Shedding Light on the Dark Sector: Exploring Hidden Portals at the LHC

Hyunyong Kim
Seoul National University

UNIVERSITY OF SEOUL
Department of Physics
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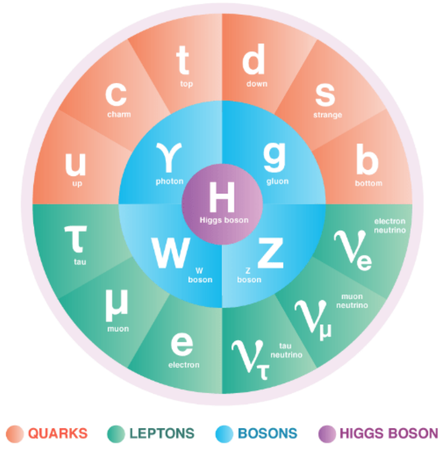
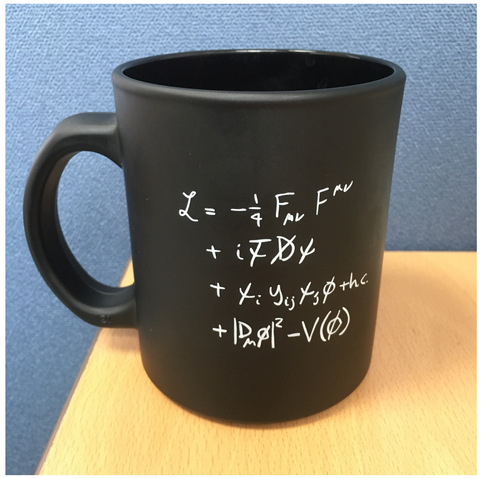
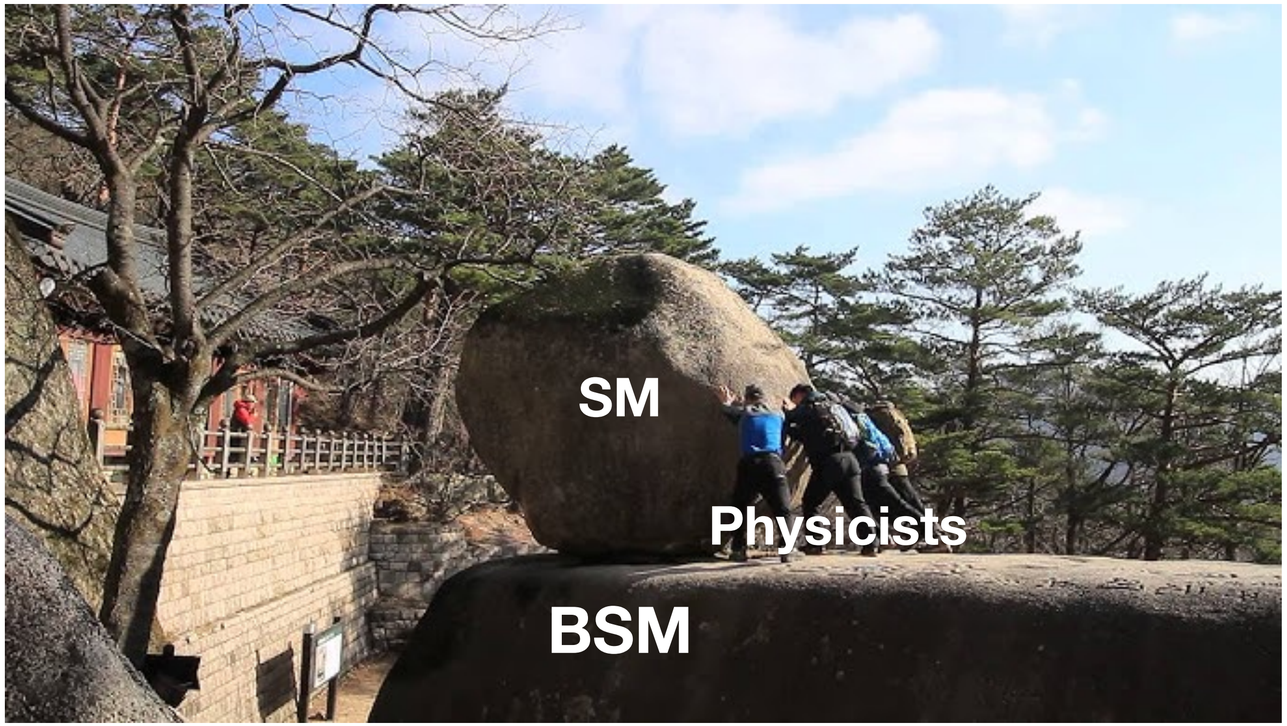
Eternal Questions

What is matter made of?

Standard Model!

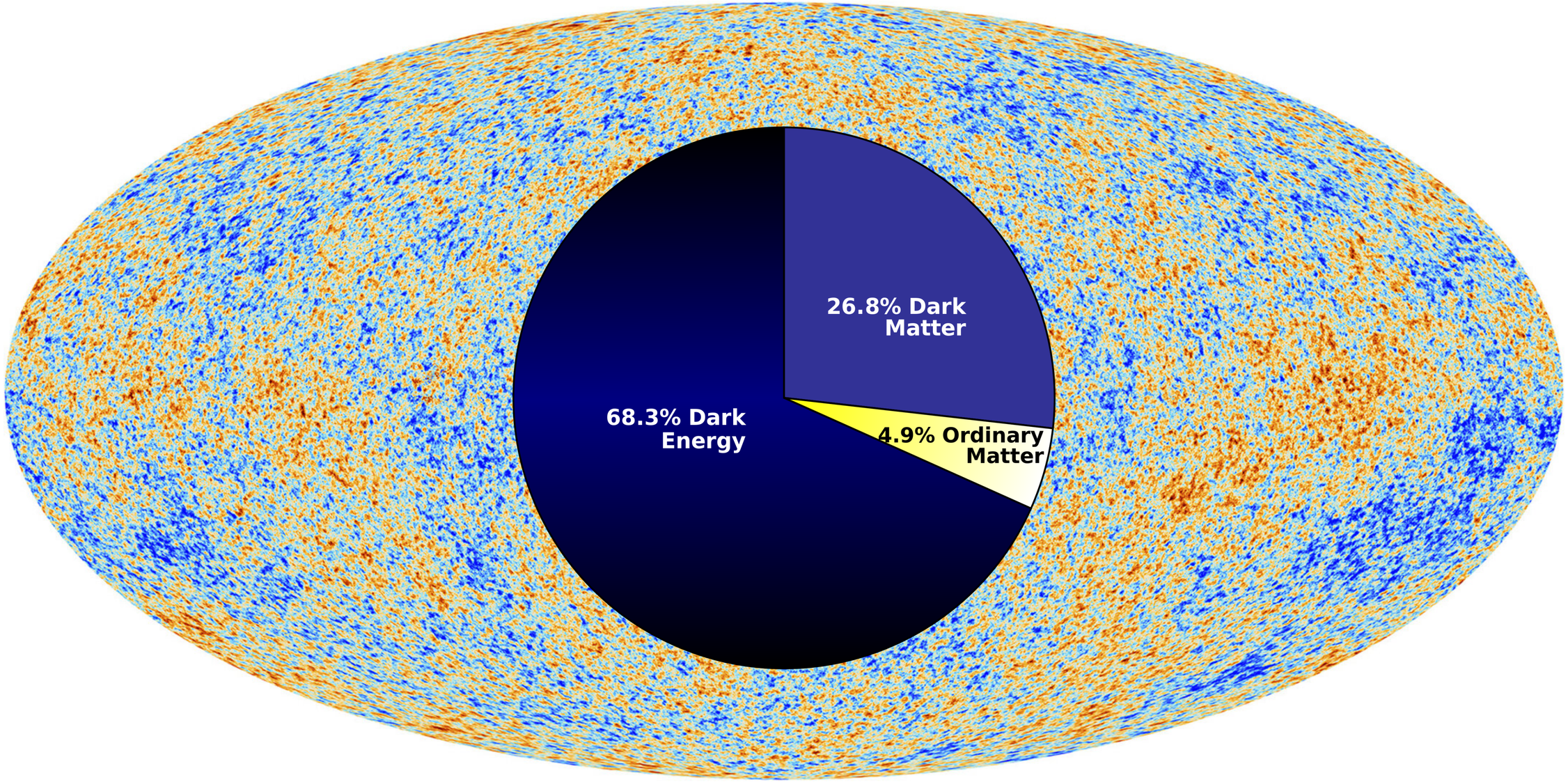




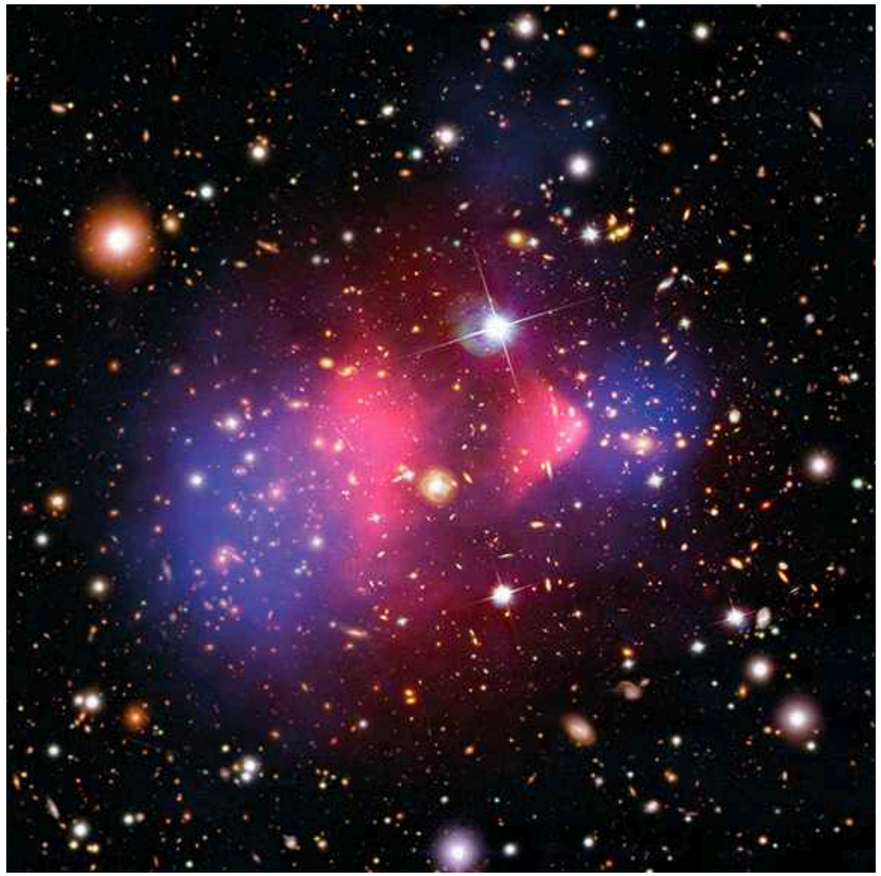


Rocking stone in Korea

What is the Universe made of?

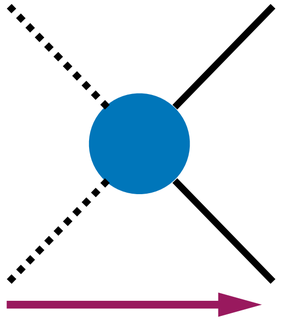


Dark Matter



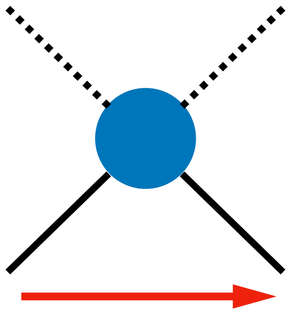
Dark matter obviously exists!

Dark matter Searches

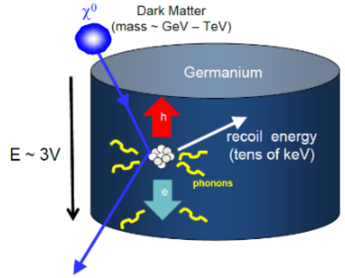


DM indirect search

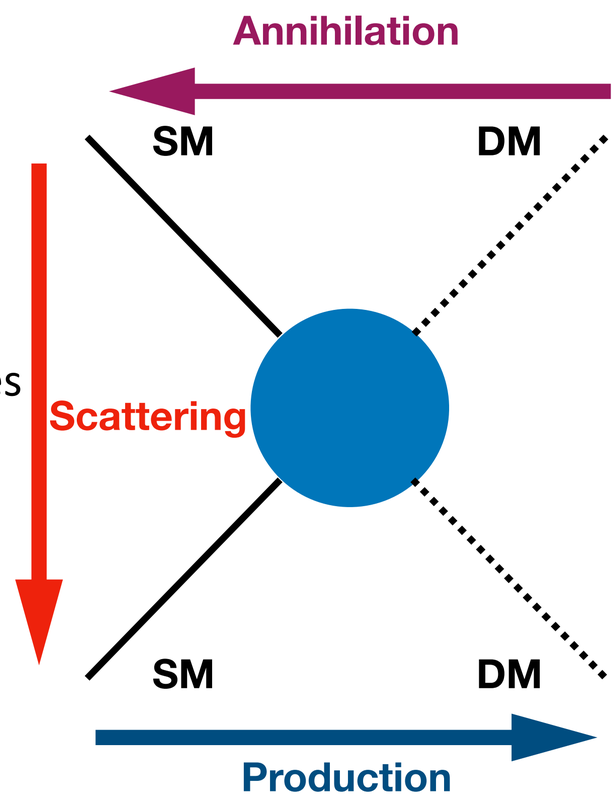
- DM annihilation/decay to the SM particles

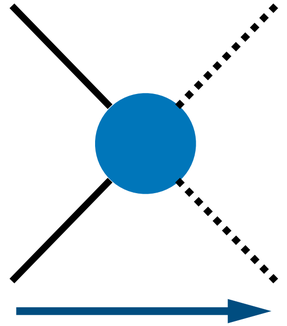


DM direct search



- DM scattering off target nuclei



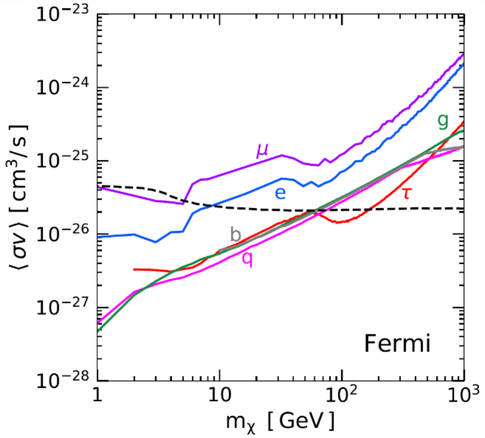


DM production

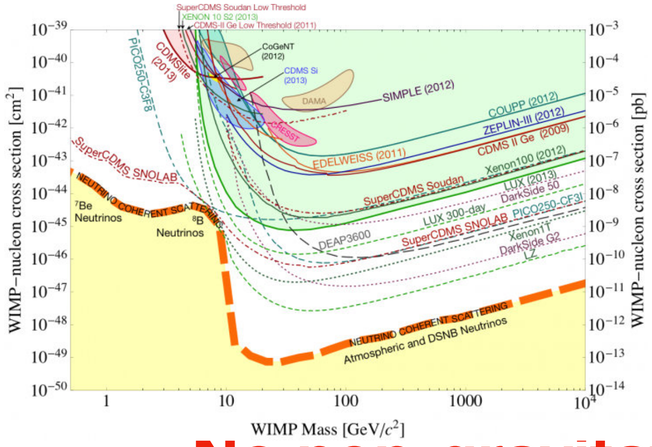
- Active DM production at colliders
- Mono-X searches

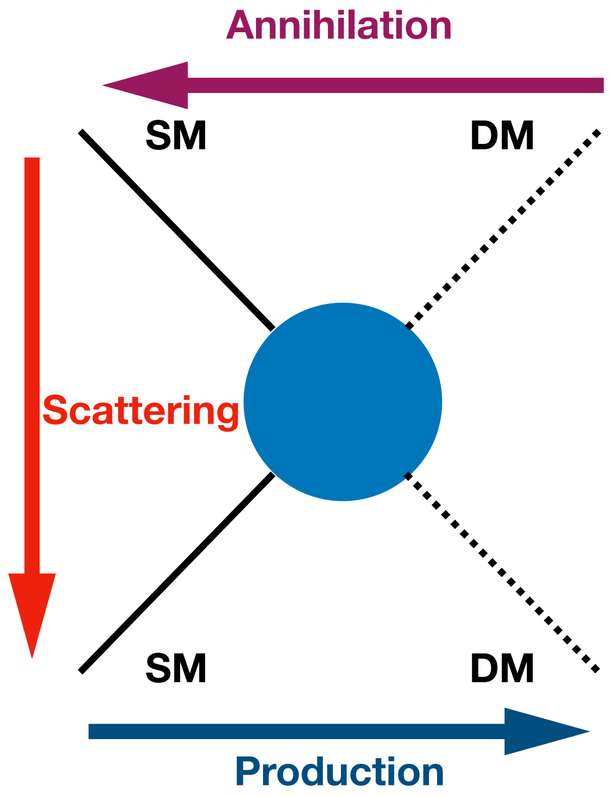
Status of Dark Matter Searches

DM indirect search

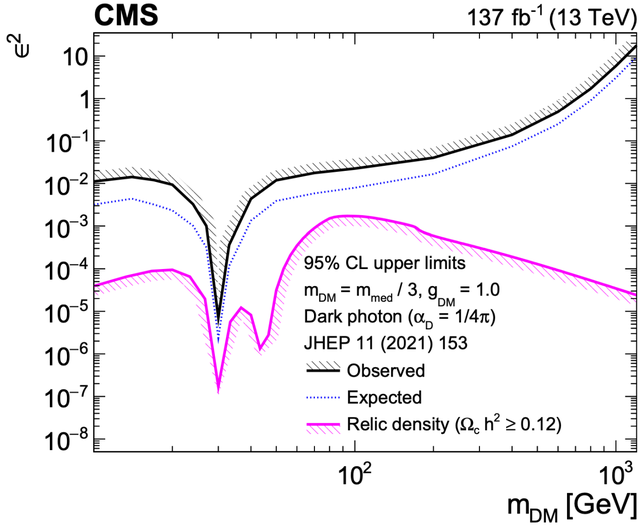


DM direct search





DM production



No non-gravitational interactions have been detected so far.

Weakly Interacting Massive Particle

[Lee, Weinberg, PRL (1977)]

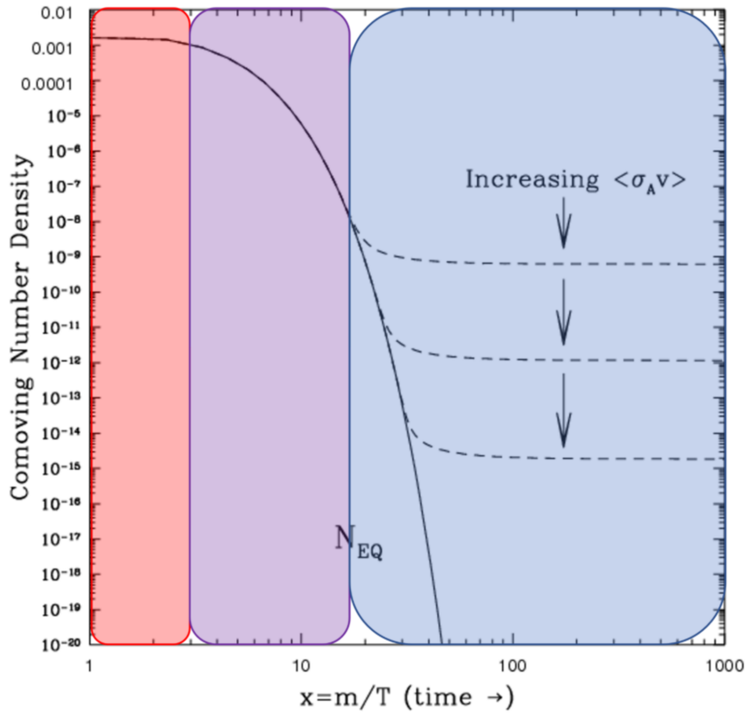


Image credit: A. Green

1) Creation & annihilation processes are in thermal equilibrium.
2) When temperature drops below the DM mass, DM is exponentially depleted.
3) When the DM density becomes too sparse, it is hard to find other DM to get annihilated with. ⇒ **Thermal Freeze-out**!

Observed relic abundance

$$\langle \sigma v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s} \propto \frac{g_\chi^2 g_{\mathrm{SM}}^2 m_\chi^2}{M_W^4}$$

$$g_\chi \sim g_{\mathrm{SM}} \sim \mathcal{O}(1)$$

$$m_\chi \sim M_W \sim 100\ \mathrm{GeV}$$

WIMP Miracle!

A New Hope

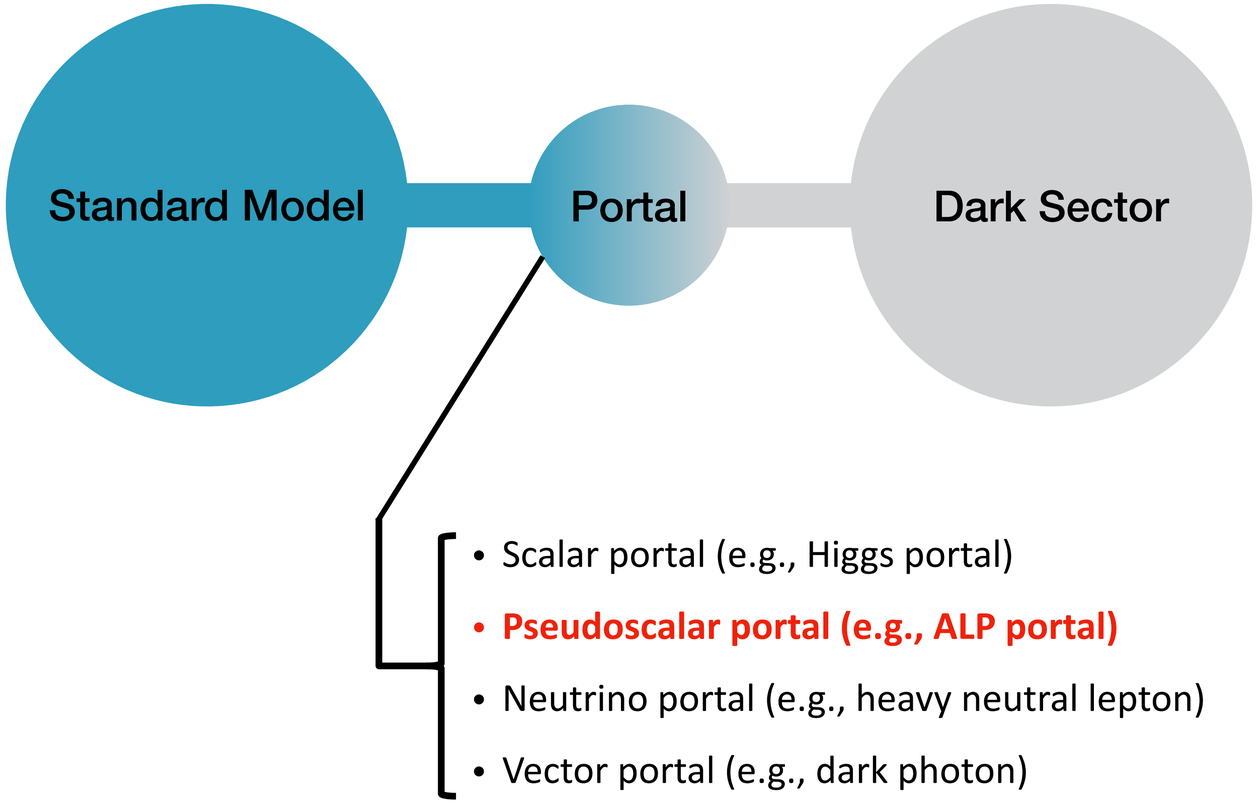
- Thermal dark matter remains viable — now explored through **dark sector interactions** with light mediators.
- Dark sectors naturally reproduce the relic abundance while avoiding WIMP-era constraints.

$$\frac{g_\chi^2 g_{\mathrm{SM}}^2 m_\chi^2}{M^4}$$

- $m_\chi : 100\ \mathrm{GeV} \rightarrow 0.1\ \mathrm{GeV}$
- $g_{\mathrm{SM}} : \mathcal{O}(1) \rightarrow \mathcal{O}(0.001)$
- $M : 100\ \mathrm{GeV} \rightarrow 0.1\ \mathrm{GeV}$

MeV–scale mediators and dark matter are well motivated.

Dark Sector and Portal Scenarios

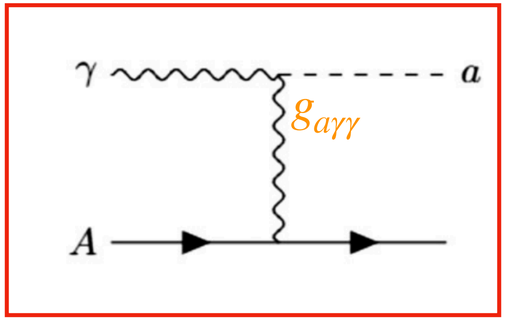


The **dark sector** is **feebly** coupled with the visible sector **via a portal (mediator) interaction.**

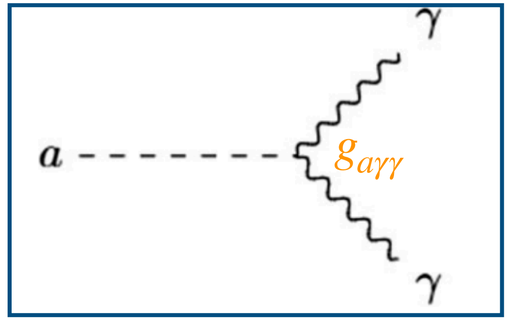
ALP

- Axion: clean up the strong CP problem
- **ALP (Axion-Like Particle)** are extensions of the axion
- Mediators that allow dark matter particles to communicate with Standard Model particles
- In particular, our focus is on the search for ALP mediators that are coupled to photons → $g_{a\gamma\gamma}$: the interaction strength between the ALP and the SM photon

$$-\mathscr{L}_{\text{int}} \supset \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

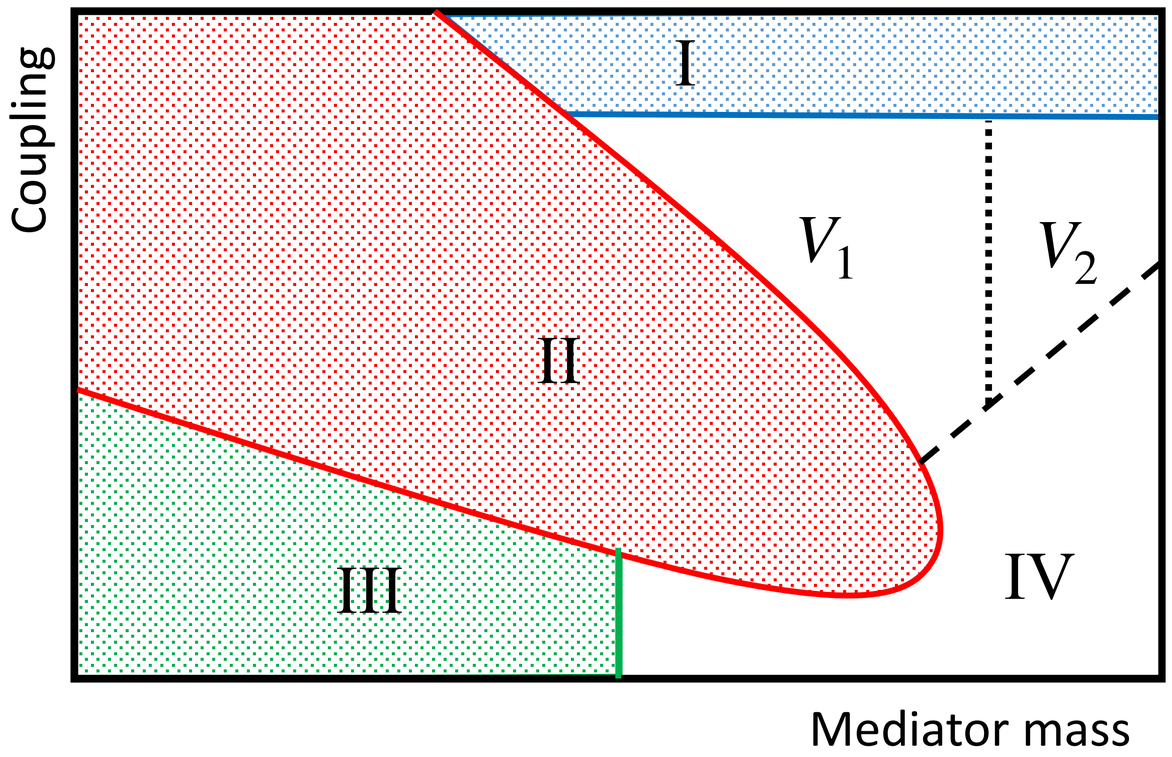


Primakoff process



ALP decay

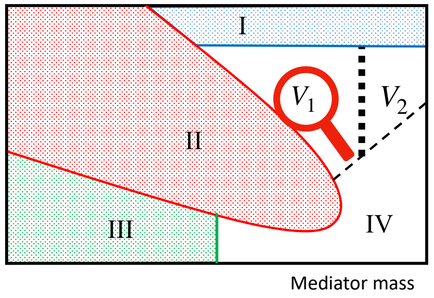
Dark Sector Search Scheme



- **Region I**: Constrained by collider searches
- **Region II**: Constrained by beam-dump searches
- **Region III**: Constrained by astrophysical and cosmological considerations, including:
  - SN1987a
  - Cosmic Microwave Backgrounds
  - Big-Bang Nucleosynthesis
- **Region IV**: Open and can be explored by increasing statistics
- **Region V**: The region of primary interest is the prompt-decay region, where we aim to expand our search

V_1 : MeV − scale, V_2 : GeV − scale

*Proton mass ~ 1 GeV



Beam Dump Experiment

Larger coupling = shorter $c\tau$

Beam

Decay

Short $c\tau$ ALP without boost

Boosted the short $c\tau$ of ALP but the detector distance is too far

Detector distance

Detector

Short distance

Short $c\tau$ ALP with high-boost

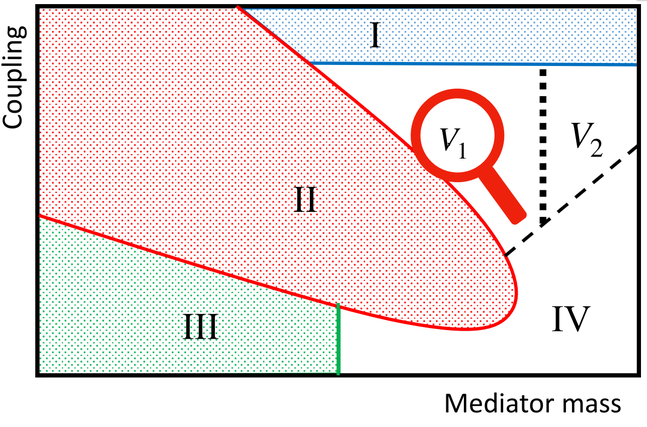
Dump

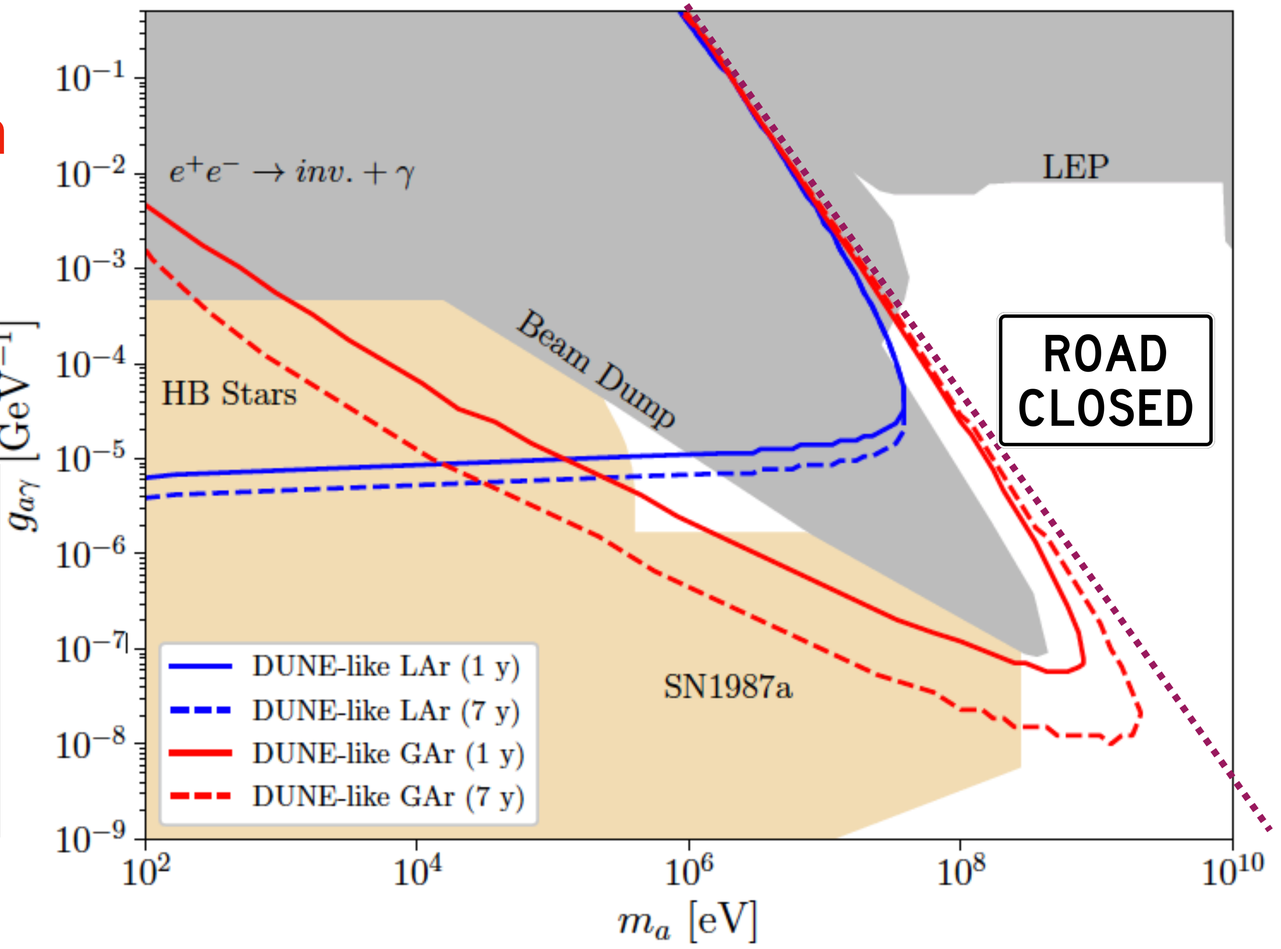
Detector

Not to scale

Beam Dump “Ceiling”

How can we overcome the Beam Dump “Ceiling"?



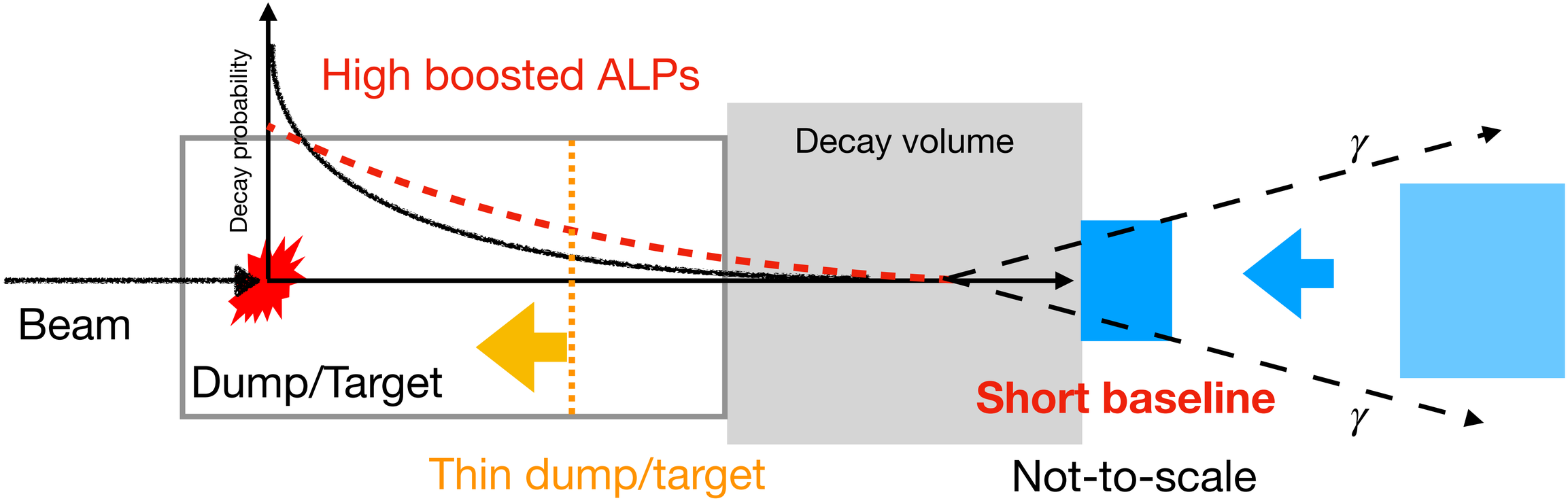


There is a limitation known as the **beam dump "ceiling"** that significantly hinders sensitivity improvement, despite increasing statistics.

Beam Dump “Ceiling”

The beam dump ceiling depends only on the experimental setup, including the boost factor and the distance of the detector.

Overcome “Ceiling”



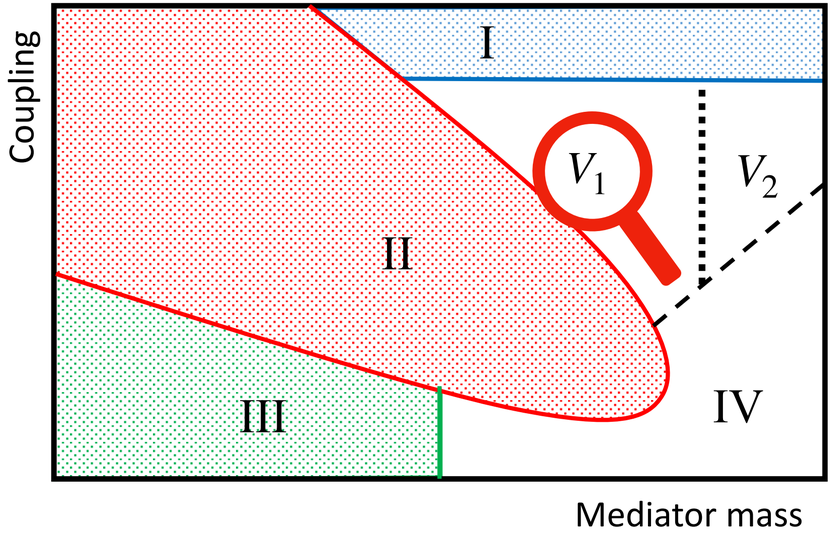
To overcome the Beam-dump “ceiling”, the experiment setup should have;

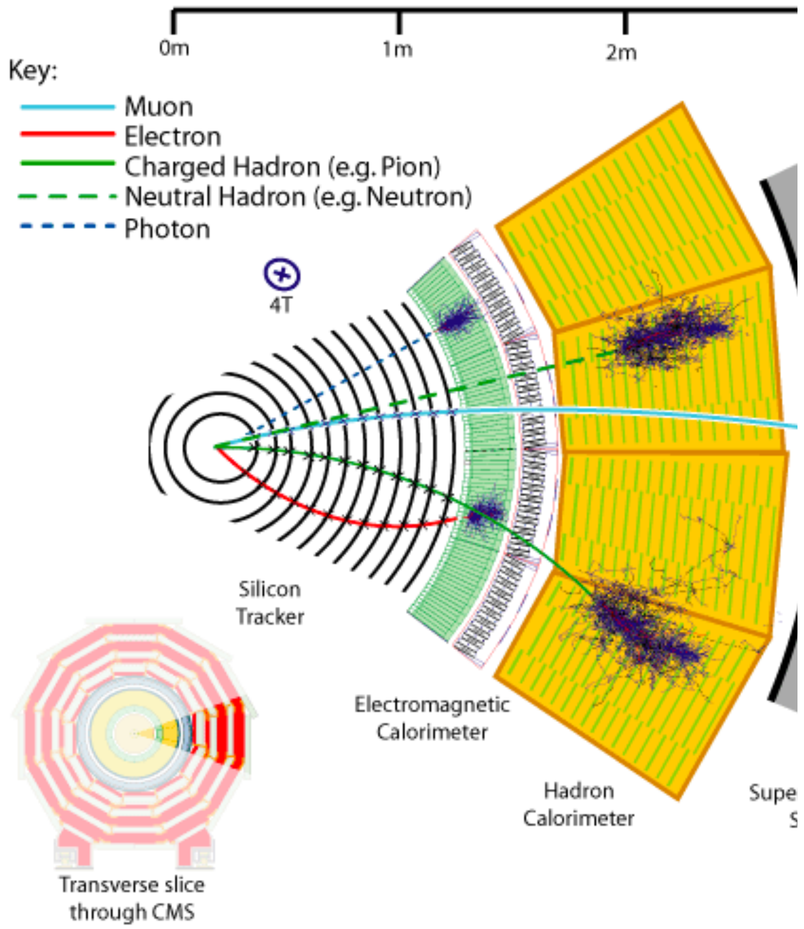
1. **High boost factor**
2. **Thin dump/target**
3. **Close detector location**

CMS Beam Dump

- The CMS calorimeters produce numerous photons, electrons, and charged mesons from jets

- It means there are many fixed target collisions
  →Beam Dump Experiment!

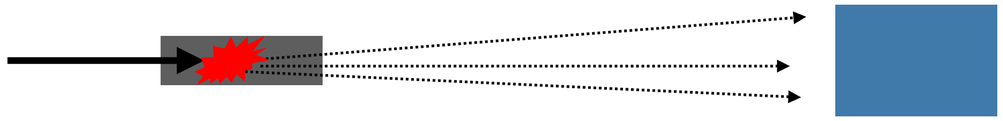




Beam Dump Experiments

Beam Dump

- Low energy beam ~ 1–100 GeV
- High intensity beam ~ 10^{20}–10^{23}/year
- Long distance detector ~ 0.5—1 Km
- Narrow solid angle

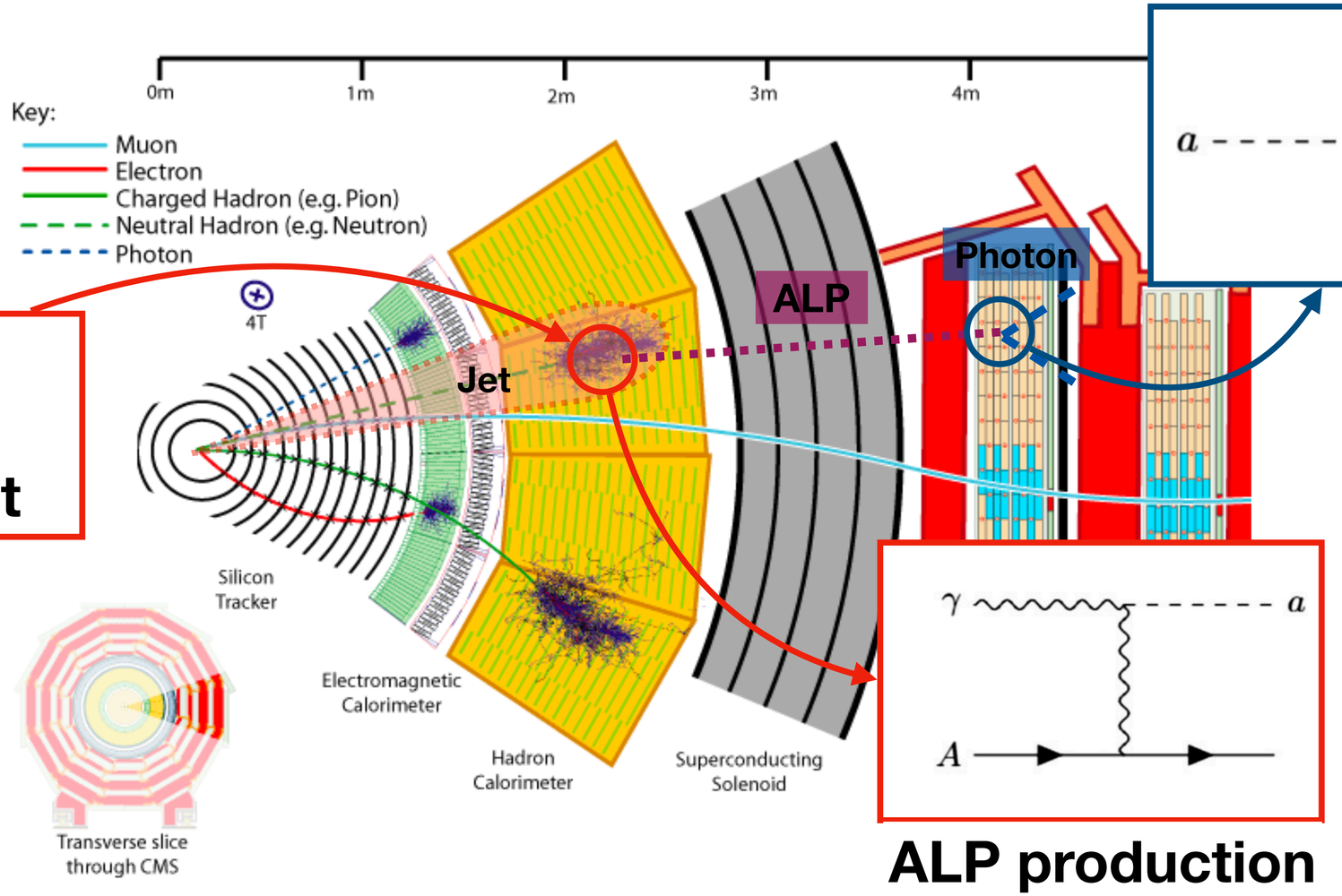


CMS Beam Dump

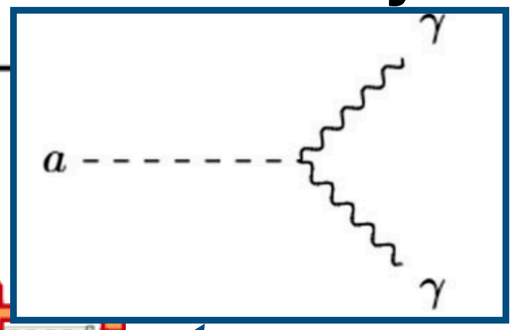
- 14 TeV collision
- **Energetic photons → high boost factor**
- The total production of photons is enormous
- **Short distance detector ~ 1 m**
- 4 π coverage detector
- **Cover other parameter space!**

Primakoff Process

Secondary particles of particles in a jet

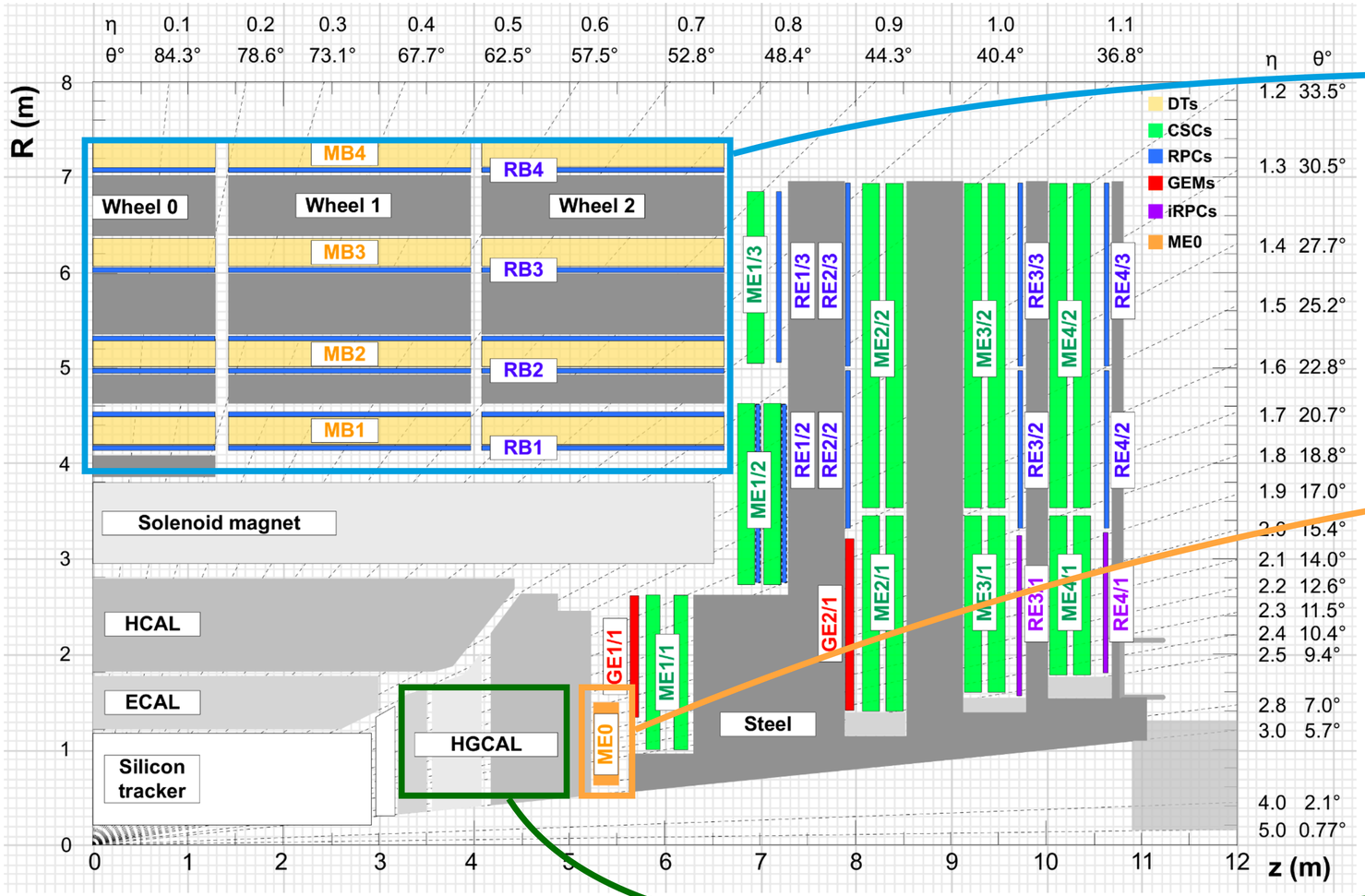


ALP decay

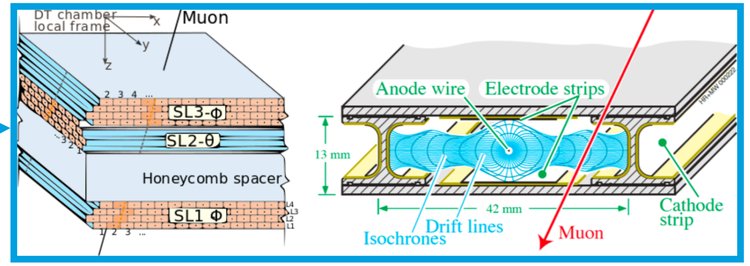


ALP production via Primakoff process

CMS Beam Dump Detectors

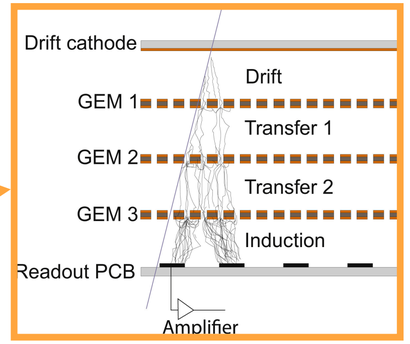


DT



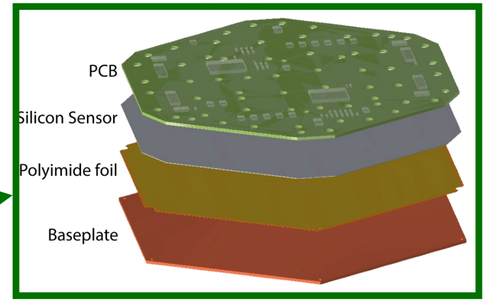
Detector distance: 2—8 m

ME0



Detector distance: 0.5—2 m

HGCAL

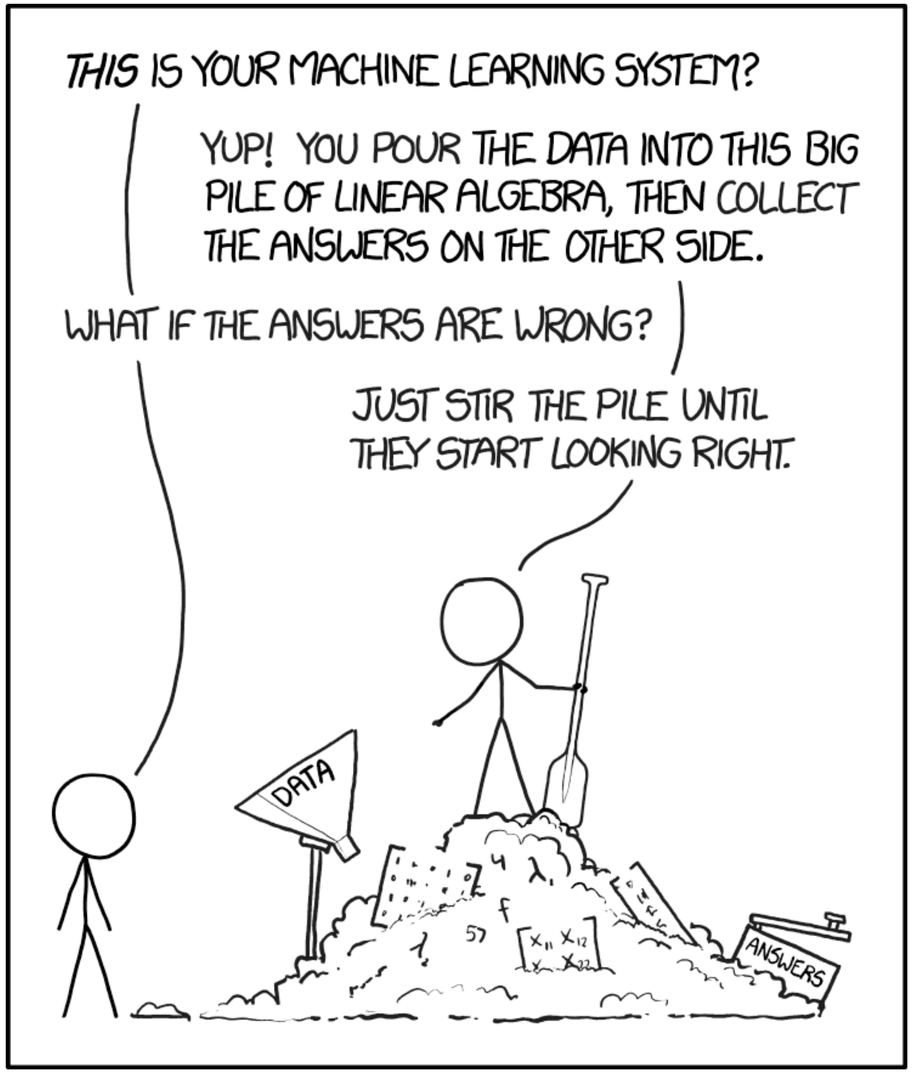


Detector distance: 0—2 m

Challenges

- **Signal simulation**
  - How to implement the new concept of physics process in the calorimeter and muon system simulation
- **Background**
  - How to distinguish the background, e.g., neutron gas, $K_S^0 \to \pi^0\pi^0$
- **Photon detection/reconstruction with muon chambers**
  - Geant4 and Garfield simulation
  - Photon signal efficiency
- **Trigger**
  - How to make dedicated triggers

Machine Learning in HEP



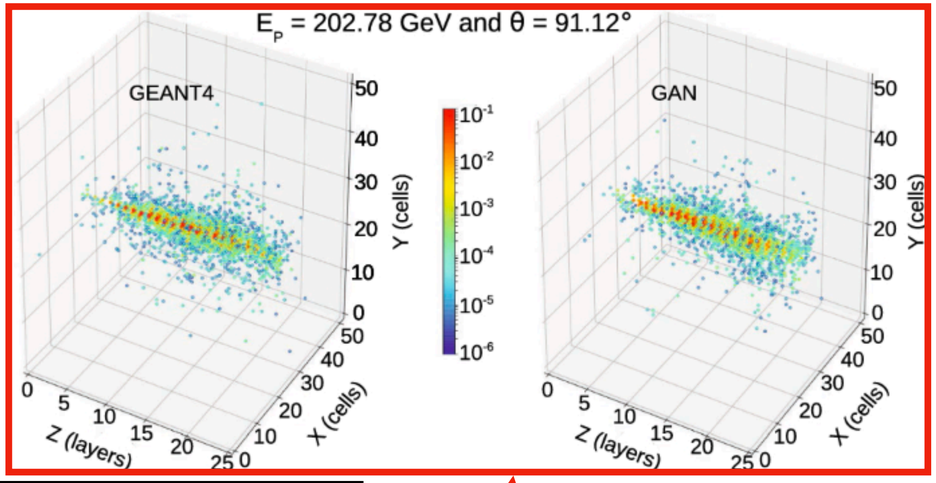
- Event Classification
- Trigger Systems
- Particle Identification
- Detector Optimization
- Data Analysis
- Simulation

Signal Simulation

- Signal simulation is important
  - To understand the signal feature
  - Reconstruction efficiency
  - To design the triggers
- Regular simulation chain
  - Collision event generator → detector simulation → reconstruction

Input any new physics models

Common configuration part



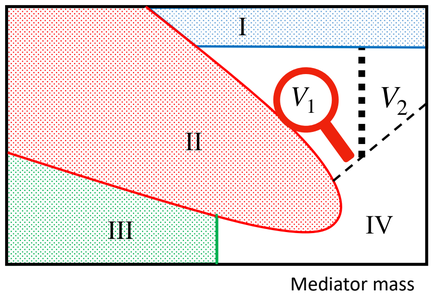
DMG4?

Generative Adversarial Network (GAN) ?

- **CMS beam dump simulation chain**
  - Collision event generator → detector simulation → reconstruction

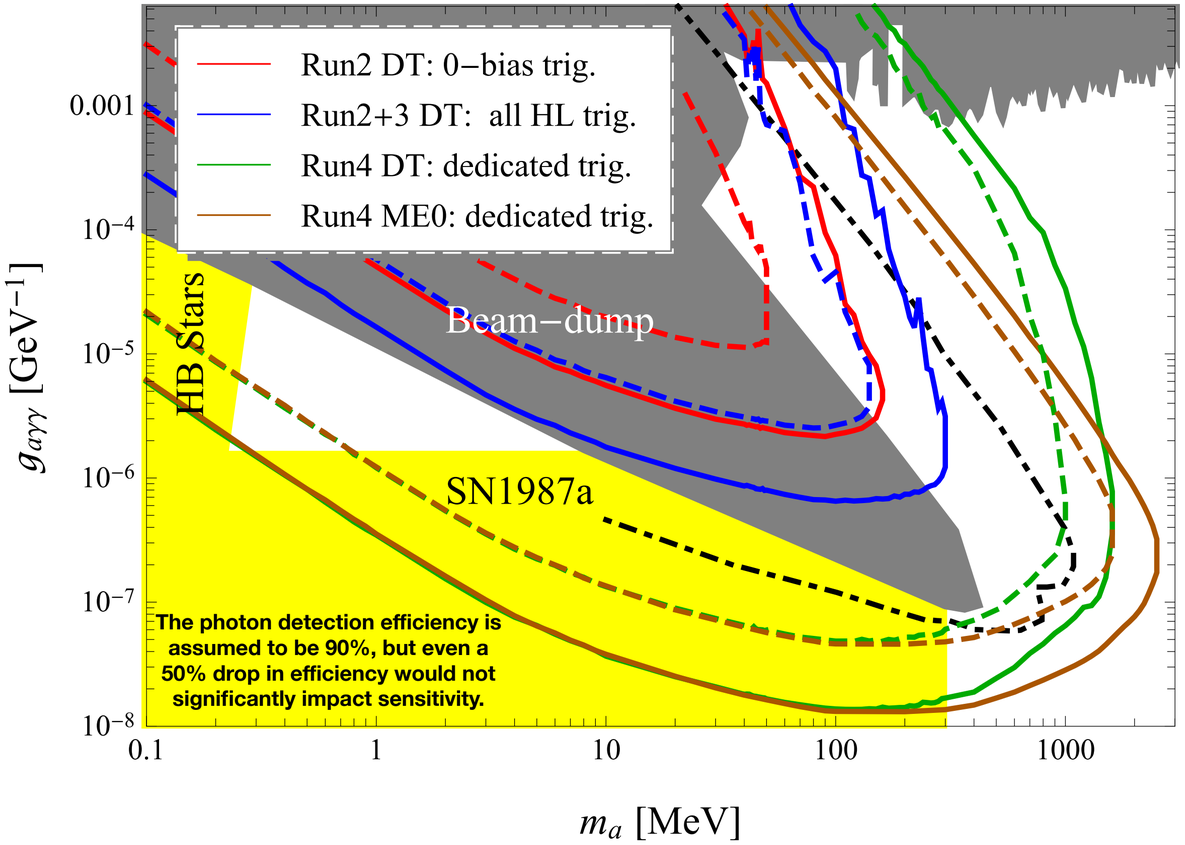
ALP Primakoff process and decay

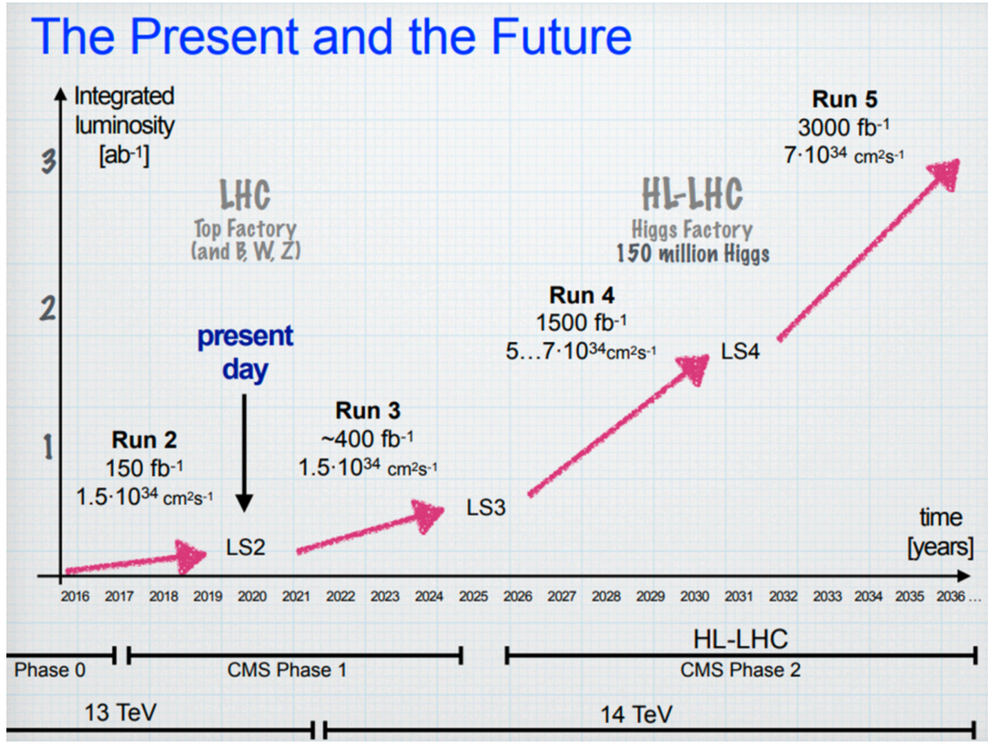
Photon reconstruction in muon chambers



Expected Sensitivity

Expected 90% CL limits [Dutta, Kim, **HK**, arXiv:2305.16383, PLB (2025)]



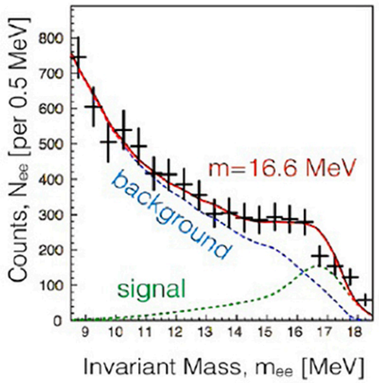


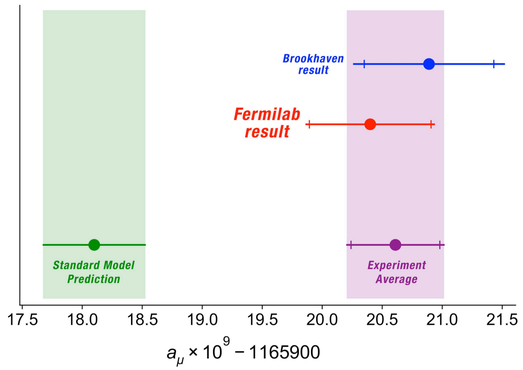
CMS beam dump has not yet reached the beam dump ceiling, despite covering unexplored large parameter space.

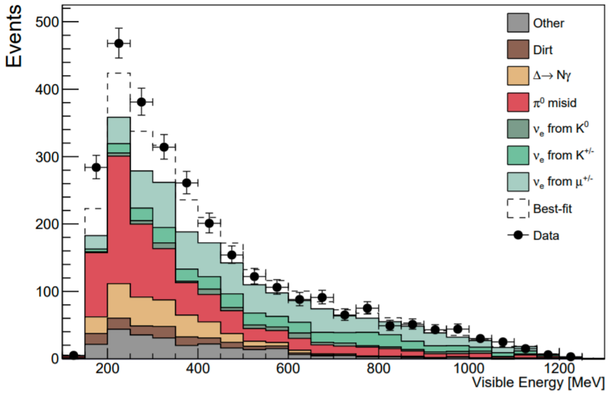
Other Models

Background:

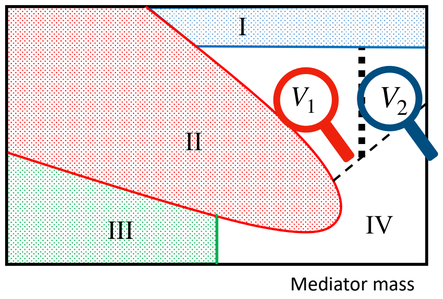
- **Dark sector**
- **Anomalies: ATOMKI, muon g-2, and MiniBooNE excess**



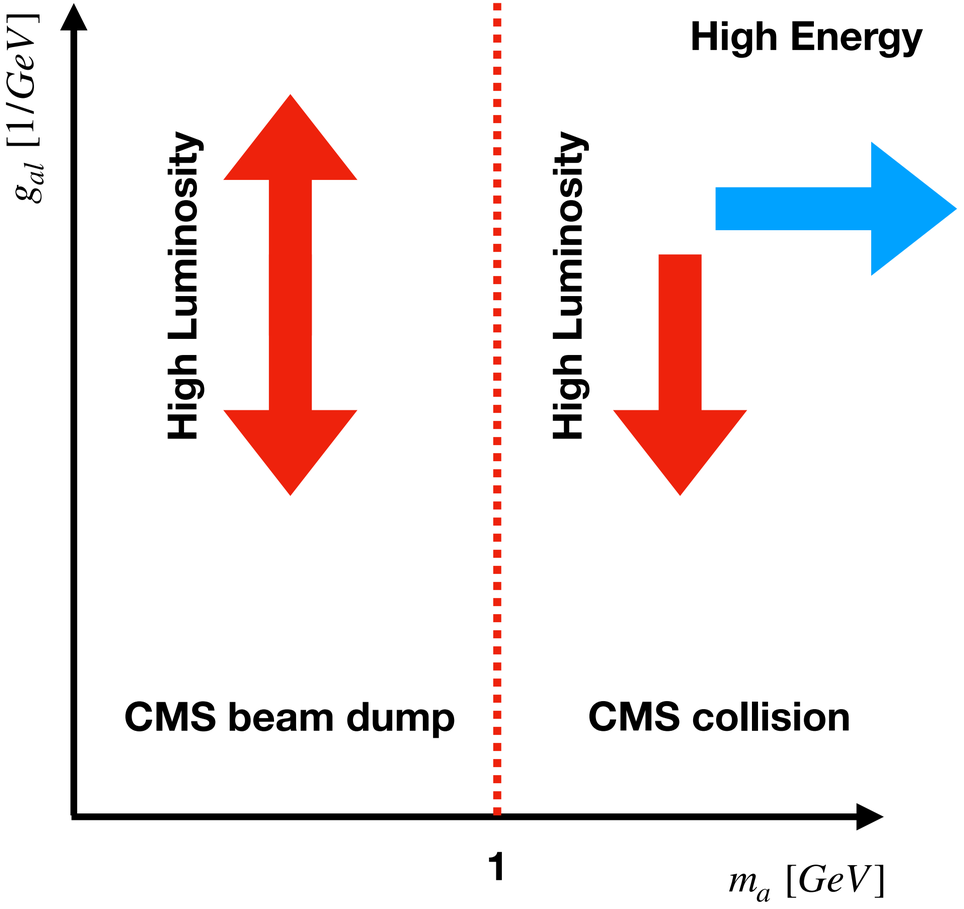


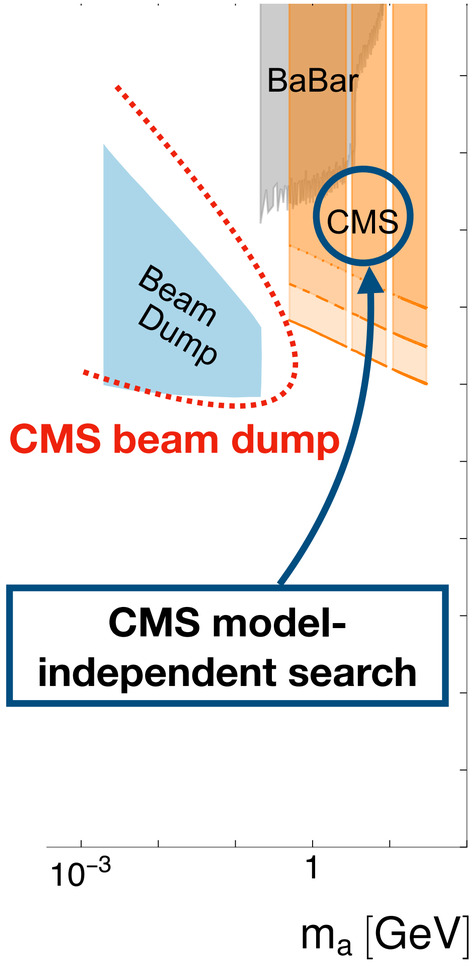


ALP mediators can be coupled to leptons, enabling the exploration of additional models, such as final states involving electrons and muons.

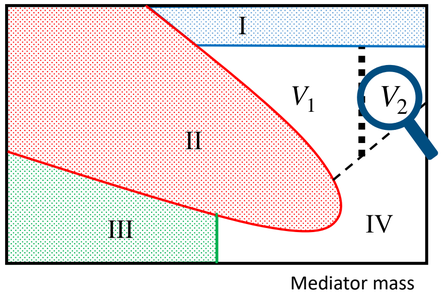


ALP Lepton Channel

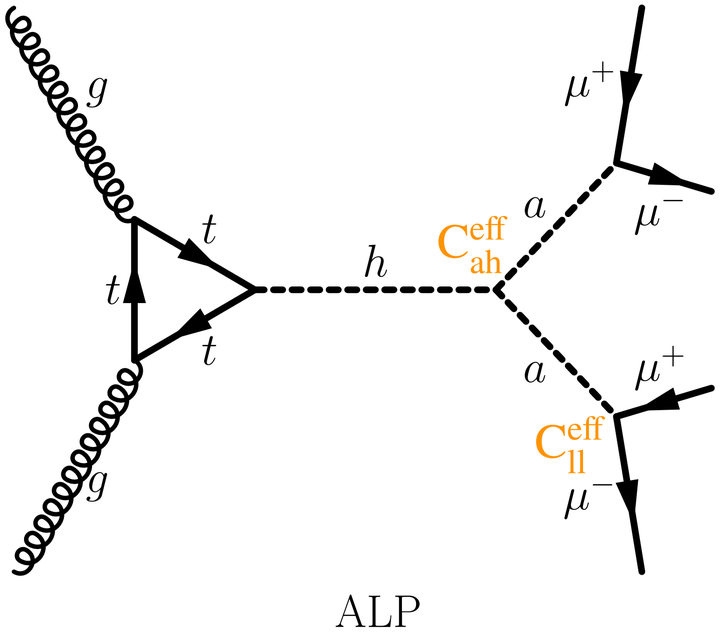




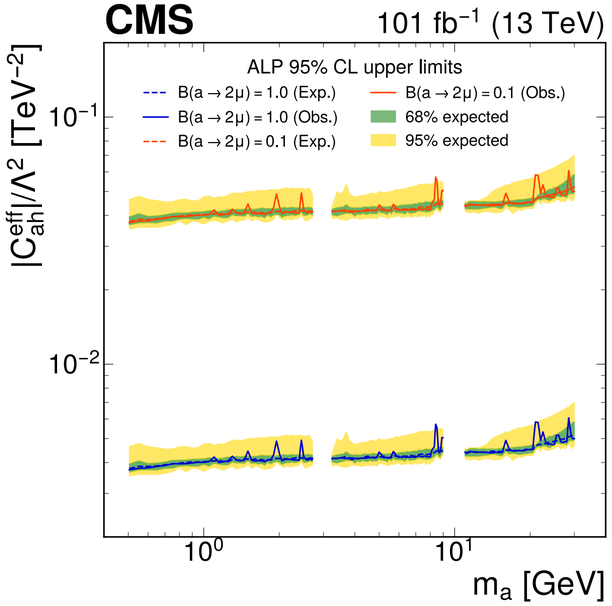
CMS beam dump and collision searches cover a large parameter space from the MeV-scale to the GeV-scale.

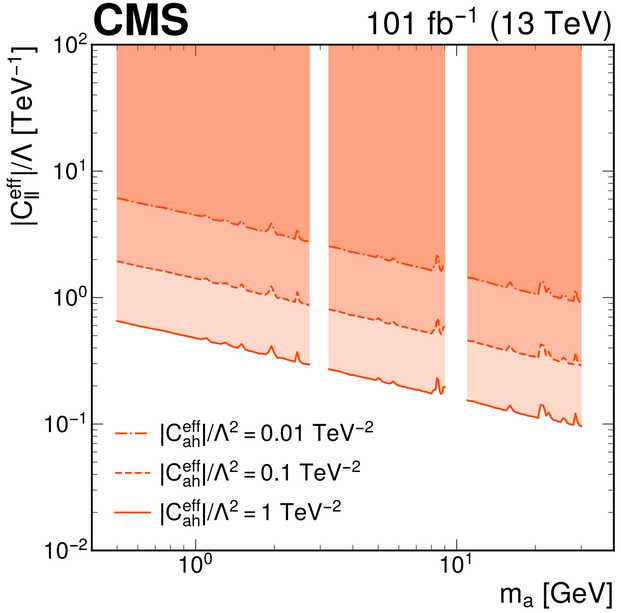


ALP in CMS Collision



ALP



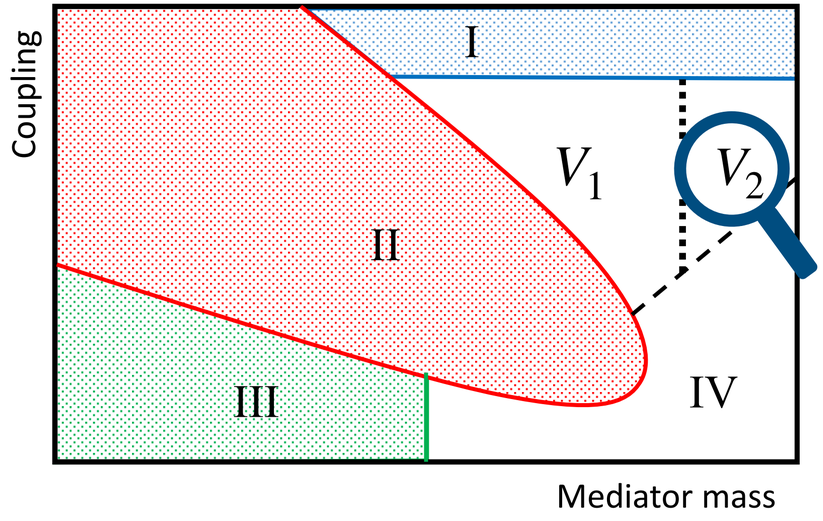


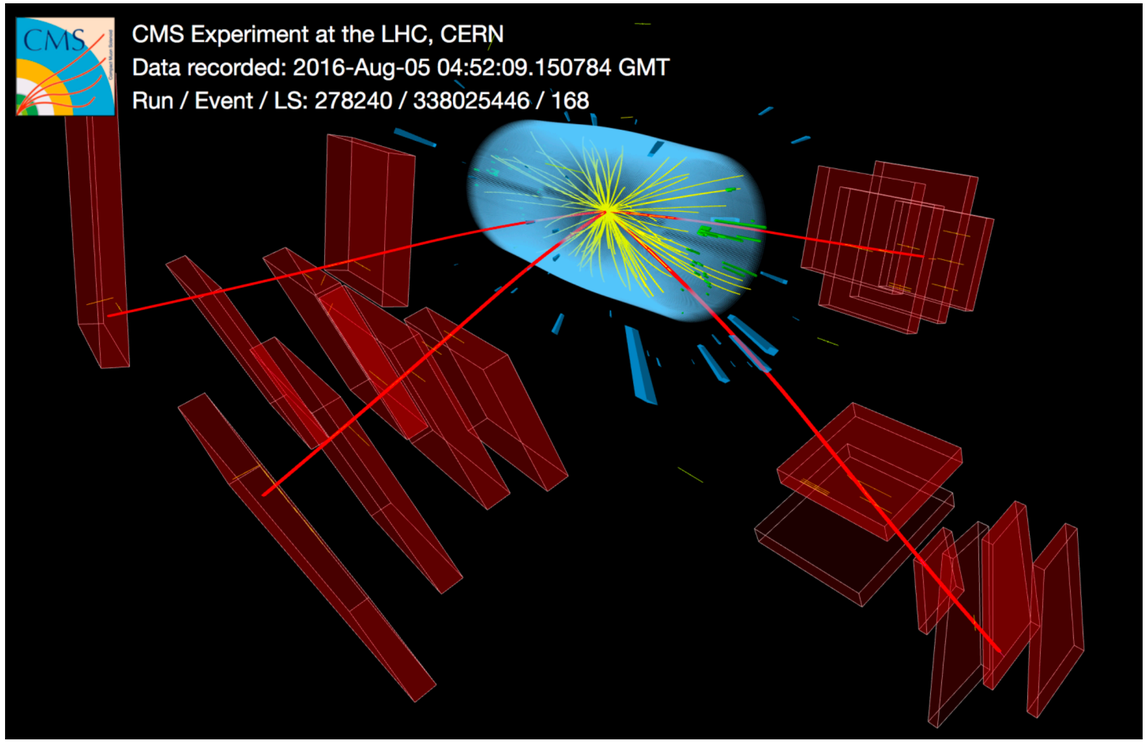
- Λ: new physics scale (1 TeV)
- C_{ll}^{eff}: coupling of the ALP to leptons, effective Wilson coefficient
- C_{ah}^{eff}: coupling of the SM-like Higgs to the ALP, effective Wilson coefficient

The CMS model-independent search results can be interpreted as the ALP model through the Higgs portal.

Dark Sector Research at CMS

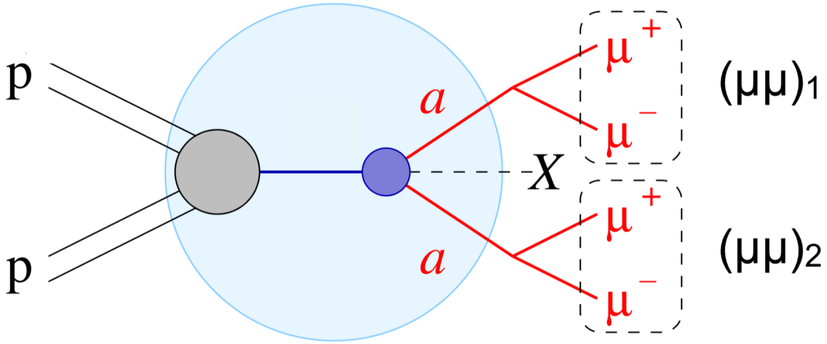
- **The LHC is a Higgs factory**
- Higgs portal
  - A simple extension of the Standard Model
- Energy frontier experiment
- HL-LHC → increasing statistics

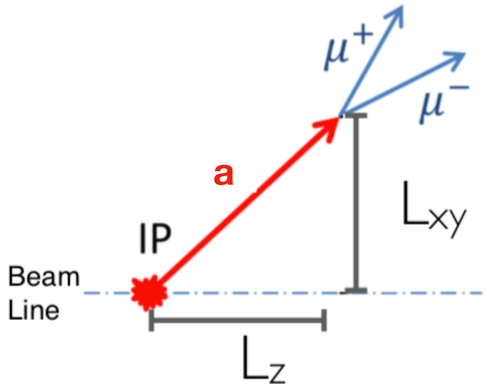




Model-Independent Search

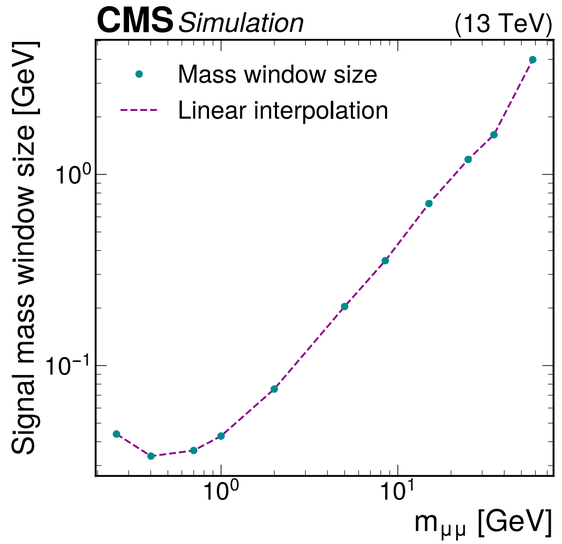
- Model-independent search uses the four-muon final state
- Prompt or long-lived two particles decay to two dimuon pairs
  - The identical invariant mass for each dimuon pairs
- **The result can be interpreted in many models with similar signature**
  - Three Higgs portal and one Vector portal benchmarking models (4 in 1 analysis)
- Large mass coverage 0.21—60 GeV and $c\tau$ < 100 mm

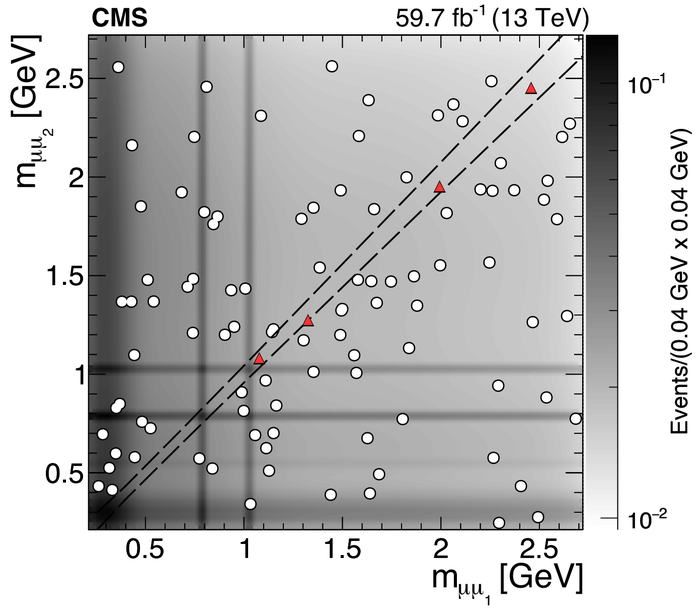




Analysis Strategy

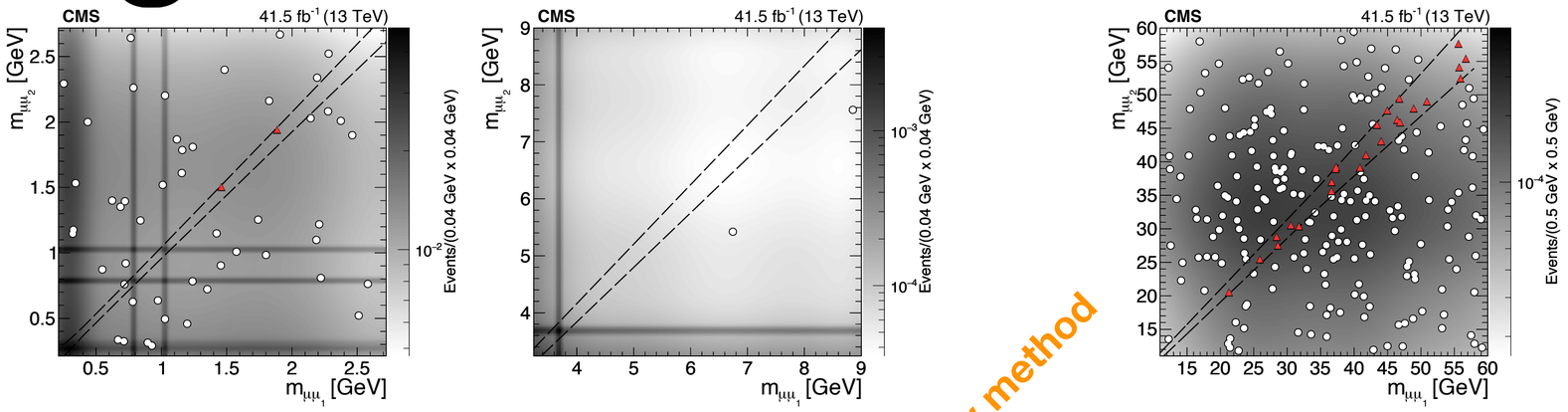
- Get a 2D background PDF of $m_{\mu\mu 1}$ and $m_{\mu\mu 2}$ from the signal-like events (three-muon events)
- Integrated the PDF of the signal region (SR) and control region (CR)
- $$\frac{I_{SR}}{I_{CR}} \times N_{CR} = N_B$$
- Calculate the model independent limit then the result is interpreted in each benchmark model





Background Estimation

2017 Dataset



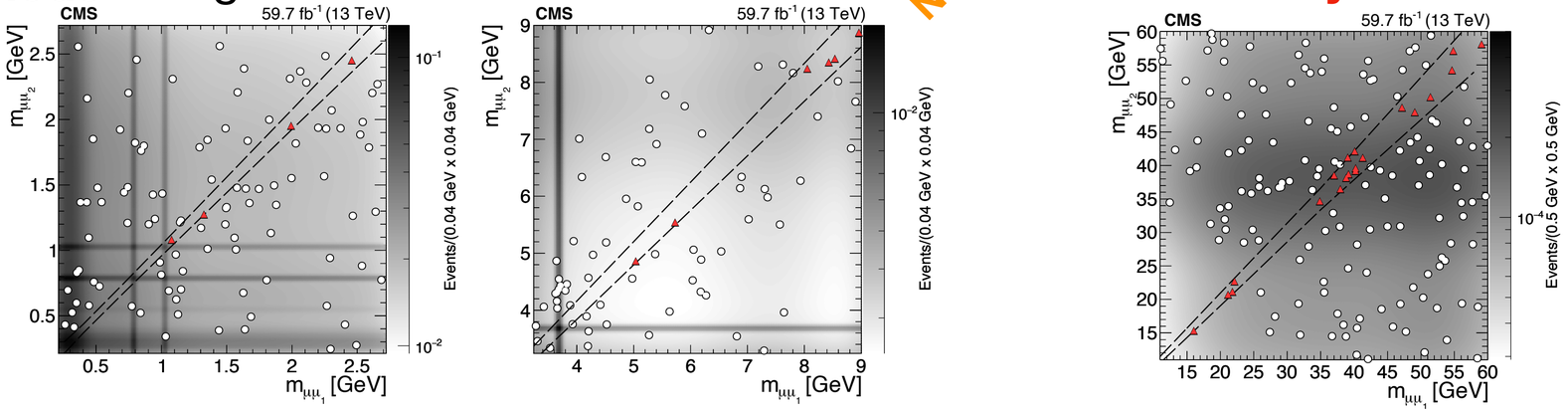
BKG Estimation PDF methods

Signal-like three muon events

New method

Kernel Density Estimation (KDE)

2018 Dataset

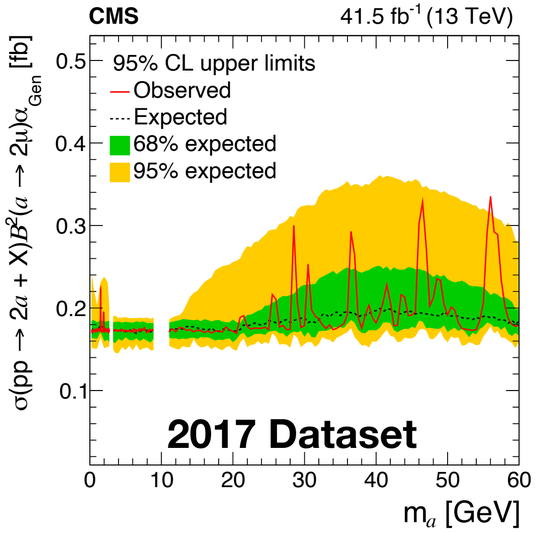


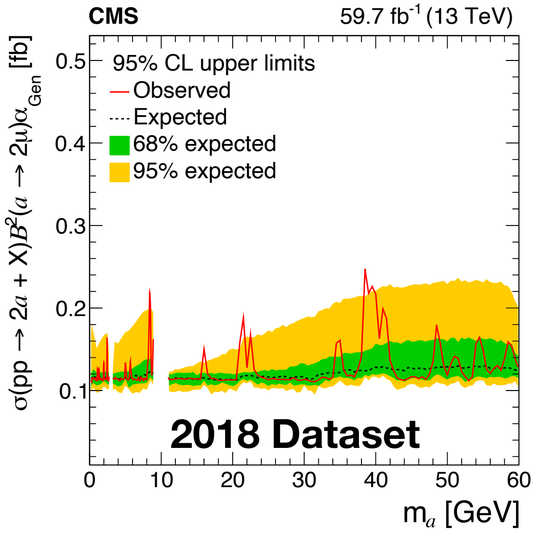
Expected BKG events and Observed events in SR

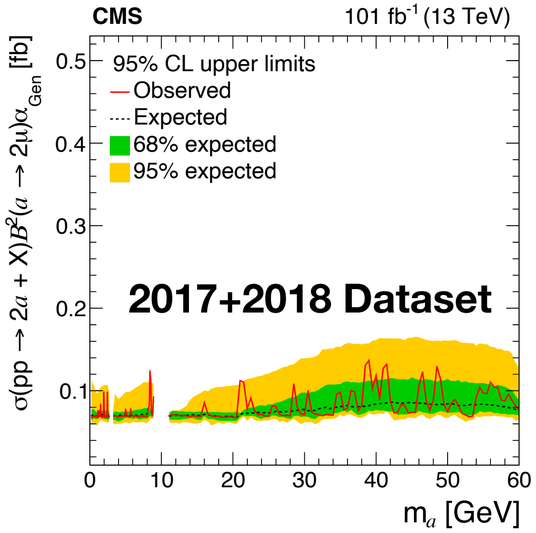
Region	Quantity	Year 2017	2018
Below J/ψ	Exp. events in SR	$2.62 \pm 0.32\,(\text{stat}) \pm 0.14\,(\text{syst})$	$4.34 \pm 0.44\,(\text{stat}) \pm 0.18\,(\text{syst})$
	Obs. events in SR	2	4
Above J/ψ, Below Υ	Exp. events in SR	$0.19 \pm 0.14\,(\text{stat}) \pm 0.01\,(\text{syst})$	$6.16 \pm 0.76\,(\text{stat}) \pm 0.09\,(\text{syst})$
	Obs. events in SR	0	6
Above Υ	Exp. events in SR	$18.10 \pm 1.23\,(\text{stat}) \pm 4.49\,(\text{syst})$	$13.81 \pm 1.16\,(\text{stat}) \pm 5.39\,(\text{syst})$
	Obs. events in SR	24	20

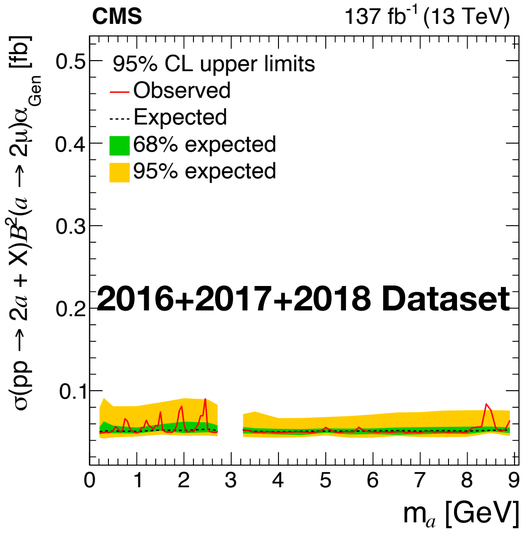
95% CL Upper Limits

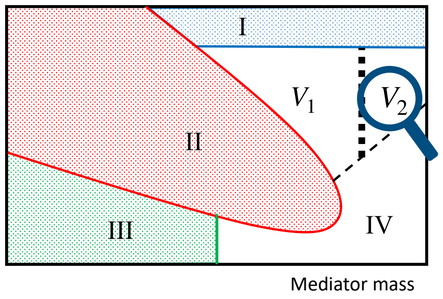
- **The 2017 dataset** includes only prompt events
- **The 2018 dataset** includes both prompt and long-lived events
- **The 2017+2018 dataset** is interpreted using only the prompt signal
- **The 2016+2017+2018** dataset is analyzed up to 9 GeV and is interpreted using only the prompt signal





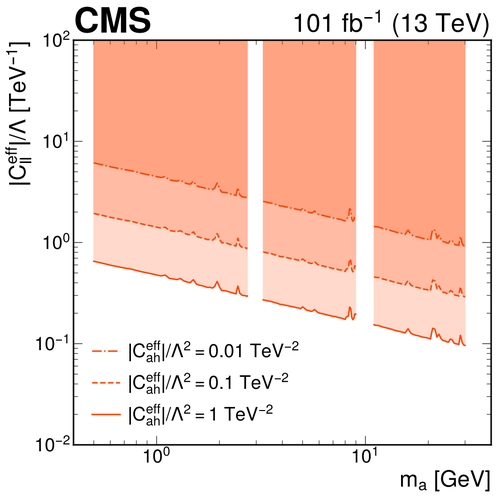


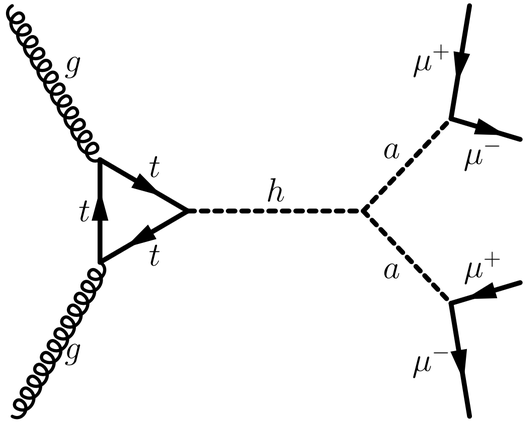


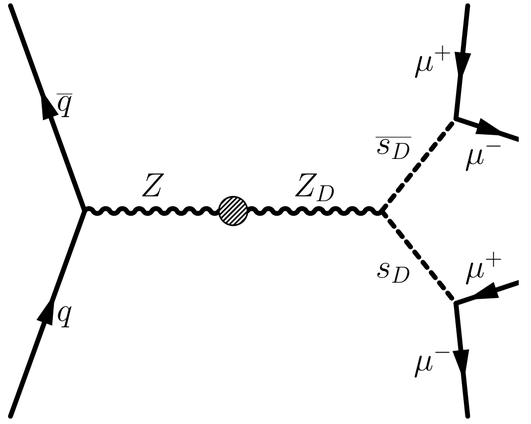


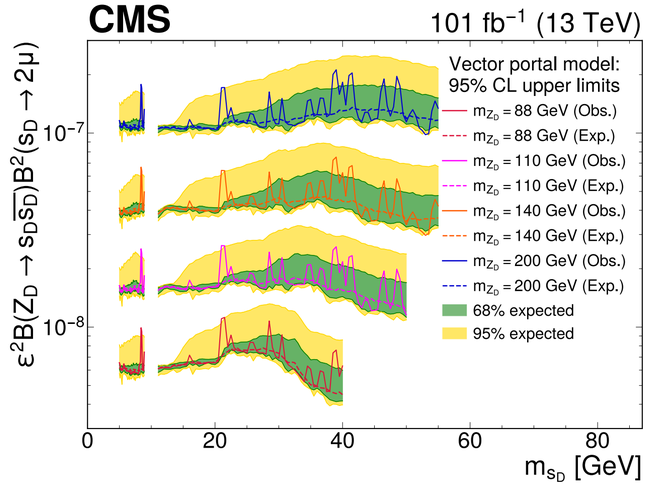
Benchmark Models

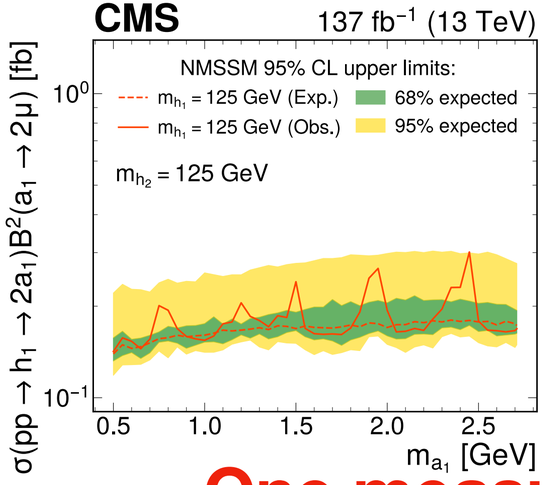
[CMS Collaboration, arXiv:2407.20425, JHEP (2024)]

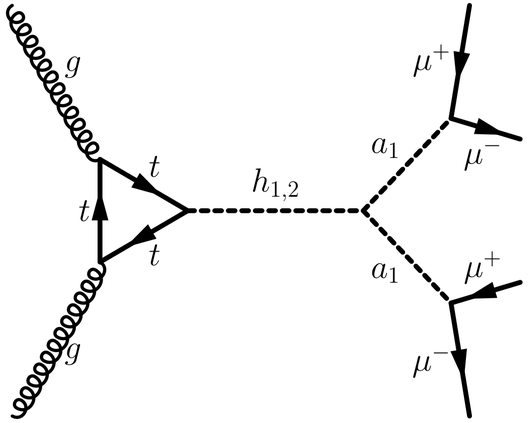


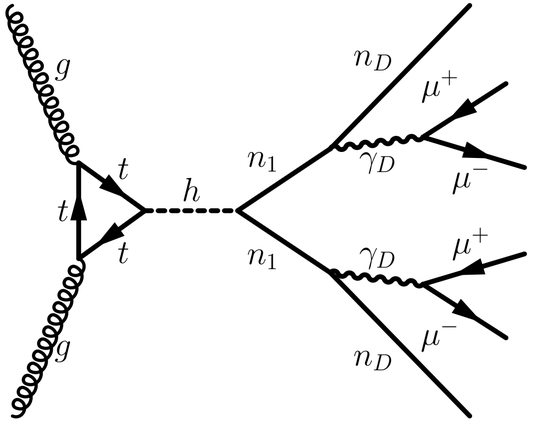


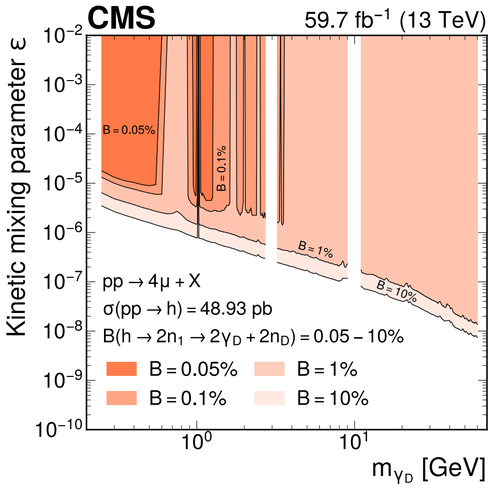




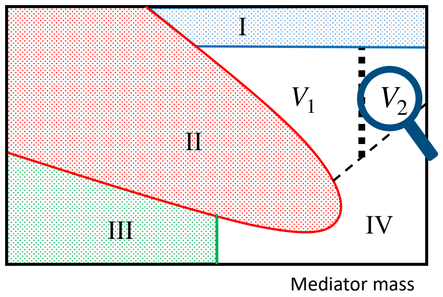






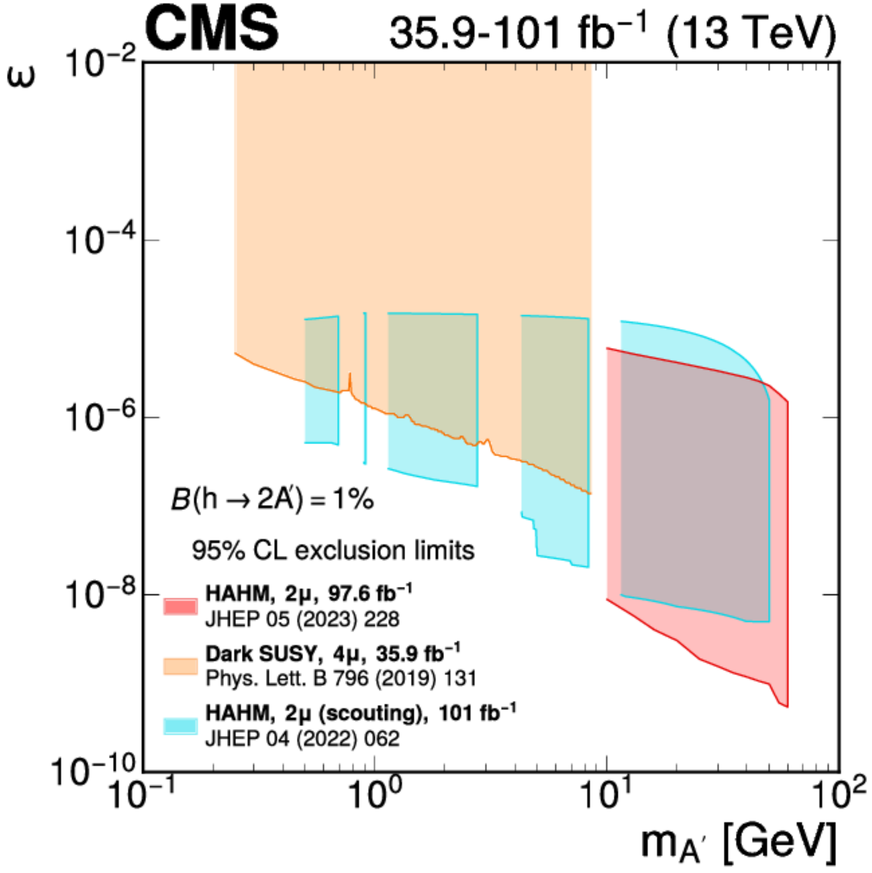


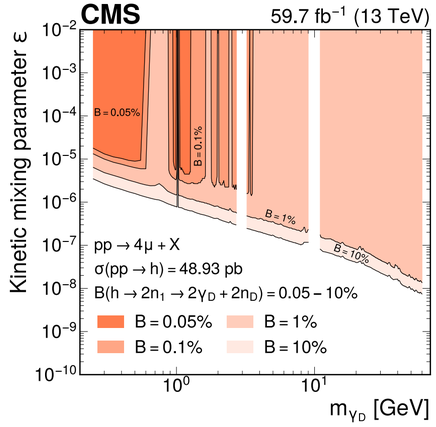
One measurement sets the limit for four models simultaneously.



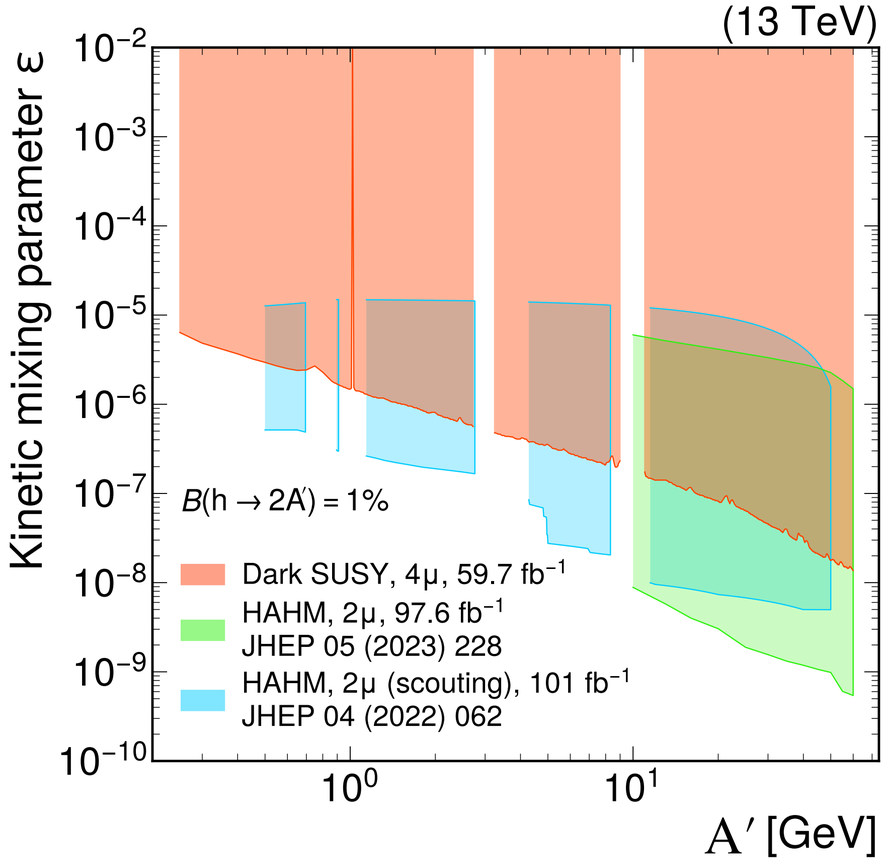
Dark Photon

[CMS Collaboration, arXiv:2405.13778, Physics Reports (2025)]

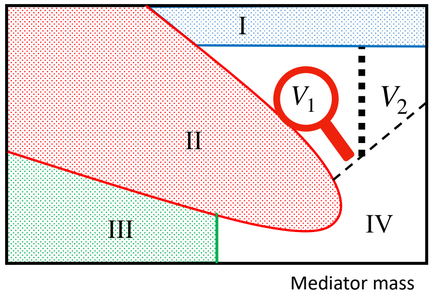




Update with 59.7 fb^{-1} result

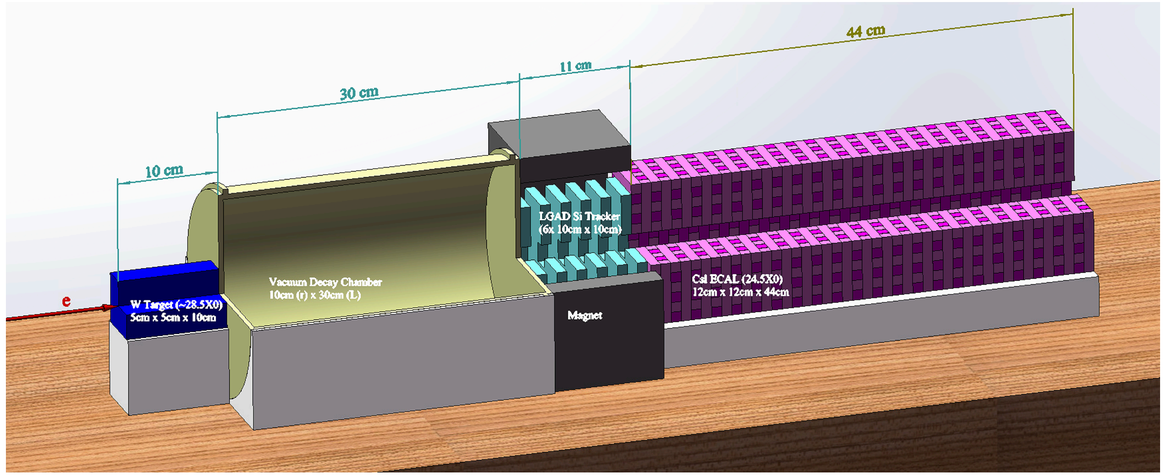


Smaller ε = Longer $c\tau$



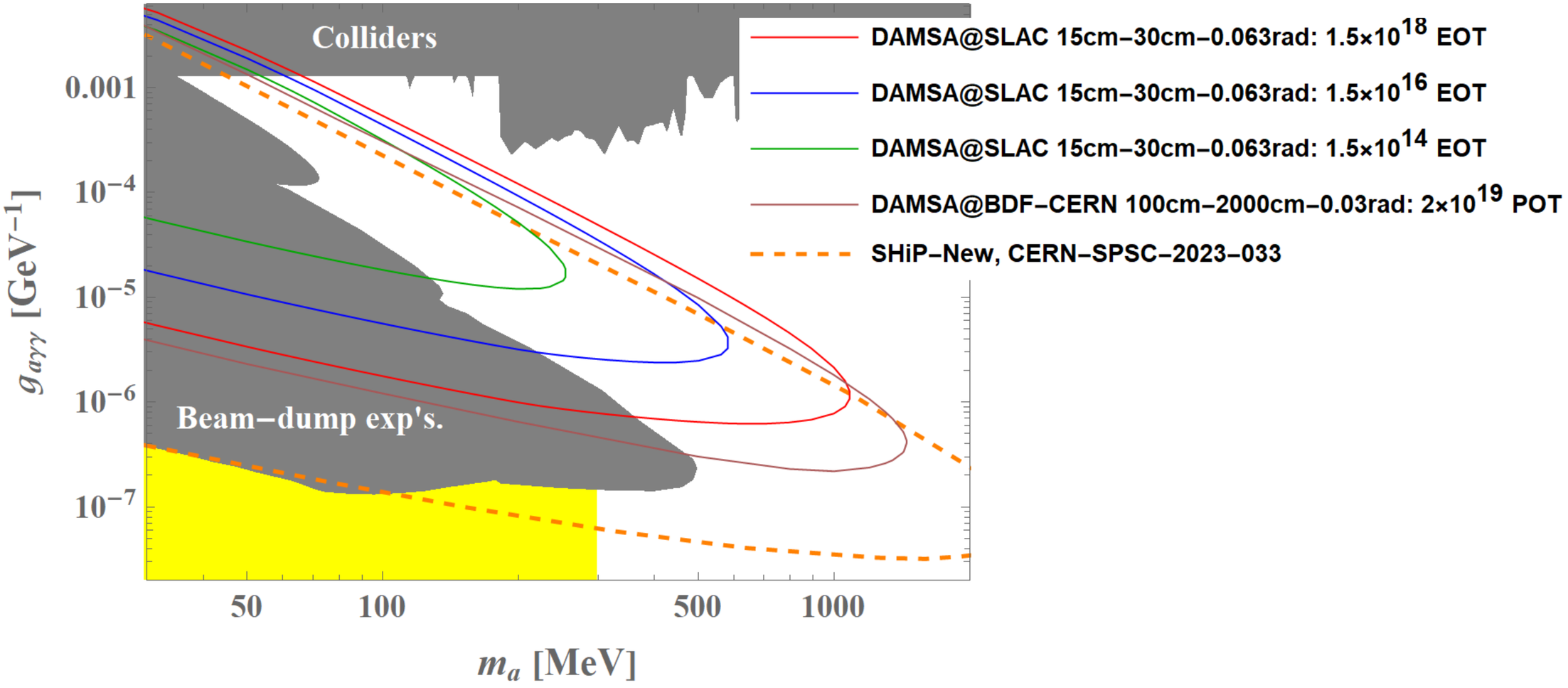
DAMSA Experiment

- What is **DAMSA**?
  - Stands for **DA**rk **M**essenger **S**earches at an **A**ccelerator (DAMSA)
  - 담사 (潭思) = 깊은생각 – Rumination or Reflection
  - **DAMSA is a unique dark sector search using high-intensity beams at a super-short baseline (~0.5 m) and short target length**
  - **This challenging approach sets it apart from other beam dump experiments**
- Aims to explore the dark sector break through the beam dump ceiling with a **portable detector**
- The 800 MeV PIP-II and the ACE beams at Fermilab fit the bill
- DAMSA can be at any accelerator facility, including CERN

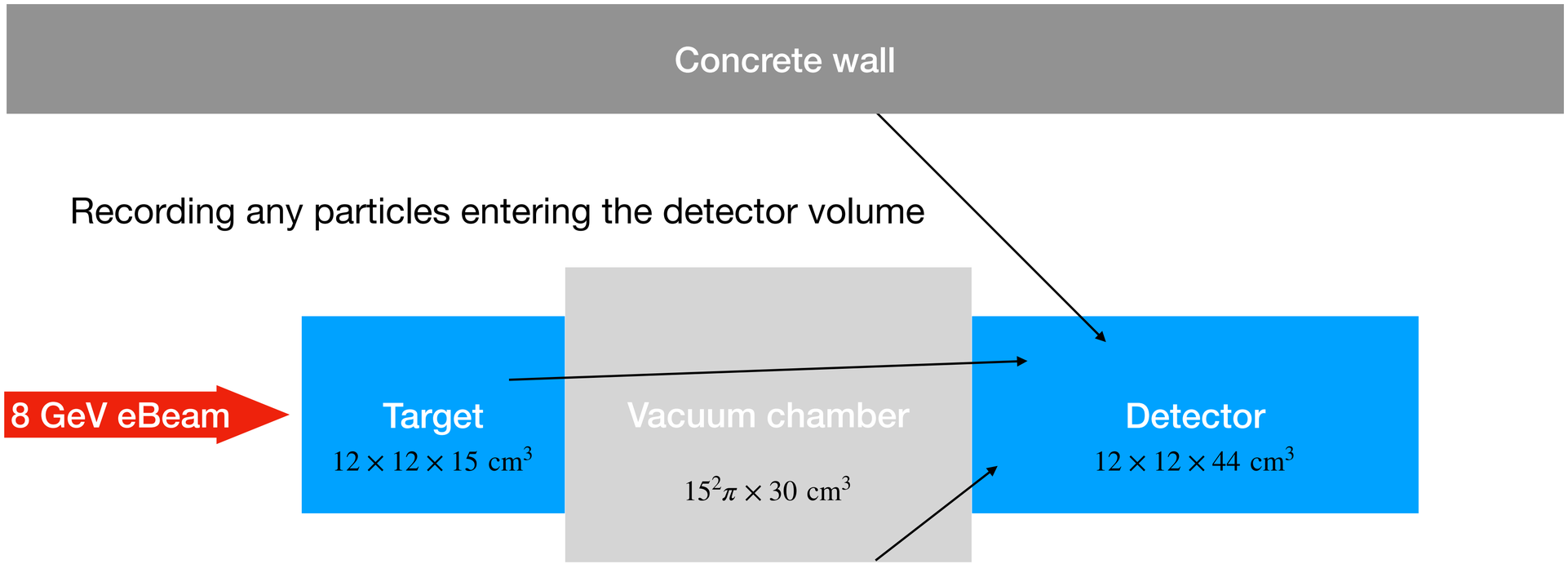


8 GeV Electron Beam

E_{beam} = 8 GeV, E_{cut} = 0.5 GeV, θ_{cut} = 1 Deg.

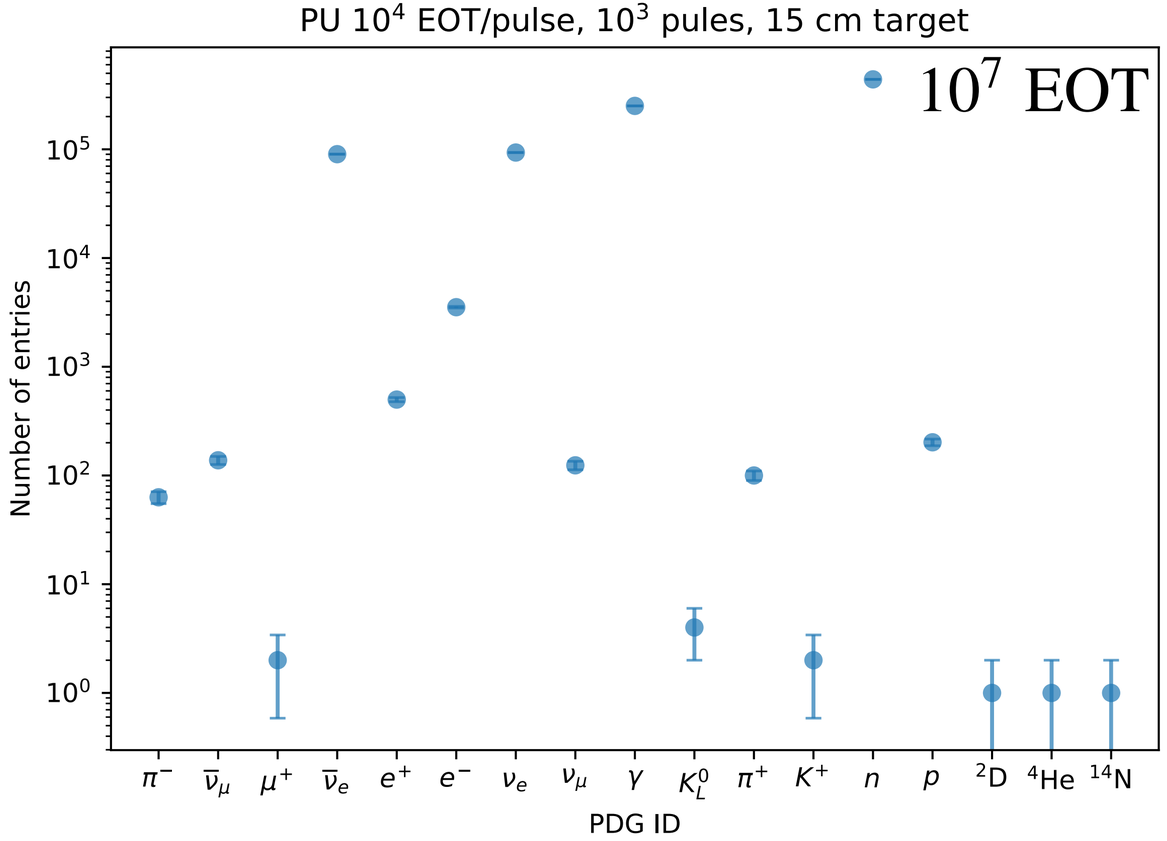


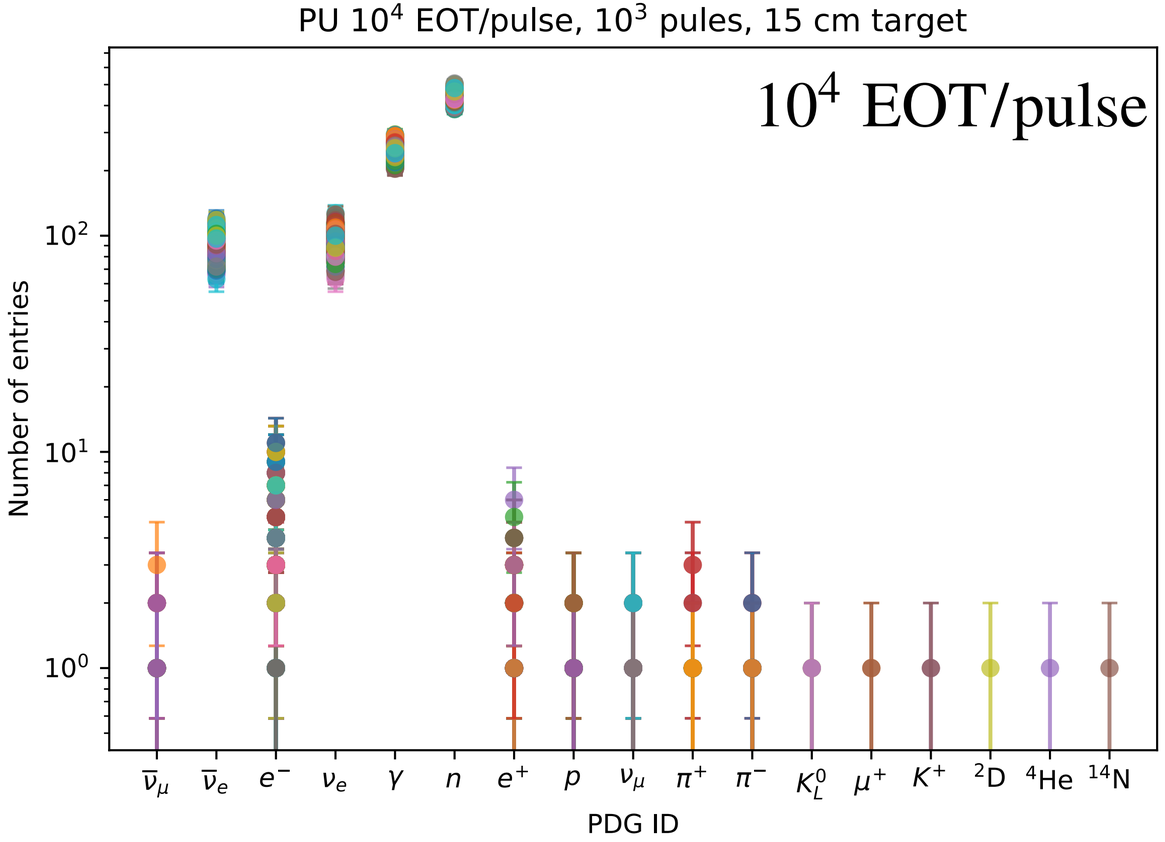
Geometry



Not-to-scale

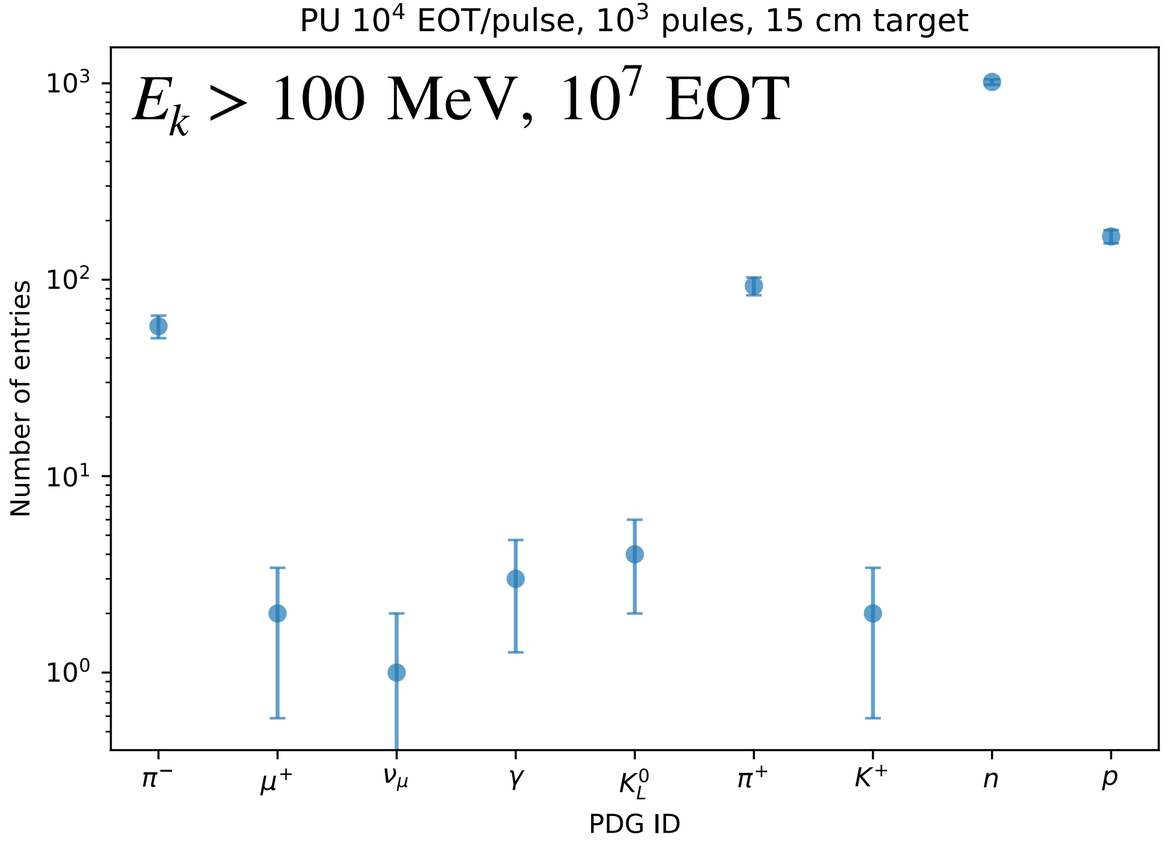
All Pile-Up Particles

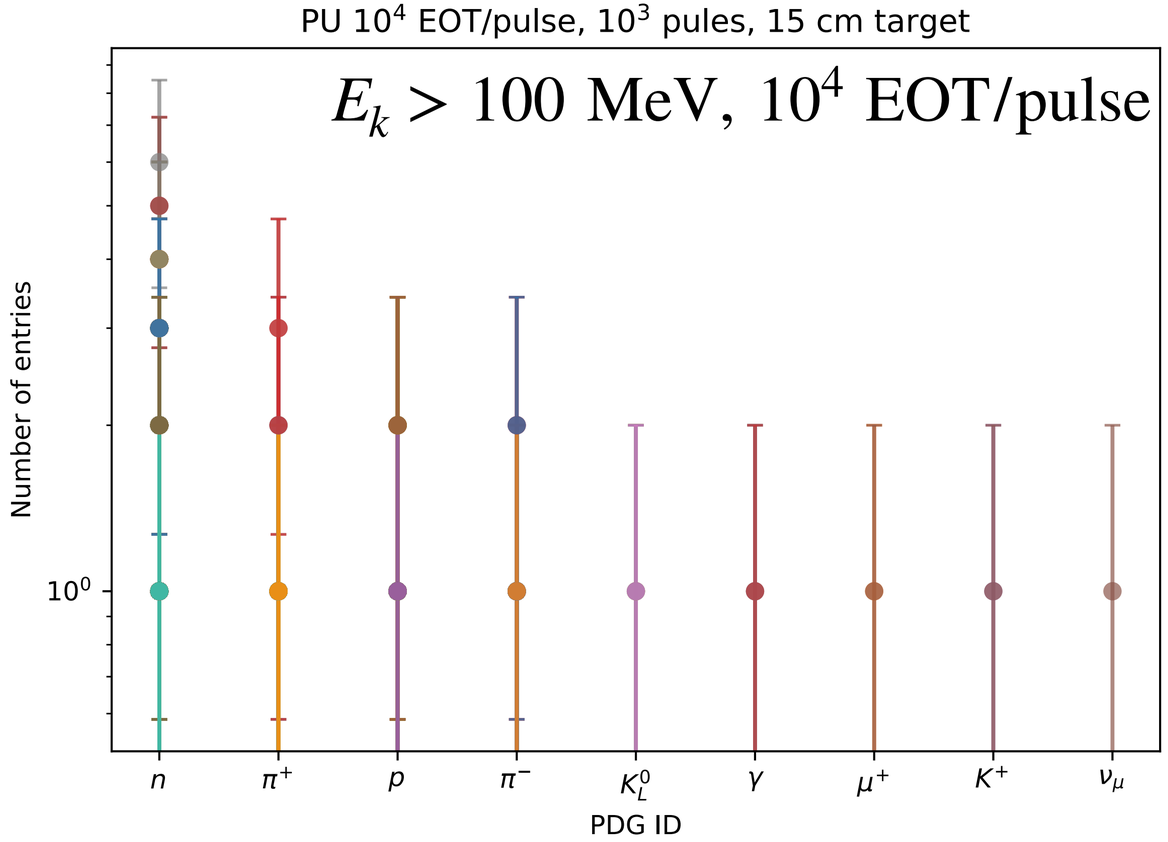




All pile-up particles entering the detector volume, categorized by particle ID. Total counts (left) and counts per pulse (right).

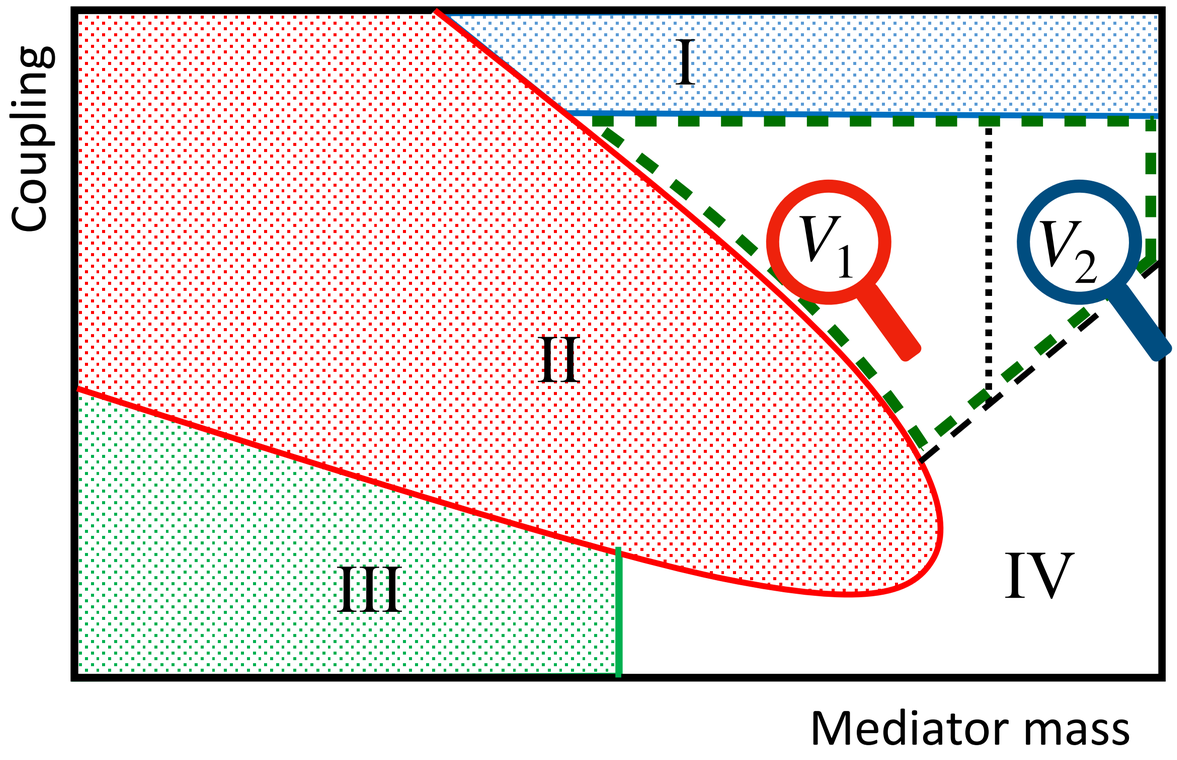
100 MeV Cut


PU 10^4 EOT/pulse, 10^3 pules, 15 cm target
$E_k > 100$ MeV, 10^7 EOT
Number of entries
10^3
10^2
10^1
10^0
π^- μ^+ ν_μ γ K_L^0 π^+ K^+ n p
PDG ID


PU 10^4 EOT/pulse, 10^3 pules, 15 cm target
$E_k > 100$ MeV, 10^4 EOT/pulse
Number of entries
10^0
n π^+ p π^- K_L^0 γ μ^+ K^+ ν_μ
PDG ID

Summary

The **dark sector** is **feebly** coupled with the visible sector via a **portal** interaction.



Region V: The region of primary interest is the prompt-decay region, where we aim to expand our search

V_1 : MeV – scale

→ **CMS beam-dump experiment**

DAMSA experiment

V_2 : GeV – scale

→ **CMS model-independent search**