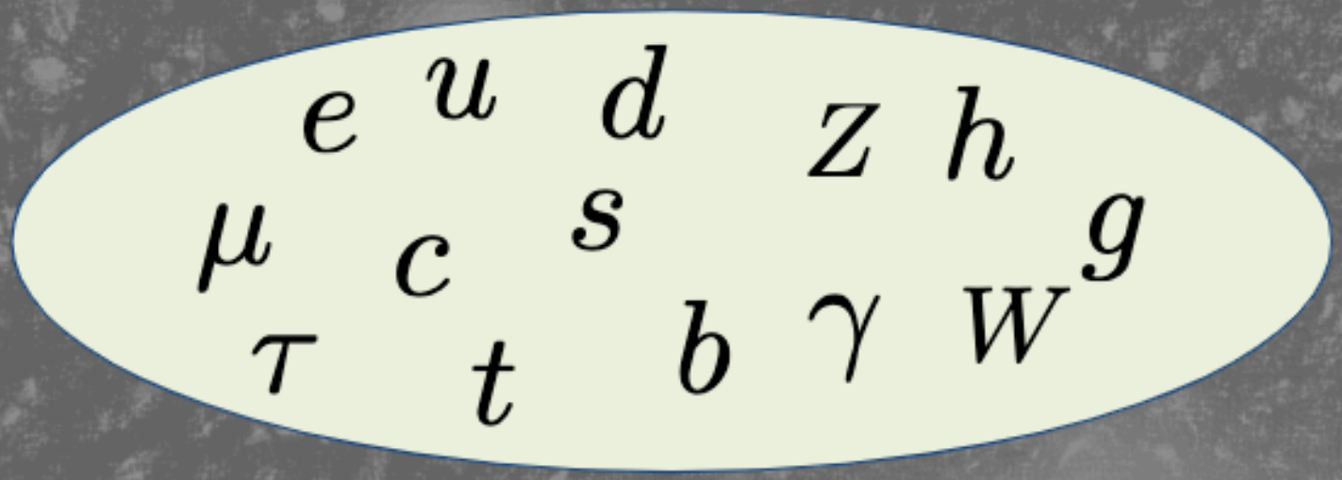
Dark showers summary

On behalf of the working group

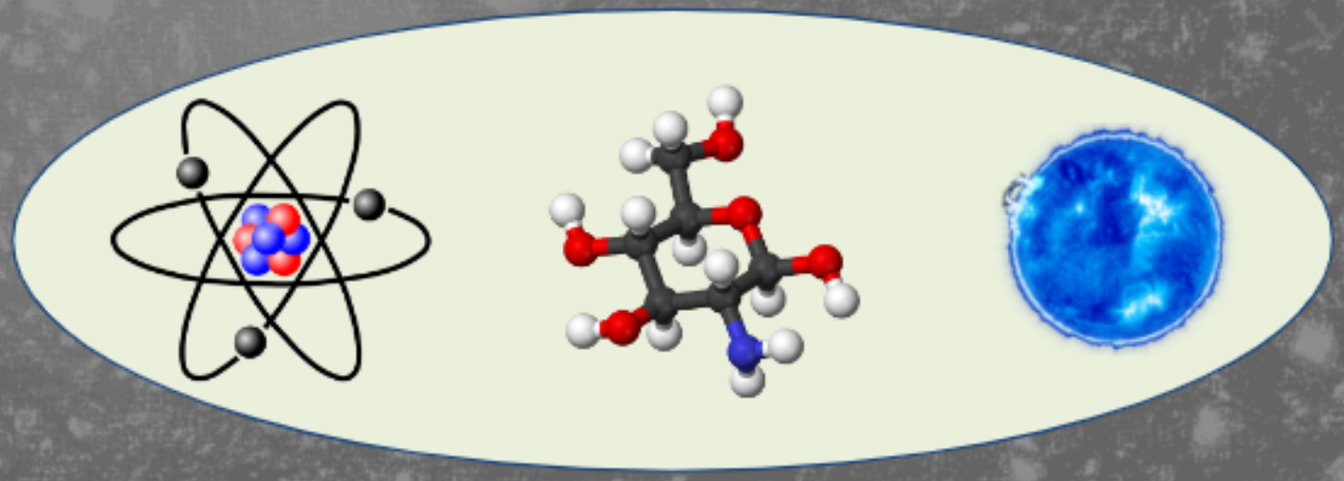
8th LLP workshop
(11/16/2020)

Matthew McCoullough

Only 18% of all matter in Universe is visible.



Within that 18% we observe extraordinary complexity.



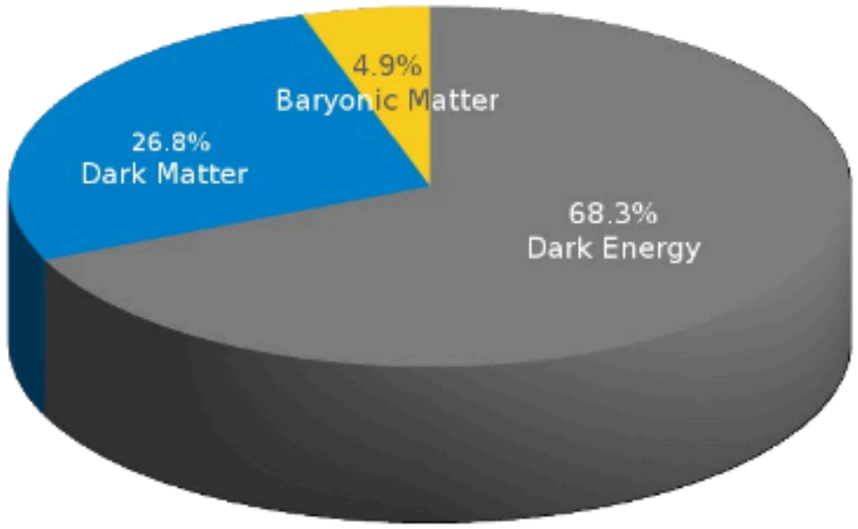
Similarly, it may be the light mediators, or other states, that open the window to the dark sector.

Guiding principle: Early Universe cosmology

- The **one thing** we know about dark matter is **how much** there is in the Universe:

$$\Omega h^2 = 0.1199 \pm 0.0027$$

- Any model of dark matter must provide a mechanism to **explain this number**



Possible route:

1) Take inspiration from the Standard Model (SM) and construct DM models in **analogy**
   Pythia HV module
2) Require consistent cosmology that **reproduces the observed DM relic abundance**
   Asymmetric DM, SIMP, Twin Higgs * (Or hierarchy problem)
3) Explore **phenomenological consequences** and constrain parameter space
   SUEP, emerging jets, semi-visible jets

** Even these "motivated" models still have a lot of knobs to dial :/*

Caleb Gemmell

Indirect Detection and Dark Showers

One benefit of indirect detection experiments is that they probe astrophysical length scales, possibly giving insight into more of the dark sector spectrum, not just the short living states

- How can astrophysical dark showers arise? Most plausible mechanism is probable DM annihilation or decay. (Fairly specific model needed)
- Cosmo constraints (e.g. BBN) are fairly loose and model dependent
- Cosmology and DM self-interactions can be accommodated most easily if > 1 GeV (but exceptions can be cooked for sure)

Conclusions

- Well motivated to consider additional (strong) interactions within the dark sector
- Many different ways to obtain phenomenologically viable dark matter candidates
- Dark showers can induce many different LHC signatures depending on the fraction of unstable particles and their decay length
  - **QCD-like jets:** Challenging to distinguish from backgrounds
  - **Semi-visible jets:** Promising machine-learning techniques for jet tagging
  - **Emerging jets:** Experimental searches ongoing
  - **Displaced vertices + MET:** Current searches not sensitive, improvements possible
  - Jets with weird particle content: photon jets, lepton jets etc
- New tools and searches needed to map out the full parameter space of strongly-interacting dark sectors

Marat Freytsis

Dark simulation landscape

- The workhorse: Pythia8 hidden valley module
  - stripped down version of QCD p_T-ordered dipole shower
  - provides basic treatment of parton show + hadronization
  - basic hard processes provided, integration with MG, etc.
  - decays to SM must be added by hand
  - suitable for SM-like shower dynamics

Emerging jets: Schwaller, Stolarski, Weiler [1502.05409]

Semi-Visible Jets: Cohen, Lisanti, Lou, Mishra-Sharma [1503.00009, 1707.05326]

- Ad hoc and one-off approaches
  - Generate soft events via parametrized model

Knapen, Pagan Griso, Papucci, Robinson [1612.00850]

Pythia8 plugin at https://gitlab.com/simonknapen/suep_generator

  - Extra-dimensional simplified models

Cesarotti, Reece, Strassler [2009.08981]

Beware of hadronization unknowns: e.g. is the $\rho \to \pi\pi$ channel open in the dark sector?

Particle multiplicity is NOT a good variable (except if >>> SM, as in SUEP)

For DV searches it is critical though, so develop inclusive approach: e.g. bin in # DV

Problem and goal

SK, J. Shelton, D. Xu: To appear

Problem:

- The pythia 8 hidden valley module allows for a tremendous amount of freedom, which is bewildering when trying to scan the parameter space
- Pythia has no opinion on how the dark pions should decay and with what lifetime

Goal:

- Inject some additional theory prejudice to help pick benchmarks
- Implement decays for various well motivated portals:
  - Higgs portal
  - dark photon portal
  - Vector portal
  - Gluon portal
  - Photon portal

→ Predict branching ratios and lower bound on $c\tau$

↓

Predict lower bound on mass

EVENT ISOTROPY

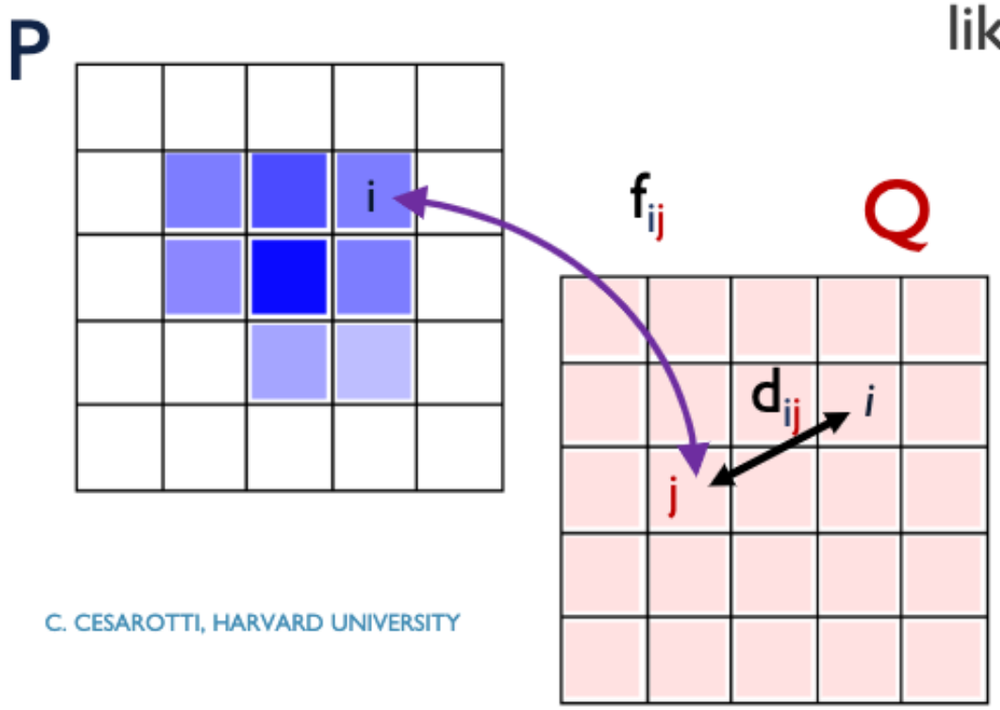
We propose a new event shape observable: event isotropy

CC, J.Thaler 2020

Energy mover's distance (EMD):

P. Komiske, E. Metodiev, J.Thaler 2019

What is the minimum work to rearrange the energy distribution in event *P* to look like event *Q*?



$$\mathrm{EMD}(P,Q) = \min_{\{f_{ij}\}} \sum_{ij} f_{ij} d_{ij}$$

f_{ij} : energy transported

d_{ij} : distance measure

$$f_{ij} \geq 0 \qquad \sum_{ij} f_{ij} = E_P^{\mathrm{tot}} = E_Q^{\mathrm{tot}} = 1$$

Promising future directions:

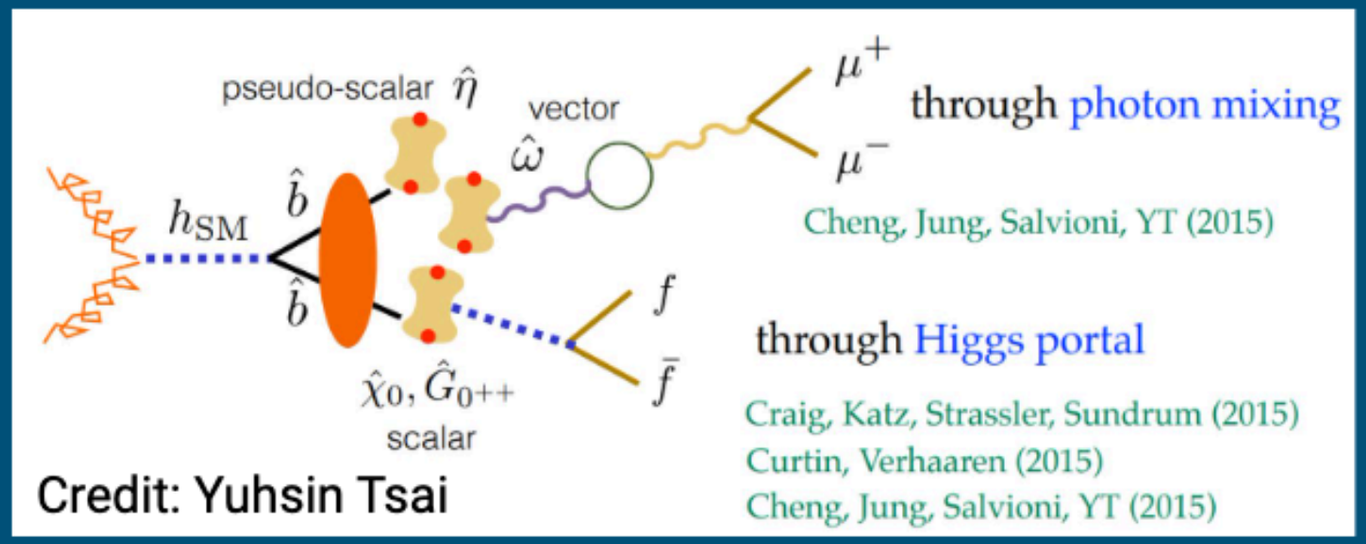
- New & faster algorithms
- Effects of pile-up

Conclusion

- CMS Dark QCD program is expanding
  - Investigating semi-visible jets, emerging jets, SUEPs
- Generators work sufficiently to provide signal samples to optimize and interpret analysis results
  - But many wish list items to improve capabilities
  - Generator uncertainties are a hot topic
- Currently, primarily jet-based trigger strategies are pursued
  - Other strategies ($\not{E}_T$, displaced, etc.) under consideration
  - Future prospects are good: L1 track trigger, anomaly detection
- Simulation and reconstruction also pose some (technical) challenges
- Look forward to more Run 2 results soon!
  - Later: Run 3 and Phase 2 datasets will improve statistical limitations

Lots of improvements in the pipeline especially on the trigger side

We do search for displaced (see Igor's talk):



Credit: Yuhsin Tsai

- (b-, c-)jets (e.g. EPJC 77 812):
  - Removal of **hardware trigger** (softer tracks for clustering).
  - Jet substructure for Run 3?
- Muons (e.g. PRL 124 041801):
  - Recast the results in your favorite model, see JHEP 10 (2020) 156.

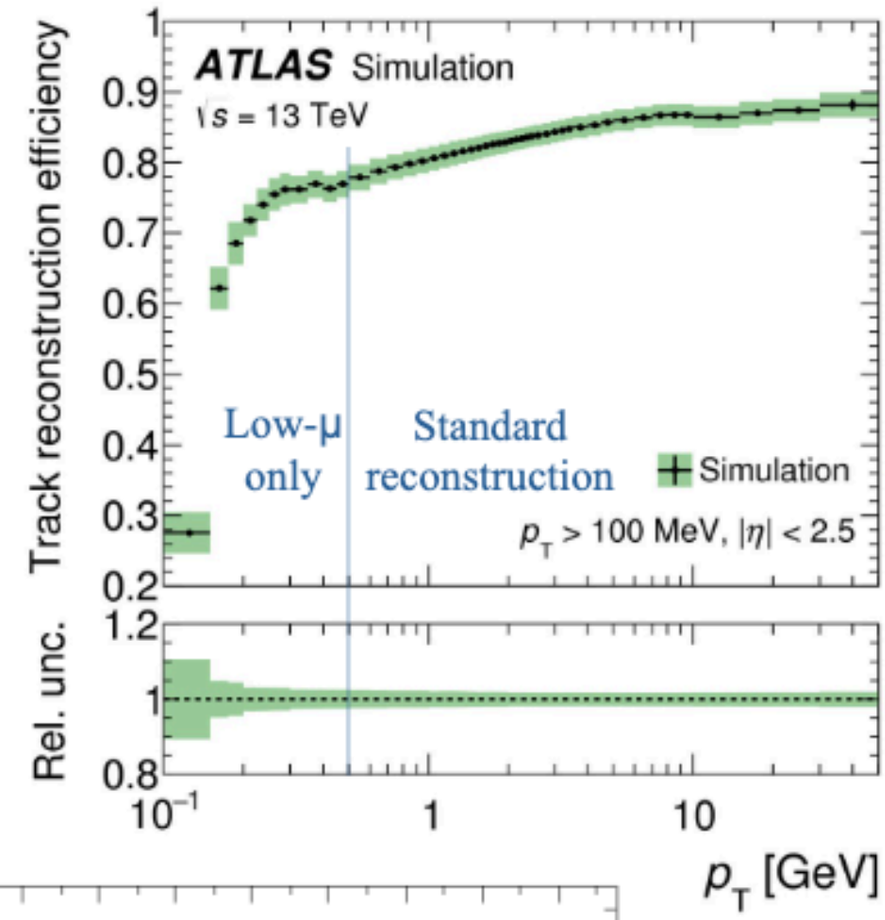
- **Hadron (K, π) vertices (e.g. low mass dark showers):**
  - Higgs → dark (scalar) hadrons → ... → SM hadrons
  - Dark hadron mass range ~ O(GeV), final states considered: K+K-, π+π-
    * very hard for ATLAS and CMS
  - **Physical backgrounds (other than material interactions and fakes):**
    - Strange (Ks, Lambda) - long-lived, **easy to veto**
    - Charm and beauty - displaced, tau ~ O(ps) (too many different decays - **hard to veto**)
  - Good sensitivity to large (>2) dark hadron multiplicities in LHCb acceptance!

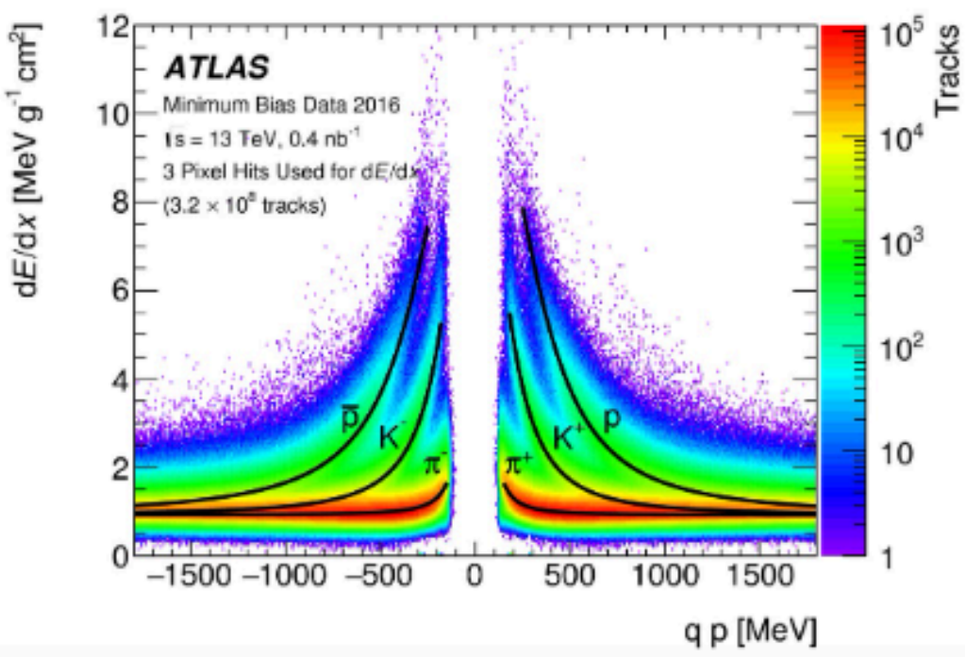
tl;dr - if your model predicts a low mass (less than 100 GeV) LLP, with soft final state particles - O(MeV) for leptons, O(GeV) for hadrons and no invisibles (not more than one 😊) - LHCb is your friend!

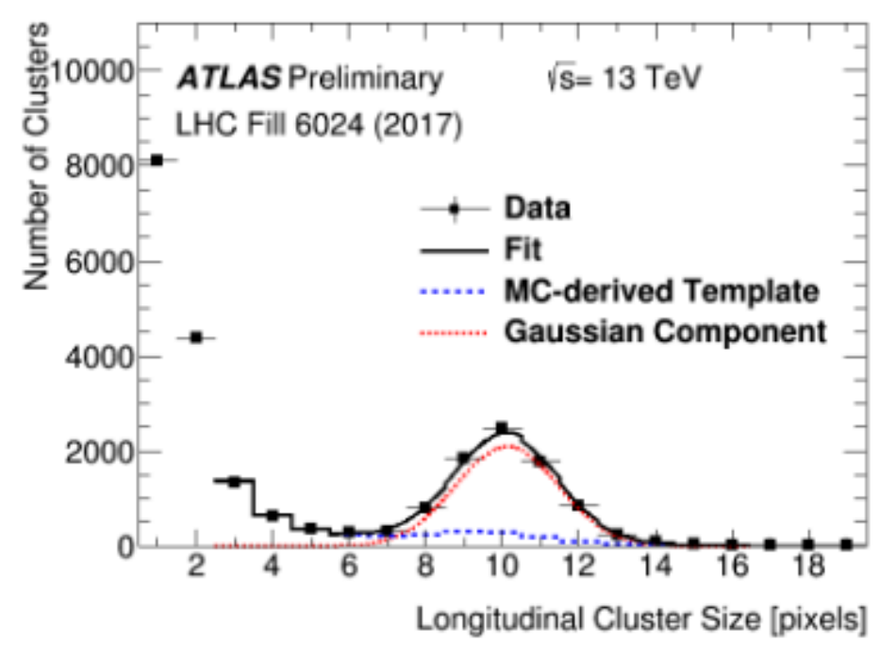
Carlos Vázquez Sierra

Low p_T activity - II

- Charged particles: inner tracker tracks
  - Large combinatorics, CPU time / disk space limit minimum p_T (compromise)
  - Several dedicated reconstruction setups (been, being and to be) developed need some "pre-selection" of interesting data
  - Synergy in pushing boundaries of what we can reconstruct and maintain flexibility in running custom reconstruction algorithms
- dE/dx, cluster shapes aid to tracking or stand-alone







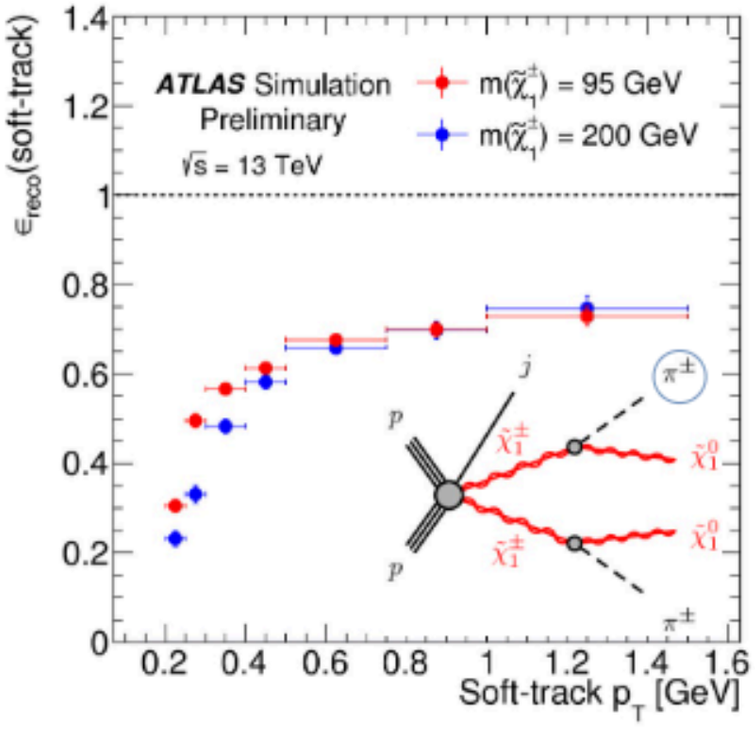
e.g. separating clusters on the outer modules of IBL coming from the IP

Displaced Vertices

- Wish to relax cuts on track multiplicity / m(DV) / ...
  - Suppress higher background with other handles: large multiplicity, other prompt activity, … ?

Valuable message for theorists!

- … and track p_T!
  - Soft-displaced activity seems hard, but not impossible:
    - e.g. disappearing track dev →
    - Need some sort of "seed" to focus reconstruction, e.g. a DV



- Larger pile-up → larger combinatorics
  - Need aggressive R&D to use at the best upcoming luminosity

Snowmass

If you'd like to get involved & timelines

- Timeline:
  - We aim at first draft of white paper around May 2021
  - Submission deadline for Snowmass whitepapers is end of July 2021
- We are creating shared documents / repositories to share information
  - A common github community is created here, we are committing model files and their documentation
- Mailing list <<dark-showers-snowmass21>> can be subscribed to via CERN e-groups - feel free to sign up if you want to get involved!
- More information
  - Link to our Letter Of Intent is here
  - Link to our meetings is here
  - Next meeting in about three weeks, doodle will be circulated on the mailing list

Dark showers session -- conclusions and next steps

The following topics have been extracted from the live notes of the session as potential topics that can be developed in future meetings / activities

- Investigation of LHCb constraints on e.g. dark pion mass range for ATLAS/CMS dark shower benchmarks [see also this paper]
- Compile a list of theory/experimental suggestions for future dark shower searches (e.g. "inclusive approach" as in slide 6 / "extra handles for suppressing background in given signatures" in slide 12)
  - Also interplay with reinterpretation WG
- [general] Identify measurements that can cross-checks anomalous signatures / events in tails with small SM uncertainties
- Connect experimental software community with tools / generator community to help with implementations towards speed-up of calculation time and validation [happening in Snowmass effort]

Astrophysics, cosmology, and dark showers

Many good ideas explored, with not enough time to cover them in detail

- What can we get away with regarding production of dark shower and final decay modes?
- Would it make sense to do a “zoology of the shower” (similar to simplified-models approach)?
- Classification of models that you could write down (possibly IR-confining spectra, # of flavors, # of colors…)
- These exercises could illuminate space of signatures for experimentalists

→ Outcome: Potential dedicated workshop on dark showers and astrophysics, in collaboration with astro theorists, as well

Further coordination

Snowmass 2021 dark showers CERN egroup (from Suchita):

dark-showers-snowmass21

Mattermost channel as a possible coordination resource:

https://mattermost.web.cern.ch/llpcommunity/channels/dark-showers

To join:

https://mattermost.web.cern.ch/signup_user_complete/?id=5jhtr4fen78g5goscy55kgddfh