ALP searches at the High Energy Frontier

Axion Quest 2024
08/08/2024

Jeremi Niedziela
for ATLAS, CMS, and TOTEM Collaborations

Outline

Introduction

- ALPs vs. axions
- High-mass ALPs:
  - new decay channels
  - different experimental approaches

ALP-photon coupling

- Tagged protons
  - CMS + TOTEM PRD 110 012010
  - ATLAS JHEP 07 (2023) 234
- Heavy Ions
  - ATLAS JHEP 03 (2021) 243
  - CMS HIN-21-015

Other ALP couplings

- ALP-top/invisible coupling
  - ATLAS EXOT-2018-62
  - CMS EXO-22-014
- ALP-bosons coupling
  - ATLAS EXOT-2019-27, HDBS-2019-19
  - CMS EPJC 81 (2021) 13, JHEP 07 (2023) 148, EXO-22-022

Summary

- ALPs in UPCs
- Quark, boson, and DM channels at LHC
- Comparison with direct DM experiments

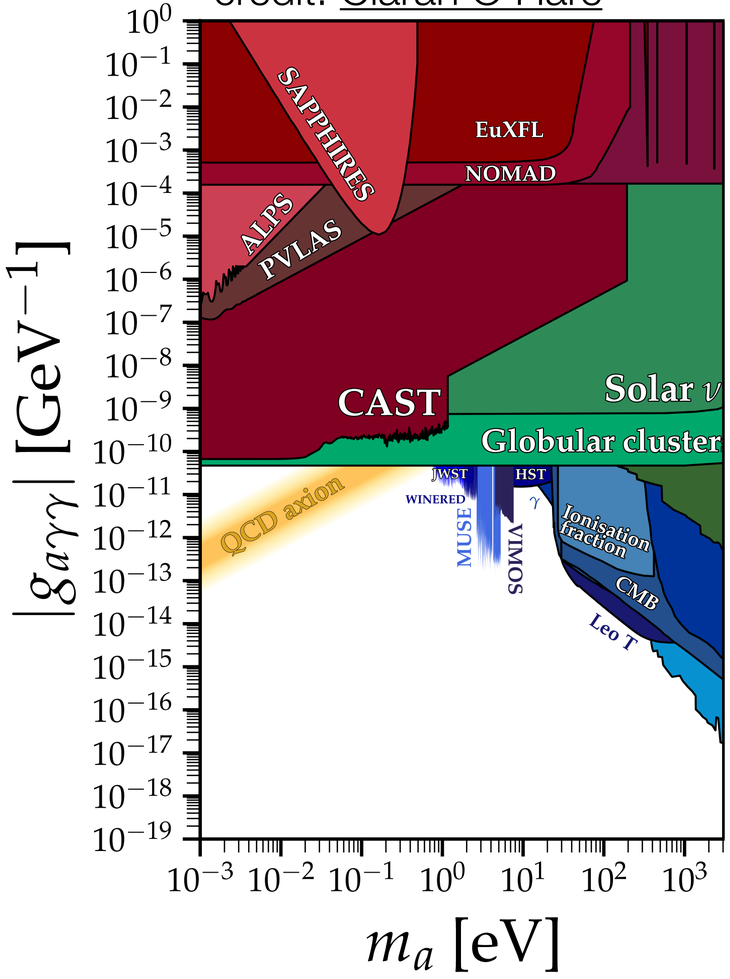
Introduction

Axions and Axion-Like Particles

QCD axions

- need no introduction
- characteristic **two-photon vertex**
- searches using:
  - light-through-the-wall
  - helioscopes
  - haloscopes
  - …

credit: Ciaran O'Hare



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Axion-Like Particles

- mass-coupling relation not fixed
- appear in many SM extensions
- **more decay channels** open at higher masses
- can be **probed at colliders**

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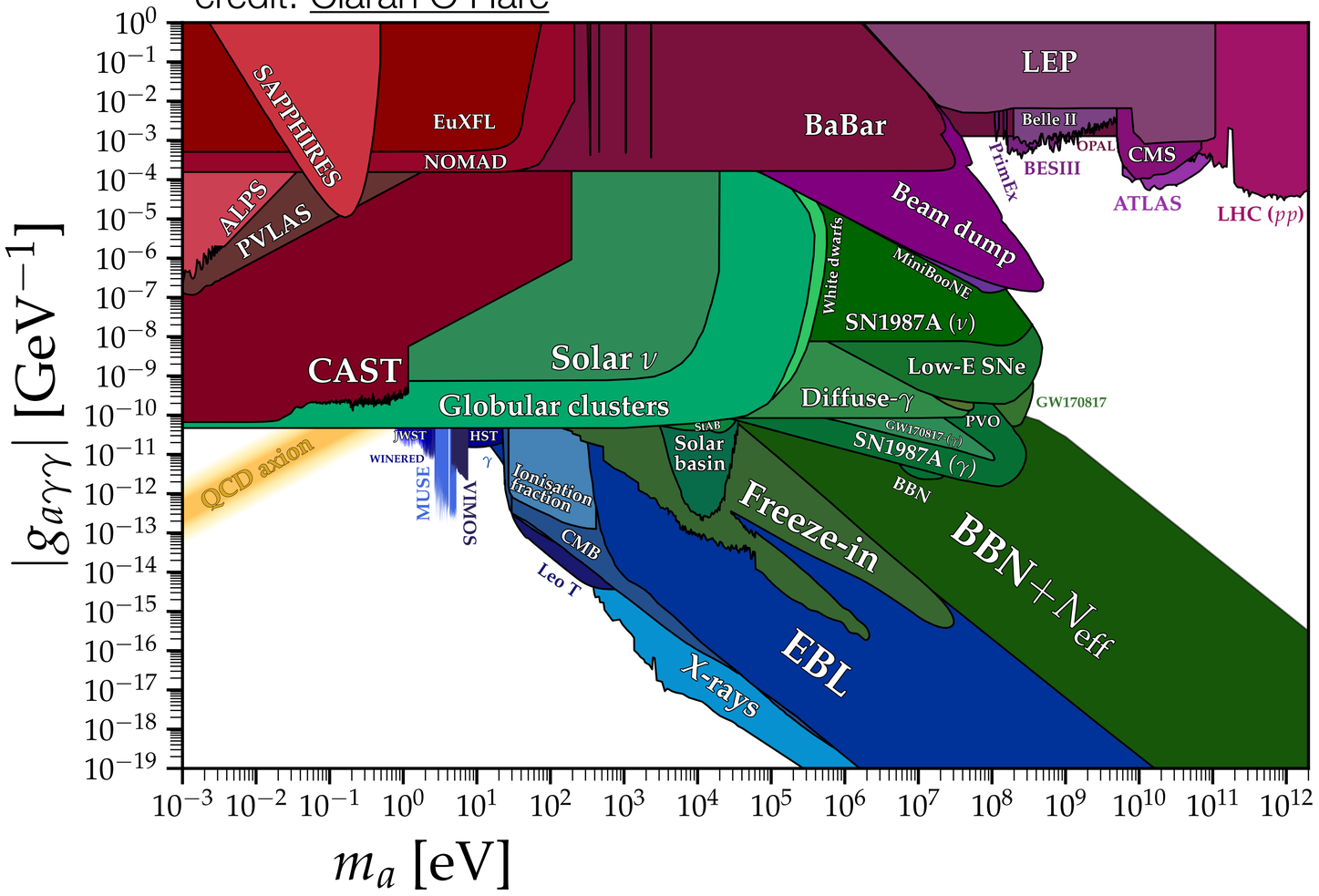

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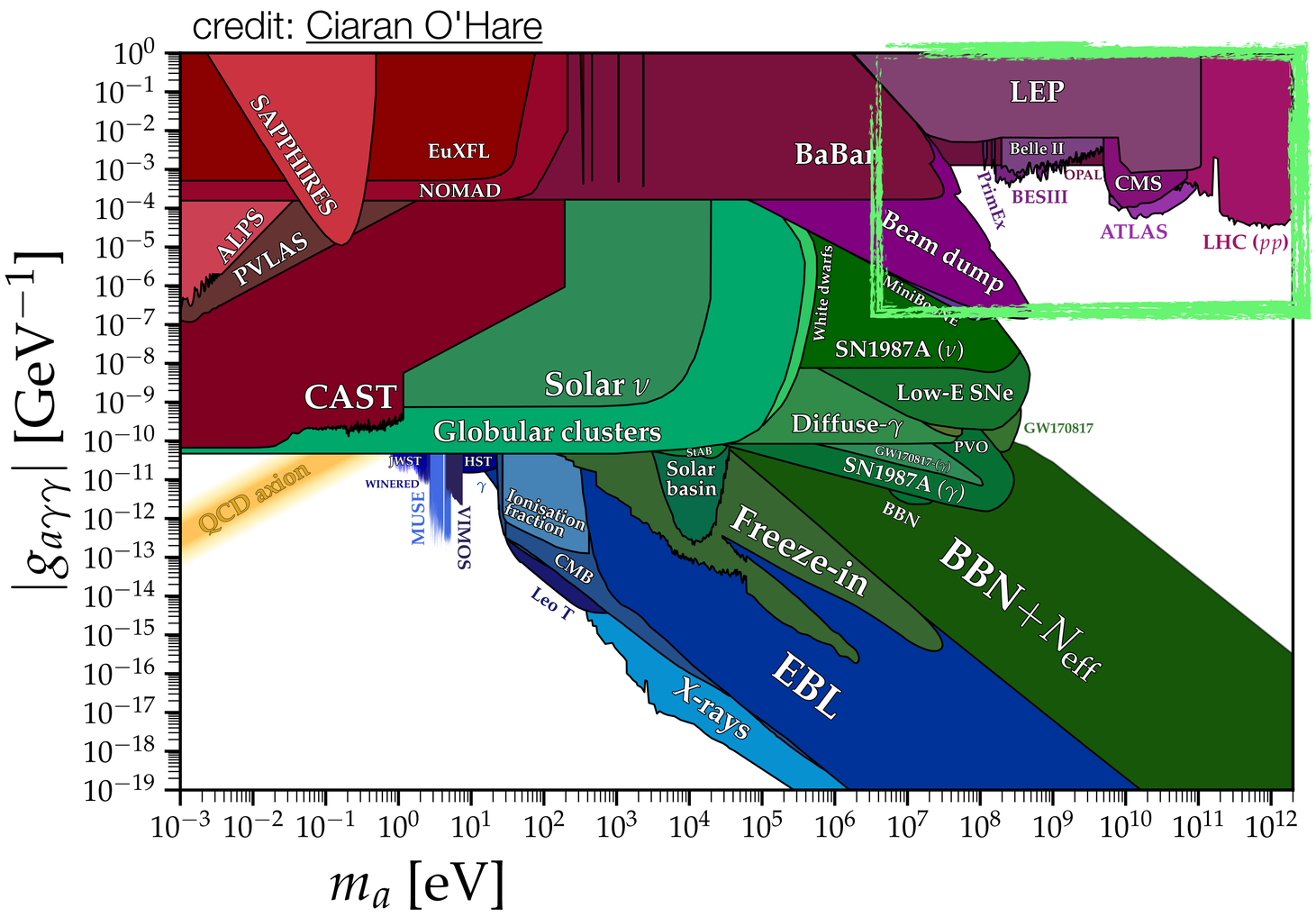

ALP-photon Coupling

ALPs in UPCs

Ultraperipheral Collisions at the LHC

- **non-overlapping** protons/ions → **EM interaction**
- allows for **photon-induced processes**:
  - light-by-light scattering
  - Breit—Wheeler process
  - $\gamma\gamma \rightarrow \mu\mu$
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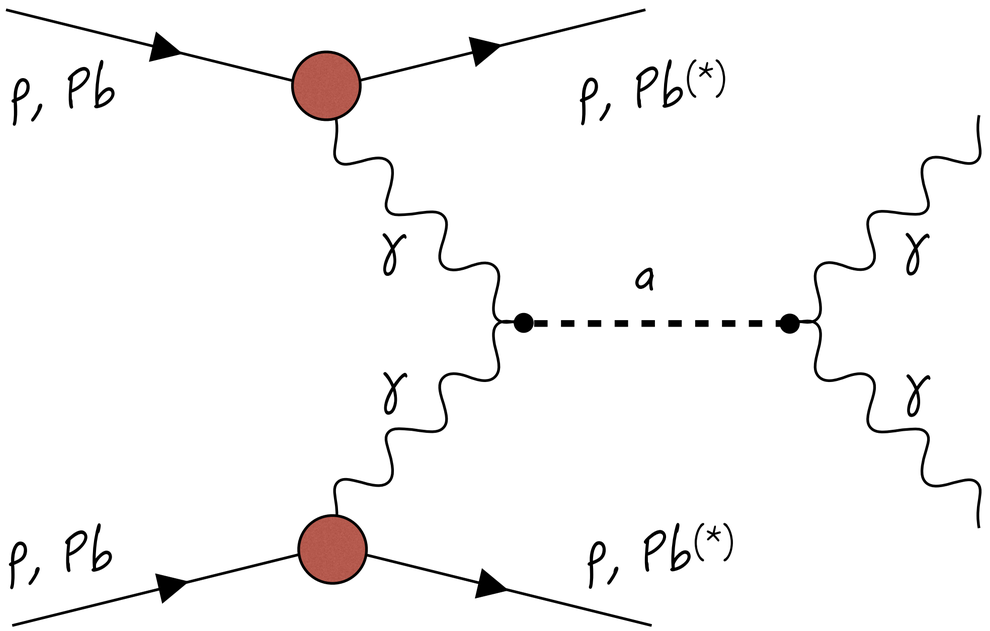

ALPs in UPCs

- **ALPs** could be produced in **photon-fusion**
  - quasi-real photons → ALPs **produced at rest**
  - decaying to back-to-back photons
- photon flux **scales with Z^2**
  - for PbPb: Z^4 = **$5 \cdot 10^7$ higher cross-section** than in pp or e^+e^-

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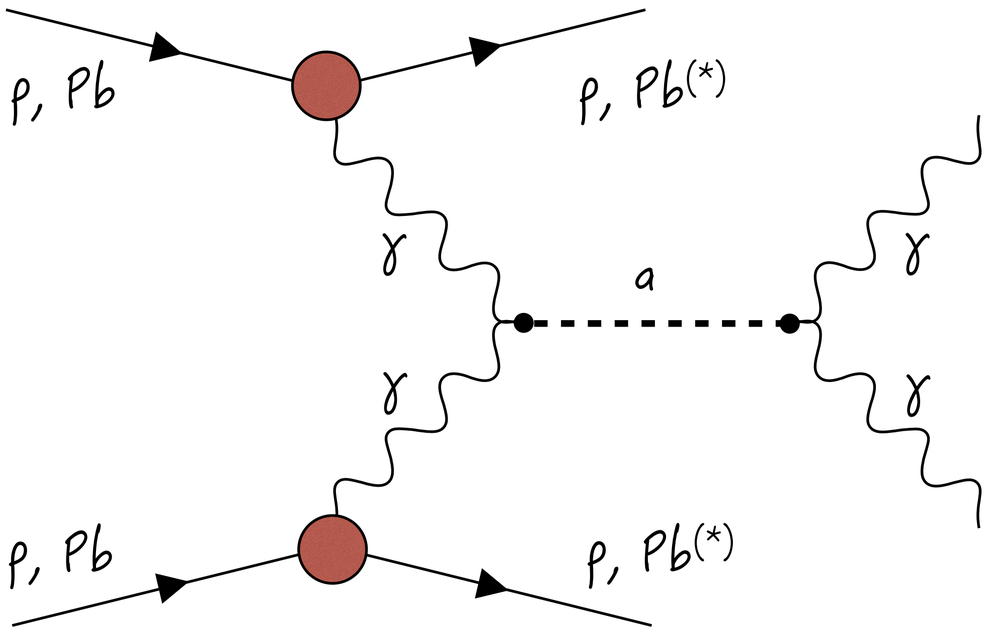

Heavy Ions

- **no pileup**
- **lower** statistics
- lower energies (≈5 TeV)
- m_{inv}: 5-100 GeV

Protons

- need to fight **with pileup**
- **larger** statistics
- higher energies (≈13 TeV)
- m_{inv}: ≳100 GeV

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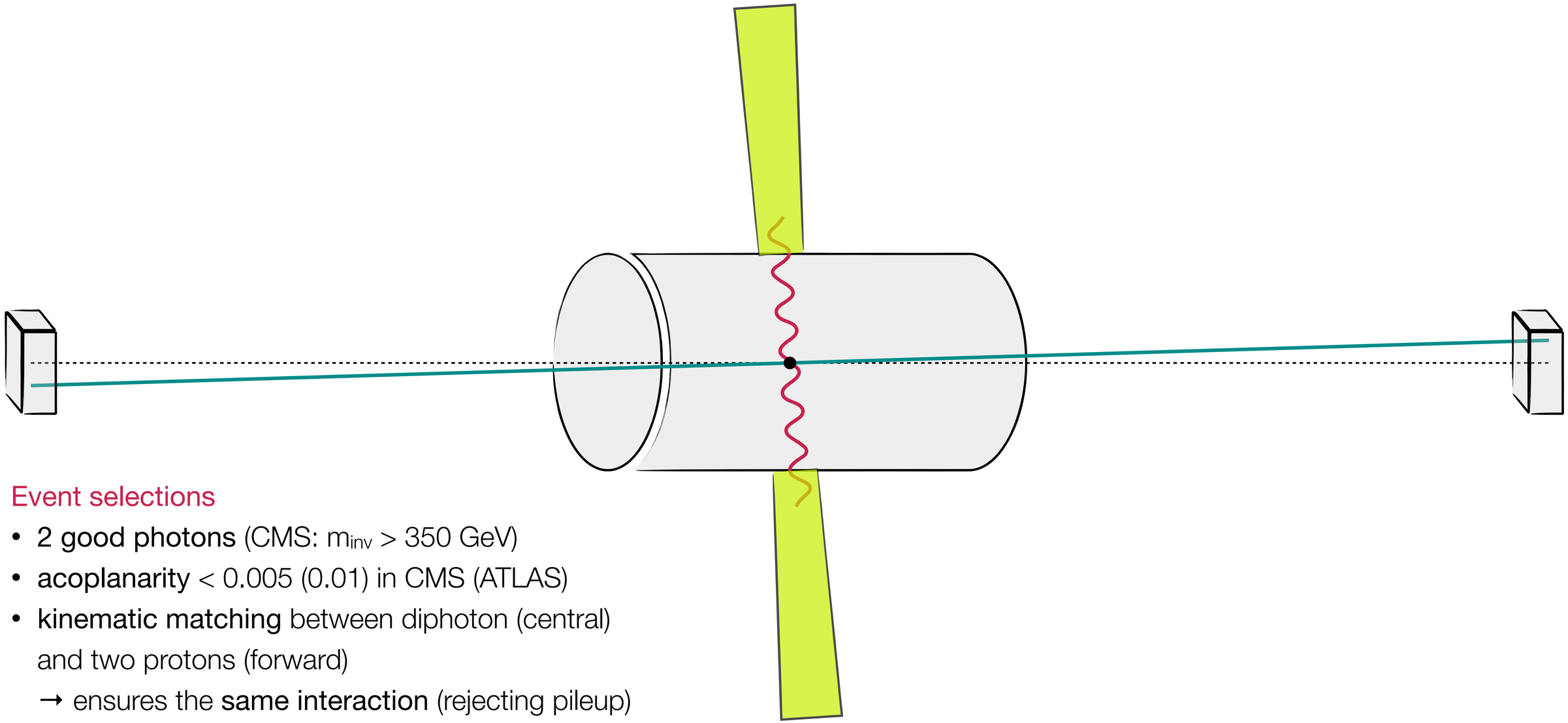
Exclusive γγ + tagged protons

CMS PRD 110 012010
ATLAS JHEP 07 (2023) 234



Event selections

- **2 good photons** (CMS: $m_{inv} > 350$ GeV)
- **acoplanarity** < 0.005 (0.01) in CMS (ATLAS)
- **kinematic matching** between diphoton (central) and two protons (forward)
  → ensures the **same interaction** (rejecting pileup)

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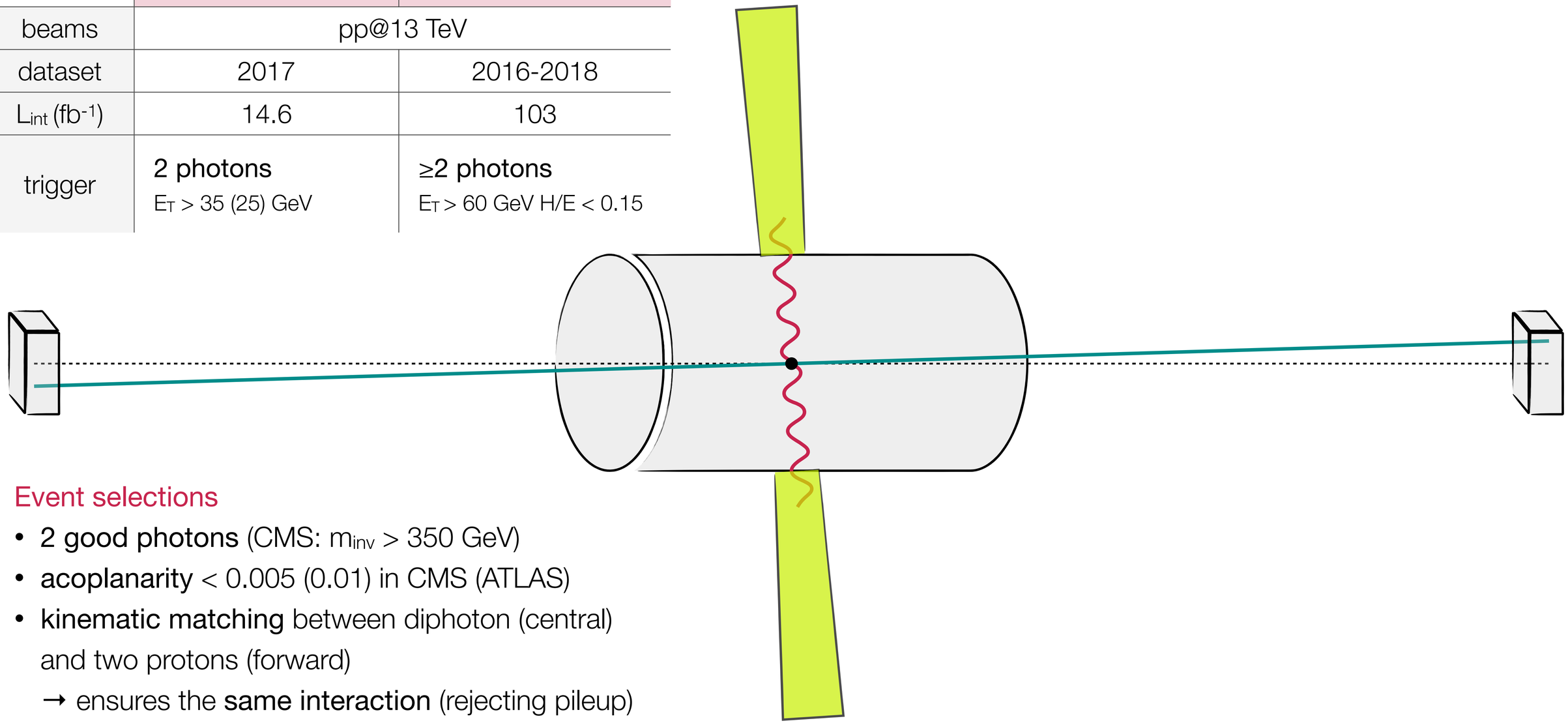
beams	pp@13 TeV	
dataset	2017	2016-2018
L_{int} (fb^{-1})	14.6	103
trigger	**2 photons** E_T > 35 (25) GeV	**≥2 photons** E_T > 60 GeV H/E < 0.15



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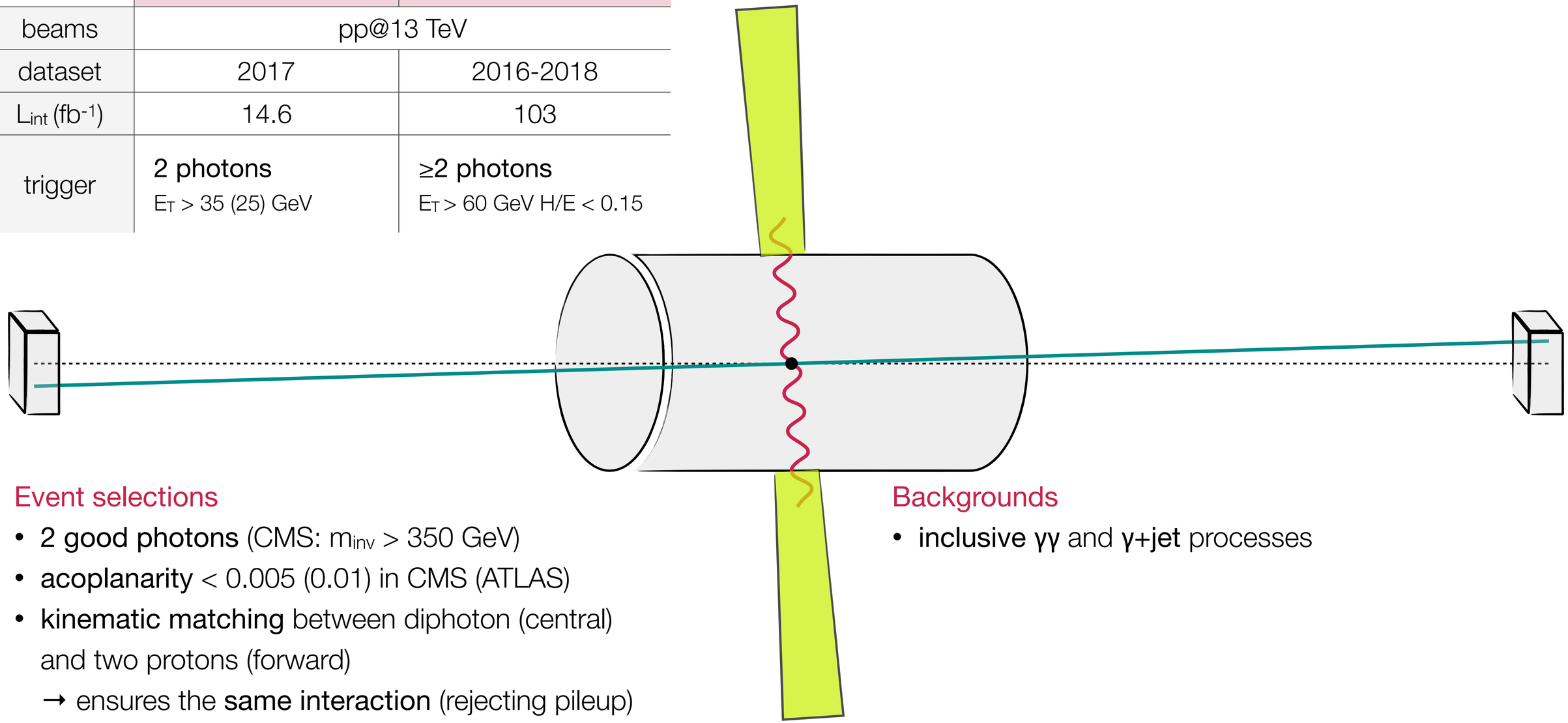

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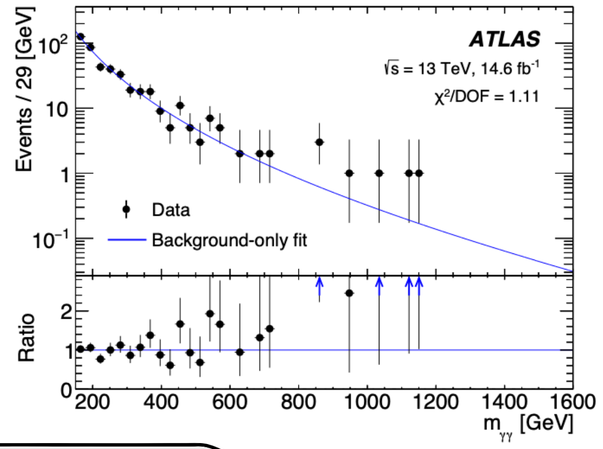

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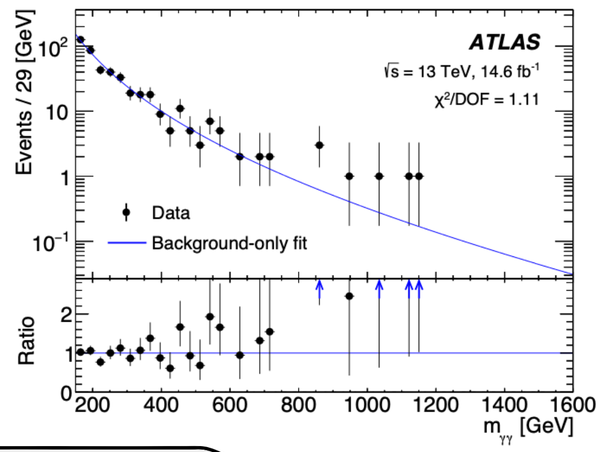

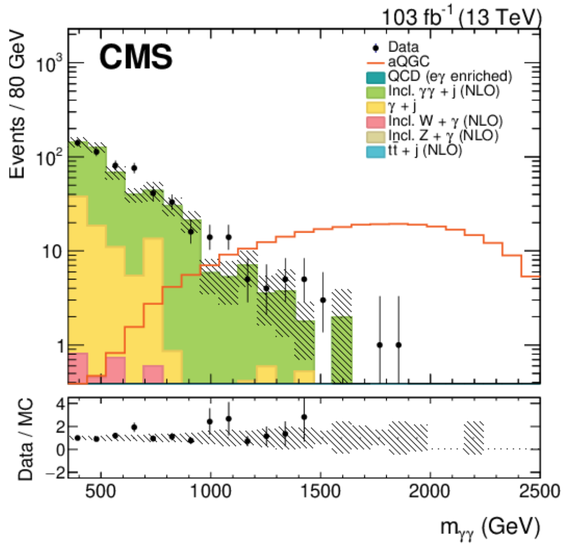

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Backgrounds

- **inclusive γγ** and **γ+jet** processes
- ATLAS: background-only fit to data
- CMS: estimated from **pseudo-events** combining:
  - diphoton kinematics sampled from a template
  - two-proton kinematics from real events

Exclusive γγ + tagged protons

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ATLAS JHEP 07 (2023) 234

Light-by-light and BSM signals

- light-by-light scattering has too small a cross-section to be observed
  → e.g. in CMS **expected <0.02 LbL events**

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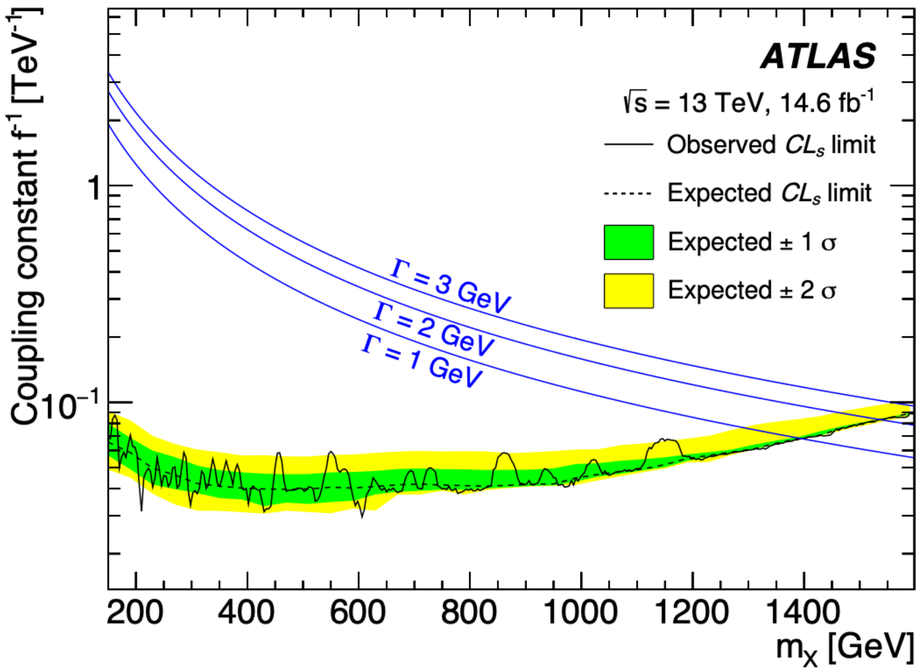
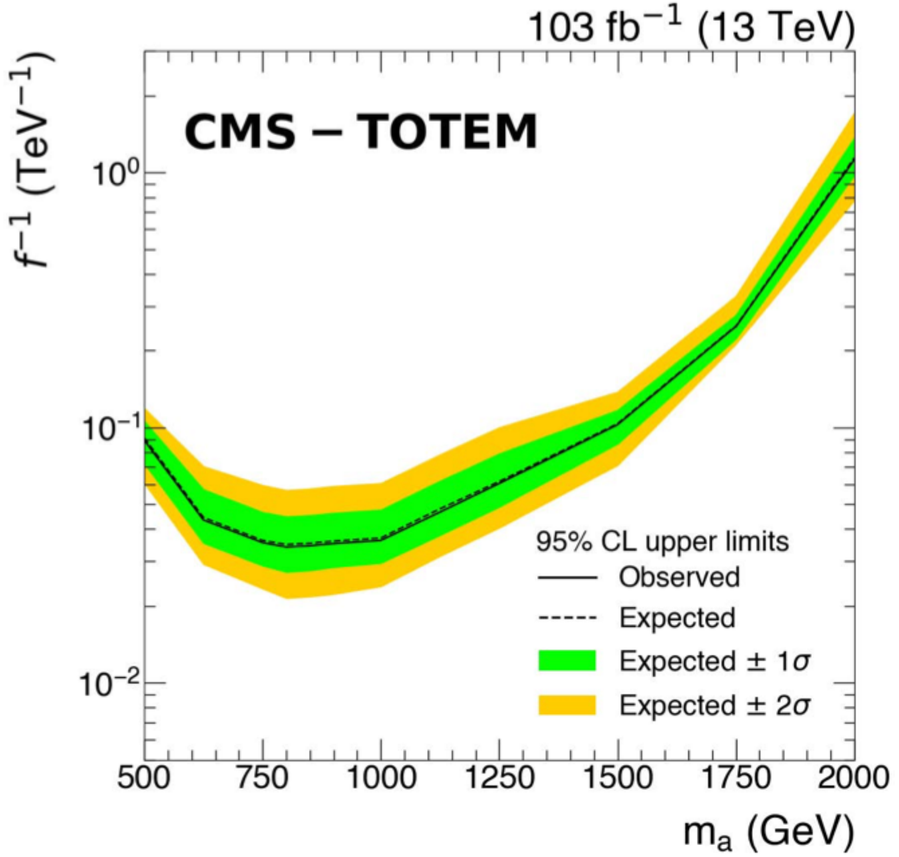
Light-by-light and BSM signals

- light-by-light scattering has too small a cross-section to be observed
  → e.g. in CMS **expected <0.02 LbL events**
- given no excess events observed, limits in the **coupling-mass plane** are derived by both ATLAS and CMS





Ultra-Peripheral PbPb Collisions

ATLAS JHEP 03 (2021) 243
CMS HIN-21-015

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dataset	2015+2018	
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Signature

- very **empty events**
- no tracks, muons, jets…
- only **2 back-to-back photons**

Event selections

- **exactly 2 photons** with m_{inv} > 5 GeV
- **charged & neutral exclusivity**
- diphoton p_T < 1-2 GeV
- **acoplanarity** < 0.01

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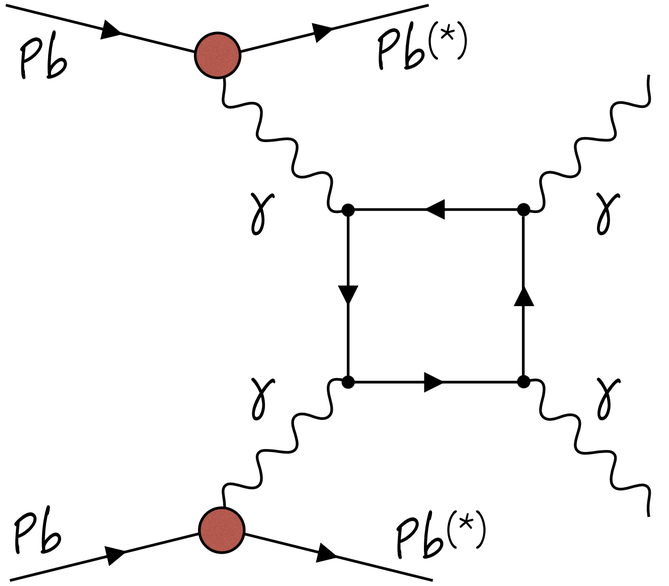

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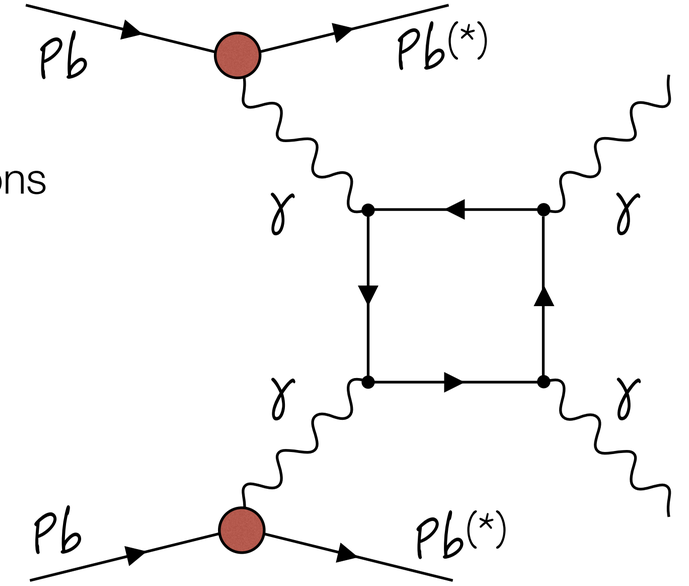

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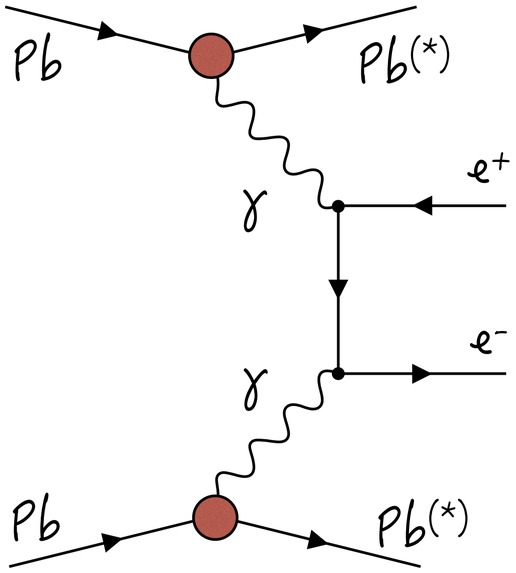

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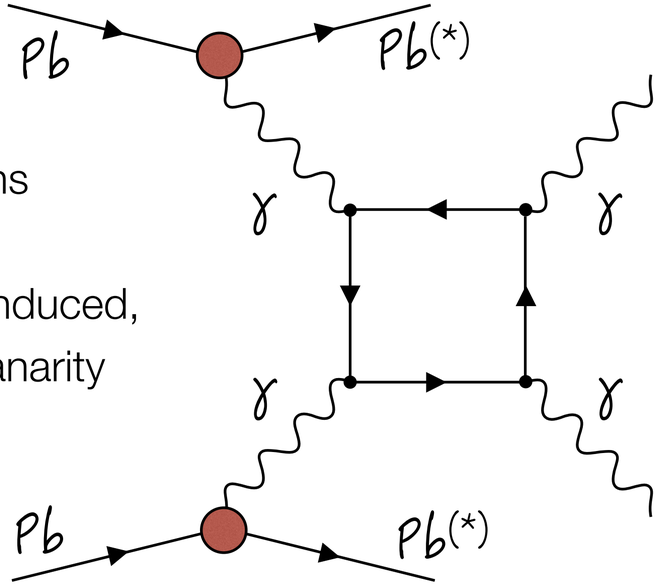
- **Breit—Wheeler** (B—W) process with electrons misidentified as photons
- **Central Exclusive Production** (CEP): gluon-induced, larger momentum exchange → higher acoplanarity



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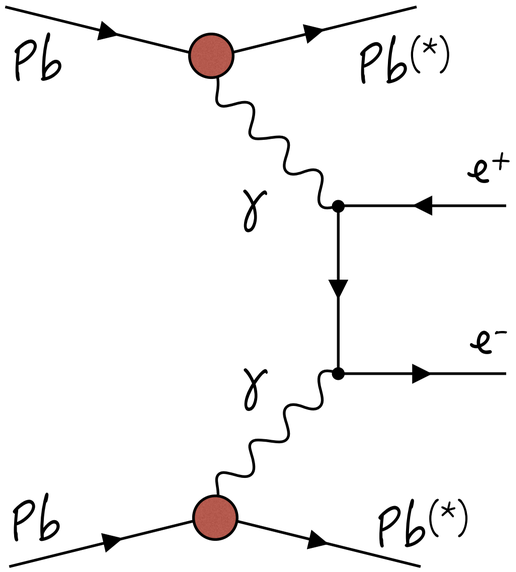
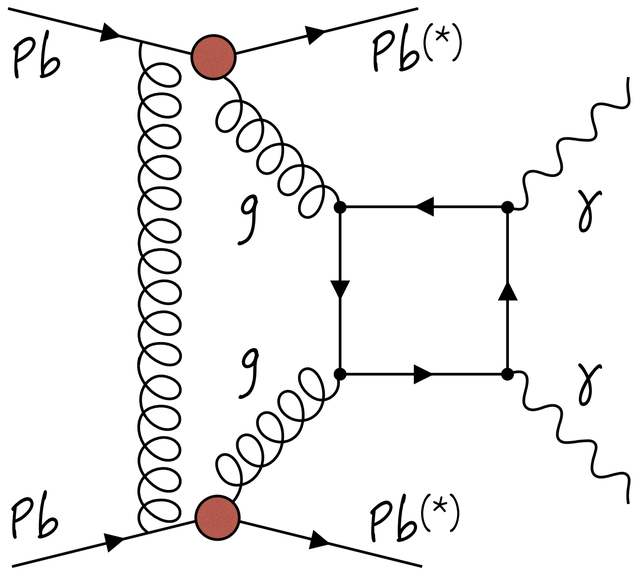
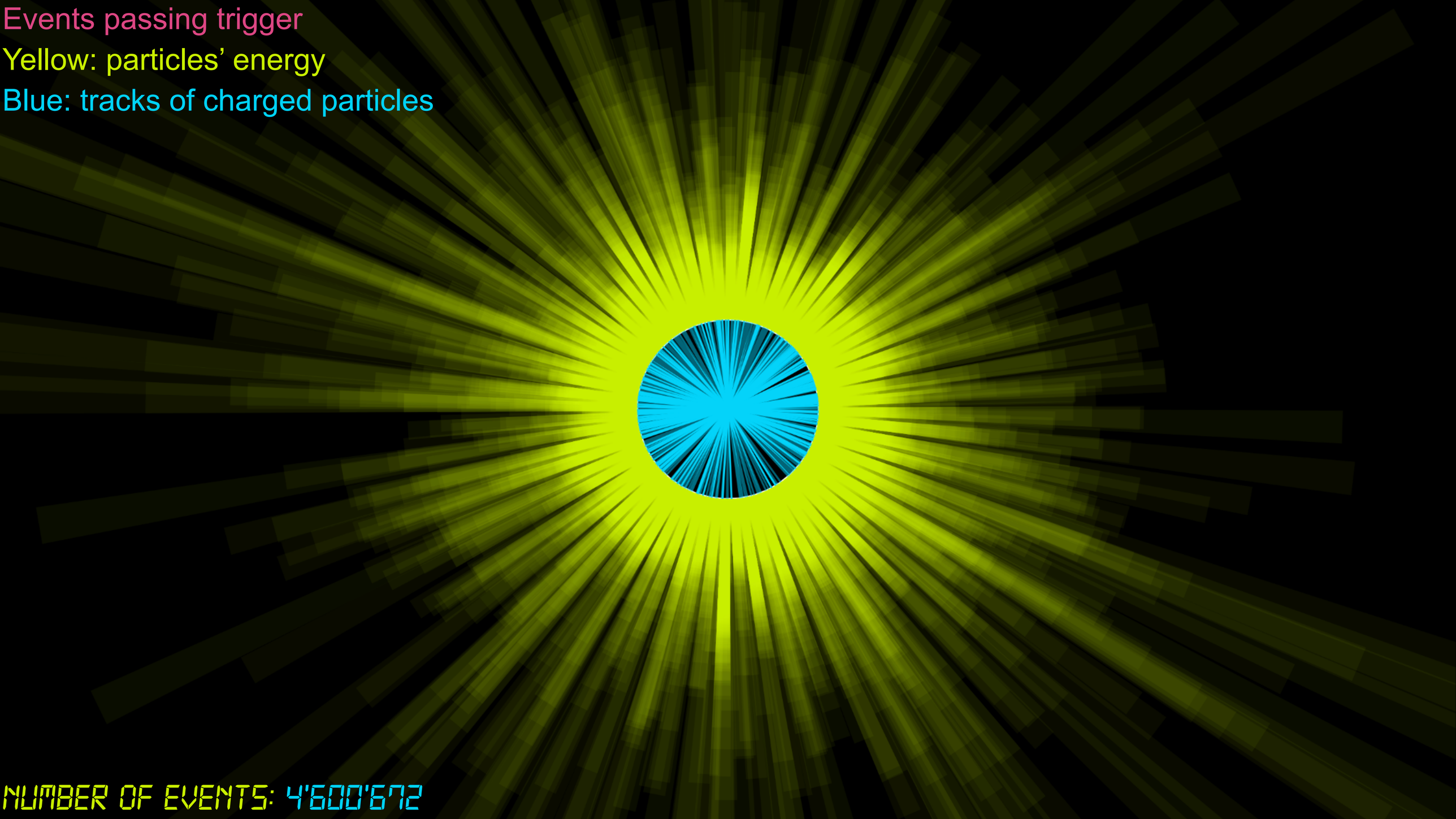
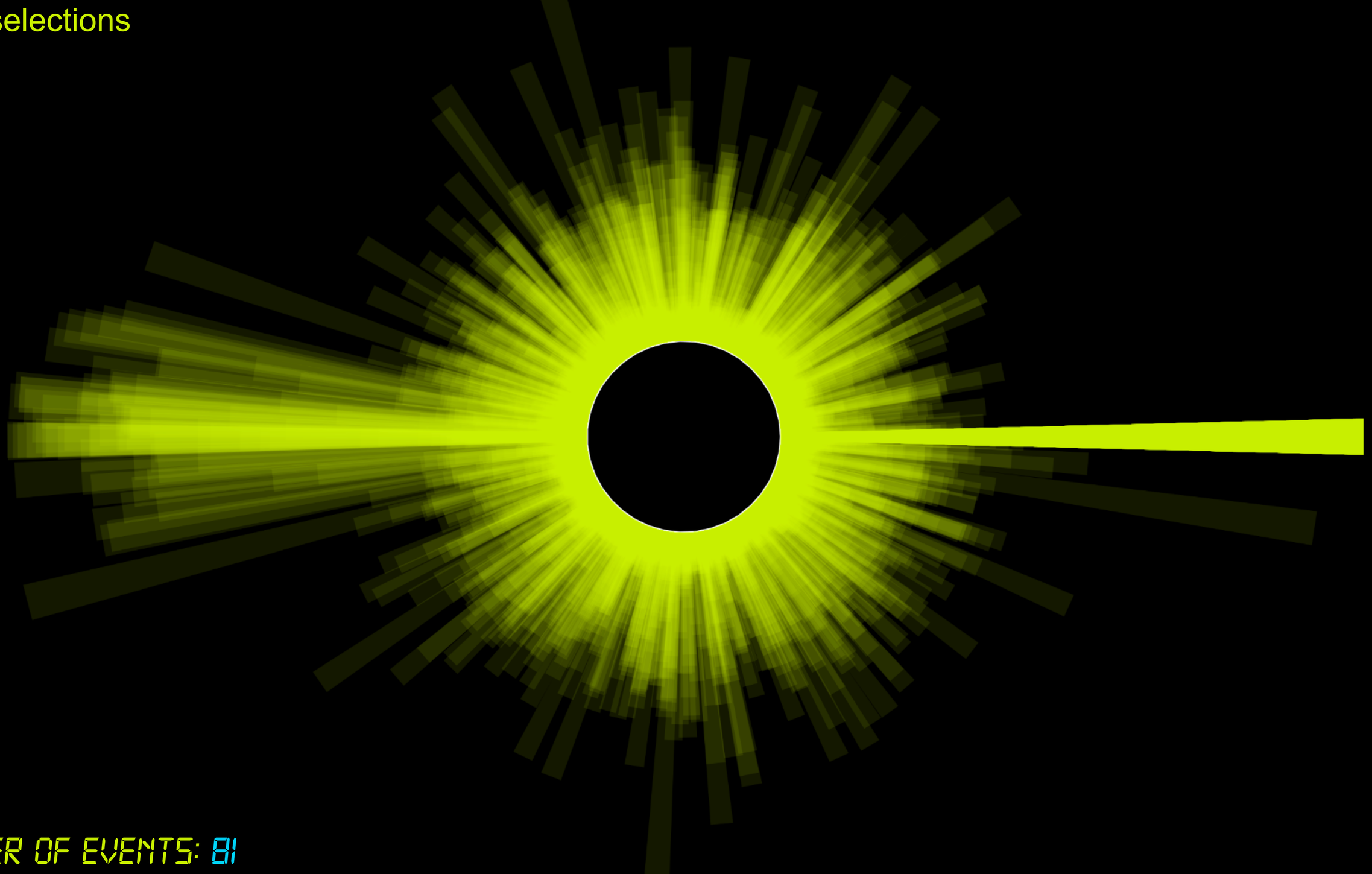




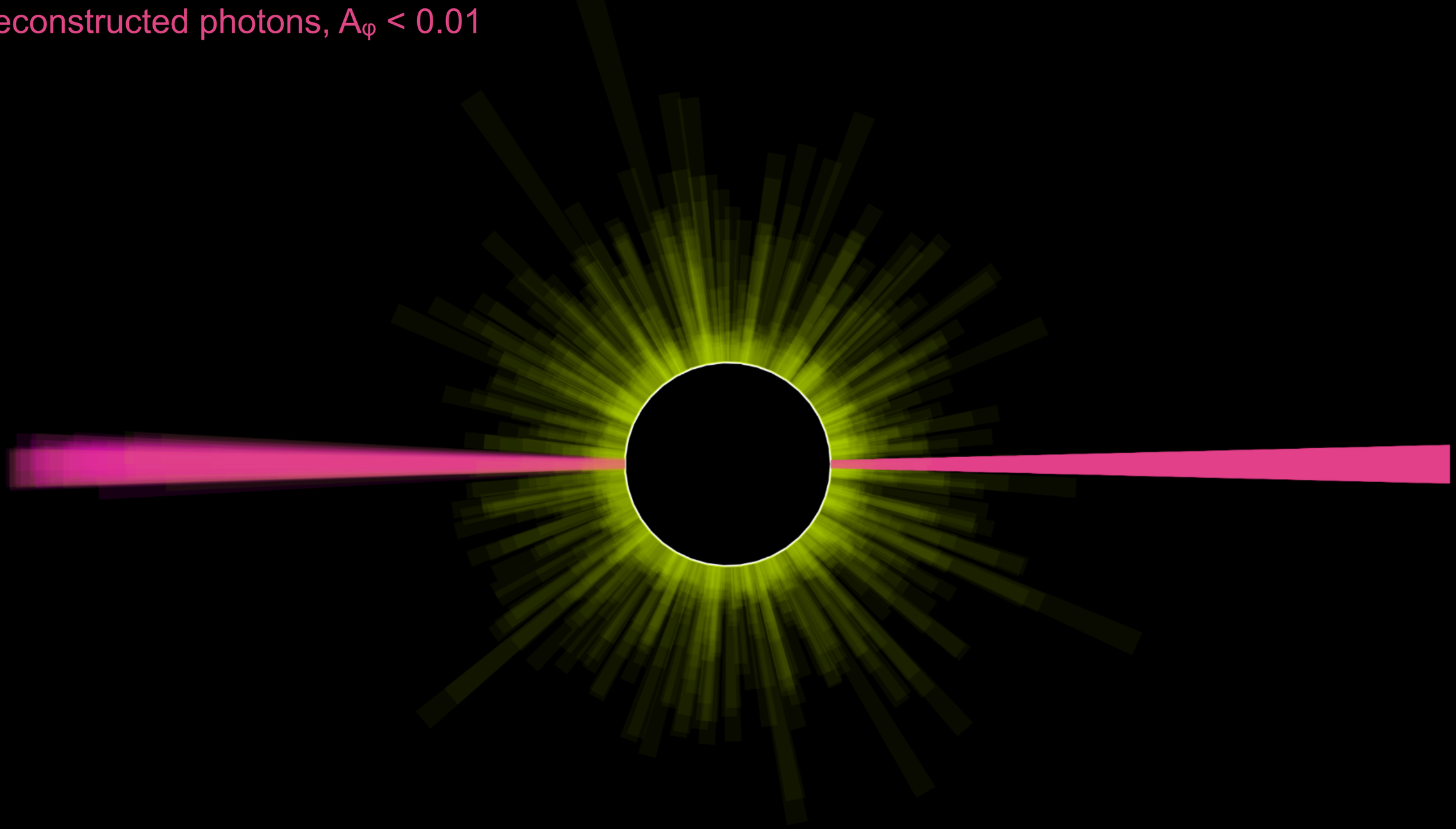

Events passing trigger
Yellow: particles’ energy
Blue: tracks of charged particles
NUMBER OF EVENTS: 4'600'672

After selections



NUMBER OF EVENTS: 81

Well reconstructed photons, $A_\varphi < 0.01$



NUMBER OF EVENTS: 26

Ultra-Peripheral PbPb Collisions

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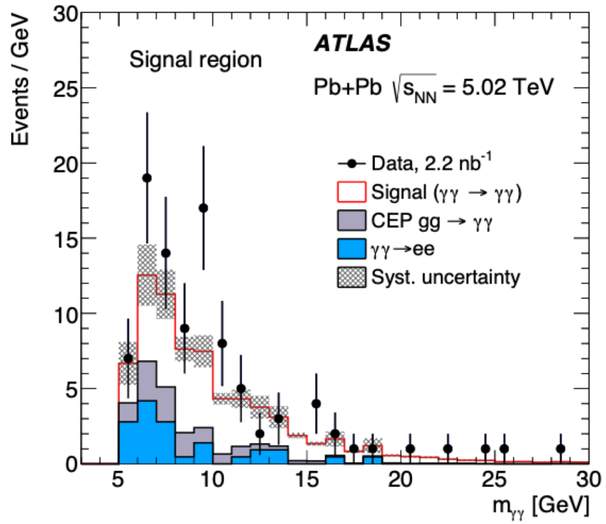

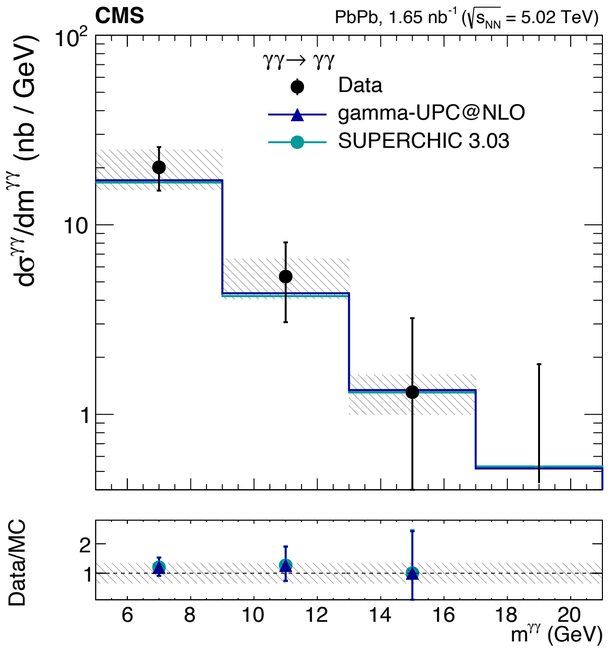

Limits on ALPs

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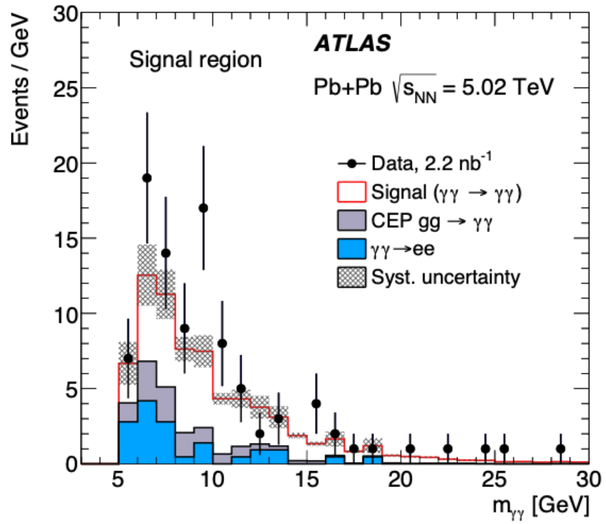
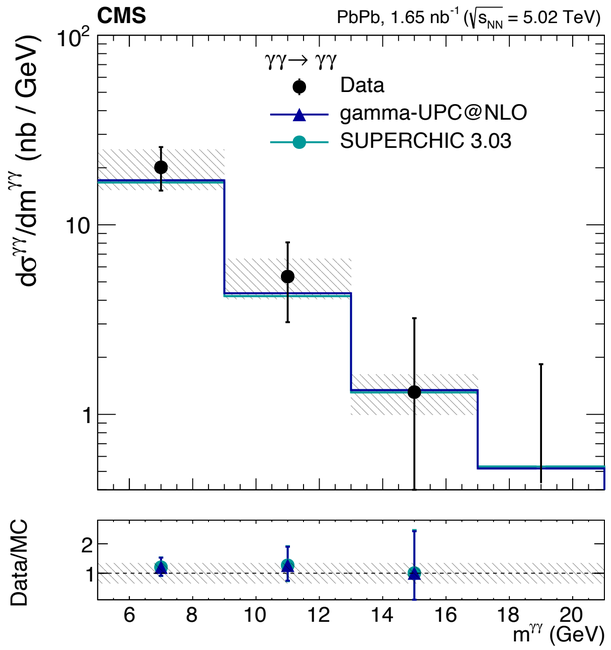
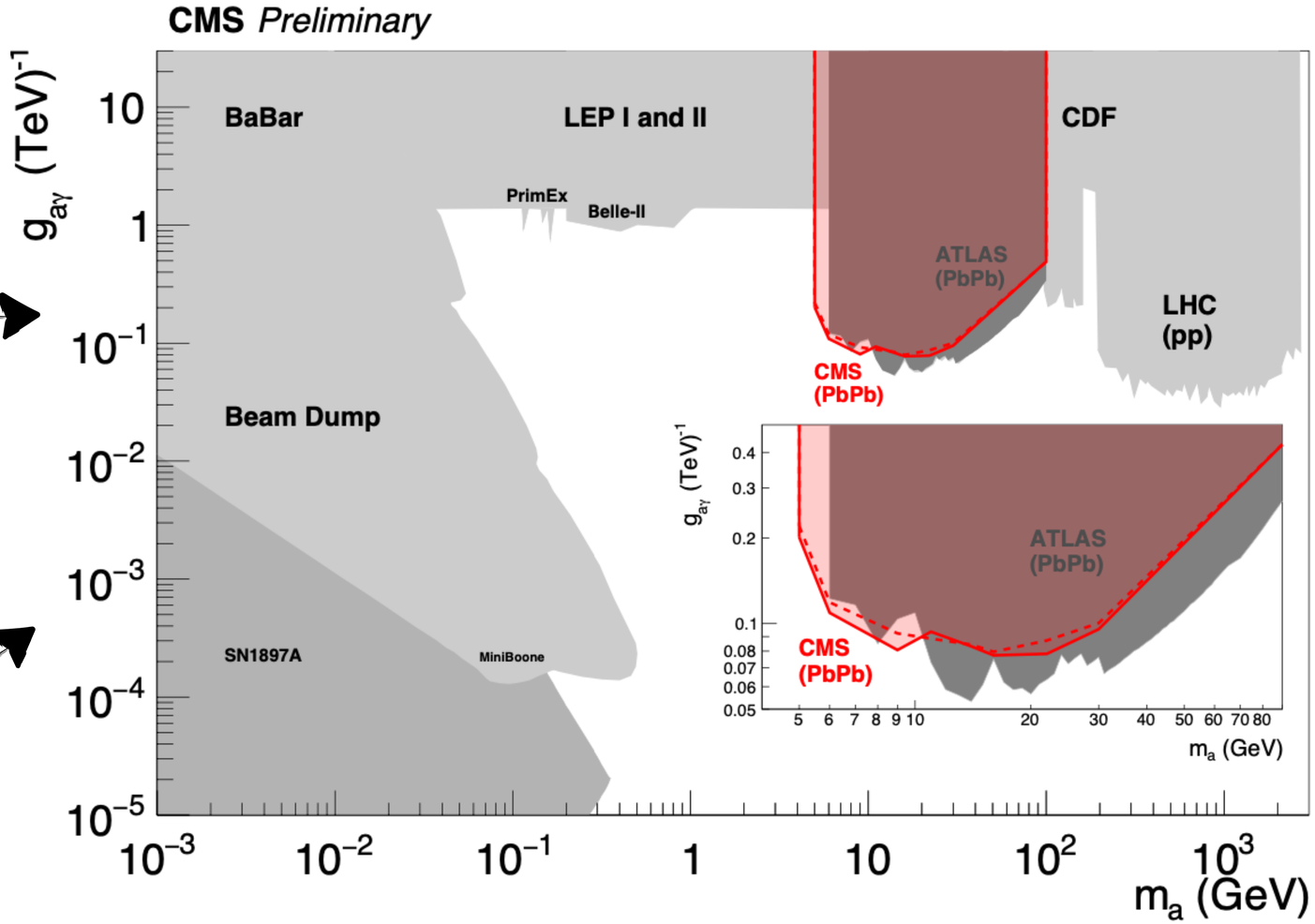






Limits on ALPs

- no significant excess in m_{inv}
- best limits in the **5-100 GeV** range

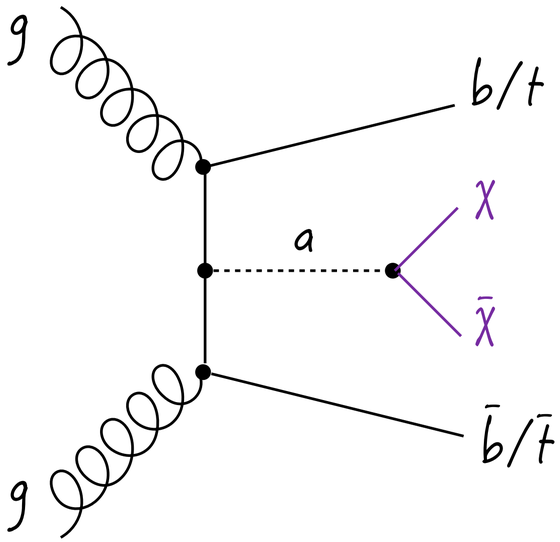
Other ALP Couplings

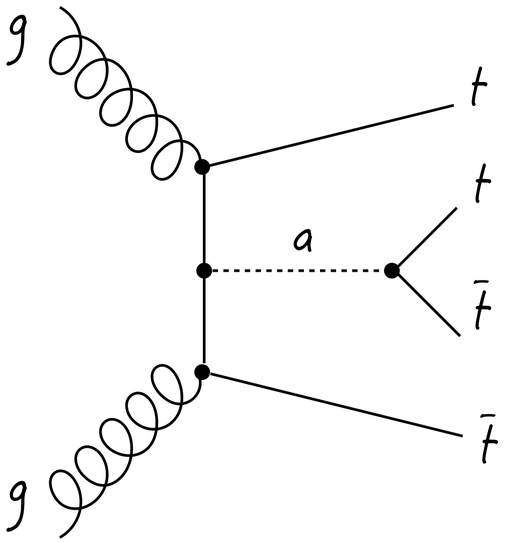
Top and Invisible couplings

ATLAS EXOT-2018-62
CMS EXO-22-014

High-mass ALPs

- higher masses
  → **other production mechanisms** and **decay channels** possible
- spin-0 pseudo-scalar “a”, assuming Minimal Flavor Violation
  → Higgs-like Yukawa couplings with SM particles





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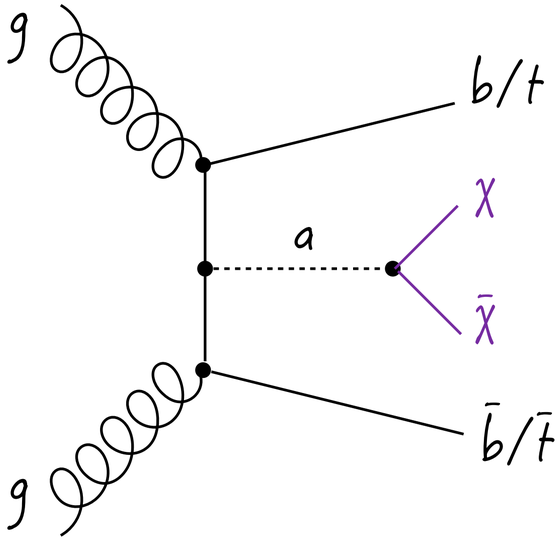
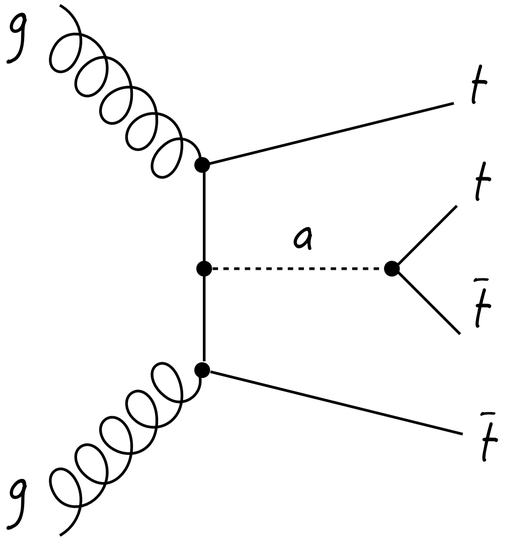
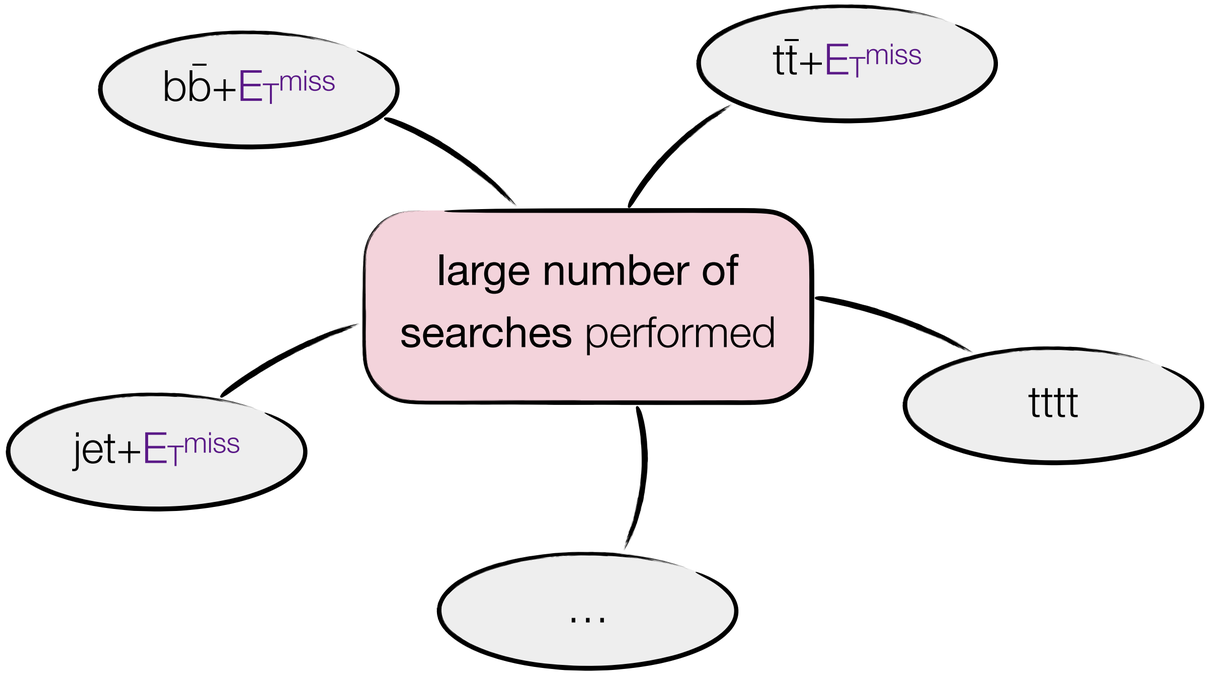






Different analyses and final states

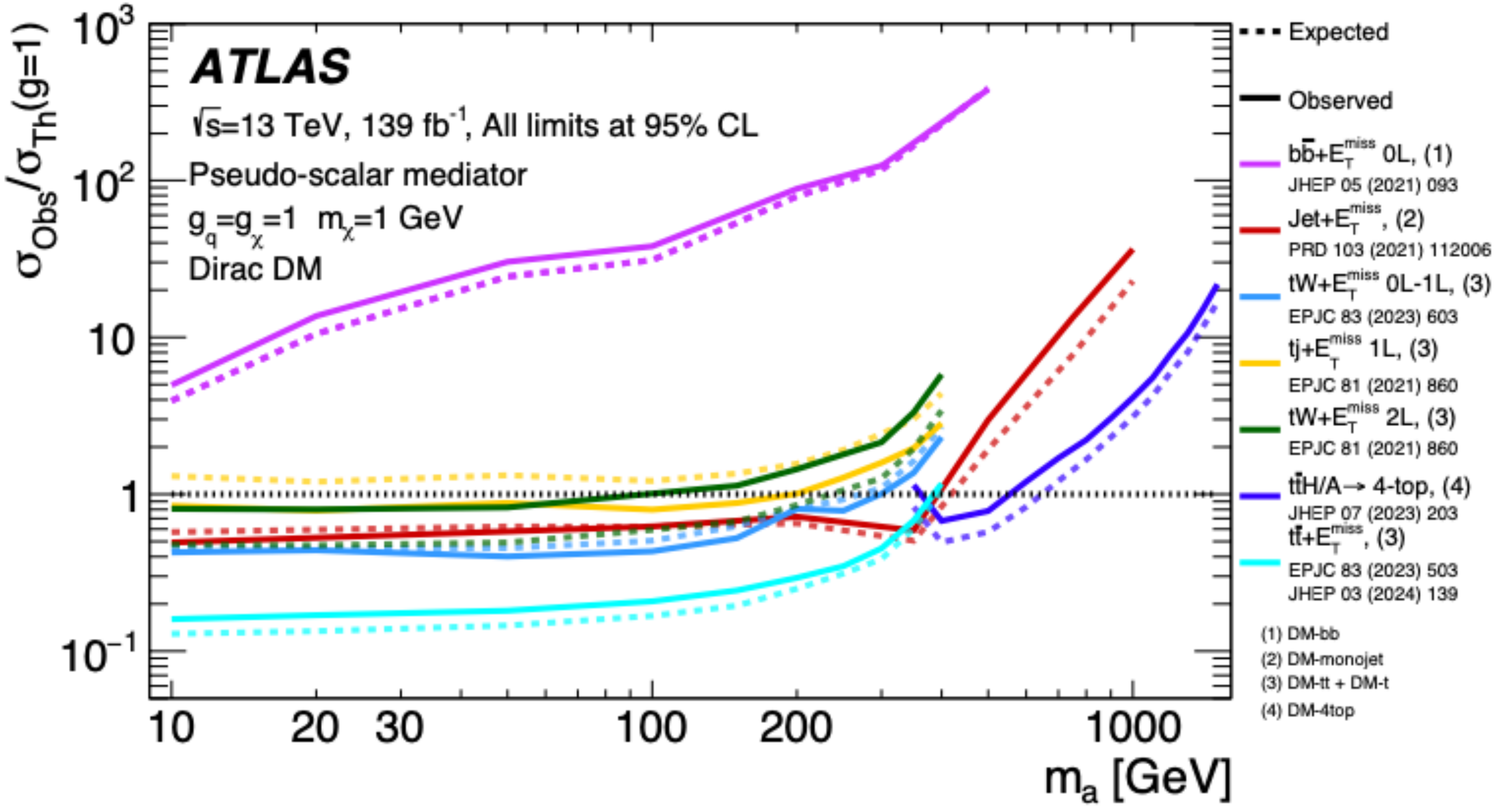
- different analyses use **different datasets, triggers, selections**
- combination/reinterpretation of these results allows to set **strong limits on ALP models**

Top and Invisible couplings

ATLAS EXOT-2018-62
CMS EXO-22-014

Limits

- strongest **limits on signal strength** from ATLAS come from:
  - <350 GeV: $t\bar{t}+E_T^{miss}$
  - >350 GeV: tttt

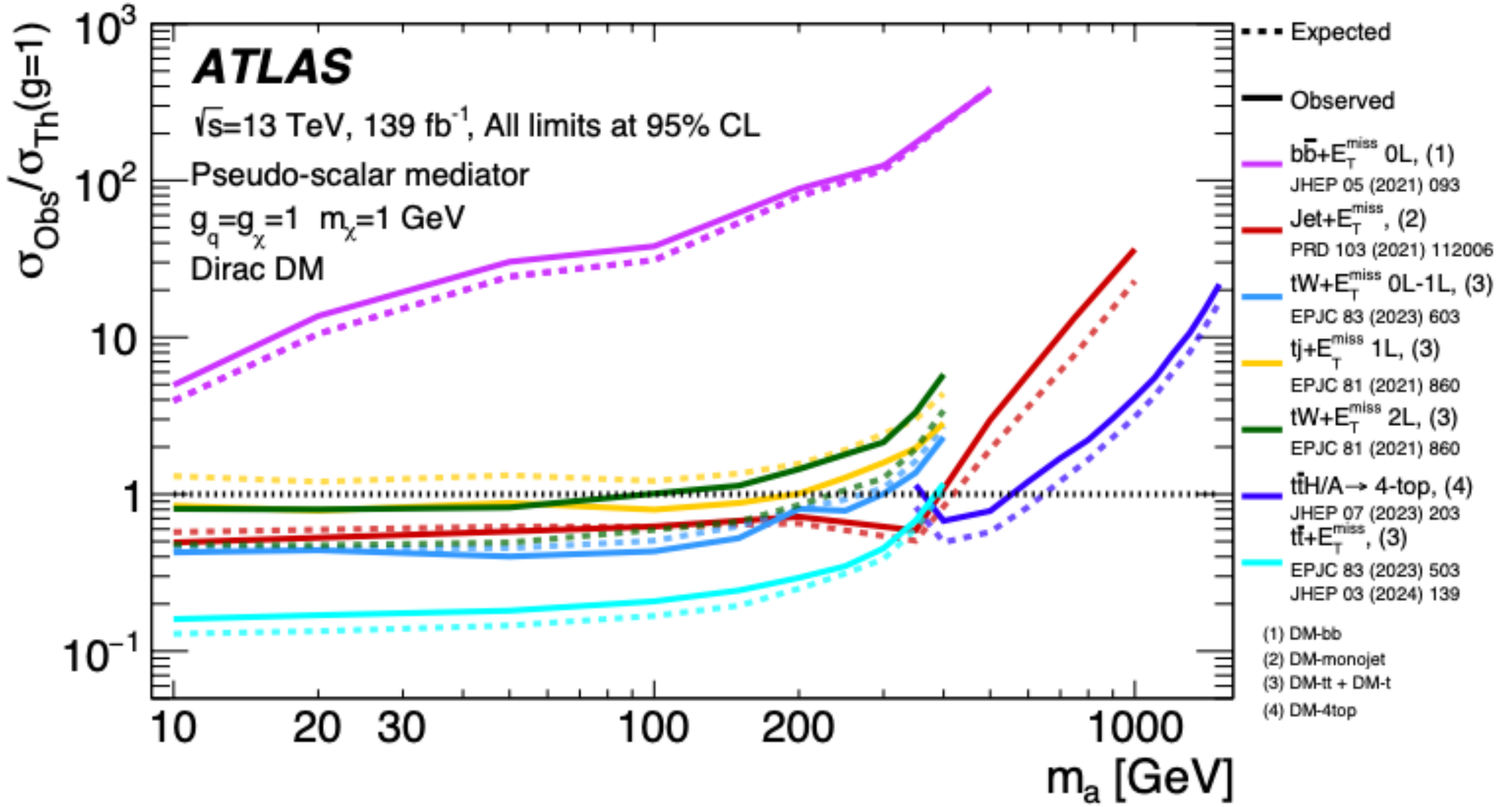


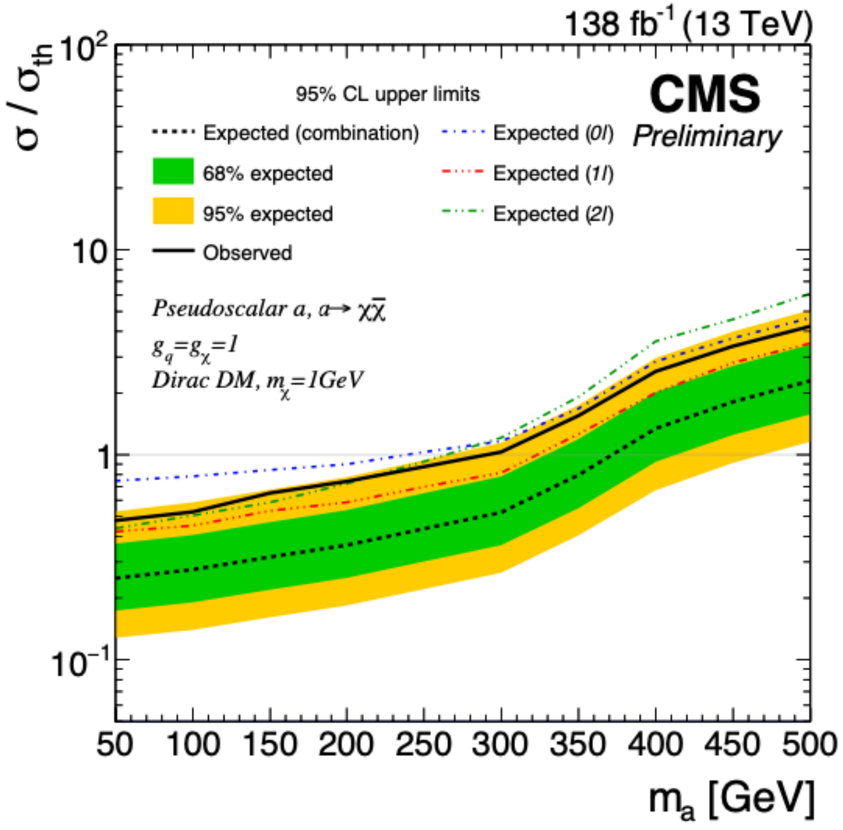
Top and Invisible couplings

ATLAS EXOT-2018-62
CMS EXO-22-014

Limits

- strongest **limits on signal strength** from ATLAS come from:
  - <350 GeV: $t\bar{t}+E_T^{miss}$
  - >350 GeV: tttt
- CMS: **comparable limits** in 50-500 GeV range from a **combination of 0l+1l+2l** Signal Regions



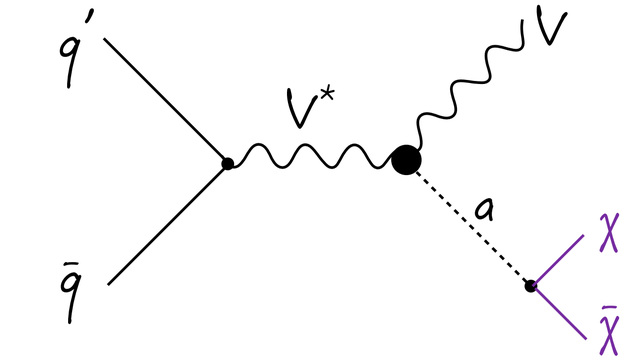


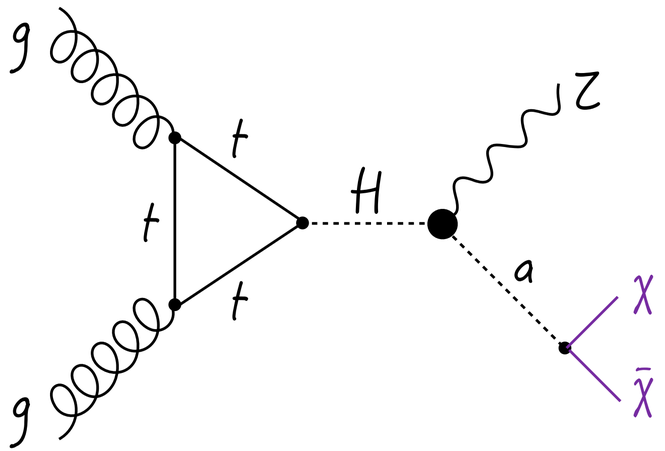
Boson couplings (Z/W)

ATLAS EXOT-2019-27
CMS EPJC 81 (2021) 13

Models and signatures

- ALPs can also **couple to W and Z bosons**
- these analyses focus on E_T^{miss} + V signatures





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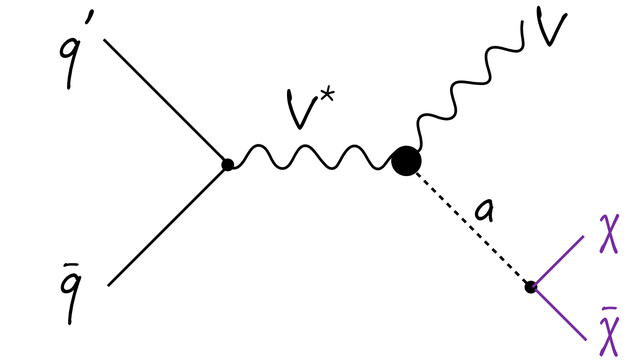

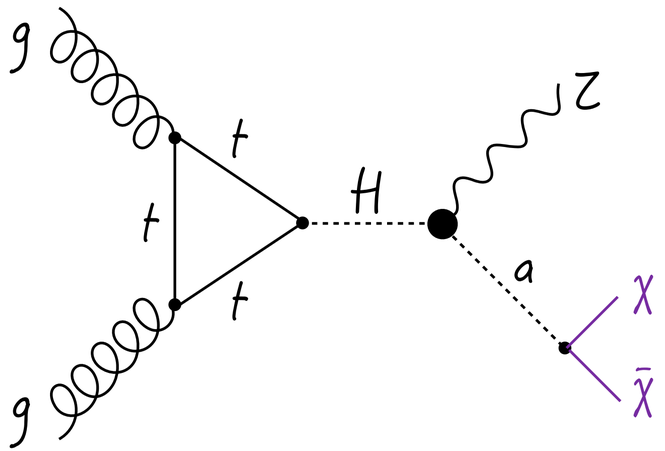

	ATLAS	CMS
beams	pp@13 TeV	
dataset	Run 2	
L_{int} (fb^{-1})	≈140	
trigger	**E_T^{miss}** > 70-110 GeV	**dilepton** p_T ≳ 20 (10) GeV leading (subleading)

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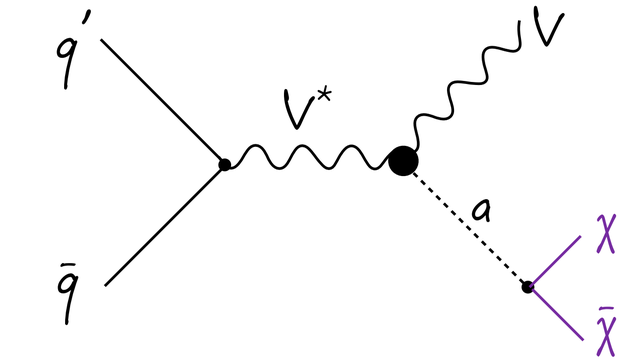

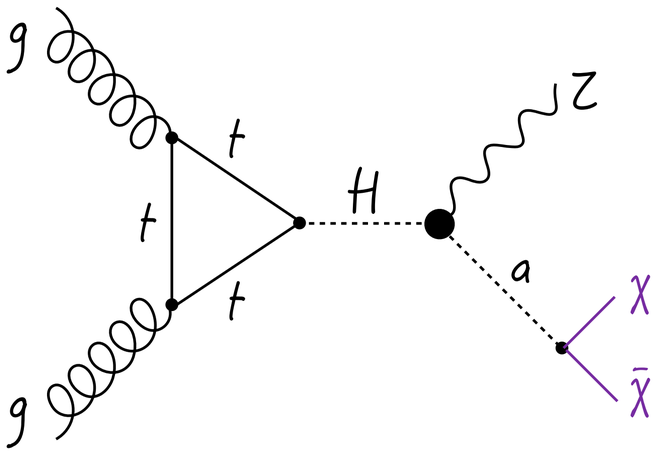

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Backgrounds

- most common backgrounds are:
  - Z(→νν)+jets
  - diboson
  - W(→lν)+jets
  - $t\bar{t}$
- constrained from di-leptonic and single-leptonic **CRs + simulation**

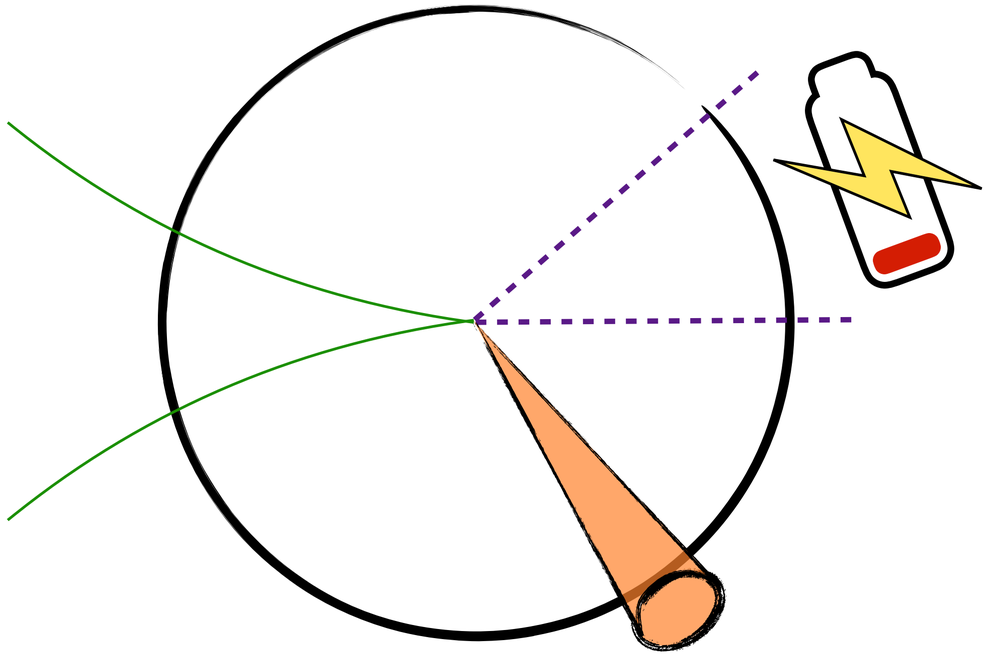
Boson couplings (Z/W)

ATLAS EXOT-2019-27
CMS EPJC 81 (2021) 13

Event selections

Different selections for **merged or resolved** topologies, some differences between CMS and ATLAS. In general:

- **large E_T^{miss}** > 100-200 GeV
- **number of jets**, **b-jets**, and **leptons** requirements → reduces top and WZ backgrounds
- **Δφ between E_T^{miss} and jets/dileptons** must be sufficiently large → suppressing energy mismeasurement
- additional requirements on the **dijet/dilepton system** (angles, m_{inv}) → suppresses non-resonant and DY backgrounds



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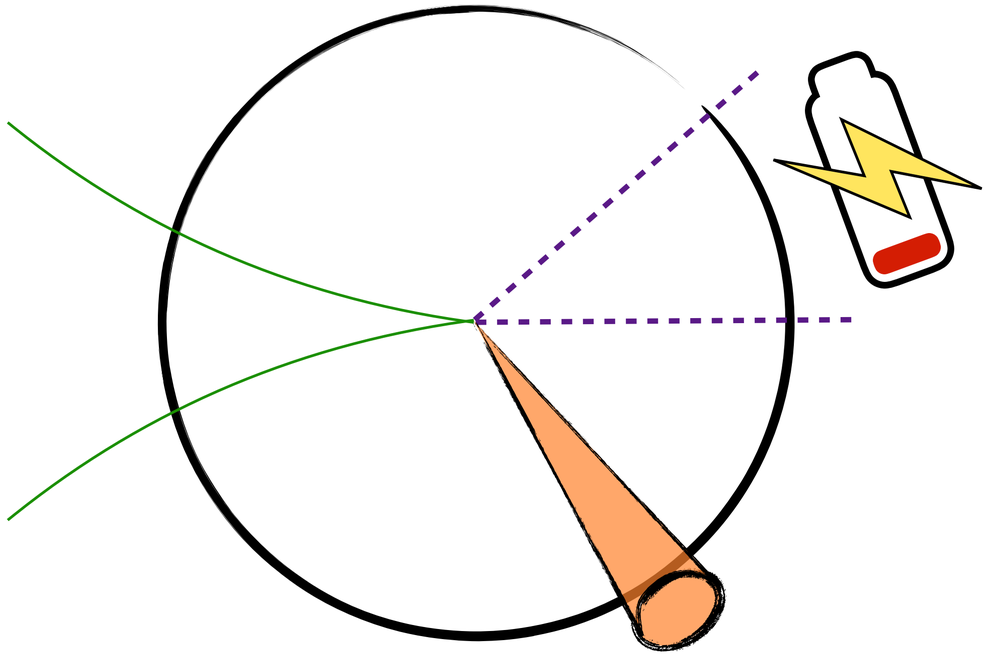
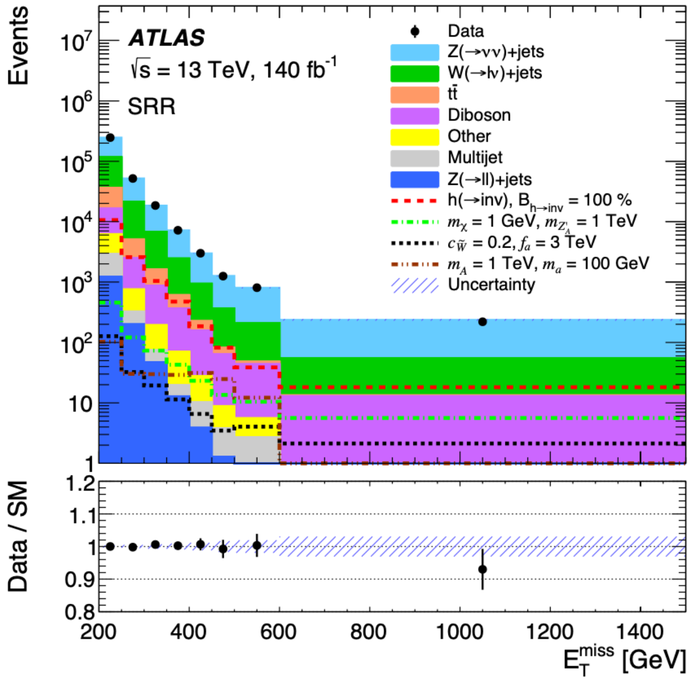
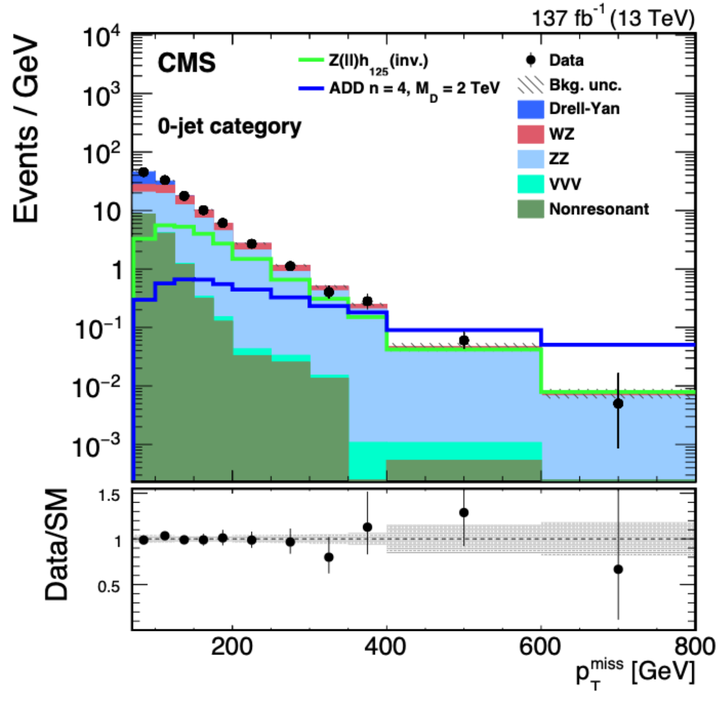




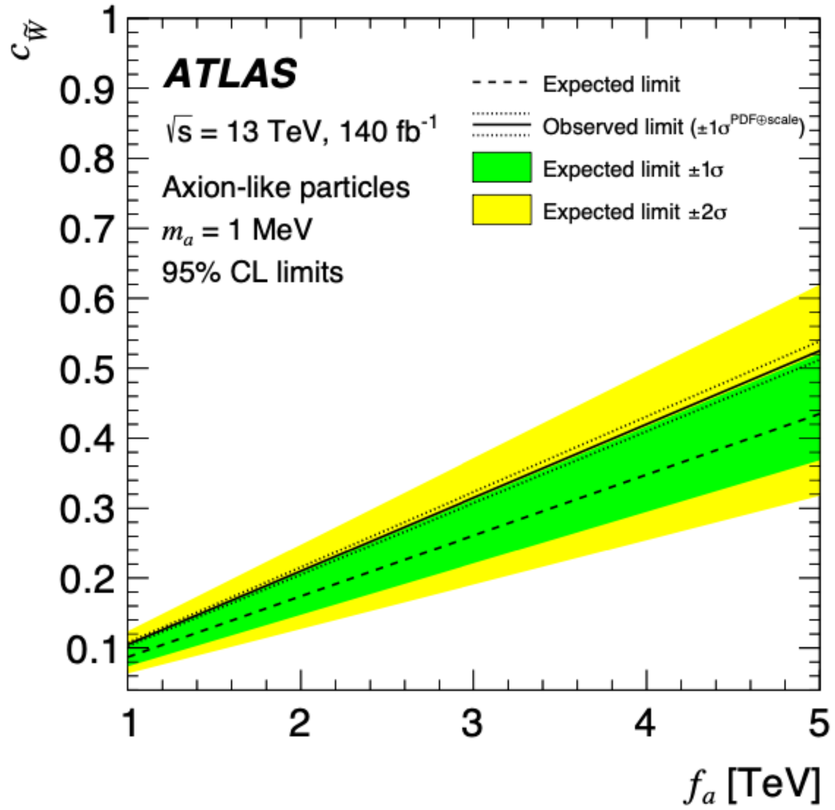


Boson couplings (Z/W)

ATLAS EXOT-2019-27
CMS EPJC 81 (2021) 13

ATLAS

- placing limits on **ALP-W coupling** as a function of the **effective scale f_a**
- fixed **m_a = 1 MeV** (doesn't change much until up to 1 GeV)
- c_W/f_a above 0.11/TeV are excluded



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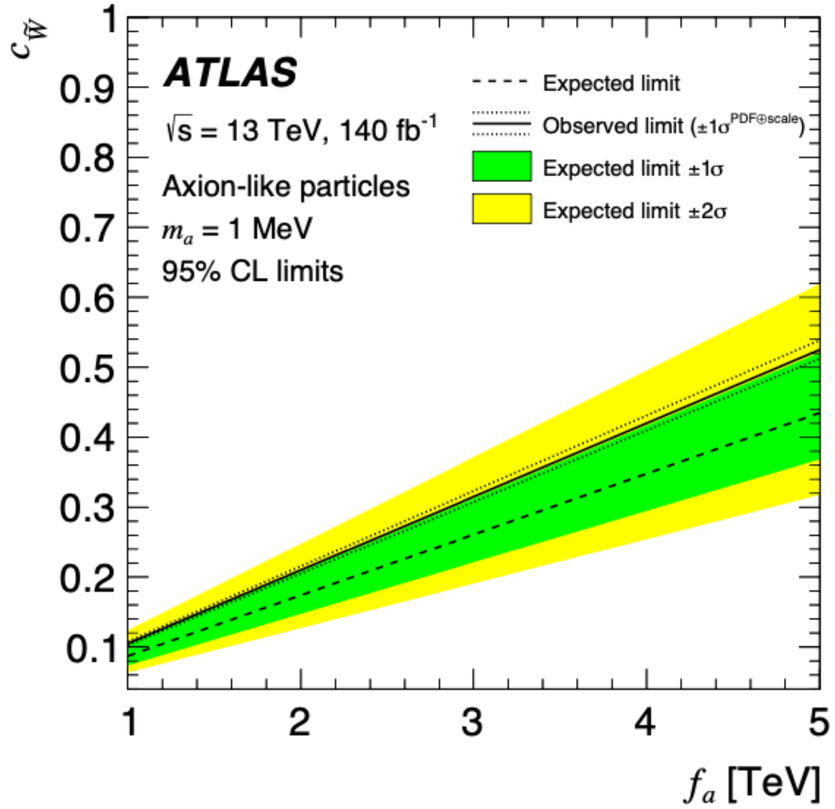
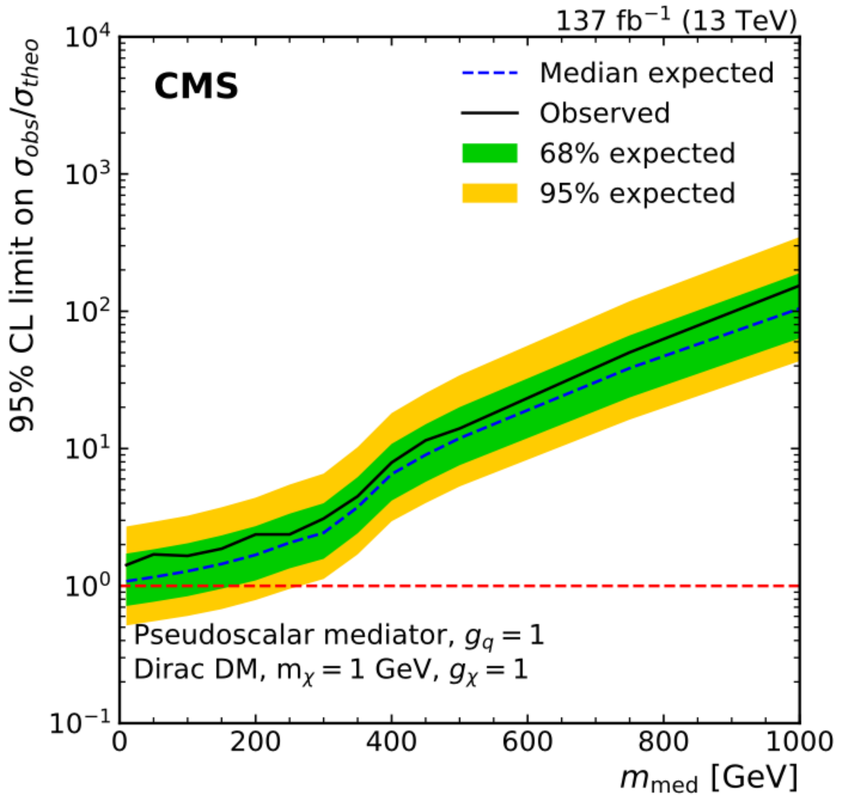




CMS

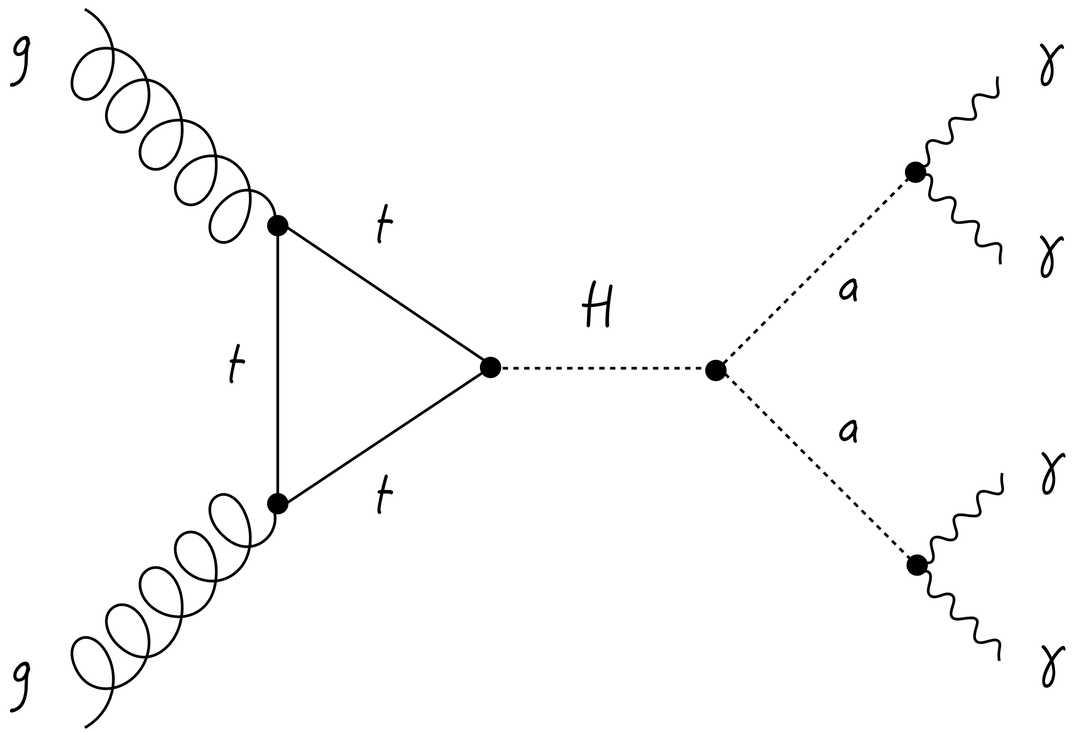
Limits on **signal strength** as a function of **ALP mass** (with DM mass fixed at 1 GeV)

Boson couplings (Higgs)

ATLAS HDBS-2019-19
CMS JHEP 07 (2023) 148
EXO-22-022

Models and signatures

- ALPs can **couple to the Higgs boson**
- signatures with 4 photons in the final state



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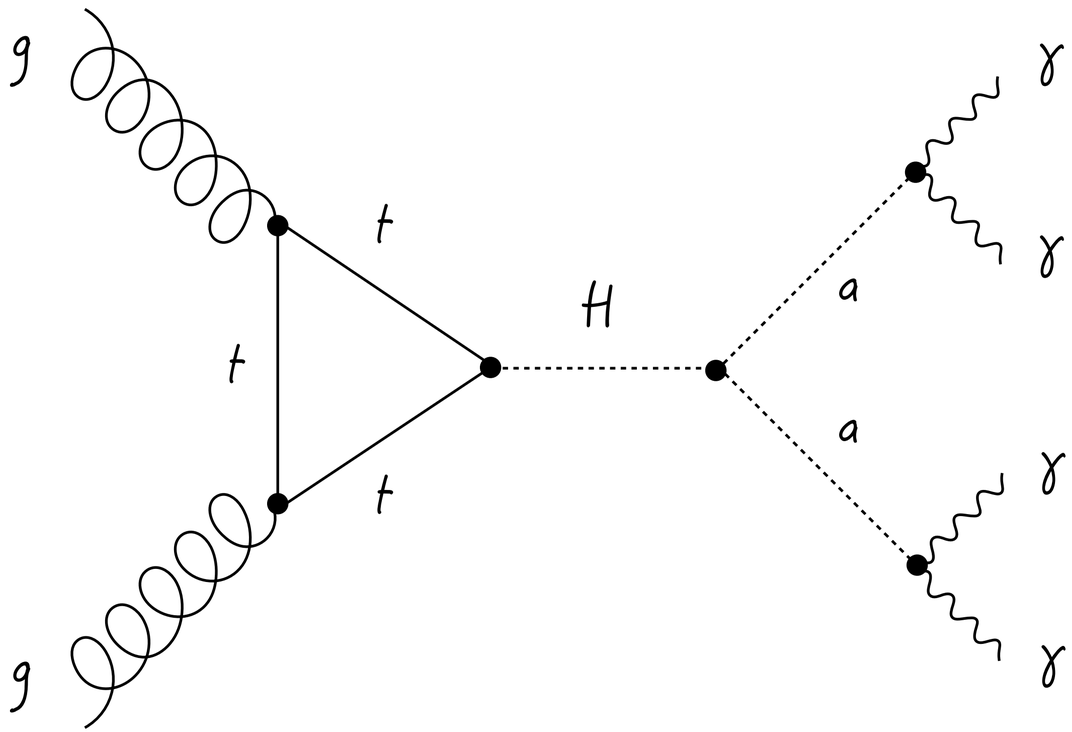

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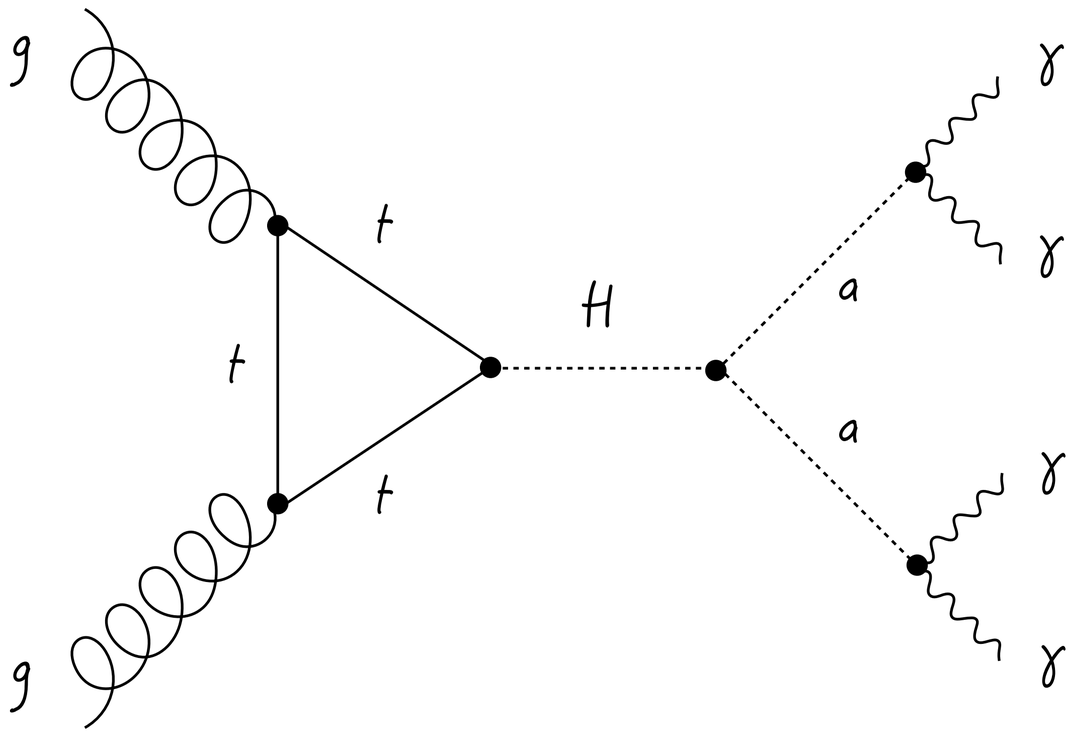

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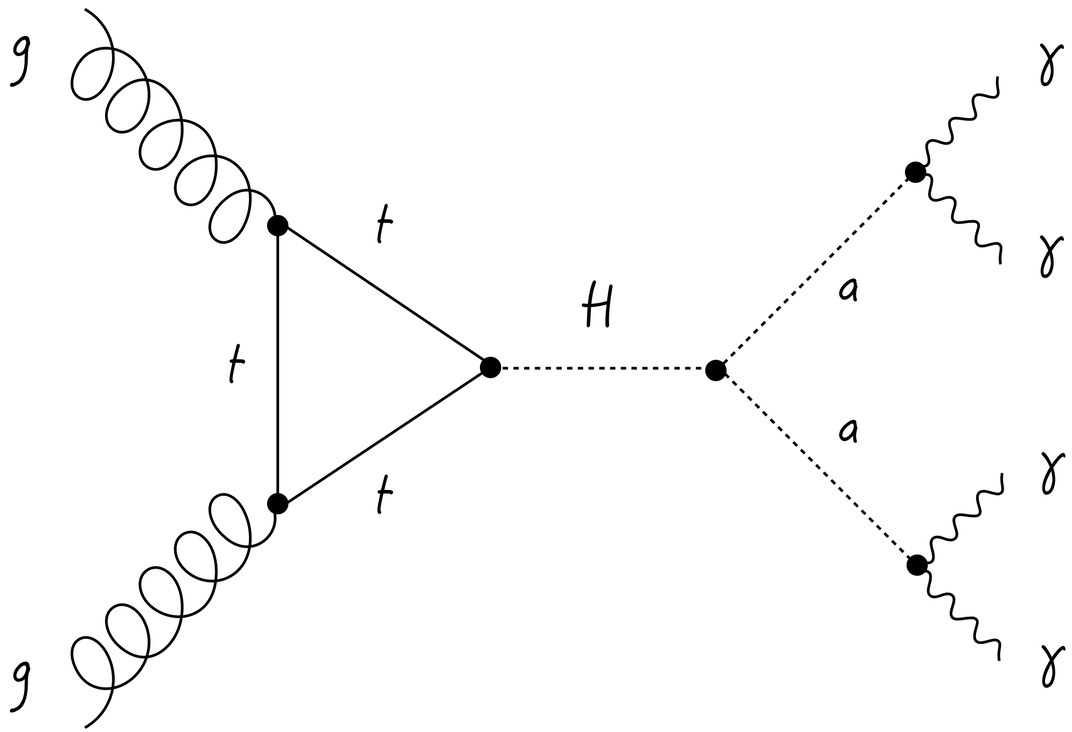

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Background estimation:

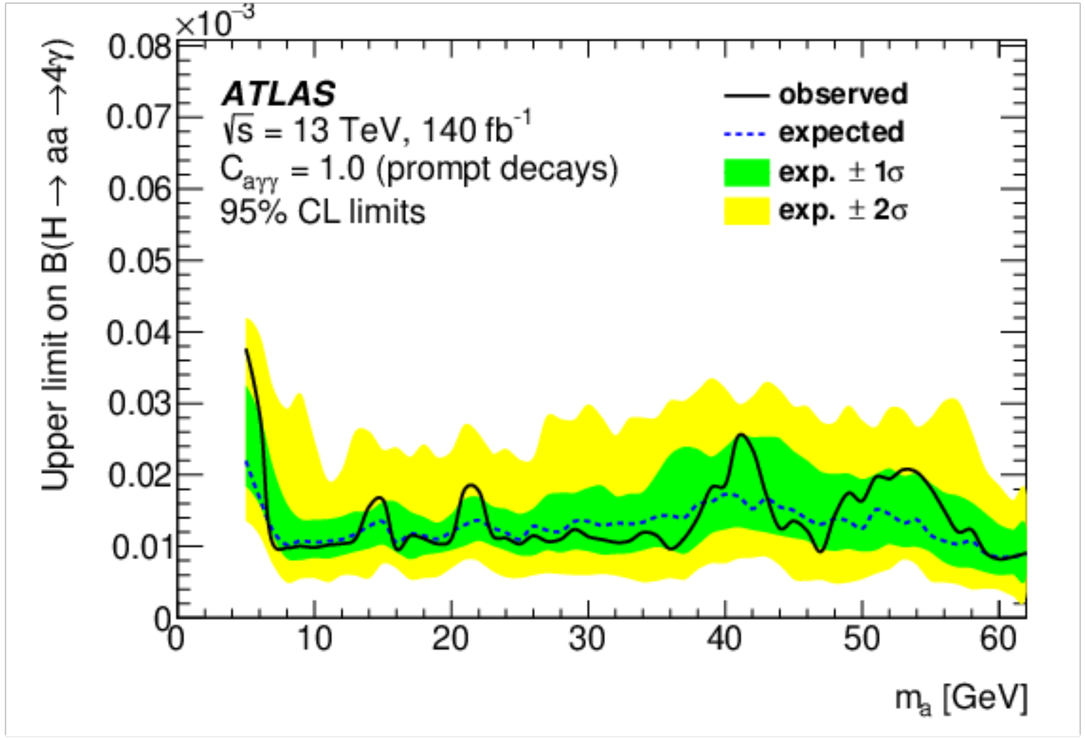
- ATLAS: searching for a signal around 125 GeV
  → using **sidebands**
- CMS: using a 4-photon **event classifier**

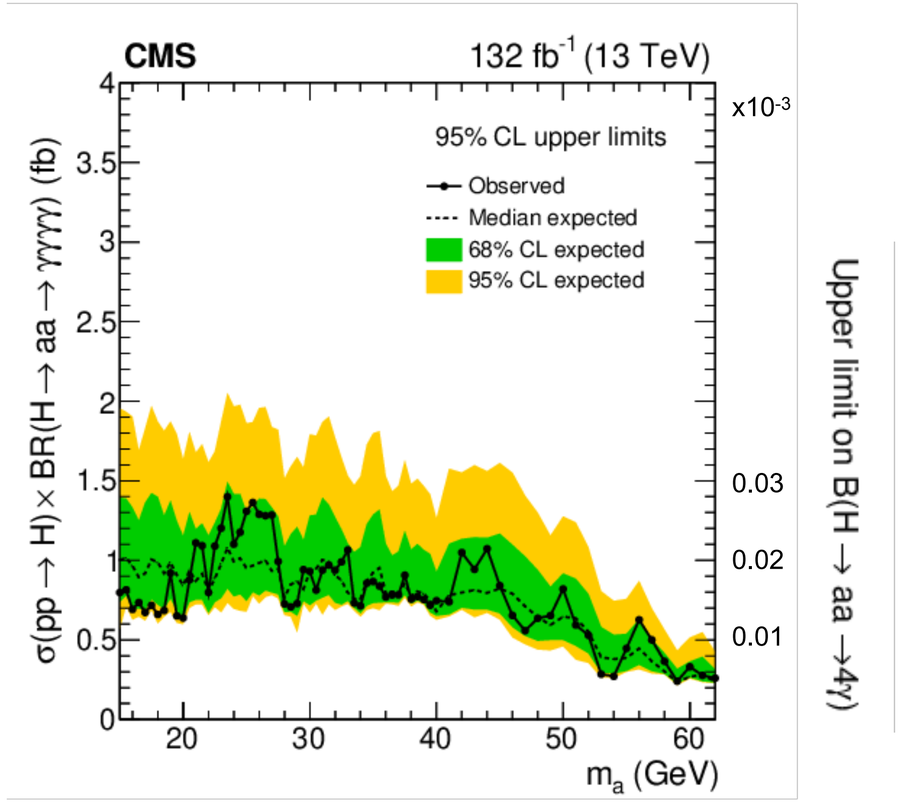
Boson couplings (Higgs)

ATLAS HDBS-2019-19
CMS JHEP 07 (2023) 148
EXO-22-022

Limits

- no significant excesses → limits are placed on the **Branching Ratio of H→aa**
- similar results from ATLAS and CMS: **BR above $\approx 10^{-5}$ excluded** (for masses in range 5-60 GeV)





Direct Dark Matter searches

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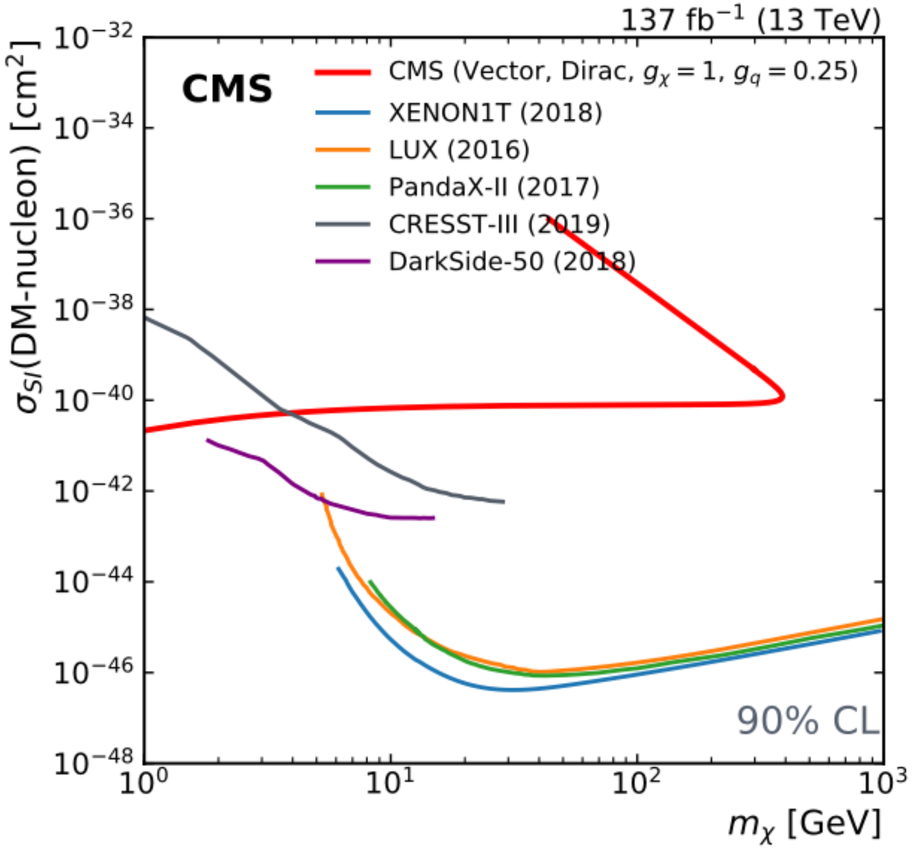

Direct Dark Matter searches

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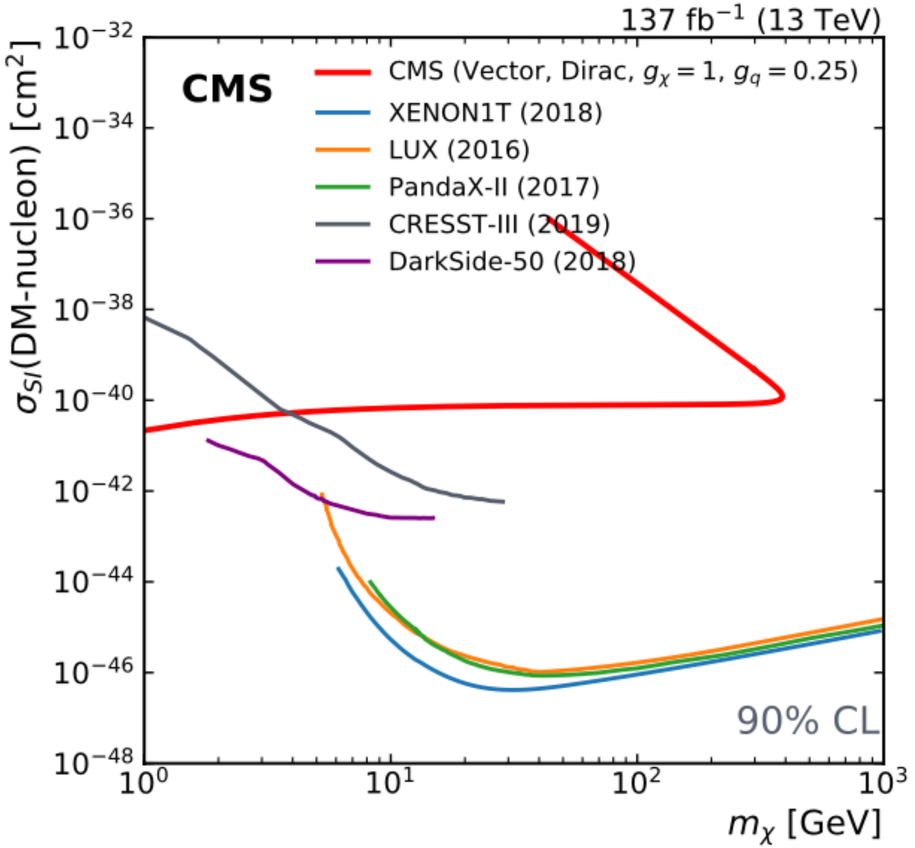
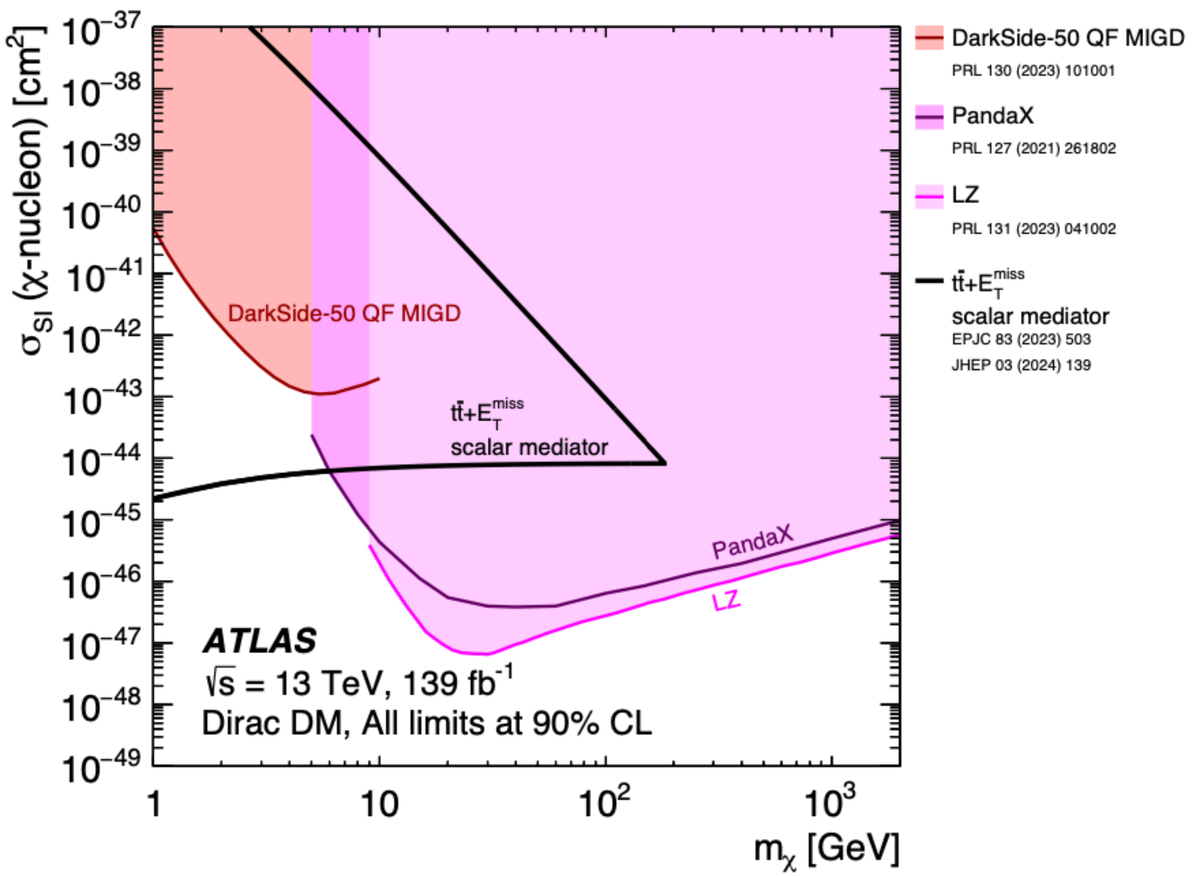
- **new ATLAS** results are also competitive with direct searches in the **1-6 GeV range**





SUMMARY

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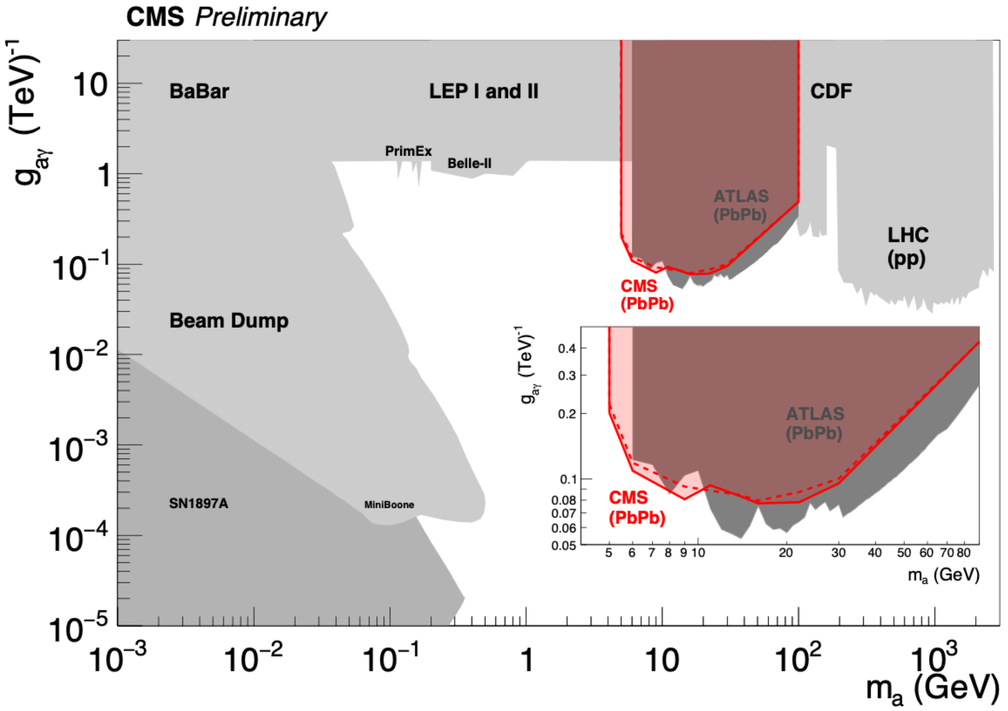
UPCs of protons and Heavy Ions

- **great tool** for high-mass ALP searches
- best limits in the **5-2000 GeV** range



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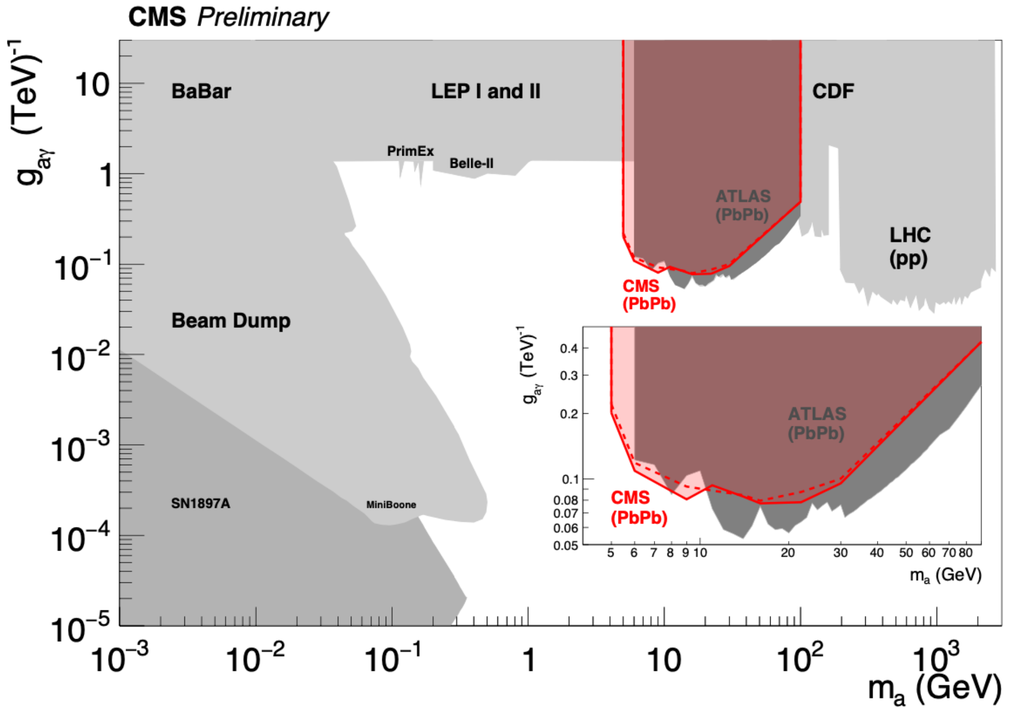

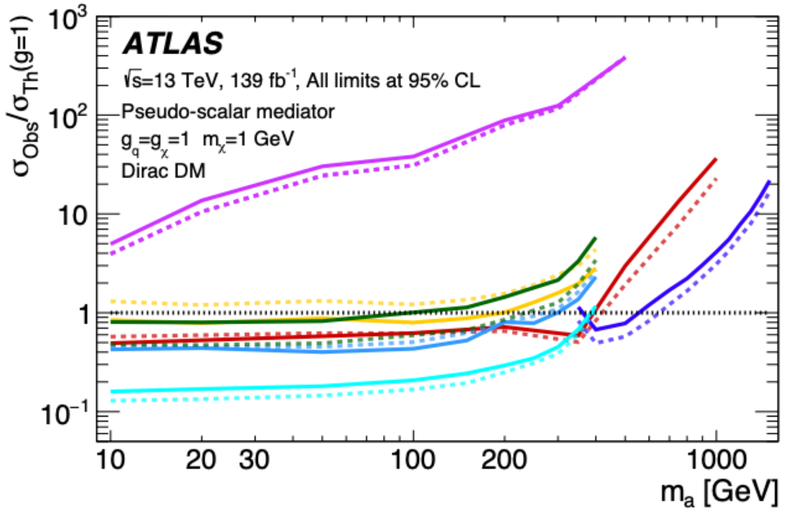

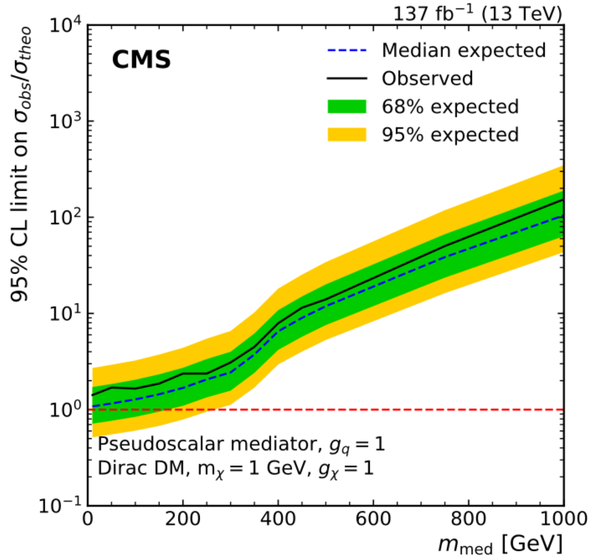

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Dark Matter searches

LHC searches for ALPs→invisible **complementary to direct detection** experiments → good in $m_\chi \in [1, 6]$ GeV range