Searches for Axion-Like Particles, or ALPs

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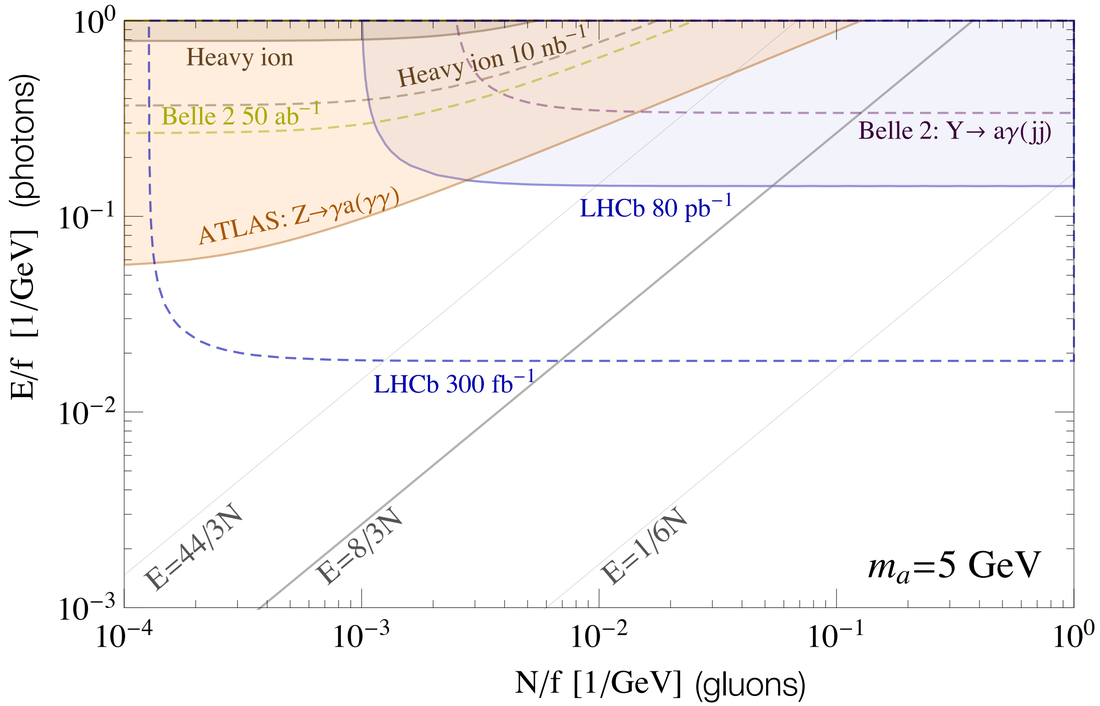
Axion Like Particles

- ALPs are pseudo Nambu-Goldstone bosons associated to Spontaneous Symmetry Breaking
  - Appear in many BSM models
- ALPs may couple to different sectors of the SM
- Considering the ALPs energy scale f_a lies beyond the EW scale: $f_a >> v$ effective interactions to the SM:
  - Coupling to gauge sector: gluons, photons Z and W

$$\mathscr{L}_{\text{eff}} \supset \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{a}{f}\sum_{i=1}^{3} c_i \frac{\alpha_i}{4\pi} F_{i,\mu\nu}\tilde{F}_i^{\mu\nu}$$

- Where the decay widths to photons and gluons depend on $N(c_3)$ and $E(c_1, c_2)$:
  - $\Gamma_{\gamma\gamma} = \frac{\alpha_{\text{em}} E^2 m_a^2}{64\pi^3 f_a^2}, \Gamma_{gg} = \frac{\alpha_s N^2 m_a^2}{8\pi^3 f_a^2}$
- Couplings to the Z and W vector bosons also considered
- Interactions with fermion sector and Higgs sector also possible
  - Chiral expansion realisations favor coupling to Higgs [Phys.Rev.Lett. 124 (2020) 5, 051802]



JHEP 01 (2019) 113

Signatures

- $pp \to a \to \text{jet} + E_T^{\text{miss}}$
- $pp \to a \to \gamma + E_T^{\text{miss}}$
- $\text{Pb Pb} \to a \to \gamma\gamma$

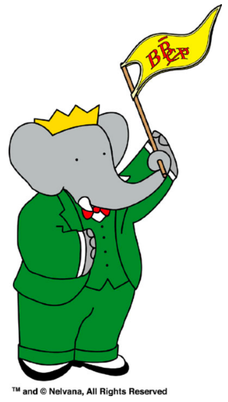
$K^+ \to \pi^+ a, a \to$ invisible

- $pp \to a^* \to ZH, ZV$
- $\text{Pb Pb} \to a \to \gamma\gamma$

- $e^- Z \to a \to \gamma\gamma$
- $e^- Z \to X \to$ invisible
- $e^- Z \to a \to e^+ e^-$

$e^+ e^- \to \gamma a, a \to \gamma\gamma$

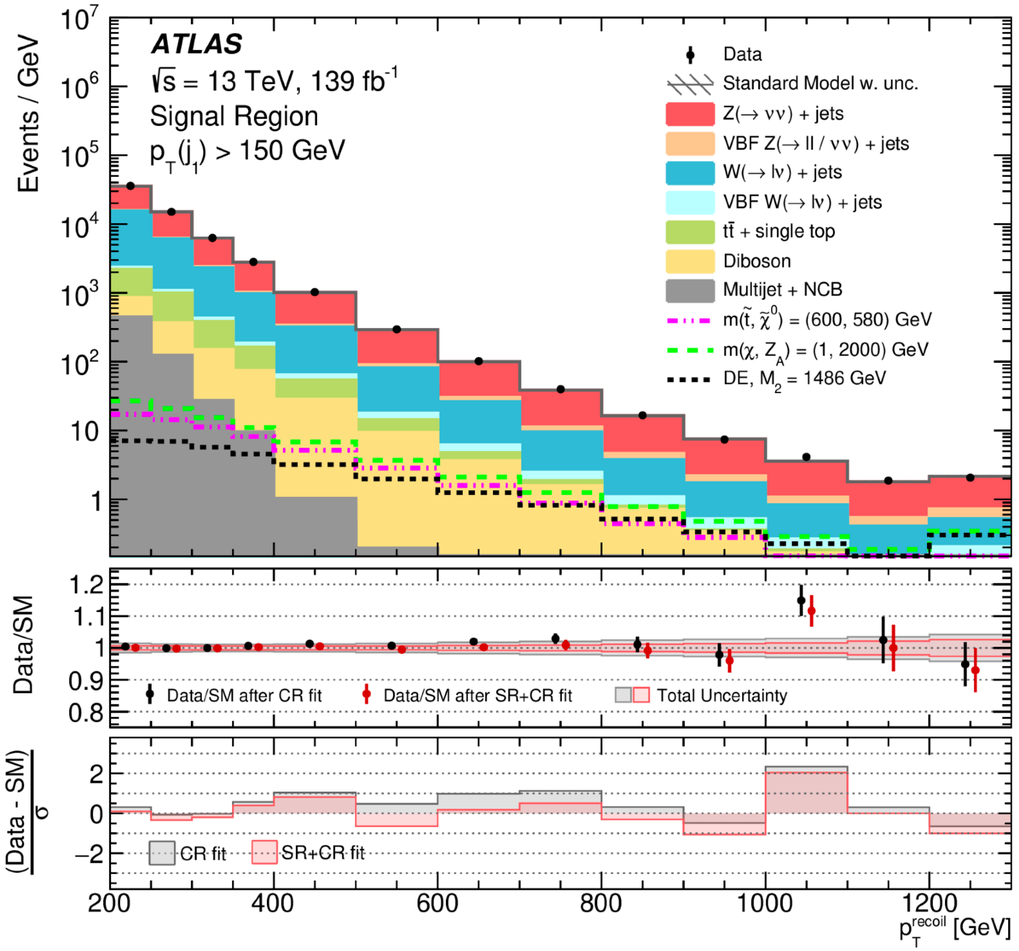
$pp \to a \to \gamma\gamma$



$B \to Ka, a \to \gamma\gamma$

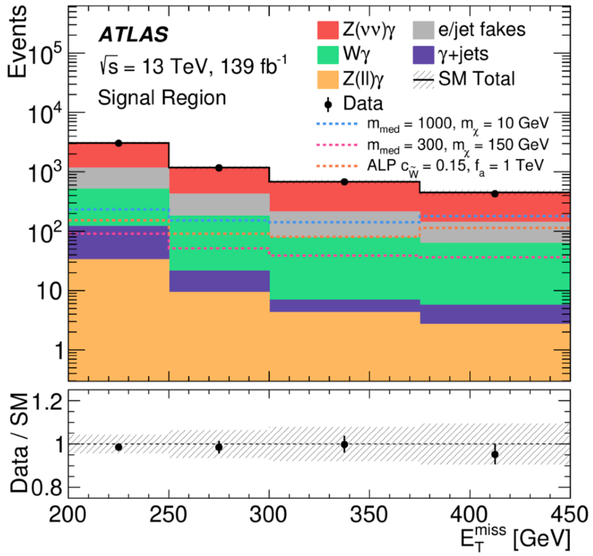
ATLAS: jet + E_T^{miss} [Phys. Rev. D 103 (2021) 112006]

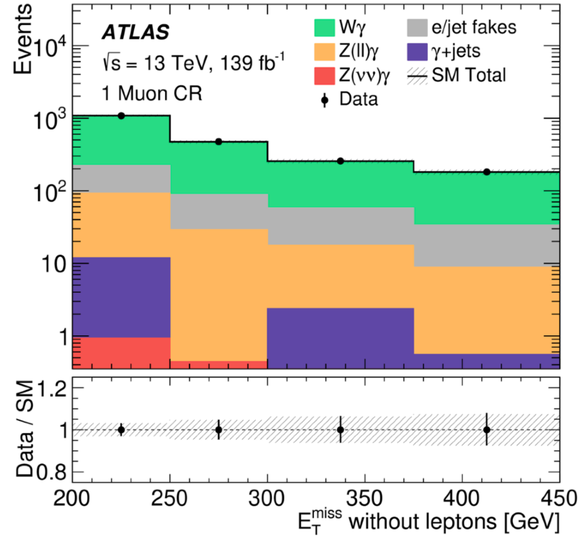
- Dataset
  - Run 2 data: $139\ \text{fb}^{-1}$
  - $\sqrt{s} = 13\ \text{TeV}$
- Search for a $\text{ALP} + \text{gluon jet}$ production
- Signature of an ALP exiting the detector + gluon jet:
  - Jet with $p_T > 150\ \text{GeV}$
  - $E_T^{\text{miss}} > 200\ \text{GeV}$ (mapped in inclusive bins)
- Event selection:
  - Veto events with e, μ tracks and hadronic τ mesons and γ
- Main backgrounds:
  - $Z + \text{jets}$
  - $W + \text{jets}$
  - $t\bar{t}$
- Simultaneous fit to the p_T^{recoil} (proxy for E_T^{miss} quantity)
  - Signal regions + control regions with electrons and muons
- $Z + \text{jets}$ and $W + \text{jets}$ events reweighted
  - Higher order corrections (NNLO QCD + NLO electroweak)

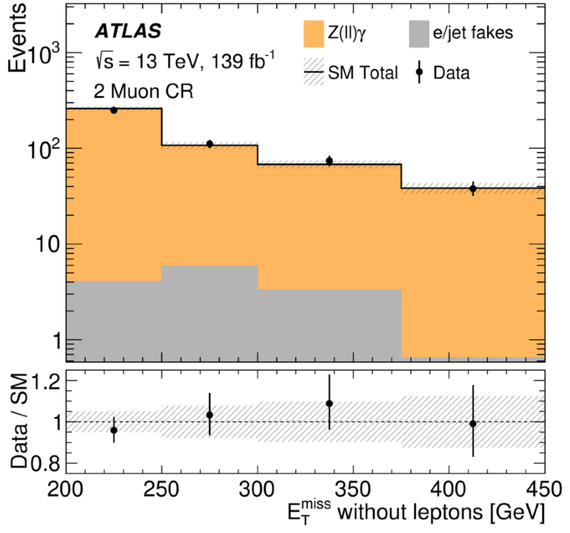


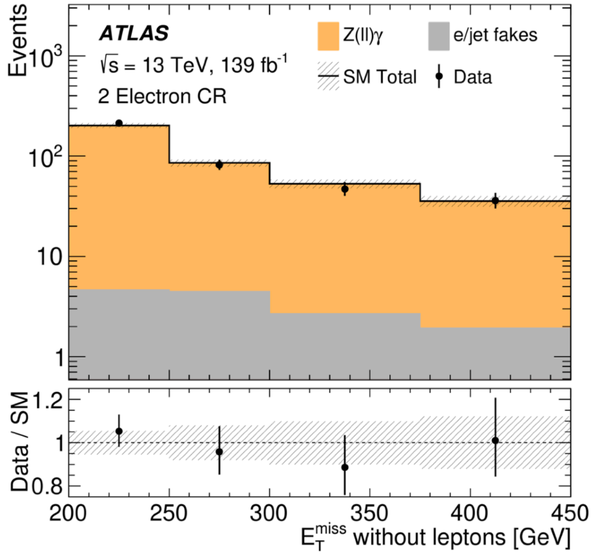
ATLAS: $\gamma + E_T^{\text{miss}}$ [JHEP 02 (2021) 226]

- Dataset:
  - Run 2 data: $139\ \text{fb}^{-1}$
  - $\sqrt{s} = 13\ \text{TeV}$
- Signature of an ALP produced w. γ
  - $E_T^{\gamma} > 150\ \text{GeV}$
    - Both unconverted and converted photons
  - $E_T^{\text{miss}} > 200\ \text{GeV}$ (mapped in inclusive bins)
  - Events with leptons (e, μ, τ) are vetoed
- Backgrounds:
  - Processes with isolated photons + E_T^{miss}
    - $Z(\rightarrow \nu\bar{\nu})\gamma$
  - Processes with jets misidentified as photons:
    - $\gamma + \text{jets}$
    - $Z/W + \text{jets}$
  - Processes with leptons
    - $W(\rightarrow \ell\nu)\gamma$
    - $Z(\rightarrow \ell\ell)\gamma$





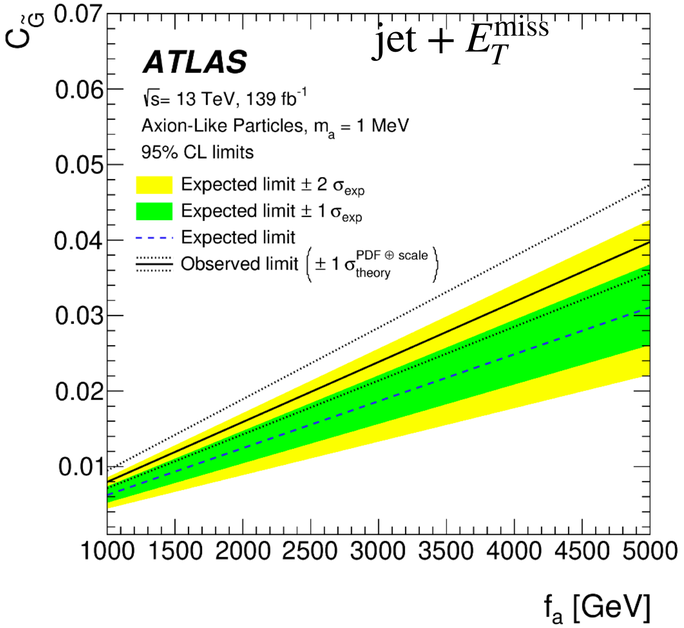


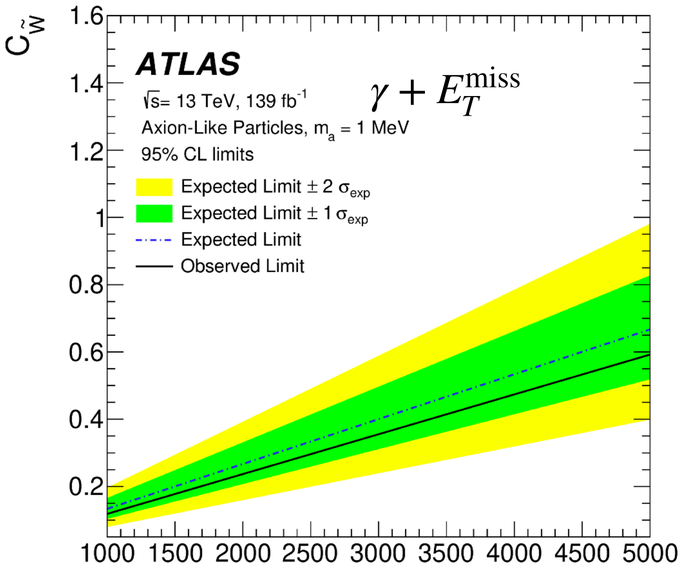


ATLAS: jet + E_T^{miss} and $\gamma + E_T^{\text{miss}}$

[Phys. Rev. D 103 (2021) 112006]
[JHEP 02 (2021) 226]

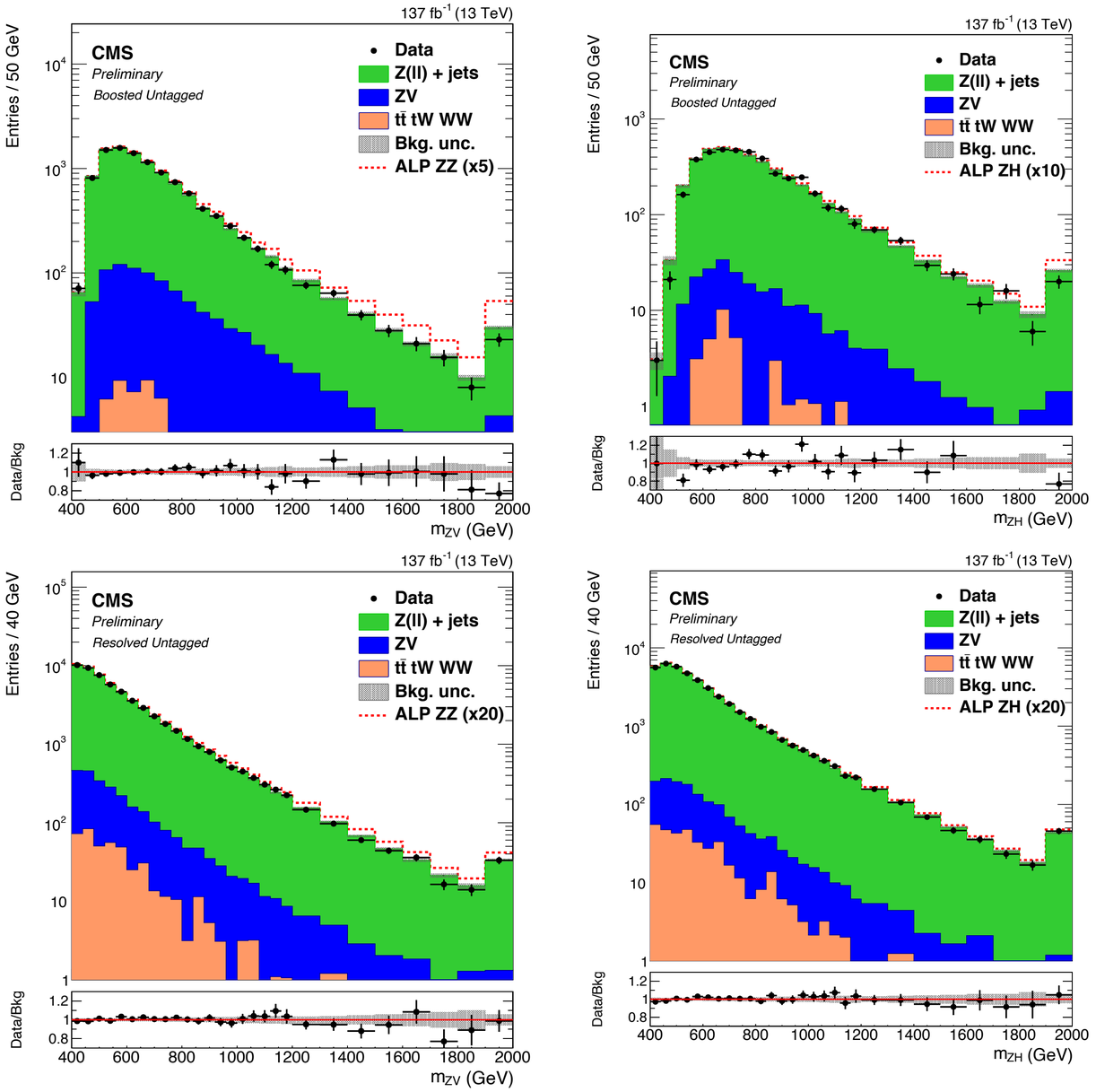
- Limits on $c - f_a$ plane for $m_a = 1\ \text{MeV}$ for both analyses
- Upper limits:
  - Simultaneous likelihood fit to control and signal regions and CL_s prescription
    - Fit performed in bins of E_T^{miss} for better sensitivity
  - Limit at $f_a = 1\ \text{TeV}$, very small mass dependence:
    - $c_{\tilde{G}}/f_a < 8 \times 10^{-6}$ for $m_a \in [1\ \text{MeV}, 1\ \text{GeV}]$
    - $c_{\tilde{W}}/f_a < 1.2 \times 10^{-4}$ for $m_a \in [1\ \text{MeV}, 1\ \text{GeV}]$
  - f_a exclusion scales linearly with $c_{\tilde{G}}/c_{\tilde{W}}$ according to cross-section re-scaling
- ALP EFT invalid for $\sqrt{\hat{s}} > f_a$:
  - $\sqrt{\hat{s}}$ correlated to higher E_T^{miss} events
  - Suppressing weighting factor for events out of this bound: $f_a^4/\hat{s}^2$
  - $\gamma + E_T^{\text{miss}}$: negligible
  - $\text{jet} + E_T^{\text{miss}}$: yield reduction $\mathcal{O}(5\%)$ for $f_a = 2\ \text{TeV}$
    - Negligible already at $f_a = 3\ \text{TeV}$





CMS: non resonant $pp \rightarrow a^* \rightarrow ZH, ZV$ [CMS-B2G-20-013]

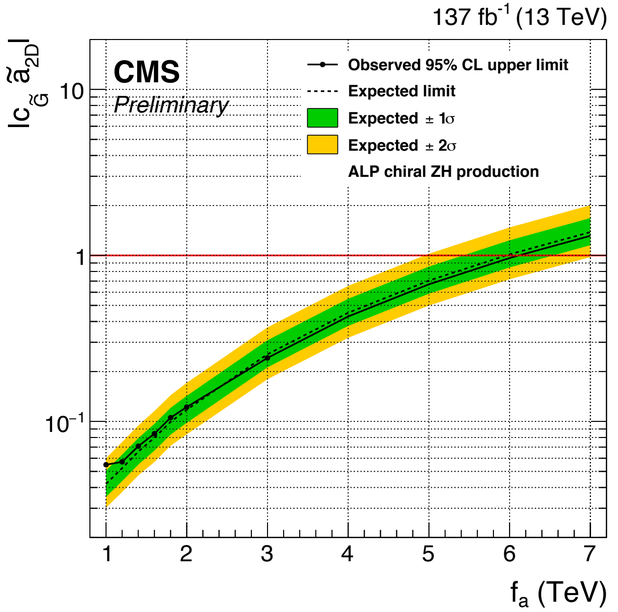
- Dataset:
  - $137\ \text{fb}^{-1}$ of Run 2 data: 2016-2018
  - $\sqrt{s} = 13\ \text{TeV}$
- Signature:
  - $Z \rightarrow \ell^+\ell^-$
  - Merged J or resolved jj di-jet
- Search for ALP mediated production of
  - **Z boson + Higgs (chiral model)**
  - **Z boson + Z boson (linear model)**
- Main background:
  - $Z + \text{jets}$
- Details about the signal modes [Phys.Rev.Lett. 124 (2020) 5, 051802]

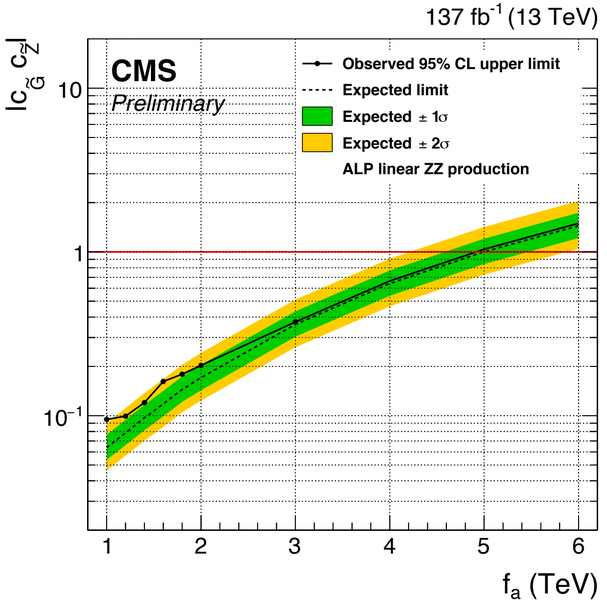


CMS: non resonant $pp \to a^* \to ZH, ZV$ [CMS-B2G-20-013]

- Combined maximum likelihood fit to the mass distribution
- Exclusion region on the $c_i c_j - f_a$ plane for the chiral and linear models
  - $95\,\%$ CL limits obtained using $\mathrm{CL_s}$ method
  - $f_a > 3$ TeV excluded extrapolating $f_a = 3$ TeV point linearly
- $m_a < 100$ GeV: region where cross-section diverges by less than $10\,\%$
- Limits on c_i/f_a:
  - $|c_{\tilde{G}} c_{\tilde{Z}}|/f_a^2 < 0.0415(0.0400)\ \mathrm{TeV}^{-2}$
  - $|c_{\tilde{G}} \tilde{a}_{2D}|/f_a^2 < 0.0269(0.0281)\ \mathrm{TeV}^{-2}$
- Energy dependance only valid for $m_{ZH,ZV} = \sqrt{\hat{s}} < f_a$
  - Same argumentation as in the ATLAS searches

- More ATLAS and CMS results for Higgs coupling interpretation:
  - ATLAS:
    - $H \to Za$ [Phys. Rev. Lett. 125 (2020) 221802]
    - $H \to aa \to 4b$ [Phys. Rev. D 102 (2020) 112006]
    - $H \to aa \to 2b2\mu$ [ATLAS-CONF-2021-009]
  - CMS
    - $H \to Za$ [Eur. Phys. J. C 81 (2021) 13]

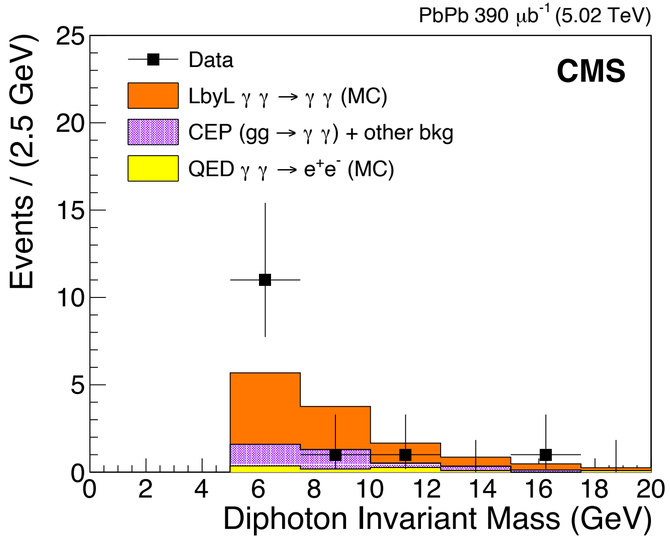


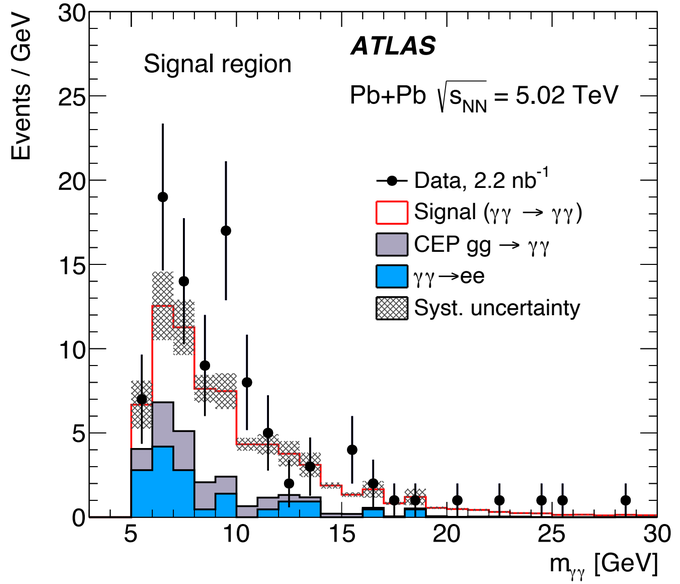


ATLAS and CMS: Searches in PbPb collisions

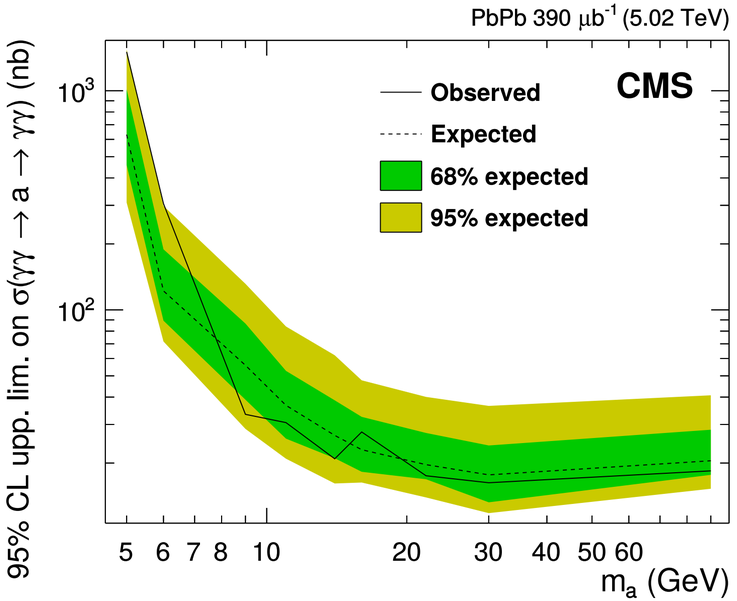
[JHEP03(2021)243]
[Phys.Lett.B 797 (2019) 134826]

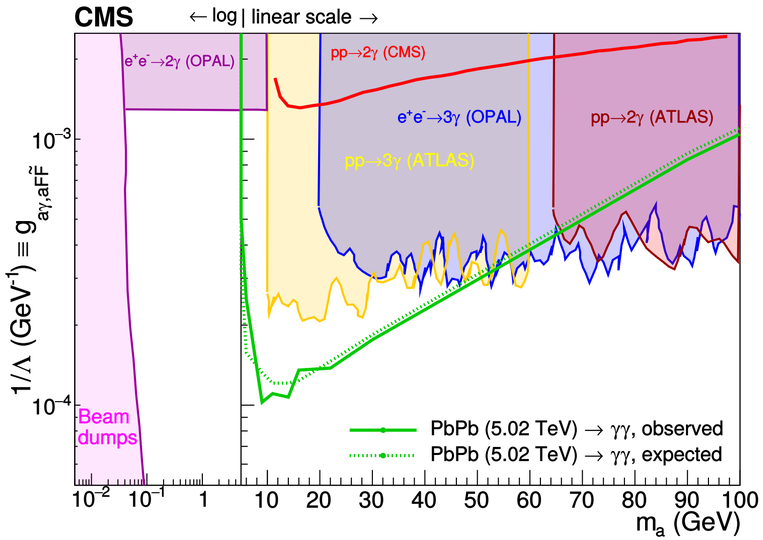
- Dataset of ultraperipheral $\mathbf{PbPb}$ collisons at $\sqrt{s} = 5.02\ \mathrm{TeV}$
  - CMS: $390\ \mu\mathrm{b}^{-1}$
  - ATLAS: $2.2\ \mathrm{nb}^{-1}$
- Very similar selection of $a \to \gamma\gamma$ for both experiments
  - $E_T^\gamma > 2\ \mathrm{GeV}$ (unconverted photons)
  - $|\eta| \lesssim 2.4$ (forward)
  - $m_{\gamma\gamma} > 5\ \mathrm{GeV}$ (reduce e^+e^-)
  - $p_T^{\gamma\gamma} \lesssim 1\ \mathrm{GeV}$ (ensure exclusive production)
  - Low general activity in the detector
- Backgrounds:
  - QED e^+e^- production
  - CEP $\gamma\gamma$



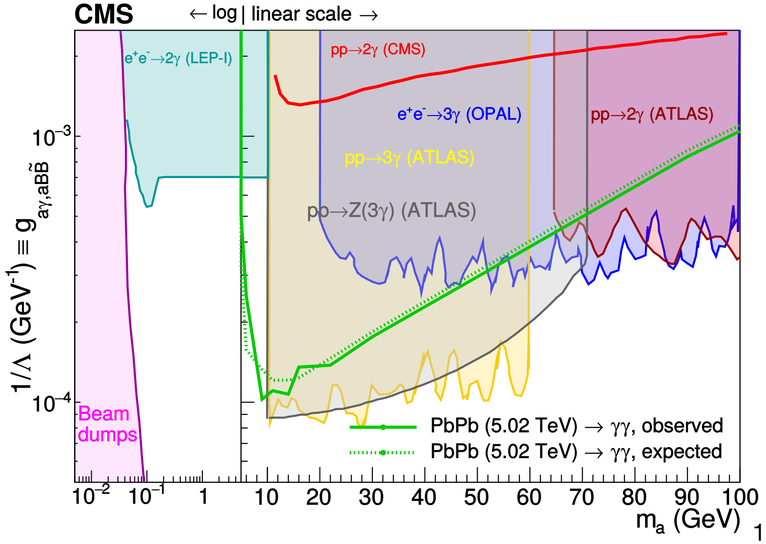


CMS: Searches in PbPb collisions [Phys.Lett.B 797 (2019) 134826]



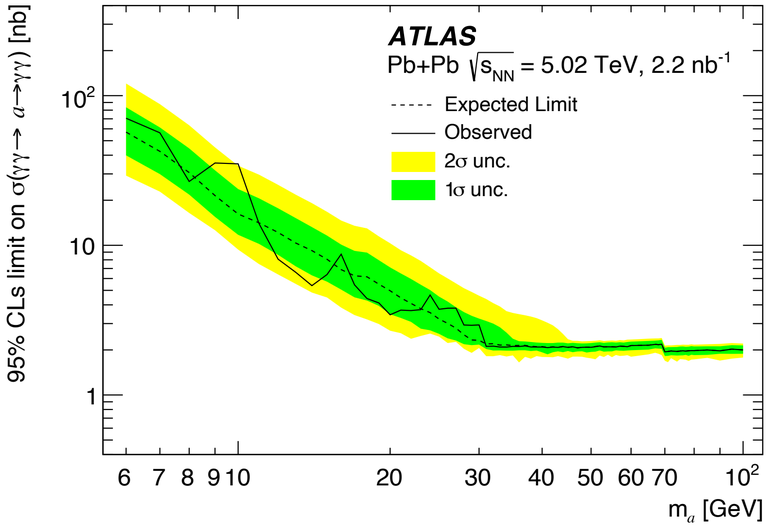


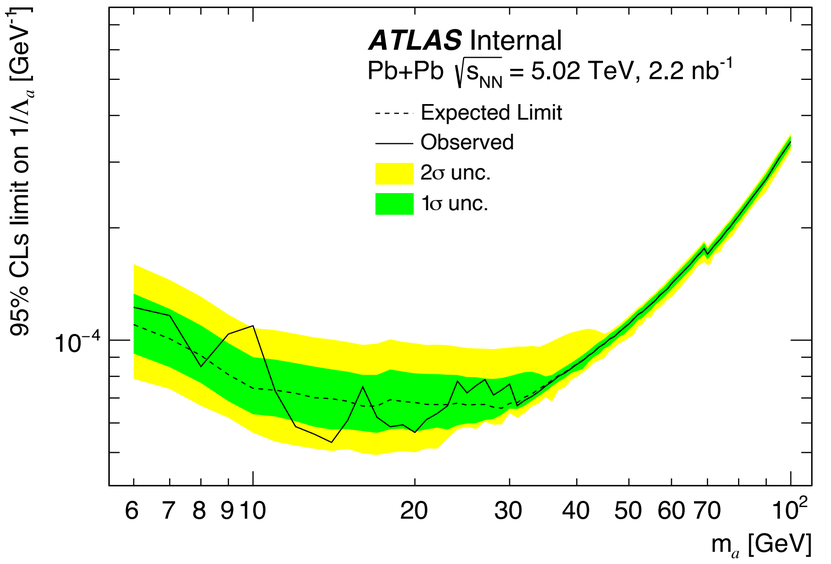
- Cross section upper limits:
  - $\mathrm{CL_s}$ prescription with profile likelihood ratio at $95\ \%\ \mathrm{CL}$
- Cross section limits interpreted as limits on the ALP couplings:
  - ALPs only coupling to photons: $g_{a\gamma,aF\tilde{F}}$
  - ALPs coupling also to Z: $g_{a\gamma,aB\tilde{B}}$

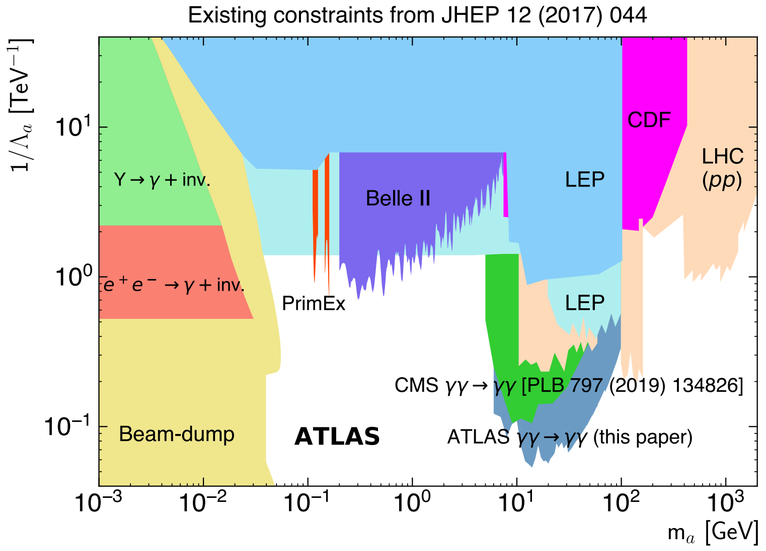


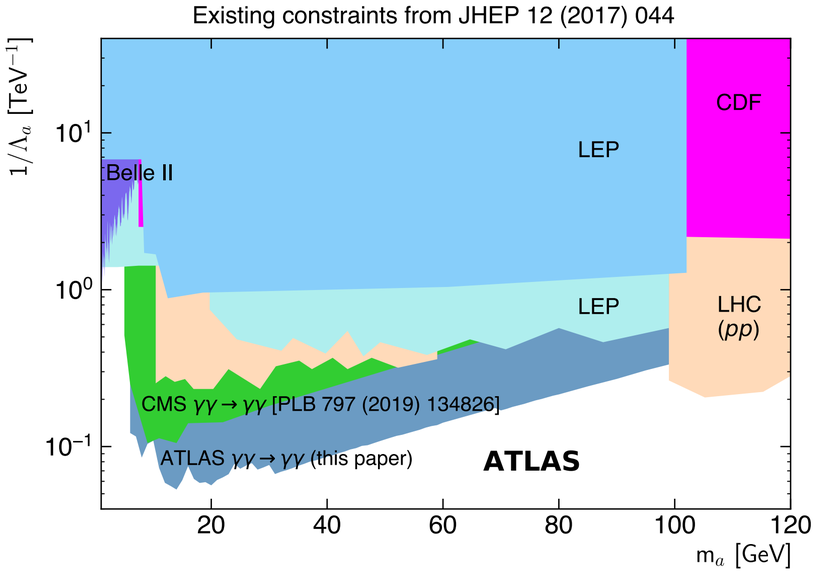
ATLAS: Searches in PbPb collisions [JHEP03(2021)243]

- Cross section upper limits:
  - $\mathbf{CL_s}$ prescription with profile likelihood ratio at $\mathbf{95\,\%\,CL}$
- Cross section limits interpreted as limits on the ALP couplings:
  - ALPs only coupling to photons



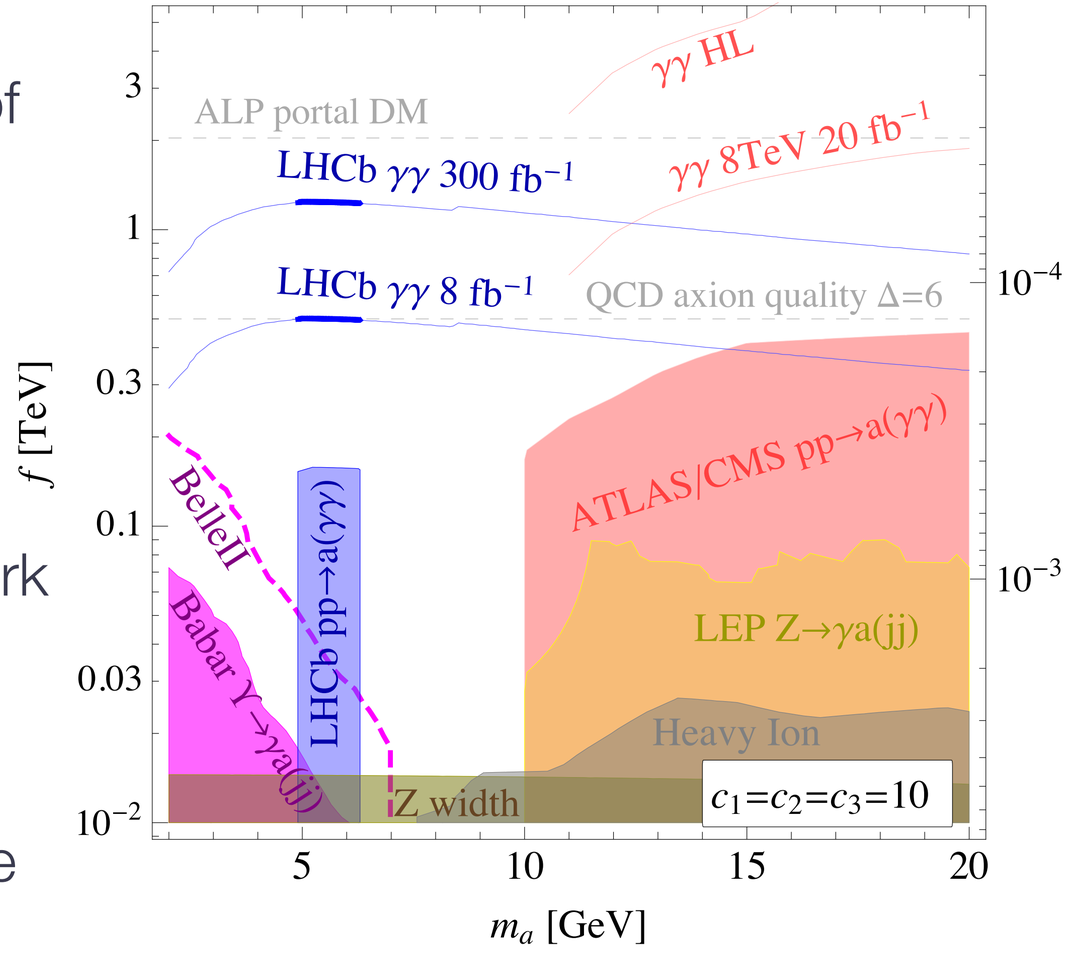






LHCb [JHEP 01 (2019) 113]

- Light ALPs not reachable for ATLAS and CMS
- Current **best limits** in mass gap done with $\mathbf{80\ pb^{-1}}$ of **public LHCb data**
  - Existing trigger for $B_s \to \gamma\gamma$. Analysis similar and could be done in parallel
  - Trigger mass range extended in 2018. Before that only sensitive to $m \sim m(B_s)$
  - Novel software trigger based on MLP neural network **[SciPost Phys. 7, 062 (2019)]**
  - Experimental analysis ongoing:
    - Currently relying only on unconverted photons
    - Potential to include photon conversions: improve sensitivity.



LHCb [JHEP 01 (2019) 113]

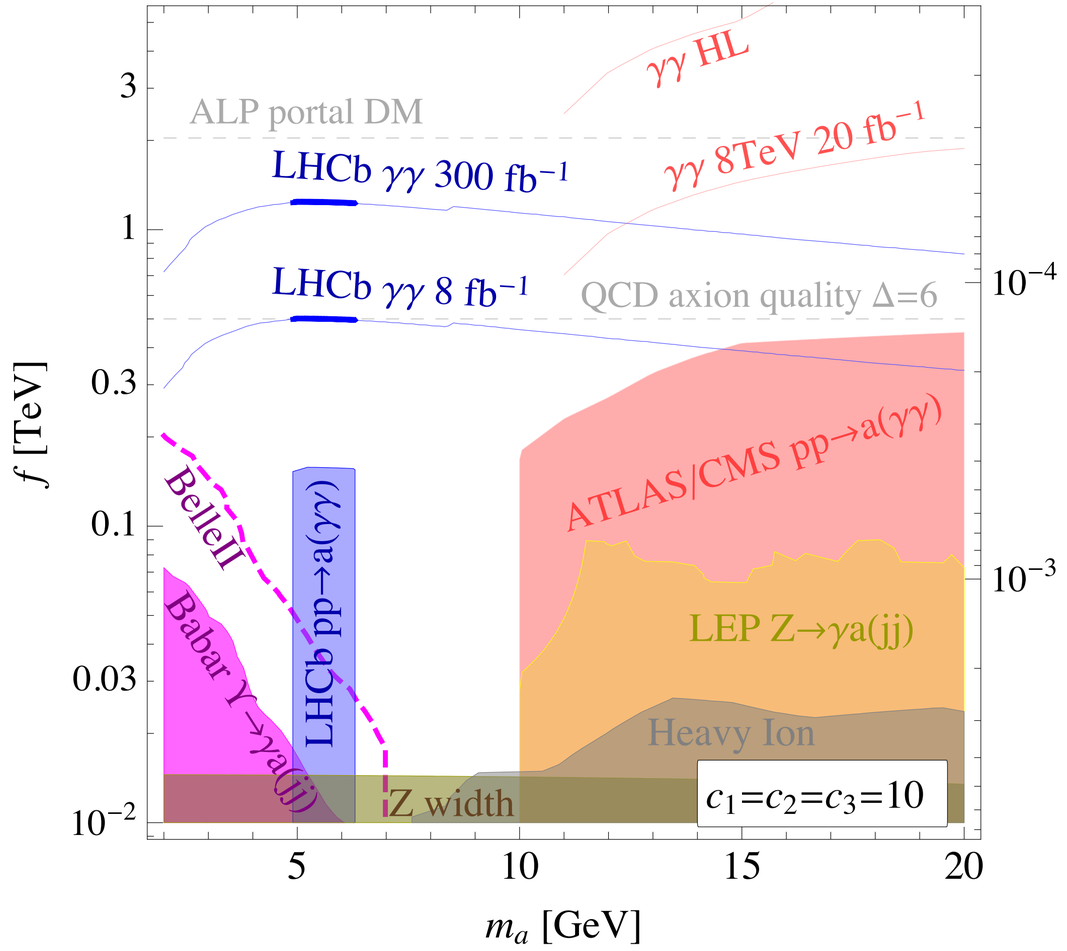
I. ATLAS:
- Isolated photon pair production at $\sqrt{s} = 7$ TeV [JHEP 01, 086 (2013)]
- Cross section of isolated photon pair production at $\sqrt{s} = 8$ TeV [Phys. Rev. D95, 112005 (2017)]

II. CMS:
   I. Differential cross section of isolated photon pair production at $\sqrt{s} = 7$ TeV [Eur. Phys. J. C74, 3129 (2014)]

III. BaBar:
   I. Search for hadronic decays of Light Higgs Boson [Phys. Rev. Lett. 107, 221803 (2011)]
   Using result $\mathrm{BR}(\Upsilon_{2S,3S} \to \gamma a(jj)) < 10^{-4},\ 10^{-6}$

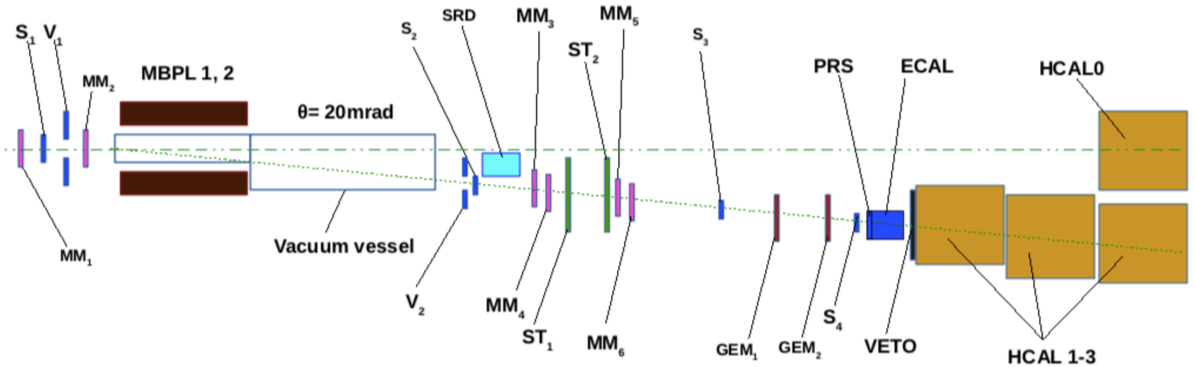
IV. BelleII:
   I. Extrapolating results from the above reference assuming $\times 10$ better sensitivity: statistically dominated and 100 times more Υ_{3S}

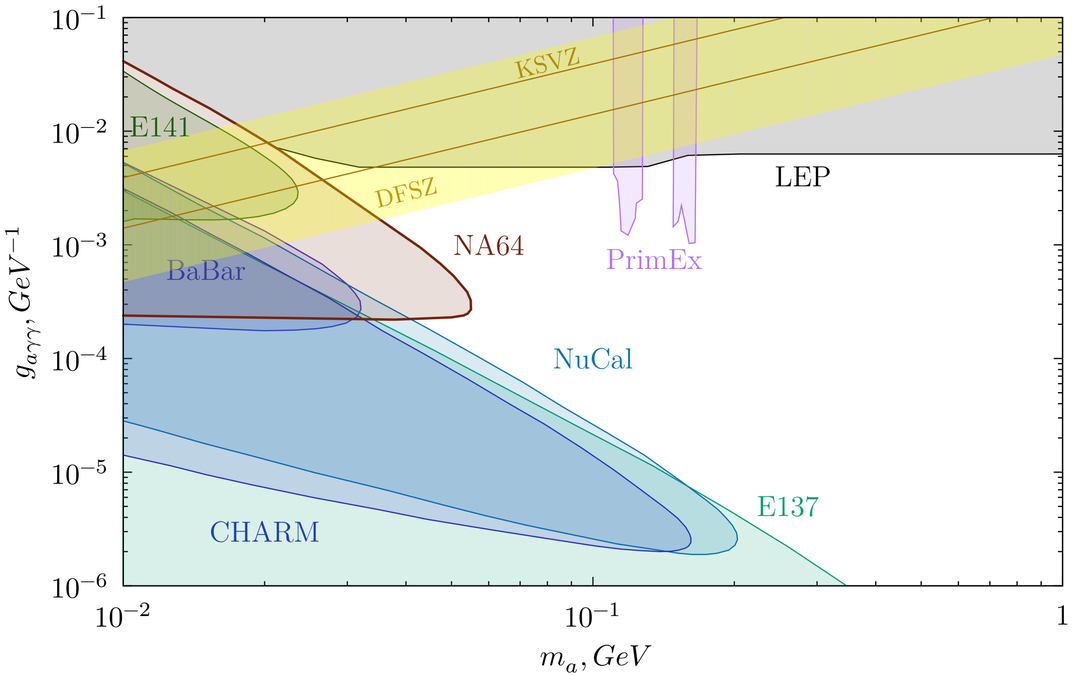
LHC sensitivities: assuming gluon fusion production

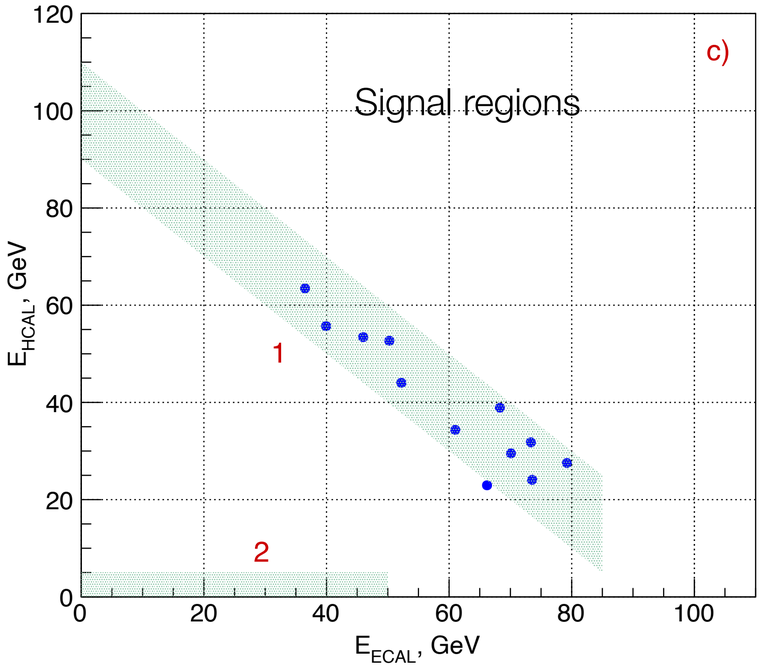


NA64: $e^-Z \to a \to \gamma\gamma$ [Phys. Rev. Lett. 125, 081801]

- Setup:
  - $100\ \mathrm{GeV}\ e^-$ beam
  - Invisible mode setup:
    - Beam dumped into active PRS+ECAL target
- ALPs would be generated via Primakoff effect:
  - $e^-Z \to e^-Z\gamma;\ \gamma Z \to aZ;\ a \to \gamma\gamma$
- Two signatures:
  - $\gamma\gamma$ signal reconstructed in the two last HCAL modules
    - first module used to veto background activity
  - ALP decays downstream: missing energy event

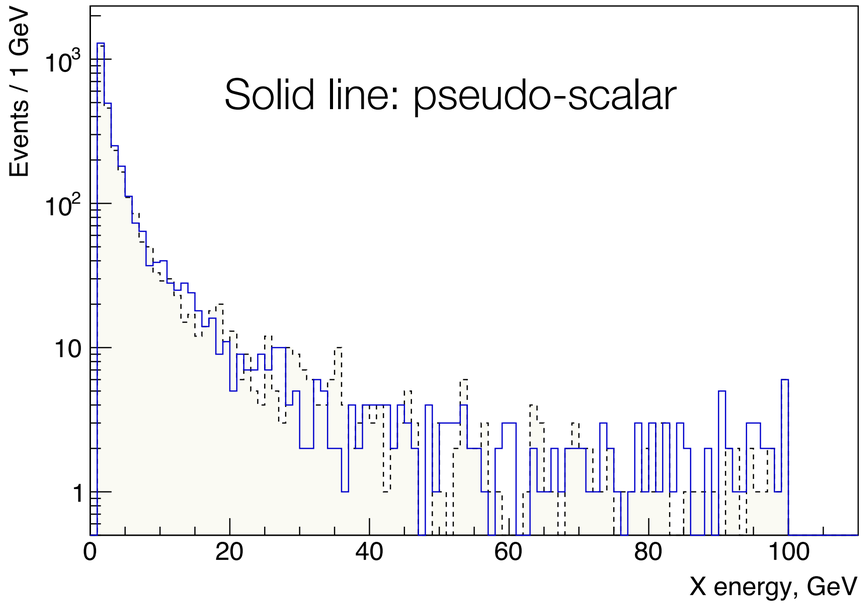




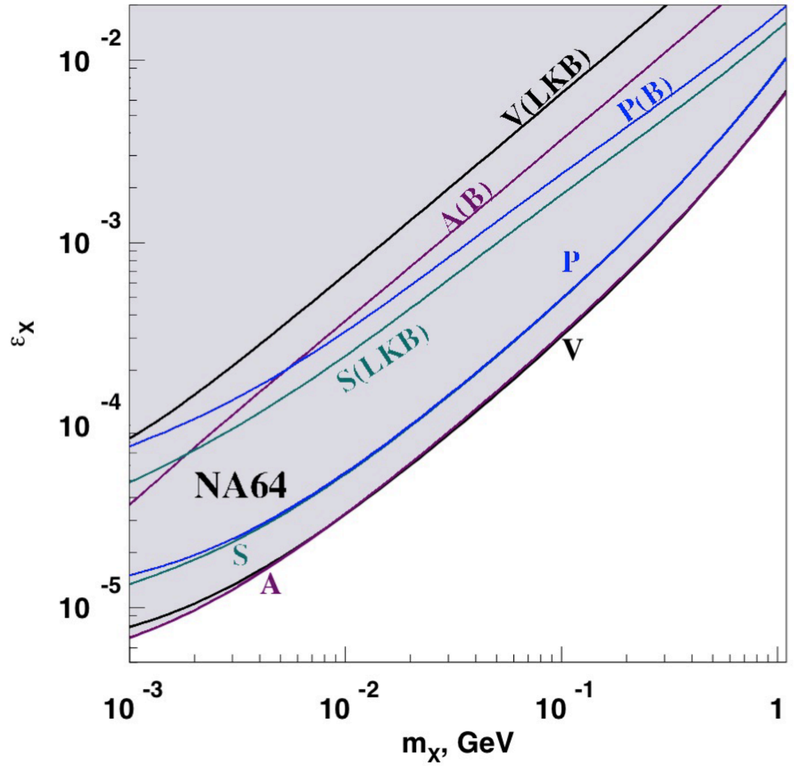


NA64: $e^-Z \rightarrow X \rightarrow$ invisible [Phys. Rev. Lett. 126, 211802]

- Generic X boson search:
  - in particular a pseudo-scalar
- Boson produced via Primakoff effect:
  - $e^-Z \rightarrow e^-ZX;\ X \rightarrow$ invisible



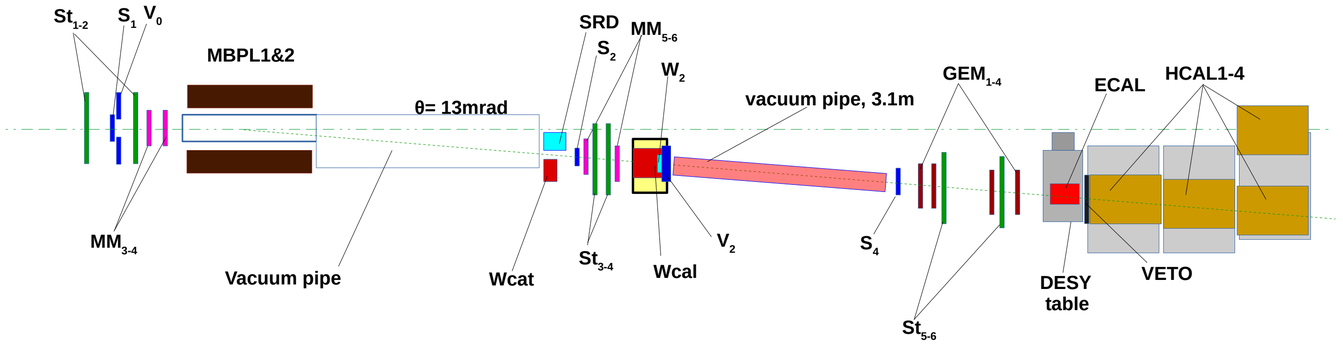
- Missing energy spectrum of the pseudo-scalar

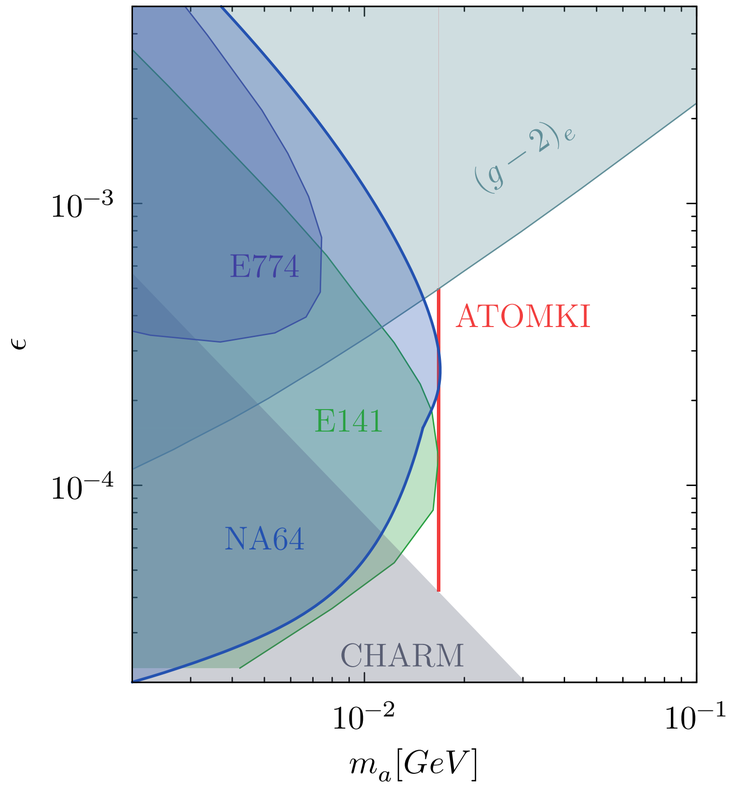


- $m_X - \epsilon_X$ exclusion regions
  - Compared to LKB and Berkley results

NA64: $e^- Z \rightarrow a \rightarrow e^+ e^-$ [2104.13342]

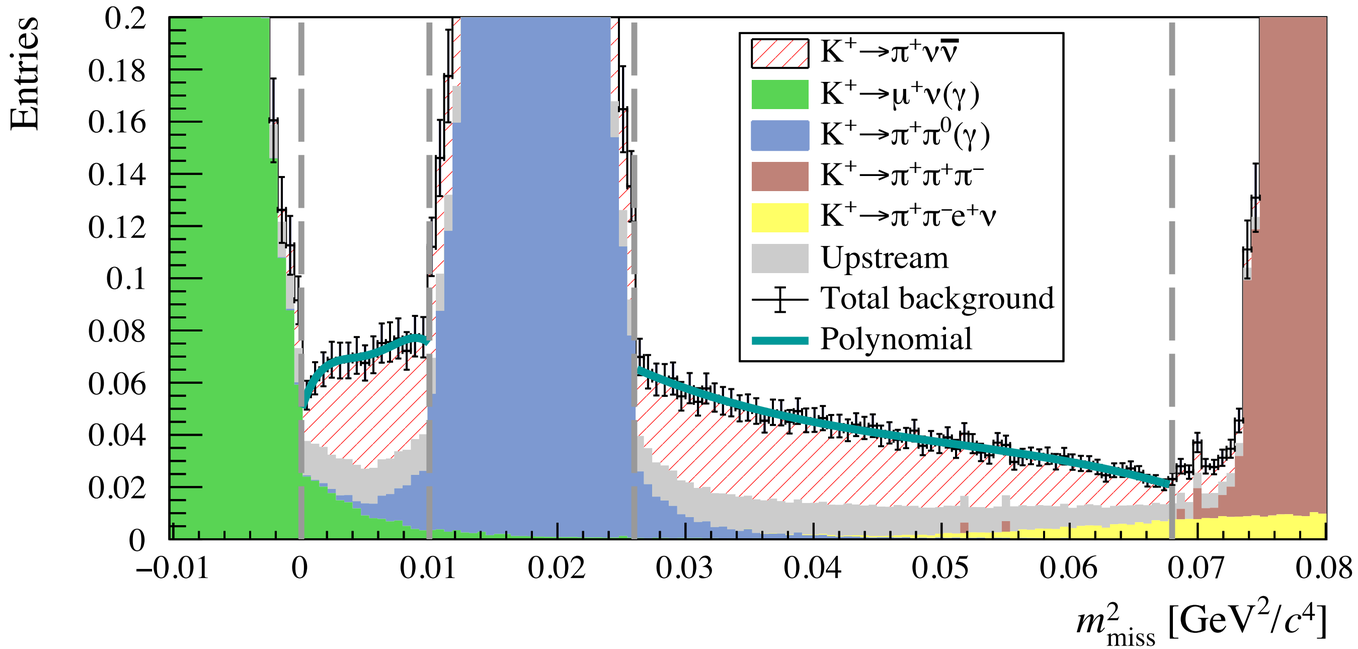
- e^- electron beam with energies:
  - 100 GeV for 2017 data
  - 150 GeV for 2018 data
- Visible mode setup:
  - Addition of active target WCAL
- For smaller couplings also invisible setup used
  - Life time long enough to decay in HCAL2 volume
- Signature:
  - $e^+ e^-$ pair
  - Detected as double EM shower
    - WCAL active target shower
    - ECAL shower
- Exclusion region:
  - $m_a \in [1,17.1]$ MeV
  - ATOMKI anomaly located at 16.7 MeV
    - More statistics needed to cover this effect





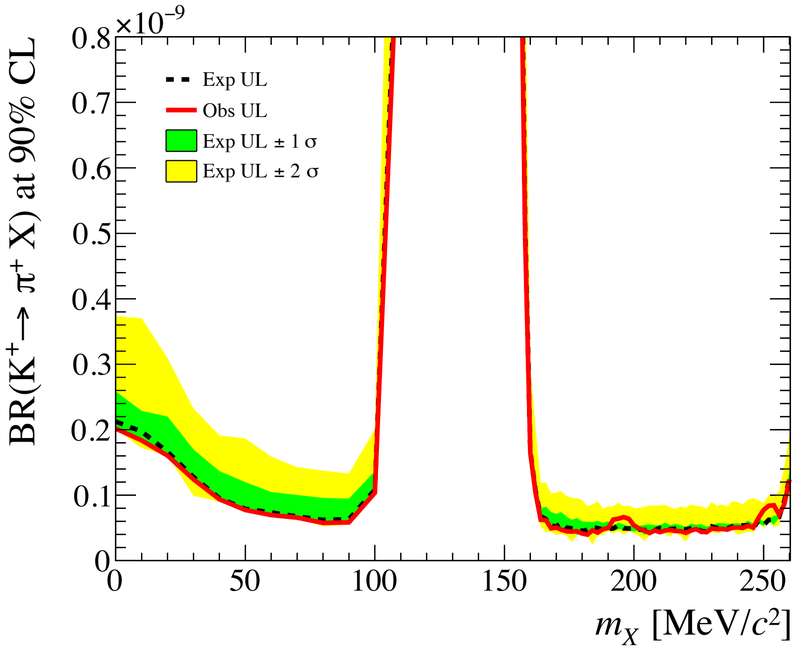
NA62: $K^+ \to \pi^+ a,\ a \to$ invisible [JHEP 03 (2021) 058]

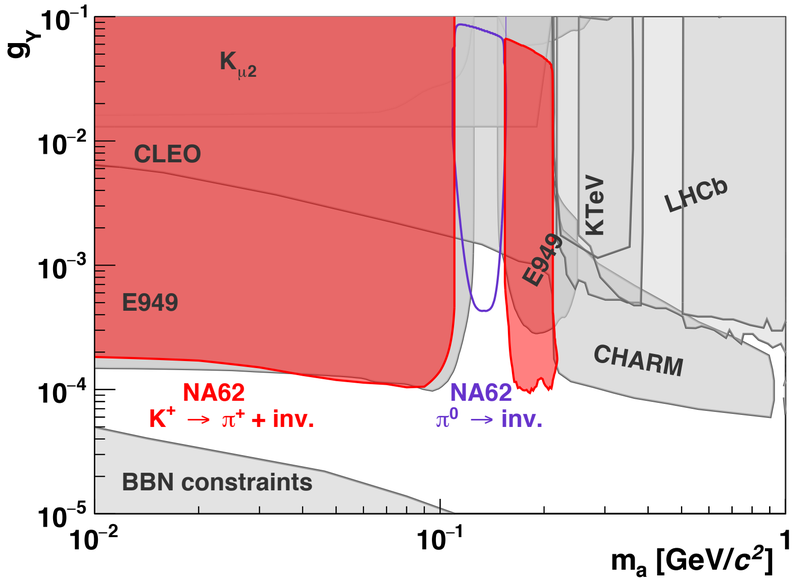
- Search for the $K^+ \to \pi^+ X$ decay
  - X interpreted as an ALP
  - X decays invisible to the detector
- Backgrounds:
  - $K^+ \to \pi^+ \nu \bar{\nu}$ (using search based on this channel)
  - $K^+ \to \pi^+ \pi^0$
  - $K^+ \to \mu^+ \nu_\mu$
  - $K^+ \to \pi^+ \pi^+ \pi^-$
- Selection:
  - $m_a \in [0,110] \cup [160,250]$ MeV explored
  - $m^2_{\text{miss}} = (P_K - P_\pi)^2$ used as discriminating variable

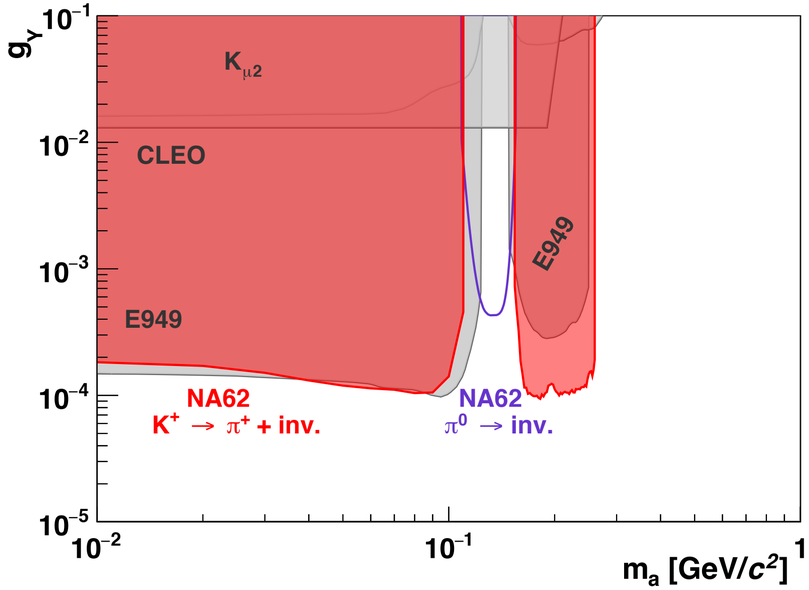


NA62: $K^+ \to \pi^+ a,\ a \to$ invisible [JHEP 03 (2021) 058]

- Frequentist hypothesis test with m^2_{miss} as observable
  - Unbinned profile likelihood ratio test statistic
  - Two compatible events found at $m_X = 196,\ 252$ MeV
- Upper limits on $\text{BR}(K^+ \to \pi^+ X)$ using CL_s method at 90 % CL
  - Two category limits on the coupling to ALPs derived from those
    - ALPs decaying to visible particles
    - ALPs decaying invisibly

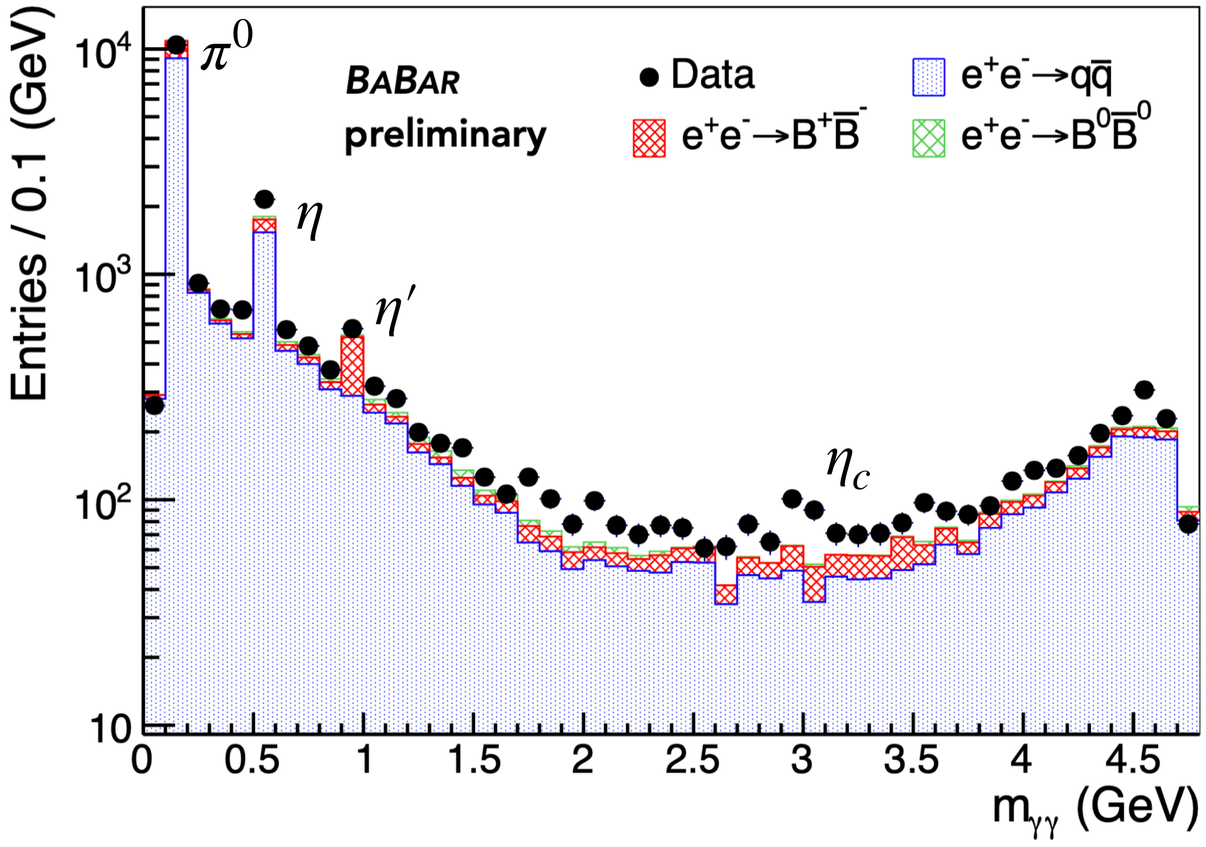






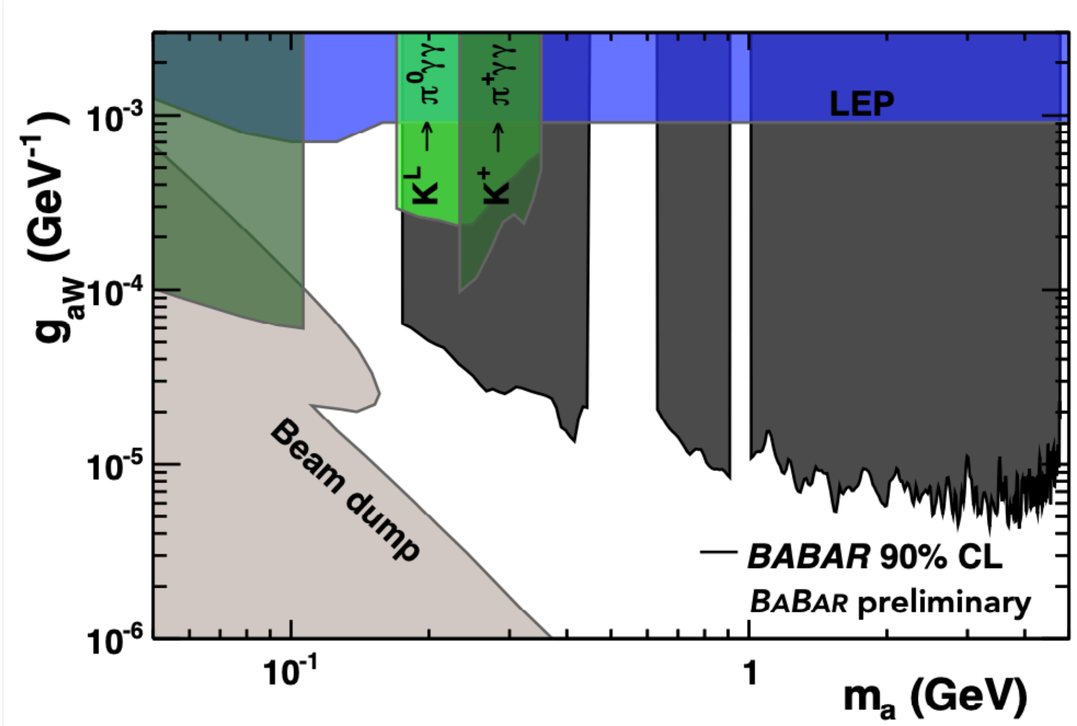
BaBar [Brian Shuve talk at ICHEP]

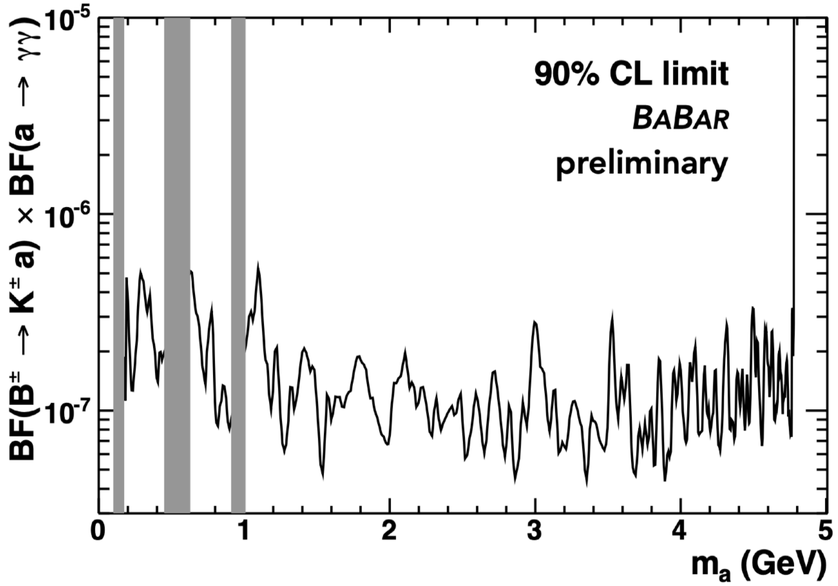
- Search for ALPs in $B^{\pm} \to K^{\pm} a,\ a \to \gamma\gamma$ channel
  - Bump hunt for a narrow peak
- Final results waiting:
  - Blind analysis using only $8\ \%$ of total data
- Prompt search for
  - $m_a \in [0.1,\ 4.78]\ \mathrm{GeV}$
- Displaced search for:
  - $m_a < 2.5\ \mathrm{GeV}$
  - $c\tau_a = 1,\ 10,\ 100\ \mathrm{mm}$
- Main backgrounds:
  - $e^+e^- \to q\bar{q}\ (q = u,\ d,\ s,\ c)$
  - $e^+e^- \to B\bar{B}$
  - Peaking resonances: $\pi^0,\ \eta,\ \eta'$

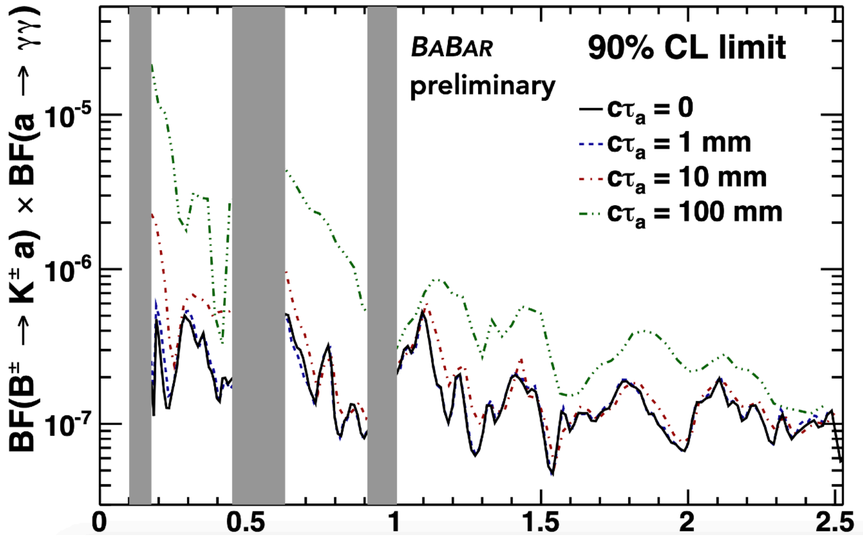


BaBar [Brian Shuve talk at ICHEP]

- Unbinned maximum likelihood fit to $m_{\gamma\gamma}$
- $90\ \%\ \mathrm{CL}$ limits placed for prompt and long lived ALPs on $\mathrm{BF}(B^{\pm} \to K^{\pm} a,\ a \to \gamma\gamma)$
- $\mathrm{BF}(\tau)$ used to set limits on coupling to vector boson W
  - Improving current bounds by many orders of magnitude !
- Signature to also be covered by Belle II in the near future as reported in EPS conference !

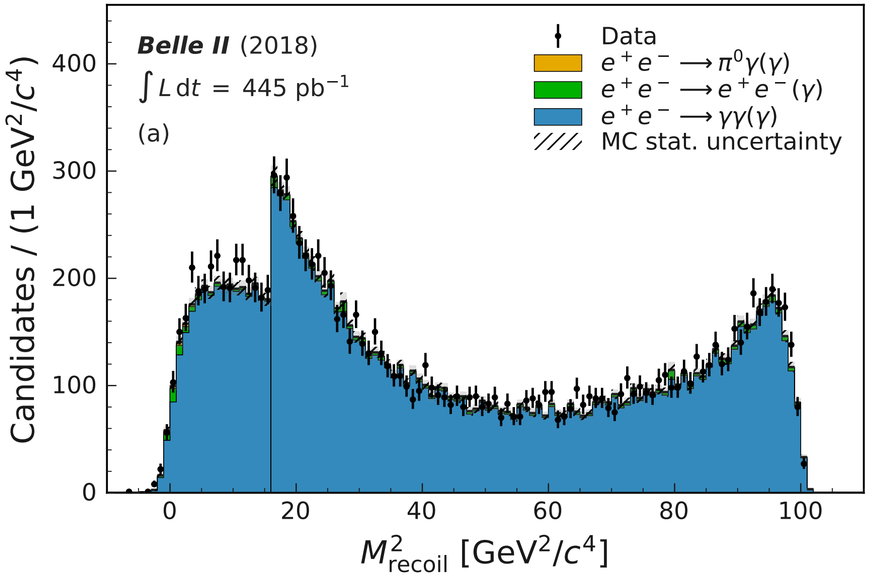


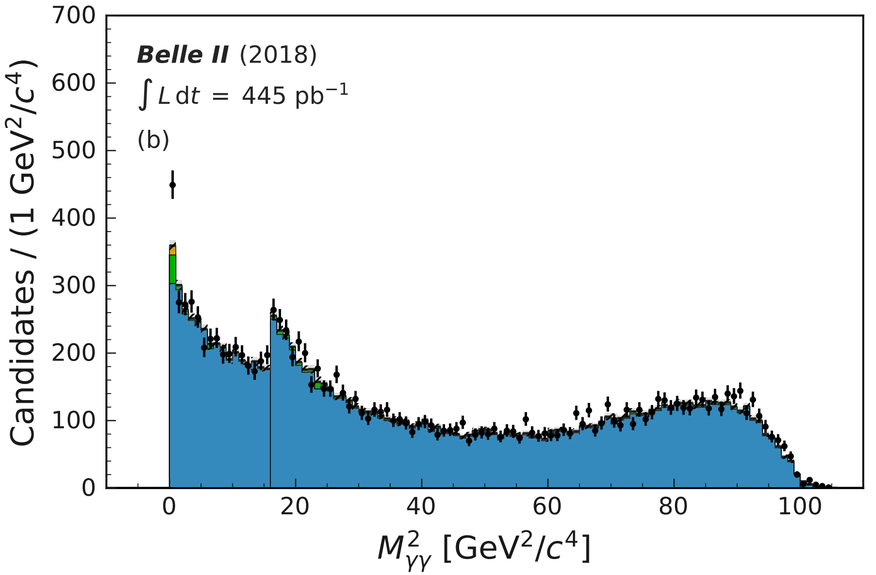




Belle II: $e^+e^- \to \gamma a, a \to \gamma\gamma$ [Phys. Rev. Lett. 125, 161806]

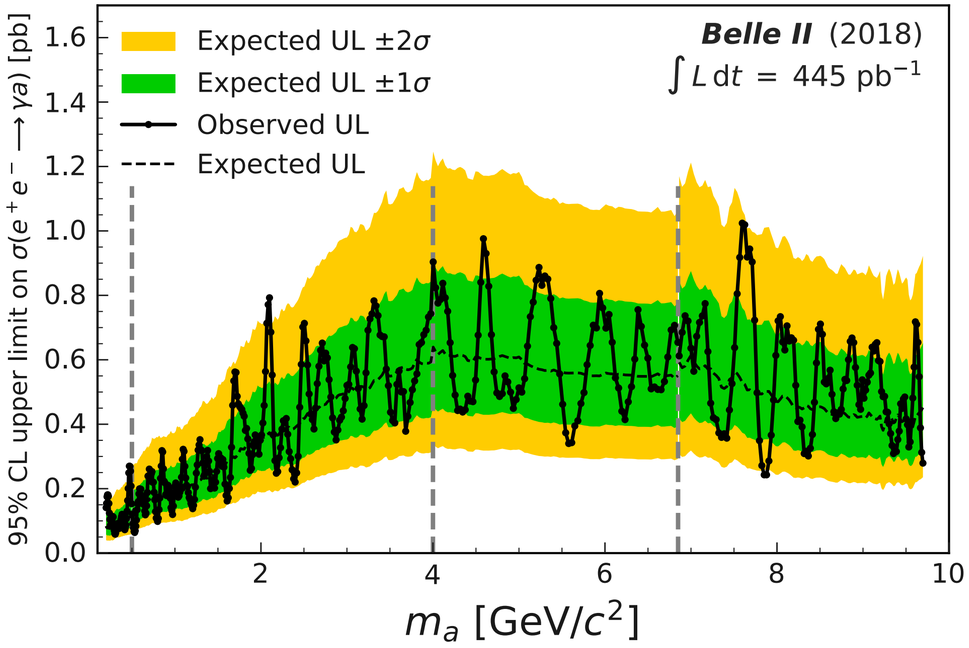
- Dataset: $445\ \mathrm{pb}^{-1}$ from 2018 pilot run
- Search for ALPs produced together with a γ
- Signature:
  - 3 isolated photons
- Selection:
  - $0.88\sqrt{s} \leq M_{\gamma\gamma\gamma} \leq 1.03\sqrt{s}$
- Backgrounds:
  - $e^+e^- \to \gamma\gamma\gamma$
  - $e^+e^- \to e^+e^-\gamma$
- Binned extended maximum likelihood fits:
  - $m_a \in [0.2,\ 6.85]\ \mathrm{GeV}$ to the $M^2_{\gamma\gamma}$ distribution
  - $m_a \in [6.85,\ 9.7]\ \mathrm{GeV}$ to the M^2_{recoil} distribution

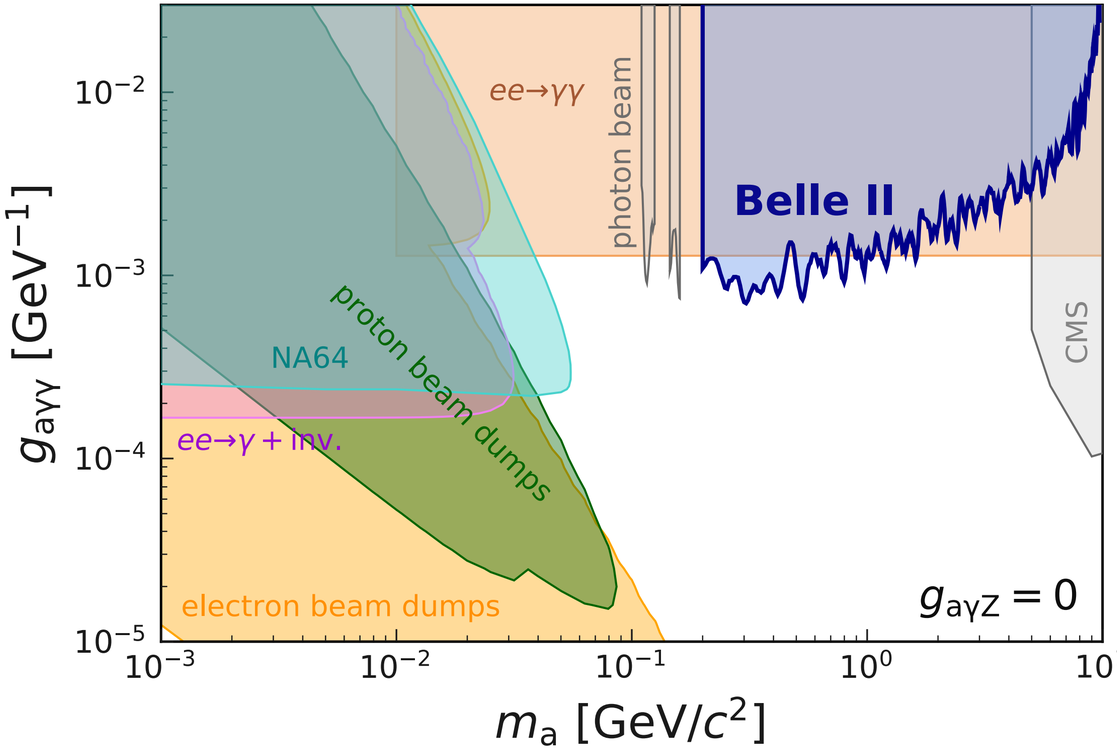




Belle II: $e^+e^- \to \gamma a, a \to \gamma\gamma$ [Phys. Rev. Lett. 125, 161806]

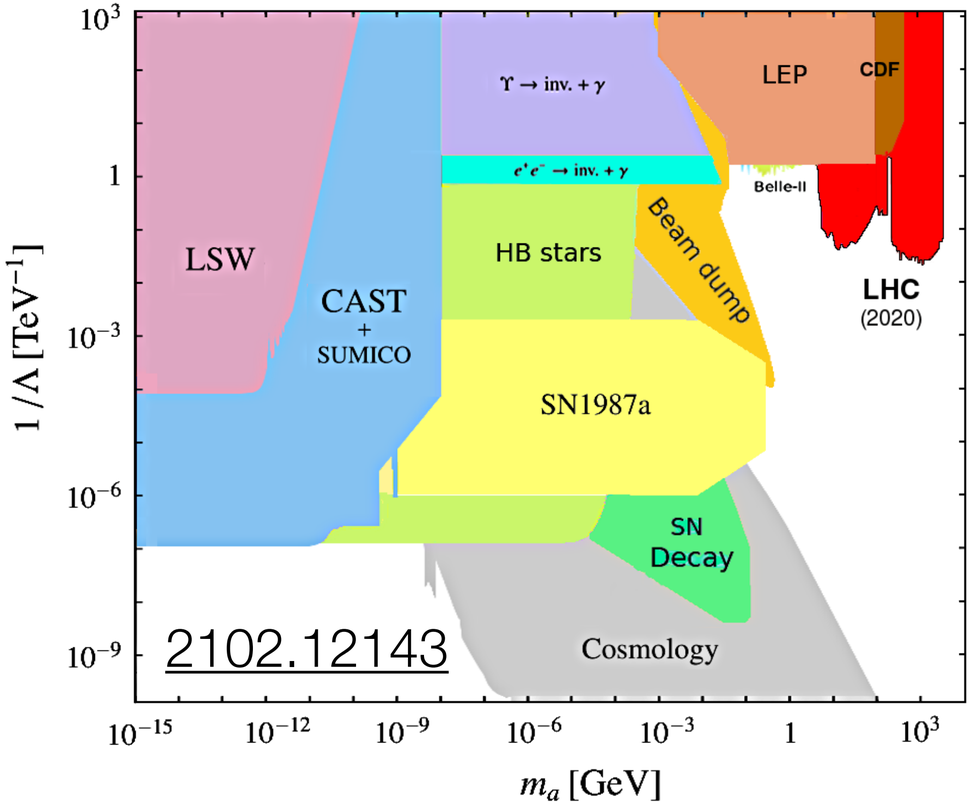
- Binned extended maximum likelihood fits over the mass range
  - $m_a \in [0.2,\ 6.85]\ \mathrm{GeV}$ to the $M^2_{\gamma\gamma}$ distribution
  - $m_a \in [6.85,\ 9.7]\ \mathrm{GeV}$ to the M^2_{recoil} distribution
- $95\ \%\,\mathrm{CL}$ upper limits on the signal cross section translated into $g_{a\gamma\gamma}$





Take home

- ALPs are pseudo Nambu-Goldstone bosons associated to Spontaneous Symmetry Breaking
- ALPs couple to different sectors of the SM
- Different signatures probing various couplings covered in this talk:
  - Gluons, photons, Vector gauge bosons, Higgs...
- Bright future ahead with new prospects coming from different experiments



BACKUP

B→Ka Torben Feber @ EPS

- Search for ALPs that predominantly couple to electroweak gauge bosons
- Dominant decay for $m_a \ll m_W$ into photons:

$$\Gamma(a \to \gamma\gamma) = \frac{g_{aW}^2 \sin^4\theta_W M_a^3}{64\pi}$$

- Light ALPs naturally long-lived, but decay in general model-dependent