

# ALP searches in beam dumps

## with some focus on NA62

Babette Döbrich (CERN)

CERN, 22/05/17

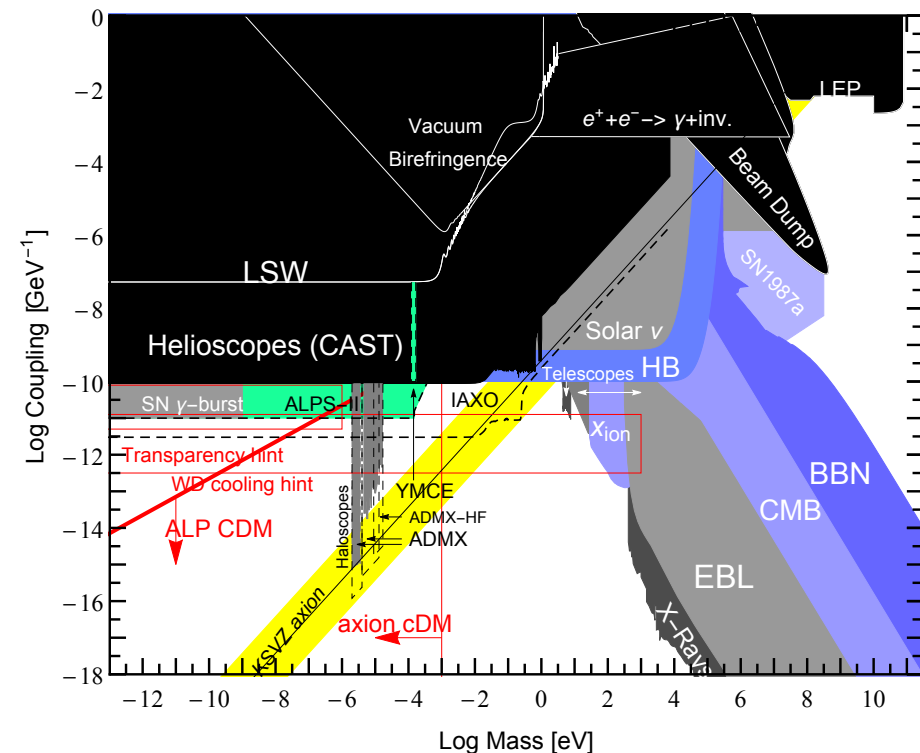
The screenshot displays a complex monitoring interface for the ALP search in beam dumps. It is divided into several panels:

- Trigger Flow:** Shows the flow of triggers through levels L0, L1, and L2. L0 has 25117 triggers from L0TP. L1 and L2 show 0 triggers in and out, with a 'REQUESTED' status. A 'Merger' section shows 0 in and 0 out.
- Primitives Count:** Lists various primitives and their counts: CHOD (6.53e+02), RICH (0.00e+00), LAV (3.68e+02), MUV (1.61e+04), NCHOD (7.32e+04), TALK (0.00e+00), LKr (5.00e+00).
- Exp. scalars:** Lists experimental scalars and their values: QX (0.00e+00), Q1-OR (0.00e+00), MUV1 OR MUV2 (0.00e+00), MUV3 (1.95e+03), NHOD (0.00e+00), IRC (0.00e+00), CHANTI (3.77e+02), ECN3\_008 (0.00e+00), ECN3\_009 (0.00e+00), ECN3\_010 (0.00e+00), ECN3\_011 (0.00e+00), ECN3\_012 (0.00e+00), ARGONION (1.30e+05).
- Beam Infos:** Shows 'Page1 comment' as 'End of North Area proton run' and 'Lead NA setting up'.
- Run Infos:** Displays run details: Run Type (Run\_2016\_AXION), Start Time (2016.11.14 03:22:17.735), End Time (2016.11.14 06:01:49.419), Beam Type, Shift crew (Biino; Dobrich;), StartRun Comment (Removed target, P42 TAX is 7.5/10, K12 TAX closed, took out GTK, mask0: Q2/1, mask1: Q1/5, Control: E>3 GeV/1), EndRun Comment (Stop the run END of 2016 DATA TAKING), RunNumber (6912), Burst # (340), and Burst State.
- Global TDAQ:** A central diagram showing the detector layout with components like MUV3, IRC, CHOD, RICH, LAV, STRAW, CHANTI, GTK, and KTAG. A penguin icon is also present.
- PCFarm:** A table showing the per burst sum for various detectors.

| Detector | MEPs/Producer | Lost | Choke/Errors |
|----------|---------------|------|--------------|
| LOTP     | 0             | 0    | 0            |
| KTAG     | 0             | 0    | 0            |
| CHANTI   | 0             | 0    | 0            |
| LAV      | 0             | 0    | 0            |
| STRAW    | 0             | 0    | 0            |
| RICH     | 0             | 0    | 0            |
| CHOD     | 0             | 0    | 0            |

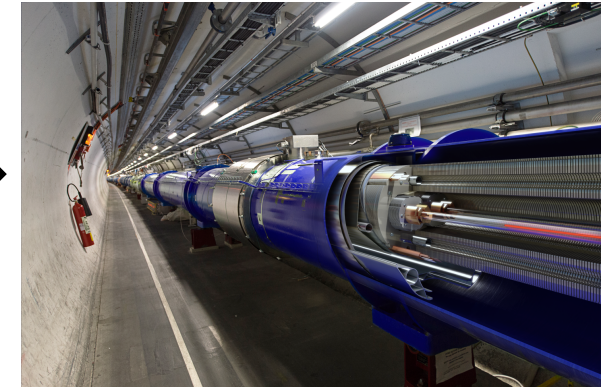
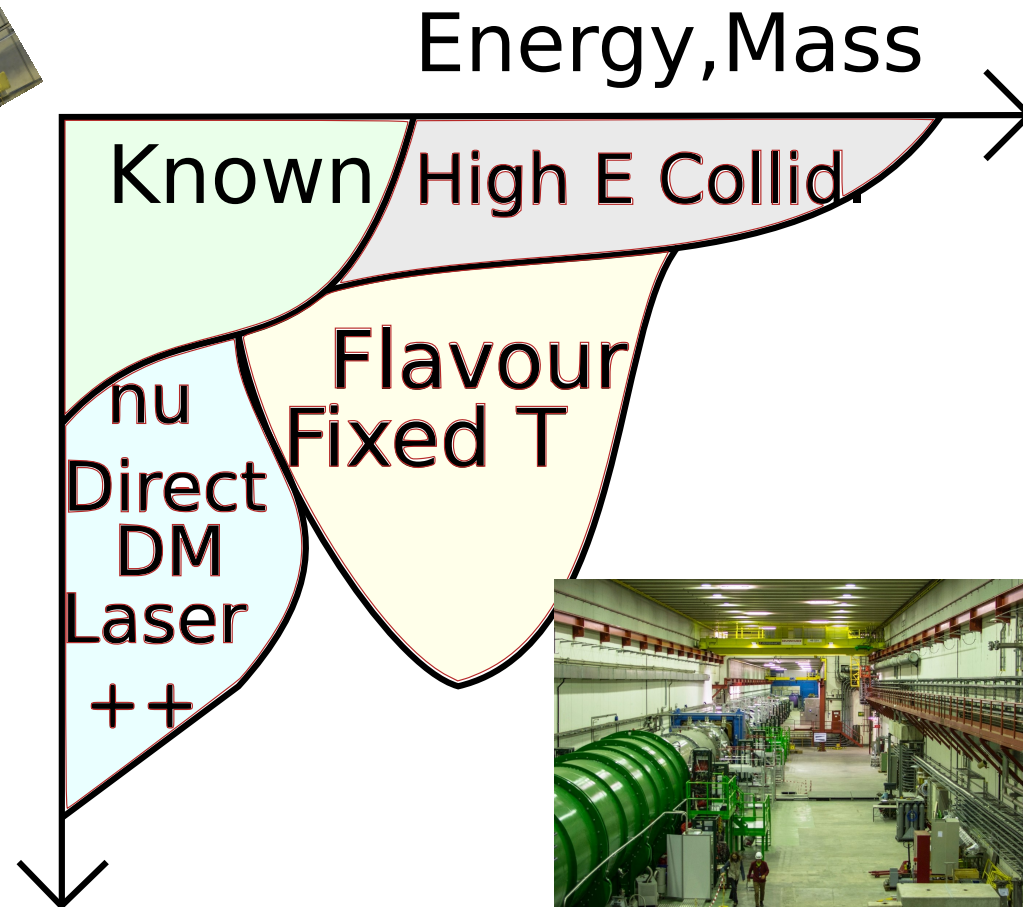
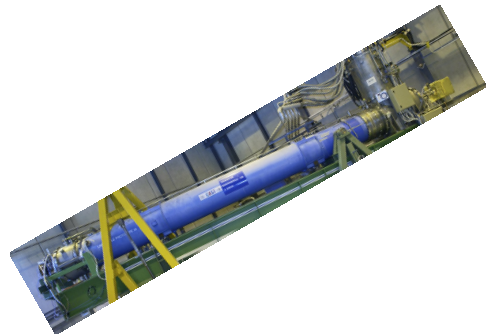
# Axions and Axion-like particle, a brief bestiary

- Axions as solution for strong CP problem in QCD
- may be cold Dark matter in certain parameter range
- relevant band t.b. covered by direct DM searches (e.g. cavities)
- Axion-like particle: pseudoscalar, not connected to CP, e.g. interesting as Dark Matter mediator (see later)
- often shown: two-photon coupling ↙



If you don't know where you're going...

.. any road may take you there [Lewis Carroll]

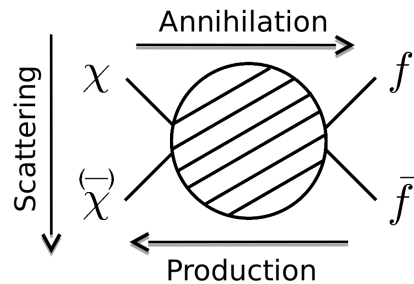


↑ high intensity **and** high energy  
MeV-GeV, weakly coupled

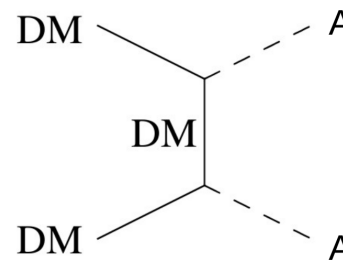
# Why MeV-GeV? Why Axion-like?

## Why MeV-GeV, very weakly coupled

- comparatively little explored, 'Hidden Sectors'
- compelling phenomenology as 'Dark Matter mediators'



thermal  
DM freeze out  
exp. constraints:



DM can annihilate to  
intermediate states  
then to SM

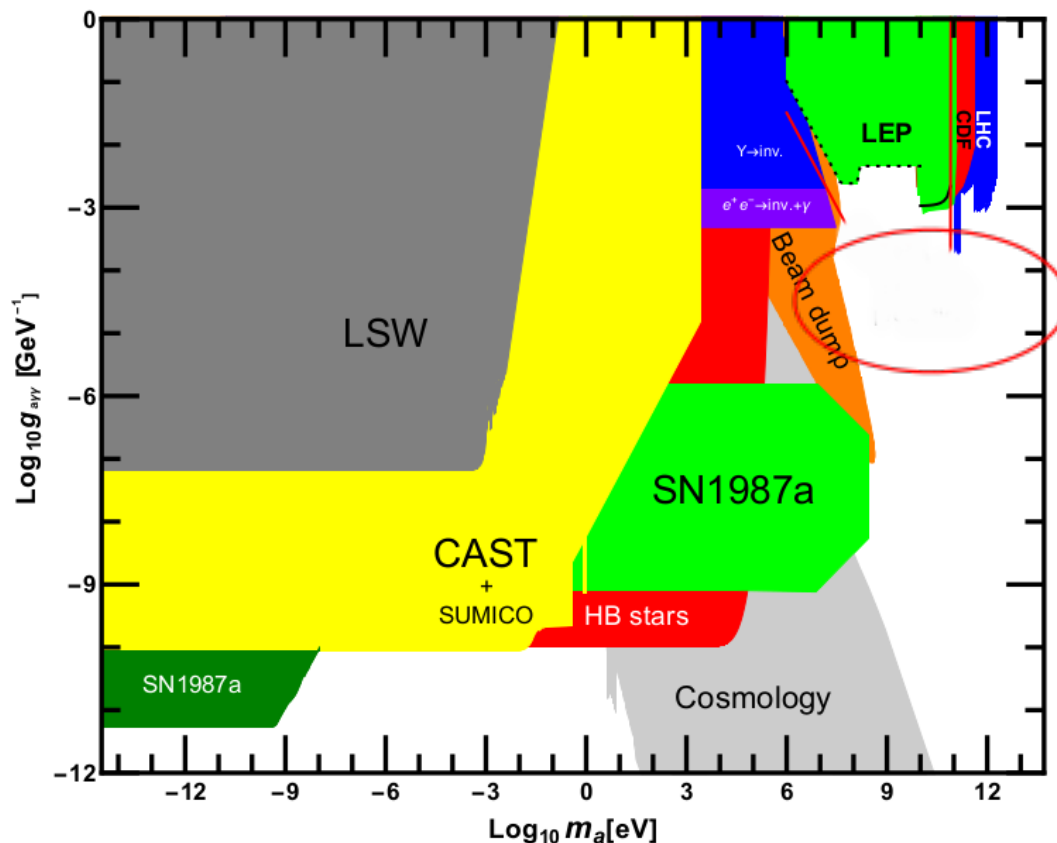
difficult to avoid overproduction (not enough decay)

## why pseudoscalar $\rightarrow$ th + pheno

- 1) fundamental scalar exists 2) natural in Higgs-sector extensions (Two Higgs doublet) 3) Nambu-Goldstone boson (axion)
- DM mediator coupling through spin, not mass [Freytsis & Ligeti, arXiv:1012.5317]
- heavy QCD axion e.g. JHEP 0410 (2004)

# Heavy ALP parameter space

- mediator idea allows: **Pseudoscalar (Axion-like)**, Vector (Dark Photon), Scalar (Higgs-like), Neutrino (sterile Neutrinos)
- ALP two-photon coupling constrained by astro + lab
- weak coupling: high reaction rate, longer lifetimes, sufficient energy  
→ Proton fixed target facility



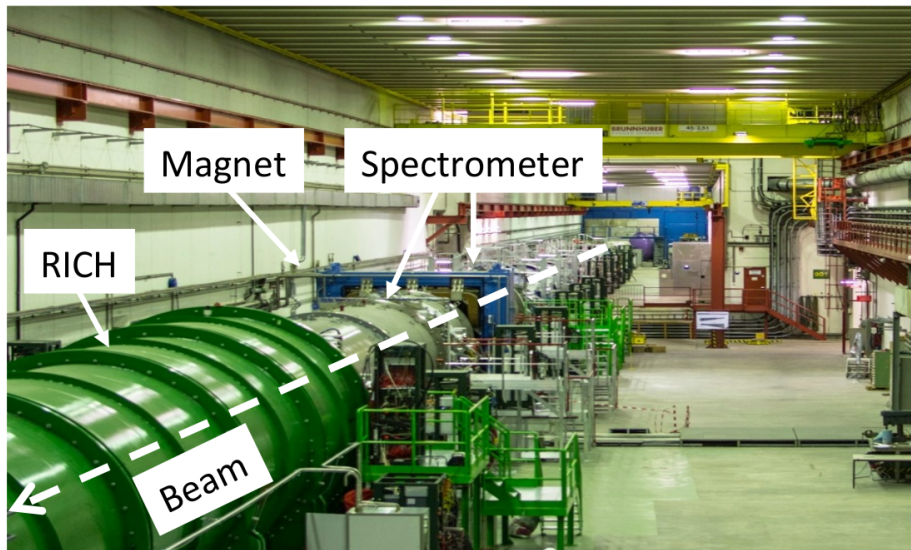
ALP coupled to two photons

taken from [Phys.Lett. B753,482]

$$\mathcal{L}_{\text{int,PS}} \sim g_{\phi\gamma\phi} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

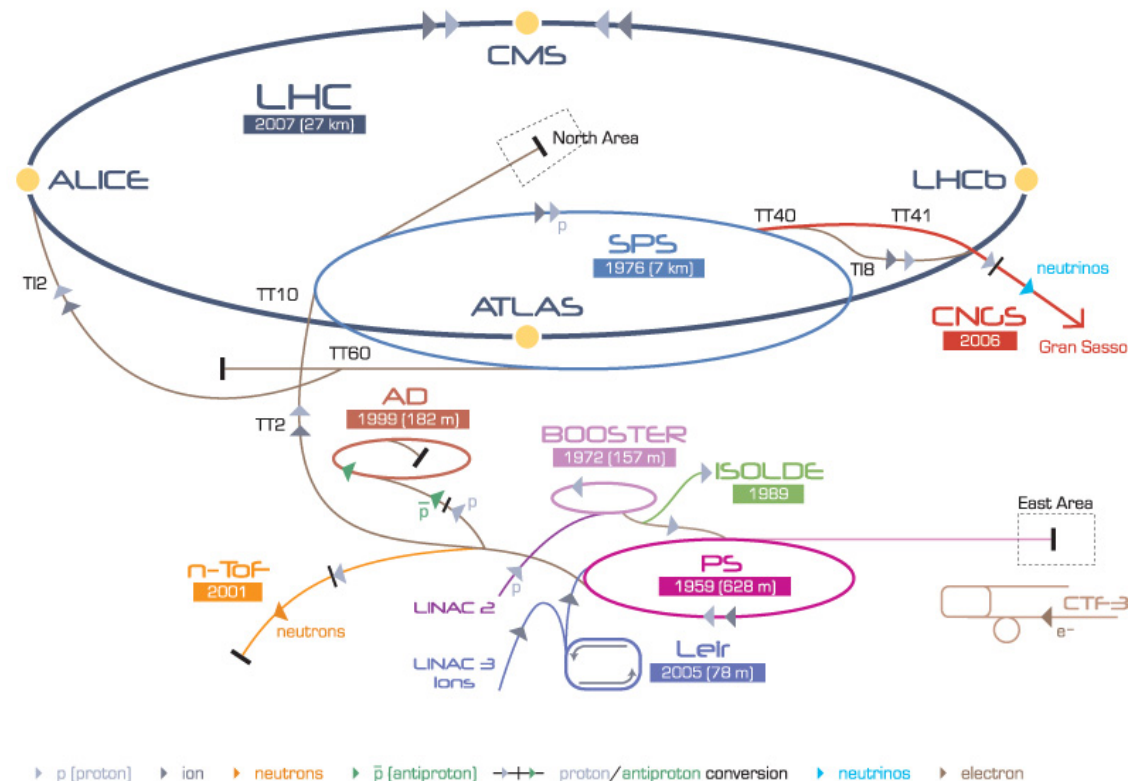
# NA62 at CERN *see arXiv:1703.08501*

na62.web.cern.ch/NA62/



- NA62 wants to measure  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  at CERN SPS, aim: BR at  $\mathcal{O}(10\%)$  total uncertainty within  $\sim 2$  years

## CERN Accelerator Complex



### The beam and detector of the NA62 experiment at CERN

#### The NA62 collaboration

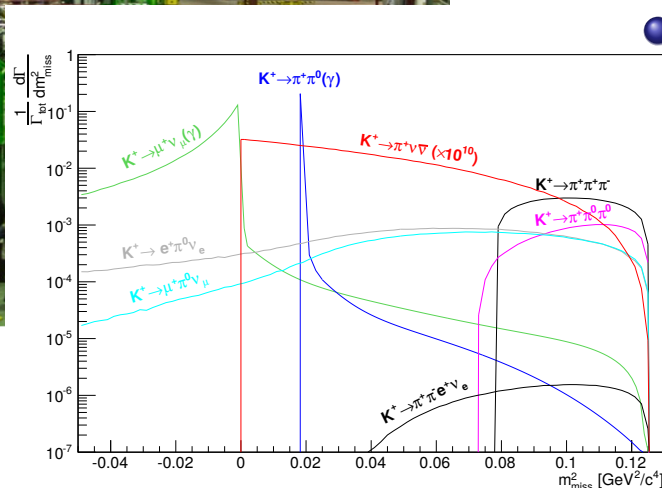
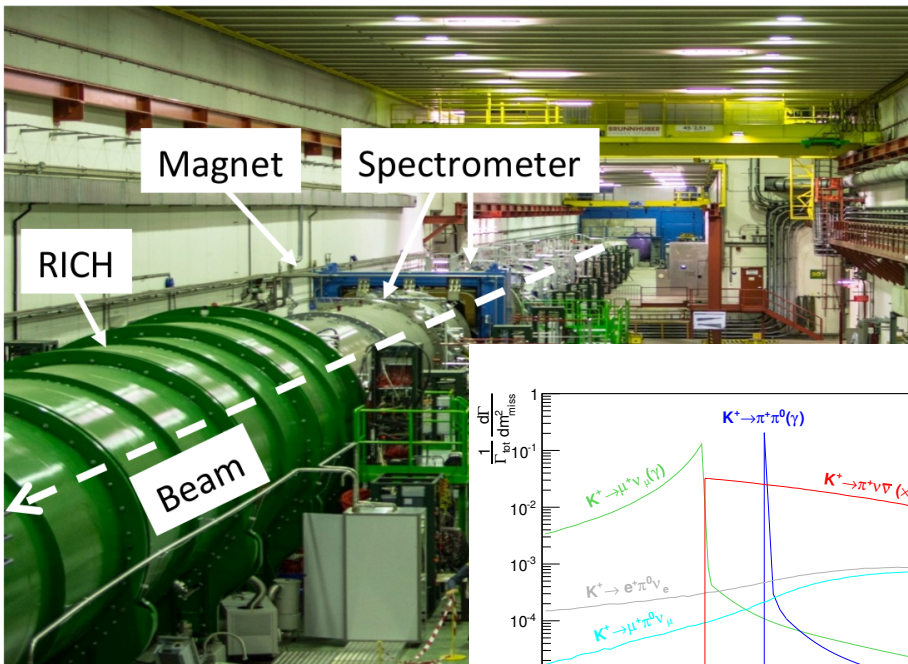
**ABSTRACT:** NA62 is a fixed-target experiment at the CERN SPS dedicated to measurements of rare kaon decays. Such measurements, like the branching fraction of the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay, have the potential to bring significant insights into new physics processes when comparison is made with precise theoretical predictions. For this purpose, innovative techniques have been developed, in particular, in the domain of low-mass tracking devices. Detector construction spanned several years from 2009 to 2014. The collaboration started detector commissioning in 2014 and will collect data until the end of 2018. The beam line and detector components are described together with their early performance obtained from 2014 and 2015 data.

**KEYWORDS:** Large detector systems for particle and astroparticle physics.

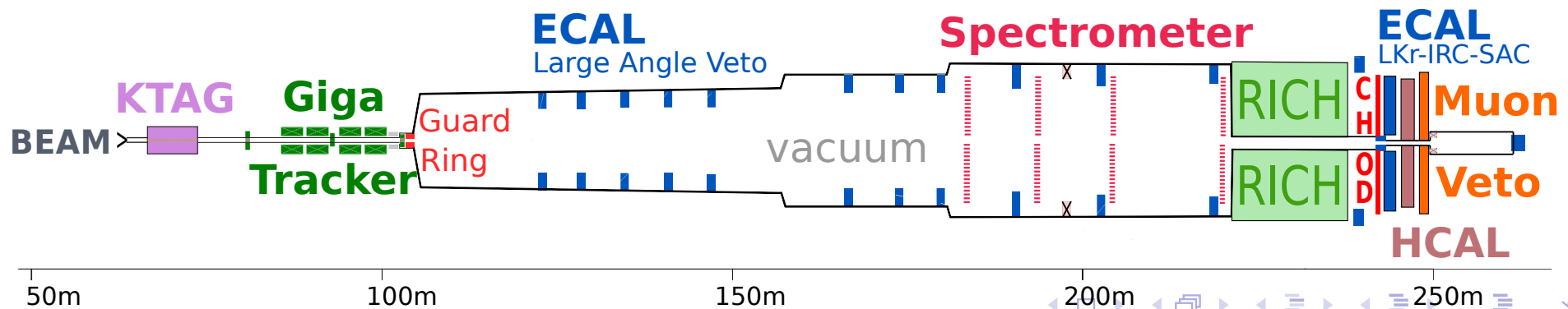
v1 [physics.ins-det] 24 Mar 2017

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na62.web.cern.ch/NA62/

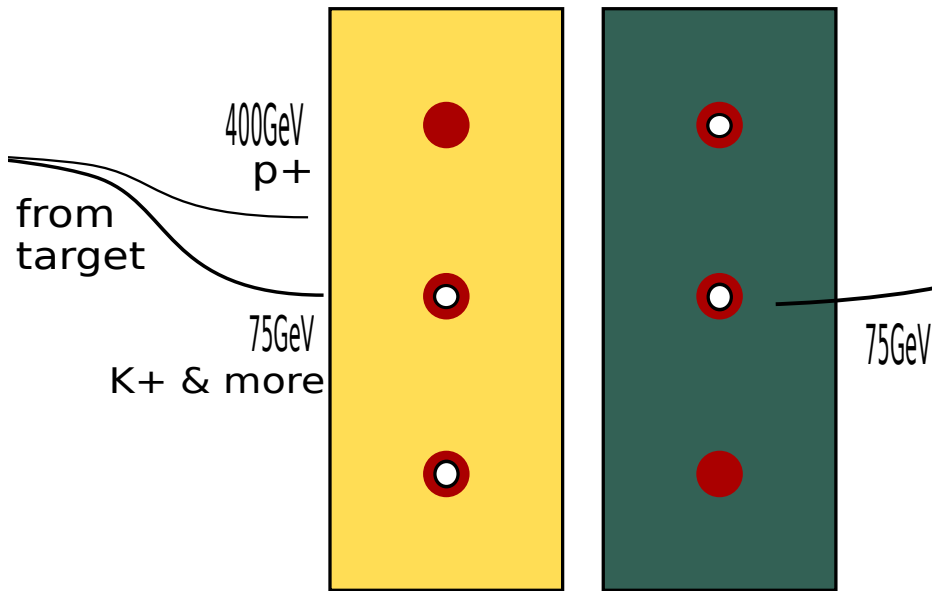


- NA62 wants to measure  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  at CERN SPS, aim: BR at  $\mathcal{O}(10\%)$  total uncertainty within  $\sim 2$  years
- track 750 MHz beam (6%  $K^+$ ) at  $\sim 75$  GeV: Particle ID, high-efficiency Veto + Kine

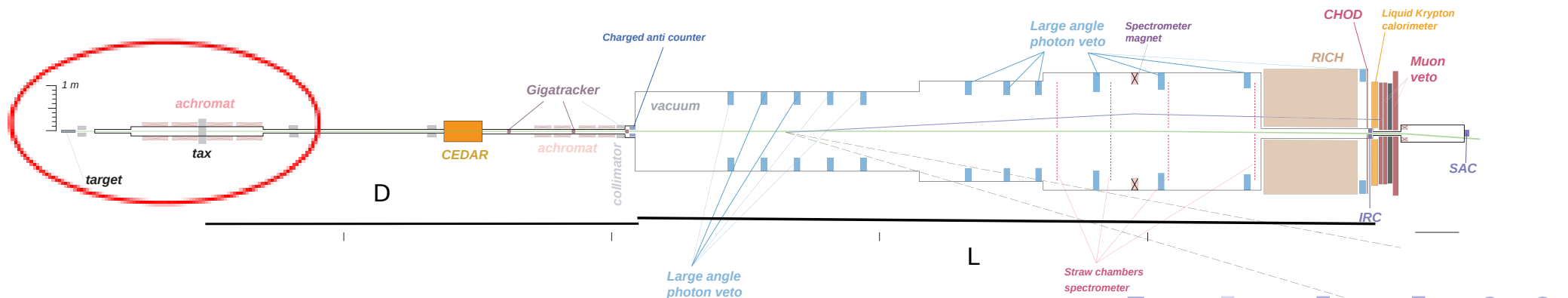


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na62.web.cern.ch/NA62/

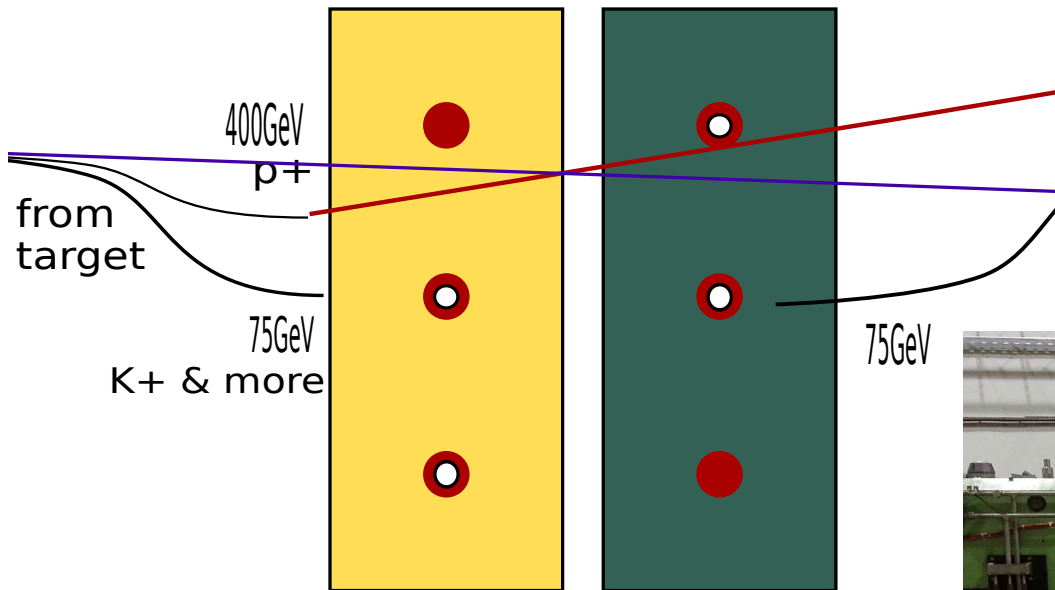


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- track 750 MHz beam (6%  $K^+$ ) at  $\sim 75$  GeV: Particle ID, high-efficiency Veto + Kine
- $K^+$  secondary from Beryllium target, large fraction of SPS protons continuously ‘dumped’

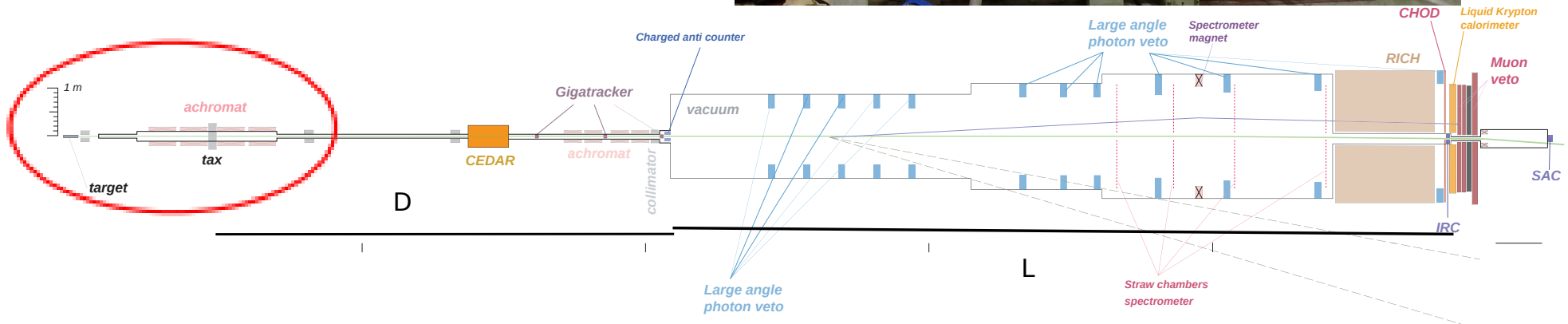




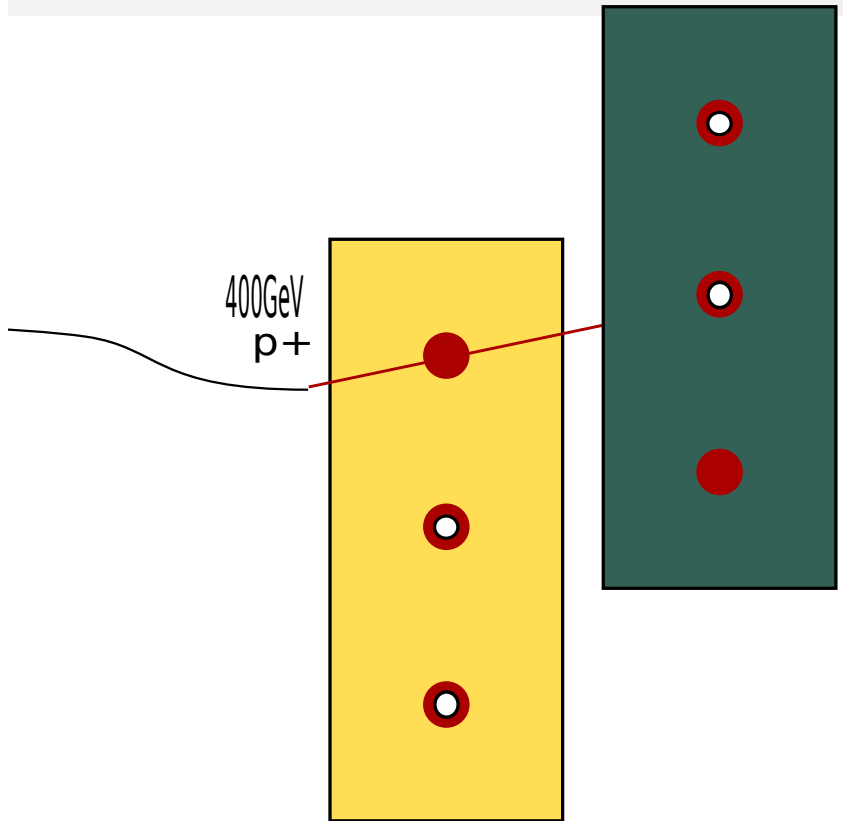
# Upstream production of long-lived particles



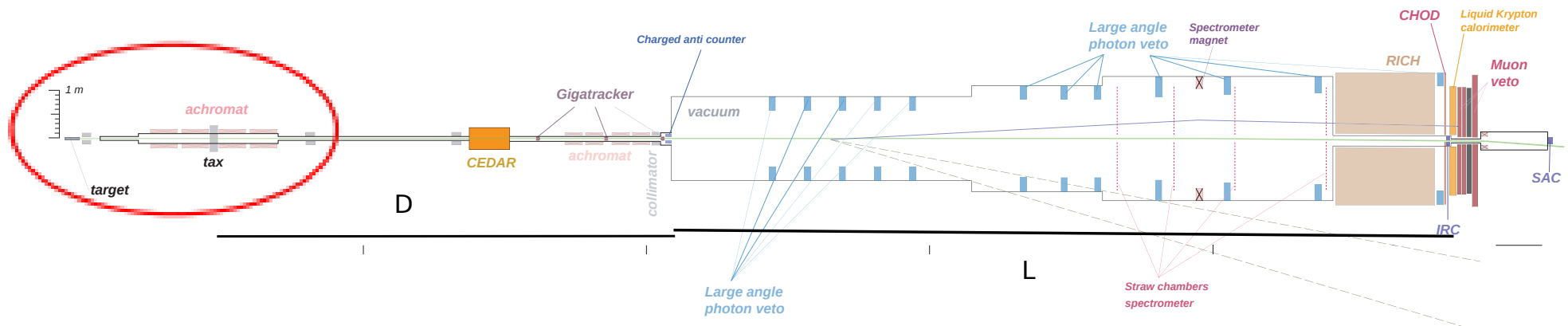
- long-lived, weakly-interacting particles produced along with nominal beam **directly** / **decay**



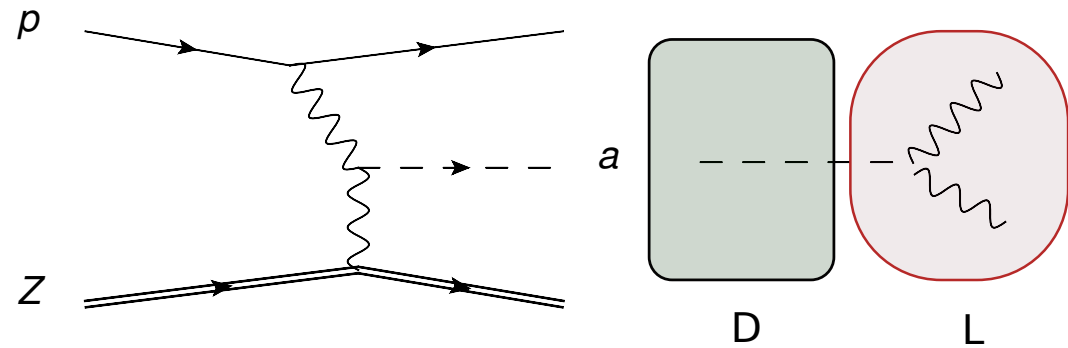
# Upstream production of long-lived particles



- long-lived, weakly-interacting particles produced along with nominal beam **directly** / **decay**
- possibility to dump entire beam by closing TAX ( $\sim 10^{12}$  p/effective second) and removing target
- collected  $\sim 2.5 \times 10^{15}$  POT in dump in end of 2016

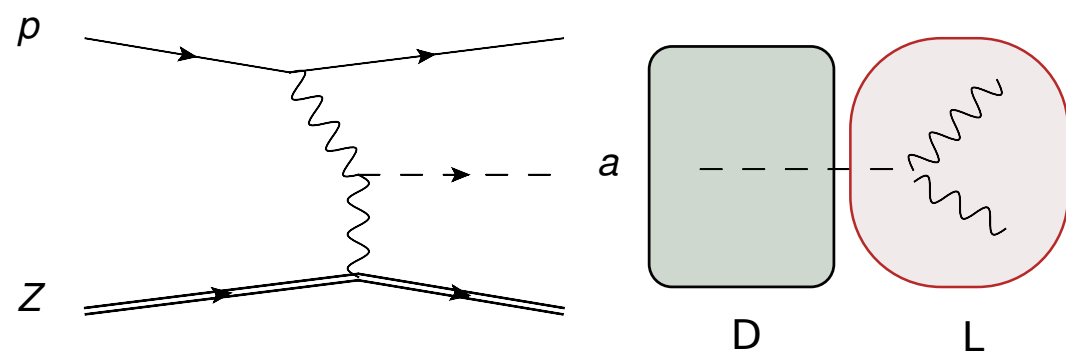
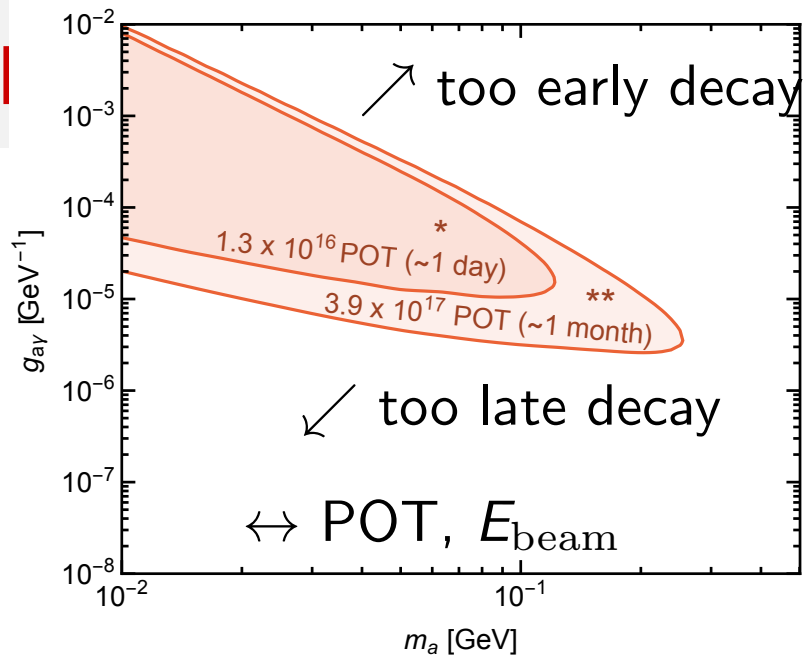


# Example: Axion-like particle production from TAX



- pseudoscalar ALP created by photon fusion
- copper TAX  $\rightarrow$  coherent  $Z^2$  enhancement with charge

# particle production from TAX

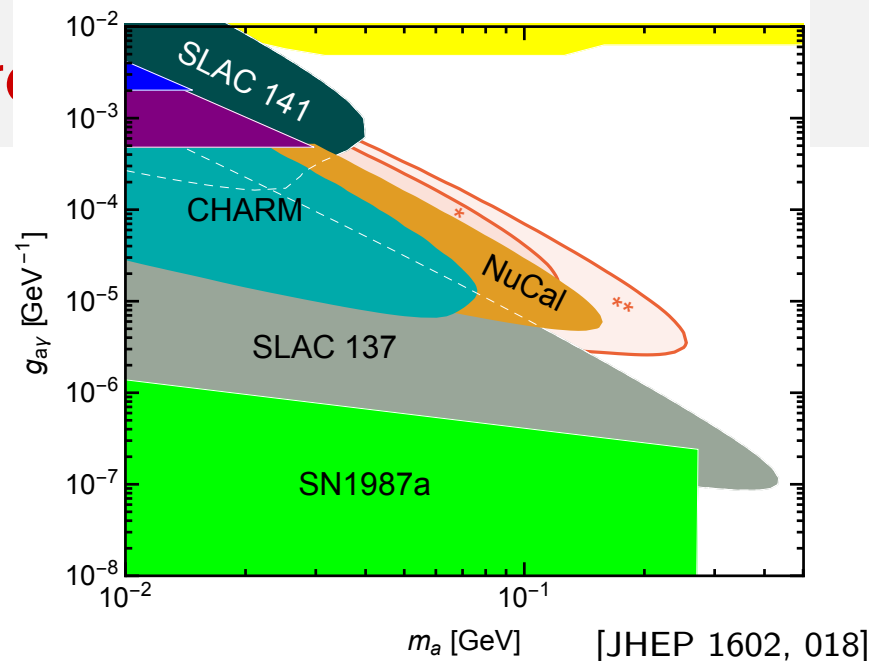


- pseudoscalar ALP created by photon fusion
- copper TAX  $\rightarrow$  coherent  $Z^2$  enhancement with charge
- decay length  $\gamma\beta\tau$ , ALP lifetime  $\tau \sim 1/(g_{a\gamma}^2 m_a^3)$
- the projected limits fold as input: 1. the differential cross-section for production, 2. coincidence and acceptance in EM calorimeter, 3. probability to decay within the decay volume

# Example: Axion-like particle production

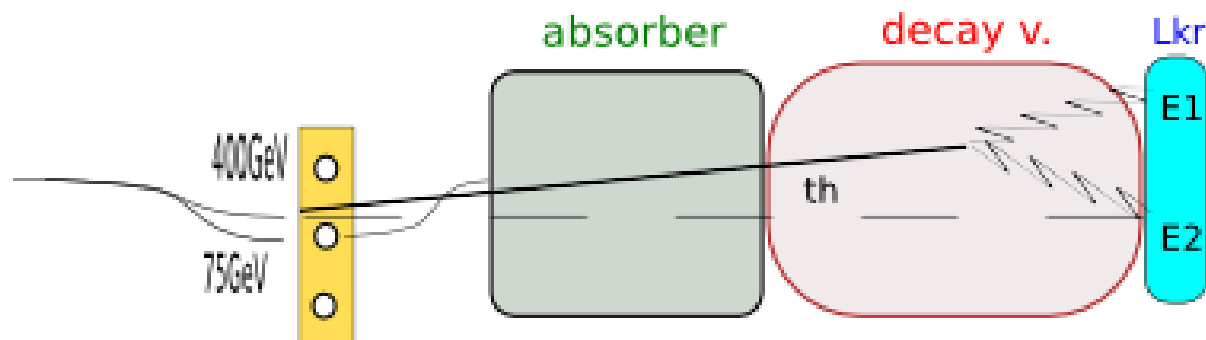
red: ★ 1 day (toy projection)

red: ★★ 1 month (toy projection)

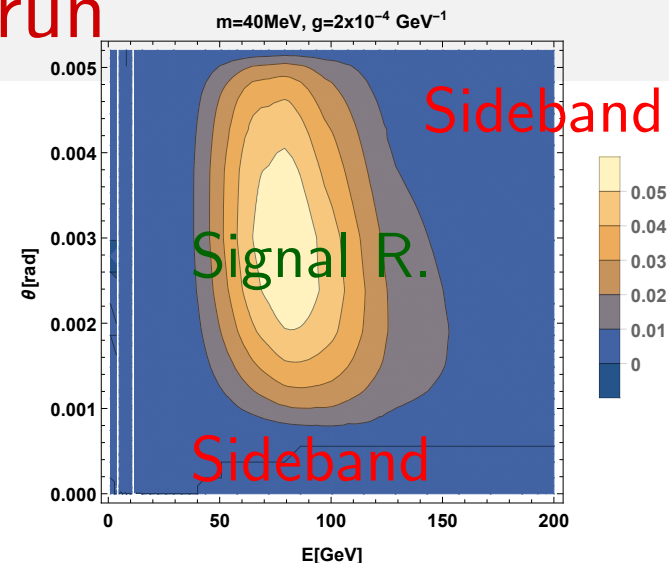


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- the projected limits fold as input: 1. the differential cross-section for production, 2. coincidence and acceptance in EM calorimeter, 3. probability to decay within the decay volume
- NA62  $\rightarrow$  small  $d$ , large  $E$ : one day runtime as ‘dump’ is sensitive to new physics (90% confidence at 0 background)

# Axion-like Particles from 2016 dump run

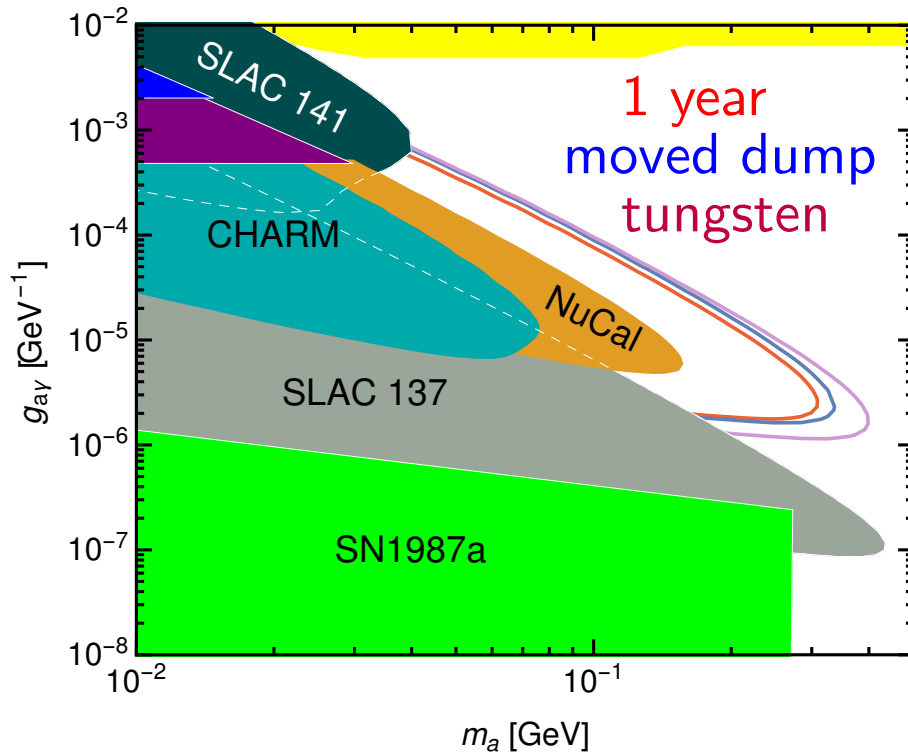
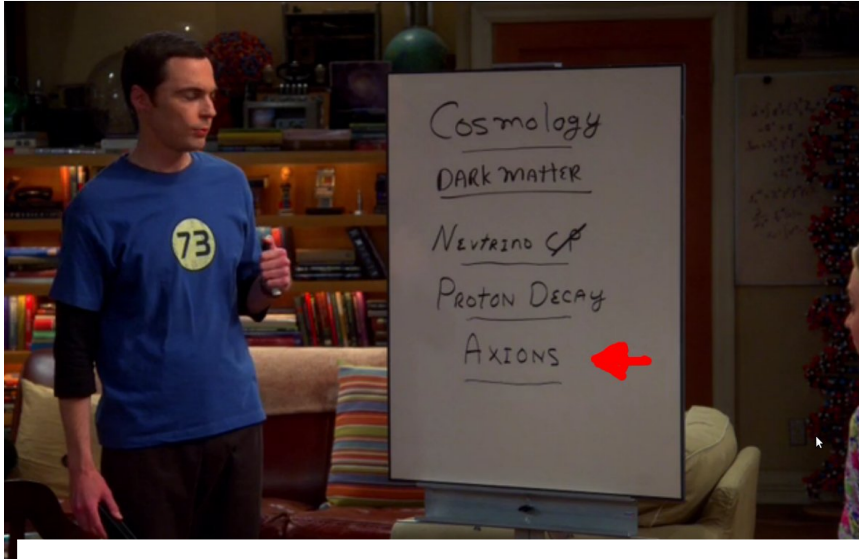


from toy MC



- **problem:** photon is not tracked: know only  $E_1, E_2, d$  in Ecal, need to impose mass or decay point to discriminate
- **mitigation:** only extend beyond existing limits at small  $l_d$ : decay in absorber  $\sim \exp(-l_{\text{abs}}/l_d)$ ,  $l_d = \gamma\beta\tau \sim \frac{E_a}{m} \frac{64\pi}{m^3 g^2}$
- yields the ALPs in reach **highly boosted**  $E_a = E_{\gamma_1} + E_{\gamma_2}$
- their barycenter enclose a (computable) non-zero **angle**  $\theta$
- compare **charged sample in side-band**, deduce **expected background in signal region**  $\rightarrow$  optimization of signal efficiency for  $(g, m)$  in full MC on the way  $\rightarrow$  stay tuned

# Thank you for your attention

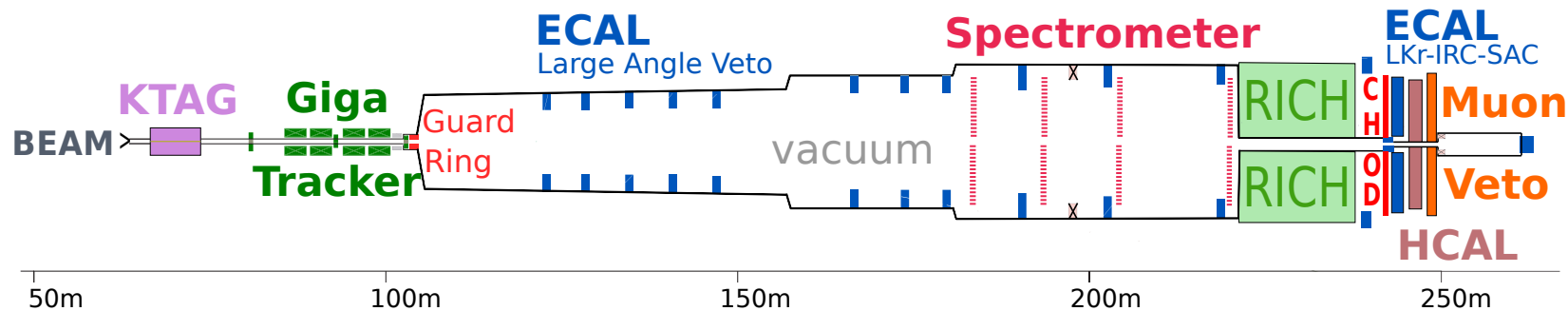
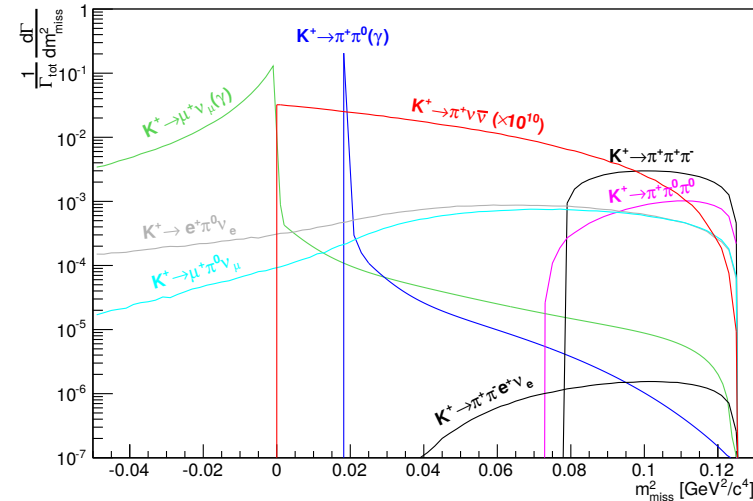


- Axions and ALPs have compelling physics
- MeV range: Sensitivity of proton beam dumps for ALPs coupled predominantly to Photons (PHOTON 2017!)
- NA62 2016 run, few hours of dump data, evaluation under way
- potential improvements in dump: “NA62++”, SHiP...
- other possibilities: B-decays  
Phys.Rev.Lett. 118 no.11, LHC lead-lead  
Phys.Rev.Lett. 118, no.17,  $e^+ e^-$  PADME, ...





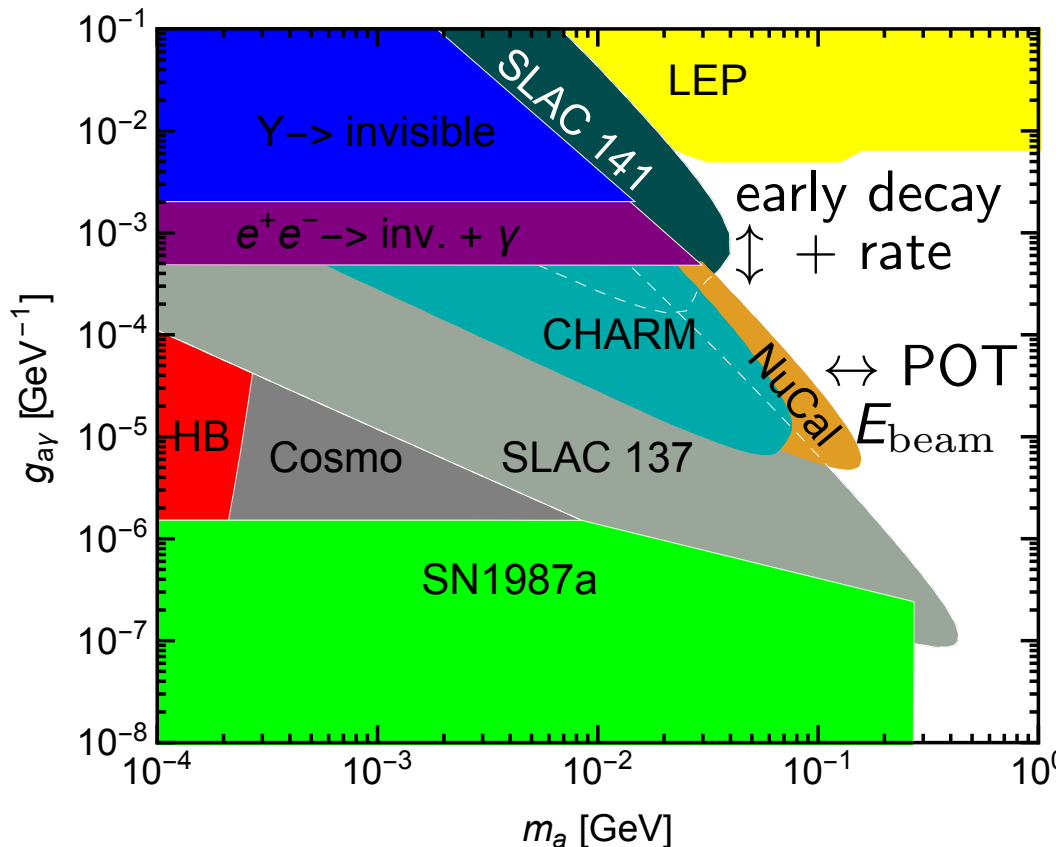
- Kinematic rejection of main K decay modes  $10^4 - 10^5$
- Particle ID:  $\mu$  vs  $\pi$  rejection of  $\mathcal{O}(10^7)$  for  $15 < p_{\pi^+} < 35\text{GeV}$
- high-efficiency veto,  $10^8$  rejection of  $\pi^0$  for  $E(\pi^0) > 40\text{GeV}$



# ALPs from dumps, literature (re-)evaluation

$$N_{\text{det}} \sim N_{\text{pot}} \sigma_a / \sigma_p \left[ \underbrace{\exp\left(-\frac{D}{\gamma\beta\tau}\right)}_{\text{decay in vac}} - \underbrace{\exp\left(-\frac{D+L}{\gamma\beta\tau}\right)}_{\text{decay in detector}} \right]$$

- decay length  $\gamma\beta\tau$ , ALP lifetime  $\tau \sim 1/(g_{a\gamma}^2 m_a^3)$
- $\rightarrow R, L, N_{\text{pot}}, E_{\text{pot}}$  large  
 $\rightarrow D$  small

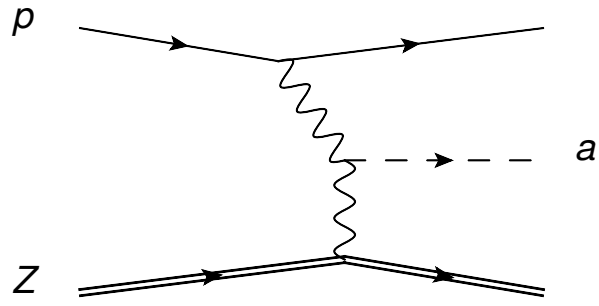


- **CHARM** 400 GeV,  $N_{\text{pot}} = 2.4 \times 10^{18}$  on copper,  $D = 480\text{m}$ ,  $L = 35\text{m}$  (off-axis: 7-12 mrad)
- **NuCal** 70GeV,  $N_{\text{pot}} = 1.7 \times 10^{18}$  on iron,  $D = 64\text{m}$ ,  $L = 23\text{m}$ , on-axis 0-15 mrad
- **SLAC141** 9GeV,  $N_{\text{pot}} = 2 \times 10^{15}$  on tungsten,  $D = 35\text{m}$
- **SLAC137** 20GeV,  $N_{\text{pot}} = 2 \times 10^{20}$  on aluminum,  $D = 200\text{m}$

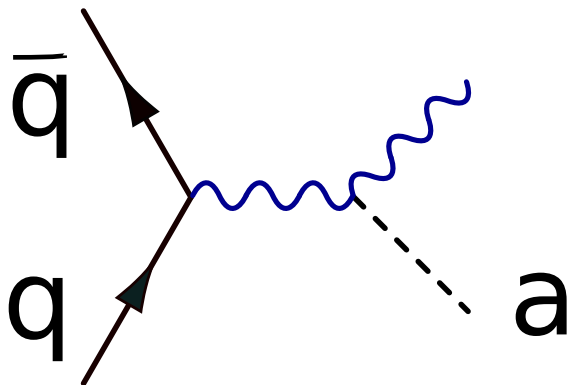
CHARM+NuCal: [BD, Jaeckel, Kahlhoefer, Ringwald, Schmidt-Hoberg JHEP 1602, 018]

# Axion-like particles from proton beam dumps

keep:

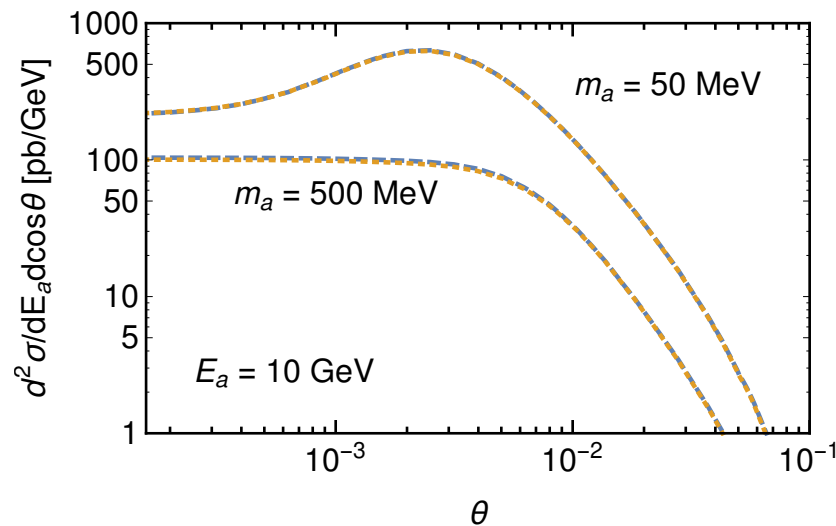
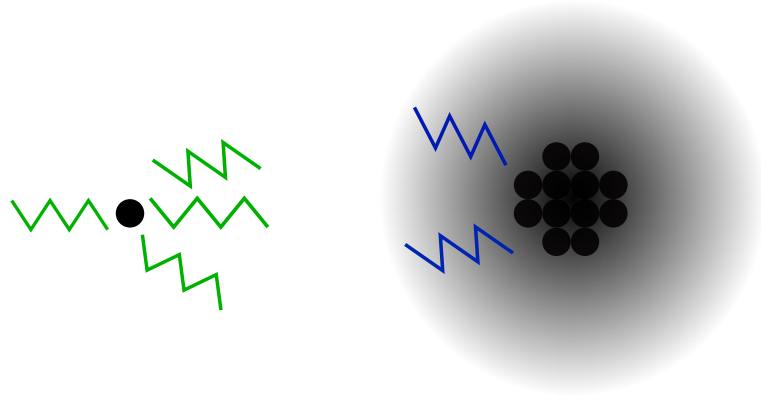


neglect:



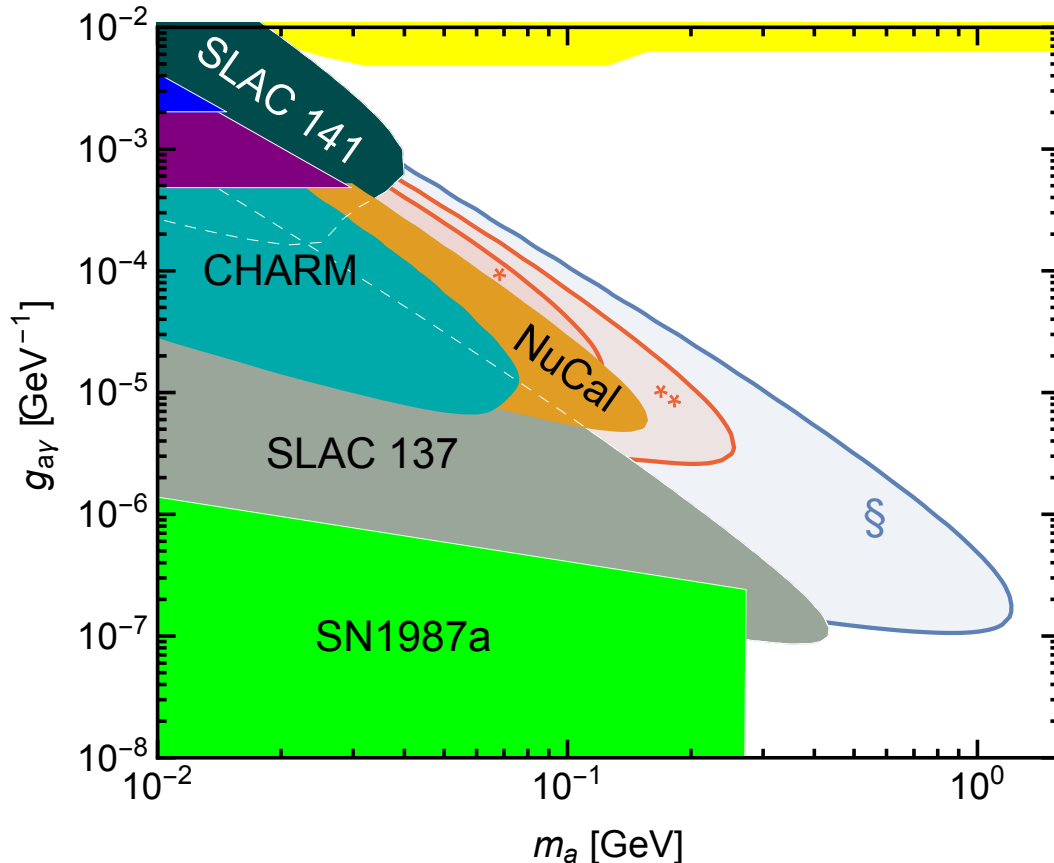
- lowest order: **Primakoff-like** and 'ALPstrahlung'
- former is reliably calculable (perturbative) & has a coherent  $Z^2$  enhancement
- typical for photon with energy  $\omega$ :  
 $q_t/\omega = m_p/E_{\text{beam}}$ , thus  
 $\theta_{\text{max}} \sim 2.5 \text{ mrad}$

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- not justified to take ALP exactly on axis,  $\sigma_a(\theta = 0)$  especially detector is ‘far away’ and not exactly forward

# SHiP estimate for coherent (Primakoff) production



- proposed dedicated Dump facility for SPS (mainly for Heavy Neutral Leptons)
- SHiP estimate  $\xi$  based on  $\sim 2 \times 10^{20}$  POT (molybdenum,  $Z = 42$ )  $\rightarrow$  run-time of 5 years, see [1504.04956]
- $D = 70\text{m}$ ,  $L = 50\text{m}$ , calorimeter radius 2.5m
- note that the ALP sensitivity estimate in SHiP theory paper [1504.04855] is based on *incoherent* production, i.e.  $q + \bar{q} \rightarrow a + \gamma$