Plans and Prior Work on Muon Jets

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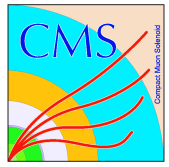
Proposed search strategy

- The theoretical motivation for lepton jets is a broad idea, rather than a specific model, so we want to keep our search general
- This is common problem: model-specific searches are limiting, but unspecific searches are not well defined— how do we look for "anything interesting"? How to balance definiteness with generality?
- Proposal: let the backgrounds define the search; look for all the ways that a signal could peek out from under the Standard Model
  - (a) tightly collimated group of leptons with $N_{\text{leptons}} > 2$: background for $N_{\text{leptons}} = 2$ is large ($b \to \ell c \to \ell\ell s$) but not $N_{\text{leptons}} > 2$. Could be useful to add electrons and even pions for this kind of search, since the acceptance for muons-only falls as $\sim \left(\frac{1}{2}\right)^{N_\mu/2}$ (lepton universality)
  - (b) more than one tightly collimated group of leptons (at first, only look for groups of muons, maybe add electrons later)
  - (c) one group of muons and large missing energy
  - (d) *muon* pair or group with significantly displaced vertex (not electrons; background from conversions)

Proposed search strategy

- Motivations by event topology:
  - (a) tightly collimated group of leptons with $N_{\text{leptons}} > 2$: background for $N_{\text{leptons}} = 2$ is large ($b \to \ell c \to \ell\ell s$) but not $N_{\text{leptons}} > 2$. Could be useful to add electrons and even pions for this kind of search, since the acceptance for muons-only falls as $\sim \left(\frac{1}{2}\right)^{N_\mu/2}$ (lepton universality)
    Cascades of new resonances, all of which are light:
    $a_2 \to a_1 a_1 \to 4\ell$, $a_3 \to a_2 a_2 \to 4a_1 \to 8\ell$, etc.
  - (b) more than one tightly collimated group of leptons (at first, only look for groups of muons, maybe add electrons later)
    One of the new resonances is heavy: e.g. NMSSM Higgs
    $h \to aa \to 4\ell$ with $m_h \sim 100$ GeV, $m_a \sim 2$ GeV
  - (c) one group of muons and large missing energy
    Final state radiation of a dark photon off of a WIMP
  - (d) *muon* pair or group with significantly displaced vertex (not electrons; background from conversions)
    New resonance with very small couplings to Standard Model particles

Aysen's physics interests



- Aysen Tatarinov is a grad student at A&M
- He's specifically interested in a "two well-separated muon jets" topology (case (b))
- We published a phenomenology paper on this recently (Phys. Rev. D 81, 075021 (2010), arXiv:1002.1956)

LHC discovery potential of the lightest NMSSM Higgs in the $h_1 \to a_1 a_1 \to 4\mu$ channel

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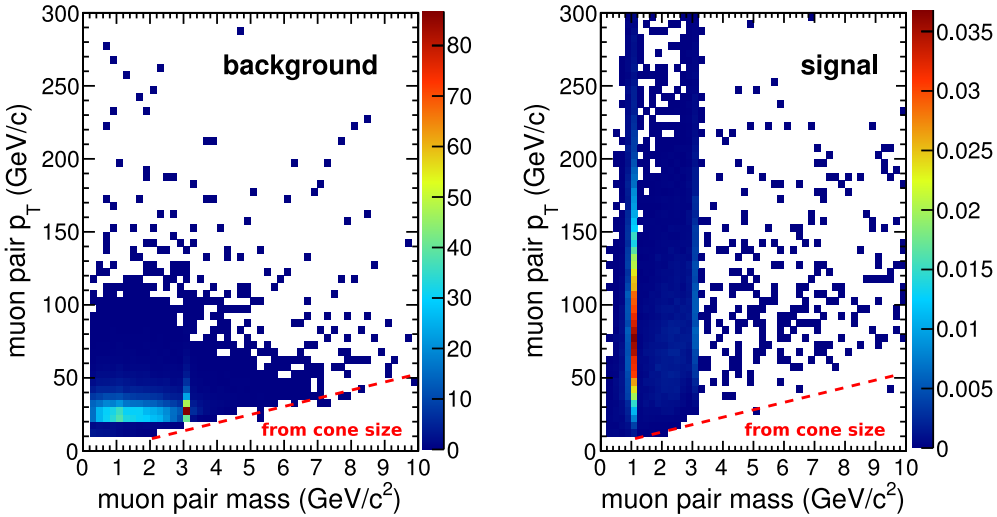
[3] *Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA*

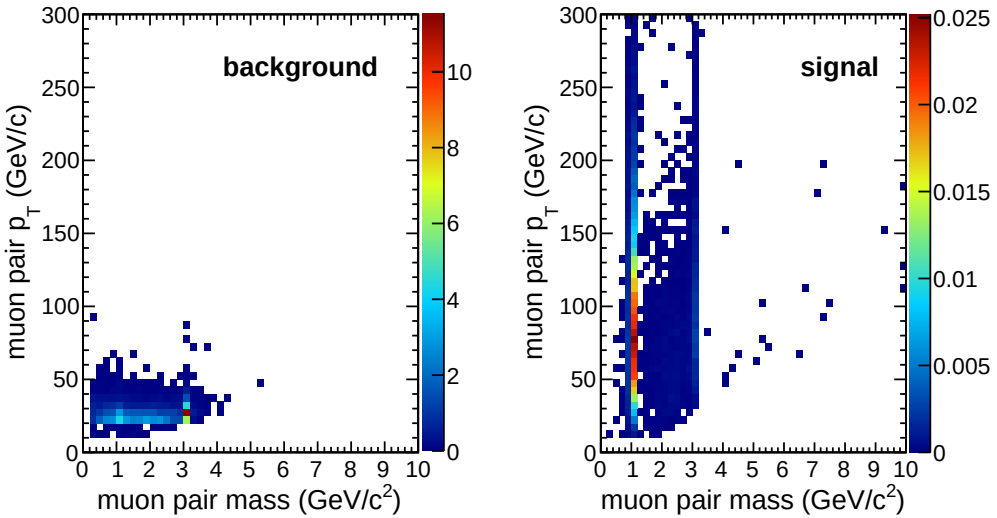
We explore the potential of the Large Hadron Collider to observe the $h_1 \to a_1 a_1 \to 4\mu$ signal from the lightest scalar Higgs boson (h_1) decaying into the two lightest pseudoscalar Higgs bosons (a_1), followed by their decays into four muons in the Next-to-Minimal Supersymmetric Standard Model (NMSSM). The signature under study applies to the region of the NMSSM parameter space in which $m_{a_1} < 2m_\tau$, which has not been studied previously. In such a scenario, the suggested strategy of searching for a four-muon signal with the appropriate background suppression would provide a powerful method to discover the lightest CP-even and CP-odd NMSSM Higgs bosons h_1 and a_1.

Quick backgrounds estimations

- "background" = InclusiveMu15
- "signal" = typical 1 pb^{-1} model ($\mathcal{U}(1)_{\text{dark}}$ with 1 GeV Z_{dark}, 3 GeV h_{dark})



No cuts. Color scale is cross-section per bin; note the different scales!

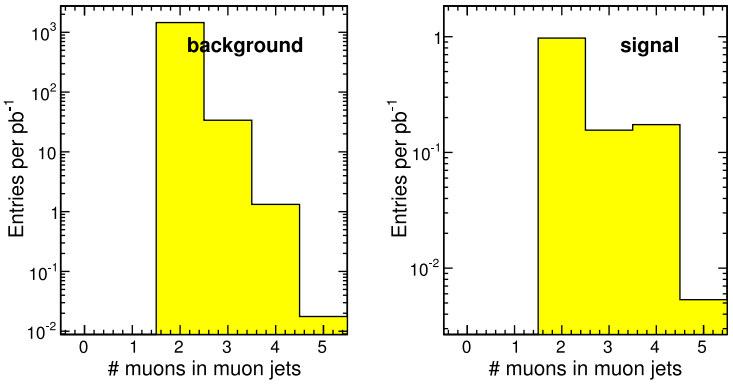


Same with a reasonable isolation cut (factor of 10 for background)

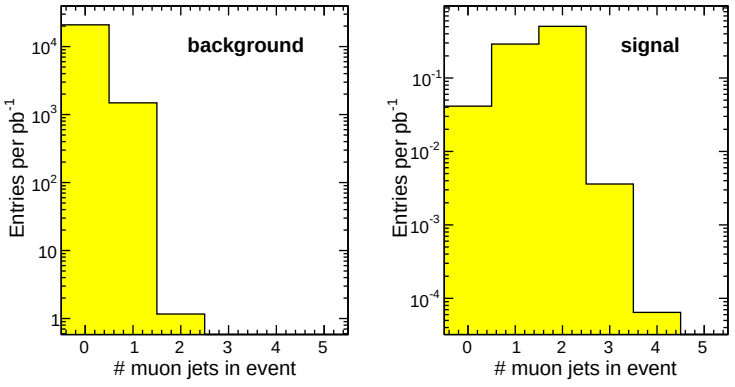
Quick backgrounds estimations

Vertical axis is cross-section per bin; note the different scales!

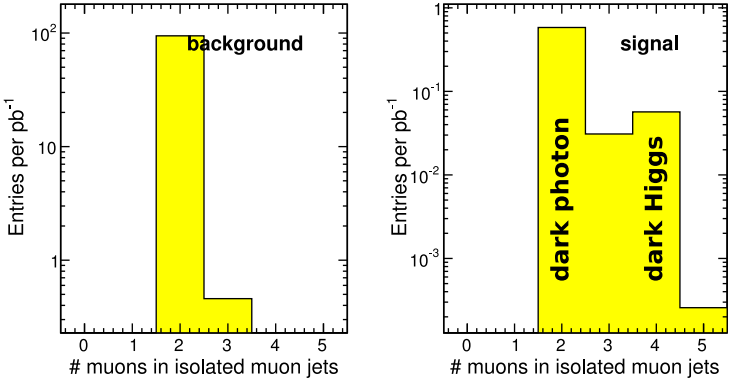
Motivating case (a)



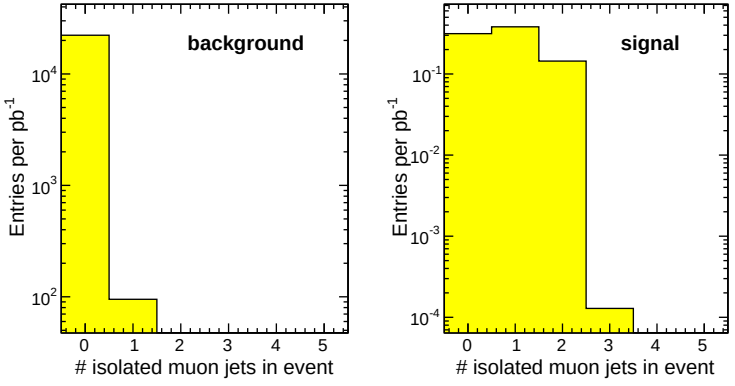
Motivating case (b)



with isolation:

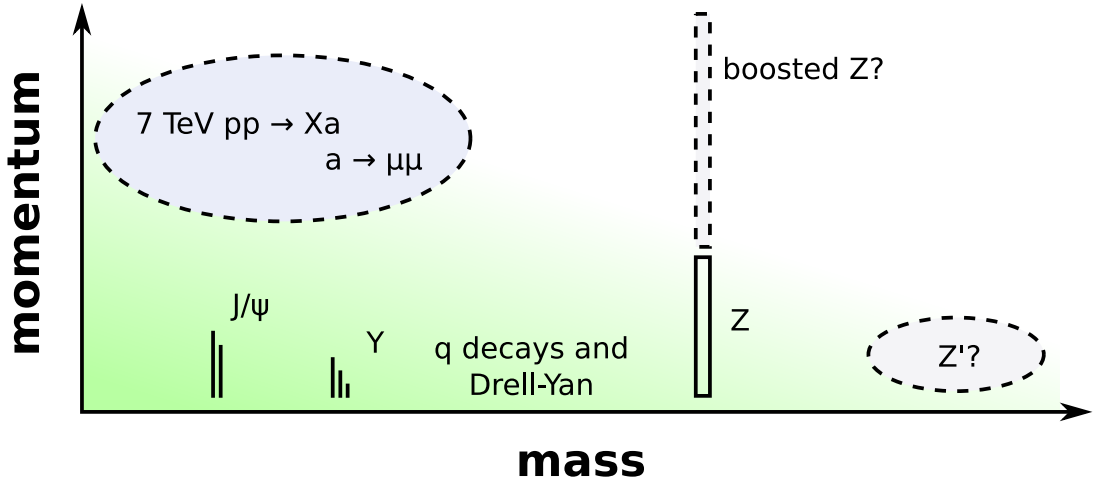


with isolation:



Sources of backgrounds

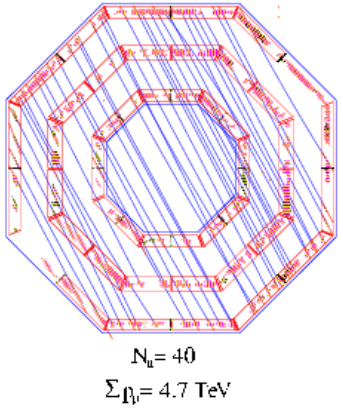
- Physics
  - heavy flavor double-semileptonic: continuum in mass
  - light flavor decay-in-flight: cut with vertex probability
  - quarkonium resonances: also useful as standard candles
  - Drell-Yan, diboson: weak and usually large ΔR

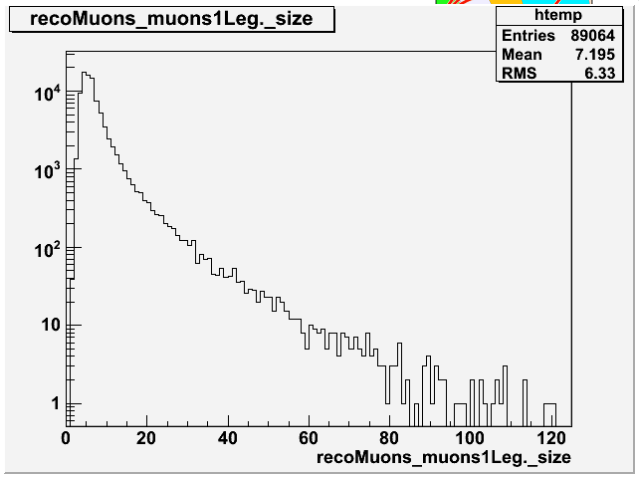


- Misreconstruction: small number of muons misreconstructed as a larger number of muons
  - similar to efficiency issues: large number of muons misreconstructed as a smaller number of muons

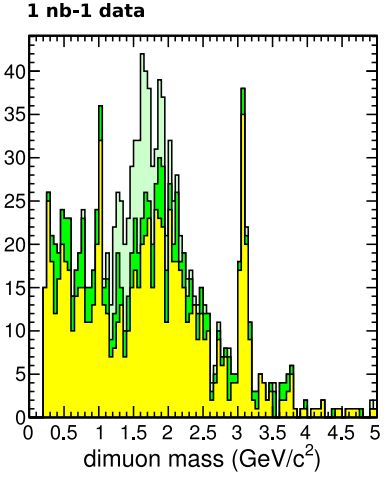
Potentially useful datasets

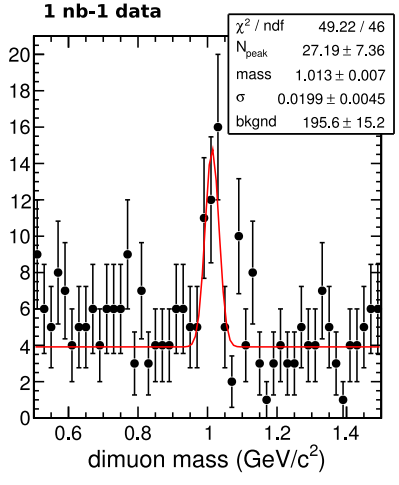
- Cosmic ray air showers: already-available source of multi-muon events; some may be close enough to each other to study two-muon efficiency/misreconstruction



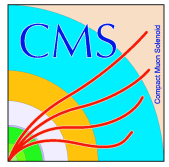


- High-intensity beam-halo: same argument for endcaps, assuming that the LHC beam-halo production process yields any multiple-muon events (unchecked)
- J/ψ and $\phi(1020)$ resonances: high-momentum tail of J/ψ, ϕ distributions are standard-candle lepton jets— how high in momentum can we expect to find them?





Studying misreconstruction



low-level: Select nearby pairs of RPC hits or DT/CSC segments in cosmic air showers: look for segments in an adjacent chamber

medium-level: Identify real trackerMuon pairs with J/ψ mass cut and check standAloneMuon reconstruction efficiency

high-level: Dissect trackerMuons/standAloneMuons/globalMuons

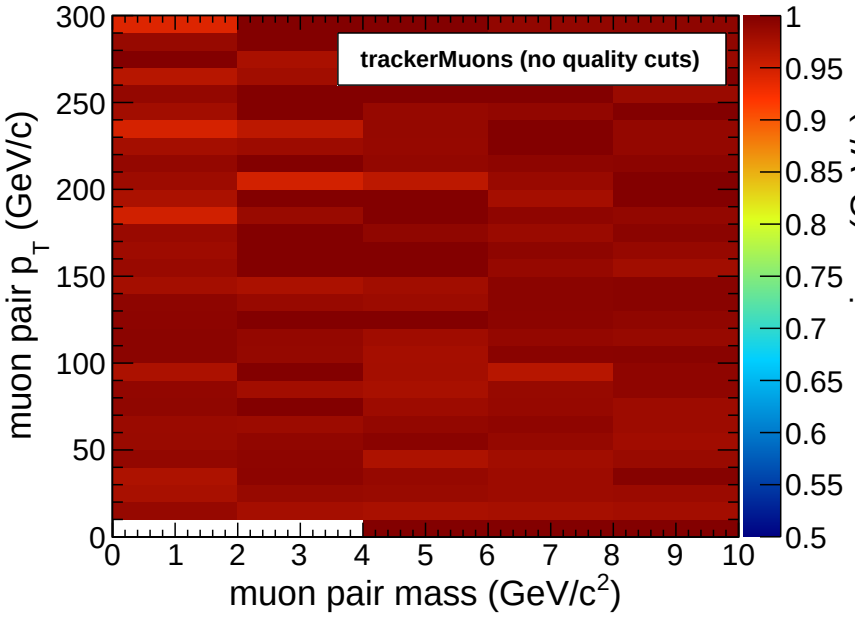
Standard "muons" collection contains muons derived from all algorithms, but each algorithm has different efficiencies and backgrounds, especially for close-by muons

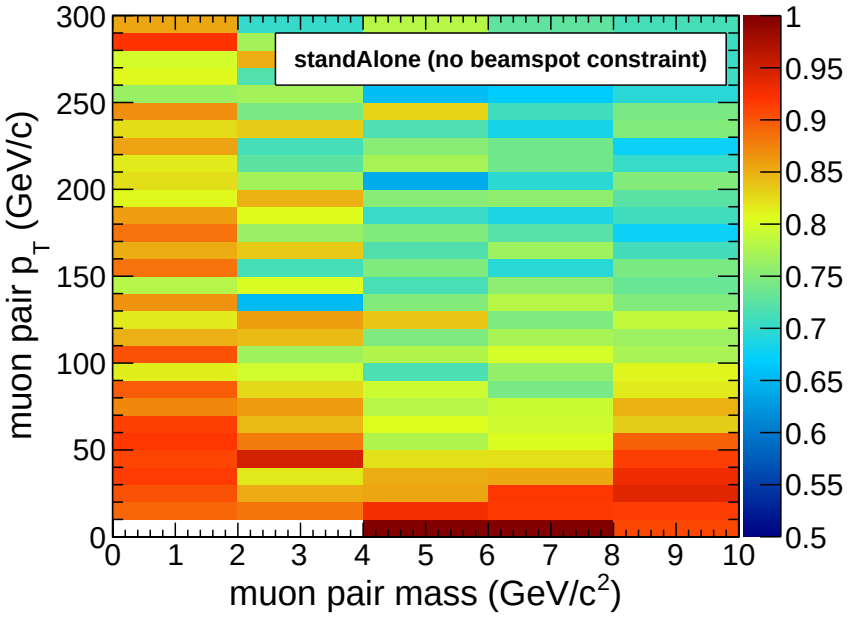
- trackerMuons: large backgrounds from two or more tracks matched to one muon's segments
- standAloneMuons: low efficiency from reconstruction algorithm with nearby segments
- globalMuons: should inherit low efficiency from standAloneMuons

Build single-algorithm collections and perform analysis independently on each

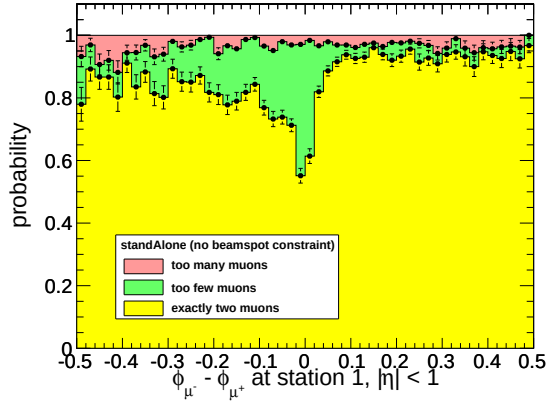
Early misreconstruction studies

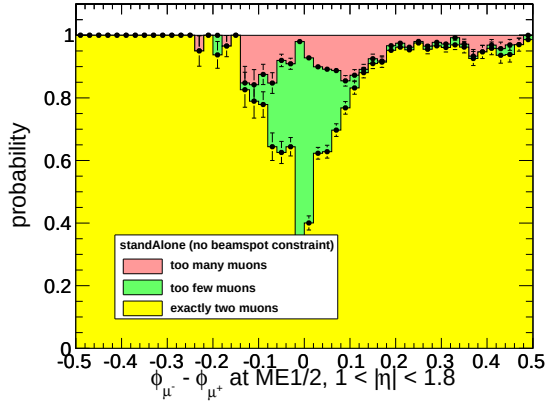
Opposite-sign muon pair gun: color scale is probability of reconstructing exactly two muons (no underlying event to add backgrounds to trackerMuons)

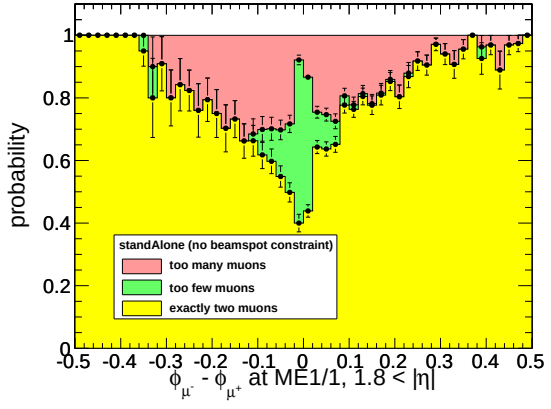




Directly related to how close they approach each other in muon system:



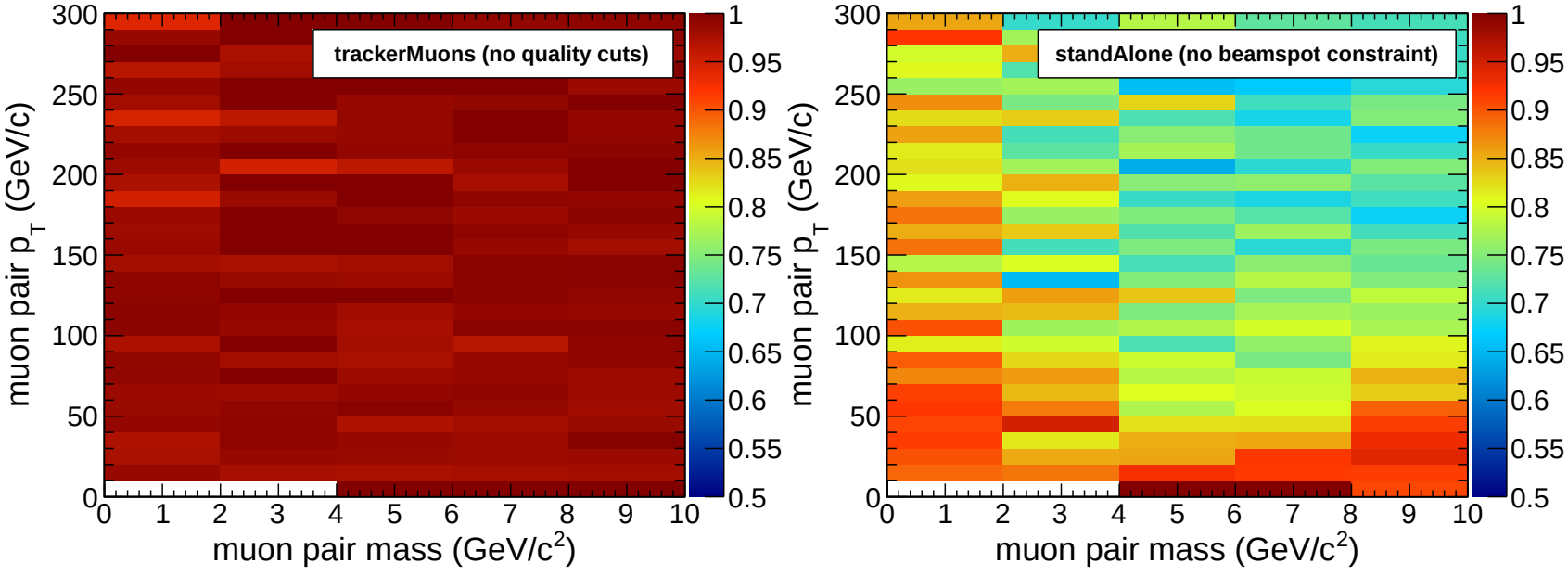




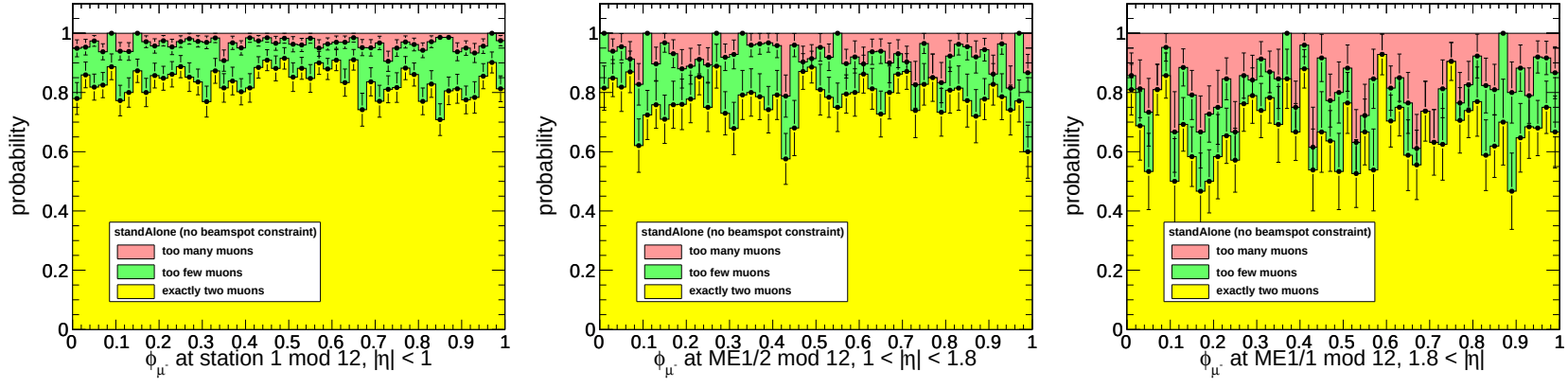
Early misreconstruction studies

Jim Pivarski

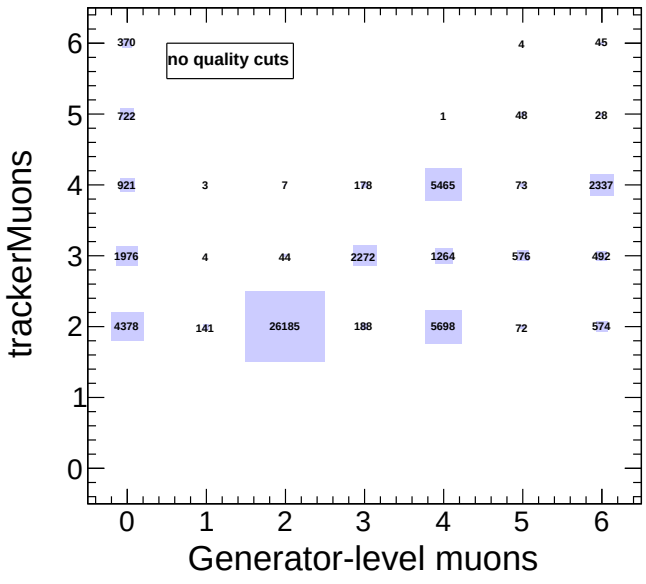
Opposite-sign muon pair gun: color scale is probability of reconstructing exactly two muons (no underlying event to add backgrounds to trackerMuons)

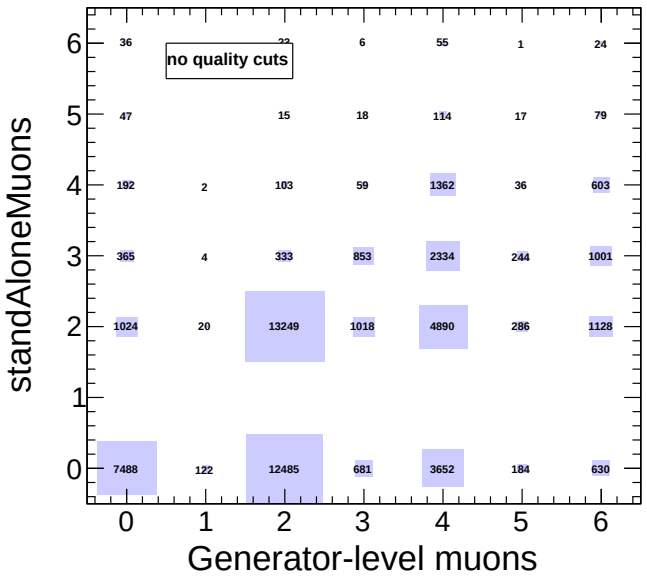


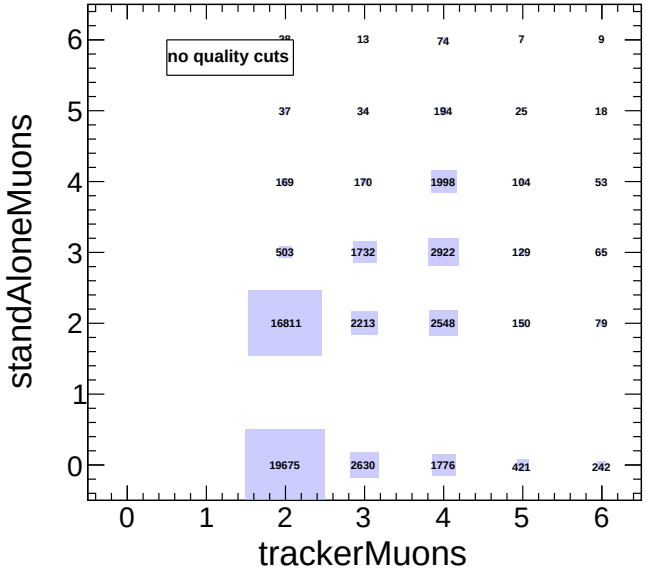
Interestingly little dependence on position in chamber (such as edges):

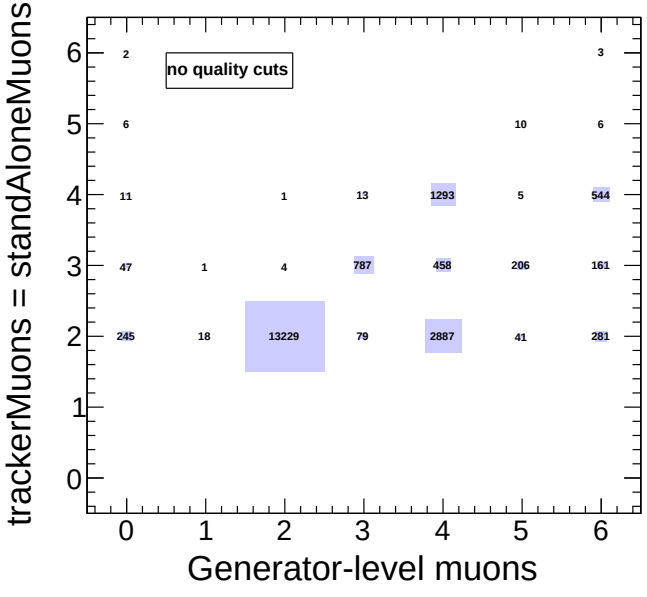


Early misreconstruction studies



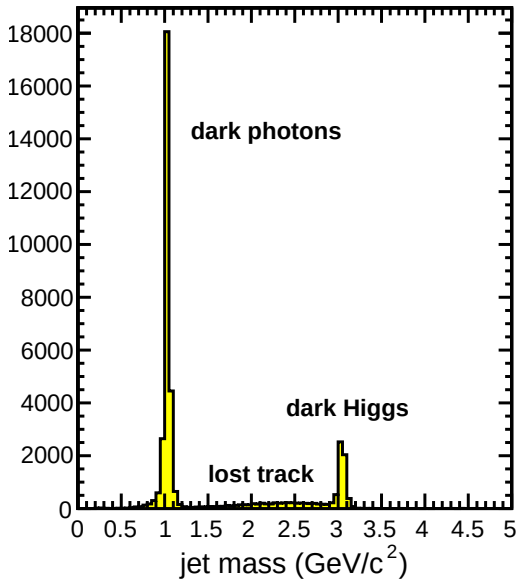


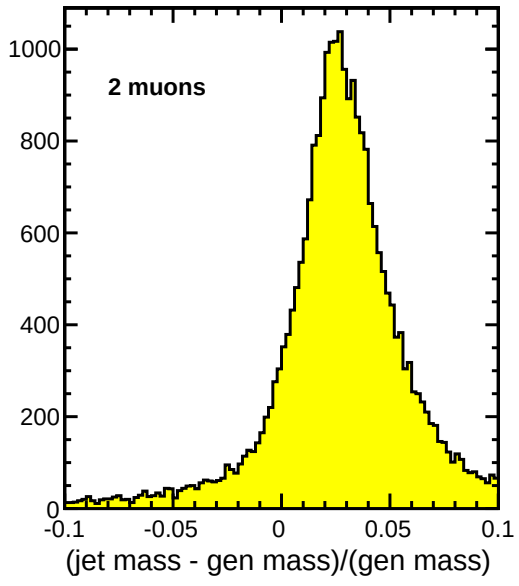


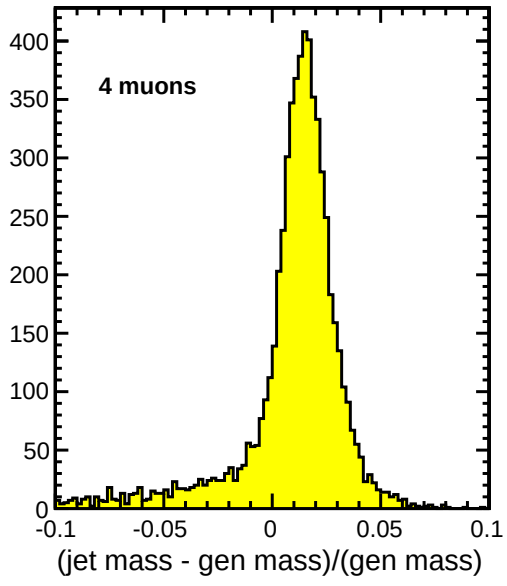


- Realistic model MC ($\mathcal{U}(1)_{\text{dark}}$) with underlying event and multiple interactions
- trackerMuons and standAloneMuons independently grouped; comparing $N_{\text{muons per group}}$ (with $|\eta| < 2.4$ and $p_T > 2.5$ GeV)
- We can see trackerMuon fakes and standAloneMuon inefficiencies

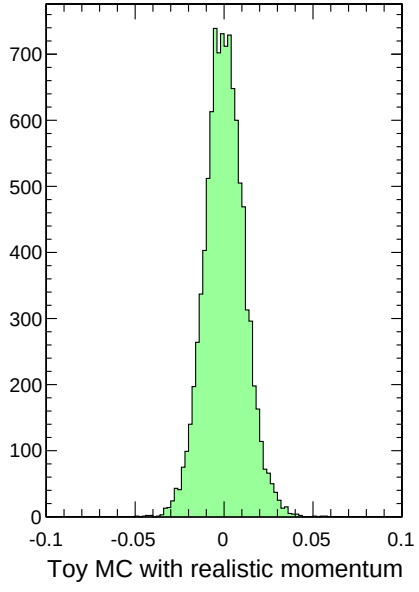
Mass/momentum resolution

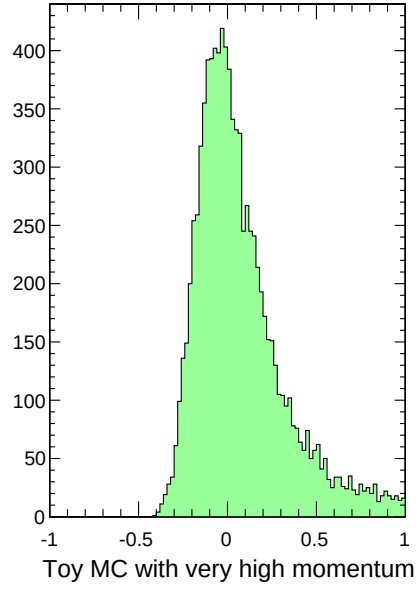






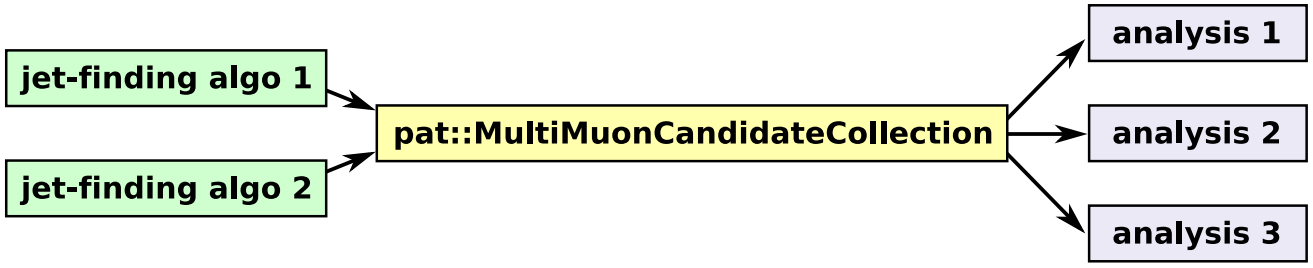
- $\mathcal{O}(1\text{–}3\%)$ bias in mass of trackerMuon jets
- Boosted mass distributions can be asymmetric because Δp_T is one-sided, but that's not responsible for the above asymmetry





Software framework

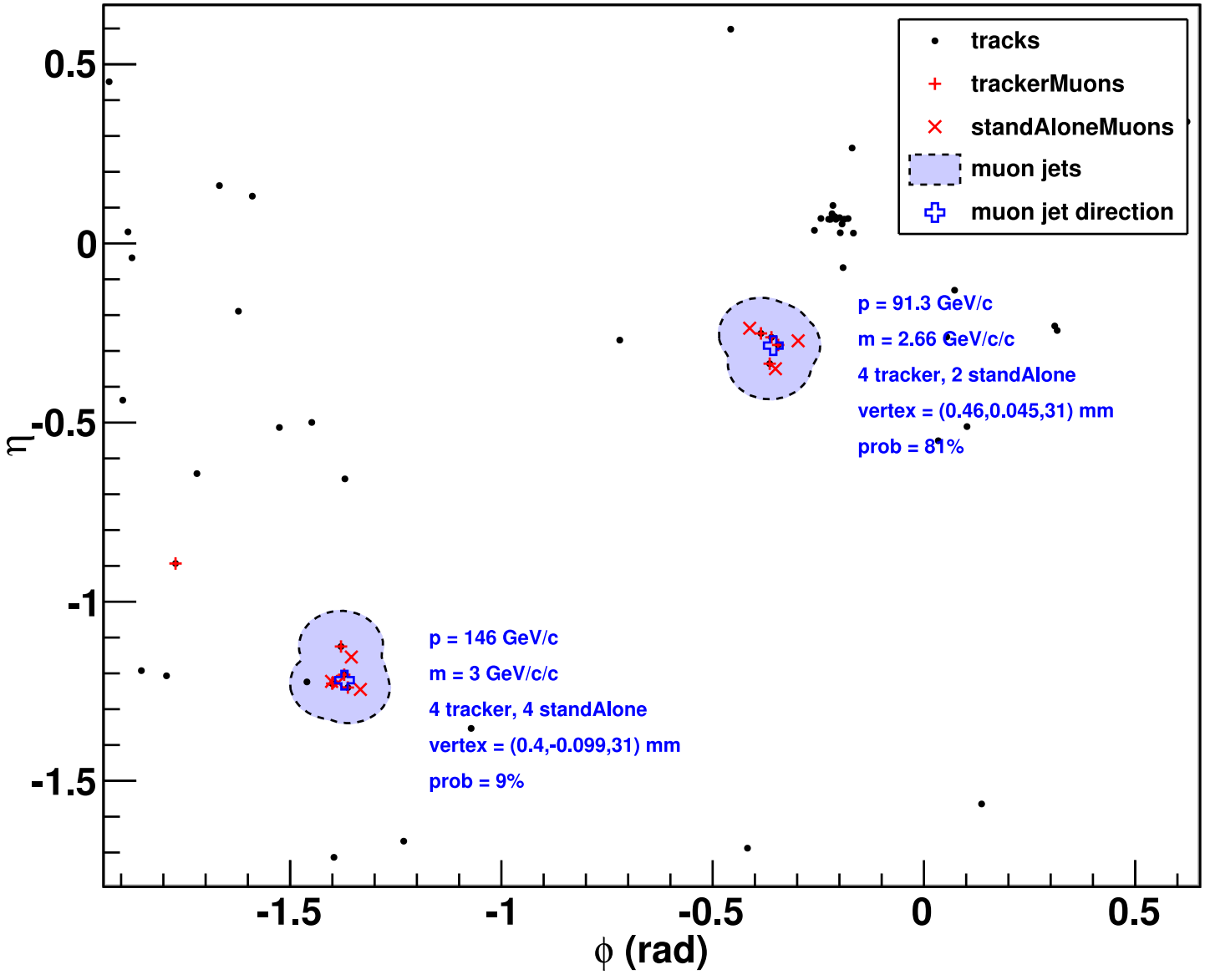
- pat::MultiMuonCandidate represents a group of nearby muons
  - useful for organizing muon jet analyses:



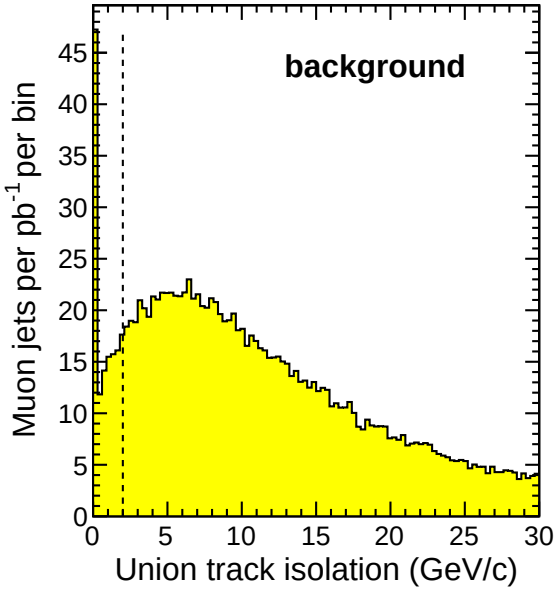
- Provides useful variables for cuts, pre-calculated:
  - vertexing, vertex probability
  - isolation (properly ignoring the muons in the isolation cone)
  - matching trackerMuonJets and standAloneMuonJets for comparison
  - variables to identify ME1/1a triplets
  - propagating MC match to composite object
- Simple clustering algorithm LeptonJetsEquivalenceClassProducer
  - all muons within a given ΔR of a group are included in the group

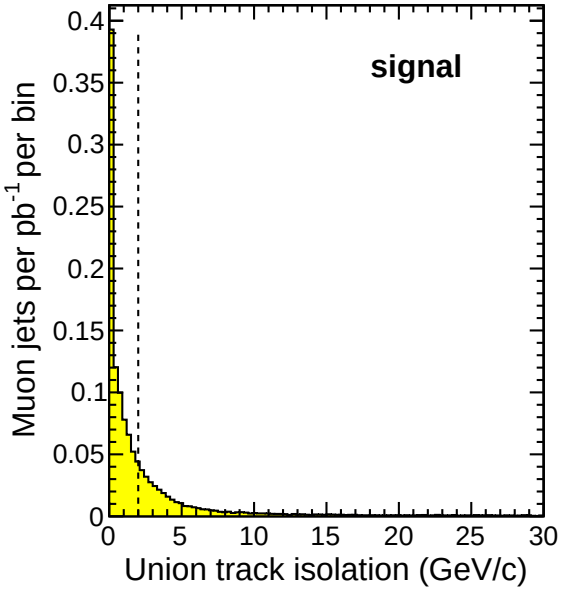
Software framework

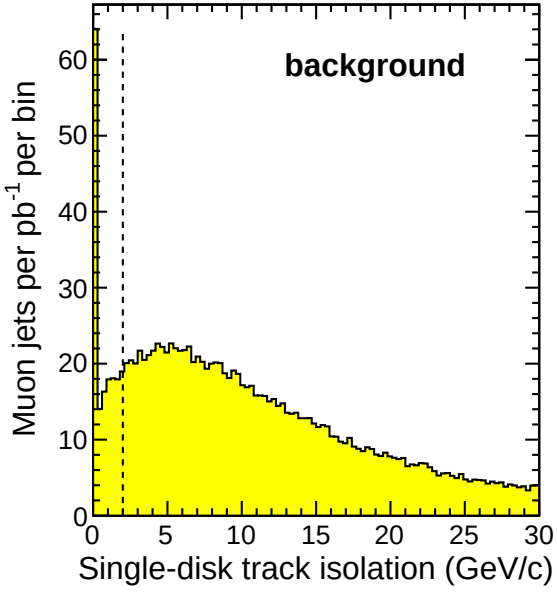
Example event display, illustrating pat::MultiMuonCandidate variables

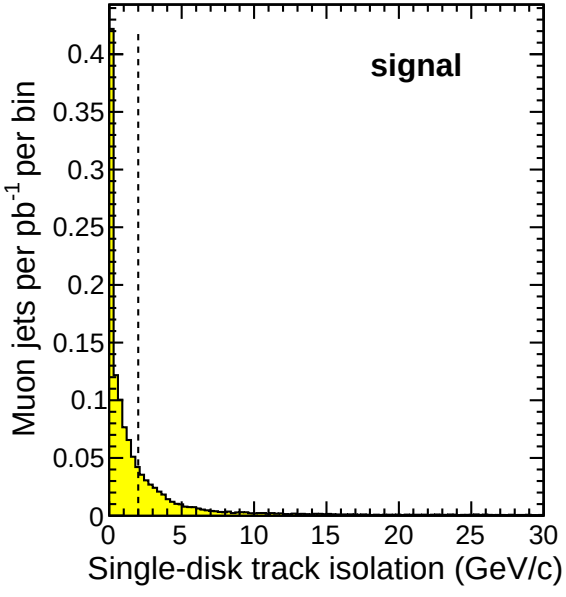


Software framework

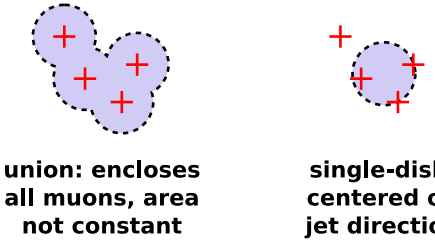






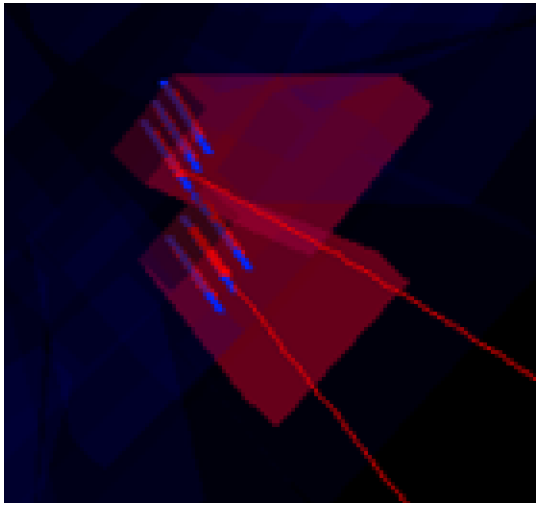


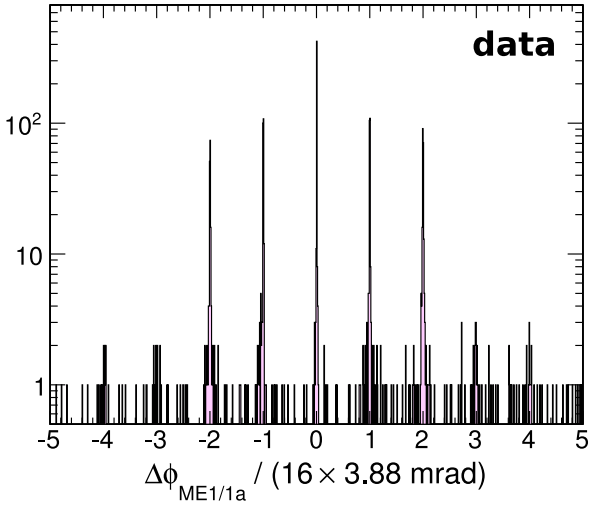
- $\sum p_T$ in isolation cone must not count the other muons in the cone, and must not double-count overlapping cones
- Multi-muon cone definitions:

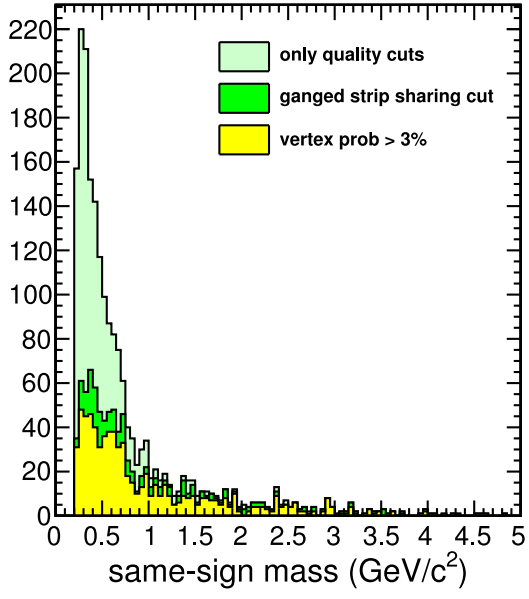


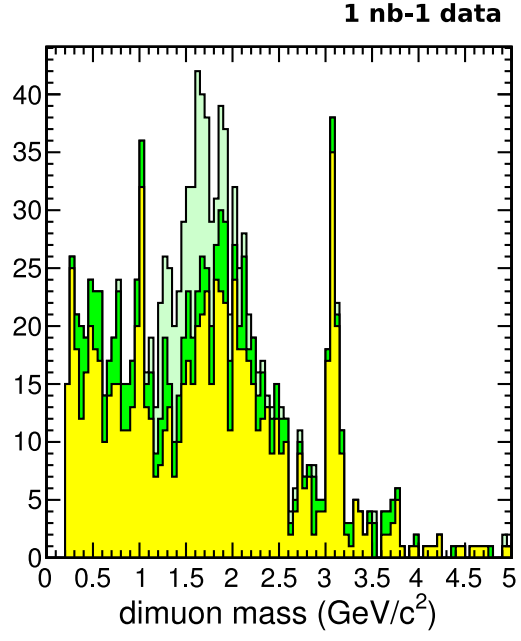
- Single-disk is preferred because the area is constant (backgrounds are uniform in η-ϕ)

Software framework



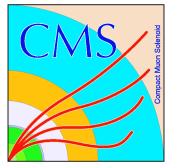




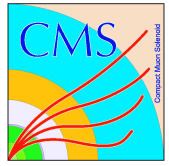


- ME1/1a strips are ganged, generating fake segments and therefore fake muon pairs (and triplets) in the forward region
- Variables included to identify such cases
- Bottom: cleaning real data without losing J/ψ or $\phi(1020)$ peaks

Conclusions



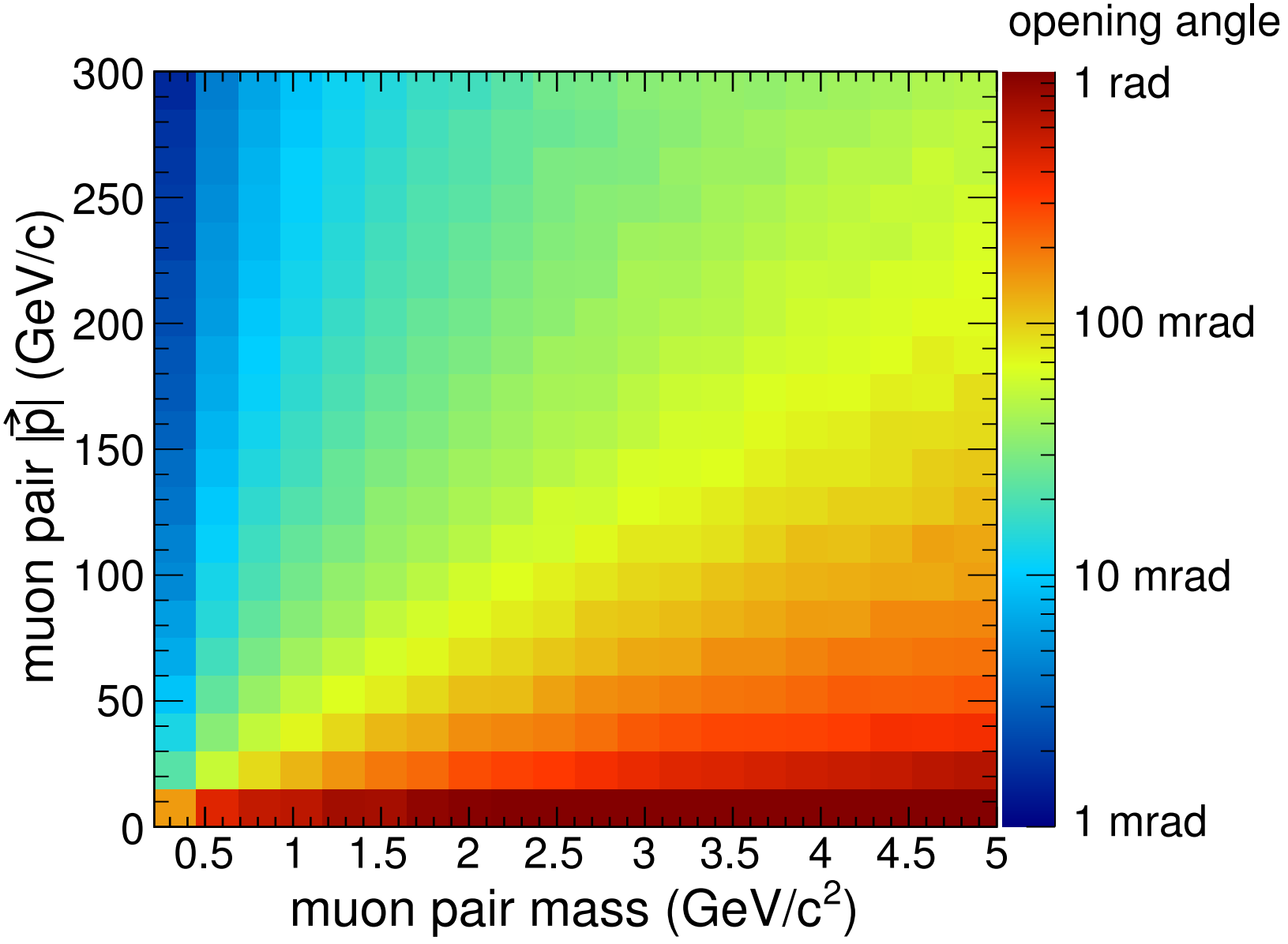
- There are several ways that lepton jets can distinguish themselves from background; target searches for each general case
- Aysen's (A&M) physics interests are in case (b)
- We'll need to consider misreconstruction as both an inefficiency and as a major background
- We've developed a software framework for organizing these studies


CMS
Compact Muon Solenoid

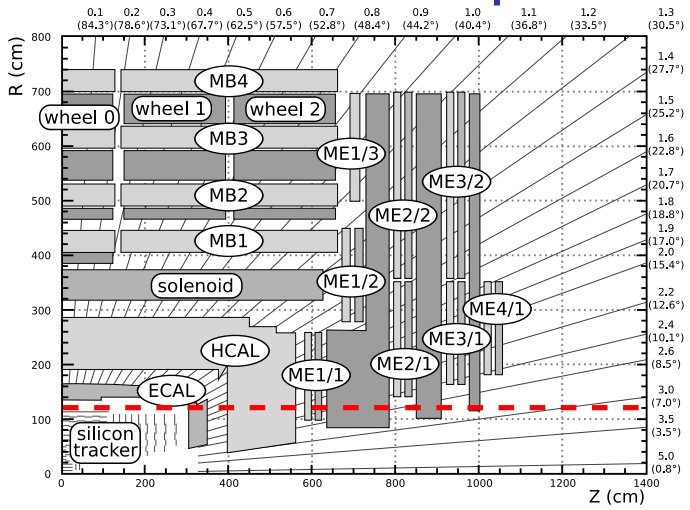

THE TEXAS A&M UNIVERSITY SYSTEM
1876

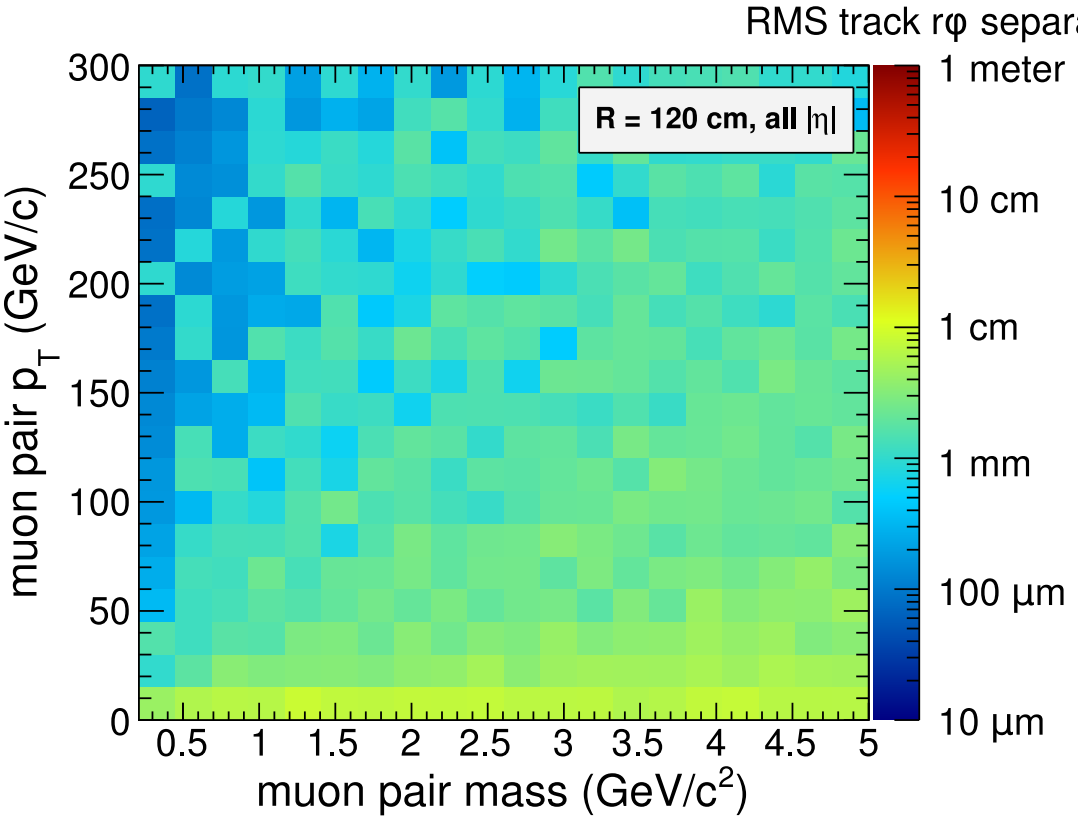
BACKUP

$|\vec{p}|$, m vs. opening angle

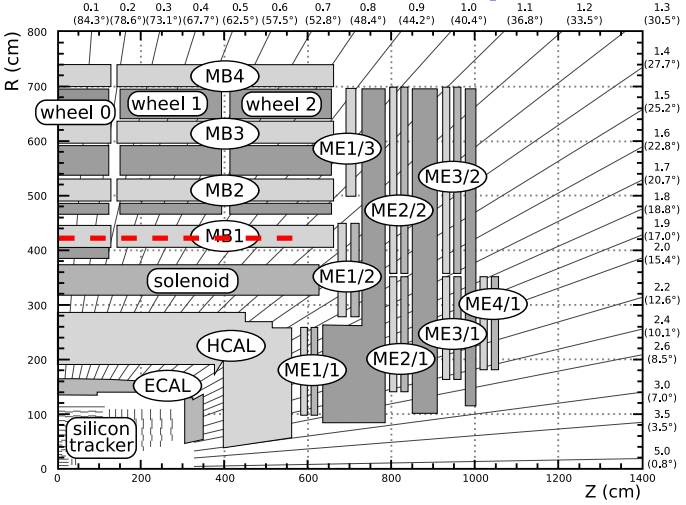


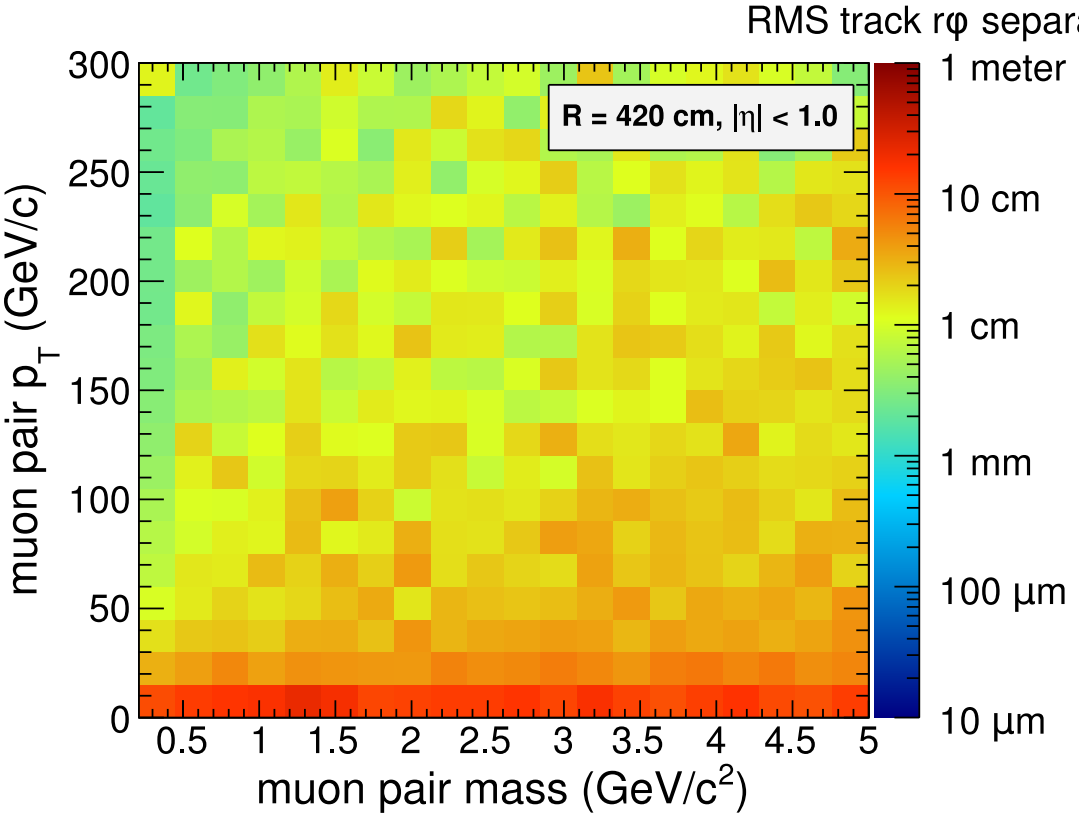
p_T, m vs. track separation



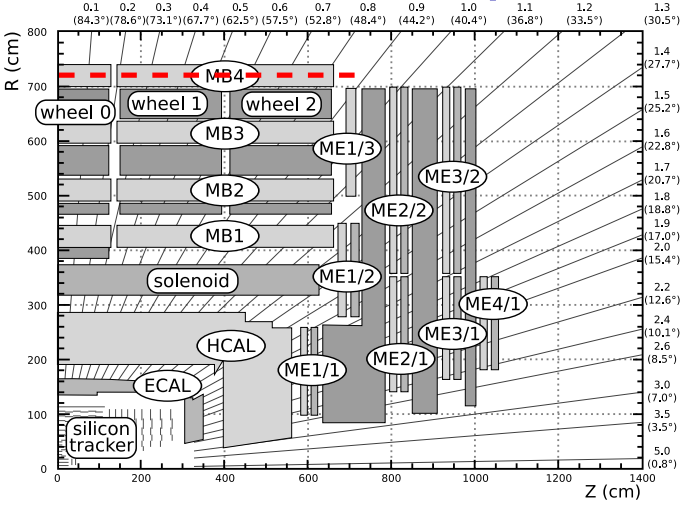


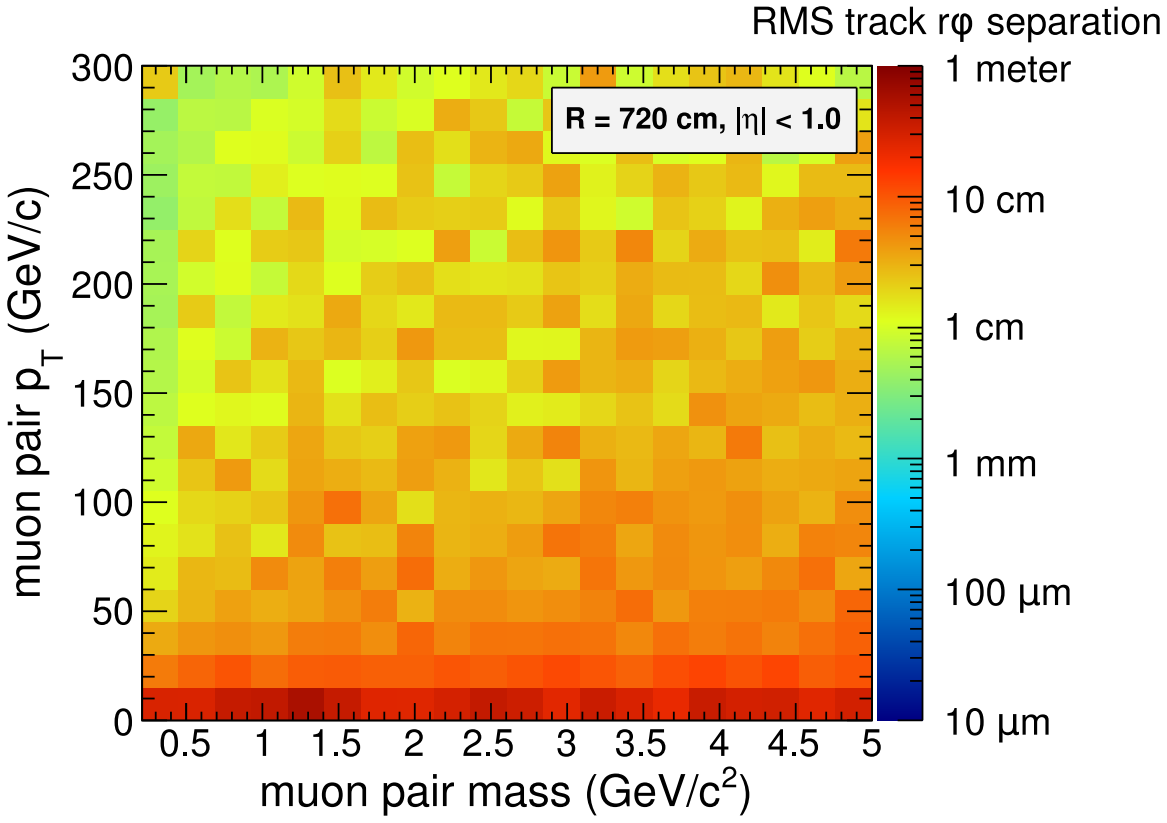
p_T, m vs. track separation



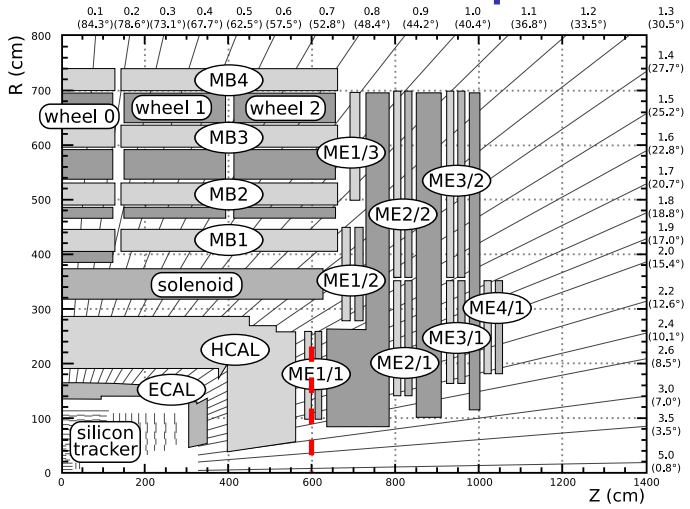


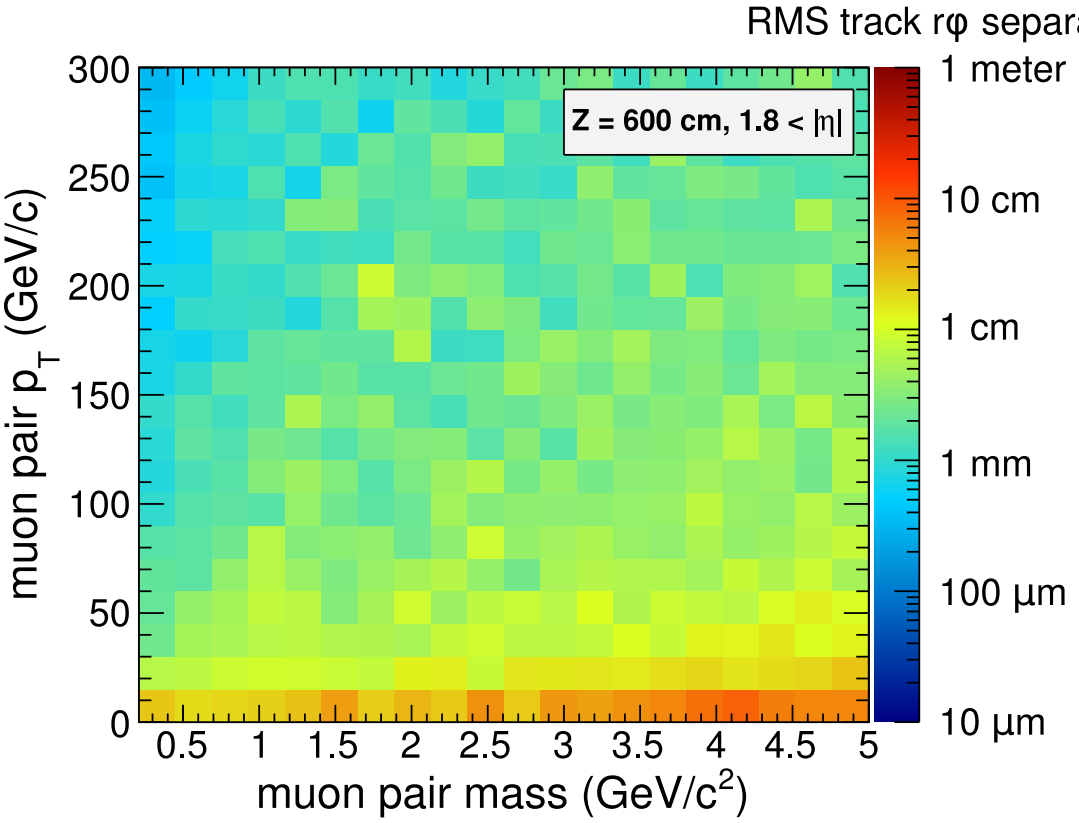
p_T, m vs. track separation



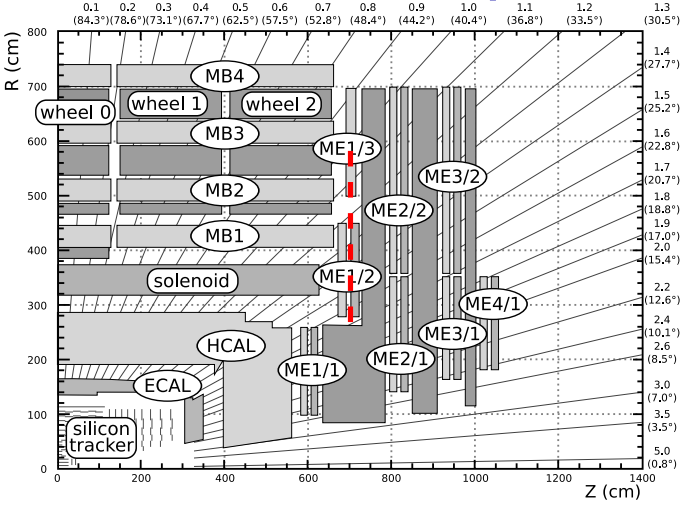


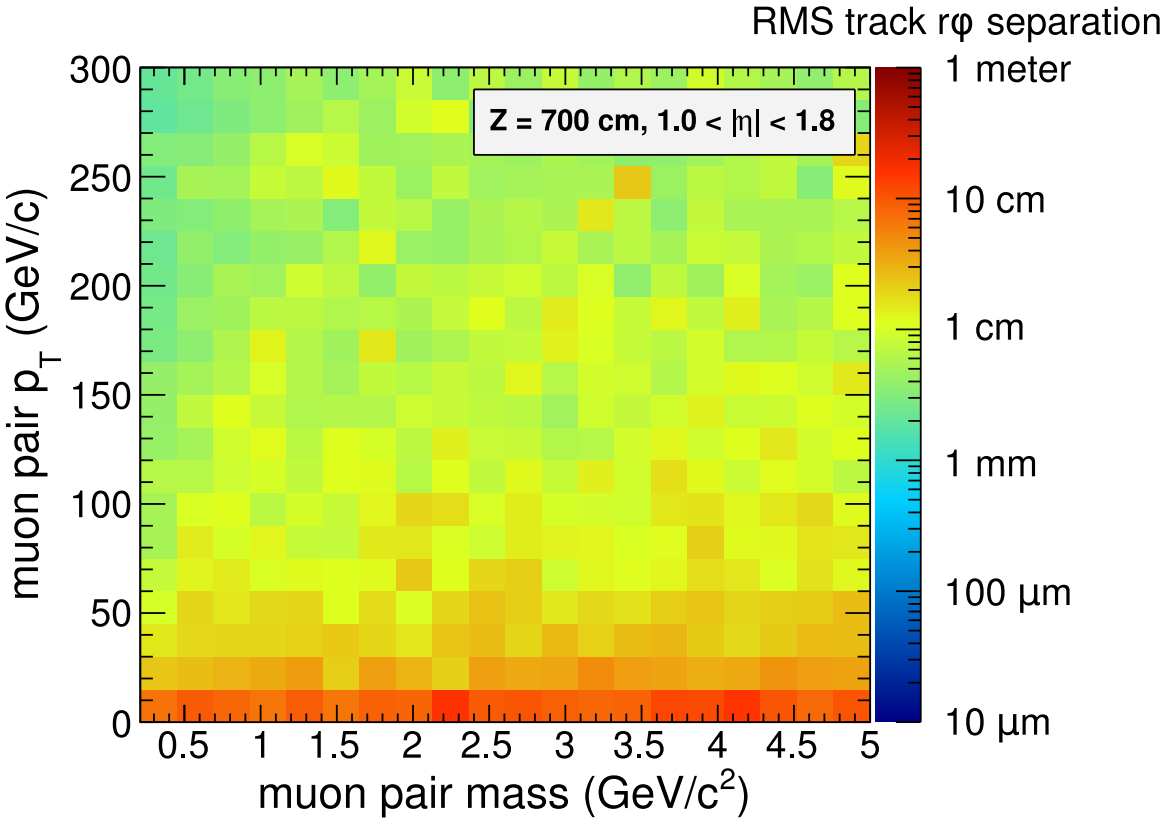
p_T, m vs. track separation





p_T, m vs. track separation





p_T, m vs. track separation