Sensitivity to Long-Lived Dark Photons at the ILC

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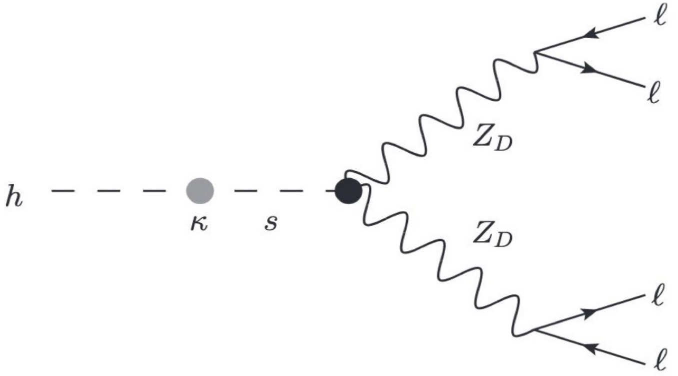
Introduction

- Our project seeks to study the production of long-lived dark photons at the ILC, to provide a benchmark for long-lived studies at the ILC
- Because of the clean environment found in linear colliders, and the high rate of Higgs production, we would expect the ILC to be a good environment for studying low mass long-lived weakly coupled particles
- Link to our LOI

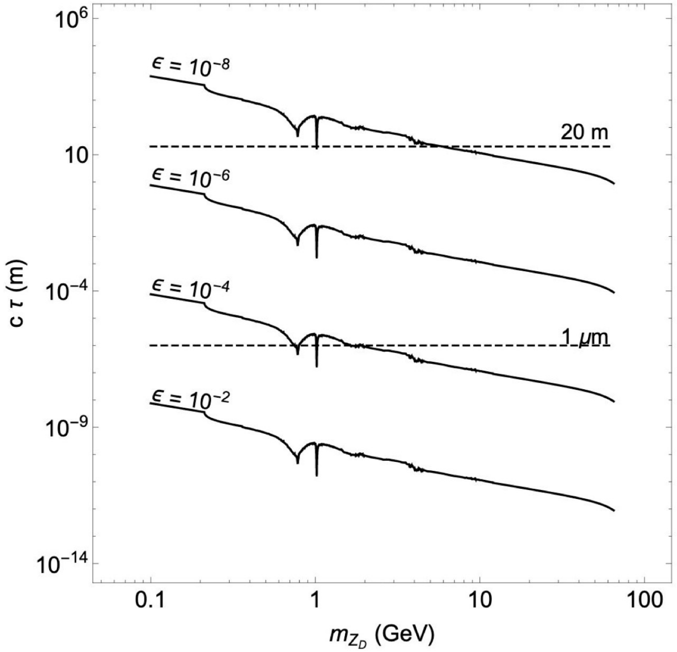
Dark Photons (Z_D)

- Mediators of a broken dark U(1) gauge theory that mixes kinematically with the standard model hypercharge, with mixing ε
- Dark sector could have a dark Higgs, which can mix with the SM Higgs with mixing κ
- We're studying production via exotic Higgs decay: $H \rightarrow Z_D Z_D$
  - Z_D can decay either hadronically or leptonically
- If ε < ~ 10^{-5}, the dark photons will be long-lived



Above: Dark photon production mechanism

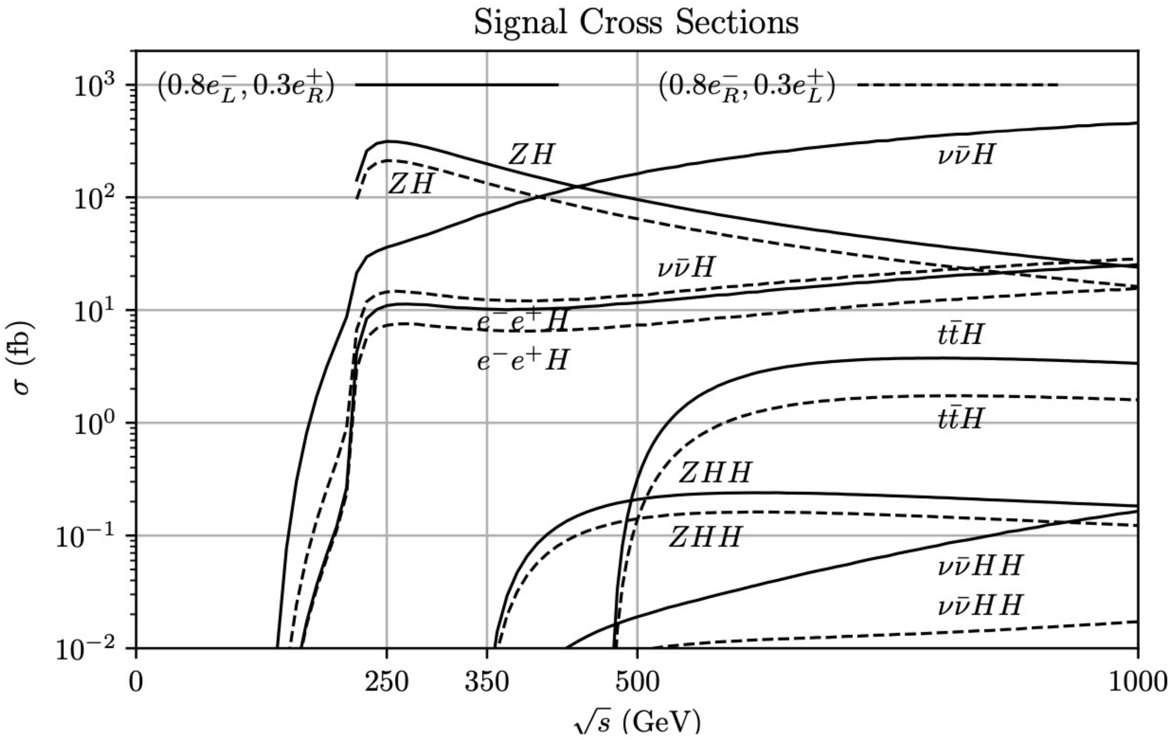
Right: Relationship between ε, c τ, and dark photon mass



Curtin, Essig, Gori, & Shelton, arXiv:1412.0018

Dark Photons at the ILC

- The proposed ILC should generate a large number of Higgs, so dark photon production via the Higgs could be observable
- Relative to hadron colliders, the clean environment of a linear collider should be favorable for reconstructing low mass displaced vertices
- Targeting a dataset with a luminosity of 2 ab^{-1} at $\sqrt{s} = 250$ GeV
- This energy is tuned for studying the Higgstrahlung process ($e^+e^- \rightarrow ZH$)

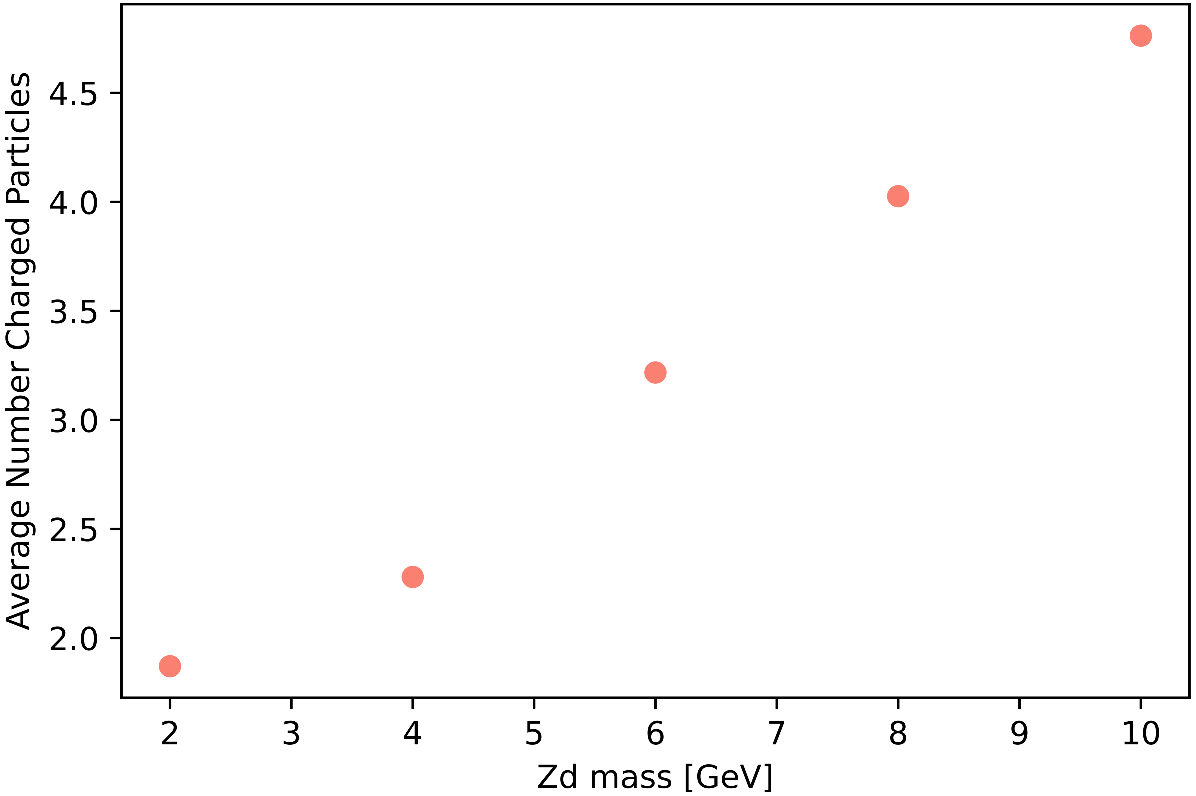

Signal Cross Sections

Cross section of Higgstrahlung process at different $\sqrt{s}$ energies

Potter, arXiv:2002.02399

Benefits of ILC - Hadronic Decays

- The background to a low mass hadronic decay is greatly reduced in ILC compared to hadron colliders because of the clean environment
- Opens sensitivity to a type of decay that we might not be able to study as well at a hadron collider
- Because of this, studying $Z_D \to q\bar{q}$ in addition to $Z_D \to 2l$ at low mass



Average number of final state charged particles from each dark photon as a function of dark photon mass

Dark Photon Studies At Other Experiments

HL-LHC sensitivity to this model

- Prompt decays of dark photons from exotic Higgs production in HL-LHC

Sensitivity at CEPC and FCC-ee

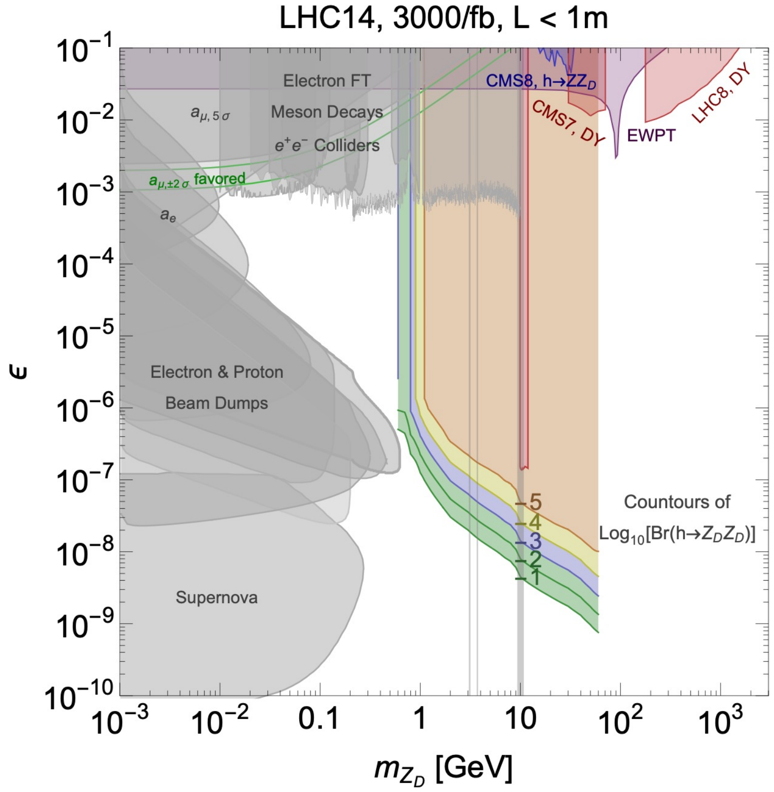
- Hadronic decays of LLPs from exotic Higgs decays in future e^+e^- colliders

Sensitivity via H-> inv

- Studying Higgs decays at future colliders

Sensitivity of dark Higgs via direct decay

European Strategy Report 2020



Sensitivity to dark photon production for different dark photon masses, branching ratios of $H \to Z_D Z_D$*, and epsilons*

Curtin, Essig, Gori, & Shelton, arXiv:1412.0018

Goals of our study

- Determine ILC sensitivity to long-lived dark photon production for our particular signal ($H \rightarrow Z_D Z_D$), Z_D mass in 1 to 10s of GeV
  - Calculate sensitivity as a function of the Z_D mass, lifetime, and ε as well as the branching ratio of Higgs to Z_D for different fiducial requirements
- Provide a benchmark for future SiD long-lived particle performance studies
- Study truth level acceptance
- Study default signal reconstruction efficiency and potential background sources in full simulation

Our Samples

- MC Generation
  - Using MG5@NLO + Pythia8
  - Using this model: from arXiv:1412.0018

- Fast Simulation w/Delphes for prompt decays and truth-level
- Full Simulation w/ILCSoft

Our signature:

$e^+e^- \rightarrow ZH \rightarrow ZZ_DZ_D$; $Z_D \rightarrow 2l$ or $Z_D \rightarrow q\bar{q}$

- Created samples of different lifetimes by setting epsilon and the width
- Validated samples at truth-level

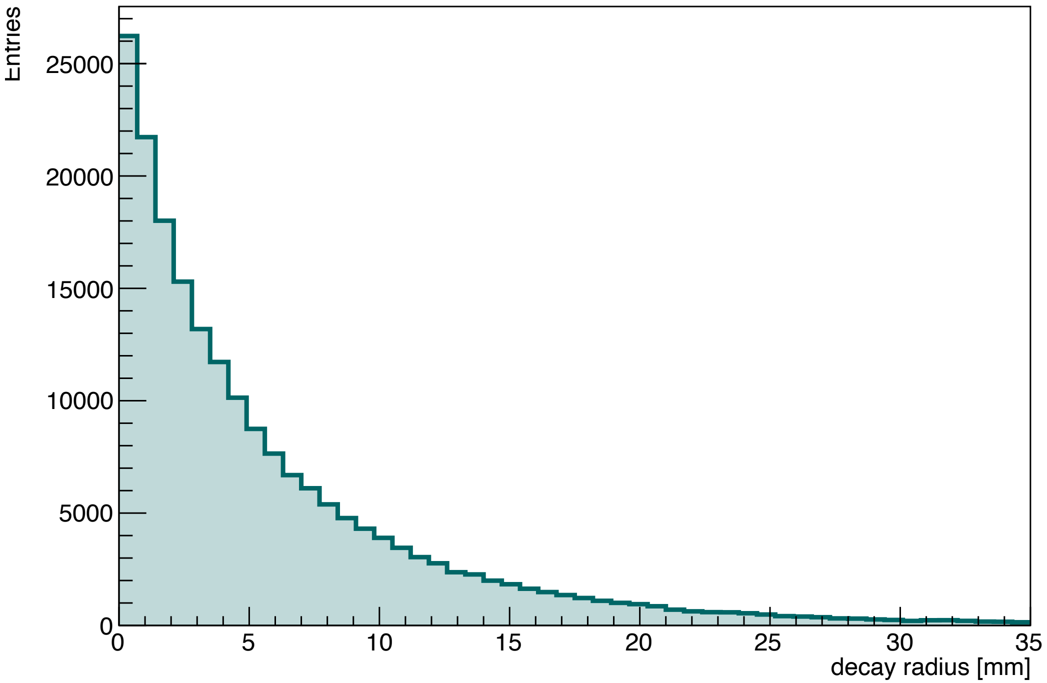
Model Parameters:

- *Z_D Mass*
- *ε and Z_D width*
- *Higgs Branching ratio*
  - *Dark Higgs mass*
  - *Higgs/Dark Higgs mixing ($\varkappa$)*

Dark Photon Decay Distance

- At truth-level
- Taken as the distance from the IP to the production vertex of the Z_D decay products
- Fits initial calculations using $\beta\gamma$ and cτ

	Decay constant from exponential [mm]
M(Z_D) = 10 GeV, ε = $1 * 10^{-6}$	6.16
M(Z_D) = 10 GeV, ε = $1 * 10^{-7}$	608
M(Z_D) = 2 GeV, $\varepsilon = 3.16 * 10^{-5}$	24.0
M(Z_D) = 2 GeV, $\varepsilon = 3.16 * 10^{-6}$	2400



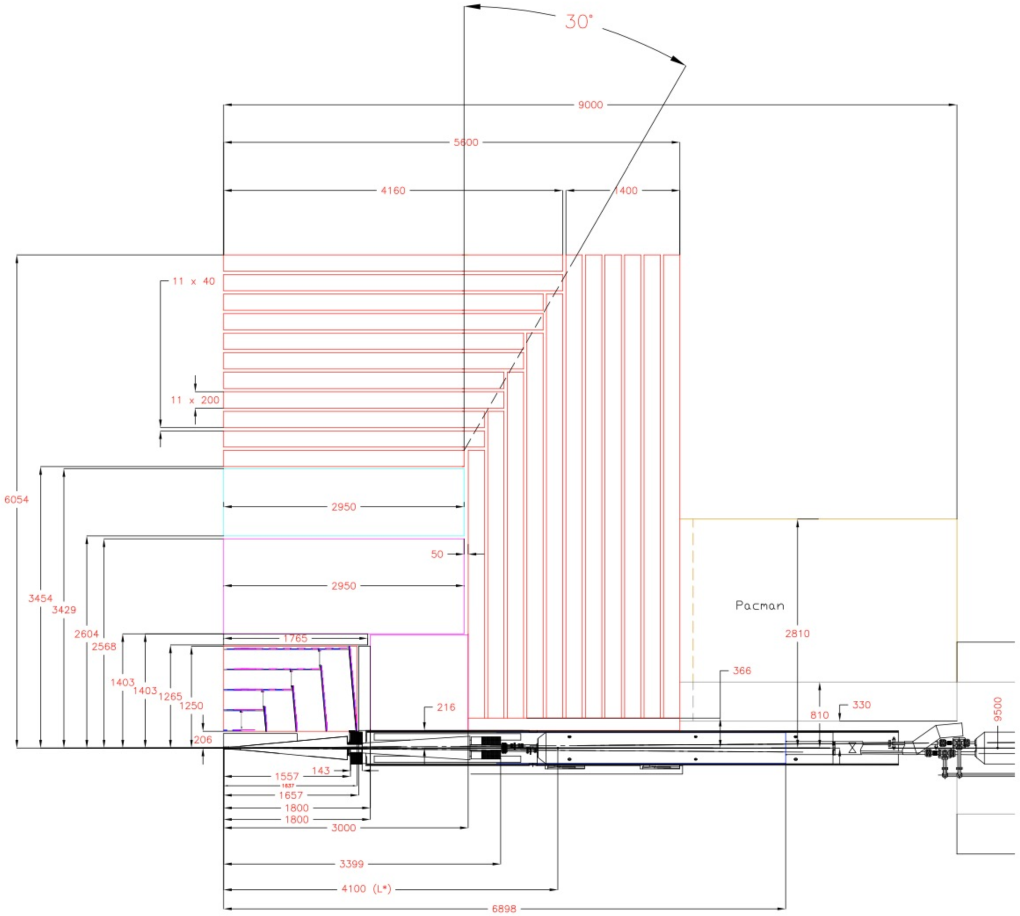
Decay radius of 10 GeV dark photon with $\varepsilon = 1 * 10^{-6}$
(Decay constant 6)

Dark Photon Acceptance

- Look at how the dark photon acceptance varies throughout the detector systems
    - Looking separately at hadronic and leptonic acceptance
- Select fiducial volumes that restrict dark photon decays to specific detector regions
    - Decaying within the vertex detector to study tracker performance
    - Decaying before the calorimeters – includes decays that don't get reconstructed in the inner tracker
- Only require one dark photon in each event to pass the requirements for the regions

Defining Acceptance Regions

- Region 1:
  - Dark photon decaying within the vertex detector
    - 2 mm < Decay Radius < 60 mm
  - Minimum radius is much higher than the lowest possible radius, but choosing a larger minimum will help eliminate b quark backgrounds
- Region 2:
  - Dark photon decaying before the calorimeters
    - 2 mm < Decay Radius < 1250 mm
- General Requirements for both regions:
  - Both decay products need to have:
    - $p > .3$ MeV for Region 1, $p > 1$ GeV for Region 2
    - $\theta > 20$ degrees
    - $d0 > 2$ mm
  - For hadronic decays, each event needs a certain min. number of charged particles to pass requirements
    - Acceptances calculated for min. 3 and min. 4 charged



Potter, arXiv:2002.02399

Acceptance values

- Acceptance values for the two fiducial regions
  - Region 1 – Before end of vertex detector
  - Region 2 – Before beginning of calorimeters

$Z_D \rightarrow q\bar{q}, 3\ pass\ reqs.$

	Region 1	Region 2
M(Z_D) = 10 GeV, ε = $1 * 10^{-6}$	66.3%	69.6%
M(Z_D) = 10 GeV, ε = $1 * 10^{-7}$	23.6%	88.5%
M(Z_D) = 2 GeV, ε = $3.16 * 10^{-5}$	12.0%	14.0%
M(Z_D) = 2 GeV, ε = $3.16 * 10^{-6}$	1.03%	8.92%

$Z_D \rightarrow l^+l^-$

	Region 1	Region 2
M(Z_D) = 10 GeV, ε = $1 * 10^{-6}$	86.7%	86.7%
M(Z_D) = 10 GeV, ε = $1 * 10^{-7}$	20.9%	98.1%
M(Z_D) = 2 GeV, ε = $3.16 * 10^{-5}$	95.0%	98.7%
M(Z_D) = 2 GeV, ε = $3.16 * 10^{-6}$	4.76%	61.7%

$Z_D \rightarrow q\bar{q}, 4\ pass\ reqs.$

	Region 1	Region 2
M(Z_D) = 10 GeV, ε = $1 * 10^{-6}$	59.1%	63.0%
M(Z_D) = 10 GeV, ε = $1 * 10^{-7}$	20.3%	82.1%
M(Z_D) = 2 GeV, ε = $3.16 * 10^{-5}$	11.8%	14.0%
M(Z_D) = 2 GeV, ε = $3.16 * 10^{-6}$	1.01%	8.92%

Back of the Envelope Max. Sensitivity

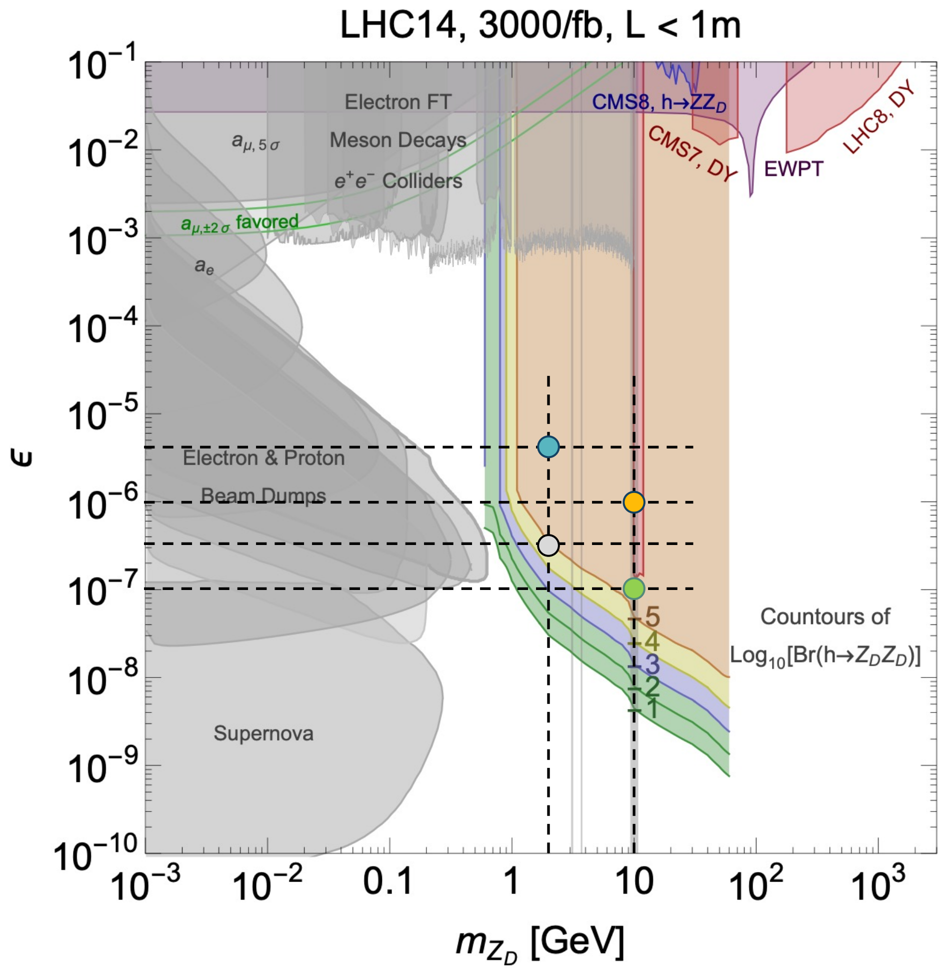
- From the acceptance values, we can calculate the minimum branching ratio of $H \rightarrow Z_D Z_D$ in order to have sensitivity to a signal
- Assuming zero background and 100% efficiency
- If we expect zero background, we'll have sensitivity to signals that predict 3 or more dark photons
- $BR(Z_D \rightarrow ll)$ depends on the Z_D mass
- Cross section of Higgs production controlled by higgstrahlung (~310 fb)

$$N_{events\_signal\_exp} = Lumi \times \sigma_H \times BR_{H \rightarrow Z_D Z_D} \times (BR_{Z_D \rightarrow ll})^2 \times A \times E$$

Sensitivity Results

- Minimum branching ratio of Higgs to $Z_D Z_D$ for us to be able to detect the dark photons

$Z_D \to l^+ l^-$	Min. BR(H→$Z_D Z_D$) Region 1	Min. BR(H→$Z_D Z_D$) Region 2
● M(Z_D) = 10 GeV, ε = $1 * 10^{-6}$	$6.20 * 10^{-5}$	$6.20 * 10^{-5}$
● M(Z_D) = 10 GeV, ε = $1 * 10^{-7}$	$2.58 * 10^{-4}$	$5.48 * 10^{-5}$
● M(Z_D) = 2 GeV, ε = $3.16 * 10^{-5}$	$2.23 * 10^{-4}$	$2.14 * 10^{-4}$
● M(Z_D) = 2 GeV, ε = $3.16 * 10^{-6}$	$6.20 * 10^{-3}$	$3.24 * 10^{-4}$
$Z_D \to q\bar{q}$, 3 charged pass reqs.		
● M(Z_D) = 10 GeV, ε = $1 * 10^{-6}$	$4.19 * 10^{-5}$	$1.11 * 10^{-5}$
● M(Z_D) = 10 GeV, ε = $1 * 10^{-7}$	$1.49 * 10^{-5}$	$1.42 * 10^{-5}$
● M(Z_D) = 2 GeV, ε = $3.16 * 10^{-5}$	$5.60 * 10^{-5}$	$4.79 * 10^{-5}$
● M(Z_D) = 2 GeV, ε = $3.16 * 10^{-6}$	$6.53 * 10^{-4}$	$7.53 * 10^{-5}$



Curtin, Essig, Gori, & Shelton, arXiv:1412.0018

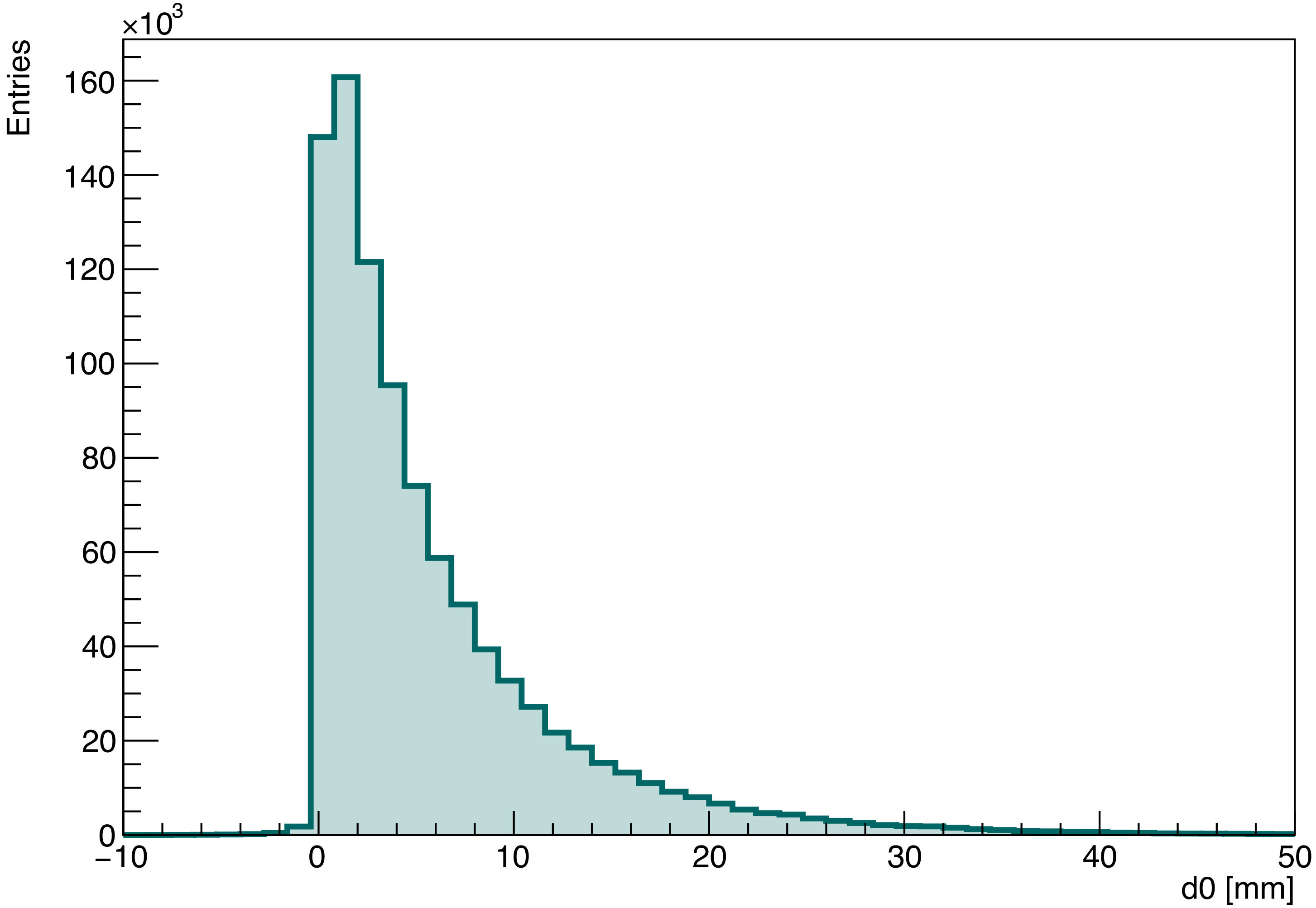
Outlook

- Look at the signal in full simulation
- Look at full simulation to study the effects from backgrounds
  - ZH, ZZ, Ze^+e^- ($Z \rightarrow bb$, K_s) possible backgrounds

Thank you!

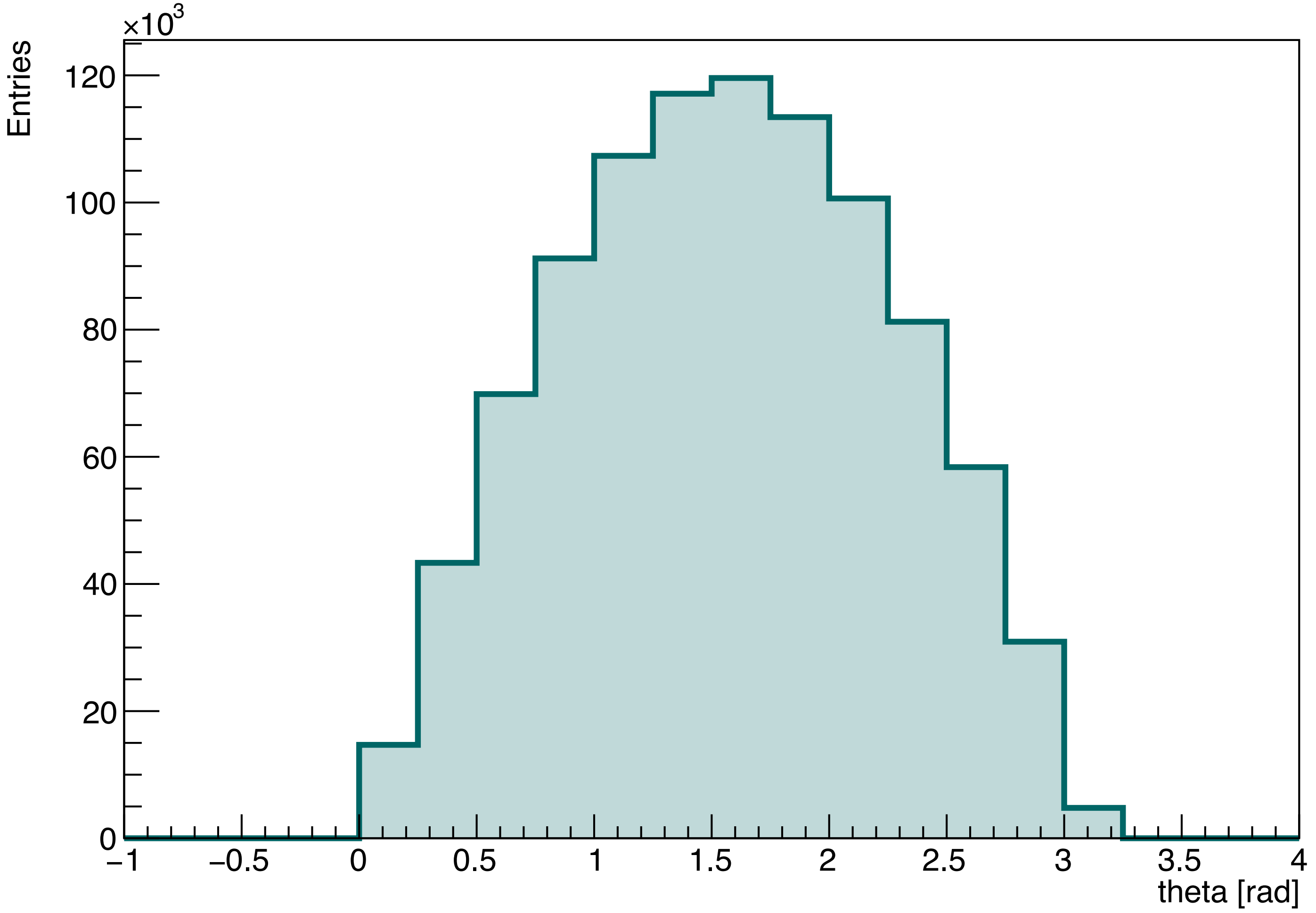
Backup Slides

|d0| of charged final state from Zd



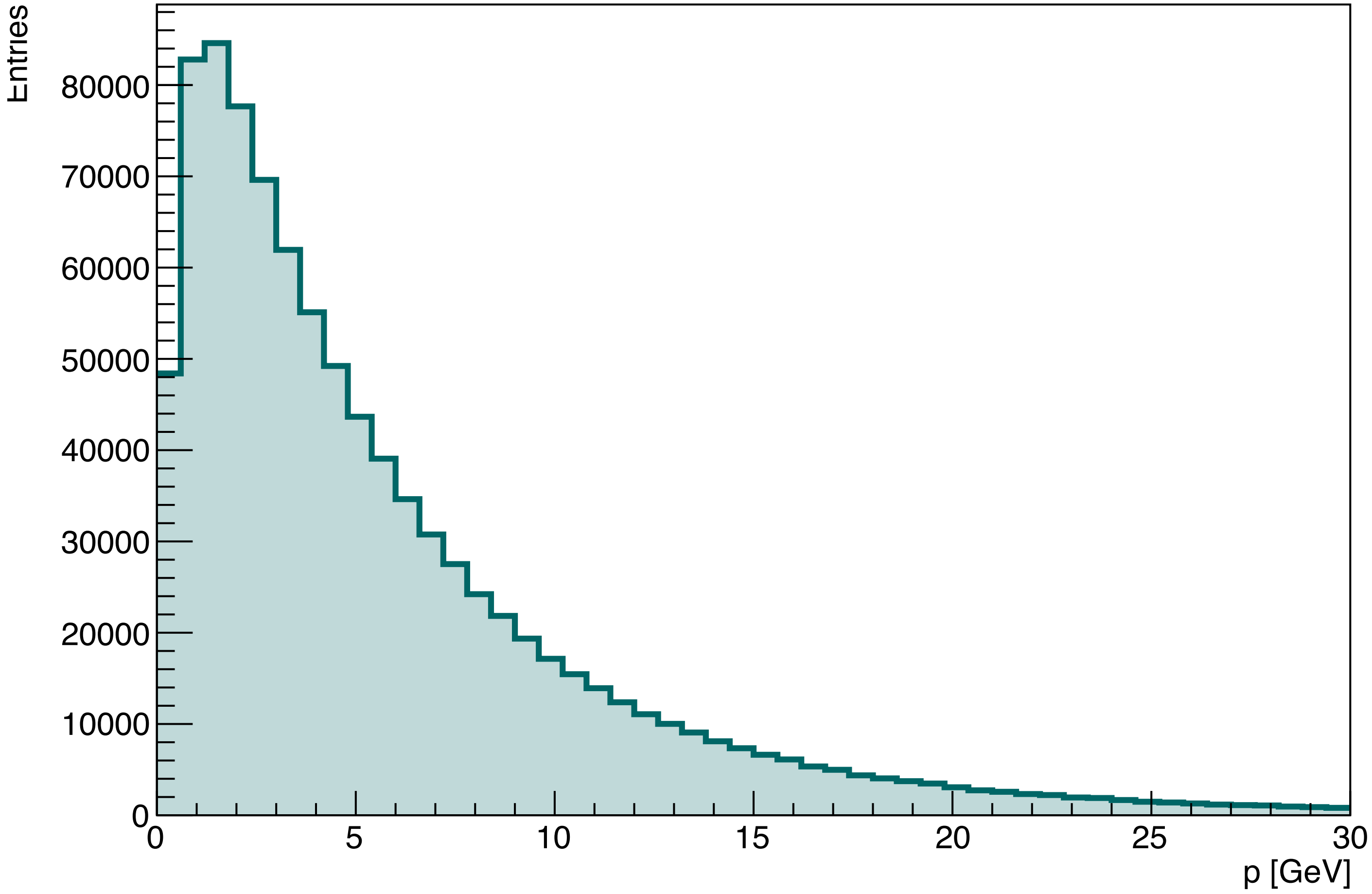
10 GeV dark photon with $\varepsilon = 1 * 10^{-6}$; $Z_D \rightarrow q\overline{q}$

Theta of charged final state from Zd



10 GeV dark photon with $\varepsilon = 1 * 10^{-6}$; $Z_D \rightarrow q\overline{q}$

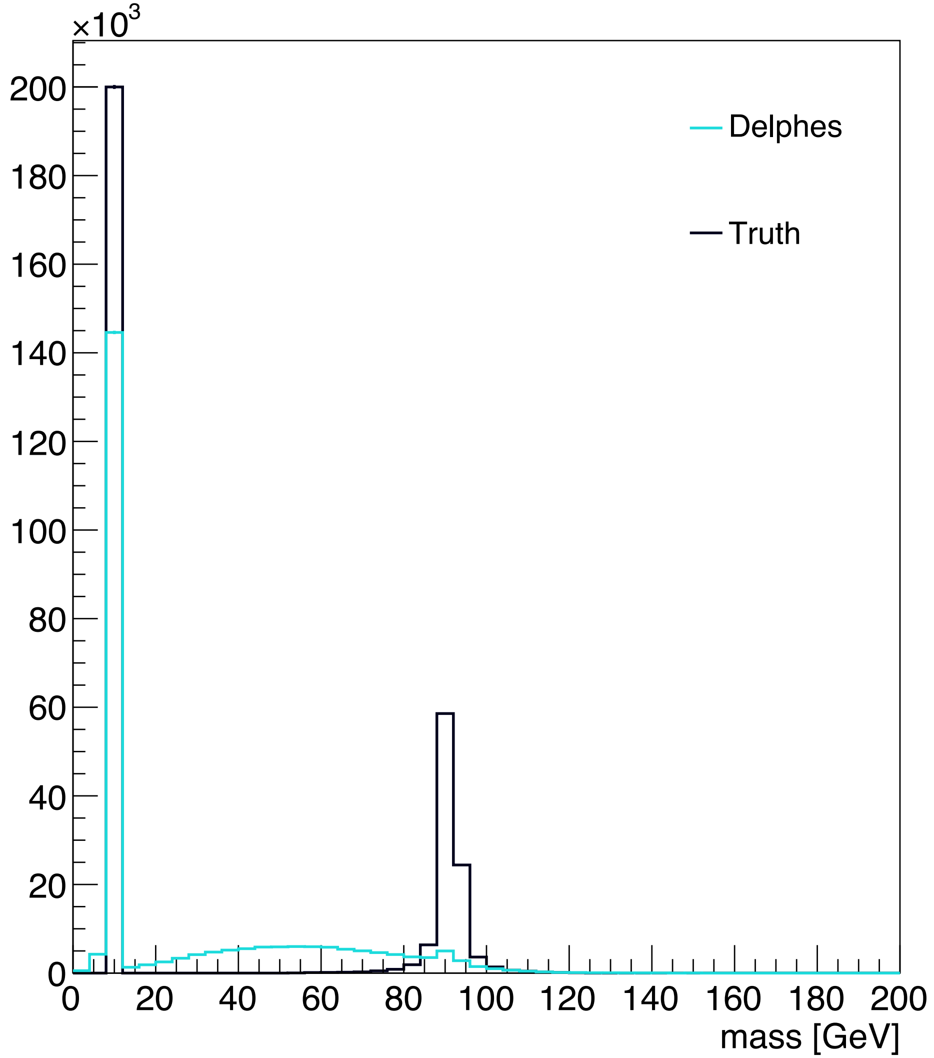
p of charged final state from Zd



10 GeV dark photon with $\varepsilon = 1 * 10^{-6}$; $Z_D \rightarrow q\bar{q}$

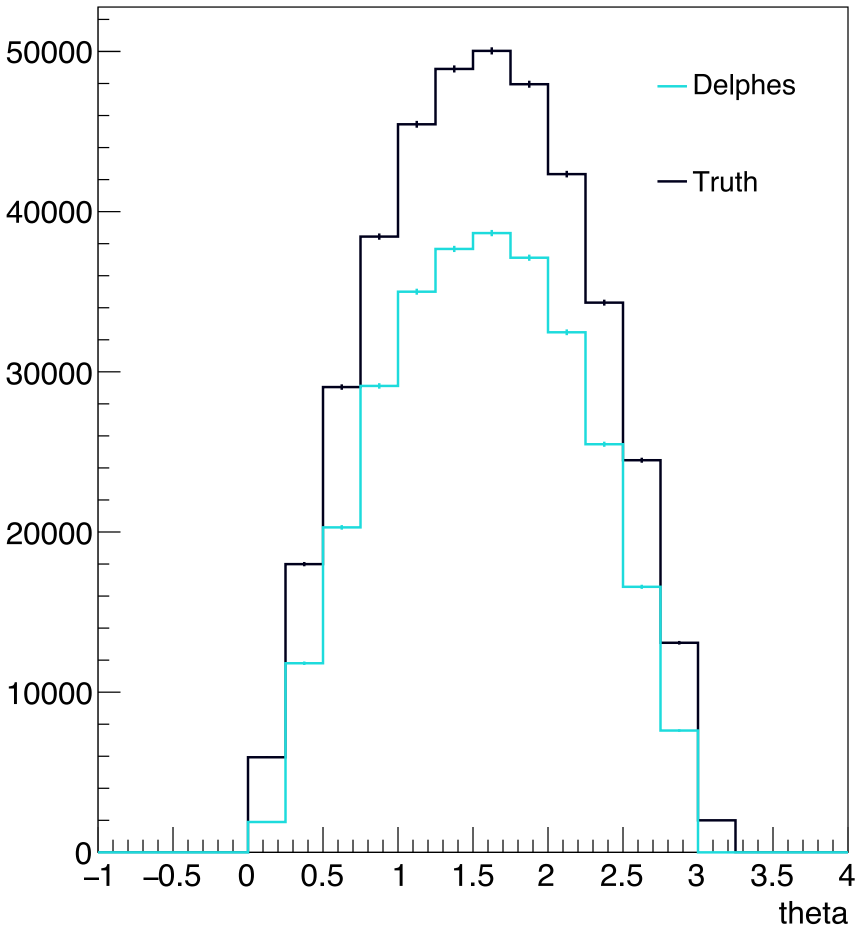
Truth-level Validation: Invariant mass; $Z_D \to l^+l^-$

- Comparison of invariant mass at truth level and in fast simulation (Delphes)
  - Delphes treats displaced decays as prompt
- Truth level: Mass of dark photons and Z bosons
- Reconstruction: Invariant mass of all l^+l^- pairs for p > 5 GeV
  - Leptons are mainly from Z decays and dark photon decays, most Z decay products are hadronic, so we see a small peak in reconstruction at the Z mass from leptons



$M(Z_D) = 10\ GeV$, $\varepsilon = 1 * 10^{-6}$
100,000 events

Truth Level Validation: Z_D Decay Product θ, p



- Reasonable coverage in theta, momentum centered around half the Z_D momentum as expected
- $Z_D \rightarrow l^+ l^-$

$M(Z_D) = 10$ GeV, $\varepsilon = 1 * 10^{-6}$

100,000 events