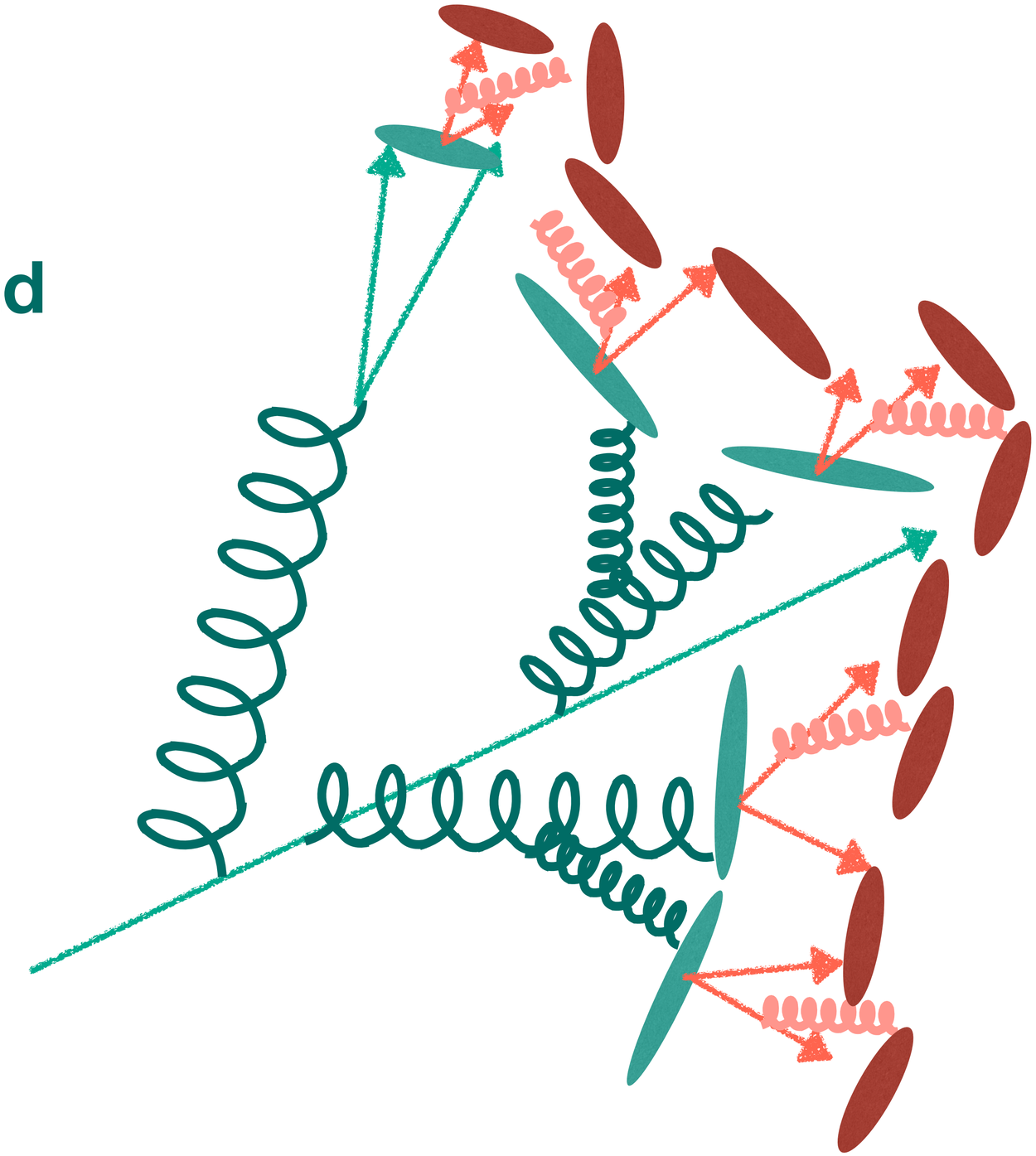
Dark Sector Showers and the Lund Jet Plane

Tim Cohen, Jennifer Roloff, Christiane Scherb

https://arxiv.org/abs/2301.07732

August 1, 2023

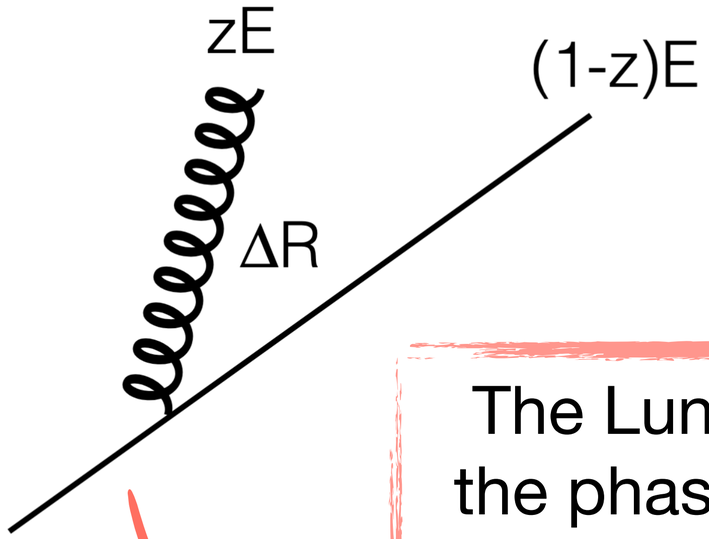


Brookhaven National Laboratory

a brief reminder: the lund plane

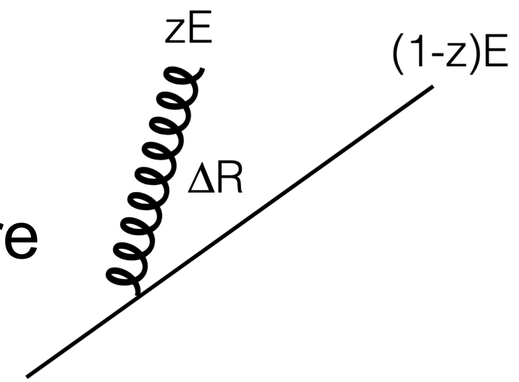
- A jet may be approximated as soft emissions around a hard core which represents the originating quark or gluon

- Emissions may be characterized by
  - k_t = transverse momentum of emission relative to the jet core
    - *(Or alternatively, z = relative momentum of emission relative to the jet core)*
  - ΔR = angle of emission relative to the jet core



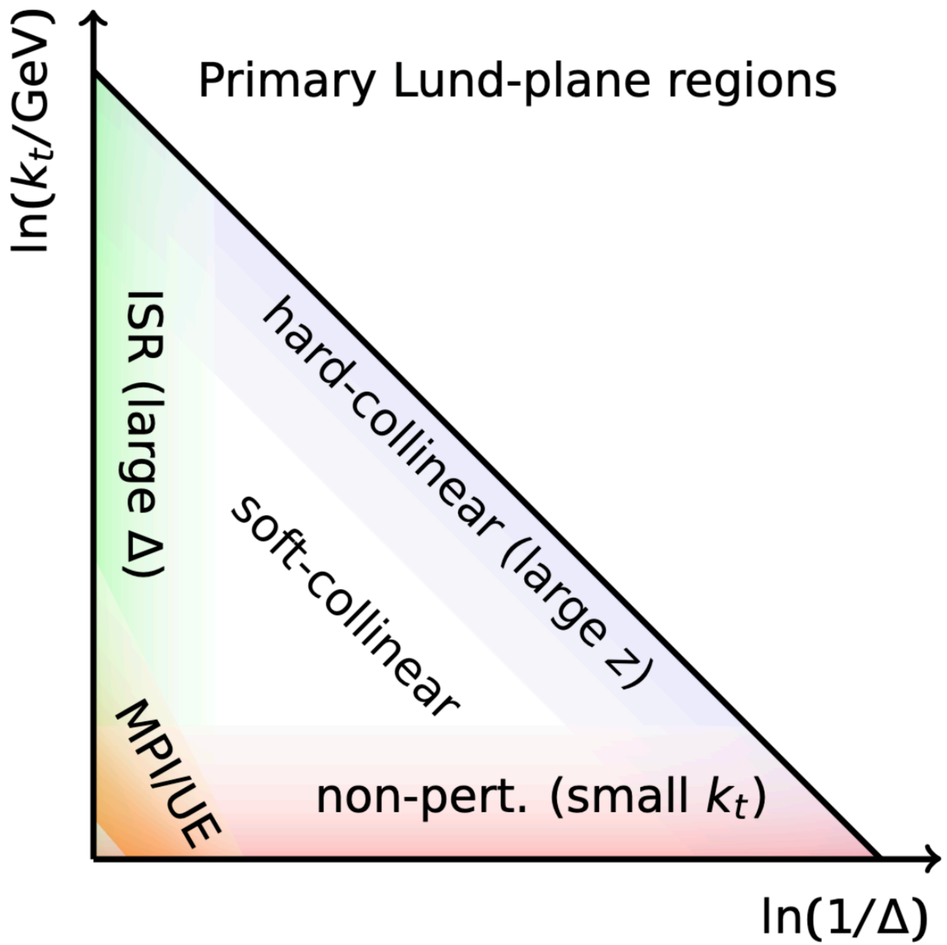
The Lund Plane is the phase space of these emissions: it naturally factorises perturbative and non-perturbative effects, UE/MPI, etc.

a brief reminder: the lund plane



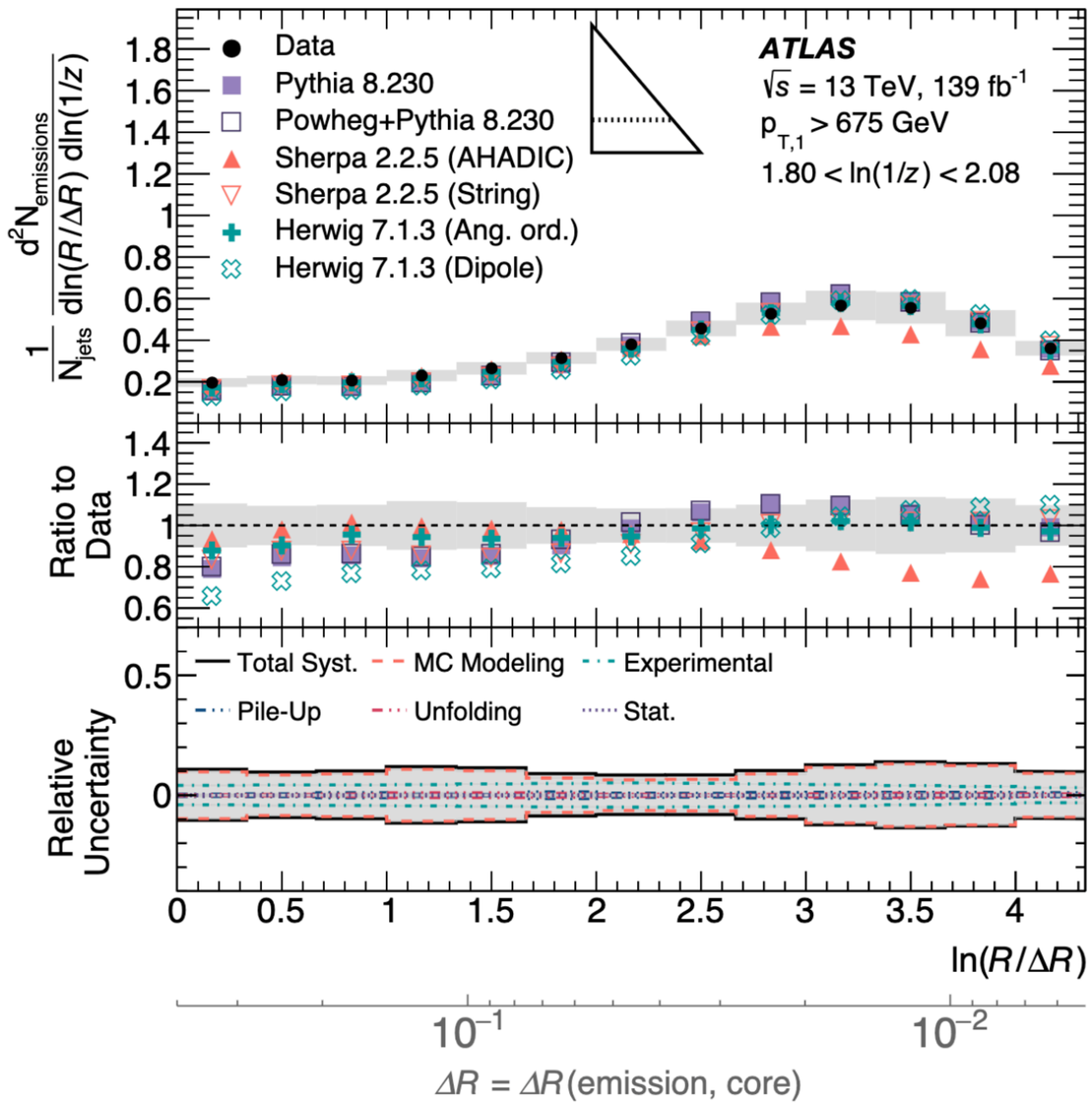
- A jet may be approximated as soft emissions around a hard core which represents the originating quark or gluon

- Emissions may be characterized by
  - k_t = transverse momentum of emission relative to the jet core
    - *(Or alternatively, z = relative momentum of emission relative to the jet core)*
  - ΔR = angle of emission relative to the jet core



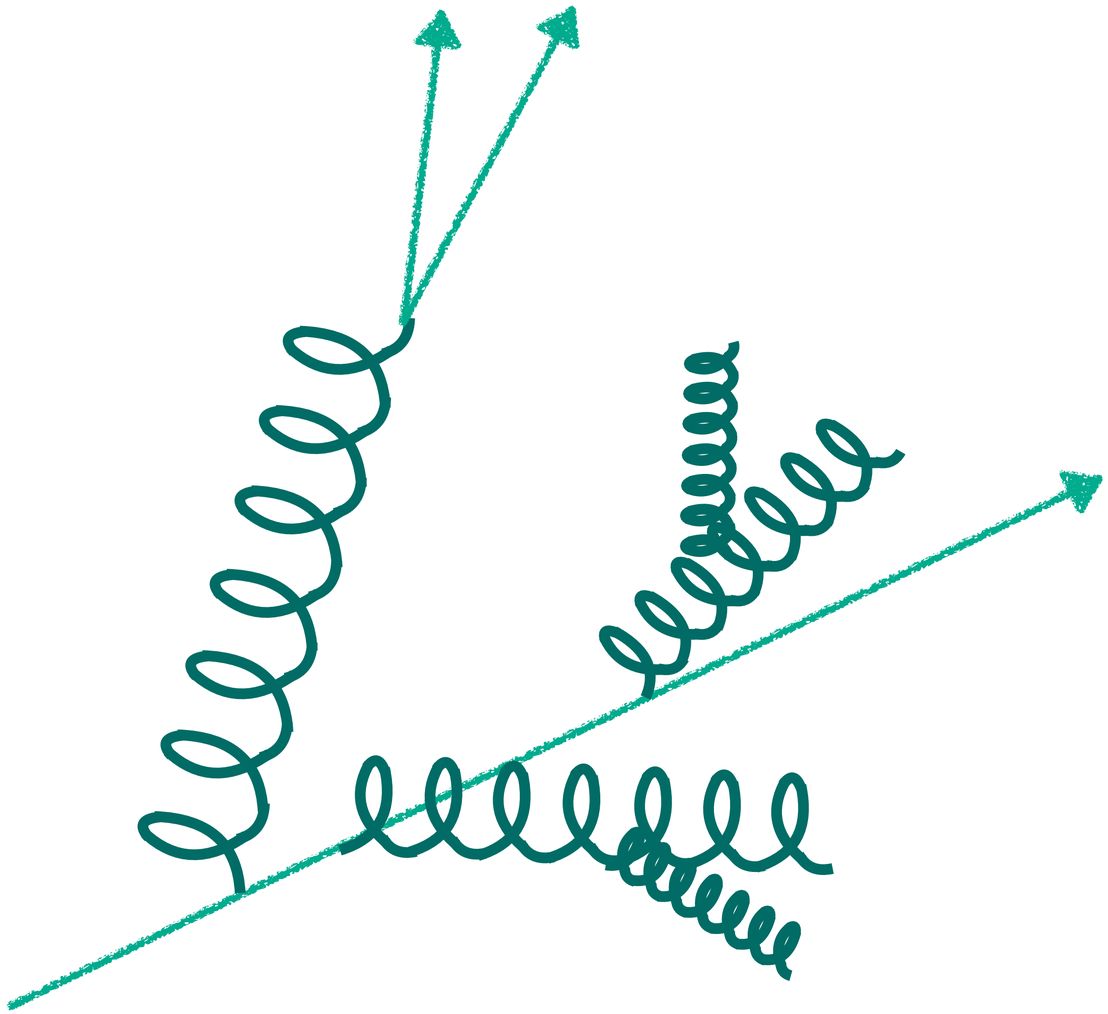
qcd

- Jet formation is complex, predictions rely heavily on tuned parameters
- Models of perturbative effects (i.e. parton showers) can be systematically improved
  - Comparison to measurements useful as tests of the underlying theory, and in practice have some tunable parameters
  - *See PanScales, ALARIC, etc.*
- Many ongoing developments for non-perturbative effects (i.e. hadronization)
  - Rely heavily on comparisons to measurements
- *No single model completely describes the structure of our jets!*



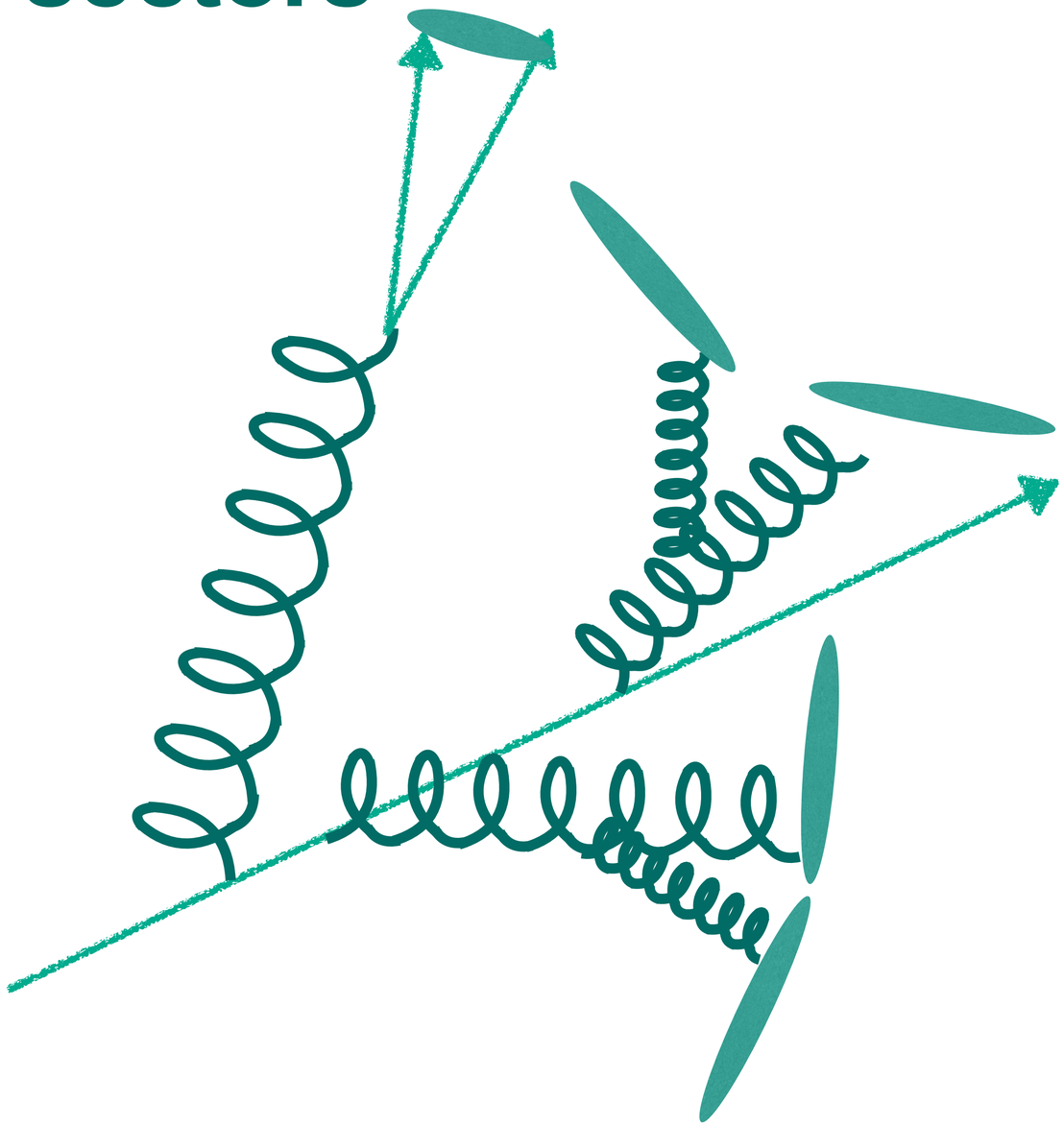
strongly coupled dark sectors

- Imagine a strongly interacting dark sector
  - Similar to QCD, but with different color/flavor factors, coupling constant, etc.
  - Same principles of QCD showers will also apply here



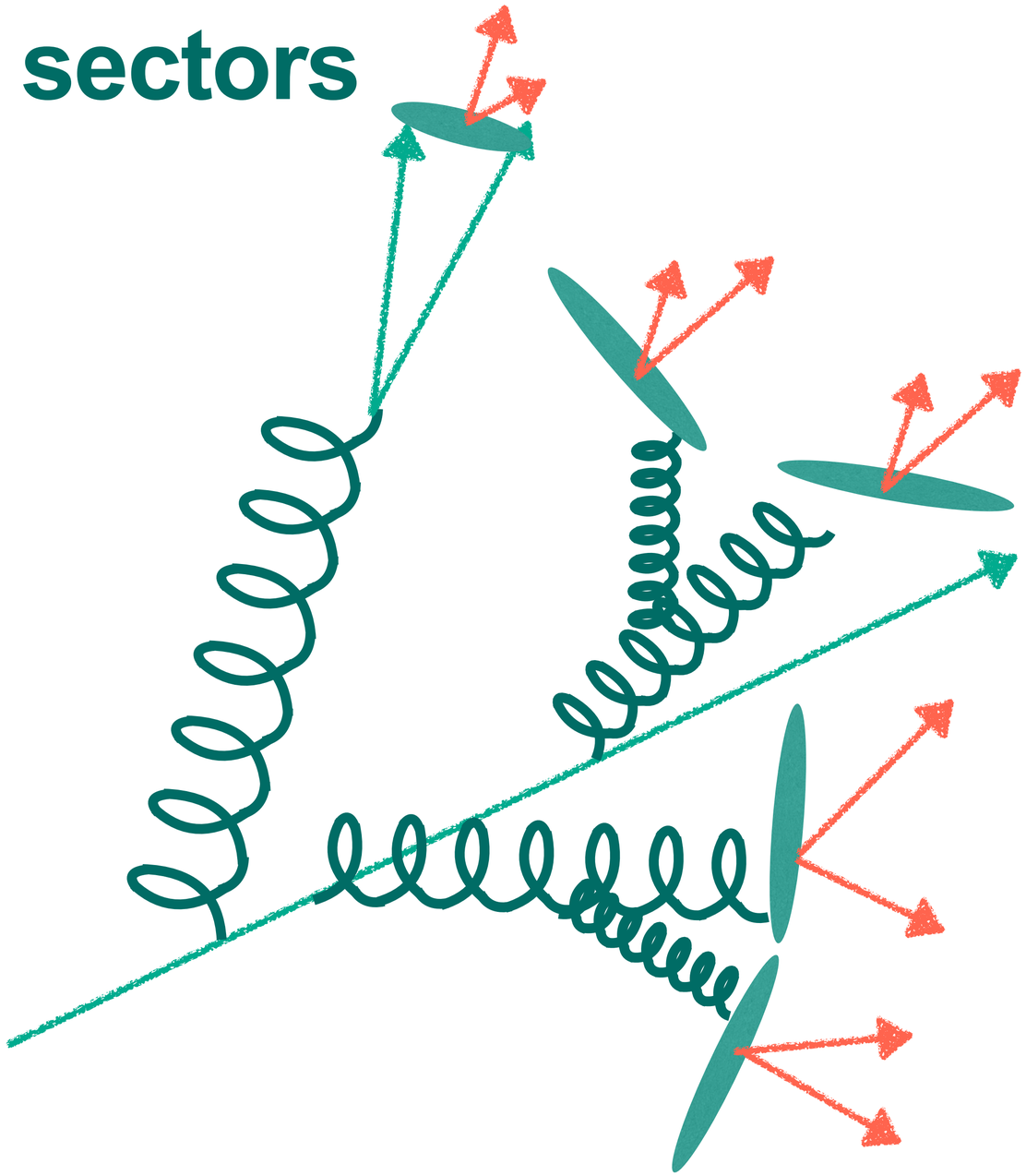
strongly coupled dark sectors

- Imagine a strongly interacting dark sector
  - Similar to QCD, but with different color/flavor factors, coupling constant, etc.
  - Same principles of QCD showers will also apply here
  - These partons can then hadronize into dark hadrons



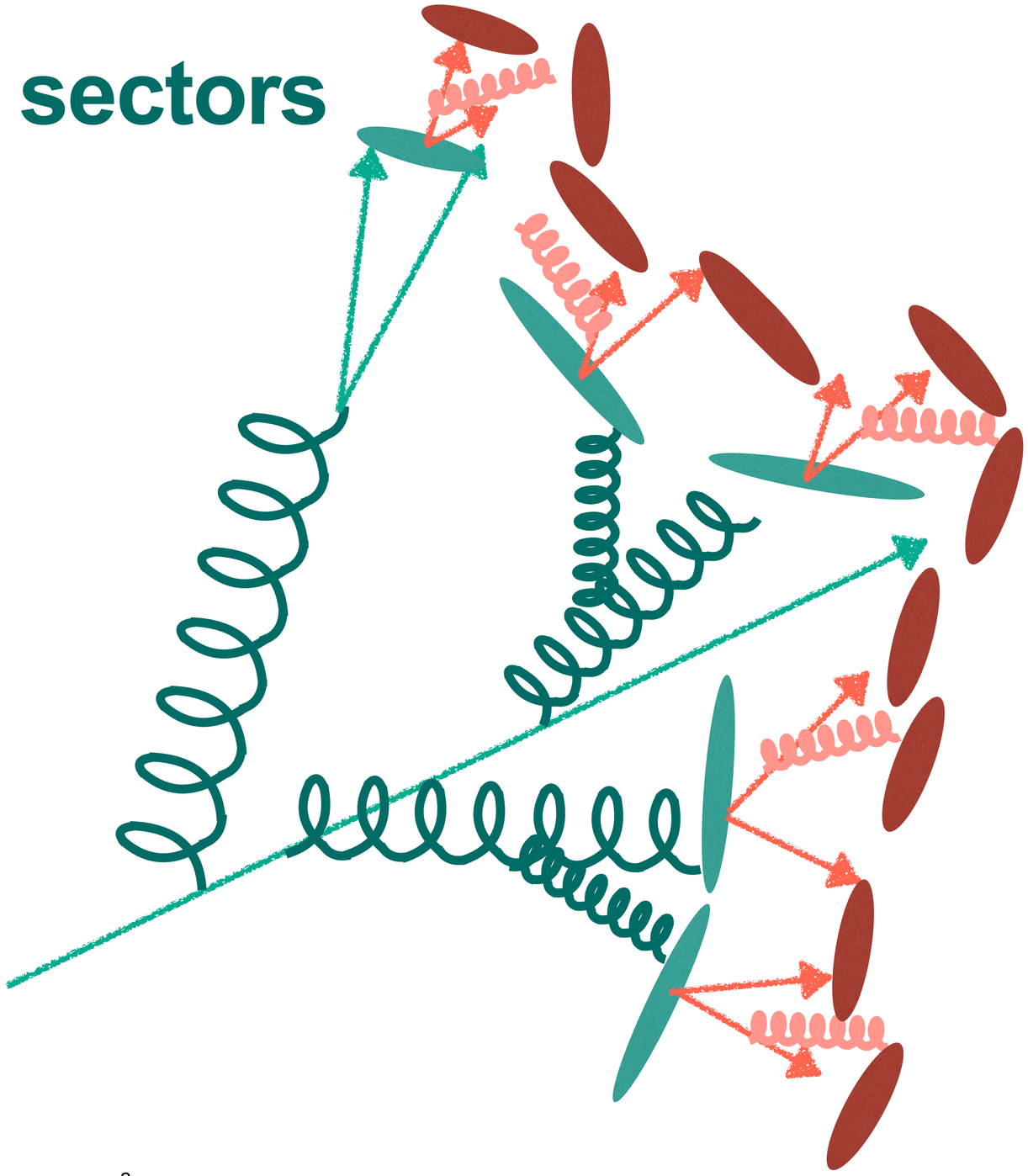
strongly coupled dark sectors

- Imagine a strongly interacting dark sector
  - Similar to QCD, but with different color/flavor factors, coupling constant, etc.
  - Same principles of QCD showers will also apply here
  - These partons can then hadronize into dark hadrons
  - Depending on the model, some or all of these can decay into Standard Model particles (quarks and gluons)



strongly coupled dark sectors

- Imagine a strongly interacting dark sector
  - Similar to QCD, but with different color/flavor factors, coupling constant, etc.
  - Same principles of QCD showers will also apply here
  - These partons can then hadronize into dark hadrons
  - Depending on the model, some or all of these can decay into Standard Model particles (quarks and gluons)
  - These will then shower and hadronize, leaving a very complicated system
  - Much like the SM, can reconstruct into jets

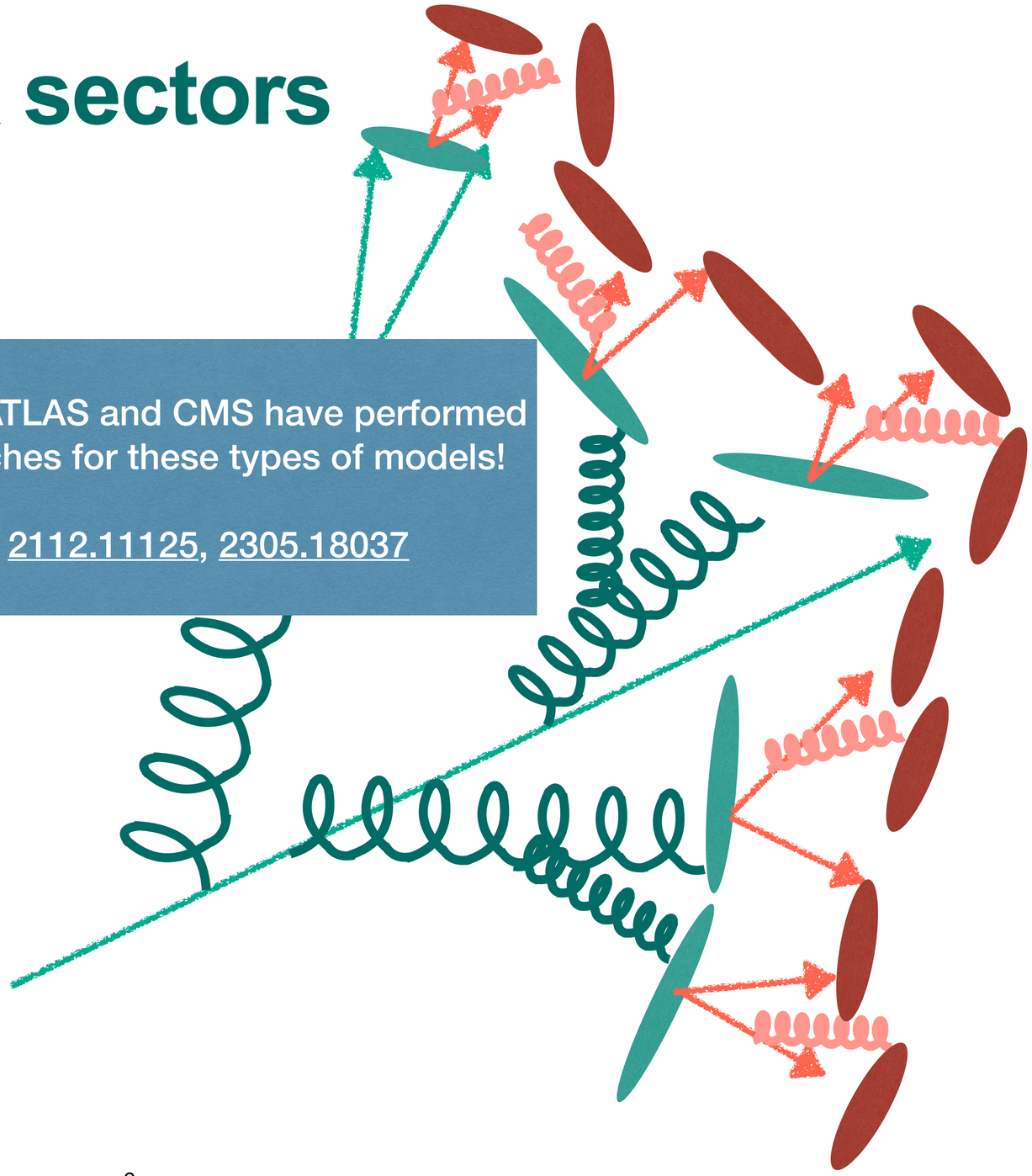


strongly coupled dark sectors

- Imagine a strongly interacting dark sector
  - Similar to QCD, but with different color/flavor factors, coupling constant, etc.
  - Same principles of QCD showers will also apply here
  - These partons can then hadronize into dark hadrons
  - Depending on the model, some or all of these can decay into Standard Model particles (quarks and gluons)
  - These will then shower and hadronize, leaving a very complicated system
  - Much like the SM, can reconstruct into jets

Both ATLAS and CMS have performed searches for these types of models!

2112.11125, 2305.18037



strongly coupled dark sectors

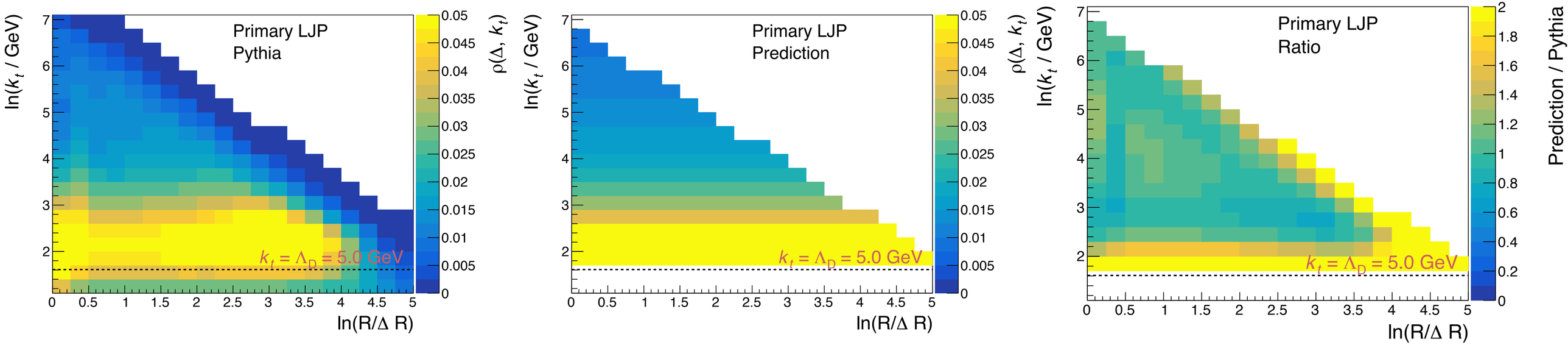
- Rich phenomenology of models, but not enough time to cover this in detail!
  - *Focusing on the case where dark sector hadronizes before decay to SM, and all dark hadrons decay to SM particles promptly*
- Many challenges in constraining models involving dark showers
  - Unlike a boosted resonance, cannot tag N-prong structure (more akin to quark/gluon tagging)
  - Hard to write a robust model of their behavior
    - Dark hadronization cannot be constrained with Standard model measurements
  - Many physical parameters which significantly change the properties of the reconstructed jets
    - When looking at the jet structure, no single parameter (like mass) which can be used for limits
- Exploring two questions today:
  - Can we apply our knowledge of SM jet substructure to improve our understanding of dark sector jets?
  - Can we design robust searches which are not overly dependent on parts of the model that we don’t know how to constrain (like hadronization)?

dark showers and the lund plane

- As a first check, can see if the Monte Carlo predictions reproduce the expected behavior
  - *Only using the dark partons, no hadronization or decays to SM particles*
- Can compare to a leading-logarithmic prediction of the expected density
  - Ratio is close to 1, demonstrating a basic validation of the simulation

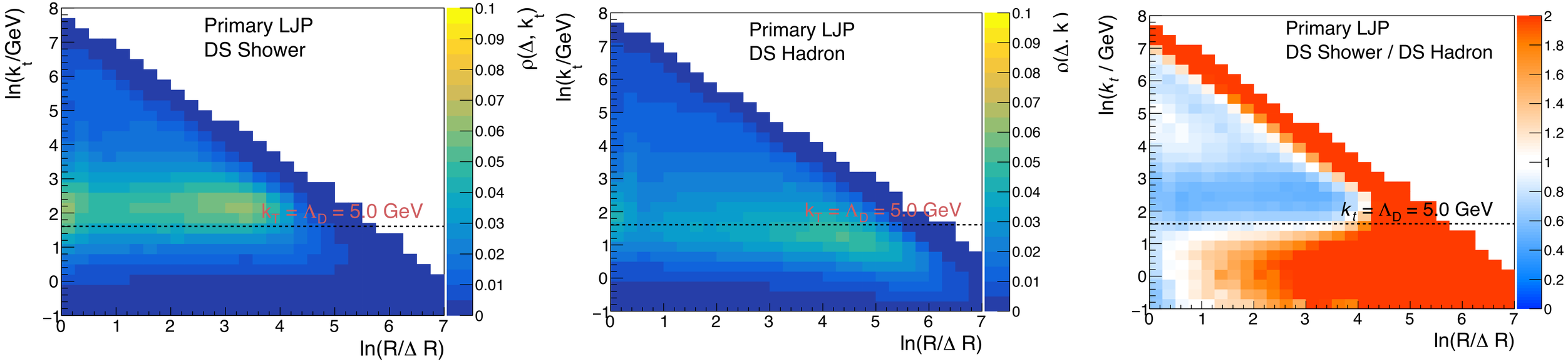
Expected density:

$$\frac{2\alpha_{\mathrm{D}}(k_t)C_F}{\pi}$$



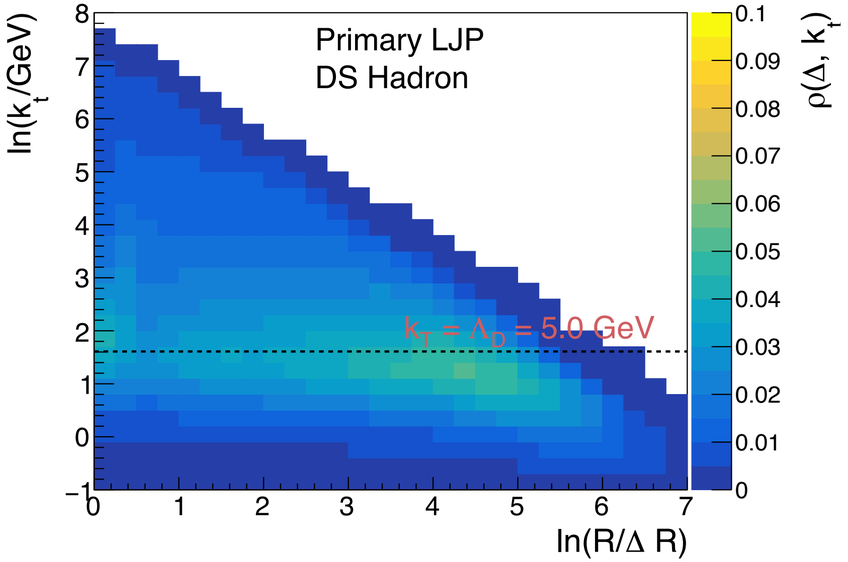
dark sector showers in the lund jet plane

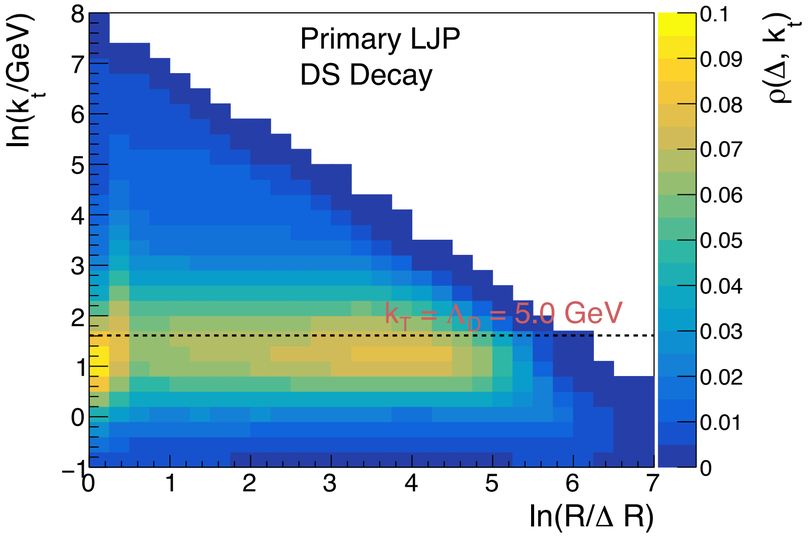
- Can look at Lund jet plane for jets at different stages of the event generation
  - Dark hadronization tends to have the largest impact on low-k_t emissions, though some changes throughout the plane

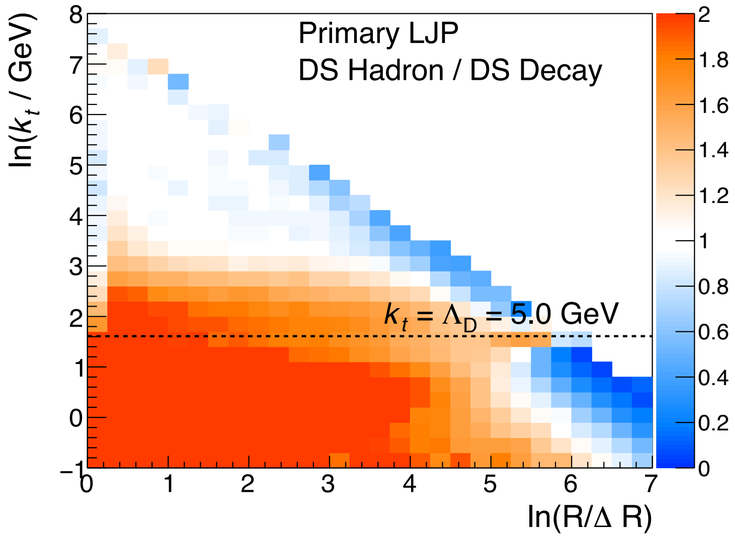


dark sector showers in the lund jet plane

- Can look at Lund jet plane for jets at different stages of the event generation
  - The dark hadron decays to Standard Model particles results in brighter band in the part of the plane affected by non-perturbative effects

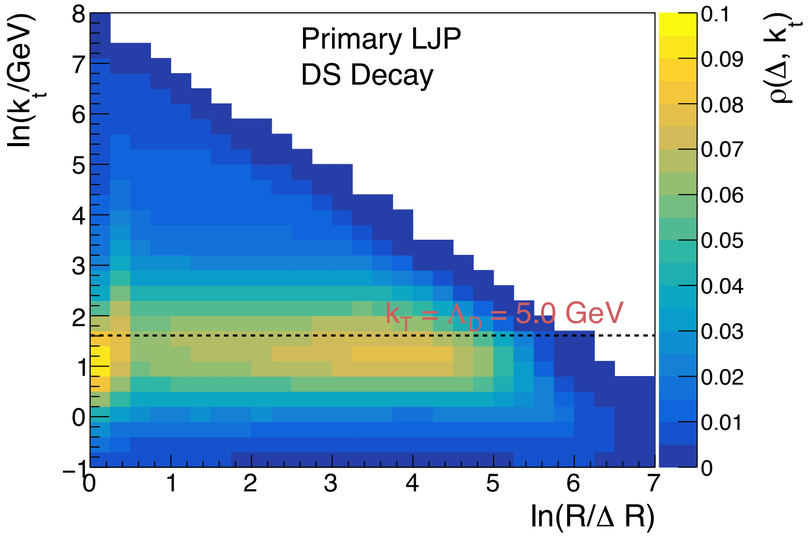


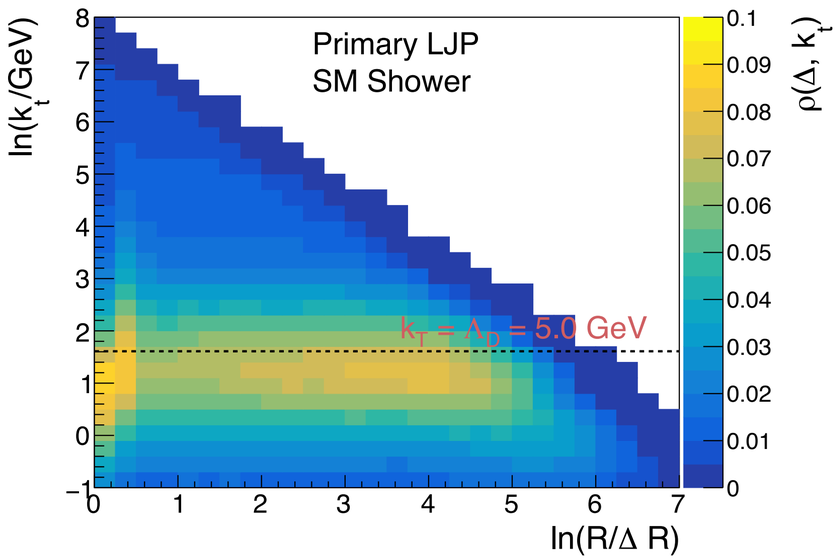


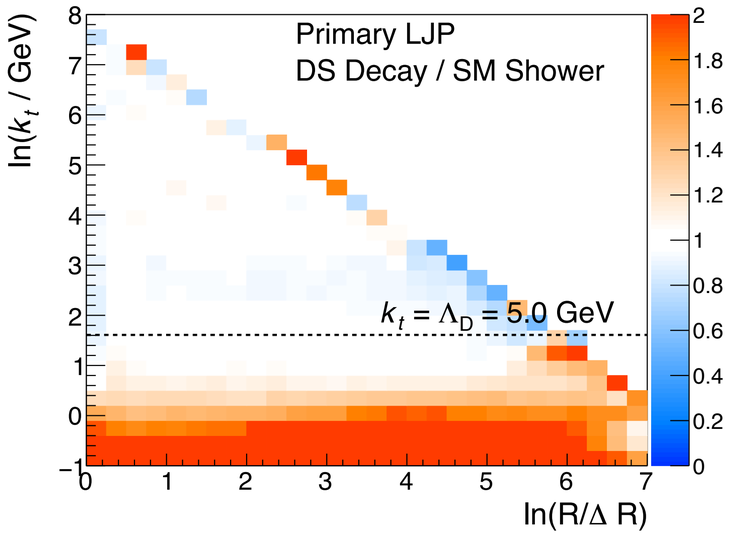


dark sector showers in the lund jet plane

- Can look at Lund jet plane for jets at different stages of the event generation
  - Very little impact from the Standard Model QCD shower
    - The dark hadrons are relatively low-mass, so very little showering happens for this choice of parameters

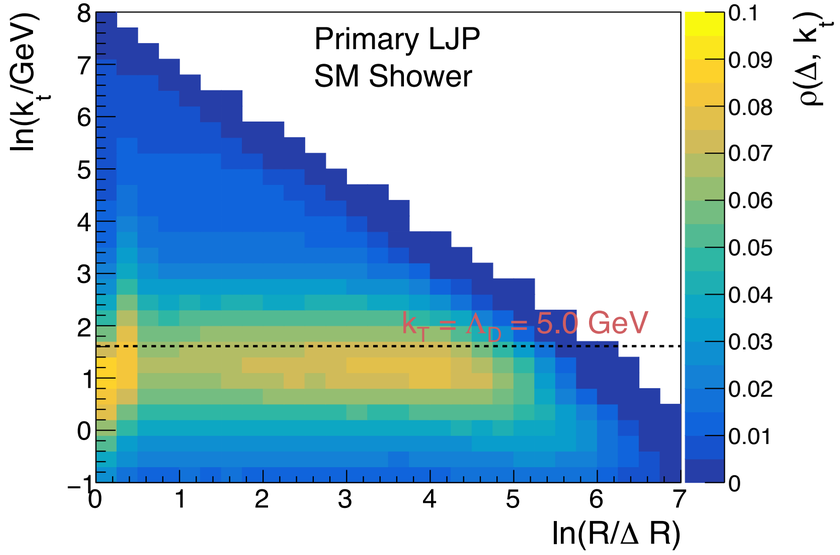


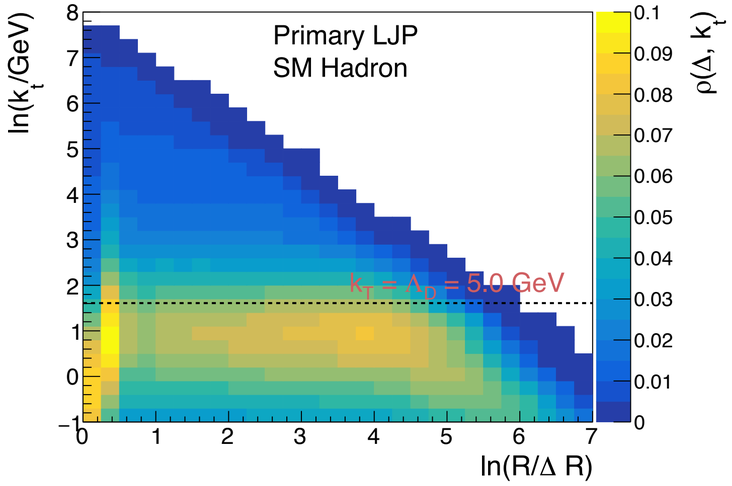


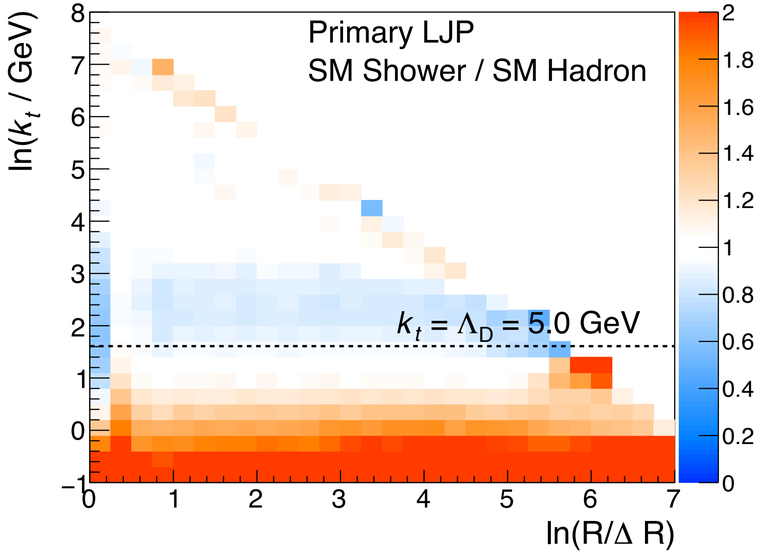


dark sector showers in the lund jet plane

- Can look at Lund jet plane for jets at different stages of the event generation
  - Some changes from the Standard Model hadronization, but mostly confined to low-k_t region

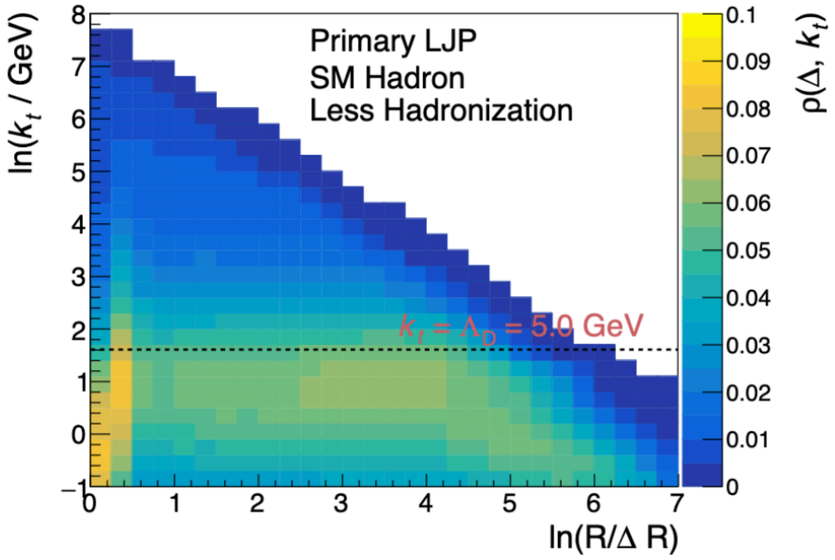


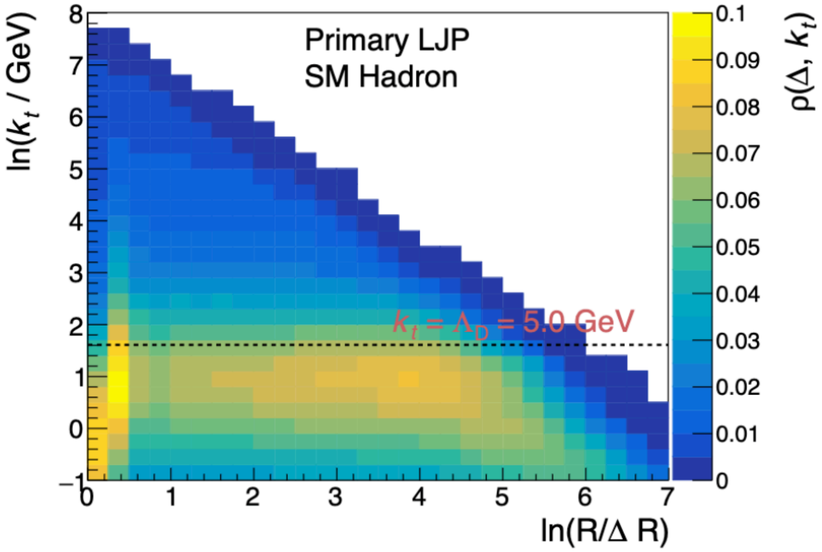


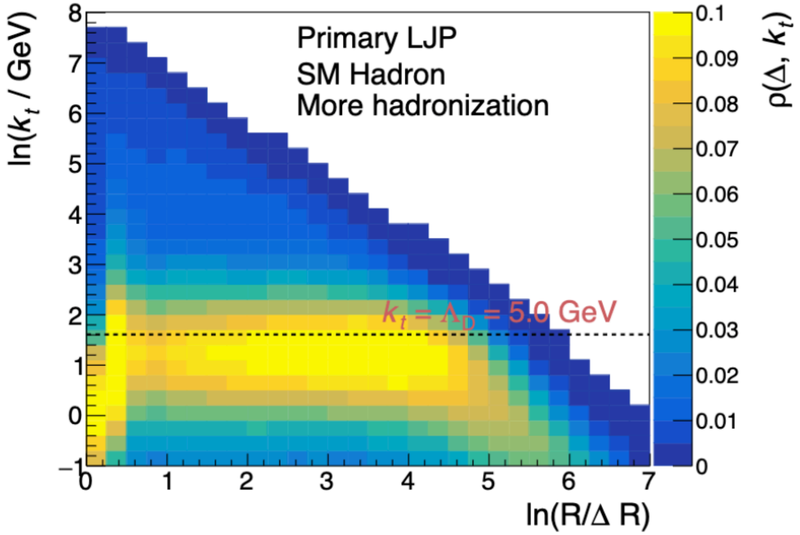


using lund jet planes for searches

- Different hadronization choices produce very different Lund jet planes
  - Translates into large differences in observables like the number of tracks
  - These hadronization choices are unconstrained by Standard Model measurements

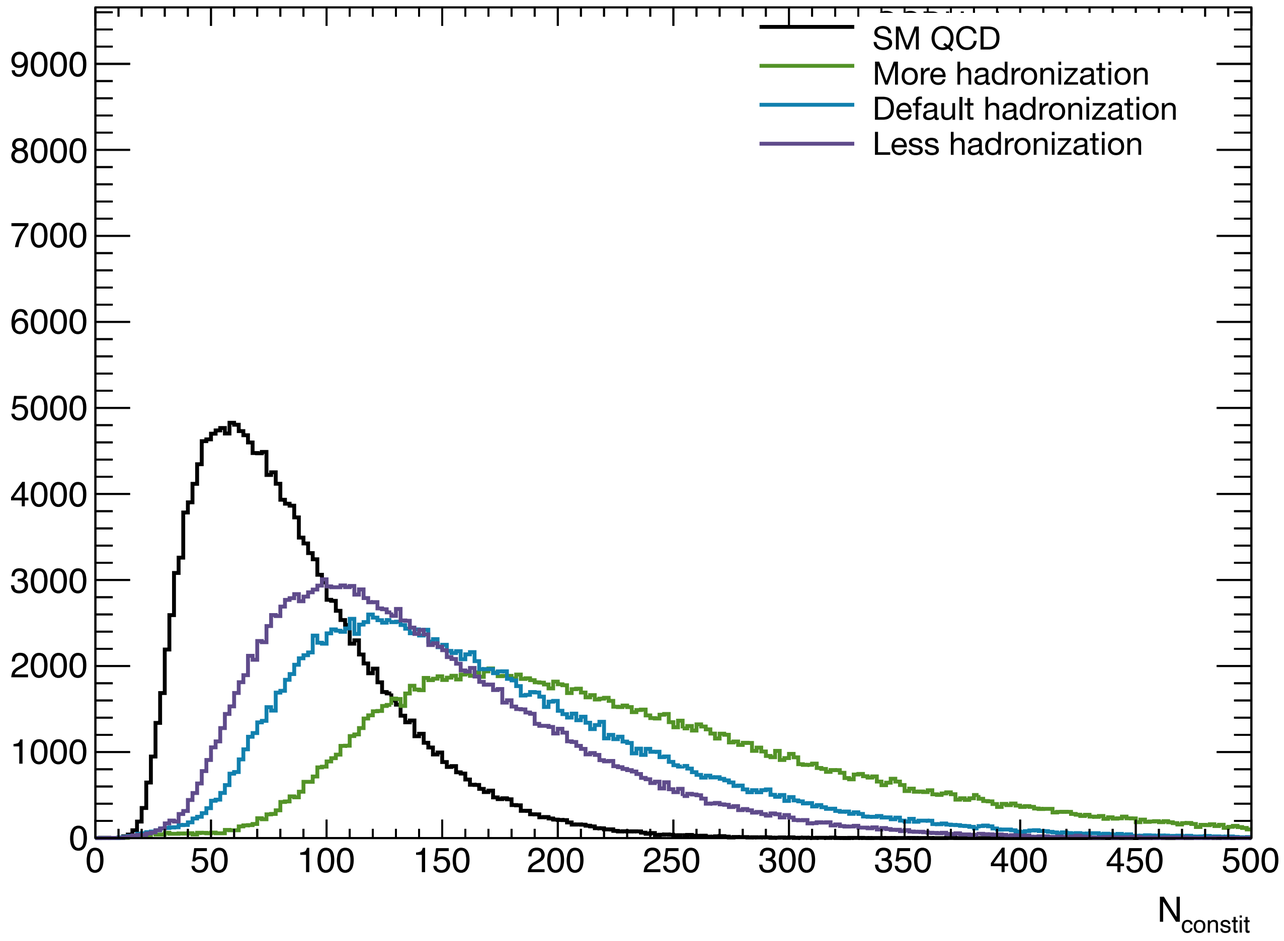






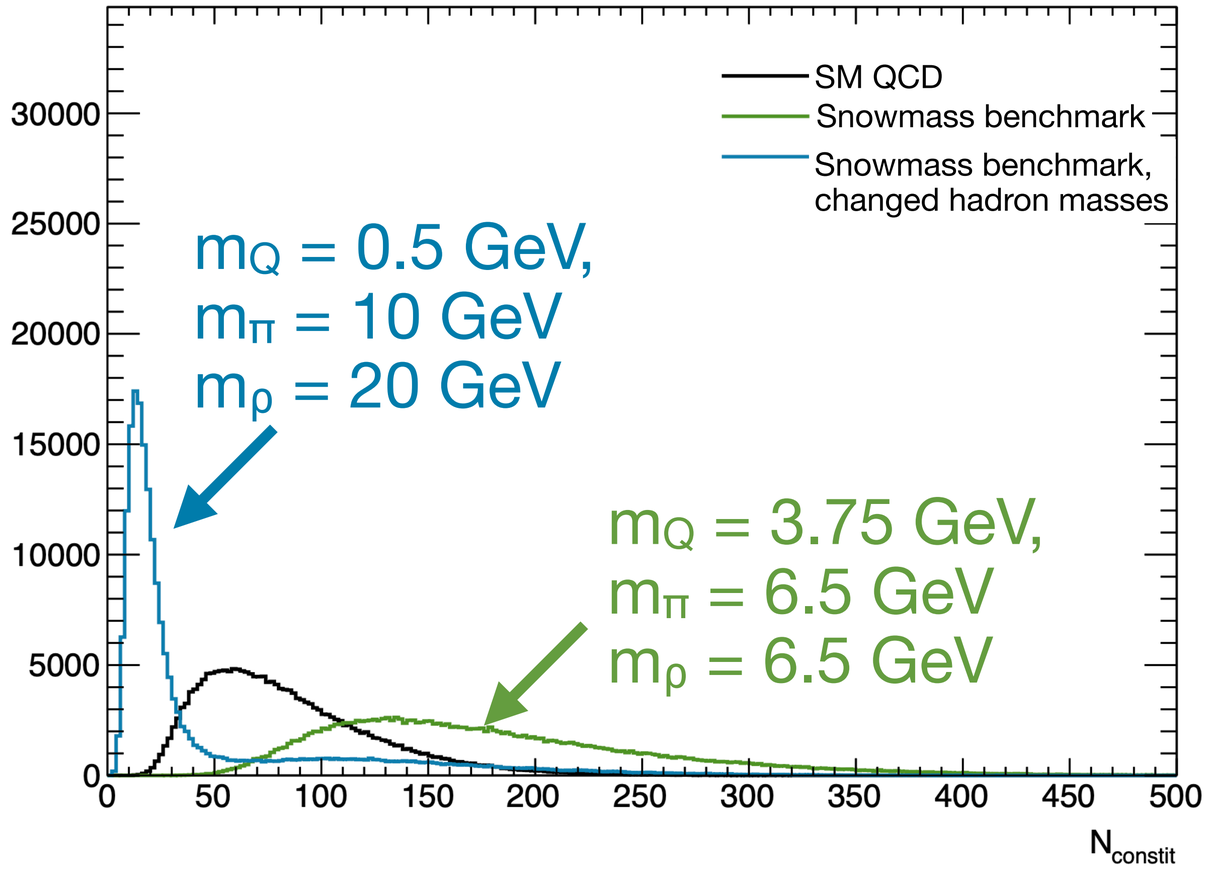
thoughts on hadronization

- The number of constituents in a jet is very susceptible to different hadronization models
  - Analyses which cut on something like this would be hard to interpret
- Generally, QCD has a lot fewer constituents than the dark shower models
  - This makes sense, because the dark showers have the secondary showering+hadronization
  - *Even this assumption depends on the model!*
- This is the best-case scenario
  - Once you start including correlations, etc, any tagger can easily result in bad features



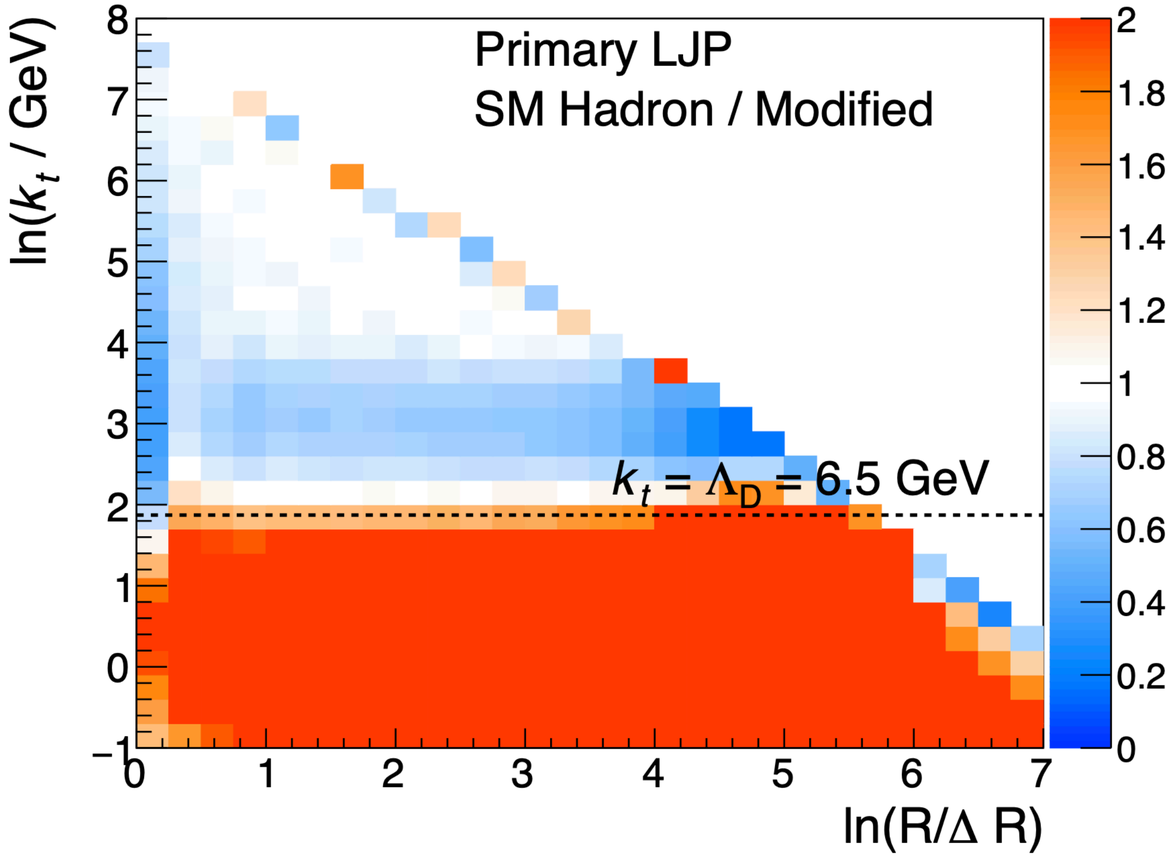
thoughts on hadronization

- Depending on what parameters you scan over, the behavior can become very problematic
  - *For instance, just changing the dark hadron masses can result in major changes to the substructure!*
  - Keeps the same number of colors & flavors, Λ_{dark}, hadronization parameters



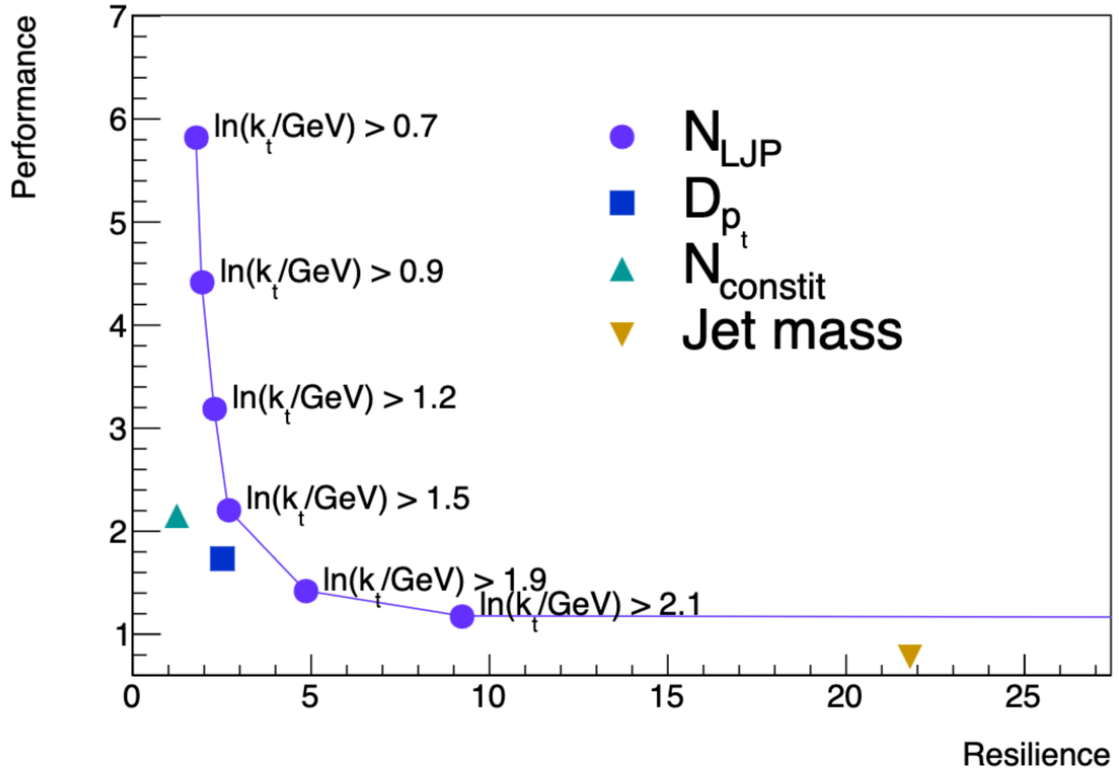
thoughts on hadronization

- Depending on what parameters you scan over, the behavior can become very problematic
  - *For instance, just changing the dark hadron masses can result in major changes to the substructure!*
  - Keeps the same number of colors & flavors, Λ_{dark}, hadronization parameters
  - Compare this to the LJP, where there is a clear region where this is not significantly changed, even with different hadron masses



quantifying the robustness

- In searches, care about the performance as well as the robustness
  - Various ways of quantifying these, but choose one option based on the signal and background efficiency
    - Performance = $p = \frac{\epsilon_{\mathrm{D}}}{\sqrt{\epsilon_{\mathrm{QCD}}}}$
      - Determined using a one-sided tagger cut on an observable
    - Resilience = $\zeta = \left(\frac{\Delta\epsilon_{\mathrm{D}}}{\langle\epsilon_{\mathrm{D}}\rangle}\right)^2$
      - Δε determined using different hadronization choices
- *Using the number of emissions in the Lund jet plane can provide more robust taggers!*



summary

- Dark sector jets have a rich phenomenology, but also pose significant challenges
- Can use the Lund jet plane to construct observables which are relatively insensitive to the dark shower hadronization model
  - The same principles that apply to SM QCD also apply here, even after the decays and showers of the SM particles
  - Can tune observables to balance stability vs. sensitivity
- The Lund jet plane is not the only solution, and it also comes with its own challenges
  - Lots of potential to continue exploring other alternatives, more complex observables
  - Can apply intuition from the Standard Model to design robust strategies for dark sector searches

backup

hidden valley parameters

	n_C	n_F	Λ_{D}	$m_{Q_{\mathrm{D}}}$	$m_{\pi_{\mathrm{D}}}$	$m_{\rho_{\mathrm{D}}}$	a_L	$b_{m^2_{Q_{\mathrm{D}}}}$	$r_{Q_{\mathrm{D}}}$	fraction ρ_{D}
primary benchmark	3	3	5 GeV	2.5 GeV	5 GeV	5 GeV	0.3	0.8	1	default ($= 0.75$)
large hadronization	3	3	5 GeV	2.5 GeV	5 GeV	5 GeV	2	0.2	2	default
small hadronization	3	3	5 GeV	2.5 GeV	5 GeV	5 GeV	0	2	0	default
snowmass benchmark	3	2	6.5 GeV	0.5 GeV	10 GeV	20 GeV	0.3	0.8	1	default
dark QCD scale Λ_{D}	3	3	50 GeV	2.5 GeV	5 GeV	5 GeV	0.3	0.8	1	default

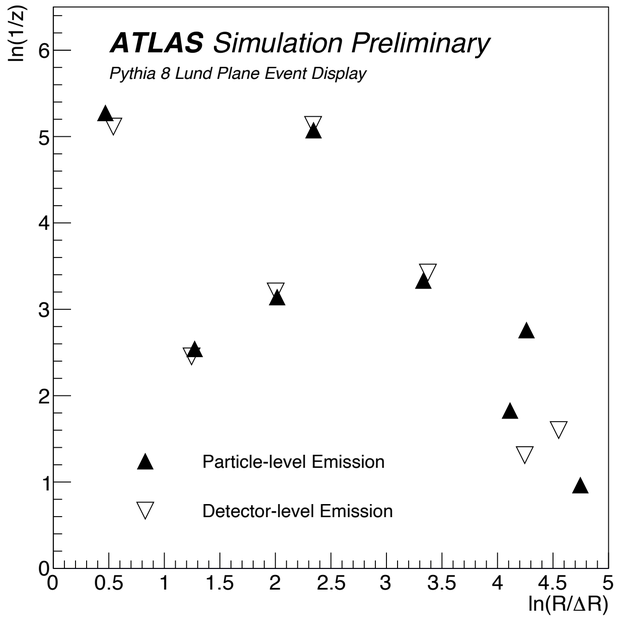
the lund jet plane

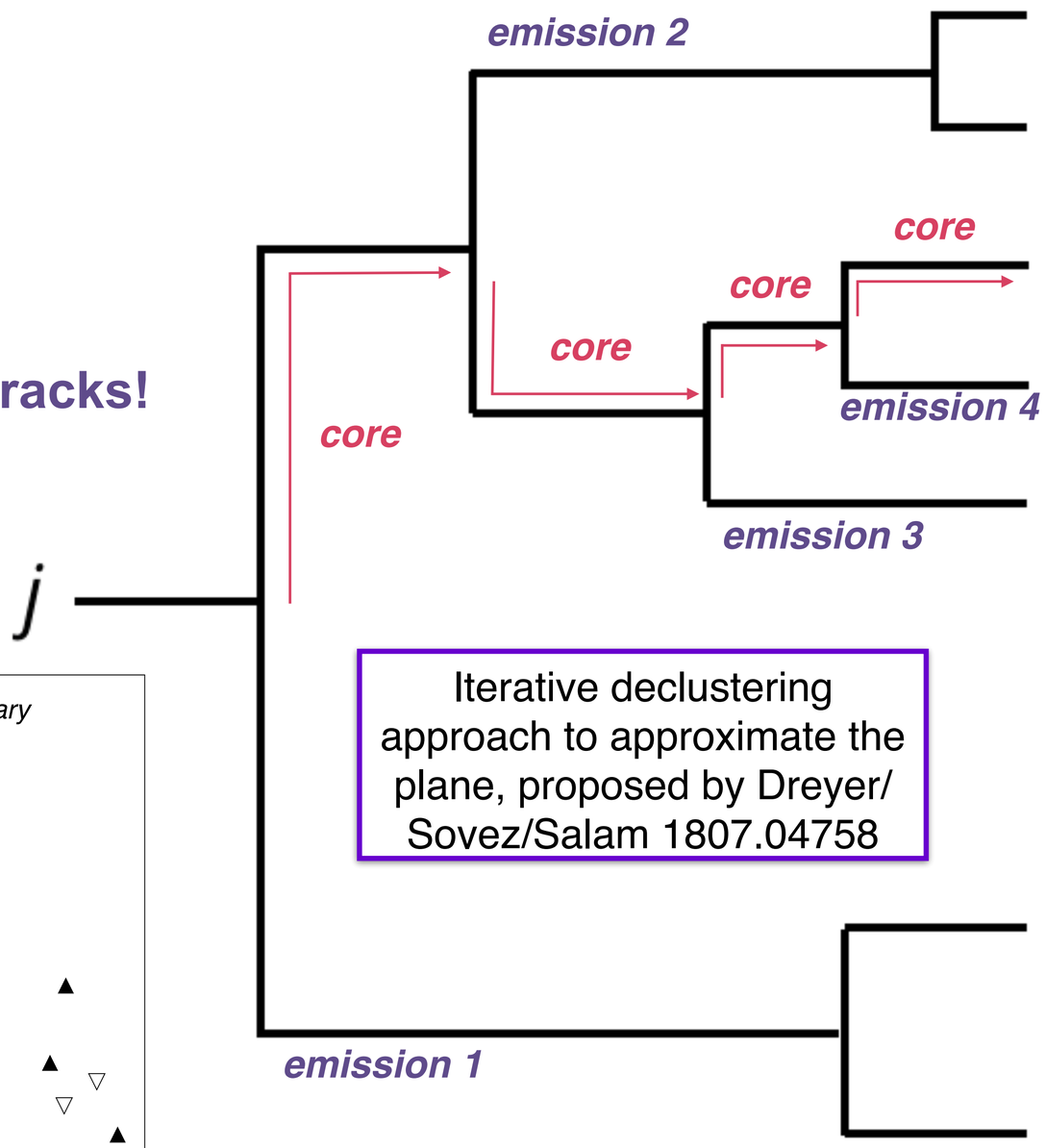
1. Jet Finding:
Cluster jets using your favorite jet algorithm

2. C/A Reclustering:
Combine closest pairs of **charged particles or tracks!**

3. C/A Declustering:
Unwind, widest angles first. Each step is an **emission**, or, a point in the Lund Jet Plane!

4. Plot Emissions:
Characterize emissions based on their angle (ΔR), and the hardness of the splitting and $z = p_T^{emission} / p_T$





Iterative declustering approach to approximate the plane, proposed by Dreyer/Sovez/Salam 1807.04758