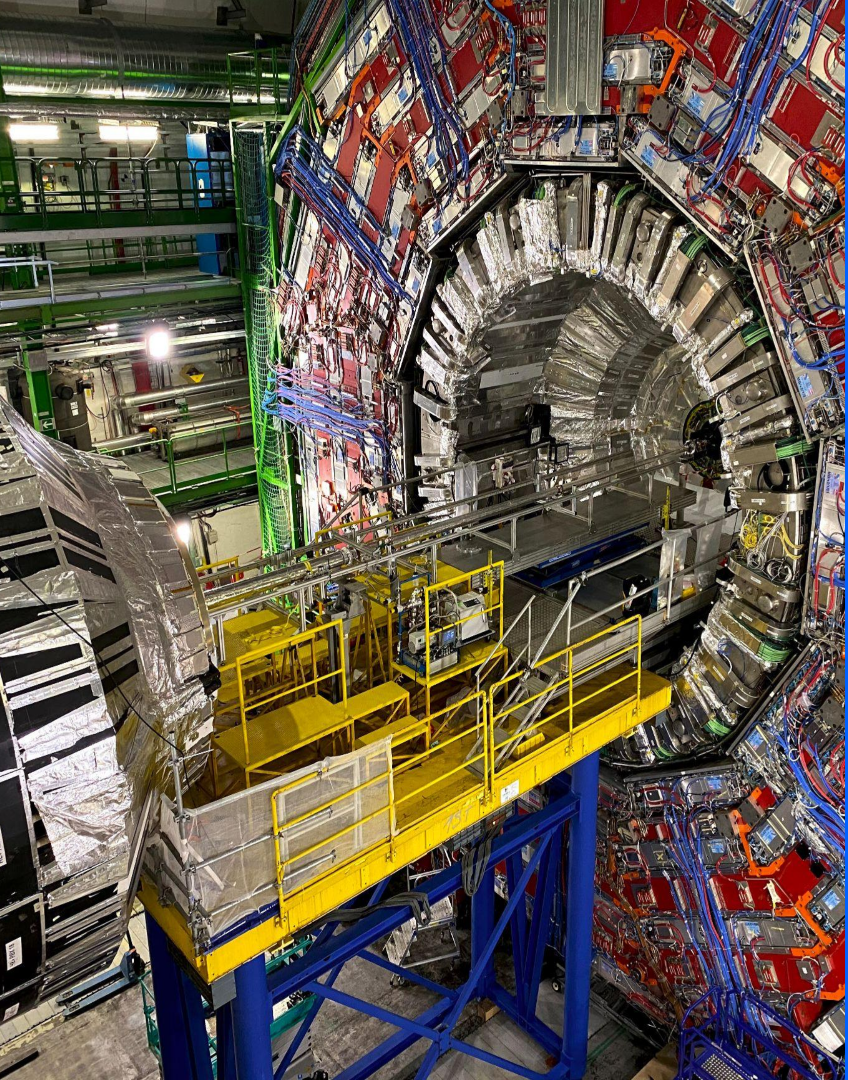


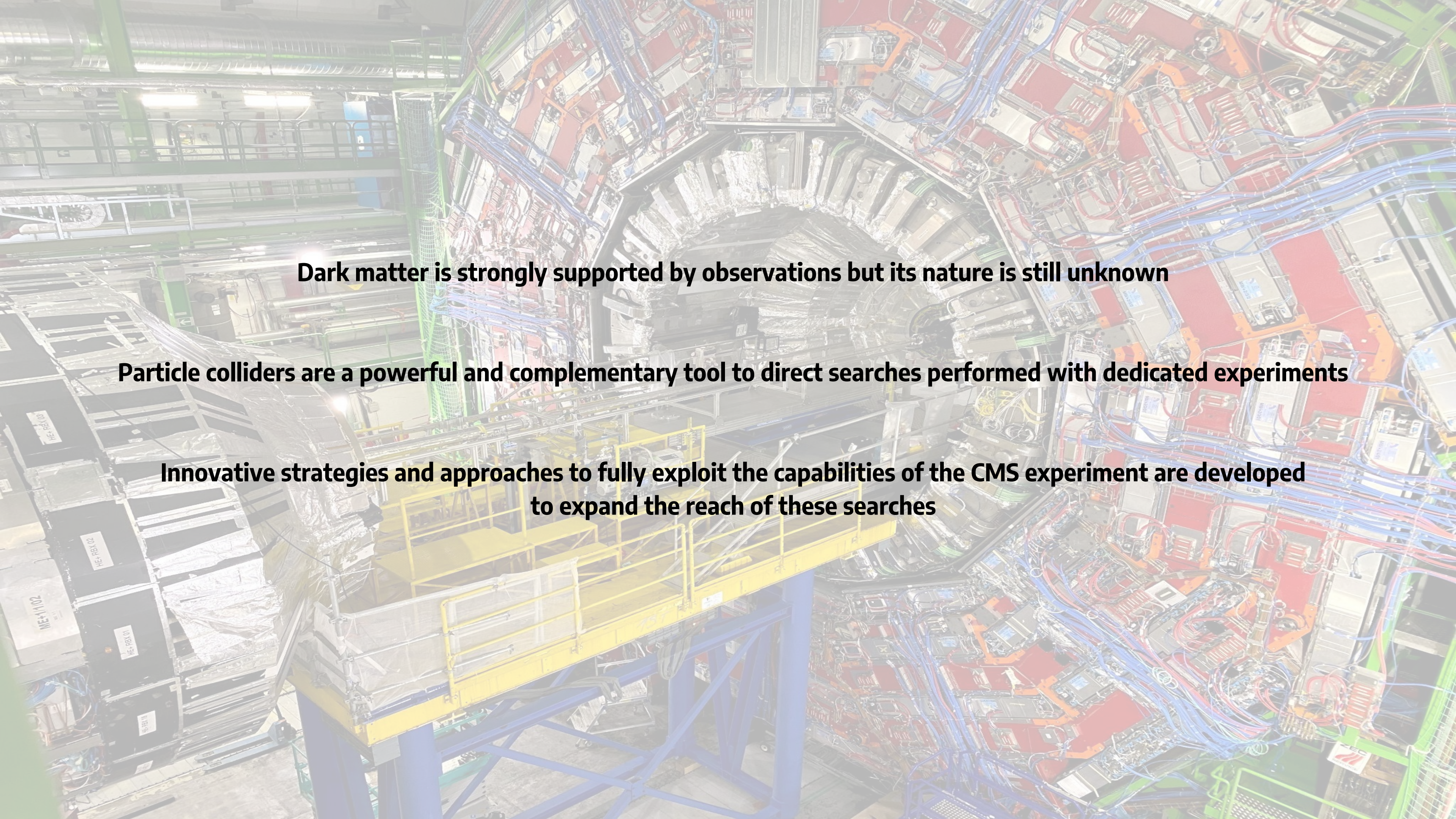
2023 LHC DM WG Spring Meeting

May 16th, 2023

CMS Dark Photon Results

ELISA FONTANESI

on behalf of the CMS Collaboration



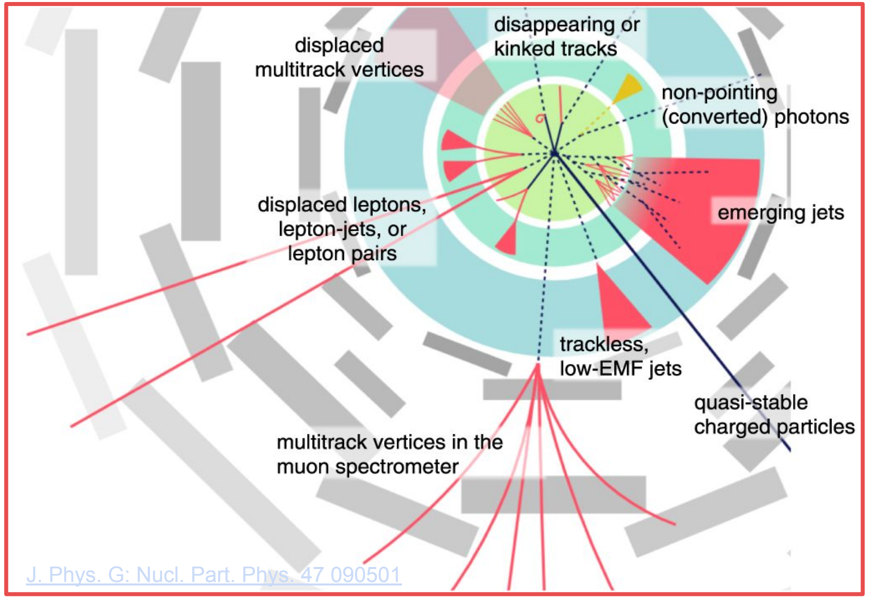
Dark matter is strongly supported by observations but its nature is still unknown

Particle colliders are a powerful and complementary tool to direct searches performed with dedicated experiments

Innovative strategies and approaches to fully exploit the capabilities of the CMS experiment are developed to expand the reach of these searches

New strategies and new CMS dark photon results

Innovative strategies and approaches to fully exploit the capabilities of the CMS experiment are developed to expand the reach of these searches



First dedicated collider search for inelastic dark matter using Run 2 data (138 fb^{-1})

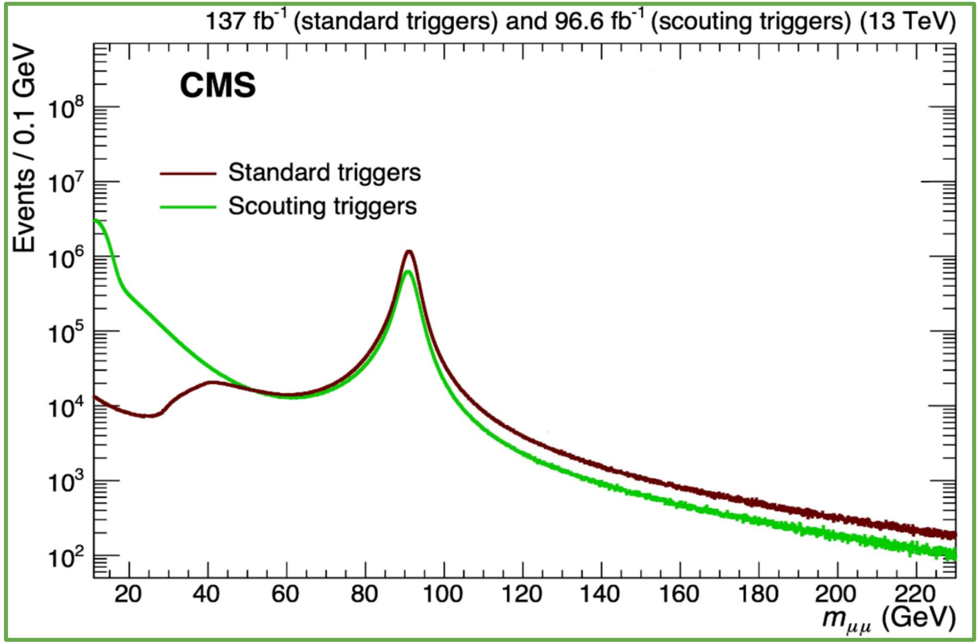
- Collider-based searches for long-lived particles (LLPs) can probe a wider range of DM models than previously explored → unique signatures
- Novel search targeting a **displaced-decay signature** with a pair of muons in the final state collimated with missing transverse momentum

New strategies and new CMS dark photon results

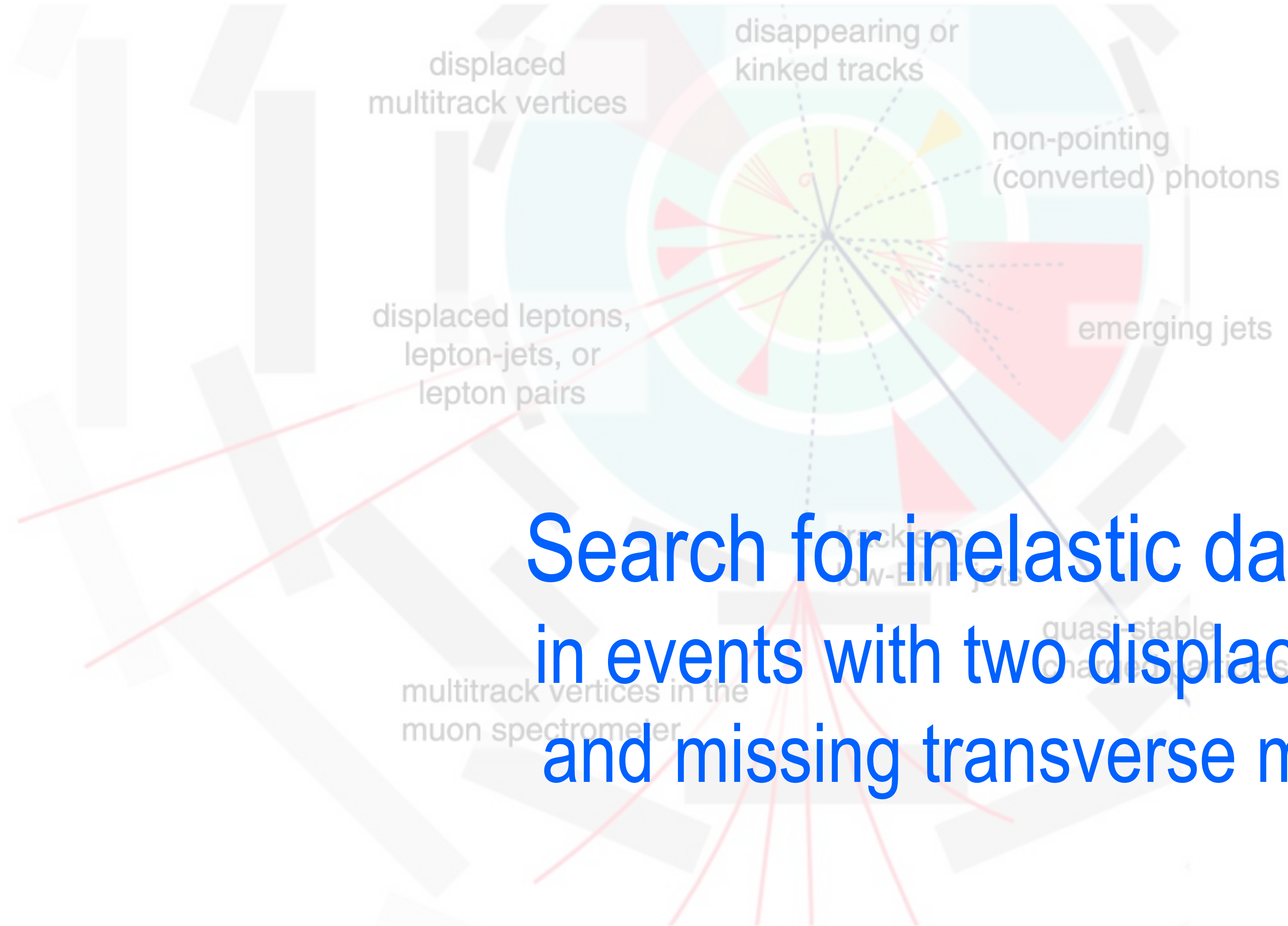
Innovative strategies and approaches to fully exploit the capabilities of the CMS experiment are developed to expand the reach of these searches

Search for prompt production of a GeV scale dimuon resonance using 2017-2018 data scouting (96.6 fb^{-1})

- Search for a narrow dimuon resonance at very low mass using a **high-rate dimuon trigger stream** called "scouting" going even lower in the mass spectrum w.r.t. the previous CMS result providing a dark photon interpretation (PhysRevLett.124.131802)
- Increased efficiency for dimuon events → reduced events size by storing only essential information

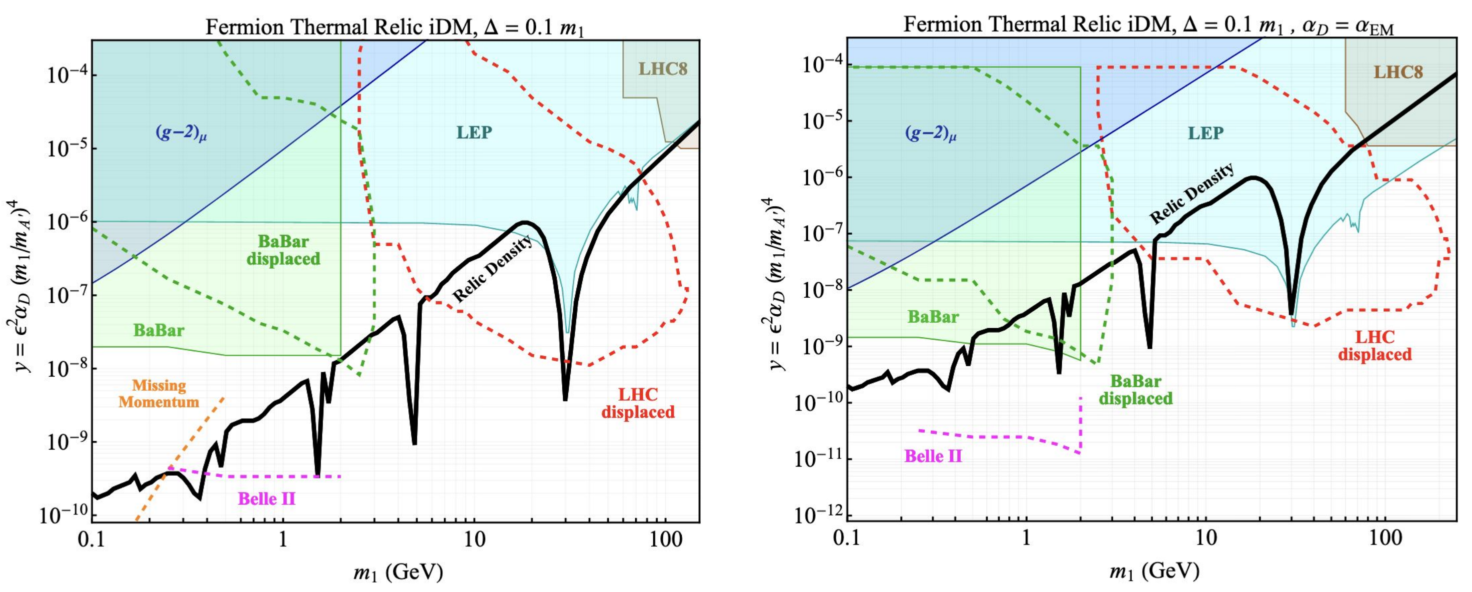


Search for inelastic dark matter in events with two displaced muons and missing transverse momentum



Motivation

Probing an inelastic dark matter model (iDM) that postulates the existence of at least **two inelastically coupled dark matter states** coupled via a **dark photon** that kinetically mixes with the SM hypercharge with mixing coefficient ε:
it could explain the observed thermal-relic DM abundance in the universe (1508.03050)



Signature and analysis strategy

Probing an inelastic dark matter model (iDM) that postulates the existence of at least **two inelastically coupled dark matter states** coupled via a **dark photon** that kinetically mixes with the SM hypercharge with mixing coefficient ε:
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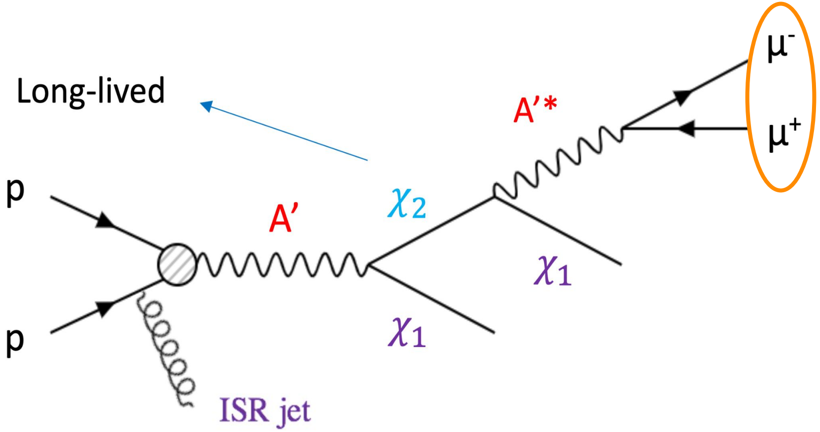


Event signature:

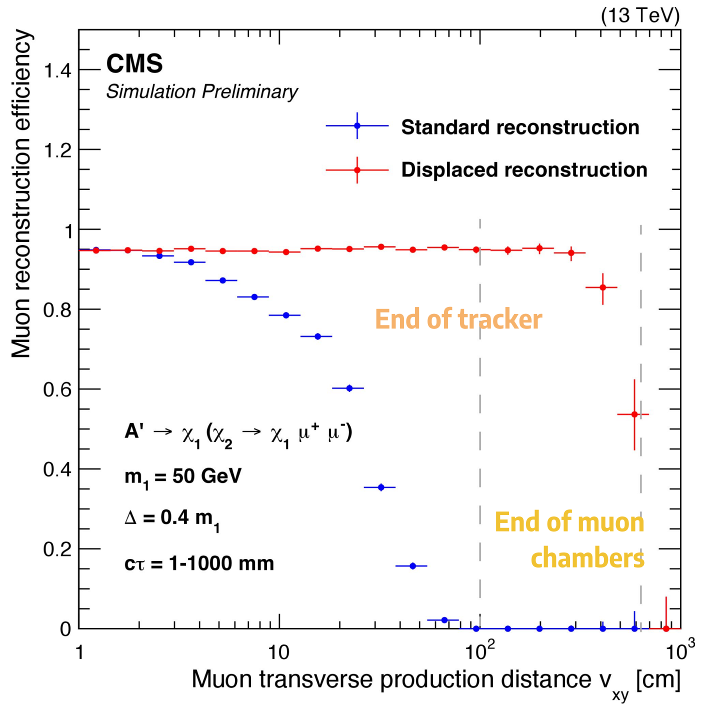
- Dark photon A' produced in the proton-proton collision recoiling off an initial-state radiation jet
- Decaying to two dark matter states with near mass-degeneracy: a light not detectable state χ_1 and a heavy state χ_2 with a long lifetime $c\tau \propto (m_{A'})^4/(\Delta m_{DM})^5$
  - Soft decay products with small angular separation: pair of displaced muons
  - Sizeable missing transverse momentum collimated with the muon pair from escaping χ_1 particles

Trigger selection relies on MET instead of the muons → too soft
Main background sources are: QCD events with genuine or misidentified muons, top-quark production, and W/Z+jets; cosmic and beam halo muons are not significant sources of background

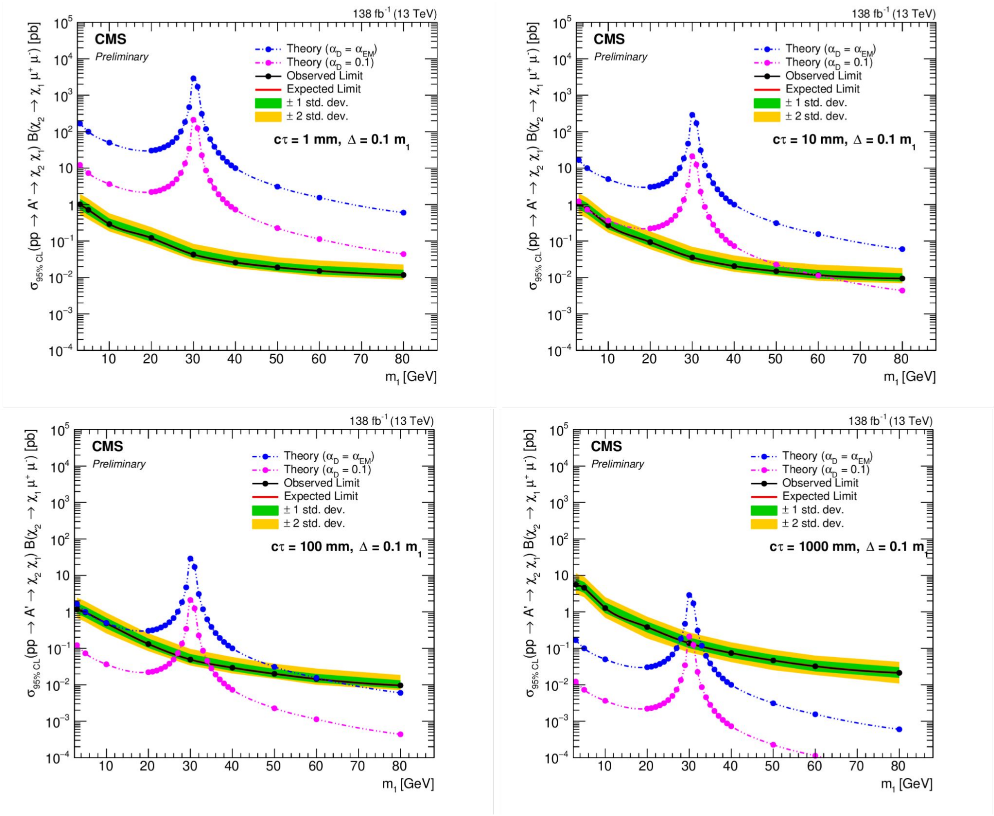
Event selection

- **Event selection:**
  - At least one energetic jet with p_T > 80 GeV and $|\eta|$ < 2.4
    - Only one other jet is allowed in the event
    - Veto on jets originating form b quarks
  - Pair of collimated displaced muons reconstructed with the displaced standalone algorithm (DSA)
    - p_T > 5 GeV, $|\eta|$ < 2.4; p_T resolution less than 1
    - DSA muon reconstruction efficiency about 90%; ΔR matching to a PF muon to recover some of the performance at lower displacements
  - Significant MET collimated with muons

- **Event categorization and background estimation:**
  - Three categories based on the number of PF-DSA matches found (0–2)
    - Fewer matches ⟹ larger displacement
  - Use kinematics, isolation, and muon d_{xy} to both suppress and estimate background (mostly QCD)
  - Dedicated ABCD procedure for background estimation on data
    - Instrumental and QCD backgrounds have poor MC modeling



Observed limits versus mass



A' production cross section times $\chi_2 \to \chi_1 \mu^+ \mu^-$ BR as a function of m_1 for an inelastic dark matter model with mass splitting $\Delta = 0.1 * m_1$ and $c\tau$ = 1/10/100/1000 mm

- Signal cross-section decreases with increasing mass, mass splitting, α_D, and $c\tau$
- Experimental sensitivity increases with mass and mass splitting
- $c\tau$ = 0.1 cm $\Rightarrow$ signal has large backgrounds
  $c\tau$ = 100 cm $\Rightarrow$ signal has low efficiency

Observed limits 2D

cms-results

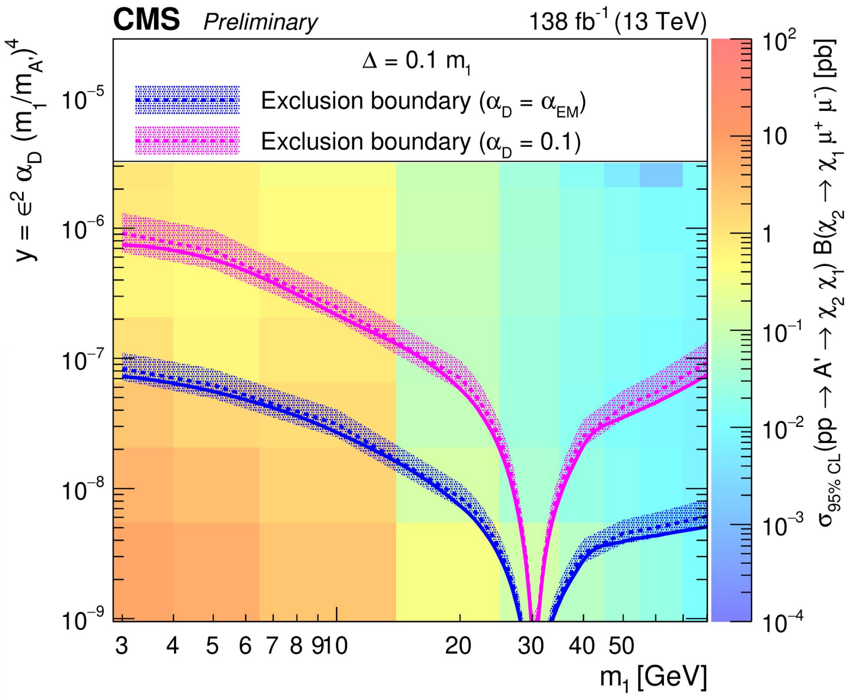
The strongest sensitivity to exclude parameter space is obtained when considering the 10% splitting case

as a function of m_1 and y:

$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_1}{m_{A'}}\right)^4 = \frac{15\pi}{4\,\alpha\,x^5}\,\frac{\hbar c}{\tau\, m_1}$$

- 40% splitting cross-sections are very small
- Sensitivity amplified near Z-A' mixing due to enhancement
- $\alpha_D = \alpha_{EM}$ scenario more sensitive, but $\alpha_D = 0.1$ scenario more cosmologically relevant

No significant excess is observed over SM expectations; **the sensitivity to m_1 is significantly expanded above the GeV scale**



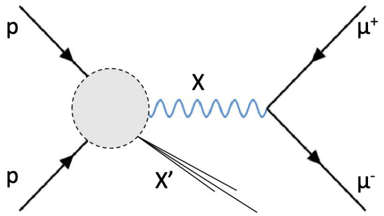
Search for prompt production of a GeV scale resonance

decaying to a pair of muons

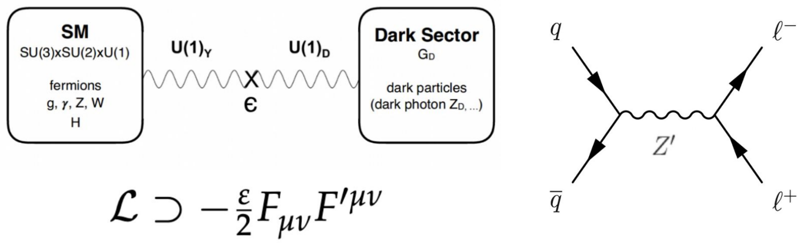
Analysis strategy and motivation

cms-results

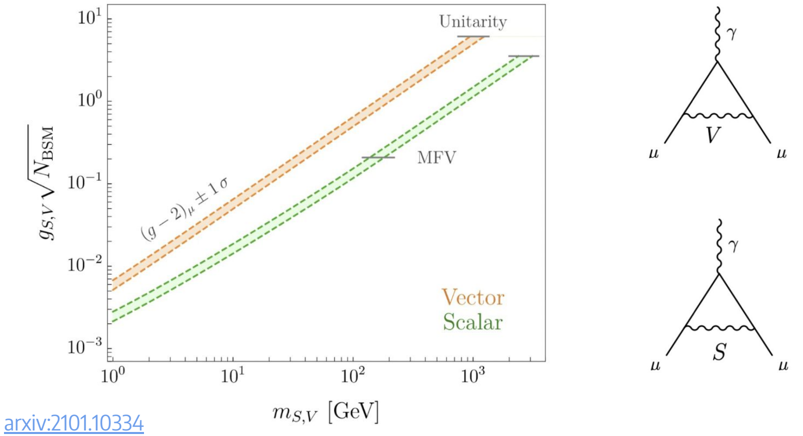
- Data driven search for a narrow dimuon resonance at low mass **below 10 GeV** using 2017-2018 Run 2 scouting data recorded by CMS
  - Bump hunt on the dimuon mass using analytical signal and background PDFs



- New states at the GeV scale are motivated from several perspectives:
  - Vector portal interaction in thermal dark matter models
  - New scalar or vector coupling to muons could help explain muon (g-2) anomaly



$$\mathcal{L} \supset -\frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$



arxiv:2101.10334

Analysis strategy and motivation

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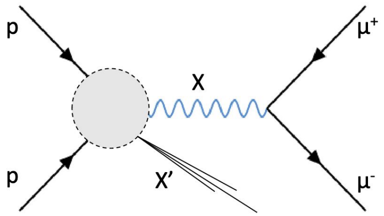
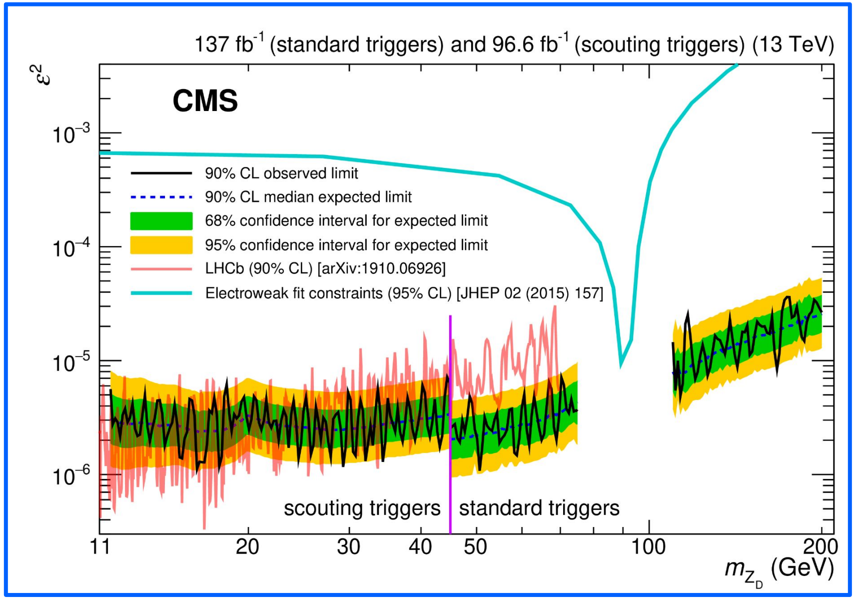


- Previous CMS result (PhysRevLett.124.131802) investigated the [45, 75] GeV and [110, 200] GeV resonance mass ranges exploiting conventional triggers and event reconstruction techniques and the 11.5–45 GeV mass range relying on scouting data.



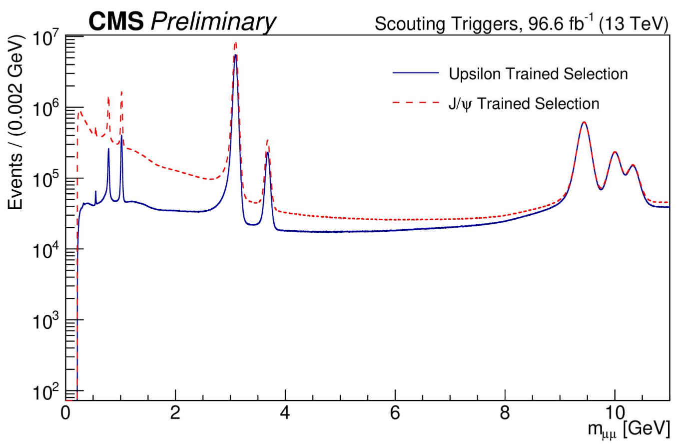
Event selection and categorization

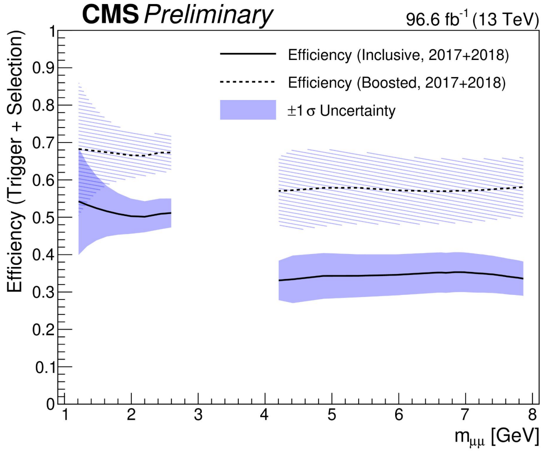
Two signal categories to target inclusive and boosted production optimal for different production mechanisms (e.g. DY or ggF)

Simple fiducial volume: Two muons with p_T^{μ} > 4 (5) GeV and |η| < 1.9

- Data-driven multivariate identification to target prompt production and suppress misidentified muons
- Additional requirement L < 0.015 cm for high mass inclusive category
- Vertex resolution degrades for inclusive low mass and boosted categories → cut on displacement significance

Preselection	$L < 0.2\,\mathrm{cm}$, $\lvert\eta^{\mu}\rvert < 1.9$, OS			
Category	Inclusive		Boosted	
Mass Range	$m_{\mu\mu} < 2.6\,\mathrm{GeV}$	$m_{\mu\mu} > 4.2\,\mathrm{GeV}$	$m_{\mu\mu} < 2.6\,\mathrm{GeV}$	$m_{\mu\mu} > 4.2\,\mathrm{GeV}$
p_T^{μ}	$> 4\,\mathrm{GeV}$		$> 5\,\mathrm{GeV}$	
BDT ID	J/ψ ID > -0.1	Υ ID > 0.0	J/ψ ID > -0.1	
Vertex	$\sigma_L < 3.5L$	$L < 0.015\,\mathrm{cm}$	$\sigma_L < 3.5L$	
$p_T^{\mu\mu}$	–	–	$> 35\,\mathrm{GeV}$	$> 20\,\mathrm{GeV}$

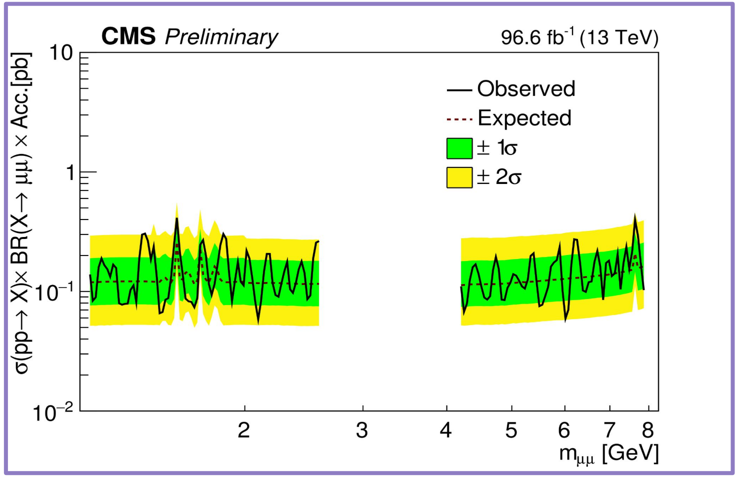




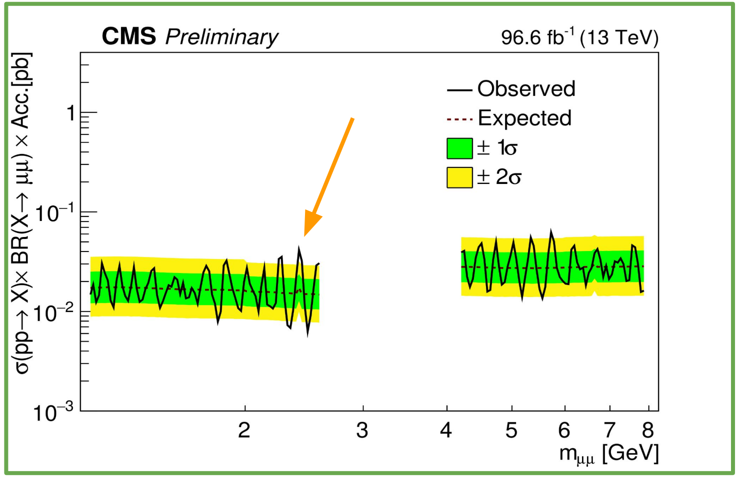
Observed model independent limits

- Analytical signal and background PDFs are used for the modelling
  - Signal modeled from fits to SM resonances: Double Crystal Ball + Gaussian (20% uncertainty on resolution)
  - Combinatorial background modelling based on the discrete profiling method
    - 4th order Bernstein polynomial + 3 empirical functions
- Model independent limit on σ × B × α: largest excess observed in the boosted category at 2.41 GeV (3.2σ local significance, 1.3σ global significance) → LHCb (JHEP10(2020)156) reports a 3.1σ local excess at 2.42 GeV in one event category (X+b, 10<pT(X)<20 GeV)

Inclusive selection



Boosted selection



From model independent limits to interpretations

Computing σ × B × α in specific models, limits on model parameters are also set
and can be compared with results provided by other experiments

Two specific models are chosen to constrain model parameters, relying on theoretical calculations of cross sections, branching ratio, and experimental acceptance:

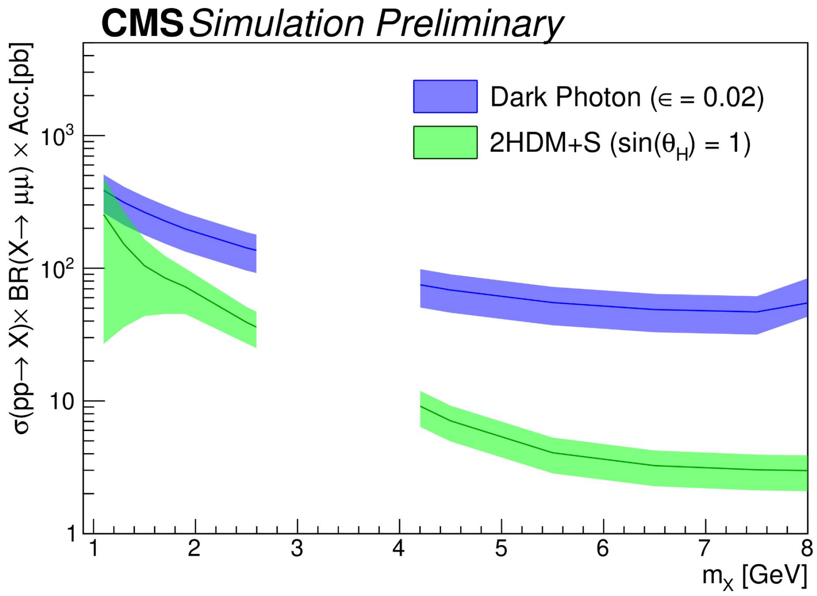
- **DY production of vector boson (dark photon)**
  - Dark photon cross section and BR calculated with MadGraph
  - NNLO corrections and acceptance from DYTurbo (EPJ 80 (2020) 251)

$$\sigma_{pp\to Z_D} \cdot \epsilon^2 \cdot \mathcal{B} \cdot A = \sigma_{limit}$$

- **Gluon fusion production of pseudoscalar (2HDM+S)**
  - Gluon fusion cross section from HIGLU (arxiv:hep-ph/9510347) & BR from (JHEP 03 (2018) 178)
  - Acceptance from MadGraph and Pythia

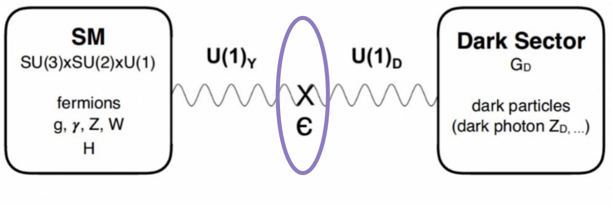
$$\sigma_{pp\to a} \cdot \sin^2(\theta_H) \cdot \mathcal{B} \cdot A = \sigma_{limit}$$

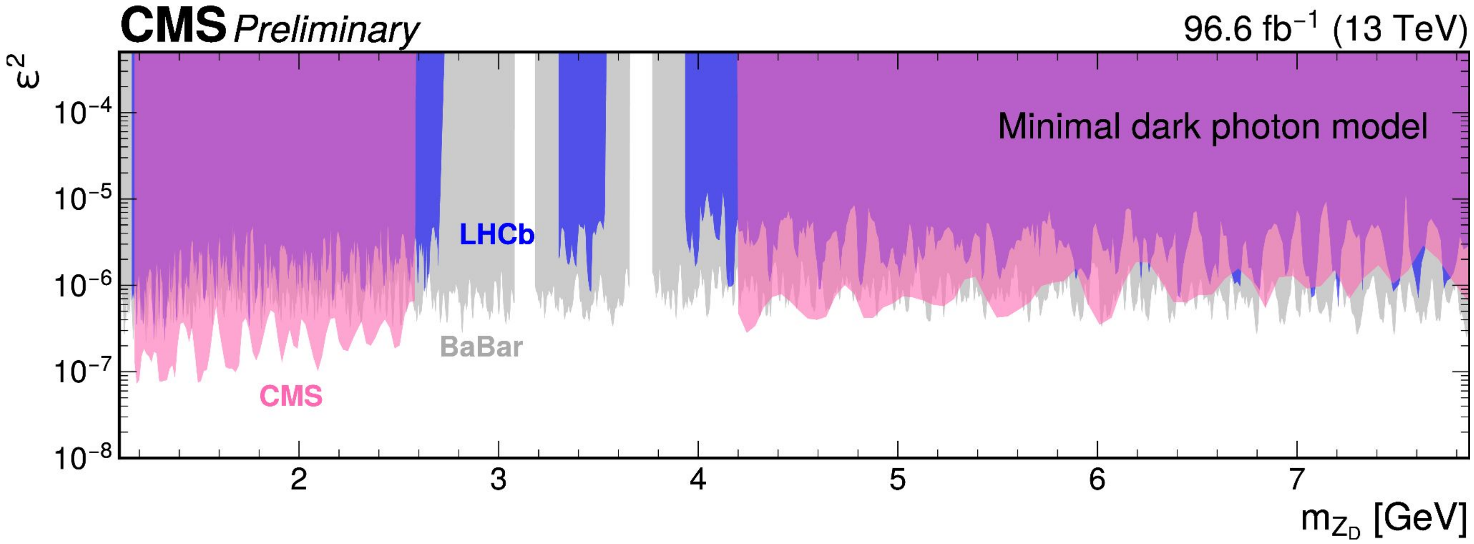
→ Very similar strategy for the recasting by CMS and LHCb!



Limit interpretation: dark photon model

- Results from the inclusive category are exploited to set limits on kinetic mixing parameter ε^2 in dark photon model
- CAVEAT: The overall strategy is different by the LHCb approach
  - Theory cross sections, detector efficiency, or luminosity are not used





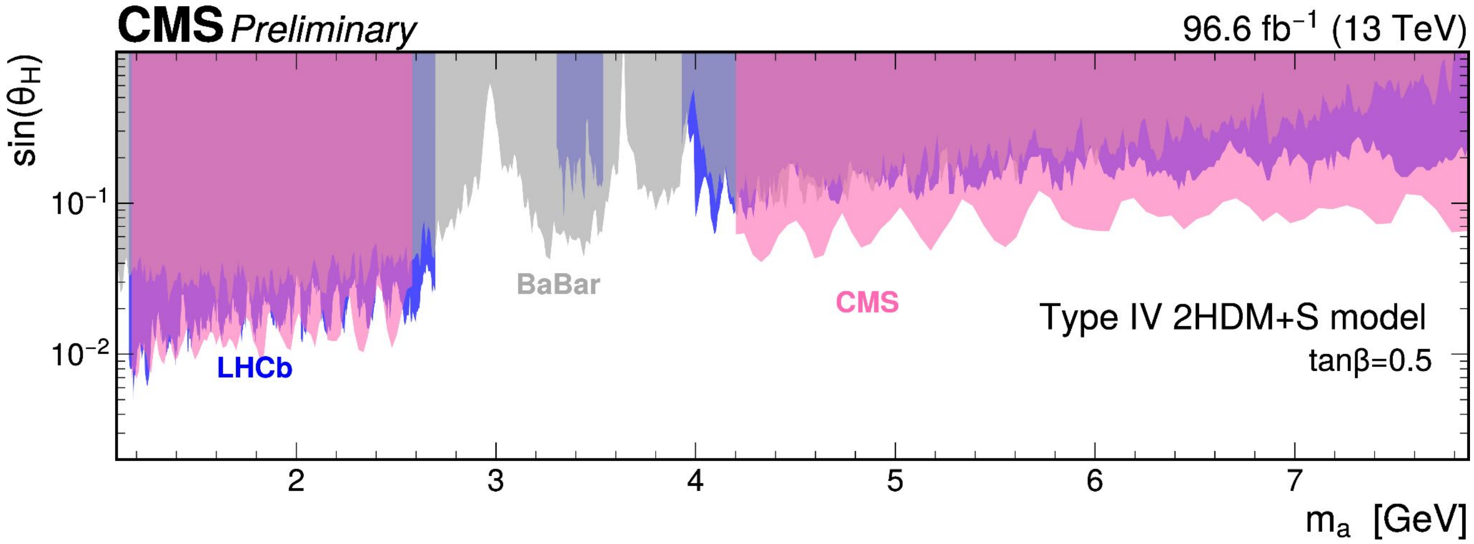
Limit interpretation: 2HDM+S

cms-results

- Two-Higgs-doublet model with an extra complex scalar singlet (2HDM+S) features a light pseudoscalar boson **a** (CP=0$^-$) ⟹ couplings to the SM particles are determined by its mixing with the Higgs doublets
  - Parameterized by the mixing angle θ_H and the ratio of the Higgs-doublet vacuum expectation values tanβ
- Results from the boosted category are exploited to set limits on sin(θ_H)

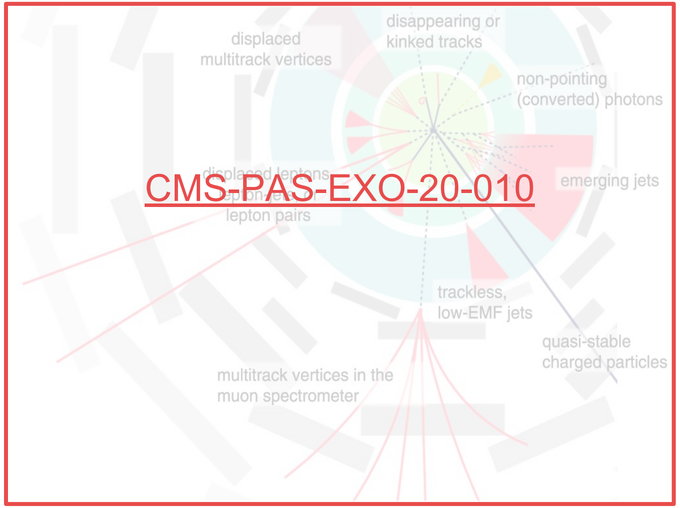
type	I	II	III	IV
up-type quarks	s_θ/t_β	s_θ/t_β	s_θ/t_β	s_θ/t_β
down-type quarks	$-s_\theta/t_\beta$	$s_\theta t_\beta$	$-s_\theta/t_\beta$	$s_\theta t_\beta$
charged leptons	$-s_\theta/t_\beta$	$s_\theta t_\beta$	$s_\theta t_\beta$	$-s_\theta/t_\beta$

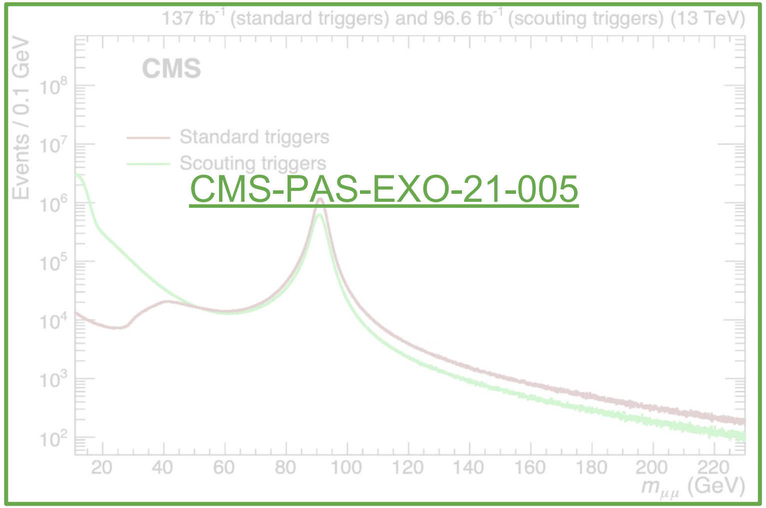
JHEP03(2018)178



Summary

Two new CMS results including an interpretation for a dark photon are based on two innovative strategies and approaches that allowed to expand notably the reach of these searches:





The Run 3 focus on the improvement of the scouting strategy and of the LLP triggers will provide very interesting data to look at!

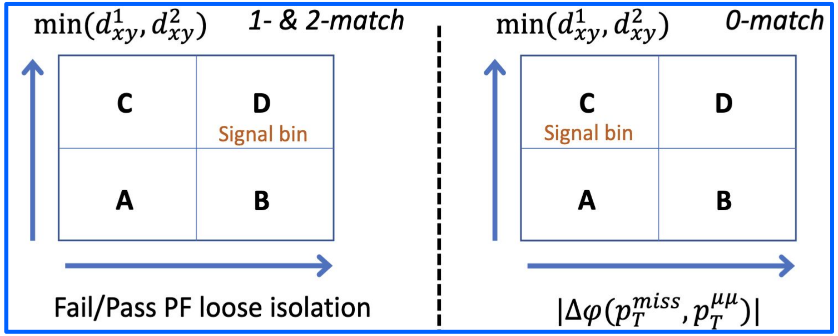
Thank you for listening!

Additional slides

Questions? Comments?

ABCD method

- **Background estimation on data: Dedicated ABCD procedure**
  - Instrumental and QCD backgrounds have poor MC modeling
  - Two independent observables used to estimate the background in 4 bins of the 2D plane using only 3 fit parameters: normalization and horizontal and vertical transfer coefficients.
  - Use muon displacement, PF isolation, and $\Delta\varphi(p_T^{miss}, p_T^{\mu\mu})$ to maximize the sensitivity for each match-category

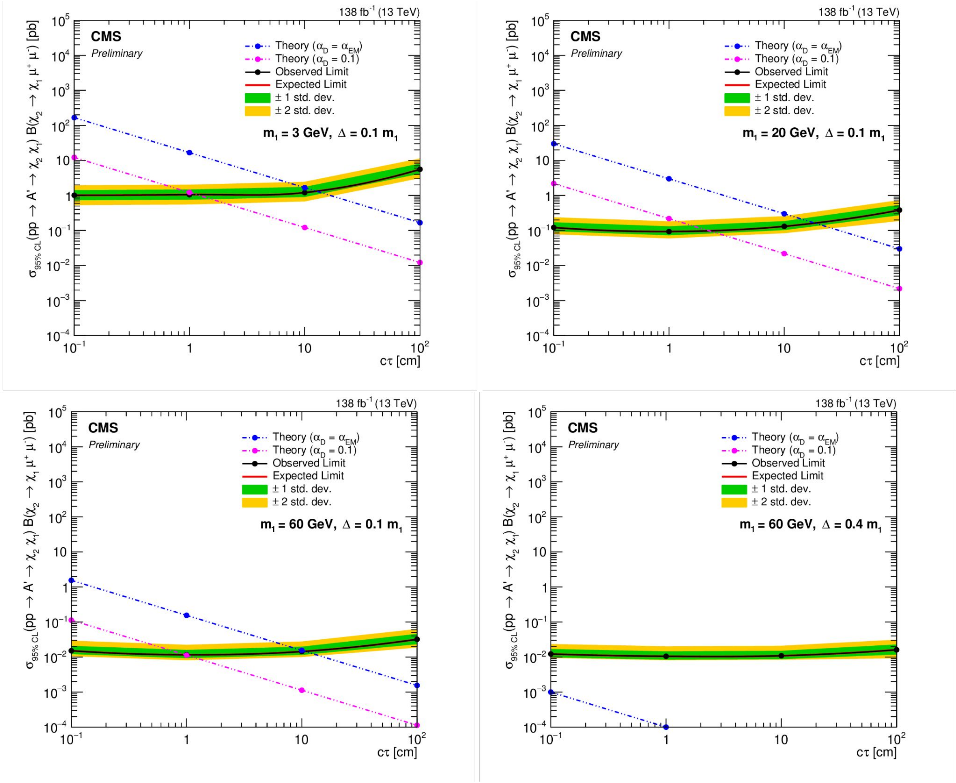


There is one degree of freedom left which can be used to fit the signal

Background and signal are fitted simultaneously using these four fit parameters: background normalization, transfer coefficients, and signal rate

Observed limits versus $c\tau$

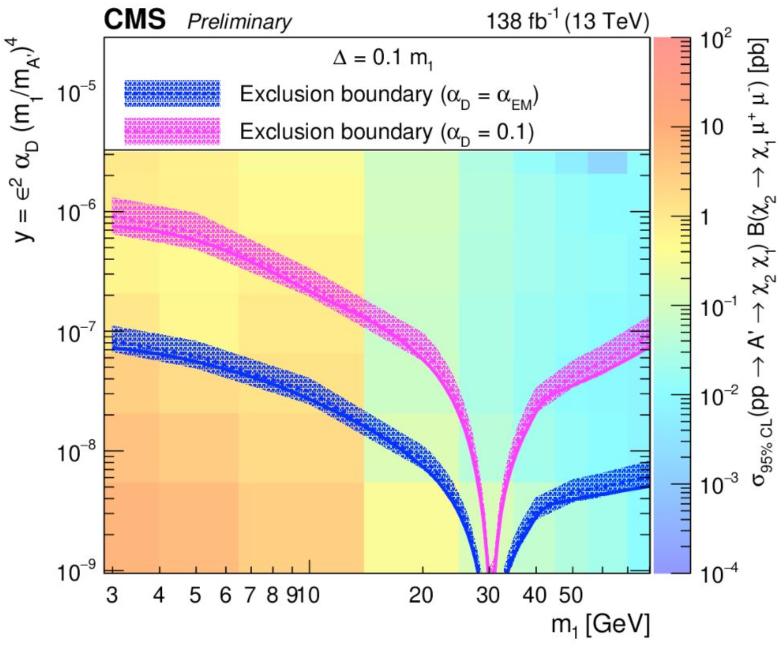
cms-results

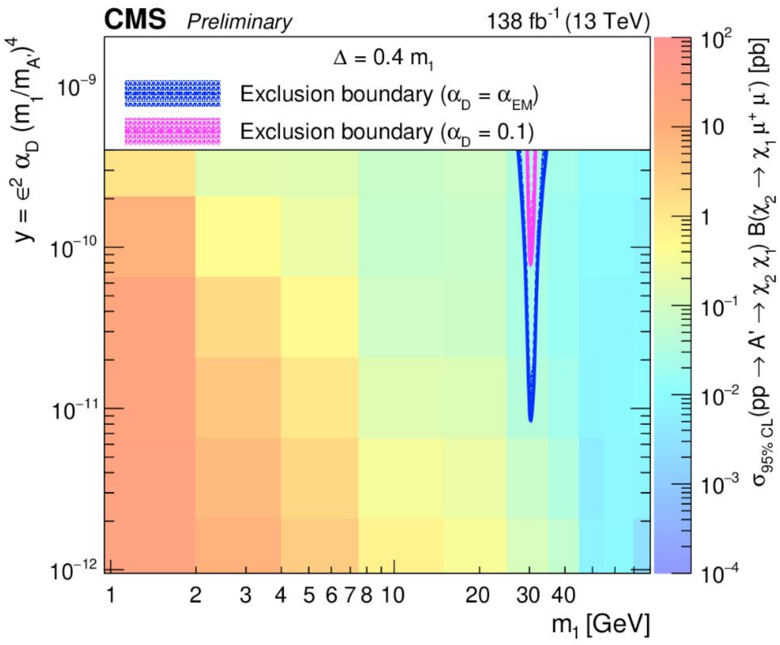


Observed limits 2D

cms-results

The strongest sensitivity to exclude parameter space is obtained when considering the 10% splitting case

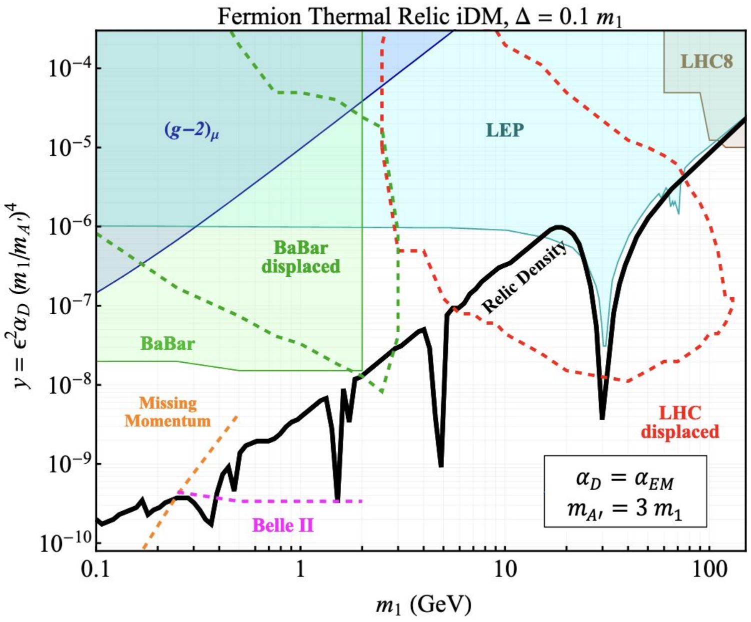


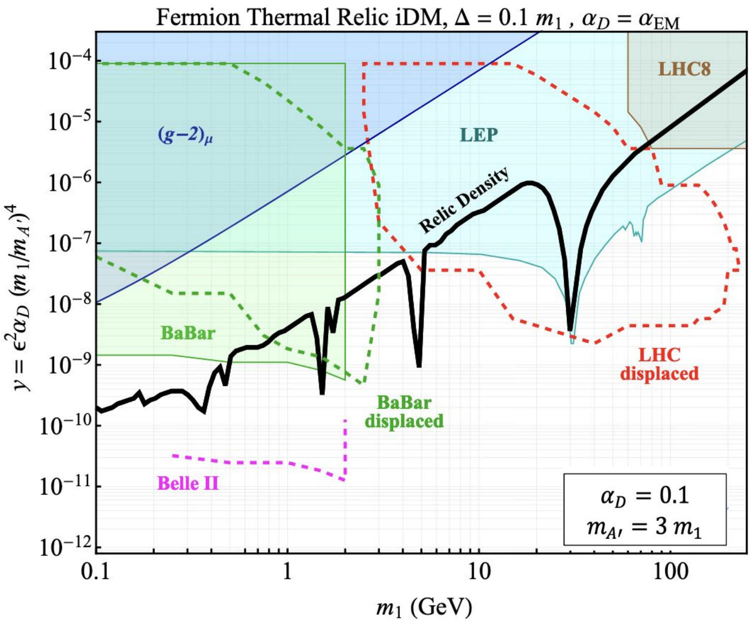


Inelastic dark matter: Theory paper

Reference theory paper (1508.03050): **Discovering Inelastic Thermal-Relic Dark Matter at Colliders**

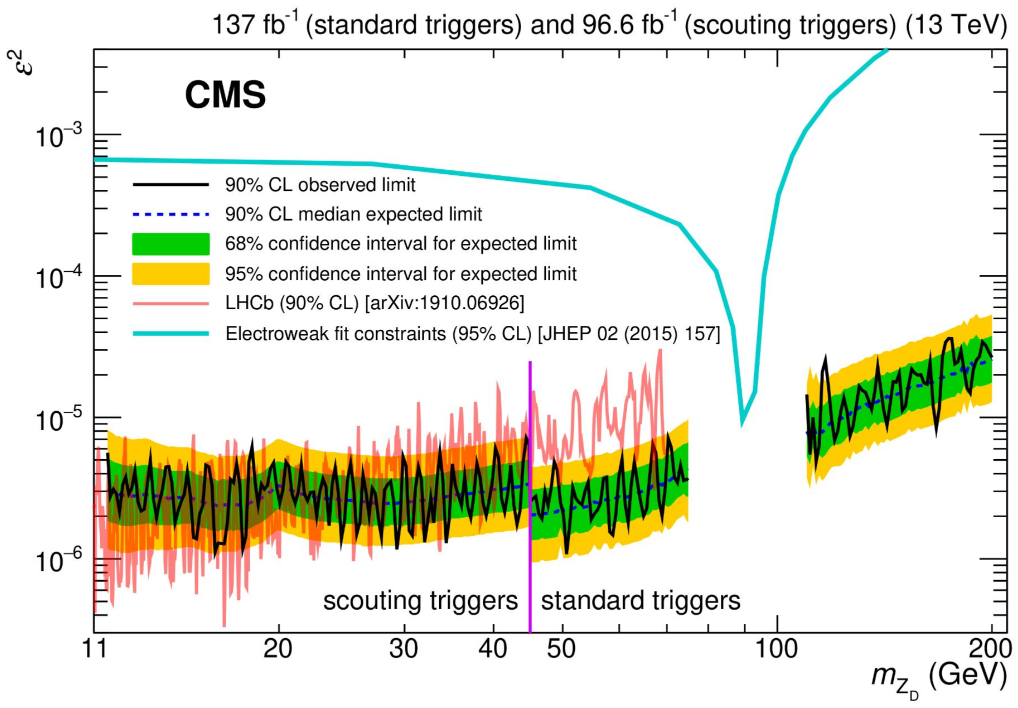
The current results will be compared with the theory prediction at 300 fb^{-1}





Prompt dimuon resonances: previous CMS result

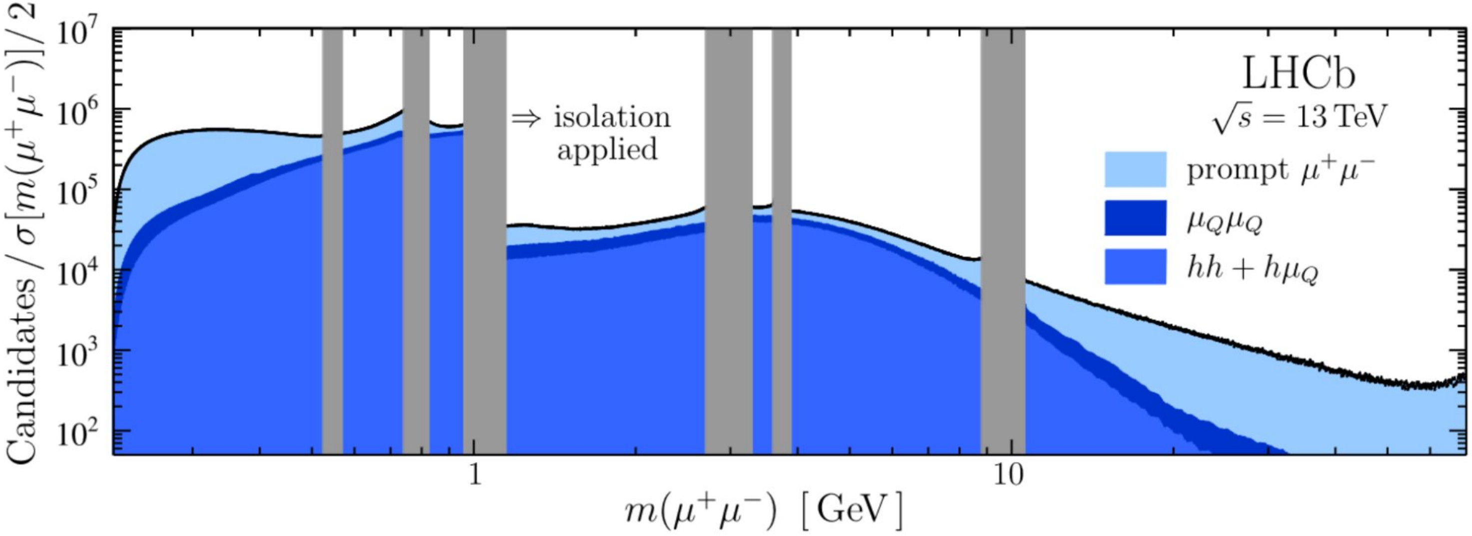
PhysRevLett.124.131802



LHCb prompt dimuon analysis

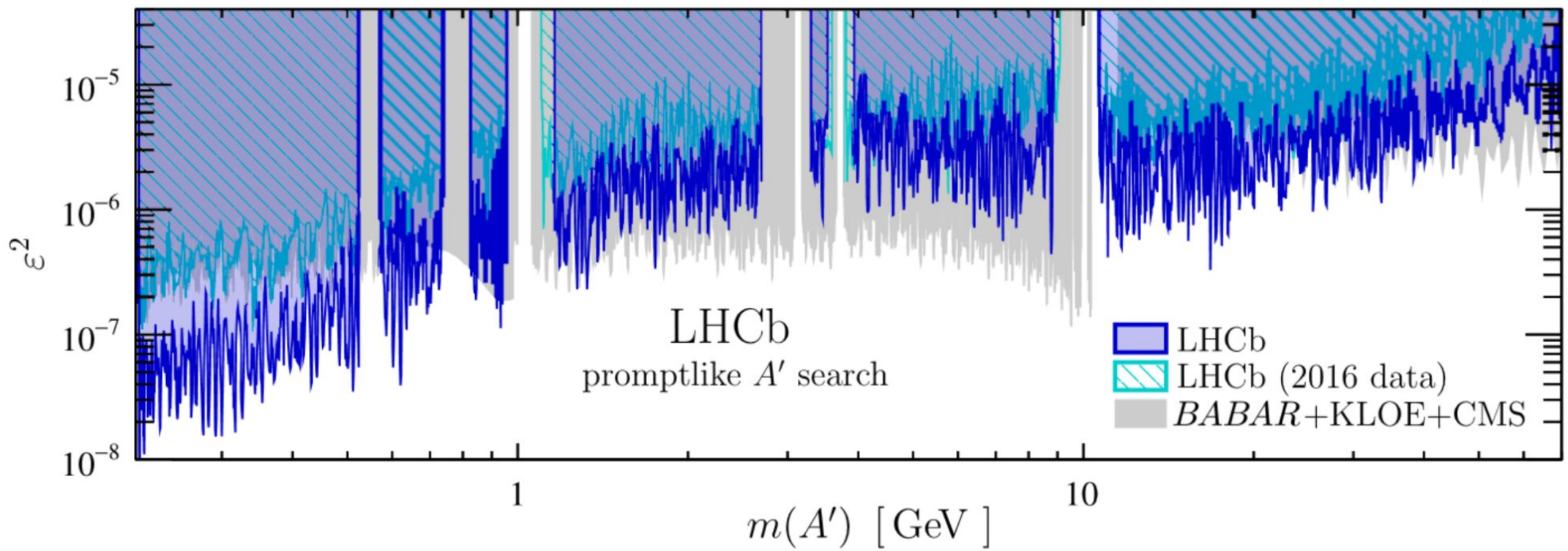
PhysRevLett.124.041801

- Same mechanism for γ* and dark photon production
- Non-prompt γ* background estimated using SS sample → subtract from observation
- Ratio between the observed γ* yield and signal yield proportional to ε^2
    - Theory cross sections, detector efficiency, or luminosity are not used

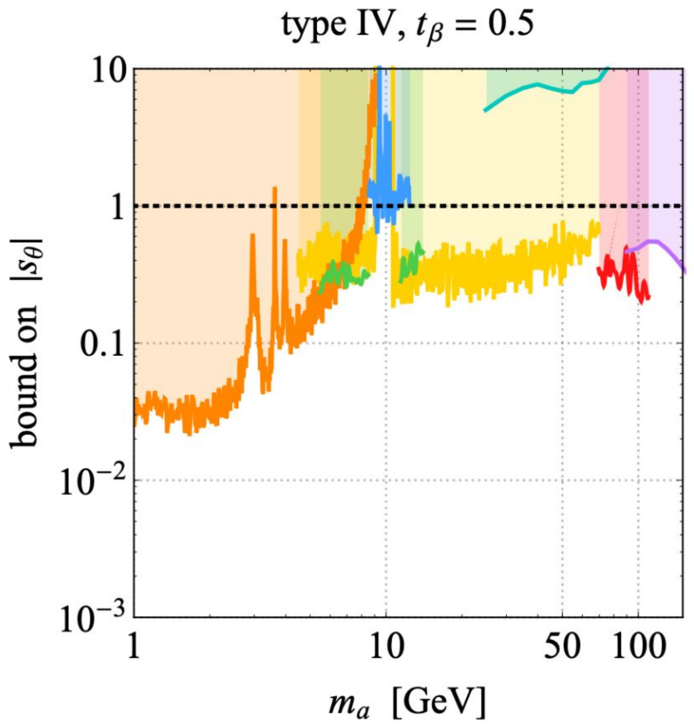


Dark photon limit: LHCb comparison

PhysRevLett.124.041801



2HDM+S: theory paper



type	I	II	III	IV
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charged leptons	$-s_\theta/t_\beta$	$s_\theta t_\beta$	$s_\theta t_\beta$	$-s_\theta/t_\beta$

JHEP03(2018)178

Figure 3. Limits on $|s_\theta|$ in the 2HDM+S of type I with $t_\beta = 1$ (top left), type II with $t_\beta = 2$ (top right), type III with $t_\beta = 5$ (bottom left) and type IV with $t_\beta = 0.5$ (bottom right). The green, turquoise, red, purple, orange, blue and yellow exclusions correspond to the searches for $a \to \mu^+\mu^-$ [25], $pp \to ab\bar{b} \to \tau^+\tau^- b\bar{b}$ [26], $pp \to a \to \gamma\gamma$ [28], $pp \to a \to \tau^+\tau^-$ [30] and $\Upsilon(1S) \to a\gamma \to \mu^+\mu^-\gamma$ [32], the measurements of Υ production [15, 34] and the inclusive dimuon cross section [36], respectively. The dashed black lines indicate $|s_\theta| = 1$ and all coloured regions are excluded at 95% CL apart from the orange and yellow contours which only hold at 90% CL.