Dark Photons (& Friends) @ LHCb

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On behalf of the LHCb Collaboration
Implications Workshop
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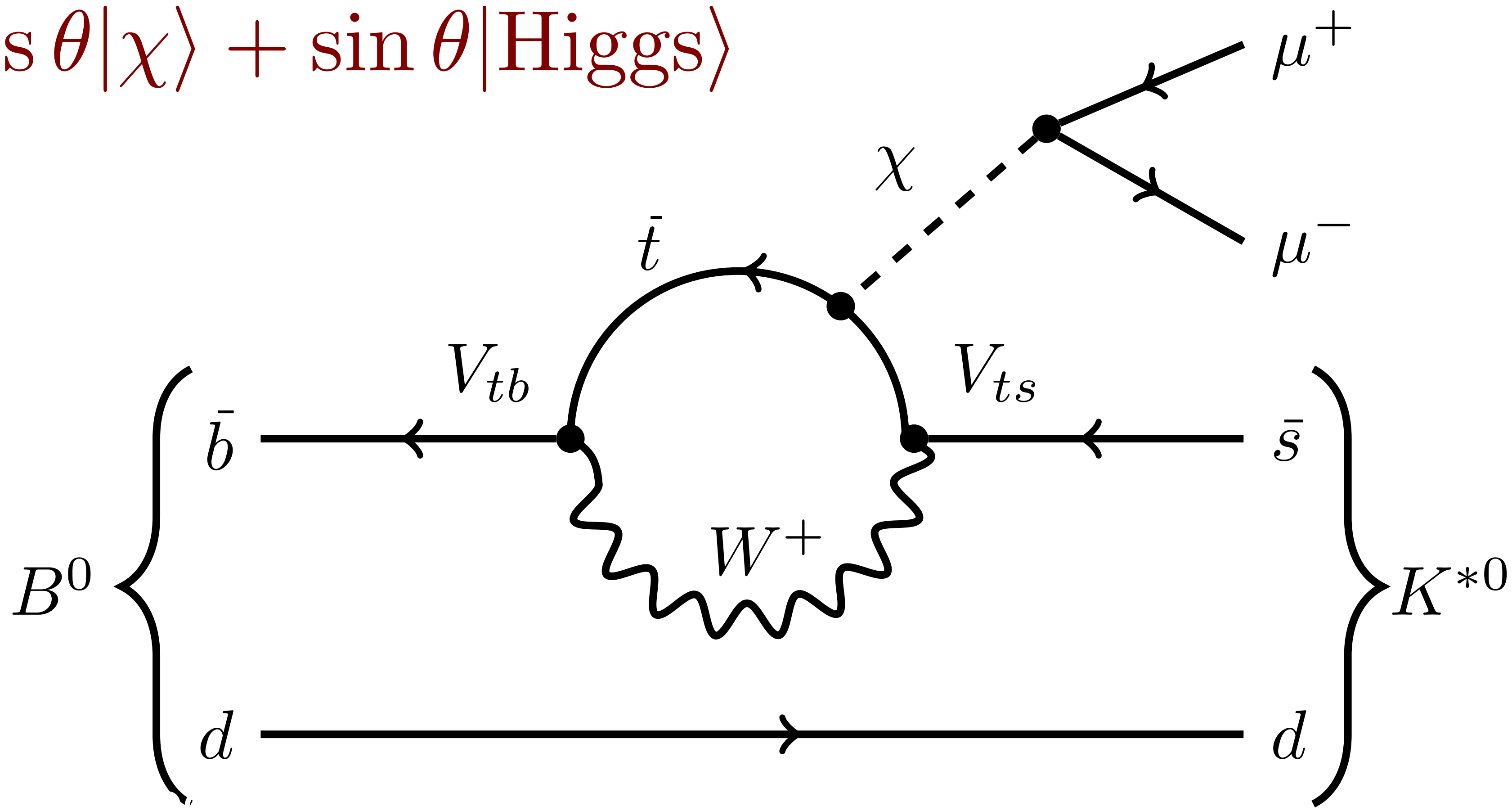
Hidden Sectors

PRL 115 (2015) 161802
LHCb-PAPER-2015-036

$b \to s$ penguin decays are an excellent place to search for low-mass hidden-sector particles (e.g., anything that mixes with the Higgs sector).

$$|\chi\rangle_{\text{phys}} = \cos\theta|\chi\rangle + \sin\theta|\text{Higgs}\rangle$$

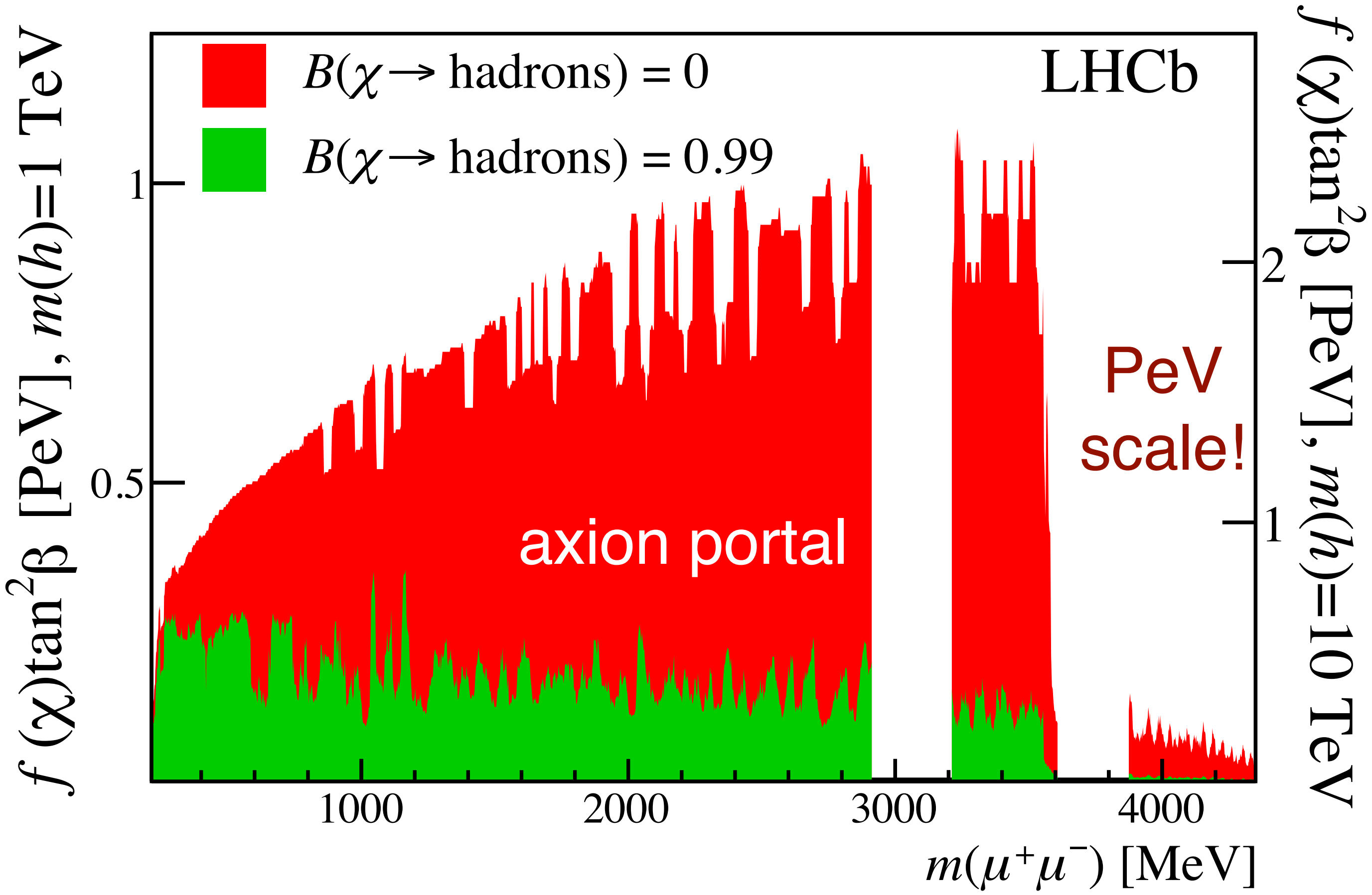


Search for $B \to K^*X$, $X \to \mu\mu$ by scanning m(μμ) and allowing (not requiring) non-zero τ(μμ). Strategy handles possible qq resonance contributions (MW [1503.04767]), and uses a novel "uniform BDT" (J.Stevens, MW [1305.7248]).

Hidden Sectors

Model-independent limits set. Can also look at constraints on specific models:

Freytsis, Ligeti, Thaler [arXiv:0911.5355]



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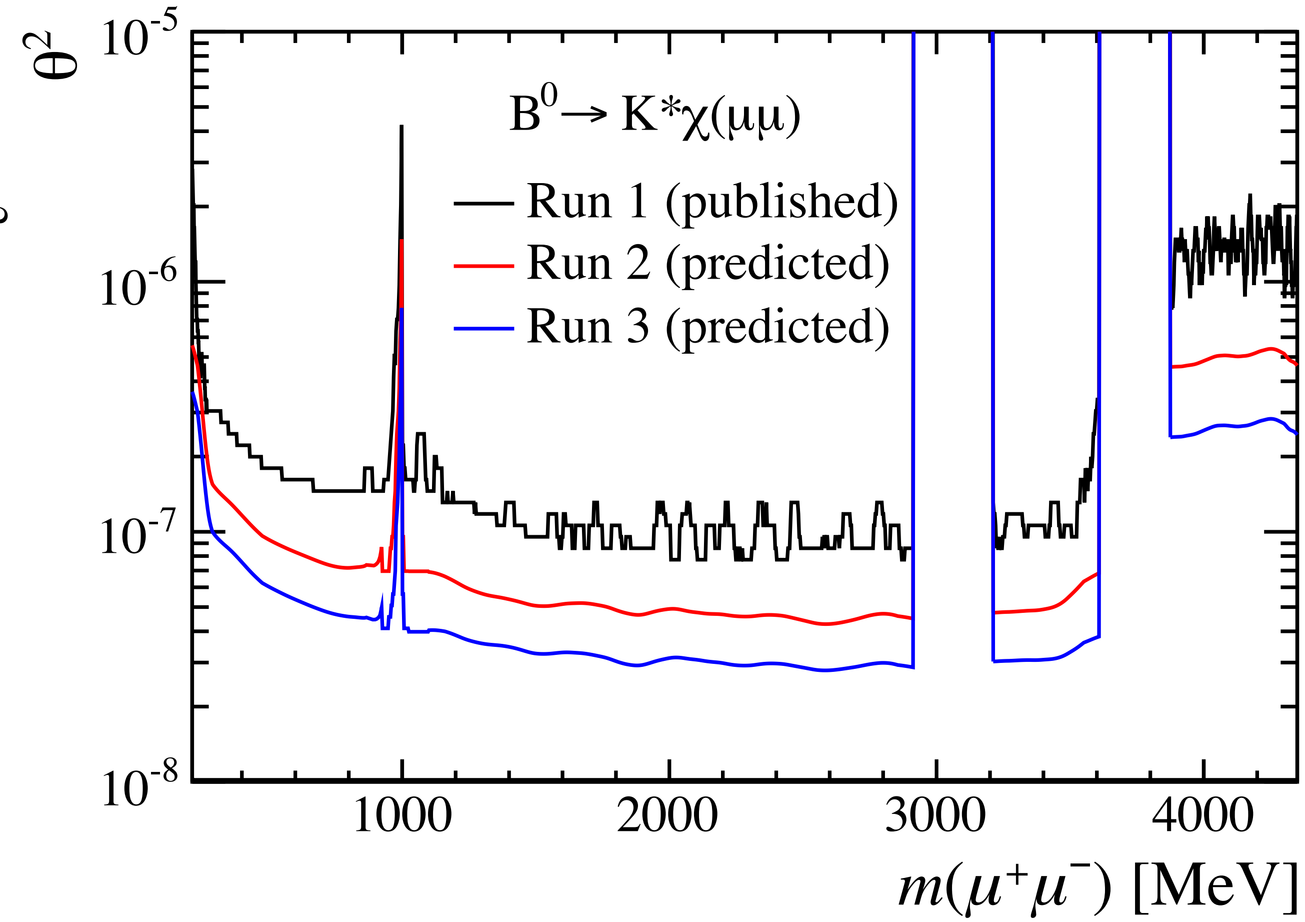


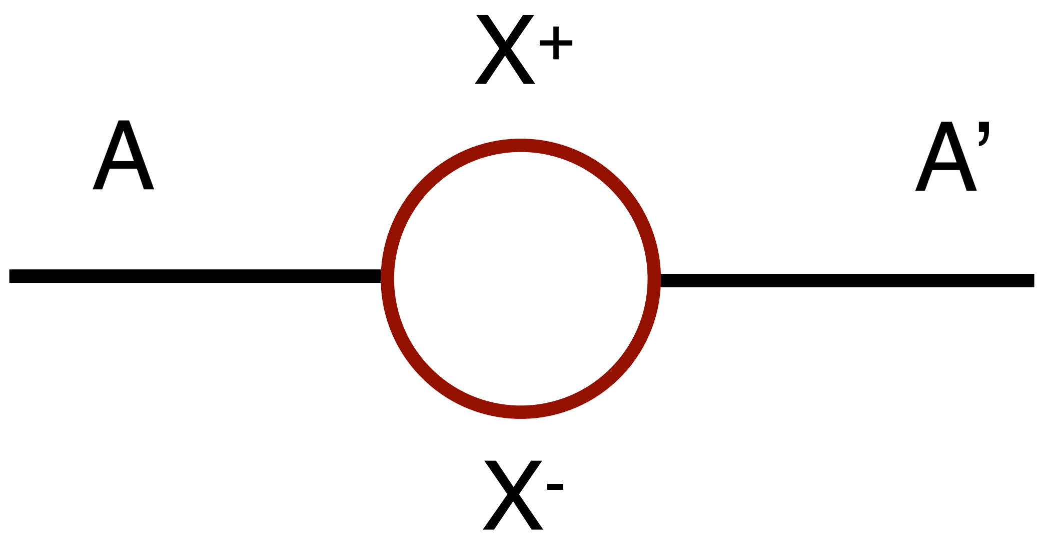
By far the strongest constraints on a scalar in the mass range $2m(\mu)<m<2m(\text{tau})$ that mixes with the Higgs (SHiP will cover $\sim10^{-7}$-10^{-10}).

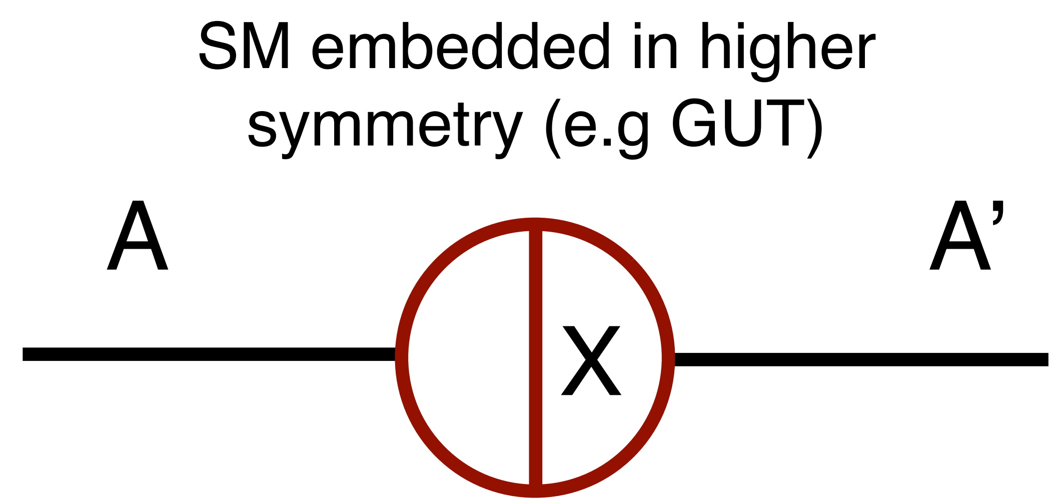
LHCb has also performed a similar search for Majorana neutrinos in B decays with same-sign muons [PRL 112 (2014) 131802].

We’ve already made important contributions -- what else can we do?

Dark Photons

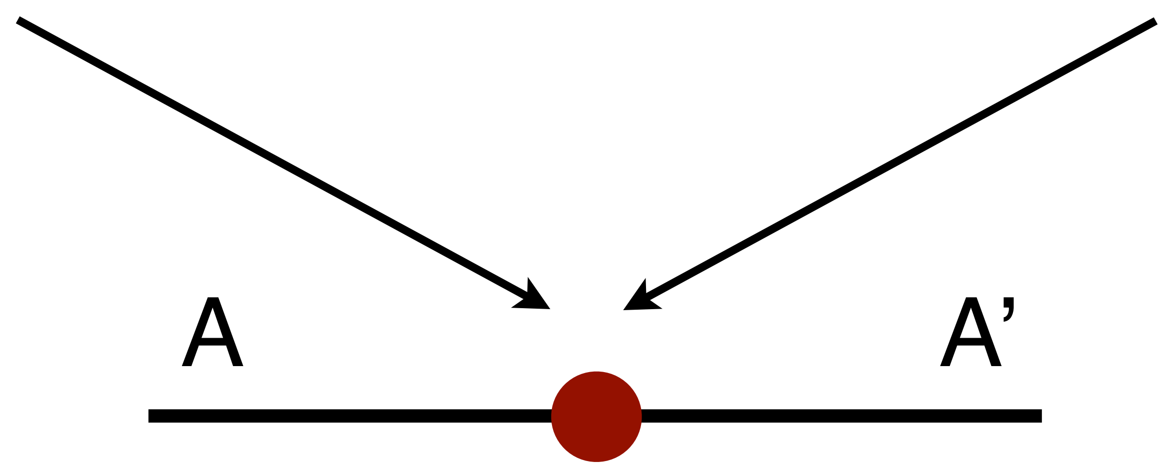
The minimal dark photon scenario introduces a new U(1)' gauge symmetry that is broken resulting in a massive vector A' boson.





$\varepsilon \sim eg_D/16\pi^2 \sim O(10^{-3})$

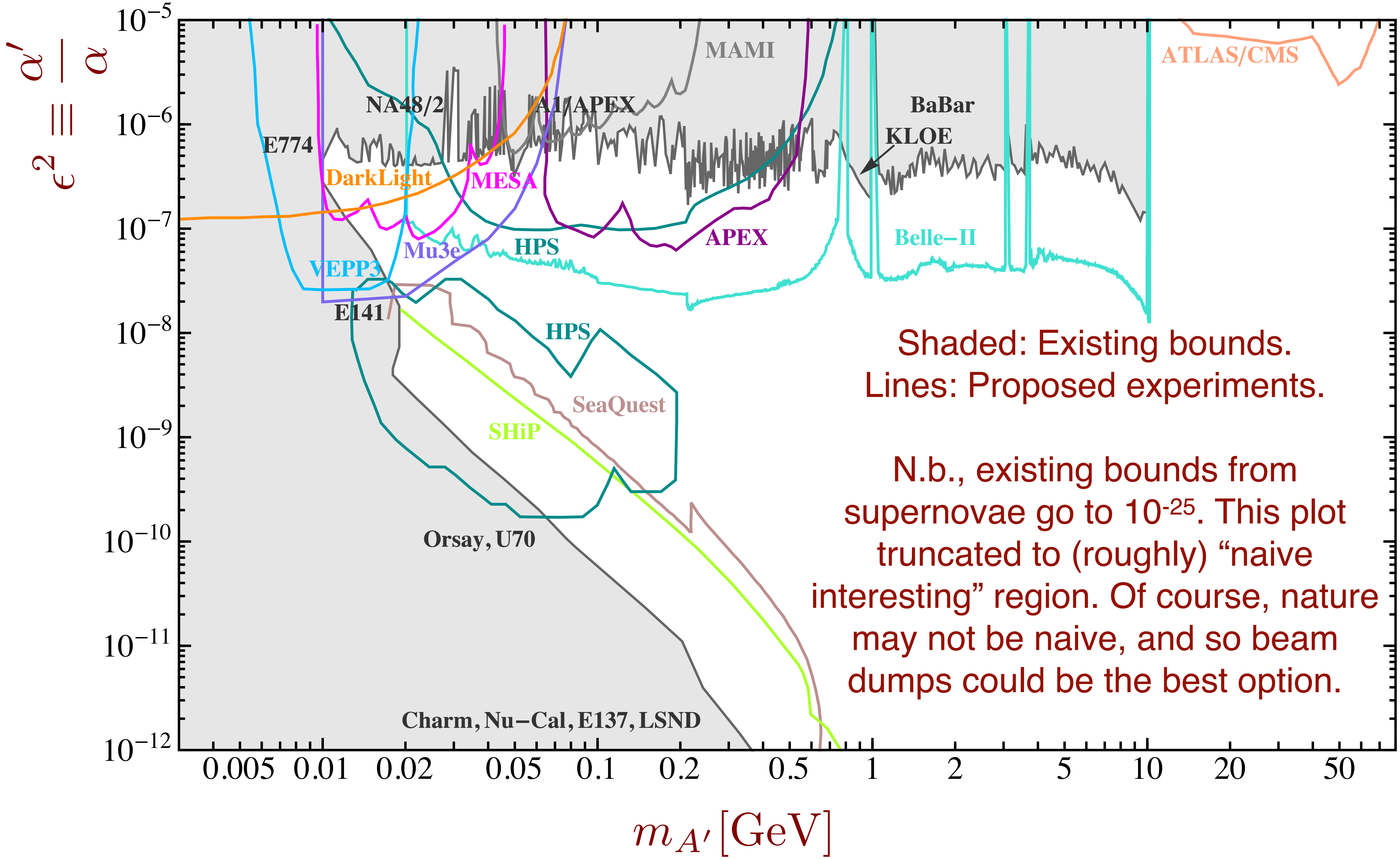
$\varepsilon \sim [eg_D/16\pi^2]^2 \log(m_{GUT}/m_X) \sim O(10^{-5})$



In the absence of any tree-level A'-SM coupling, the A' picks up suppressed coupling to SM particles perturbatively by quantum effects.

Dark Photons

If it exists, the dark photon should kinetically mix with our photon. Dedicated worldwide effort to devise ways to search for dark photons.



Dark Photons

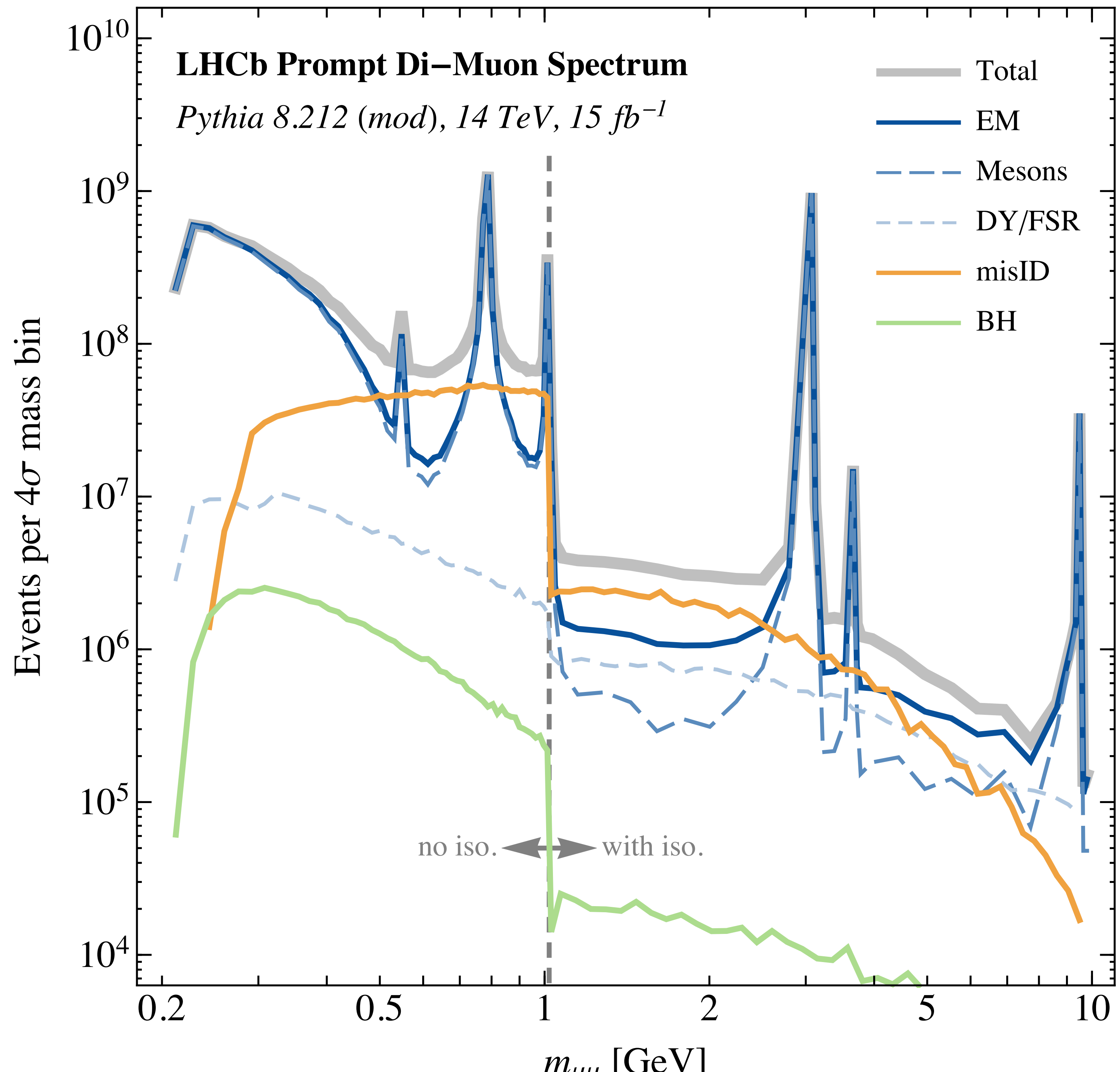
Ilten, Soreq, Thaler, MW, Xue
[1603.08926]

The most experimentally favorable A' decay mode is di-muon. The A' rate can be inferred from the prompt $\gamma^* \to \mu\mu$ rate making this a **fully data-driven search** at the LHC!

We estimated all contributions to the prompt di-muon spectrum for $p_T(\mu) > 0.5$ GeV, $p(\mu) > 10$ GeV, and $2 < \eta(\mu) < 5$, to permit estimating the possible reach using $A' \to \mu\mu$ at LHCb.

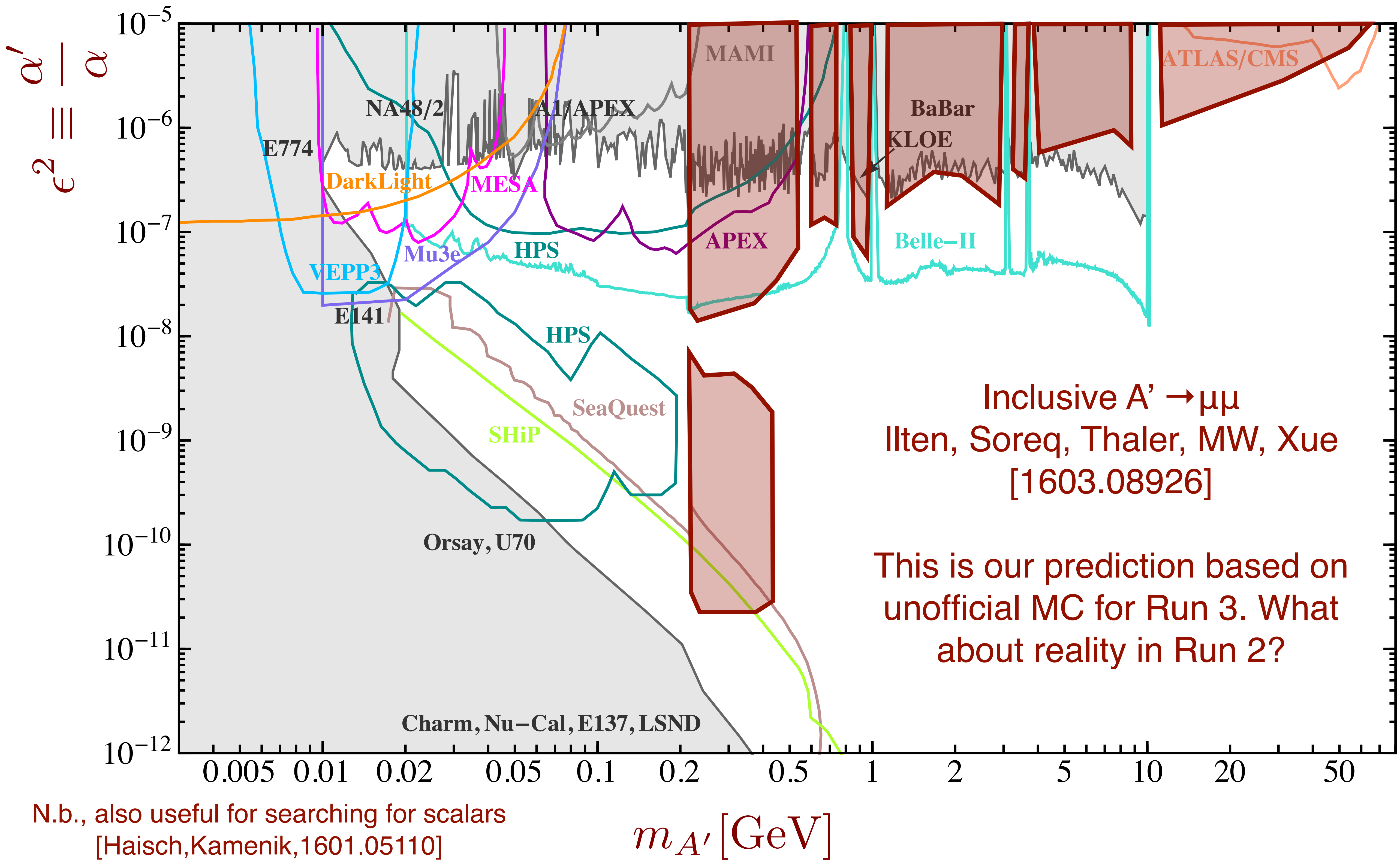
For concreteness, we considered only the 15/fb expected in Run 3 (everything scales as √lumi).

"Mesons" and "DY/FSR" can produce A', "BH" and "misID" cannot.



Dark Photons

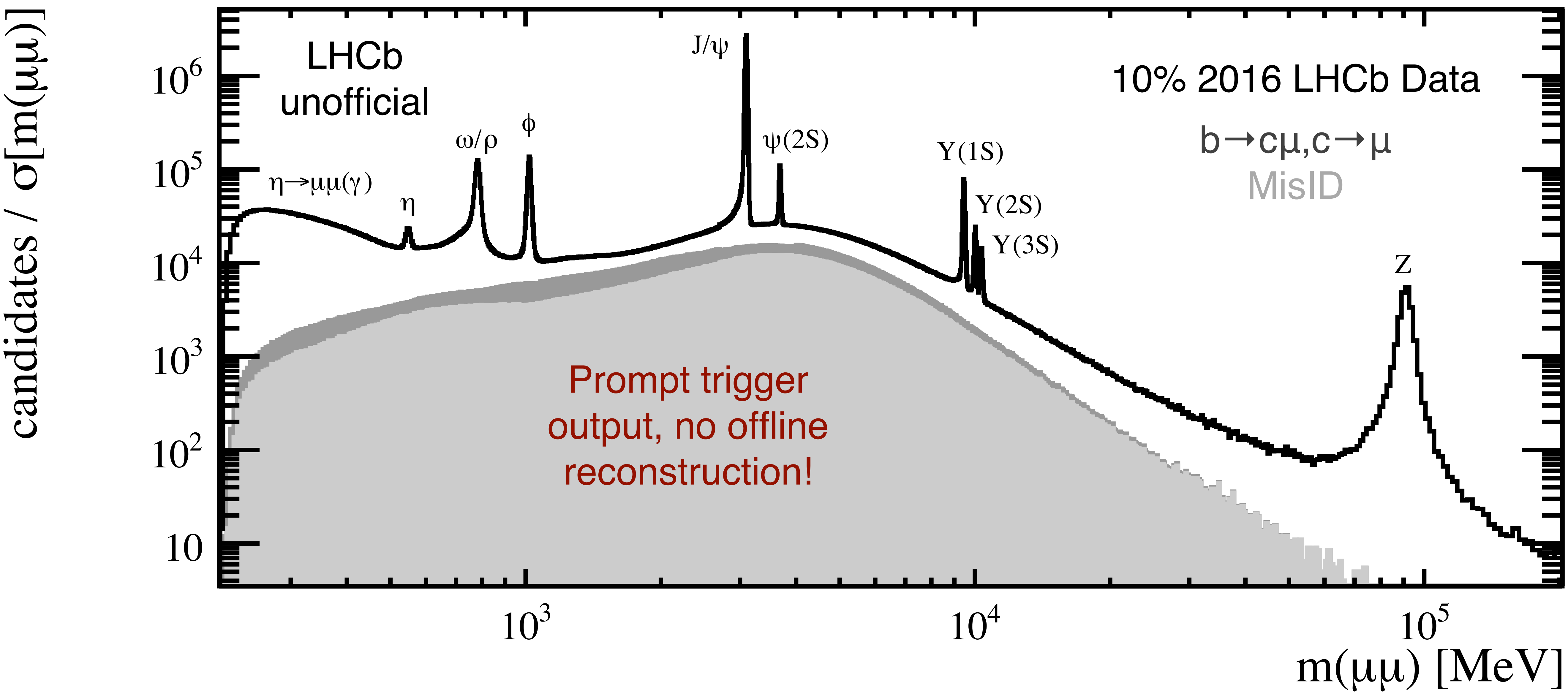
Prompt search is a bump hunt. Displaced has two regions: (pre-material) huge b→cμ(X),c→μ(Y) BKGD and (post-material) material interaction BKGD.



N.b., also useful for searching for scalars [Haisch,Kamenik,1601.05110]

2016 Data

New triggers produced for 2016 to do both the prompt and displaced di-muon searches (rely heavily on advances to the LHCb online system in Run 2).

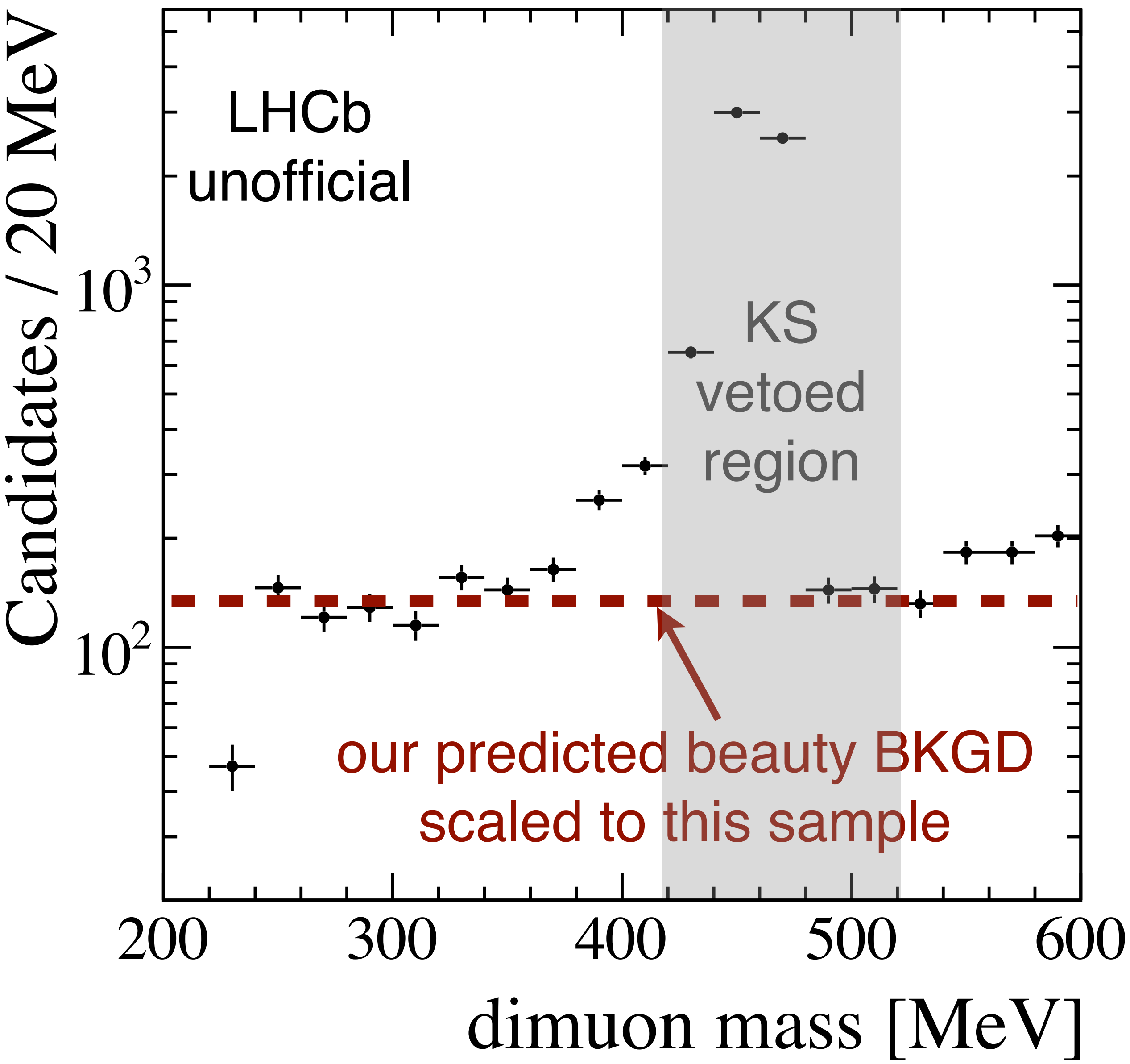


In 2016, require $p_T(\mu) > 1$ GeV (instead of 0.5 GeV) due to limitations in the muon ID in the first software-trigger stage. Working to improve this for 2017. SM rate agrees with our prediction, which means that the potential A' production rate does too.

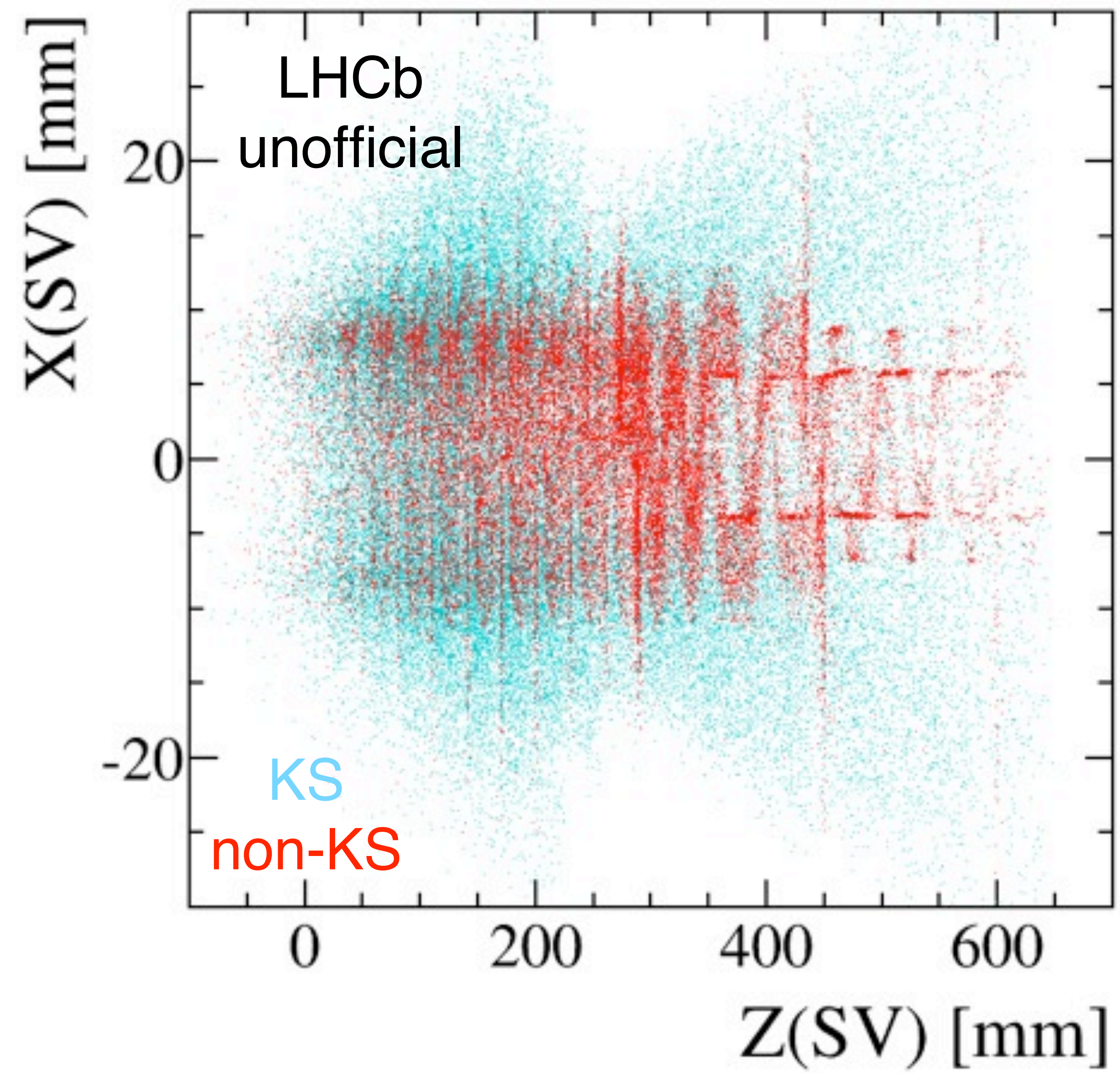
2016 Data

Displaced search split into pre-module and post-module regions, where the dominant BKGDs are b→cμ,c→μ and material interactions, respectively.

pre-module
(selection directly from our PRL)



post-module
(no material veto applied)

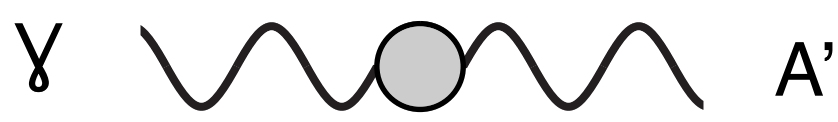


Preliminary estimates suggest that we can probe unexplored parameter space in both the prompt and displaced searches in Run 2.

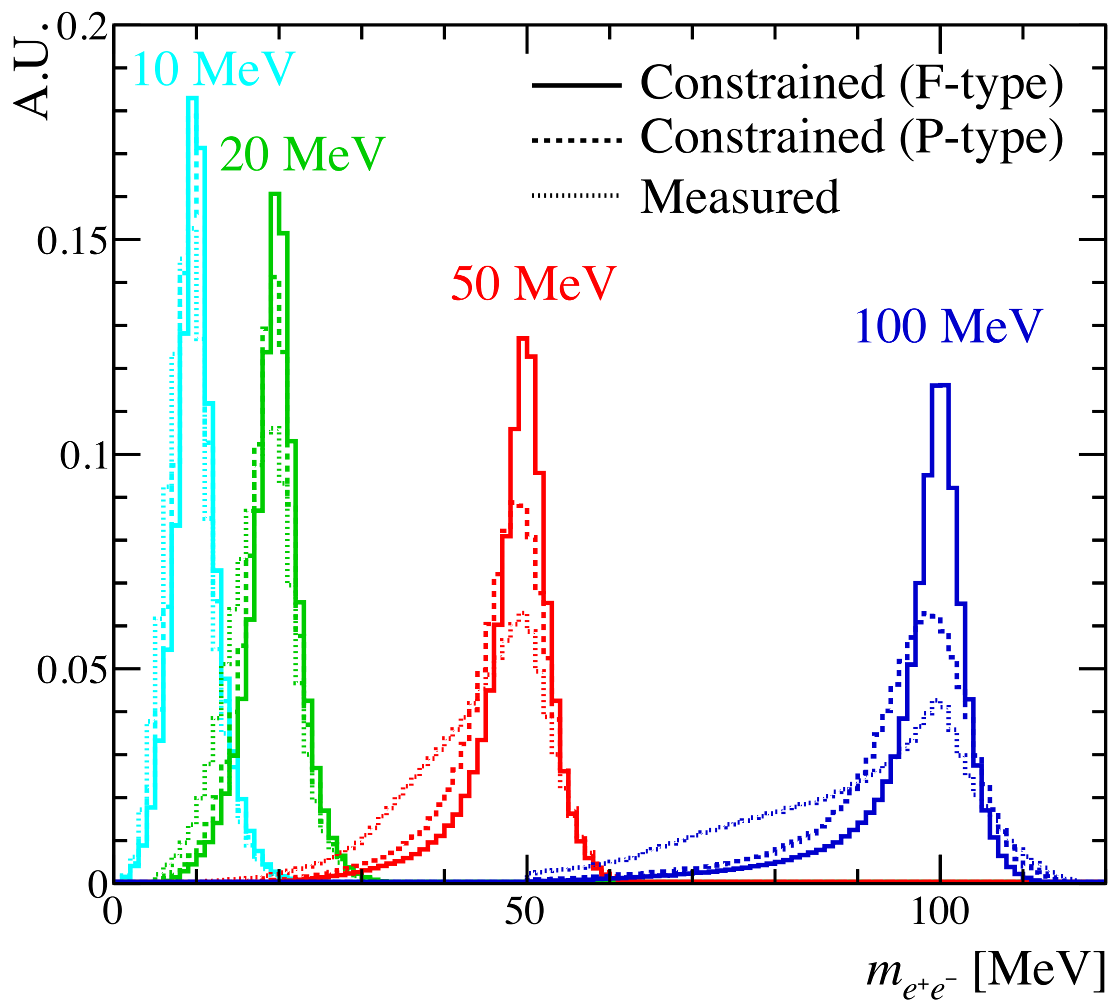
Dark Photons

For the low-mass region, consider the decay $D^{*0} \rightarrow D^0 A'(ee)$, which can potentially probe the region 2m(e) to ~142 MeV. The SM decay $D^{*0} \rightarrow D^0 \gamma$ will occur within LHCb acceptance at almost 1 MHz in Run 3.

Ilten, Thaler, MW, Xue [1509.06765]



$$\frac{\Gamma(D^{*0} \to D^0 A')}{\Gamma(D^{*0} \to D^0 \gamma)} = \epsilon^2 \left(1 - \frac{m_{A'}^2}{\Delta m_D^2}\right)^{3/2},$$

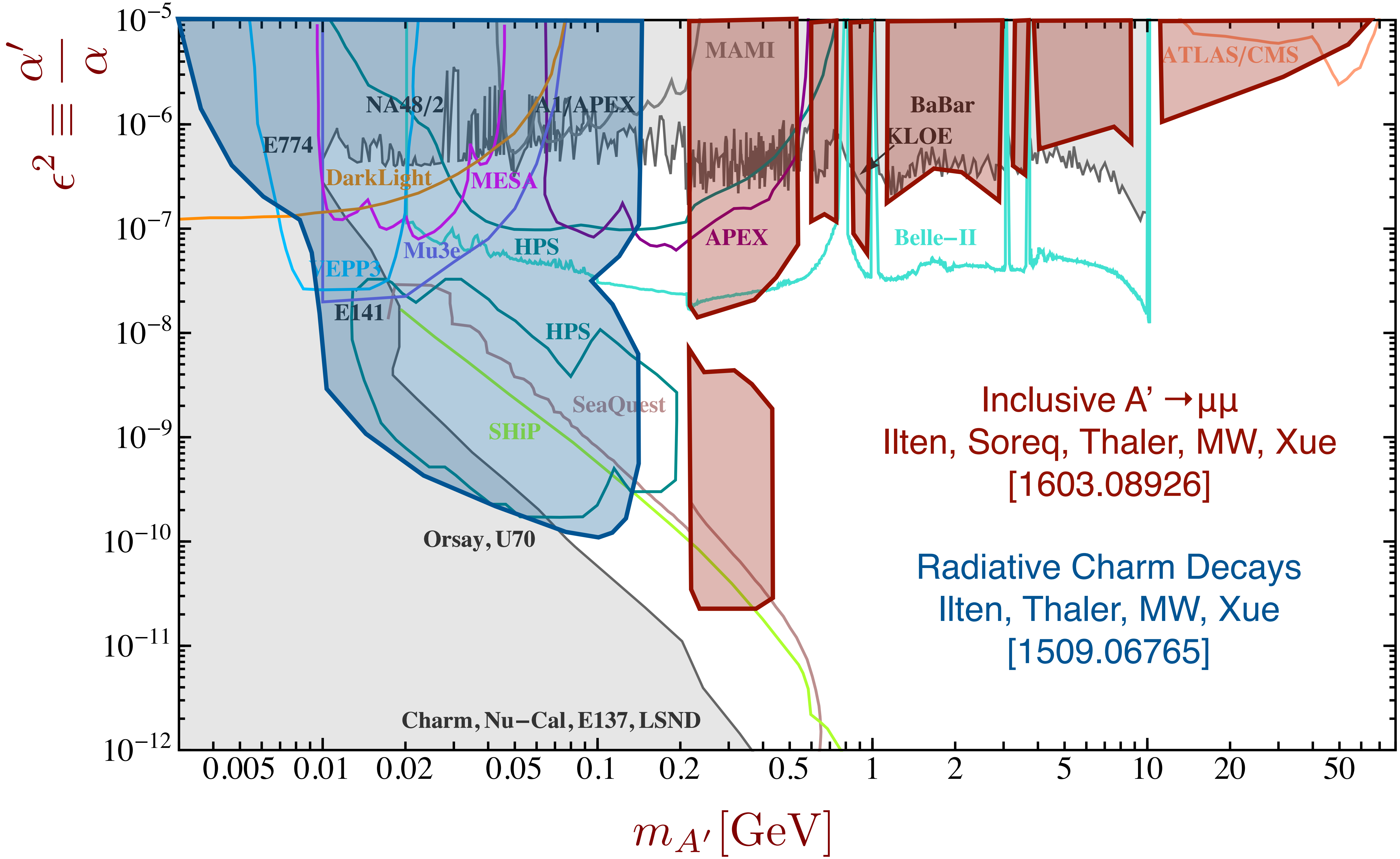


We required A’ decays before reaching material to suppress conversions.

Poor m(ee) resolution due to BREM can be greatly improved by performing a mass-constrained fit using known $m(D^{*0})$ and well-measured D^0. Cutting on $m(D^0ee)$ will suppress combinatorial BKGD.

Dark Photons

Move to a triggerless detector readout in Run 3 will have a huge impact on low-mass BSM searches, including dark photons.

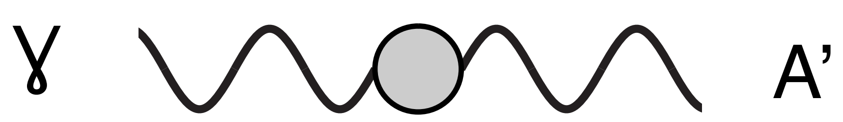


2016 Data

The D* mode is considerably more challenging than the di-muon search, and both the Run 2 hardware trigger and larger VELO RF foil material budget degrade the sensitivity of this search for Run 2.

A trigger was added in 2016 that can be used to look for $D^* \to D0(K\pi)A'(ee)$ which can be used to perform a first search, and to produce more inclusive triggers for future running.

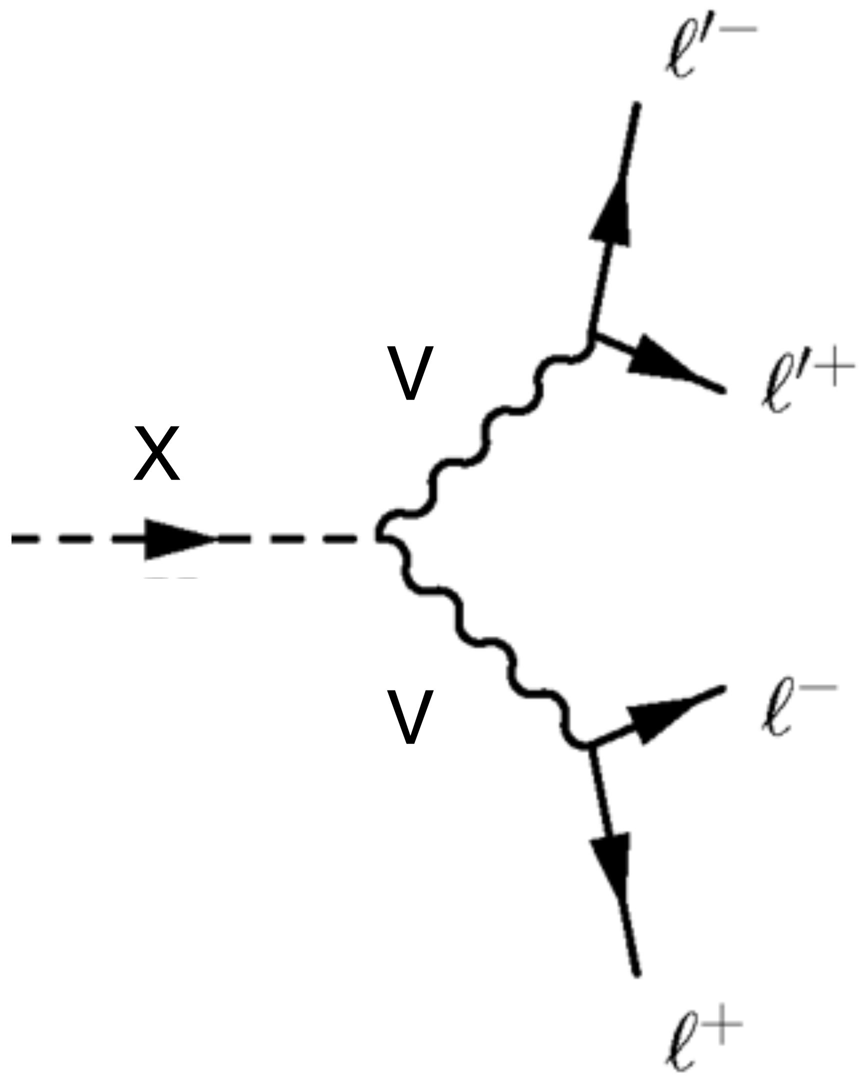
Any SM process that can produce an off-shell gamma can also produce an A', provided that $Q^2 = m(A')$ is kinematically allowed in the SM process.



There are many other potential channels we could use, though most require O(100/fb) of data, or don't provide a way of improving the poor ee mass resolution. We have found a few possible candidates that may work in Run 2, and are investigating these now.

4 Muons

A similar search involves looking for the decay of a particle (likely a scalar, or possibly a dark bound state) into a pair of new vector particles that then decay into leptons.

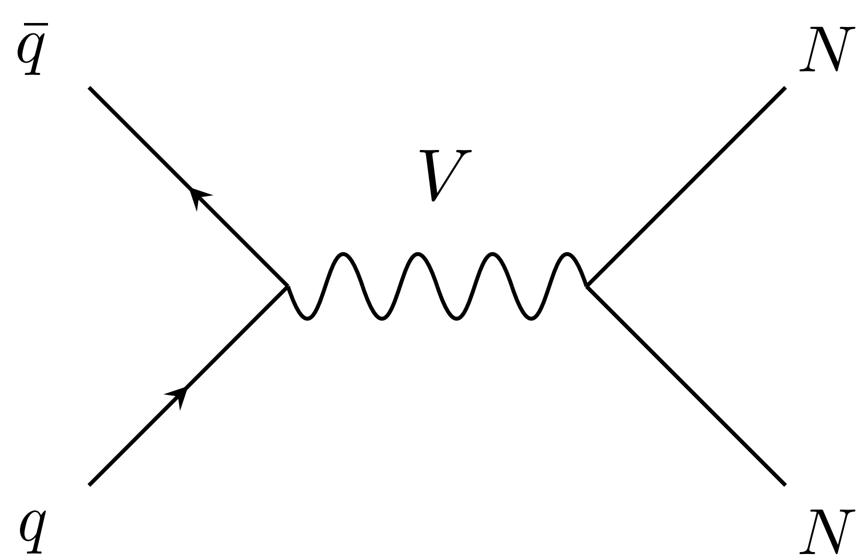


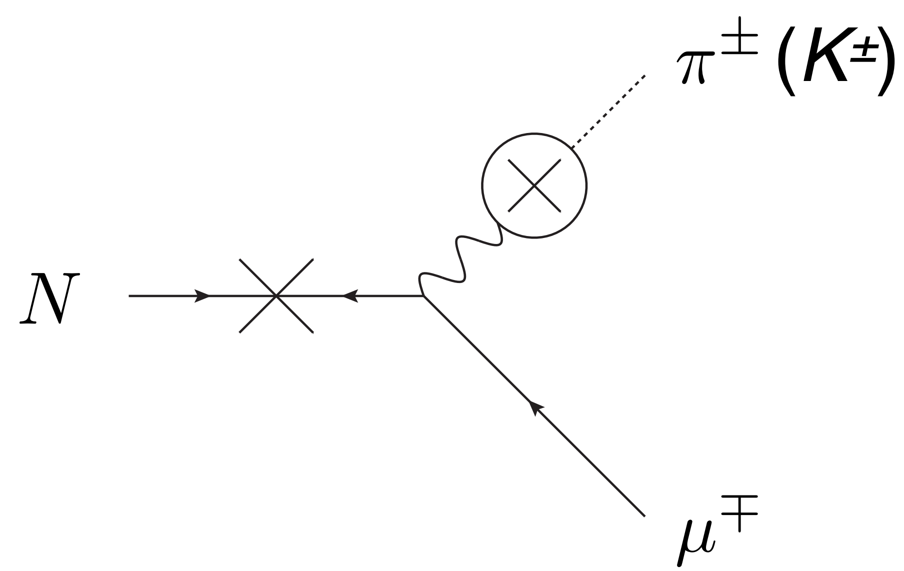
LHCb developed new triggers for this signature for 2016 with a muon pT threshold of 0.5 GeV (expect ~1.5/fb of this data this year).

RH Neutrinos

A new gauge (e.g. B-L) mediator (V) could be produced via pp → *V* then decay into a pair of right-handed neutrinos. At low mass, the N will often decay into a muon and a hadron (pion or kaon).

Batell, Pospelov, Shuve [1604.06099]





N is expected to have a macroscopic lifetime, so LHCb can look for a pair of displaced hadron-μ (hμ) vertices consistent with a 2-body decay topology. New trigger added in July 2016 that requires a single hμ candidate with τ>1ps, can search for pair production offline (expect ~1/fb of this data this year).

Summary

LHCb has unique capabilities that make it uniquely sensitive to certain classes of dark-sector models.

Dark Photons

$$\mathcal{L}_{\gamma A'} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m^2_{A'} A'^{\mu} A'_{\mu} + \epsilon\, e\, A'_{\mu} J^{\mu}_{\mathrm{EM}} \,.$$

$$\Gamma_{A' \to \ell^+\ell^-} = \frac{\epsilon^2 \alpha_{\mathrm{EM}}}{3} m_{A'} \left(1 + 2\frac{m_\ell^2}{m_{A'}^2}\right) \sqrt{1 - 4\frac{m_\ell^2}{m_{A'}^2}} \,,$$

$$\Gamma_{A' \to \mathrm{hadrons}} = \Gamma_{A' \to \mu^+\mu^-} \mathcal{R}_\mu(m^2_{A'}) \,.$$

assumed to be zero when setting limits

$$\Gamma_{A'} = \sum_\ell \Gamma_{A' \to \ell^+\ell^-} + \Gamma_{A' \to \mathrm{hadrons}} + \Gamma_{A' \to \mathrm{invisible}} \,.$$

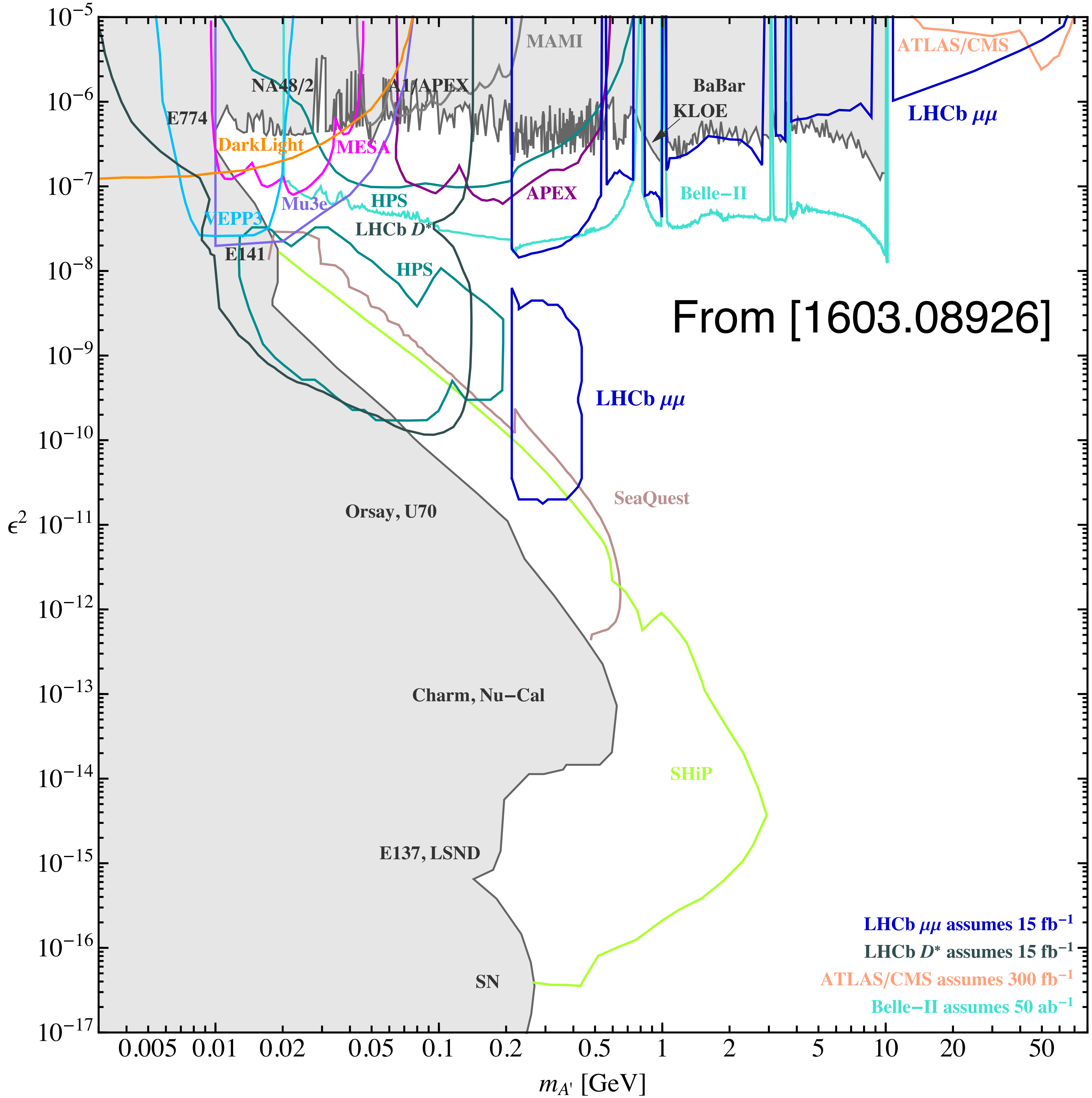
Inclusive Production

$$\frac{S}{B_{\mathrm{EM}}} \approx \epsilon^4 \frac{\pi}{8} \frac{m^2_{A'}}{\Gamma_{A'} \sigma_{m_{\mu\mu}}} \approx \frac{3\pi}{8} \frac{m_{A'}}{\sigma_{m_{\mu\mu}}} \frac{\epsilon^2}{\alpha_{\mathrm{EM}}(N_\ell + \mathcal{R}_\mu)} \,,$$

Production in Charm Decays

$$\frac{\Gamma(D^{*0} \to D^0 A')}{\Gamma(D^{*0} \to D^0 \gamma)} = \epsilon^2 \left(1 - \frac{m^2_{A'}}{\Delta m^2_D}\right)^{3/2} \,,$$

Bigger Picture



More Data?

Roughly how the reach scales with luminosity (from [1603.08926]).