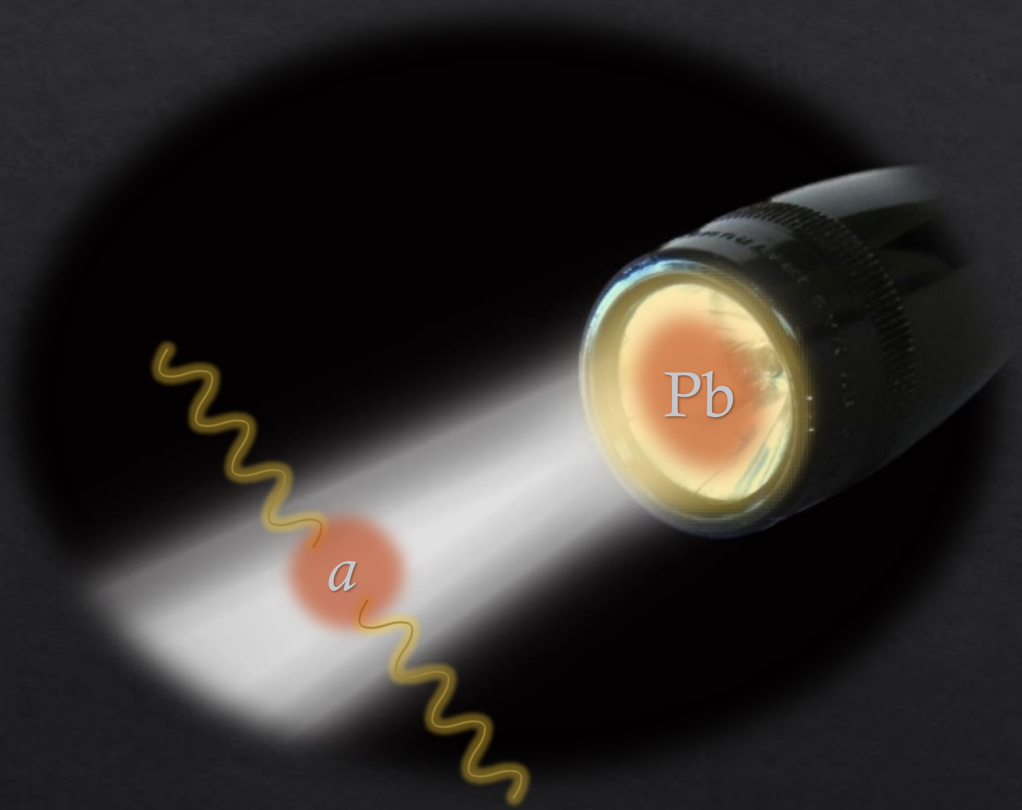
Light Dark Matter 2017

# Searching for Axion-like particles with heavy-ions




Hou Keong (Tim) Lou,

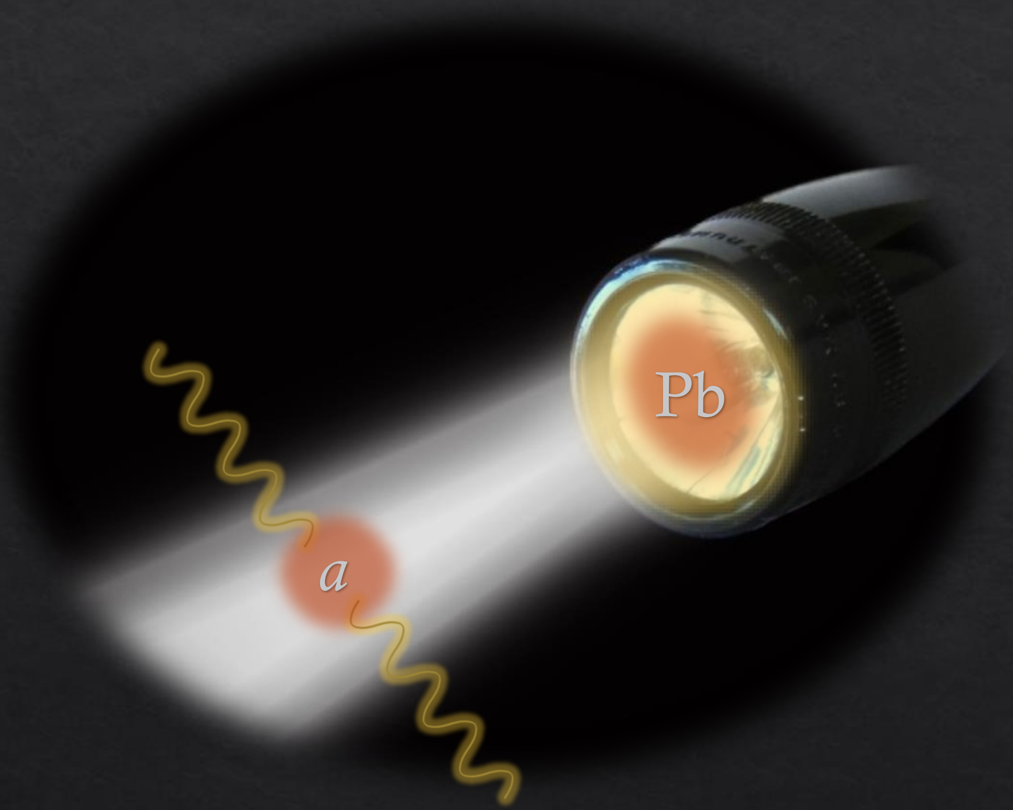
Simon Knapen, Tongyan Lin and Tom Melia

PhysRevLett.118.171801

*Disclaimer: Not Dark Matter! Sorry!

“Light”? “Dark”? ~~Matter~~ Sector 2017

# Searching for Axion-like particles with heavy-ions





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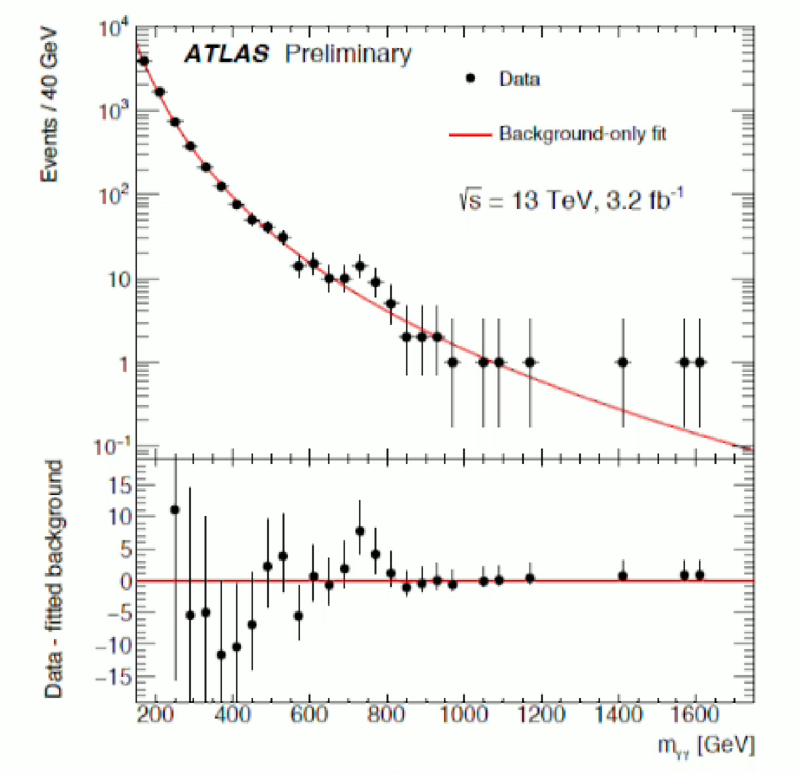
# New Physics @LHC

- Must leave no stone unturned!
- There may be many surprises!
    - 750 GeV (false alarm)
- Can we be missing cousins of 750 GeV?
- Possibly: What if resonance is lighter?



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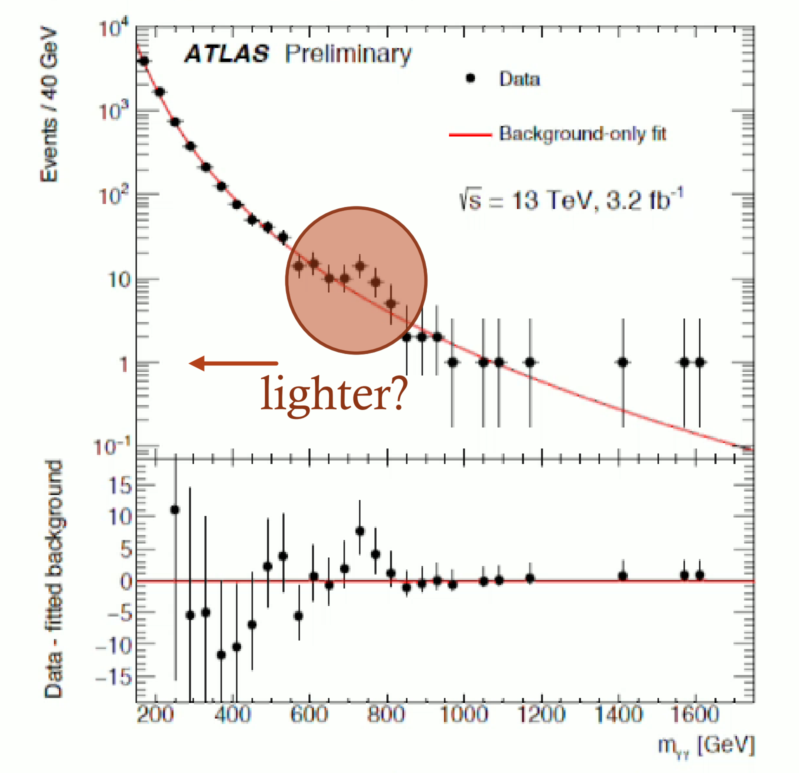


# Axion-like Particle

- Only couple to EM

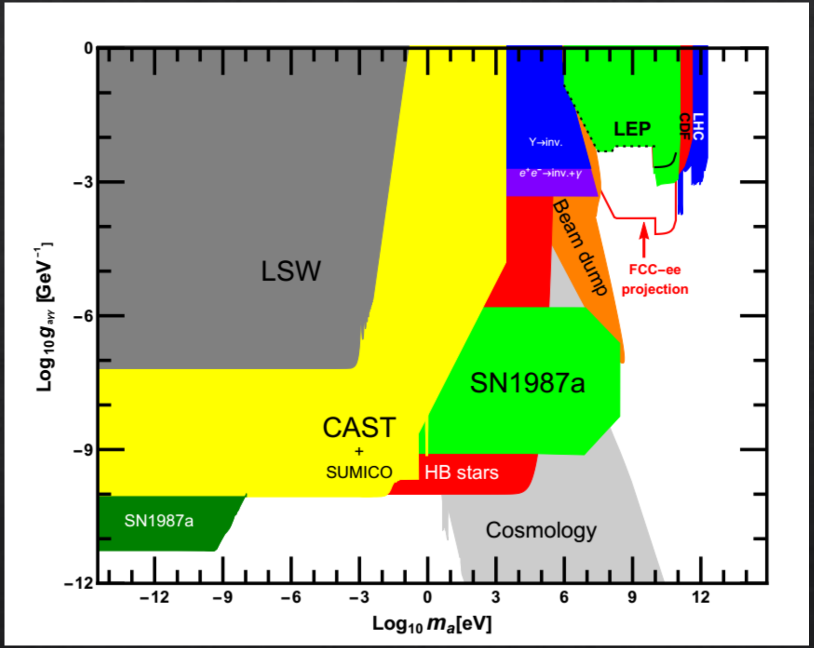
$$\mathcal{L}_a = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{a}{4\Lambda}F\widetilde{F}$$

- Decay rate

$$\Gamma_{a\to\gamma\gamma} = \frac{1}{64\pi}\frac{m_a^3}{\Lambda^2}$$

- Can we improve limits ~ GeV range? (Not DM! sorry!)

- Existing Constraints




J. Jaeckel et.al. 1509.00476

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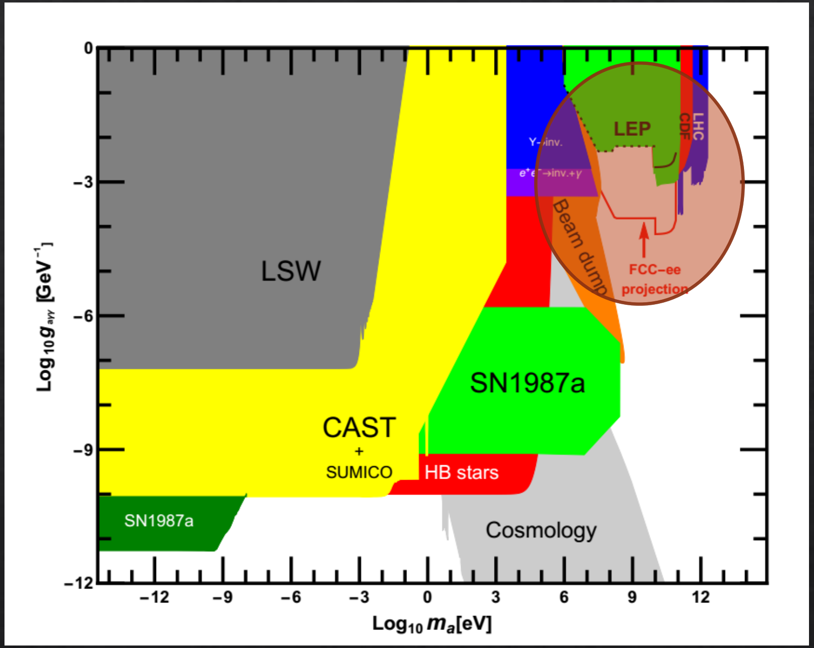


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# How to look for ALPs

## Light ALPs

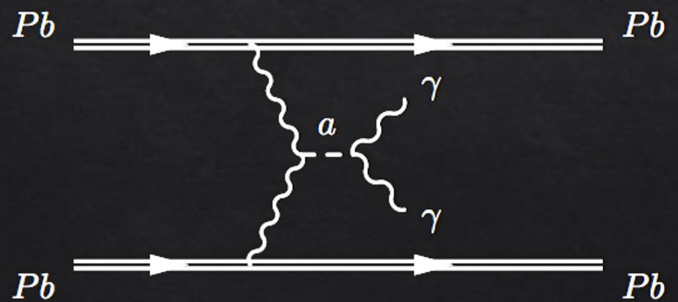
- Beam dumps/fixed targets
- Decays of mesons
- Astrophysics
- Cosmology

## Heavy ALPs

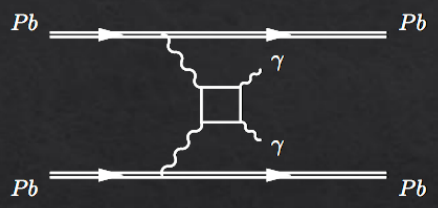
- Main limits from colliders
- Production rates limited by $\sqrt{s}$
- LHCb, CMS, ATLAS, ALICE
- p-p, Pb-p, Pb-Pb

# Heavy-ion as a $\gamma$ source

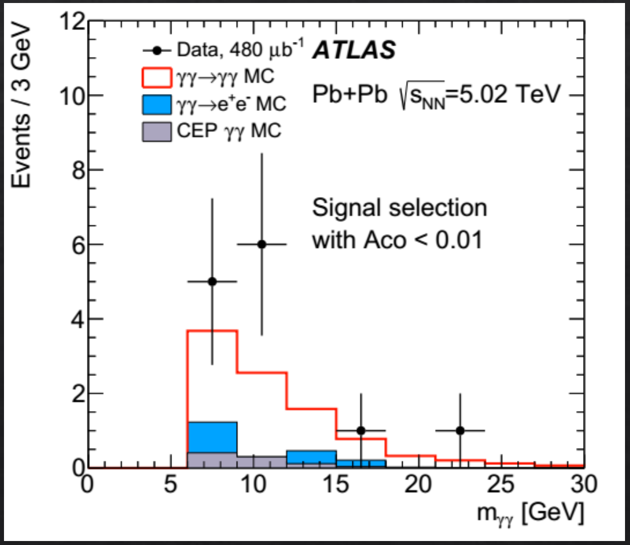
- Old idea A. Balantekin et.al. 1985, M. Greiner et.al. 1993…
- Enhanced production at Heavy-ion collisions (~GeV)
- QED is strongly coupled!
- $Z^4 \sim 50 \times 10^6$ enhancement




- Can observe LBL scattering!




D. d'Enterria et.al. 1305.7142




ATLAS 1702.01625

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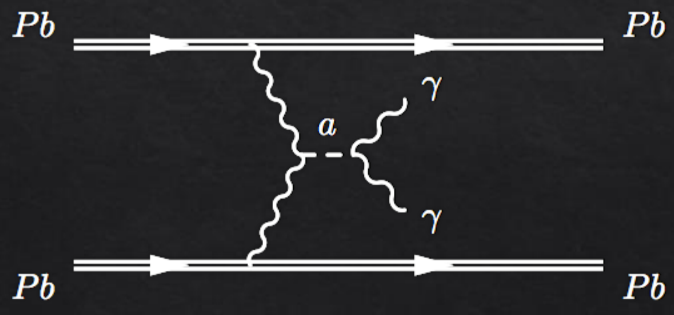


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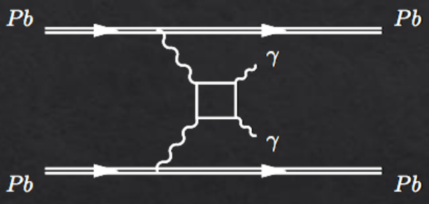


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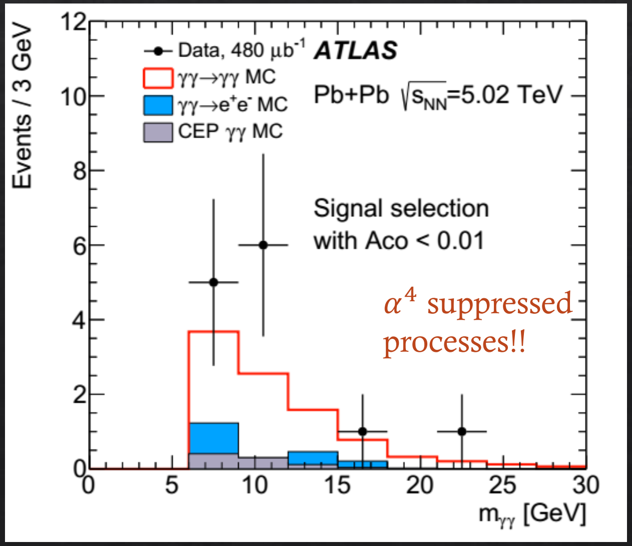
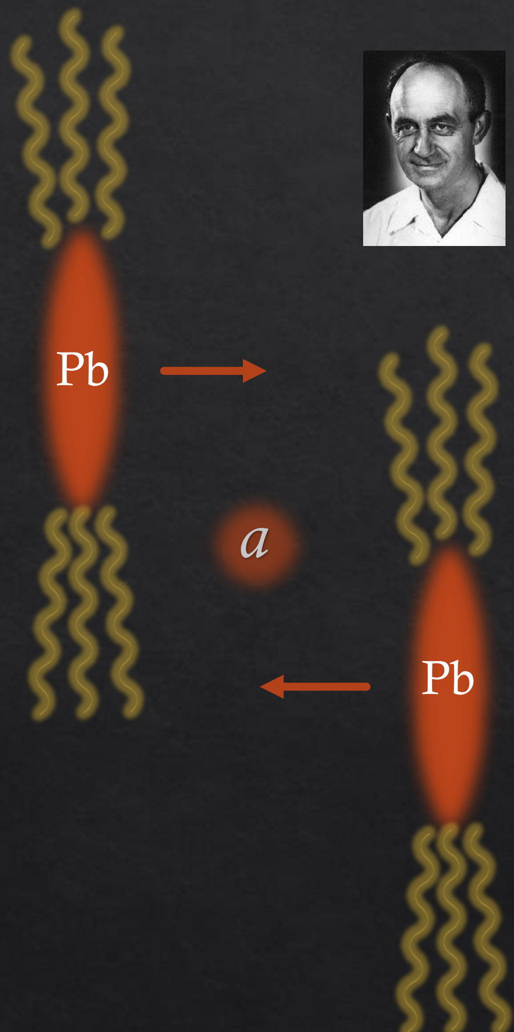


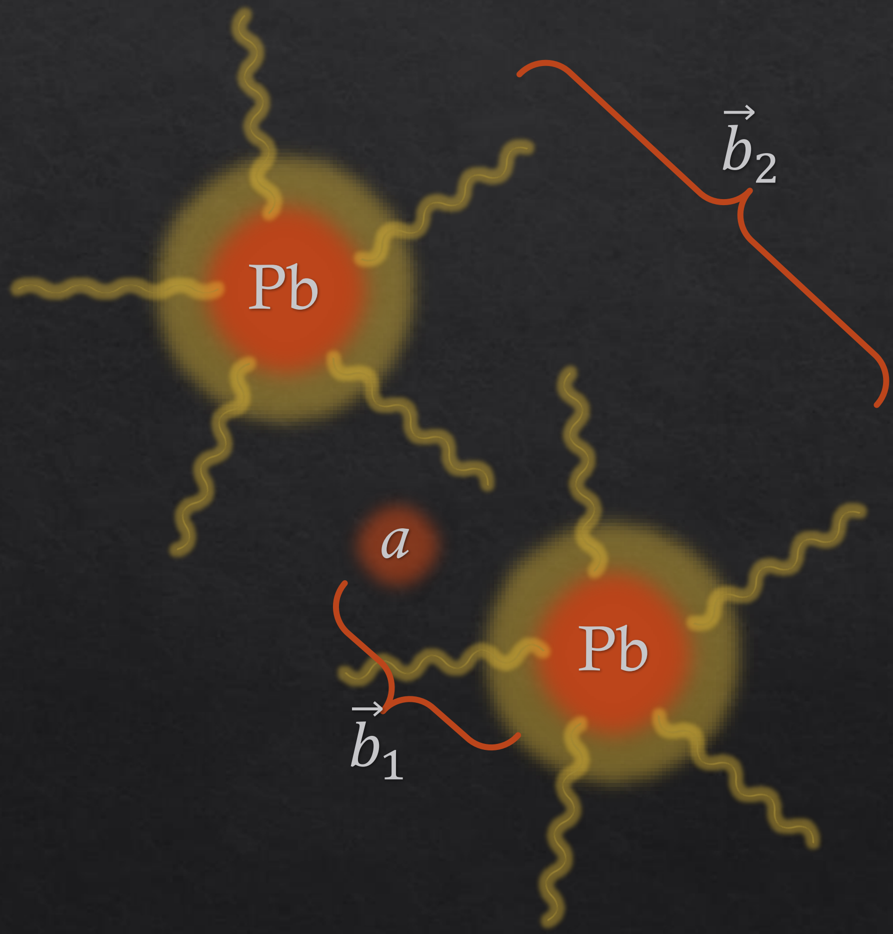

ATLAS 1702.01625

# Ultra-Peripheral Collisions




- Grazing collision, ions do NOT breakup
- ALPs are created in the strong EM field of the ions (photons almost on-shell)
- Luminosity ~ classical formula (lead flashlight!)
- Coherence requires photon wavelength $\gtrsim$ Pb radius / boost
- $2E_\gamma < 170 \text{ GeV} \left(\frac{7 \text{ fm}}{R}\right) \left(\frac{\sqrt{s_{NN}}}{5.5 \text{ TeV}}\right)$

# Photon Luminosity




- Photon-photon luminosity:

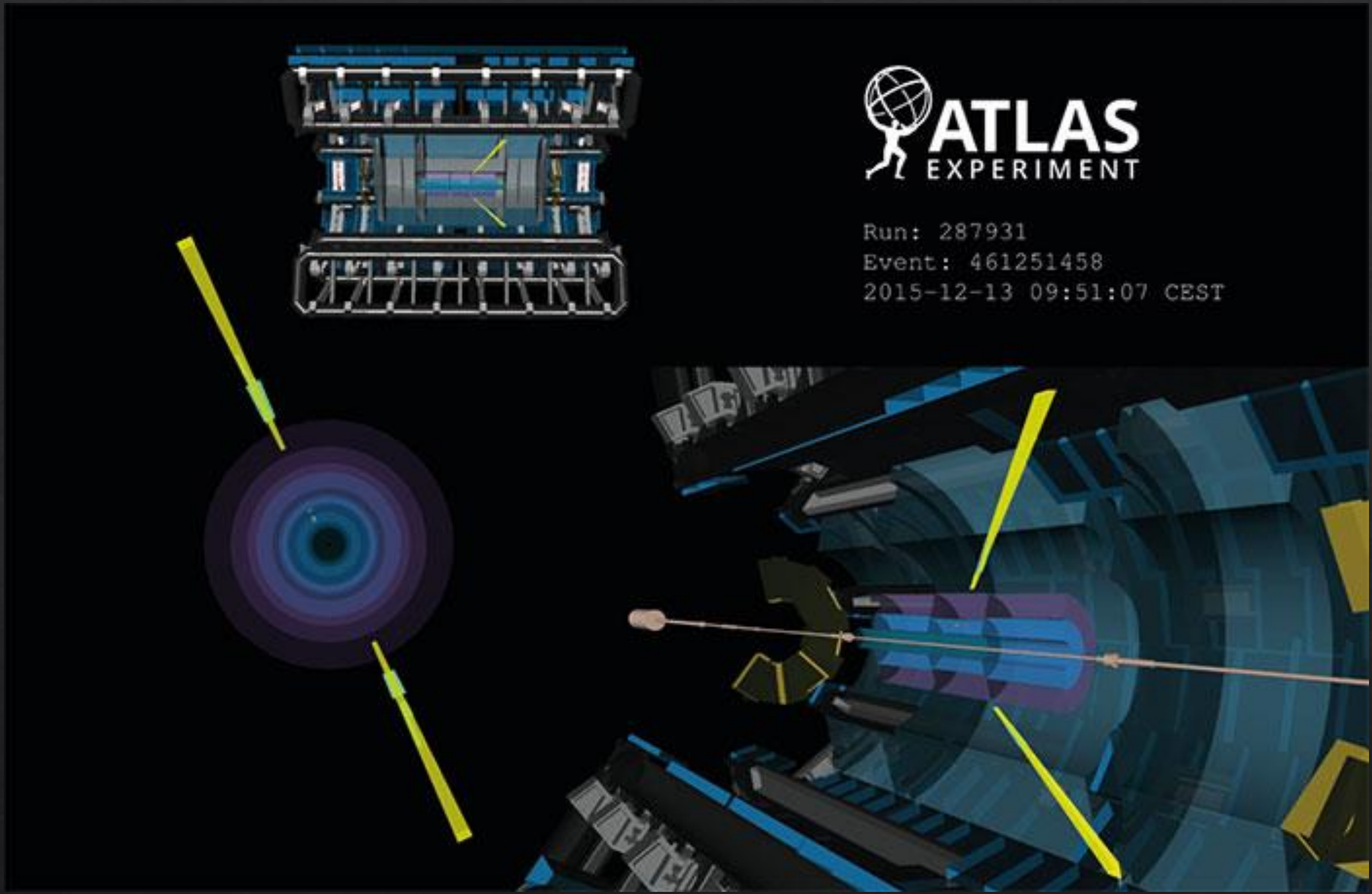
$$\mathcal{L}_{\gamma\gamma} = \frac{1}{\hat{s}} \int db_{1,2} dE_{1,2}\, N_1 N_2 \times \delta(\hat{s} - 4E_1 E_2) P$$

  - $N_{1,2}$ = flux from Pb
  - $P$ = probability that no breakup occurs
- $N_{1,2} \sim$ charge form factor
  - Low energy $\sim \frac{2\alpha Z^2}{\pi} \log \frac{E_{\max}}{E_\gamma}$
- $P \sim \theta(b_2 - 2R)$
- Requires nuclear physics to get all factors correct

# Proton vs Pb

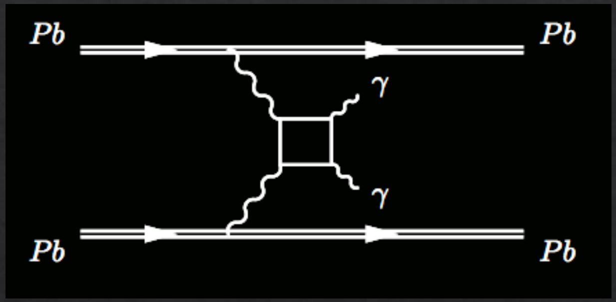
| | p-p Collisions | Pb-Pb Collisions |
|---|---|---|
| Luminosity | ~ 1000 $fb^{-1}$ | ~ $10^{-6}$ $fb^{-1}$ (1 $nb^{-1}$) |
| $Z^4$ Enhancement | None | ~ $5 \times 10^7$ |
| Max $\gamma$ Energy | ~ 1 TeV (elastic) | ~ 170 GeV |
| Background | Large pile-up background | Clean exclusive events |
| Regions of sensitivity | $m_a$~100 GeV | $m_a$~10 GeV |


when p and Pb collide…

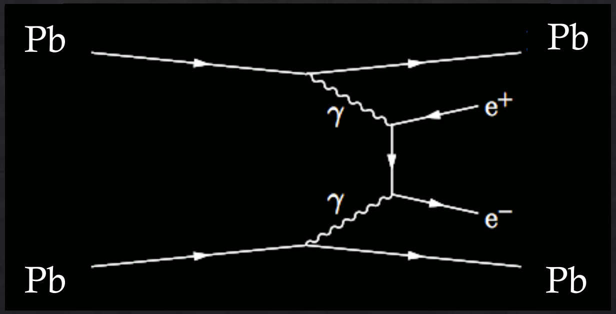

ATLAS
EXPERIMENT
Run: 287931
Event: 461251458
2015-12-13 09:51:07 CEST

# Main Background

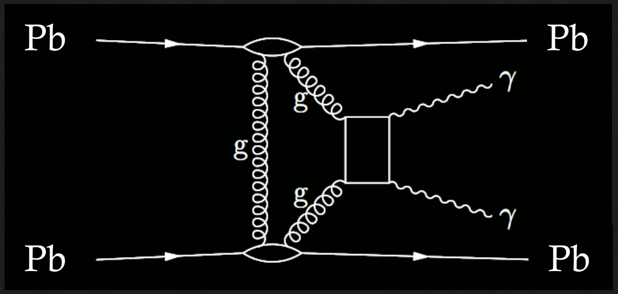
- Light by Light scattering




- Fake photons / electron brem.




- Central Exclusive Production



# Signal & Background

## Signal

- Intact Pb-Pb ions, no tracks, very little calorimeter activity
- Veto on tracks
- Two ~GeV back to back photons (cut on $\Delta\phi_{\gamma\gamma}$)
  - Otherwise ions will likely breakup
- Intact ions may be tagged
- Prominent mass peak!

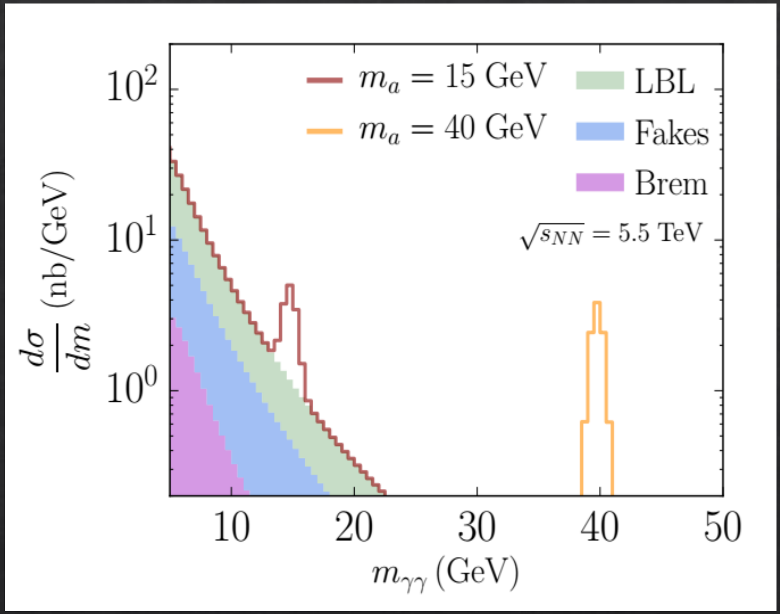
## Background

- LBL scattering
  - Irreducible
  - Has been measured! Can be calculated reliably
- Electrons fakes/brem or CEP (photons from QCD)
  - Photons not back to back
- All background smoothly falling in $m_{\gamma\gamma}$!

# Search Strategy

## Signal Selection

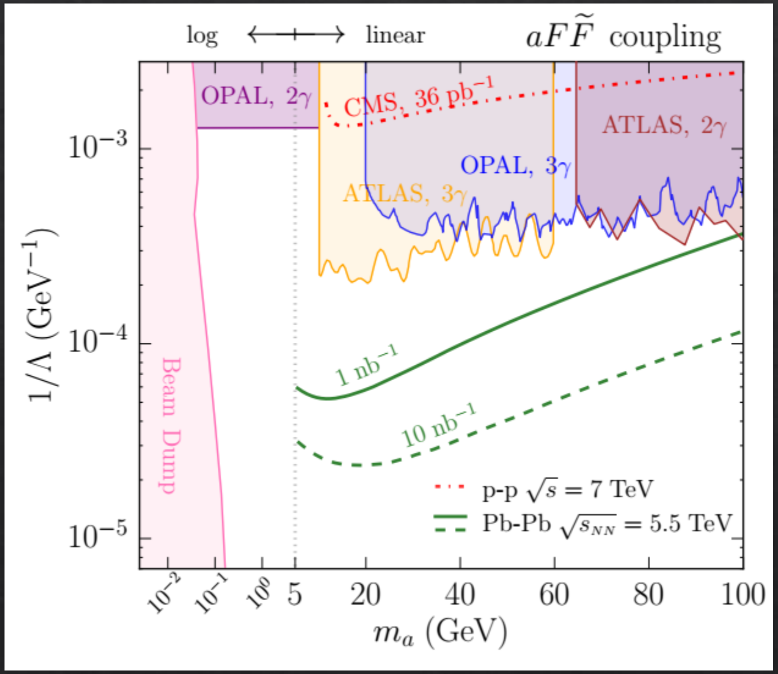
- Veto tracks with ($p_T > 1$ GeV, $|\eta| < 2.5$)
- Two photons ($p_T > 2$ GeV, $|\eta| < 2.5$)
- $|\Delta\phi_{\gamma\gamma} - \pi| < 0.04$
- Efficiency ~70% low mass to ~90% at high mass
- Signal MC implemented in Starlight
- Background:
  - Analytic approx. for $\gamma\gamma$-lumi
  - ME done analytically / Madgraph5




Integrated lumi. ~ nb

# Results

## Standard ALP coupling

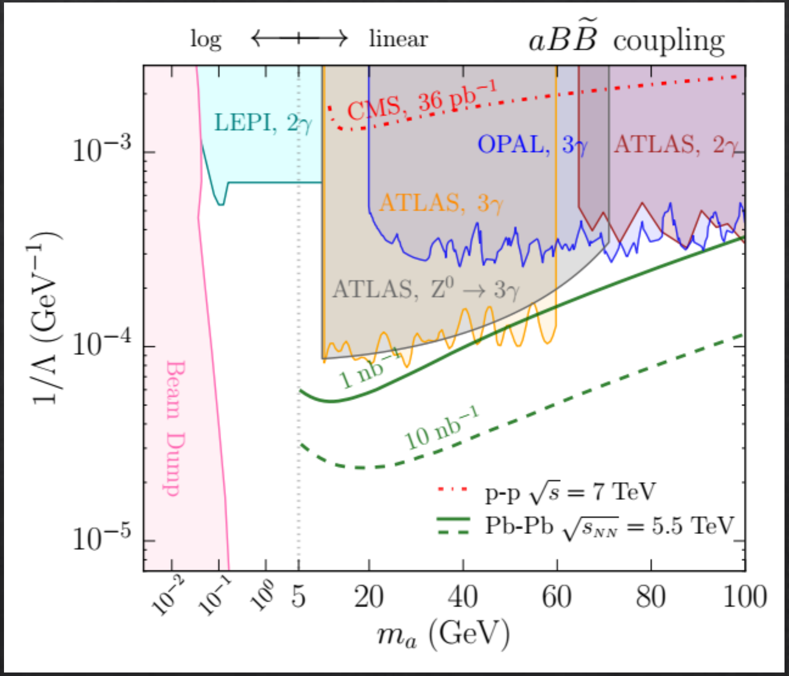



- p-p collider searches dominated by associated production
  - Photon fusion sub-dominant
  - $p + p \rightarrow \gamma^* \rightarrow a + \gamma$
  - LEP/CMS/ATLAS comparable
- 8 TeV re-cast
  - high lumi results will be stronger

# Results

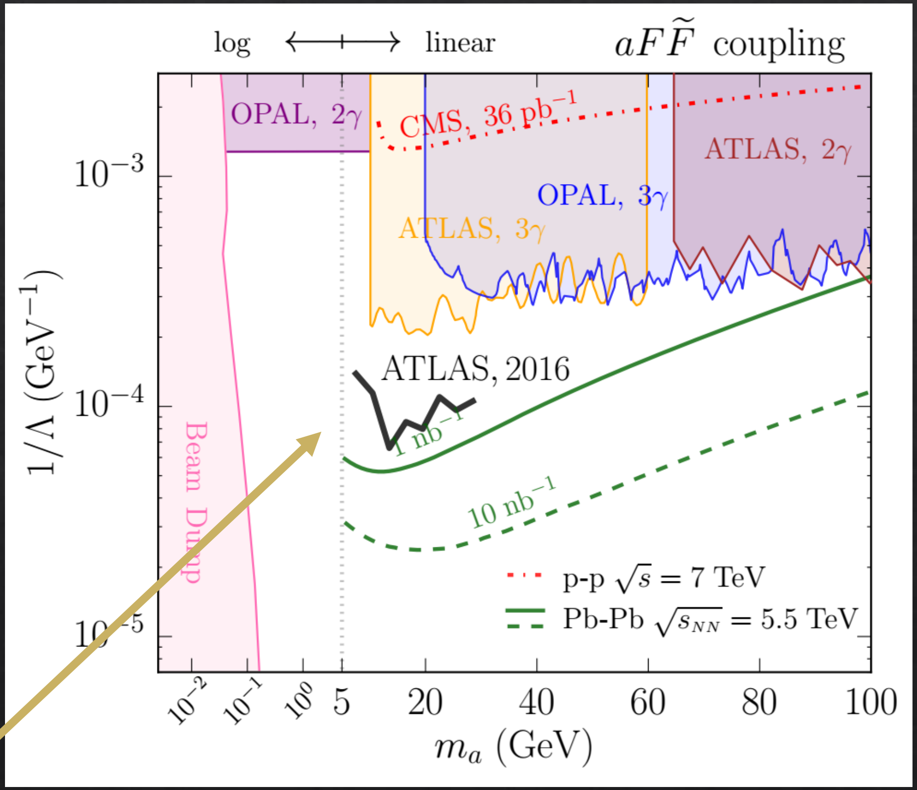
- Introduces $aZ\gamma$ coupling
  - $p + p \to \gamma/Z^* \to a + \gamma/Z$
  - On-shell $Z \to a + \gamma$
- Heavy-ion limits comparable to 8 TeV results
- High-Luminosity LHC will likely yield stronger limits

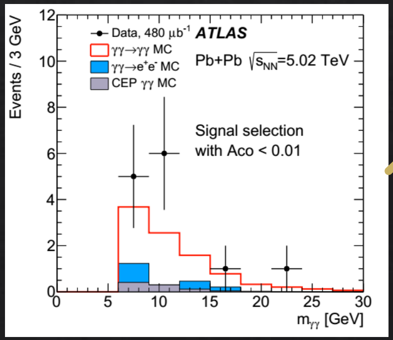
## Hypercharge coupling



# ATLAS recast

- $\sqrt{s_{NN}} = 5.02$ TeV
- $\int L dt = 480\ \mu b^{-1}$
- Current best limit on ALPs with EM coupling!
- First time heavy-ion yields best limit on BSM physics



# Future Directions ?

## New decay channel?

- $b\bar{b}/\tau\tau$ decay for light scalar mixing with higgs?
- Invisible decay? Can we measure the outgoing beam?
- Exotic decay into hidden sector? e.g. long-lived particles?

## New production?

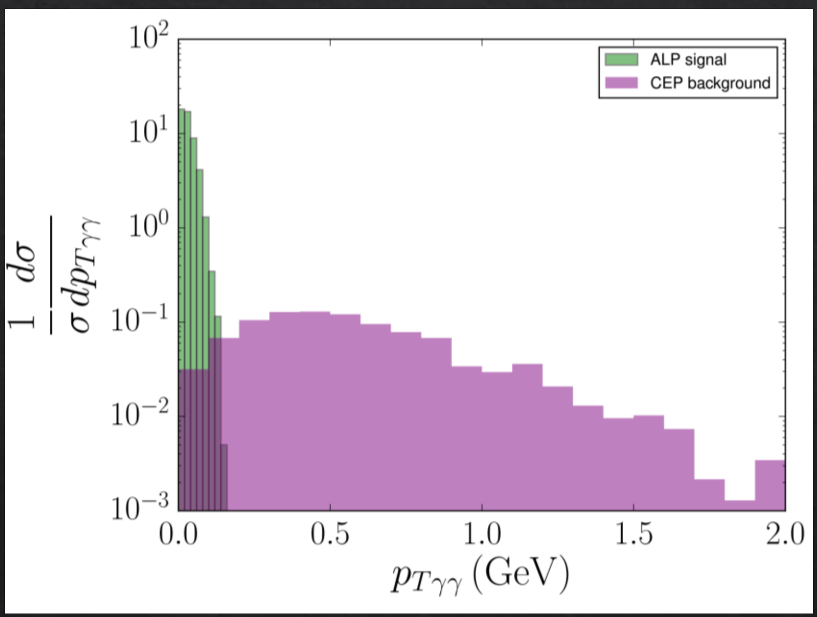
- New kinds of coherent enhancement (baryon number)?
- Lighter ALPs? (pair production and off-shell rates are too small)
- Changes in inclusive elastic cross-sections?

# Conclusion

- Heavy-ion collisions open a new window into ~ GeV ALPs/Hidden sector
- ATLAS Heavy-ion search places the best constraint for ~ GeV ALPs
  - CMS results forthcoming
- Hidden sector may show up in unexpected places!


Where are the ALPs?
I think I've found it with my lead-flashlight!
Thank You!

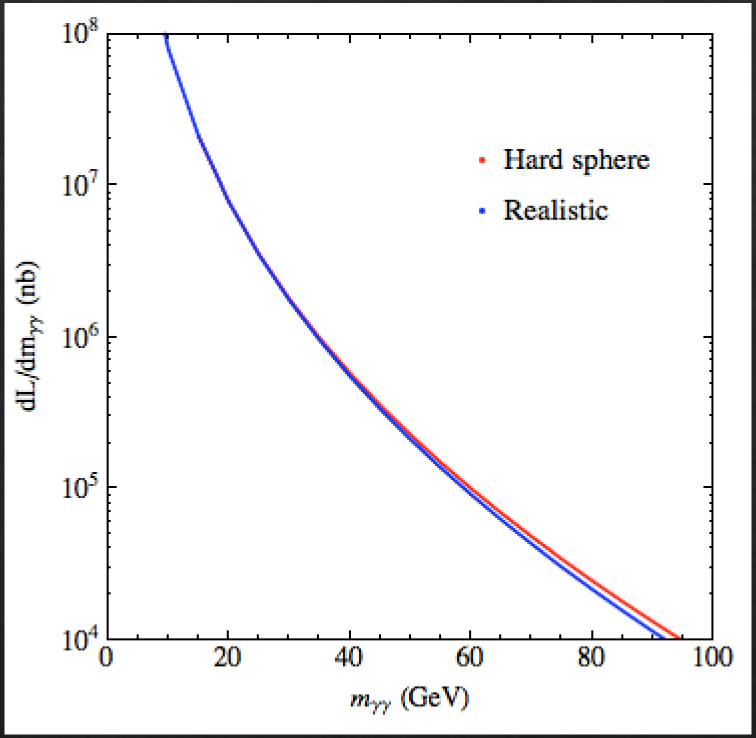
# $p_T$ recoil distribution

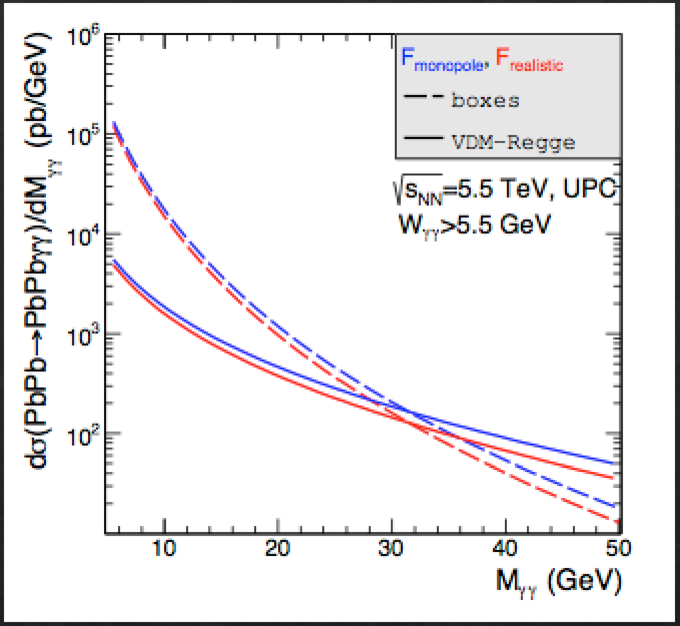



- $p_T$ ~ virtuality of the photon
- Correction beyond equivalent photon approximation

- ALPs: $p_T \sim 1/R \sim 60$ MeV
- CEP: $p_T \sim \Lambda \sim$ GeV
  - p-p collisions shown
  - Pb-Pb requires convolution with breakup factor

# Form Factors Effects




M. Klusek-Gawenda et.al.
1601.07001