Dark sectors searches at high-intensity colliders

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There exist only three (four?) portals:

1. The dark photon portal, thanks to which a new (generically) massive photon and the Z-boson of the SM

2. The Higgs portal, thanks to which a new dark scalar will interact with the Higgs of the SM. This portal can also induce the mixing of the dark scalar with the SM Higgs

3. The neutrino portal, thanks to which a new dark fermion (a sterile neutrino) will mix with the SM neutrinos (See Elena's talk)

4. Gravity...

Two strategies of searching for mediators at accelerators:
- Not decaying in the detector (signal proportional to $<\text{coupling}>4$)
- Decaying in the detector (signal proportional to $<\text{coupling}>2$)
Dark sector far detectors at LHC / 1

- Long-lived particles (LLP) that decay in detector volume
- Fractionally charged particles directly interact in detector
LHCb detector / 1

- **LHCb** is a dedicated flavour experiment in the **forward region** at the LHC (1.9 < η < 4.9) (~1°-15°)

- **Precise vertex reconstruction** < 10 μm vertex resolution in transverse plane

- Lifetime resolution of ~ 0.2 ps for τ = 100 ps

- **Muons** clearly identified and triggered: ~ 90% μ± efficiency

- Great **mass resolution**: e.g. couple MeV for J/psi (see bkup)

- **Low p_T trigger** means low masses accessible. Ex: p_Tμ > 1.5 GeV
LHCb detector / 3

- Precise knowledge of the location of the material in the LHCb VELO is essential to reduce the background in searches for long-lived exotic particles.
- LHCb data calibration process can align active sensor elements, an alternative approach is required to fully map the VELO material.
- **Real-time calibration** in Run 2.
- Hardware trigger is still there, and only ~10% efficient at low pT.
Jet physics at LHCb / 1

- Efficiency above 90% for jets with p_T above 20 GeV
- Jets reconstructed both online and offline!
- **b and c jet tagging**
  - Require jets with a secondary vertex reconstructed close enough
  - **Light jet** mistag rate < 1%, $\varepsilon_b \sim 65\%$, $\varepsilon_c \sim 25\%$
- SV properties (**displacement**, **kinematics**, **multiplicity**, etc) and jet properties combined in two BDTs
  - $\text{BDT}_{\text{blc}}$ optimised for b versus c discrimination
  - $\text{BDT}_{\text{bc|udsg}}$ optimised for heavy flavour versus light discrimination

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![BDT plot](image)

**LHCb data**

Initial (no-tagging) sample:
70% light parton, 22% charm, 8% beauty.
Higgs→LLP→μ+jets / 1

- Massive LLP decaying in μ+qq (jets)
- **Single displaced vertex** with several tracks and a high $p_T$ muon; based on Run-1 dataset
- Production of LLP could come e.g. from Higgs like particle decaying into pair of LLPS
- $m_{LLP}=[20; 80]$ GeV and $\tau_{LLP}=[5; 100]$ ps
- Background dominated by bb
- No excess found: result interpreted in various models

\[ H(125) \]

\[ \tilde{\chi}_1^0 \]

\[ \chi^0 \]

\[ d \]

\[ u \]
Higgs→LLP→μ+jets / 2

Minimum $B$ excluded at 95% CL

- 50 %
- 25 %
- 10 %
- 5 %
- 2.0 %
- 1.0 %
- 0.5 %
- 0.1 %
- 0.05 %
- 0.02 %

LHCb results

$\int \mathcal{L} \, dt = 2 \, \text{fb}^{-1}$

LHCb simulation

$\int \mathcal{L} \, dt = 23 \, \text{fb}^{-1}$

LHCb simulation

$\int \mathcal{L} \, dt = 50 \, \text{fb}^{-1}$

LHCb simulation

$\int \mathcal{L} \, dt = 300 \, \text{fb}^{-1}$

$m_{\tilde{\chi}_1^0} [\text{GeV}/c^2]$ vs. $\tilde{\chi}_1^0 c\tau$ [m]
Higgs → LLP → μ+jets / 3

Bf(Higgs → LLP+LLP) < 2 %  
Bf(Higgs → LLP+LLP) < 0.5 %
Massive LLP decaying → bb+bb with bb → jets

- Single displaced vertex with two associated tracks; based on Run-1 dataset
- Production of LLP could come e.g. from Higgs like particle decaying into pair of LLPs (e.g. πν)
- \( m_{\pi \nu} = [25; 50] \text{ GeV} \) and \( \tau_{\pi \nu} = [2; 500] \text{ ps} \)
- Background dominated by QCD
- No excess found: result interpreted in various models
H→μτ decays

- Higgs-like boson decaying → μτ charged-lepton flavour-violating (CLFV)
- Analysis is separated into four channels
- \(m_H=[45; 195] \text{ GeV}\) and minimal flight distance (impact parameter) of the reconstructed candidate is imposed
- Three different selections based on \(m_H\) w.r.t. \(m_Z\)
- Background dominated by QCD, \(Z→ττ\), \(V_j\)
- No excess found
Searching in the $Y$ mass region / 1

- Other light spin-0 particles in which LHCb can do well are light bosons from pp; **only Run 1**
- Spin-0 boson, $\phi$, using Run 1 prompt $\phi \rightarrow \mu^+\mu^-$ decays, have been searched for
- Use **dimuon** final states:
  - Access to different mass window w.r.t $\gamma\gamma$ or $\tau\tau$ searches in 4$\pi$ experiments
- Done in **bins of kinematics** ($[p_T, \eta]$) to maximise sensitivity
- Precise modelling of $Y(nS)$ tails to extend search range as much as possible
- **Mass independent** efficiency (uBDT)
Searching in the \( \Upsilon \) mass region / 2

- Search for dimuon resonance in \( m_{\mu\mu} \) from 5.5 to 15 GeV (also between \( \Upsilon(nS) \) peaks)
- No signal: limits on \( \sigma \cdot BR \) set on (pseudo)scalars as proposed by Haisch & Kamenik [1601.05110]
- First limits in 8.7-11.5 GeV region - elsewhere competitive with CMS
- Interpreted as a search for a scalar produced through the SM Higgs decay
Codex-b / 1

- Distance is only $\sim 4$ bunch crossing times for relativistic objects: Integrate CODEX-b into the DAQ & readout, and treat as LHCb sub-detector
- **Identification and at least partial reconstruction of the LLP event**
  - Fiducial volume (‘the box’) is $10 \times 10 \times 10 \text{ m}$; angular acceptance 1%
  - Absorb neutral hadrons in shield (**irreducible background**)
  - Veto muon-induced backgrounds with muon veto + front face of the detector (**reducible background**)
  - Precision timing and spatial resolution, 100 ps or futuristic 50 ps resolution possible required for LLP mass reconstruction
• Large theory uncertainties for $m_\phi > 1$ GeV
• Single parameter portal: Higgs-scalar mixing angle, $\theta$, controls production rate and lifetime
• LHCb information must be used to reach prospected limits
Visible (SM) dark photons / 1

- **A**: Bump hunts, visible or invisible
- **B**: Displaced vertex searches, short decay lengths
- **C**: Displaced vertex searches, long decay lengths
Searching for Dark Photons / 1

- Search for dark photons decaying into a pair of muons
- Used $1.6 \text{ fb}^{-1}$ of 2016 LHCb data (13 TeV)
- Kinetic mixing of the dark photon ($A'$) with off-shell photon ($\gamma^*$) by a factor $\varepsilon$:
  - $A'$ inherits the production mode mechanisms from $\gamma^*$
  - $A' \rightarrow \mu^+\mu^-$ can be normalised to $\gamma^* \rightarrow \mu^+\mu^-$
  - No use of MC $\rightarrow$ no systematics from MC $\rightarrow$ fully data-driven analysis
- Separate $\gamma^*$ signal from background and measure its fraction
- Prompt-like search (up to 70 GeV/c$^2$) $\rightarrow$ displaced search (214-350 MeV/c$^2$)
  - $A'$ is long-lived only if the mixing factor is really small
Search for Dark Photons / Prompt

- No significant excess found - exclusion regions at 90% C.L.
- First limits on masses above 10 GeV & competitive limits below 0.5 GeV
Search for Dark Photons / Displaced

- **Looser requirements** on muon transverse momentum
- **Material background** mainly from photon conversions
- Isolation decision tree from $B^0\rightarrow\mu^+\mu^-$ search
  - Suppress events with additional number of tracks, i.e. $\mu$ from $b$-hadron decays
- Fit in **bins of mass and lifetime** – use consistency of decay topology $\chi^2$
- Extract p-values and confidence intervals from the fit
- No significant excess found small parameter space region excluded
- **First limit ever not from beam dump**
Search for Dark Photons / Results

- The 2016 dimuon results are consistent with (better than) predictions for prompt (long-lived) dark photons as discussed in [1603.08926]. We implemented huge improvements in the 2017 triggers for low masses, so plan quick turn around on 2017 dimuon search - then onto electrons.

90% CL exclusion regions on \([m(A'), \varepsilon^2]\)

Previous Experiments

- Ilten, Thaler, Thaler, Williams, Xue

\[ m(A') \] [GeV]

50 invfb

500 invfb

LHCb

Previous Experiments

- LHCb

- Previous Experiments

• Huge forward $\pi$ rate ($\sim 10^{15}$) in FASER acceptance
• Large suppression ($\varepsilon^2$) in $\pi \rightarrow A' X$ but substantial rates of $A'$ in acceptance
• Multi-TeV LLP produced at ATLAS IP; 480 m to FASER, including 100 m of concrete
• Decay within 1.5 m decay volume to charged particle pair, e.g. $e^+e^-$
• Oppositely charged tracks separated by spectrometer B field
• Silicon strip tracker (from ATLAS) to measure charged track trajectory
• EM calorimeter (from LHCb) to measure energy, e vs. $\mu$ ID
FASER probes new parameter space with just 1 fb$^{-1}$ starting in 2021

- FASER 2 larger volume ($R = 1$ m, $L = 5$ m) and HL-LHC Lumi
Conclusions

• The search for dark matter and dark sectors at collider experiments is a broad and growing field both at existing and at feature facilities and experiments

• Important effort should also be spent in exploiting existing experiments further

• These searches can lead to major milestones in our understanding of the shortcomings of the Standard Model

• Specific mass scale of NP unknown, DM points to a dark sector of particles not interacting through the known SM forces and therefore only feebly-coupled to the SM

• [...] More than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias(es) [M. Mangano, emphasis added]
• The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being.
• But the big questions of our field remain wide open (hierarchy problem, flavour, neutrinos, DM, BAU, etc.)
• This simply implies that, more than for the past 30 years, future HEP’s progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias(es) [M. Mangano, emphasis added]

Thanks

Federico Leo Redi
Figure 14: A schematic illustration of the various track types [15]: long, upstream, downstream, VELO and T tracks. For reference the main $B_y$-field component is plotted above as a function of the $z$ coordinate.

- **Downstream tracks:** traverse only through the TT and T stations. They are important for the reconstruction of $K_0^S$ and $\pi^\pm$ particles that decay outside the VELO acceptance.

- **VELO tracks:** traverse only through the VELO and are typically large-angle or backward tracks, which are useful for the primary vertex reconstruction.

- **T tracks:** traverse only through the T stations. They are typically produced in secondary interactions, but are still useful for the global pattern recognition in RICH2.

Figure 16: Schematic diagram of track types in the LHCb detector with reference to the VELO, TT and tracking stations one, two, and three. This analysis focuses on particles decaying into a pair of long tracks.

Selection

Figure 16 shows how different tracks are categorized in LHCb. In the case of the decay $\mu^+\mu^-$, the candidate dark boson could be reconstructed using long (L) or downstream (D) tracks. This analysis uses only the LL case, due to the fact that the trigger efficiency is low (by a factor of at least 5, relative to that of LL for case using D tracks (see Sec. B and Table 20).

5.1 Reconstruction and Stripping

The offline selection begins using the $B_2K\pi X_2\mu\mu$DarkBosonLine stripping line for LL candidates from Stripping20r0p3 (Stripping20r1p3 for 2011 data). The selection criteria applied in these lines are outlined in Table 8. The variable $DOCA$ is defined as the distance of closest approach between any two pairs of tracks in the candidate. Also used is the variable $\Delta FD$, which is the change in vertex when the signal candidate tracks are associated with the PV in the vertex fit. Candidates are reconstructed using $DecayTreeFitter$, where daughter particles are constrained such that the reconstructed $K^+\pi^\pm\mu^+\mu^-$ invariant mass, $m(K^+\pi^\pm\mu^+\mu^-)$, is equal to the nominal $B_0$ mass. All references to $m$, $m(K^\pm)$ or $\tau$ are at the vertex fit has been performed.
LHCb detector / 2bk

- Lower luminosity (and low pile-up)
  - \( \sim 1/8 \) of ATLAS/CMS in Run 1
  - \( \sim 1/20 \) of ATLAS/CMS in Run 2
- Hardware L0 trigger to be removed
- **Full real-time** reconstruction for all particles available to select events (since 2015)
  - **Real-time reconstruction** for all charged particles with \( p_T > 0.5 \) GeV
  - We go from 1 TB/s (post zero suppression) to 0.7 GB/s (mix of full + partial events)
- LHCb will move to a **trigger-less readout system** for LHC Run 3 (2021-2023), and process 5 TB/s in real time on the CPU farm

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**Present trigger**

- 40 MHz bunch crossing rate
  - L0 Hardware Trigger: 1 MHz readout, high \( E_T / p_T \) signatures
    - 450 kHz \( h^+ \)
    - 400 kHz \( \mu / \mu \)
    - 150 kHz \( e / \gamma \)
  - Partial event reconstruction, select displaced tracks/vertices and dimuons
  - Buffer events to disk, perform online detector calibration and alignment
  - Full offline-like event selection, mixture of inclusive and exclusive triggers
  - 12.5 kHz (0.6 GB/s) to storage

**Upgraded trigger**

- 30 MHz inelastic event rate (full rate event building)
  - Software High Level Trigger
  - Full event reconstruction, inclusive and exclusive kinematic/geometric selections
  - Add offline precision particle identification and track quality information to selections
  - Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers
  - 2-5 GB/s to storage
Figure 1: Efficiency-corrected dimuon mass distributions for (left) $\sqrt{s} = 7$ TeV and (right) $\sqrt{s} = 8$ TeV samples in the region $3 < p_T < 4$ GeV$/$c, $3.0 < y < 3.5$. The thick dark yellow solid curves show the result of the fits, as described in the text. The three peaks, shown with thin magenta solid lines, correspond to the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ signals (left to right). The background component is indicated with a blue dashed line. To show the signal peaks clearly, the range of the dimuon mass shown is narrower than that used in the fit.
Searching for Dark Photons / 1bk

- Suppressing misidentified (non-muon) backgrounds and reducing the event size enough to record the prompt-dimuon sample
- Accomplished these by moving to real-time calibration in Run 2
- Hardware trigger is still there, and only ~10% efficient at low pT


Trigger output

![Graph of Candidates / \(\sigma[m(\mu^+\mu^-)]/2\) vs. \(m(\mu^+\mu^-)\) in MeV] (LHCb \(\sqrt{s} = 13\) TeV)

- Prompt-like sample \(p_T(\mu) > 1\) GeV, \(p(\mu) > 20\) GeV
- \(\mu^+\mu^-\)
- \(\mu^+\mu^+\)

Final A' sample

![Graph of Candidates / \(\sigma[m(\mu^+\mu^-)]/2\) vs. \(m(\mu^+\mu^-)\) in MeV] (LHCb \(\sqrt{s} = 13\) TeV)

- Prompt-like sample \(p_T(\mu) > 1\) GeV, \(p(\mu) > 20\) GeV
- \(\mu^+\mu^-\)
- \(\mu\mu_Q\)
- \(hh + h\mu_Q\)

N.b., bump follows isolation applied
Searching for Dark Photons / 2bk

- Background dominated by material interactions for displaced searches at LHCb
- Precise knowledge of the location of the material in the LHCb VELO is essential to reduce the background in searches for long-lived exotic particles
- LHCb data calibration process can align active sensor elements, an alternative approach is required to fully map the VELO material

\[ \text{Figure 1.} \]

\[ \text{Figure 7.} \]

\[ \text{LHCb} \]

\[ \text{arXiv:[1803.07466]} \]
H→μτ decays / 1bk
from top to bottom: μτ_e, μτ_h1, μτ_h3, μτμ
from L to R: μτμ, μτ_e, μτ_h1, μτ_h3,
Neutrino detector at TI18 and/or TI12 / 1bk

- Charged current neutrino-nucleon cross section measurements show a gap in measurements
- First detection of collider neutrinos in far forward location, where high-energy neutrino flux is concentrated
- Cross-section measurements of all flavours in unexplored energy region
- Search for new physics effects in high-energy neutrino interactions
Higgs→LLP→jets pairs / 1bk

Minimum $\mathcal{B}$ excluded at 95% CL

- 75%
- 50%
- 30%
- 20%
- 5%
- 2%
- 1%

LHCb results
$\int \mathcal{L} \, dt = 2 \text{ fb}^{-1}$

ATLAS and CMS dominated
$\int \mathcal{L} \, dt = 23 \text{ fb}^{-1}$

LHCb simulation
$\int \mathcal{L} \, dt = 50 \text{ fb}^{-1}$

ATLAS and CMS dominated
$\int \mathcal{L} \, dt = 300 \text{ fb}^{-1}$

LHCb simulation

Minimum $\mathcal{B}$ excluded at 95% CL
Higgs → LLP → jets pairs / 2bk

Bf(Higgs → πν+πν) < 20 %

Bf(Higgs → πν+πν) < 2 %
Introduction / 1bk

- Naturalness does not seem to be a **guiding principle** of Nature
- There are some **anomalies in flavour physics** which (if true) seem again to point out that our theory prejudice was wrong
- We should therefore not forget that we have a **2D** problem (Mass VS Coupling)
- Low coupling → Long Lived

Intensity frontier: *Flavour physics, lepton flavour violation, electric dipole moment, dark sector*
The Intensity frontier is a **broad** and **diverse**, yet **connected**, set of science opportunities: heavy quarks, charged leptons, hidden sectors, neutrinos, nucleons and atoms, proton decay, etc...

In this talk, I will concentrate on **dark sector** and related physics searches.

**Landscape**: LHC results in brief:

- Direct searches for **NP** by **ATLAS** and **CMS** have not been successful so far
  - Parameter space for popular **BSM** models is **decreasing rapidly**, but only < 5% of the complete HL-LHC data set has been delivered so far
  - NP discovery **still may happen**!

- **LHCb** reported intriguing hints for the violation of lepton flavour universality
  - In $b \rightarrow c \mu \nu / b \rightarrow c \tau \nu$, and in $b \rightarrow s e^+e^- / b \rightarrow s \mu^+\mu^-$ decays
  - Possible evidence of **BSM** physics **if substantiated** with further studies (e.g. **BELLE II**)