Search for Dark Matter and hidden sectors in CMS

TeVPA2023: TeV Particle Astrophysics Conference,
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On behalf of CMS collaboration

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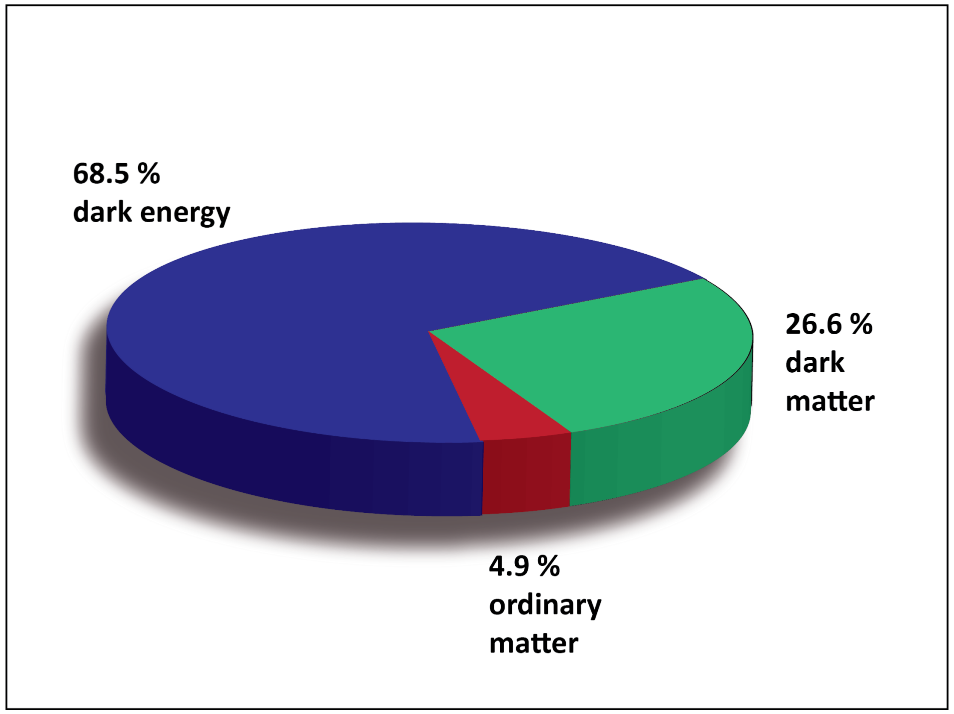
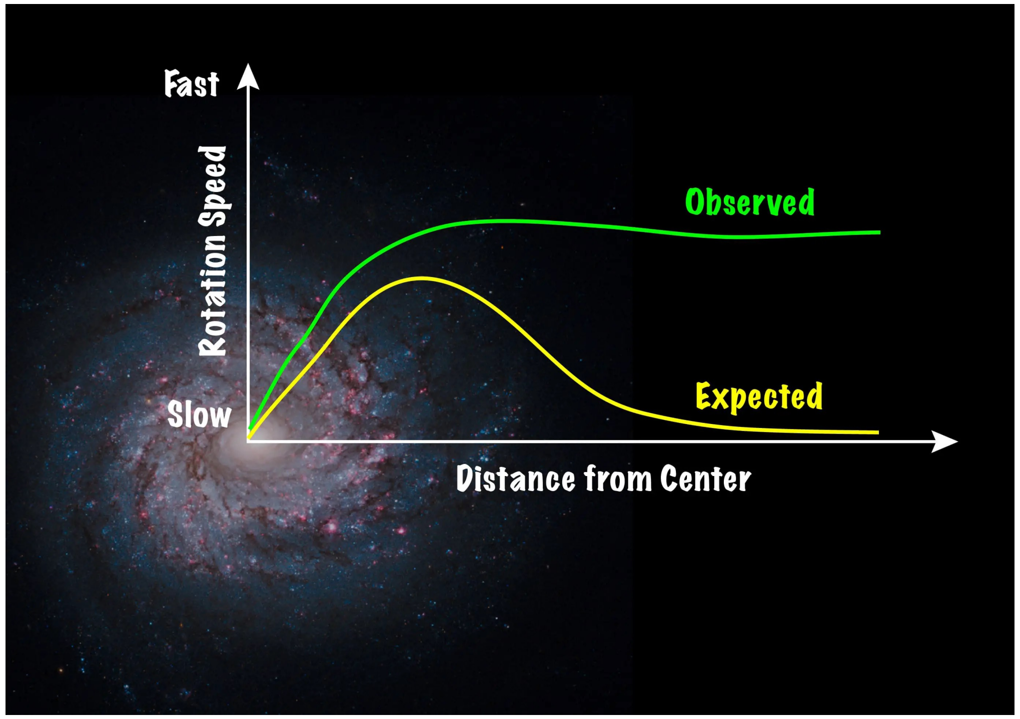
What is the Universe Made of?



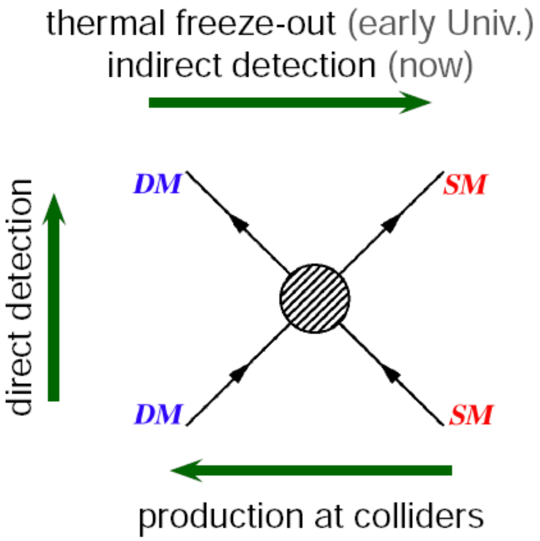
- Experiment Results:
  - Universe is not empty.
- Matter in the Universe:
  - Occupies less than 5% of the total universe.
- Unexplained 95%:
  - Majority of the universe's composition is unknown.
  - Referred to as "dark matter.”
  - Exists in space, yet its nature remains a mystery.

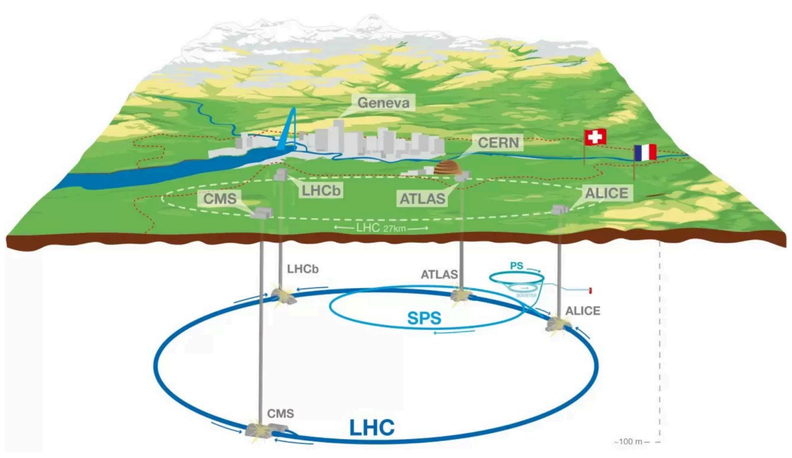
- Strong Evidence for Dark Matter:
  - We have convincing proof from studying the sky and how things are pulled by gravity.
- Galaxy Spin Mystery:
  - Galaxies spin in a way that suggests something we can't see (Dark Matter) is affecting them.
- Bending of Light:
  - Light from faraway objects is bent because of an invisible force (Dark Matter).
- Clues in Cosmic Background:
  - Patterns in the early universe's radiation tell us about Dark Matter's role in shaping the cosmos.



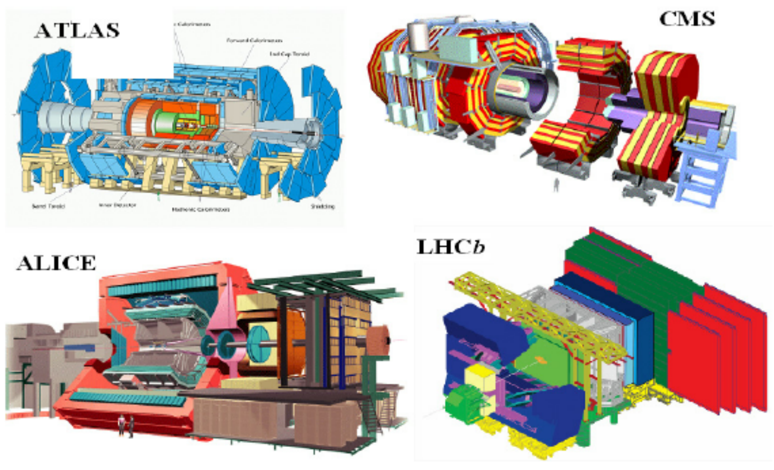
What could dark matter be?

- **Different ways to solve the puzzle:**
  - Scientists use various methods to uncover the secrets of Dark Matter (DM).
- Indirect Detection (ID):
  - This method looks for clues in the particles produced when DM particles collide or annihilate, as seen in experiments like HESS and IceCube.
- Direct Detection (DD):
  - DD involves looking for signs of DM by detecting the tiny impacts it has when it interacts with atomic nuclei. Examples include XENON and SNOLAB experiments.
- Collider Experiments:
  - At places like the Large Hadron Collider (LHC), scientists recreate high-energy conditions to produce DM particles directly.
  - This approach allows researchers to investigate how DM is created.
  - It complements DD and ID methods in the search for DM.



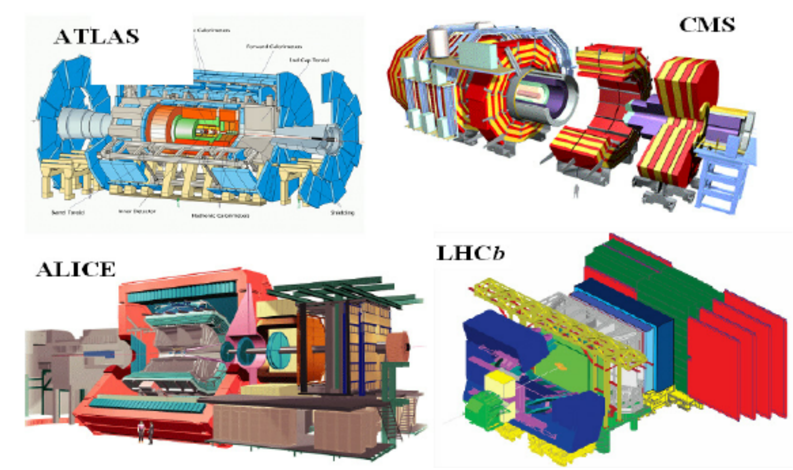


Large Hadron Collider ...



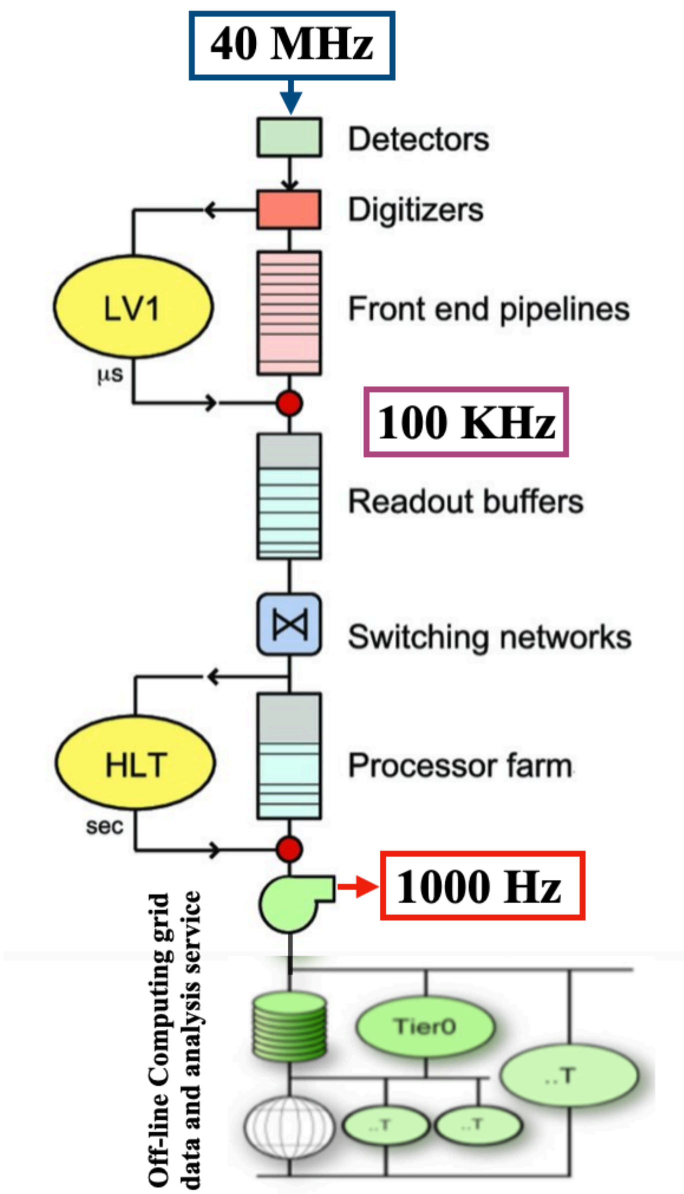
Large Hadron Collider

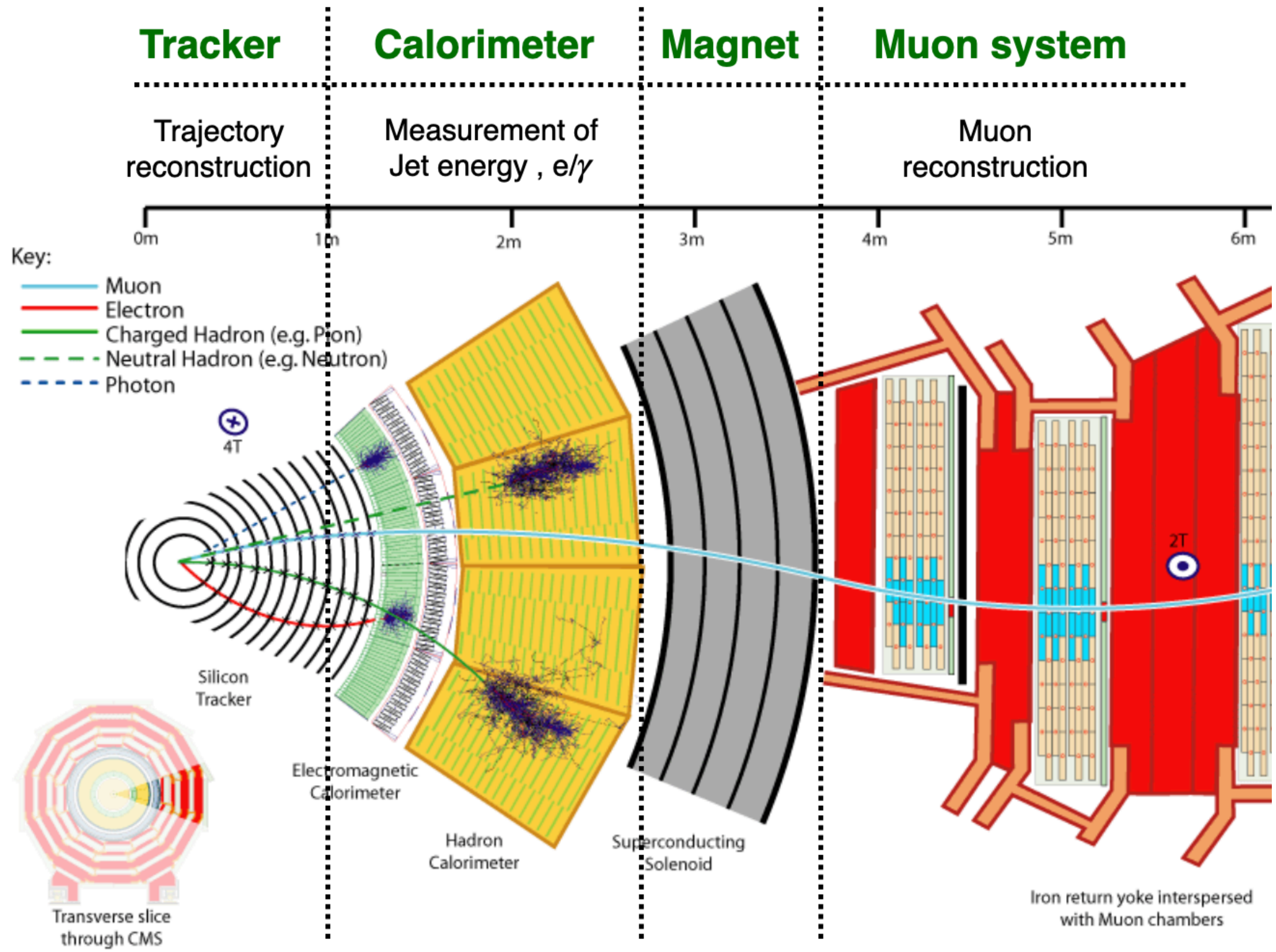
- The Large Hadron Collider (LHC) at CERN is the largest and most powerful particle accelerator ever built.
- Particle collisions occur where the beams interact, at four specific locations where the giant detectors Alice, Atlas, CMS, and LHCb are installed.
- The LHC is a Discovery Machine, run at 7/8/13/13.6 TeV started in 2008.
- Primary physics targets
  - ☑ Origin of mass
  - ☐ Nature of Dark Matter
  - ☐ Understanding space time
  - ☐ Matter versus antimatter
  - ☐ Primordial plasma
  - ☐ Exotica Particles
- LHC is ~ 100m underground
- LHC is 27 Km long
- LHC has ~ 1200 magnets 8.3 Tesla
- LHC 40 million proton-proton collision per second



Compact Muon Solenoid (CMS)

CMS acts as a giant, high-speed camera, taking 3D "images" of the collision for further analysis.



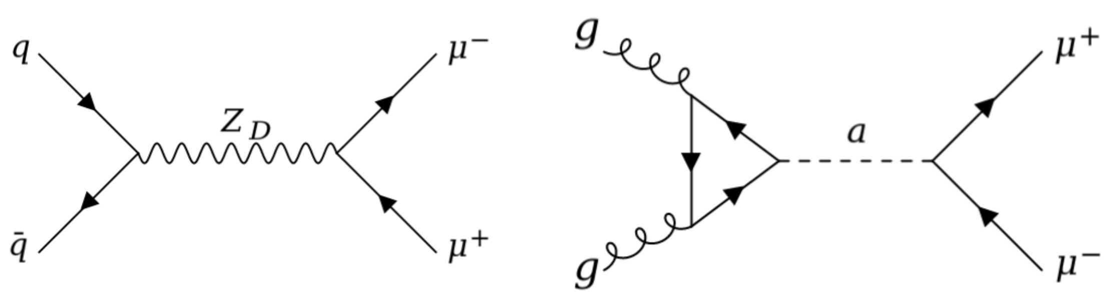


The layout of the CMS trigger design :

- ☑ Level 1 based on hardware trigger 40 MHz to 100 KHz
- ☑ HLT based on software trigger 100 KHz to 1000 Hz

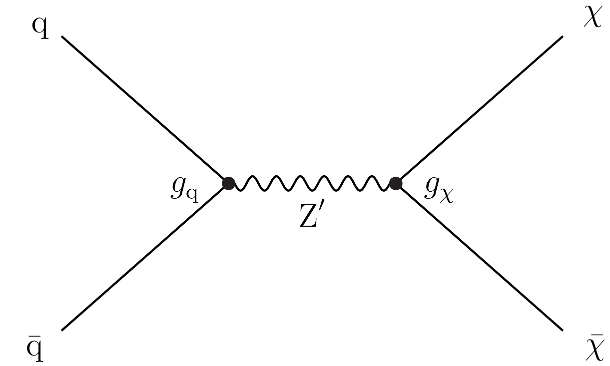
CMS Dark Matter Searches

Dark Photon and 2HDM+S



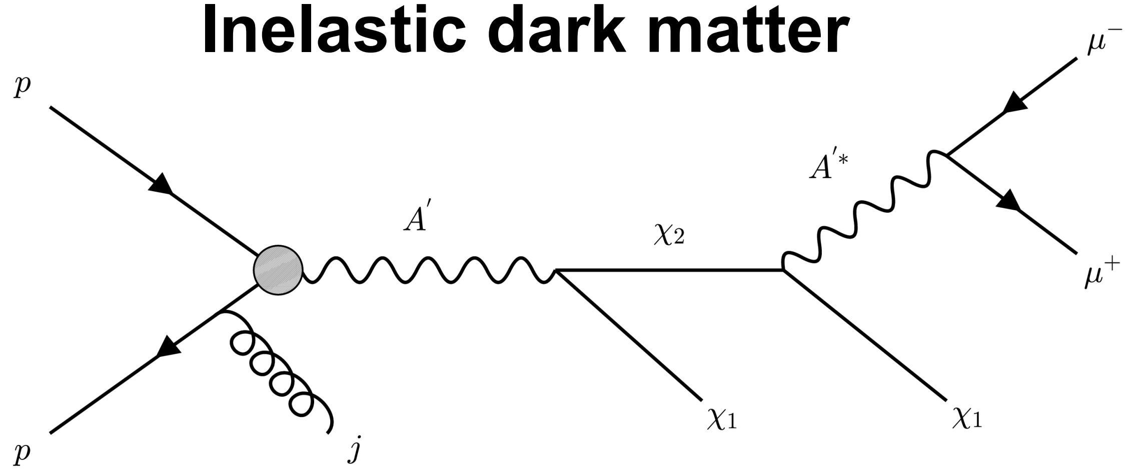
- Dark photon (Z_D) → New U(1)D gauge field that mixes with the SM hypercharge gauge field U(1)Y field.
- 2HDM+S → coupling of the light pseudoscalar boson to SM particles through its mixing with the Higgs fields.
- Such a particle could act as a portal between Standard Model fields and unknown dark sectors.

Semi-visible Jets



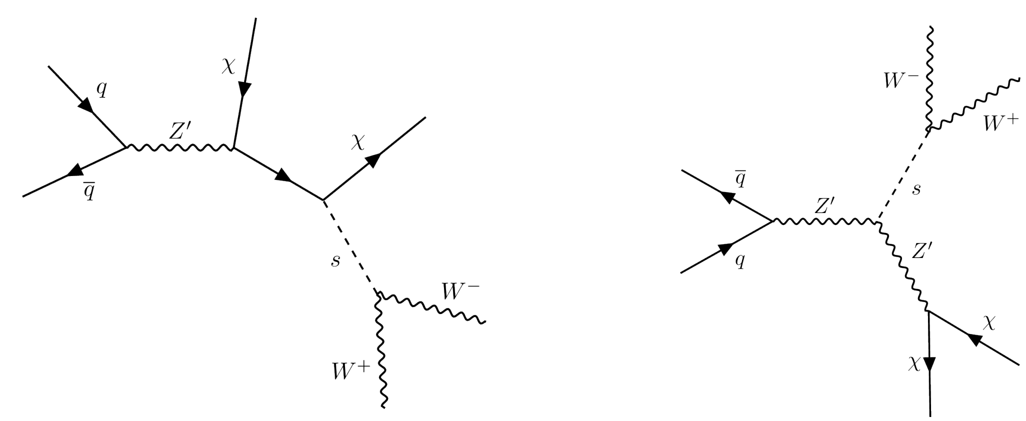
- SM-DM boson mediator:
- Spin-0: Scalar (S) or pseudo-scalar (a)
- Spin-1: Vector (V/Z') or axial- vector (A)
- Minimal set of parameters: m_χ , $m_{mediator}$, g_χ , g_q
- Final state is a mixture of visible and invisible particles

Inelastic dark matter



- Two dark mater states close in mass: χ_1 and χ_2
- Kinetic mixing between photon and dark photon: A', ϵ
- Inelastic (off-diagonal) coupling between χ_1 and χ_2

Dark Higgs

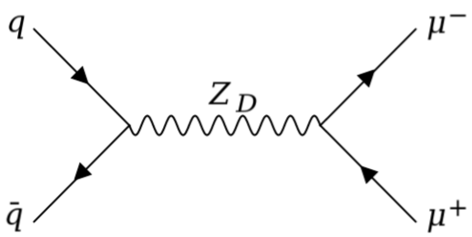


- More complete models involving a dark Higgs.
- The dark Higgs mass is considered to be above the W^+W^- mass threshold.
- First dark Higgs attempt at CMS

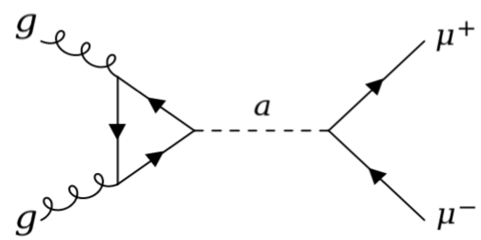
Dark Photon and 2HDM+S

CMS: CMS-PAS-EXO-21-005

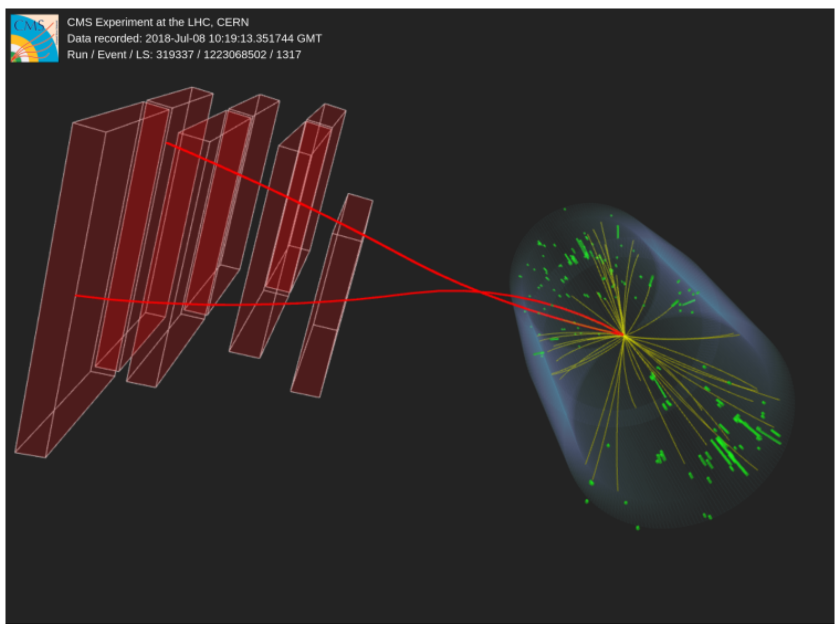
Dark Photon Z_D



Light Beyond- SM Pseudoscalar Boson

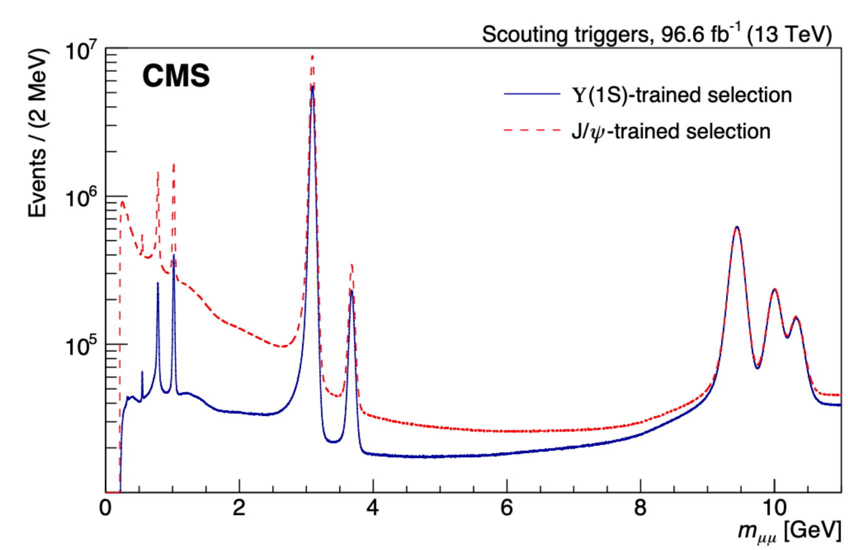


Low-mass dimuon events displays



- Searching for a light (1-8 GeV) BSM mediator decaying into a pair of opposite sign muons, i.e., looking for narrow peaks in the dimuon mass spectrum within the ranges of 1.1–2.6 GeV and 4.2–7.9 GeV.
- Main Backgrounds :
  - DY production of dimuon pairs in the low $m_{\mu\mu}$ region (1 < $m_{\mu\mu}$ < 10 GeV)
  - Resonant dimuon production via J/ψ, Υ(1S).
  - D^0 mesons decay resonances → pions and kaons misreconstructed as muons
- Trigger → CMS high-rate data scouting trigger records events with two muons with p_T > 3 GeV
- Event selections :
  - At least 2 OS muons at p_T > 4 GeV, |η| < 1.9
    - (The restriction on η is imposed to ensure optimal dimuon mass resolution without incurring a significant loss in acceptance.)
  - Transverse primary vertex displacement (L) cut:
    - |PrimaryVertex - BeamSpot| L_{xy}< 0.2 cm (0.015 cm → dark photon)
  - Boosted signal cuts (optimized for 2HDM+S model)
    - Single muon p_T > 5 GeV
    - Pair p_T > 20(35) GeV for $m_{\mu\mu}$ less than(greater than) 4 GeV

- Main Discriminator :
  - Muons should passed a muon identification based on MVA techniques (BDT).
  - Two MVA discriminants are optimized to each mass ranges.
  - MVAs inputs are : muon track quality, relative isolation, and vertex association.
  - Above 4 GeV, the Upsilon trained selection is used
  - Below 4 GeV, the J/ψ trained selection is used

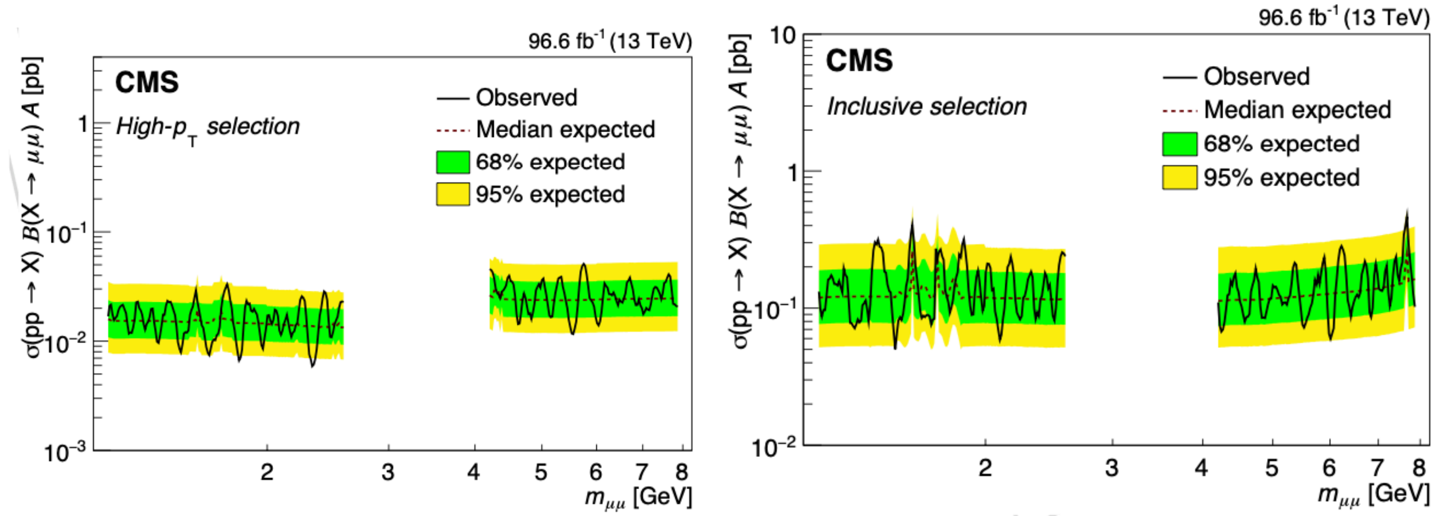


2HDM+S → Two Higgs doublet model with an extra complex scalar singlet.

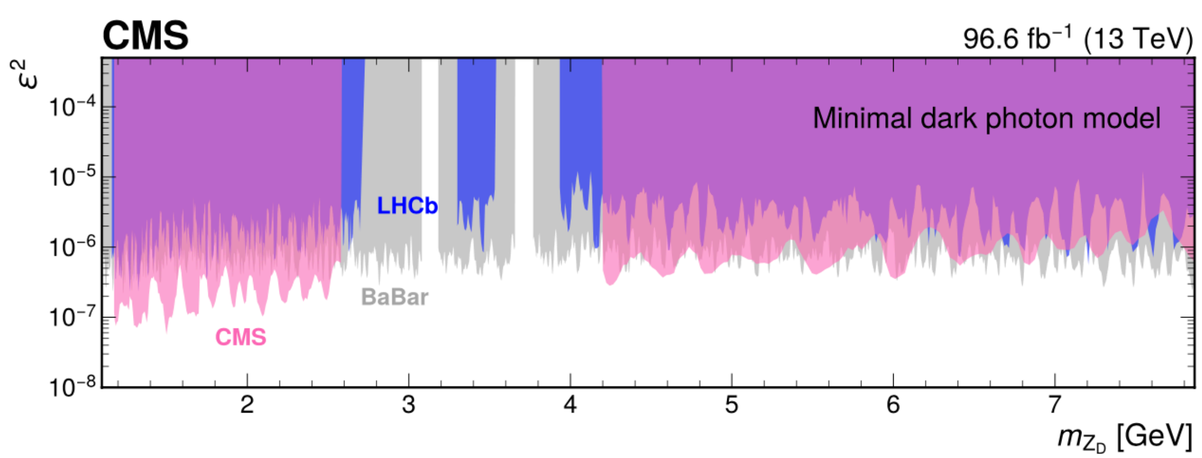
Dark Photon and 2HDM+S

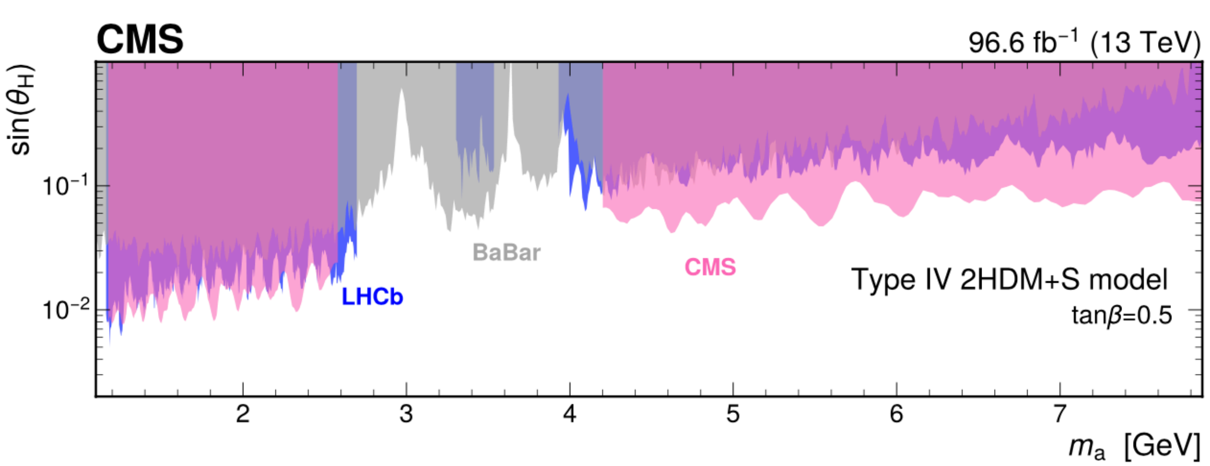
- The excess is observed in the high-pT selection at 2.42 GeV
- local significance of 2.6σ and a global significance of 0.6σ.
- This coincides with a 3.1σ excess observed by LHCb at 2.42 GeV in a comparable analysis.
- The upward deviations in the expected limits below 2 GeV are due to the peaking background associated with D^0 meson decays. (inclusive selection)

Boosted Selection Inclusive Selection



Exclude the regions around the J/ψ, $\psi(2S)$, and $\Upsilon(1S)$ resonances.





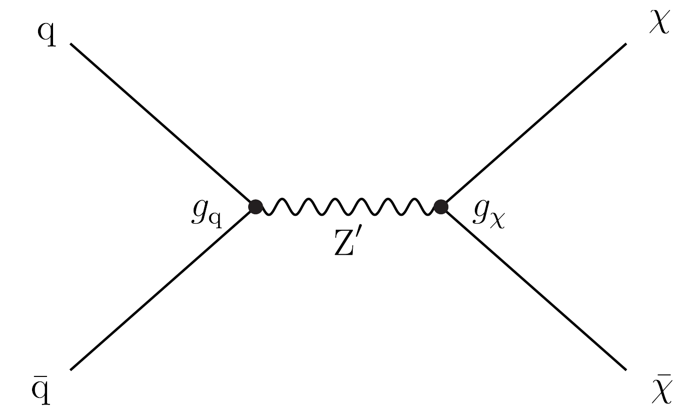
- ☑ Increased sensitivity at lower masses due to higher DY production cross-section at lower energy scales.
- ☑ The low-mass limits region are competitive with recently LHCb results.

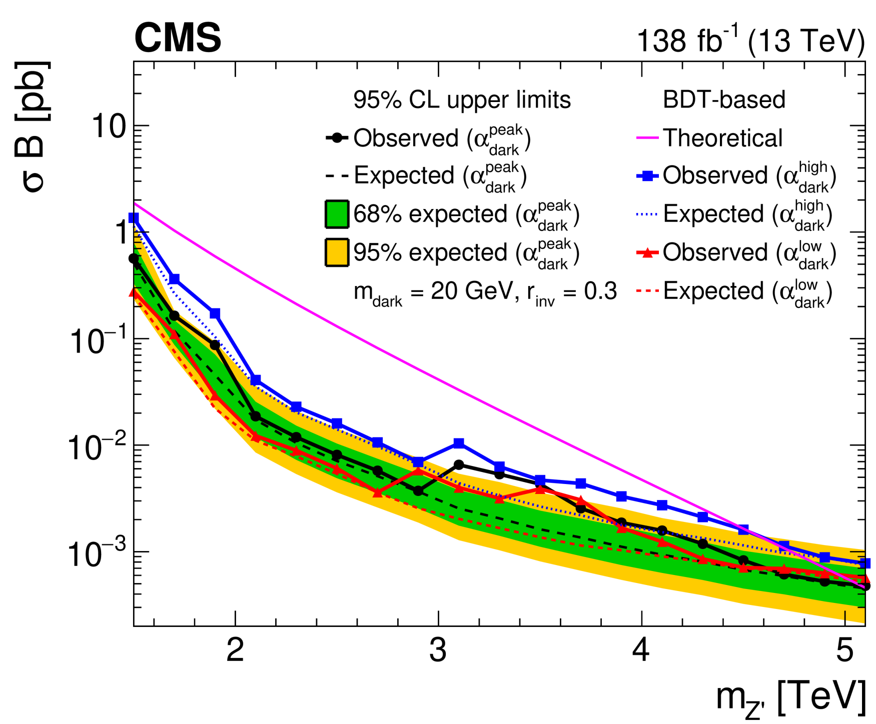
Semi-visible Jets

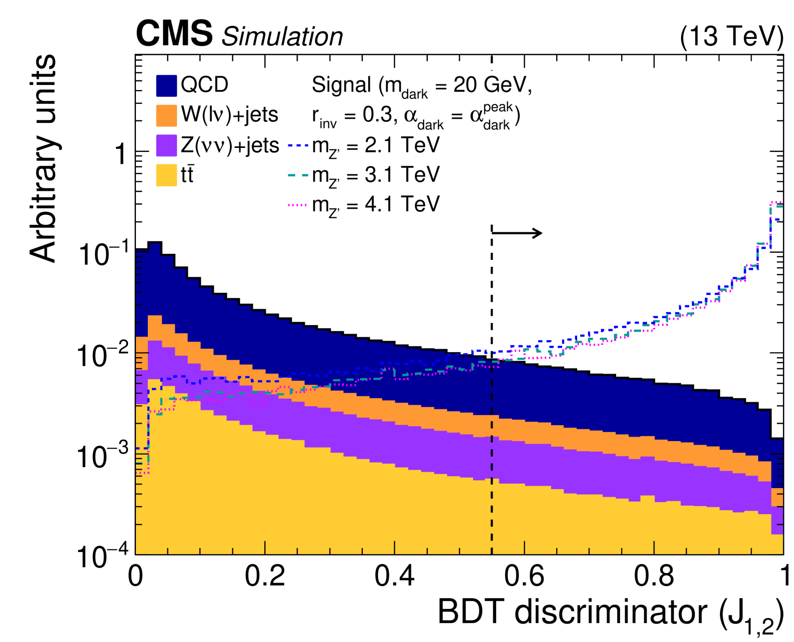
CMS: JHEP 06 (2022) 156

Dark sector strongly-interaction → Dark quarks form bound dark hadron states

- Dark sector consists of various dark quark types ($\chi_1, \chi_2, \ldots$)
- Dark quarks combine to create dark hadrons
- Dark hadrons can be stable or unstable
- Unstable dark hadrons quickly decay into SM (Standard Model) quarks
- Stable dark hadrons are potential Dark Matter (DM) candidates and leaves the detector without interacting
- The final state therefore are "semivisible" jets (SVJ), consisting of a mixture of visible and invisible particles
- Z' boson mediator effective parameters cross section, $m_{Z'}$, m_{dark}, α_{dark}, and r_{inv}
  - α_{dark} coupling strength of the dark QCD force.
  - Fraction stable $r_{\text{inv}} = N\text{stable}/(N\text{stable} + N\text{unstable})$





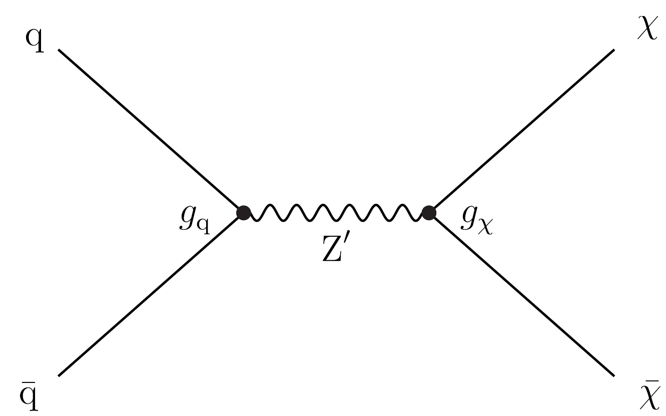


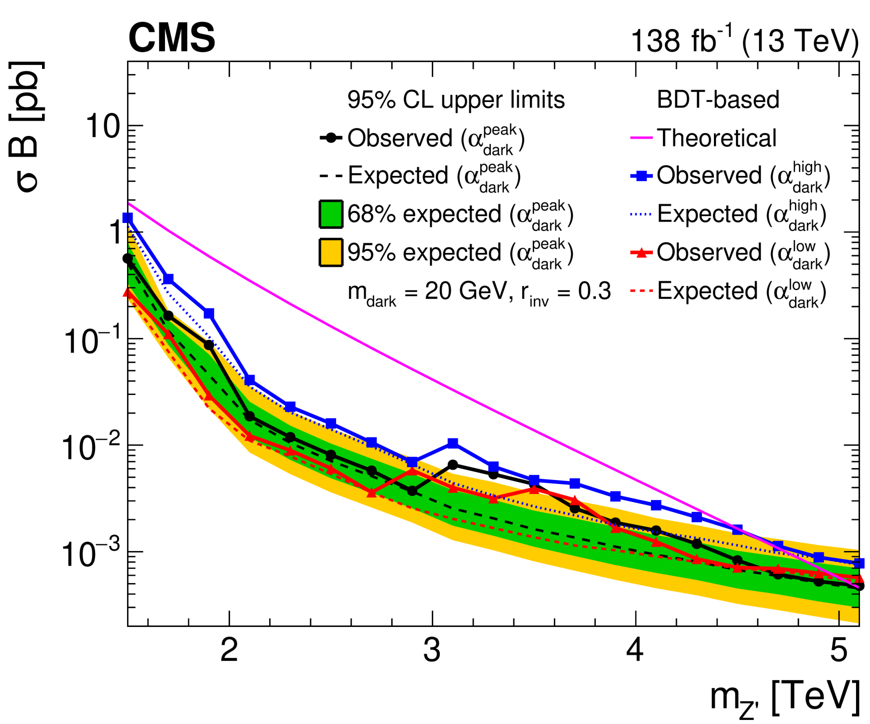
Semi-visible Jets

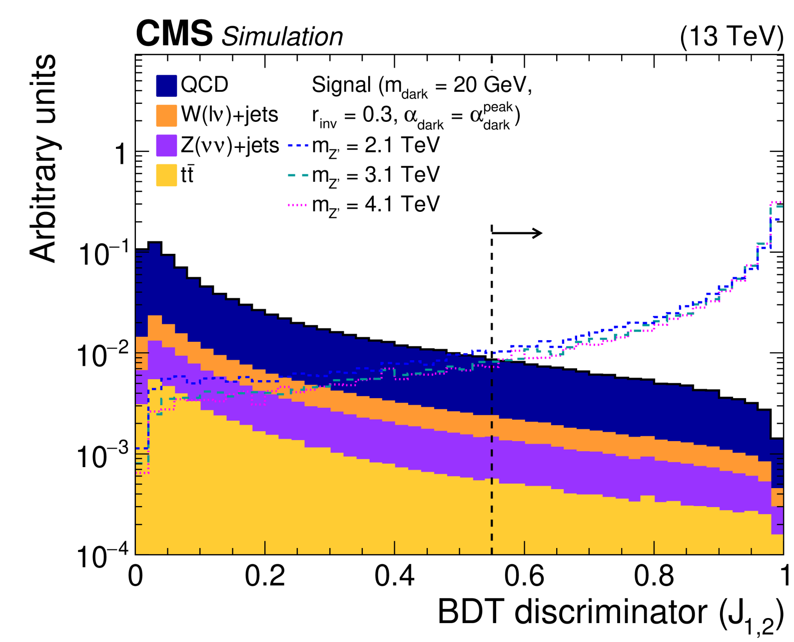
CMS: JHEP 06 (2022) 156

Dark sector strongly-interaction → Dark quarks form bound dark hadron states

- Experimental signature : Pair of jets along with the E_T^{miss} that is aligned with one of the jets.
  (Previous searches for jets+ E_T^{miss} not sensitive)
- Trigger : on jet p_T or on the H_T , $H_T = \sum (p_{T > 30\ \mathrm{GeV},\ |\eta| < 3.0})$ (Jet p_T)
- Leptons : Veto on (μ or e)
- Sensitive variables: Di-jet transverse mass m_T, E_T^{miss} and $R_T = P_T^{miss} / m_T$
- Dominant background : QCD multi-jets, rejected by R_T > 0.15 and this reject t-channel as well
- Using BDT for semivisible jet identification improves the mediator mass exclusion to 5.1 TeV.







- Excluding 1.5 ≤ $m_{Z'}$ ≤ 5 TeV for r_{inv}= 0.3
- Excluding 0.01 ≤ r_{inv} ≤ 0.77 for m_{dark} = 20 GeV
- Small excess around $m_{Z'}$ = 3.5 TeV with no real significance (~ 2σ local)

Inelastic dark matter

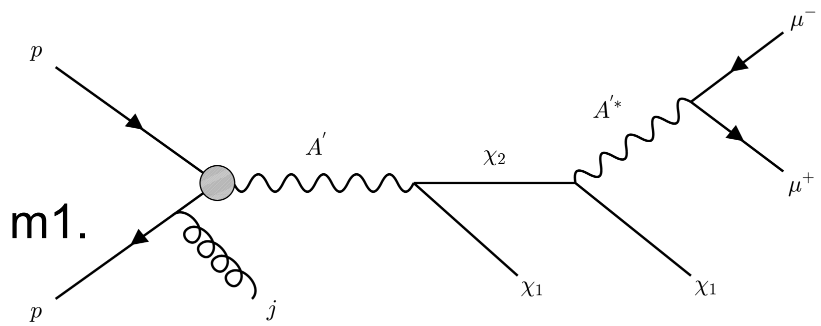
CMS: CMS-PAS-EXO-20-010

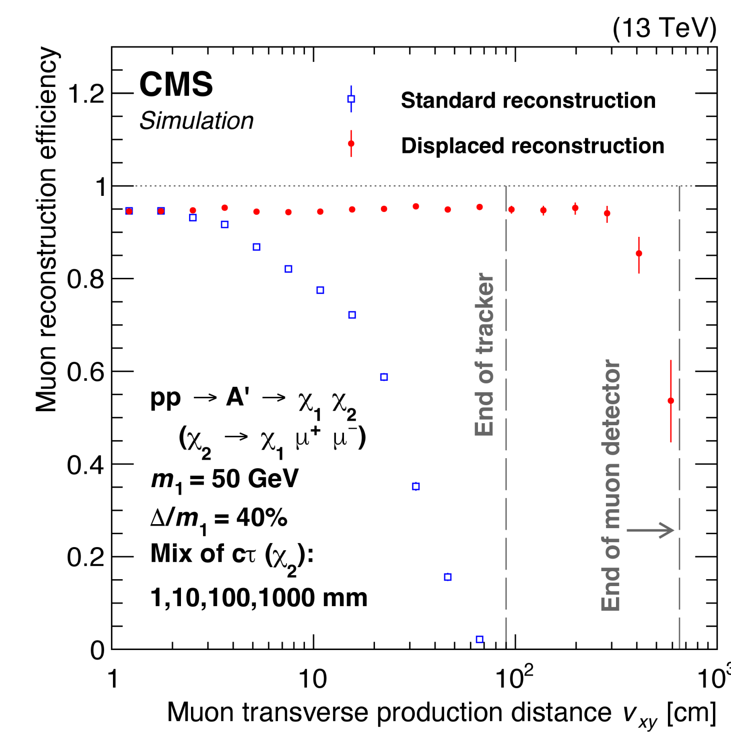
Search for dark matter using displaced muons for leverage

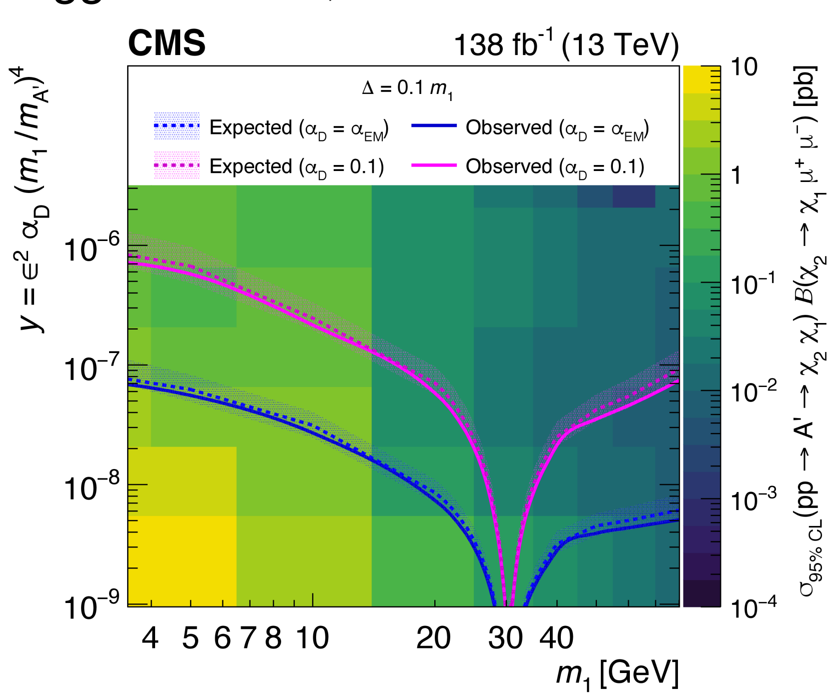
- The dark photon A′ promptly decays into two closely-massed states, χ_1 and χ_2.
- χ_1 (mass m1) remains stable and undetectable.
- χ_2 (mass m2) travels a distance before decaying

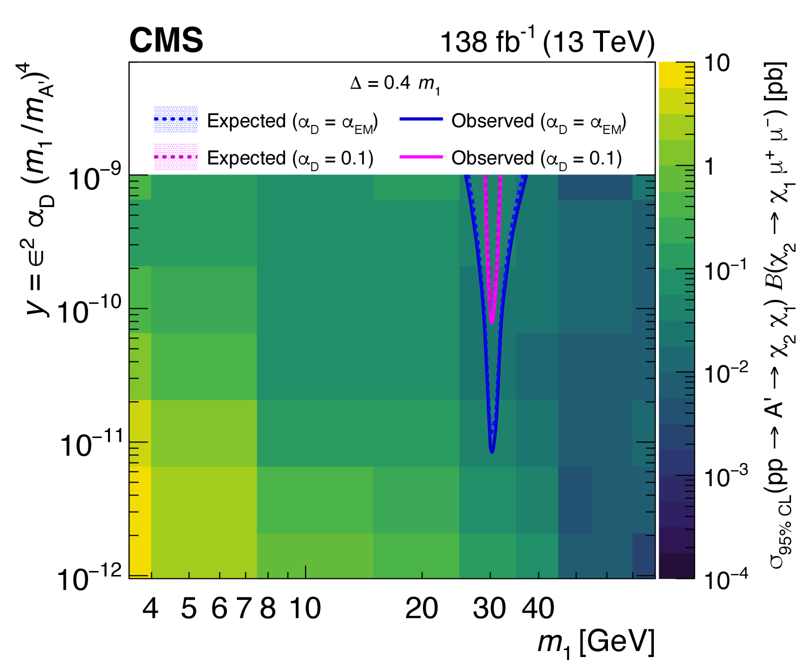
  into χ_1 and SM particles through an off-shell dark photon
- The mass difference (Δ) between χ_2 and χ_1 is relatively small, typically 10-40% of m1.
- The small mass difference results a "soft" decay products

  low transverse momentum (p_T < 15 GeV) and small angular separation.
- Experimental signature:
  - Pair of soft, displaced, collimated muons
  - Significant MET collimated with muons
  - Energetic recoiling jet opposite to DM system
- Trigger on MET, not soft muons









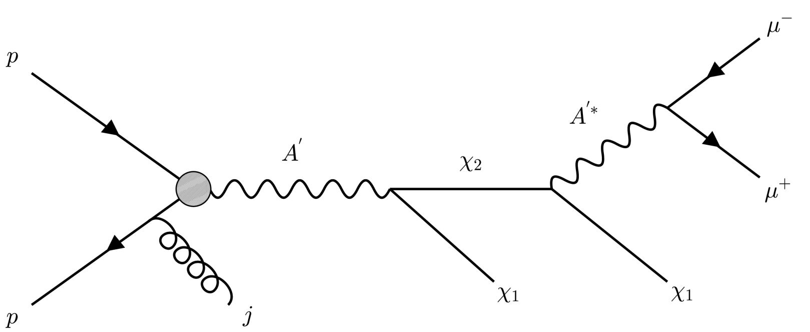
Inelastic dark matter

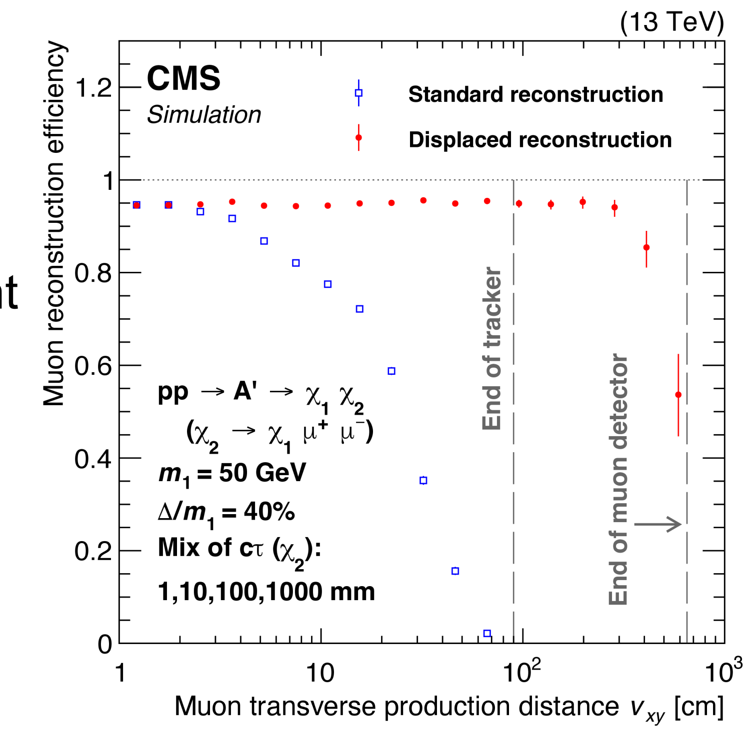
CMS: CMS-PAS-EXO-20-010

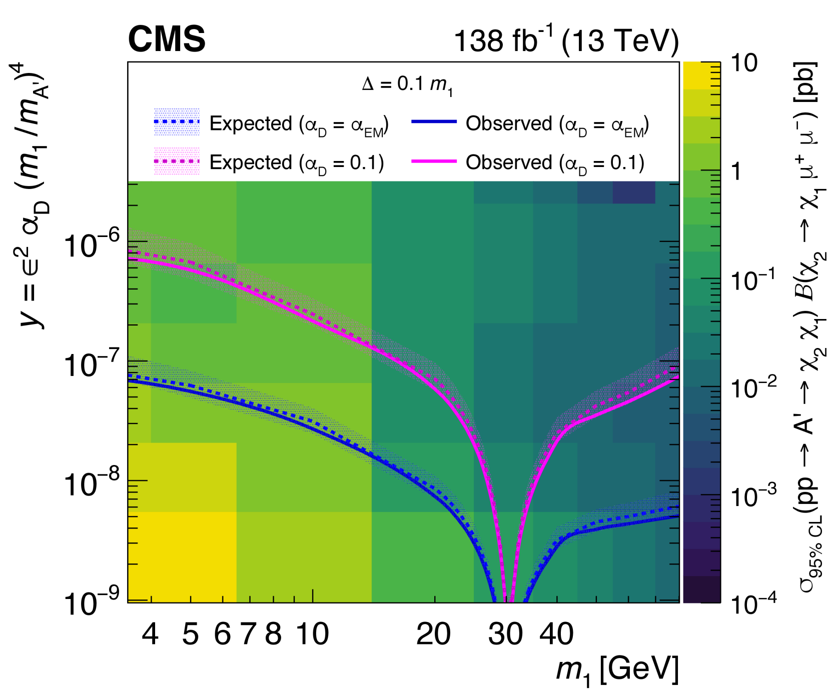
Search for dark matter using displaced muons for leverage

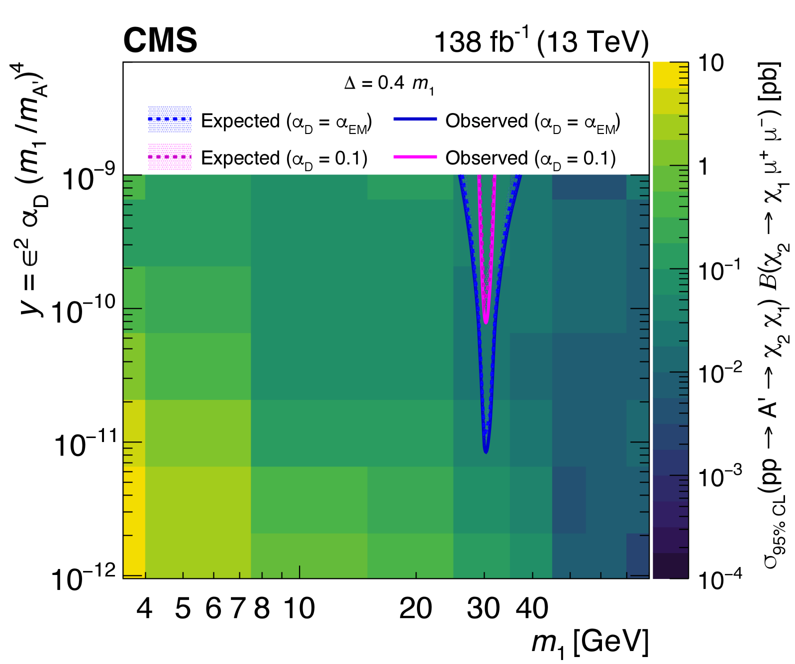
- Signal region :
  - Apply dR(< 0.2) matching between the displaced muons pair and PF at outermost hit.
  - Split SR into 3 match categories: 0, 1, or 2
- Dominant background : QCD dominates in all match categories
- Limits : m_1 of the DM state vs the interaction strength $y \equiv \varepsilon^2 \alpha_D (m_1/m_{A'})^4$

  (allows the relevant variables to be scaled with the thermal-relic abundance in a straightforward way)
- Sensitivity to exclude parameter space is strongest in the 10% splitting case
- 40% splitting cross-sections are very small
- The sensitivity amplified near $m_1 \approx 30$ GeV or $m_{A'} \approx 90$ GeV due to the A' mixing with the Z boson in that mass range.
- $\alpha_D = \alpha_{EM}$ scenario more sensitive, but $\alpha_D = 0.1$ scenario more cosmologically relevant



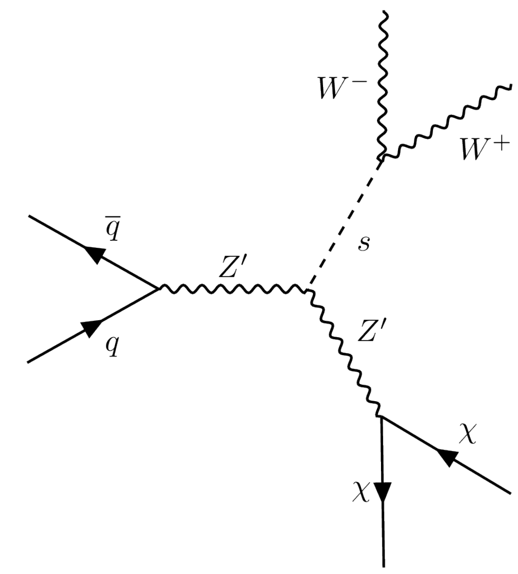


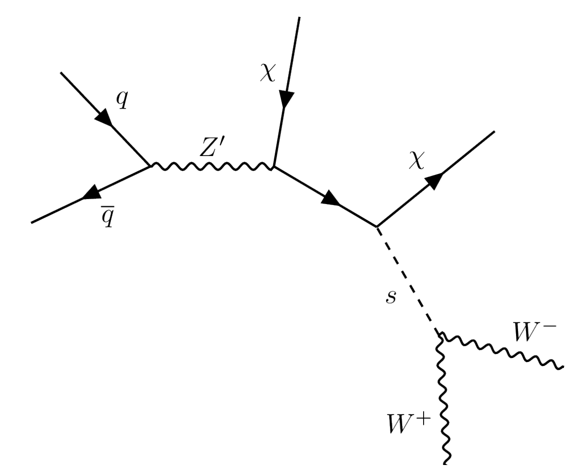


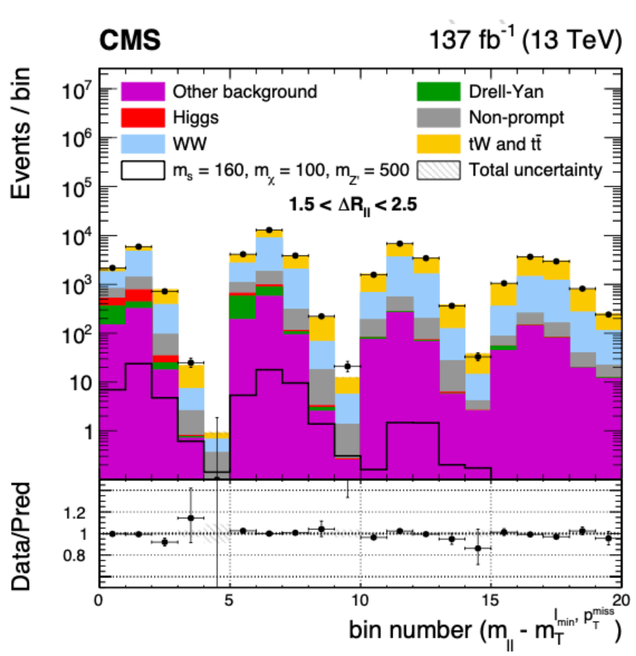


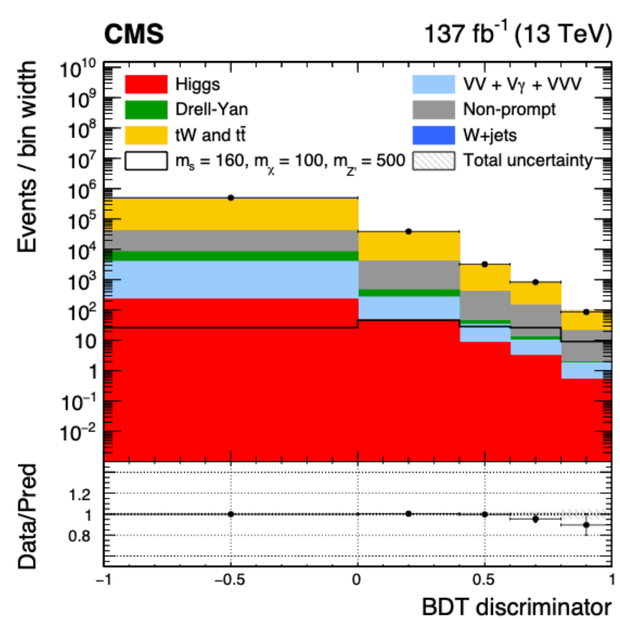
Dark Higgs

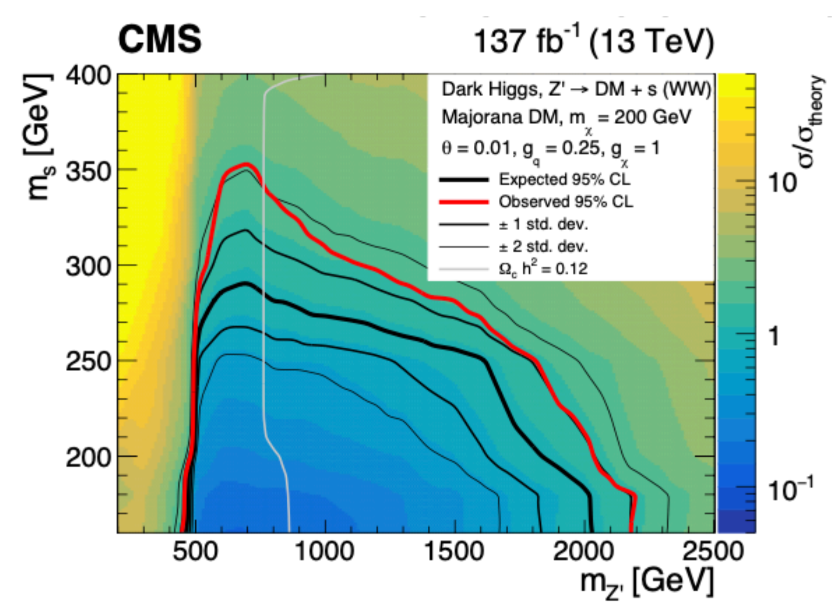
- Search for dark matter particles produced in association with a dark Higgs boson.
- Dark Higgs boson decays to a pair of visible W bosons.
- Both W bosons decay either fully leptonically (2l2v) or semi-leptonically (lvjj).
- Experimental signature :
  - Fully leptonic : Double lepton (opposite-sign / different-flavor) + MET
  - Semi leptonic Signal lepton + Di-jet + MET
- Triggers: single lepton for (lvjj) / double lepton for (2l2v)
- Dominant background: $W^+ W^-$, $t\bar{t}$ + tW and Drell-Yan (constrained in CRs enriched in these events by investing some the SR cuts [N b-jets, ΔR_{ll} and $M_T(ll, p_T^{miss})$]











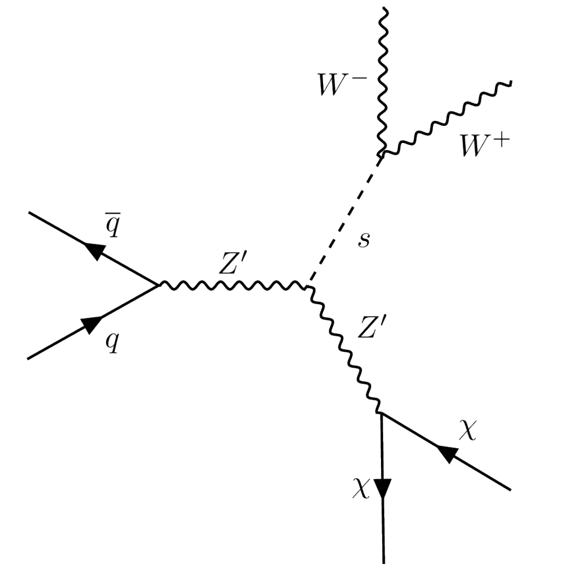
Dark Higgs

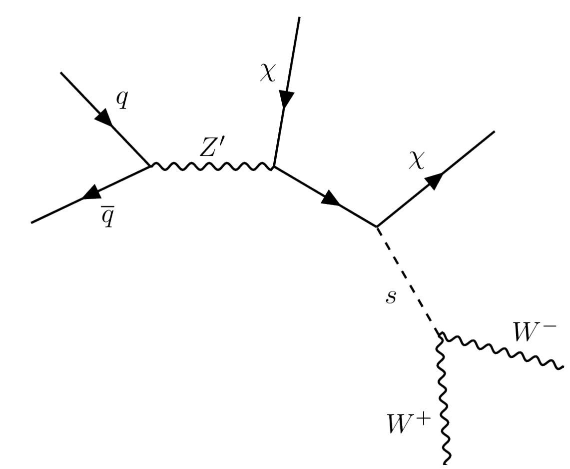
CMS: CMS-PAS-EXO-20-013

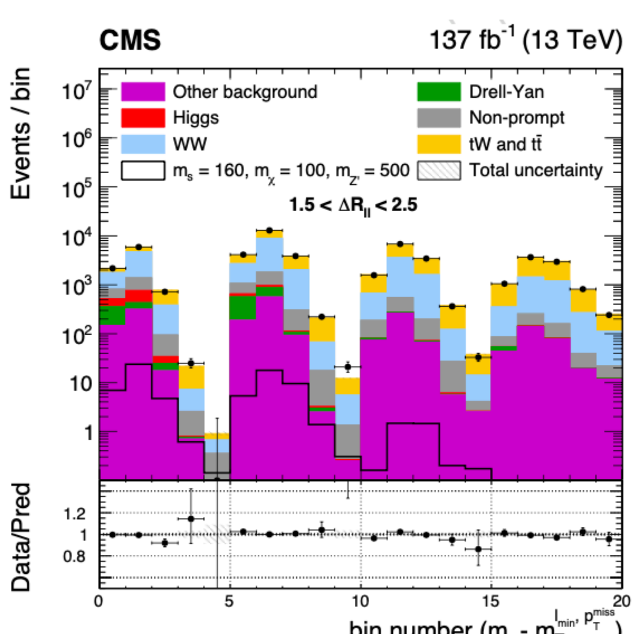
- Analysis Strategy :
  - Fully leptonic channel : cut-based analysis using variables $\Delta\varphi(p_T^{miss}, p_T^{l_{min}})$, m_{ll}, $m_T(l_{min}, p_T^{miss})$
  - Semi-leptonic channel : Apply BDT discriminator
- Signal regions :
  - Fully leptonic channel : 3SR defined

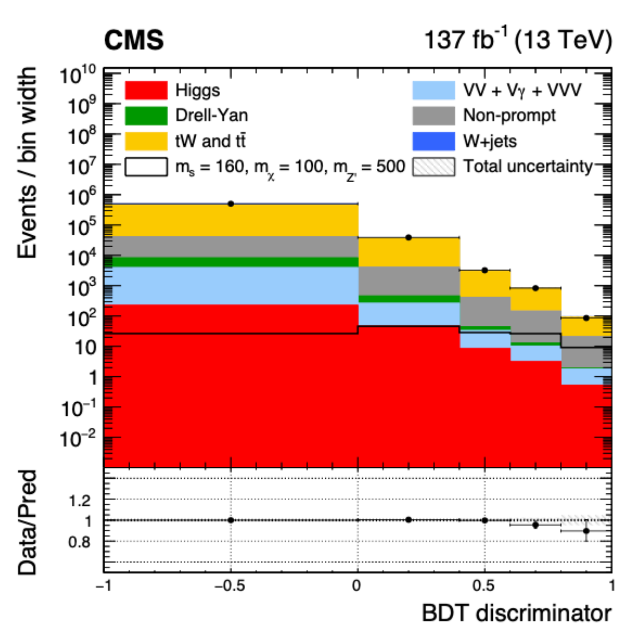
    → SR1 (ΔR_{ll} < 1.0 high boost), SR2 (1.0 < ΔR_{ll} < 1.5 medium boost),

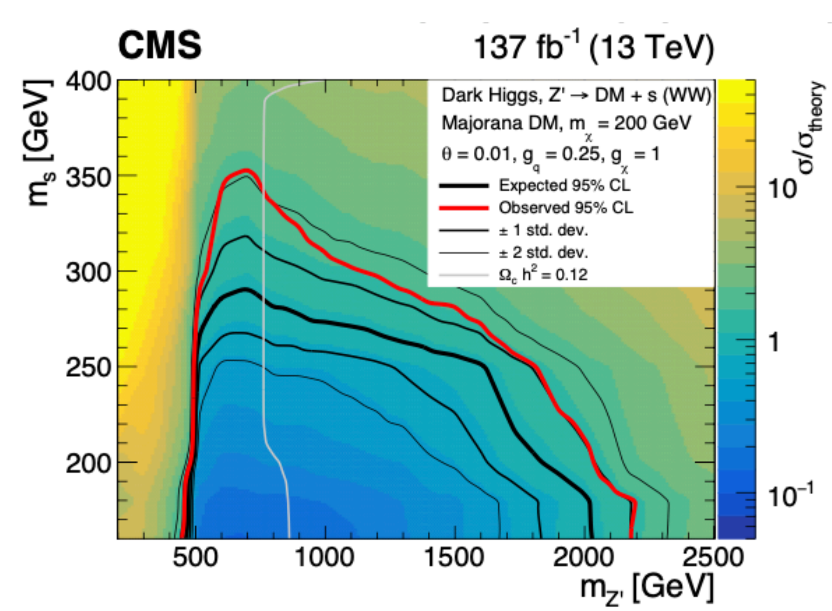
    SR3 (1.5 < ΔR_{ll} < 2.5 low boost)
  - Semi-leptonic channel : 1 SR defined BDT > 0.6
- Results : Extends the search from previous public results to a wider DM mass range, from 100 GeV to 300 GeV.
  - Stringent limits: m_{DM} = 200GeV, excluding m_s masses up to ≈ 350GeV at $m_{Z'}$ masses of 700GeV, and up to $m_{Z'}$ ≈ 2200GeV for m_s = 160GeV.











Summary

- Dark matter is a mysterious substance that makes up about 85% of the matter in the universe.
- Both astrophysical and terrestrial searches are needed to uncover a complete dark matter model.
- The LHC has explored a wide range of dark matter parameter space, but no hint so far.
- Dark matter could be hiding in a region of parameter space that we have not yet explored
- Observed complementarity between collider and non-collider dark matter searches,
- The LHC started Run3 on July 5, 2022, with stable proton-proton collisions at energy of 13.6 TeV.
- Stay tuned for new results of Run 3.

Thank You for Your Attention!