Dark Sectors with LHCb and Beyond

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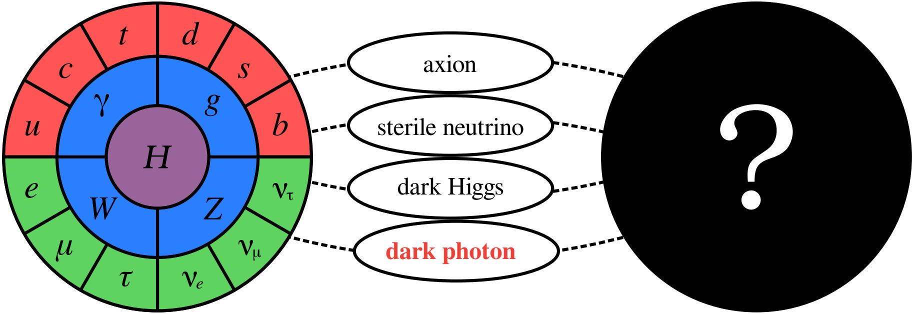
Dark Interactions 2024

Hidden Sectors

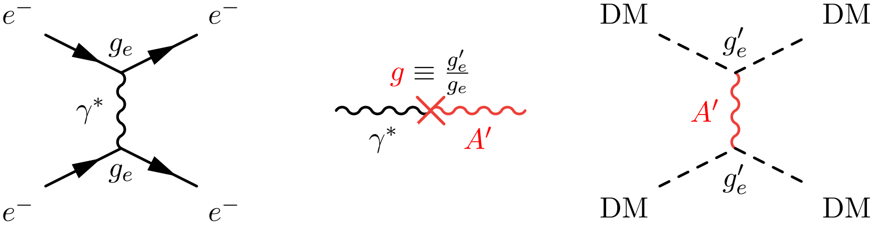


❶ broken $U(1)$ gauge symmetry in dark sector

❷ allow mixing between dark and SM hypercharge fields

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{{m_{A'}}^2}{2}A'_\mu A'^\mu + g_e J^\mu A_\mu + g g_e J^\mu A'_\mu$$

Dark Photons



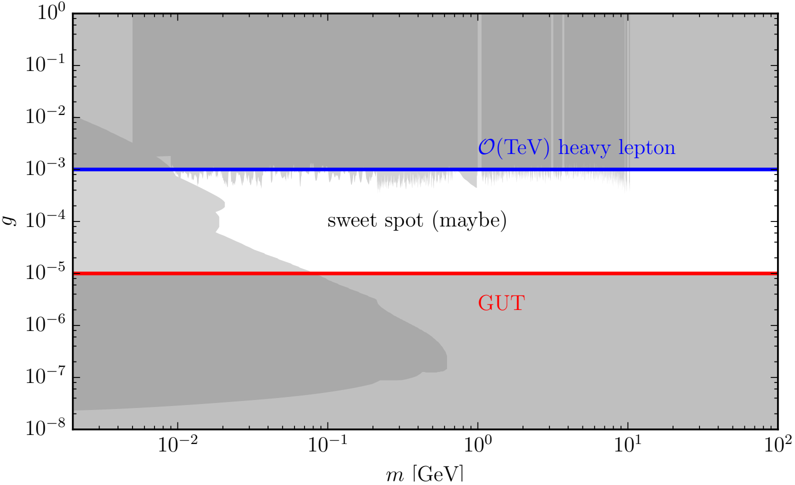
❶ mass of the dark photon, $m_{A'}$, and mixing, g, are free parameters

❷ the dark photon couples like the photon, modified by g

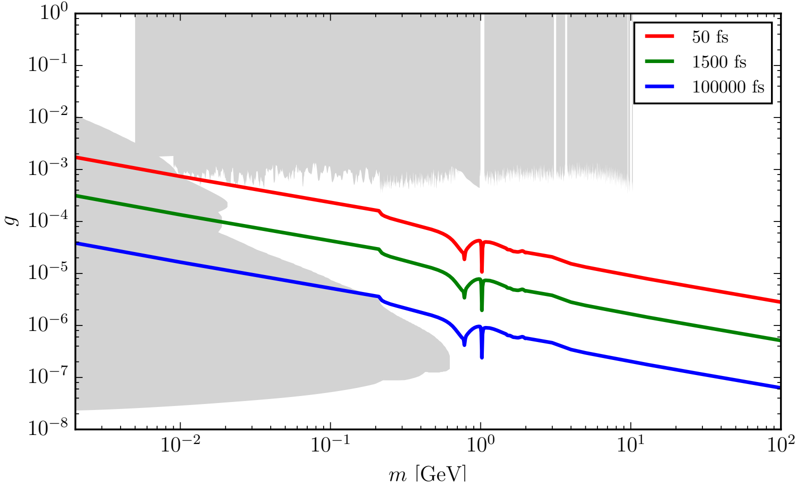
❸ if $m_{A'} < 2m_{\mathrm{DM}}$ then dark photon decays visibly

- what happens if ❷ and ❸ are relaxed?
- require $m_{A'}$, g, 12 fermion couplings, and an invisible width
- *dark photon limits can be recast to any general vector model*

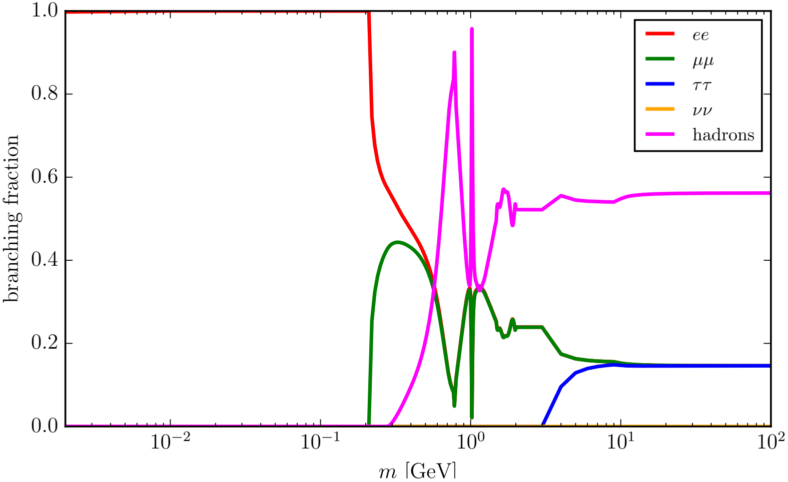
Parameter Space



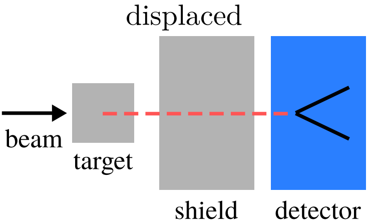
Lifetime

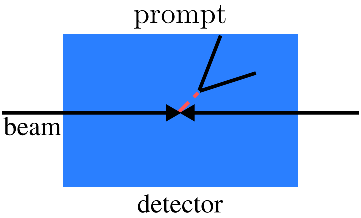

50 fs
1500 fs
100000 fs
g
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
m [GeV]

Decay Products



Search Strategies



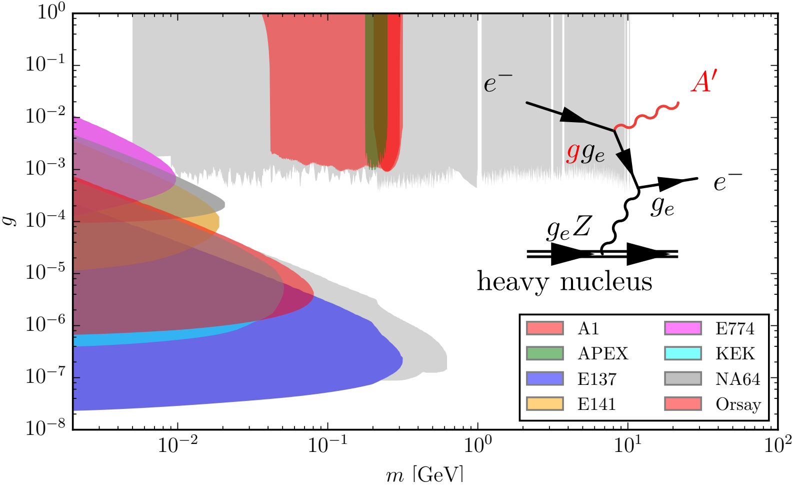


- sensitive to long lifetimes
- EM background free
- difficult to normalize

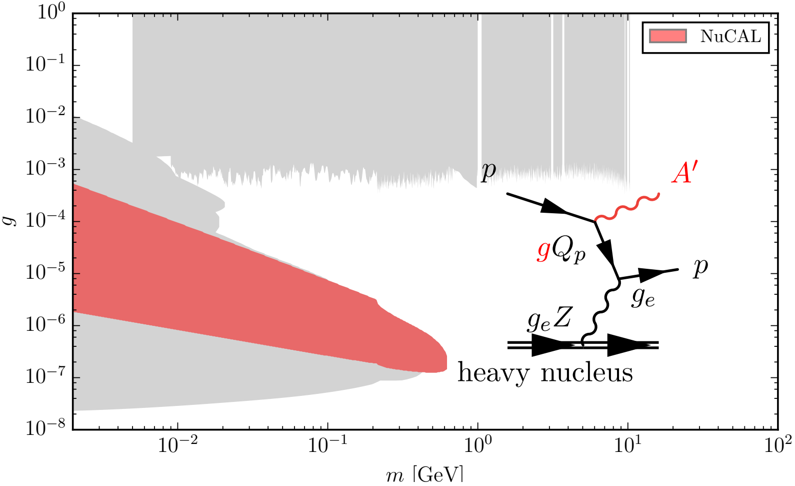
- sensitive to shorter lifetimes
- bump hunt on large EM background
- normalized from sidebands

- do both simultaneously for best of both worlds

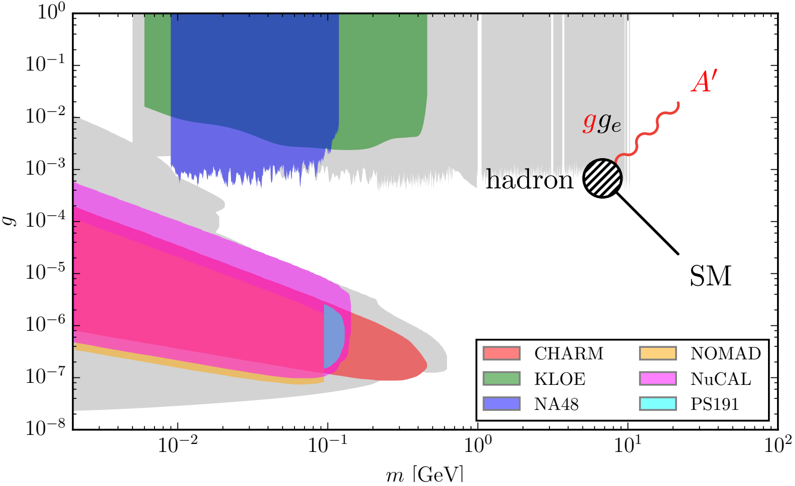
Production: Electron Bremsstrahlung



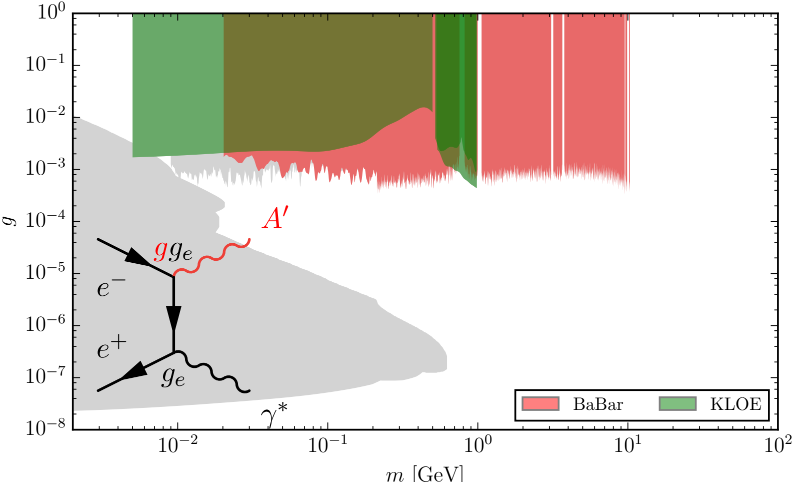
Production: Proton Bremsstrahlung



Production: Hadron Decays



Production: Electron-Positron Annihilation

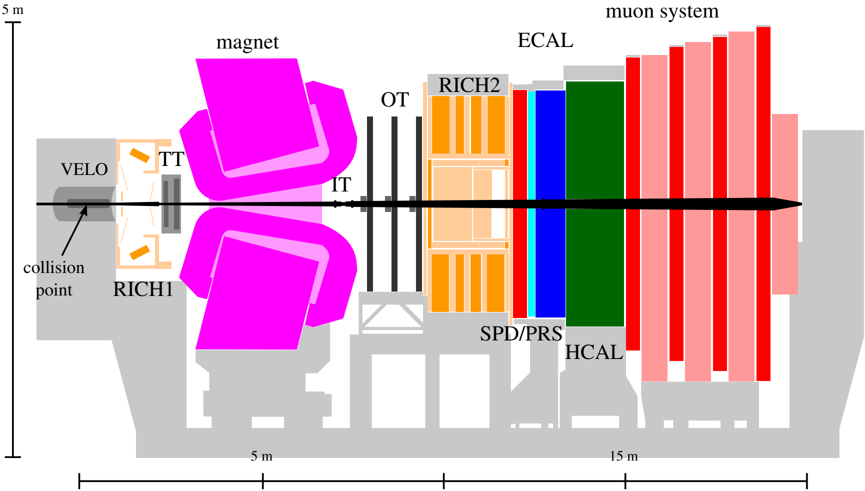


Searching with LHCb
in theory . . .

Ilten, Soreq, Thaler, Williams, Xue
Phys. Rev. Lett. **116**, no. 25, 251803 (2016)

Ilten, Thaler, Williams, Xue
Phys. Rev. D **92**, no. 11, 115017 (2015)

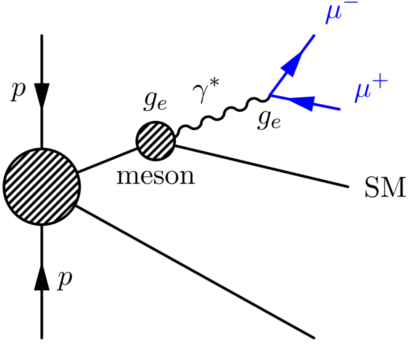
LHCb Detector



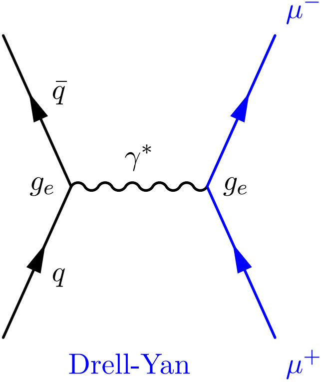
❶ good momentum, mass, and vertex resolution

❷ very low or no trigger thresholds

Good Backgrounds (*prompt*)

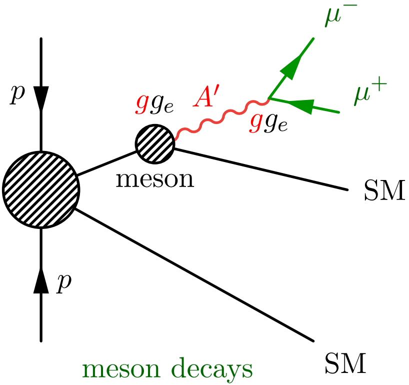


meson decays

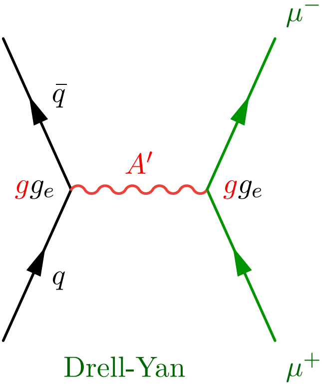


Drell-Yan

Signal (*prompt* and *displaced*)



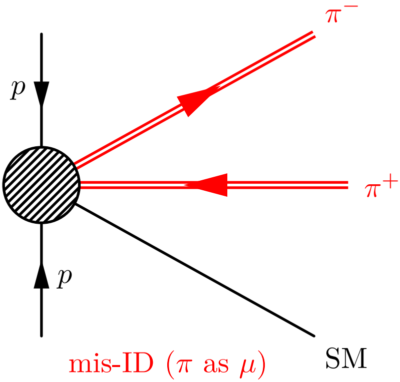
meson decays

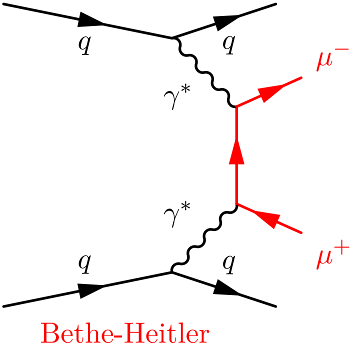


Drell-Yan

$$N_{\text{signal}} = \frac{g^4 m_{\mu\mu}^4}{(m_{\mu\mu}^2 - m_{A'}{}^2)^2 + m_{A'}{}^2 \Gamma_{A'}^2(g, m_{A'})} N_{\text{good}}$$

Bad Backgrounds (*prompt*)

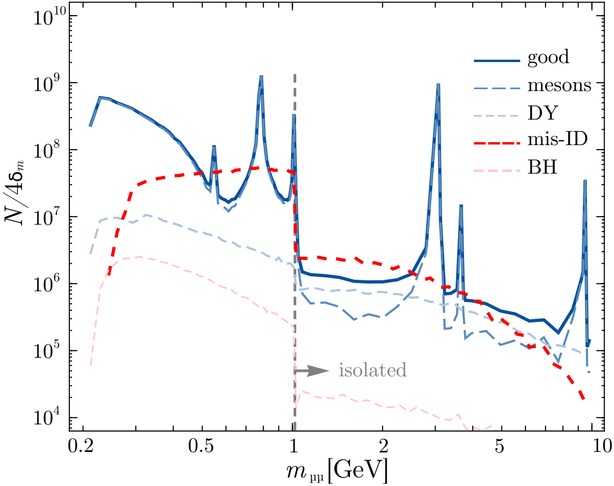




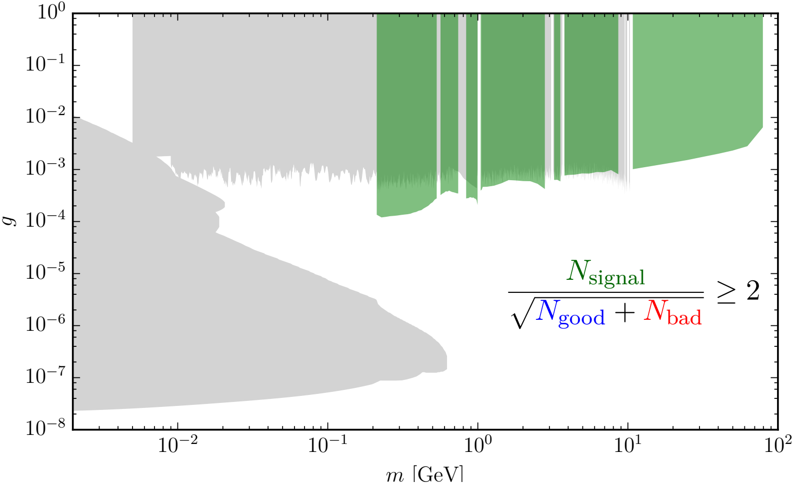
N_{signal} is not proportional to N_{bad}

LHCb mis-ID probability ≈ 1 out of 1000

Production in Theory

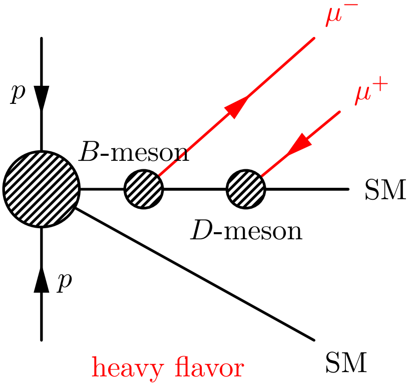


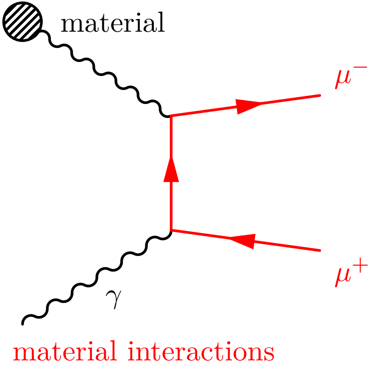
Reach (*prompt*) in Theory



$$\frac{N_{\text{signal}}}{\sqrt{N_{\text{good}} + N_{\text{bad}}}} \geq 2$$

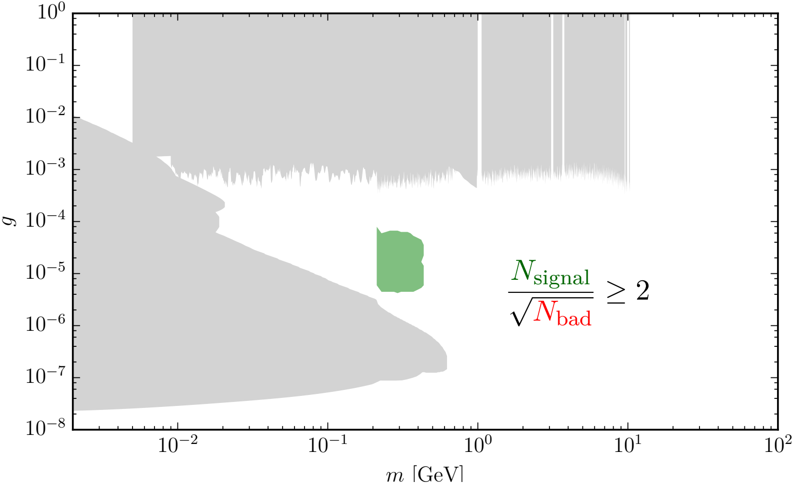
Bad Backgrounds (*displaced*)





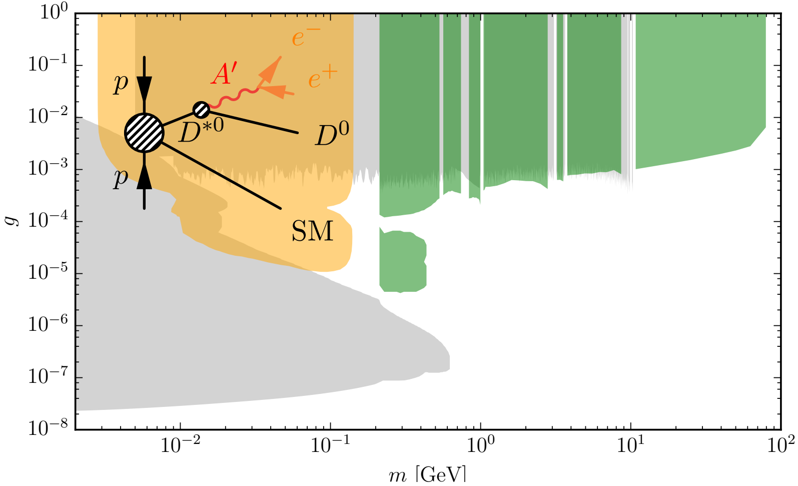
$N_{\text{heavy}} \approx 10000$ per $4\delta_m$

Reach (*displaced*) in Theory



$$\frac{N_{\text{signal}}}{\sqrt{N_{\text{bad}}}} \geq 2$$

Full Reach in Theory



Searching with LHCb
in practice . . .

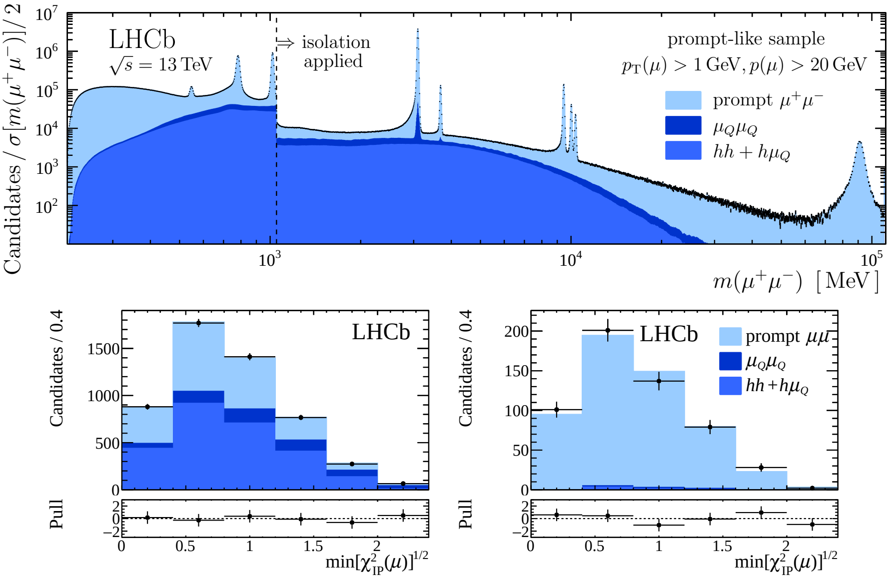
LHCb Collaboration
Phys. Rev. Lett. **120**, no. 6, 061801 (2018)

LHCb Collaboration
JINST **13**, no. 06, P06008 (2018)

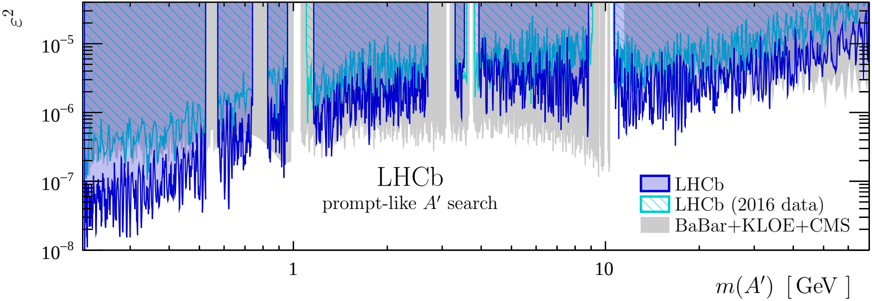
LHCb Collaboration
Phys. Rev. Lett. **124**, no. 4, 041801 (2020)

LHCb Collaboration
JHEP **10**, 156 (2020)

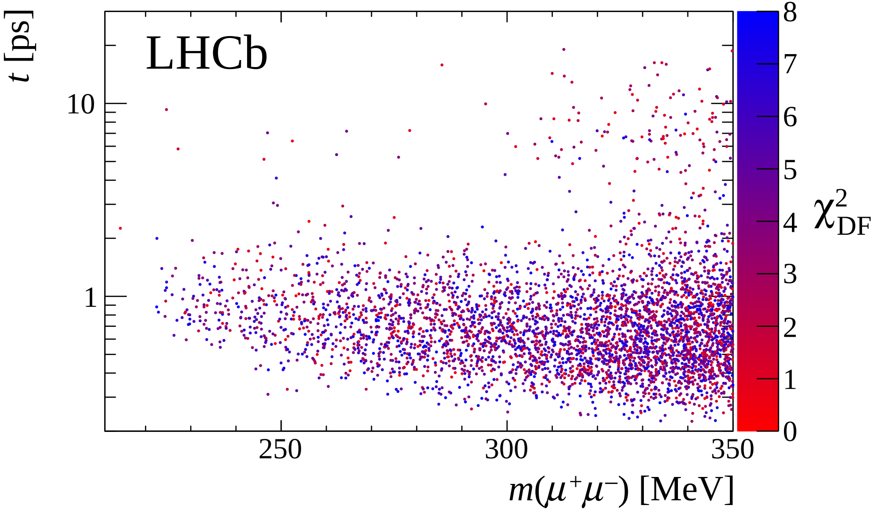
Real Data (*prompt*)



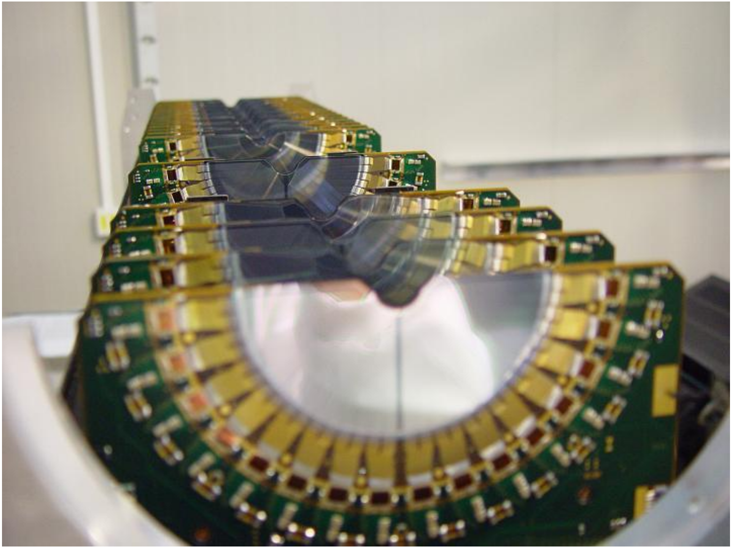
Limits (*prompt*)



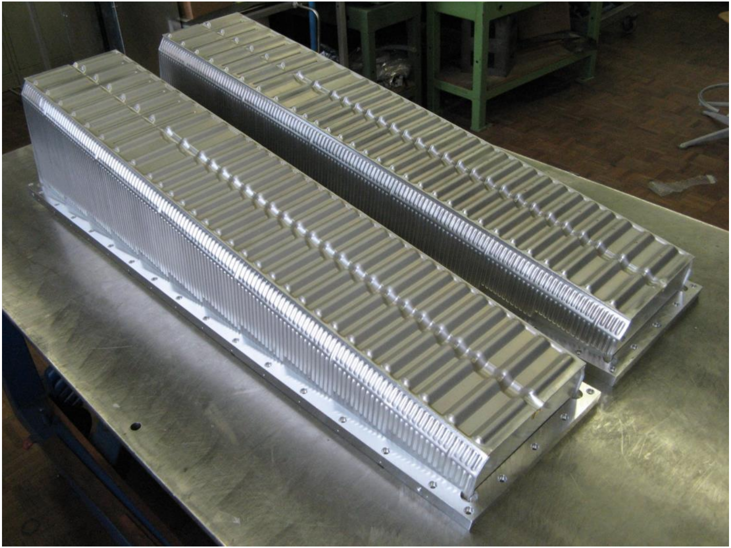
Real Data (*displaced*)



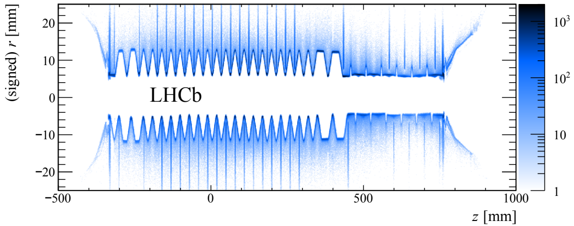
VELO Sensors

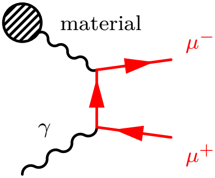


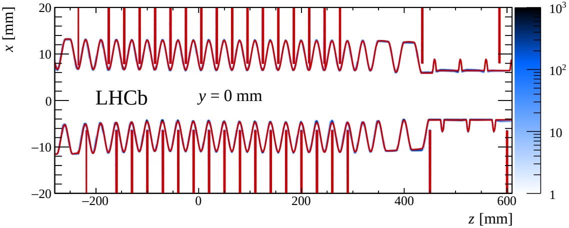
RF Foil

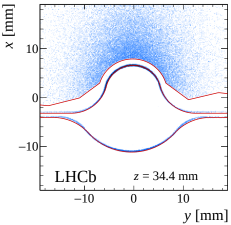


Bad Backgrounds (*displaced*)

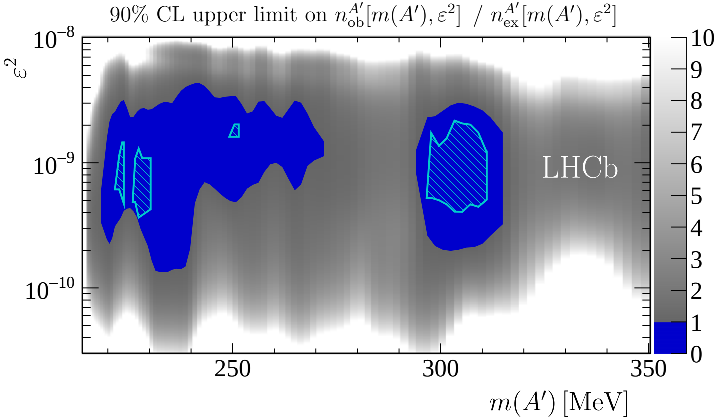








Limits (*displaced*)



Dark Photons
and beyond . . .

Ilten, Soreq, Williams, Xue
JHEP **1806**, 004 (2018)

Cid Vidal, Ilten, Plews, Shuve, Soreq
Phys. Rev. D **100**, no. 5, 053003 (2019)

Baruch, Ilten, Soreq, Williams
JHEP **11**, 124 (2022)

DARKCAST

- recast to any general model, *e.g.* 15 free parameters

- available at `gitlab.com/philten/darkcast`
- accompanying papers *Serendipity in dark photon searches* and *Axial vectors in Darkcast*

```
import darkcast
model = darkcast.Limit("B_boson.py")                       # Load a model.
limit = darkcast.Limit("LHCb_Aaij2017rft_displaced") # Load a limit.

# Recast the limit.
recast = limit.recast(model)

# Write out the recast.
recast.write("darkcast.lmt")

# Plot the recast.
for x, y in recast.plots(): pyplot.fill(x, y)
```

The Recipe

- given (m, g_A) for model A, solve to find (m, g_B) for model B

$$\sigma_A(m, g_A)\mathcal{B}_A(m)\varepsilon(\tau_A(m, g_A)) = \sigma_B(m, g_B)\mathcal{B}_B(m)\varepsilon(\tau_B(m, g_B))$$

- absolute cross-section can be tricky, ratios are easier

$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)}\frac{\varepsilon(\tau_A(m, g_A))}{\varepsilon(\tau_B(m, g_B))}\frac{\mathcal{B}_A(m)}{\mathcal{B}_B(m)} = 1$$

❶ branching fraction ratio: hidden local symmetries

❷ cross-section ratio: hidden local symmetries

$$V \in (\rho, \omega, \phi, K^*, \bar{K}^*) \text{ generated from } U(3)_V$$

❸ efficiency ratio: define proper time fiducial region with t_0 and t_1

$$\varepsilon(\tau) = e^{-t_0/\tau} - e^{-t_1/\tau}$$

Widths

- width can be calculated perturbatively for fermions

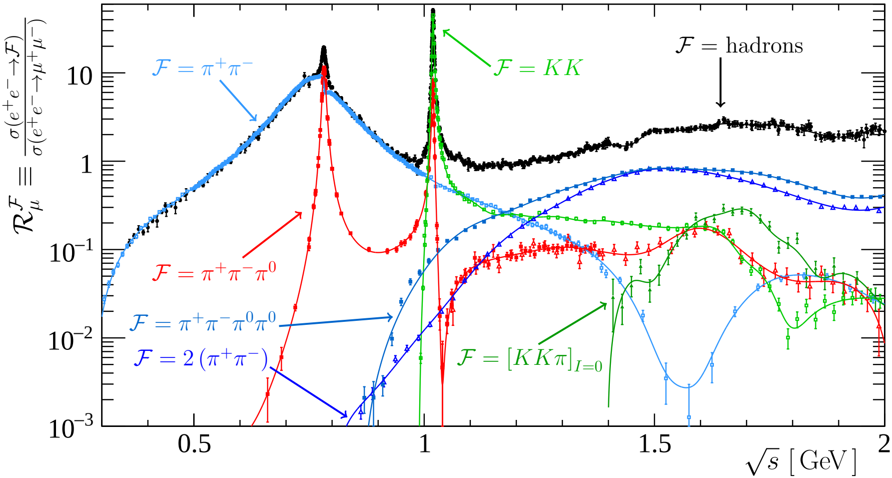
$$\Gamma_{ff}(m, g) = \frac{g^2 c_f \left(x_V^f\right)^2}{12\pi} m \left(1 + \frac{m_f^2}{m}\right) \sqrt{1 - 4\frac{m_f^2}{m}}$$

- but . . . below 2 GeV this prediction is no longer reliable
- use data instead!

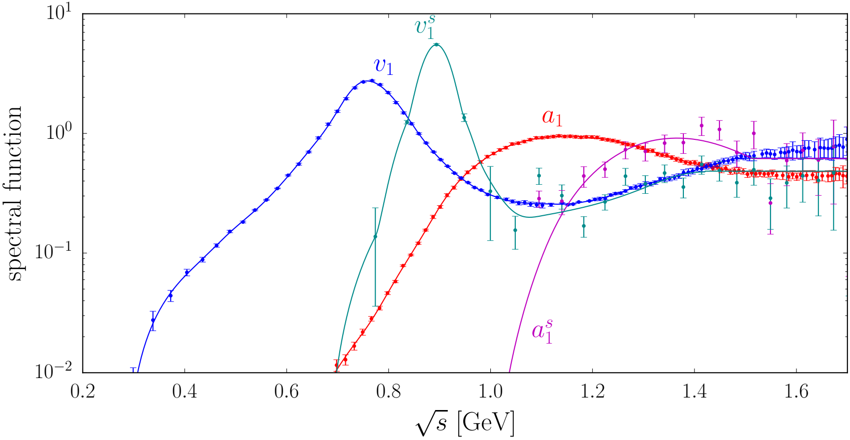
$$\begin{aligned}\Gamma_{\text{hadrons}}(m, g) &= \Gamma_{\mu\mu}(m, g)\mathcal{R}(m) \\ &\quad + \frac{g^2 m}{4\pi}\bigg[(x_A^u - x_A^d)^2 a_1(m^2) + (x_A^s)^2 \Theta(m^2 - 4m_K^2) \\ &\quad \times \left(\frac{1}{4}a_1(m^2) + a_1^s(m^2) - \cos(\phi)\sqrt{a_1(m^2)a_1^s(m^2)}\right)\bigg]\end{aligned}$$

- $\mathcal{R}(m)$ is $\sigma(ee \to \text{hadrons})/\sigma(ee \to \mu\mu)$
- $a_1^{(s)}(m)$ are τ axial spectral functions from ALEPH

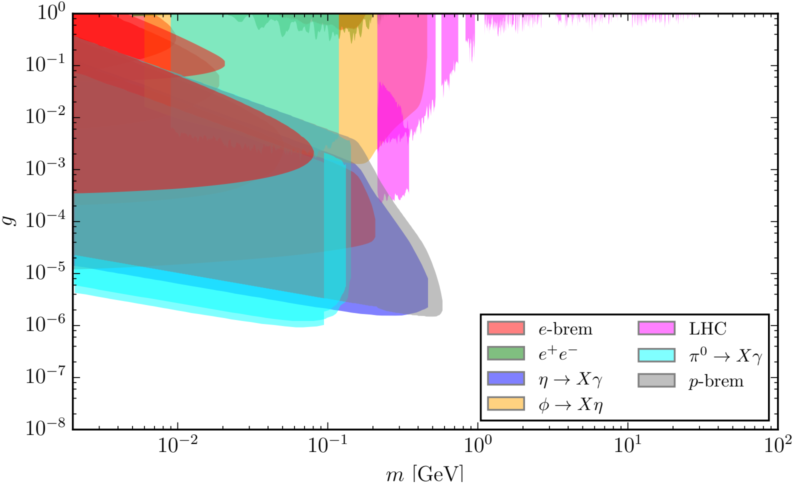
The Data!


$\mathcal{R}_\mu^\mathcal{F} \equiv \frac{\sigma(e^+e^-\to\mathcal{F})}{\sigma(e^+e^-\to\mu^+\mu^-)}$
10^{-3}
10^{-2}
10^{-1}
1
10
0.5
1
1.5
2
$\sqrt{s}$ [GeV]
$\mathcal{F} = \pi^+\pi^-$
$\mathcal{F} = KK$
$\mathcal{F} =$ hadrons
$\mathcal{F} = \pi^+\pi^-\pi^0$
$\mathcal{F} = \pi^+\pi^-\pi^0\pi^0$
$\mathcal{F} = 2\,(\pi^+\pi^-)$
$\mathcal{F} = [KK\pi]_{I=0}$

The Data!

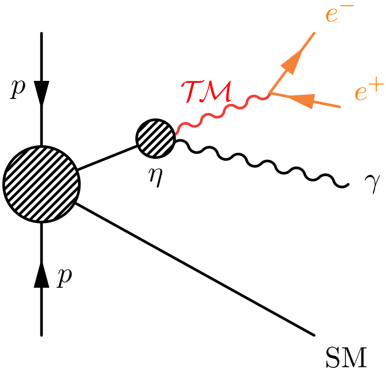

10^1
10^0
10^{-1}
10^{-2}
spectral function
v_1^s
v_1
a_1
a_1^s
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
$\sqrt{s}$ [GeV]

B Boson


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
g
10^{-2}
10^{-1}
10^0
10^1
10^2
m [GeV]
e-brem
e^+e^-
$\eta \to X\gamma$
$\phi \to X\eta$
LHC
$\pi^0 \to X\gamma$
p-brem

A Special Case

- *true* muonium is a $\mu^+\mu^-$ state, not yet observed!
- different spin configurations, most abundant are ${}^1S_0$ and ${}^3S_1$
- ${}^1S_0 \to \gamma\gamma$ and ${}^3S_1 \to e^+e^-$



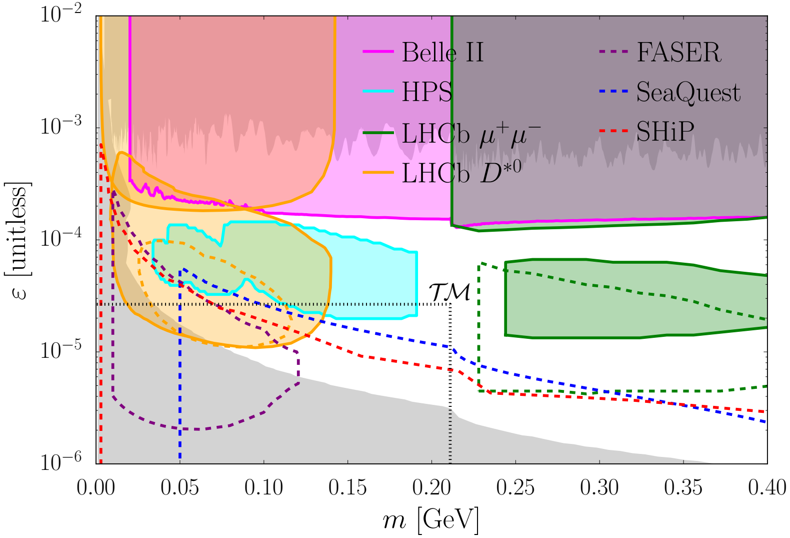
$$E_B \approx m_\mu \alpha^2/4 = 1.41\,\text{keV}$$

$$m_{\mathcal{TM}} \approx 2m_\mu - E_B \approx 211\,\text{MeV}$$

$$g_{\mathcal{TM}} \approx \alpha^2/2 \approx 2.66 \times 10^{-5}$$

$$\tau_{\mathcal{TM}} \approx \frac{6}{\alpha^5 m_\mu} \approx 1800 \text{ fs}$$

Zooming In

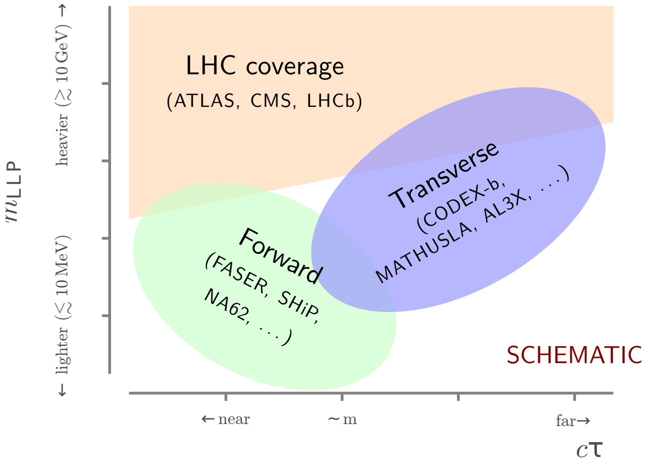

Belle II
HPS
LHCb $\mu^+\mu^-$
LHCb D^{*0}
FASER
SeaQuest
SHiP
$\mathcal{TM}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ε [unitless]
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
m [GeV]

LHCb
and beyond . . .

CODEX-b Collaboration
Eur. Phys. J. C **80**, no. 12, 1177 (2020)

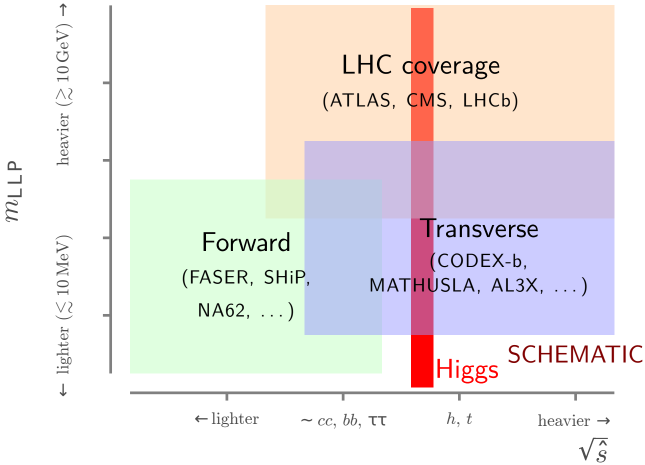
CODEX-b Collaboration
arXiv:2406.12880 [physics.ins-det]

Mind the Coverage Gap



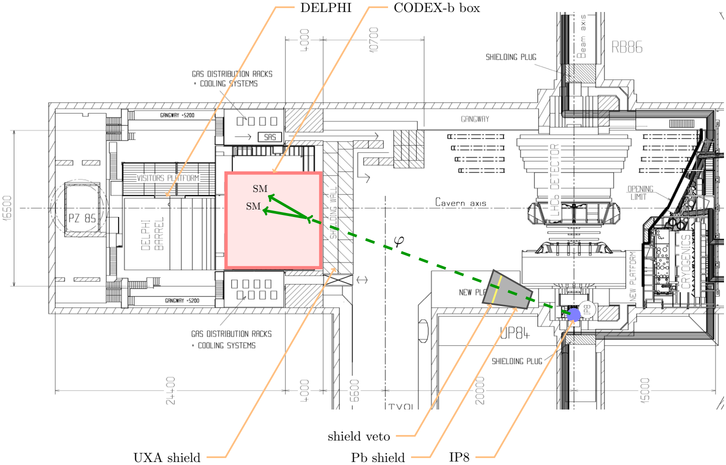
- there is a large gap in search parameter space

Mind the Coverage Gap



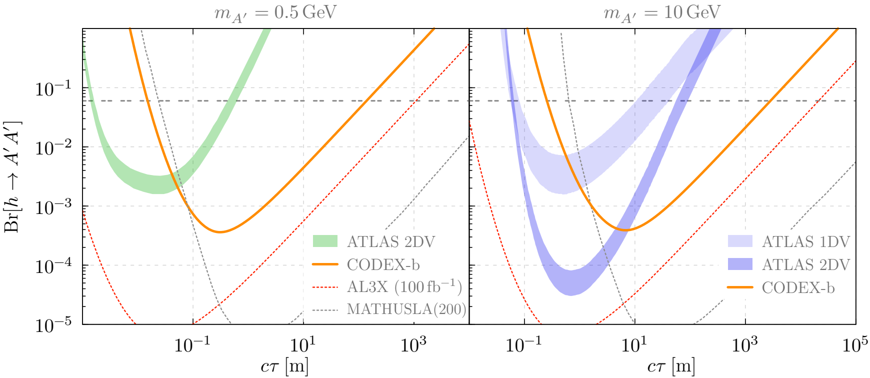
- the LHC accesses unique high COM

A Modest Proposal



- need low background large volume detector
- use space around LHCb → CODEX-b proposal

Dark Photon Again



- example coverage from non-minimal dark photon production via the SM Higgs

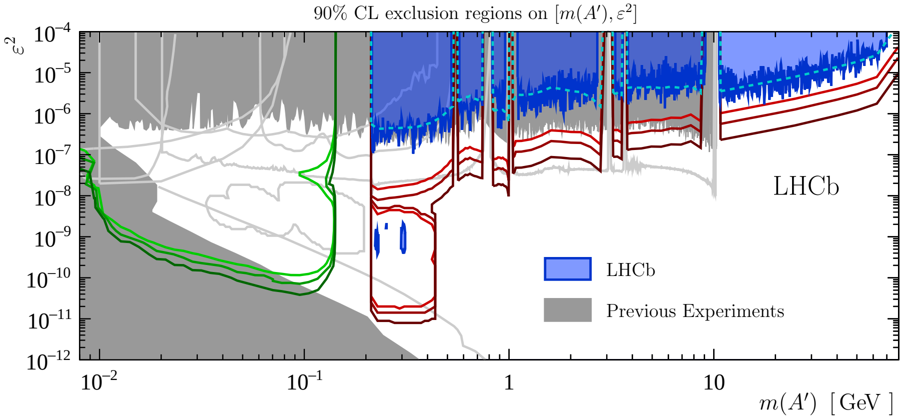
Building It!

- CODEX-β approved as time limited LHCb R&D project
- independent of LHCb, including members from CMS and ATLAS

CODEX-b Collaboration

- CODEX-b collaboration is always looking for collaborators!
- MATHUSLA and ANUBIS are also excellent off-axis opportunities

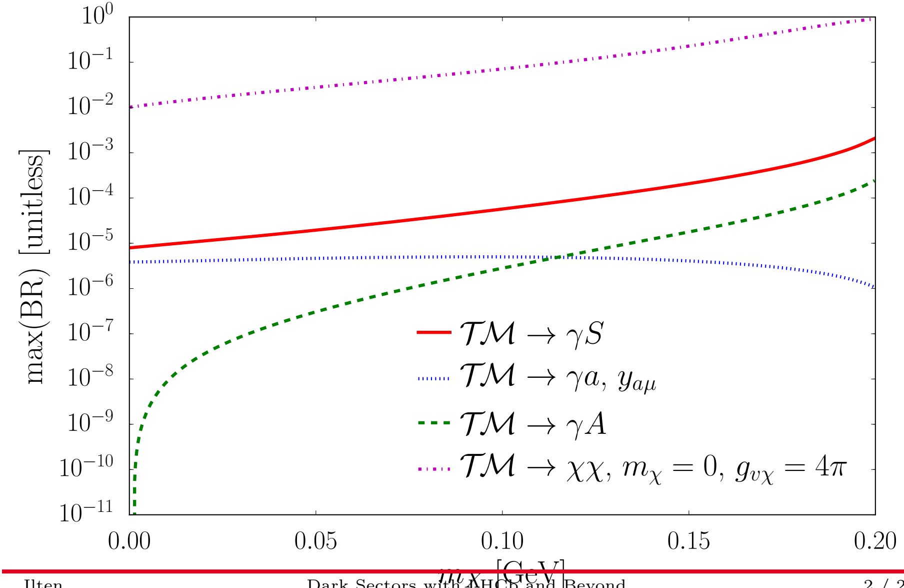
Conclusions



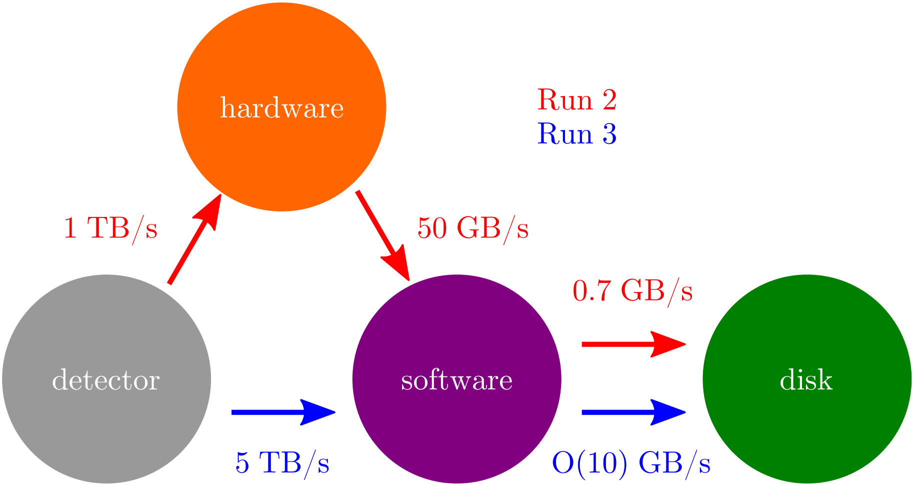
- LHCb search with $\approx 4\%$ of Run 2 + Run 3 data is promising
- DARKCAST at `gitlab.com/darkcast/releases`
- true muonium is within reach at LHCb
- off-axis (transverse) detectors necessary for LLPs at high $\sqrt{s}$

Appendix

New Physics in TM



Data Taking



Run 2

Run 3

hardware

1 TB/s

50 GB/s

detector

software

disk

0.7 GB/s

5 TB/s

O(10) GB/s

Hidden Symmetries

- but what about flavor dependent couplings?
- use hidden local symmetries framework for VMD
- vector mesons $V \in (\rho, \omega, \phi, K^*, \bar{K}^*)$ are gauge bosons of hidden $U(3)_V$ symmetry
- vertices take the form PV_iV_j with P from the pseudoscalar nonet $P \in (\pi, \eta, \eta', K, \bar{K})$

$$\mathrm{Tr}(T_{V_i}, T_{V_j}, T_P)$$

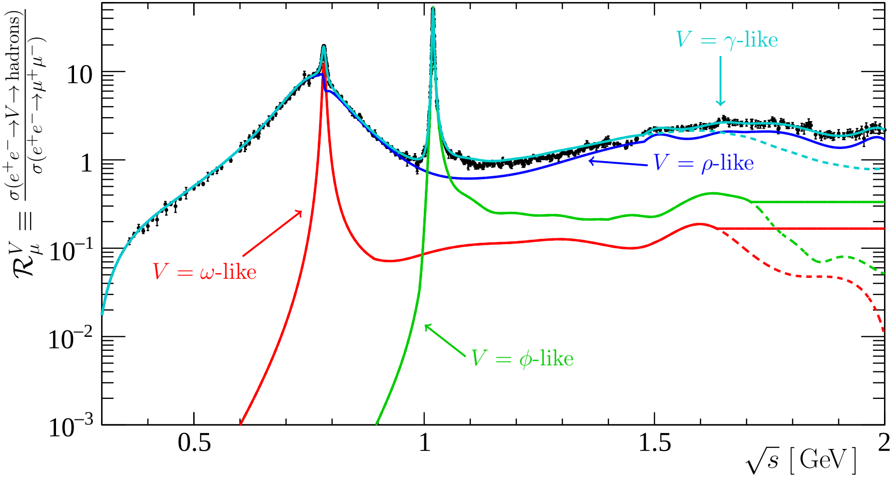
- T are the meson generators, *e.g.* $T_\omega = \frac{1}{2}(1, 1, 0)$
- external gauge fields mix through V

$$\mathrm{Tr}(T_V, Q)$$

- Q is the fermion coupling vector (Q_u, Q_d, Q_s)

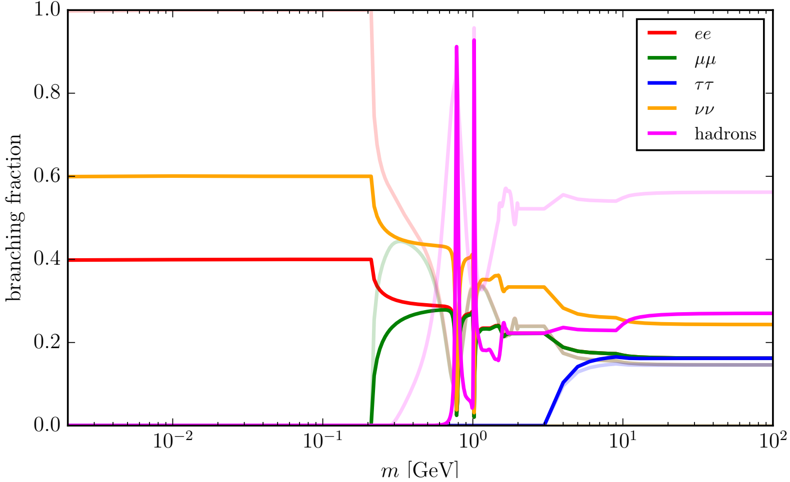
Vector Decomposition

$$\Gamma_{\mathcal{F}}(m) = \frac{g^2}{12\pi} m \sum_{V_i - V_j} c_{V_i} c_{V_j} \mathrm{Tr}(T_{V_i}, Q) \mathrm{Tr}(T_{V_j}, Q) \mathcal{R}_{\mathcal{F}}^{V}(m)$$

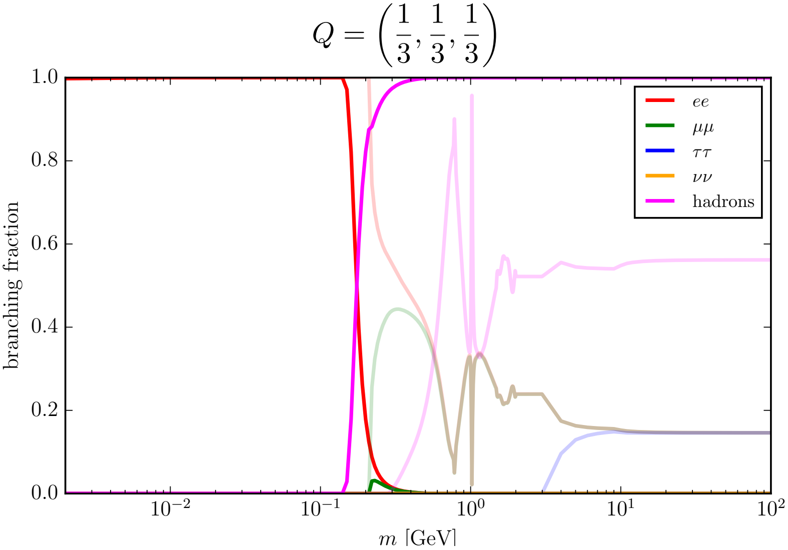


$B - L$ Boson

$$Q = \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$$

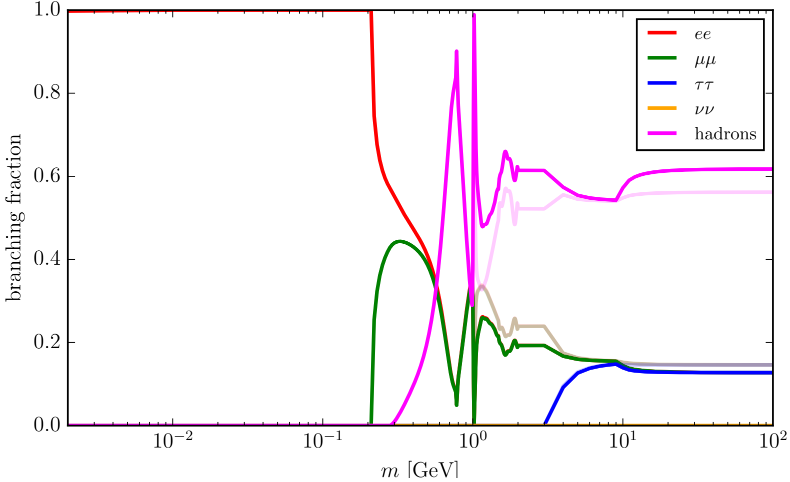


B Boson


$Q = \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$
branching fraction
0.0
0.2
0.4
0.6
0.8
1.0
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
m [GeV]
ee
$\mu\mu$
$\tau\tau$
$\nu\nu$
hadrons

Protophobic Boson

$$Q = \left(\frac{1}{3}, \frac{2}{3}, \frac{2}{3}\right)$$



Production Ratios

- electron-positron annihilation and electron bremsstrahlung

$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)} = \frac{{g_A}^2 {Q_A^e}^2}{{g_B}^2 {Q_B^e}^2}$$

- proton bremsstrahlung

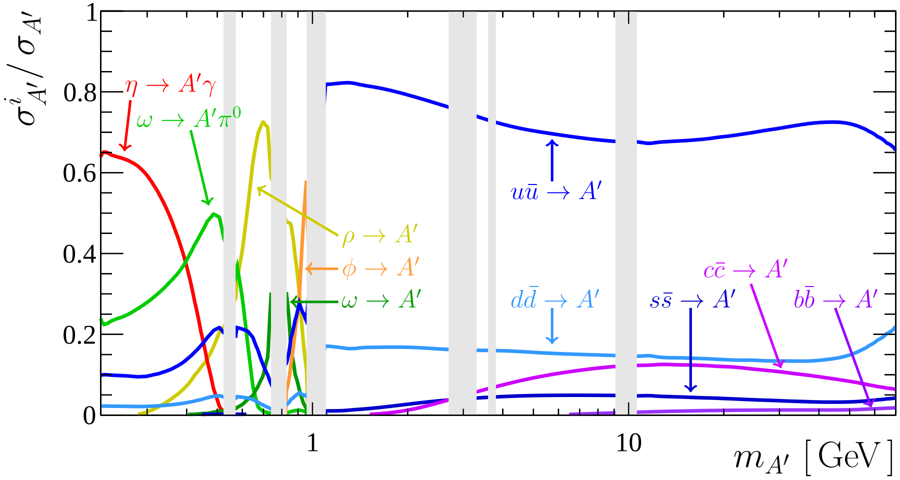
$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)} = \frac{{g_A}^2 (2Q_A^u + Q_A^d)^2}{{g_B}^2 (2Q_A^u + Q_A^d)^2}$$

- hadron decays of the form $X \to Y A$

$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)} = \frac{{g_A}^2 \sum_V \mathrm{Tr}(T_X, T_Y, T_V)\mathrm{Tr}(T_V, Q_A)\mathrm{BW}_V(m)}{{g_B}^2 \sum_V \mathrm{Tr}(T_X, T_Y, T_V)\mathrm{Tr}(T_V, Q_B)\mathrm{BW}_V(m)}$$

LHCb Production Fractions

- templates taken from Monte Carlo and fit against LHCb result



Efficiencies

- define proper time fiducial region with t_0 and t_1

$$\varepsilon(\tau) = e^{-t_0/\tau} - e^{-t_1/\tau}$$

- for prompt limits, $t_0 = 0$ and t_1 depends on the boost

$$t_1 = \frac{L_{\mathrm{max}}}{\gamma}$$

- for displaced beam-dump limits, relate t_0 and t_1

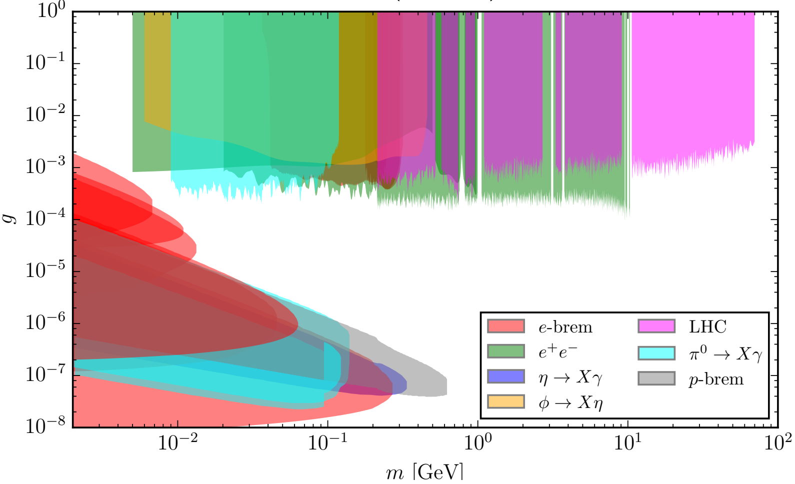
$$t_1 = t_0 + \frac{L_{\mathrm{detector}}}{L_{\mathrm{shield}}}$$

→ upper and lower limits are solutions, equate and solve for t_0:

$$\sigma(m, g_{\mathrm{max}})\mathcal{B}(m)\varepsilon\left(\tau(m, g_{\mathrm{max}})\right) = \sigma(m, g_{\mathrm{min}})\mathcal{B}(m)\varepsilon\left(\tau(m, g_{\mathrm{min}})\right)$$

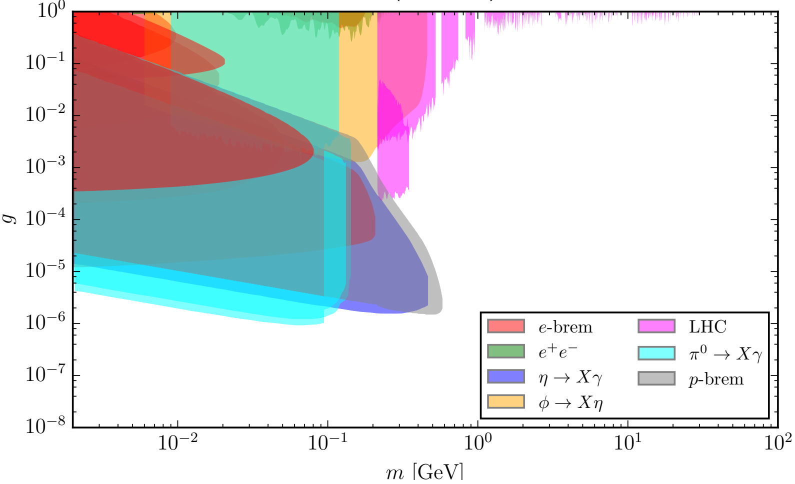
$B - L$ Boson

$$Q = \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$$



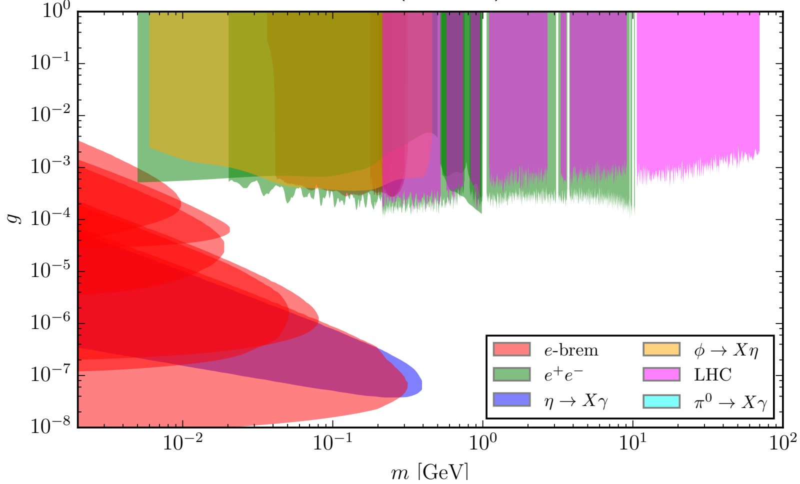
B Boson

$$Q = \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$$

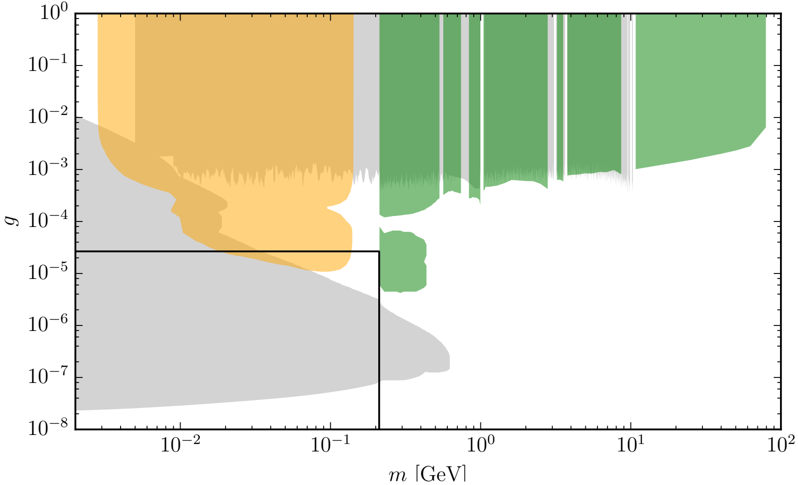


Protophobic Boson

$$Q = \left(\frac{1}{3}, \frac{2}{3}, \frac{2}{3}\right)$$



Mind the Gap

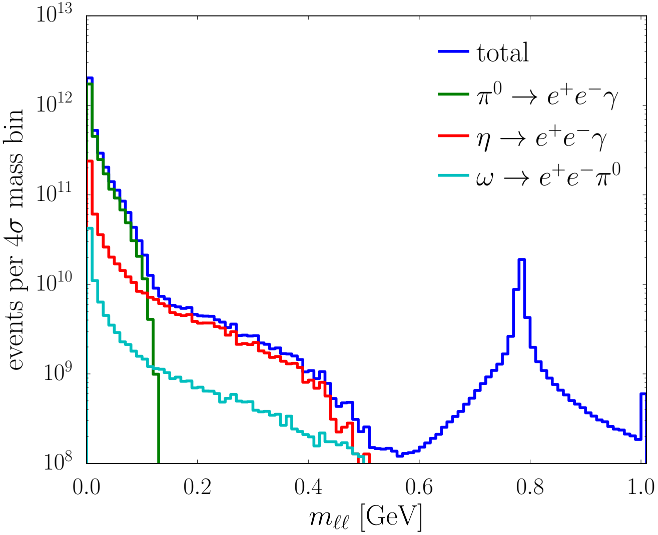


What's in an Event?

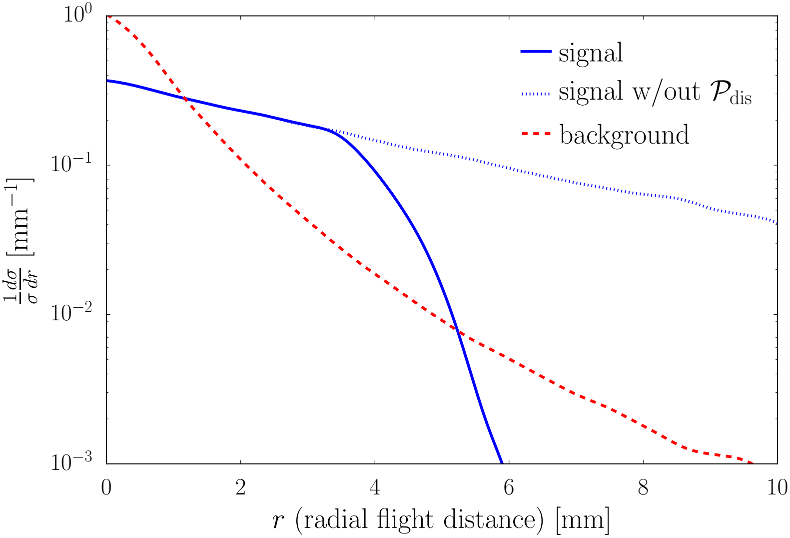
- need final states that produce di-electrons

meson	meson/event	e^+e^-/event
π^+	1.27×10^1	–
π^0	7.08×10^0	8.50×10^{-2}
ρ^+	1.96×10^0	2.36×10^{-2}
K^+	1.44×10^0	–
ρ^0	1.02×10^0	2.36×10^{-5}
ω	9.87×10^{-1}	1.24×10^{-2}
n	9.71×10^{-1}	–
p	9.51×10^{-1}	–
η	8.31×10^{-1}	1.80×10^{-2}
K_S^0	7.08×10^{-1}	5.25×10^{-3}
K_L^0	7.07×10^{-1}	–

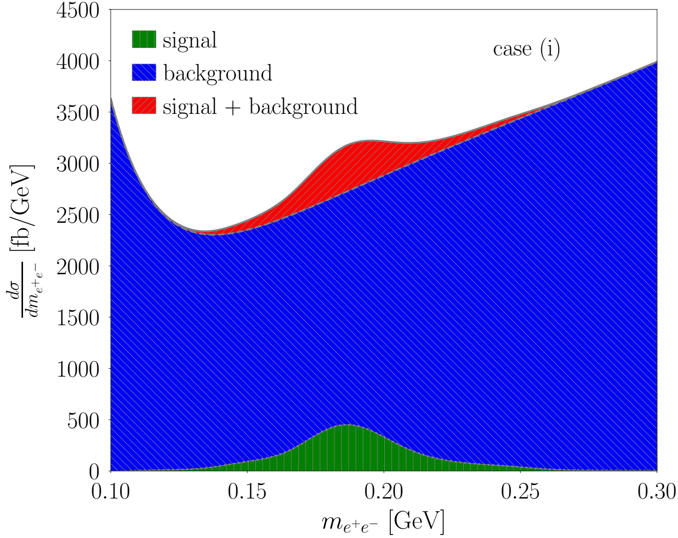
$e^+e^-\gamma$ Production



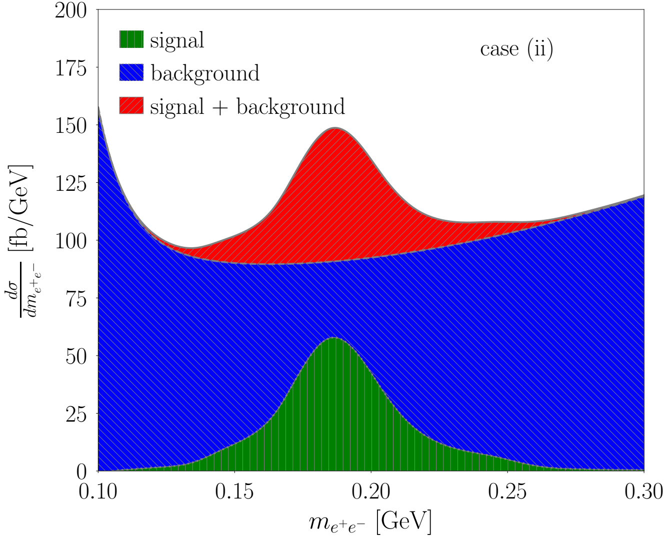
Dissociation



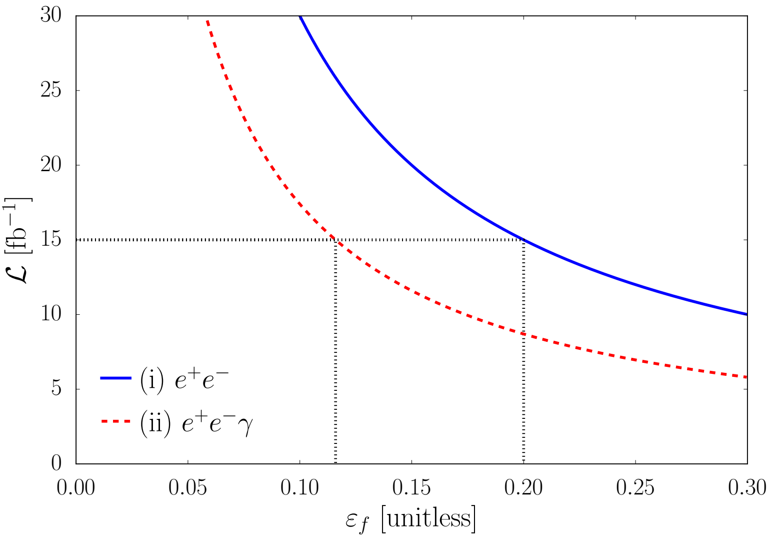
Detector Effects: Case (i)



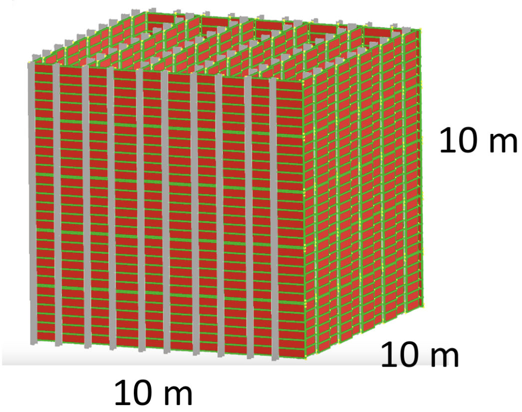
Detector Effects: Case (ii)



Discovery Potential

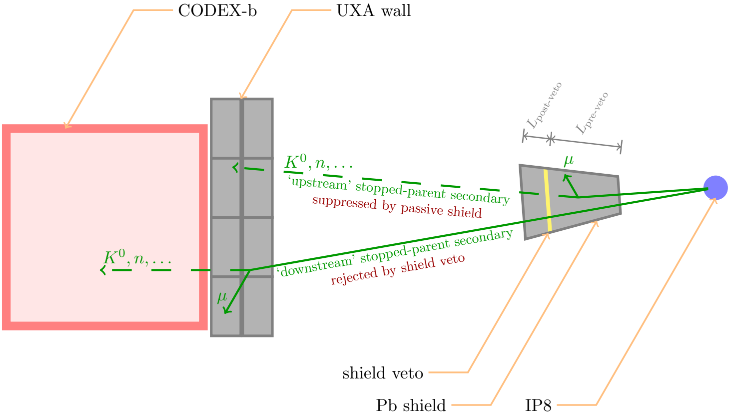


A Large Cube



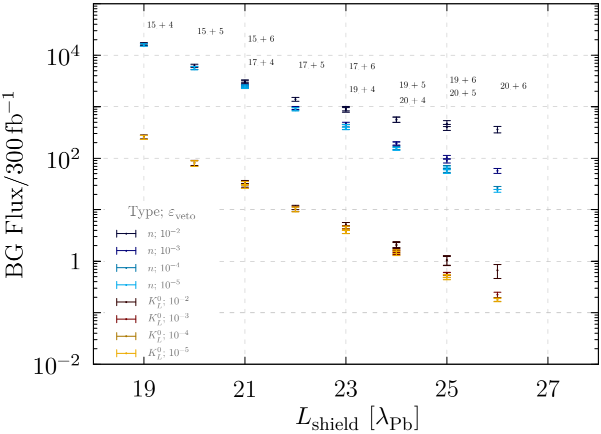
- $10 \times 10 \times 10$ m baseline configuration
- use resistive plate chambers (1 mm spatial and 100 ps timing)
- sensitive to LLP masses via opening angle of LLP decay

Raising the Shields



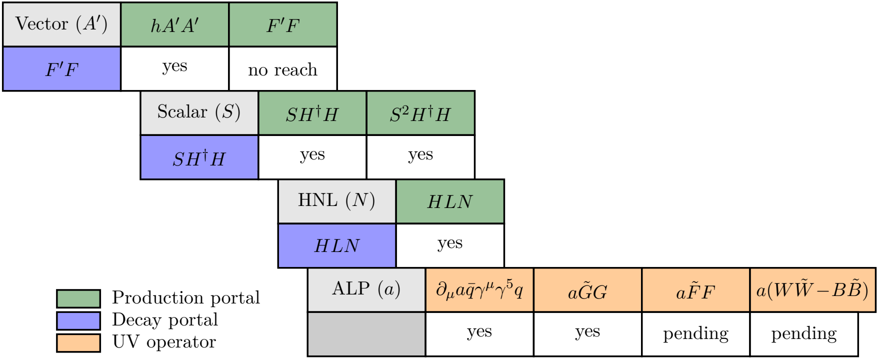
- active shielding is necessary for background reduction

Raising the Shields



- target less than one event over entire run of CODEX-b

Models Overview



Vector (A')	$hA'A'$	$F'F$
$F'F$	yes	no reach

Scalar (S)	$SH^\dagger H$	$S^2H^\dagger H$
$SH^\dagger H$	yes	yes

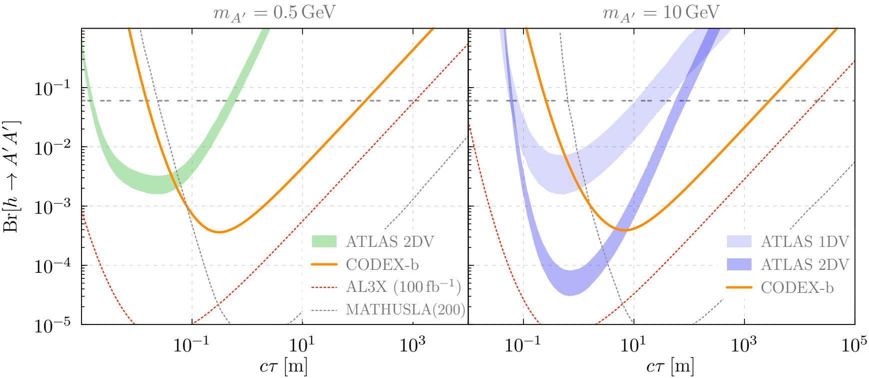
HNL (N)	HLN
HLN	yes

ALP (a)	$\partial_\mu a\bar{q}\gamma^\mu\gamma^5 q$	$a\tilde{G}G$	$a\tilde{F}F$	$a(W\tilde{W}-B\tilde{B})$
	yes	yes	pending	pending

🟩 Production portal
🟦 Decay portal
🟧 UV operator

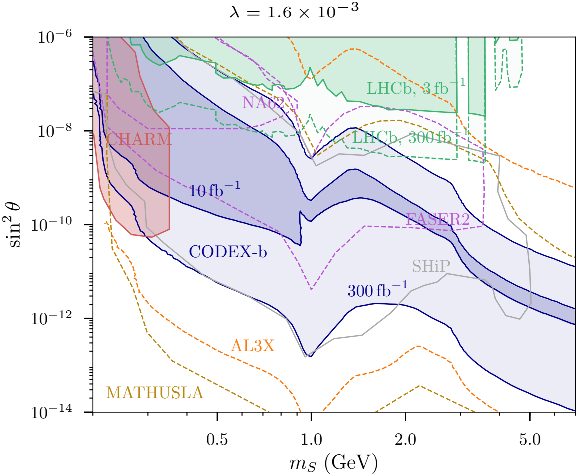
- CODEX-b has sensitivity to a wide variety of general and specific models

Dark Photon



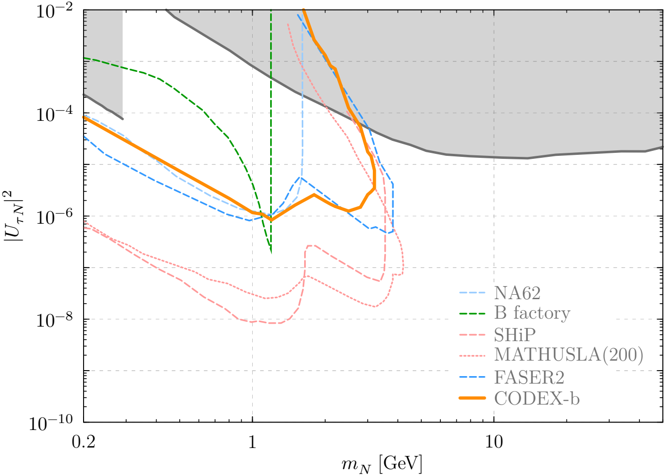
- production via the SM Higgs makes this currently only possible at the LHC

Higgs Portal



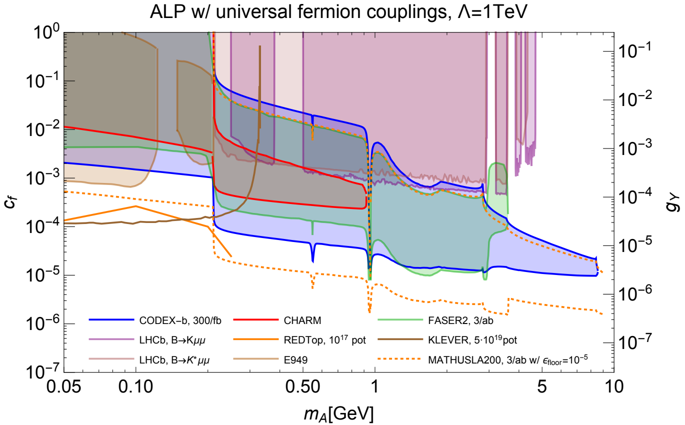
- searches via B decays, limits from LHCb are lifetime constrained

Heavy Neutral Leptons



- large portions of HNL space remain unexplored

Fermion Coupled Axion-Like Particles



- ALPs can both provide a dark matter candidate and “clean up” the strong CP problem