Search for Dimuon Resonances in “Lepton Jets”

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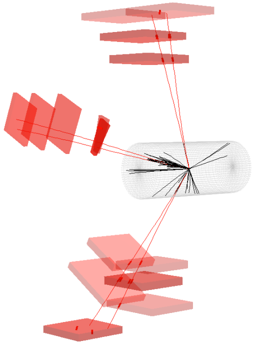
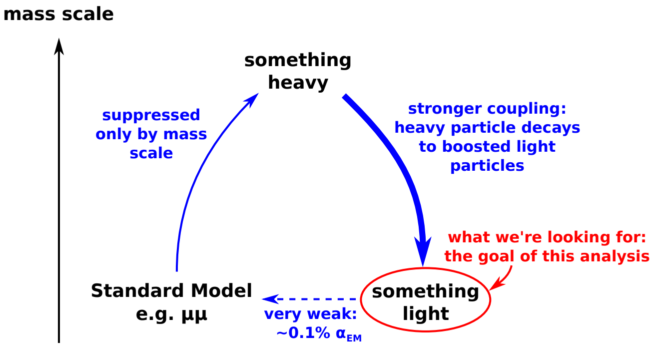
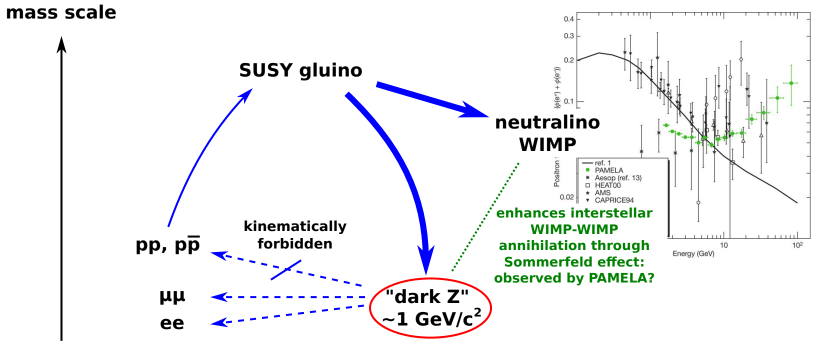


Sketch of the basic goal



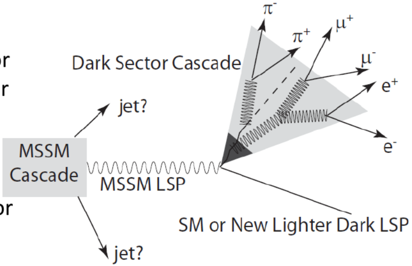
- Hidden-valley picture: predicts new low-mass, high-momentum particles decaying to Standard Model pairs like $\mu\mu$
- We want to maximize our sensitivity to "something like this"

Motivation from PAMELA result



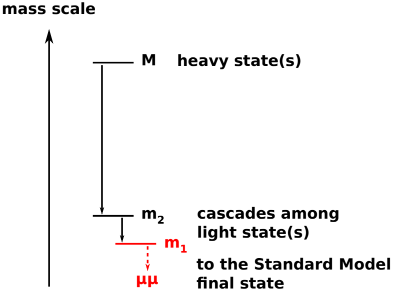
- Sub-class motivated by PAMELA positron excess
  - the "something light" is a long-range force between WIMPs
  - unobserved antiproton excess is kinematically forbidden
- Would appear in *pp* collisions as high-$\vec{p}$, low-mass Z/γ-like objects

- Phenomenology:
  - MSSM LSP decays to a dark sector cascade plus either SM particle or something else
    - e.g. new (heavy) dark matter particle
  - The cascade always ends in one or more dark photons and possibly something stable (or long living)
    - The "typical" number of dark photons is extremely dependent on assumptions (couplings and complexity of the dark sector)
  - Dark photon decays like a photon
    - Although possible to modify couplings, e.g. only couple to leptons

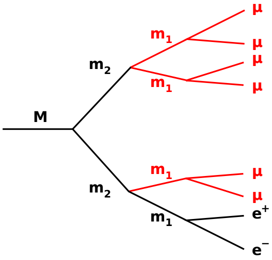


- Conclusion: expect muon pairs mixed with electron pairs
  - At all costs <u>avoid isolation</u>, instead rely on categorization to cope with backgrounds

Reminder of the method (1/5)

Theoretical consideration	Experimental method
couplings within the hidden sector (dark matter, NMSSM Higgs, etc.) are stronger than couplings to the Standard Model, so only the lightest hidden particle (m_1) decays visibly	search for one new low-mass particle
	
assume no fine splittings ($M_2 - M_1 \gg m$), such that some low-mass m_i is on-shell	search for m_1 or m_2 resonance peak

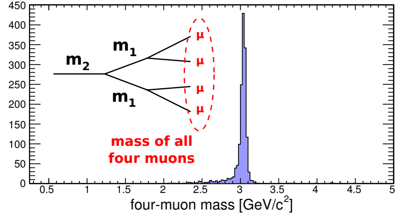
Theoretical consideration	Experimental method
several m_1 may appear per event, and their decay products may overlap cascades of low-mass particles would be collimated by a high-momentum boost	identify well-separated groups with a clustering algorithm

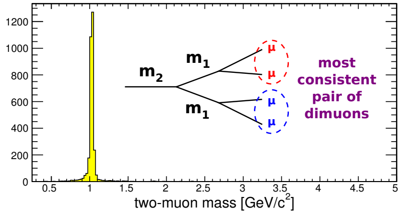


$\mathcal{B}(m_1 \to \mu\mu)$ is likely to be high (DY-like if m_1 mixes with γ, $\sim$20% if Higgs-like, ...) but non-$\mu\mu$ decays would also happen, so $m_1 \to \mu\mu$ could overlap electrons/pions	look for dimuons, but neither require nor exclude other particles (e.g. do not apply an isolation cut)

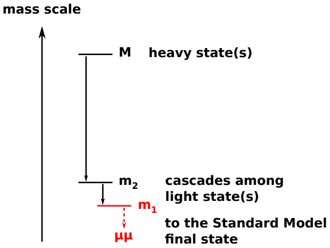
Reminder of the method (3/5)

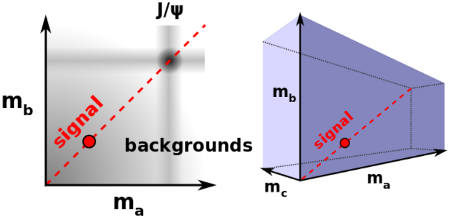
Theoretical consideration	Experimental method
narrow groups of four or more muons come from cascades like $m_2 \to m_1 m_1$ with both $m_1 \to \mu\mu$	resolve combinatorics within each group by finding the most consistent combination of dimuon masses (a and b such that $m_a \approx m_b$)





Theoretical consideration	Experimental method
only the lightest hidden state decays to muon pairs, so only one new mass	in the dimuon mass-dimuon mass plane, signal is a peak on the $m_a \approx m_b$ diagonal, background is diffuse

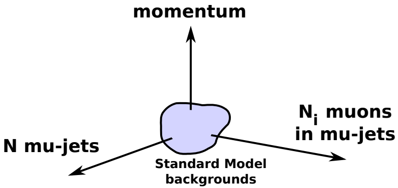




determine signal and background yields from a simultaneous fit, where the "side-band" is the non-diagonal part

shape of fit function derived from similar datasets

Theoretical consideration	Experimental method
cross-section $\lesssim \mathcal{O}(\text{pb})$	design search regions to exclude backgrounds rather than seek any particular topology
many topologies possible; typically high-momentum and/or high muon multiplicity	



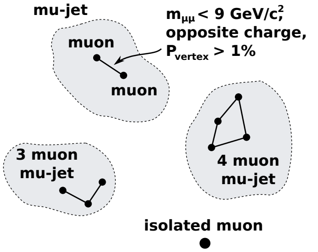
divide momentum and multiplicity space into non-overlapping signal regions, excluding low-momentum, low multiplicity

(listed on next page)

Event selection/signal regions

All signal events must have:

- at least one $p_T > 15$ GeV/c, $|\eta| < 0.9$ muon
- HLT_Mu15 or equivalent
- at least one cluster of muons (“mu-jet”)



Specific signal regions:

name	description	min mu-jet p_T	old name
R^1_2	high-p_T dimuon	80 GeV/c	(a-1)
R^1_4	four nearby muons	30 GeV/c	(a-2)
R^2_{22}	two separate dimuons	20, 10 GeV/c	(b-1)
R^N_{5+}	high multiplicity	same as above	many

$R^N_{n_1 \cdots n_N}$ has N mu-jets, n_i muons in mu-jet i

no cuts on the number of isolated muons

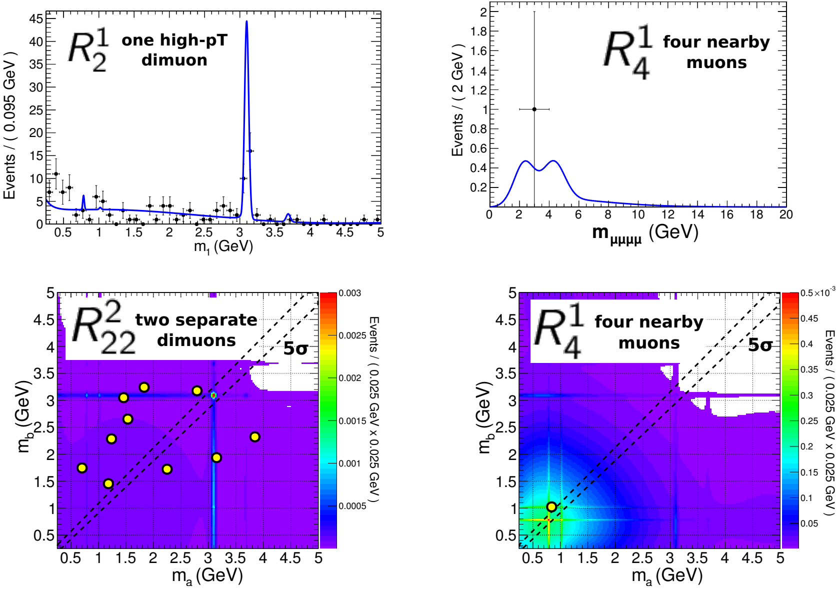
R^1_3 is not signal

$R^{2+}_{\ldots 3 \ldots}$ is signal

Muon cuts: TrackerMuon $p_T > 5$ GeV/c, $|\eta| < 2.4$, arbitrated seg. ≥ 2, tracker hits ≥ 8, $\chi^2/N_{\mathrm{dof}} < 4$

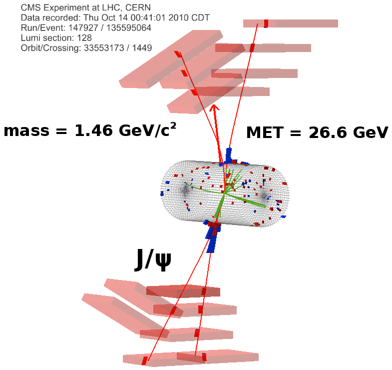
Yields with background PDFs

Zero events in R^N_{5+}, nothing on-diagonal in any 2-D region

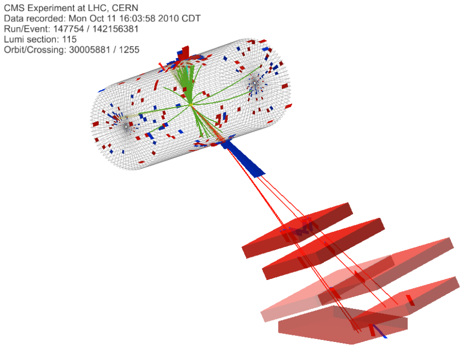


Event displays

R^2_{22}: two separate dimuons (sample event)



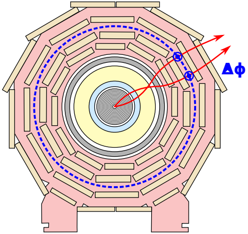
R^1_4: four nearby muons (only event)

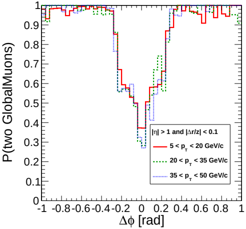


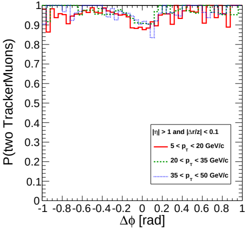
- Muon selection, trigger selection, and efficiencies
- Modeling the signal shape
- Analysis of background physics
- Modeling the background shapes
- Fitting technique and model-independent results
- Benchmark models and model-dependent results

Muon selection, trigger selection, and efficiencies

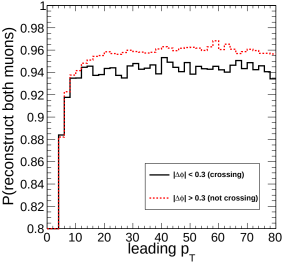
StandAloneMuons, and hence GlobalMuons, are inefficient when crossing:

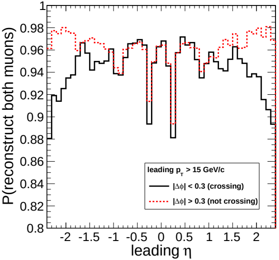






Efficiency of reconstructing *dimuon* with TrackerMuons + analysis cuts:





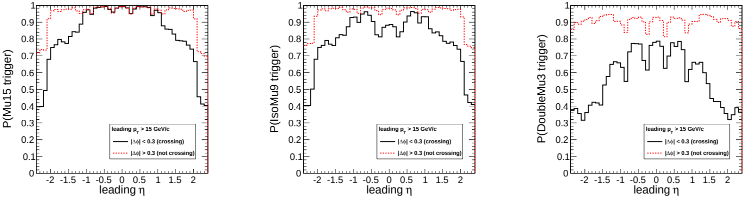
black: crossing in muon system

red: not crossing

Trigger efficiency

Trigger efficiencies are strongly dependent on whether muons cross in the muon system, with the exception of single-muon unisolated barrel trigger (middle of left plot)

single-muon (HLT_Mu15) | single-muon isolated (HLT_IsoMu9) | double-muon (HLT_DoubleMu3)



black: crossing in muon system

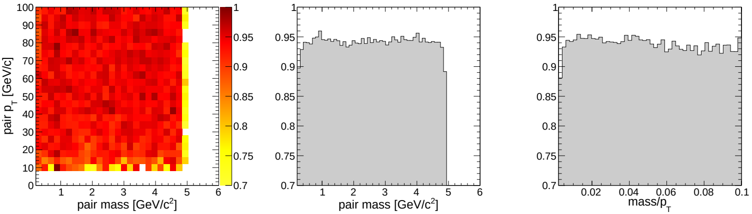
red: not crossing

Accepting endcap-triggered events would introduce a strong efficiency dependence on dimuon kinematics; therefore, we require at least one $|\eta| < 0.9$ muon above trigger threshold ($p_T > 15$ GeV/c)

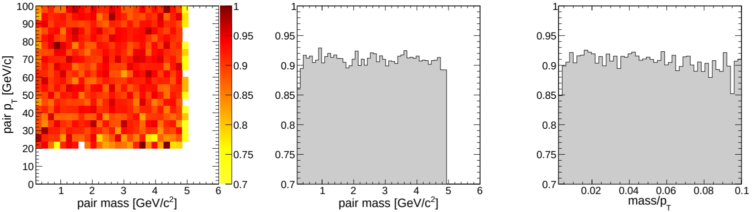
Full-chain dimuon efficiency

The probability to reconstruct, cluster, and trigger on a mu-jet is only weakly dependent on the mass and opening angle $\Delta\varphi \sim \text{mass}/p_T$

- Reconstructing a two-muon mu-jet ($p_T > 10$ GeV/c, $|\eta| < 2.4$):

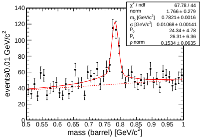


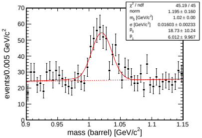
- Triggering *and* reconstructing ($p_T > 20$ GeV/c, $|\eta| < 0.9$):

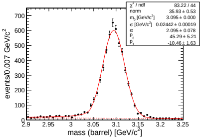


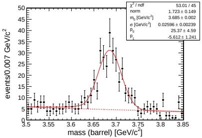
Modeling the signal shape

A hidden-sector particle must, by definition, have a narrow width, so use narrow Standard Model resonances to determine detector resolution

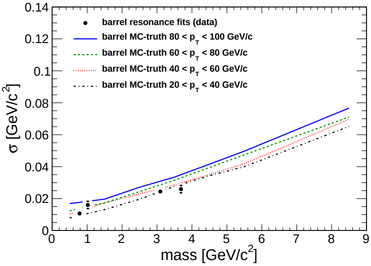


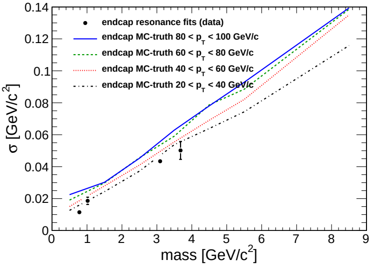






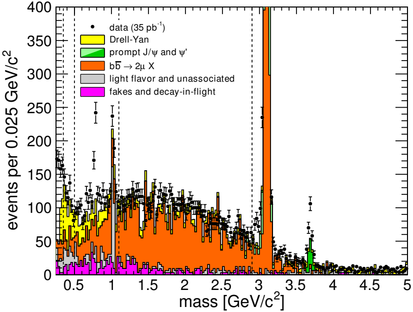
These resonances are on the lowest-p_T edge of our desired range: determine p_T-scaling (and fill in gaps between masses) with Monte Carlo





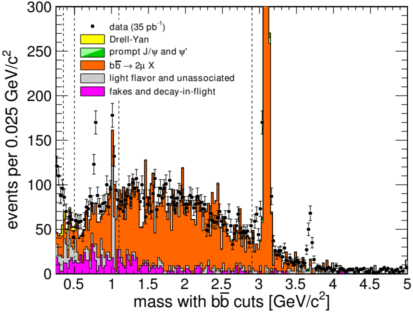
Analysis of background physics

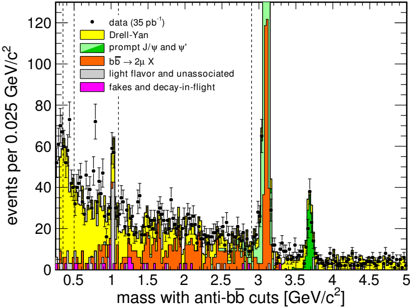
Physics of dimuon backgrounds



Data/MC comparison study to understand all background sources

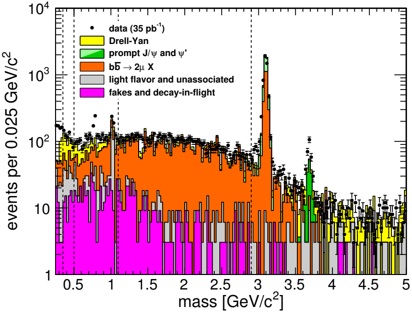
- diagnostic tool: $b\bar{b}$ cuts $=$ $Iso > 4.5$ GeV$/c$ or $L_{xy} > 2$ mm
- "low-mass rise" now understood to be Drell-Yan (though MC is incomplete)





Physics of dimuon backgrounds

Jim Pivarski



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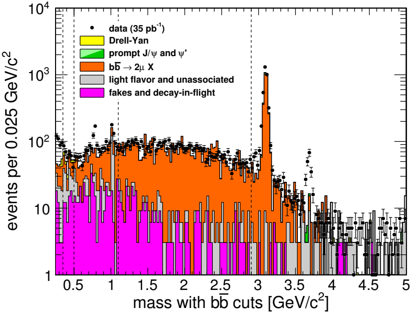
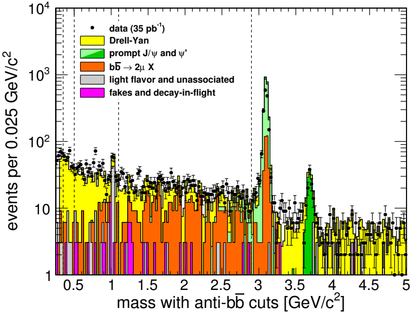


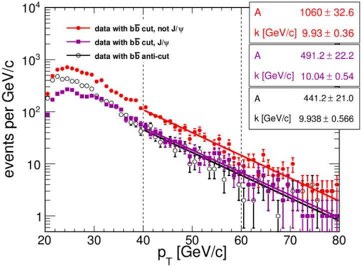


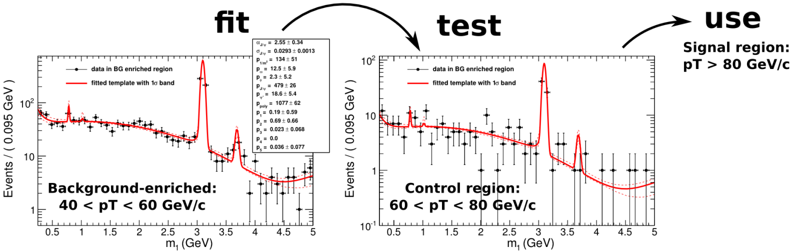
Modeling the background shapes

Background shape of R_2^1

Different physics sources contribute to each signal region, so the background shape templates must be individually constructed

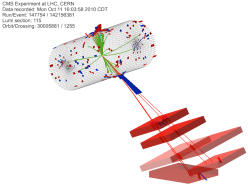
- For R_2^1: note that the prompt and isolated, $b\bar{b}$-like, and J/ψ components all scale as $\exp(-p_T/10\text{ GeV})$ above 40 GeV/c
- Derive shape from high-statistics low-p_T data, test in medium-p_T, and use in high-p_T signal search





Background shape of R_4^1

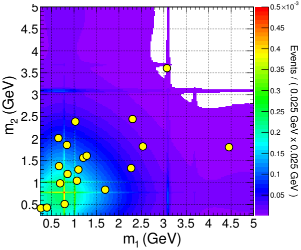
For R_4^1: four nearby muons

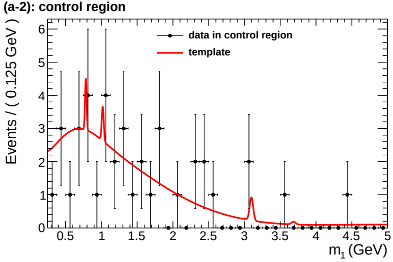


- Dominant Standard Model backgrounds: decays-in-flight and misreconstruction (fakes)
- Simulate fake muons by putting non-muon tracks into mu-jets:

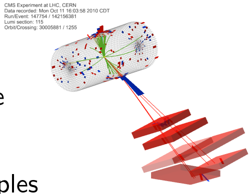
Background-enriched	Control	Signal Region
2 muons, 2 tracks	3 muons, 1 track	4 muons

- Plots of control region with template shape overlaid:





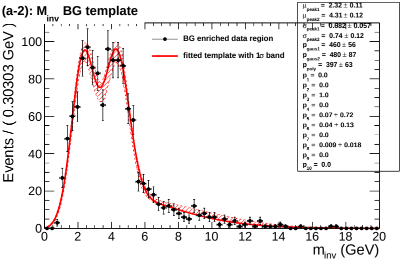
Still R^1_4: four nearby muons



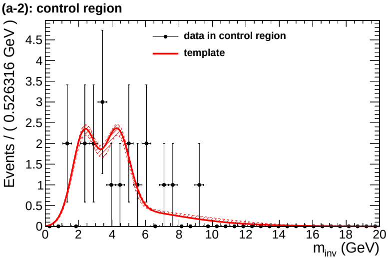
Considering the case of $m_2 \to m_1 m_1 \to 4\mu$ with m_1 off-shell but m_2 on-shell, we prepare a template for the four-muon mass

- background-enriched, control, and signal samples are the same as on the previous page
- four-muon mass has a two-peak structure: second peak is J/ψ

background-enriched fit

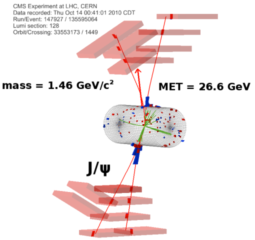


control sample test



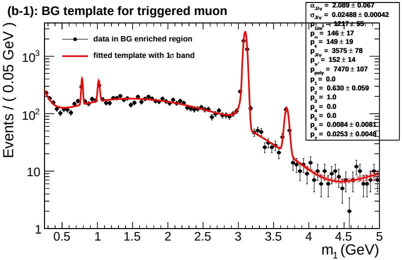
Background shape of R^2_{22}

For R^2_{22}: two separate dimuons

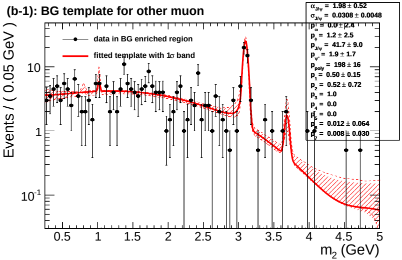


- Dominant Standard Model backgrounds: $b\bar{b}$ with both b-quarks producing $\mu\mu X$ by double-semileptonic decay, resonances, etc.
- Assume that each b-quark decays independently and construct 2-D distribution from Cartesian product of 1-D $b \to \mu\mu X$ distributions
- Complication: requiring a $p_T > 15$ GeV$/c$ trigger muon changes the distribution; need templates for both cases

template for dimuon with trigger



template for any dimuon



Fitting technique and model-independent results

Signal + background fit in each signal region with data:

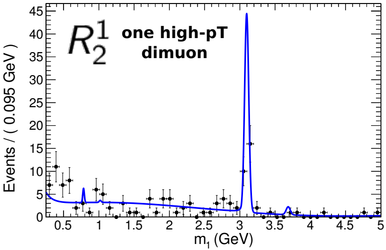
- only normalizations float; shapes are treated as nuisance parameters
- binned likelihood method

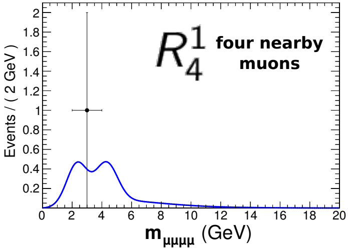
Quantity	Value	Uncertainty	Distribution
Luminosity	35 pb^{-1}	11%	log-normal
$\epsilon_\alpha = \alpha_{\mathrm{gen}}/\alpha_{\mathrm{rec}}$	see below	2%	log-normal
Signal Shape (Crystal Ball parameters):			
barrel σ_0	0.00675	0.00325	log-normal
endcap σ_0	0.0075	0.0040	log-normal
barrel $d\sigma/dm$	0.0070	–	–
endcap $d\sigma/dm$	0.0140	–	–
α, n	1.8, 2.0	0.16, 0.6	bi-variate Gauss (−90% correlated)
α_{EB}/α_{BB}	0.55	0.05	log-normal
Background Shapes:			
template parameters	-	-	full correlation matrices

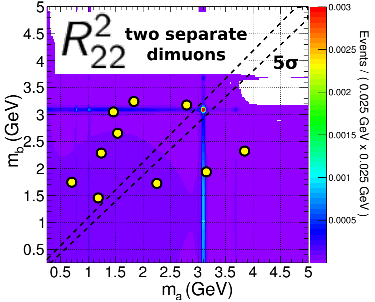
$\epsilon_\alpha = 94.7\%$ (R^1_2 dimuon), 79.3% (R^1_4 four muons), 89.8% (R^2_{22} separate dimuons)

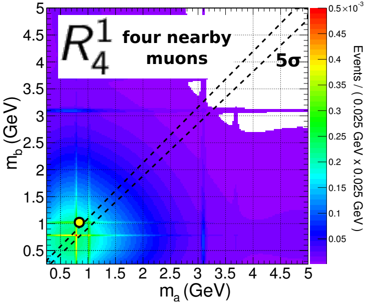
Fits of signal regions (again)

Zero events in R^N_{5+}, nothing on-diagonal in any 2-D region





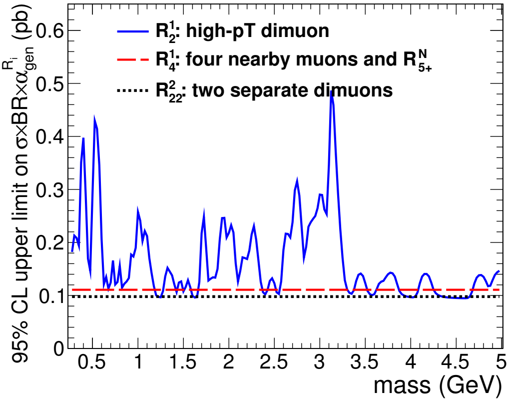




Model-independent limits

Upper limit on cross-section × branching fraction × acceptance, where acceptance must be supplied by the model in question

- acceptance = probability that an event satisfies basic p_T, η, mass, and multiplicity requirements of a given region R_i

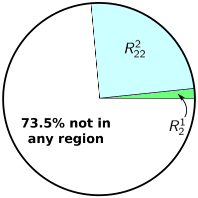


Benchmark models and model-dependent results

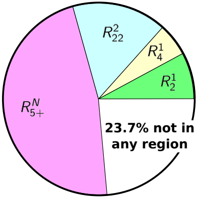
Calculate model-dependent limits from acceptances of each model into each signal region

- three sample models: one NMSSM Higgs and two dark matter
- depends strongly on $\mathcal{B}(\gamma_{\mathrm{dark}} \to \mu\mu)$ (assumed to be 100% here)

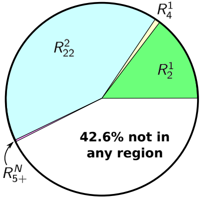
NMSSM Higgs
produce Higgs, decays to dimuons: $h_1 \to a_1 a_1$ with $a_1 \to \mu\mu$



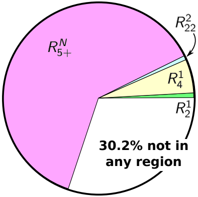
MSSM + mixed
produce gluino, mixed decays: $\gamma_{\mathrm{dark}} \to \mu\mu$ and $h_{\mathrm{dark}} \to \gamma_{\mathrm{d}}\gamma_{\mathrm{d}} \to 4\mu$



MSSM + γ_{dark}
produce squark, decays to dimuons: $\gamma_{\mathrm{dark}} \to \mu\mu$

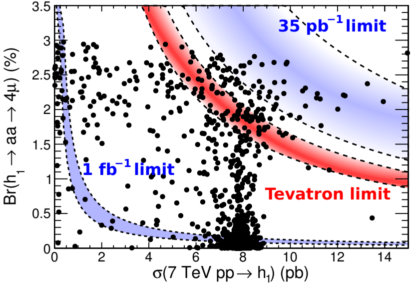


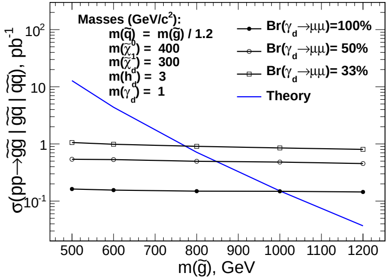
MSSM + h_{dark}
produce squark, decays to quadmuons: $h_{\mathrm{dark}} \to \gamma_{\mathrm{d}}\gamma_{\mathrm{d}} \to 4\mu$

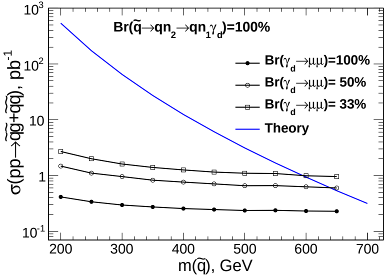


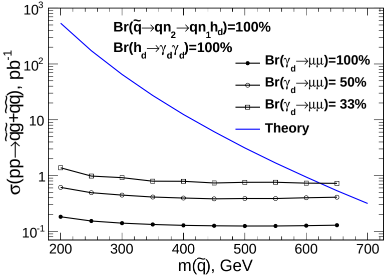
Benchmark model limits

Same arrangement as previous page









Conclusions

- We present a complete search for cascade decays in a hidden sector decaying (at least partly) to $\mu\mu$, with either the lightest (m_1) or second lightest (m_2) state on-shell
- Reconstruction methods were chosen for uniform, predictable efficiencies and independence from signal kinematics
- Sources of backgrounds are understood using Monte Carlo
- Template shapes for signal and background fit well-tested in control samples
- Fit yields robust 0.1 pb limit on $\sigma \times \mathcal{B} \times \alpha$ for all all regions with more than one dimuon; 0.1–0.5 pb for one dimuon
- Demonstrated application with several benchmark models

Backup

- If two muons satisfy

$$\Big((\text{mass} < 9\ \text{GeV}/c^2 \text{ and } P_{\text{vertex}} > 1\%) \text{ or } \Delta R < 0.01\Big) \text{ and opposite charge}$$

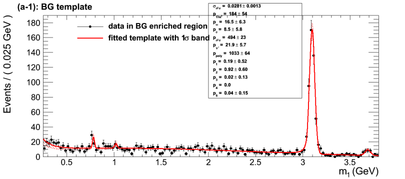
  then they are "close" to one another
- Each mu-jet is a connected subgraph of "close" muons
- There is *no* order dependence at all in the clustering process

Test of the algorithm on background Monte Carlo: $b\bar{b}$ with each $b \to 2\mu X$. The algorithm should not merge the muons from different b quarks.

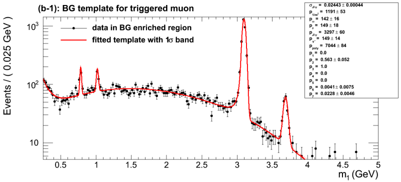
Clustering threshold	two separate mu-jets	one big mu-jet
mass < 5 GeV$/c^2$	6015	6
mass < 9 GeV$/c^2$	6019	6
mass < 15 GeV$/c^2$	5870	172

Templates with many bins

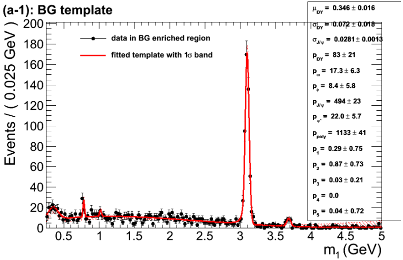
R^1_2

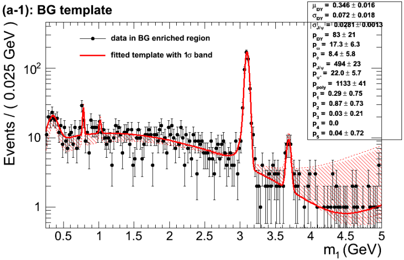


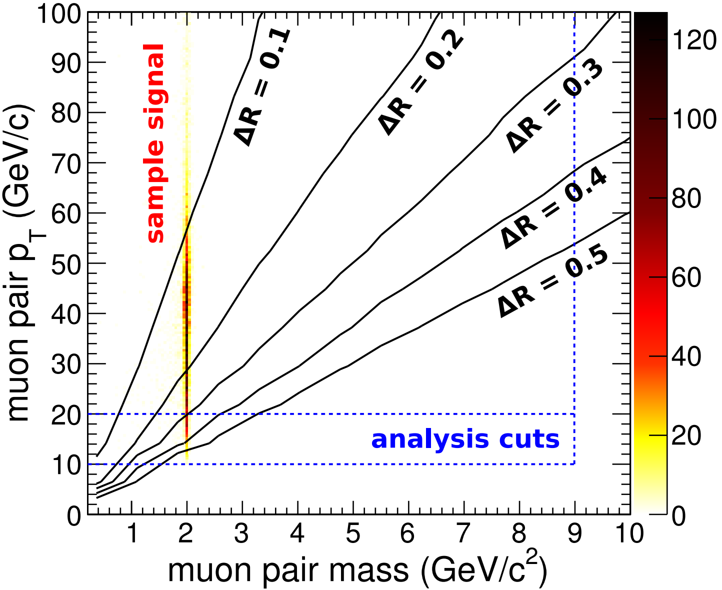
R^2_{22} with trigger muon



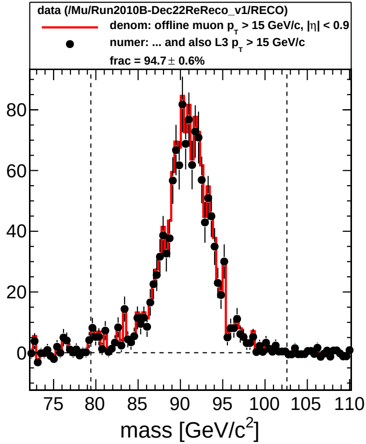
R^1_2 single high-p_T dimuon shape template:

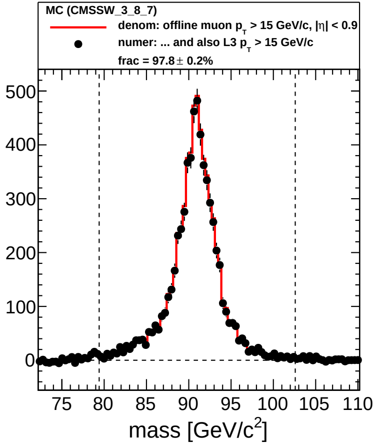




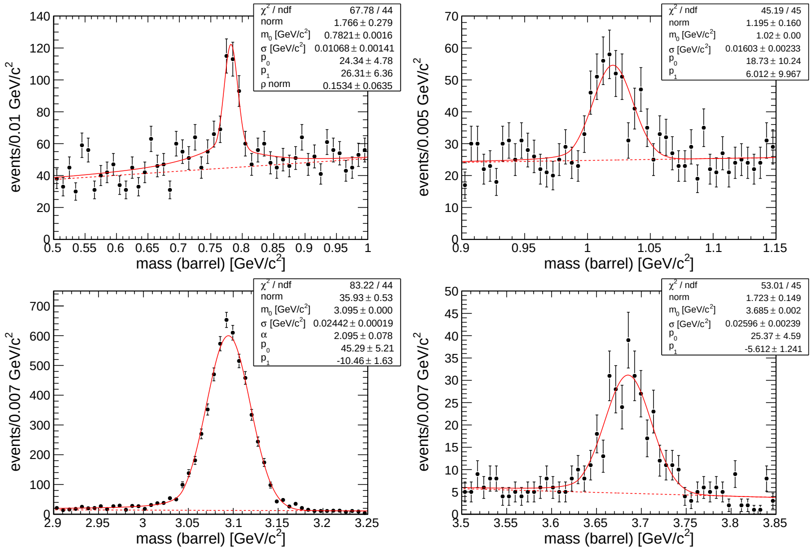

muon pair p_T (GeV/c)
muon pair mass (GeV/c^2)
sample signal
ΔR = 0.1
ΔR = 0.2
ΔR = 0.3
ΔR = 0.4
ΔR = 0.5
analysis cuts
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8
9
10
0
20
40
60
80
100
120

Trigger tag-and-probe

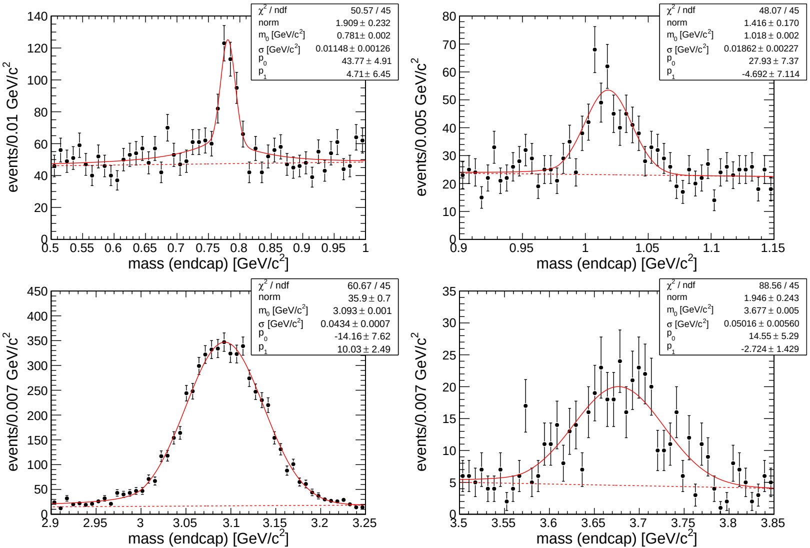




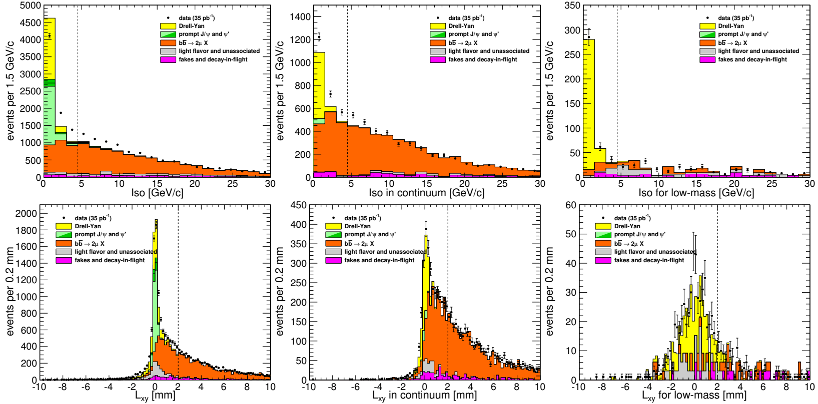
Resonance fits: barrel



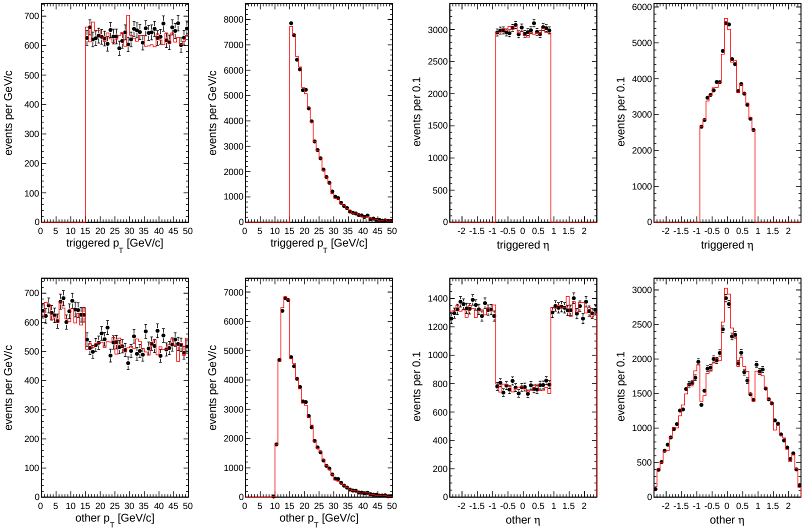
Resonance fits: endcap



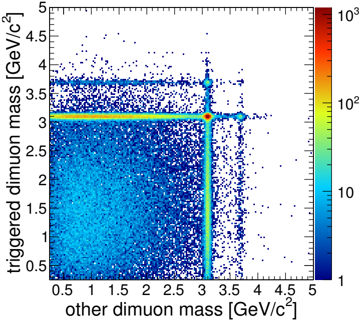
Iso and L_{xy} of dimuons

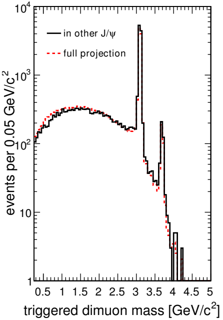


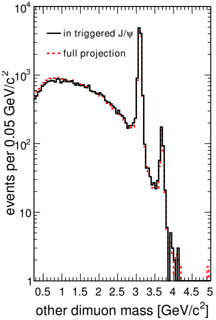
Labelling in R^1_{22} (MC)



Factorizability of R^1_{22} (MC)







R^2_{22} in ΔR

Two separate dimuons (R^2_{22}), plotted as $\Delta R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$

- Same 11 events, plotted differently
- Dashed lines show signal ($\Delta R < 0.1$) and background-enriched ($0.3 < \Delta R < 0.7$) regions of EXO-11-011 two-lepjet case
- Caveat: our events do not have isolation or hadronic jet requirements, which would reduce yields