Muon Jets Analysis

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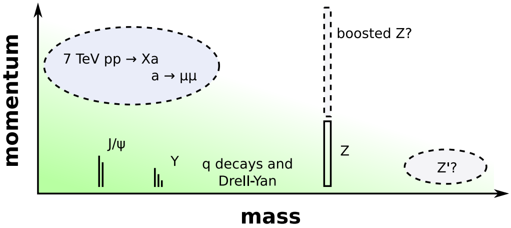
Motivation 1: dark matter

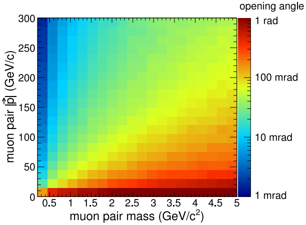
1. PAMELA expreiment saw an excess of high-energy positrons in primary cosmic rays
   - cannot be galactic modelling (even pushing parameters beyond the limit can't make the spectrum *increase* with energy
   - could be as-yet unknown young pulsars near Earth
   - could be decay products of WIMP-WIMP annihilation, except the cross-section is too high
2. Adding a long-range force that couples strongly to WIMPs, weakly to SM, could explain it:
   - "dark photon," a $\sim$1 GeV boson, acts as a long-range force attracting slow-moving WIMPs, more likely to collide
   - doesn't change the "WIMP miracle" in the early universe (fast-moving WIMPs)
   - 1 GeV boson is kinematically constrained to decay into e^+e^-, $\mu^+\mu^-$, $\pi\pi\pi$, all of which would eventually give an excess of positrons (observed) and not antiprotons (not observed)
3. In the LHC, this would show up as a low-mass but high-momentum resonance (it must be produced in top-down decays, since it has not been discovered already in low-energy collisions)

- NMSSM $h \to aa \to 4\mu$: unexplored region of parameter space that could be hiding the Higgs boson
  1. electroweak precision fits want a light Higgs ($\sim$100 GeV), but limits *assuming SM-like branching fractions* are at 114 GeV
  2. not a contradiction yet, but some 2σ-ish tension in the fit
  3. the Higgs boson responsible for electroweak symmetry breaking must have partial widths proportional to mass-squared of the decay products (Γ_{SM})
  4. but if there are multiple Higgses (h, a, and others), and Higgs-to-Higgs partial widths are large (Γ_{H-H}), then SM-like branching fractions would be smaller than we're assuming: $\mathcal{B}_X = \Gamma_X / \sum_i \Gamma_i$
  5. we found a region of NMSSM parameter space in which $\mathcal{B} \to aa$ is high ($\sim$100%), $a \to \mu\mu$, so a 100 GeV h would disappear into 4μ rather than SM-like modes
- Generic: this topology wouldn't necessarily be caught by other analyses, though our detector should be very sensitive to it
  - theories seem to be satisfied with a wide variety of things thrown into this hidden sector: we should look

Signature

- Most generally, at least two muons with high momentum (comes from a top-down decay) and low mass
- There may be other light resonances in the sector: this can lead to more than two muons in a small cone:
  $pp \to X$ light $\to$ lightest lightest $\to > 2\mu$
- There may be other heavy resonances in the sector: this can lead to multiple pairs/groups of muons in the same event:
  $pp \to X$ heavy $\to$ light light $\to 2\mu, 2\mu$
- They may be accompanied by missing energy (WIMPs) or they may have highly displaced vertices (if they couple very weakly to the SM)

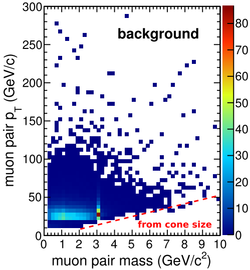


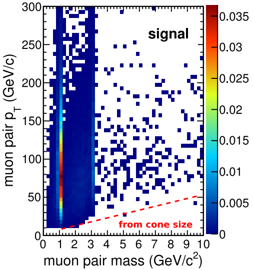


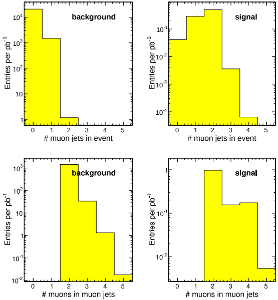
- This is a search-and-discovery (or place limits); the important points are
  - be general: cast a wide net so that we don't miss a discovery
    - must identify signature-based variables and quote limits in those variables, so that they are applicable to many different theories: what variables identify this signature?
  - understand the backgrounds, so that we don't falsely claim a discovery
    - must find variables in which the signature is clearly distinct from backgrounds
    - data-driven backgrounds estimates: can be estimated from variables that are nearly independent of one another

What we know: backgrounds

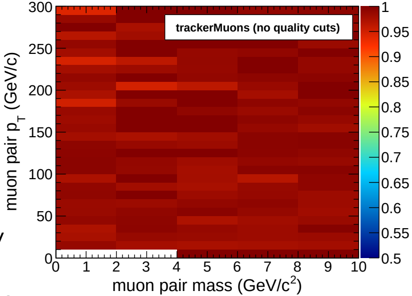
- From quick backgrounds studies (in April/May):
  - 1 pb (target signal cross-section) is $\sim 10^3$ times smaller cross-section than background
  - single-"muon jet" analysis should require > 2 muons, high p_T cuts, and careful segment arbitration to suppress $pp \to X\mu$
  - multiple-"muon jet" analysis with > 1 jet is pretty safe, especially as a mass-peak search (e.g. NMSSM analysis)
  - isolation (defined properly for multi-muons) suppresses background by a factor of 10



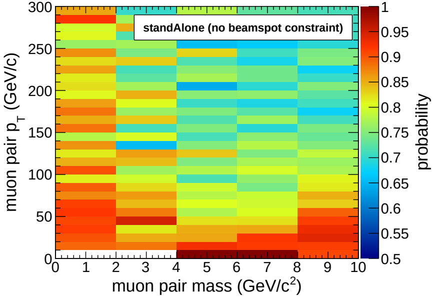


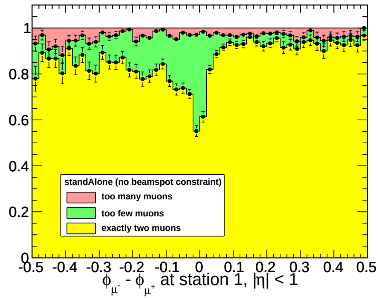


- Tracker muons (e.g. prev page) have high efficiency but high backgrounds
  - backgrounds are higher than they need to be because multiple tracker tracks can be associated with the same segments
  - "arbitration:" assigning each segment with exactly one track, is provided by several standard algorithms, but they are "greedy algorithms" and therefore order-dependent (leading muon gets all of the best segments)
  - something that might not be appropriate: I have an idea for calculating a unique optimal arbitration (later slide), can check to see how close the standard algorithms get to optimal arbitration as a function of ΔR



What we know: reconstruction





- Stand-alone muons: low efficiency, especially when the two muons cross each other in the muon system
  - appears to be a cut in the stand-alone muon finding
- Global muons: built from stand-alone muons, so they should inherit this inefficiency
- Something to try: the "SET" stand-alone algorithm under development by Ingo, Stoyan, and others

Current status

1. Pilot study, to know what to look for in general study — done
2. Building framework and datasets for general study — 99% done
3. Exploration of the datasets, figuring out which plots to put in a general analysis note — a little bit
4. Systematically making all of the plots so that everything (all cuts, etc) is mutually consistent and can be repeated
5. Putting them into an analysis note
6. Doing the same with data, data/MC comparisons, another analysis note
7. Writing a paper...

This means that I have no plots to show, but I can show a lot of the work that has been done:
https://twiki.cern.ch/twiki/bin/view/CMS/ExoticaMuonJets
(I've been filling this out like a lab notebook as I go along)

Event samples

- pat::Muon collections created from several sources:
  - NormalMuons: the collection provided by the muon POG (the set of all globalMuons are a subset of this)
  - TrackerMuons: all muons that can be identified with the trackerMuons algorithm, no arbitration
  - TrackerMuonsConv: same with tracks produced using the exhaustive 7-iteration tracking developed for e^+e^- conversions, may extend the range of displaced-vertex searches
  - StandAloneDefault and StandAloneSET: stand-alone muons with the default and SET algorithms (no beamline constraint)
- Very loose skim cut: ≥ 2 muons in any collection
- Carefully chosen reduced set of branches makes the above practical (all MET variables, trigger data, MC truth included)
- Skims of all InclusiveMu5_PtX
- Example signal samples (extra-$\mathcal{U}(1)$ dark matter and NMSSM)
- Many muon-jet guns, generated uniformly in resonance mass and momentum, some with large displace vertices, with & w/o pile-up

Software

- Tools for gluing groups of muons together according to various criteria: ΔR, m_{inv}, and vertex probability (non-greedy algorithm)
  - access to Muon POG-approved selectors (for all the appropriate comparisons)
- Tools for working with groups of muons
  - vertexing and kinematic variables at the common vertex
  - group-isolation: $\sum p_T$ and number-above-threshold-p_T in a cone around the jet momentum, *excluding* the muons in the muon-jet
  - optimized arbitration: minimum

$$\chi^2 = \sum \left(\frac{\text{track} - \text{segment}}{\text{uncertainty}} \right)^2$$

    for *all possible* assignments of segments to tracks, such that
    - every segment* is assigned to exactly one track
    - *only considering segments that were initially assigned to one of the unarbitrated trackerMuons
- Fully documented on webpage

- Of the time dedicated to this project in the past 2–3 months, at least 90% of it went into running CRAB
  - not unexpected features or bugs in CRAB, just CRAB doing what it's supposed to do (jobs failing, resubmit, fail again, check all the logfiles, eliminate duplicate output, so that the background samples have exactly the integrated luminosity that they're supposed to)
- Now the samples are complete, and I'm almost done implementing the optimal arbitration
- This week, I'll start making all of the plots, filling in an analysis note as I go along, just like I filled in the twiki with the technical stuff
- There's an Exotica-Muons meeting this Thursday. I could get a talk's worth of interesting results by then and show them, but I couldn't do that and inform the other muon-jets analysis teams first
  - this is a lot of work; they should be informed...