

# Search For Self-Interacting Dark Matter With Displaced Lepton Jets

## Lepton Jet Reconstruction Efficiency

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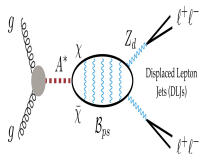
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- ① SIDM Model
- ② Lepton Jets (LJs)
- ③ LJ Reconstruction Efficiency Definition
- ④ Lepton Collimation
- ⑤  $e\gamma$  LJ Reconstruction Efficiency
- ⑥  $\mu$  LJ Reconstruction Efficiency
- ⑦ Conclusion



- 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))**

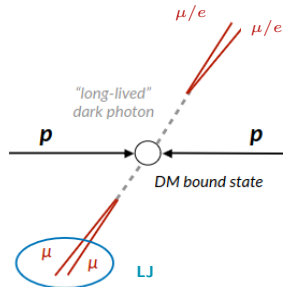
### Free Parameters:

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

### Signal:

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

**Final states :  $2\mu 2e$  or  $4\mu$**



- Group of collimated leptons in a tight cone.
- We apply anti-  $k_T$  clustering ( $\Delta R = 0.4$ ) to **PF  $e$** , **PF  $\gamma$** , **PF  $\mu$**  and **DSA  $\mu$** .

### 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 $\gamma$		20 GeV	Loose	Loose
PF $\mu$		5 GeV	Loose	None
DSA $\mu$		10 GeV	DSA	None

### Categories of LJs:

- $e\gamma$  ( $N_\mu = 0$ )
- $\mu$  ( $N_\mu \geq 1$ )

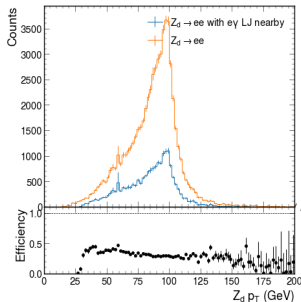
### Events Categories:

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

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  $Z_d \rightarrow ee$  ( $e\gamma$  LJ) and  $Z_d \rightarrow \mu\mu$  ( $\mu$  LJ) separately, as they behave differently in the detector.
- In the figure, the numerator is  $Z_d \rightarrow ee$  with  $e\gamma$  LJ nearby, and the denominator is  $Z_d \rightarrow ee$ .



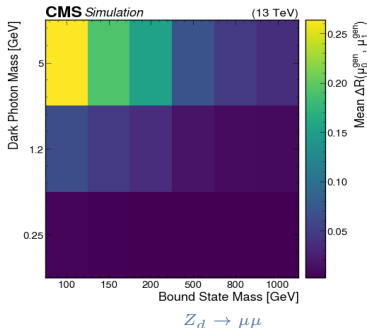
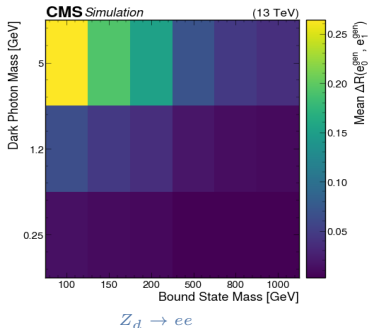
We are considering a wide range of  $L_{xy}$ , a wide range of lepton  $p_T$ , and a wide range of lepton collimation, including extremely collimated final states.

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

- $Z_d p_T$
- $Z_d L_{xy}$
- $\Delta R(\text{Leptons})$

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

# Lepton Collimation



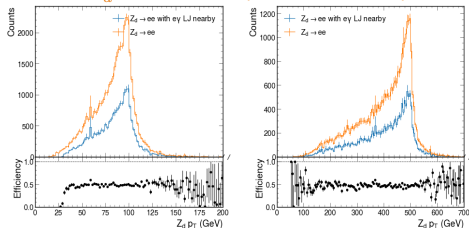
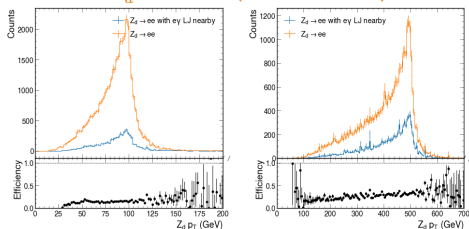
- Both  $m_B$  and  $m_{Z_d}$  affect the collimation of the leptons.
- For fixed  $m_B$ , smallest  $m_{Z_d}$  has the highest collimation.

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

To learn more about kinematics, refer to the previous talk's slides [here](#)

# $e\gamma$ Lepton Jet Reconstruction Efficiency



$L_{xy} < 150 \text{ cm}$ 
 $Z_d \rightarrow ee, Z_d < L_{xy} > = 300 \text{ cm}$ 
 $m_{Z_d} = 0.25 \text{ GeV}$  (more collimated)

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

 $m_B = 200 \text{ GeV}$ 
 $m_B = 1000 \text{ GeV}$ 

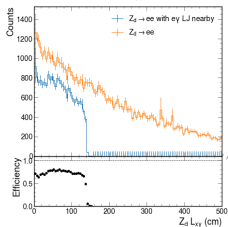
Note: The x ranges are different in these plots

- 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  $p_T > 30 \text{ GeV}$ .
- For less collimated leptons, as the  $p_T$  increases, the efficiency increases.
- Overall lower efficiency for the less collimated leptons.

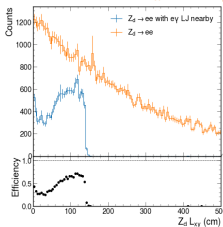
$$Z_d L_{xy}$$

$$Z_d p_T > 30 \text{ GeV}$$

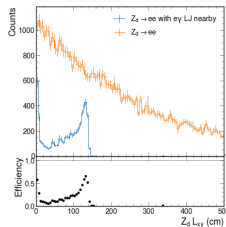
$$Z_d \rightarrow ee, m_B = 200 \text{ GeV}, Z_d < L_{xy} > = 300 \text{ cm}$$



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



$m_{Z_d} = 1.2 \text{ GeV}$

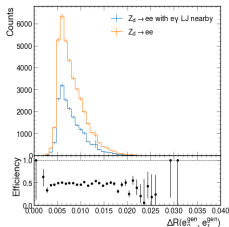


$m_{Z_d} = 5 \text{ GeV}$   
(less collimated)

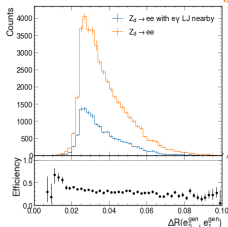
- Efficiency extends to the end of ECAL and is basically flat in the more collimated case.
- Efficiency in the somewhat displaced region drops as the collimation decreases (reason for overall low efficiency in the less collimated sample).
- Current electron ID limits the electron reconstruction to only 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.

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

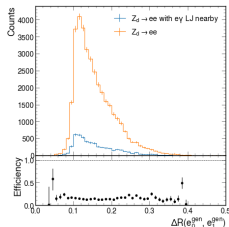
$Z_d p_T > 30 \text{ GeV}, Z_d L_{xy} < 150 \text{ cm}$   
 $Z_d \rightarrow ee, m_B = 200 \text{ GeV}, Z_d < L_{xy} > = 300 \text{ cm}$



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



$m_{Z_d} = 1.2 \text{ GeV}$



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

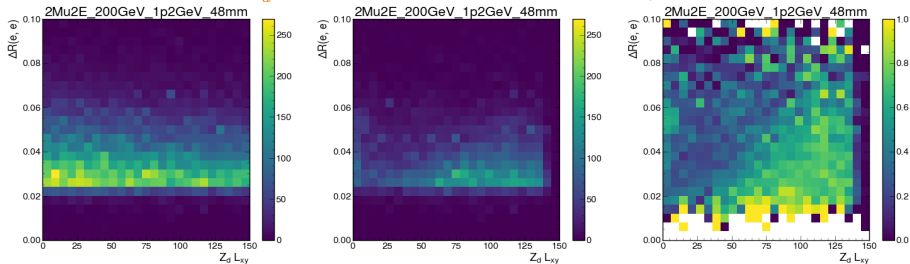
- We see non-zero efficiency in the whole range of  $\Delta R$ .
- Efficiency is not changing much as a function of  $\Delta R$ .
- Overall lower efficiency for less collimated electrons as we saw earlier in the  $L_{xy}$  plot.

Note: The x ranges are different in these plots

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

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

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



den:  $Z_d \rightarrow ee$

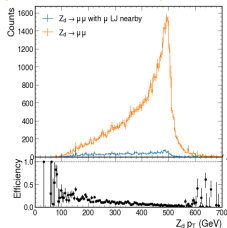
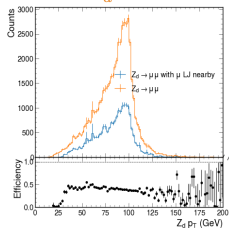
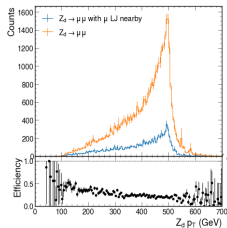
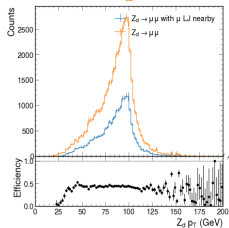
num:  $Z_d \rightarrow ee$  with  $e\gamma$  LJ nearby

Efficiency

- High efficiency at low  $\Delta R$ , 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!

# $\mu$ Lepton Jet Reconstruction Efficiency

$L_{xy} < 400 \text{ cm}$ 
 $Z_d \rightarrow \mu\mu, Z_d < L_{xy} > = 300 \text{ cm}$ 
 $m_{Z_d} = 0.25 \text{ GeV (more collimated)}$ 

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

 $m_B = 200 \text{ GeV}$ 
 $m_B = 1000 \text{ GeV}$ 

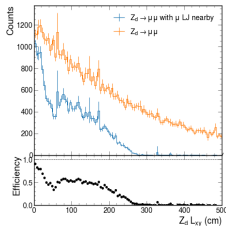
- We see a sharp turn-on at 30 GeV, the cut on  $p_T$  we applied on the LJs.
- After the turn-on, efficiency slightly decreases as the  $p_T$  increases for both cases.
- Overall lower efficiency at higher  $p_T$  for more collimated muons (we suspect it's due the correlation with collimation).

Note: The x ranges are different in these plots

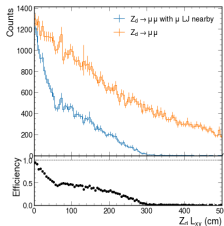
$$Z_d L_{xy}$$

$$Z_d p_T > 30 \text{ GeV}$$

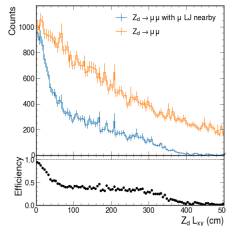
$$Z_d \rightarrow \mu\mu, m_B = 200 \text{ GeV}, Z_d < L_{xy} > = 300 \text{ cm}$$



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



$m_{Z_d} = 1.2 \text{ GeV}$



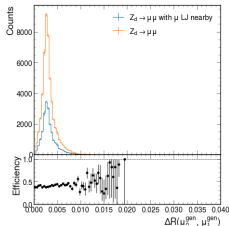
$m_{Z_d} = 5 \text{ GeV}$   
(less collimated)

- 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.

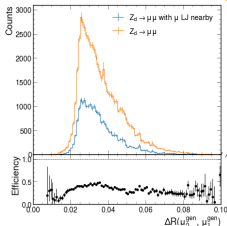
$$\Delta R(\mu_0^{gen}, \mu_1^{gen})$$

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

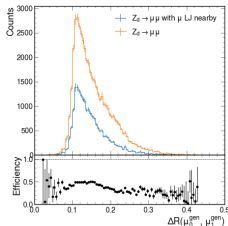
$$Z_d \rightarrow \mu\mu, m_B = 200 \text{ GeV}, Z_d < L_{xy} > = 300 \text{ cm}$$



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



$m_{Z_d} = 1.2 \text{ GeV}$



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

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

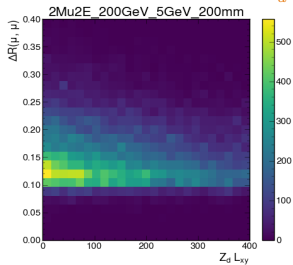
Note: The x ranges are different in these plots



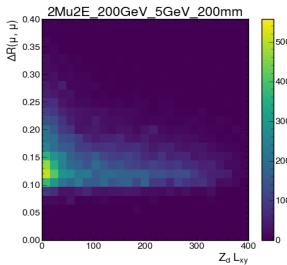
$$\Delta R(\mu_0^{\text{gen}}, \mu_1^{\text{gen}}) \text{ and } Z_d L_{xy}$$

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

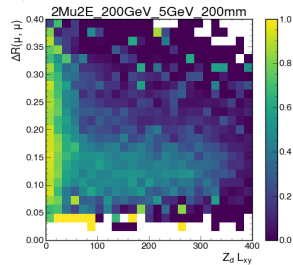
$$Z_d \rightarrow \mu\mu, m_{Z_d} = 5 \text{ GeV}, m_B = 200 \text{ GeV}, Z_d < L_{xy} > = 300 \text{ cm}$$



den:  $Z_d \rightarrow \mu\mu$



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



Efficiency

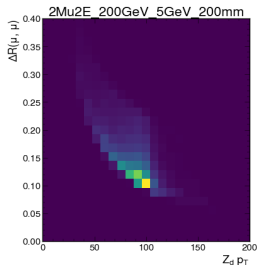
- Overall high efficiency for low  $L_{xy}$  region.
- At higher  $L_{xy}$ , the efficiency falls as  $\Delta R$  increases (DSA muon region).
- This is totally counterintuitive; we expect muon reconstruction to be easier at higher  $\Delta R$  and thereby high efficiency.

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

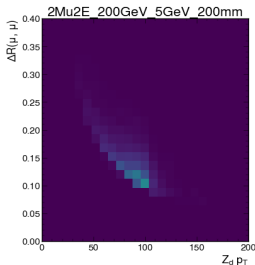
$$\Delta R(\mu_0^{\text{gen}}, \mu_1^{\text{gen}}) \text{ and } Z_d p_T$$

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

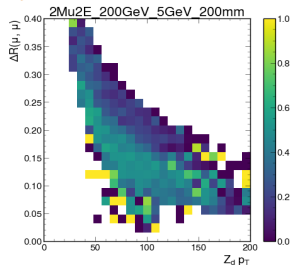
$$Z_d \rightarrow \mu\mu, m_{Z_d} = 5 \text{ GeV}, m_B = 200 \text{ GeV}, Z_d < L_{xy} > = 300 \text{ cm}$$



den:  $Z_d \rightarrow \mu\mu$



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

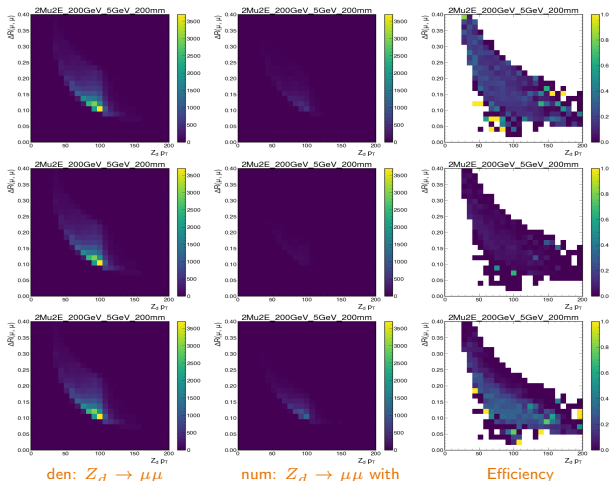


Efficiency

- Overall high efficiency in low  $\Delta R$  region.
- For a fixed  $p_T$ , low efficiency for higher  $\Delta R$  region.

We need to study the higher  $\Delta R$  region more!

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



PF-PF: No strong dependence on  $\Delta R$ .

PF-DSA: Not strong dependence on  $\Delta R$ .

DSA-DSA: For a given  $p_T$ , efficiency falls as  $\Delta R$  increases.

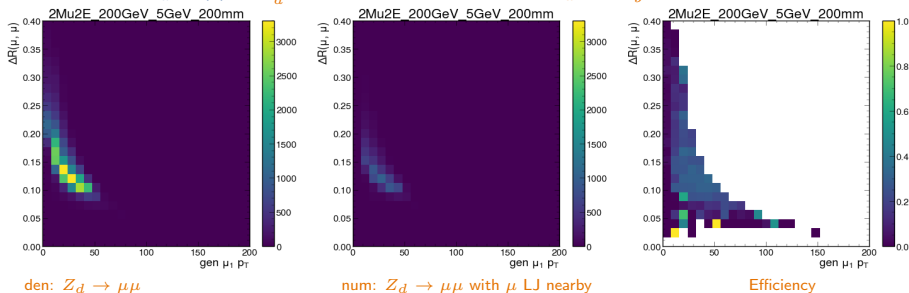
We need to study the DSA-DSA  $\mu$ -type LJs more!

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

Looking at only DSA-DSA  $\mu$  LJs

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

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



- Low efficiency is concentrated in the low sub-leading muon  $p_T$  region.
- High  $\Delta R$  corresponds to low sub-leading  $p_T$ .

We check whether it is true for a fixed leading  $\mu p_T$ .

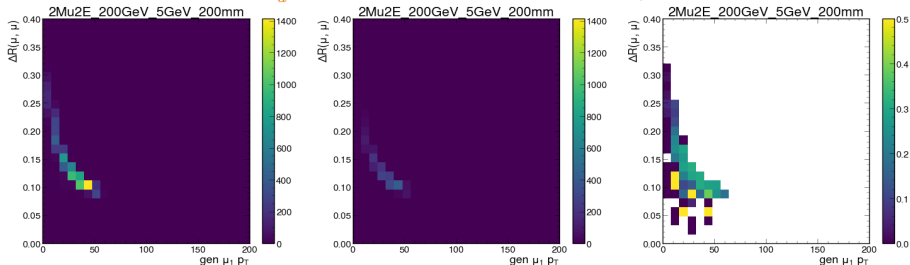
# Applying Cut On Leading $\mu$ $p_T$

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

Looking at DSA-DSA  $\mu$  LJ

$$Z_d p_T > 30 \text{ GeV}, Z_d L_{xy} < 150 \text{ cm}, 50 \leq \mu_0^{gen} p_T \leq 60 \text{ GeV}$$

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



den:  $Z_d \rightarrow \mu\mu$

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

Efficiency

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

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

**For  $Z_d \rightarrow ee$  ( $e\gamma$  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  $Z_d \rightarrow \mu\mu$  ( $\mu$  LJ):**

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

# THANK YOU

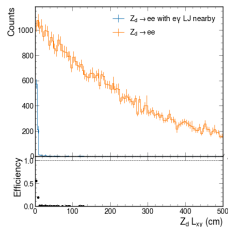
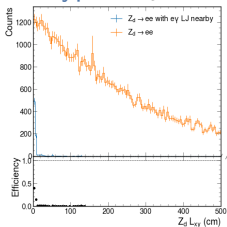
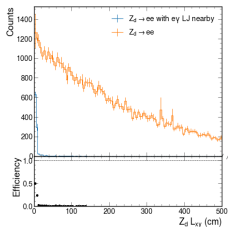
# BACK UP



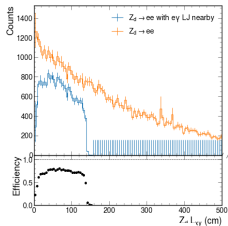
# Separating the $e\gamma$ LJs

$$Z_d L_{xy}$$

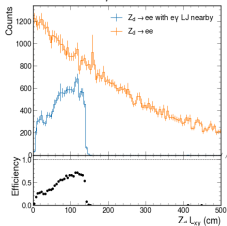
$e$ -type:  $N_e > 0$



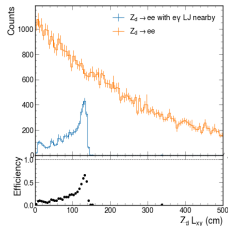
$\gamma$ -type:  $N_\gamma > 0, N_e = 0$



$$m_{Z_d} = 0.25 \text{ GeV}$$



$$m_{Z_d} = 1.2 \text{ GeV}$$

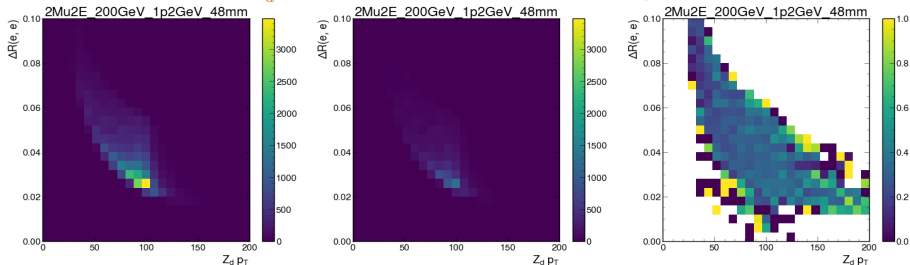


$$m_{Z_d} = 5 \text{ GeV}$$

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

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

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

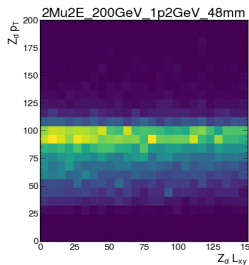


- Efficiency doesn't have a huge change in the range shown.

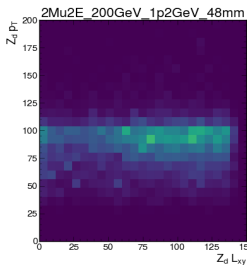
# $Z_d L_{xy}$ and $Z_d p_T$

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

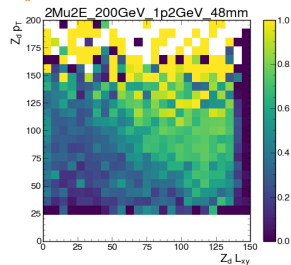
$Z_d \rightarrow ee, m_{Z_d} = 1.2 \text{ GeV}, m_B = 200 \text{ GeV}, Z_d < L_{xy} > = 300 \text{ cm}$



den:  $Z_d \rightarrow ee$



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



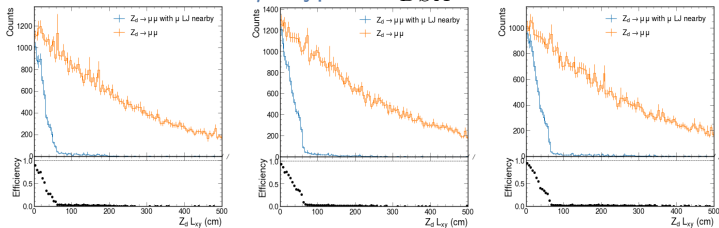
Efficiency

- 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.

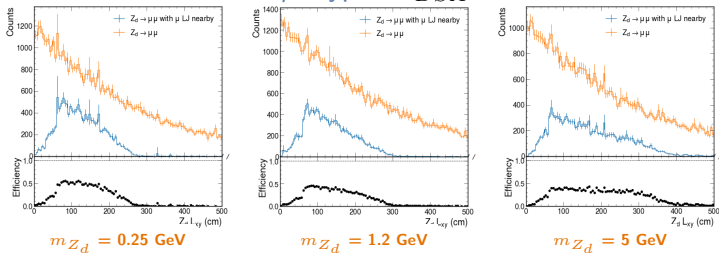
# Separating the $\mu$ LJs

$Z_d L_{xy}$

PF $\mu$ -type :  $N_{DSA} = 0$



DSA  $\mu$ -type:  $N_{DSA} > 0$

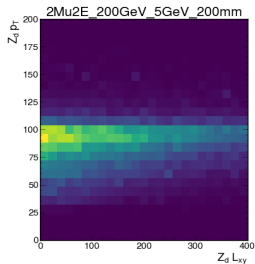


# LJ Reconstruction Efficiency w.r.t

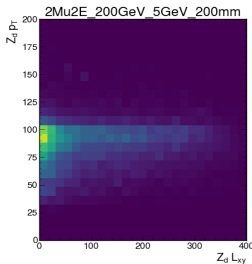
$$Z_d L_{xy} \text{ and } Z_d p_T$$

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

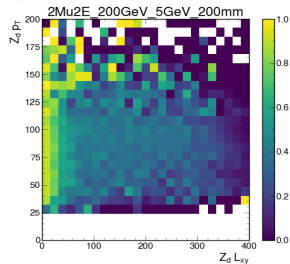
$$Z_d \rightarrow \mu\mu, m_{Z_d} = 5 \text{ GeV}, m_B = 200 \text{ GeV}, Z_d < L_{xy} > = 300 \text{ cm}$$



den:  $Z_d \rightarrow \mu\mu$



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



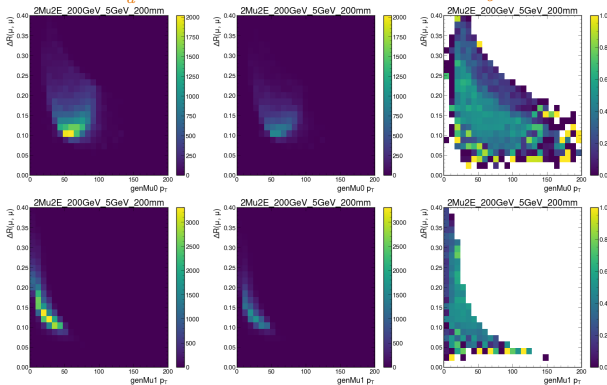
Efficiency

- 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.

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

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

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



den:  $Z_d \rightarrow \mu\mu$

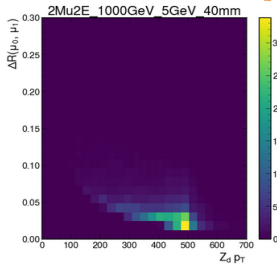
num:  $Z_d \rightarrow \mu\mu$  with  $\mu$  LJ nearby

Efficiency

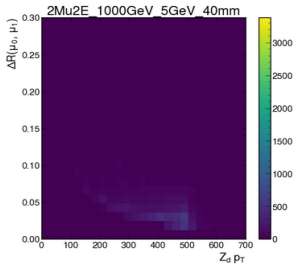
# $Z_d p_T$ and $\Delta R(e_0^{gen}, e_1^{gen})$

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

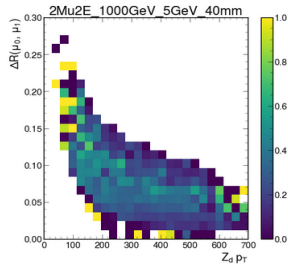
$Z_d \rightarrow \mu\mu, m_{Z_d} = 1.2 \text{ GeV}, m_B = 200 \text{ GeV}, Z_d < L_{xy} > = 300 \text{ cm}$



den:  $Z_d \rightarrow \mu\mu$



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



Efficiency