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on behalf of the LHCb collaboration

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Overview of dark sectors searches at LHCb:

- See talk (Shining light on the dark sector with LHCb) by Martino on Wednesday.

This talk – focus in two particular searches:

- Dark Photons searches (prompt and long-lived) at LHCb \cite{PRL2018}
- Massive long-lived particles (LLPs) decaying to jet pairs \cite{EPJC2017}
Search for dark photons decaying into a pair of muons:

- Kinetic mixing of the dark photon ($A'$) with off-shell photon ($\gamma^*$) by a factor $\varepsilon$:
  1. $A'$ inherits the production mode mechanisms from $\gamma^*$.
  2. $A' \rightarrow \mu^+\mu^-$ can be normalised to $\gamma^* \rightarrow \mu^+\mu^-$.
  3. 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.
- Used 1.6 fb$^{-1}$ of 2016 LHCb data (13 TeV).
Selection:
- **Prompt** requirements: $p_T(\mu) > 1$ GeV/c (reduce input from L1 trigger), $p(\mu) > 20$ GeV/c.
- Fake muon veto ($\mu\mu$ pairs shares zero hits in the muon system): inefficiency of $\mathcal{O}(1\%)$.
- L0 trigger (HW) requirement as $p_T(\mu) > 1.8$ GeV/c || $p_T(\mu_1)p_T(\mu_2) > 1.5$ (GeV/c)$^2$.
- Jet-based isolation criteria – improves sensitivity in the region above the $\phi$ meson mass.

**misID ($hh + h\mu_Q$) backgrounds:**
- Double misID ($hh$): $\mu$ as prompt $h$, most likely a pion.
- misID ($h$) + misRECO ($\mu_Q$): $\mu$ from a SL b(c)-hadron decay and reconstructed as prompt.
- $hh$ dominates at low mass, $h\mu_Q$ is comparable at larger masses.

**Displaced backgrounds:**
- Double misRECO ($\mu_Q\mu_Q$): not only $\mu$ from SL hadron decays but also from $b\rightarrow\mu c\rightarrow\mu\mu$.
- Vertex and $\text{min}(IP)$ $\chi^2$ average values different from signal: $\mu$ do not originate at PV.

**Background subtraction strategy:**
- Build vertex and $\text{min}(IP)$ $\chi^2$ data-driven **templates** (see next slide) in bins of $m(\mu\mu)$.
- **Categorise** the prompt spectrum by fitting these templates.
Dark Photons – analysis strategy [PRL (2018) 120 061801]

Using templates for min[$\chi^2_{1p}$] (small mass dep):
- $\mu^+\mu^-$ from data at $m(J/\psi)$ and $m(Z)$
- $\mu_Q\mu_Q$ from simulation (validated)
- $hh + h\mu_Q$ from same-sign dimuons (corrected)

($\mu_Q$ is a muon from a heavy-flavour decay)

- LHCb $m(A^+) = 0.5$ GeV
- LHCb $m(A^+) = 5$ GeV
- LHCb $m(A^+) = 50$ GeV

LHCb $\sqrt{s} = 13$ TeV

Isolation applied

Prompt-like sample:
- $p_T(\mu) > 1$ GeV, $p(\mu) > 20$ GeV

Candidates / $\sigma[m(\mu^+\mu^-)]/2$

Candidates / $\sigma[\mu_Q\mu_Q]$

Candidates / $\sigma[hh + h\mu_Q]$

$m(A^+) [\text{MeV}]$
No significant excess found - exclusion regions at 90% C.L.:
→ First limits on masses above 10 GeV & competitive limits below 0.5 GeV.
Looser requirements on muon transverse momentum.

Material background mainly from photon conversions (see next slide).

Isolation decision tree from $B_s^0 \rightarrow \mu^+ \mu^-$ search:
→ Supress 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.
Material veto map [LHCBDP-2018-002]

- Background dominated by material interactions for displaced searches at LHCb.
- Mandatory to **keep control** of material interactions – veto them in an efficient way:

  - Background mainly due to $\gamma$ conversions (left plot).
  - A new VELO material map has been developed:
    - Model in **great detail** both sensors & envelope.
    - Sensitivity improvement by $O(10)$ to $O(100)$.
    - Based on data from **beam-gas collisions** (plot below).
Massive LLPs decaying to jet pairs [EPJC (2017) 77:812]

- HV $\pi_\nu$ decaying to $b\bar{b}$, especially SM-like $H^0 \rightarrow \pi_\nu \pi_\nu$ production.
- In most of the cases only one of the two $\pi_\nu$ decays into the LHCb acceptance.
- Candidates are reconstructed using tracks originated within the VELO region.
- Experimental signature is a single displaced vertex with two associated jets:
Massive LLPs decaying to jet pairs [EPJC (2017) 77:812]

- Efficiencies dominated by the detector acceptance (from 5.5% to 13%).
- Use $\pi_v$ detachment ($R_{xy}$) to discriminate between signal and background.
- Background dominated by heavy flavour ($b\bar{b}$) events and material interactions.
- L0 trigger requires a high-$p_T$ $\mu$; or a $h$ with high-$E_T$ in the hadronic calorimeter.

Analysis procedure step-by-step:

1. Trigger on tracks passing a displaced vertex selection.
2. Reconstruct the displaced vertex and find two associated jets.
3. Quality cuts on jets – di-jet should point back to the candidate vertex.
4. Exclude material interactions + displaced vertices from heavy flavour (HF).
5. Fit the di-jet invariant mass in 6 bins of $R_{xy}$ (0.4 – 50 mm).
Massive LLPs decaying to jet pairs [EPJC (2017) 77:812]

Background model:
- Material interactions with VELO sensors and envelope,
- Heavy flavour ($b\bar{b}$) & back-to-back di-jet events.

Signal model (35 GeV/$c^2$, 10 ps) for $B(H^0 \rightarrow \pi\nu\pi\nu) = 1$.

Best-fit signal model (35 GeV/$c^2$, 10 ps).
Massive LLPs decaying to jet pairs [EPJC (2017) 77:812]

- Search with full LHCb Run I (3 fb$^{-1}$) dataset published – limits at 95% C.L.:

- No excess found – plan to analyse LHCb Run II + go to lower $\pi_\nu$ masses:
  - Develop jet substructure tools to study multi-jets at lower masses.
Conclusions

- **LHCb proved to be very competitive for these kind of searches:**
  - Hidden Valley $\pi_\nu$ from SM-like Higgs decays,
  - Dark photons from meson decays and Drell-Yan.

- **Prospects from existing results and ideas:**
  - HV $\pi_\nu$ searches at lower masses, lower lifetimes, dark showering models.
  - Extend dark photon searches to other models and final states.

- Plenty of other LLPs LHCb searches not shown – see i.e. [LHCb-TALK-2017-326]

- Large community devoted to LLP searches at the LHC:
  - Community white paper (status & prospects) in preparation, to be released soon!
  - Second workshop held at Trieste last year, third workshop at CERN on 16-18 May.

- We are looking forward to ideas for new signatures and techniques:
  - **Do not hesitate to contact us if interested!**

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**Thanks for your attention!**

(and one million thanks to Martino for presenting the slides 😊)