Hidden Valley/Dark Sector Theory Landscape

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Purpose: Set Context and Provide Motivation

- The Hidden Valley/Dark Sector (HV/DS) context
  - Why are we holding this focused workshop?
  - What topics lie just outside our focus?

- How can we explore HV/DS most effectively?
  - We will discuss certain methods in this workshop
  - But should keep in mind they are not the only methods
  - How to improve our methods?

What is a Hidden Valley?

MJS & Zurek 2006

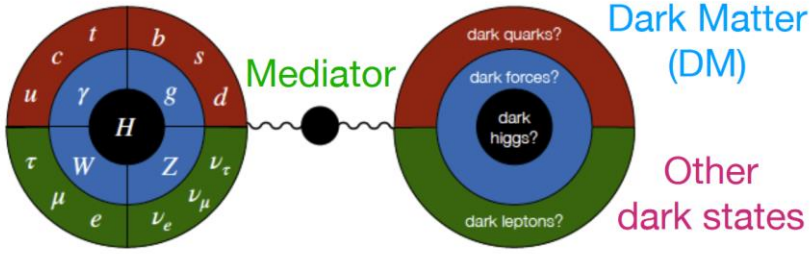
A sector of SM-neutral particles which

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)


SM
Mediator
HV

What's a dark sector?



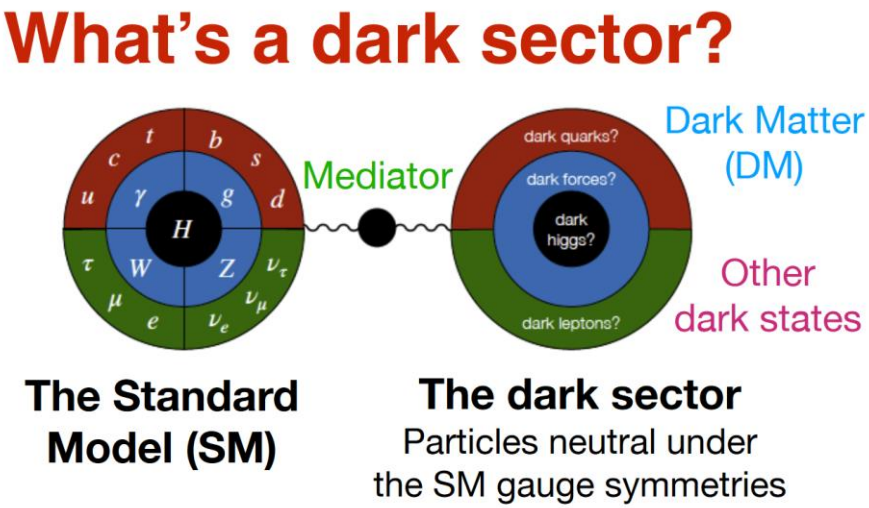
The Standard Model (SM)

The dark sector
Particles neutral under the SM gauge symmetries

S. Gori

WHY HV/DS?

- Bottom-Up: dark matter
- Top-Down: string theory, ~~SUSY~~



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SM — *Mediator* — HV

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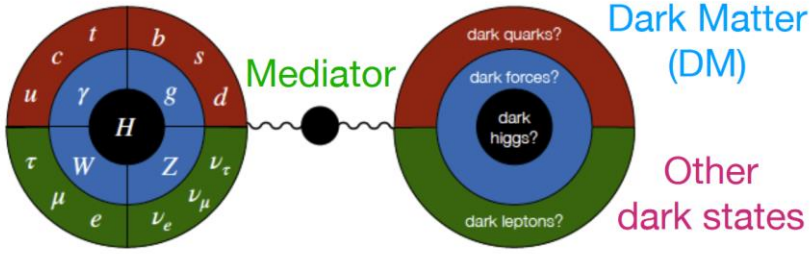

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The Territory of HV/DS

MJS & Zurek 2006

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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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"Dark Jets"

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"Semi-Visible Jets"

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"Emerging Jets"

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"SUEP"

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Potential Dramatic Impact:

- When added to existing theory (e.g. Higgs, SUSY, Little Higgs) can completely change its pheno signatures
  - *classic example: SM + HV = exotic Higgs decays, Z decays*

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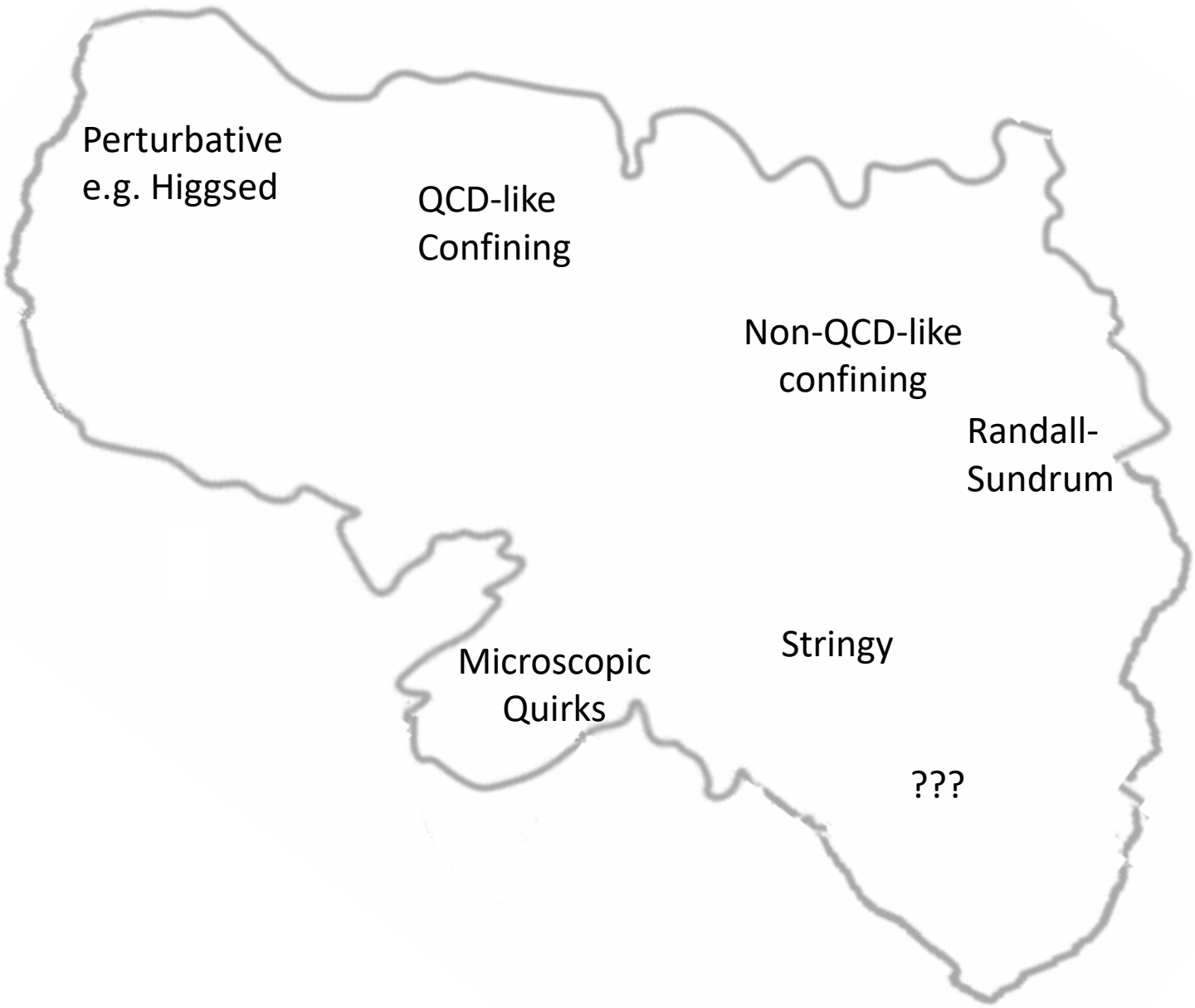
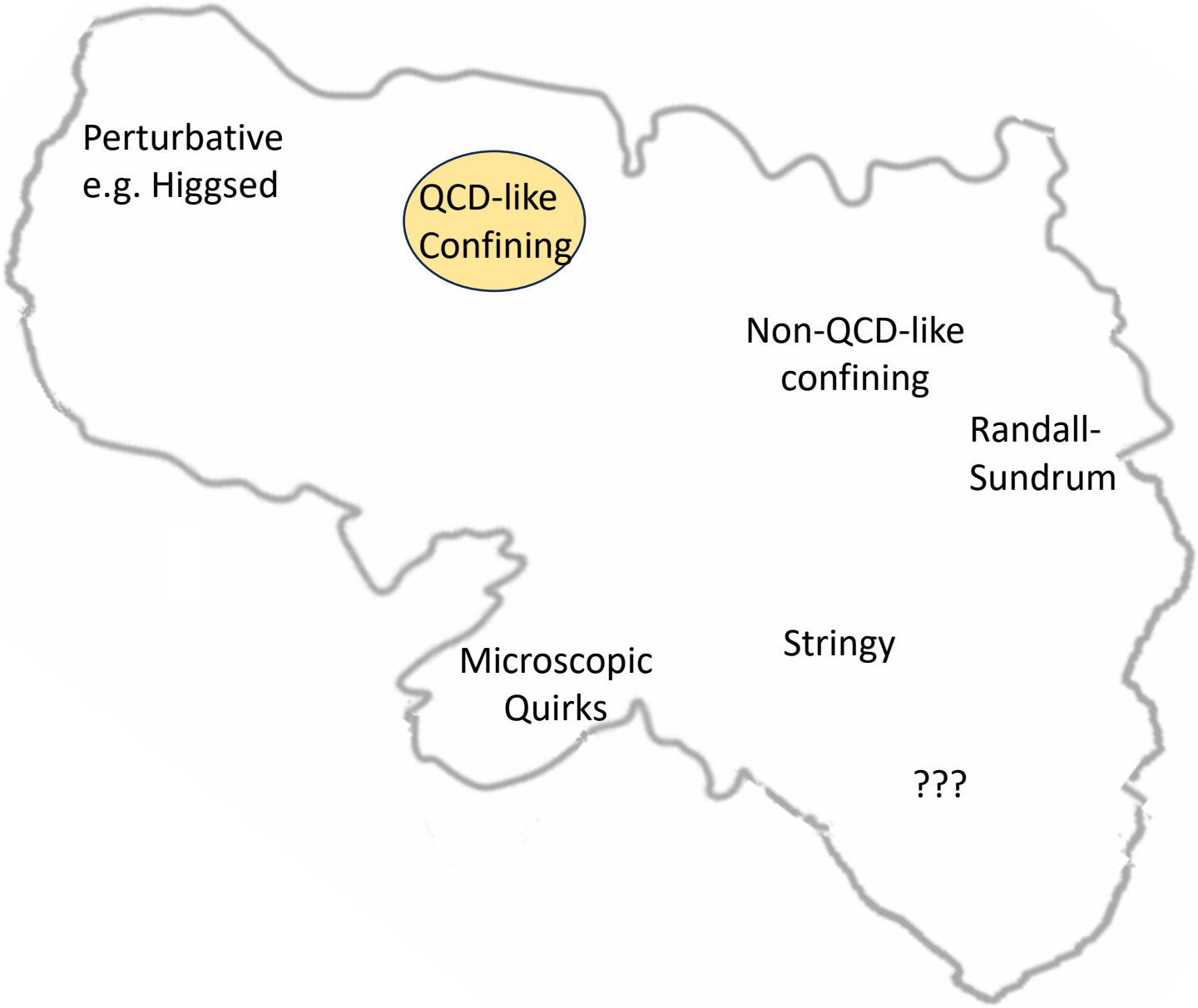

Perturbative
e.g. Higgsed
QCD-like
Confining
Non-QCD-like
confining
Randall-
Sundrum
Stringy
Microscopic
Quirks
???

Why Are We Studying QCD-Like HV/DS?



Why Are We Studying QCD-Like HV/DS? *LAMP POST!*

we need quantitative predictions for LHC searches

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How to Search a Huge Territory

Potential discovery more important than placing limits!

- Best not to optimize for a particular model
- Use general approach when possible
- Hope that the techniques are effective in the Guesswork region

1. Use Easy models to make studies, limit-setting, recasting easier
2. Use QCD knowledge to explore Feasible region in detail

Meanwhile, theorists will hopefully make progress in the Guesswork region so that predictions can someday be made

1. Searching the Territory from the Easy Region

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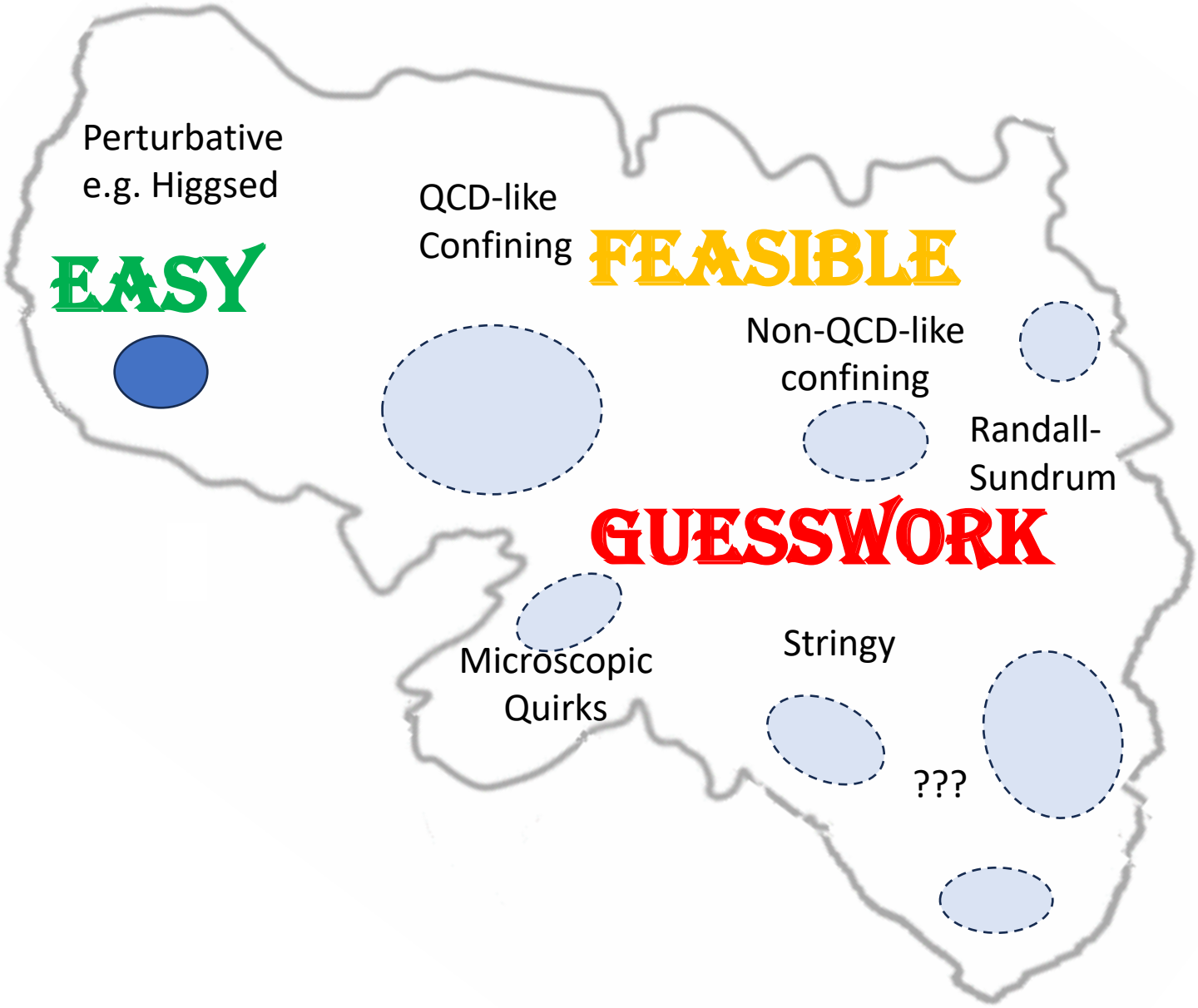


1. Searching the Territory from the Easy Region

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

$$Z \to A_D h_D \to A_D A_D A_D$$

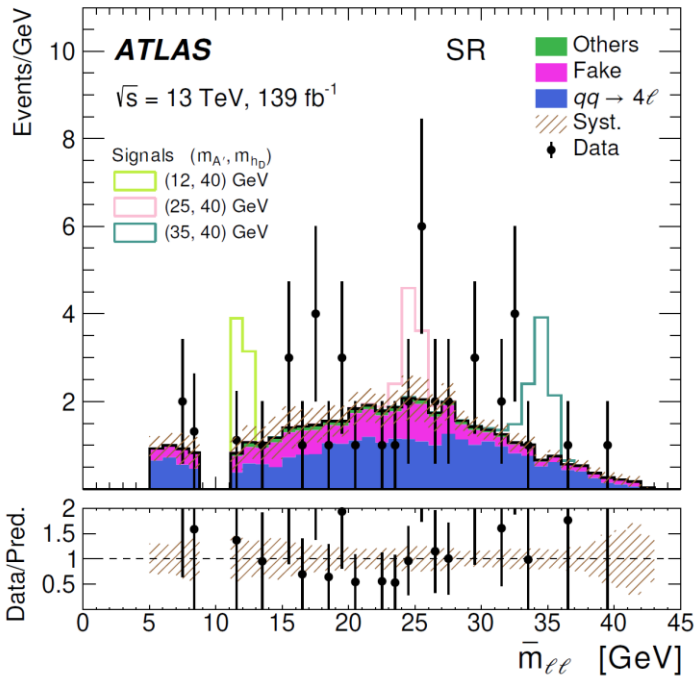
Simple, general search strategy

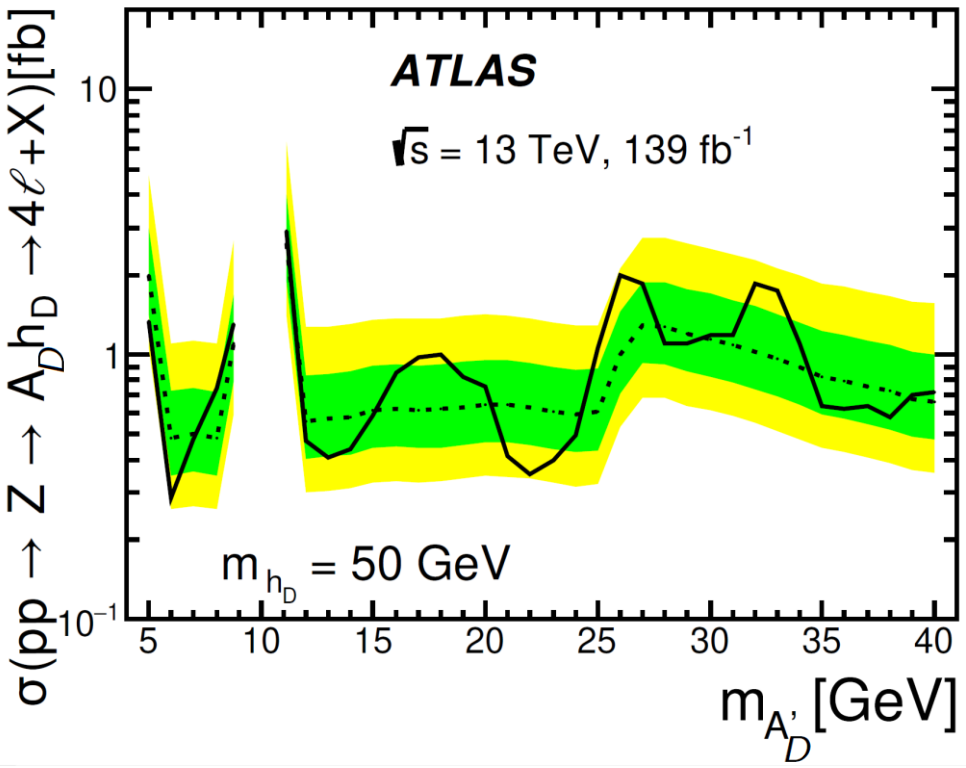
- require 2 SFOC pairs of isolated, loose leptons, $m_{4\ell} < M_Z$
- require two $A_D \to \ell^+\ell^-$ candidates of equal mass
- Avoid $m_{\ell\ell} < 5$ GeV and $m_{\ell\ell}$ near Upsilon

Constrains dark jets containing dark hadron/photon $X \to \ell^+\ell^-$

arXiv:2306.07413

$$Z \to A_D h_D \to A_D A_D A_D$$





Limits can be recast for models with HV/DS jets Chen, Hussain, Li & MJS 24?

Limitations:

- Requires $m_{4\ell} < M_Z$, $m_{2\ell} < M_Z/2$; this could be relaxed
- Requires lepton isolation; bad for HV/DS jets.
  - Replace isolation with tight IP cut?

cf. Dilepton Search in CMS Open Data, 1902.04222

If Leptons Absent or Rare?

Do Easy searches for models with fat jets containing

- MET
- Many displaced tracks (from heavy flavor or long-lived particles)
- Many subjets (from high multiplicity)
- Subjets with a common mass

Target both "Easy" & "Feasible" QCD-like models.

- Coverage of "Easy" searches in "Feasible" region can be studied
- Coverage in "Guesswork" region is, well... guesswork.

2. Expanding the Feasible Region

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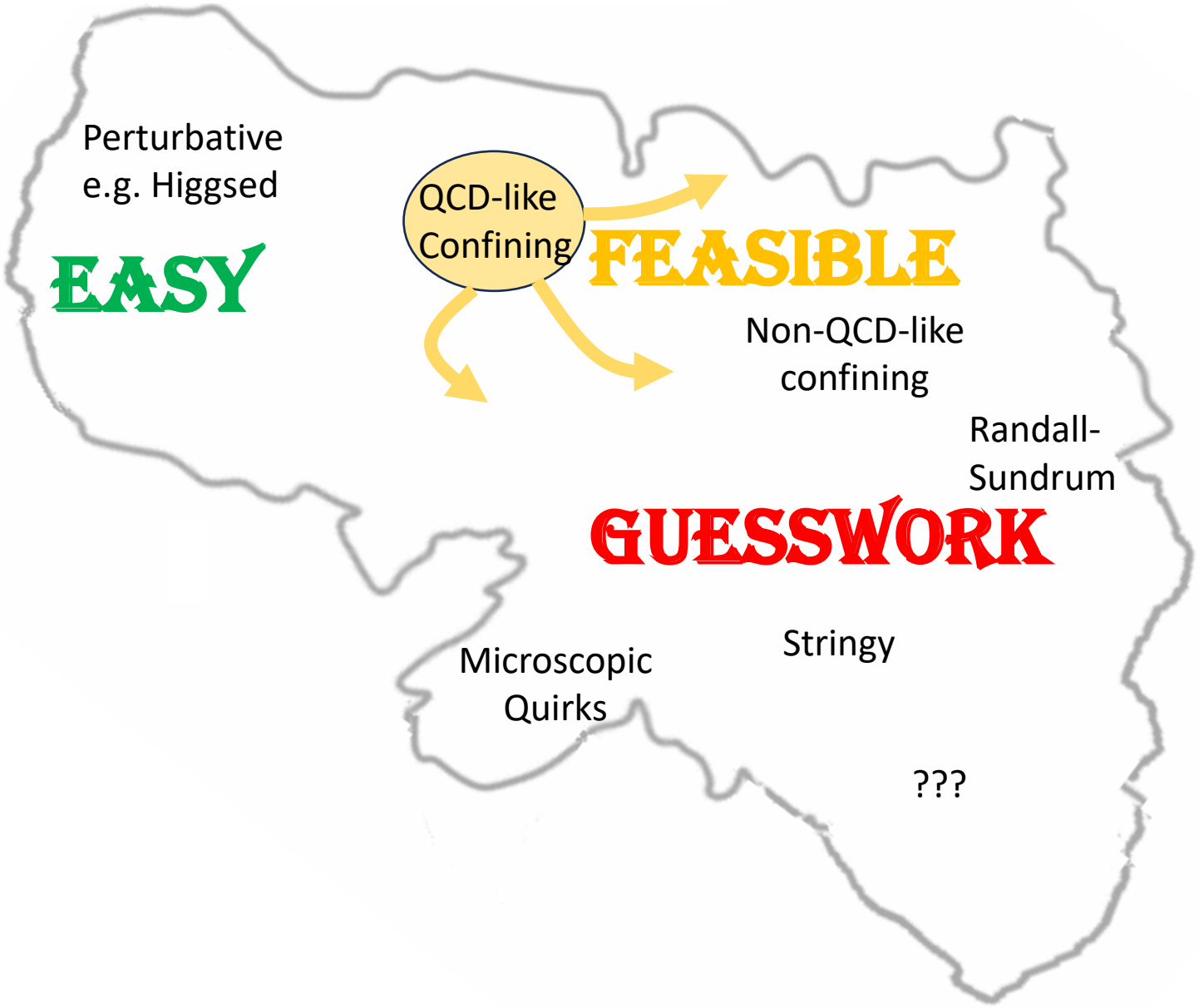
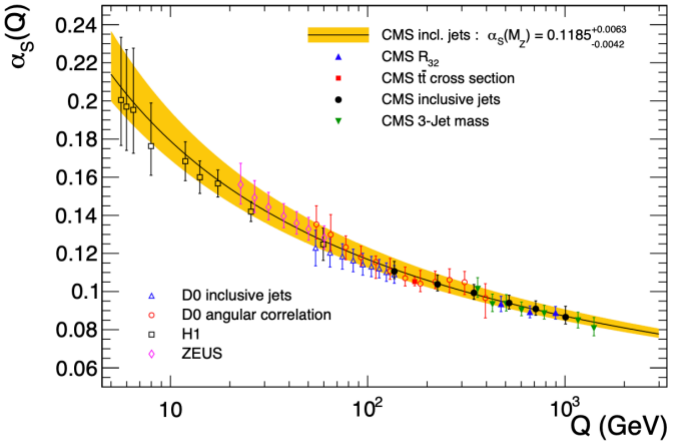


2. Expanding the Feasible Region

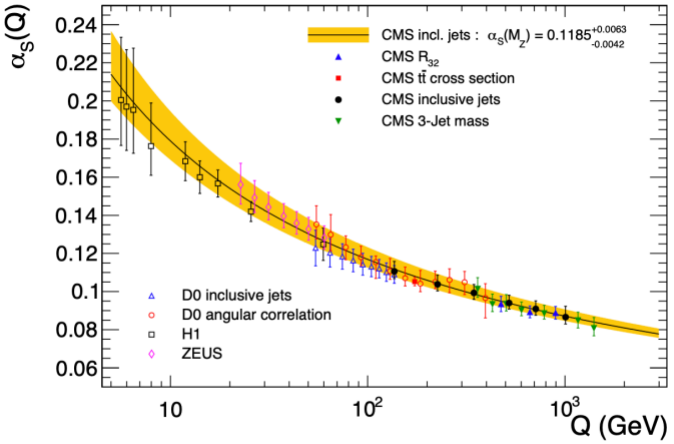
QCD: well-understood

- Spectrum calculable
- Shower $\alpha_s(\mu)$ determines jet shape
- Hadronization still a black box fit to data



arXiv:1512.05194

2. Expanding the Feasible Region



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QCD-like: $SU(N)$ with $F \ll 3N$ flavors of quarks of mass m_i

See talk by S. Kulkarni

- All m_i equal, $\lesssim \Lambda$: understood, simple; PYTHIA ok
- Unequal m_i, some $\lesssim \Lambda$: understood, complex; PYTHIA ok (?)

  cascade decays as in $K_D \to \pi_D + SM,\ \pi_D \to SM$

Added for Snowmass but not tested yet

- All $m_i \gg \Lambda$: somewhat understood; PYTHIA not ok

Note Curtin et al. attempt

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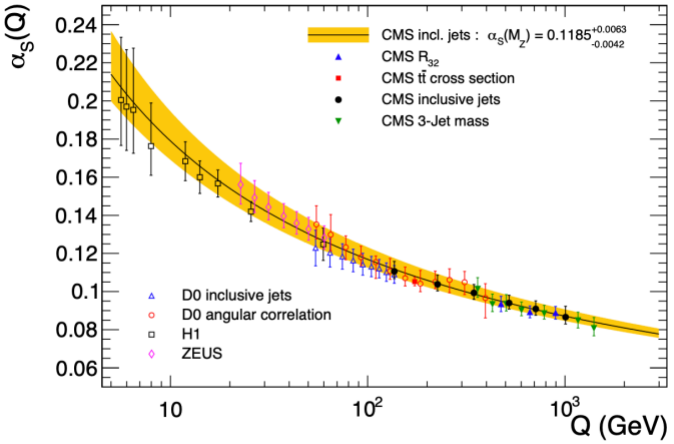

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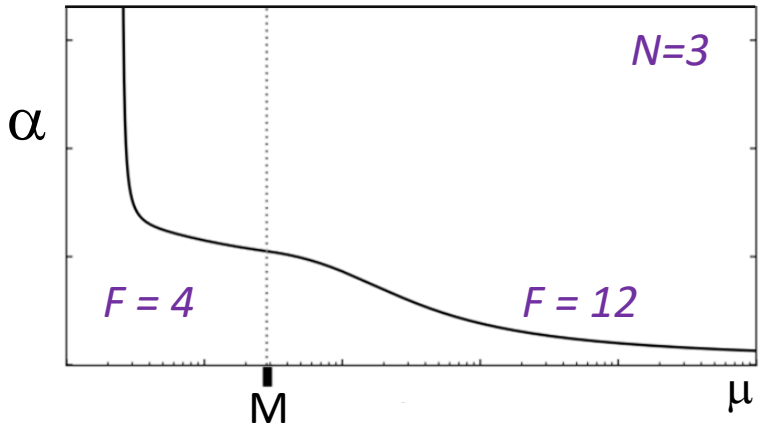
Less QCD-like: $SU(N)$ with $F \gg 3N$ flavors of quarks

- equal m_i: somewhat understood, PYTHIA not ok
- unequal m_i (many large, some small): understood, **PYTHIA soon**



See J. Lockyer's talk

Summary

- Hidden Valleys/Dark Sectors pose major LHC challenge
- All display typical qualitative, challenging expt signatures
- Theoretical quantitative prediction can be difficult/impossible

- Broad searches important
  - "Guesswork" region can't be explored in targeted searches
- Broad searches in "Easy" region can give general constraints
- Searches in the growing "Feasible" region are the frontier
  - slow, steady progress in theory, simulation and experiment

Looking forward to the presentations at this workshop!

BACKUP

FAQ: Aren't "Hidden Valleys" = confining hidden sectors?

No; and indeed this would make no sense, thanks to dualities in Field Theory.