Recent LHC Dark Sector Results

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(for the ATLAS, CMS and LHCb Collaborations)

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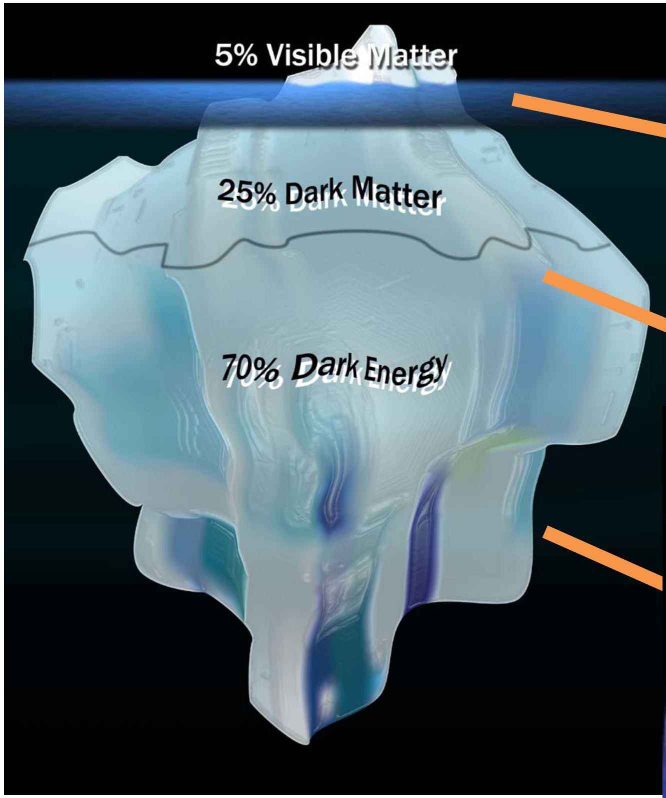
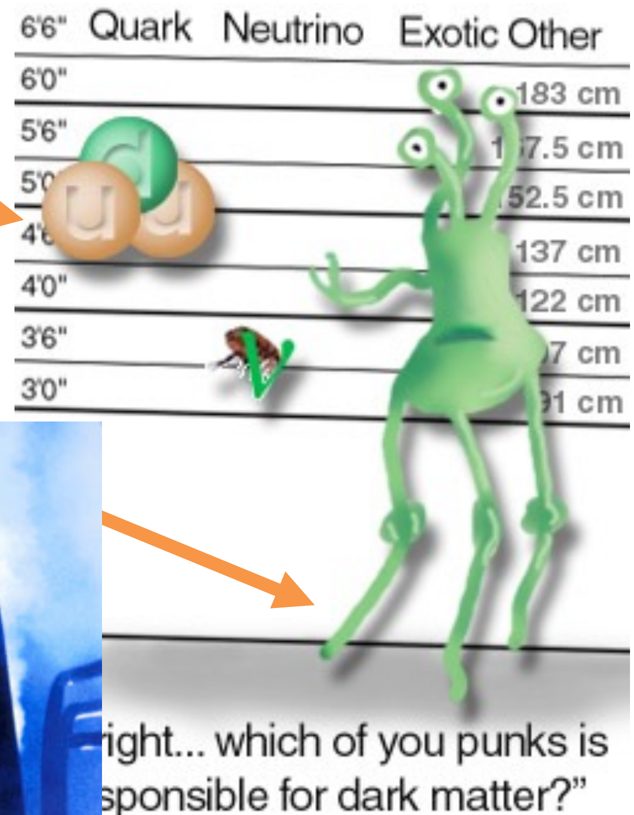
TeVPA2021

Standard Model: open questions

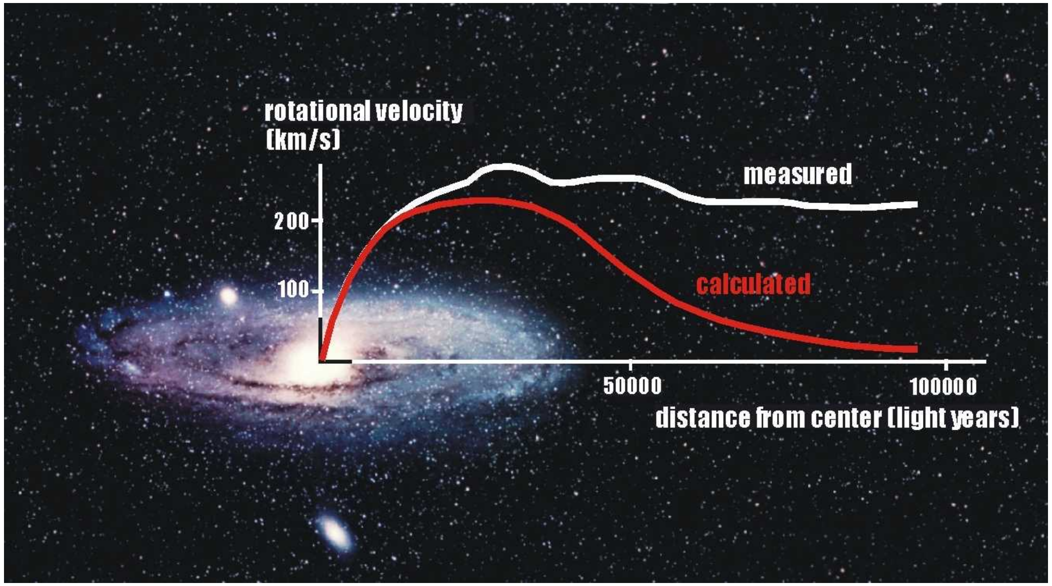


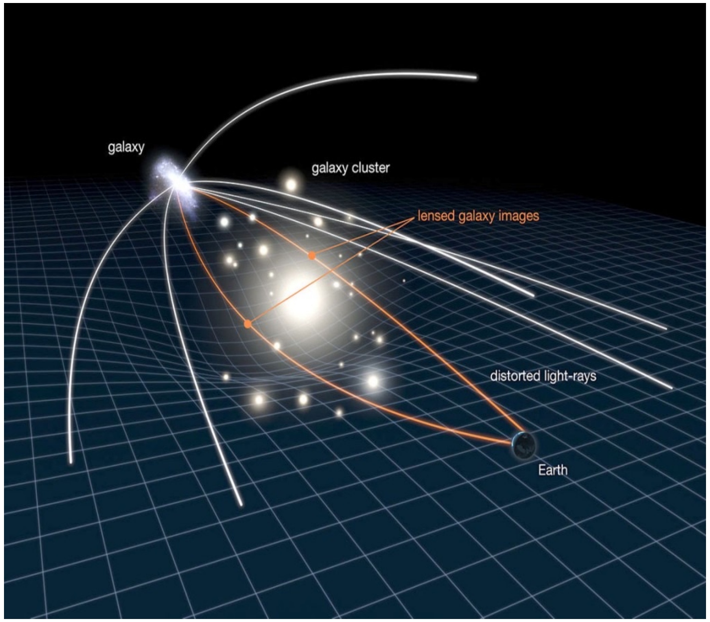


Are new particles the solution ?

Dark Matter exists!

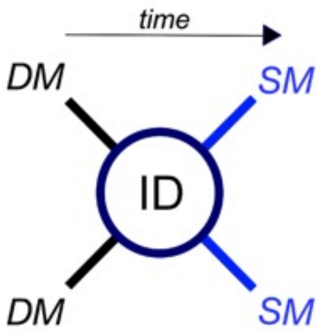
- Classic evidence: rotation curves

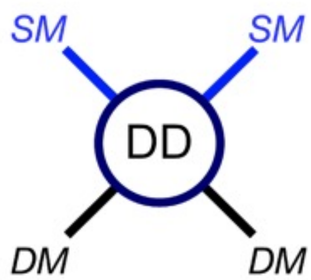


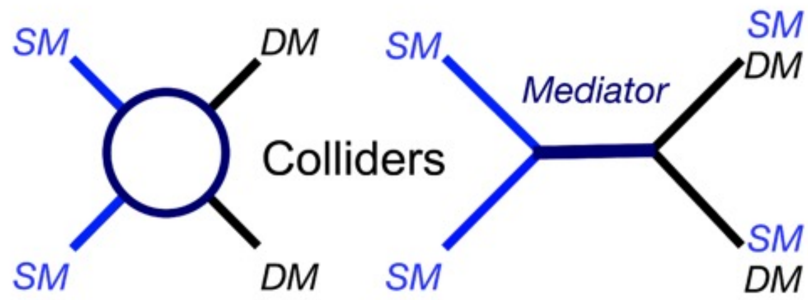


- This evidence has now been supplemented by many other observations, all pointing to the same amount of dark matter
  - Early and late cosmology, Clusters of galaxies, Galactic rotation curves….
- *The fundamental nature of dark matter is still a mystery!*
  - What is it and how does it interact ?

Dark Matter (DM) Searches

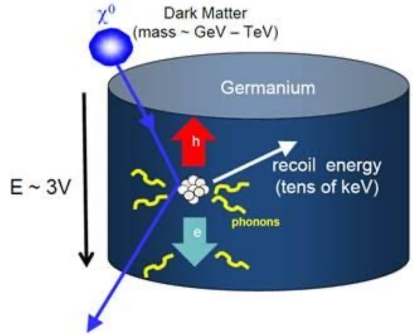




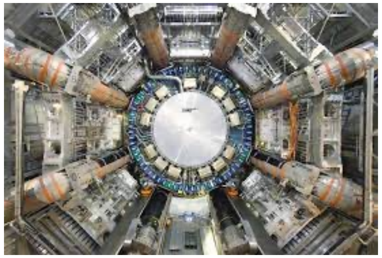


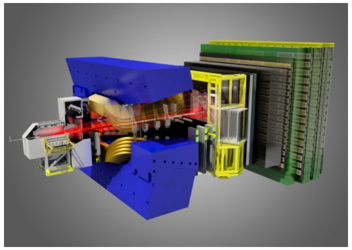
Indirect direction: products from DM annihilation

Direct detection: nuclear recoils from DM-nuclei scattering

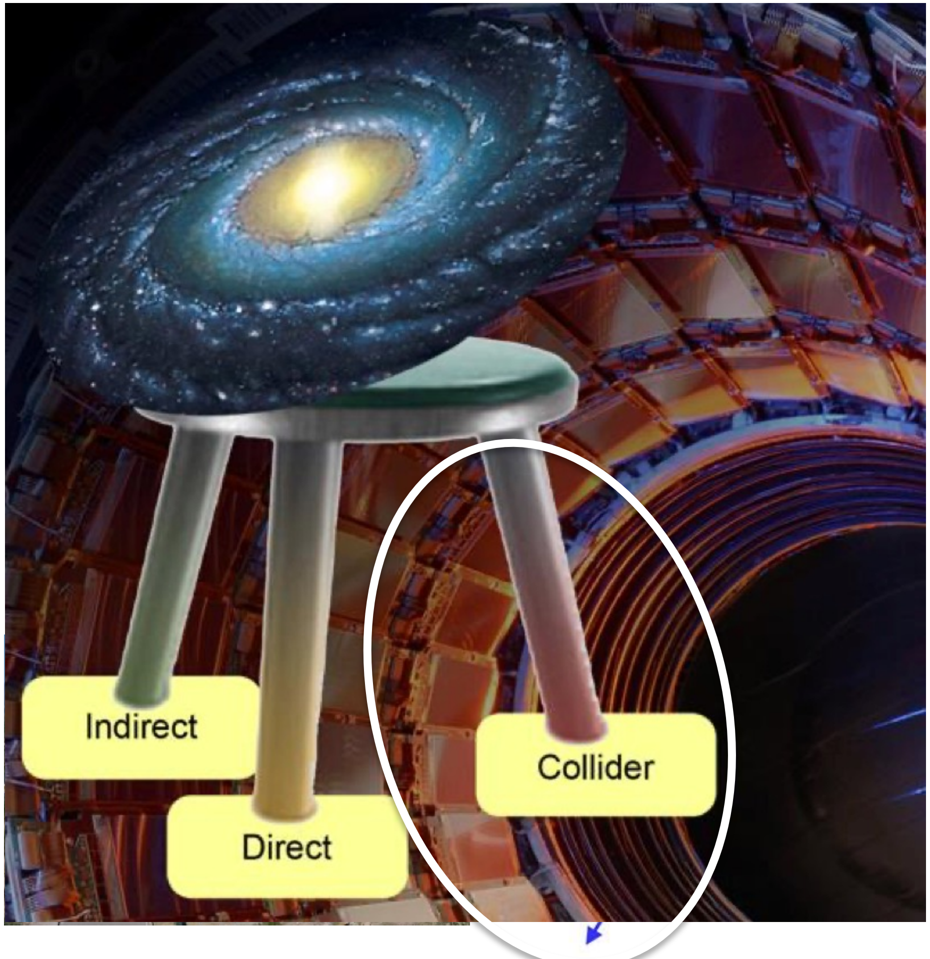


Collider Searches

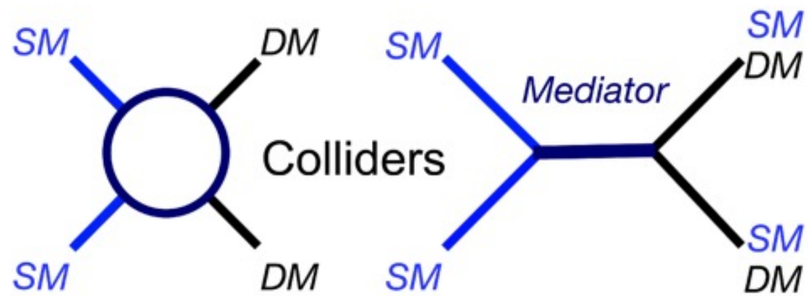




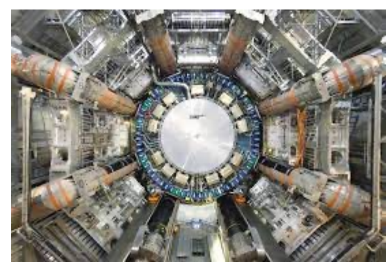
Dark Matter (DM) Searches

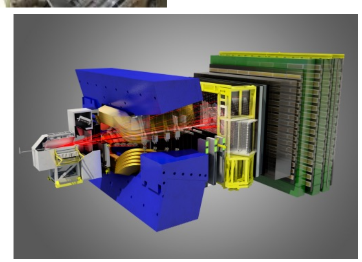


Will focus on LHC searches in this talk: mostly analyses that were made public in 2021



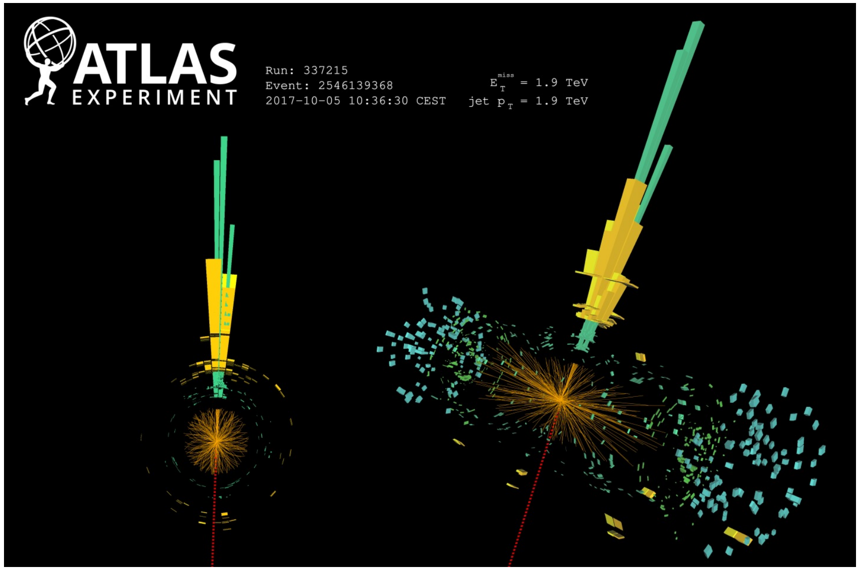
Collider Searches

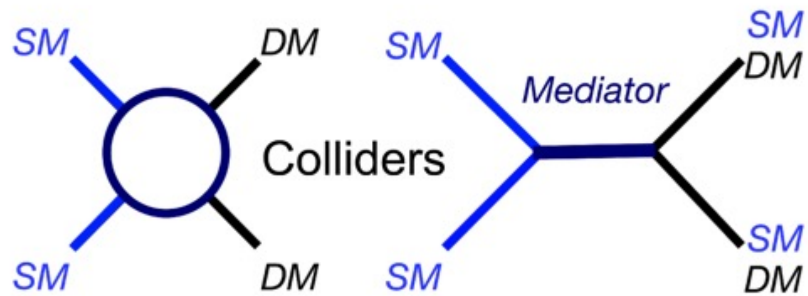




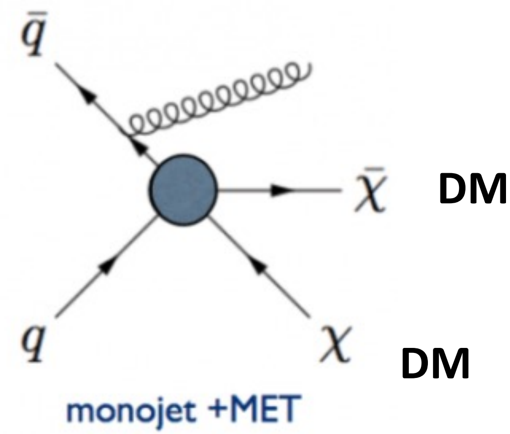
Physics beyond colliders:
See [review article]

Dark Matter Searches @ LHC





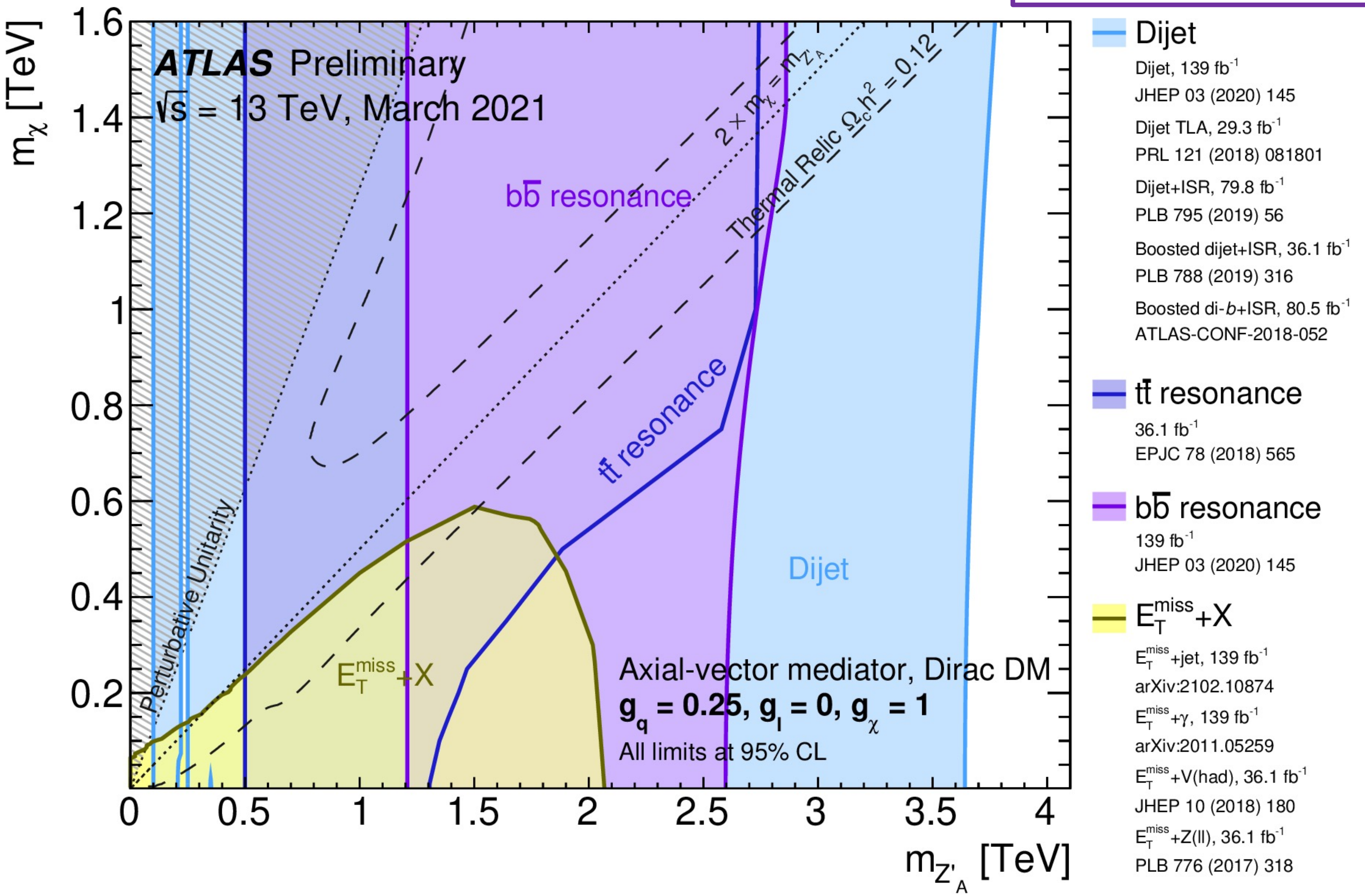
- Invisible DM particles escape detection.
- Could create a p_T imbalance ***(MET or ET$_{miss}$)***
- Strategies:
  - tag events using recoiling object (*visible particle)* (“mono” searches)
  - can look for both invisible and visible decays of the mediator



Dark matter candidates in the form of weakly interacting particles (WIMPs) with masses in the GeV-TeV range extensively studied

Dark Matter Searches @ LHC

ATL-PHYS-PUB-2021-006

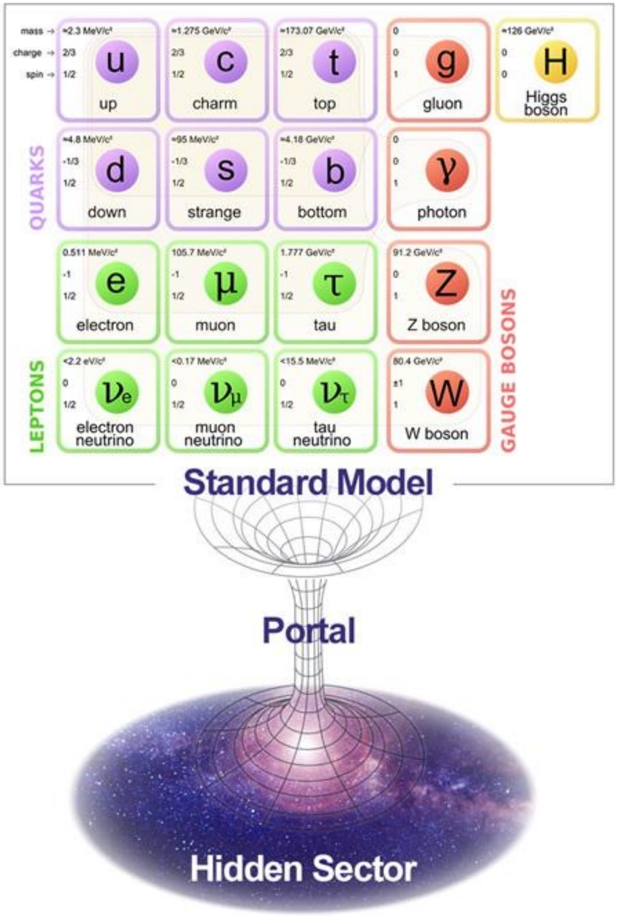


DM in Dark Sector ?

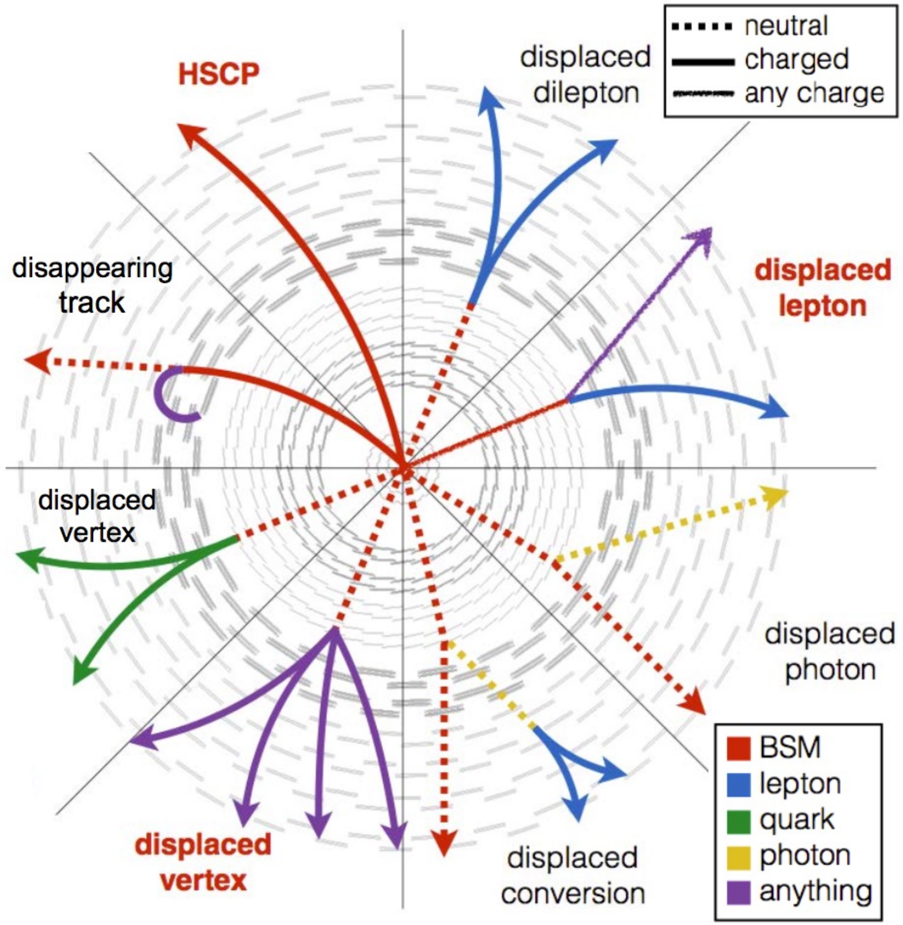
Credit: Kristian Buus

Dark Sectors

- What if DM exists in a hidden “dark” sector, consisting of particles that do not interact with the known strong, weak, or electromagnetic forces ?
- May communicate w/ SM via mediators, which could be DM candidates OR provide “portals” to them
  - Different portals depending on the spin of the mediator
    - Vector (spin 1): vector A′ → dark Z, dark Ɣ
    - Neutrino (spin ½): fermion, N → sterile neutrino
    - Higgs (scalar): scalar ϕ → dark H
    - Axion (pseudo-scalar): ɑ → axion
- Coupling to SM encoded in a mixing term in the Lagrangian
  - Small mixing cases → long lifetime



Non-conventional final states



Credits: J. Antonelli

New and rich phenomenology:

- Very weakly coupled to SM
- Long-lived particles
- Masses below the EW scale

Searches need to often overcome challenges in trigger, reconstruction & background estimation

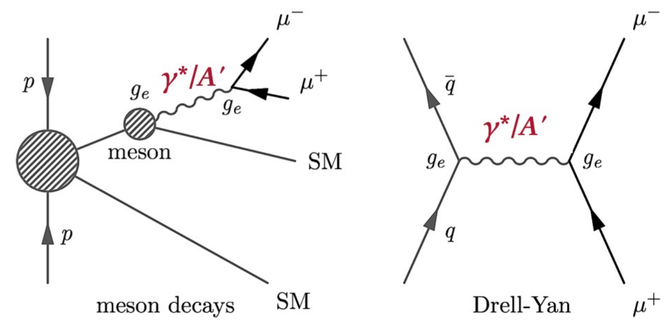
Need to deal with unusual backgrounds (e.g. beam-induced backgrounds)

Excellent detector understanding is absolutely critical

Taking advantage of several topologies currently

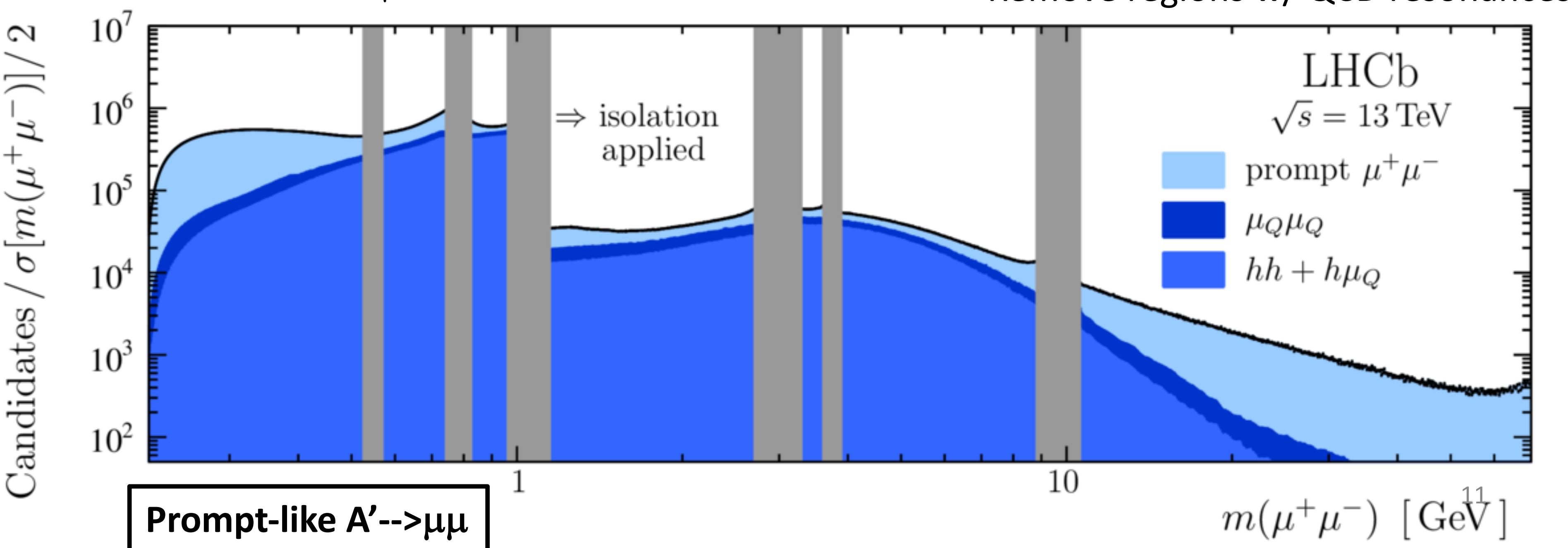
Dark Photons

- **Dark photon (A')** may feebly couple SM particles to to a hidden, dark sector of particles.
- The strength of the coupling with SM fermions is determined by the kinetic mixing coefficient ϵ
- LHCb: inclusive search for A'→ μμ
  - Prompt-like and long-lived decays
  - Leverages online-analysis capabilities to go down to $2m_\mu$



PRL 124 (2020) 041801

Peak hunt on top of large bkg
Remove regions w/ QCD resonances

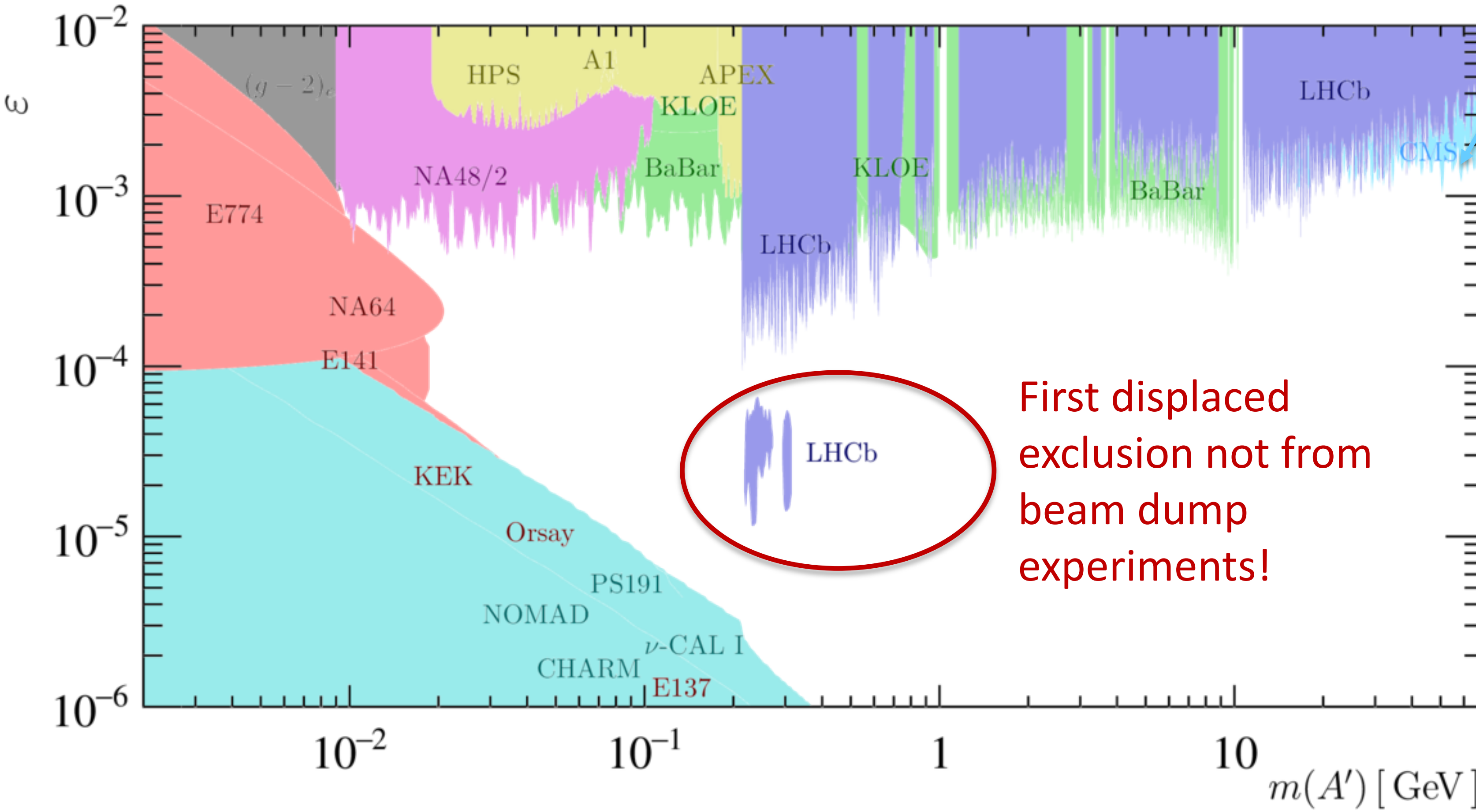


Prompt-like A'-->μμ

Dark Photons

PRL 124 (2020) 041801

CMS: PRL 124, 131802 (2020)

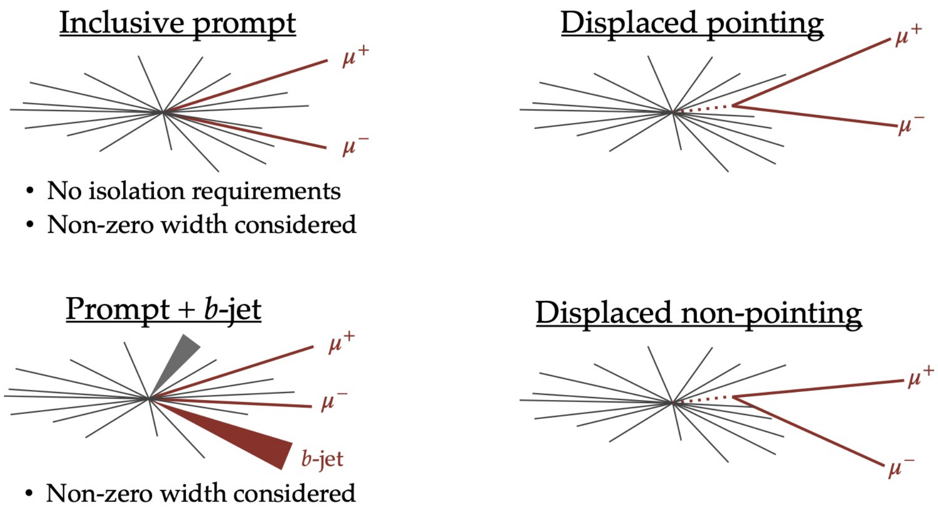


First displaced exclusion not from beam dump experiments!

Triggerless readout in Run 3 (and x5 more luminosity) expected to increase potential yield at low mass by O(100)

Extending to other vector particles

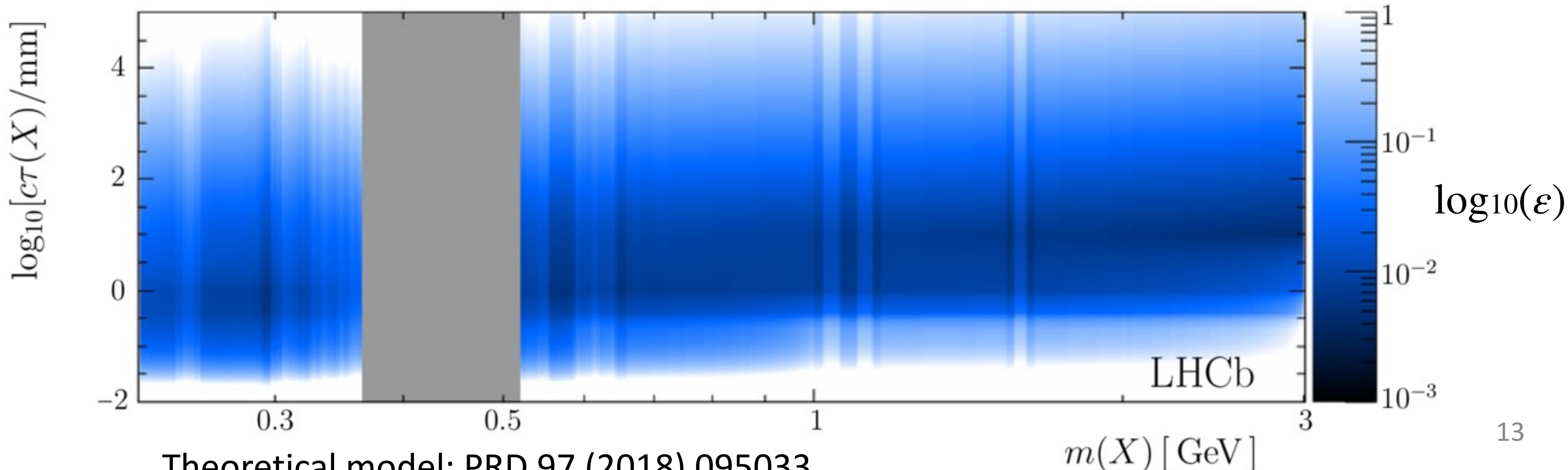
- Probe additional dark sectors in di-muon final state (e.g. hidden valley scenarios)
- Search for low mass X→ μμ
  - Prompt and displaced searches
  - **displaced search** used to place limits on Hidden Valley model with "dark showers" of light hidden hadrons



JHEP 10 (2020) 156

$< N_{HV} > \simeq 10$

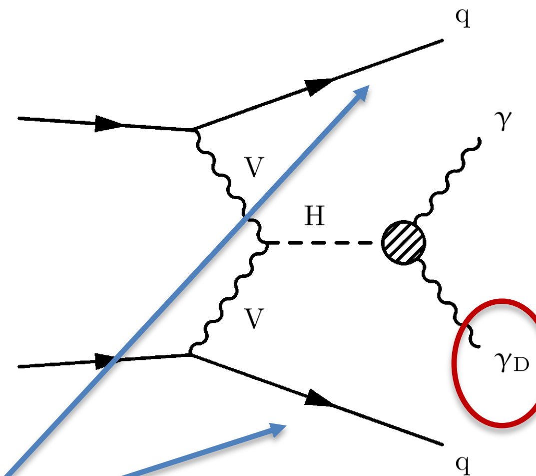
90% upper limits on kinetic mixing between γ and heavy Z_{HV}

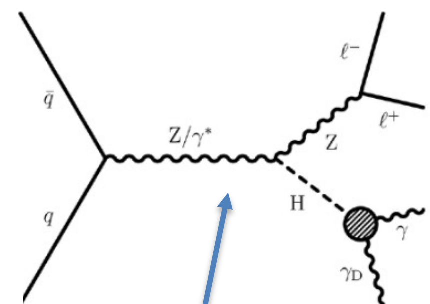


Theoretical model: PRD 97 (2018) 095033

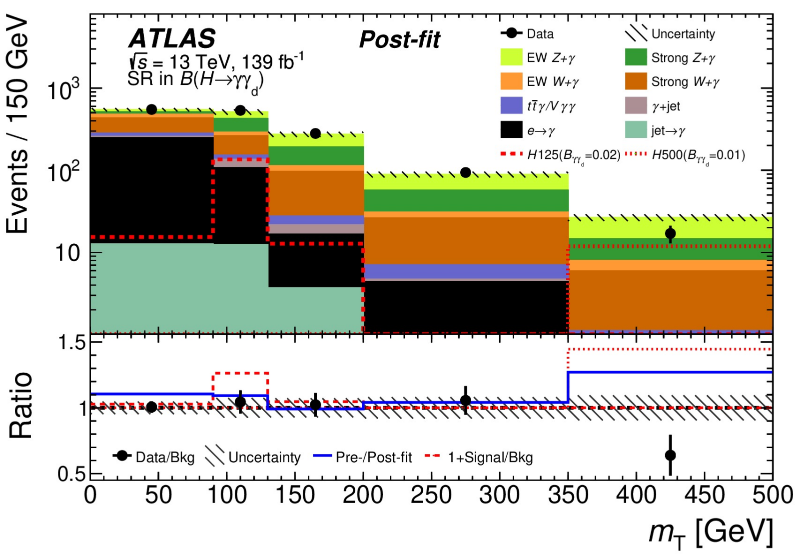
Dark Photons

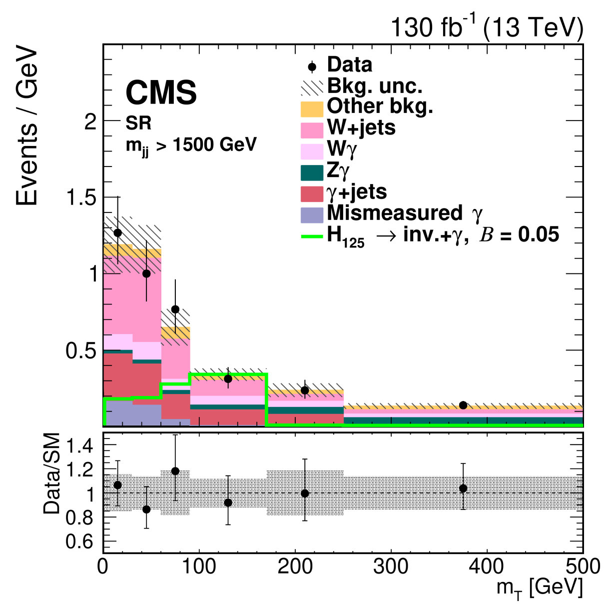
- Consider a scalar Higgs boson coupling to a **dark photon** through a dark sector
- Dark photon-Higgs coupling probed via Higgs boson production (VBF production & Z associated prod.)
- New results from ATLAS and CMS for VBF prod.
  - Takes advantage of 2 large |Δη|, light jets recoiling against MET + γ
  - Use transverse mass as a discriminating variable



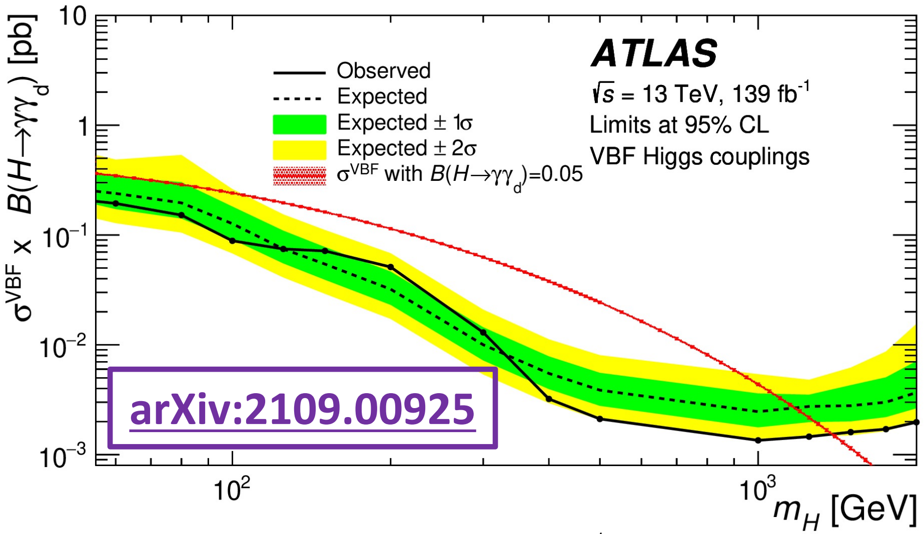


JHEP 10 (2019) 139

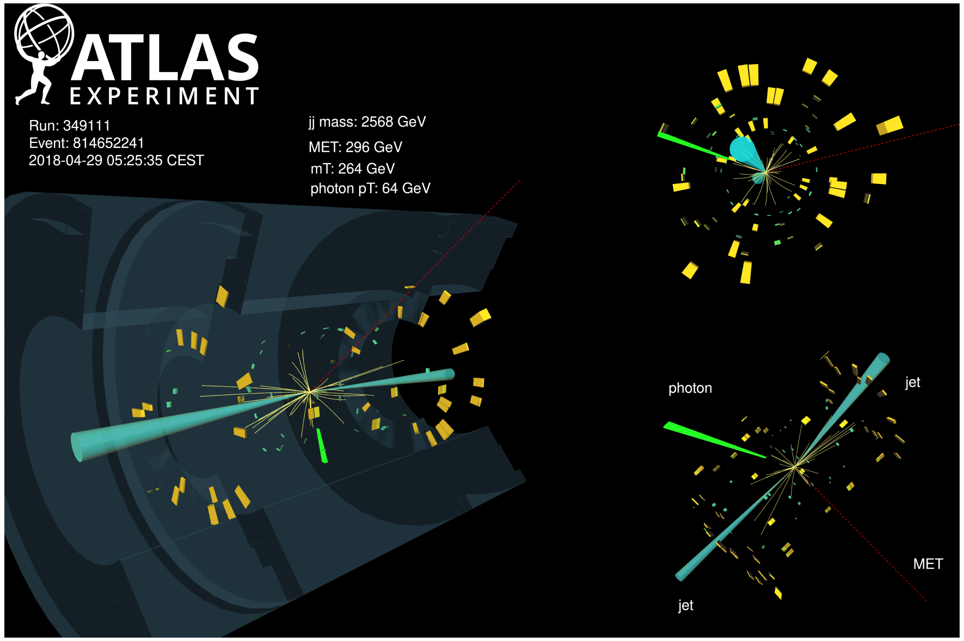


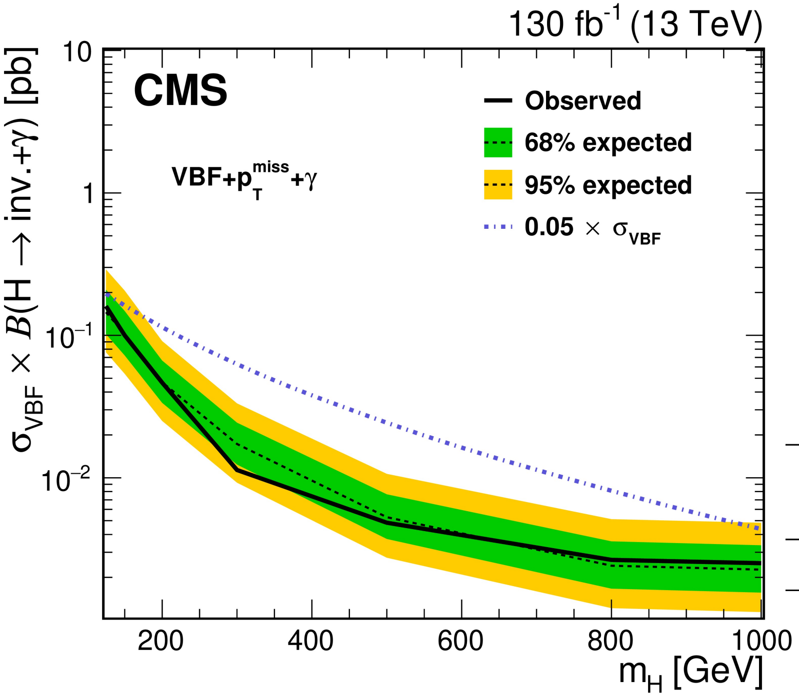


Dark Photons



arXiv:2109.00925





JHEP 03 (2021) 011

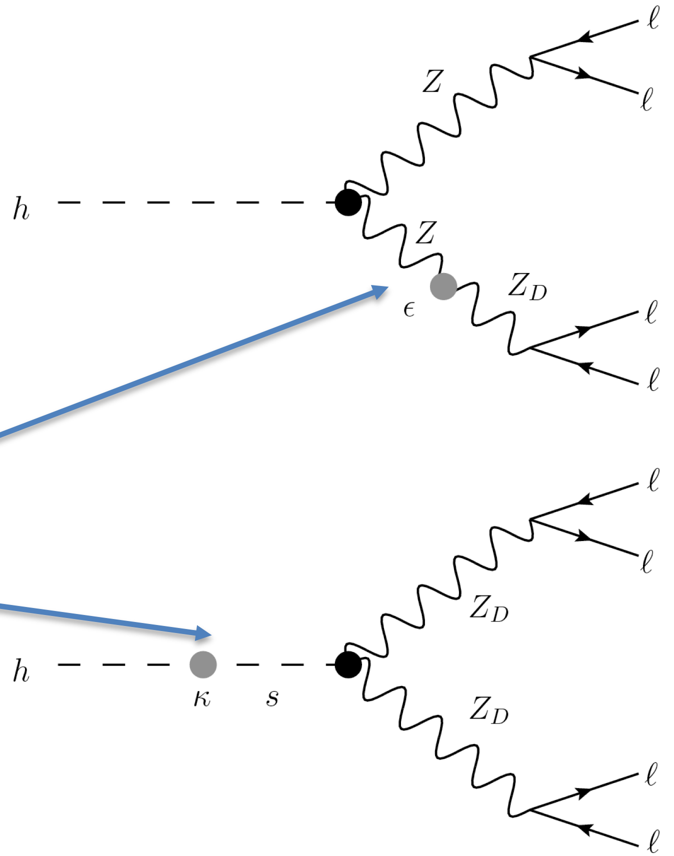
Observed and expected 95% CL limits on BR($H\to\gamma\gamma_D$) for m_H=125 GeV

VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.4	$2.7^{+1.2}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+0.9}_{-0.6}$

JHEP 10 (2019) 139

Displaced di-muons

- Consider a Higgs decaying to one or more **dark Z (Z_D)**
- Hidden sector interacts with the SM through
  - hypercharge portal, via the kinetic mixing coupling (ε)
  - Higgs portal, via the Higgs mixing (κ)
- Proper dark photon lifetime $c\tau_0$ inversely proportional to ε^2
  - If $\varepsilon < 10^{-4}$, then Z_D may be long-lived
- Signature considered by new CMS analysis: events with at least 2 displaced muons and an associated displaced vertex (DV)

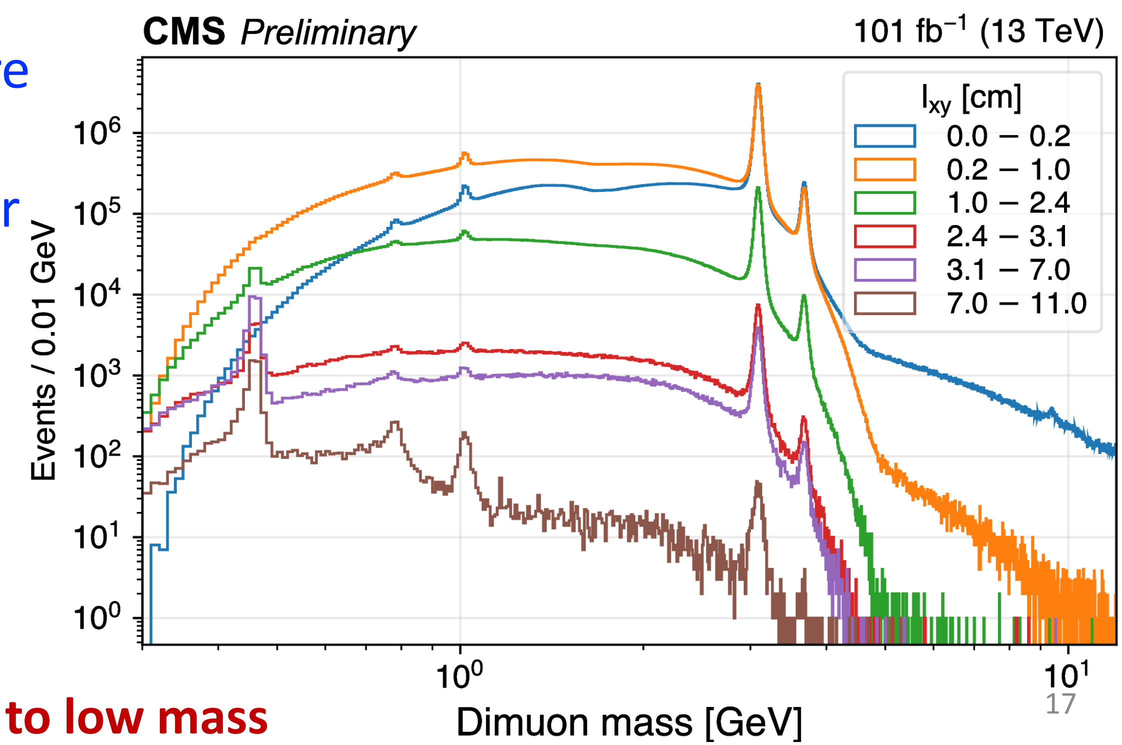


Consider masses down to ~ $2m_\mu$ and displacements (from interaction point) up to 11 cm by using "scouting" or trigger-level analysis

“Scouting” or “Trigger-level” analyses

Traditional trigger algorithms usually require high thresholds (e.g. on p_T and mass) to reduce the event rate, and then readout the full event info.

- The limit is the total bandwidth
  - Can reduce the event size to collect events at a higher rate (i.e. lower thresholds)
  - reduction of event size to O(10kB) allows trigger rates of several kHz
- Reconstruct at the software trigger stage, keeping limited information (trigger objects)
  - needs adequate calibration and validation against full reconstruction

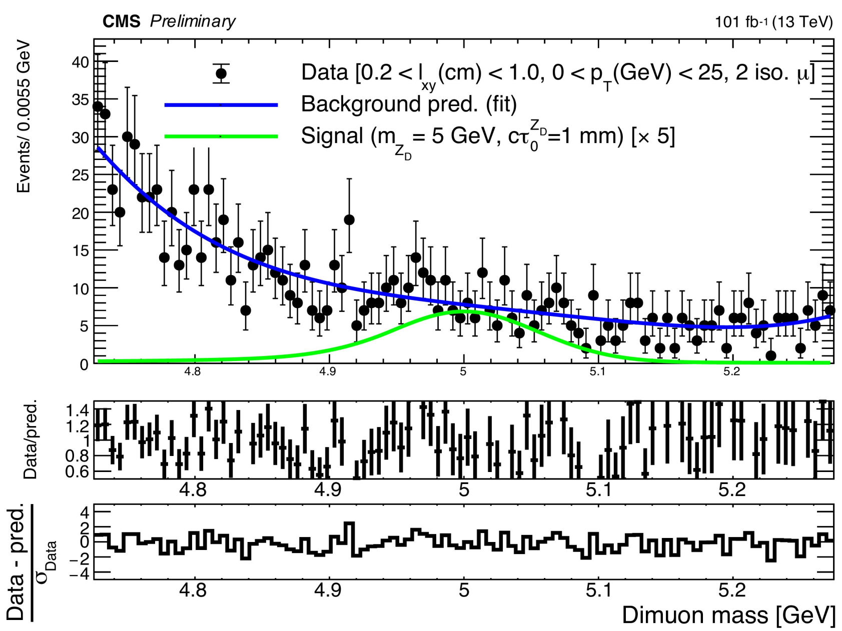


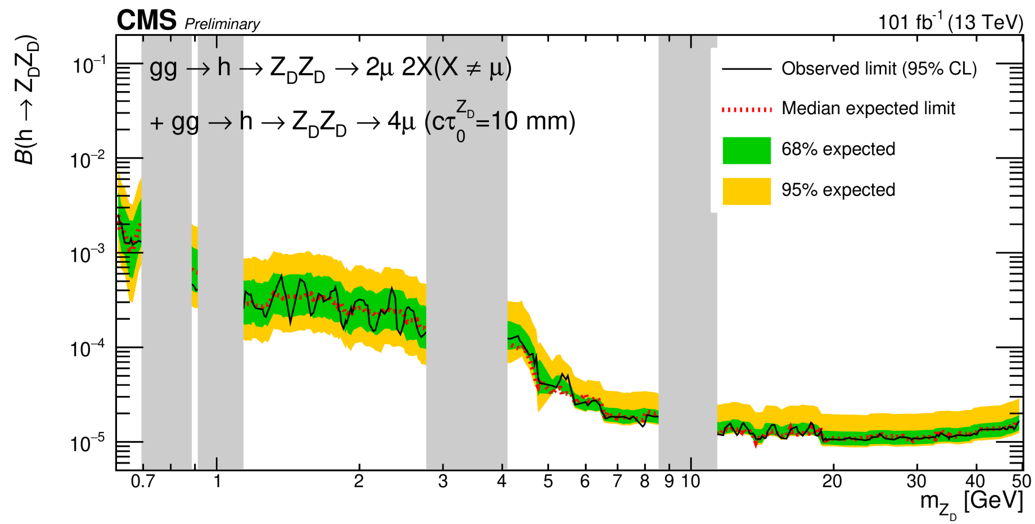
Scouting data enables access to low mass

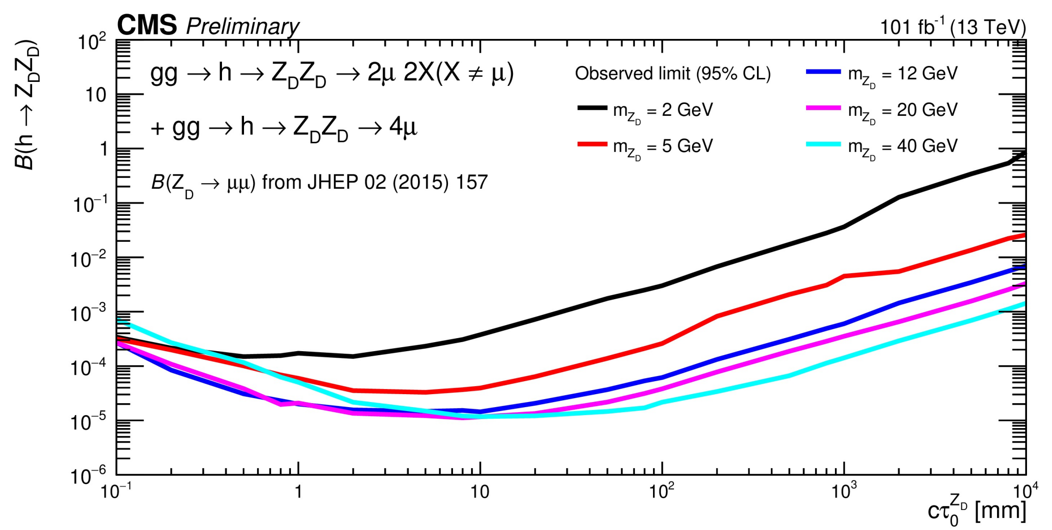
Displaced di-muons

CMS-PAS-EXO-20-014

- Fit to dimuon mass distr.
  - known resonances mass ranges excluded from search







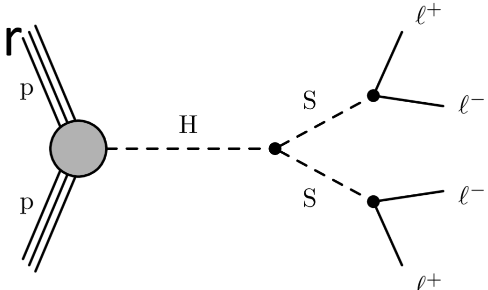
$0.5\ \text{GeV} \leq m(Z_D) \leq 50\ \text{GeV}$
$0.1\ \text{mm} \leq c\tau_0(Z_D) \lesssim 1000\ \text{mm}$

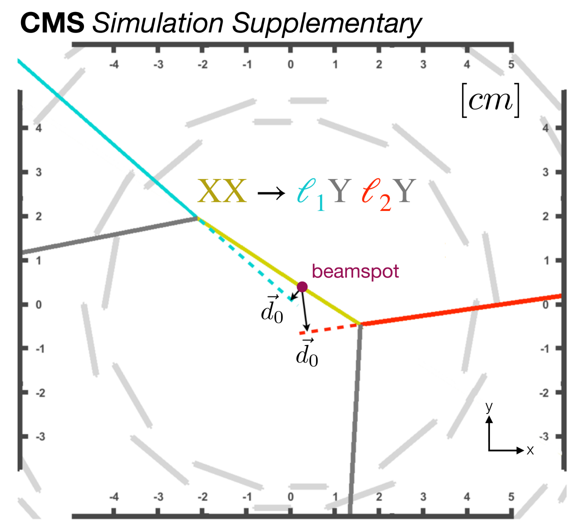
See also ATLAS result: JHEP 06 (2018) 166

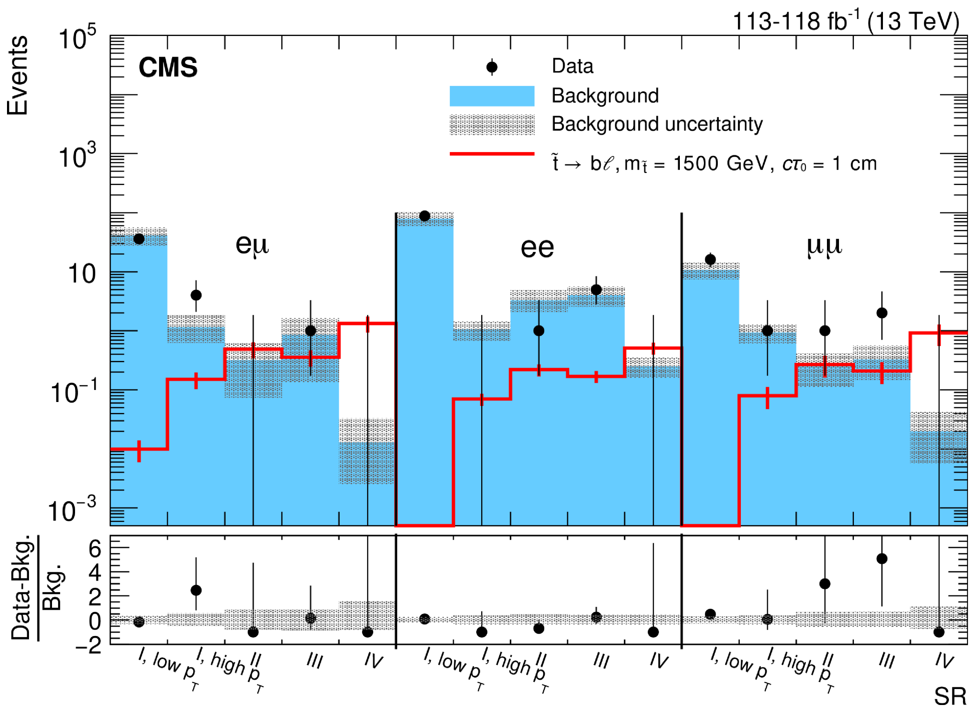
Displaced leptons

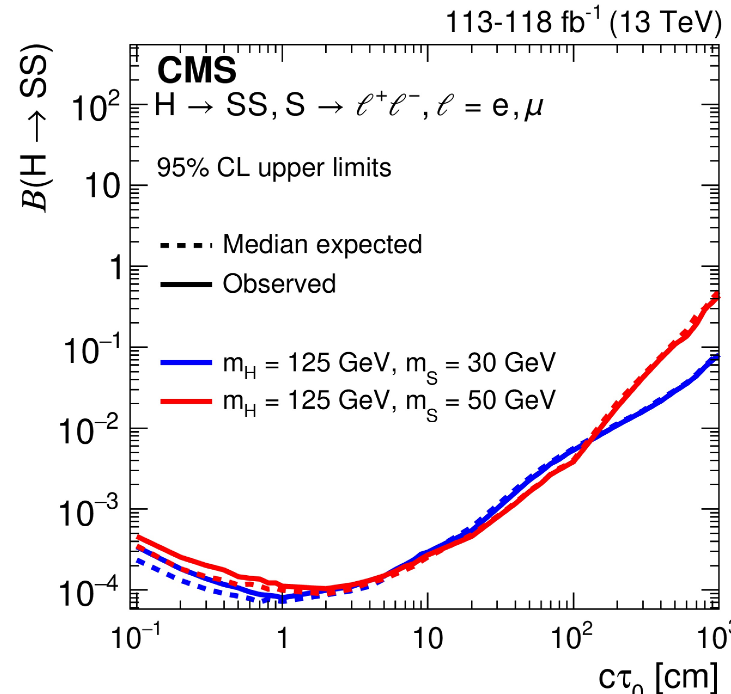
- Inclusive search for displaced leptons, w/o requiring a common vertex and look for eμ, ee, μμ final states where both leptons have large transverse impact parameter

[arXiv:2110.04809]



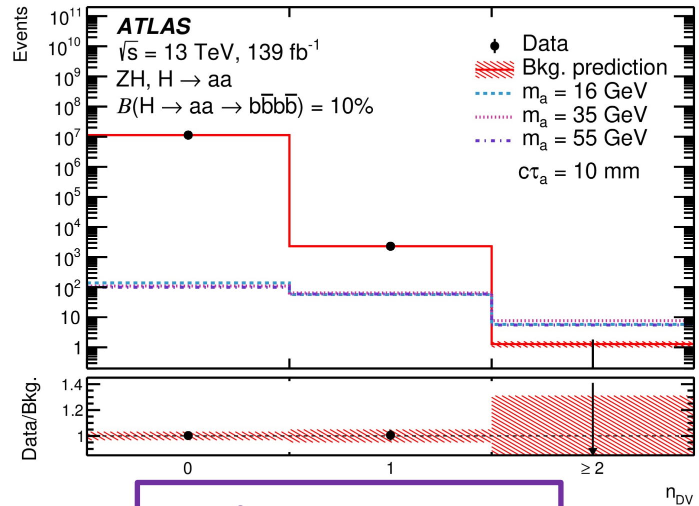






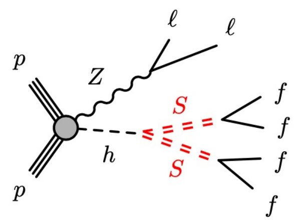
Displaced jets

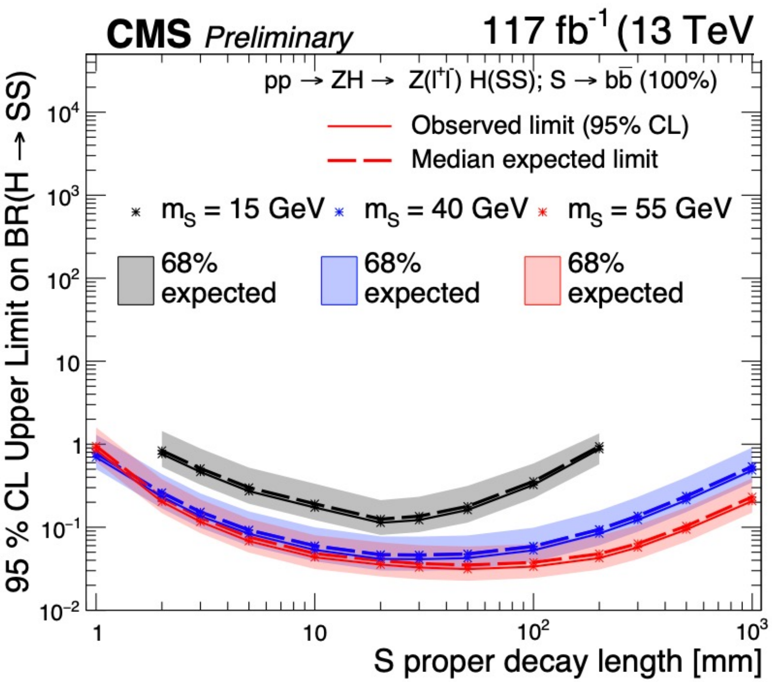
- Prompt dilepton (trigger) and displaced jet final state associated production
  - Enables access to low p_T LLP's jets
- Displaced jet tagging relying on tracking detector info: tracks' IP, PV-association…

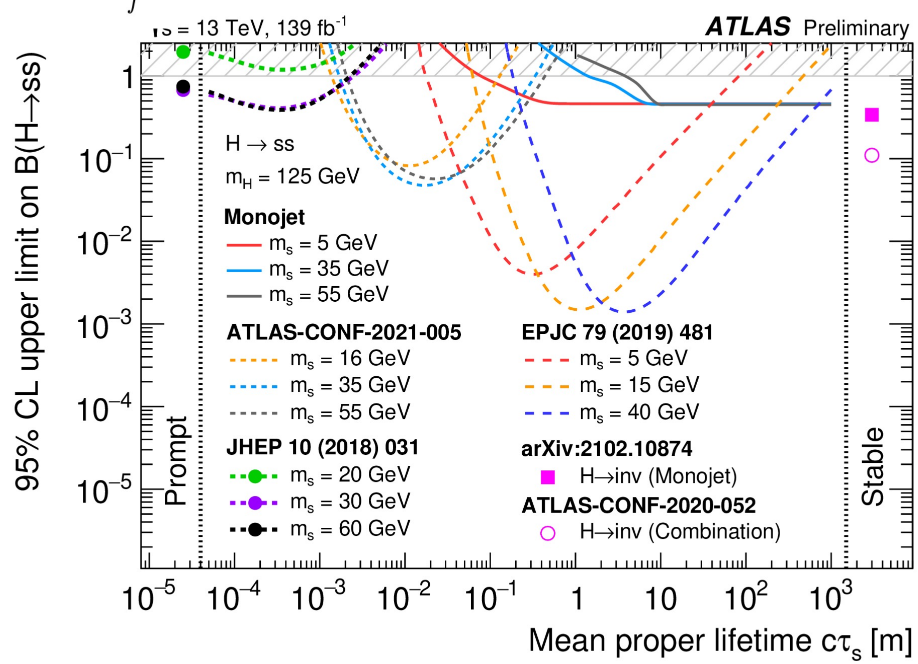


arXiv:2107.06092

CMS-PAS-EXO-20-003

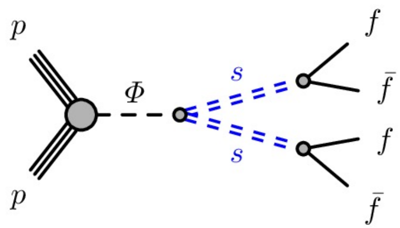


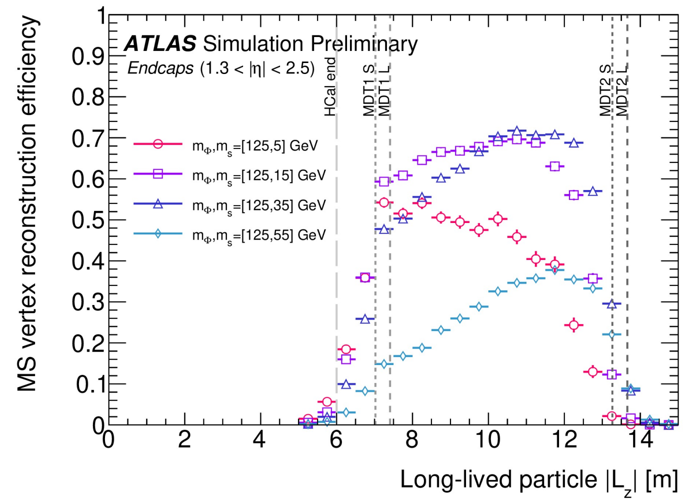




H->ss->4 jets

- LLPs may decay to jets far from the interaction point (IP)

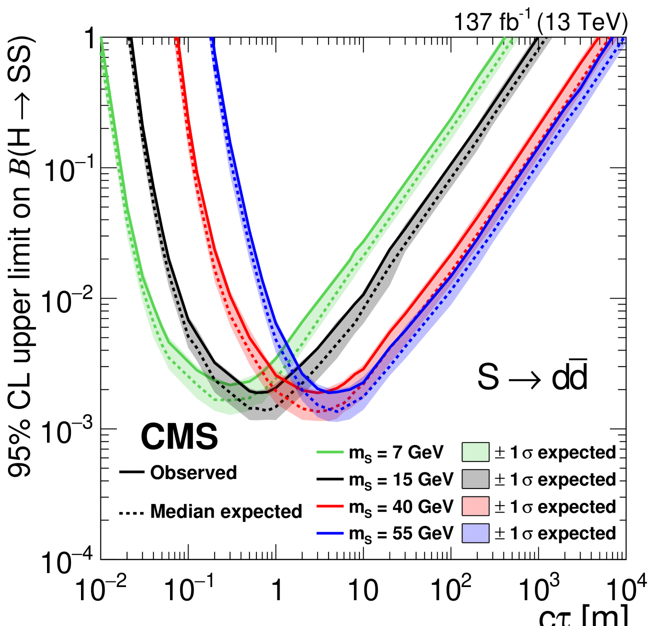




- Can use the muon system like a sampling calorimeter

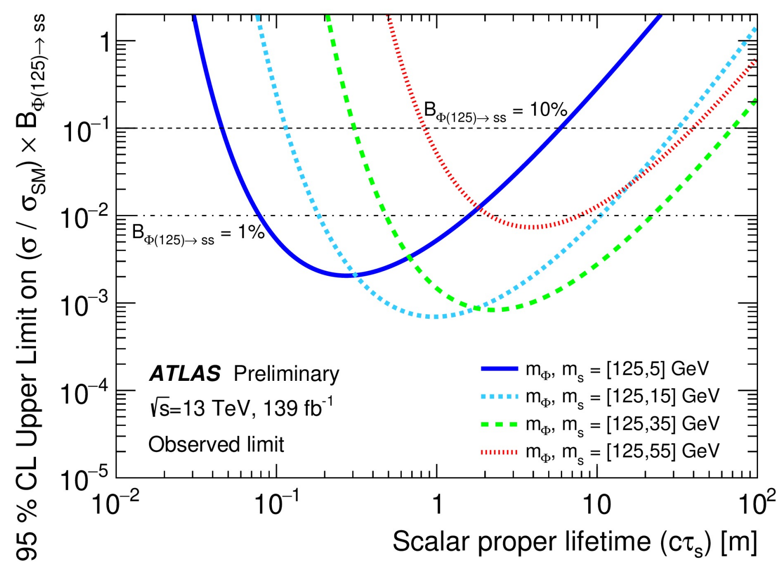
Use clusters in muon system

arXiv:2107.04838



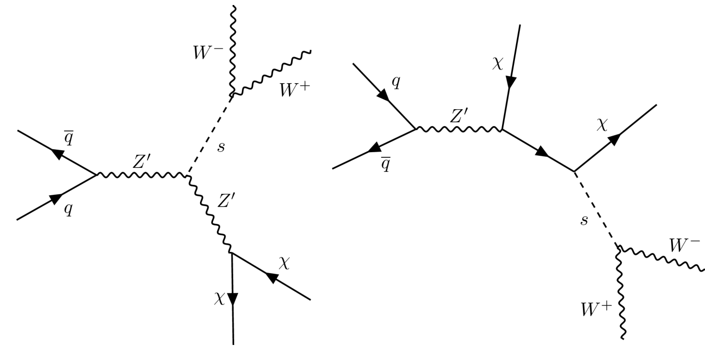
ATLAS-CONF-2021-032

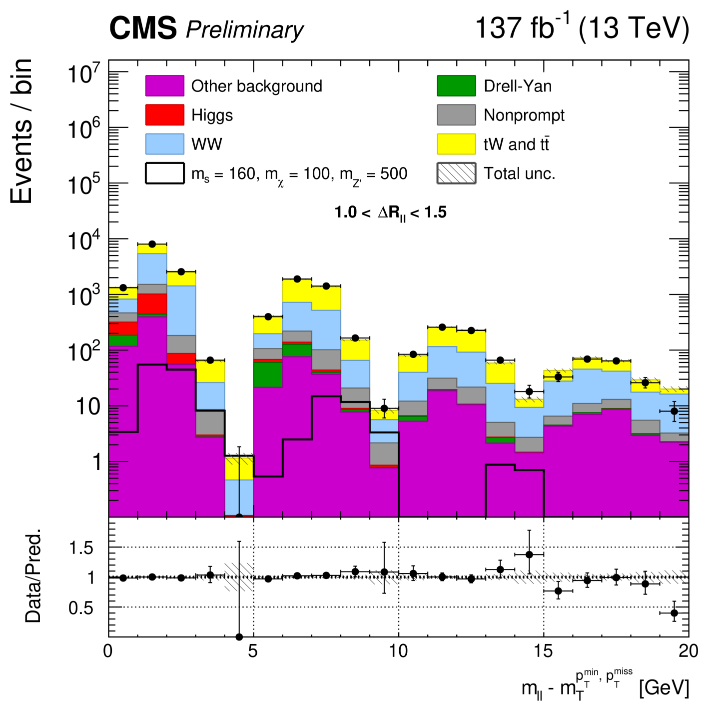
Standalone vertex finding in muon system



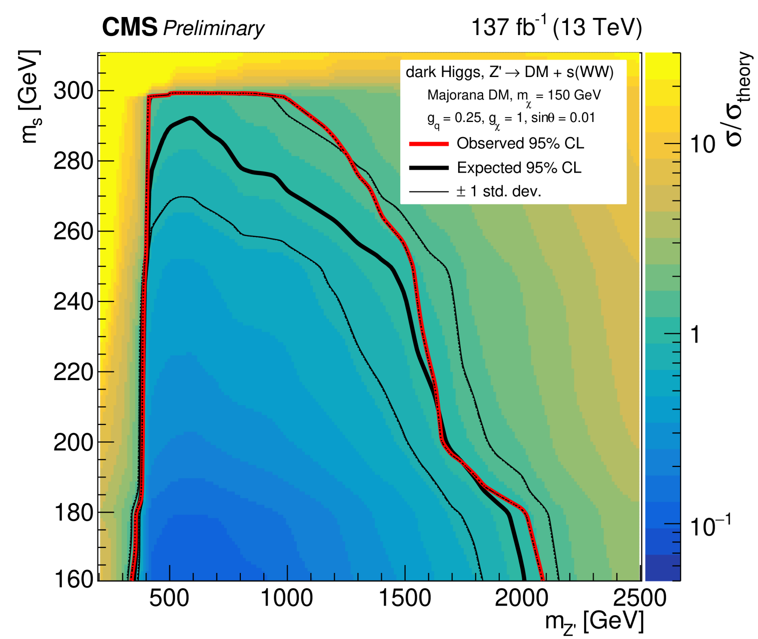
Dark Higgs → W^+W^-

- Majorana DM particle under a new U(1) local gauge symmetry, which yields a new physical dark Higgs boson s singlet and an additional massive spin-1 vector boson Z’
  - WW decay mode dominates for s > 160 GeV
  - Signal extraction: fit to ΔR_{ll}, m_{ll} , and $m_T(l_{min}$, p_T^{miss})





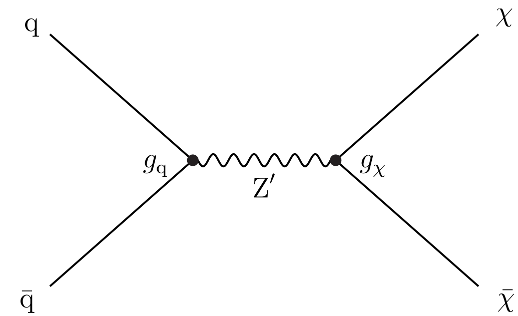
CMS-PAS-EXO-20-013



See also ATLAS result for s->WW and ZZ: Phys. Rev. Lett. 126 (2021) 121802

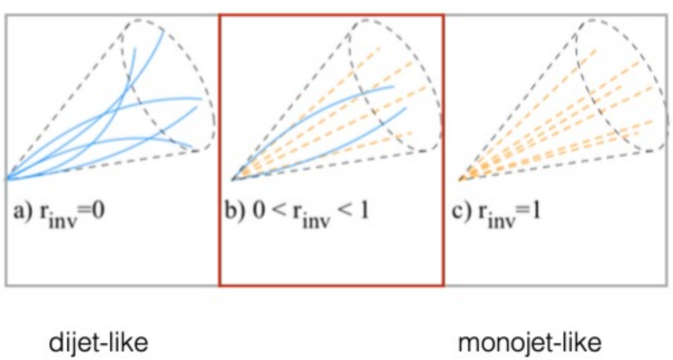
Dark Showers

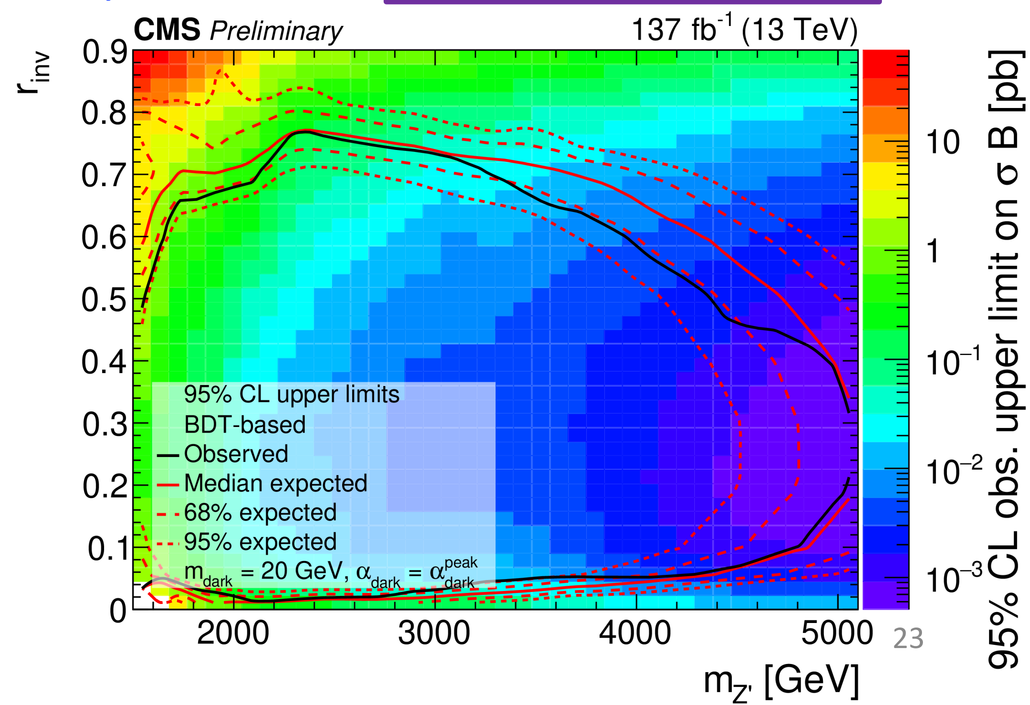
- First collider search for resonant production of DM from a strongly-coupled hidden sector
- Benchmark: hidden sector coupling to the SM via a heavy leptophobic Z’ mediator arising from a broken U(1) symmetry
- Signature: two “semi-visible” jets (contain both visible matter and invisible DM), one aligned with MET



CMS-PAS-EXO-19-020

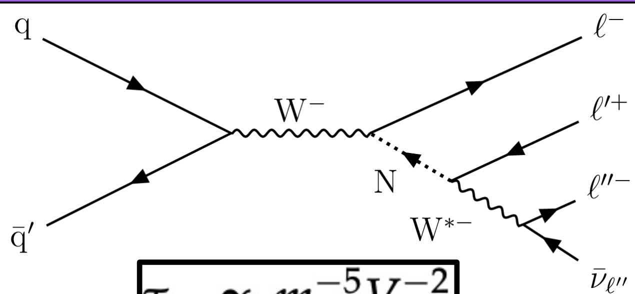
$$r_{inv} = \left\langle \frac{\textit{N stable dark hadrons}}{\textit{N dark hadrons}} \right\rangle$$



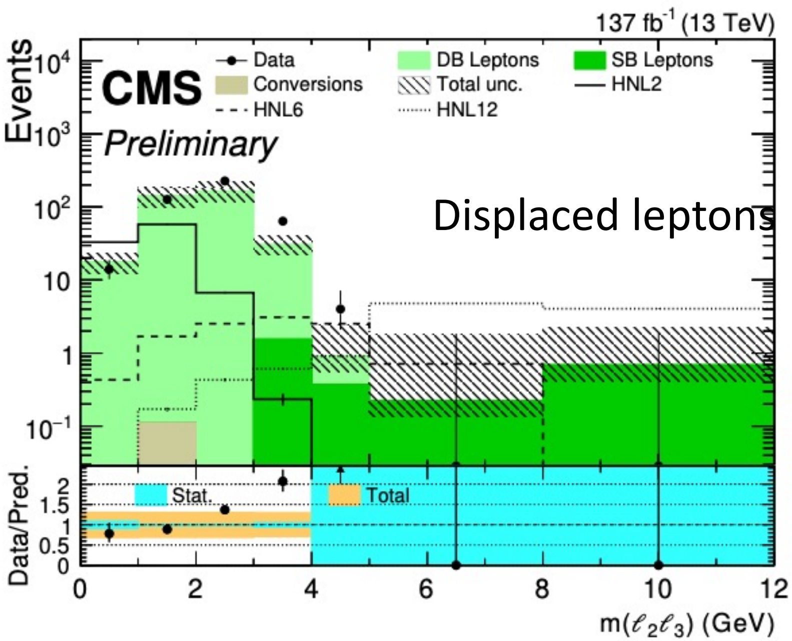


Heavy Neutral Leptons

- HNLs can be produced at the LHC through mixing with SM neutrinos
- For small values of the HNL mass (< 20 GeV) and V_{Nl}, decay length can be large enough to produce a resolved secondary vertex
- Signature: 1 prompt lepton, 2 displaced leptons



$$\tau_N \propto m_N^{-5} V_{N\ell}^{-2}$$



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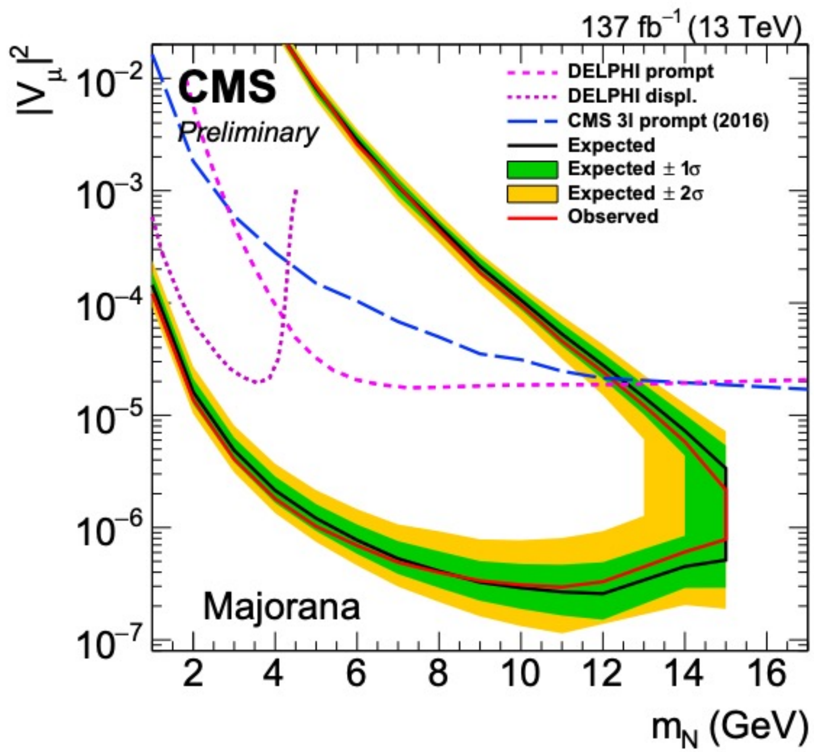
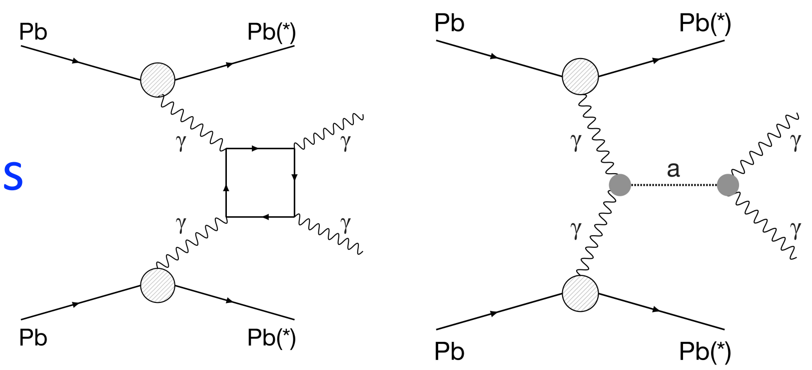


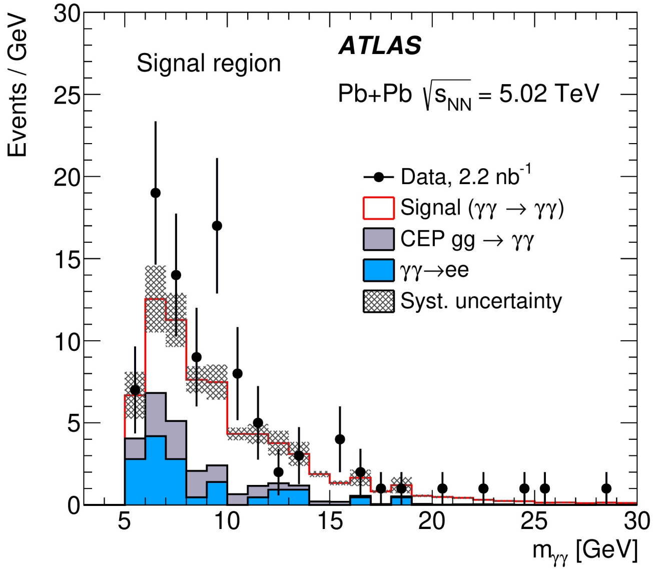
See also [LHCb result in W⁺ → μ⁺μ± jet decays]

Axion-like particles (ALPs)

- Relativistic Pb nuclei can be treated as a beam of quasi-real photons
- Photon flux associated with each nucleus scales with Z^2
  - Light-by-light scattering cross-section strongly enhanced w.r.t pp collisions
  - Look for narrow diphoton resonances in EM calo, little tracker activity



scattering may arise from SM QED box diagram OR an ALP



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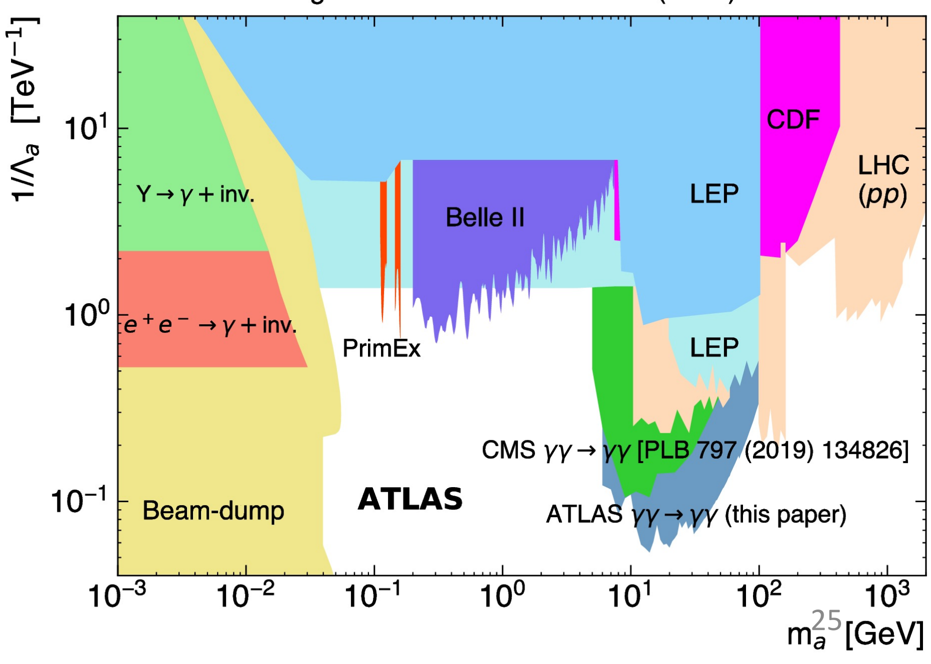
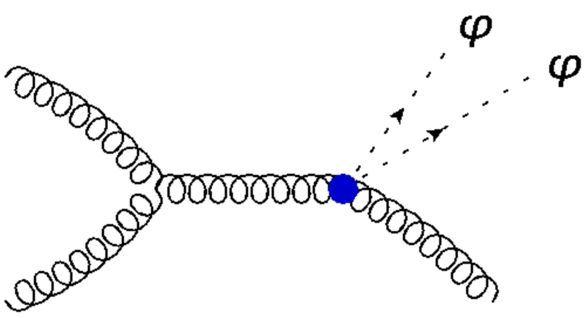
Existing constraints from JHEP 12 (2017) 044



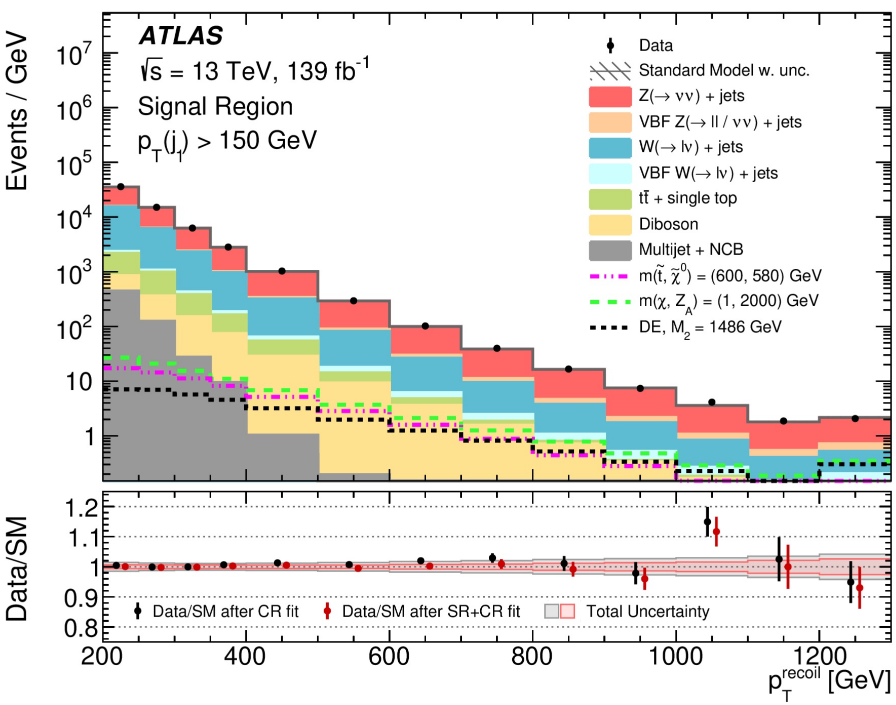
Dark Energy

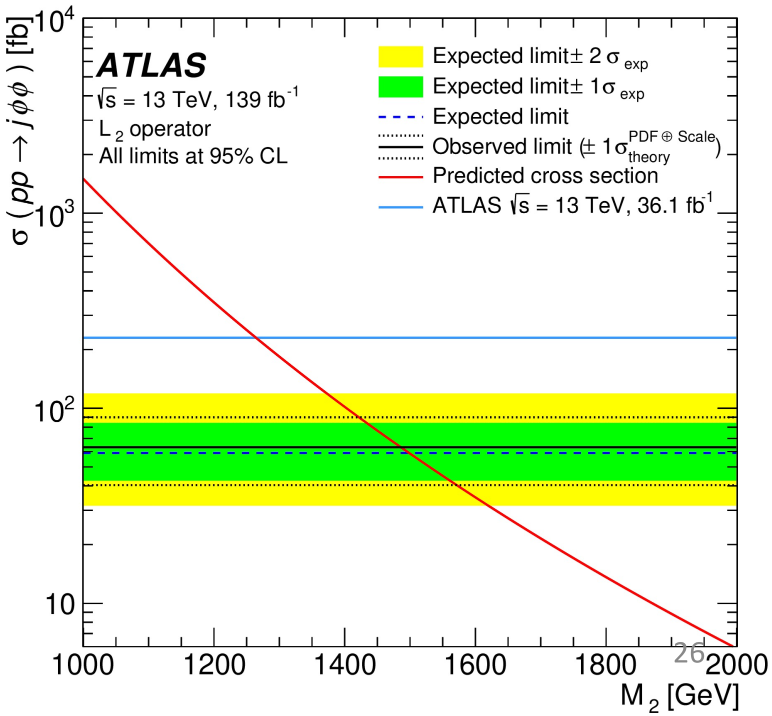
- Horndeski model in EFT: introduce dark-energy scalar fields, creating MET signature in colliders
- Interpret new mono-jet results and set 95% CL limits on suppression scale (M_2)
    - Also set limits on ALPs w/ coupling to gluons



Horndeski DE w/ m_ϕ = 0.1 GeV, c_2 = 1, c_i= 0 (i != 2)

PRD 103, 112006 (2021)



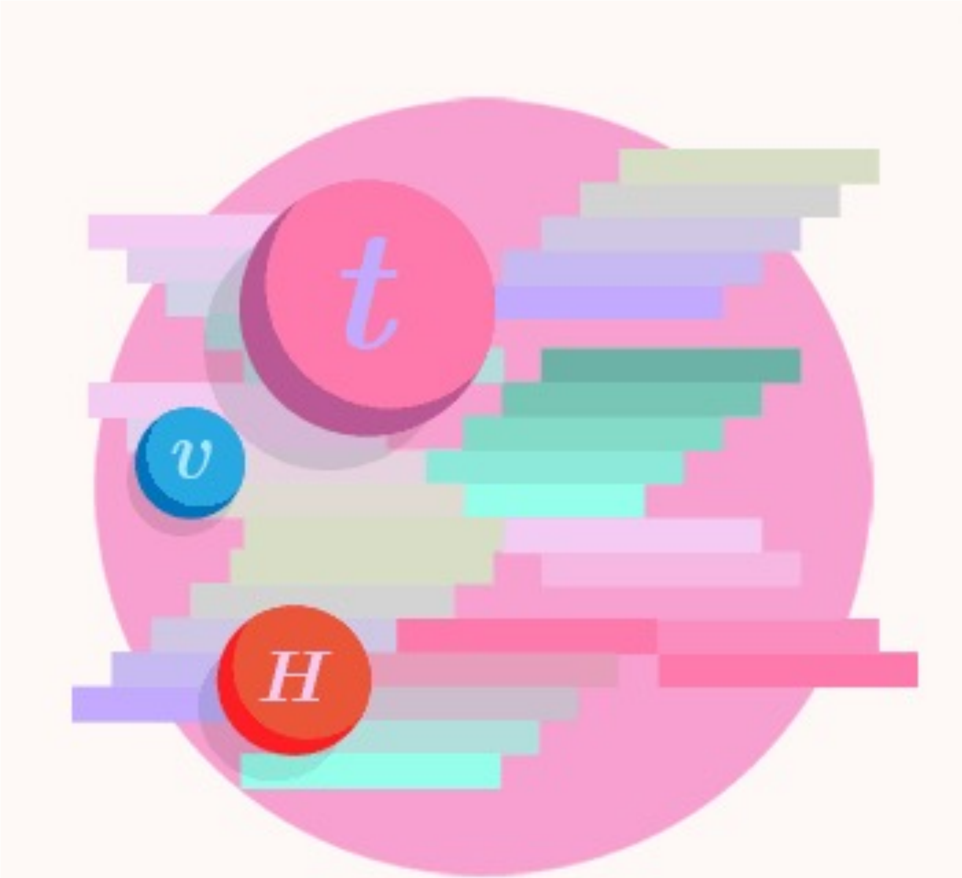


Summary & Conclusions

- The dark sector search program at the LHC is extensive and covers a diverse range of unconventional final states
- Huge amounts of BSM parameter space ruled out
- At the same time, innovative strategies for triggering, data-taking and analysis are providing access to previously unexplored territory!
- An exciting time to develop and implement new ideas
  - Go in directions where no one has gone before!
- <u>Run 3 will start next year and 95% of the total LHC data still to come (and be studied)!</u>
  - High luminosity LHC upgrades will provide improved sensitivity

Summary & Conclusions

And perhaps this voyage into the dark sector will shed light onto one of the biggest mysteries in particle physics and lead us to a hidden world of new particles



Credit: Symmetry Magazine