Search for Dimuon Resonances in “Lepton Jets”

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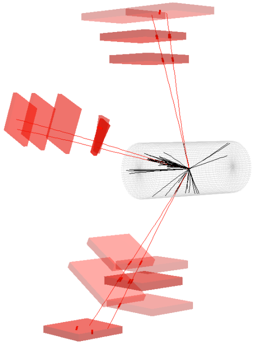
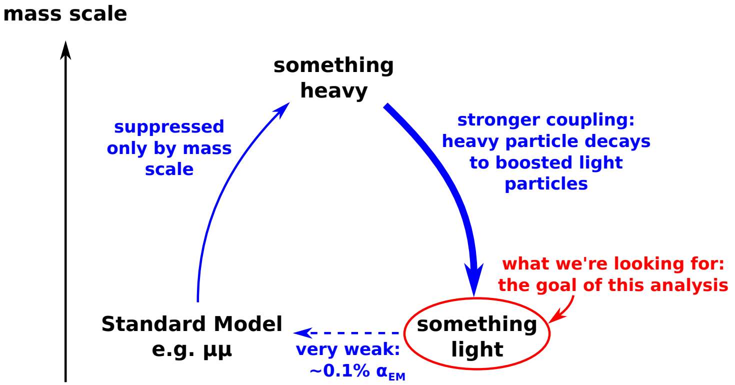
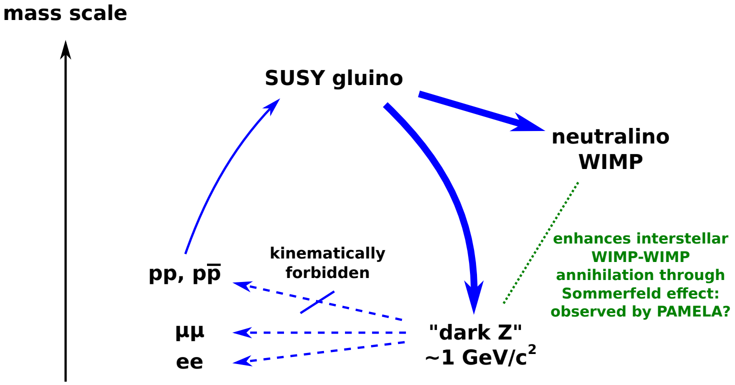


Generic phenomenology (sketch)



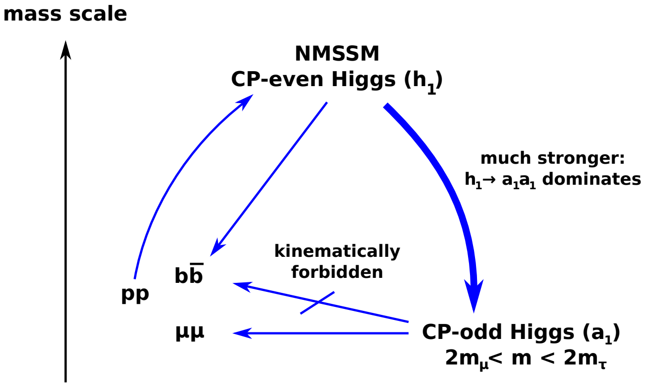
- Hidden-valley picture: predicts new low-mass, high-momentum particles decaying to Standard Model pairs like $\mu\mu$
- We want to maximize our sensitivity to "something like this"

Dark SUSY example



- Sub-class motivated by PAMELA positron excess (and lack of antiproton excess) when interpreted as WIMP-WIMP annihilation

NMSSM Higgs example



- A region of NMSSM parameter space allows the Higgs to escape LEP limits by decaying to lighter Higgs bosons rather than $b\bar{b}$, $\tau^+\tau^-$, etc.
- Same basic picture, same signature

Analysis strategy

Motivated by phenomenology:

- Hidden sector's spectrum is unknown, but weak coupling to the Standard Model implies that it predominantly passes through the lightest hidden state

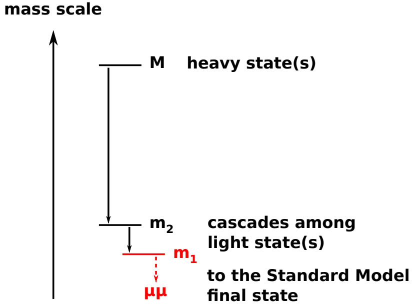
  $\longrightarrow$ search for low-mass dimuons

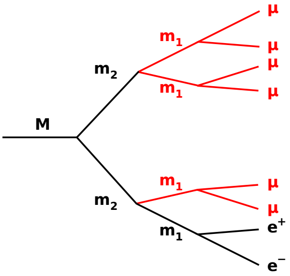
- Muon pairs may overlap, but cascades of light particles would be collimated in groups by their boost

  $\longrightarrow$ first identify well-separated groups, then resolve combinatorics

- $\mathcal{B}(m_1 \to \mu\mu)$ is likely to be high, but not necessarily 100%

  $\longrightarrow$ look for muons, but neither require nor exclude other particles (e.g. by applying an isolation cut)





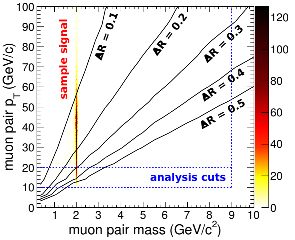
Analysis strategy

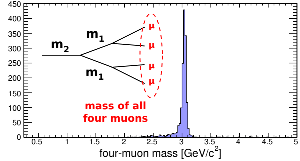
- Unless the hidden spectrum has a very close degeneracy, the lightest state (m_1) will be on-shell

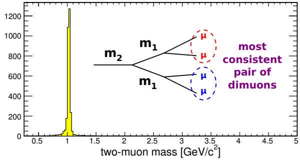
  $\longrightarrow$ search for a resonance peak
- Groups of four or more muons represent $m_2 \to m_1 m_1$ cascades

  $\longrightarrow$ split them into the most consistent assignment of dimuon masses (assumes on-shell m_1)
- Different event topologies have different backgrounds

  $\longrightarrow$ partition signal region by number of collimated groups ("mu-jets") and number of dimuons within each mu-jet

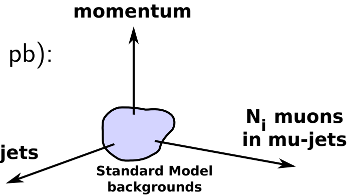






Signal topologies

- Look for new resonance in all channels that have small backgrounds
- Any one of the following reduce Standard Model backgrounds to $\mathcal{O}(1\text{ pb})$:
  - $p_T \gtrsim 80$ GeV/c
  - ≥ 2 mu-jets in an event
  - ≥ 4 muons in a mu-jet



- Define non-overlapping signal regions:

  (a) exactly one mu-jet per event

  (a-1) $p_T > 80$ GeV/c mu-jet containing two muons ($m_1 \to 2\mu$)
  (a-2) any mu-jet containing four muons ($m_2 \to m_1 m_1 \to 4\mu$)
  (a-3) more than four

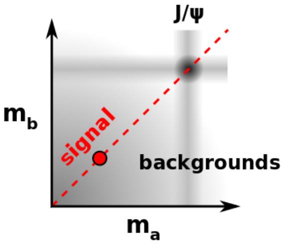
  (b) two mu-jets per event

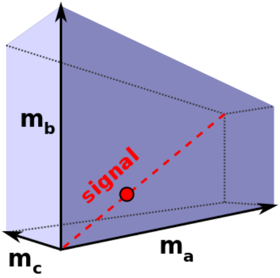
  (b-1) 2μ, 2μ ($M \to m_1 m_1$, which is the NMSSM signature)
  (b-2) 2μ, 4μ ($M \to m_1 m_2$)
  (b-3) 4μ, 4μ ($M \to m_2 m_2$)
  (b-4) either has more than four

  (c) more than two mu-jets per event

Signal extraction

- Unlike jets, our signals have a well-defined but unknown mass
  - all on-shell m_1 particles in an event have the same mass
  - backgrounds fill the space of dimuon masses more uniformly
- Measure signal and backgrounds in a single "fit with sidebands"
  - topologies with n dimuons per event form an n-dimensional space of observables
  - signal is a sharp peak somewhere along the diagonal
  - background distribution is a Cartesian product of shapes derived from data





Outline for the rest of the talk

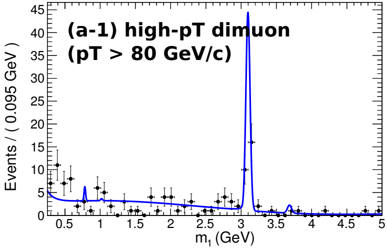
In reverse historical order!

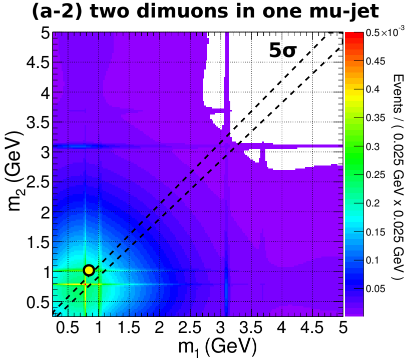
- Opening the box: results unblinded last weekend
- Deriving the shape templates
- Detector issues; acceptance and efficiency
- Implications for benchmark models

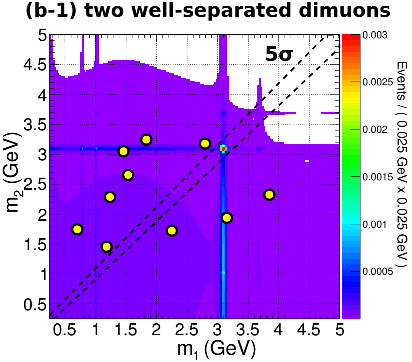
Opening the Box

Results: all consistent with SM

137	events with a single, high-p_T dimuon (SM-like distribution)
1	event with a 4-μ mu-jet
11	events with two 2-μ mu-jets
0	events within 5σ (detector resolution) of a 2-D diagonal
0	events with 3 or more dimuons

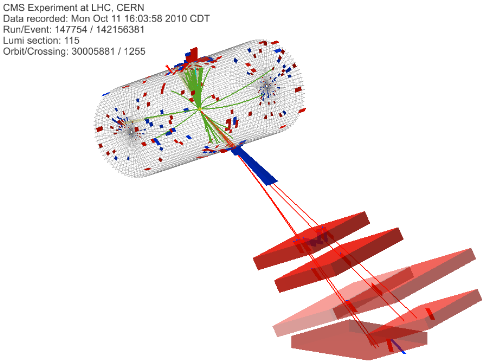




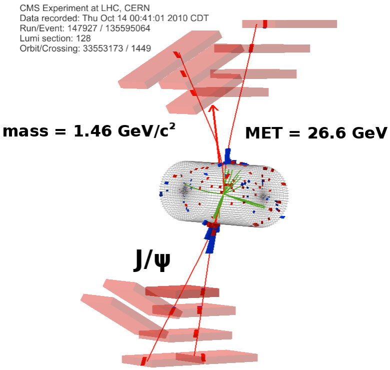


Event displays of double-dimuons (which have unequal masses)

(a-2) two dimuons in one mu-jet



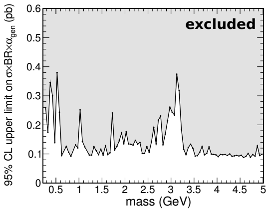
(b-1) two well-separated dimuons



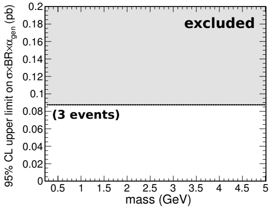
Limits

- Limit-setting in RooFit/RooStats using the MCMC method
- Luminosity, efficiency, and background shape systematics folded in (to be described later)
- Set limits on $\sigma \times \mathcal{B} \times \alpha_{\text{gen}}$, where α_{gen} is the acceptance for a given model in a given signal region
  - signature-based limit, applicable to future theories

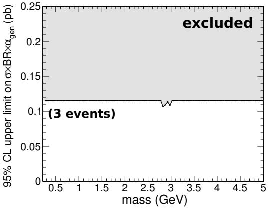
(a-1) one high-p_T dimuon



(a-2) two dimuons in one mu-jet



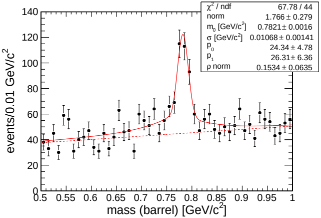
(b-1) two well-separated dimuons

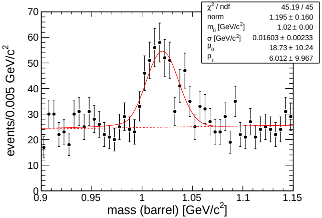


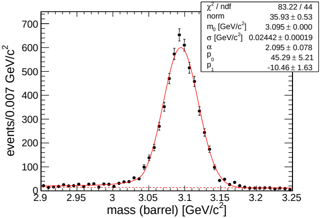
All other signal regions (3 or more dimuons per event) are also excluded at the level of 0.1 pb, independent of m_1 mass < 5 GeV/c^2

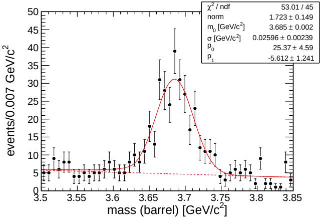
Fit Shape Templates

- Since the hidden sector couples weakly to the Standard Model, the m_1 resonance width must be dominated by detector resolution
- We have four Standard Model resonances in our background-enriched dataset (single dimuon, $p_T < 80$ GeV$/c$)

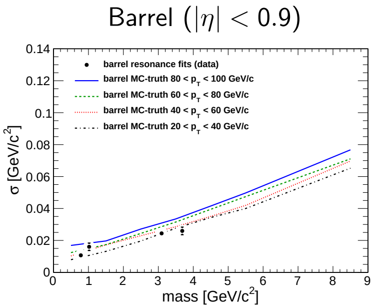


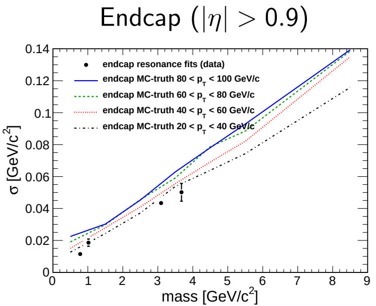






Signal shape (the easy part)





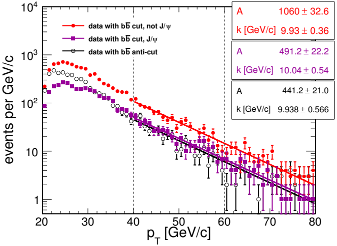
- Different resolution in the barrel and endcap
- Filled in resolution vs. mass and p_T with MC pair-gun
- Data agree well with the minimum-p_T curve
- Modeled in final fit as double-Gaussian (barrel and endcap) with a Crystal Ball radiative tail, p_T variation is a systematic uncertainty

Background shape

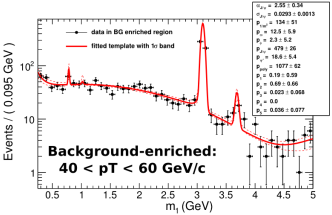
- Different physics sources contribute to each signal region, so the background shape templates must be individually constructed

- For (a-1): prompt & isolated, $b\bar{b}$-like, and J/ψ components all scale as $\exp(-p_T/10\text{ GeV})$ above 40 GeV$/c$

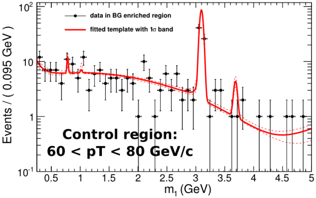
- Derive shape from high-statistics low-p_T data, test in medium-p_T, and use in high-p_T signal search



fit



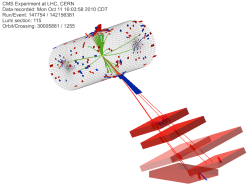
test



use

Signal region: pT > 80 GeV/c

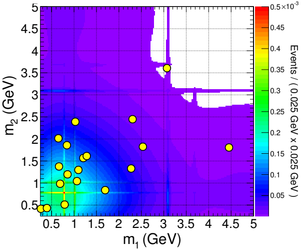
Background shape

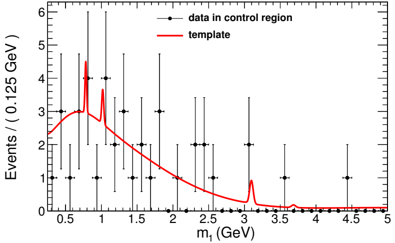


- Region (a-2): 4 muons in one mu-jet
- Dominant Standard Model backgrounds: decays-in-flight and misreconstruction (fakes)
- Simulate fake muons by putting non-muon tracks into mu-jets:

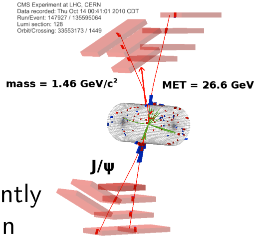
Background-enriched	Control	Signal Region
2 muons, 2 tracks	3 muons, 1 track	4 muons

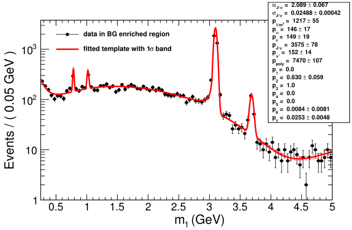
- Plots of control region with template shape overlaid:

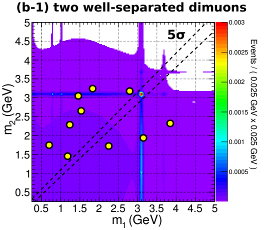




- Region (b-1): 2 mu-jets with 2 muons each
- Dominant Standard Model backgrounds: $b\bar{b}$ with both b-quarks producing $\mu\mu X$ by double-semileptonic decay, resonances, etc.
- Assume that each b-quark decays independently and construct 2-D distribution from Cartesian product of 1-D $b \to \mu\mu X$ distributions
- Background-enriched: selected dimuons (left); control region: off-diagonal part of signal (right; already seen)





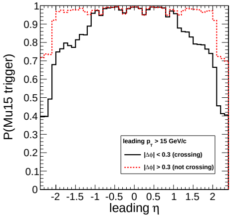


Detector Issues and Acceptance

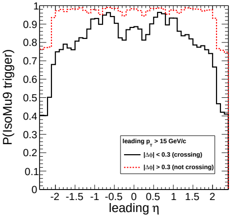
Trigger efficiency

- Some triggers' efficiencies depend strongly on whether the muon trajectories cross in the muon system
  - this is a problem for a model-independent study because different models have different fractions of muon crossing
  - parameterizing it would make the results too complicated
- Trigger efficiency vs. η for crossing and non-crossing muons:

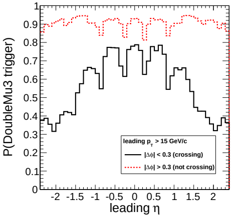
single-muon (Mu15)



isolated (IsoMu9)



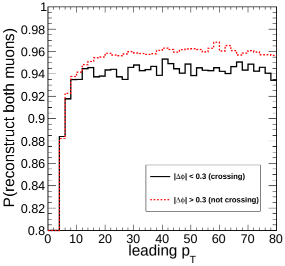
double-muon (DMu3)

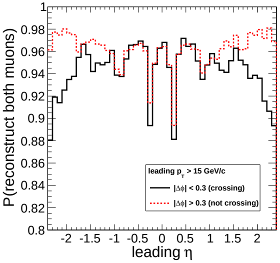


- Only the single-muon barrel trigger is highly efficient for nearby muons, regardless of crossing, so we define acceptance:

  each event must have at least one $p_T > 15$ GeV$/c$, $|\eta| < 0.9$ muon

- GlobalMuons are also inefficient for crossing muons ($\varepsilon \sim 50\%$)
- TrackerMuons are much less sensitive to crossing, so all muons in the analysis must be:
  - TrackerMuons with at least 2 arbitrated segments,
  - $p_T > 5$ GeV/c, $|\eta| < 2.4$,
  - track normalized $\chi^2 < 4$, at least 8 hits.
- Quality TrackerMuon efficiency for crossing and non-crossing muons:



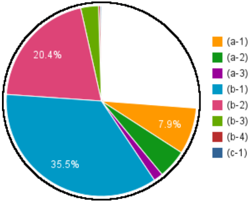


Implications for Benchmark Models

SUSY dark matter + extra $\mathcal{U}(1)_{\text{dark}}$
(inspired by PAMELA)

$z_d \to 2\mu$ and $h_d \to z_d z_d \to 4\mu$

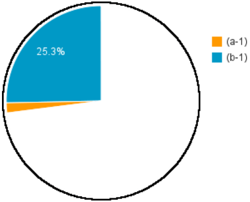
$m_{z_d} = 1$ GeV$/c^2$, $m_{h_d} = 3$ GeV$/c^2$



NMSSM Higgs
(inspired by hidden Higgs)

$h \to aa \to 2\mu, 2\mu$

$m_h = 100$ GeV$/c^2$, $m_a = 2$ GeV$/c^2$



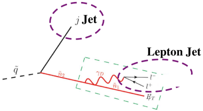
- Extra-$\mathcal{U}(1)$ model produces complicated events that have high acceptance but fall into many signal regions
  - (a-1): 1 high-p_T mu-jet with 2 muons
  - (b-1): 2 mu-jets with 2 muons each
  - (b-2): 2 mu-jets: one with 2 muons, the other with 4 muons
- Because NMSSM is a heavy $\to$ light light model, it produces 2 well-separated mu-jets, each with exactly 2 muons: (b-1)

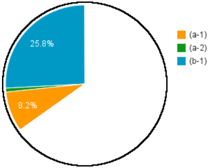
Benchmark model acceptance

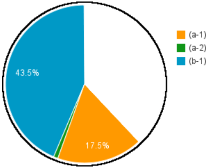
- This is the Dark SUSY model used in the Princeton studies

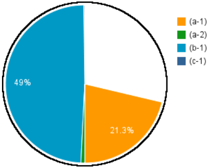
$m_{\tilde{q}} = 200$ GeV$/c^2$ $m_{\tilde{q}} = 400$ GeV$/c^2$ $m_{\tilde{q}} = 600$ GeV$/c^2$

$\tilde{n}_2 \to \tilde{n}_1 \gamma_{\mathrm{dark}} \to 2\mu$

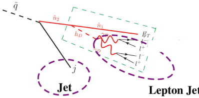


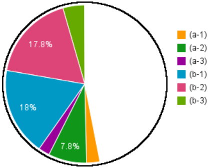


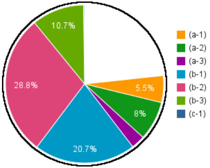


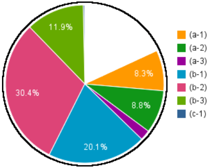


$\tilde{n}_2 \to \tilde{n}_1 h_{\mathrm{dark}} \to 4\mu$





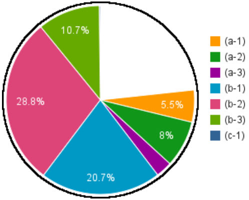




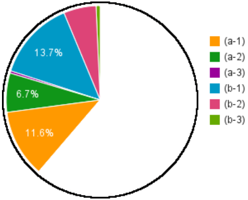
- Increasing $\tilde{q}$ mass doesn't change the topology of events, but does increase the overall acceptance

- Hidden sector particles may not have a preference for muons
  - if some decay to electrons or pions, the acceptance would drop
  - but also the event topologies would change

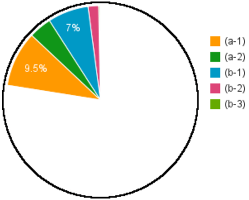
$\mathcal{B}(\gamma_{\text{dark}} \to \mu\mu) = 100\%$



$\mathcal{B}(\gamma_{\text{dark}} \to \mu\mu) = 50\%$



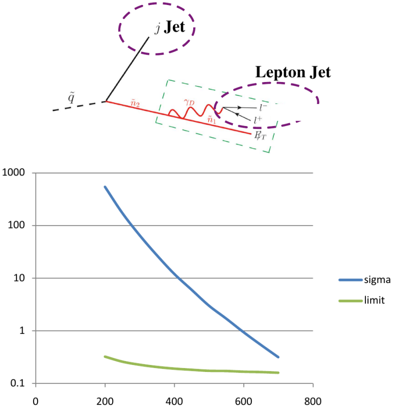
$\mathcal{B}(\gamma_{\text{dark}} \to \mu\mu) = 33\%$



- $\mathcal{B} = 100\%$: primarily (b-1) (2μ, 2μ) and (b-2) (2μ, 4μ)
- $\mathcal{B} = 33\%$: primarily (a-1) (single dimuon)

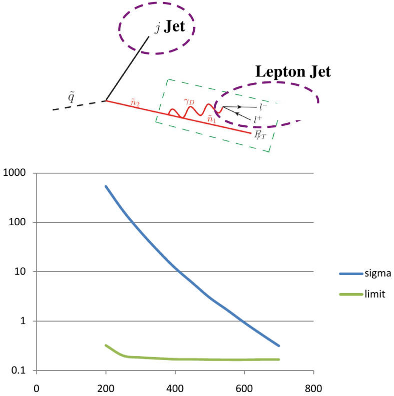
Limits on Dark SUSY

$\tilde{n}_2 \to \tilde{n}_1 \gamma_{\text{dark}} \to 2\mu$



$m_{\tilde{q}}$ [GeV/c^2]

$\tilde{n}_2 \to \tilde{n}_1 \gamma_{\text{dark}} \to 2\mu$

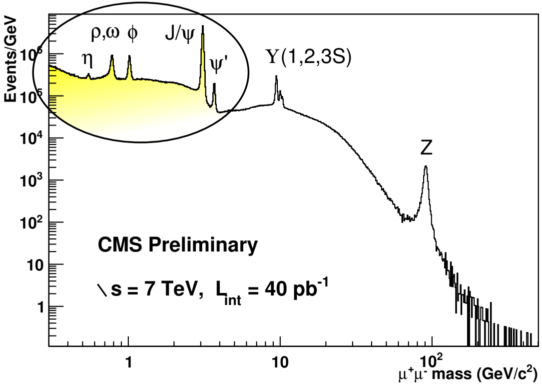


$m_{\tilde{q}}$ [GeV/c^2]

Conclusions

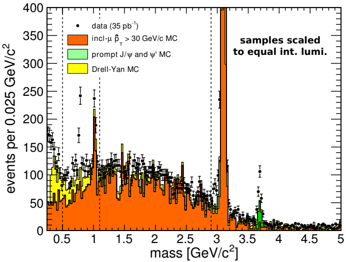
- High mass scale of the LHC presented a new opportunity to discover or constrain a general class of hidden valley models
- We cast a wide net for discovery: any model that produces several on-shell resonances per event **or** one high-p_T resonance, decaying inclusively to muon pairs
- No events were found compatible with several resonances per event; high-p_T spectrum is compatible with the Standard Model
- Many different signal regions made this a complicated analysis!
- To put the sensitivity of these results into concrete terms, we set limits on three benchmark models

Backup: Understanding the Low-Mass Dimuon Spectrum

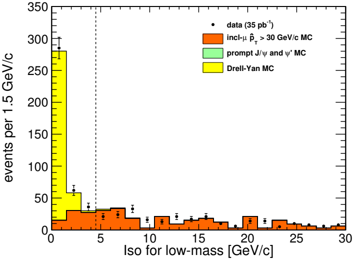


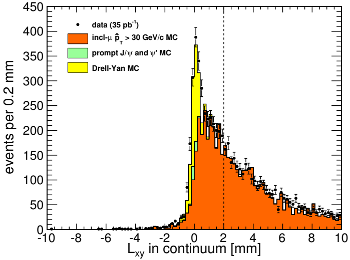
Low-mass dimuons

- "Raw" mass spectrum has several components:
  - resonances (prompt and from b decays)
  - double-semileptonic $b \to \mu\mu X$ continuum
  - low-mass Drell-Yan



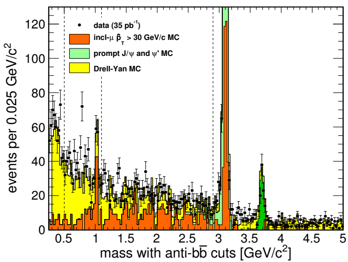
- MC isn't perfect: study data/MC differences using isolation (defined such that $\mu\mu$ doesn't self-veto) and distance of flight (L_{xy})

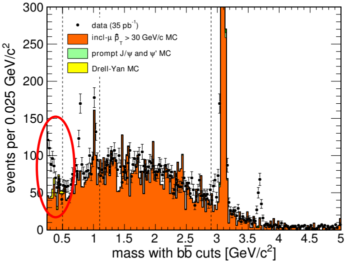




- Split sample into $b\bar{b}$ and Drell-Yan/prompt resonances with this cut:

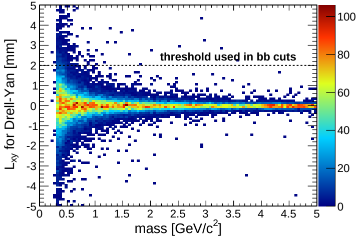
$$Iso > 4.5\ \text{GeV}/c\ \textbf{or}\ L_{xy} > 2\ \text{mm}$$





- Much of the low-mass spectrum is Drell-Yan (not in any official samples, so we generated it with Pythia 8)
- Some resonances are not in inclusive-muon MC: $\omega(782)$, $\psi'(3686)$
- There's also a low-mass excess (red circle), too wide to be a resonance peak, and too low in mass to be $\eta \to \mu\mu\gamma$

- Part of the explanation: the cut $Iso > 4.5$ GeV$/c$ **or** $L_{xy} > 2$ mm depends on L_{xy}, which becomes imprecise for nearly collinear tracks: Drell-Yan leaks into the "$b\bar{b}$" sample



- This mass region is below the Pythia generator-level mass cut-off...
- About $1/10^{\text{th}}$ of what remains passes $Iso > 4.5$ GeV$/c$ alone: misreconstructed Drell-Yan?
- History of this study is a geometric progression of explaining 90%, then explaining 90% of what's left, etc..