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

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1902.04222

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Phenomenology 2019 Symposium

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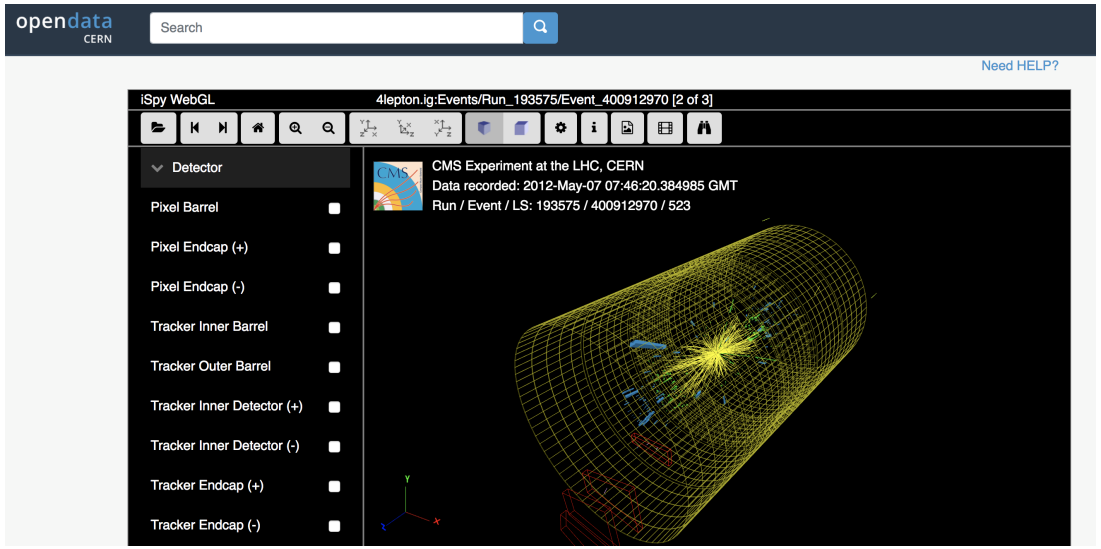
[4] Center for Theoretical Physics, MIT

Open Data



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

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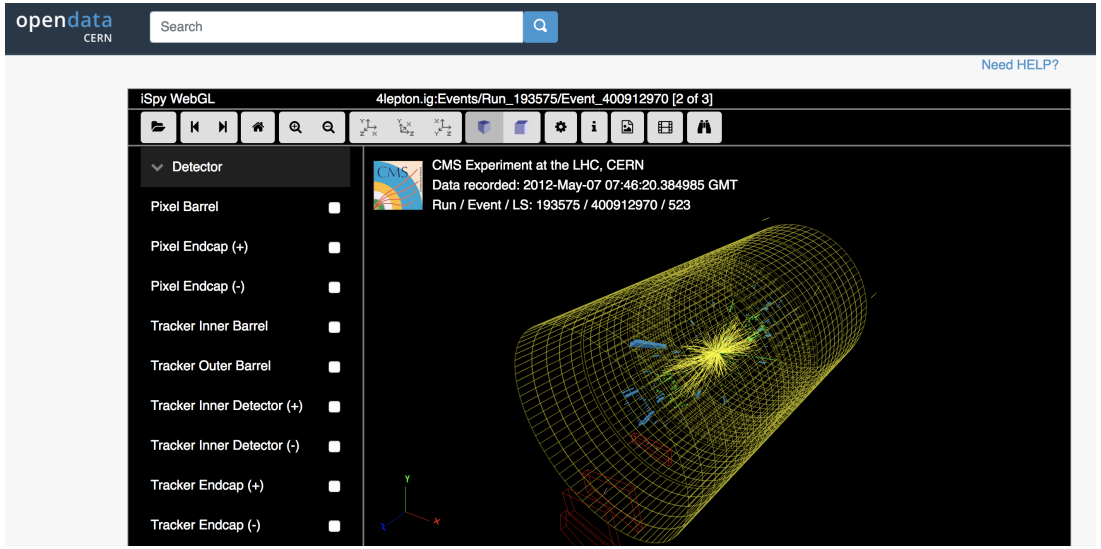

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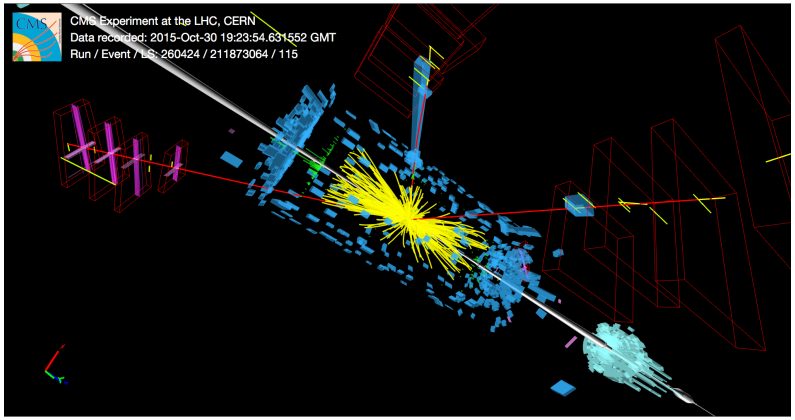
  CMS Run 2011a: $\sqrt{s} = 7$ TeV, $\mathcal{L} = 2.11$ fb^{-1}, $13\mu 8\mu$ Trigger
- First ever BSM search with LHC Open Data

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
  $\rightarrow$ How you look determines what you find
  $\rightarrow$ New physics signature buried in phase space

Consider motivated, model independent extensions of SM: new physics with dimuon signatures and substantial $p_T^{\mu\mu}$



Overview

We propose a model independent search strategy that increases sensitivity for semi-inclusive searches with indirect production of new particle $V \to \mu^+\mu^-$

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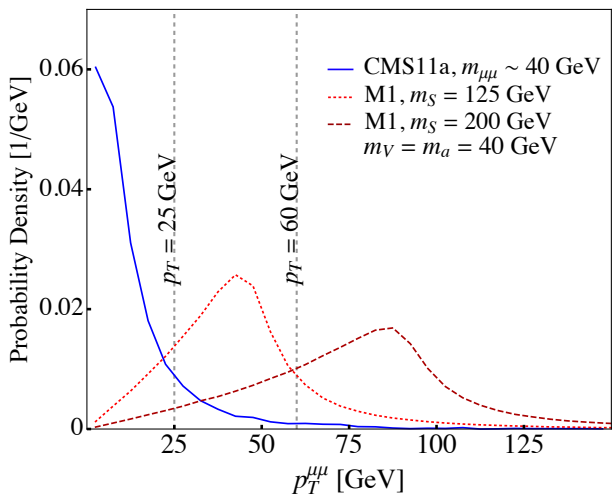
- Cut on $p_T^{\mu\mu}$ preserves signal while reducing background (Strassler, 2008, 2010 conference talks)



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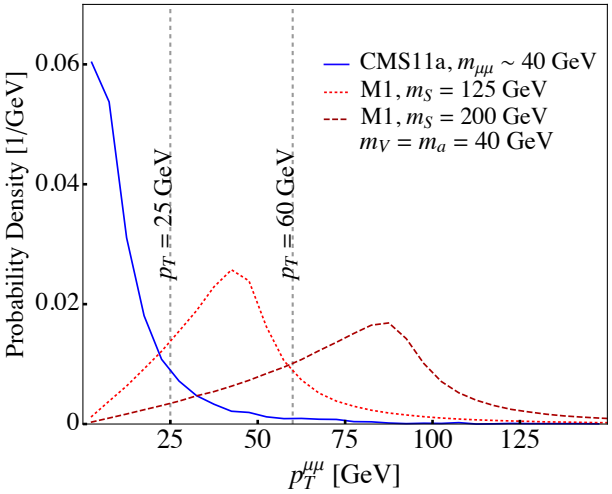
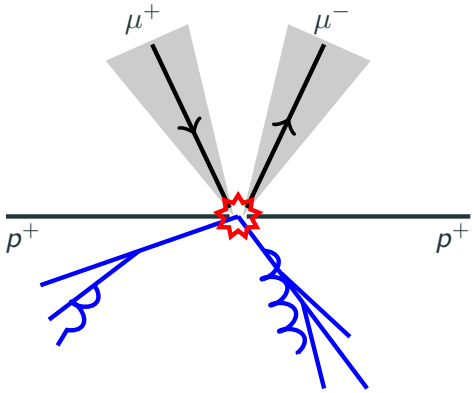
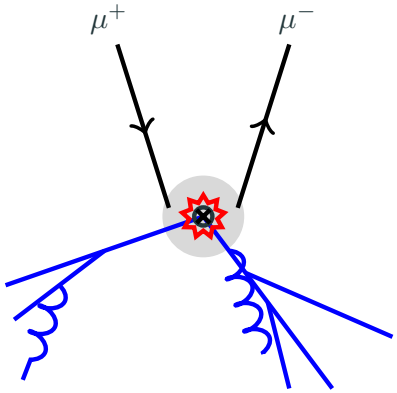
- Produced via decay: substantial p_T^V from recoil
- Cut on $p_T^{\mu\mu}$ preserves signal while reducing background (Strassler, 2008, 2010 conference talks)
- Further reduce background: isolation and promptness cuts
  $\to$ Need Open Data to understand prompt



Indirect production



Isolated condition

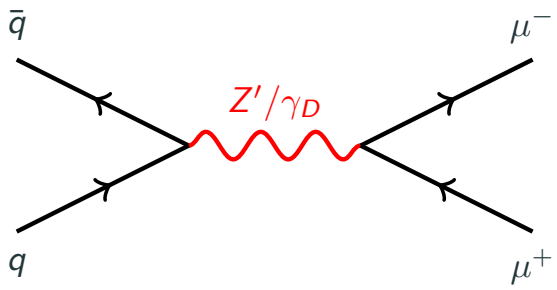


Prompt condition

New Physics at LHC

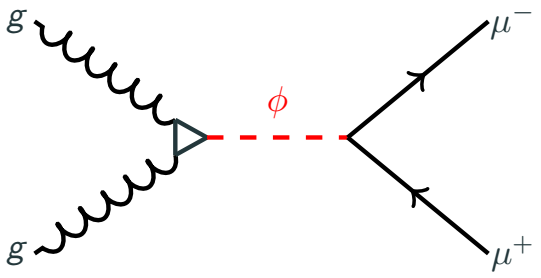
Previous searches at ATLAS & CMS with dimuons: $m_{\mu\mu}$ resonances

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



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

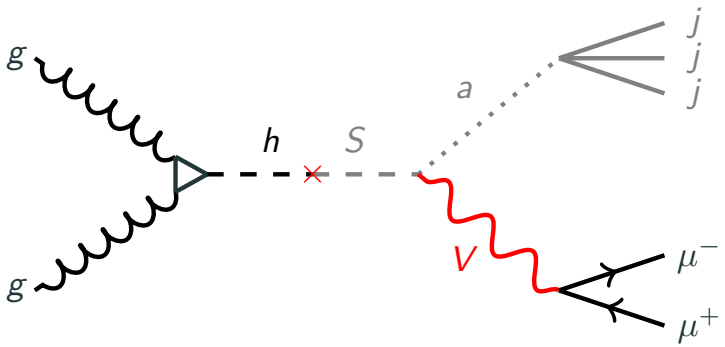
- $10.6\text{ GeV} < m_\phi < 70\text{ GeV}$
  (LHCb, 1710.02867)



Models

We are considering a new vector particle V produced via decay, therefore **with substantial** p_T^V

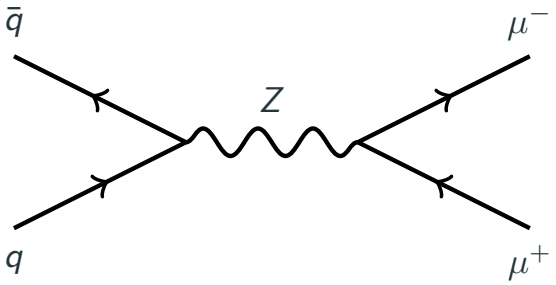
- Decays to dimuon pairs ($\mu^+\mu^-$)
- Produced by SM ($W/Z/\text{Higgs}/t$) or new particle
- Probing mass range of **14 GeV to 66 GeV**

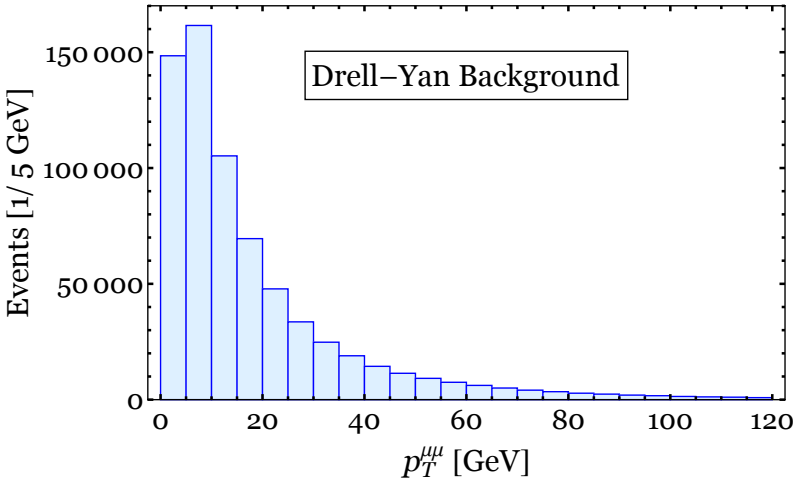


New Physics Search

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

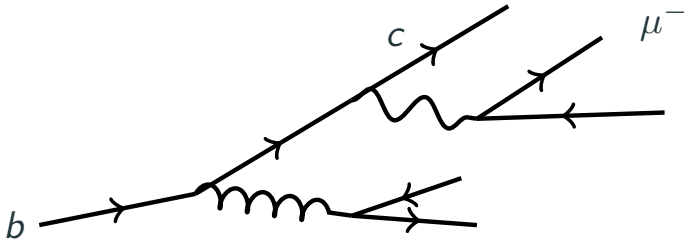
Drell-Yan





Suppressed by $p_T^{\mu\mu}$ cuts

Heavy Flavor (QCD)



Further suppressed by isolation or promptness cuts

Isolated vs. Prompt Sample

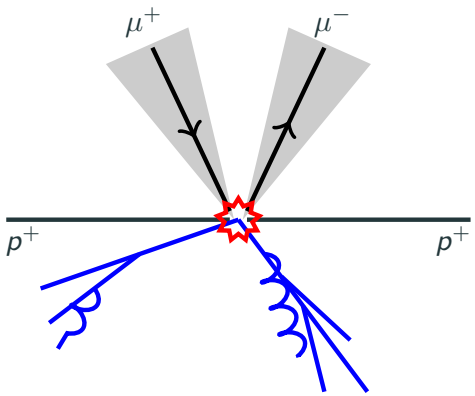
Isolated

Prompt

Isolated vs. Prompt Sample

Isolated

- Both μ are isolated in detector
- Virtually eliminates QCD (heavy flavor) background



Prompt

Isolated vs. Prompt Sample

Isolated

- Both μ are isolated in detector
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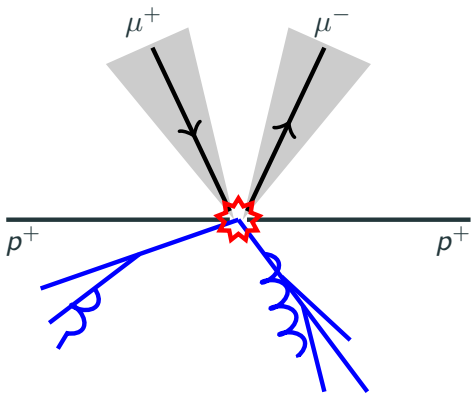
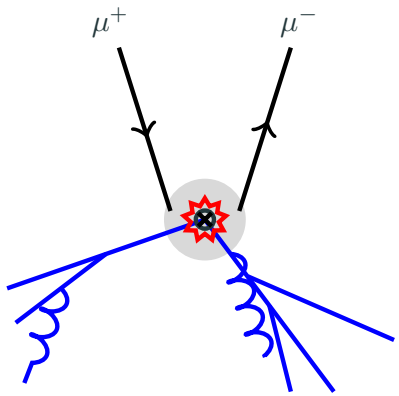


Prompt

- 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:

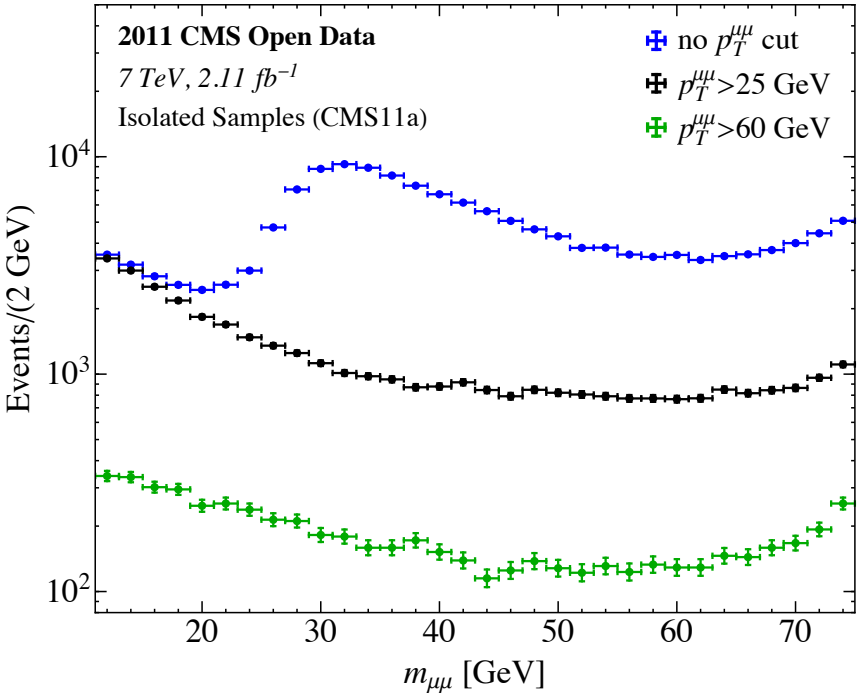
$$\frac{N_V}{\mathcal{L}} = \sigma\left(pp \to V + X\right) \mathcal{B}\left(V \to \mu^+\mu^-\right) A_V \epsilon_{\text{tr}}^V \epsilon_{\text{iso}}^V$$

Goal: Increase sensitivity by imposing $p_T^{\mu\mu}$ cuts.

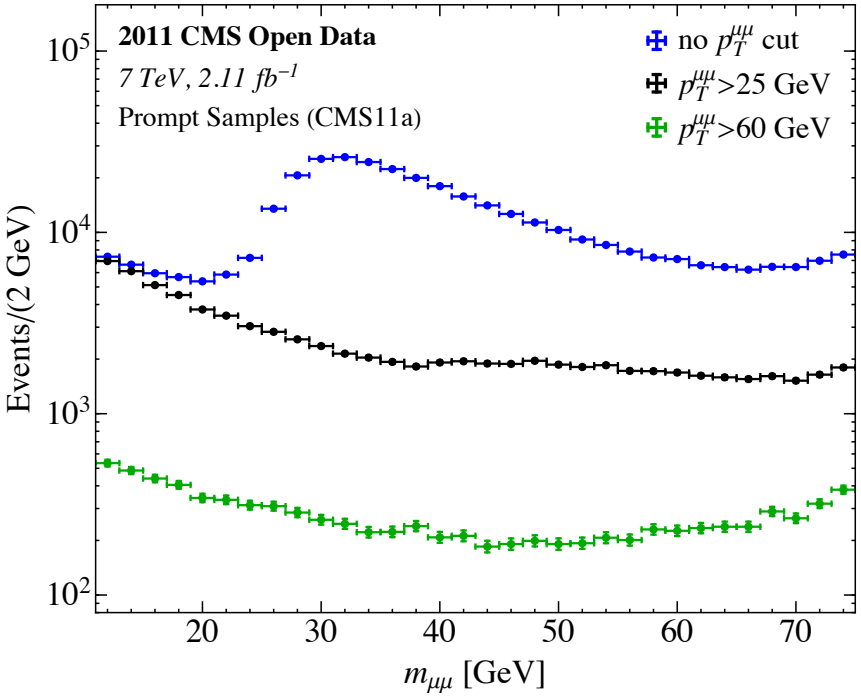
- Dimuon trigger ($p_T^{1,2} > 13, 8$ GeV)
- Only opposite-sign (OS) muons
- Define **isolated** and **prompt** samples
- Apply increasingly restrictive $p_T^{\mu\mu}$ cuts (substantial p_T^V) $\to p_T^{\mu\mu} > 25$ GeV, > 60 GeV
- Look for a bump

Prompt vs. Isolation

Isolated Sample



Prompt Sample



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

No p_T cut

$p_T > 25$ GeV

$p_T > 60$ GeV

Resonance Search

Place new bound on $pp \to V + X, V \to \mu\mu$

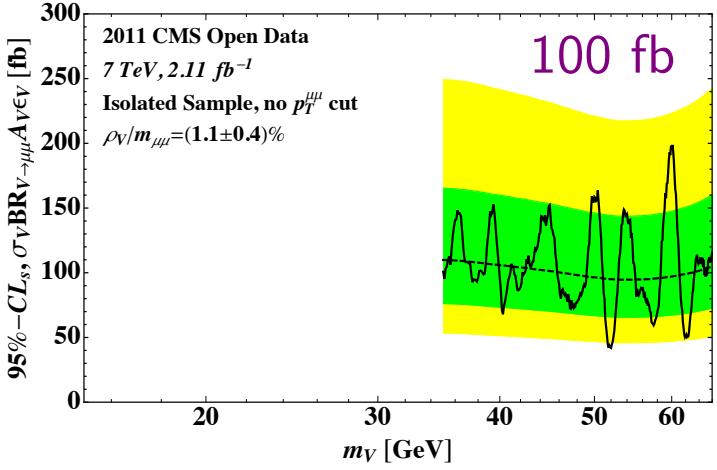
95% CL$_s$ upper limits on
$\sigma\,(pp \to V + X)\,\mathcal{B}\,(V \to \mu^+\mu^-)\,A_V \epsilon_{\text{tr}}(\epsilon_{\text{iso}})$

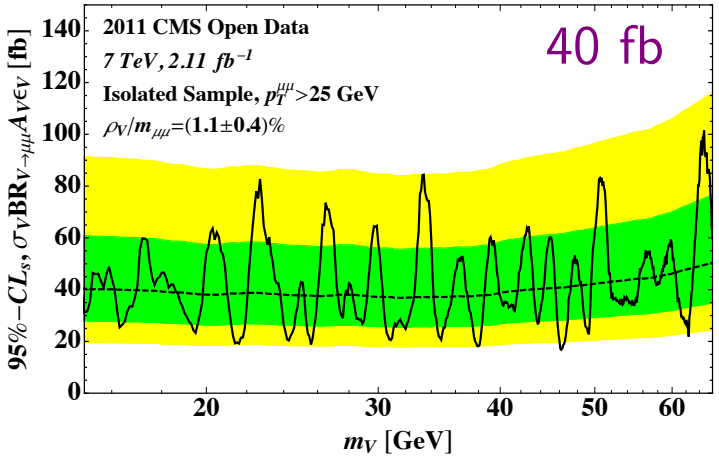
- Acceptance A_V and isolation ϵ_{iso} have some model dependence
- We only gain on cross section bound if we don't lose acceptance

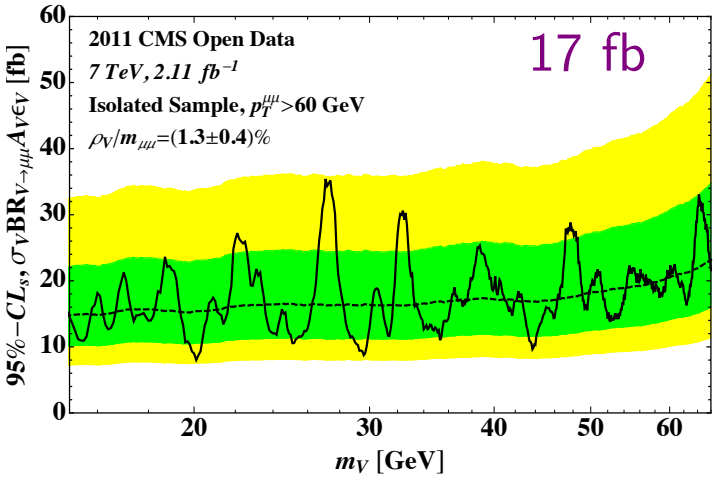
Resonance Search

95% CL$_s$ on $\sigma\left(pp \to V + X\right)\mathcal{B}\left(V \to \mu^+\mu^-\right)A_V\epsilon_{\mathbf{tr}}\epsilon_{\mathbf{iso}}$

Isolated Sample



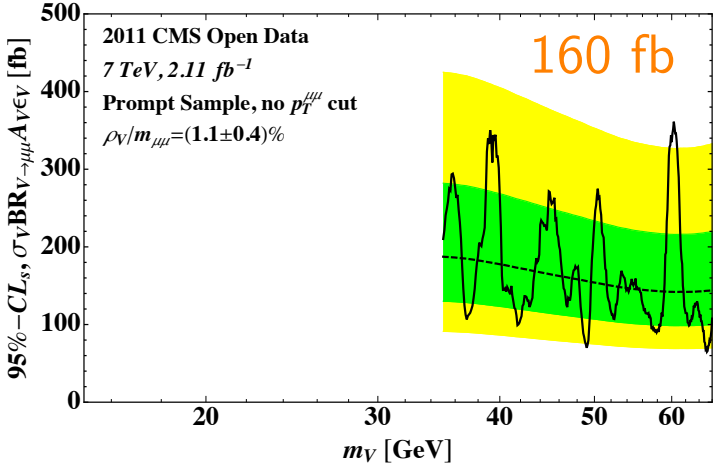


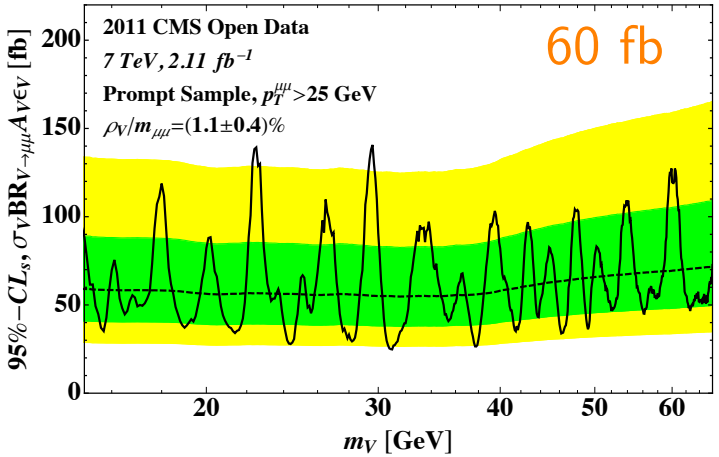


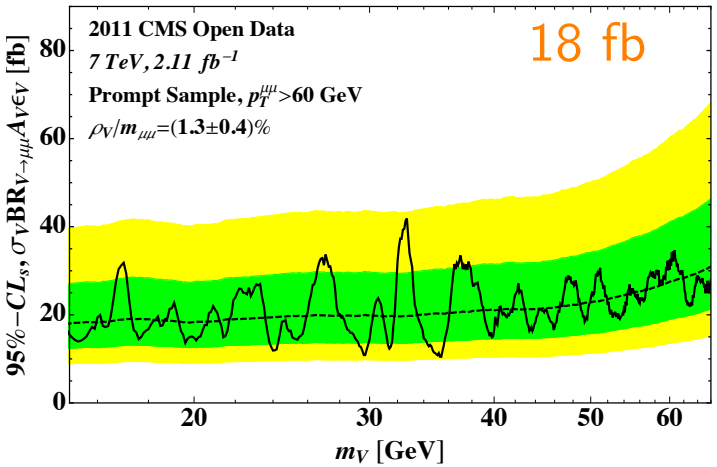
Resonance Search

95% CL_s on $\sigma\left(pp \to V + X\right)\mathcal{B}\left(V \to \mu^+\mu^-\right)A_V\epsilon_{\mathbf{tr}}$

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

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

$p_T^{\mu\mu}$ Cut	Isolated Upper Lim.	Prompt Upper Lim.
No $p_T^{\mu\mu}$ cut	100 fb	160 fb
$p_T^{\mu\mu} > 25$ GeV	40 fb (2.5x)	60 fb (2.5x)
$p_T^{\mu\mu} > 60$ GeV	17 fb (6x)	18 fb (9x)

Benchmark Scenarios

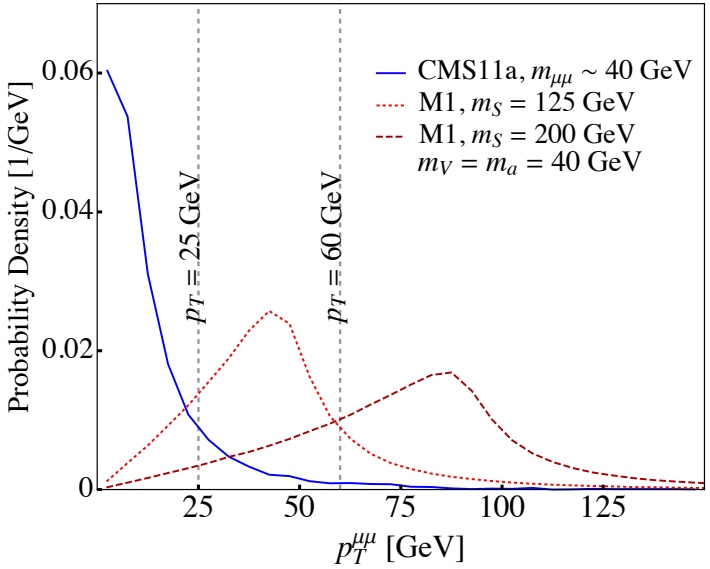
What models will retain acceptance across $p_T^{\mu\mu}$ cuts?

Models where V is produced with substantial p_T

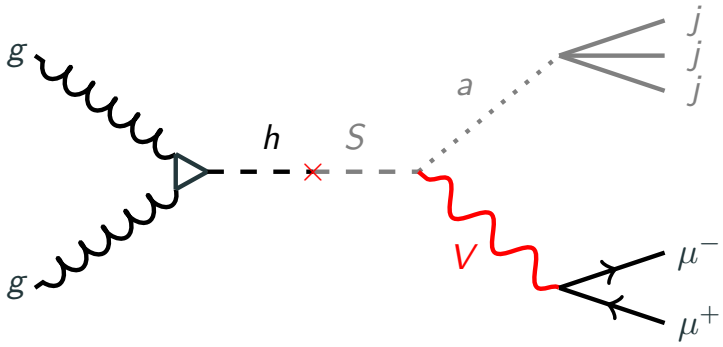
Consider example model with scalar S and vector V (e.g. $m_S = 125$ GeV, $m_V = 40$ GeV)

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

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



$$pp \to S \to V + a$$
$$V \to \mu^+\mu^-$$

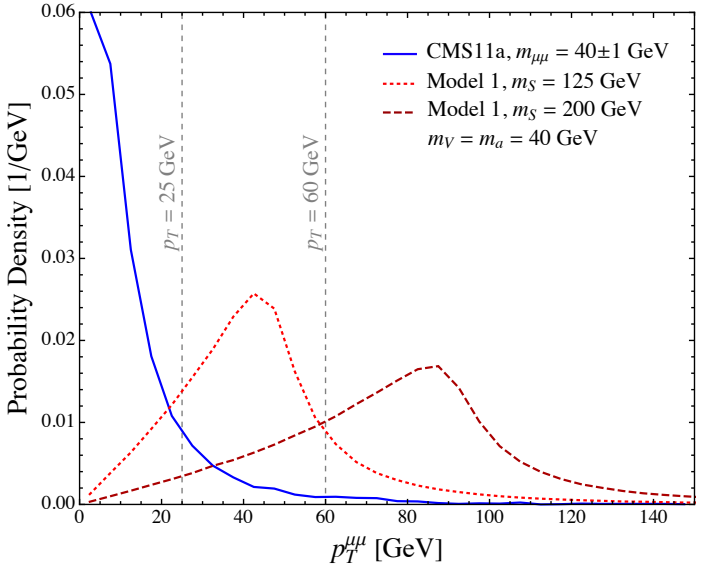


Conclusions

- Performed largely **model-independent** analysis for $V \to \mu^+\mu^-$
- Improve sensitivity on many models by exploiting moderately boosted kinematics

  $\longrightarrow$ ATLAS & CMS can improve limits by an **order of magnitude** using Run II
- Prompt limits improve sensitivity to certain classes of BSM models

  $\longrightarrow$ Analysis need knowledge of QCD background, impossible without Open Data



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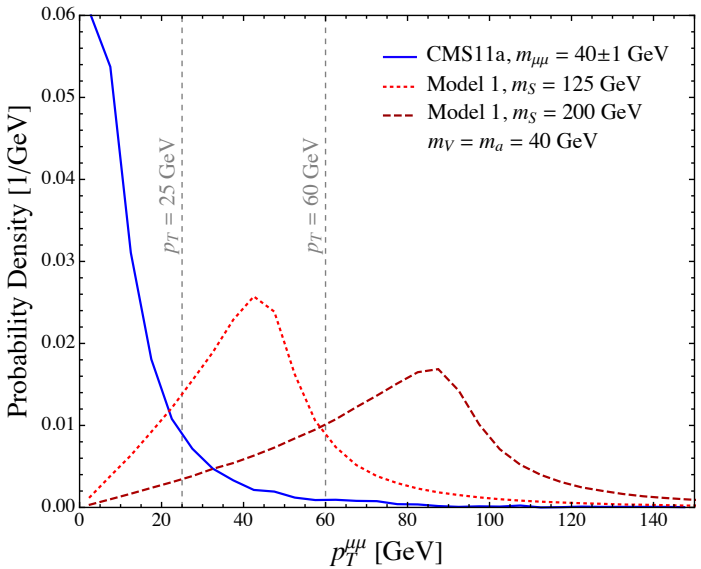
Open Data can be used to test BSM analysis strategies!

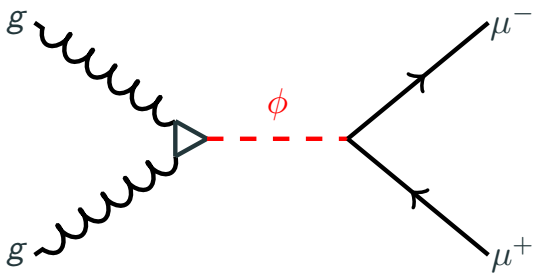


Back-ups

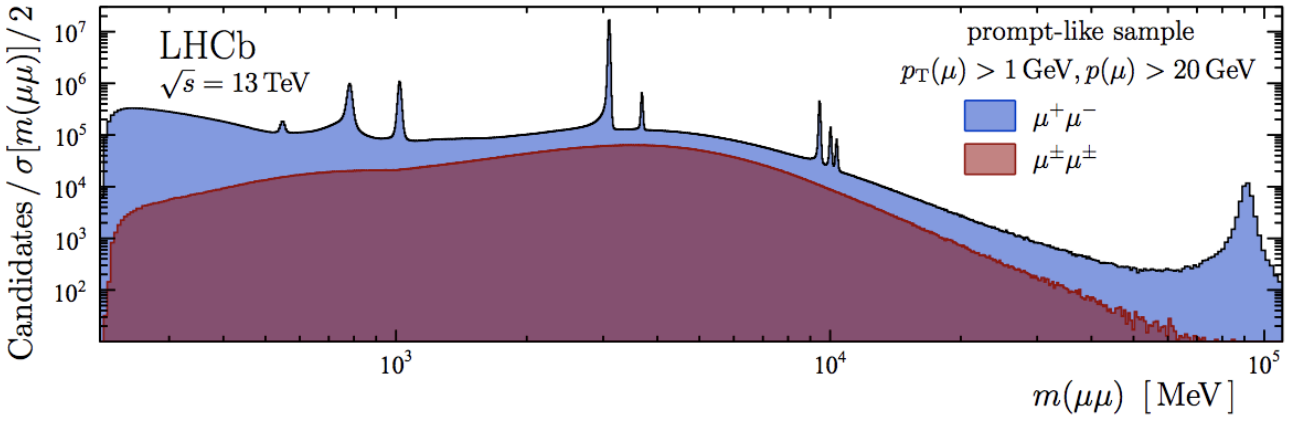
Previous Searches at LHC

LHCb searched for light new physics from direct production in pp collisions

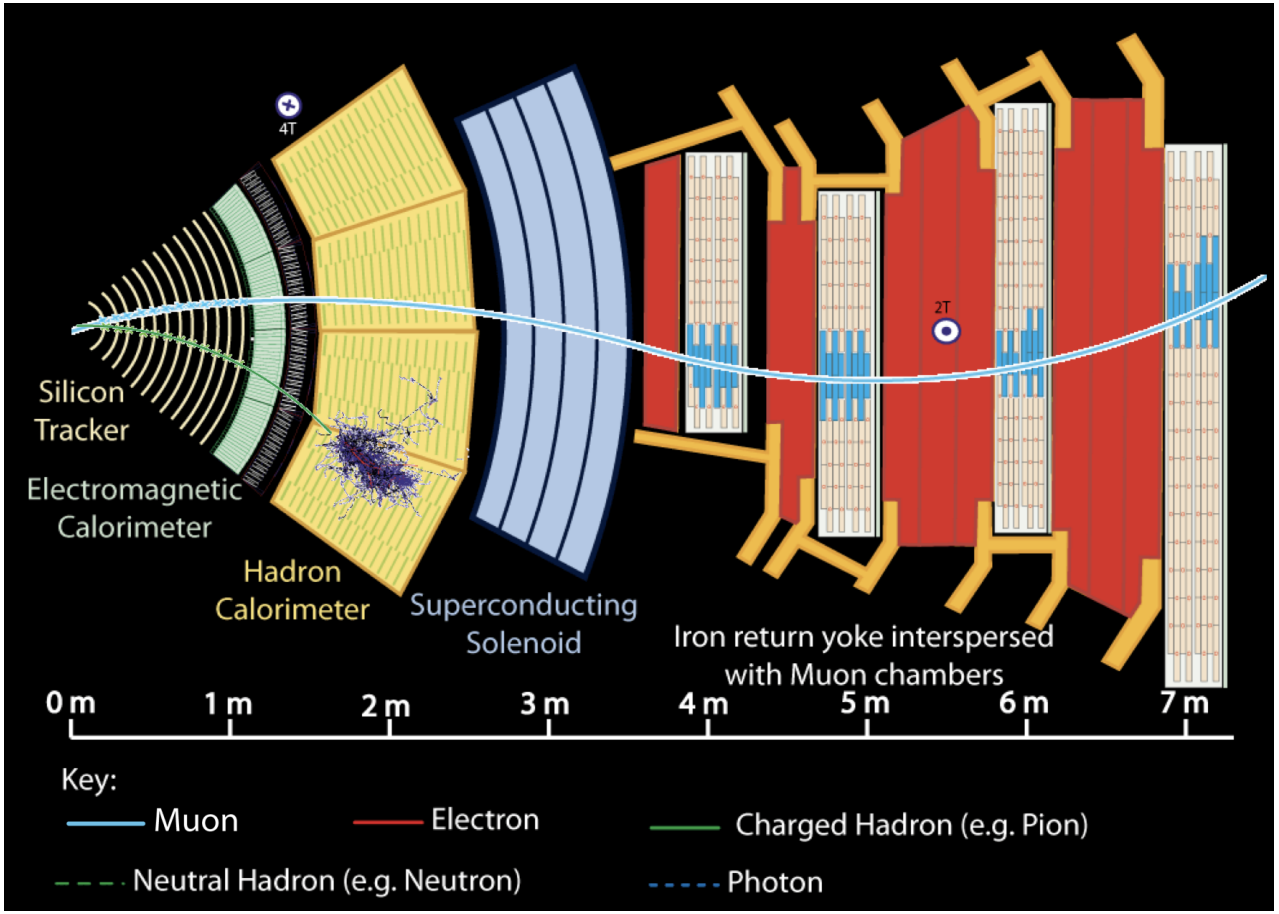
- $m_\phi < 70$ GeV
- Excellent mass resolution, low p_T^μ trigger
- Inclusive search



LHCb, 1710.02867



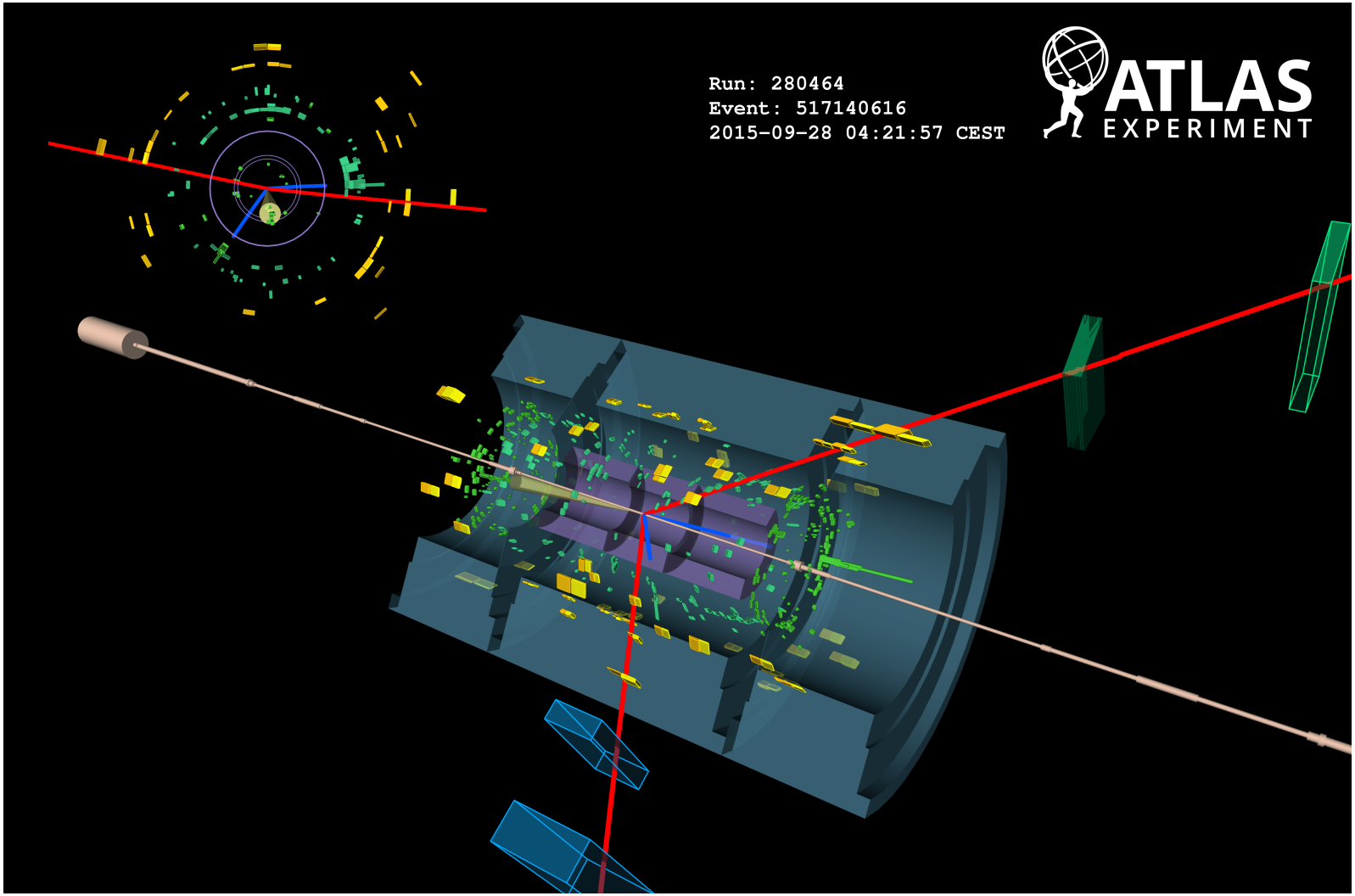
Slice of CMS Experiment: Detecting Muons



CMS Collaboration 2011

New Physics at LHC

ATLAS Run 280464, $H \to e^+e^-\mu^+\mu^-$



ATLAS Collaboration 2015

New Physics at LHC

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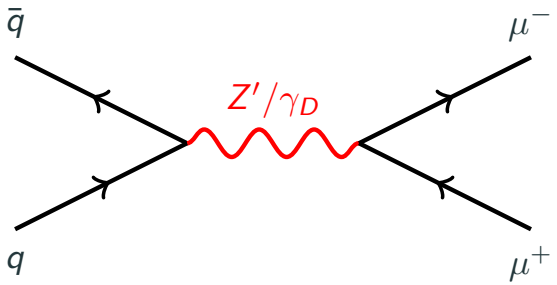
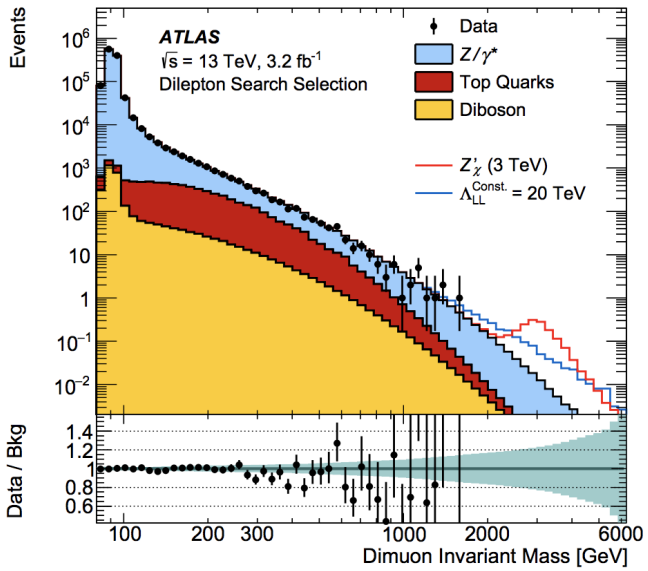
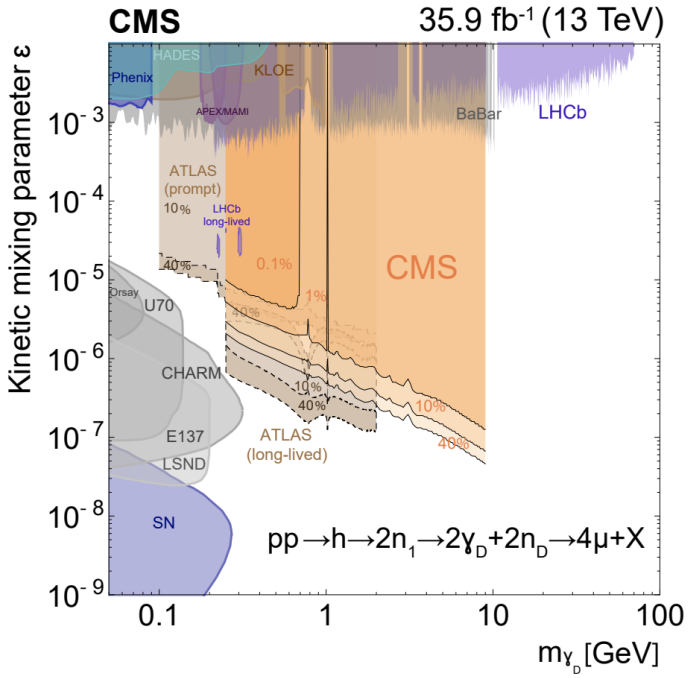
- Pairs of light bosons: $m_{\gamma_D} \in [0.25, 8.5]$ GeV





ATLAS, 1607.03669



CMS, 1812.00380

Open Data Specs

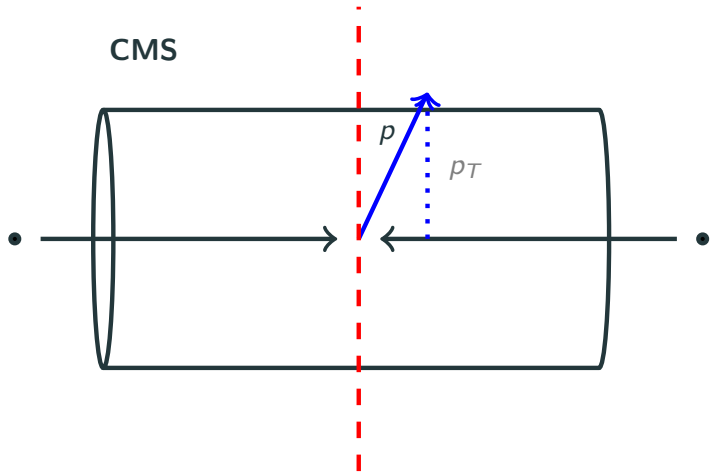
DoubleMu Primary Dataset from CMS Run 2011a (CMS11a)

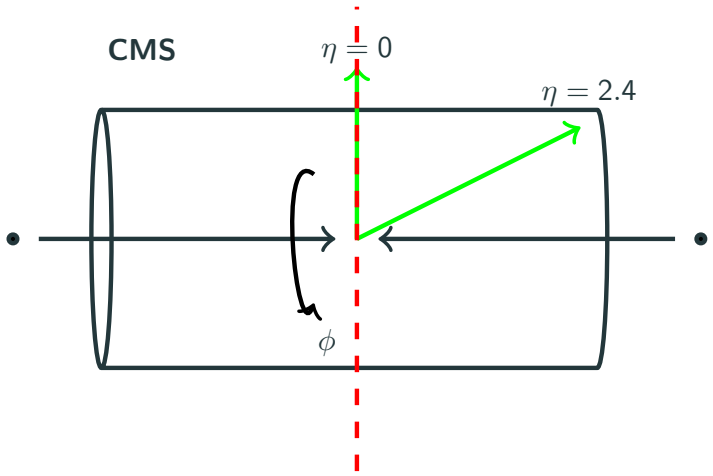
- $\sqrt{s} = 7$ TeV, $\mathcal{L} = 2.11$ fb^{-1}

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

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

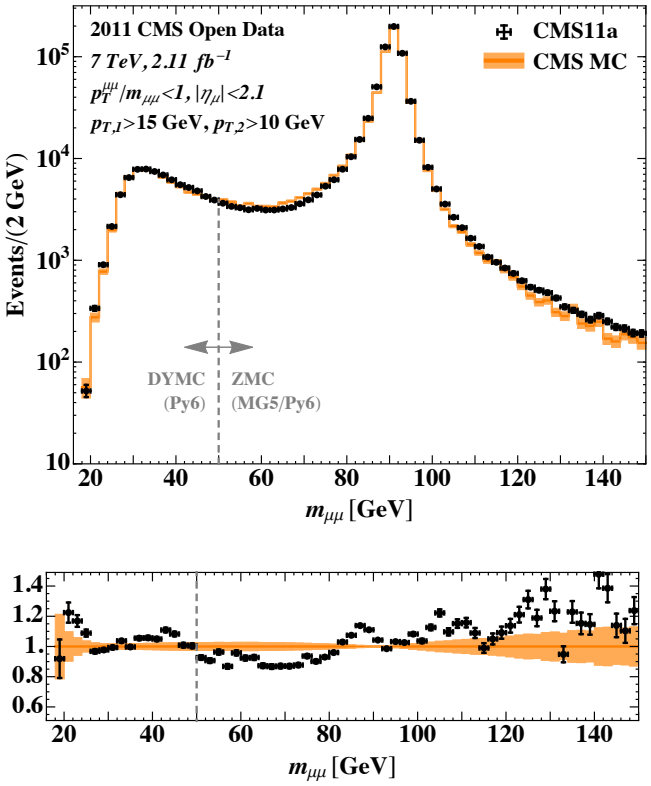
- Further cut: $p_T^1 > 15$ GeV, $p_T^2 > 10$ GeV
- Impose $|\eta^{1,2}| < 2.1$





Monte Carlo Simulation

Are we using the data/MC correctly?



Produced by CMS with GEANT4, Pythia6, MadGraph5

Validation Studies

Validation study: measure inclusive Z cross section with CMS11a

The inclusive Z cross section measurement has similar baseline selection criteria to our analysis

Validation Studies

Validation study: measure inclusive Z cross section with CMS11a

Modeled on CMS measurement from 2010 (1107.4789)

$$\sigma_{Z\mu\mu} = \sigma\left(pp \to Z + X\right) \times \mathcal{B}\left(Z \to \mu^+\mu^-\right) = \frac{N_Z}{\mathcal{L} A_Z \epsilon_{\text{tr}}^Z \epsilon_{\text{iso}}^Z}$$

- A_Z is geometric acceptance (cuts on $p_T^{1,2}$, $\eta^{1,2}$)
- ϵ_{tr}^Z is dimuon trigger efficiency
- ϵ_{iso}^Z is dimuon isolation efficiency

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CMS11a

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

Validation Studies

Validation study: measure inclusive Z cross section with CMS11a

- Modeled on CMS measurement from 2010 (1107.4789)

$$\sigma_{Z\mu\mu} = \sigma\left(pp \to Z + X\right) \times \mathcal{B}\left(Z \to \mu^+\mu^-\right) = \frac{N_Z}{\mathcal{L} A_Z \epsilon_{\text{tr}}^Z \epsilon_{\text{iso}}^Z}$$

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, $|\eta| < 2.1$

Validation Studies

Impose the same kinematic cuts on CMS11a from CMS analysis such that acceptance is the same

$$\text{Measuring } \sigma_{Z\mu\mu} = \sigma\left(pp \to Z + X\right) \times \mathcal{B}\left(Z \to \mu^+\mu^-\right)$$

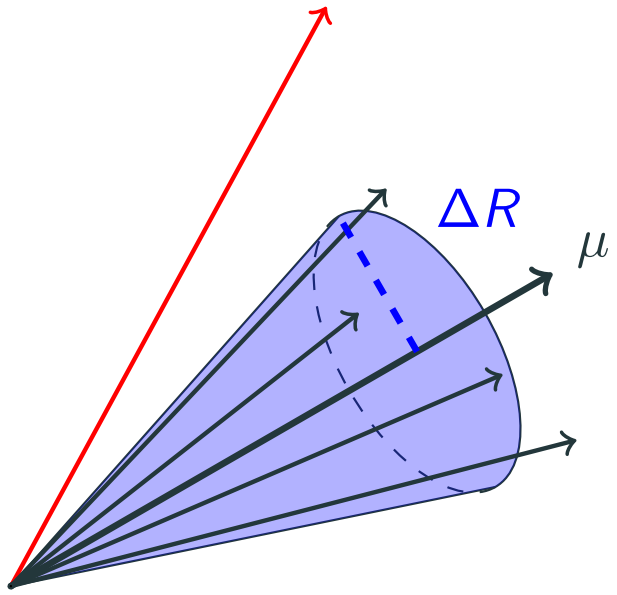
- 60 GeV $< m_{\mu\mu} <$ 120 GeV
- Further cut $p_T^{1,2} >$ 20 GeV
- $|\eta^{1,2}| < 2.1$
- Opposite sign, isolated μ pairs

Validation Studies

Isolation dramatically reduces QCD (heavy flavor) background

$$I_{\text{comb}} = \frac{\left(p_T^{\text{track}} + E_T^{\text{ECAL}} + E_T^{\text{HCAL}}\right)_{\Delta R}}{p_T^{\mu}}$$

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \quad < 0.3$$



Define isolation variable I_{comb}: The sum of the p_T from track, energy deposit in HCAL, and energy deposit in ECAL for **all particles** within a radius ΔR from muon, **divided by** the p_T of the muon

- Isolation Condition: $I_{\text{comb}} < 0.15$

Validation Studies

Important part of analysis is **determining efficiencies**

$$\sigma_{Z\mu\mu} = \frac{N_Z}{\mathcal{L} A_Z \epsilon^Z_{\text{tr}} \epsilon^Z_{\text{iso}}}$$

Comparison: CMS11a Validation Study to CMS 2010 Analysis

	Central Value	Uncertainty	CMS Analysis
$\mathcal{L}$	$2.11\,\text{fb}^{-1}$	2.2%	
A_Z	0.392	2.4%	0.3978 ± 0.0004
Single μ trigger eff.	0.924	2.4%	0.9203 ± 0.0019
Single μ isolation eff.	0.966	1.5%	0.9813 ± 0.0010
Background	—	1.0%	
Combined	$0.659\,\text{fb}^{-1}$	5.3%	

Validation Studies

Important part of analysis is **determining efficiencies**

$$\sigma_{Z\mu\mu} = \frac{N_Z}{\mathcal{L} A_Z \epsilon^Z_{\text{tr}} \epsilon^Z_{\text{iso}}}$$

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Background	—	1.0%	
Combined	$0.659\,\text{fb}^{-1}$	4.9%	

Cuts are chosen so that acceptances are the same

Validation Studies

Important part of analysis is **determining efficiencies**

$$\sigma_{Z\mu\mu} = \frac{N_Z}{\mathcal{L} A_Z \epsilon^Z_{\text{tr}} \epsilon^Z_{\text{iso}}}$$

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Background	—	1.0%	
Combined	$0.659\,\text{fb}^{-1}$	4.9%	

Efficiencies differ as trigger and isolation conditions are different

Validation Studies

Cut flow for the analysis of $\sigma_{Z\mu\mu}$ using the CMS11a data set

	Dimuon Events	
CMS11a $\mu 13 \mu 8$	6,241,576	
Baseline Acceptance ($p_{T,1} > 15$ GeV, $p_{T,2} > 10$ GeV, $\lvert\eta_\mu\rvert < 2.1$)	2,961,681	
Tight Muon Cuts (χ^2/d.o.f. < 10, $n_{\mathrm{hit}} \geq 10$, $d_0 < 2$ mm, $z_0 < 10$ mm)	2,155,900	
	OS Events	SS Events
Opposite Sign vs. Same Sign	1,895,756	260,144
Z-mass Region ($m_{\mu\mu} \in [60, 120]$ GeV)	794,623	30,105
$p_T^\mu > 20$ GeV	699,270	9,726
Muon Isolation ($I_{\mathrm{comb}} < 0.15$)	642,219	78

Same sign events are a measure of QCD background

$$N_Z = 642,219$$

Validation Studies

Compare cross section measurements

$$\sigma_{Z\mu\mu} = \frac{N_Z}{\mathcal{L} A_Z \epsilon^Z_{\text{tr}} \epsilon^Z_{\text{iso}}}$$

Our measurement with CMS11a:

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

Validation Studies

Compare cross section measurements

$$\sigma_{Z\mu\mu} = \frac{N_Z}{\mathcal{L} A_Z \epsilon^Z_{\text{tr}} \epsilon^Z_{\text{iso}}}$$

Our measurement with CMS11a:

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

Compare to LHC analysis result:

$\sigma_{Z\mu\mu} = 970 \pm 30$ pb	NLO SM prediction (1107.4789)
$\sigma_{Z\mu\mu} = 974 \pm 44$ pb	Measured value, CMS 2010, e/μ averaging (1107.4789)
$\sigma_{Z\mu\mu} = 986 \pm 31$ pb	Measured value, CMS 2011 (1310.7291)

Prompt Sample

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

General Search Strategy

Cut flow for the $V \to \mu^+\mu^-$ search on CMS11a

	Dimuon Events	
Baseline Acceptance and Tight Muons Cuts ($p_{T,1} > 15$ GeV, $p_{T,2} > 10$ GeV, $\lvert\eta_\mu\rvert < 2.1$, $d_0 < 2$ mm, $z_0 < 10$ mm)	2,155,900	
Search Region (OS, $m_{\mu\mu} \in [11, 78]$ GeV, $d_0 < 250\,\mu$m, $z_0 < 2000\,\mu$m)	561,364	
	Isolated Sample ($I_{\mathrm{comb}} < 0.15$)	Prompt Sample ($IP_{xy} < 100\,\mu$m)
$p_T^{\mu\mu} > 0$	188,924	412,002
$p_T^{\mu\mu} > 25$ GeV	46,798	91,264
$p_T^{\mu\mu} > 60$ GeV	7,668	11,208

Resonance Search

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

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

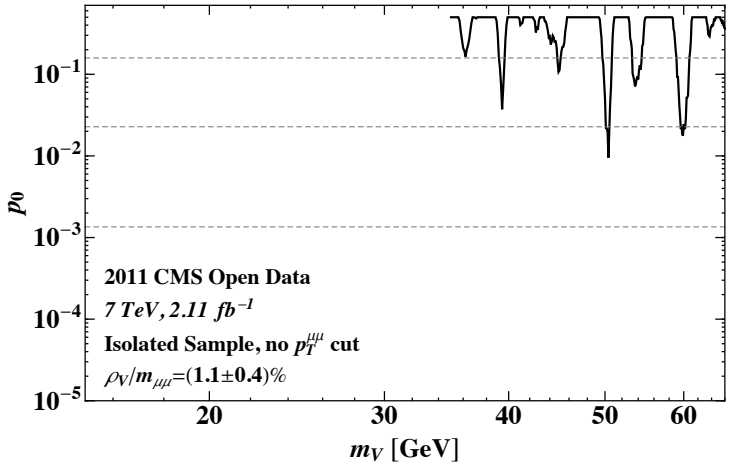
	Central Value	Uncertainty	Incremental Effect on Expected Limit
Resolution	1.1% (1.3%)	0.4%	10% (7%) (profiled)
Line Shape Modeling	1	5%	
$\mathcal{L}$	$2.11\,\text{fb}^{-1}$	2.2%	0.6% (multiplicative)
ϵ_{IP}^{V} (prompt sample only)	0.97	1.5%	

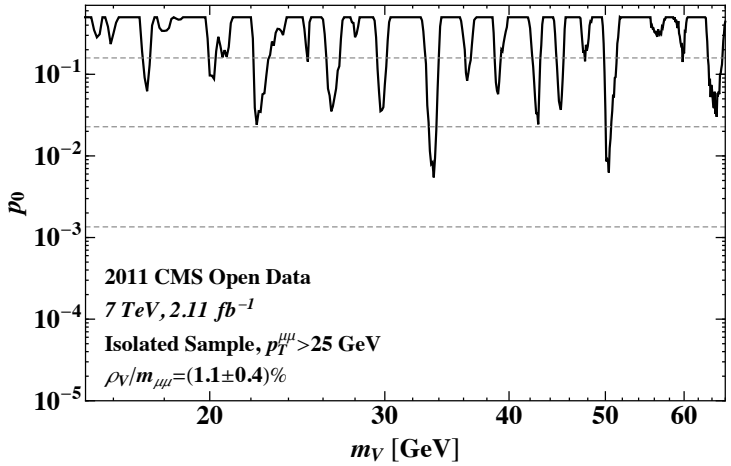
Table 1: A summary of the systematic uncertainties on our fitting results, showing the size of the uncertainty and the effect on our limits.

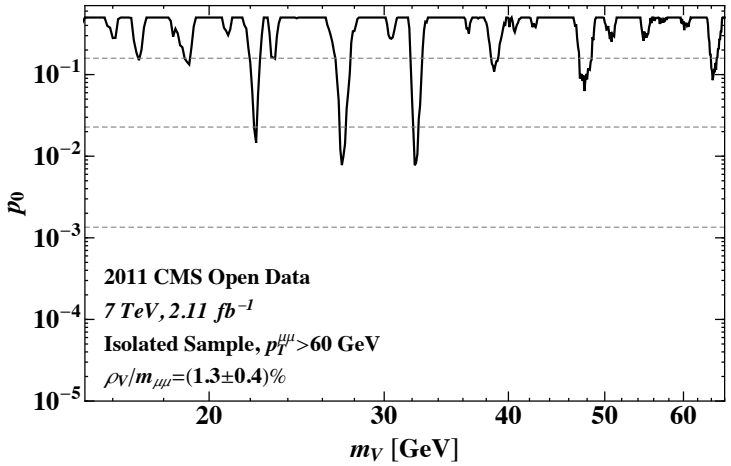
Resonance Search

p-value for rejecting background-only hypothesis

Isolated Sample



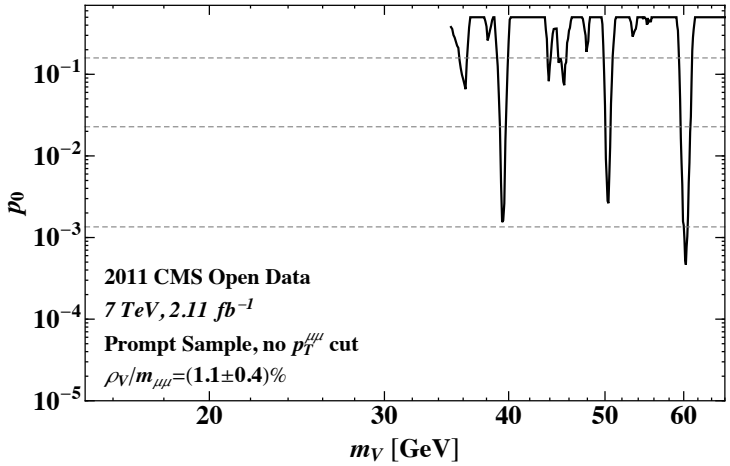


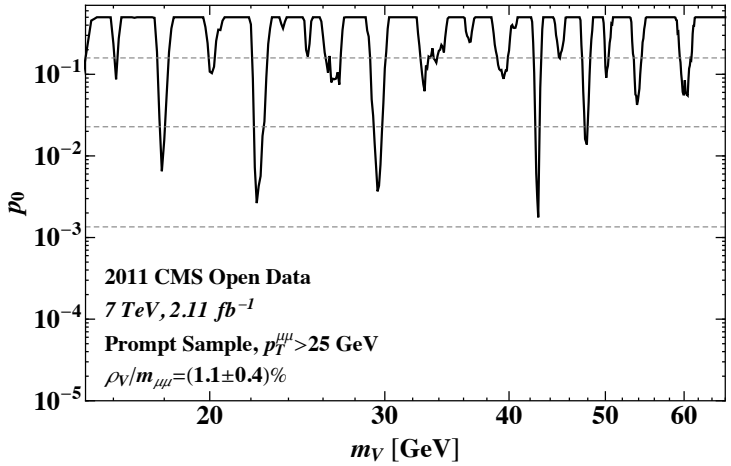


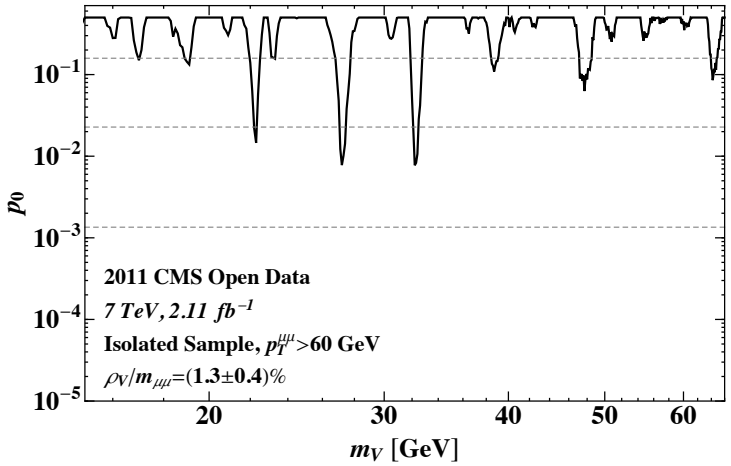
Resonance Search

p-value for rejecting background-only hypothesis

Prompt Sample



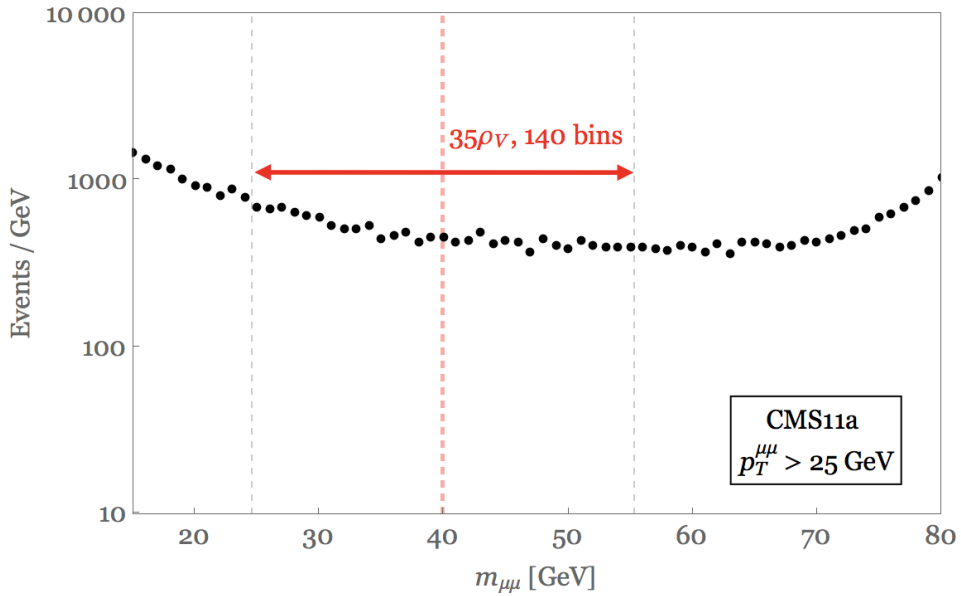




Resonance Search

Background fit with polynomial

- Center window around $m_{\mu\mu}$
- Width of window is 35 ρ_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 μ, logarithmic dependence on m_V
- p_T resolution (& dimuon mass resolution), function of p_T, η
- CMS11a data & MC both show non-Gaussian tails

Crystal ball line shape studied with J/ψ peak

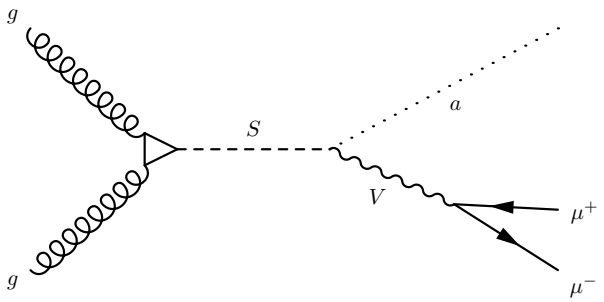
- Muons are highly boosted $\rightarrow$ similar in η, p_T
- Fit with Crystal Ball shape, can estimate p_T resolution
- MC underestimates resolution in data by 10%
- Muon resolution not published in Open Data
  $\rightarrow$ recommended $\pm 0.6\%$ on $p_T \Rightarrow \pm 0.4\%$ on $m_{\mu\mu}$
- Scale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

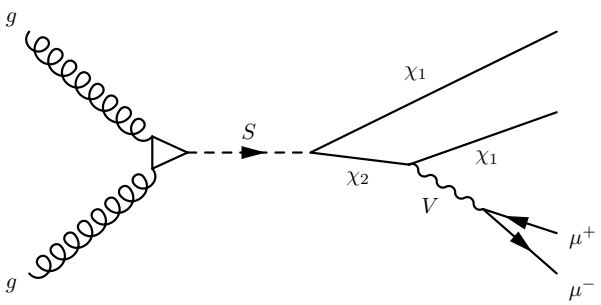
Benchmark Scenarios

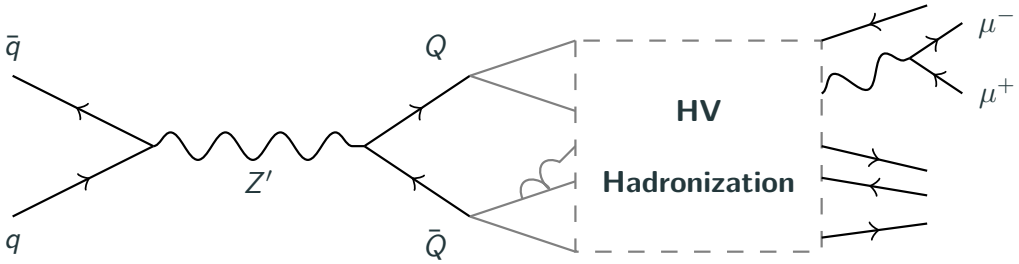
What models will retain acceptance across $p_T^{\mu\mu}$ cuts?

Models where V is produced with substantial p_T

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



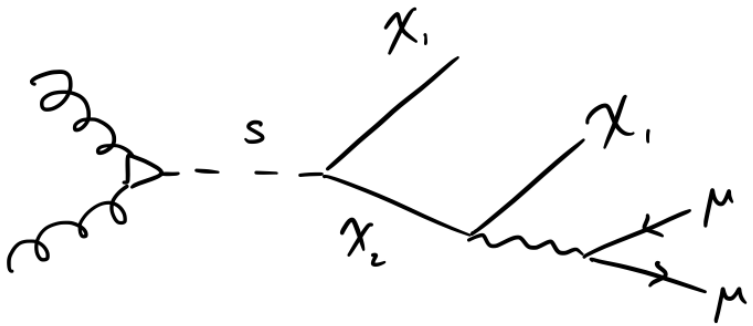




Model 2

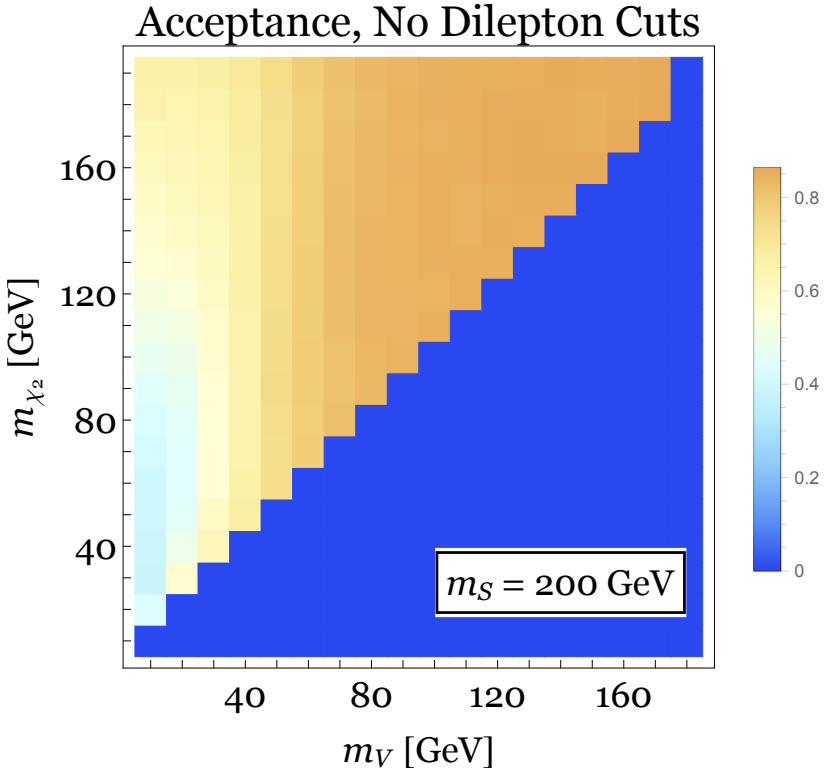
$$S \to \chi_1 \chi_2, \qquad \chi_2 \to \chi_1 V$$

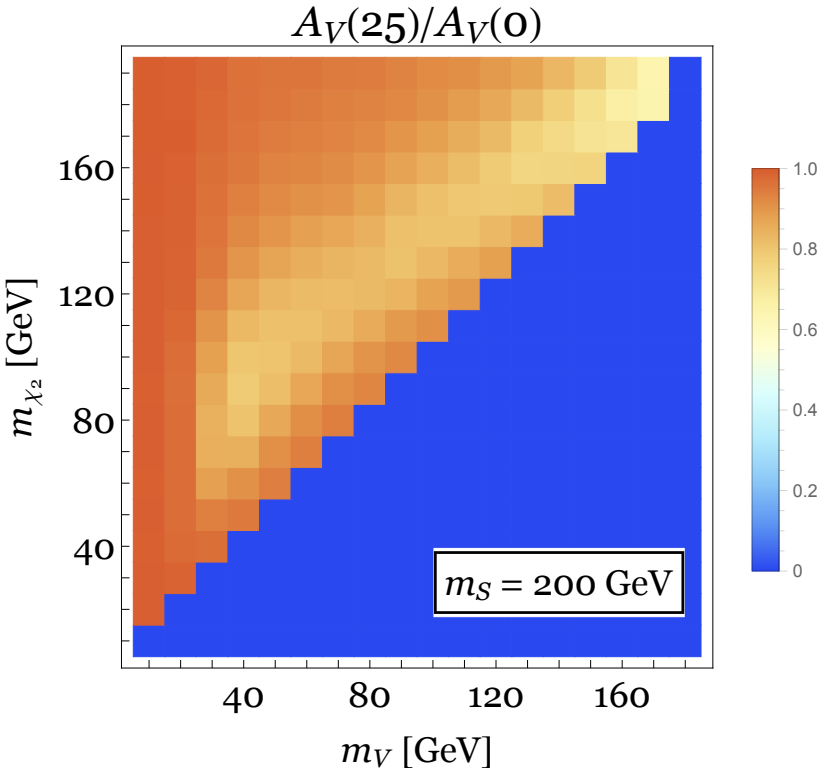
- Isolation or prompt cut depends on mass hierarchy
- For $\chi_2 \ll m_S$, χ_2 boosted, decay products are collimated
  $\to$ Ruin isolation, use prompt



Model 2

$m_S = 200$ GeV, $m_{\chi_1} = 10$ GeV





Acceptance ratio $\gg$ 50% for most of kinematic range

Good candidate for p_T enhanced search

Resonance Search

Why study this range and $p_T^{\mu\mu}$ cuts?

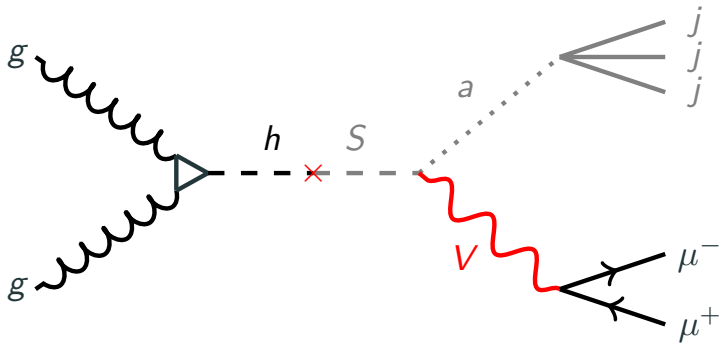
- At low mass m_V and/or large $p_T^{\mu\mu}$, muons are too collimated and triggering begins to fail
- At high mass m_V and/or large $p_T^{\mu\mu}$, fewer event counts $\rightarrow$ larger uncertainty

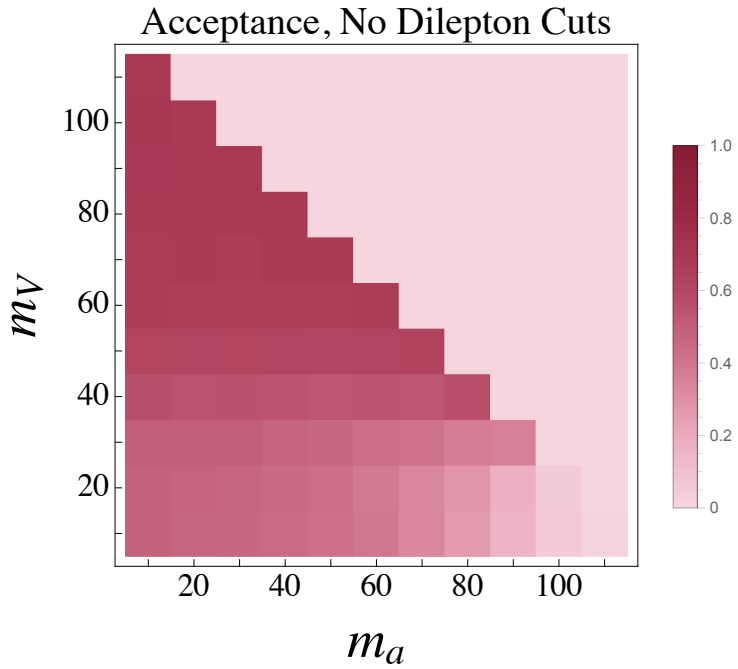
Experimentalists with better trigger/reco knowledge and larger data set could extend kinematic regions!

Benchmark Scenarios

Case 1: $m_S = m_h = 125$ GeV (BSM Higgs Decay)

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





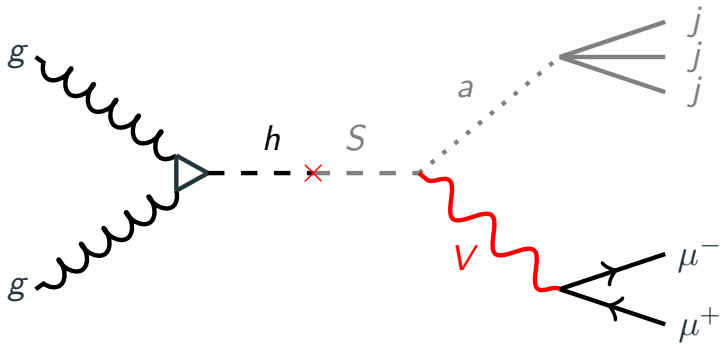
$A_V\,(0)$

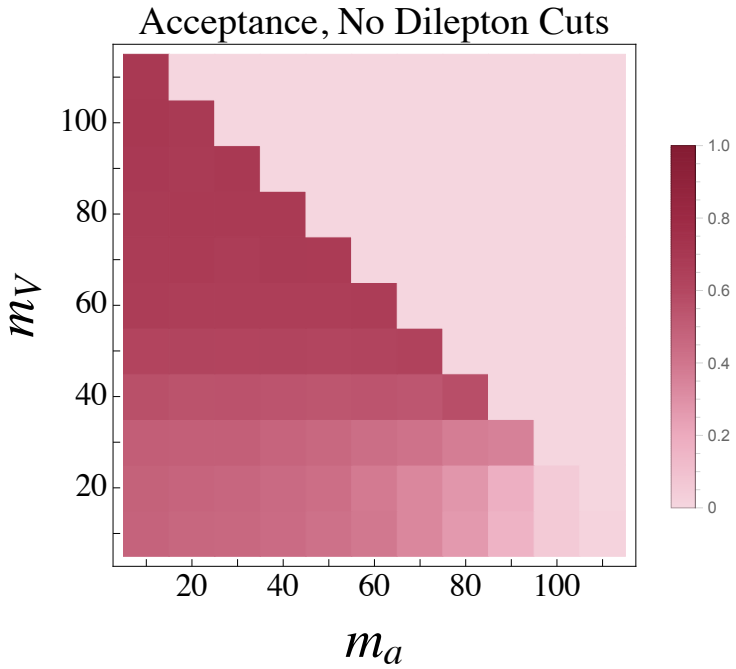
$A_V\,(25)$

Benchmark Scenarios

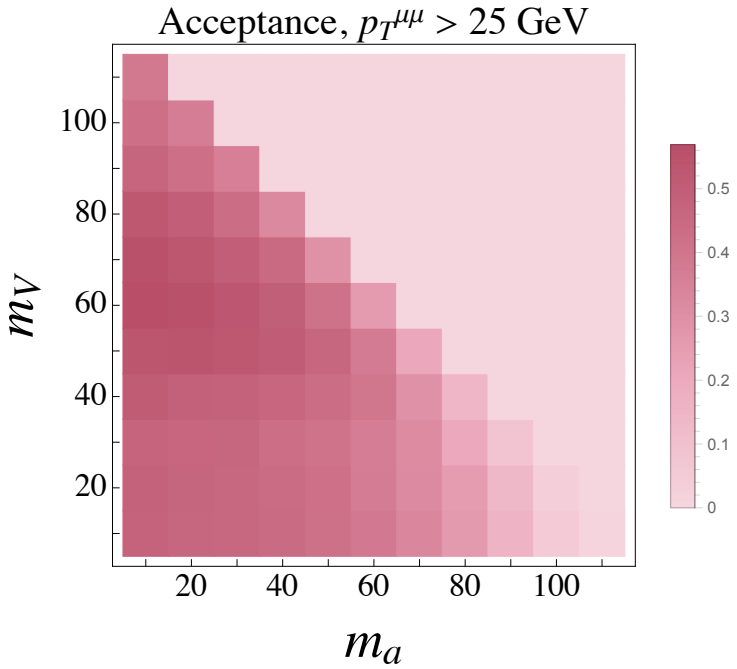
Case 1: $m_S = m_h = 125$ GeV (BSM Higgs Decay)

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





$A_V\,(0)$

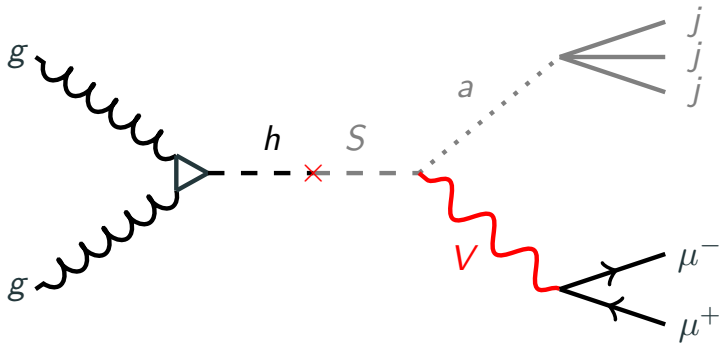


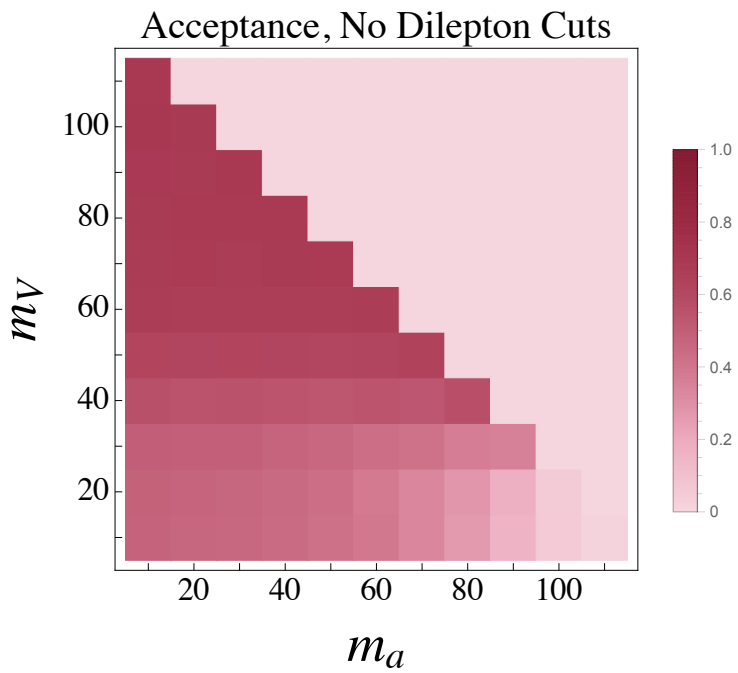
$A_V\,(25)$

Benchmark Scenarios

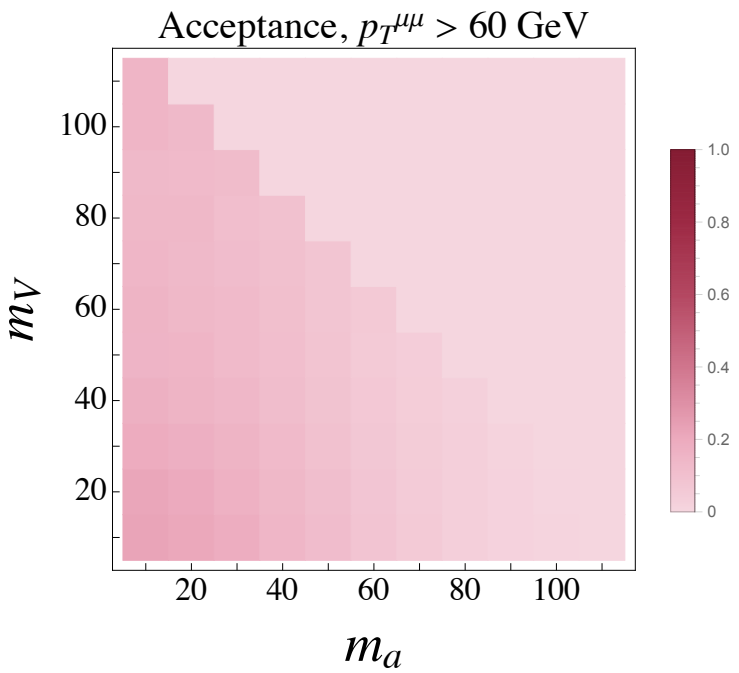
Case 1: $m_S = m_h = 125$ GeV (BSM Higgs Decay)

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





$A_V\,(0)$

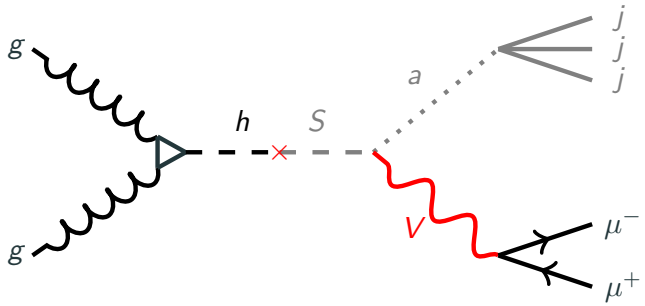


$A_V\,(60)$

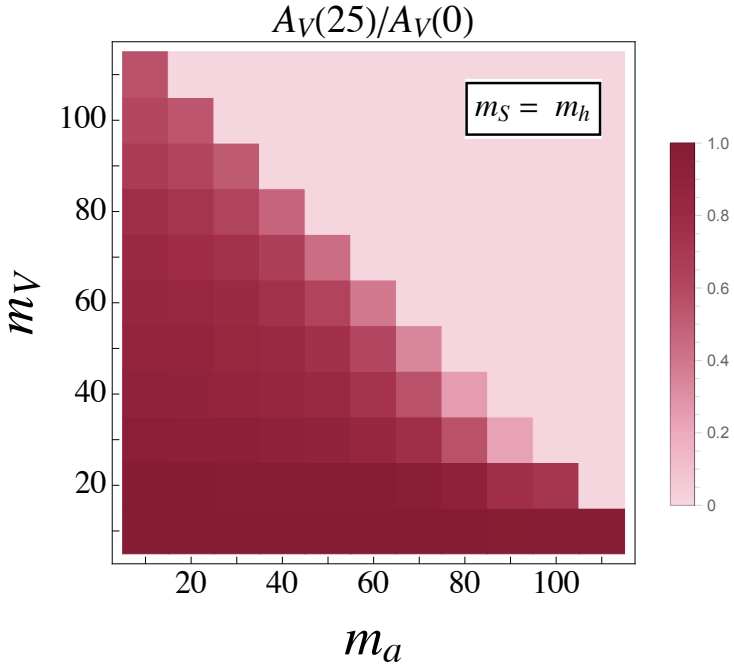
Model 1

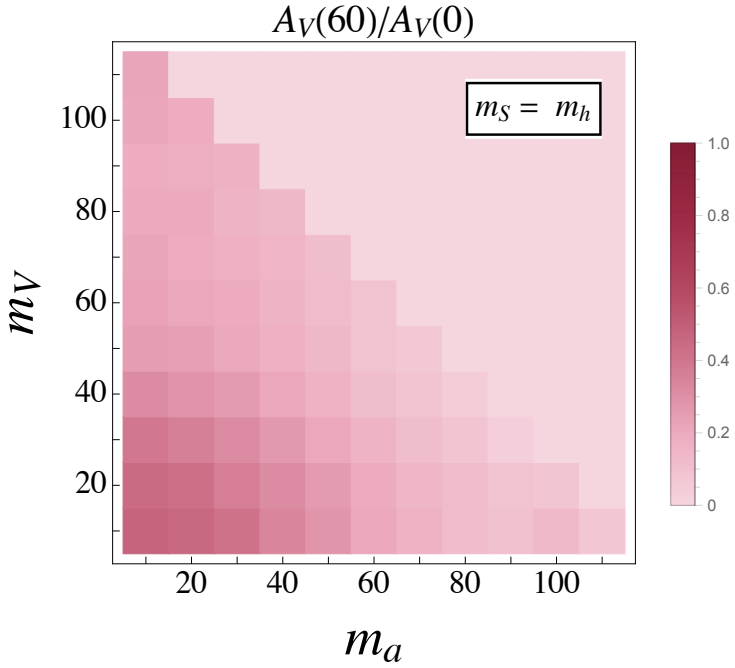
Case 1: $m_S = m_h = 125$ GeV (BSM Higgs Decay)

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



- 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

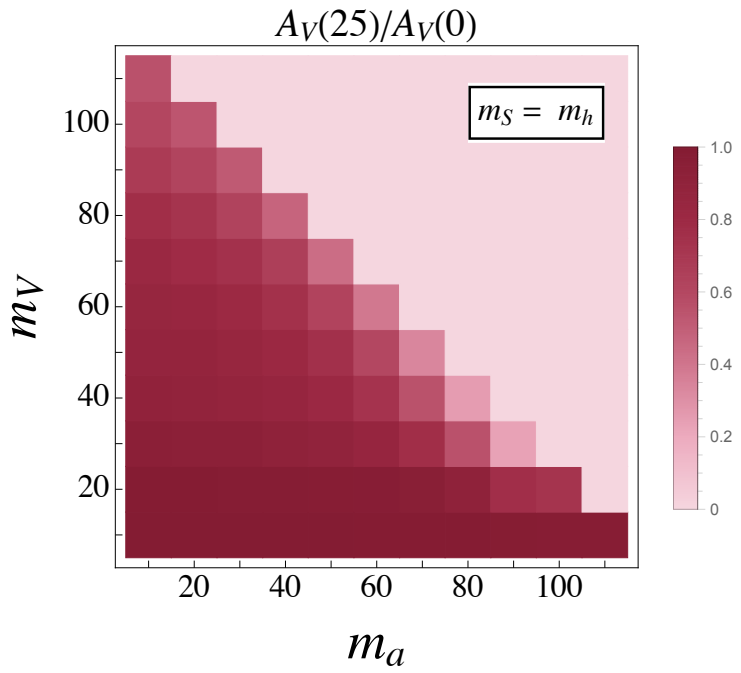




Model 1

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
- $A_V(0) = 54\%$, $A_V(25) = 47\%$
  $\rightarrow A_V(0)/A_V(25) \sim 85\%$
- $\epsilon_{\text{tr}} \sim 85\%$, $\epsilon_{\text{iso}} \sim 85\%$



$$\mathcal{B}(h \rightarrow Va)\,\mathcal{B}(V \rightarrow \mu\mu) \lesssim 7 \times 10^{-3}$$

Model 1

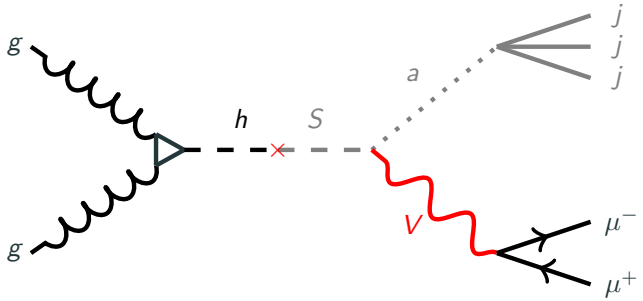
Our search sets competitive if not stronger bounds on certain classes of models

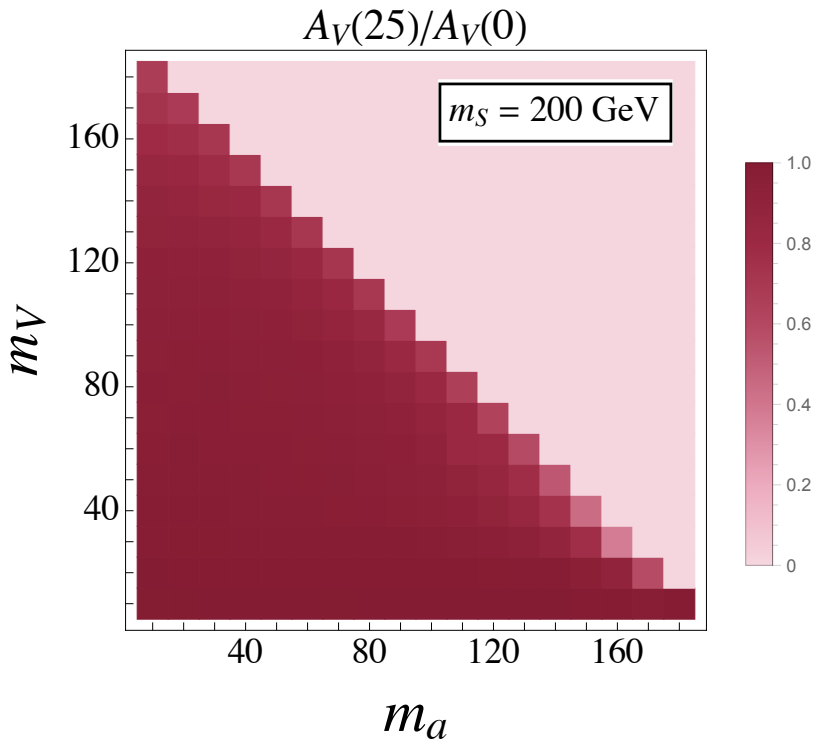
Improve limits in comparison to inclusive searches on Run I

Model 1

Case 2: $m_S = 200$ GeV

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



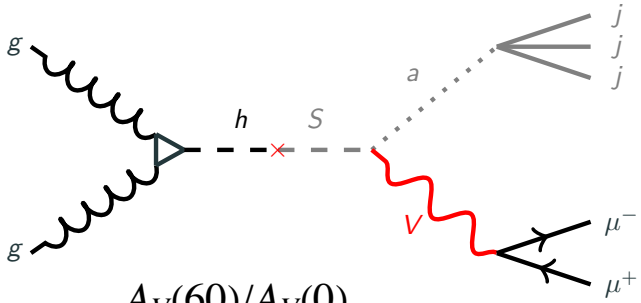


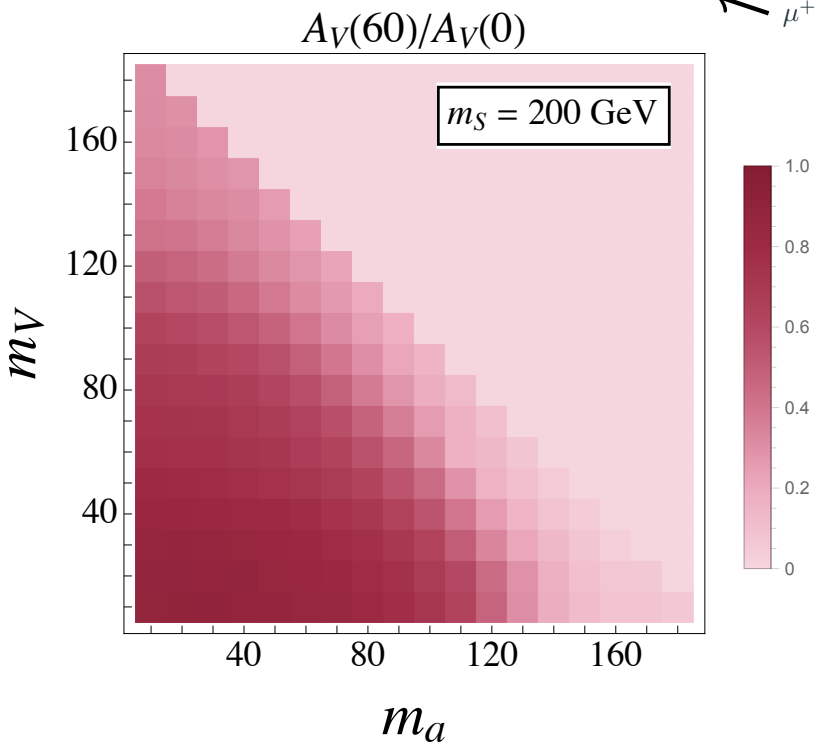
- Larger mass splitting $\to$ higher $p_T^{\mu\mu}$
- $m_V + m_a \lesssim 175$ GeV ($p_T^{\mu\mu} > 25$ GeV)

Model 1

Case 2: $m_S = 200$ GeV

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



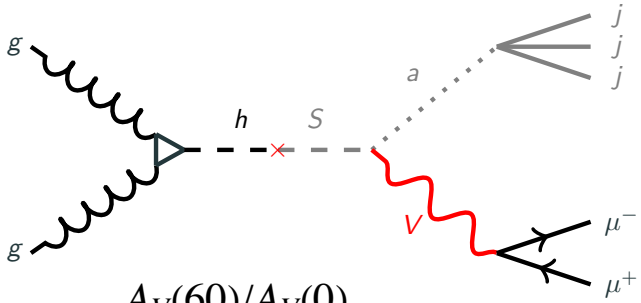


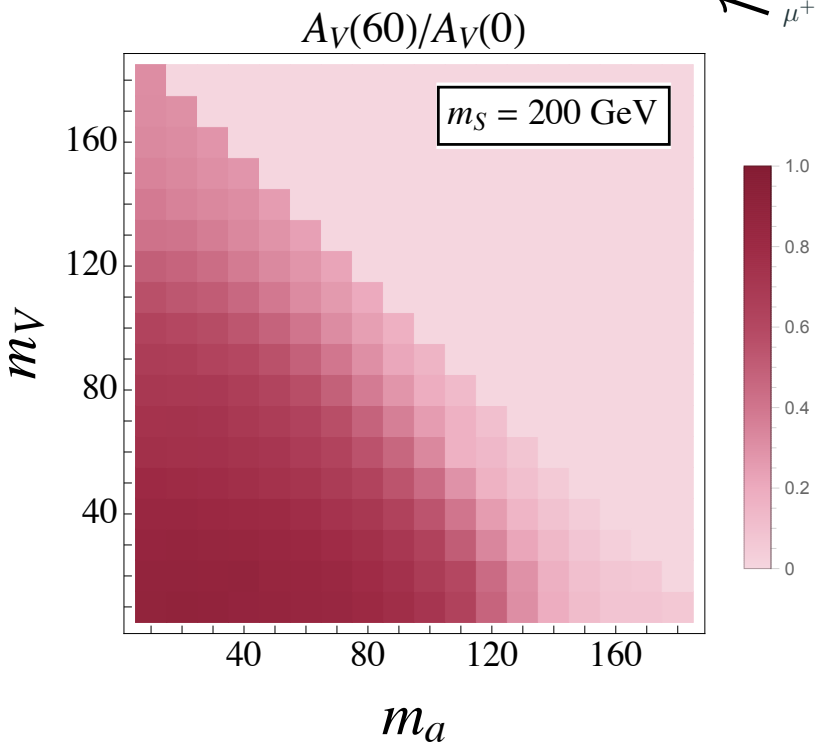
- Larger mass splitting $\to$ higher $p_T^{\mu\mu}$
- $m_V + m_a \lesssim 140$ GeV ($p_T^{\mu\mu} > 60$ GeV)

Model 1

Case 2: $m_S = 200$ GeV

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





- Larger mass splitting $\to$ 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**