Search for Dimuon Resonances in “Lepton Jets”

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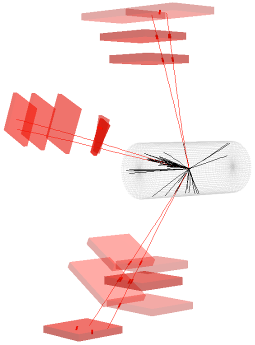
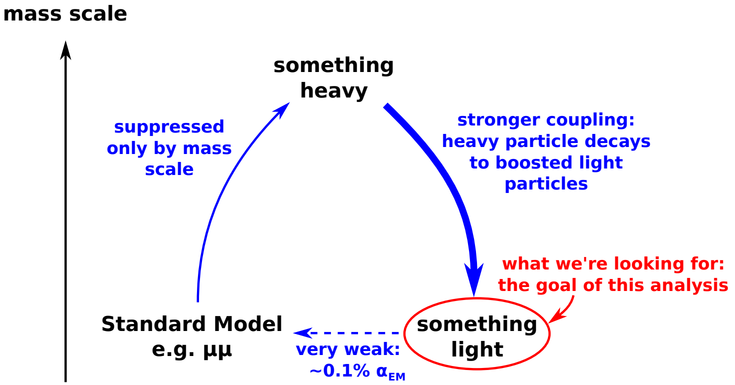
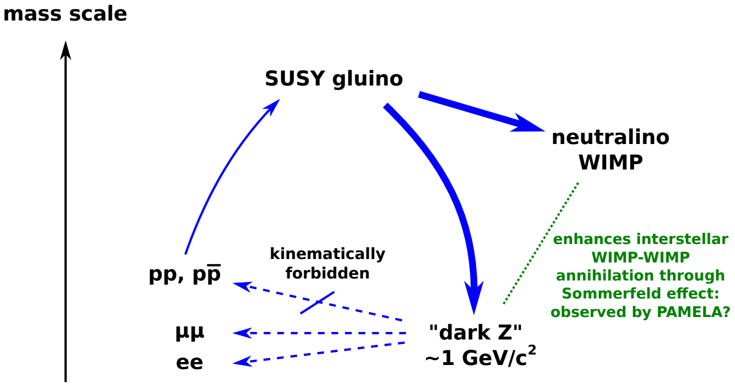




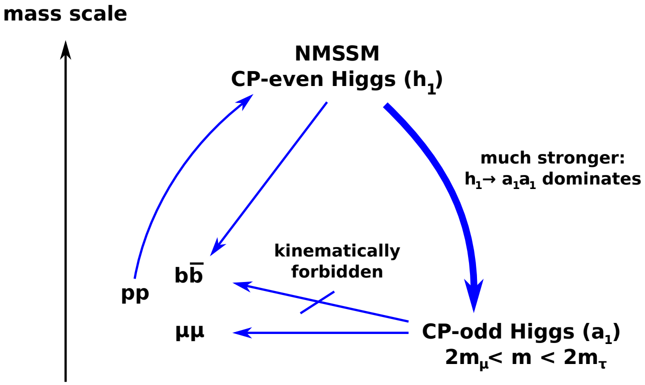
- Generic hidden-valley picture: predicts new low-mass, high-momentum particles decaying to states like $\mu\mu$

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 could have any spectrum, but due to weak coupling, only the lightest state decays to Standard Model pairs

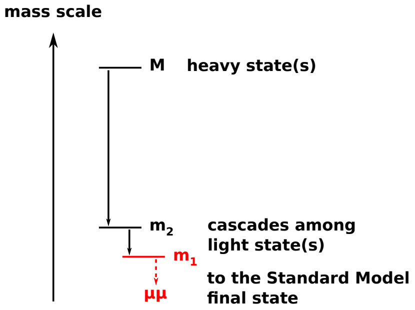
  $\longrightarrow$ search for a single m_1 resonance peak

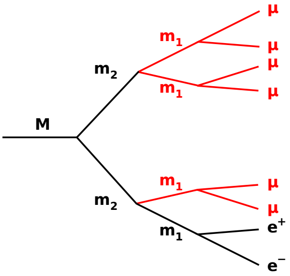
- Visible pairs may overlap, but the light cascades would be separated by their boost

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

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

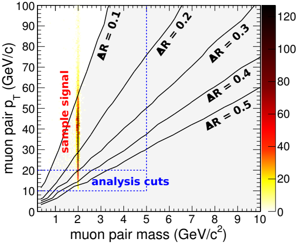
  $\longrightarrow$ look for the resonance in muons, but don't exclude other particles (e.g. with isolation)

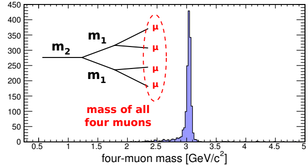


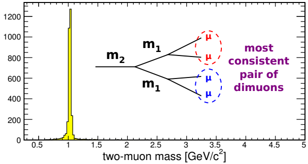


Analysis details

- Identify groups of muons ("mu-jets") by mass and momentum separately, rather than ΔR, to avoid cutting out large parts of phase space
- Categorize signal topologies by the number and composition of mu-jets: each has different backgrounds
- Identify the most consistent dimuon mass combinations within each mu-jet, look for a resonance peak in all dimuons simultaneously
- Neither require events to contain hadronic jets, missing energy, other leptons, nor exclude them

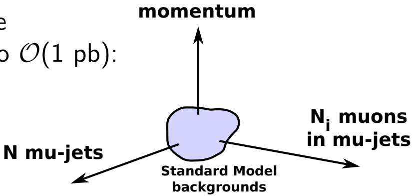






Signal topologies

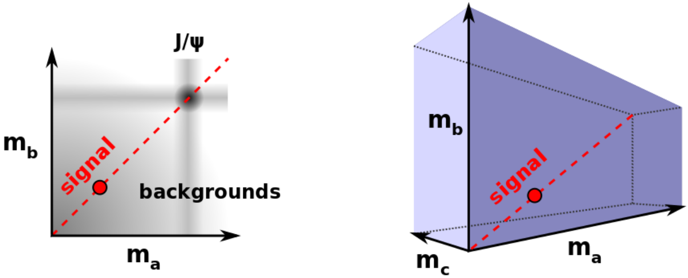
- Look for a new resonance in all channels with small backgrounds
- Any one of the following reduce Standard Model backgrounds to $\mathcal{O}(1\ \mathrm{pb})$:
  - $p_T \gtrsim 100$ GeV$/c$
  - ≥ 2 mu-jets in an event
  - ≥ 4 muons in a mu-jet



- 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

- Use the fact that a real m_1 mass must be equal for all dimuons, while the background is uncorrelated
  - 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



- Fit to both components yields a data-driven background estimate and a signal limit/discovery with the same data

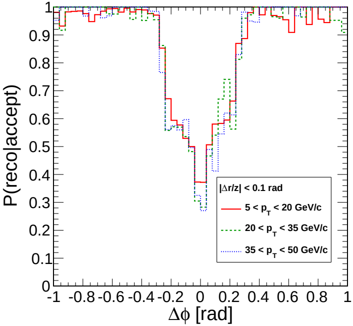
- Detector issues; choosing an appropriate acceptance region
- Understanding the low-mass dimuon mass spectrum
- Deriving background shape templates
- Fit results in control regions

Detector issues

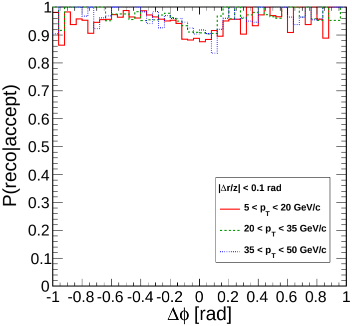
Summary of Oct 4 μPOG talk:
http://indico.cern.ch/conferenceDisplay.py?confId=94649

- We don't use GlobalMuons because they are inefficient for good muons ($p_T > 5$ GeV/c, $|\eta| < 2.4$) that cross in the muon system
  - plot efficiency vs. distance between muons in the muon system:

GlobalMuons



quality TrackerMuons

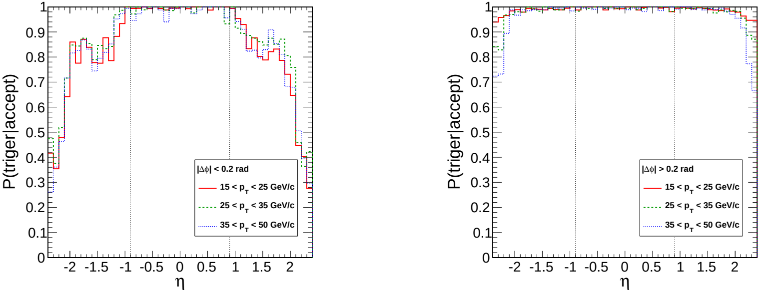


- We instead use "quality TrackerMuons" (≥ 2 arbitrated segments, ≥ 8 tracker hits, $\chi^2/N_{\mathrm{dof}} < 4$), which have the same low fake-rate as GlobalMuons, yet high efficiency for close-by muons

Trigger efficiency

- Lowest unprescaled, unisolated, single-muon trigger: HLT_Mu15
- Single-muon trigger efficiency is highly dependent on whether the muon trajectories cross in the CSCs (endcap only)

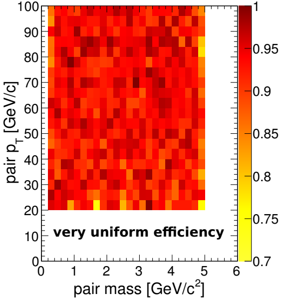
muons cross each other | muons do not cross



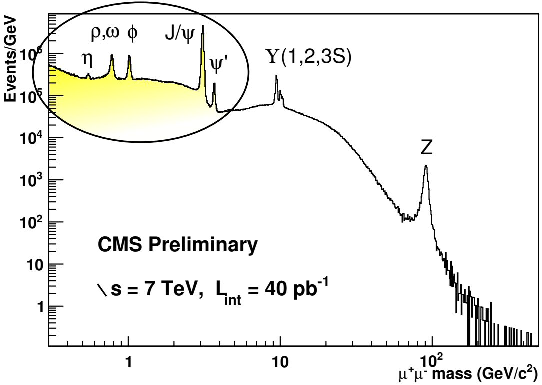
- Trajectory-crossing depends on the precise kinematics of the events, which depends on the theoretical model in question
- Most models predict higher momentum, lower mass than J/ψ: tag-and-probe would underestimate the inefficiency for those models

Acceptance definition

- We therefore require at least one $p_T > 15$ GeV/c, $|\eta| < 0.9$ (barrel) muon offline
  - post-acceptance trigger efficiency is $\sim$97% and independent of model kinematics
  - all other muons are much looser: $p_T > 5$ GeV/c, $|\eta| < 2.4$
- Provides for a robust analysis at the expense of acceptance
- Each signal region specifies additional cuts on the number and properties of mu-jets
- Mu-jets are built recursively from opposite sign muon pairs with
  - pairwise invariant mass < 5 GeV/c^2
  - vertex χ^2 probability $> 1\%$
  - $\Delta R < 0.01$ (tiny) if the above fail
- $\sim$99% mu-jet forming efficiency, $\sim$95% folding in reconstruction of two muons (right)

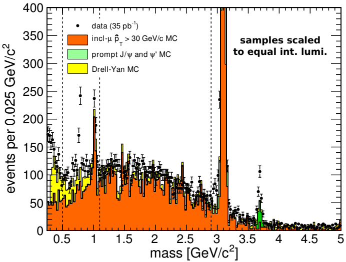


Understanding the low-mass dimuon spectrum

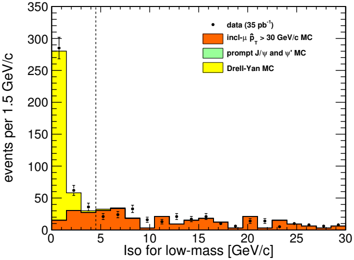


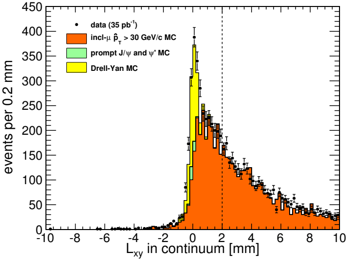
Low-mass dimuons

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



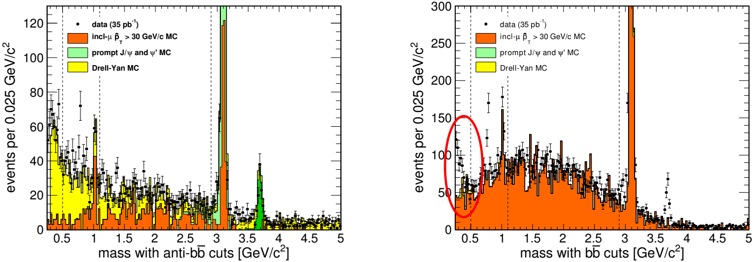
- MC isn't perfect: study data/MC differences using isolation (defined such that $\mu\mu$ doesn't self-veto) and distance of flight (L_{xy})





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

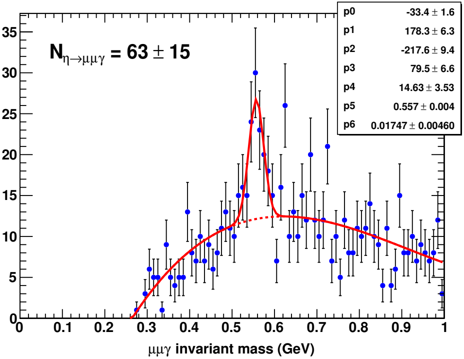
$$Iso > 4.5 \text{ GeV}/c \textbf{ or } L_{xy} > 2 \text{ mm}$$

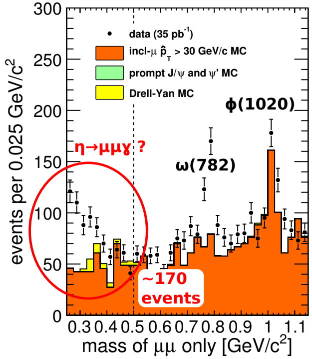


- Much of the low-mass spectrum is Drell-Yan (not in any official samples, so we generated it with Pythia 8)
- Some resonances are not in inclusive-muon MC: $\omega(782)$, $\psi'(3686)$
- There's also a low-mass excess (red circle) not shaped like a resonance peak

The low-mass excess

- The excess is a broad spectrum with an endpoint below $m_\eta = 0.55$ GeV$/c^2$: could be $\eta \to \mu\mu\gamma$
- $\mathcal{B}(\eta \to \mu\mu\gamma) = 3 \times 10^{-4} \approx \mathcal{B}(\omega \to \mu\mu) \approx \mathcal{B}(\phi \to \mu\mu)$
- Search for exactly one PF-photon in $\Delta R < 0.1$, plot $\mu\mu\gamma$ spectrum





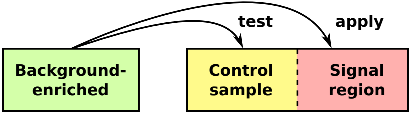
- $\eta \to \mu\mu\gamma$ accounts for at least 1/3 of the excess
- We will assume that it is a part of the background

Background shape templates

Method

- Signal + background fits determine the number of background events in the signal regions, but with too few events to also determine the shapes

1. Get the shapes from "background-enriched" samples with the same kinematics, constructed from large-statistics samples that have the same physics content

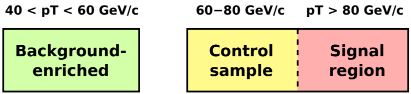


2. Test template shapes in control samples close to the signal regions
3. Use background $B(m_a, m_b)$ and signal $S(m_a, m_b; m_1)$ shapes in the signal region fits:

$$\alpha B(m_a, m_b) + \beta S(m_a, m_b; m_1)$$

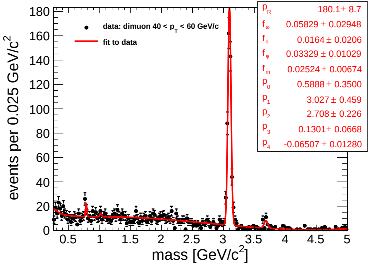
- Background estimate is effectively a sideband with a known shape

Region (a-1): high-p_T dimuon

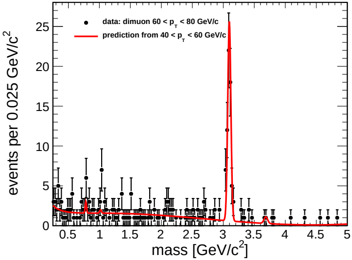


- For the single, high-p_T dimuon case, get the background shape from lower-p_T dimuon spectrum
- Above 40 GeV/c, $b\bar{b}$ to non-$b\bar{b}$ ratio is constant (see backup)
- Fit background-enriched sample to a smooth curve, overlay the fitted curve on control sample, allowing only normalization to float:

background-enriched



control

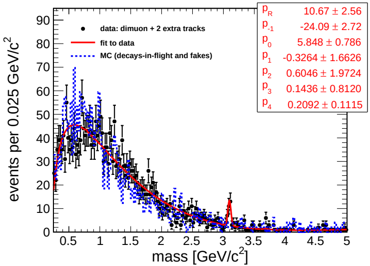


Region (a-2): high μ multiplicity

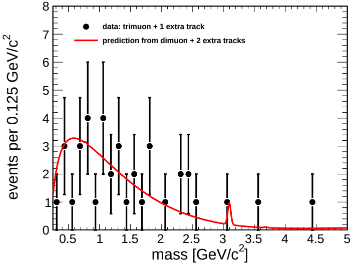
2 muons + 2 tracks	3 muons + 1 track	4 muons
Background-enriched	**Control sample**	**Signal region**

- For the many-muons-in-one-jet case, get the background shape by adding tracks as though they were fake muons
- Resonances are dwarfed by a low-mass rise
- MC dimuons with a muon known to be fake or decay-in-flight at generator level (blue) reproduces the same spectrum

background-enriched



control



Region (b-1): two dimuons

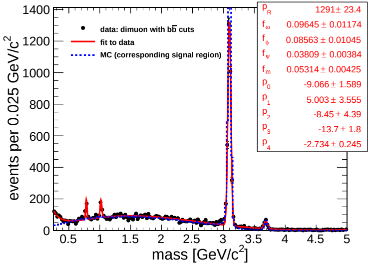
dimuon with $b\bar{b}$ cuts — **Background-enriched**

off-diagonal — **Control sample**

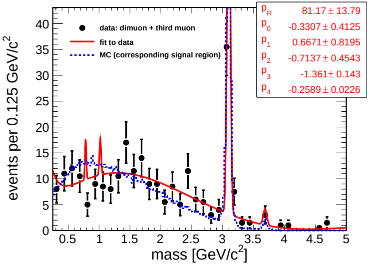
whole plane — **Signal region**

- The only Standard Model source that can give two low-mass dimuons in the same event is $b\bar{b}$ with both $b \to \mu\mu X$
- Technicality: dimuon required to trigger the event ($p_T > 20$ GeV/c) has a different distribution than the other dimuon ($p_T > 10$ GeV/c)
  - background-enriched (triggered): apply the $b\bar{b}$ cuts (page 16)
  - background-enriched (other): request a third muon (from the other b-quark) to satisfy the trigger

background-enriched (triggered)

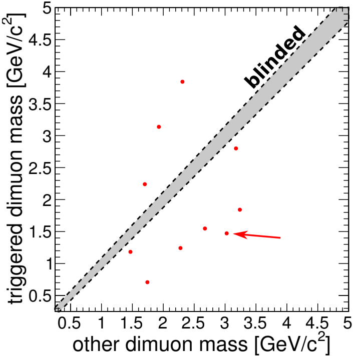


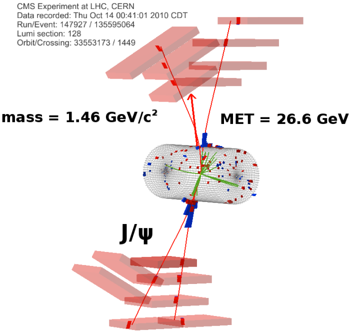
background-enriched (other)



Region (b-1): two dimuons

- Control region is the off-diagonal part of the mass-mass plane
- Number of observed events is consistent with back-of-the-envelope scaling (0.2% of b-quarks produce two $p_T > 5$ GeV$/c^2$ muons)
- About 10% of the background distribution is in the blinded region: observation of 10 events outside implies 1.1 ± 0.4 inside

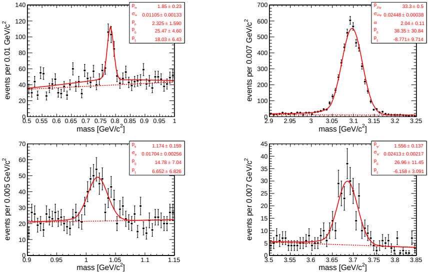


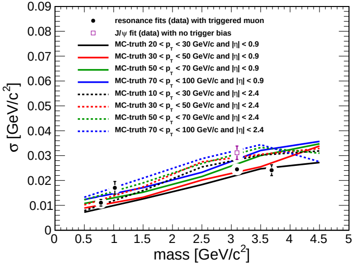


- Control events all look like J/ψ and double-semileptonic in $b\bar{b}$

Signal shape systematics

- Apart from the usual integrated luminosity and efficiency corrections, only important signal systematic is the resonance width
- Resonance width is determined exclusively be detector resolution and muon final state radiation (m_1 decay width is small)
- Measure detector resolution with ω, ϕ, J/ψ, and ψ', then test high-p_T dependence with Monte Carlo





- Nice agreement, minimal dependence on p_T: signal shape is well-understood

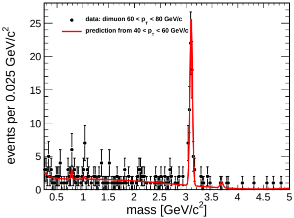
Fit results in control regions

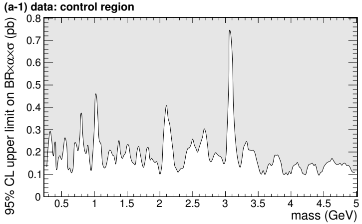
- Sets upper limits on cross-section × branching fraction × acceptance as a function of m_1 resonance mass for each topology
  - acceptance must be provided for a specific model
- Implemented in RooFit/RooStats: using MCMC method with systematics modeled as log-normal distributions
- Working values for systematic uncertainties (in progress):

Integrated luminosity	11%	
Efficiency	5%	estimate
Detector resolution	27%	from resonance fits
Template shape: p_R (all resonances)	10%	(a-1) background-enriched
Template shape: f_ω	50%	(a-1) background-enriched
Template shape: f_ϕ	125%	(a-1) background-enriched
Template shape: $f_{\psi'}$	30%	(a-1) background-enriched

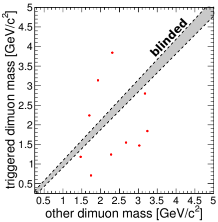
- Currently a Gaussian signal shape: adding Crystal Ball tail
- Test the full framework by calculating upper limits in the control regions, rather than the signal regions

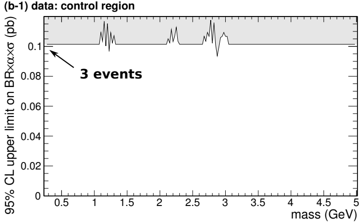
- The (a-1) control region: single dimuon with $60 < p_T < 80$ GeV/c





- The (b-1) control region: two dimuons per event, $m_a \approx m_b$ blinded
- The blinded region is modeled as containing zero events in this test





Conclusions

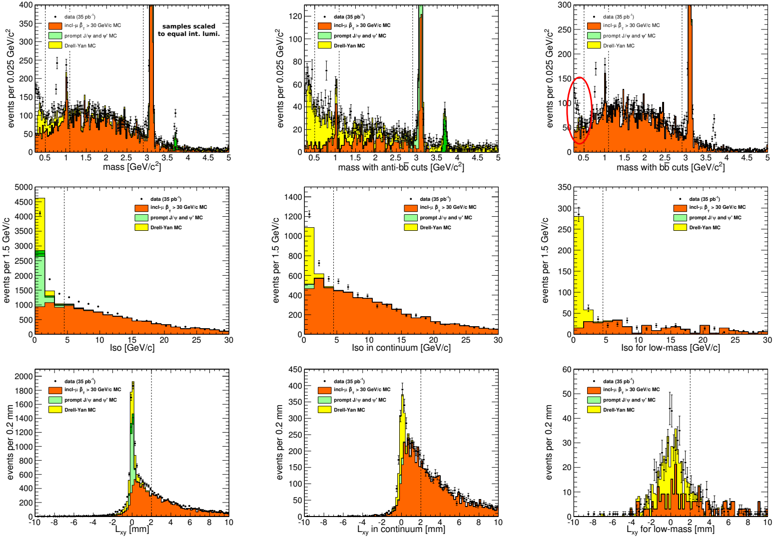
- "Lepton jets" are overlapping resonance decays with well-defined mass
- We search for a $\mu\mu$ mass peak using a signal + backgrounds fit, which provides a signal yield and background estimate at the same time, with the same data
- Deriving the background-shape templates requires some care: select events by physics type to produce the right kinematics and test in control regions before using in the fit
- The control regions are conforming to expectations, and the fitter is producing meaningful results
- We'll be unblinding the signal soon

Backup

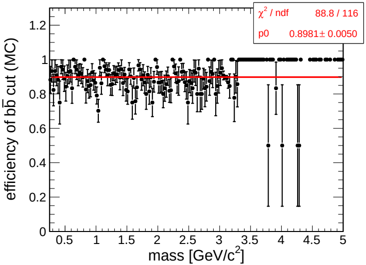
Low-mass dimuons

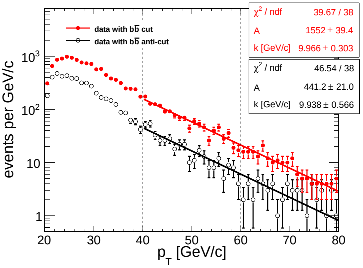
Drell-Yan output from Pythia output, rather than Z-scaling. All plots range 0.25–5 GeV$/c^2$ in 190 bins.

"Low-mass" is 0.35–0.5 GeV$/c^2$, "continuum" is 1.1–2.9 GeV$/c^2$. $b\bar{b}$ cuts are: *Iso* > 4.5 GeV$/c$ **or** $L_{xy} > 2$ mm.

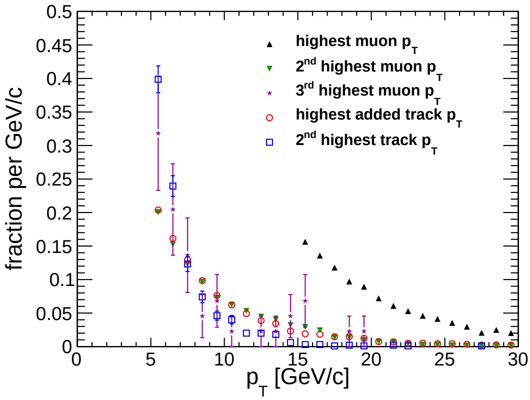


- $b\bar{b}$ cuts do not bias the shape of the mass spectrum for real $b\bar{b}$ (left)
- Drell-Yan/prompt resonances and $b\bar{b}$ components scale proportionally above $p_T > 40$ GeV/c (right)

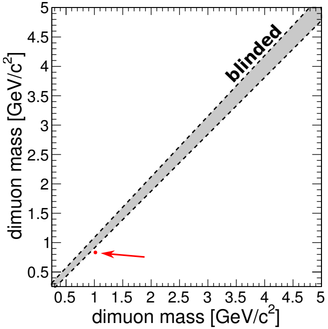


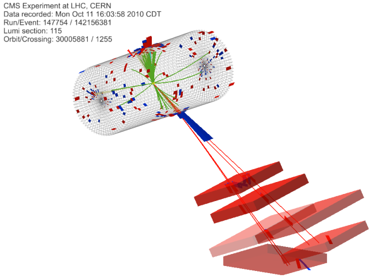


- When we add tracks to the mu-jet to simulate fake muons, do they have the same kinematics as muons?
- Yes, they do (except for the highest-p_T muon, which is special because it is selected to satisfy the trigger).



- Another control region: the off-diagonal part of the mass-mass plane
- Only one event outside of blinded region; it has low mass, as expected of fakes
- Three of these muons have only 2 segments each (the minimum number)





- Demonstration that the distribution factorizes with high-statistics $b\bar{b} \to 2\mu\, 2\mu$ MC