Hunt for dark photons

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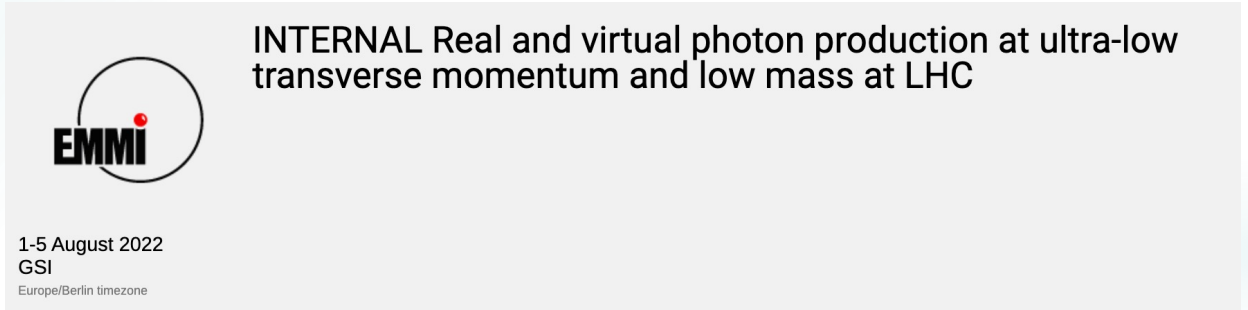

White Paper

https://arxiv.org/pdf/2203.05939.pdf

Snowmass 2021 White Paper*

Opportunities for new physics searches with heavy ions at colliders

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Abstract

Opportunities for searches for phenomena beyond the Standard Model (BSM) using heavy-ions beams at high energies are outlined. Different BSM searches proposed in the last years in collisions of heavy ions, mostly at the Large Hadron Collider, are summarized. A few concrete selected cases are reviewed including searches for axion-like particles, anomalous τ electromagnetic moments, magnetic monopoles, and dark photons. Expectations for the achievable sensitivities of these searches in the coming years are given. Studies of CP violation in hot and dense QCD matter and connections to ultrahigh-energy cosmic rays physics are also mentioned.

*White paper submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021).

- BSM via photon-photon collisions
  - The resonant production of axion-like particles
  - Search for magnetic monopoles
  - Searches for anomalous electromagnetic moments of the τ lepton

Adam, tomorrow

- **Searches for dark photons**
  - **One of the possible candidate particles proposed as DM mediators**

- Chiral effects in hot and dense QCD matter
  - Studies of structures with nontrivial topology in the QCD vacuum, which determine the behavior of the P/CP fundamental symmetries in hot quark-gluon matter

Dark Photons: Introduction

- Dark Photons are hypothetical extra-U(1) gauge bosons, which are motivated by:
  - antiproton spectrum in the cosmic rays measured by AMS Collaboration
  - positron excess in the cosmic rays observed earlier by PAMELA and confirmed by FERMI and AMS
  - muon anomalous magnetic moment of the muon, $(g-2)\mu$.

$$L = L_{SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m^2_{A'}A'_{\mu}A'^{\mu} + \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$

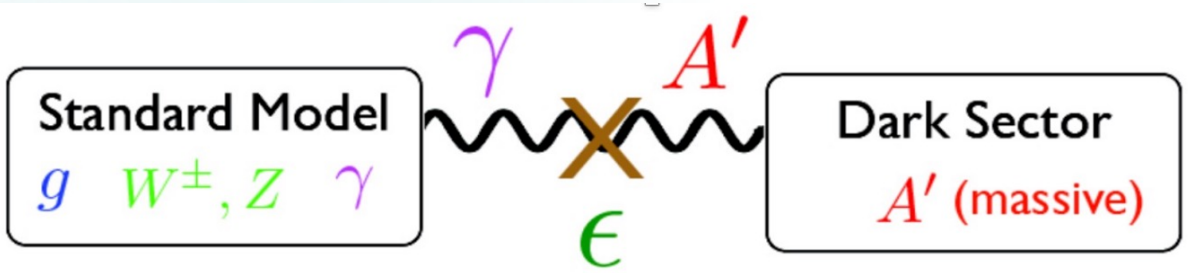
Standard Model Lagrangian

Additional U(1) symmetry describing the new force carried by a massive vector boson, ***the Dark photon A'***

Kinetic mixing term with the ***standard photon γ***

The kinetic mixing between the SM photons and the hypothetical Dark Photon.

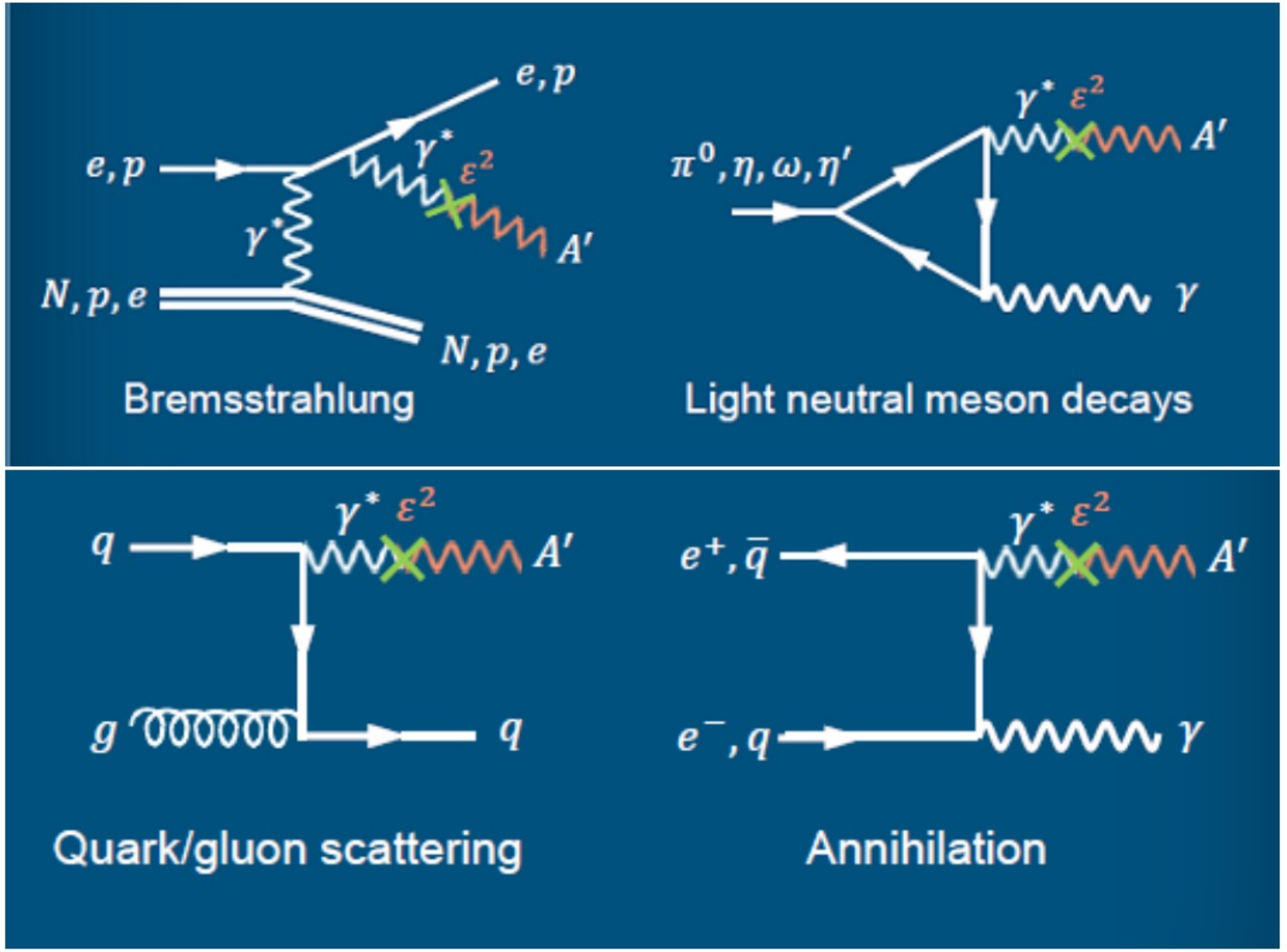
Interaction between the Standard Model sector and the Dark Sector via a Dark Photon



$m_{A'}$ and ε

Dark Photons: Production

- Production:
  - Bremsstrahlung
  - Meson decays
  - Annihilation
    - ee, qqbar
  - Quark-gluon scattering
  - V(ϱ, ω, ϕ) – A′ mixing

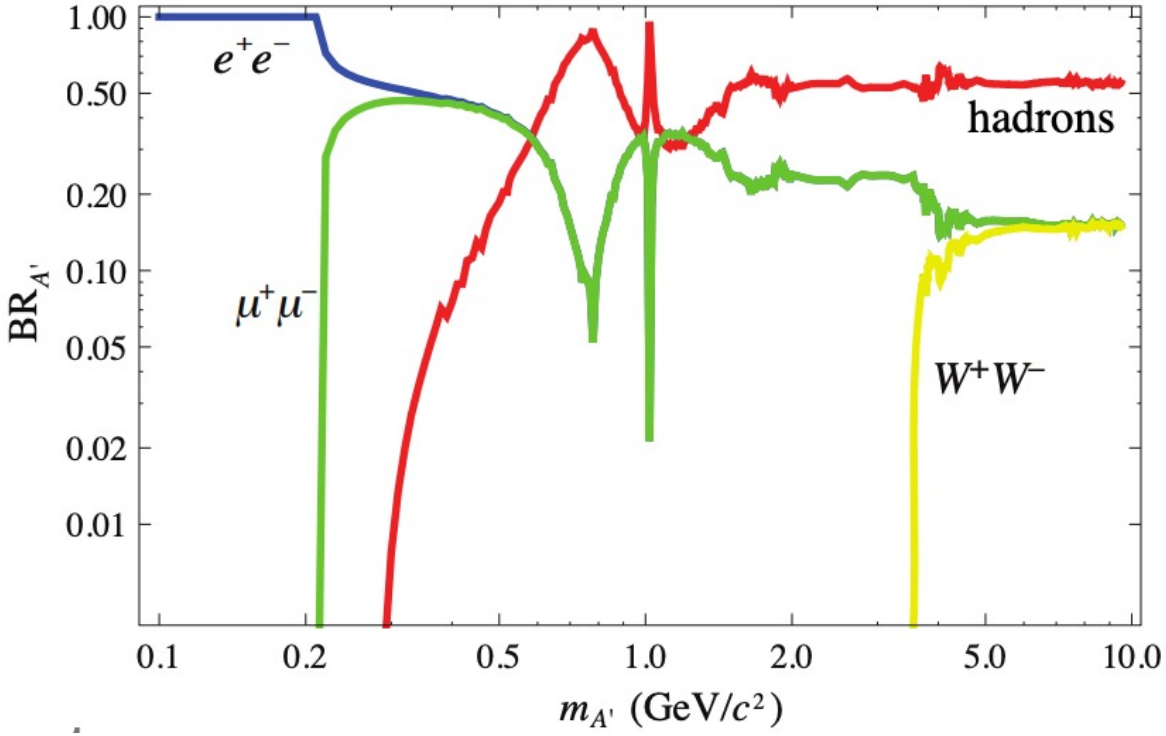


R. Jacobsson (CERN)
LHC Operations
Workshop, Evian, 2019

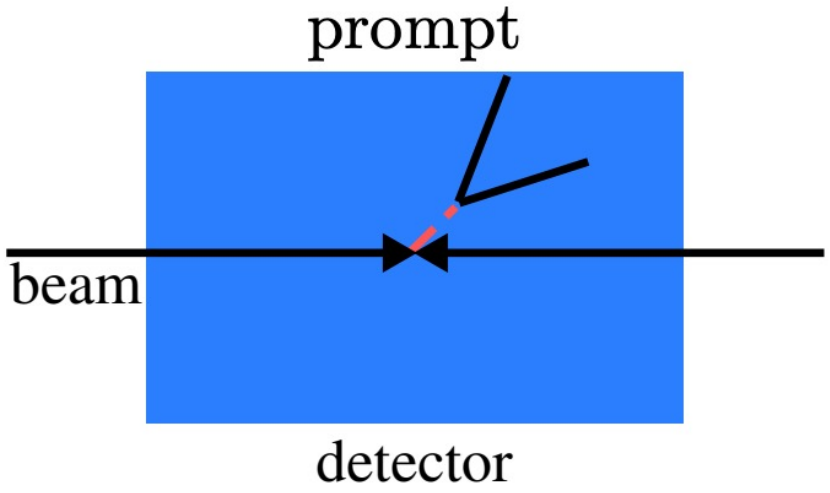
Dark Photons: Decays

- Decays:
  - Visible decays (No DM with $m_{DM} < m_{A'}/2$)
    - $A' \rightarrow$ SM particles
  - Invisible decays (DM with $m_{DM} < m_{A'}/2$ exists)
    - $A' \rightarrow$ DM with BR~1
      - SM decays suppressed by a factor ε^2

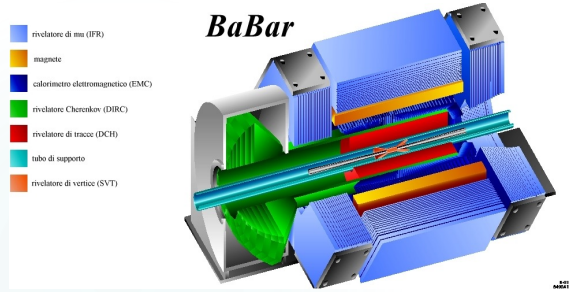
A′ visible decay Br



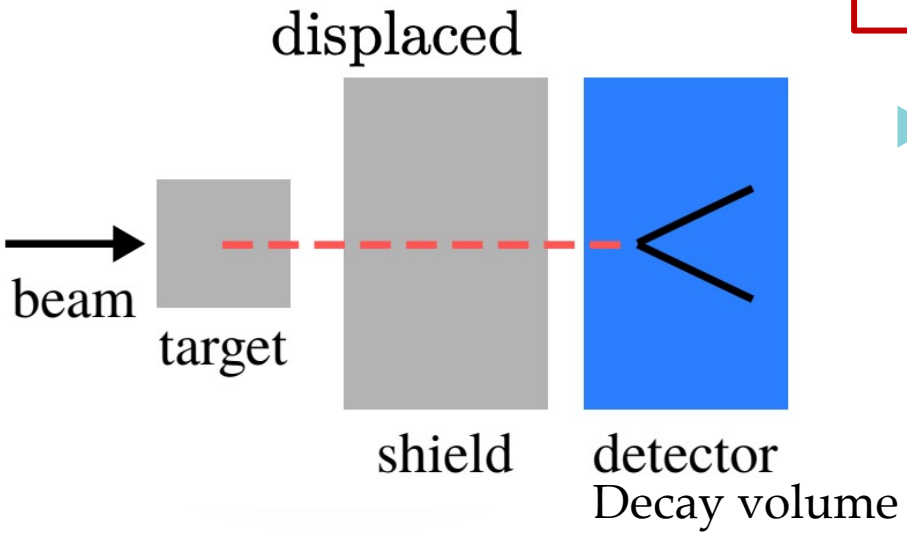
Dark Photons: Searches



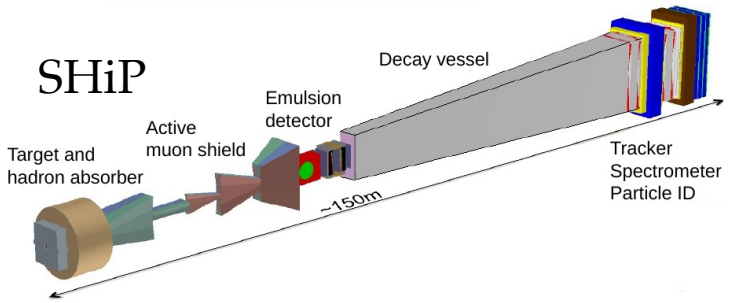
- Prompt searches
  - Sensitive to shorter lifetimes
  - Bump hunt on large background

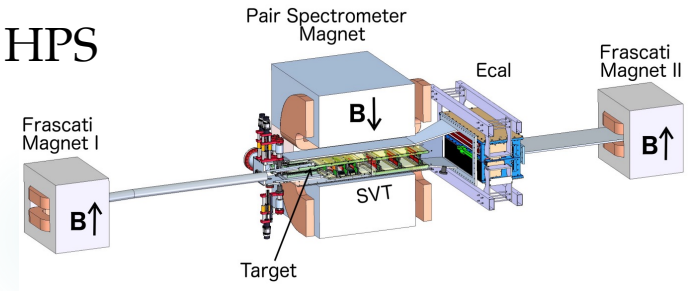


$$\tau\left(\mathrm{A}'\right) \propto \left[m\left(\mathrm{A}'\right)\epsilon^2\right]^{-1}$$

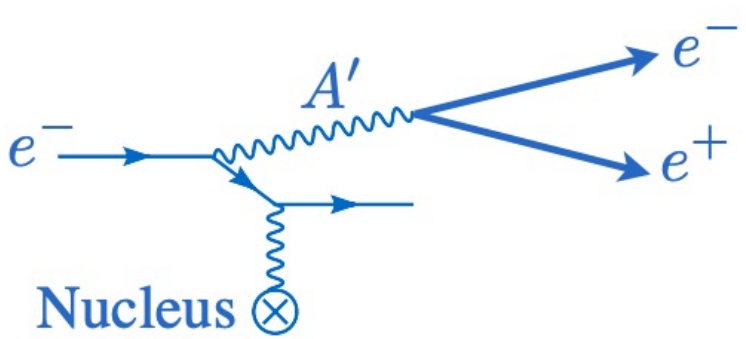


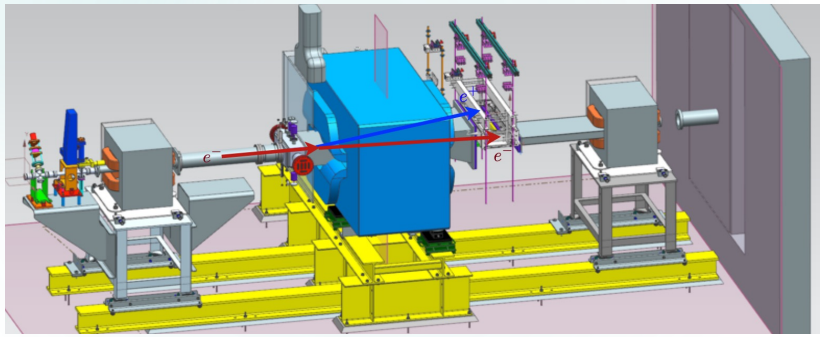
- Displaced searches
  - Sensitive to longer lifetimes (smaller ε region)
  - Background free



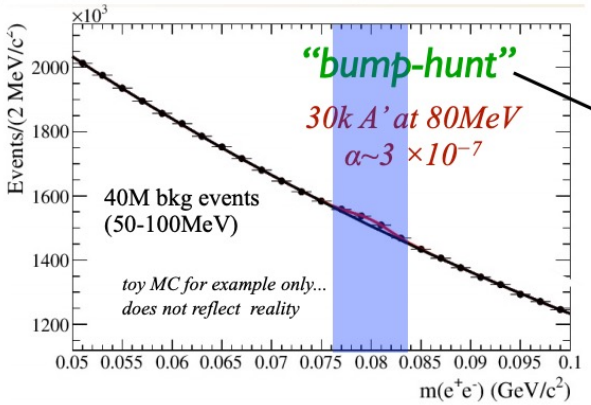


HPS (The Heavy Photon Search) at J-Lab.



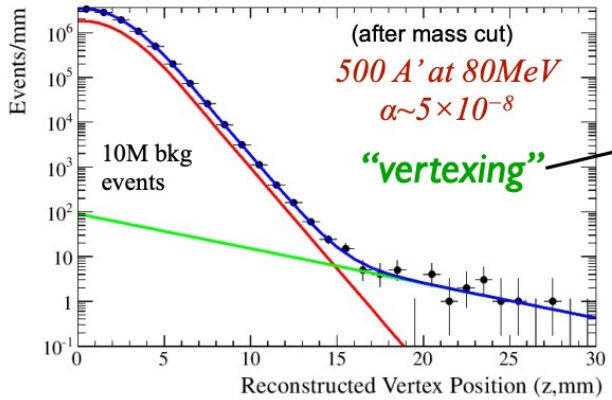


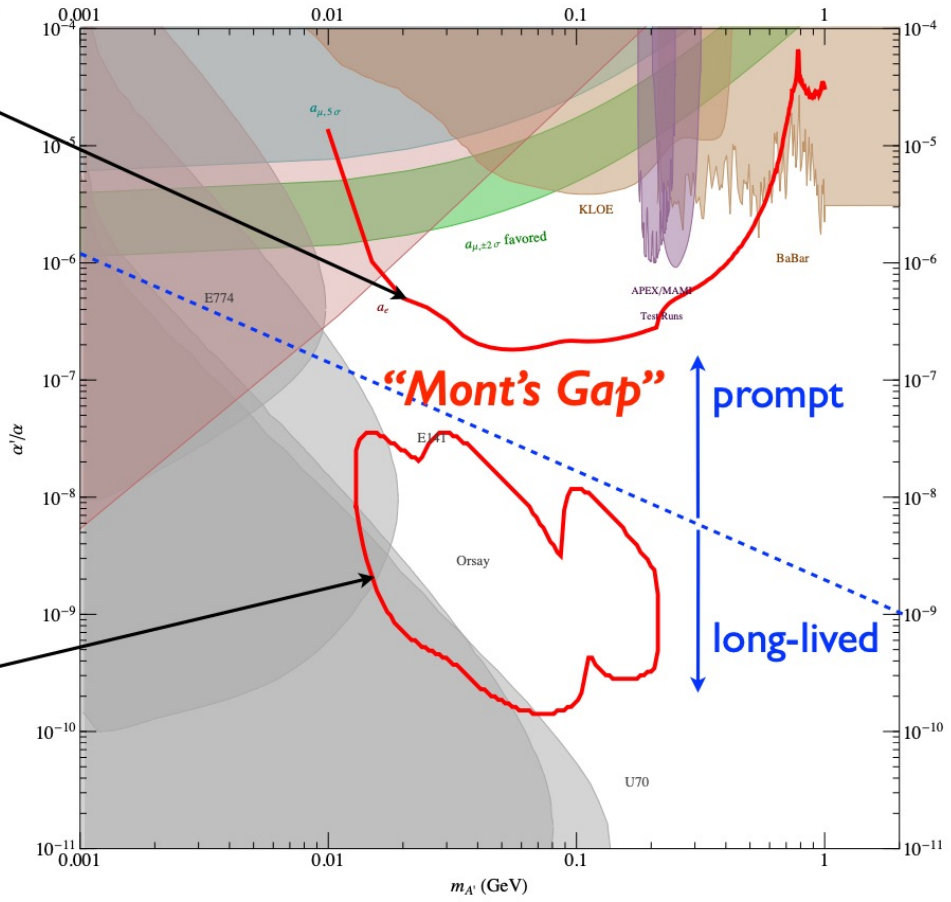
Large signal, *HUGE* background



vertexing

Small signal, *NO* background

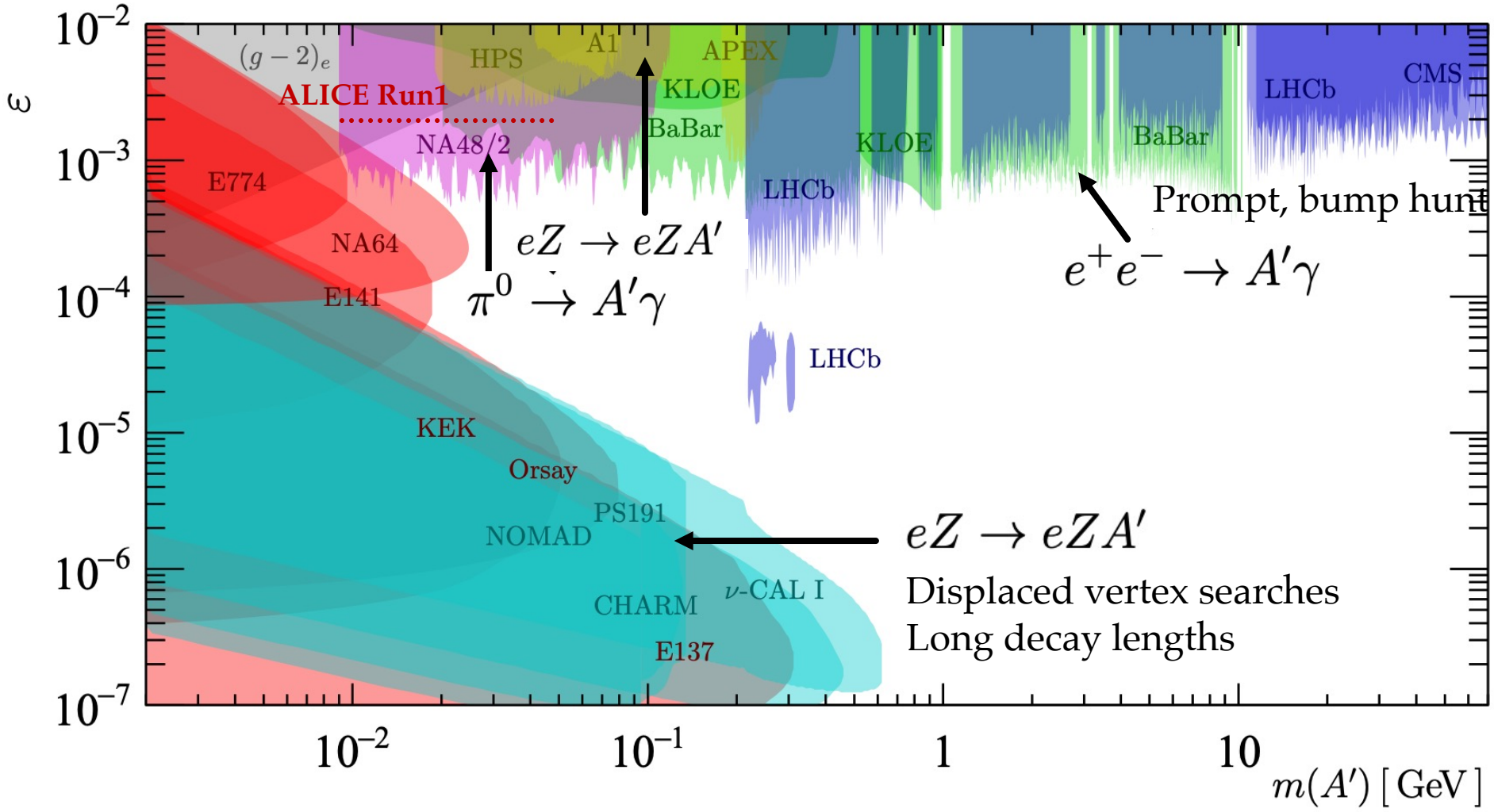




$$\tau\left(\mathrm{A}'\right) \propto \left[m\left(\mathrm{A}'\right)\epsilon^2\right]^{-1}$$

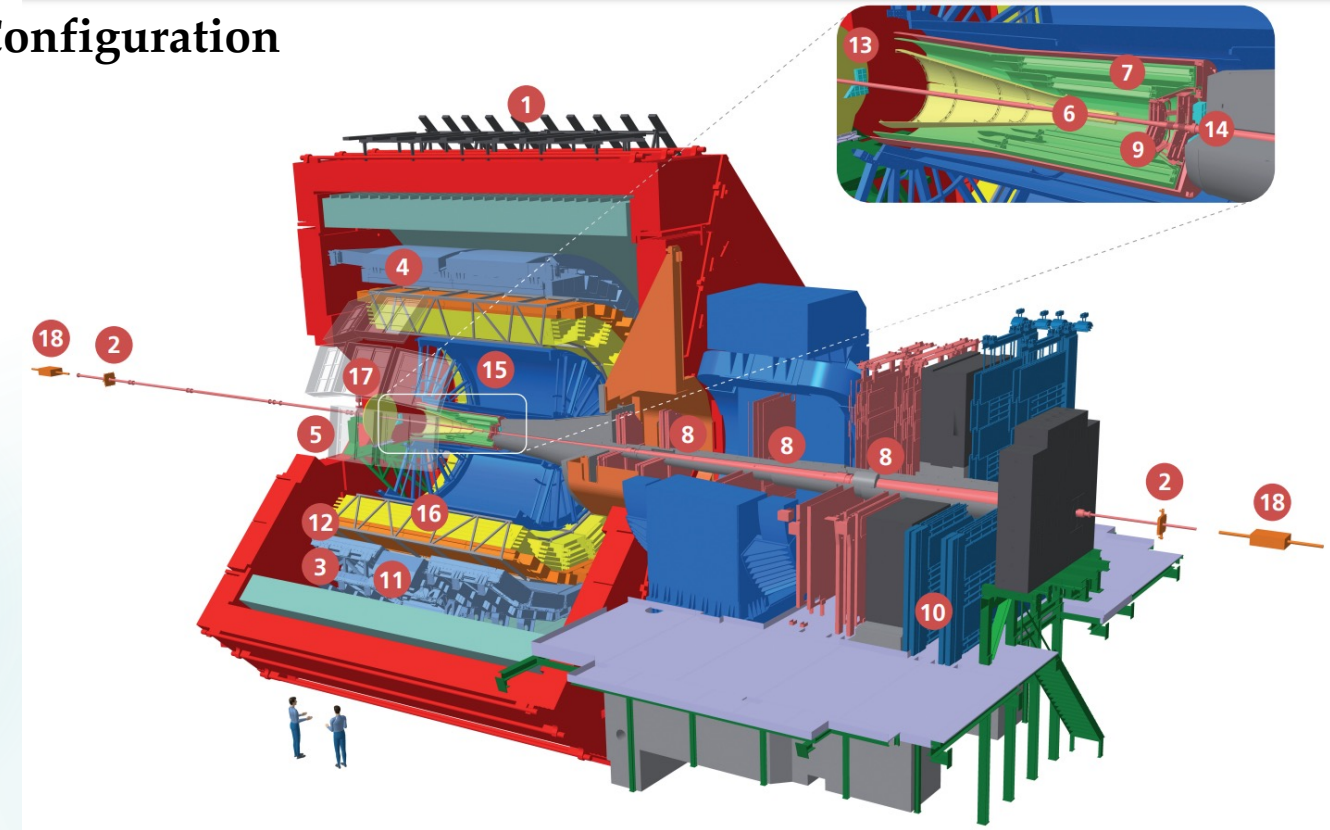
Current Limits

arXiv:2104.10280



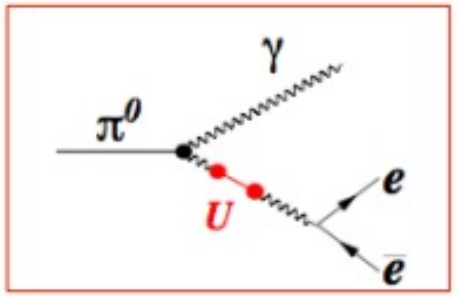
ALICE Detectors

Run3 Configuration



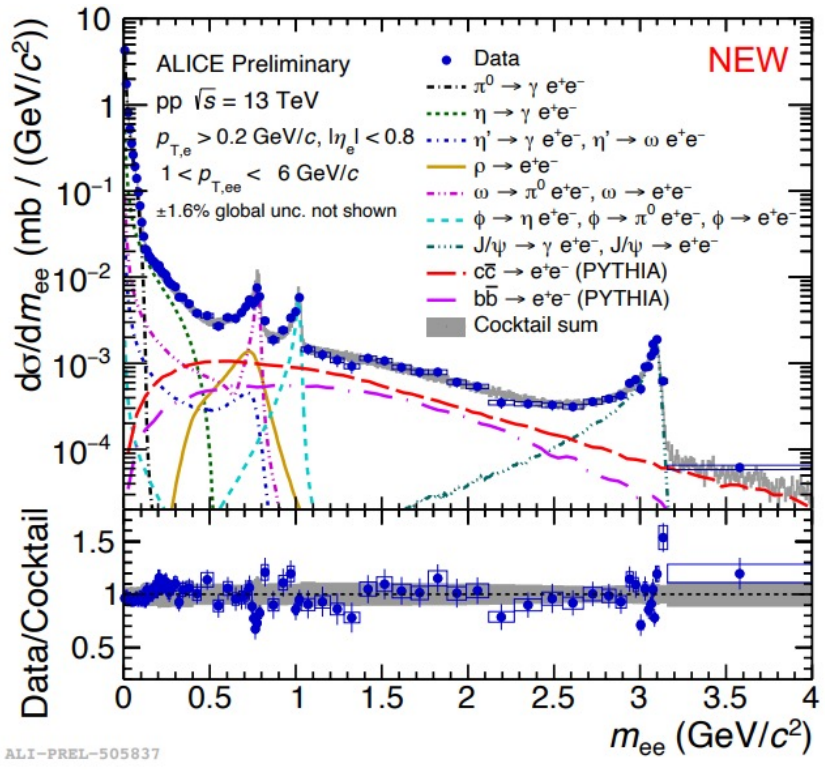
1. **ACORDE** | ALICE Cosmic Rays Detector
2. **AD** | ALICE Diffractive Detector
3. **DCal** | Di-jet Calorimeter
4. **EMCal** | Electromagnetic Calorimeter
5. **HMPID** | High Momentum Particle Identification Detector
6. **ITS-IB** | Inner Tracking System - Inner Barrel
7. **ITS-OB** | Inner Tracking System - Outer Barrel
8. **MCH** | Muon Tracking Chambers
9. **MFT** | Muon Forward Tracker
10. **MID** | Muon Identifier
11. **PHOS / CPV** | Photon Spectrometer
12. **TOF** | Time Of Flight
13. **T0+A** | Tzero + A
14. **T0+C** | Tzero + C
15. **TPC** | Time Projection Chamber
16. **TRD** | Transition Radiation Detector
17. **V0+** | Vzero + Detector
18. **ZDC** | Zero Degree Calorimeter

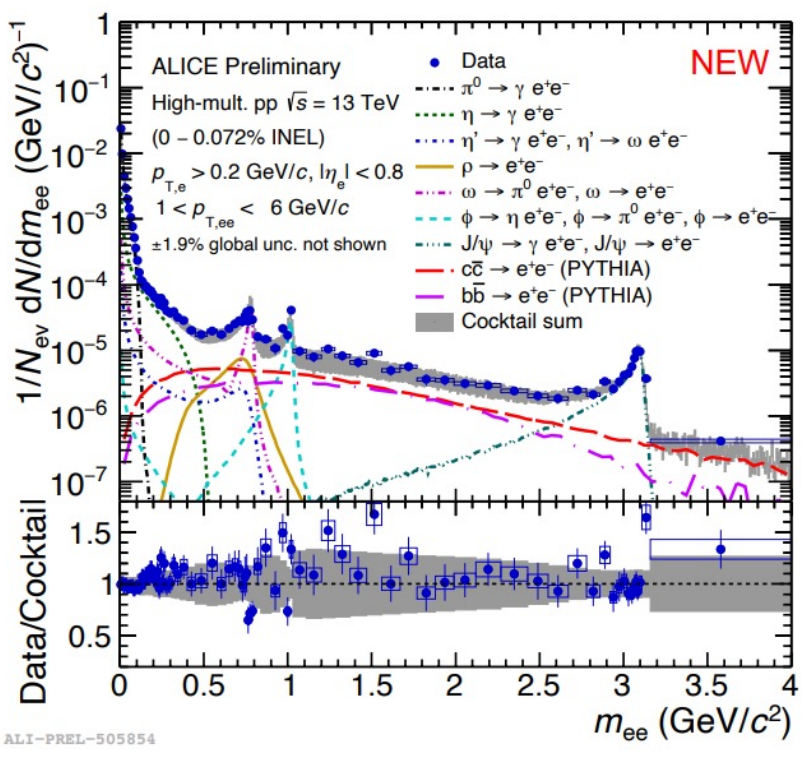
- Dedicated to the heavy-ion physics at the LHC
- Multi-purpose experiment with different detectors to measure PID-hadrons, leptons, photons, heavy flavors, and jets.
- Large acceptance for lower p_T electrons
- Dark photon searches through dielectron channels

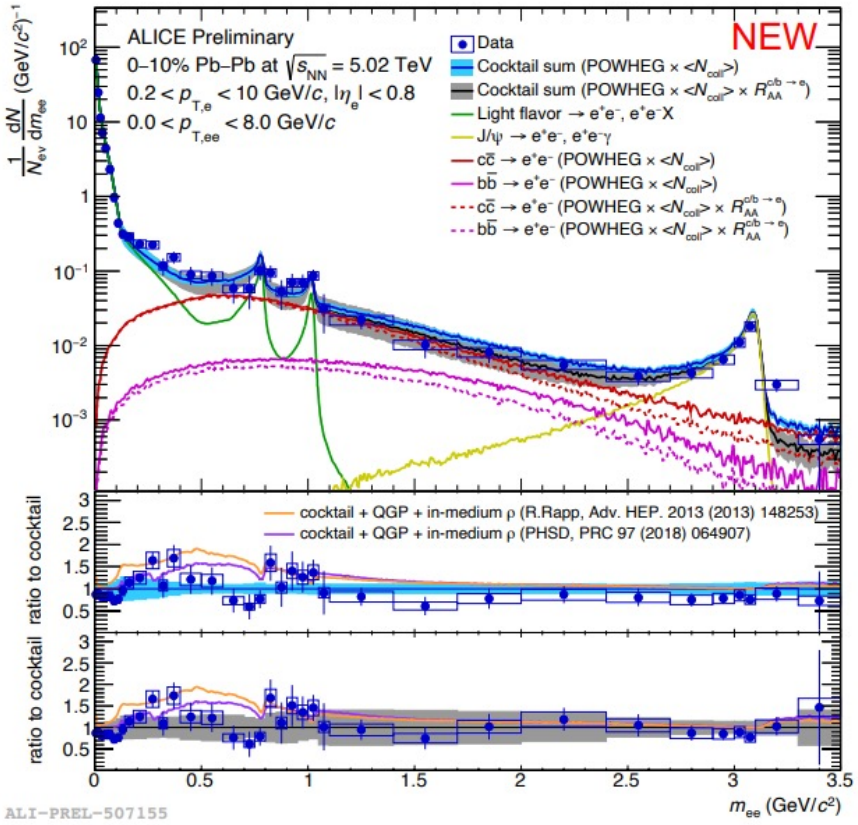


Dielectron measurements in ALICE

Latest results from Run2 for pp and Pb-Pb collisions







Low mass dielectron yields are well consistent with cocktail calculations
Dark Photon searches with ALICE using Meson Dalitz decays

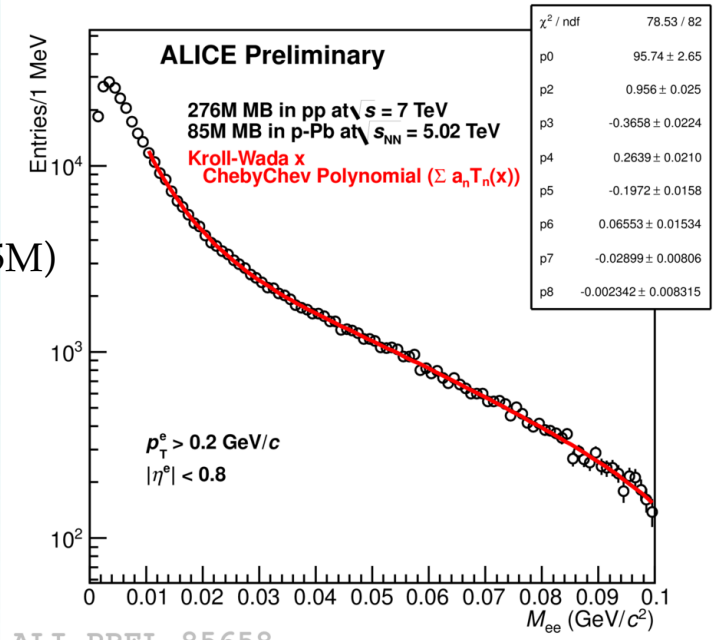
ALICE RUN1 limits

- LMee in π^0 Dalitz decays
  - 20 <M_{ee} < 100 MeV
    - Prompt-like (no displaced vertex)
    - Free from conversions (>20 MeV)
  - Run1 data
    - pp 7 TeV (276 MB), p-Pb 5.02 TeV (85 M)

pp (276M) and p-Pb (85M)

92k pairs in

20< M_{ee}<100 MeV.

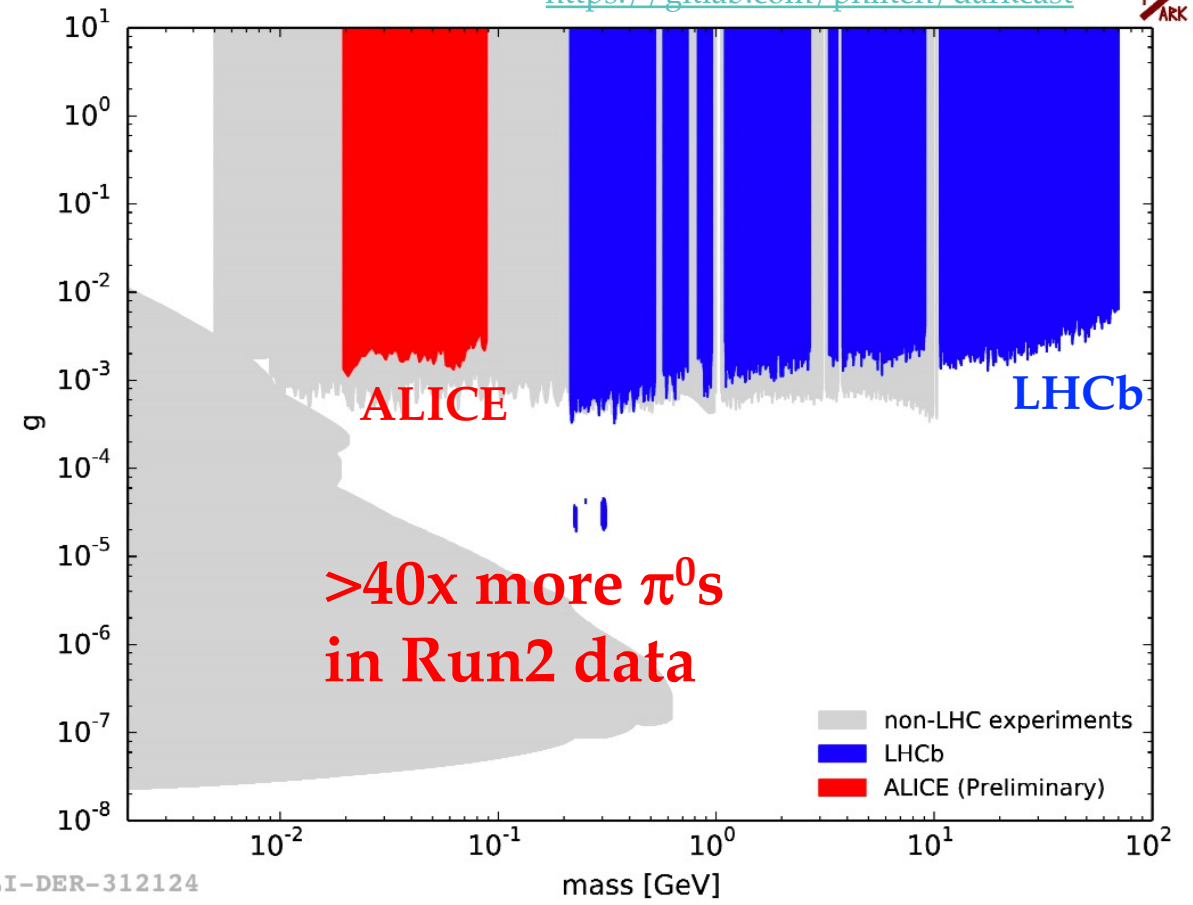


ALI-PREL-85658

$$R(m_U) = (dN_{ee}/dm_{ee})_{\pi^0,\eta\to\gamma U}/(dN_{ee}/dm_{ee})_{\pi^0,\eta\to\gamma e^+e^-},$$

$$\varepsilon^2 = \frac{2\alpha_{EM}}{3\pi}\frac{\sigma}{m_U}\sqrt{2\pi}R(m_U)$$

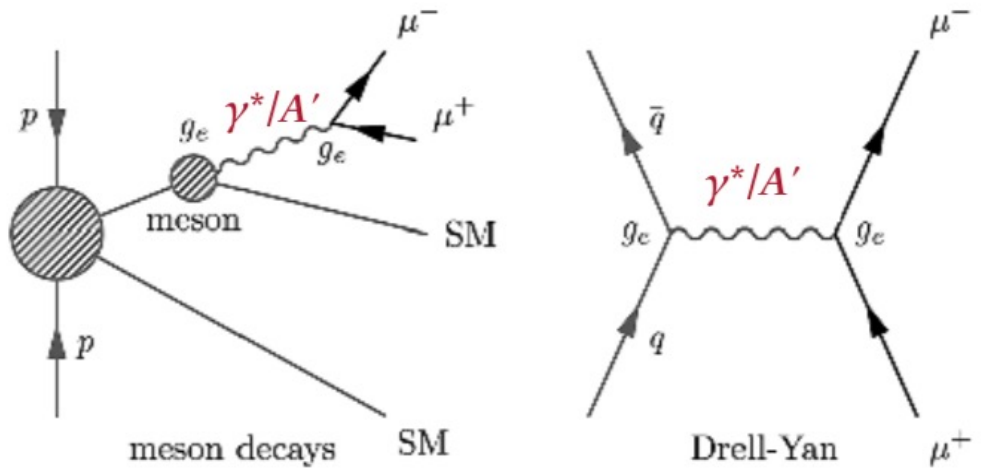
https://gitlab.com/philten/darkcast

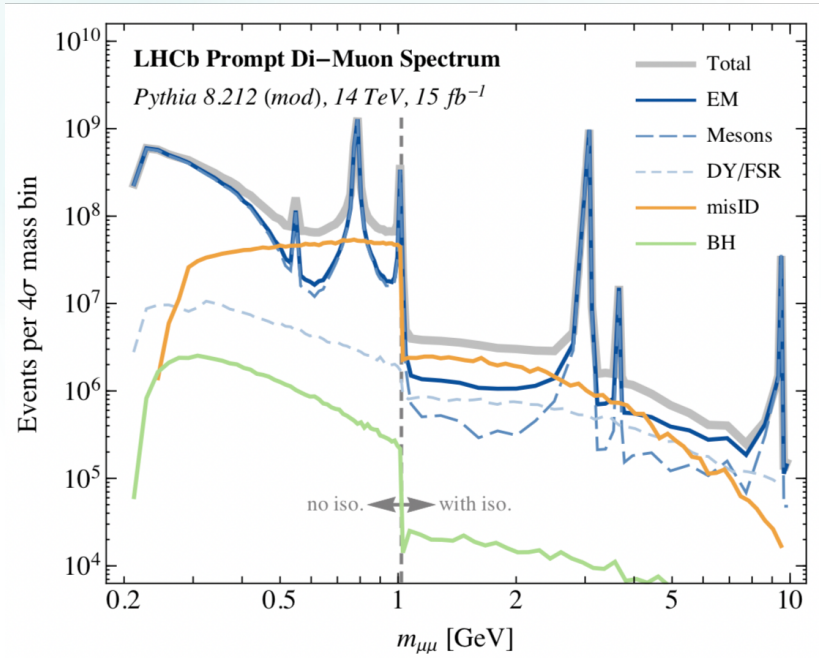


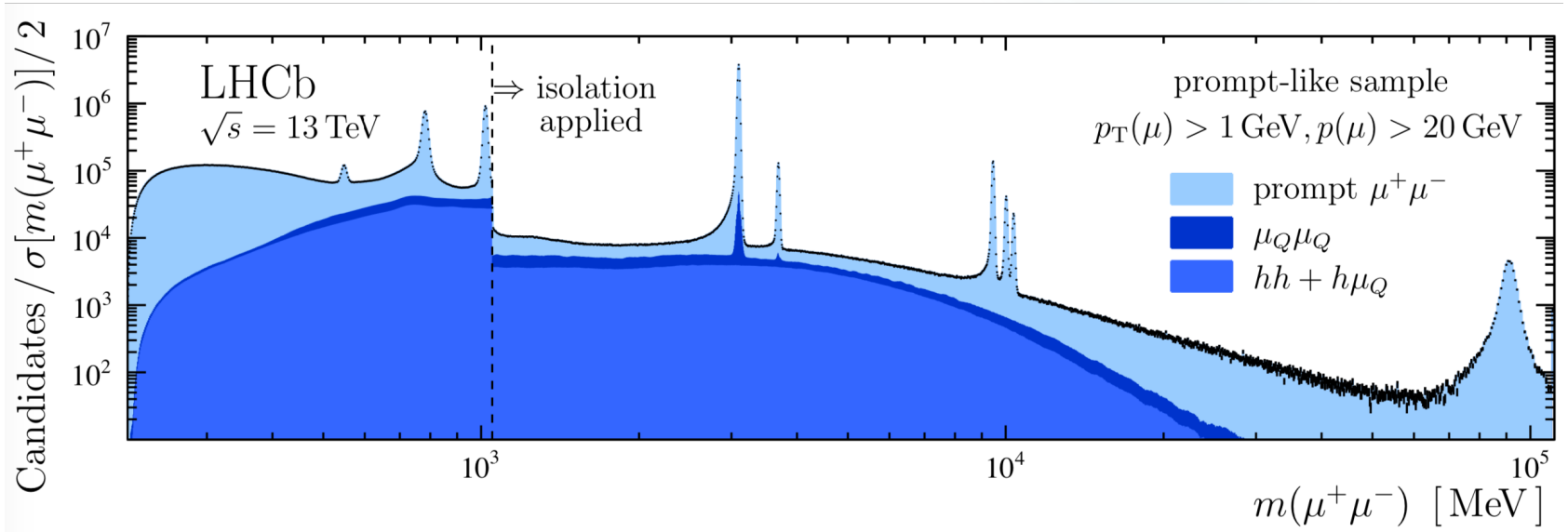
ALI-DER-312124

Dark Photon searches in LHCb

- Search for dark photons decaying into **a pair of muons**
  - **Prompt searches**
    - **Meson decays : M(A′)<1 GeV**
    - **Drell-Yan: M(A′)> 1 GeV**

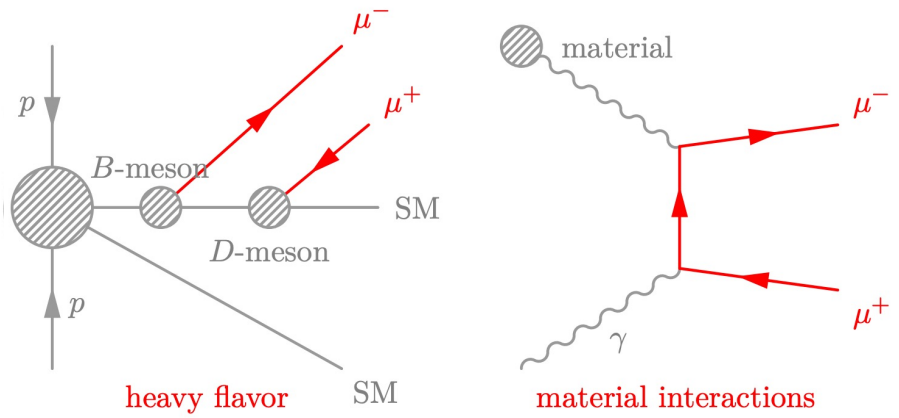


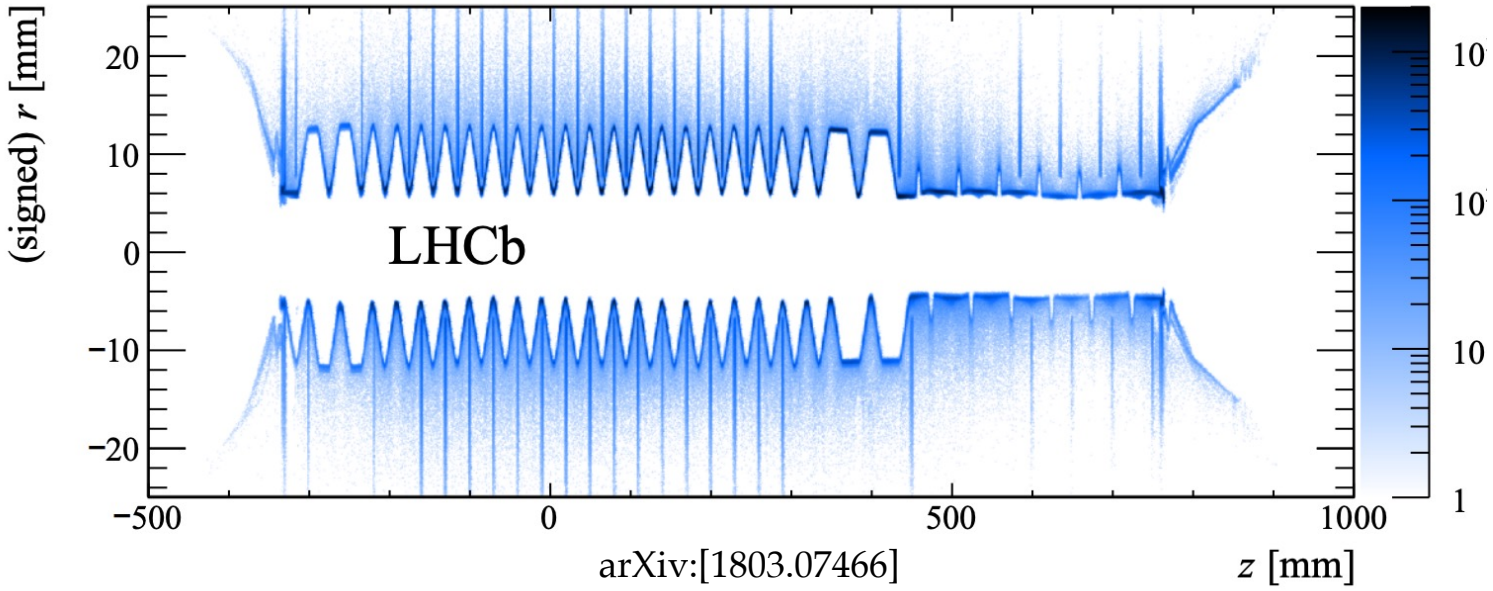




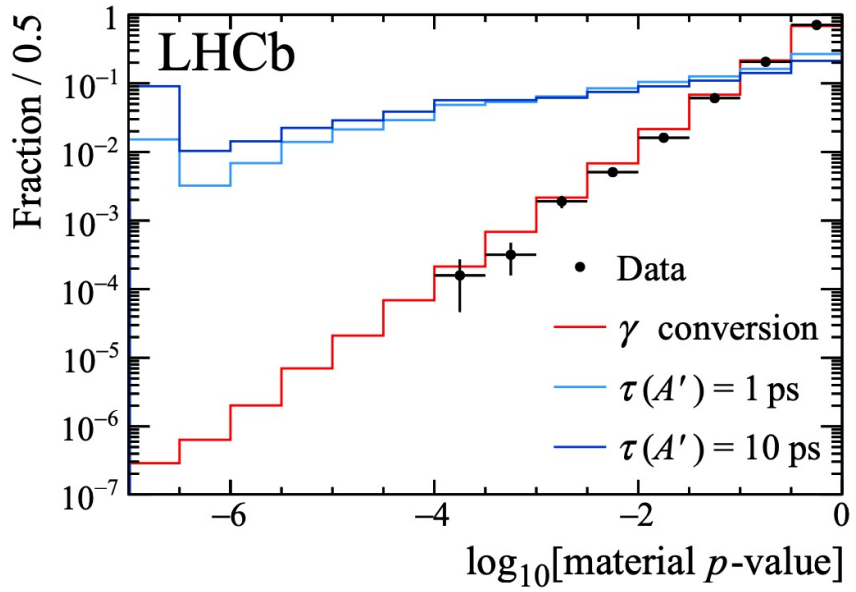
Dark Photon searches in LHCb

- Search for dark photons decaying into **a pair of muons**
  - **Displaced searches (0.1 – 1cm) for long lived A′ search**
    - Background dominated by **material interactions**
    - Precise knowledge of the location of the material in the LHCb VELO is essential to reduce the background in searches for long-lived exotic particles



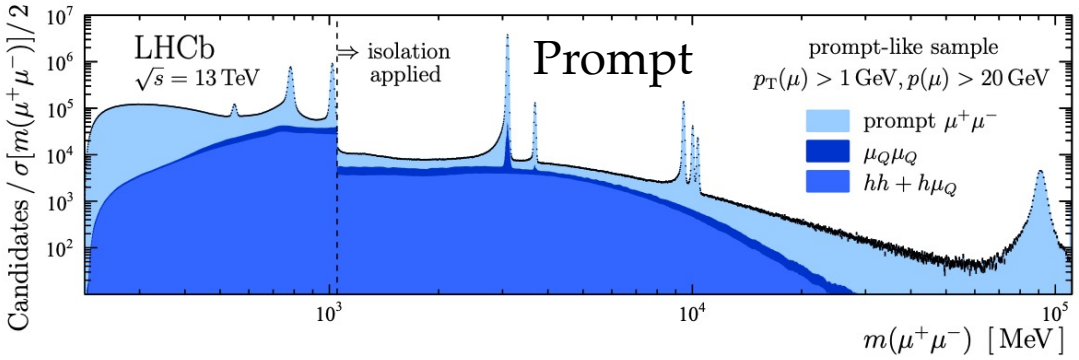


arXiv:[1803.07466]

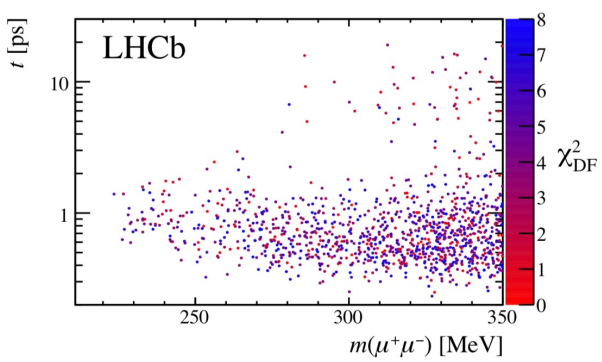


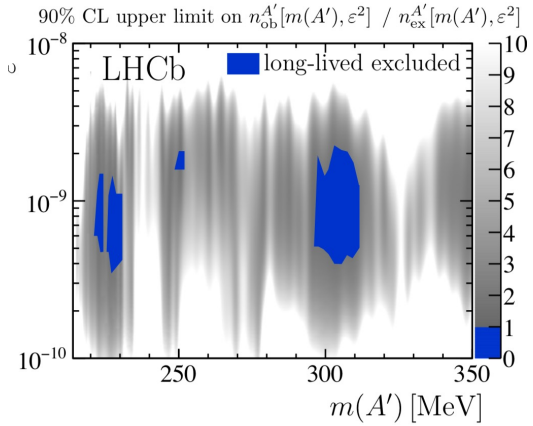
LHCb limits

- LHCb
  - Prompt-like and long-lived dark photons
  - pp 13 TeV 1.6 fb^{-1} (Run1+Run2: 9 fb^{-1})



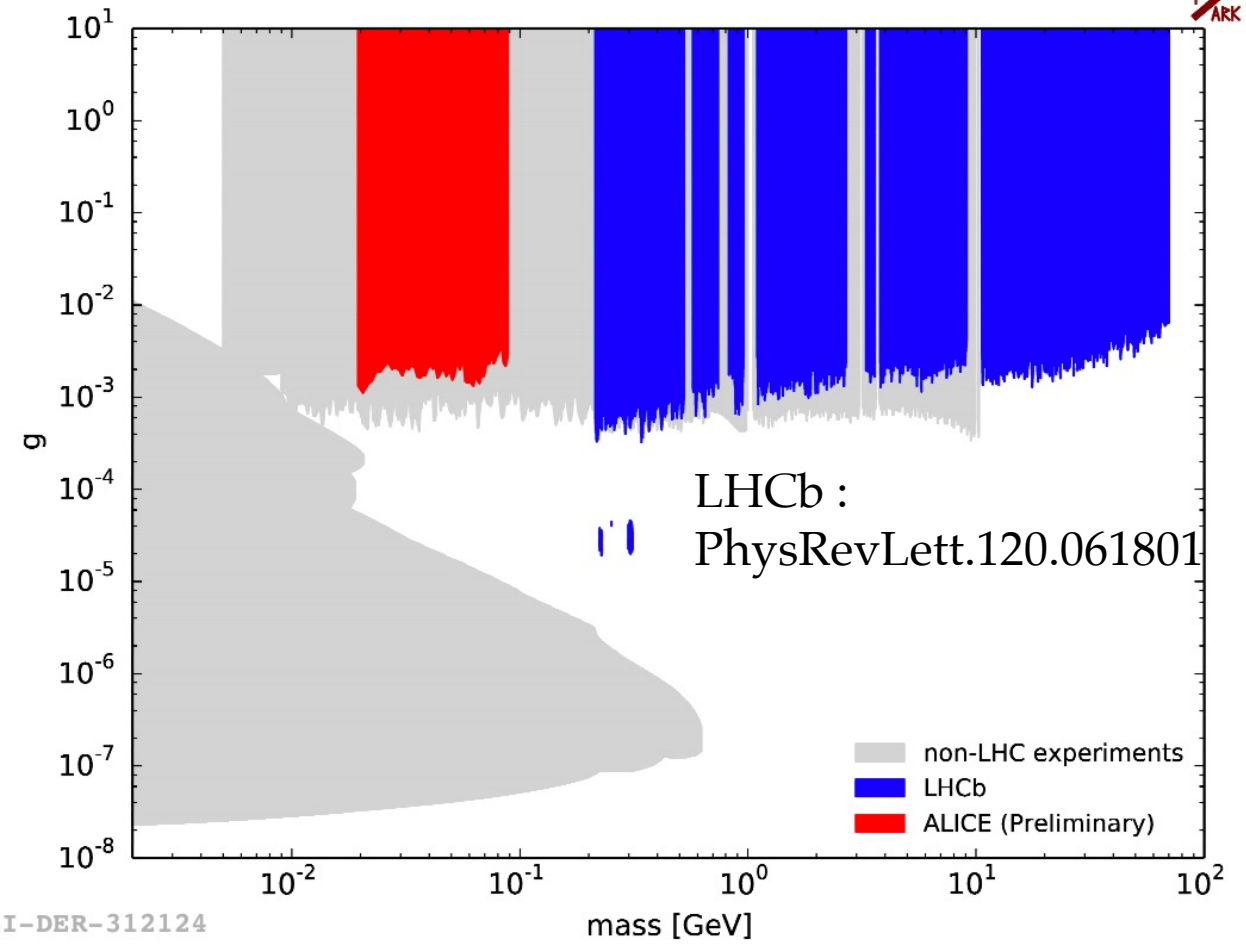
Displaced





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

https://gitlab.com/philten/darkcast



ALICE and LHCb Run3+Run4

- ALICE
  - 6 pb^{-1} MB recorded for pp, 0.3 pb^{-1} for p-Pb
  - 13 nb^{-1} for Pb-Pb (B=0.5+0.2T)

0.4 G pairs from pp 6 pb^{-1} $0<M_{ee}<100$ MeV
2.3 G pairs from p-Pb 0.3 pb^{-1}
1.8 G pairs from Pb-Pb 10 nb^{-1} (0.5T, $p_T>0.2$)
2.3 G pairs from Pb-Pb 3 nb^{-1} (0.2T, $p_T>0.2$)

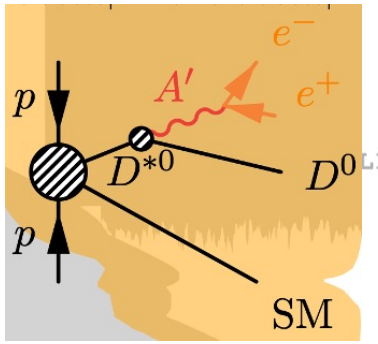
  - displaced dark photons around 10 MeV?
    - $c\tau$ ~ O(100um) at $\varepsilon^2=10^{-7}$

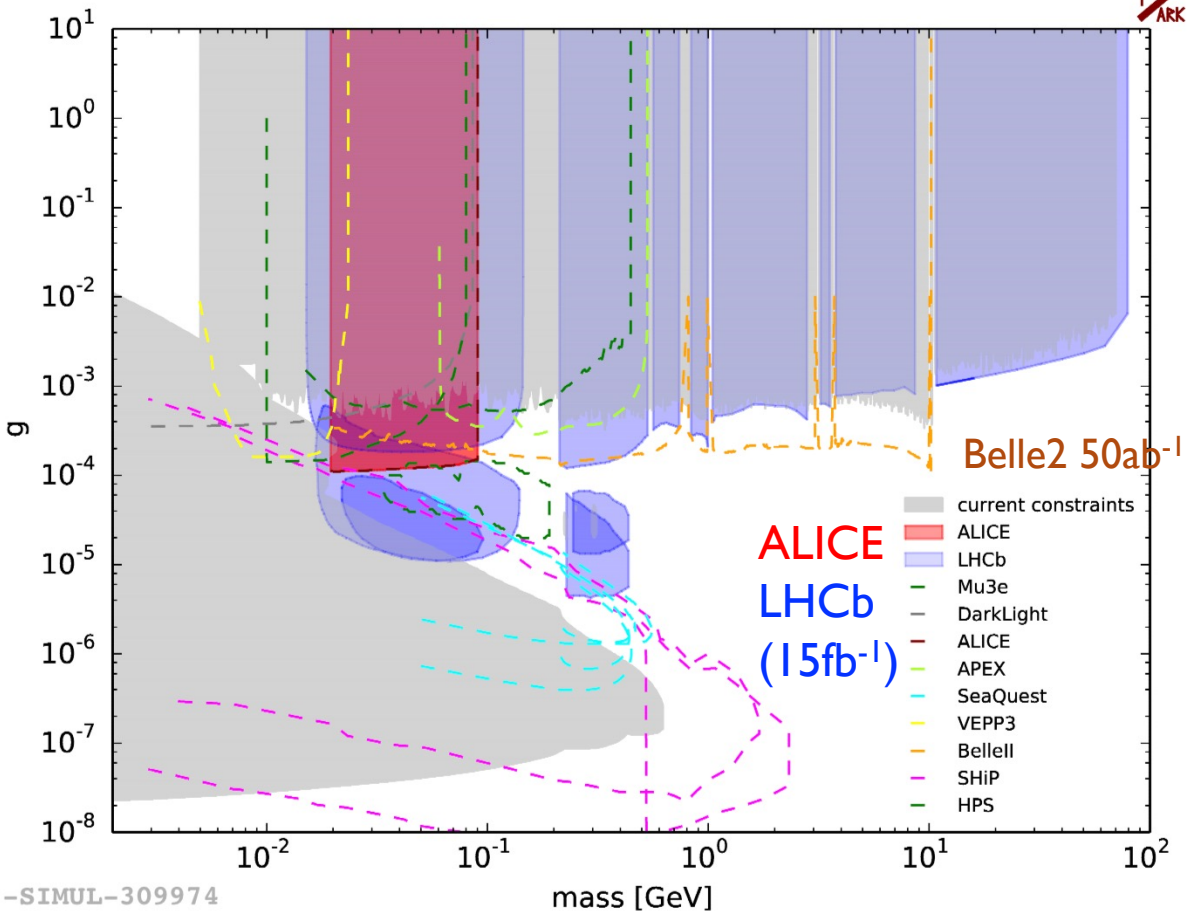
- LHCb
  - 15 fb^{-1} pp in Run3
  - **New constraints**

below 125 MeV using D^{*0}

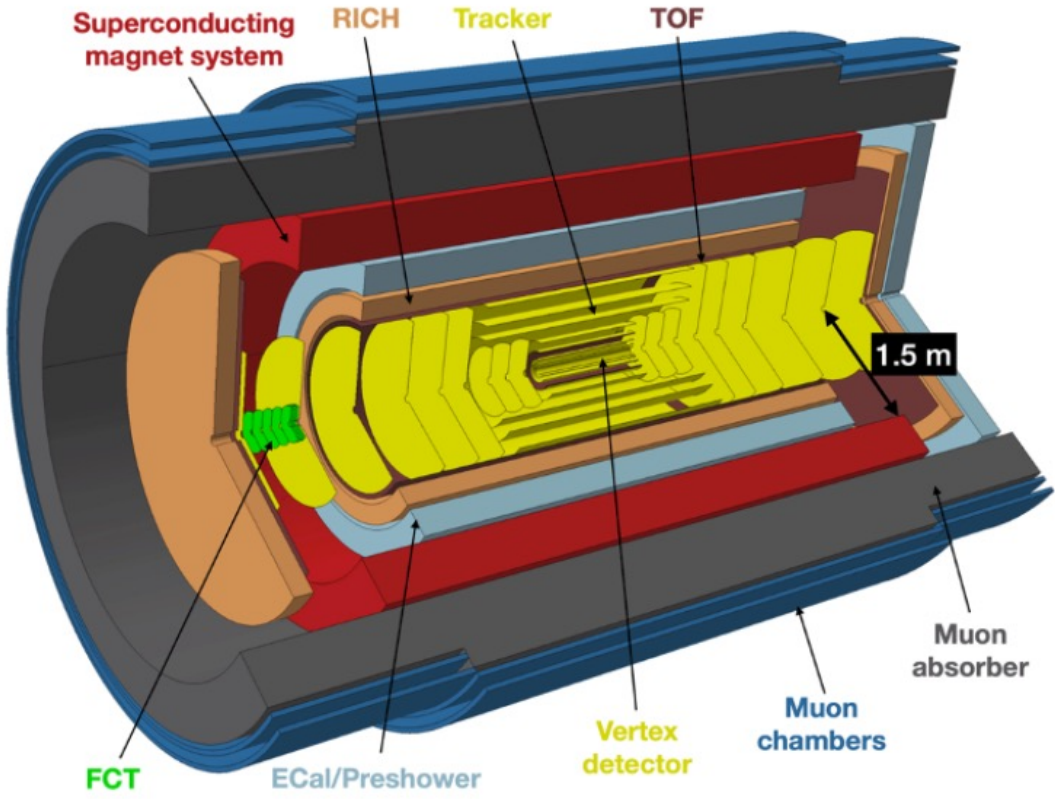
  - **$D^{*0} \rightarrow A'D^0$, $A' \rightarrow ee$**

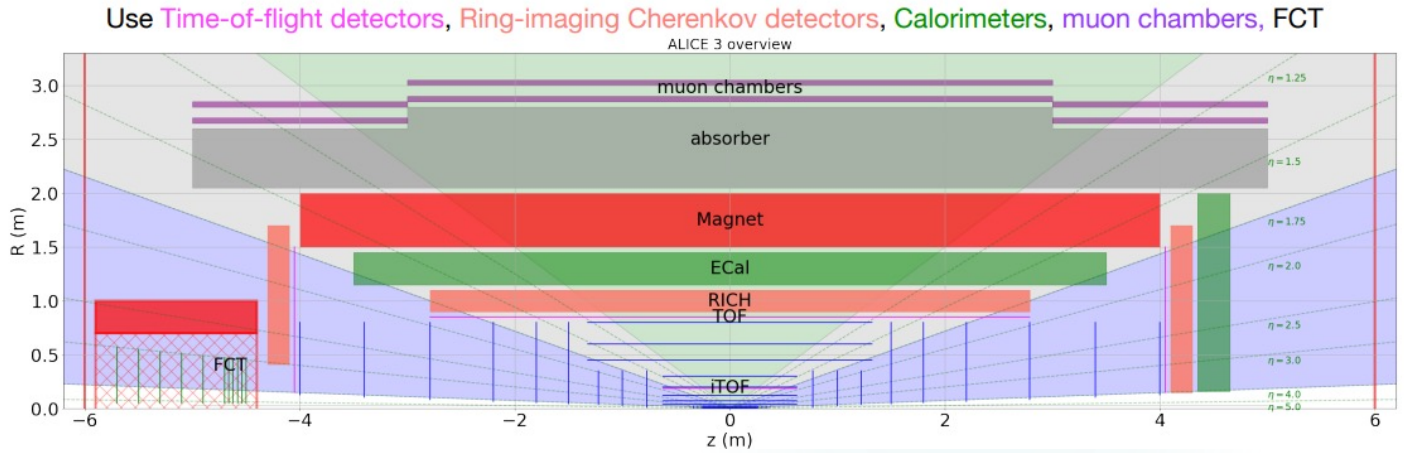
arXiv:1603.08926
arXiv:1509.06765

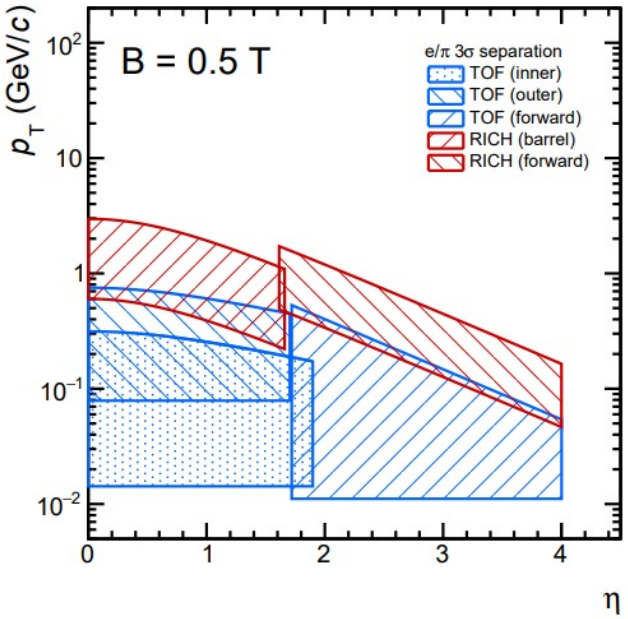




ALICE3 from Run5







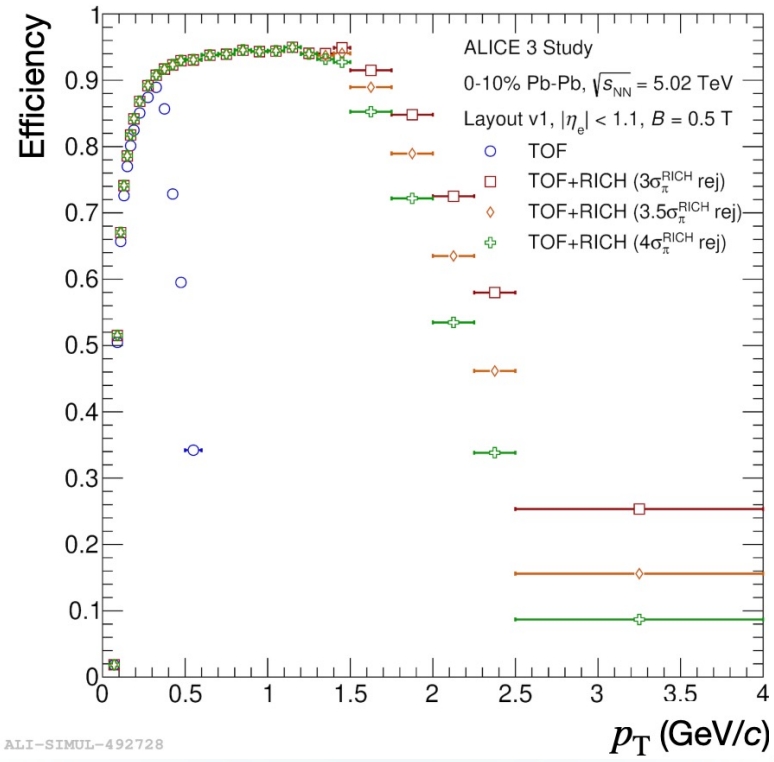
Large coverage up to $|\eta| = 4$

Electron identification

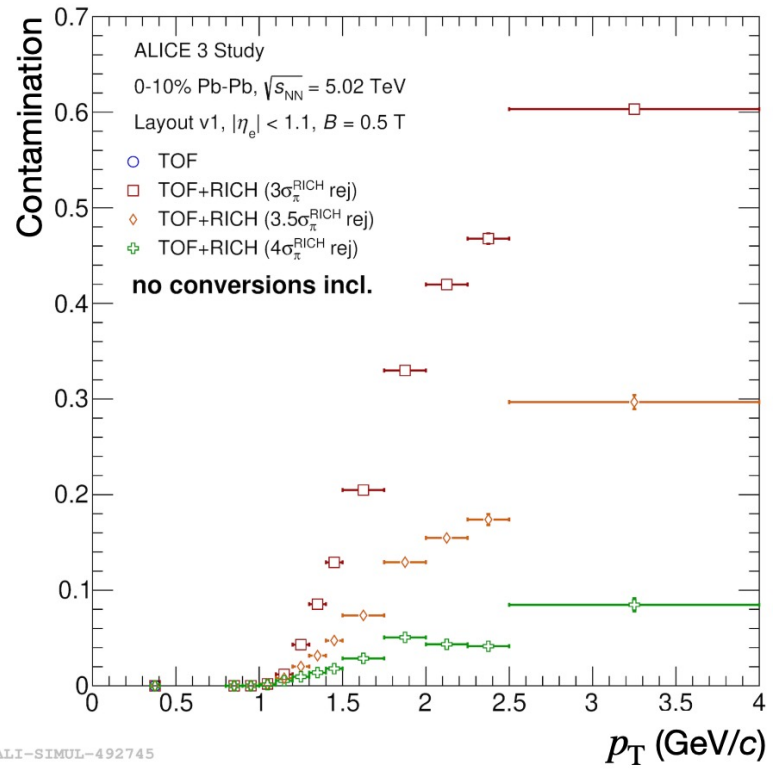
- Down to $p_T = 15$ MeV (B=0.5T) using iTOF at 20 cm
- Up to 2 GeV using outer TOF and RICH at 1 m
- ECAL for higher p_T

eID performance in ALICE3

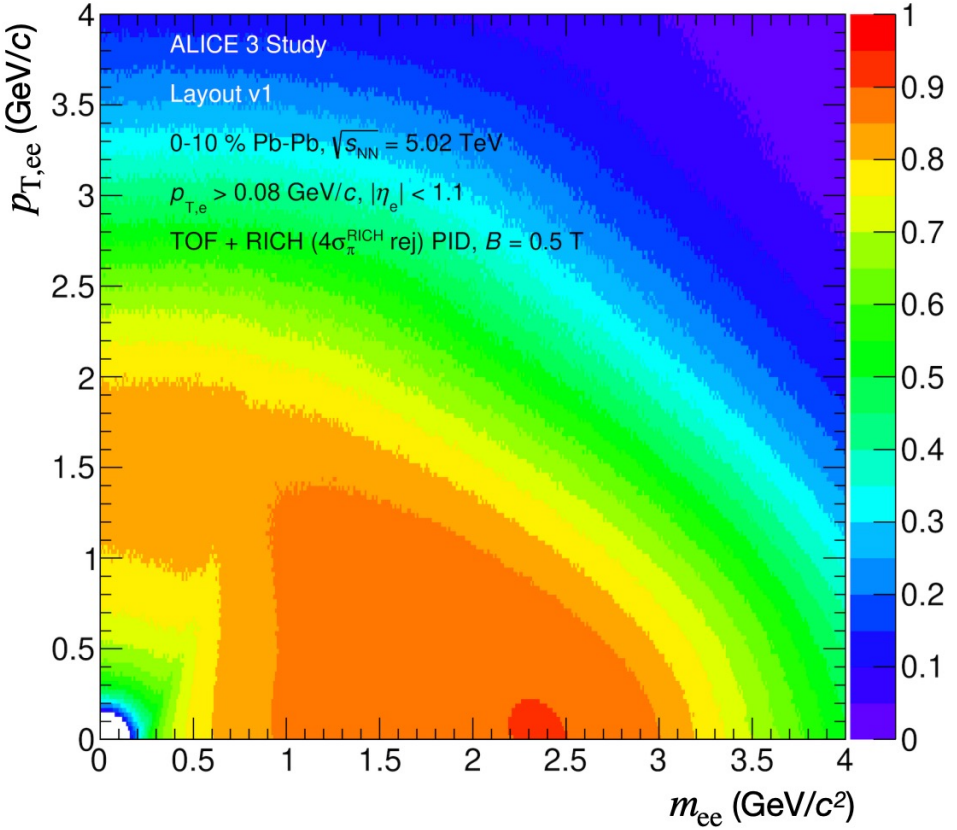
Electron efficiency



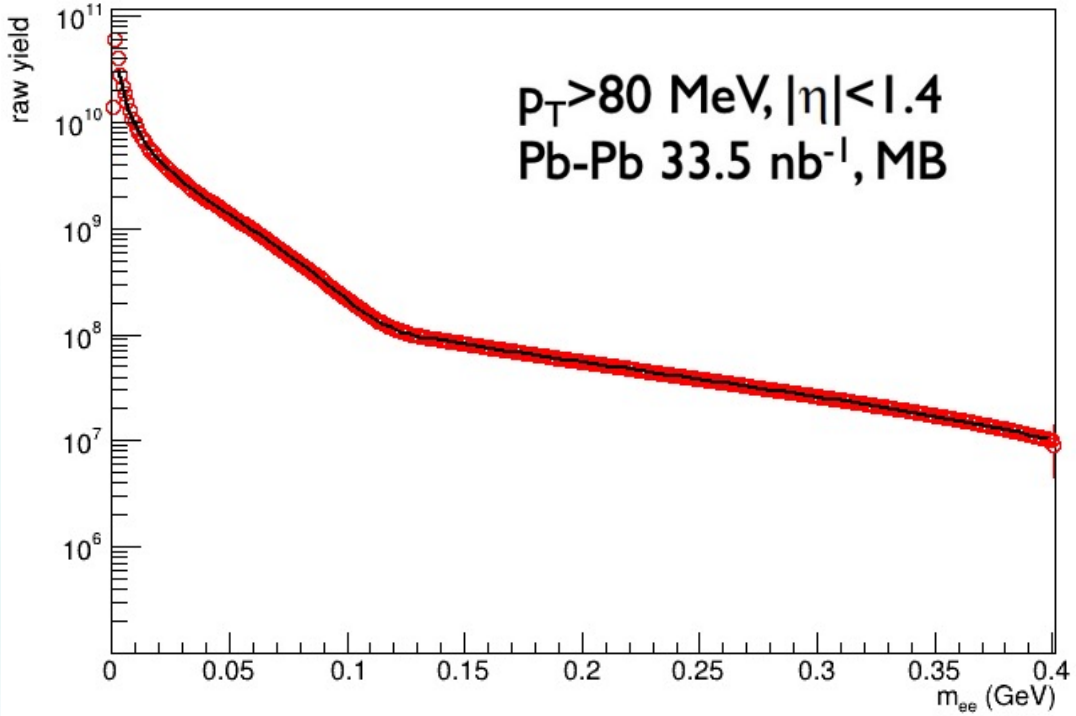
Contamination



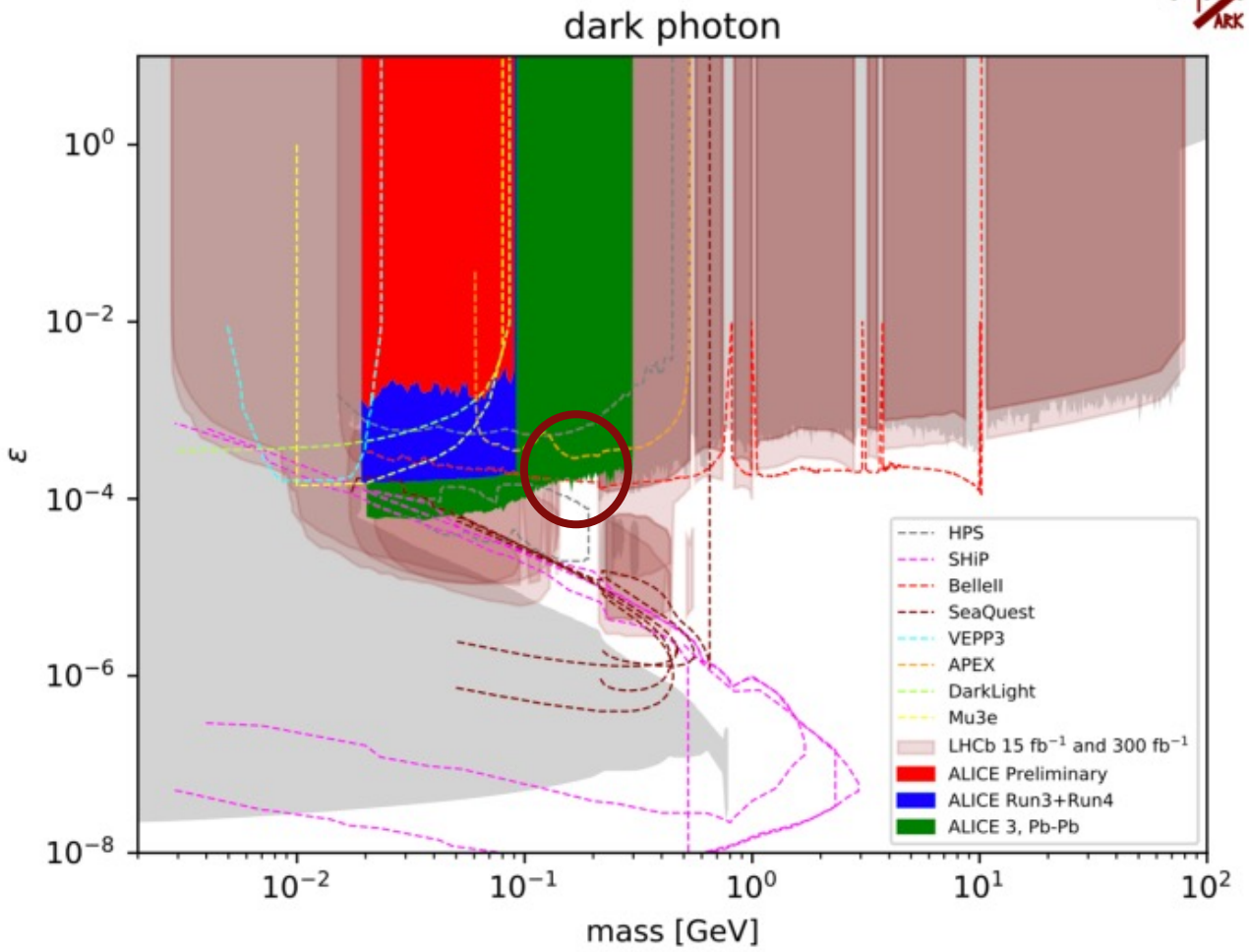
Dielectron efficiency with outer TOF and RICH, B = 0.5 T



ALICE3 limits by dielectrons



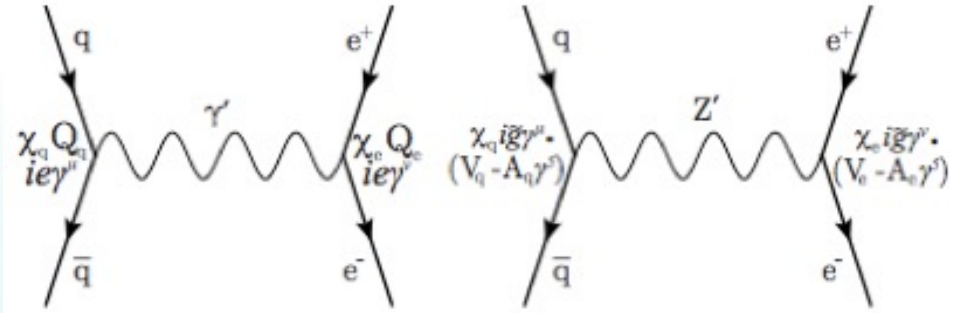
400 G π^0 pairs with p_T>80 MeV
(cf) 6.8 G π^0 pairs from Run3+Run4

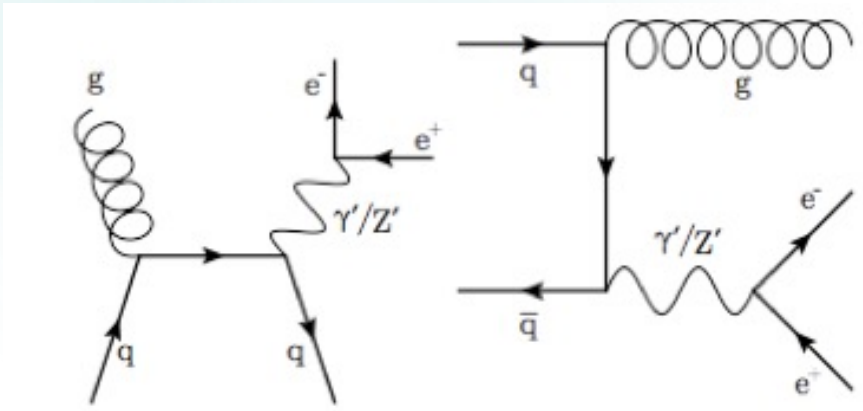


Another estimation using forward disks
Another channels (D*→DA' like LHCb, thermal dielectrons)

Dark Photon at GeV scales

Constraints on intermediate mass (O(1) GeV) resonances are looser [JHEP07(2009)051]





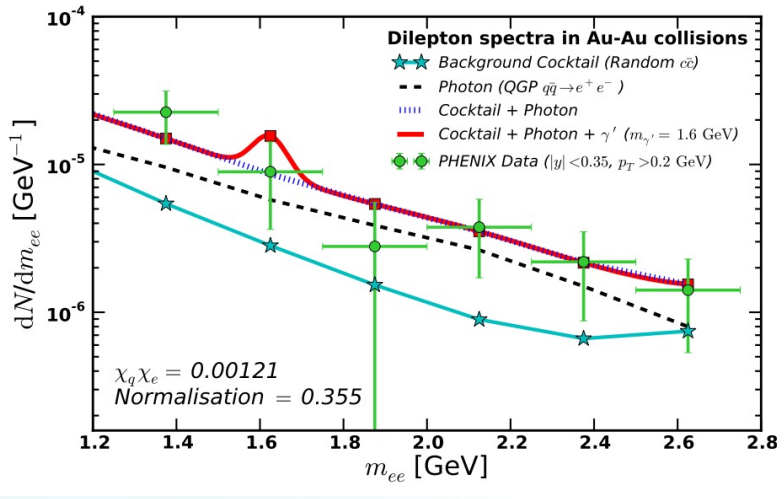
The use of PbPb collisions to search for new O(1) GeV gauge bosons could be favored wrt pp, where the Drell-Yan production of dileptons is much smaller than the hadronic background (ccbar, bbar decays)
[Phys. Rev. C 81, 034911]

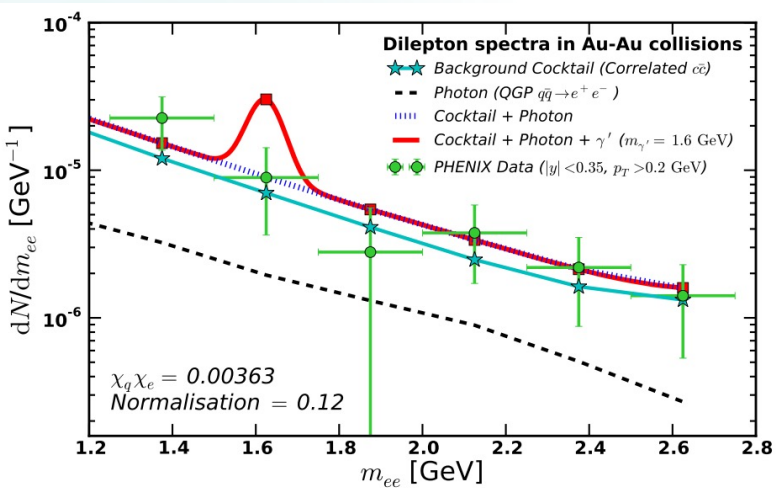
→ QGP may provide an additional thermal source of dileptons in intermediate mass region (direct thermal radiation).

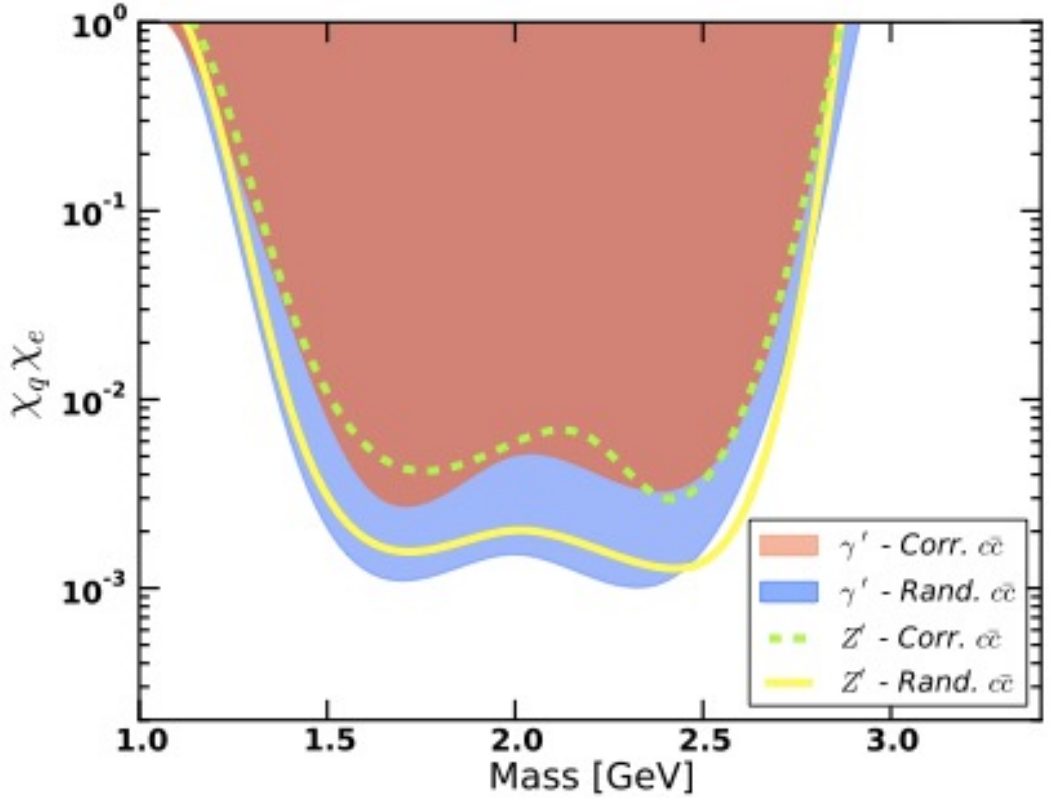
[J. Phys. G38, 025105] [Phys. Rev. D 54, 2399]

Dark Photon at GeV scales

Earlier estimation from PHENIX Au+Au dielectron data

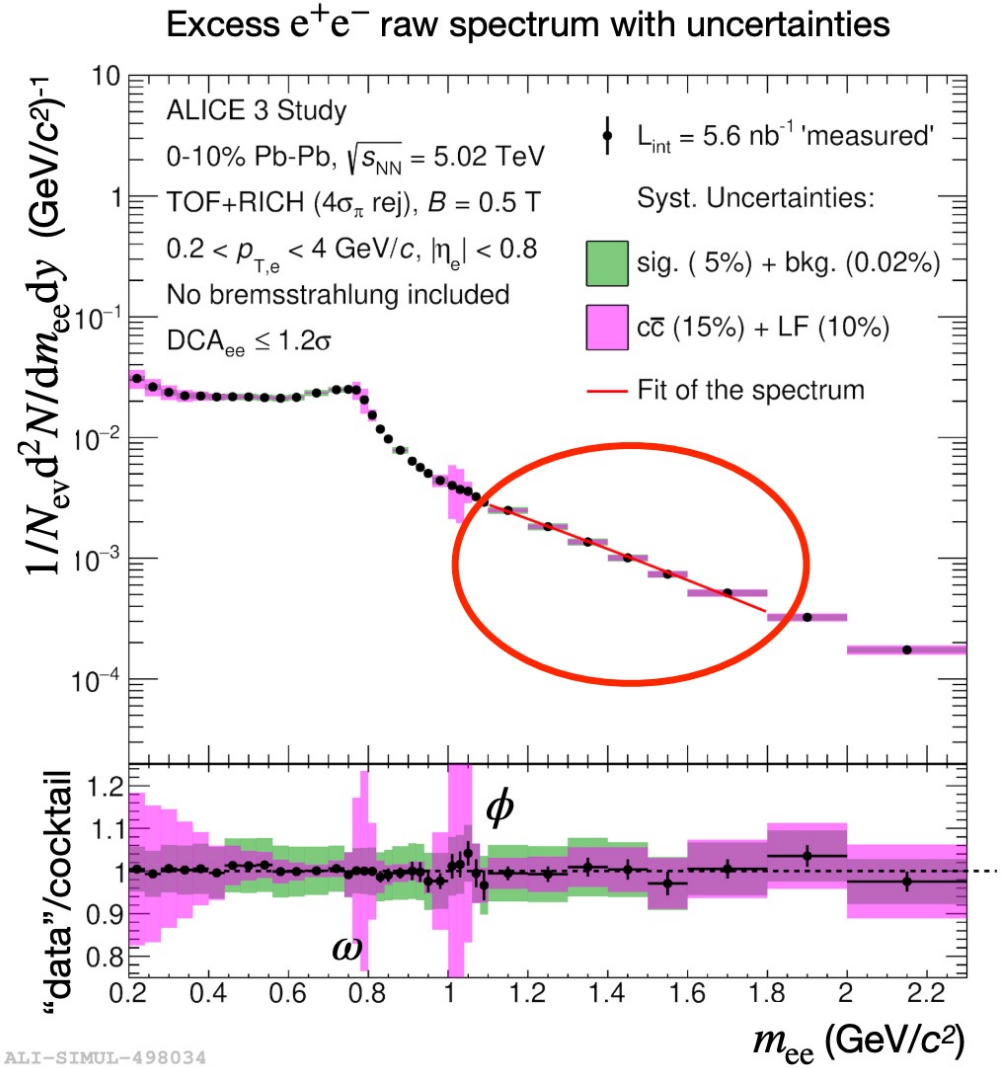


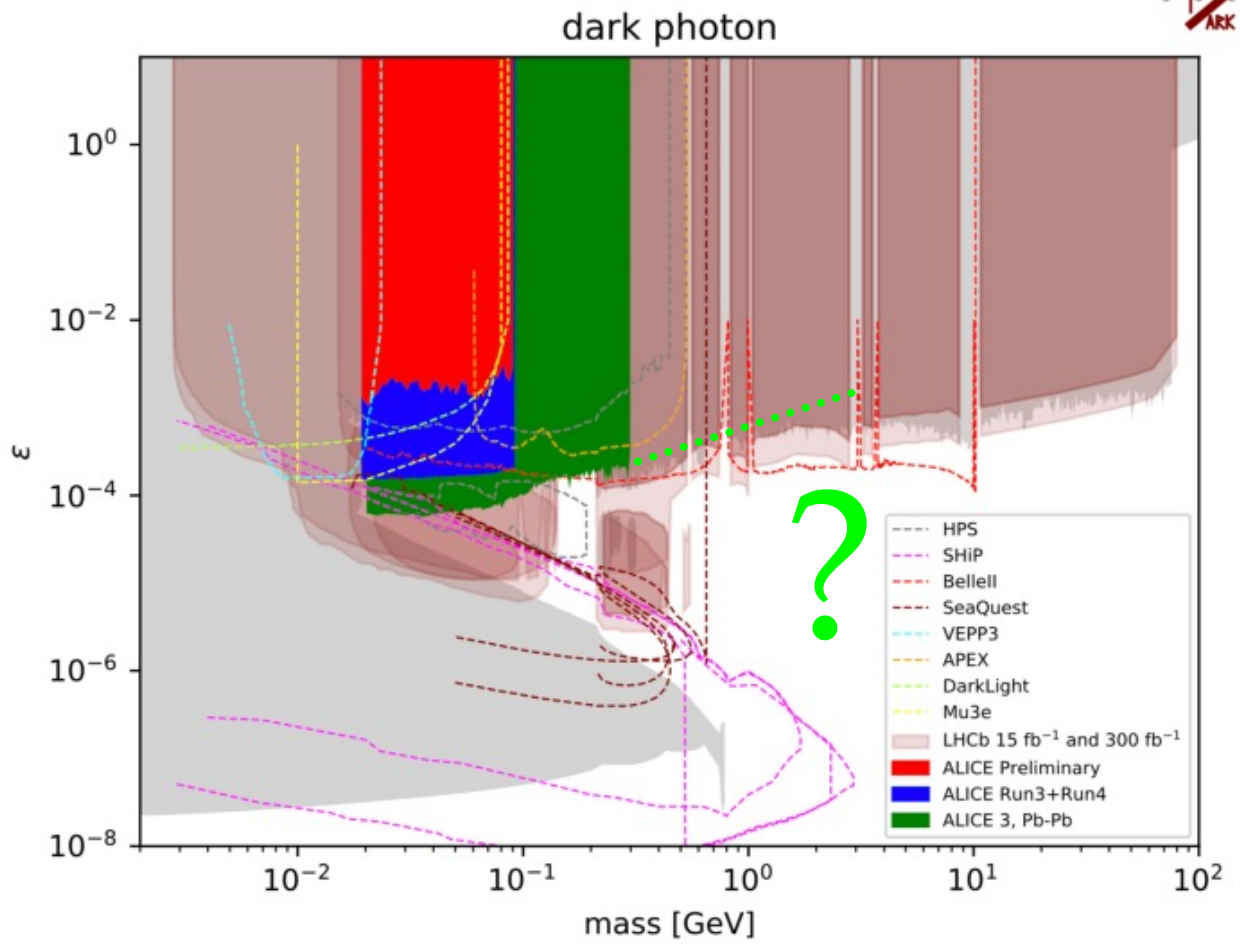




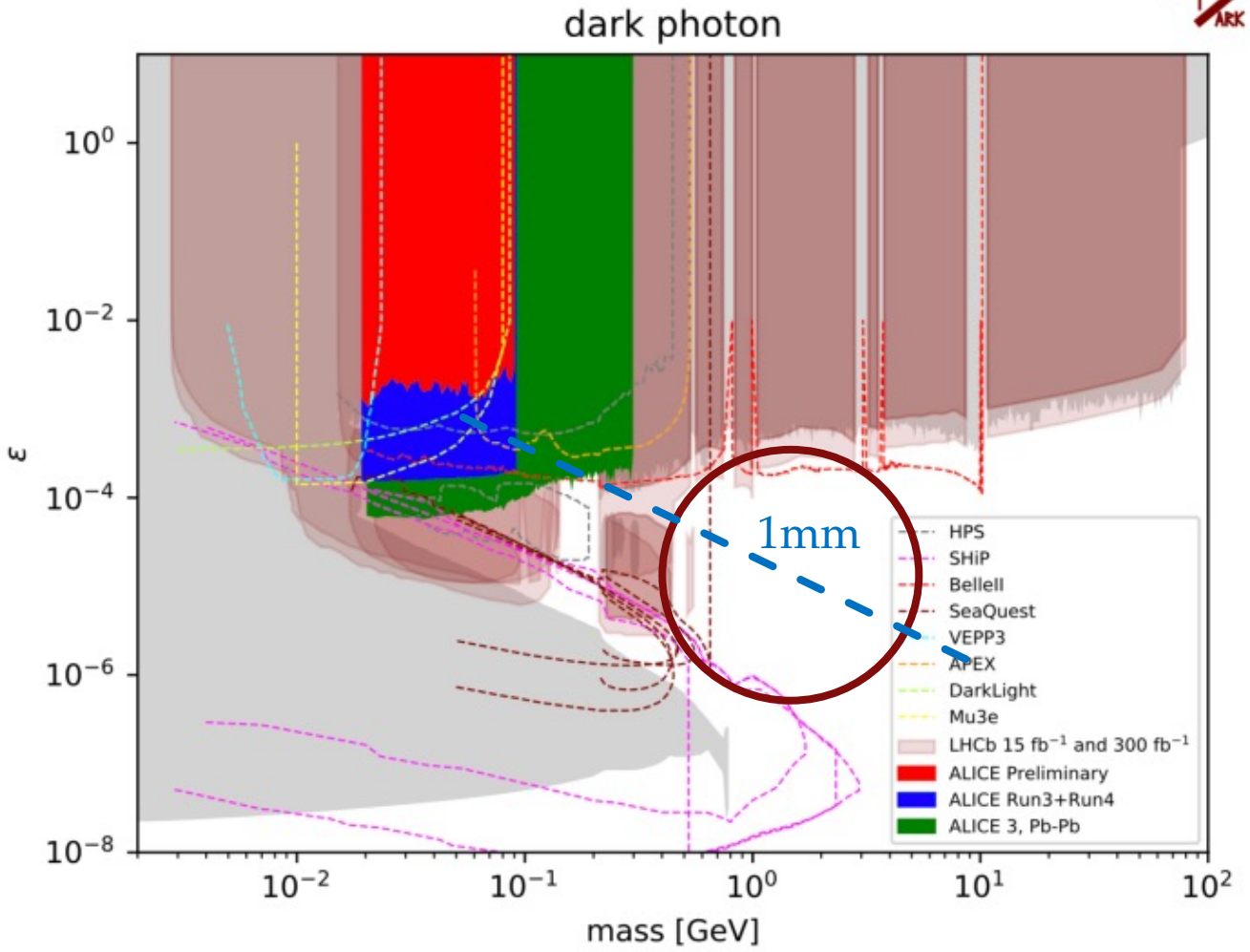
J.H.Davis C.Boehm,
arXiv:1306.3653

ALICE3?


Excess e+e− raw spectrum with uncertainties
ALICE 3 Study
0-10% Pb-Pb, √sNN = 5.02 TeV
TOF+RICH (4σπ rej), B = 0.5 T
0.2 < pT,e < 4 GeV/c, |ηe| < 0.8
No bremsstrahlung included
DCAee ≤ 1.2σ
Lint = 5.6 nb-1 'measured'
Syst. Uncertainties:
sig. (5%) + bkg. (0.02%)
cc̄ (15%) + LF (10%)
Fit of the spectrum
1/Nev d2N/dmee dy (GeV/c2)-1
"data"/cocktail
ϕ
ω
mee (GeV/c2)
ALI-SIMUL-498034


dark photon
ε
mass [GeV]
?
HPS
SHiP
BelleII
SeaQuest
VEPP3
APEX
DarkLight
Mu3e
LHCb 15 fb-1 and 300 fb-1
ALICE Preliminary
ALICE Run3+Run4
ALICE 3, Pb-Pb

How to improve the limits?



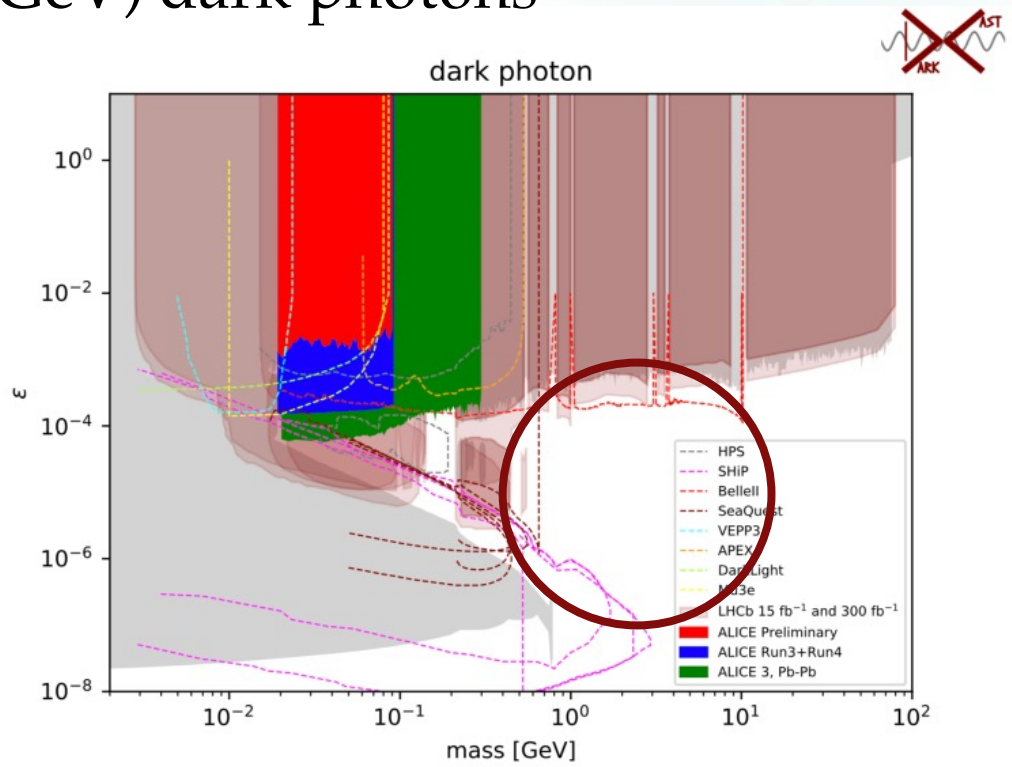
- Using pp data?
  - ~400 pb^{-1} MB recorded gives 400 GB π^0 pairs.
- Different channels
  - $D^* \rightarrow DA'$ like LHCb. Other radiative decays
  - Thermal dielectrons/muons for O(GeV)
  - Drell-Yan in pp
  - Displaced searches
  - Forward rapidity

$$\ell_{A'} \simeq 16\,\mathrm{mm} \left(\frac{\gamma_{\mathrm{boost}}}{10^2}\right) \left(\frac{10^{-8}}{\epsilon^2}\right) \left(\frac{50\ \mathrm{MeV}}{m_{A'}}\right)$$

- Detector technologies
  - High rate capability and pile-up identification to use high intensity pp collisions
  - Electron/muon ID for IMR and HM pairs
  - Online selection capabilities

Summary

- ALICE and ALICE3 have a good potential to search for dark photons though dielectrons at very low mass.
- Studies for ALICE3 are not completed. We need to investigate other channels and other phase spaces for aiming at O(GeV) dark photons
  - Thermal radiations
  - Drell-Yan pairs
  - Other radiative decays
  - Displaced searches
- New ideas are welcome.

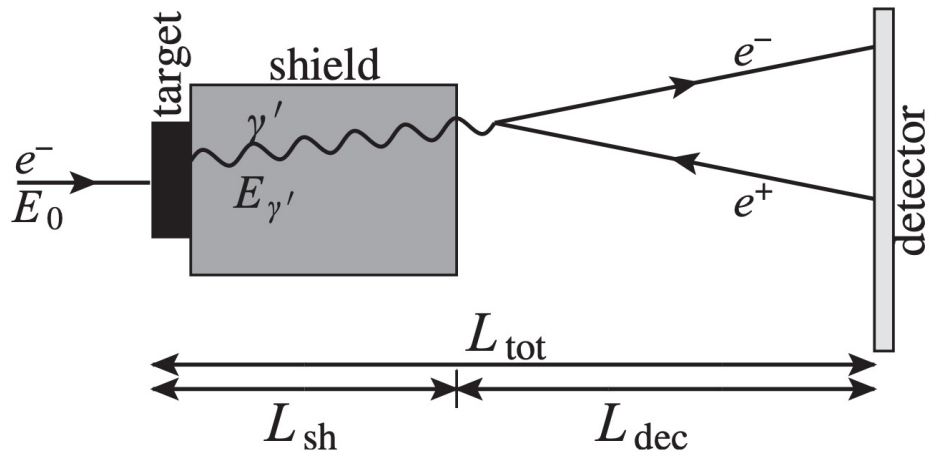


backup

Electron Beam Dump experiments

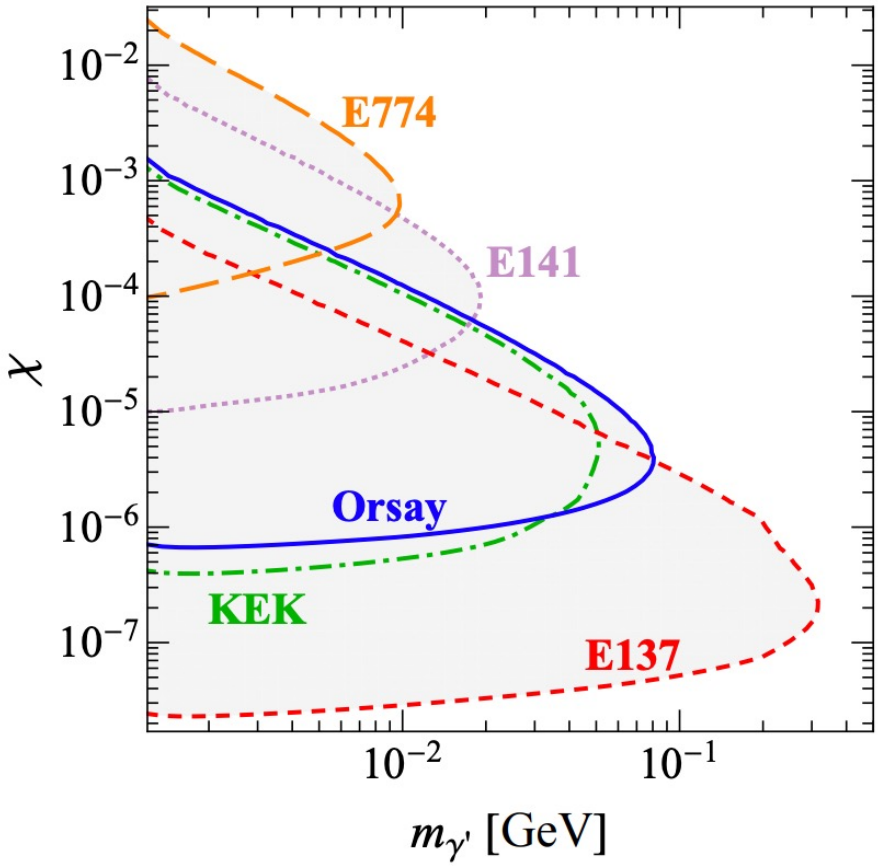
- a high-intensity beam dumped onto a thick fixed target provides the large luminosity
- Search for long lived dark photons → probe very smaller mixing region

$$\tau\left(\mathrm{A}'\right) \propto \left[m\left(\mathrm{A}'\right)\epsilon^2\right]^{-1}$$



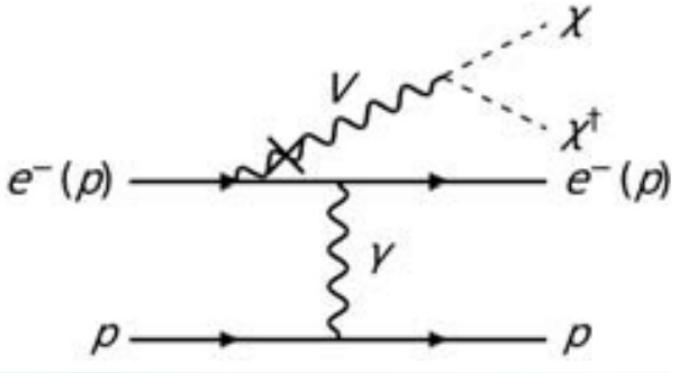
arXiv:1209.6083

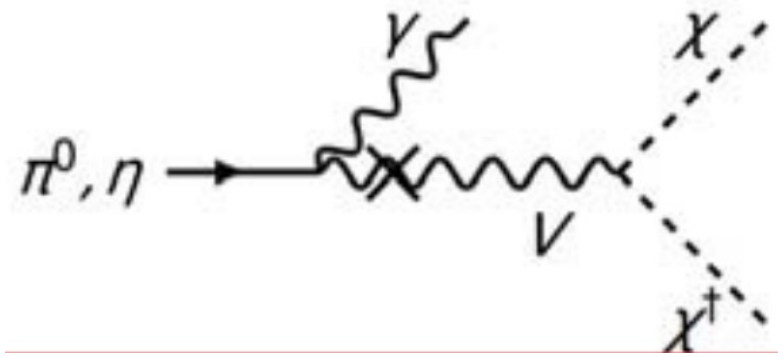
Experiment	Target	E_0 (GeV)	N_{el}	L_{sh} (m)	L_{dec} (m)
KEK [50]	W	2.5	$1.69 \cdot 10^{17}$	2.4	2.2
E141 [51]	W	9	$2 \cdot 10^{15}$	0.12	35
E137 [52]	Al	20	$1.87 \cdot 10^{20}$	179	204
E774 [53]	W	275	$5.2 \cdot 10^{9}$	0.3	2
Orsay [54]	W	1.6	$2. \cdot 10^{16}$	1	2



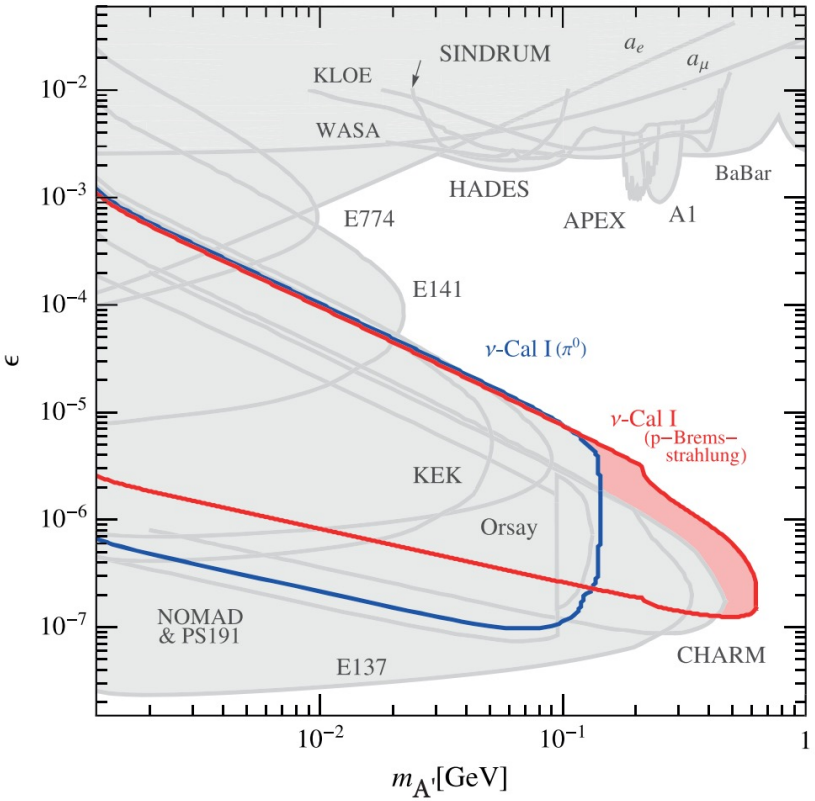
Proton Beam Dump experiments

- In proton dump experiments, dark photon can be produced either directly, via proton or lepton (A′-strahlung) or indirectly (in mesons decay chains like $p^0 \rightarrow gA$).



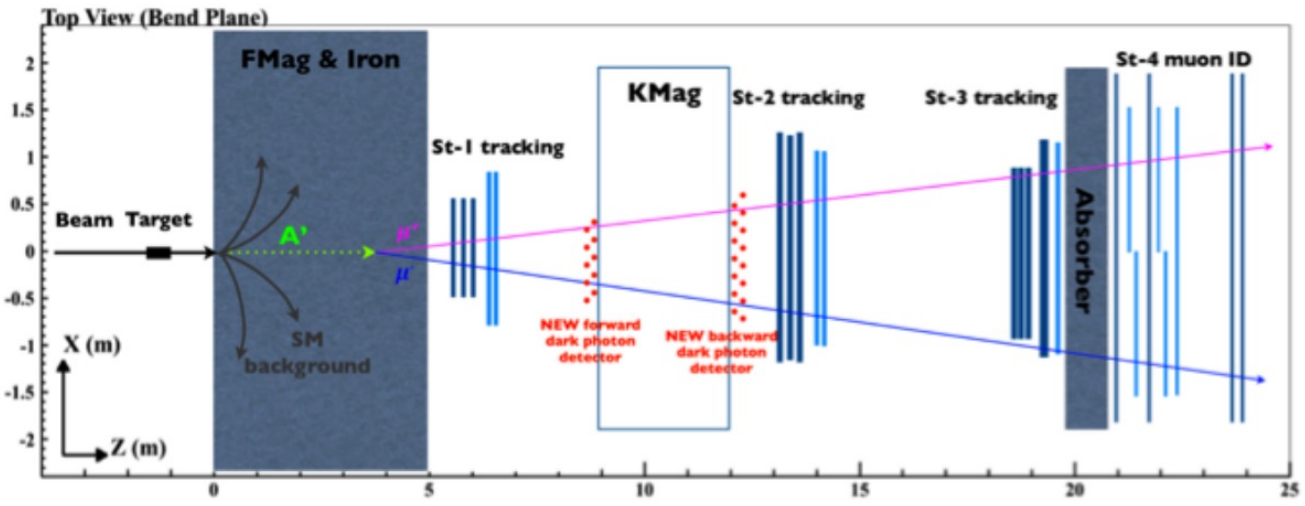


Experiment	Target	E_0 (GeV)	N_p	$L_{\rm sh}$ (m)	$L_{\rm dec}$ (m)
CHARM [56]	Cu	400	$2.4 \cdot 10^{18}$	480	35
PS191 [57]	Be	20	$8.6 \cdot 10^{18}$	128	12
NOMAD	Be	450	$4.1 \cdot 10^{19}$	835	7.5
NuCal [38]	Al	70	$1.7 \cdot 10^{18}$	64	23

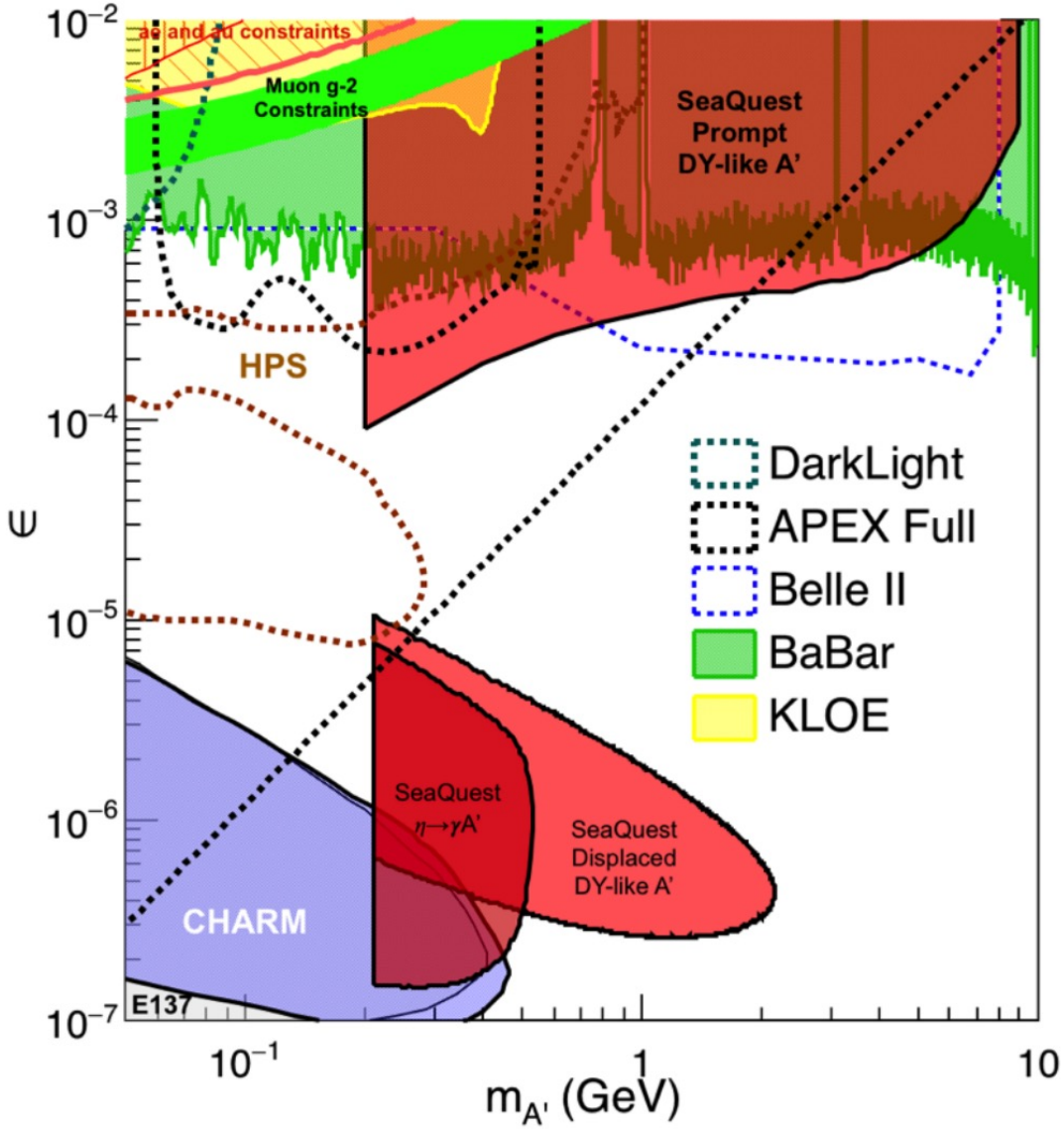


Fixed target experiments (incl. beam dump)

- SpinQuest (SeaQuest) at FNAL
  - Approved to have 1.4×10^{18} protons on target (POT) over a period of two years.



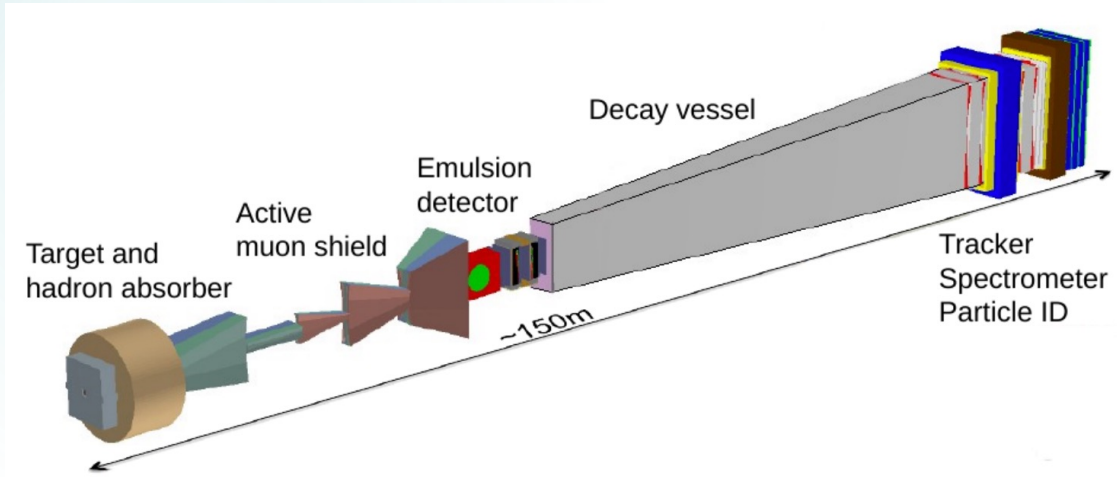
https://arxiv.org/pdf/1910.07142.pdf

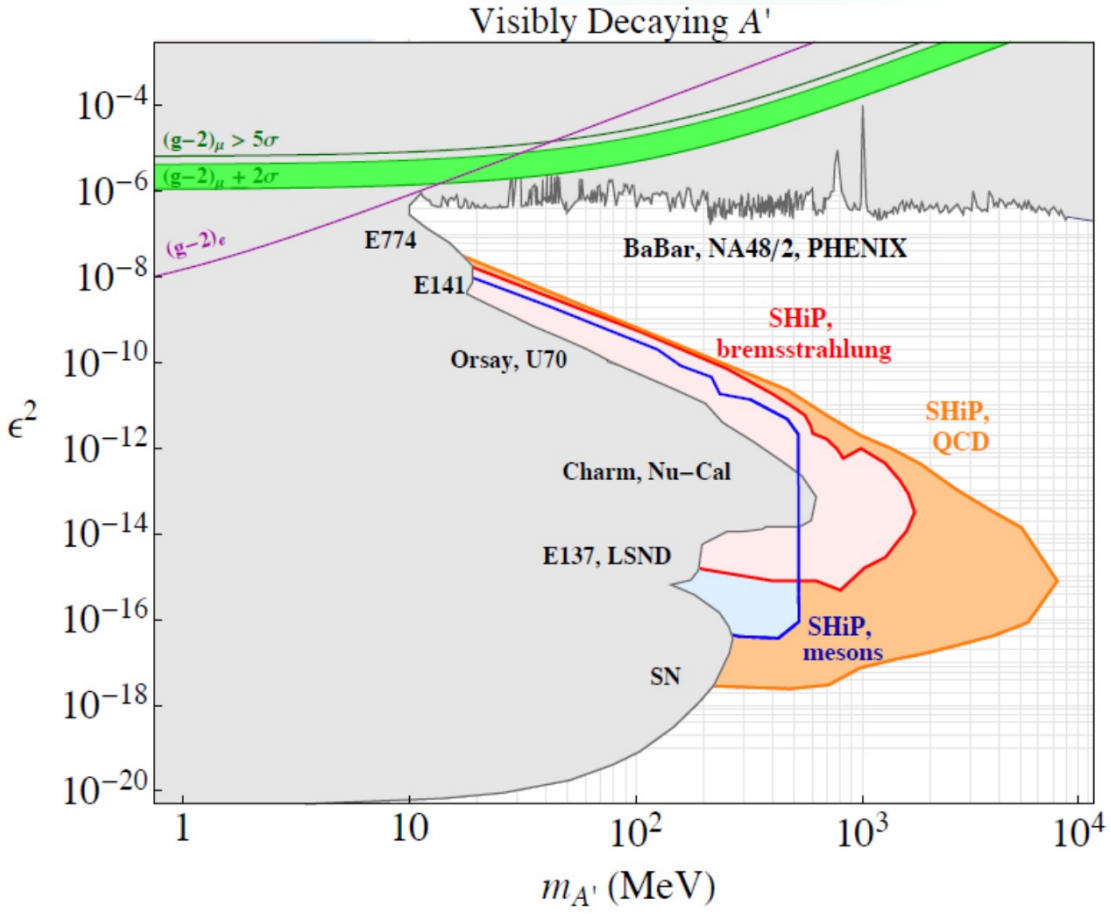


Fixed target experiments (incl. beam dump)

- SHiP at SPS (>2026)
  - 2×10^{20} protons on target (5 years of operation)
  - Meson decays: $(\pi^0, \eta, \eta', \omega) \rightarrow \gamma$ A' (decay of K, D, B subdominant)
  - Proton bremsstrahlung process pp → ppA'
  - perturbative QCD production of vector states via the underlying q + q → A' ; q + g → q + A'

https://arxiv.org/pdf/1512.03069.pdf
https://arxiv.org/pdf/1712.01768.pdf
https://arxiv.org/pdf/1504.04956.pdf

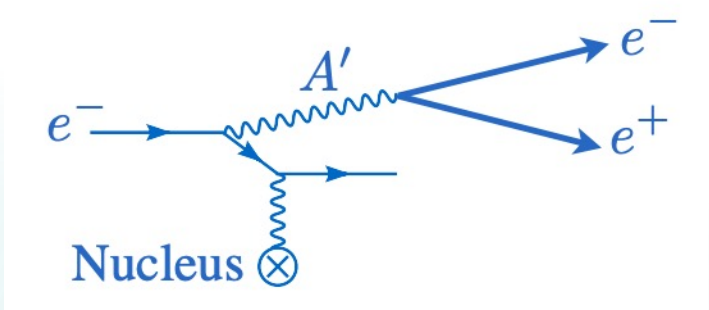


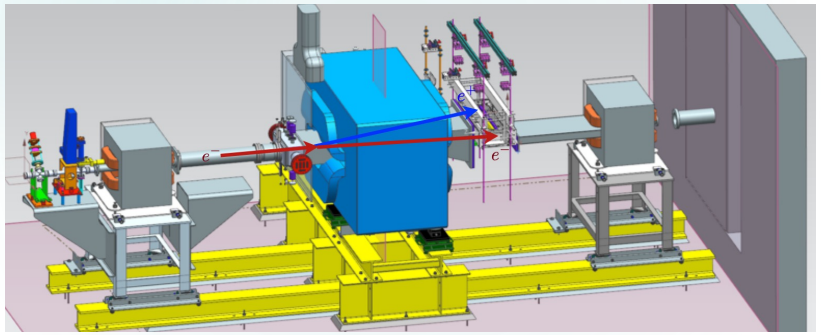


Fixed target experiments (incl. beam dump)

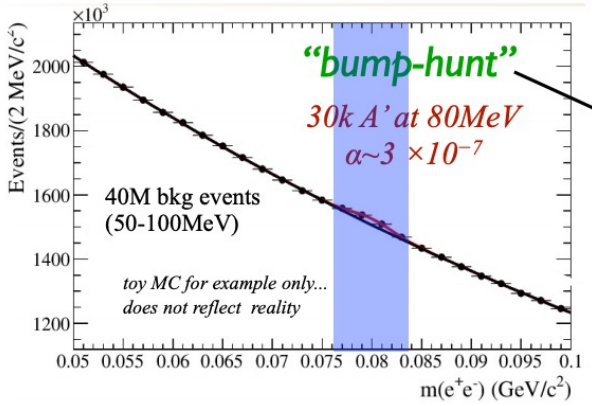
- HPS (The Heavy Photon Search) at J-Lab.

https://indico.cern.ch/event/507783/



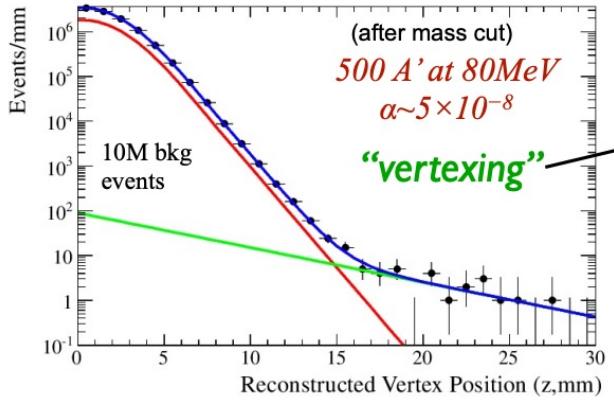


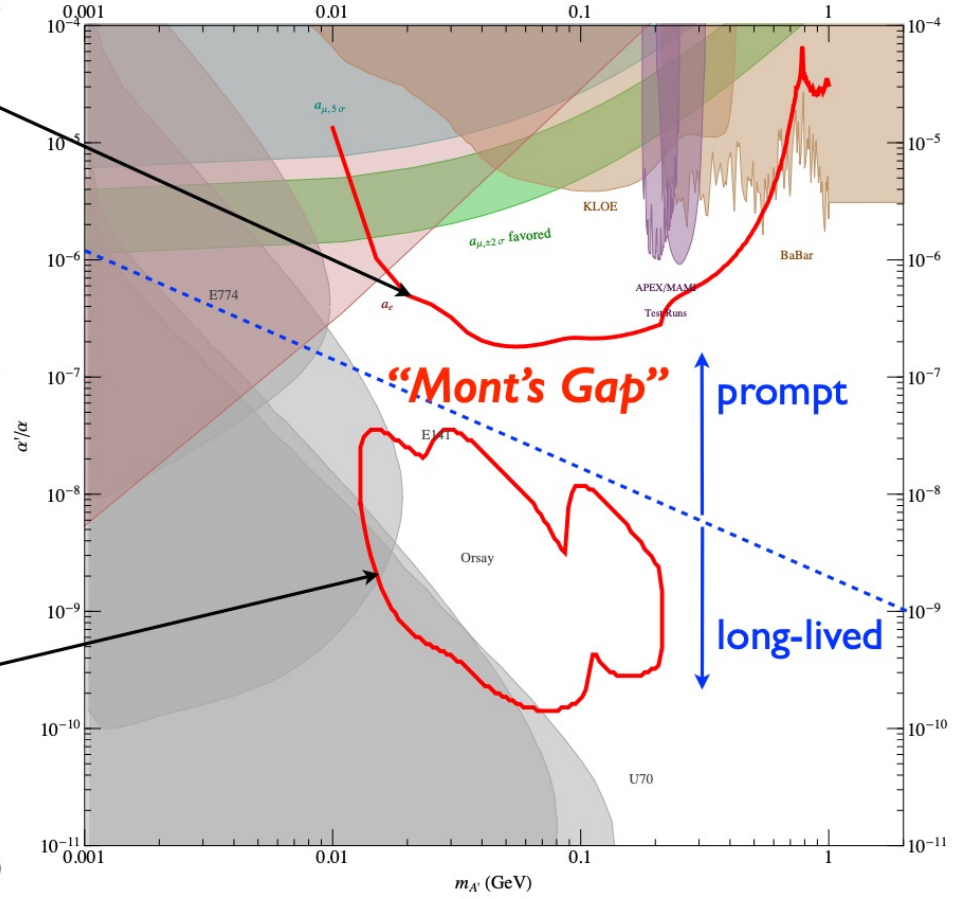
Large signal, *HUGE* background



vertexing

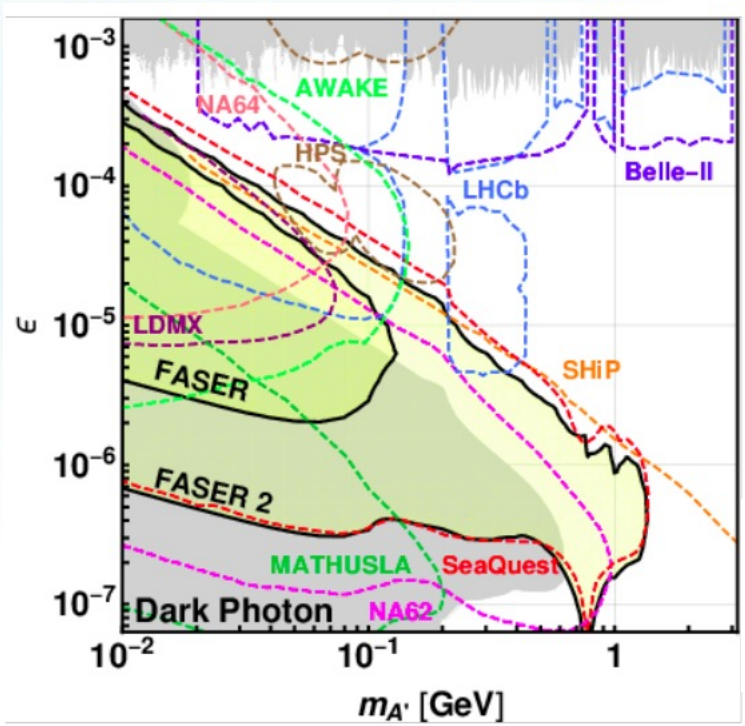
Small signal, *NO* background

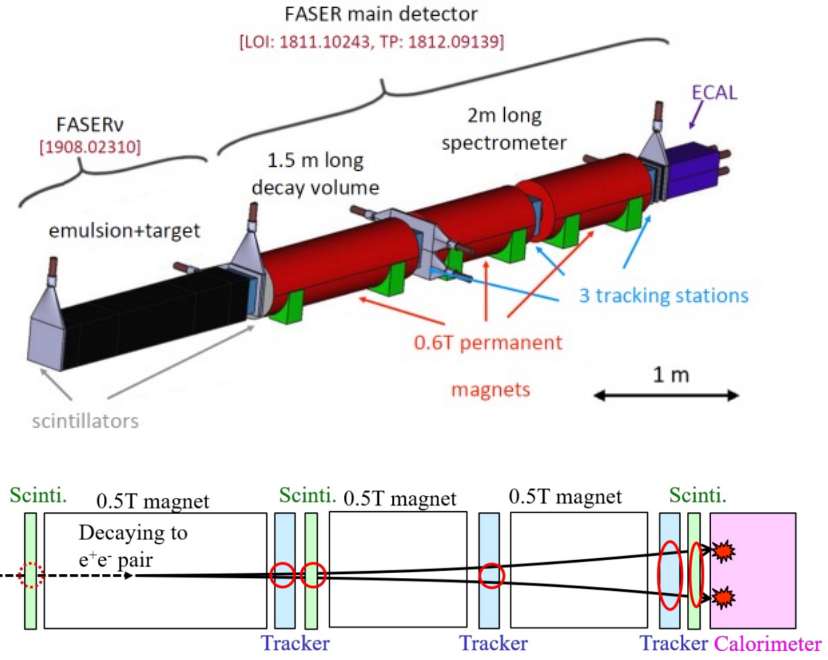


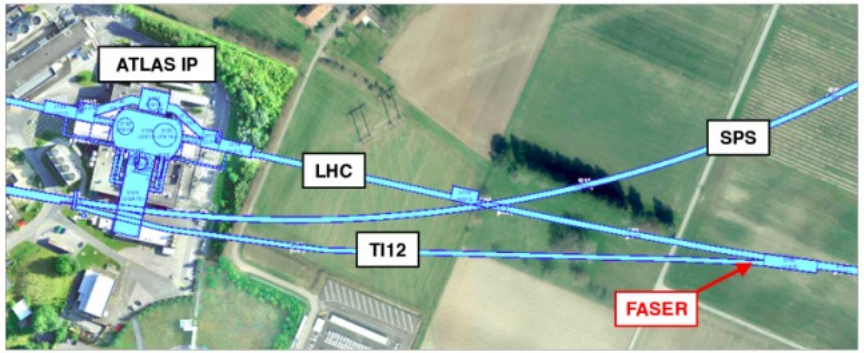


FASER

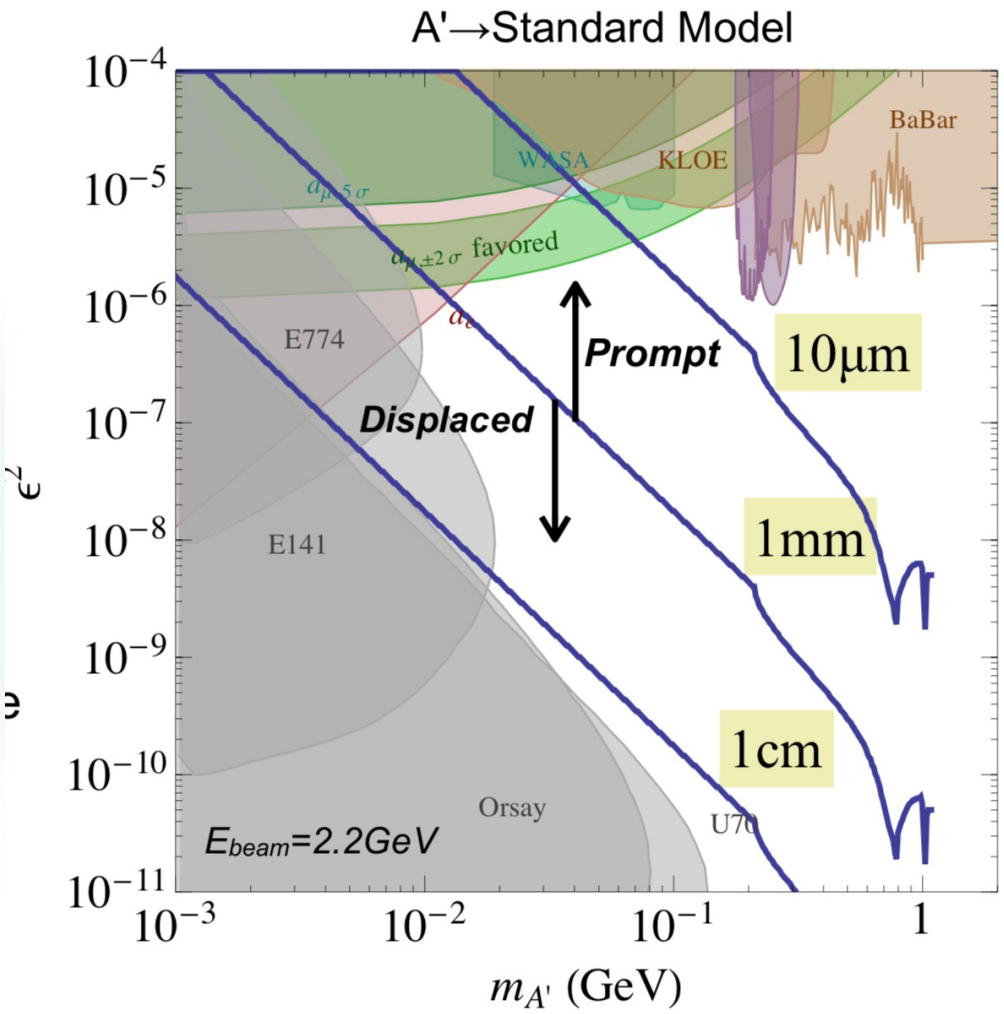
- FASER Experiment currently under construction will enter the game in Run-3
  - ~480m down the beam axis at ATLAS IP, at TI12 connection tunnel between LEP/LHC and SPS
  - Exploits mainly large number of □0->ɣɣD(ɣD->ee) decays produced at high pseudo-rapidities (~2% within acceptance)



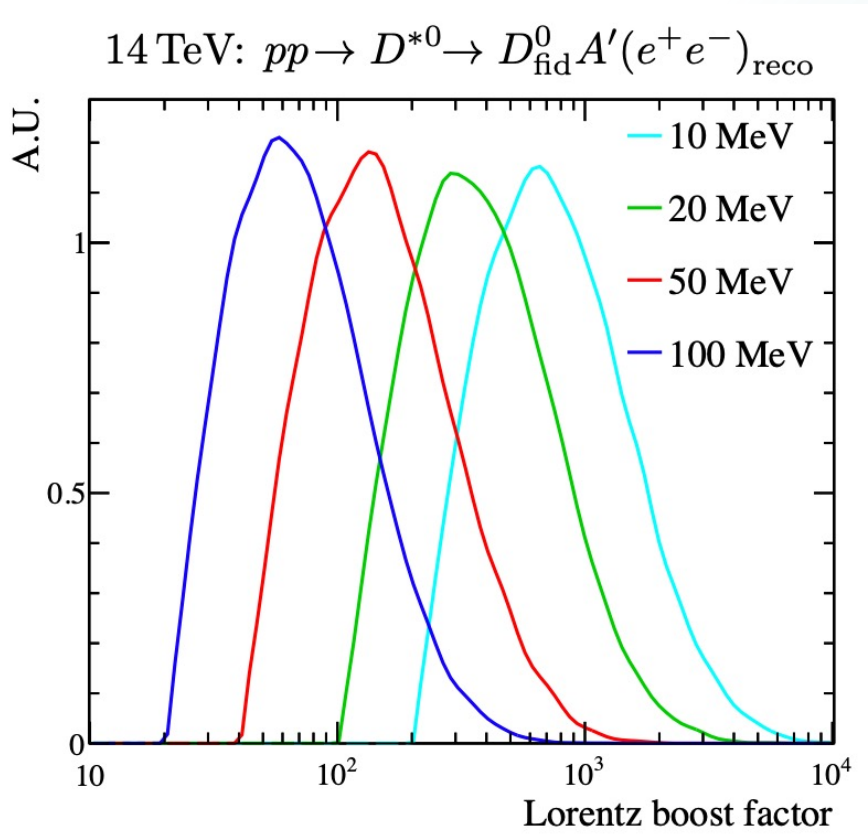




Dark Photons



$$\ell_{A'} \simeq 16\,\text{mm} \left(\frac{\gamma_{\text{boost}}}{10^2}\right)\left(\frac{10^{-8}}{\epsilon^2}\right)\left(\frac{50\ \text{MeV}}{m_{A'}}\right)$$



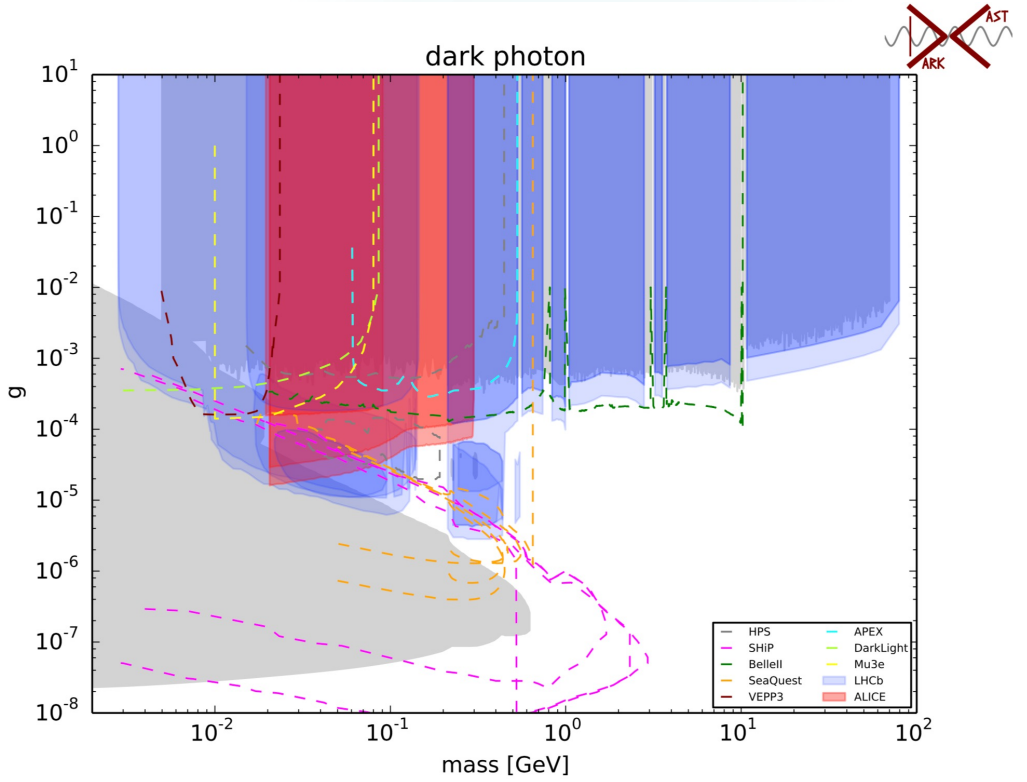
pe > 1 GeV and 2 < ηe < 5

1509.06765

Prospects for ALICE3

- Many searches will be possible and be worthwhile to be studied:
  - Meson decays such as π^0,η, ϕ Dalitz decays etc, D^{*0} decays, radiative J/ψ and Υ decays
  - Displaced searches (M(A')<20 MeV)
  - **FSR, Drell-Yan and Thermal radiation for M(A') >1 GeV (constrains are much less)**

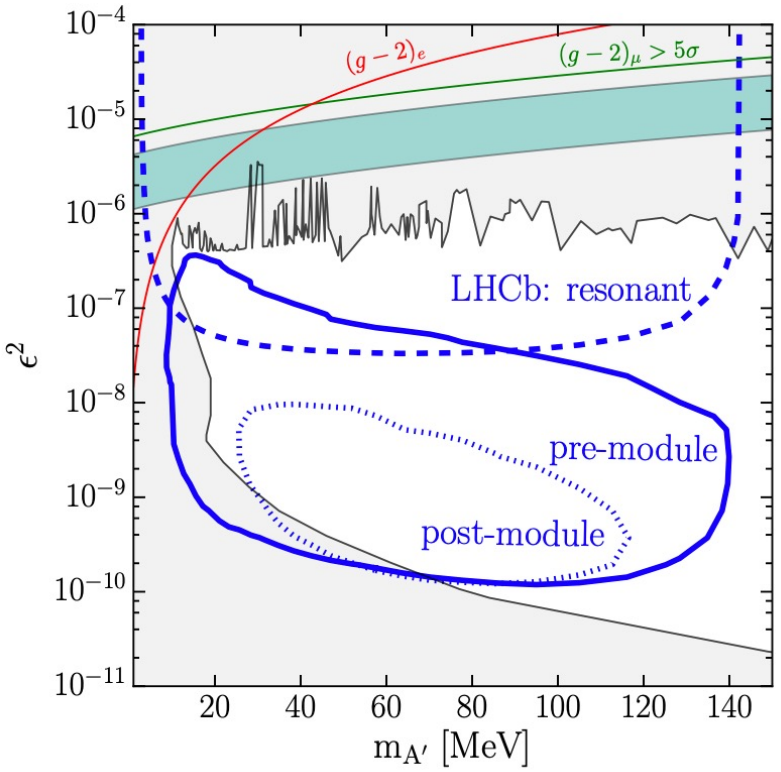
- Requirements for ALICE3
  - High rate capability and in-bunch pileup separation
  - Good electron identification capability for wide momentum range (low momenta from pi0 Dalitz decays to high momenta from DY and thermal dielectrons)
  - Good vertexing to separate thermal dielectrons and HF decay pairs



LHCb $D^{*0} \to A'D^0$, $A' \to ee$ Run3+Run4

arXiv: 1509.06765.

- The resonant search, relevant at larger values of ε^2, looks for an $A' \to e^+e^-$ resonance peak over the continuum SM background.
  - This search benefits from the large yield of $D^{*0} \to D^0A'$ decays during LHC Run 3



To define the fiducial region, we require the D^0 meson to satisfy the following transverse momentum and pseudorapidity requirements:

$$p_T(D^0) > 1 \text{ GeV}, \quad 2 < \eta(D^0) < 5. \tag{5}$$

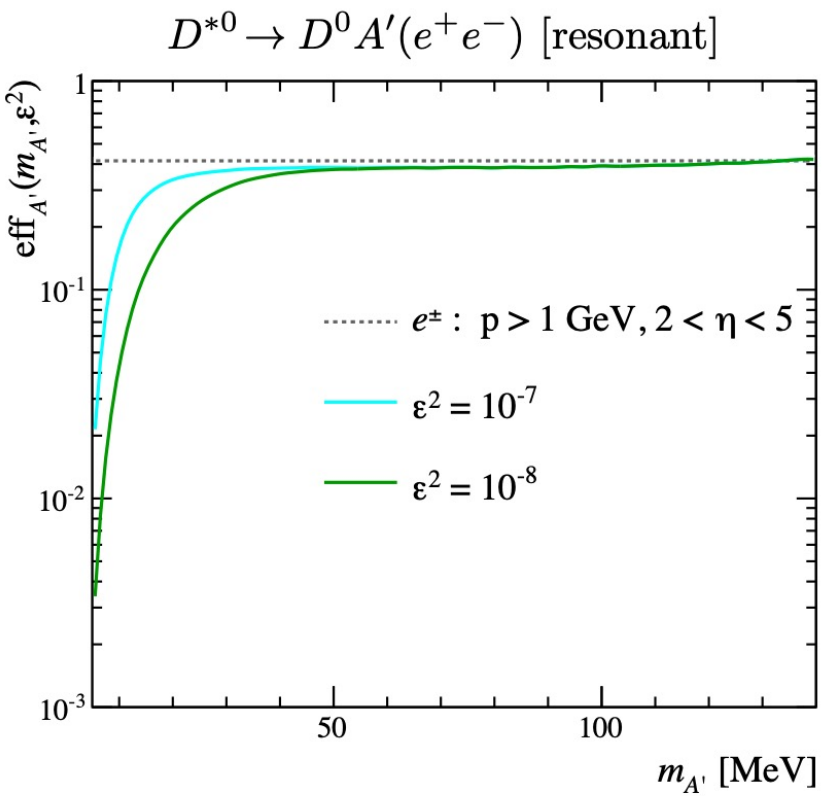
Note that this requirement is placed on the D^0 meson, not on the D^{*0}, to suppress backgrounds to the D^0 component of the signal. The D^{*0} production cross section within this fiducial region is

$$\sigma(pp \to D^{*0} \to D^0_{\text{fid}}) = 0.95 \text{ mb}, \tag{6}$$

excluding secondary production of D^{*0} mesons from b-hadron decays. It may be possible to make use of some secondary decays; in this analysis, however, we require that the A' originates from the pp collision to suppress backgrounds (see Sec. IV A).

The nominal instantaneous luminosity expected at LHCb during Run 3 is $2\,\text{nb}^{-1}$ per second [51], which will produce D^{*0} mesons at a rate of almost 2 MHz (equivalently, $D^{*0} \to D^0\gamma$ at 0.7 MHz). Assuming an integrated luminosity of $15\,\text{fb}^{-1}$ in Run 3,[7] this results in an estimated yield of 14 trillion D^{*0} mesons produced within this fiducial region, or

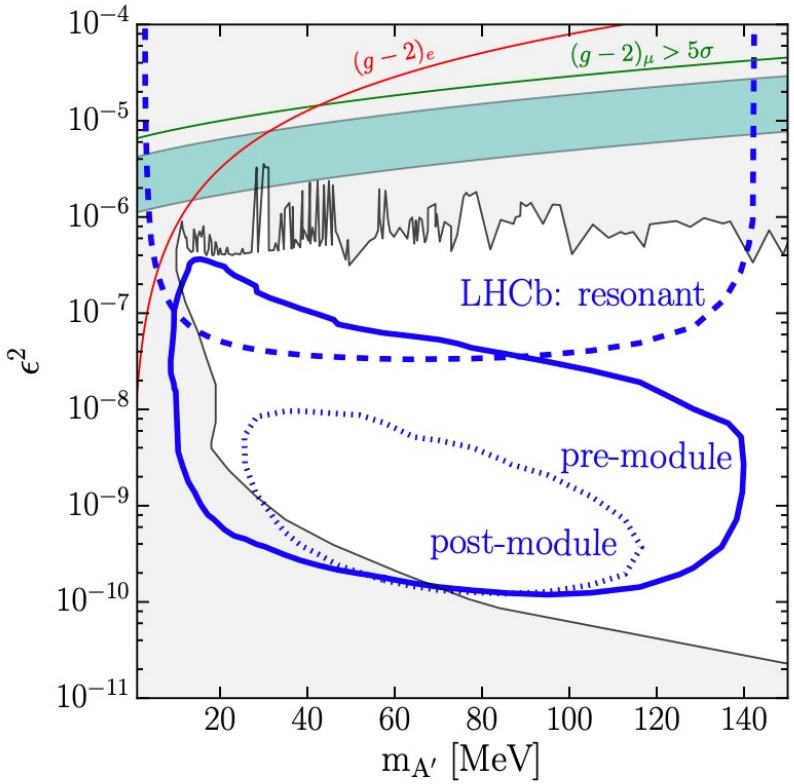
$$N(D^{*0} \to D^0\gamma) = 5.4 \times 10^{12}, \tag{7}$$



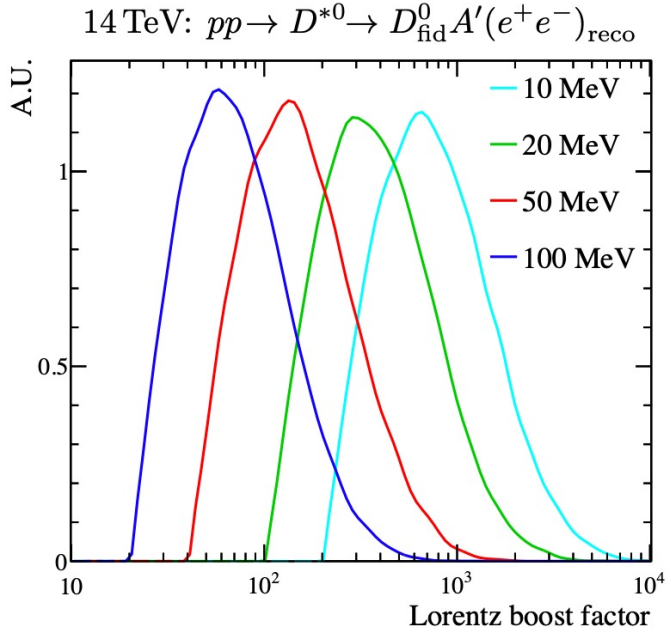
LHCb $D^{*0} \to A'D^0$, $A' \to ee$ Run3+Run4

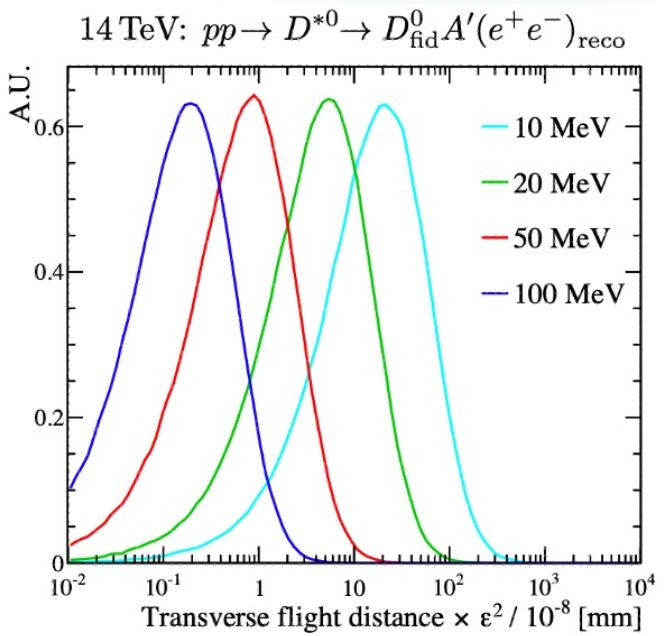
arXiv: 1509.06765.

- The displaced search, relevant at smaller values of ε^2 , looks for an $A' \to e^+e^-$ decay vertex that is significantly displaced from the pp collision.
  - A′ gains a transverse momentum kick from pp collisions, the A′ flight trajectory intersects the LHCb detector, making it possible to identify displaced e^+e^- pairs with smaller opening angles



$$\ell_{A'} \simeq 16\,\text{mm} \left(\frac{\gamma_{\text{boost}}}{10^2}\right)\left(\frac{10^{-8}}{\epsilon^2}\right)\left(\frac{50\ \text{MeV}}{m_{A'}}\right)$$

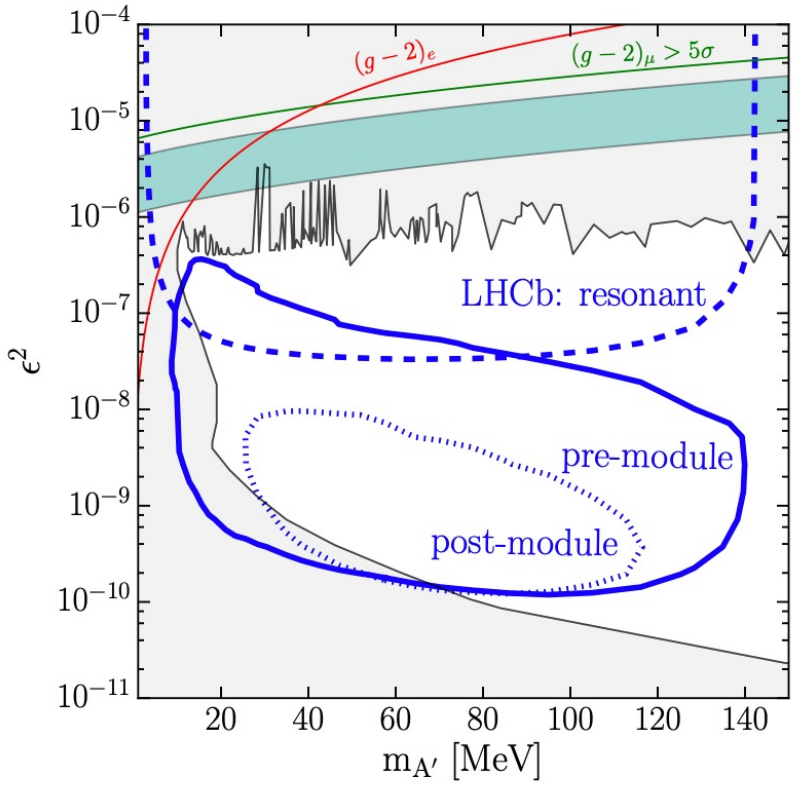




LHCb $D^{*0} \to A'D^0$, $A' \to ee$ Run3+Run4

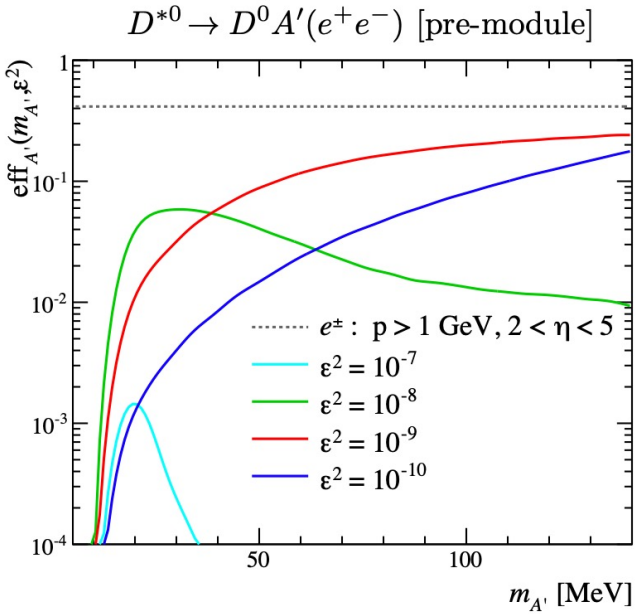
arXiv: 1509.06765.

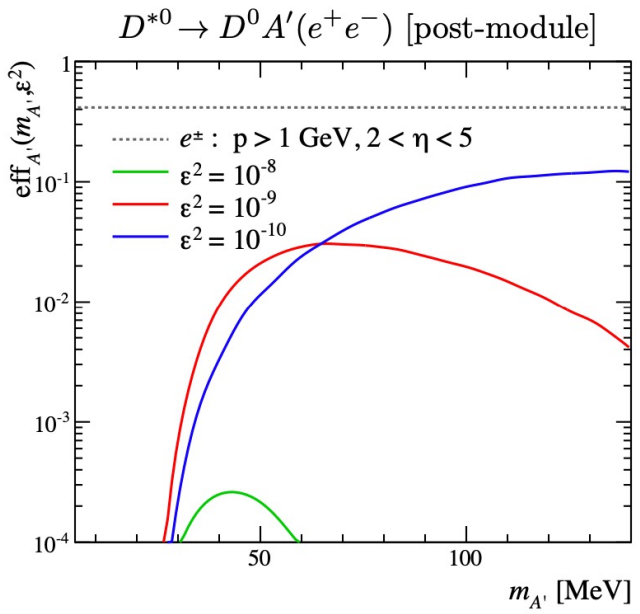
- The displaced search, relevant at smaller values of ε^2 , looks for an $A' \to e^+e^-$ decay vertex that is significantly displaced from the pp collision.
  - A′ gains a transverse momentum kick from pp collisions, the A′ flight trajectory intersects the LHCb detector, making it possible to identify displaced e^+e^- pairs with smaller opening angles



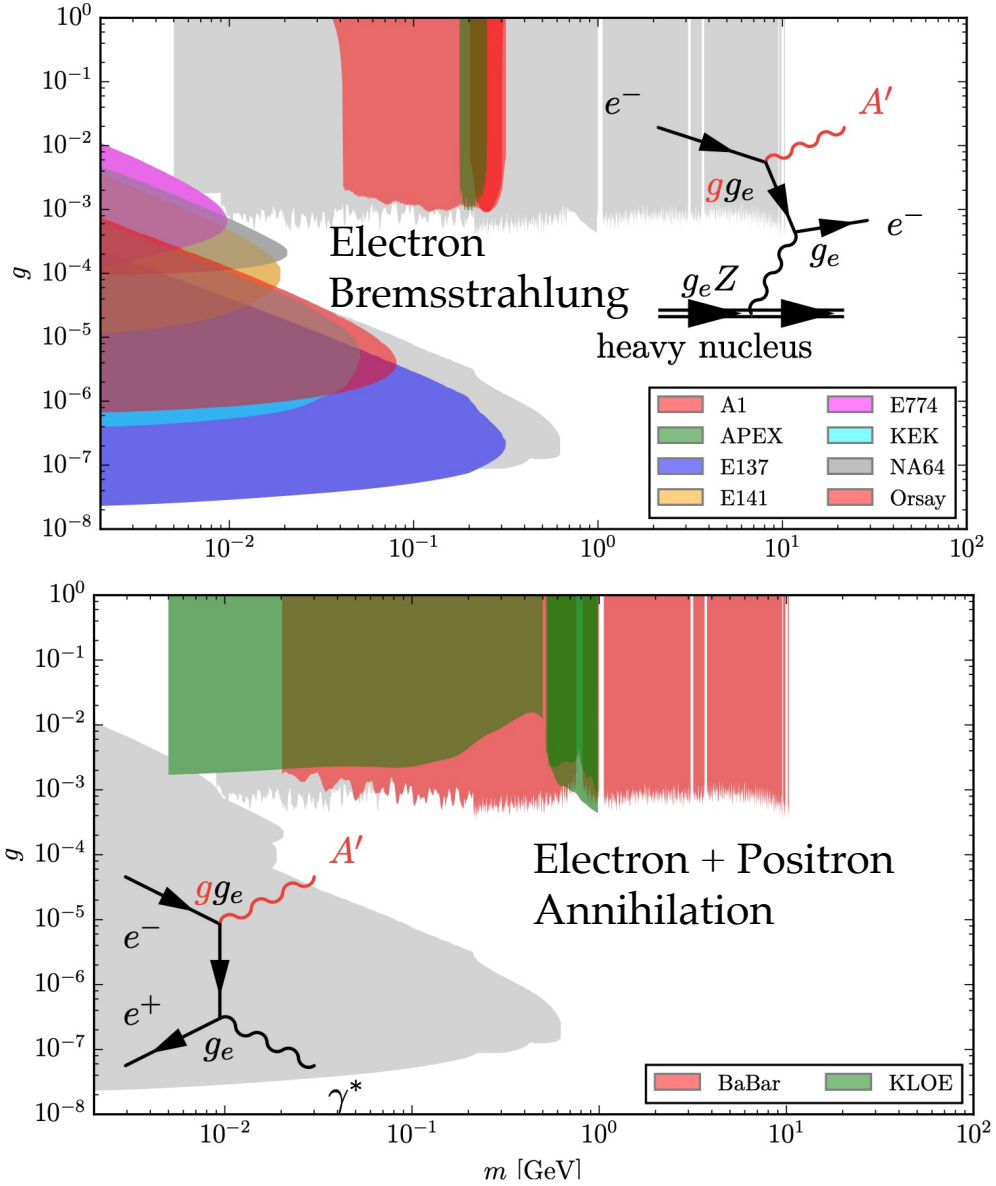
$$S(m_{A'}, \epsilon^2) = N(D^{*0} \to D^0\gamma)\,\frac{\Gamma(D^{*0} \to D^0 A')}{\Gamma(D^{*0} \to D^0\gamma)}\,\mathrm{eff}_{\Delta m_D} \times \left(\mathrm{eff}_D^{\mathrm{F}} + \mathrm{eff}_D^{\mathrm{P}}\right)\mathrm{eff}_{A'}(m_{A'}, \epsilon^2)$$

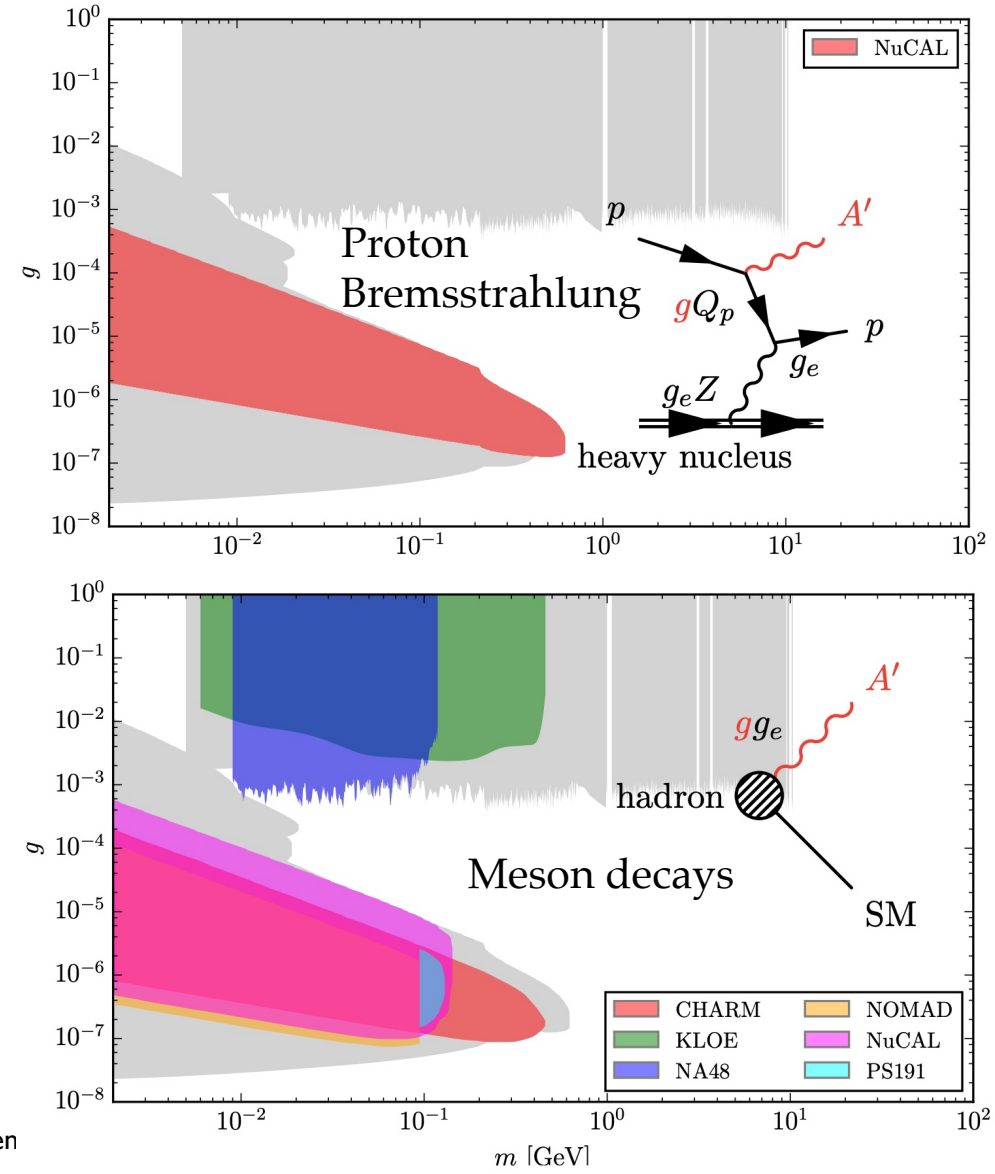
$$\simeq 85\left(\frac{\epsilon^2}{10^{-10}}\right)\left(1 - \frac{m_{A'}^2}{\Delta m_D^2}\right)^{3/2}\mathrm{eff}_{A'}(m_{A'}, \epsilon^2).$$





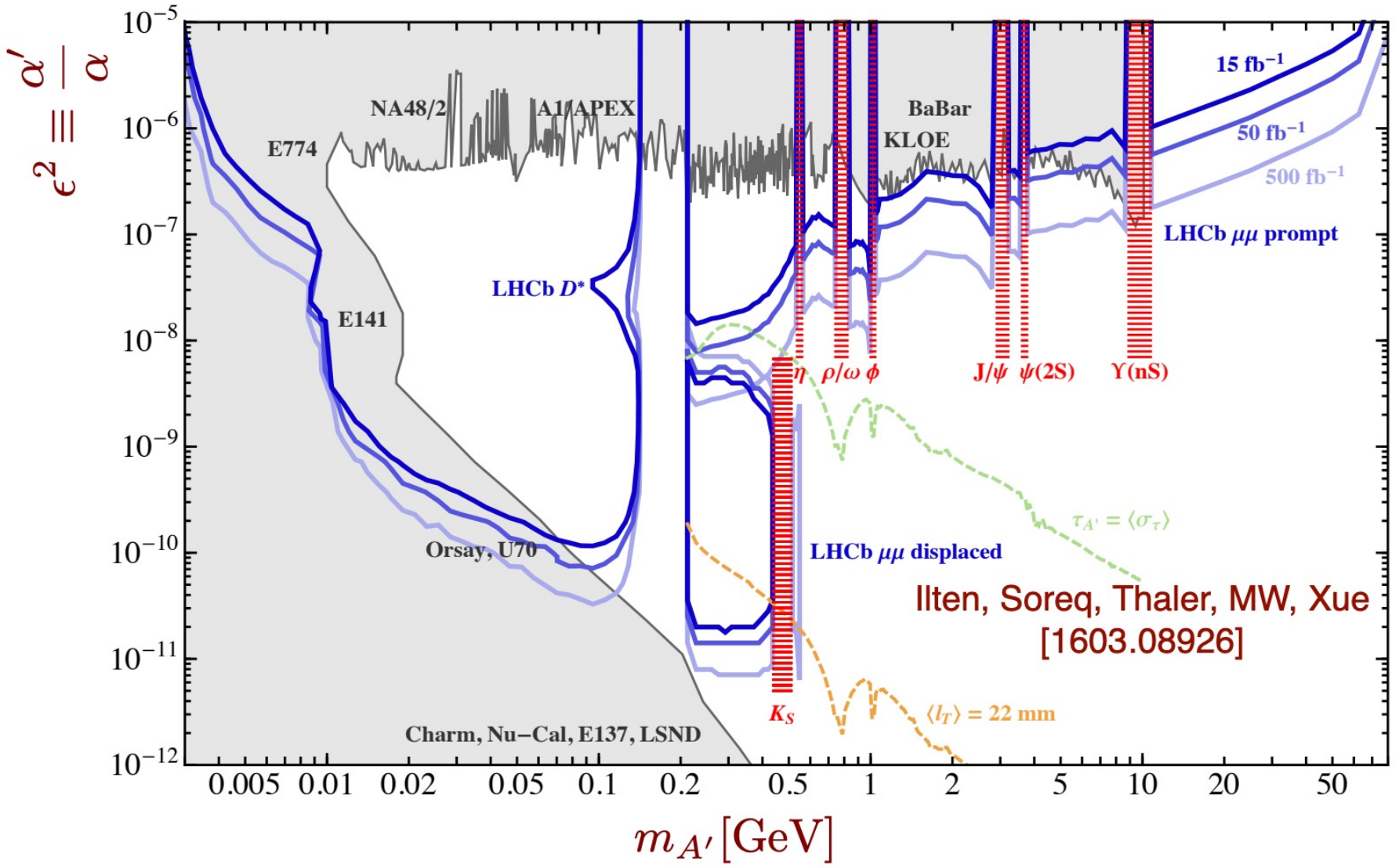
Current limits





LHCb from Run4+Run5

50 fb^{-1} – 500 fb^{-1}



Sensitivity in the next 5 years

arXiv:2104.10280