Axion-Like Particle (ALP) searches at the LHC

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September 6, 2023

- ✓ Resonant and non-resonant searches
- ✓ Higgs and beyond
- ✓ Associated production
- ✓ Heavy Ion collisions
- ✓ Looking forward: Photon-photon collisions

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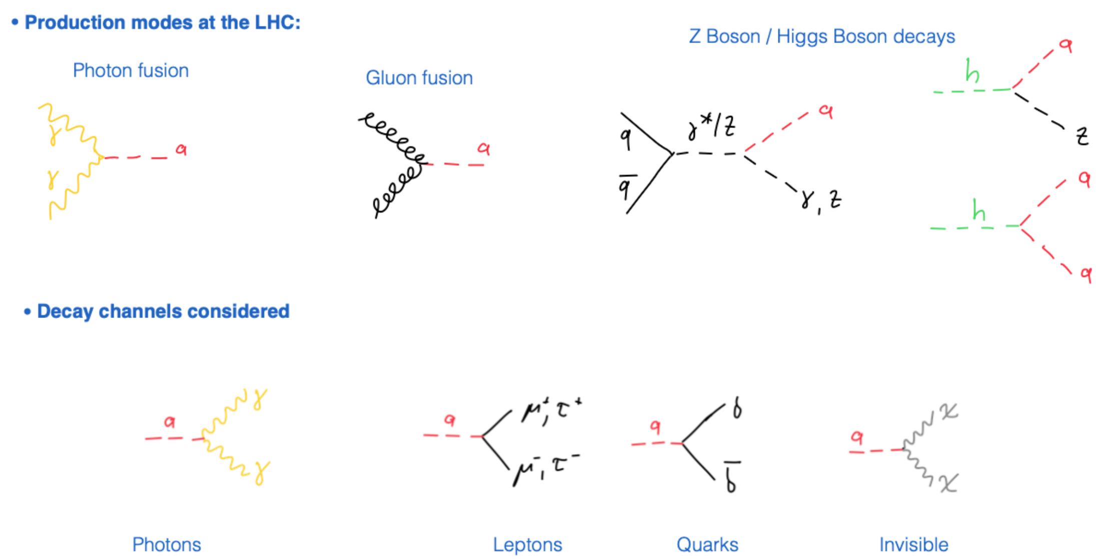
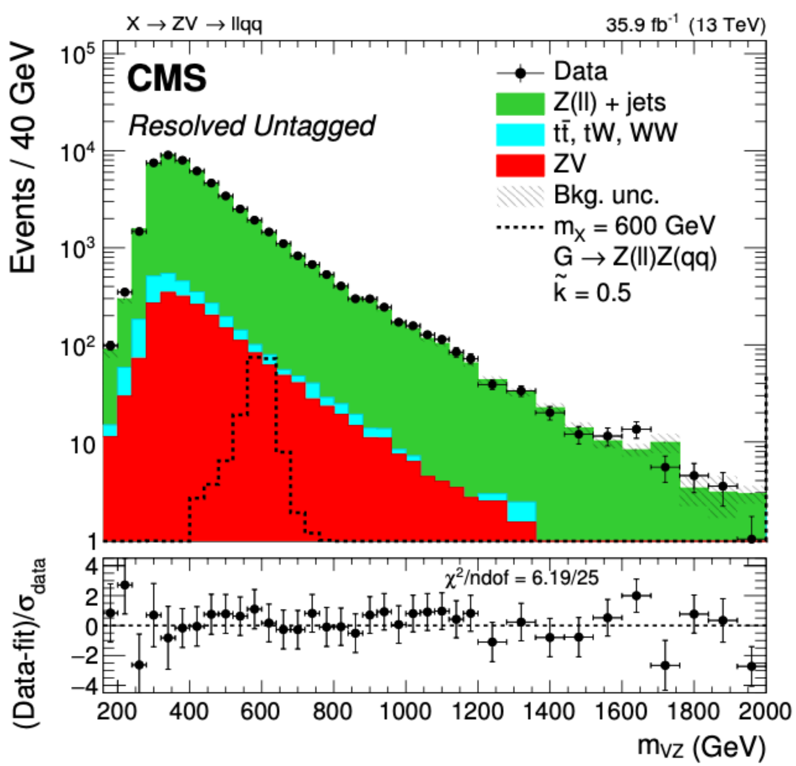
ALPs at the LHC

- Axions postulated by Peccei-Quinn (1977) as a solution to the strong CP problem
- While axions are expected to be very light (sub-eV), ALPs can be heavy
- ALP is a neutral pseudo-scalar boson
  - ALPs defined as pseudo-Goldstone bosons from spontaneous breaking of BSM symmetry
- Can solve the strong CP problem, act as a DM candidate, explain the muon (g-2) discrepancy
  - access to couplings to heavy SM particles
  - access to heavy ALPs (m_a>a few GeVs)



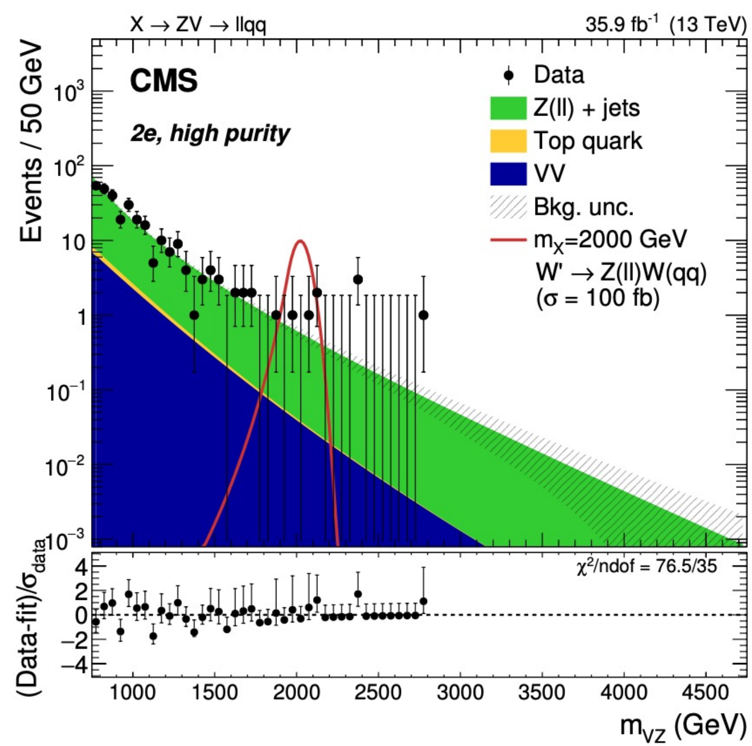
Heavy resonances

- Search for heavy resonance to ZZ/ZW in $2\ell 2q$ final state
- Hadronic vector boson decay: merged or resolved, (un)tagged
- Optimized for low- and high-mass resonances



← low-mass

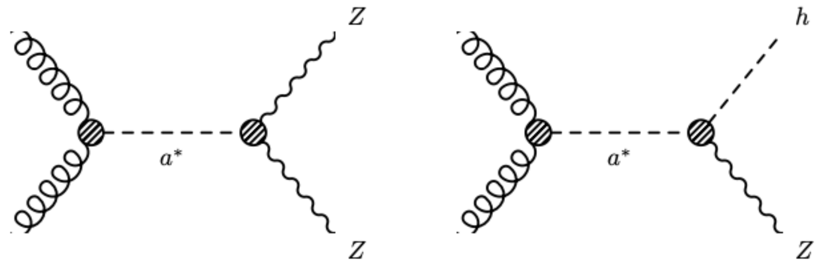
high-mass →



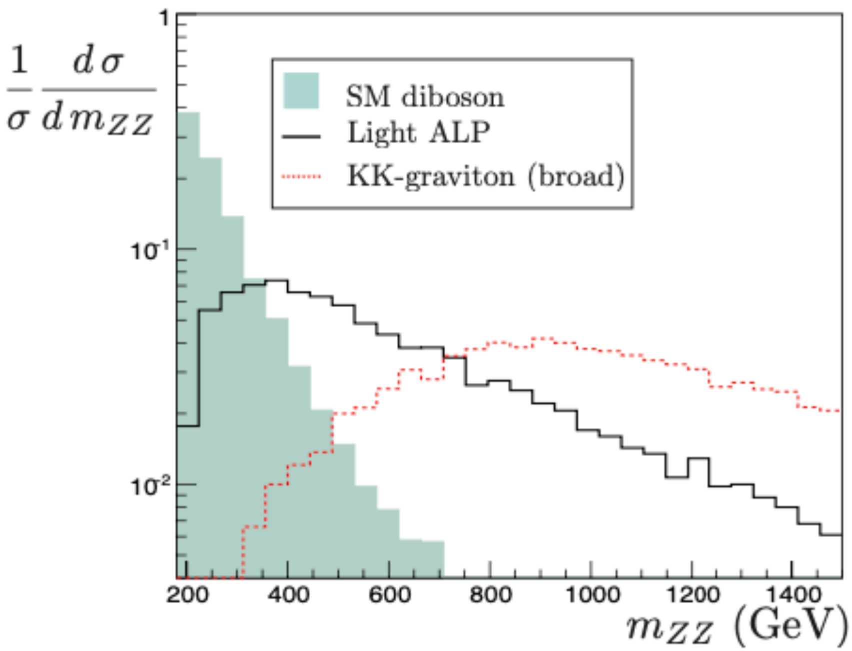
Non-resonant ALPs at LHC

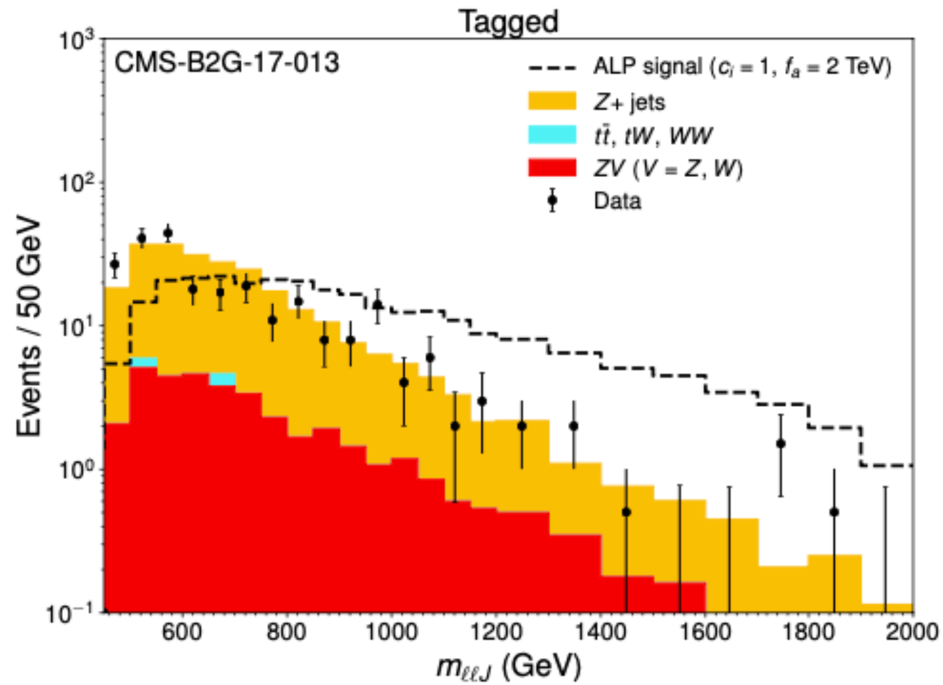
arXiv:1905.12953

- ALP as an off-shell mediator in s-channel
  - Higgs, EWK gauge bosons (W,Z,γ) in the final state
- Process mediated by a virtual ALP
- Enhancing cross section for $\sqrt{s} \gg \mathrm{m_a}$
- Cross section independent of $\mathrm{m_a}$



$$\sigma_{V_1 V_2} \propto g_{agg}^2\, g_{aV_1V_2}^2\, \hat{s} \sim \frac{\hat{s}}{f_a^4}$$



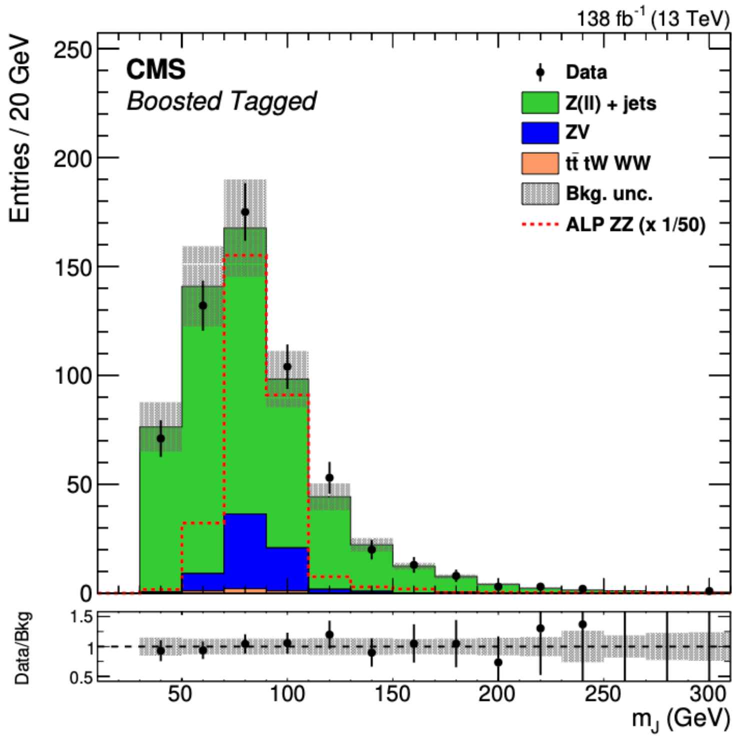


Non-resonant ALPs (cont.)

JHEP 04(2022)087

- Diboson signatures can be used to search for ALPs

  ⇒Look for deviations from SM in the tails of VV mass distribution
- $2\ell 2q$ final state in ZV (V=W,Z,H) processes
- ALP interaction can be parametrized in a EFT model-independent approach
- Use jet substructure variables (subjettiness, τ_{21}, etc.), merged/resolved jets



⇒ set limits on non-resonant ALP-mediated ZZ/ZH production for energy scale f_a=3TeV, m_a<100GeV

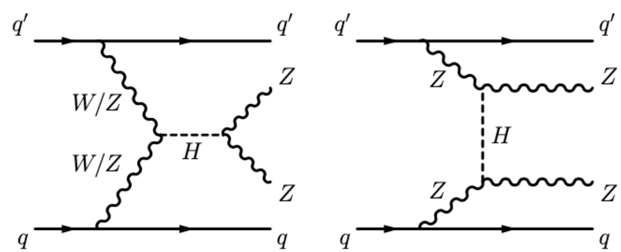
Upper limits (in fb)

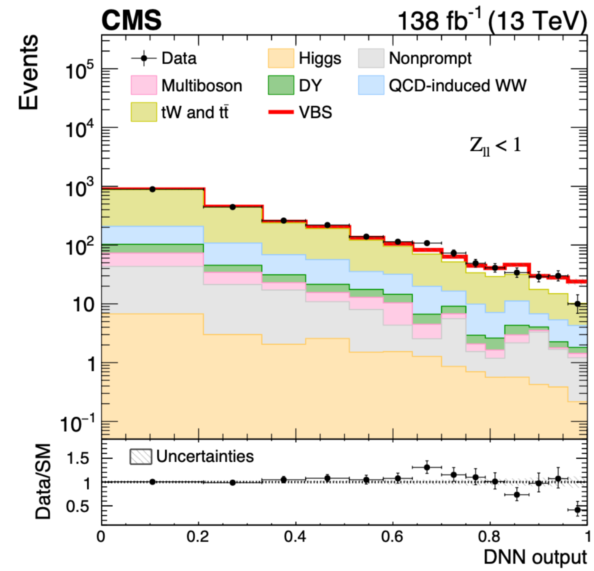
Model	Expected -2σ	Expected -1σ	Expected Median	Expected $+1\sigma$	Expected $+2\sigma$	Observed
ALP linear ZZ	79	107	151	218	304	162
ALP chiral ZH	32	39	64	94	134	57

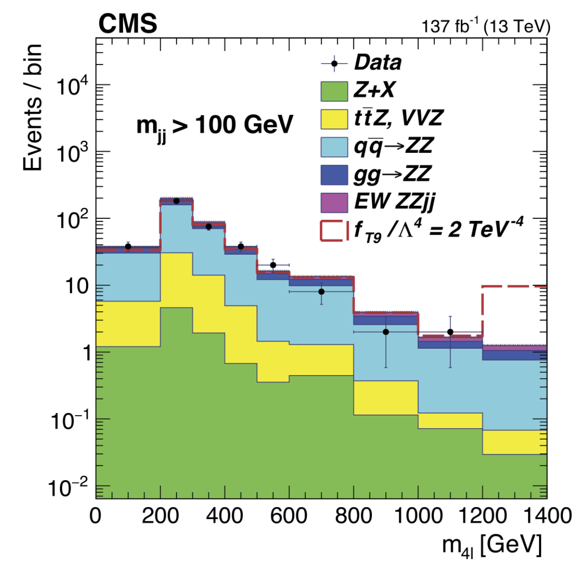
ALPs in VBS processes

arxiv:2205.05711, arXiv:2008.07013, PLB 809(2020)135710, arXiv:2004.10612, CMS-SMP-22-008

- ALPs in non-resonant VBS processes
  - ALP too light for resonant production
- WWjj:
  - EW production dominant over QCD
  - Distinct same-sign (SS) lepton final state with low bkg ("golden channel")
  - Electrons, muons, taus
  - Study polarization
- ZZjj:
  - Fully reconstructed final state provides maximal information



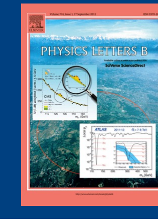




Absolute and normalized differential cross section measurements

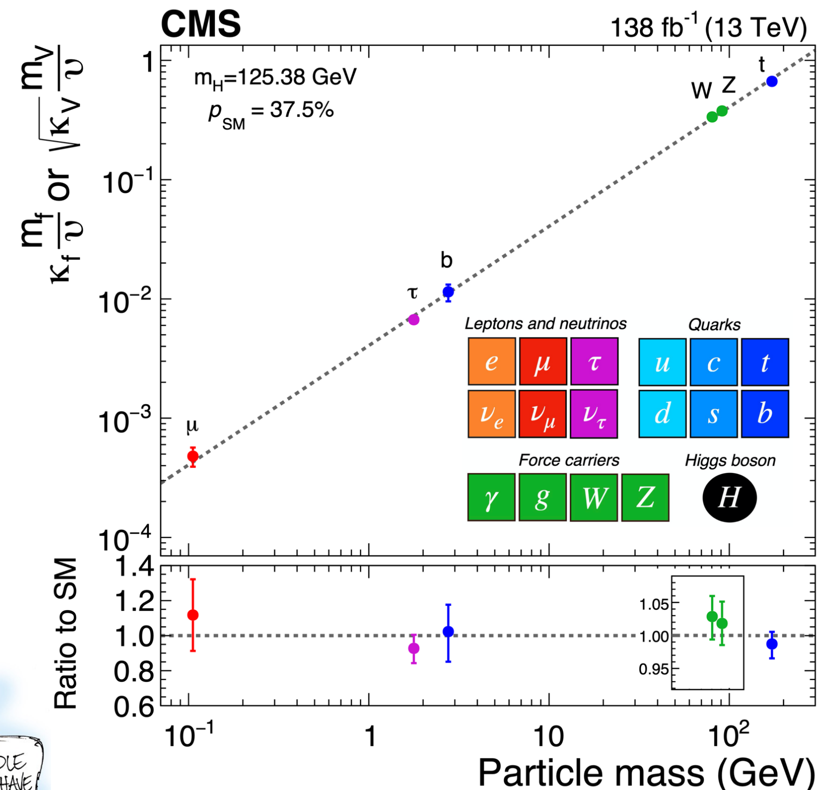
EW ssWW: far above 5σ
EW osWW: 5.6(5.2)σ
EW ZZ: far above 5.5(3.9)σ

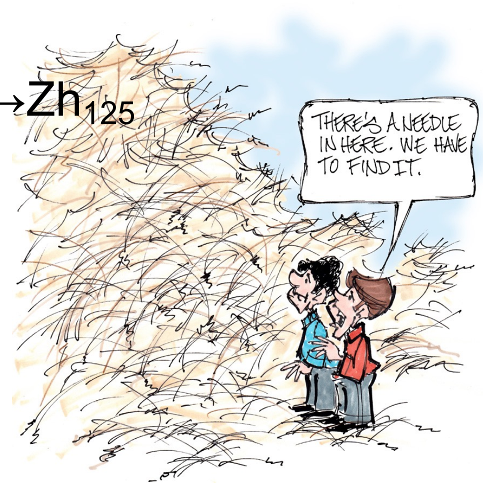
The Higgs and beyond



- Recently discovered (2012)
- Extended Higgs sectors are motivated and provide a rich phenomenology

- Minimal Supersymmetric SM (MSSM)
  - Neutral Higgs: $\phi\rightarrow\tau\tau/bb/\mu\mu$
  - Charged Higgs
- Next-to-MSSM
  - Light pseudoscalar: $h\rightarrow aa$
  - Non-SM decays: $h\rightarrow 2a\rightarrow 4\tau/4\mu$
  - Heavy Higgs: $H\rightarrow h_{125}h_{125}$ or $A\rightarrow Zh_{125}$
- etc.

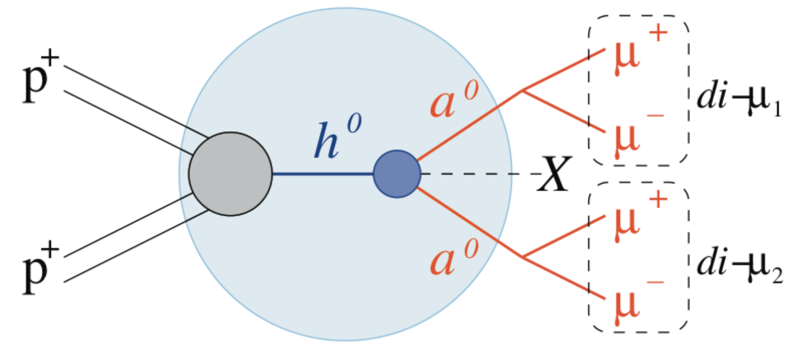




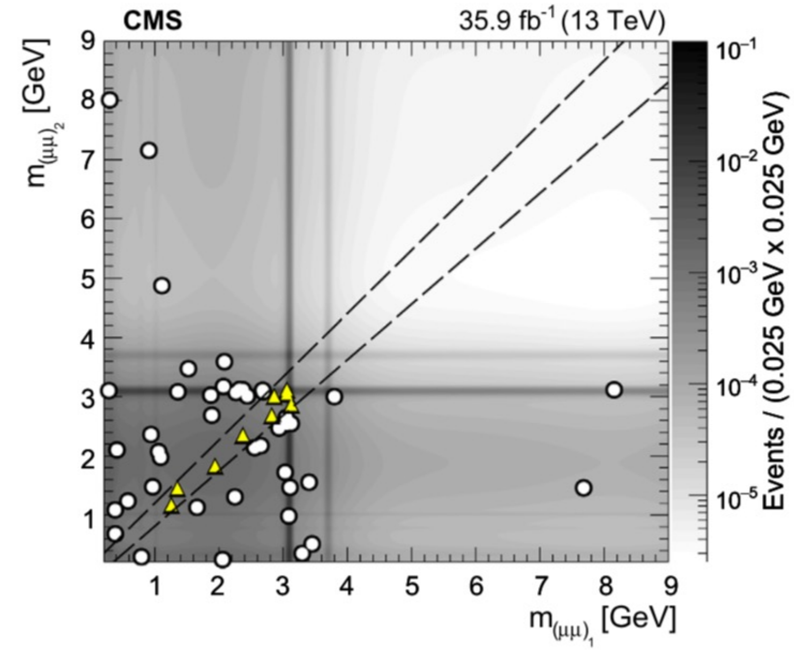
non-SM Higgs decay: h→aa→4μ

PLB796(2019)131

- Standard search for light (pseudo)- scalar Higgs with $m_a<m_h/2$
  - generic prediction of BSM theories (extended Higgs sector, NMSSM, etc.)
  - Final states go to fermions (b, τ, μ, …)
  - BR depends on boson mass, model parameters



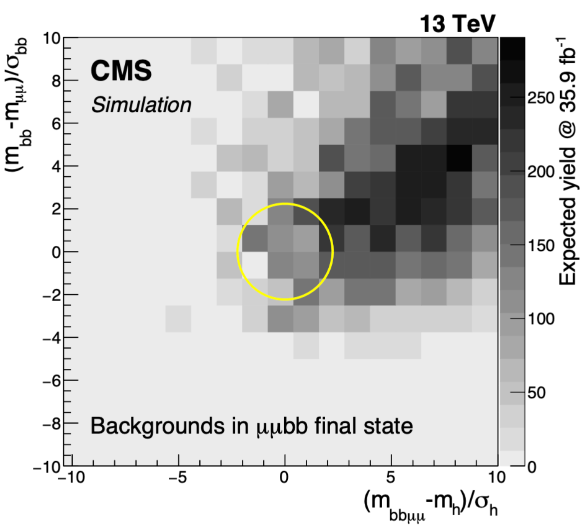
- Explore non-SM decays of a Higgs boson (h)
  - Higgs boson (h) can be SM or not
  - include production of two new light boson (a^0)
- Search for generic Higgs decays: h→2a+X→4μ+X
  - Require two dimuon pairs with consistent masses
  - Signal region: 9 event (~8±2 bkg)
  - Limits on production rates, benchmark models

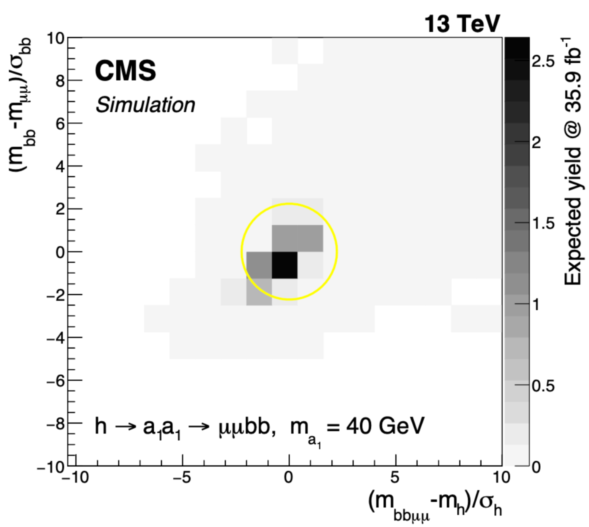


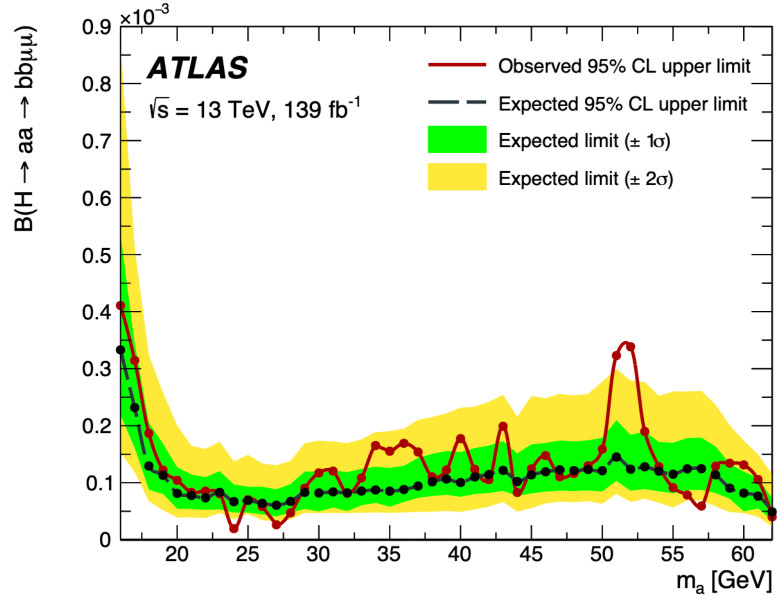
Non-SM Higgs decays: bbμμ

arxiv:1812.06359, arXiv:2110.00313

- Search for Higgs exotic decays: $H \rightarrow aa \rightarrow bb\mu\mu$
  - ATLAS uses a kinematic fit, CMS a relative mass difference of b- and μ-pairs
- Search for a narrow resonance in $m_{\mu\mu}$ distribution
- Use BDT classifiers trained to select signal
- Upper limits for $m_{\mu\mu}$~16-62 GeV
  - Largest significance at 52 GeV with local(global) significance of 3.3(1.7)σ



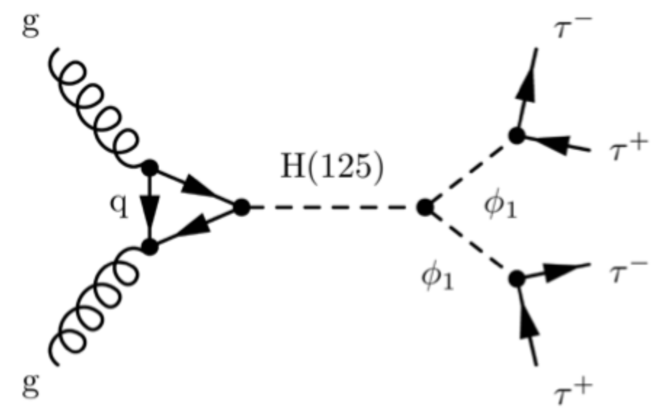


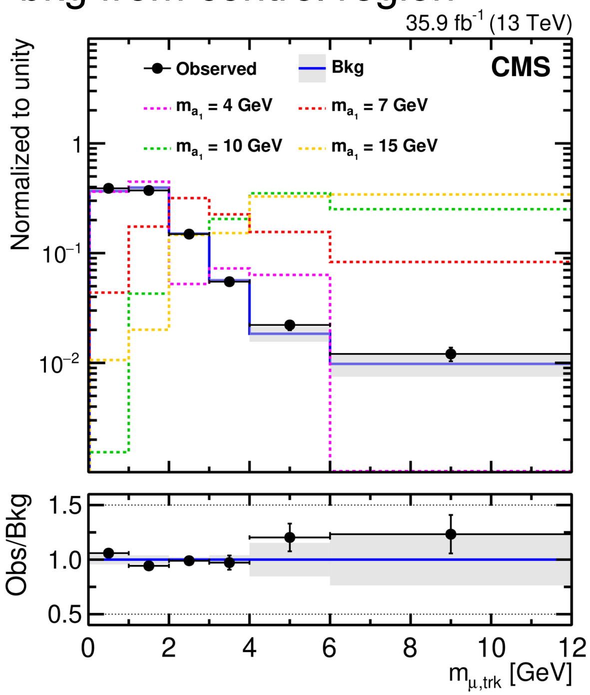


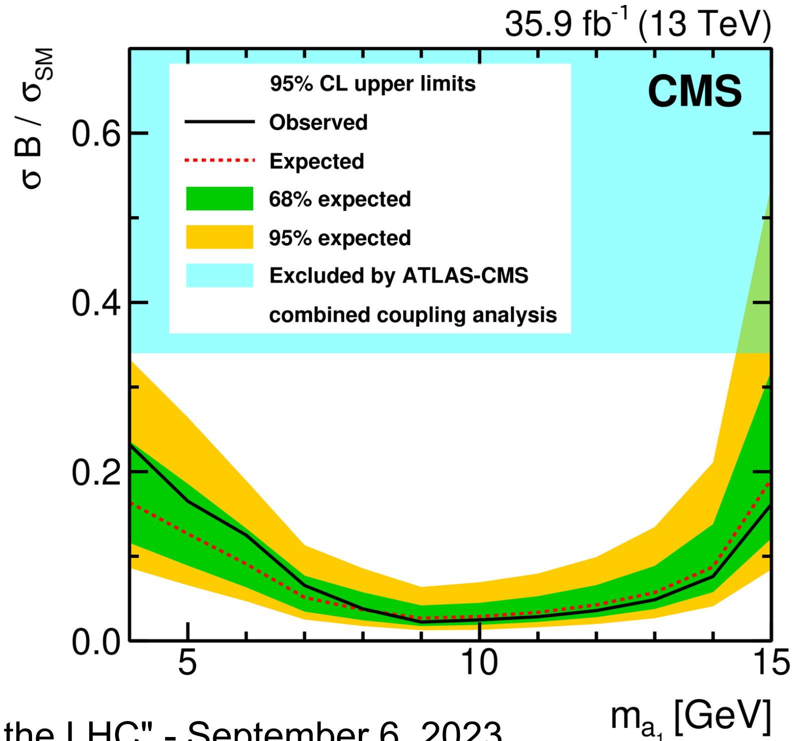
non-SM Higgs decay: ττττ

JHEP01(2016)079, PLB 800(2019)135087

- Search for very light Higgs in NMSSM
  - H(125)⟶light pseudoscalar (ϕ) bosons
  - One ϕ decays to a τ pair, the other to τ/μ pair
- Reconstruct μ-track invar. mass (m_1,m_2)
  - SS dimuon sample (removes DY)
  - bin in 2-dim distribution, fit signal and bkg
  - QCD bkg from control region



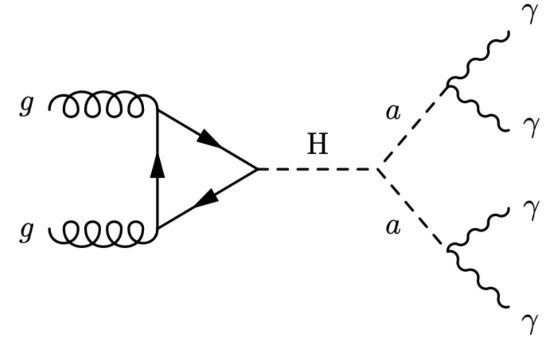




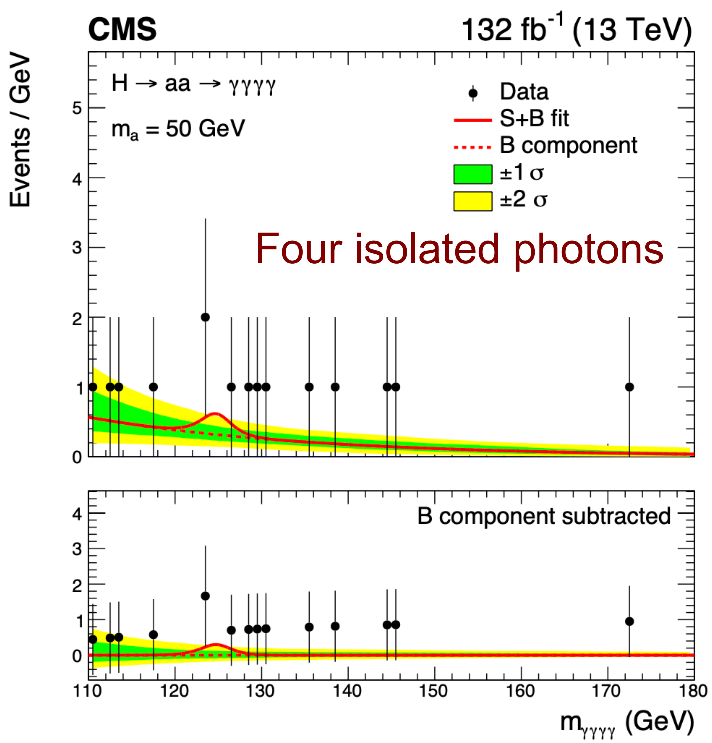
Non-SM Higgs decays: $(\gamma\gamma)\gamma\gamma$

arxiv:2208.01469, arXiv:2211.04172

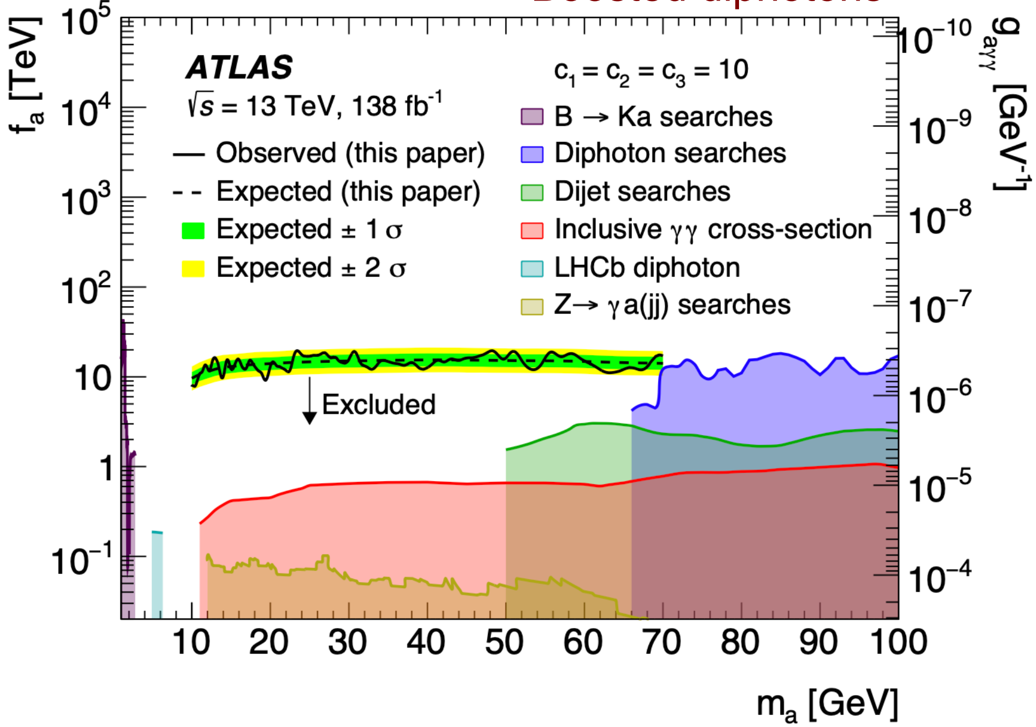
- Search for Higgs exotic decays
  - Boosted diphoton resonance
  - Four well isolated photons
- Explore invariant masses down to 10-15 GeV
- Set upper limits for m_a~15-62 GeV



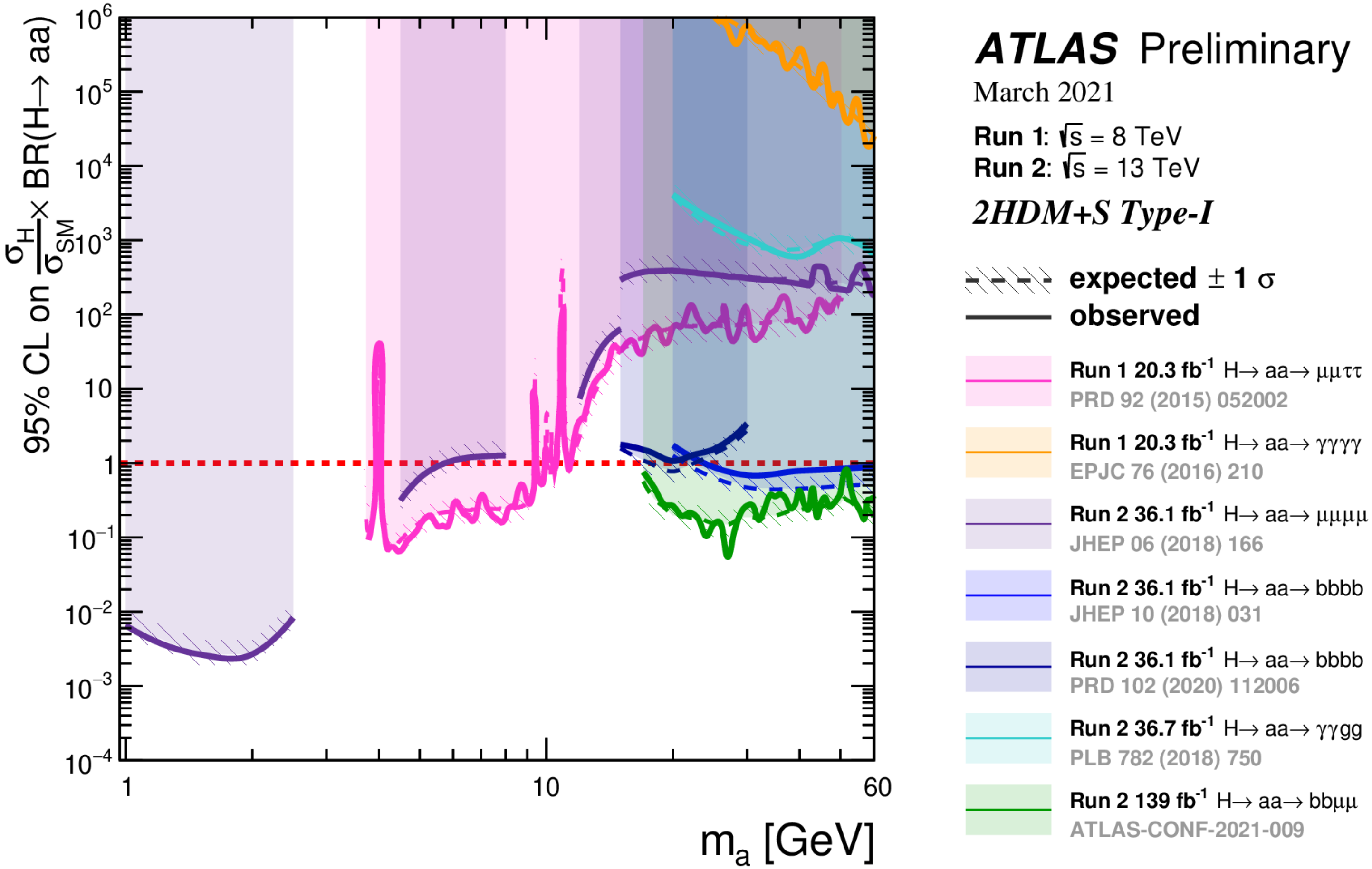
Four isolated photons



Boosted diphotons



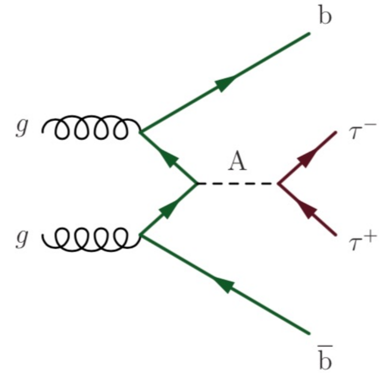
Summary: Higgs exotic decays

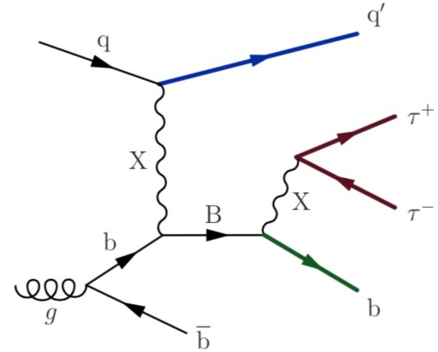


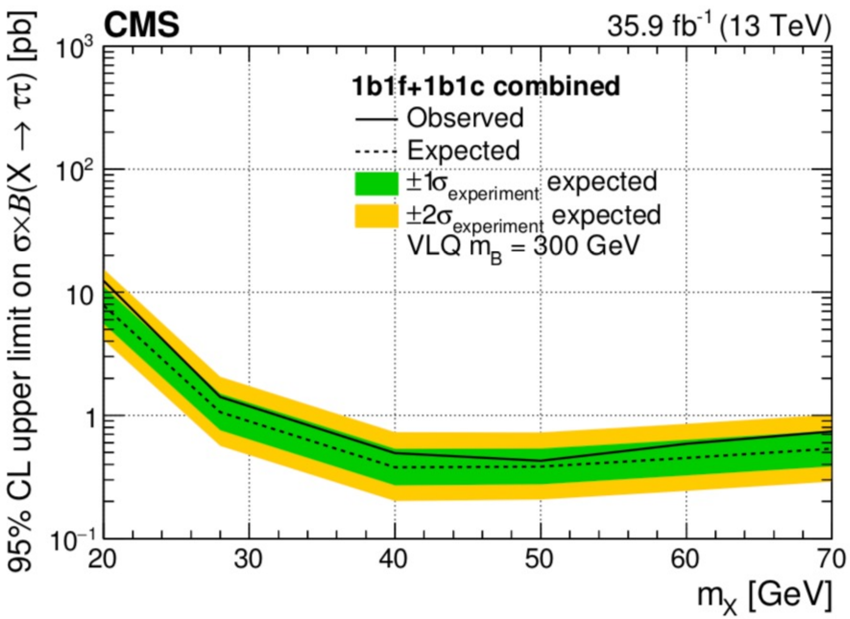
Associated production: a(→ττ)bb

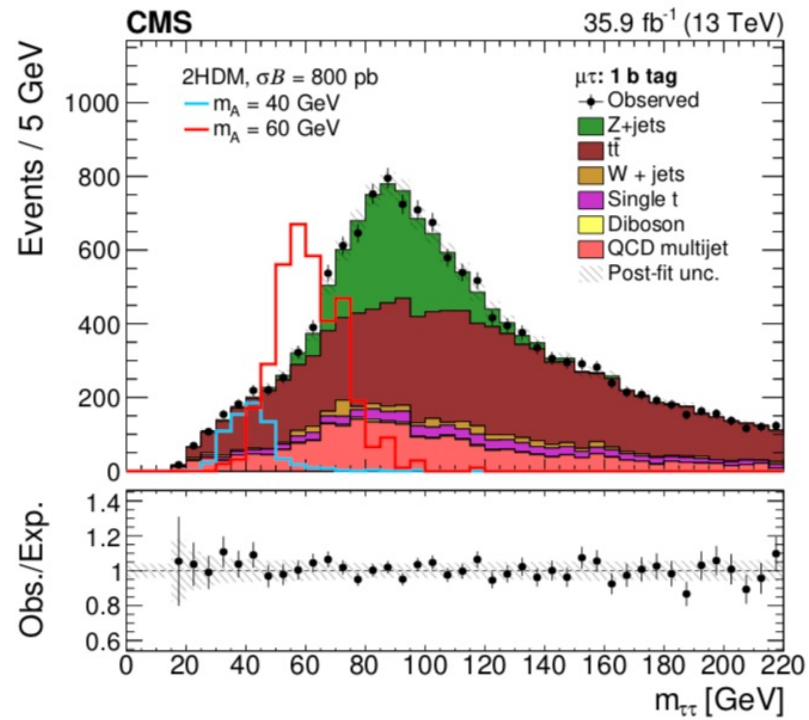
arXiv:1511.03610, JHEP05(2019)210

- Low mass Higgs in the NMSSM
- Low mass pseudo-scalar (*a*→ττ) in association with bbar: *a*bb→ττ bb
- Similar strategy to H→ττ
- Search for *a* masses below Z mass
- No evidence for signal
- Set limits: σxB~20-0.3 pb





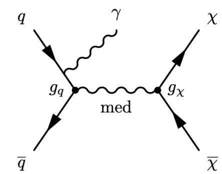


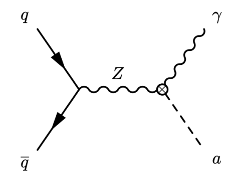


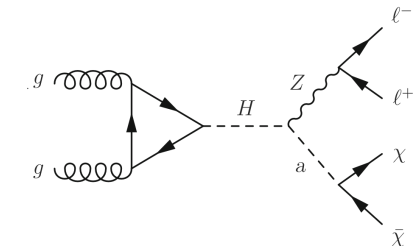
Invisible decays: mono-X

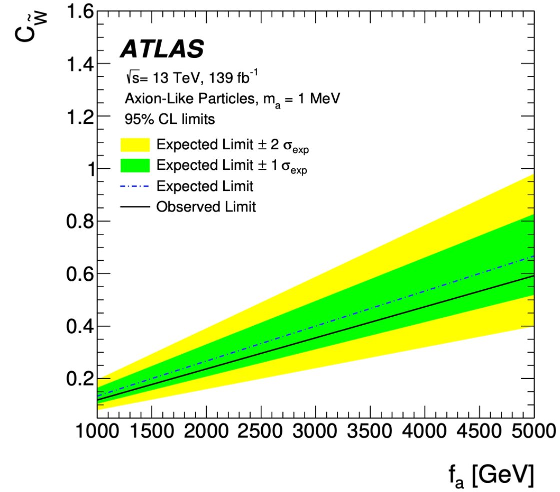
arXiv:2008.04735, arXiv:2011.05259

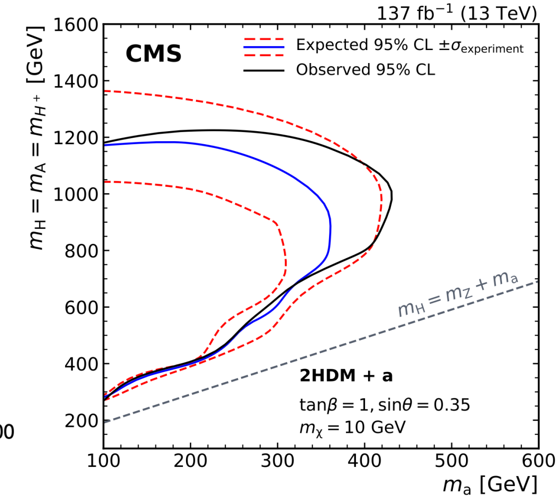
- Signature occurs if ALPs live long enough to escape the detector or it decays to invisible particles
- ALPs produced in association with a “visible” particle
  - Referred to as “mono-X” signature
- Sensitive to different ALP couplings
  - $Z \to a\gamma, h \to aZ, gg \to ag$
  - Events exhibit significant MET, e.g. ≥200 GeV
  - Difficult to reconstruct ALP mass
- Results interpreted in EFT operators
- No excess over bkg is observed

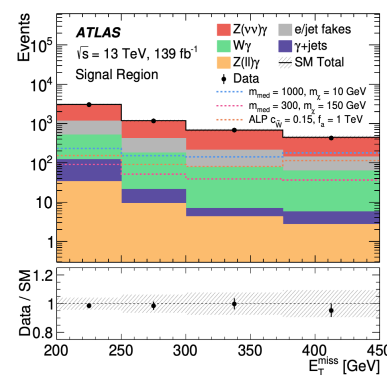


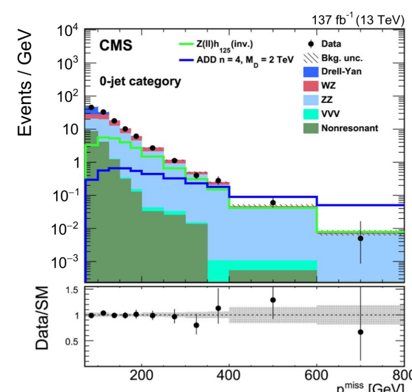








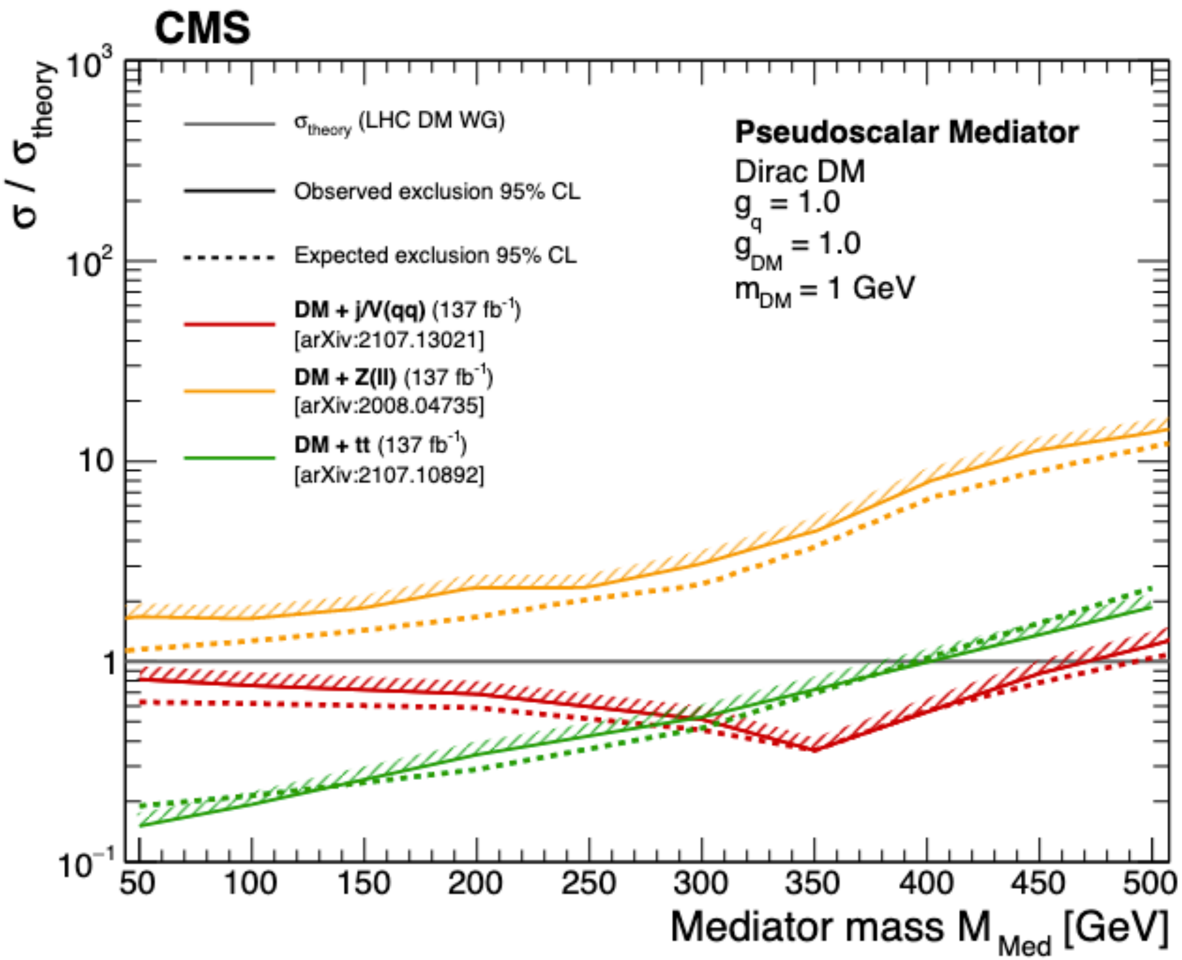


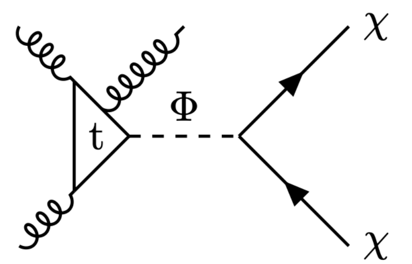


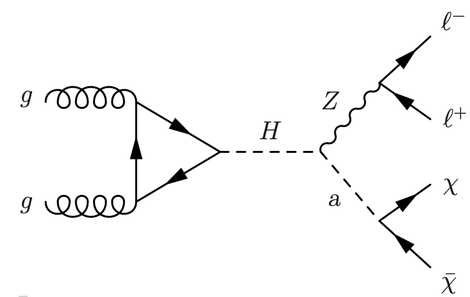
Mono-X: Pseudoscalar mediator

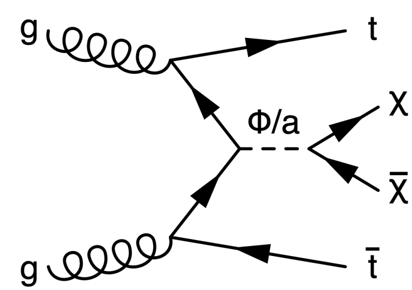
arXiv:2107.13021, arXiv:2008.04735, arXiv:2107.10892

- Search for MET-based mono-X signatures for pseudoscalar model





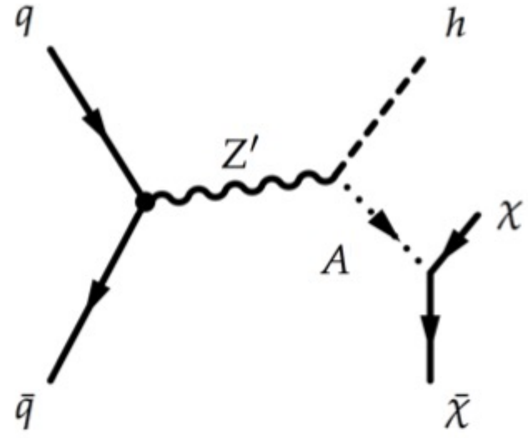


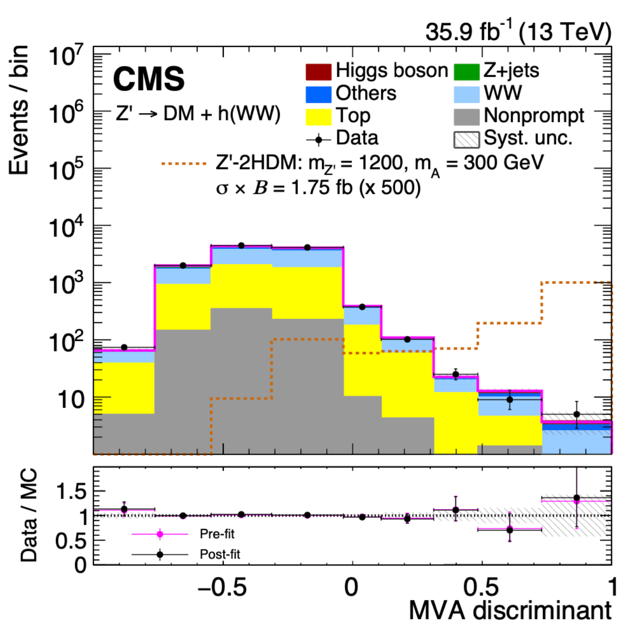


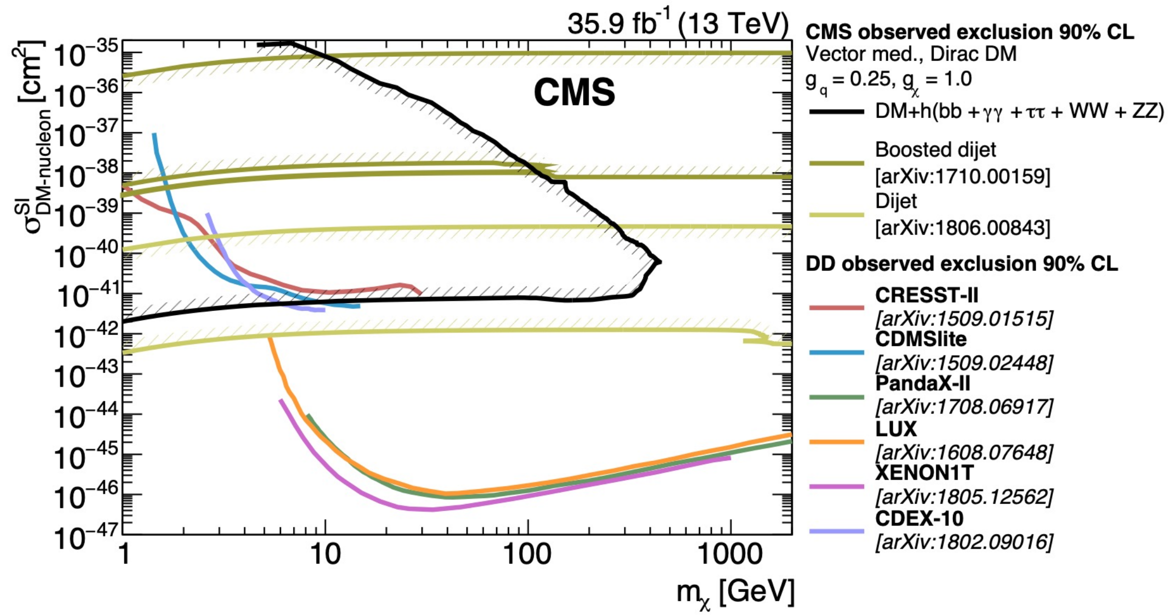
Associated production: DM+Higgs

arXiv:1908.01713

- DM search in associated Higgs production with H(→bb,γγ,ττ,WW,ZZ)
- ISR strongly suppressed due to small Higgs couplings to light quarks
- Z' 2HDModel
- No significant excess



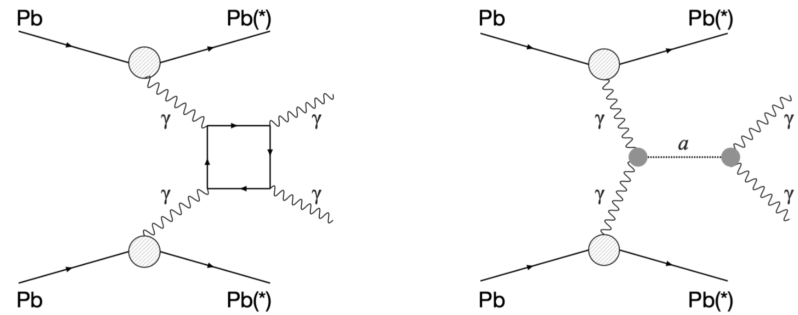


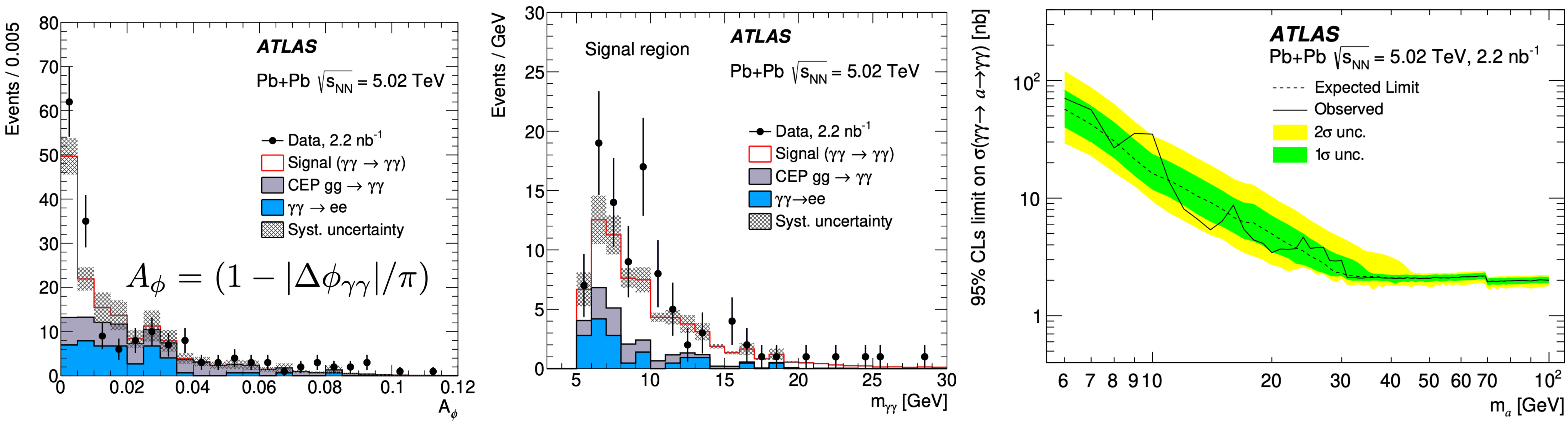


Heavy Ions: UltraPeripheral Collisions

arXiv:2008.05355, arXiv:1810.04602

- LbyL sensitive channel to study BSM processes
- LbyL scattering in PbPb UPCs
  - HI beams at LHC excellent source of HE photons
  - Equivalent photon flux scales with Z^4
- Exclusive diphoton final state ($m_{\gamma\gamma}$>5 GeV)
  - Data-driven bkg estimate for DY(ee)
  - Simulated evts for ALP couplings, m_a=5-100 GeV
  - Efficiency: 20(45)% for m_a=6(12)GeV
- Set limits on ALP production





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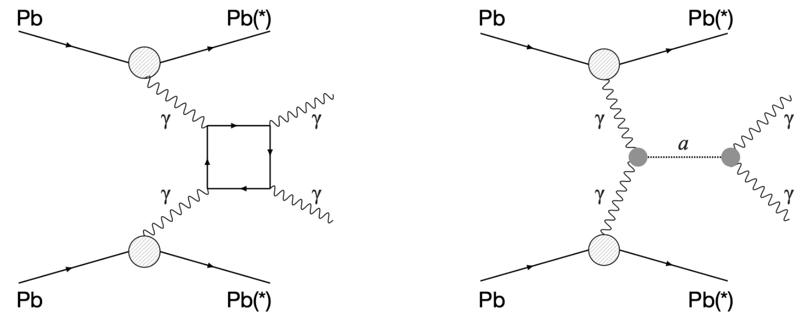
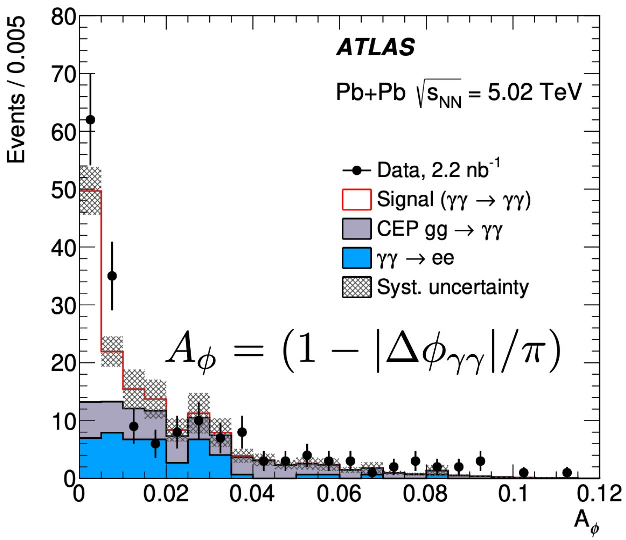
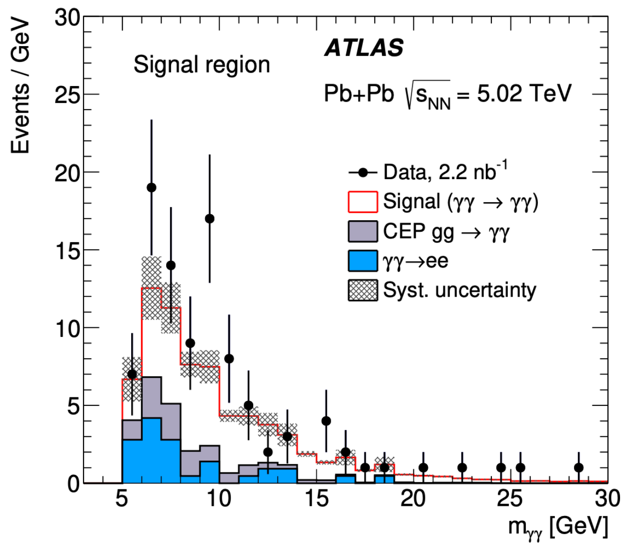
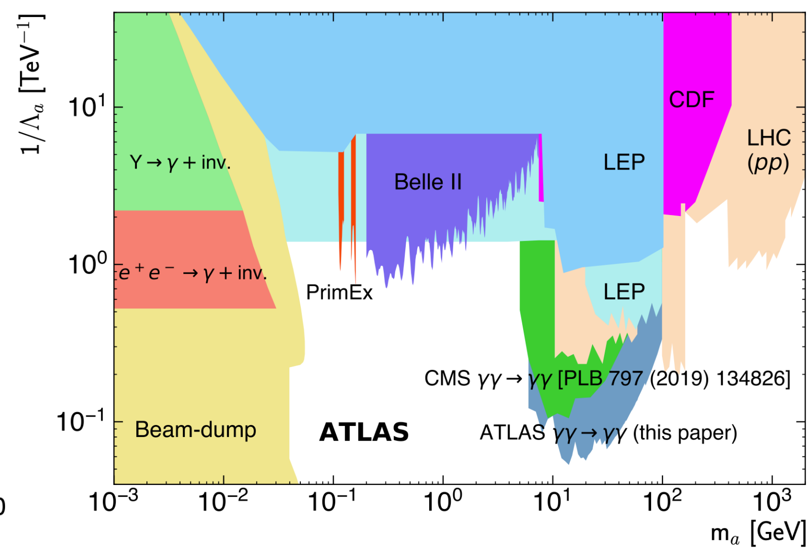


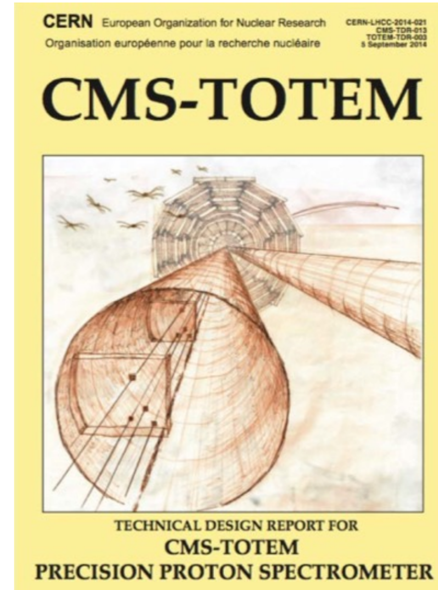




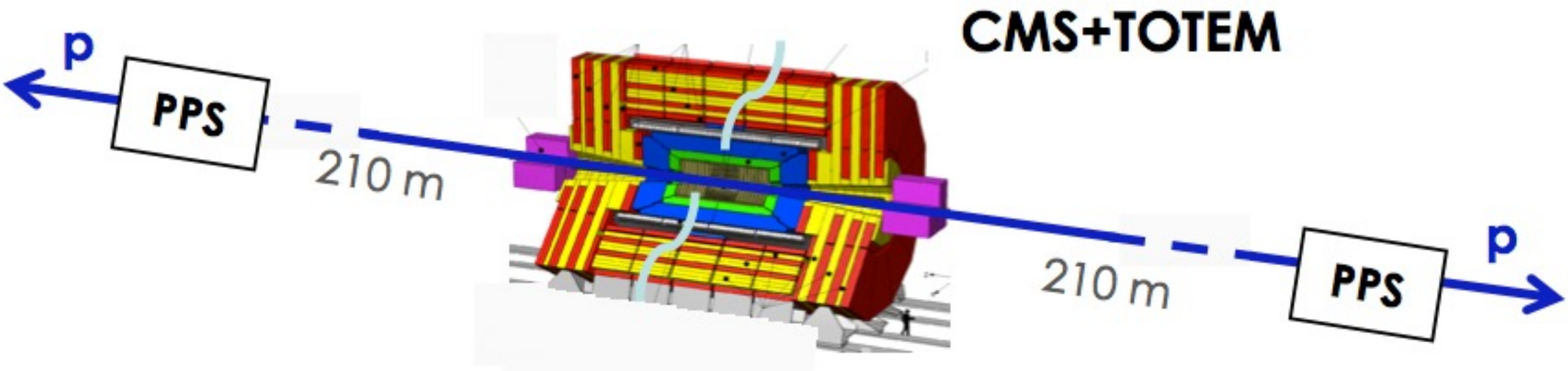


Looking forward: LHC as a $\gamma\gamma$ collider

- ALPs always couple to photons
  - Clean signature, no pileup
- PPS a joint CMS and TOTEM project that aims at measuring the surviving scattered protons on both sides of CMS in standard running conditions
  - Tracking and timing detectors inside the beam pipe at ~210m from IP5
  - Approved (2014), exploratory phase in 2015, data taking started in 2016, pixels from 2017, full detectors in 2018
  - Collected ~100fb^{-1} of pp collisions in Run2



CERN-LHC-2014-021

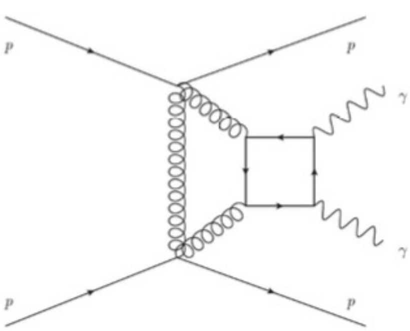


Photon-induced processes

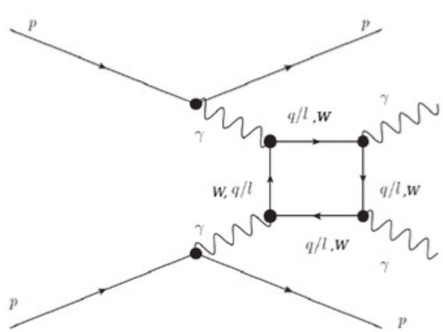
JHEP02(2015)165

Not all exclusive processes are photon-induced (QED)

- Exclusive dilepton production a purely QED process
- Exclusive $\gamma\gamma$ is:
  - QCD-dominated at low mass
  - QED-dominated at high mass



QCD



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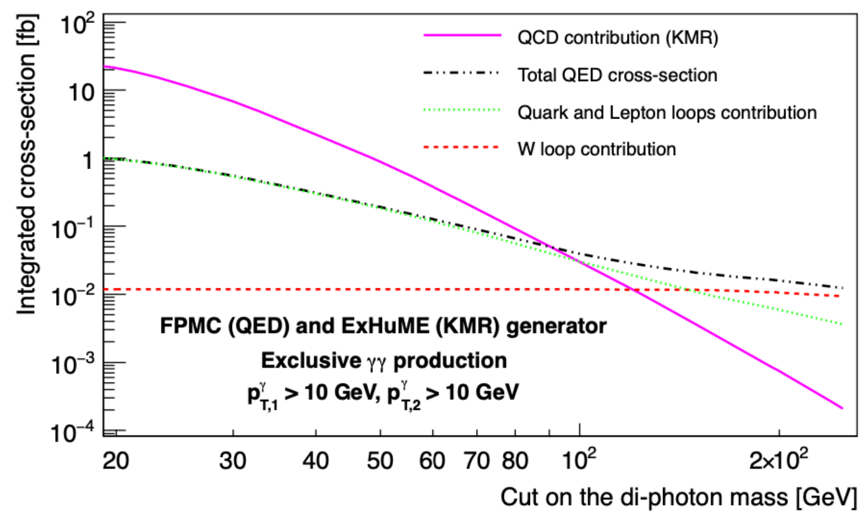
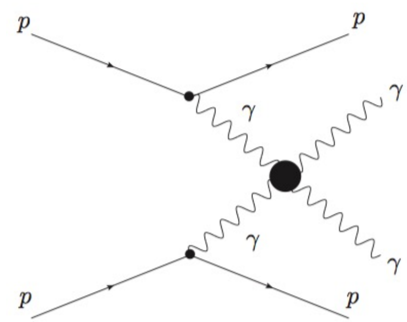
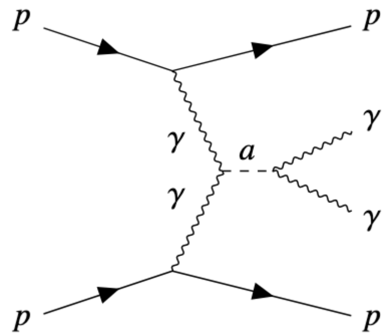


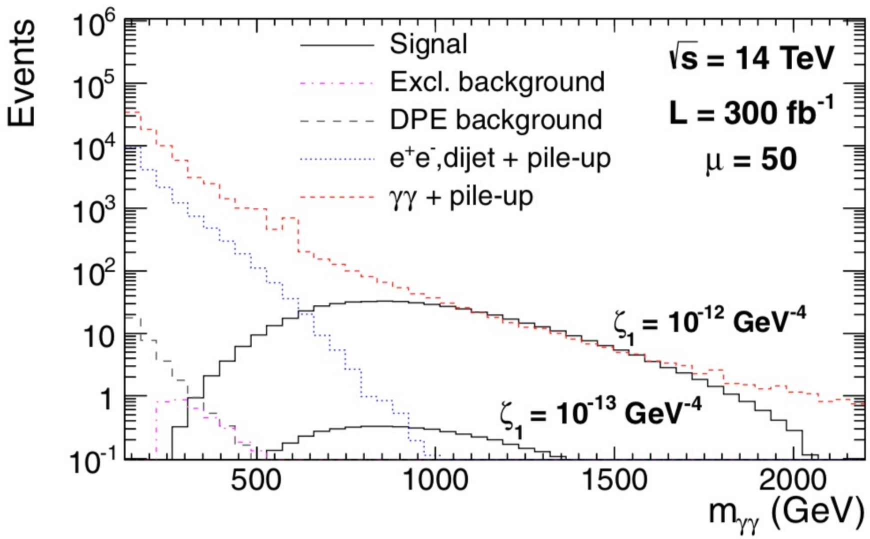
$\gamma\gamma \to \gamma\gamma$: light-by-light scattering

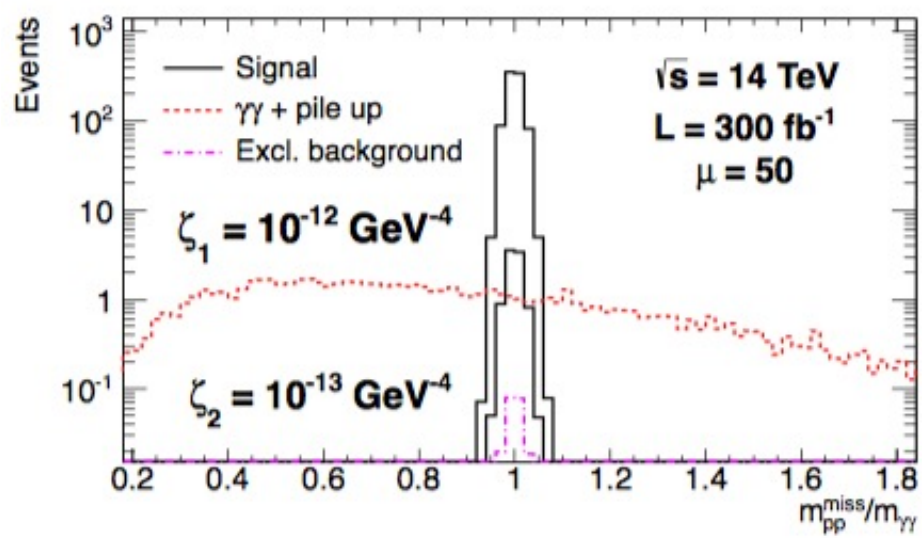
PRD 89(2014)114004

- Indirect search: neutral quartic gauge couplings (forbidden in SM) in $\gamma\gamma \to \gamma\gamma$
- Expect to provide best sensitivity at LHC
- Sensitive to ALPs









Exclusive $\gamma\gamma$ production

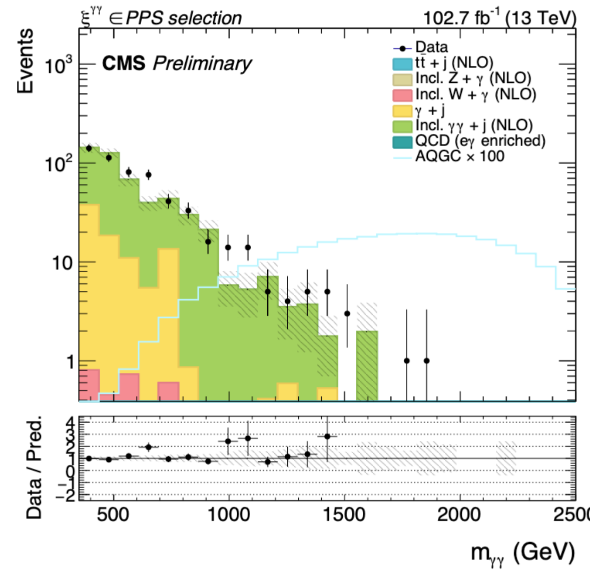
PRL 129(2022)011801, CMS-EXO-21-007, arXiv:2304.10953

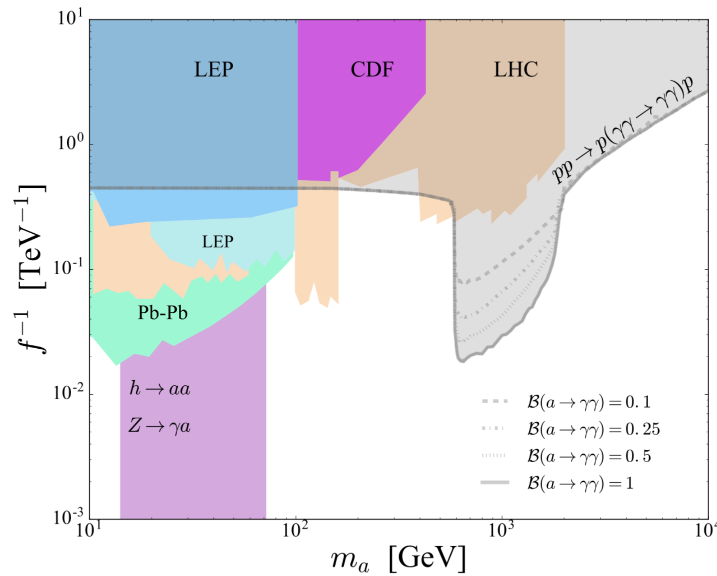
- Complementary to HI running (low-mass, xsec grows with Z^4)
- Light-by-light scattering
  - Study $m_{\gamma\gamma}$ > 350 GeV
  - Matching mass & rapidity: pp vs $\gamma\gamma$
  - 1 events observed (1.1 expected)

$$\sigma(pp \to p\gamma\gamma p | \xi_p \in \xi^{\text{PPS}}) < 0.61 \text{ fb}$$

- Set limits on $\gamma\gamma$ scattering
  - Direct limits on anomalous couplings (four-photon interation):

$$| \zeta_1 | < 7.3(7.1) \times 10^{-14} \text{ GeV}^{-4} \quad (\zeta_2 = 0)$$
$$| \zeta_2 | < 1.5(1.5) \times 10^{-13} \text{ GeV}^{-4} \quad (\zeta_1 = 0)$$

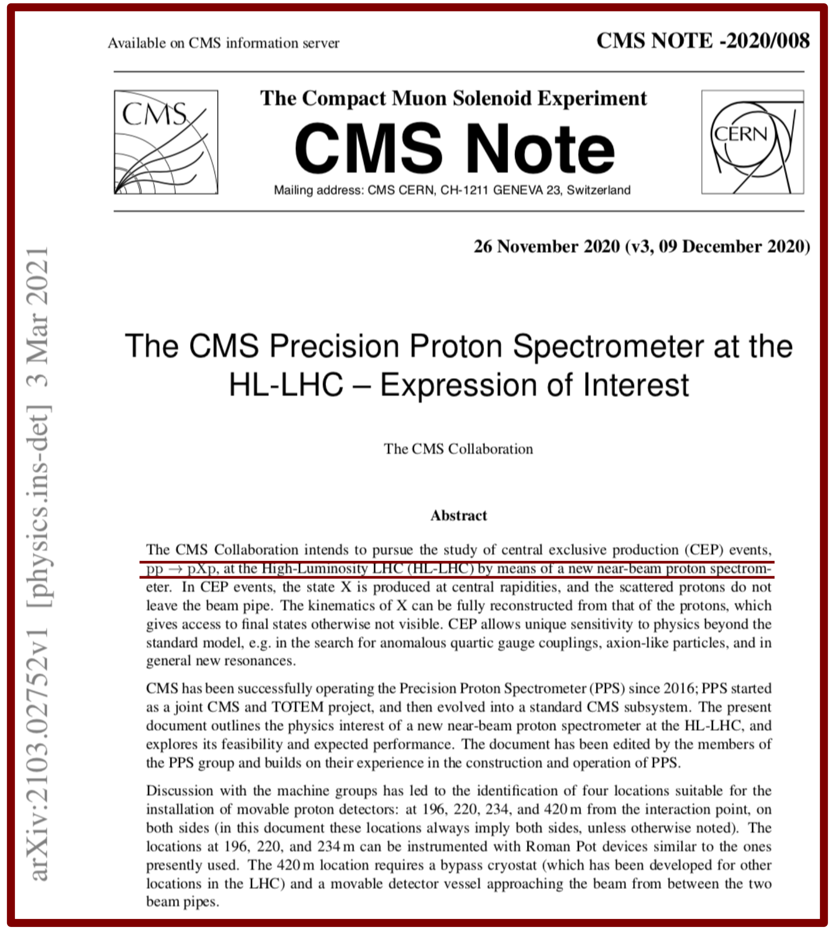




PPS @ HL-LHC

arXiv:2103.02752

- HL-LHC studies detailed in EoI
- Re-install PPS-like spectrometer for HL-LHC approved by the CMS collaboration
- 4 locations identified: near 200m (current location) and 420m (new technology)
- Expanded physics program
- Synergies with other future detector upgrades



Available on CMS information server CMS NOTE -2020/008

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

26 November 2020 (v3, 09 December 2020)

arXiv:2103.02752v1 [physics.ins-det] 3 Mar 2021

The CMS Precision Proton Spectrometer at the HL-LHC – Expression of Interest

The CMS Collaboration

Abstract

The CMS Collaboration intends to pursue the study of central exclusive production (CEP) events, pp → pXp, at the High-Luminosity LHC (HL-LHC) by means of a new near-beam proton spectrometer. In CEP events, the state X is produced at central rapidities, and the scattered protons do not leave the beam pipe. The kinematics of X can be fully reconstructed from that of the protons, which gives access to final states otherwise not visible. CEP allows unique sensitivity to physics beyond the standard model, e.g. in the search for anomalous quartic gauge couplings, axion-like particles, and in general new resonances.

CMS has been successfully operating the Precision Proton Spectrometer (PPS) since 2016; PPS started as a joint CMS and TOTEM project, and then evolved into a standard CMS subsystem. The present document outlines the physics interest of a new near-beam proton spectrometer at the HL-LHC, and explores its feasibility and expected performance. The document has been edited by the members of the PPS group and builds on their experience in the construction and operation of PPS.

Discussion with the machine groups has led to the identification of four locations suitable for the installation of movable proton detectors: at 196, 220, 234, and 420 m from the interaction point, on both sides (in this document these locations always imply both sides, unless otherwise noted). The locations at 196, 220, and 234 m can be instrumented with Roman Pot devices similar to the ones presently used. The 420 m location requires a bypass cryostat (which has been developed for other locations in the LHC) and a movable detector vessel approaching the beam from between the two beam pipes.

Summary

- ALP searches very active field as they are potential DM candidates
- LHC is a versatile tool for ALP searches in a wide mass range, and different production/decay modes
- Searches covering mass range from 0.5GeV to 1+TeV
- Various production and decay modes
- Preparing for Run3 and beyond with upgraded detectors and tools