Search For Self-Interacting Dark Matter With Displaced Lepton Jets

Lepton Jet Reconstruction Efficiency

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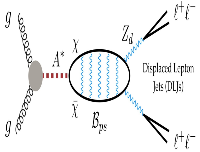
Outline

Self Interacting Dark Matter (SIDM) Model



1. Light Z_d $\rightarrow$ Boosted Z_d
2. Small Z_d - SM Coupling $\rightarrow$ Long-Lived Z_d
3. Displaced decays of boosted Z_d $\rightarrow$ Displaced, collimated leptons (Displaced Lepton Jets (LJs))

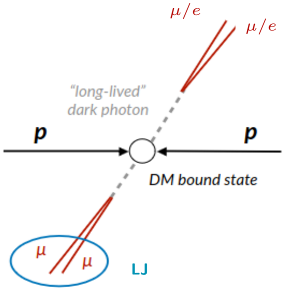
Free Parameters:

- Bound state mass (m_B)
- Dark photon mass (m_{Z_d})
- Kinetic mixing between Z_d and SM, ϵ

Signal:

- m_B ϵ [100, 150, 200, 500, 800, 1000] GeV
- m_{Z_d} ϵ [0.25, 1.2, 5] GeV
- Z_d L_{xy} ϵ [0.3, 3, 30, 150, 300] cm

Final states : $2\mu 2e$ **or** 4μ



Lepton Jets (LJs)

- Group of collimated leptons in a tight cone.
- We apply anti- k_T clustering (ΔR $=$ 0.4) to **PF** e**, PF** γ**, PF** μ and **DSA** μ.

Conditions to reconstruct an LJ:

- $|\eta| <$ 2.4
- $p_T >$ 30 GeV
- $\sum Q_\mu$ =0 (to prevent b-quark cascade decays)

Object Cuts	$\eta <$	$p_T >$	ID	Isolation
PF e	2.4	10 GeV	Loose	Loose
PF γ		20 GeV	Loose	Loose
PF μ		5 GeV	Loose	None
DSA μ		10 GeV	DSA	None

Categories of LJs:

- $e\gamma$ (N_μ =0)
- μ (N_μ >=1)

Events Categories:

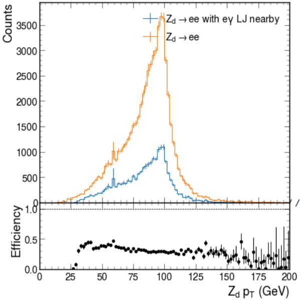
- 4μ: 2 μ-type LJs
- $2\mu 2e$: 1 $e\gamma$ -type LJ and 1 $\mu-$ type LJ

Lepton Jet (LJ) Reconstruction Efficiency

What fraction of the Z_d decays can we reconstruct as Lepton Jets?

$$\text{Efficiency} = \frac{\text{Number of } Z_d\text{s with } \Delta R(Z_d, \text{LJ}) < 0.4}{\text{Total number of } Z_d\text{s}}$$

- We study this w.r.t various parameters and cuts.
- We consider $Z_d \to ee$ ($e\gamma$ LJ) and $Z_d \to \mu\mu$ (μ LJ) separately, as they behave differently in the detector.
- In the figure, the numerator is $Z_d \to ee$ with $e\gamma$ LJ nearby, and the denominator is $Z_d \to ee$.



Parameters Considered

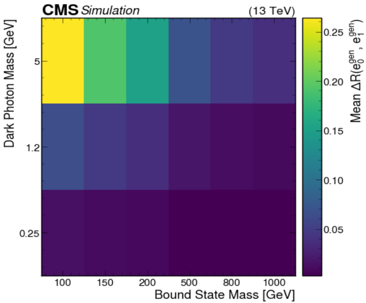
We are considering a wide range of L_{xy}, a wide range of lepton p_T, and a wide range of lepton collimation, including extremely collimated final states.

Therefore, to get an idea about the LJ reconstruction efficiency in that whole space, we consider the following parameters:

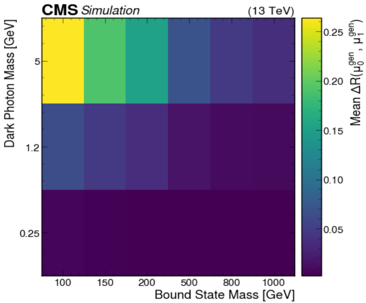
- $Z_d\ p_T$
- $Z_d\ L_{xy}$
- ΔR(Leptons)

These variables are highly correlated; we are trying to understand the efficiency while accounting for their correlation.

Lepton Collimation



$Z_d \to ee$



$Z_d \to \mu\mu$

- Both m_B and m_{Z_d} affect the collimation of the leptons.
- For fixed m_B, smallest m_{Z_d} has the highest collimation.

$m_{z_d} = 0.25$ GeV $\longrightarrow$ More collimated.
$m_{z_d} = 5$ GeV $\longrightarrow$ Less collimated.

To learn more about kinematics, refer to the previous talk's slides here

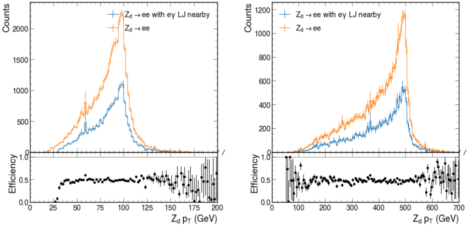
$e\gamma$ Lepton Jet Reconstruction Efficiency

$Z_d\ p_T$

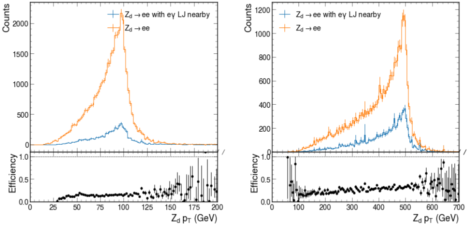
$L_{xy} < 150$ cm

$Z_d \to ee$, $Z_d < L_{xy} > = 300$ cm

$m_{Z_d} = 0.25$ GeV (more collimated)



$m_{Z_d} = 5$ GeV (less collimated)



$m_B = 200$ GeV $m_B = 1000$ GeV

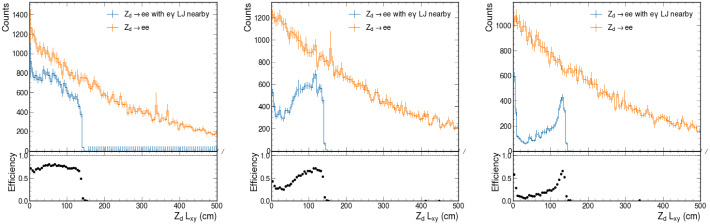
Note: The x ranges are different in these plots

- We see a sharp turn-on at 30 GeV, the cut on p_T we applied on the LJs.
- For more collimated leptons, efficiency is more or less constant after $p_T > 30$ GeV.
- For less collimated leptons, as the p_T increases, the efficiency increases.
- Overall lower efficiency for the less collimated leptons.

$Z_d \; L_{xy}$

$Z_d \; p_T > 30$ GeV

$Z_d \to ee$, $m_B = 200$ GeV, $Z_d < L_{xy} > = 300$ cm



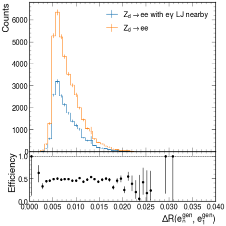
$m_{Z_d} = 0.25$ GeV (more collimated) | $m_{Z_d} = 1.2$ GeV | $m_{Z_d} = 5$ GeV (less collimated)

- Efficiency extends to the end of ECAL and is basically flat in the more collimated case.
- Efficiency in the somewhat displaced region drops as the collimation decreases (reason for overall low efficiency in the less collimated sample).
- Current electron ID limits the electron reconstruction to only few cms.
- We are good at reconstructing the Z_d decays as photons if the decay happens in ECAL or electrons are more collimated. Other displaced decays are more likely to fail the electron/photon ID.

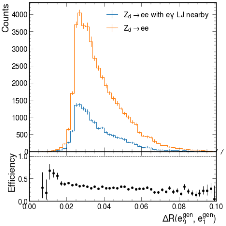
$\Delta R(e_0^{gen}, e_1^{gen})$

$Z_d\ p_T > 30$ GeV, $Z_d\ L_{xy} < 150$ cm

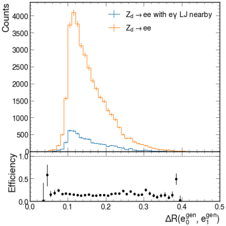
$Z_d \rightarrow ee$, $m_B = 200$ GeV, $Z_d < L_{xy} > = 300$ cm



m_{Z_d} **= 0.25 GeV**
(more collimated)



m_{Z_d} **= 1.2 GeV**



m_{Z_d} **= 5 GeV**
(less collimated)

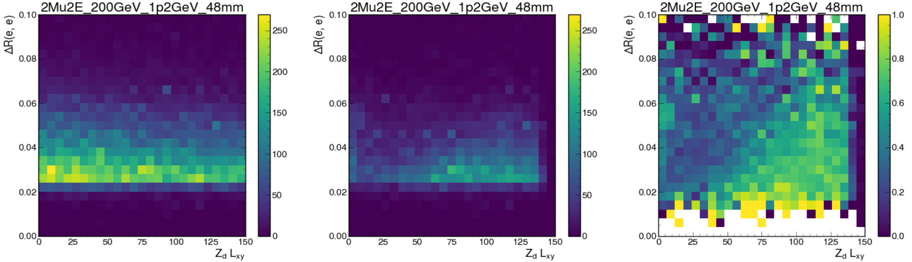
- We see non-zero efficiency in the whole range of ΔR.
- Efficiency is not changing much as a function of ΔR.
- Overall lower efficiency for less collimated electrons as we saw earlier in the L_{xy} plot.

Note: The x ranges are different in these plots

$\Delta R(e_0^{gen}, e_1^{gen})$ and $Z_d\ L_{xy}$

$Z_d\ p_T > 30$ GeV, $Z_d\ L_{xy} < 150$ cm

$Z_d \to ee$, $m_{Z_d} = 1.2$ GeV, $m_B = 200$ GeV, $Z_d < L_{xy} > = 300$ cm



den: $Z_d \to ee$ num: $Z_d \to ee$ with $e\gamma$ LJ nearby   Efficiency

- High efficiency at low ΔR, high L_{xy} Region.
- If the L_{xy} is bigger than a few cms, we cannot reconstruct them as electrons. If the electrons are too far apart, we fail to identify them as photons.

We will try to improve this efficiency by changing the electron/photon ID!

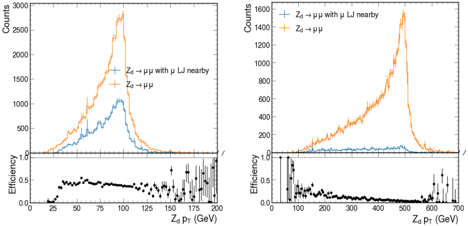
μ Lepton Jet Reconstruction Efficiency

$Z_d\ p_T$

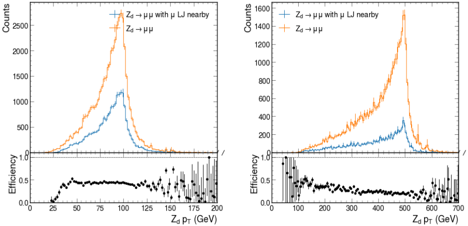
$L_{xy} < 400$ cm

$Z_d \to \mu\mu$, $Z_d < L_{xy} > = 300$ cm

$m_{Z_d} = 0.25$ GeV (more collimated)



$m_{Z_d} = 5$ GeV (less collimated)



m_B = **200 GeV** m_B = **1000 GeV**

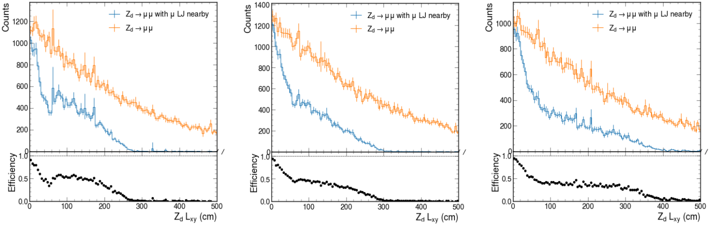
Note: The x ranges are different in these plots

- We see a sharp turn-on at 30 GeV, the cut on p_T we applied on the LJs.
- After the turn-on, efficiency slightly decreases as the p_T increases for both cases.
- Overall lower efficiency at higher p_T for more collimated muons (we suspect it's due the correlation with collimation).

$Z_d \; L_{xy}$

$Z_d \; p_T > 30$ GeV

$Z_d \to \mu\mu$, $m_B = 200$ GeV, $Z_d < L_{xy} > = 300$ cm



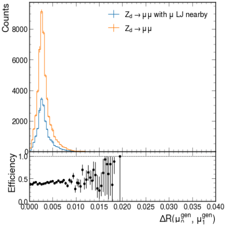
m_{Z_d} = **0.25 GeV** (more collimated) | m_{Z_d} = **1.2 GeV** | m_{Z_d} = **5 GeV** (less collimated)

- We have efficiency for a wide range of L_{xy}.
- Efficiency extends to higher L_{xy} for the less collimated muons.
- There is a drop in the efficiency at the transition point of PF to DSA for the more collimated sample. We suspect it is due to failure in PF-DSA cross-cleaning/duplicate removal.

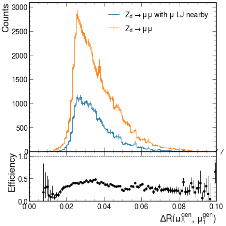
$\Delta\text{R}(\mu_0^{gen}, \mu_1^{gen})$

$Z_d\ p_T > 30$ GeV, $Z_d\ L_{xy} < 400$ cm

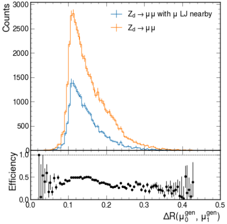
$Z_d \rightarrow \mu\mu$, $m_B = 200$ GeV, $Z_d < L_{xy} > = 300$ cm



m_{Z_d} = **0.25 GeV**
(more collimated)



m_{Z_d} = **1.2 GeV**



m_{Z_d} = **5 GeV**
(less collimated)

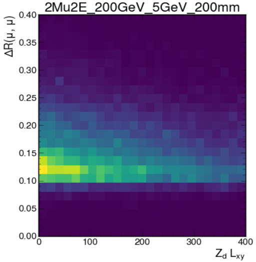
- We see non-zero efficiency in the entire range of ΔR.
- No strong dependence on ΔR, but interesting trend which we can explore more through 2D Efficiency.

Note: The x ranges are different in these plots

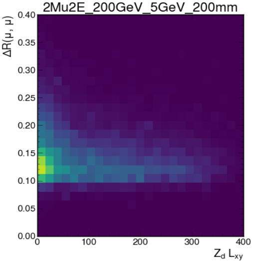
$\Delta R(\mu_0^{gen}, \mu_1^{gen})$ and $Z_d\ L_{xy}$

$Z_d\ p_T > 30$ GeV, $Z_d\ L_{xy} < 400$ cm

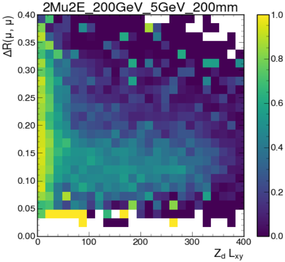
$Z_d \to \mu\mu$, $m_{Z_d} = 5$ GeV,$m_B = 200$ GeV, $Z_d < L_{xy} > = 300$ cm



den: $Z_d \to \mu\mu$



num: $Z_d \to \mu\mu$ with μ LJ nearby



Efficiency

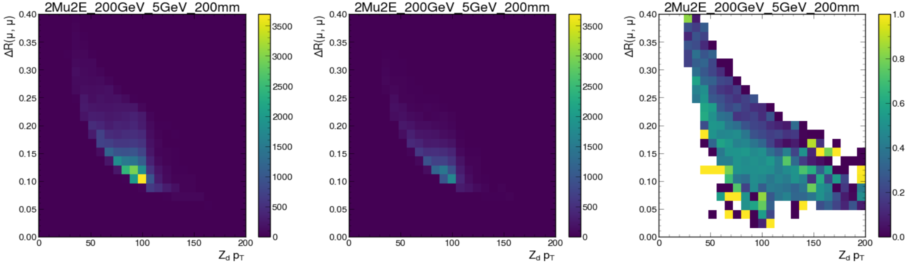
- Overall high efficiency for low L_{xy} region.
- At higher L_{xy}, the efficiency falls as ΔR increases (DSA muon region).
- This is totally counterintuitive; we expect muon reconstruction to be easier at higher ΔR and thereby high efficiency.

We can look at this again with another variable $Z_d\ p_T$!

$\Delta R(\mu_0^{gen}, \mu_1^{gen})$ and $Z_d\ p_T$

$Z_d\ p_T > 30$ GeV, $Z_d\ L_{xy} < 400$ cm

$Z_d \to \mu\mu$, $m_{Z_d} = 5$ GeV,$m_B = 200$ GeV, $Z_d < L_{xy} > = 300$ cm



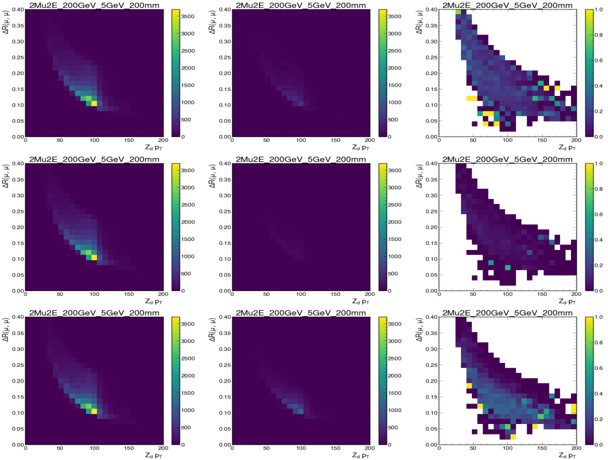
den: $Z_d \to \mu\mu$ num: $Z_d \to \mu\mu$ with μ LJ nearby Efficiency

- Overall high efficiency in low ΔR region.
- For a fixed p_T, low efficiency for higher ΔR region.

We need to study the higher ΔR region more!

Looking at PF-PF, PF-DSA, DSA-DSA Separately

$\Delta R(\mu_0^{gen}, \mu_1^{gen})$ and μ_0^{gen} p_T



den: $Z_d \rightarrow \mu\mu$

num: $Z_d \rightarrow \mu\mu$ with μ LJ nearby

Efficiency

PF-PF: No strong dependence on ΔR.

PF-DSA: Not strong dependence on ΔR.

DSA-DSA: For a given p_T, efficiency falls as ΔR increases.

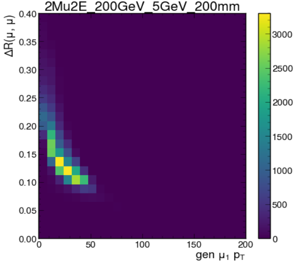
We need to study the DSA-DSA μ-type LJs more!

$\Delta R(\mu_0^{gen}, \mu_1^{gen})$ and μ_1^{gen} p_T

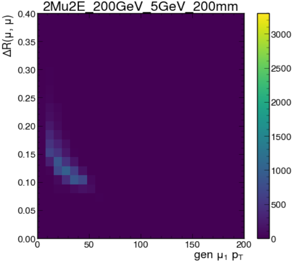
Looking at only DSA-DSA μ LJs

Z_d $p_T > 30$ GeV, Z_d $L_{xy} < 400$ cm

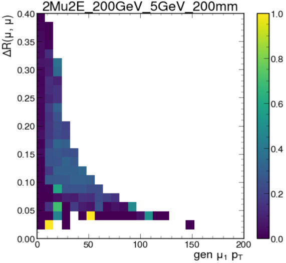
$Z_d \to \mu\mu$,$m_{Z_d} = 5$ GeV,$m_B = 200$ GeV, $Z_d < L_{xy} > = 300$ cm



den: $Z_d \to \mu\mu$



num: $Z_d \to \mu\mu$ with μ LJ nearby



Efficiency

- Low efficiency is concentrated in the low sub-leading muon pT region.

- High ΔR corresponds to low sub-leading p_T.

  We check whether it is true for a fixed leading μ p_T.

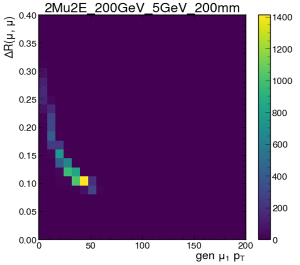
Applying Cut On Leading μ p_T

ΔR(μ_0^{gen}, μ_1^{gen}) and μ_1^{gen} p_T

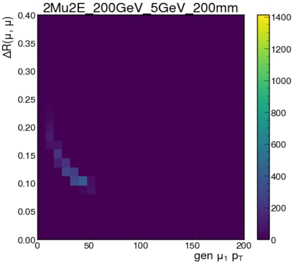
Looking at DSA-DSA μ LJ

Z_d p_T $>$ 30 GeV, Z_d L_{xy} $<$ 150 cm, 50 $<=$ μ_0^{gen} p_T $<=$ 60 GeV

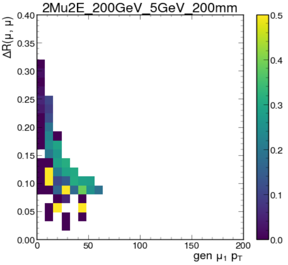
$Z_d \rightarrow \mu\mu$, m_{Z_d} = 5 GeV,m_B = 200 GeV, Z_d $< L_{xy} >$ = 300 cm



den: $Z_d \rightarrow \mu\mu$



num: $Z_d \rightarrow \mu\mu$ with μ LJ nearby



Efficiency

- We observe that the high ΔR corresponds to low sub-leading p_T. And the lower p_T muons don't pass our 10GeV cut.

Conclusion

We see good efficiency in a large range of the parameter space we are considering.

For $Z_d \to ee$ ($e\gamma$ LJ):

- No serious dependence on p_T for both more collimated and less collimated electrons
- We see behaviours which depend on the collimation of the electrons. In the most collimated case, we are really good at reconstructing at all displacements. We see low efficiency in the somewhat displaced region (decay in the tracker) when the electrons are less collimated.
- We are actively investigating how to improve the electron/photon ID to recover efficiency.

For $Z_d \to \mu\mu$ (μ LJ):

- Efficiency extends out to very high displacements, even for extremely collimated muon pairs.
- We see a drop in efficiency in the higher ΔR regions, as the higher ΔR regions corresponds to the low sub-leading μ p_T and they fail to pass the cuts applied.

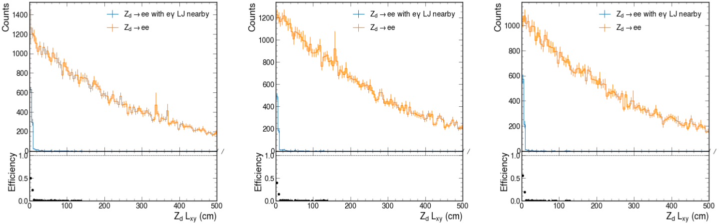
THANK YOU

BACK UP

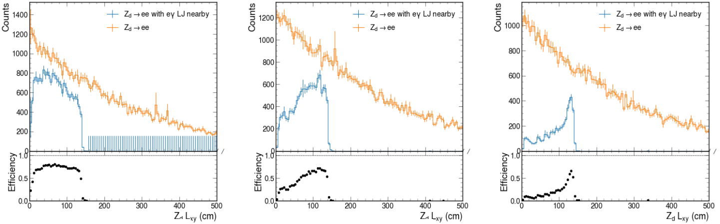
Separating the $e\gamma$ LJs

$Z_d\ L_{xy}$

e -type: $N_e > 0$



γ -type: N_γ >0, $N_e = 0$

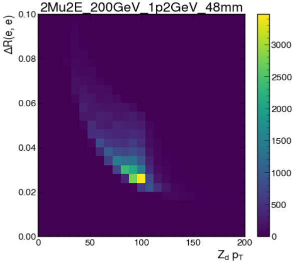


m_{Z_d} = **0.25 GeV** m_{Z_d} = **1.2 GeV** m_{Z_d} = **5 GeV**

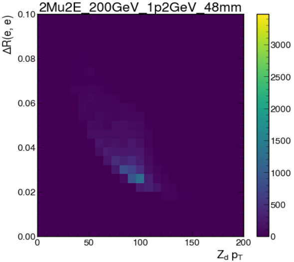
$\Delta R(e_0^{gen}, e_1^{gen})$ and $Z_d\ p_T$

$Z_d\ p_T > 30$ GeV, $Z_d\ L_{xy} < 150$ cm

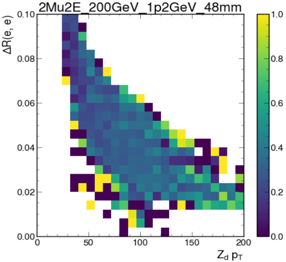
$Z_d \to ee$, $m_{Z_d} = 1.2$ GeV, $m_B = 200$ GeV, $Z_d < L_{xy} > = 300$ cm



den: $Z_d \to ee$



num: $Z_d \to ee$ with $e\gamma$ LJ nearby



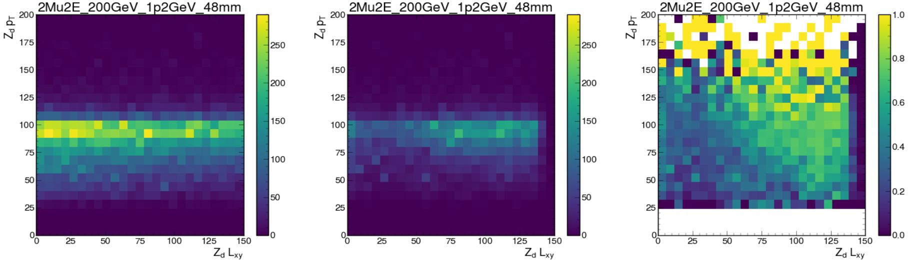
Efficiency

- Efficiency doesn't have a huge change in the range shown.

Z_d L_{xy} and Z_d p_T

Z_d $p_T > 30$ GeV, Z_d $L_{xy} < 150$ cm

$Z_d \to ee$, $m_{Z_d} = 1.2$ GeV, $m_B = 200$ GeV, $Z_d < L_{xy} > = 300$ cm



den: $Z_d \to ee$

num: $Z_d \to ee$ with $e\gamma$ LJ nearby

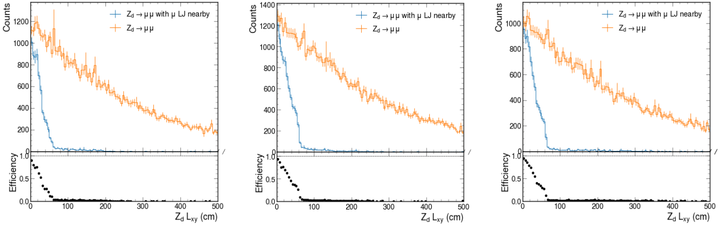
Efficiency

- High Efficiency at high p_T and high L_{xy} region.
- Very low efficiency for low L_{xy} and low p_T.
- The correlation between L_{xy} and p_T is something we already saw before.

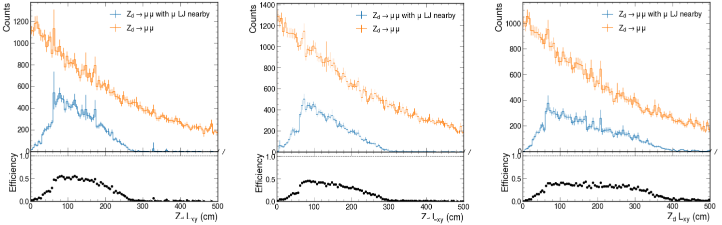
Separating the μ LJs

$Z_d\ L_{xy}$

PFμ -type : $N_{DSA} = 0$



DSA μ -type: $N_{DSA} > 0$

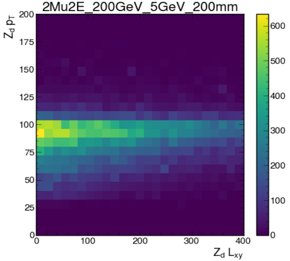


m_{Z_d} **= 0.25 GeV** m_{Z_d} **= 1.2 GeV** m_{Z_d} **= 5 GeV**

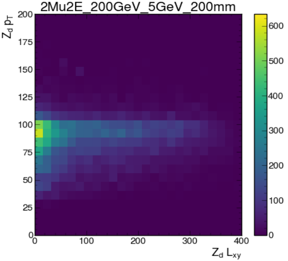
LJ Reconstruction Efficiency w.r.t Z_d L_{xy} and Z_d p_T

Z_d $p_T > 30$ GeV, Z_d $L_{xy} < 400$ cm

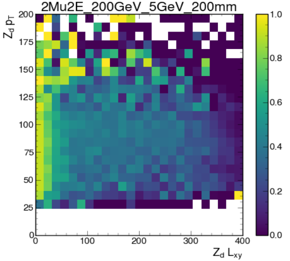
$Z_d \to \mu\mu$, $m_{Z_d} = 5$ GeV,$m_B = 200$ GeV, $Z_d < L_{xy} > = 300$ cm



den: $Z_d \to \mu\mu$



num: $Z_d \to \mu\mu$ with μ LJ nearby



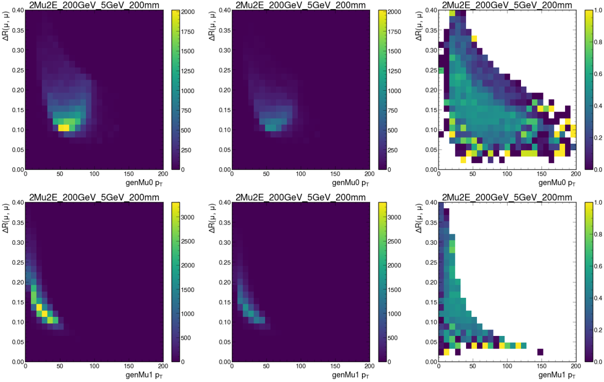
Efficiency

- High Efficiency for low L_{xy} regions.
- For a fixed p_T, low L_{xy} region show high efficiency.
- For a fixed L_{xy}, p_T is not varying that much.

$\Delta R(\mu_0^{gen}, \mu_1^{gen})$ and $\mu_0^{gen} / \mu_1^{gen}$ p_T

$Z_d\ p_T > 30$ GeV, $Z_d\ L_{xy} < 400$ cm

$Z_d \to \mu\mu$, $m_{Z_d} = 5$ GeV,$m_B = 200$ GeV, $Z_d < L_{xy} > = 300$ cm



den: $Z_d \to \mu\mu$

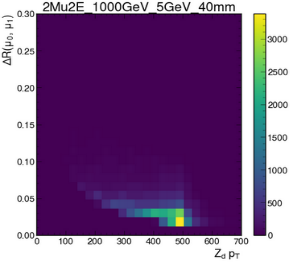
num: $Z_d \to \mu\mu$ with μ LJ nearby

Efficiency

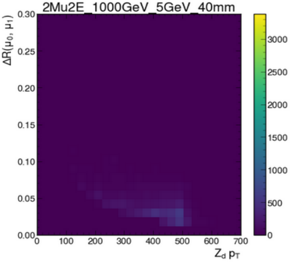
$Z_d\ p_T$ and $\Delta R(e_0^{gen},\ e_1^{gen})$

$Z_d\ p_T > 30$ GeV, $Z_d\ L_{xy} < 150$ cm

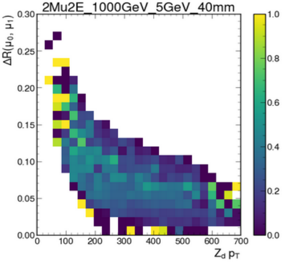
$Z_d \to \mu\mu$, $m_{Z_d} = 1.2$ GeV,$m_B = 200$ GeV, $Z_d < L_{xy} > = 300$ cm



den: $Z_d \to \mu\mu$



num: $Z_d \to \mu\mu$ with μ LJ nearby



Efficiency