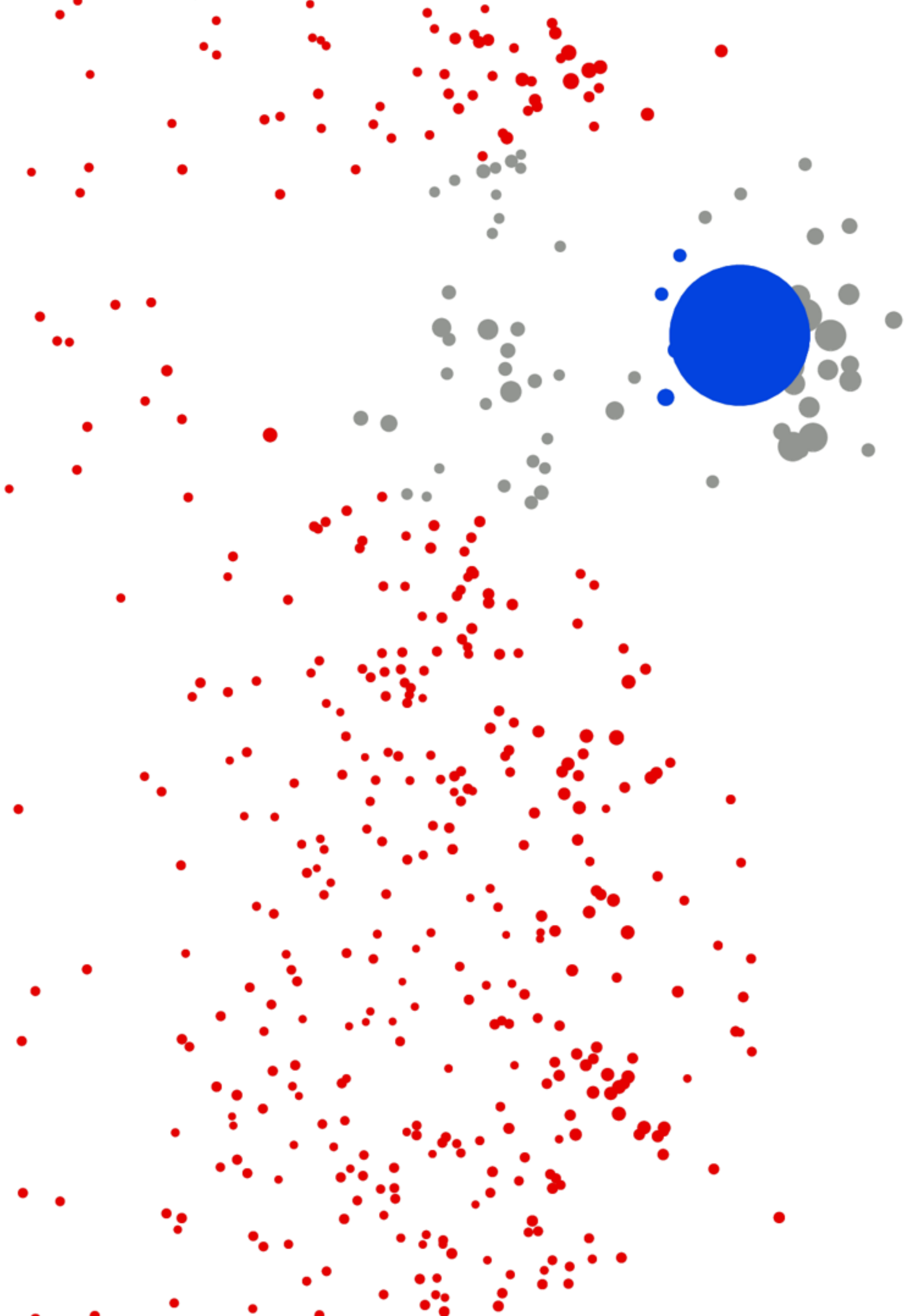
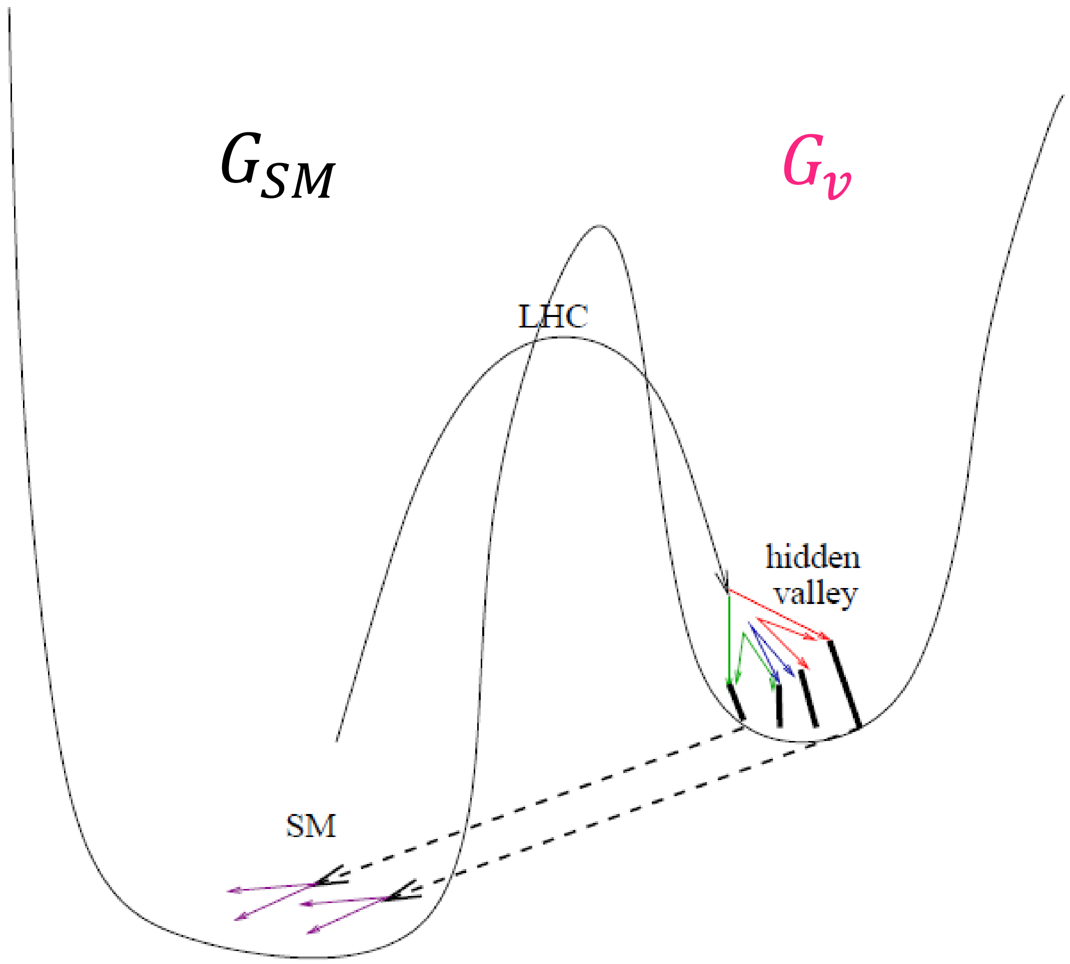


Soft Unclustered Energy Patterns

via gluon-gluon fusion

Luca Lavezzo (MIT) on behalf of the CMS Collaboration

Hidden Valleys



From arXiv:0801.0629

Defining characteristics:

+ Confining, non-Abelian gauge group to extend SM
+ Coupling through a mediator
+ Multi-particle production process in the dark sector
+ Mass gap favors decay back to SM

Rich phenomenology of models! Several predictions for possible signatures at colliders:

+ Stable dark hadrons
  - MET+X – Missing energy in the detector, golden standard of DM searches, heavily covered
  - Semivisible jets (arXiv:2112.11125) – dark jets which partially decay back to the SM
+ Long lived particles
  - Emerging jets (arXiv:2403.01556) – jets with large displaced vertices
+ Promptly decaying, large ‘t Hooft coupling
  - Soft unclustered energy patterns (SUEPs)

SUEPs

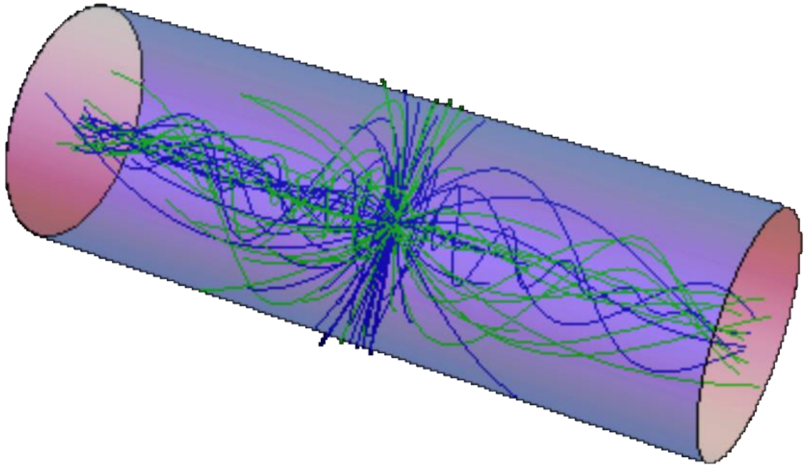
+ Quasi-conformal dark sector with ‘t Hooft coupling $\lambda \equiv g^2 N_{colors} \gg 1$
  - Dark mesons produced with mass scales smaller than mediator
  - Showering process is efficient over a larger energy range than SM QCD

SUEPs

+ Quasi-conformal dark sector with ‘t Hooft coupling $\lambda \equiv g^2 N_{colors} \gg 1$
  - Dark mesons produced with mass scales smaller than mediator
  - Showering process is efficient over a larger energy range than SM QCD

Soft Unclustered Energy Patterns (SUEPs):

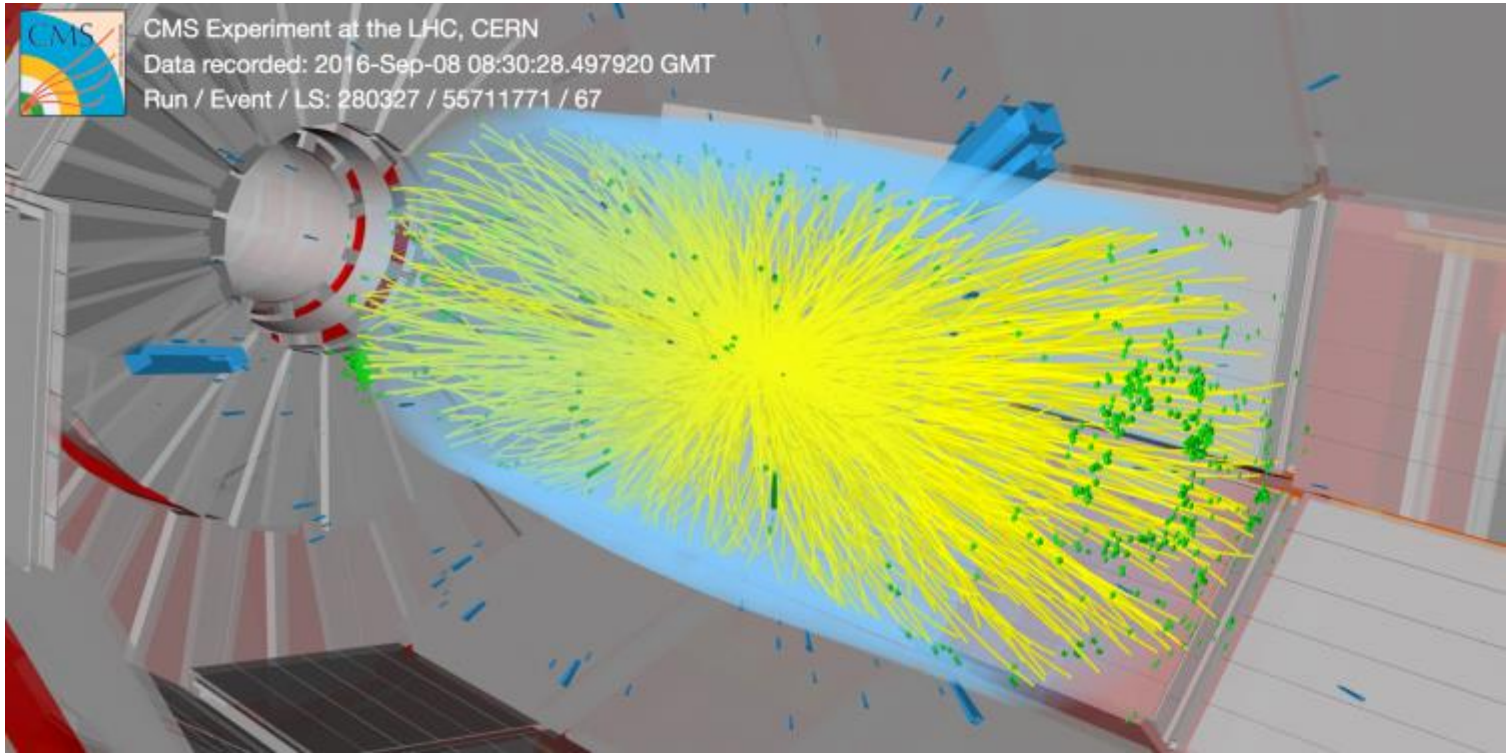
high multiplicity, isotropic, low p_T tracks final state



From arXiv:1612.00850

Experimental Challenges

"A spray of low p_T tracks? Have you heard of pileup?"



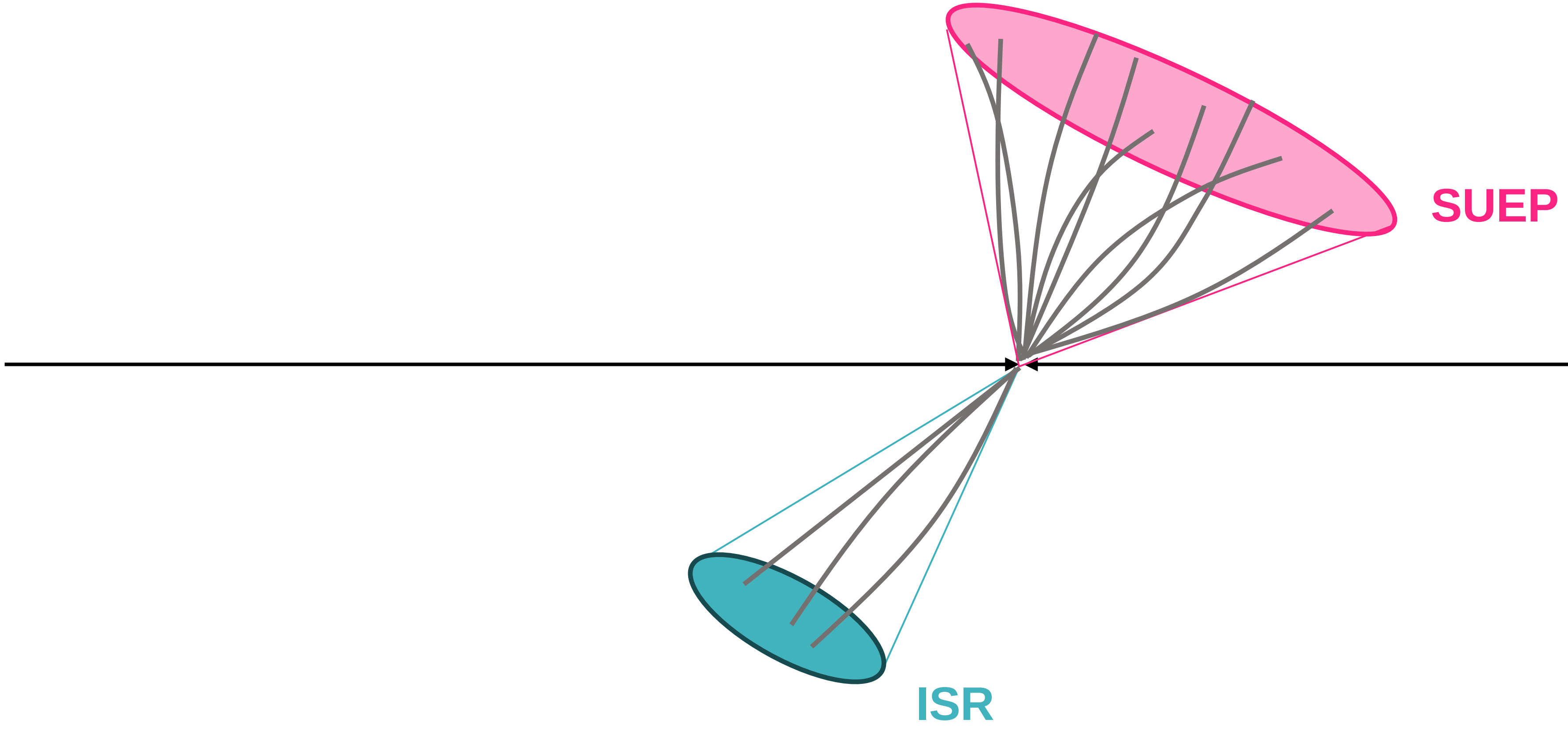
Average event at CMS: quite hard to distinguish SUEP from so-called "pileup", the additional overlapping pp interactions that happen concurrently with the interaction of interest.

From https://cms.cern/news/how-cms-weeds-out-particles-pile

Experimental Challenges

"A spray of low p_T tracks? Have you heard of pileup?"

Key idea: use events with high hadronic activity ($\Sigma p_T^{AK4jets} \equiv H_T$ > 1200 GeV) to select recoiling SUEP-ISR system



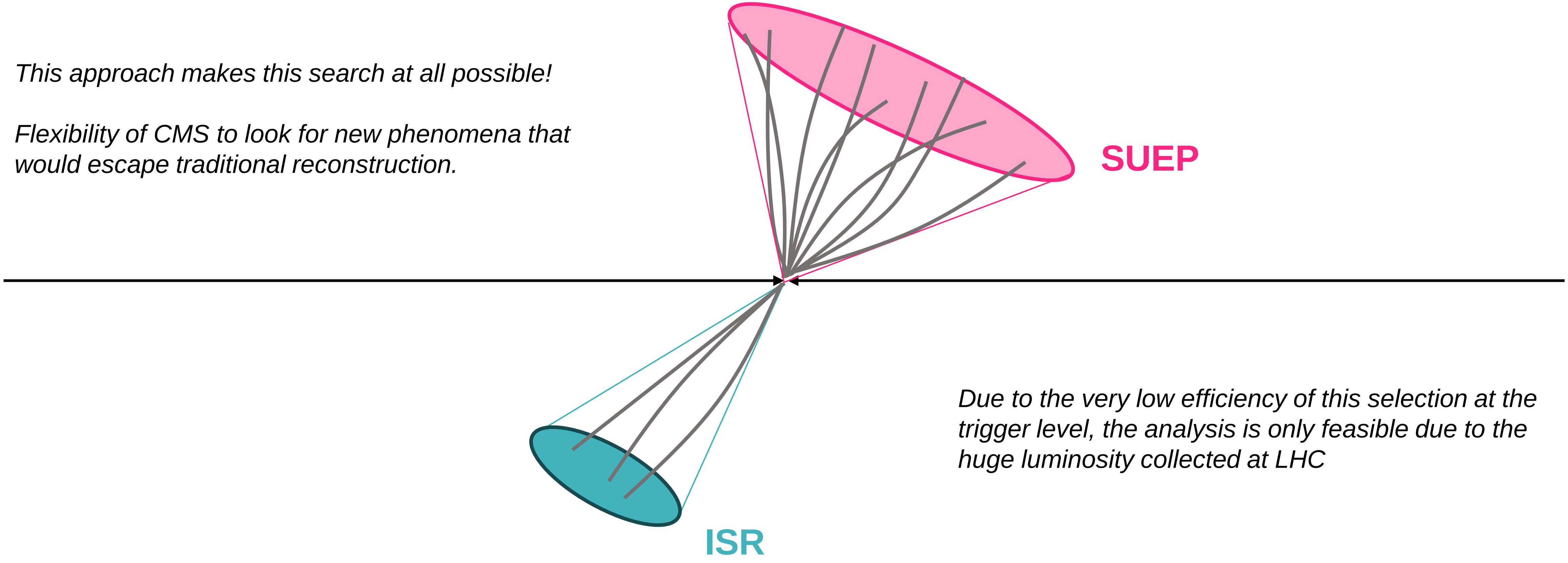
Experimental Challenges

"A spray of low p_T tracks? Have you heard of pileup?"

Key idea: use events with high hadronic activity ($\Sigma p_T^{AK4jets} \equiv H_T$ > 1200 GeV) to select recoiling SUEP-ISR system

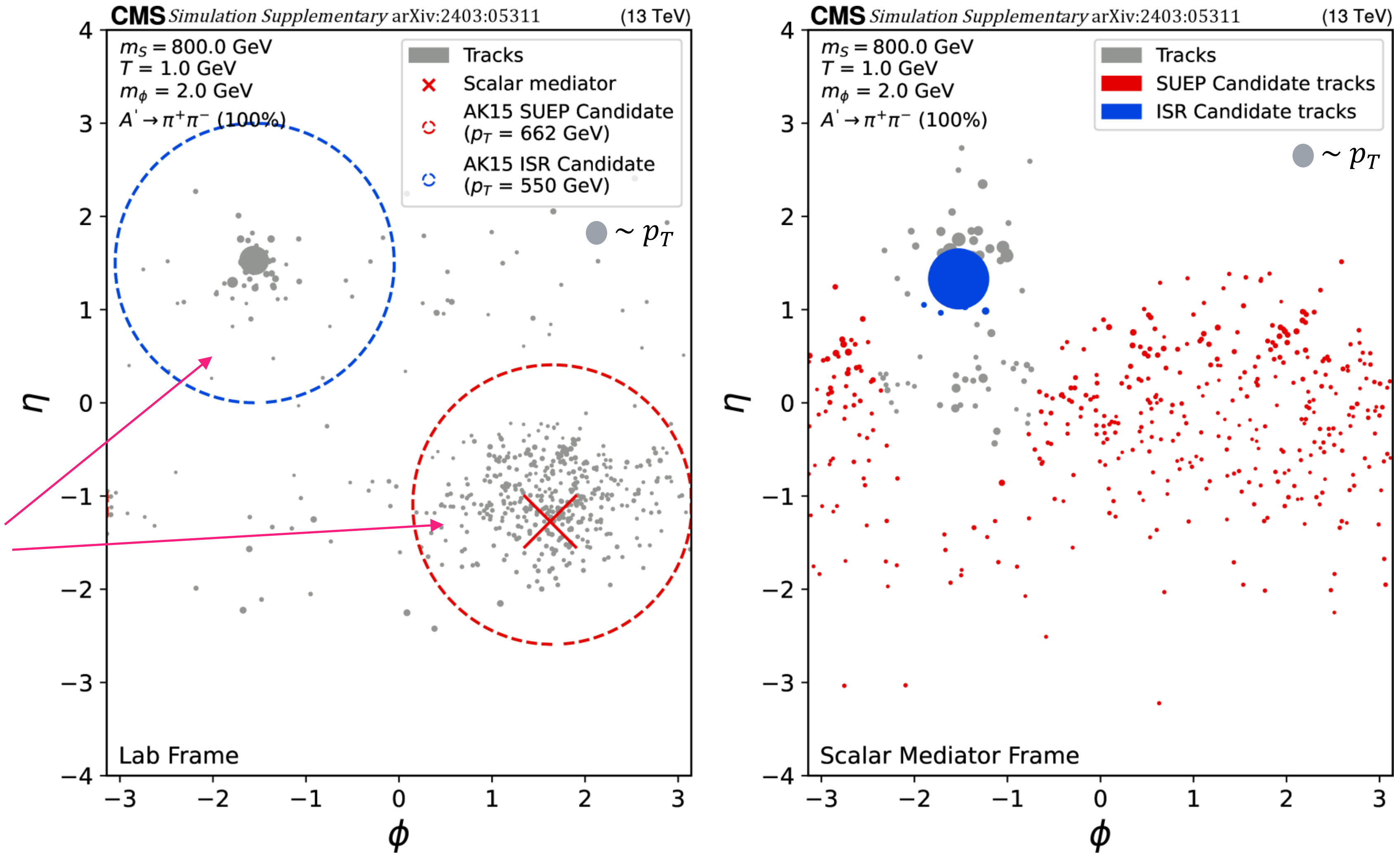
This approach makes this search at all possible!

Flexibility of CMS to look for new phenomena that would escape traditional reconstruction.



Due to the very low efficiency of this selection at the trigger level, the analysis is only feasible due to the huge luminosity collected at LHC

Event Display

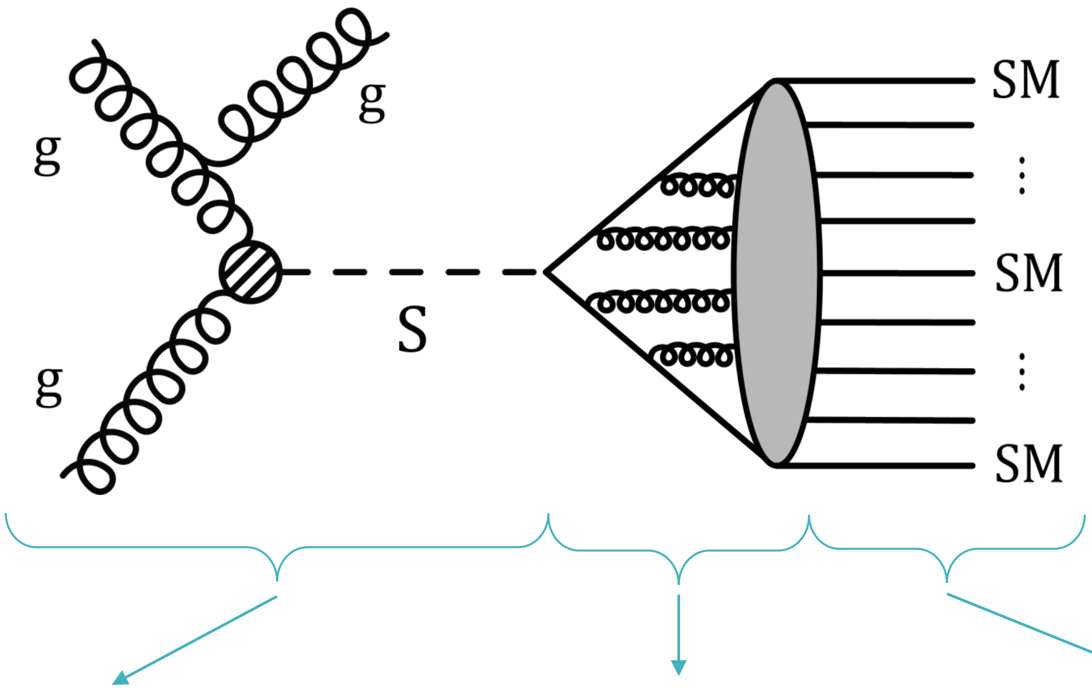


Recoiling SUEP and ISR systems

Boosting into the SUEP frame of reference recovers sphericity!

Benchmark Model

* Thanks to Simon Knapen for putting together a suep_generator!



Production (m_S)
Scalar narrow resonance (mediator S) produced through gluon-gluon fusion

Showering (m_ϕ, T_D)
Mediator S decays into dark mesons (ϕ) due to dark QCD

Decay ($m_{A'}$)
Dark mesons (ϕ) decay promptly to SM particles through dark photons (A')

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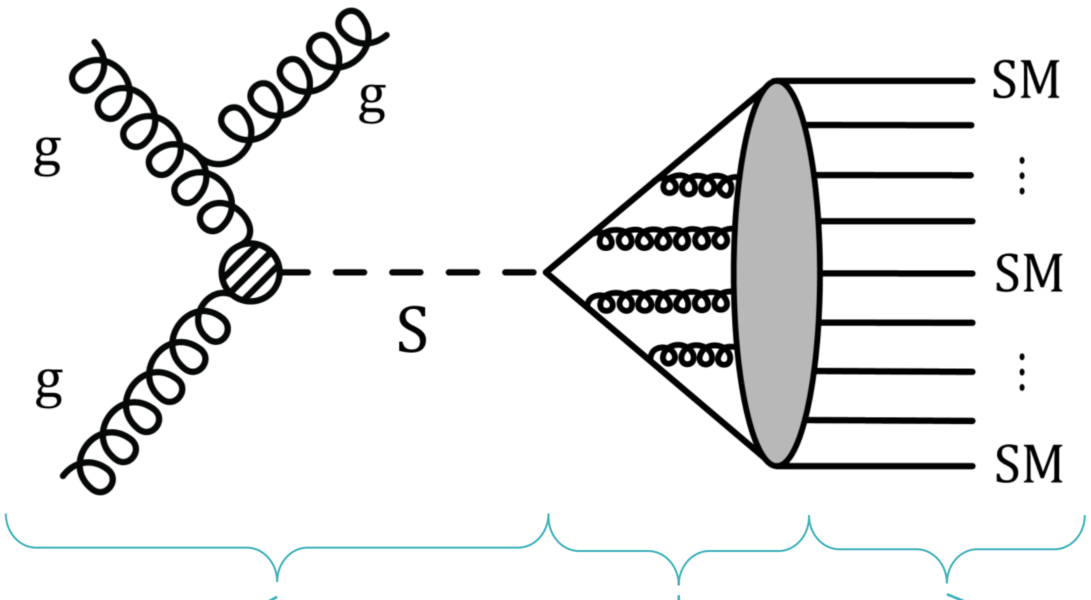

Production (m_S)
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Mediator S decays into dark mesons (ϕ) due to dark QCD

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Dark mesons (ϕ) decay promptly to SM particles through dark photons (A')

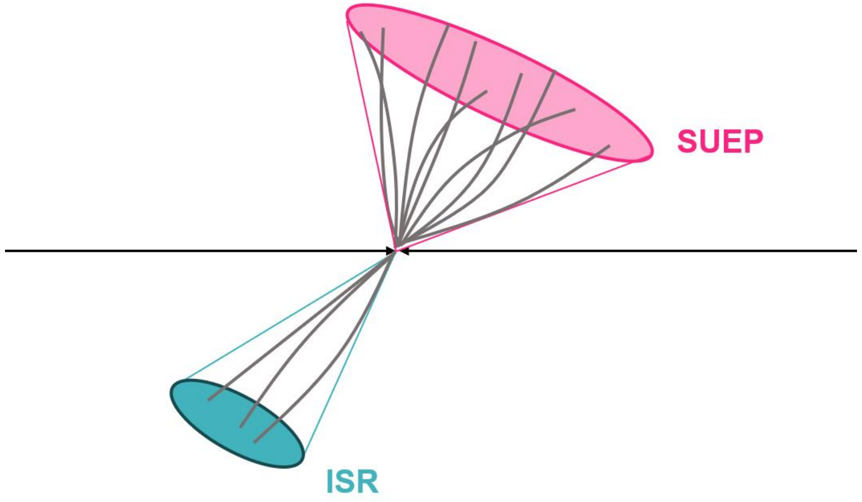
Varying these 4 parameters, can access a very large phase space of final state topologies that share their SUEP-ness: spherical and high multiplicity!

Event Selection

+ Extremely minimal event selection to keep analysis as general as possible

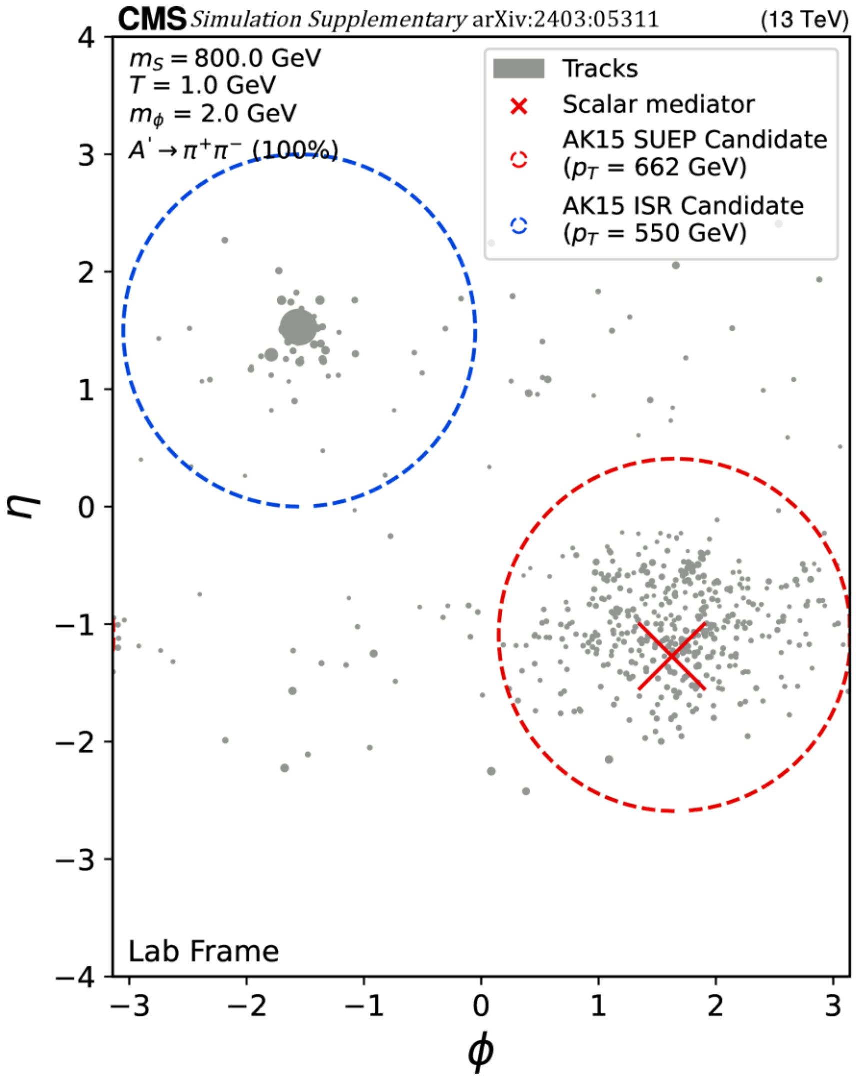
1. $H_T > 1200\ GeV$
   - High hadronic activity
2. No leptons
3. At least two AK-15 clusters
   - Tracks $p_T > 0.75\ GeV, |\eta| < 2.5$ tightly fit to PV
   - Clustering with anti-kT, R=1.5 to collect as many tracks as possible
   - Two leading clusters are defined to be the SUEP-ISR system
   - SUEP candidate defined to be the highest multiplicity of the two
4. Boost into frame of SUEP & calculate Sphericity tensor

$$S_{boosted}^{SUEP} = \left(\frac{3}{2}\right)(\lambda_0 + \lambda_1)$$



Background Estimation

+ Use sphericity ($S^{SUEP}_{boosted}$) and number of constituents ($n^{SUEP}_{constituent}$) to discriminate between background and signal
    - As shown on left, typical SUEP cluster has much higher constituents and sphericity than the typical QCD cluster
+ Dominant background: QCD multijet events
+ Problem 1: QCD Monte Carlo is not reliable in the tails, so how can we estimate this background?
+ Problem 2: traditional data-driven estimation methods such as ABCD do not account for correlations between variables

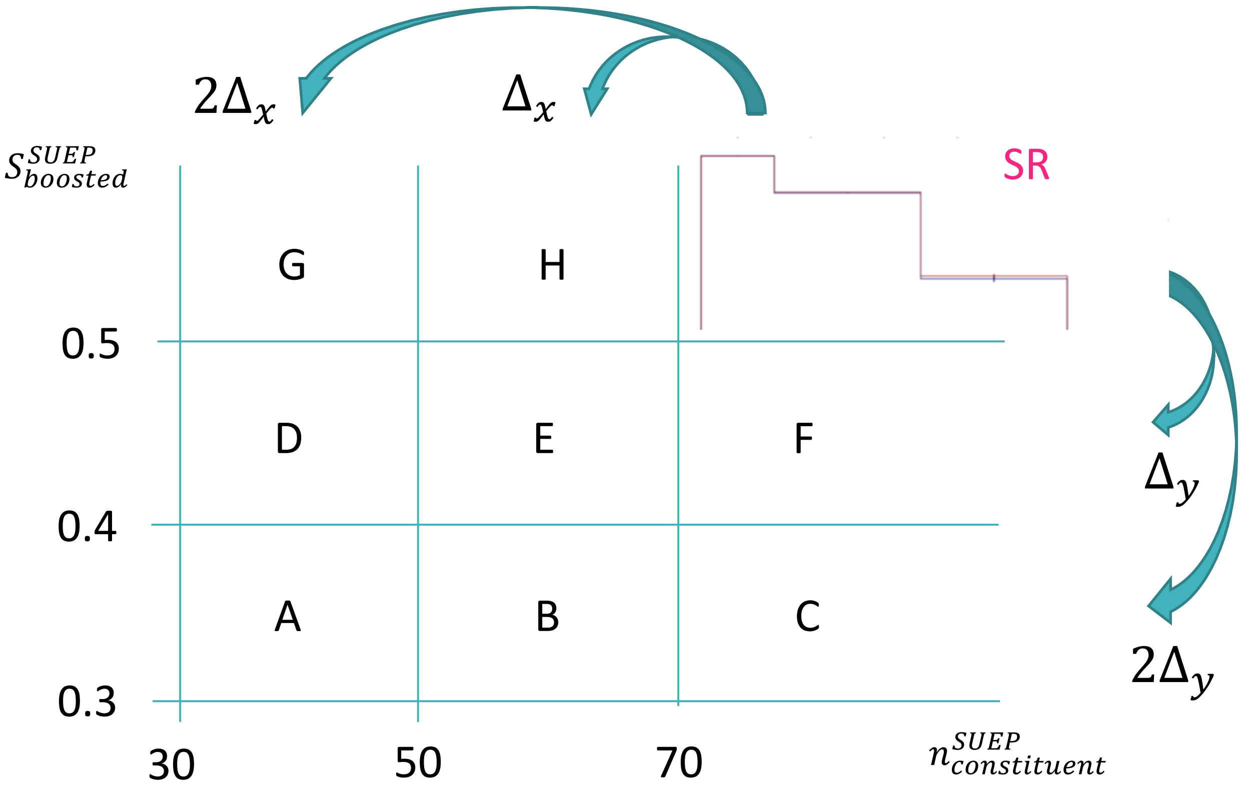


Extended ABCD Method [arxiv: 1906.10831]

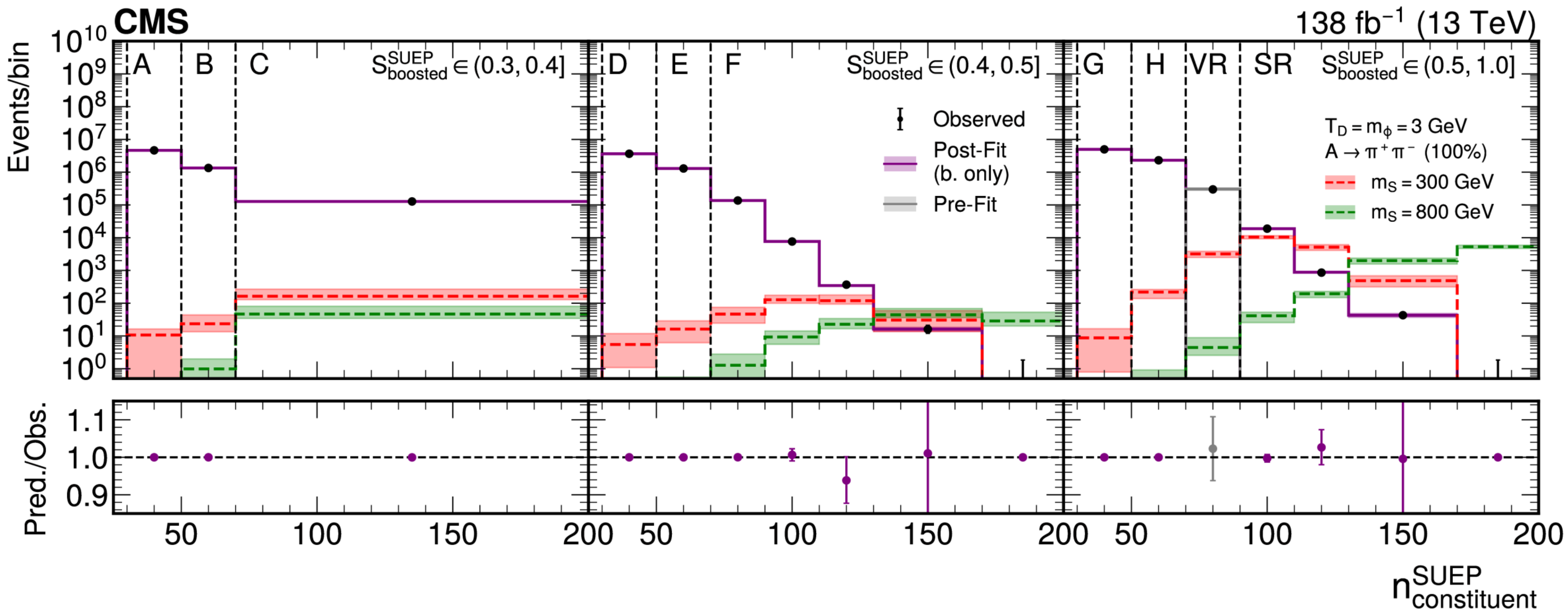
- Fully data-driven method to predict background in signal region (SR)
- Account for linear correlations in variables
- Plenty of QCD events in CRs: small uncertainties and little signal contamination
- Shape prediction for SR

$$SR^{Bin\,i} \approx F^{Bin\,i}\,\underbrace{\frac{H^2 F\, D^2 B^2}{G\, C\, A\, E^4}}_{\text{Scaling factor applied to F histogram}} + O(\Delta^4)$$

Scaling factor applied to F histogram

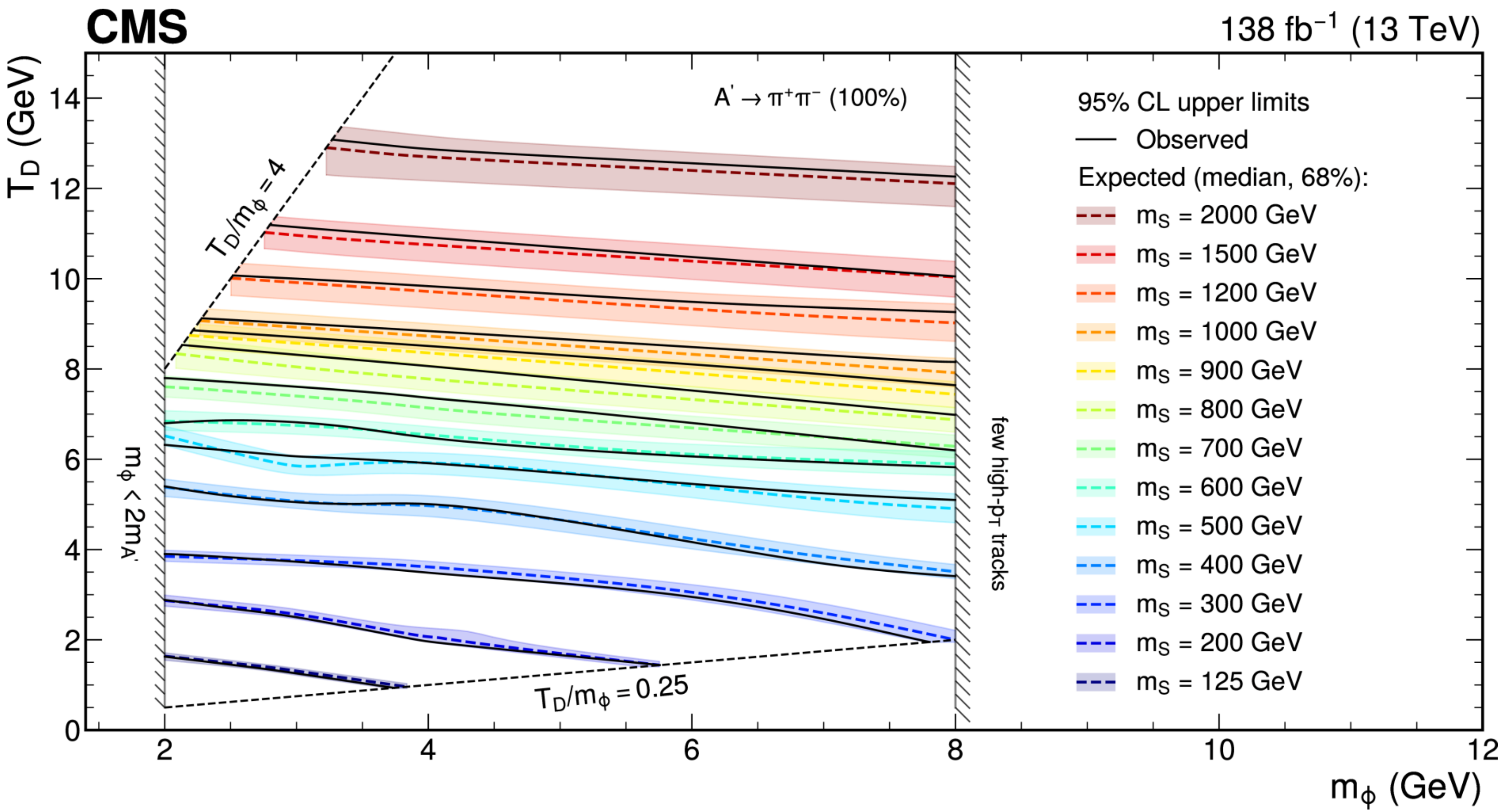


Results



- **Post-fit** compared to **data** is shown for all ABCD regions: excellent agreement with Standard Model prediction
- Validation region (VR) used to verify the ABCD prediction in data
- Yield systematic on ABCD prediction from orthogonal selection (ISR), shape systematic from F/C shape

Limits



+ Can put stringent limits on SUEP production
+ Particularly for high m_S, and T_D, m_ϕ; independent of decay mode ($m_{A'}$), see backup

Conclusions

- First search for SUEPs, novel signature motivated by Hidden Valley theories
- Demonstrated novel use of CMS detector to reconstruct non-traditional objects
- Novel background estimation technique employed, and developed procedures to validate in data and apply systematics

- Stringent limits put on wide areas of the phase space for a benchmark model
- Similar topologies in instantons, theories with extra spatial dimensions, and many-step decays in a hidden sector

- Submitted to PRL
- arXiv:2403.05311
- Supplementary figures
- HEPdata

Backup

Hidden Valleys

Confining, non-Abelian gauge group to extend SM

$$G_{SM} \times G_v$$

↓

Stable, neutral DM: global flavor symmetry in dark sector

Naturalness: from confinement, we have a natural scale, Λ_{dark}

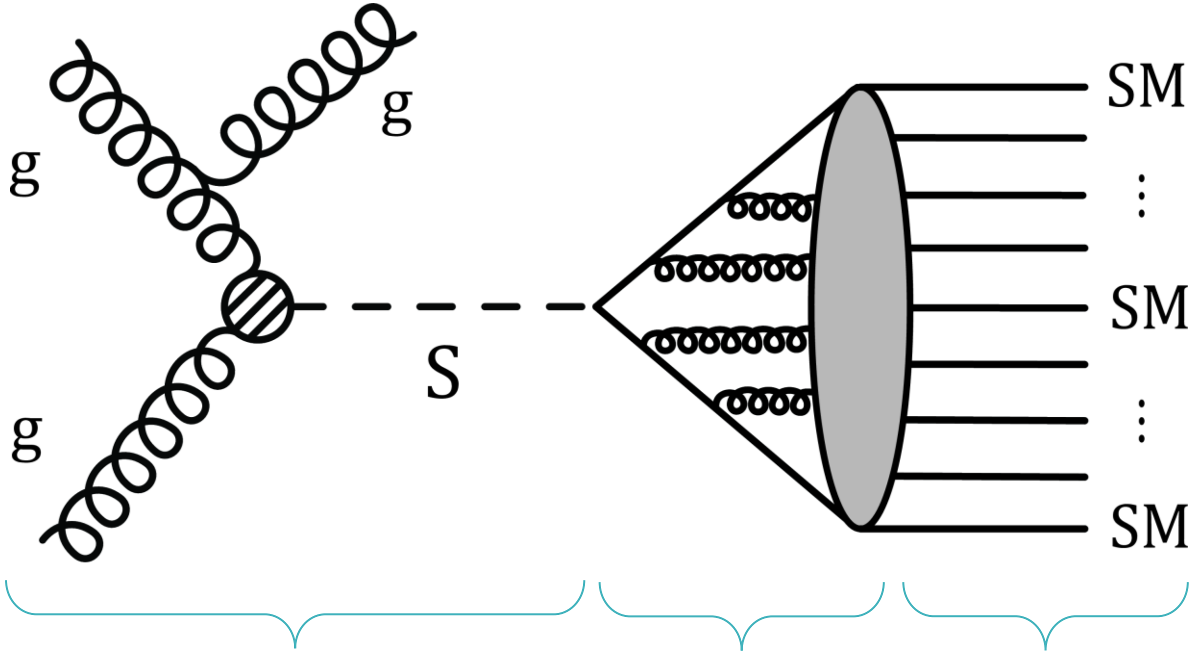
Suppressed interactions with SM: EFT below confinement suppressed by powers of Λ_{dark}

Self-interactions: which may explain galactic structure anomalies

See arXiv:hep-ph/0604261, arXiv:1809.10152, arXiv:1604.04627, arXiv:1306.4676

Model Parameters

* Thanks to Simon Knapen for putting together a suep_generator!



m_S
- Affects final state multiplicity

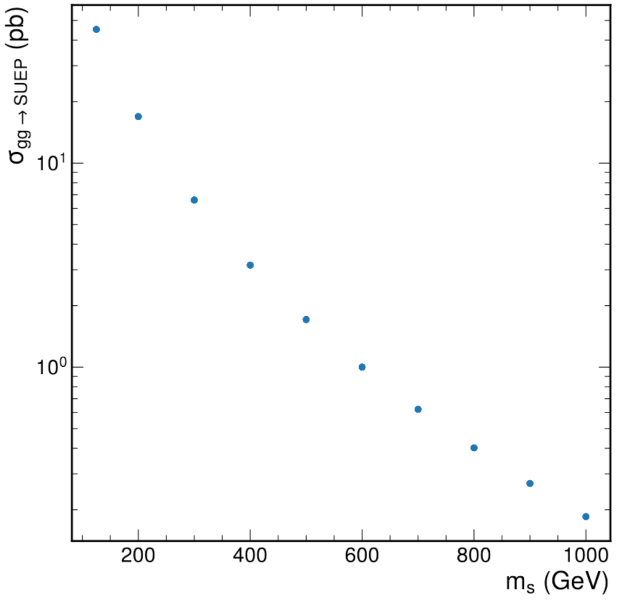
m_ϕ, T_D
- Affect momenta and number of particles produced

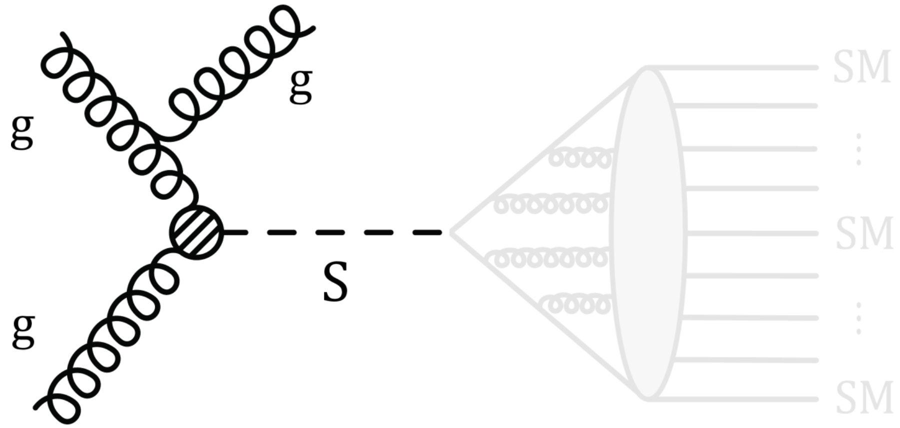
$m_{A'}$
- Demanding promptness, can fix A'-SM coupling: $m_{A'}$ free param.
- Varies what type of charged particle is produced

Production

- SM particles linked to hidden sector via scalar mediator S
- The cross section for a scalar particle S which couples to the SM via an effective point-like ggS operator is considered
- Cross section corresponds to gg fusion of a BSM Higgs (recommended by LHC Higgs WG Yellow report)

$$\mathcal{L}_{eff} \supset -\frac{C}{4v} S G^{a}_{\mu\nu} G^{\mu\nu}_{a}$$





Parameters: m_S

Showering

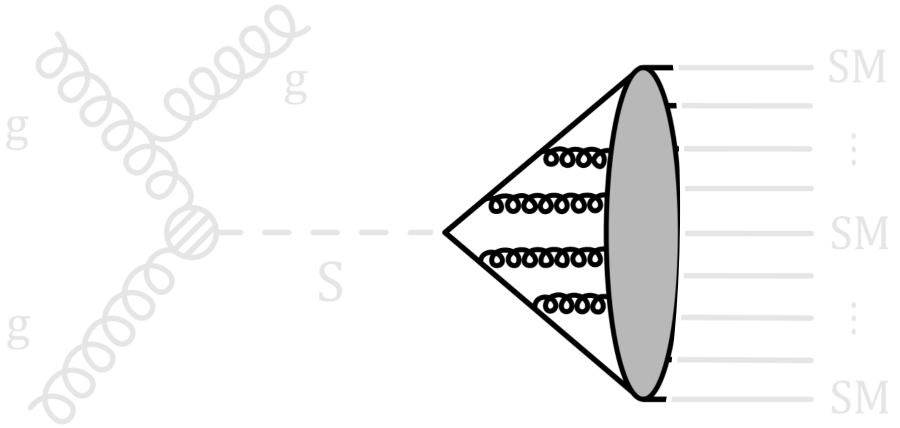
- Dark quark matter masses below Λ_D → dark quarks hadronize in "dark shower"
- Large 't Hooft coupling → dark particles emitted isotropically
  - In QCD/Yang-Mills with coupling constant *g* and *N* colors, 't Hooft coupling is *gN*
- Mass gap b/w dark hadrons < mass of portal state → high multiplicity of soft dark particles
- LO Boltzmannian thermal model is employed for the decay

$$\frac{dN_\phi}{dp} \propto e^{-\sqrt{p^2+m^2}/T}$$

- Keep sampling distribution until all energy is used up → multiplicity related by:

$$N \sim \frac{m_S}{m_\phi} \sim \frac{m_S}{T}$$

Parameters: m_ϕ, T



Decay to SM

- Dark hadrons decay promptly to SM particles through dark photons (A')
- Consider 3 cases:

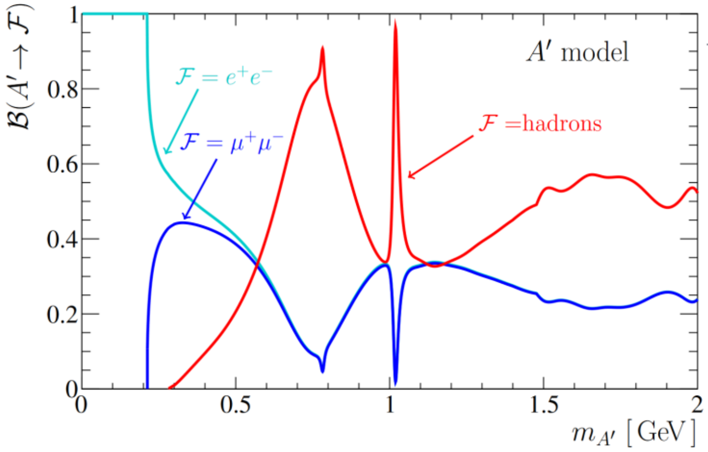
  $m_{A'}$ = 0.5 GeV, A' → e^+e^- (40%), $\mu^+\mu^-$ (40%), $\pi^+\pi^-$ (20%)

  $m_{A'}$ = 0.7 GeV, A' → e^+e^- (15%), $\mu^+\mu^-$ (15%), $\pi^+\pi^-$ (70%)

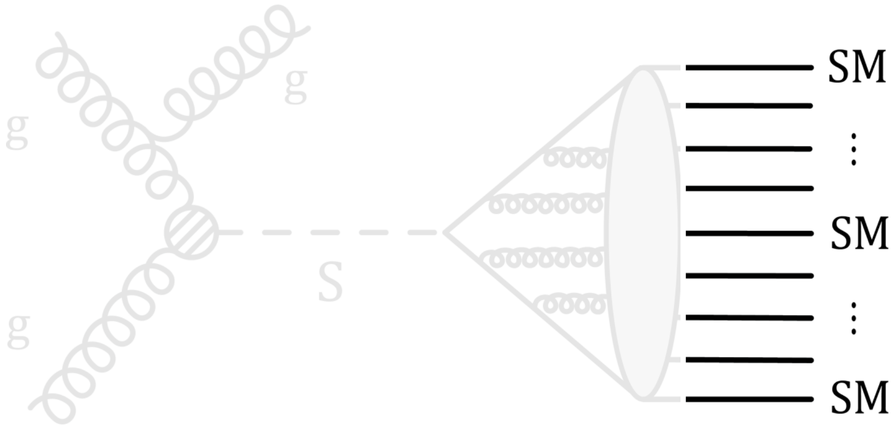
  $m_{A'}$ = 1.0 GeV, A' → $\pi^+\pi^-$ (100%)

$$\Gamma[A' \to \ell^+\ell^-] \simeq \frac{m_{A'}\alpha\varepsilon^2\cos^2(\theta_W)}{3}\left(1+\frac{2m_\ell^2}{m_{A'}^2}\right)\sqrt{1-\frac{4m_\ell^2}{m_{A'}^2}}\,.$$

- $c\,\tau < 1\,mm$ at these masses corresponds to approx. $\epsilon > 10^{-5}$, leaving plenty of non-excluded dark photon $\epsilon - m_{A'}$ phase space

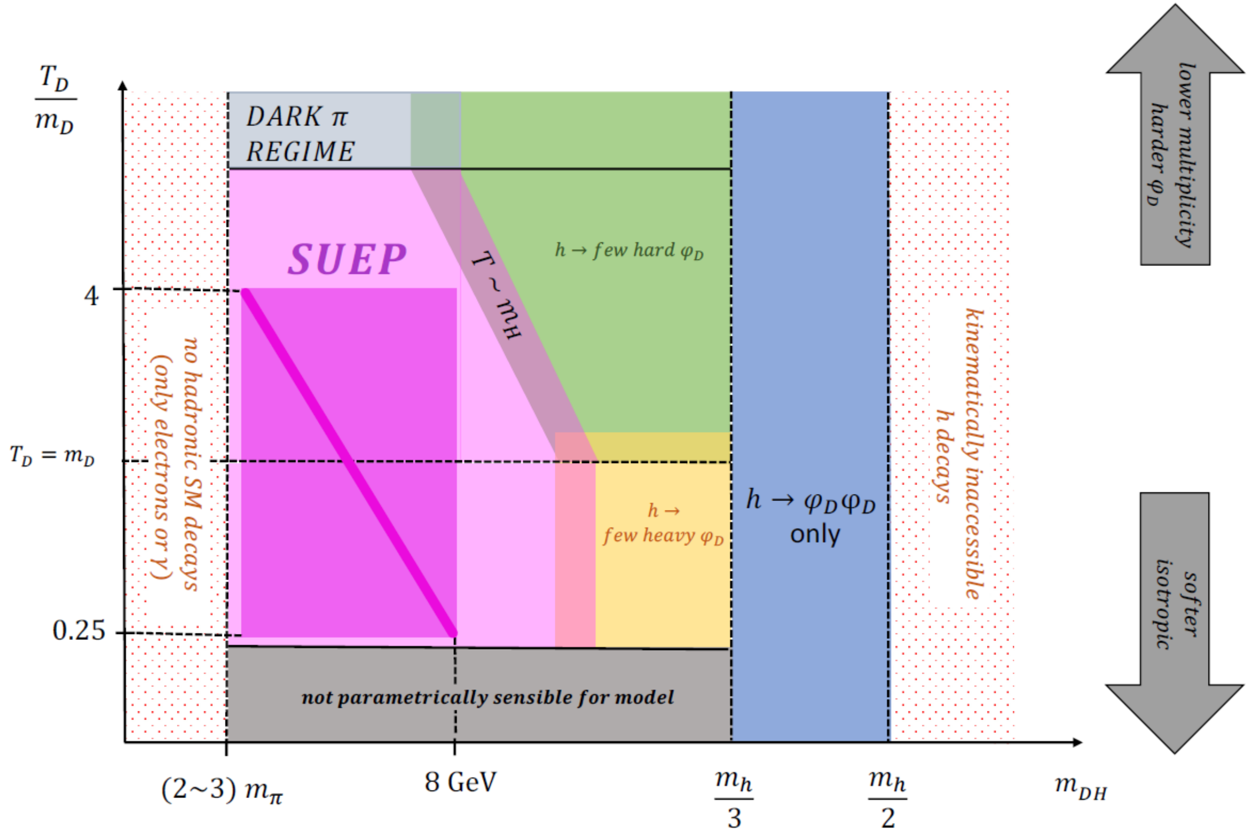


From arXiv:1801.04847



Parameters: $m_{A'}$

SUEP in Context



From arXiv:2107.12379v1

- SUEP signature shown in the parameter space of the strongly coupled dark sector models
- Use this to bound the temperature, mass of the dark pseudoscalar meson that we analyze

Parameter	Values [GeV]
m_S	125, 200, 300,400,500,600,700,800,900,1000
m_ϕ	2* $m_{A'}$, 2, 3, 4
T/m_ϕ	0.5, 1, 2 (for m_S =400, 700 GeV: 0.25, 0.5, 0.75, 1, 2, 3, 4)
$m_{A'}$	generic (1 GeV), hadronic (0.7 GeV), leptonic (0.5 GeV)

Event Selection

m_S [GeV]	$m_{A'}$ [GeV]	$H_T^{gen} > 1000$ GeV	Lepton Veto	Trigger	$H_T > 1200$ GeV	One AK15 Cluster	$n^{SUEP}_{constituent} > 70$	$S^{SUEP}_{boosted} > 0.5$	Efficiency
125	1	0.002596	0.9994	0.87	0.703	0.946	0.062	0.58	0.0207
125	0.5	0.002596	0.9989	0.864	0.717	0.945	0.058	0.5	0.0169
125	0.7	0.002596	0.9943	0.784	0.776	0.942	0.047	0.5	0.0132
200	1	0.004823	0.99972	0.8762	0.745	0.9491	0.695	0.932	0.402
200	0.5	0.004823	0.99916	0.8755	0.756	0.9443	0.65	0.937	0.38
200	0.7	0.004823	0.9915	0.819	0.797	0.9431	0.595	0.93	0.338
300	1	0.009036	0.99939	0.876	0.783	0.9469	0.9799	0.9705	0.617
300	0.5	0.009036	0.99915	0.8835	0.782	0.9454	0.9771	0.9736	0.621
300	0.7	0.009036	0.9922	0.8433	0.799	0.9468	0.9695	0.971	0.596
400	1	0.01467	1.0	0.869	0.823	0.944	0.9928	0.9856	0.66
400	0.5	0.01467	0.99871	0.8755	0.809	0.9485	0.992	0.9792	0.652
400	0.7	0.01467	0.9942	0.8493	0.808	0.9465	0.9882	0.9813	0.627
500	1	0.02172	0.99987	0.8574	0.8522	0.9508	0.9959	0.9768	0.676
500	0.5	0.02172	0.9997	0.866	0.828	0.954	0.9978	0.9782	0.668
500	0.7	0.02172	0.9954	0.8501	0.8332	0.9477	0.9944	0.9787	0.65
600	1	0.0302	1.0	0.83	0.88	0.954	0.9966	0.9795	0.68
600	0.5	0.0302	0.99942	0.8478	0.8632	0.9532	0.9981	0.9809	0.683
600	0.7	0.0302	0.9958	0.8449	0.8536	0.9503	0.9972	0.979	0.666
700	1	0.04009	0.99954	0.8102	0.9042	0.9578	0.99926	0.9801	0.687
700	0.5	0.04009	1.0	0.823	0.878	0.956	0.9995	0.977	0.675
700	0.7	0.04009	0.9967	0.8305	0.8675	0.9549	0.9986	0.9797	0.671
800	1	0.05141	0.99967	0.7778	0.9268	0.9617	0.99977	0.9814	0.68
800	0.5	0.05141	0.99974	0.794	0.909	0.959	0.9996	0.9777	0.676
800	0.7	0.05141	0.9969	0.821	0.886	0.969	0.9993	0.9813	0.689
900	1	0.06415	1.0	0.717	0.958	0.969	0.9993	0.9854	0.656
900	0.5	0.06415	1.0	0.762	0.931	0.968	1.0	0.9811	0.674
900	0.7	0.06415	0.9979	0.7814	0.9123	0.968	0.99978	0.9835	0.677
1000	1	0.0783	0.99957	0.685	0.9727	0.9772	1.0	0.985	0.641
1000	0.5	0.0783	0.9991	0.697	0.958	0.9725	1.0	0.9807	0.636
1000	0.7	0.0783	0.99791	0.7489	0.9255	0.9755	0.99993	0.982	0.663
1200	1	0.1919	1.0	0.541	0.9923	0.988	1.0	0.99	0.525
1200	0.7	0.1919	0.9992	0.66	0.954	0.992	1.0	0.983	0.613
1200	0.5	0.1919	0.9997	0.585	0.981	0.9903	1.0	0.9914	0.563
1500	1	0.5856	0.99967	0.36	0.9942	0.9988	1.0	0.993	0.355
1500	0.7	0.5856	0.9986	0.512	0.9767	1.0	1.0	0.9965	0.498
1500	0.5	0.5856	1.0	0.407	0.9953	0.9979	1.0	0.9948	0.402
2000	1	1	0.99986	0.771	0.9989	1.0	1.0	0.9976	0.768
2000	0.7	1	0.9996	0.9814	0.9988	1.0	1.0	0.9971	0.977
2000	0.5	1	1.0	0.914	0.9982	1.0	1.0	0.9974	0.91

Systematics for Extended ABCD

- Yield uncertainty
  - Cover higher order correlations between the variables
  - Repeat the analysis using the ISR jet (no signal contamination there), and check the total yield closure in this the ISR signal region
  - Any non-closure is taken as a systematic on the total yield prediction (8%)

	2016	2017	2018
Observed Yield	835	1078	1373
Predicted Yield	828 ± 96	1130 ± 120	1160 ± 110
Ratio	1.01 ± 0.13	0.96 ± 0.09	1.18 ± 0.11

- Shape uncertainty
  - Differences between SR and F estimated via $(F_{bin}/F)/(C_{bin}/C) \approx (SR_{bin}/SR)/(F_{bin}/F)$
  - Fit a parametrized line using Bins 0 and 1 to predict value of F/C in Bins 2-4
  - Systematic is correlated among bins in the fit

Signal Systematics

Applied to signal samples:

1. Track reconstruction: track killing technique from Lund jet plane analysis
2. Trigger scale factors
3. Jet energy corrections
4. Pileup weights, with up and down variations, applied as function of # of true interactions in MC
5. Parton shower weights
6. Pre-fire weights
7. p_T reweighting on the Higgs (mS = 125 GeV only)

Items 1–6: 0-4% effect

Item 7: ~10% effect

No further theoretical uncertainties applied:

+ Theoretical uncertainty on the dark shower is so much larger than any LO to NLO correction uncertainty that it is not worth adding them

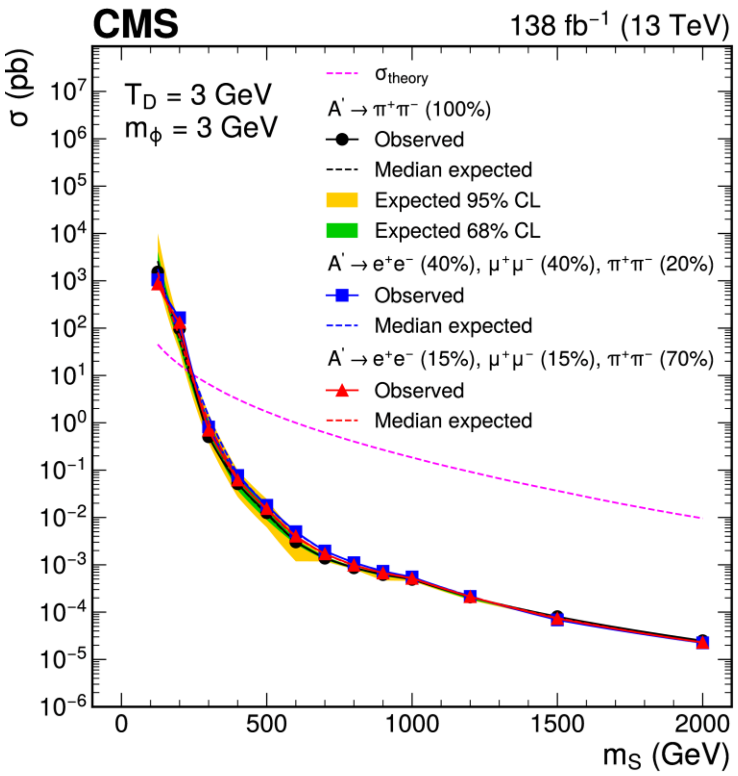
Validation Region

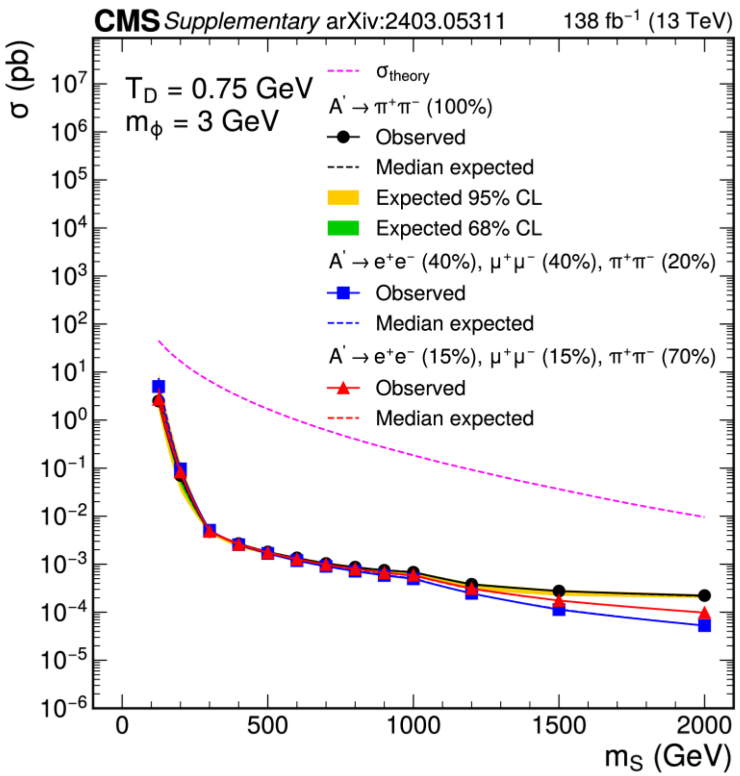
- Use the first bin of the SR, which has negligible contamination from signal, as a validation for the method
- Subsequently not utilized for the fit

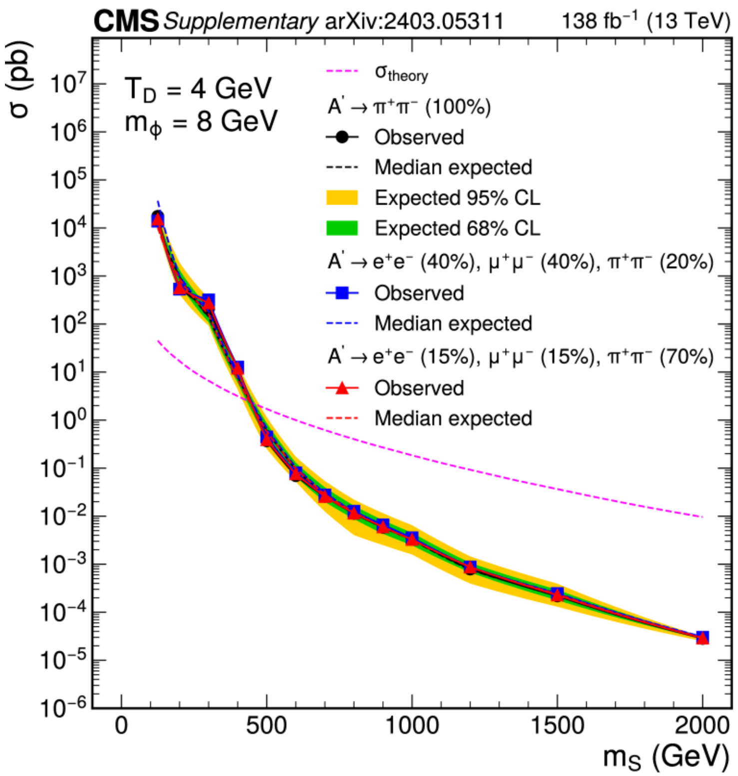
	2016	2017	2018
Observed Yield	79518	100728	137527
Predicted Yield	81200 ± 1200 (stat) ± 6500 (syst)	105000 ± 1000 (stat) ± 8000 (syst)	136000 ± 2000 (stat) ± 11000 (syst)
Ratio	0.98 ± 0.01 (stat) ± 0.08 (syst)	0.96 ± 0.01 (stat) ± 0.08 (syst)	1.01 ± 0.01 (stat) ± 0.08 (syst)

- Good closure in all years!

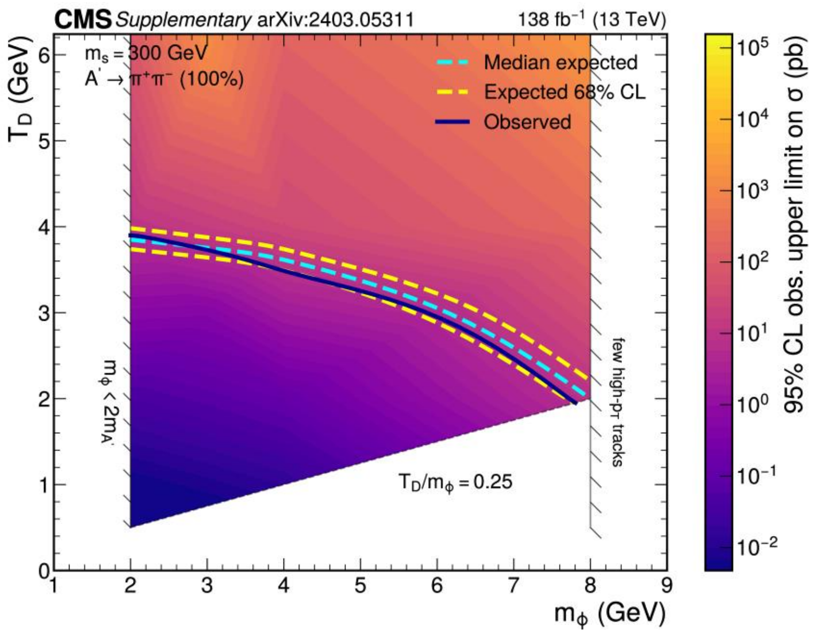
Limits

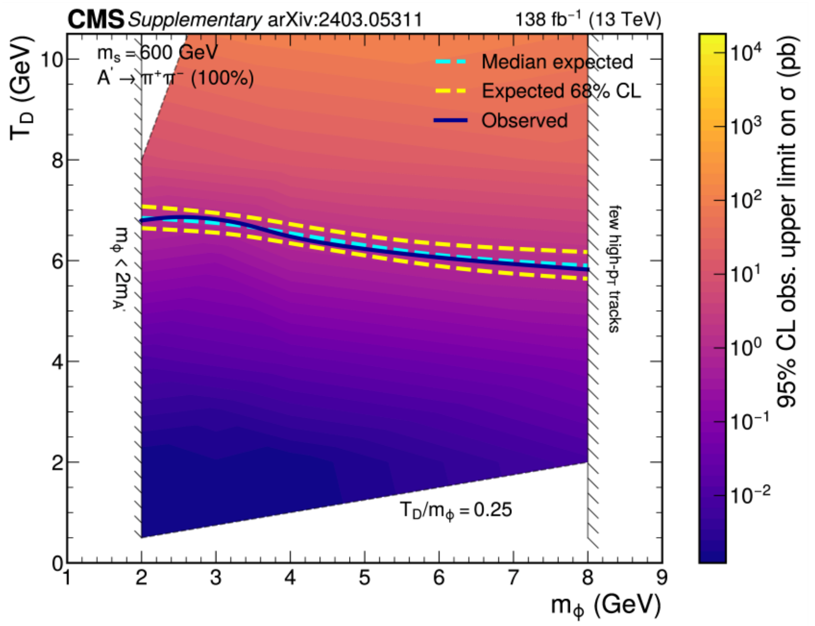

CMS
138 fb^{-1} (13 TeV)
T_D = 3 GeV
m_ϕ = 3 GeV
σ_{theory}
$A' \to \pi^+\pi^-$ (100%)
Observed
Median expected
Expected 95% CL
Expected 68% CL
$A' \to e^+e^-$ (40%), $\mu^+\mu^-$ (40%), $\pi^+\pi^-$ (20%)
Observed
Median expected
$A' \to e^+e^-$ (15%), $\mu^+\mu^-$ (15%), $\pi^+\pi^-$ (70%)
Observed
Median expected
σ (pb)
m_S (GeV)

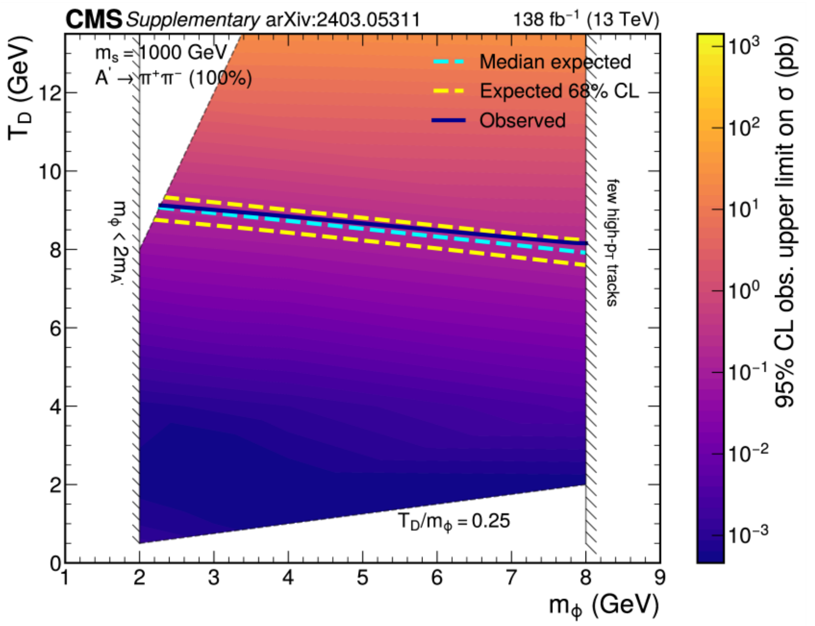

CMS Supplementary arXiv:2403.05311
138 fb^{-1} (13 TeV)
T_D = 0.75 GeV
m_ϕ = 3 GeV
σ_{theory}
$A' \to \pi^+\pi^-$ (100%)
Observed
Median expected
Expected 95% CL
Expected 68% CL
$A' \to e^+e^-$ (40%), $\mu^+\mu^-$ (40%), $\pi^+\pi^-$ (20%)
Observed
Median expected
$A' \to e^+e^-$ (15%), $\mu^+\mu^-$ (15%), $\pi^+\pi^-$ (70%)
Observed
Median expected
σ (pb)
m_S (GeV)


CMS Supplementary arXiv:2403.05311
138 fb^{-1} (13 TeV)
T_D = 4 GeV
m_ϕ = 8 GeV
σ_{theory}
$A' \to \pi^+\pi^-$ (100%)
Observed
Median expected
Expected 95% CL
Expected 68% CL
$A' \to e^+e^-$ (40%), $\mu^+\mu^-$ (40%), $\pi^+\pi^-$ (20%)
Observed
Median expected
$A' \to e^+e^-$ (15%), $\mu^+\mu^-$ (15%), $\pi^+\pi^-$ (70%)
Observed
Median expected
σ (pb)
m_S (GeV)

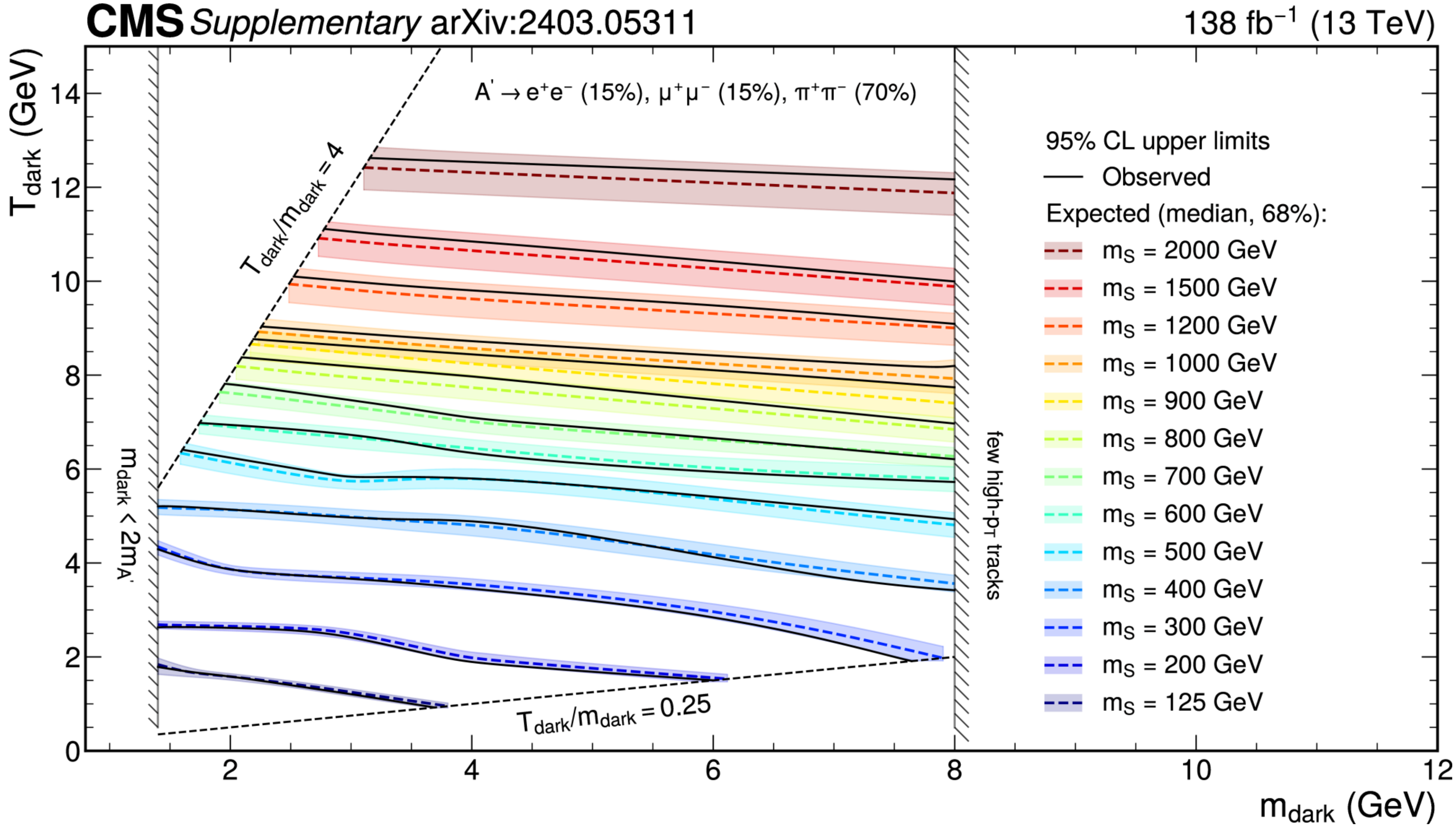
Limits


CMS Supplementary arXiv:2403.05311
138 fb^{-1} (13 TeV)
m_s = 300 GeV
$A' \to \pi^+\pi^-$ (100%)
Median expected
Expected 68% CL
Observed
$m_\phi < 2m_{A'}$
few high-p_T tracks
$T_D/m_\phi = 0.25$
T_D (GeV)
m_ϕ (GeV)
95% CL obs. upper limit on σ (pb)


CMS Supplementary arXiv:2403.05311
138 fb^{-1} (13 TeV)
m_s = 600 GeV
$A' \to \pi^+\pi^-$ (100%)
Median expected
Expected 68% CL
Observed
$m_\phi < 2m_{A'}$
few high-p_T tracks
$T_D/m_\phi = 0.25$
T_D (GeV)
m_ϕ (GeV)
95% CL obs. upper limit on σ (pb)

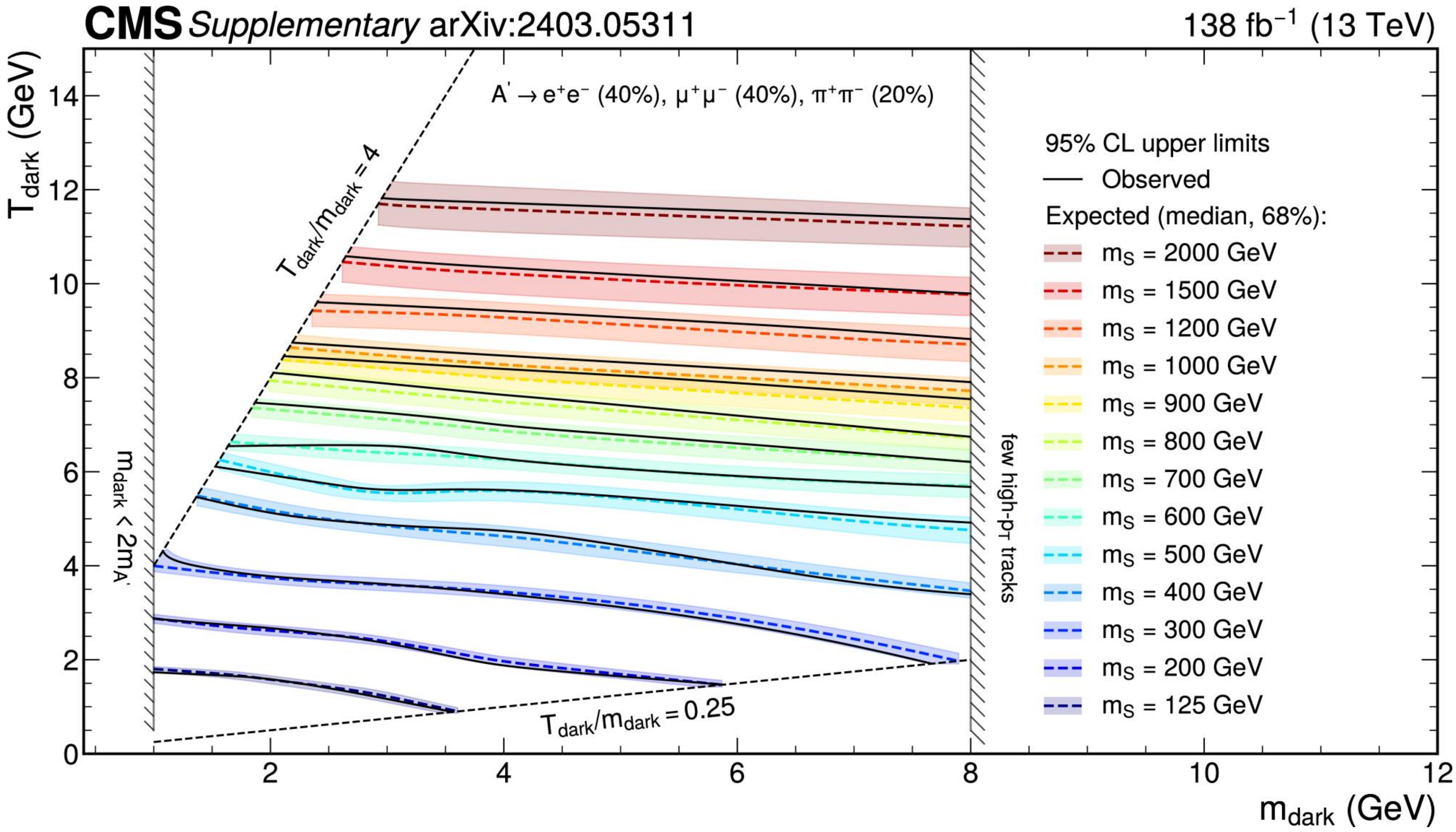

CMS Supplementary arXiv:2403.05311
138 fb^{-1} (13 TeV)
m_s = 1000 GeV
$A' \to \pi^+\pi^-$ (100%)
Median expected
Expected 68% CL
Observed
$m_\phi < 2m_{A'}$
few high-p_T tracks
$T_D/m_\phi = 0.25$
T_D (GeV)
m_ϕ (GeV)
95% CL obs. upper limit on σ (pb)

Limits



CMS Supplementary arXiv:2403.05311
138 fb⁻¹ (13 TeV)
A' → e⁺e⁻ (15%), μ⁺μ⁻ (15%), π⁺π⁻ (70%)
95% CL upper limits
Observed
Expected (median, 68%):
m_S = 2000 GeV
m_S = 1500 GeV
m_S = 1200 GeV
m_S = 1000 GeV
m_S = 900 GeV
m_S = 800 GeV
m_S = 700 GeV
m_S = 600 GeV
m_S = 500 GeV
m_S = 400 GeV
m_S = 300 GeV
m_S = 200 GeV
m_S = 125 GeV
T_dark/m_dark = 4
T_dark/m_dark = 0.25
m_dark < 2m_A'
few high-p_T tracks
T_dark (GeV)
m_dark (GeV)

Limits



CMS Supplementary arXiv:2403.05311
138 fb^{-1} (13 TeV)
$A' \to e^+e^-$ (40%), $\mu^+\mu^-$ (40%), $\pi^+\pi^-$ (20%)
$T_{dark}/m_{dark} = 4$
$T_{dark}/m_{dark} = 0.25$
$m_{dark} < 2m_{A'}$
few high-p_T tracks
95% CL upper limits
Observed
Expected (median, 68%):
m_S = 2000 GeV
m_S = 1500 GeV
m_S = 1200 GeV
m_S = 1000 GeV
m_S = 900 GeV
m_S = 800 GeV
m_S = 700 GeV
m_S = 600 GeV
m_S = 500 GeV
m_S = 400 GeV
m_S = 300 GeV
m_S = 200 GeV
m_S = 125 GeV
T_{dark} (GeV)
m_{dark} (GeV)