Search for Dark Photons at LHCb

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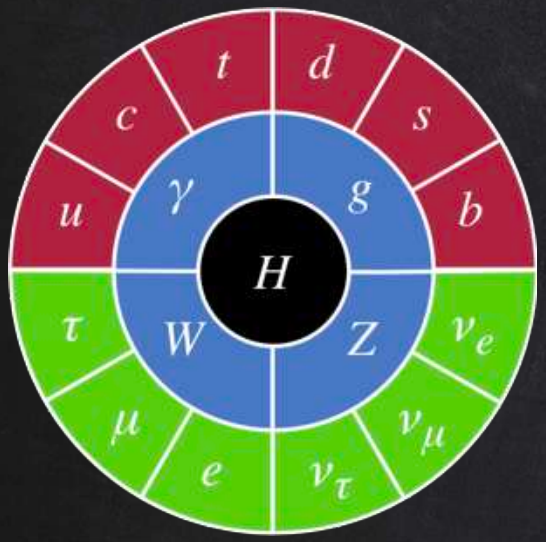
LHCP May 29th 2020

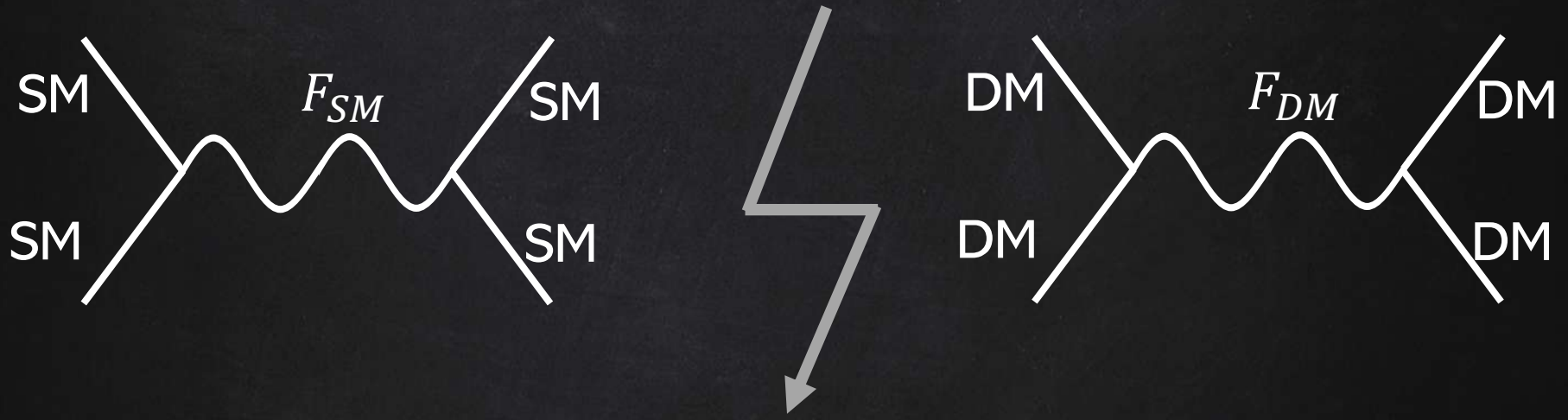
The Chasm



Lightest DM particle could be stable because it is (dark) charged

What if there is no connection between the SM and Dark Sector up to the Planck Scale?

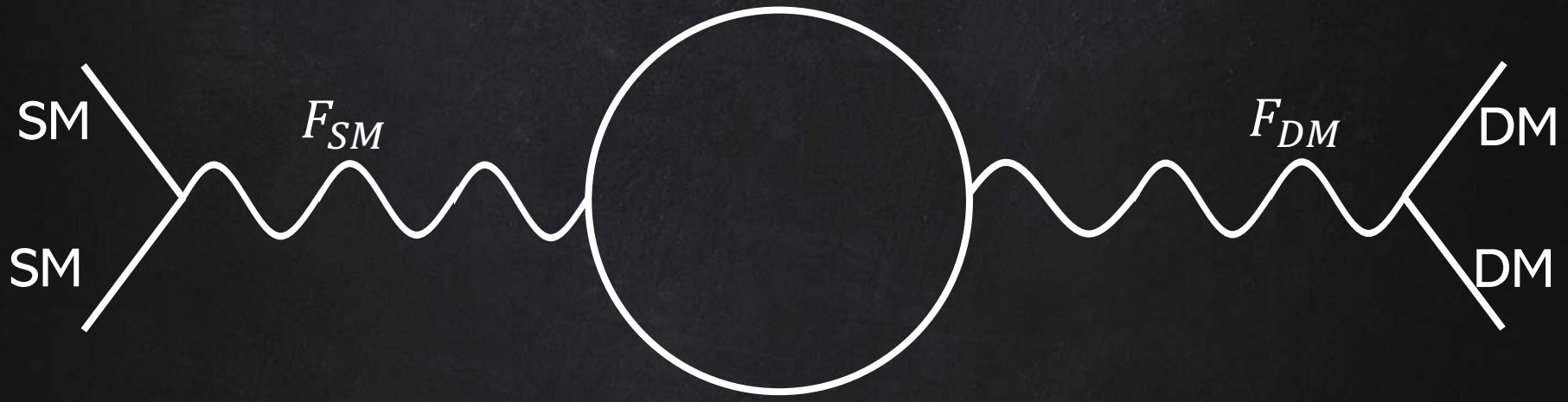
The Chasm



Lightest DM particle could be stable because it is (dark) charged

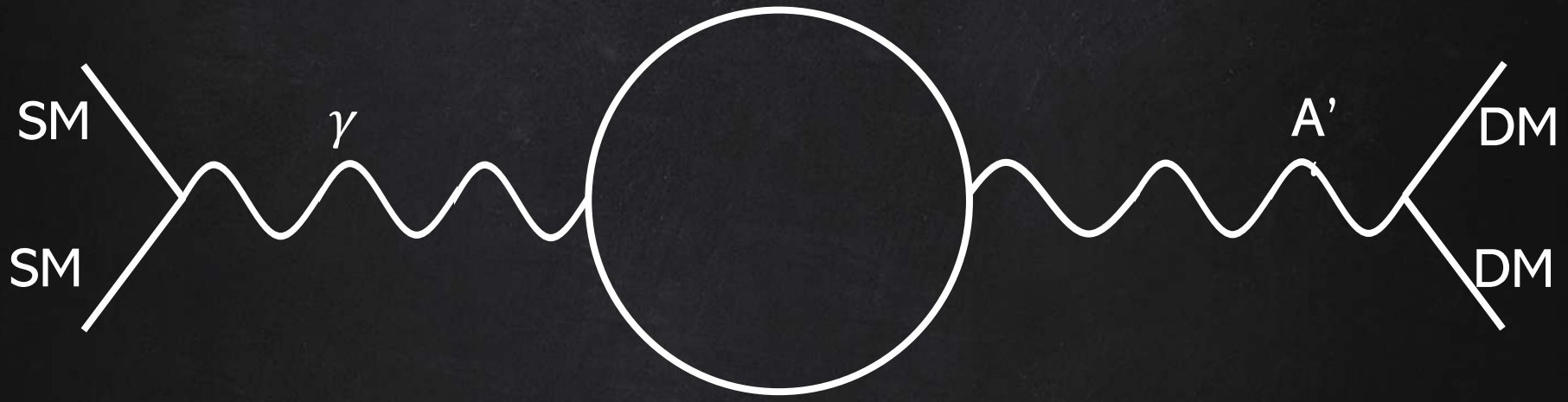
What if there is no connection between the SM and Dark Sector up to the Planck Scale?

Portals



The force carriers of the two sectors can couple if the sectors are somehow connected (even at a large mass scale).

Vector (Dark Photon) Portal

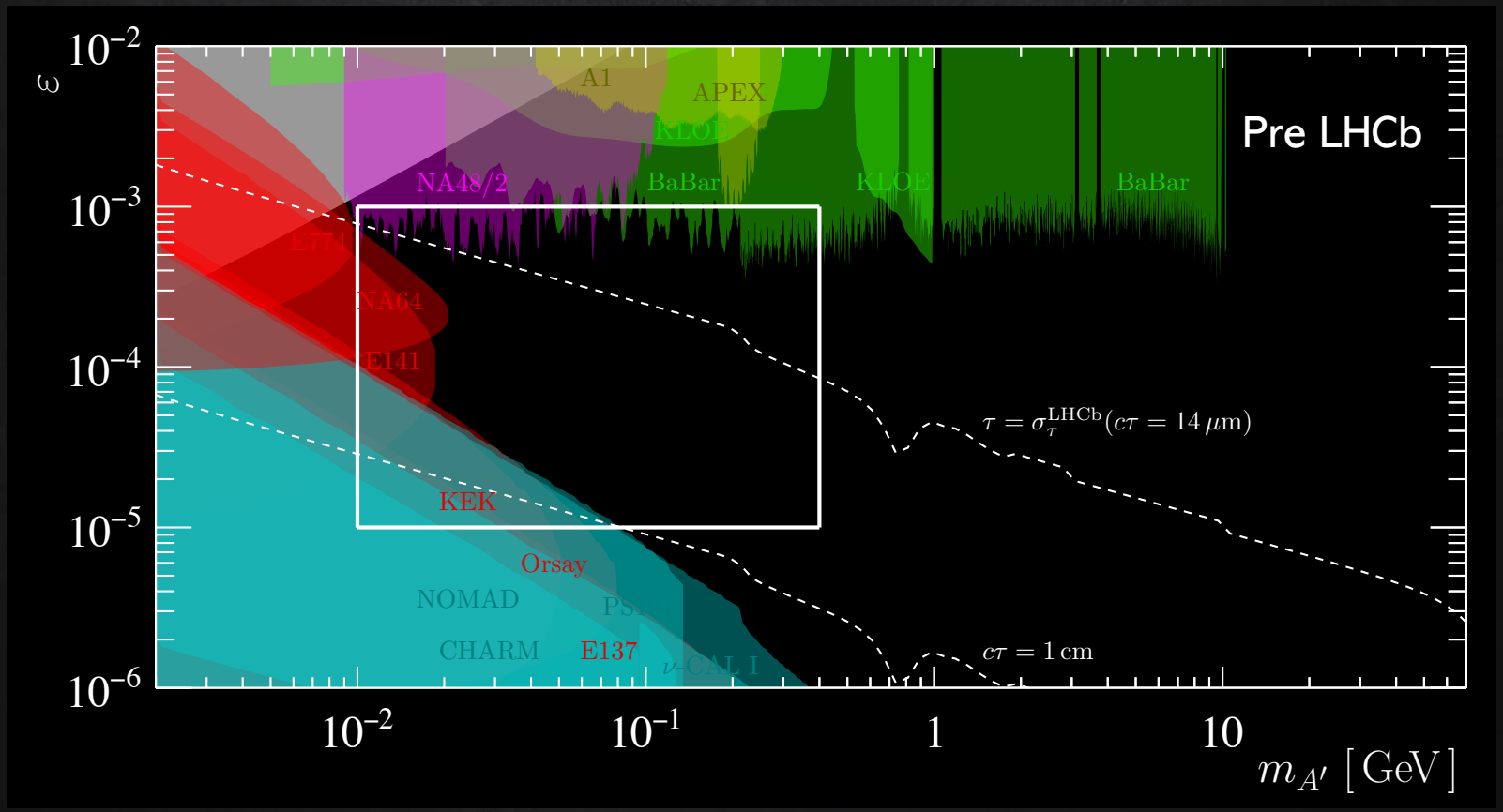


$$\alpha' = \epsilon^2 \alpha_{EM}$$

The dark photon mixes with the SM photon.
The coupling to SM particles is proportional to electric charge.

1 or 2 loops: naively $10^{-5} \lesssim \epsilon \lesssim 10^{-3}$

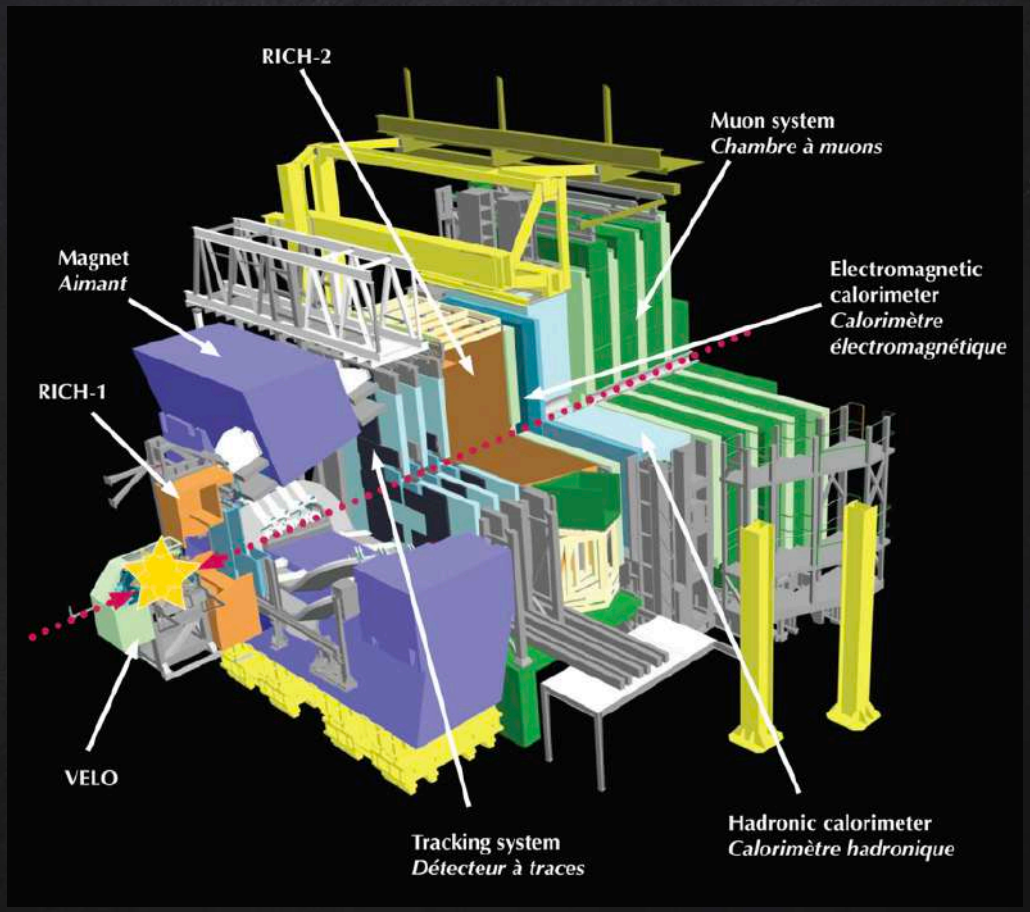
Visible A' Decays



DM-DM self interactions and 1 or 2 loop regime bound a naively interesting region.

Ilten et al. JHEP06 (2018) 004 [1801.04847]

LHCb



- Single-arm forward spectrometer ($2 < \eta < 5$; $1 < \theta < 15^{\circ}$)
- Excellent lifetime ($\sigma_\tau = 45 fs$) and mass ($\sigma_m = 0.4\%$) resolution
- Unique particle ID and flexible triggering.

LHCb, JINST 3 (2008) S08005

LHCb Int.J.Mod.Phys. A 30 (2015) 1530022 [1412.6352]

LHCb Inclusive A' $\rightarrow \mu^+ \mu^-$

Production: Pseudoscalar Meson Decay, Drell Yan, …

1. Count A' Candidates
2. Compare to Prompt γ^*
3. Set Limits / Claim Discovery

$\Rightarrow$ Fully Data-driven Search

Ilten et al. PRL 116, 251803 (2016) [1603.08926]

Prompt Backgrounds

1. $\gamma^* \to \mu^+\mu^-$ production [Irreducible]
2. Resonant decays to $\mu^+\mu^-$ [Veto these regions]
3. Various types of misreconstruction:

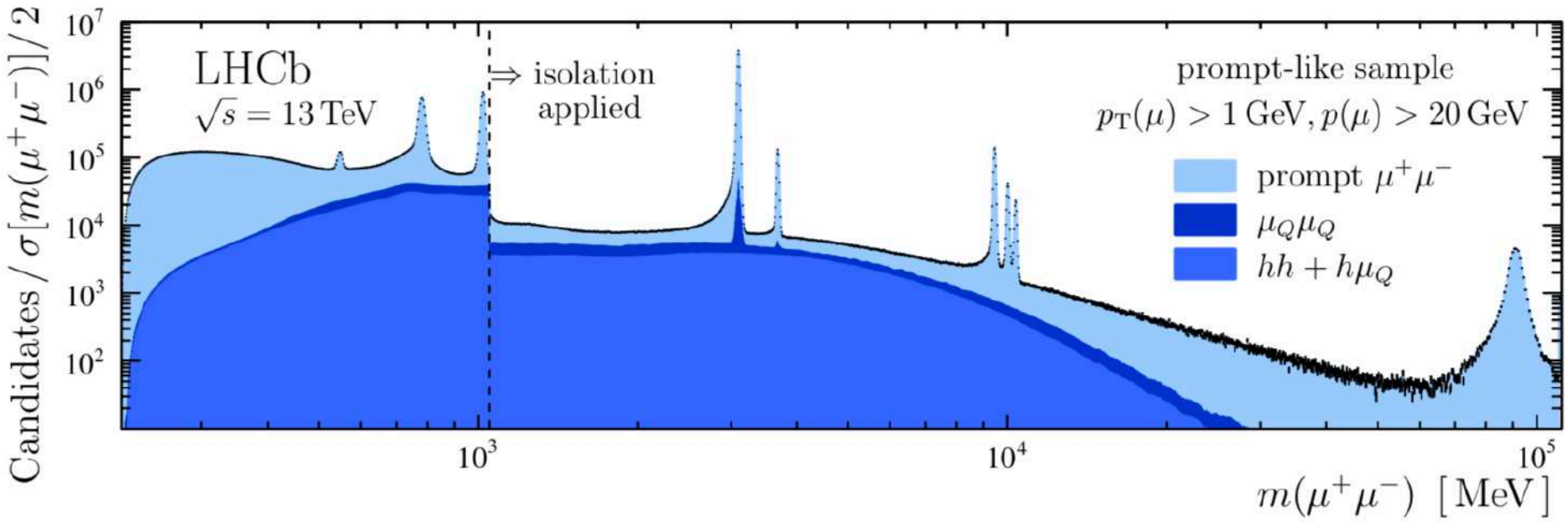
Muons from heavy-flavor quark decays misreconstructed as prompt [Fits]

Double misidentification of prompt hadrons as muons [$\mu^{\pm}\mu^{\pm}$ sample]

A mix of these two [$\mu^{\pm}\mu^{\pm}$ sample]

Above $m'_A > 1.1\ GeV$ misreconstruction still dominates. [Isolation]

Dimuon Spectrum



2016 only plot

LHCb PRL 120 (2018) 061801 [1710.02867]

Prompt Strategy

Compare to bump hunt

What we fit for normalisation

Efficiency Ratio = 1 for $\tau'_A \ll$ resolution

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

What we set limits on

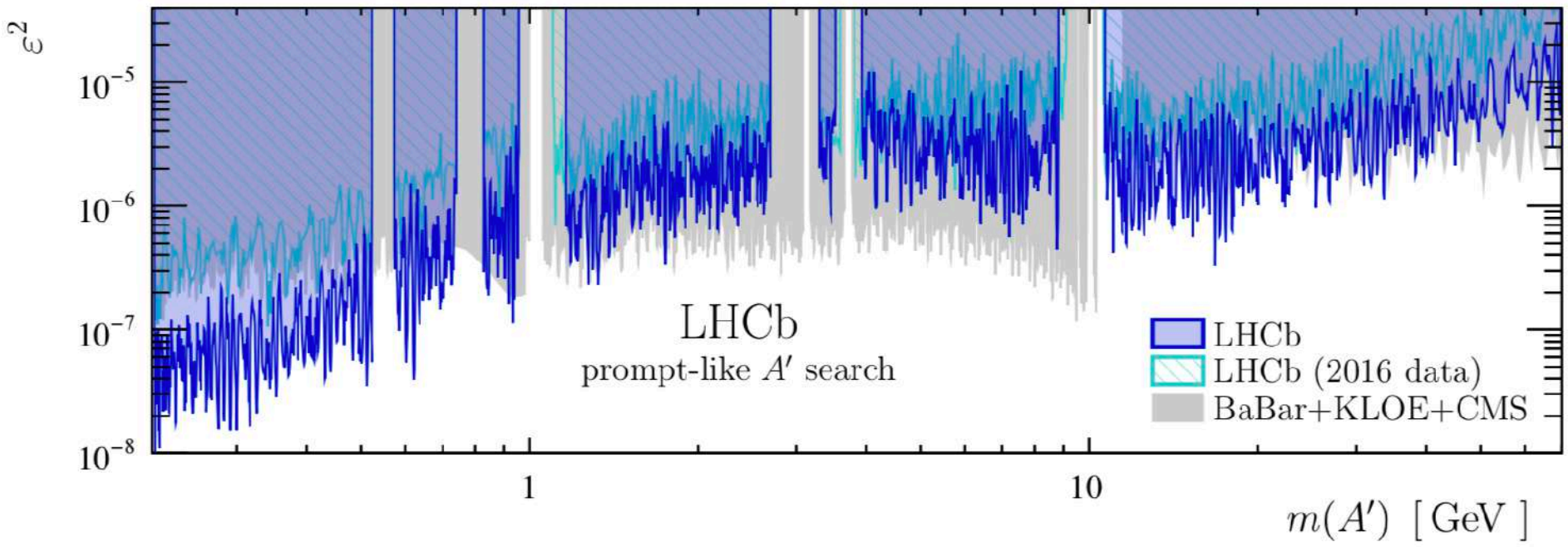
Known factors

No knowledge of the detector efficiency or luminosity is needed.

Anywhere but close to the Z mass

Prompt Results

Run 2 90% CL prompt exclusion limits from dimuon threshold to 70 GeV



This analysis produces the most stringent constraints on dark photons with 214 < m(A′) < 740 MeV and 10.6 < m(A′) < 30GeV.

LHCb PRL 124 (2020) 041801 [1910.06926]

Displaced Backgrounds

1. B-hadron decay chains that produce two muons

[Require decay topology to be consistent with a 2-body long-lived particle decay that originated at a PV ;
Rejected if selected by inclusive heavy-flavor software trigger + BDT classifiers]

2. $K_S^0 \to \pi^+\pi^-$ tail

[This limits the mass range for the displaced search.
Subtracted by extrapolation]

3. Photon conversions to μ+μ− in the silicon-strip vertex detector

[Rejected by material veto tool]

Prompt Strategy

Compare to bump hunt

What we fit for normalisation

Efficiency Ratio = 1 for $\tau'_A \ll$ resolution

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

What we set limits on

Known factors

Anywhere but close to the Z mass

Displaced Strategy

Compare to fit

Still using the prompt fits

No longer 1; determined by data-driven resampling

~~Compare to bump hunt~~

What we fit for normalisation

Efficiency Ratio = 1 for $\tau'_A \ll$ resolution

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

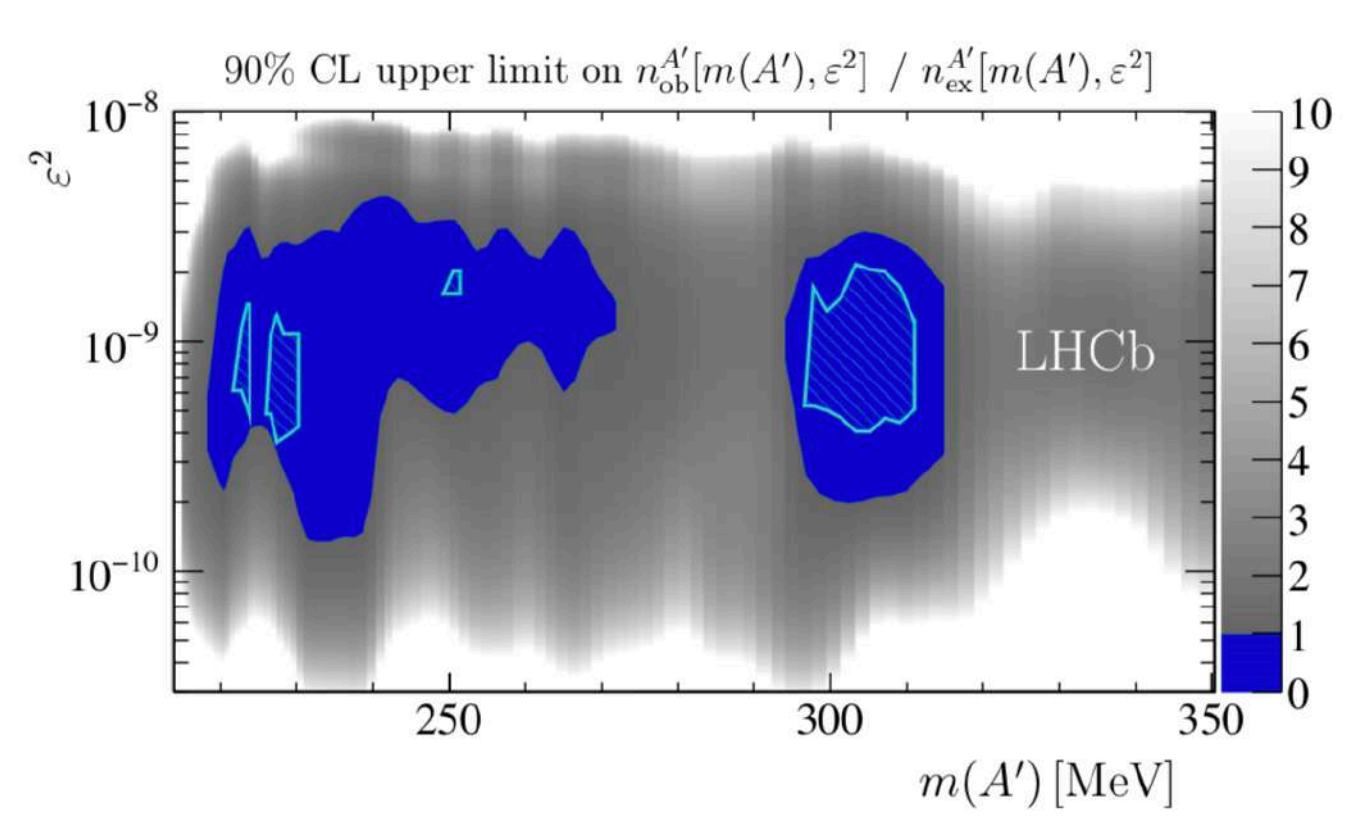
What we set limits on

Known factors

Anywhere but close to the Z mass

Displaced Results

Ratio of the observed upper limit on $n^{A'}[m(A'), \epsilon^2]$ at 90% CL to the expected dark photon yield, $n^{A'}_{\text{ex}}[m(A'), \epsilon^2]$

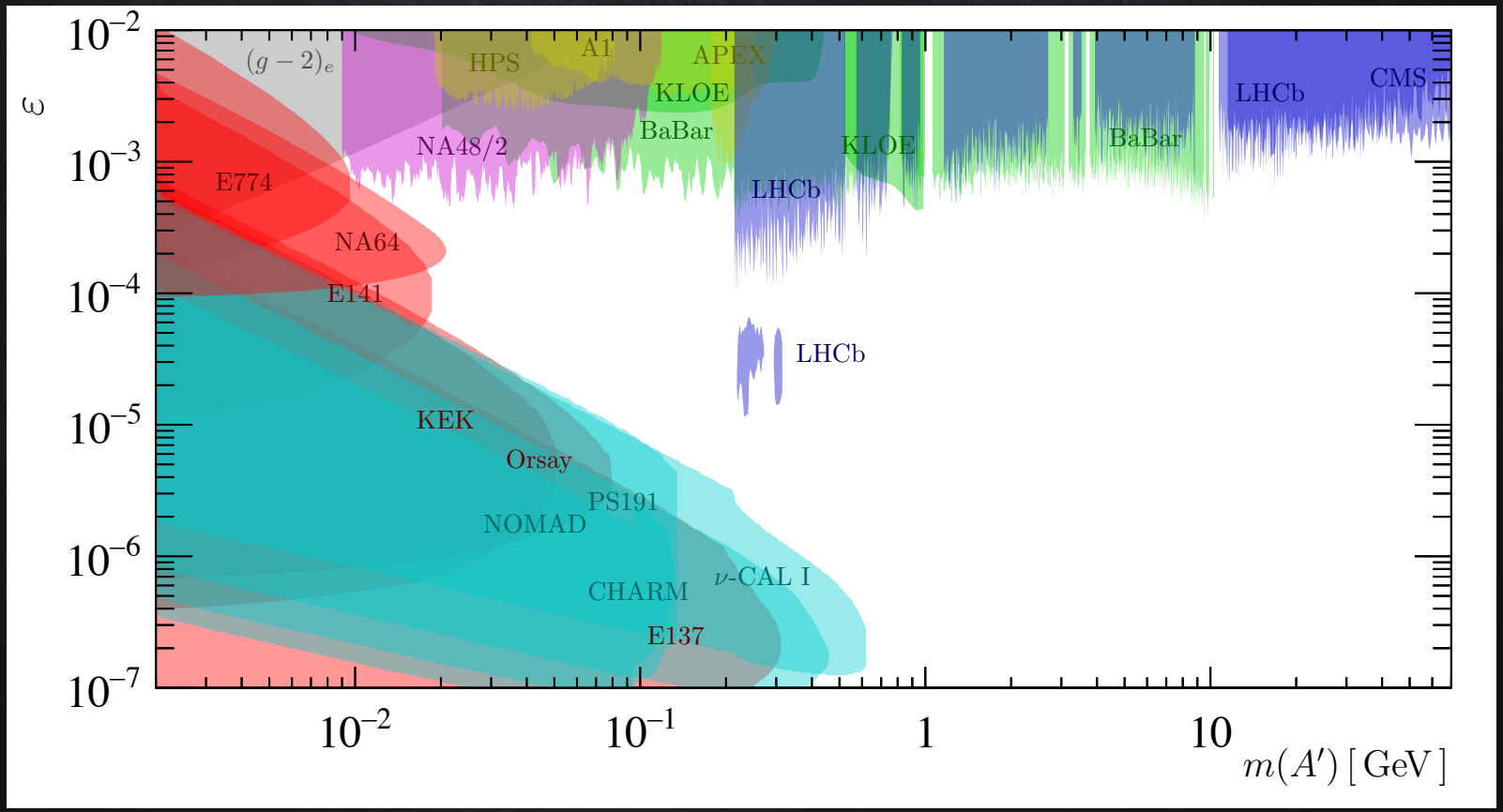


Regions less than unity are excluded.
Almost all regions are close to exclusion.

LHCb PRL 124 (2020) 041801 [1910.06926]

LHCb Limits: Run 2 Data

Significantly larger regions of space ar expected to be covered in run 3.



Can recast as searches for other vector models (B, B-L, protophobic, …)

LHCb PRL 124 (2020) 041801 [1910.06926]
ϒ: LHCb JHEP 8 (2018) 147 [1805.09820]

Ilten et al. JHEP06 (2018) 004 [1801.04847]

Non-Minimal Searches

Probe additional dark matter scenarios by

- Relaxing kinetic mixing assumption
- Applying extra cuts for dedicated searches

Now need to

- Calculate absolute efficiencies and luminosity
- Provide results in bins of mass and p_T

Non-Minimal Searches

NEW

Prompt:

Inclusive

Beauty Associated

Displaced:

Promptly produced

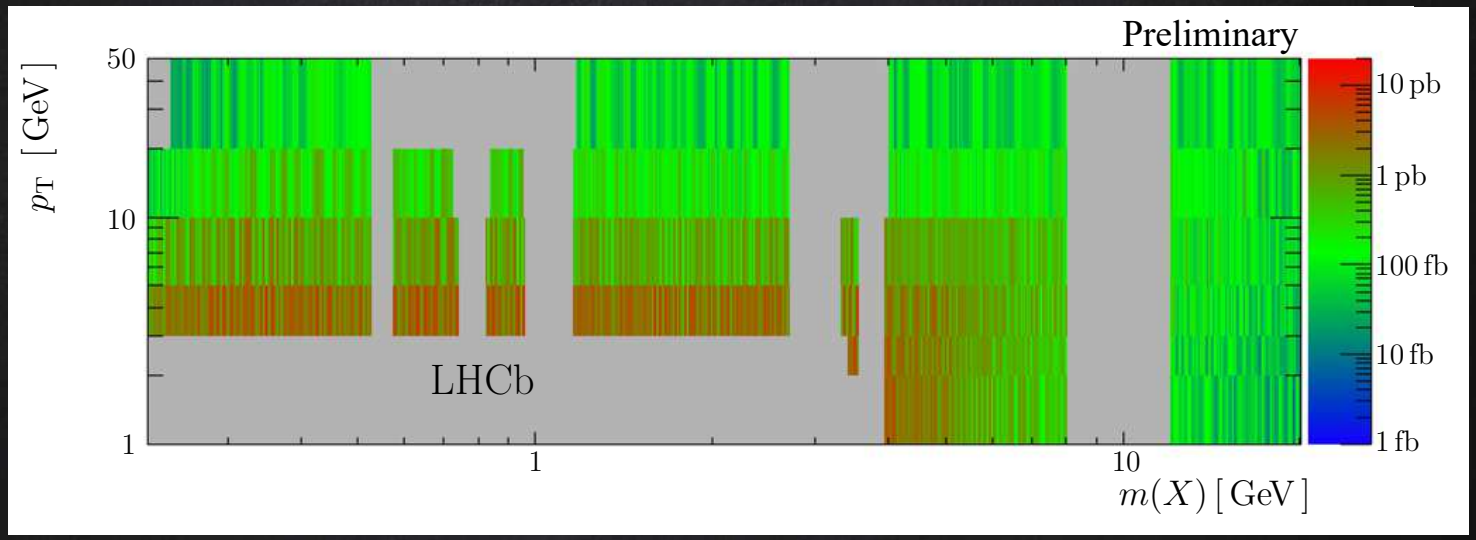
Inclusive

No signal found!

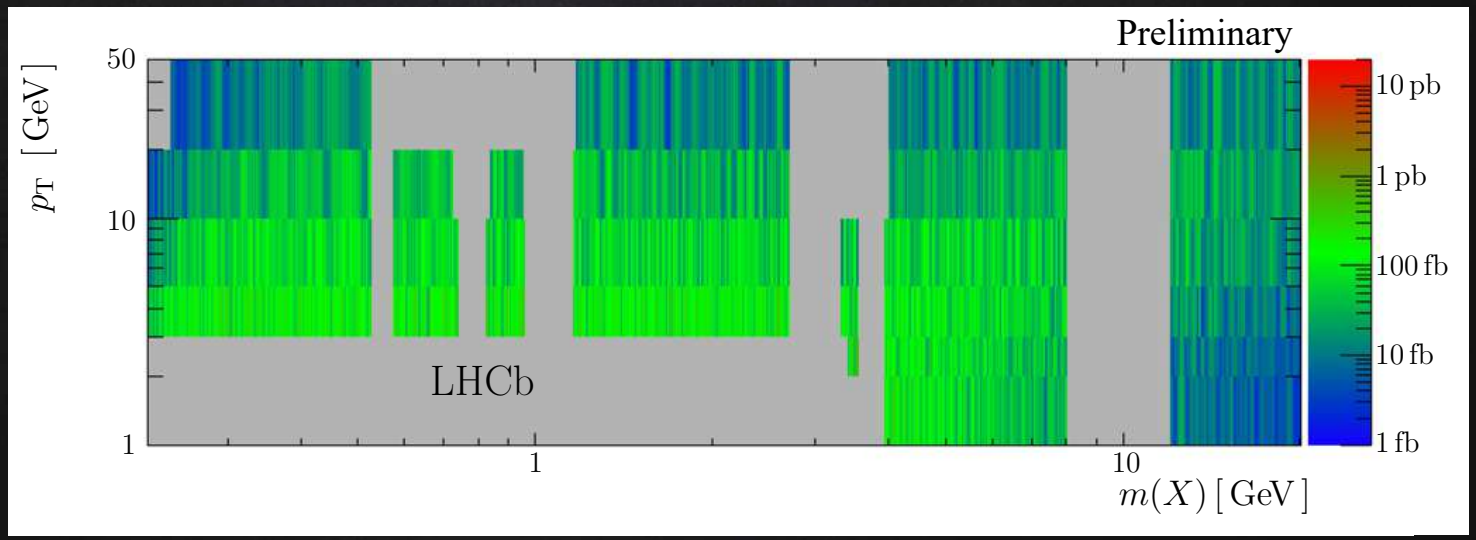
Prompt Non-Minimal Results

NEW

Inclusive



Beauty Associated



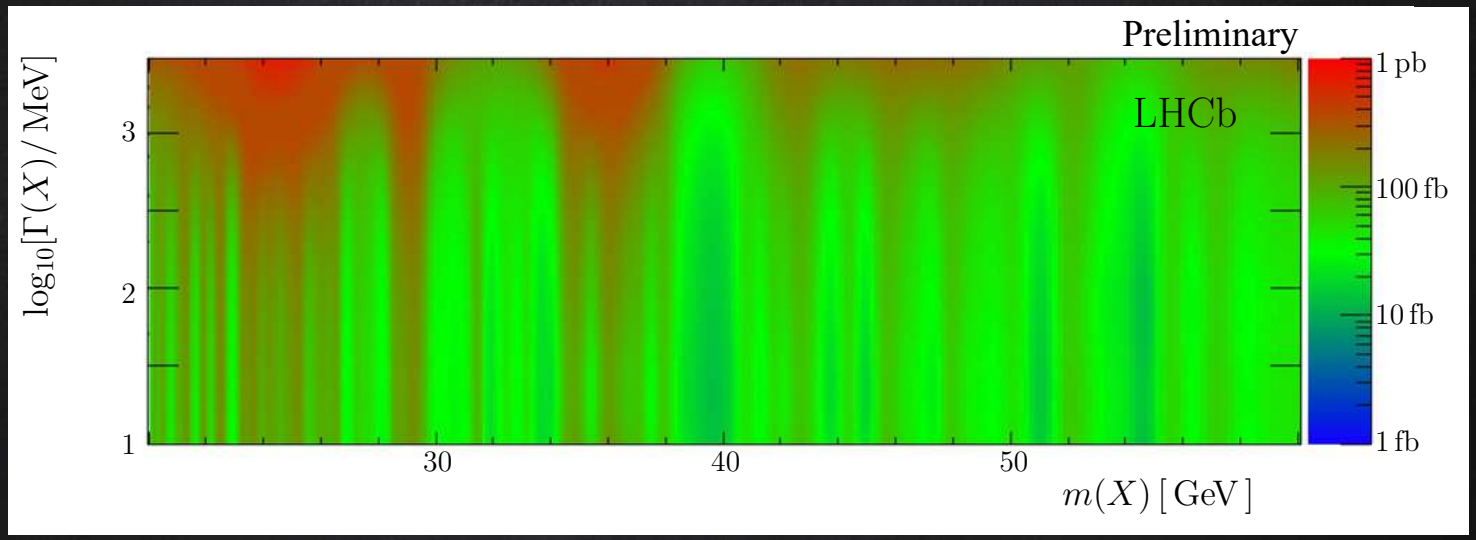
Low mass upper limits at 90% CL on $\sigma(X \to \mu^+\mu^-)$

LHCb-PAPER-2020-013 in preparation

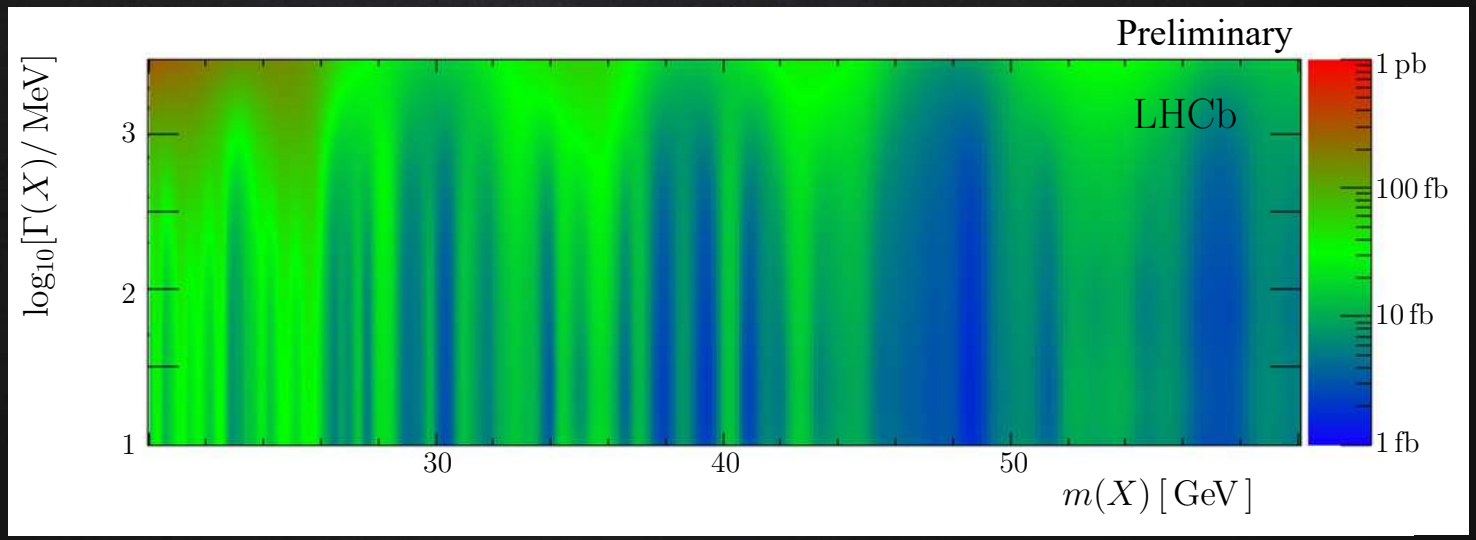
Prompt Non-Minimal Results

NEW

Inclusive



Beauty Associated



Non-zero Gamma at higher masses considered

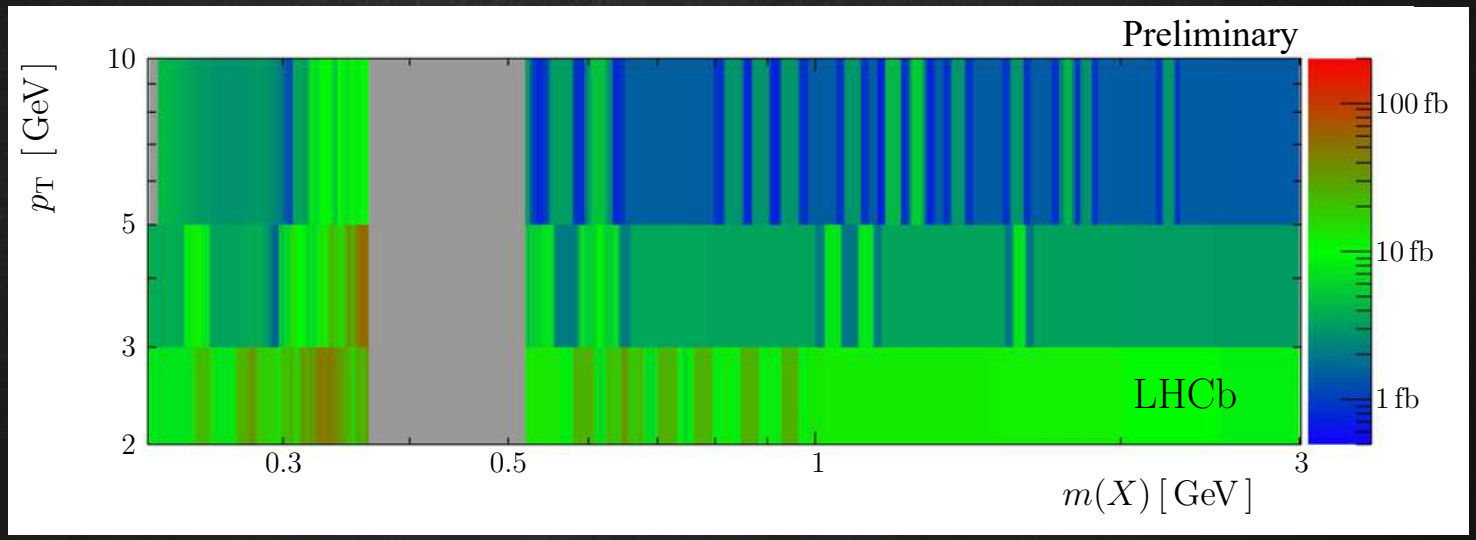
High mass upper limits at 90% CL on $\sigma(X \to \mu^+\mu^-)$

LHCb-PAPER-2020-013 in preparation

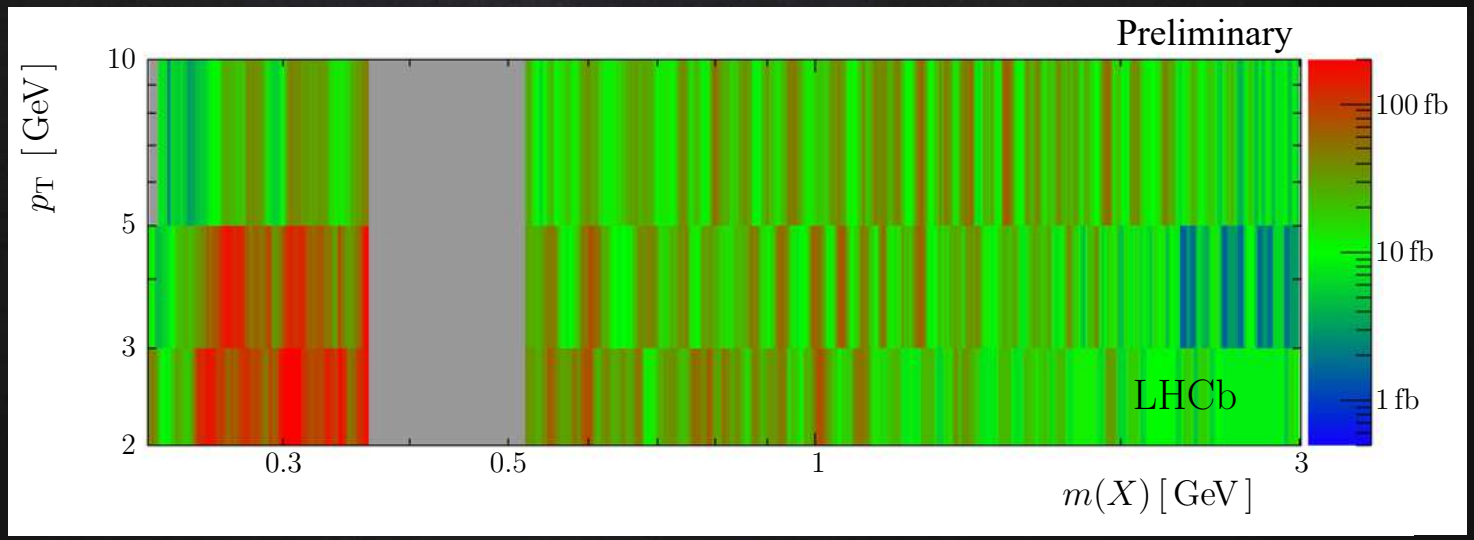
Displaced Non-Minimal Results

NEW

Promptly Produced



Inclusive

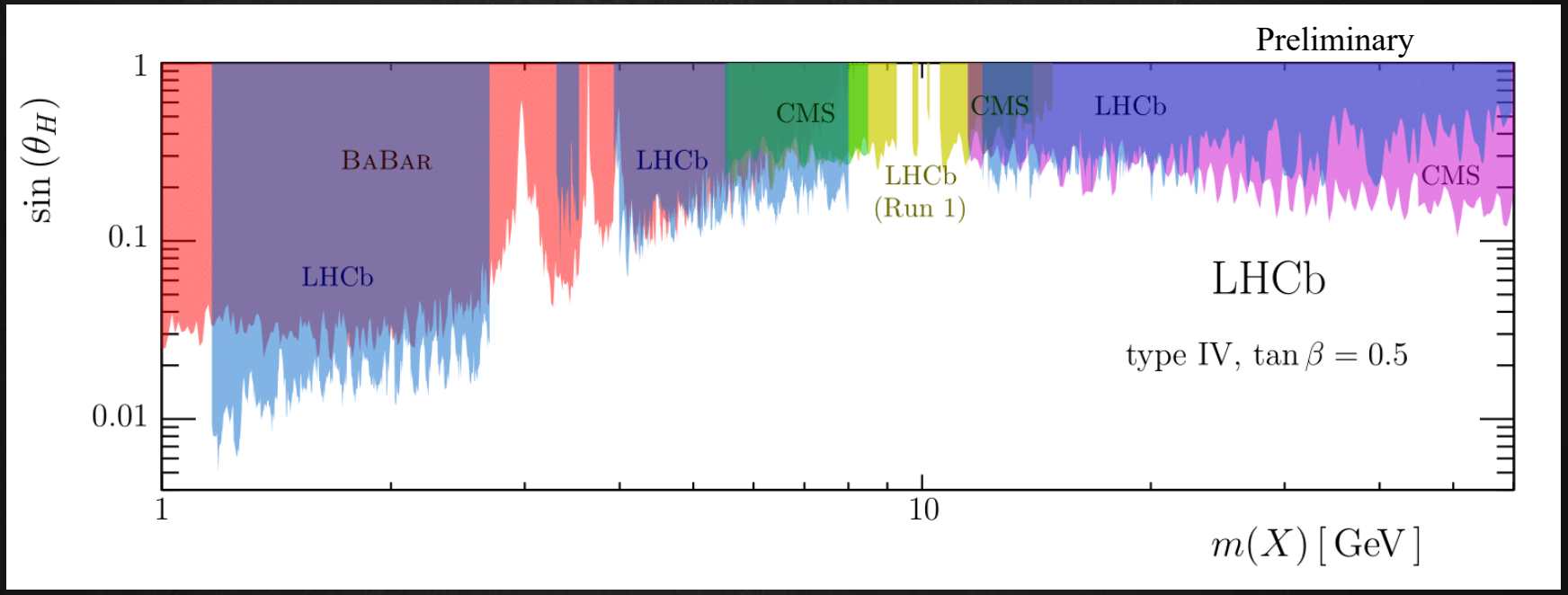


Upper limits at 90% CL on $\sigma(X \to \mu^+\mu^-)$

LHCb-PAPER-2020-013 in preparation

Two-Higgs Doublet

NEW



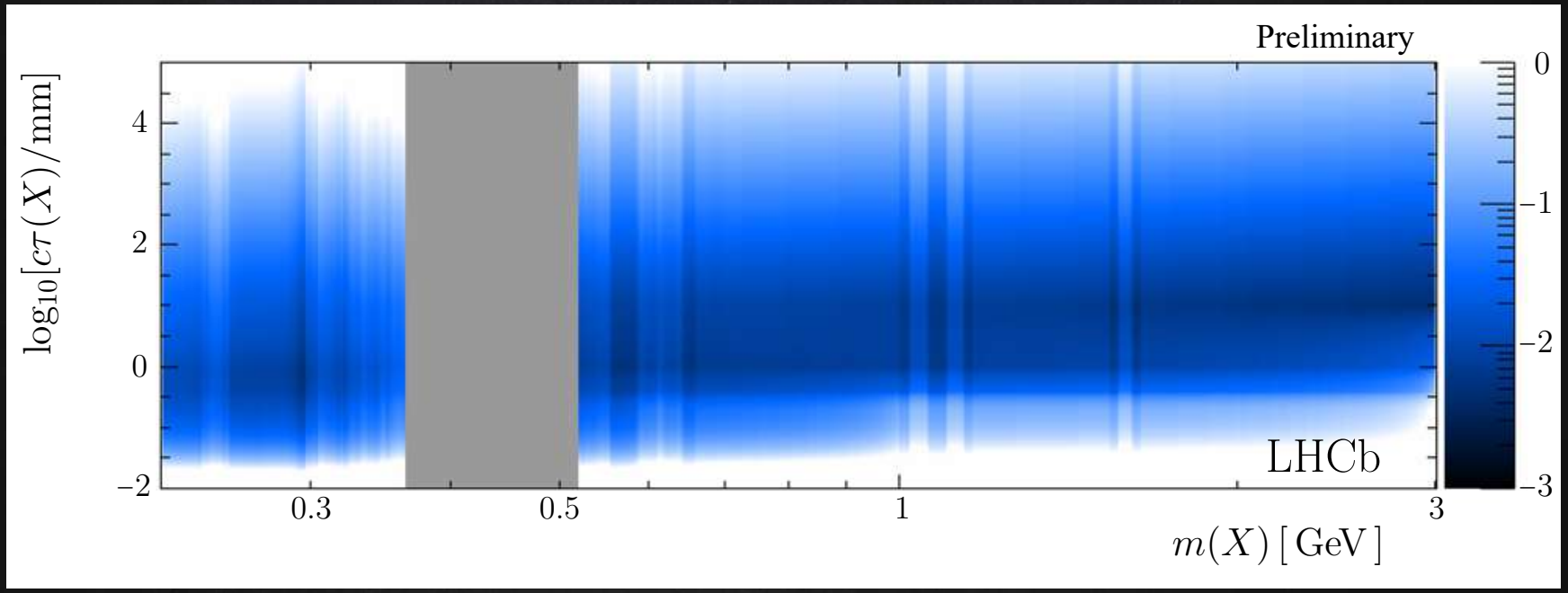
Upper limits at 90% CL on X–H mixing angle for the 2HDM scenario

Phys. Rev. D 93, 055047 (2016) [1601.05110]

LHCb-PAPER-2020-013 in preparation

Hidden Valley

NEW



Upper limits at 90% CL on γ Z_{HV} kinetic mixing strength for the HV scenario

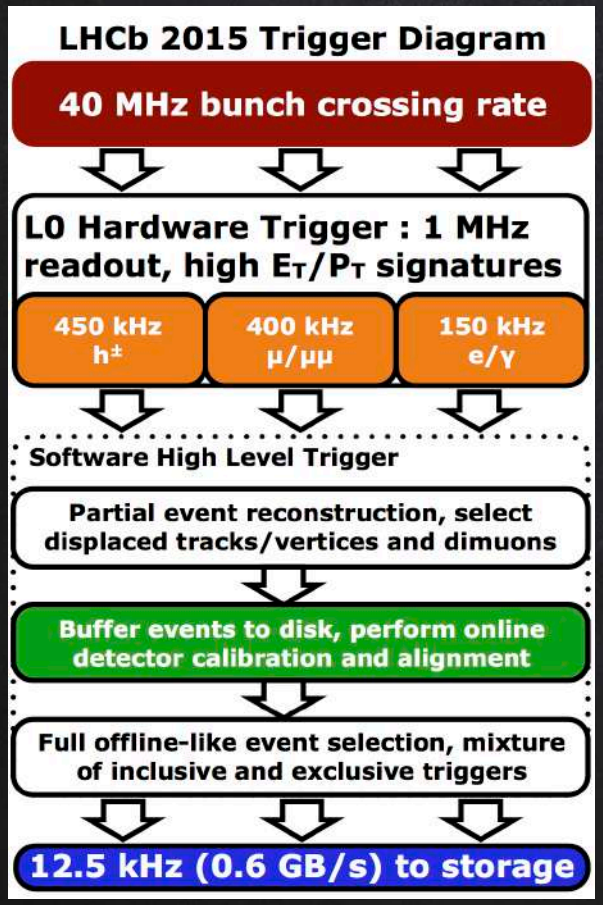
Dark Sectors are dark matter scenarios worth exploring

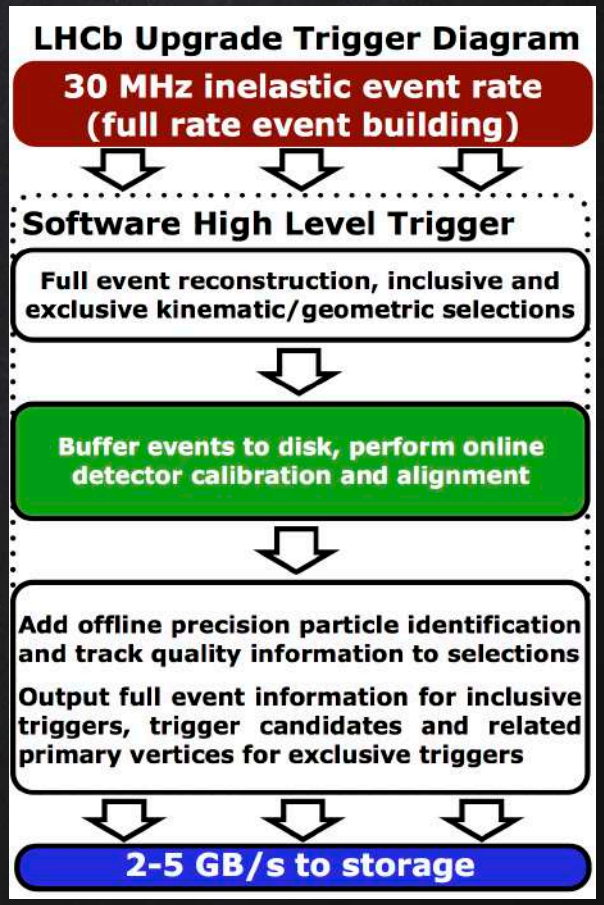
LHCb has world leading sensitivity to different models

Non-Minimal Fiducial Regions

all searches
$p_{\mathrm{T}}(\mu) > 0.5\,\mathrm{GeV}$, $10\,\mathrm{GeV} < p(\mu) < 1\,\mathrm{TeV}$, $2 < \eta(\mu) < 4.5$, $\sqrt{p_{\mathrm{T}}(\mu^+) p_{\mathrm{T}}(\mu^-)} > 1\,\mathrm{GeV}$
$5 \leq n_{\mathrm{charged}}(2 < \eta < 4.5, p > 5\,\mathrm{GeV}) < 100$ (from same PV as $X \to \mu^+\mu^-$)
prompt-like $X \to \mu^+\mu^-$ decays
$1 < p_{\mathrm{T}}(X) < 50\,\mathrm{GeV}$, X proper decay time $< 0.1\,\mathrm{ps}$, $\alpha(\mu^+\mu^-) > 1\,\mathrm{mrad}$
$20 < p_{\mathrm{T}}(b\text{-jet}) < 100\,\mathrm{GeV}$, $2.2 < \eta(b\text{-jet}) < 4.2$ ($X + b$ only)
displaced $X \to \mu^+\mu^-$ decays
$2 < p_{\mathrm{T}}(X) < 10\,\mathrm{GeV}$, $2 < \eta(X) < 4.5$, $\alpha(\mu^+\mu^-) > 3\,\mathrm{mrad}$, $12 < \rho_{\mathrm{T}}(X) < 30\,\mathrm{mm}$

LHCb Trigger





A flexible triggering scheme is needed to select low energy candidates.

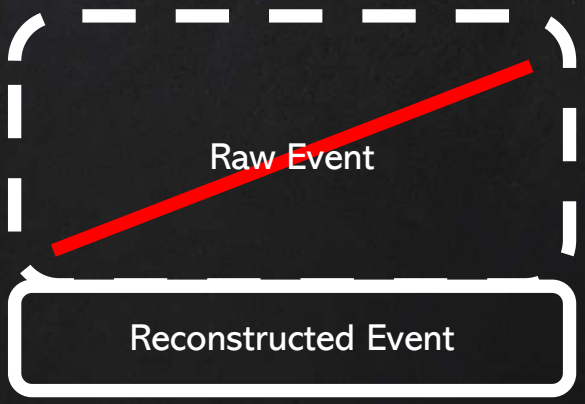
CERN-LHCb-DP-2019-001
JINST 14 (2019) P04013 [1812.10790]

Turbo

Full Stream

10 kHz
~70 kB per event
700 Mb/s output rate

Turbo Stream



2.5 kHz
~5 kB per event
12.5 Mb/s output rate

LHCb Inclusive A' $\rightarrow \mu^+ \mu^-$

Two oppositely charged tracks with good-quality vertex satisfying stringent muID

p_T(A') > 1GeV; 2 < η(μ) < 4.5; p_T((μ) > 0.5 GeV; p(μ) > 10 GeV

Prompt

Dimuons originating from a PV

p_T(μ+) p_T(μ−) > 1.0 GeV²

Isolation for $m'_A > 1.1\ GeV$

No Shared Muon Hits

Displaced

Displaced A' originating from a PV

2 < η(A') < 4.5

Heavy Flavor Veto

Material Veto

Numbers for 2017–2018, tighter for 2016

Prompt Normalisation

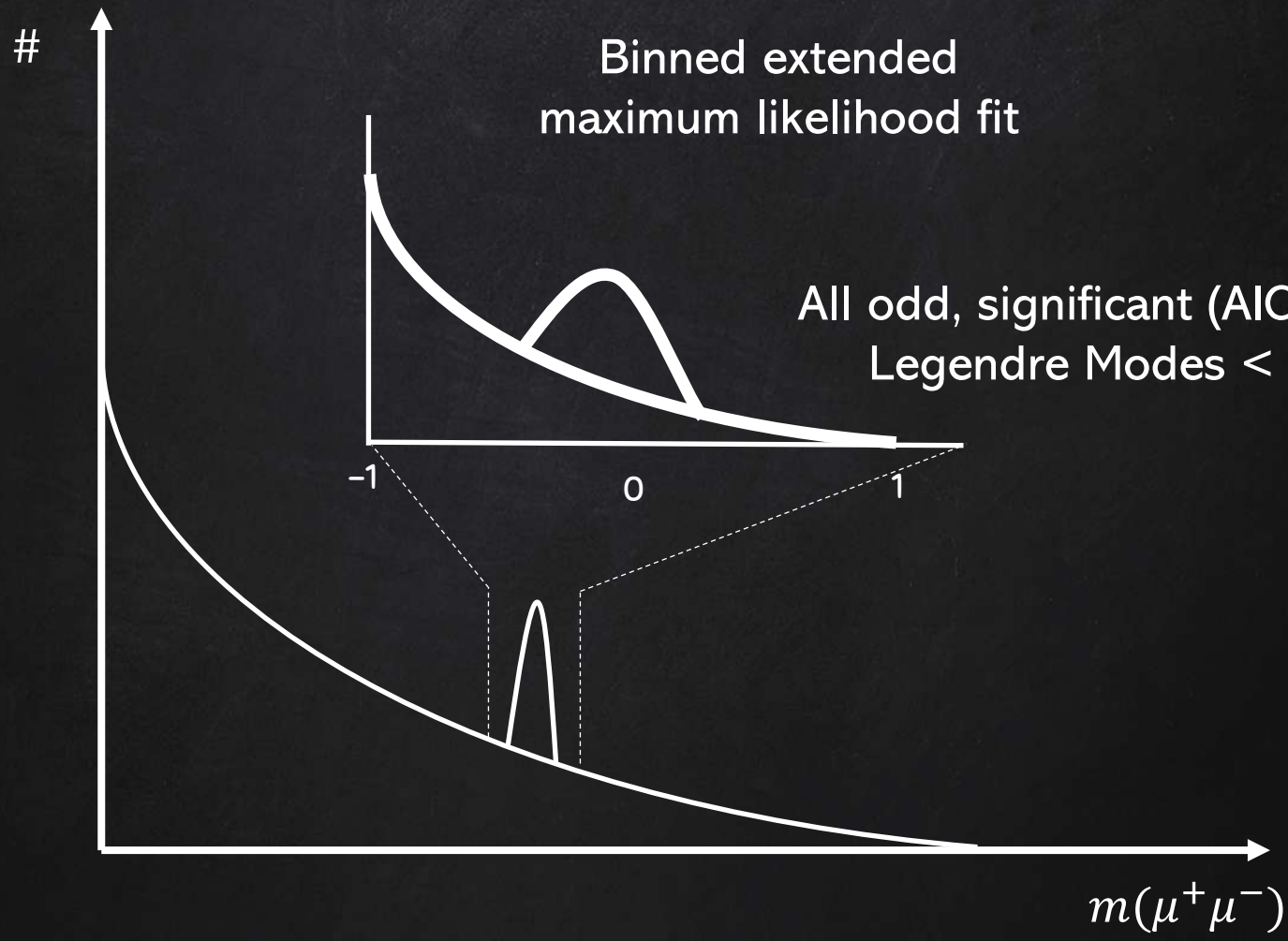
Determine observed off-shell photon yield:

1. Estimate misID background by subtracting $\mu^{\pm}\,\mu^{\pm}$ yields

2. Estimate heavy flavor background by performing binned extended maximum likelihood fits to the $\min[\chi^2 IP(\mu^{\pm})]$ distributions

$\chi^2_{\mathrm{IP}}(\mu^{\pm})$: difference in the vertex-fit χ^2 when the PV is reconstructed with and without the muon

Bump Hunt

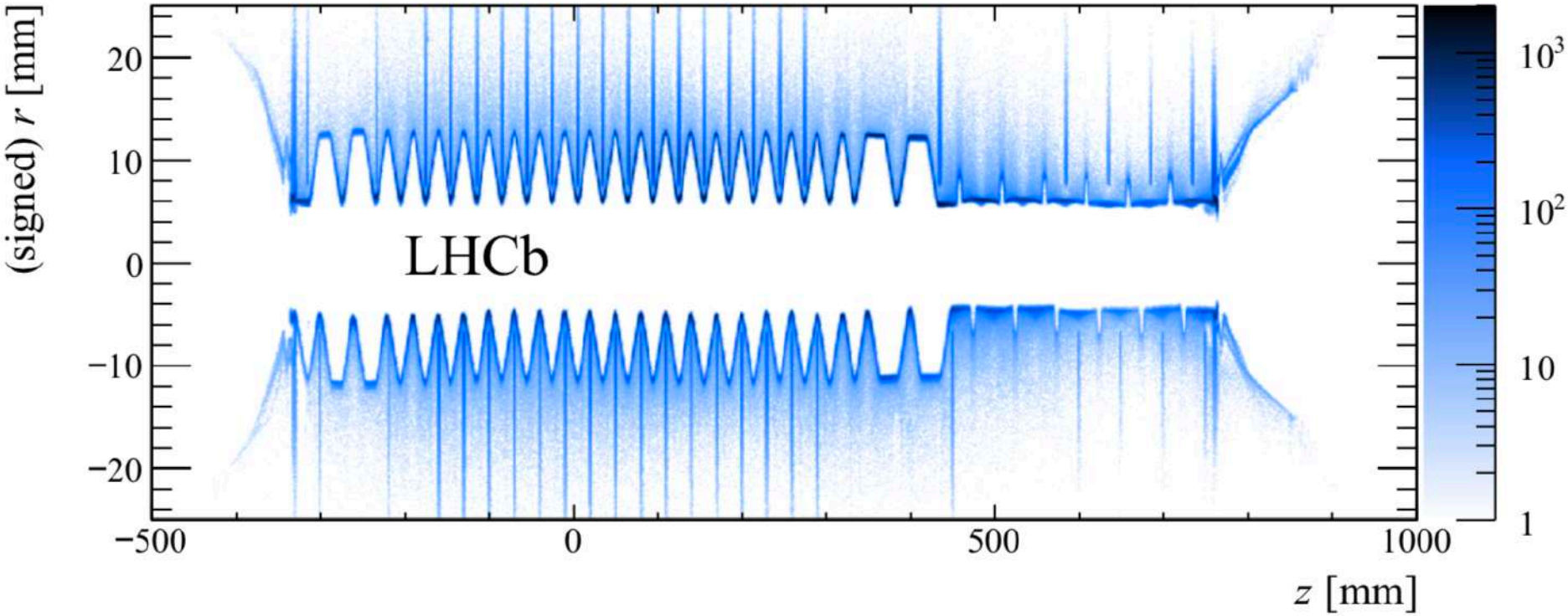


No significant access found

JINST 12, P09034 (2017) [1705.03578]

Velo Material Map

High-precision material map produced from secondary hadronic interactions

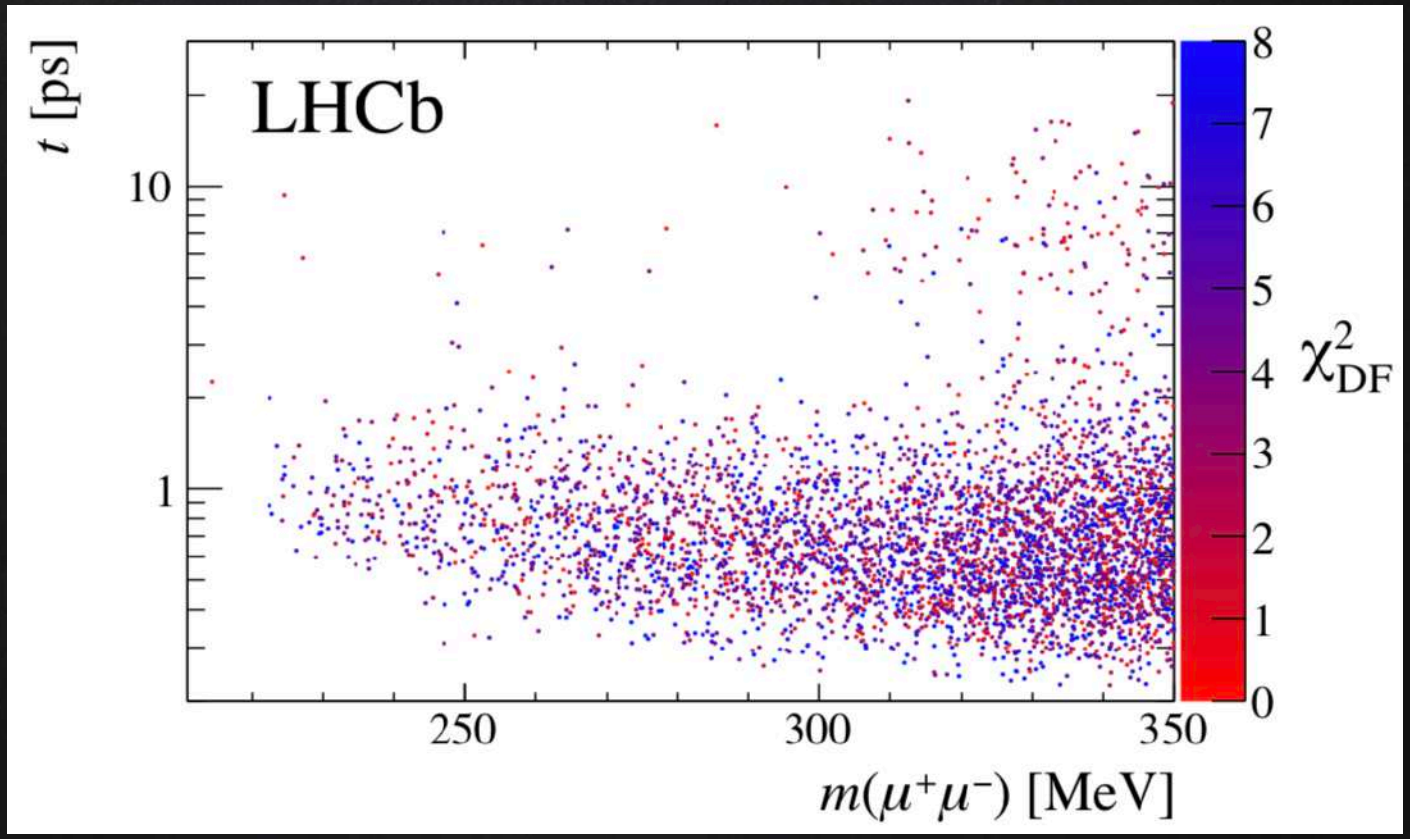


A p-value is assigned to the photon-conversion hypothesis for candidate
A m(A') dependent cut is applied on this p-value.

JINST 13, P06008 (2018) [1803.07466]

Displaced Fits

3D binned extended maximum likelihood fits
Templates are derived from control samples.
Conversions are extrapolated from candidates rejected by cut.



For visible decays $\tau(A') \propto \frac{1}{m(A')\epsilon^2}$: $n^{A'}[m(A'), \tau(A')]$ -> $n^{A'}[m(A'), \epsilon^2]$

Most significant excess: 2 σ

PRL 124, 041801 (2020) [1910.06926]

Non-Minimal Prompt Norm

Simulation
Tag & Probe

$J/\psi \to \mu^+\mu^-$
Tag and Probe

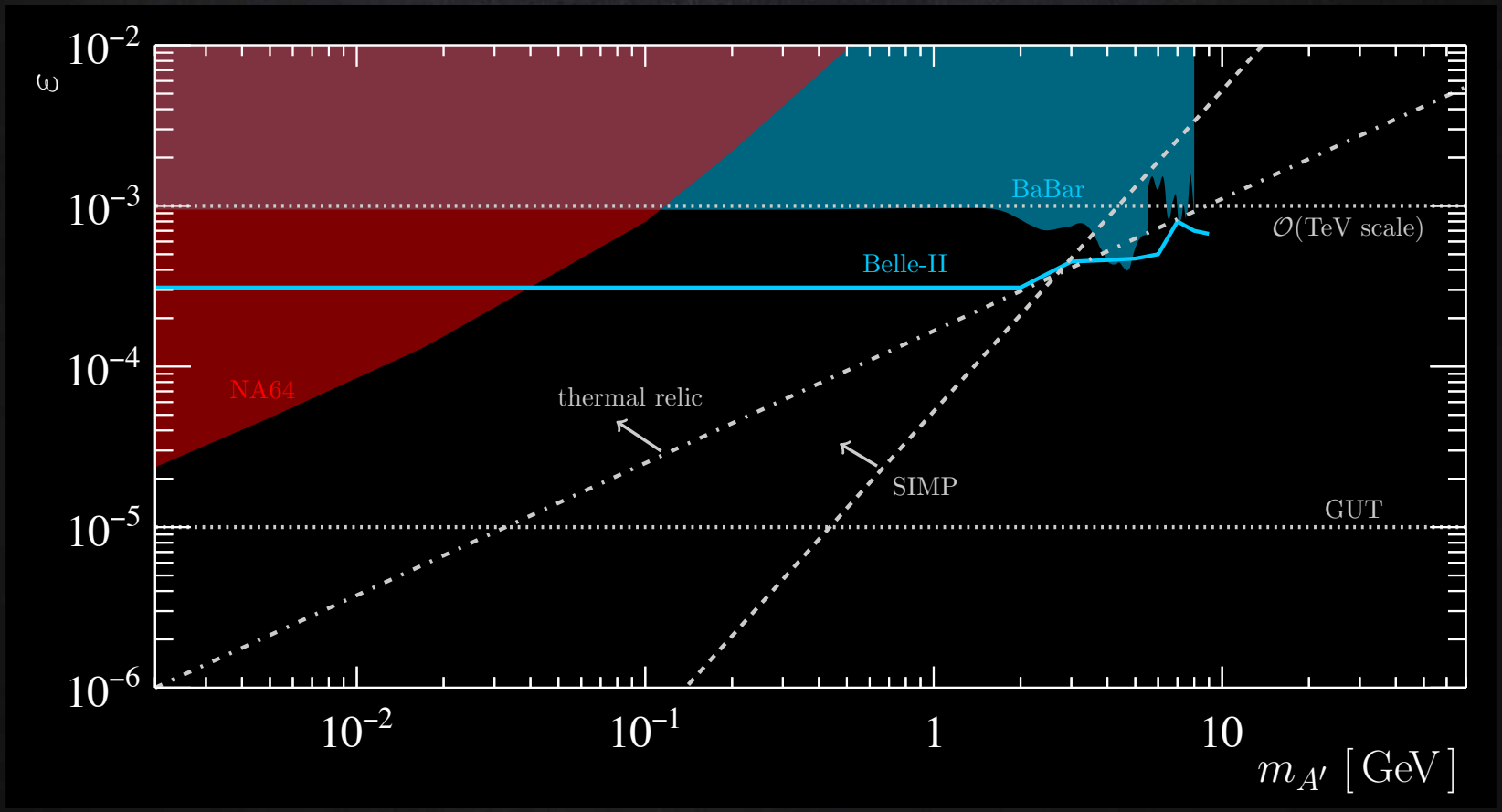
$$\varepsilon(A' \to \mu^+\mu^-) = \varepsilon_{\text{reco}}(\mu^+)\varepsilon_{\text{reco}}(\mu^-)\varepsilon_{\text{L0}}(\mu^+\mu^-)\varepsilon_{\text{PID}}(\mu^+)\varepsilon_{\text{PID}}(\mu^-)\varepsilon_{\text{sel}}(\mu^+\mu^-),$$

$J/\psi \to \mu^+\mu^-$
TIS TOS

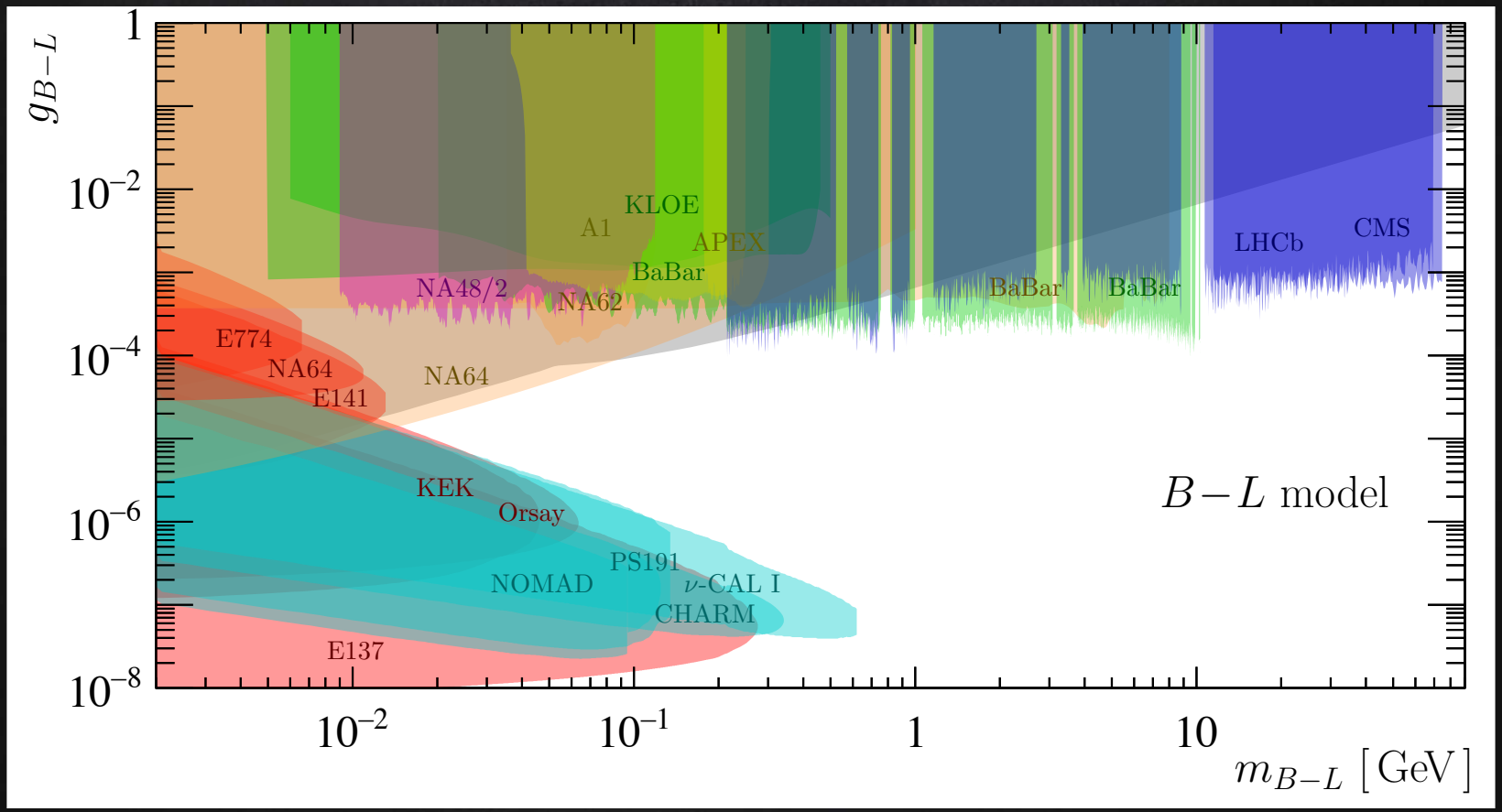
Various Known efficiencies

No official luminosity calibration
-> use reconstructed $Z \to \mu^+\mu^-$

Invisible A' Decays



Serendipity in A' Searches



Accounting for production, branching ratio and detection efficiency, existing and future searches can be recast to any vector model.

Recasting A' as any Vector

	l	nu	u type	d type
A'	$-g_e$	0	$\frac{2g_e}{3}$	$-\frac{g_e}{3}$
B	$-\left(\frac{g_e}{4\pi}\right)^2$	0	$\frac{1}{3}$	$\frac{1}{3}$
B-L	-1	-1	$\frac{1}{3}$	$\frac{1}{3}$
Proto phobic	-1	0	$-\frac{1}{3}$	$\frac{2}{3}$

Ilten, Soreq, Thaler, Williams, Xue [1801.04847]