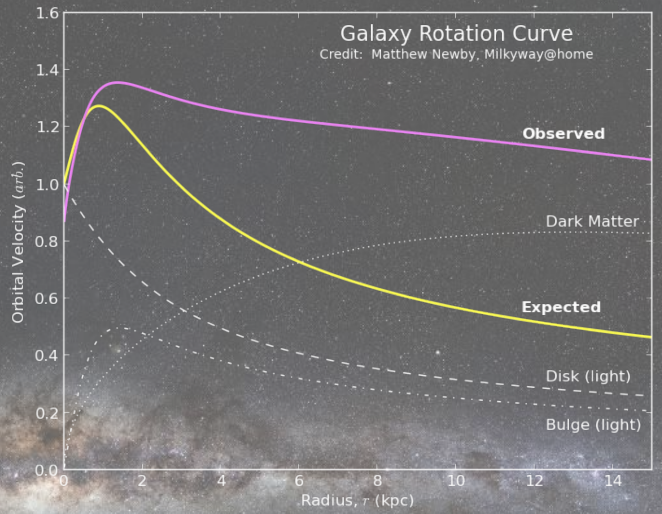
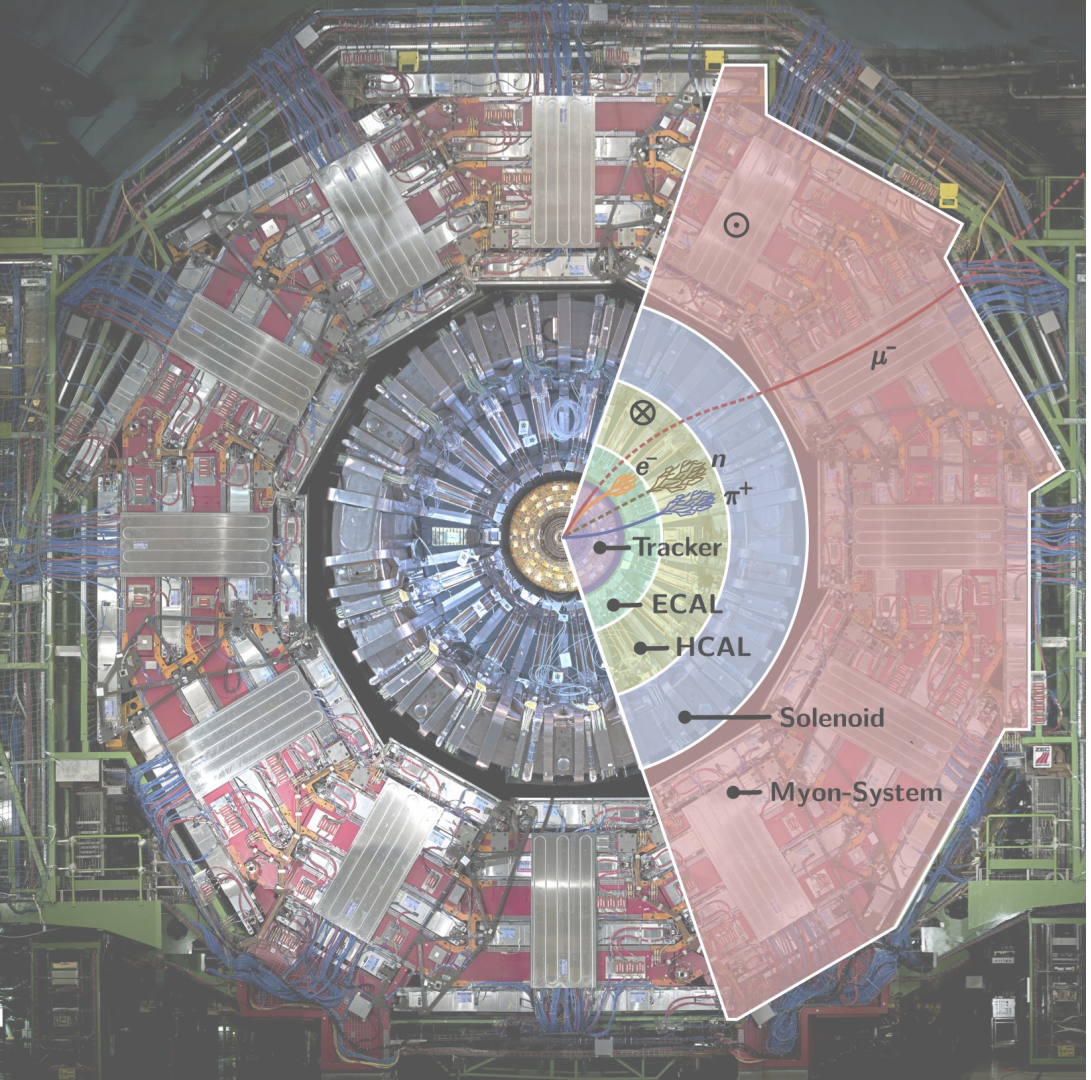


A Shot in the Dark

Hunting for dark matter with the CMS detector at the LHC

Benedikt Maier

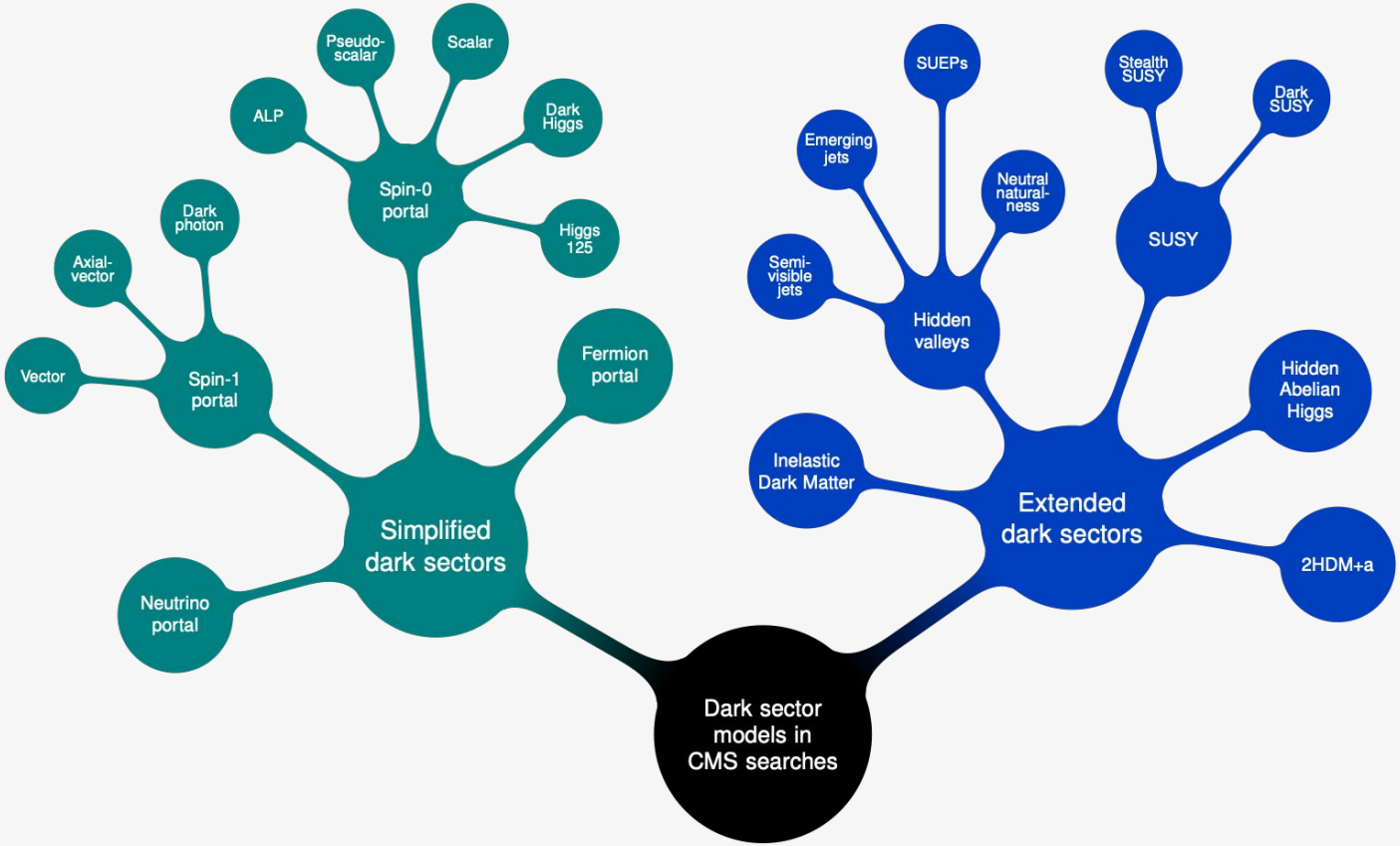
Jan 7, 2025



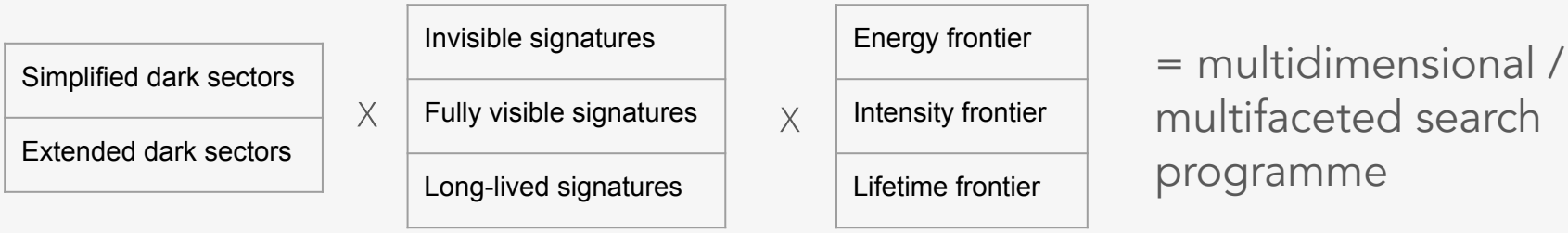
CMS uses **Particle Flow** reconstruction:

- Aimed at reconstructing each particle individually
- “Follow” the path of a particle through the detector
- Match deposits between subdetectors
- For each particle combine subdetector information for best E/momentum measurement

The landscape of dark sector models



The landscape of dark sector models



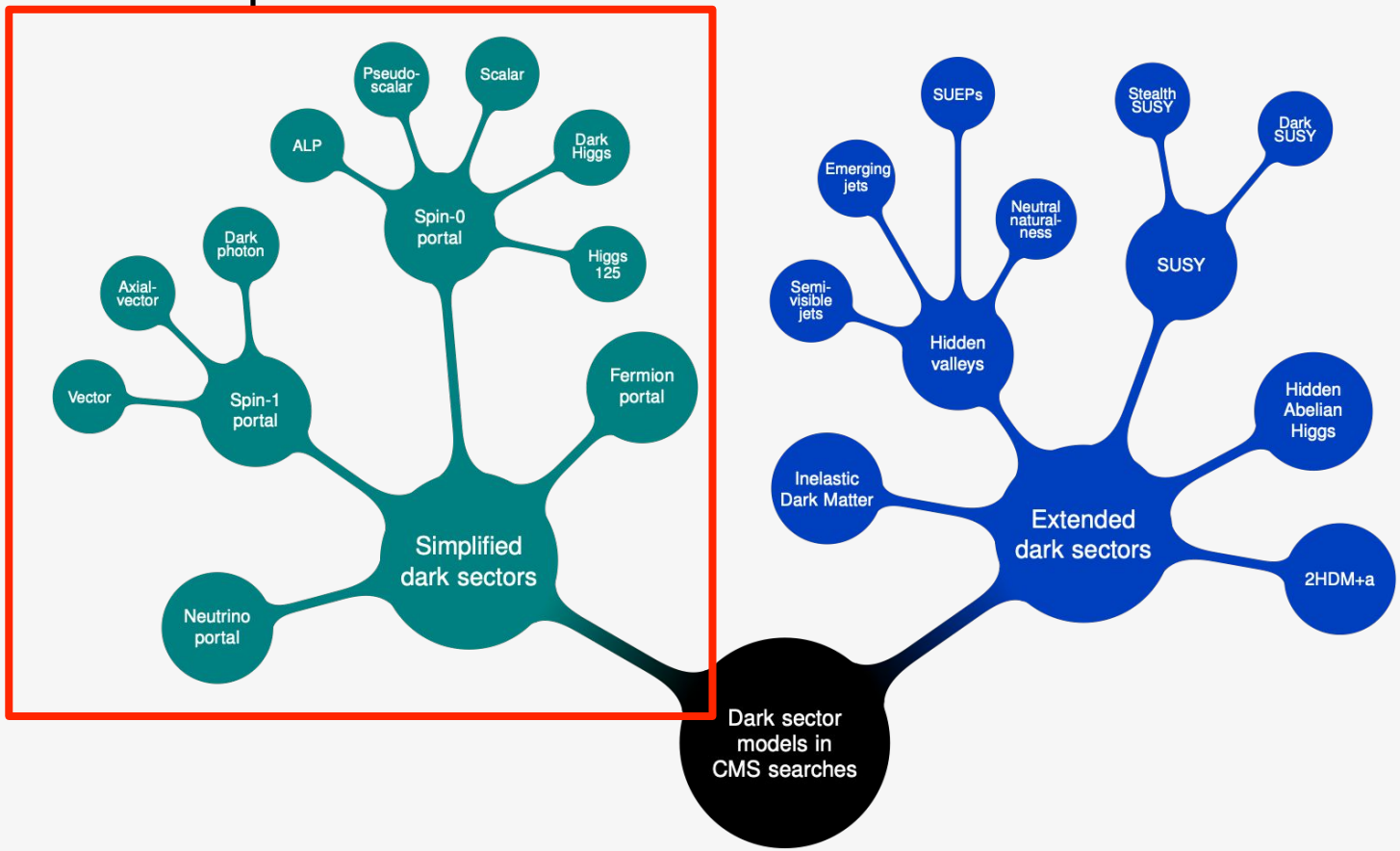
The landscape of dark sector models

https://doi.org/10.1016/j.physrep.2024.09.013

Model		Experimental signature		Phase space
Simplified dark sectors	X	Invisible signatures	X	Energy frontier
Extended dark sectors		Fully visible signatures		Intensity frontier
		Long-lived signatures		Lifetime frontier

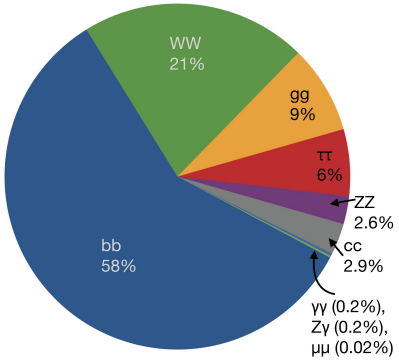
Idea: Summarize this dark sectors search program and draw overall conclusions in a review paper (featuring over 40 results with data collected during LHC Run-2 2016-2018)

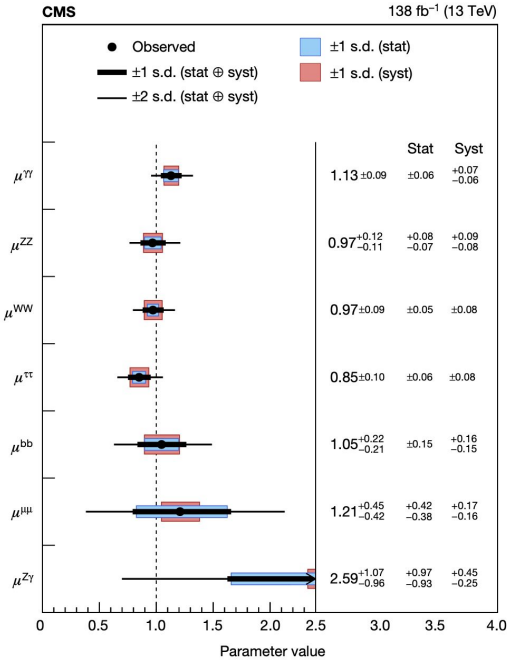
The landscape of dark sector models



Higgs boson discovery, CERN, 2012

How do Higgs bosons decay according to the Standard Model?



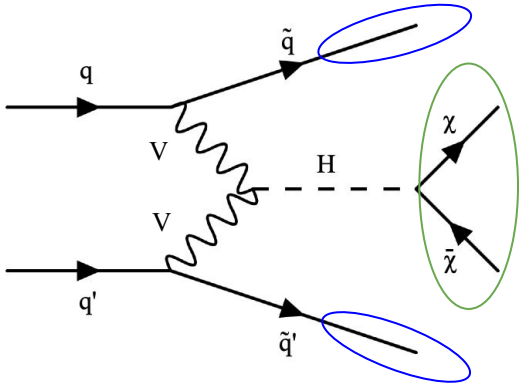


Nature 607, 60–68 (2022)

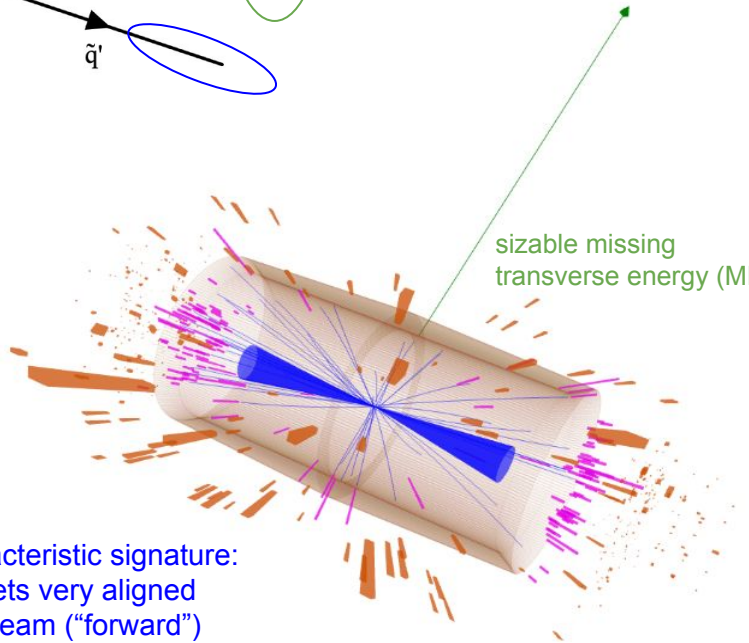
Combination of all Higgs analyses currently allows an **upper limit of 15%** for new, unknown particles as decay products

→ **Motivates search for decay to dark matter particles**

Disappearing Higgs Bosons (“Higgs portal”)

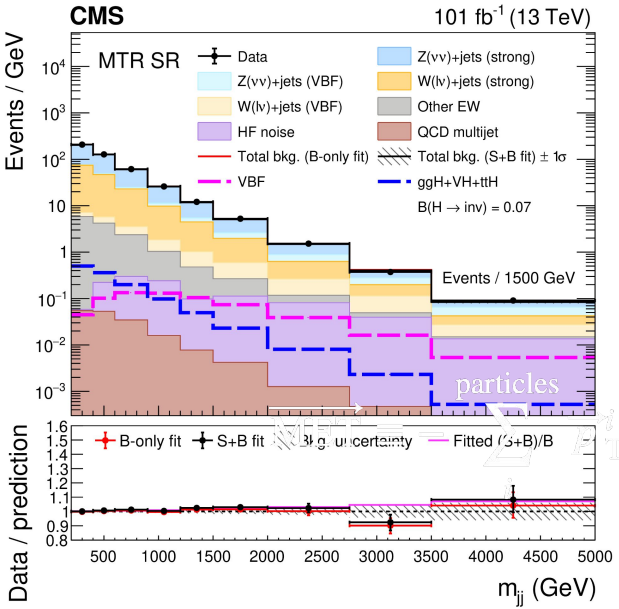


Dark matter, by definition, does not interact with the detector



sizable missing transverse energy (MET)

Characteristic signature:
Two jets very aligned with beam (“forward”)



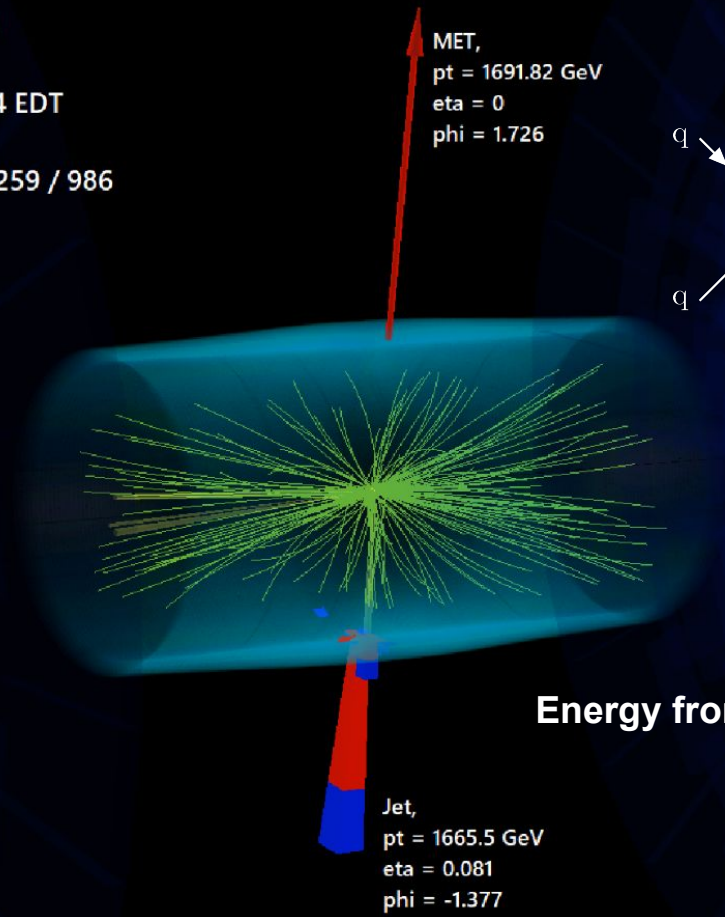
Statistical analysis of observed m_{jj} spectra reveals no excess

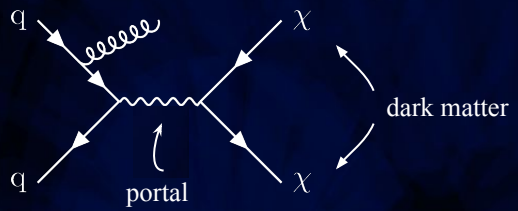
→ Obtained an 18% upper limit for branching ratio H → invisible

CMS Experiment at the LHC, CERN

Data recorded: 2018-Jul-14 21:03:24 EDT

Run / Event / LS: 319639 / 1418428259 / 986



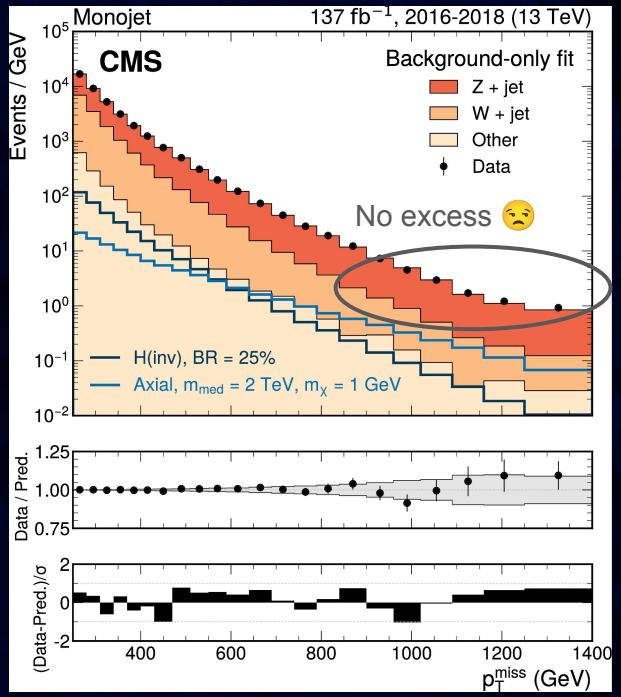


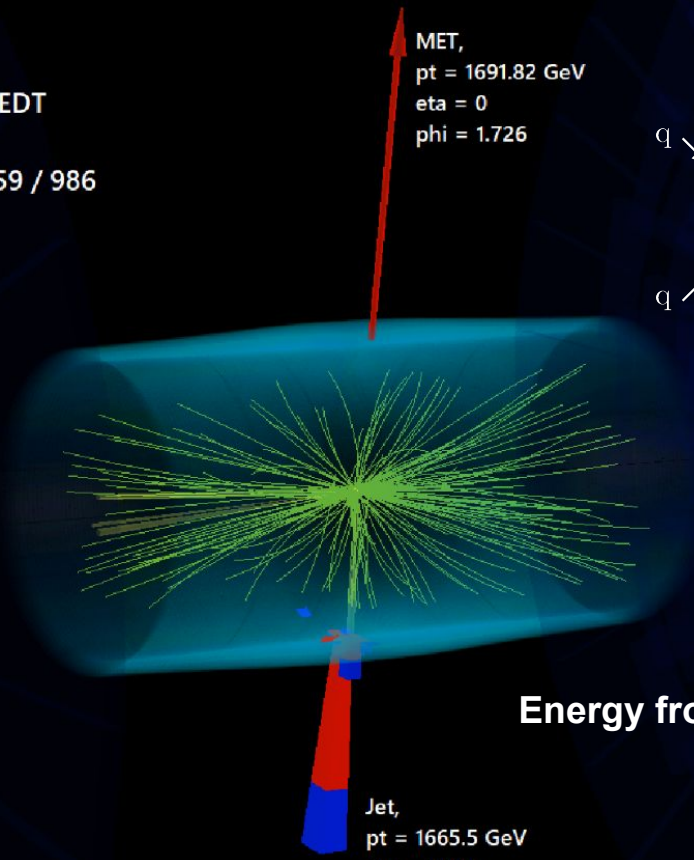
Energy frontier

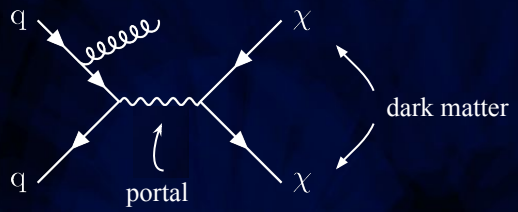
CMS Experiment at the LHC, CERN

Data recorded: 2018-Jul-14 21:03:24 EDT

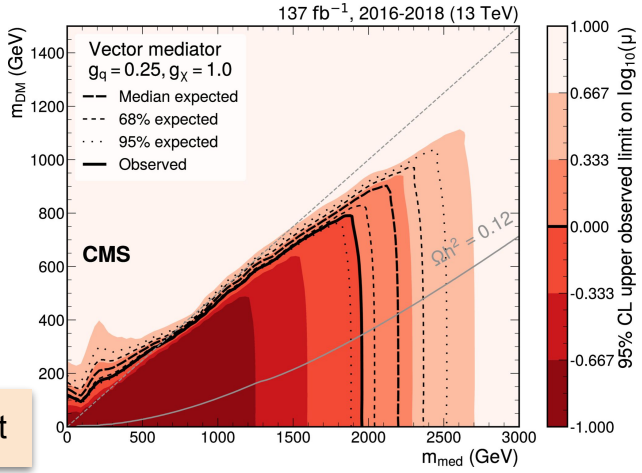
Run / Event / LS: 319639 / 1418428259 / 986



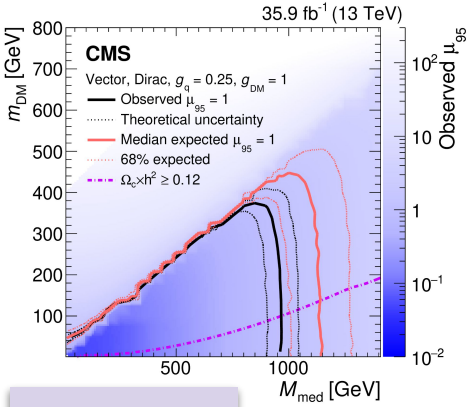




Energy frontier

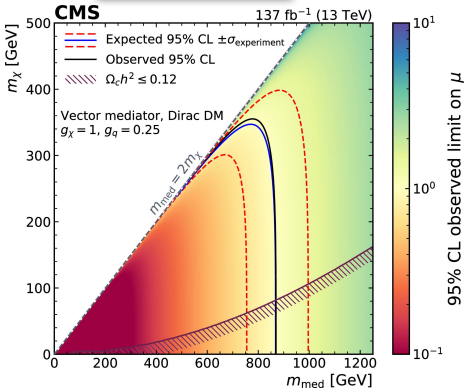


mono-jet



mono-photon

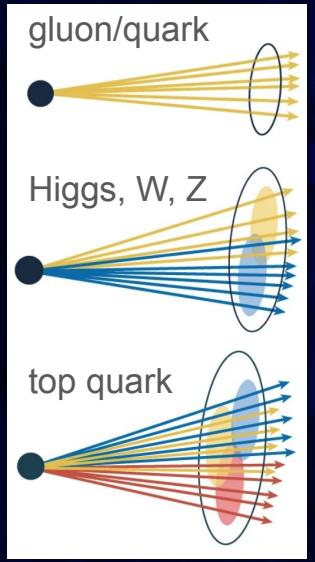
mono-Z(ll)

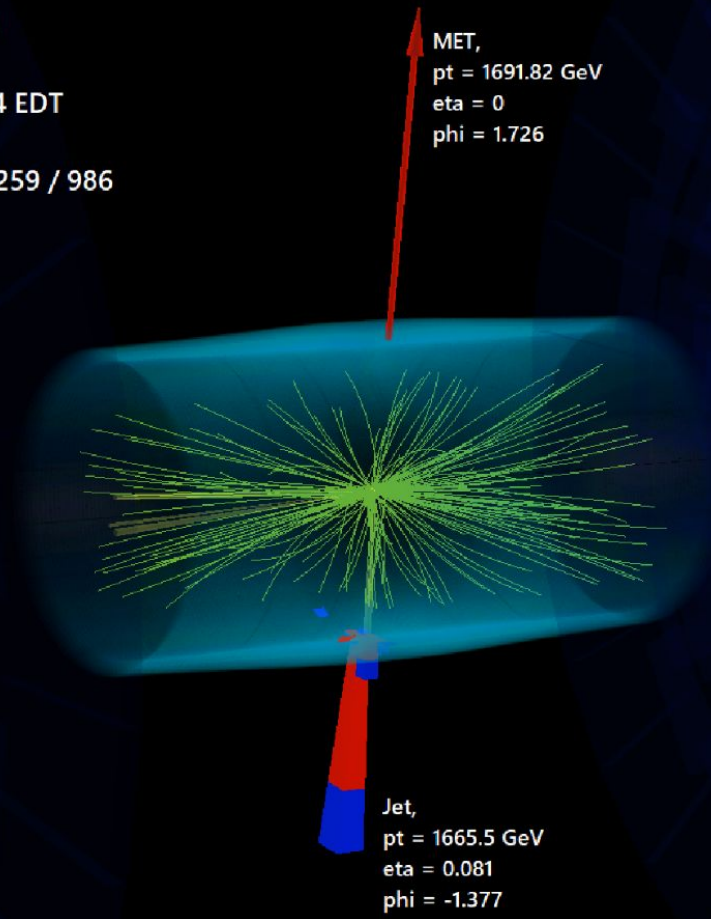


CMS Experiment at the LHC, CERN

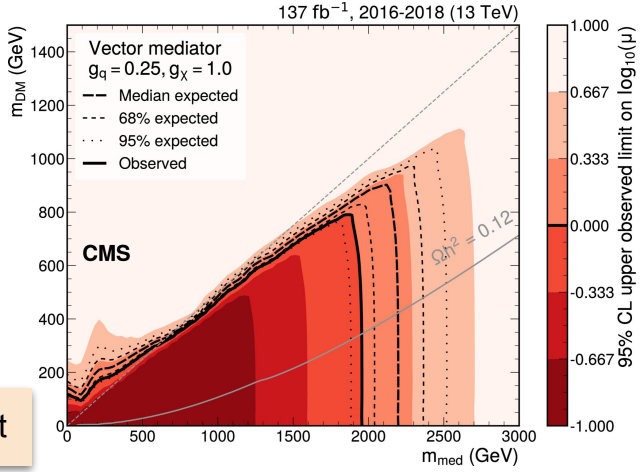
Data recorded: 2018-Jul-14 21:03:24 EDT

Run / Event / LS: 319639 / 1418428259 / 986

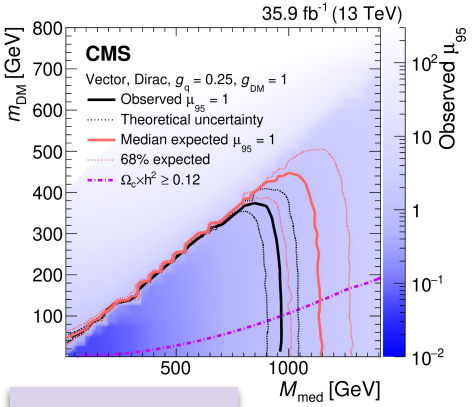




Jet tagging with deep learning techniques
(graph neural networks, transformers)

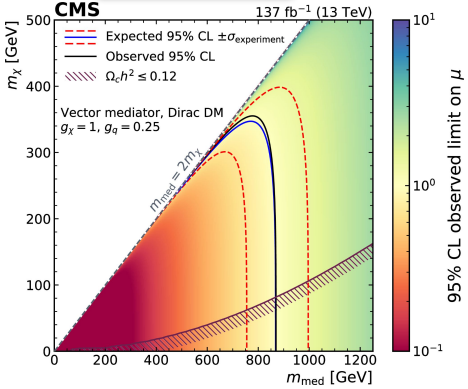


mono-jet

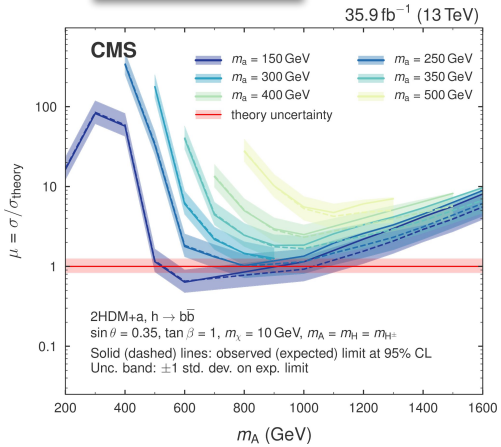


mono-photon

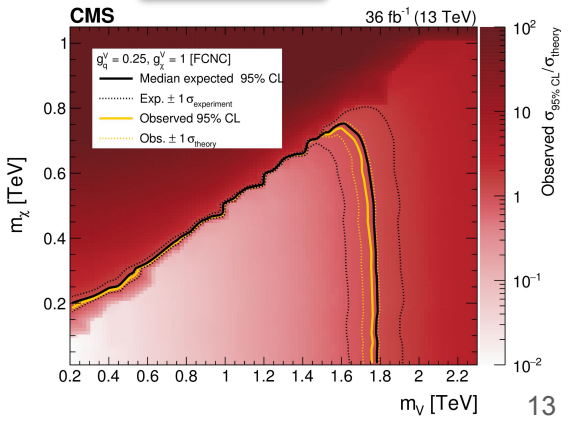
mono-Z(ll)



mono-H(bb)



mono-top

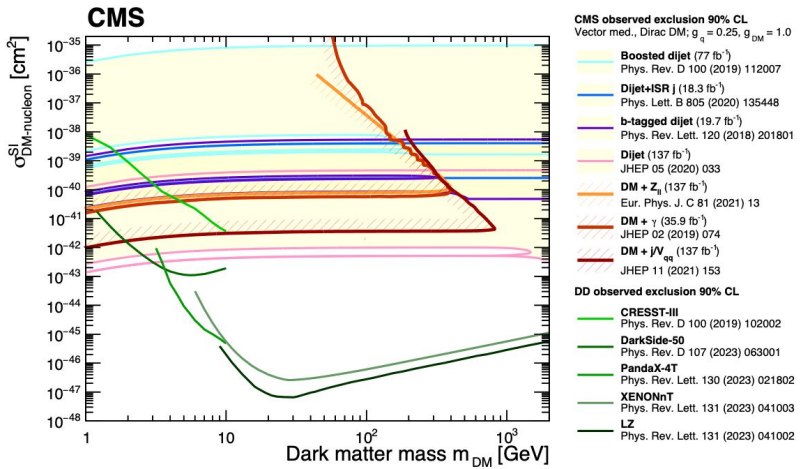


Comparison with Direct Detection

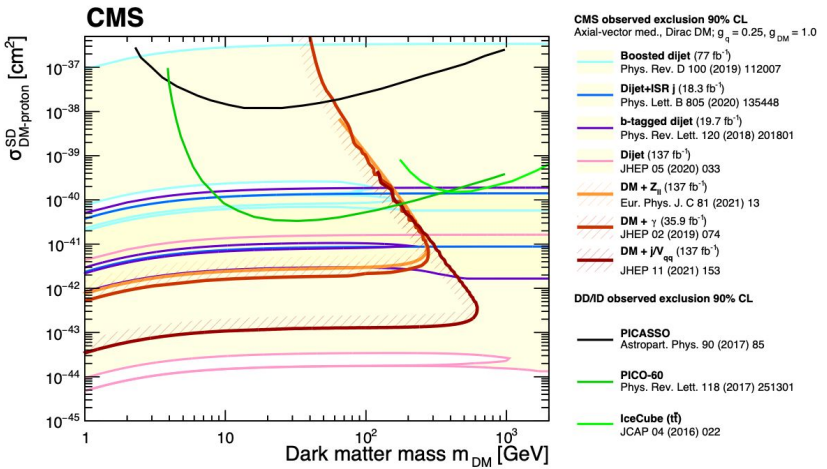
Simplified dark sectors
Spin 1

- Vector mediator → spin-independent DM-nucleon scattering cross section
- Axial-vector mediator → spin-dependent DM-nucleon
- Allows for comparison with direct-detection experiments

Spin-Independent



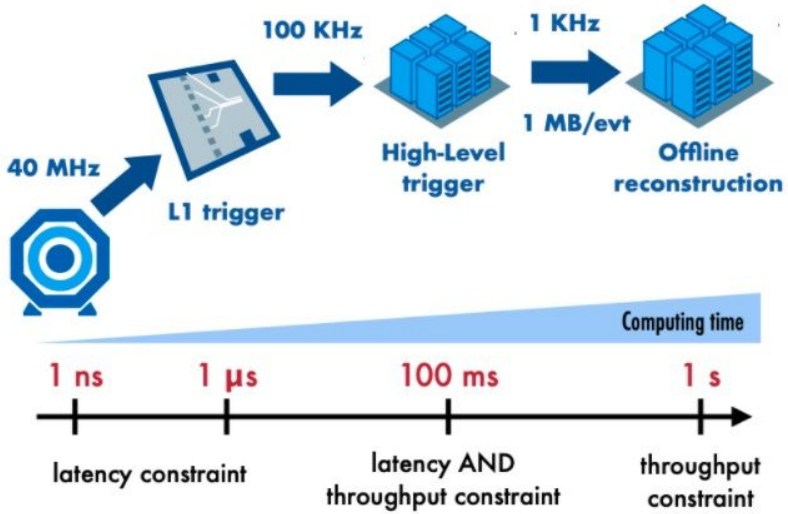
Spin-Dependent

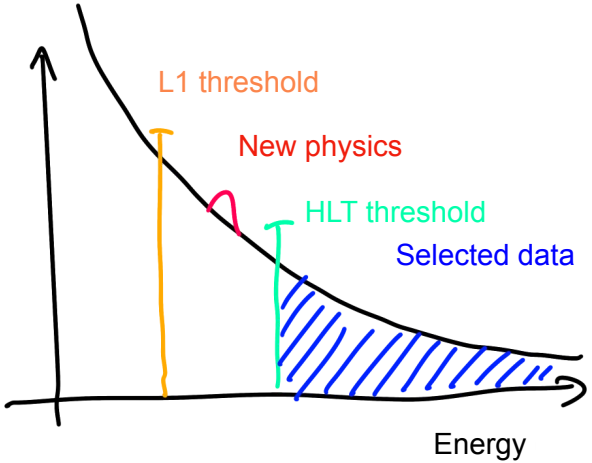


Intensity frontier

Look at smaller masses and higher rates

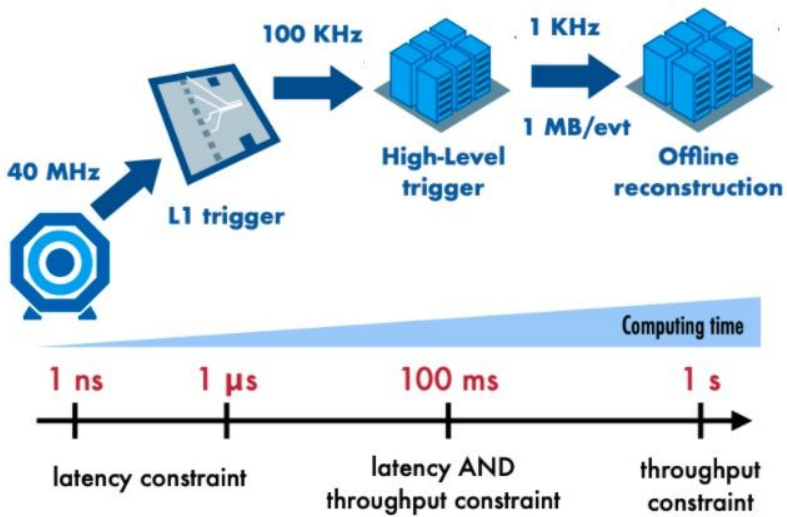
Data Scouting

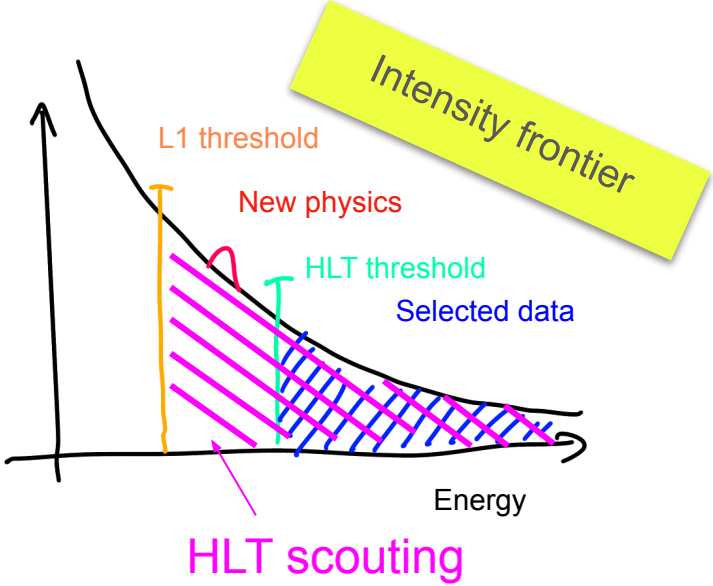




Limited bandwidth and disk space → cannot afford to save the full detector information for every event to disk

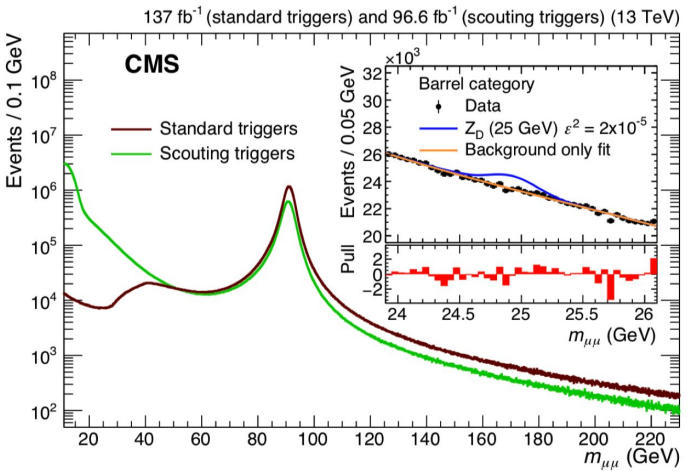
Data Scouting





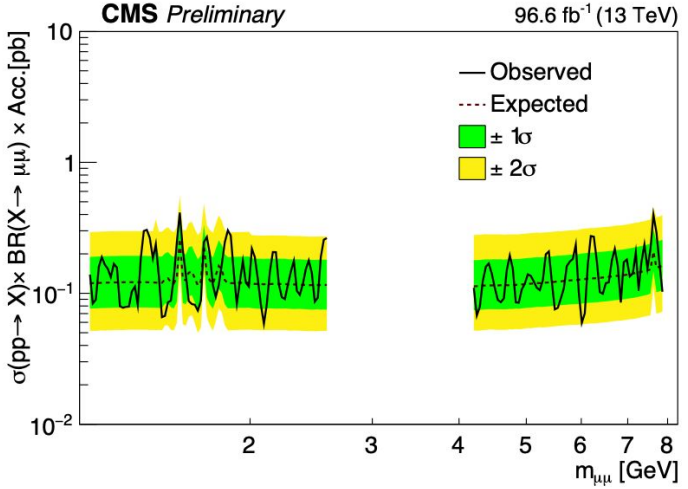
Limited bandwidth and disk space → cannot afford to save the full detector information for every event to disk

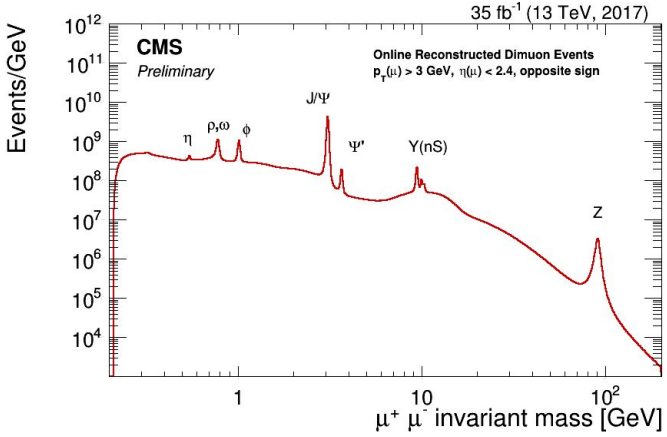
Idea: → Lower thresholds by changing event content to accommodate lower thresholds, store only trigger level information



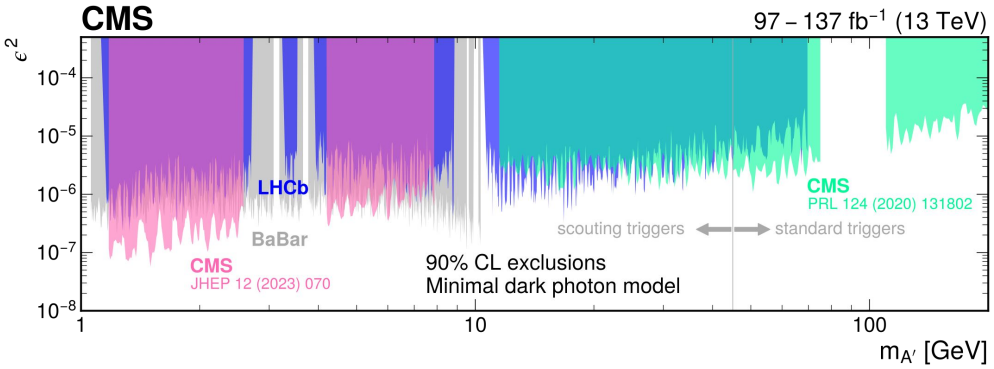
Dark Photons

- Dark photon —> two muons
- **Novel MVA muon identification** increases sensitivity by 30%
  - Track quality
  - Isolation
  - Vertex information
- Extract signal from fit to dimuon mass distribution

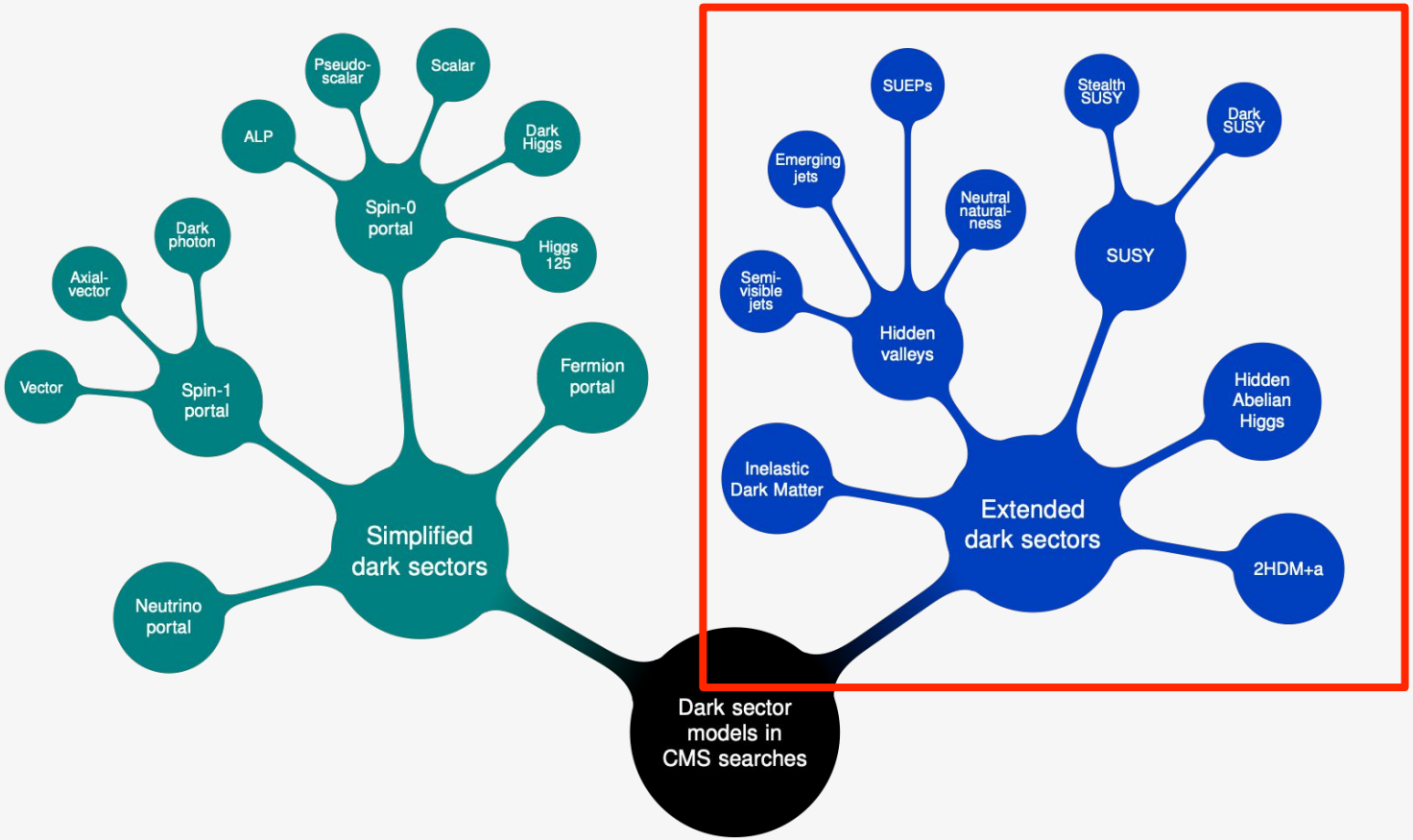




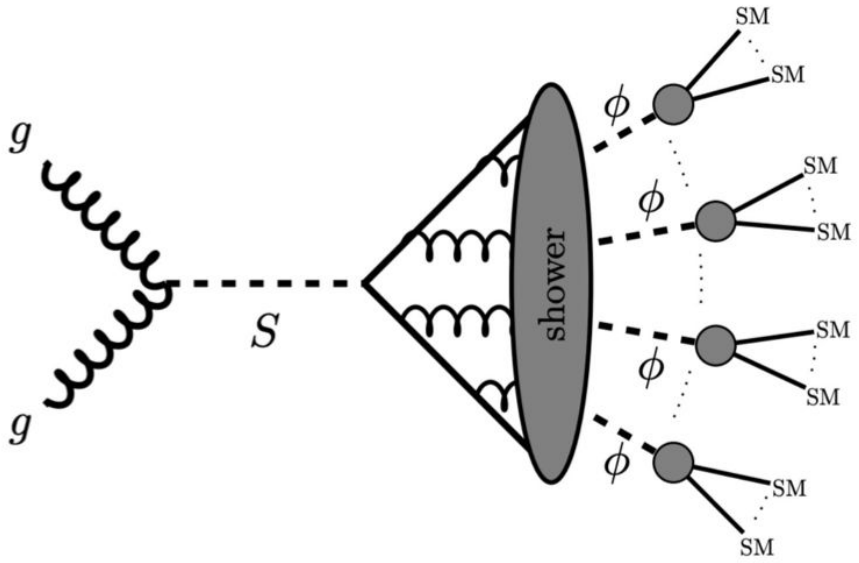
As sensitive as LHCb or BaBar with "2nd-grade" data 😋



The landscape of dark sector models



Hot off the press: Soft unclustered energy patterns (SUEPs)



A model of Dark QCD

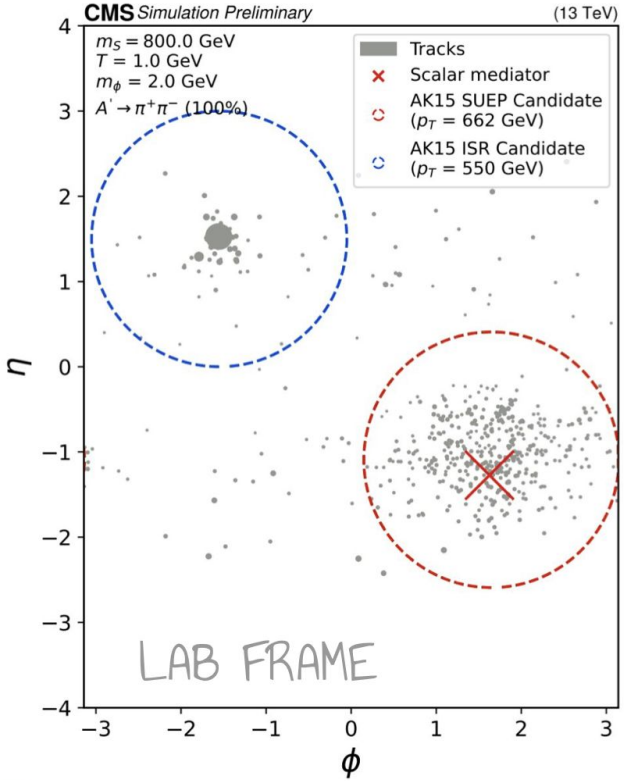
“Dark” version of strong force

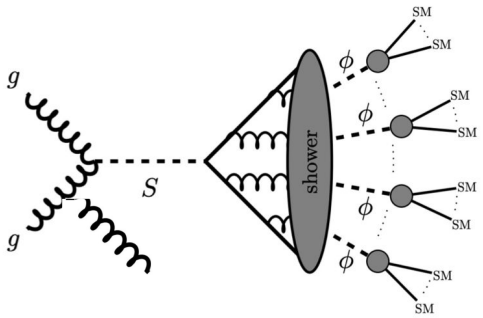
In certain coupling regimes: Radiation off dark quarks happens at large angles → soft decay products

→ Soft, spherically distributed decay products

→ Very difficult to trigger on

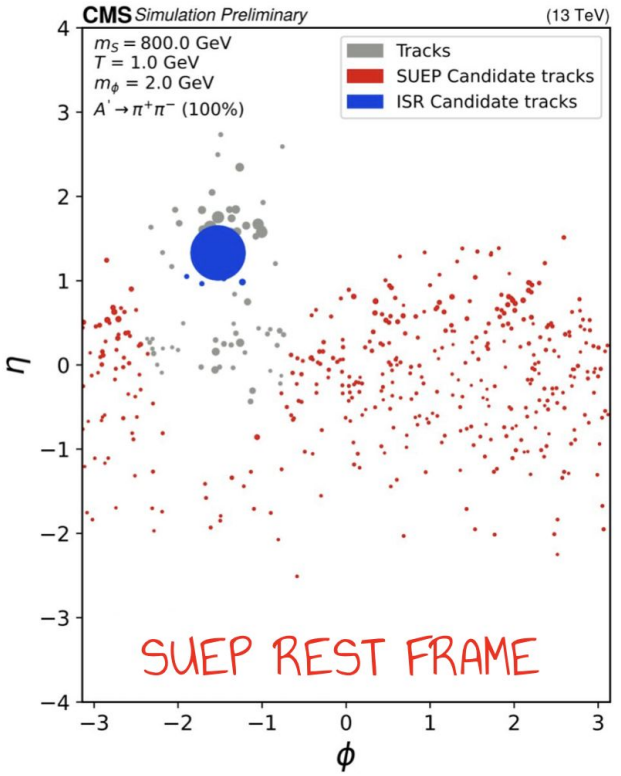
Hot off the press: Soft unclustered energy patterns (SUEPs)



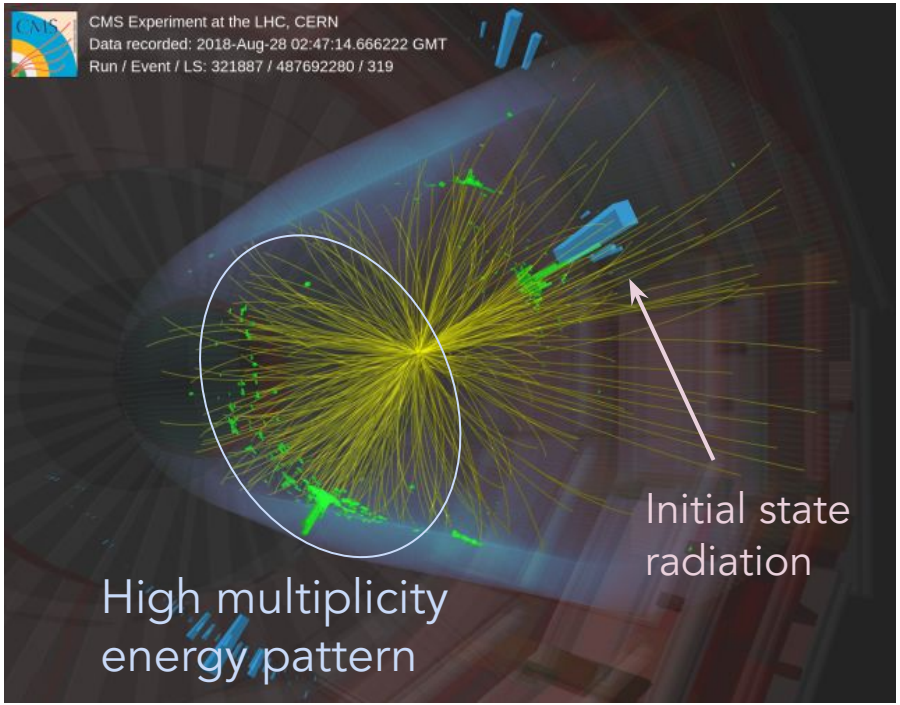


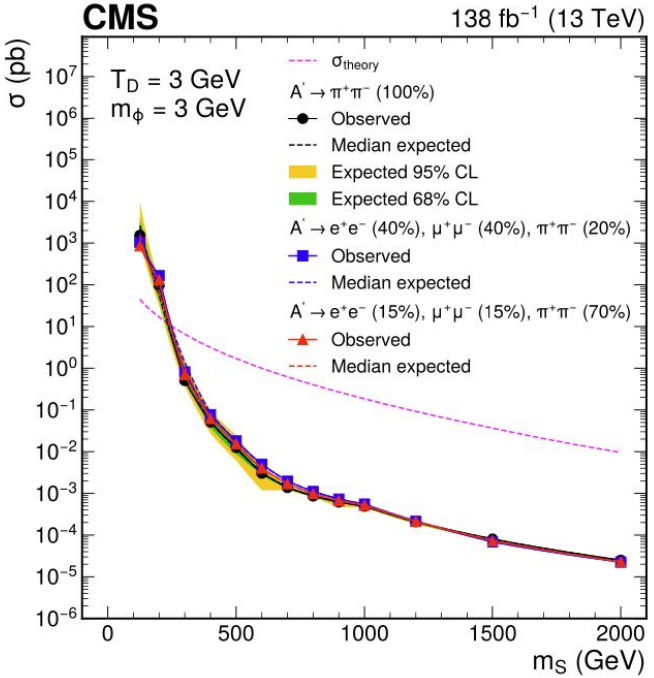
Initial-state radiation

boosting



Hot off the press: Soft unclustered energy patterns





[Phys Rev Lett 133 (2024) 191902]

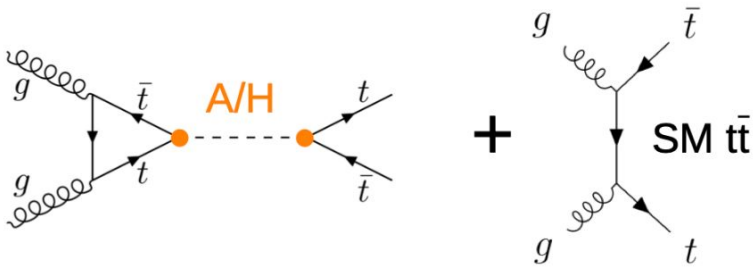
Editors' suggestion

Signal modeling: A/H

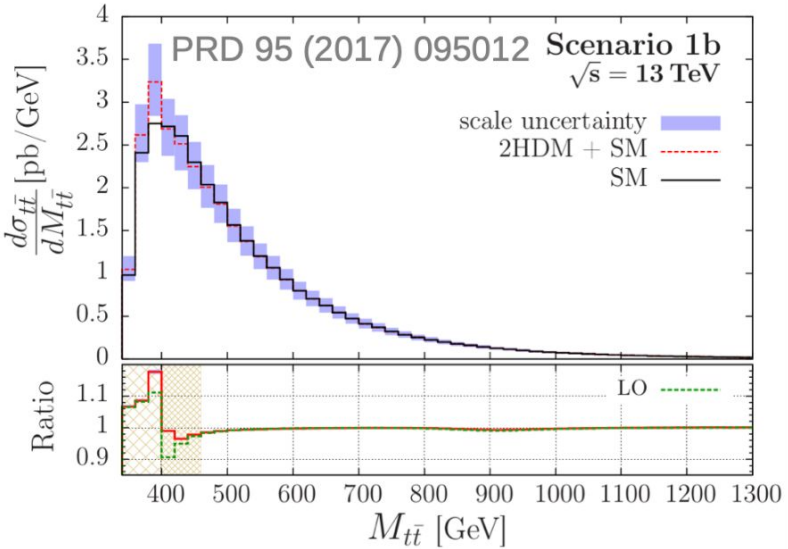
- Generic heavy pseudoscalar (A) or scalar (H) coupling solely to top quarks
- Production in gluon fusion via top quark loop

$$\mathcal{L}_A^{\text{int}} = ig_{\text{At}\bar{\text{t}}}\frac{m_{\text{t}}}{v}\bar{\text{t}}\gamma_5\text{tA}$$

$$\mathcal{L}_H^{\text{int}} = -g_{\text{Ht}\bar{\text{t}}}\frac{m_{\text{t}}}{v}\bar{\text{t}}\text{tH}$$

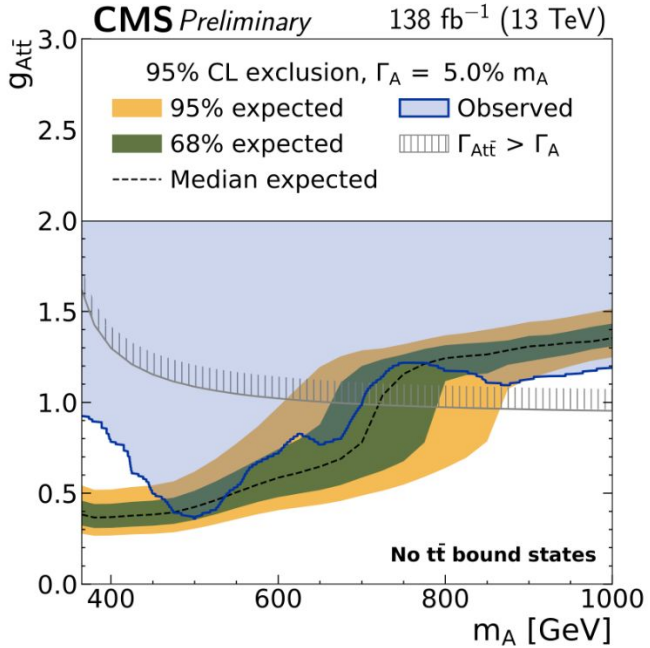


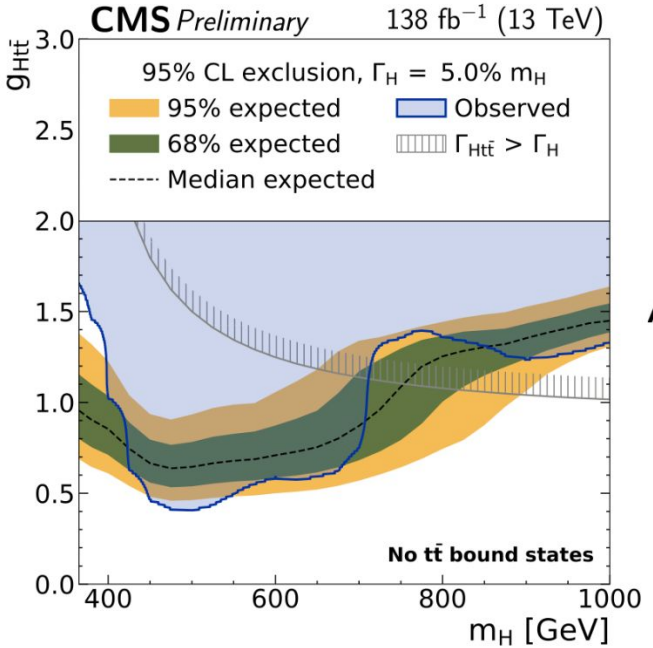
- Same final state as SM $t\bar{t}$ → interference → peak-dip structure in m_{tt}



A/H interpretation

- Limits on A or H using only the perturbative QCD+EW background model
- Excess at low m_{tt} visible at low A/H masses – stronger for A

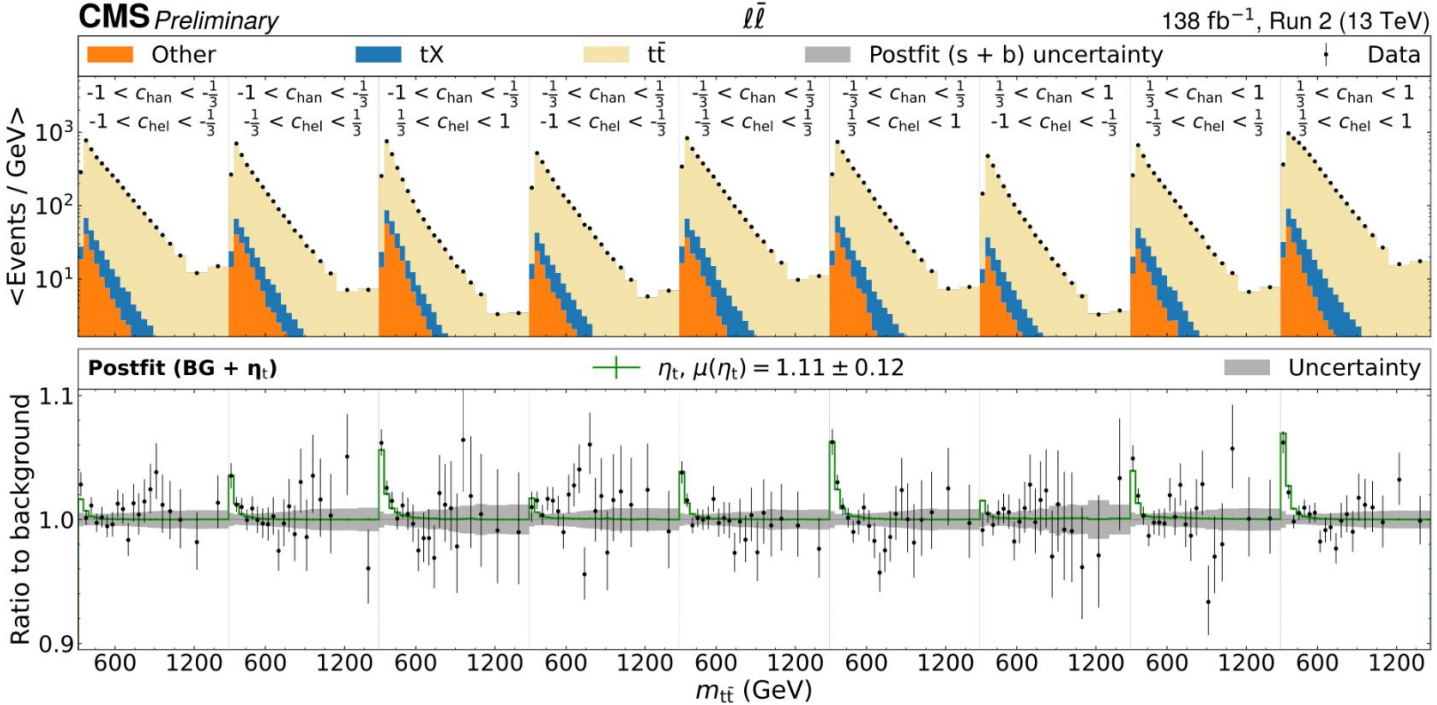




A/H width: 5%

Postfit distributions: η_t ($\ell\ell$)

Postfit for η_t model describing the data well

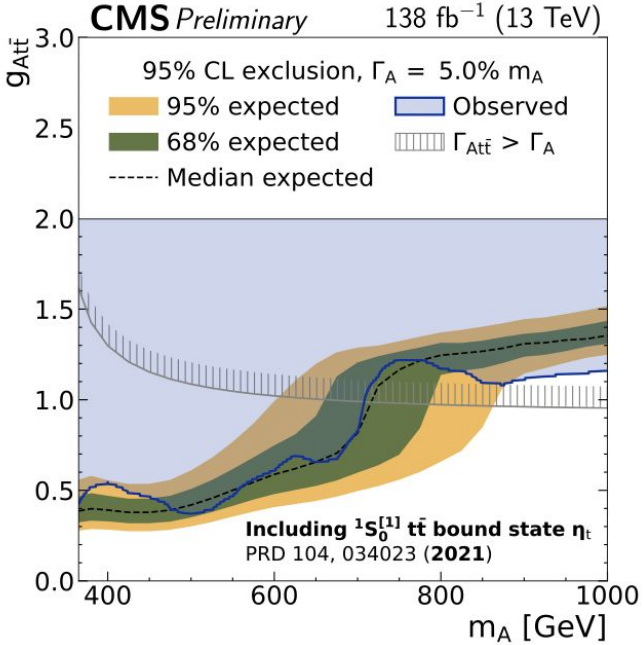


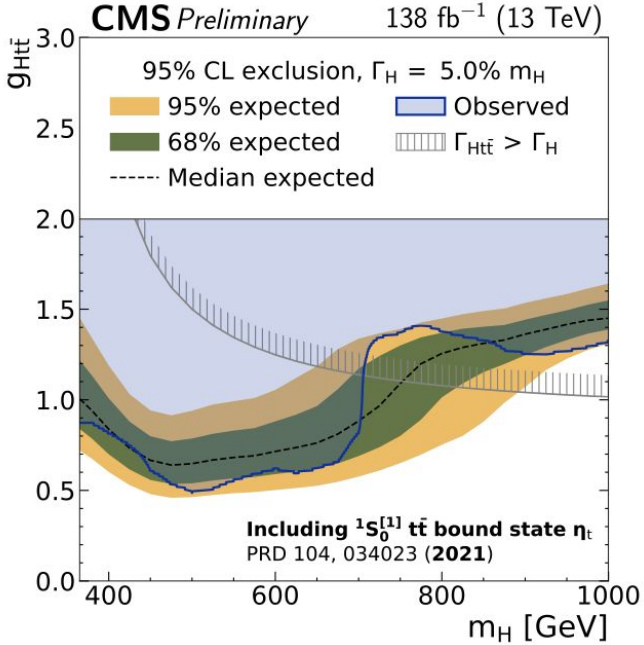
A/H limits including η_t

- QCD + η_t describes data well → set (BSM) A/H limits
  → η_t added as an additional BG process with free-floating normalization

Cannot distinguish η_t and low-mass A

→ Excess no longer present





→ Probable observation of toponium!!

Kung Fu Panda

Lifetime frontier

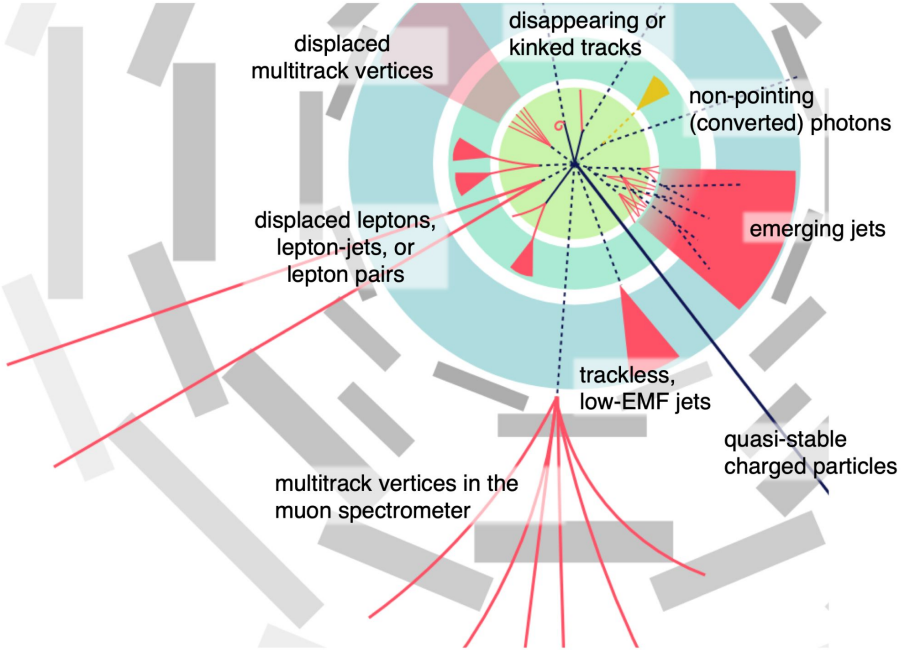
Unlocking displaced signatures

$$\Gamma \propto \varepsilon^2 \left(\frac{m}{\Lambda}\right)^{2n} \Phi$$

Why long-lived particles are tricky

CMS was **not designed** to look for **displaced** new physics

Reconstruction algorithms, cylindrical geometry, trigger, all designed assuming particles emerge from the collision point

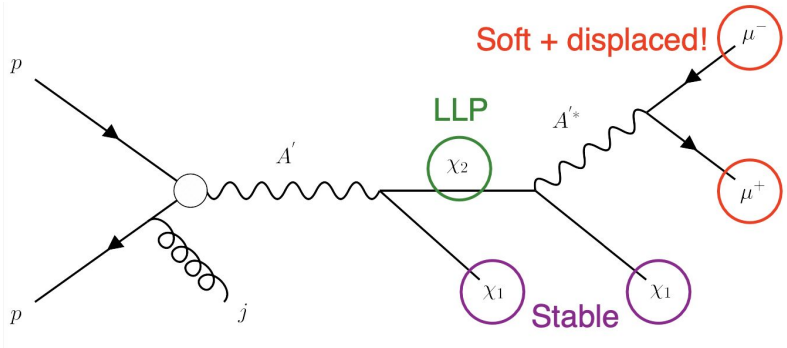


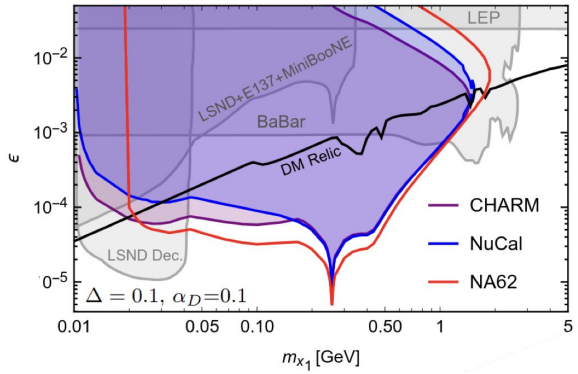
Inelastic Dark Matter with displaced muons

Two dark matter states with **small mass gap** coupled via dark photon. Depending on Δm_{DM}: no direct detection ("inelastic")

Heavier DM (χ_2) has **long lifetime due to small mass splitting**
→ Pair of soft displaced muons + MET (from χ_1)

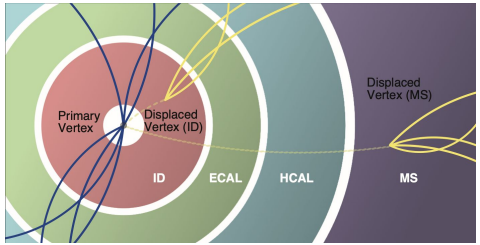
$$c\tau \propto \frac{(m_{A'})^4}{(\Delta m_{DM})^5}$$; target 1mm - 1000mm range





Highly constrained by beam-dump experiments for < 1 GeV

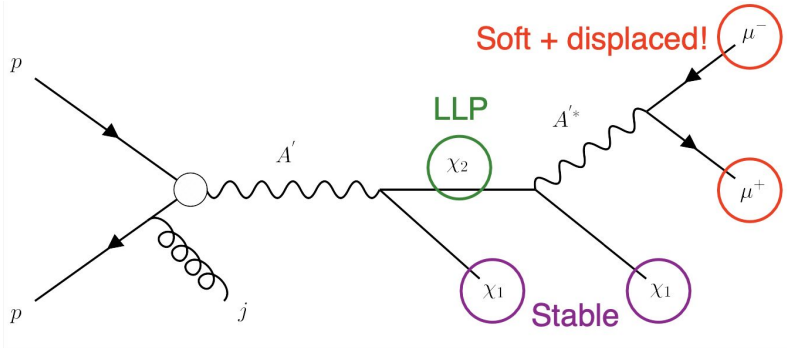
Inelastic Dark Matter with displaced muons



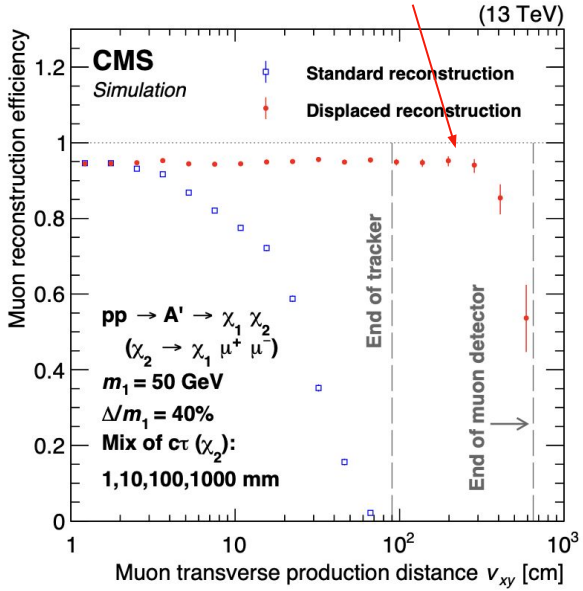
Two dark matter states with **small mass gap** coupled via dark photon. Depending on Δm_{DM}: no direct detection ("inelastic")

Heavier DM (χ_2) has **long lifetime due to small mass splitting**
→ Pair of soft displaced muons + MET (from χ_1)

$$c\tau \propto \frac{(m_{A'})^4}{(\Delta m_{DM})^5}$$; target 1mm - 1000mm range



Dedicated muon reconstruction using only muon system



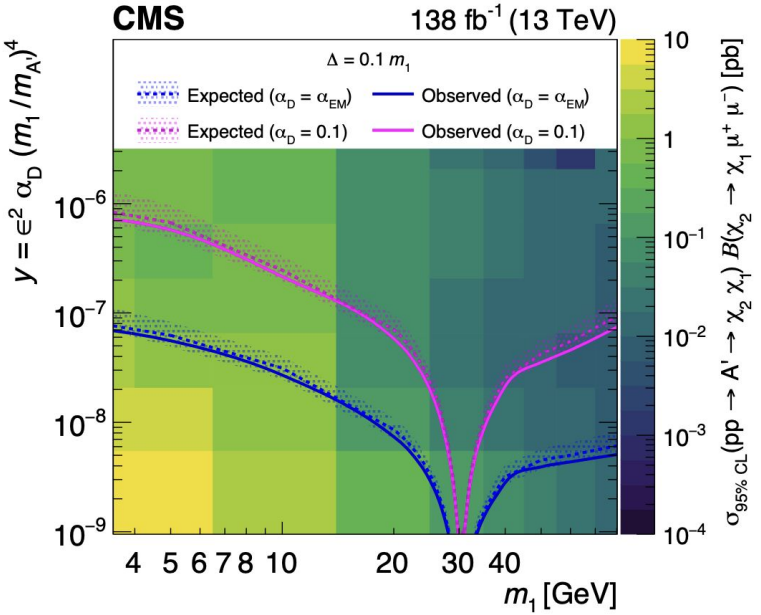
Inelastic Dark Matter with displaced muons

$m_{A'} = 3\,m_1$

Categorize by number of displaced muons that match in direction to a standard muon

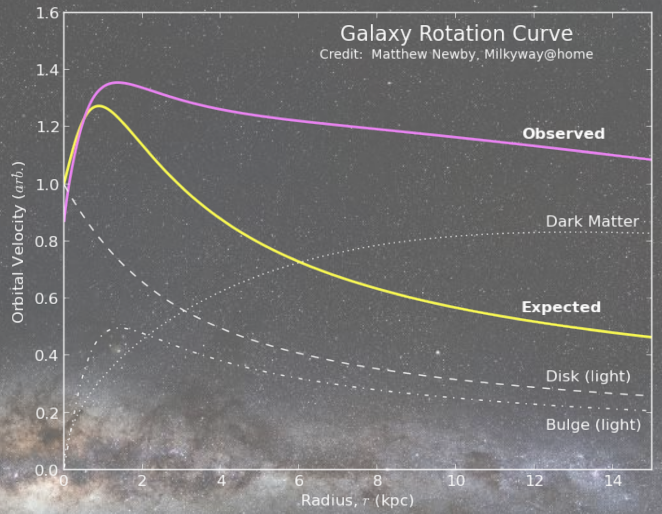
- Fewer matches → larger displacement
- Use kinematics, isolation, displacement parameter to both suppress and estimate background (mostly QCD)

	Events per SR category		
	0-match	1-match	2-match
Pred.	1.2 ± 0.6	0.5 ± 0.3	0.5 ± 0.3
Obs.	2	0	0



First such search at a hadron collider!


Stay tuned for Run-3 results!
Spin-0 portal
Pseudo-scalar
Scalar
ALP
Dark Higgs
Higgs 125
Spin-1 portal
Vector
Neutrino portal
Simplified dark sectors
Hidden valleys
SUEPs
Emerging jets
Neutral natural-ness
Semi-visible jets
SUSY
Stealth SUSY
Dark SUSY
Hidden Abelian Higgs
2HDM+a
Dark Matter
dark sectors
Dark sector models in CMS searches



~~A Shot in the Dark~~ We have a plan

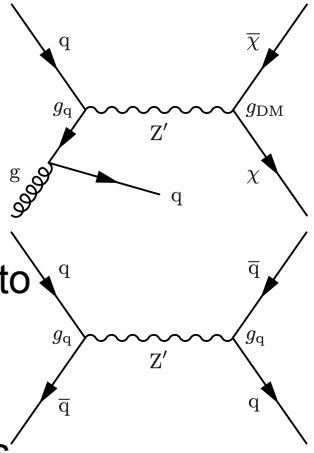
Hunting for dark matter at the LHC

Benedikt Maier
Jan 7, 2025

Backup

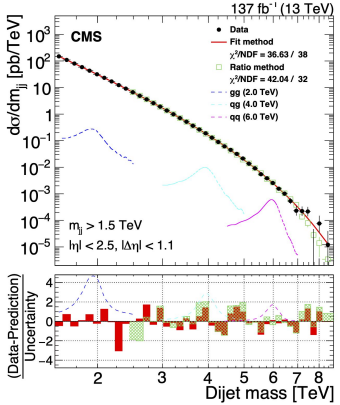
Vector and Axial-Vector Portals

- Vector and axial-vector mediators arise from a broken U(1) symmetry, with couplings to the SM and the dark sector
- Included searches:
  - Dijet searches (visible final states, mediator coupling to SM)
  - Mono-X searches (invisible final states, mediator coupling to DM)
- Benchmark scenarios from LHC DM WG recommendations

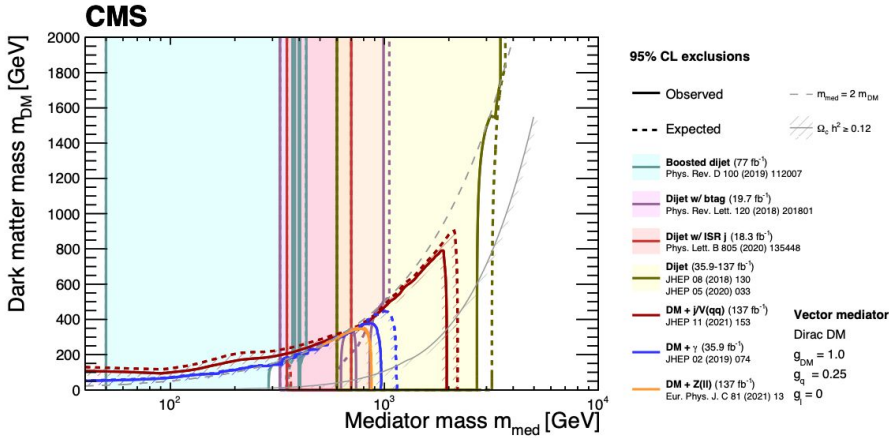


Simplified dark sectors

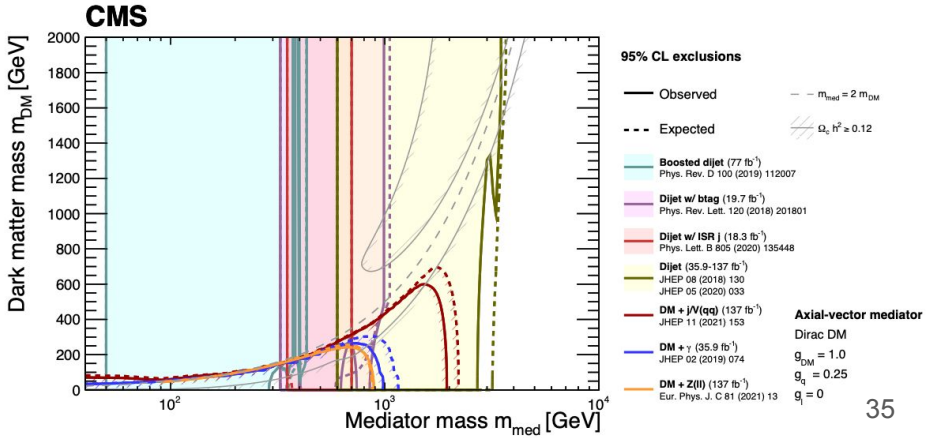
Spin 1



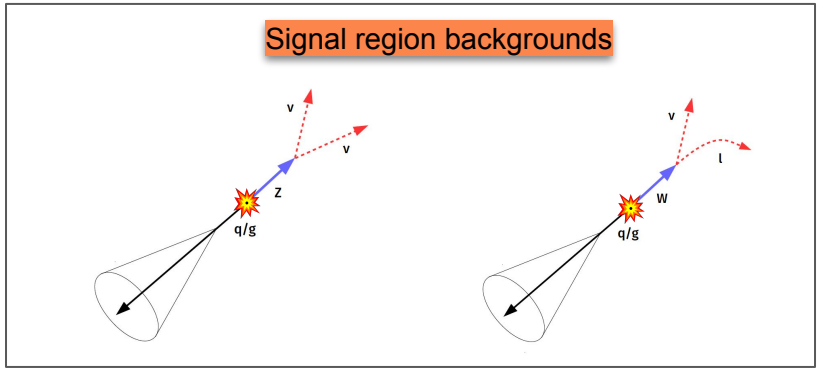
Vector Mediator



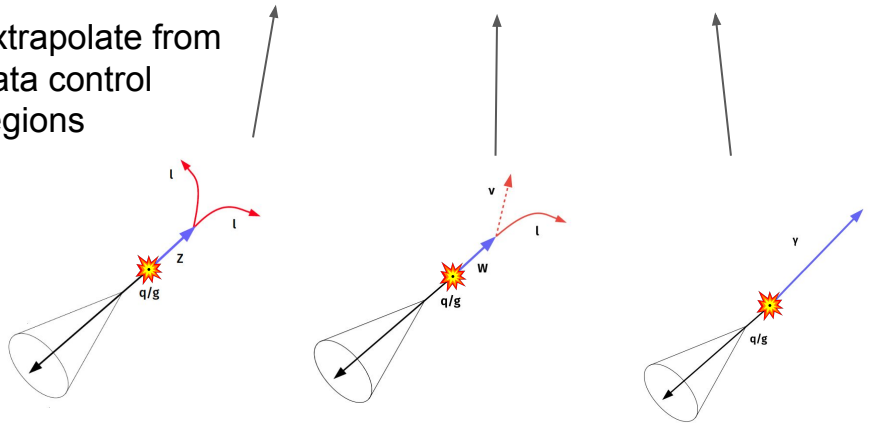
Axial-Vector Mediator



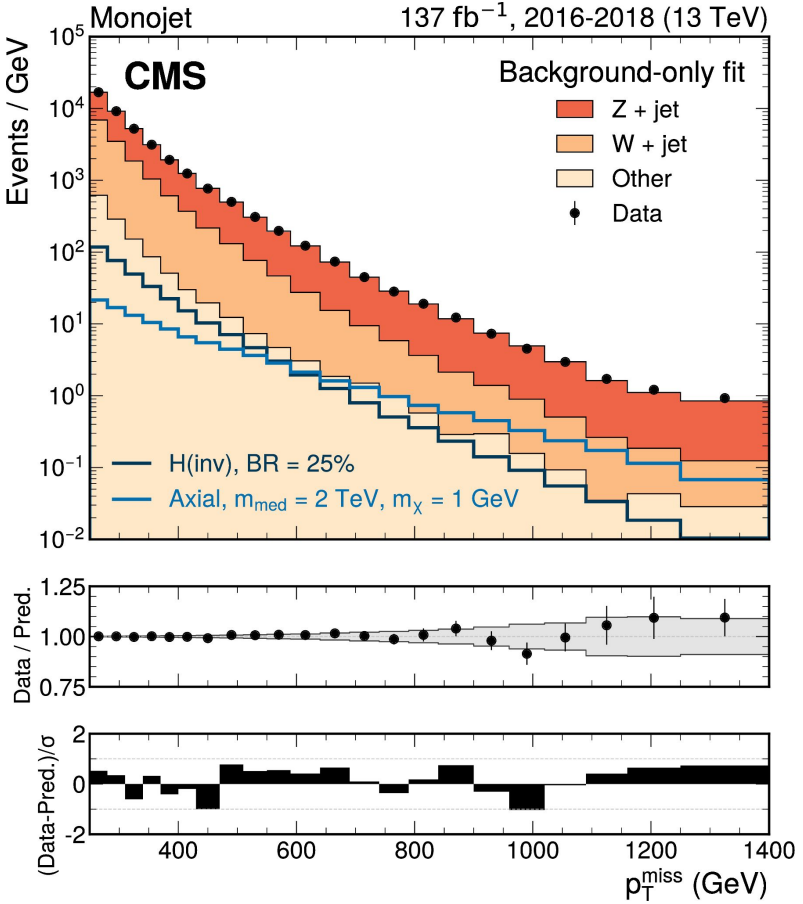
Signal region backgrounds



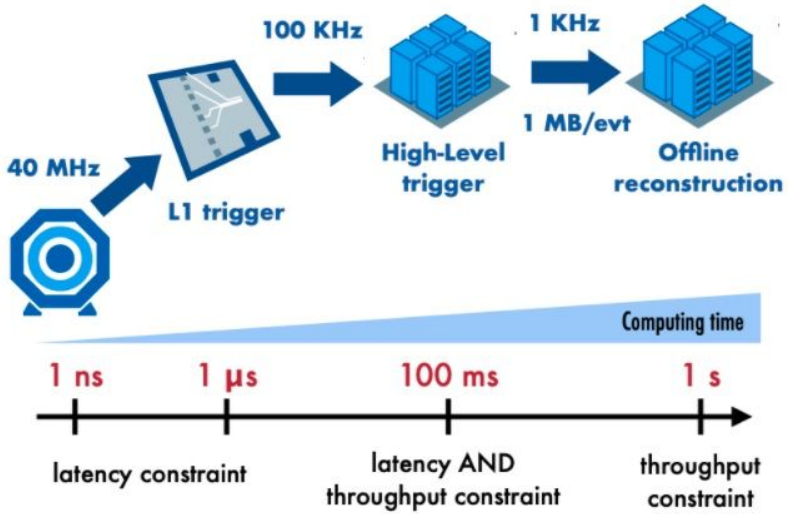
extrapolate from data control regions

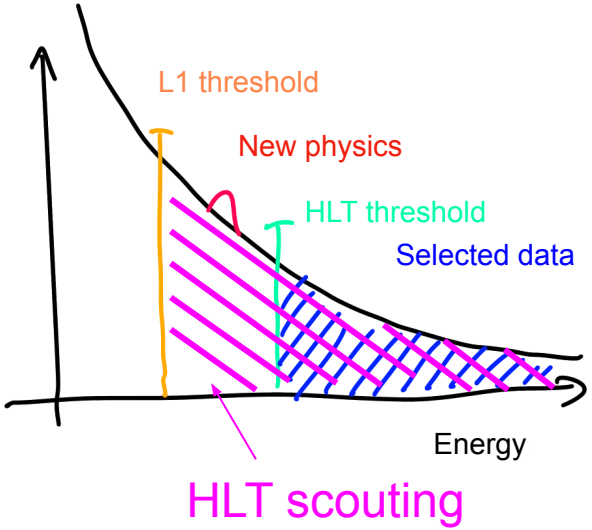


Control regions



Remedy: Scouting





Limited bandwidth and disk space → cannot afford to save the full detector information for every event to disk

→ Lower thresholds by changing event content to accommodate lower thresholds

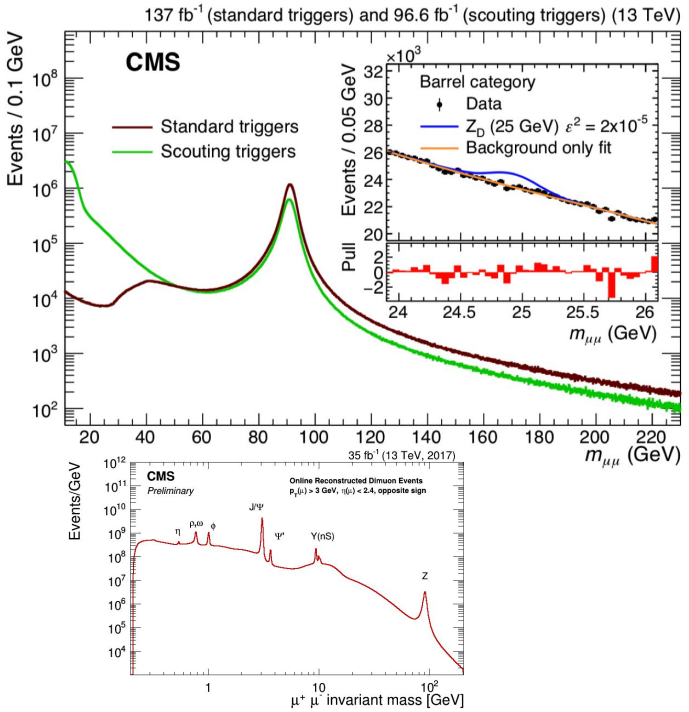
Scouting at CMS during Run-2

Dedicated low-precision data stream saving almost all the information used by HLT algorithm for years 2017-2018

(and onwards for Run-3)

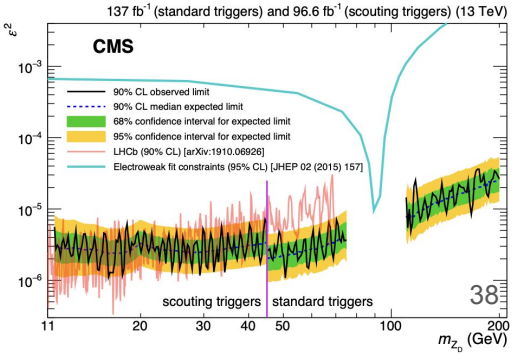
Loose Cuts at HLT

Scouting Path	Selection	Rate [kHz]	Proc. Time [ms]
Muon Calo-Scouting (2017–2018)	$(2\mu,\ p_T > 3$ GeV)	2.7	350
H_T Calo–Scouting (2016–2018)	$(H_T > 250$ GeV)	3	160
H_T PF–Scouting (2016–2018)	$(H_T > 410$ GeV)	0.7	1200



Dimuon mass resolution slightly worse than LHCb (1-1.5%), not much worse than offline

Resolution for 2 TeV resonance using calo jets -20% compared to offline



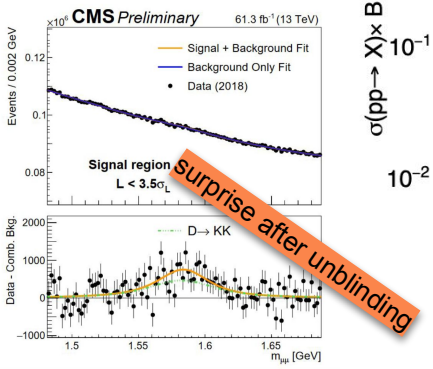
Taking it to the extreme (i.e., below the Y)

Fully exploiting HLT Scouting data by selecting events with two muons p_T > 4 GeV (very soft!)

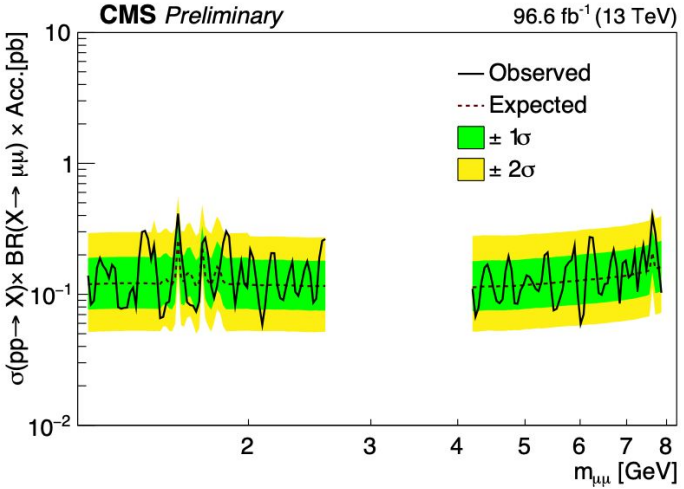
Novel MVA muon identification increases sensitivity by 30%

- Track quality
- Isolation
- Vertex information

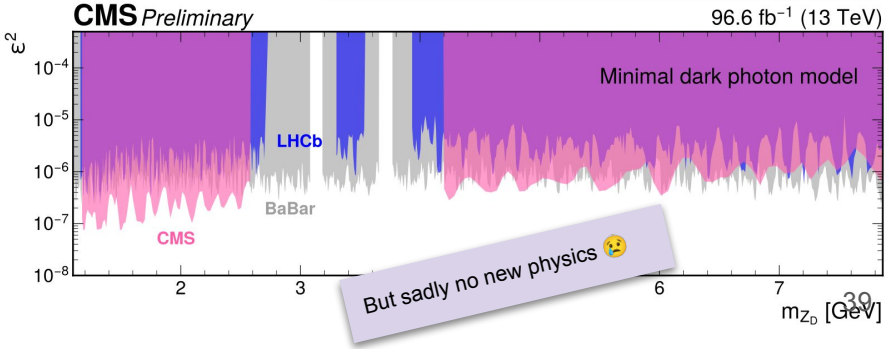
Extract signal from fit to dimuon mass distribution



Surprise after unblinding



More sensitive than LHCb or BaBar with "2nd-grade" data 😋



But sadly no new physics 😢