Hidden Valleys/Dark Sectors: Novel Signatures and Experimental Approaches

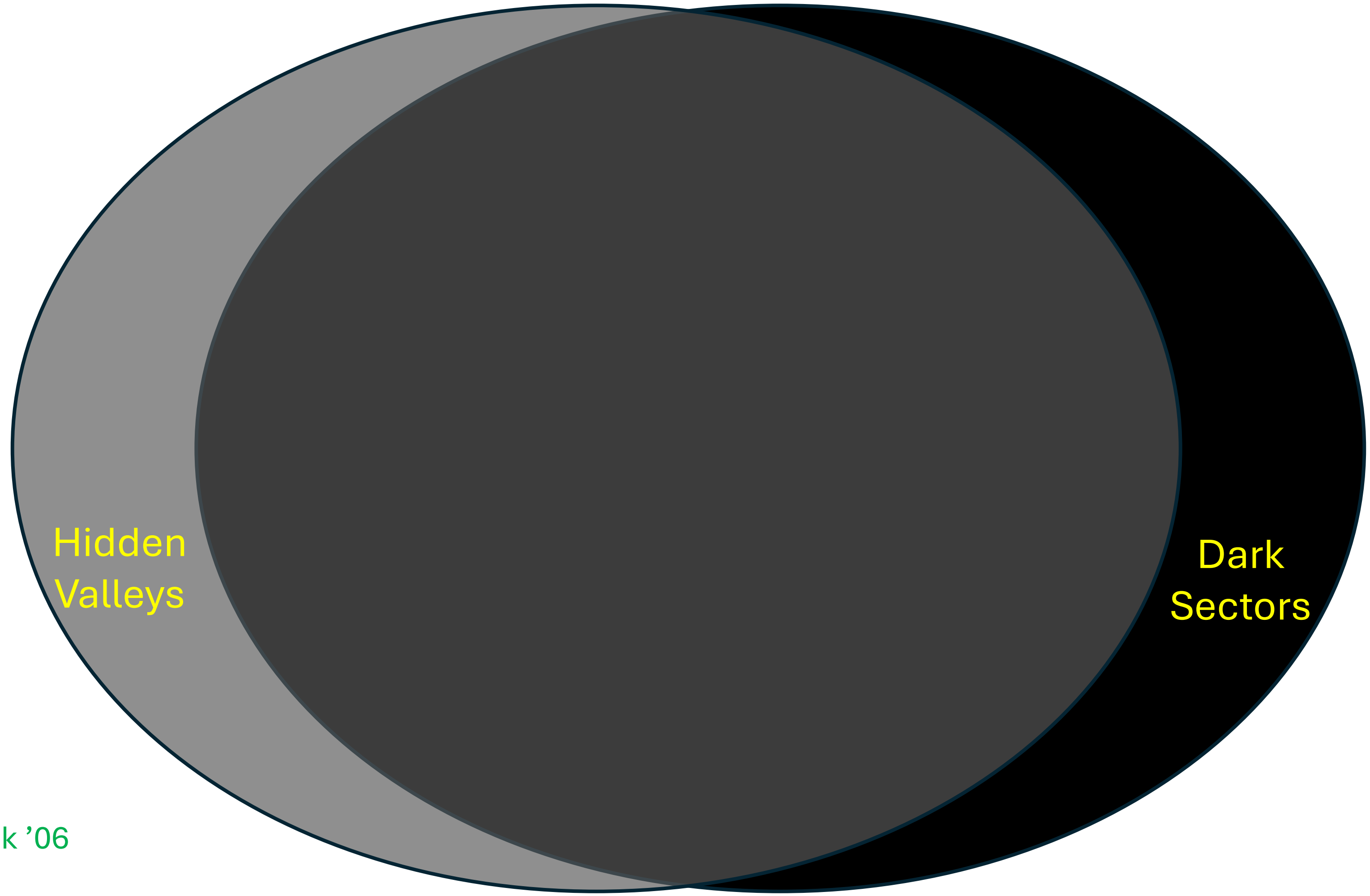
Matt Strassler

Harvard University

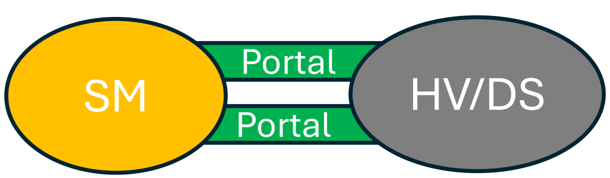
Dark Shower Workshop

January 2025

HV/DS



MJS & Zurek ’06



The Territory of HV/DS

MJS & Zurek 2006

Why useful to give this giant class of theories a single name?

Qualitative Predictions (alone or in combination)

- Multiple neutral particles decaying to SM particles (and often MET)
- High-multiplicity production
- Unusual clustering
- Displaced vertices

Back in 2006, all of these were off the radar

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MET fraction

Odd Jets

Lifetime

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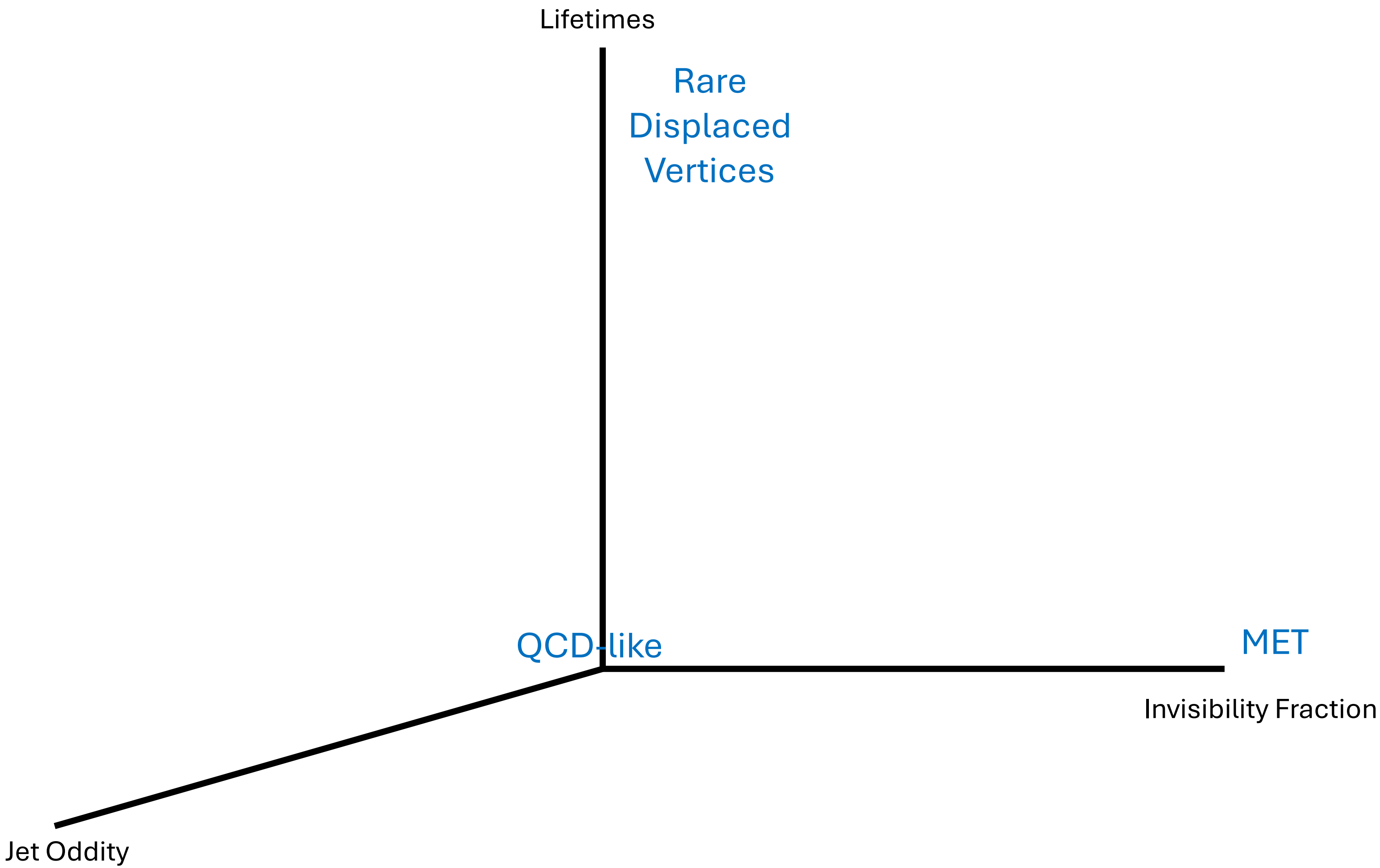
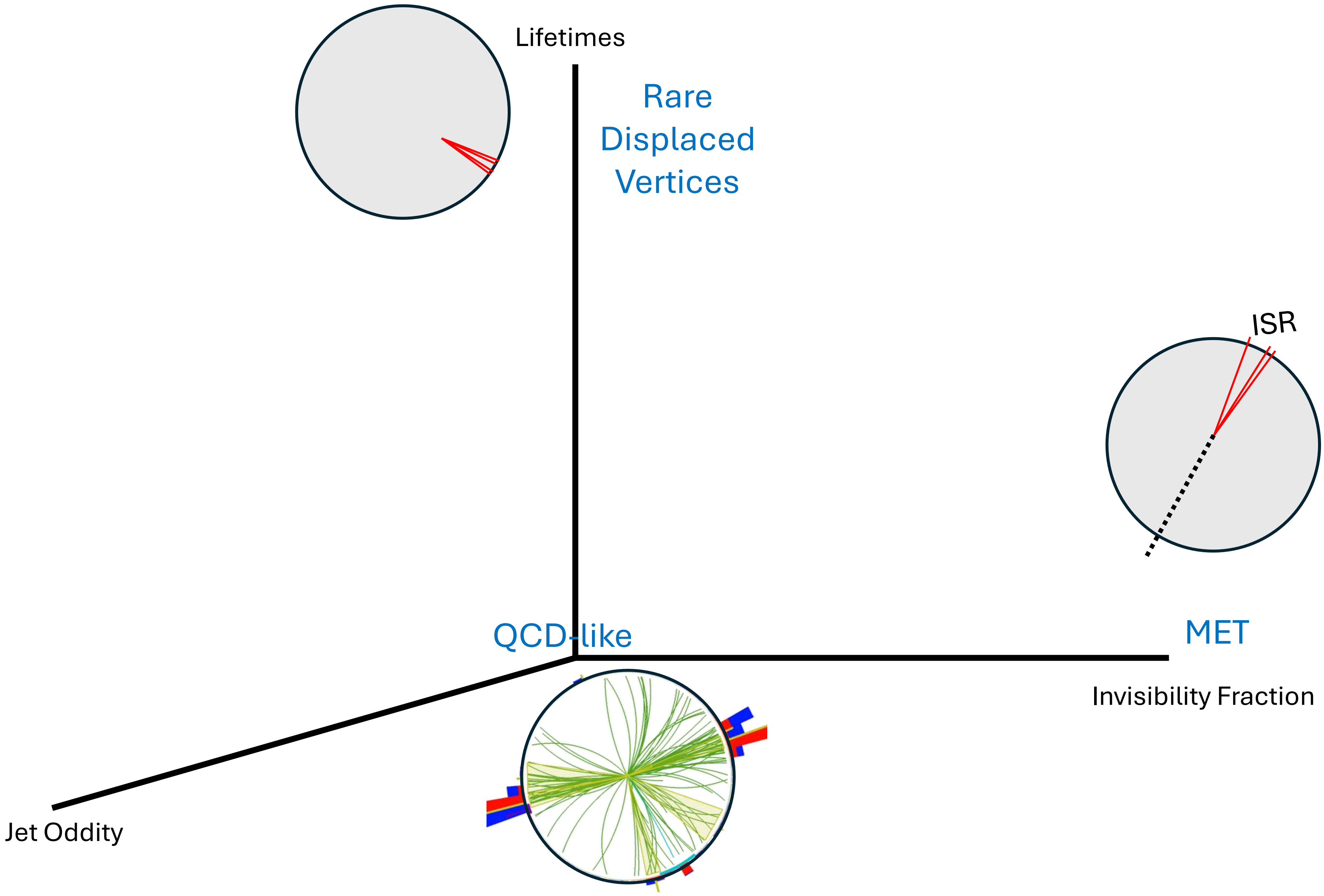

Lifetimes
Rare
Displaced
Vertices
QCD-like
MET
Invisibility Fraction
Jet Oddity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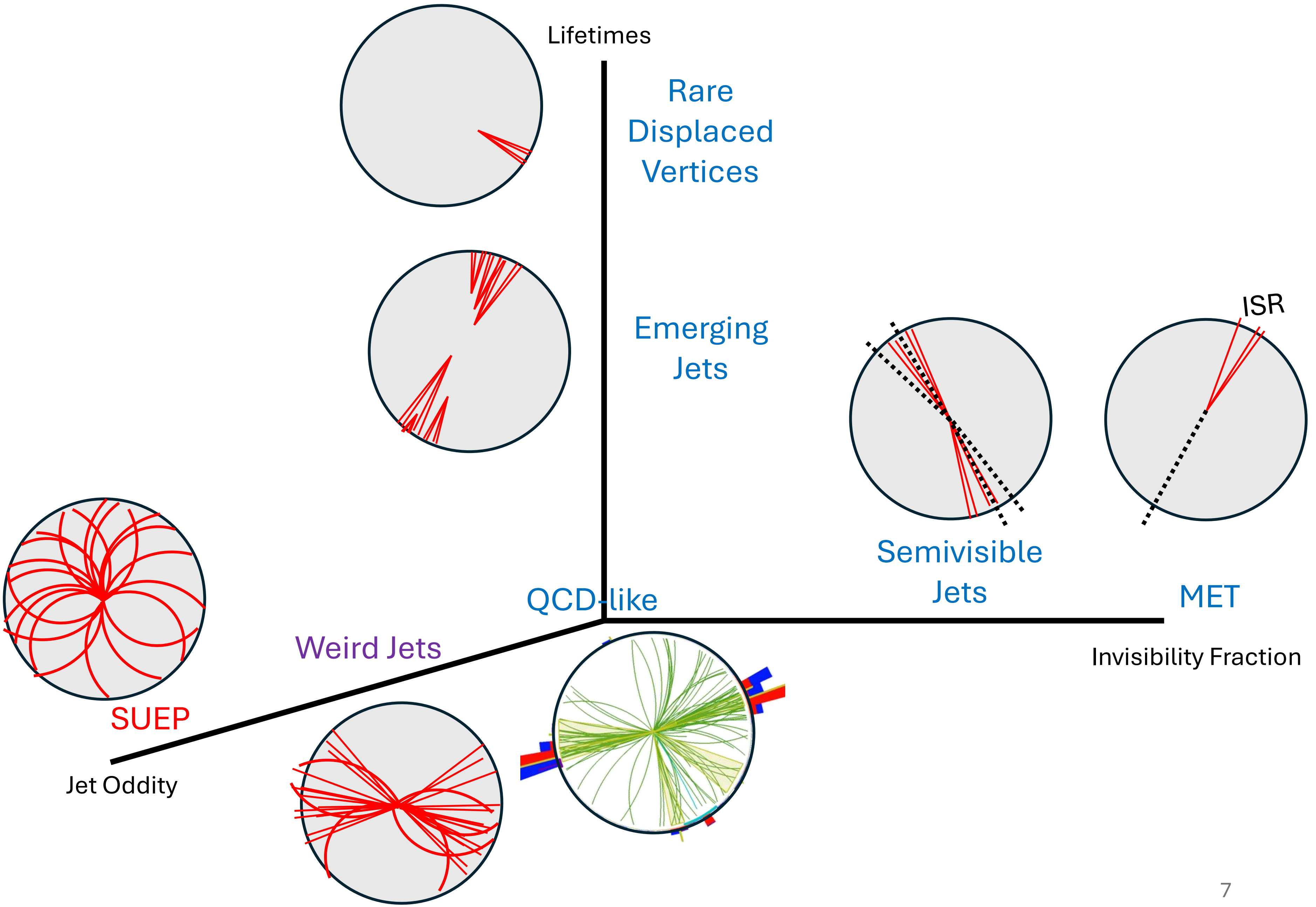
Lifetimes
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Weird Jets
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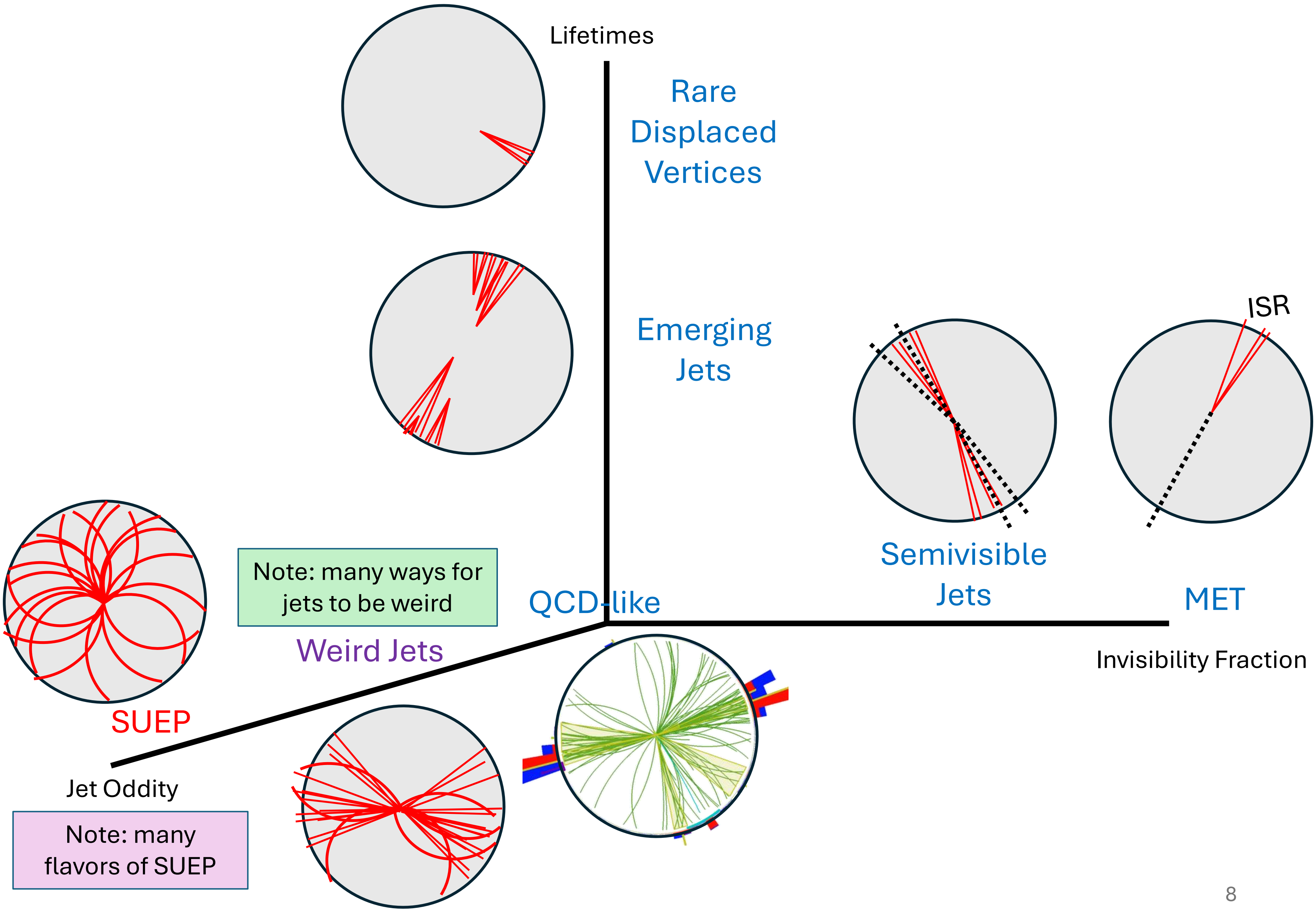
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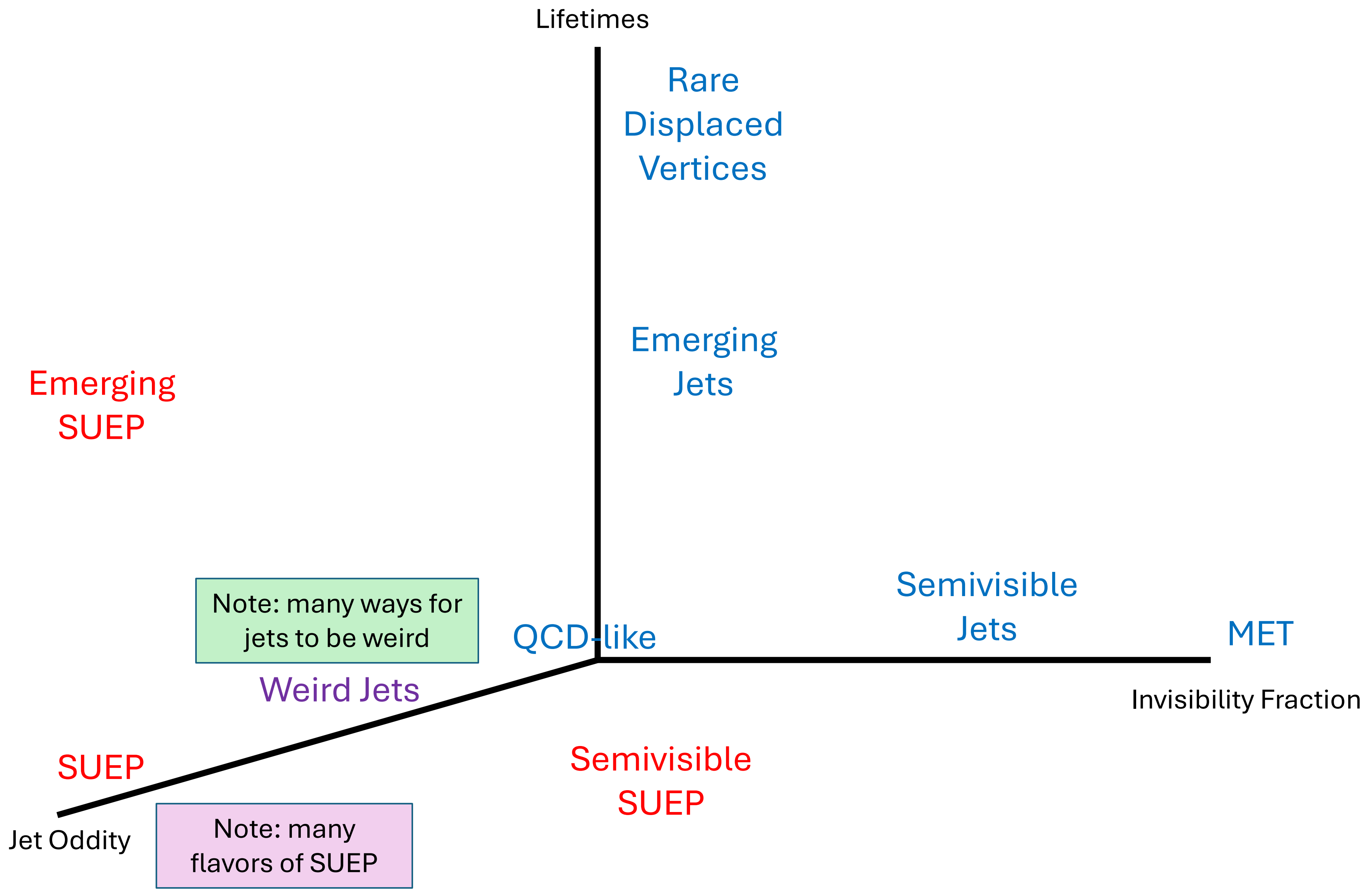
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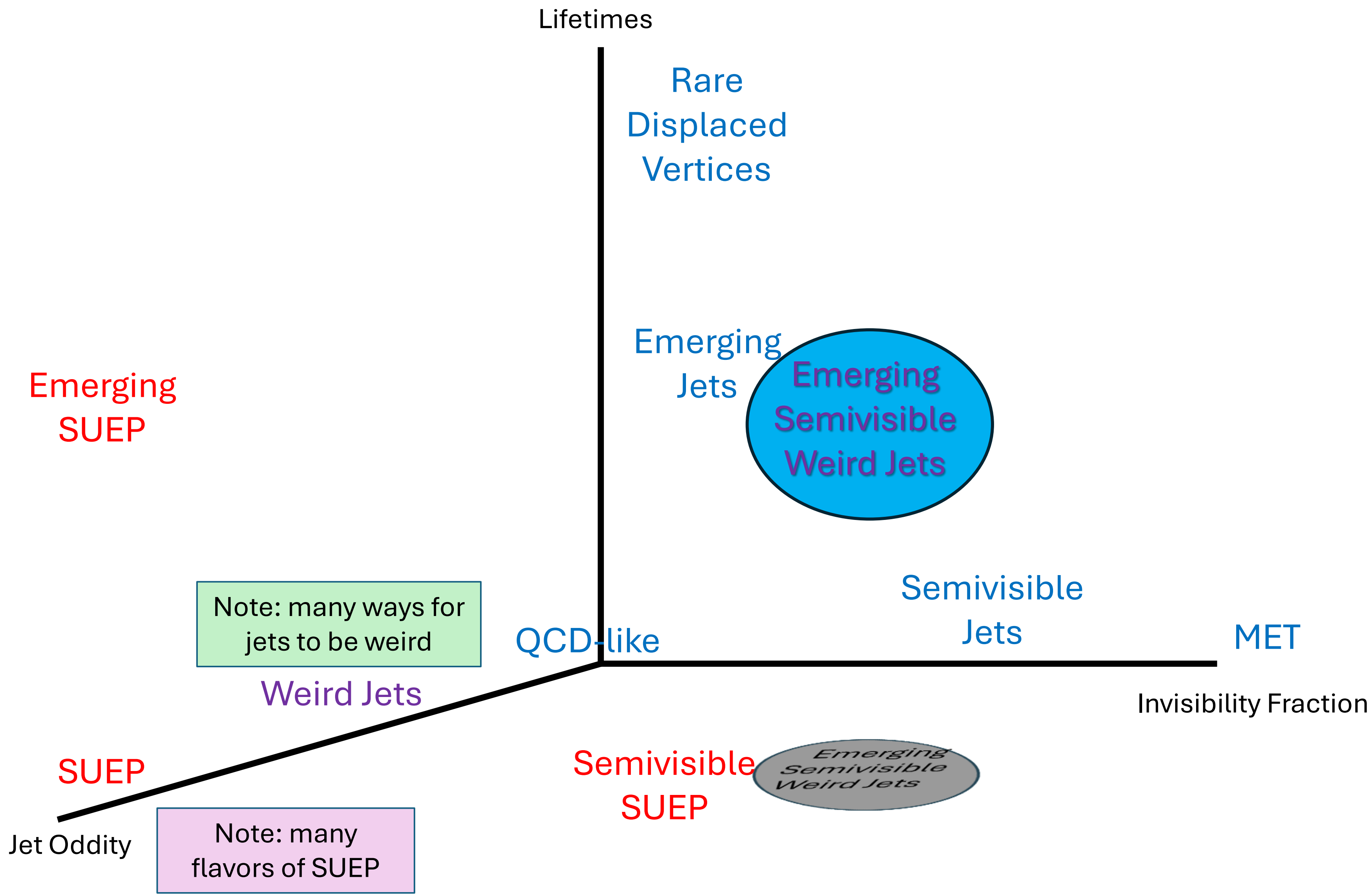
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Need to Go Beyond the Lamp Post of QCD

How to Do So?

Leptons and Photons : General experimental approach

1. **Pair** them & use invariant mass; or
2. **Count** them

- Limit use of (model-dependent) jet information until these are done
  - Theory uncertainties only enter in recasting

- Weird jets / weird events: Develop improved theory/simulations
  - Showering
  - Hadronization
- Also need more work on hadron spectrum and hadronic decays

Leptons using jet-independent searches

Signature: leptons + X	Typically <2 ll pairs	Typically 2 ll pairs	Typically >> 2 ll pairs
Resonant	A	B	B, C
Resonant but less isolated	A’	A’, B	B, C
Non-resonant	A’’	A’’?	C
Displaced	D	D	D

A: **2-lepton** bump hunt in semi-exclusive Drell-Yan events

A’: same as A but no isolation and tight d_0 cut

A’’: same as A but endpoint instead of bump hunt

B: **4 leptons in two equal-mass pairs**, bump hunt

C: **5 or more leptons**

D: **Displaced** lepton pair

Photons ~~Leptons~~ using jet-independent searches

Signature: ~~leptons~~ photons + X	Typically <2 γγ pairs	Typically 2 γγ pairs	Typically >> 2 γγ pairs
Resonant	A	B	B, C
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B: **4 ~~leptons~~** photons **in two equal-mass pairs**, bump hunt

C: **5 or more ~~leptons~~** photons [or even just 4!]

D: **Displaced** ~~lepton pair~~ photons

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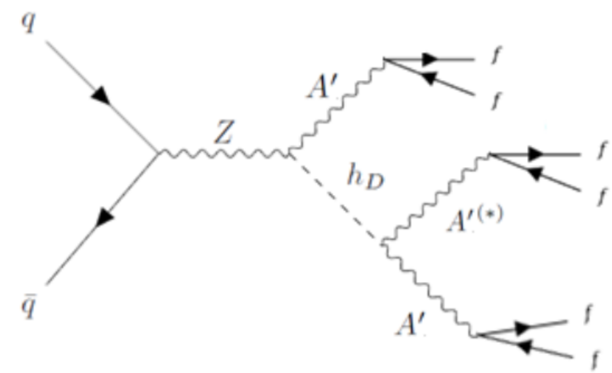
General Searches for Leptons

B Pairing Example: ATLAS search in $U(1)$ HV/DS 2306.07413

$$Z \to A' h_D \to A' A' A'$$

Cf. Schabinger and Wells '05



- Require two pairs of loosely isolated $\ell^+\ell^-$ with $m_{4\ell} < M_Z$
- Require two $A_D \to \ell^+\ell^-$ candidates of equal mass
- Avoid $m_{\ell\ell} < 5$ GeV and $m_{\ell\ell}$ near Upsilon

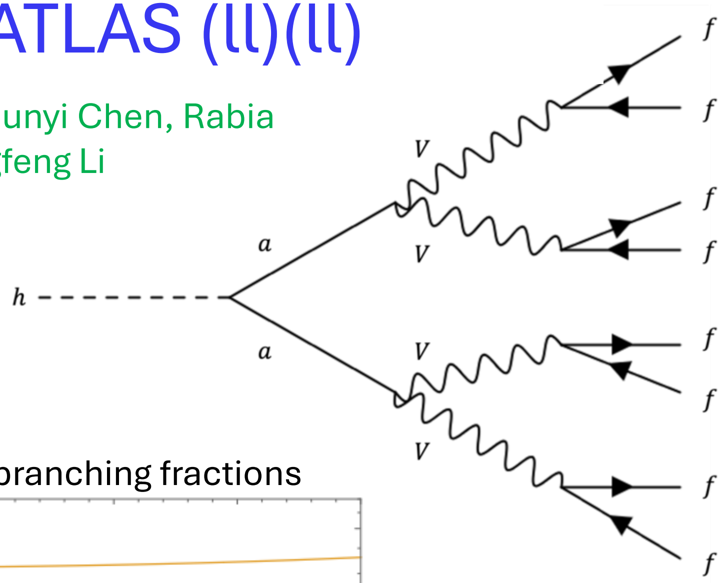
C Counting Example: ATLAS Search for multileptons 2103.11684

- Typical search for several isolated leptons, sometimes with MET
- Includes bin with ≥ 5 leptons, no MET requirement

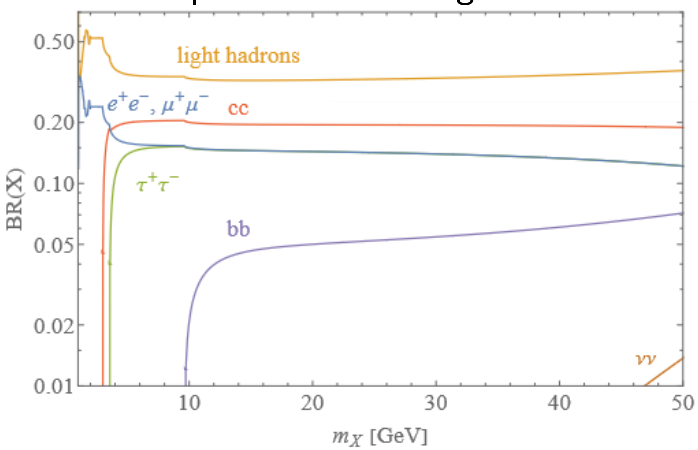
Recommended by Izaguirre and Stolarski 2018

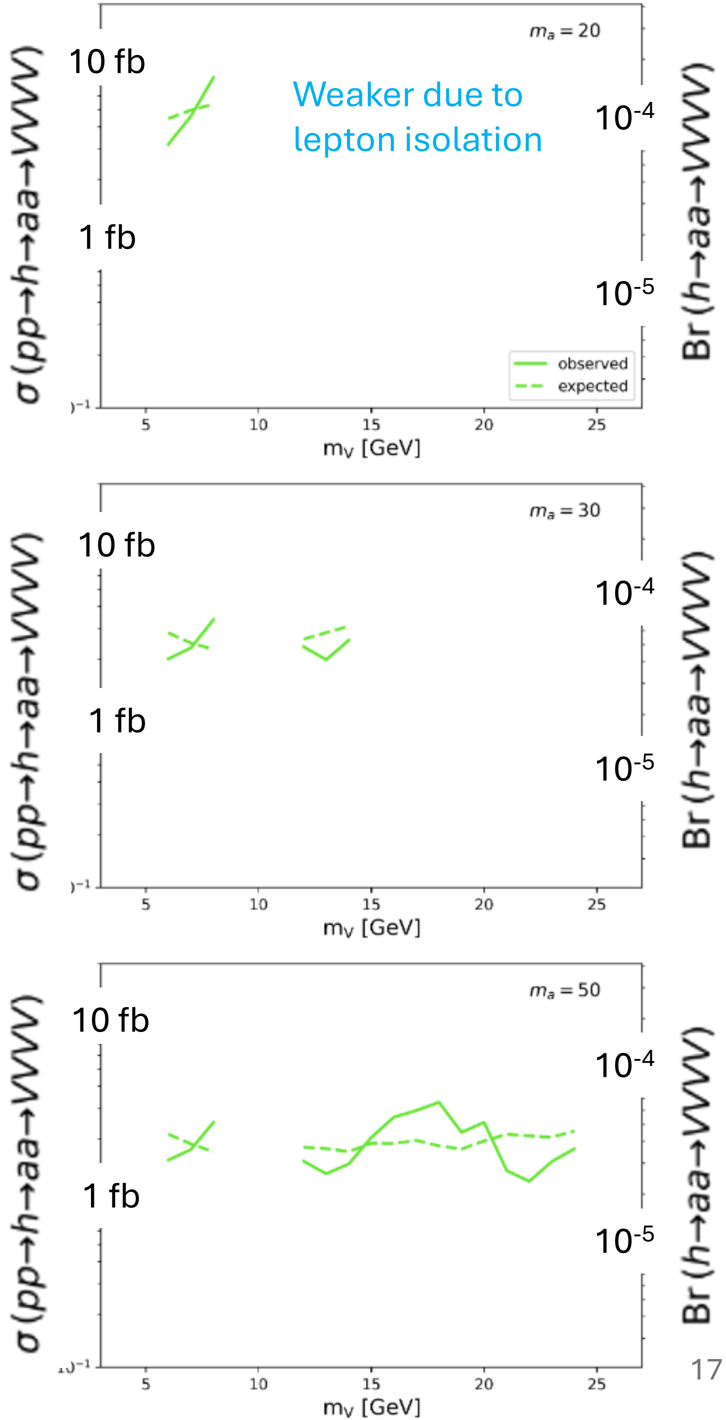
Recast B: ATLAS (ll)(ll)

2412.14452 with Junyi Chen, Rabia Hussein, and Lingfeng Li



Dark photon branching fractions





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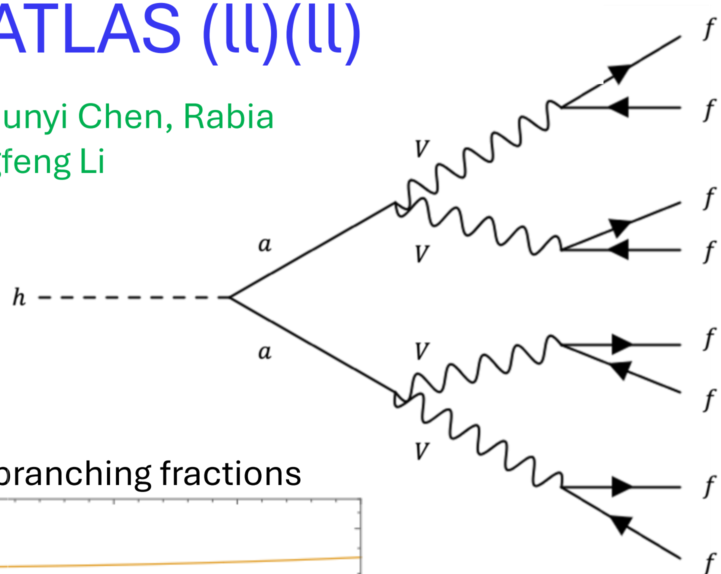

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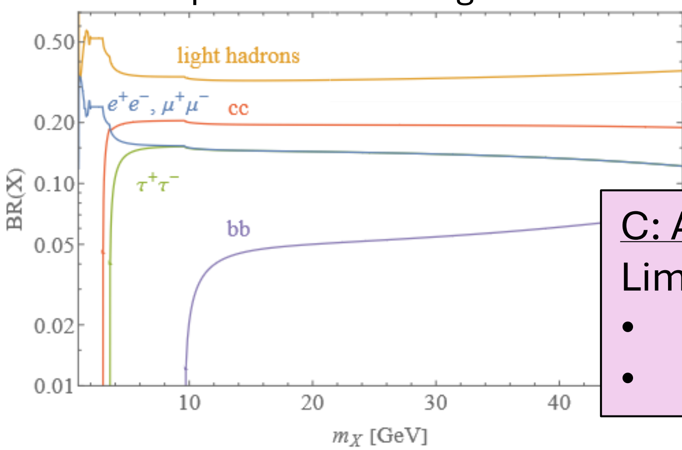
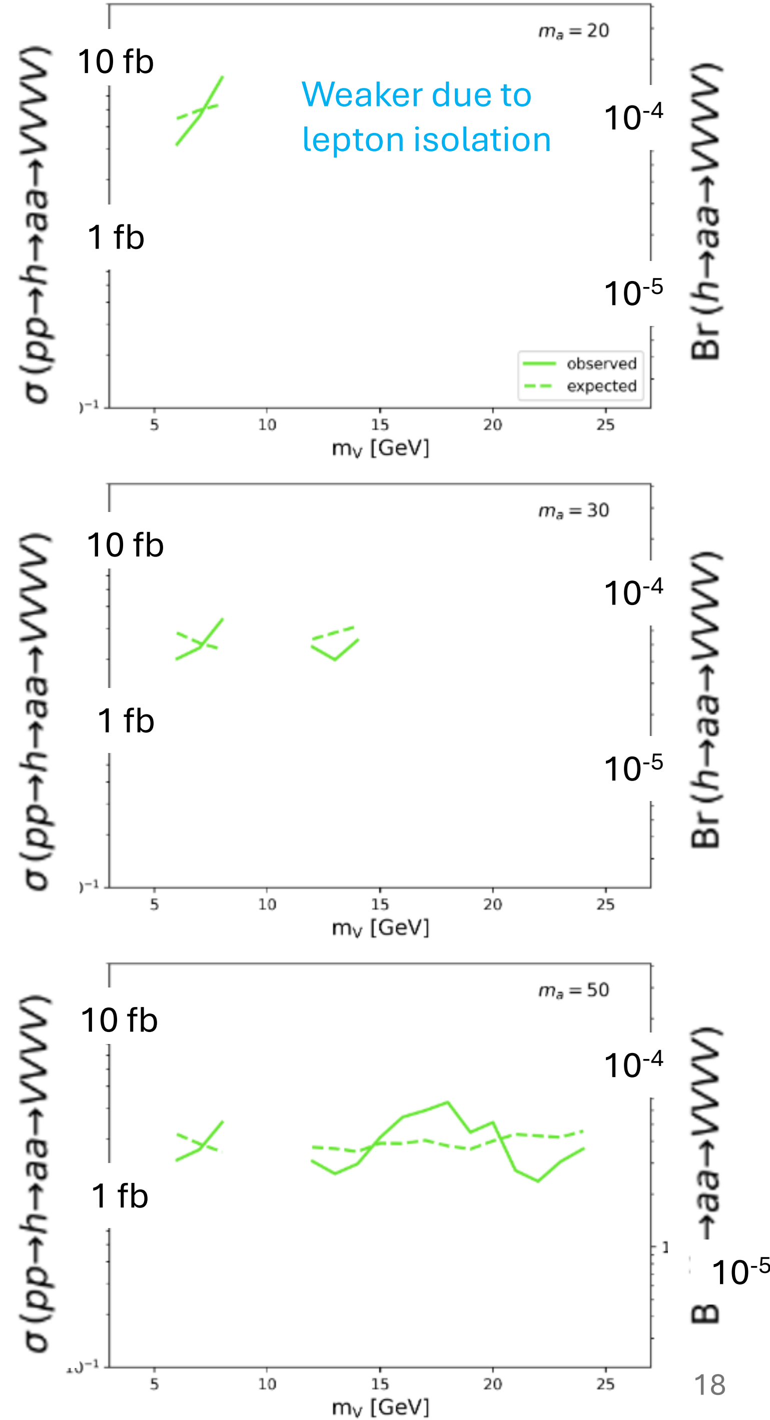


C: ATLAS multilepton

Limits slightly weaker

- Higher pT cuts
- Upward fluctuation



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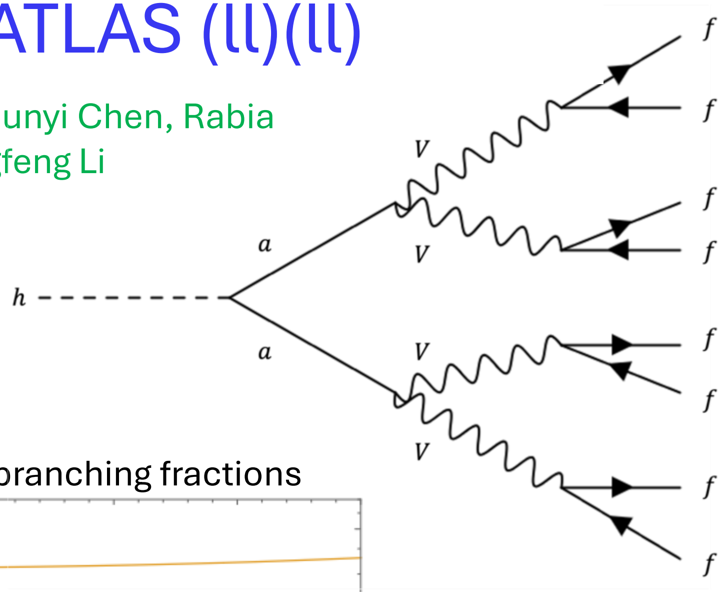

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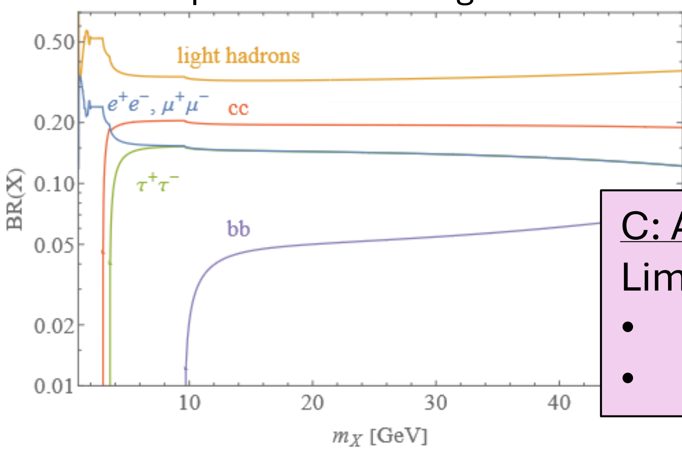

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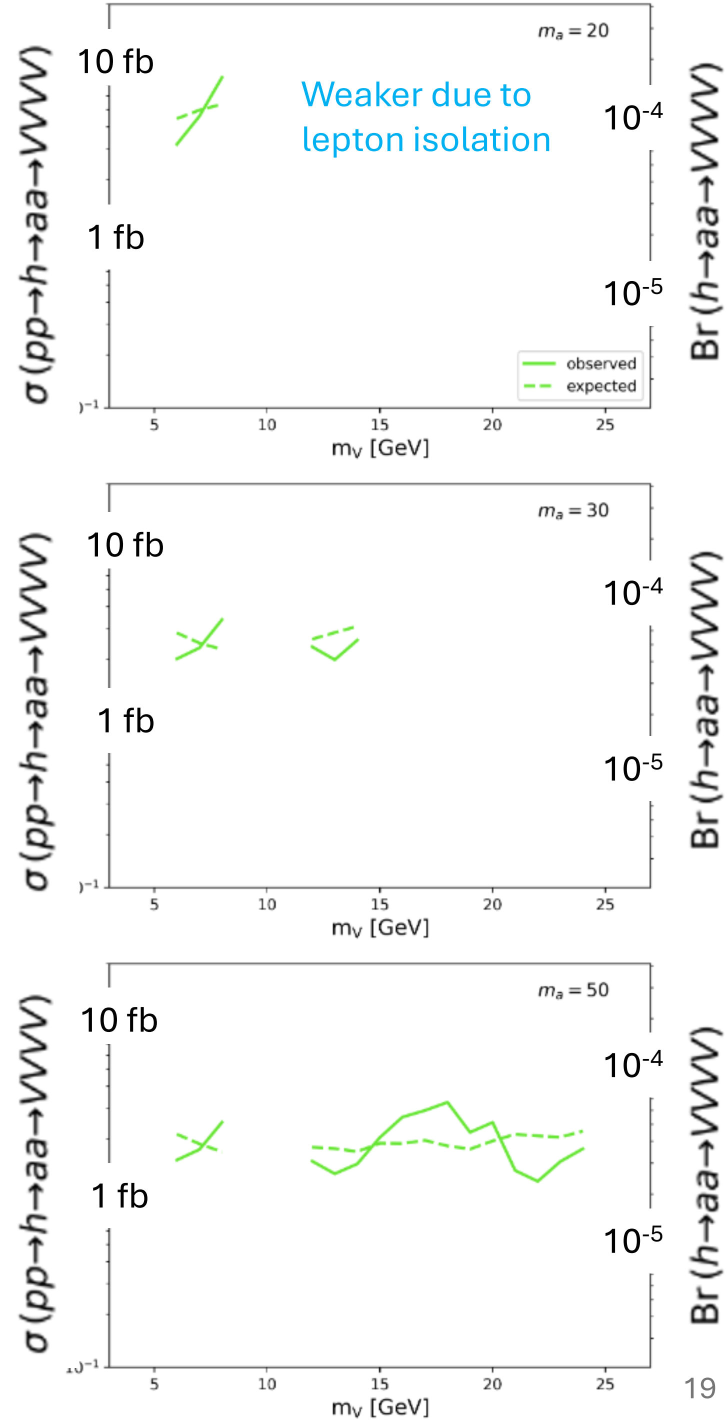

Recast for HV/DS with Dark Showers?

Uncertainty from hadronization?

Effects of lepton isolation?

Generalize to HV/DS with Leptons

Many HV/DS with a dark vector boson (γ_D, ρ_D, etc.) produce leptons

- SM QCD: $m_\pi \ll m_\rho \Rightarrow \text{Br}(\rho \to \pi\pi) \sim 100\% \Rightarrow$ no leptons
- Common HV/DS: $2m_{\pi_D} > m_{\rho_D} \Rightarrow$ no $\rho_D \to \pi_D \pi_D$
  - Often $\text{Br}(\rho_D \to \text{SM}) \sim 100\% \Rightarrow \text{Br}(\rho_D \to \ell^+\ell^-) \sim 10\% - 30\%$

But can we simulate jets reliably with $2m_{\pi_D} > m_{\rho_D}$?

Hadronization:

- No analytic methods, lattice methods, lower-dimensional models
- Standard approaches for QCD (NOTE: both assume $N_f \sim N_c \gg 1$)
  - Lund string model (PYTHIA)
  - HERWIG clustering model

Hadronization Uncertainties

In progress with Junyi Chen, Rabia Hussein, and Lingfeng Li

PYTHIA Lund model

- forms a flux tube string between color sources,
- then breaks it into pieces (hadrons) using a probability distribution
- requires there be light quarks in the fundamental representation

It has four relevant parameters

- a, b control momentum along string direction
- σ, controls momentum transverse to string
- `probVec` controls spin-1 vs spin-0 probability

Two sources of uncertainties

1. Intrinsic to PYTHIA hadronization parameters in QCD
   - how well constrained are $a, b, \sigma,$ `probVec` by QCD data?
2. Arising from difference between our HV/DS and QCD
   - how do $a, b, \sigma,$ `probVec` vary with e.g. m_q?

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NOTE: **New Version of PYTHIA HV**

- **Corrects** settings for *b* and σ
- **Updates** defaults to Monash tune
- **Changes** some parameter details

Caution for backwards compatibility!

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Hadron Spectrum

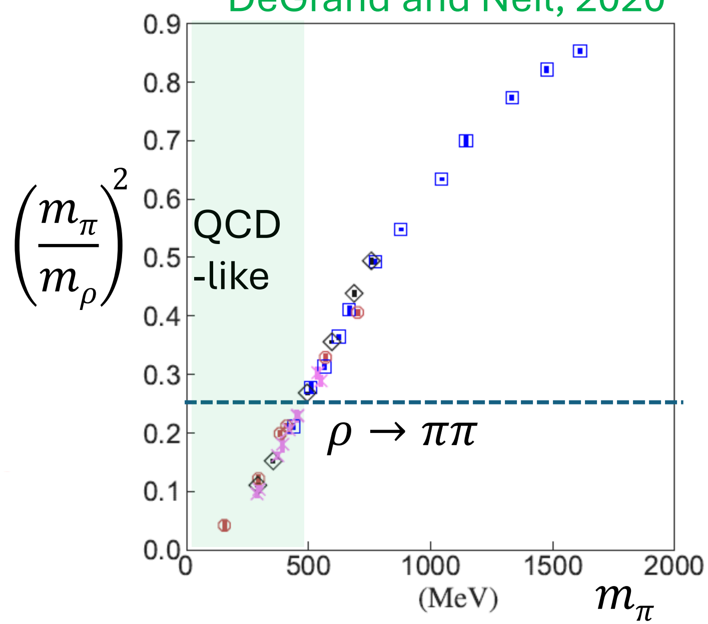
In progress with Junyi Chen, Rabia Hussein, and Lingfeng Li

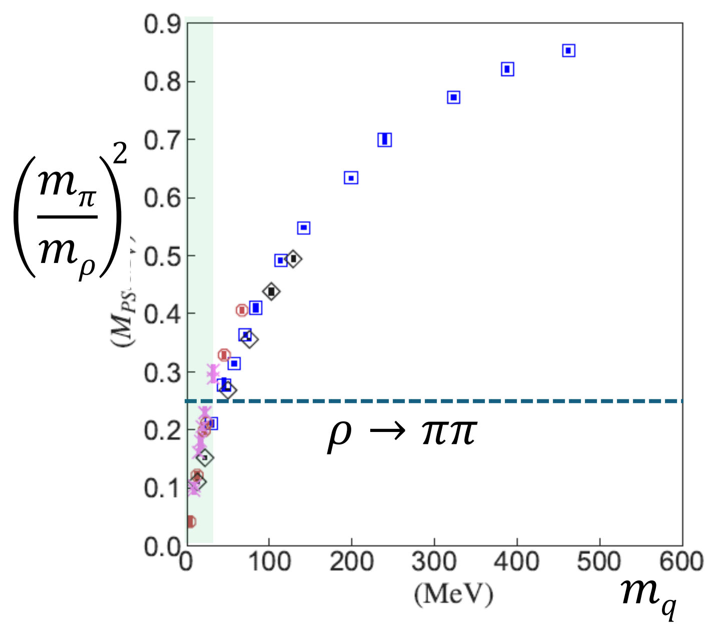
Lattice Gauge Theory: m_π, m_ρ vs. m_q

Regimes

- $m_q \ll \Lambda$: $m_\pi \ll m_\rho$ as in QCD

DeGrand and Neil, 2020





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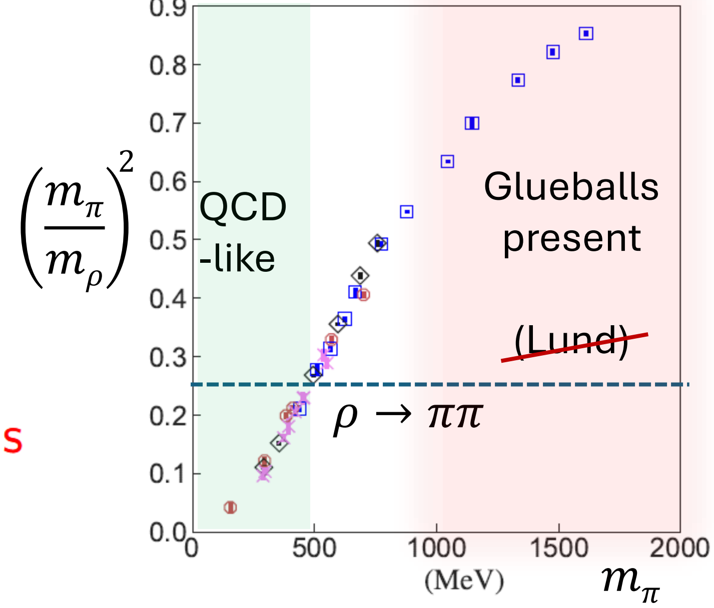

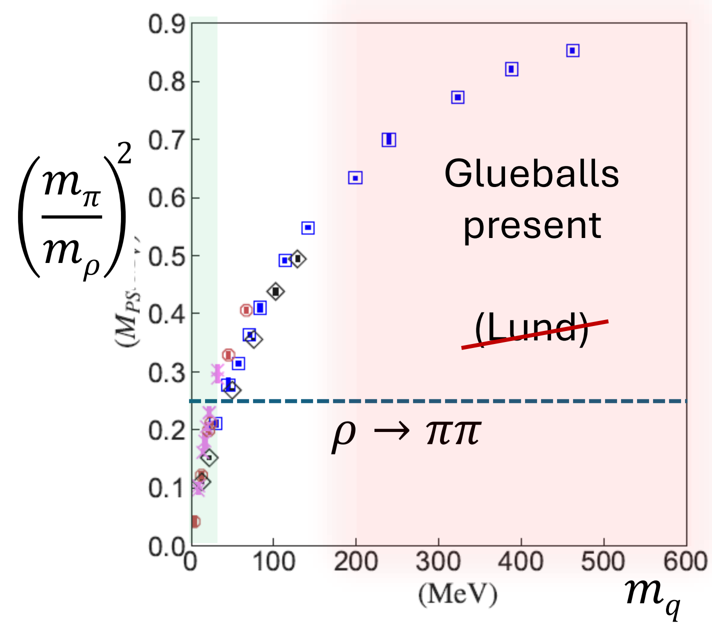

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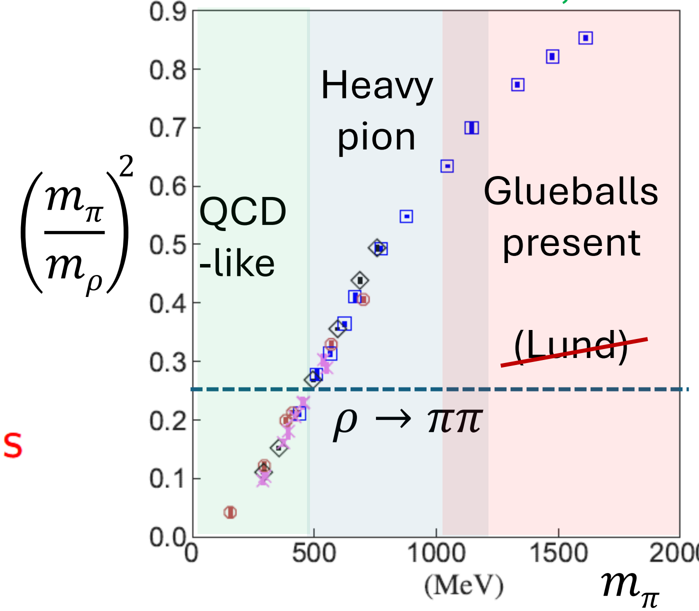

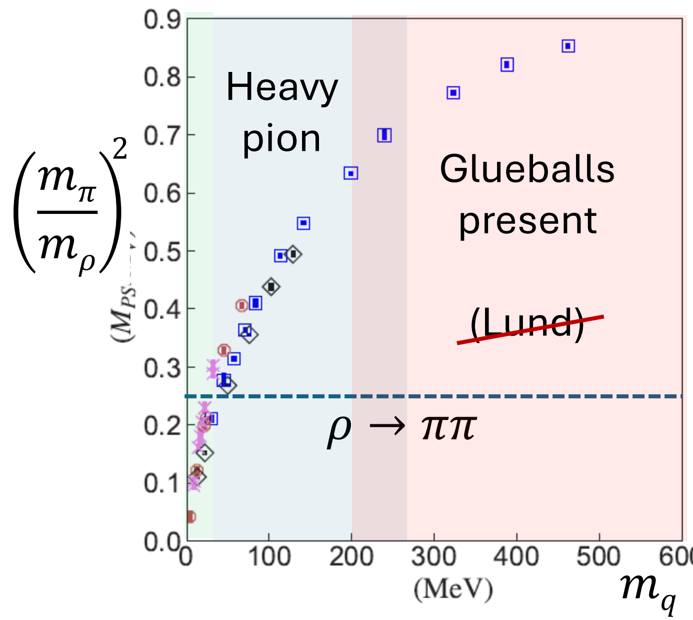

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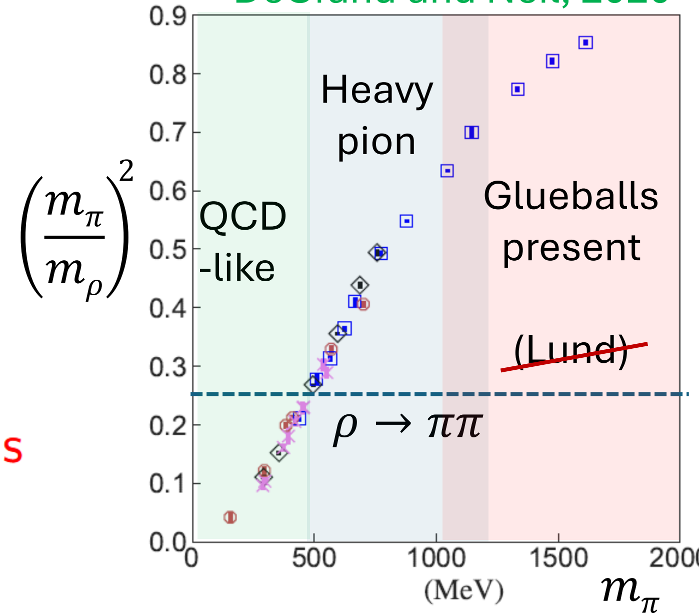
Preliminary Claim:
Lund model parameters need only minor adjustments

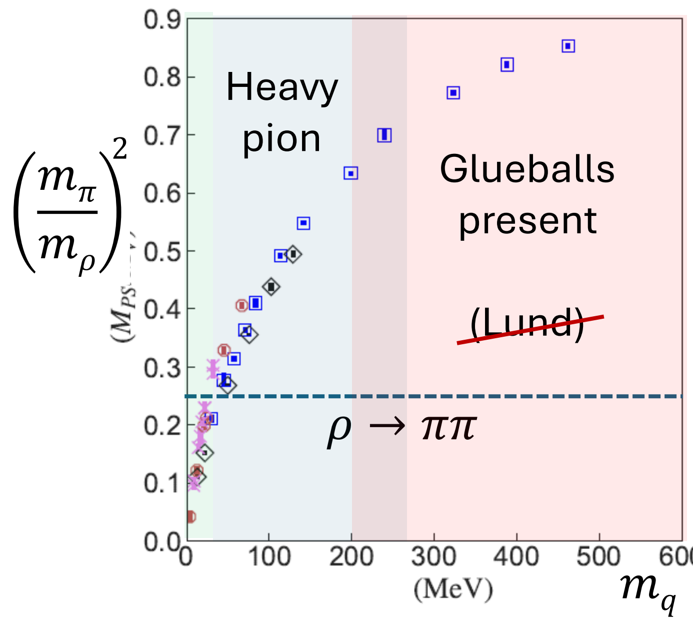
Main uncertainty from probVec

- $m_\pi = m_\rho \Rightarrow \texttt{probVec} = 0.75$
- $m_\pi \sim 0.2 m_\rho \Rightarrow \texttt{probVec} \sim 0.50 - 0.62$

Example: 8 visible hadrons
- probVec = ¾ ➔ 6 rho ➔ P(≥4 leptons) = 68%
- probVec = ½ ➔ 4 rho ➔ P(≥4 leptons) = 35%

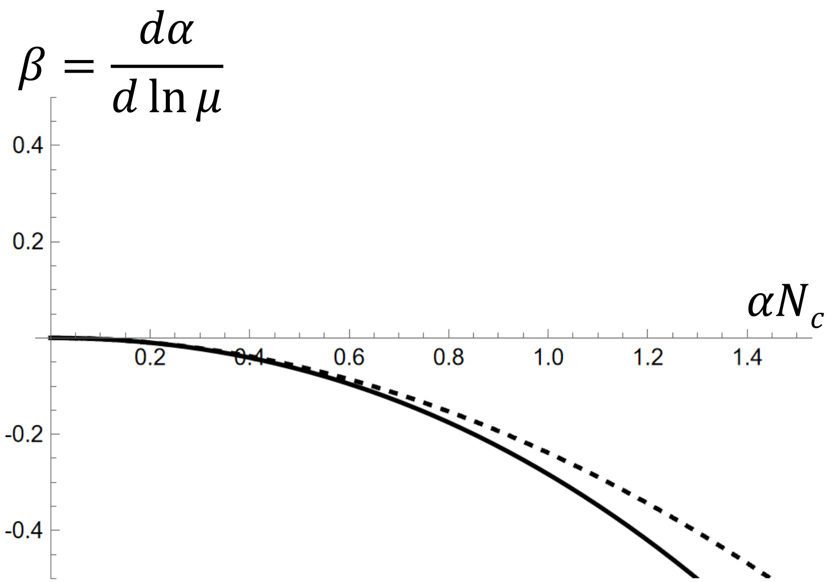
DeGrand and Neil, 2020

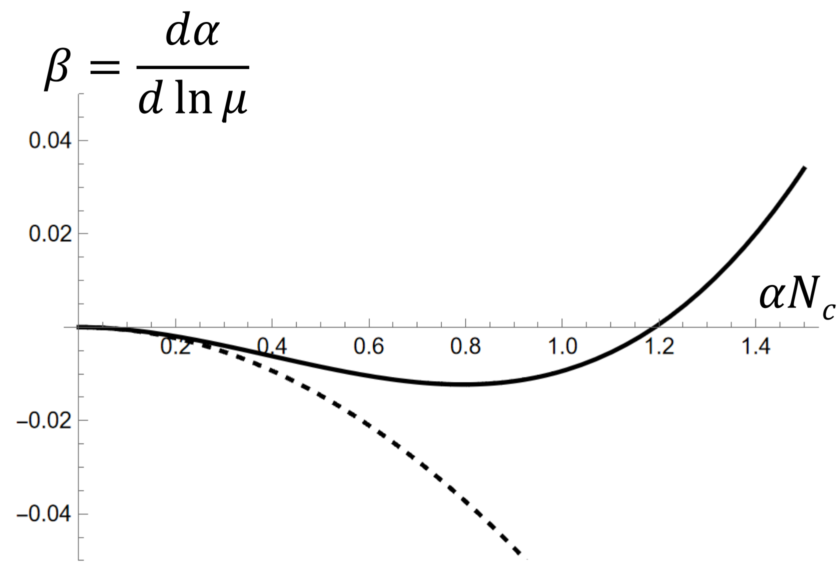




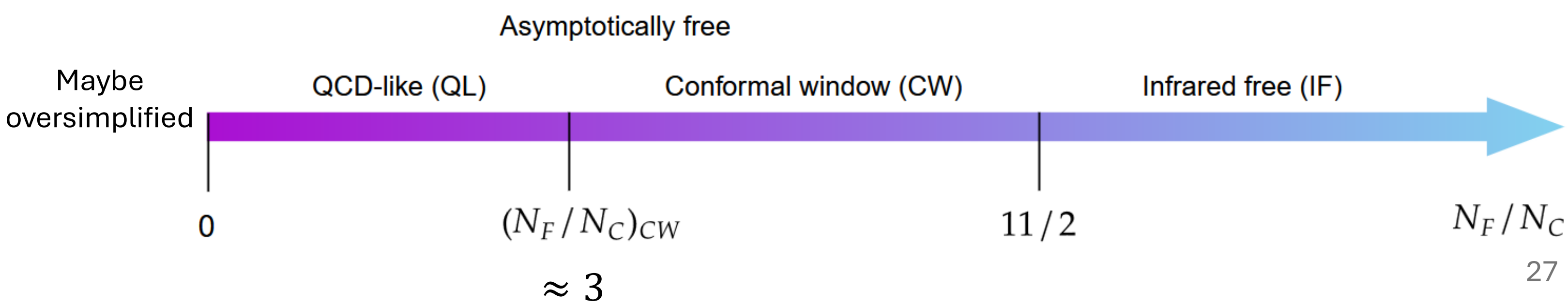
Large N_f and Approx Fixed Points

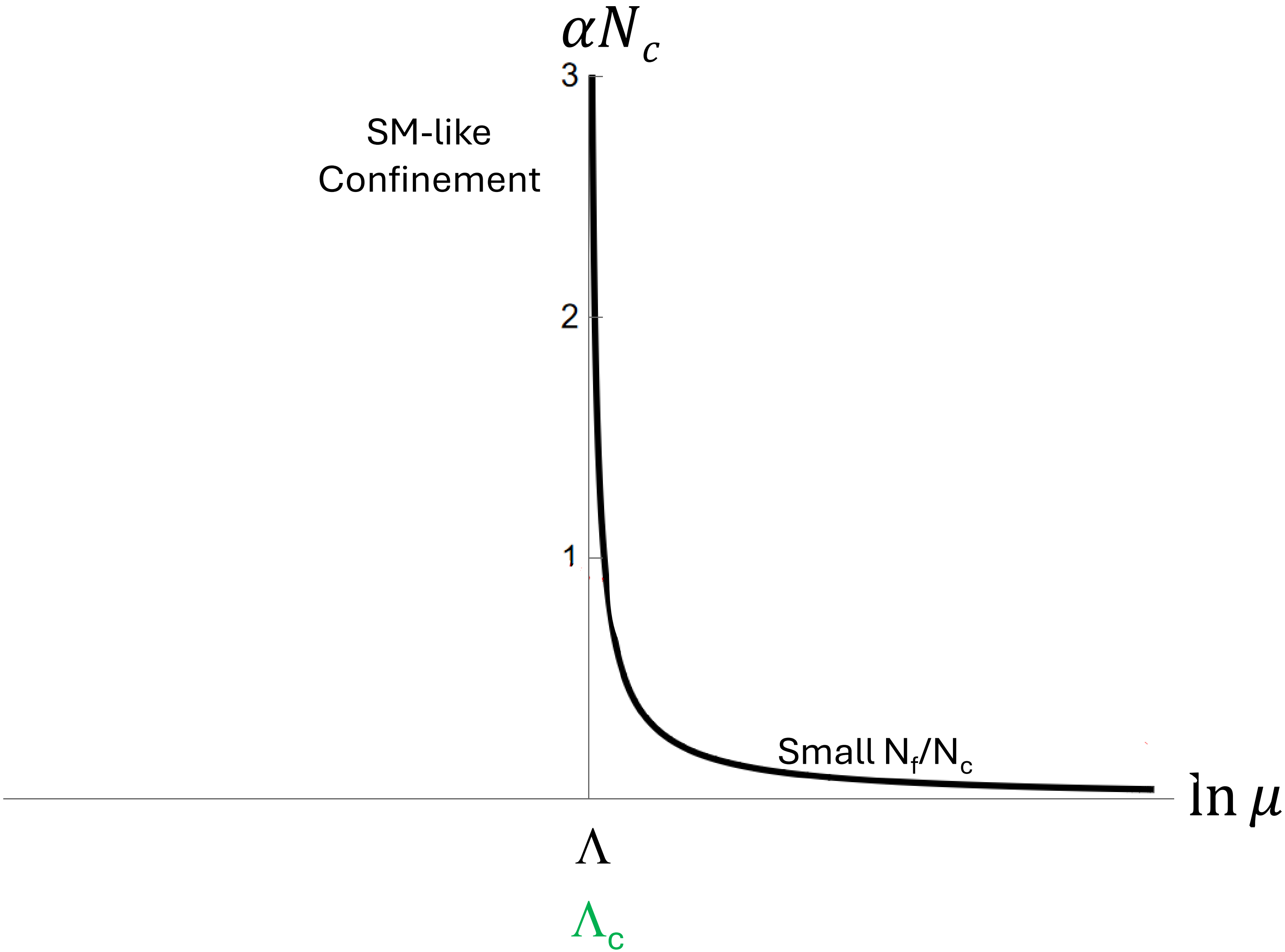
In progress with Suchita Kulkarni and Joshua Lockyer





If $\beta_1 < 0 < \beta_2$, then 2-loop fixed points at $\alpha = \alpha_* = -\dfrac{\beta_0}{\beta_1}$





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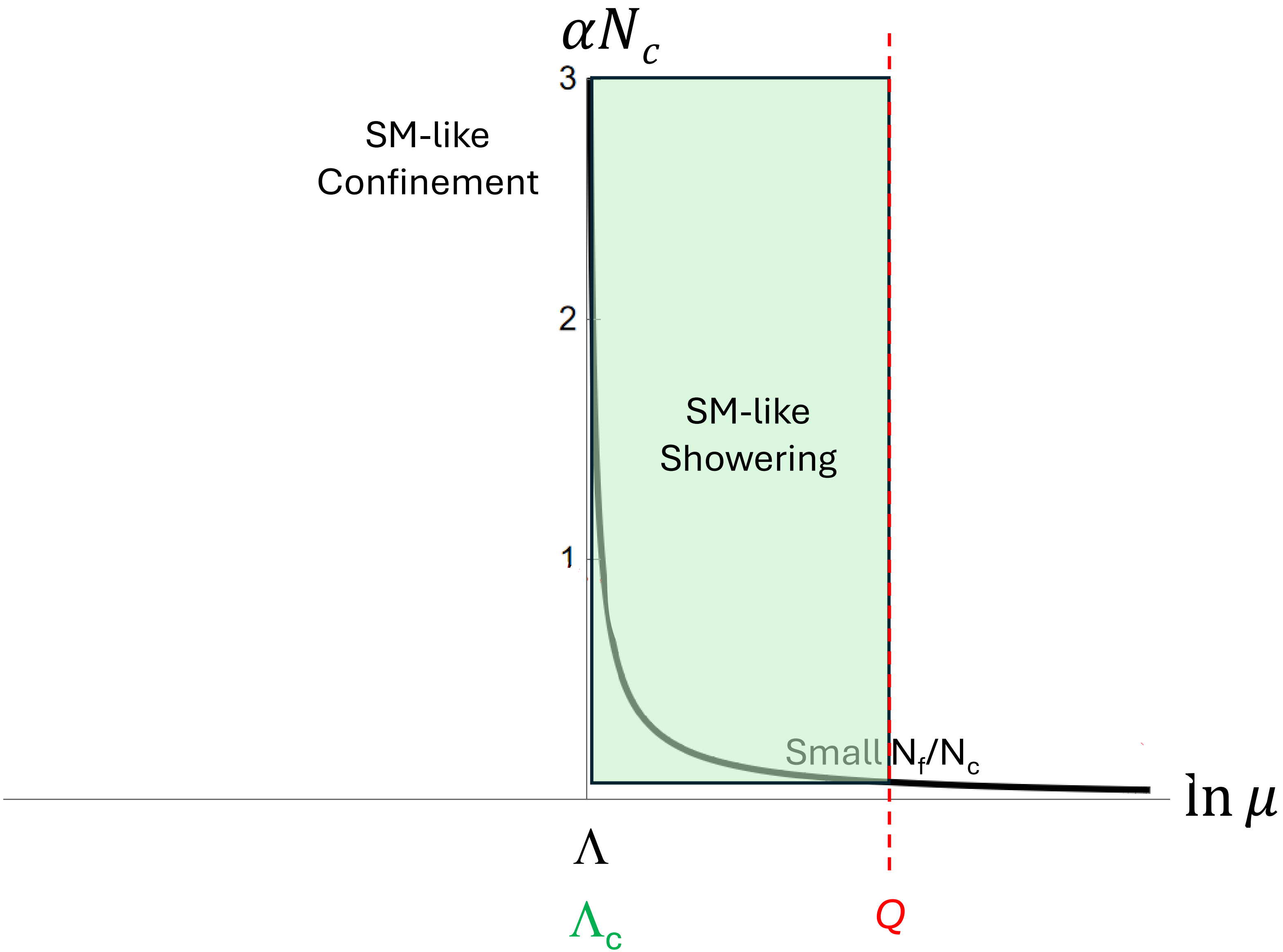
SM-like
Confinement
Small N_f/N_c
$\ln\mu$
Λ
Λ_c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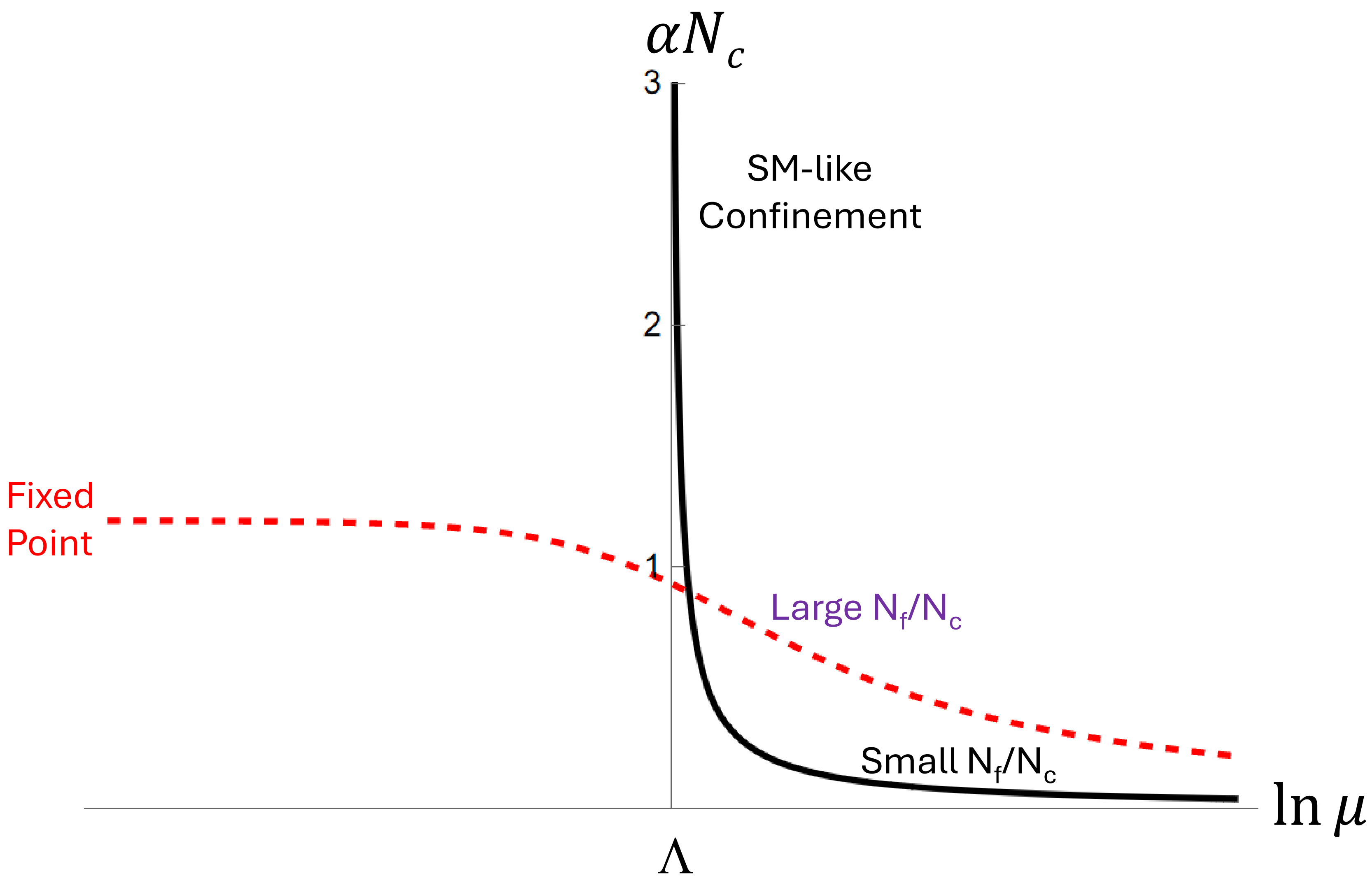
ln μ
Λ
Λ_c
Q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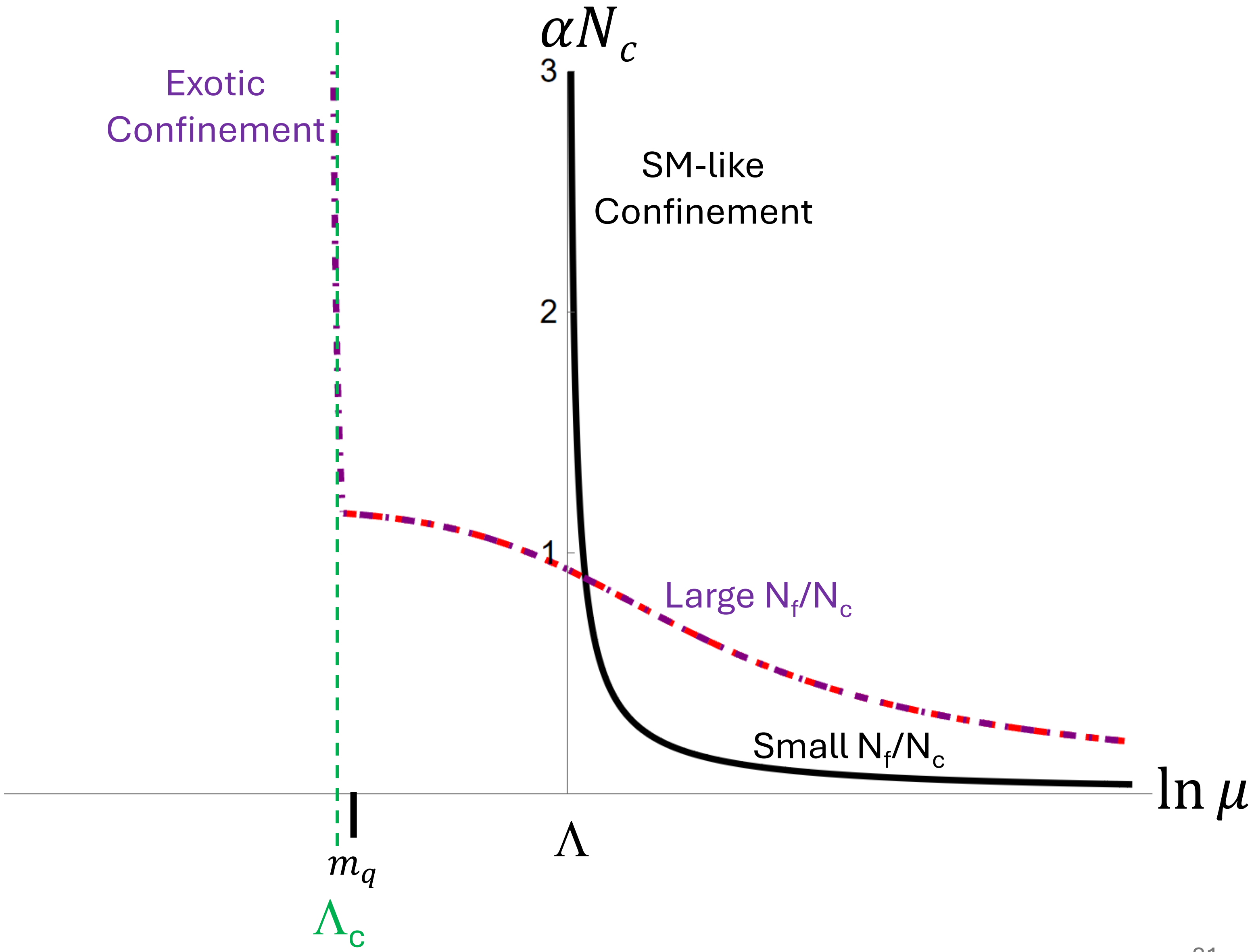

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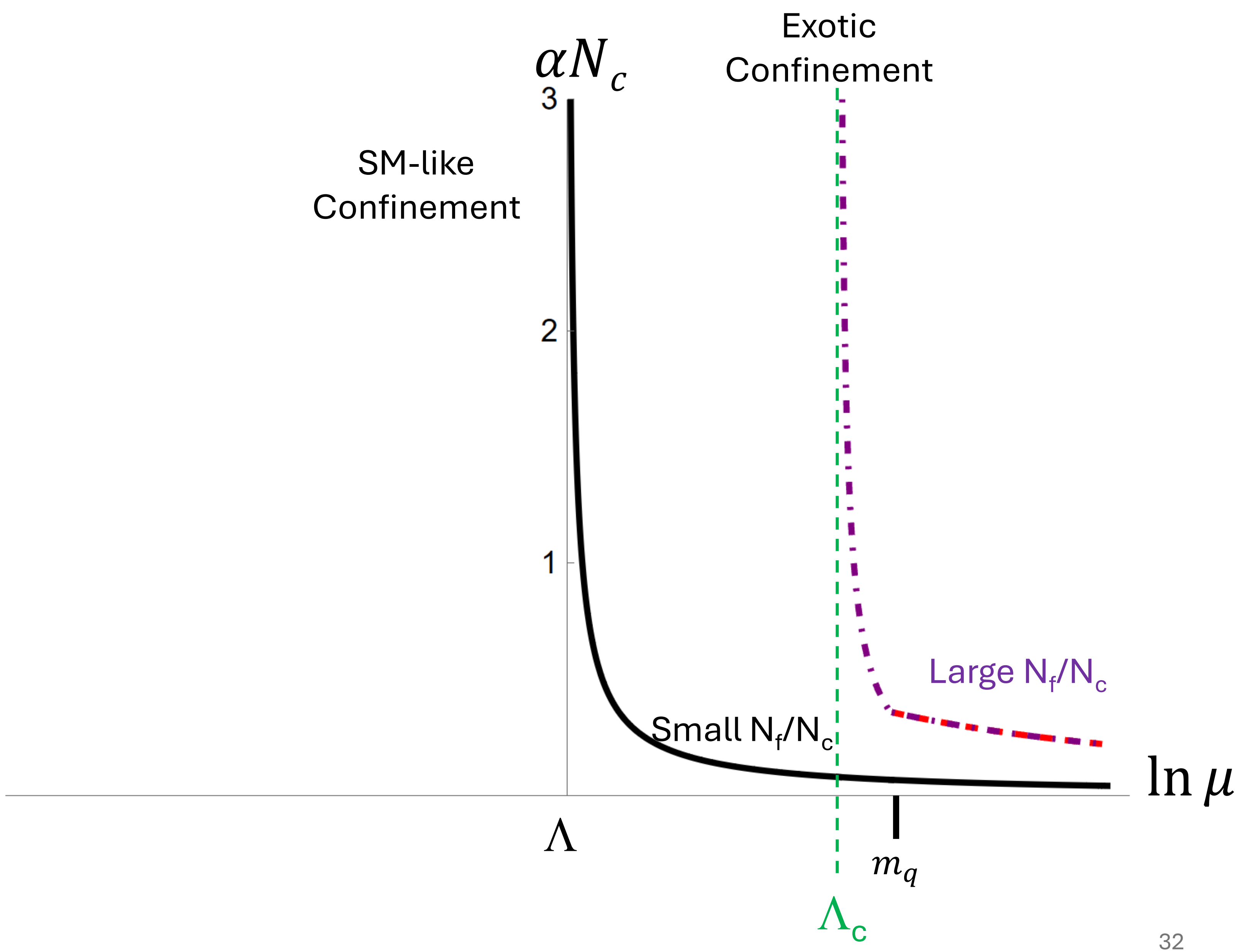
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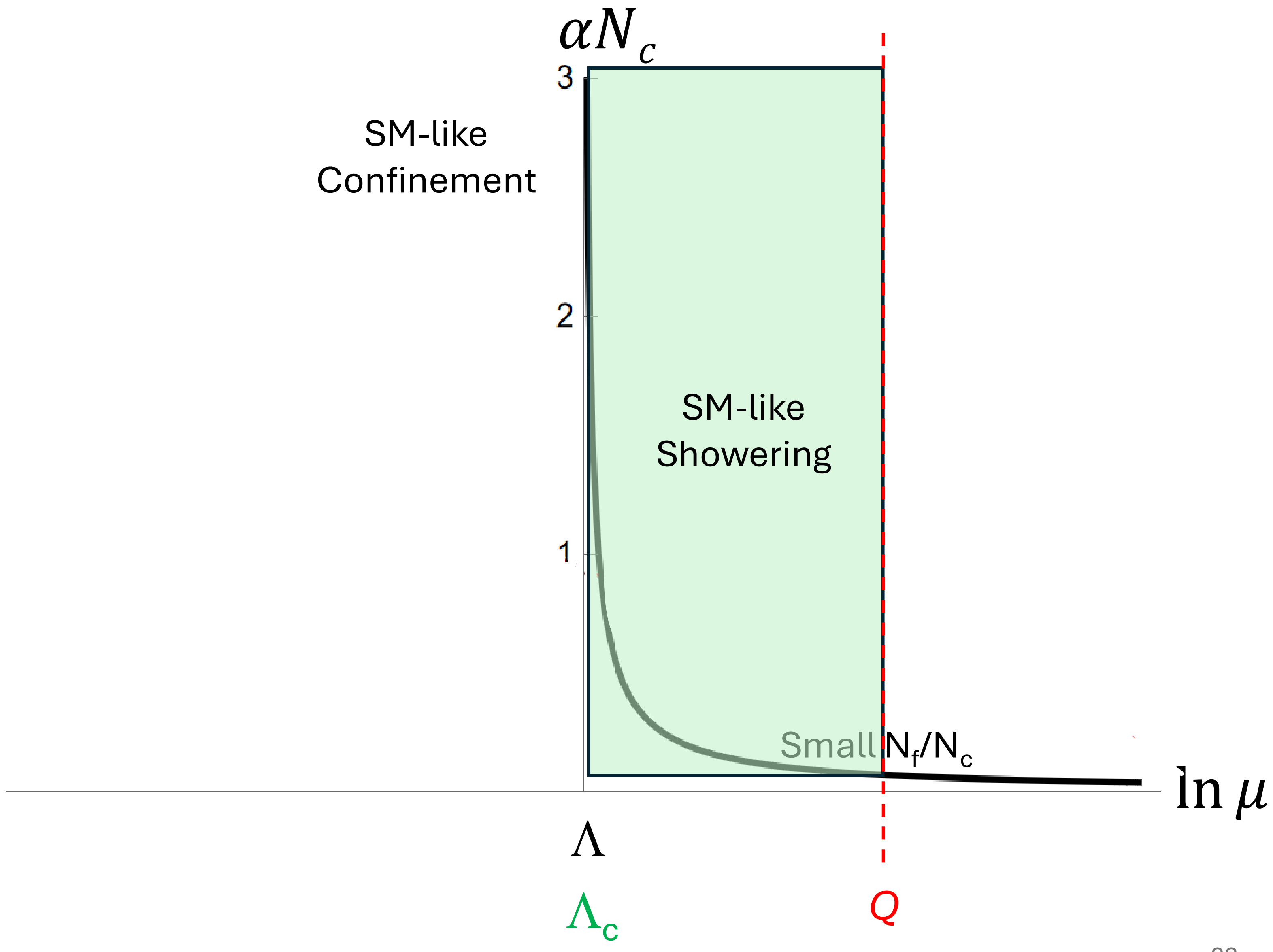

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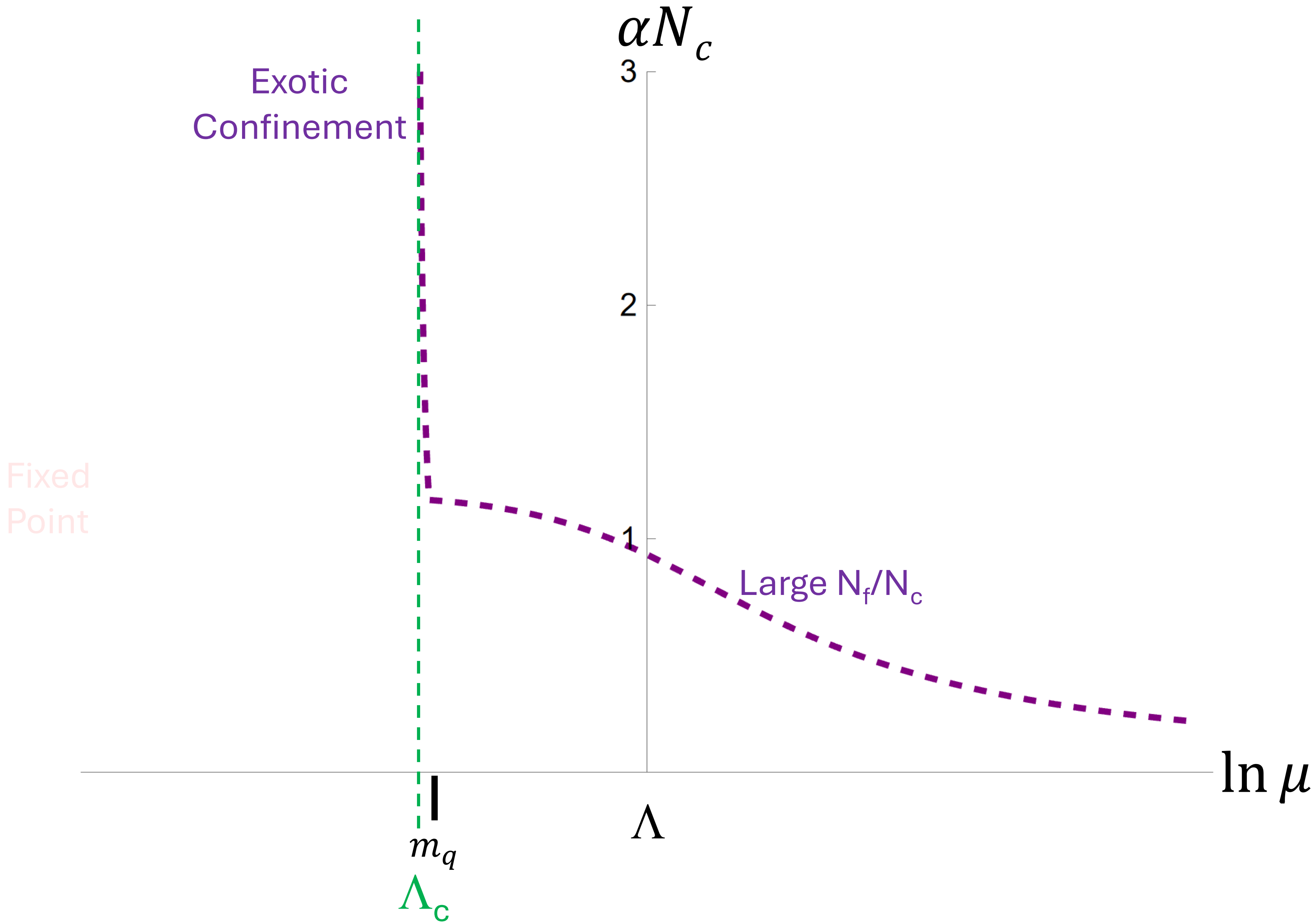

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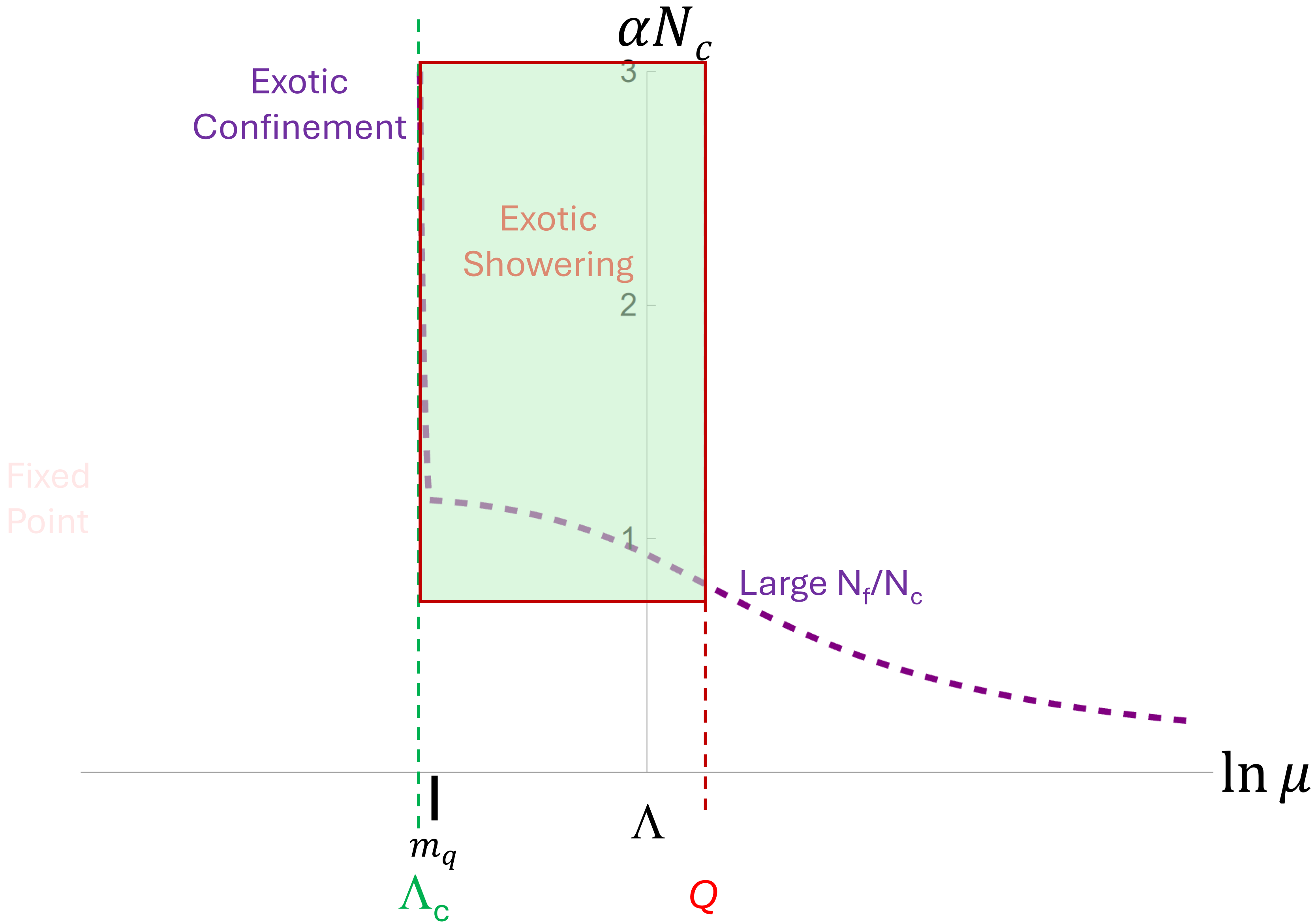

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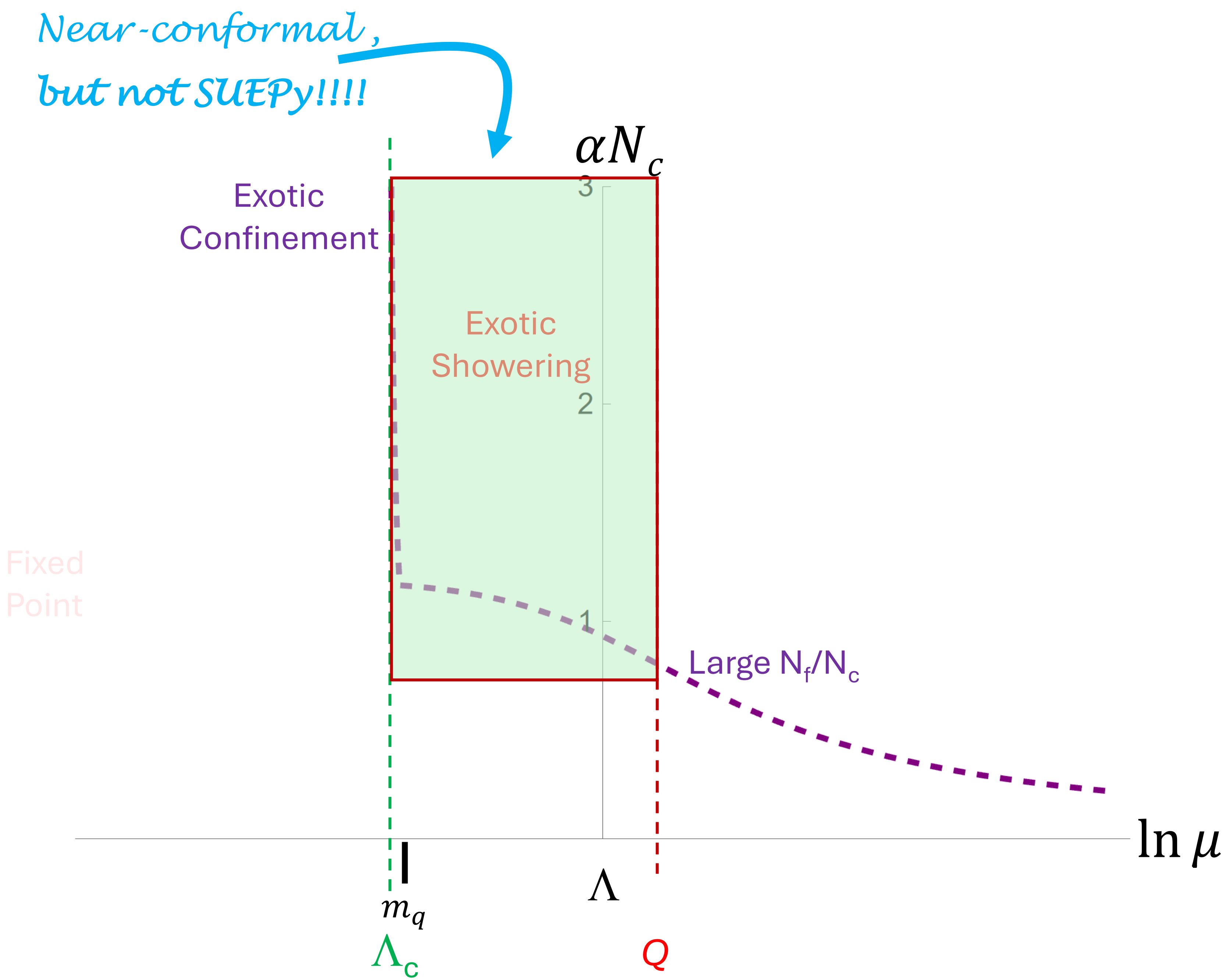

Near-conformal,
but not SUEPy!!!!
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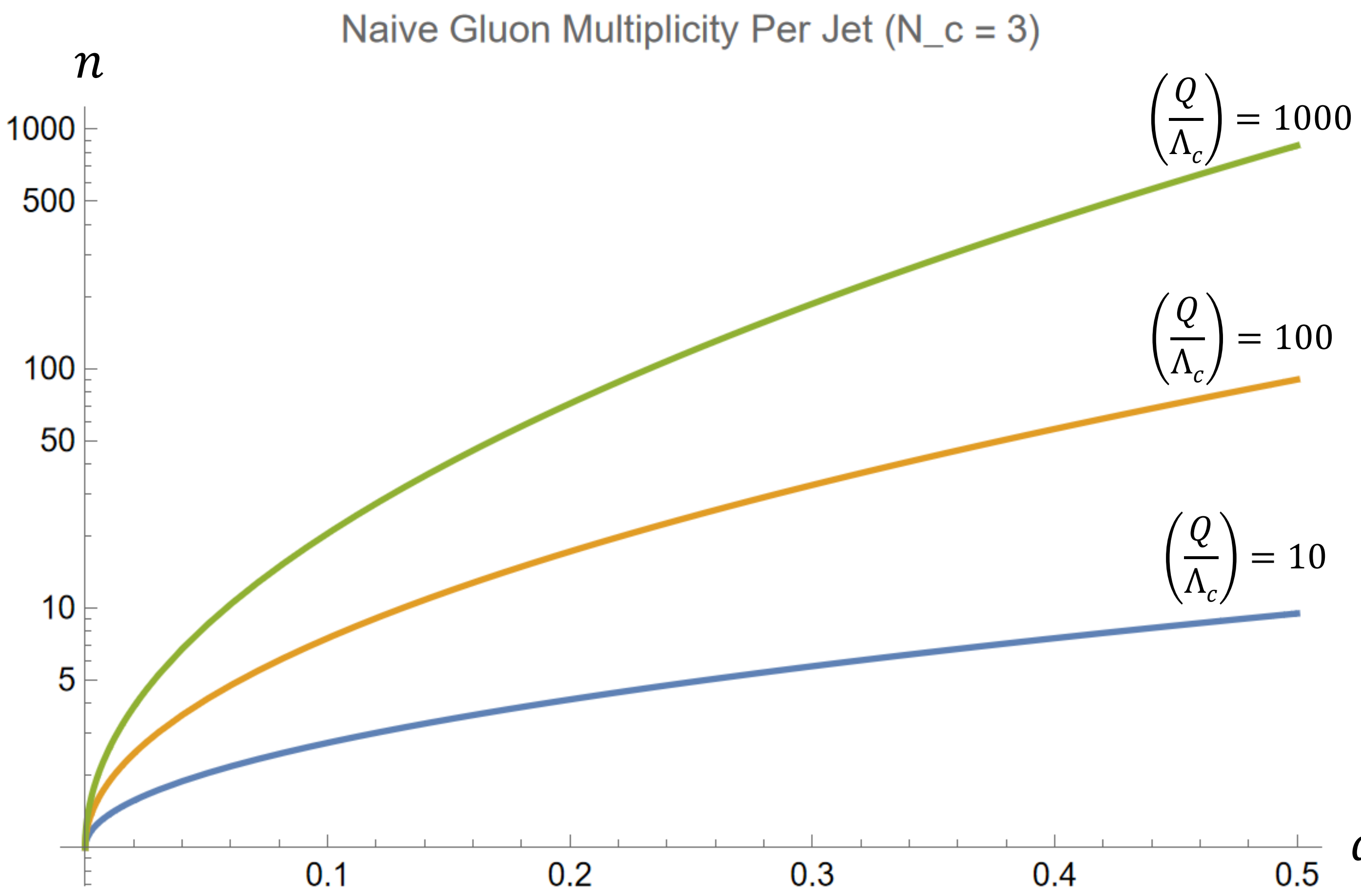
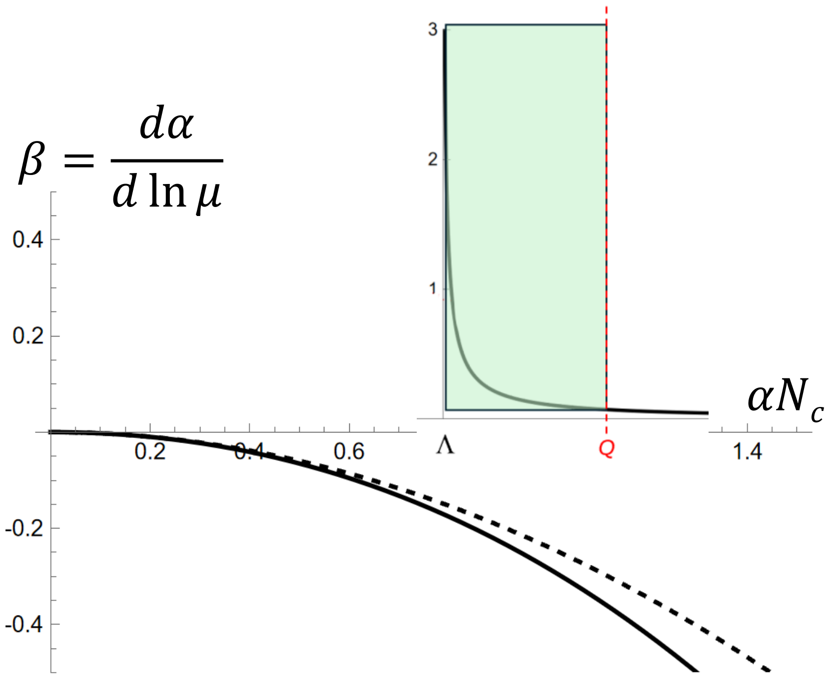
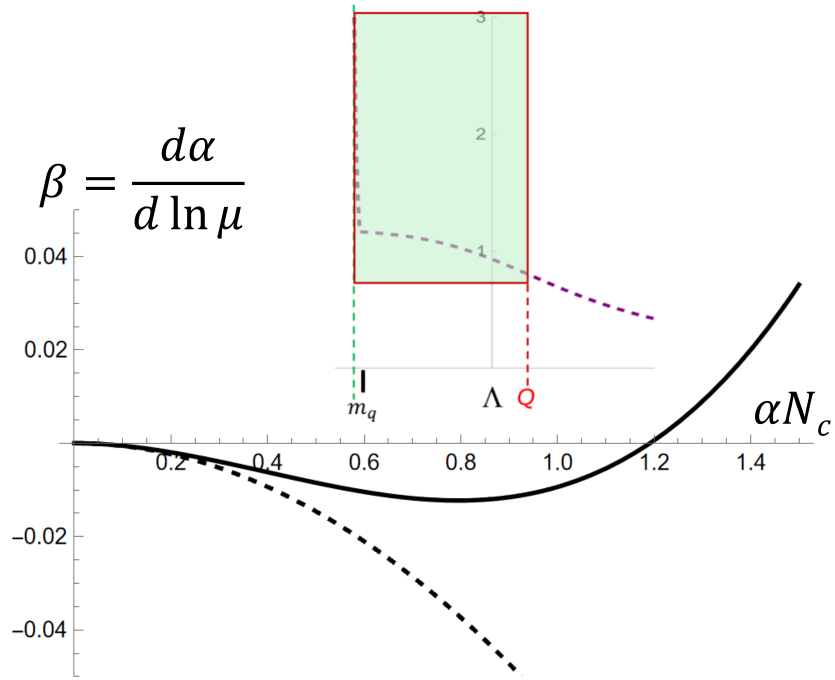
Multiplicity of Emitted Radiation in Jet

$n \sim (Q / \Lambda_c)^{\sqrt{\# \alpha N_c}}$ for constant α



Large N_f and Approx Fixed Points





Compared to QCD, the coupling runs slower, but is larger in the UV, so more radiation (at larger angles) happens in the UV

Might these unfamiliar dark jets escape from ATLAS/CMS search strategies that assume SM-QCD-like dark jets?

Technical Issues Blocking Conformal Window Simulation

Coupling: PYTHIA uses PDG approximation for 2-loop α

Parton Shower: requires Sudakov factor

Hadron Spectrum: Max N_f in PYTHIA HV is currently 8

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Parton Shower: requires Sudakov factor

Hadron Spectrum: Max N_f in PYTHIA HV is currently 8

Exact and Approximate 2-Loop Coupling

$$\beta_\alpha = -\alpha^2(\beta_0 + \beta_1 \alpha)$$

If $\beta_1 < 0 < \beta_2$, then 2-loop fixed points at $\alpha = \alpha_* = -\dfrac{\beta_0}{\beta_1}$

Exact

Gardi Karliner 1998

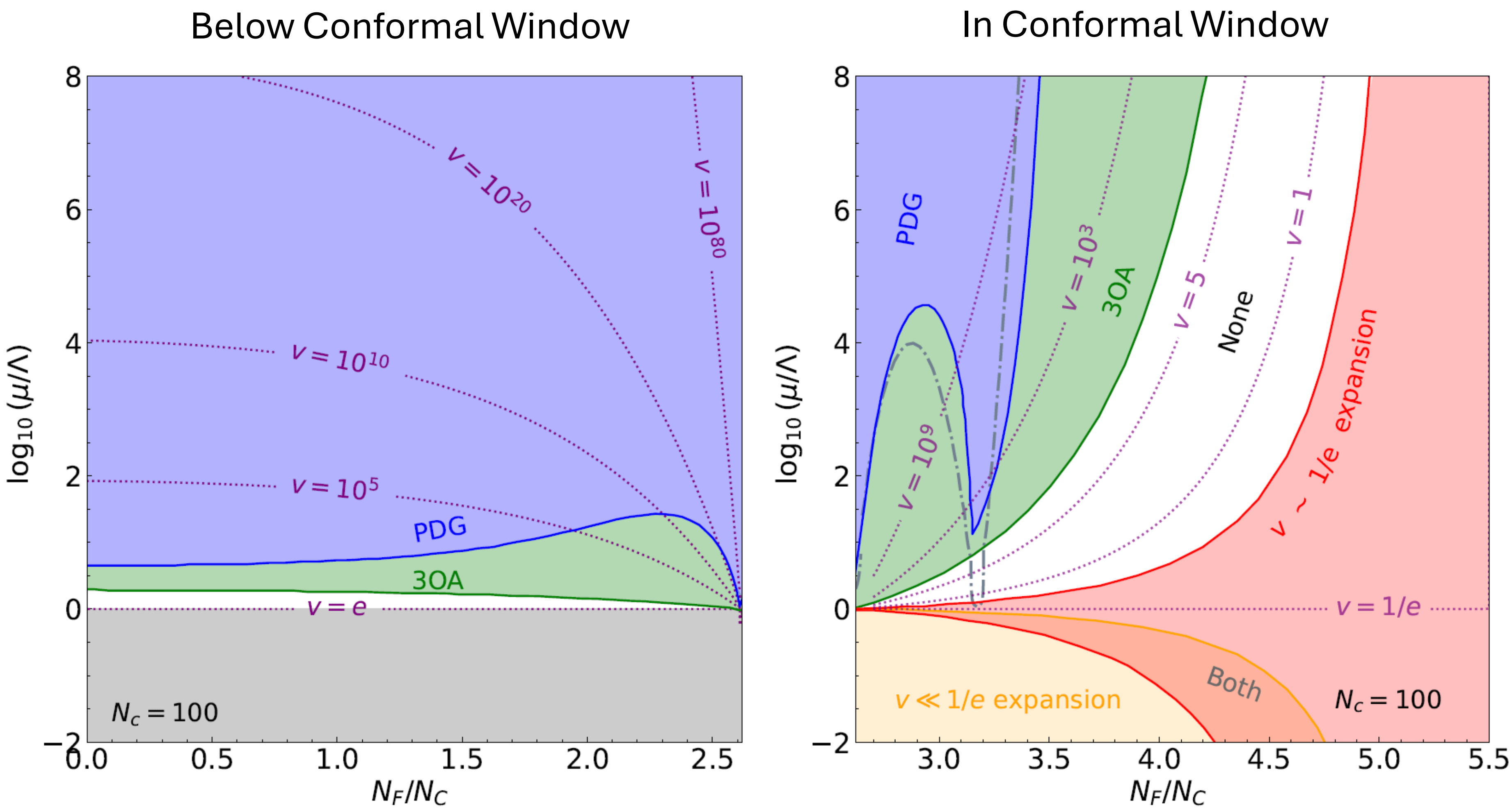
$$\frac{\alpha_*}{\alpha} = \begin{cases} 1 + W_{-1}(-z) & \text{SM QCD and similar} \\ 1 + W_0(z) & \text{Conformal Window} \end{cases}$$

$$z \equiv \frac{1}{e}\left(\frac{\mu}{\Lambda}\right)^{2\gamma} \qquad \gamma = \left.\frac{\partial \beta}{\partial \alpha}\right|_{\alpha=\alpha_*},$$

PDG

(Assumes $\ln|\gamma|$ small)

$$\alpha(\mu^2) = \frac{1}{\beta_0 \ln(\mu^2/\Lambda^2)}\left(1 - \frac{\beta_1}{\beta_0^2}\frac{\ln[\ln(\mu^2/\Lambda^2)]}{\ln(\mu^2/\Lambda^2)}\right)$$



Below Conformal Window
In Conformal Window
PDG
3OA
$v = 10^{20}$
$v = 10^{80}$
$v = 10^{10}$
$v = 10^{5}$
$v = e$
$N_c = 100$
$\log_{10}(\mu/\Lambda)$
N_F/N_C
$v = 10^{9}$
$v = 10^{3}$
$v = 5$
None
$v = 1$
$v \sim 1/e$ expansion
$v = 1/e$
Both
$v \ll 1/e$ expansion

Exact and Approximate 2-Loop Coupling

$$\beta_\alpha = -\alpha^2(\beta_0 + \beta_1\alpha)$$

If $\beta_1 < 0 < \beta_2$, then 2-loop fixed points at $\alpha = \alpha_* = -\dfrac{\beta_0}{\beta_1}$

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Do not approximate the 2-loop α; use its exact form

Parton Shower: requires Sudakov factor

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Probability not to radiate between Q_1 and Q_2

$$\Delta_a\left(Q_2^2, Q_1^2\right) = \exp\left(-\int_{Q_2^2}^{Q_1^2} \frac{dQ'^2}{Q'^2}\frac{\alpha(Q'^2)}{2\pi}\int_{\xi_{min}(Q'^2)}^{\xi_{max}(Q'^2)} \sum_{b,c} P_{a\to bc}(\xi')d\xi'\right) ,$$

Sudakov Factors and Veto Algorithms

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$$\sim \exp\left(- \int_{Q_2^2}^{Q_1^2} \frac{dQ'^2}{Q'^2} \frac{\alpha(Q'^2)}{2\pi} \right) \exp\left(\int_{\xi_{min}(Q_0{}^2)}^{\xi_{max}(Q_0{}^2)} \sum_{b,c} \tilde{P}_{a\to bc}(\xi') d\xi' \right)$$

2nd term: veto algorithm to obtain ξ_2

$$\left(\frac{W(z_2)}{W(z_1)} \right)^{1/\beta_0} \qquad \left[\text{where } z_i = \frac{1}{e} \left(\frac{Q_i^2}{\Lambda^2} \right)^{\gamma} \right]$$

With this result, $R = \Delta_a(Q_1, Q_2)$ **can** be solved for Q_2

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Use a simpler method based on the exact form of the 2-loop coupling

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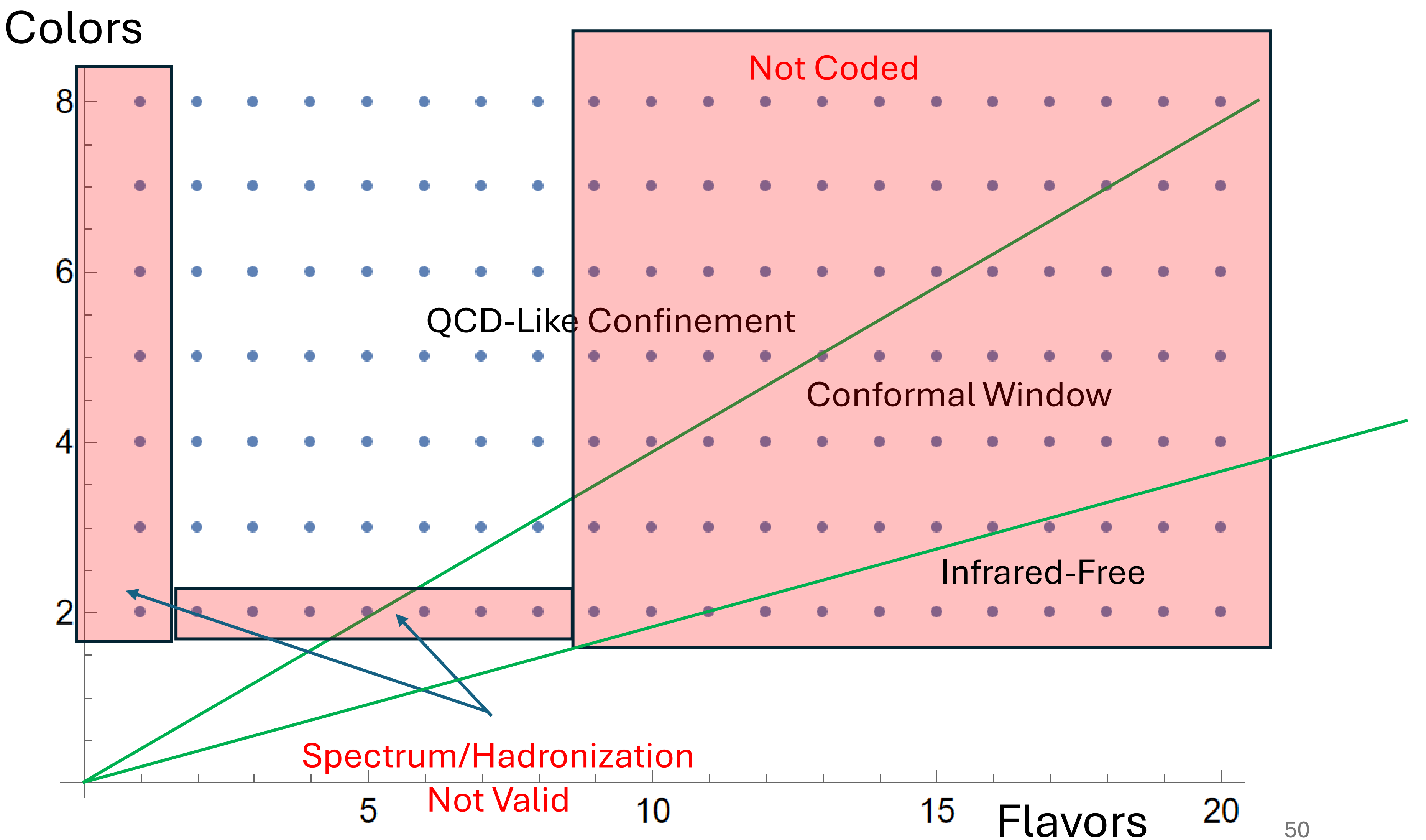
Hadron Spectrum: Max N_f in PYTHIA HV is currently 8

- For $N_c = 3$ conformal window $N_f \gtrsim 8 - 15$
- For $N_c > 3$, $N_f \gtrsim (2.6 - 5.5)N_c > 8$
- $N_c = 2$ PYTHIA not reliable (baryons = mesons)

PYTHIA capabilities: Do not use in red region



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Short-term workarounds?
Long-term solutions?

Summary

To advance our reach for HV/DS discovery requires diverse methods

Sure, let’s look for QCD-like jets – but nature may not provide them

Need to look more widely, yet not be dominated by theoretical uncertainties

Options discussed here:

- Don’t focus on the jets, just look for the leptons and photons
  - Discoveries are possible without assuming a model

- Focus on the jets, but improve theory/simulation
  - Need to search for & train on non-QCD-like jets (e.g. large N_f / N_c)
  - But can only do that with better theory/simulation
    - Understand spectrum, showering, hadronization more broadly

Backup Slides

What is a Hidden Valley?

MJS & Zurek 2006

A sector of SM-neutral particles which

1. can be produced in SM collisions with a reasonable rate
   (not gravitationally-coupled hidden sectors)
2. include states that can decay within 1 sec
   (not sectors with massless final states or coupled too weakly)
3. have self-interactions that complicate the dynamics
   (i.e. not sectors of single dark photon or single free fermion)

Often called "dark sectors" or "rich dark sectors" nowadays
(especially if sector contains dark matter)

The Territory of HV/DS

MJS & Zurek 2006

Why useful to give this giant class of theories a single name?

Qualitative Predictions (alone or in combination)

- Multiple neutral particles decaying to SM particles (and often MET)
- High-multiplicity production
- Unusual clustering
- Displaced vertices

"Dark Jets"

Back in 2006, all of these were off the radar

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"Semi-Visible Jets"

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"Emerging Jets"

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"SUEP"

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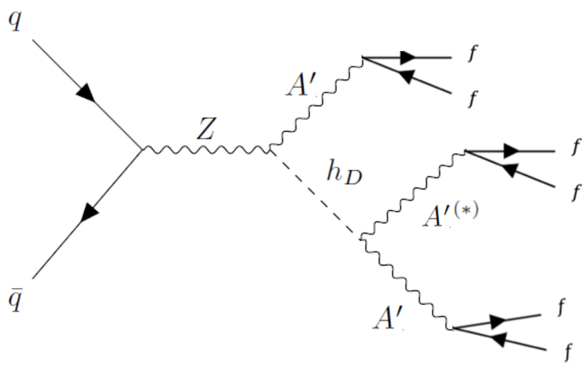
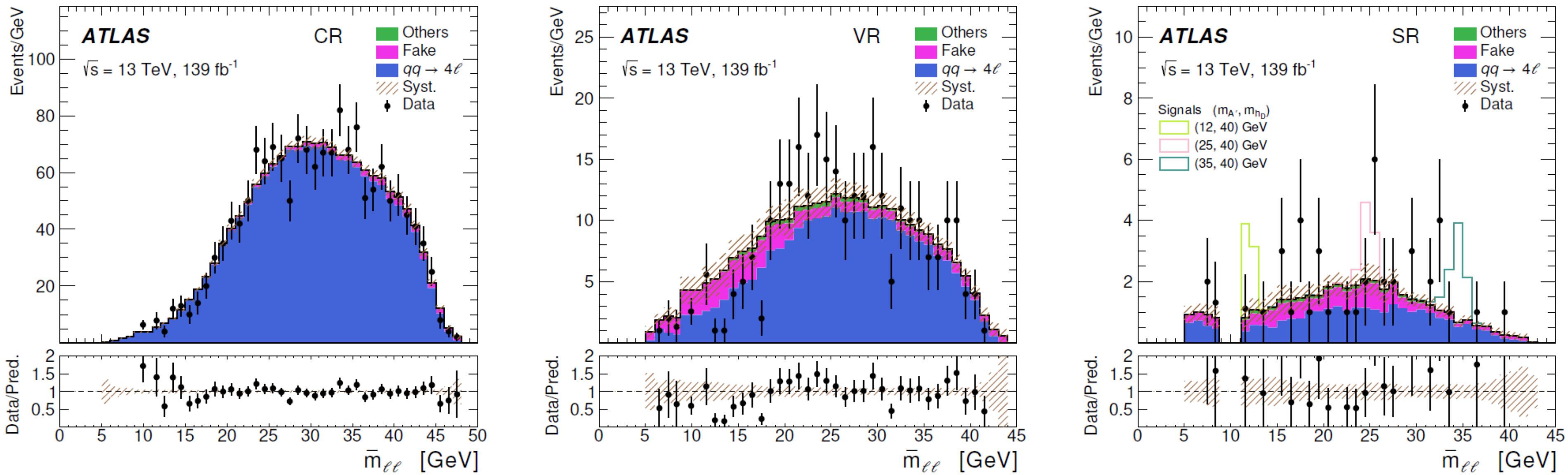
Reproduction of ATLAS Search

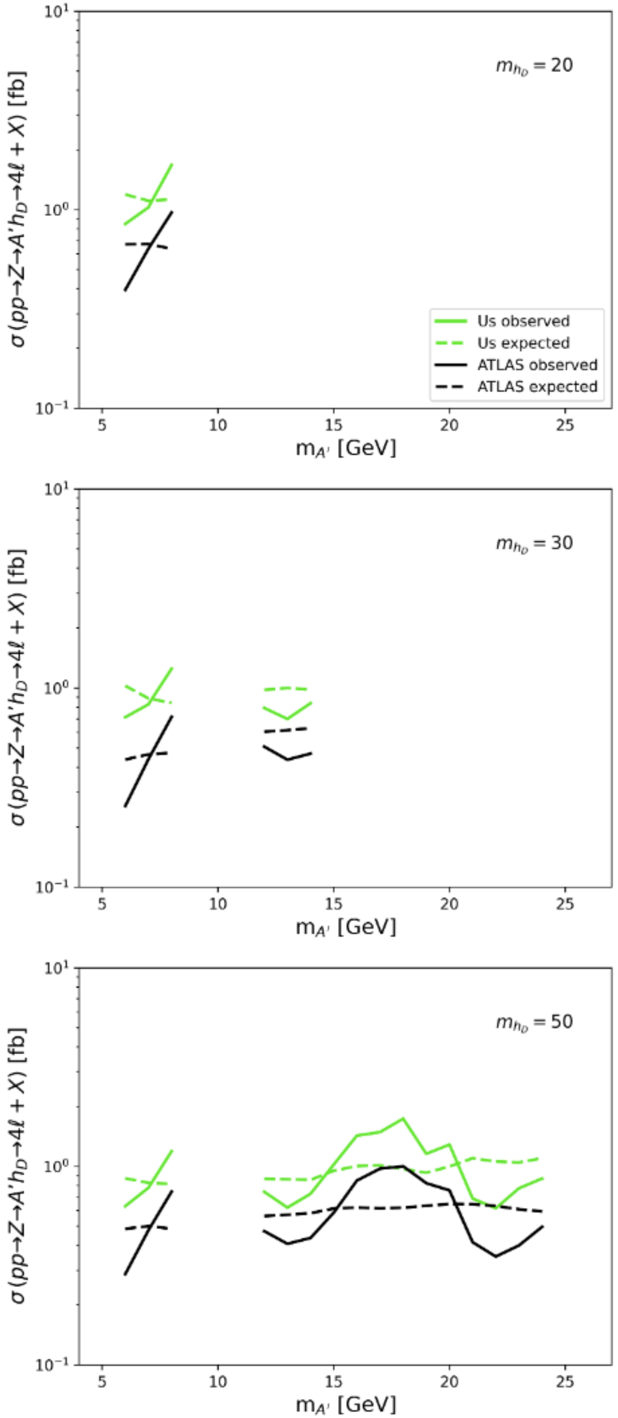




Reproduction of ATLAS Search

Our results are consistent with ATLAS, and consistently weaker by a bit less than a factor of 2.

This gives us confidence to recast the search.



Herwig++ Physics and Manual

M. Bähr[1], S. Gieseke[1], M.A. Gigg[2], D. Grellscheid[2], K. Hamilton[3], O. Latunde-Dada[4], S. Plätzer[1], P. Richardson[2], M.H. Seymour[5,6], A. Sherstnev[4], J. Tully[2], B.R. Webber[4]

7 Hadronization

After the parton shower, the quarks and gluons must be formed into the observed hadrons. The colour preconfinement property [74] of the angular-ordered parton shower is used as the basis of the cluster model [2], which is used in Herwig++ to model the hadronization. This model has the properties that it is local in the colour of the partons and independent of both the hard process and centre-of-mass energy of the collision [2, 3].

PRECONFINEMENT AS A PROPERTY OF PERTURBATIVE QCD

D. Amati and G. Veneziano

CERN -- Geneva

PRECONFINEMENT AS A PROPERTY OF PERTURBATIVE QCD 1979

D. Amati and G. Veneziano

CERN -- Geneva

The first important point to realize is that, in the axial gauge and at the leading log level we are working in, all relevant graphs are planar[2]. It follows that the final quanta can be *ordered*, as shown in Fig. 1. Furthermore, there is a natural way to group them (Fig. 1) into sets C_i of adjacent partons each consisting of a quark, an antiquark and a number of gluons. These systems contain a dominant singlet component and, indeed, are pure colour singlets*) in the $N \to \infty$ limit**), which incidentally, does also select planar diagrams.

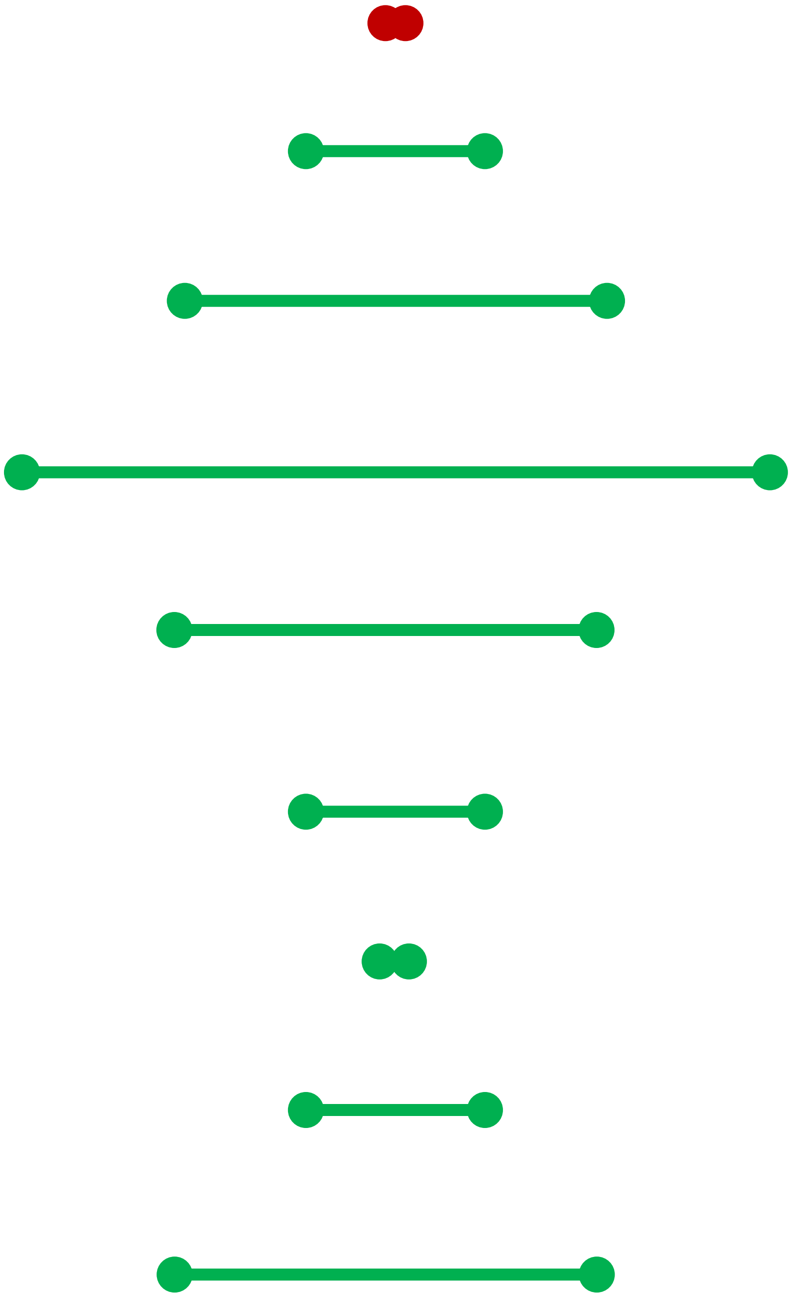
It will be the mass of these colourless systems (e.g. of C_1) that we shall find to be cut off by a power law of the form $(M_{C_1}/Q_0)^{-\lambda}$. Moreover, this result will make use of all the basic properties of QCD, i.e. its non-Abelian character,

*) Another amusing consequence of this planarity is that neither OZI-violating processes, nor glueball formation is allowed in the leading log approximation.

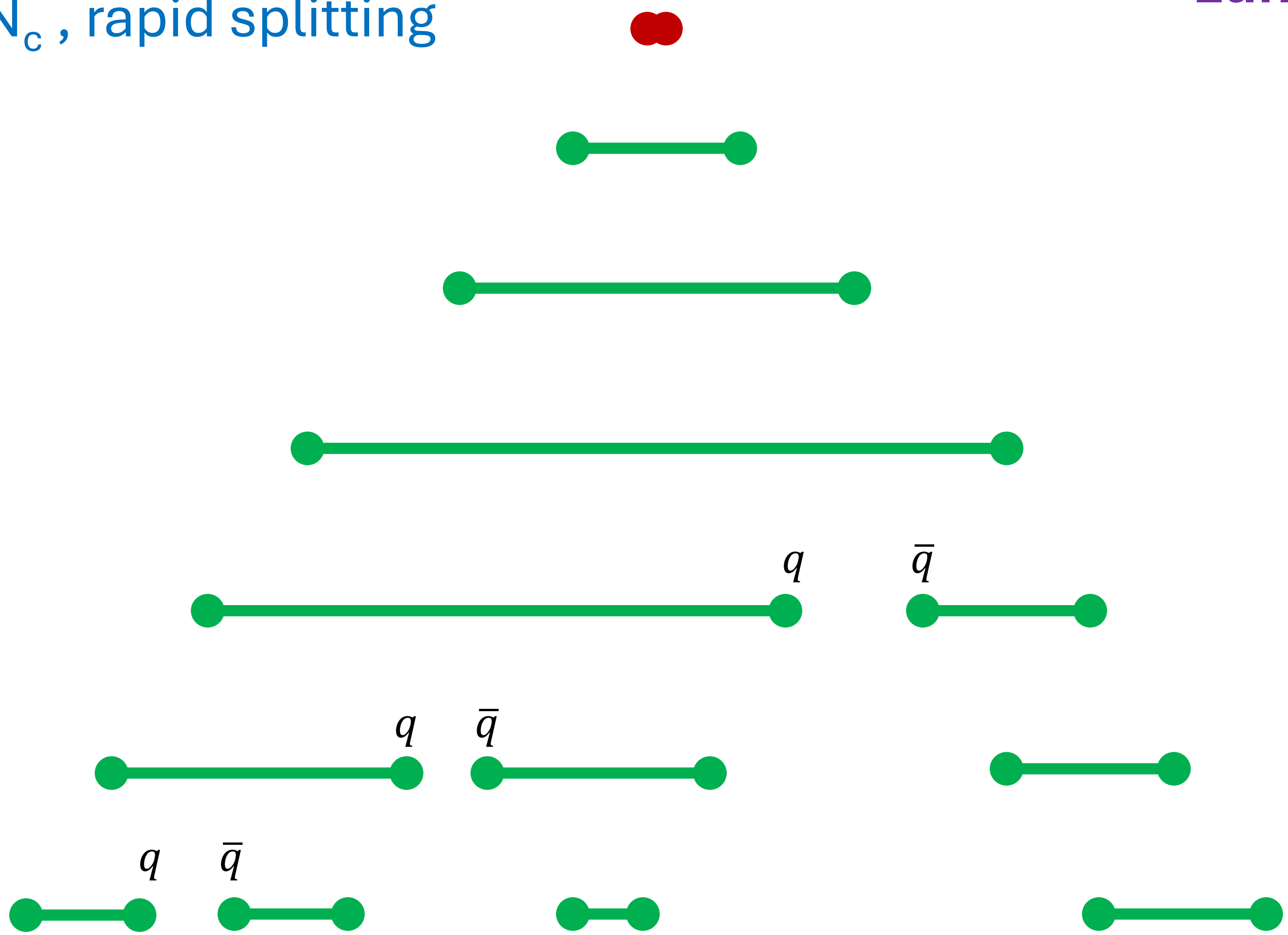
**) The appropriate limit here is the one[3] in which N_c (number of colours) goes to infinity with $\alpha_s N_c$ fixed and N_f/N_c fixed (N_f is the number of quark flavours).

None of this is true for hadronization into glueballs

No splitting



$N_f \sim N_c$, rapid splitting



Splitting completes before oscillation;

Splittings are space-like separated!

Create $q\bar{q}$ pairs **from one end of string**

- Pick next $q_i\bar{q}_i$ flavor with some m_q-dependent probability
- Pick next hadron: spin-1 with prob. `probVec`, otherwise spin-0
- Pick q_i transverse momentum to the string

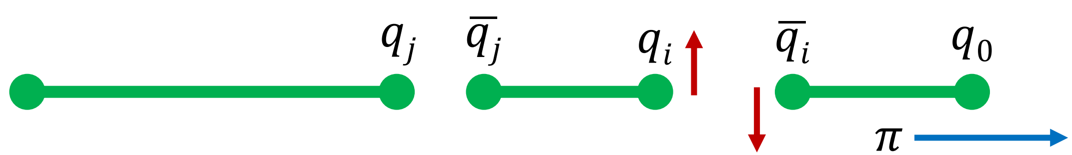
$$P(p_\perp) = e^{-p_\perp^2/\sigma^2}$$

- Give hadron $p_+ = z_i P_+$ (remaining long. momentum) according to

$$P(z) = \mathcal{N}\frac{(1-z)^a}{z}e^{-bm_\perp^2/z} \quad \text{(from symmetry)}$$

where $m_\perp^2 = m_{hadron}^2 + p_\perp^2$

- Repeat



Create $q\bar{q}$ pairs **from one end of string**

- Pick next $q_i\bar{q}_i$ flavor with some m_q-dependent probability
- Pick next hadron: spin-1 with prob. `probVec`, otherwise spin-0
- Pick q_i transverse momentum to the string

$$P(p_\perp) = e^{-p_\perp^2/\sigma^2}$$

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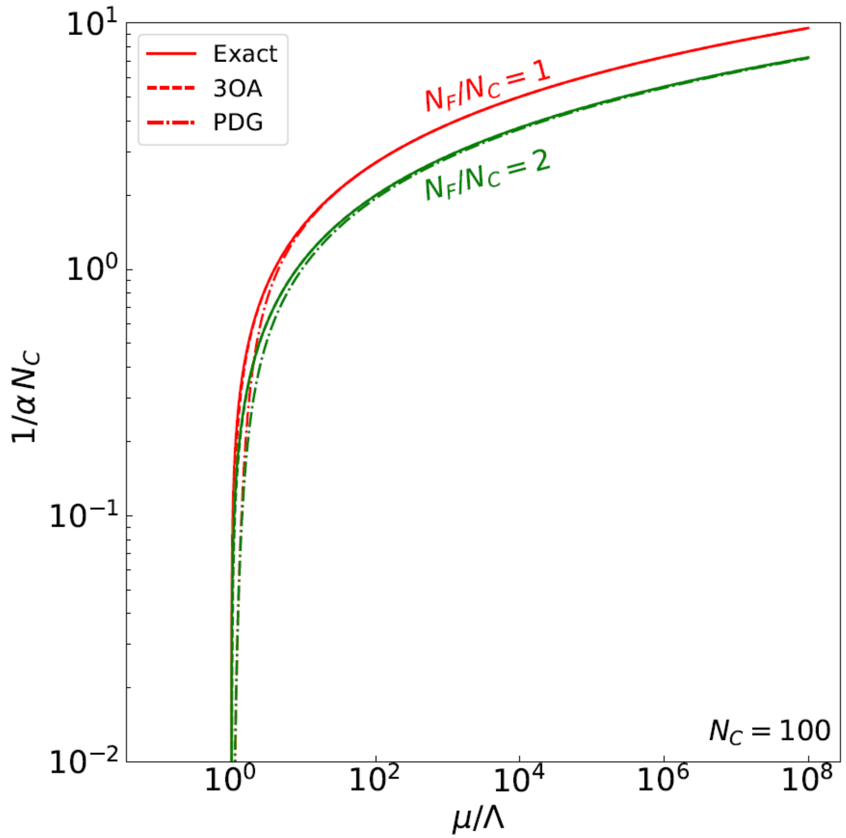
  where $m_\perp^2 = m_{hadron}^2 + p_\perp^2$
- Repeat

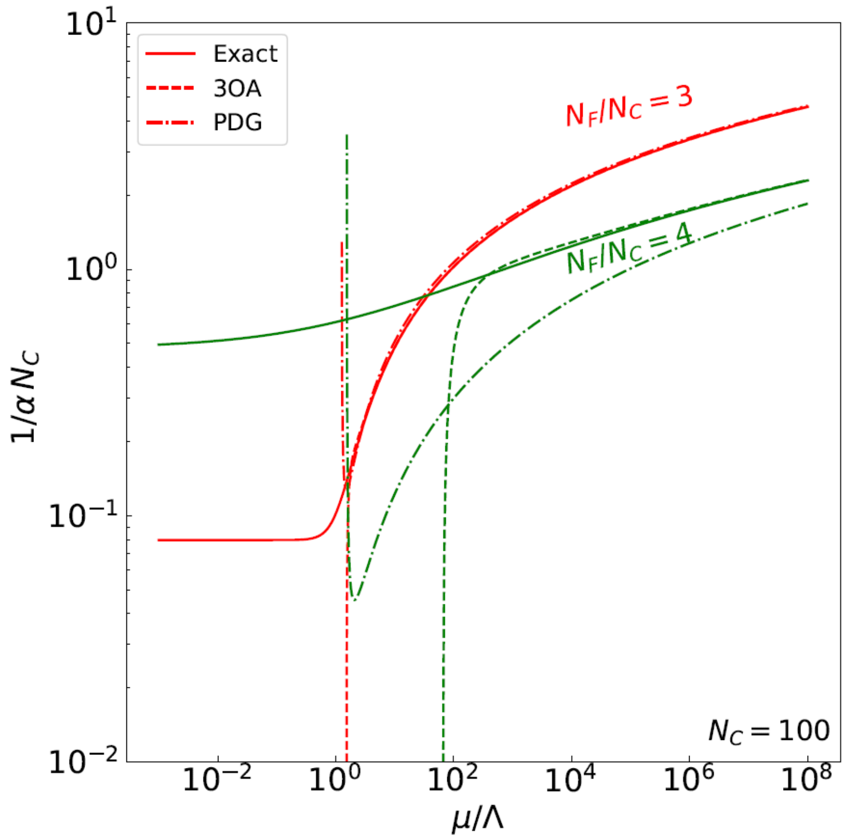
For $m_{q_i} \ll \Lambda$, only parameters are $\texttt{probVec}, \sigma, a, b$

- Last three have to do with string breaking: depend mainly on Λ, not m_q

Below Conformal Window



In Conformal Window



Sudakov Factors and Veto Algorithms

Probability not to radiate between Q_1 and Q_2

$$\Delta_a\left(Q_2^2, Q_1^2\right) = \exp\left(-\int_{Q_2^2}^{Q_1^2} \frac{dQ'^2}{Q'^2}\frac{\alpha(Q'^2)}{2\pi}\int_{\xi_{min}(Q'^2)}^{\xi_{max}(Q'^2)}\sum_{b,c} P_{a\to bc}(\xi')d\xi'\right) ,$$

Given Q_1, need to find (lower) Q_2 where next parton is radiated:

Trick: choose random number R, solve $R = \Delta_a(Q_1, Q_2)$ for Q_2.

Problem: can't solve it analytically

Trick: find overestimate for integrand of Δ_a such that ↗ can be solved analytically, then correct for the overestimate ("veto algorithm")

Problem: good at 1-loop, but at 2-loop, using PDG formula, can't solve analytically

Trick: overestimate includes replacing 2-loop by 1-loop formula and veto algorithm

Problem: not an overestimate in conformal window, and PDG formula diverges in IR

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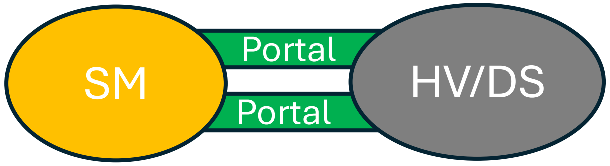
$$\sim \exp\left(-\int_{Q_2^2}^{Q_1^2} \frac{dQ'^2}{Q'^2}\frac{\alpha(Q'^2)}{2\pi}\right)\exp\left(\int_{\xi_{min}({Q_0}^2)}^{\xi_{max}({Q_0}^2)}\sum_{b,c}\tilde{P}_{a\to bc}(\xi')d\xi'\right)$$

2nd term: veto algorithm to obtain ξ_2

HV/DS Signatures

MJS & Zurek '06, MJS '06, '08

Hidden Valley / Dark Sector Scenario:



- Wide variety of unusual signatures can result
  - New neutral particles, possibly low mass
  - Some invisible and/or some visible, some resonances, some LLPs
  - Odd clustering ➔ weird jets, weird events
  - Large fluctuations event-to-event
  - Exotic H/Z/W/t decays

- Among models, most common signals from new objects:
  - New vectors V ➔ dileptons – easy
  - New scalars S ➔
    - Di-heavy (bb, cc, $\tau\tau$) – good target for searches, but almost ignored!
    - Di-gluon, with rare diphoton – challenging unless $\gamma\gamma$ somewhat common
  - New fermions F ➔ $S^{(*)}$ + MET or $V^{(*)}$ + MET – a little harder, not so different

HV/DS Signatures

MJS & Zurek ’06, MJS ‘06, ‘08

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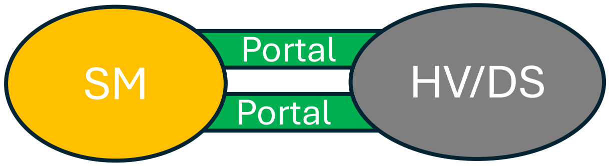
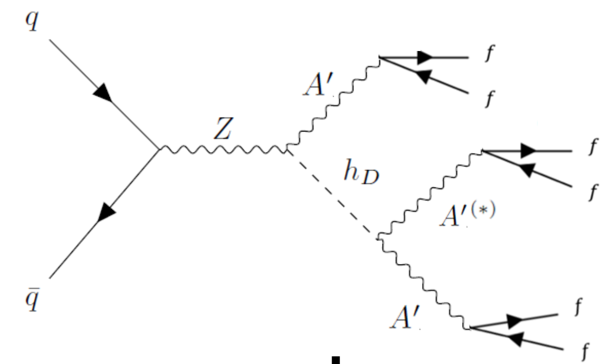


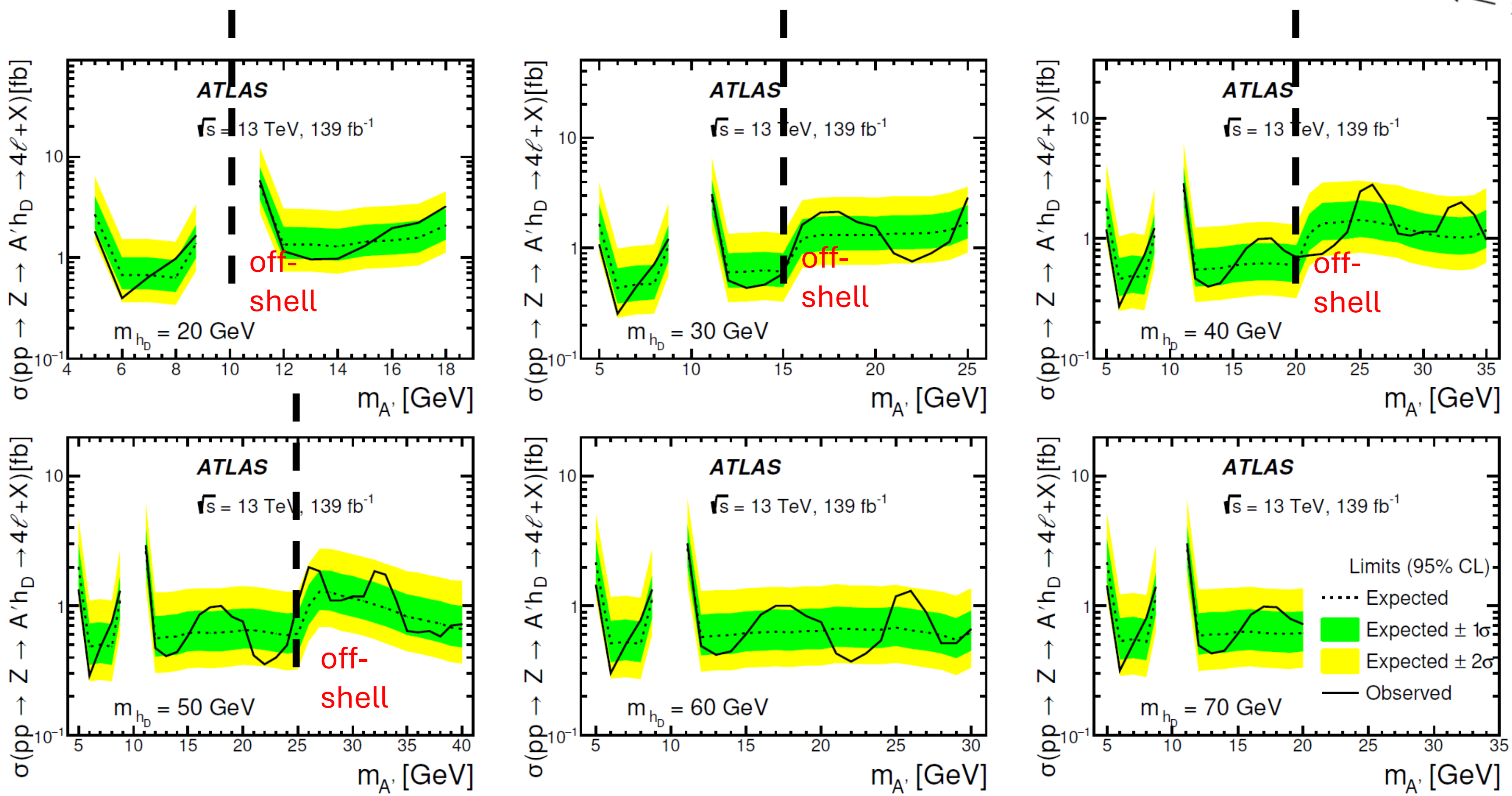
- Motivations vary
  - Naturalness: e.g. variations on Twin Higgs Chako, Goh, Harnik ’05 ; Craig et al. ‘14
  - Dark Matter: many models now , e.g. Kribs et al. ‘09, Hochberg et al. ’15 (SIMPs), …

- In recent years, some signatures have been given memorable names
  - “Emerging Jets”: clustered LLPs with few/no prompt tracks Schwaller, Stolarski & Weiler ‘15
  - “Semi-Visible Jets”: w/ both invisible and visibly-decaying objects Cohen, Lisanti & Lou ‘15
  - “Soft Unclustered Energy Pattern” (SUEP): spherical blob of soft-ish particles

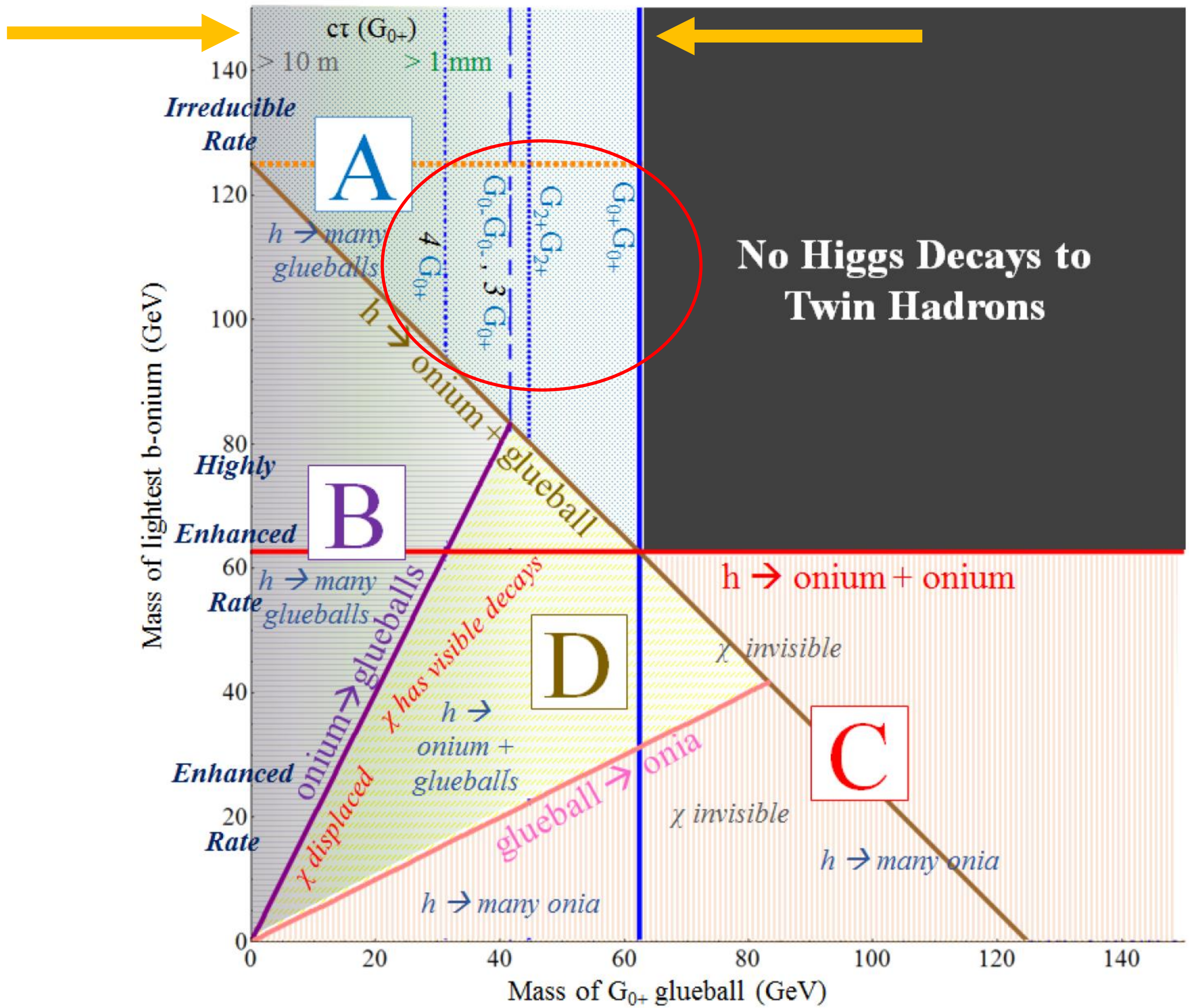
replaces “soft bomb”, Knapen et al. ‘16

Reproduction of ATLAS Search





Dark Hadron Production in Fraternal Twin Higgs Model



Misconceptions About SUEP

From String Theory
MJS 08
Alday & Maldacena 08
Also Hatta, Iancu & Mueller 08

1. "SUEP is due to conformally invariant physics (CFT)" (i.e. scale-invariant)

   Simply wrong. *Physics depends on the CFT's coupling constant* α_*

   - CFT can give QCD-like jets, fatter jets, many soft jets, or SUEP

   $\alpha_* N_c << 1$ ⟶ $\alpha_* N_c >> 1$

2. "SUEP is spherical, smooth distribution"

   Not necessarily. Only if: $\alpha_* N_c >> 1$, $M_{UV} >> \Lambda_{IR}$ *not far above* Λ_{QCD}

   - If dark hadrons heavy enough ($\Lambda_{IR} >> 1$ GeV), many soft jets ➔ spiky
   - If $M_{UV} >> \Lambda_{IR}$ not large or $\alpha_* N_c$ not so large, few dark hadrons ➔ spiky + soft
   - If some dark hadrons stable i.e. invisible, then gaps ➔ spotted
   - If unfamiliar confinement (e.g. only gluons) ➔ far from spherical

The First SUEP Simulation *(with many soft b's)*

MJS '08

QCD-like

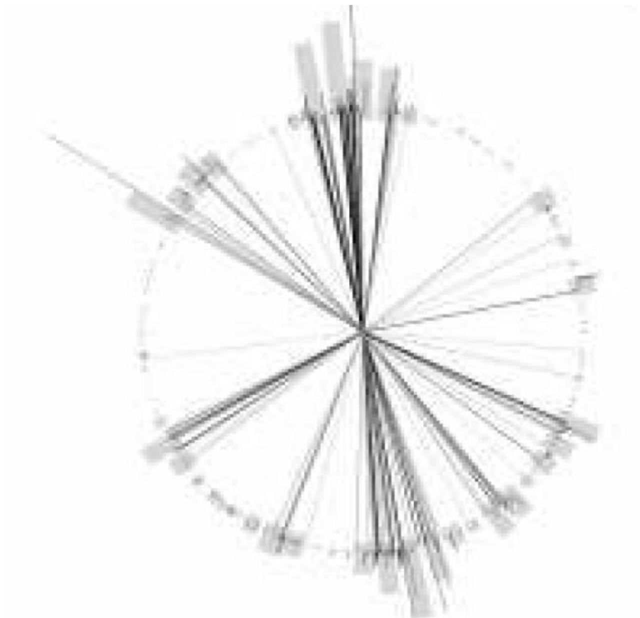


FIG. 25: An event (generated with HVMC 0.5) in which a 3.2 TeV Z' decays to 30 GeV v-pions (see [1] for definitions) in a hidden sector which has a weak coupling above $\sim$ 100 GeV. Notice the thrust axis is roughly vertical, though the events are by no means not pencil-like. The event shown contains roughly twenty bottom quarks and tau leptons.

SUEP-y

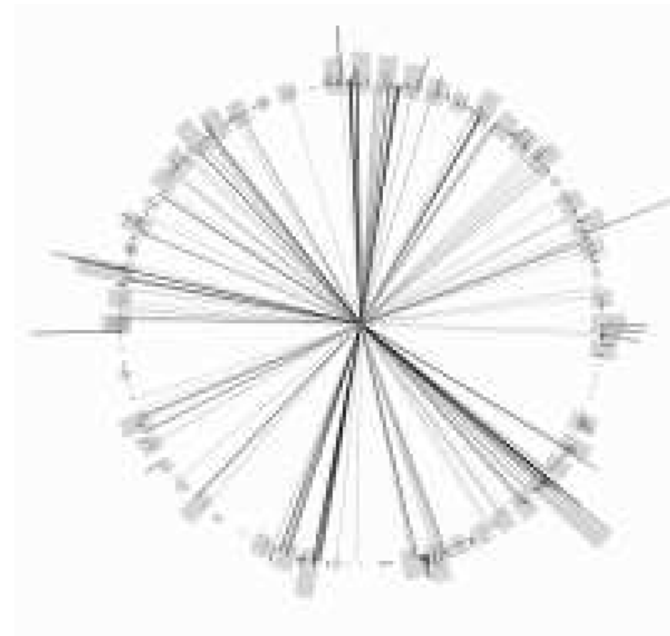


FIG. 26: An event (generated with HVMC 0.5) in which a 3.2 TeV Z' decays to 30 GeV v-pions (see [1] for definitions) in a hidden sector which has a strong coupling at all energies. Notice the event is now spherical. The event shown contains roughly fifty bottom quarks and tau leptons.

For related study, see also Cesarotti, Reece & MJS '20

Long-Lived Particles: Subtleties

- Process with many b's or many short-lived LLPs
  - Many displaced tracks
  - High multiplicity of low-track-multiplicity vertices

  Can these be found with only L1 tracks from the outer tracker?

- Clustered Long-Lived Particles
      - E.g. HV/DS "emerging jets"
  - Prompt tracks and decays in outer tracker/HCAL/muon system
    - Will these interfere with one another?