LHCb, CODEX-b, and the Quest for Longevity

Philip Ilten

UNIVERSITY OF BIRMINGHAM

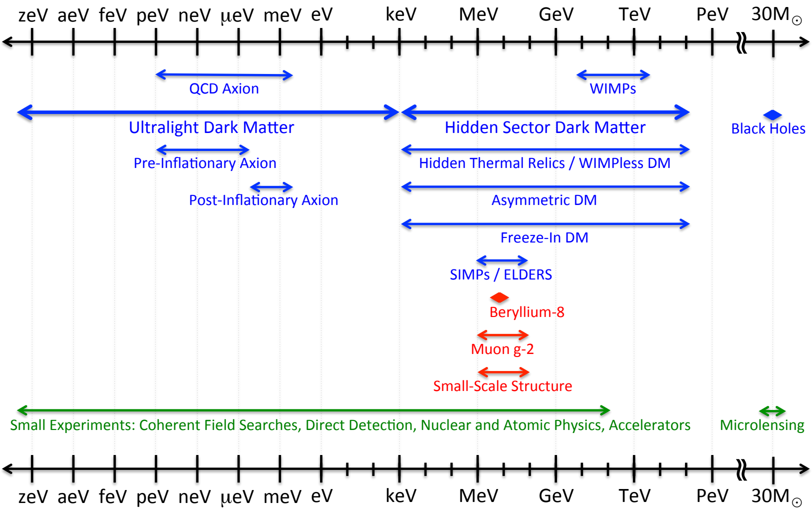
April 23, 2020

Lund Seminar

Widening the Net

arXiv:1707.04591 [hep-ph]

Dark Sector Candidates, Anomalies, and Search Techniques



It's Complicated

arXiv:1903.04497 [hep-ex]

displaced multitrack vertices

disappearing or kinked tracks

non-pointing (converted) photons

displaced leptons, lepton-jets, or lepton pairs

emerging jets

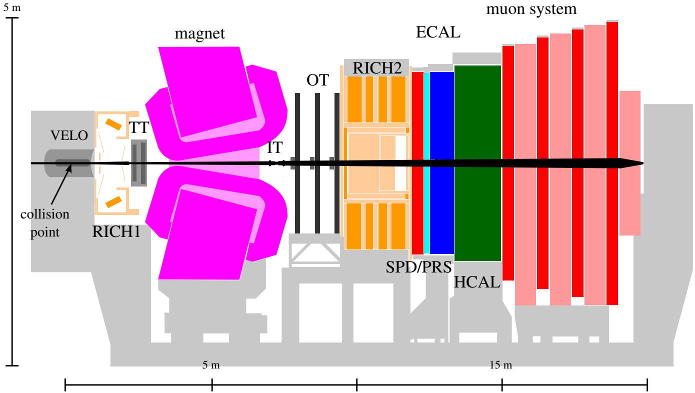
trackless, low-EMF jets

quasi-stable charged particles

multitrack vertices in the muon spectrometer

Detector

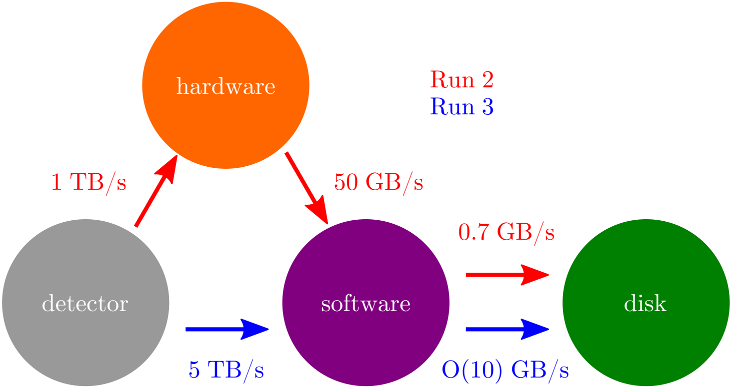
IJMPA 30 (2015)



- momentum resolution between 0.5% at 5 GeV to 1% at 200 GeV
- impact parameter resolution of $13 - 20$ μm for tracks
- secondary vertex precision of $0.01 - 0.05(0.1 - 0.3)$ mm in $xy(z)$

Trigger

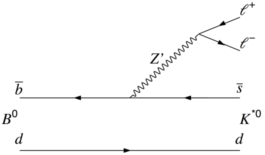
LHCb, JINST 8 (2013)

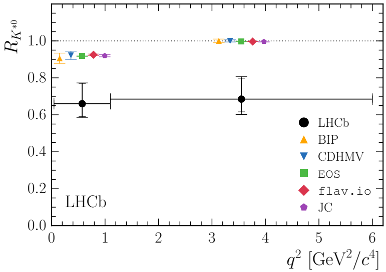


- real-time calibration and full event reconstruction in Run 2
- inclusive dimuon from threshold and jet triggers in Run 2
- full detector readout in Run 3

Indirect Measurements

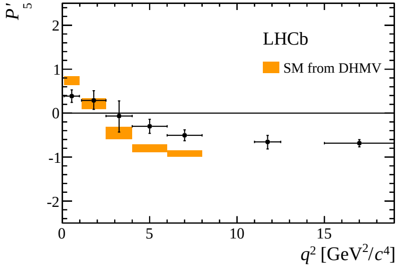
JHEP 08 (2017)





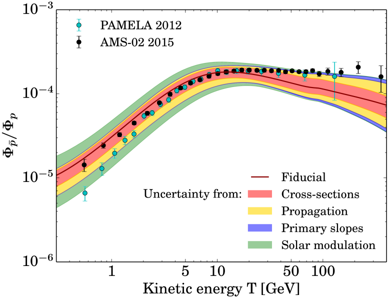
JHEP 02 (2016)

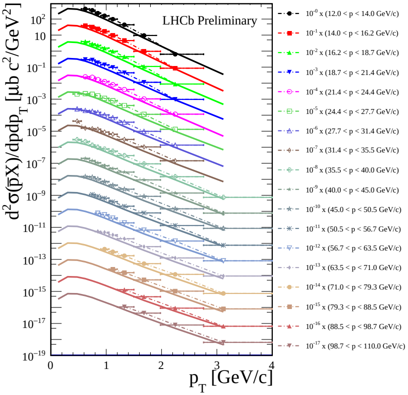
$$B^0 \to K^{*0}\mu\mu$$



Supporting Measurements

PRL 121 (2018)





- use LHCb as fixed target with SMOG
- measurement of $\bar{p}$ cross-section in $p + \text{He}$
- relevant to dark matter annihilation, see Geisen, *et al.*

Direct Searches

- *don't judge a fish by its ability to climb a tree*

- areas where LHCb cannot compete
  - **luminosity**: 10× less luminosity than ATLAS and CMS
  - **acceptance**: 10% for 100 GeV, 1% for 1 TeV, ...

- areas where LHCb does well
  - **flavor**: anything that requires PID other than pions/leptons
  - **displaced**: 50 fs lifetime resolution
  - **narrow**: 0.4% mass resolution (muons)
  - **trigger**: flexible with real time calibration and full reconstruction (tracks down to $p_{\mathrm{T}} > 0.5$ GeV)

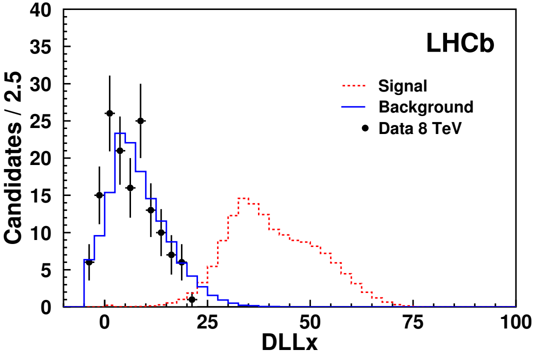
- all results here are run 1 except dark photon

Long Lived Particles

Massive Charged Particle

EPJC 75 (2015)

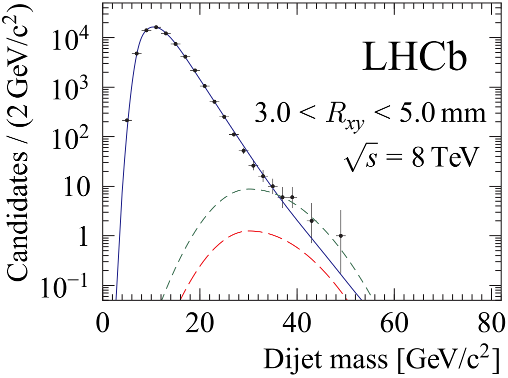
- search for heavy, charged, very long lived particles, *e.g.* $\tilde{\tau}$
- utilise absence of light in RICH in addition to minimal energy loss
- Drell-Yan production with SPS7 benchmark scenarios
- results not competitive (see backup) but idea interesting



Single Displaced Particle

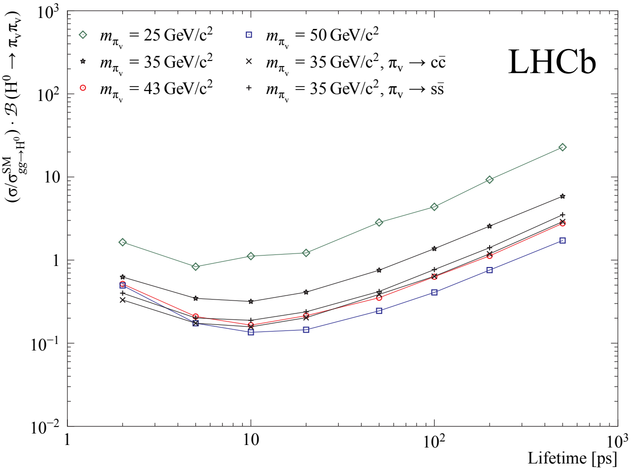
EPJC 77 (2017)

- search for single long lived particle decaying into jet pair, *e.g.* π_V
- production from SM-like Higgs decay



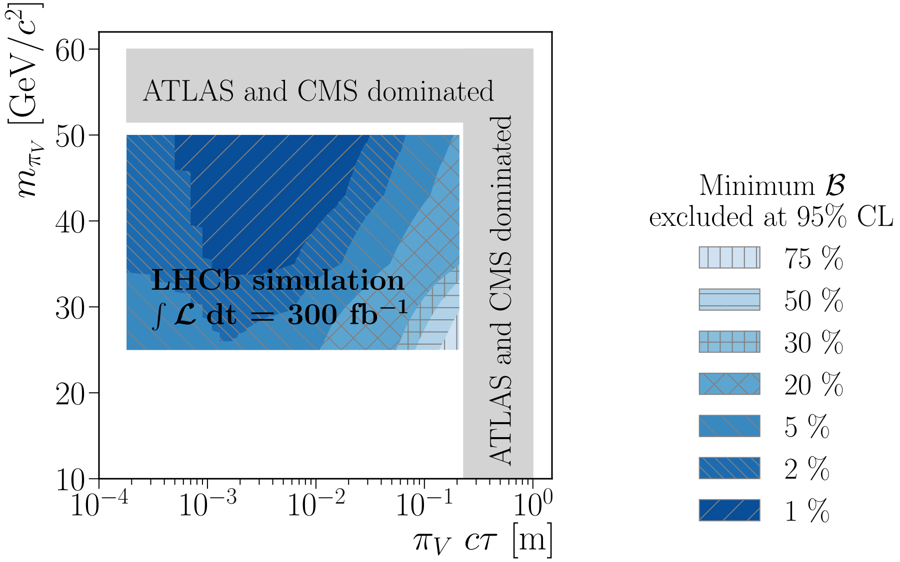
Single Displaced Particle

EPJC 77 (2017)



Single Displaced Particle

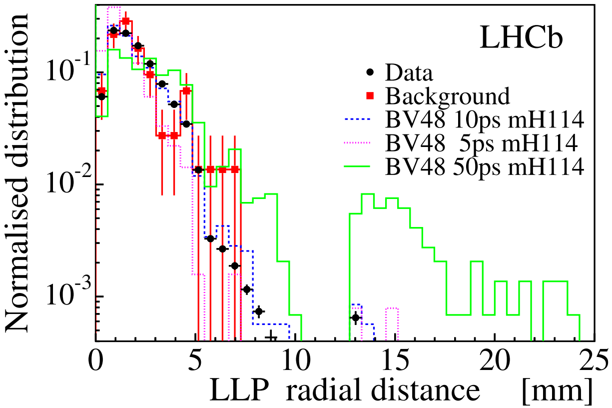
LHCb-CONF-2018-006



Two Displaced Particles

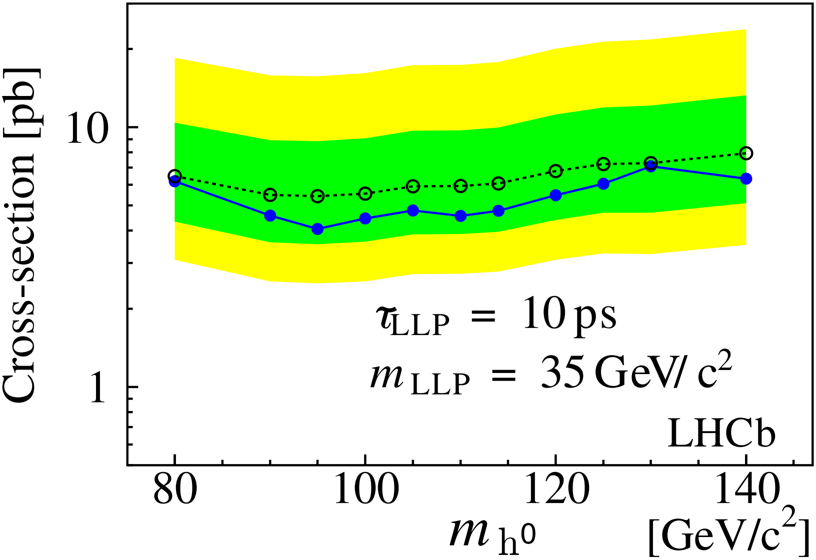
EPJC 76 (2016)

- search for two long lived particles, *e.g.* χ_1^0
- SM-like Higgs decay with baryon number violation
- masses from 20 – 60 GeV and lifetimes from 5 – 100 ps



Two Displaced Particles

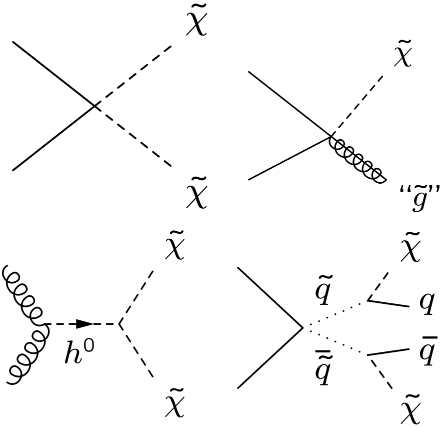
EPJC 76 (2016)



Displaced with Muon

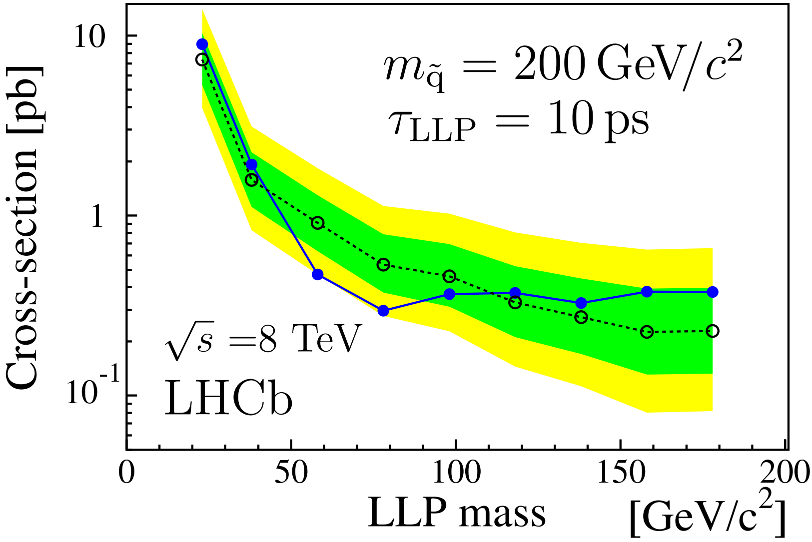
EPJC 77 (2017)

- search for long lived particle decaying into di-quark and muon
- consider full PYTHIA model and four simplified models
- utilises excellent secondary vertex reconstruction



Displaced with Muon

EPJC 77 (2017)

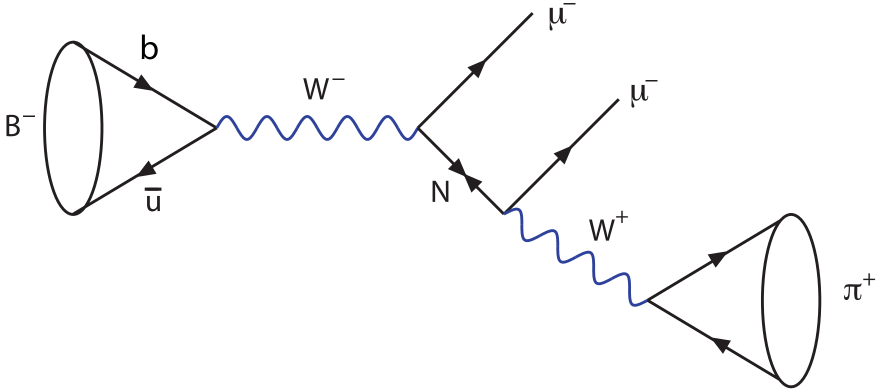


Light Dark Sector

Heavy Neutral Leptons

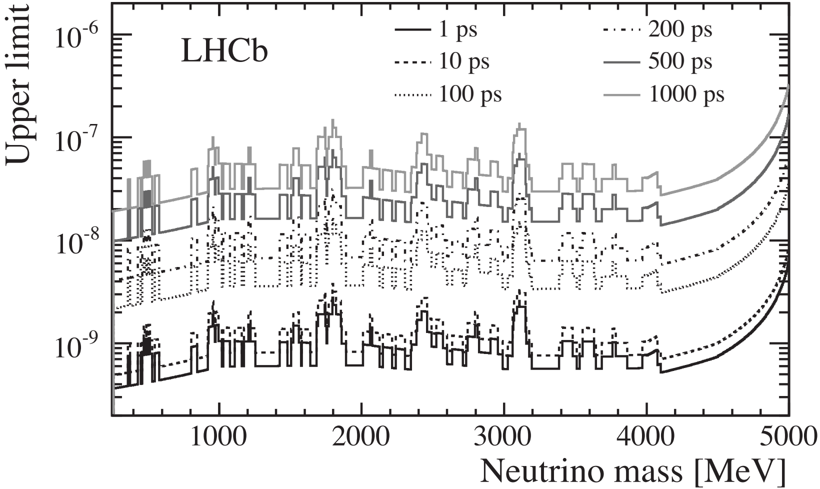
PRL 112 (2014)

- lepton violating $B^- \to \pi^+\mu^-\mu^-$ search
- correction of mixing angle limits by Peskin and Shuve
- new analyses underway



Heavy Neutral Leptons

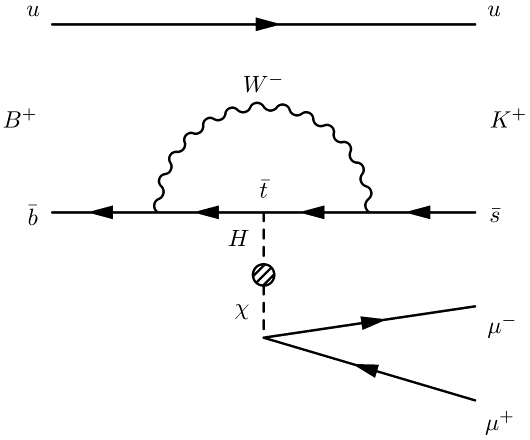
PRL 112 (2014)



Resonances in B Decays

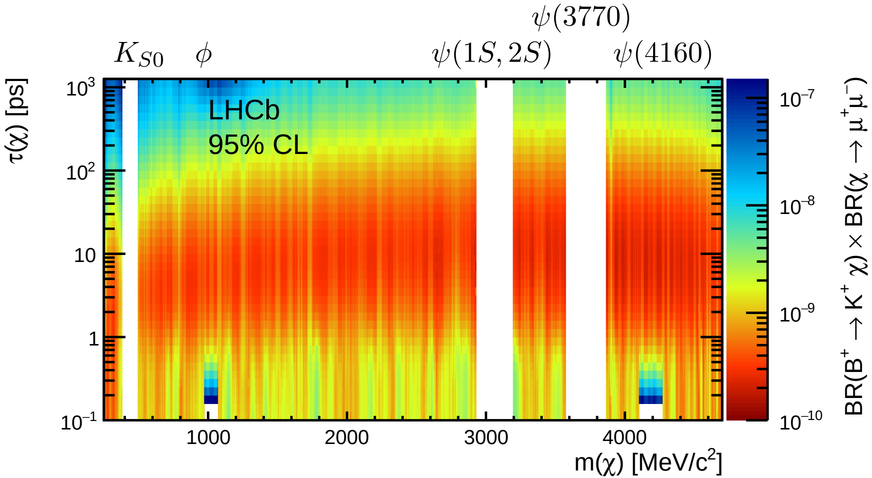
PRD 95 (2017)

- $B^0 \to K^{*0}\mu\mu$ and $B^+ \to K^+\mu\mu$
- perform both prompt and displaced search simultaneously
- model independent limits provided for re-casting



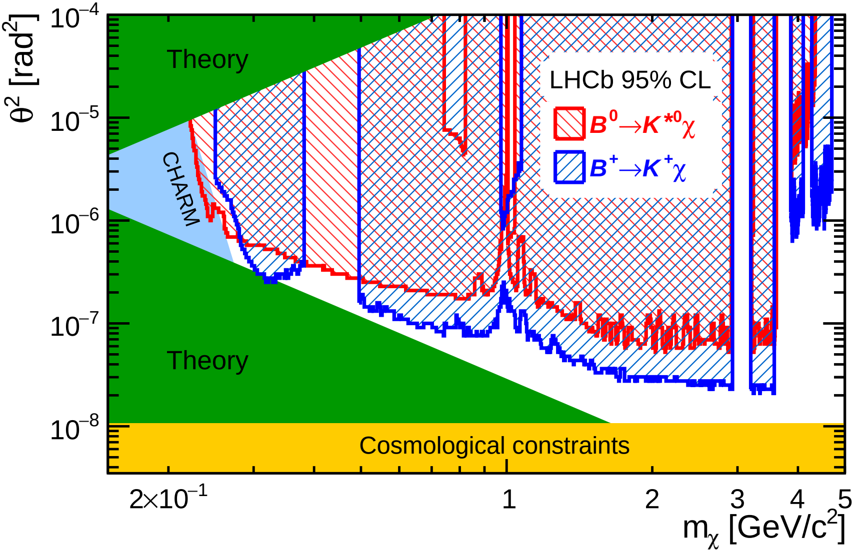
Resonances in B Decays

PRD 95 (2017)



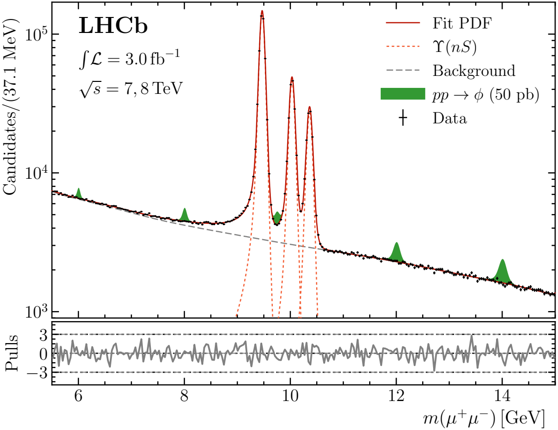
Resonances in B Decays

PRD 95 (2017)



Resonances on Resonances

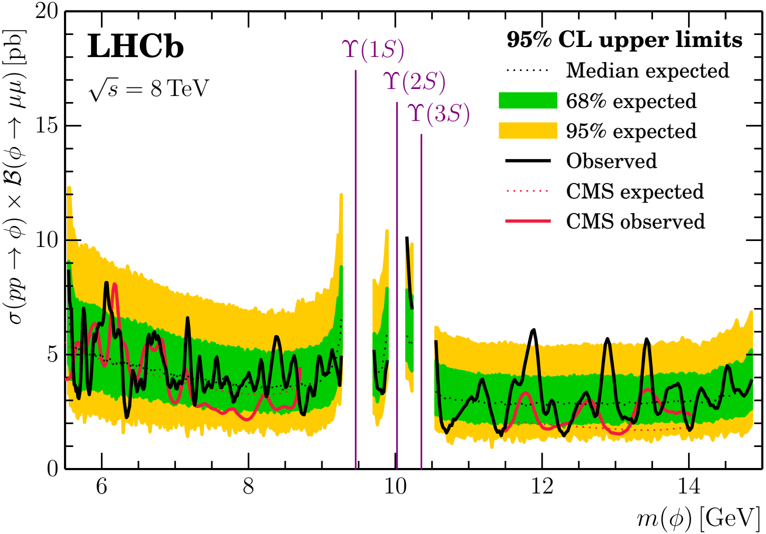
JHEP 147 (2018)



- example of scalar resonance in plot, limits also for vectors and double scalar production (see backups)

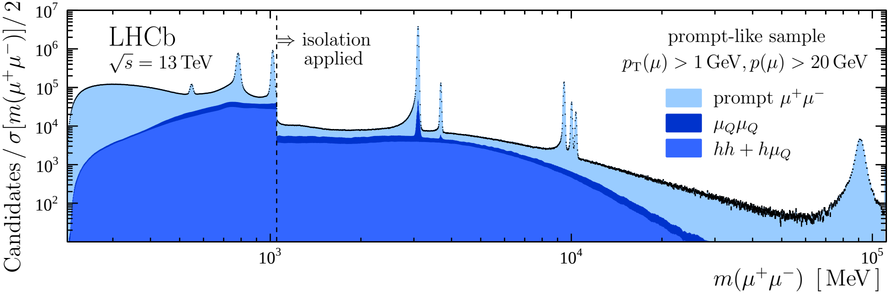
Resonances on Resonances

JHEP 147 (2018)



Dimuon Spectrum

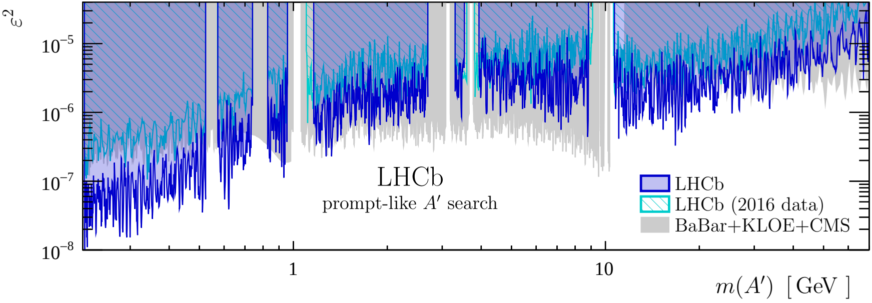
PRL 120 (2018)



- heavy flavour background ($\mu_Q\mu_Q$), mis-ID background (hh), and mis-ID with heavy flavour background ($h\mu_Q$)
- jet isolation above ϕ-mass to remove QCD background (primarily Drell-Yan production)

Prompt Dark Photons

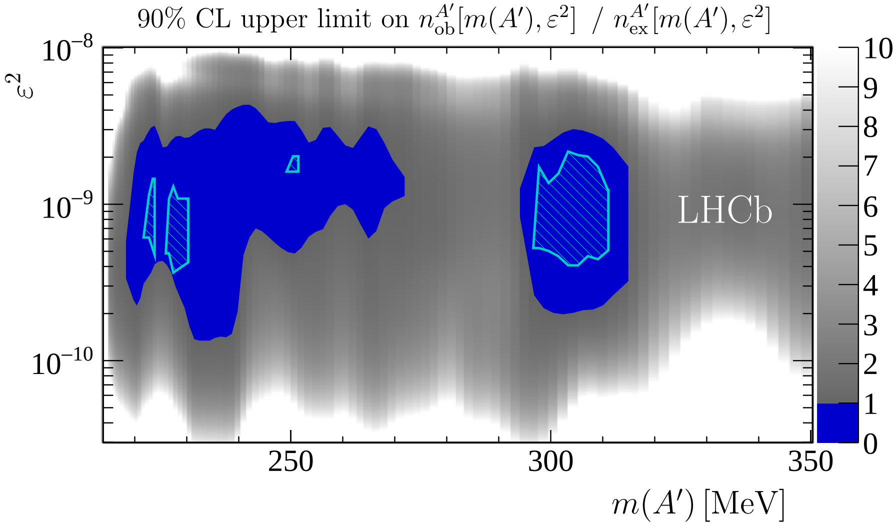
PRL 124 (2020)



- both prompt and displaced can be recast to general vector-like model (see backups)

Displaced Dark Photons

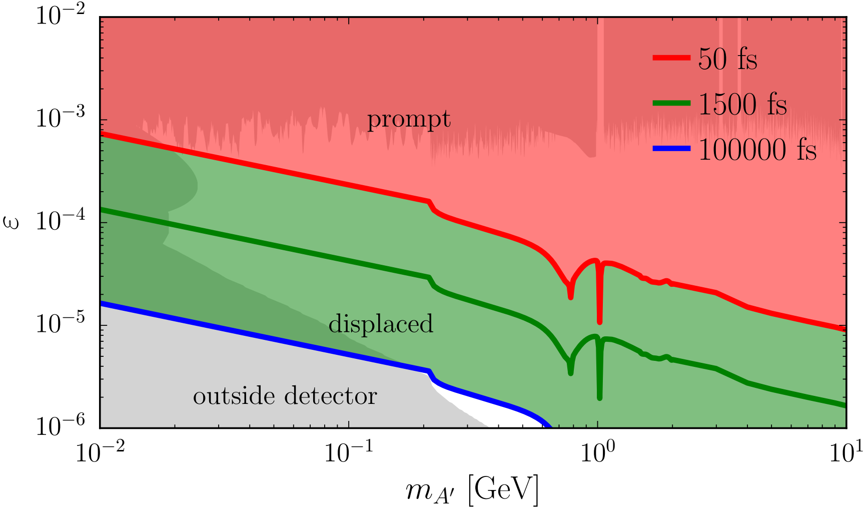
PRL 124 (2020)



- material a problem but under control (see backup)

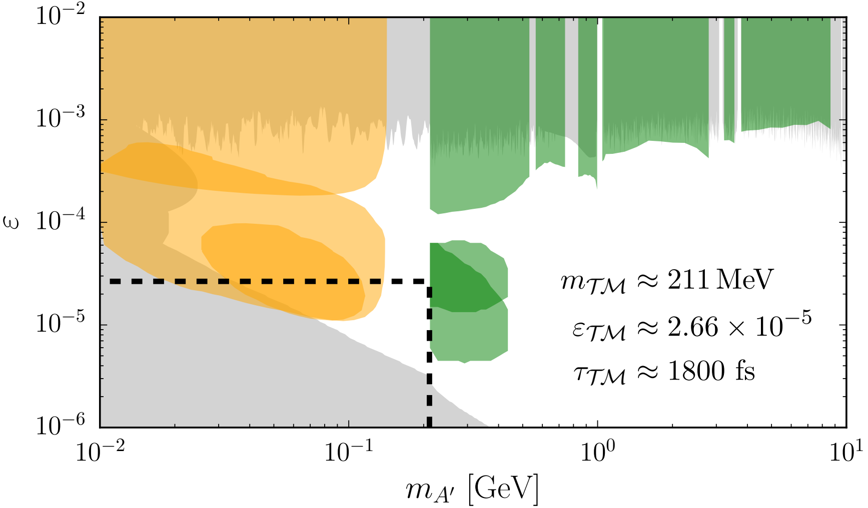
Lifetime

JHEP 06 (2018)



Mind the Gap

PRD 100 (2019)



- *para-true* muonium is a $\mu^+\mu^-$ vector state, not yet observed!

CODEX-b

Expression of Interest

arXiv:1911.00481 [hep-ex]

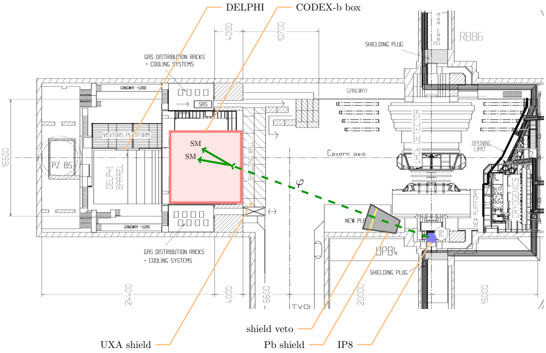
Expression of Interest for the CODEX-b Detector

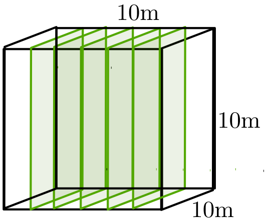
Giulio Aielli,[1] Roberto Cardarelli,[2] Matthew John Charles,[3] Xabier Cid Vidal,[4] Victor Coco,[5] Biplab Dey,[6] Raphael Dumps,[5] Jared A. Evans,[7] George Gibbons,[8] Olivier Le Dortz,[3] Vladimir V. Gligorov,[3] Eli Ben Haim,[3] Philip Ilten,[8] Simon Knapen,[9] Jongho Lee,[5,10] Saul López Soliño,[4] Benjamin Nachman,[11] Michele Papucci,[11,12] Francesco Polci,[3] Robin Quessard,[13] Harikrishnan Ramani,[11,14] Dean J. Robinson,[11] Heinrich Schindler,[5] Michael D. Sokoloff,[7] Paul Swallow,[8] Riccardo Vari,[15] Nigel Watson,[8] and Mike Williams[16]

- letter of interest released last November, arXiv:1911.00481 [hep-ex]
- letter of intent submitted
- collaboration growing: 28 contributors and 16 institutes

CODEX-b in a Nutshell

- A **Co**mpact **D**etector for **Ex**otics at LHC**b**

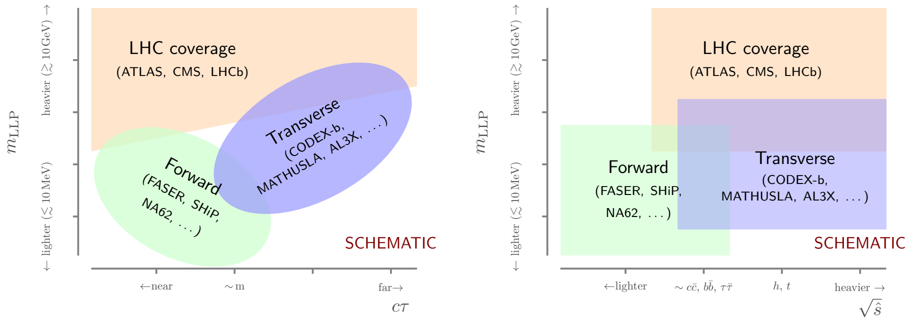




Why CODEX-b?

1. probes a wide range of LLP models; complementary or competitive with existing/proposed detectors
2. accessible zero background location with necessary services, DELPHI/UXA cavern
3. integration with LHCb trigger-less readout
4. compact size and modest cost with ability to extend

A Picture is Worth . . .



1. ATLAS/CMS/LHCb: heavy LLPs with wide lifetime range
2. FASER/SHiP/NA62: light LLPs with medium/long $c\tau$ and low $\sqrt{\hat{s}}$
3. MATHUSLA/CODEX-b: light LLPs with long $c\tau$ and high $\sqrt{\hat{s}}$

Model 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

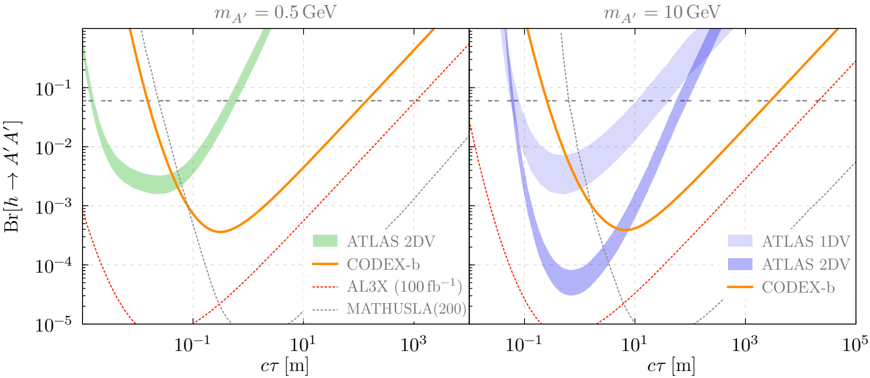
HNL (N)	HLN
HLN	yes

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

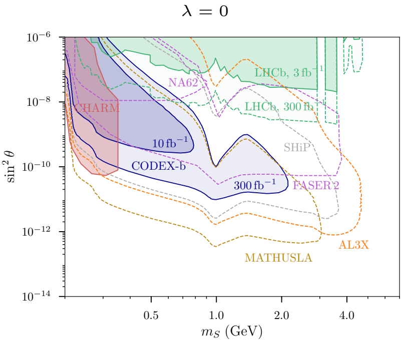
Production portal (green)
Decay portal (blue)
UV operator (orange)

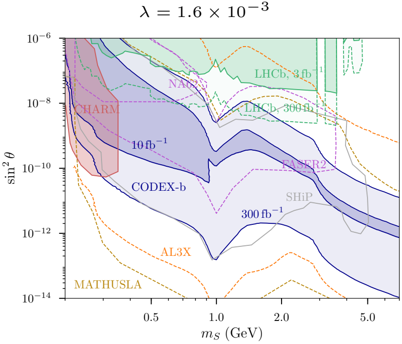
Dark Photon

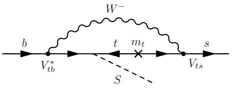
- no sensitivity to inclusive production from EM currents
- sensitive to production from $H \to A'A'$ decays

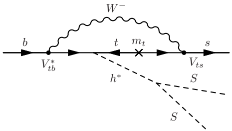


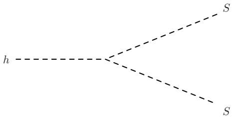
Higgs Portal



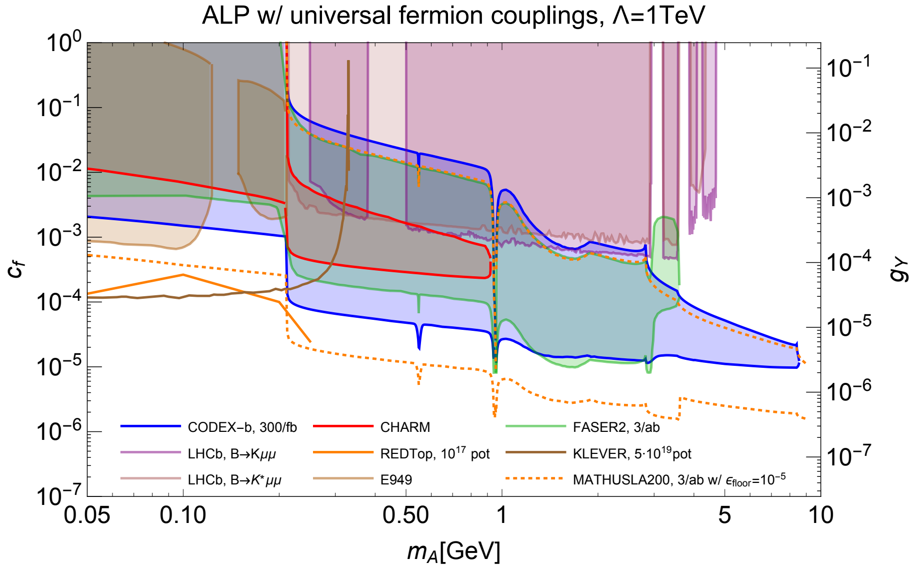




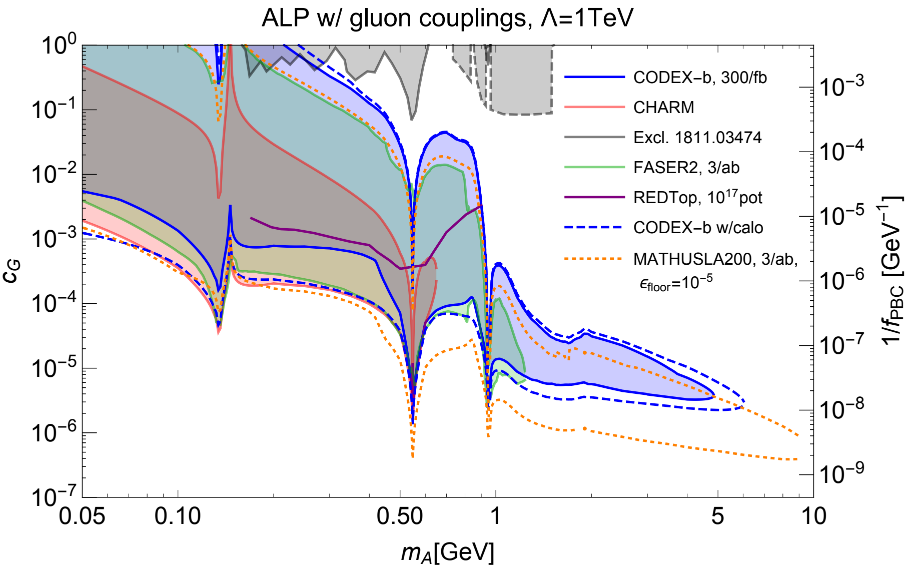




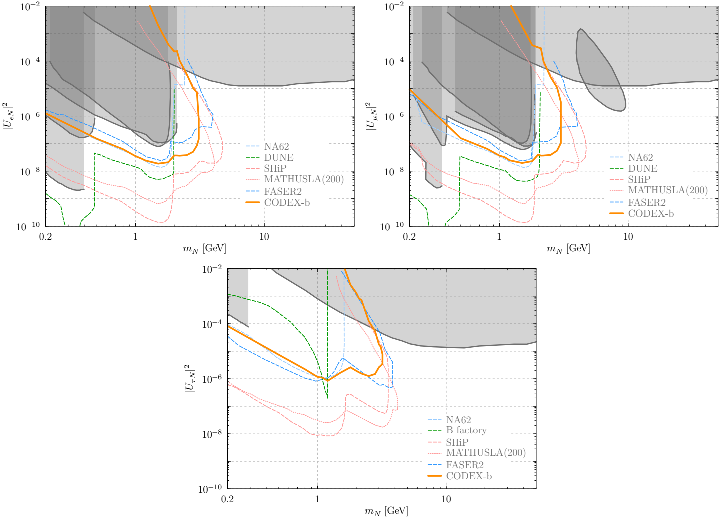
Fermion Coupled ALPs



Gluon Coupled ALPs



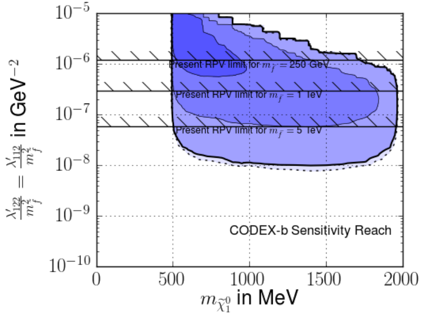
Heavy Neutral Leptons



R-parity Violating Supersymmetry

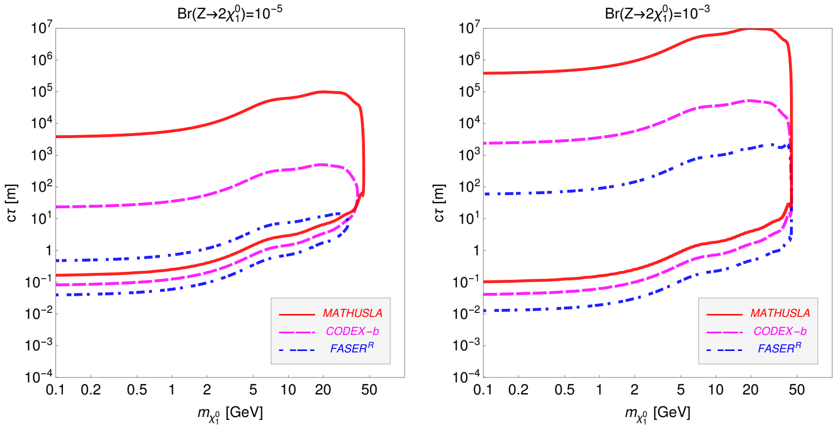
- study from Dercks, Vries, Dreiner, and Wang in PRD 99 055039 (2019)

benchmark	coupling	production	decay products
1	$\lambda'_{122},\ \lambda'_{112}$	$D_s^{\pm} \to \tilde{\chi}_1^0 + e^{\pm}$	$\eta, \eta', \phi, K^{0,\pm} + \nu_e,\ e^{\mp}$
4	$\lambda'_{131},\ \lambda'_{121}$	$B^{0,\pm} \to \tilde{\chi}_1^0 + X^{0,\pm}$	$D^{\pm}, D^{*\pm} + e^{\mp}$



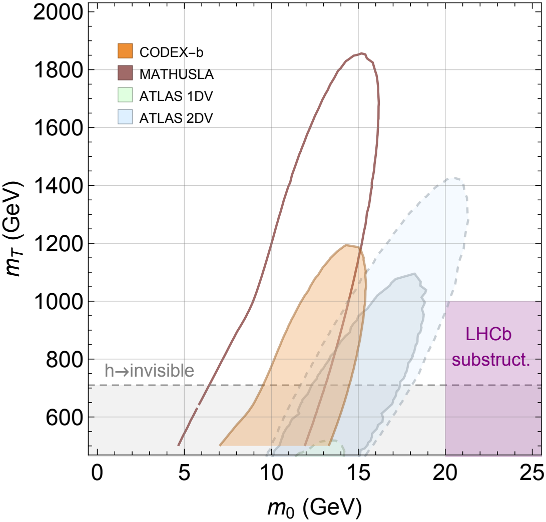
R-parity Violating Supersymmetry

- study from Helo, Hirsch, and Wang in JHEP 07 056 (2018)



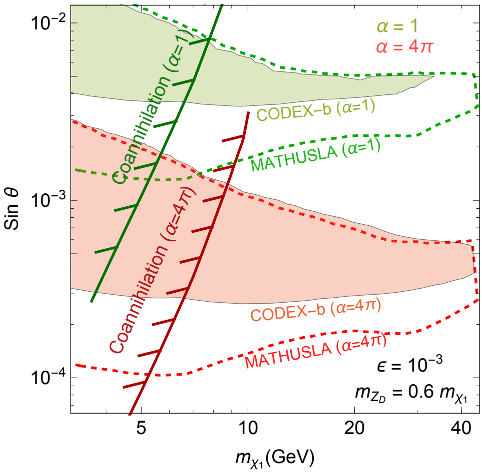
Neutral Naturalness

- consider fraternal twin Higgs model and search for glueball



Dark Matter Models

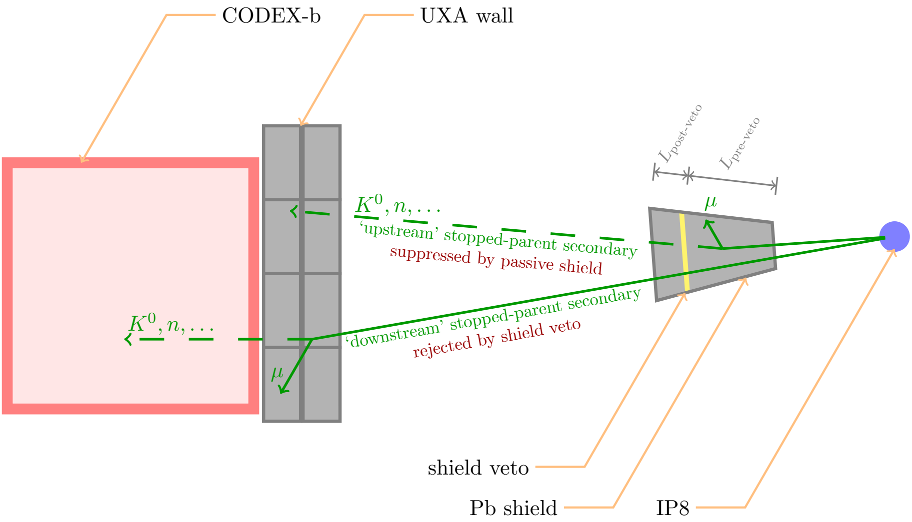
- a number of models considered including inelastic, co-scattering, co-annihilation, *etc.*



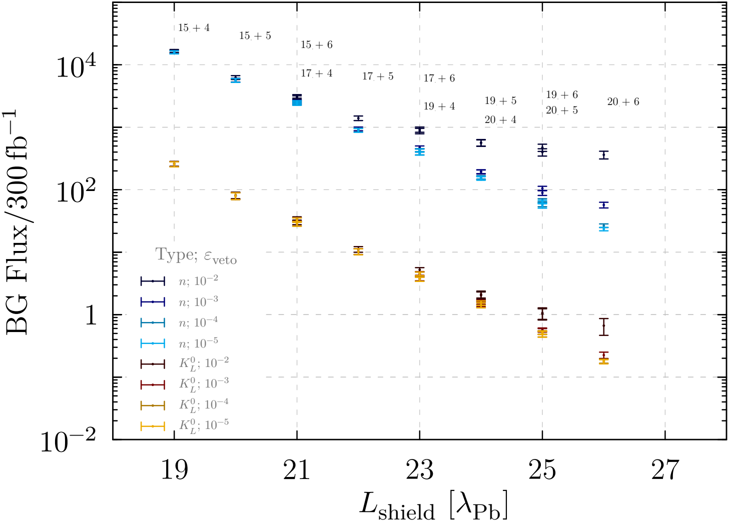
Backgrounds

- 10^{14} neutrons and K_L^0 per 300 fb^{-1}
- this requires 32λ of shielding
- 7λ from UXA wall, 25λ from lead shield
- expect $\approx 10^9$ muons per 300 fb^{-1} which can produce secondaries
- 10^3 K_L^0 per 300 fb^{-1} pass through the shield
- need active layer in shield for vetoing
- update of previous studies with detailed Geant4 study

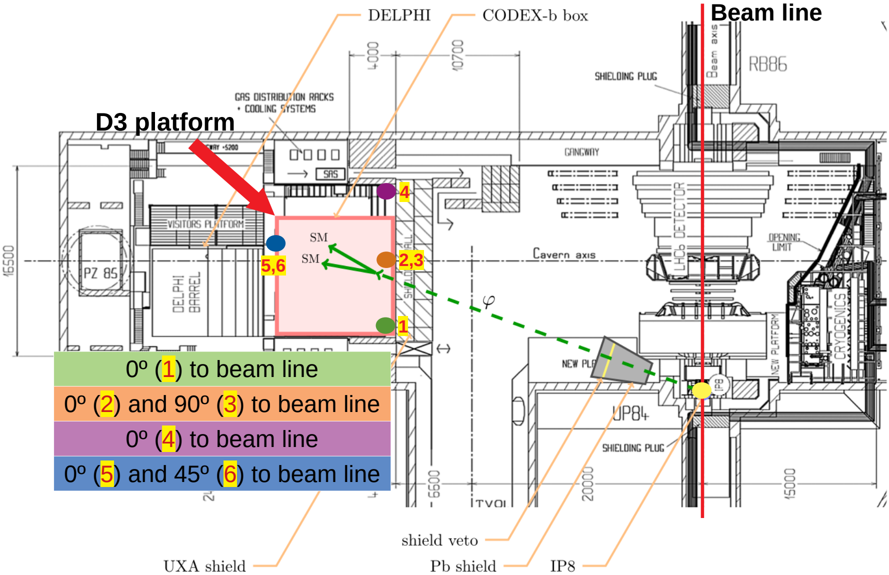
Shielding


CODEX-b
UXA wall
$L_{\text{post-veto}}$
$L_{\text{pre-veto}}$
$K^0, n, \ldots$
μ
'upstream' stopped-parent secondary
suppressed by passive shield
$K^0, n, \ldots$
μ
'downstream' stopped-parent secondary
rejected by shield veto
shield veto
Pb shield
IP8

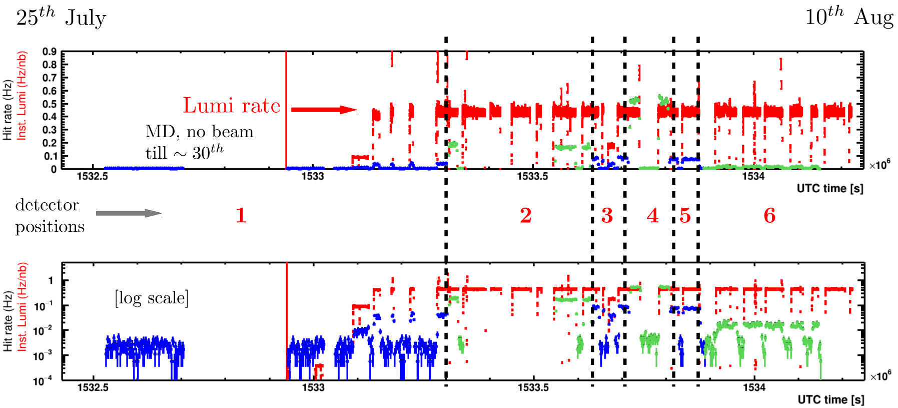
Background Simulation



Background Measurement



Background Measurement



- 0.2 Hz hit rate at point 2 indicates GEANT4 prediction of 10 Hz is conservative

CODEX-β

- $2 \times 2 \times 2$ m^3 with central layer, each layer with triplet of RPCs
- each layer made of 2×1 m^2 RPC block, 42 such layers
- expected hardware cost of 150k EUR

1. *Demonstrate the ability to detect and reconstruct charged particles which penetrate into the DELPHI cavern as well as the decay products of neutral particles decaying within the DELPHI cavern.*
2. *Detect and reconstruct a reasonable rate of neutral particles decaying inside the hermetic detector volume.*
3. *Show that CODEX-b can be integrated into the LHCb DAQ and demonstrate an ability to give a trigger to LHCb to retain an event that looks interesting in CODEX-b.*

Outlook

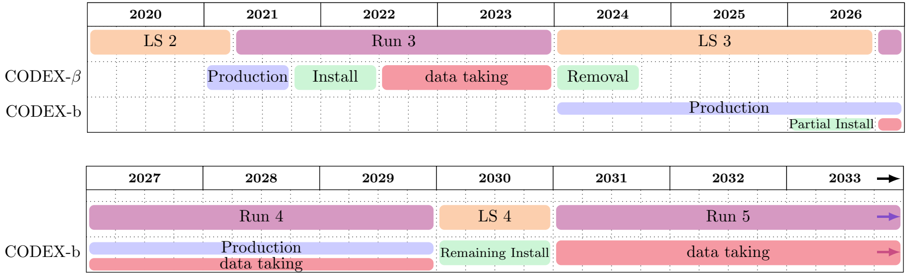
Some Thoughts

- mature long-lived particle search program at LHCb

- **flavor**: anything that requires PID other than pions/leptons
- **displaced**: 50 fs lifetime resolution
- **narrow**: 0.4% mass resolution
- **trigger**: flexible with real time calibration and full reconstruction

- all LHCb results available here
- inclusive di-muon dataset not exhausted
- di-photons are possible, see SciPost Phys 7 (2019)
- electrons should also be possible!

Timing is Key

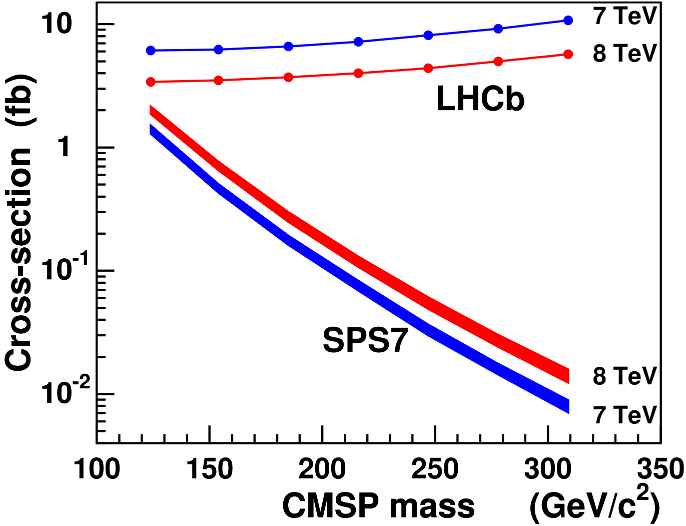


- significant progress has been made
- priority is finalising CODEX-β design and plans
- Birmingham working on technical drawings
- more detailed design informed from CODEX-β

Backups

Massive Charged Particle

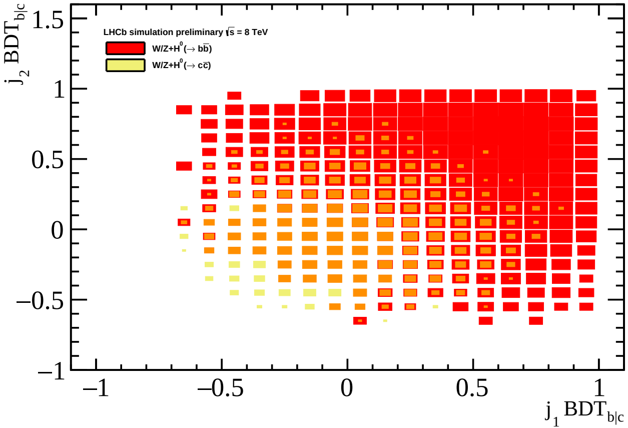
EPJC 75 (2015)



Higgs Decay into $Q\bar{Q}$

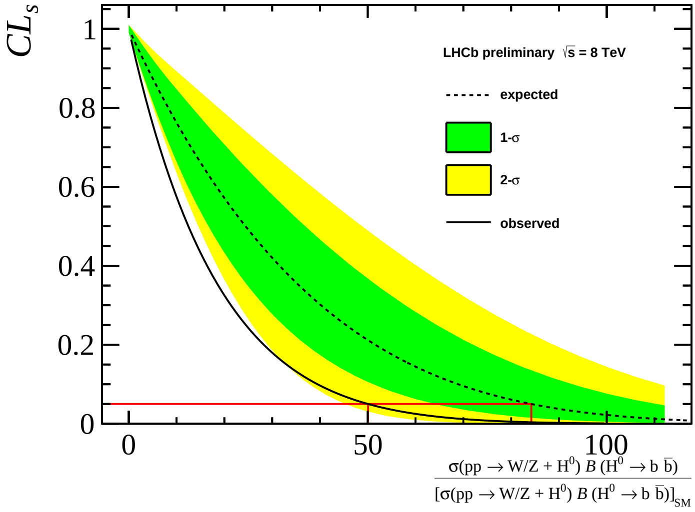
LHCb-CONF-2016-006

- search in association with W/Z
- utilise excellent heavy flavor tagging and b/c separation
- limits not competitive with SM, but important proof-of-concept



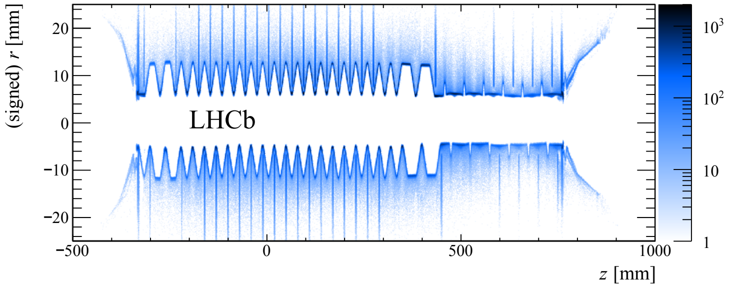
Higgs Decay into $Q\bar{Q}$

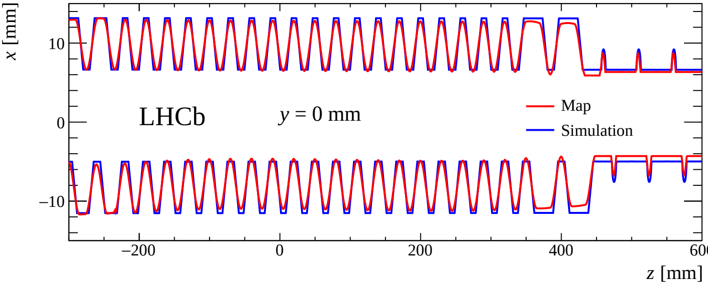
LHCb-CONF-2016-006



What Material?

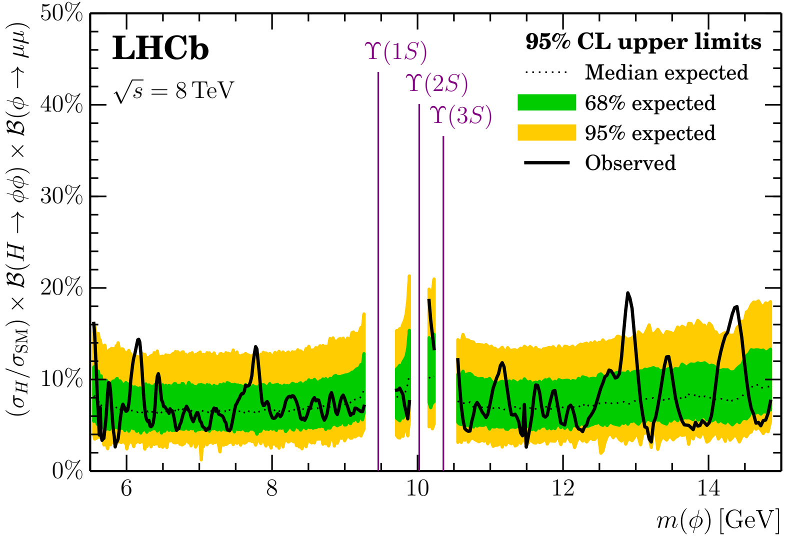
JINST 13 (2018)



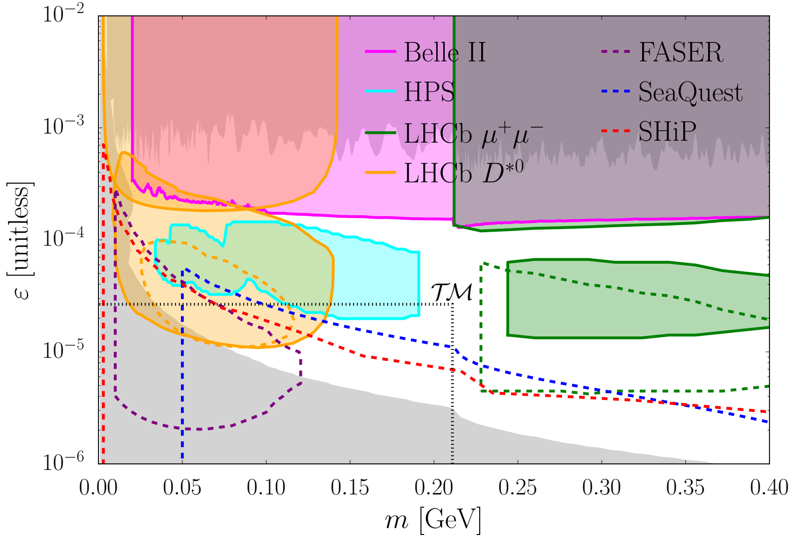


Resonances on Resonances

JHEP 147 (2018)

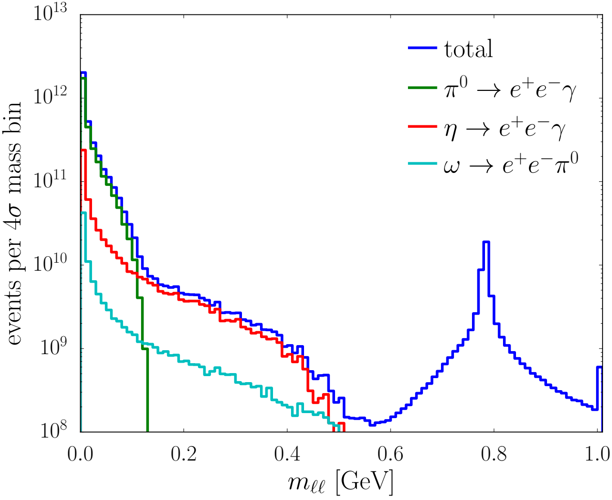


Mind the Gap

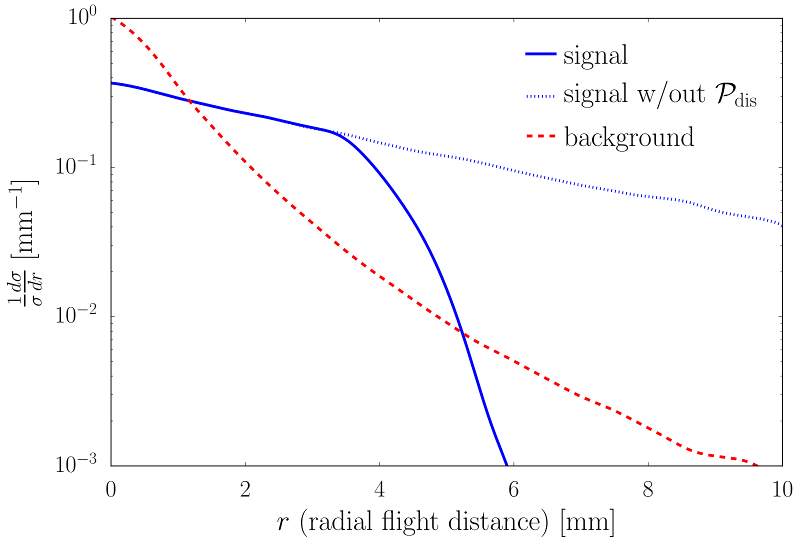


10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ε [unitless]
Belle II
HPS
LHCb $\mu^+\mu^-$
LHCb D^{*0}
FASER
SeaQuest
SHiP
$\mathcal{TM}$
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
m [GeV]

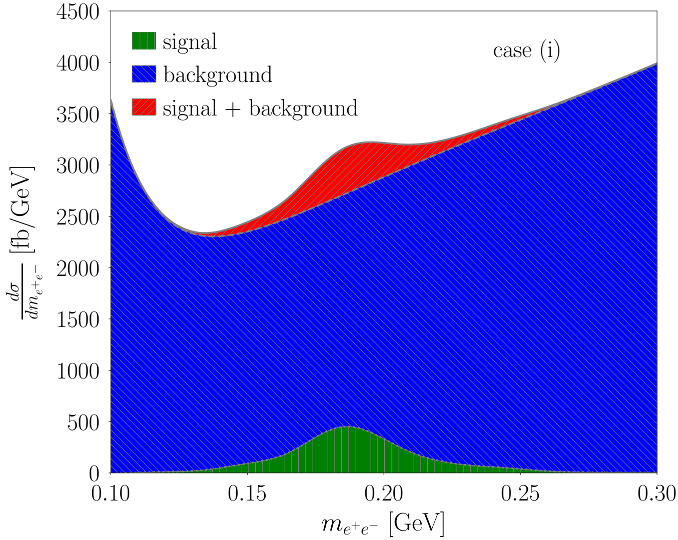
Inclusive Production



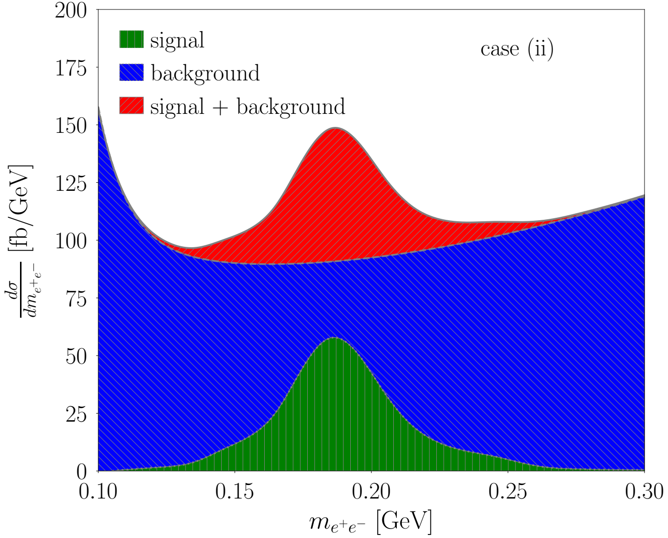
Dissociation



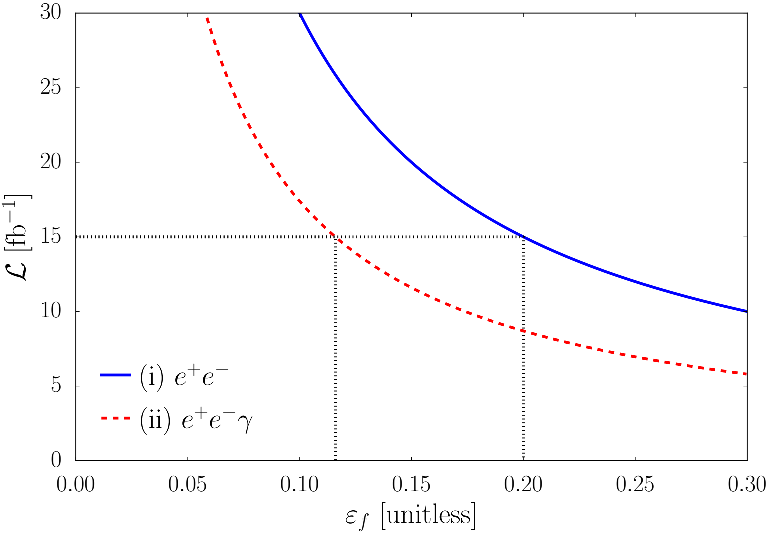
Detector Effects: Case (i)



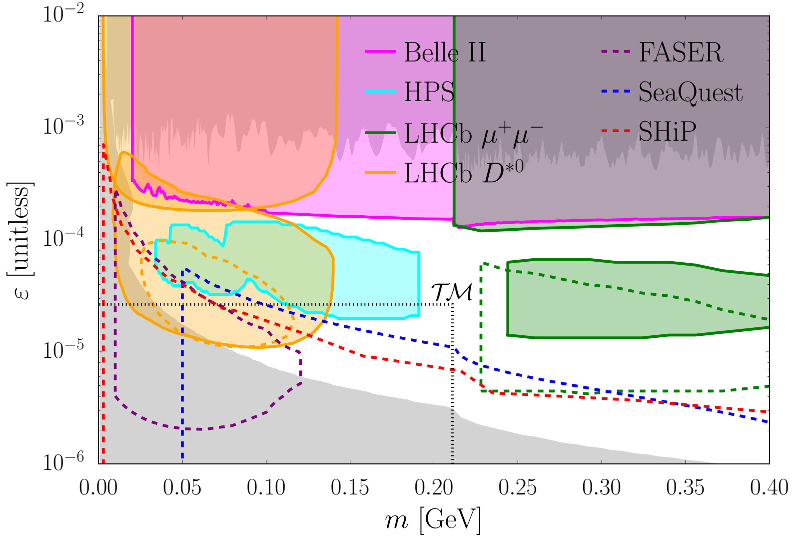
Detector Effects: Case (ii)



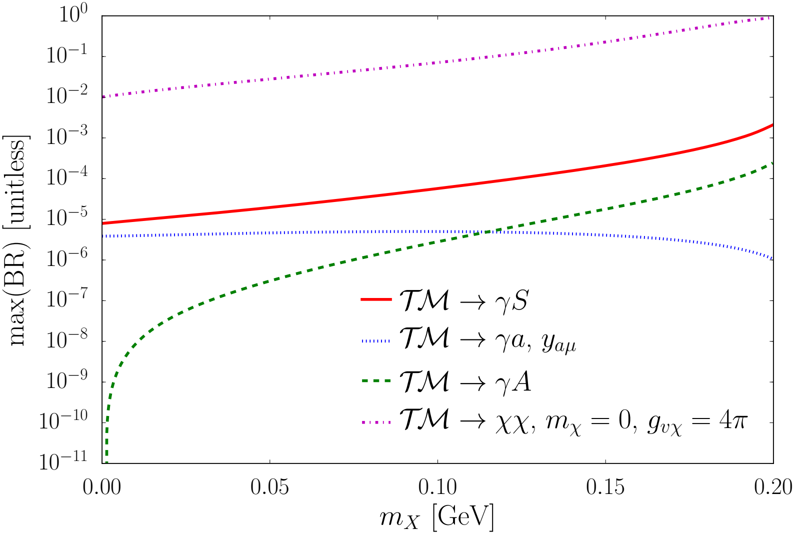
Discovery Potential



The Competition

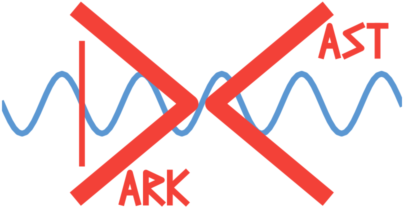


New Physics in TM



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

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

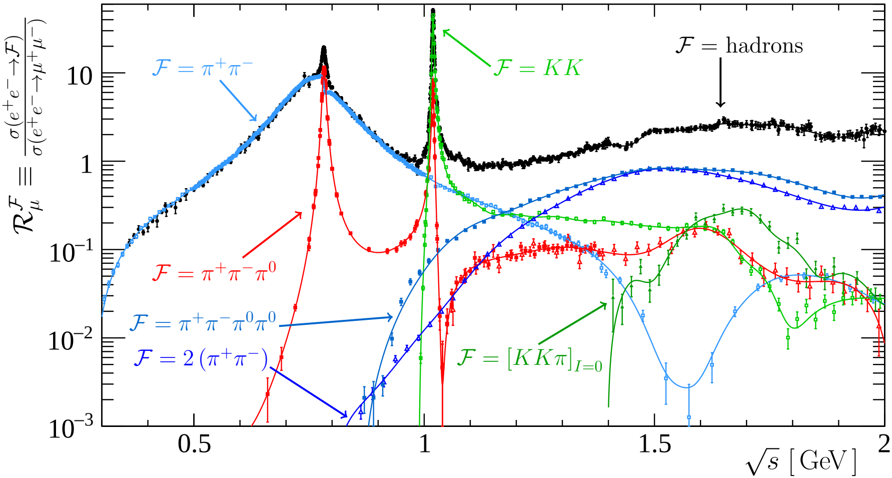
- c_f is 1 for charged leptons, 3 for quarks, and 1/2 for neutrinos
- Q_f is the model coupling for that fermion

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

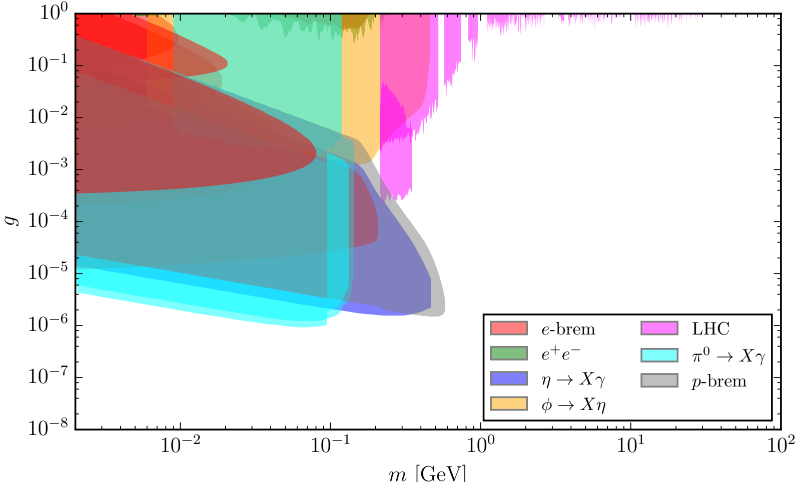
$$\Gamma_{\text{hadrons}}(m, g) = \Gamma_{\mu\mu}(m, g)\mathcal{R}(m)$$

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

The Data!


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

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 $P \in (\pi, \eta, \eta', K, \bar{K})$

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

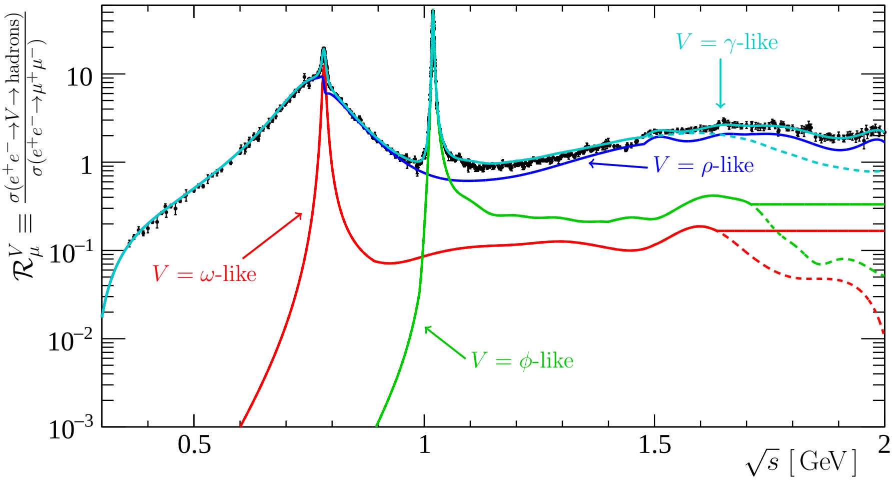
- T are the meson generators, *e.g.* $T_\omega = \frac{1}{2}(1, 1, 0)$
- external gauge fields mix through V

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

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

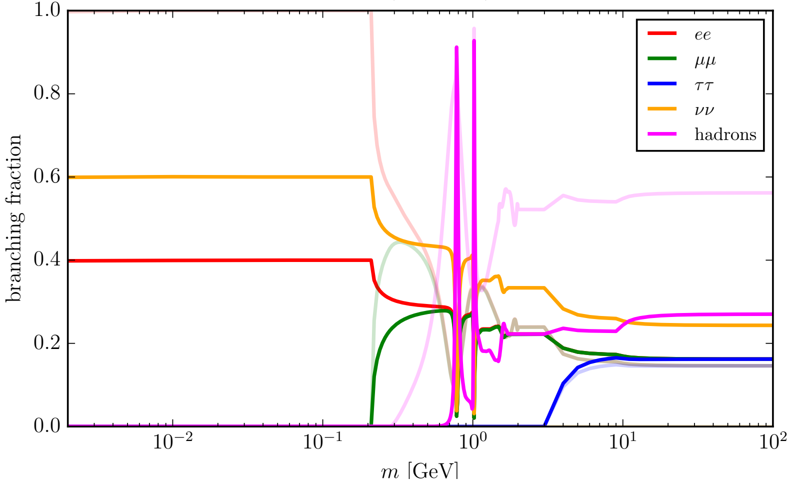
Vector Decomposition

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

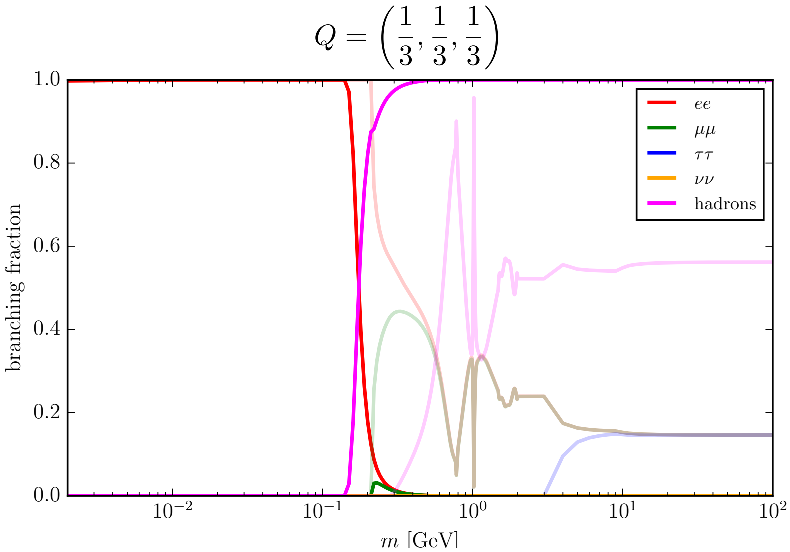


$B - L$ Boson

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

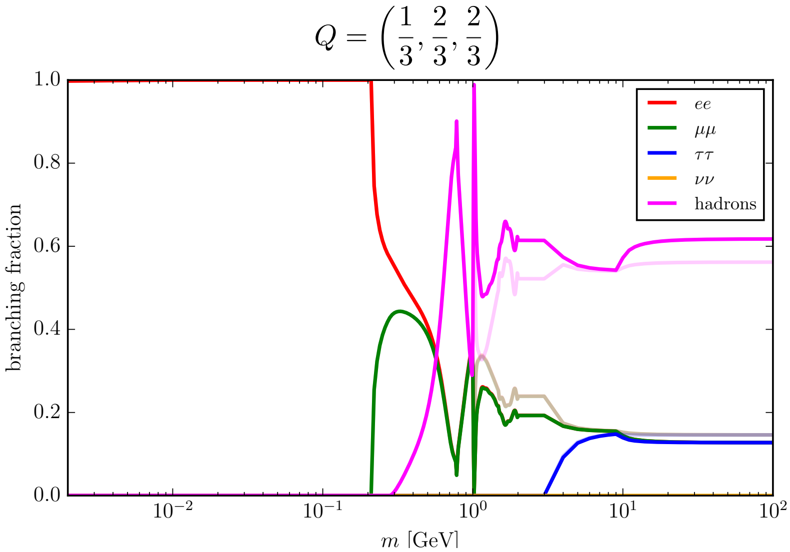


B Boson



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

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

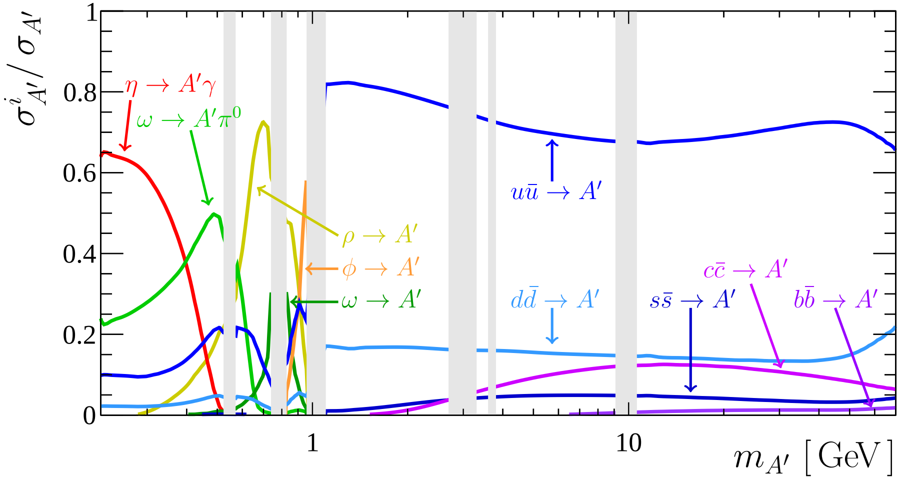
$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)} = \frac{{g_A}^2 (2Q^u_A + Q^d_A)^2}{{g_B}^2 (2Q^u_A + Q^d_A)^2}$$

- 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



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

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

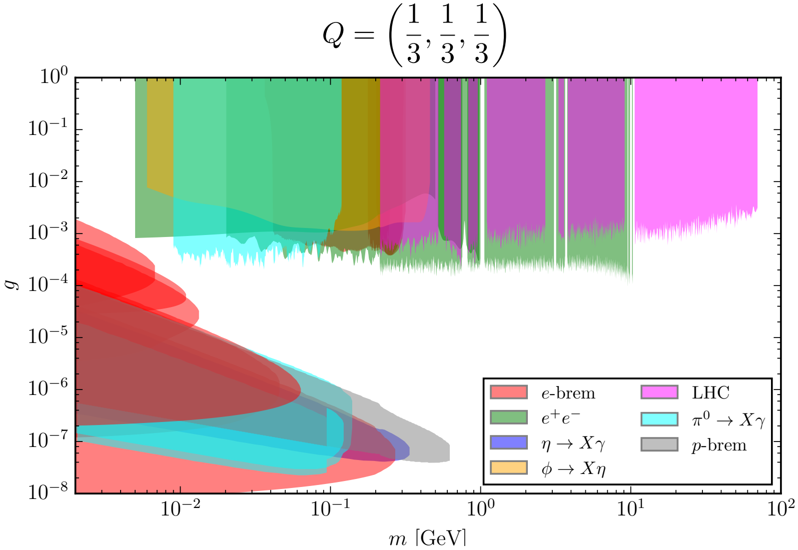
- for displaced beam-dump limits, relate t_0 and t_1

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

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

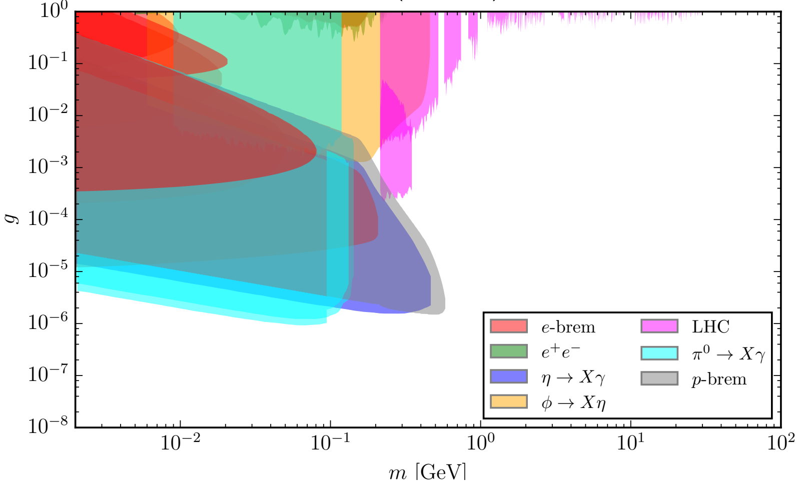
$$\sigma(m, g_{\mathrm{max}})\mathcal{B}(m)\varepsilon\left(\tau(m, g_{\mathrm{max}})\right) = \sigma(m, g_{\mathrm{min}})\mathcal{B}(m)\varepsilon\left(\tau(m, g_{\mathrm{min}})\right)$$

$B - L$ Boson


$Q = \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$
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]
e-brem
e^+e^-
$\eta \to X\gamma$
$\phi \to X\eta$
LHC
$\pi^0 \to X\gamma$
p-brem

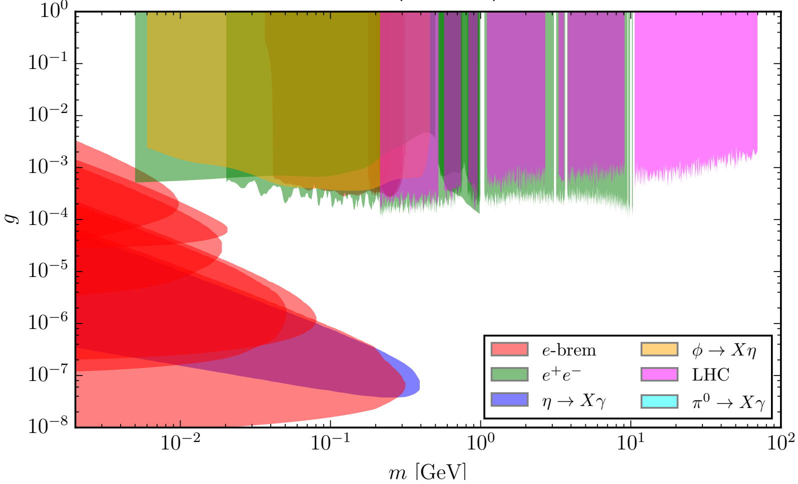
B Boson

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



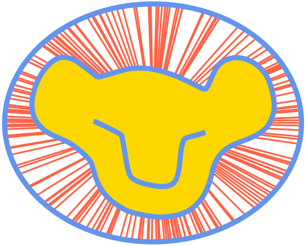
Protophobic Boson

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



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()
```