# Quick Write-up on Displaced-Vertex Muon-Groups

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## 1 Intro

I'm really glad that you're interested in studying this channel— I had only been studying it because I wanted to be sure that the muon-group infrastructure I was developing would not unnecessarily reject groups of muons if they are displaced from the beamline. There are good reasons to expect hidden-valley models to produce di-muons or multi-muons with displaced vertices: the key aspect of these models is that the dark bosons are only weakly coupled to the Standard Model, which can be pushed to the extreme of making the dark bosons metastable. Figure 1 shows an example from a realistic model.

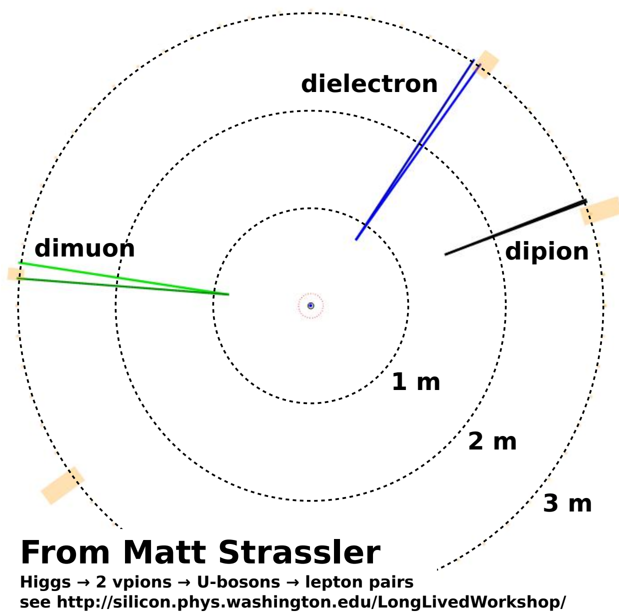


Figure 1: Event display from a hidden valley model in a PGS simulation (see Ref. [1]).

Moreover, the Standard Model provides some nice targets to show that your analysis is working. There's a (very rare) resonance peak from $K_L \to \mu^+\mu^-$ ($\mathcal{B} = 6 \times 10^{-9}$); it might be worth checking the efficiency-corrected yield of $K_S$ to see if this would ever be feasible. Even if the peak is too small, there would be a smear at lower masses from $K_L \to \mu^+\mu^-\gamma$ and $\mu^+\mu^-\gamma\gamma$ with a few orders of magnitude higher branching fraction ($\mathcal{B} = 10^{-7\text{-}8}$). If that, also, is too rare to see, well at least it won't be a background. Also, photon conversion can result in di-muons[2], so you may be able to see the pixel detector supports in the vertex distribution, just as you would in the di-electron channel (with a much higher rate).

I'm writing up what I know about this channel in the hope that it will be useful for you. Afterward, I'll focus on the prompt pairs of muon-groups: I'm just glad that this important channel won't be ignored. (When I suggested that we work on different signatures which could have qualitatively different issues, this was one of the four.)

# 2 Range of sensitivity

I checked out-of-the-box Monte Carlo efficiencies for this channel, and show them as two of the curves in Fig. 2. Since then, I learned that there are major reasons to be suspicious of the Monte Carlo trigger simulation, particularly in the endcap (there are even L1 algorithms that were not propagated into the L1Emulator until a very recent CMSSW release). Nevertheless, what we see in the figure (CMSSW_3_6_3) makes qualitative sense:

- L1 is not very sensitive to the distance of the di-muon from the beamline ($v_{xy}$);
- HLT_Mu5 is, and that's (presumably) because this HLT algorithm requires a StandAloneMuon constrained to the beamspot (a highly-displaced StandAloneMuon with such a constraint would appear to be curved like a low-momentum muon).

Thus, the trigger sets a limit on $v_{xy}$ acceptance at about 60 cm. From a technical point of view, this could easily be loosened: just add an HLT trigger without the beamspot constraint in the StandAloneMuon fit. However, adding a trigger requires a long-term commitment to study and monitor the trigger— not a small investment.

Reconstruction efficiency similarly cuts off at about 60 cm, though for a different reason. At some level in TrackerMuon and GlobalMuon reconstruction, at least 8 valid hits are required from the tracker (not strictly, but there is some cut at some level: see Fig. 4). At high $v_{xy}$, the number of tracker hits necessarily decreases as the muons range out of the tracker.

The third reconstruction option, with very slightly more efficiency than TrackerMuons, is TrackerMuons with conversions-like reconstruction [3] (an additional two track-finding passes to look for very displaced tracks). It doesn't seem to help much, and that might be because it's tuned for GSF electron tracking, or it might be because the 8-hit requirement cuts out the good tracks that it finds, or some other reason.

Searches for highly displaced vertices with StandAloneMuons suffer from the poor resolution of the StandAloneMuons: prompt muons smearing into the signal region becomes a lot more significant (I looked briefly at this, but it was so bad that I never made a finalized plot— sorry).

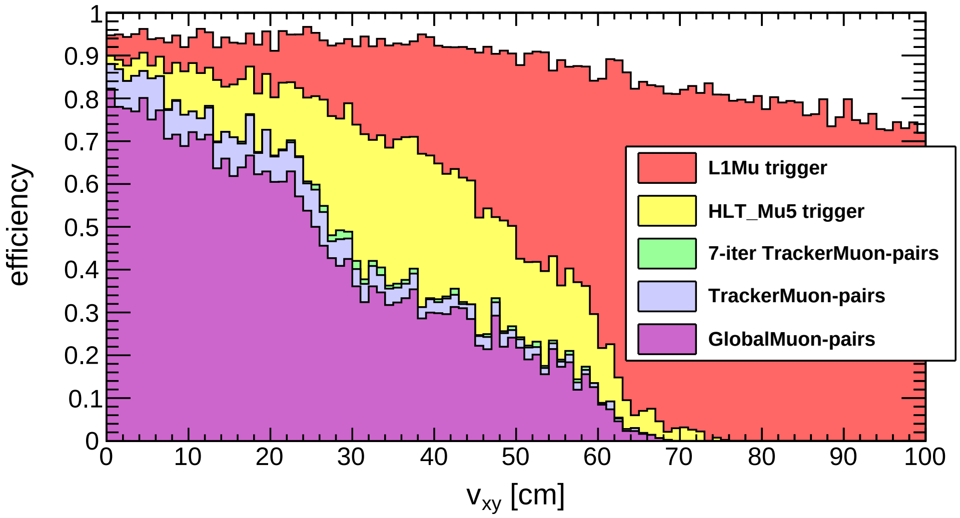


Figure 2: Efficiency of triggers and reconstruction algorithms as a function of displaced vertex $v_{xy}$, for $2m_\mu < m_{\text{inv}} < 5$ GeV/$c^2$ di-muons with $p_T > 5$ GeV/$c$ and $|\eta| < 2.4$ for each muon.

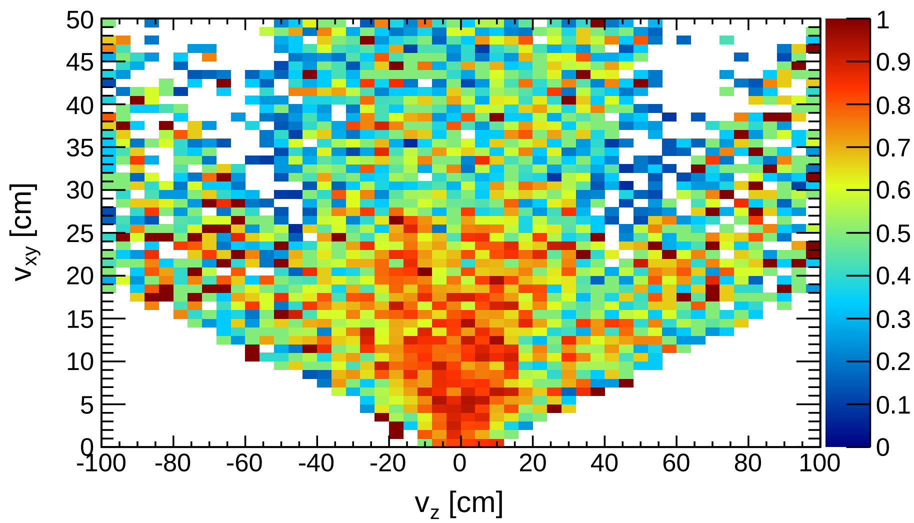


Figure 3: Reconstruction efficiency (color scale) as a function of distance from the beamline $v_{xy}$ and longitudinal distance from the collision point $v_z$, same denominator as Fig. 2. Some of the projective structure of the muon system (or tracker?) can be seen.

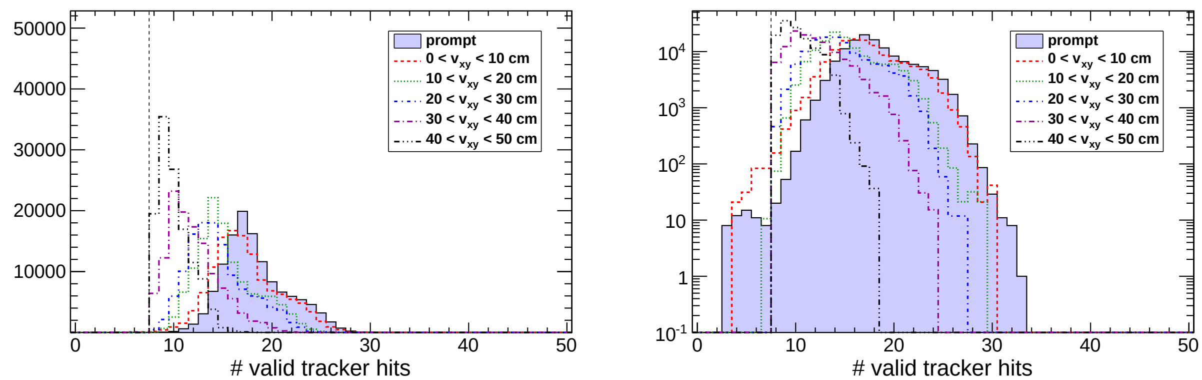


Figure 4: Distribution of valid tracker hits for prompt di-muons (filled) and displaced di-muons (open lines); each distribution is normalized to the same area; linear scale on left, log scale on right. No explicit cut was placed at analysis level, but something in TrackerMuon reconstruction requires at least 8 hits.

# 3 TrackerMuons vs. GlobalMuons

The reason we might want to be careful about GlobalMuons is that they are inefficient when they cross in the muon system, and this inefficiency can be hard to model (see my talks). The TrackerMuon alternative doesn't have this problem, and with at least two arbitrated segments, TrackerMuons are as background-free as GlobalMuons, for both the prompt and the displaced cases. This is illustrated in Fig. 5. Figure 6 shows that this cut is stable with respect to distance from the beamline.

# 4 Other cuts

The following cuts are stable with respect to distance from the beamline:

- normalized $\chi^2$ of tracker track (Fig. 7)
- uncertainty in $\phi$ parameter of tracker track (Fig. 8)

and the following are unstable:

- uncertainty in $\eta$ parameter of tracker track (Fig. 9)
- uncertainty in $d_{xy}$ parameter of tracker track (Fig. 10)
- uncertainty in $d_z$ parameter of tracker track (Fig. 11).

All of the referenced figures show these cuts placed on TrackerMuons with $N_{\text{segments}} \geq 2$; naturally, they do the same thing to GlobalMuons (furnished upon request).

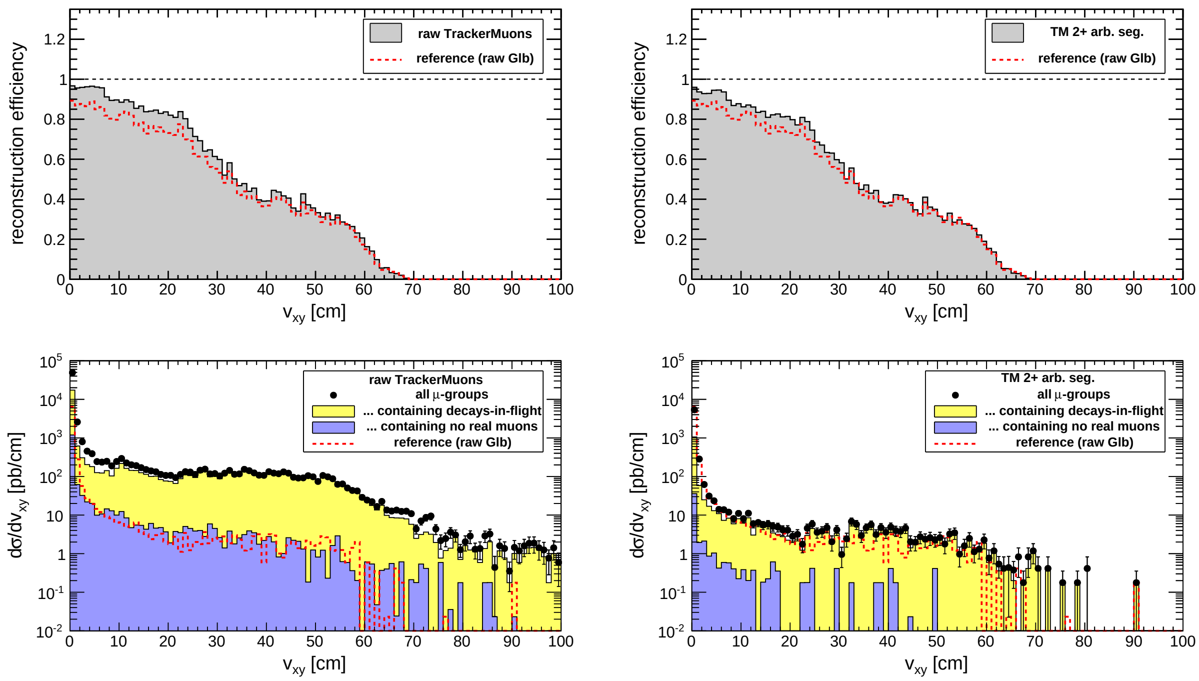


Figure 5: Top: reconstruction efficiency for $2m_\mu < m_{\rm inv} < 5$ GeV/$c^2$ di-muons with $p_T >$ 5 GeV/$c$ and $|\eta| < 2.4$ for each muon. Bottom: InclusiveMu5_Pt* backgrounds, colored by source. Left: all TrackerMuons (GlobalMuon reference in red). Right: TrackerMuons with $N_{\rm segments} \geq 2$ cut (same reference). Background events are labeled "decay-in-flight" if one of the muons' parents was a charged pion, charged kaon, or strange baryon.

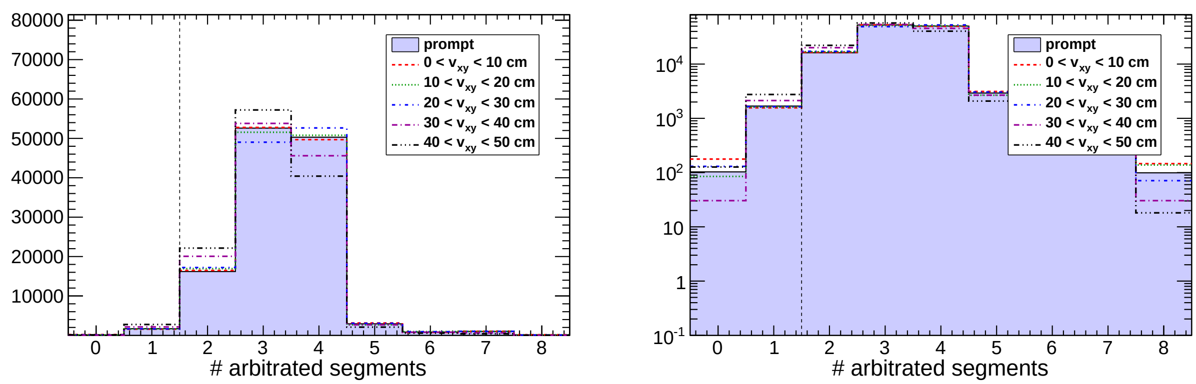


Figure 6: Number of arbitrated segments for prompt di-muons (filled) and displaced di-muons (open lines); each distribution is normalized to the same area; linear scale on left, log scale on right.

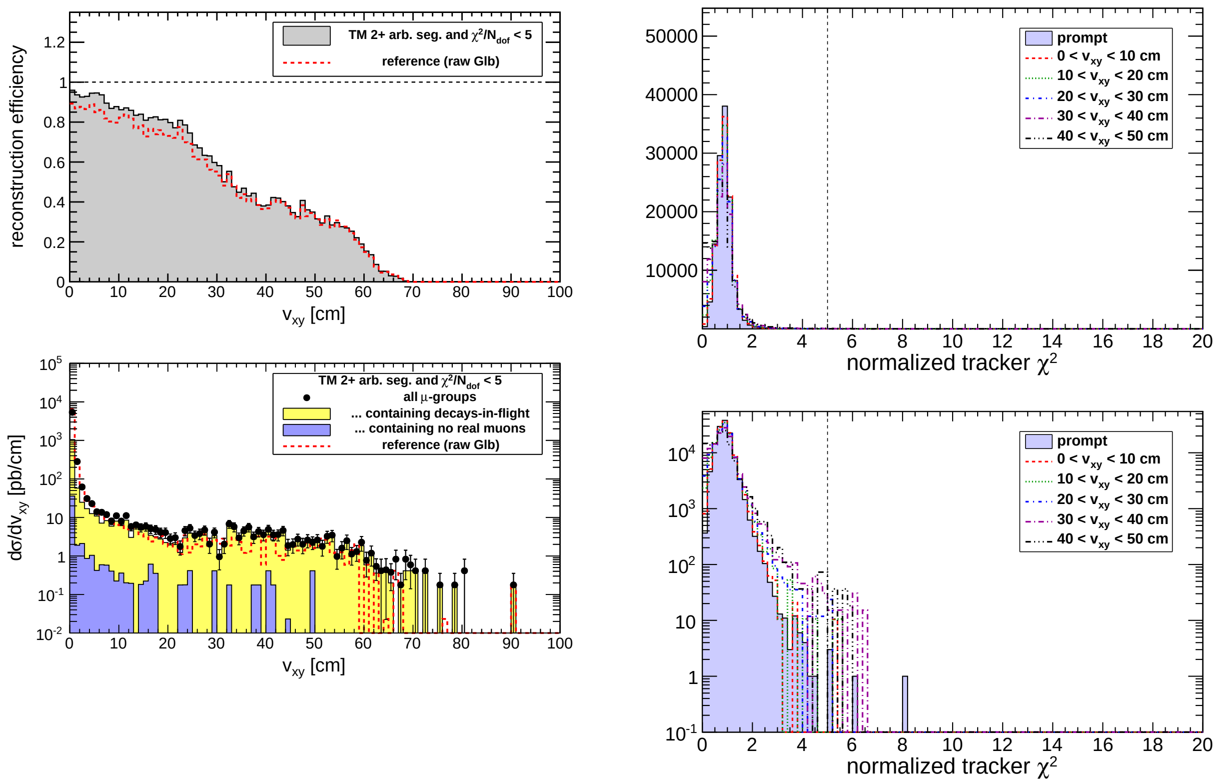


Figure 7: Performance of normalized tracker $\chi^2$ cut. Left: TrackerMuon (with $N_{\text{segments}} \geq 2$) efficiency and backgrounds vs. $v_{xy}$ with the cut; right: linear and log distributions of the cut with the threshold indicated by a vertical line.

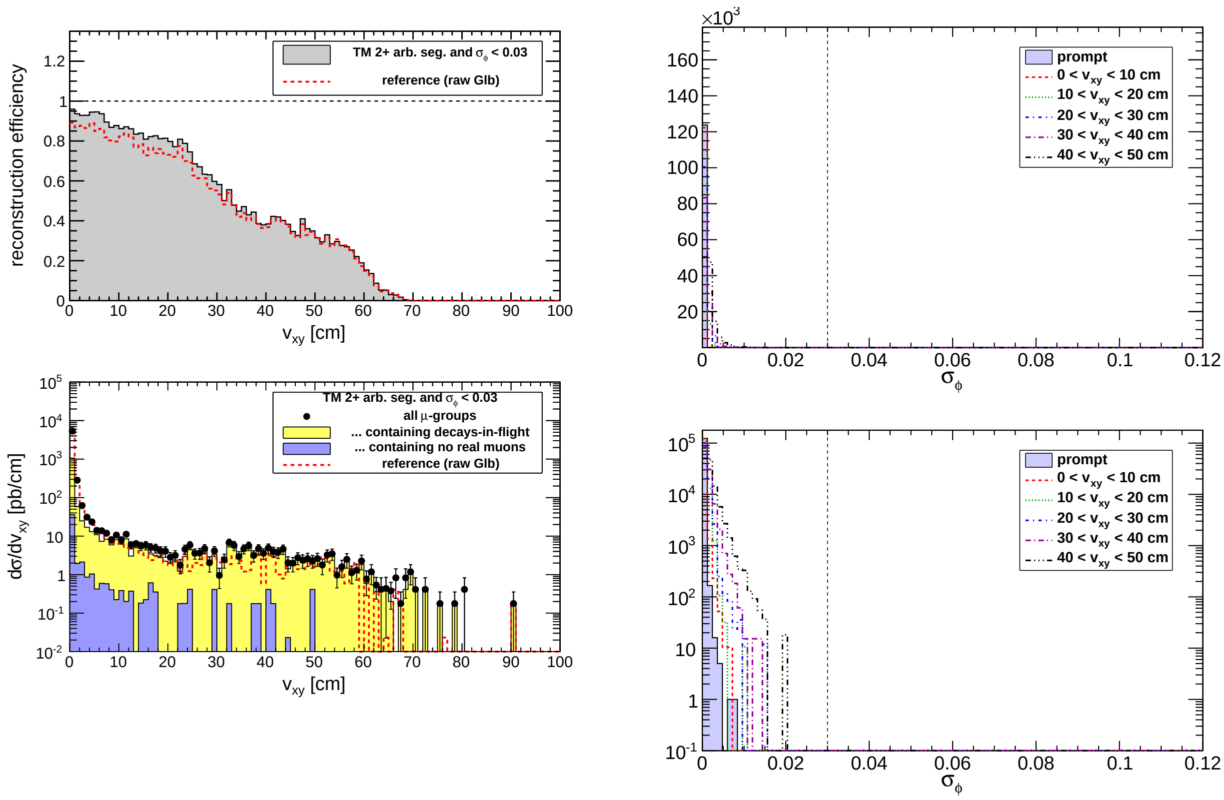


Figure 8: Performance of uncertainty in tracker $\phi$ cut. Left: TrackerMuon (with $N_{\text{segments}} \geq 2$) efficiency and backgrounds vs. $v_{xy}$ with the cut; right: linear and log distributions of the cut with the threshold indicated by a vertical line.

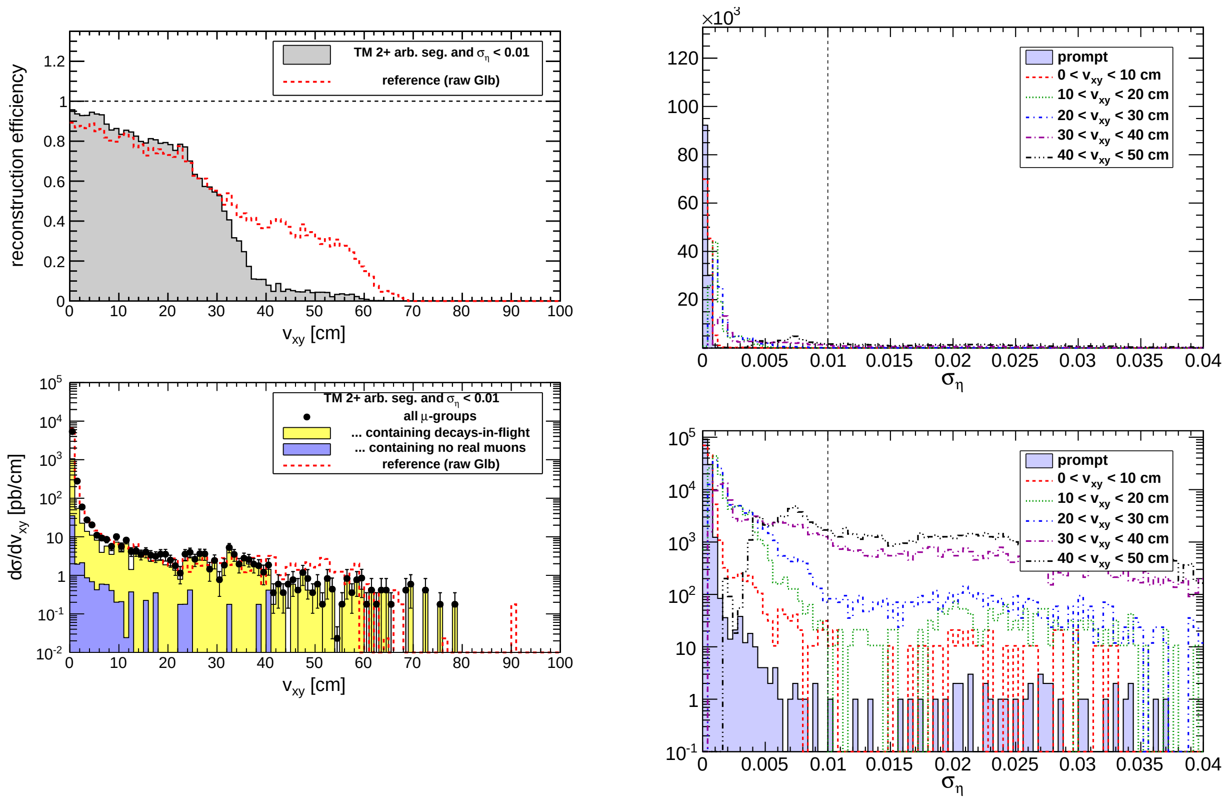


Figure 9: Performance of uncertainty in tracker $\eta$ cut. Left: TrackerMuon (with $N_{\text{segments}} \geq 2$) efficiency and backgrounds vs. $v_{xy}$ with the cut; right: linear and log distributions of the cut with the threshold indicated by a vertical line.

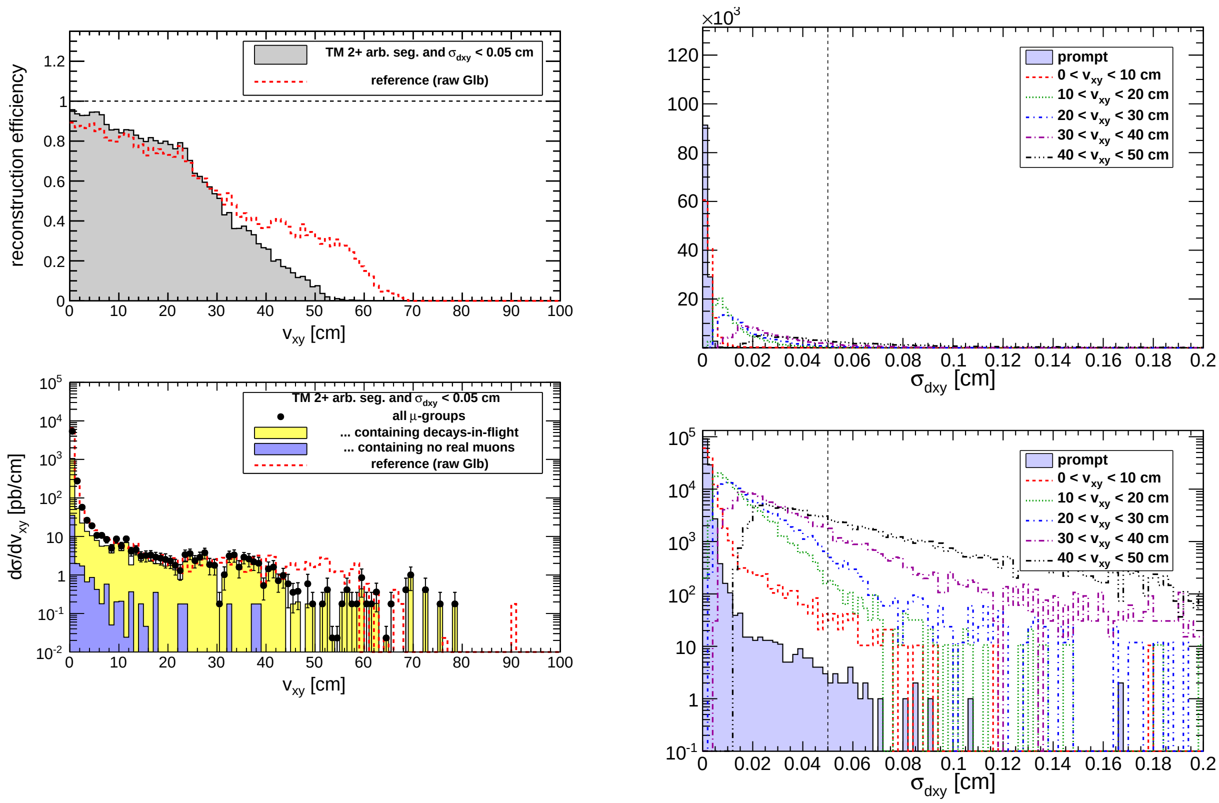


Figure 10: Performance of uncertainty in tracker $d_{xy}$ cut. Left: TrackerMuon (with $N_{\text{segments}} \geq 2$) efficiency and backgrounds vs. $v_{xy}$ with the cut; right: linear and log distributions of the cut with the threshold indicated by a vertical line.

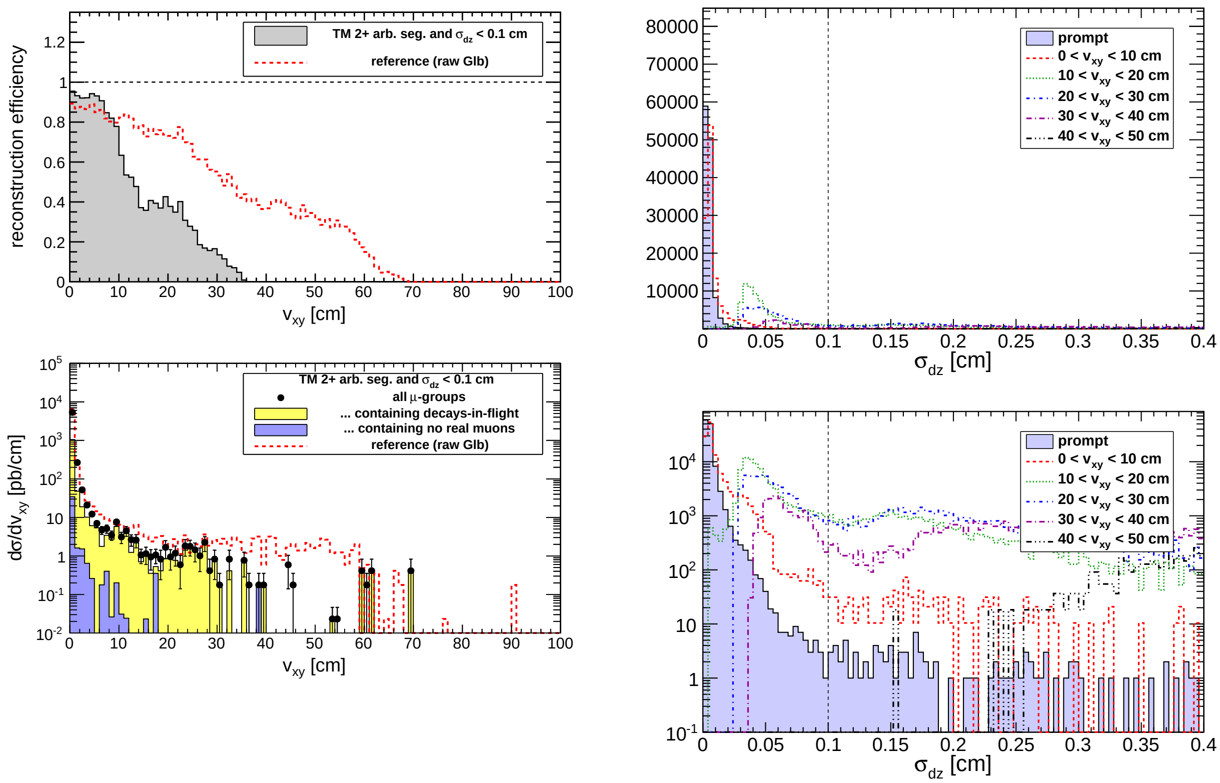


Figure 11: Performance of uncertainty in tracker $d_z$ cut. Left: TrackerMuon (with $N_{\text{segments}} \geq 2$) efficiency and backgrounds vs. $v_{xy}$ with the cut; right: linear and log distributions of the cut with the threshold indicated by a vertical line.

# 5 Advertisement

I've developed a set of tools for identifying and studying multi-muons [4] that were designed with displaced vertices in mind from the very beginning. They use the same KalmanVertexFitter as the $K_S$ and $\Lambda$-finding code (I learned about vertexing by helping the Colorado group find the $\Xi$ cascade) but have the additional advantage that multi-muons are identified as easily as di-muons (one can always cut later). If we used the same objects, it would be easier to work together on characterizing the overlap of our analyses (there's a continuum between prompt and displaced vertices). The real work is in studying the physics and the detector, which you've started; the software is just to make it more convenient to do so.

I should also point out that the SVN repository[5] has a custom particle gun MC generator (`IOMC/ParticleGuns/src/MultiParticleByMassGunProducer.cc`) that produces events uniformly distributed in mass, $p_T$, and most importantly (for you) $v_{xy}$. This makes it easier to do object-level efficiency and resolution studies.

# 6 Conclusions?

Not really. Good luck!

# References


[1] `http://www.physics.rutgers.edu/~strassler/hv/hv.htm`

[2] `http://geant4.cern.ch/G4UsersDocuments/UsersGuides/PhysicsReferenceManual/html/node28.html`

[3] `https://twiki.cern.ch/twiki//bin/view/CMS/TRK10003DedicatedTracking`

[4] `https://twiki.cern.ch/twiki/bin/view/CMS/ExoticaMuonJets`

[5] `https://svnweb.cern.ch/cern/wsvn/LeJOG/trunk/`