Kinematics-based lepton jets search with muons

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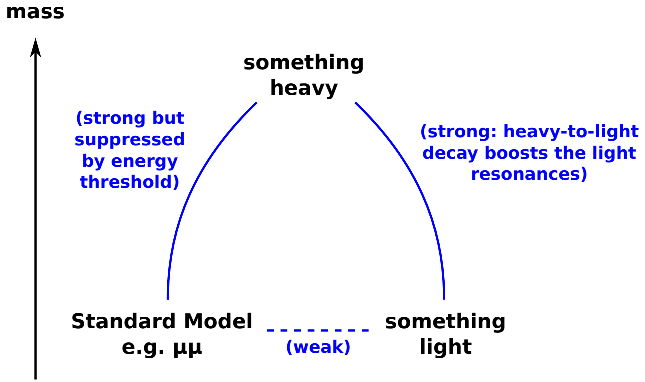
- This is a continuation of our work on searches for new physics with nearby muons
  - previous talks have focused on detector issues
  - this talk will present the overall analysis strategy

Outline

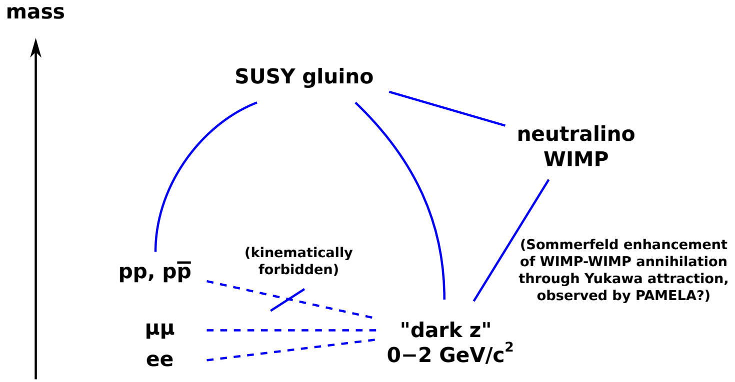
- Physics considerations that motivate the analysis strategy
- Signal regions and background control samples
- Data-driven background estimates and fitting procedure

What we're looking for



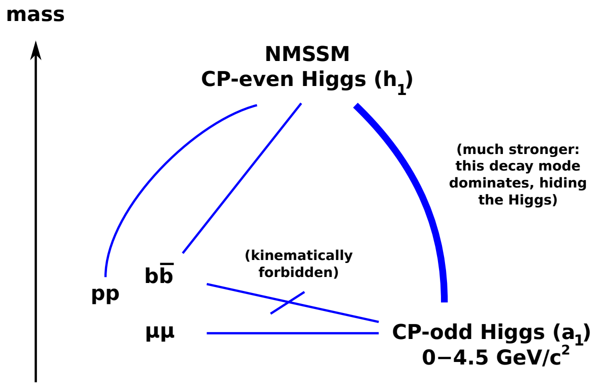
- Generic hidden-valley picture: predicts low-mass, high-momentum new particles

What we’re looking for



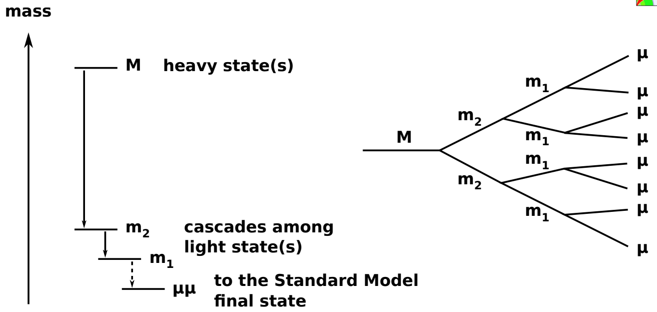
- Special case motivated by PAMELA positron excess (and no antiproton excess) when interpreted as WIMP-WIMP annihilation

What we're looking for



- A region of NMSSM parameter space allows the Higgs to escape LEP limits; same basic picture, same signature
- This was the first case our group studied: $h_1 \to a_1 a_1 \to 2\mu\, 2\mu$
- Topology motivates mass-peak fit in "2μ mass vs. 2μ mass" plane to find a bump corresponding to the a_1 mass (hep-ex/1002.1956)

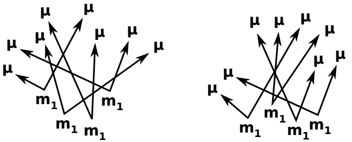
What we're looking for



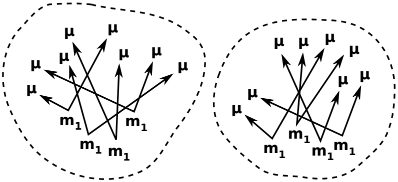
- Since we don't know the physics of the hidden sector, we can't rule out complex decay chains leading to "jets" of $\mu^+\mu^-$ (and e^+e^-, $\pi\pi$)
- Assuming that the $m_i \cdot \gamma$ couplings are much weaker than the $m_i \cdot m_j$ couplings, cascades will need to decay down to the bottom of the chain before the slow transition to the Standard Model: this implies that all of the muon pairs come from m_1 decays
- We're looking for <u>*one*</u> new $m_1 \to \mu^+\mu^-$ resonance, possibly many instances per event, possibly overlapping

- The basic problem is combinatoric: identify which opposite-sign muon pairs belong to which m_1 decays, and then look for an m_1 dimuon mass peak by fitting all of them
- Grouping neaby muons into "jets" helps to distinguish muons from different heavy M decays and provides a classification scheme for different signal topologies with different backgrounds:
  - (a) exactly one mu-jet per event
    - (a-1) mu-jet contains two muons with high momentum ($m_1 \to 2\mu$)
    - (a-2) mu-jet contains 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

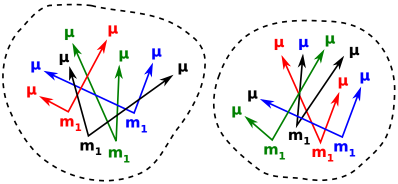
Analysis method



0. Start with a clean set of muons



1. Identify mu-jets by kinematics, rather than geometry (next slide), so that everything within a mu-jet came from the decay of something lighter than 5 GeV/c^2



2. Find the combination of pairs in which the dimuon masses are most consistent with being equal:

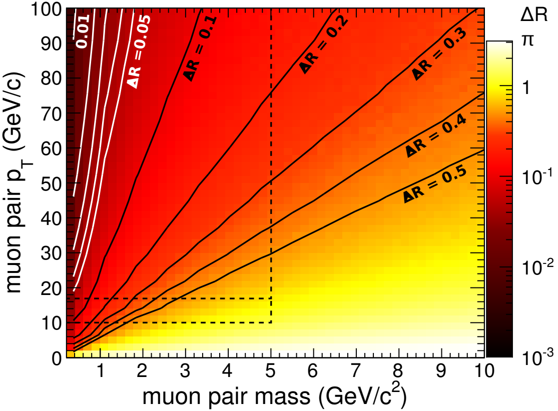
$$m_a \approx m_b \approx m_c \approx m_d$$

3. N-D fit to the dimuon masses

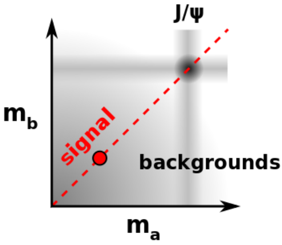
- Put two muons in the same mu-jet if

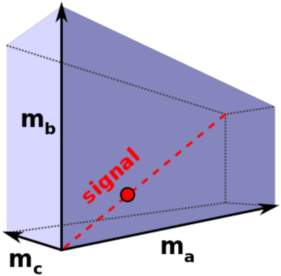
$$\left(m_{\text{pair}} < 5\ \text{GeV}/c^2 \textbf{ and } P_{\text{vertex}} > 0.01\right) \textbf{ or } \Delta R < 0.01$$

- Sensitive to a rectangular region in the (p_T, mass) plane
  - the signal would be a narrow vertical smear on this plane



- After grouping muons into mu-jets (step 1) and decomposing them into fundamental dimuons (step 2), we have N dimuons per event (value of N depends on the subsample, categorized by mu-jets)
- Fit background and potential signal to a single ansatz: signal must be on the diagonal because $m_a \approx m_b \approx m_1$





- Shape of background comes from control samples, normalization is fitted simultaneously with the signal (like any bump-hunt)

Analysis method

Background templates are different for each signal channel

(a) exactly one mu-jet per event

(a-1) mu-jet contains two muons with high momentum

- backgrounds: p_T tails of Standard Model dimuon resonances
- control: dimuons of intermediate momentum

(a-2) mu-jet contains four muons

(a-3) more than four (n)

- backgrounds: physical dimuon with fake muons attached
- control: two muons + $(n-2)$ tracks

(b) two mu-jets per event

(b-1) 2μ, 2μ

- backgrounds: $b\bar{b}$ with each $b \to 2\mu X$ (semileptonic or fake)
- control: $b \to 2\mu X$ dimuons (isolation, displaced vertex) carefully account for trigger bias in one of the dimuons

(b-2) 2μ, 4μ

(b-3) 4μ, 4μ

(b-4) either has more than four

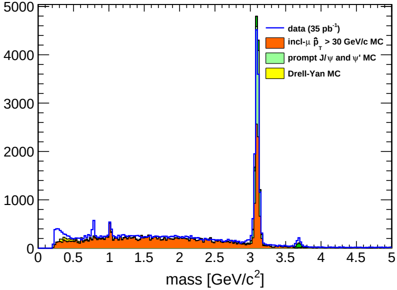
- combinations of the above

(c) more than two mu-jets per event: more combinations of the above

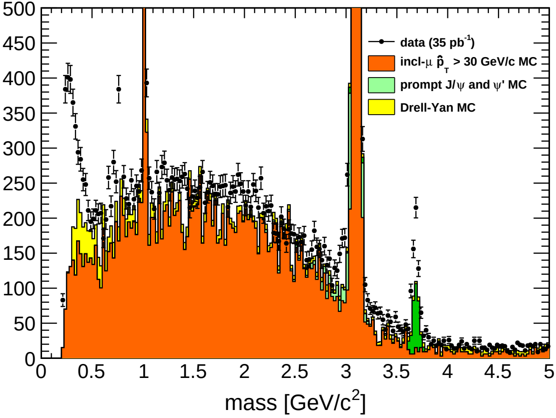
Analysis method

- Acceptance cuts:
  - at least one $p_T > 12$ GeV/c, $|\eta| < 0.9$ muon (trigger plateau)
  - all other muons have $p_T > 5$ GeV/c, $|\eta| < 2.4$ (reco plateau)
  - signal regions defined by number of mu-jets and number of muons in mu-jets
- No analysis cuts on isolation
  - $m_1 \to e^+e^-$, $\pi\pi$ are just as possible as $m_1 \to \mu^+\mu^-$, so isolation doesn't sequester the signal
  - there may be hadronic jets nearby from SUSY decays
- No cuts on missing energy, hadronic jets, isolated leptons, etc. (they're neither required nor rejected)
- All data-driven backgrounds come from fits for normalization and control samples for shapes
- Signal peak resolution from data (fit to ω, ϕ, J/ψ, and ψ')
- Single-valued or η-dependent efficiency correction from Z tag-and-probe: regions with complicated efficiency dependence have already been rejected with acceptance cuts

- In the next few slides, we'll take a close look at single-dimuon events with vector-sum $p_T < 80$ GeV$/c$
  - Standard Model dominates over potential $\mathcal{O}(1\text{ pb})$ signals (determined by Monte Carlo before looking at data)
- It will be important to understand this distribution well enough to know what physics produced it and which processes will be active in the signal regions, to make the right extrapolations
- Monte Carlos: inclusive-muon ($\hat{p}_T > 30$ GeV$/c$), prompt J/ψ, ψ', and privately-generated low-mass Drell-Yan ($\hat{p}_T > 10$ GeV$/c$, Pythia8 to avoid a hard cut-off in Pythia6)



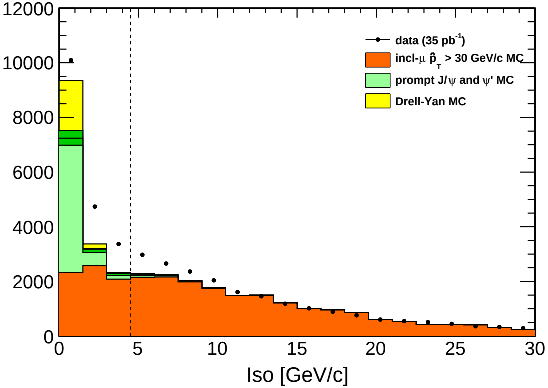
- Inclusive-muon MC is missing resonances: ψ', ω, and possibly $\eta \to \mu\mu\gamma$ (η mass is 0.5 GeV/c^2, need to reconstruct γ to be sure)
- Inclusive-muon and ψ' are normalized to their Pythia-calculated cross-sections, J/ψ is normalized to its mass peak, and Drell-Yan is normalized to the Z



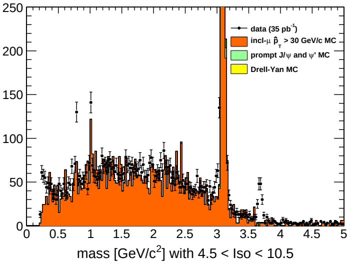
- Isolation variable to study this sample:

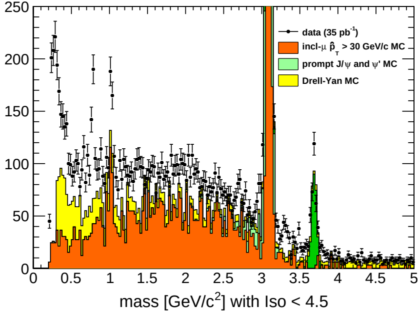
$$Iso = \sum_{\text{tracks}} p_T \text{ if } p_T > 1.5 \text{ GeV}/c,\ \Delta R < 0.4, \text{ and } \underline{\text{not a muon}}$$

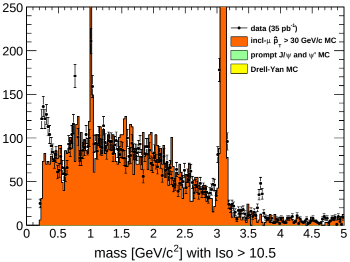
- Minimum p_T avoids dependence on pile-up (MC-tested)
- Optimized to give a flat region in inclusive-muon MC near zero



- Plots of mass with isolation cuts
- Non-isolated regions can be described by inclusive-muon and the missing resonances
- Isolated component is missing a continuum of mid-range masses

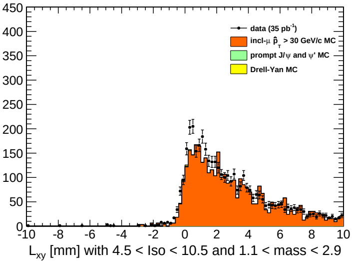


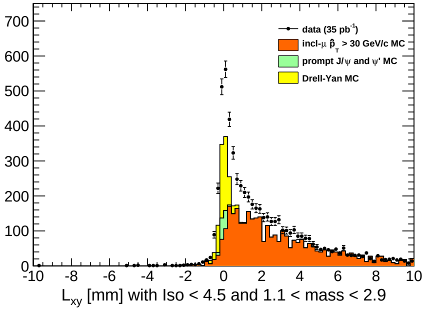


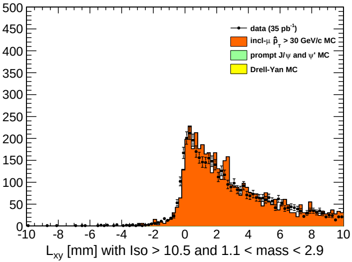


Study of low-p_T dimuon control

- L_{xy}: displacement of dimuon vertex from primary vertex in the x-y direction of flight
- Missing isolated continuum in mid-range masses is displaced with a smaller $(\gamma c\tau)_T$ than incl-μ MC: qualitatively consistent with $\hat{p}_T < 30$ GeV/c $b\bar{b}$

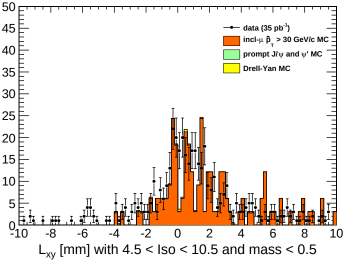


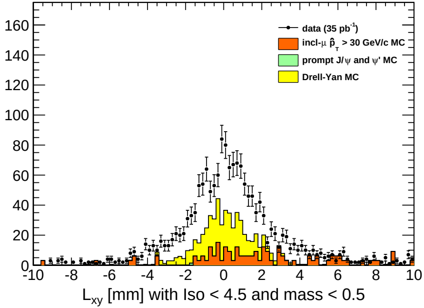


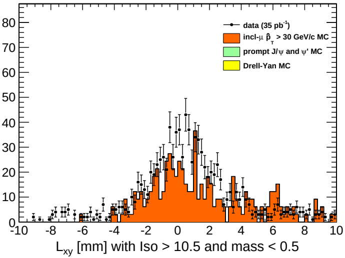


Study of low-p_T dimuon control

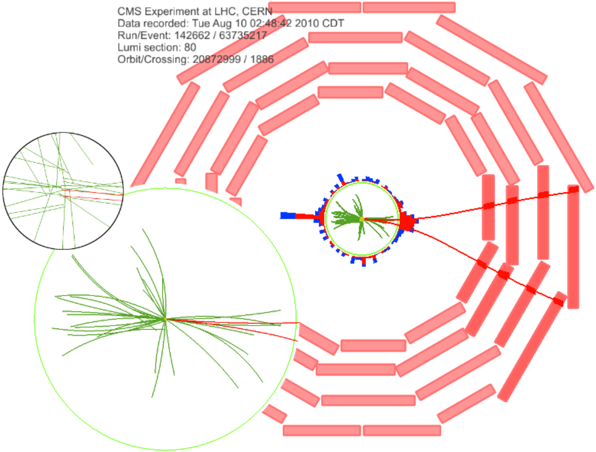
- Low-mass excess is inconclusive in L_{xy} because vertex resolution for nearly collinear muons is poor
- However, they're definitely not $\gamma \to \mu\mu$ conversions (the beampipe is at 30 mm)







- The low-mass dimuons are good muons (both the isolated and the non-isolated low-mass excesses)



- Also checked muon quality distributions (backup slides)

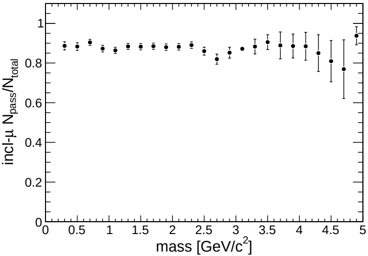
- Tentative conclusions (gathered onto one slide):
  - continuous *Iso* < 4.5 GeV$/c$, $1.1 <$ mass < 2.9 GeV$/c^2$ data-excess is likely the $\hat{p}_T < 30$ GeV$/c$ part of the inclusive-muon
    - simply wasn't generated (it's CPU-intensive in Pythia)
    - regions dominated by high-$\hat{p}_T$ match perfectly
    - ppMuX (no $\hat{p}_T$ cut) has this continuous shape
  - narrow data-excess in mass < 0.5 GeV$/c^2$:
    - is *not* due to fake muons
    - is too wide to be a resonance, but has an endpoint at the η mass, so $\eta \to \mu\mu\gamma$ is possible ($\mathcal{B}(\eta \to \mu\mu\gamma) = 3 \times 10^{-4}$, $\mathcal{B}(\eta \to \mu\mu) = 6 \times 10^{-6}$, similar to $\mathcal{B}(\omega, \phi \to \mu\mu) \sim 10^{-4}$)
    - the isolated part could be partially Drell-Yan (normalization from the Z may not be correct when scaled down to zero mass)
    - but a significant part of it is non-isolated (η produced in b-jets? Could be hard to find the γ inside jets)
- Currently using only $0.3 < mass < 5$ GeV$/c^2$ part of the spectrum; could push lower, depending on level of confidence with these incompletely understood events

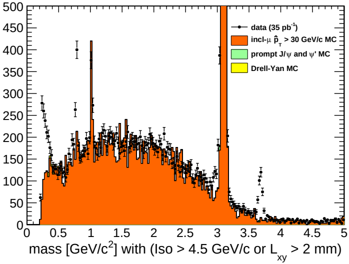
Deriving a mass template

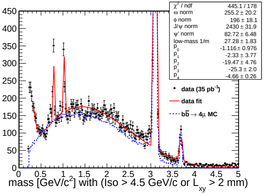
- The control region contains $b\bar{b}$, Drell-Yan, and prompt resonances
- Backgrounds in the dimuon-dimuon signal region (b-1) are dominated by $b\bar{b}$, because each b-quark can produce two nearby muons and there are two b-quarks in $b\bar{b}$ events (other processes would require coincidences to produce four muons)
- To reject Drell-Yan and prompt resonances, select

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

- Selection is loose, purifies $b\bar{b}$ (including resonances in $b\bar{b}$), and has a constant efficiency across the mass spectrum: this is the template

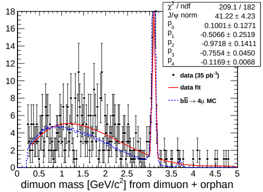






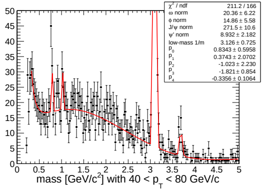
Purpose: in the dimuon-dimuon channel (b-1), this is for the dimuon that contains a high-p_T barrel muon to satisfy the trigger

Derived from: $b\bar{b}$-enriched low-p_T dimuon control sample (previous page)



Purpose: in the dimuon-dimuon channel (b-1), this is for the other dimuon

Derived from: dimuon + orphaned muon control sample, where the orphaned muon was selected to satisfy the trigger



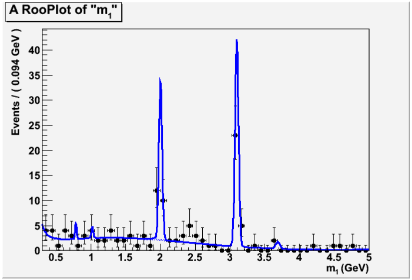
Purpose: this is for the $p_T > 80$ GeV/c dimuon channel (a-1)

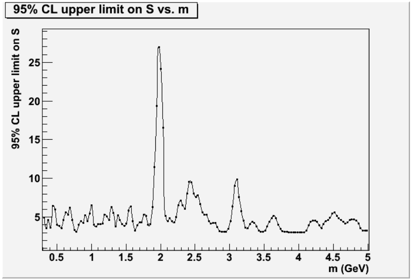
Derived from: all events ($b\bar{b}$, Drell-Yan, prompt) in $40 < p_T < 80$ GeV/c, since their ratio is constant above 40 GeV/c

Similarly, templates for “4 muons in one mu-jet” (a-2, b-2, b-3) will be derived from “2 muons + 2 tracks” control sample

Sample fitter output

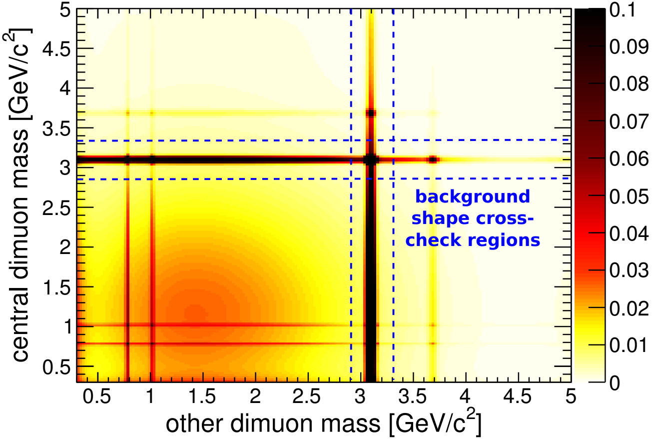
- A fitter originally for the NMSSM case is being generalized to N-dimuon mass fits and ported to RooFit
- Top-right: a 1-dimuon fit with data-driven backgrounds template, fake 2 GeV/c^2 signal, and simulated data
  - 20 signal events, 100 background events
- Bottom-right: upper limits on yield as a function of m_1 mass





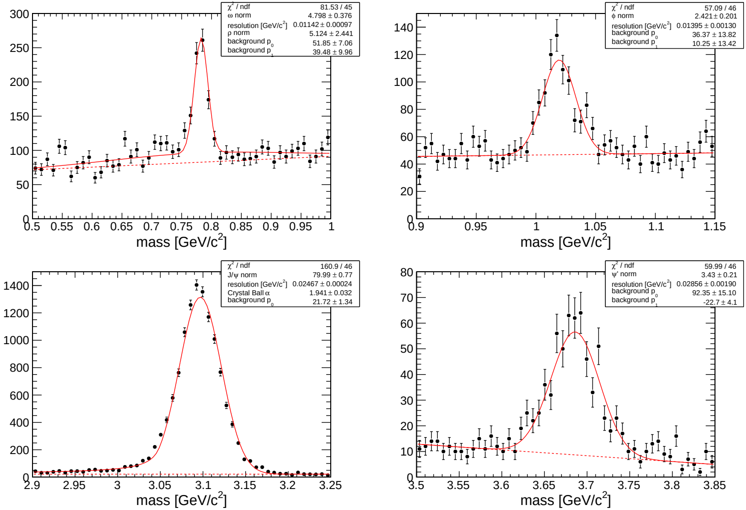
2-D mass template

- Since the two b-quarks decay or attach fake muons to themselves independently, we construct a mass template by a Cartesian product
- We can cross-check the shape of both distributions with the slices that include the J/ψ:



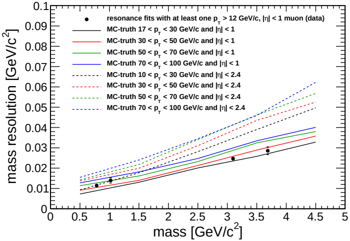
Mass resolution

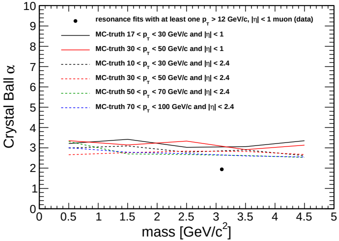
- Hidden sector bosons have negligible intrinsic width, so we can determine the width of the signal peak from our four narrow Standard Model resonances: ω, ϕ, J/ψ, and ψ'



Mass resolution

- The low-p_T Standard Model resonances don't necessarily represent resolution for high-p_T new physics, so check with a dimuon gun MC
- Most of the difference is barrel vs. endcap, with only a weak dependence on momentum





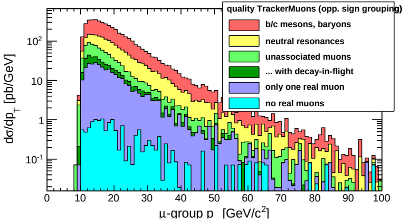
- Two reasons to distinguish between the "central" dimuon (satisfying the trigger) and the "other" dimuon:
  - slightly different background shapes
  - different signal resolutions

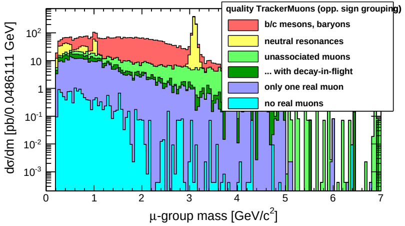
Conclusions

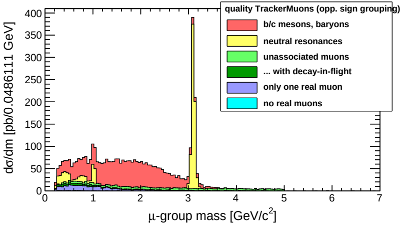
- The physics models that inspired lepton jets searches are models of new resonances, conducive to "bump hunts"
- The hidden sector may be complicated, but if decays must pass through a lightest hidden state m_1, then all of the resulting muon pairs have the same invariant mass (unless they're misidentified)
- Fitting that mass spectrum allows us to determine the backgrounds normalization in the same step, and we can get the shapes of those templates from the data, too

Composition of inclusive MC

- Plots of the inclusive-muon sample, divided up by generator-level information
- Decays-in-flight and fakes are simulated, but not significant







- These are old plots (July), but they're perfectly relevant for a $p_T > 10$ GeV$/c$, $|\eta| < 2.4$ dimuon (no changes in cuts or clustering)

Why require a barrel muon?

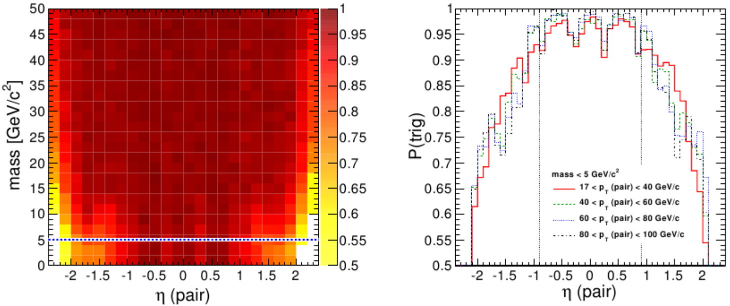


Figure 2: HLT_Mu11 trigger efficiency as a function of mass, momentum, and pseudorapidity of dimuons in a dimuon-gun simulation. In both plots, trigger efficiency is the fraction of event passing the trigger in a sample with at least one $p_T > 12$ GeV/c muon, the other unconstrained.

Why require a barrel muon?

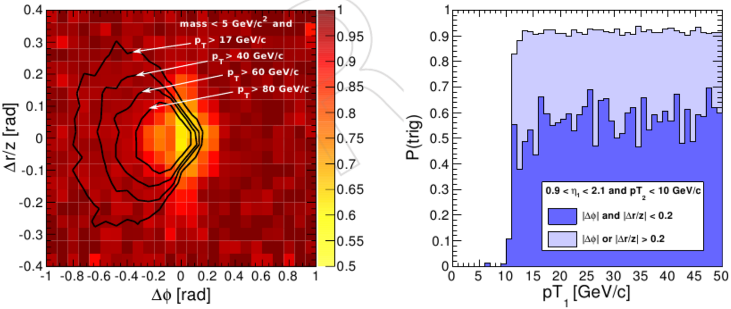
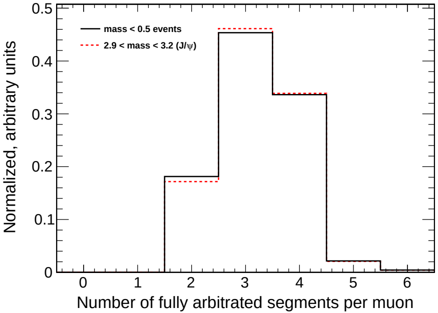
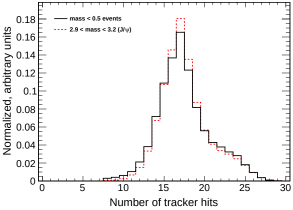


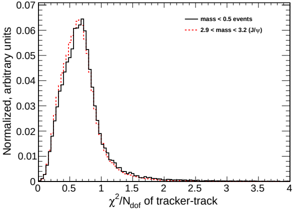
Figure 3: Diagnostic of HLT_Mu11 p_T dependence in $0.9 < |\eta| < 2.1$. Left: trigger efficiency (color scale) with one $p_T > 12$ GeV/c muon, the other unconstrained, as a function of separation of muons in the muon system. Different mass/momentum combinations (the labeled contour lines) sample this spot to differing degrees. The trigger turn-on curve in the spot is unaffected; it is the plateau efficiency that is lowered.

Quality of low-mass dimuons

- Compare muon quality distributions in the mass $< 0.5\ \mathrm{GeV}/c^2$ region (black) with the same distributions in the J/ψ peak (red)
- Normalized to equal area (all data)







- Residuals distributions in station 1 (of both barrel and endcap)