Searching for New Dimuon Resonances at the LHC with CMS Open Data

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4 Center for Theoretical Physics, MIT
CERN Open Data Portal: http://opendata.cern.ch/

What is Open Data?

- LHC data publicly available for long term archive
- Research grade data from CMS made public in 2014
  CMS Run 2011a: $\sqrt{s} = 7$ TeV, $\mathcal{L} = 2.11$ fb$^{-1}$, 13$\mu$8$\mu$ Trigger
What is Open Data?

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- Research grade data from CMS made public in 2014
  CMS Run 2011a: $\sqrt{s} = 7$ TeV, $\mathcal{L} = 2.11$ fb$^{-1}$, 13µ8µ Trigger
- First ever BSM search with LHC Open Data
New Physics at LHC

Where can we look for new physics?

- LHC is powerful probe in energy, intensity frontier
- Might have looked in the wrong place for new physics
  → How you look determines what you find
  → New physics signature buried in phase space

Consider motivated, model independent extensions of SM: new physics with dimuon signatures and substantial $p_T^{\mu\mu}$
We propose a model independent search strategy that increases sensitivity for semi-inclusive searches with indirect production of new particle $V \rightarrow \mu^+ \mu^-$.
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- Produced via decay: substantial $p_T^V$ from recoil
- Cut on $p_T^{\mu\mu}$ preserves signal while reducing background (Strassler, 2008, 2010 conference talks)
We propose a model independent search strategy that increases sensitivity for semi-inclusive searches with indirect production of new particle $V \rightarrow \mu^+ \mu^-$

- Produced via decay: substantial $p_T^V$ from recoil
- Cut on $p_T^{\mu\mu}$ preserves signal while reducing background (Strassler, 2008, 2010 conference talks)
- Further reduce background: isolation and promptness cuts
  $\rightarrow$ Need Open Data to understand prompt
New Physics at LHC

Previous searches at ATLAS & CMS with dimuons: $m_{\mu\mu}$ resonances

- **High-mass**: $m_{Z'} \in [120 \text{ GeV}, 3.36 \text{ TeV}]$
- **Pairs of light bosons**: $m_{Z'} \in [0.25, 8.5] \text{ GeV}$
- **Dimuon + b jets**: $m_{\mu\mu} \in [12, 70] \text{ GeV}$
  \[ \rightarrow 28 \text{ GeV excess} \]
(CMS, 1609.05391, 1812.00380, 1808.01890)

LHCb performed **inclusive** search for light new physics from **direct production** in $pp$ collisions

- **10.6 \text{ GeV} < m_\phi < 70 \text{ GeV}**
  
  (LHCb, 1710.02867)
We are considering a new vector particle $V$ produced via decay, therefore with substantial $p_T^V$.

- Decays to dimuon pairs ($\mu^+\mu^-$)
- Produced by SM ($W/Z$/Higgs/$t$) or new particle
- Probing mass range of 14 GeV to 66 GeV
New Physics Search

Dominant backgrounds for $V \rightarrow \mu\mu$ channel

Drell-Yan

Heavy Flavor (QCD)

Further suppressed by isolation or promptness cuts

Suppressed by $p_T^{\mu\mu}$ cuts
<table>
<thead>
<tr>
<th>Isolated</th>
<th>Prompt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both $\mu$ are isolated in detector</td>
<td>No isolation cut imposed</td>
</tr>
<tr>
<td>Virtually eliminates QCD background $p + p \rightarrow \mu^+ \mu^-$</td>
<td>$IP_{xy} &lt; 100 \mu m$</td>
</tr>
<tr>
<td></td>
<td>QCD bgd. $\sim$ DY bgd.</td>
</tr>
</tbody>
</table>
Isolated vs. Prompt Sample

Isolated

- Both $\mu$ are isolated in detector
- Virtually eliminates QCD (heavy flavor) background

Prompt

$\mu^+$ $\mu^−$ $\mu^+$ $\mu^−$ $p^+$ $p^+$
Isolated vs. Prompt Sample

**Isolated**

- Both $\mu$ are isolated in detector
- Virtually eliminates QCD (heavy flavor) background

**Prompt**

- No isolation cut imposed
- $IP_{xy} < 100\mu m$
- QCD bgd. $\sim$ DY bgd.
- **Need Open Data to understand**
General Search Strategy

New, largely model-independent, analysis strategy for limits on:

\[ \frac{N_V}{\mathcal{L}} = \sigma (pp \rightarrow V + X) \mathcal{B} (V \rightarrow \mu^+ \mu^-) A_V \epsilon_{tr} \epsilon_{iso} \]

**Goal:** Increase sensitivity by imposing \( p_T^{\mu \mu} \) cuts.

- Dimuon trigger \((p_T^{1,2} > 13, 8 \text{ GeV})\)
- Only opposite-sign (OS) muons
- Define **isolated** and **prompt** samples
- Apply increasingly restrictive \( p_T^{\mu \mu} \) cuts (substantial \( p_T^V \))
  \[ \rightarrow p_T^{\mu \mu} > 25 \text{ GeV}, > 60 \text{ GeV} \]
- Look for a bump
Prompt vs. Isolation

Isolated Sample

2011 CMS Open Data
7 TeV, 2.11 fb⁻¹
Isolated Samples (CMS11a)

- no $p_T^{\mu\mu}$ cut
- $p_T^{\mu\mu} > 25$ GeV
- $p_T^{\mu\mu} > 60$ GeV

Prompt Sample

2011 CMS Open Data
7 TeV, 2.11 fb⁻¹
Prompt Samples (CMS11a)

- no $p_T^{\mu\mu}$ cut
- $p_T^{\mu\mu} > 25$ GeV
- $p_T^{\mu\mu} > 60$ GeV

Each $p_T^{\mu\mu}$ cut shrinks background by factor of $\sim 6$

- No $p_T$ cut
- $p_T > 25$ GeV
- $p_T > 60$ GeV
Place new bound on $pp \rightarrow V + X, V \rightarrow \mu\mu$

<table>
<thead>
<tr>
<th>95% CL$_s$ upper limits on</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(pp \rightarrow V + X) \mathcal{B}(V \rightarrow \mu^+\mu^-) A_V \epsilon_{tr}(\epsilon_{iso})$</td>
</tr>
</tbody>
</table>

- Acceptance $A_V$ and isolation $\epsilon_{iso}$ have some model dependence
- We only gain on cross section bound if we don’t lose acceptance
Resonance Search

95% $C_L_s$ on $\sigma (pp \rightarrow V + X) \mathcal{B} (V \rightarrow \mu^+ \mu^-) A_V \epsilon_{\text{tr}} \epsilon_{\text{iso}}$

Isolated Sample

2011 CMS Open Data
7 TeV, 2.11 $fb^{-1}$
Isolated Sample, no $p_T^{\mu\mu}$ cut
$\rho_{\nu}/m_{\mu\mu} = (1.1 \pm 0.4)\%$

100 fb

2011 CMS Open Data
7 TeV, 2.11 $fb^{-1}$
Isolated Sample, $p_T^{\mu\mu} > 25$ GeV
$\rho_{\nu}/m_{\mu\mu} = (1.1 \pm 0.4)\%$

40 fb

2011 CMS Open Data
7 TeV, 2.11 $fb^{-1}$
Isolated Sample, $p_T^{\mu\mu} > 60$ GeV
$\rho_{\nu}/m_{\mu\mu} = (1.3 \pm 0.4)\%$

17 fb
95% CL on $\sigma \,(pp \to V + X) \, B \,(V \to \mu^+\mu^-) \, A_V \epsilon_{tr}$

Prompt Sample
Resonance Search

- Consider region $m_{\mu\mu} \sim 35 - 45$ GeV
- $p_T$ cuts improve sensitivity if $A_V$ does not drop too rapidly

$$\sigma(pp \rightarrow V + X) B(V \rightarrow \mu^+ \mu^-) A_V \epsilon_{tr} \epsilon_{iso}$$

<table>
<thead>
<tr>
<th>$p_T^{\mu\mu}$ Cut</th>
<th>Isolated Upper Lim.</th>
<th>Prompt Upper Lim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>No $p_T^{\mu\mu}$ cut</td>
<td>100 fb</td>
<td>160 fb</td>
</tr>
<tr>
<td>$p_T^{\mu\mu} &gt; 25$ GeV</td>
<td>40 fb (2.5x)</td>
<td>60 fb (2.5x)</td>
</tr>
<tr>
<td>$p_T^{\mu\mu} &gt; 60$ GeV</td>
<td>17 fb (6x)</td>
<td>18 fb (9x)</td>
</tr>
</tbody>
</table>
Benchmark Scenarios

What models will retain acceptance across $p_T^{\mu\mu}$ cuts?

Models where $V$ is produced with substantial $p_T$

Consider example model with scalar $S$ and vector $V$ (e.g. $m_S = 125$ GeV, $m_V = 40$ GeV)

No $p_T^{\mu\mu}$ cut: $\mathcal{B}(h \rightarrow Va) \mathcal{B}(V \rightarrow \mu\mu) \lesssim 2 \times 10^{-2}$

$p_T^{\mu\mu} > 25$ GeV: $\mathcal{B}(h \rightarrow Va) \mathcal{B}(V \rightarrow \mu\mu) \lesssim 7 \times 10^{-3}$

$pp \rightarrow S \rightarrow V + a$

$V \rightarrow \mu^+\mu^-$
Conclusions

- Performed largely **model-independent** analysis for $V \rightarrow \mu^+\mu^-$
- Improve sensitivity on many models by exploiting moderately boosted kinematics
  - ATLAS & CMS can improve limits by an **order of magnitude** using Run II
- Prompt limits improve sensitivity to certain classes of BSM models
  - Analysis need knowledge of QCD background, impossible without Open Data
Conclusions

- Performed largely **model-independent** analysis for $V \rightarrow \mu^+\mu^-$
- Improve sensitivity on many models by exploiting moderately boosted kinematics
  → ATLAS & CMS can improve limits by an order of magnitude using Run II
- **Prompt limits** improve sensitivity to certain classes of BSM models
  → Analysis need knowledge of QCD background, impossible without Open Data

Open Data can be used to test BSM analysis strategies!
Back-ups
LHCb searched for light new physics from direct production in pp collisions

- $m_\phi < 70$ GeV
- Excellent mass resolution, low $p_T^{\mu}$ trigger
- Inclusive search

LHCb, 1710.02867
New Physics at LHC

Slice of CMS Experiment: Detecting Muons

CMS Collaboration 2011
ATLAS Run 280464, $H \rightarrow e^+ e^- \mu^+ \mu^-$
New Physics at LHC

Previous searches at ATLAS & CMS with dimuons: $m_{\mu\mu}$ resonances

- High-mass: $m_{Z'} \in [120 \text{ GeV}, 3.36 \text{ TeV}]$
- Pairs of light bosons: $m_{\gamma_D} \in [0.25, 8.5] \text{ GeV}$

ATLAS, 1607.03669

CMS, 1812.00380
DoubleMu Primary Dataset from CMS Run 2011a (CMS11a)

- $\sqrt{s} = 7$ TeV, $\mathcal{L} = 2.11$ fb$^{-1}$

**Dimuon Trigger**

$p_T^1 > 13$ GeV, $p_T^2 > 8$ GeV

- Further cut: $p_T^1 > 15$ GeV, $p_T^2 > 10$ GeV
- Impose $|\eta^{1,2}| < 2.1$

$p_T^1$ is leading, $p_T^2$ is subleading

![Diagram](image-url)
Monte Carlo Simulation

Are we using the data/MC correctly?

Produced by CMS with GEANT4, Pythia6, MadGraph5
Validation studies: measure inclusive Z cross section with CMS11a

The inclusive Z cross section measurement has similar baseline selection criteria to our analysis.
Validation study: measure inclusive Z cross section with CMS11a

Modeled on CMS measurement from 2010 (1107.4789)

\[
\sigma_{Z\mu\mu} = \sigma (pp \rightarrow Z + X) \times B (Z \rightarrow \mu^+ \mu^-) = \frac{N_Z}{\mathcal{L} A_Z \epsilon^{Z\mu}_{tr} \epsilon^{Z\mu}_{iso}}
\]

- $A_Z$ is geometric acceptance (cuts on $p_T^{1,2}$, $\eta^{1,2}$)
- $\epsilon^{Z\mu}_{tr}$ is dimuon trigger efficiency
- $\epsilon^{Z\mu}_{iso}$ is dimuon isolation efficiency
Validation study: measure inclusive $Z$ cross section with CMS11a

- Modeled on CMS measurement from 2010 ($1107.4789$)

\[
\sigma_{Z\mu\mu} = \sigma_{pp \rightarrow Z + X} \times B(Z \rightarrow \mu^+\mu^-) = \frac{N_Z}{\mathcal{L} A_Z \epsilon_{tr}^{Z} \epsilon_{iso}^{Z}}
\]

CMS11a

- $\mathcal{L} = 2.11$ fb$^{-1}$
- Dimuon Trigger
  \[ p_T^1 > 13 \text{ GeV}, \ p_T^2 > 8 \text{ GeV} \]
Validation study: measure inclusive $Z$ cross section with CMS11a

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**CMS11a**

- $\mathcal{L} = 2.11$ fb$^{-1}$
- Dimuon Trigger
  - $p_T^1 > 13$ GeV, $p_T^2 > 8$ GeV

**CMS Data, April - Aug 2010**

- $\mathcal{L} = 36$ pb$^{-1}$
- Single Muon Trigger
  - $p_T > 9$ GeV, $|\eta| < 2.1$
Impose the same kinematic cuts on CMS11a from CMS analysis such that acceptance is the same

Measuring $\sigma_{Z\mu\mu} = \sigma(pp \rightarrow Z + X) \times B(Z \rightarrow \mu^+\mu^-)$

- $60 \text{ GeV} < m_{\mu\mu} < 120 \text{ GeV}$
- Further cut $p_T^{1,2} > 20 \text{ GeV}$
- $|\eta^{1,2}| < 2.1$
- Opposite sign, isolated $\mu$ pairs
Validation Studies

Isolation dramatically reduces QCD (heavy flavor) background

\[ I_{\text{comb}} = \frac{(p_{T}^{\text{track}} + E_{T}^{\text{ECAL}} + E_{T}^{\text{HCAL}})}{p_{T}^{\mu}} \Delta R \]

\[ \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} < 0.3 \]

Define isolation variable \( I_{\text{comb}} \): The sum of the \( p_T \) from track, energy deposit in HCAL, and energy deposit in ECAL for all particles within a radius \( \Delta R \) from muon, divided by the \( p_T \) of the muon

- Isolation Condition: \( I_{\text{comb}} < 0.15 \)
Important part of analysis is **determining efficiencies**

\[ \sigma_{Z\mu\mu} = \frac{N_Z}{\mathcal{L} A_Z \epsilon_{tr} \epsilon_{iso}} \]

**Comparison:** CMS11a Validation Study to CMS 2010 Analysis

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Important part of analysis is **determining efficiencies**

\[
\sigma_{Z\mu\mu} = \frac{N_Z}{\mathcal{L} A_Z \epsilon_{Z\mu\mu} \epsilon_{Z\mu\mu}^{\text{tr}} \epsilon_{Z\mu\mu}^{\text{iso}}}
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**Cuts are chosen so that acceptances are the same**
Validation Studies

Important part of analysis is determining efficiencies

$$\sigma_{Z\mu\mu} = \frac{N_{Z}}{\mathcal{L} A_{Z} \varepsilon_{tr} \varepsilon_{iso}}$$

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Efficiencies differ as trigger and isolation conditions are different
Cut flow for the analysis of $\sigma_{Z\mu\mu}$ using the CMS11a data set

<table>
<thead>
<tr>
<th>Dimuon Events</th>
<th>OS Events</th>
<th>SS Events</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CMS11a $\mu13\mu8$</strong></td>
<td>6,241,576</td>
<td></td>
</tr>
<tr>
<td>Baseline Acceptance</td>
<td>2,961,681</td>
<td></td>
</tr>
<tr>
<td>($p_{T,1} &gt; 15$ GeV, $p_{T,2} &gt; 10$ GeV, $</td>
<td>\eta_{\mu}</td>
<td>&lt; 2.1$)</td>
</tr>
<tr>
<td>Tight Muon Cuts</td>
<td>2,155,900</td>
<td></td>
</tr>
<tr>
<td>($\chi^2$/d.o.f. &lt; 10, $n_{hit} \geq 10$, $d_0 &lt; 2$ mm, $z_0 &lt; 10$ mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Opposite Sign vs. Same Sign</strong></td>
<td>1,895,756</td>
<td>260,144</td>
</tr>
<tr>
<td><strong>Z-mass Region ($m_{\mu\mu} \in [60, 120]$ GeV)</strong></td>
<td>794,623</td>
<td>30,105</td>
</tr>
<tr>
<td>$p_{T}^{\mu} &gt; 20$ GeV</td>
<td>699,270</td>
<td>9,726</td>
</tr>
<tr>
<td><strong>Muon Isolation ($I_{comb} &lt; 0.15$)</strong></td>
<td>642,219</td>
<td>78</td>
</tr>
</tbody>
</table>

Same sign events are a measure of QCD background

$N_Z = 642,219$
Compare cross section measurements

\[ \sigma_{Z\mu\mu} = \frac{N_Z}{\mathcal{L} A_Z \epsilon_{tr}^{Z} \epsilon_{iso}^{Z}} \]

Our measurement with CMS11a:

\[ \sigma_{Z\mu\mu} = 974 \pm 1 \pm 52 \text{ pb} \]
Compare cross section measurements

\[ \sigma_{Z\mu\mu} = \frac{N_Z}{L \cdot A_Z \cdot \epsilon_{tr} \cdot \epsilon_{iso}} \]

Our measurement with CMS11a:

\[ \sigma_{Z\mu\mu} = 974 \pm 1 \pm 52 \text{ pb} \]

Compare to LHC analysis result:

\[ \sigma_{Z\mu\mu} = 970 \pm 30 \text{ pb} \]
\[ \sigma_{Z\mu\mu} = 974 \pm 44 \text{ pb} \]
\[ \sigma_{Z\mu\mu} = 986 \pm 31 \text{ pb} \]

NLO SM prediction (1107.4789)

Measured value, CMS 2010, e/\mu averaging (1107.4789)

Measured value, CMS 2011 (1310.7291)
Why is the prompt cut interesting?

Potential signals suppressed by isolation cuts:

- $V$ may be produced with other BSM particles
  $\rightarrow$ clustered decay products in detector
- Events with many jets, from SM or BSM
  $\rightarrow$ muons coincidentally end up ‘in’ jets
Cut flow for the $V \rightarrow \mu^+ \mu^-$ search on CMS11a

<table>
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<td><strong>Baseline Acceptance and Tight Muons Cuts</strong></td>
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<tr>
<td>($p_{T,1} &gt; 15$ GeV, $p_{T,2} &gt; 10$ GeV, $</td>
<td>\eta_\mu</td>
</tr>
<tr>
<td><strong>Search Region</strong></td>
<td>561,364</td>
</tr>
<tr>
<td>(OS, $m_{\mu\mu} \in [11, 78]$ GeV, $d_0 &lt; 250$ $\mu$m, $z_0 &lt; 2000$ $\mu$m)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
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<th>Prompt Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{comb} &lt; 0.15$</td>
<td>188,924</td>
<td>412,002</td>
</tr>
<tr>
<td>$I_{P_{xy}} &lt; 100$ $\mu$m</td>
<td>46,798</td>
<td>91,264</td>
</tr>
<tr>
<td>$p_T^{\mu\mu} &gt; 0$</td>
<td>7,668</td>
<td>11,208</td>
</tr>
<tr>
<td>$p_T^{\mu\mu} &gt; 25$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T^{\mu\mu} &gt; 60$ GeV</td>
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Resonance Search

- Line shape is Gaussian core with radiative tail (Crystal ball)
- Width is mass resolution, function of $m_{\mu\mu}$: $\rho(V|m_{\mu\mu}) = \xi m_{\mu\mu}$

$$\xi = \begin{cases} 
1.1\% & p_T^{\mu\mu} > 0 \text{ GeV} \\
1.1\% & p_T^{\mu\mu} > 25 \text{ GeV} \\
1.3\% & p_T^{\mu\mu} > 60 \text{ GeV} 
\end{cases}$$

Table 1: A summary of the systematic uncertainties on our fitting results, showing the size of the uncertainty and the effect on our limits.
Resonance Search

$p$-value for rejecting background-only hypothesis

**Isolated Sample**

![Graph 1](image1.png)

- 2011 CMS Open Data
- $7 \text{TeV}, 2.11 \text{ fb}^{-1}$
- Isolated Sample, no $p_T^{\mu\mu}$ cut
- $\rho/\mu_m = (1.1 \pm 0.4)\%$

![Graph 2](image2.png)

- 2011 CMS Open Data
- $7 \text{TeV}, 2.11 \text{ fb}^{-1}$
- Isolated Sample, $p_T^{\mu\mu} > 25 \text{ GeV}$
- $\rho/\mu_m = (1.1 \pm 0.4)\%$

![Graph 3](image3.png)

- 2011 CMS Open Data
- $7 \text{TeV}, 2.11 \text{ fb}^{-1}$
- Isolated Sample, $p_T^{\mu\mu} > 60 \text{ GeV}$
- $\rho/\mu_m = (1.3 \pm 0.4)\%$
Resonance Search

\( p \)-value for rejecting background-only hypothesis

Prompt Sample
Resonance Search

Background fit with polynomial

- Center window around $m_{\mu\mu}$
- Width of window is $35 \rho_V$
- Bin size is $\rho_V/4 \rightarrow 140$ bins
- Fit with fifth-order polynomial ($x^0$ to $x^5$)
- Calculate local $p$-value, set expected limits
Model Dependence in Fitting Procedure

- **Radiative tail** from QED emission off $\mu$, logarithmic dependence on $m_\nu$
- $p_T$ resolution (and dimuon mass resolution), function of $p_T$, $\eta$
- CMS11a data & MC both show non-Gaussian tails
Crystal ball line shape studied with $\psi / J$ peak

- Muons are highly boosted $\rightarrow$ similar in $\eta$, $p_T$
- Fit with Crystal Ball shape, can estimate $p_T$ resolution
- MC underestimate resolution in data by 10%
- Muon resolution not published in Open Data
  $\rightarrow$ recommended $\pm 0.6\%$ on $p_T$ $\Rightarrow$ $\pm 0.4\%$ on $m_{\mu\mu}$
- Scale factor $1.000 \pm 0.002$, too small for our analysis
  (https://twiki.cern.ch/twiki/bin/view/CMSPublic/MuonReferenceResolution)
Benchmark Scenarios

What models will retain acceptance across $p_T^{\mu\mu}$ cuts?
Models where $V$ is produced with substantial $p_T$

- Our search is for substantial $p_T^{\mu\mu} + \text{anything}$
- Some examples:
Model 2

\[ S \rightarrow \chi_1\chi_2, \quad \chi_2 \rightarrow \chi_1 V \]

- Isolation or prompt cut depends on mass hierarchy
- For \( \chi_2 \ll m_S \), \( \chi_2 \) boosted, decay products are collimated
  \( \rightarrow \) Ruin isolation, use prompt
\(m_S = 200 \text{ GeV}, \ m_{\chi_1} = 10 \text{ GeV}\)

Acceptance ratio \(\gg 50\%\) for most of kinematic range

Good candidate for \(p_T\) enhanced search
Why study this range and $p_T^{\mu\mu}$ cuts?

- At low mass $m_V$ and/or large $p_T^{\mu\mu}$, muons are too collimated and triggering begins to fail
- At high mass $m_V$ and/or large $p_T^{\mu\mu}$, fewer event counts $\rightarrow$ larger uncertainty

Experimentalists with better trigger/reco knowledge and larger data set could extend kinematic regions!
Case 1: $m_s = m_h = 125$ GeV (BSM Higgs Decay)

$$\sigma (pp \rightarrow V + a) \mathcal{B} (V \rightarrow \mu^+ \mu^-) A_V \epsilon_{tr} \epsilon_{iso}$$
Case 1: \( m_S = m_h = 125 \text{ GeV} \) \(^{(\text{BSM Higgs Decay})}\)

\[ \sigma (pp \rightarrow V + a) \mathcal{B} (V \rightarrow \mu^+ \mu^-) A_V \epsilon_{\text{tr}} \epsilon_{\text{iso}} \]
Case 1: \( m_S = m_h = 125 \text{ GeV} \) (BSM Higgs Decay)

\[
\sigma (pp \rightarrow V + a) \mathcal{B} (V \rightarrow \mu^+ \mu^-) A_V \varepsilon_{tr} \varepsilon_{iso}
\]
Case 1: $m_S = m_h = 125$ GeV (BSM Higgs Decay)

$$\sigma (pp \to V + a) \mathcal{B} (V \to \mu^+ \mu^-) A_V \epsilon_{tr} \epsilon_{iso}$$

- For strategy to be useful, the acceptance must be similar after $p_T^{\mu\mu}$ cuts
- When $m_V + m_a \lesssim 100$ GeV, $p_T^{\mu\mu} > 25$ GeV is effective
In some regions of $m_{\mu\mu}$, our search strategy cut strengthens cross section limit by factor of $\gtrsim 2$.

- Consider the $m_V = m_a = 40$ GeV
- $A_V(0) = 54\%, A_V(25) = 47\%$
  $\rightarrow A_V(0)/A_V(25) \sim 85\%$
- $\epsilon_{\text{tr}} \sim 85\%, \epsilon_{\text{iso}} \sim 85\%$

$$\mathcal{B}(h \rightarrow V a) \mathcal{B}(V \rightarrow \mu \mu) \lesssim 7 \times 10^{-3}$$
Our search sets competitive if not stronger bounds on certain classes of models

Improve limits in comparison to inclusive searches on Run I
Case 2: $m_S = 200$ GeV

$$\sigma (pp \rightarrow V + a) \mathcal{B} (V \rightarrow \mu^+ \mu^-) A_V \epsilon_{tr} \epsilon_{iso}$$

- Larger mass splitting $\rightarrow$ higher $p_T^{\mu\mu}$
- $m_V + m_a \lesssim 175$ GeV ($p_T^{\mu\mu} > 25$ GeV)
Case 2: $m_S = 200$ GeV

$$\sigma (pp \rightarrow V + a) \mathcal{B} (V \rightarrow \mu^+ \mu^-) A_V \epsilon_{tr} \epsilon_{iso}$$

- Larger mass splitting $\rightarrow$ higher $p_T^{\mu\mu}$
- $m_V + m_a \lesssim 140$ GeV ($p_T^{\mu\mu} > 60$ GeV)
Case 2: $m_S = 200$ GeV

$$\sigma (pp \rightarrow V + a) \mathcal{B} (V \rightarrow \mu^+ \mu^-) A_V \epsilon_{tr} \epsilon_{iso}$$

- Larger mass splitting $\rightarrow$ higher $p_T^{\mu\mu}$
- $m_V + m_a \lesssim 140$ GeV ($p_T^{\mu\mu} > 60$ GeV)

$p_T^{\mu\mu} > 60$ GeV cut strengthens cross section limit by factor of 5