Low Mass Particles in LHC Experiments

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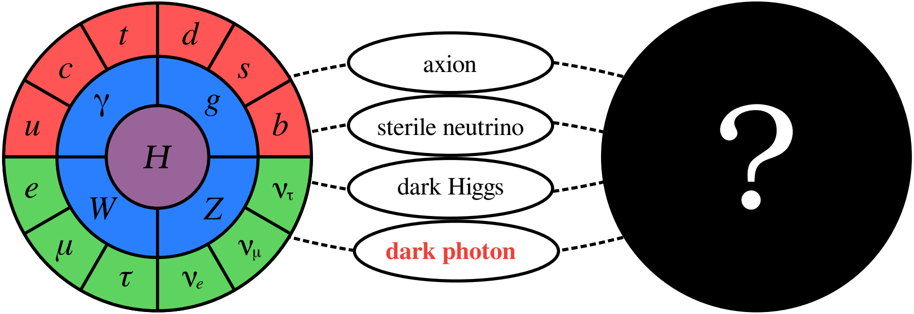
New Physics on the Low-Energy Precision Frontier

An Event at LHCb

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}	–

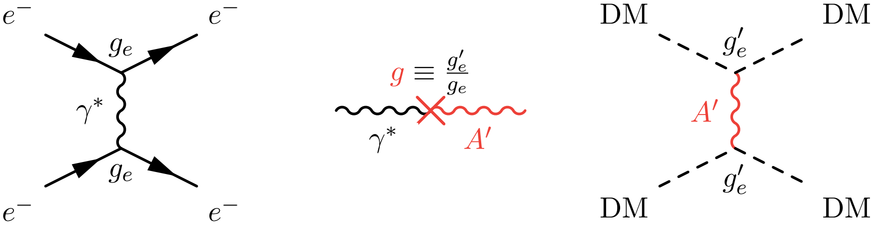
Hidden Sectors



1. broken $U(1)$ gauge symmetry in dark sector
2. allow mixing between dark and SM hypercharge fields

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

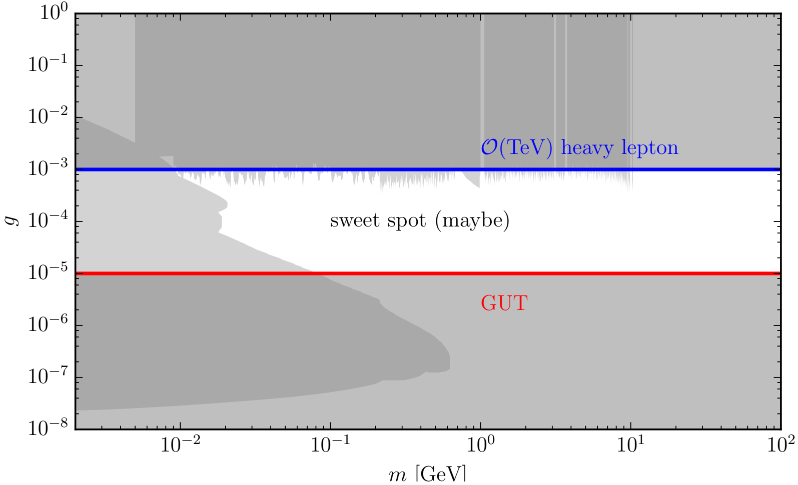
Dark Photons



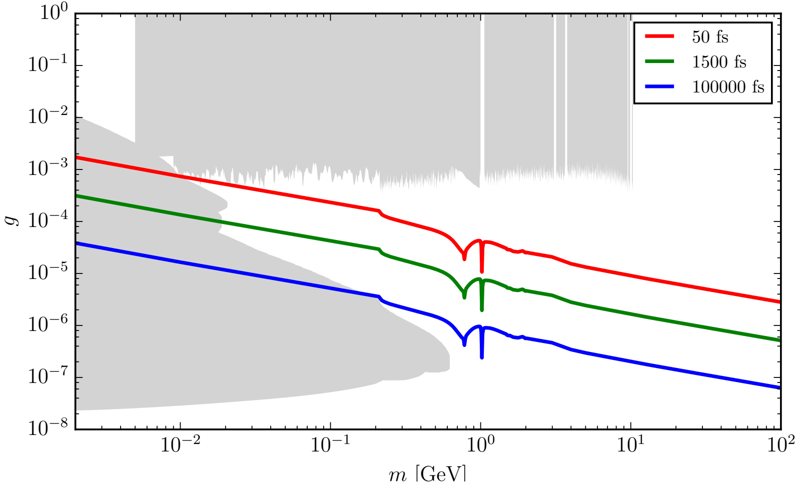
1. mass of the dark photon, $m_{A'}$, and mixing, g, are free parameters
2. the dark photon couples like the photon, modified by g
3. if $m_{A'} < 2m_{\text{DM}}$ then dark photon decays visibly

- what happens if 2 and 3 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

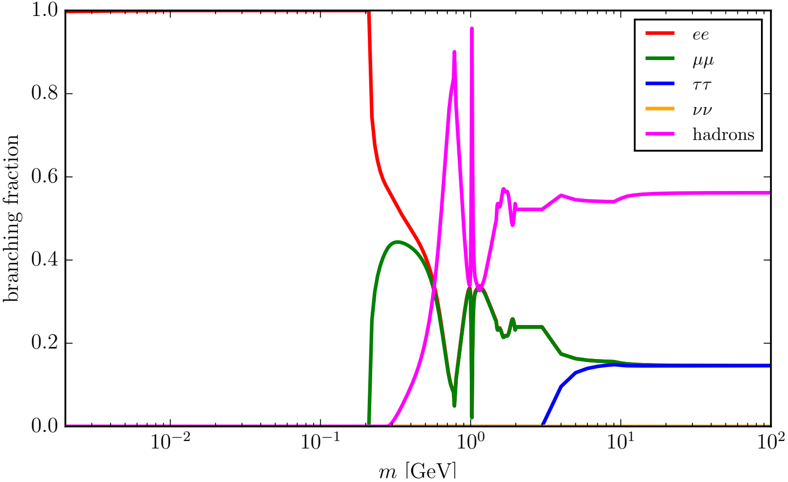


Lifetime

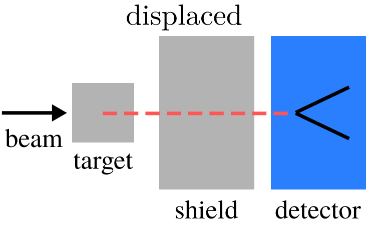


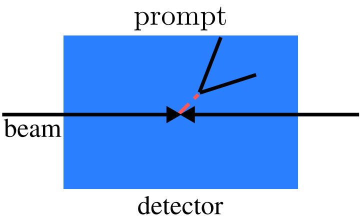
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
g
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
m [GeV]
50 fs
1500 fs
100000 fs

Decay Products



Search Strategies



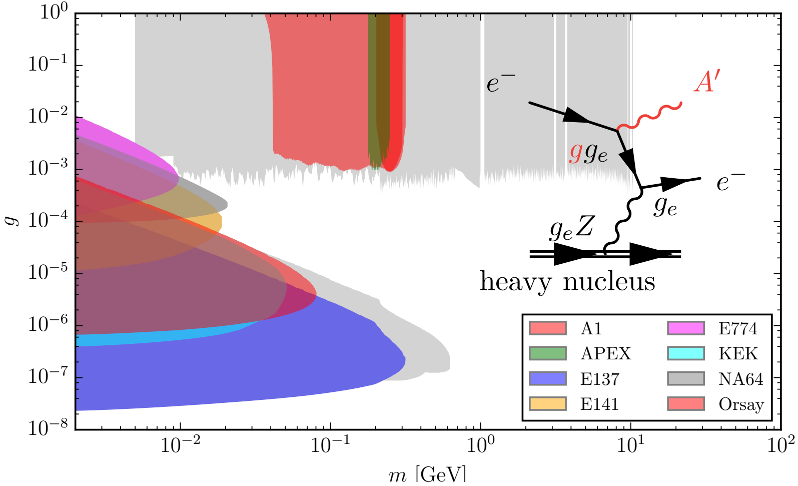


- sensitive to long lifetimes
- EM background free
- difficult to normalise

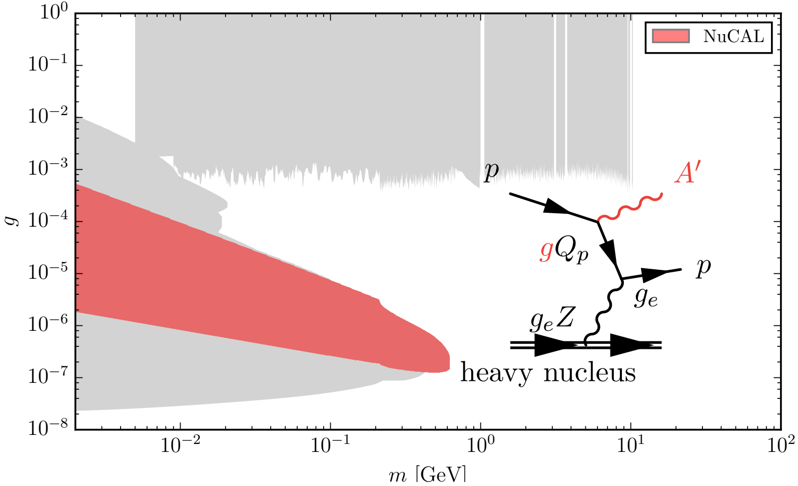
- sensitive to shorter lifetimes
- bump hunt on large EM background
- normalised from sidebands

- do both simultaneously for best of both worlds

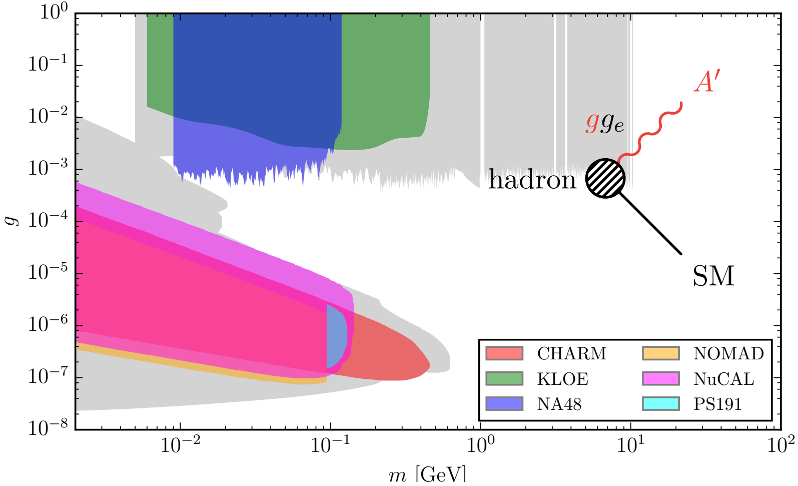
Production: Electron Bremsstrahlung



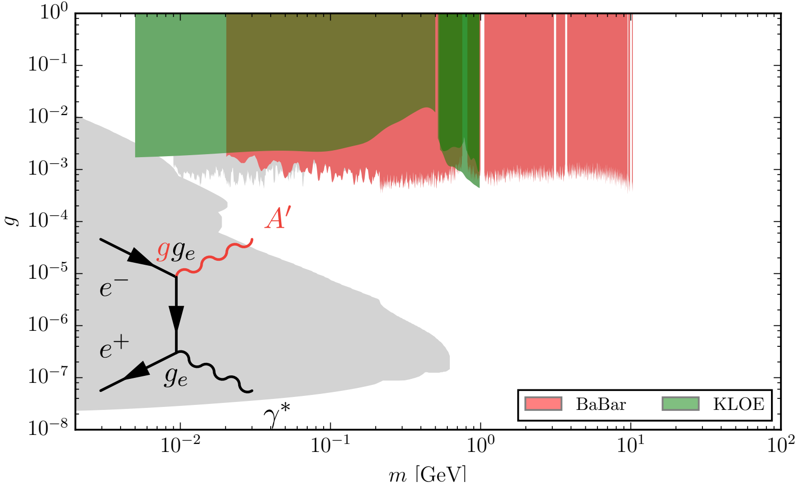
Production: Proton Bremsstrahlung



Production: Hadron Decays



Production: Electron-Positron Annihilation

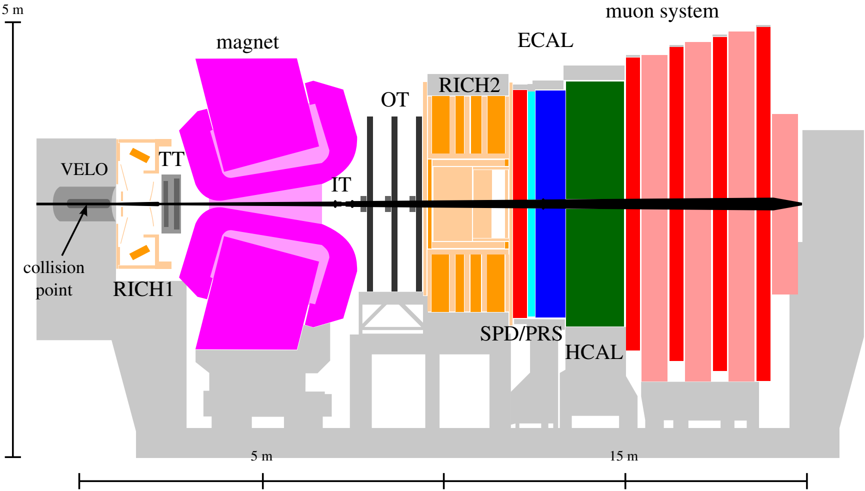


Searching with LHCb
in theory . . .

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

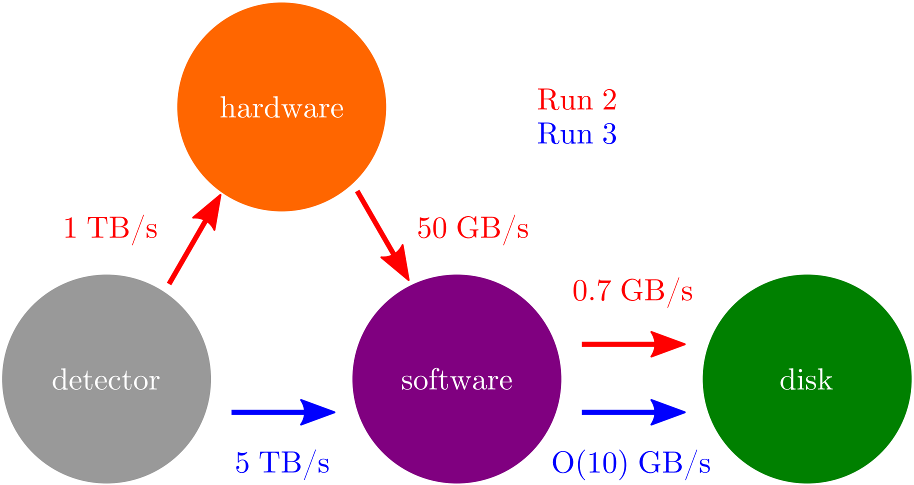
Ilten, Thaler, Williams, Xue
Phys. Rev. D **92**, no. 11, 115017 (2015)

LHCb Detector

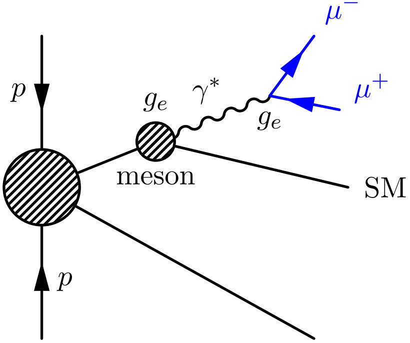


1. good momentum and mass resolution
2. excellent secondary vertex resolution

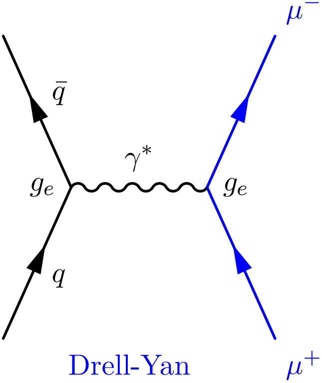
Data Taking


hardware
Run 2
Run 3
1 TB/s
50 GB/s
0.7 GB/s
detector
software
disk
5 TB/s
O(10) GB/s

Good Backgrounds (*prompt*)

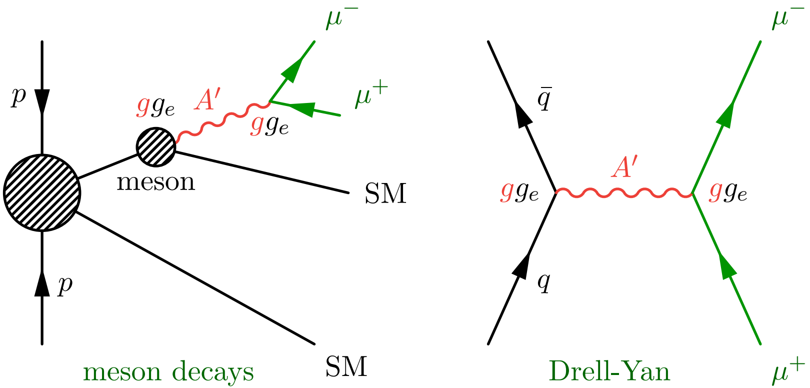


meson decays



Drell-Yan

Signal (*prompt* and *displaced*)

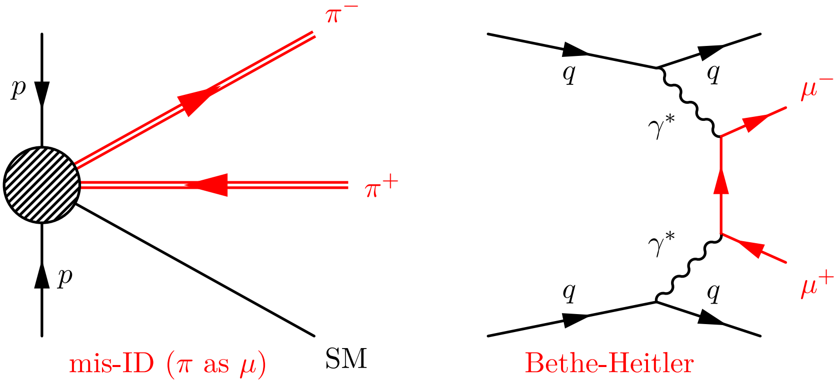


meson decays

Drell-Yan

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

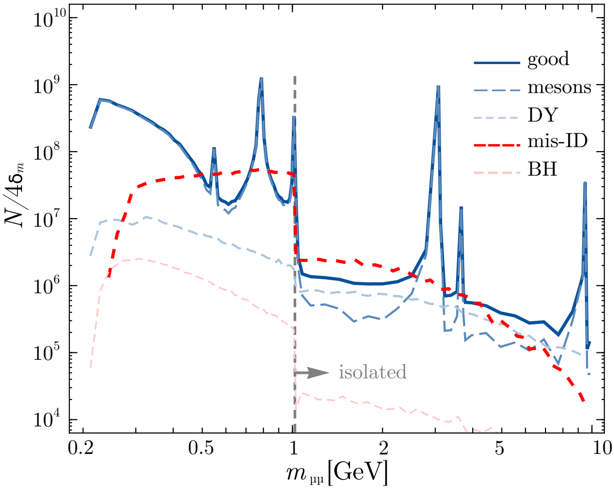
Bad Backgrounds (*prompt*)



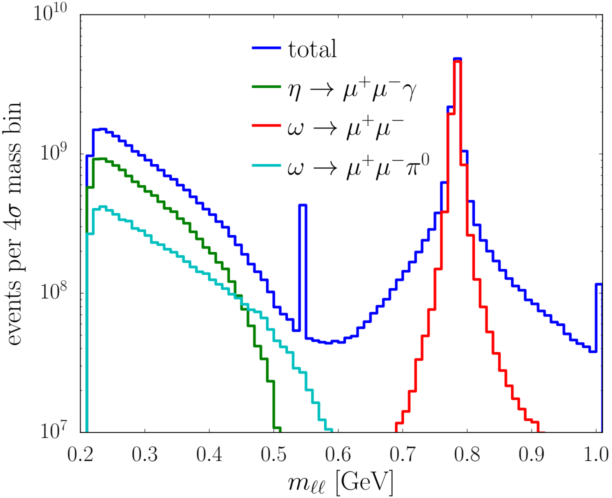
N_{signal} is not proportional to N_{bad}

LHCb mis-ID probability $\approx$ 1 out of 1000

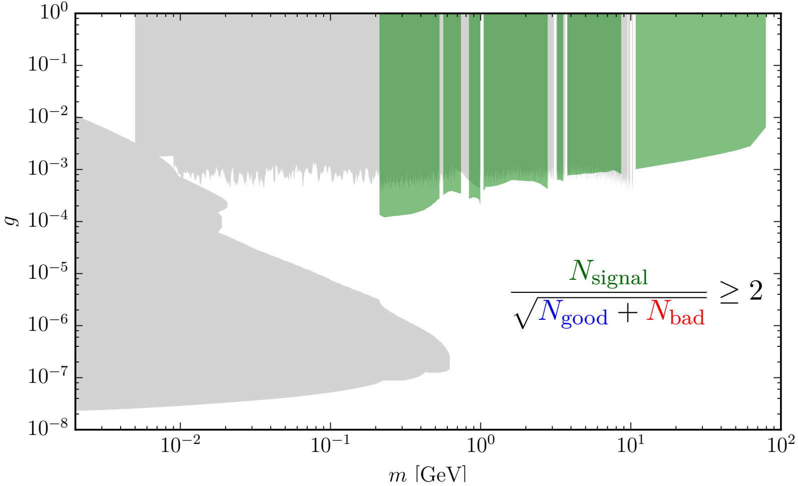
Production in Theory



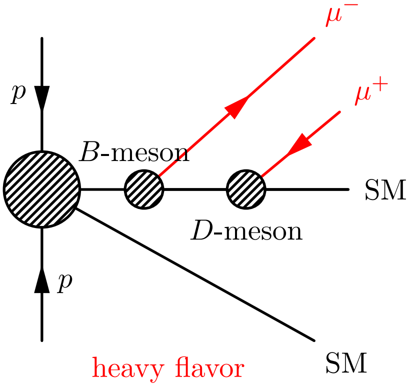
Low Mass Breakdown

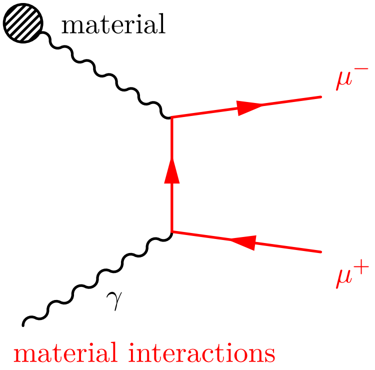


Reach (*prompt*) in Theory



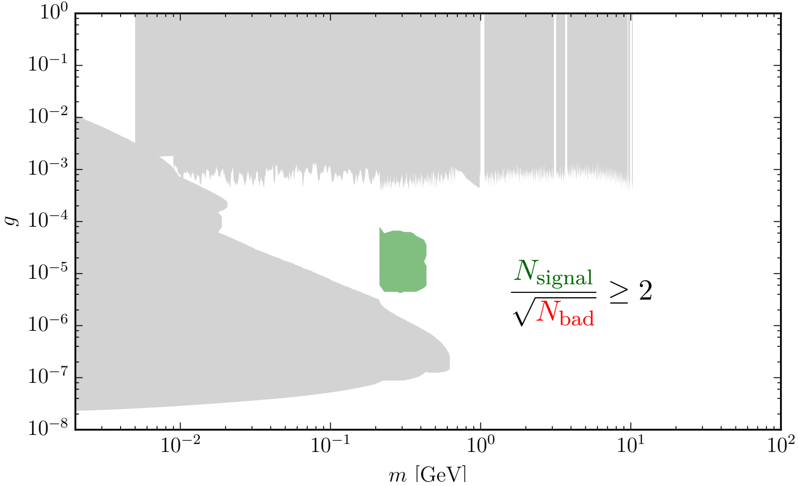
Bad Backgrounds (*displaced*)



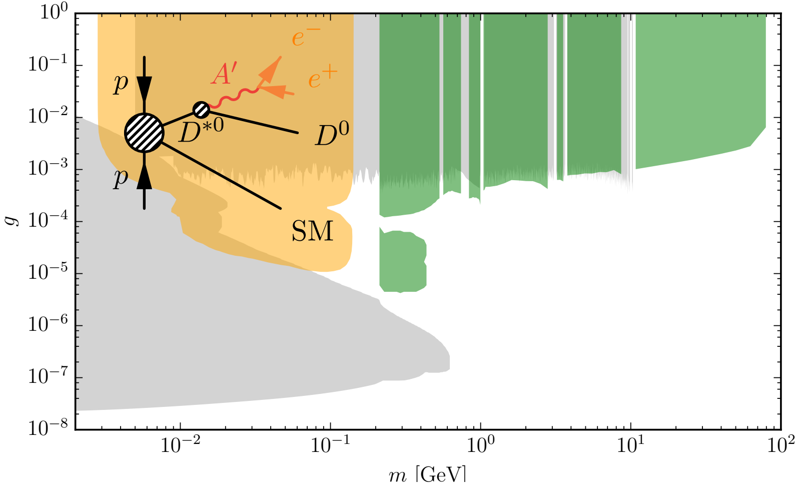


$N_{\text{heavy}} \approx 10000$ per $4\delta_m$

Reach (*displaced*) in Theory



Full Reach in Theory



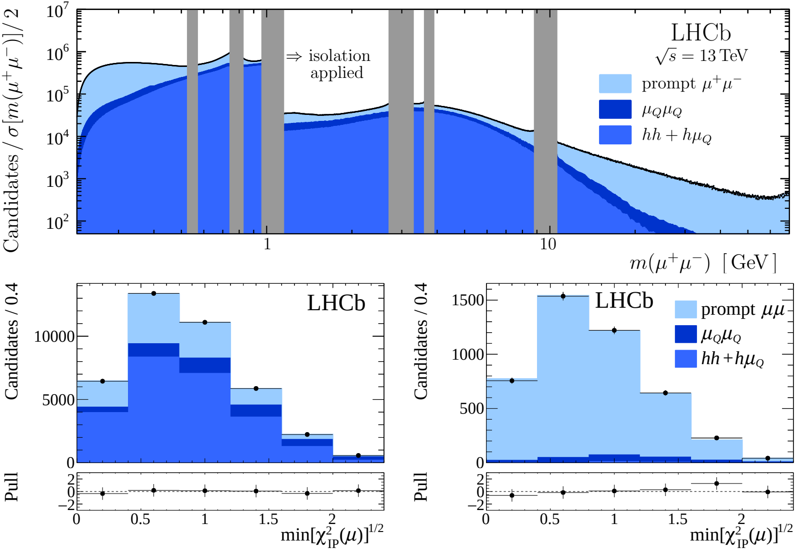
Searching with LHCb
in practice . . .

LHCb Collaboration
LHCb-PAPER-2019-031 (2019)

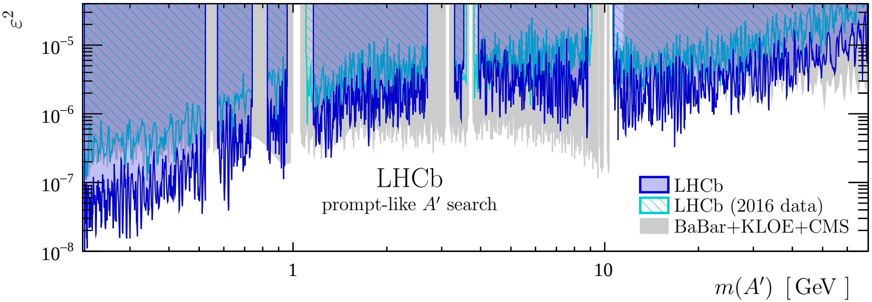
LHCb Collaboration
Phys. Rev. Lett. **120**, no. 6, 061801 (2018)

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

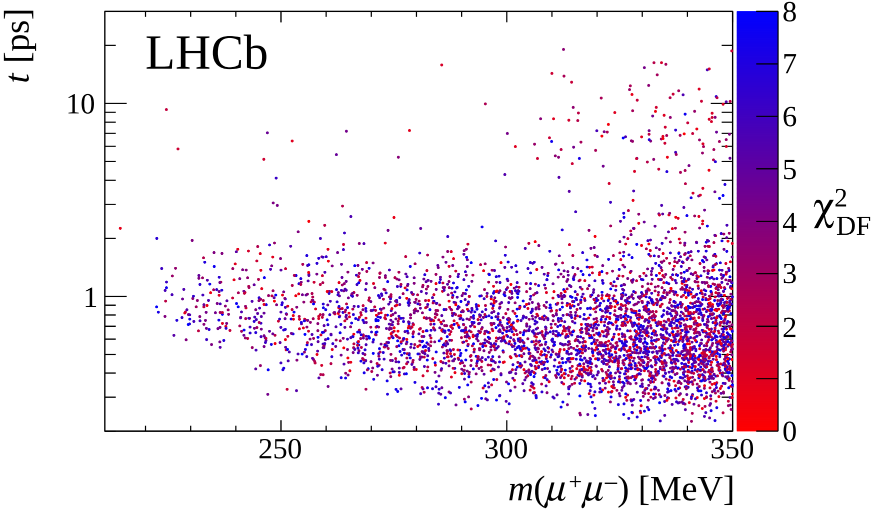
Real Data (*prompt*)



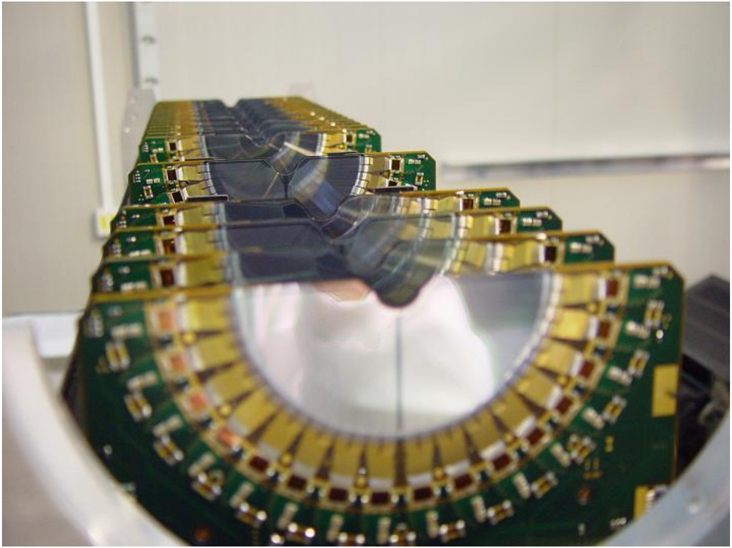
Limits (*prompt*)



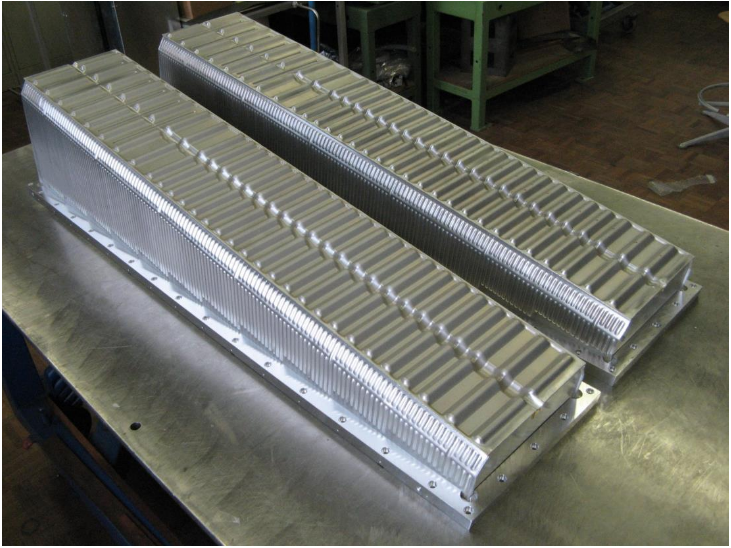
Real Data (*displaced*)



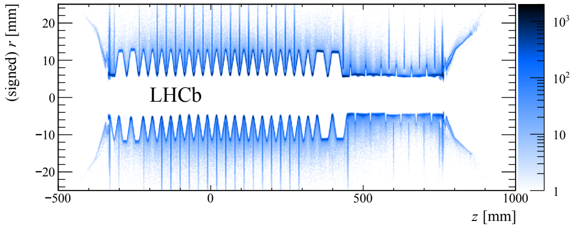
VELO Sensors

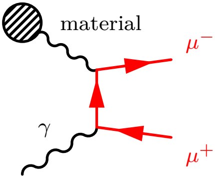


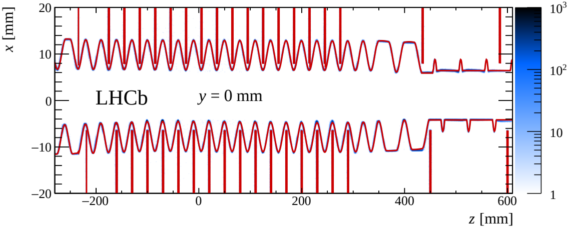
RF Foil

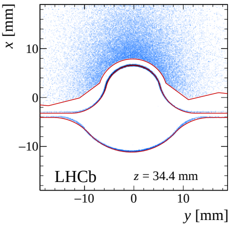


Bad Backgrounds (*displaced*)

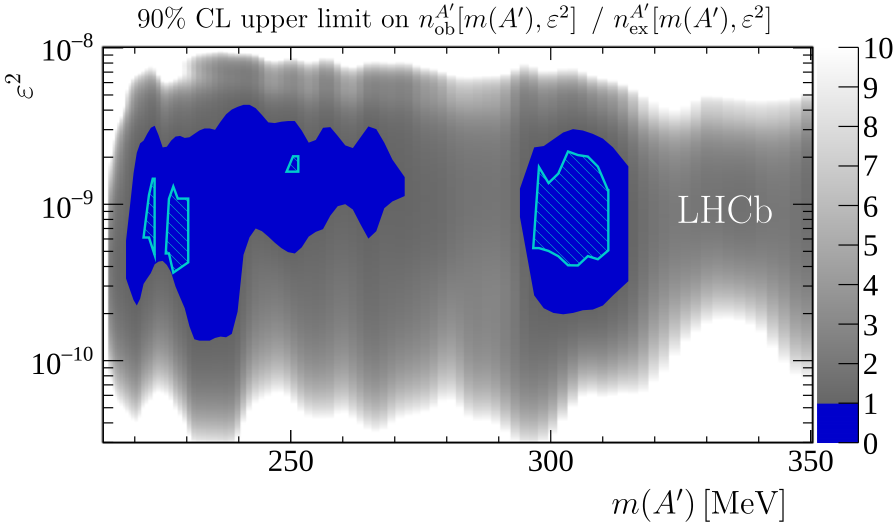








Limits (*displaced*)

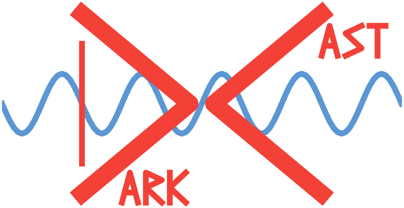


Dark Photons
and beyond . . .

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

DarkCast

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



- available at gitlab.com/philten/darkcast
- accompanying paper *Serendipity in dark photon searches*

```
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 Master Plan

- 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

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

1. branching fraction ratio: hidden local symmetries
2. cross-section ratio: hidden local symmetries

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

3. 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

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

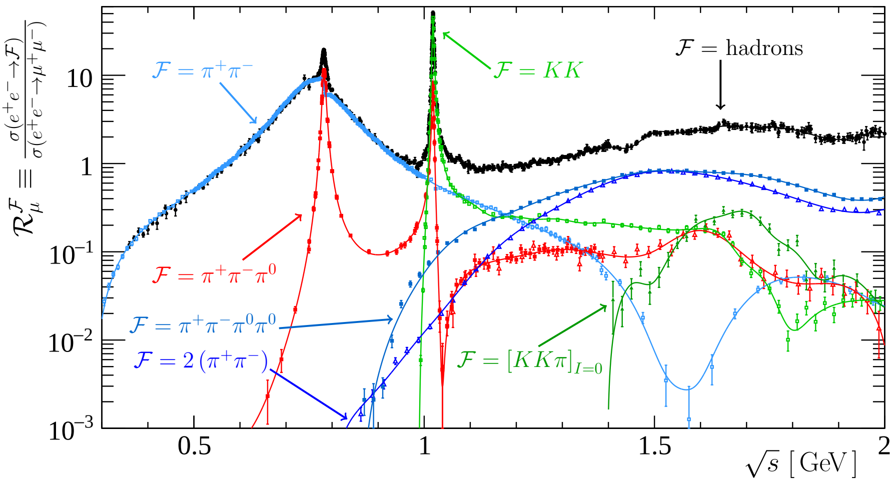
- c_f is 1 for charged leptons, 3 for quarks, and 1/2 for neutrinos
- Q_f is the model coupling for that fermion

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

$$\Gamma_{\text{hadrons}}(m, g) = \Gamma_{\mu\mu}(m, g)\mathcal{R}(m)$$

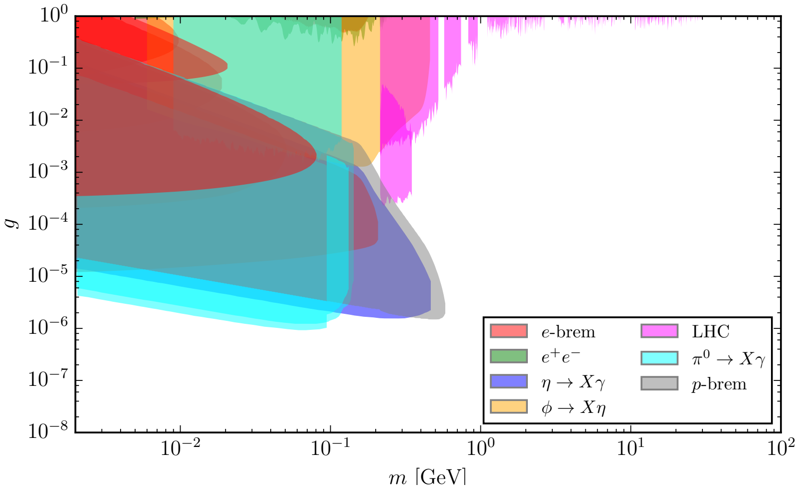
- $\mathcal{R}(m)$ is $\sigma(ee \to \text{hadrons})/\sigma(ee \to \mu\mu)$

The Data!



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

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

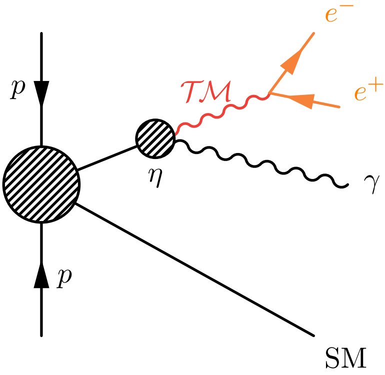
True Muonium

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

Ilten
arXiv:1908.08353 [hep-ph] (2019)

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 ${}^3S_1 \to e^+e^-$



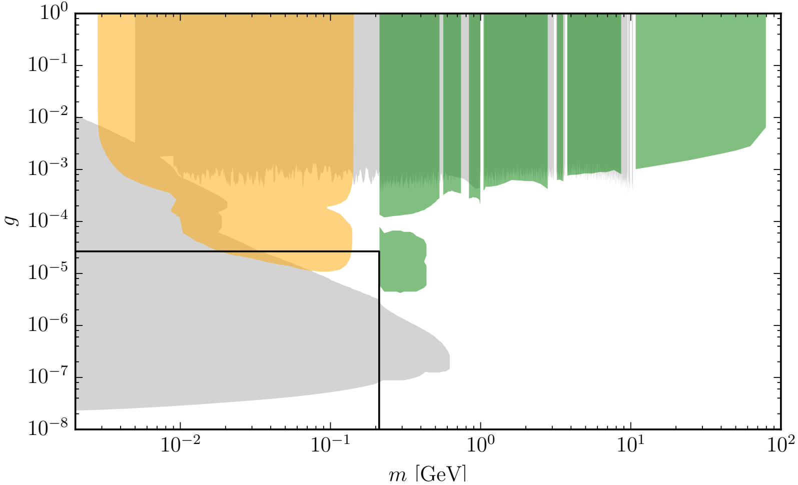
$$E_B \approx m_\mu \alpha^2/4 = 1.41\,\text{keV}$$

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

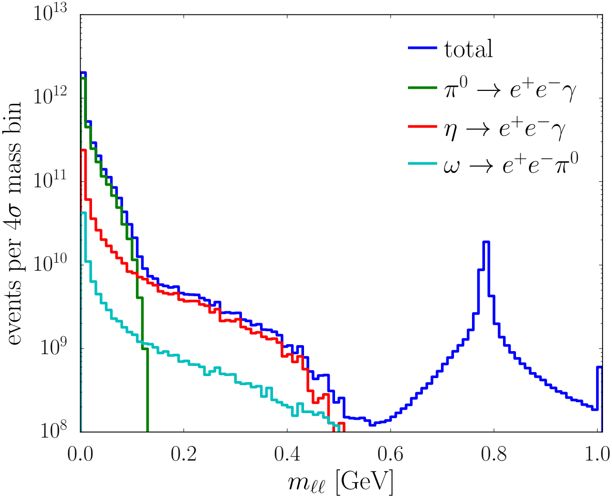
$$g_{\mathcal{TM}} \approx \alpha^2/2 \approx 2.66 \times 10^{-5}$$

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

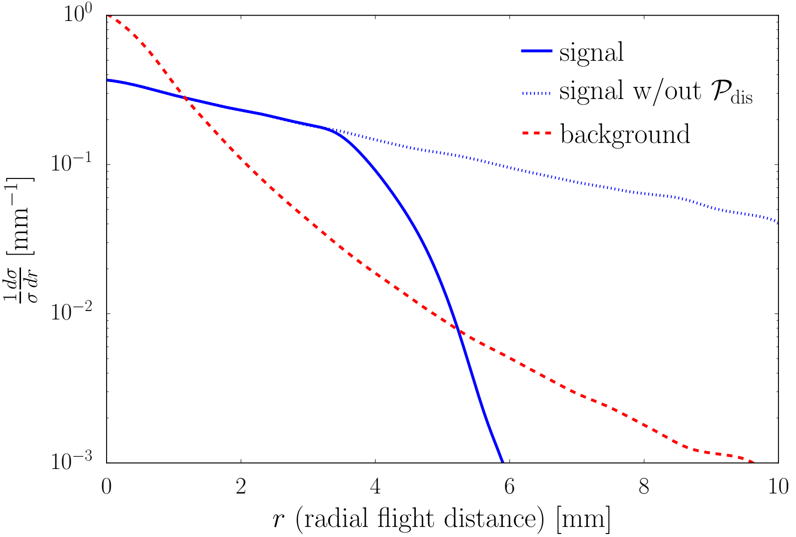
Mind the Gap



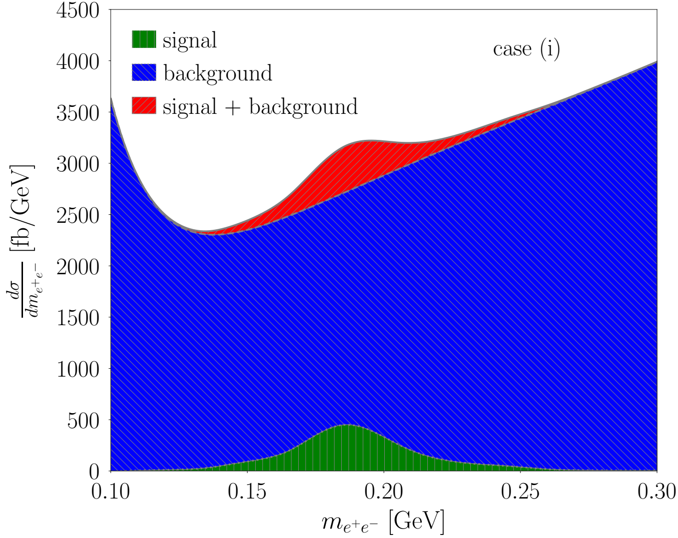
Inclusive Production



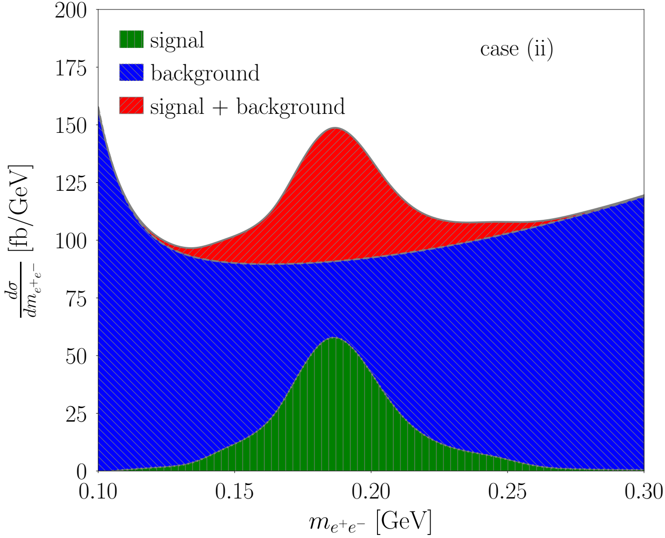
Dissociation



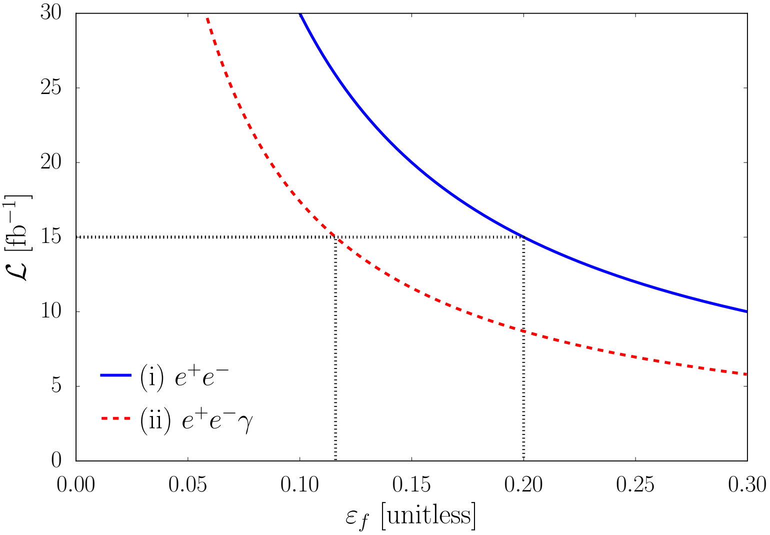
Detector Effects: Case (i)



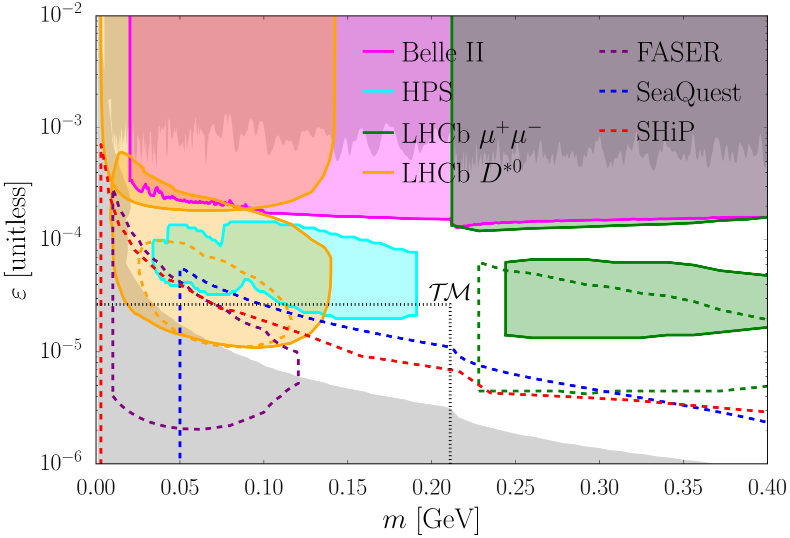
Detector Effects: Case (ii)



Discovery Potential



The Competition

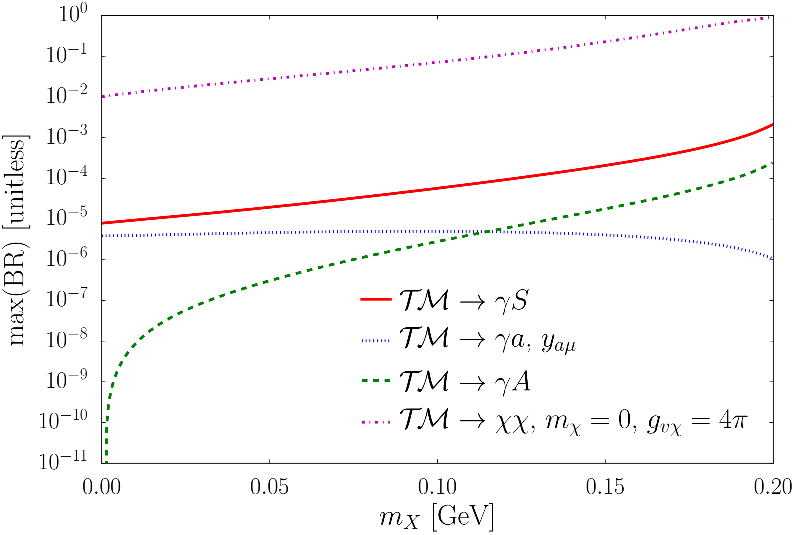


Final Thoughts

- LHC events provide huge fluxes of hadrons
  - triggering can be possible
  - requires some handle like leptons or displaced topology
- many analyses beyond LHCb dark photon
  - dark photon analysis down to 10 GeV from CMS
  - scalar searches at Υ peaks from LHCb
  - Majorana neutrino search with $B^- \to \pi^+ \mu^- \mu^-$ from LHCb
  - axion search with $B^0 \to K^{*0} \mu^+ \mu^-$ from LHCb
- possibility to extend to longer-lived particles with CODEX-b
- tools available for recasting like Darkcast and Cimba

Appendix

New Physics in TM



Hidden Symmetries

- but what about flavour 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 $P \in (\pi, \eta, \eta', K, \bar{K})$

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

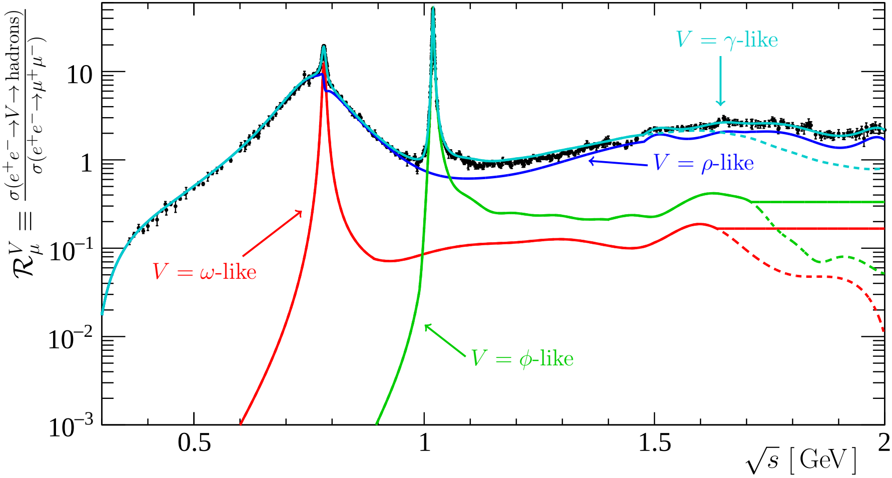
- T are the meson generators, *e.g.* $T_\omega = \frac{1}{2}(1, 1, 0)$
- external gauge fields mix through V

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

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

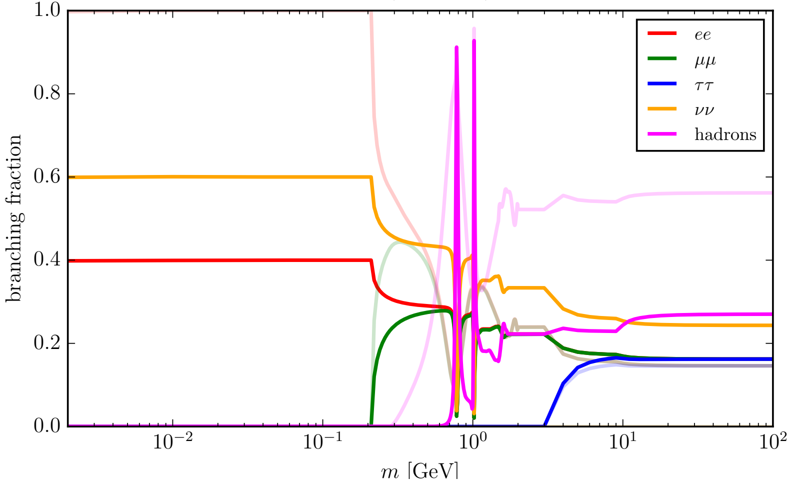
Vector Decomposition

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



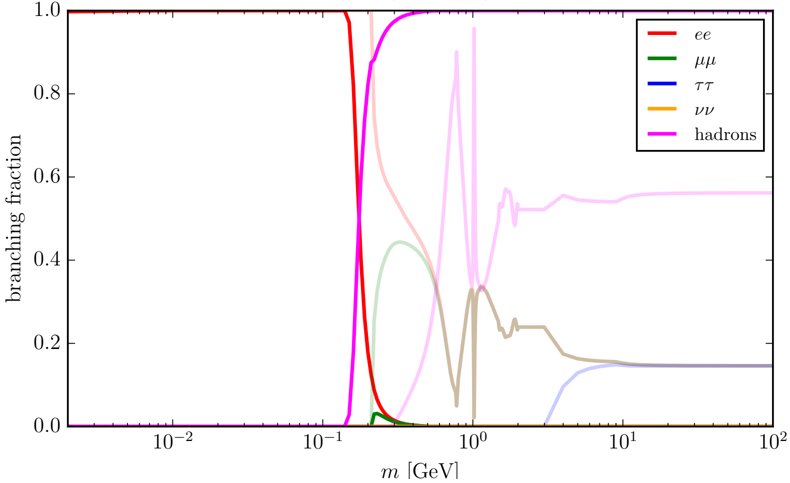
$B - L$ Boson

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

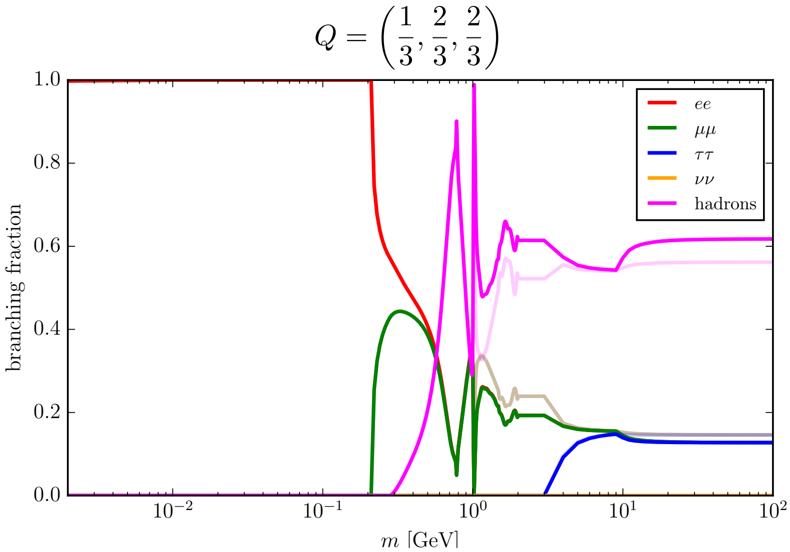


B Boson

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



Protophobic Boson



Production Ratios

- electron-positron annihilation and electron bremsstrahlung

$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)} = \frac{{g_A}^2 {Q^e_A}^2}{{g_B}^2 {Q^e_B}^2}$$

- proton bremsstrahlung

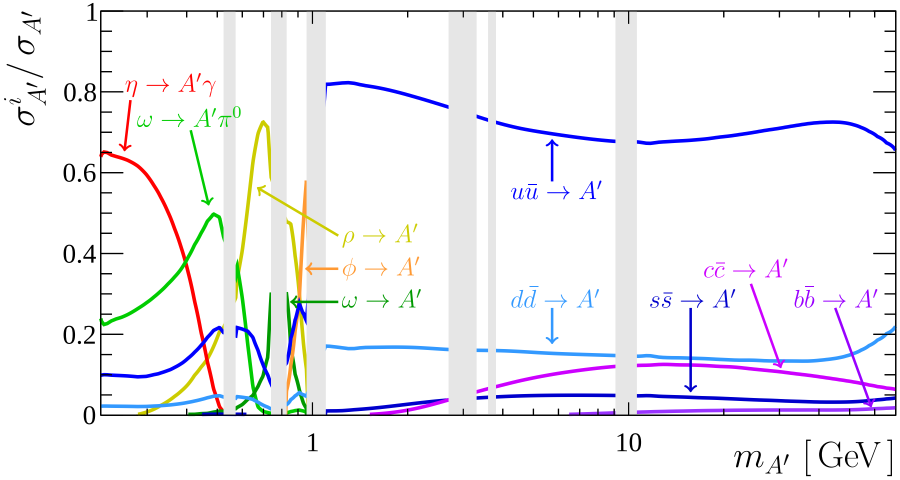
$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)} = \frac{{g_A}^2 (2Q^u_A + Q^d_A)^2}{{g_B}^2 (2Q^u_A + Q^d_A)^2}$$

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

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

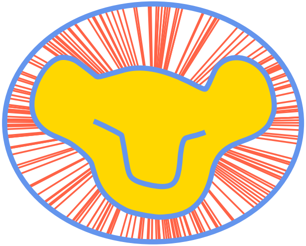
LHCb Production Fractions

- templates taken from Monte Carlo and fit against LHCb result



Cimba

- quickly generate single particles from minimum bias events



- available at gitlab.com/philten/cimba
- accompanying paper *CIMBA: fast Monte Carlo generation using cubic interpolation*

```
import cimba, random
# Create the random number generator.
rng  = random.Random()

# Load the interpolation grid.
grid = cimba.grid("data/pp14TeV.pkl")

# Create the particle gun.
pgun = cimba.ParticleGun(grid, "all/211", rng.random, ptlim, etalim)

# Generate a particle.
pgun()
```

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

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

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

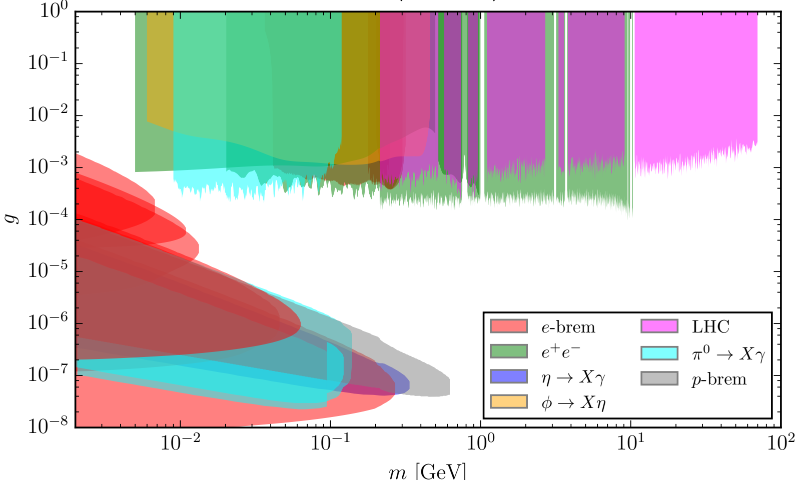
$$t_1 = t_0 + \frac{L_{\text{detector}}}{L_{\text{shield}}}$$

$\rightarrow$ upper and lower limits are solutions, equate and solve for t_0:

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

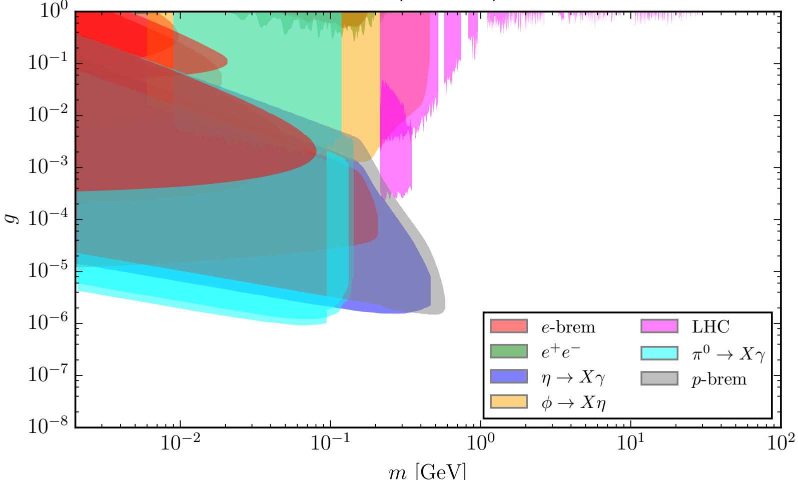
$B - L$ Boson

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



B Boson

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



Protophobic Boson