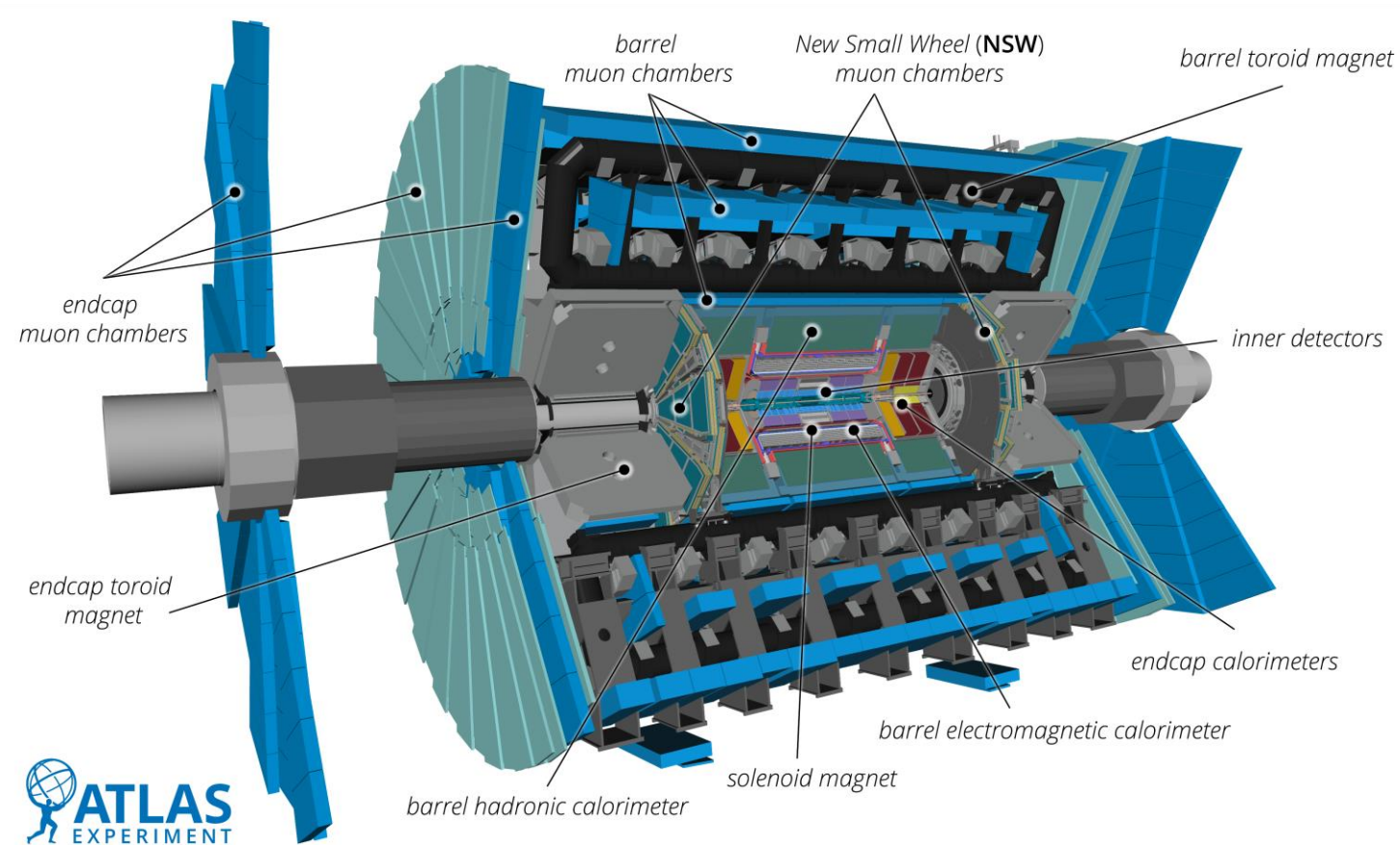


Searching for Soft Unclustered Energy Patterns with the ATLAS Detector

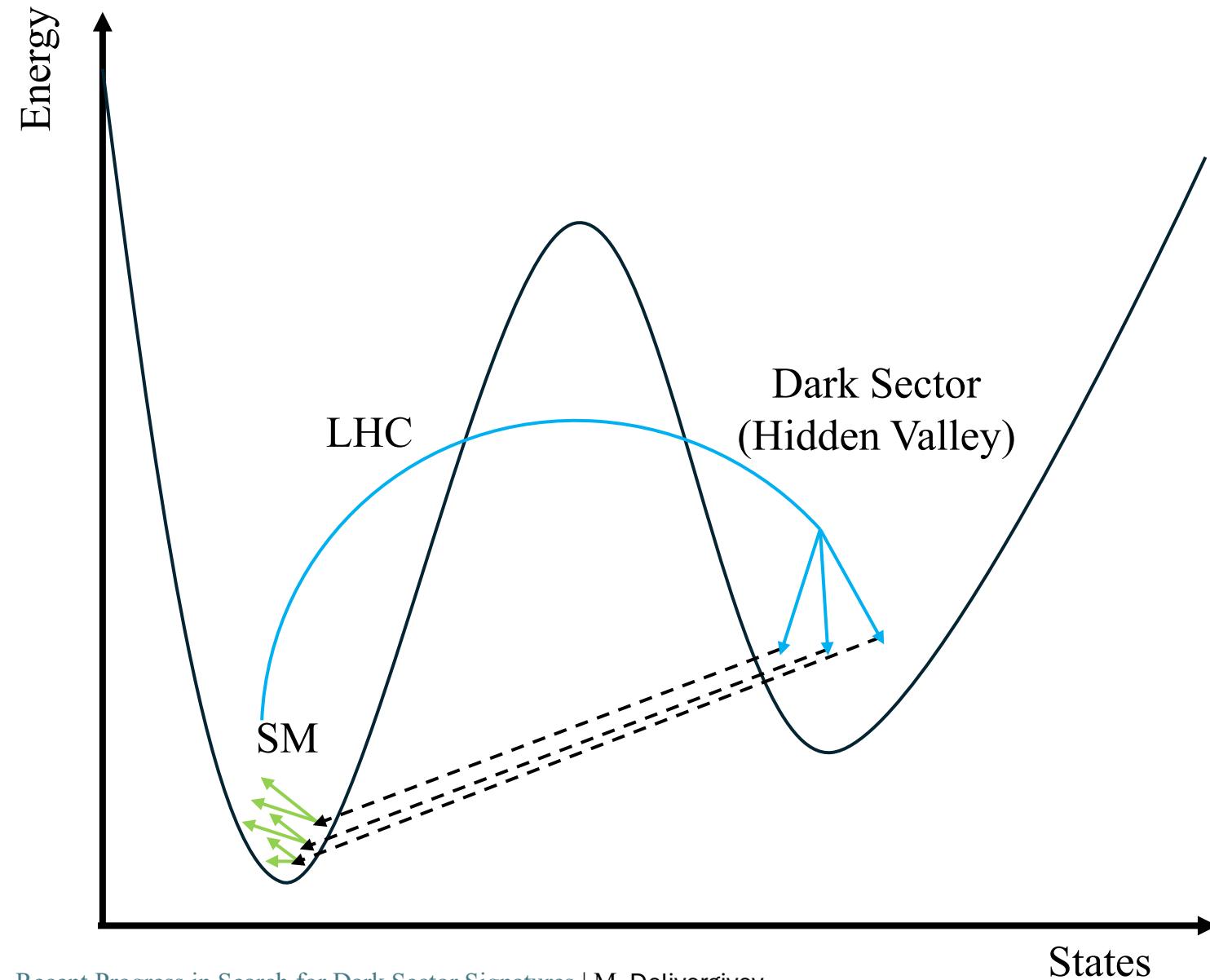
William Rettie

The ATLAS Detector



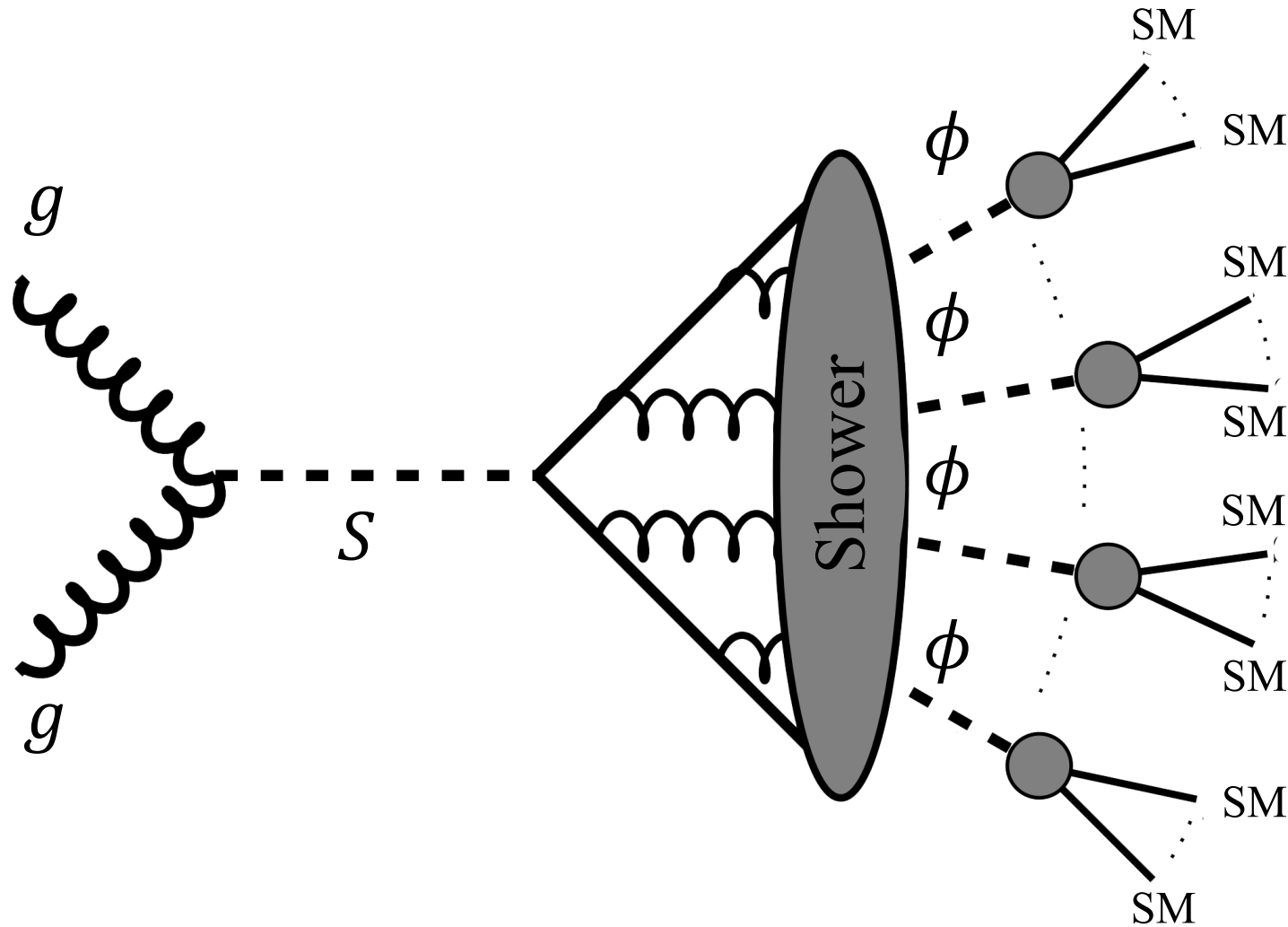
- General purpose detector located at the Large Hadron Collider (LHC)
- Observes high energy proton-proton collisions
- Layered detector design measures energy and momentum of particles
- Explores a variety of exotic searches, including dark matter

Hidden Valley Models



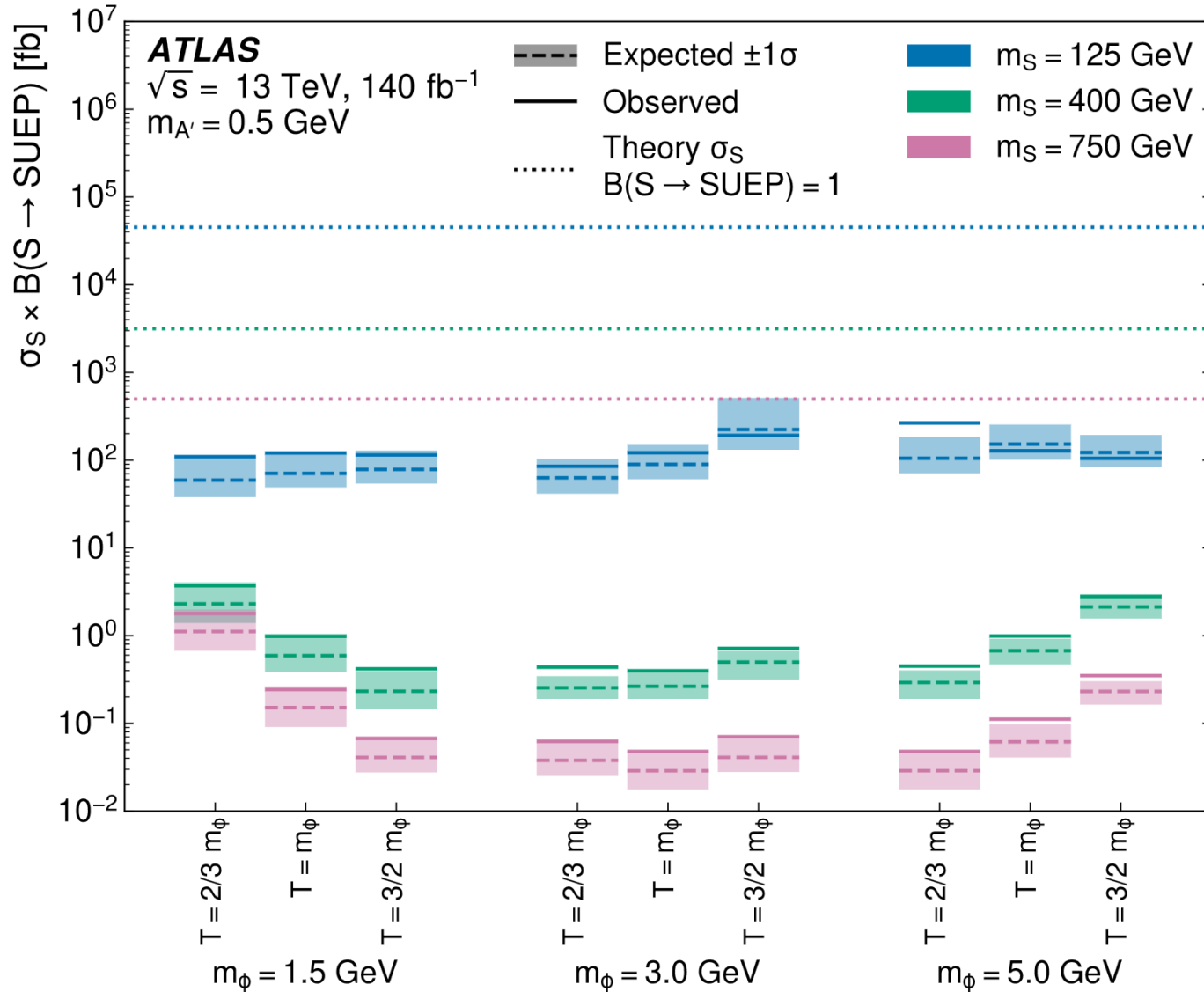
- Dark sector resides at a higher energy threshold than we can normally access
- The LHC may produce mediator particles that interact within the dark sector, and decay back into our universe through standard model (SM) particles
- Detecting this decay would indicate the existence of the dark sector containing a viable dark matter candidate

Soft Unclustered Energy Patterns (SUEP)

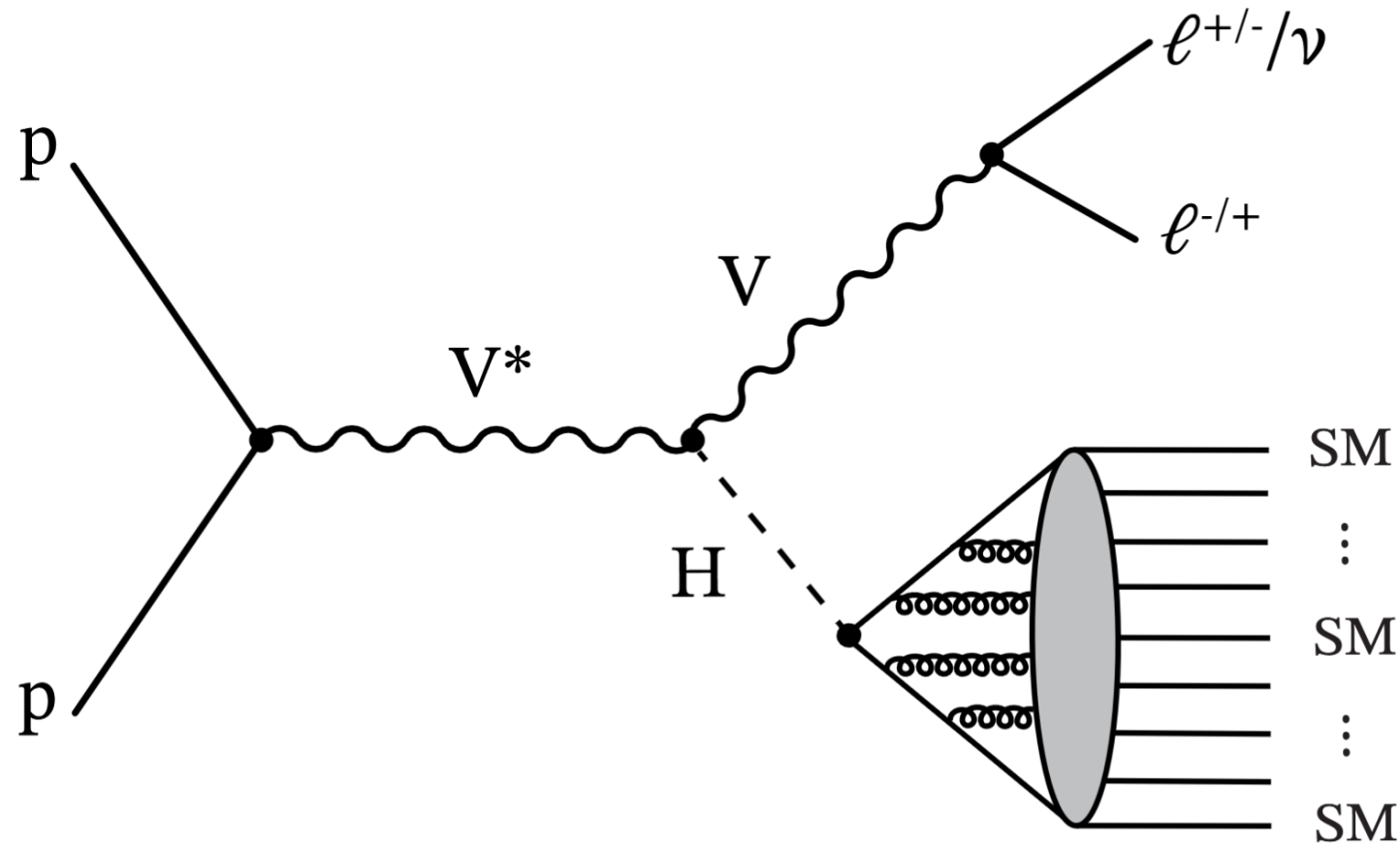


- Scalar boson S is produced (predominantly through gluon-gluon fusion)
- S showers in the dark sector into dark mesons ϕ
- ϕ decay through dark photons, producing an isotropic distribution of low-momentum SM particles
- Signature is difficult to trigger on due to high amount of low-momentum particles

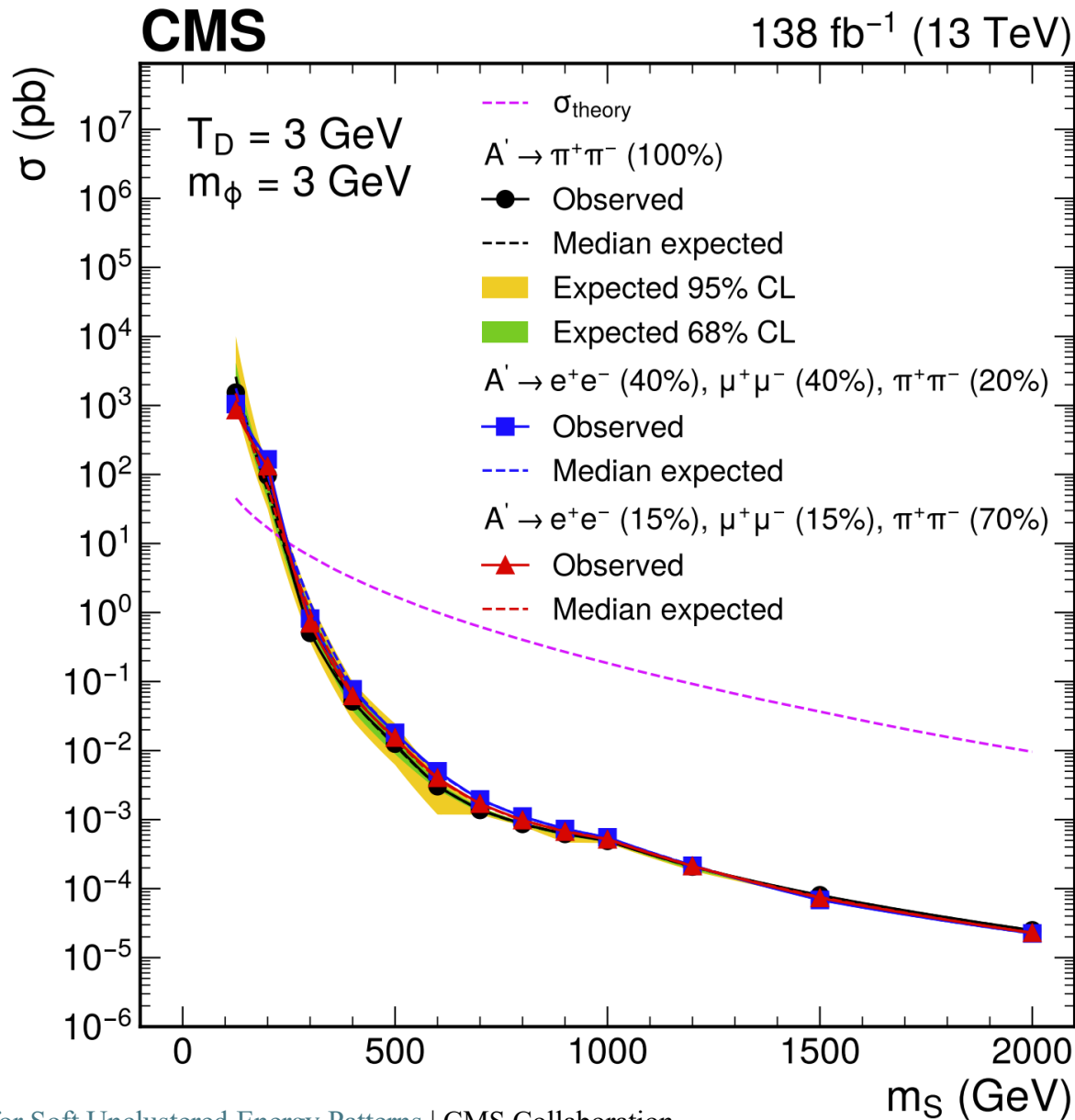
Previous Searches for SUEP



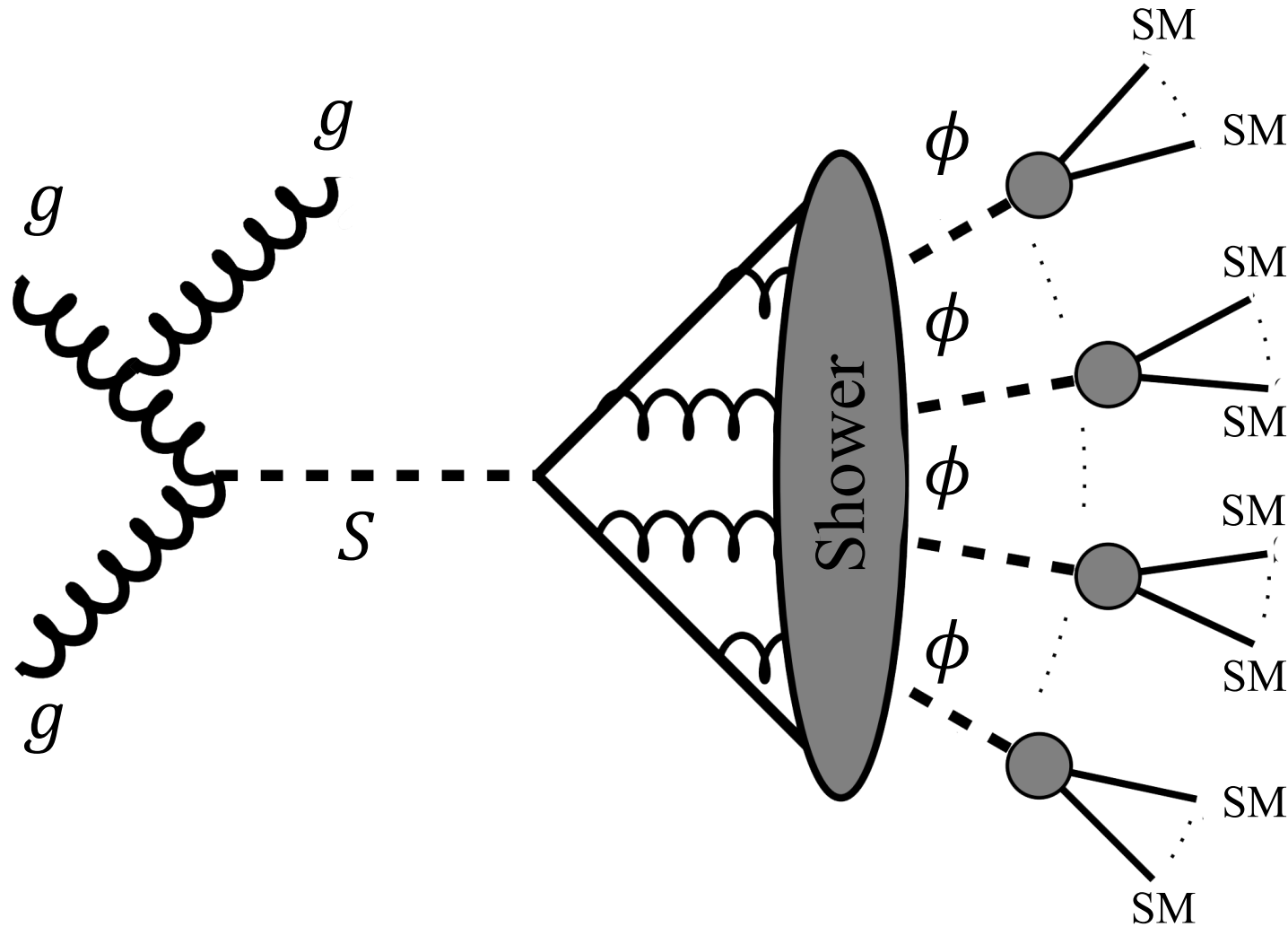
- ATLAS Run 2: Focused on a muonic final state, using multi-muon triggers. SUEP events contain prompt muons whereas background events contain non-prompt muons



- [ATLAS Run 2](#): Focused on a muonic final state, using multi-muon triggers. SUEP events contain prompt muons whereas background events contain non-prompt muons
- [CMS Run 2 VH](#): S scalar is Higgs boson (H) produced in association with a W or Z boson (V), which decays to a lepton. Triggers based on final-state electrons and muons

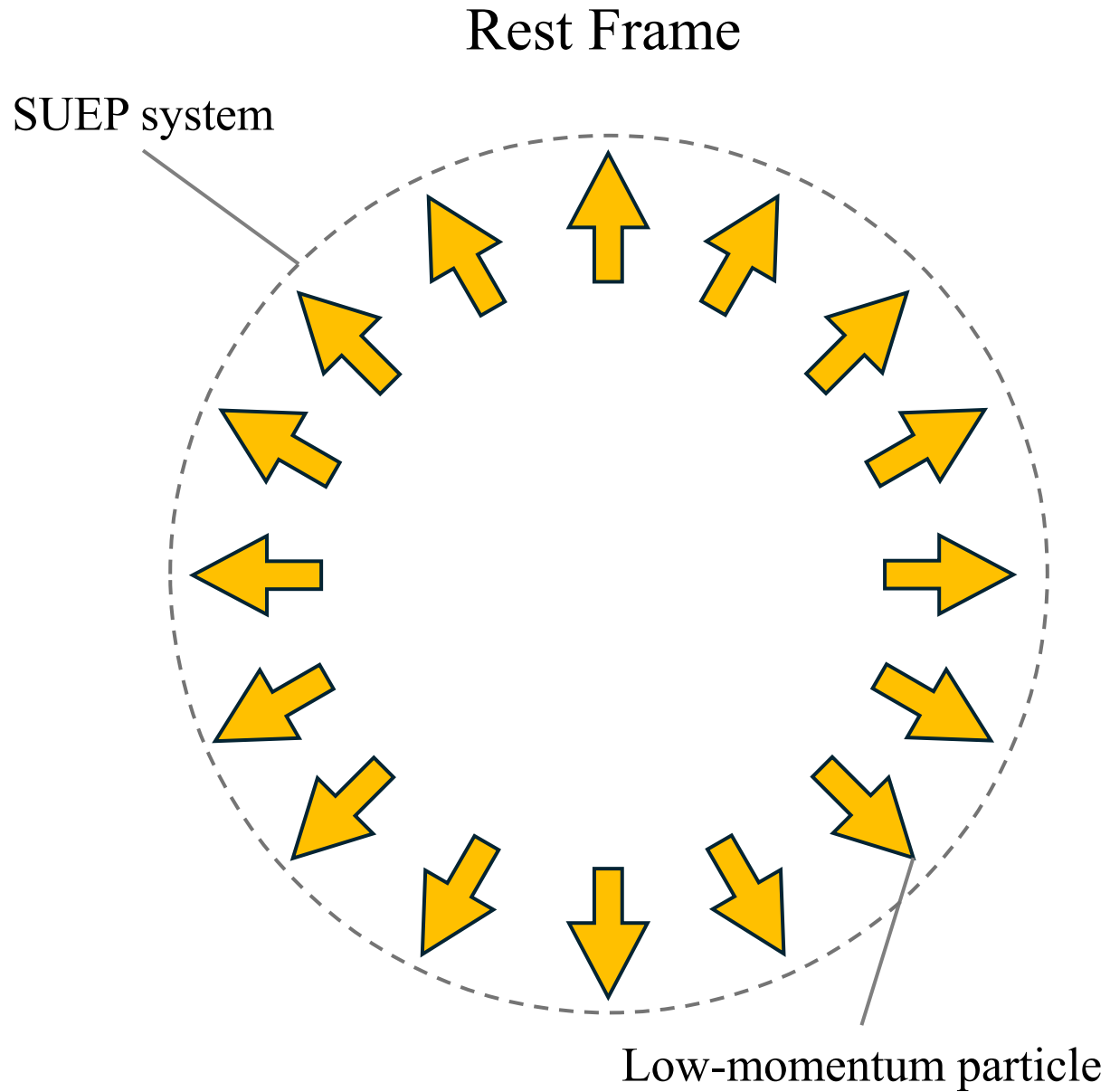


- [ATLAS Run 2](#): Focused on a muonic final state, using multi-muon triggers. SUEP events contain prompt muons whereas background events contain non-prompt muons
- [CMS Run 2 VH](#): S scalar is Higgs boson (H) produced in association with a W or Z boson (V), which decays to a lepton. Triggers based on final-state electrons and muons
- [CMS Run 2](#): Triggers on high hadronic activity (H_T). Sensitivity drops at low m_S . There is still phase space around the $m_S \sim m_H$ region left to explore



- Initial state radiation (ISR) boosts SUEP system into a high-momentum jet, giving us high H_T which can be triggered on
- ATLAS has lower H_T triggers in Run 3, allowing for better sensitivity to boosted SUEP events
- Fully hadronic final state, the first SUEP search of this type at ATLAS
- Higher luminosity by using the Run 2 and 3 datasets from the LHC

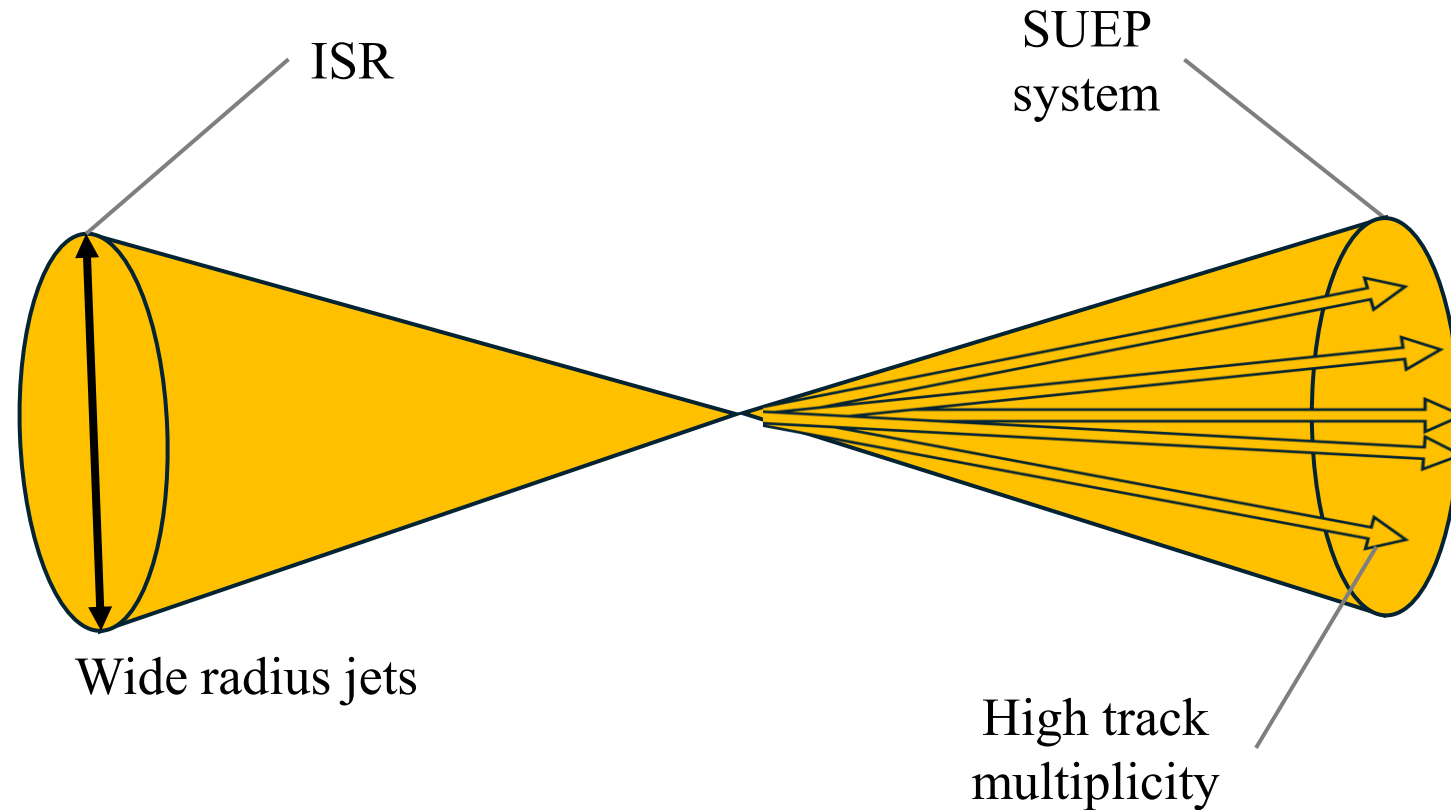
Boosting the SUEP System with an ISR



- In its rest frame, the SUEP system produces low-momentum particles spherically

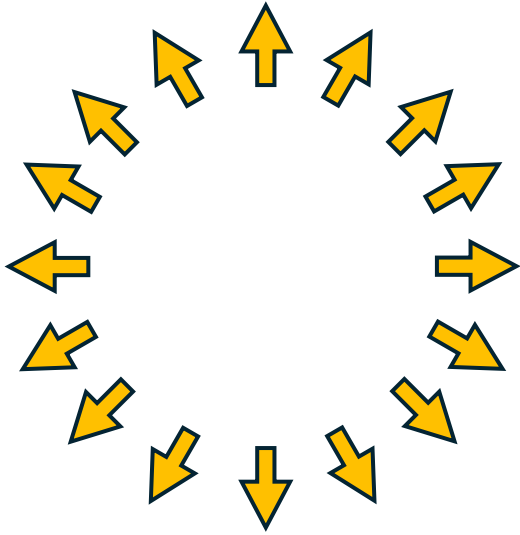
Boosting the SUEP System with an ISR

Lab Frame

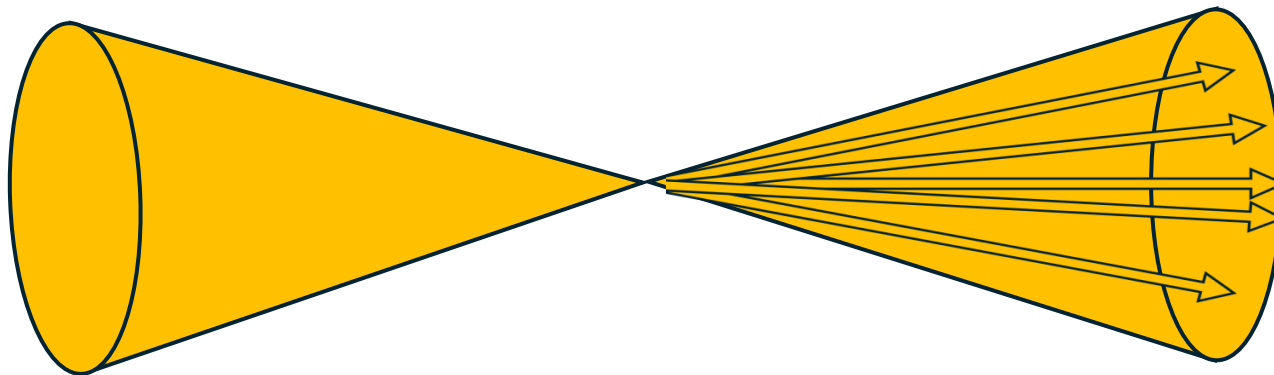


- In its rest frame, the SUEP system produces low-momentum particles spherically
- In the lab frame, the ISR boosts the SUEP system, forcing the low-momentum particles into a high-momentum collimated structure with high track multiplicity, a jet

Sphericity in Rest Frame



N_{Tracks} in Lab Frame



- In its rest frame, the SUEP system produces low-momentum particles spherically
- In the lab frame, the ISR boosts the SUEP system, forcing the low-momentum particles into a high-momentum collimated structure with high track multiplicity, a jet
- We can now distinguish our SUEP candidate from our ISR:
 - Trigger on H_T
 - Identify two wide radius jets
 - SUEP candidate has higher N_{Tracks}
 - Analyze SUEP sphericity further

	Low Track Multiplicity	High Track Multiplicity
Low Sphericity	A (Control region)	B (Control region)
High Sphericity	C (Control region)	D (Signal region)

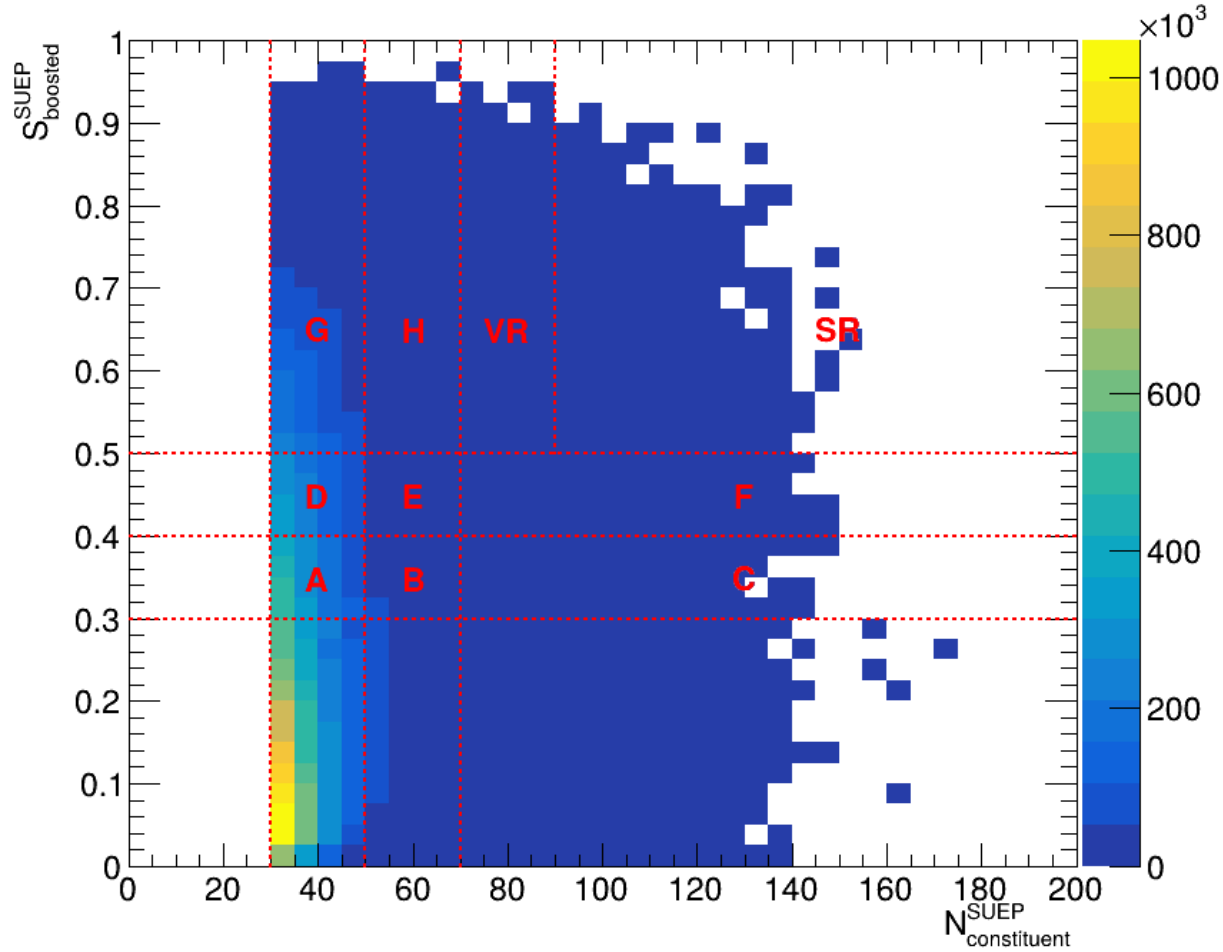
- Data-driven background estimation technique
- Two uncorrelated observables are chosen, defining four regions:
 - Control regions A, B, and C, dominated by background
 - Signal region D
- The background yield in the signal region can be predicted using:

$$N_D^{pred} = \frac{N_B N_C}{N_A}$$

Current Simulation Results

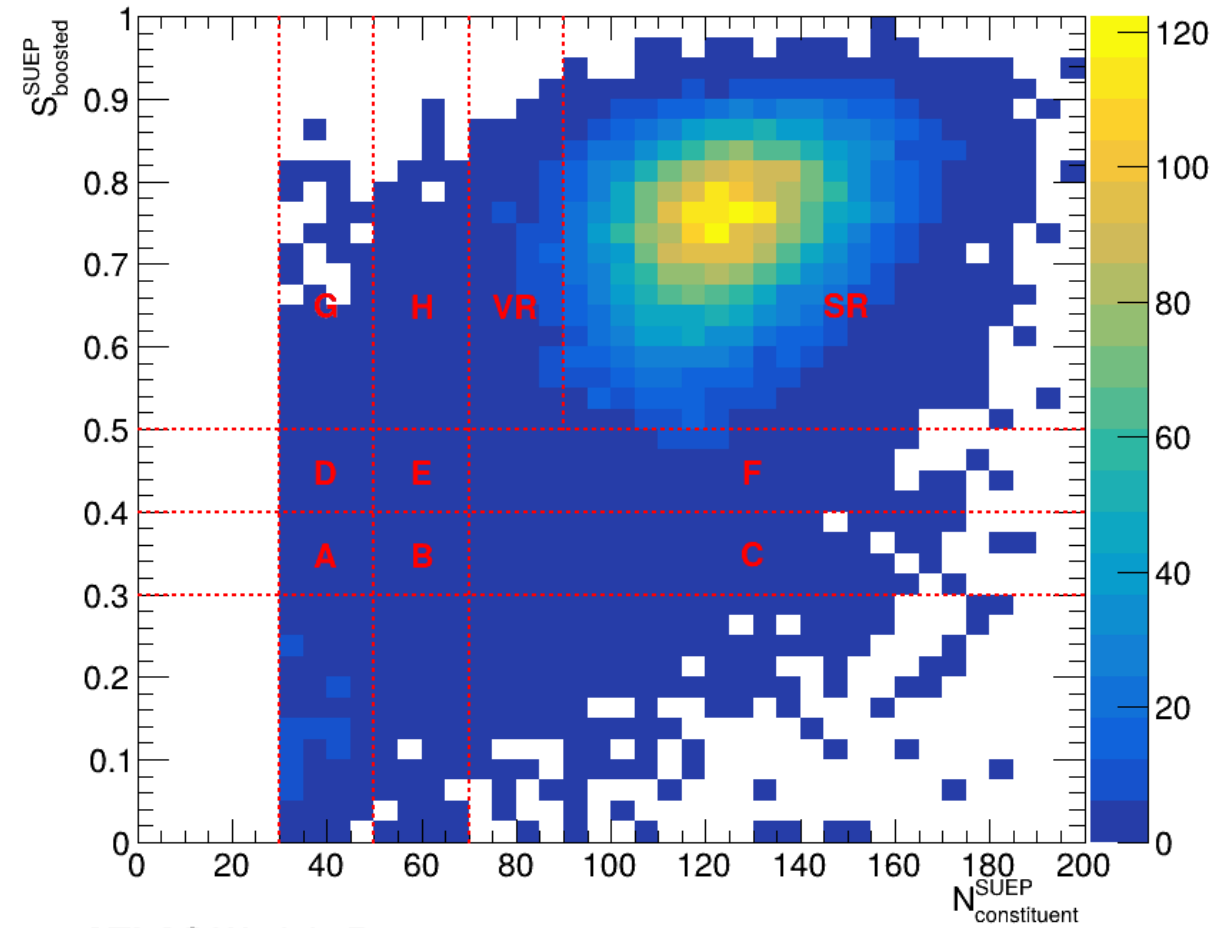
ABCD Plane of N_{Track} vs sphericity, $m_S = 500$ GeV

Background



ATLAS Work in Progress

Signal

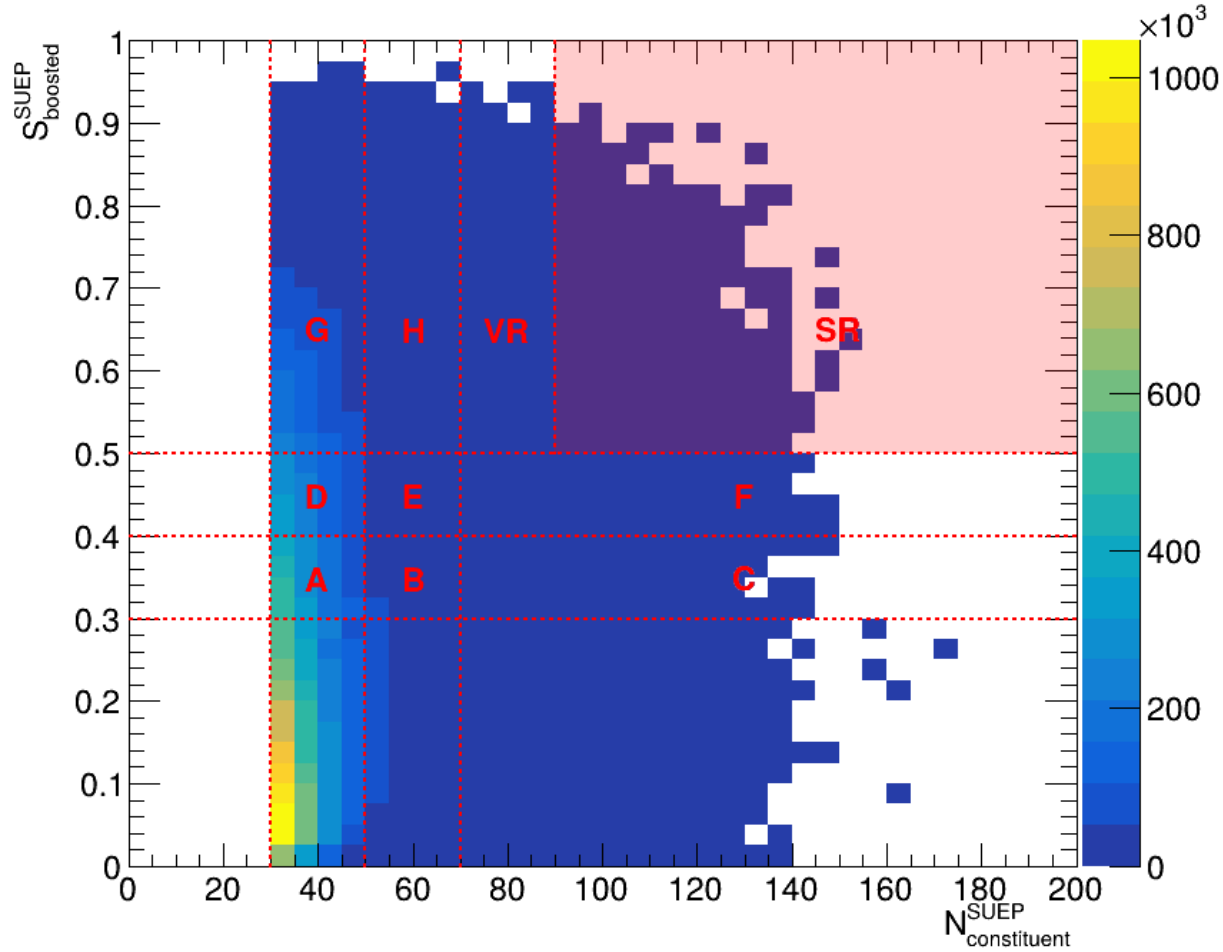


ATLAS Work in Progress

Current Simulation Results

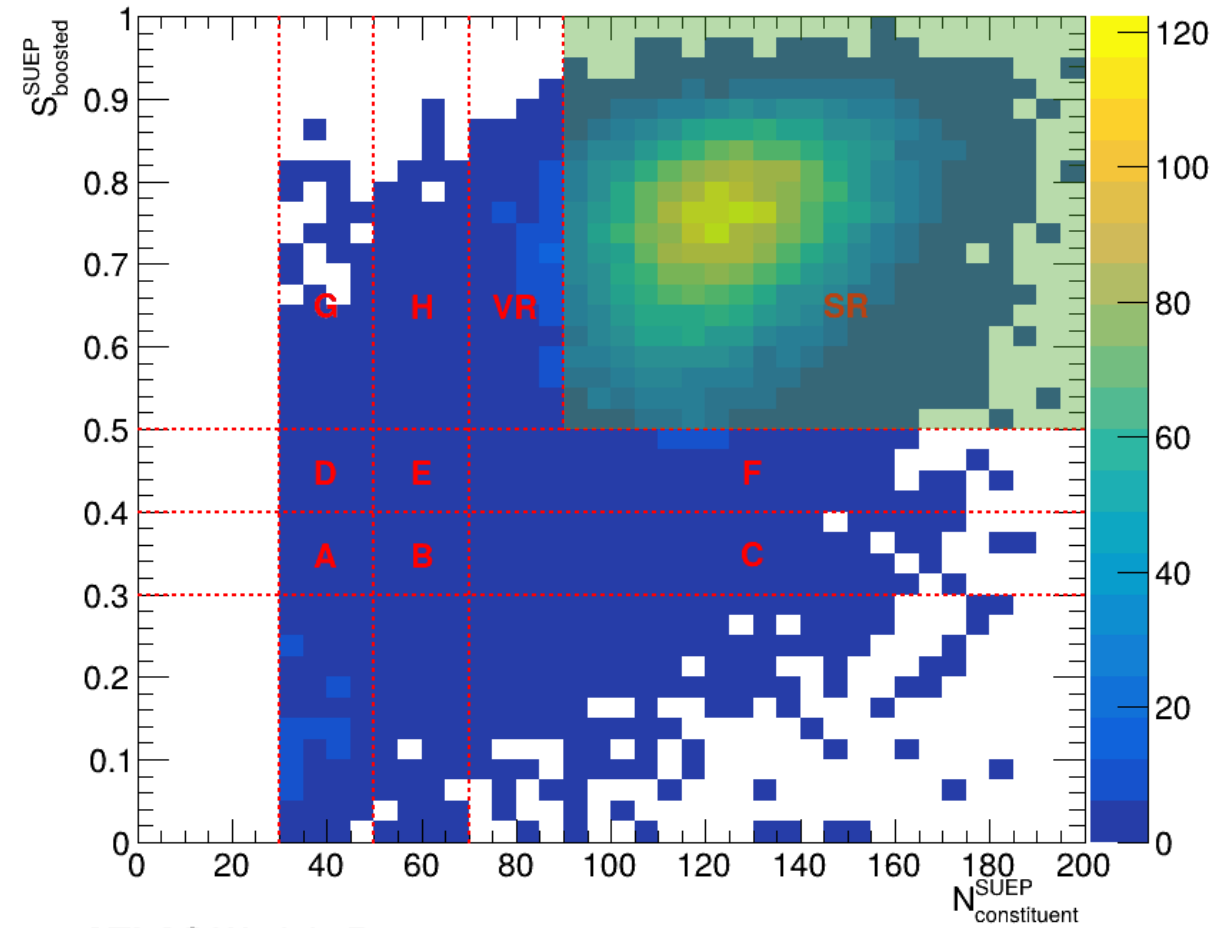
ABCD Plane of N_{Track} vs sphericity, $m_S = 500$ GeV

Background



ATLAS Work in Progress

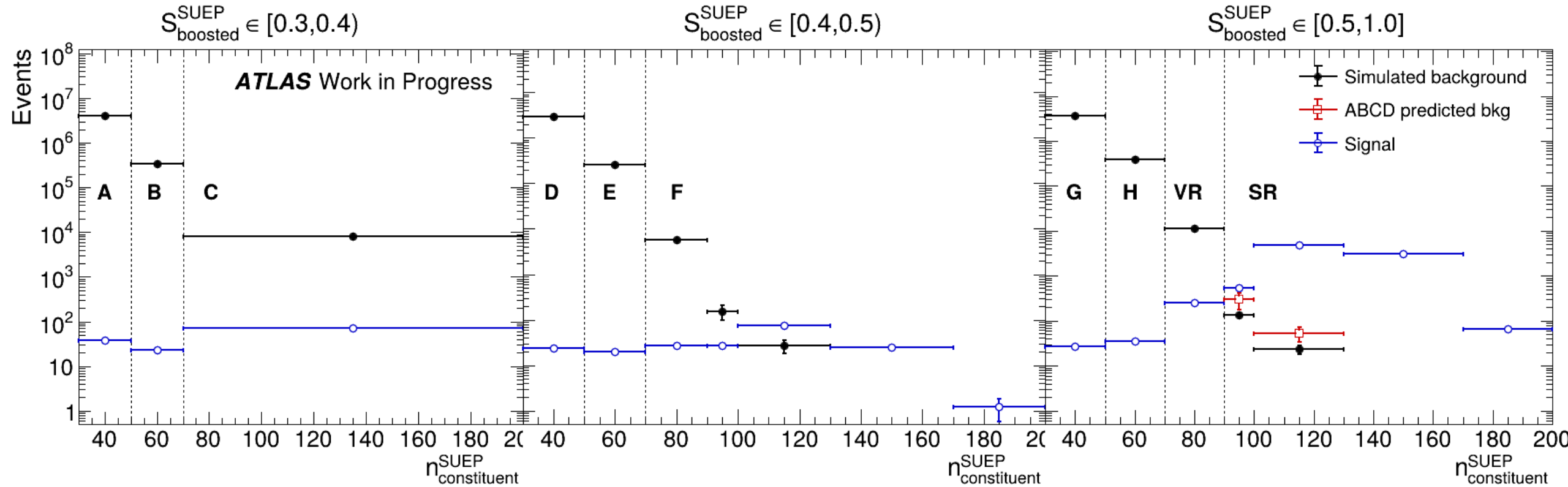
Signal



ATLAS Work in Progress

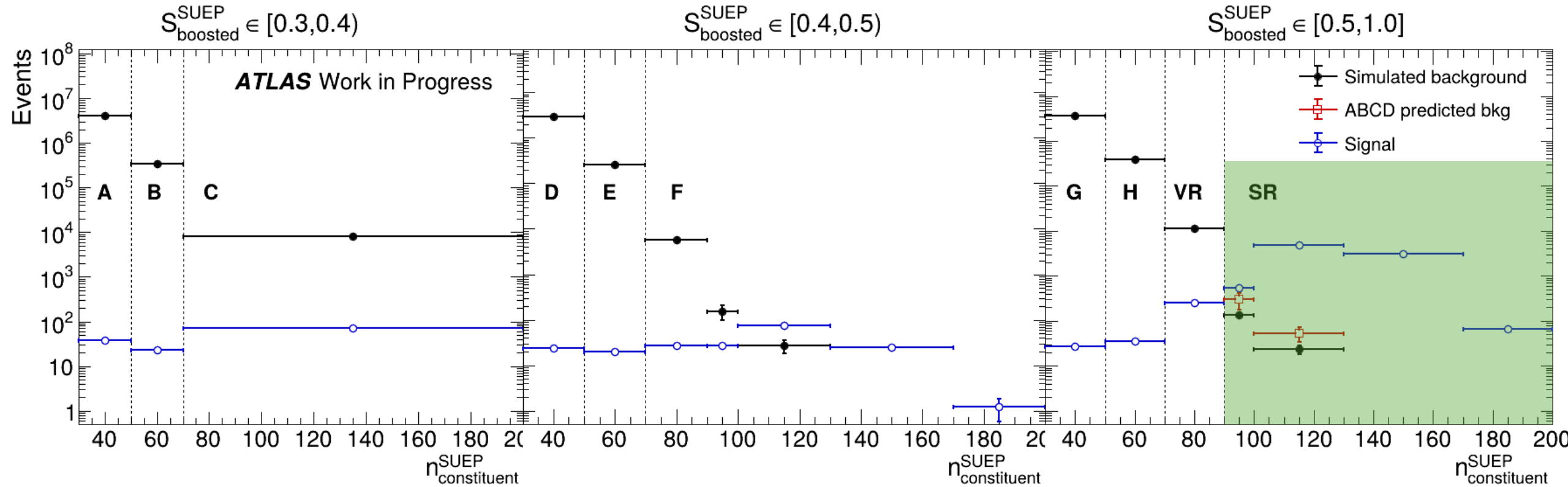
Current Simulation Results

Current results with $m_S = 500$ GeV



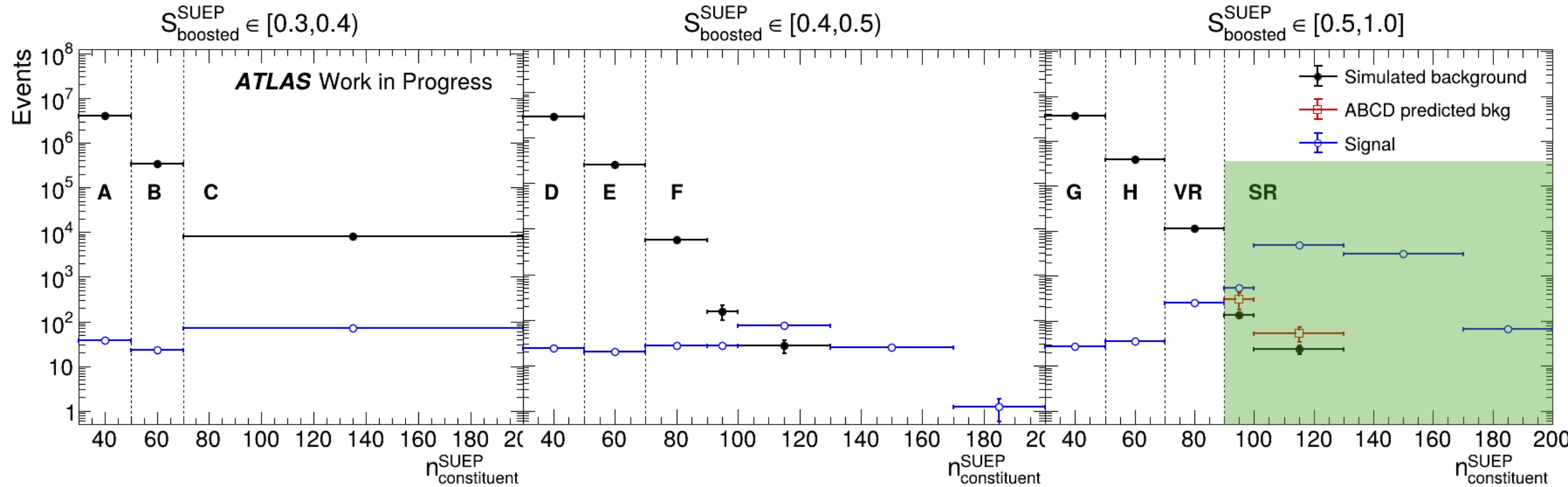
Current Simulation Results

Current results with $m_S = 500$ GeV



Current Simulation Results

Current results with $m_S = 500$ GeV



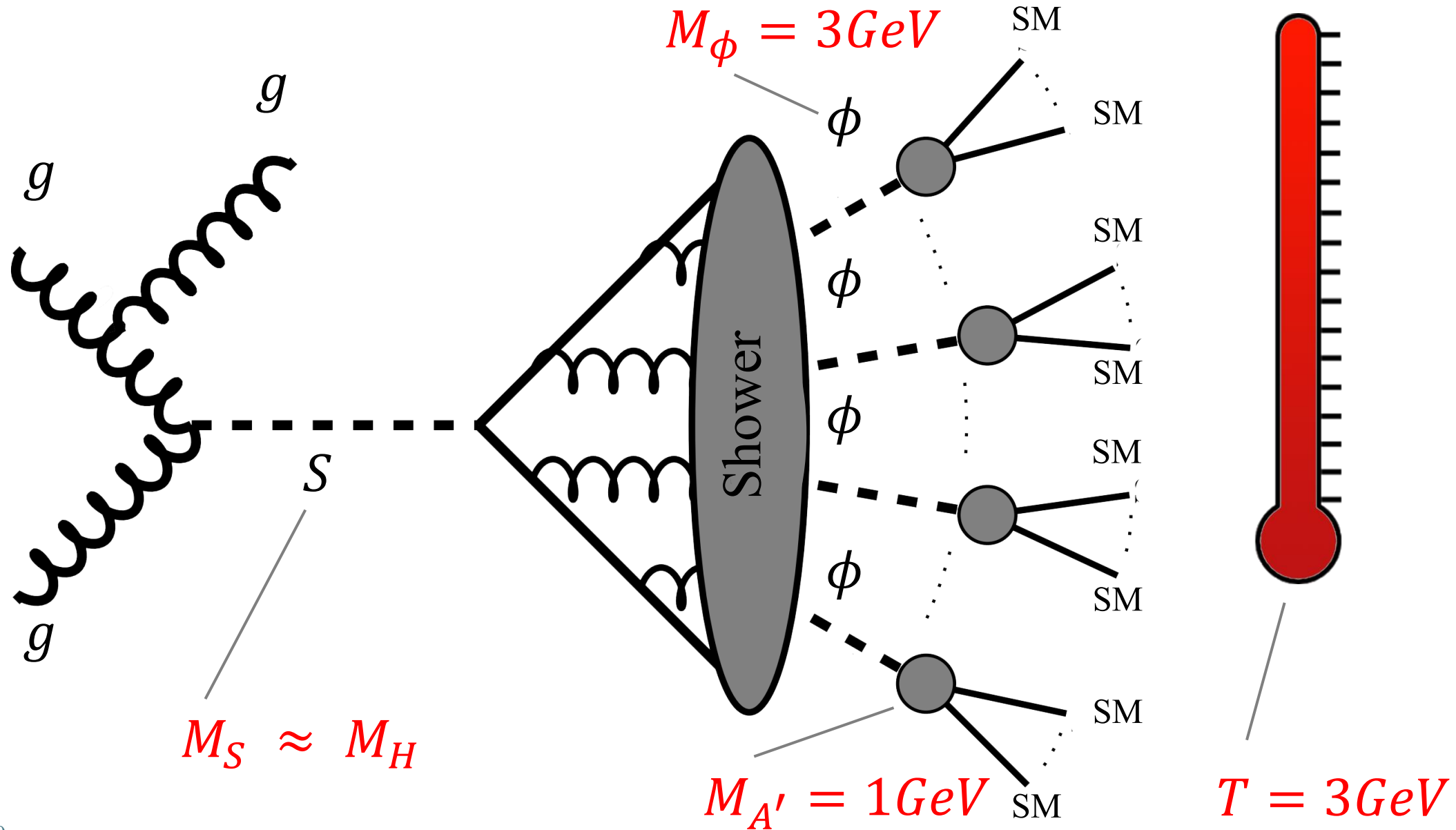
Further samples will be produced in the 200-400 GeV range

- Dark matter search using the SUEP model
- Identified a yet-unexplored SUEP phase-space
- Implemented an ABCD framework to isolate our signal region
- Showed sensitivity in initial simulation samples
- Further samples will be produced in the 200-400 GeV range

Thanks for listening!
Any questions?

Backup slides

SUEP Model Parameters



- M_S : Higher or lower mass influences how much energy is in the system, dictating the amount of particles in the final state
- M_ϕ : Higher or lower mass influences how many ϕ are produced by the S decay, dictating the amount of particles in the final state
- $M_{A'}$: Influences the branching ratio of SM particles produced (see CMS limit plot legend for BRs)
- T : Higher or lower value influences how much energy each final state particle will have. Energy of system must be conserved, so this dictates how many final state particles there are (and how energetic each one is)

- The analysis assumes that the dark sector hadronizes into a single species of dark meson with mass M_ϕ and temperature T . To stay within a physically meaningful and realistic regime:
“ T/M_ϕ should be $O(1)$. We therefore consider temperatures of $2/3$, 1 , or $3/2$ of M_ϕ ”.
- This ratio controls the overall shape of the energy distribution. Low T/M_ϕ produces a softer, more collimated shape whereas high T/M_ϕ produces harder, more jet-like shapes:
“ $T = M_\phi = 3\text{GeV}$ seems to be a good middle ground and are the parameters for which the limits are the strongest”
- Provides high enough final-state p_T to pass muon triggers, while retaining soft SUEP-like characteristics

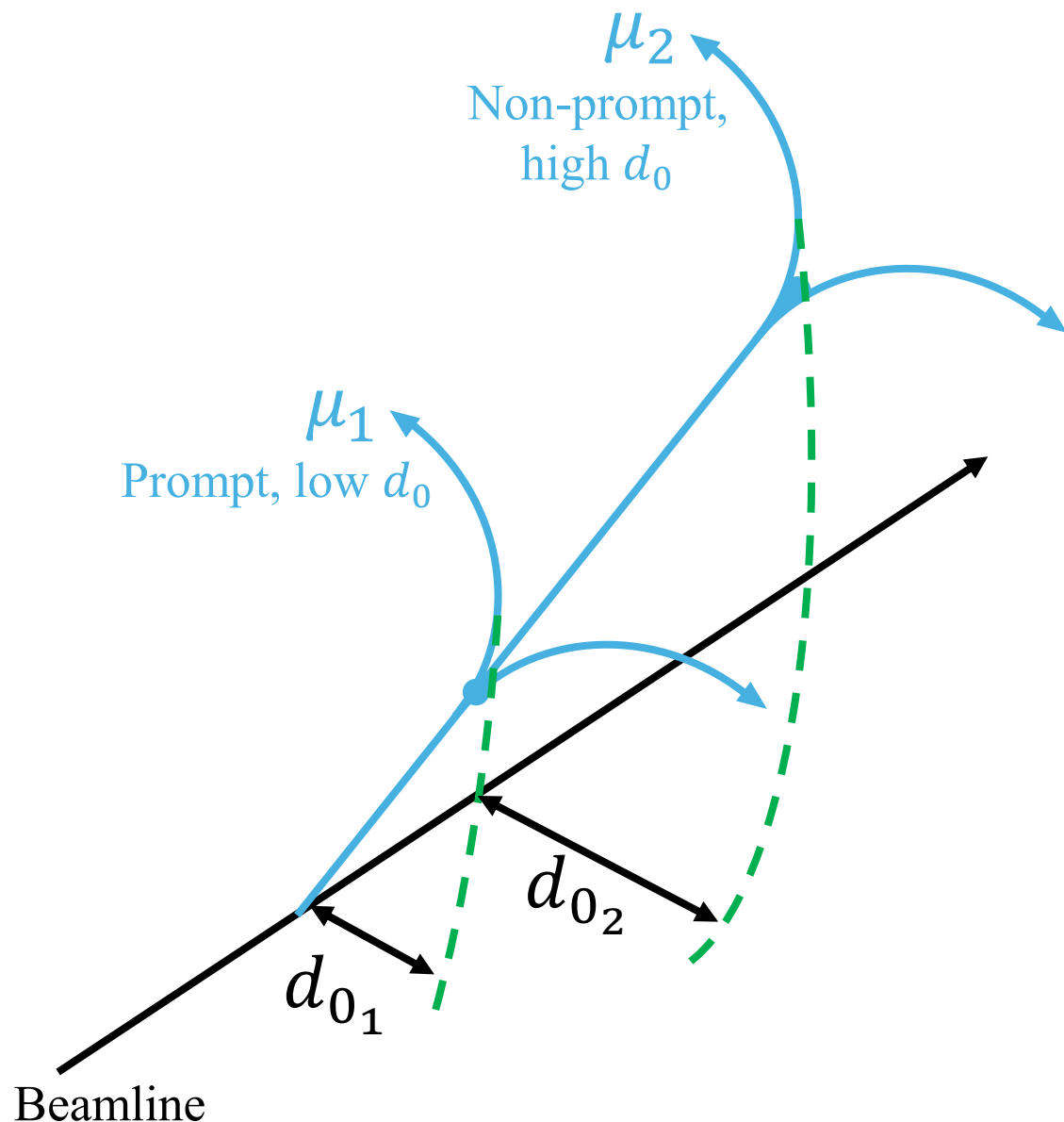
What Does The HV Temperature Mean?

- If a hidden sector is very strongly coupled, the resulting dark shower may behave like a thermal system.
- The “temperature” T models the momentum spectrum of hidden sector particles.
- Reference in Pythia documentation as a Boltzmann-like distribution, where T sets the typical p_T scale of dark hadrons

$$\frac{dN}{dp_T} \propto P_T^2 \cdot \exp\left(-\frac{P_T}{T}\right)$$

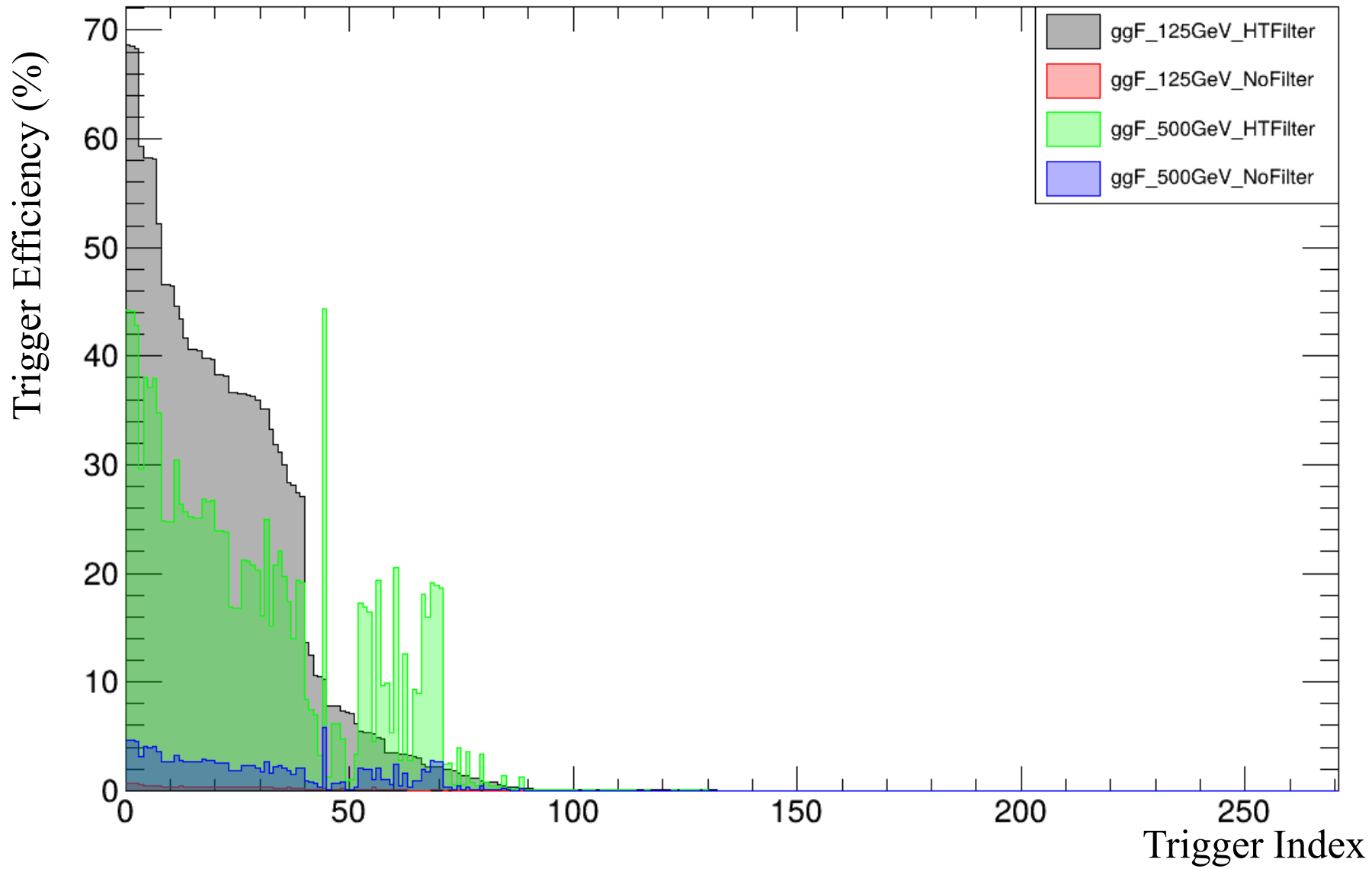
- It controls how soft and isotropic the final state looks.
- Lower $T \rightarrow$ more tracks, lower energy per track, harder to detect.

- $M_S = 125$ GeV, $M_m = T = 3.0$ GeV, full hadronic decay, ggH production
- $M_S = 500$ GeV, $M_m = T = 3.0$ GeV, full hadronic decay, ggH production
- Both samples have a version with an HT filter of 900 GeV applied

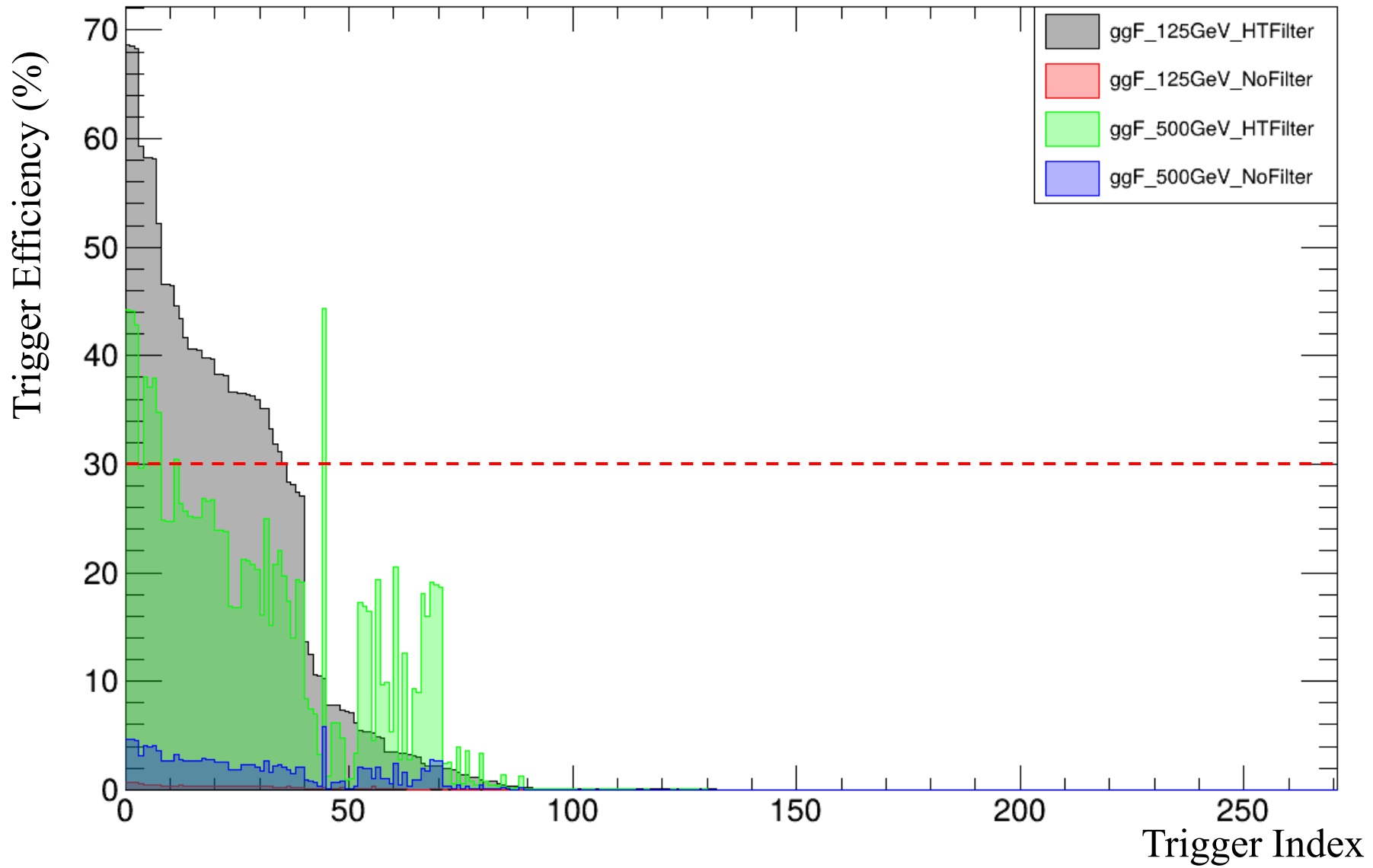


- Muonic final state for SUEP events
- Multi-muon triggers, requiring at least 5 muons
- ABCD-plane: Leading muon d_0 significance vs track multiplicity
- SUEPs contain prompt muons, whereas background events contain non-prompt muons (such as heavy-flavour multijets)
- Much lower backgrounds because muons are rare in multijet events.

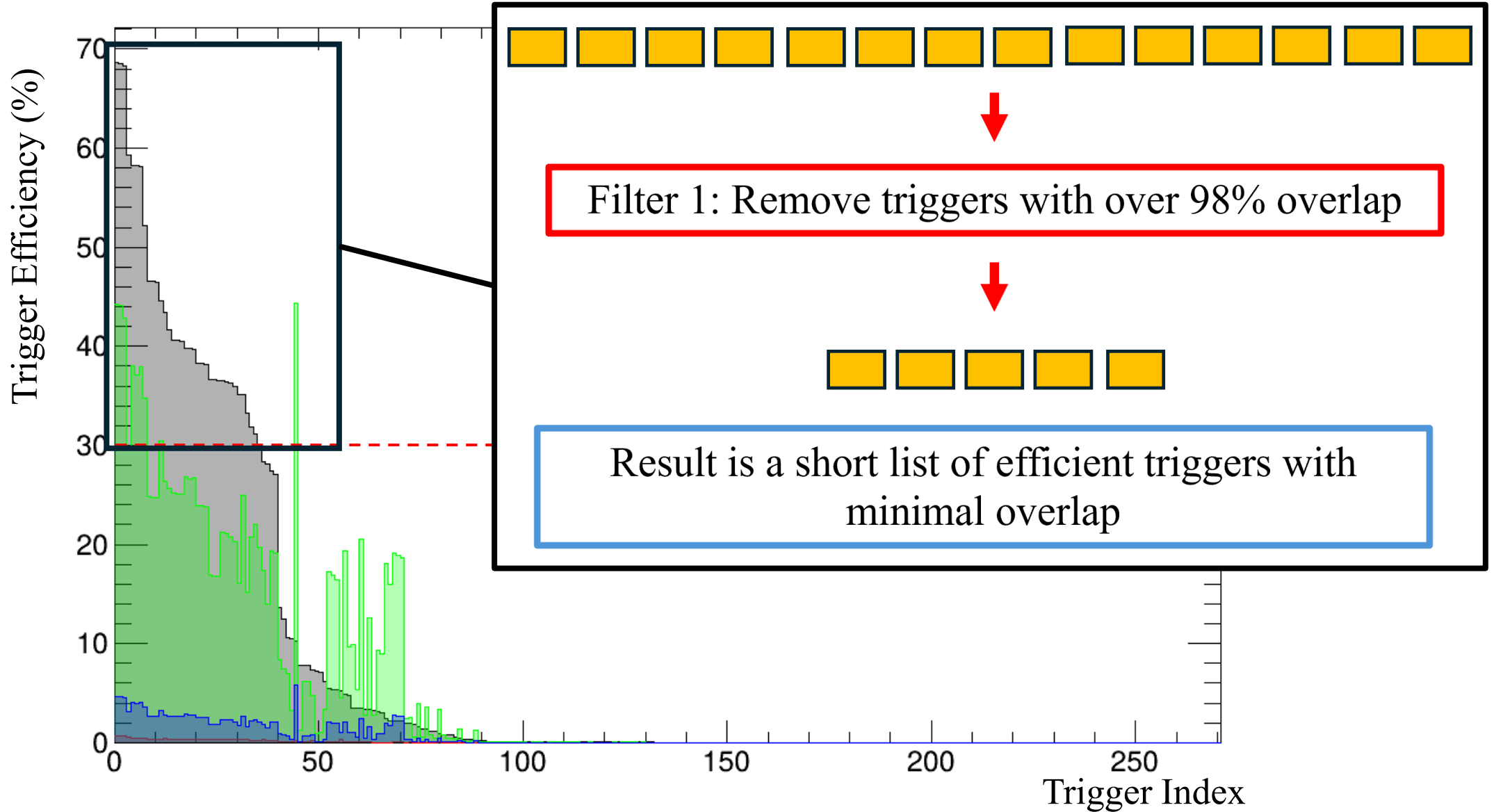
Triggers in 160k Events



Triggers in 160k Events



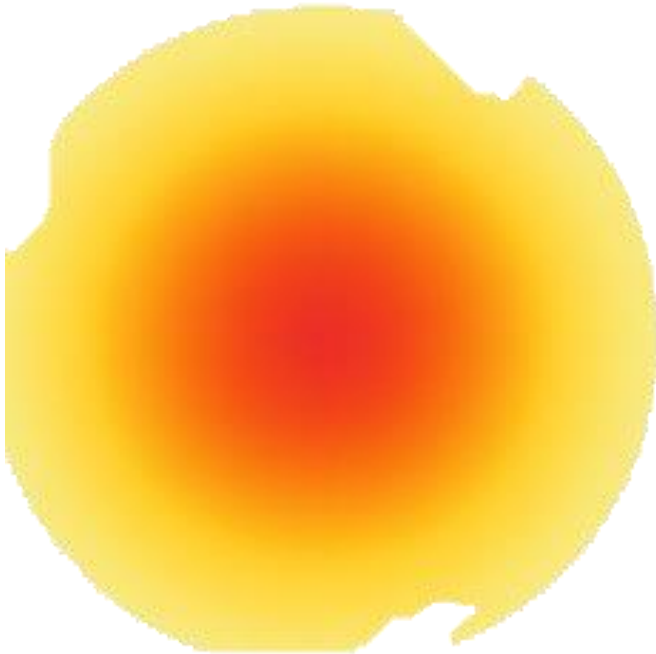
Triggers in 160k Events



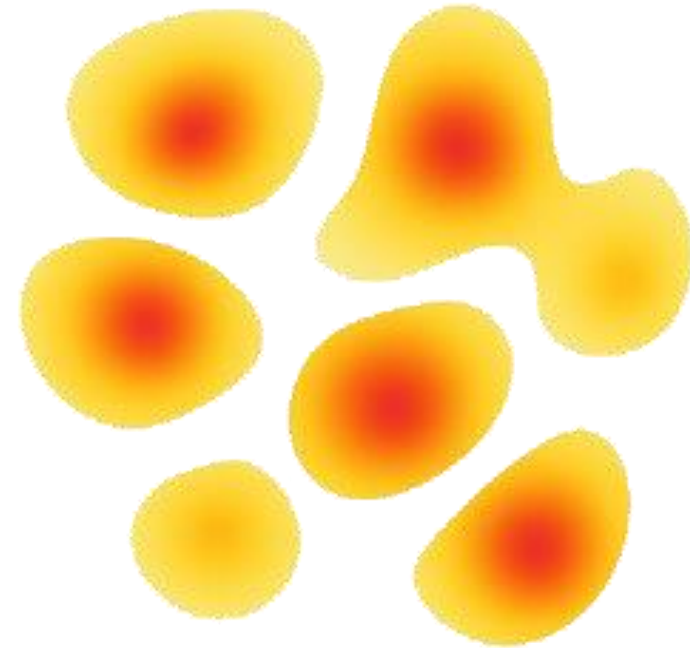
Trigger Studies

Trigger	ggF_125GeV_HTFilter	ggF_500GeV_HTFilter
HLT_j420_35smcINF_a10sd_cssk_pf_jes_ftf_prese lj225_L1jLJ140	68.69%	44.21%
HLT_j400_pf_ftf_prese lj225_L1jJ160	59.25%	-----
HLT_j360_60smcINF_j360_a10sd_cs sk_pf_jes_ftf_prese lj225_L1SC111- CjJ40	43.47%	-----
HLT_2j330_35smcINF_a10sd_cssk_p f_jes_ftf_prese lj225_L1jLJ140	36.51%	-----
HLT_2j330_35smcINF_a10t_lcw_jes _L1jLJ140	36.70%	-----
HLT_6j35c_020jvt_pf_ftf_prese lj6c25 _L14jJ40	-----	44.36%
HLT_j460_a10sd_cssk_pf_jes_ftf_pre se lj225_L1jLJ140	-----	38.02%
HLT_j0_HT1000_L1jJ160	35.09%	-----

Unboosted Framework to Study Earth Mover Distance (EMD)



Low EMD



High EMD

- EMD relies on measuring how much “work” it takes to morph one distribution into another
- Each energy deposit is treated like a “pile of dirt”
- Work = amount of energy x distance it needs to move in the (η, ϕ) space
- The EMD value is the minimum total work required to match the observed event to the reference distribution
- For SUEP, the lower the EMD, the more isotropic the distribution, which is the signal we want

Extended ABCD Method

	Low Track Multiplicity	Medium Track Multiplicity	High Track Multiplicity
Low Sphericity	A	B	C
Medium Sphericity	D	E	F
High Sphericity	G	H	I

- Standard ABCD assumes negligible variable correlations.
- Additional validation regions test this assumption and quantify any non-closure arising from residual correlations.
- These extra constraints are incorporated into a likelihood-based fit, improving the stability and reliability of the final background prediction.