DARK SHOWERS IN CMS

Roberto Seidita - ETHZ

On behalf of the CMS dark showers teams

With valuable input from Jannicke Pearkes, Yi-Mu Chen, and Kevin Pedro

ETH zürich

A GROWING FIELD

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Search for new particles decaying to a jet and an emerging jet

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PHYSICAL REVIEW LETTERS **133,** 191902 (2024)
Editors' Suggestion | Featured in Physics

Search for Soft Unclustered Energy Patterns in Proton-Proton Collisions at 13 TeV

A. Hayrapetyan *et al.*[*]
(CMS Collaboration)

(Received 8 March 2024; accepted 6 September 2024; published 5 November 2024)

The first search for soft unclustered energy patterns (SUEPs) is performed using an integrated luminosity of 138 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV, collected in 2016–2018 by the CMS detector at the LHC. Such SUEPs are predicted by hidden valley models with a new, confining force with a large 't Hooft coupling. In events with boosted topologies, selected by high-threshold hadronic triggers, the multiplicity and sphericity of clustered tracks are used to reject the background from standard model quantum chromodynamics. With no observed excess of events over the standard model expectation, limits are set on the cross section for production via gluon fusion of a scalar mediator with SUEP-like decays.

DOI: 10.1103/PhysRevLett.133.191902

I will be brief on this given the time constraint

EMERGING JETS

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SIGNAL MODELLING

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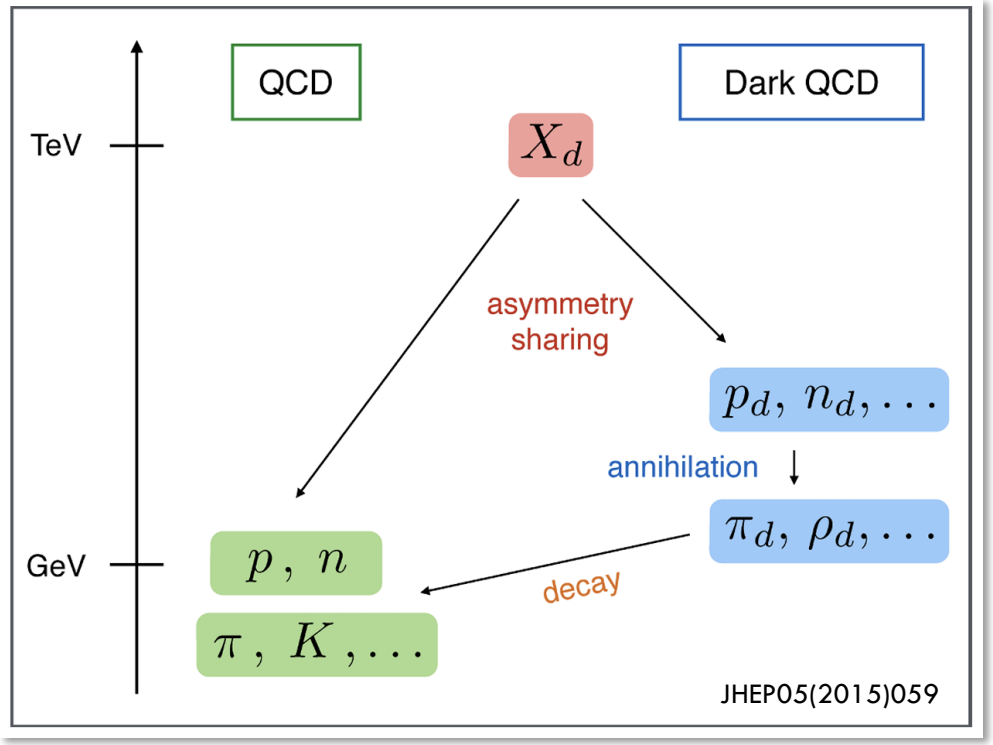
Search for dark QCD with emerging jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

- Based on JHEP05(2015)059
- SM gauge group is extended by new QCD-like force → $G_{\mathrm{SM}} \times \mathrm{SU}(N_d)_{DS}$
- Assume dark sector (DS) contains N_f dark quark states
- Dark QCD confines in the infrared at a scale $\Lambda_d \sim m_{p_d}$
- The lightest dark baryon is stable → DM candidate
- Mesons may decay back to the SM
- Scalar mediator $\mathrm{X_{DK}}$ living in the fundamental representation of both $\mathrm{SU}(3)_{SM}$ and $\mathrm{SU}(N_d)_{DS}$



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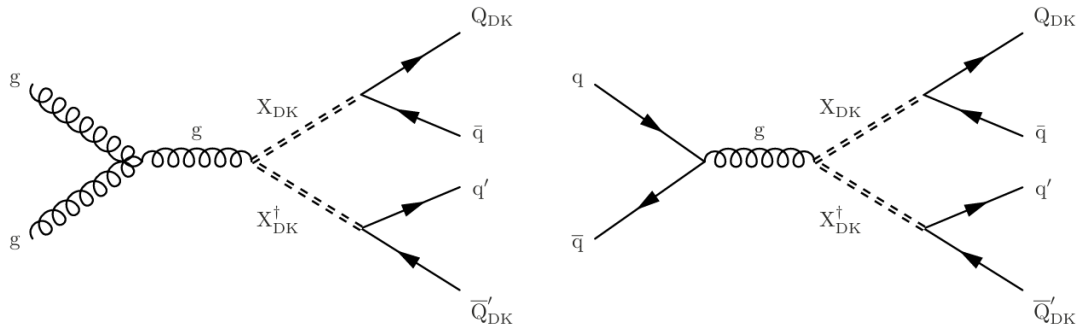
- Mediator X_{DK} is a color triplet and carries electric charge of 1/3 or 2/3
- Can be produced in pairs via ggF or $q\bar{q}$ annihilation and decay to a dark quark and a SM quark



- "Unflavored" model: assume simple flavor structure of k_{ij} + FCNC constraints → assume only decays to d quarks non-negligible

$$m_{ij}\bar{Q}_{Li}Q_{Rj} + \kappa_{i\alpha}\kappa^{*}_{j\beta}\frac{1}{M_X^2}\bar{Q}_{Li}\gamma_\mu Q_{Lj}\,\bar{d}_{R\alpha}\gamma^\mu d_{R\beta} + \text{h.c.}$$

Yukawas

$$c\tau \approx 80\,\text{mm}\left(\frac{1}{\kappa^4}\right)\left(\frac{2\,\text{GeV}}{f_{\pi_{\text{DK}}}}\right)^2\left(\frac{100\,\text{MeV}}{m_{\text{down}}}\right)^2\left(\frac{2\,\text{GeV}}{m_{\pi_{\text{DK}}}}\right)\left(\frac{m_{X_{\text{DK}}}}{1\,\text{TeV}}\right)^4$$

π_{DK} decay constant

SIGNAL MODELLING

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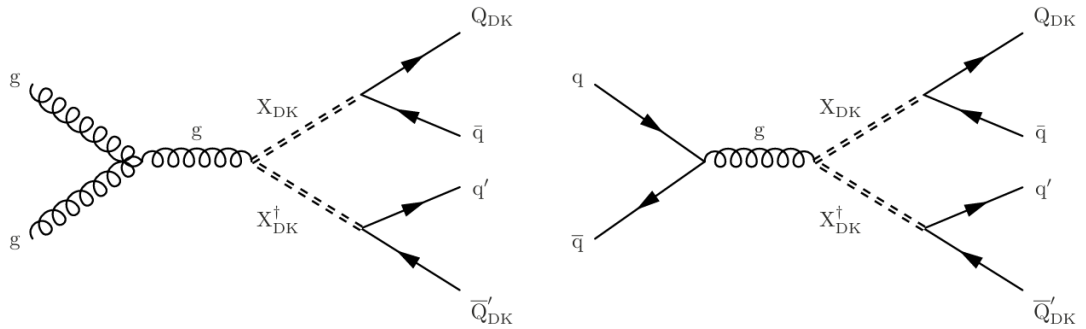

- More involved flavor structures can also be considered, e.g. JHEP08(2018)052

$$c\tau^{\alpha\beta}_{\pi_{\text{dark}}} = \frac{8\pi m^4_{X_{\text{dark}}} c\hbar}{N_c m_{\pi_{\text{dark}}} f^2_{\pi_{\text{dark}}} \sum_{i,j} |\kappa_{\alpha i}\kappa^*_{\beta j}|^2 \left(m_i^2 + m_j^2\right) \sqrt{\left(1 - \frac{(m_i+m_j)^2}{m^2_{\pi_{\text{dark}}}}\right)\left(1 - \frac{(m_i-m_j)^2}{m^2_{\pi_{\text{dark}}}}\right)}}$$

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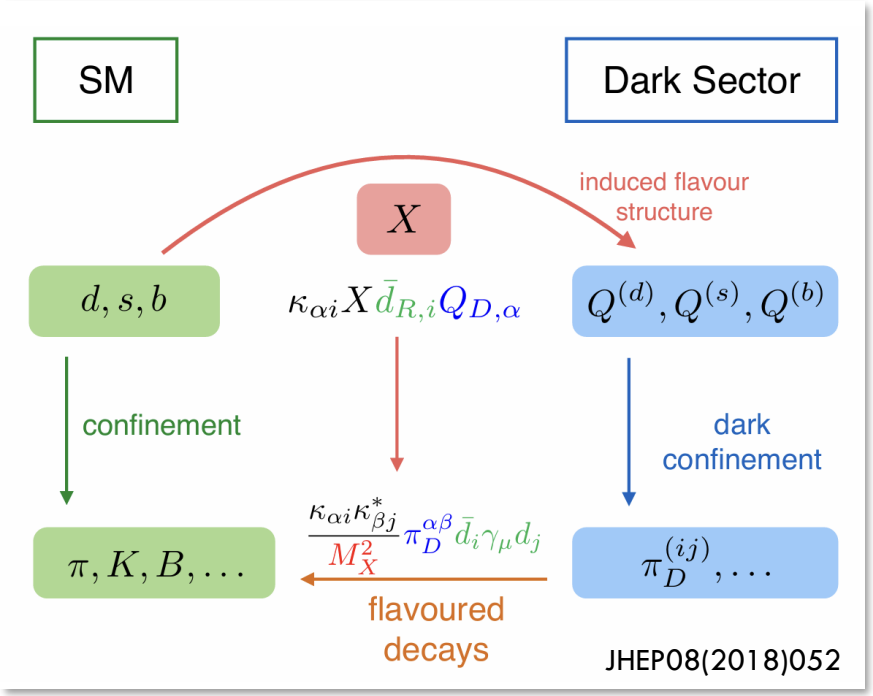

Focus on "flavor aligned" scenario with 3 dark flavors that couple to d-type quarks via couplings $k_{\alpha i} = k_0 \delta_{\alpha i}$

SIMULATION

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Search for dark QCD with emerging jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

- Signals generated with the hidden valley module in PYTHIA 8.212
- Free parameters: $m_{X_{DK}}, \Gamma_{X_{DK}}, N_d, N_f, \kappa_{ij}, \Lambda_d, m_{Q_{d,i}}, m_{\pi_d}, m_{\rho_d}, c\tau_{\pi_{DK}}$
- Assume $m_{Q_{d,i}} = m_{Q_d} = \Lambda_d = 2m_{\pi_{DK}} = m_{\rho_d}/2 \ \forall\, i$

	"Unflavored"	"Falvor-aligned"
N_d	3	3
N_f	7	3
$m_{X_{DK}}$ [GeV]	1000, 1200, 1400, 1500, 1600, 1800, 2000, 2200, 2400, 2500	1000, 1200, 1400, 1500, 1600, 1800, 2000, 2200, 2400, 2500
$\Gamma_{X_{DK}}$ [GeV]	10	10
m_{π_d} [GeV]	10, 20	6, 10, 20
$c\tau_{max}$ [mm]	1, 2, 5, 25, 45, 60, 100, 150, 225, 300, 500, 100	5, 25, 45, 100, 500

ANALYSIS STRATEGY (IN A TINY TINY NUTSHELL)

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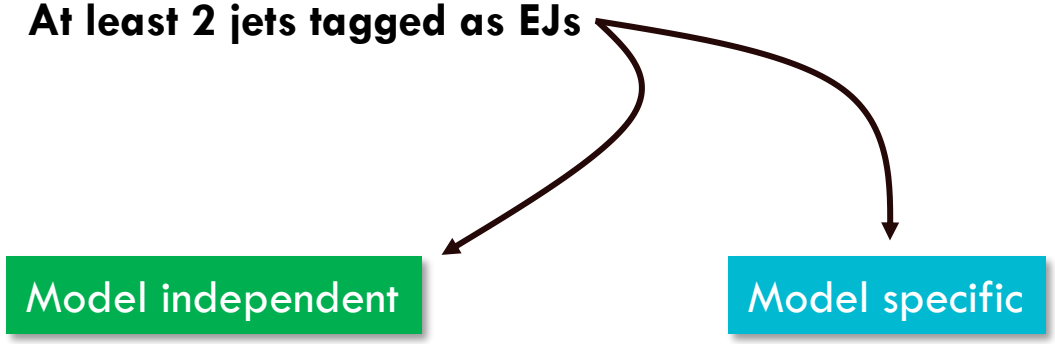
- High jet p_T and H_T triggers
- At least 4 AK4 jets with $p_T > 100$ GeV, $|\eta| < 2$
- Tracks associated to jets via ΔR matching
- **At least 2 jets tagged as EJs**



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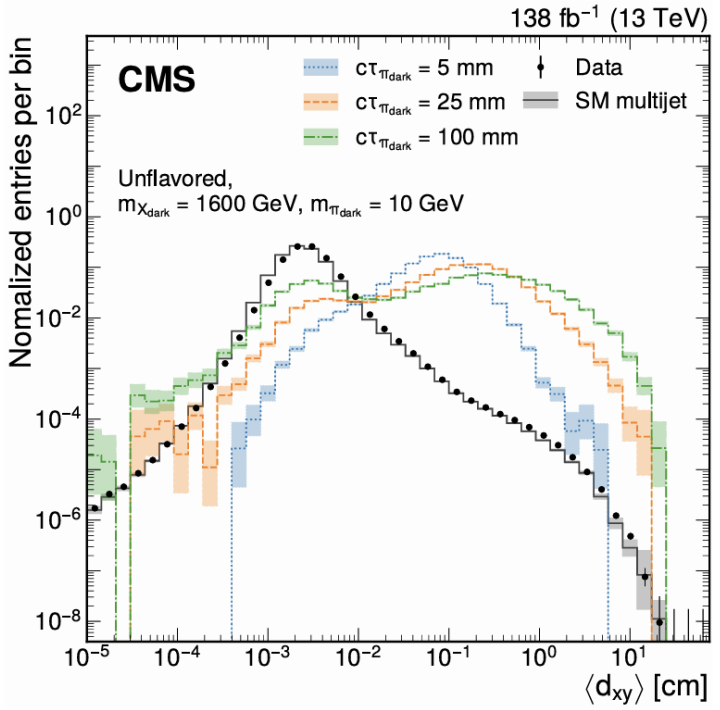
Model independent

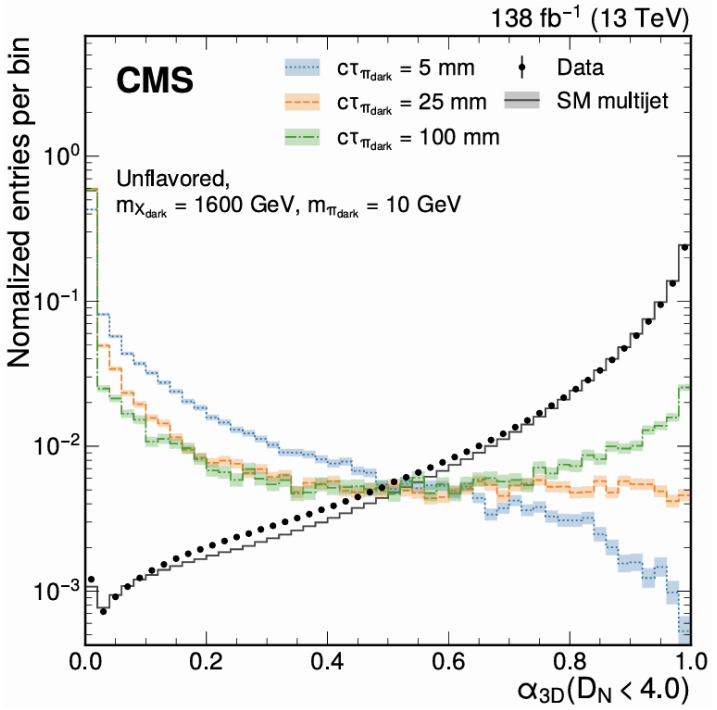
- Unflavored:

Median transverse displacement $\langle d_{xy} \rangle$

$$\alpha_{3D} = \frac{\sum_{D_N < D_N^{max}} p_T^{track}}{\sum p_T^{track}}, \text{ with}$$

$$D_N = \sqrt{\left(\frac{d_z}{0.01\ \text{cm}}\right)^2 + \left(\frac{d_{xy}}{\sigma(d_{xy})}\right)^2}$$





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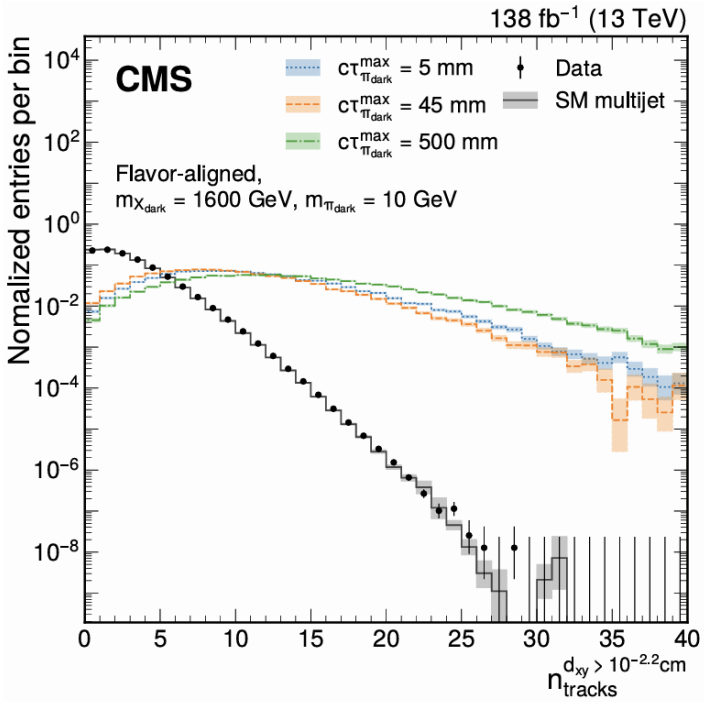
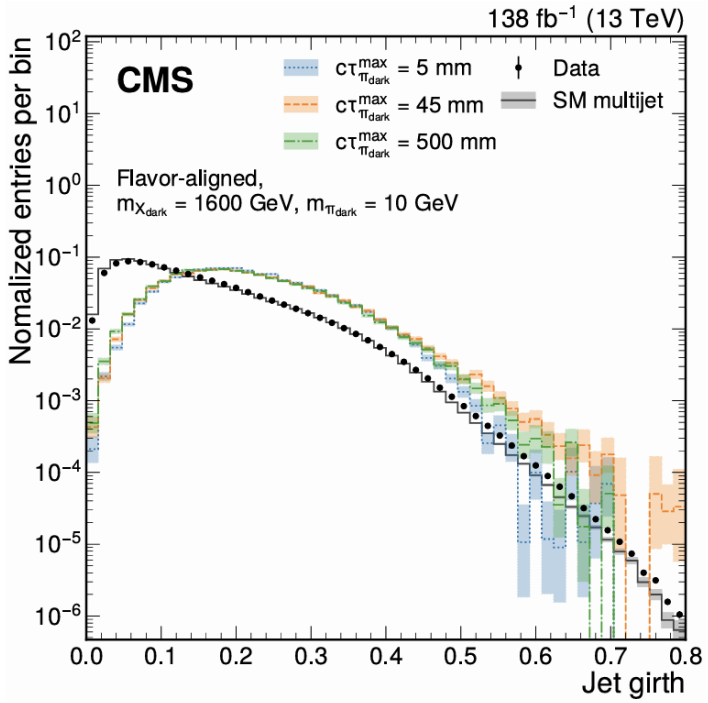
Model independent

- Flavor-aligned:

$n_{\text{track}}^{d_{xy} > d_{xy}^{\min}}$, explots heavy-flavor content

$$\text{Jet girth} = \frac{\sum_i p_T^i \Delta R(i,\text{jet})}{\sum_i p_T^i}$$





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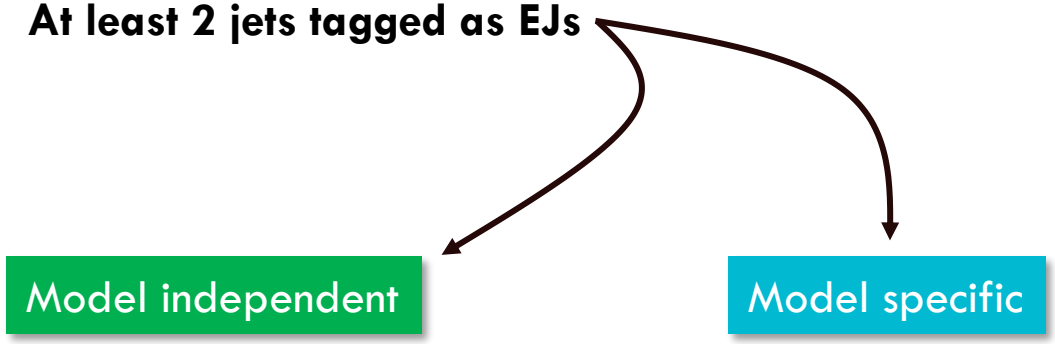

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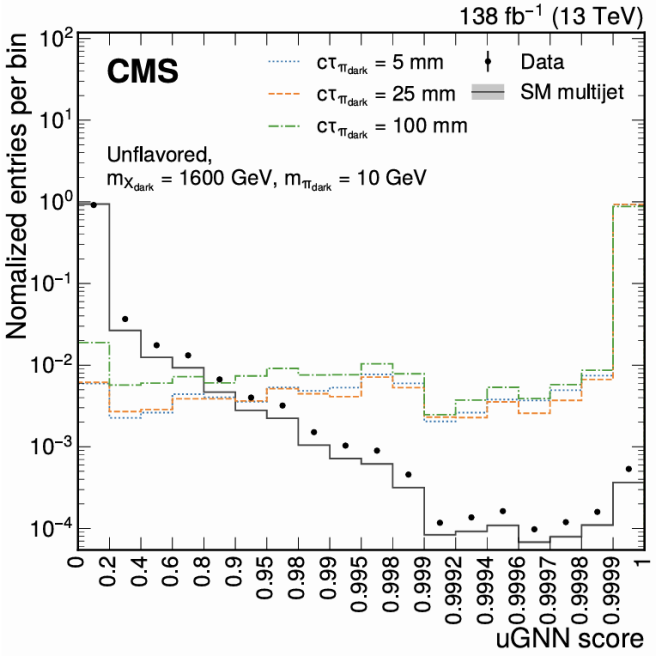
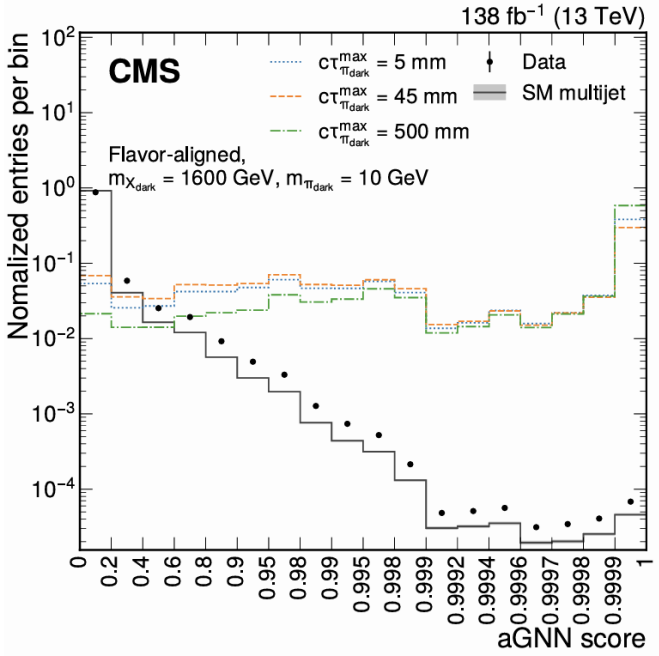
Model specific

- GNN tagger, separately trained on unflavored and flavor-aligned signals
- Inputs are matched tracks represented with 5 coordinates:
  - $\Delta R(\text{track}, \text{jet})$
  - $\ln(p_T^{\text{track}}/1\ \text{GeV})$, $\ln(p_T^{\text{track}}/\sum p_T^{\text{track}})$
  - $T(d_{xy})$, $T(d_z)$ where $T(x) = \text{sign}(x) \ln\left(\left|\frac{x}{1\ \text{cm}}\right| + 1\right)$





RESULTS

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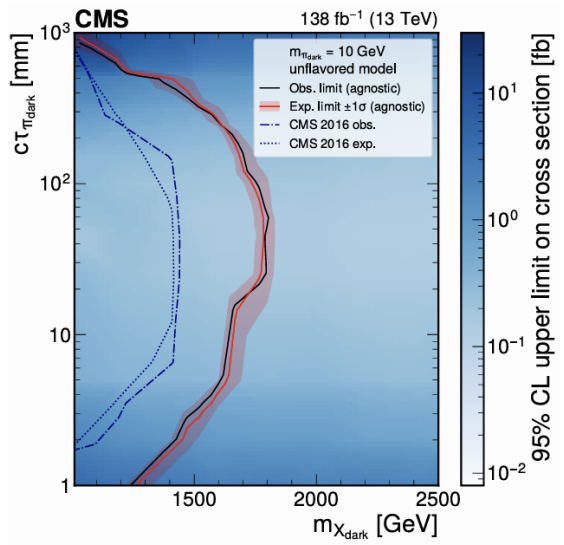
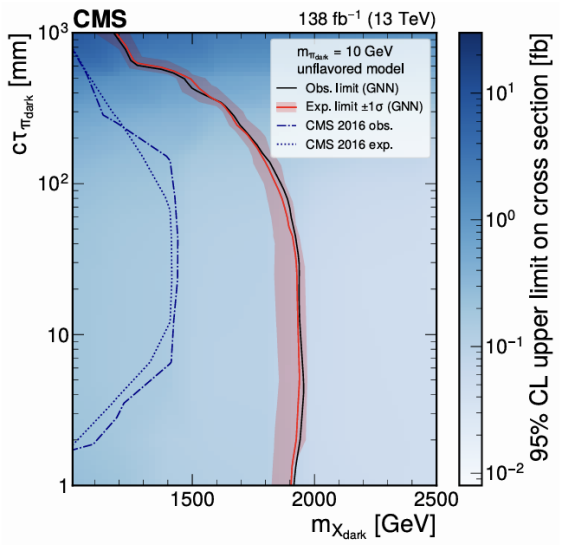
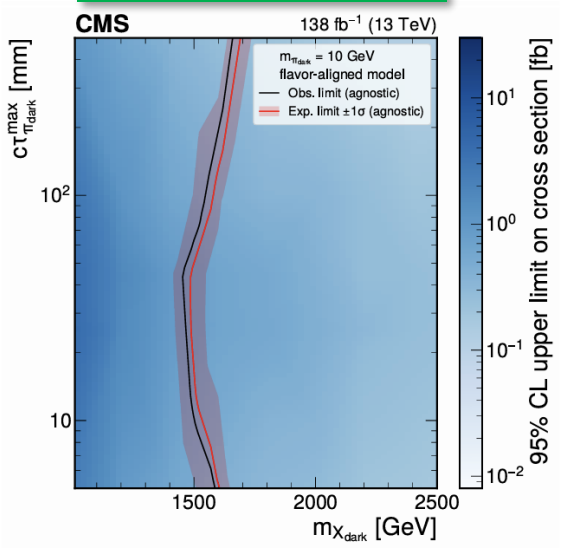
Unflavored, agnostic



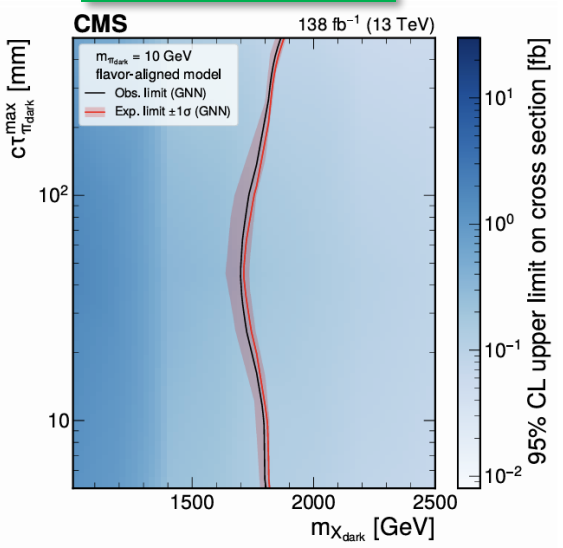
Unflavored, GNN



Aligned, agnostic



Aligned, GNN



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SEMIVISIBLE JETS

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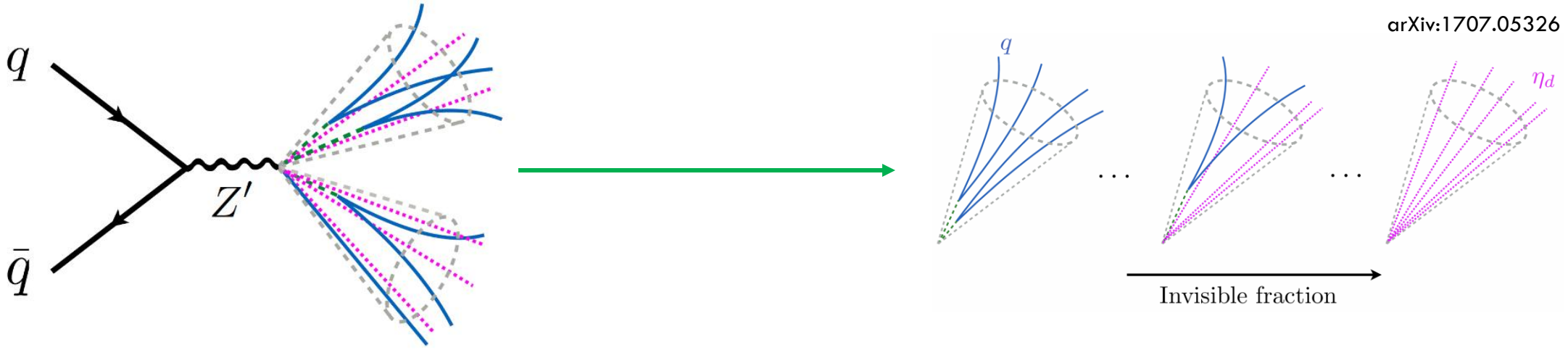
- Again, DS with new $\mathrm{SU}(N_d)$ confining force
- Connected to SM via a leptophobic vector (Z')
- χ shower in the DS producing scalar and vector dark mesons π_{dark} and ρ_{dark}
- Some dark hadrons may be stable (DM candidates) while others may decay back to the SM



arXiv:1707.05326

SIGNAL MODELLING

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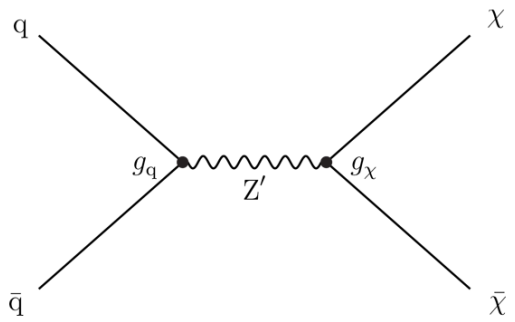
- Dark quark production follows LHC DM recommendations:
  - $g_q = 0.25, g_\chi = 1.0/\sqrt{N_c^d N_f^d} = 0.5, \Gamma_{Z'}/m_{Z'} = 5.6\%$



- DS dynamics:
  - $N_c^d = 2, N_f^d = 2, 2m_\chi = m_{\pi_{dark}} = m_{\rho_{dark}} \equiv m_{dark}$
  - ρ_{dark} decay democratically to all allowed flavors
  - π_{dark} decay through mass insertion → favor heavy flavor

$$r_{inv} \equiv \left\langle \frac{\#\text{stable dark hadrons}}{\#\text{dark hadrons}} \right\rangle$$

SIMULATION

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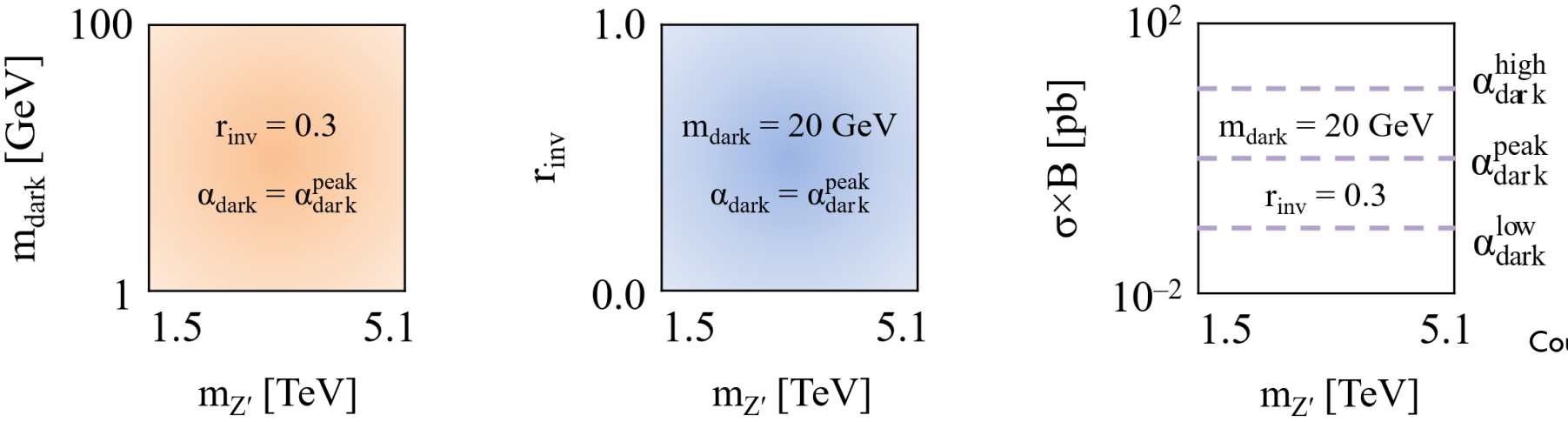
Search for resonant production of strongly coupled dark matter in proton-proton collisions at 13 TeV

- Pythia 8.230 (8.226 for 2016 data) with HV module
- With assumptions above, 4 free parameters remain: $m_{Z'}, m_{dark}, r_{inv}, \alpha_{dark}$
  - Define α_{dark}^{peak} that maximizes dark hadron multiplicity, $\alpha_{dark}^{high} = 1.5\alpha_{dark}^{peak}$, and $\alpha_{dark}^{low} = 0.5\alpha_{dark}^{peak}$
  - Perform 3 2D scans in parameter space:



Courtesy of Kevin Pedro

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- High jet p_T and H_T triggers
- At least 2 AK8 jets with $p_T > 200$ GeV and $|\eta| < 2.4$
- $R_T = p_T^{miss}/m_T > 0.15$
- $\Delta\eta(J_1, J_2) < 1.5$
- $m_T > 1.5$ TeV
- No isolated electrons or muons
- $\boldsymbol{\Delta\phi_{\min}(\vec{J}_i, \vec{p}_T^{miss}) < 0.8}$ → **SVJ topology**

Model agnostic

- **Tag SVJs** → Model specific

$$m_{\mathrm{T}}^2 = \left[E_{\mathrm{T,JJ}} + E_{\mathrm{T}}^{\mathrm{miss}}\right]^2 - \left[\vec{p}_{\mathrm{T,JJ}} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right]^2$$
$$= m_{\mathrm{JJ}}^2 + 2p_{\mathrm{T}}^{\mathrm{miss}}\left[\sqrt{m_{\mathrm{JJ}}^2 + p_{\mathrm{T,JJ}}^2} - p_{\mathrm{T,JJ}}\cos(\phi_{\mathrm{JJ,miss}})\right]$$

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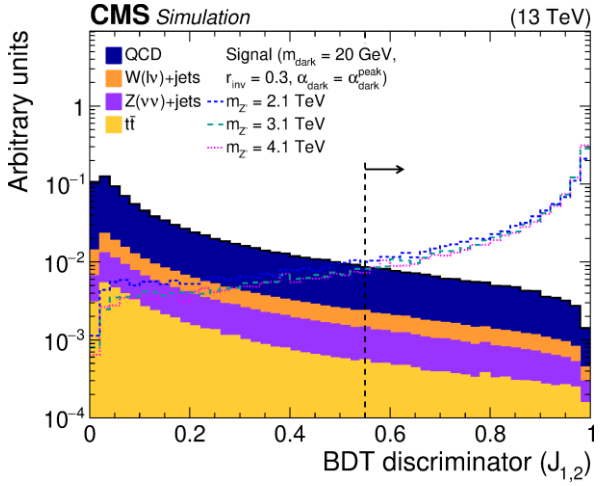
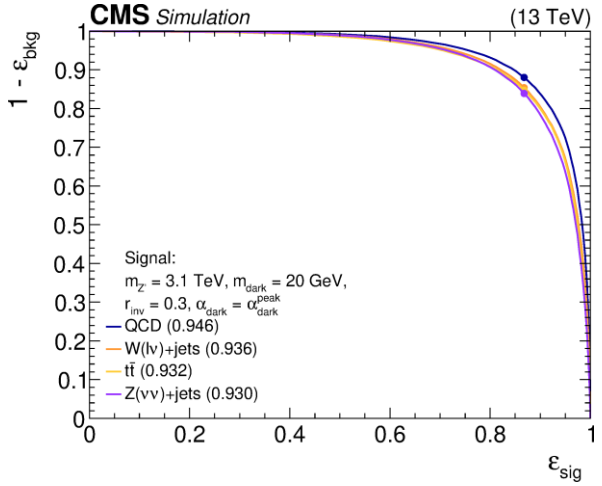
Model specific

- Exploit a DBT trained on jet substructure:
  - Heavy object tagging: m_{SD}, τ_{21}, τ_{32}, $N_2^{(1)}$, $N_3^{(1)}$
  - Quark-gluon discrimination: D_{p_T}, σ_{major}, σ_{minor}, girth
  - Flavor (energy fractions): f_γ, $f_{h^\pm}$, f_{h0}, f_e, f





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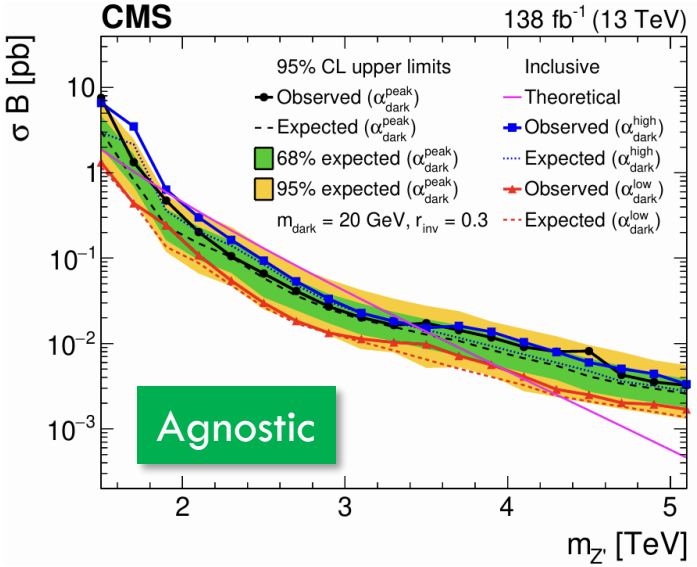
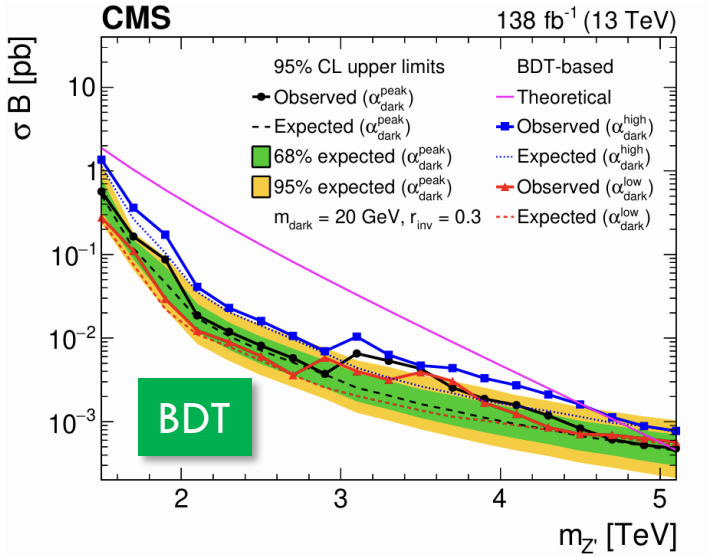
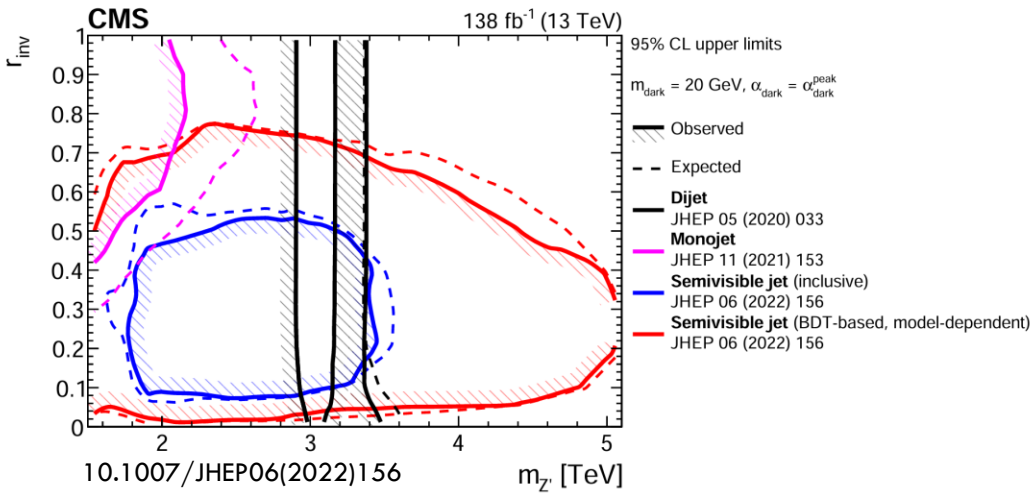






ONE WORD ON SUEPS

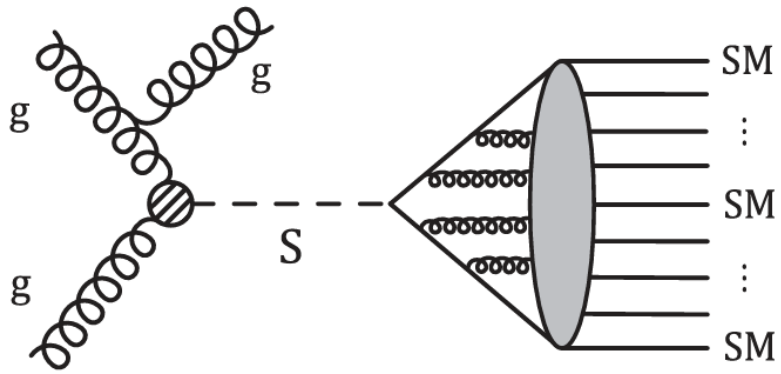
PHYSICAL REVIEW LETTERS **133,** 191902 (2024)

Editors' Suggestion | Featured in Physics

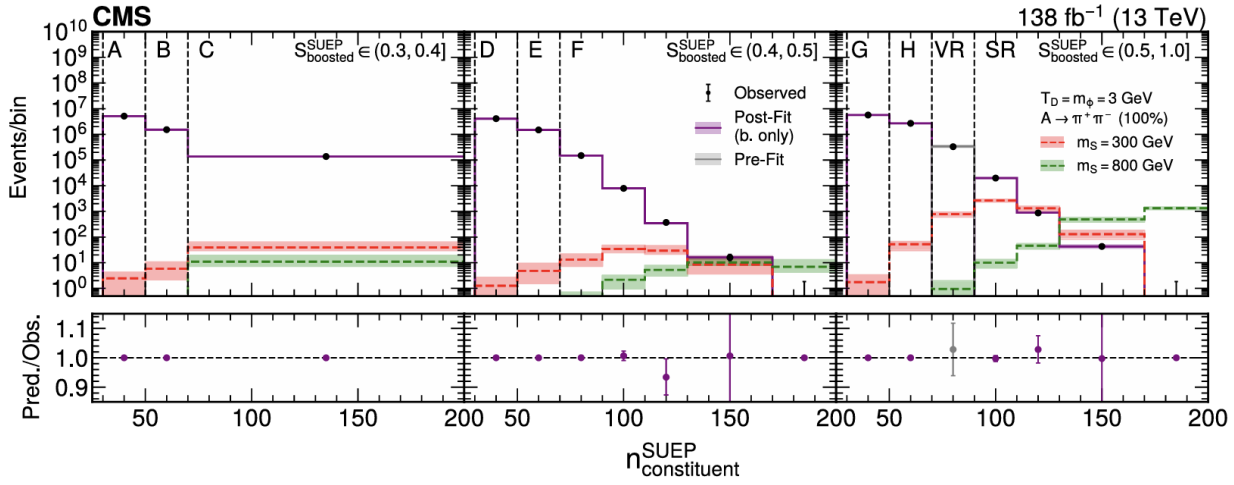
Search for Soft Unclustered Energy Patterns in Proton-Proton Collisions at 13 TeV

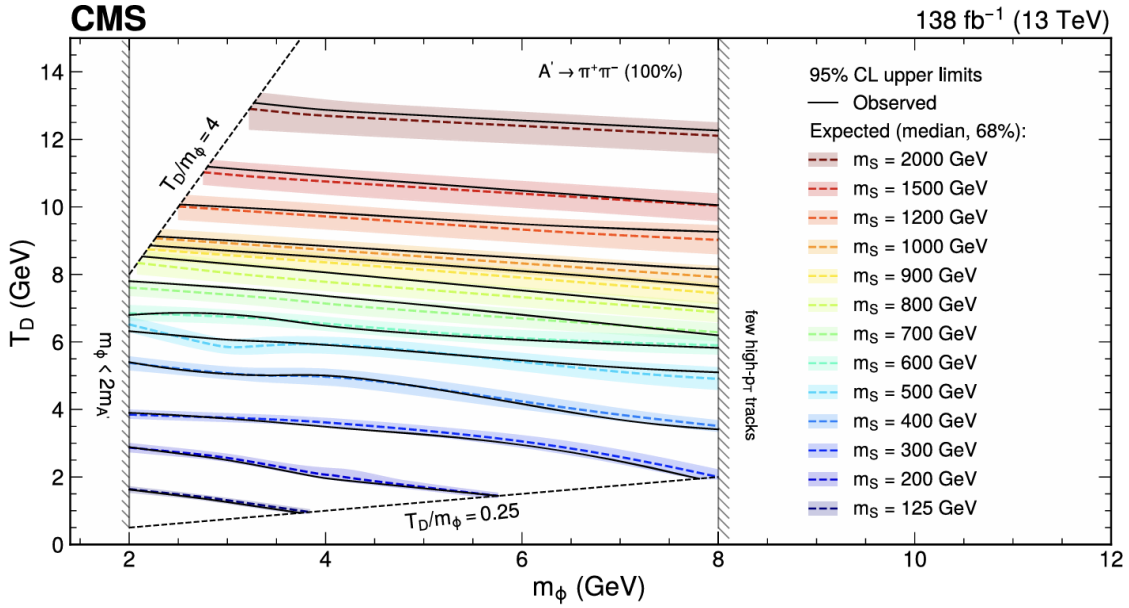
A. Hayrapetyan *et al.*[*]
(CMS Collaboration)

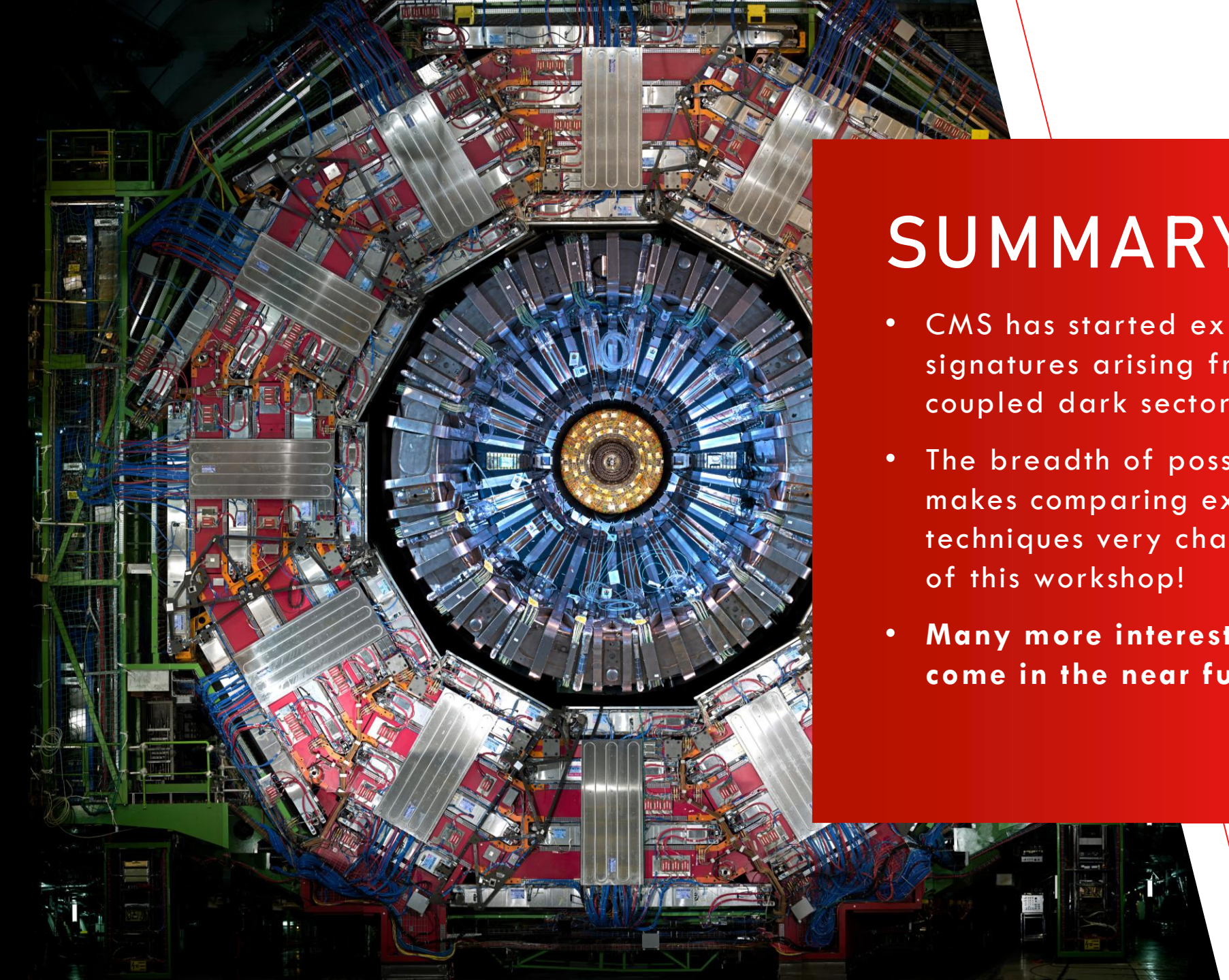
(Received 8 March 2024; accepted 6 September 2024; published 5 November 2024)



- Scalar mediator S decaying to dark quarks, in turn showering to dark mesons ϕ with a thermal p_T distribution controlled by T_D
- Trigger on hadronic activity H_T
- Extended ABCD fit in the sfericity-$n_{constituents}$ plane







SUMMARY

- CMS has started exploring the novel signatures arising from strongly-coupled dark sectors
- The breadth of possible models makes comparing experimental techniques very challenging → focus of this workshop!
- **Many more interesting results to come in the near future**

THANK YOU

« Ce qui est admirable, ce n'est pas que le champ des étoiles soit si vaste, c'est que l'homme l'ait mesuré. »

Jacques Anatole François Thibault