WHAT ARE DARK SECTORS?

- New set of particles typically charged under some “dark” forces
- Weak coupling (mediator or mixing or loop-induced) allows interactions between the SM and the dark sector
Kinetic mixing: dark photon mixes with standard photon and induces coupling to fermions

\[ \mathcal{L} \supset -\frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} \quad \Rightarrow \quad \mathcal{L} \supset \epsilon e \bar{\phi} \gamma^\mu \phi A'_\mu \]
CMS SEARCHES FOR DARK SECTORS

Higgs portal

\[ Z(l^+l^-)H(\gamma \gamma_D) \text{ [EXO-19-007]} \]
\[ H(\text{inv.}) \text{ [arXiv:1809.05937]} \]
\[ H \rightarrow \gamma_D \gamma_D + X \rightarrow 4\mu + X \text{ [arXiv:1812.00380]} \]

A. Hall Thurs. PM
CMS SEARCHES FOR DARK SECTORS

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A. Hall Thurs. PM

Dark QCD mediator

emerging jets [JHEP 02 (2019) 179]

semi-visible jets

M. Kazana Thurs. PM
CMS SEARCHES FOR DARK SECTORS

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**Minimal dark photon**

high mass dilepton [JHEP 06 (2018) 120]
low mass dimuon (data scouting)

**Dark QCD mediator**

emerging jets [JHEP 02 (2019) 179]
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high mass dilepton [JHEP 06 (2018) 120]
low mass dimuon (data scouting)

Dark QCD mediator

emerging jets [JHEP 02 (2019) 179]
semi-visible jets

M. Kazana Thurs. PM

Simplified DM mediator

boosted dijet+jet [EXO-18-012]
boosted bb+jet [PRD 99, 012005 (2019)]
boosted dijet+\(\gamma\) [EXO-17-027]
dijet [EXO-17-026]
monojet [PRD 97, 092005 (2018)]
mono Higgs [EXO-18-011]

D. Yu Tues. AM
1. DARK PHOTONS IN ZH DECAYS

2. DARK QCD WITH EMERGING JETS

3. OUTLOOK
HIGGS DECAY TO PHOTON + DARK PHOTON

- \( H \rightarrow \gamma \gamma_D \) induced at loop level (no kinetic mixing) [arXiv:1603.01377]

- ZH production mode with \( Z \rightarrow l^+l^- \)
  - Signature: \( Z(l^+l^-) + \gamma + p_T^{miss} \)

- Main backgrounds:
  - Nonresonant: top, WW
  - Resonant (3l): WZ
  - Resonant (2l + \( \gamma \)): WZ, ZZ
  - Resonant (no MET): \( Z \gamma \), Z+jets
  - Other: VVV
Selection to reduce $Z\gamma$ and $Z+$jets to < 5% of total background

<table>
<thead>
<tr>
<th>Variable</th>
<th>Selection</th>
<th>Reject</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
<td>2 leptons, $p_T &gt; 25/20$ GeV</td>
<td>WZ, ZZ, VVV</td>
</tr>
<tr>
<td>Photons</td>
<td>1 photon, $E_T^\gamma &gt; 25$ GeV</td>
<td>All but $Z\gamma$</td>
</tr>
<tr>
<td>$</td>
<td>m_{\ell\ell} - m_Z</td>
<td>$</td>
</tr>
<tr>
<td>Anti b tagging</td>
<td>Applied medium working point</td>
<td>Top-quark, VVV</td>
</tr>
<tr>
<td>Jet counting</td>
<td></td>
<td>Top-quark, VVV</td>
</tr>
<tr>
<td>$\Delta \phi_{\ell\ell,\mathcal{P}_T^{miss}+E_T^\gamma}$</td>
<td>&gt; 2.5 radians</td>
<td>$Z\gamma$</td>
</tr>
<tr>
<td>$</td>
<td>\mathcal{P}_T^{miss}+E_T^\gamma - \mathcal{P}_T^{ell}</td>
<td>/\mathcal{P}_T^{ell}$</td>
</tr>
<tr>
<td>$\Delta \phi_{\text{jet},\mathcal{P}_T^{miss}}$</td>
<td>&gt; 0.5</td>
<td>$Z\gamma$</td>
</tr>
<tr>
<td>$\mathcal{P}_T^{ell}$</td>
<td>&gt; 60 GeV</td>
<td>$Z\gamma$</td>
</tr>
<tr>
<td>$m_{\ell\ell\gamma}$</td>
<td>&gt; 100 GeV</td>
<td>$Z\gamma$</td>
</tr>
<tr>
<td>$\mathcal{P}_T^{miss}$</td>
<td>&gt; 110 GeV</td>
<td>$Z\gamma$</td>
</tr>
<tr>
<td>$m_T$</td>
<td>&lt; 350 GeV</td>
<td>WW, top-quark</td>
</tr>
</tbody>
</table>

4 Background estimation

A combination of data-based methods and detailed simulation studies is used to estimate background contributions. Uncertainties related to the theoretical and experimental predictions are taken into account, as described in Section 6. Background contributions are categorized based on whether they produce at least one lepton pair from the decay of a Z boson (resonant contributions) or no such lepton pair (nonresonant contributions). The expected yield for the irreducible background from $H\rightarrow ZZ\rightarrow 4\ell$ is less than 0.1 events and is therefore ignored in the analysis.

4.1 Nonresonant dilepton backgrounds

The contribution from nonresonant dilepton background, mostly $W^+W^-$ and top-quark processes, is estimated by exploiting the lepton flavor symmetry in the final states of these processes [44]. The branching fraction to the $e^\pm\mu^\pm$ final state is twice that of the $e^+e^-$ or $\mu^+\mu^-$ final states. Therefore, the $e^\pm\mu^\pm$ control region is used to extrapolate these backgrounds to the $e^+e^-$ and $\mu^+\mu^-$ channels. The method considers differences between the electron and muon identification efficiencies when extrapolating from the different-flavor final states to the same-flavor final states. The data driven estimates agree well with the number of background events expected when applying the same method to the simulation. After the full selection, but requiring $e\mu$ pairs, 2.8 $\pm$ 0.5 (stat.) events are expected from the simulation while 3 events are observed in data.
**EVENT SELECTION**

- Selection to reduce $Z\gamma$ and $Z+$jets to $< 5\%$ of total background
- Key analysis variables: $m_T$ and $|\eta_\gamma|$

$\begin{align*}
m_T &= \sqrt{2p_T^{\text{miss}}E_T^\gamma[1 - \cos(\Delta\phi_{\vec{p}_T^{\text{miss}}, \vec{E}_T^\gamma})]}\end{align*}$
## EVENT SELECTION

- **Selection to reduce $Z\gamma$ and $Z+$jets to < 5% of total background**

- **Key analysis variables:** $m_T$ and $|\eta|$

### Table 1: Summary of the selection and the main background processes rejected by a given variable.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Selection</th>
<th>Reject</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
<td>2 leptons, $p_T &gt; 25/20$ GeV</td>
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</tr>
<tr>
<td>Photons</td>
<td>$\geq 1$ photon, $E_T^\gamma &gt; 25$ GeV</td>
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<td>$</td>
<td>m_{\ell\ell} - m_Z</td>
<td>$</td>
</tr>
<tr>
<td>Anti b tagging</td>
<td>Applied medium working point $\leq 2$</td>
<td>Top-quark, VVV</td>
</tr>
<tr>
<td>Jet counting</td>
<td>$\Delta \phi_{\ell\ell, p_T^{miss} + E_T^\gamma} &gt; 2.5$ radians</td>
<td>$Z\gamma$</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>p_T^{miss} + E_T^\gamma - p_T^{\ell\ell}</td>
</tr>
<tr>
<td></td>
<td>$\Delta \phi_{\ell\ell, p_T^{miss}} &gt; 0.5$</td>
<td>$Z\gamma$</td>
</tr>
<tr>
<td></td>
<td>$p_T^{\ell\ell} &gt; 60$ GeV</td>
<td>$Z\gamma$</td>
</tr>
<tr>
<td></td>
<td>$m_{\ell\ell\gamma} &gt; 100$ GeV</td>
<td>$Z\gamma$</td>
</tr>
<tr>
<td></td>
<td>$p_T^{miss} &gt; 110$ GeV</td>
<td>$Z\gamma$</td>
</tr>
<tr>
<td></td>
<td>$m_T &lt; 350$ GeV</td>
<td>WW, top-quark</td>
</tr>
</tbody>
</table>

$$ m_T = \sqrt{2p_T^{miss}E_T^\gamma[1 - \cos(\Delta \phi_{p_T^{miss}, E_T^\gamma})]} $$

- **Control regions isolate $WZ$, $ZZ$, and top/WW backgrounds for data-driven estimate**
WZ region: lepton from W instead of photon satisfies selection criteria
CONTROL REGIONS

WZ region: lepton from W instead of photon satisfies selection criteria

ZZ region: dilepton from Z instead of photon satisfies selection criteria
**WZ region:**
lepton from W instead of photon satisfies selection criteria

**ZZ region:**
dilepton from Z instead of photon satisfies selection criteria

**CMS Preliminary**

**eμ region:**
opposite flavor instead of same flavor dilepton
Signal \((m_H = 125 \text{ and } 200 \text{ GeV})\) with \(B(H \to \text{inv. } + \gamma) = 10\%\)

- No excess observed

**SIGNAL REGIONS**

![Graph](image_url)

137.4 fb\(^{-1}\) (13 TeV)
## RESULTS

### Process Yields

<table>
<thead>
<tr>
<th>Process</th>
<th>Yields</th>
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</thead>
<tbody>
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<td>Data</td>
<td>14</td>
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<tr>
<td>Nonresonant bkg.</td>
<td>2.4 ± 1.1</td>
</tr>
<tr>
<td>WZ</td>
<td>8.1 ± 2.0</td>
</tr>
<tr>
<td>ZZ</td>
<td>1.5 ± 0.3</td>
</tr>
<tr>
<td>Zγ</td>
<td>0.7 ± 0.7</td>
</tr>
<tr>
<td>Other bkg.</td>
<td>0.6 ± 0.3</td>
</tr>
<tr>
<td>Total bkg.</td>
<td>13.3 ± 3.8</td>
</tr>
<tr>
<td>ZH125 (BR=10%)</td>
<td>17.9 ± 1.2 (1.42 ± 0.09 %)</td>
</tr>
<tr>
<td>ZH200 (BR=10%)</td>
<td>12.3 ± 0.8 (4.32 ± 0.28 %)</td>
</tr>
<tr>
<td>ZH300 (BR=10%)</td>
<td>3.9 ± 0.2 (6.80 ± 0.34 %)</td>
</tr>
</tbody>
</table>

- **Observed (expected)** 95% CL upper limit for 125 GeV Higgs $B(H \to \text{inv. } + \gamma) < 4.6\%$ (3.6\%)

- First upper limits on final states with undetected dark photons using Higgs boson decays at the LHC!
Q_{DK} fermions charged under dark QCD $SU(N_{C_{DK}})$

$X_{DK}$ mediator charged under both QCD and dark QCD
- $X_{DK}$ pair produced in gluon fusion or quark-antiquark annihilation
- Decays to $Q_{DK}$ $q$
EMERGING JETS

\(X_{DK}\) pair produced in gluon fusion or quark-antiquark annihilation

- Decays to \(Q_{DK} q\)

- Dark mesons and dark baryons form which decay to SM hadrons after non-negligible lifetime

- Lightest dark pion lifetime (probe 1-10^3 mm)

\[c\tau \approx 80 \text{ mm} \left( \frac{1}{\kappa^4} \right) \left( \frac{2 \text{ GeV}}{f_{\pi_{DK}}} \right)^2 \left( \frac{100 \text{ MeV}}{m_{\text{down}}} \right)^3 \left( \frac{2 \text{ GeV}}{m_{\pi_{DK}}} \right) \left( \frac{m_{X_{DK}}}{1 \text{ TeV}} \right)^4\]

- Emerging jets!
Tag emerging jets using track impact parameter variables

CMS Simulation

- QCD light jets
- Dark pion mass 1 GeV
- Dark pion mass 2 GeV
- Dark pion mass 5 GeV
- Dark pion mass 10 GeV

\( cT = 25 \text{ mm} \)
Tag emerging jets using track impact parameter variables

Require 4 jets with

- 2 tagged emerging jets
- 1 tagged and $p_T^{\text{miss}} > 200$ GeV for large $c\tau$
- trigger on $H_T = \sum p_T(j_{1,2,3,4})$

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QCD light jets
- Dark pion mass 1 GeV
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- Categorize with tagging WPs and kinematic selection $\rightarrow$ 7 signal regions
Tag emerging jets using track impact parameter variables

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  - 1 tagged and $p_T^{\text{miss}} > 200$ GeV for large $c\tau$
  - trigger on $H_T = \sum p_T(j_{1,2,3,4})$

- Categorize with tagging WPs and kinematic selection → 7 signal regions

- Background estimation: misid. rate (from $\gamma$ CR) × QCD CR yield = SR yield
RESULTS

- Observed data agree with background predictions (within uncertainties)
- Limits do not depend strongly on $m_{\pi_{DK}}$
- Exclude $m_{X_{DK}}$ between 400 and 1250 GeV for $c\tau_{\pi_{DK}}$ between 5 and 225 mm

<table>
<thead>
<tr>
<th>Set number</th>
<th>Expected</th>
<th>Observed</th>
<th>Signal</th>
<th>$m_{X_{DK}}$ [GeV]</th>
<th>$m_{\pi_{DK}}$ [GeV]</th>
<th>$c\tau_{\pi_{DK}}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>168 ± 15 ± 5</td>
<td>131</td>
<td>36.7 ± 4.0</td>
<td>600</td>
<td>5</td>
<td>1</td>
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<tr>
<td>2</td>
<td>31.8 ± 5.0 ± 1.4</td>
<td>47</td>
<td>(14.6 ± 2.6) × 10^2</td>
<td>400</td>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>19.4 ± 7.0 ± 5.5</td>
<td>20</td>
<td>15.6 ± 1.6</td>
<td>1250</td>
<td>1</td>
<td>150</td>
</tr>
<tr>
<td>4</td>
<td>22.5 ± 2.5 ± 1.5</td>
<td>16</td>
<td>15.1 ± 2.0</td>
<td>1000</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>13.9 ± 1.9 ± 0.6</td>
<td>14</td>
<td>35.3 ± 4.0</td>
<td>1000</td>
<td>2</td>
<td>150</td>
</tr>
<tr>
<td>6</td>
<td>9.4 ± 2.0 ± 0.3</td>
<td>11</td>
<td>20.7 ± 2.5</td>
<td>1000</td>
<td>10</td>
<td>300</td>
</tr>
<tr>
<td>7</td>
<td>4.40 ± 0.84 ± 0.28</td>
<td>2</td>
<td>5.61 ± 0.64</td>
<td>1250</td>
<td>5</td>
<td>225</td>
</tr>
</tbody>
</table>
1. DARK PHOTONS IN ZH DECAYS

2. DARK QCD WITH EMERGING JETS

3. OUTLOOK
Standard dilepton triggers have thresholds of 10–20 GeV on lepton $p_T$.

Difficult to trigger at lower dilepton mass offline $m_{\mu\mu} < 40$ GeV.
Standard dilepton triggers have thresholds of 10–20 GeV on lepton $p_T$

Difficult to trigger at lower dilepton mass offline $m_{\mu\mu} < 40$ GeV

LHCb best sensitivity for $m_{\mu\mu} > 10$ GeV

[**PRL 120, 061801**]
Data scouting: record less information per event to decrease event size and increase data rate

Potential to improve CMS sensitivity to low-mass dimuon resonances

Challenges: lower resolution, custom calibration, muon ID, larger background
MUON DATA SCOUTING

- Data scouting: record less information per event to decrease event size and increase data rate
- Potential to improve CMS sensitivity to low-mass dimuon resonances
- Challenges: lower resolution, custom calibration, muon ID, larger background

Online $m_{\mu\mu} < 10$ GeV:
L1:
$\Delta R_{\mu\mu} < 1.4$ and $p_T^{\mu} > 4$ GeV or $|\eta^{\mu}| < 1.5$

L1-Trigger Selection Requirements
- $\mu^+ \mu^-$ invariant mass [GeV]

Online Reconstructed Dimuon Events

CMS Preliminary

35 fb$^{-1}$ (13 TeV, 2017)
MUON DATA SCOUTING

- Data scouting: record less information per event to decrease event size and increase data rate
- Potential to improve CMS sensitivity to low-mass dimuon resonances
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L1-Trigger Selection Requirements

Online $m_{\mu\mu} < 10$ GeV:
L1:
$\Delta R_{\mu\mu} < 1.4$ and $p_T^{\mu} > 4$ GeV or $|\eta^{\mu}| < 1.5$

Online $m_{\mu\mu} 10-20$ GeV:
L1:
$7 < m_{\mu\mu} < 18$ GeV and $p_T^{\mu} > 4.5$ GeV

35 fb$^{-1}$ (13 TeV, 2017)
Data scouting: record less information per event to decrease event size and increase data rate

Potential to improve CMS sensitivity to low-mass dimuon resonances

Challenges: lower resolution, custom calibration, muon ID, larger background
CMS has a broad program of searches for dark sectors
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- Higgs portal: first limits on final states with undetected dark photons using Higgs decays at the LHC
  - Full LHC Run 2 data!
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  - Full LHC Run 2 data!

- Dark QCD: unique *emerging jet* signature excludes dark sector with mediator masses between 400 and 1250 GeV and dark pion lifetimes between 5 and 225 mm

- Minimal dark photon: low-mass dimuon search with data scouting forthcoming!
REFERENCES

- EXO-18-001: [JHEP 02 (2019) 179](http://dx.doi.org/10.1007/JHEP02(2019)179)
- EXO-16-047: [JHEP 06 (2018) 120](http://dx.doi.org/10.1007/JHEP06(2018)120)
- HIG-17-023: [accepted by PLB](http://dx.doi.org/10.1007/JHEP06(2018)120)
### Results

#### Best signal region sensitivity

<table>
<thead>
<tr>
<th>Criteria group</th>
<th>$PU_{4z}$ ($&lt;$) [cm]</th>
<th>$D_{N} (&lt;)$</th>
<th>$\langle IP_{2D} \rangle$ ($&gt;$) [cm]</th>
<th>$\alpha_{3D} (&lt;)$</th>
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<tr>
<td>EMJ-1</td>
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<td>0.05</td>
<td>0.25</td>
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<td>EMJ-2</td>
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<td>EMJ-3</td>
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<td>0.05</td>
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<table>
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<tr>
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<th>$p_{T,1}$</th>
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</table>

### Table 6: Expected (mean $\pm$ uncertainty) event yields for each selection set. Un-
suppressed systematic uncertainties from sources discussed in Table 4. The “Signal” column shows the expected

event yield for the heaviest mediator mass that can be excluded for each set, with the systematic

certainties due to the limited number of events in the control sample and statistical uncertain-

<table>
<thead>
<tr>
<th>Set number</th>
<th>Expected $m_{X_{DK}}$ [GeV]</th>
<th>Expected $m_{\tau_{DK}}$ [GeV]</th>
<th>Expected $c\tau_{\tau_{DK}}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>168 ± 15 ± 5</td>
<td>131</td>
<td>36.7 ± 4.0</td>
</tr>
<tr>
<td>2</td>
<td>31.8 ± 5.0 ± 1.4</td>
<td>47</td>
<td>(14.6 ± 2.6)×10²</td>
</tr>
<tr>
<td>3</td>
<td>19.4 ± 7.0 ± 5.5</td>
<td>20</td>
<td>15.6 ± 1.6</td>
</tr>
<tr>
<td>4</td>
<td>22.5 ± 2.5 ± 1.5</td>
<td>16</td>
<td>15.1 ± 2.0</td>
</tr>
<tr>
<td>5</td>
<td>13.9 ± 1.9 ± 0.6</td>
<td>14</td>
<td>35.3 ± 4.0</td>
</tr>
<tr>
<td>6</td>
<td>9.4 ± 2.0 ± 0.3</td>
<td>11</td>
<td>20.7 ± 2.5</td>
</tr>
<tr>
<td>7</td>
<td>4.40 ± 0.84 ± 0.28</td>
<td>2</td>
<td>5.61 ± 0.64</td>
</tr>
</tbody>
</table>

| Model parameters |
|------------------|------------------|------------------|
| $m_{X_{DK}}$ [GeV] | $m_{\tau_{DK}}$ [GeV] | $c\tau_{\tau_{DK}}$ [mm] |
| 600              | 5                | 1                |
| 400              | 1                | 60               |
| 1250             | 1                | 150              |
| 1000             | 1                | 2                |
| 1000             | 2                | 150              |
| 1000             | 10               | 300              |
| 1250             | 5                | 225              |
Dark SUSY cascade decay

\[ h \rightarrow 2n_1 \rightarrow 2\gamma_D + 2n_D \rightarrow 4\mu + X \]
1. The dark photon can decay into various final states, with branching fractions depending on the dark photon mass.

2. The dark photon could be massive or massless, as in the case of [17].

3. Electrically milli-charged particles [19] are represented by all the particles in the dark sector that couple to $A'$. 

4. In the described model, all the processes are determined by the single parameter, the mixing $\epsilon$. As a result, the model benefits from high predictivity and this is the reason why the kinetic mixing is usually used as a benchmark model describing the phenomenology of the dark photon as a whole.

5. An example for this is the partial decay width of the dark photon, which in the case of $M_{A'} > 2m_l$ and $l^+l^-$ pair in the final state is given by [20]

$$\Gamma_{A' \rightarrow l^+l^-} = \frac{1}{3} \frac{\alpha^2 M_{A'}}{\sqrt{1 - 4m_l^2 M_{A'}^2}} \left(1 + \frac{2m_l^2 M_{A'}^2}{1 + 2m_l^2 M_{A'}^2}\right)^{3/2},$$

(9)

while for hadrons it can be written as

$$\Gamma_{A' \rightarrow \text{hadrons}} = \frac{1}{3} \frac{\alpha^2 M_{A'}}{\sqrt{1 - 4m_\mu^2 M_{A'}^2}} \Gamma(e^+e^- \rightarrow \text{hadrons}) \Gamma(\mu^+\mu^- \rightarrow \text{hadrons})(E = M_{A'}).$$

(10)

6. Summarizing eqs. (9) and (10), the decay fraction of the dark photon into Standard Model particles is shown in fig. 1.
• **Generalize** \( H(bb) \) search for spin-0 dark mediators \( \Phi/A(bb) \) from 50 to 350 GeV

• Larger masses require using a **larger jet** cone, re-optimizing substructure cuts, and **re-training** the double-b tagger
• **Pseudoscalar** $A(bb)$ hypothesis at 260 GeV

• Sensitive to $O(1)$ couplings between mediator and SM
SEARCHING FOR $\Phi(B\bar{B})$

$$\mathcal{L}_A = ig_A A A \bar{X} \gamma_5 X + \frac{i}{\sqrt{2}} \sum_f g_{qA} y_f \bar{f} \gamma_5 f$$

CMS

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

- Observed
- Expected ± 1 s.d.
- Expected ± 2 s.d.

$2 f \quad L_A = ig_A A A \bar{X} \gamma_5 X + \frac{i}{\sqrt{2}} \sum_f g_{qA} y_f \bar{f} \gamma_5 f$
THE LARGE HADRON COLLIDER
THE LARGE HADRON COLLIDER

proton-proton collider @ 13 TeV center-of-mass energy
THE LARGE HADRON COLLIDER

proton-proton collider @ 13 TeV center-of-mass energy
4 interaction points
proton-proton collider @ 13 TeV center-of-mass energy
4 interaction points
40 million collisions / second
THE LARGE HADRON COLLIDER

proton-proton collider @ 13 TeV center-of-mass energy
4 interaction points
40 million collisions / second
trigger selects ~1000 collisions / second
proton-proton collider @ 13 TeV center-of-mass energy
4 interaction points
40 million collisions / second
trigger selects ~1000 collisions / second
COMPACT MUON SOLENOID

Specialized components to measure different particles

CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm) ~16m² ~66M channels
- Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
- Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO₄ crystals

HADRonen CALORIMETER (HCAL)
- Brass + Plastic scintillator ~7,000 channels

100 million channels
Quarks and gluons interact via the strong force and are never seen in isolation → become *jets* of hadrons (bound states)
Quarks and gluons interact via the strong force and are never seen in isolation → become jets of hadrons (bound states)
HOW CMS SEES QUARKS AND GLUONS

- Quarks and gluons interact via the strong force and are never seen in isolation → become *jets* of hadrons (bound states)

- Cluster the tracks and energy into a cone-shaped jet
HOW DO WE PRODUCE HIGGS BOSONS AT THE LHC?

Table 11.1: State-of-the-art of the theoretical calculations in the main Higgs production channels in the SM, and the major MC tools used in the simulations

- **Fixed order:**
  - NNLO QCD + NLO EW
  - NLO QCD
  - POWHEG

- **Resummed:**
  - NNLO + NNLL QCD
  - NLO QCD + NLO EW
  - VH@NNLO

- **Higgs:**
  - NNLO+NNLL

- **Jet Veto:**
  - N3LO+NNLL

**Figure 11.1:** Main Leading Order Feynman diagrams contributing to the Higgs production in (a) gluon fusion, (b) Vector-boson fusion, (c) Higgs-strahlung (or associated production with a gauge boson), (d) associated production with a pair of top (or bottom) quarks, (e-f) production in association with a single top quark.
LHC mostly collides **gluons**, which don’t interact directly with the Higgs.
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But interactions can be “generated” through virtual **particles**, like the **top quark**
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- But interactions can be “generated” through **virtual particles**, like the **top quark**
- Could new **even heavier** particles contribute?

$$g \rightarrow t \rightarrow H$$

$$g \rightarrow g$$
LHC mostly collides **gluons**, which don’t interact directly with the Higgs

- But interactions can be “generated” through *virtual particles*, like the **top quark**

- Could new **even heavier** particles contribute?

*Figure 11.1: Main Leading Order Feynman diagrams contributing to the Higgs strahlung (or production with a pair of top quarks).*

*Table 11.1: Production channels in the SM, and the major MC tools used in the simulations.*

If the new particle is too heavy to be produced, this looks like a new interaction!
Ref. [36–38]. These references also contain state of the art on the determination of SM parameters involved in the calculations, as summarized in Fig. 11.3 [39]. A detailed discussion, including the impact of loop corrections to the Higgs boson decay rates, is desirable to solve other outstanding problems concerning Higgs physics. Theoretical calculations due to missing higher order effects in (a) gluon fusion, (b) weak-boson fusion, (c) Higgs-strahlung (or associated production with a gauge boson) and (d) associated production with top quarks. Figure 11.2 depicts representative diagrams contributing to the Higgs production cross sections, which, with an emphasis on generic Feynman diagrams, can be found in Refs. [32–38].

Table 11.1, from Refs. [36,38], summarizes the Higgs boson production processes, including bands indicating the theoretical uncertainties, PDF's uncertainties, QCD scale uncertainties and experimental uncertainties, as well as uncertainties due to hadronization and parton-shower simulations. August 21, 2014 13:18

How do we detect Higgs bosons?

The main production mechanisms at the Tevatron and the LHC are gluon fusion, weak-boson fusion, associated production with a gauge boson, and Higgs-strahlung (or associated production with top quarks). Figure 11.2:

The cross sections for the production of a SM Higgs boson as a function of mass energy, for example, with an emphasis on generic Feynman diagrams contributing to the Higgs production cross sections, which, with an emphasis on generic Feynman diagrams, can be found in Refs. [32–38].
II.4. Higgs production and decay mechanisms

The main production mechanisms at the Tevatron and the LHC are gluon fusion, weak-boson fusion, Higgs-strahlung, and associated production with a gauge boson (or associated production with top quarks). Figure 11.2 depicts representative diagrams for these processes:

- **Gluon Fusion** (87%)
- **Weak-Boson Fusion**
- **Higgs-Strahlung**
- **Associated Production**

The cross sections for the production of a SM Higgs boson as a function of mass energy, for production processes, can be found in Refs. [32–38]. These references also contain state of the art assessments of theoretical calculations due to missing higher order corrections and uncertainties in the theoretical calculations due to missing higher order effects. Procedures when including higher order corrections match PDF's uncertainties, QCD scale uncertainties and uncertainties due to hadronization and parton-shower simulations.

Higgs boson discovery at the LHC leaves all these options open. Still, physics at lower energies, with an emphasis on the determination of SM parameters involved in the calculation of mass energy, for production processes, can be found in Refs. [36–38]. These references also contain state of the art assessments of theoretical calculations due to missing higher order effects.

Mysteries of the universe such as dark matter or the matter-antimatter asymmetry are desirable to solve other possible flat directions. Still, physics at lower energies, with an emphasis on the determination of SM parameters involved in the calculation of mass energy, for production processes, can be found in Refs. [32–38]. These references also contain state of the art assessments of theoretical calculations due to missing higher order effects.
Luminosity ($L$) ~ number of collisions per unit time