Lepton Jets Progress from the A&M group

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Stages

1. Quick, early studies: to figure out what's important — DONE
2. Infrastructure development: to organize and streamline later work — DONE
3. Thorough optimization of analysis — Begun (this talk)
4. Study of data
5. Internal and public notes

Goal of analysis

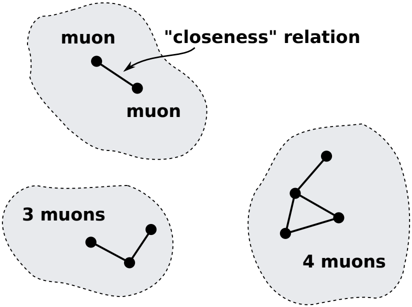
- "Lepton Jets" is a general theoretical idea, not a model that we can optimize for
- However, it predicts the phenomena of new low-mass, high-momentum resonances decaying to $\mu^+\mu^-$ (sometimes several overlapping $\ell^+\ell^-$)
- We can optimize a search for these, given CMS's detector capabilities and SM backgrounds

Method

- Develop a "μ-group" object, like any other object in CMS
- Study its performance
- Use it in searches

Infrastructure

- pat::MultiMuonCandidate
  - a group of muons that were found to be close to each other
  - can be stored in .root files, used to calculate μ-group quantities like ΔR, μ-group isolation, vertex compatibility…
- LeptonJetsEquivalenceClassProducer
  - a now-mature algorithm for grouping muons (only muons)
- MultiParticleByMassGunProducer
  - MC generator to make N di-particle pairs uniformly in mass and momentum (rather than ΔR)
- LeJOG ("Lepton Jet Object Group") SVN repository
  - https://svnweb.cern.ch/cern/wsvn/LeJOG/trunk/
  - where all the code is stored
  - problem: limited access— Aysen still doesn't have access rights
- https://twiki.cern.ch/twiki/bin/viewauth/CMS/ExoticaMuonJets
  - *thorough* documentation of the above, as well as MC samples



Muons are grouped if

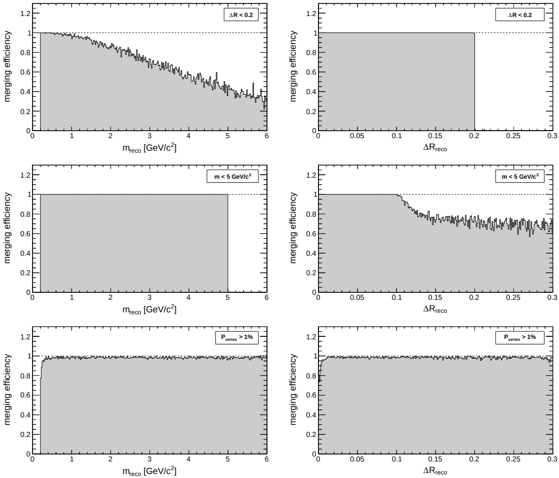
- they are "close" to each other
- they're close to another muon which is close to another, etc.

No dependence on the order of the grouping process, easy to analyze

- Definition of "closeness" is tunable, with these ingredients:
  - ΔR: geometrically close in a metric with uniform background
  - m_{inv}: guarantees that low-mass objects will be found, regardless of boost
  - P_{vertex}: requires a consistent track vertex
  - opposite charge: avoids connecting groups that can't be from the same neutral resonance

Merging muons into groups

Grouping efficiency vs. reconstructed mass and ΔR
(denominator: found two muons, numerator: grouped them)



$\Delta R < 0.2$

$m_{\text{inv}} < 5$ GeV$/c$

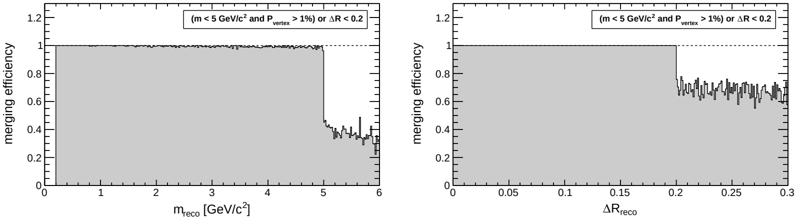
$P_{\text{vertex}} > 1\%$

(Note low efficiency due to vertexing failures for collinear muons)

Optimization: group by

$$(m_{\text{inv}} < 5\text{ GeV}/c \textbf{ and } P_{\text{vertex}} > 1\%) \textbf{ or } \Delta R < 0.1$$

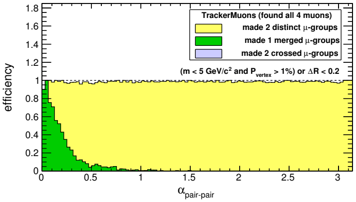
- We guarantee that we get low-mass objects
- Usually require them to vertex well
- Except when they're very close together

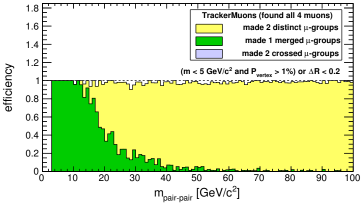


Leave the opposite-sign requirement for later

Merging muons into groups

- If we have two low-mass ($m < 5$ GeV$/c^2$) dimuons in an event, what is the probability that they will be merged into two groups or one group?
  - $\alpha_{\text{pair-pair}}$ is the 3D angle between dimuons
  - $m_{\text{pair-pair}}$ is the parent particle mass
  - "crossed" means 1-2, 3-4 gets reconstructed as 1-3, 2-4



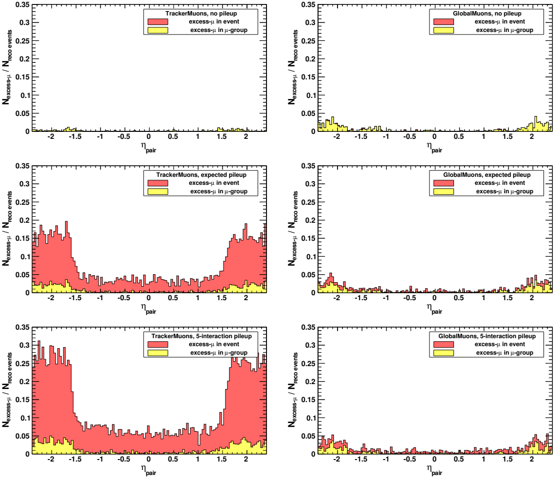


- Can be tuned with grouping criteria: loose "closeness" criteria yield higher efficiency for pairs and higher probability of pair-merging
- The plots above came from a flat-generated pair-pair gun; should try with realistic cascades because it could depend on kinematics

Extra muons in group

- μ-groups can absorb an extra muon from unrelated tracks in the event
- Below: simulations with increasing amounts of pile-up ($\frac{N_{\text{extra}}}{N_{\text{total}}}$ vs. η)

  left: TrackerMuon-groups, right: GlobalMuon-groups

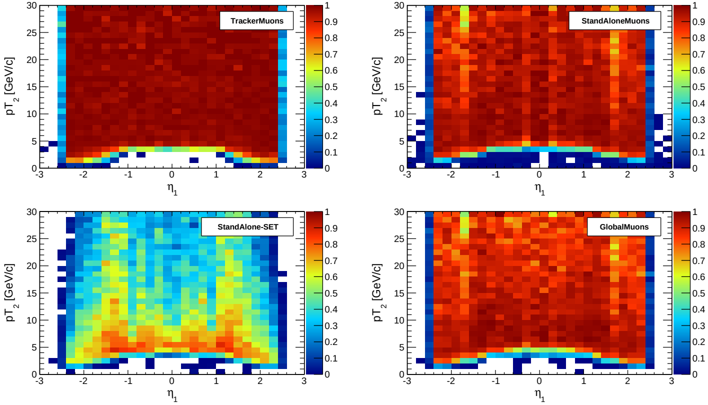


Despite extra tracks identified as muons (red), the extra-muons-in-group (yellow) is controlled by $P_{\text{vertex}} > 1\%$

We'll also soon see that fake TrackerMuons can be controlled with quality cuts

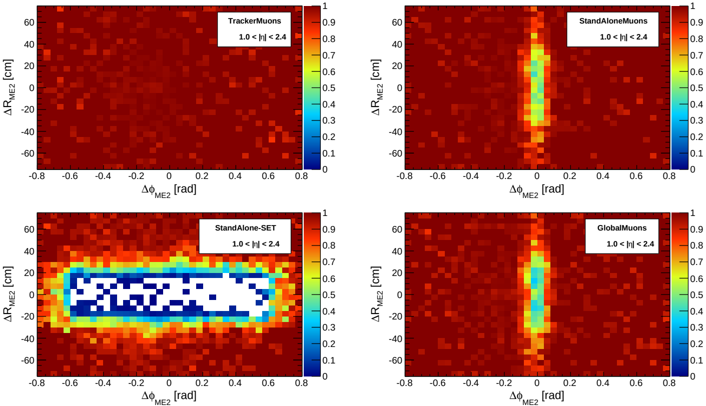
Acceptance and efficiency

- Acceptance region of a dimuon defined by $pT_2 > 5$ GeV$/c$ and $|\eta_1| < 2.4$ where pT_2 is the second-highest p_T muon and η_1 is the highest-$|\eta|$ muon in the event
- Try reconstructing muons in four different ways: TrackerMuons, StandAloneMuons, StandAlone-SET algorithm, and GlobalMuons



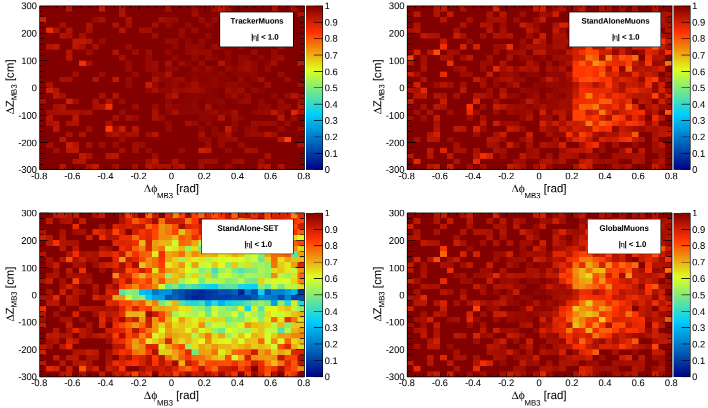
- TrackerMuons have high efficiency everywhere, but they also have (curably) high backgrounds
- StandAloneMuon efficiency depends on how close the muons approach each other in the muon system (next slide)
- GlobalMuon efficiency $\leq$ StandAloneMuon efficiency
  - probability of crossing in the muon system depends on kinematics of the decay
  - this would make it more complicated to quote limits on Lepton Jets derived from GlobalMuons
- I tried StandAlone-SET because I knew that it is an alternative to the standard StandAloneMuons
  - it doesn't seem to be designed for nearby-muon efficiency
  - we won't be using it

- StandAloneMuon inefficiencies are driven by reconstruction issues for muons that overlap in the muon system
- Test: propagate generator-level muons to planes of constant-z in the endcap and cylinders around the beamline in the barrel
- Plot efficiency as a function of trajectory intersections: $\Delta\phi_{\mathrm{ME2}}$ is $\phi_{\mu^+} - \phi_{\mu^-}$ at $z = 828.561$ cm, ΔRME2 is radial difference

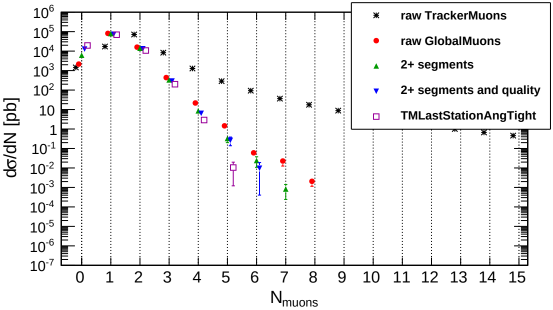


Efficiency vs. crossing

- Same thing in the barrel: $\Delta\phi_{MB3}$ and ΔZ_{MB3} on a cylinder of radius 618.269 cm
- Not completely understood: inefficiencies are off-centered from zero
- Suggests that this plot is "out of focus"— the intersection that drives inefficiency is perhaps at smaller radius than barrel?



- Before moving on, we should address backgrounds with TrackerMuons
- Number of reconstructed muons N_{muons} in the InclusiveMu5_Pt* samples (all QCD backgrounds, including decay-in-flight):



All sets of track cuts include $p_T > 5$ GeV/c

"Quality" means

$N_{\text{trkr hits}} \geq 8$

$\chi^2{}_{\text{trkr}}/N_{\text{dof}} < 5$

$\sigma_\phi < 0.03$

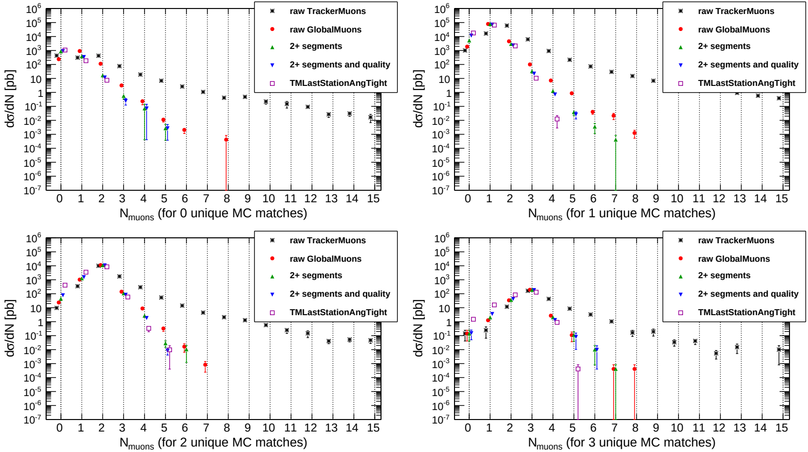
$\sigma_\eta < 0.01$

$\sigma_{d_{xy}} < 0.05$ cm

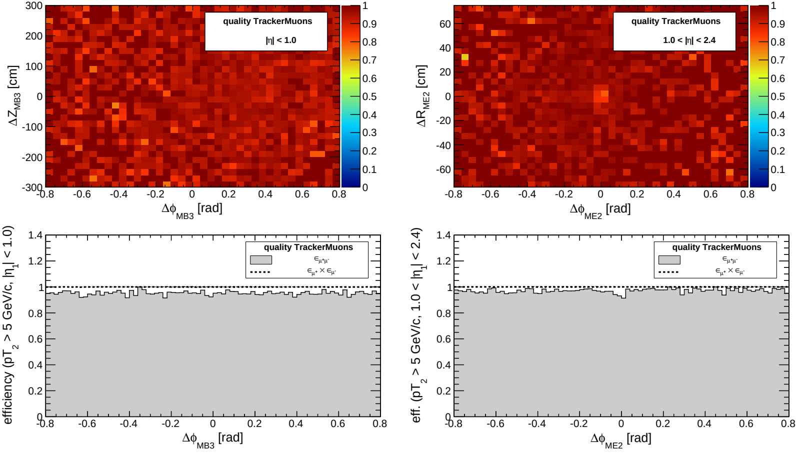
$\sigma_{d_z} < 0.1$ cm

- The *one cut* that makes TrackerMuons as pure as other reconstruction methods is $N_{\text{segments}} \geq 2$ for arbitrated segments

- Same plot, split up by the number of real muons in the event
- As you can see, TrackerMuons with $N_{\text{segments}} \geq 2$ (green triangles) are narrowly distributed around the true number of muons



- Even with quality cuts and $N_{\text{segments}} \geq 2$, TrackerMuon efficiency is $\sim$95% without a hard-to-model dip when pairs cross each other

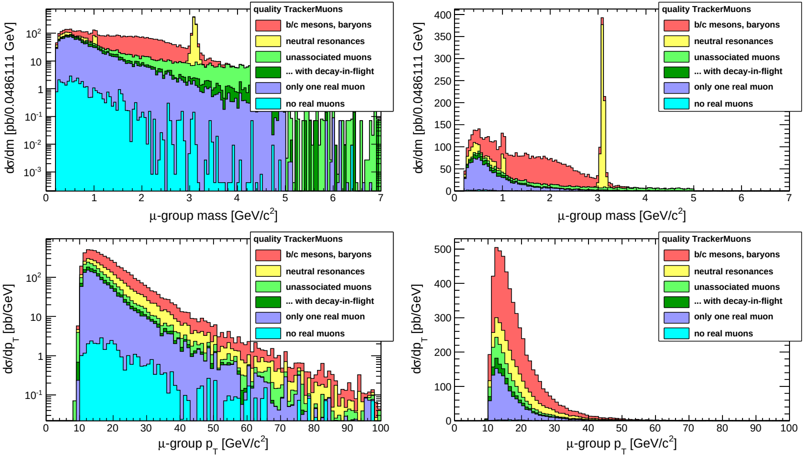


Trigger efficiency

- Significant issues in L1:
  - when multiple muons pass through the same chamber, only one may be read out
  - if an L1 muon is constructed from some μ^+ segments and some μ^- segments, they may fail to be reconstructed as a single high-p_T muon
  - this is not fully modeled in the L1 emulator! (not for the CMSSW_3_6_3 version that I'm using, anyway...)
- Significant issues in HLT:
  - uses StandAloneMuon reconstruction, with the inefficiencies I presented already
  - only need to reconstruct one StandAloneMuon at HLT, but reconstruction can be confused by overlaps
- Also, time-dependence as trigger conditions change
- I've made some basic trigger plots in MC, but the above must be addressed to meaningfully understand our trigger efficiencies

QCD backgrounds: one μ-group

- The Standard Model has two clear signals in the one μ-group channel: J/ψ and $\phi(1020)$ (yellow)
- $b \to c \to s$ with two semi-leptonic decays also correlates muons (red)



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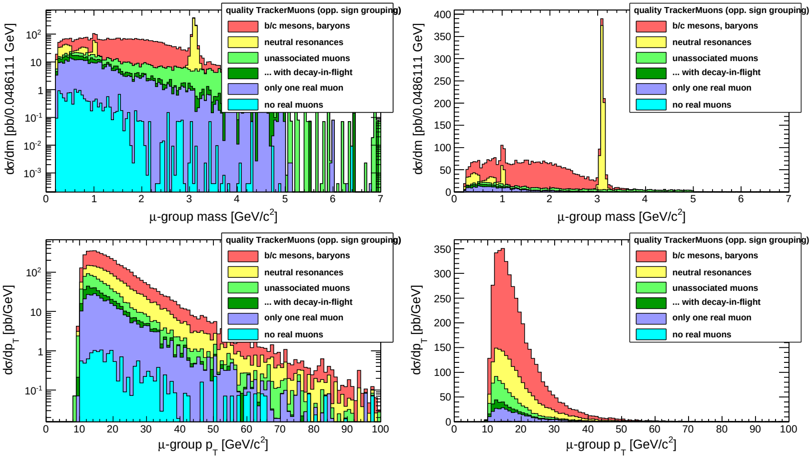
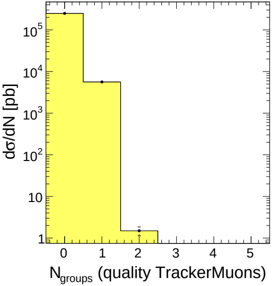
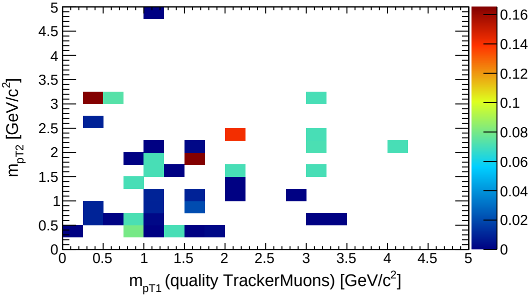
- The Standard Model has two clear signals in the one μ-group channel: J/ψ and $\phi(1020)$ (yellow)
- $b \to c \to s$ with two semi-leptonic decays also correlates muons (red)
- Only-one-muon (darker blue) suppressed with opposite-sign grouping



Multiple μ-groups

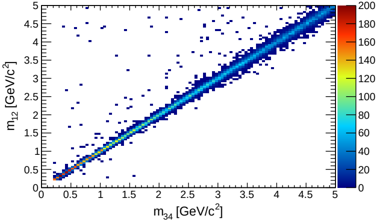
- Asking for a second μ-group reduces the QCD backgrounds to 1 pb
- Many of the models we've looked at have $\sim$pb cross-sections or at least limits can be set with 1–100 pb^{-1}
- Since we're looking for new resonances, we get more sensitivity by searching for peaks: the QCD backgrounds are roughly flat in mass



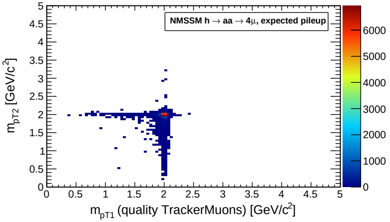


Signals: mass peaks

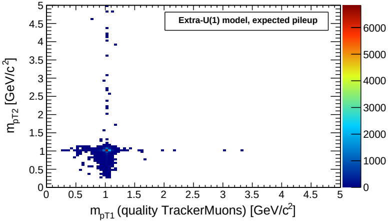
Pair-pair μ gun with both pairs having the same mass



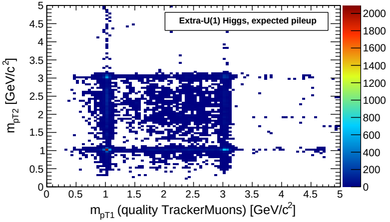
NMSSM Higgs with $h \to aa \to 4\mu$ ($m_h = 100$, $m_a = 2$ GeV$/c^2$)



Extra-$\mathcal{U}(1)$ dark matter model with $\gamma_{\text{dark}} \to \mu^+\mu^-$, $m_\gamma = 1$ GeV$/c^2$



Same with $h_{\text{dark}} \to \gamma_{\text{dark}}\gamma_{\text{dark}}$, $m_\gamma = 3$ GeV$/c^2$



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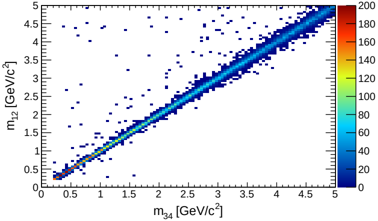

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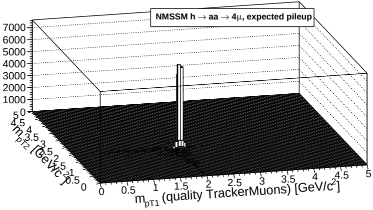

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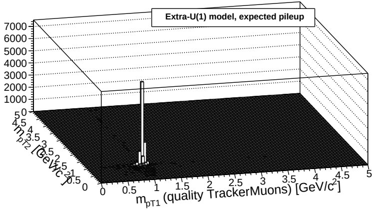

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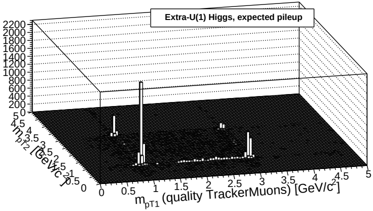
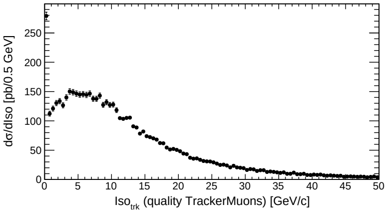
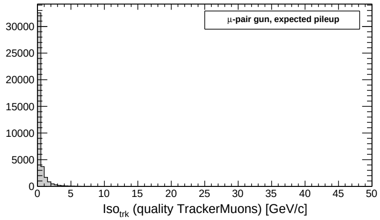


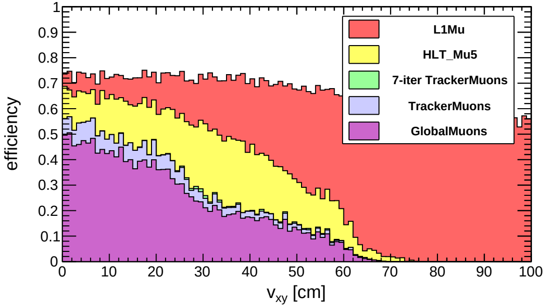
Isolation variables

- If we were to apply the standard muon isolation, neighboring muons would cancel each other out
- Redefined $\sum |p_T|$ and number-over-threshold isolation variables to exclude all muons in a muon group
- Applying this isolation can further suppress QCD backgrounds by about a factor of 10 (100 pb^{-1} analysis $\rightarrow$ 1 fb^{-1} analysis)
- QCD backgrounds (one μ-group) on left, pair-gun signal with pileup on right (example signals are similar)



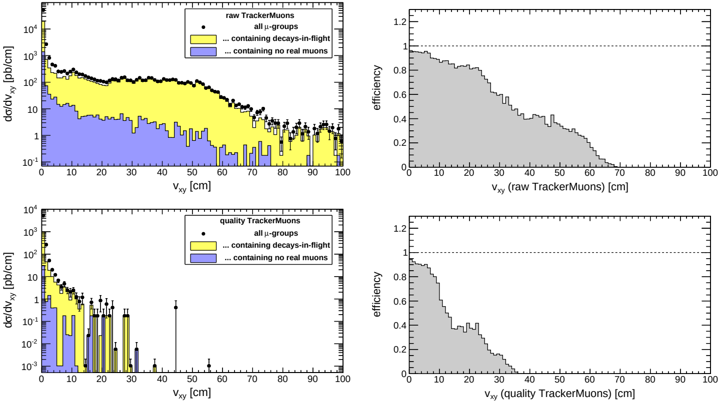


- Lepton Jets models require the new resonances to have weak couplings to Standard Model particles
  - in extreme limit, they would be displaced from the beamline (v_{xy})
- L1 trigger is sensitive to a wide range of v_{xy}, but HLT isn't because its StandAloneMuons are reconstructed with a beamline constraint
- Track reconstruction is only sensitive up to about half of the tracker
- Special 7-iteration tracking developed for γ conversions-finding (green) doesn't help much (it was worth a try)



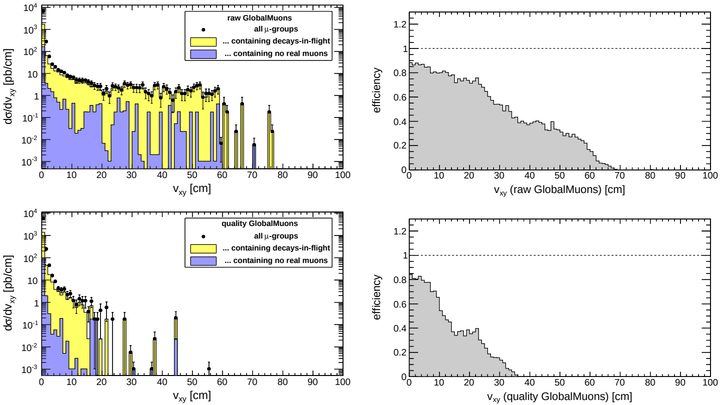
Displaced vertices

- Quality cuts seem to be cutting both signal and background: something should possibly be loosened for the displaced-vertex case
- Left: QCD background effective cross-section; right: signal efficiency
- Top: no quality cuts; bottom: with quality cuts



Displaced vertices

- Quality cuts seem to be cutting both signal and background: something should possibly be loosened for the displaced-vertex case
- Left: QCD background effective cross-section; right: signal efficiency
- Top: no quality cuts; bottom: with quality cuts
- GlobalMuons without quality cuts are sensitive at the level of 1 pb/cm



Conclusions

- Physics results
  - muon-grouping algorithm is now mature, guaranteed to find low-mass resonances, and safe against pile-up
  - StandAlone/GlobalMuon inefficiencies traced to overlapping segments in endcap, still not clear in the barrel
  - TrackerMuons are safe to use as long as we require $N_{\text{segments}} \geq 2$
  - understanding the exact trigger efficiency will be challenging
  - two μ-group QCD backgrounds are 1 pb and $\sim$flat in mass
  - displaced vertex ("case (d)") has not been fully optimized
- Perspective
  - it was important to develop μ-group objects, because now they can be used as an analysis tool
  - we've laid the groundwork for a ≥ 2 μ-group analysis ("case (b)")