Recent Results on Dark Photon Search at the LHC

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2024.8.24-27, Kunming, Yunnan

Dark photons

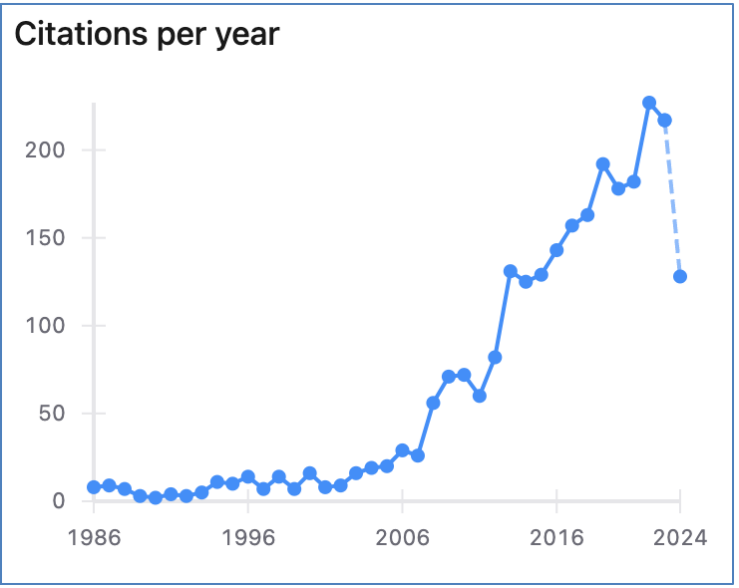
- Dark photon was originally proposed as a hypothetical vector boson that couples to charged particles only through kinetic mixing

Two U(1)'s and Epsilon Charge Shifts

Bob Holdom (Toronto U.)
Oct, 1985

3 pages
Published in: *Phys.Lett.B* 166 (1986) 196-198
Published: 1986
DOI: 10.1016/0370-2693(86)91377-8
Report number: UTPT-85-30
View in: ADS Abstract Service

cite claim reference search 2,560 citations



$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{A'}$$

$$\mathcal{L}_{A'} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}B_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m^2_{A'}A'_{\mu}A'^{\mu}$$

ϵ: kinetic mixing term
$B^{\mu\nu}$: hyper charge field strength
$F'^{\mu\nu}$: $U'(1)$ field strength

Dark photons

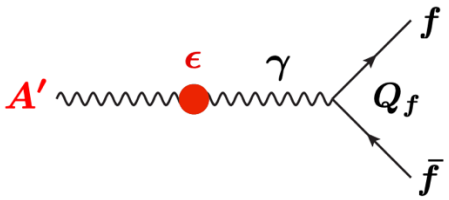
- Many similar particles to the original dark photon have been proposed, with different names in various contexts
  - Dark photons: massive A', massless γ_D via the kinematic mixing coupling
  - Extra gauge bosons: direct gauge coupling
    - Z': $U(1)_{B-L}$ Z', $U(1)_{L_\alpha - L_\beta}$ Z' ($\alpha, \beta \in \{e, \mu, \tau\}$, B: baryon number, L_α lepton flavor number)
  - Hidden sectors:
    - Dark Z bosons: Z_D via the Higgs $H - H_D$ mixing coupling
    - Dark photon dark matter models
- The common feature of these particles: New massive force mediator of new Abelian gauge symmetry $U'(1)$ (or $U(1)_D$)
- In this talk, all these new force mediators are referred as dark photons

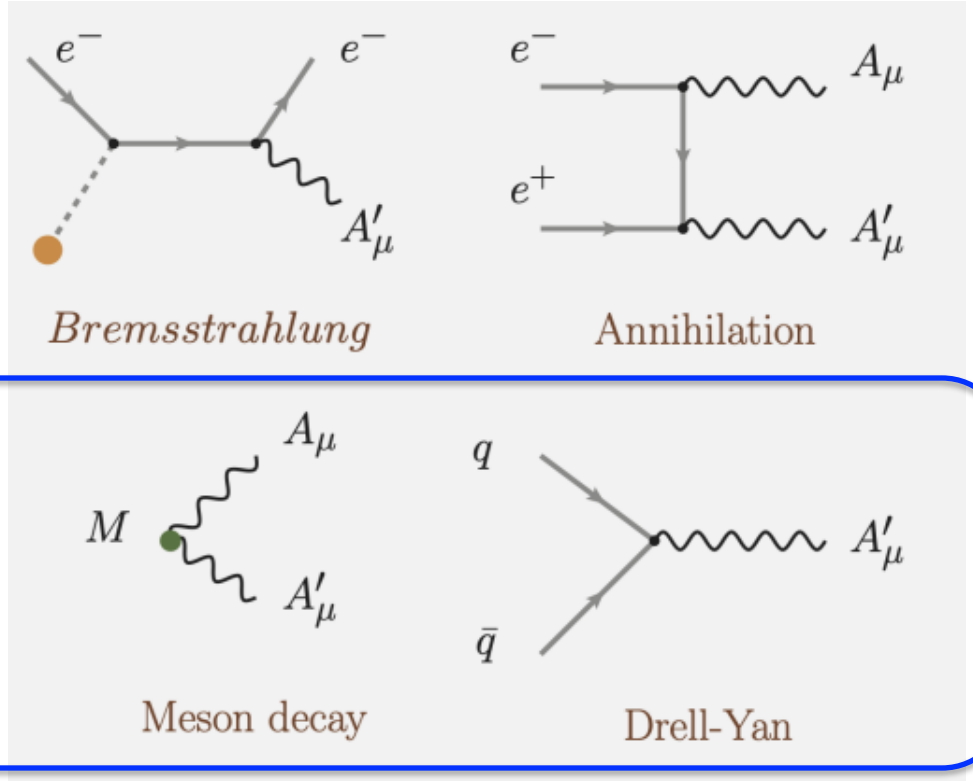
For the topic of massless A', see Vu Ngoc Khanh's talk

Minimal dark photon models: massive A'

Minimal A'

- No direct interaction between dark photon and the SM fermions exists
- Dark photon can couple to the SM fermions through the kinetic mixing
- Only two free parameters: $m_{A'}, \epsilon$
- Production: Bremsstrahlung, Annihilation, Meson decay and Drell-Yan





Targets at the LHC

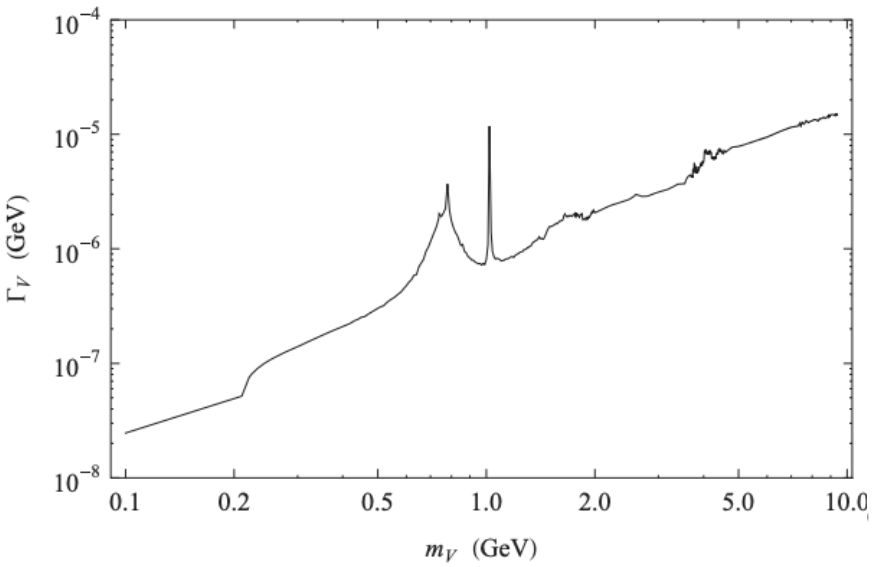
Emidio Gabrielli et al, arXiv:2005.01515

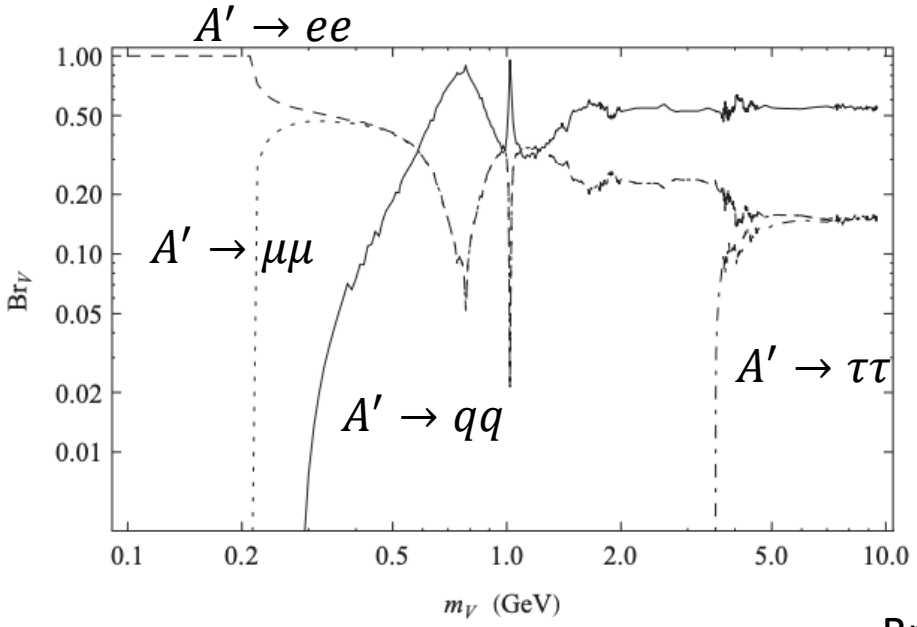
Minimal A'

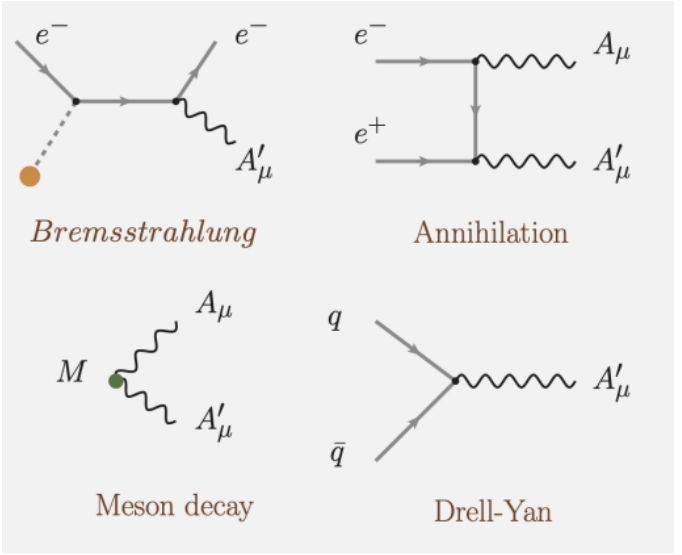
- Decay: $A' \to ff$

$$\Gamma(A' \to \ell^+\ell^-) = \frac{1}{3}\alpha\,\varepsilon^2 m_{A'}\sqrt{1-\frac{4m_\ell^2}{m_{A'}^2}}\left(1+\frac{2m_\ell^2}{m_{A'}^2}\right)$$

$$\Gamma(A' \to \text{hadrons}) = \frac{1}{3}\alpha\varepsilon^2 m_{A'}\sqrt{1-\frac{4m_\mu^2}{m_{A'}^2}}\left(1+\frac{2m_\mu^2}{m_{A'}^2}\right)R$$







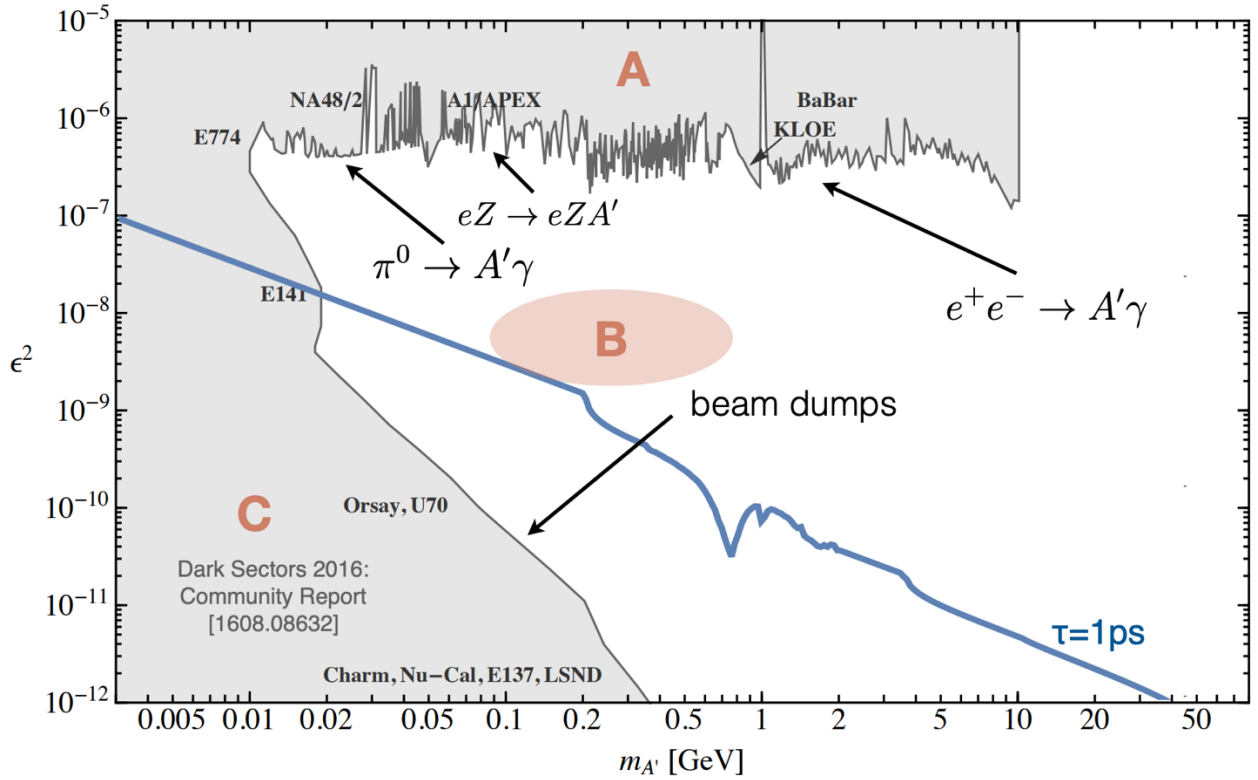
$$R \equiv \sigma_{e^+e^-\to\text{had}}/\sigma_{e^+e^-\to\mu^+\mu^-}$$

Brian Batell et al, arXiv:0903.0363

Minimal A': experimental searches

- Experimental search: $A' \to ff$ resonances in beam-dump, fixed target, and collider experiments $(pp, p\bar{p}, ee)$
- Prompt searches
  - Sensitive to shorter lifetimes
  - Bump hunt on large background
- Displaced searches
  - Sensitive to longer lifetimes
    - smaller ϵ region
  - Background free

$$\tau_{A'} \propto [m_{A'}\epsilon^2]^{-1}$$

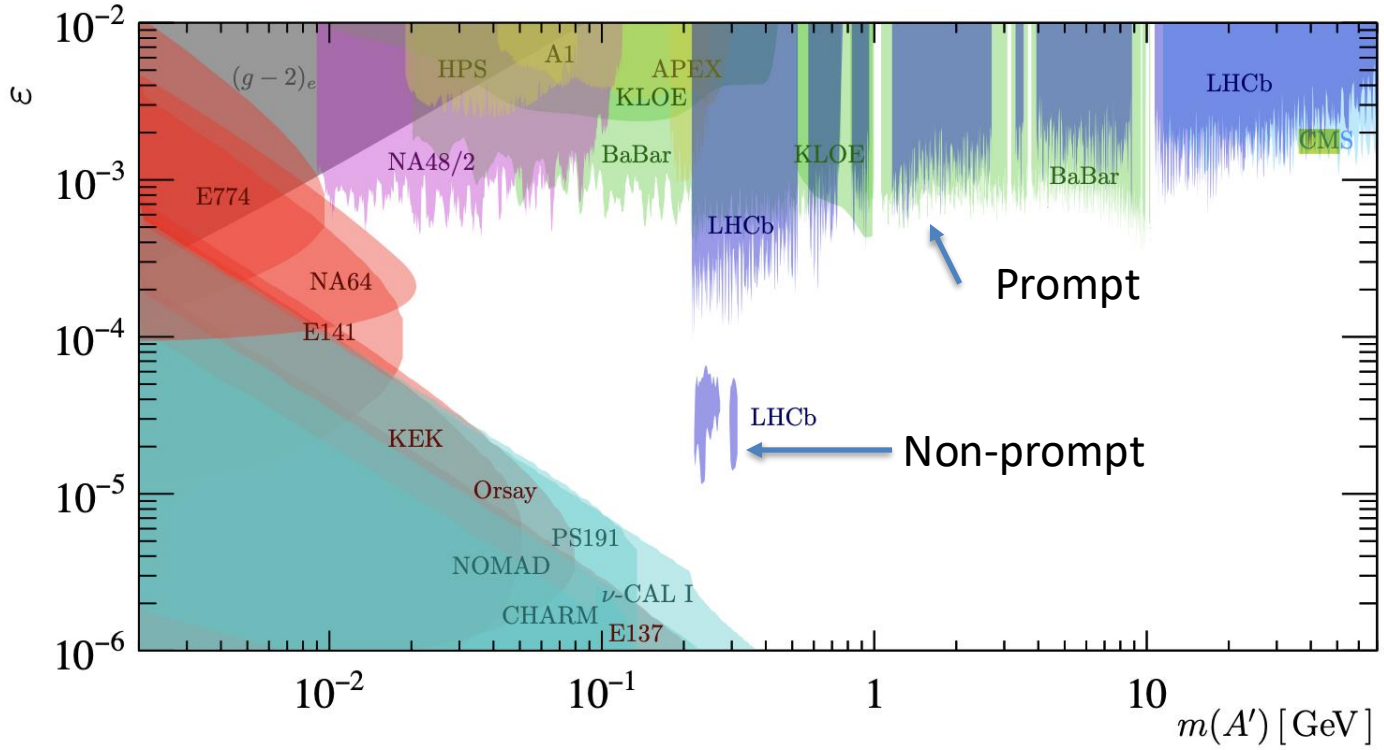


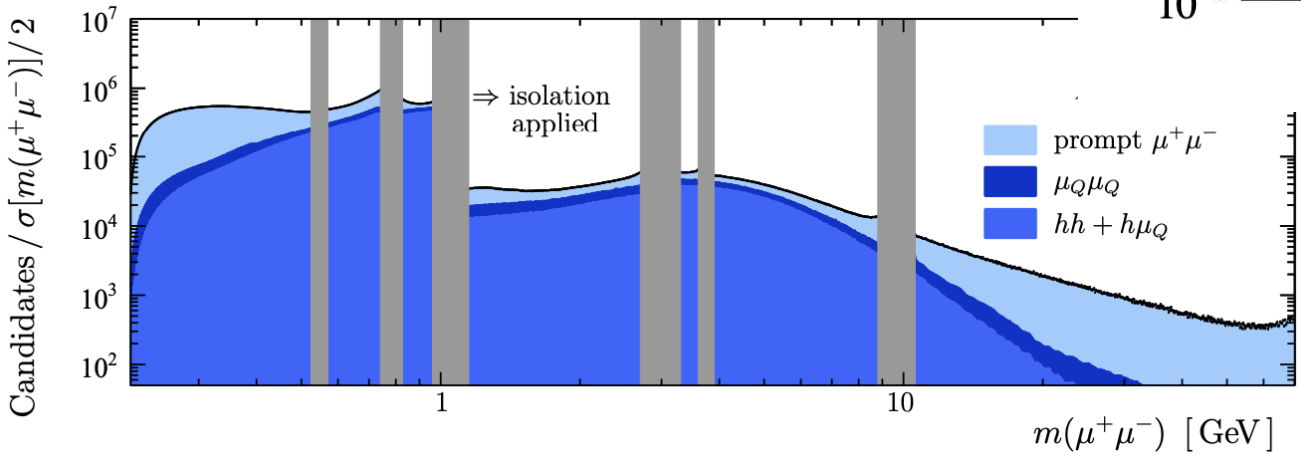
- **A**: bump hunts
- **B**: displaced vertex searches, short decay lengths
- **C**: displaced vertex searches, long decay lengths

LHCb $A' \to \mu\mu$ search

PRL 124, 041801 (2020)

- Used 5.5fb^{-1} Run2 data
- Prompt searches
  - Meson decays : $m_{A'} < 1\ GeV$
  - Drell-Yan: $m_{A'} > 1\ GeV$
- Displaced searches (0.1 – 1cm) for long lived A' search
  - $214 < m_{A'} < 350\ MeV$

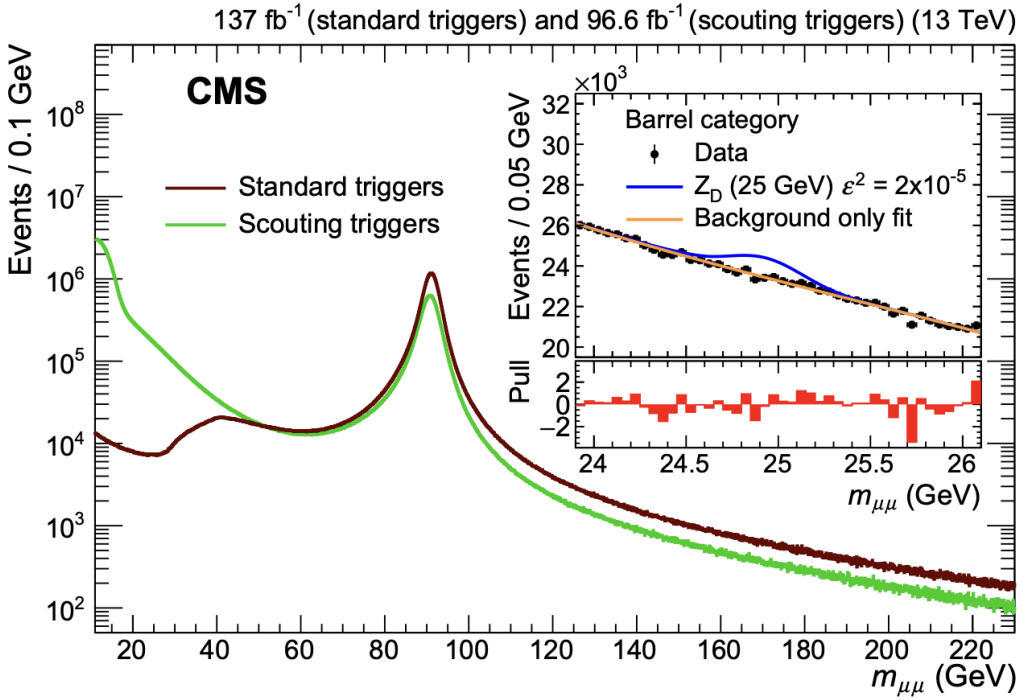


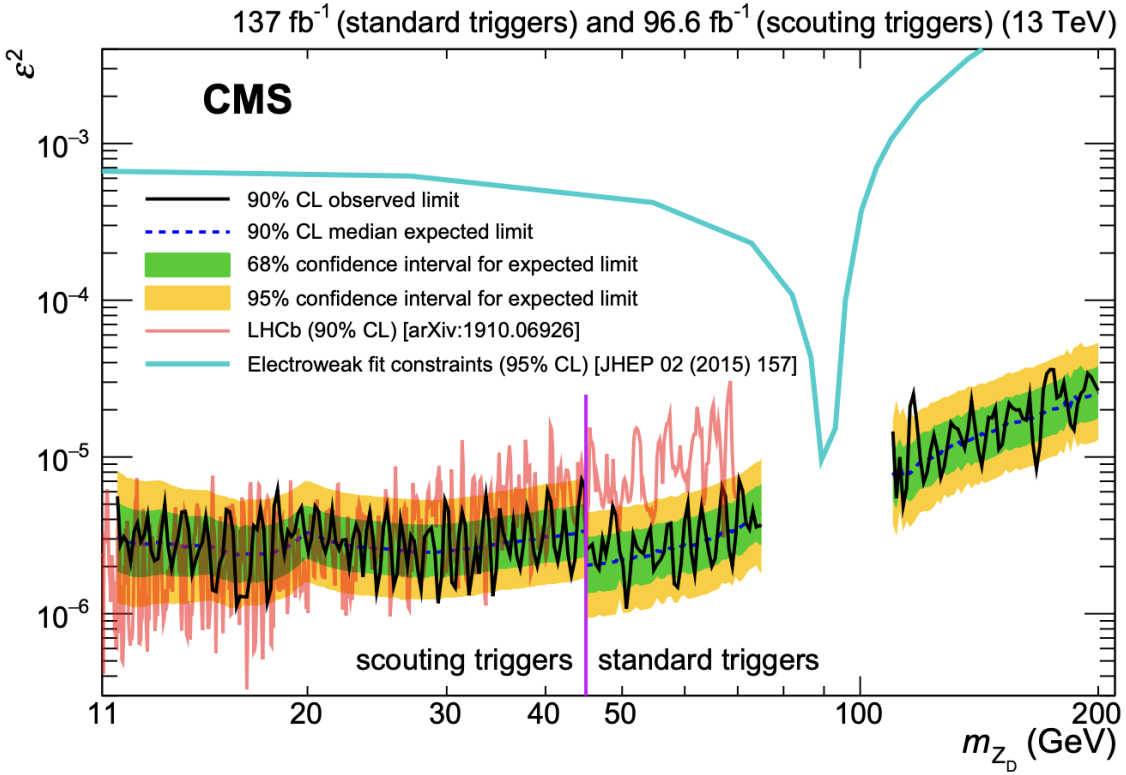


CMS $A' \to \mu\mu$ prompt search

PRL 124, 131802 (2020)

- Data driven search for a narrow dimuon resonance in [11.5, 200] GeV
  - Bump hunt on the dimuon mass using analytical signal and background PDFs
  - The [45, 75] GeV and [110, 200] GeV resonance mass ranges exploiting conventional triggers
  - The [11.5, 45] GeV mass range relying on scouting triggers
    - A dedicated high-rate trigger stream that records events with two muons but does not include the full event information

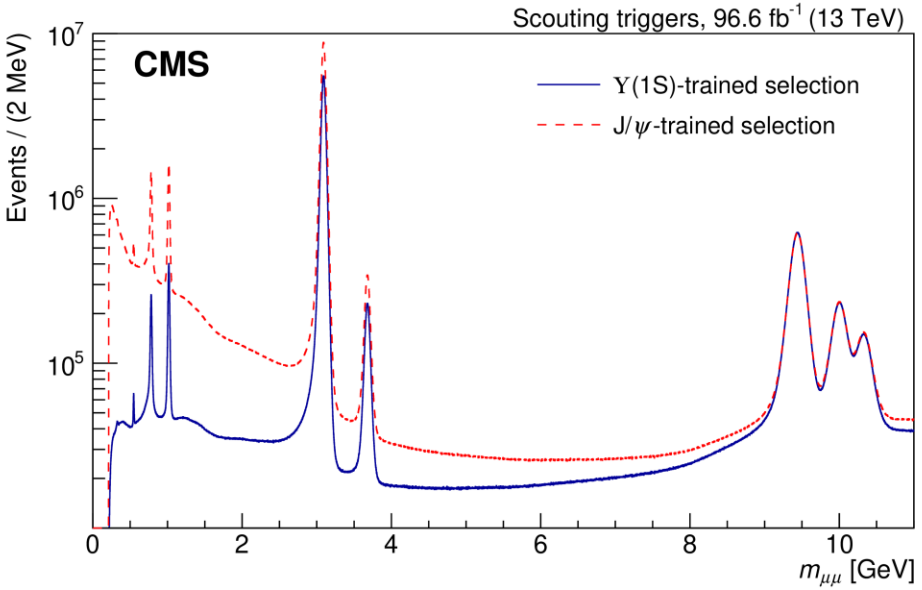


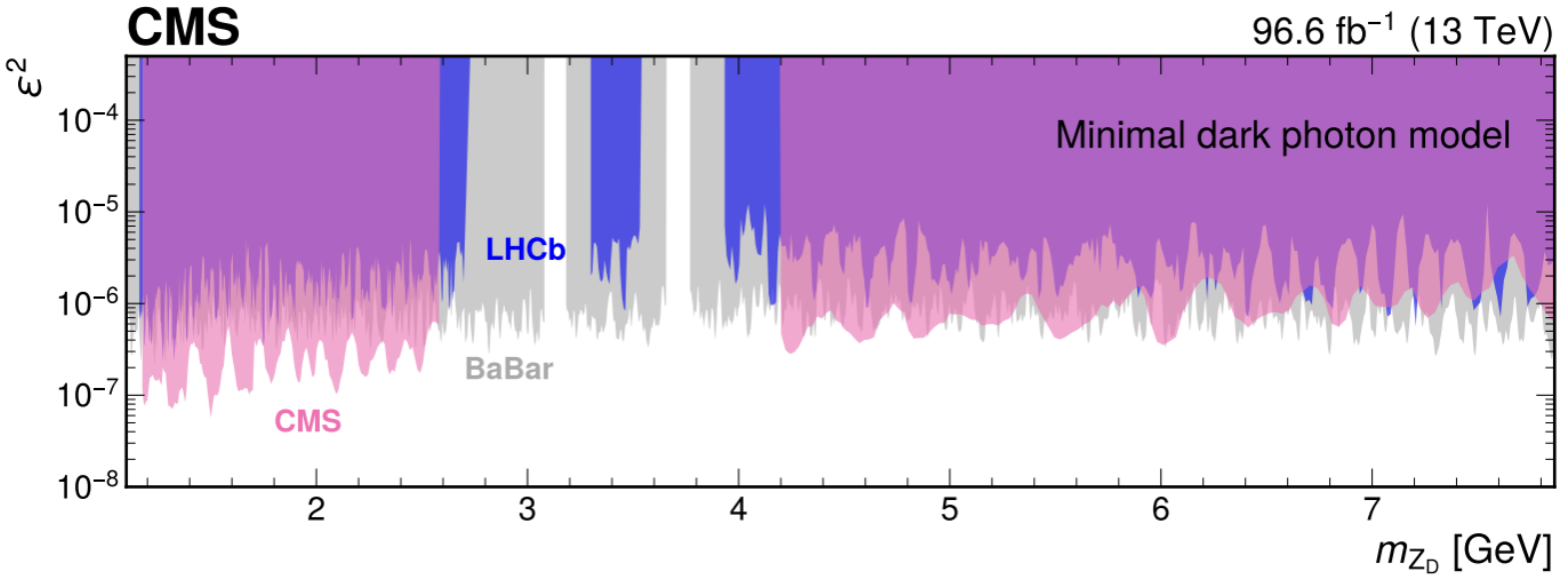


CMS $A' \to \mu\mu$ prompt search (2)

JHEP 12 (2023) 070

- Search for GeV-scale $A' \to \mu\mu$ ([1, 8] GeV)
- Use scouting data with trigger p_T threshold down to 3 GeV





Extra gauge bosons: Z’

$L_\mu - L_\tau$ Z'

- Beyond the minimal model, dark photon can have direct interactions with the SM particles
- Well motivated and studied symmetries are
  - $U(1)_{B-L}$ Z'
  - $U(1)_{L_\alpha - L_\beta}$ Z'

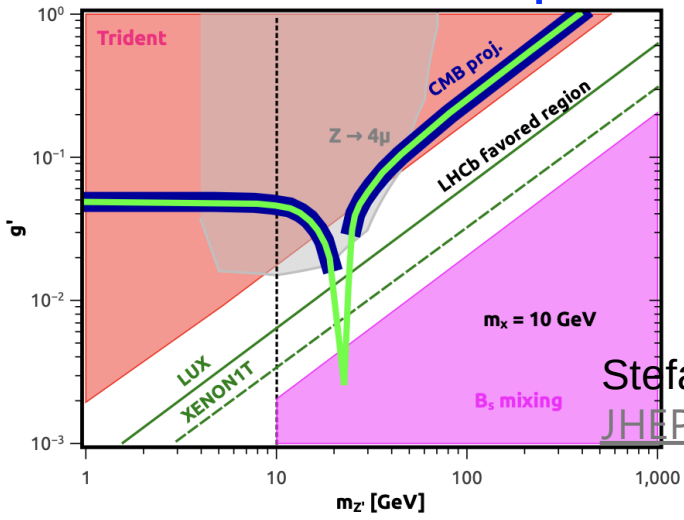
B: baryon number, L_α lepton flavor number
$\alpha, \beta \in \{e, \mu, \tau\}$,

$$L_{Z'} = -\frac{1}{4}F_{\alpha\beta}F^{\alpha\beta} + \frac{1}{2}M_{Z'}^2 Z'^\alpha Z'_\alpha - g_{Z'} Z'_\alpha (\bar{\ell}_2 \gamma^\alpha \ell_2 + \bar{\mu}\gamma^\alpha \mu - \bar{\ell}_3 \gamma^\alpha \ell_3 - \bar{\tau}\gamma^\alpha \tau),$$

- Less constrained and almost anomaly free
  - Possible explanation of muon g-2 and flavor anomalies

Xiao-Gang He *et al*, PRD 44 (1991) 2118-2132

- $L_\mu - L_\tau$ Z' is particularly interesting since it is the least constrained experimentally
  - Z' only couplings to $\mu, \tau, \nu_\mu, \nu_\tau$
- Only two free parameters: $m_{Z'}$, g
- Produced in Drell-Yan production at the LHC
  - Rare Z decays: $pp \to Z^{(*)} \to Z'\mu\mu$
  - Rare W decays: $pp \to W^{\pm(*)} \to Z'\mu\nu$

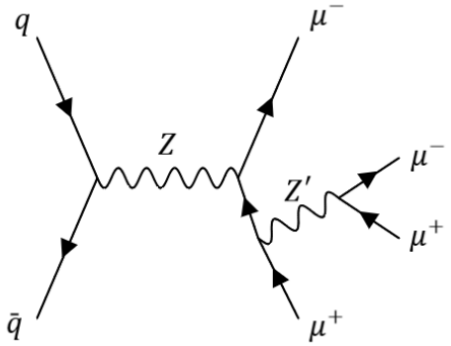


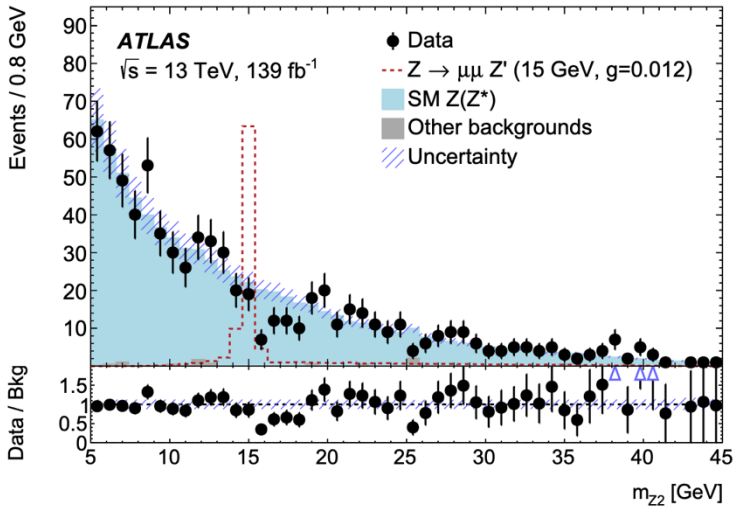
Stefano Profumo et al, JHEP12(2016)106

ATLAS $L_\mu - L_\tau$ Z' search in rare Z decay

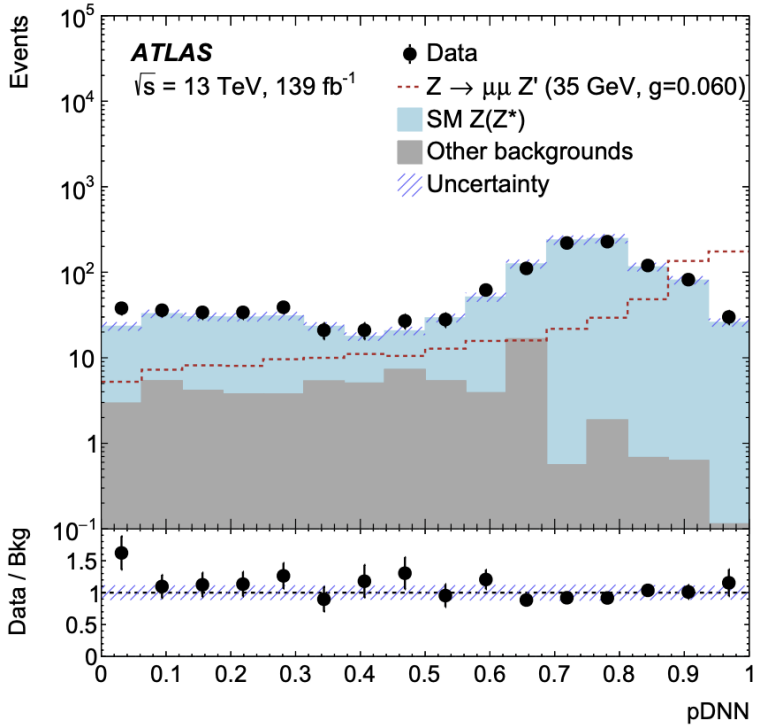
- 4μ final state: $pp \to Z^{(*)} \to Z'\mu\mu \to 4\mu$

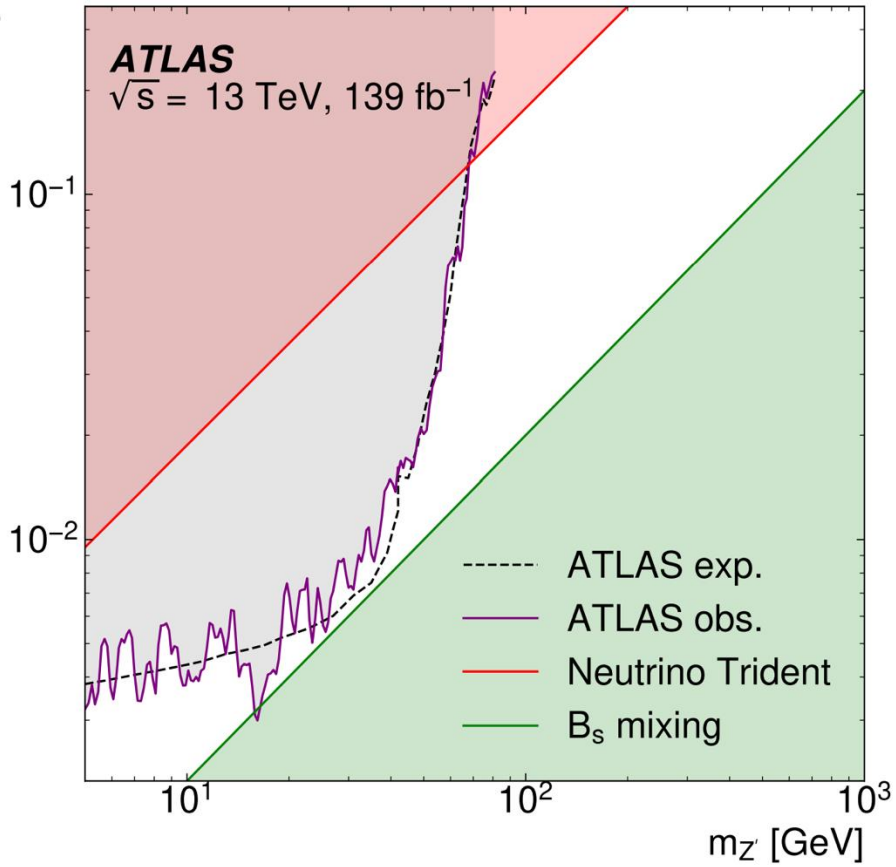
JHEP 07 (2023) 90





A mass $m_{Z'}$ parameterized Deep Neural Network (pDNN) is used

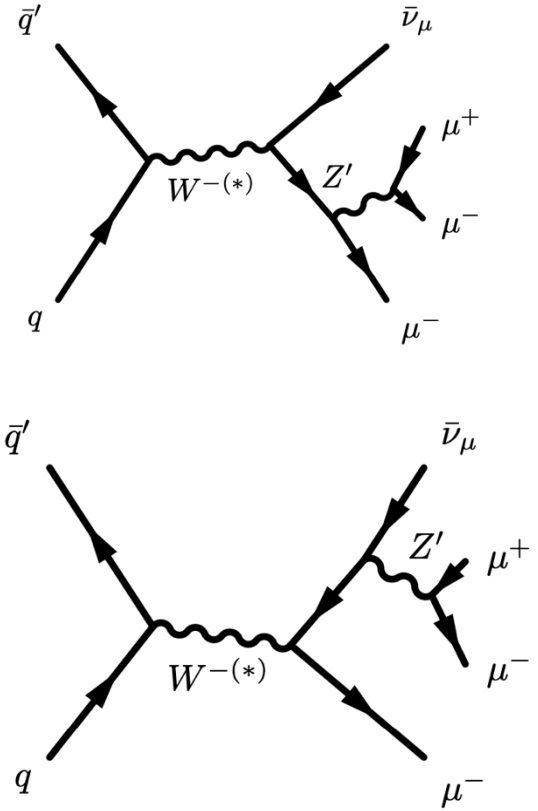


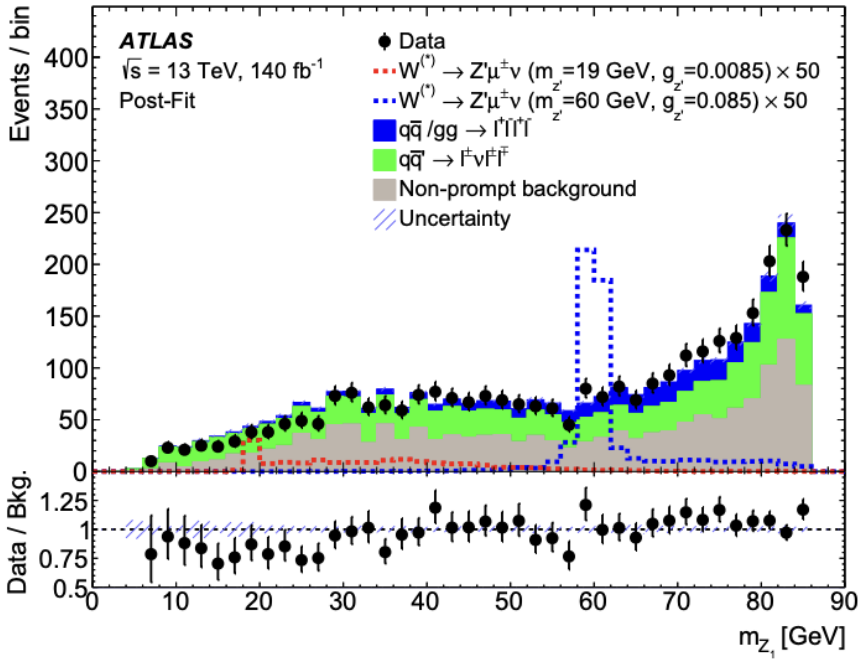


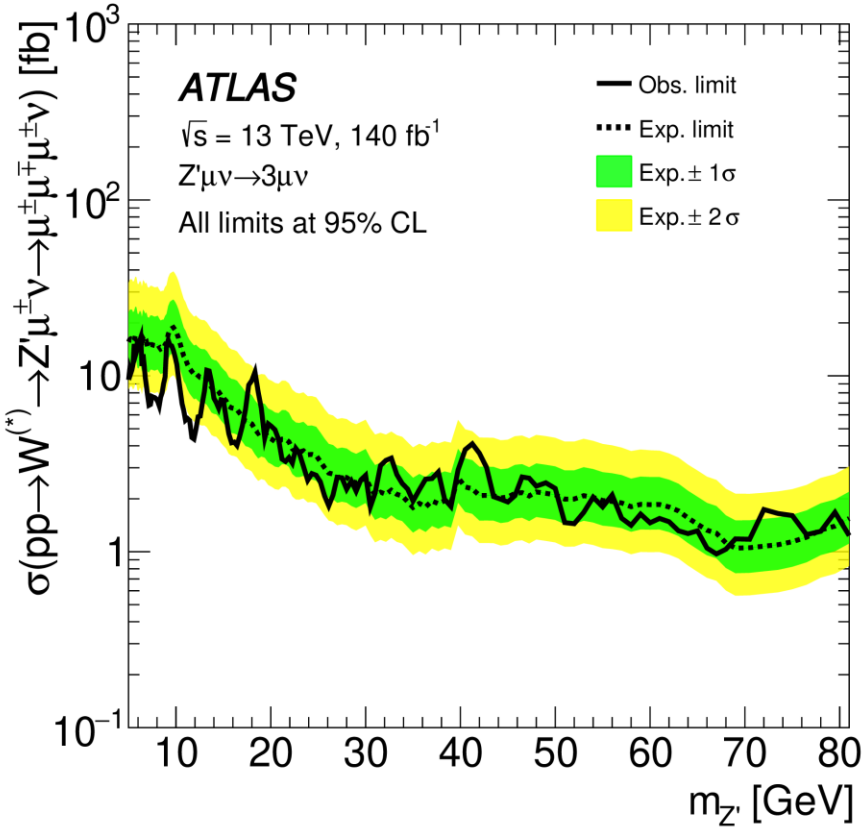
ATLAS $L_\mu - L_\tau$ Z' search in rare W decay

- 3μ final state: $pp \to W^{\pm(*)} \to Z'\mu\nu \to \mu\mu\mu\nu$

arXiv:2402.15212





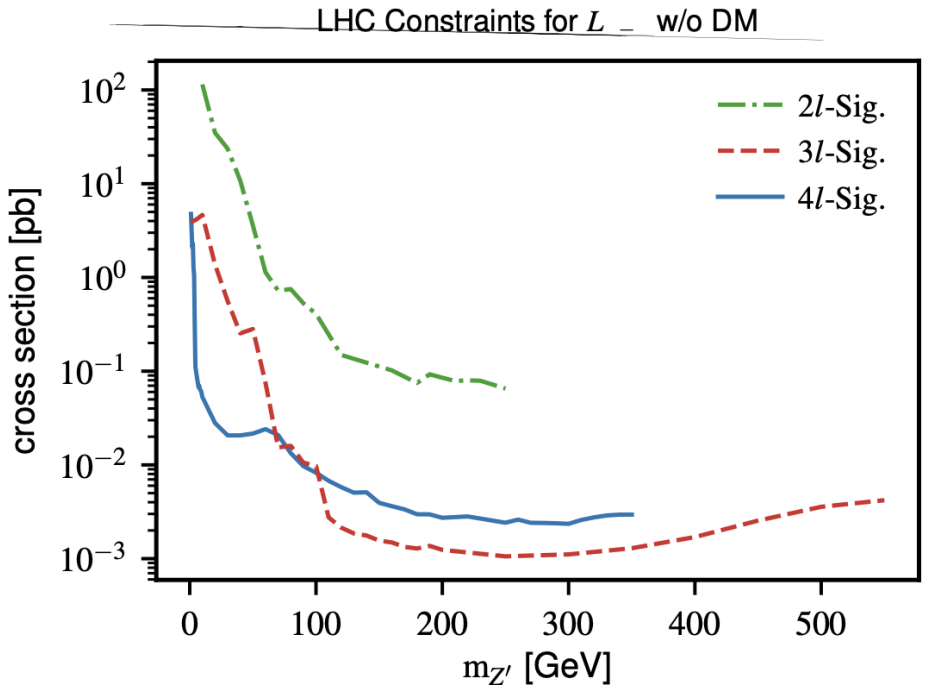


Model-independent limits

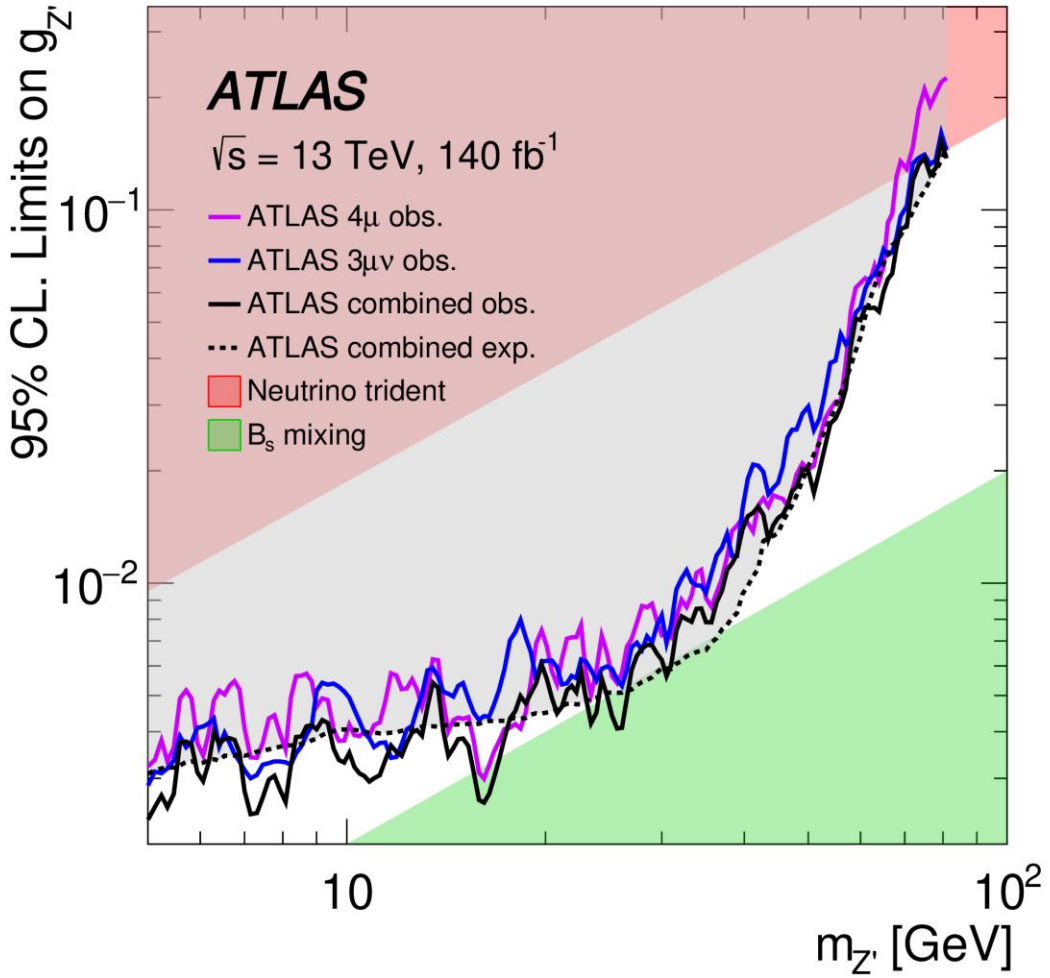
ATLAS $L_\mu - L_\tau$ Z' search

- Statistical combination of 3μ and 4μ final states

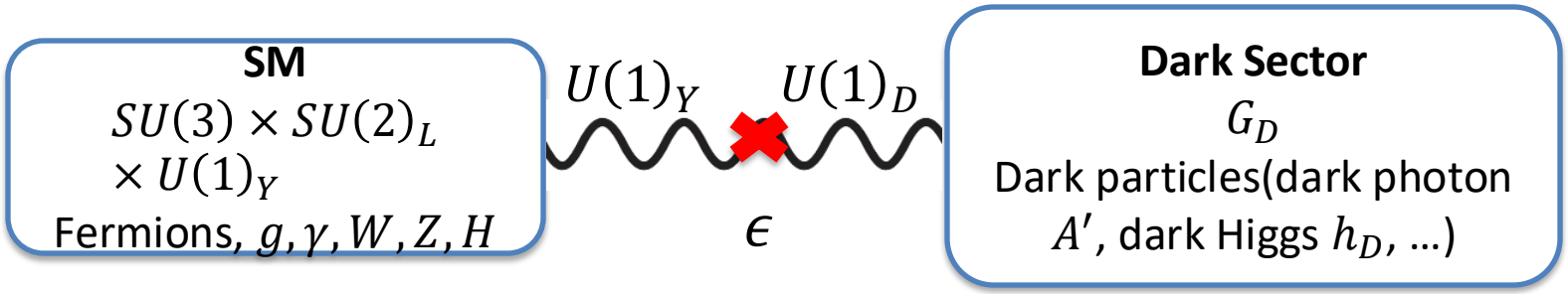
arXiv:2402.15212



Manuel Drees et al, *PLB 791 (2019) 130-136*



Hidden sectors:
Dark Higgs, Dark Matter



The Higgs portal

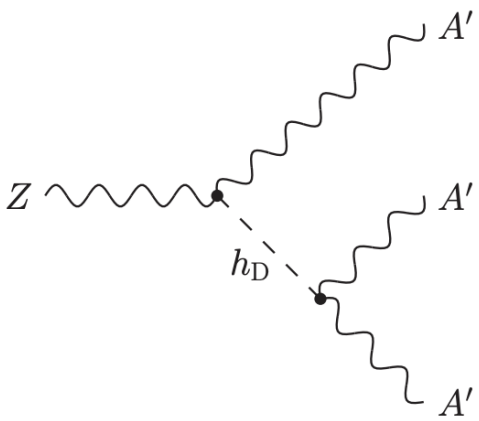
- Mass of dark photon indicates that $U(1)_D$ is spontaneously broken
- A' can acquire a mass from a dark Higgs mechanism → A new scalar (dark Higgs boson, H_D)

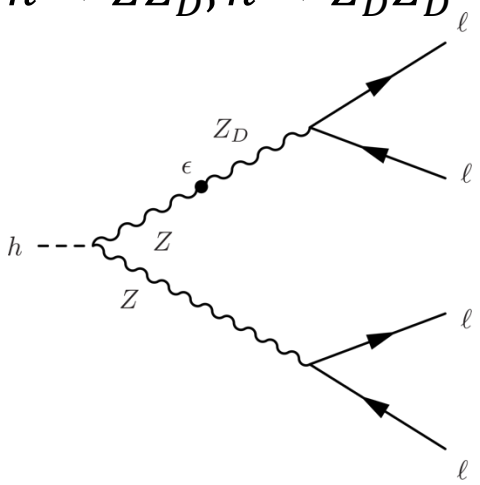
$$V(H, H_D) = -\mu_H^2|H|^2 - \mu_{H_D}^2|H_D|^2 + \kappa|H|^2|H_D|^2 + \lambda|H|^4 + \lambda_D|H_D|^4$$

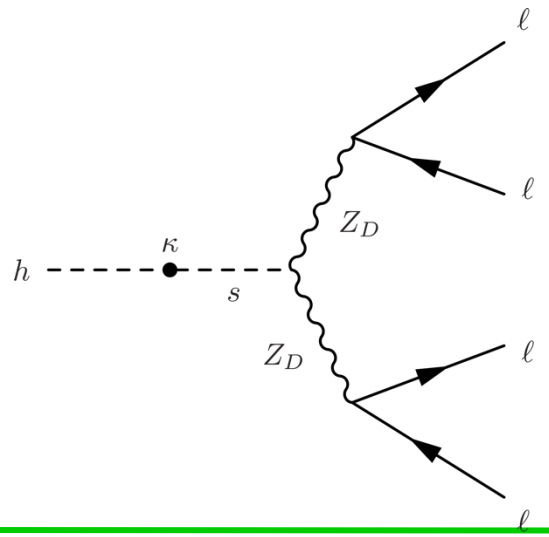
κ: mixing between the SM Higgs and the dark Higgs

- Give rise to rich phenomenology
  - Rare Z boson decays: $Z \to A' h_D$
  - Rare Higgs boson decays: $h \to ZZ_D, h \to Z_D Z_D$

David Curtin et al, arXiv:1412.0018



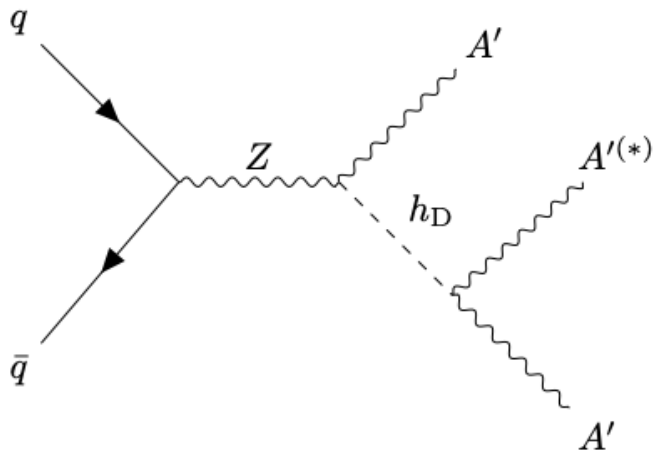




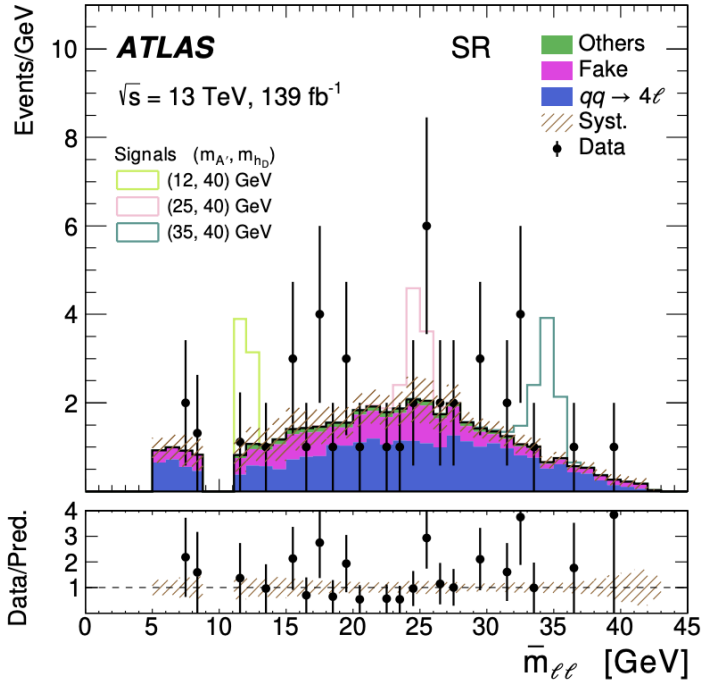
ATLAS A' search in rare Z decays

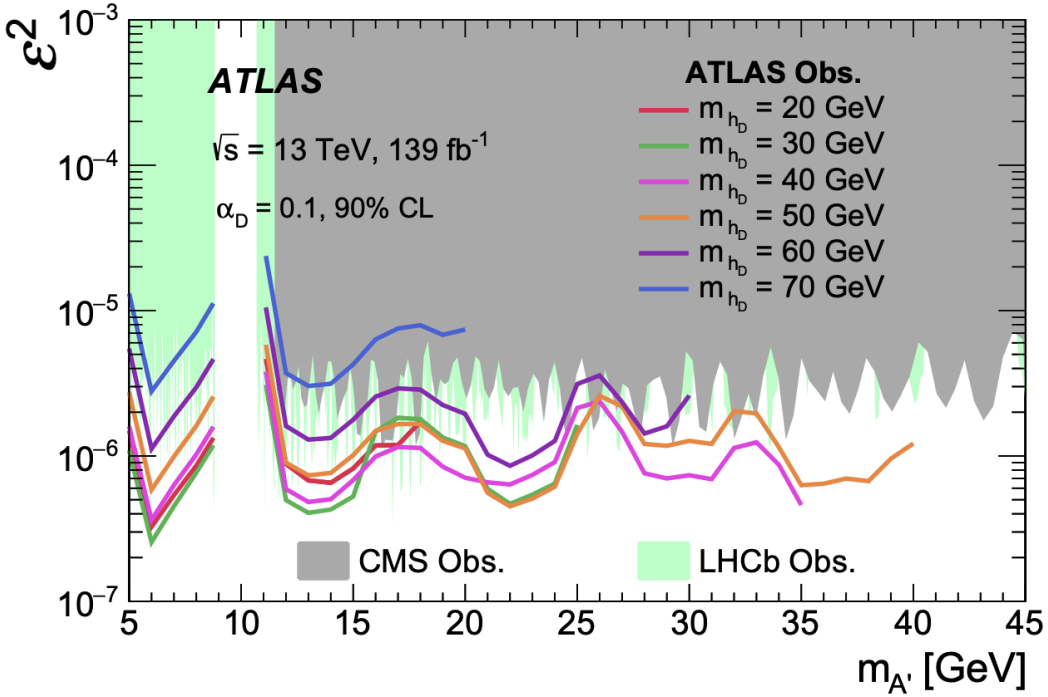
- Dark Higgs-strahlung process in $Z \to A' h_D, h_D \to A' A'^{(*)}, A' \to ff$
  - Final state: $4l + X\ (4e, 4\mu, 2e2\mu)$
  - $m_{h_D} > 2m_{A'}$: three on-shell A'
  - $m_{A'} < m_{h_D} < 2m_{A'}$: two on-shell A'

PRL 131 (2023) 251801



$$\bar{m}_{\ell\ell} = (m_{\ell_1\ell_2} + m_{\ell_3\ell_4})/2$$

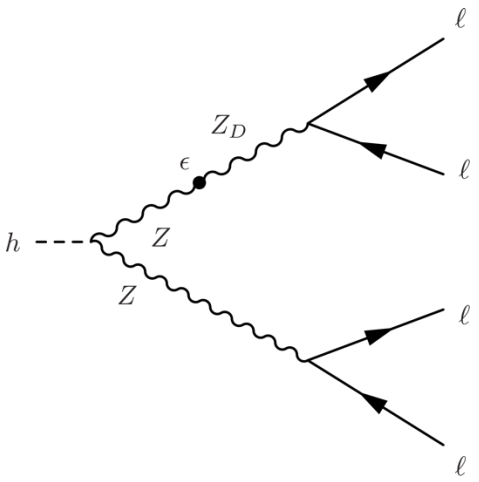


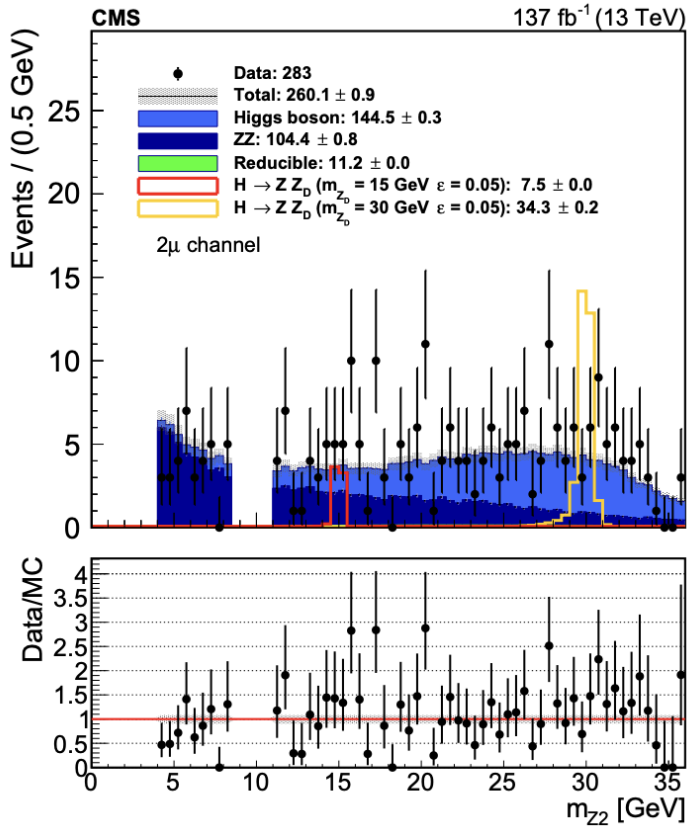


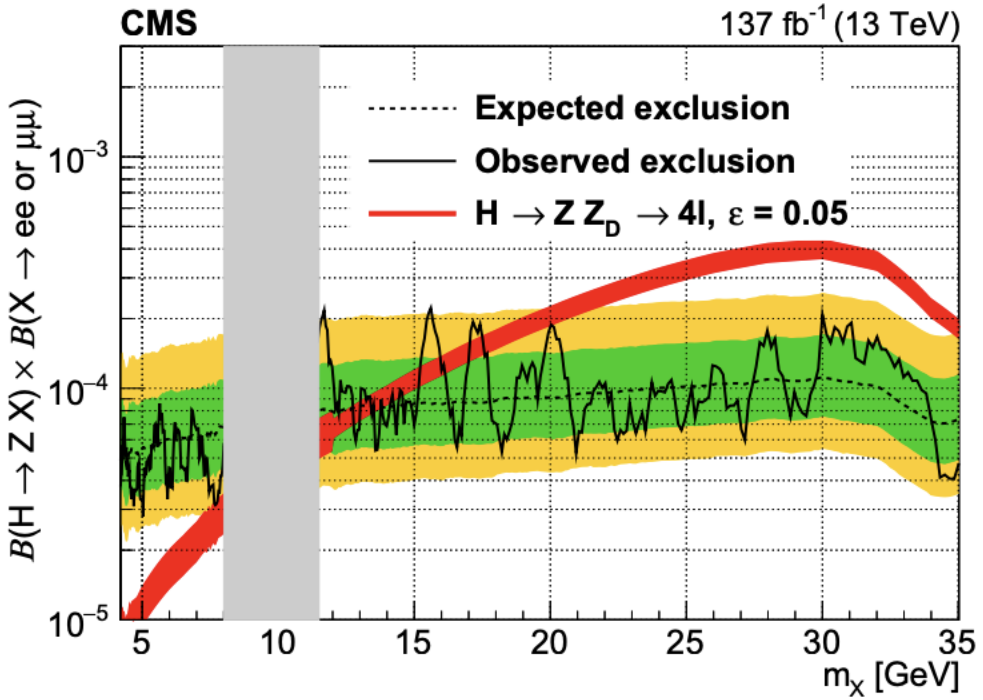
CMS A' search in rare Higgs decays

- $h \to ZZ_D$: through $Z - Z_D$ mixing, the kinetic-mixing parameter ϵ
  - $118 < m_{4l} < 130\ GeV, 40 < m_{Z1} < 120\ GeV$

EPJC 82 (2022) 290





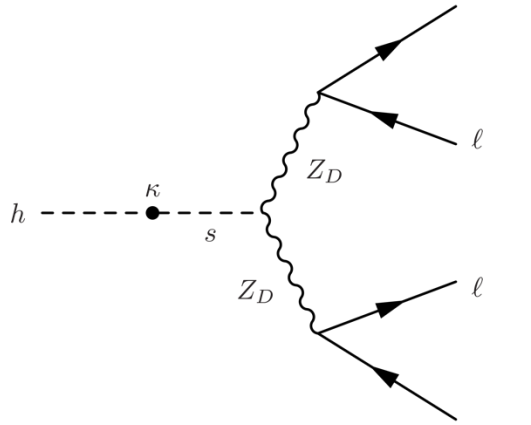


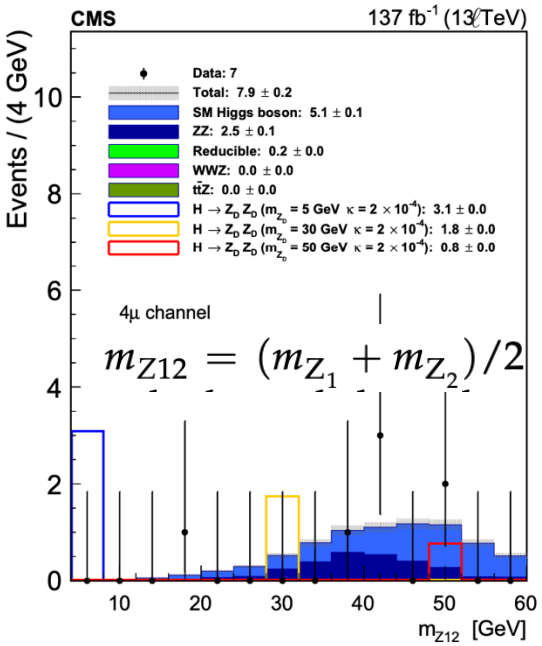
Model-independent limits

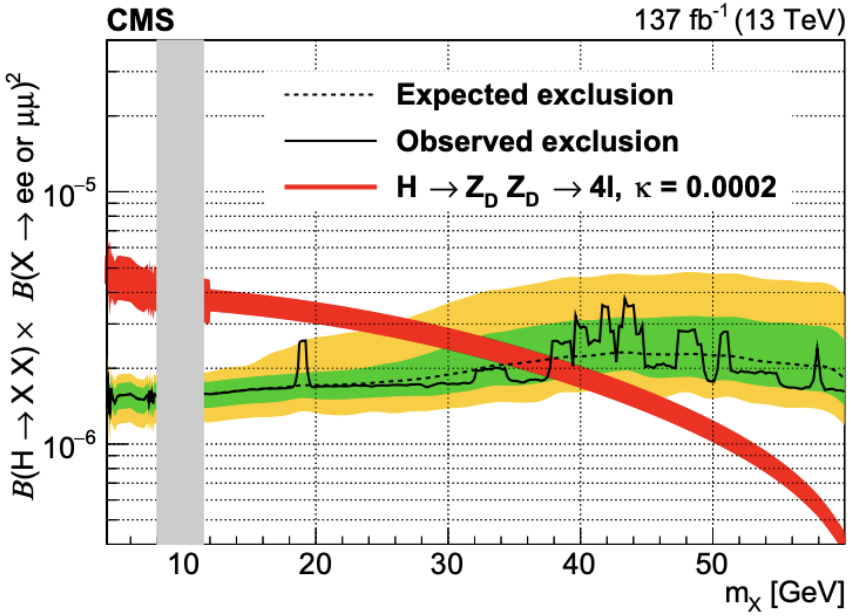
CMS A' search in rare Higgs decays

- $h \to Z_D Z_D$: through $h - h_D$ mixing, the Higgs mixing parameter κ
  - $118 < m_{4l} < 130\ GeV, 4 < m_{Z1}, m_{Z2} < 62.5\ GeV$

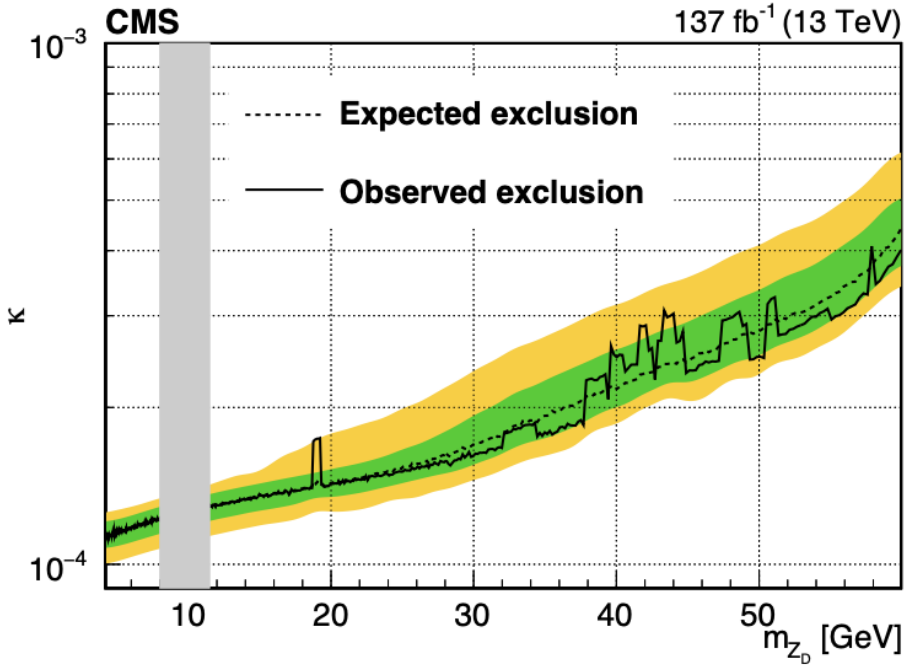
EPJC 82 (2022) 290







Model-independent limits

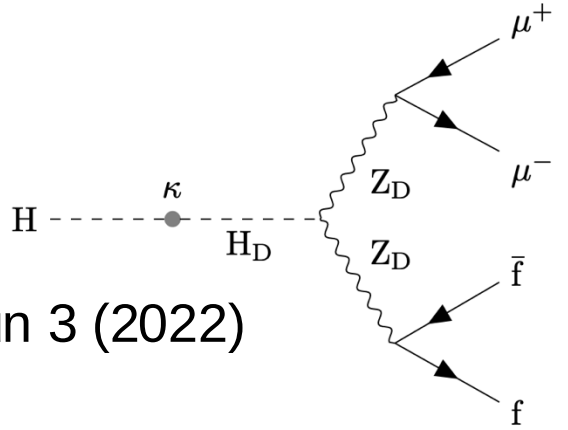


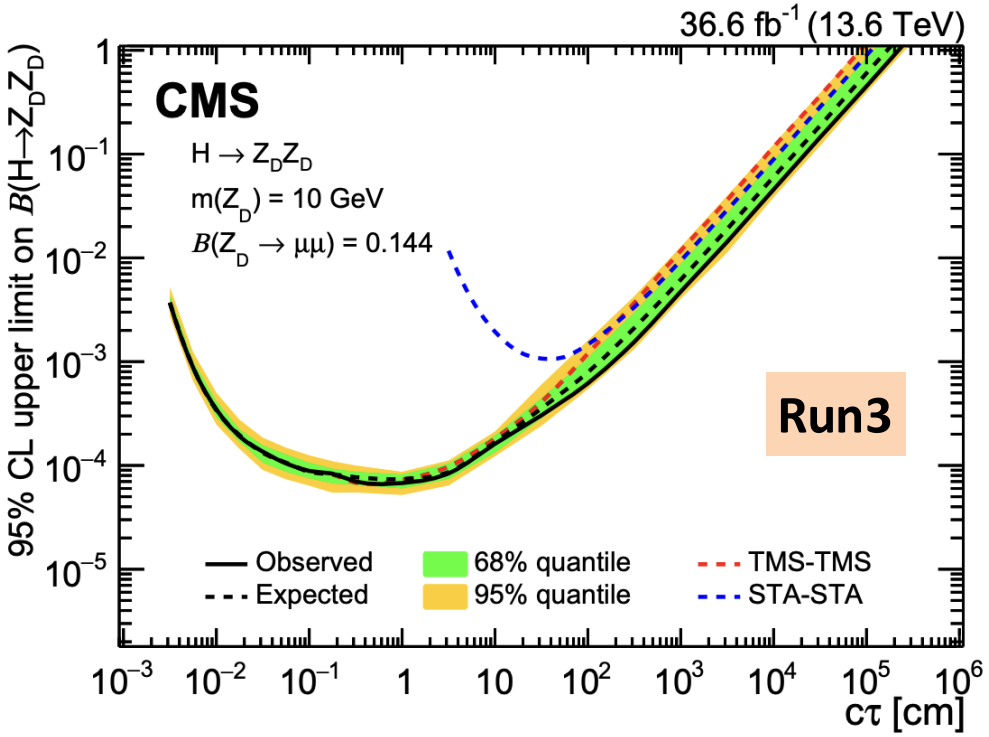
Dark photon interpretation on the mixing κ (assume $\kappa \gg \epsilon$)

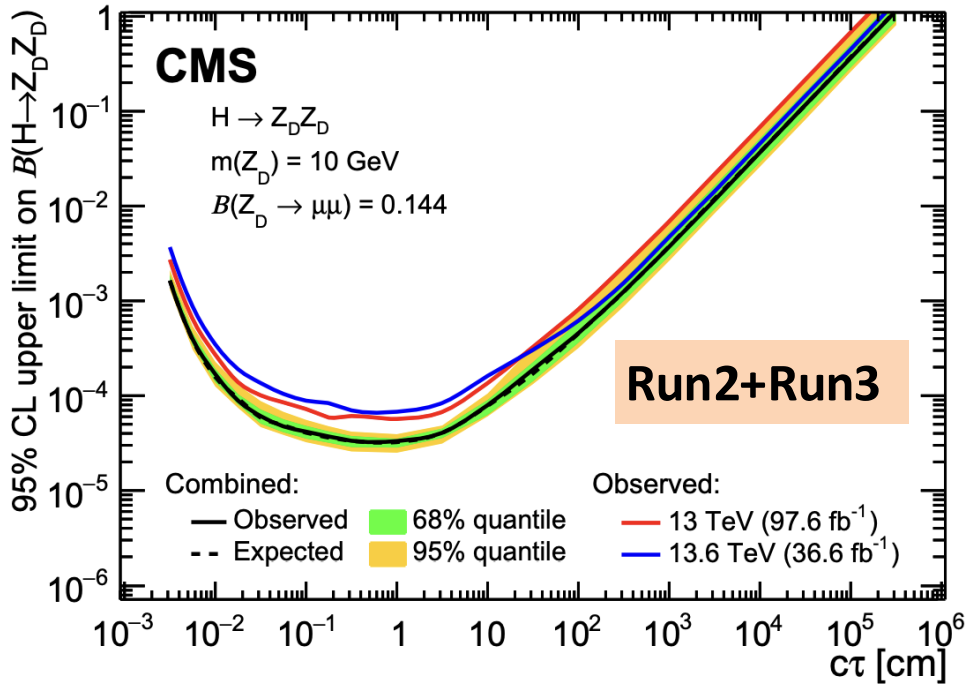
CMS A' non-prompt search

JHEP 05 (2024) 047

- Search for long-lived A' via the Higgs portal
- Use early Run3 data at 13.6 TeV (36.6 fb^{-1} collected in 2022)
- Run 3 trigger improvements to mitigate efficiency
  - Achieved similar sensitivity to Run 2 data with only 1/3 of the luminosity in Run 3 (2022)





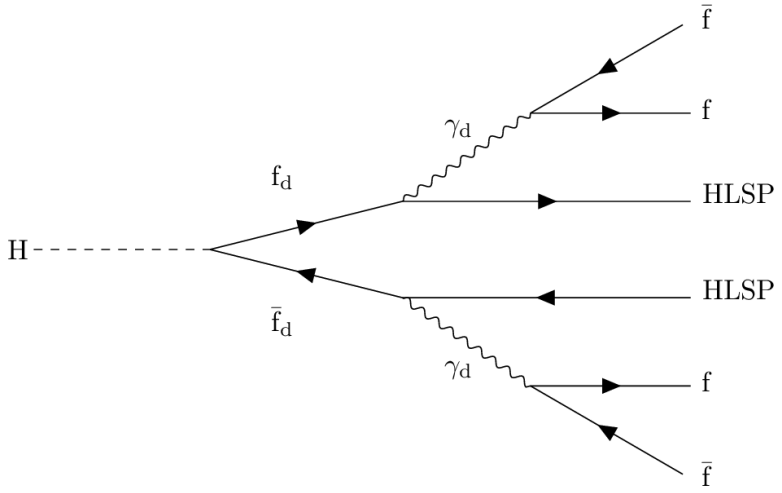


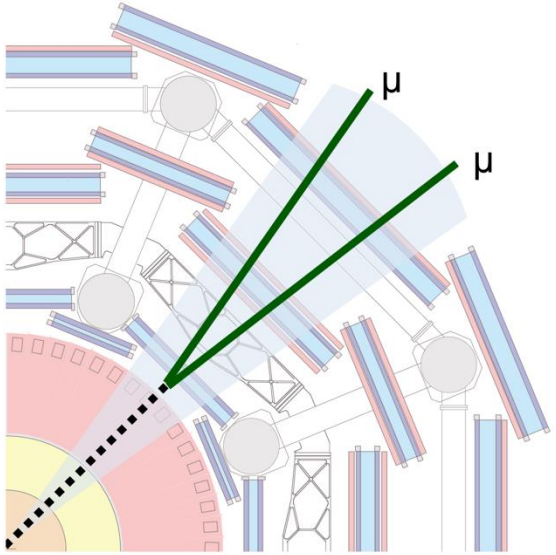
Signature：
- ≥ 1 displaced dimuon vertex

ATLAS A' non-prompt search

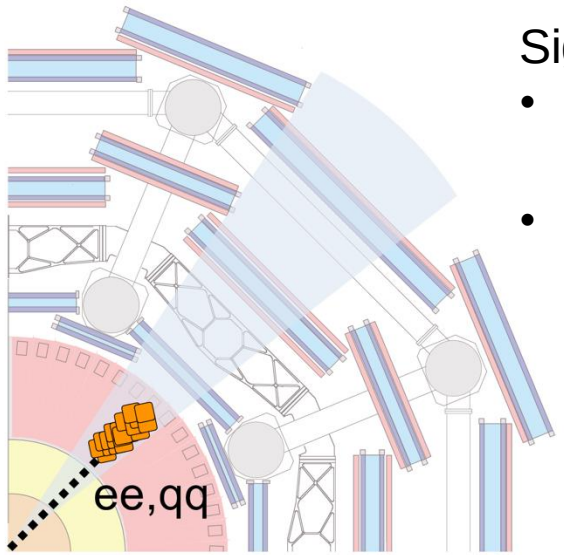
EPJC 84 (2024) 719

- Search for long-lived A' with $m_{A'} \in [0.1,15]\ GeV$ from exotic Higgs decays
- The Falkowski-Ruderman-Volansky-Zupan (FRVZ) model is used as a benchmark signal
  - Higgs decays into a pair of dark fermions $H \to f_d f_d$
  - f_d further decays into a long-lived A' and an undetected hidden lightest stable particle (HLSP):
    - Due to the large Lorentz boosts, A' decay products are collimated→ referred to as dark-photon jets (DPJ) (JHEP 06 (2023) 153)





muonic DPJ



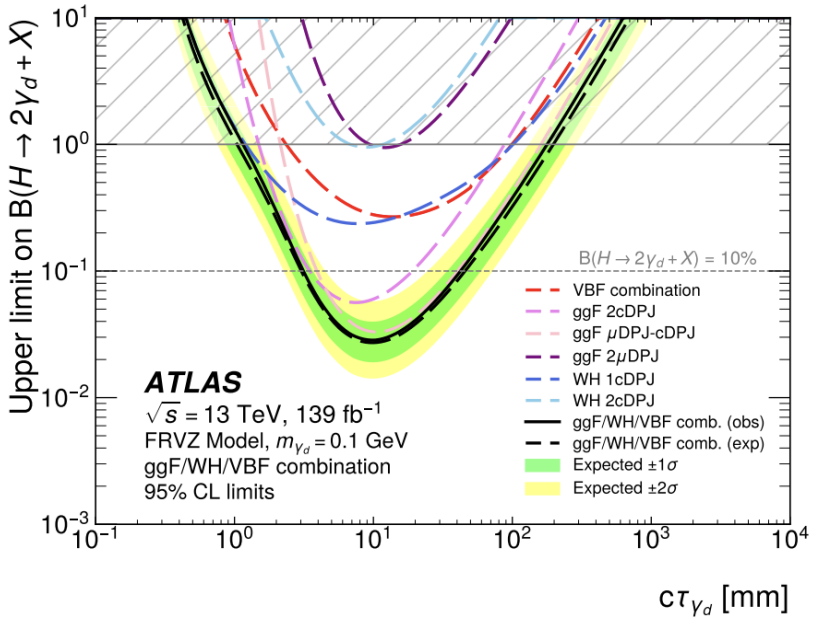
calorimeter DPJ

Signature：
- ≥ 1 displaced Dark Photon Jet (DPJ)
- $E_T^{miss} > 100\ GeV$

ATLAS A' non-prompt search

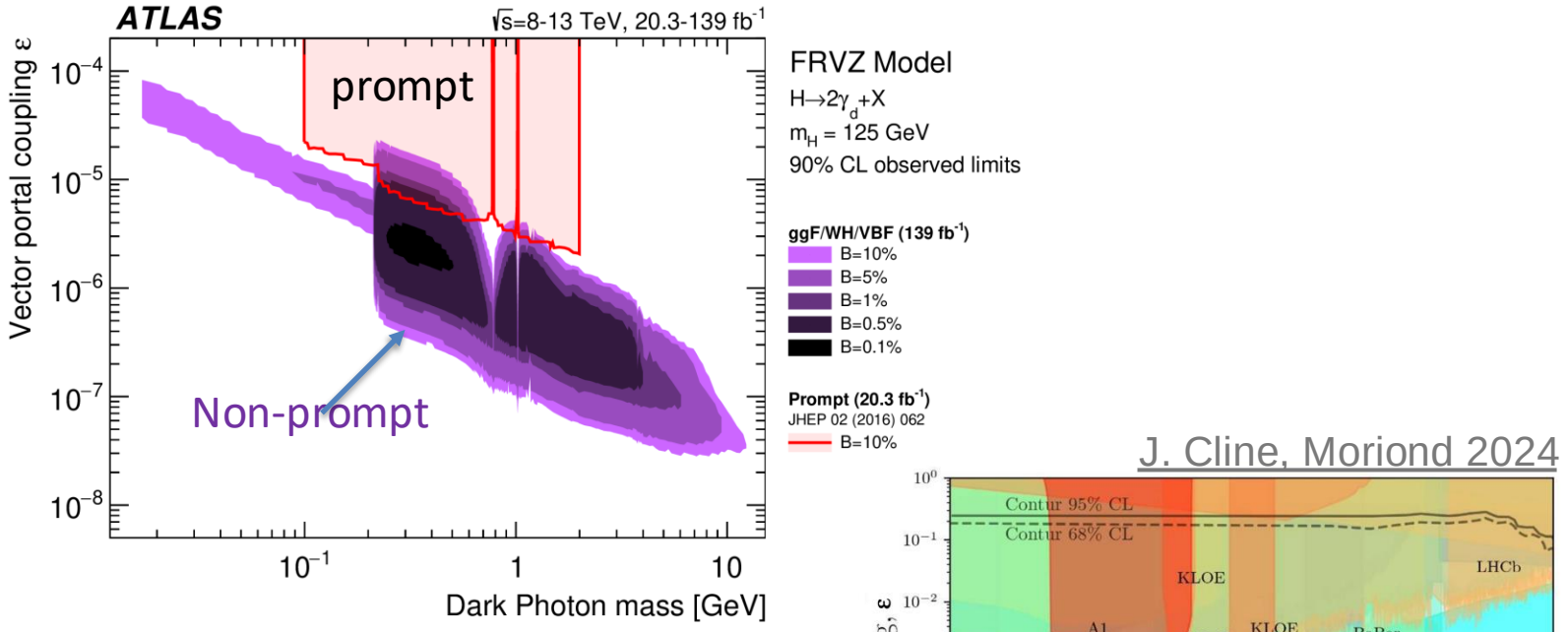
EPJC 84 (2024) 719

- Search for long-lived A' with $m_{A'} \in [0.1,15]\ GeV$ from exotic Higgs decays
- The Falkowski-Ruderman-Volansky-Zupan (FRVZ) model is used as a benchmark signal



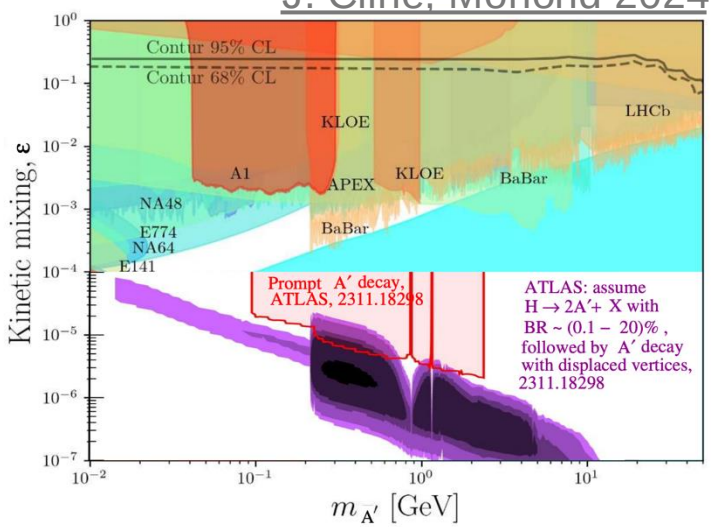
Combination of ggF/WH/VBF Higgs production

Model-independent limits



Dark photon limits (ϵ, $m_{A'}$), assuming different values of $B(H \to A'A' + X)$

J. Cline, Moriond 2024

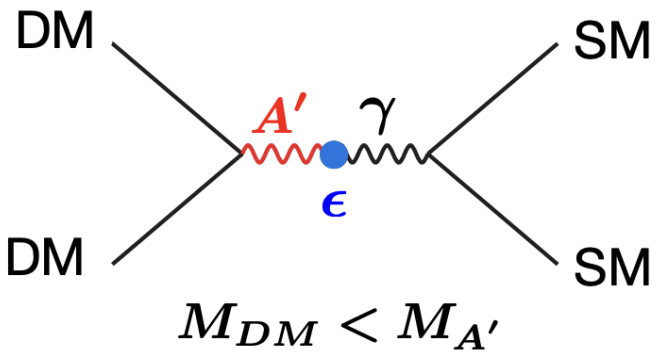


Invisible decays: $A' \to \chi\chi$

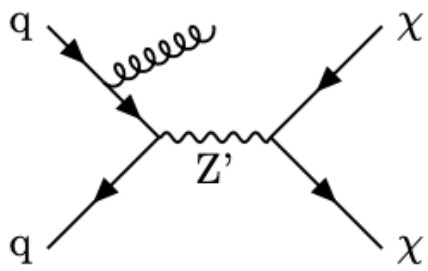
- The minimal dark sector model:

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{A'} + \mathcal{L}_{DM}$$

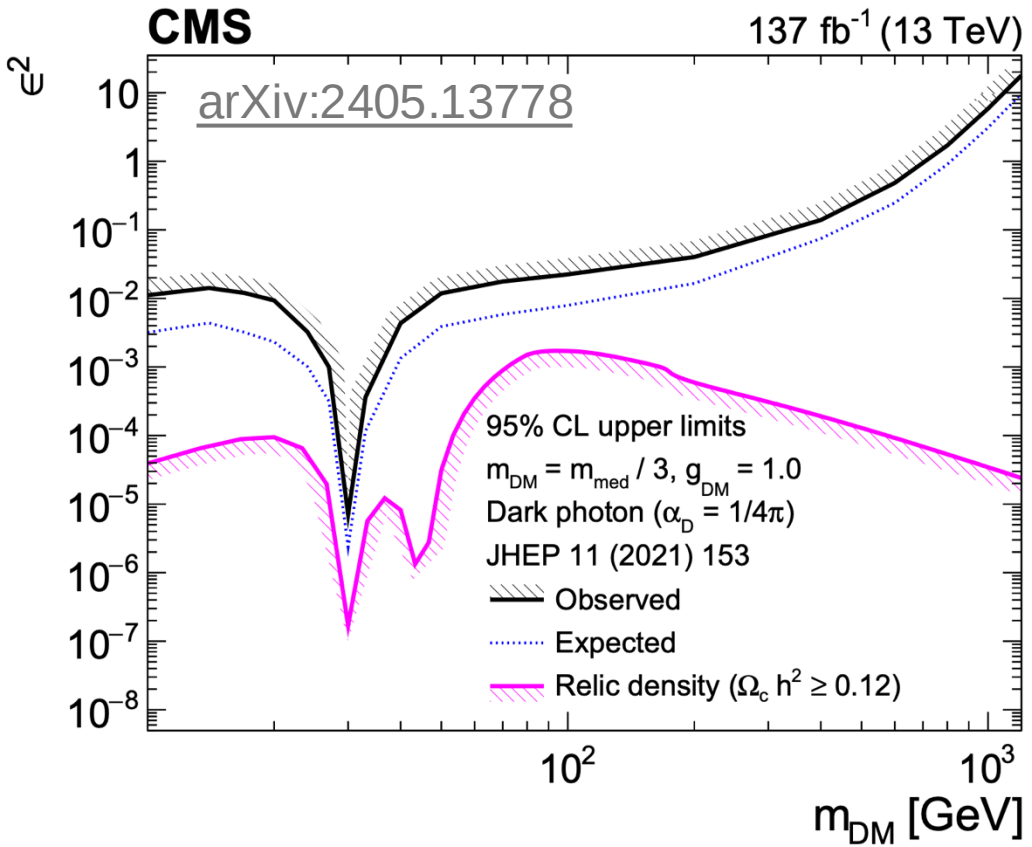
$$\Gamma(A' \to \chi\bar{\chi}) = \frac{1}{3}\alpha_D\, m_{A'}\sqrt{1-\frac{4m_\chi^2}{m_{A'}^2}}\left(1+\frac{2m_\chi^2}{m_{A'}^2}\right)$$



$M_{DM} < M_{A'}$

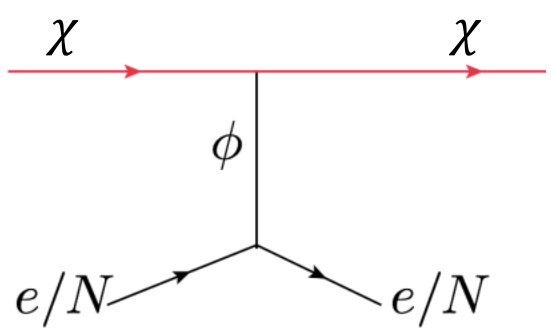


- CMS reinterpreted the mono-jet dark matter search (JHEP 11 (2021) 153) to constrain dark photon dark matter

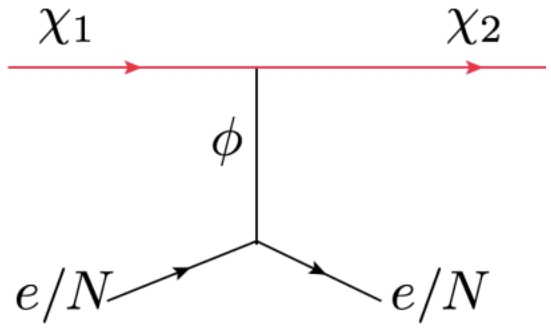


Inelastic Dark Matter: $A' \rightarrow \chi_1\chi_2$

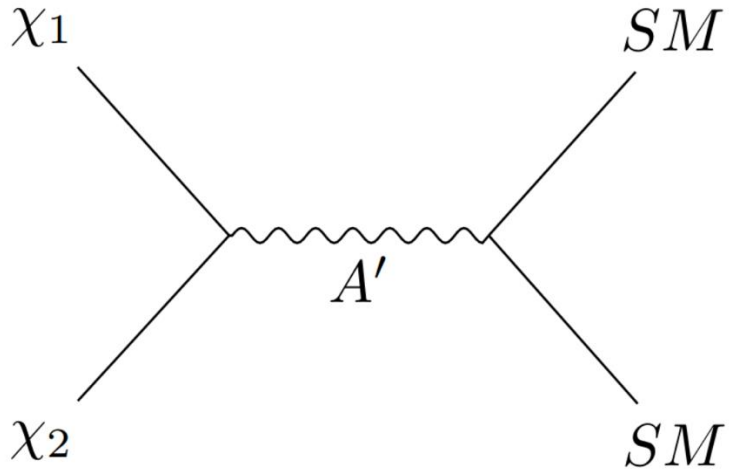
- Direct detection has put strong constraints on WIMP
- An elegant option to evade direct detection constraints is to consider inelastic Dark Matter
- Inelastic Dark Matter:
  - Two new DM mass eigenstates with a predominantly off-diagonal (inelastic) coupling and a small mass splitting
  - A dark photon serves as the portal to the SM



Elastic scattering



Inelastic scattering



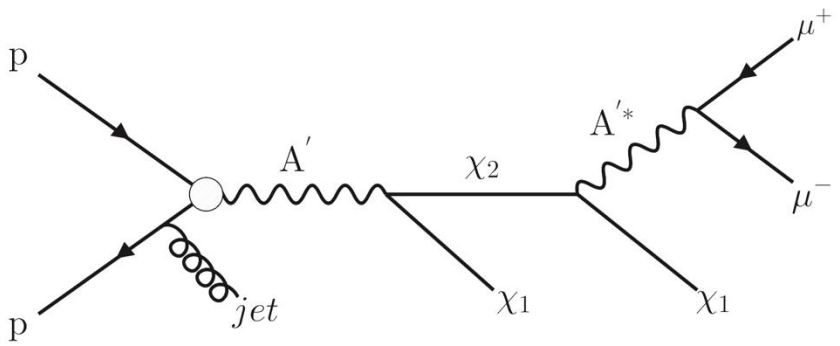
David Smith, Neal Weiner, *PRD 64 (2001) 043502*

CMS search for Inelastic Dark Matter: $A' \rightarrow \chi_1\chi_2$

- First dedicated collider search for inelastic dark matter: $pp \rightarrow A' \rightarrow \chi_1\chi_2, \chi_2 \rightarrow \chi_1\mu\mu$
  - χ_1: a light not detectable state
  - χ_2: a heavy state with a long lifetime

PRL 132 (2024) 041802

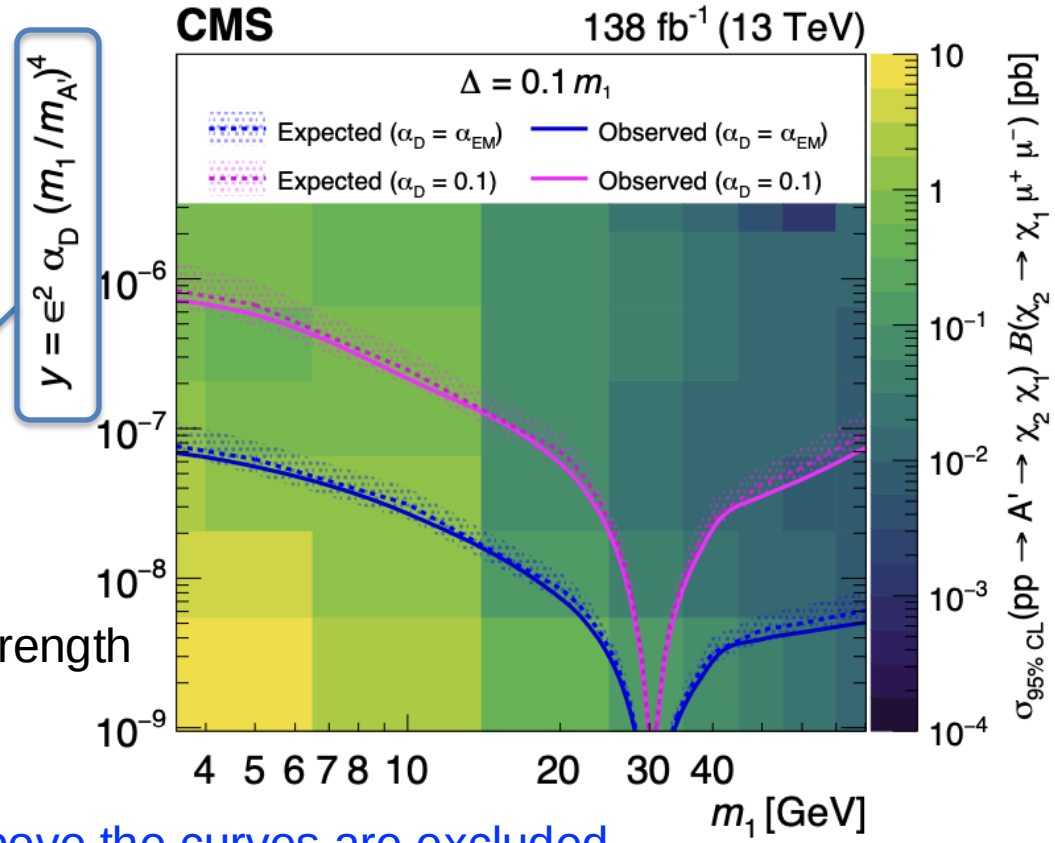
Signature :
- An ISR jet ($p_T > 80\ GeV$) helps triggering
- ≥1 pair of collinear, soft, displaced, non-resonant dimuon
- $\mathrm{E}_T^{miss} > 200\ GeV$ collimated with the dimuon pair



$$\sigma v \propto \epsilon^2 \alpha_D \left(\frac{m_1}{m_{A'}}\right)^4 \equiv y$$

dimensionless interaction strength

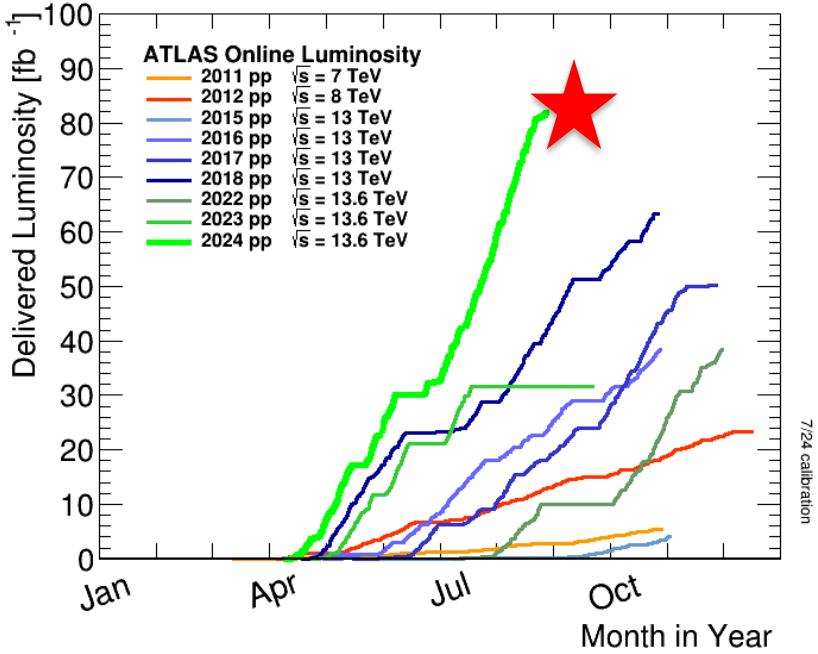
Mass splitting $\Delta \equiv m_{\chi_2} - m_{\chi_1}$



Regions above the curves are excluded

Summary

- Rich exploration of the dark photon and related dark sectors at the LHC
  - Minimal A', extra gauge boson Z', other dark sector particles(h_D, χ), …
  - Both prompt and displaced signatures
- Innovative strategies and approaches exploited to expand notably the reach of these searches
  - Scouting triggers, reconstruction techniques for LLPs, triggers for LLPs, …
- Looking forward for the future:
  - New ideas from theorists
  - Run3 data and beyond

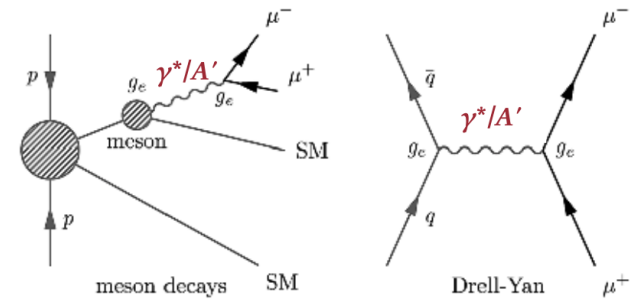


Backup

LHCb $A' \to \mu\mu$ search

PRL 124, 041801 (2020)

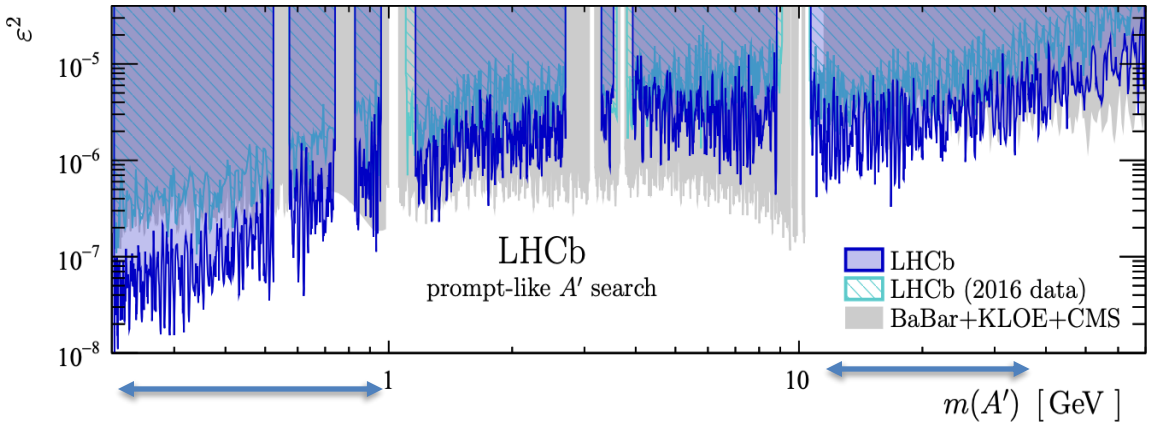
- Search for dark photons decaying into **a pair of muons**
- Used **5.5 fb^{-1}** of Run 2 LHCb data (13 TeV)
- Kinetic mixing of the dark photon (A′) with **off-shell photon** (γ*) by a factor ε:
  - A′ inherits the production mode mechanisms from γ*
  - A′ → μ⁺μ⁻ can be **normalised** to γ* → μ⁺μ⁻
  - No use of MC → no systematics from MC → fully **data-driven** analysis
- Separate γ* signal from background and measure its fraction
- Prompt-like search (up to 70 GeV/c²) → displaced search (214-350 MeV/c²)
  - A′ is long-lived only if the mixing factor is really small

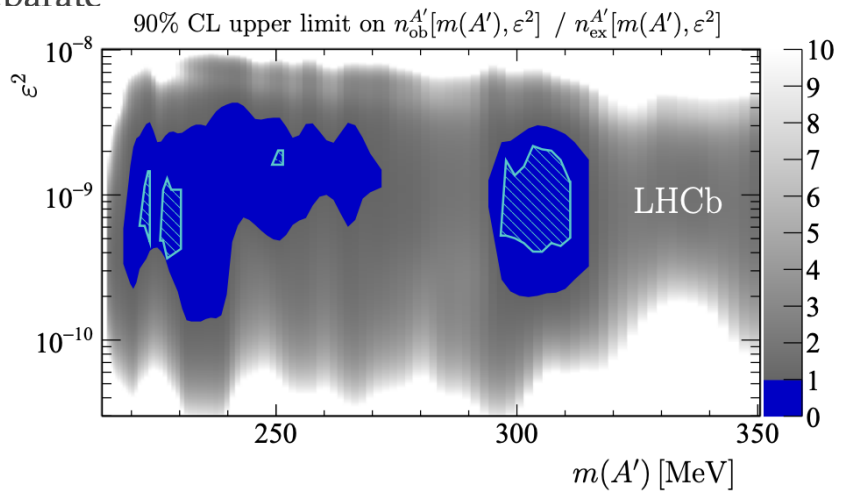


$$n_{\rm ex}^{A'}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n_{\rm ob}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]\, \epsilon_{\gamma^*}^{A'}[m(A'),\tau(A')]$$

off-shell photon | phase-space | A′/γ* eff ratio, ϵ=1 for prompt

Need to separate from bacl

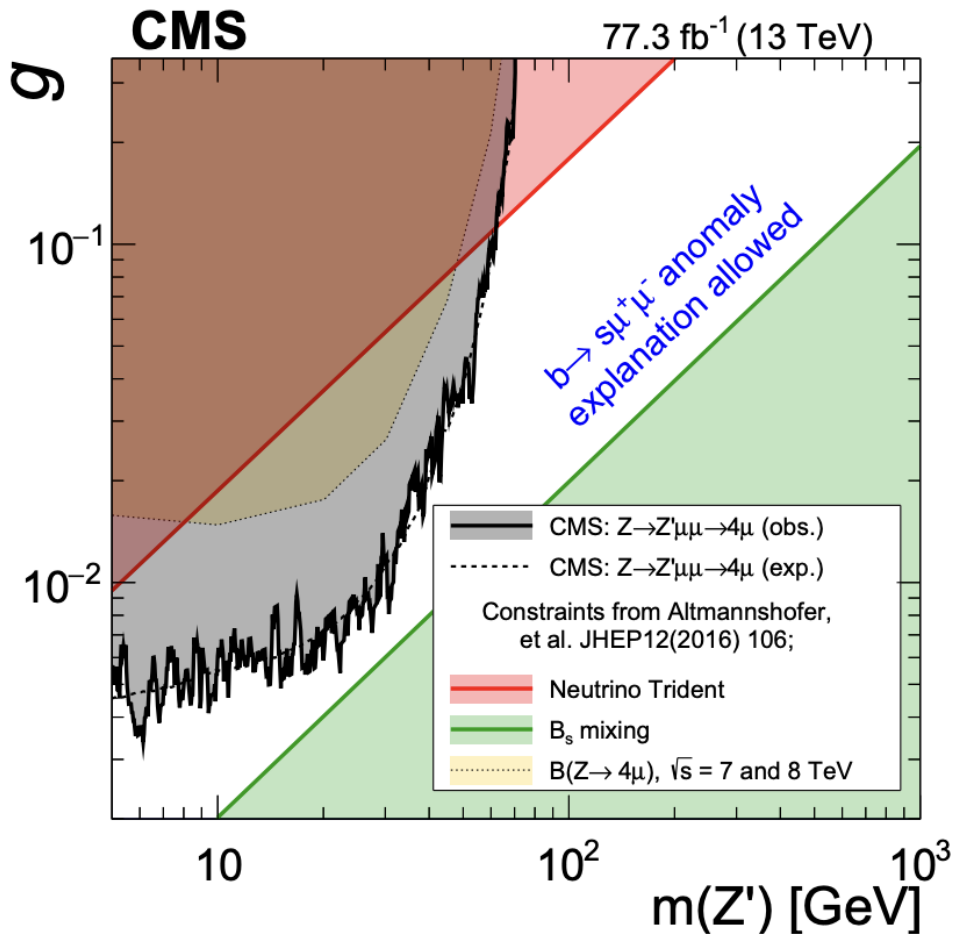




CMS $L_\mu - L_\tau$ Z' search in rare Z decay

- 4μ final state: $pp \to Z^{(*)} \to Z'\mu\mu \to 4\mu$

PLB 792 (2019) 345



ATLAS A' in rare Z decays