Light Dark Matter searches at accelerators

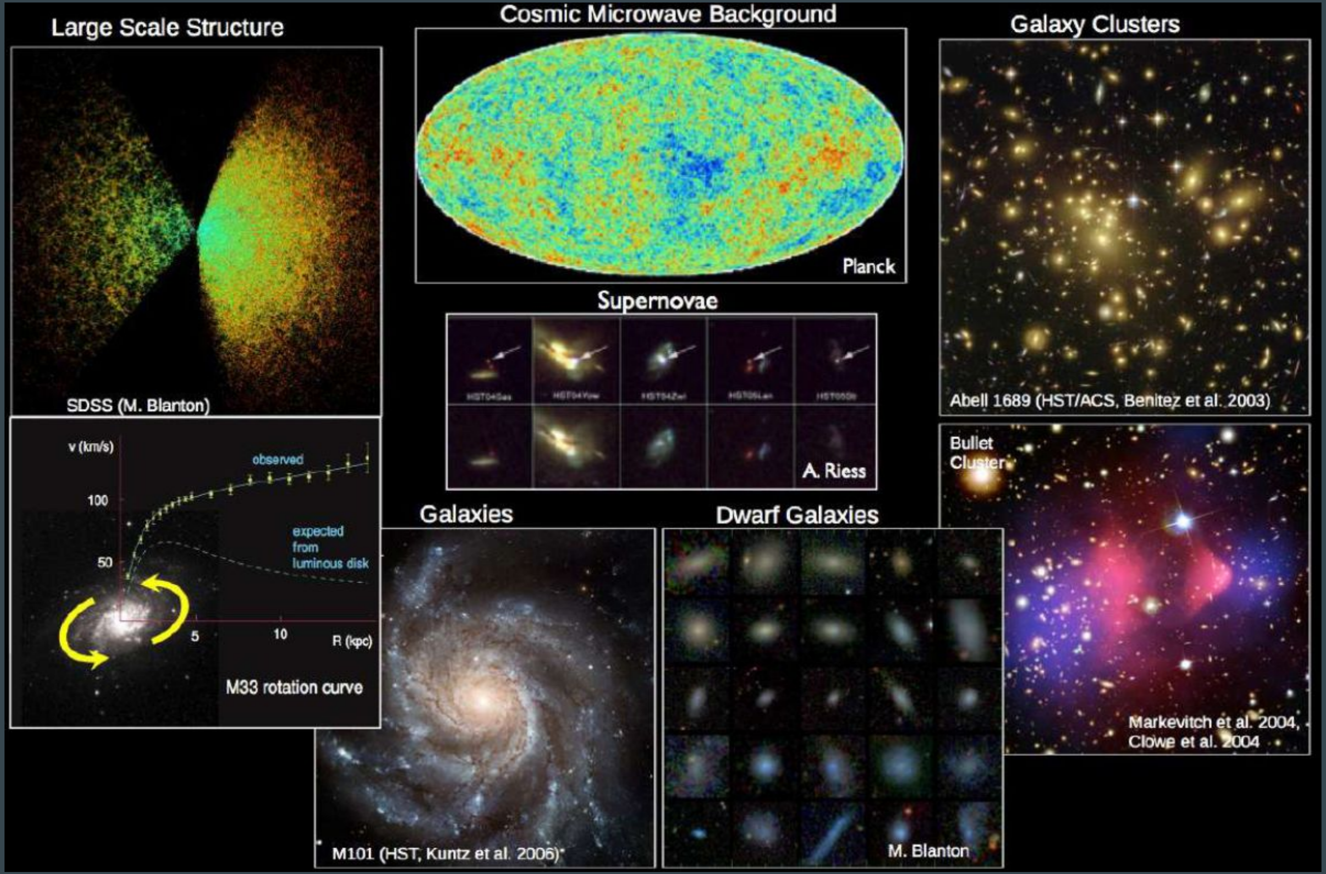
Luca Marsicano - INFN Genova
Second School on Dark Matter and Neutrino Detection
ICTP SAIFR

INFN
Istituto Nazionale di Fisica Nucleare

Content of the lectures (tentative)

- Introduction: brief description of the Light Dark Matter model considered
- LDM Searches at colliders
  - focus on the LHCb searches for visible Dark Photon decays
- Fixed thin target experiments
  - the Heavy Photon Search at JLab
  - the X17 search at PADME
- Beam-dumps
  - the Beam Dump eXperiment (BDX)
  - SHIP@CERN
- Missing energy/momentum experiments
  - NA64-e
  - NA64-mu

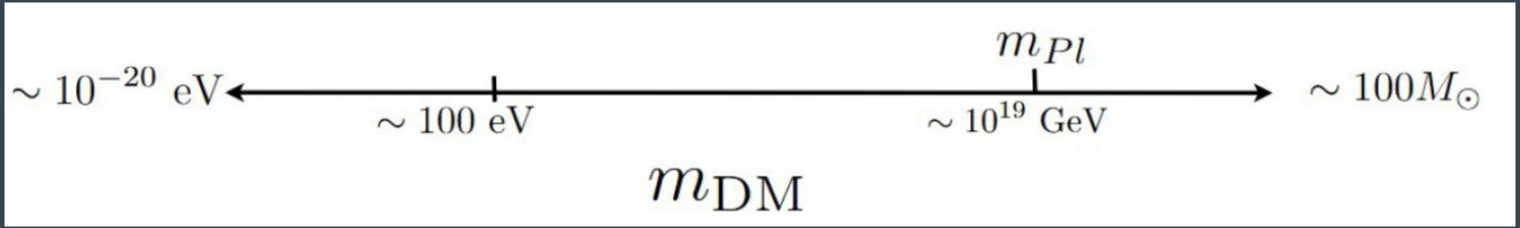
DM: it is (most probably) there, but what it is made of?



see lectures by Graciela Gelmini

DM: From particles to black holes

- All Dark Matter evidences come from the observation of its gravitational effects
- No hints on DM particle properties (mass, cross section) from particle physics experiment
- The viable DM mass window is dauntingly large:



Theoretical guidance is needed to narrow the search window!

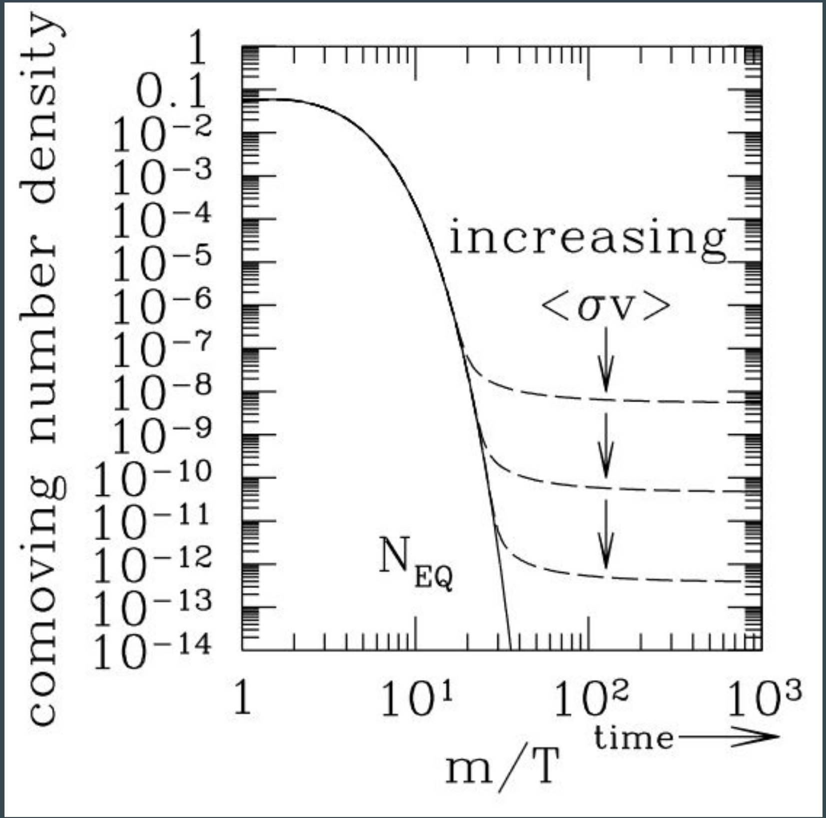
Thermal DM Hypothesis

Cosmological Hypothesis: DM particles were in equilibrium with primordial thermal bath in early universe $\chi + \bar{\chi} \leftrightarrow f + f$

- Early universe: high-T, relativistic regime. Both reactions ($\leftarrow$ and $\rightarrow$) permitted

- As Universe expands and cools down below χ mass, only $\rightarrow$ reaction occurs. DM number density is exponentially suppressed: Boltzmann regime

- Eventually, DM number density is too low for χ to find each other $\rightarrow$ annihilation stops $\rightarrow$ Freeze Out



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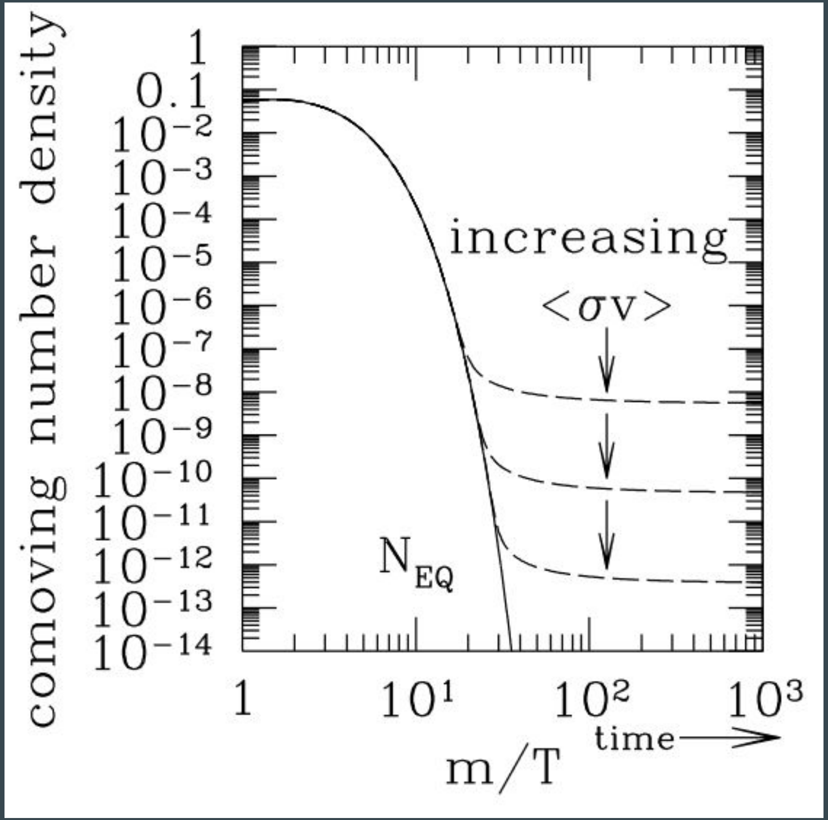
Thermal DM Hypothesis

In the thermal DM scenario, DM density today can tell us about DM → SM model annihilation cross-section: $\chi + \bar{\chi} \leftrightarrow f + f$

- If annihilation-cross section is too high (small), DM particles would stay longer in equilibrium in the Boltzmann regime, resulting in a lower (higher) number density at present
- DM particle mass and annihilation cross-section are bound
- If $m_\chi \sim 100$GeV → typical weak Interaction cross section: WIMP Miracle



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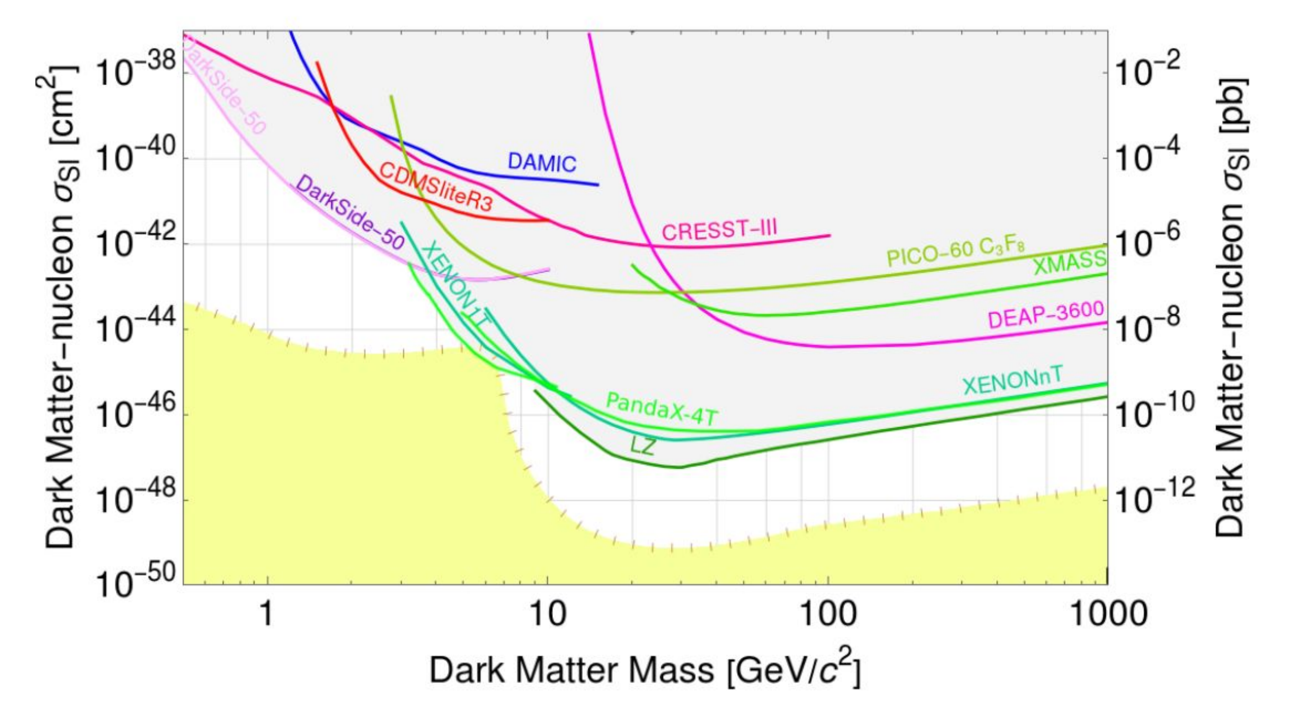
Status of WIMP searches

- So far, no clear evidence for WIMP-like DM from direct search
- Experiment are reaching coherent neutrino floor
- Where to look next?

  Direct detection program is crucial, only way to probe cosmogenic DM signals



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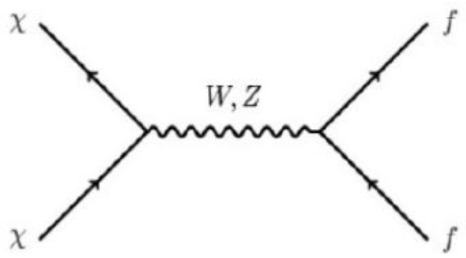
A “light” WIMP?

A light WIMP does not reproduce correct relic abundance, in the thermal origin hypothesis



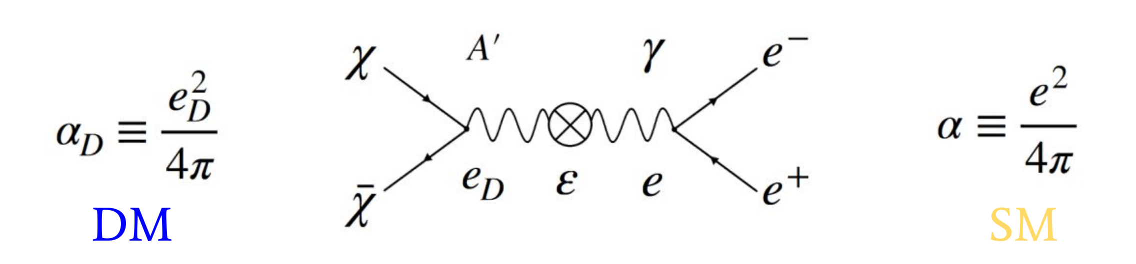
$$\langle \sigma v \rangle_{\mathrm{WIMP}} \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1} \left(\frac{\mathrm{TeV}}{m_\chi} \right)^2$$

If $m_\chi \sim 1GeV : \; \langle \sigma v \rangle \ll \langle \sigma v \rangle_{relic} \simeq 3 \times 10^{-26} \; cm^3 s^{-1}$

Need for a new interaction acting as a “portal” between DM and SM

Vector Mediator: the Dark Photon

Simplest possibility: “vector-portal”. DM-SM interaction through a new U(1) gauge-boson (“dark-photon”) coupling to electric charge Dark QED



DM charged under new mediator
Small A’-photon mixing $\varepsilon \ll 1$

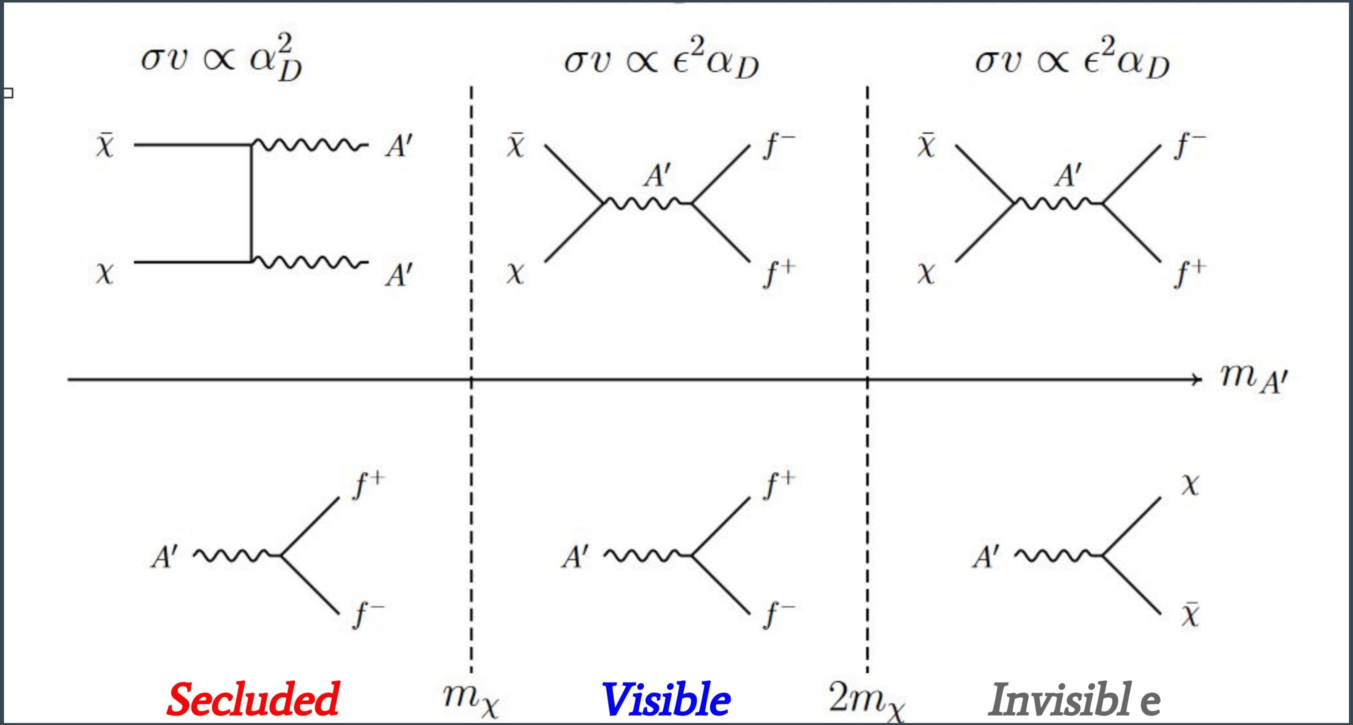
- By requiring that freeze-out mechanism reproduces today’s relic abundance, a target in the parameters space can be derived:
- Define a new variable optimized for thermal targets:

$$\langle \sigma v \rangle \propto \frac{\varepsilon^2 \alpha_D m_\chi^2}{m_{A'}^4} = \alpha_D \varepsilon^2 \left(\frac{m_\chi}{m_{A'}}\right)^4 \frac{1}{m_\chi^2} = \frac{y}{m_\chi^2}$$

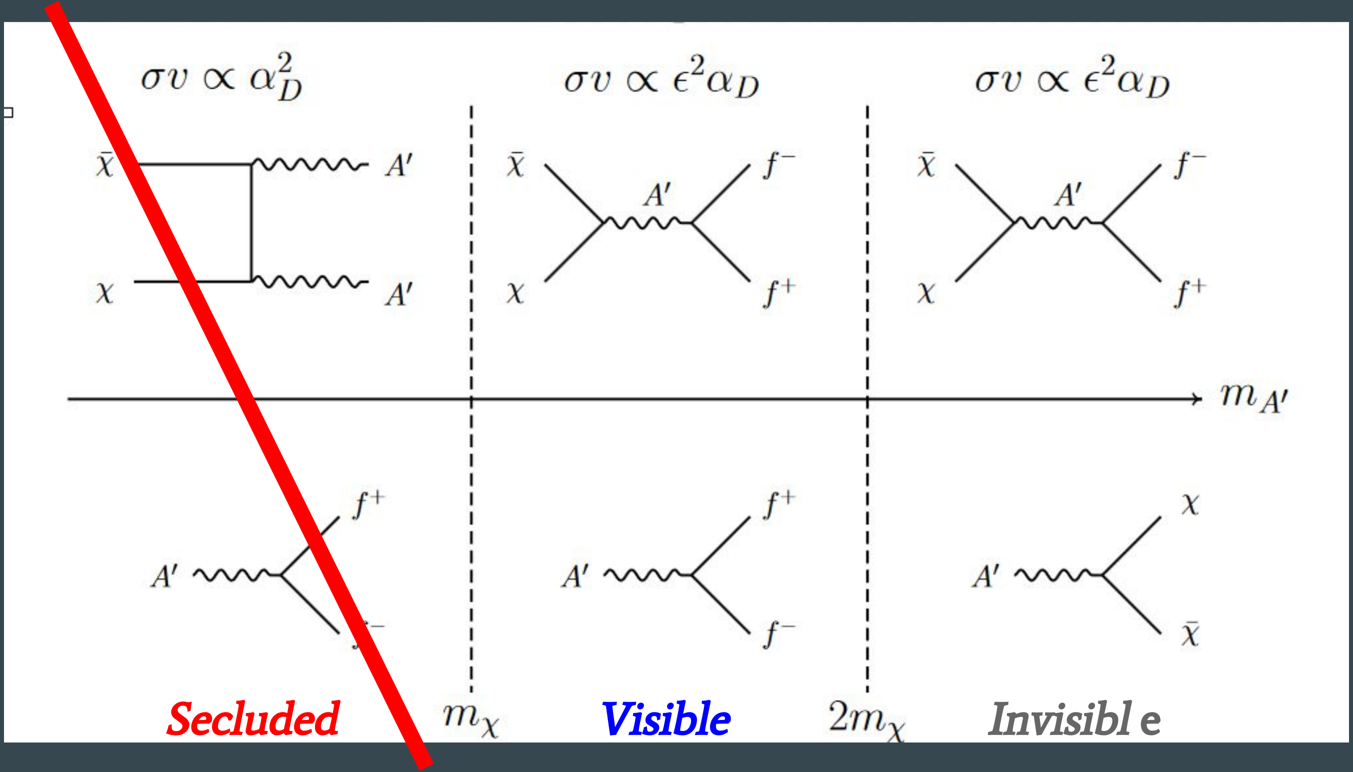
For a given value of m_χ, thermal origin imposes one value of y

1707.04591, 2005.01515, 2011.02157

LDM annihilation channels



LDM annihilation channels



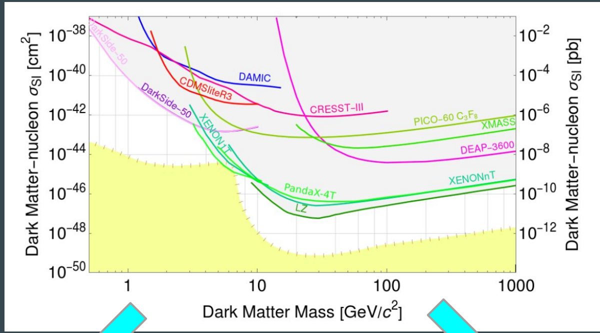
- Secluded scenario: provides no thermal target for accelerator-based experiments: any ε value is allowed

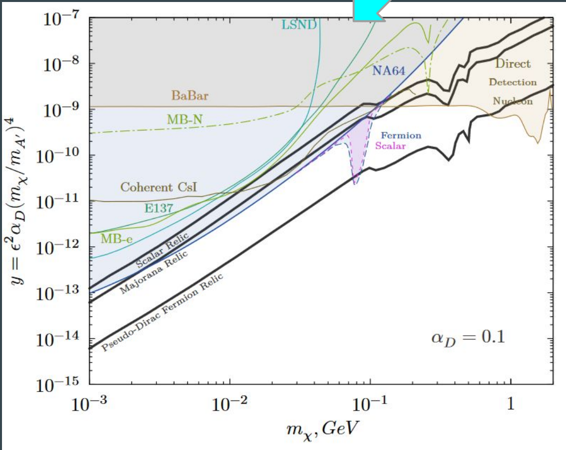
Light DM - Direct Searches

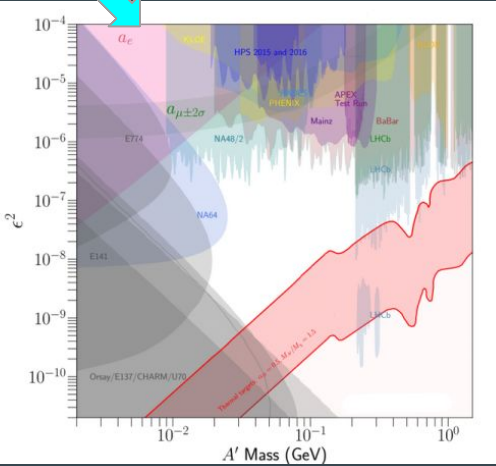
Dark Matter direct detection experiments, typically optimized for $m_\chi \geq 1$ GeV, have a limited sensitivity in the sub-GeV range

- $E_{rec} \propto \frac{m_\chi^2}{m_N}$
- Many ongoing efforts to overcome this limitation
- Given the mass range and expected couplings, collider and accelerator experiments are particularly well suited to search for LDM candidates

Parameter spaces - from WIMPs to LDM







Dark Photon phenomenology

- The mixing between the A' and the SM photon results in a suppressed coupling to the EM current
→ A' can decay both to SM hadrons and leptons (if kinematically admissible)

$$\mathcal{L}_{\gamma A'} \supset -\frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m^2_{A'} A'^{\mu} A'_{\mu} + e\varepsilon j_{\mu} A'\mu$$

$$\Gamma_{A'} = \sum_l \Gamma_{A' \to l^+ l^-} + \Gamma_{A' \to hadrons} + \Gamma_{A' \to invisible}$$

$$\tau_{A'} = \frac{\hbar}{\Gamma_{A'}}$$

Dark Photon decay widths

Due to the considered values for ε and α_D the branching ratio to invisible states is dominant, provided that $m_{A'} > 2\ m_\chi$

$$\Gamma_{A' \to leptons} = \frac{\varepsilon^2 \alpha_{EM}}{3} m_{A'} \left(1 + 2\frac{m_l^2}{m_{A'}^2}\right) \sqrt{1 - 4\frac{m_l^2}{m_{A'}^2}}$$

$\varepsilon = 10^{-3} - 10^{-9}$

$$\Gamma_{A' \to \chi\bar{\chi}} = \frac{\alpha_D}{3} m_{A'} \left(1 + 2\frac{m_\chi^2}{m_{A'}^2}\right) \sqrt{1 - 4\frac{m_\chi 2}{m_{A'}^2}}$$

$\alpha_D = 0.1 - 0.5$

Dark Photon decay widths

- Invisible scenario: negligible A' lifetime (prompt decay)
- Visible scenario: extremely varying lifetime depending on the considered region of the parameter space (from ~10^{-10} *s* to ~100 *s*!)

$$\Gamma_{A' \to leptons} = \frac{\varepsilon^2 \alpha_{EM}}{3} m_{A'} \left(1 + 2\frac{m_l^2}{m_{A'}^2}\right) \sqrt{1 - 4\frac{m_l^2}{m_{A'}^2}}$$

$$\Gamma_{A' \to \chi\bar{\chi}} = \frac{\alpha_D}{3} m_{A'} \left(1 + 2\frac{m_\chi^2}{m_{A'}^2}\right) \sqrt{1 - 4\frac{m_\chi 2}{m_{A'}^2}}$$

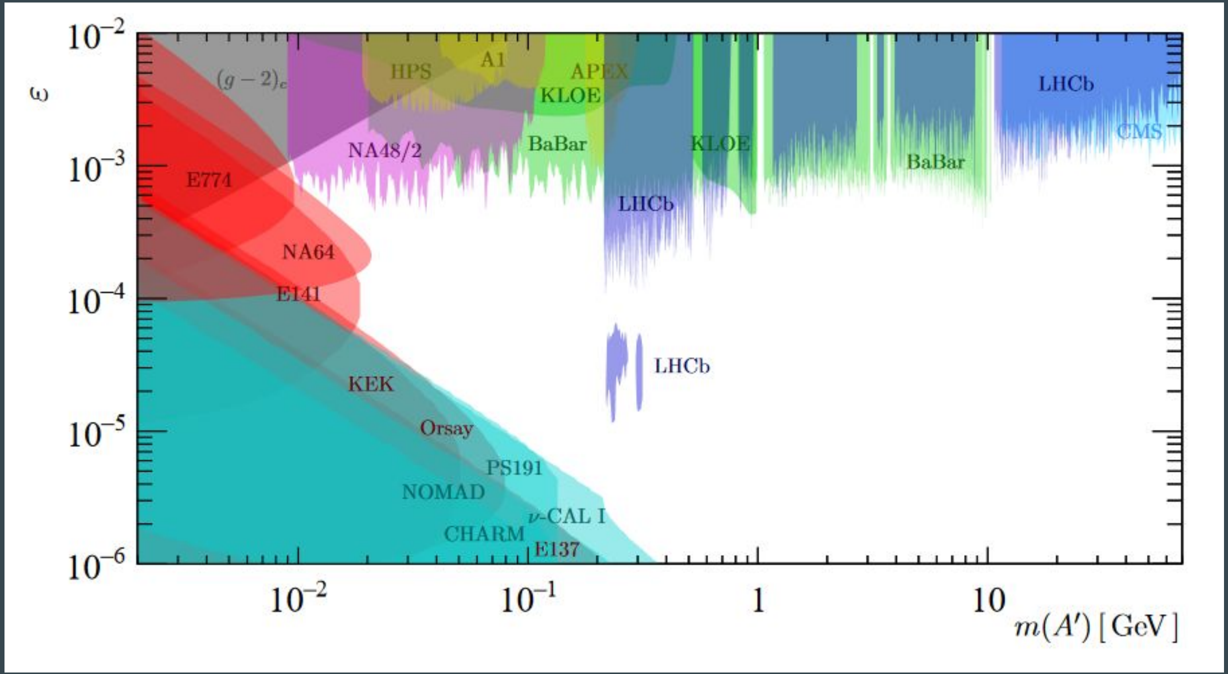
"visible" scenario:

$$m_{A'} < 2m_\chi$$

$$\Gamma_{A'} = \sum_l \Gamma_{A' \to l^+ l^-} + \Gamma_{A' \to hadrons} + \cancel{\Gamma_{A' \to invisible}}$$

Visible scenario phenomenology

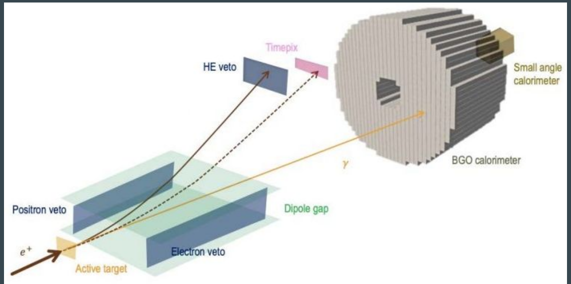
large cross-section

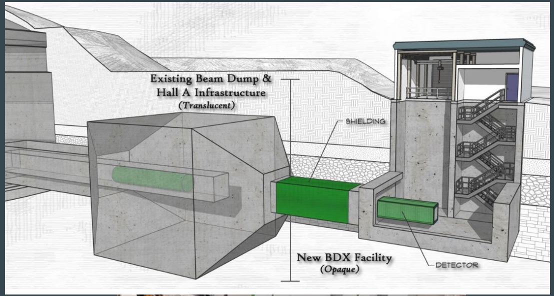


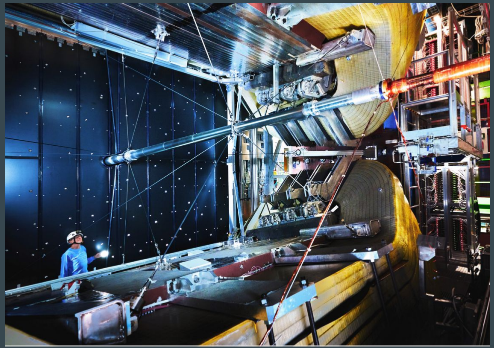
long-lived

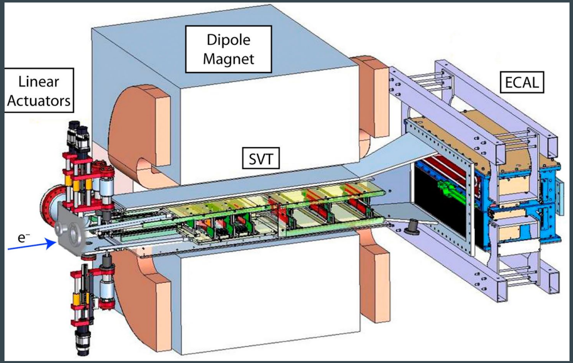
Light DM searches at accelerators

- Many ongoing and future efforts: high energy/intensity colliders, beam-dumps, fixed targets



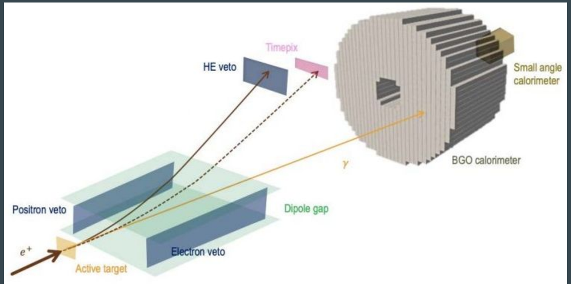


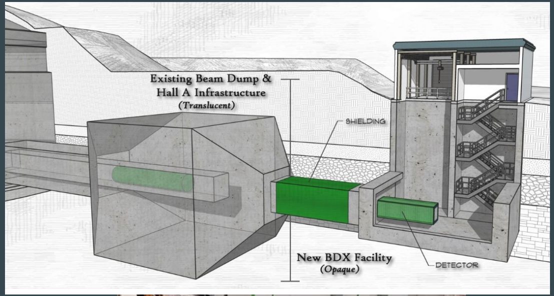


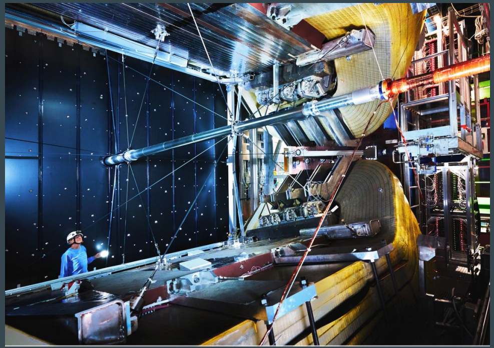


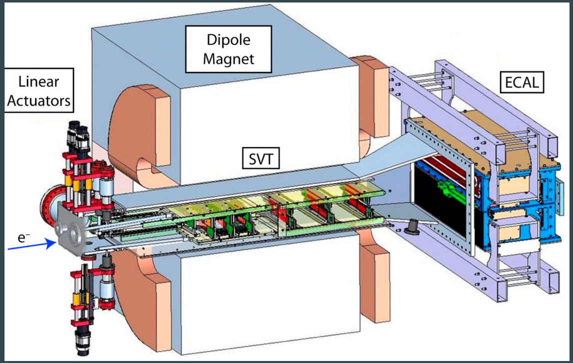
Light DM searches at accelerators

❖ Many ongoing and future efforts: high energy/intensity colliders, beam-dumps, fixed targets

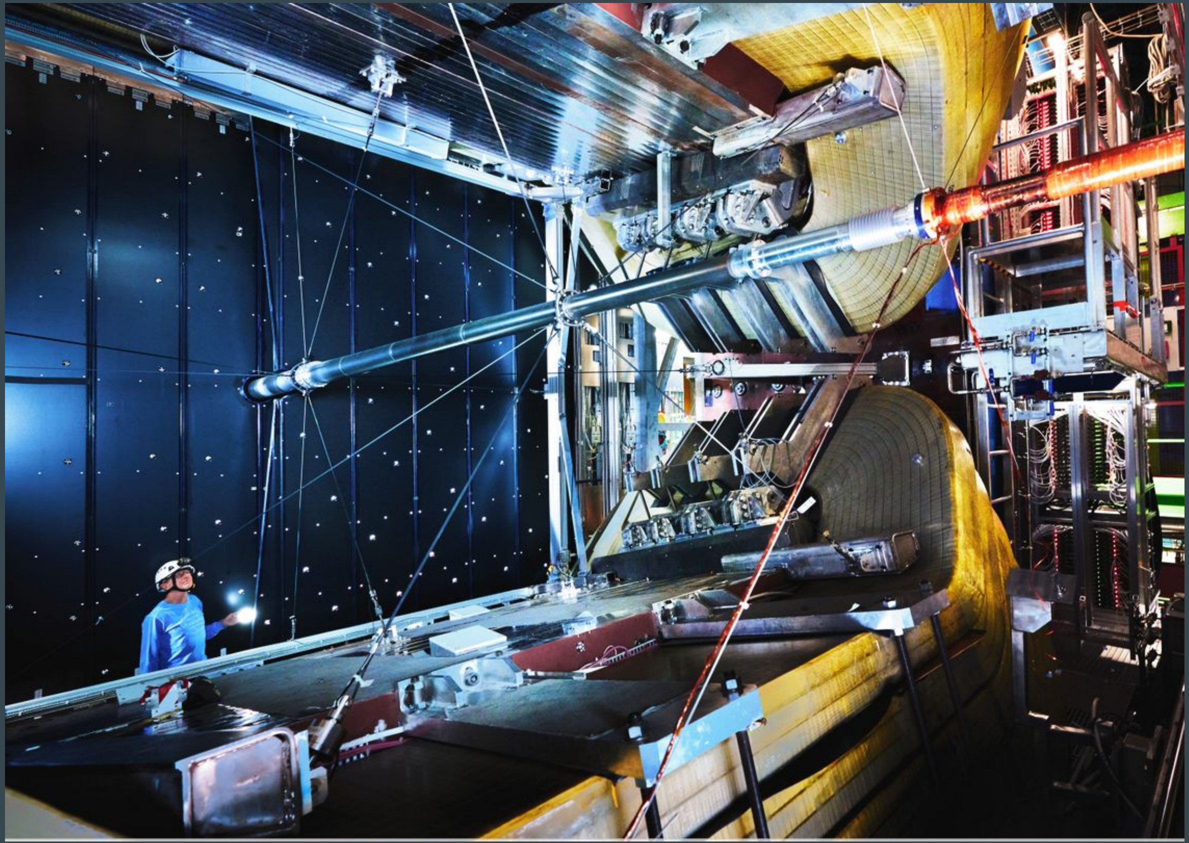








Search for visible *A'* decay at LHCb



The Large Hadron Collider

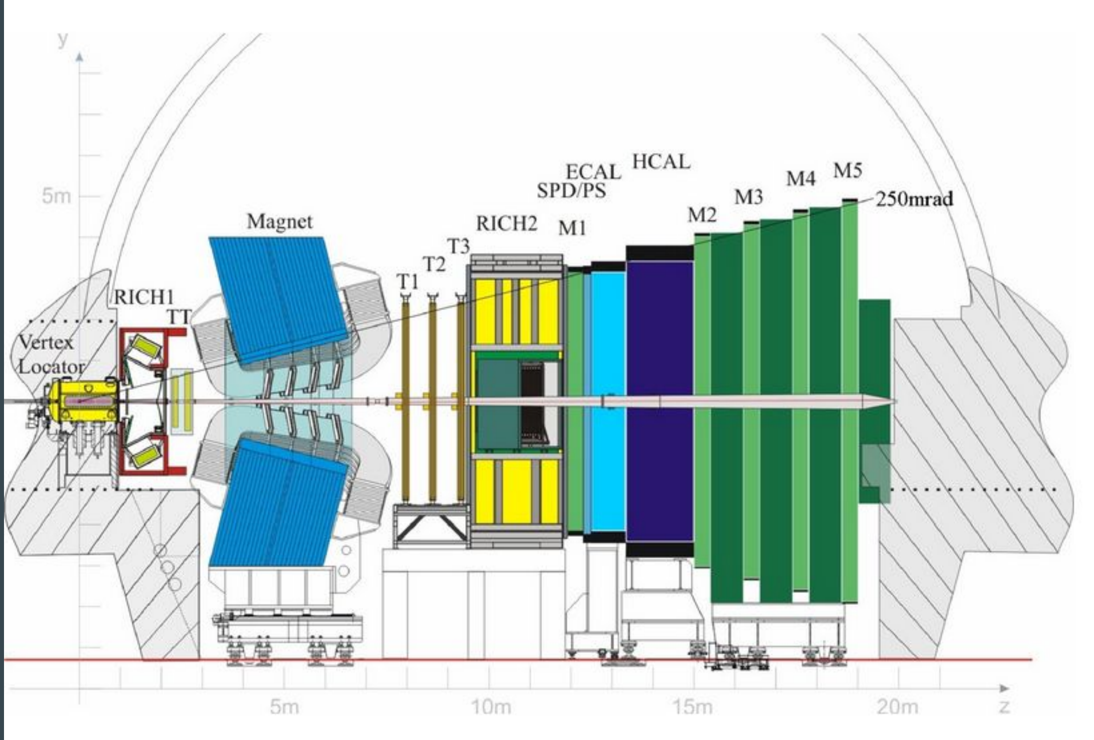
- LHC is the largest collider in the world:
  - ~27 km diameter, located at CERN (Geneva)
  - 1232 dipole magnets, (15-m long) for beam bending
  - 392 quadrupole magnets, (5–7 m- long) for beam focusing
  - pp collisions at sqrt(s)=13 TeV

- Four main interactions points, where the ATLAS, CMS, ALICE and LHCb detectors are located

- Fundamental physics goals: investigate the origin of the baryon masses, Higgs physics (discovery in 2012), dark matter search, CP violation, supersymmetry...

LHCb Experiment

- Single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$
- Designed for the study of particles containing *b* or **c** quarks
- 21 metres long, 10 metres high and 13 metres wide

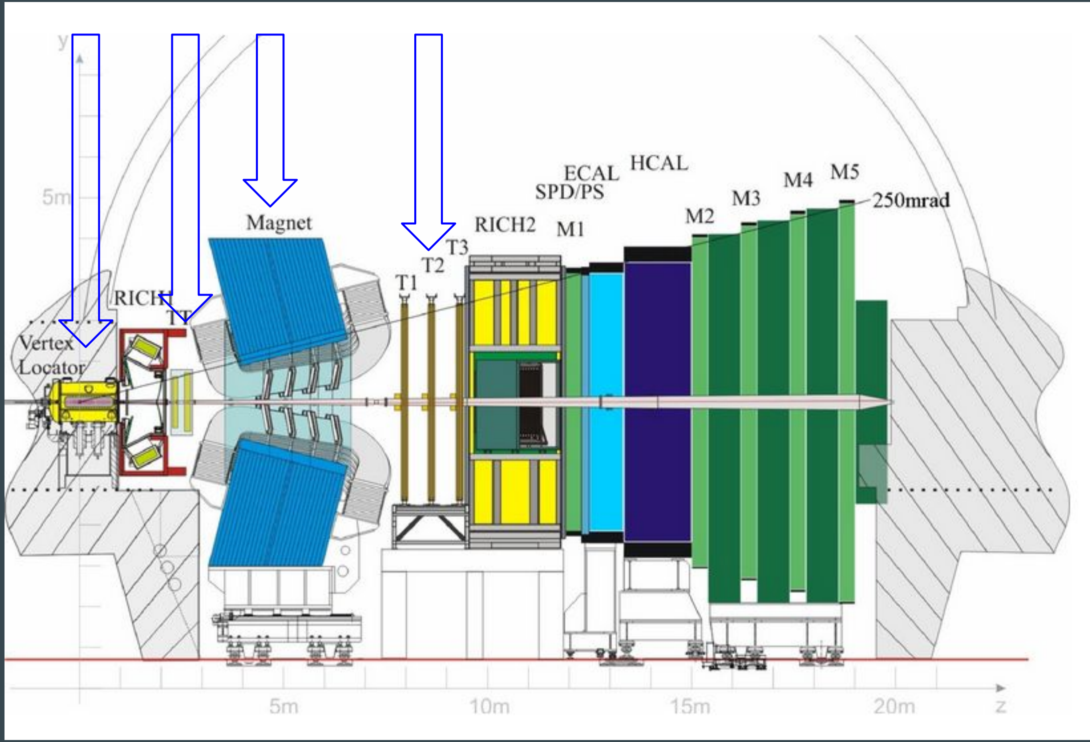


JINST 3 (2008) S08005, arXiv:1412.6352

LHCb Tracking System

The tracking system of LHCb is composed of different elements:

- ❖ Inner vertex locator (VELO): silicon microstrips surrounding the pp interaction region
- ❖ Large-area silicon-strip detector
- ❖ Bending Magnet (bending power ~4 Tm)
- ❖ Three stations of silicon-strip detectors and straw drift tubes



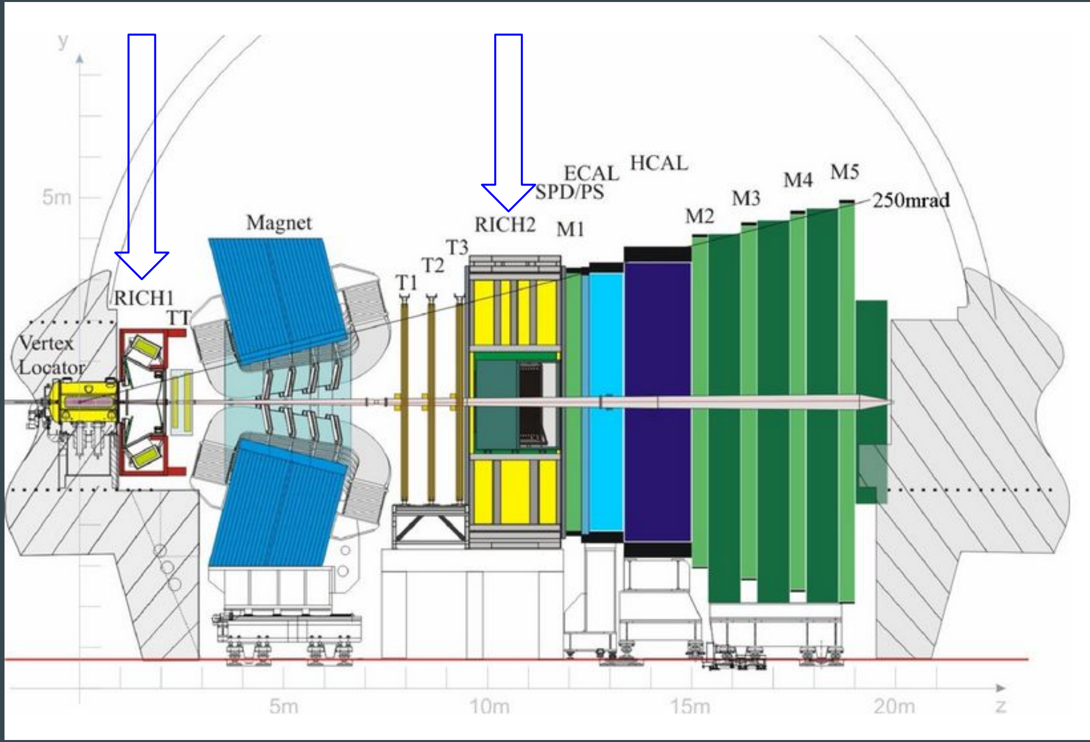
Overall performance: $\Delta p/p = 1.0\%$ at 200 GeV/c. Impact parameter resolution: (15 + 29/ pT(GeV)) µm

Aaij R et al. 2014 JINST 9 P09007, Arink R et al. 2014 JINST 9 P01002

LHCb RICH detectors

The Ring Imaging Cherenkov detectors are crucial to identify different charged hadrons

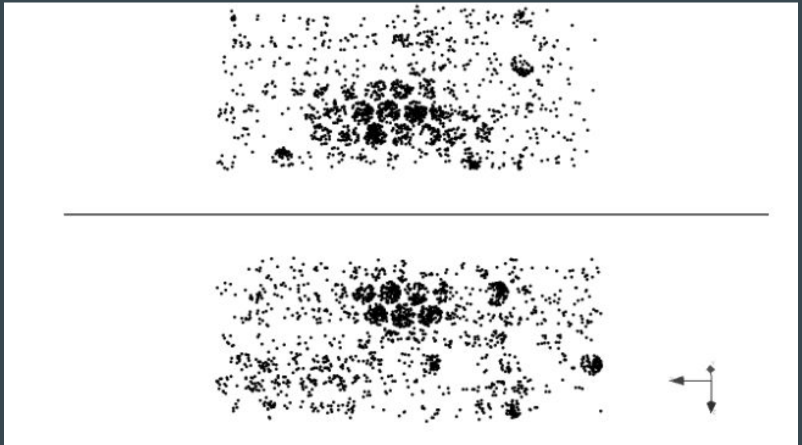
- RICH 1: Located at the exit of the the VELO detector. Momentum region covered 2 - 40 GeV/c (angular range 15–120 mrad). Material budget 8% X_0
- RICH 2: covering high momentum region: 15–100 GeV/c (angular range 15–120 mrad). Material budget 15% X_0
- Radiators: C_4F_{10} (RICH 1 n=1.0014) and CF_4 (RICH 2 n= 1.0005) operated at 0 C, 101.325 kPa

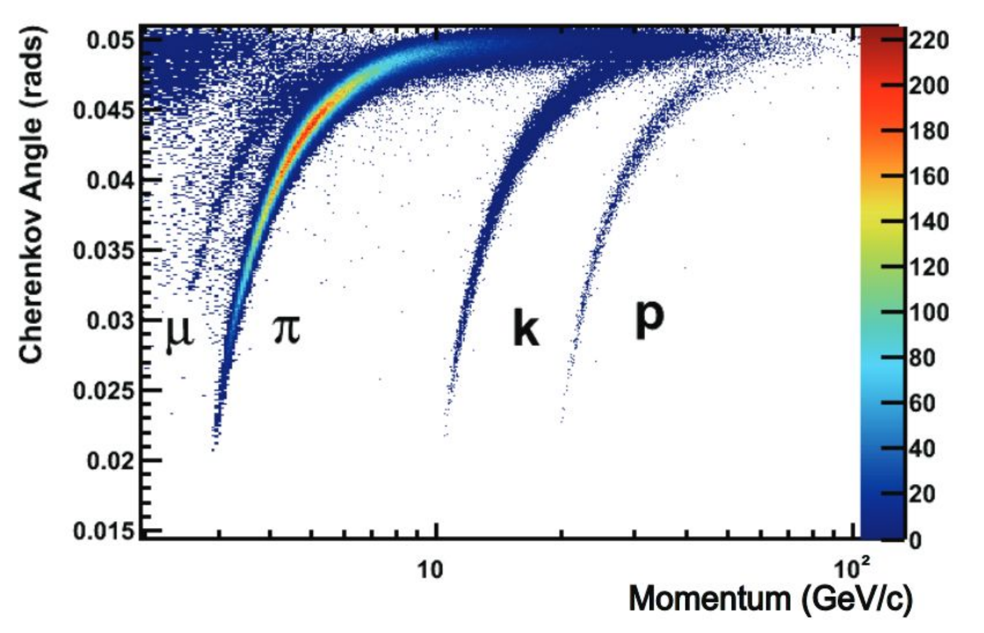


Adinolfi M et al. 2013 Eur. Phys. J. C73 2431

LHCb RICH detectors - particles separation

Typical LHCb event seen in RICH 1



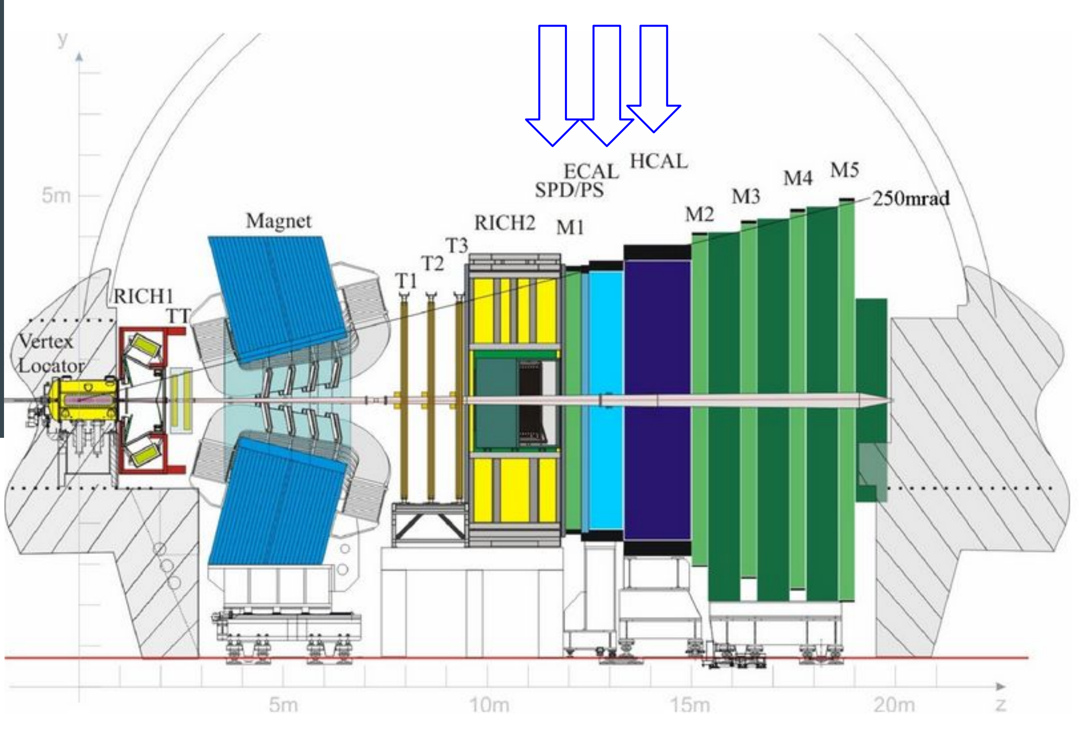


Adinolfi M et al. 2013 Eur. Phys. J. C73 2431

LHCb Calorimeter system

Divided in 4 sub-detectors, all using the same technology (Pb/Fe plates + plastic scintillator fibers)

- Scintillator Pad Detector (SPD)
- PreShower (PS)
- Electromagnetic CALorimeter (ECAL)
- Hadronic CALorimeter (HCAL),



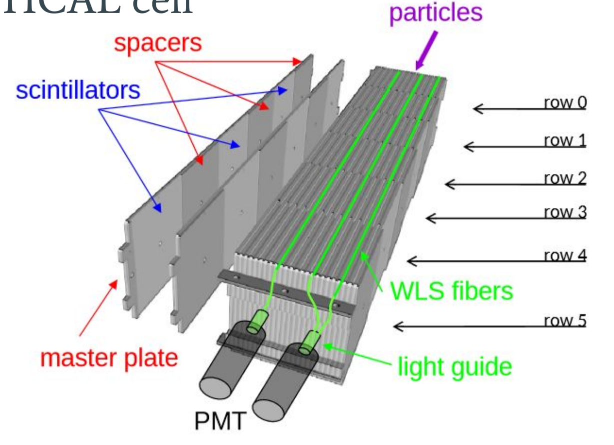
sub-detector	SPD/PS	ECAL	HCAL
number of channels	2×6016	6016	1488
overall lateral dimension in x, y	6.2 m × 7.6 m	6.3 m × 7.8 m	6.8 m × 8.4 m
cell size (mm) Inner	39.7 (SPD), 39,8 (PS)	40.4	131.3
cell size (mm) Middle	59.5 (SPD), 59.76 (PS)	60.6	
cell size (mm) Outer	119 (SPD), 119.5 (PS)	121.2	262.6
depth in z	180 mm, 2.5 X_0, 0.1 λ_{int}	835 mm, 25 X_0, 1.1 λ_{int}	1655 mm, 5.6 λ_{int}
light yield	~20 p.e./MIP	~3000 p.e./GeV	~105 p.e./GeV
dynamic range	0 - 100 MIP 10 bits (PS), 1 bit (SPD)	0 - 10 GeV E_T 12 bits	0 - 20 GeV E_T 12 bits

arXiv:2008.11556

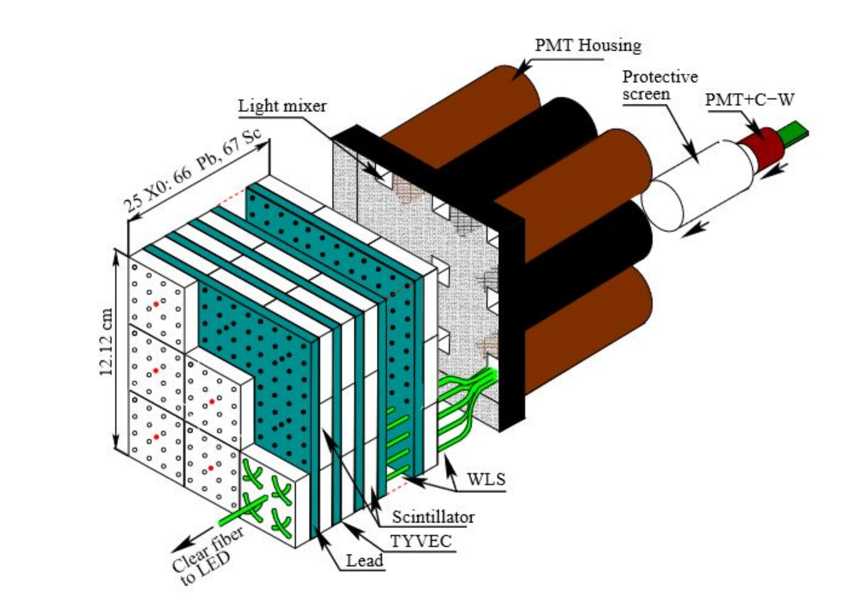
LHCb Calorimeter system

SPD cell

HCAL cell



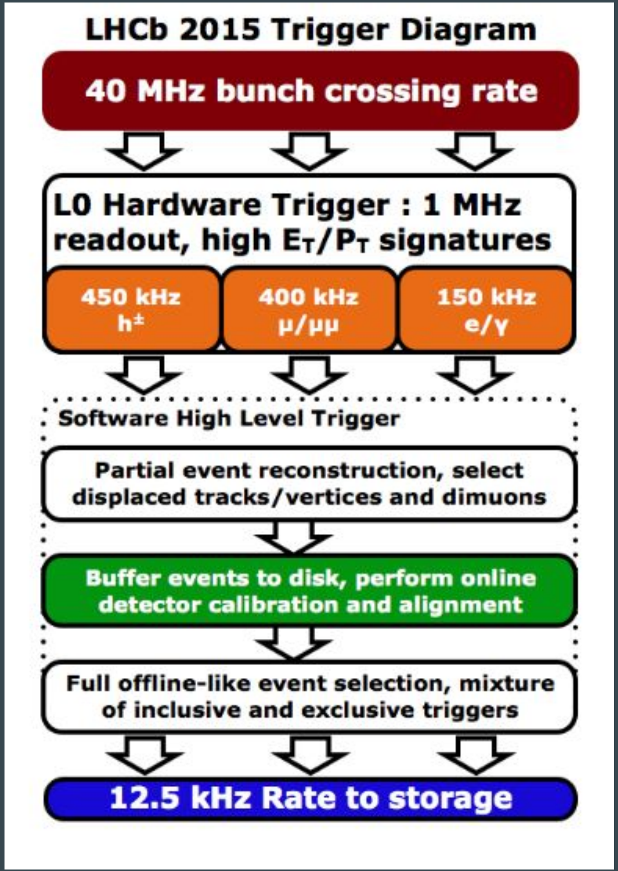
ECAL cell



arXiv:2008.11556

LHCb Detector - Trigger

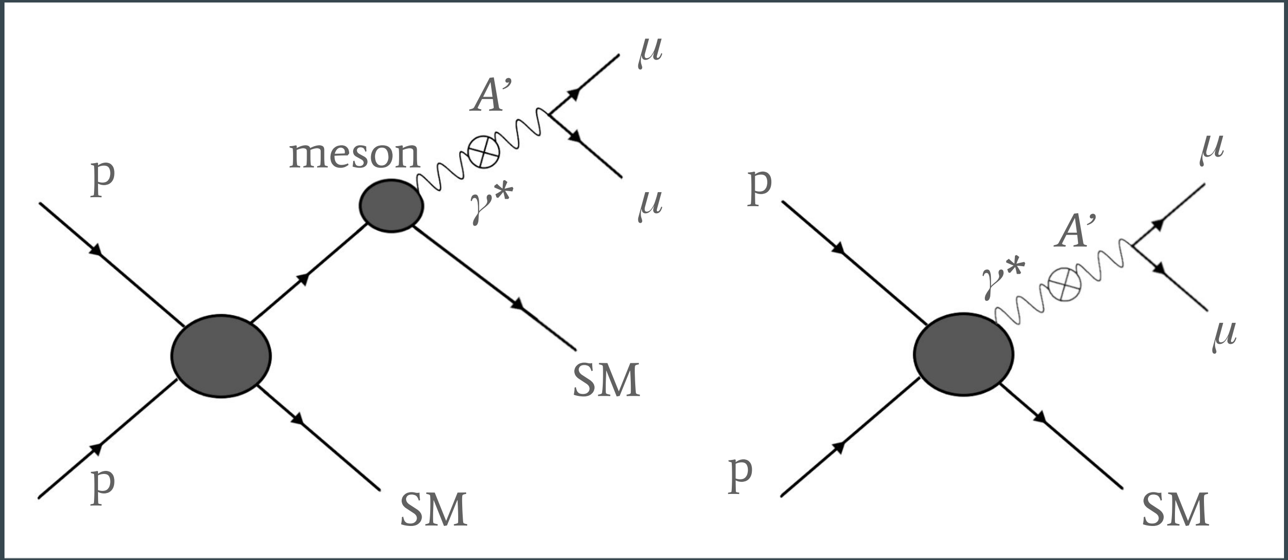
- ❖ Need to cope with very large events rate (40 MHz crossing rate during Run 2)
- ❖ Typical event dimension order of ~200 kB
- ❖ Critical to select events online to reduce the data stream to save to disk
- ❖ Multi-level trigger and online calibration procedure of the sub-detectors
  - ➢ L0: hardware level - information from calorimeters and muon systems
  - ➢ HLT1 & HLT2: high level software trigger: include tracking and RICH information to event selection



Aaij R et al. 2013 JINST 8 P04022
J. Phys. Conf. Ser. 664 (2015) 082010

Dark Photon Production in pp collisions

- Dark Photon production through different processes: meson decays (M(A’)<1 GeV) Drell-Yan (M(A’)> 1 GeV)
- In the visible decay scenario, A decay dominantly to SM leptons
- If **$m_{A'} > 2\, m_{\mu}$** dominant decay to muons → *clear signature at LHCb*



LHCb Dark Photon search

A' search in a data sample corresponding to an integrated luminosity of 1.6 fb^{-1}, collected with the LHCb detector in 2016 (LHC Run 2).

- *A'* inherits the production mode from the "original" γ^*
- the $A' \to \mu^+\mu^-$ yield can be normalised to $\gamma^* \to \mu^+\mu^-$
- Fully data-driven analysis

expected $\gamma^* \to \mu^+\mu^-$ yield

A'/γ^* detection efficiency ratio

$$n_{\mathrm{ex}}^{A'}[m(A'), \varepsilon^2] = \varepsilon^2 \left[\frac{n_{\mathrm{ob}}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]\, \epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')]$$

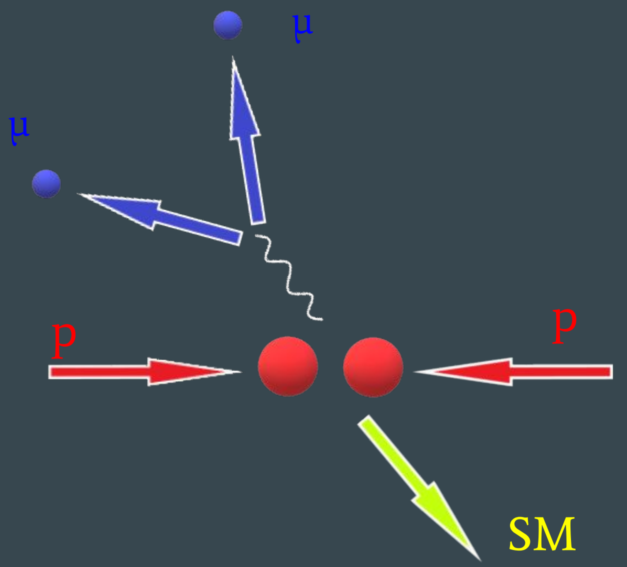
expected $A' \to \mu^+\mu^-$ yield

phase-space (known)

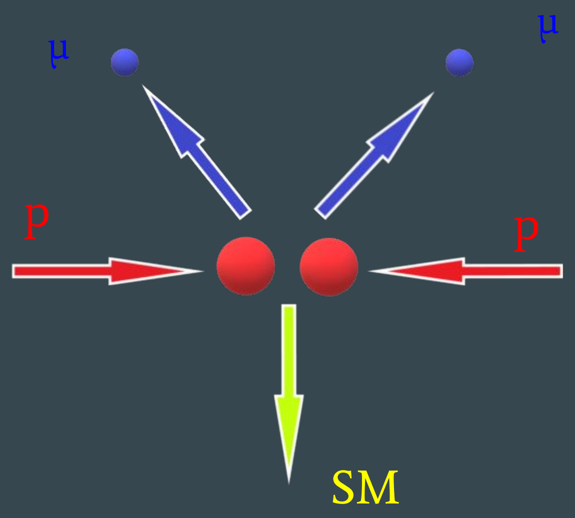
Data sample split: prompt VS long lived

Distinct signatures depending on the addressed region of the *A'* parameter space: if $c\tau_{A'}$ is larger than the detector vertex resolution, search for displaced vertex
→ Divide the data sample in two sub-sets, depending if the reconstructed vertex is consistent with primary vertex

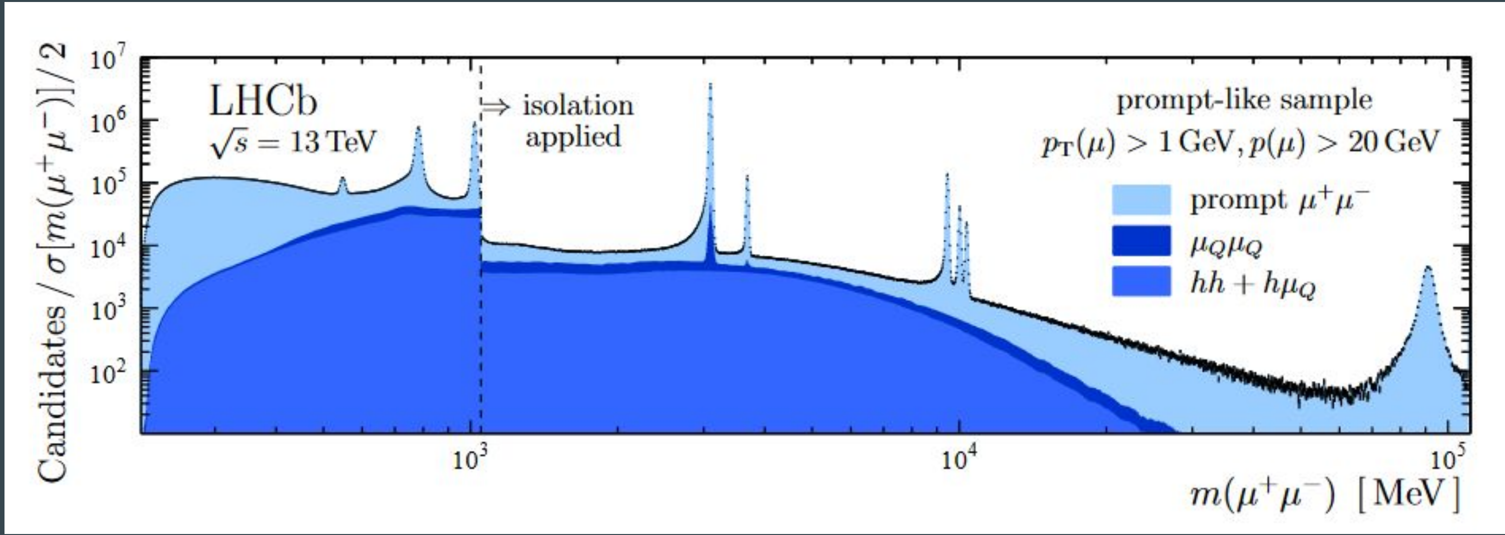
Displaced vertex



Prompt



Prompt Muon Spectrum



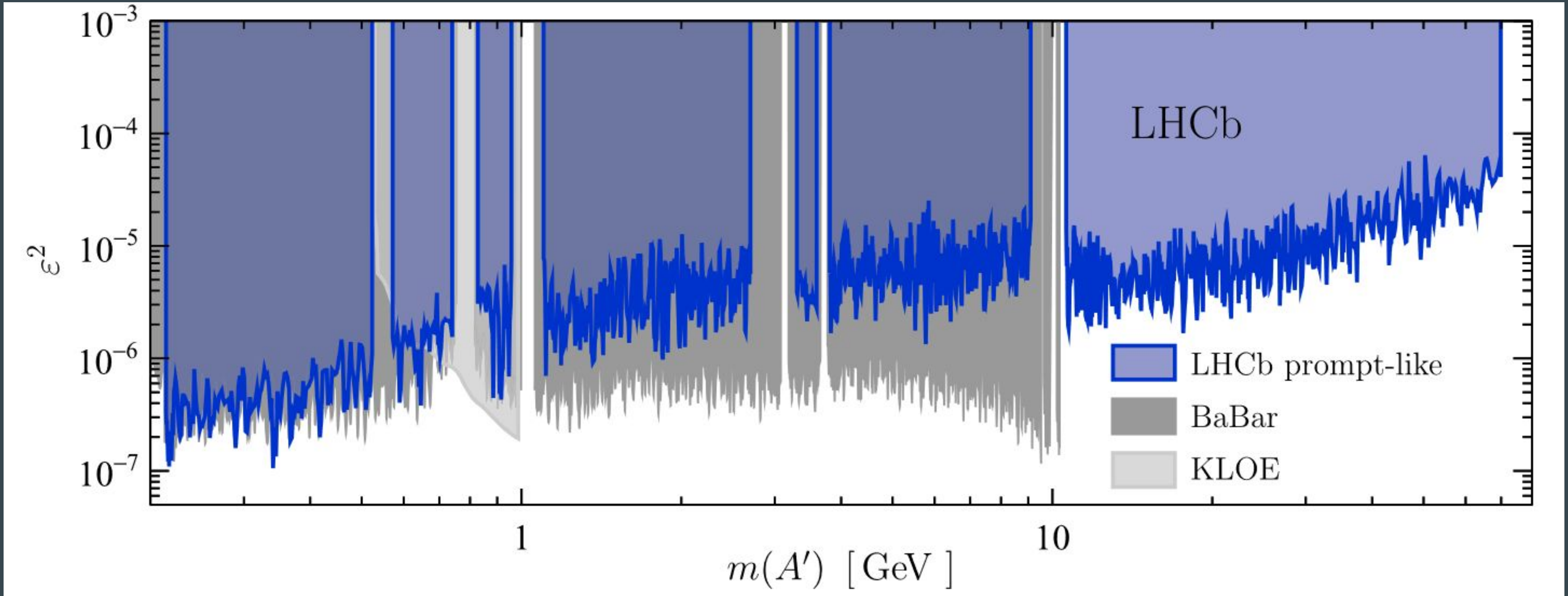
Main backgrounds for the prompt analysis:

- $\mu_Q\mu_Q$: 2 muons produced in a decay of a hadron containing a heavy-flavor quark, Q.
- *hh*: double misidentification of prompt hadrons as muons
- $h\mu_Q$: misidentified prompt hadron + muon produced in a decay of a hadron containing a heavy-flavor quark, Q.
- prompt γ* → μ+μ− production
- hadron resonant decays to μ+μ−

Search for Dark Photon - Prompt

Mass spectrum scanned in steps of σ[m(μ+μ−)]/2 searching for A′ → μ+μ− contributions. At each mass, a binned extended maximum likelihood fit is performed using all prompt-like candidates in a ±12.5σ[m(μ+μ−)] window around m(A′).

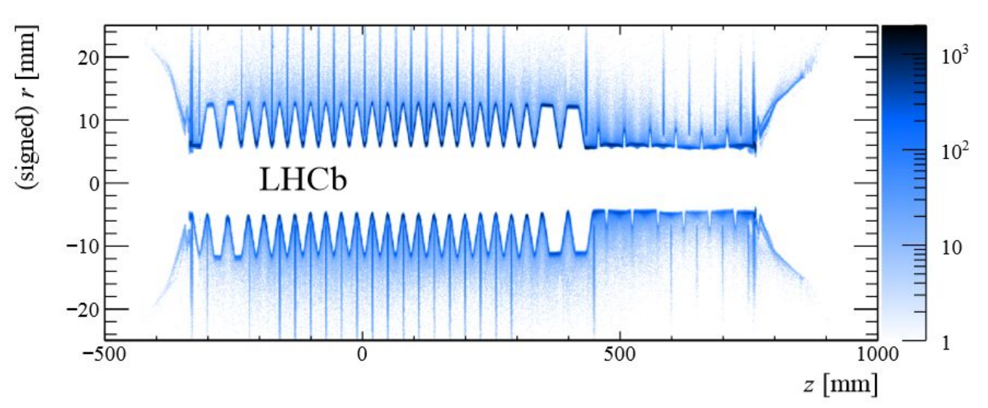
No significant excess found - exclusion regions at 90% C.L.



arXiv:1710.02867v2

Background for the long-lived *A'* search

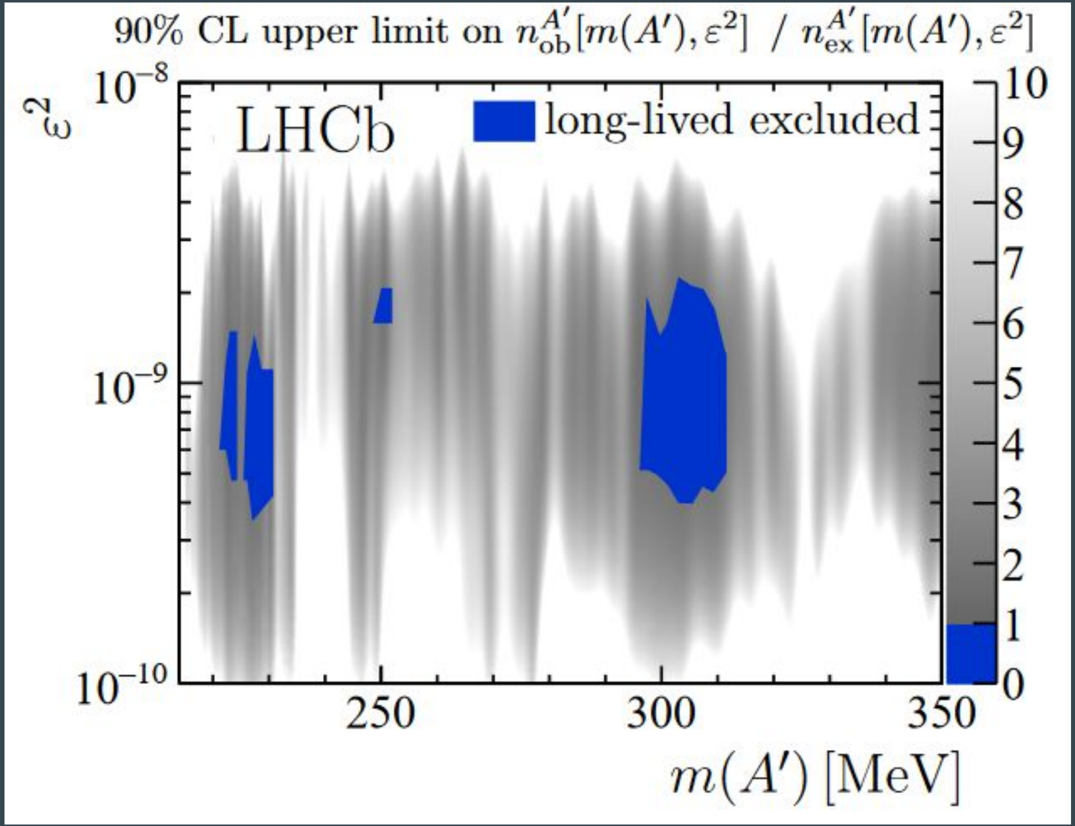
- Background dominated by photon conversion to a muon pair in the VELO detector material budget
- A high-precision three-dimensional material map was produced from a data sample of secondary hadron interactions
- A p-value is assigned to the photon-conversion hypothesis for each long-lived $A' \to \mu^+\mu^-$ candidate. A mass-dependent requirement is applied to the p-values, reducing the expected photon-conversion yields to a negligible level



arXiv:1803.07466

Search for Dark Photon - long lived

- Long-lived *A'* search limited to the 214-350 MeV mass range
- Loose requirements on the event selection w.r.t. the prompt analysis → larger efficiency
- Negligible contamination from prompt $\gamma^* \to \mu^+\mu^-$
- Fit in bins of mass and lifetime
- Extract p-values and confidence intervals from the fit
- No significant excess observed → set limits in a small region of the parameter space



arXiv:1710.02867v2

Other visible *A'* searches at colliders

Other relevant results in the *A'* visible decay search from the BaBar and CMS experiments.

- BaBar: e+e- collider, search for *A'→e+e-*
- CMS: search for A' → μ+μ− from Higgs decays