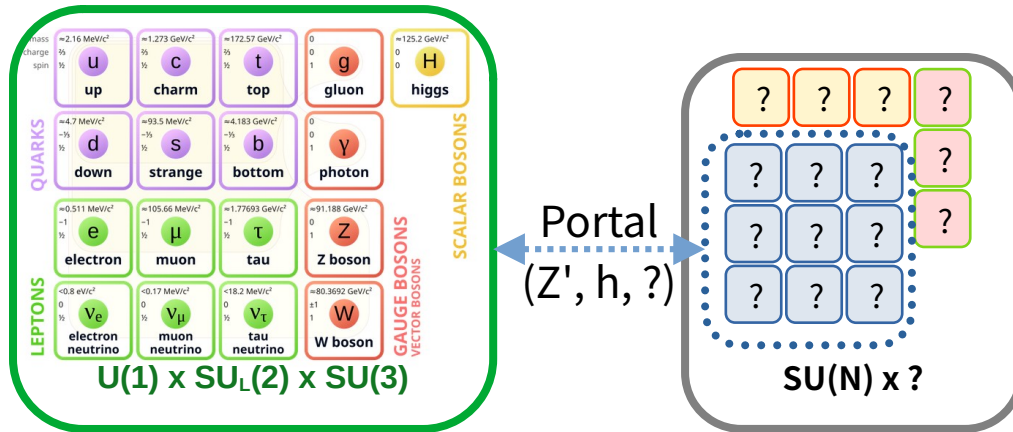


Report from the dark shower task force

Yi-Mu Chen, on behalf of the LHC dark shower task force
LHC BSM working group general meeting

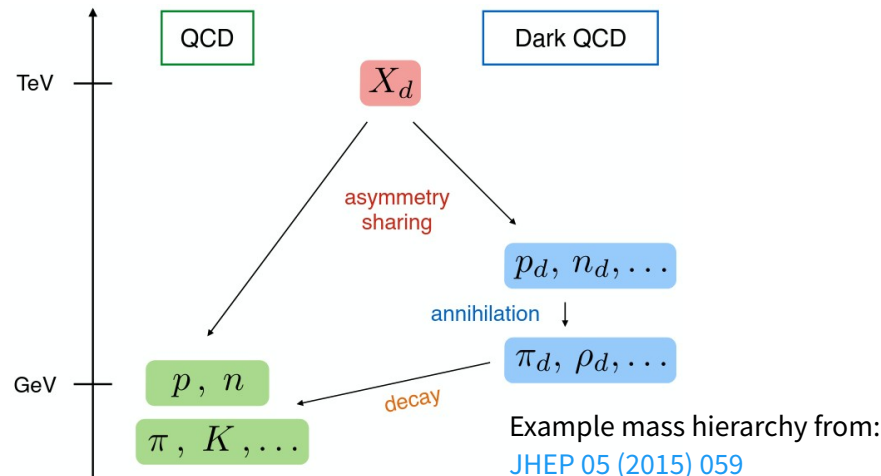
2025.Nov.10

Overview of the dark sector models



New sector of particles with QCD-like, self-confining strong interactions*

- Provide dark matter candidates
- Provides explanations for hierarchy problem/neutral naturalness
- Some portal to SM that is probe-able with LHC experiment



Rich phenomenology depending on dark sector dynamics!

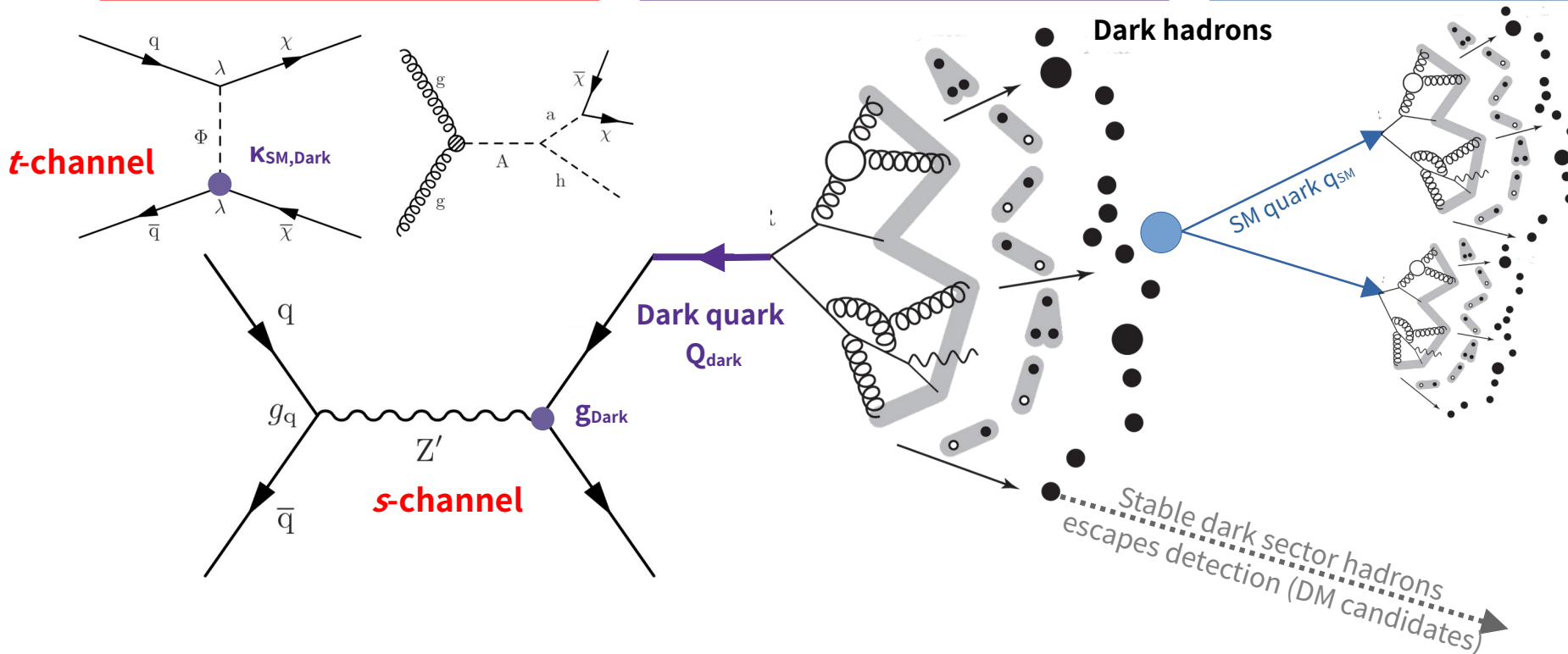
(*[Phys. Lett. B651:374-379, 2007](https://arxiv.org/abs/hep-th/0605209))

Stages of Dark showers

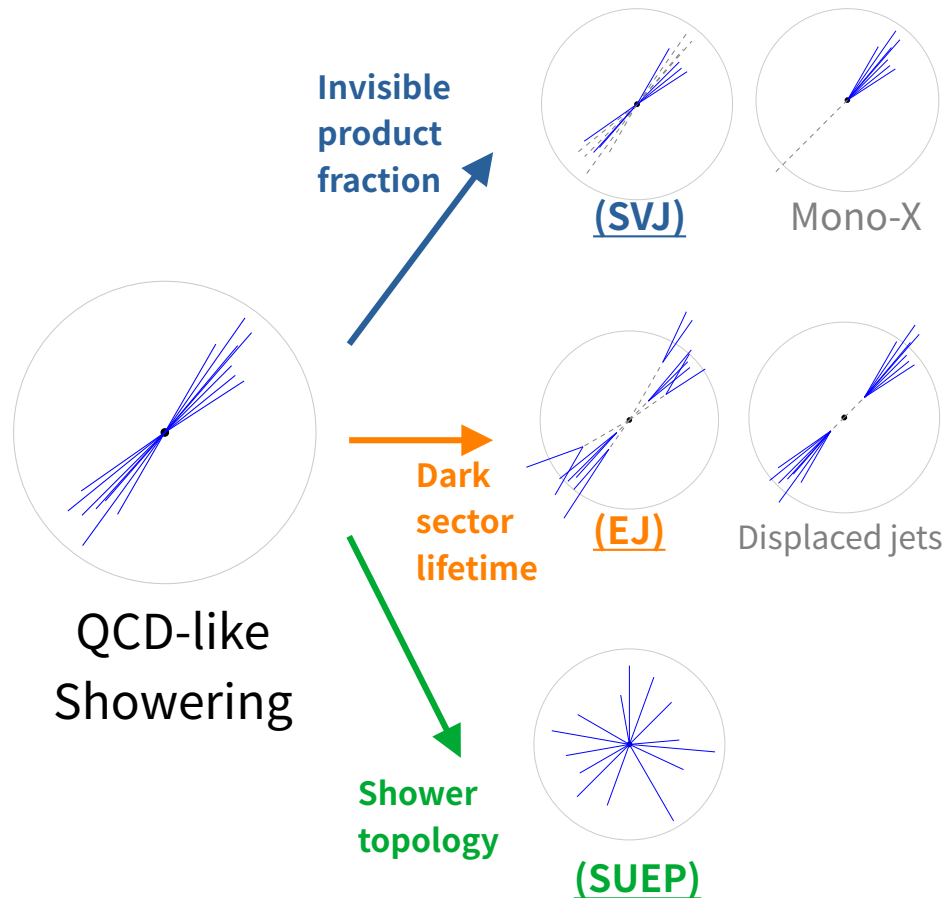
Mediator production

Dark sector showering/hadronization

SM showering / hadronization / decay



Existing search efforts at LHC



Semivisible jets (SVJ):

- ATLAS t-channel non-resonant (Run 2) [Phys. Lett. B 848 \(2024\) 138324](#)
- ATLAS s-channel (Run 2) [Phys. Rev. D 112 \(2025\) 012021](#)
- CMS s-channel, hadronic (Run 2) [JHEP 06 \(2022\) 156](#)
- CMS s-channel, leptonic (Run 2) [CMS-PAS-EXO-24-029](#)

Emerging jets (EJ):

- ATLAS t-channel pair production (Run 2) [ATLAS-EXOT-2018-20](#)
- ATLAS s-channel (Run 3) [Rep. Prog. Phys. 88 \(2025\) 097801](#)
- CMS t-channel pair production (2016): [JHEP02\(2019\)179](#)
- CMS t-channel+flavor structure (Run 2): [JHEP 07 \(2024\) 142](#)
- CMS s-channel (Run 3, reinterpret): [Rep. Prog. Phys. 88 \(2025\) 037801](#)

Soft uncluster energy pattern (SUEP):

- CMS ggF production (Run2): [Phys.Rev. Lett. 133. 191902](#)
- CMS WH production (Run 2): [CMS-PAS-EXO-23-003](#)
- CMS ZH production (Run 2): [CMS-PAS-EXO-24-030](#)

Goal of dark shower task force

- Establish common benchmark models and descriptions
- Refining dark shower modeling and simulations
- Facilitate cross-collaboration between experiments and theorists

Benchmarking – common model descriptions

“Top-down”, theory-motivated approach

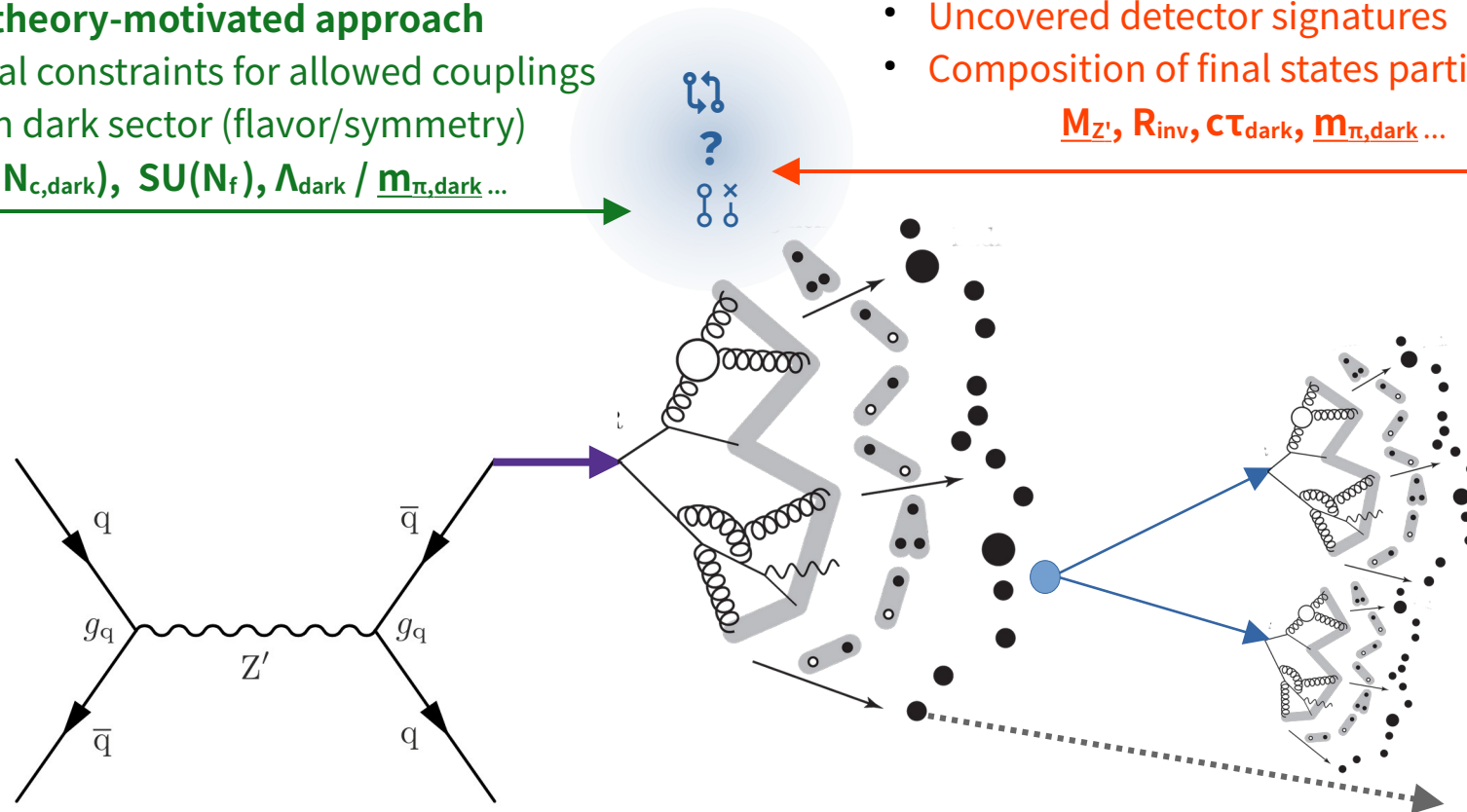
- Cosmological constraints for allowed couplings
- Structures in dark sector (flavor/symmetry)

$M_{Z'}$, $SU(N_{c,dark})$, $SU(N_f)$, Λ_{dark} / $m_{\pi,dark} \dots$

“Bottom-up”, Pheno-motivated approach

- Uncovered detector signatures
- Composition of final states particles

$M_{Z'}$, R_{inv} , CT_{dark} , $m_{\pi,dark} \dots$



Towards a common benchmark model

Can we formulate a “reasonable” model set that spans existing phenomenological search space?

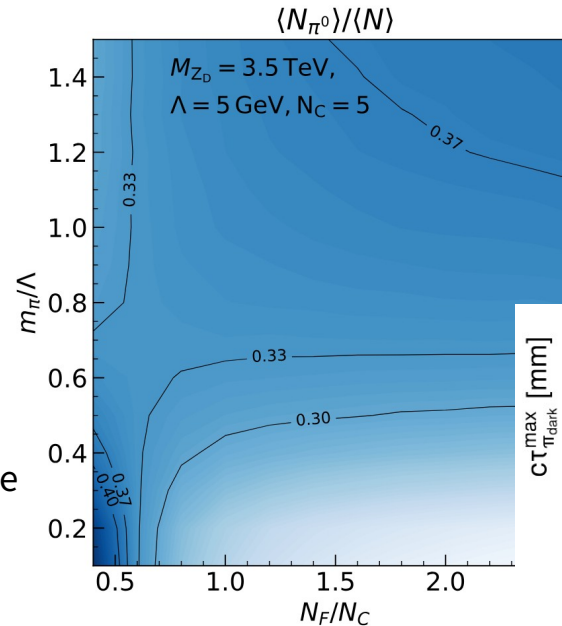
- Example candidate frameworks (still in discussion):
 - s-channel: Z', Higgs
 - t-channel: [JHEP06\(2025\)198](#)
 - Others?

Ongoing discussions:

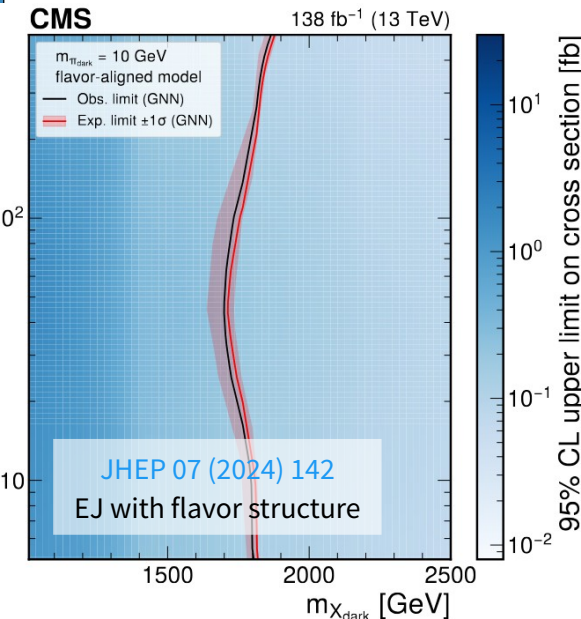
- How to prioritize degeneracy between different phase space parameterization schemes? (ex: r_{inv} v.s. N_F/N_C)
 - More works still needs to be done for $1 \rightarrow 3$ decays
- Most expressive method for displaying results?

Commonly used: ($m_{\text{Med}}, r_{\text{inv}}$), (m_{Med} v.s. $c\tau$)

There has been cases where “observables” is not optimal (right)



Long-lived dark hadron fraction as function of theory parameters
[Phys.Rev.D 112 \(2025\) 7, 075029](#)



Towards a common benchmark model

Can we formulate a “reasonable” model set that spans existing phenomenological search space?

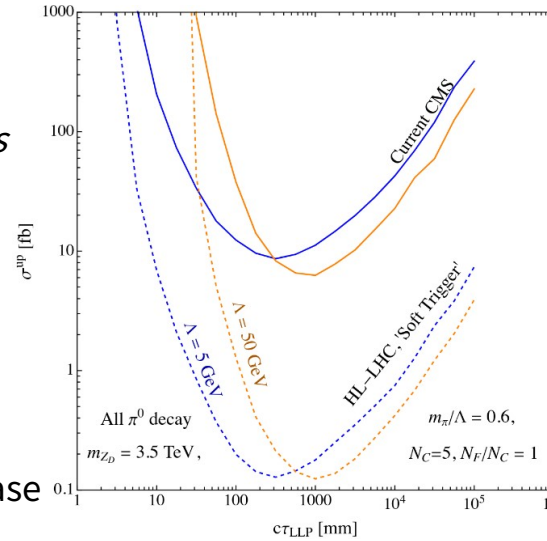
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Ongoing discussions:

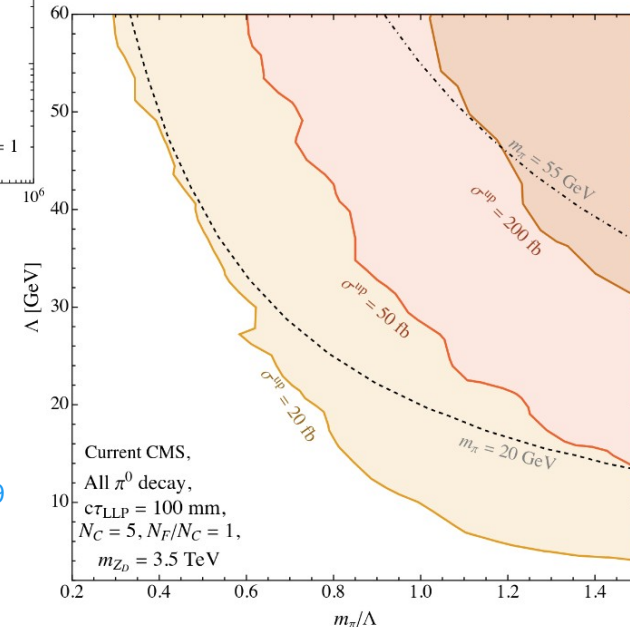
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- Most expressive method for displaying results?

Commonly used: $(m_{\text{Med}}, r_{\text{inv}})$, $(m_{\text{Med}}$ v.s. $c\tau$)

There has been cases where “observables” is not optimal (right)



Example of results reinterpreted with different parameterization
[Phys.Rev.D 112 \(2025\) 7, 075029](#)

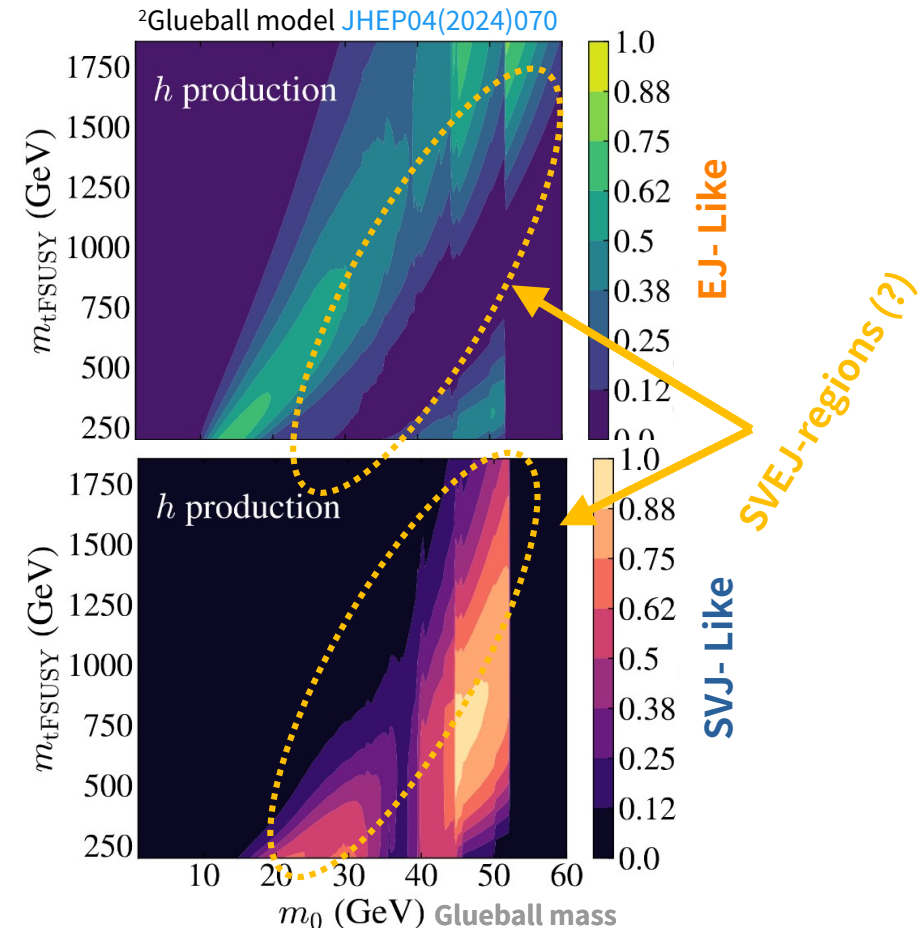


New targets arising from benchmark model

Several “proto-benchmarks” show interesting new signatures!

Example: lifetime spectrums of dark hadrons:

- Additional symmetry structure in dark sector¹
- $N_f=0$ “dark glueball” scenario²
- “Semivisible emerging jets (SVEJ)” looks to be a generic signature for many dark sector models!
 - **How sensitive are existing SVJ/EJ search efforts to these signatures?**
- **What other signatures are uncovered?**



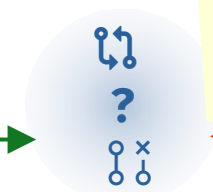
Reinterpreting existing analysis efforts

Lessons from existing comparison efforts

- *Development of common benchmark models (pages 7-9)*
 - Always keep “all” model parameters listed
- *Keep searches “generic”, avoid over-optimization.*
 - **Best method of presenting ML-based results for reinterpretation efforts?**
Just publishing the ML model is not sufficient, as there are non-trivial detector resolution effects rolled in.
 - **Even without ML, what about other detector effects?**

“Top-down” approach

Cover as much “model space” as possible with minimal/elementary assumptions



“Let experimentalist works on experiments, and theorist work on theory”
(How to make this work in practice)

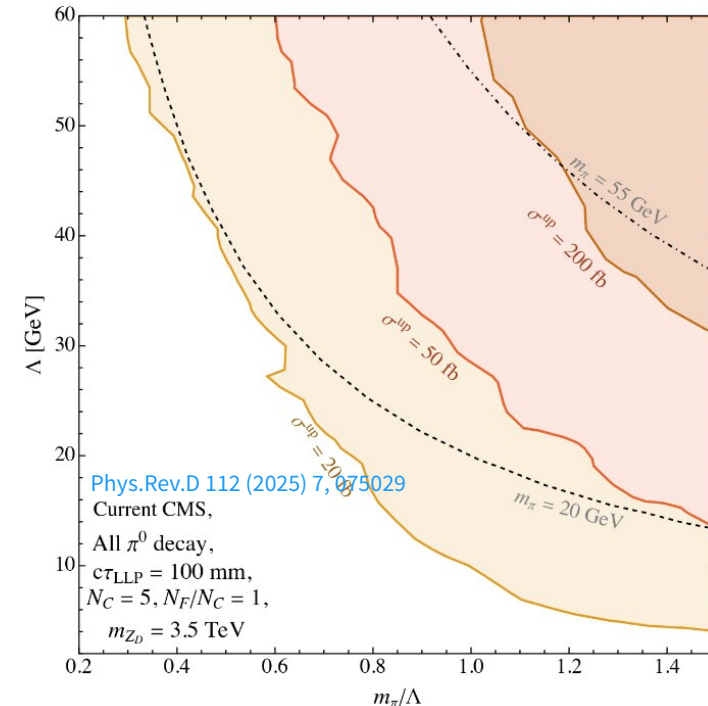
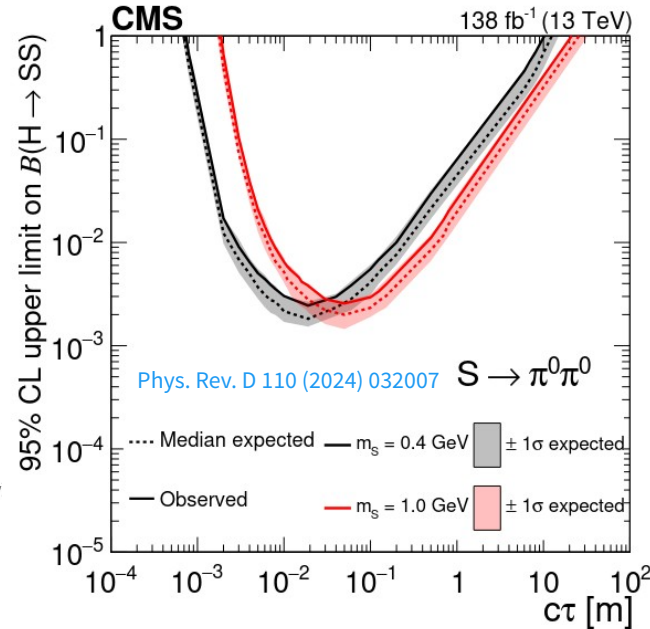
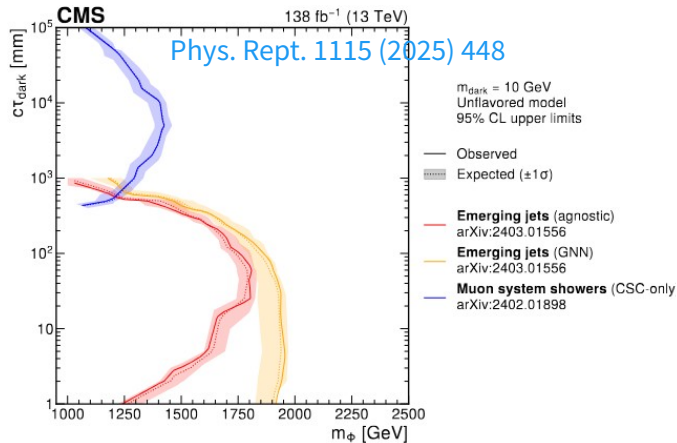
“Bottom-up”, approach

Demonstrate best capability of detectors

Reinterpretation efforts – Muon System

Extending lifetime reach using muon system in CMS:

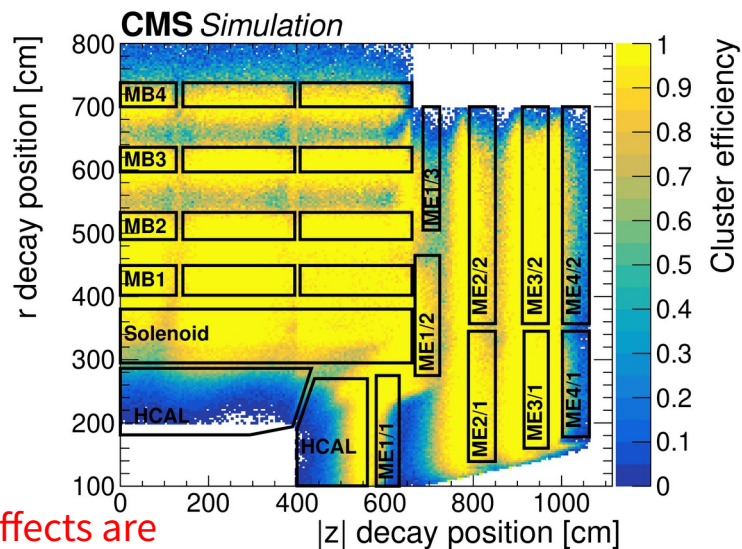
- Large multiplicity of activity in CSC
- Originally designed for low mass LLP shower.
- Reinterpreted for emerging jets by CMS
- Also reinterpreted to other BSM models [1 2](#)



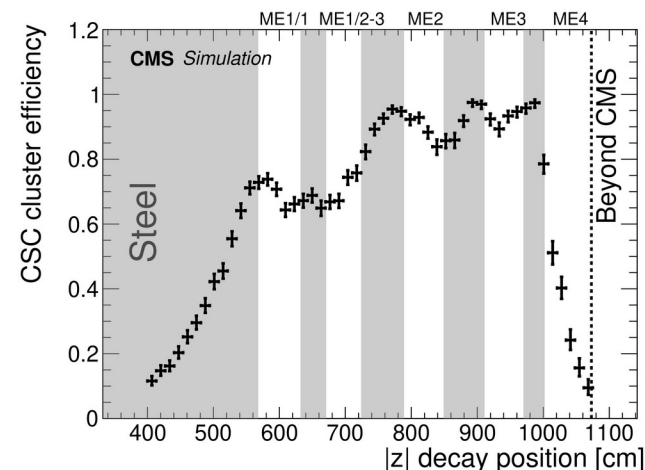
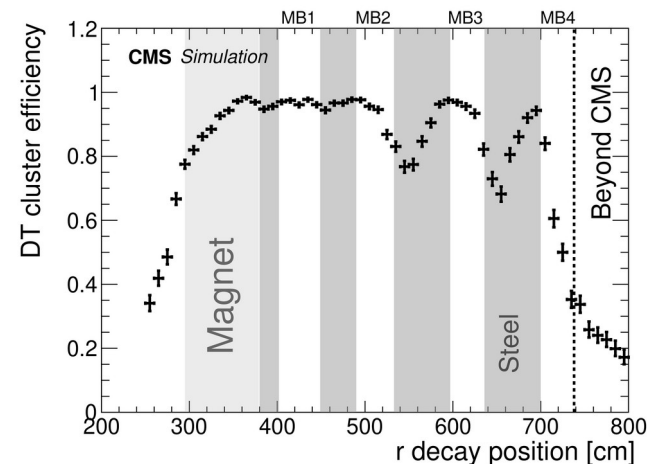
Reinterpretation efforts – Muon System

Extending lifetime reach using muon system in CMS:

- Large multiplicity of activity in CSC
- Originally designed for low mass LLP shower.
- Reinterpreted for emerging jets by CMS
- Also reinterpreted to other BSM models [12](#)

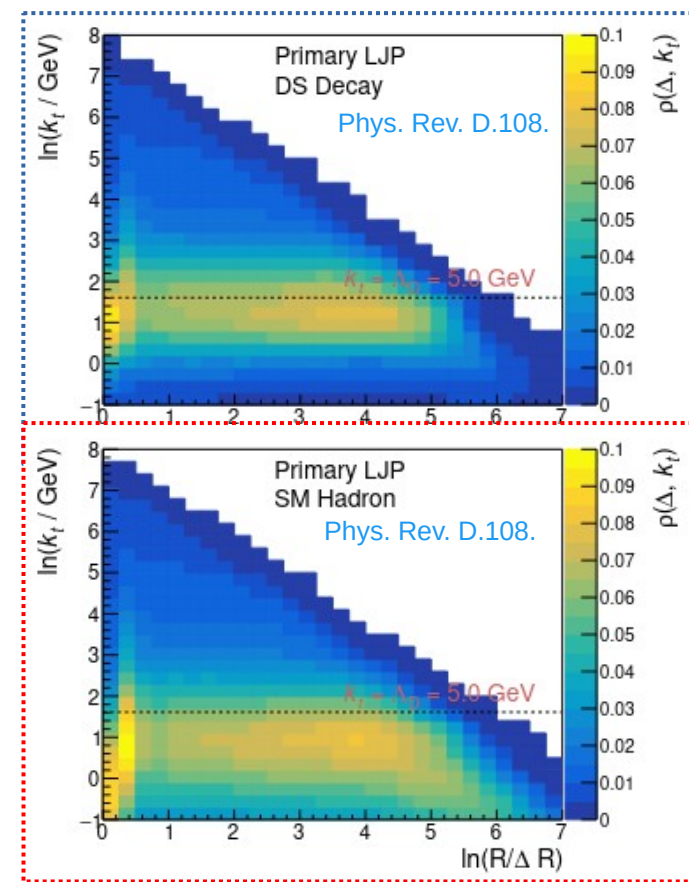
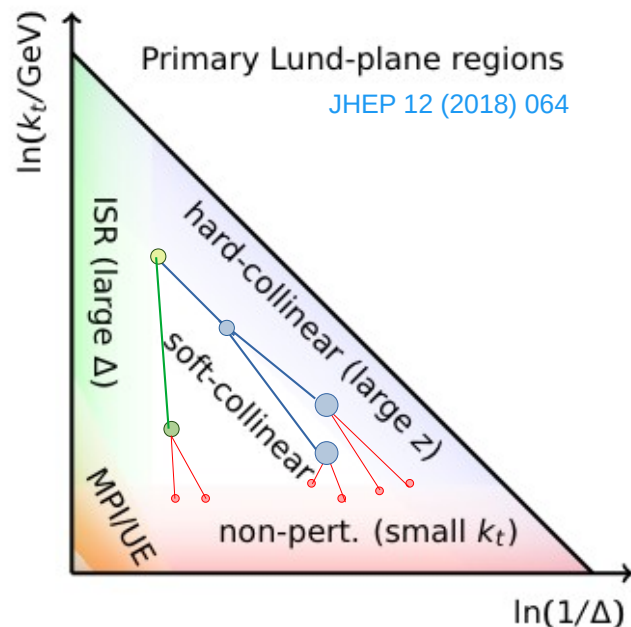
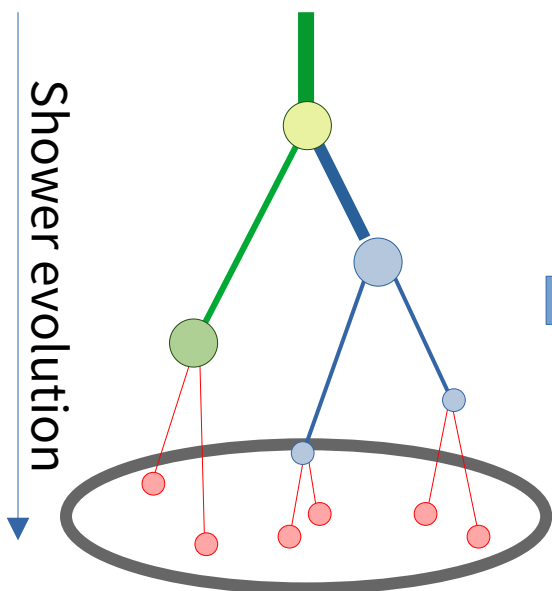


Primary detector effects are provided in digestable format



Common tools - LundJet tagging

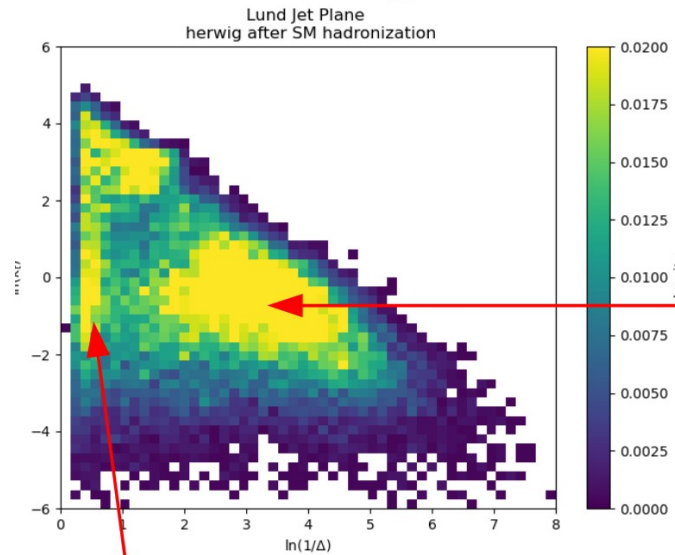
- Reclustering jet constituents as proxy for the particle shower history in the Lund plane
- Multistage showering benefits greatly from the extraction of this information for jet tagging!



Common tools - LundJet tagging

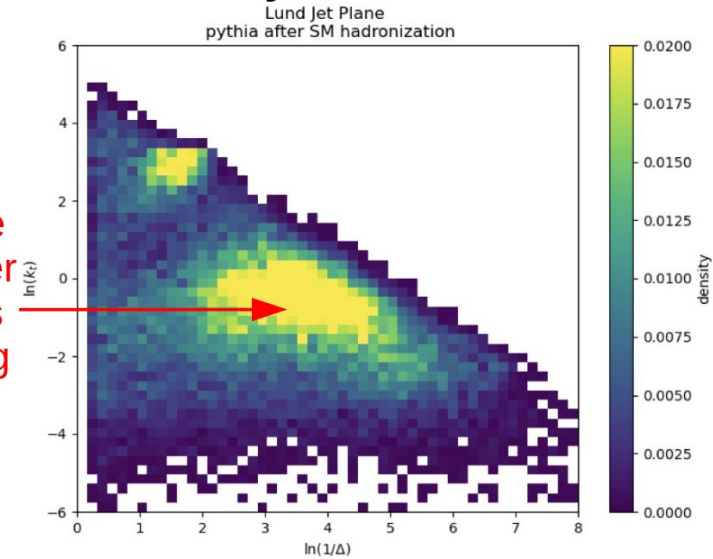
- Also a helpful tool for studying generator differences and uncertainties!
 We want to make sure analysis efforts do not fixated on generator implementation details

Herwig (7.4 preliminary)



Some difference
 in shape of lower
 energy splittings
 – QCD modeling
 also important

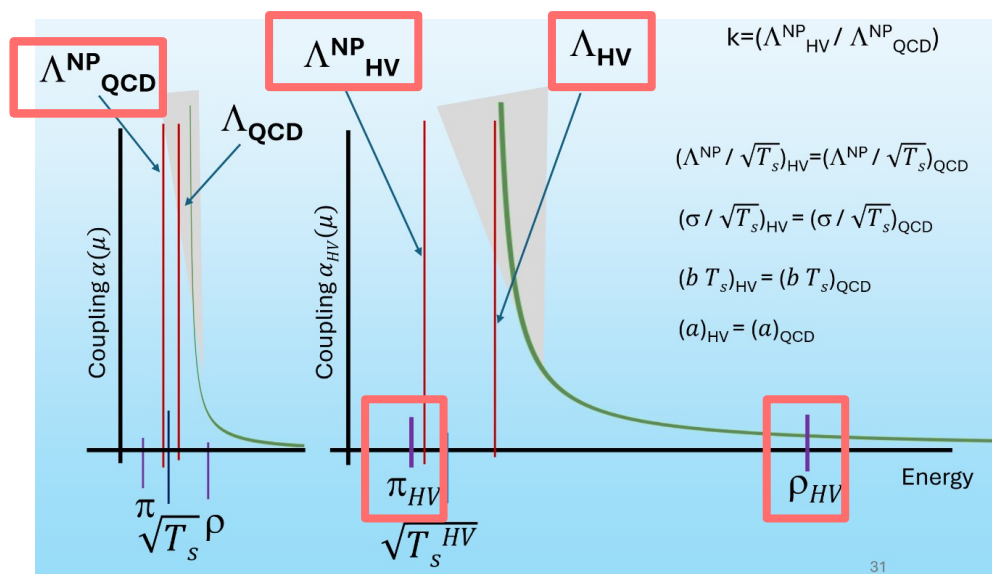
Pythia (8.312)



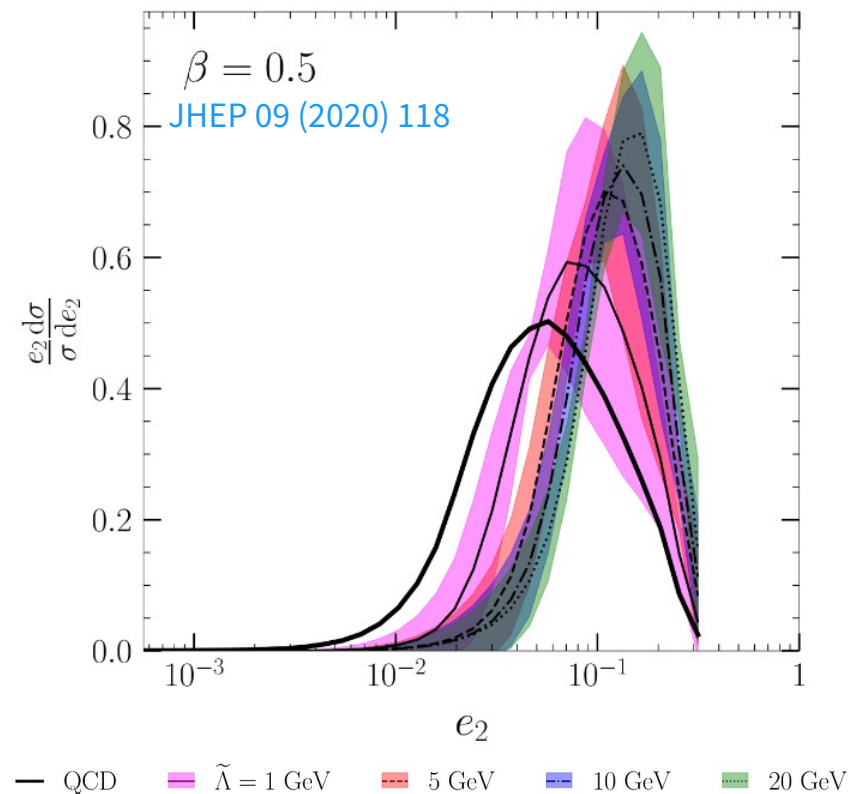
23 Lower energy large angle
 splittings - ρ_D at edge of jet?

Development of generators studies

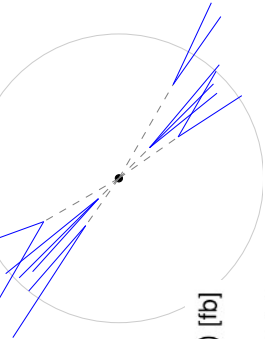
- Pythia 8.313 to be released with refined controls on dark sector showering
- Developing uncertainty studies of BSM showering



User adjustable parameters in Pythia 8.313

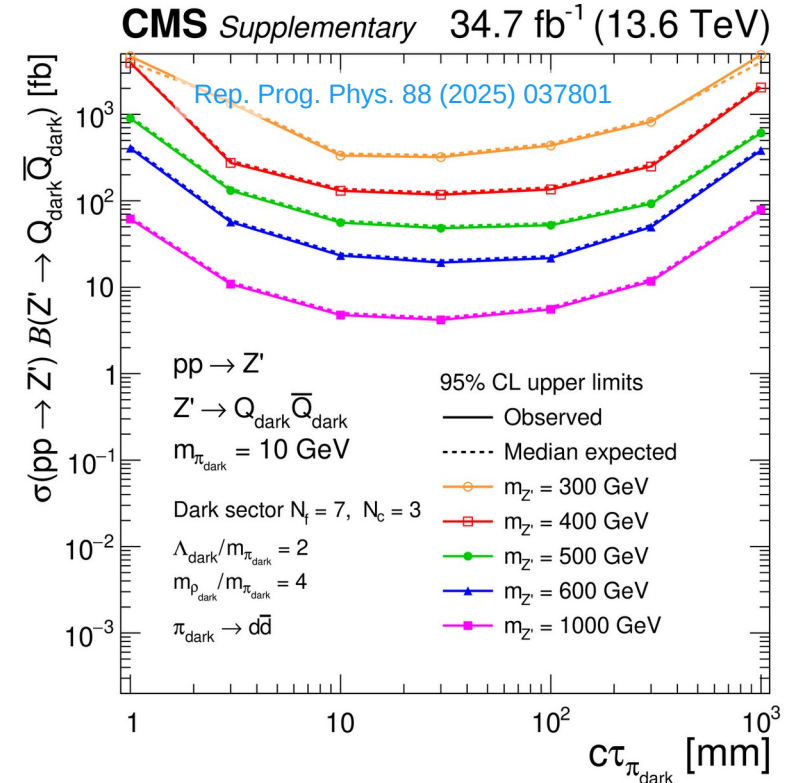
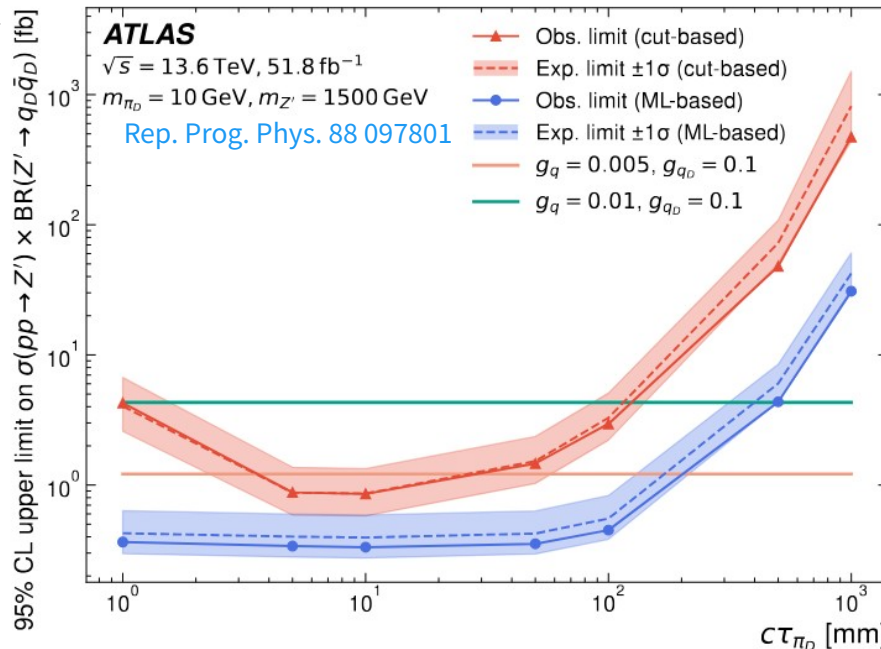


Common tools – trigger design



New triggers developed for Run 3! Directly triggering on BSM jet signature
 Jets composed mainly of displaced tracks

- **ATLAS** dedicated EJ trigger
- **CMS** displaced jet trigger

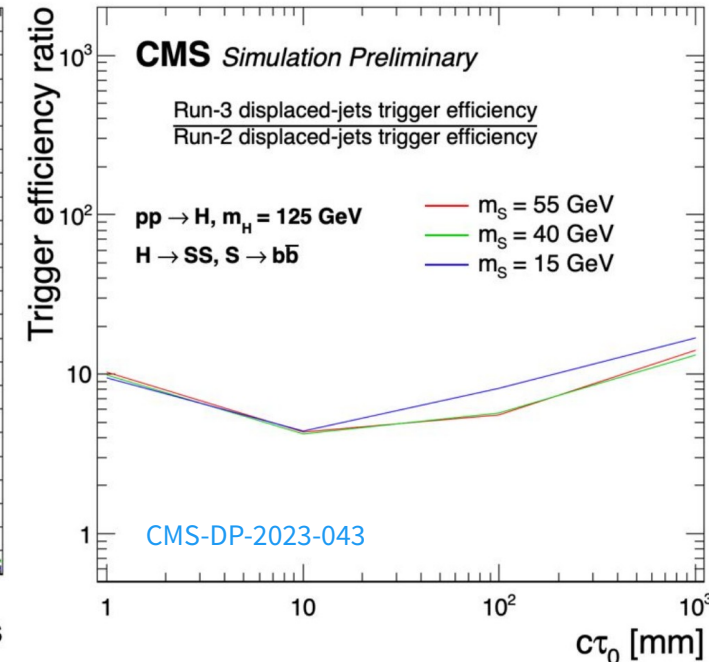
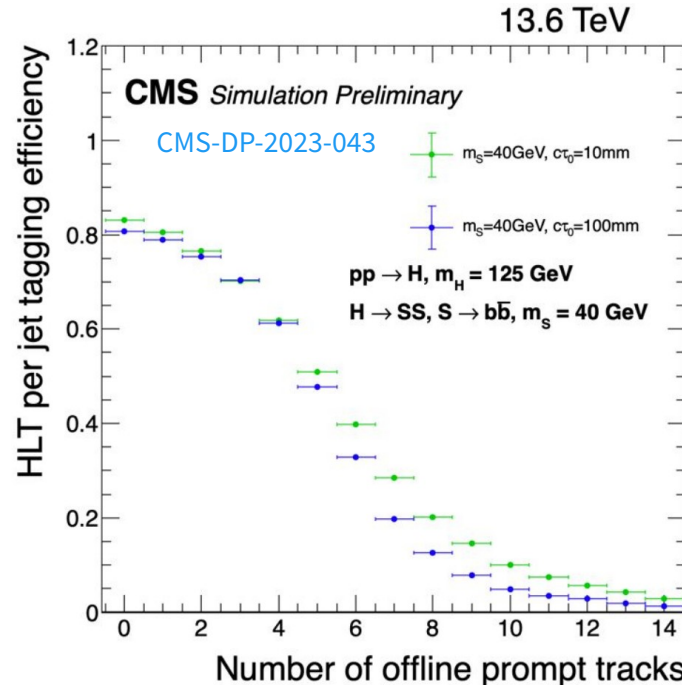


Trigger design for LLP signatures

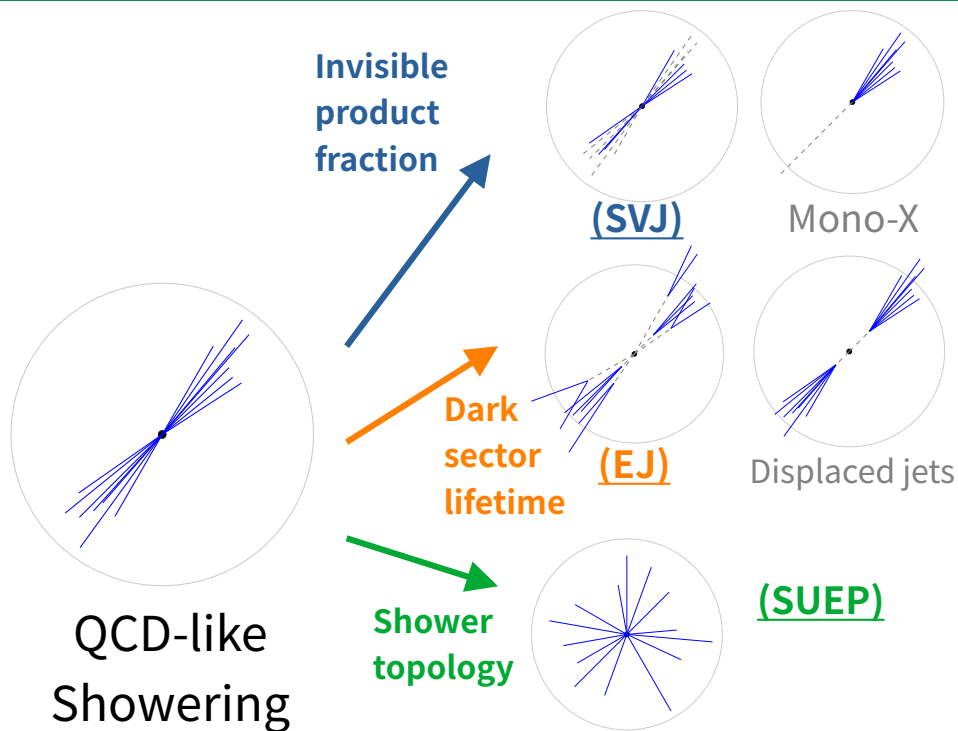
CMS trigger was designed for **Displaced jets** generated from **exotic Higgs decay**:

- Jets cannot contain prompt tracks ($IP_{2D} < 0.5\text{mm}$, $\sigma_{IP2D} < 5$)
- Generically powerful BSM trigger for tracker-based searches!

Cross search-efforts on trigger design can be extremely beneficial!



Many potential paths to take!



- Dark sector generator developments
- Generator uncertainties?
- Dependence on decay modes (3-body decay)

Semivisible jets (SVJ):

- Allowed decay products? “Photonic” SVJ?
- Low mass mediators
 - Low HT data stream (scouting)
 - Boosted topology?

Semivisible emerging jets (SVEJ)?

Emerging jets (EJ):

- Lifetime/flavor structure?
- Detector sensitivity gaps
 - Dedicated trigger v.s. existing LLP triggers

Soft uncluster energy pattern (SUEP):

- Dedicated multiplicity trigger?
- Alternate production topologies?

Anomaly trigger?

Summary of task force goals

Dark shower Workshop, Oct 2025

- **Establish common benchmark models and descriptions**
 - Candidate models in discussion based on snowmass recommendations
 - Exploring new signatures in proto-benchmark
- **Refining dark shower modeling and simulations**
 - Herwig dark shower is nearing release
 - Uncertainties envelope for dark shower in development
- **Facilitate cross-collaboration between experiments and theorists**
 - Common tools for broader BSM community
 - Common methods to best utilize expertise of experimentalists and theorists

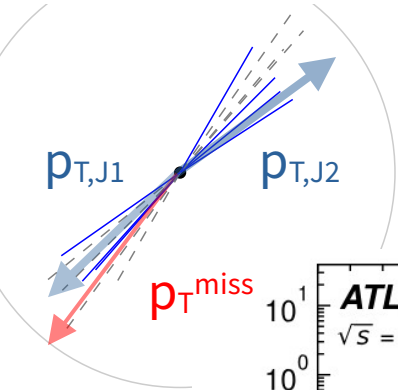


Targetting whitepaper early/mid 2026!

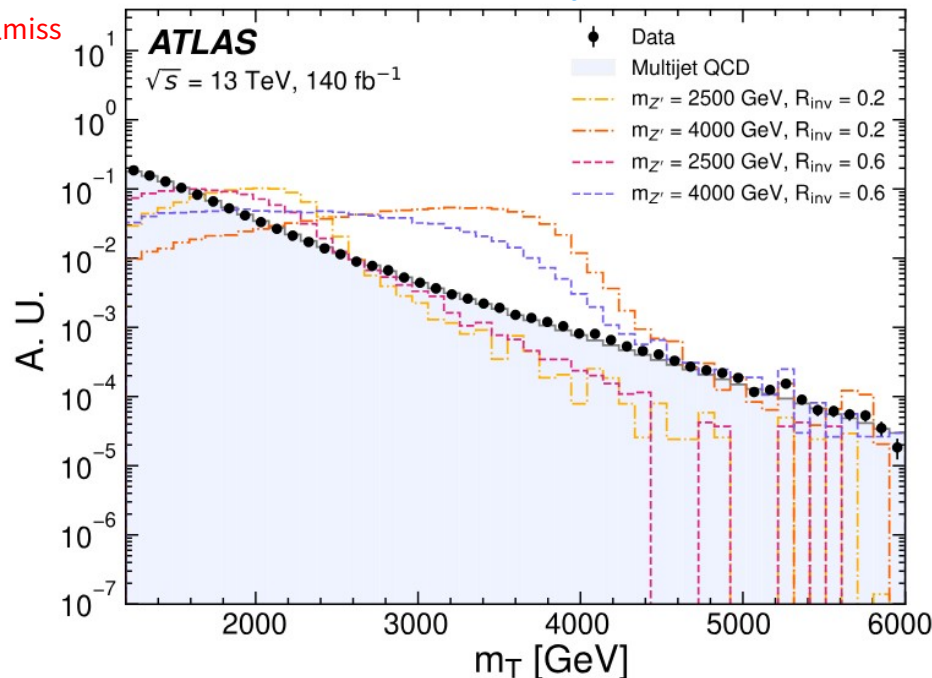
Thanks for you attention!

Supplementary material

Semivisible jets searches - s-channel



Phys. Rev. D 112, 012021



Common signature:

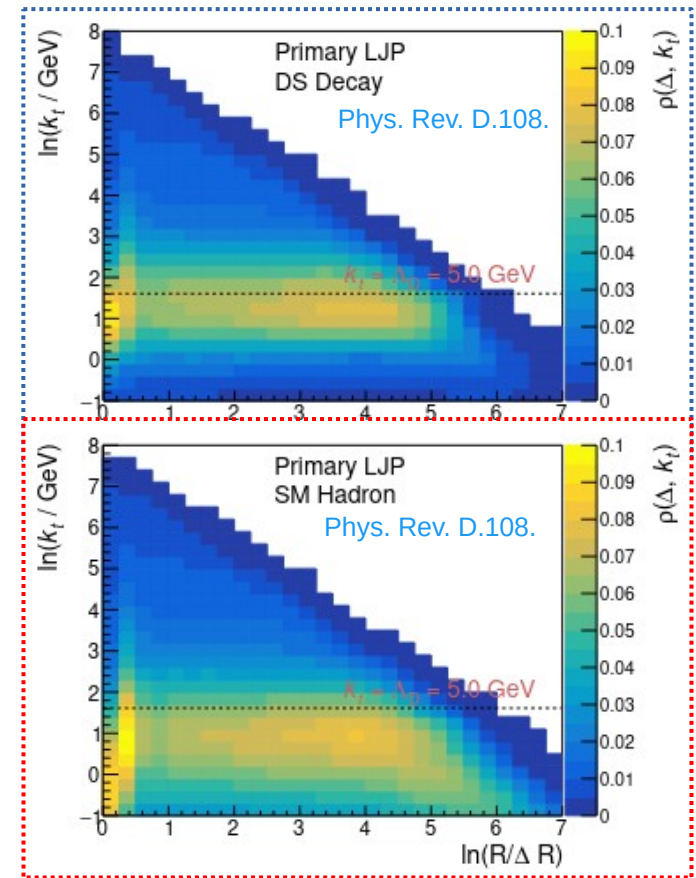
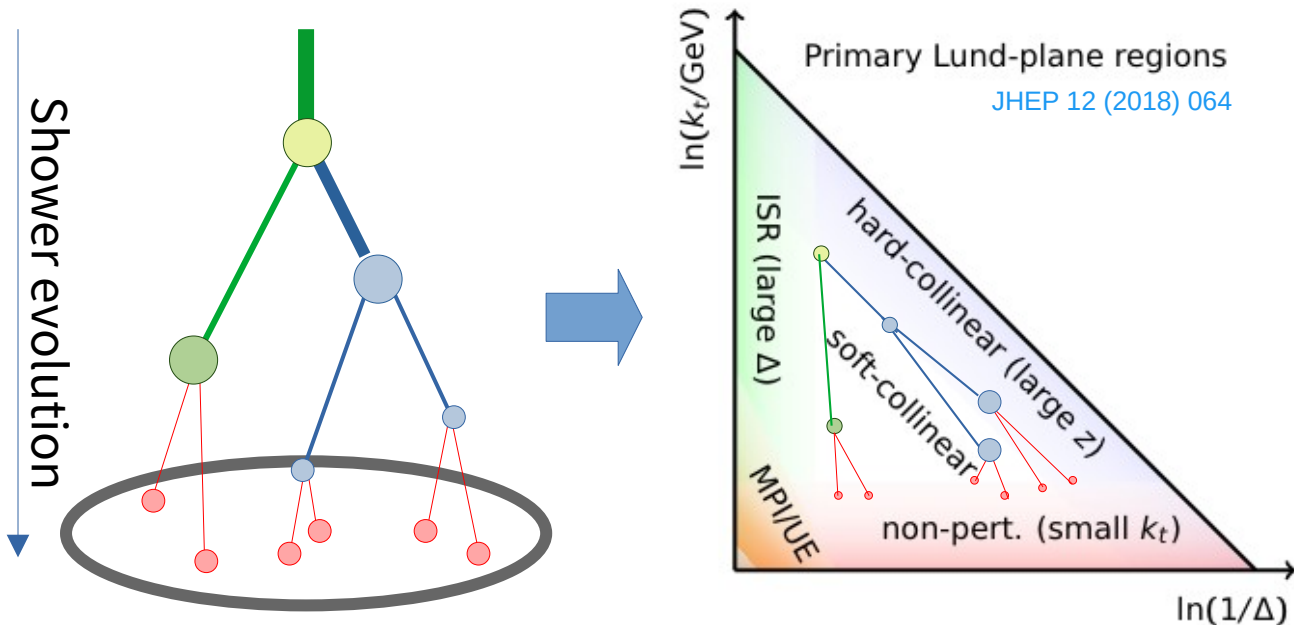
- Modest E_T^{miss} , aligned with di-jet axis
- Bump in di-jet transverse mass m_T :

$$\begin{aligned}
 m_T^2 &= (E_{T,JJ} + E_T^{\text{miss}})^2 - (\vec{p}_{T,JJ} + \vec{p}_T^{\text{miss}})^2 \\
 &= m_{JJ}^2 + 2p_T^{\text{miss}} \left(\sqrt{m_{JJ}^2 + p_{T,JJ}^2} - p_{T,JJ} \cos(\phi_{JJ,\text{miss}}) \right)
 \end{aligned}$$

- Jet structure tagging to boost signal-to-background ratio:
 - Jet energy correlation measures, N-subjettiness, subjet mass... etc.
 - **ML-based tagging**

Semivisible jet - LundJet tagging

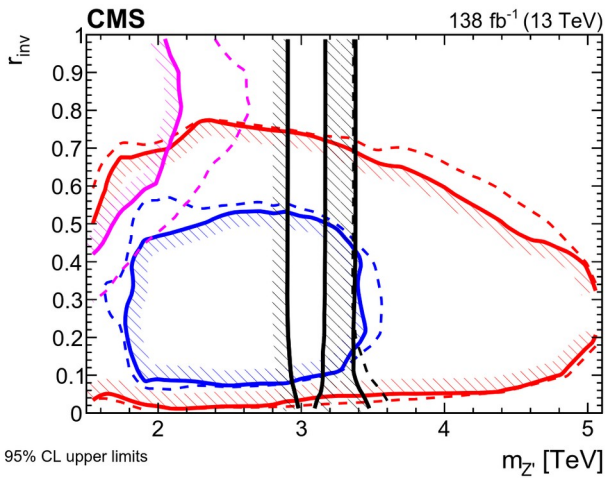
- Reclustering jet constituents as proxy for the particle shower history in the Lund plane
- Multistage showering benefits greatly from the extraction of this information for jet tagging!



Semivisible jet s-channel results

CMS Z' s-channel production

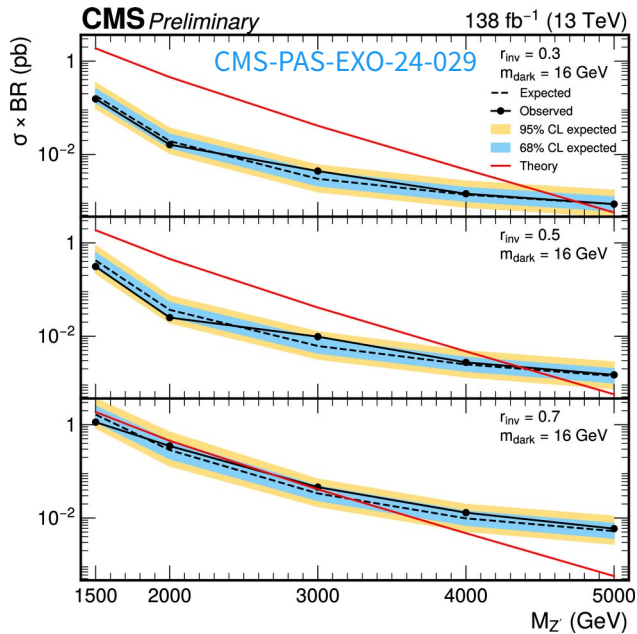
Hadronic (Run 2)
Cutbased/BDT jet-tagging



95% CL upper limits
 $m_{\text{dark}} = 20 \text{ GeV}, \alpha_{\text{dark}} = \alpha_{\text{dark}}^{\text{peak}}$

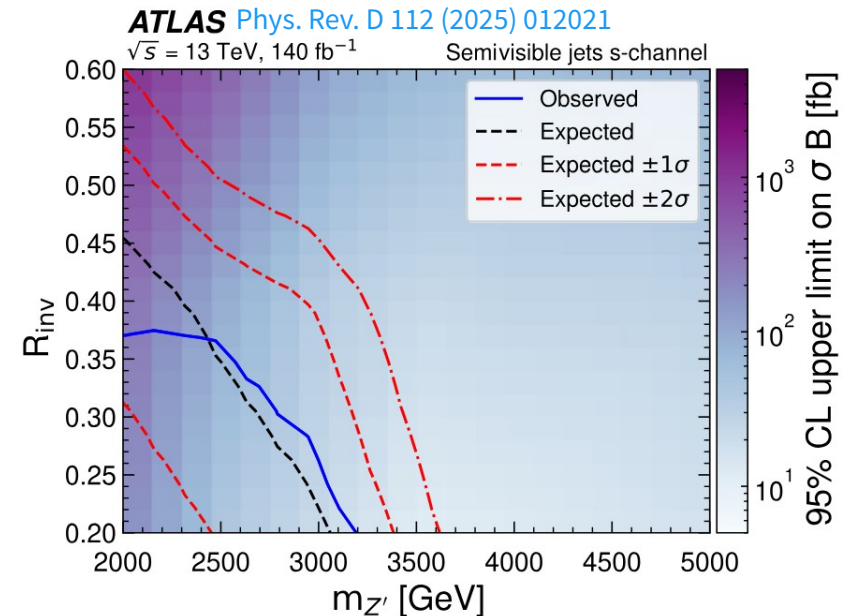
- Observed
- - Expected
- Dijet**
- JHEP 05 (2020) 033
- Monojet**
- JHEP 11 (2021) 153
- Semivisible jet (Inclusive)**
- JHEP 06 (2022) 156
- Semivisible jet (BDT-based, model-dependent)**
- JHEP 06 (2022) 156

Leptonic (Run 2)
Cutbased/Lund jet-tagging

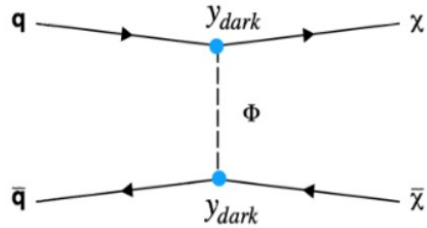


ATLAS, Z' s-channel production

Hadronic (Run 2)
ParticleFlow network (ML)/Anomaly tagging

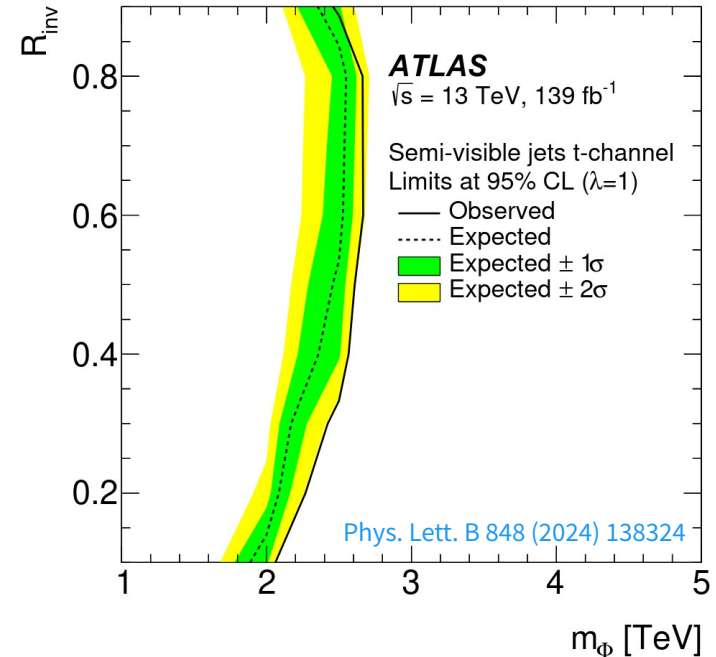
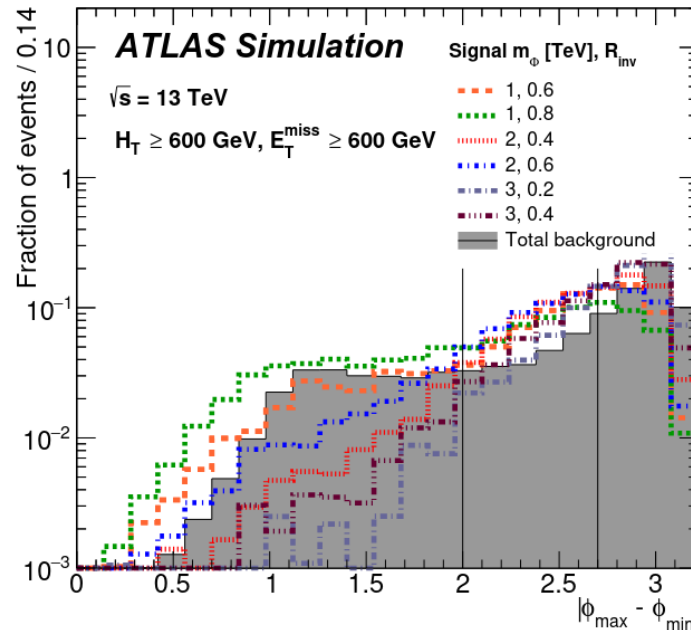
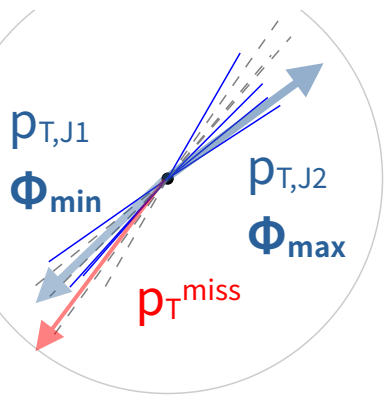


Semivisible jet t-channel



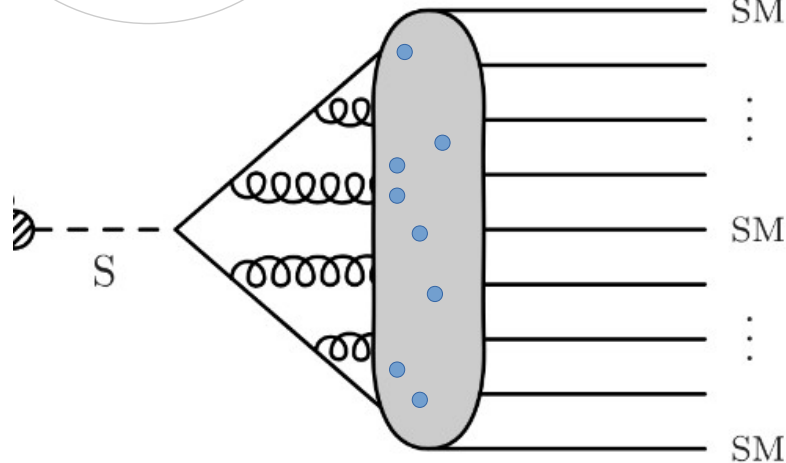
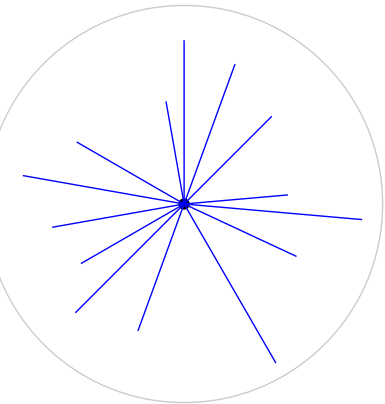
No resonance peak as target variable

- How aligned jets are with p_T^{miss} is key variable
- Lepton veto to eliminate vector boson/top background

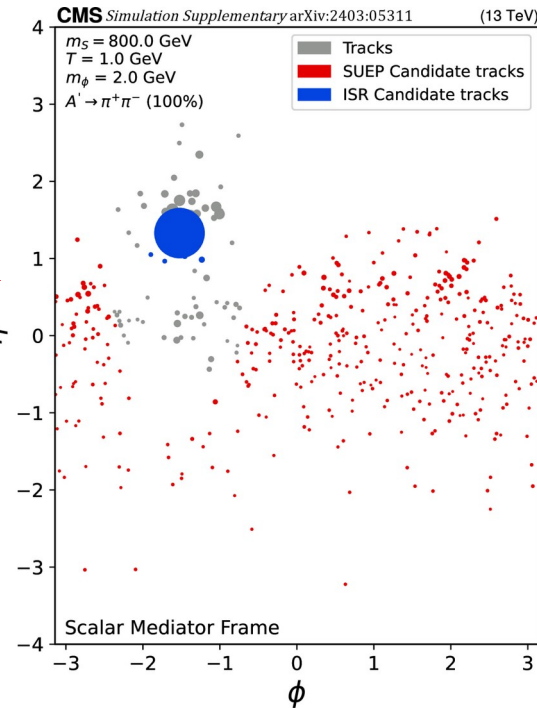
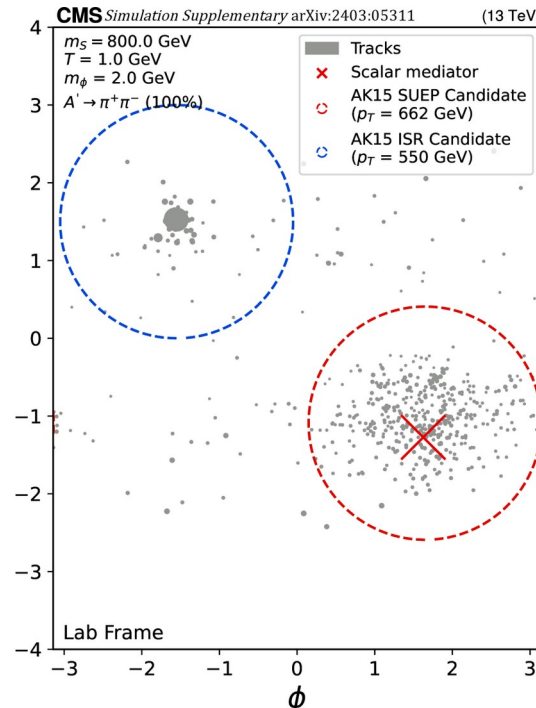


SUEP searches

- Dark shower generates a isotropic spray, not collimated jets
- Recoil off of some SM product
- Recover isotropy signature “ S_{boosted} ” in boosted frame

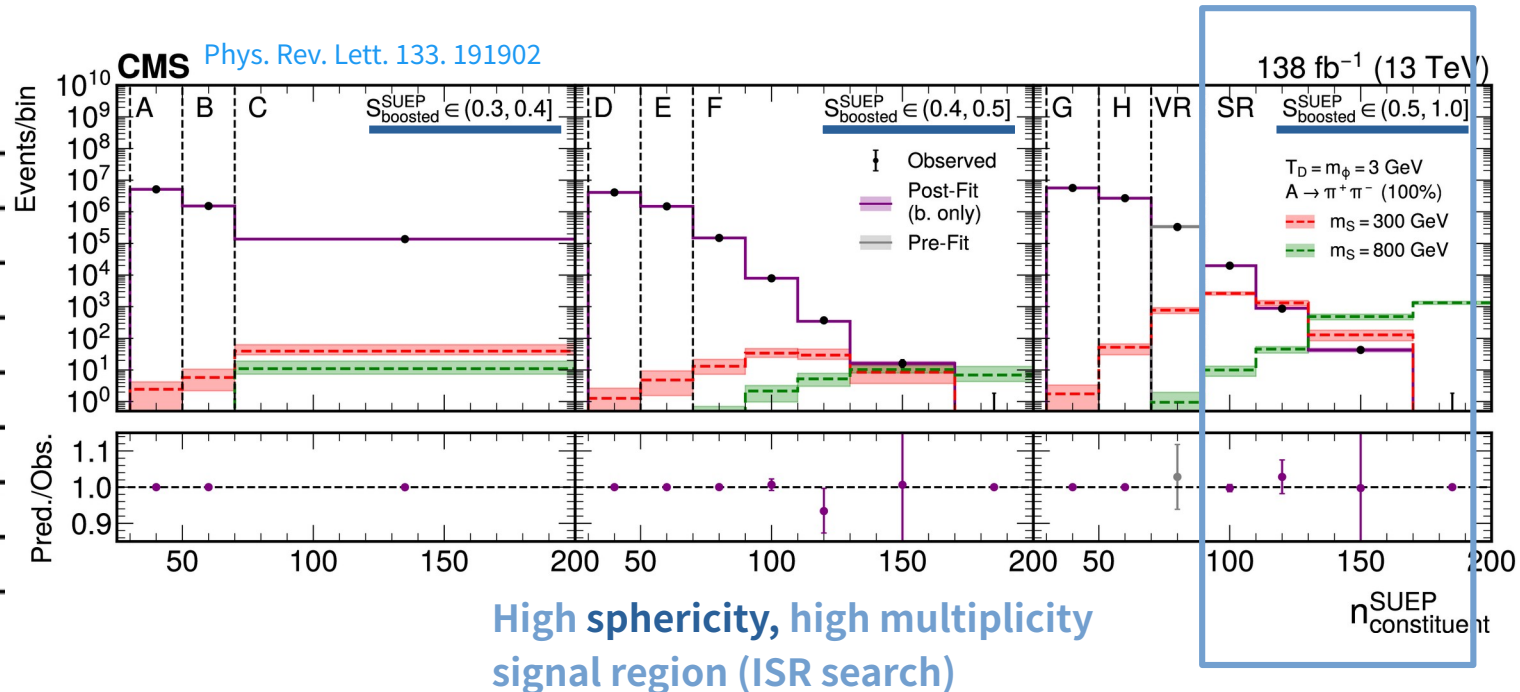
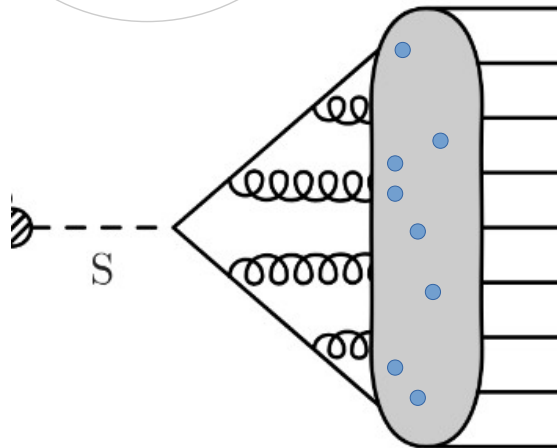
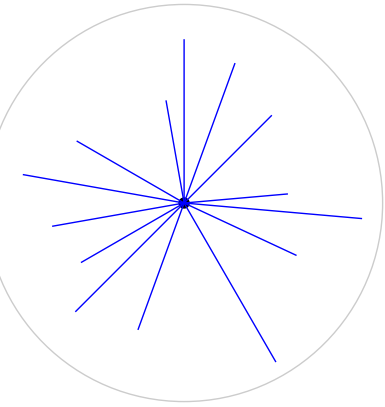


Dark meson m_ϕ generated following Boltzman distribution (T_D)



SUEP searches

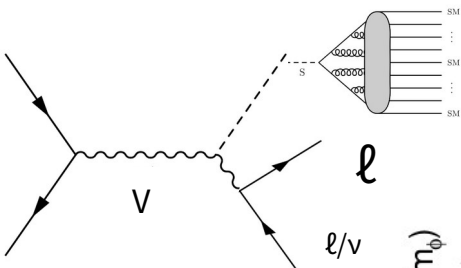
- Dark shower generates a isotropic spray, not collimated jets
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- Recover isotropy signature “ S_{boosted} ” in boosted frame.



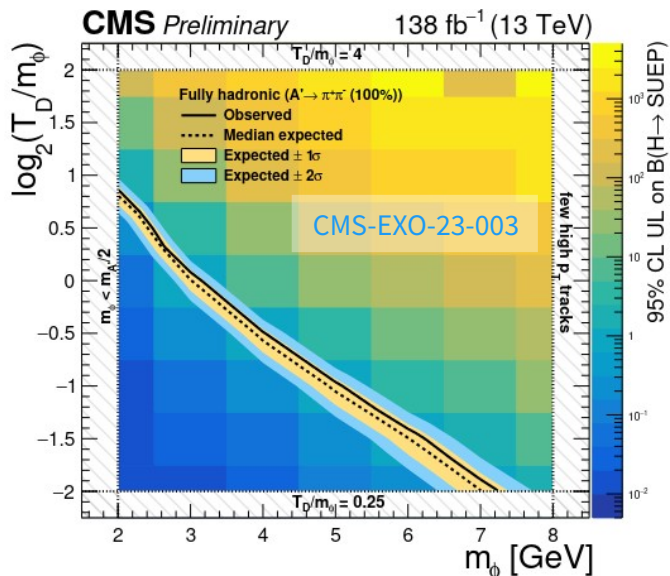
SUEP searches @ CMS

VH scattering

Lepton trigger from vector boson (W/Z); Higgs decays to SUEP

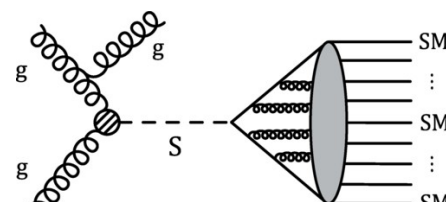


Combined results coming soon!

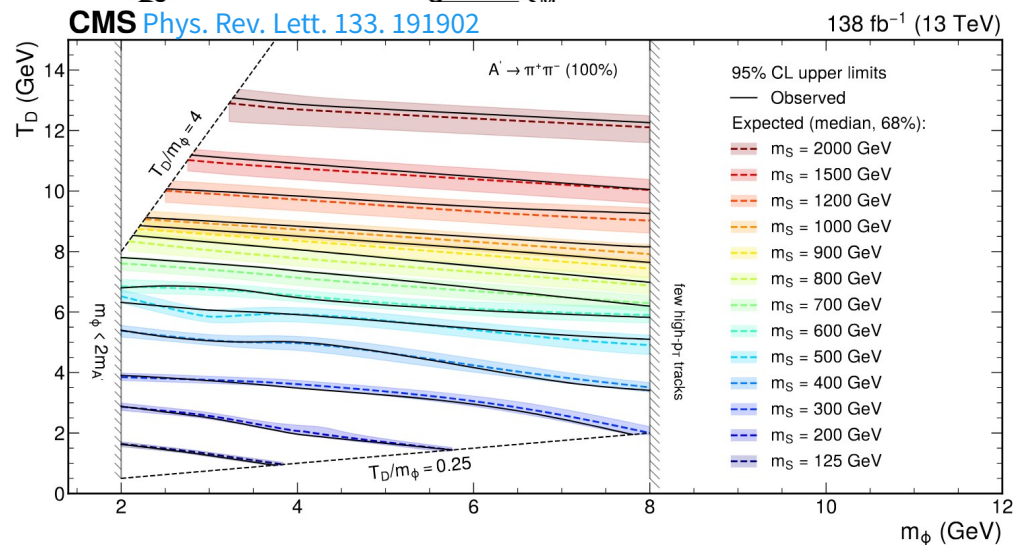


ggF production

ISR Jet for triggering; heavy scalar decays to SUEP

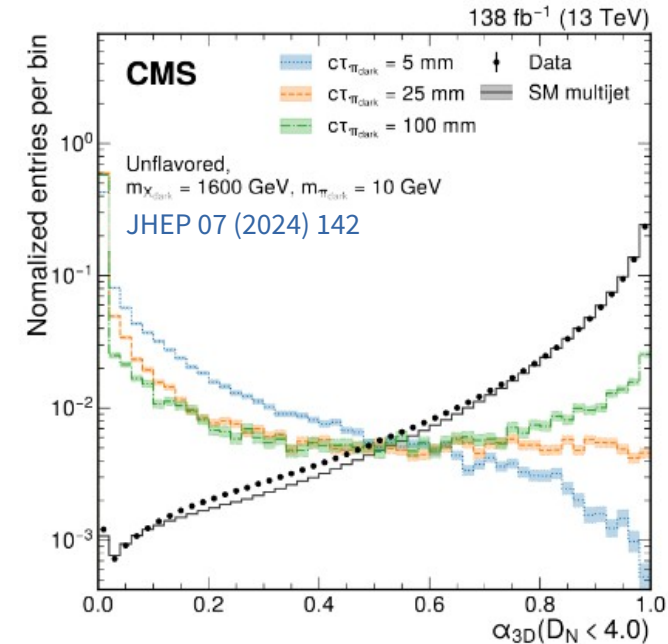
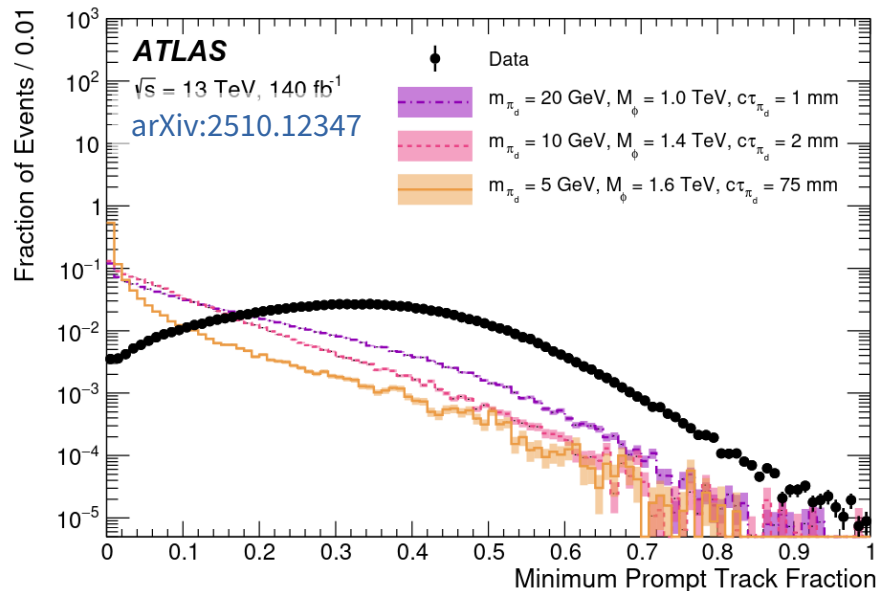
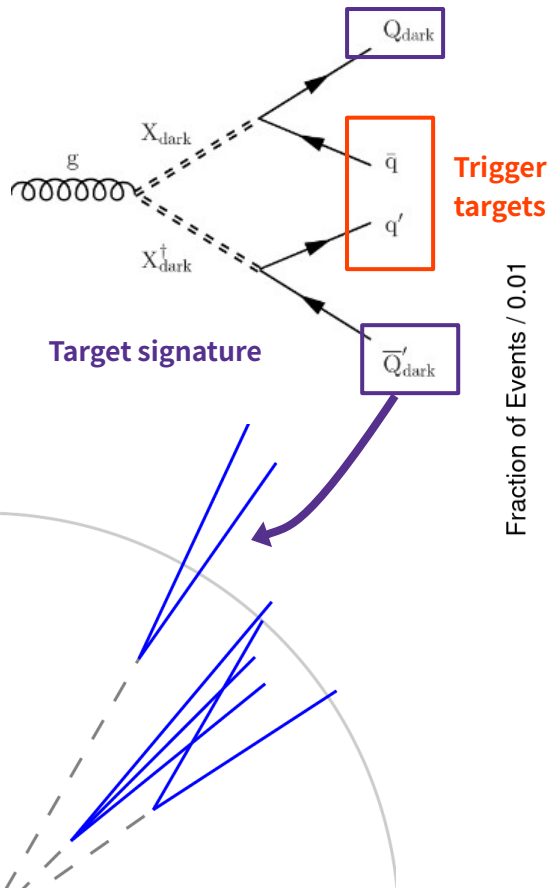


CMS Phys. Rev. Lett. 133, 191902



Emerging jets searches - t-channel

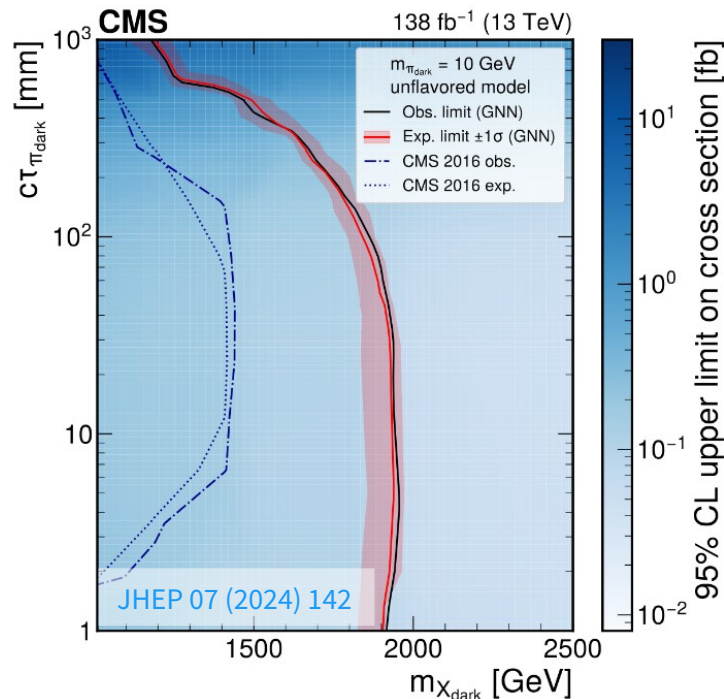
- No guaranteed E_T^{miss} trigger, trigger on accompanying SM product
- Displaced signature used to boost signal-to-noise ratio
 - Displaced objects in jets for Jet tagging (CMS)
 - Displaced object count for signal/control region separation (ATLAS)



Emerging jets t-channel results

CMS t-channel pair production (Run 2)

- $H_T > 1050 \text{ GeV}$ trigger on accompanying SM product
- Track displacement for jet tagging (cut-based, GNN/ML)



ATLAS, t-channel pair production (Run 2)

- 4Jet $p_T > 120 \text{ GeV}$ trigger on SM product
- Energy shower distribution for jet tagging
- Displaced object count for signal/control separation

