The Theory of Exotic Signatures at the HL-LHC

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What are exotic signatures?

Q: What are "exotic signatures" at colliders?
A: Anything that's very different from what the SM produces
(modest multiplicities of prompt jets, leptons & MET & ~mm displaced τ, c, b)

Mainstream Exotic: MATHUSLA physics case 1806.07396

- BSM long-lived particles (LLPs): displaced vertices, disappearing tracks, anomalously ionizing tracks
- High-multiplicity (soft) stuff: dark showers, SUEPs, …

Strassler, Zurek hep-ph/0604261 Strassler 0801.0629; Knapen, Griso, Papucci, Robinson 1612.00850

True Freaks:

- Quirks Kang, Luty 0805.4642; Harnik, Wizansky 0810.3948
- Monopoles Mavromatos, Mitsou 2005.05100
- Stopped particles? MoEDAL 1405.7662
- *?? <your creation here>*

Next Generation Trigger Upgrades (NGT)

Exotic signatures are often **trigger constrained** since they weren't designed in as a primary physics target. L1 or L2/HLT might not pick them up and discard the event.

As a result, many 'exotics' searches historically would rely on other, more standard objects for triggering. (MET, ISR jet, VBF, …) ⇒ reduced sensitivity.

NGT Upgrades at the HL-LHC can be a game-changer:

- reconstructed tracker information at L0/L1:
  >2-4 GeV tracks, vertices, possibly with O(30ps) timing?
- More available processing power at low trigger level may even enable tagging of specific exotic objects?

A great new opportunity

Both theorists and experimentalists learn to work with what's possible.

While theorists have been working on *highly motivated* exotic signatures for a long time, their experimental uptake has been limited by detector realities. Over decades, these learned boundaries can guide but also constrain our thinking.

We know BSM physics exists, and we haven't seen any of it at the LHC so far.

Extremely simple theories can give rise to extremely weird and complicated dynamics in the IR! (QCD is only normal because we've become familiar.)

⇒ **Let's remind ourselves how highly motivated weird signatures are.**
⇒ **What could we find if there weren't *any* trigger limitations?**
⇒ **Are there even weirder signatures that are motivated, but we haven't considered them because they could never be searched for in the past?**

Theory Motivation for Exotic Signatures

Just, like… QFT, man!

Bottom-up weirdness

QFT uses the language of symmetries → it's very easy to have a 'separate sector' with its own particles and forces that is entirely separate from the SM, and then connected by subdominant portal type interactions (high mass mediators, small photon or higgs mixing, …).

Strassler, Zurek, hep-ph/0604261

Confinement relates the UV to the IR in several interesting ways:

- makes it easy to dynamically generate **small mass scales** (naturalness, huge range of plausible dark hadron masses)
- provides a mechanism for converting high energy/low multilicity into **low energy/high multiplicity** (hidden valleys, dark showers, …)

The phenomenology for a confining dark sector can take several interesting forms: QCD-like, glueballs, quirks, SUEP. [anything else?]

Long Lifetimes Are Common

Sectors that are 'mostly separate' give rise to long lifetimes when states that are stable in the dark sector are able to decay to the SM via the small effective couplings that connect the sectors:

- $\epsilon F F_D$ small U(1) mixing
- $\lambda |H|^2 |S|^2$ small higgs portal
- heavy mediators $\rightarrow \psi_{SM}\psi_{SM}\psi_D\psi_D/\Lambda^n$
- …

Bot the existence and small-ness of these portal couplings is often a consequence of considering how these dark sectors and the SM can be UV-completed.

MATHUSLA physics case 1806.07396

The Hierarchy Problem

… still has teeth

Any heavy physics at scale M with coupling g to the Higgs will generate a ***finite*** loop correction to its mass:

$$\Delta m_H^2 \sim \frac{g^2}{4\pi} M^2 \qquad \Rightarrow \qquad \text{If } M \gg m_H^{exp} = 125 \text{ GeV, you have a severe tuning.}$$

It is highly plausible that such heavy physics exists:

- we know for a fact that there is BSM physics (Dark Matter, Baryogenesis)
- There is plenty of evidence which suggests some new physics at high mass scales (grand unification? inflation! leptogenesis? quantum gravity!…)
- $|H|^2$ is an *everything*-singlet $\rightarrow$ it will couple to ***everything***.

$\Rightarrow$ Some solution for the Hierarchy Problem is as needed as ever.

Minimal Solutions

There are just two symmetry-based solutions to the Hierarchy Problem:
(1) Supersymmetry
(2) Higgs compositeness / extra dimensions ($\leftrightarrow$ AdS/CFT)

Natural implementations of these mechanisms **yielding the SM at low energy robustly** predict new QCD-charged states near the EW scale

Matsedonskyi, Panico, Wulzer 1204.6333,
Martin hep-ph/9709356

The LHC hasn't found those.

Maybe tuning is just a fact of life?

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How naturalness superfans look at people who don't care about the hierarchy problem.

Anthropics?

We are happy with severe tuning in **ONE** context: the cosmological constant.

This is for two reasons:

- five decades of everyone trying to find symmetry-based solutions have found… a b s o l u t e l y   n o t h i n g

- Anthropics is a genuine explanation for the small CC if you have three things:
  1) a mechanism for generating a vacuum landscape (e.g. string theory)
  2) a way of populating that landscape (eternal inflation?)
  3) a genuine selection criterion (having a universe with… anything?)

Weinberg 1987

Anthropics for the Higgs?

The anthropics argument for a small CC is quite special, since its selection criterion is extremely minimal (universe is not blown apart by expansion of space) and therefore a very robust necessary condition for a universe with observers.

I find similar arguments for the Higgs mass much less convincing

- atomic principle (mini-split SUSY) only makes sense if you don't vary Yukawas
- If the string landscape scans over matter and gauge content, surely standard natural technicolor or SUSY occupies a much larger fraction of vacua.

Arkani-Hamed, Dimapoulos hep-th/0405159; Giudice, Romanino hep-ph/0406088; Harnik, Kribs, Perez hep-ph/06040276; Giudice, Perez, Soreq 1207.4861

Of course, there could be a vacuum selection mechanism that ties small m_H to a small CC… or inherently selects for a light Higgs… but that is model-dependent.

Giudice, McCullough, You, 2105.08617; Graham, Kaplan, Rajendran 1504.07551; Bellazzini, Csaki, Hubisz, Serra, Terning 1305.3919; Csaki, D'Agnolo, Geller, Ismail 2007.14396; ….

Accepting electroweak tuning by analogy to the CC is a bit of a cop-out.

What else could be going on?

Personal opinion:
The SM is by no stretch of the imagination minimal (and have you seen GUT or DSB models??), so let's not be too precious about its low-energy structure.

What if vanilla SUSY/CH didn't break down to the low-energy SM, but to… ~SM² at a scale of ~ 10 TeV?

E.g.

$$SU(6) \otimes SU(4) \otimes SU(2) \rightarrow \mathrm{SM}_A \otimes SM_B \otimes \mathbb{Z}_2$$

Skipping some details, simplifying for illustration

$\supset$ an $SU(2)_A \otimes SU(2)_B$ Higgs sector, fermions x 2, strong force x 2, etc…

Twin Mechanism

Chacko, Goh, Harnik hep-ph/0506256

The $\mathbb{Z}_2$ discrete symmetry between the two SMs gives rise to the *twin mechanism*:

Quadratic corrections to the Higgs potential obey accidental SU(4) symmetry

$$\Delta V \supset y_A^2 |H_A|^2 \Lambda^2 + y_B^2 |H_B|^2 \Lambda^2 \to y^2(|H_A|^2 + |H_B|^2)\Lambda^2 \sim y^2 |\mathbf{H}|^2 \Lambda^2$$

→ angular mode of this 'SU(4) multiplet' does not receive quadratic corrections at 1-loop → solves the 'little hierarchy problem' for our light higgs

Motivates SUSY/CH solving the Hierarchy Problem down to ~ 10 TeV, and then the presence of such a discrete symmetry explains our light Higgs.

Embracing Generalized Naturalness

Explicit models:
Twin Higgs: Minimal, Fraternal, Orbifold, …
Folded SUSY
Quirky Little Higgs
Hyperbolic Higgs …

Burdman, Chacko, Goh, Harnik hep-ph/0609152
Craig, Katz, Strassler, Sundrum 1501.05310
Craig, Knapen, Longhi 1410.6808
Barbieri, Hall, Harigaya 1706.05548
Barbieri, Greco, Rattazzi, Wulzer 1501.07803
Cai, Cheng, Terning 0812.0843
Cohen, Craig, Giudice, McCullough 1803.03647
…

They all have in common dark sector(s) related to the SM by such a discrete symmetry.

Low energy phenomenology:

- **Higgs portal & Higgs coupling modifications.**
- **Hidden Valleys, Dark Showers, Glueballs, quirks, LLPs**
- **Twin baryon DM candidates**

Vanilla Naturalness & LLPs

Of course, if any LLP is exotic to you, then the most vanilla naturalness models have plenty of those:

- RPV SUSY: small but nonzero RPV couplings give LLP
- Low-scale SUSY breaking (GMSB, ..) can have LOSP decaying to very light gravitino with 1/F0 suppressed interaction → LLP
- Split SUSY's famous long-lived gluino
- …

e.g. MATHUSLA physics case 1806.07396

Dark Matter

LLPs as the only portal to DM

Generic possibility:

Relic abundance of stable DM candidate is determined by properties of LLP in early universe plasma.

LLP carries stabilizing quantum number, decays LLP $\rightarrow$ DM + SM

DM could be almost completely sterile and impossible to see in direct detection.

LLP production at colliders and tagging of missing energy in its decay would be only way to 'discover' dark matter!

Freeze-in Dark Matter

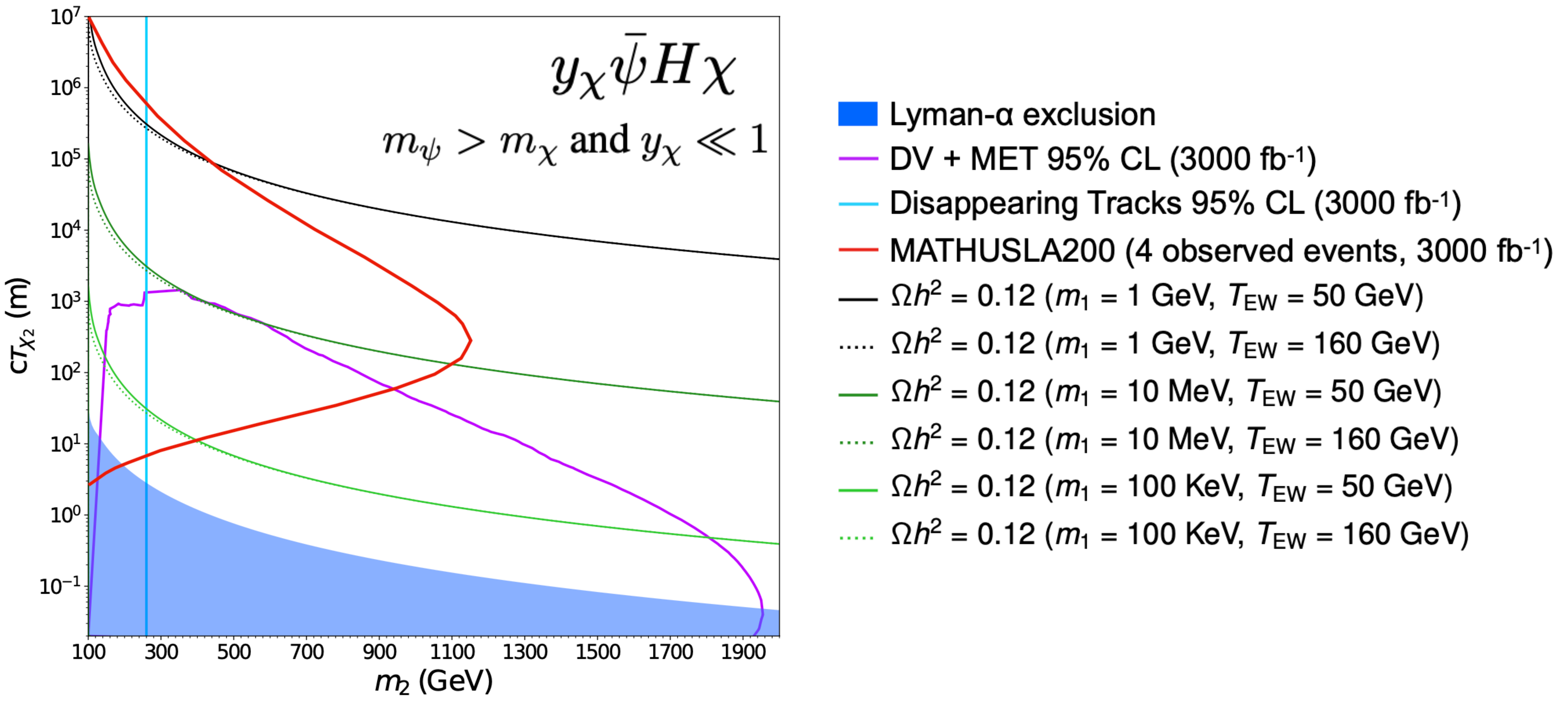
A is LLP in thermal equilibrium with the SM. DM X not produced in reheating.

While in equilibrium, A occasionally decays into the dark sector: $A \rightarrow B_{SM} + X$

LLP lifetime ↔ DM abundance

MATHUSLA physics case 1806.07396
No, Tunney, Zaldivar 1908.11387

Different DM masses m_1 pick out different $m_2 - c\tau$ relations for LLP



Inelastic Dark Matter

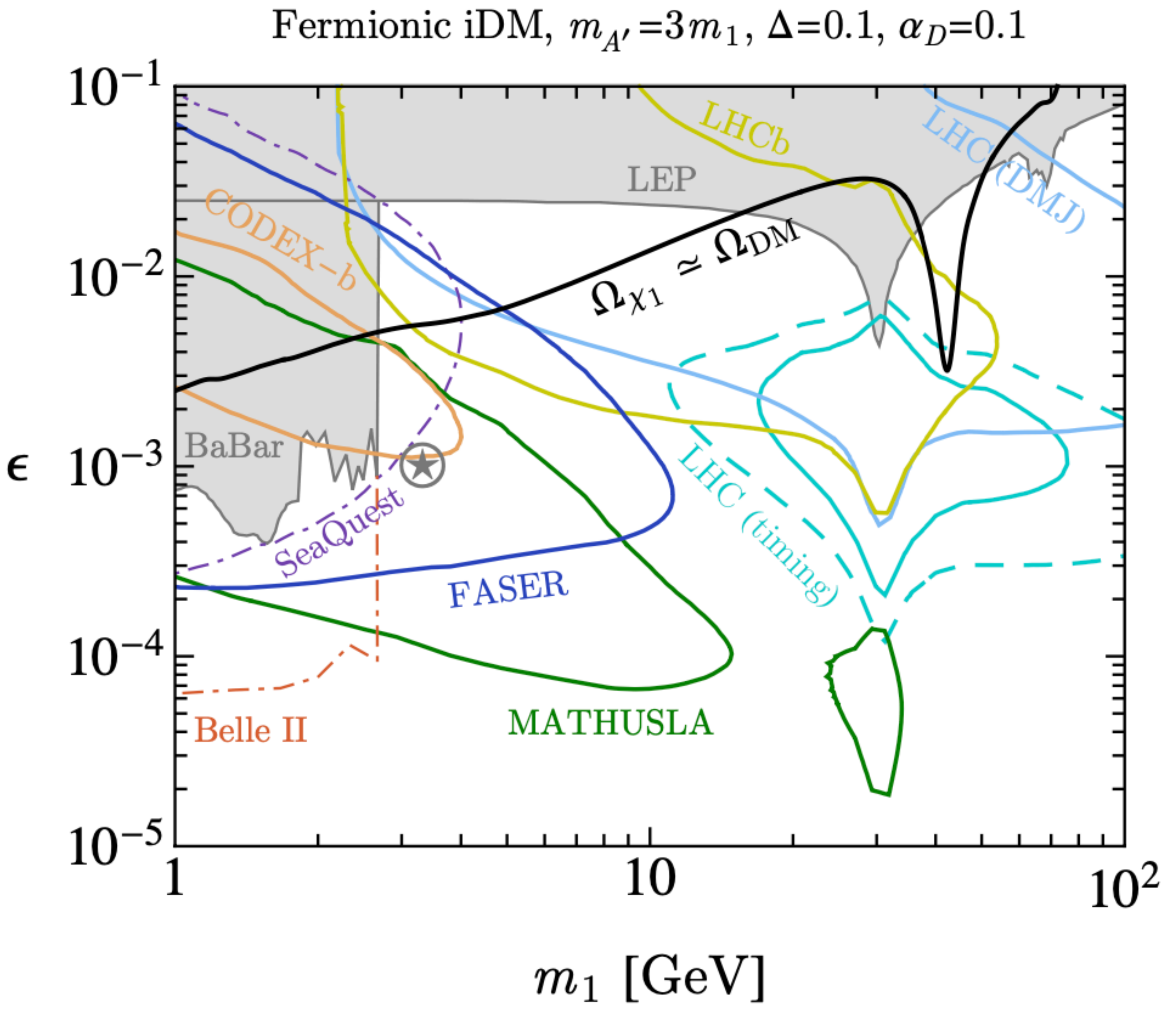
Berlin, Kling 1810.01879

Dark states χ_1, χ_2 have small mass splitting $\Delta = (m_2 - m_1)/m_1 \ll 1$, and all tree-level interactions with dark photon are off-diagonal in mass basis: $\chi_1 \gamma_\mu \chi_2 A_D^\mu$.

Direct detection (at tree-level) proceeds via upscattering $\chi_1 N \to \chi_2 N$
$\Rightarrow$ kinematically forbidden for $\Delta \gtrsim 10^{-6}$
elastic scattering via loops very small.

In regime where direct detection is blind, very " easy to have detectable macroscopic lifetime for χ_2, which can be produced at the LHC:

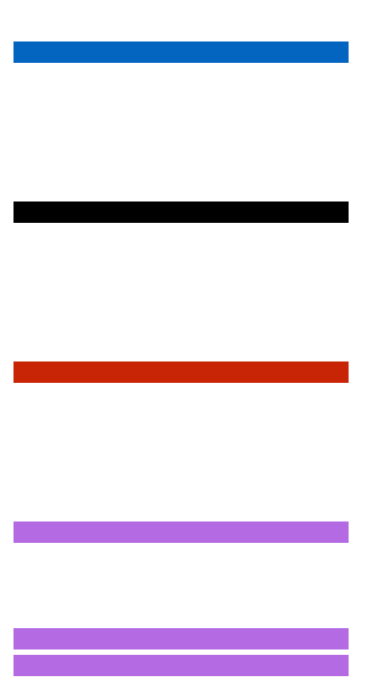
$$c\tau_{\chi_2} \sim \mathcal{O}(\mathrm{m}) \times \left(\frac{\alpha_D}{0.1}\right)^{-1} \left(\frac{\epsilon}{10^{-2}}\right)^{-2} \left(\frac{m_{A'}}{3m_1}\right)^{4} \left(\frac{\Delta}{0.05}\right)^{-5} \left(\frac{m_1}{10\ \mathrm{GeV}}\right)^{-1}$$



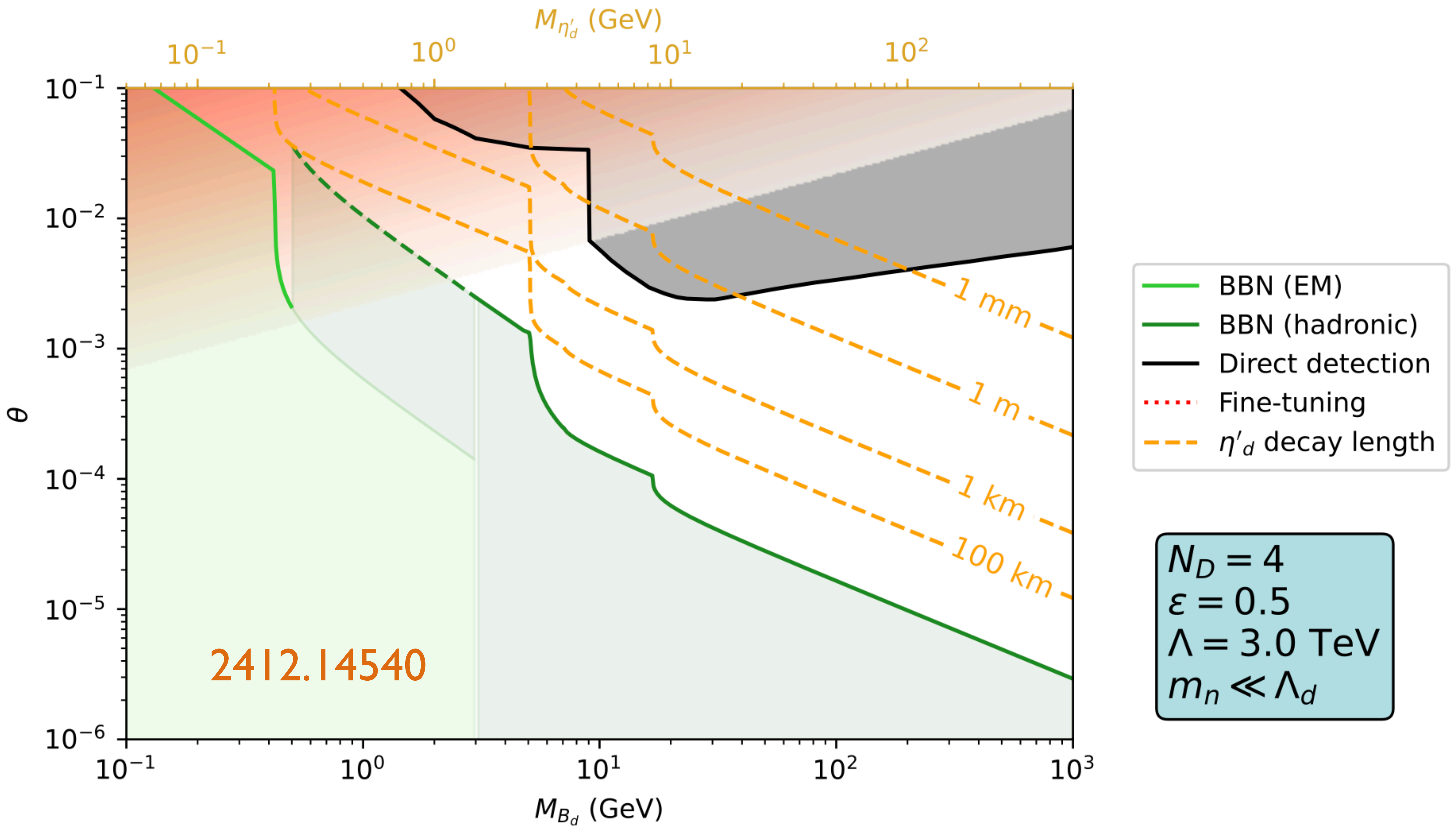
Confining Dark Sectors

e.g: Li, Tsai 1901.09936 (model-independent)
Appelquist et al 1503.04205 (Stealth DM)
Fleming, Kribs, Neil, Schaich, Vranas 2412.14540 (Hyper-Stealth DM)

In a confining dark sector, it is generic to have a spectrum like this:



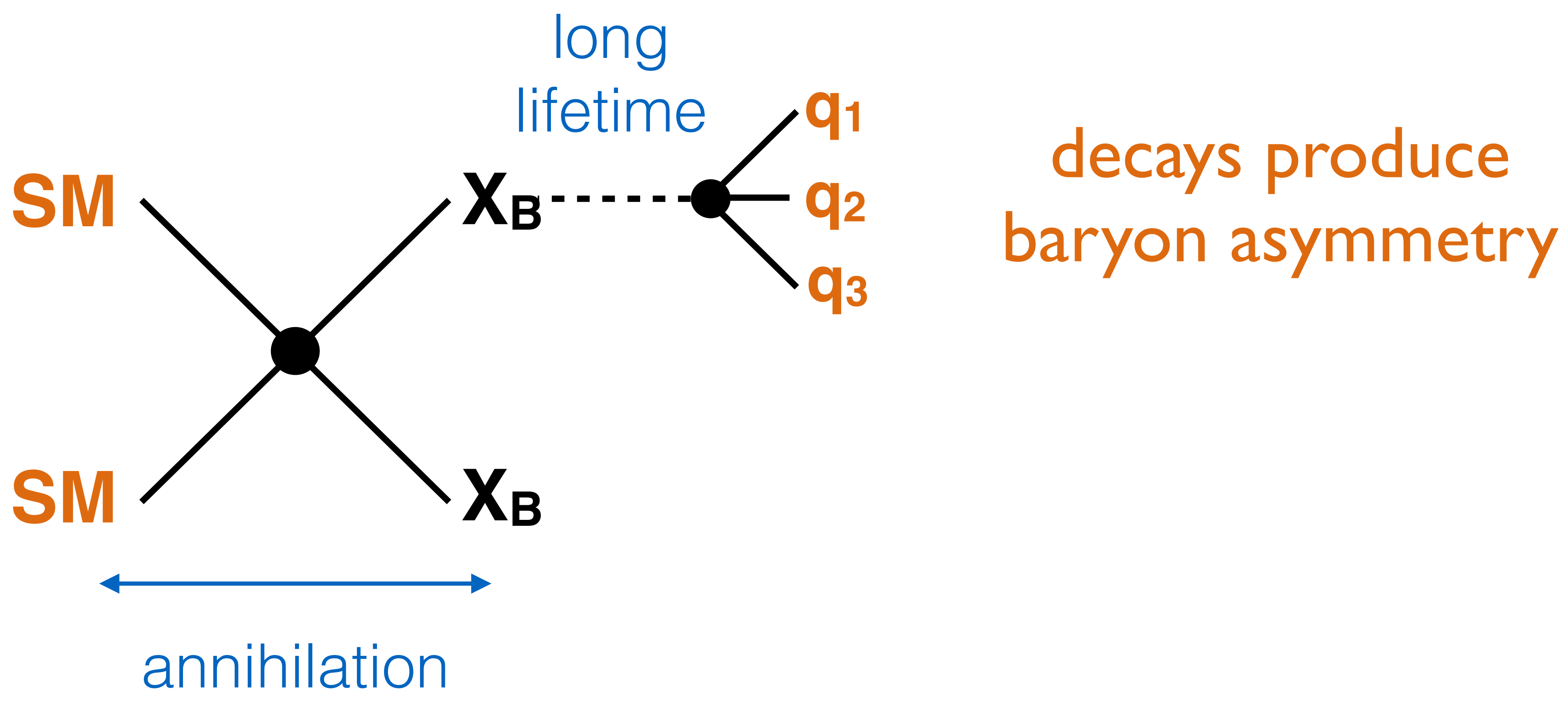
Since the same small SM coupling is responsible for direct detection and decaying the unstable dark hadrons, you get constraint plots where BBN bounds from below, direct detection from above, and in the middle there are collider-detectable LLPs!



Baryogenesis

WIMP Baryogenesis

Basic idea: WIMP-like parent particle freezes out in early universe, decays out-of-equilibrium to create baryon asymmetry.



Piggyback WIMP miracle: baryon/DM abundance similar.

Parent particle is LLP! In fact, to decay out of equilibrium, should have $c\tau_N > (2\mathrm{cm})(m_N/100\ \mathrm{GeV})^2$.

Cui, Sundrum 1212.2973

Decay after EWPT and before BBN: $c\tau \sim 0.1\mathrm{mm} - 200\mathrm{m}$. Look for at colliders!

Amusing twist on 'natural' SUSY: Anthropics & Baryogenesis

if realized in RPV, perfectly natural (< TeV superpartners) scenarios would give rise to an empty universe. Slight tuning (10 TeV squarks) makes parent gaugino meta-stable to enable creation of baryon asymmetry.

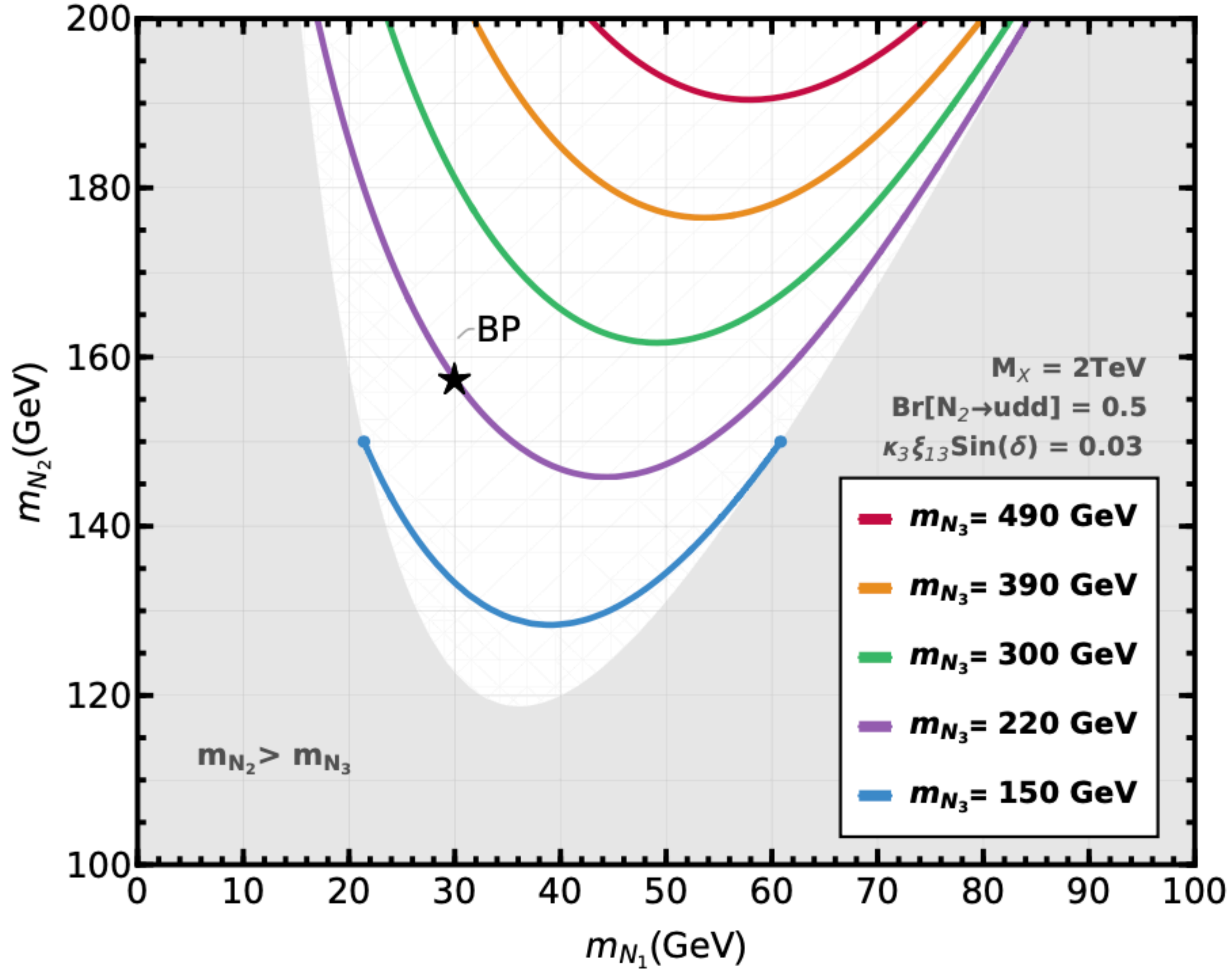
→ LLP signatures (!) & meso-tuned SUSY-like signatures (!?)

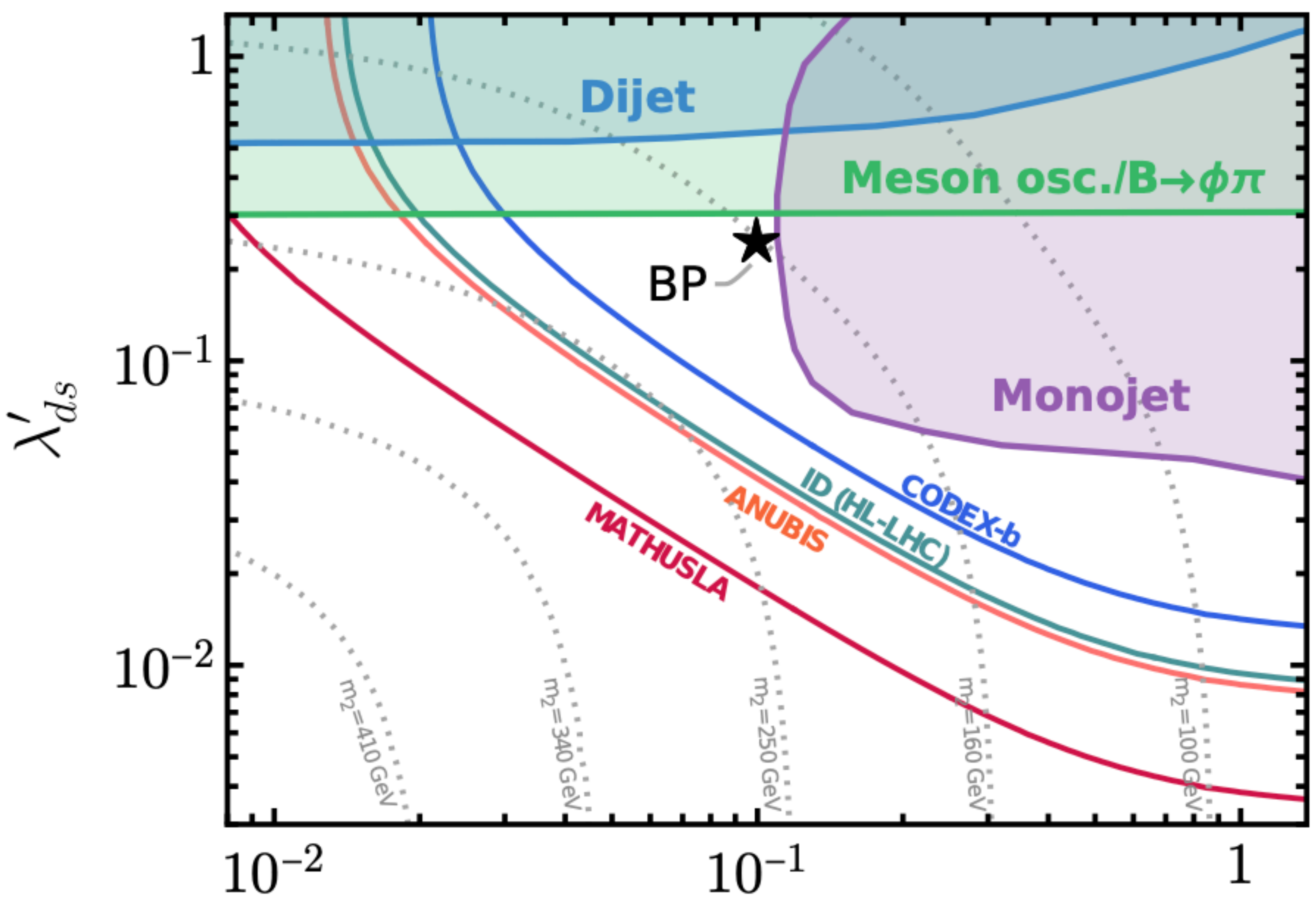
Cui 1309.2952

Example of LLP reach

Recent study by Bittar, Burdman 2410.00957. Consider three Majorana neutrino SM singlets N + new scalar Φ + UV dynamics to generate 4-fermi quark couplings, e.g. $(\mathbf{3},\mathbf{1})_{2/3}$ scalar diquark X

$$\mathcal{L}_{\rm eff} = \frac{\kappa_\alpha^{ijk}}{M_X^2}\left(\overline{N_\alpha^c}u_R^i\right)\left(\overline{d_R^c}^j d_R^k\right) + \xi_{\alpha\beta}\,\overline{N_\alpha^c}\Phi N_\beta \qquad \mathcal{L}_X = \lambda_{\alpha i} X^\dagger \overline{N_\alpha^c} u_R^i + \lambda'_{jk} X \overline{d_R^c}^j d_R^k$$





$m_{N_3} = m_{N_2} + 70\,\mathrm{GeV}$

Neutrino Masses

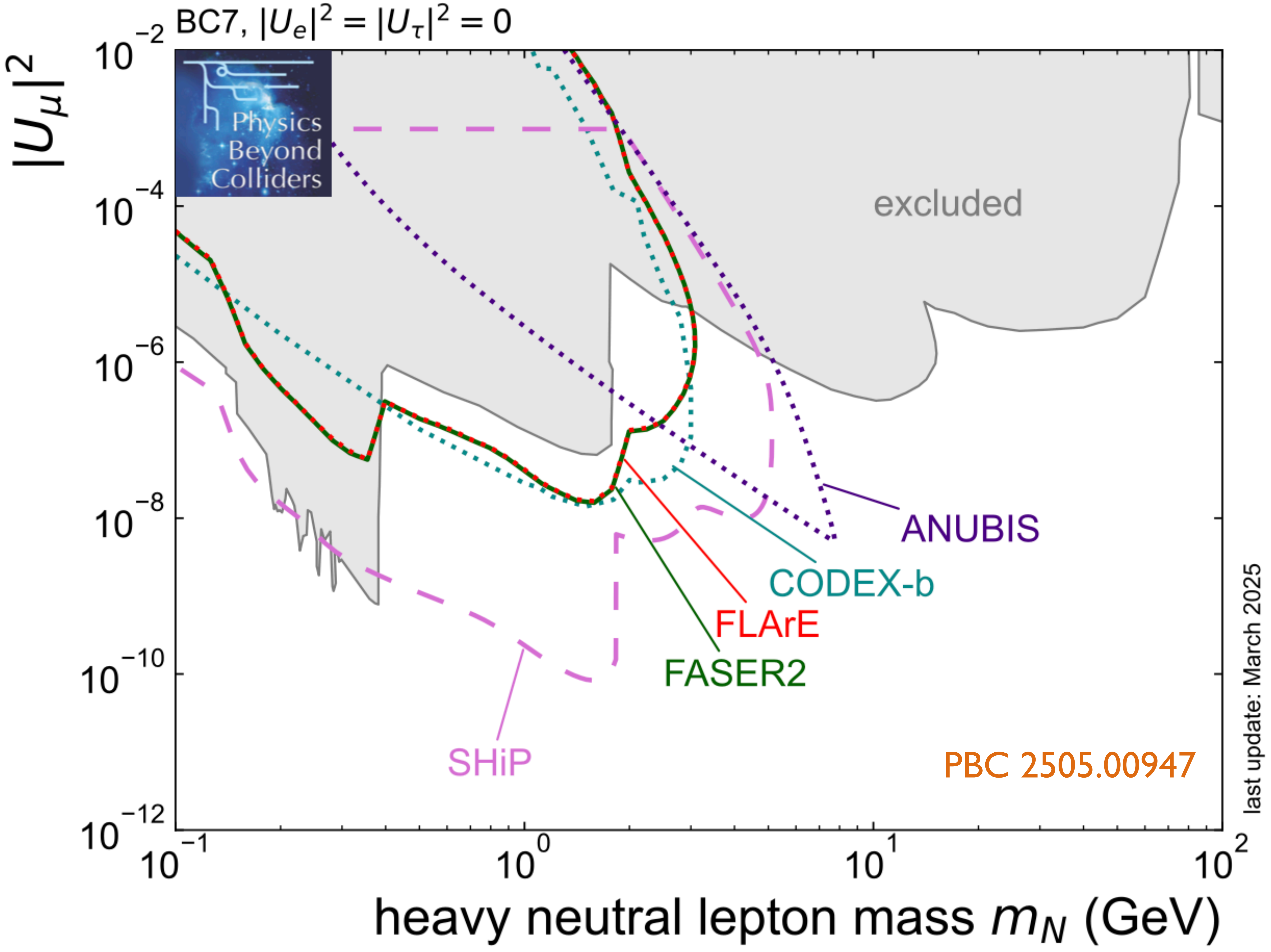
Neutrino See-Saw

$$\mathcal{L}_N = i\,\overline{\nu_{Ri}}\partial\!\!\!/\nu_{Ri} - f_{\alpha i}\overline{L}_\alpha \tilde{H}\nu_{Ri} - \frac{M_i}{2}\overline{\nu_{Ri}}^c\nu_{Ri} + \text{h.c.}\,,$$

$$M_N \simeq \mathrm{diag}(M_1, \ldots, M_n). \qquad (M_D)_{\alpha i} \equiv \frac{v}{\sqrt{2}} f_{\alpha i}$$

$$M_\nu = -M_D \frac{1}{M_N} M_D^T \qquad \theta = M_D M_N^{-1}\,,$$

$$L \simeq 2\gamma \left(\frac{3\,\mathrm{GeV}}{m_N}\right)^5 \left(\frac{10^{-9}}{U^2}\right) 200\,\mathrm{m}\,,$$



Very standard story, but GeV RHN LLPs are challenging for main detectors.

Next-Generation Triggers could help a lot!

Some Phenomenological Challenges

A comprehensive zoology of dark sectors

Can we cover every corner of dark sector signature space?

Consider confining dark sectors:

- dark QCD with $N_F \geq 1$: can be modelled *sufficiently faithfully* and searched for by using understanding gained from SM QCD.

- Dark QCD with $N_F = 0$: hadrons are now *glueballs*, qualitatively different non-perturbative dynamics

  → if you produce a heavy quark pair, you get a **quirk**.

  Quirk dynamics is famously challenging, particularly de-excitation and interaction with the detector material.

- More exotic: parton shower in quasi-conformal regime → roughly isotropic and thermal soft dark hadron emission, "SUEP" (soft unclustered energy patterns)

Modeling $N_F = 0$ *dark sectors*

Glueshower v1, v2, indirect detection, SUEP for antinuclei:

Probably dont have time to talk about this, but ask me if you want to know the best (!) empirical reason to care about SUEPs

Caleb Gemmell
(UofT → UW-Madison

DC, Gemmell, Verhaaren 2202.12899
DC, Gemmell 2211.05794
Batz, Cohen, DC, Gemmell, Kribs 2310.13731

Glueshower v2:

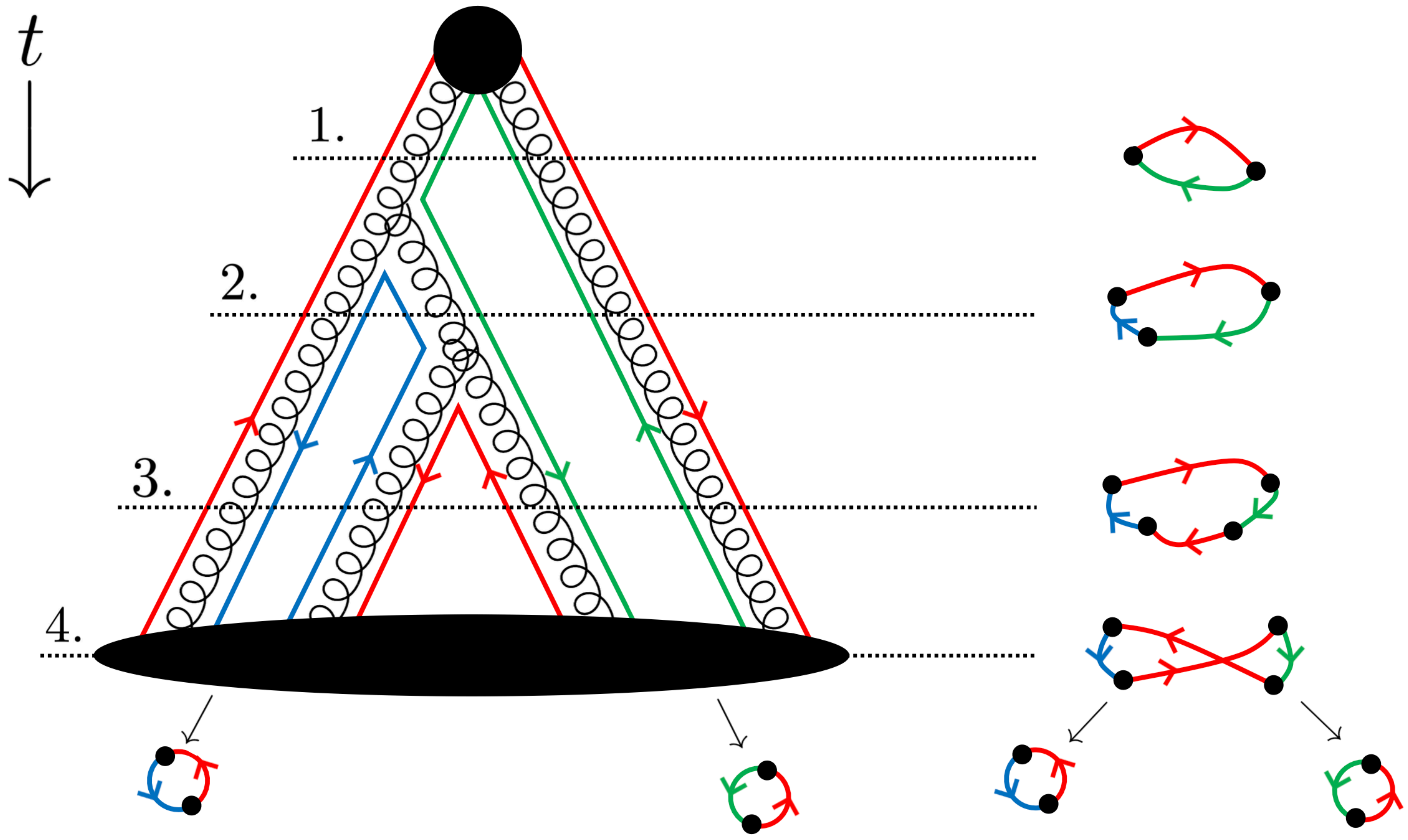
Austin Batz
Oregon

Shower and Hadronization in $N_f = 0$ QCD

Say you make a pair of dark gluons in a high energy process (e.g. $S \to g_D g_D$).

They undergo a normal perturbative parton shower…

… but then **hadronization** is qualitatively different from $N_F > 0$ case: glueballs $m > 6\Lambda$ are made by ***crossing*** **of color flux tubes.**

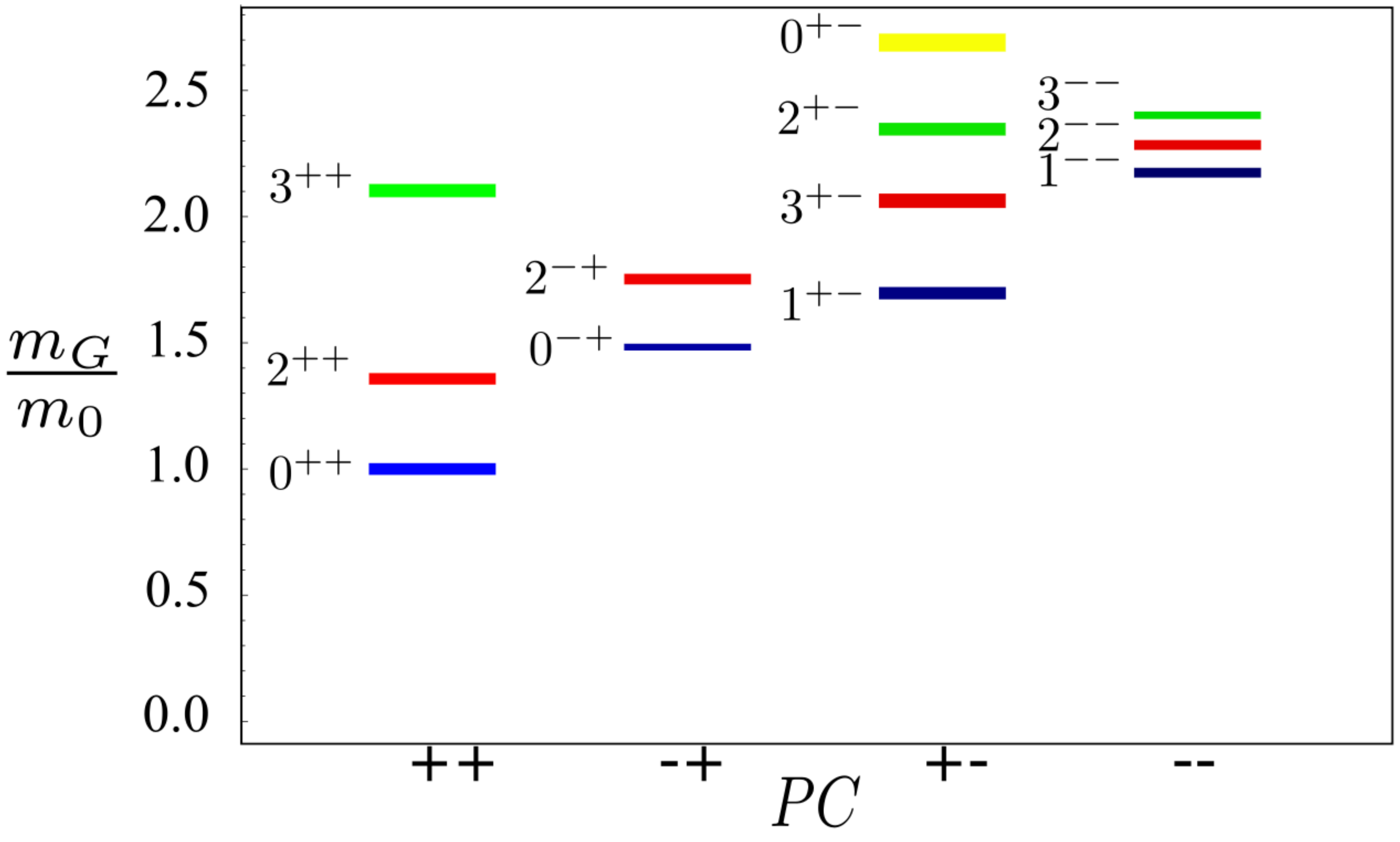


DC, Gemmell, Verhaaren 2202.12899

Glueball basics from the lattice

- **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

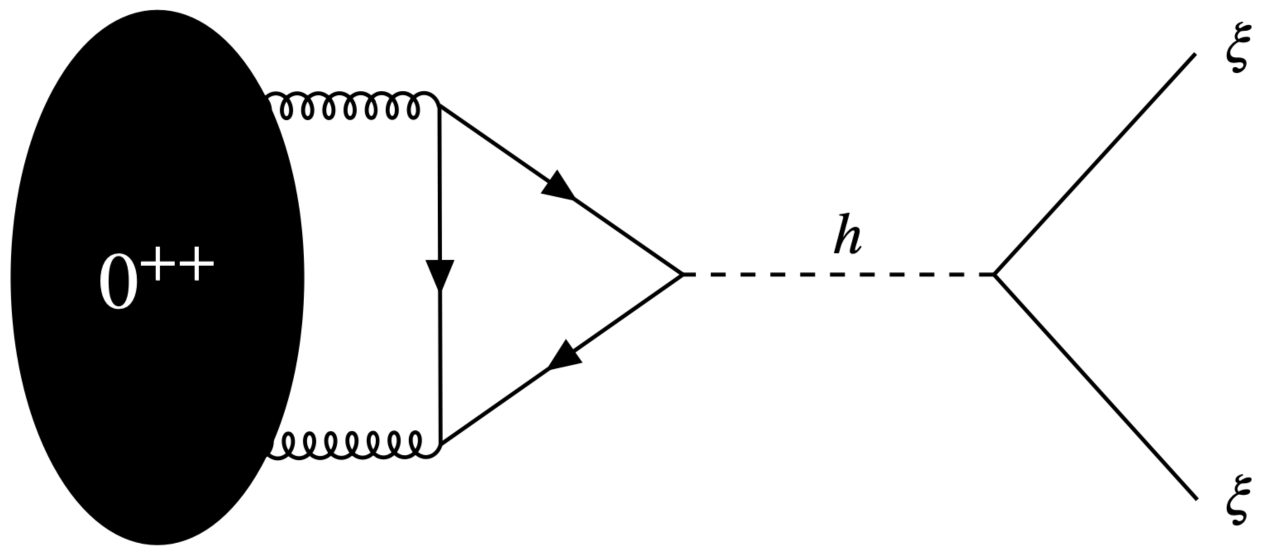


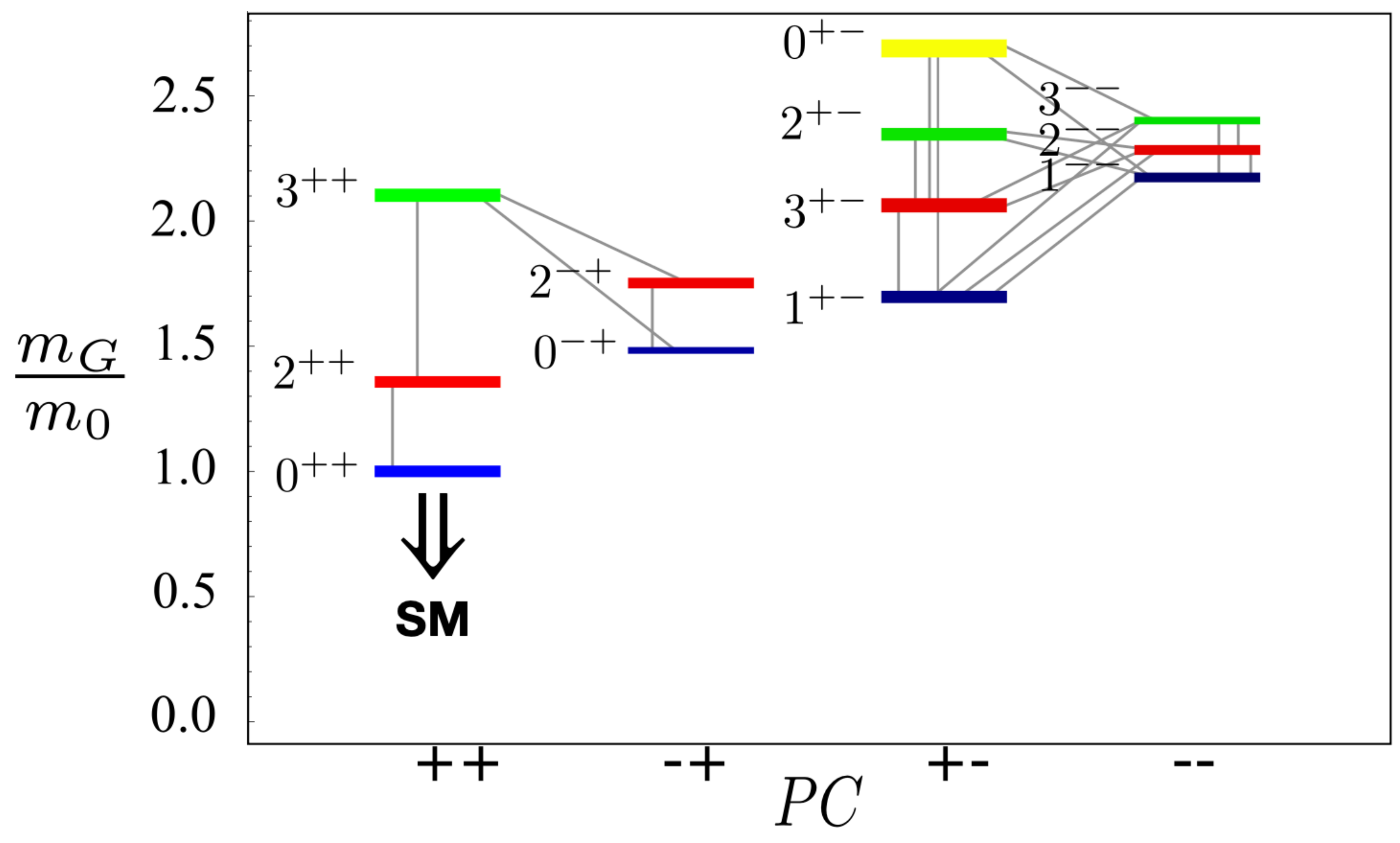
(Slide by Caleb Gemmell)

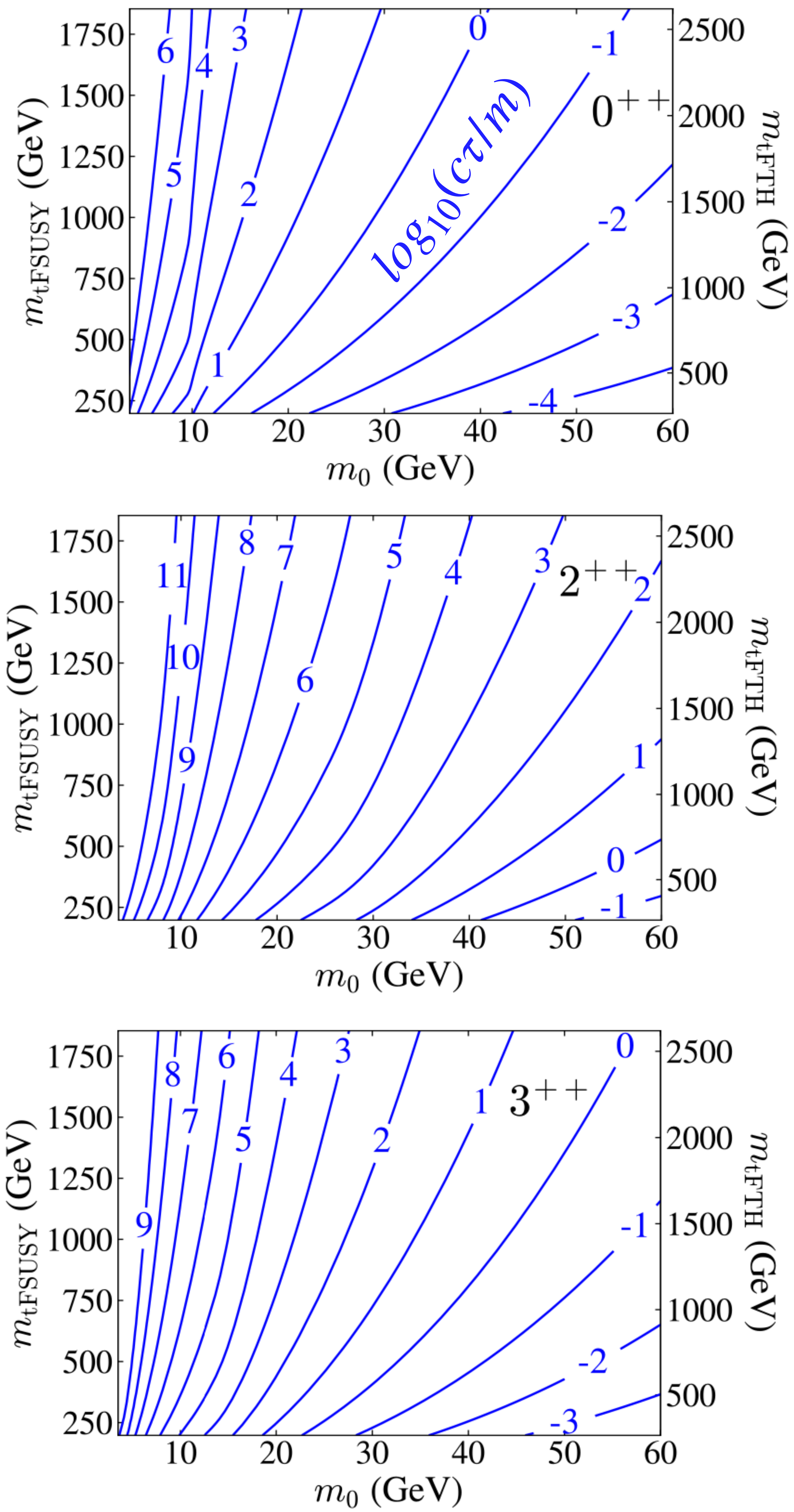
Glueball decay

Dark glueballs decay to SM via dim6 or dim8 operators, which can be generated by dark quarks coupling to higgs (dim6) or SM gauge bosons (dim8).
Dark Glueballs are usually LLPs!

Higgs portal example (most relevant to e.g. Fraternal Twin Higgs):







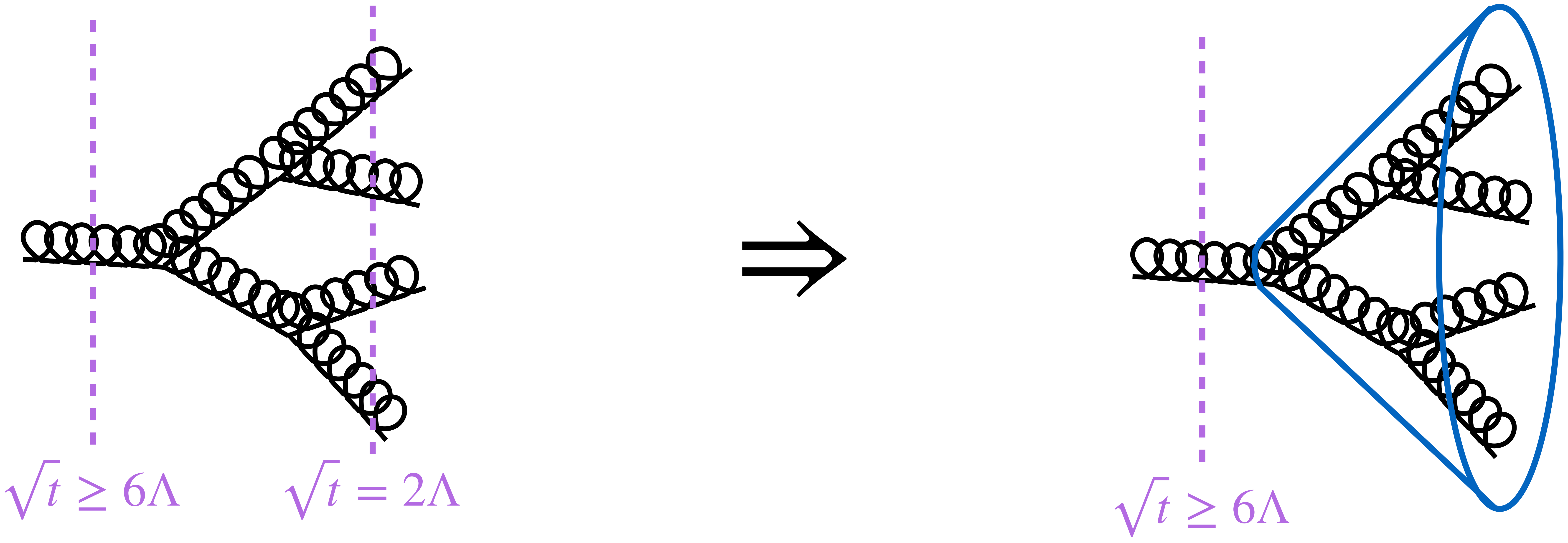
DC, Gemmell, Verhaaren 2202.12899

GlueShower v1

How to hadronize dark gluons into glueballs? Try to be maximally simple and robust.

Exploit the fact that $m_0 \approx 6\Lambda$ " $\gg$ " Λ.

Perturbative shower can "keep running" bast the kinematic threshold where final legs of the shower can split into multiple hadrons (glueballs). Instead, hadronization will *combine* legs of the shower to make up the mass required for glueballs.



Just make all this one glueball*

(*and choose glueball species from a thermal distribution)

DC, Gemmell, Verhaaren 2202.12899

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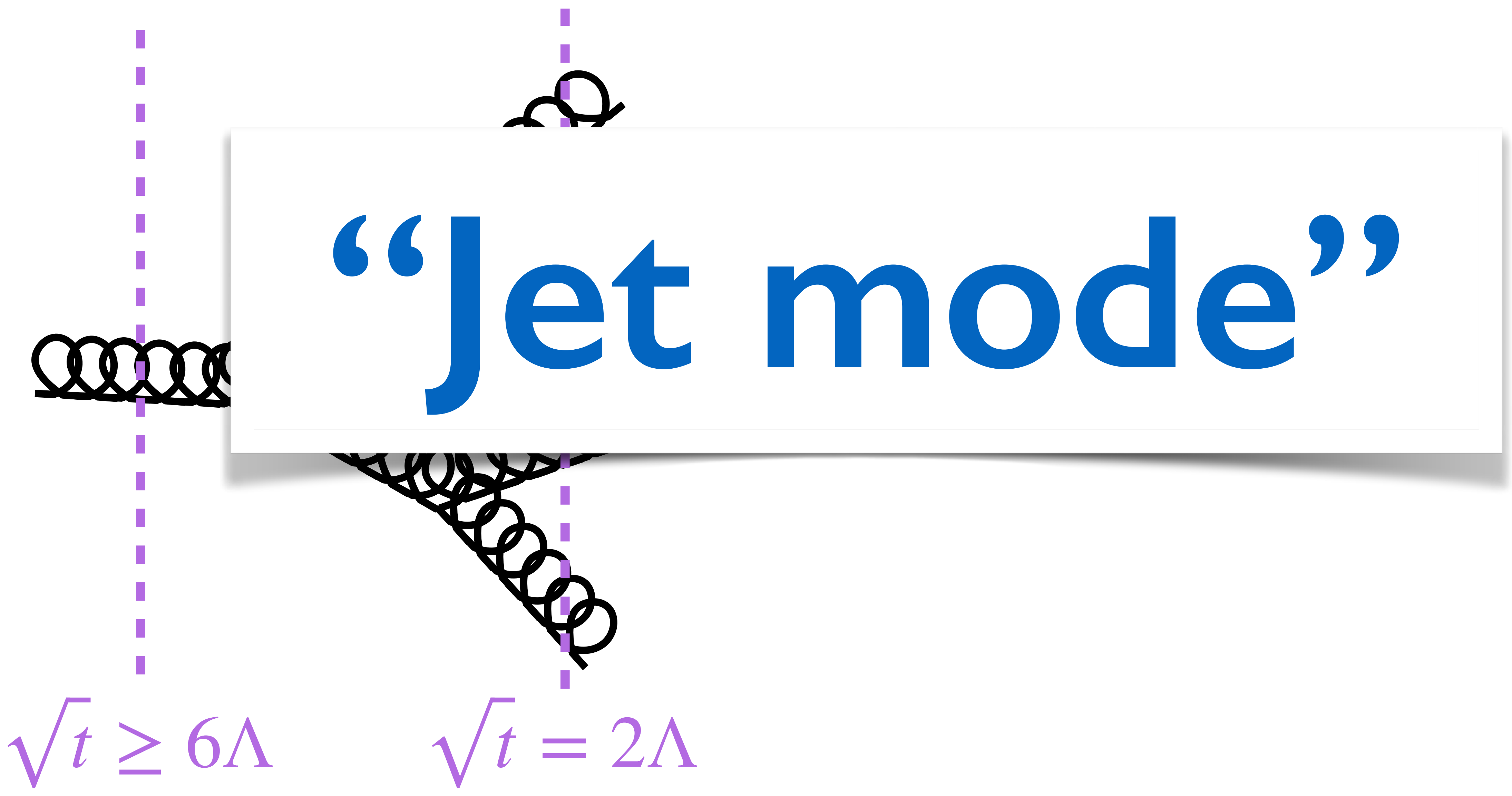

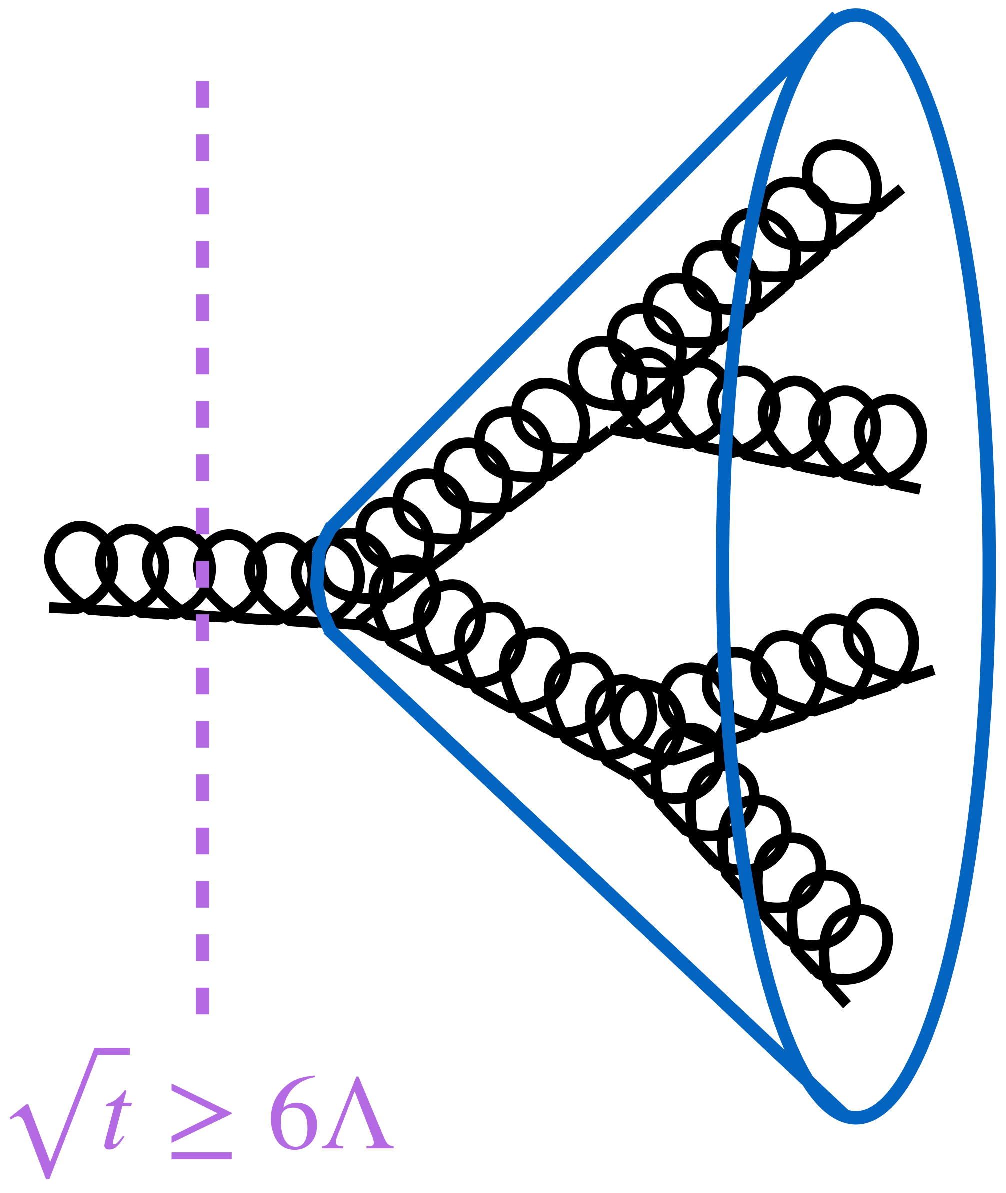

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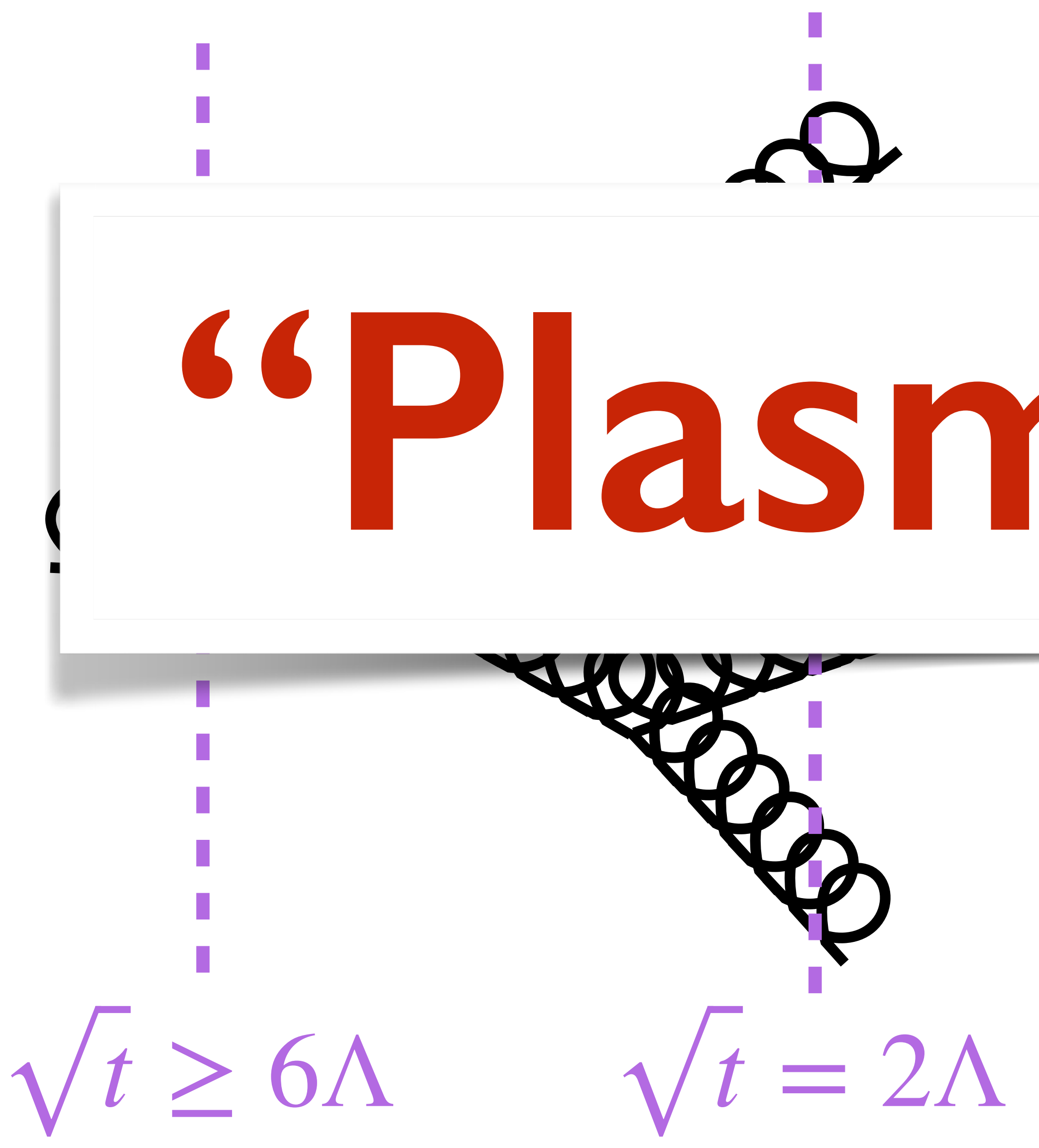
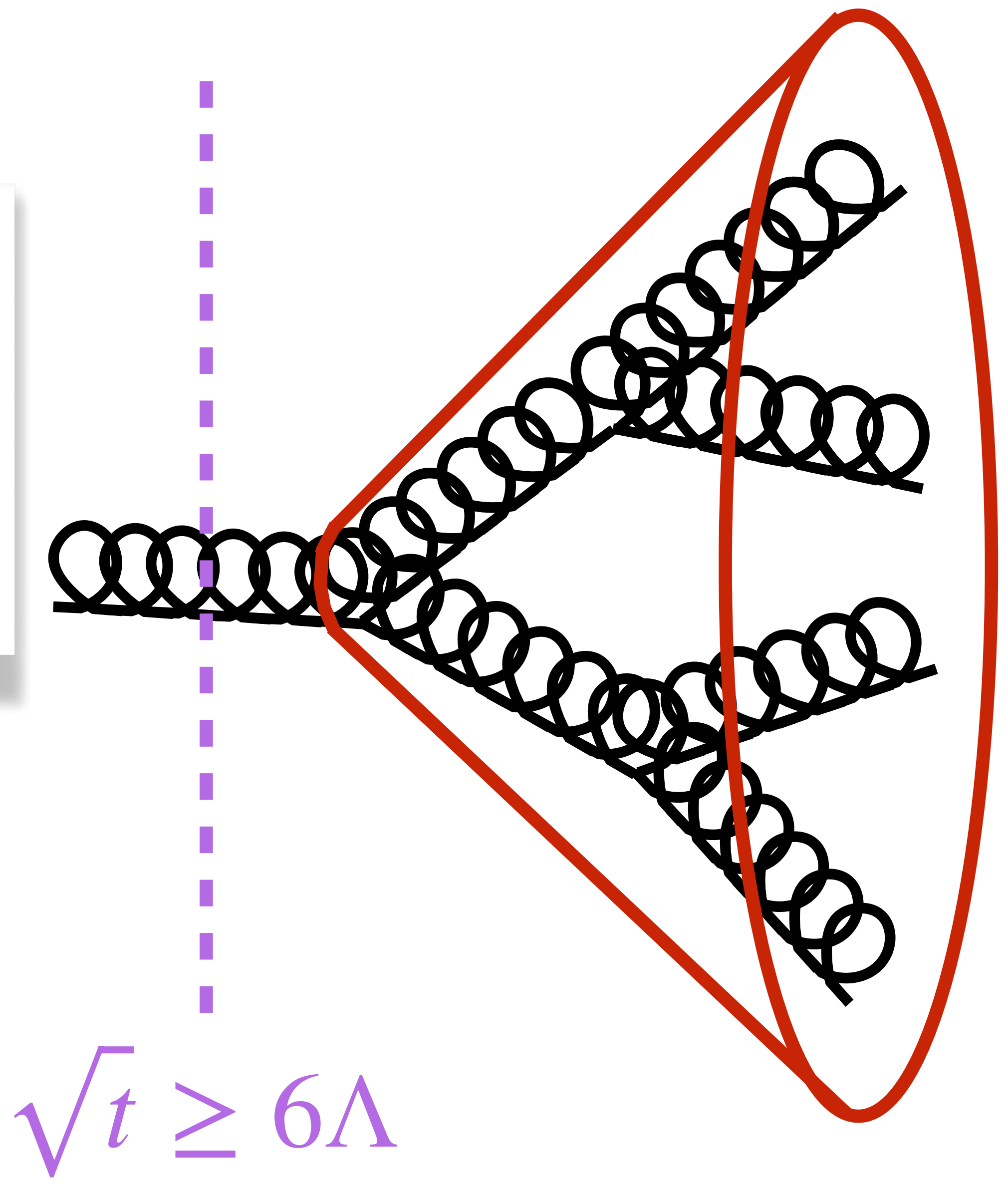


"Plasma mode"

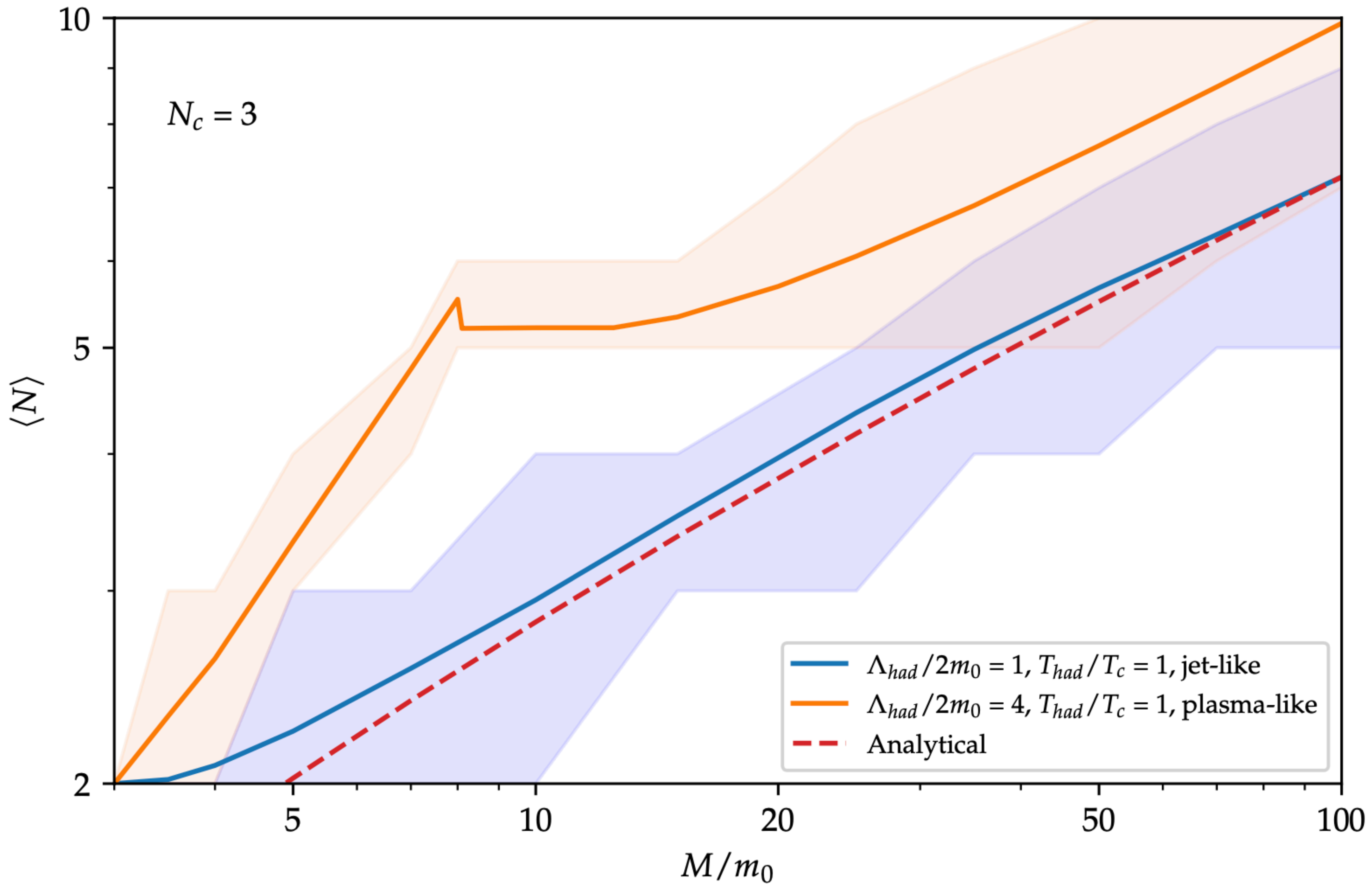


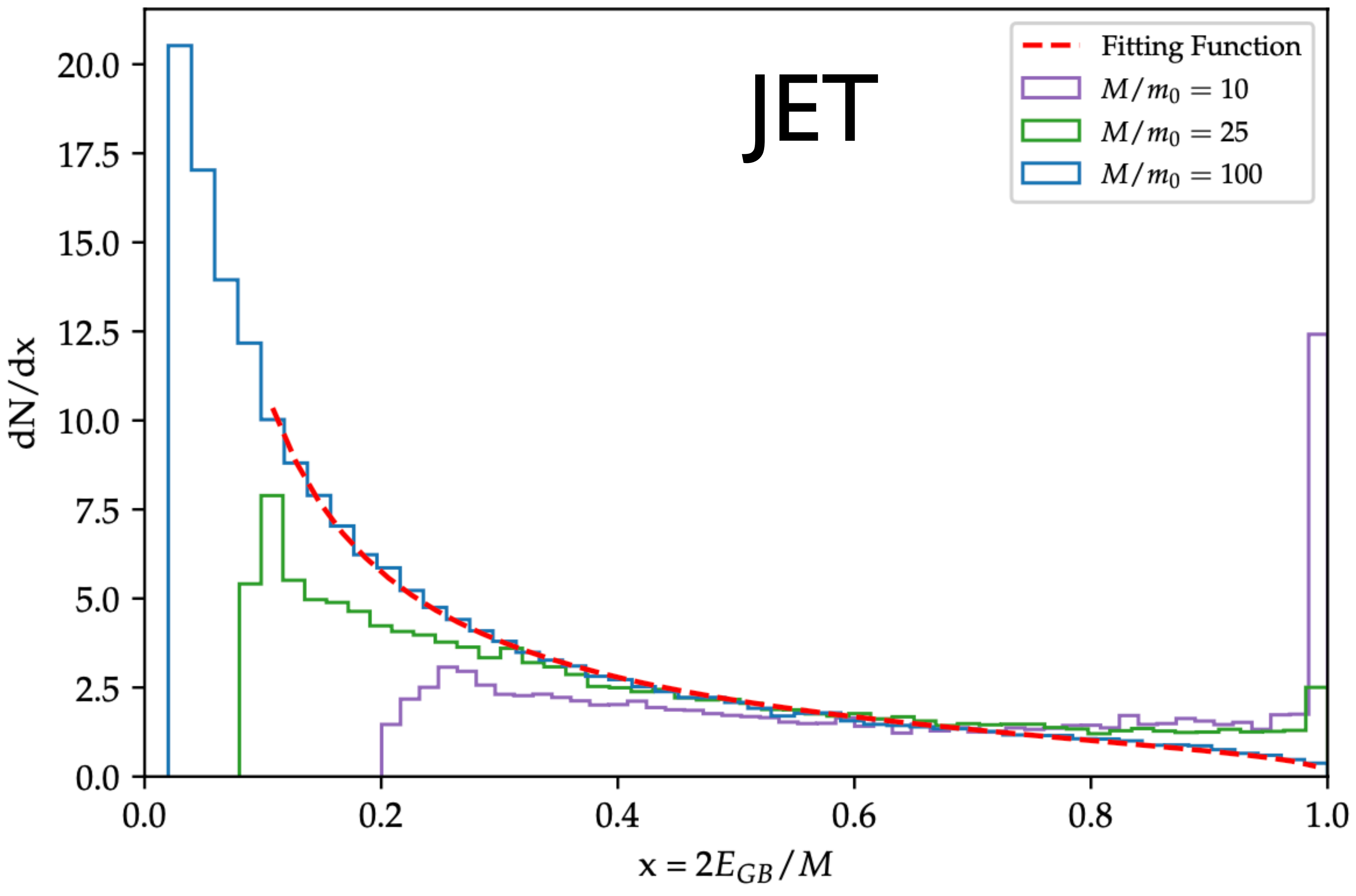
Alternatively, choose a higher cutoff, and make this branch a 'dark gluon fireball' that evaporates glueballs isotropically

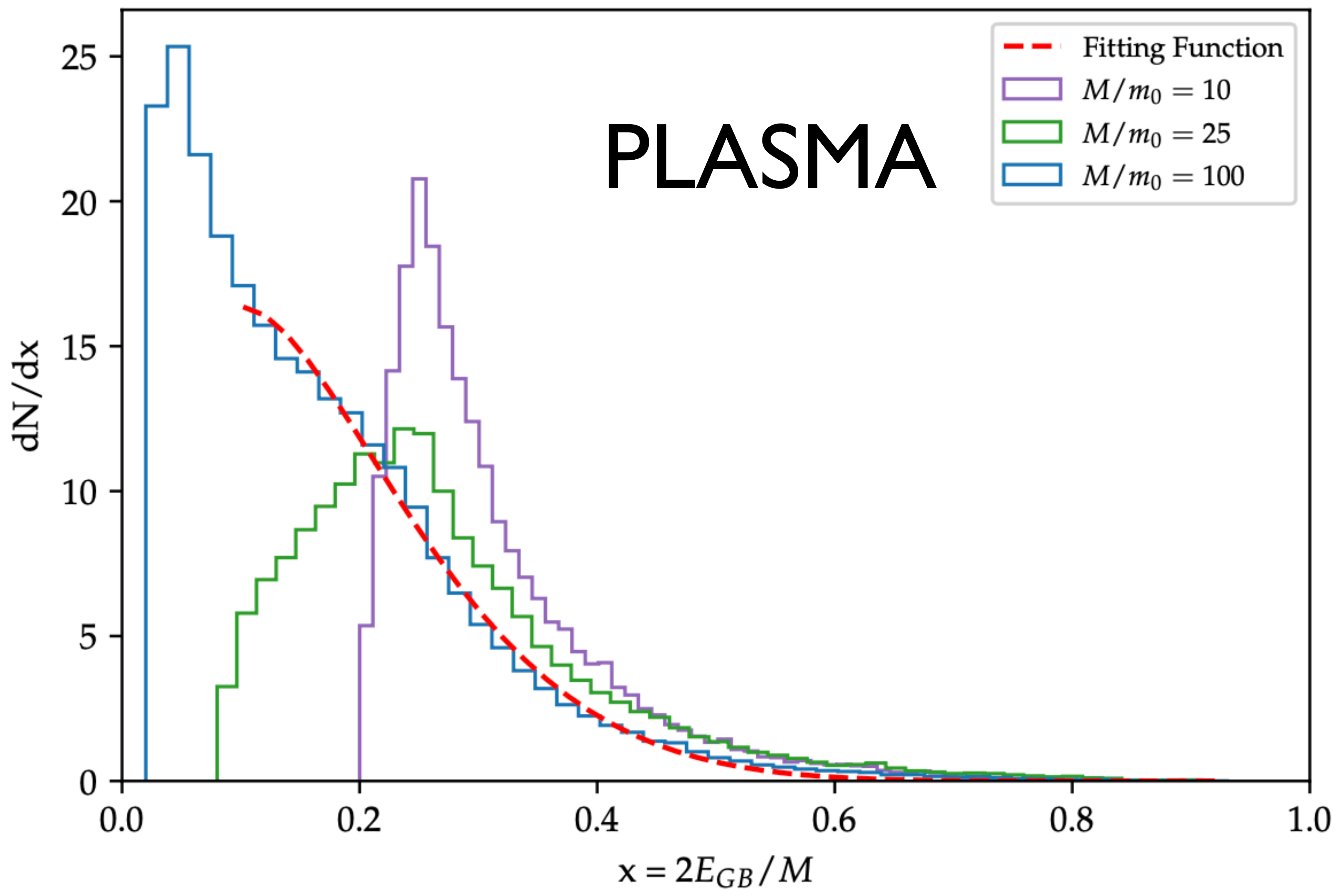
DC, Gemmell, Verhaaren 2202.12899

GlueShower v1

Varying some nuisance parameters for both JET and PLASMA mode, end up with a spread of possible glueball production phenomenology that should bracket reality.







Batz, Cohen, DC, Gemmell, Kribs 2310.13731

GlueShower v2

Glueshower v1 was extremely conservative with its assumptions. Can we do more?
→ glueball fragmentation proceeds via flux tube crossing. Model more directly?
→ in v1, we put a thermal glueball species distribution in ‘by hand’. Include in model?

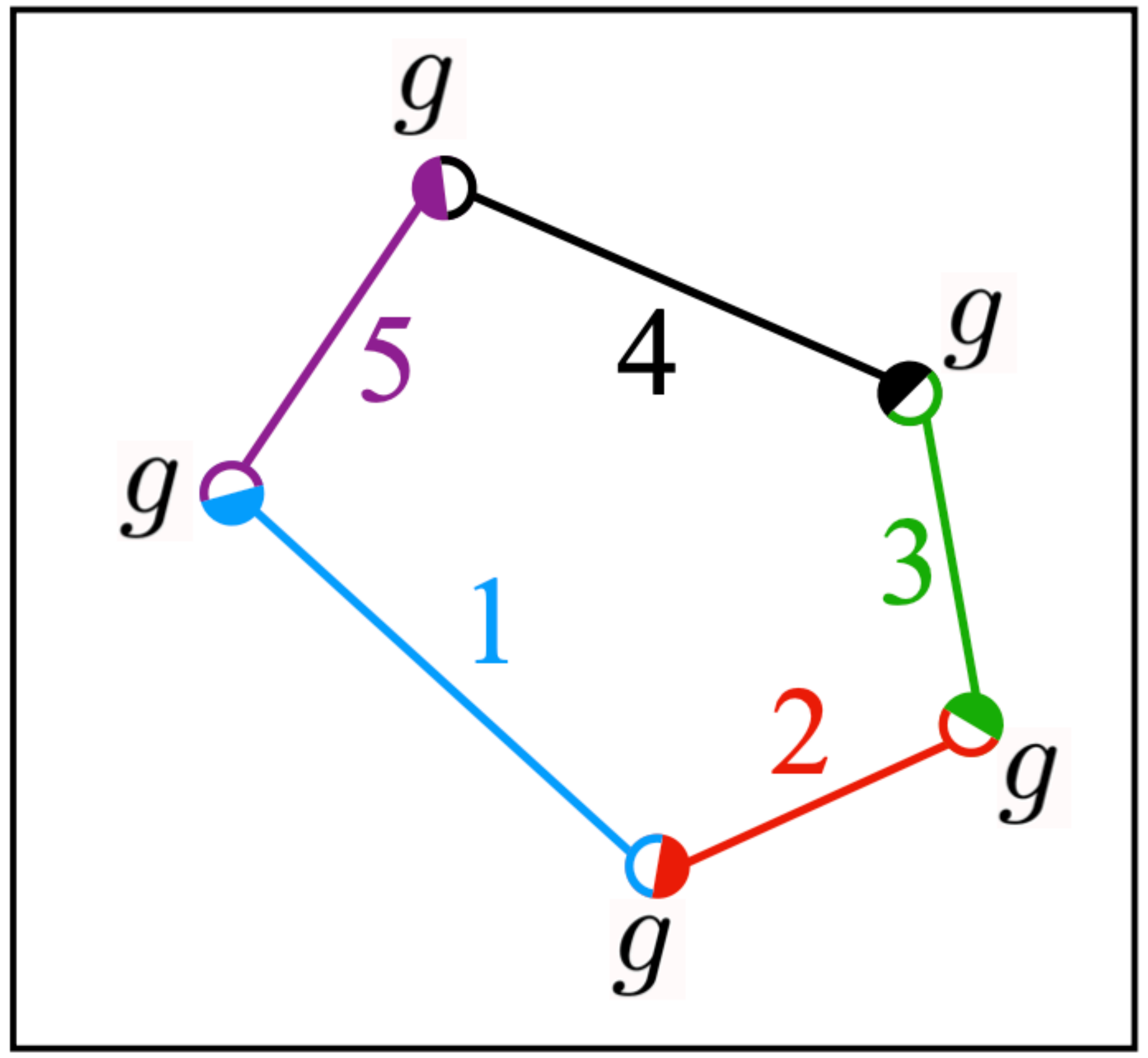
Yes! Procedure:

1. Perturbative shower in Pythia8 for $N_F = 0$ (~ same as v1)
2. Terminate shower at some p_T^{min}, and let gluon color string loops undergo color reconnection.
3. Iteratively fragment each color string loop into glueballs.

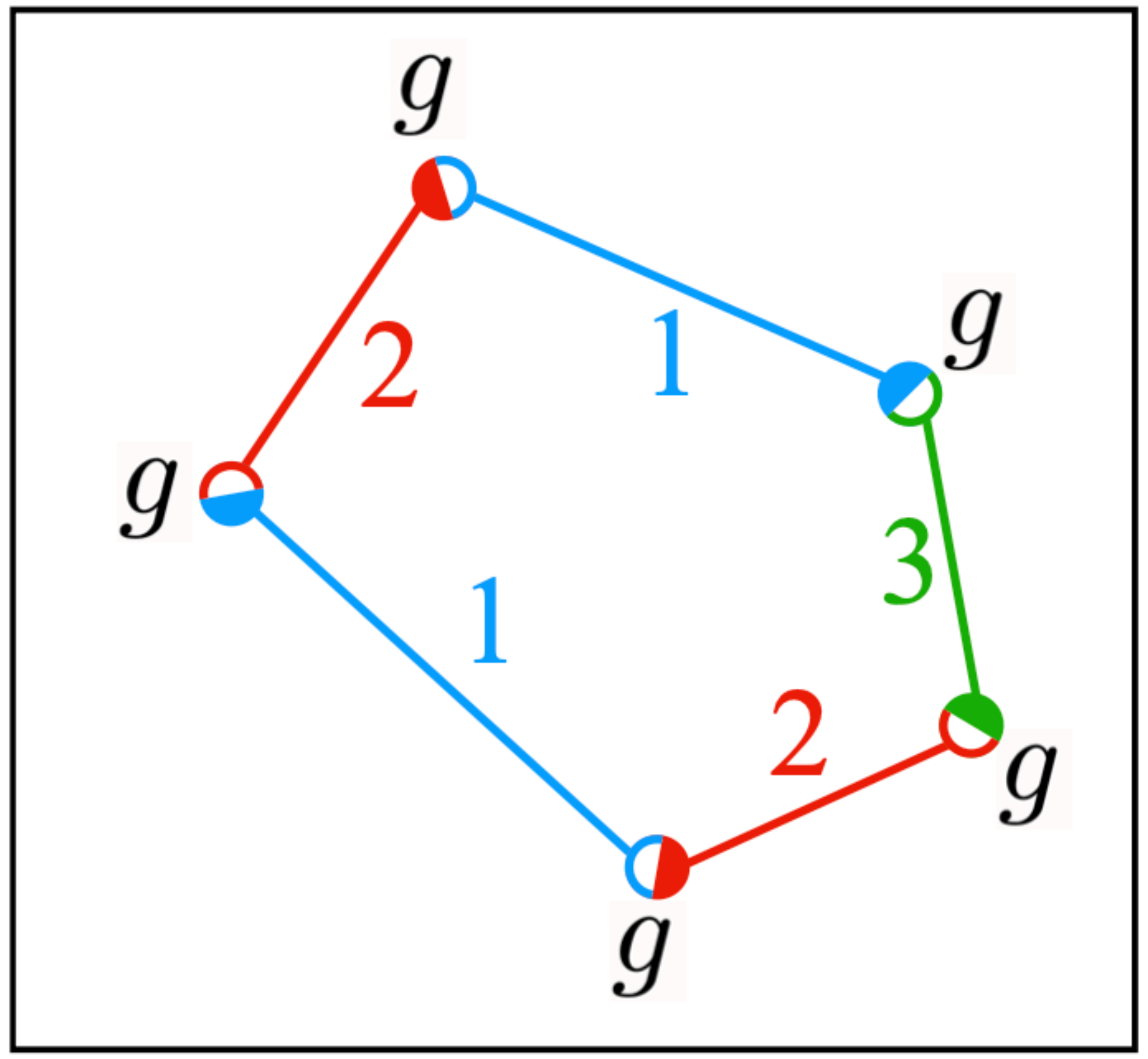
Batz, Cohen, DC, Gemmell, Kribs 2310.13731

GlueShower v2

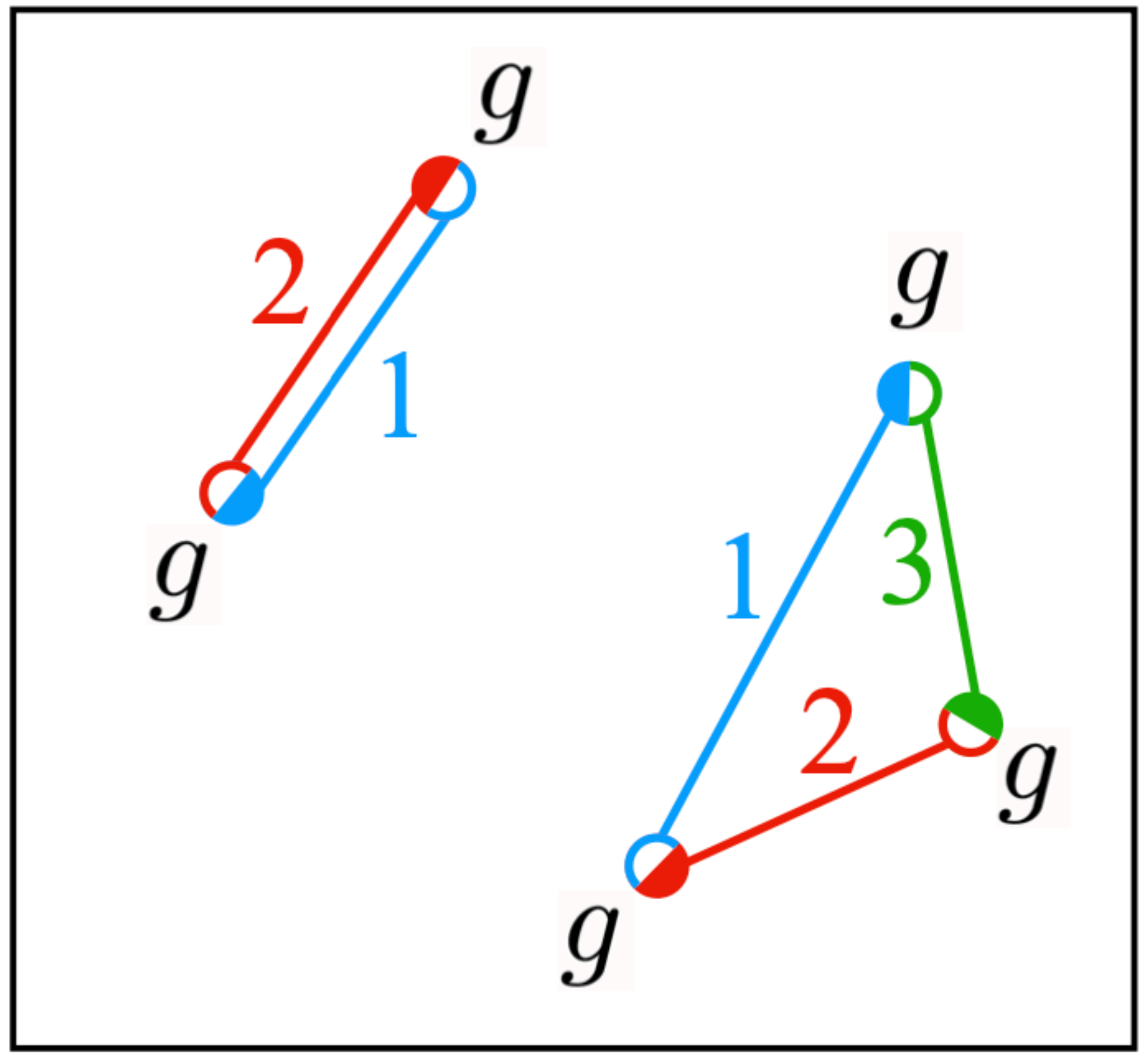
Color reconnection into color singlet flux loops



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



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



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

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

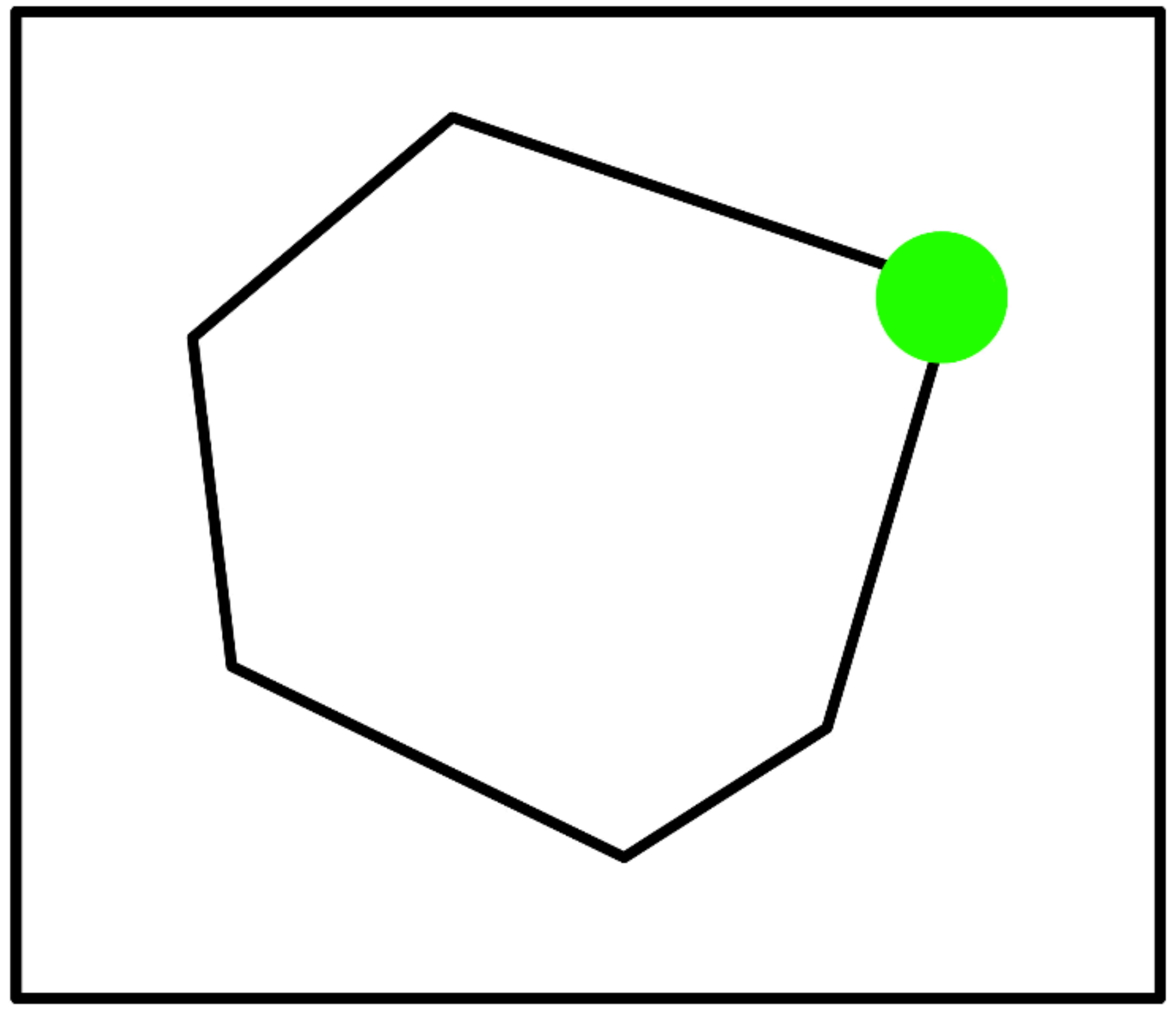
Defines the physical string topology at the end of the shower, same as Lund String model

(Slide by Caleb Gemmell)

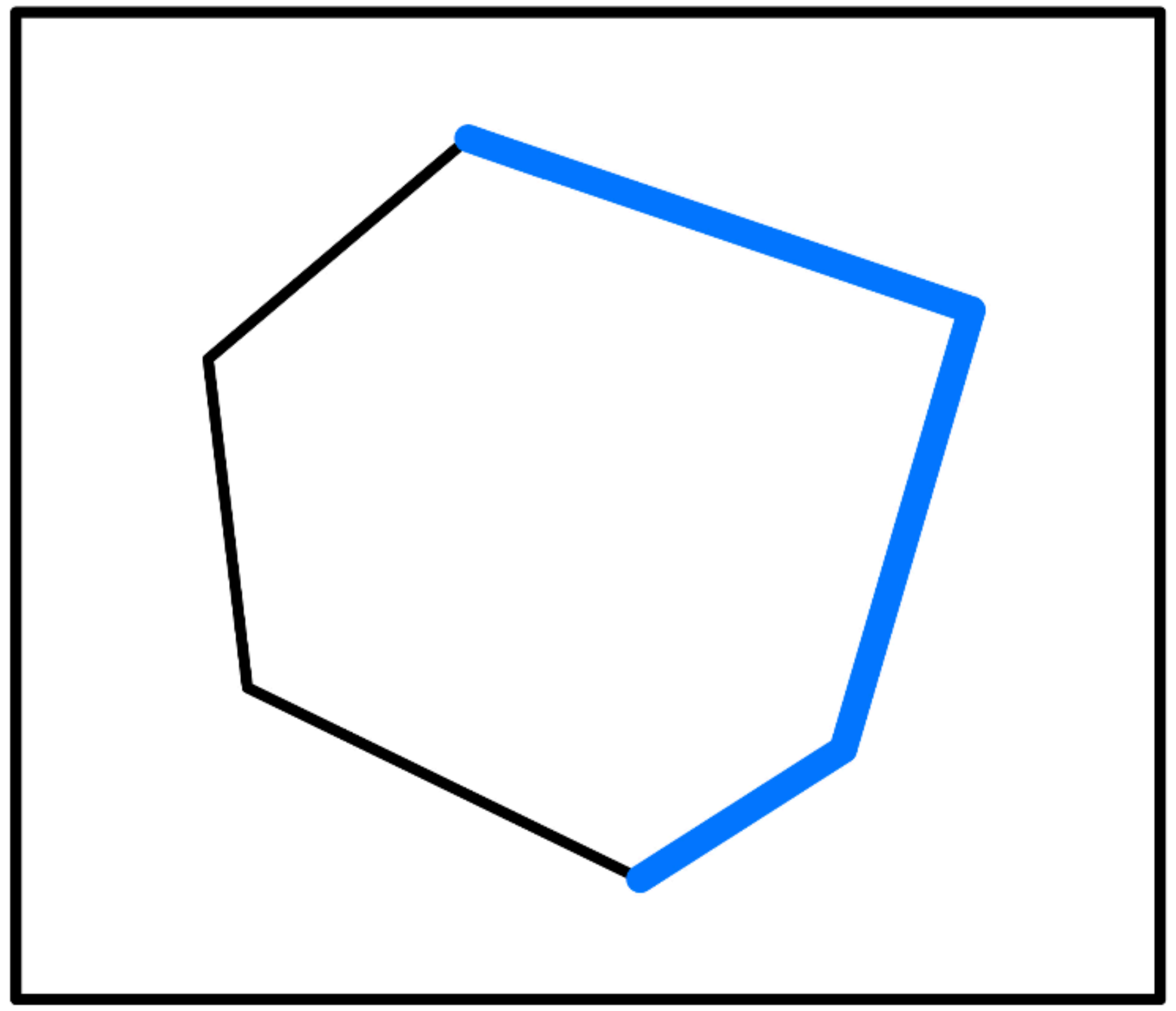
Batz, Cohen, DC, Gemmell, Kribs 2310.13731

GlueShower v2

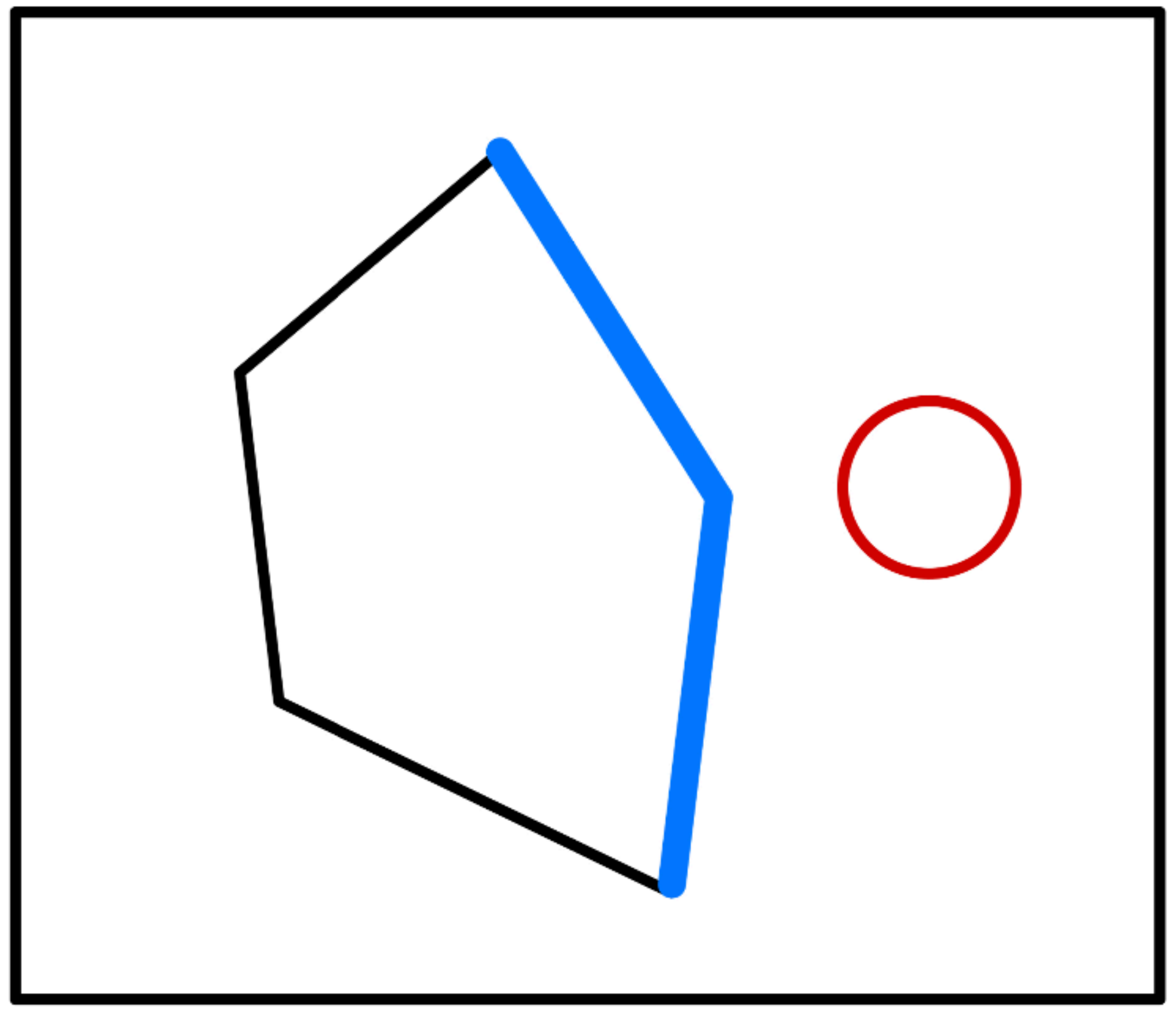
Iteratively fragment each color string loop into glueballs.



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



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



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

(Slide by Caleb Gemmell)

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GlueShower v2

Fragmentation Function

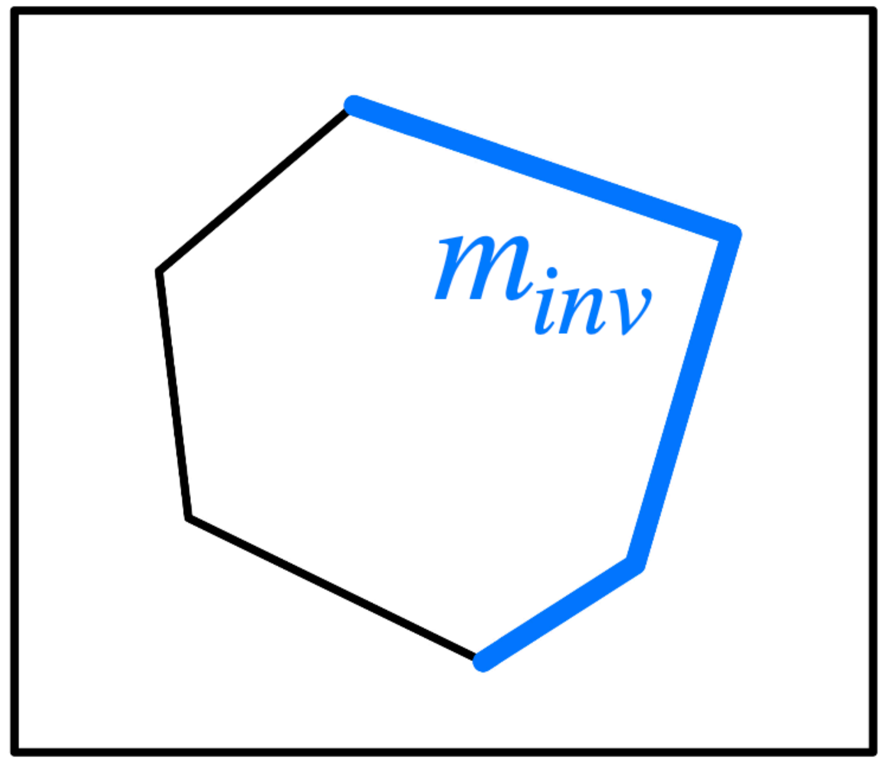
Freedom to pick fragmentation function that determines the energy 'taken' from adjoining string pieces. General forms considering below with phenomenological parameters α and b / k_β :

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

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

Choosing Glueball Species

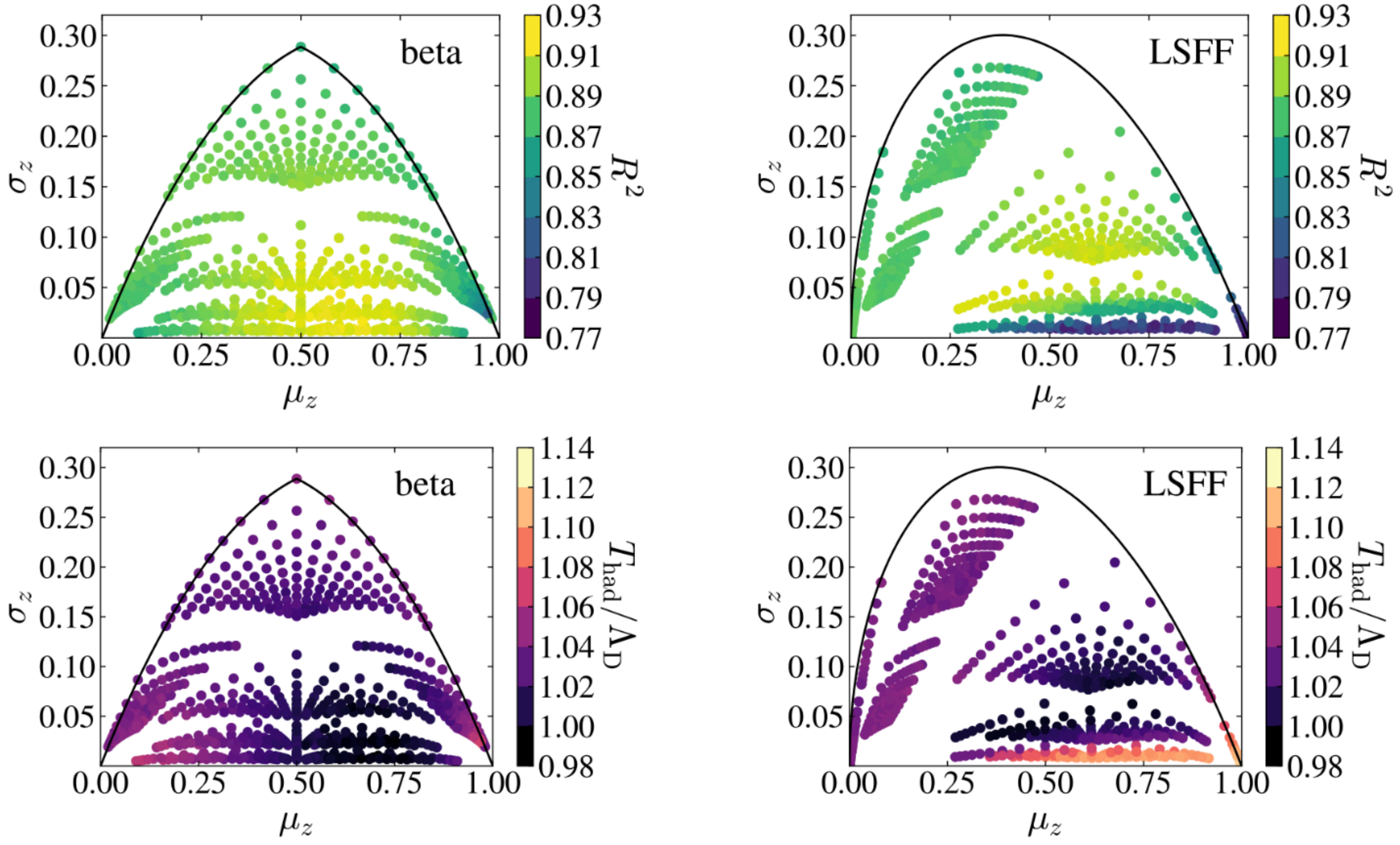
- **Species is chosen randomly, only including spin multiplicity weightings (assume no bias)**
- **However, a mass suppression does come from invariant mass of string pieces, only $m_G < m_{inv}$ glueballs accessible**



(Slide by Caleb Gemmell)

Reproduce expected thermal species distribution

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



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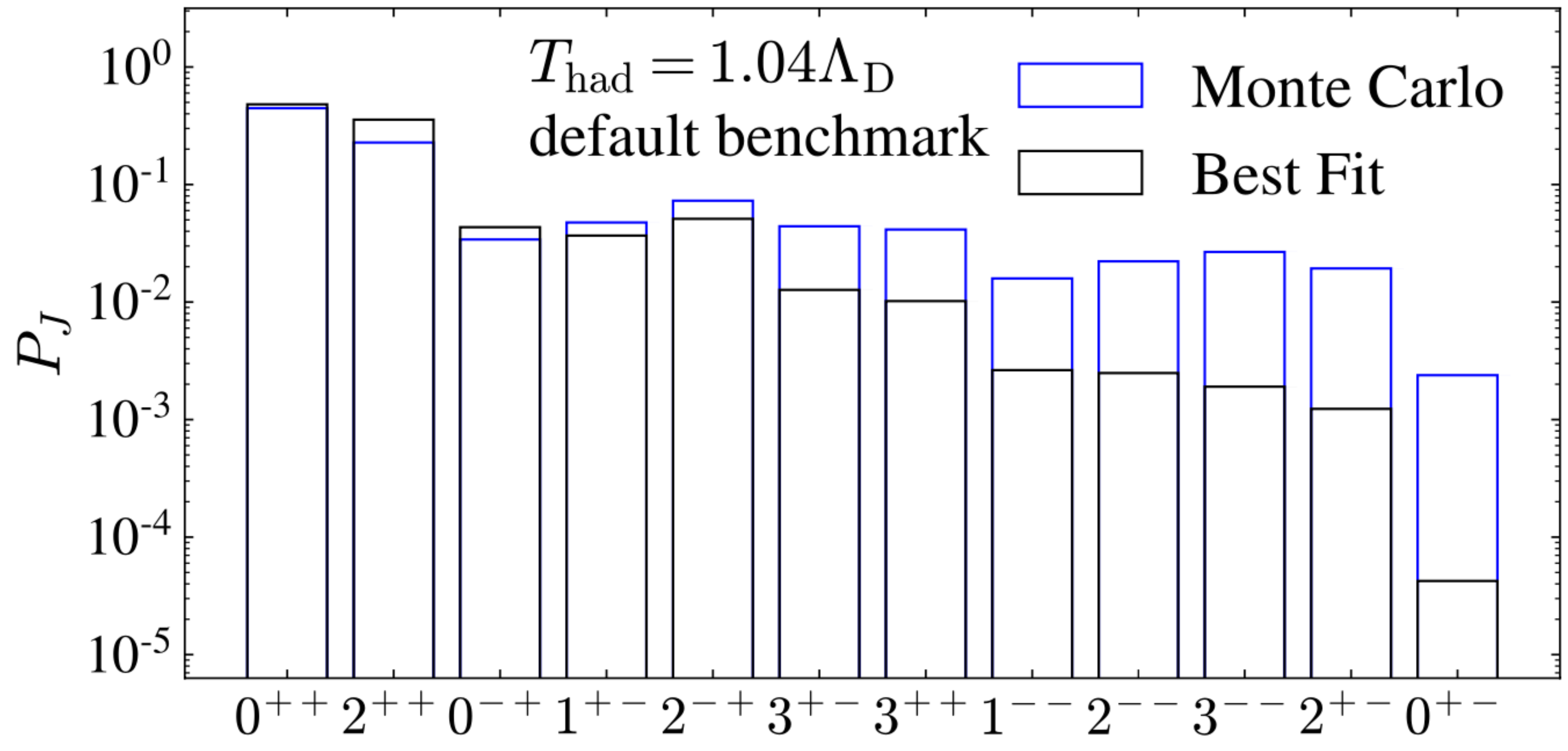
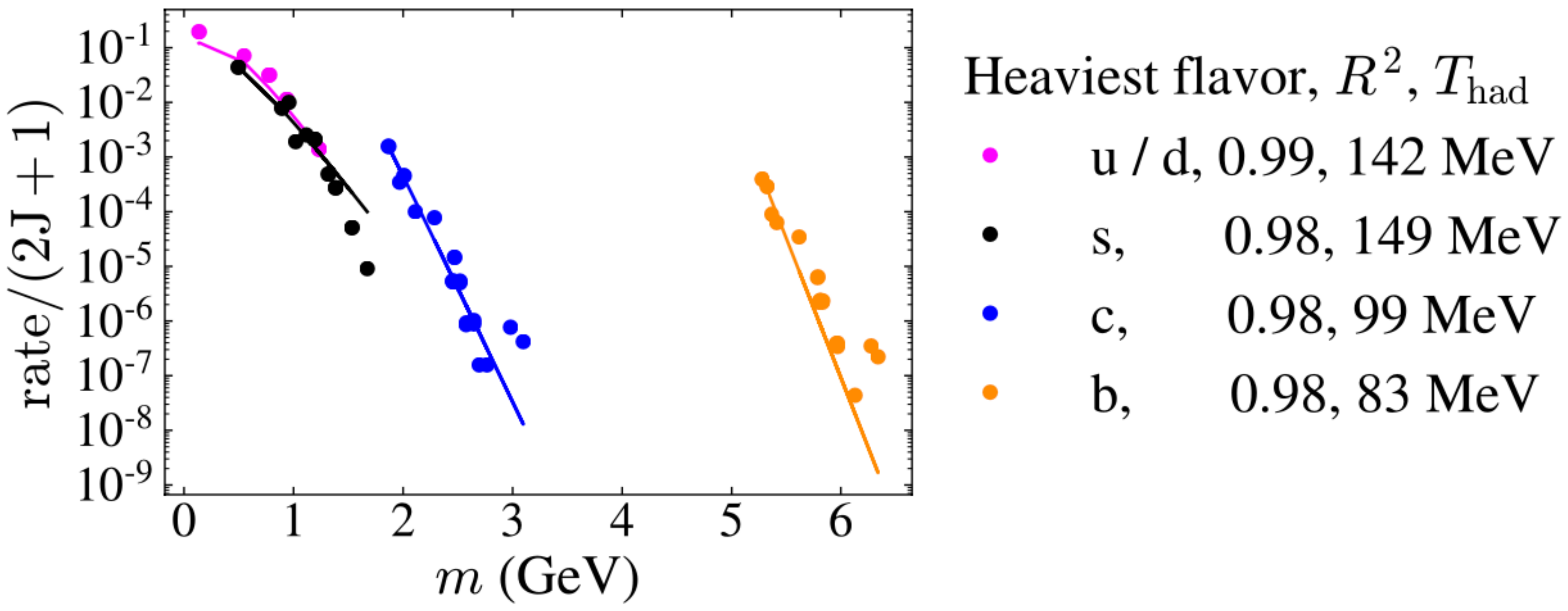
Reproduce expected thermal species distribution

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



(Slide by Caleb Gemmell)

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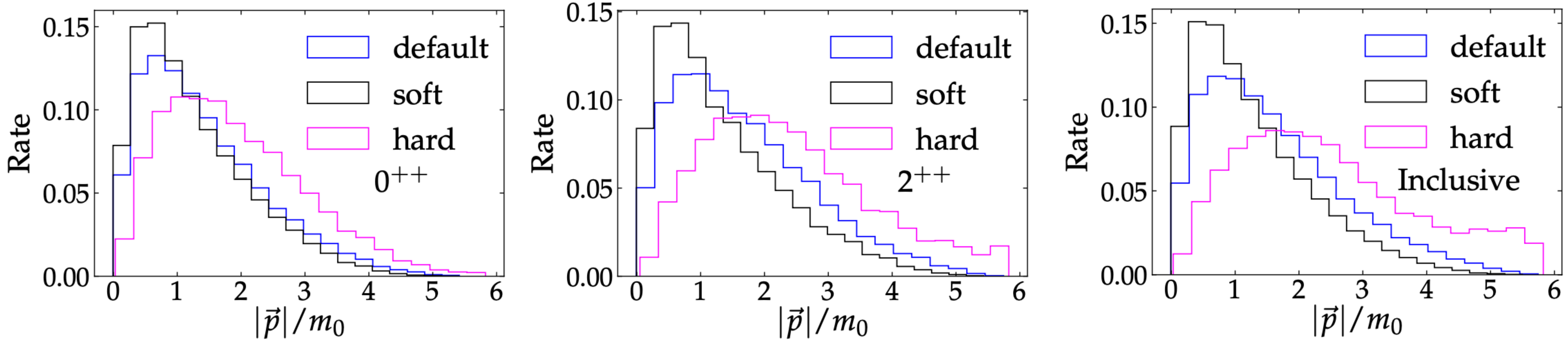
Glueshower v2 benchmarks for collider studies

3 benchmark parameter choices to bracket physically reasonable range of outcomes.

glueball momenta in shower rest frame, $m_0 = 10\ \mathrm{GeV}, \sqrt{s} = 125\ \mathrm{GeV}$



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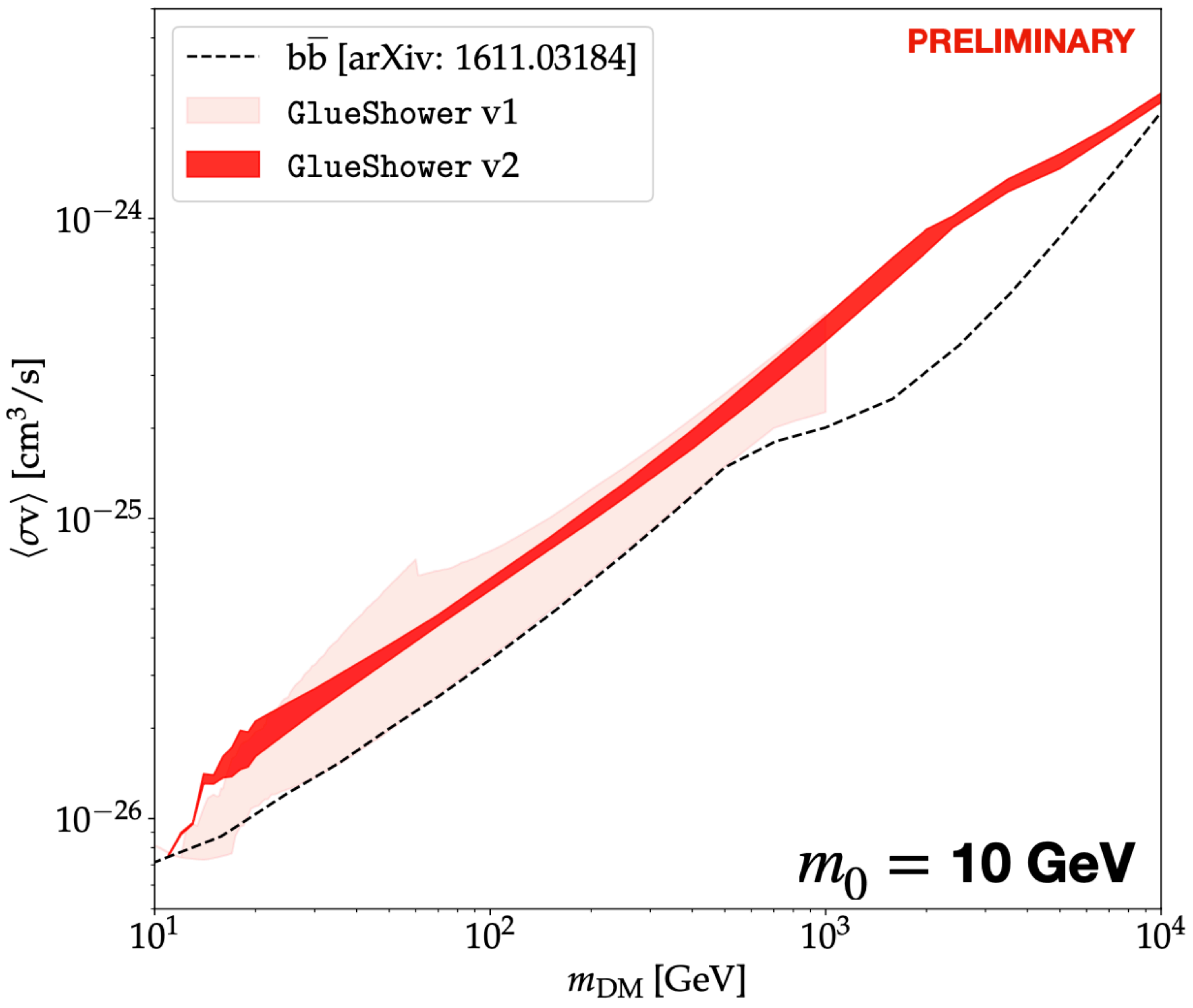
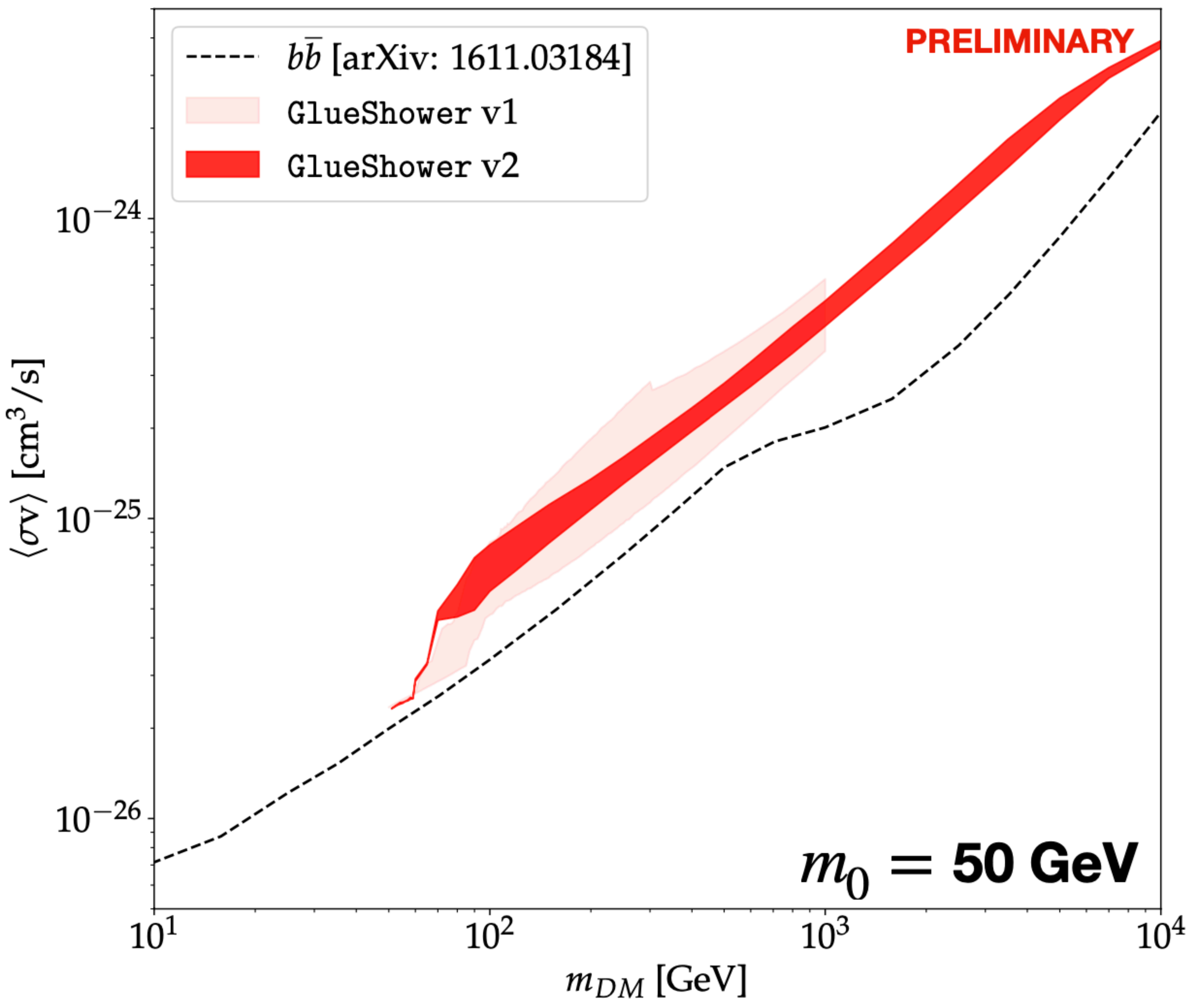
Comparison v1 vs v2 indicates robustness





DC, Gemmell, 2211.05794

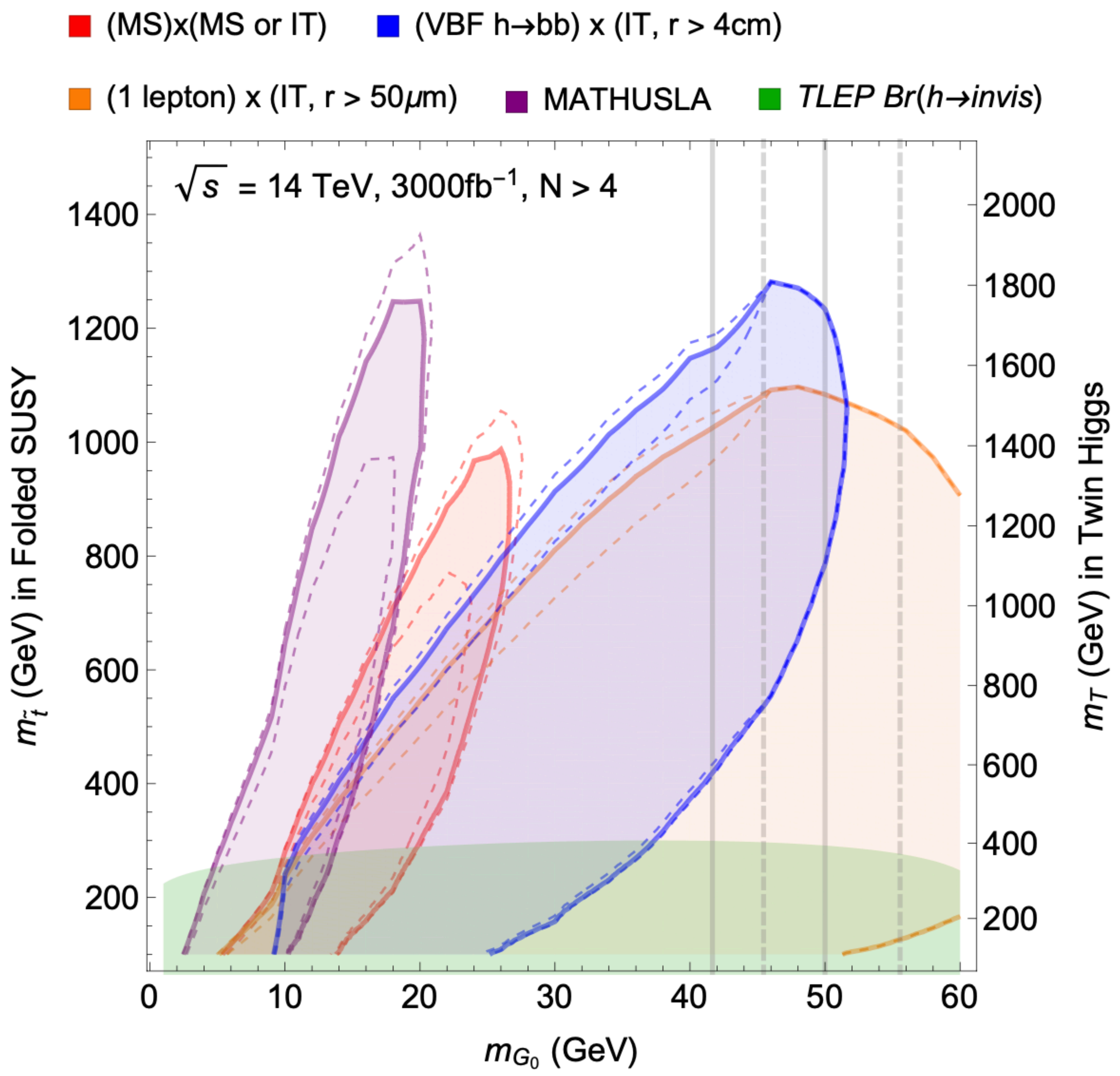
The Fraternal Twin Higgs at the LHC

In part of the parameter space, main signal is $h \to g_D g_D \to$ dark glueballs.

Various glueball species lifetimes range from mm to >> km. Can look for this in LLP searches!

Early attempts to quantify reach just assumed some fraction of higgs decays is to **pairs** of the lightest and most short-lived glueball state:

$h \to 0^{++}0^{++}$

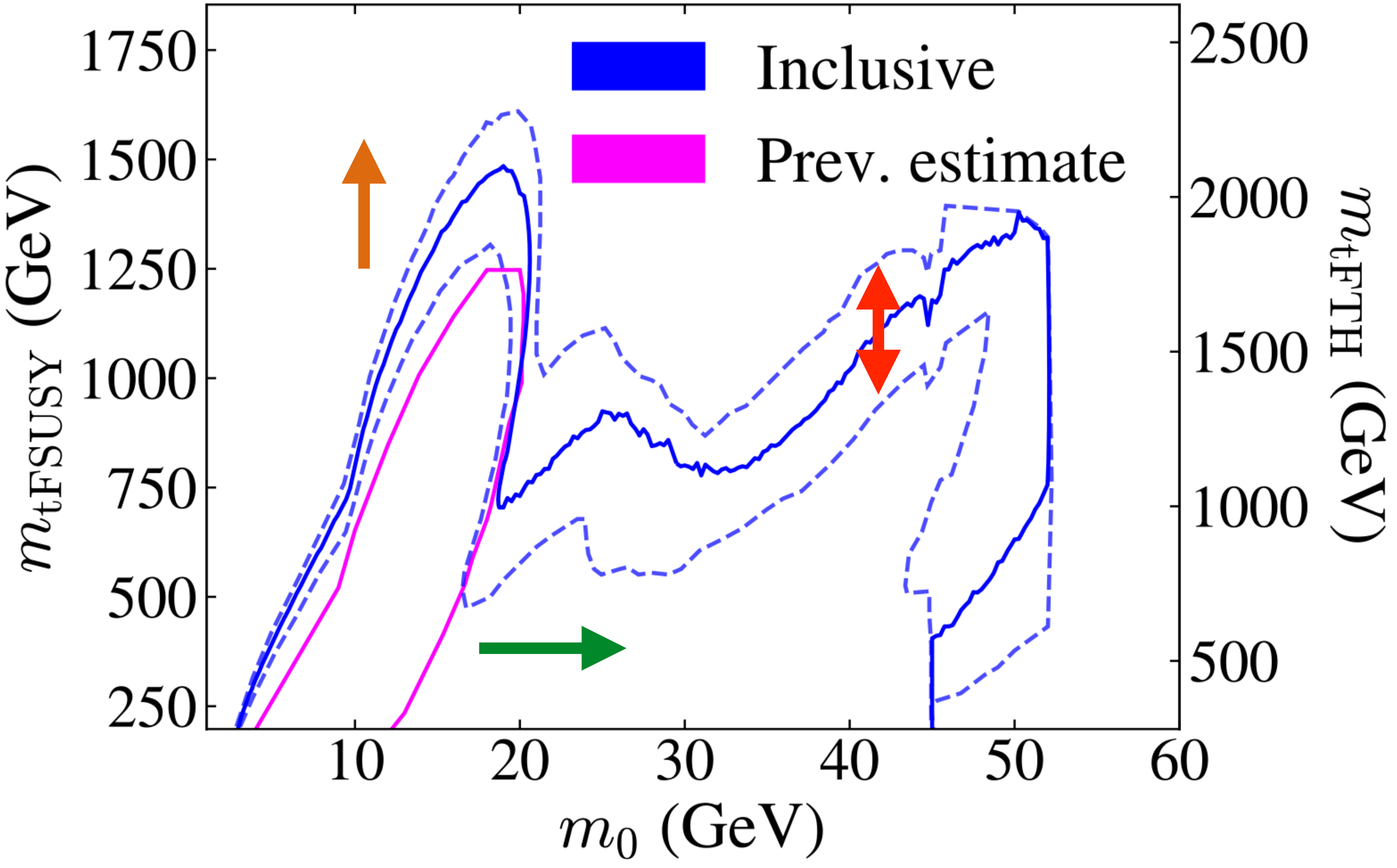


MATHUSLA physics case 1806.07396

The Fraternal Twin Higgs at the LHC

Now that we have glueshower v2, we can do this realistically, taking into account

- signal boost from higher glueball multiplicity per event
- Signal at longer 0^{++} lifetimes due to longer-lived heavier (but subdominant) glueball species
- Accurate theory uncertainties due to undetermined aspects of glueball hadronization



Did this for MATHUSLA100 @ HL-LHC.

Huge increase in reach. Should study for main detector LLP reach as well!

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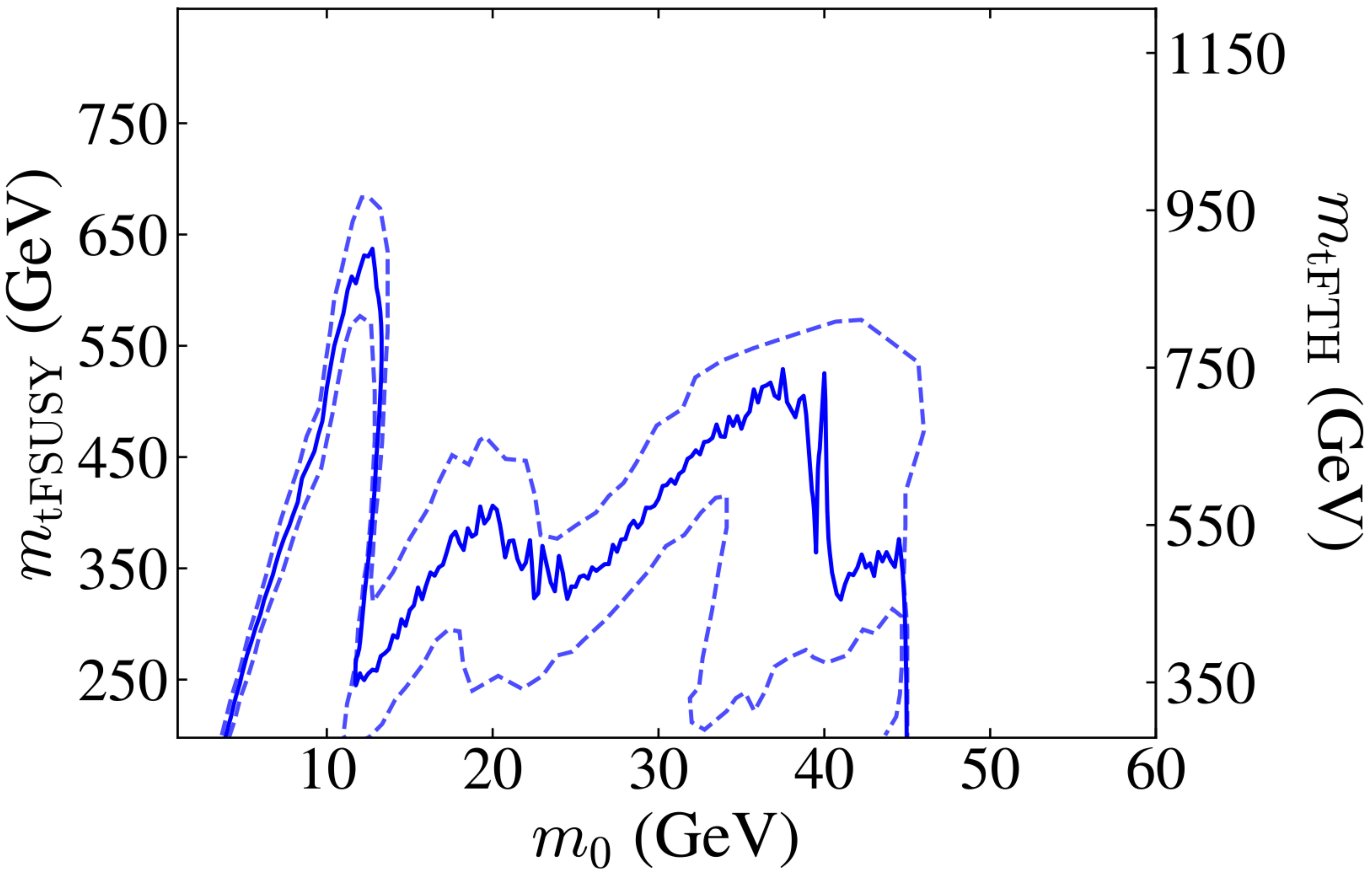
The Fraternal Twin Higgs at the LHC

By the way, here's the reach for the MATHUSLA40 we actually hope to be able to build.

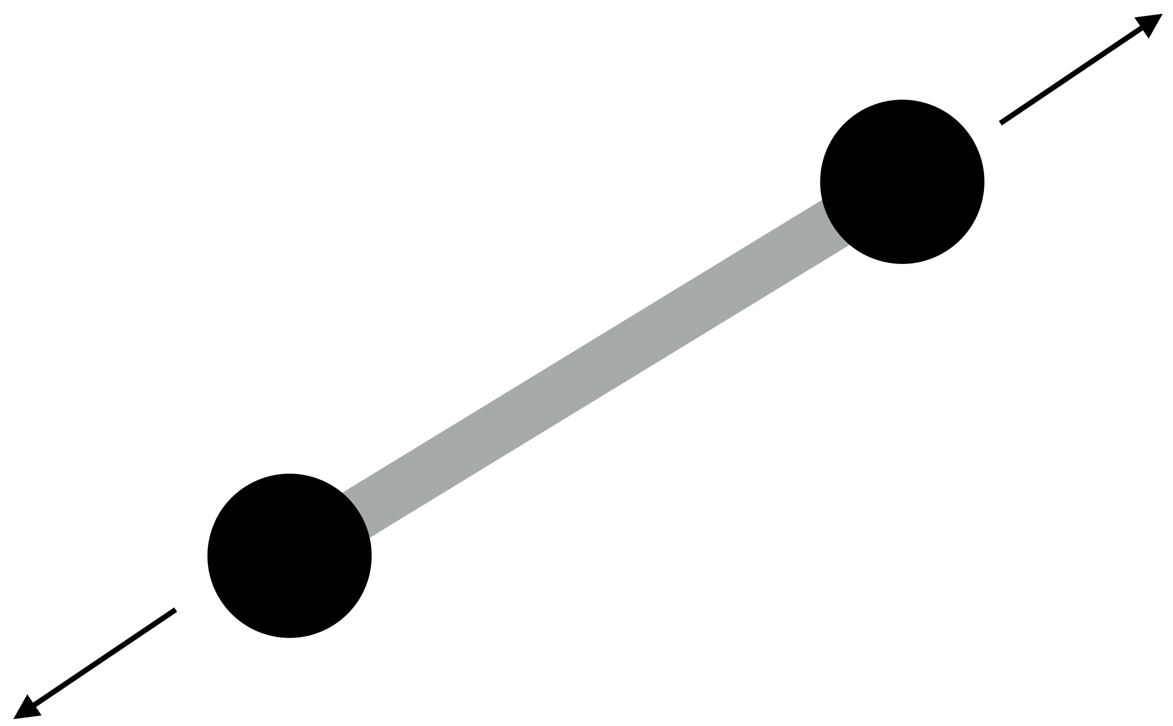


MATHUSLA CDR 2503.20893

The missing piece: Quirk de-excitation

What happens when you pair-produce a pair of **heavy dark quarks** in the QCD theory with zero light flavours?

They will form a **quirk bound state**, connected by an unbreakable color string.



Complicated/fun dynamics and phenomenology: 0805.4667, 0810.3948, 0810.1524, 0812.0843, 0909.2034, 1106.3101, 1106.2569, 1410.6409, 1501.05310, 1512.02647, 1512.05782, 1612.00850, 1703.00912, 1708.02243, 1811.08903, 1911.02223, 2002.07503, 2105.12668, 2108.06748, , 2311.15486, 2404.13814, 2410.00269, 2504.02940, …

What happens next?

- **if the dark quarks have SM charges**, they radiate photons or pions to shed their kinetic energy, eventually fall into a quirkonium ground state, then annihilate.
  - De-excitation can be modelled (photons easy, pions harder but estimable)
  - Practical challenge if the quirk is long-lived: modeling interaction with detector

DC, Dreyer, Costa, Heim, Kasieczka 2506.11192

- if the dark quarks do NOT have SM charges, they **de-excite by emitting dark glueballs**, then annihilate into glueballs. → **How to model the de-excitation?**

Modeling quirk de-excitation via glueball emission

We just started working on this now. A variety of approaches possible.

- HQEFT for dark gluon emission from heavy quarks?
- Dark glueball emission from string dynamics may be estimable by modelling string with Nambu-Goto action and estimating a self-crossing probability.

The physics is complicated, but semi-classical aspects may make it tractable if you are honest about your uncertainties parameterized with nuisance parameters.

Like for glueshower, concrete predictions with even large uncertainties will enable collider studies and help us appreciate how complex these signatures might be.
→ *e.g. finally understand phenomenology of the Fraternal Twin Higgs*

Example: due to glueball mass $m_0 = 6\Lambda$, final emission could be highly suppressed, forcing annihilation with angular momentum suppression → highly unusual quirk lifetime distribution!

Conclusions

Conclusions

"Exotic collider signals" are the most natural and expected thing in the world!

Can lead to signals both spectacular and subtle, but what they have in common is that they all need **full tracking information** to recognize.

⇒ **Full tracking and timing at L1** for the HL-LHC will **revolutionize** our ability to search for this broad class of highly motivated signatures!

⇒ Now is the time to **expand our ability to model** all kinds of dark non-perturbative dynamics and conduct **extensive phenomenology studies**.

What else have we missed because we were too bound by what was possible to search for or model in the past?