HPS 2016 SIMP Displaced Vertex Search Reach Estimate

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April 4, 2024

SCIPP
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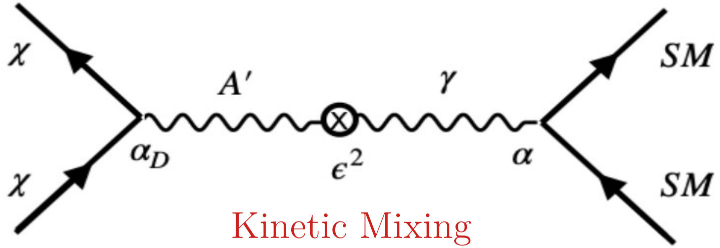
Thermal Dark Matter Hidden Sectors

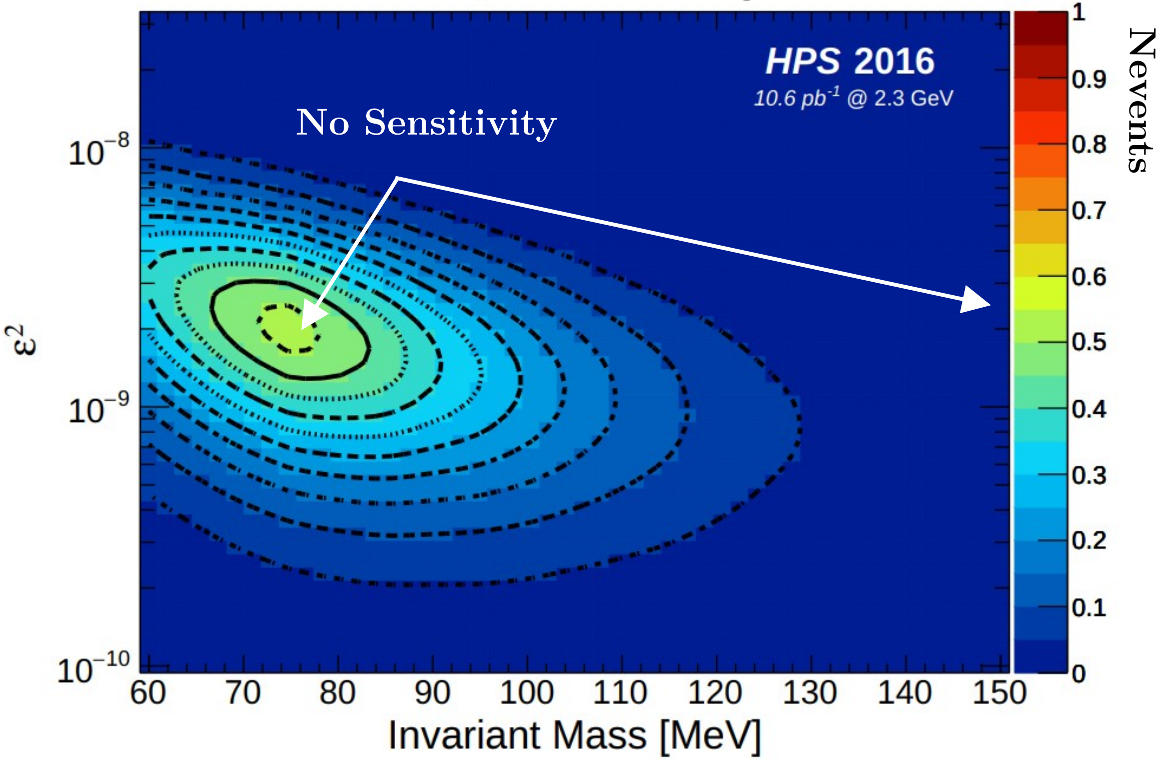
Hidden Sector (HS) models can produce the correct Dark Matter (DM) thermal relic abundance for sub-GeV DM

While not sensitive to canonical displaced A's in the 2016 Engineering run...HPS expects sensitivity to more complex Hidden Sectors



Kinetic Mixing

Expected A' Signal



Strongly Interacting Massive Particles (SIMPs)

Extend A' HS: include **strongly self-interacting massive particles (SIMPs)**[1]

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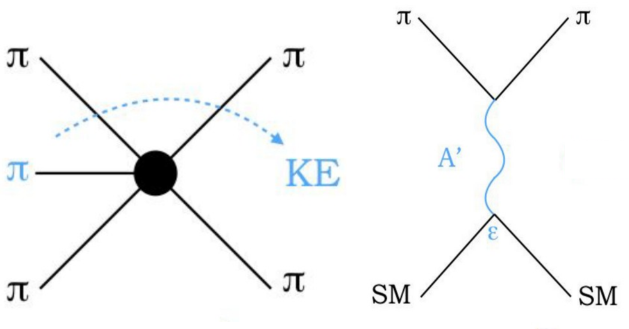

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New freeze-out mechanism 1: $3\pi_D \rightarrow 2\pi_D$ annihilation

- Correct relic abundance for strong-scale π_D self-interaction and $m_{\pi D} \sim 100$ MeV [2]
- "SIMP Miracle"

Heavy Photon maintains kinetic equilibrium

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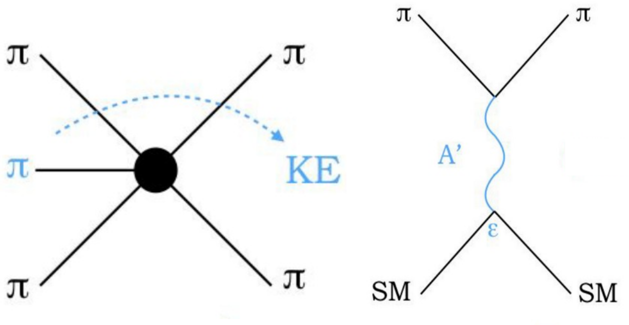

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<u>New freeze-out mechanism 2</u>: V_D "semi-annihilation" [1]

- $\pi_D \pi_D \to \pi_D V_D$, followed by **$V_D \to$SM through intermediate A'**
- Expands thermal DM mass range to ~0.01 – 1 GeV
- A' kinetic mixing ~$10^{-6} < \varepsilon < 10^{-2}$

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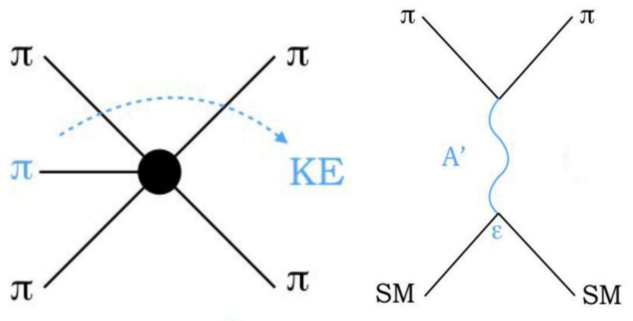

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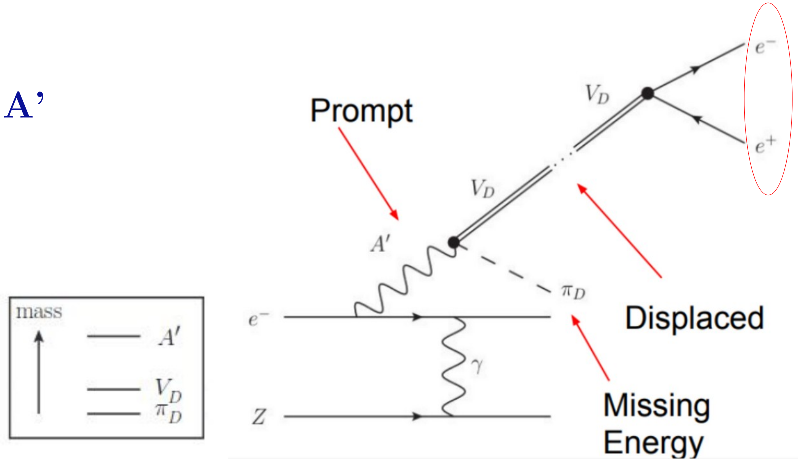
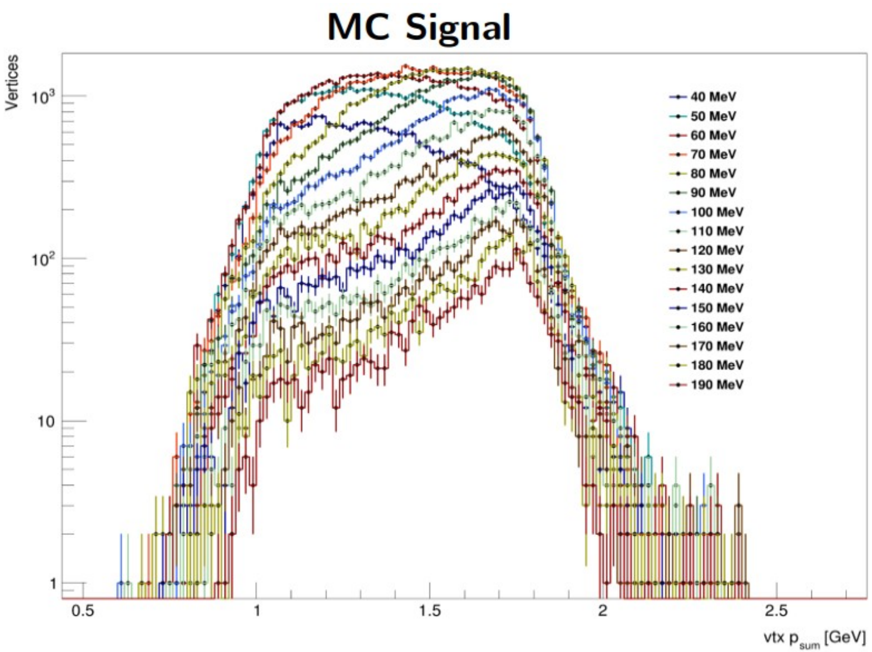
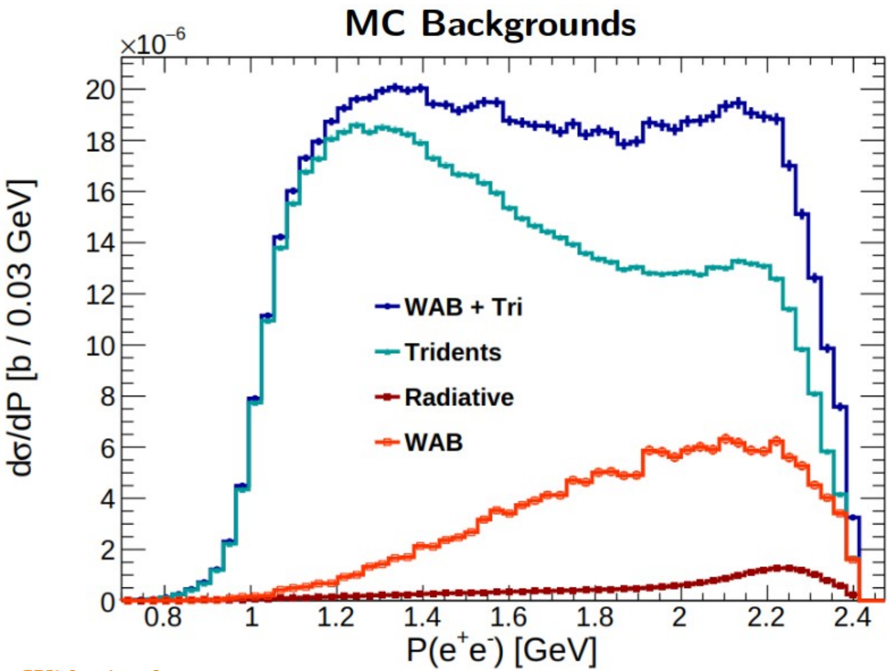
HPS is sensitive to neutral V_D (ρ and Φ) decays to e^+e^-!

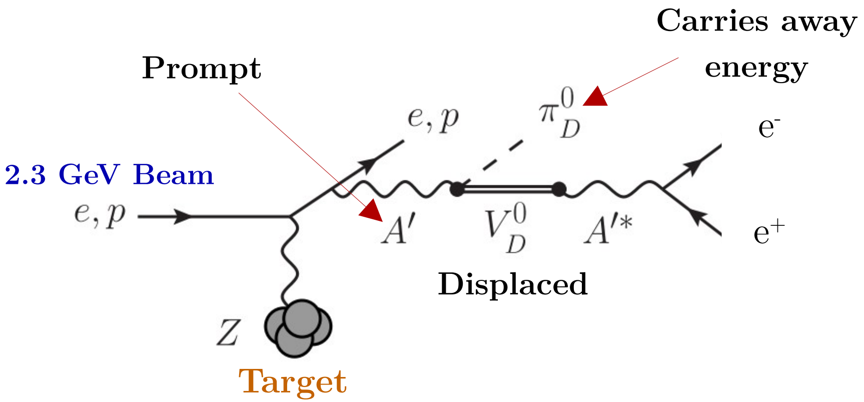


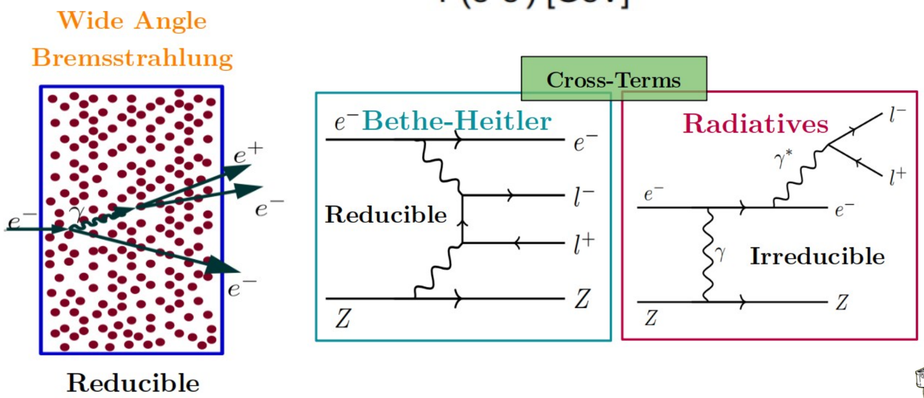
2016 SIMP Reach Estimate

Signal and Control Regions









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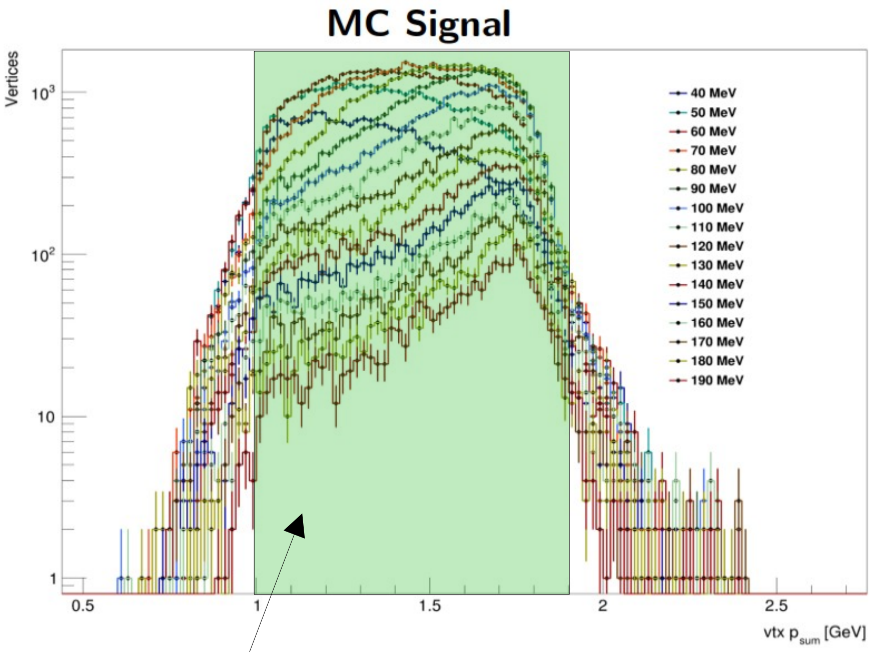
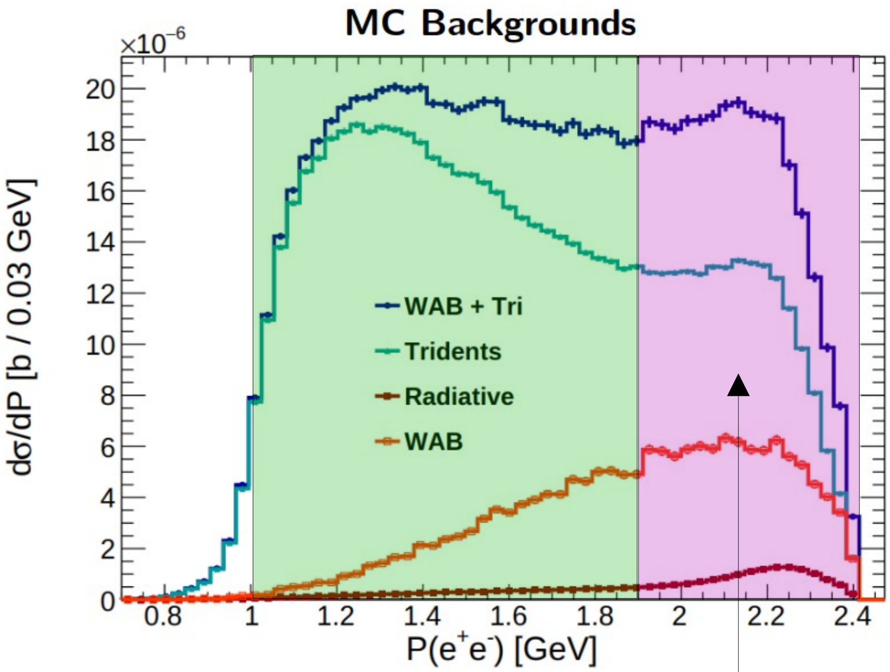
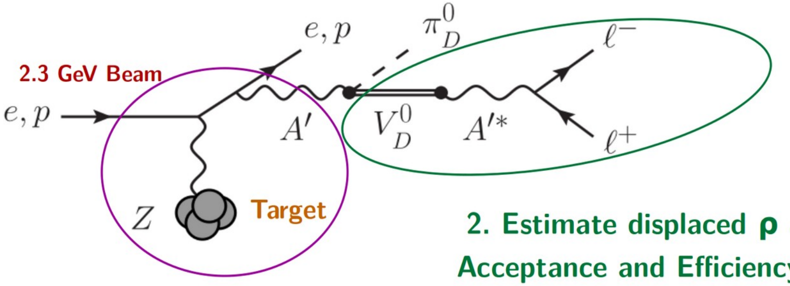




"Low Momentum"
Signal Region

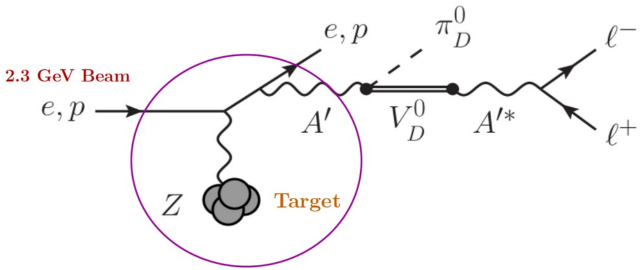


"High Momentum"
Control Region

2. Estimate displaced ρ and Φ Acceptance and Efficiency using MC Signal Region

1. Estimate Total A' Production Rate at Target using MC Control Region

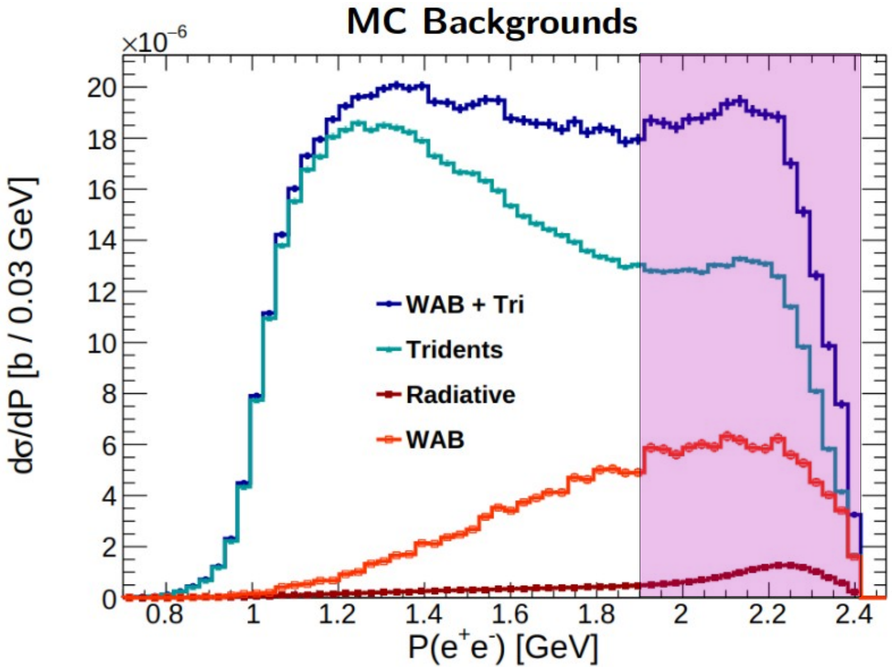
Total A' Production Rate



1. A' cross-section proportional to differential Radiative Tridents

$$\sigma_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\frac{d\sigma_{\gamma^*}}{dm_{l^+l^-}}|_{m_{l^+l^-}=m_{A'}} \quad [3]$$

2. Multiply by Luminosity to get Total A' Production Rate for $m_{A'}$

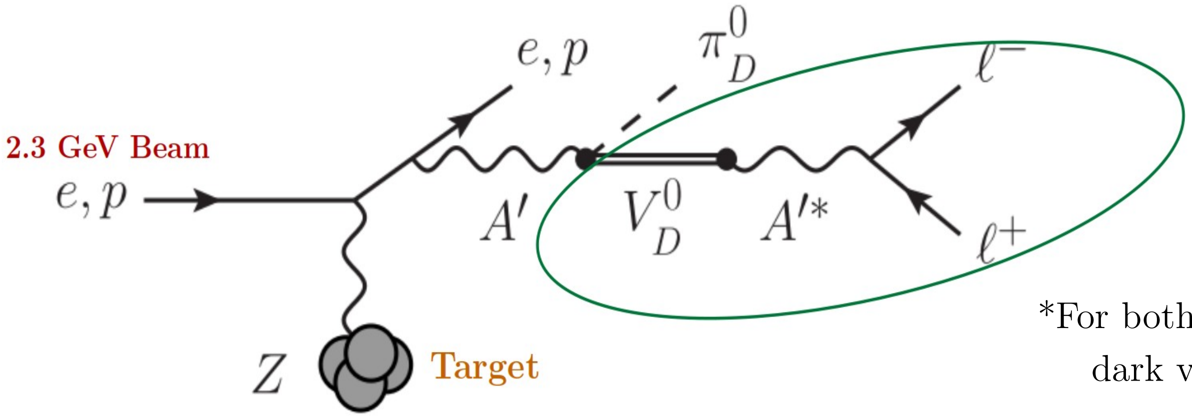


$$N_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\boxed{\frac{dN_{\gamma^*}}{dm_{A'}}}$$

Pure Radiative Tridents not real process, estimated using MC in CR

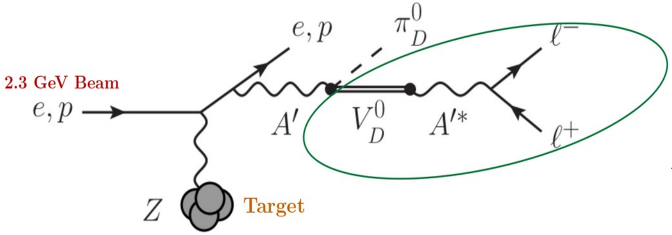
$$\frac{dN_{\gamma^*}}{dm_{A'}} = \left(\frac{dN_{\gamma^*}}{dm_{A'}} / \frac{dN_{\gamma^* CR}}{dm_{A'}}\right)\left(\frac{dN_{\gamma^* CR}}{dm_{A'}} / \frac{dN_{CR}}{dm_{reco}}\right)\frac{dN_{CR}}{dm_{reco}}$$

SIMP Displaced Vertex Acceptance and Efficiency



*For both ρ and Φ dark vectors

SIMP Expected Signal Distribution

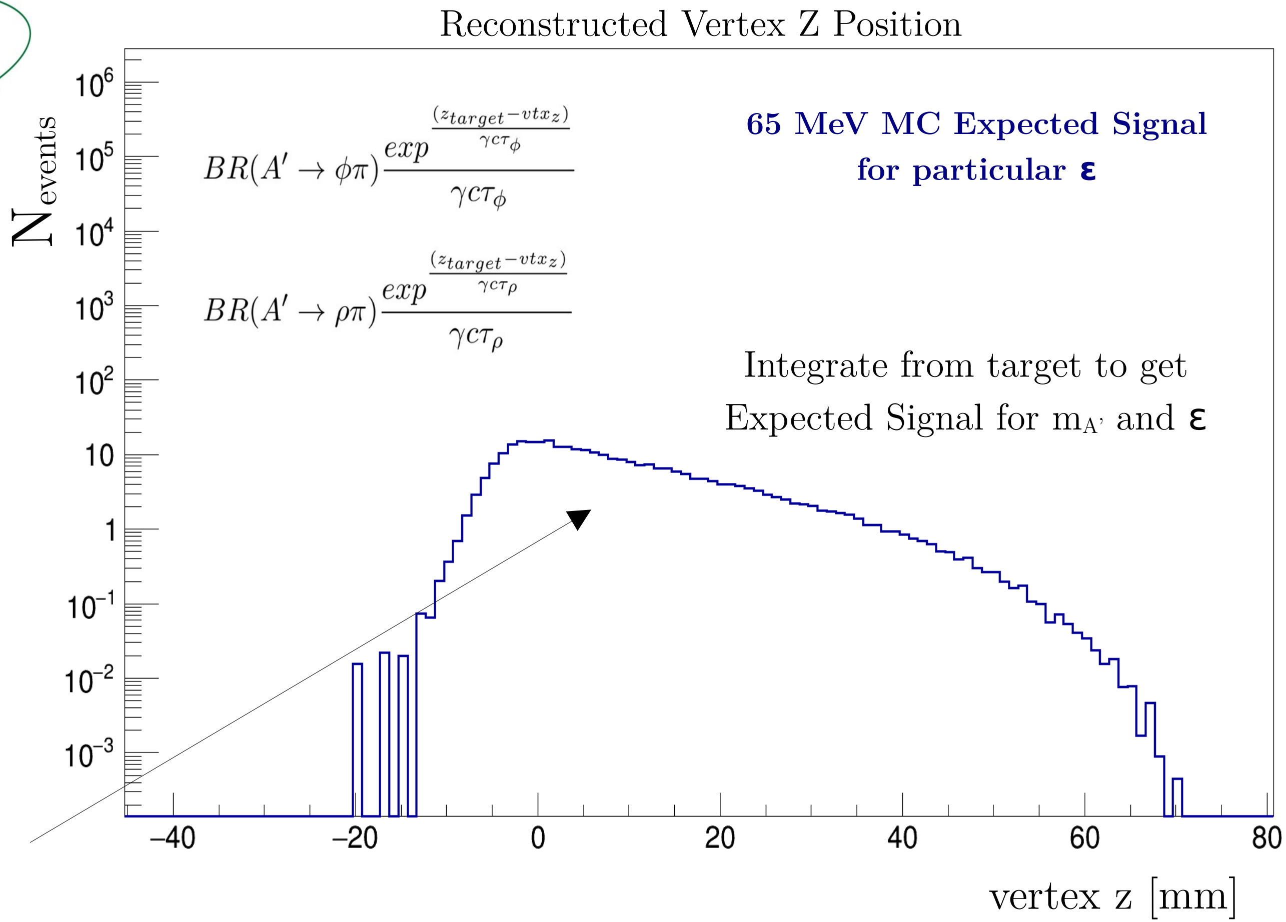


Generate MC signal with uniform decay length

Take efficiency of reconstructed+selected events, to generated events, in vertex z

Re-weight to account for ρ and Φ BR and lifetimes

Multiply by A' yield to get expected signal distribution



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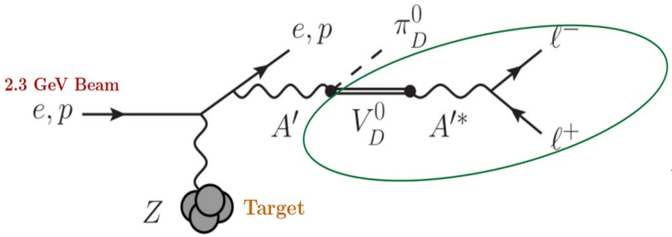

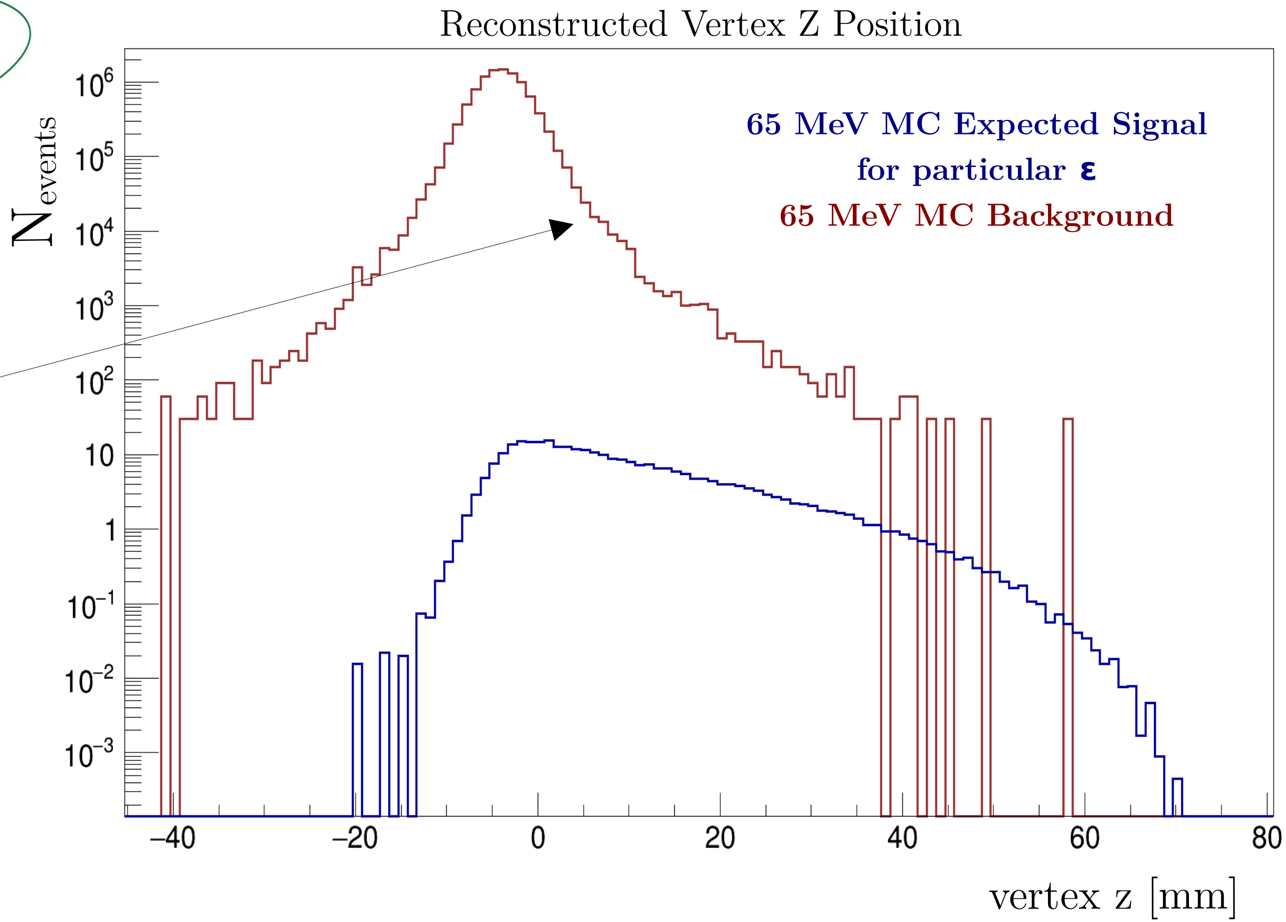

Background under current selection dominates signal

We develop "High-Z" cuts to reduce the background tail while keeping the signal efficiency high

High-Z Cuts

Target Projected Vertex Significance

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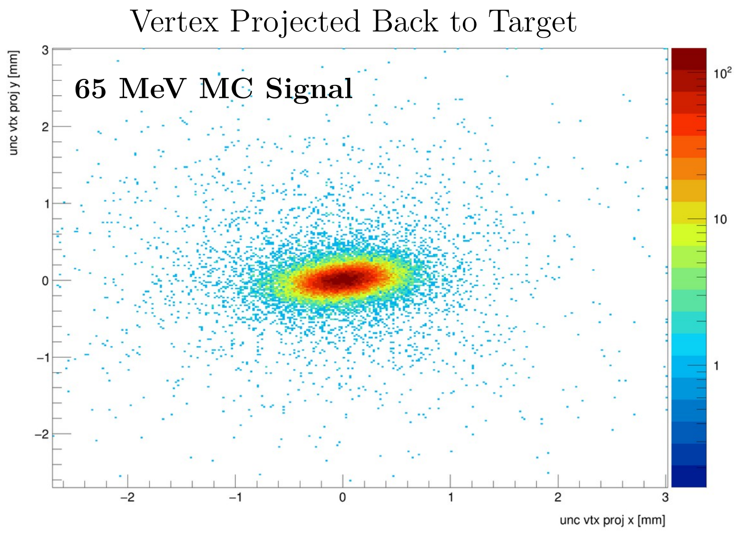
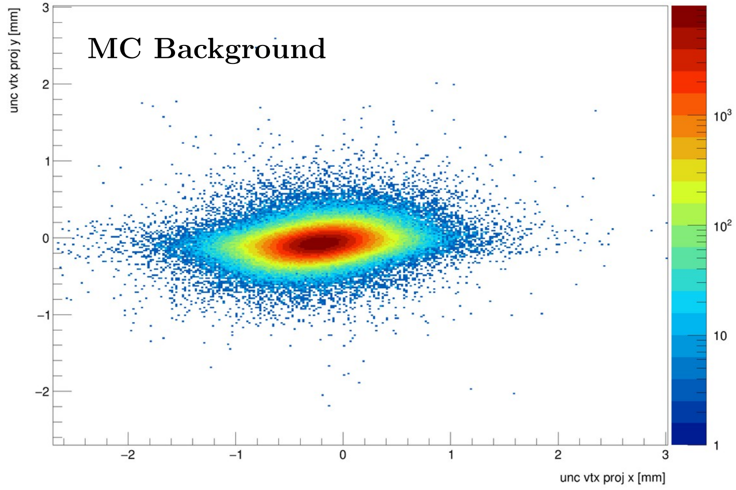
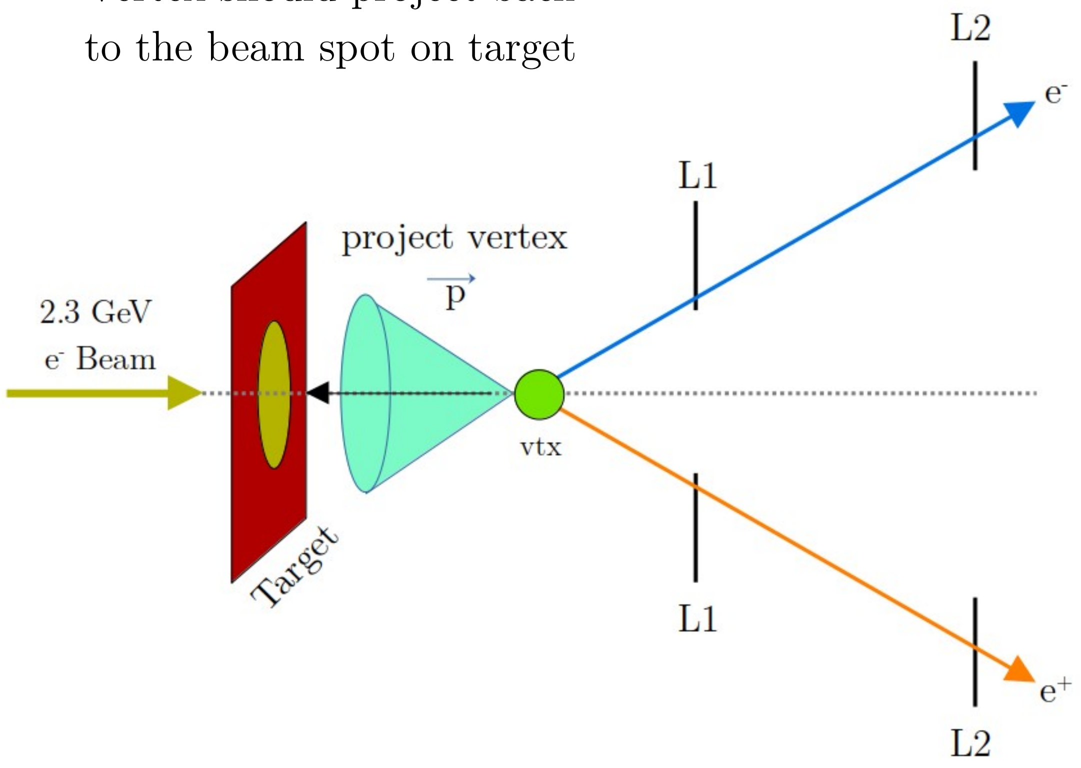




Vertex should project back to the beam spot on target



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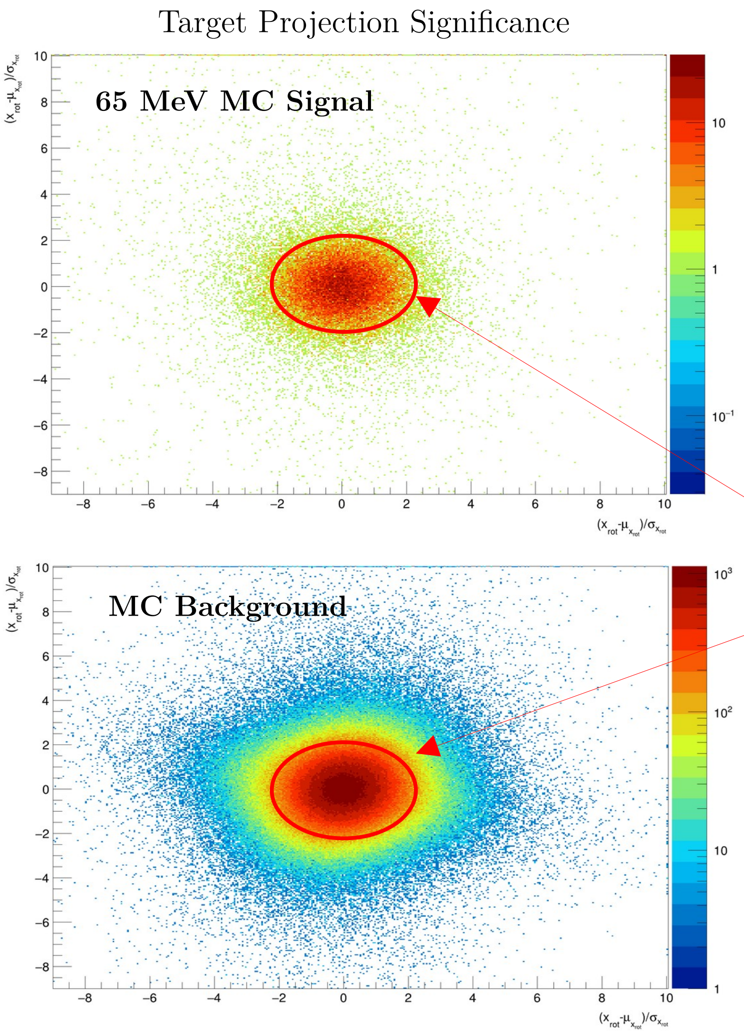
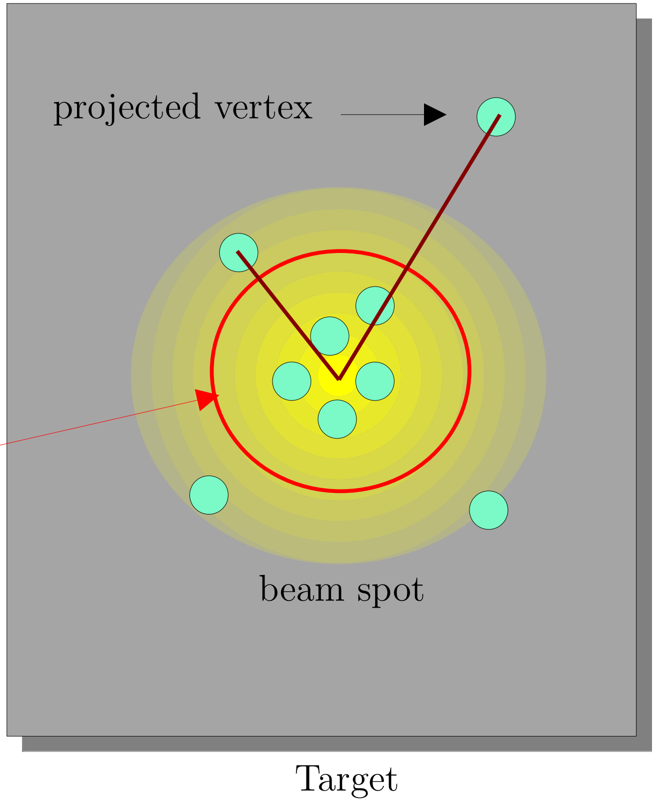


How many standard deviations is the projected vertex from fitted beam spot?



Cut events with radius > Nσ

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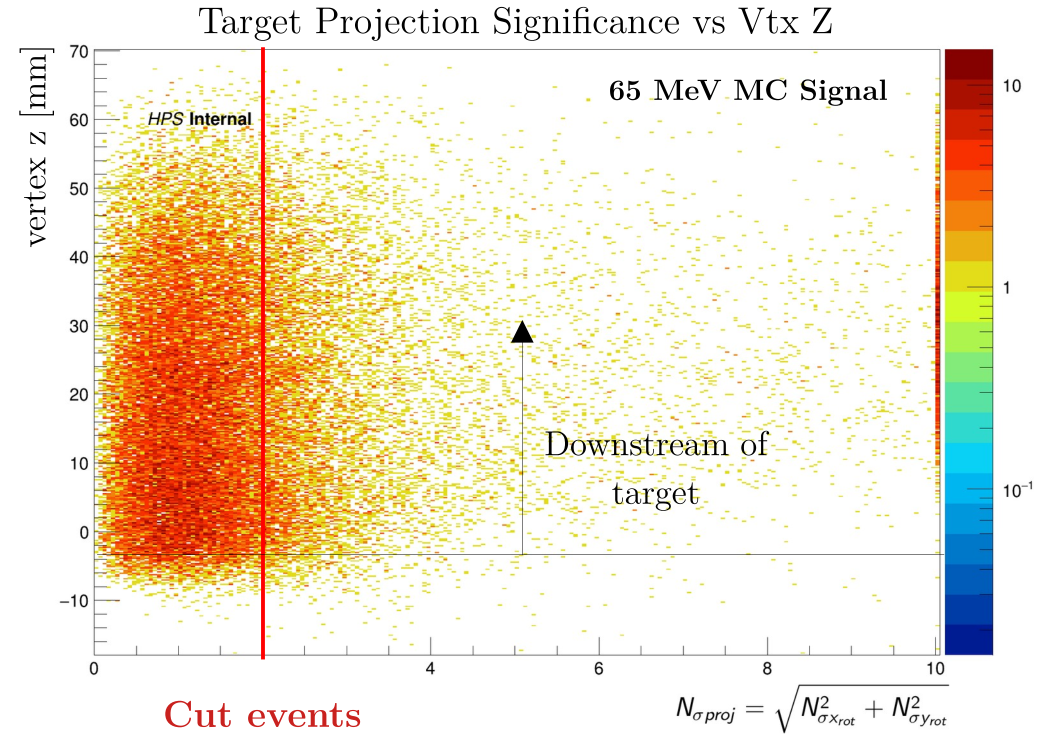
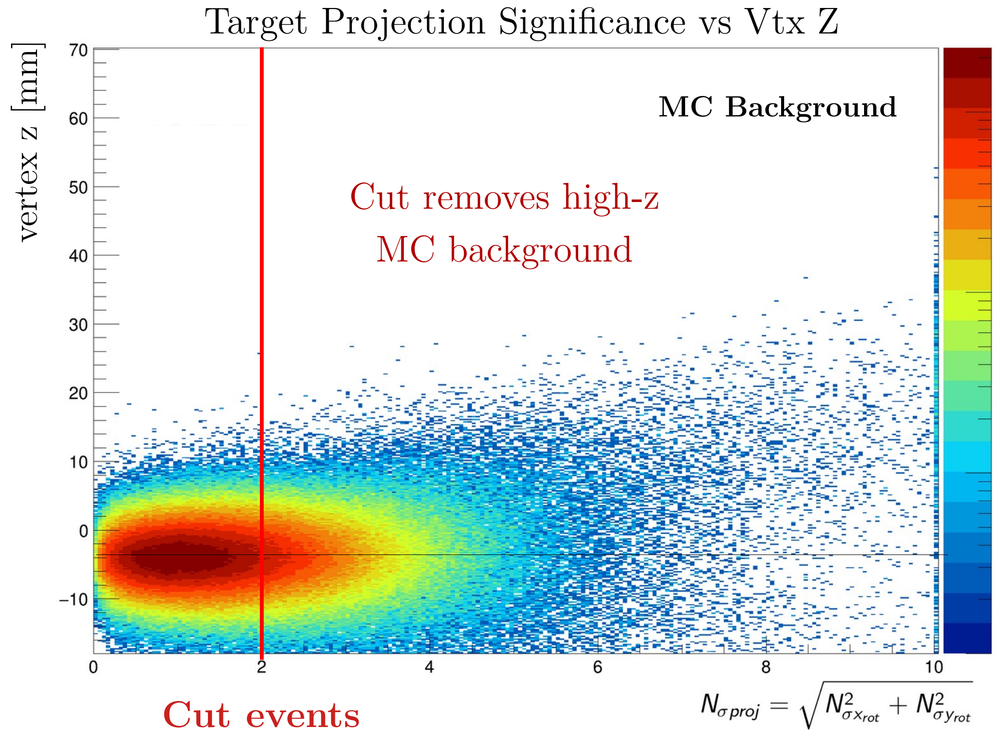


Cut events
with $N_\sigma > 2$



Cut events
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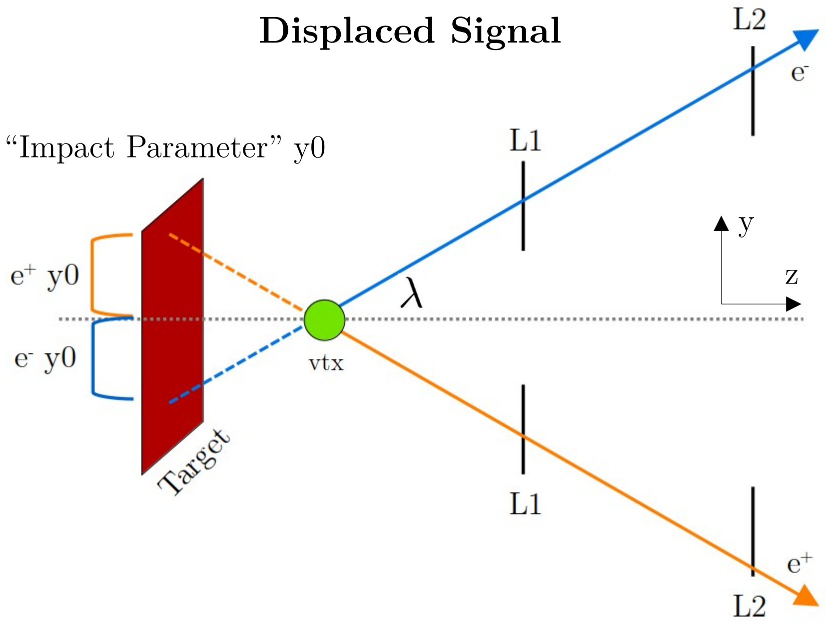
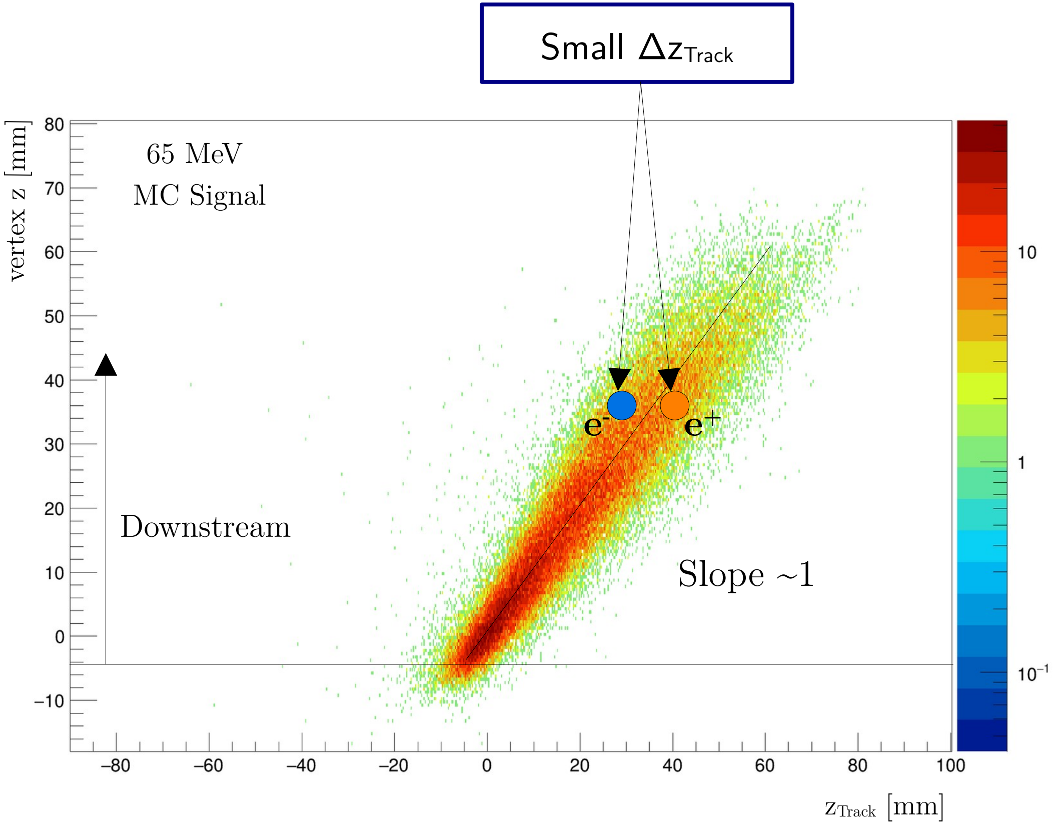
High-Z Cuts

Tracks-Vertex Consistency Δz_{Track}

High-Z Cuts: Track-Vertex Consistency Δz_{Track}

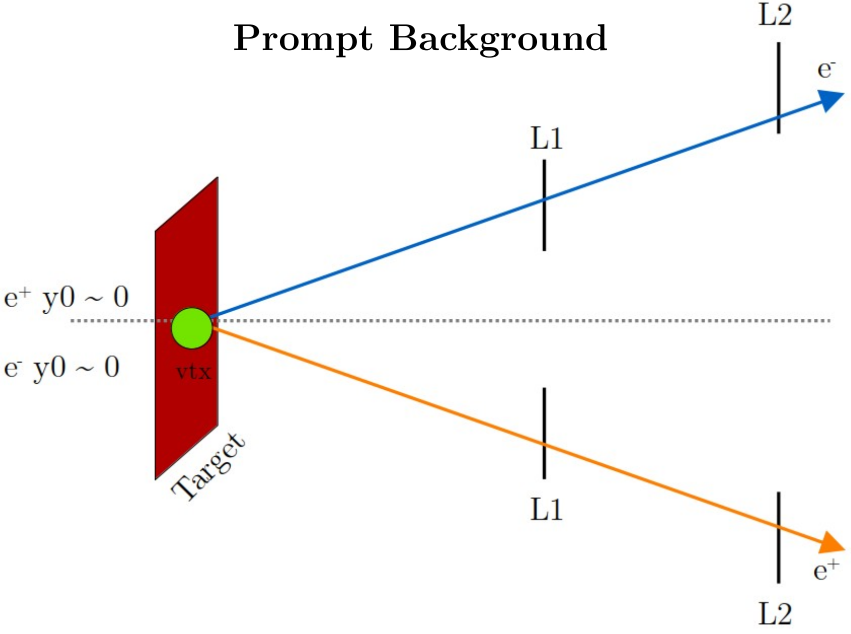


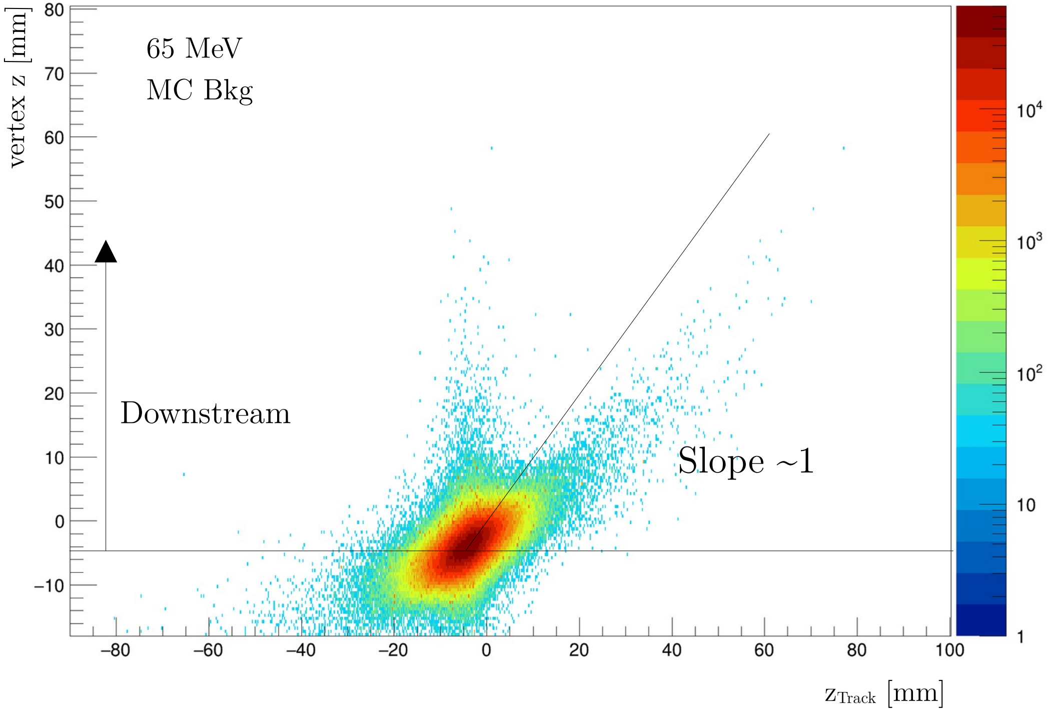


Both tracks should cross the beam-axis at a position in z (z_{Track}) consistent with the reconstructed vertex z

$$z_{Track} = \frac{-y0}{tan(\lambda)} + z_{Target}$$

High-Z Cuts: Track-Vertex Consistency Δz_{Track}



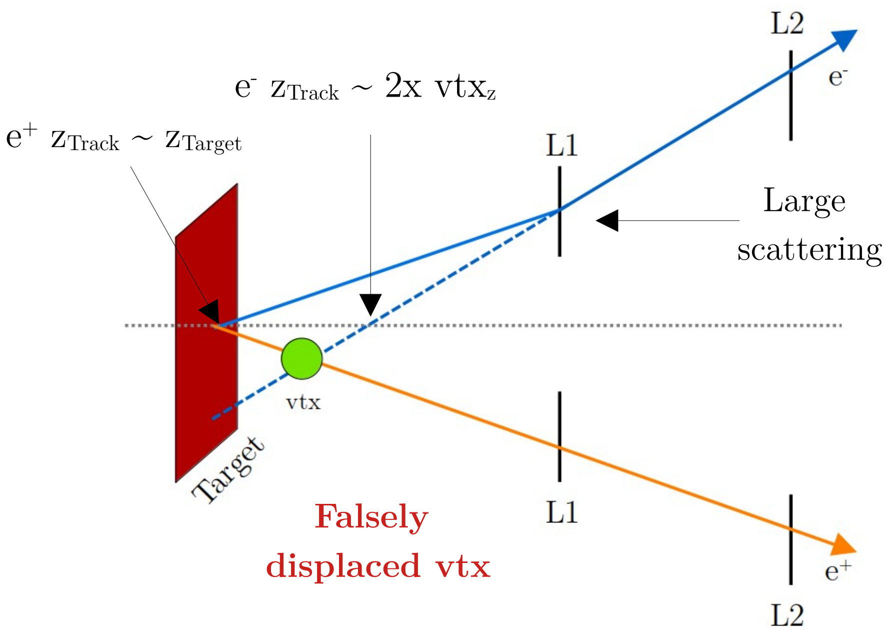


Prompt events should have y0 ~ 0,
and therefore $z_{Track} \sim z_{Target}$ for both tracks
*Spread along slope ~1 due to vertex resolution

$$z_{Track} = \frac{-y0}{tan(\lambda)} + z_{Target}$$

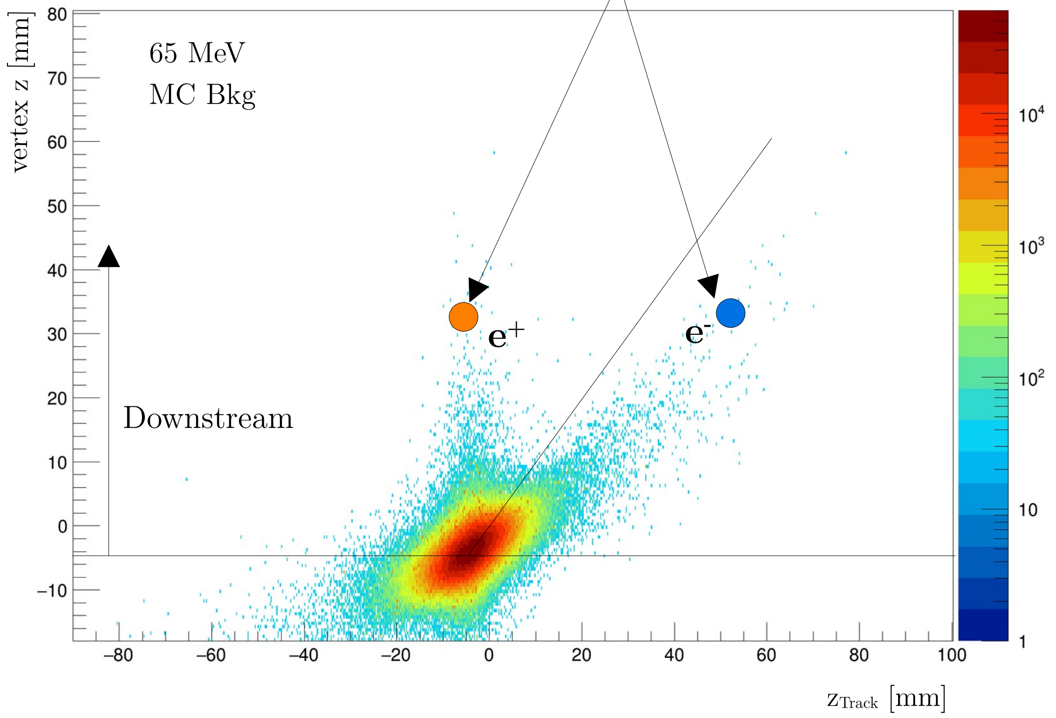
High-Z Cuts: Track-Vertex Consistency Δz_{Track}

Falsely Displaced Prompt Background



Large scattering and mis-reconstruction causes asymmetry in z_{Track}
Leads to falsely displaced vertex

Large Δz_{Track}



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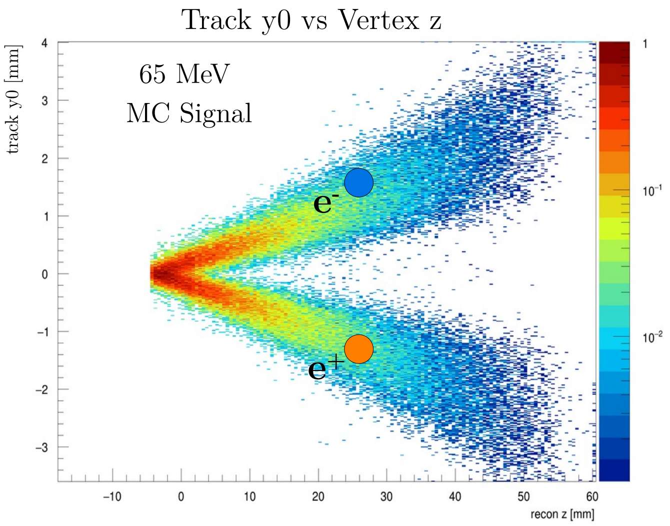
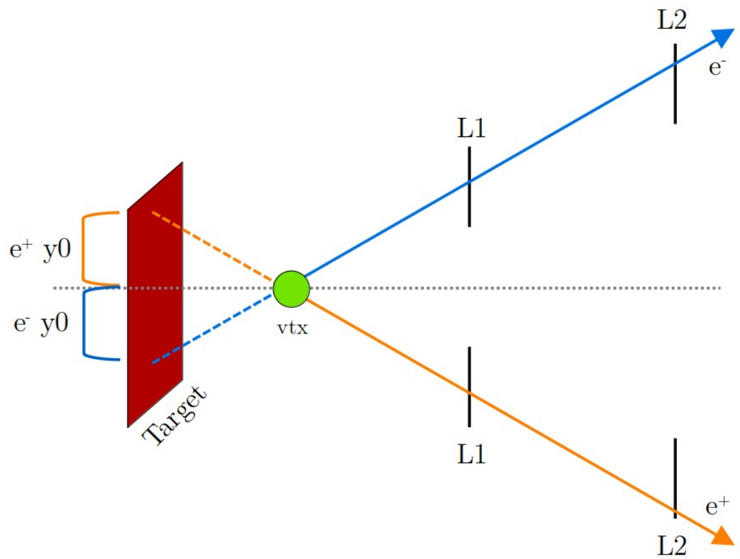
High-Z Cuts

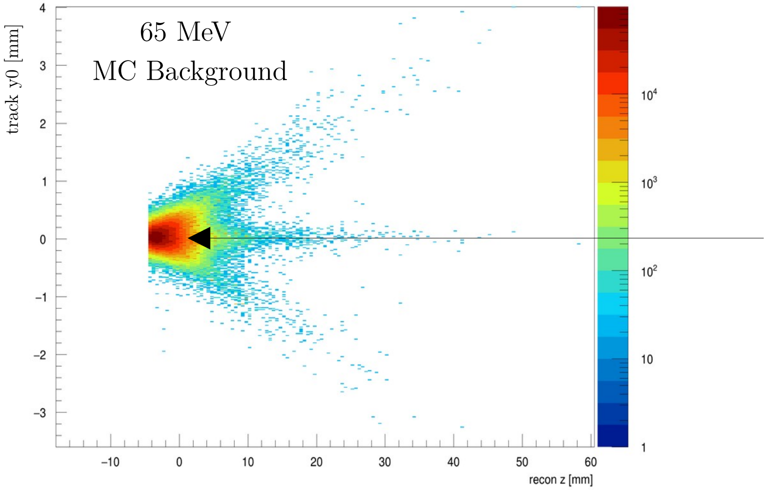
Track Impact Parameter y0

High-Z Cut: Track Impact Parameter y0

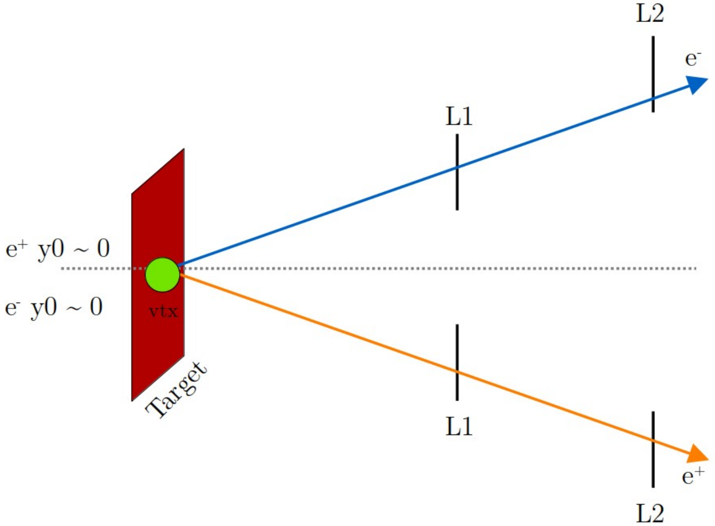


True displaced signal should have symmetric impact parameters that increase linearly with vertex z

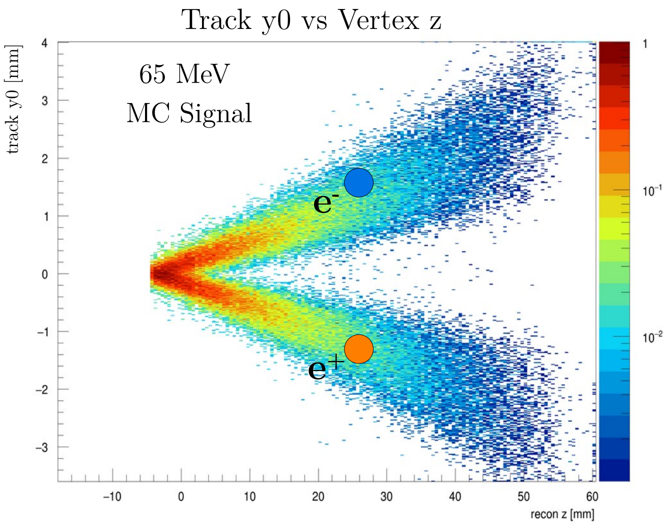


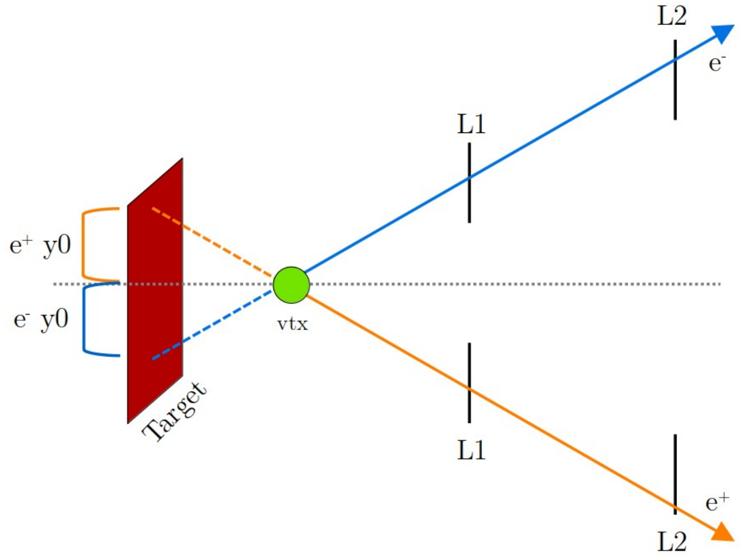


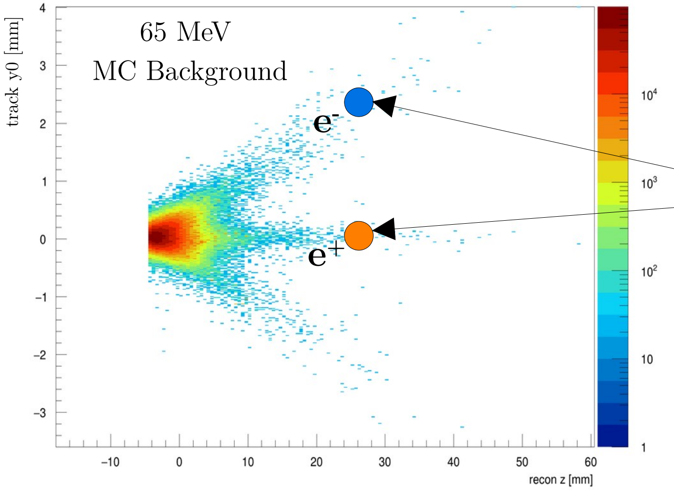
Prompt events should have two tracks with y0 close to 0mm



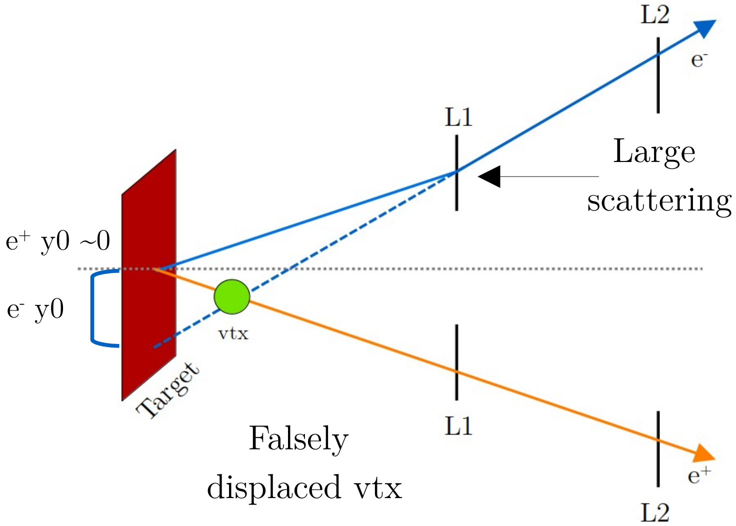
High-Z Cut: Track Impact Parameter y0





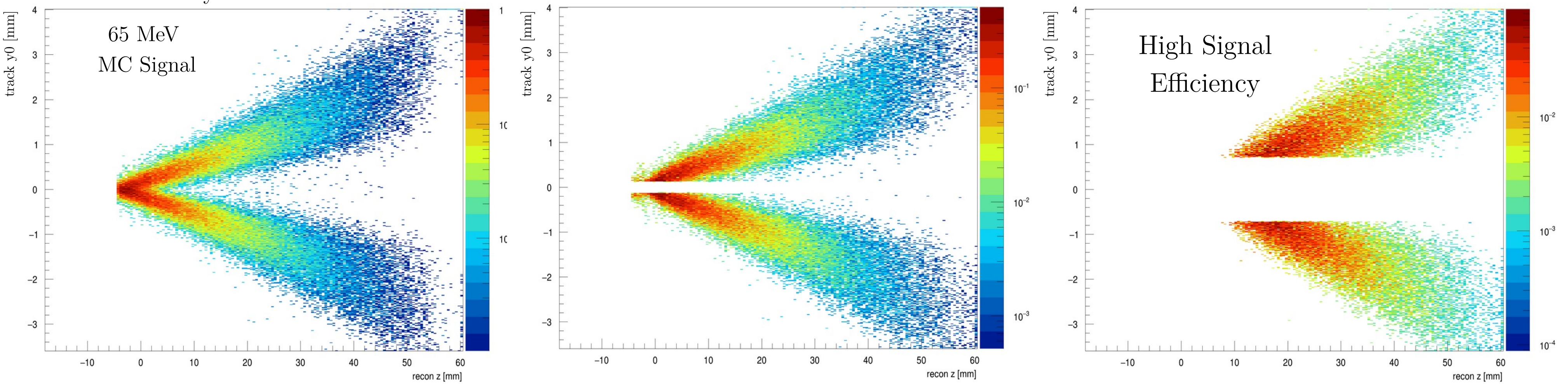


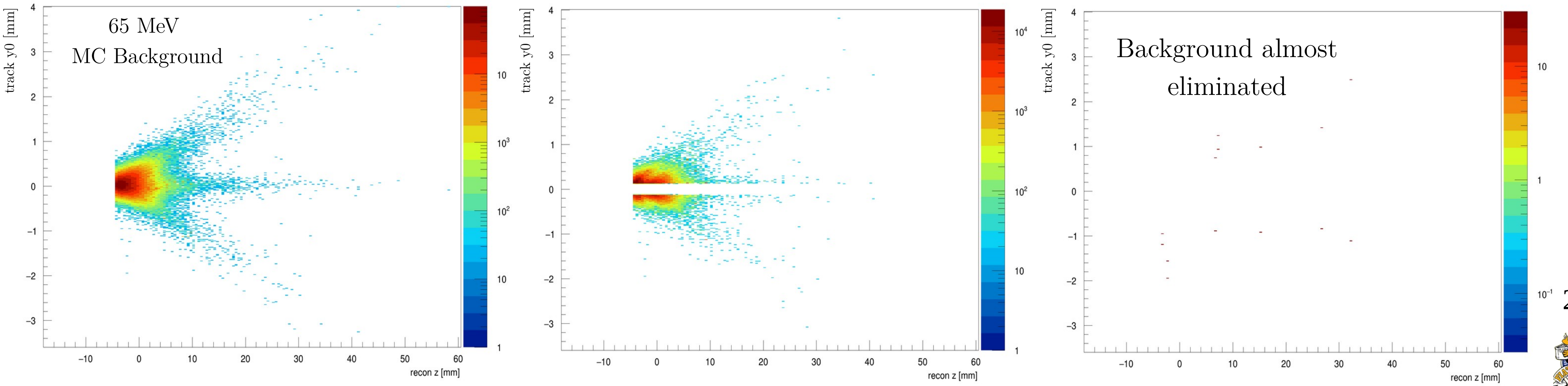
Tracks asymmetric in y0 form false displaced vertex



High-Z Cut: Track Impact Parameter y0

Track y0 vs Vertex z



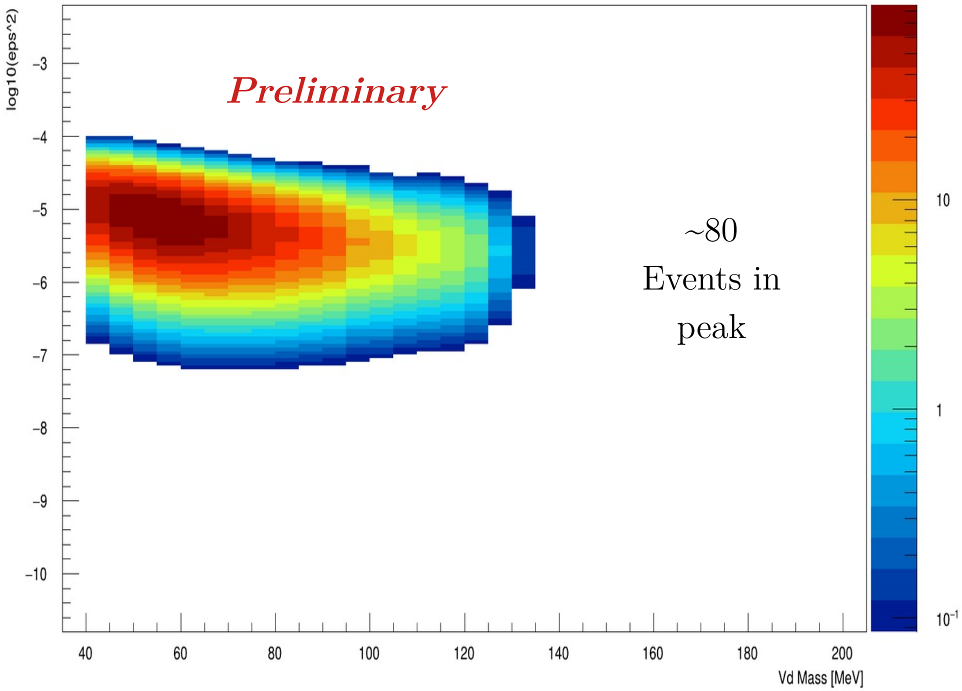


2016 SIMP Reach Estimate Results

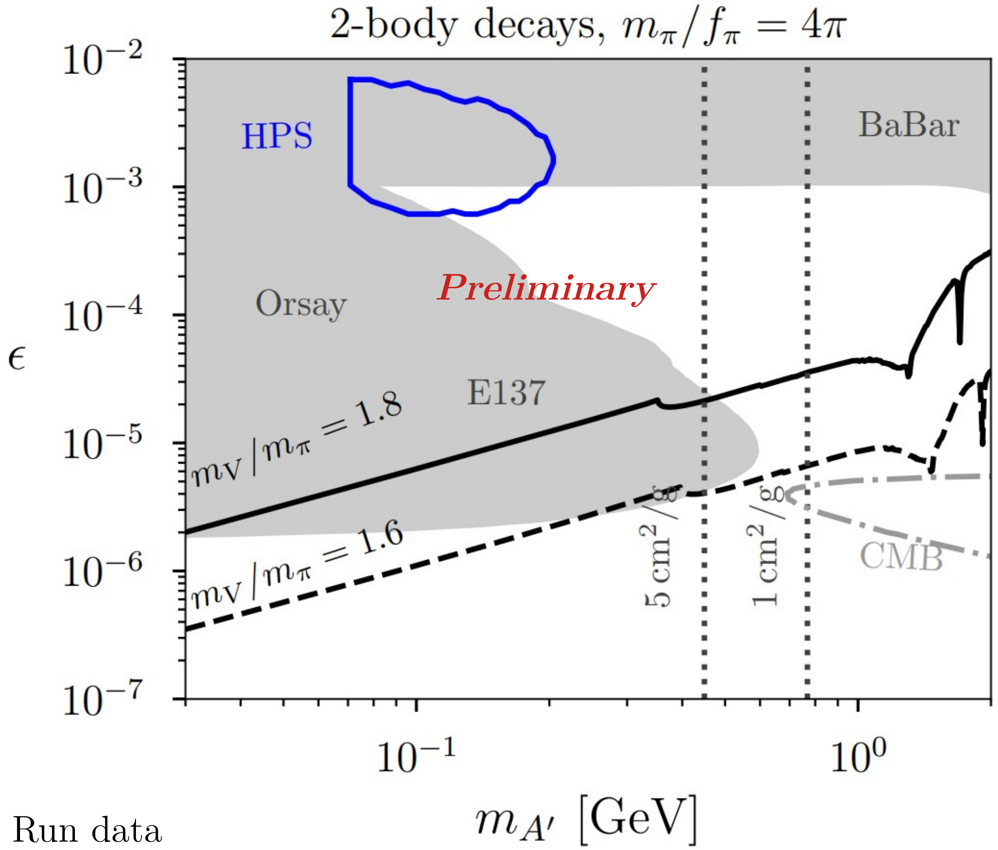
10.7 pb^{-1} (2016 Full Luminosity)

Reach Estimate Results

Expected Signal 10.7 pb^{-1}



~80
Events in
peak



Conclusion

- Expect groundbreaking sensitivity in 2016 Engineering Run data
- Working on finalizing High-Z cut variables and values
- Close to unblinding 100% data

*Remaining background accounted for in contour using Optimum Interval Method[4]

Citations

1. Asher Berlin, Nikita Blinov, Stefania Gori, Philip Schuster, and Natalia Toro. Cosmology and accelerator tests of strongly interacting dark matter. Physical Review D, 97(5), mar 2018.

2. Yonit Hochberg, Eric Kuflik, Tomer Volansky, and Jay G. Wacker. Mechanism for thermal relic dark matter of strongly interacting massive particles. Physical Review Letters, 113(17), Oct 2014.

3. James D. Bjorken, Rouven Essig, Philip Schuster, and Natalia Toro. New fixed-target experiments to search for dark gauge forces. Physical Review D, 80(7), oct 2009.

4. S. Yellin: "Finding an Upper Limit in the Presence of Unknown Background", 2002, Phys.Rev. D66 (2002) 032005; [http://arxiv.org/abs/physics/0203002 arXiv:physics/0203002]. DOI: [https://dx.doi.org/10.1103/PhysRevD.66.032005 10.1103/PhysRevD.66.032005].

Backup

Event Selection

Reconstruction Level

Cut Description	Requirement
ECal clusters in opposite volumes	$e^{-} Cluster_y \times e^{+} Cluster_y < 0$
Track-Cluster Time Difference (Data)	$\|Track_t - Cluster_t - 56\,\text{ns}\| < 10\,\text{ns}$
Track-Cluster Time Difference (MC)	$\|Track_t - Cluster_t - 43\,\text{ns}\| < 10\,\text{ns}$
Track-Cluster X Position Difference	$\|x_{TrackatEcal} - x_{Cluster}\| < 20.0\,\text{mm}$
Track-Cluster Y Position Difference	$\|TrackAtEcal_y - Cluster_y\| < 20.0\,\text{mm}$
Cluster Time Difference	$\Delta_t(Cluster_{e^-}, Cluster_{e^+}) < 2.5\,\text{ns}$
Beam electron cut	$p_{e^-} < 2.15\,\text{GeV}$
Vertex Momentum	$p_{Vtx} < 2.8\,\text{GeV}$

Layer Requirement

Cut Description	Requirement
Layer 1 Requirement	e^- and e^+ have L1 axial+stereo hit
Layer 2 Requirement	e^- and e^+ have L2 axial+stereo hit

Signal and Control Regions

Cut Description	Requirement
Control Region Momentum	$1.9\,\text{GeV} < P_{e^-} + P_{e^+} < 2.4\,\text{GeV}$
Signal Region Momentum	$1.0 < P_{e^-} + P_{e^+} < 1.9\,\text{GeV}$

Preselection

Cut Description	Requirement
Trigger	Pair1
Track Time	$\|Track_t\| < 6\,\text{ns}$
Cluster Time Difference	$\Delta_t(Cluster_{e^-}, Cluster_{e^+} < 1.45\,\text{ns}$
Track-Cluster Time Difference	$\Delta_t(Track, Cluster) < 4.0\,\text{ns}$
Track Quality	$Track\chi^2/n.d.f. < 20.0$
Beam electron cut	$p_{e^-} < 1.75\,\text{GeV}$
Minimum Hits on Track	$N_{2dhits}\,Track > 7.0$
Unconstrained Vertex Quality	$Vtx_{\chi^2} < 20.0$
Vertex Momentum	$p_{e^-+e^+} < 2.4\,\text{GeV}$

High-Z Cuts

Cut	Condition
Target Projected Vertex Significance Cut ($V0_{proj}$)	$V0_{proj} < 2.0$
DeltaZ Cut (Δz_{track})	$\Delta z_{track} < 21.2005 + 16.61e^{-2}(m)$ mm
Flat Z0 Cut ($\|z0\|$)	$\|z0\| < -4.681e^{-03}(m) + 0.921$ mm

Preliminary

SIMP Model Parameters

- **Six key SIMP parameters**
- 1. A' mass
- 2. A' kinetic mixing strength ε
- 3. HS $U_D(1)$ coupling α_D
- 4. Dark pion mass
- 5. Dark vector mass
- 6. Dark pion decay constant f_π

SIMP Parameter Constraints

$m_{A'} < 2m_\mu$ and $m_{A'} < 2m_V$
$m_{A'} > m_V + m_\pi$ and $m_{A'} > 2m_\pi$
$m_V < 2m_\pi$ and $m_V < 2m_\mu$
$\alpha_D < 1$
$10^{-6} < \epsilon < 10^{-2}$
$m_\pi / f_\pi < 4\pi$

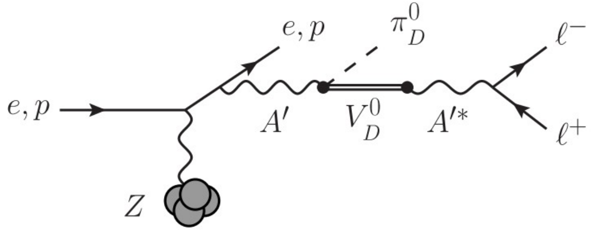
Benchmark Parameters [4]

- $\alpha_D = 0.1$
- $m_{A'}/m_{\pi D} = 3$
- $m_{VD}/m_{\pi D} = 1.8$
- $m_{\pi D}/f_{\pi D} = 4\pi$

Strongly Interacting Massive Particles (SIMPs)

HPS Signal

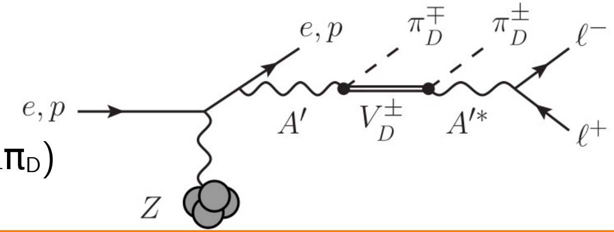
Visible 2-body decay



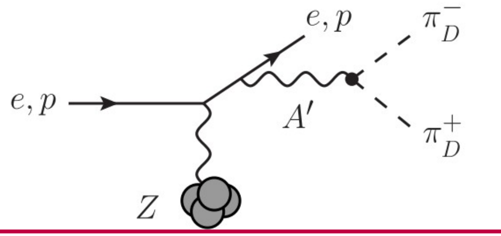
Not Considered

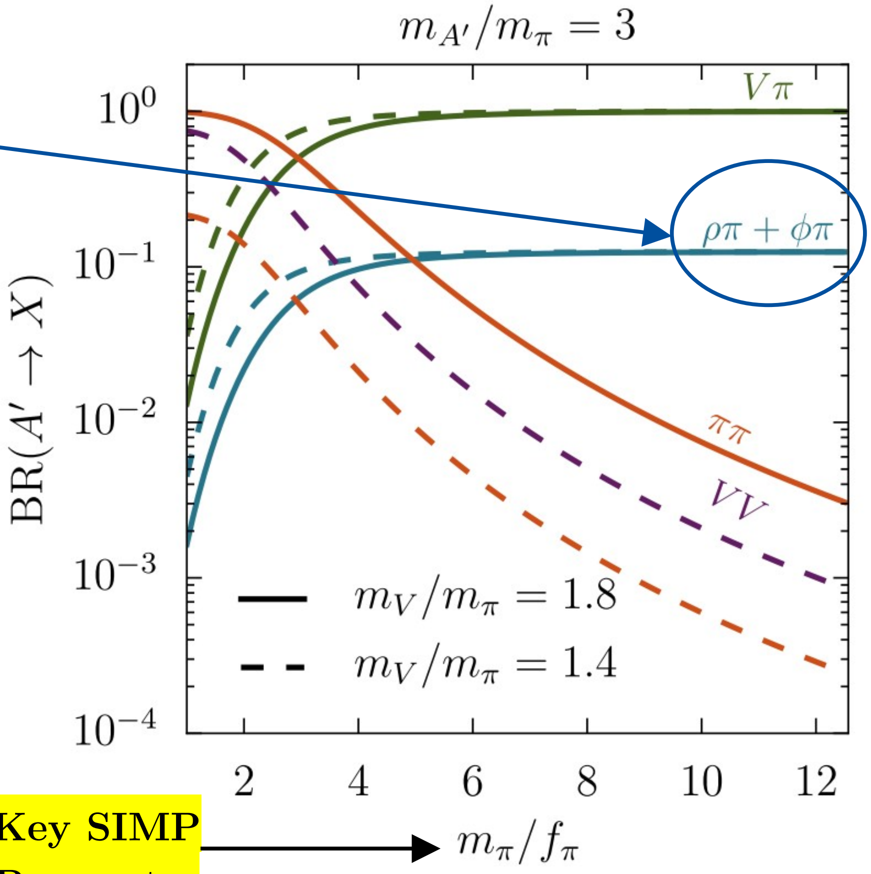
3-body decay

(Invisible if $mV_D^{+-} < 2m\pi_D$)



Invisible to HPS

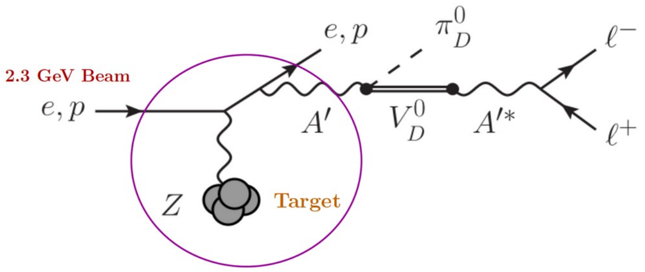




Key SIMP Parameter

A' Branching Ratio is function of dark pion mass and decay constant f_π

Total A' Production Rate



1. A' cross-section proportional to differential Radiative Tridents

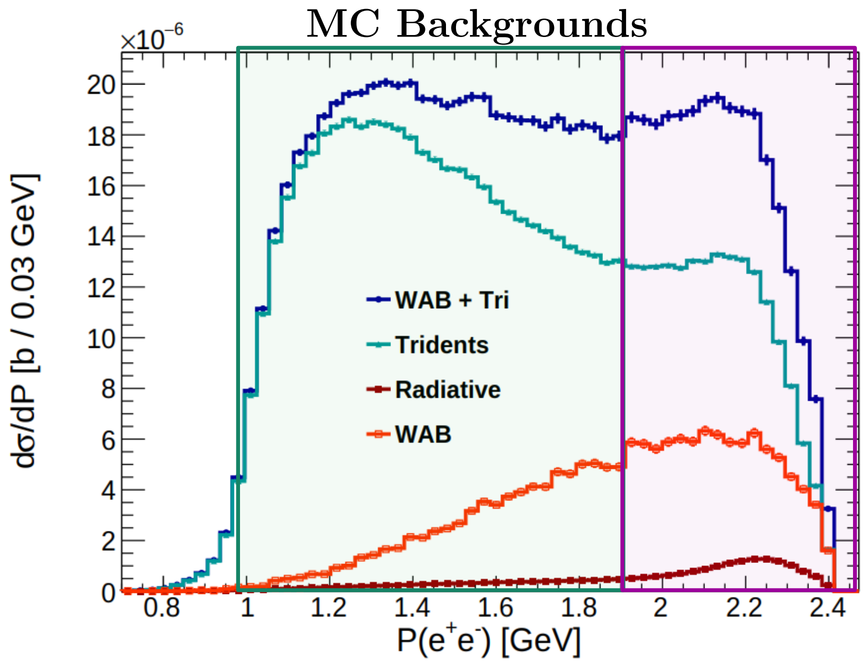
$$\sigma_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\frac{d\sigma_{\gamma^*}}{dm_{l+l-}}|_{m_{l+l-}=m_{A'}}$$

2. Multiply by Luminosity to get Total A' Production Rate for $m_{A'}$

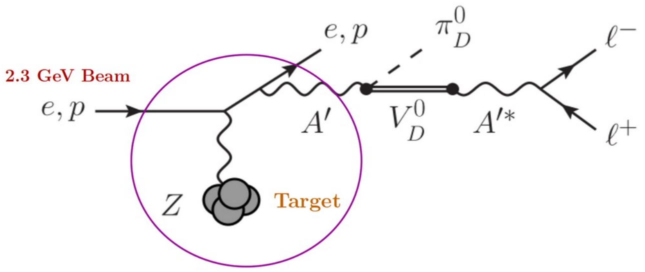
$$N_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\boxed{\frac{dN_{\gamma^*}}{dm_{A'}}}$$

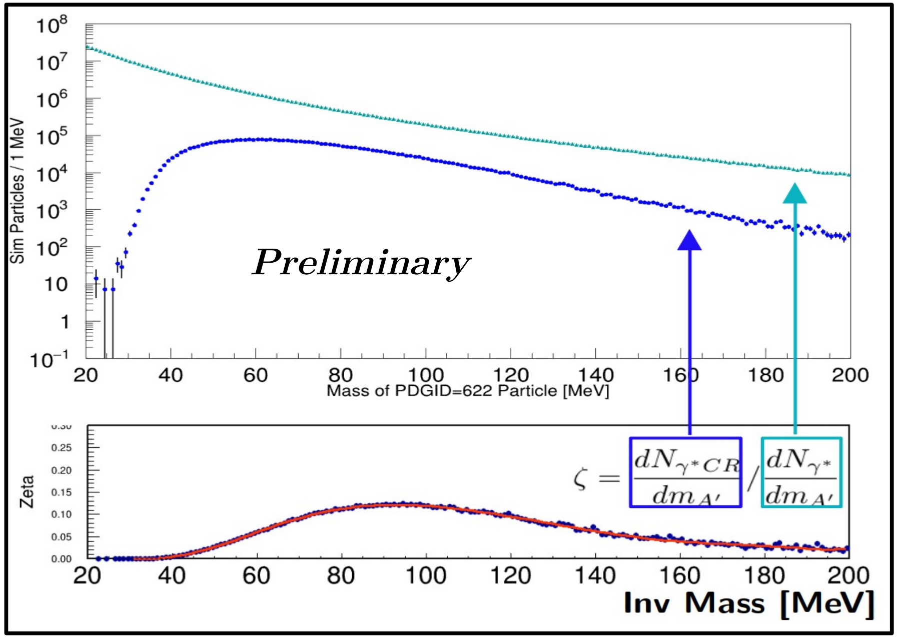
Pure Radiative Tridents not real process, estimated using MC in CR

$$\frac{dN_{\gamma^*}}{dm_{A'}} = \left(\frac{dN_{\gamma^*}}{dm_{A'}}/\frac{dN_{\gamma^*CR}}{dm_{A'}}\right)\left(\frac{dN_{\gamma^*CR}}{dm_{A'}}/\frac{dN_{CR}}{dm_{reco}}\right)\frac{dN_{CR}}{dm_{reco}}$$



Total A' Production Rate





1. A' cross-section proportional to differential Radiative Tridents

$$\sigma_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\frac{d\sigma_{\gamma^*}}{dm_{l^+l^-}}|_{m_{l^+l^-}=m_{A'}}$$

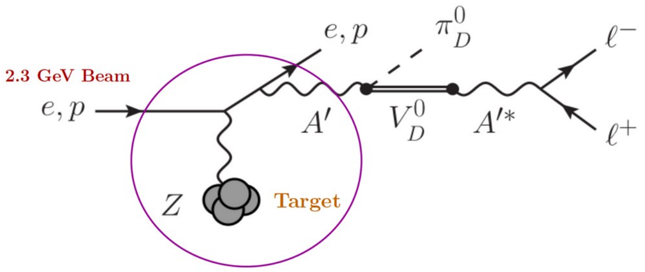
2. Multiply by Luminosity to get Total A' Production Rate for $m_{A'}$

$$N_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\boxed{\frac{dN_{\gamma^*}}{dm_{A'}}}$$

"Radiative Acceptance"

$$\frac{dN_{\gamma^*}}{dm_{A'}} = \boxed{\left(\frac{dN_{\gamma^*}}{dm_{A'}} / \frac{dN_{\gamma^* CR}}{dm_{A'}}\right)}\left(\frac{dN_{\gamma^* CR}}{dm_{A'}} / \frac{dN_{CR}}{dm_{reco}}\right)\frac{dN_{CR}}{dm_{reco}}$$

Total A' Production Rate

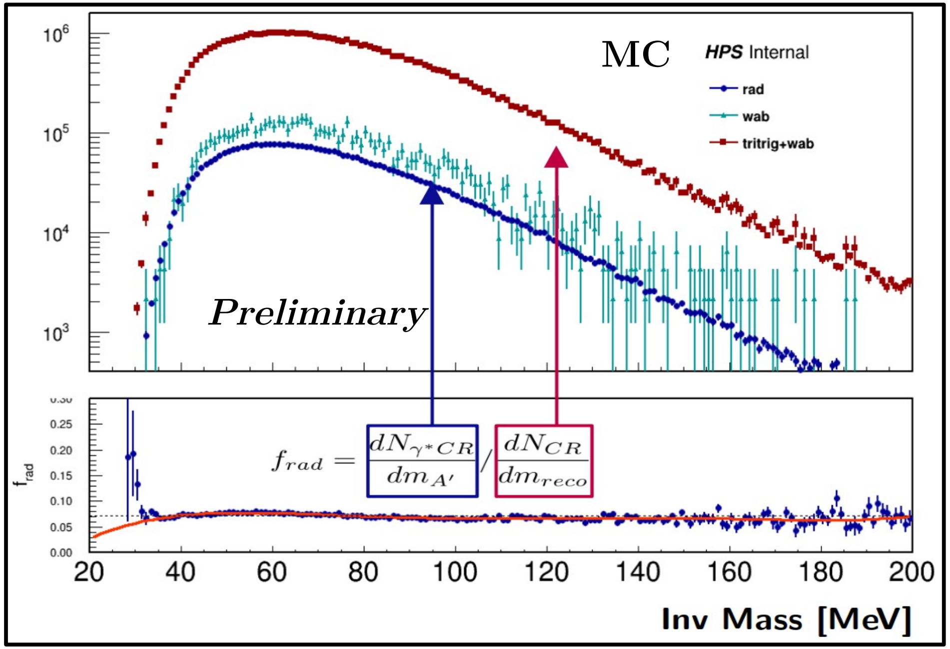


1. A' cross-section proportional to differential Radiative Tridents

$$\sigma_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\frac{d\sigma_{\gamma^*}}{dm_{l^+l^-}}|_{m_{l^+l^-}=m_{A'}}$$

2. Multiply by Luminosity to get Total A' Production Rate for $m_{A'}$

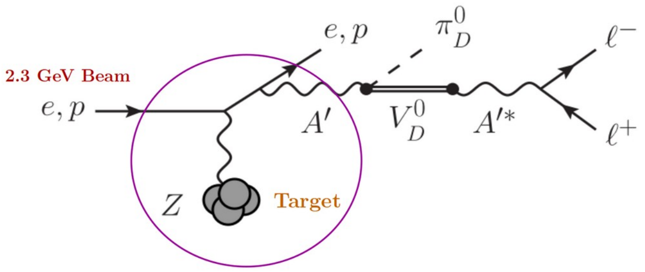
$$N_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\frac{dN_{\gamma^*}}{dm_{A'}}$$

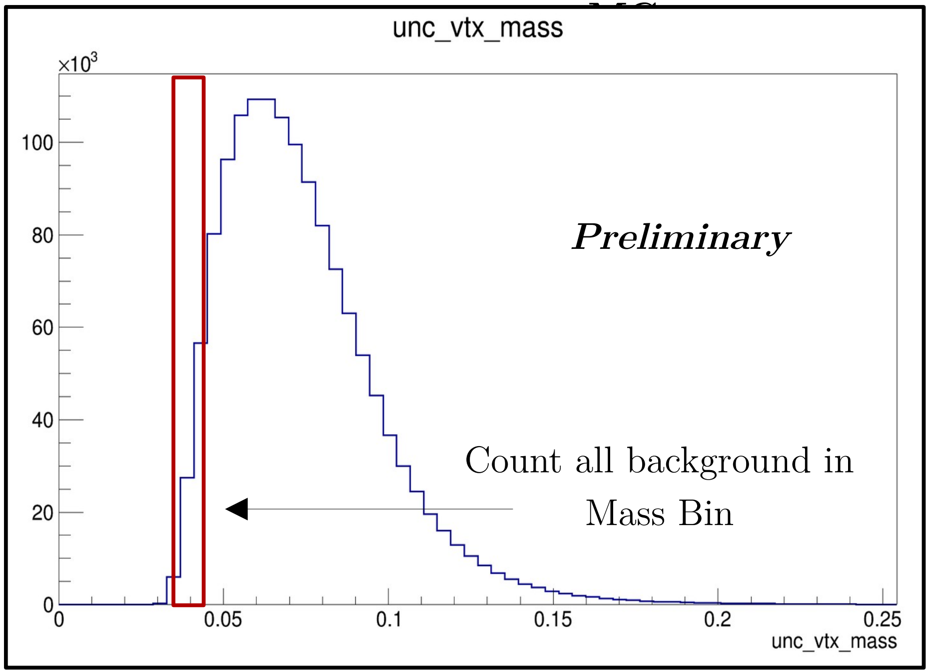


"Radiative Fraction"

$$\frac{dN_{\gamma^*}}{dm_{A'}} = \left(\frac{dN_{\gamma^*}}{dm_{A'}} / \frac{dN_{\gamma^* CR}}{dm_{A'}}\right)\left(\frac{dN_{\gamma^* CR}}{dm_{A'}} / \frac{dN_{CR}}{dm_{reco}}\right)\frac{dN_{CR}}{dm_{reco}}$$

Total A' Production Rate





1. A' cross-section proportional to differential Radiative Tridents

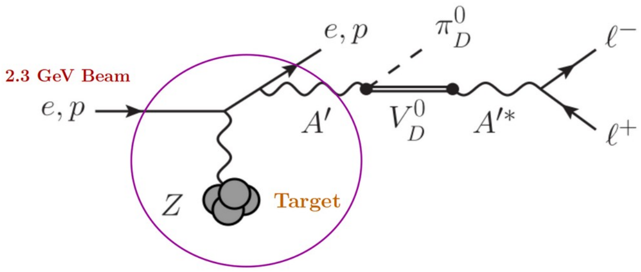
$$\sigma_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha} \frac{d\sigma_{\gamma^*}}{dm_{l^+l^-}}|_{m_{l^+l^-}=m_{A'}}$$

2. Multiply by Luminosity to get Total A' Production Rate for $m_{A'}$

"Background Rate"

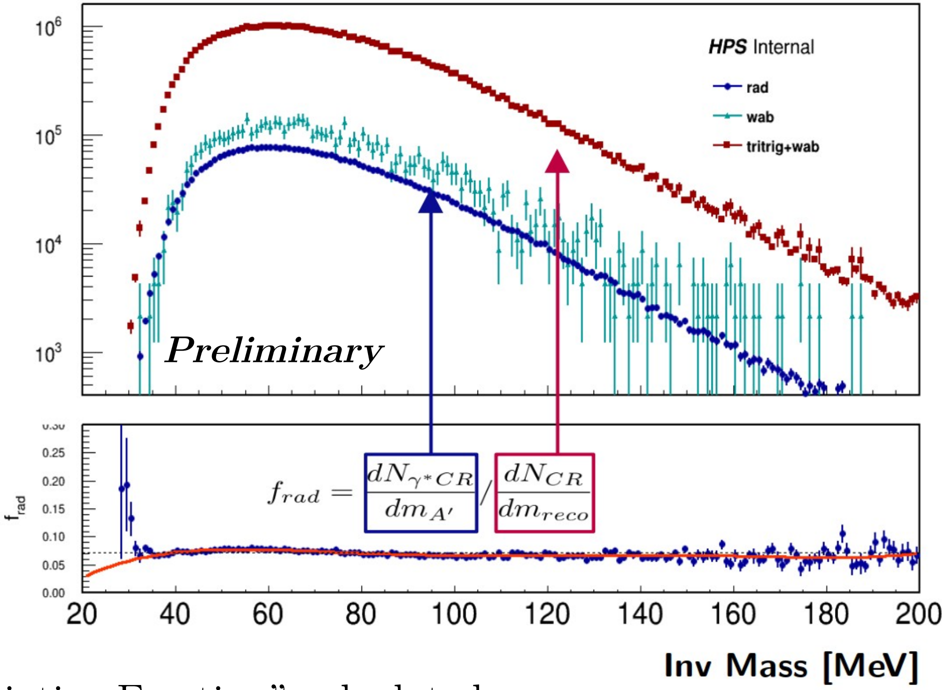
$$N_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha} \boxed{\frac{dN_{\gamma^*}}{dm_{A'}}} \rightarrow \frac{dN_{\gamma^*}}{dm_{A'}} = \left(\frac{dN_{\gamma^*}}{dm_{A'}} / \frac{dN_{\gamma^* CR}}{dm_{A'}}\right)\left(\frac{dN_{\gamma^* CR}}{dm_{A'}} / \frac{dN_{CR}}{dm_{reco}}\right)\boxed{\frac{dN_{CR}}{dm_{reco}}}$$

Total A' Production Rate



1. A' cross-section proportional to differential Radiative Tridents

$$\sigma_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\frac{d\sigma_{\gamma^*}}{dm_{l+l-}}|_{m_{l+l-}=m_{A'}} \quad [3]$$

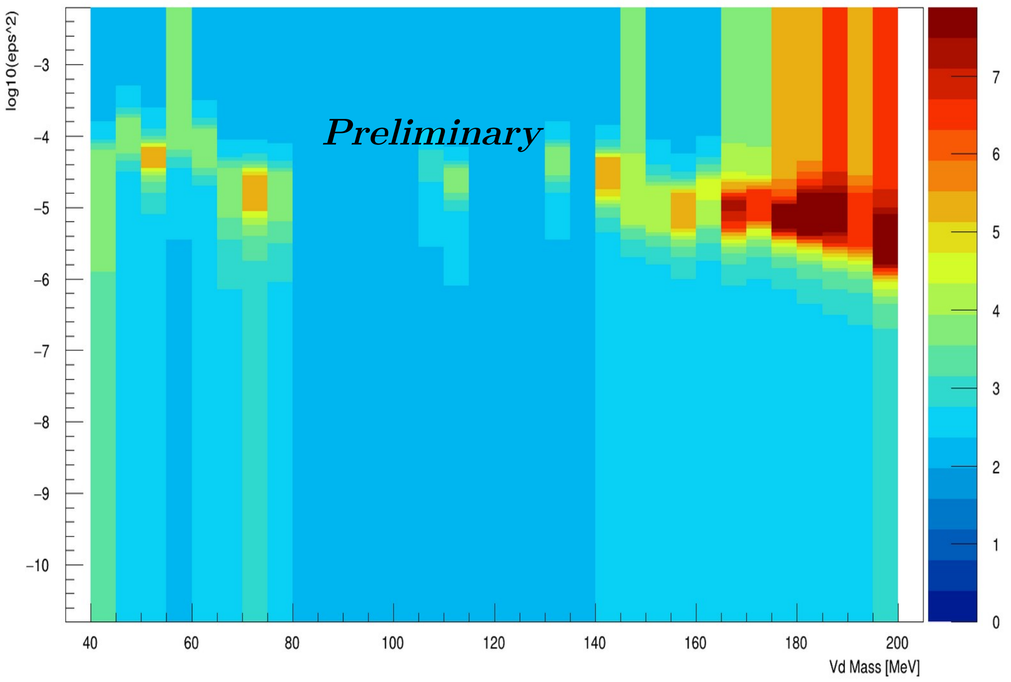


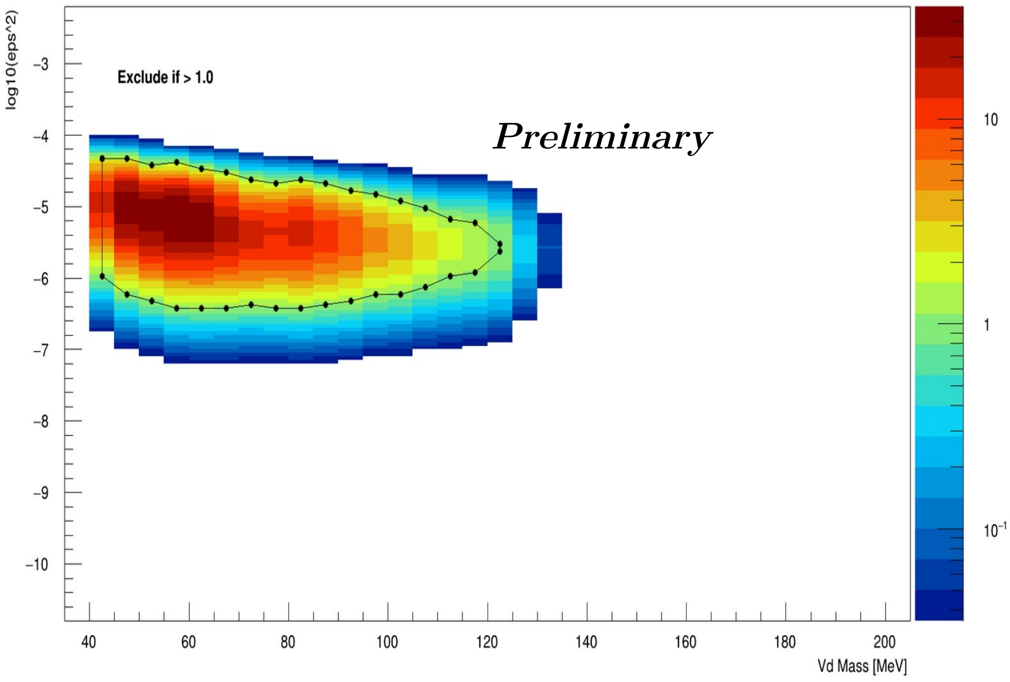
2. Multiply by Luminosity to get Total A' Production Rate for $m_{A'}$

"Radiative Fraction" calculated using MC, allows us to convert data rate to A' production rate

$$N_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\boxed{\frac{dN_{\gamma^*}}{dm_{A'}}} \rightarrow \frac{dN_{\gamma^*}}{dm_{A'}} = \left(\frac{dN_{\gamma^*}}{dm_{A'}} / \frac{dN_{\gamma^* CR}}{dm_{A'}}\right)\boxed{\left(\frac{dN_{\gamma^* CR}}{dm_{A'}} / \frac{dN_{CR}}{dm_{reco}}\right)}\frac{dN_{CR}}{dm_{reco}}$$

Optimum Interval Method Exclusion Contour

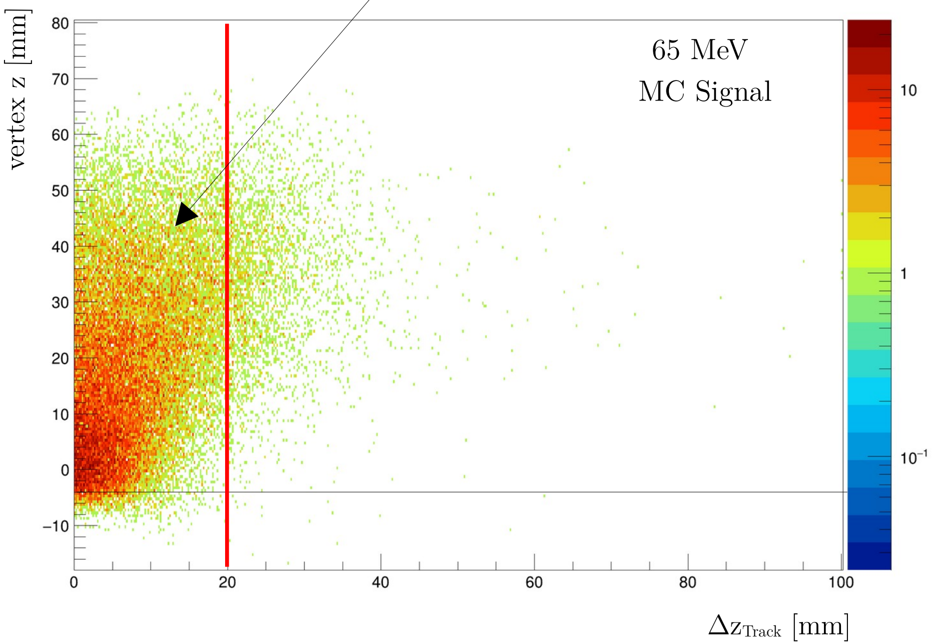


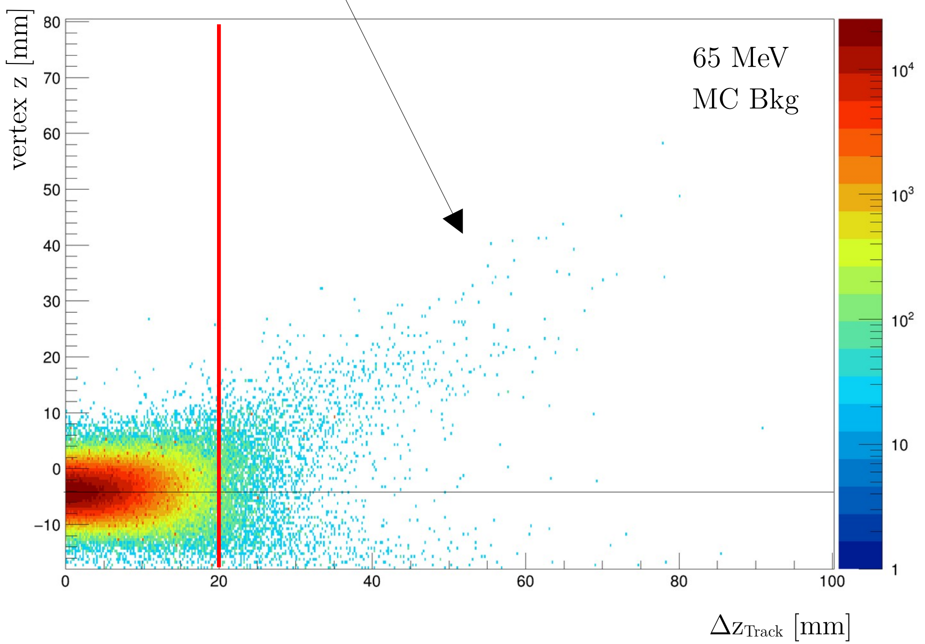


High-Z Cuts: Track-Vertex Consistency Δz_{Track}

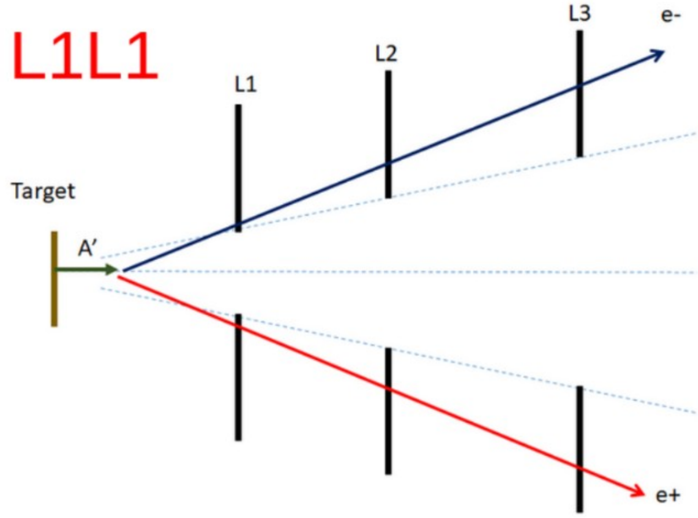
Signal efficiency remains high

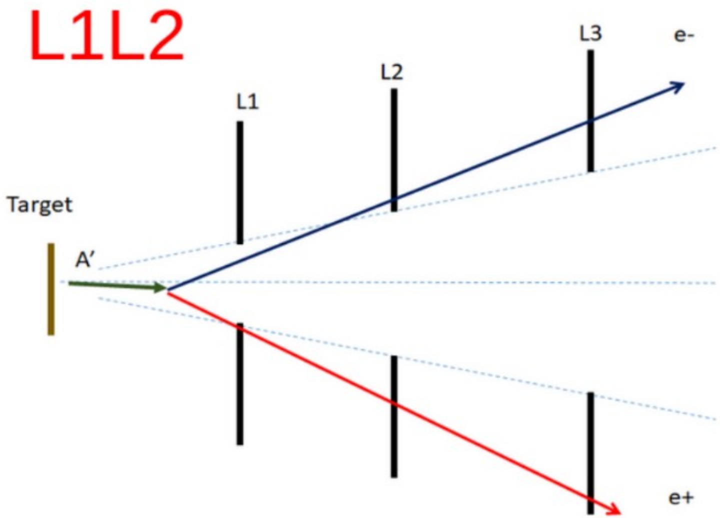
Cut on difference in z_{Track} removes high-z backgrounds



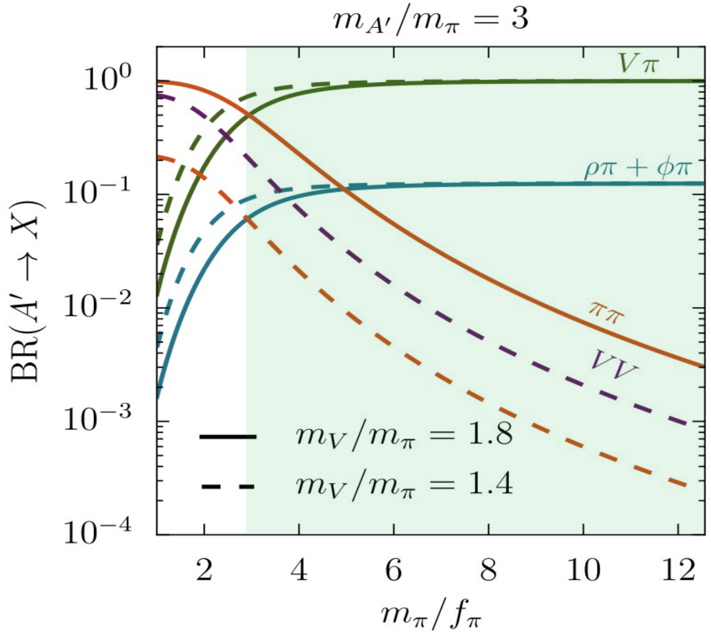


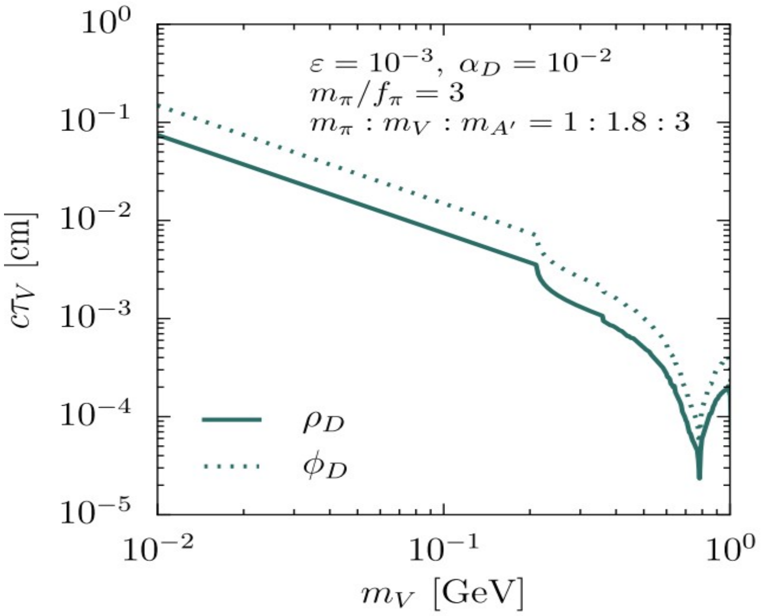
Example: Cut events with $\Delta z_{\text{Track}} > 20$ mm


L1L1
Target
A'
L1
L2
L3
e-
e+


L1L2
Target
A'
L1
L2
L3
e-
e+

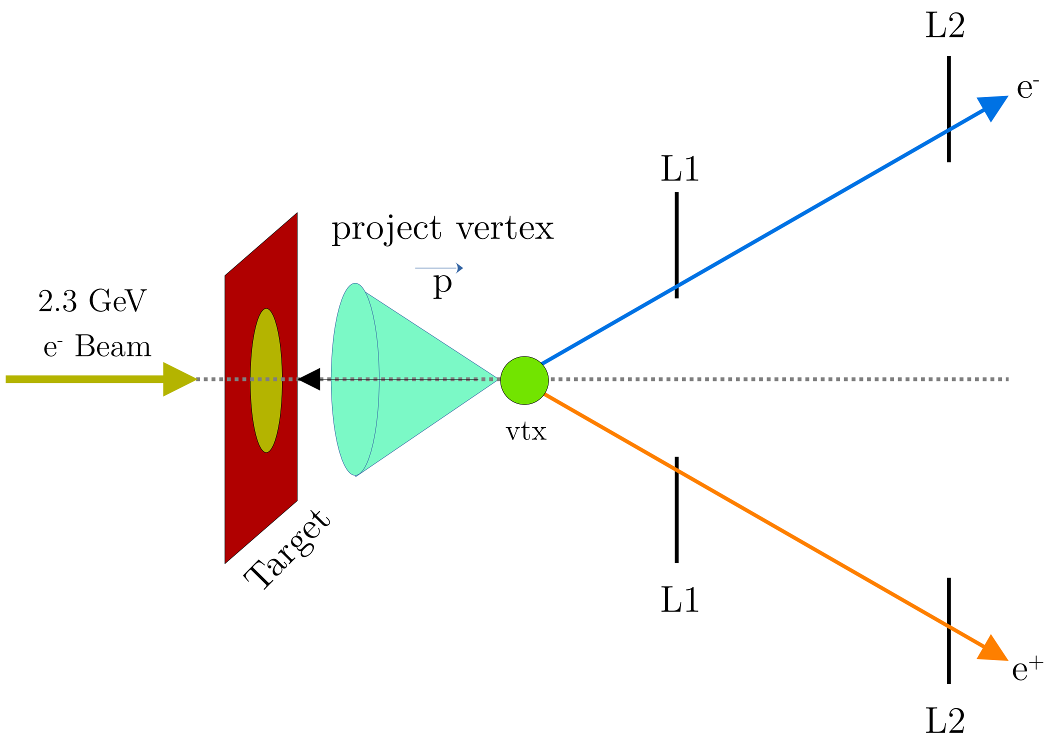
Strongly Interacting Massive Particles - Theory

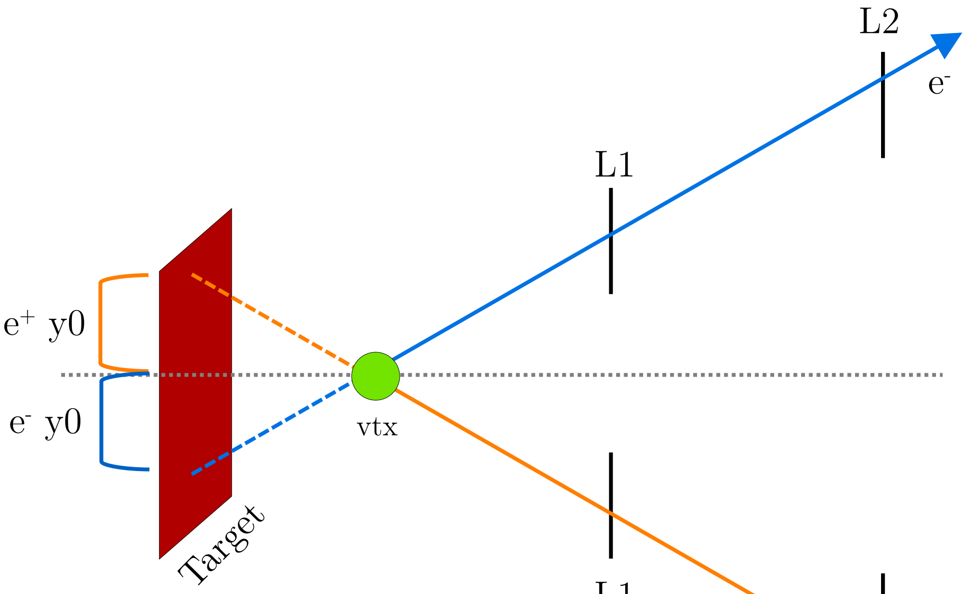




- π_D = dark pion mass (comprises DM)
- A' = couples HS to SM
- V_D = heavy dark vector meson
- ε = kinetic mixing parameter
- α_D = $U(1)_D$ gauge coupling
- $f\pi_D$ = dark sector pion decay constant

- π_D = dark pion mass (comprises DM)
- A' = couples HS to SM via kinetic mixing
- V_D = heavy dark vector meson (analogous to ϱ meson)
- ε = kinetic mixing parameter
- α_D = $U(1)_D$ gauge coupling
- $f\pi_D$ = dark sector pion decay constant


L2
e-
L1
project vertex
p
2.3 GeV
e- Beam
vtx
Target
L1
e+
L2



L2
e-
L1
e+ y0
e- y0
vtx
Target
L1
e+
L2