Search for long-lived particles decaying into two muons using data collected with high-rate triggers at CMS

June 22\textsuperscript{nd}, 2021

Mario Masciovecchio
(University of California, San Diego)

- on behalf of the CMS collaboration -
The Standard Model: a story of success

• The Standard Model (SM) has been probed over the years at the LHC (and before)
  → With great success, ranging over many orders of magnitude
  → Including prediction of Higgs boson

CMS Preliminary

June 2021

Production Cross Section, $\sigma$ [pb]

- $7$ TeV CMS measurement ($L \leq 5.0$ fb$^{-1}$)
- $8$ TeV CMS measurement ($L \leq 19.6$ fb$^{-1}$)
- $13$ TeV CMS measurement ($L \leq 137$ fb$^{-1}$)
- Theory prediction
- CMS 95%CL limits at 7, 8 and 13 TeV

All results at: http://cern.ch/go/pNJ7
The Standard Model: a story of success, with its limitations

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- **Gravitation** is not described by SM
  - Sizeable effects are expected at large energy scale
- EWK scale $[O(1 \text{ TeV})] \ll$ Planck scale $[\approx 2.4 \cdot 10^{15} \text{ TeV}]$
  - **Hierarchy problem**
  - With significant fine-tuning to achieve $m_{\text{Higgs}} \approx 125 \text{ GeV}$
- **Unification of forces** (Grand Unified Theories) is not supported
  - GUTs may explain inflationary dynamics of early Universe
- **Why** matter-antimatter imbalance in Universe?
- **Why** three generations of quarks and leptons?
- **Why** flavor anomalies?
- **Neutrinos** are predicted to be massless
  - Experimental observations imply nonzero mass
- Only *baryonic matter*, with no dark matter candidate
  - From astrophysical and cosmological observations:
    - Dark matter $\sim 22\%$ of energy in Universe
    - Dark energy $\sim 74\%$
Going beyond the Standard Model

- Limitations to SM hint to physics beyond the SM

Searches at the LHC are extensively looking for signatures of BSM physics

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Overview of CMS EXO results

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included.)
What are we looking for?

- Dark matter is expected to interact very weakly with SM, if at all

→ Possibility of hidden/dark sector of matter [1, 2]:
  - Dark particles can interact with SM via weakly interacting mediators
  - Mass and lifetime of mediators are not strongly constrained

1. Dark photon ($Z_D$):

  - Interaction with SM through hypercharge portal
    - Via kinetic mixing coupling $\varepsilon$

  - Interaction with SM through Higgs ($h$) portal
    - Via Higgs mixing $\kappa$

What are we looking for?

1. Dark photon ($Z_D$):
   - In absence of hidden-sector states below its mass, $Z_D$ will only decay to SM particles, with coupling of SM fermions to $Z_D$ proportional to kinetic mixing coupling $\varepsilon$

   - **Sizeable decay branching fraction of $Z_D \rightarrow \mu\mu$**
   - If $\varepsilon \lesssim 10^{-4}$, then $Z_D$ will be long-lived

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**Figure:**

- **Left:** Graph showing $\text{Br}(Z_D \rightarrow \text{SM})$ vs. $m_{Z_D}$ (GeV), with curves for different decay modes.
- **Right:** Graph showing $\tau$ (m) vs. $m_{Z_D}$ (GeV) for different values of $\varepsilon$. Notations include $20$ m, $1 \mu$m.
What are we looking for?

2. Singlet scalar field $(\phi)$:
   - Minimal extension to the SM adds a singlet scalar field $(\phi)$ [3, 4]
     - $\phi$ is mixing with the SM-like Higgs boson
     - Coupling of SM fermions to $\phi$ is proportional to mixing angle ($s_\theta$)
     - $\phi$ is likely long-lived (LL)

→ Scalar resonance produced in B hadron decay: $B \rightarrow \phi X$
  - With sizeable decay branching fraction of $\phi \rightarrow \mu \mu$

How do we look for it?
- The CMS detector

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• Search for a **narrow long-lived dimuon resonance**
  - With $m_{LLP} \gtrsim 2m_\mu$ and $c\tau_{0,LLP} > 0$

→ **Main features:**
  - Highly granular **tracking system**
  - Electromagnetic+hadron calorimeter
  - Superconducting solenoid ($B = 3.8$ T)
  - Robust and redundant **muon system**

From: [CERN-LHCC-2006-001](http://www.cern.ch)

From: [CMS-OUTREACH-2016-027](http://www.cms.eu)
How do we look for it?
- The CMS trigger system

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• Search for a **narrow long-lived dimuon resonance**
  - With $m_{\text{LLP}} \gtrsim 2m_\mu$ and $c\tau_{0\text{LLP}} > 0$

• Collision data delivered by LHC and collected by the CMS detector are filtered by a two-level trigger system:
  1. Level-1 Trigger (L1T)
  2. High Level Trigger (HLT)

  ➢ Only events selected at HLT are then fully reconstructed offline, due to constraints on computing and storage resources

→ Can **not** access full phase-space of interest with standard triggers
How do we look for it?
- The CMS scouting triggers

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- Standard triggers do **not** allow to access full phase-space of interest
  - Events not selected by trigger system are lost, forever

- **Data scouting**, used in CMS since 2011:
  - **Idea:** “Do more, with less”
    1. Increase of trigger acceptance rate
      - Looser (more inclusive) selections
    2. Decrease of event size, to compensate
      - Keep only HLT-level information

- Similar streams were used by ATLAS and LHCb during LHC Run-2
The CMS scouting triggers: a successful example

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- First successful applications in CMS: low-mass dijet resonances

CMS Preliminary

LHCP 2020

95% CL exclusions

- \( \Gamma_{Z'}/M_{Z'} < 100\% \)
- \( \Gamma_{Z'}/M_{Z'} < 50\% \)
- \( \Gamma_{Z'}/M_{Z'} < 30\% \)
- \( \Gamma_{Z'}/M_{Z'} < 10\% \)

Z' \rightarrow q\bar{q}

\( M_{Z'} \) [GeV]

Allowed to probe otherwise inaccessible parameter space, at low coupling \( g'_q \) (between leptophobic \( Z' \) boson and quarks) and mass in range [500, 1000] GeV
How do we look for it?

- The CMS dimuon scouting triggers

- Search for a **narrow long-lived dimuon resonance**
  - With $m_{\text{LLP}} \gtrsim 2m_\mu$ and $c\tau_{\text{LLP}} > 0$

- Standard triggers do not allow to access phase-space of interest

→ Use CMS dimuon scouting triggers (instead of standard triggers)

![Graph showing CMS dimuon data comparison between standard and scouting triggers](image-url)

**PRL 124 (2020) 131802**

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How do we look for it?
- The CMS dimuon scouting data, in detail

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• Search for a \textit{narrow long-lived dimuon resonance}
  - With $m_{\text{LLP}} \gtrsim 2m_\mu$ and $c\tau_{\text{LLP}} > 0$

✓ Standard triggers do \textbf{not} allow to access phase-space of interest

→ Use CMS \textit{dimuon scouting data} collected in 2017-2018 (101 fb\textsuperscript{-1})

✓ Content of 2016 scouting data is different

➢ Data collected at high rate with limited information as at HLT

➢ Low $p_T$ thresholds on $\mu$’s and \textit{no} constraint on displacement

✓ Presence of $\geq 2$ hits in \textit{pixel tracker} was required in Run-2

→ Range of accessible transverse displacement: $0 \leq l_{xy} < 11 \text{ cm}$

From \textit{JINST 16 (2021) 02}
An inclusive trigger selection

- Events are selected with at least two opposite-charge (OS) muons
  - With $p_T^\mu > 3$ GeV & $|\eta^\mu| < 2.4$
  - No explicit constraint on displacement
  - No explicit constraint on dimuon invariant mass ($m_{\mu\mu}$)

→ Trigger selection allows for very inclusive & general search, including low-mass LLP signatures

- Trigger efficiency is measured in data:

```
    CMS Preliminary 101 fb^{-1} (13 TeV)

    | $l_{xy}$ [cm] | Trailing muon $p_T$ [GeV] |
    |--------------|--------------------------|
    | 0.11         | 0.51         0.7          0.69          0.73          0.72   |
    | 0.14         | 0.59         0.7          0.7          0.66          0.68   |
    | 0.26         | 0.55         0.67         0.69         0.72          0.66   |
    | 0.28         | 0.64         0.71         0.75         0.74          0.71   |
    | 0.23         | 0.63         0.71         0.74         0.74          0.68   |
```
Muons and displaced vertices

- Events w/ at least a pair of $\mu$’s associated to a displaced vertex (DV)

**DV selection:**
- $\sigma(x) < 0.05$ cm
- $\sigma(y) < 0.05$ cm
- $\sigma(z) < 0.10$ cm
- $\chi^2$/dof $< 5$
- $l_{xy} < 11$ cm

**$\mu$ identification:**
- Tracker+muon system
  - # tracker layers $> 5$
  - $\chi^2$/dof $< 3$

**$\mu$ isolation:**
- Track isolation $[\Delta R<0.3] < 0.1$ (0.2) $p_T^\mu$
  - Relaxed for 2$^{nd}$ $\mu$-pair
- min $\Delta R(\mu, \text{jet}) > 0.3$
  - All HLT calo-jets ($p_T > 20$ GeV)

> If $>1$ pairs of OS $\mu$’s are selected:
  - Ranking by $\chi^2$(DV)
    - Use first (2$\mu$) or first two $\mu$-pairs (4$\mu$)
    - For 2$^{nd}$ $\mu$-pair, few selection criteria are relaxed to maximize sensitivity

> Explore isolated, partially isolated and non-isolated 2$\mu$ topologies
  - Exploit ability to search for non-isolated signatures, too
Sources of background

- Due to inclusiveness & generality of search and of scouting triggers, **background suppression** is fundamental

- **Main sources of background:**
  - Accidental crossing of cosmic $\mu$’s
  - Accidental crossing of $\mu$’s from pileup (PU)
  - Accidental crossing of $\mu$’s from QCD multijet events
  - Material vertices, from interactions with detector material
  - **Prompt** (non-displaced) $\mu$’s
  - Known dimuon mass resonances

- In the following, will refer to erroneously formed DVs as “fake”

- Dedicated selection criteria are applied to **suppress background**, while **retaining BSM signal acceptance** for wide range of signals
For BSM signal, expect dimuon system vector to be collinear with DV vector

→ Require $\Delta \phi(\mu\mu, \bar{D}V) < 0.02 (0.1)$
  - To suppress backgrounds with DV formed from accidental crossing of $\mu$-trajectories
  - Relaxed for 2nd $\mu$-pair

To further suppress backgrounds with fake DVs from cosmic $\mu$’s, $\mu$’s from PU, or $\mu$’s from QCD, also require $\Delta \phi(\mu_1, \mu_2) < 2.8$
• Reject fake DV’s from overlapping pileup (PU) μ-tracks
  o Require $\log_{10}(|\Delta \eta_{\mu\mu}|/|\Delta \phi_{\mu\mu}|) < 1.25$
  ❖ Fake DV’s from PU μ-tracks overlapping in R-φ plane and far in R-z plane
Background suppression: vs. material vertices

- Reject DV’s near pixel modules, to suppress material effects
  - DV is required to be at >0.05 cm from nearest pixel module
    - Position of module plane is extracted directly from detector geometry
Background suppression: vs. prompt muons

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- Reject muons with \# observed pixel hits > \# expected pixel hits
  - To reject “fake” displaced muons
    - If a muon is truly displaced, no hits from beamspot to DV are expected
    - Only applied for \( l_{xy} > 3.5 \) cm [i.e., beyond 1st pixel layer (L1)]

1. Propagate \( \mu \)'s outwards from DV
2. Count \# compatible pixel modules
  → Reject \( \mu \)'s with excess pixel hits

From JINST 16 (2021) 02
• Require each muon to be displaced wrt. primary vertex (PV)
  o Require $|d_{xy}/\sigma_{xy}| > 2 \ (1)$
    ❖ Relaxed for 2nd $\mu$-pair
  o Require $|d_{xy}|/(l_{xy} m_{\mu\mu}/p_{T\mu\mu}) > 0.1 \ (0.05)$
    ❖ Impact parameter is scaled by lifetime, for lifetime-independent cut
    ❖ Relaxed for 2nd $\mu$-pair

Background suppression: explicit displacement requirement
Known dimuon mass resonances

- **Known resonances** are clearly visible using CMS scouting data!
  - Here, shown in bins of transverse displacement ($l_{xy}$)
  - Known resonances, including those where π’s are mis-ID’d as μ’s, are treated as a signal: mass and width are determined by a fit
  - A range of ±5σ around each known resonant peak is masked, i.e., it is required to not overlap with any search mass window

### CMS Preliminary

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Looking for a range of BSM signals

• As we do not target a specific BSM signal model, we can not apply too specific selection criteria

→ We rather categorize events, in the attempt to maximize sensitivity to a wide range of BSM signal models

  o Aim at exploring a wide range of lifetime hypotheses
    ➢ Categorize events according to displacement ($l_{xy}$)

  o Aim at exploring different production topologies
    ➢ Categorize events according to $p_T^{\mu\mu}$
    ➢ Categorize events according to muon isolation

  o Aim at exploring a wide range of mass hypotheses
    ➢ Slide over dimuon mass spectrum in each category
Categorization of dimuon events

- After selection, categorize dimuon events in multi-dimensional bins:
  - $l_{xy}$: [0.0, 0.2, 1.0, 2.4, 3.1, 7.0, 11.0] cm
    - Driven by geometry of CMS pixel tracker
  - $p_T^{\mu\mu}$: [0, 25, $\infty$] GeV
    - $B \to \phi X$ signal is mostly at low $p_T^{\mu\mu}$
    - $h \to Z_DZ_D$ signal is mostly at high $p_T^{\mu\mu}$
  - Isolation:
    1. Fully isolated topologies
      - Both $\mu$’s are isolated
    2. Partially isolated topologies
      - Only one $\mu$ is isolated
    3. Non-isolated topologies
      - No $\mu$ is isolated

→ Total of 36 dimuon event categories
Analysis strategy

• In each dimuon event category, slide over dimuon mass spectrum
  o **Steps** and **windows** according to **signal mass resolution** ($\sigma$):
    ❖ $\sigma$ is determined from **signal fit** (double Crystal Ball + Gauss)
      ▪ $\sim 1.1\%$ of mass hypothesis and $\sim$ constant
    ➢ **Mass window** = $\pm 5 \sigma$ around signal mass hypothesis

  o **Simultaneous fit of dimuon mass spectrum in all categories**
    ❖ Use **polynomial + exponential functional forms** to fit $m_{\mu\mu}$
    ❖ Determine best **order** via (modified) **F-test**
      ➢ Systematic uncertainty to account for choice (**discrete profiling**)
    ❖ Evaluate potential bias via extensive **bias tests**
    ❖ Cross-check goodness of fit (**GOF**) via **GOF test**

⇒ **Search for narrow resonant peak over background continuum**
Analysis strategy, with a cartoon

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\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{analysis_strategy_diagram.png}
\caption{Analysis strategy for dimuon mass distribution with different isolation muon bins and fit mass distribution, resulting in a mass/\(c\tau\) hypothesis.}
\end{figure}
A look at selected dimuon events: $p_T^{\mu\mu} \geq 25$ GeV, isolated topologies

- After full event selection, for isolated $2\mu$ events with $p_T^{\mu\mu} \geq 25$ GeV
  - Here, shown for $1.0 < l_{xy} < 2.4$ cm
  - Other distributions/categories available in backup
  - Enriched in $h \rightarrow Z_D Z_D$ signal

**CMS Preliminary** 101 fb$^{-1}$ (13 TeV)

- $l_{xy} \in [1, 2.4]$ cm
- $p_T^{\mu\mu} \geq 25$ GeV
- 2 iso. $\mu$

![Graph showing dimuon mass distribution](image-url)
A look at selected dimuon events:

\( p_T^{\mu\mu} < 25 \text{ GeV}, \) **isolated** topologies

- For **isolated** 2\( \mu \) events with \( p_T^{\mu\mu} < 25 \text{ GeV} \)
  - Here, shown for \( 0.2 < l_{xy} < 1.0 \text{ cm} \)
  - Other distributions/categories available in backup

→ Enriched in \( B \rightarrow \phi X \) signal

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**CMS Preliminary**

- 101 \( \text{fb}^{-1} \) (13 TeV)

- \( l_{xy} \in [0.2, 1] \text{ cm} \)
- \( p_T(\mu\mu) < 25 \text{ GeV} \)
- 2 iso. \( \mu \)

- Data
- \( B \rightarrow \phi (2 \text{ GeV}, cT=1 \text{ mm}), \sigma=1 \text{ pb} \)
- \( B \rightarrow \phi (4 \text{ GeV}, cT=10 \text{ mm}), \sigma=1 \text{ pb} \)
A look at selected dimuon events:

- For **non**-isolated 2μ events with $p_T^{\mu\mu} < 25$ GeV
  - Here, shown for $0.2 < l_{xy} < 1.0$ cm

- Other distributions/categories available in **backup**

- Non-negligible contribution from $B \rightarrow \phi X$ signal
Upper limits: $B(B \to \phi X) \cdot B(\phi \to \mu \mu)$

- Upper limits on $B(B \to \phi X) \cdot B(\phi \to \mu \mu)$, for $B$ inclusive production
  - Using only dimuon events
  - No assumption on $B(\phi \to \mu \mu)$

Other lifetime hypotheses are available in backup
Upper limits: $B(B \rightarrow \phi X) \cdot B(\phi \rightarrow \mu \mu)$

- How do we compare to others?

  • LHCb set limits on exclusive topologies ($B^0 \rightarrow \phi K^*0$ or $B^\pm \rightarrow \phi K^{\pm}$)
    ➢ Rescale our inclusive upper limits by fraction of $B^0$’s / $B^{\pm}$’s
    → Achieve better sensitivity than LHCb at increasing mass / lifetime

- Other lifetime hypotheses are available in backup
Upper limits on $B(B\rightarrow \phi X) \cdot B(\phi \rightarrow \mu \mu)$:

$c\tau_0\phi - m_\phi$ vs. $c\tau_0\phi$

- Limits at 95% CL on $B(B\rightarrow \phi X) \cdot B(\phi \rightarrow \mu \mu)$ in $c\tau_0\phi - m_\phi$ plane and vs. $c\tau_0\phi$
  - For $B \rightarrow \phi X$ signal, we probe $m_\phi$ in range $[0.3, 5]$ GeV and $c\tau_0\phi$ in range $[0.1, 100]$ mm
  - Background is $\sim 0$ at dimuon mass $\gtrsim 5$ GeV, while it is larger at lower dimuon mass
  - Background is lower at increasing displacement from interaction point
  - At low $m_\phi$, signal acceptance decreases due to $\phi$'s boost
    - At low $m_\phi$, constraints are stronger at low $c\tau_0\phi$
    - At high $m_\phi$, constraints are stronger at high $c\tau_0\phi$
Upper limits: $B(h \rightarrow Z_D Z_D) \cdot B(Z_D \rightarrow \mu \mu)$

- Upper limits on $B(h \rightarrow Z_D Z_D) \cdot B(Z_D \rightarrow \mu \mu)$
  - Using only dimuon events
  - No assumption on $B(Z_D \rightarrow \mu \mu)$

- Upper limits on $B(h \rightarrow Z_D Z_D) \cdot B(Z_D \rightarrow \mu \mu)$
  - Using only dimuon events
  - No assumption on $B(Z_D \rightarrow \mu \mu)$

Other lifetime hypotheses are available in backup
Using events with two muon pairs (=4µ) to further constrain \( h \rightarrow Z_D Z_D \) signal

- Background is \( \sim 0 \) at \( m_{\mu\mu} \gtrsim 5 \text{ GeV} \) in high \( p_T^{\mu\mu} \) isolated 2µ categories, while it increases at lower masses.

- 4µ channel is relatively free of background at low \( m_{\mu\mu} \) wrt. 2µ.

→ Can exploit selected 4µ events to further constrain \( h \rightarrow Z_D Z_D \) signal, despite acceptance penalty for \( h \rightarrow Z_D Z_D \rightarrow 4\mu \) due to \( B^2(\mu\mu) \).
  - Require all 4 µ’s to be isolated.
  - Require \( m_{4\mu} \) to be consistent with Higgs boson (h): \( 115 < m_{4\mu} < 135 \text{ GeV} \).
  - Require \( |m_{\mu\mu,1} - m_{\mu\mu,2}| / \langle m_{\mu\mu} \rangle < 5\% \).

→ Observe exactly zero events in 4µ event category.
Upper limits: $B(h \rightarrow Z_D Z_D)$

- Upper limits on $B(h \rightarrow Z_D Z_D)$
  - Using both 2$\mu$ and 4$\mu$ events
  - Using $B(Z_D \rightarrow \mu \mu)$ from JHEP 02 (2015) 157

- Other lifetime hypotheses are available in backup
Upper limits on $B(h \rightarrow Z_D Z_D)$:
$cT_0^{Z_D} - m_{Z_D} + v$s. $cT_0^{Z_D}$

- Limits at 95% CL on $B(h \rightarrow Z_D Z_D)$ in $cT_0^{Z_D} - m_{Z_D}$ plane and vs. $cT_0^{Z_D}$
  - For $h \rightarrow Z_D Z_D$ signal, we probe $m_{Z_D}$ in range $[0.6, 50]$ GeV and $cT_0^{Z_D}$ in range $[0.1, 10^4]$ mm
  - Background is $\sim 0$ at dimuon mass $\gtrsim 5$ GeV, while it is larger at lower dimuon mass
  - Background is lower at increasing displacement from interaction point
  - At low $m_{Z_D}$, signal acceptance decreases due to $Z_D$’s boost
  - At low $m_{Z_D}$, constraints are stronger at low $cT_0^{Z_D}$
  - At high $m_{Z_D}$, constraints are stronger at intermediate $cT_0^{Z_D}$
Upper limits on $B(h \rightarrow Z_DZ_D)$: $\varepsilon$ vs. $m_{Z_D}$

- A sample of previous results

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- Previous results from ATLAS and CMS, at $\sqrt{s} = 13$ TeV
  - $B(h \rightarrow Z_DZ_D) = 10\%$ at 90% CL:
    - Exclude $\varepsilon \gtrsim 3.5 \cdot 10^{-7}$ for $m_{Z_D} \gtrsim 0.9$ GeV (ATLAS)
    - Exclude $\varepsilon \gtrsim 10^{-7}$ for $m_{Z_D} \gtrsim 7$ GeV (CMS)

<Diagram with ATLAS and CMS results>

EPJC 80 (2020) 450

EPJC 80 (2020) 450

JPCL 80 (2020) 450

35.9 fb$^{-1}$ (13 TeV)
Upper limits on $B(h \rightarrow Z_D Z_D)$: $\varepsilon$ vs. $m_{Z_D}$

- How do we compare to previous results?

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• Compare upper limits at 95% CL to 90% CL limits from ATLAS and CMS

→ Achieve stronger constraints by $\sim 2x$ to $\sim 10x$

CMS Preliminary

$B(h \rightarrow Z_D Z_D)$

$gg \rightarrow h \rightarrow Z_D Z_D \rightarrow 2\mu \ 2X (X \neq \mu) + gg \rightarrow h \rightarrow Z_D Z_D \rightarrow 4\mu$

$B(Z_D \rightarrow \mu\mu)$ from JHEP 02 (2015) 157

Acceptance at $c t_0 Z_D > 10^4$ mm (i.e., very low $\varepsilon$) is $\sim 0$
• We provide **model-independent upper limits on number of events** in each of 20 non-exclusive dimuon aggregate regions

⇒ To favor **reinterpretations of our results**

❖ **CAVEAT**: constraints are less stringent than full analysis

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<th>(l_{xy}) range [cm]</th>
<th>(p_T^{\mu\mu}) [GeV]</th>
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<td></td>
<td>(\geq 25)</td>
<td>(\geq 2) (\geq 2) (\geq 2)</td>
</tr>
</tbody>
</table>

○ Using scouting data, this search can probe otherwise/previously inaccessible phase-space
  ➢ At low dimuon mass
  ➢ With nonzero displacement

○ Unprecedented sensitivity is achieved to range of BSM long-lived physics signatures

⇒ Usage and reinterpretation of results is (hopefully) valuable
- We provide model-independent upper limits on number of events in each of 20 non-exclusive dimuon aggregate regions
  - Together with efficiency maps
  - Instructions are available in backup
Summary & outlook

• Have presented preliminary results from CMS search EXO-20-014: search for long-lived dimuon resonances in CMS scouting data
  o First search for long-lived BSM signatures using scouting data
  o Preliminary results have recently become public
  o Additional material for reinterpretation of results is available

❖ Scouting data allowed to access otherwise inaccessible phase-space
➔ Achieved most stringent constraints on a range of BSM signatures

➢ Paper will follow shortly (to be submitted to JHEP)
  o Additional material will be uploaded to HEPData
  o In the meanwhile, please contact us for any input

• Outlook, towards the LHC Run-3 (and beyond):
  ➢ Scouting triggers have been extensively developed towards Run-3
    o In terms of trigger selection and object reconstruction
  ➢ Unprecedented chance to search so far unexplored phase-space!
The end... till the LHC Run-3

THANK YOU!
The Standard Model: a story of success… with its limitations – Dark matter

- The SM fails to provide a particle candidate for **dark matter** (DM)
  - From astrophysical and cosmological observations: $\text{DM} \sim 22\%$ of the Universe

**CREDITS:**
A note on $B \to \phi X$ MC simulation

- $B \to \phi X$ signal events are generated with PYTHIA 8.2
  - $X = K^+, K^0, \phi(ss), \Lambda, D_s^+$ for $B = B^+, B^0, B_s, \Lambda_b, B_c$

- $B$ signal MC is reweighted to FONLL
  - Absolute cross-section
  - $p_T$ spectrum of the $B$ hadron
A look at selected dimuon events: 
\( p_T^{\mu\mu} < 25 \text{ GeV}, \text{ isolated topologies} \) [all]

- For isolated 2\( \mu \) events with \( p_T^{\mu\mu} < 25 \text{ GeV} \)
  - Enriched in \( B \rightarrow \phi X \) signal
A look at selected dimuon events:

\[ p_T^{\mu\mu} \geq 25 \text{ GeV}, \text{ isolated topologies [all]} \]

- For isolated 2\(\mu\) events with \(p_T^{\mu\mu} \geq 25 \text{ GeV}\)
  - Enriched in \(h \to Z_D Z_D\) signal

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For non-isolated 2µ events with $p_T^{\mu\mu} < 25$ GeV

- Non-negligible contribution from $B \rightarrow \phi X$ signal
A look at selected dimuon events: 

\( p_T^{\mu\mu} \geq 25 \text{ GeV}, \) non-isolated topologies [all]

- For non-isolated 2\( \mu \) events with \( p_T^{\mu\mu} \geq 25 \text{ GeV} \)
A look at selected dimuon events:
\[ p_T^{\mu\mu} < 25 \text{ GeV}, \text{ partially isolated topologies [all]} \]

- **For partially isolated 2\(\mu\) events with \(p_T^{\mu\mu} < 25 \text{ GeV}\)**
A look at selected dimuon events:

$p_T^{\mu\mu} \geq 25$ GeV, partially isolated topologies [all]

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- For partially isolated 2µ events with $p_T^{\mu\mu} \geq 25$ GeV
Upper limits: $B(B \to \phi X) \cdot B(\phi \to \mu \mu)$ [all]

- Inclusive limits on $B(B \to \phi X) \cdot B(\phi \to \mu \mu)$
  - Using only dimuon events
  - No assumption on $B(\phi \to \mu \mu)$
Upper limits: $B(B \rightarrow \phi X) \cdot B(\phi \rightarrow \mu \mu)$

- How do we compare to others? [all]

- LHCb set limits on exclusive topologies ($B^0 \rightarrow \phi K^0$ or $B^\pm \rightarrow \phi K^\pm$)
  - Rescale our inclusive upper limits by fraction of $B^0$'s / $B^\pm$'s
  - Achieve better sensitivity than LHCb at increasing mass / lifetime
• Using only dimuon events
  ❖ No assumption on $B(Z_D \rightarrow \mu\mu)$

Upper limits: $B(h \rightarrow Z_D Z_D) \cdot B(Z_D \rightarrow \mu\mu)$ [all]
• Using both **dimuon** and **4μ** events

- Using $B(Z_D \rightarrow \mu \mu)$ from [JHEP 02 (2015) 157](https://link.springer.com/article/10.1007%2FJHEP02%282015%29157)
Material for reinterpretation: instructions

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- We provide model-independent upper limits on number of events in each of 20 non-exclusive dimuon aggregate regions
  - Together with efficiency maps

<table>
<thead>
<tr>
<th>$l_{xy}$ range [cm]</th>
<th>$p_T^{\mu\mu}$ [GeV]</th>
<th>Number of isolated muons</th>
</tr>
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<tbody>
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<td>$\geq 0$</td>
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<tr>
<td></td>
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<td></td>
<td>$\geq 25$</td>
<td>$\geq 0$</td>
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</tbody>
</table>

How to use:

1. Select “best” aggregate signal region, based on signal of interest
2. Evaluate trigger selection efficiency
3. Evaluate signal selection efficiency
4. Use selected aggregate signal region and selection efficiency for reinterpretation of our results
Material for reinterpretation: selection efficiency maps

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0 < $m_{\mu\mu}$ < 3 GeV

3 < $m_{\mu\mu}$ < 10 GeV

$m_{\mu\mu}$ > 10 GeV
Model-independent upper limits: no $\mu$ isolation requirement, $p_T^{\mu\mu} \geq 0$ GeV

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Model-independent upper limits: with two isolated $\mu$s, $p_T^{\mu\mu} \geq 0$ GeV

Mario Masciovecchio (UCSD); June 22nd, 2021
Model-independent upper limits: no $\mu$ isolation requirement, $p_T^{\mu\mu} \geq 25$ GeV

Mario Masciovecchio (UCSD); June 22$^{nd}$, 2021
Model-independent upper limits: with two isolated $\mu$s, $p_T^{\mu\mu} \geq 25$ GeV

Mario Masciovecchio (UCSD); June 22$^{nd}$, 2021