A Search for Beyond the Standard Model Light Bosons Decaying into Muon Pairs
$2a \rightarrow 4\mu$

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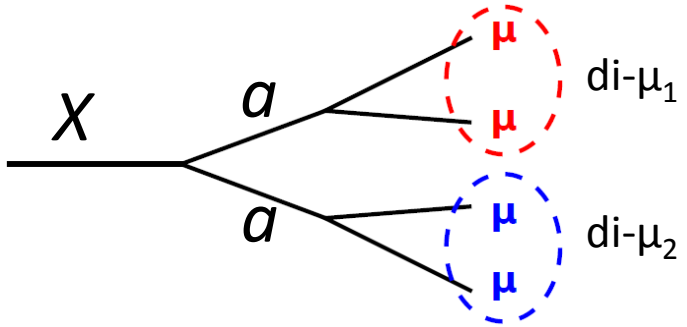
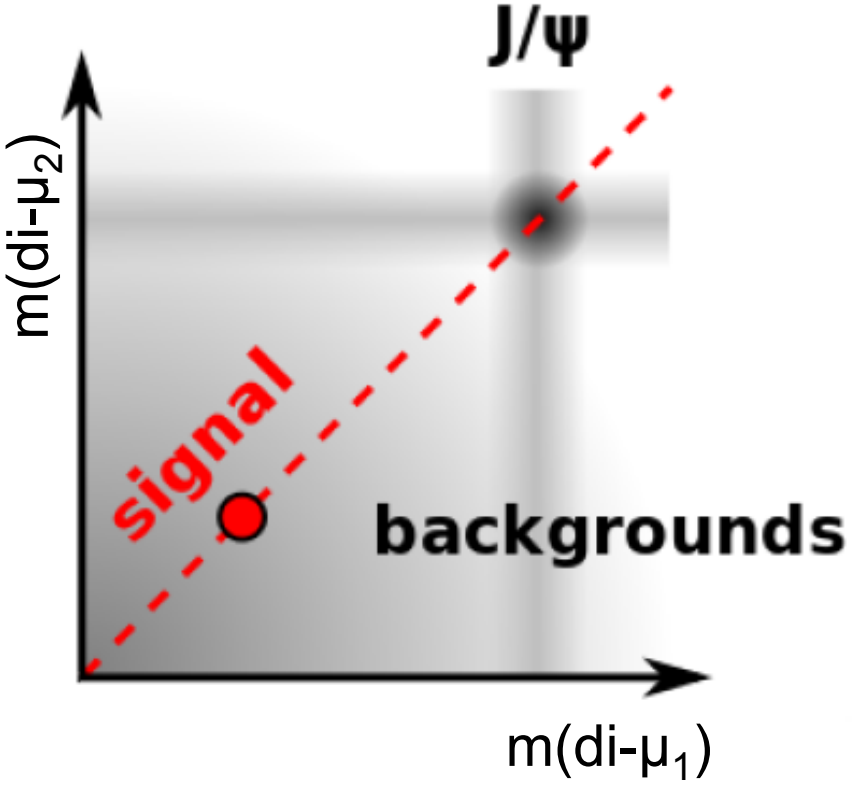
A Brief Introduction and Motivation

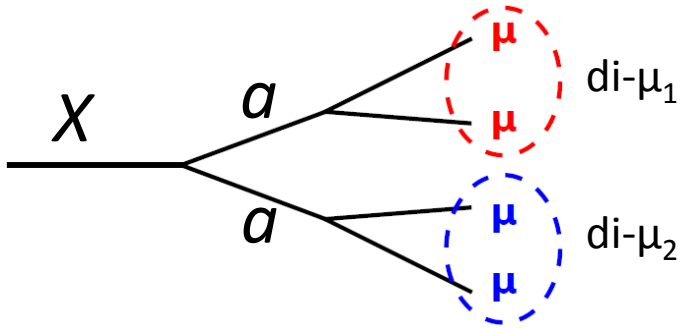
Analysis signature

- Production of 2 new light bosons (a)
  - a decays to pairs of muons (dimuons)
    - Oppositely charged
    - Boosted
    - Isolated from all remaining event activity
  - a may have a non-negligible lifetime
- Model independent signature
  - $2a \rightarrow 4\mu$
  - Results may be interpreted in context of many theories



Analysis signature – mass compatibility

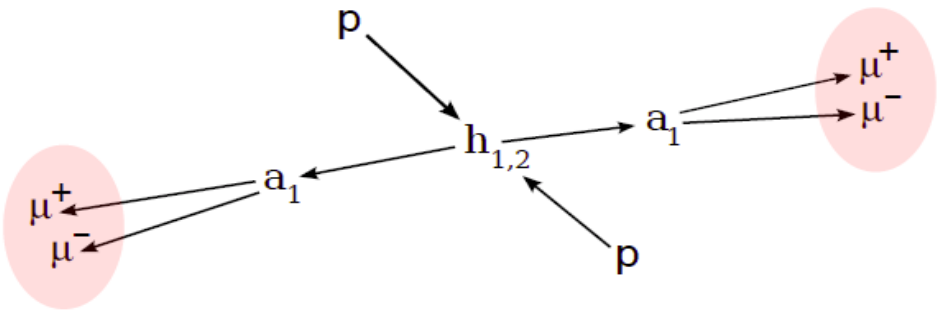


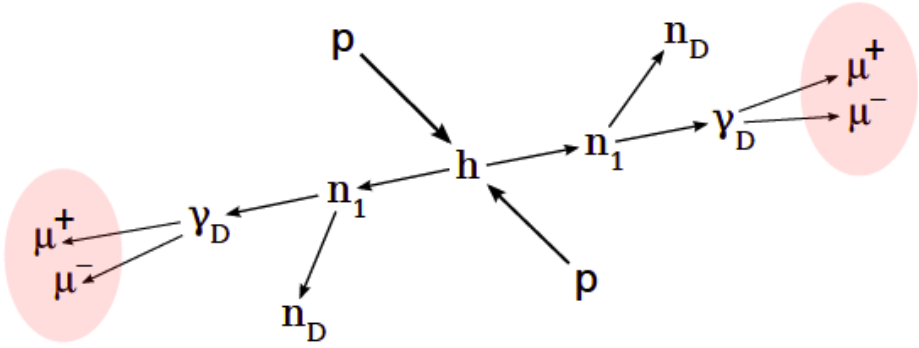


- Both dimuons decay products of same light boson
  - Invariant masses are required to be compatible

Benchmark models

- NMSSM
  - Predicts CP-even Higgs ($h_{1,2}$)
    - Could be the 125 GeV Higgs
  - Predicts lighter CP-odd Higgs (a_1)
    - a_1 decays to dimuons
- Dark SUSY (γ_D)
  - 125 GeV Higgs
  - Decays to lightest SUSY particle n_1 (neutralino)
  - n_1 decays to γ_D and a light 'dark' neutralino (n_D)





Analysis Strategy

Dark SUSY MC generation

- Parameters

m_h	125 GeV
m_{n1}	10 GeV
m_{nD}	1 GeV
$m_{\gamma D}$	0.25 – 8.5 GeV
cτ of γ_D	0 – 20 mm

- 85 total samples
  - 9 mass points
  - 9 or 11 lifetimes/mass
- 80 – 465k events/sample
  - More events for higher cτ samples
- ~25 TB total

New multimuon trigger

- HLT_TrkMu15_DoubleTrkMu5NoFiltersNoVtx_v1
  - 3 TrkMu with $p_T > 5$ GeV, $|\eta| < 2.5$
  - 1 TrkMu with $p_T > 15$ GeV, $|\eta| < 2.5$
- Backup trigger implemented with higher p_T cuts
  - HLT_TrkMu17_DoubleTrkMu8NoFiltersNoVtx_v1
- Overall trigger efficiency high (> 95%)
- Rate estimation
  - HLT_TrkMu15_DoubleTrkMu5NoFiltersNoVtx_v1
    - 1.01 ± 0.04 Hz @ 7×10^{33} $cm^{-2}s^{-1}$
  - HLT_TrkMu17_DoubleTrkMu8NoFiltersNoVtx_v1
    - 0.86 ± 0.04 Hz @ 7×10^{33} $cm^{-2}s^{-1}$

Event selection

*Currently, same as previous analysis and is subject to change

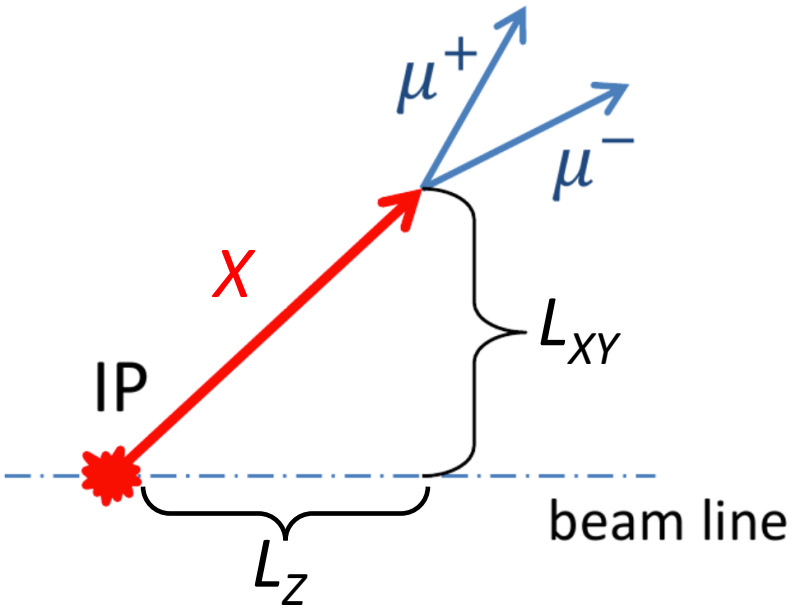
- ≥ 4 PF loose muons
  - 1 muon with $|\eta| < 0.9$ and $p_T > 17$ GeV
  - 3 muons with $|\eta| < 2.4$ and $p_T > 8$ GeV
- Construction of muon pairs
  - Common vertex OR $\Delta R(\mu^+\mu^-) < 0.01$
  - $m(\mu^+\mu^-) < 9$ GeV
- Construction of muon jets
  - Muon pairs with common muons clustered into muon jets
- Construction of dimuons
  - Muon jets with 2 muons are dimuons
- Event must have 2 dimuons

Labeling of dimuons

- Dimuon 1
  - 1 muon with
    - p_T > 17 GeV in the barrel (|η|<0.9)
  - Other muon with
    - p_T > 8 GeV with |η|< 2.4
- Dimuon 2
  - Both muons with
    - p_T > 8 GeV with |η|<2.4
- If both dimuons have p_T > 17 GeV muon in the barrel
  - Label assigned randomly

Displaced vertices

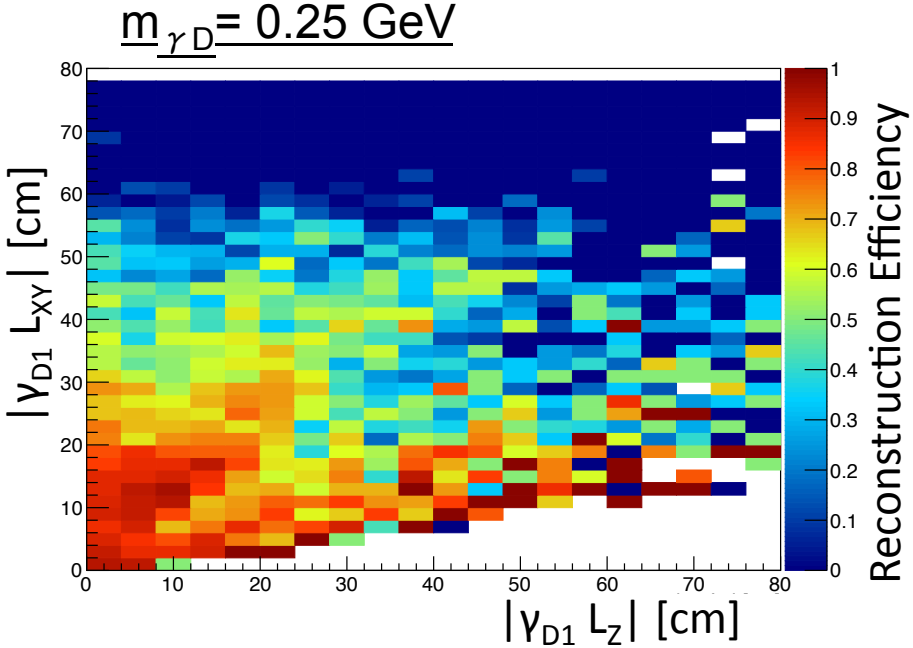
- Vertex can be hard to find
  - May be displaced
  - Dimuons are highly boosted
    - Common for low m_X
  - Muons
    - Spatially close
    - Nearly parallel
- L_{XY} is transverse decay length
- L_Z is projection of decay length on to beam line

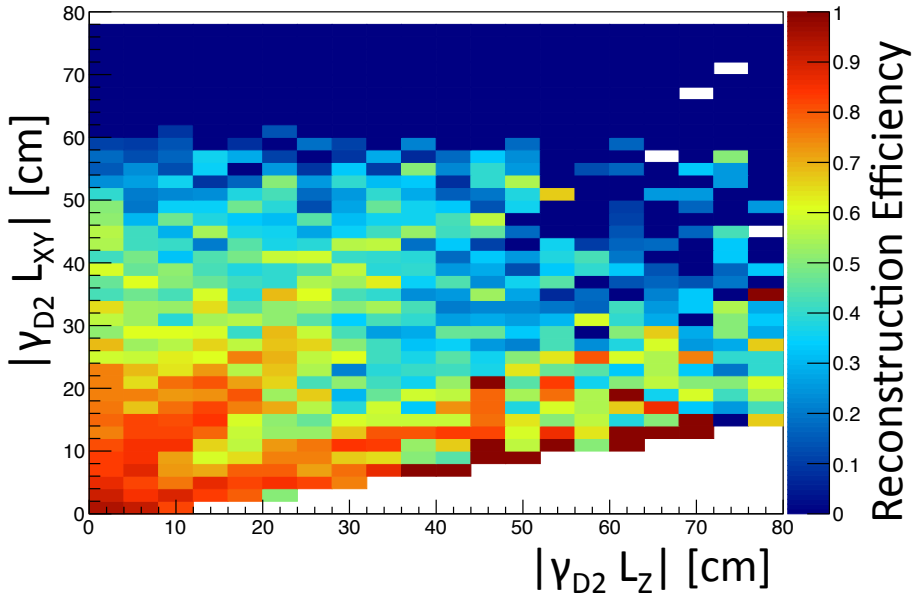


Vertex finding (in progress)

- Attempt Kalman fitter to find dimuon vertex
- If Kalman fitter fails
  - Use point of closest approach as vertex
    - Scan muon tracks within volume
    - Accept if distance of closest approach is < 0.05 cm
  - Similar to method in AN-13/250 (previous analysis)
- New vertex finding algorithm not yet incorporated in plots to be shown

Want flat dimuon efficiency (in progress)





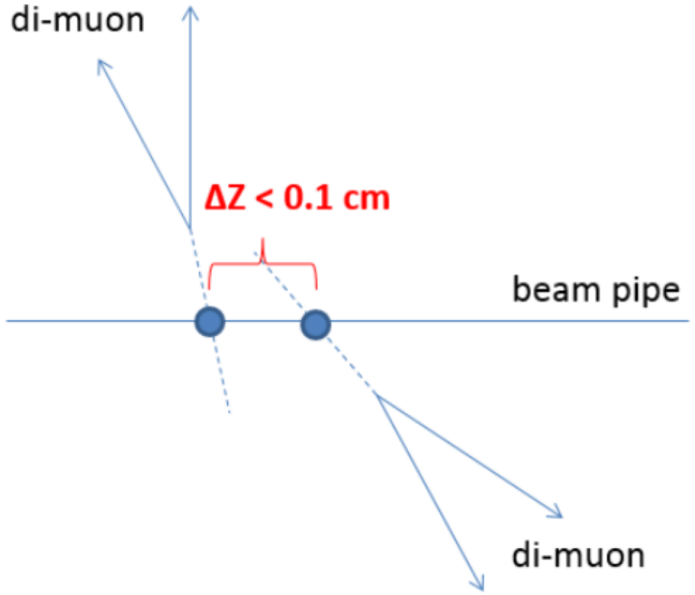
- Will define a fiducial region such that efficiency is flat

Offline selection – fiducial cut

- Fiducial search region is $L_{xy} < 4.4$ cm and $L_z < 34.5$ cm
  - This corresponds to the first pixel layer in barrel and endcap
  - In RECO require each dimuon to have a hit in the first layer of the pixel detector
  - Same cut was used in previous analysis
- Currently attempting to expand fiducial region
  - Potentially as far out as the third layer $L_{xy} < 10.2$ cm

Offline selection

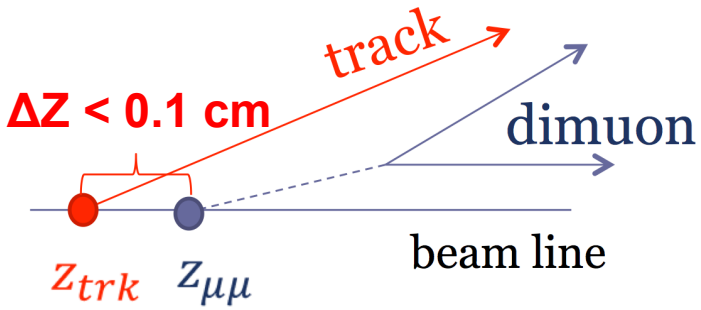
- Dimuons must have same primary vertex
  - $|\Delta z| = |z_{\mu\mu 1} - z_{\mu\mu 2}| < 0.1$ cm



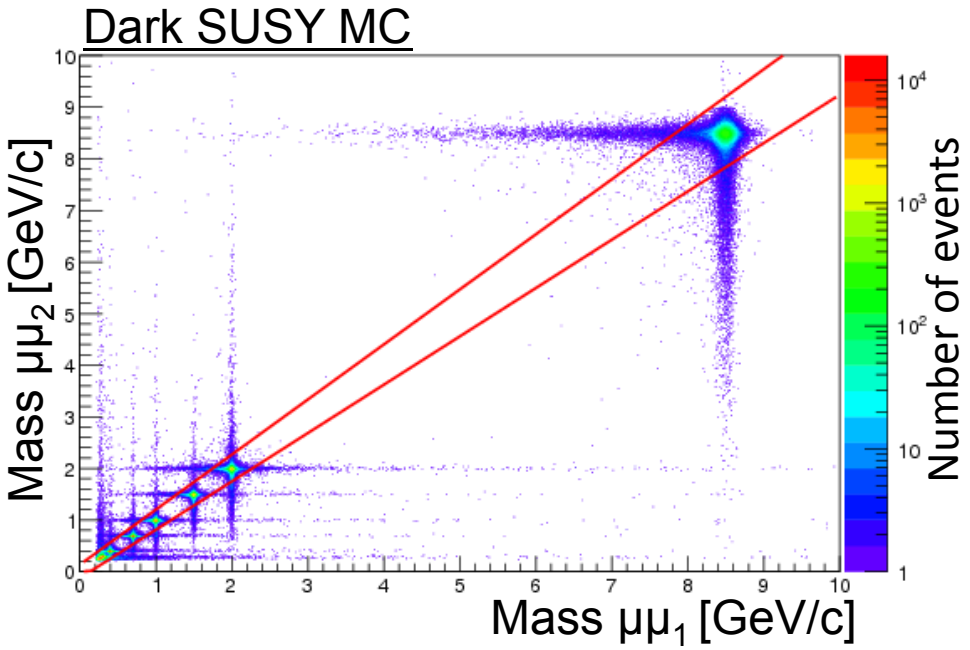
- Isolation requirement

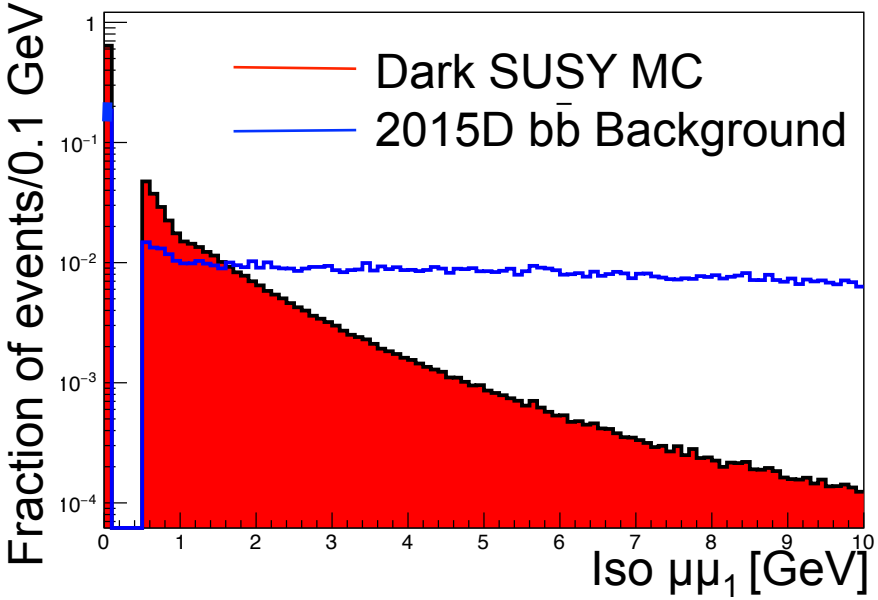
$$Iso_{\mu\mu} = \sum_{tracks} p_T(track) \;<\; 2 \;\; GeV$$

  - Sums over all reconstructed tracks
    - p_T(tracks) > 0.5 GeV
    - ΔR(track, μμ) < 0.4
    - $|z_{track} - z_{\mu\mu}| < 0.1$ cm
    - Tracks forming dimuon are excluded



Offline selection continued





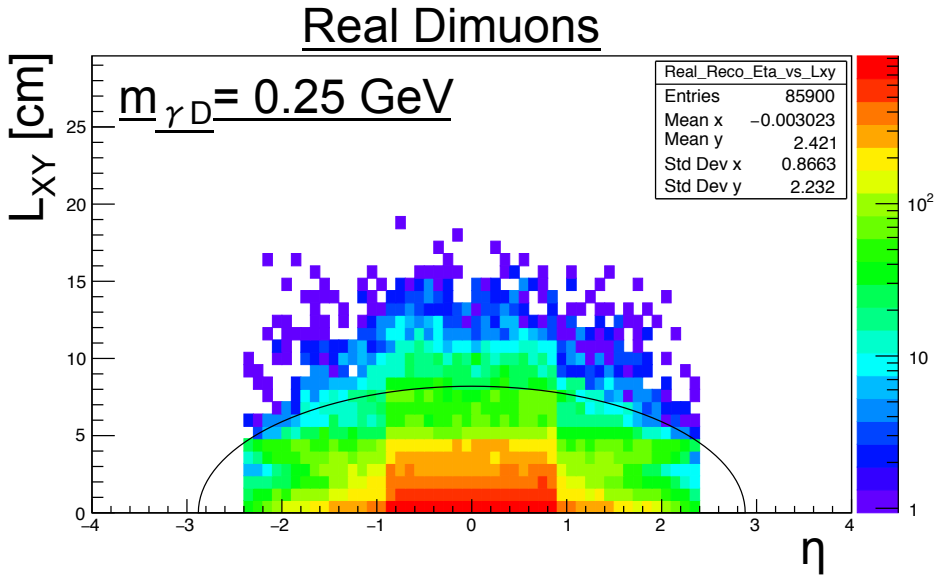
- Reconstructed dimuon masses must be compatible within detector resolution

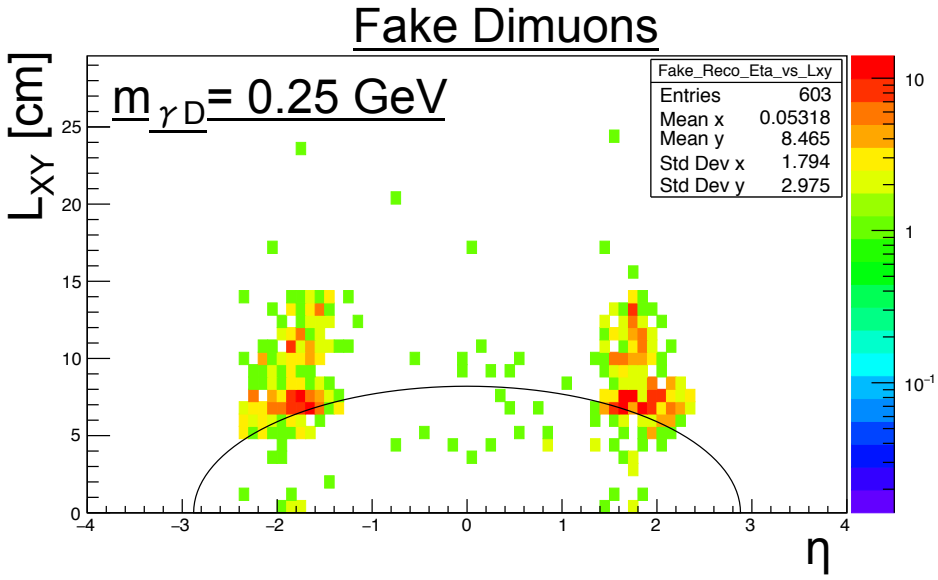
$$|\mu\mu_{mass,1} - \mu\mu_{mass,2}| < (0.13 + 0.065(\mu\mu_{mass,1} + \mu\mu_{mass,1})/2.0)$$

Mitigation of fake dimuons

- Closely spaced high η tracks
  - Small mismeasurement in η substantially moves vertex position
  - Imprecise L_{XY} measurement
- Fake dimuons pass offline selection but fail GEN fiducial cut
- Find model independent signal shape to remove fakes

Mitigation of fake dimuons



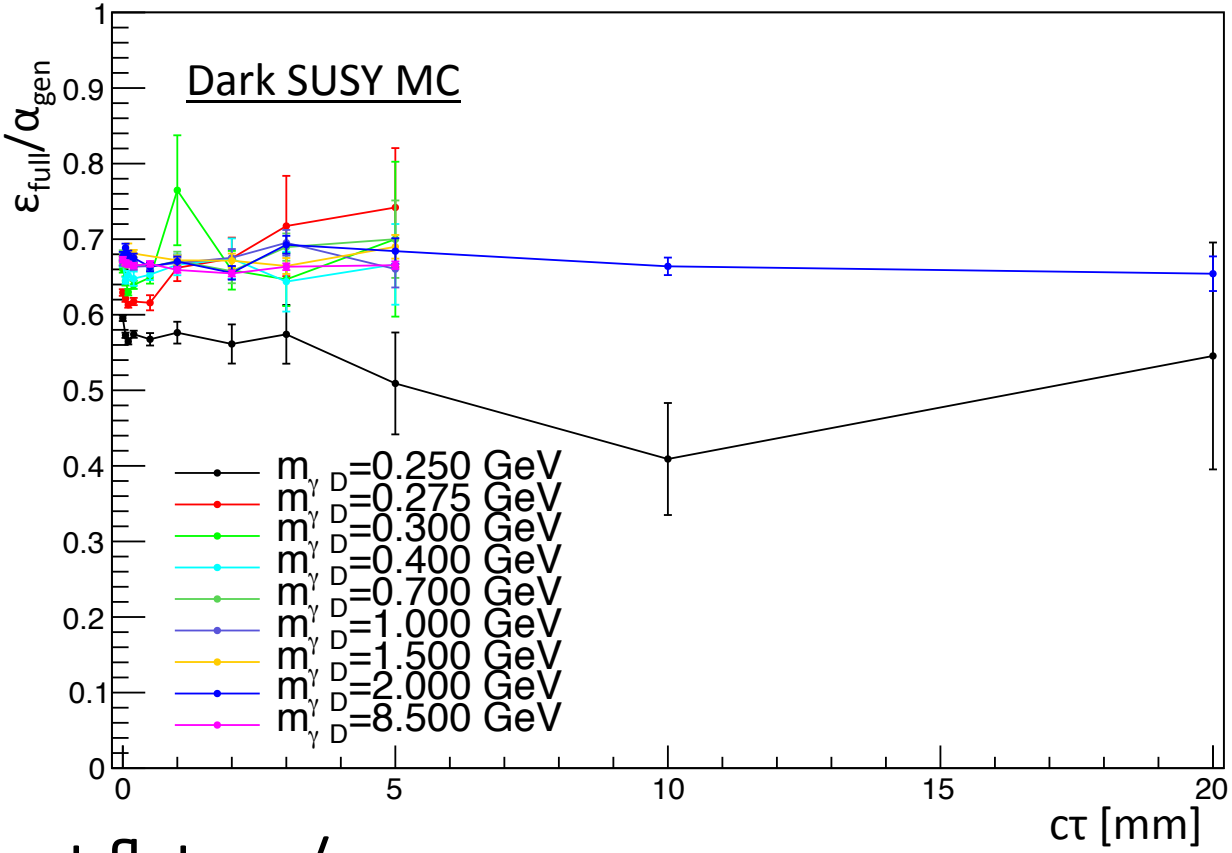


- Elliptical η-L_{XY} cut is discriminant for real and fake dimuons
  - $\frac{\eta_{\mathrm{dim}}^2}{2.88^2} + \frac{Lxy_{\mathrm{dim}}^2}{8.20^2} \leq 1$

ε_{full} and α_{gen}

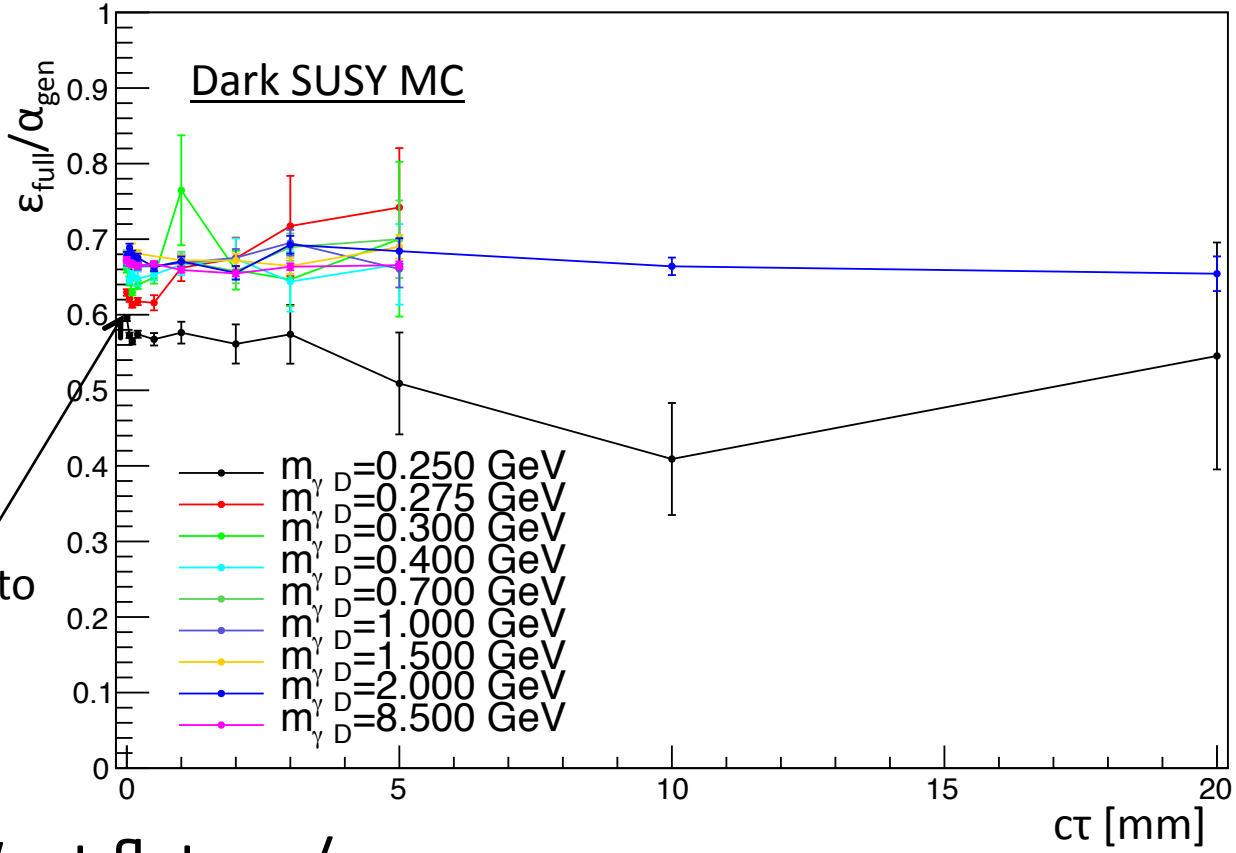
- Gen level acceptance (α_{gen})
  - 1 GEN mu pT > 17 ($|\eta| < 0.9$)
  - 4 GEN mu pT > 8 ($|\eta| < 2.4$)
  - GEN level fiducial cut
- Full analysis acceptance at RECO level (ε_{full})
  - 1 RECO mu pT > 17 ($|\eta| < 0.9$)
  - 4 RECO mu pT > 8 ($|\eta| < 2.4$)
  - Model of signal shape (elliptical cut)
  - Offline and event selection

$\varepsilon_{full}/\alpha_{gen}$



- Want flat $\varepsilon_{full}/\alpha_{gen}$
  - Independent of cτ and $m_{\gamma D}$
  - Results easily interpreted in other models

$\varepsilon_{full}/\alpha_{gen}$

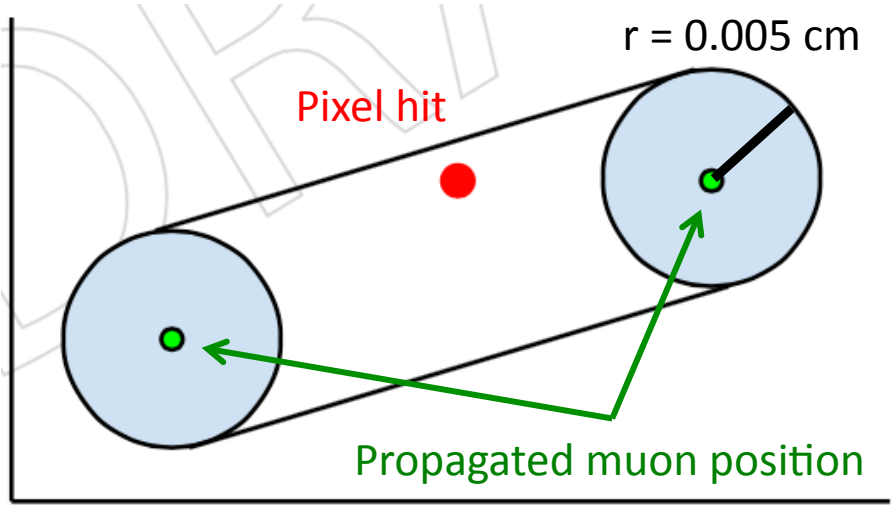


Downwards slope for low mass and low cτ dark photons due to events failing pixel hit requirement

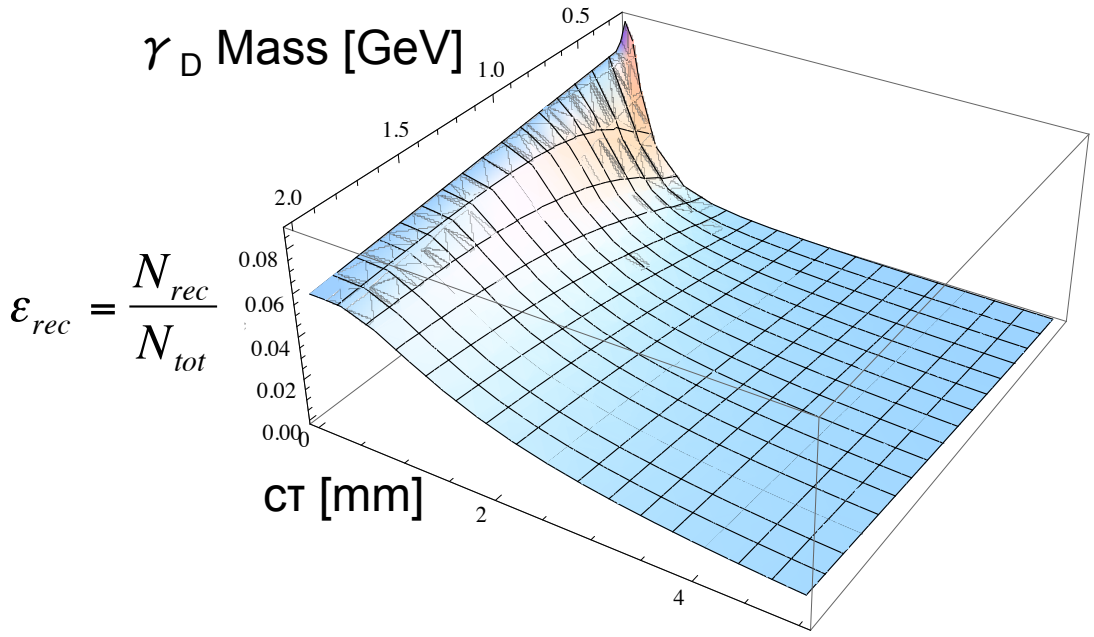
- Want flat $\varepsilon_{full}/\alpha_{gen}$
  - Independent of cτ and $m_{\gamma D}$
  - Results easily interpreted in other models

Pixel hit recovery (in progress)

- Two pixel hits can be identified as one
  - Dimuon tracks are parallel
  - Spatially close
- Extrapolate muon tracks to pixels
- Reexamine for pixel hits
- If pixel hit is found event passes pixel hit requirement
- Fixes downward slope in $\varepsilon_{full}/\alpha_{gen}$ plot



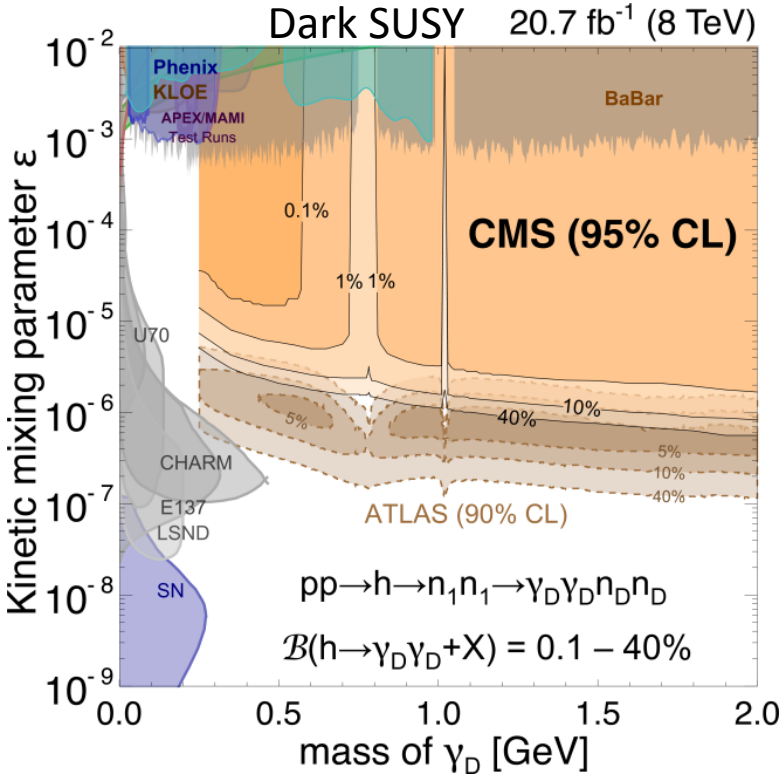
Model of the event acceptance as a function of $m_{\gamma D}$ and $c\tau_{\gamma D}$

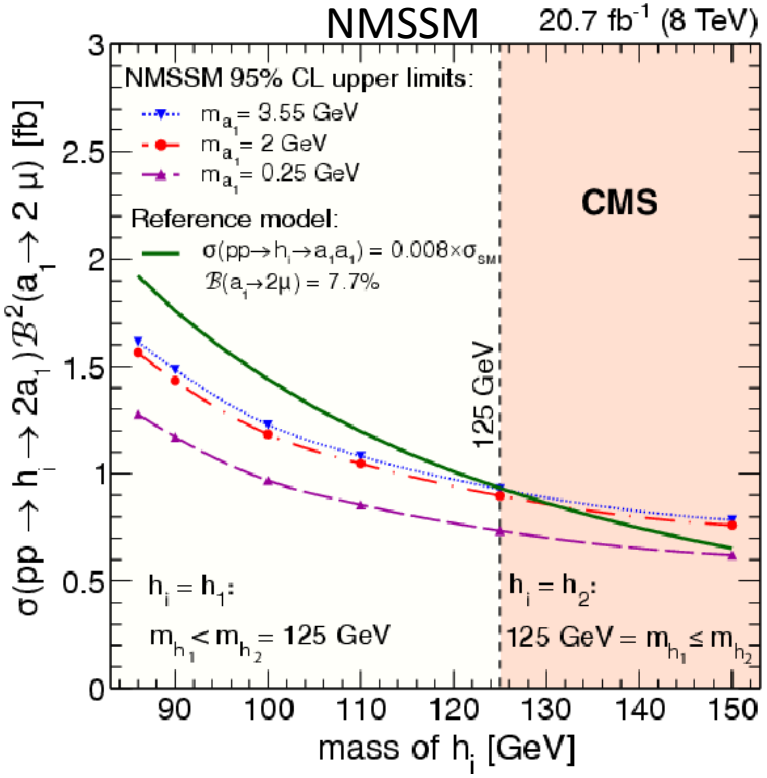


- Smooth efficiency curves must be found and input into limit machinery
- An analytic function is derived using MC
  - Assume exponential decay of dark photon
  - Assume the efficiency is a function of $m_{\gamma D}$ and $c\tau_{\gamma D}$

Limits from this analysis (in progress)

Run 1 results:





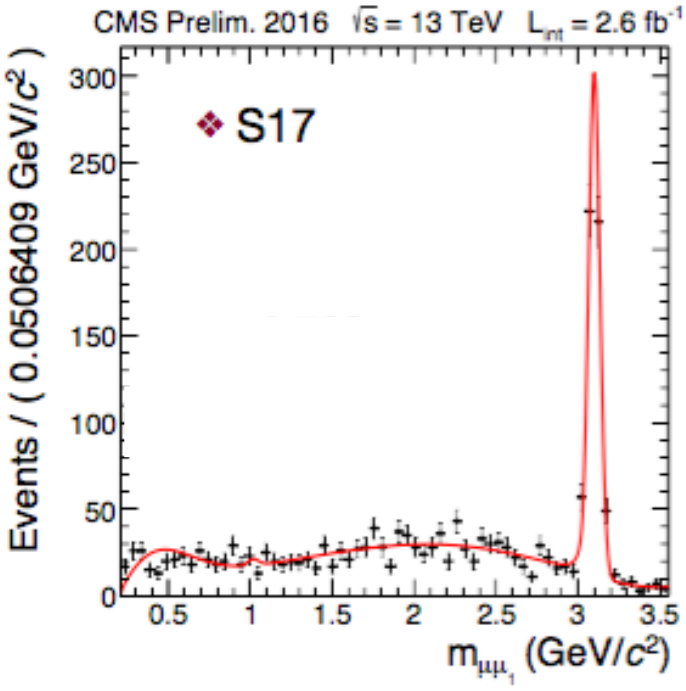
- Dark SUSY: Large previously unconstrained area of parameter space limited
- NMSSM: Models dependent on branching fractions and cross sections (h_1, h_2)
  - Provide useful results for theorists

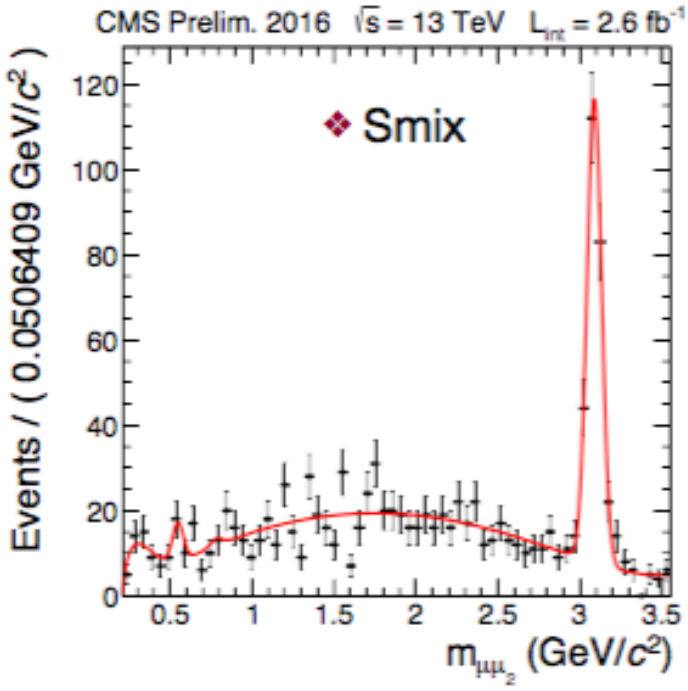
Background Estimation

Data driven $b\bar{b}$ background estimation (in progress)

- QCD $pp \rightarrow b\bar{b} \rightarrow 4\mu$
  - *b*-quarks decay to muon pairs via semileptonic decays or resonances
  - 2015D data
    - Events that fired the HLT
      - 1 dimuon
      - 1 unpaired (orphan) muon
    - Iso($\mu^+\mu^-$) < 30 GeV
- Separation into 2 samples
  - S17
    - p_T > 17 GeV muon in the barrel is part of the dimuon
  - Smix
    - p_T > 17 GeV muon in the barrel is the orphan muon

Data driven $b\bar{b}$ background estimation (in progress)

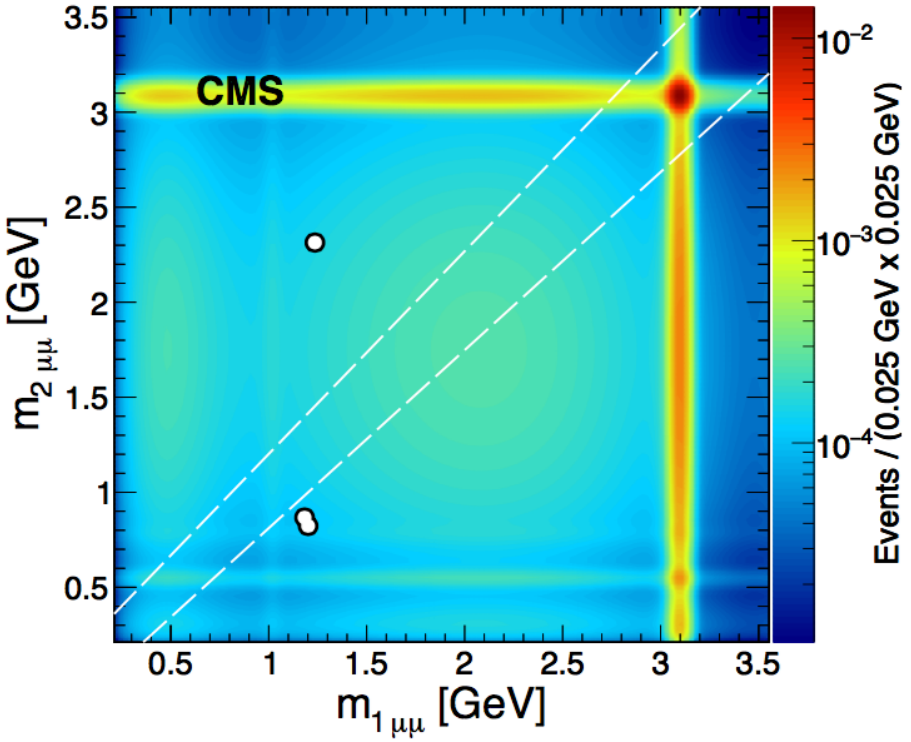




- Template fit performed
  - Resonances ρ, ω, η, and φ fitted with Gaussian
  - J/ψ fitted with crystal ball

Data driven $b\bar{b}$ background estimation (in progress)

- Cartesian product taken between S17 and Smix fit results
- White circles are background events from 2015D data
  - Signal region blinded
- Estimated 2.0 ± 0.7 events in signal region in previous 8 TeV analysis with 20.7 fb^{-1} of data

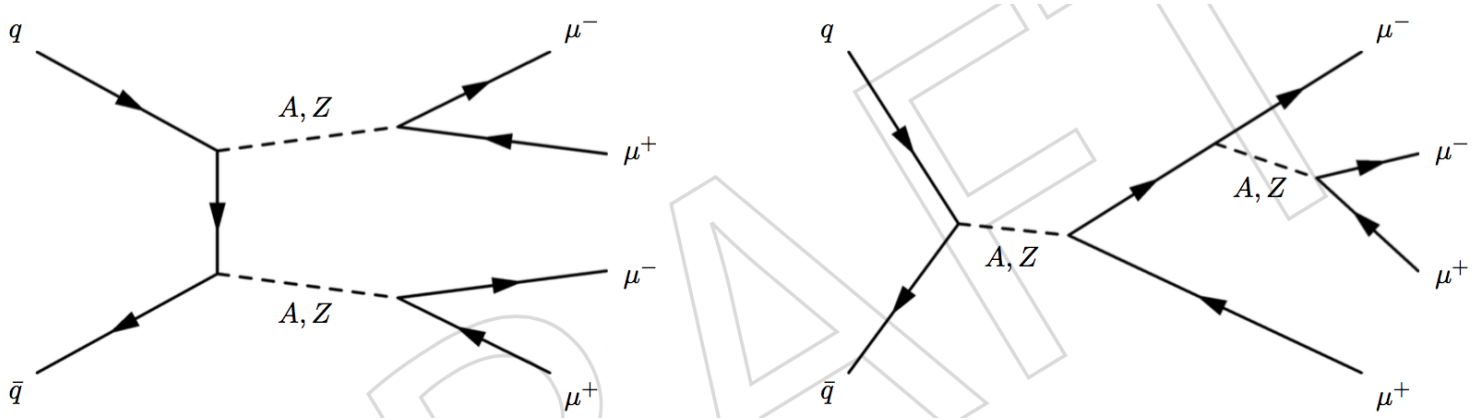


Data driven prompt double J/ψ background estimation (in progress)

- QCD Prompt $pp \rightarrow 2J/\psi \rightarrow 4\mu$
  - Non-prompt included in the $b\bar{b}$ background estimation
- 2 production mechanisms
  - Single parton scattering (SPS)
    - 2 *J/ψ's* produced from a single parton scattering
  - Double parton scattering (DPS)
    - 2 *J/ψ's* produced from independent parton scattering
- SPS and DPS MC samples (~30 TB) are used to
  - Separate SPS and DPS contributions in data
  - Separate prompt and non-prompt J/ψ production in data
- Estimated 0.058 ± 0.032 events in signal region in previous 8 TeV analysis with 20.7 fb^{-1} of data

Electroweak to 4μ background estimation (in progress)

- EWK $pp \rightarrow 4\mu$
  - Use MC
  - Estimated 0.15 ± 0.03 events in signal region in previous 8 TeV analysis with 20.7 fb^{-1} of data
- All other SM backgrounds negligible



Plans and Current Work

Plans and current work

- Extend fiducial search region to, potentially, as far out as the third pixel layer ($L_{XY} < 10.2$ cm)
- Include additional topologies including other leptons
  - *2μ2e, 4e*
- Create and analyze NMSSM MC
- Complete background estimations
- Complete vertex reconstruction
- Complete pixel hit recovery

Summary

- Performing model independent search for new light bosons
- Analysis is well advanced
- Should have results in coming months

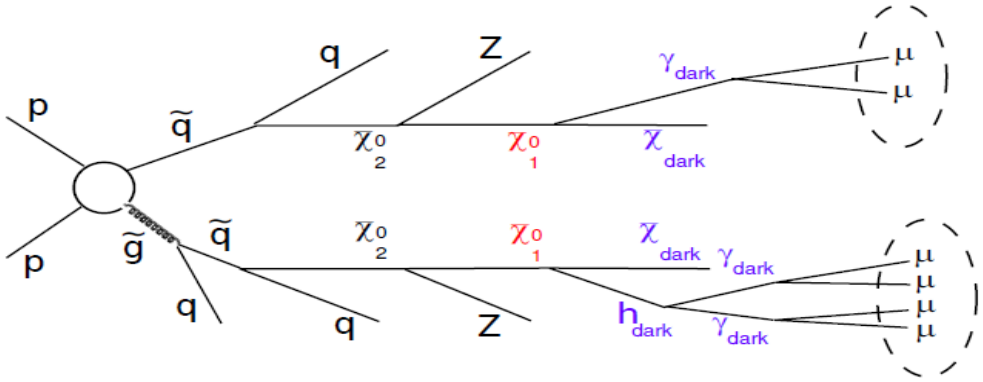
Backup

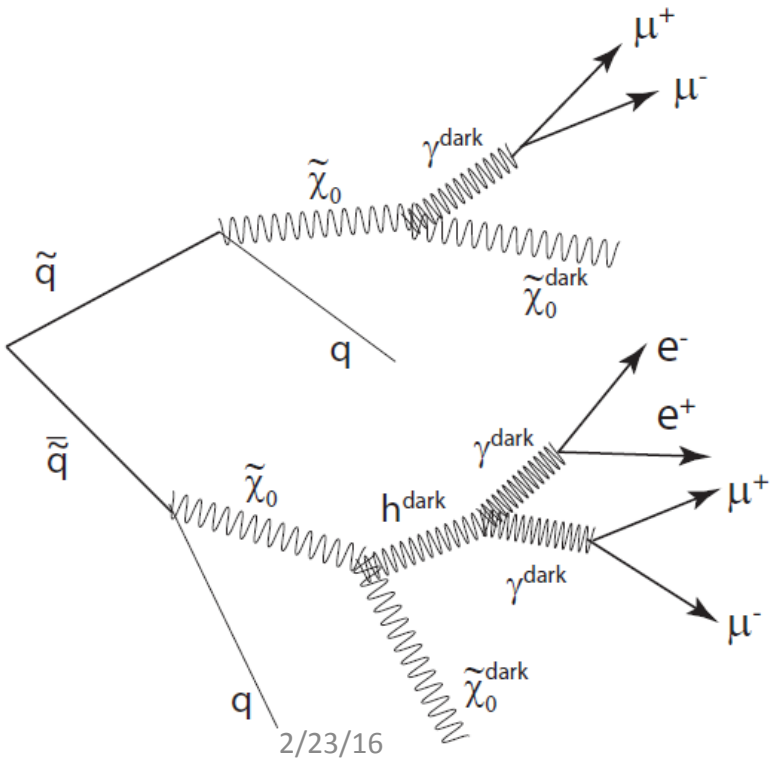
Previous and ongoing work

- Previous iterations of this analysis performed by this group
  - J. Pivarski, A. Safonov, and A. Tatarinov, “Search for collimated groups of muons”, CMS Note 2010/462 (2010)
  - CMS Collaboration, “Search for light resonances decaying into pairs of muons as a signal of new physics”, JHEP 07 (2011) 098, doi: 10.1007/JHEP07(2011)098, arXiv:1106.2375
  - Y. Pakhotin, A. Safonov, and A. Tatarinov, “Search for New Light Bosons from the Higgs Boson Decays Using Multi-Muon Events at the LHC”, CMS Note 2011/238 (2011)
  - CMS Collaboration, “Search for a non-standard-model Higgs boson decaying to a pair of new light bosons in four-muon final states”, arXiv:1210.7619. (2013)
  - CMS Collaboration, “A Search for New Light Bosons Decaying into Muon Pairs”, Phys. Lett. B 752 (2016) 146, arXiv:1506.00424 (2015)
- Current analysis note
  - A. Castaneda, et al., “A search for beyond the Standard Model light bosons decaying into muon pairs”, CMS Note 2016/044

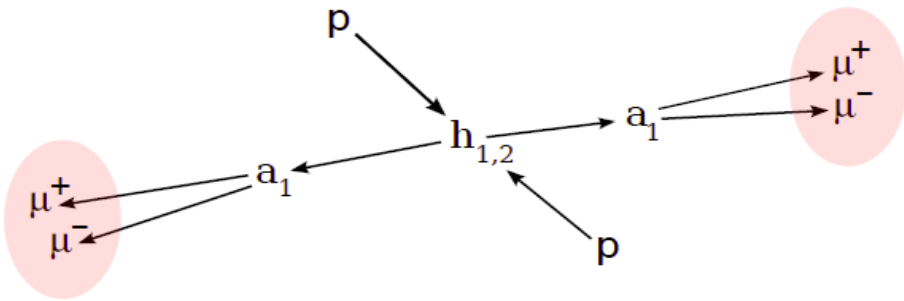
Other possible decay mechanisms

- Model independent signature
- Results may be interpreted in the context of any number of theories resulting in a 2 dimuon final state including those in which the new light boson is long lived



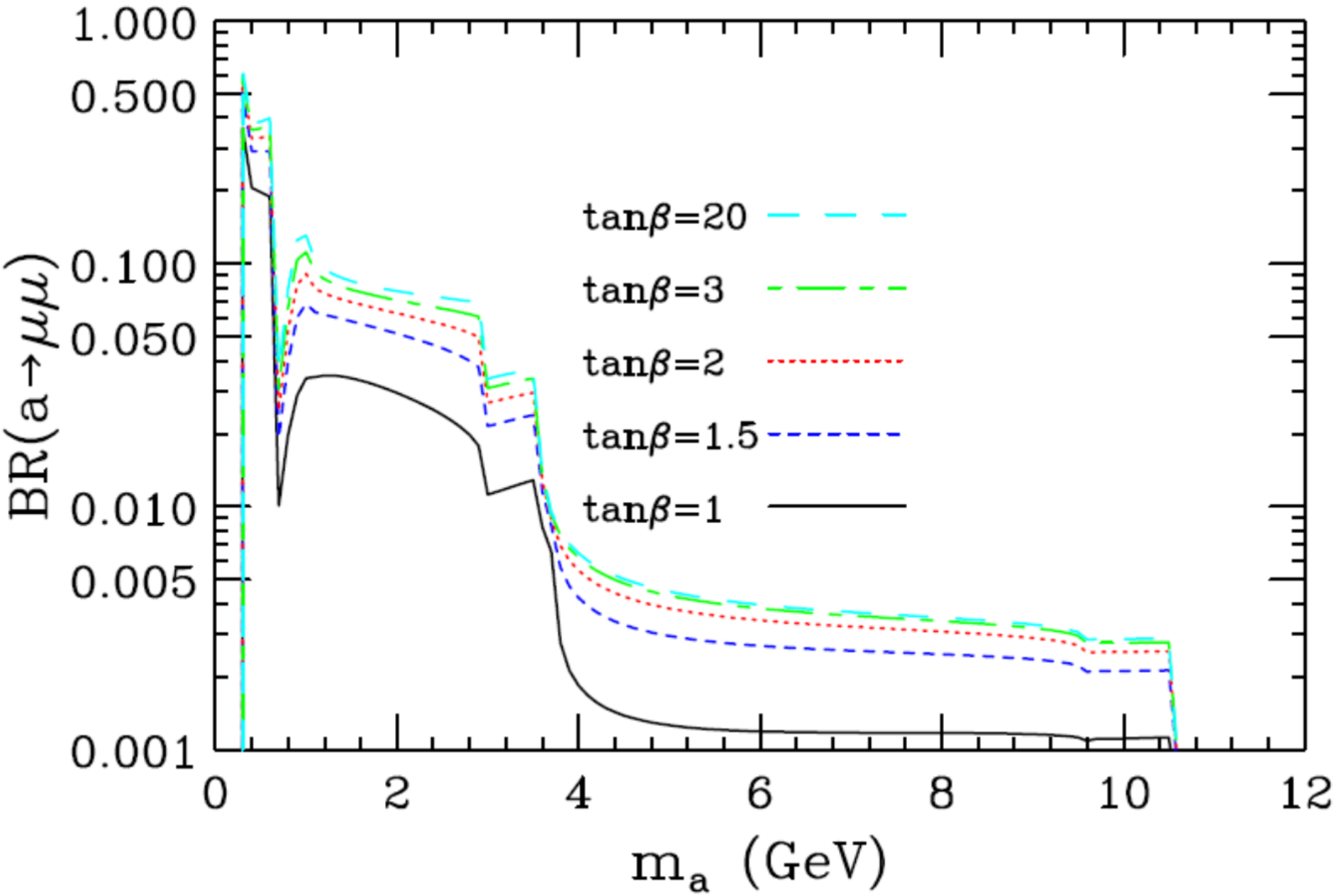


Motivation: NMSSM



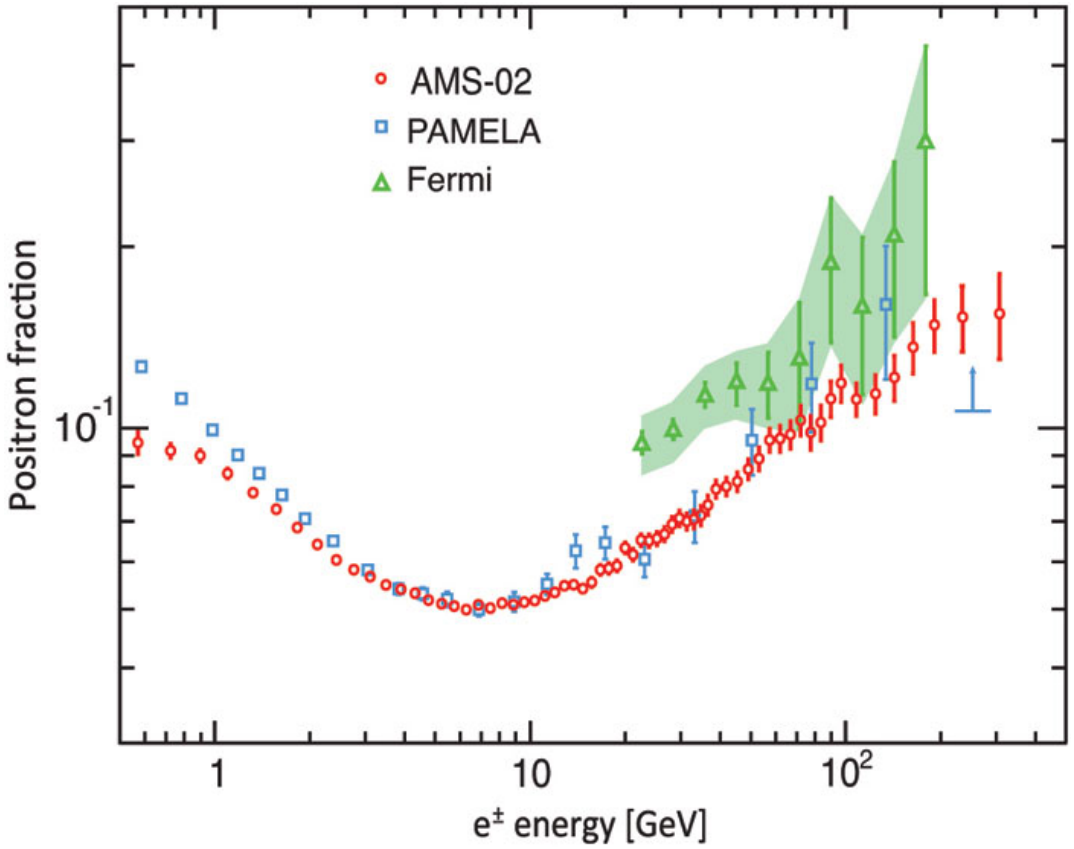
- NMSSM
  - Solves μ-problem
- Predicts CP-even Higgs ($h_{1,2}$) particles (one of which could be the observed 125GeV particle)
  - Also predicts a much lighter CP-odd Higgs (a_1)
    - a_1 decays to dimuons

NMSSM Br


1.000
0.500
0.100
0.050
0.010
0.005
0.001
BR(a→μμ)
tanβ=20
tanβ=3
tanβ=2
tanβ=1.5
tanβ=1
0
2
4
6
8
10
12
m_a (GeV)

Motivation SUSY with hidden/dark sectors

- Dark sectors
  - Could explain positron excess from satellite experiments.
    - Possibly from cold dark matter on TeV-scale annihilating in galactic halo
    - A light 'dark' photon (γ_D) acting as attractive force between dark matter particles (WIMPS)
- γ_D
  - Weakly couples to SM particles
  - Mixes with SM photon



New multimuon trigger

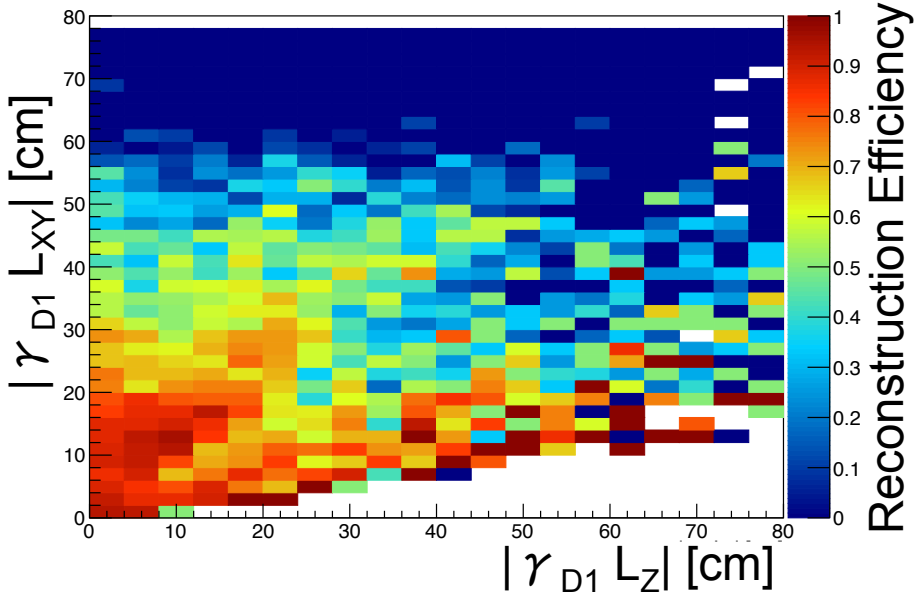
- `HLT_TrkMu15_DoubleTrkMu5NoFiltersNoVtx_v1`
  - 2 L1 muons `L1_DoubleMu_10_3p5 OR L1_DoubleMu_12_5`
  - Reconstruct L2 muons: NoVtx (already available in HLT menu)
    - 1 L2 muon with $p_T > 10$ GeV
  - Reconstruct L3 muons: NoVtx (already available in HLT menu)
  - 2 L3 muons: NoVtx with $p_T > 5$ GeV, $|\eta| < 2.5$
  - 1 L3 muon: NoVtx with $p_T > 15$ GeV, $|\eta| < 2.5$
  - Reconstruct Tracker muons using L3muon: NoVtx as input
  - 3 TrkMu with $p_T > 5$ GeV, $|\eta| < 2.5$ (requiredTypeMask = 4)
  - 1 TrkMu with $p_T > 15$ GeV, $|\eta| < 2.5$ (requiredTypeMask = 4)
- A backup trigger has also been implemented with higher p_T cuts
  - `HLT_TrkMu17_DoubleTrkMu8NoFiltersNoVtx_v1`

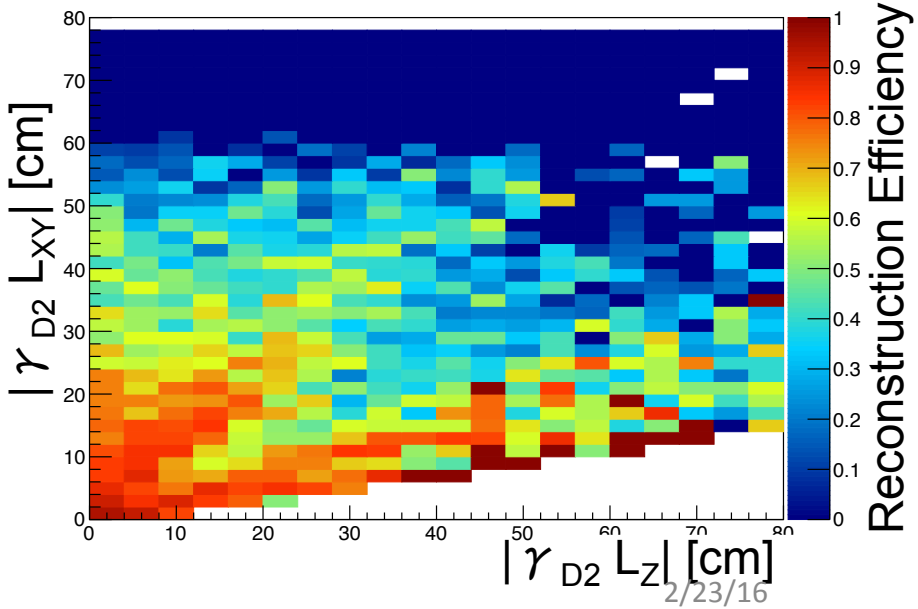
Multimuon trigger performance

- Efficiency
  - Overall trigger efficiency is very high (> 95%)
  - Trigger efficiency decreases with new light boson (*a*) mass
    - Very light bosons ($m_a \approx 2m_\mu$) produce nearly parallel, spatially close, muons and are difficult to reconstruct in the tracker resulting in lower efficiency
  - Trigger efficiency decreases with new light boson (*a*) lifetime
    - With larger displacement from the beam line there are fewer hits in the tracker. May still be constructed as StandAlone muons, they are not tracker muons as required by the trigger
- Rate estimation
  - HLT_TrkMu15_DoubleTrkMu5NoFiltersNoVtx_v1
    - 1.01 ± 0.04 Hz @ 7×10^{33} $cm^{-2}s^{-1}$
  - HLT_TrkMu17_DoubleTrkMu8NoFiltersNoVtx_v1
    - 0.86 ± 0.04 Hz @ 7×10^{33} $cm^{-2}s^{-1}$
- For more detailed information, Sven Dildick is giving a presentation on the status of the trigger on February 15 INDICO XXXXXXX

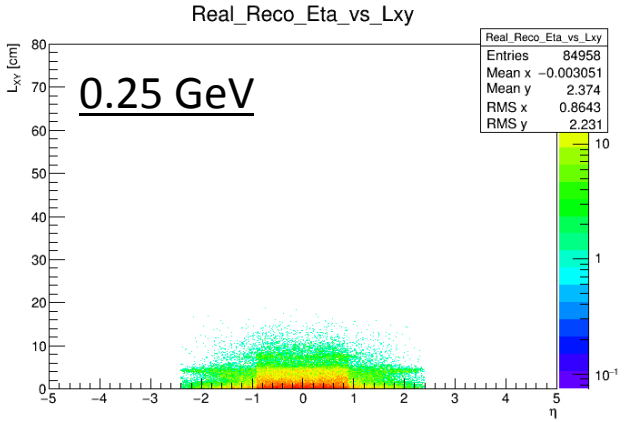
Dimuon reconstruction efficiency

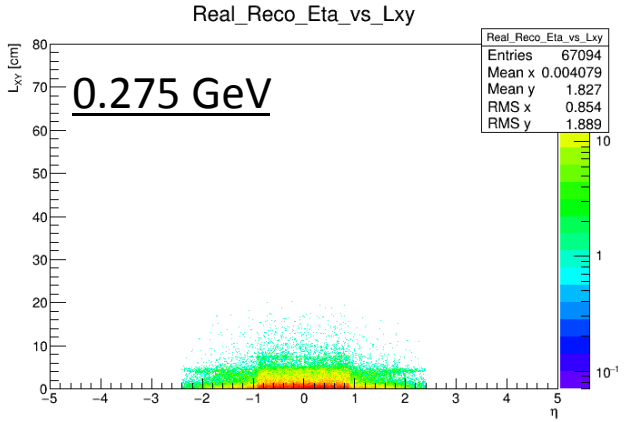
- Top: Dimuon reconstruction efficiency as a function of L_{XY} and L_Z for the dimuon pair requiring at least one muon with $p_T > 17$ GeV in the barrel ($|\eta| < 0.9$) and the other with $p_T > 8$ GeV with $|\eta| < 2.4$ for the $m_{\gamma_D} = 0.25$ GeV sample
- Bottom: Same as top but for the case where both muons are required to have $p_T > 8$ GeV with $|\eta| < 2.4$
- Denominator: 4 GEN mu $p_T > 8$ ($|\eta| < 2.4$) && 1 GEN mu $p_T > 17$ ($|\eta| < 0.9$) AND $\Delta\phi$ of dark photon > 2.5
- Numerator: Denominator && both muons in dimuon have GEN-RECO match
  - A match requires $\Delta R(\mu_{GEN}, \mu_{RECO}) < 0.1$
- Dark blue means that the numerator is zero and the denominator is non-zero, white means no data

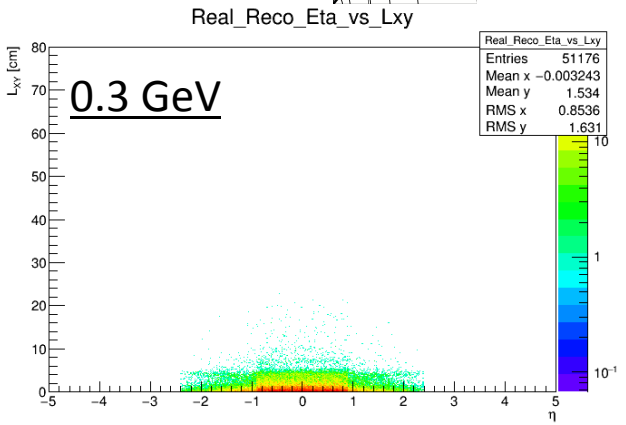


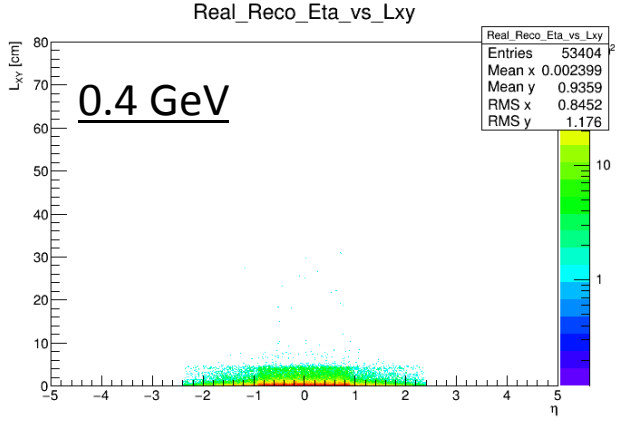


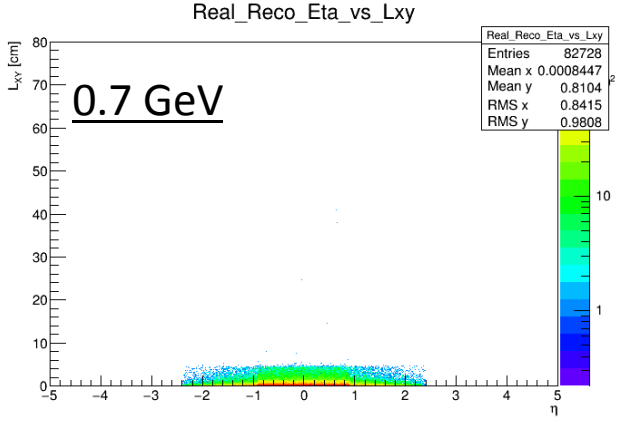
Real RECO L_{XY} vs RECO eta for individual mass samples

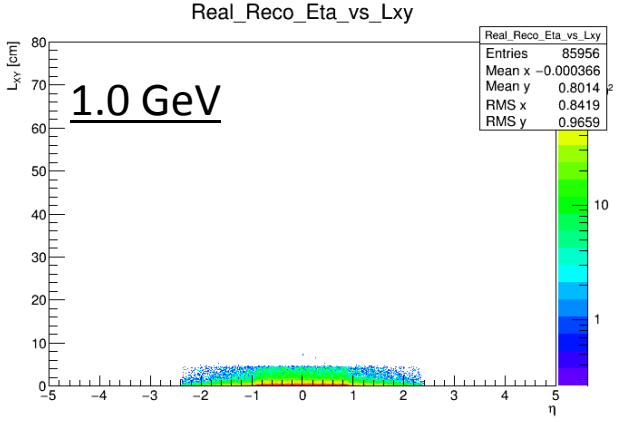


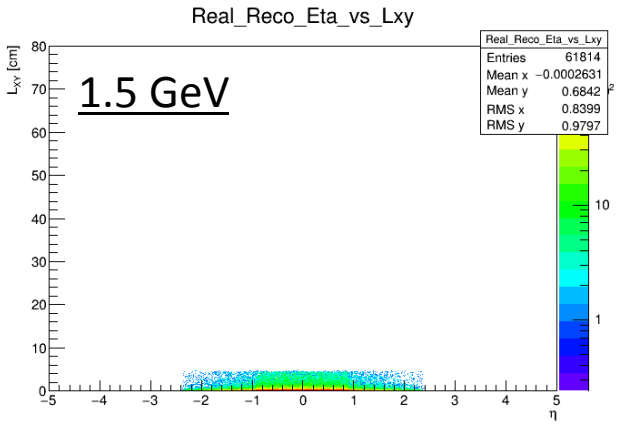


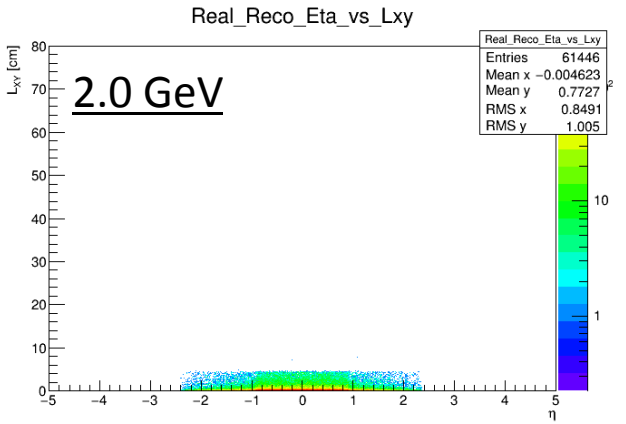


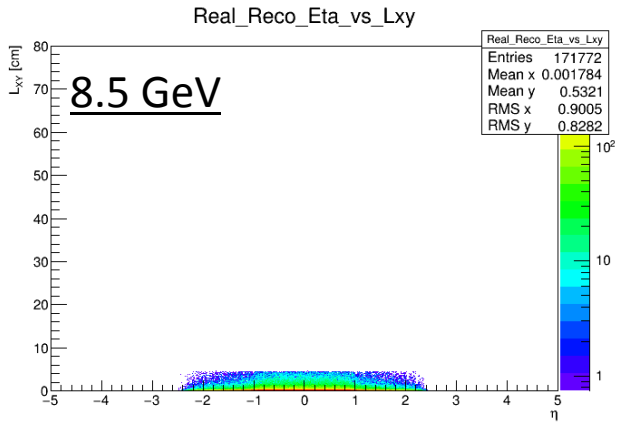




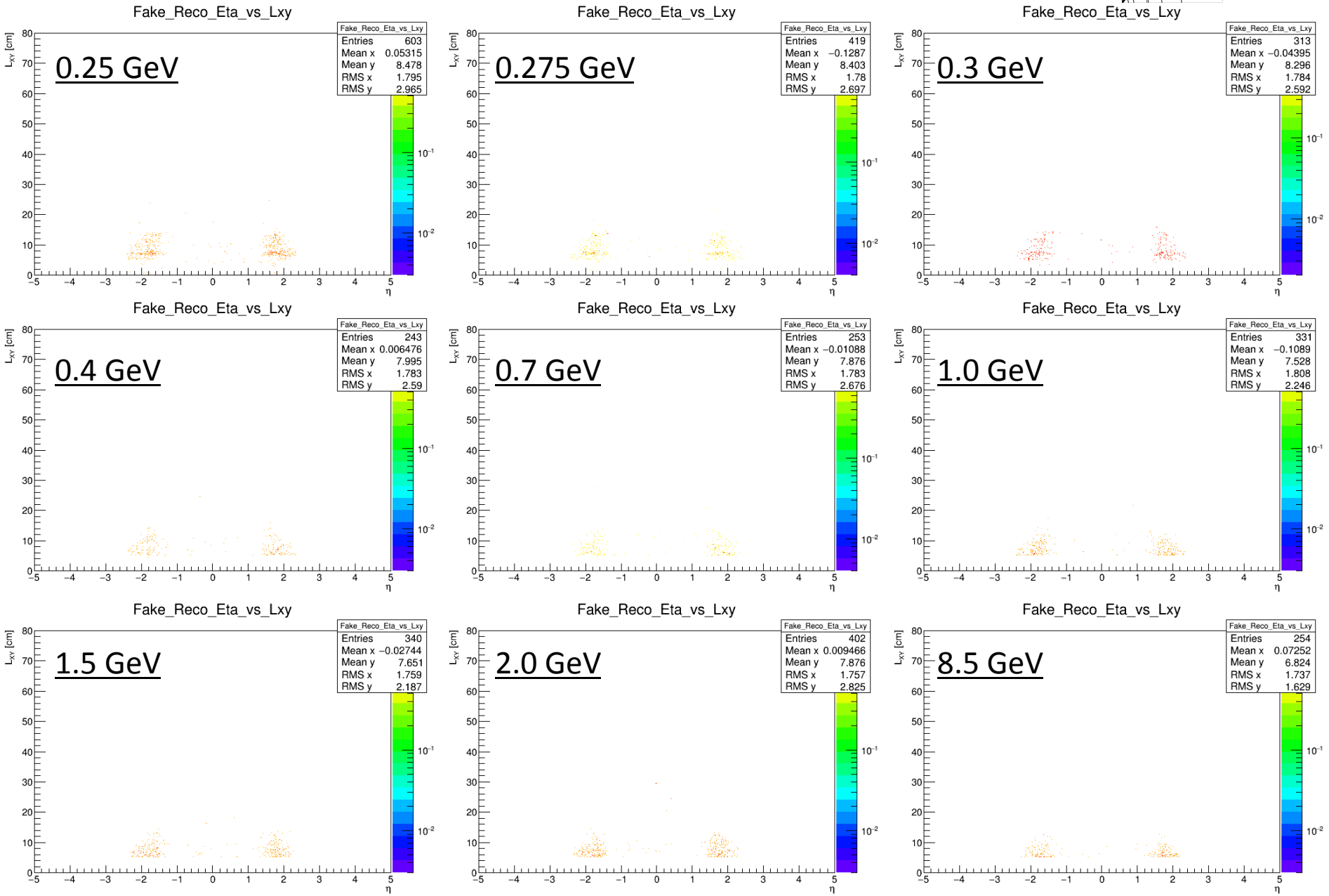




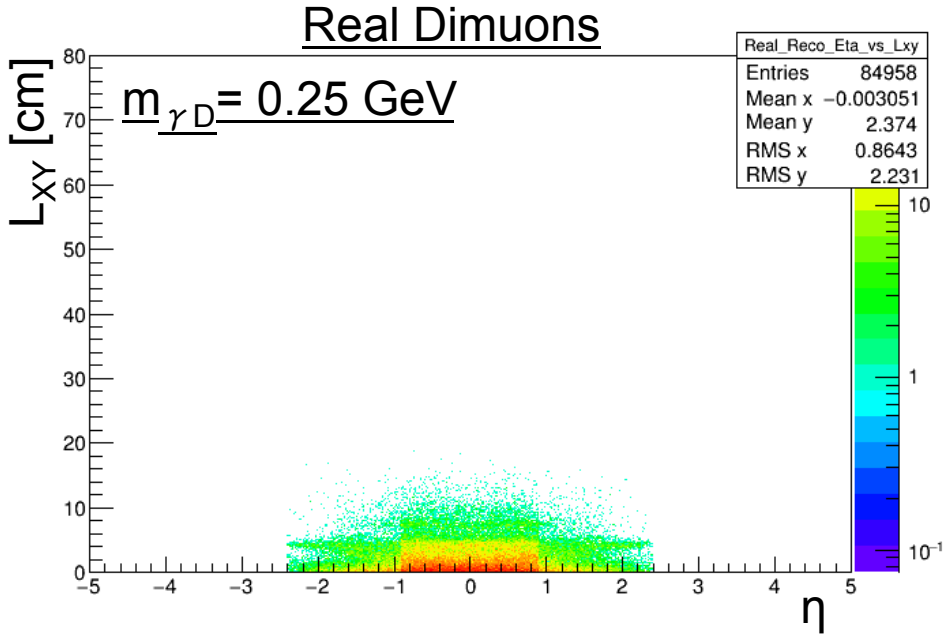


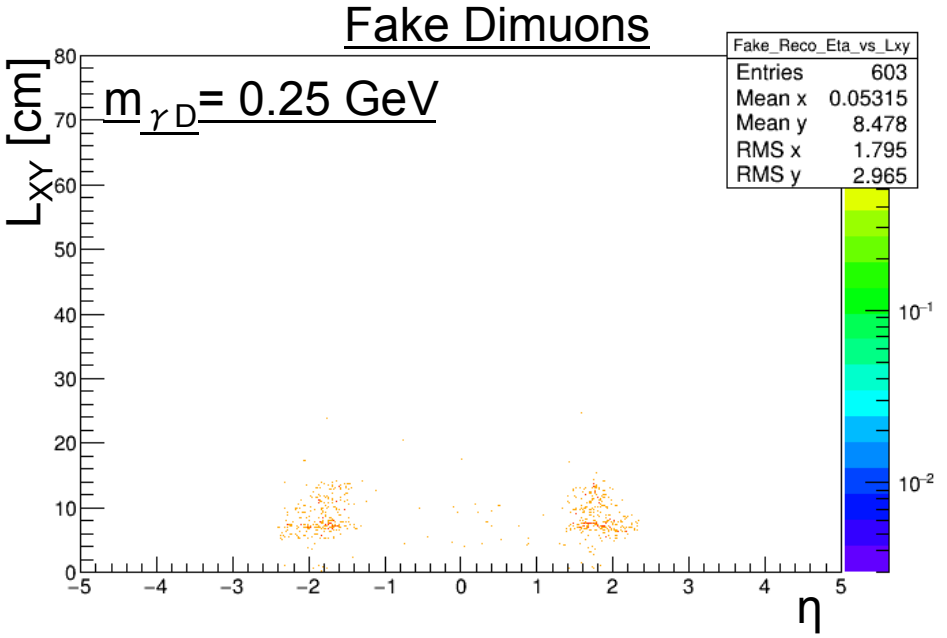


Fake RECO L_{XY} vs RECO eta for individual mass samples



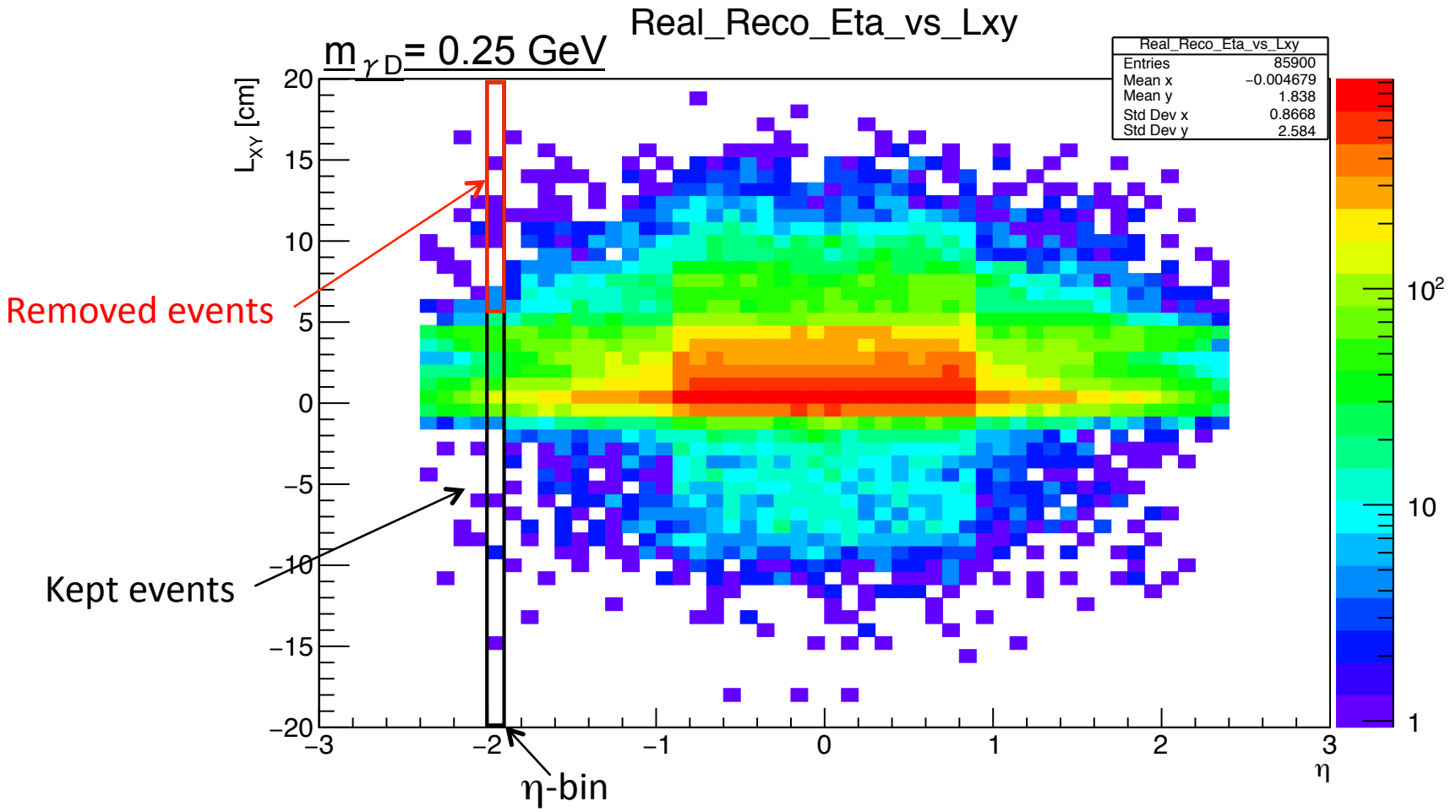
Mitigation of fake dimuons





- If dimuon passes offline selection, but not GEN fiducial AND has $L_{XY} > 5$ then dimuon is fake
- If an event passes both the reconstruction selection and the fiducial cut, then the event is labeled as “real”

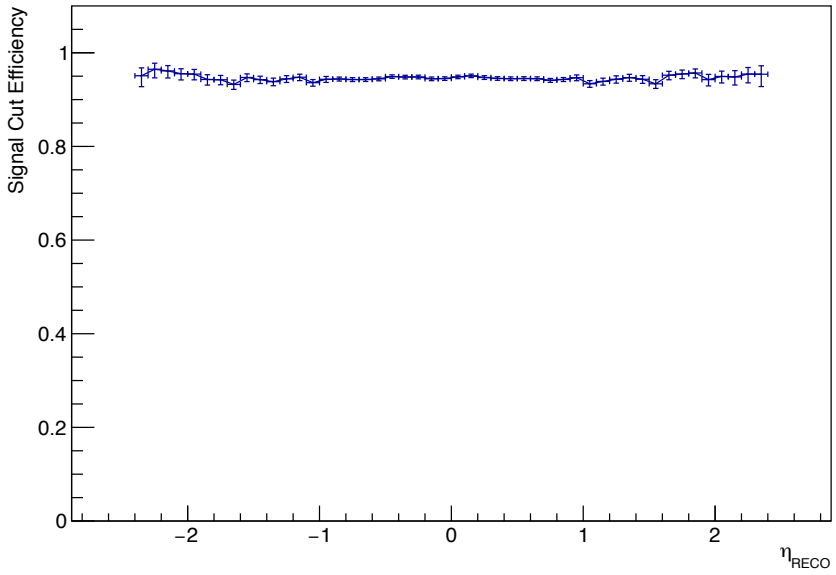
Remove 3% of highest L_{XY} events per η bin signal events

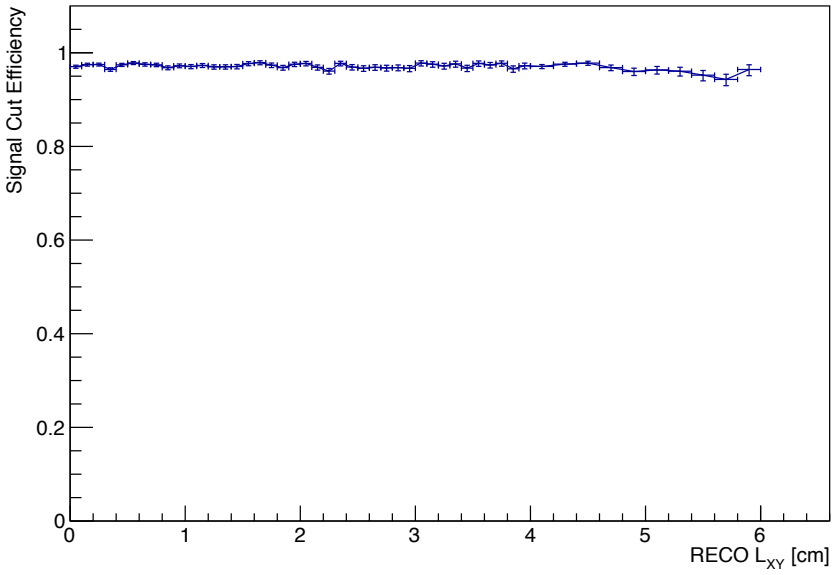


- L_{XY} allowed to be negative
- Cut made for each η-bin (individually) for $m_{\gamma D}$= 0.25 GeV sample

Cut made for each η-bin results

RECO level results:

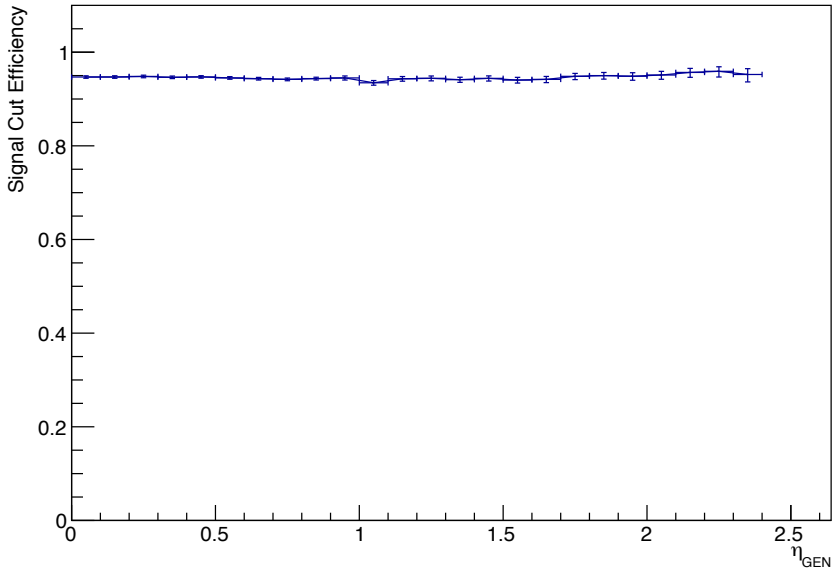


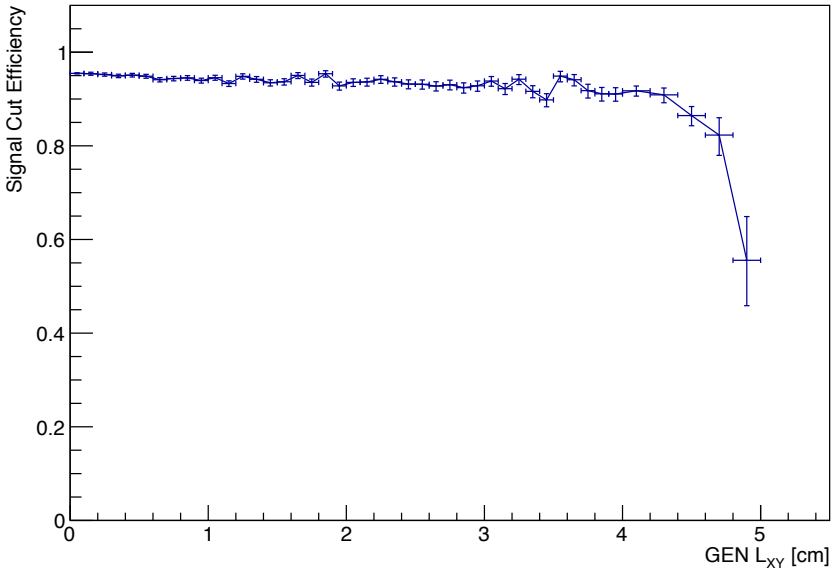


- Efficiency looks really good!
- Why is efficiency vs η not perfectly flat at ~97%?
  - When cut is determined individual dimuons are counted and removed
  - When cut is used both dimuons in an event are required to pass cut

Cut made for each η-bin results

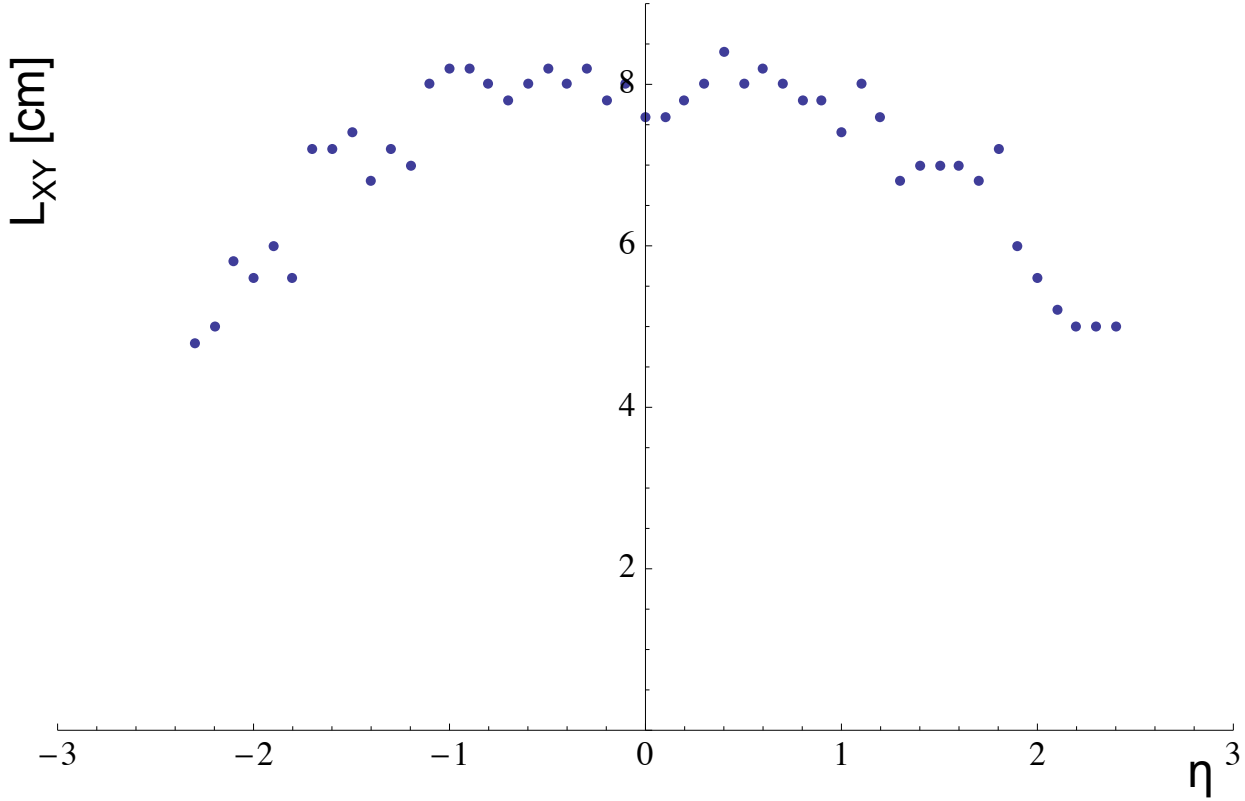
GEN level results:





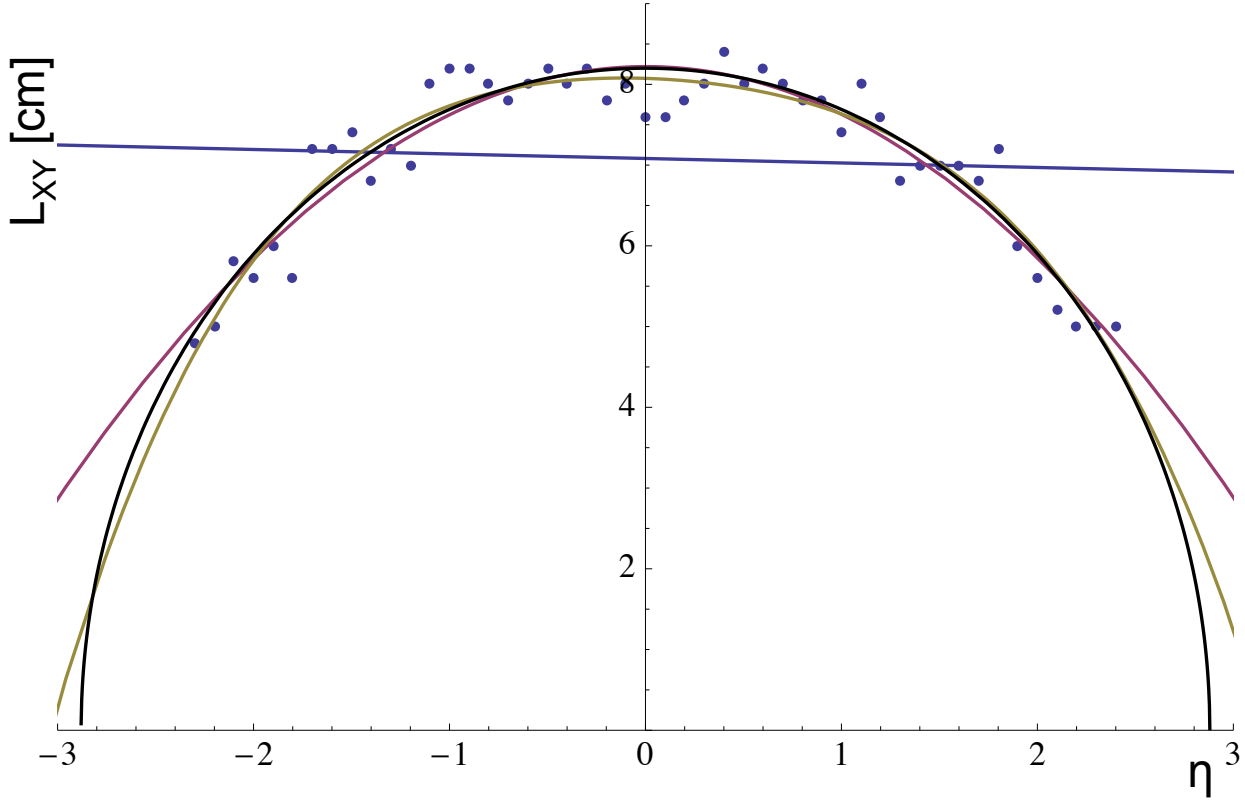
- Efficiency looks really good!
- Efficiency vs GEN L_{XY} decreases after 4.4 cm
  - This is passed the fiducial cut
  - We are unconcerned with this area at GEN level
- Recall that cut is made on RECO level quantities

Adjustment of bin-width



- Exact cut made is sensitive to bin width
- I chose a reasonable bin width that gave reasonably smooth cuts
  - Increasing → flat → decreasing
  - η-bins are 0.1 wide
  - L_{XY}-bins are 0.2 cm wide

Adjustment of bin-width



Linear

Parabola

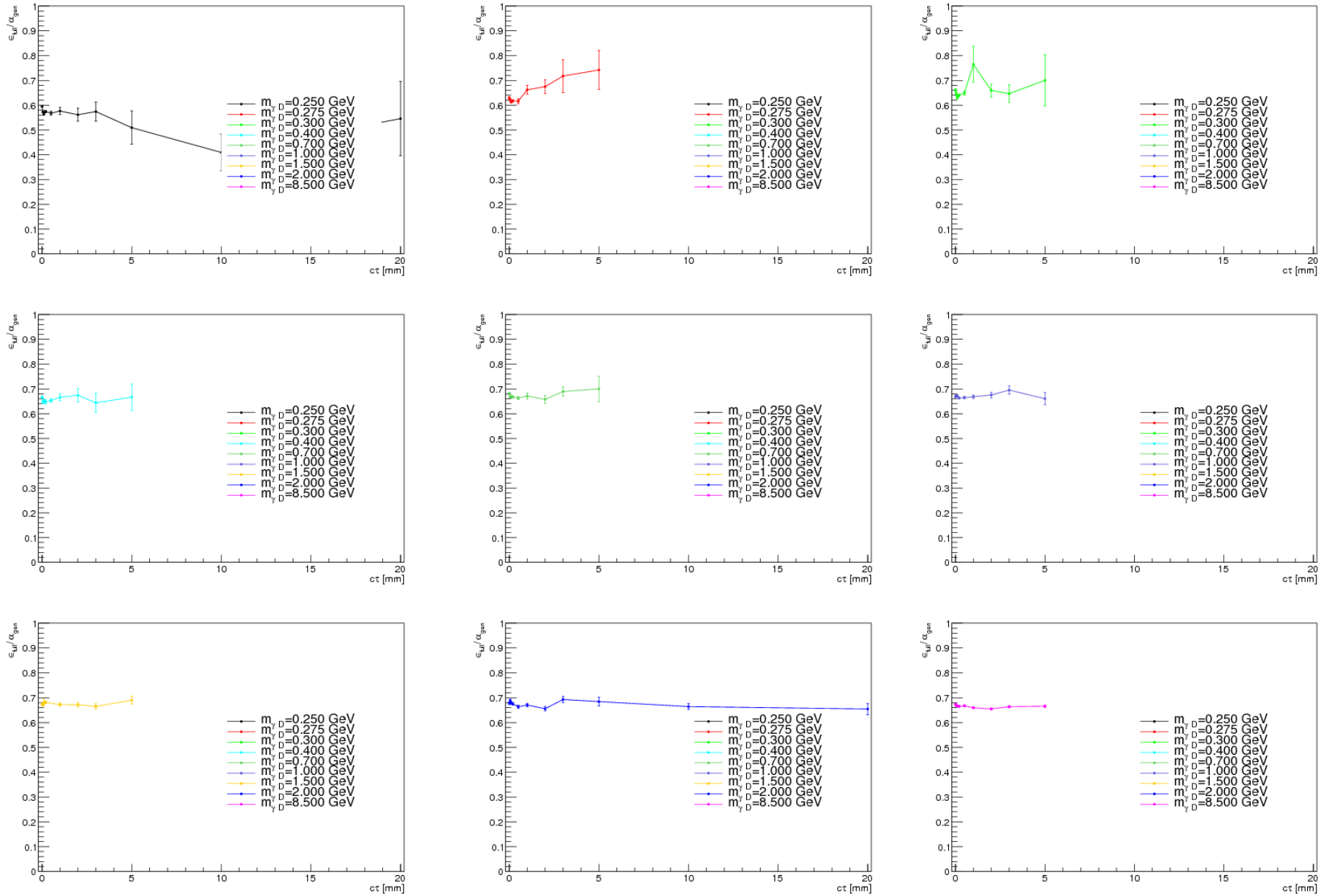
Quartic

Ellipse

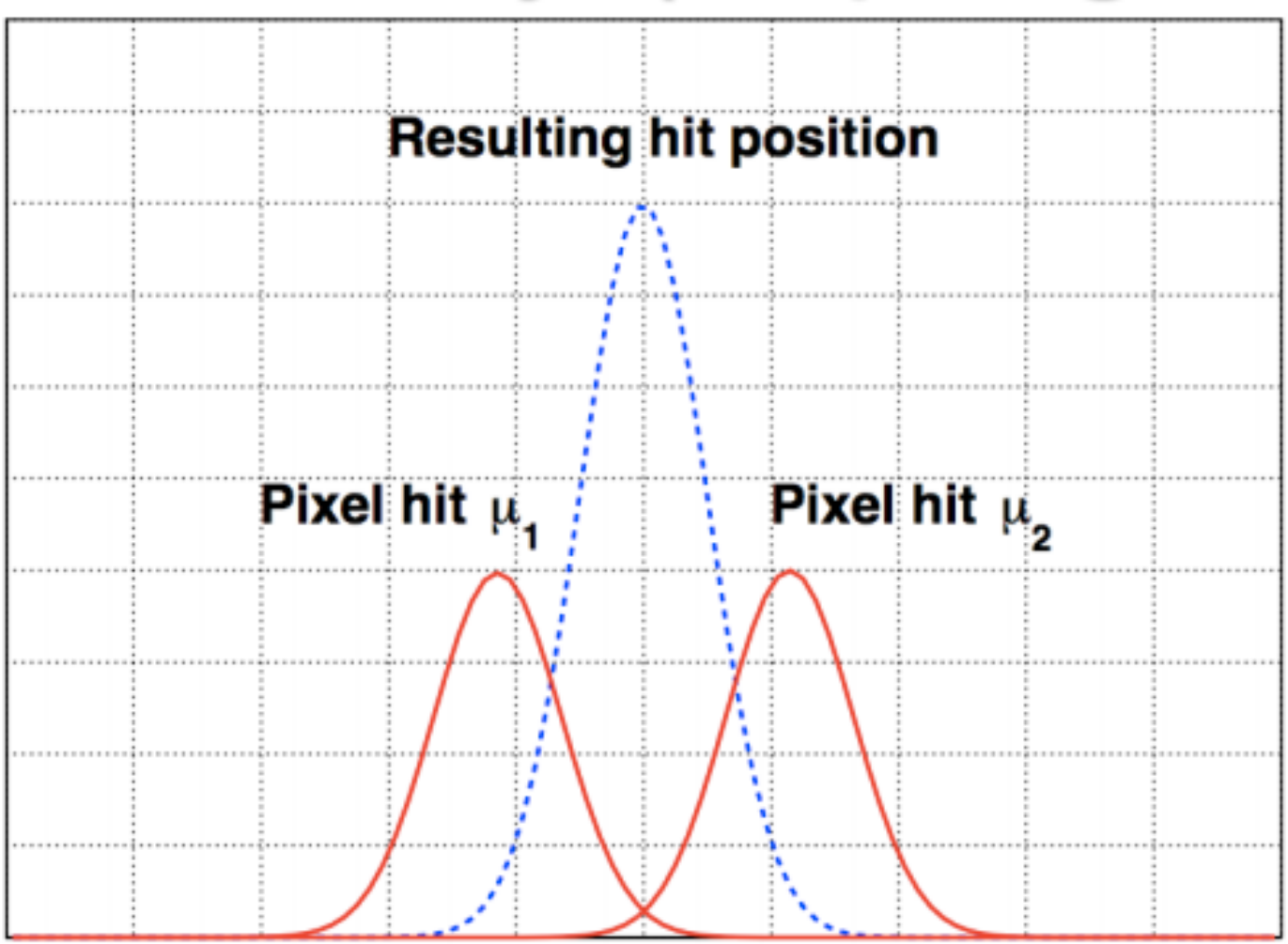
- Want smooth curve rather than discrete cut for every bin
- Several shapes attempted using
  - Linear, parabola, quartic, ellipse
  - Quartic and ellipse have reasonable χ^2
    - Increasing order of polynomial will produce arbitrarily good fit
- Using ellipse because that was initial idea and is simple

$$\frac{\eta_{\mathrm{dim}}^2}{2.88^2} + \frac{Lxy_{\mathrm{dim}}^2}{8.20^2} \leq 1$$

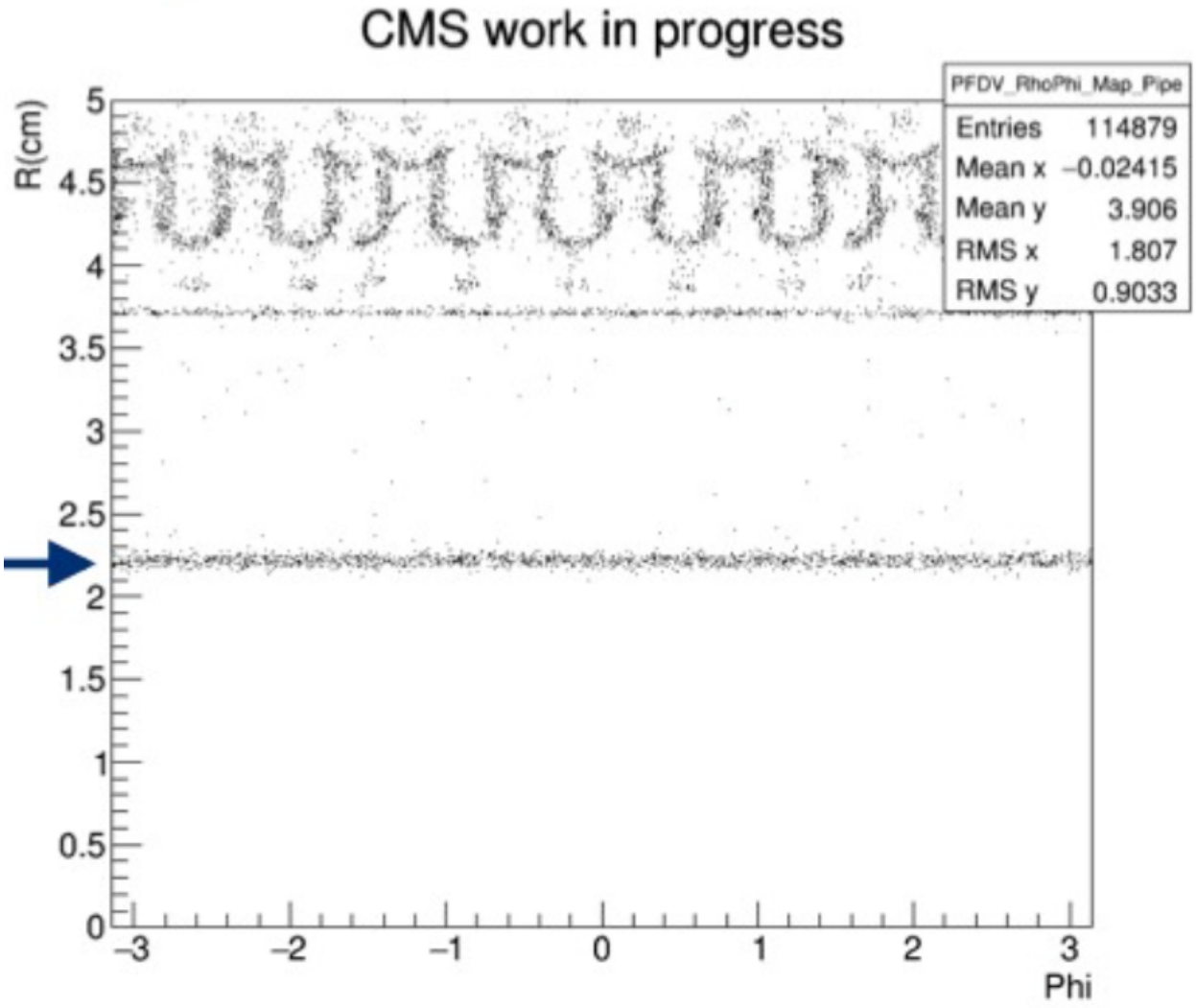
$\varepsilon_{full}/\alpha_{gen}$ with elliptical cut



Pixel hit recovery

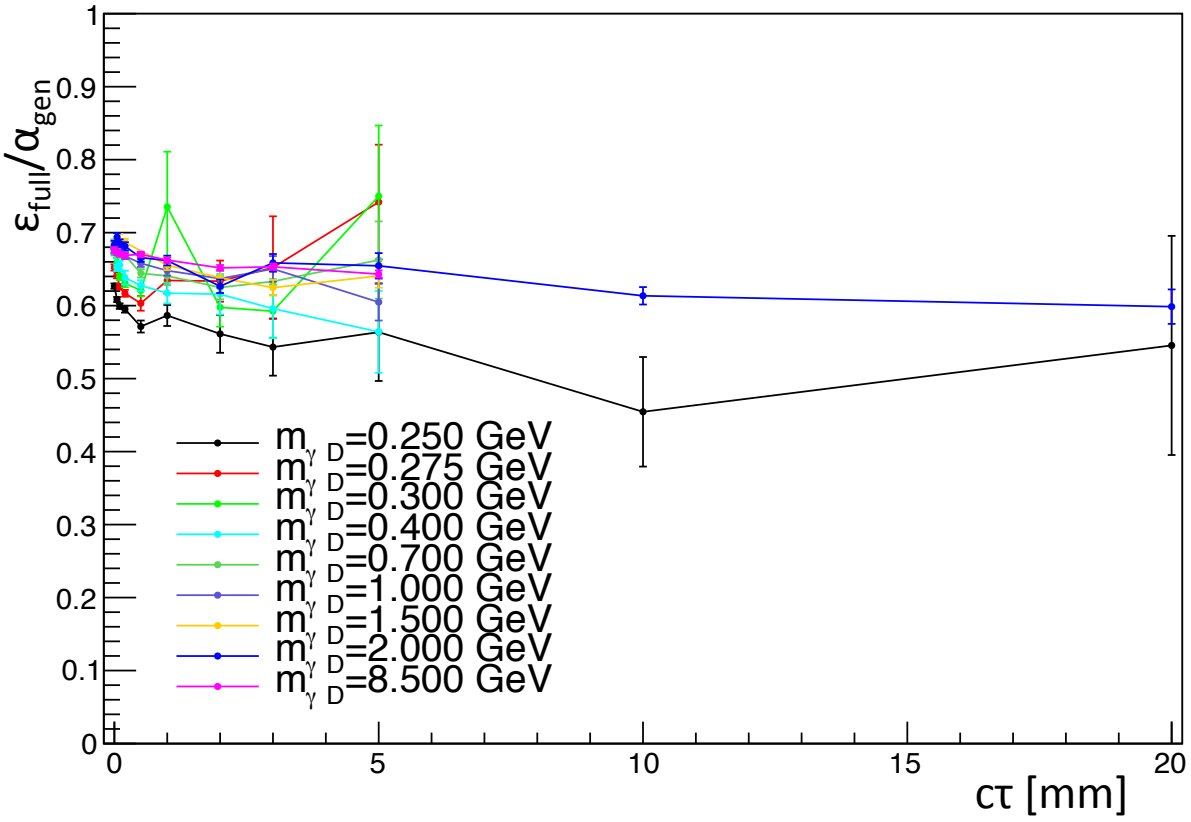


Pixel geometry



https://indico.cern.ch/event/395619/session/2/contribution/10/attachments/1125480/1606608/DPGsummary.pdf

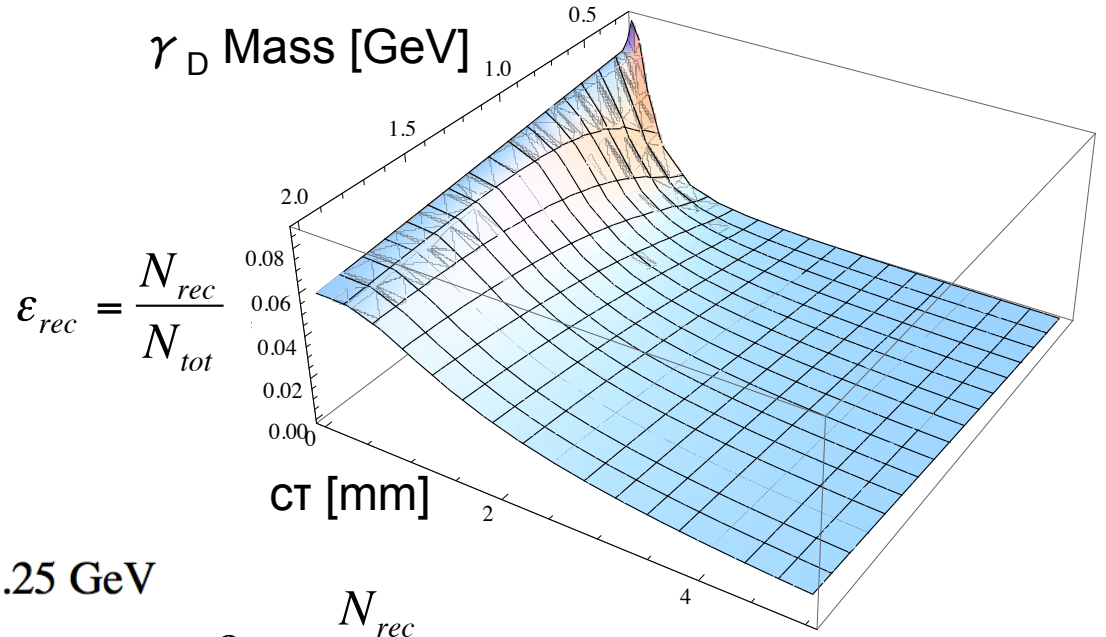
εfull/αgen (fiducial cut in numerator)



- Denominator:
  - 4 GEN mu $p_T > 8$ ($|\eta| < 2.4$) && 1 GEN mu $p_T > 17$ ($|\eta| < 0.9$)
  - Fiducial cut: Dark photon $L_{XY} < 4.4$ cm && $L_Z < 34.5$
- Numerator:
  - 4 RECO mu $p_T > 8$ ($|\eta| < 2.4$) && 1 RECO mu $p_T > 17$ ($|\eta| < 0.9$)
  - **Dark photon $L_{XY} < 4.4$ cm && $L_Z < 34.5$**
  - Event has a primary vertex, 2 dimuons in the event, both dimuons have a valid vertex, dimuon vertices pass Δz cut, both dimuons have a hit in the first pixel layer, dimuons pass mass compatability cut, fired HLT

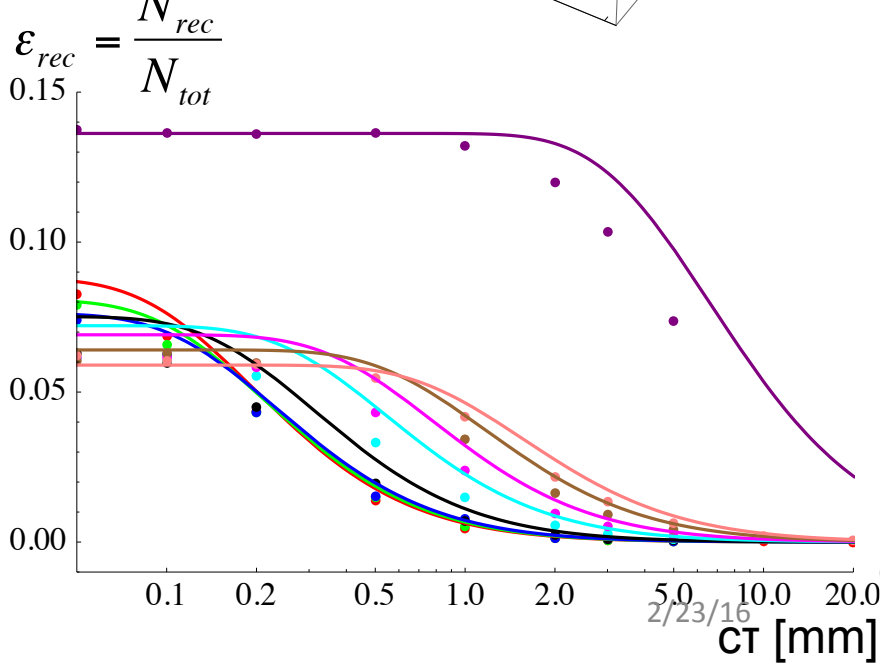
Model of the event acceptance as a function of $m_{\gamma D}$ and $c\tau_{\gamma D}$

- Smooth efficiency curves must be found and input into limit machinery
- An analytic function is derived using MC
  - Assume exponential decay of dark photon
  - Assume the efficiency is a function of $m_{\gamma D}$ and $c\tau_{\gamma D}$

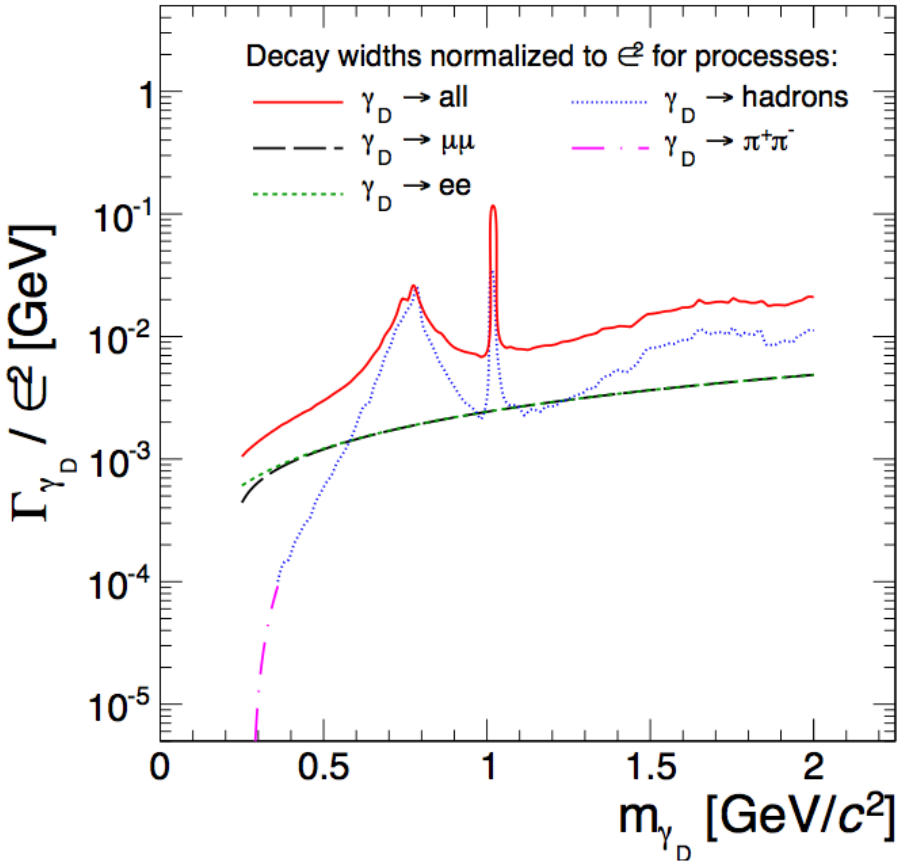


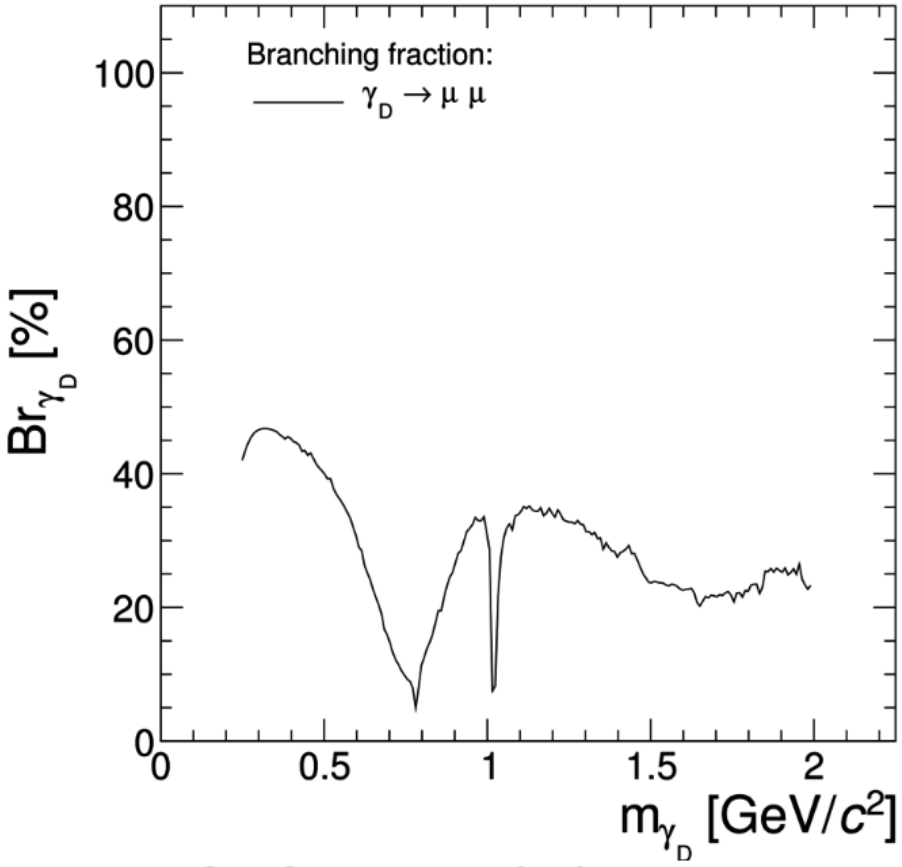
$$\varepsilon_{rec} = \frac{N_{rec}}{N_{tot}}$$

- 0.25 GeV
- 0.275 GeV
- 0.3 GeV
- 0.4 GeV
- 0.7 GeV
- 1.0 GeV
- 1.5 GeV
- 2.0 GeV
- 8.5 GeV



Kinetic mixing angle





$$\tau_{\gamma_D} = \frac{\hbar}{\Gamma_{\gamma_D Total}} = \frac{1}{\Gamma_{\gamma_D \to e^+e^-} + \Gamma_{\gamma_D \to \mu^+\mu^-} + \Gamma_{\gamma_D \to hadrons}} \quad (4)$$

275 The lifetime is directly related to the parameter ϵ and the mass of dark photon via:

$$\tau_{\gamma_D}(\epsilon, m_{\gamma_D}) = \frac{1}{\epsilon^2} \times f(m_{\gamma_D}), \quad (5)$$

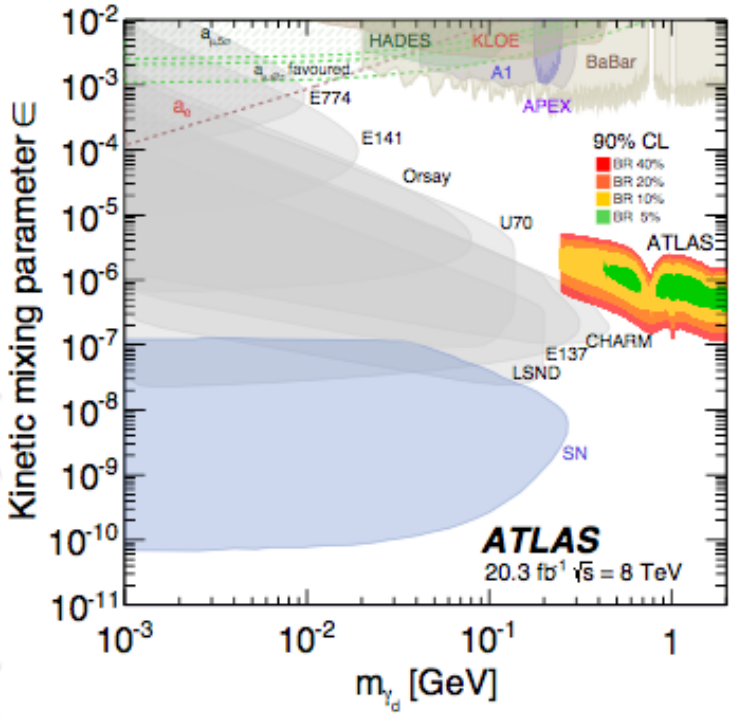


Figure 8: Experimental constraints in the plane of two parameters for the Dark SUSY scenarios: ϵ^2 and m_{γ_D} (figure from [47]).

Conclusions

- We are an experienced team
- Making good progress
- The analysis is well advanced
- Should have results in coming months
- Will report regular updates to this group