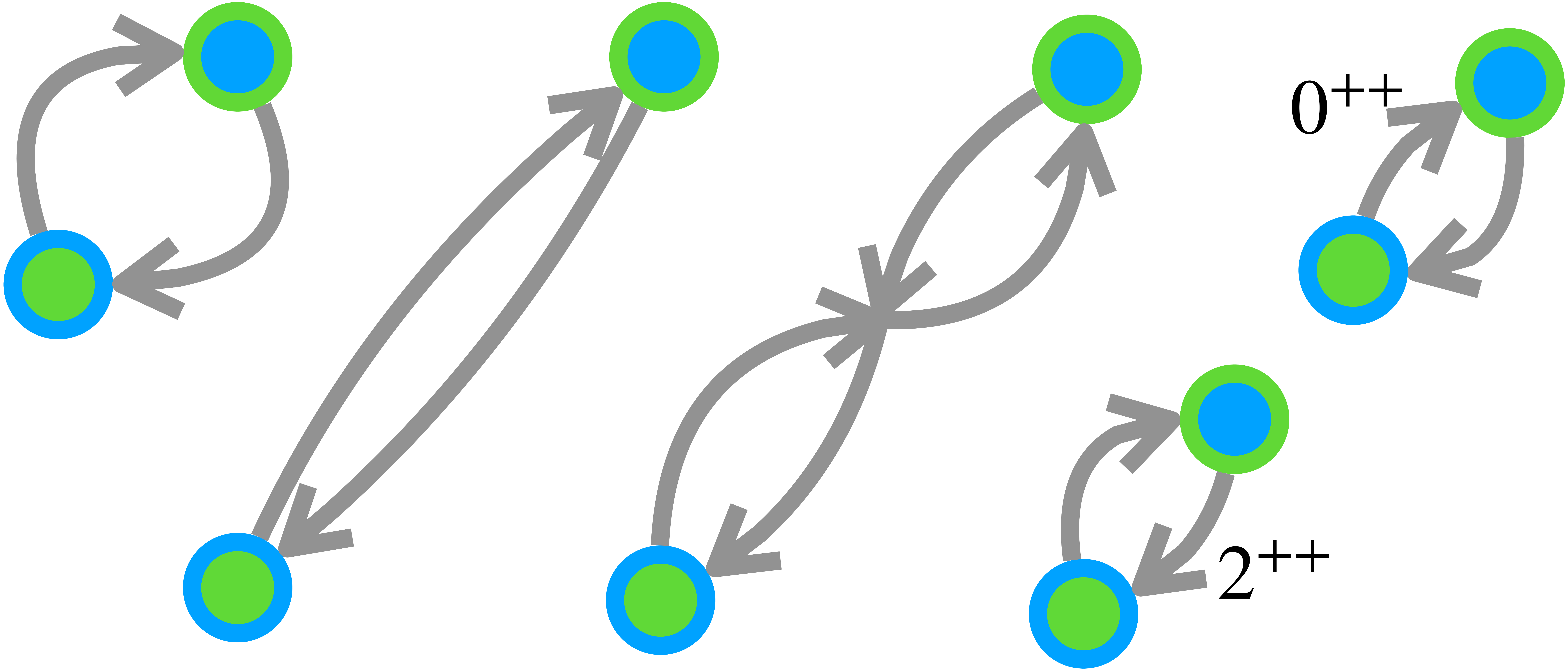


Pure Glue Hadronization

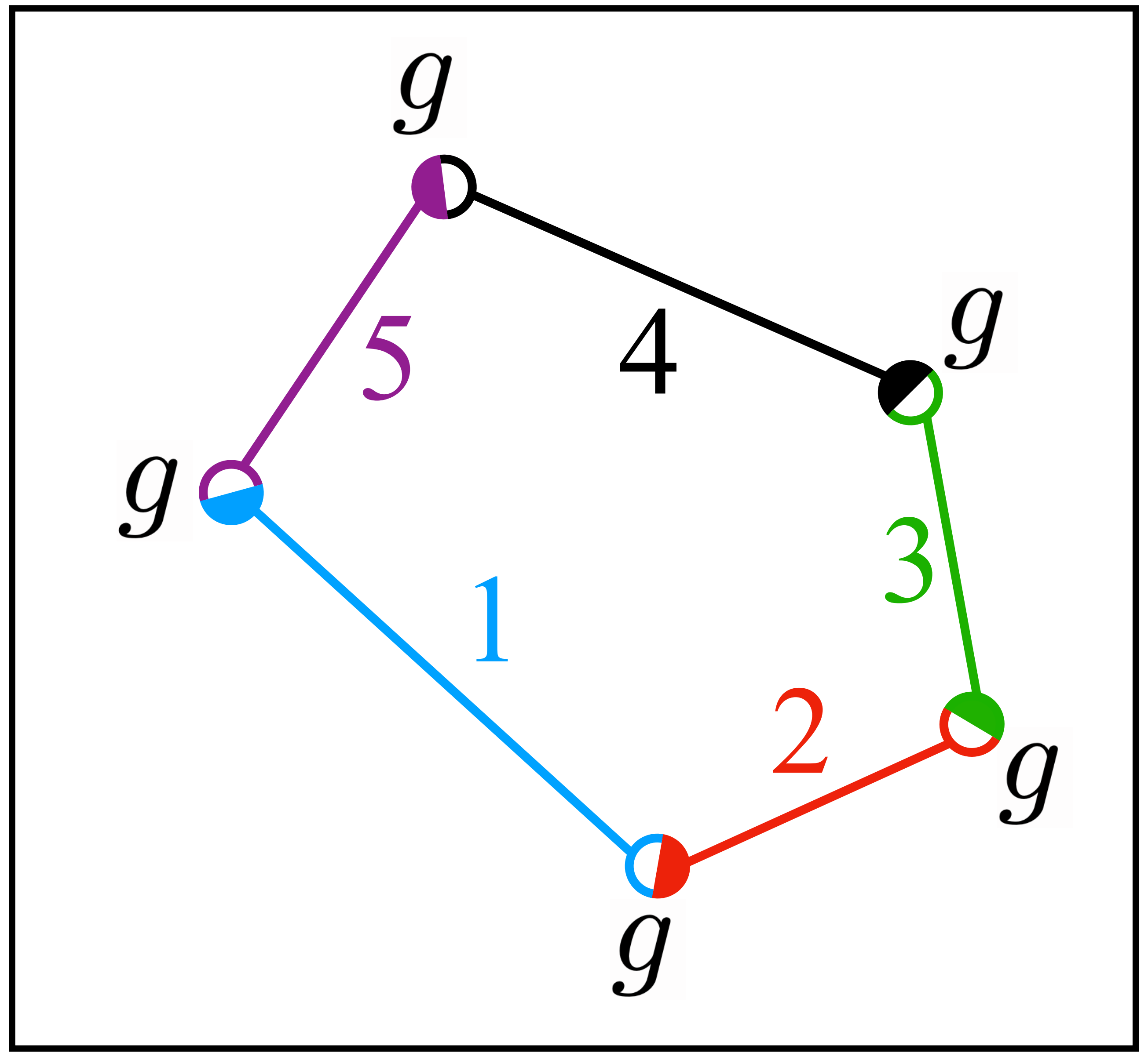
arXiv: 2310.13731 (with A. Batz, T. Cohen, D. Curtin, G.D. Kribs)

1. Perturbative shower built from the Pythia 8 module in $N_f = 0$ limit

2. Shower terminated at some $p_{T,min}$ and the gluon color string loops undergo color reconnection

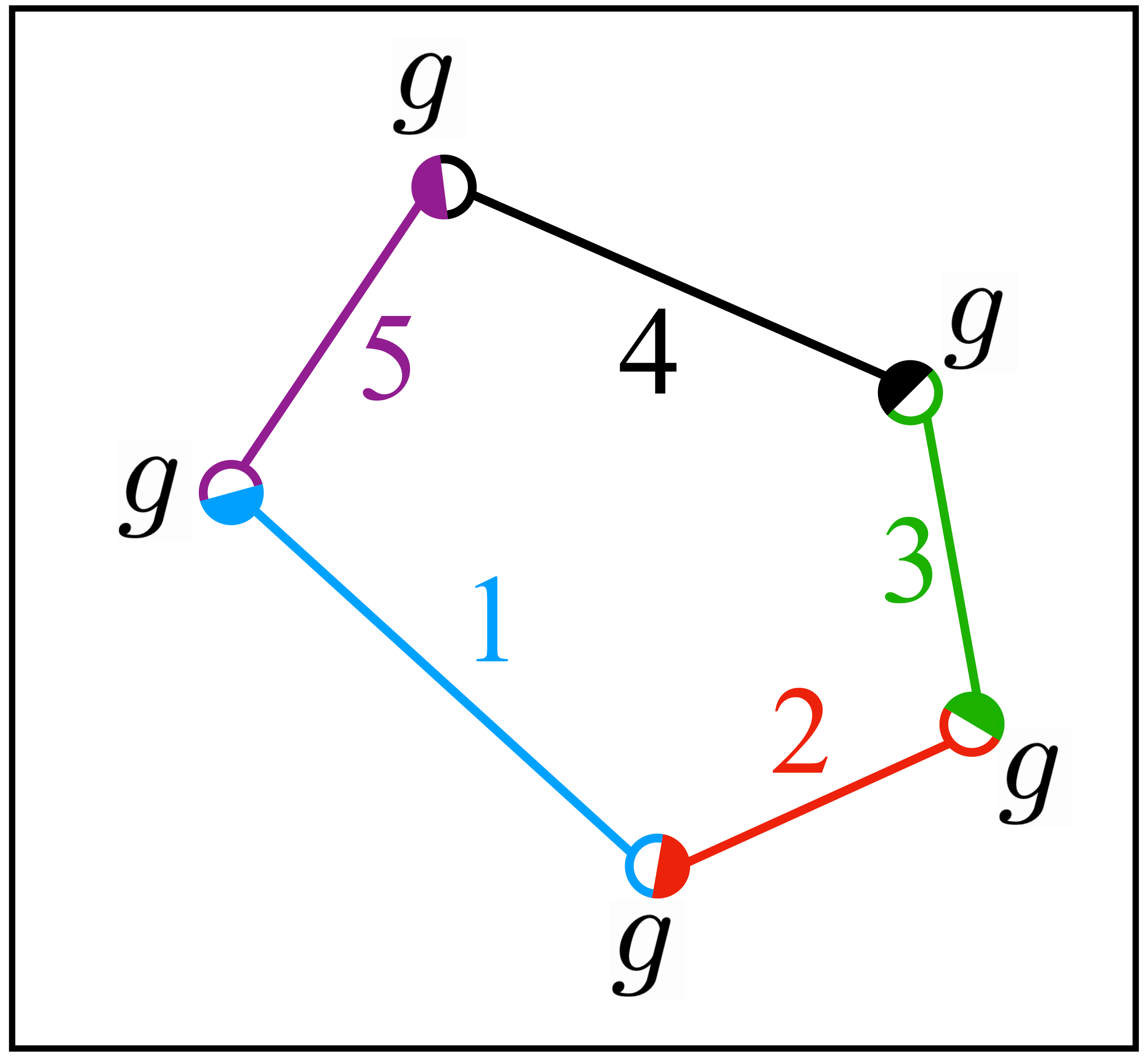
3. Each color string loop is 'fragmented' into dark glueballs

Color Reconnection



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

Color Reconnection



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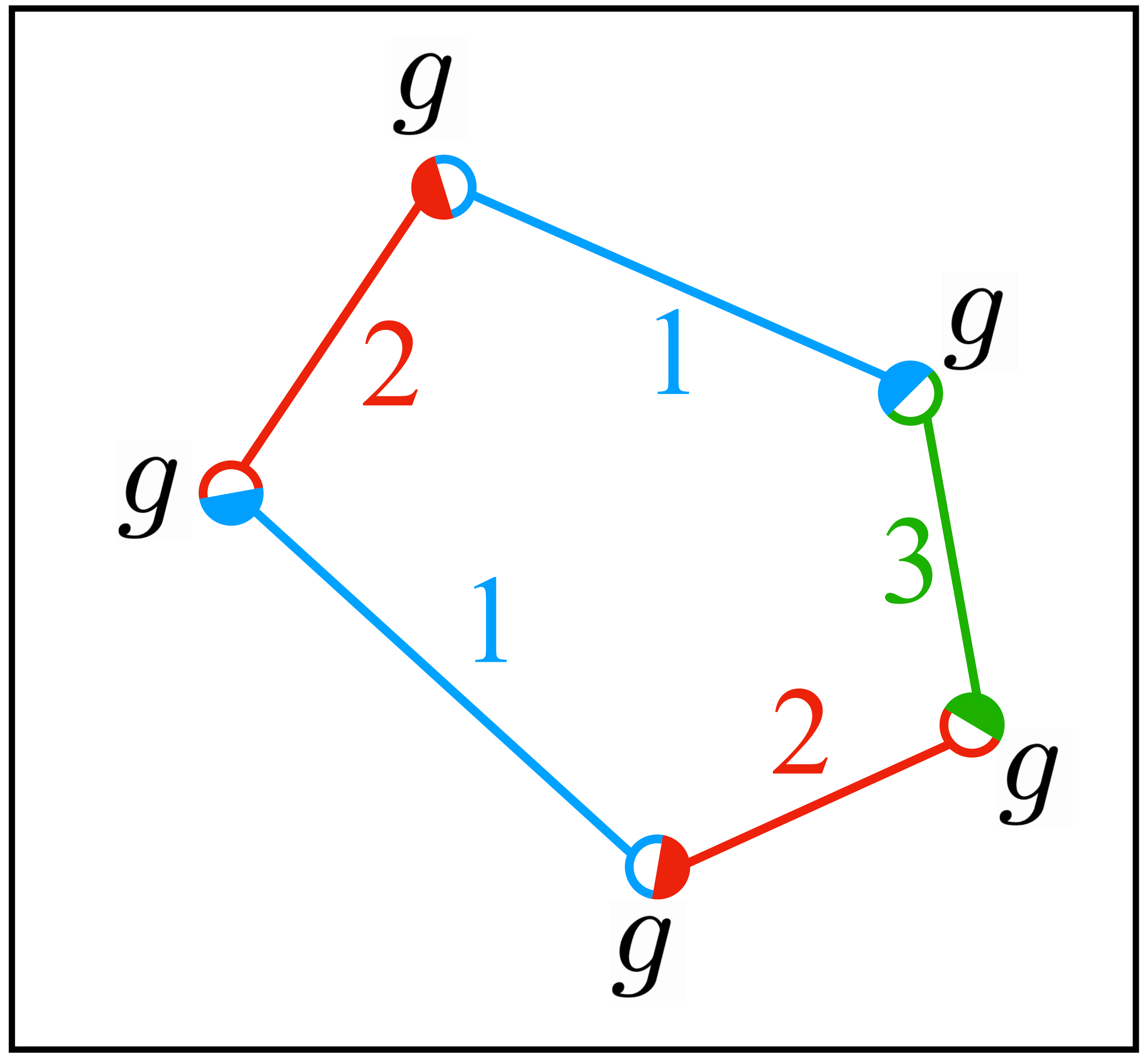
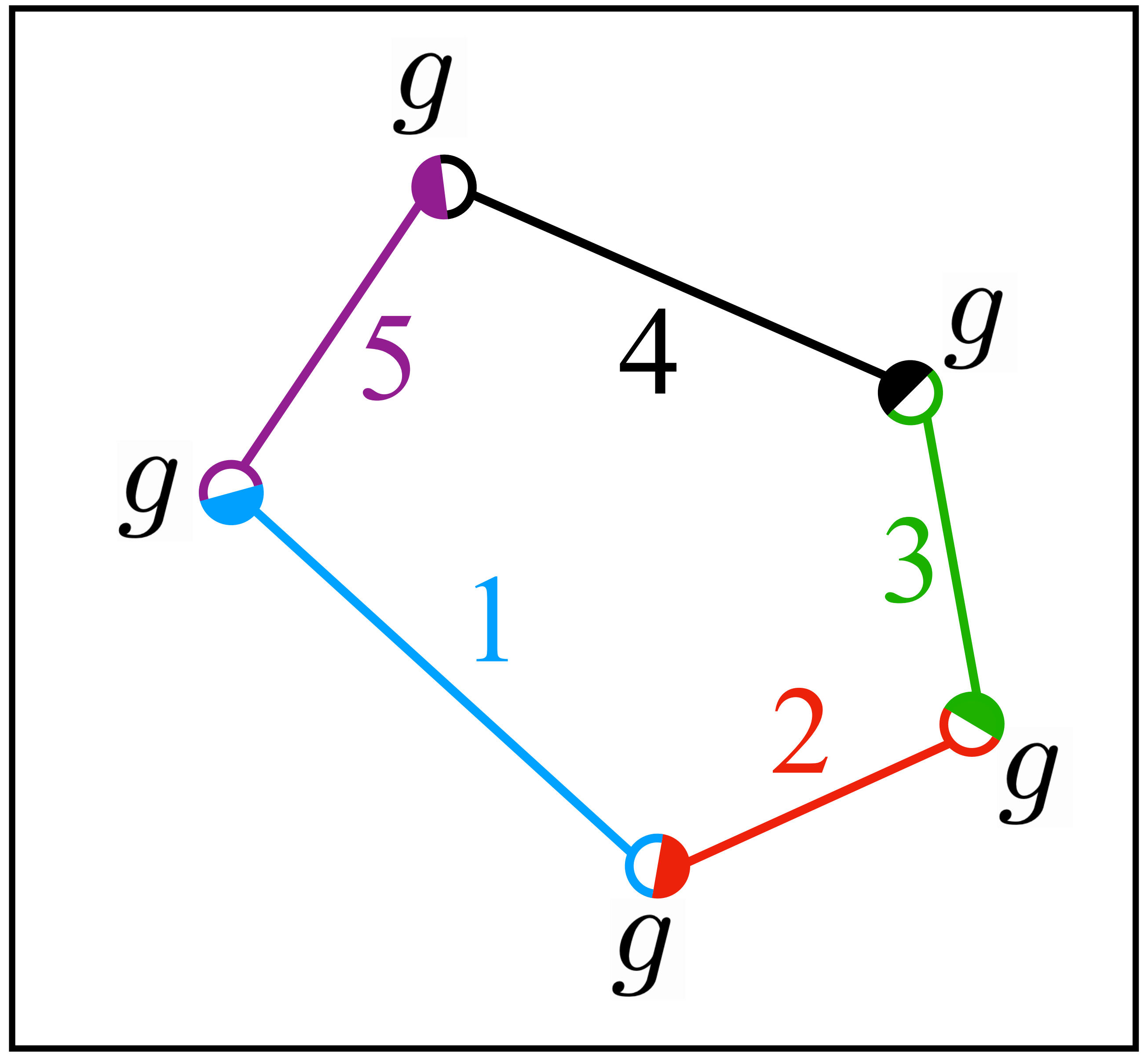


String pieces are randomly reassigned color in the $N_c = 3$ limit

Color Reconnection



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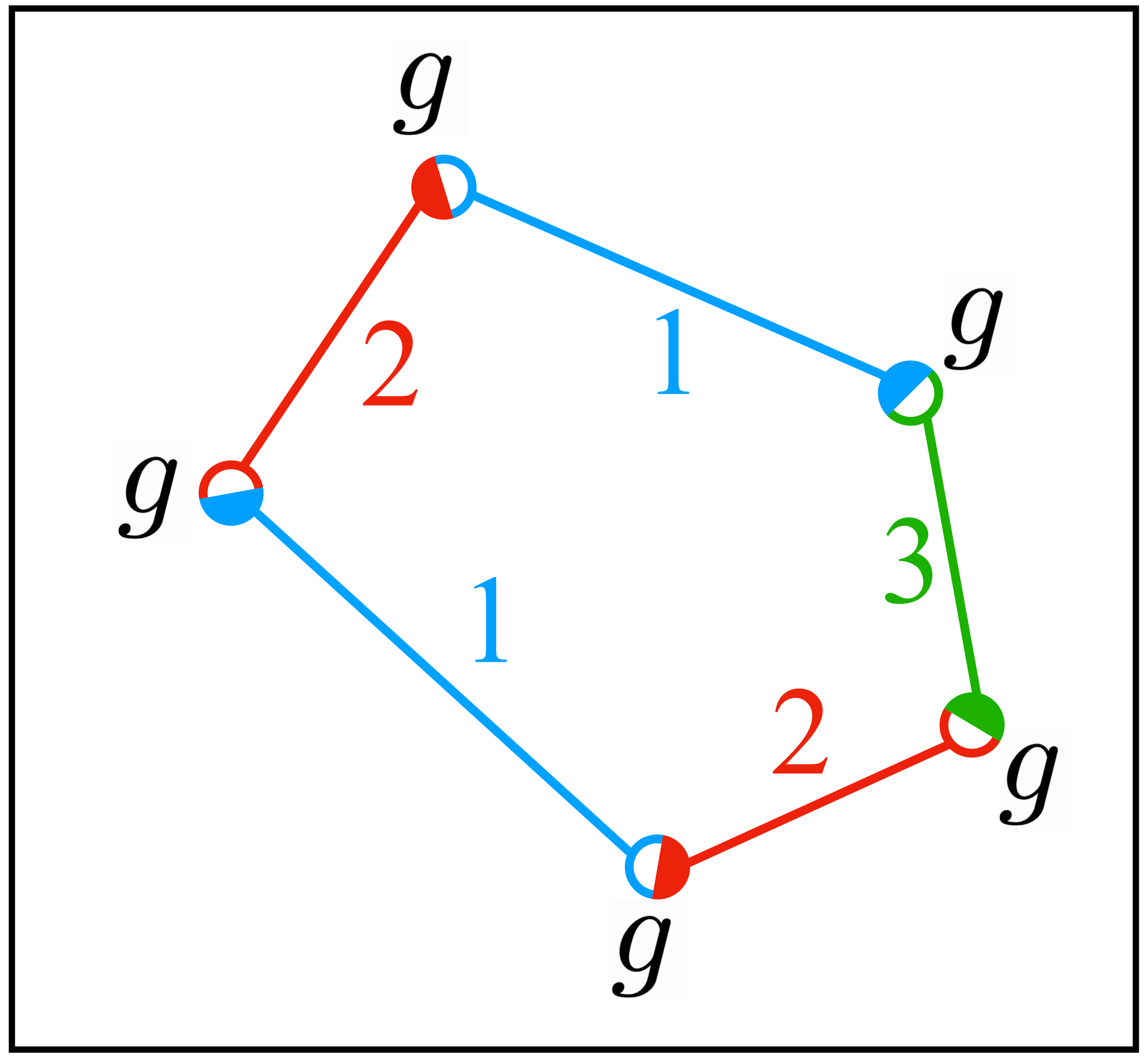

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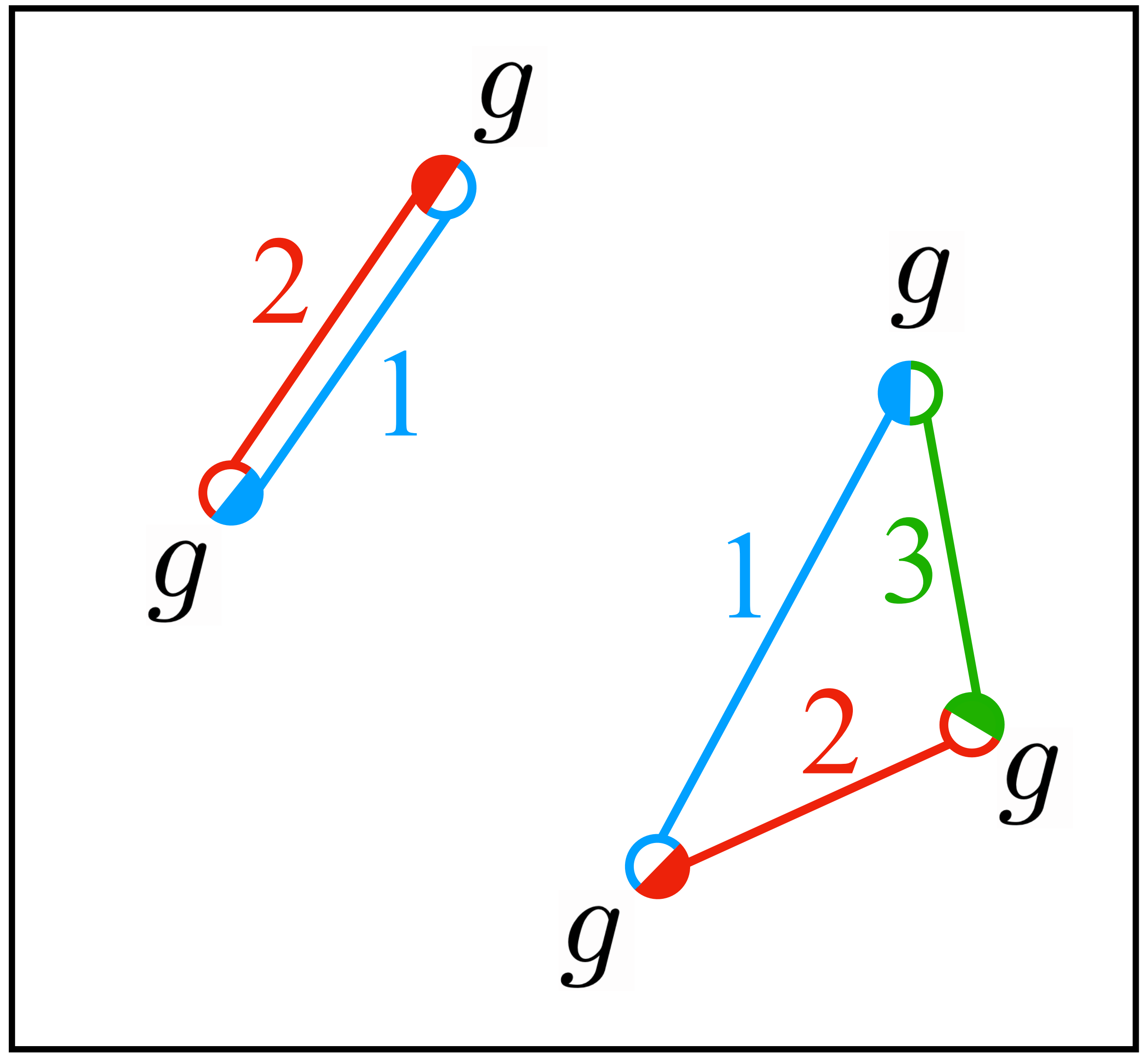
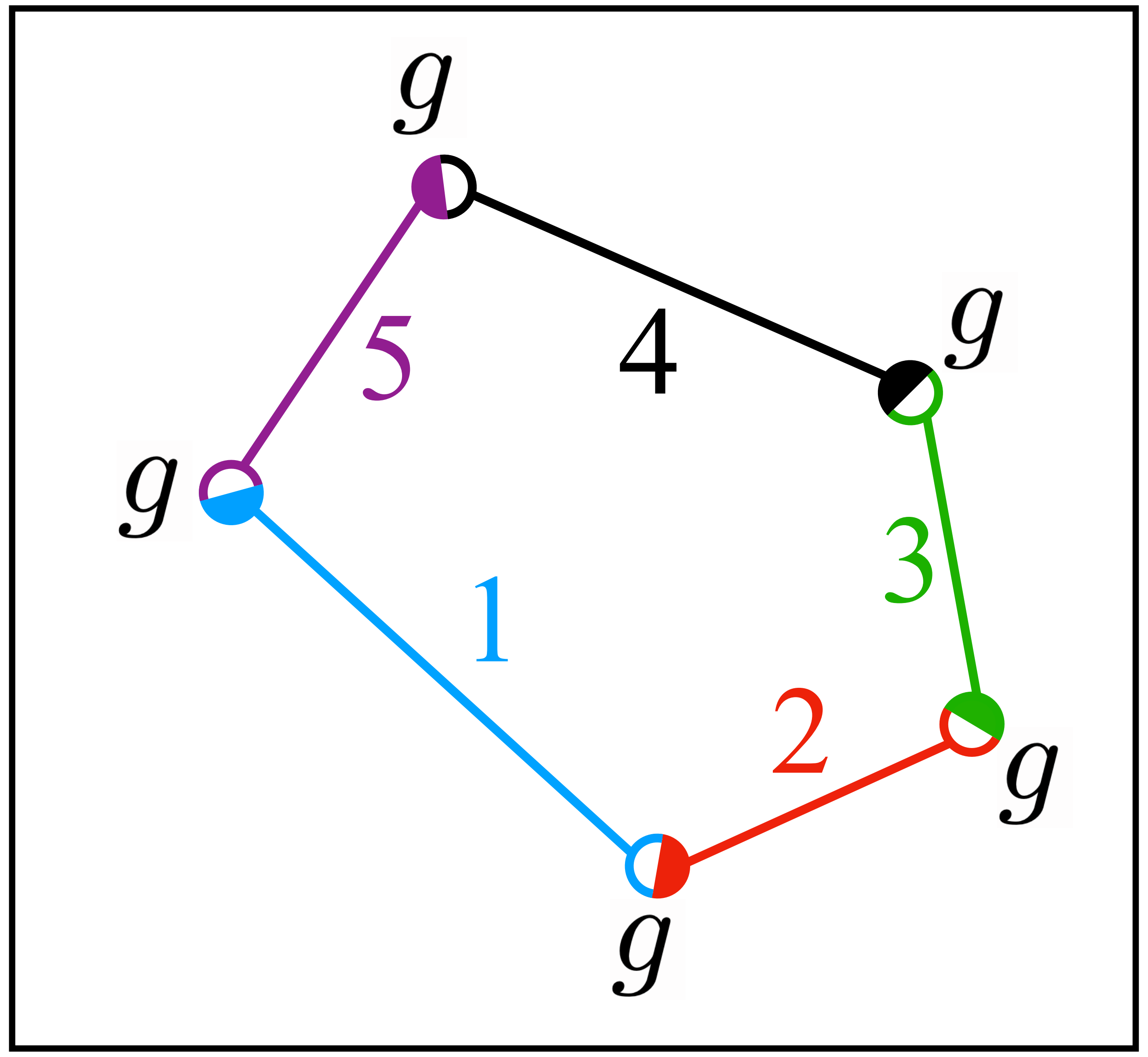


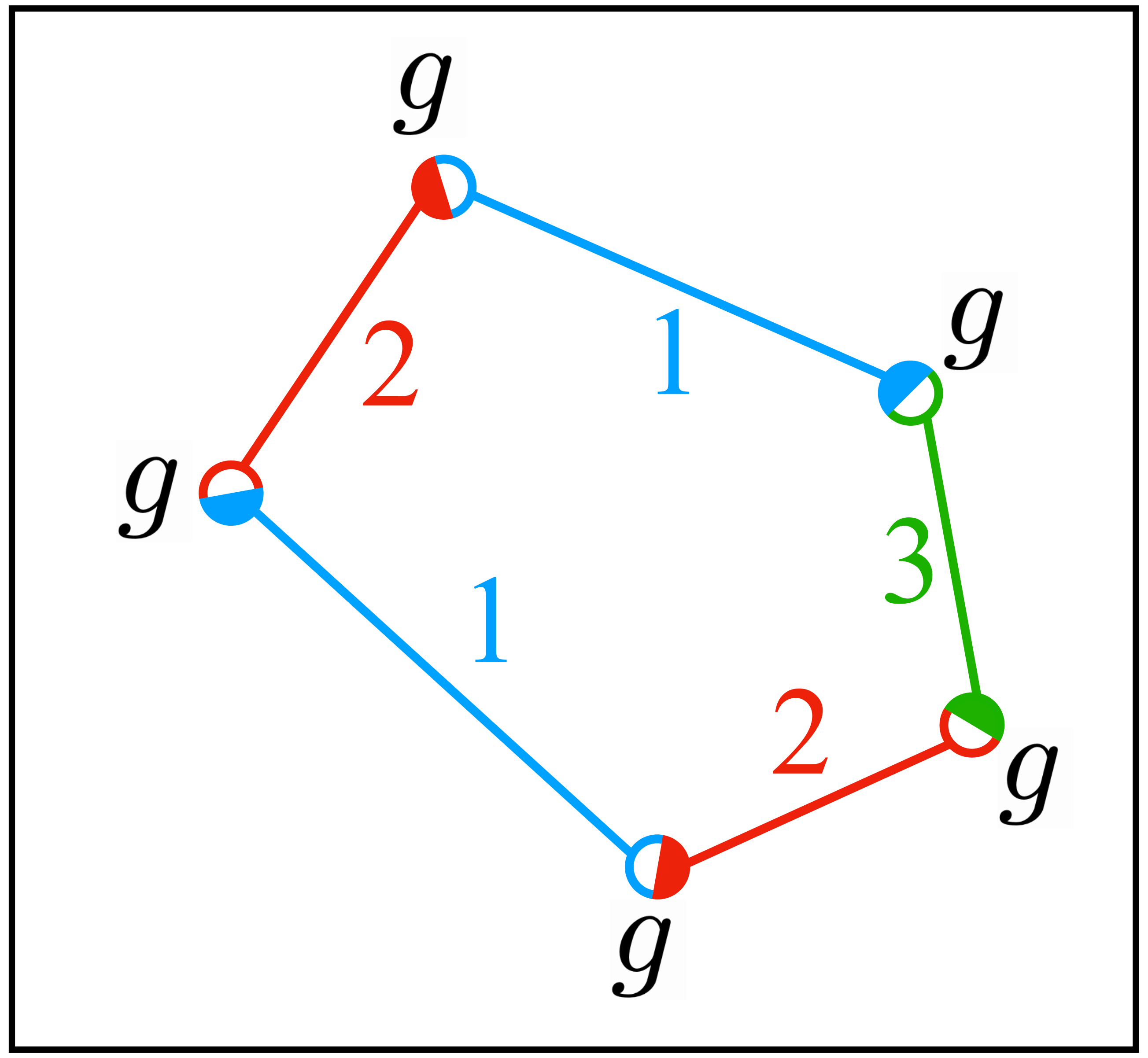
String connections are reassigned to minimise the string length quantity, λ

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

Color Reconnection



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



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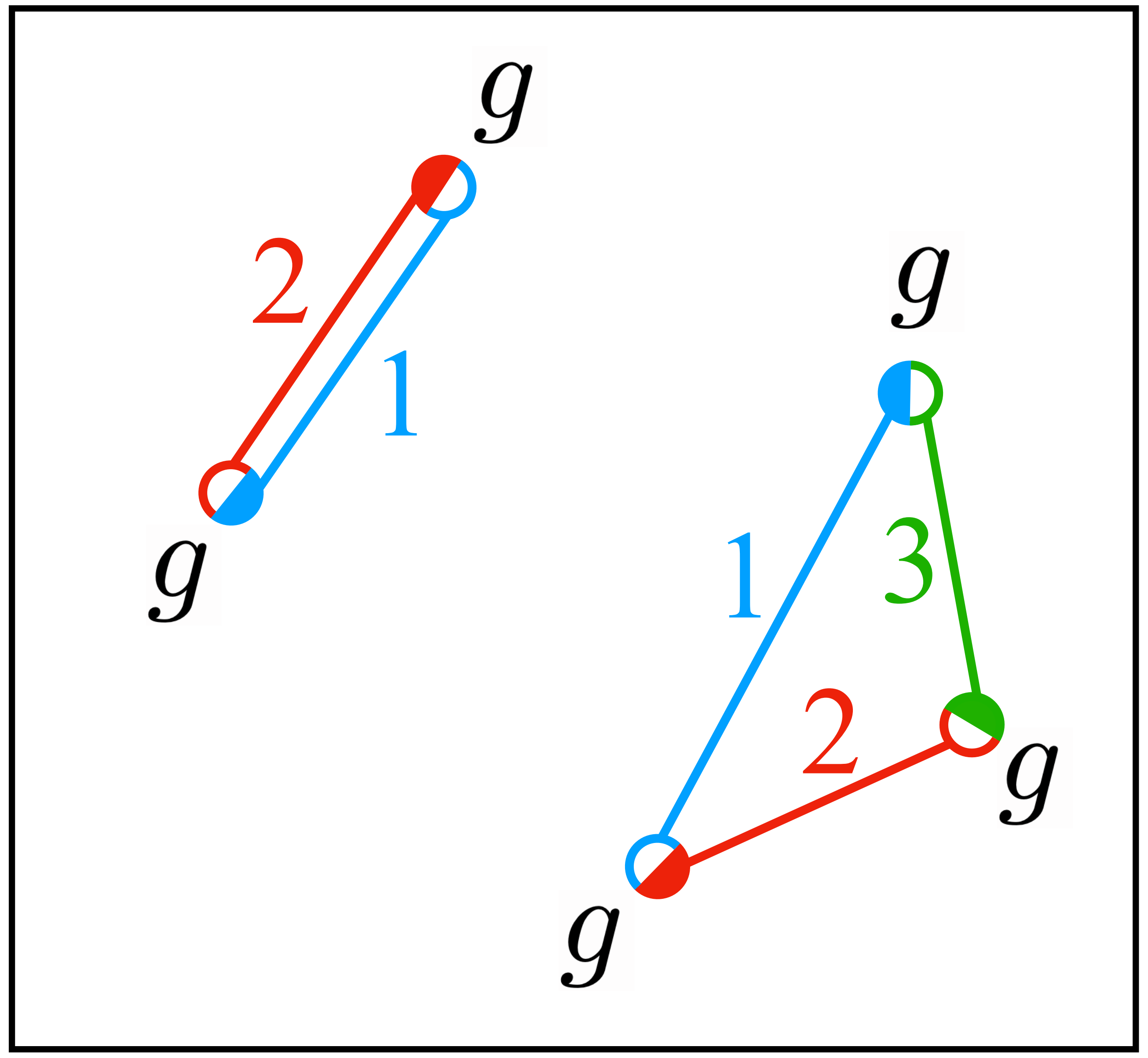

String connections are reassigned to minimise the string length quantity, λ

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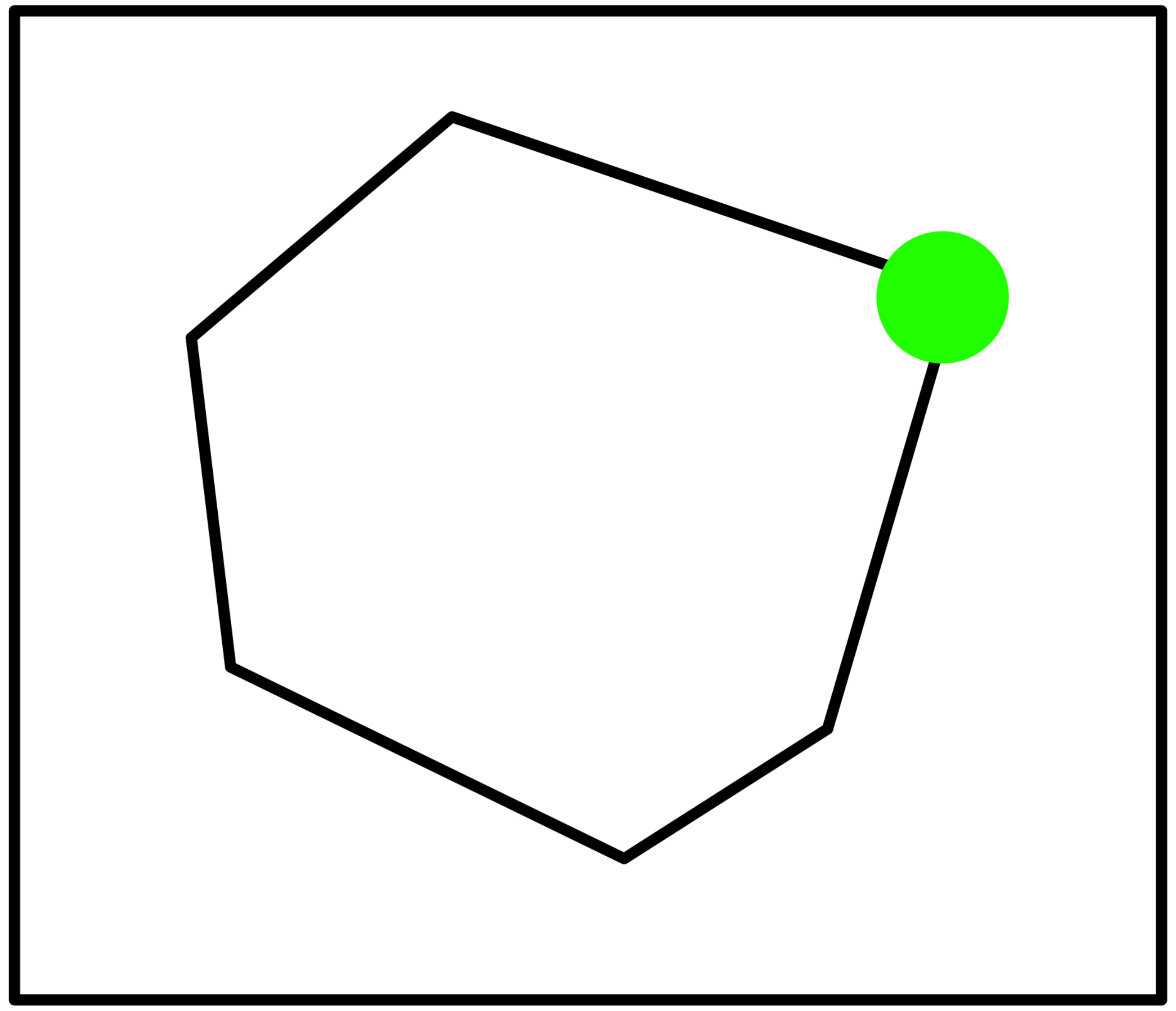
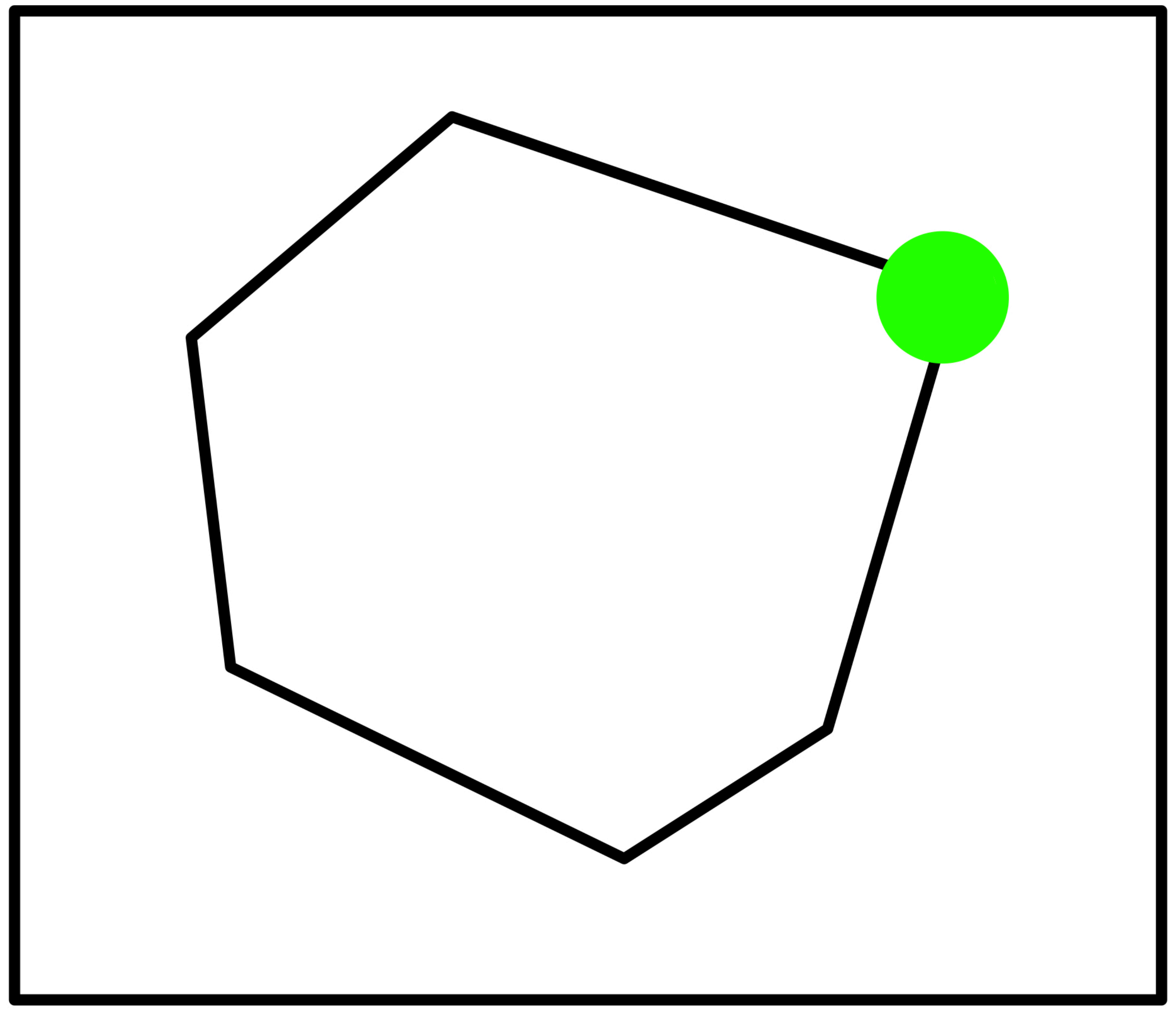
Defines the physical string topology at the end of the shower, same as Lund String model

Glueball Fragmentation



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

Glueball Fragmentation



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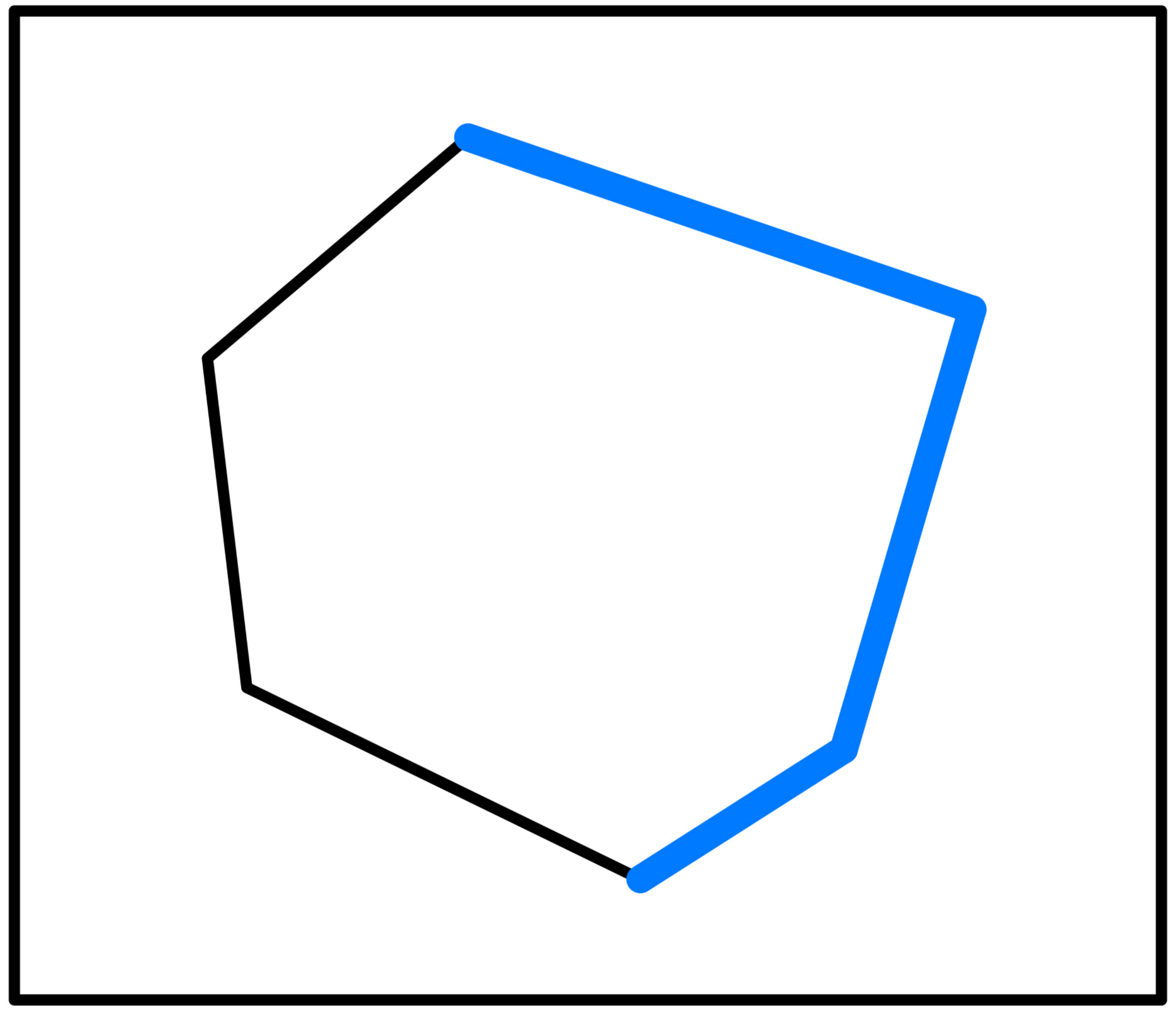
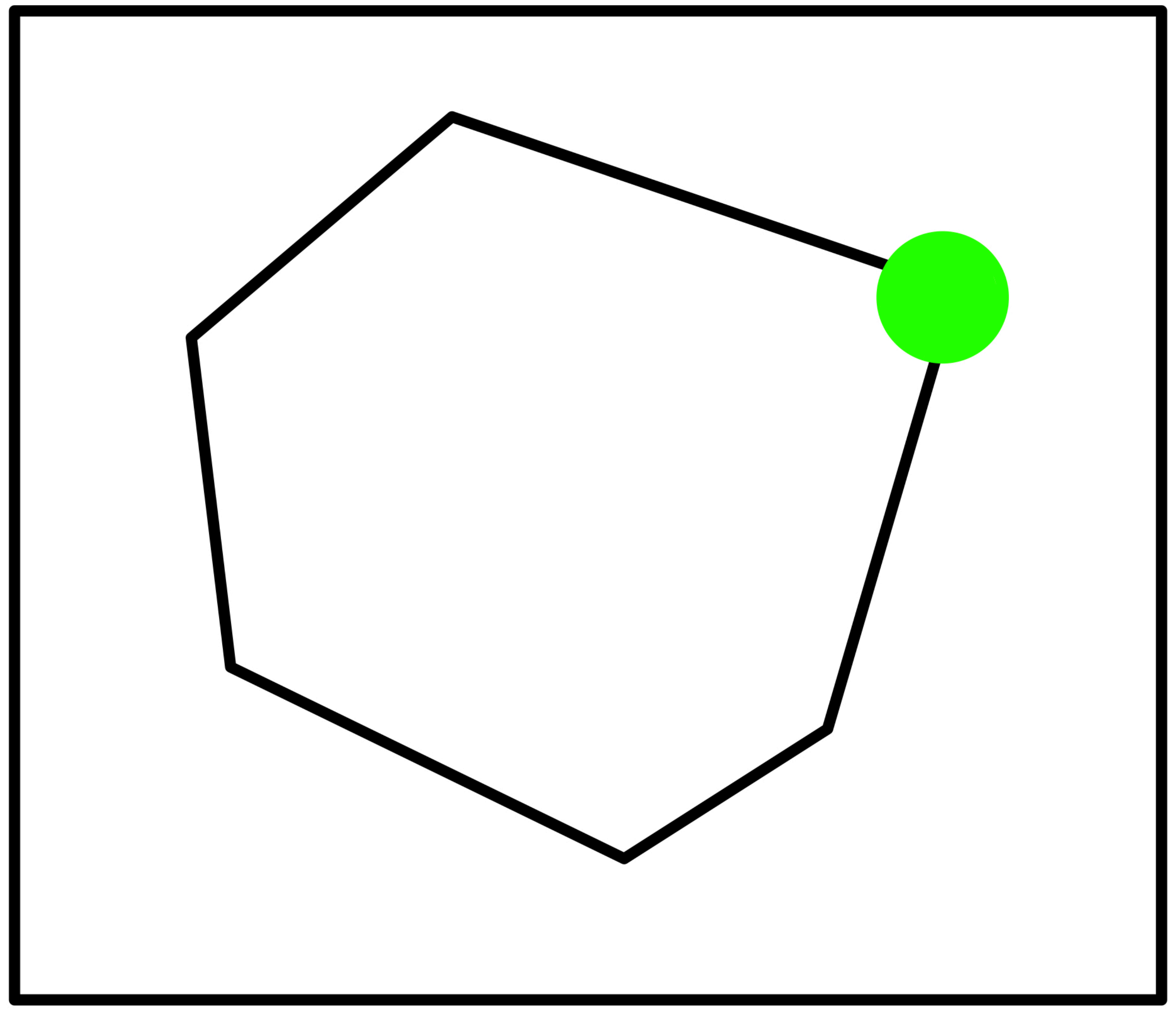


A minimal set of string pieces with total mass, $M_{\text{total}} \geq m_0$, is selected to turn into a glueball

Glueball Fragmentation



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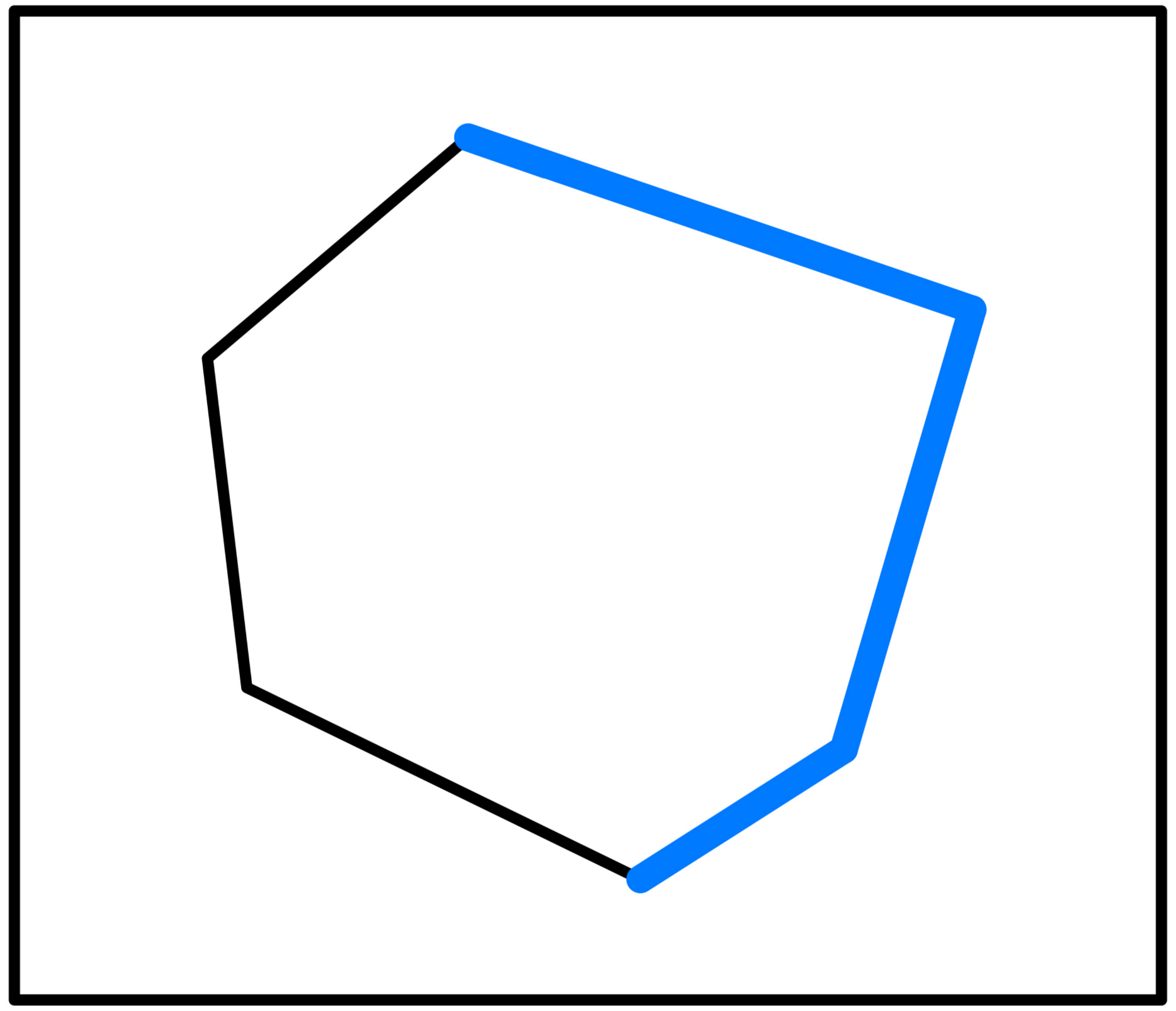

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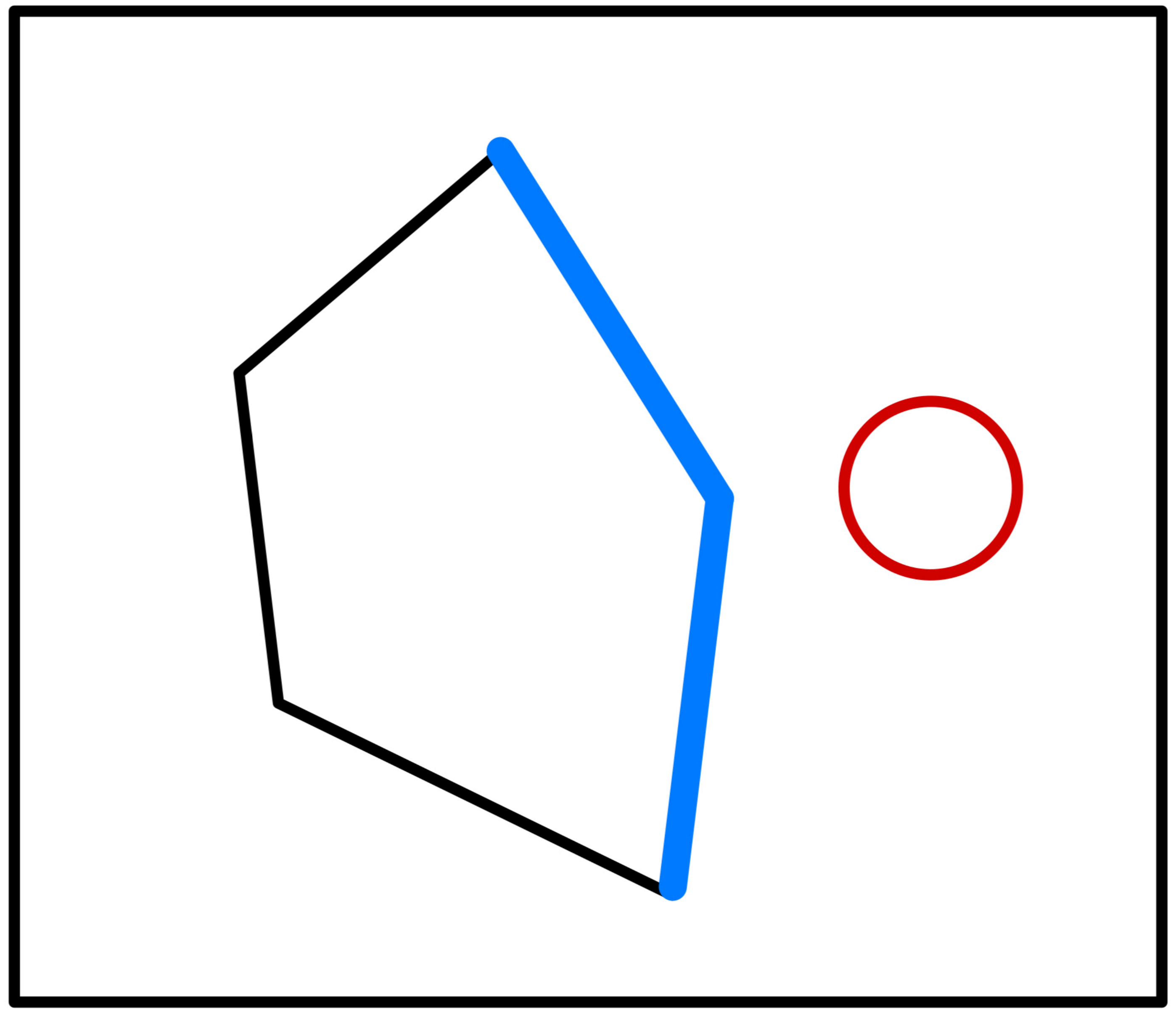


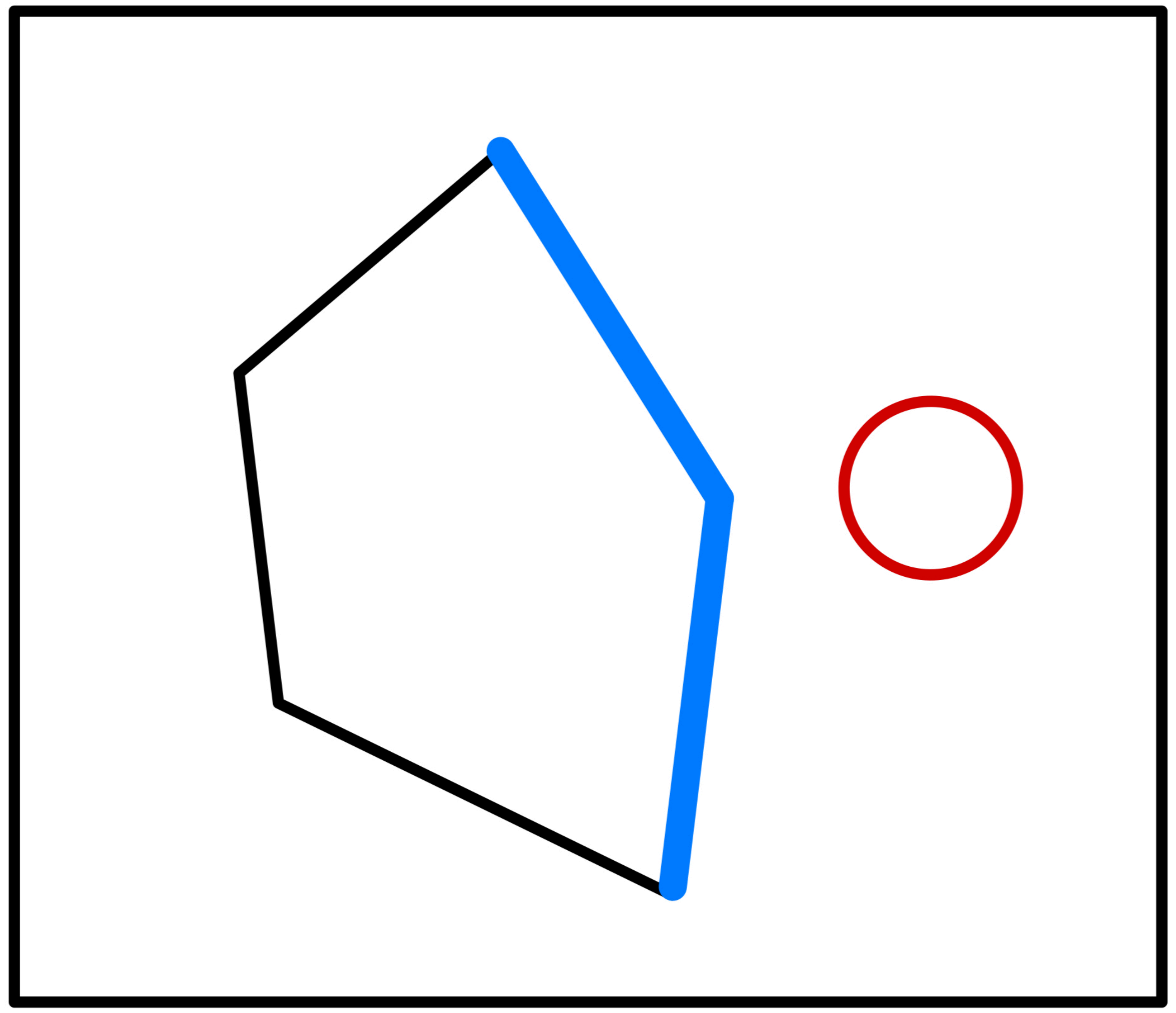
A glueball is then emitted, taking a fraction of the string pieces momenta. The remaining momenta is then distributed between the remaining string pieces

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 :

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

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



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 :

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

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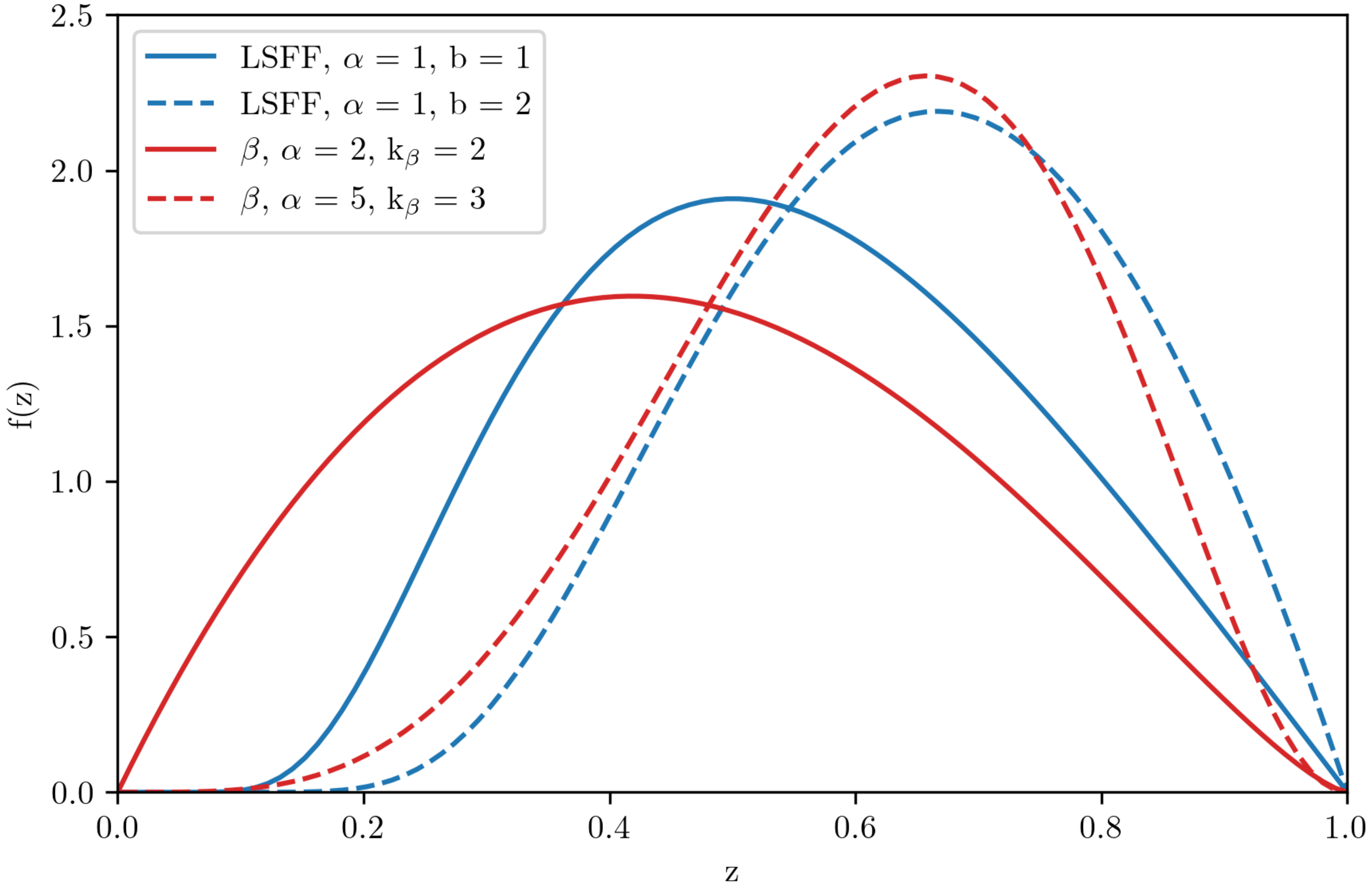

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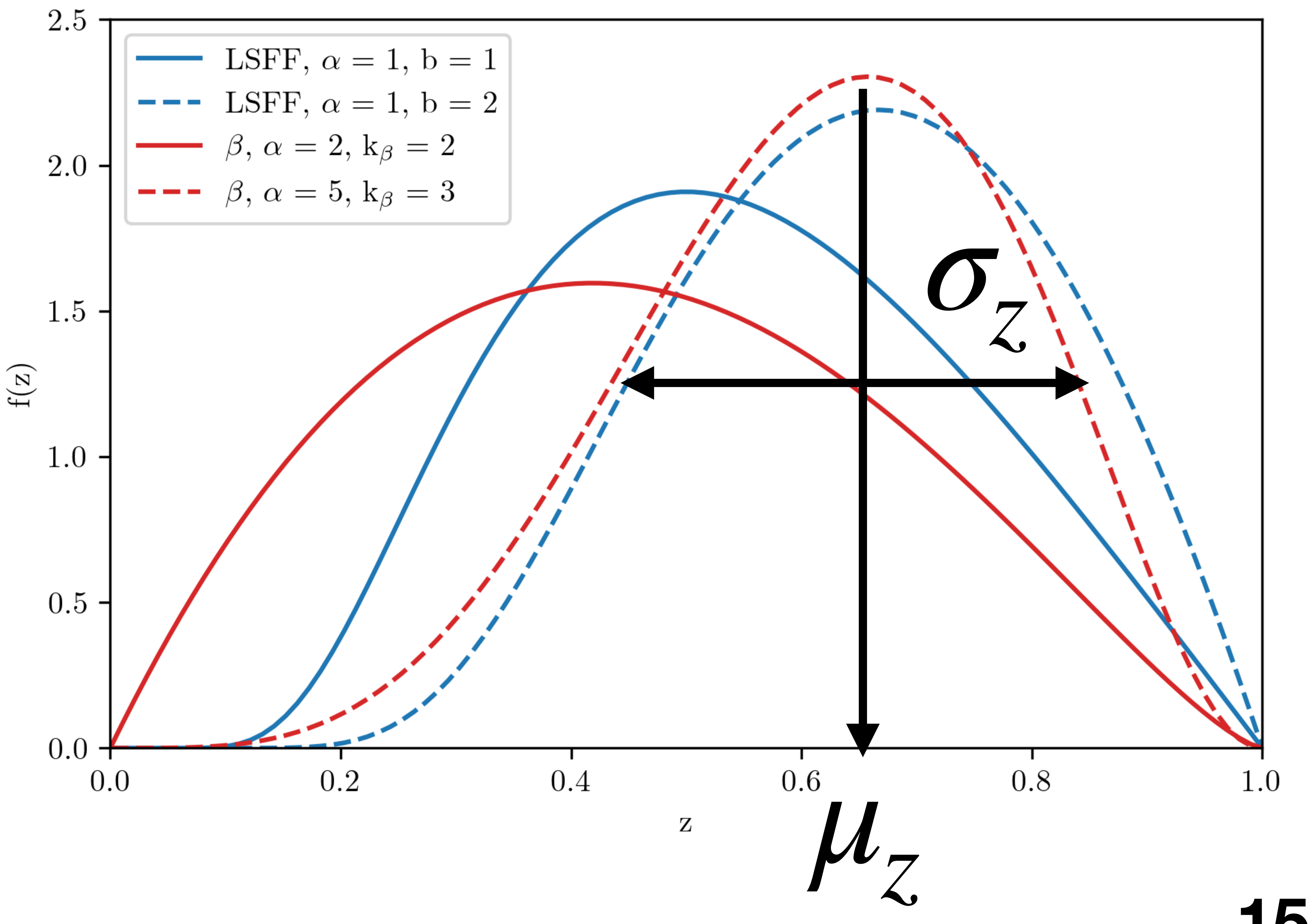
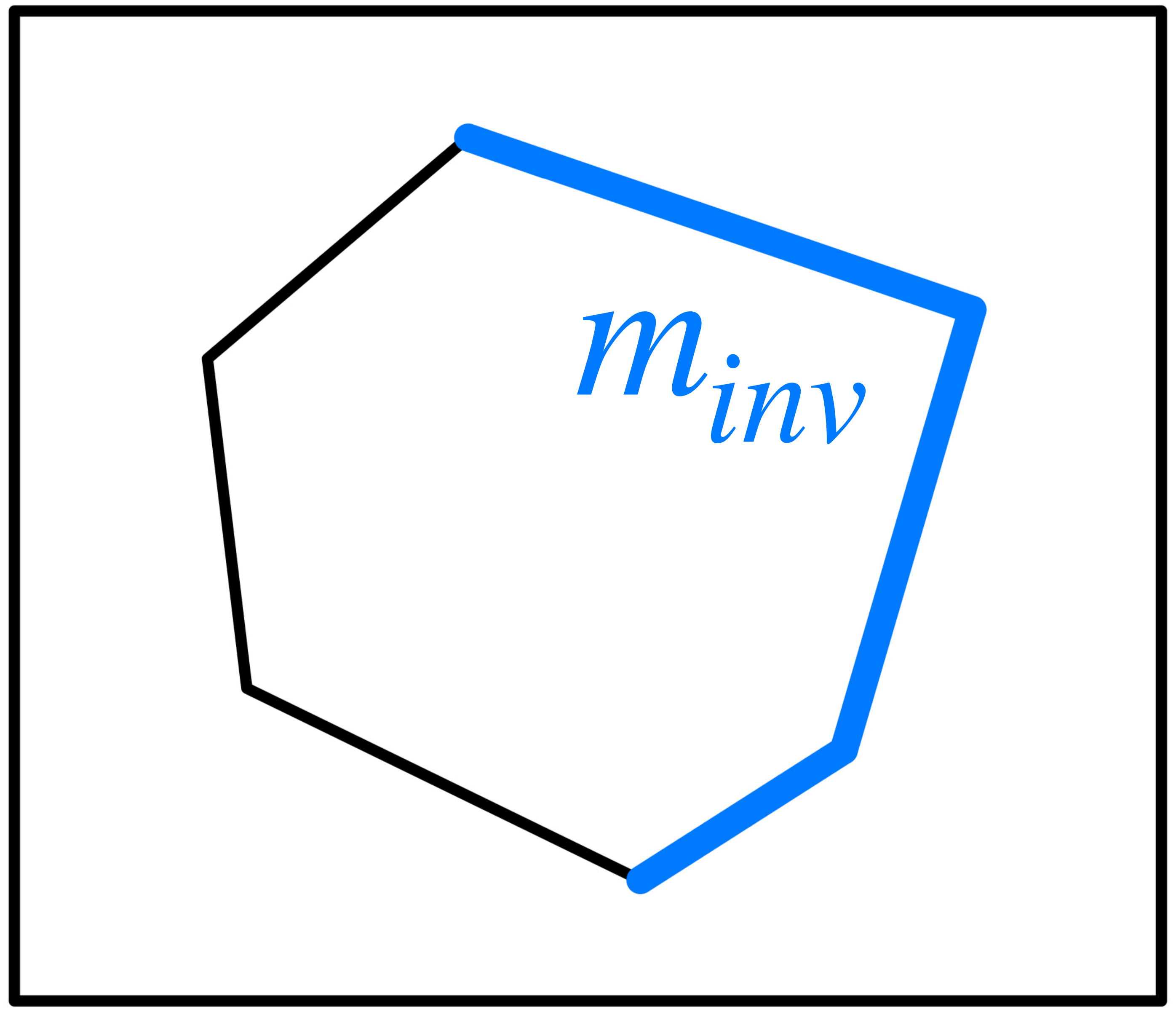


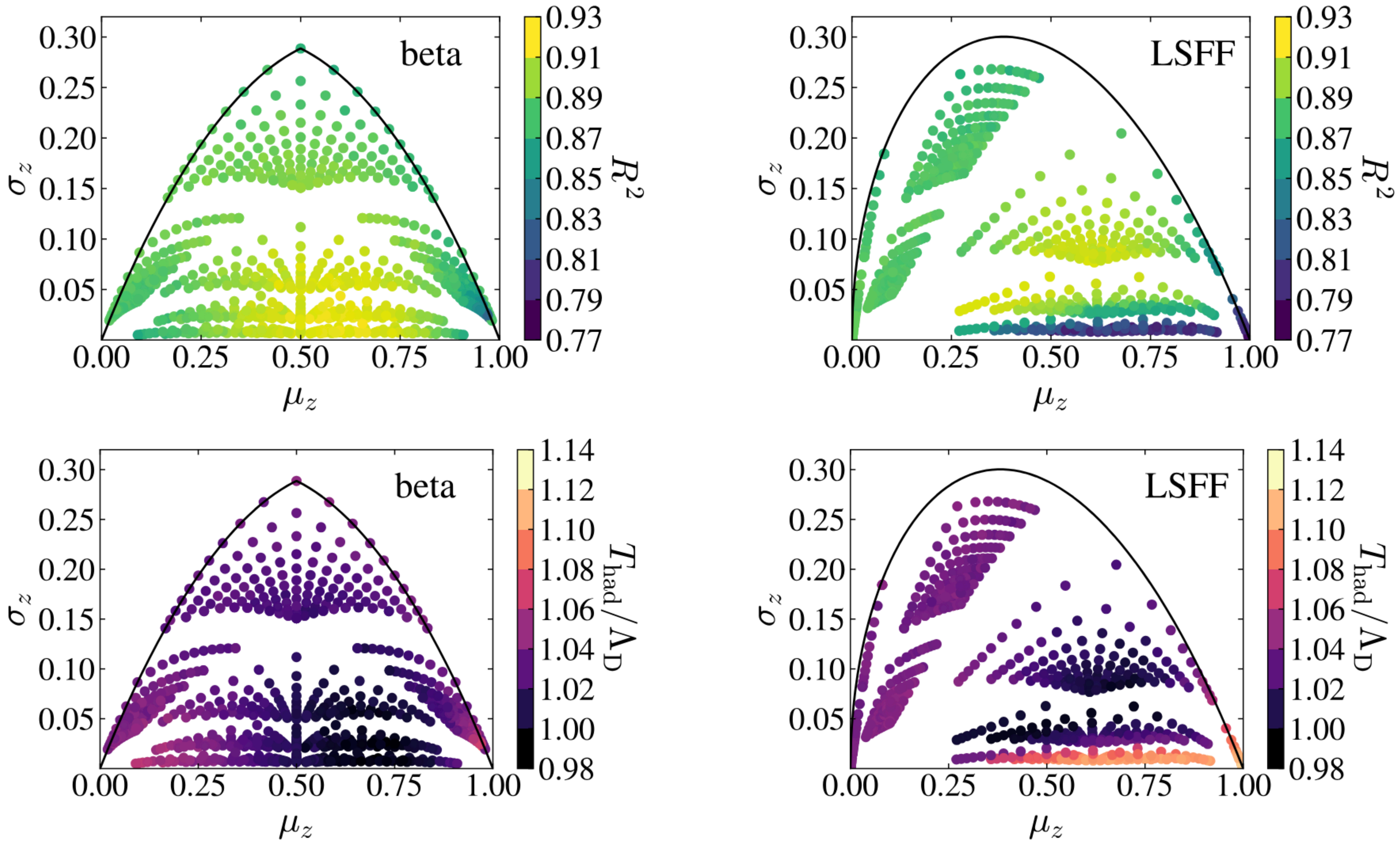
Glueball Species Distribution

- 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



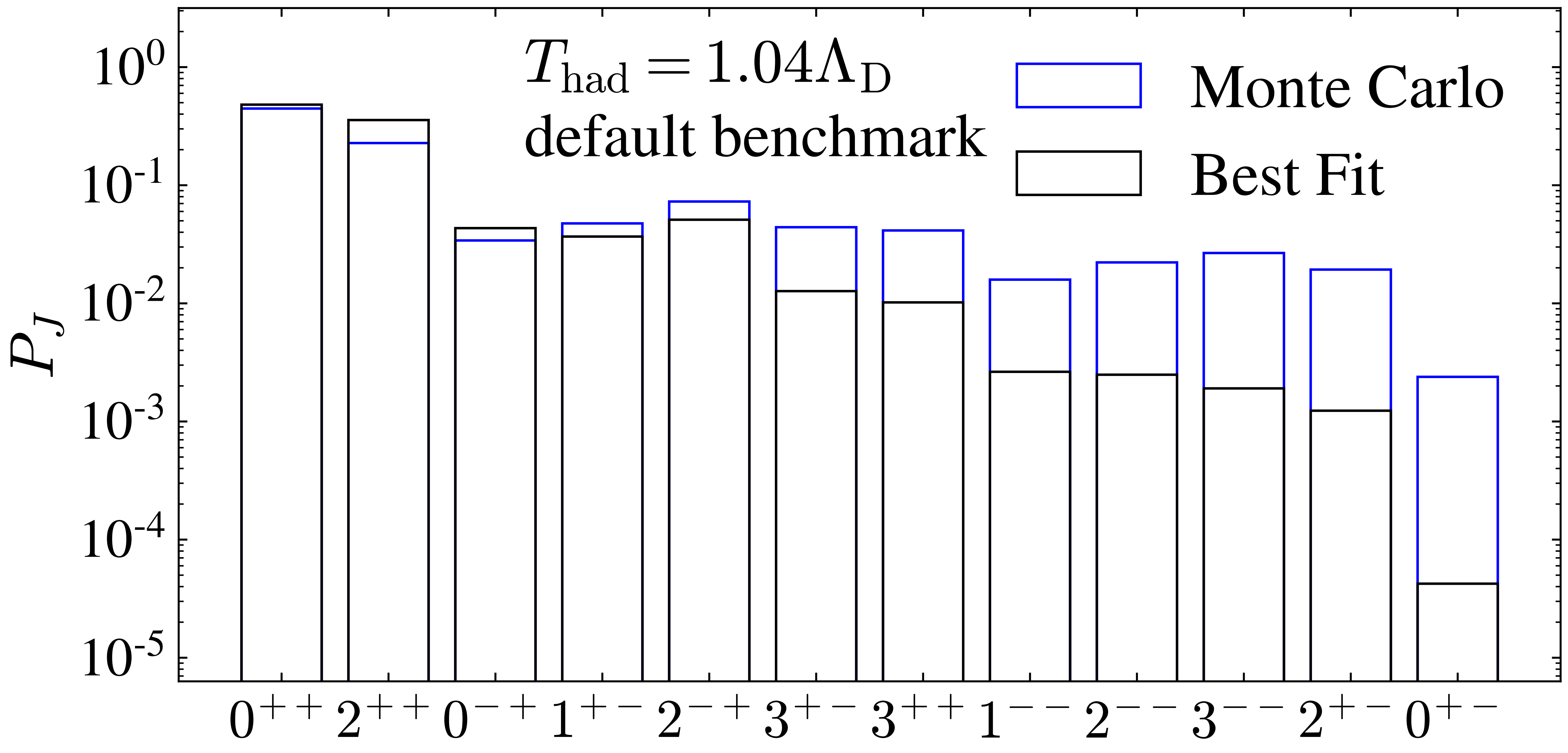
Glueball Species Distribution

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

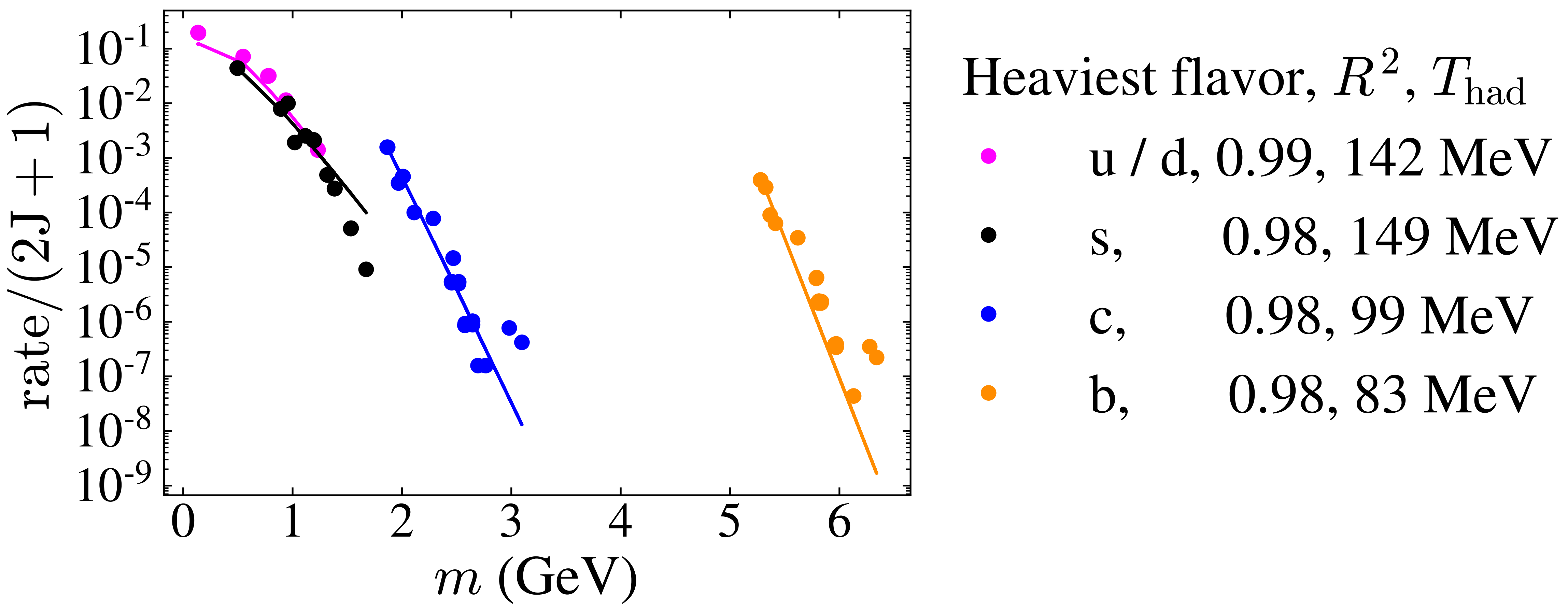


Glueball Species Distribution

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



Pure Glue Hadronization: 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

- **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 the Hidden Valley module for public release**

Collider Signatures

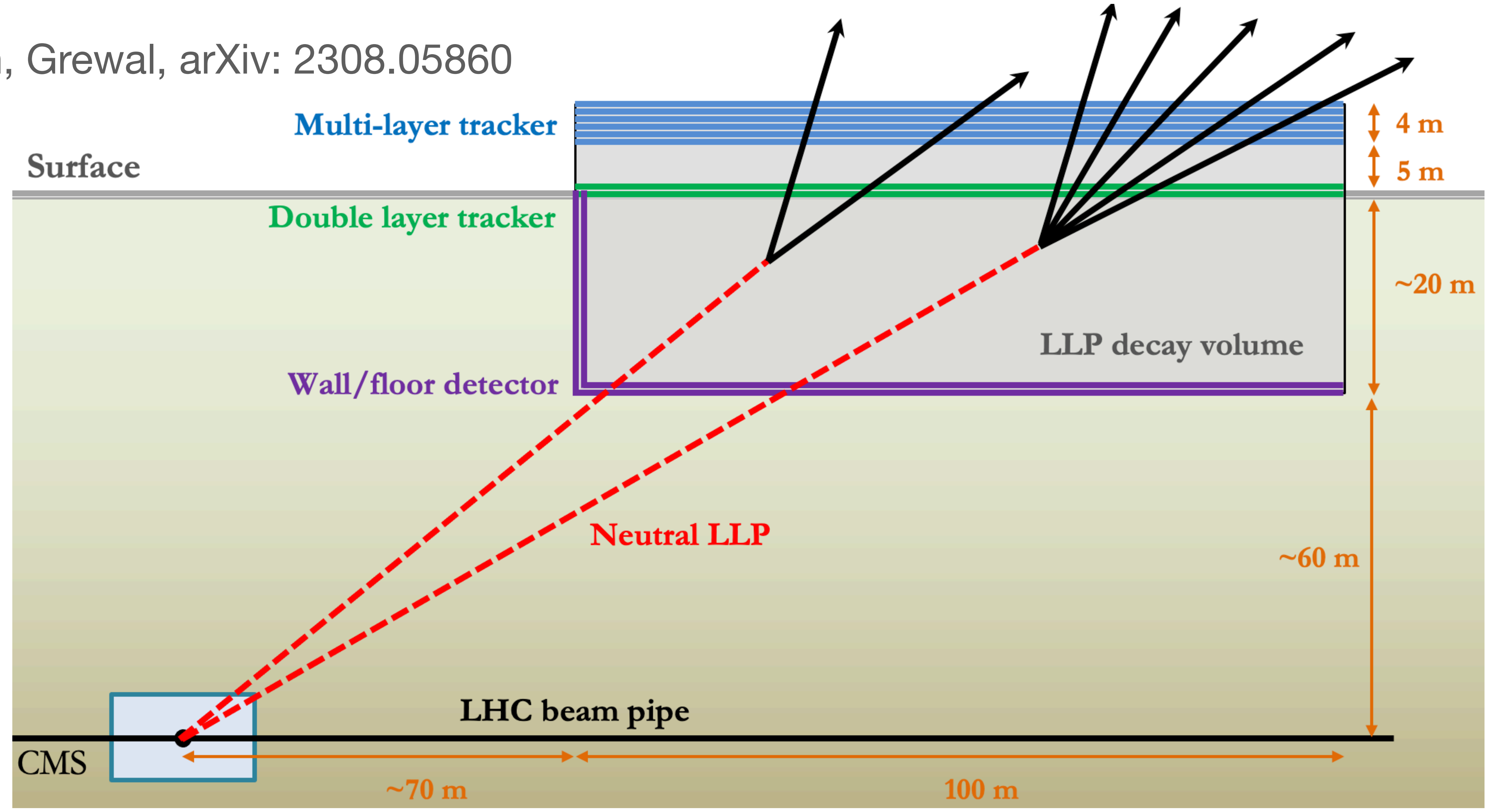
Glueballs as Long Lived Particles

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

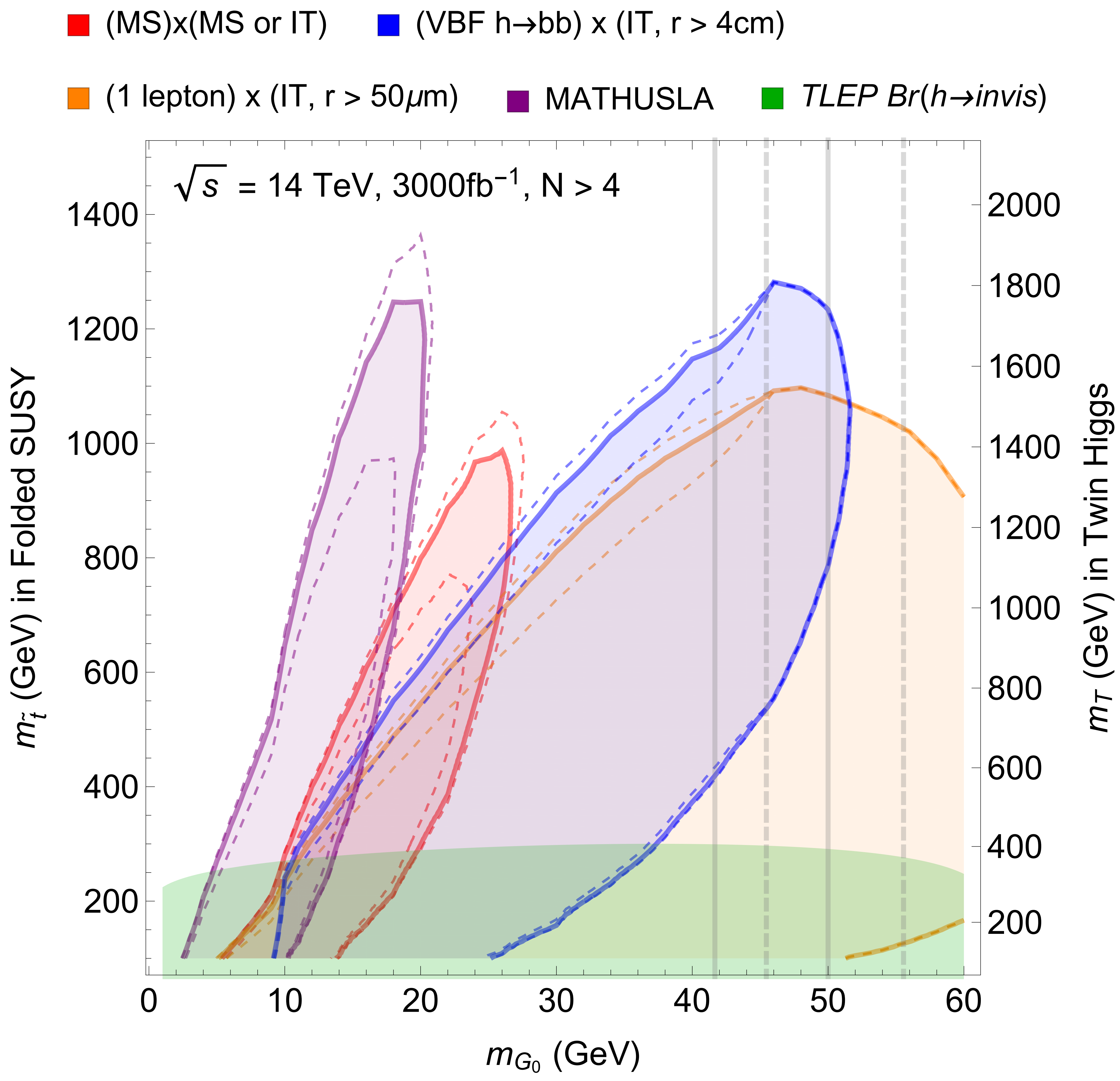
Chou, Curtin, Lubatti, arXiv:1606.06298
Alpigiani et al., arXiv:1811.00927

- **Able to probe much longer lifetimes**

Curtin, Grewal, arXiv: 2308.05860

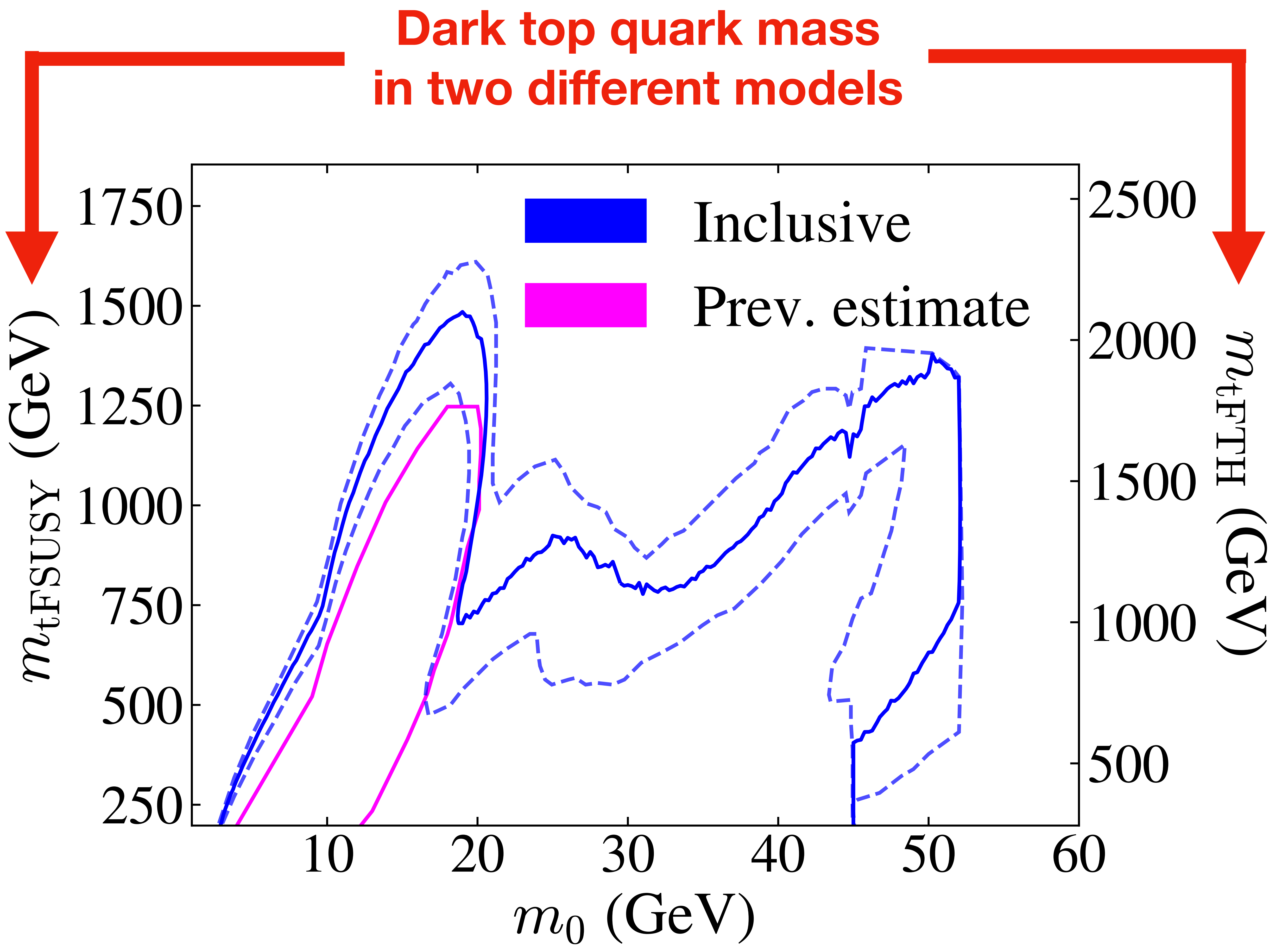


Curtin et al., arXiv: 1806.07396



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
  - Hadronization and matrix transition elements
- Probing the TeV scale is the goal of neutral naturalness models!

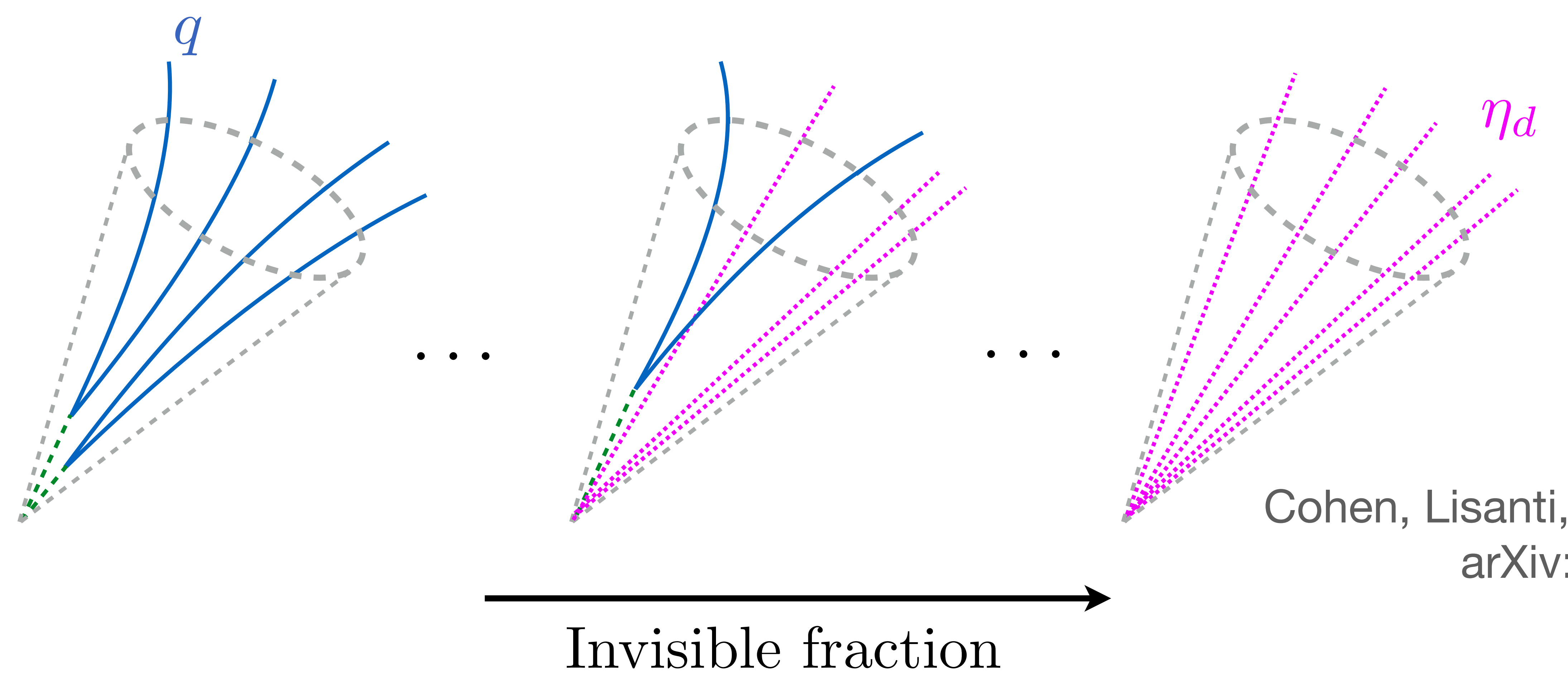


Semivisible Jets

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

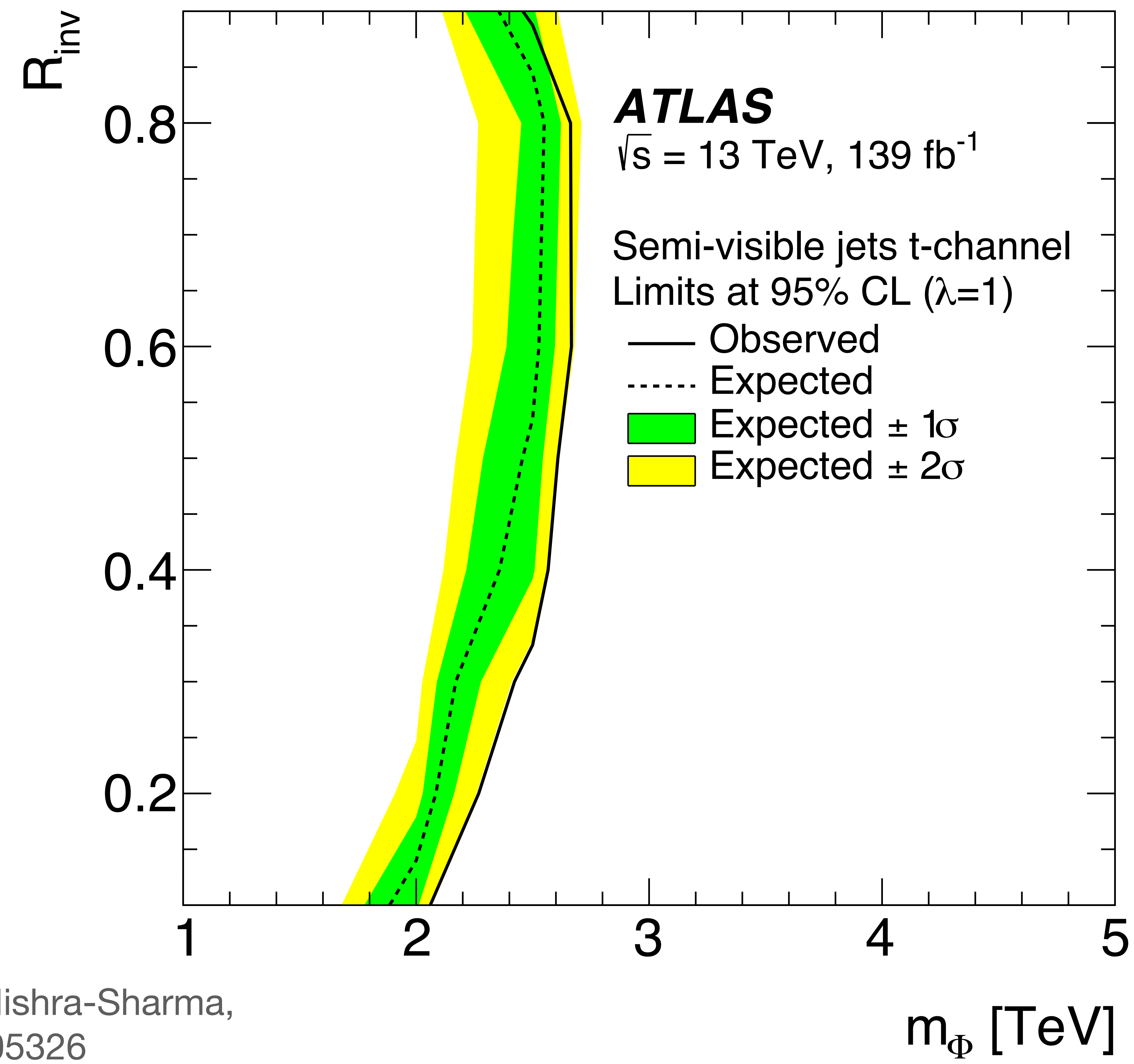
  Cohen, Lisanti, Lou, arXiv: 1503.00009

- **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**



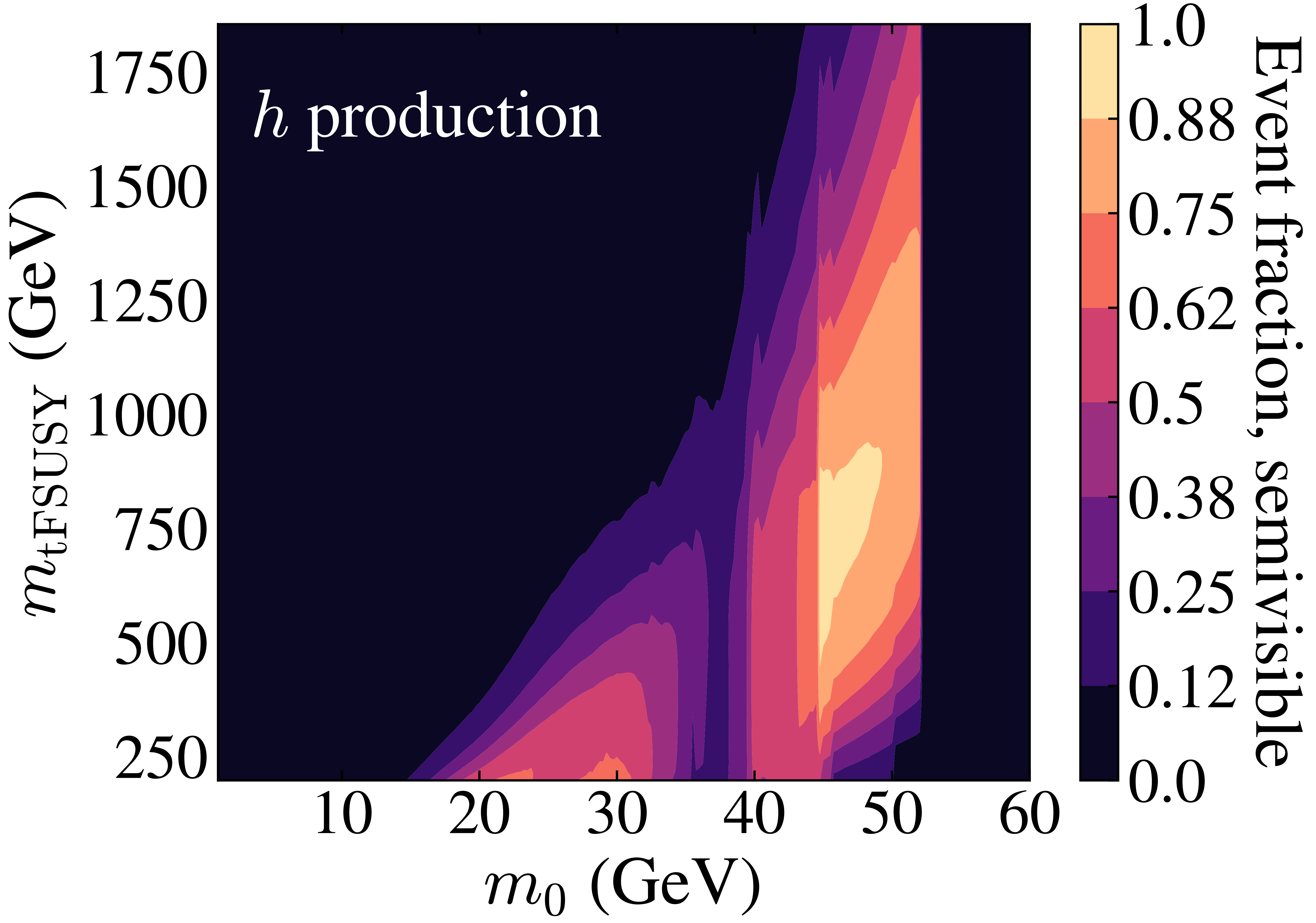
Cohen, Lisanti, Lou, Mishra-Sharma, arXiv: 1707.05326

ATLAS collab., arXiv: 2305.18037



Semivisible Jets

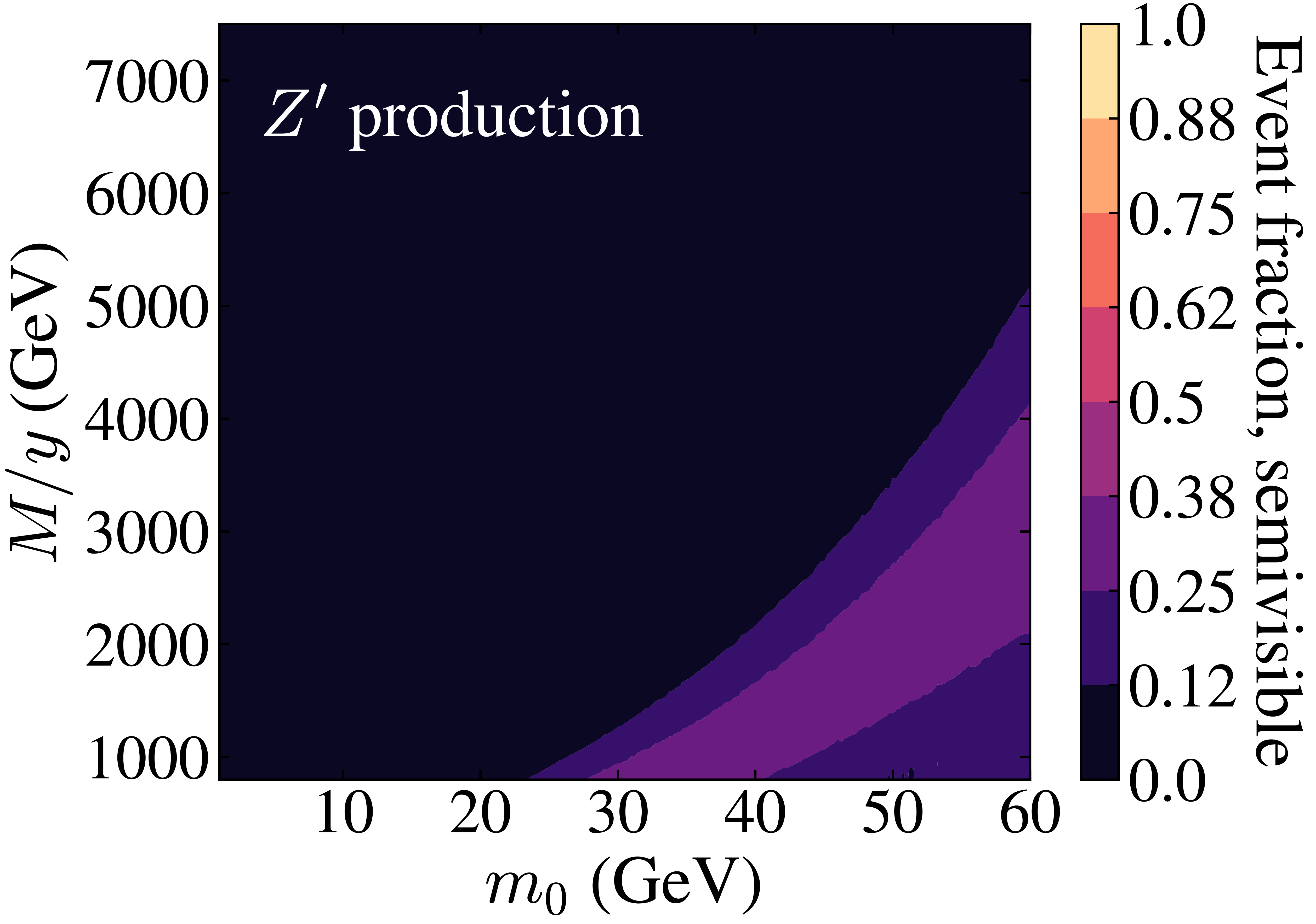
- **Higgs production**
    - **Assume gluon fusion and VBF production**
    - **Rescaled branching fraction to dark gluons**
- **Simplified analysis:**
    - **At least one glueball escape the CMS tracker**
    - **At least one prompt glueball decay within the tracker**
    - **No glueball decays within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



Semivisible Jets

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

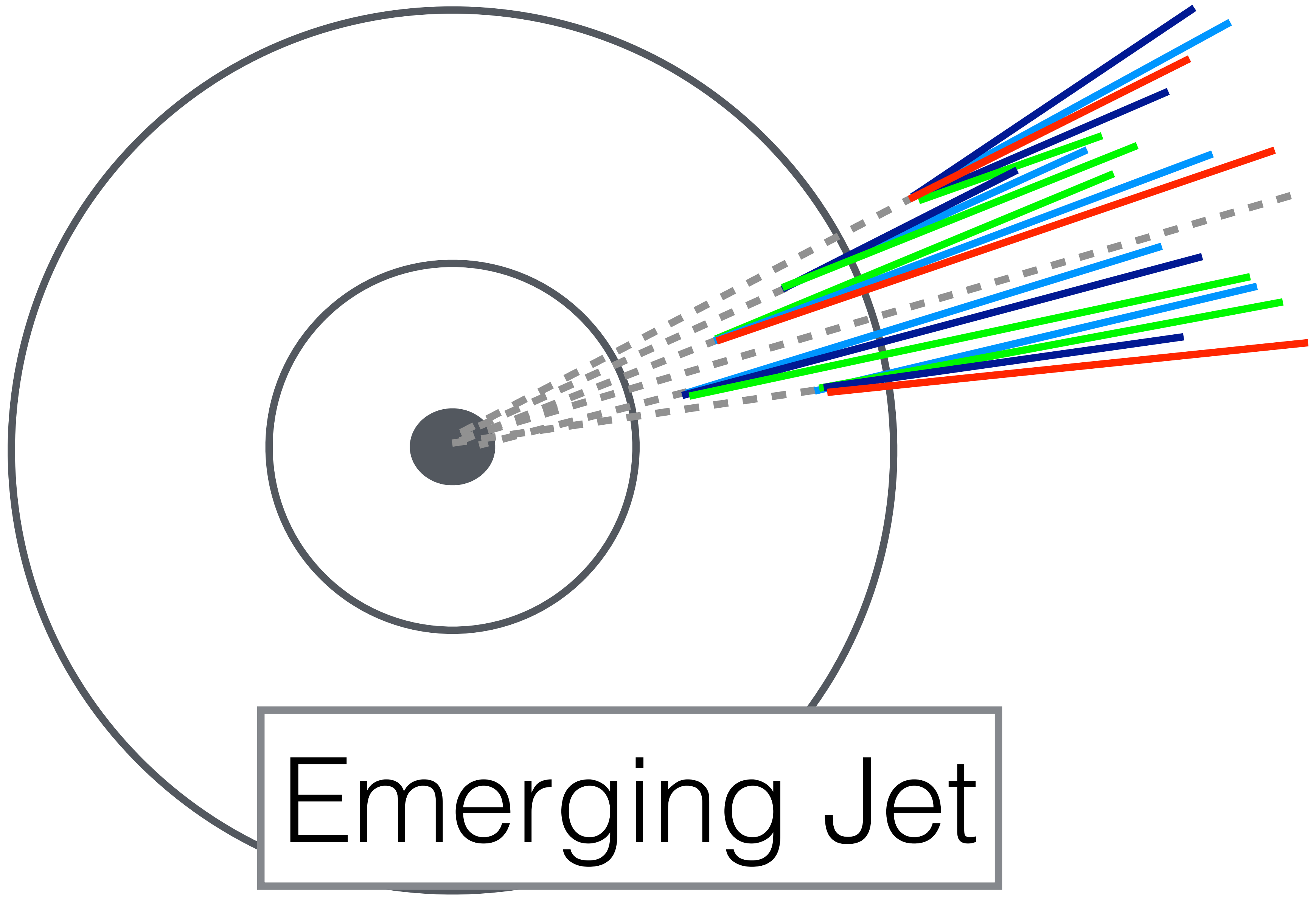
    Kang, Luty, arXiv: 0805.4642
    - **Open question, but assume** $M = M_Q \sim M_{Z'}/2$ **such that radiation is minimal**
  - $Q_D\overline{Q}_D$ **annihilate to dark gluons producing dark glueball shower**

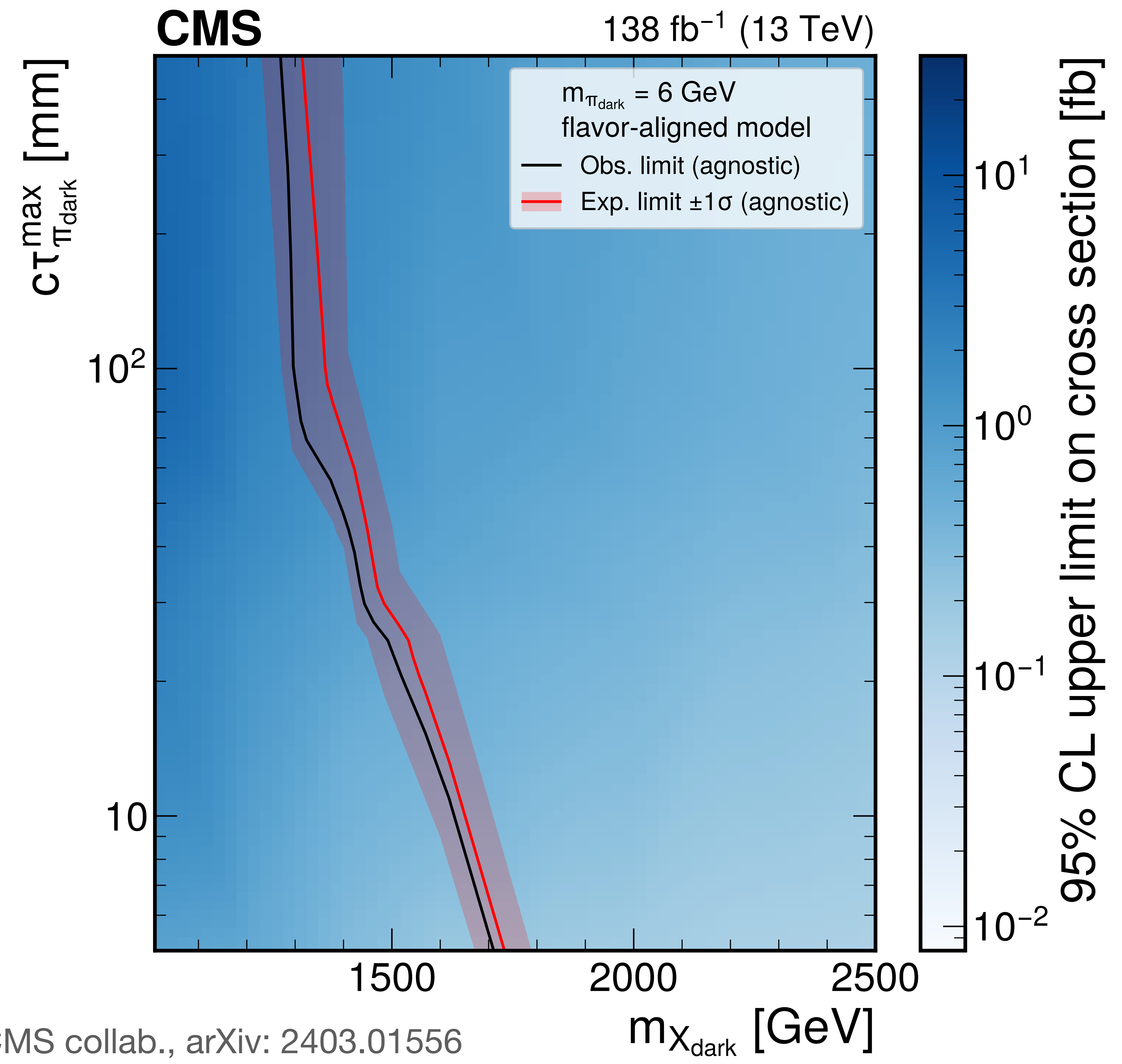


Emerging Jets

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

Schwaller, Stolarski, Weiler, arXiv: 1502.05409

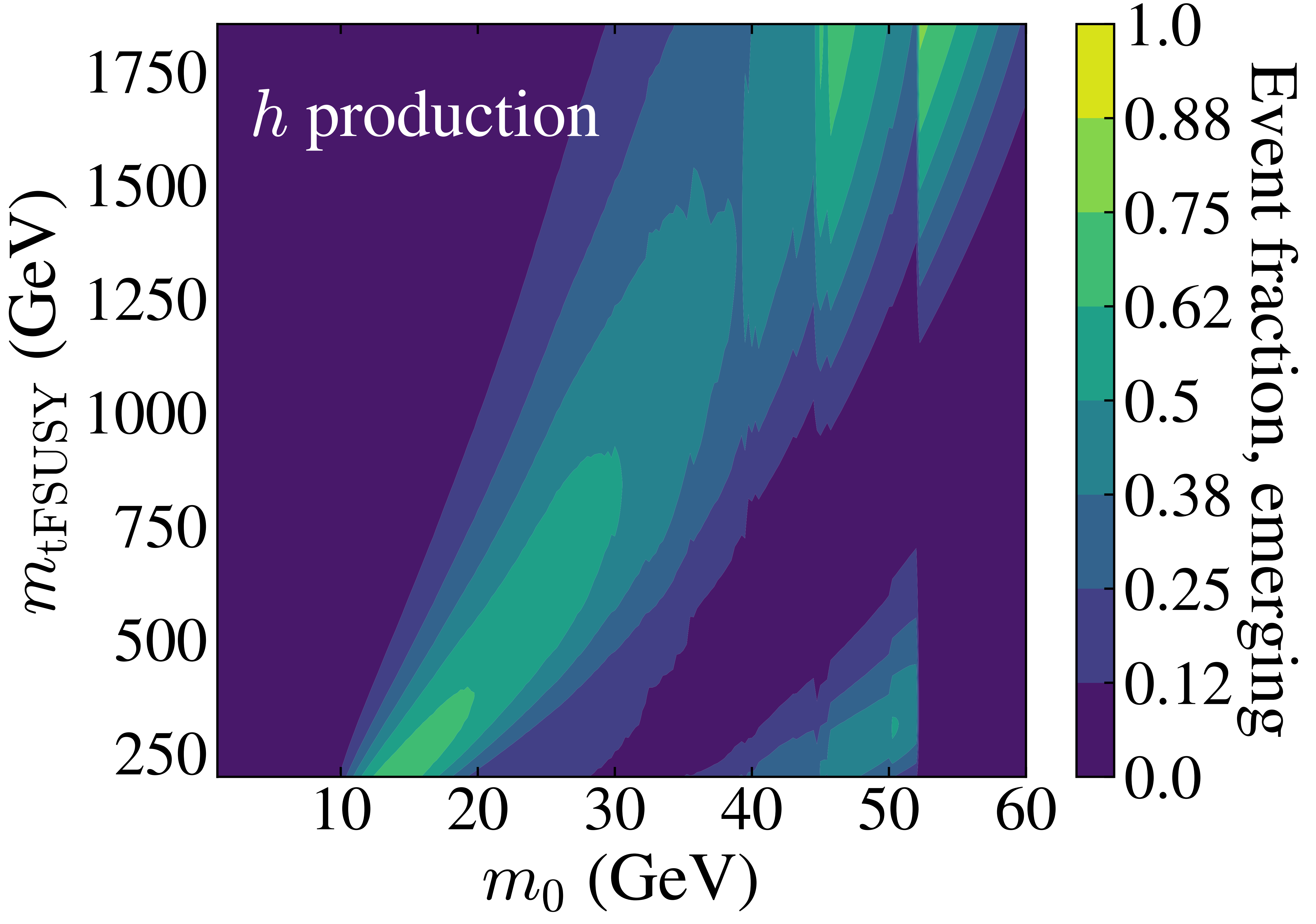




CMS collab., arXiv: 2403.01556

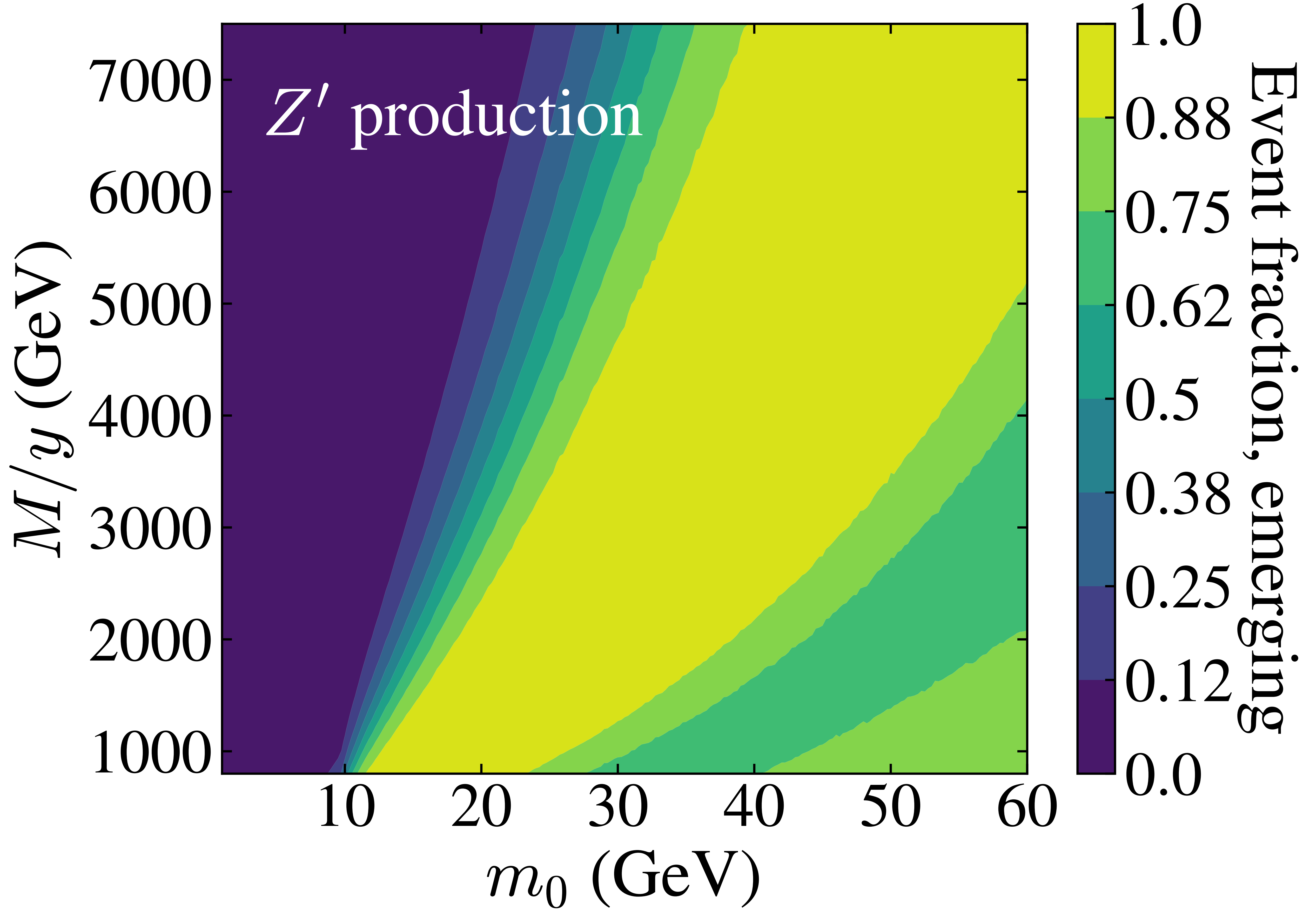
Emerging Jets

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

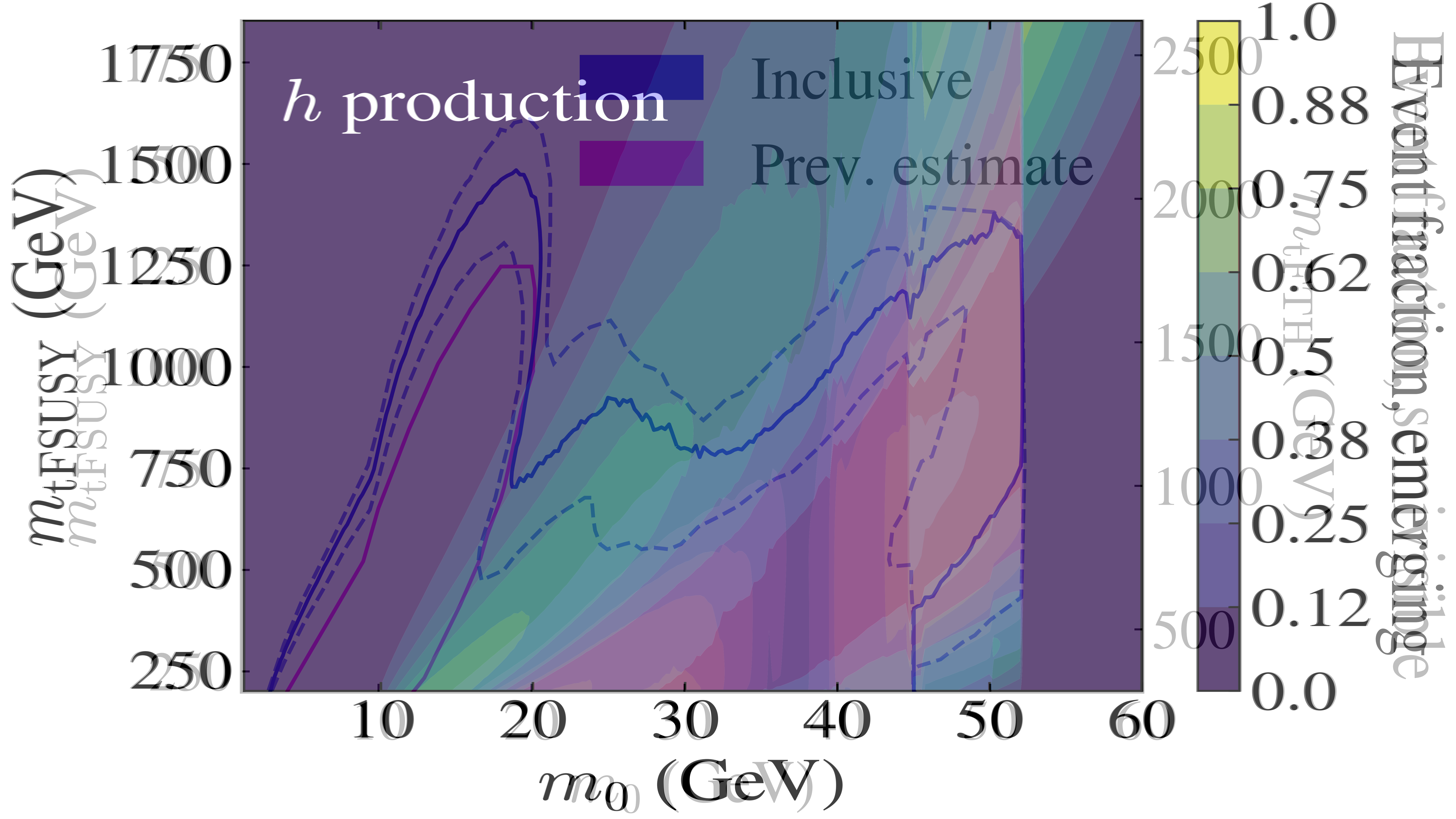


Emerging Jets

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



Complementarity!



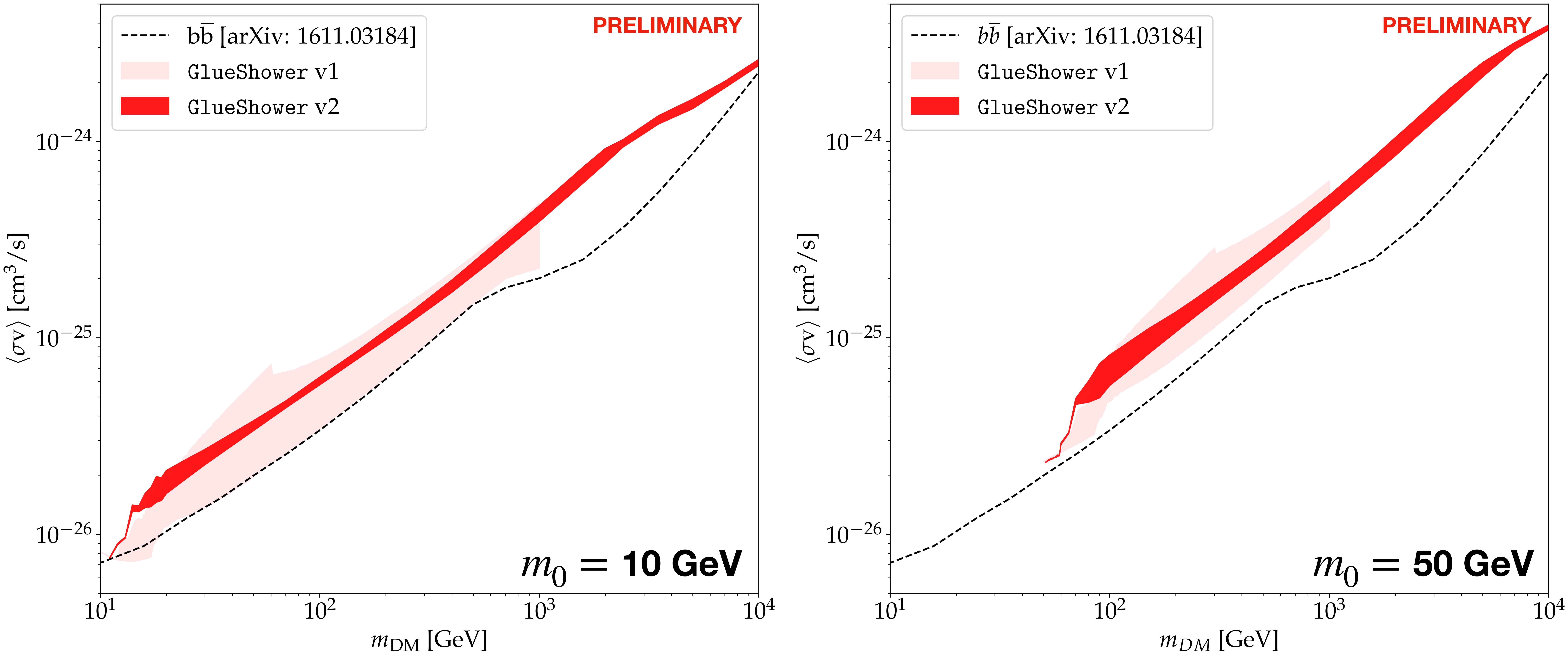
Summary

- A $N_f = 0$ dark QCD sector is both a theoretically motivated but also a relatively generic and minimal BSM extension
- This methodology allows quantitative studies of dark glueball signatures with theoretical uncertainties incorporated
- Dark glueball showers can generate LLPs in MATHUSLA, emerging jets, and semi-visible jets across the motivated parameter range

Back up Slides

Fermi-LAT constraints

arXiv: 2211.05794 (with D. Curtin)



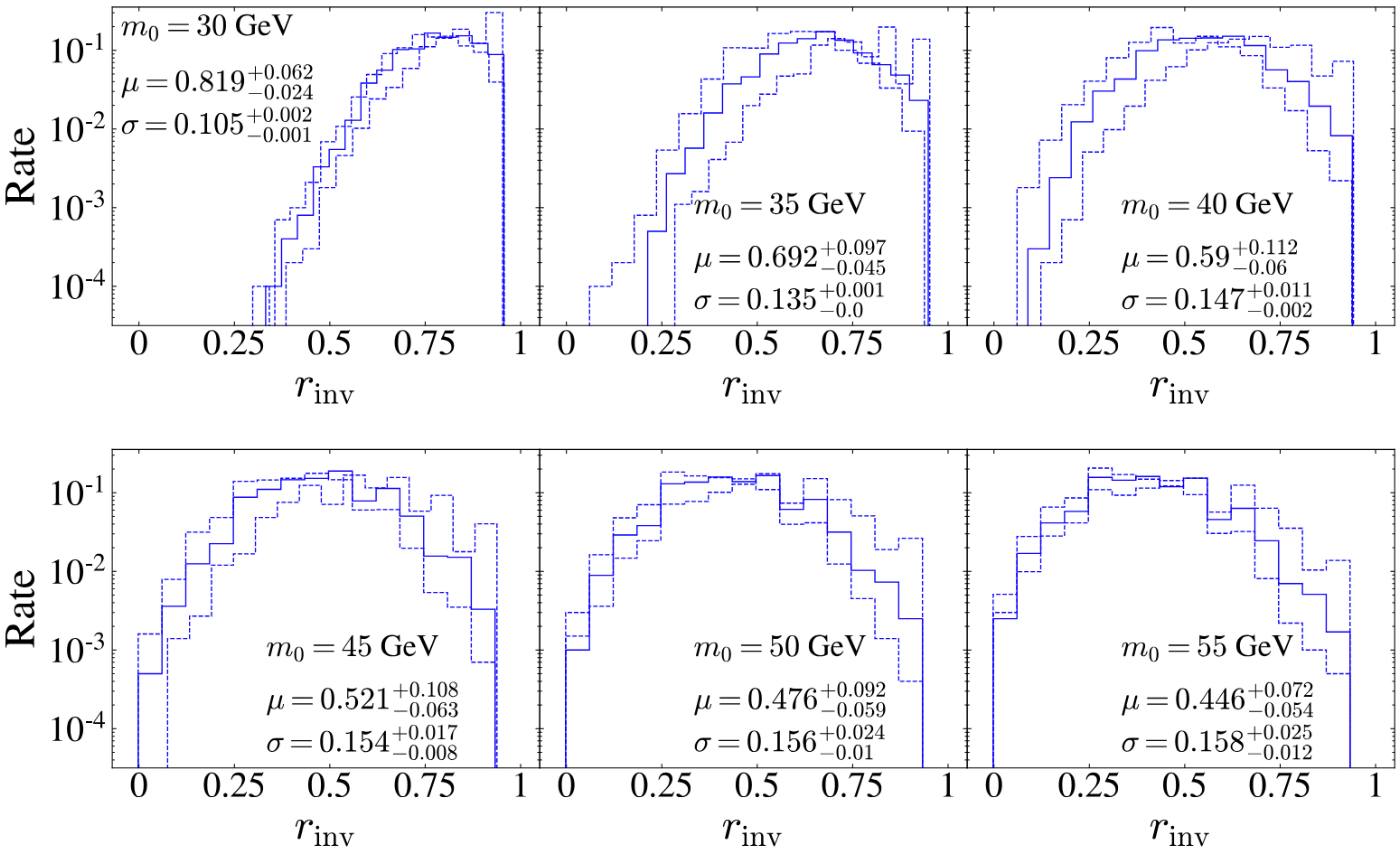


Figure 12: Distributions of $r_{\rm inv}$ for various values of the lightest glueball mass m_0 in the Z' production model with $m_{Z'} = 3$ TeV and $M_Q \sim M_{Z'}/2$, where $r_{\rm inv}$ is the fraction of dark hadrons that are invisible to the semivisible jet reconstruction. Solid histograms come from using the default hadronization benchmark, and dashed histograms come from the soft and hard variations. Means μ and standard deviations σ are displayed, with uncertainties corresponding to hadronization variations.

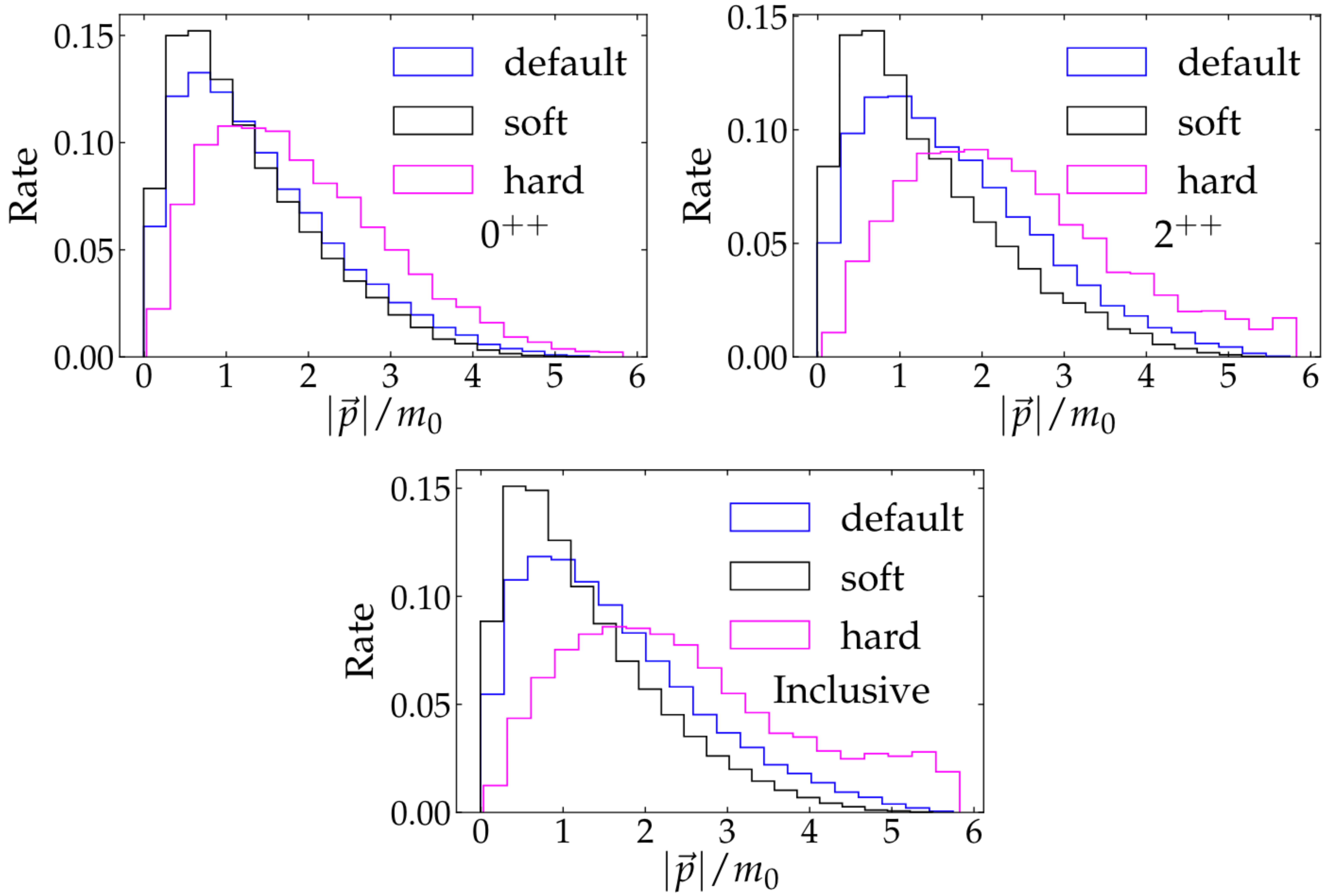


Figure 14: Distributions of $|\vec{p}|/m_0$ for the three sets of benchmark parameters listed in Table 1, measured in the rest frame of the dark gluon shower. Exclusive distributions of the two lightest species are shown, as well as the inclusive distribution. As expected, glueballs from "harder" parameter variations tend to have larger momentum.

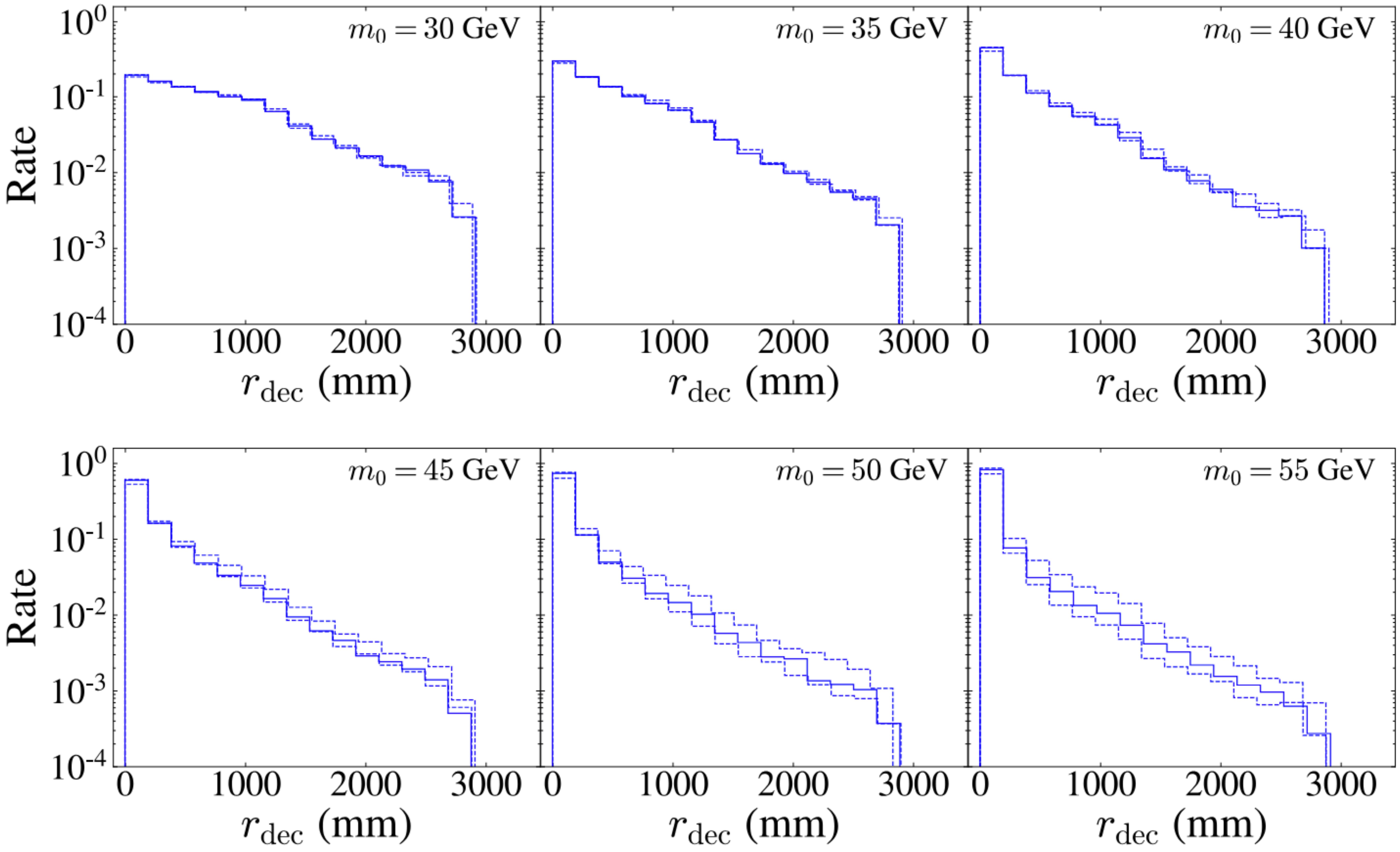
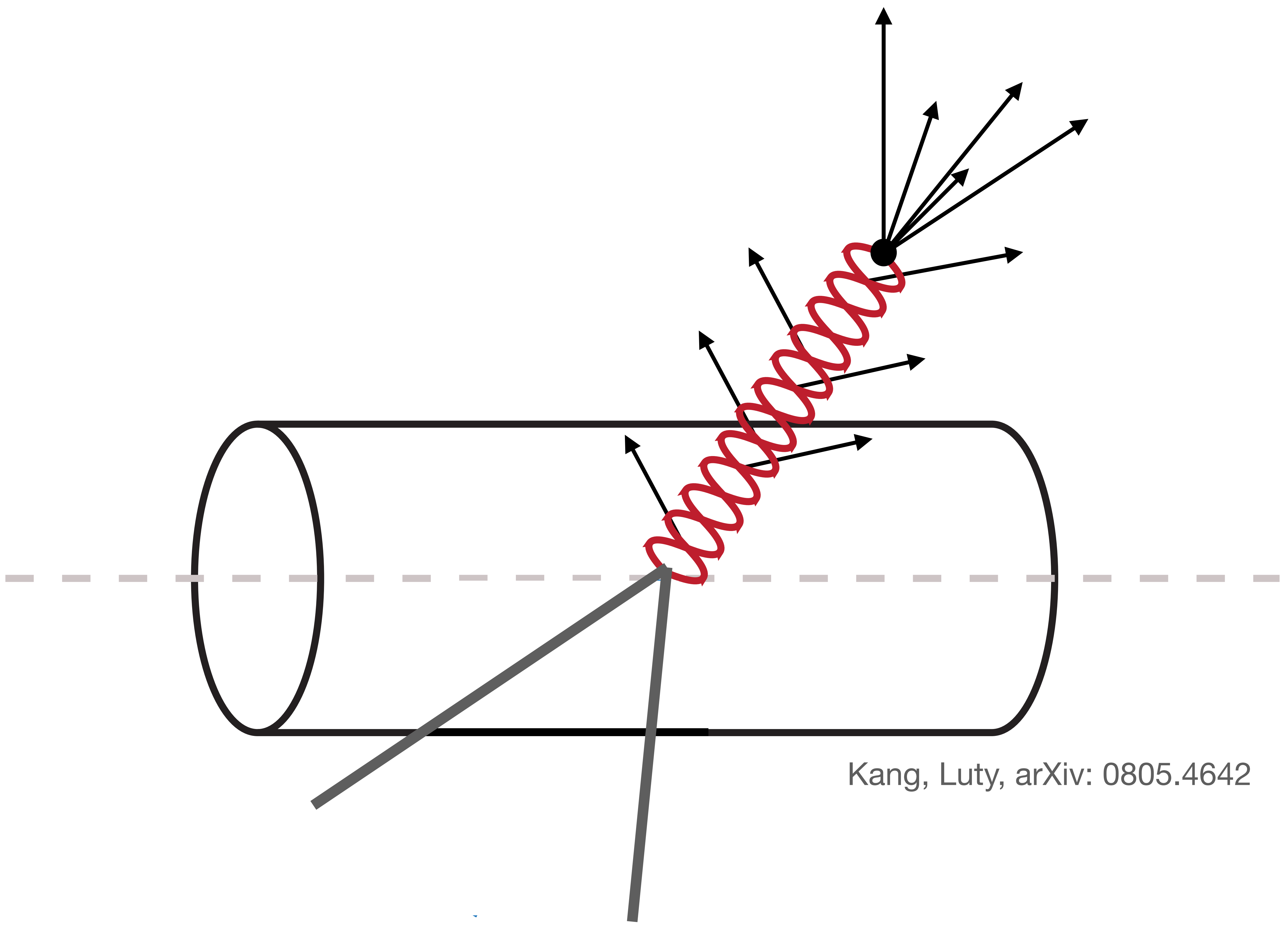


Figure 13: Distributions of $r_{\rm dec}$ for various values of the lightest glueball mass m_0 in the Z' production model with $m_{Z'} = 3\,\text{TeV}$ and $M_Q \sim M_{Z'}/2$, where $r_{\rm dec}$ is the distance of glueball decay vertices within the CMS tracker to the IP. Solid histograms come from using the default hadronization benchmark, and dashed histograms come from the soft and hard variations.

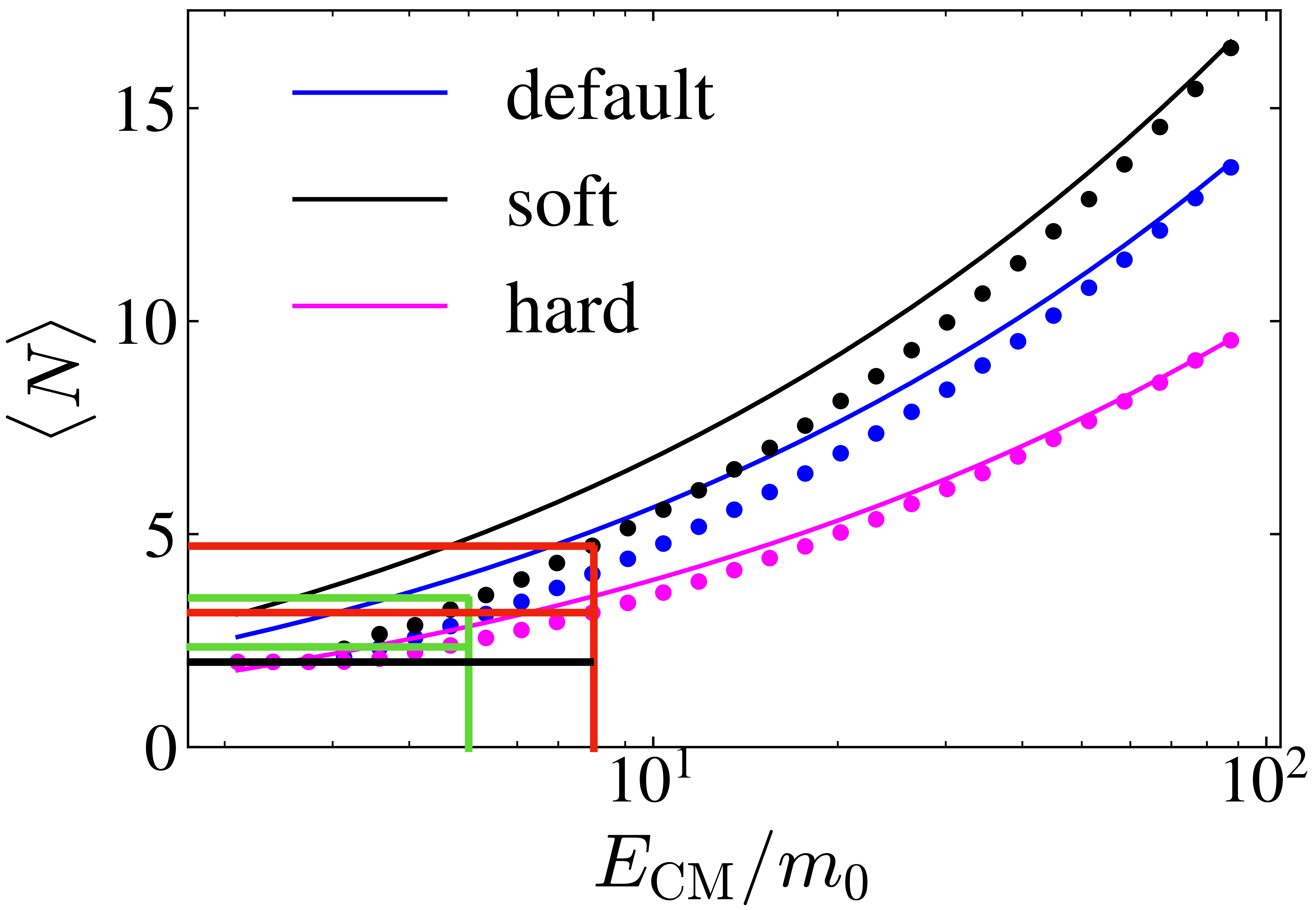
Open Questions

- 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

Hadronic Vertices



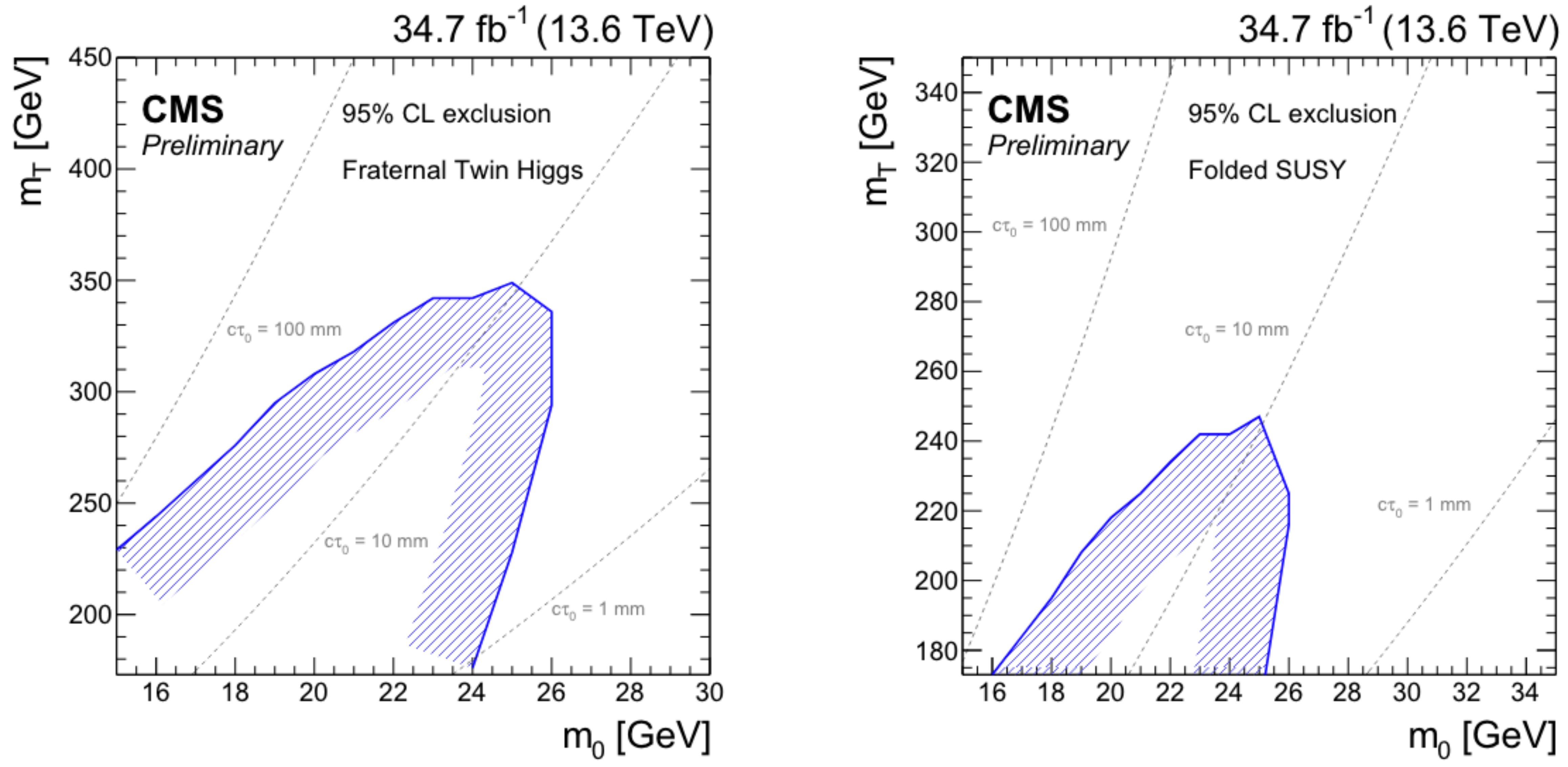


Figure 6: The 95% CL observed limits on the hidden-sector top partner mass m_T for different hidden glueball masses m_0, in the fraternal Twin Higgs model [29] (left) and the folded SUSY model [44] (right).

And need to include multiple glueball species

Dark Glueball Photon Spectra