SIMP Analysis at HPS

Jessica Fry
Stanford University
Lauren Tompkins, Stanislava Sevova
HPS Collaboration Meeting, 11/20/20

Outline

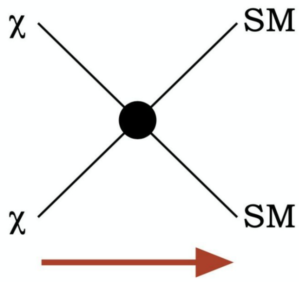
1. SIMP Theory
2. SIMP Signal at HPS
3. Tracking Determination
4. Vertex Preselection
5. SIMP Tight Cuts

WIMP vs. SIMP Model

Relic abundance set by 2 → 2 annihilations

α on the order of weak coupling

WIMP Miracle m_χ~ 100 GeV

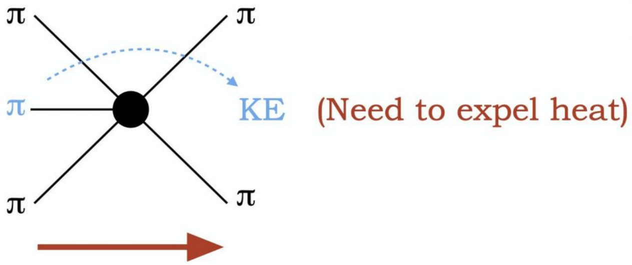


$$m_\chi \sim \alpha_\chi \ \left(T_{\rm eq} m_{\rm pl}\right)^{1/2} \sim \alpha_\chi \times 10 \text{ TeV}$$

Relic abundance set by 3 → 2 annihilations

Strong self-coupling

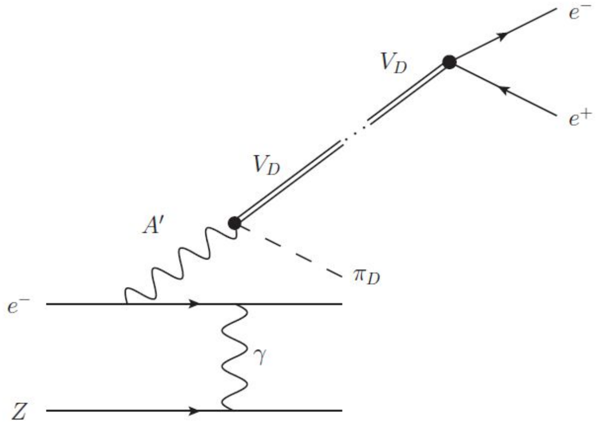
SIMP Miracle m_χ~ 0.01-0.1 GeV



$$m_\pi \sim \alpha_\chi \ \left(T_{\rm eq}^2 m_{\rm pl}\right)^{1/3} \sim \alpha_\chi \times 1 \text{ GeV}$$

SIMP at HPS

- Prompt A' decays into V_D and π_D (DM)
- Signature with a displaced vertex and missing energy
- Similar analysis to vertex analysis for A', but different kinematics
  - Expect missing energy from the π_D
  - Softer e^+e^- momenta than displaced A'



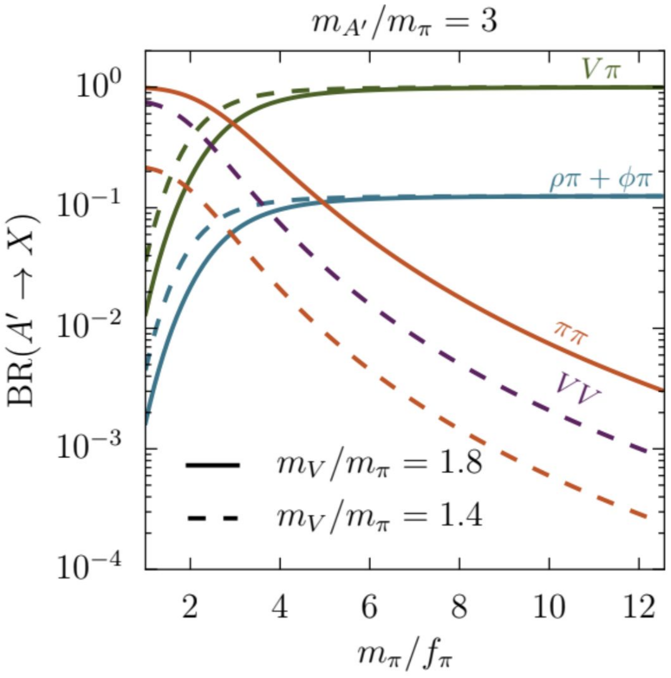
SIMP Model Parameters

- m_V -- dark vector meson mass
- m_π -- dark pion mass (DM)
- $m_{A'}$ -- dark mediator mass
- ϵ -- kinetic mixing parameter
- α_D -- dark coupling constant
- m_π/f_π -- dark pion decay constant

- Mass Hierarchy
  - $\boxed{m_V < 2\, m_\pi}$
  - $\boxed{m_{A'} > m_V + m_\pi}$
  - $m_{A'} > 2\, m_\pi$
- SM suppression in early universe and SIMP cosmology
  - $10^{-6.3} < \epsilon < 10^{-2}$
- QED-like
  - $\alpha_D \sim 0.01$
- Relic abundance
  - $m_\pi/f_\pi < 4\pi$

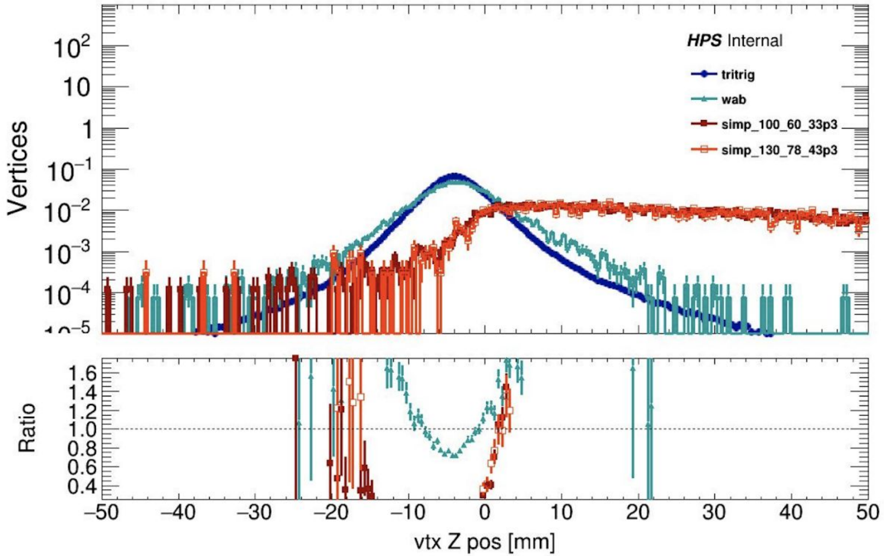
SIMP Parameters Ranges

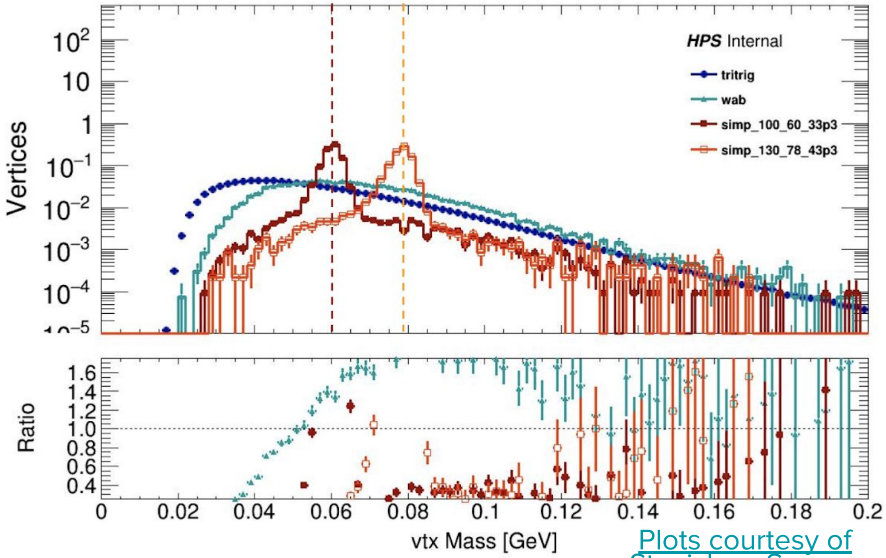
- 2 body decays of V_D are detectable at HPS so $\rho \rightarrow e^+e^-$ and $\phi \rightarrow e^+e^-$ are the BR of interest
- $m_{A'} : m_V : m_\pi = 3 : 1.8 : 1$
  - 3 : 1.4 : 1 branching ratio not accessible at HPS
- α_D = 0.1, 0.01, 0.001



SIMP Signal

m_V : m_π : $m_{A'}$
60 : 33.3 : 100 MeV
78 : 43.3 : 130 MeV





[Plots courtesy of Stanislava Sevova]

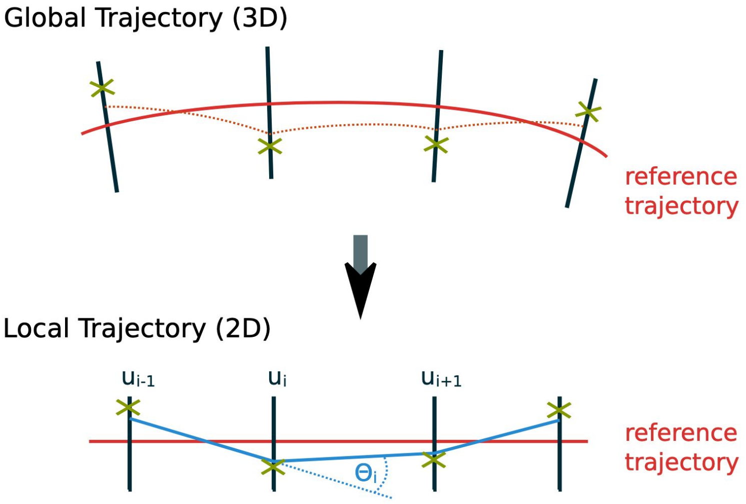
Signature with a e^+e^- displaced vertex and mass below A'

Tracking Determination

Two different algorithms to associate SVT layer hits with e^+ or e^- tracks for track reconstruction

General Broken Lines (GBL)

- Treats each sensor plane as a source of scattering
- Fits a track segment between these sensor planes to minimize the hit residuals and scattering angles
- Seed with 3D hit from a helical track, extrapolate to confirm layer, require matching hit on extend layer



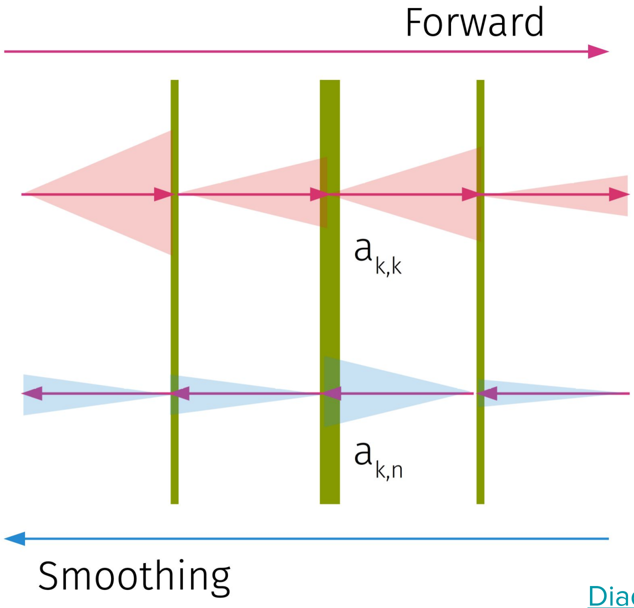
[Diagrams courtesy of Moritz Kiehn]

Tracking Determination

Two different algorithms to associate SVT layer hits with e^+ or e^- tracks for track reconstruction

Kalman Filter (KF)

- Moves from the outermost layer inwards
- Predicts hit location in next layer and improves the parameter vector and covariance matrix with each layer
- Seed with last layer, extrapolate to next layer, find compatible hits, branch with each compatible hit



Diagrams courtesy of Moritz Kiehn

Tracking Determination

1. SIMP Signal Samples and Backgrounds reprocessed with a non-standard steering file (track-to-cluster matching for GBL is removed for a one-to-one comparison with KF)
    a. Input LCIOS: `/gpfs/slac/atlas/fs1/d/ssevova/hps/hps-mc/recon/ctau10mm/100_60_33p3/*.slcio`
    b. Steering File: `/nfs/slac/g/hps2/jfry/noClusterRequirement/PhysicsRun2016FullRecon_Kalman_simps_noClustersRequired.lcsim`
    c. Reprocessed LCIOS: `/nfs/slac/g/hps2/jfry/noClusterRequirement/lcios.*.slcio`
2. Run hpstr with `kalTuple_cfg.py` and `anaKalVtxTuple_cfg.py` processors
3. Look at basic SIMP & background distributions

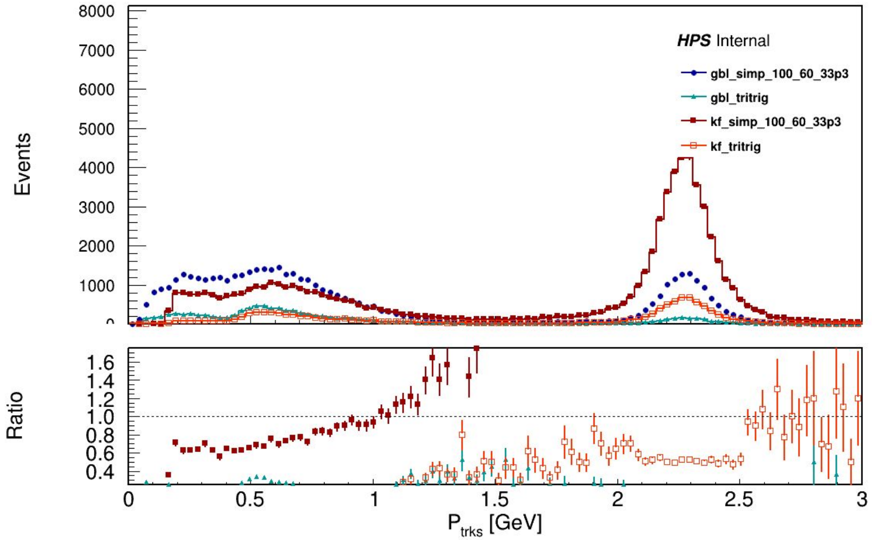
Tracking Determination no pre-selection

GBL reconstructed SIMP Signal
GBL reconstructed TRITRIG bkgd
KF reconstructed SIMP Signal
KF reconstructed TRITRIG bkgd

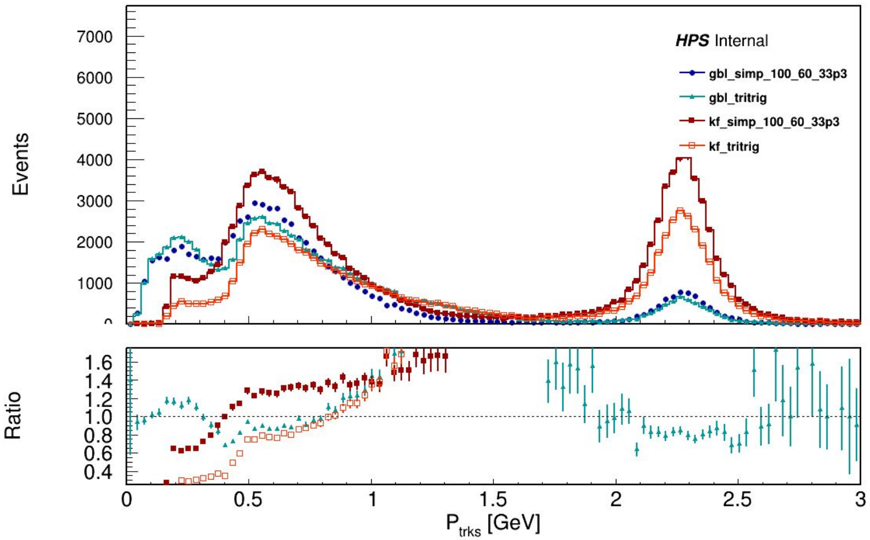
Far more FEEs reconstructed with KF

Ratios wrt GBL reconstructed SIMP signal

N(vertices) = 0



N(vertices) > 0

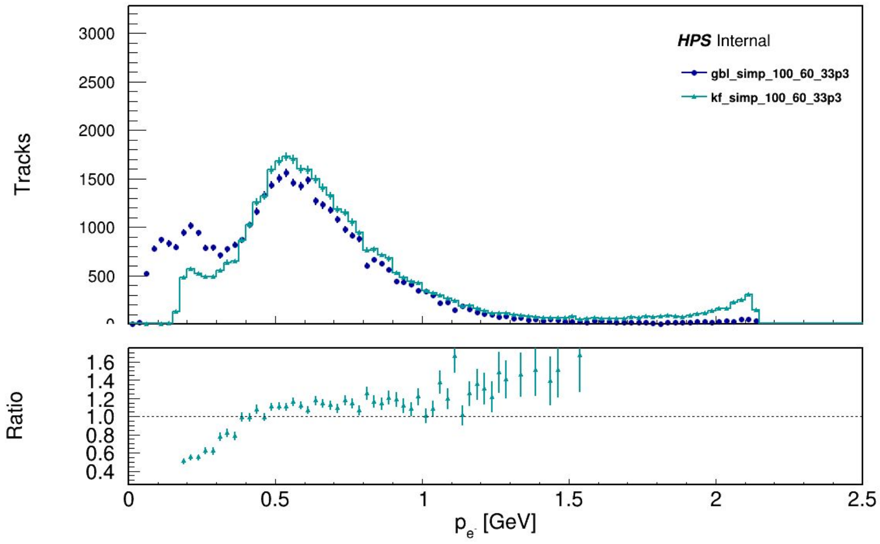


Tracking Determination no pre-selection

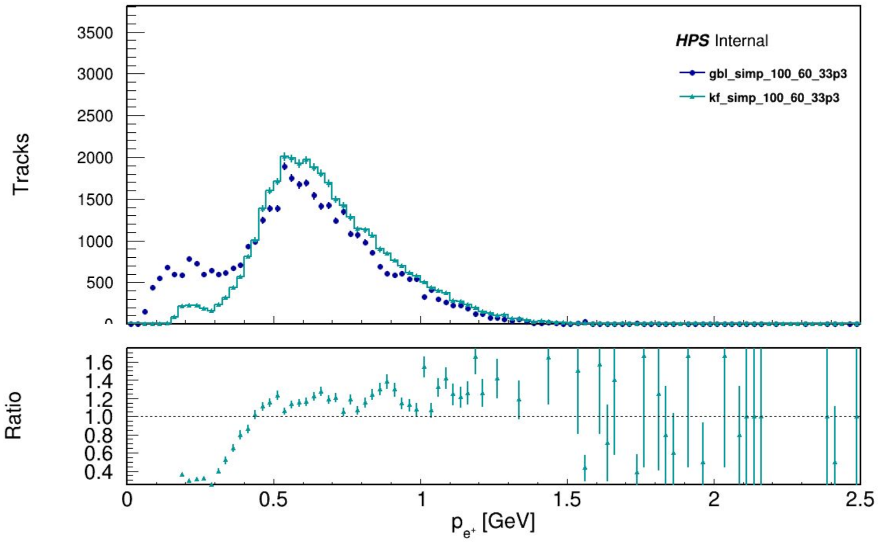
More low momentum tracks reconstructed with GBL

KF reconstructed SIMP Signal
GBL reconstructed SIMP Signal

Electron momentum



Positron momentum



Tracking Determination no pre-selection

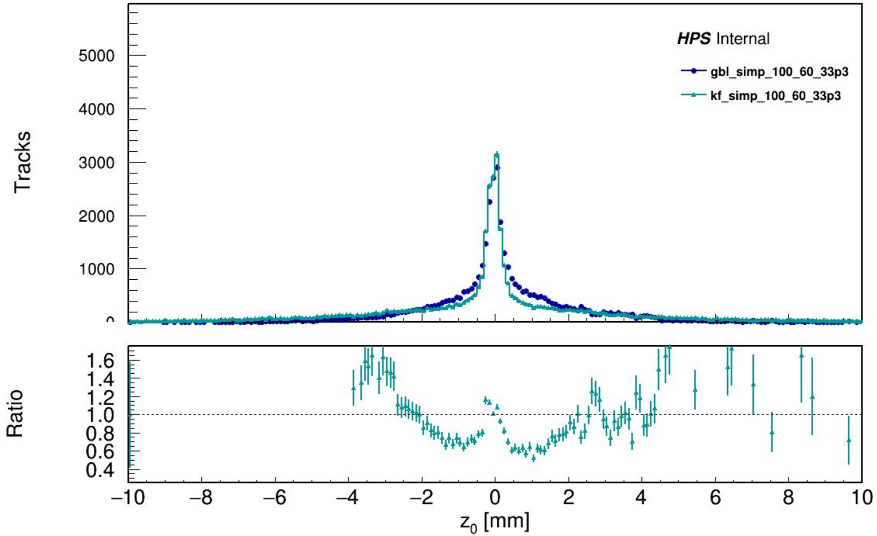
More positrons reconstructed with GBL that are closer to beamline

KF reconstructs more high Z_0

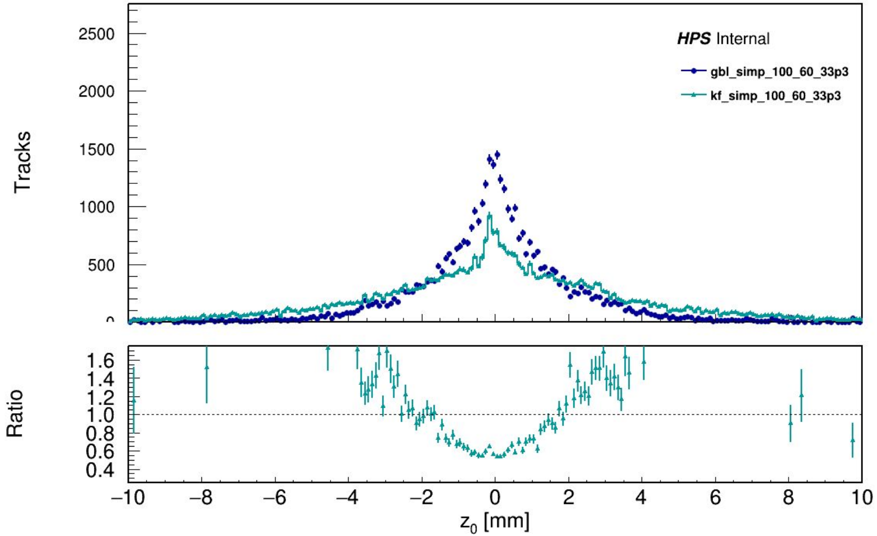
KF reconstructed SIMP Signal

GBL reconstructed SIMP Signal

Electron Z_0



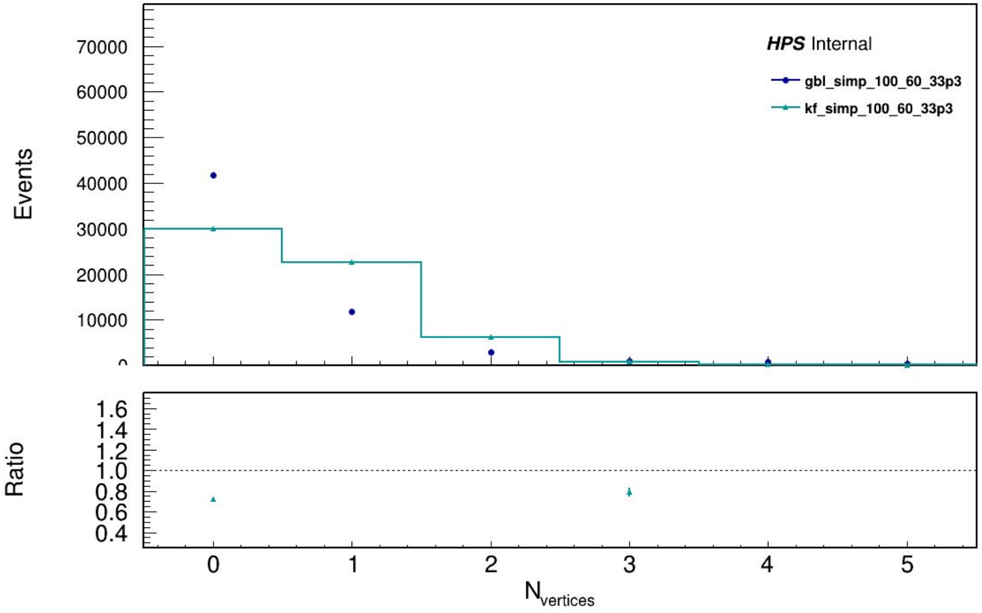
Positron Z_0



Tracking Determination no pre-selection

Fewer than 50% of SIMP signal events get reconstructed with vertices

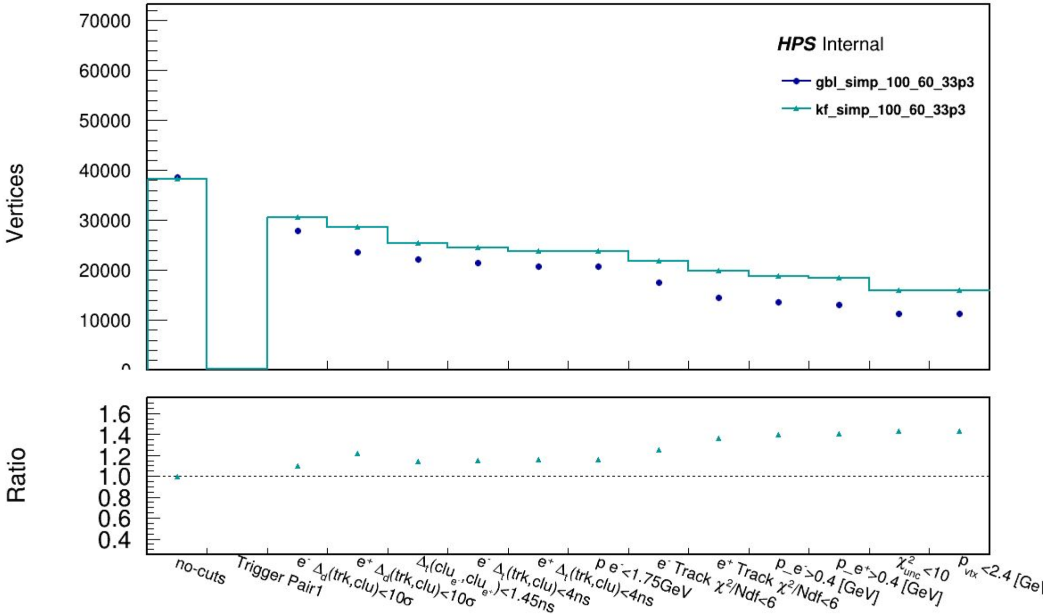
Different distribution of N(vertices) for GBL and KF reconstructed events



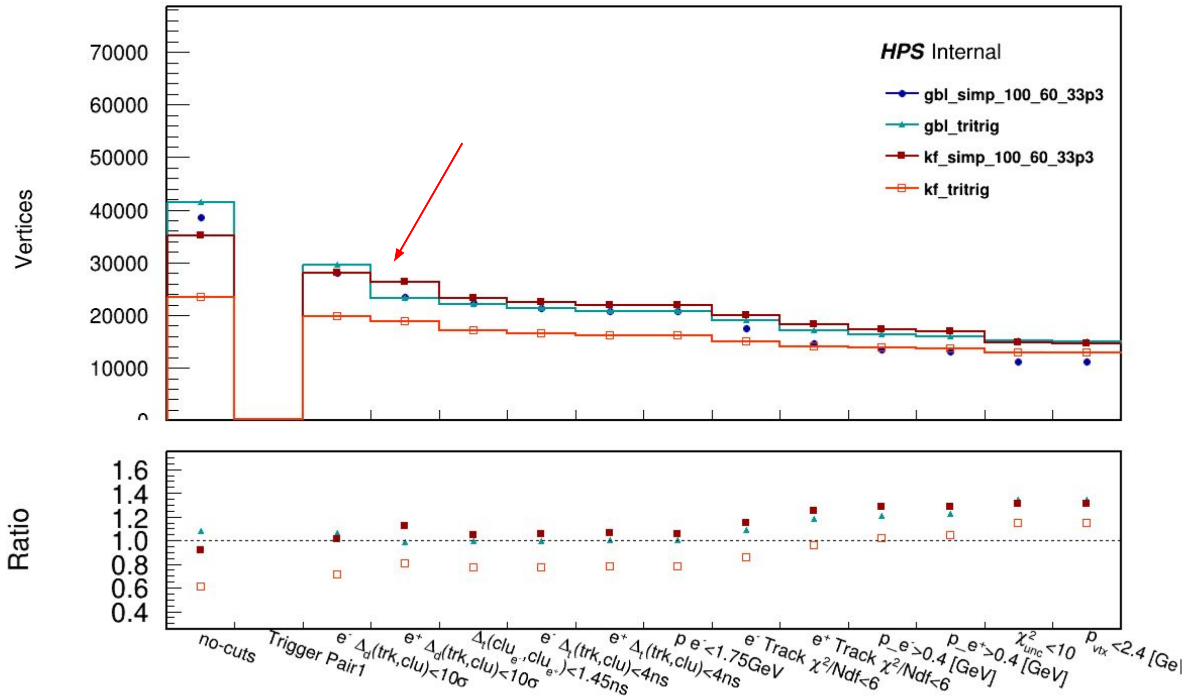
Vertex Preselection

- Apply 2016 Vertexing Analysis Preselection to SIMP signals

Trigger Pair1
$e^- \Delta_d(trk, clu) < 10\sigma$
$e^+ \Delta_d(trk, clu) < 10\sigma$
$\Delta_t(clu_{e^-}, clu_{e^+}) < 1.45\text{ns}$
$e^- \Delta_t(trk, clu) < 4\text{ns}$
$e^+ \Delta_t(trk, clu) < 4\text{ns}$
$p_{e^-} < 1.75$ GeV
e^- track $\chi^2/\text{ndf} < 6$
e^+ track $\chi^2/\text{ndf} < 6$
$p_{e^-} > 0.4$ [GeV]
$p_{e^+} > 0.4$ [GeV]
$\chi^2_{unc} < 10$
$p_{vtx} < 2.4$ [GeV]



Vertex Preselection



- More KF events pass the preselection cuts
- The signal to tritrig background appears more favorable for KF reconstructed events
  - 0.93 ➔ 0.78 $(s/b)_{GBL}$
  - 1.46 ➔ 1.17 $(s/b)_{KF}$
- A sensitivity study is needed

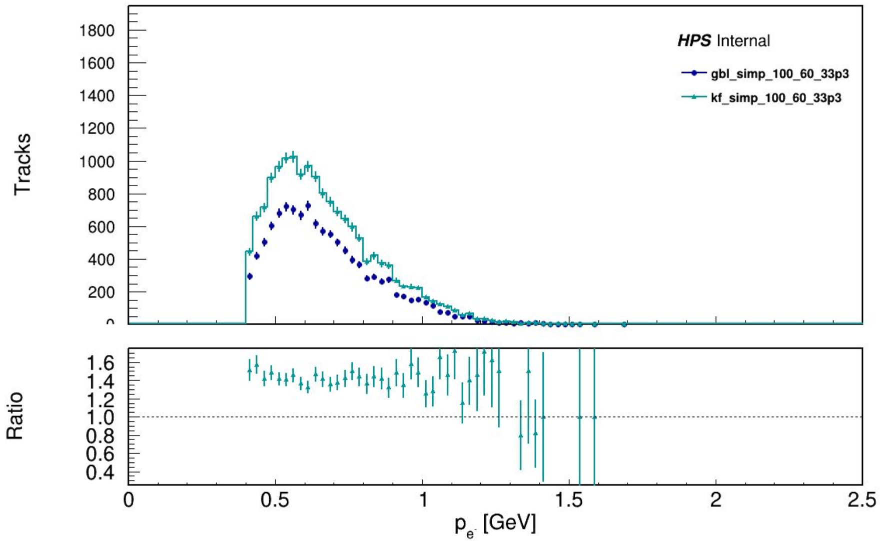
Vertex Preselection

Due to more low momentum tracks being reconstructed with GBL, more KF reconstructed signal make it past minimum p cut

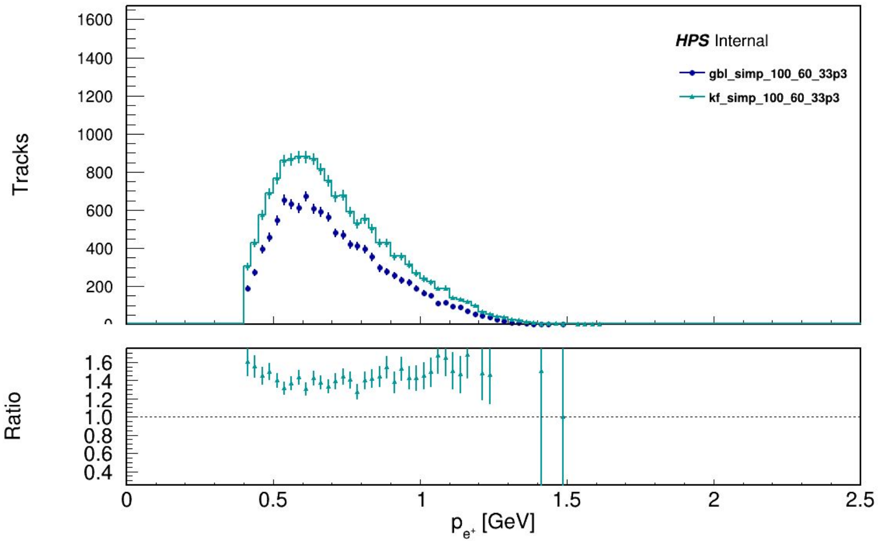
KF reconstructed SIMP Signal

GBL reconstructed SIMP Signal

Electron momentum

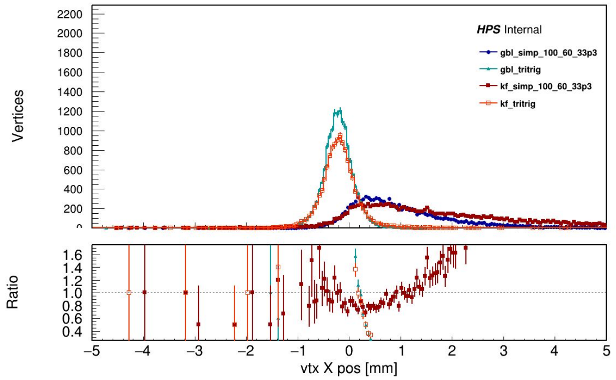


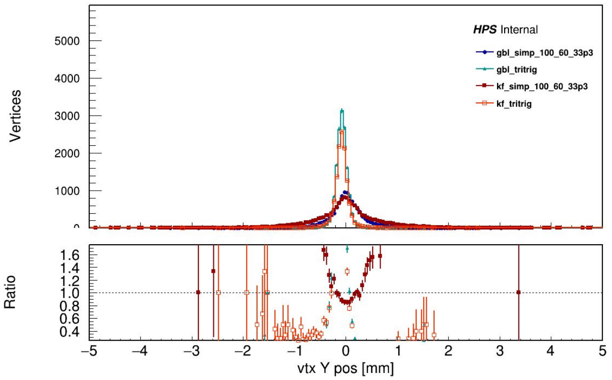
Positron momentum

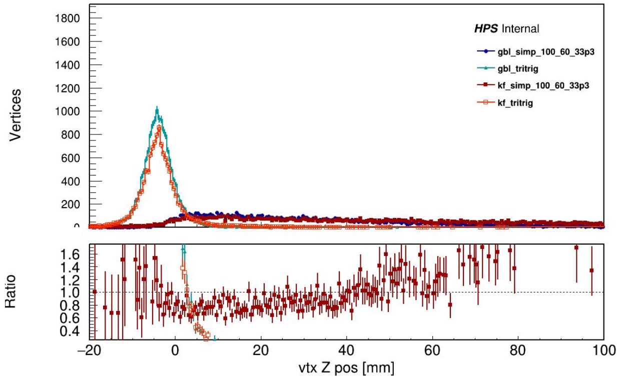


Vertex Preselection

- Vtx X, Y, and Z displacement after vertex preselection
- Note that tritrig background are not scaled relative to signal cross section





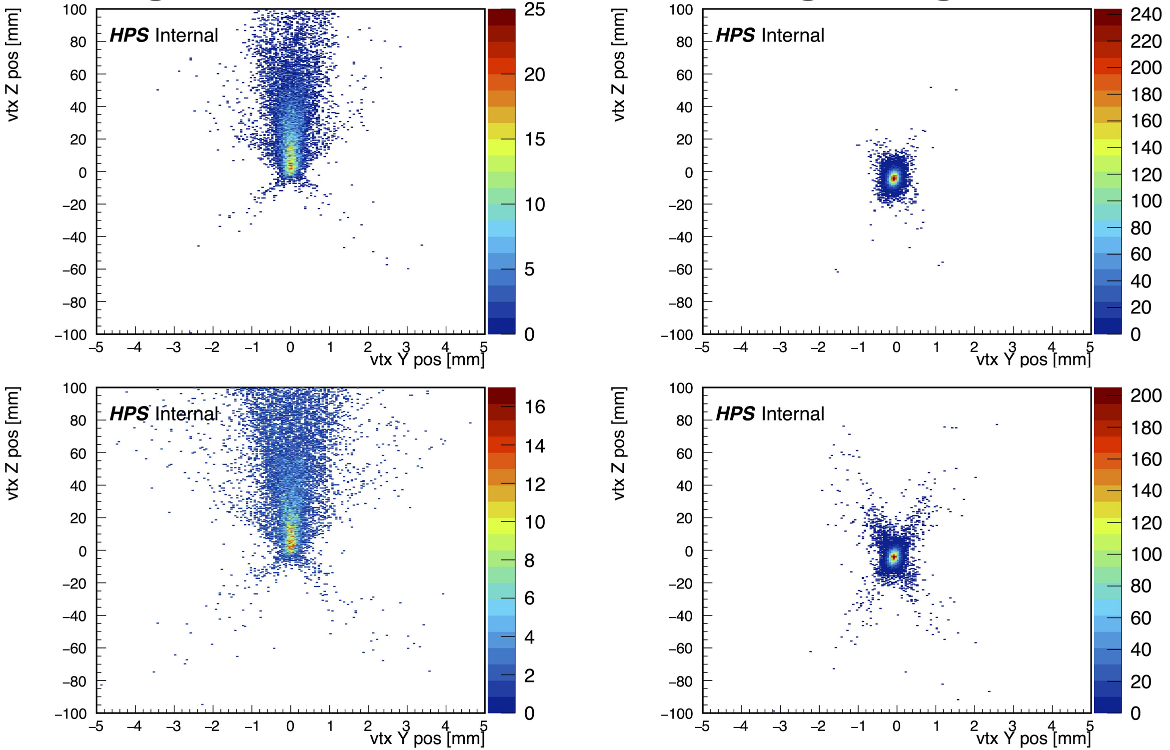


Vertex Preselection

Signal | Tritrig Background

GBL

KF



V_D production is very forward with little spread in vtx y position as compared to Tritrig

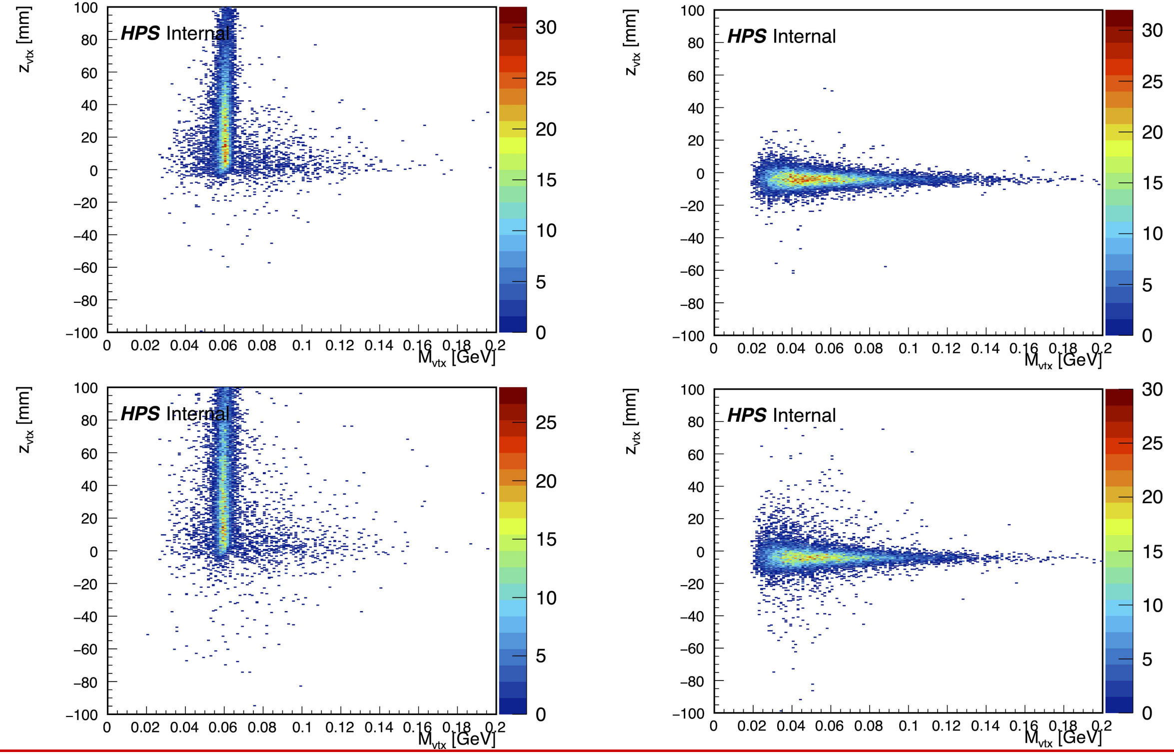
*there is no track-to-cluster matching for the GBL reconstruction upstream -- so studies must be taken with a grain of salt

Vertex Preselection

Signal | Tritrig Background

GBL

KF



*there is no track-to-cluster matching for the GBL reconstruction upstream -- so studies must be taken with a grain of salt

Tight SIMP Cuts

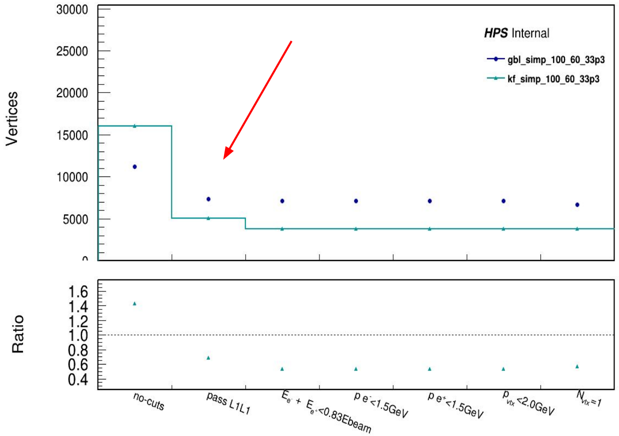
- Working towards SIMP specific discrimination cuts
- Still very preliminary
- Softer e^+e^- momenta than displaced A' due to missing π_D energy

$$L1L1 \text{ hit } || L1L2 \text{ hit } || L2L2 \text{ hit}$$
$$E_{e^-} + E_{E^+} < 0.83(E_{beam}) \approx 1.9GeV$$
$$p_{e^-} < 1.5GeV$$
$$p_{e^+} < 1.5GeV$$
$$p_{vtx} < 2.0GeV$$
$$N_{vtx} = 1$$

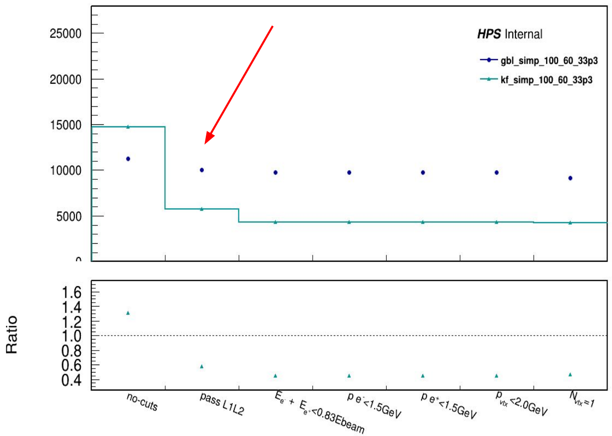
Tight SIMP Cuts

- L1L1 Cut used by displaced vertex A’ analysis to discriminate against background kills SIMP signal reconstructed with KF
- Similar layer requirements decrease signal reconstructed with KF

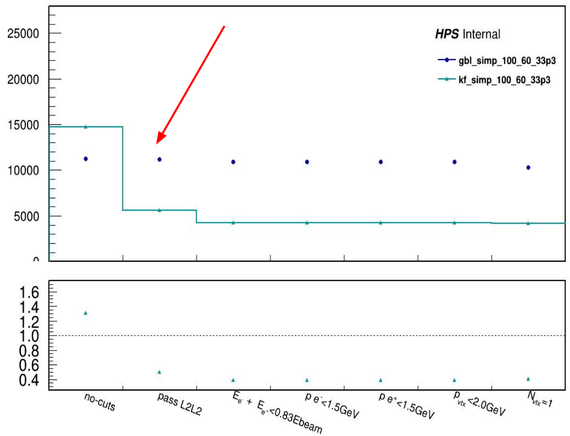
L1L1



L1L2



L2L2



Tight SIMP Cuts

- The L1L1 requirement excludes more KF signal events, than KF background

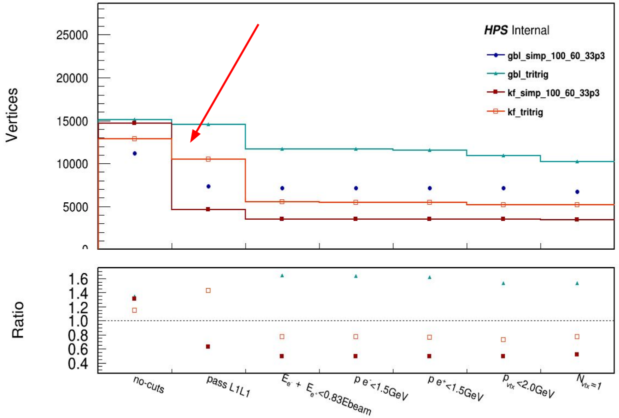
Before cuts $(s/b)_{gbl}$ ≅ 11000/15000 ≅ 0.73
$(s/b)_{kf}$ ≅ 14500/13000 ≅ 1.11

L1L1 $(s/b)_{gbl}$ ≅ 7000/10000 ≅0.70
$(s/b)_{kf}$ ≅ 4000/5000 ≅ 0.80

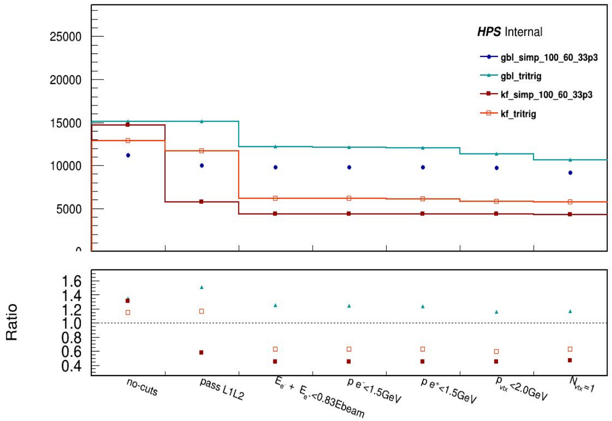
L1L1 $(s/b)_{gbl}$ ≅ 9000/11000 ≅ 0.81
$(s/b)_{kf}$ ≅ 4000/5100 ≅ 0.78

L1L1 $(s/b)_{gbl}$ ≅ 10000/10000 ≅ 1
$(s/b)_{kf}$ ≅ 4000/5100 ≅ 0.78

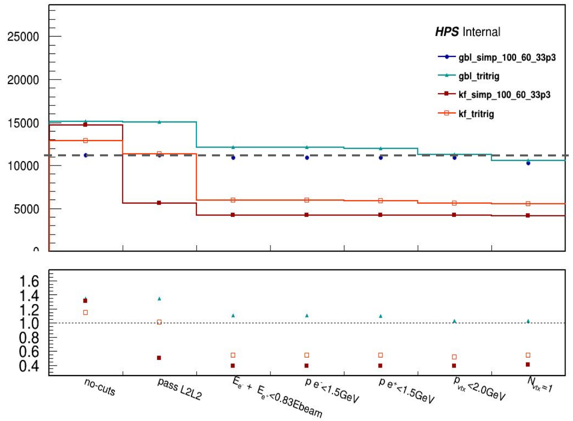
L1L1



L1L2



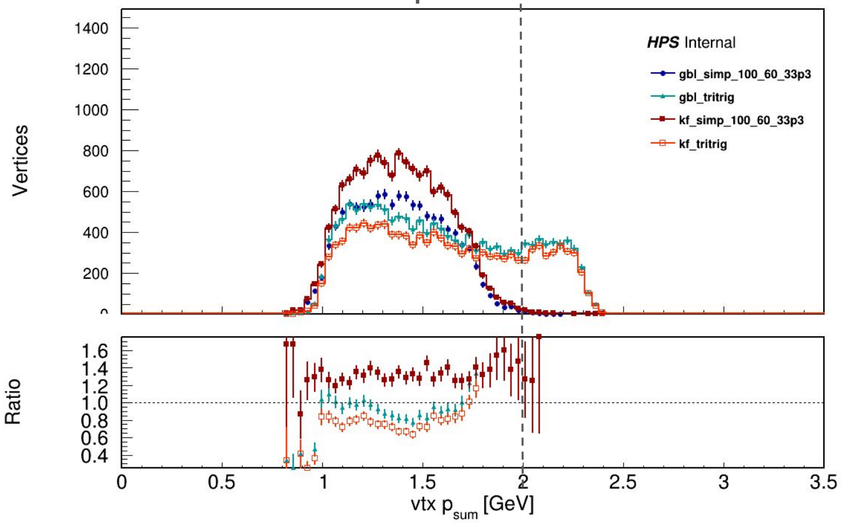
L2L2



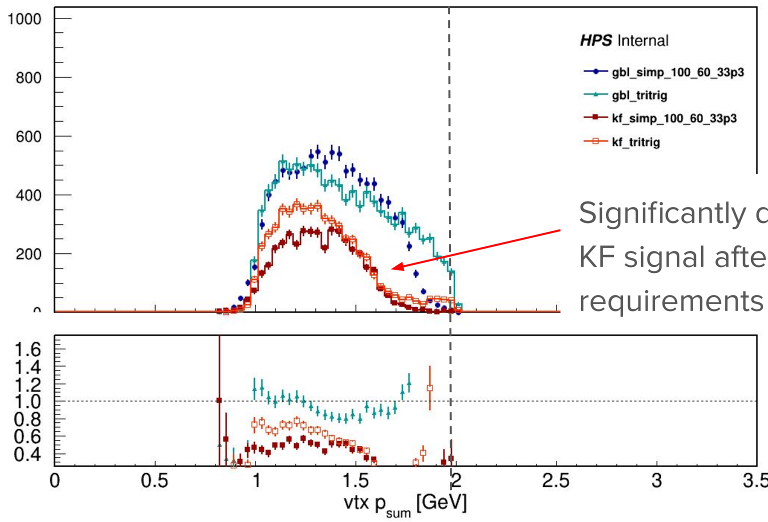
Tight SIMP Cuts

- Softer e^+e^- momenta wrt tritrig because π_D carries momentum which appears as missing

After vtx pre-selection



After SIMP L2L2

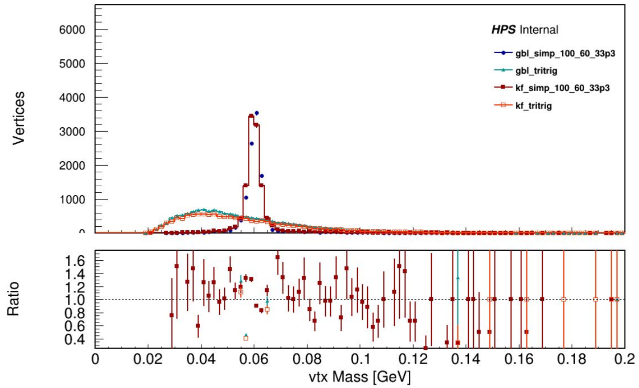


Significantly decreased KF signal after layer requirements

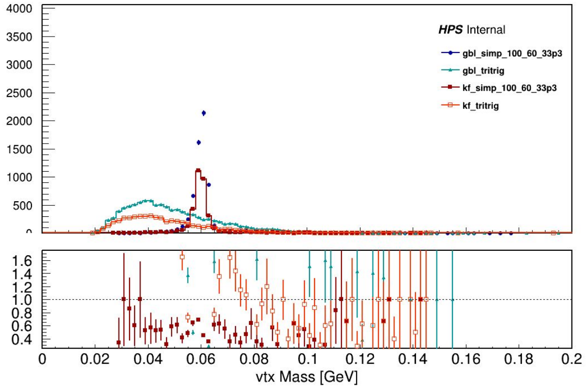
SIMP Vertex Mass

- There is no normalization applied to background yields
- Only one m_V studied so far, lower mass V_D would be less pronounced wrt background
- By using multiple layer hit categories, we can recover signal otherwise lost using just a L1L1 requirement

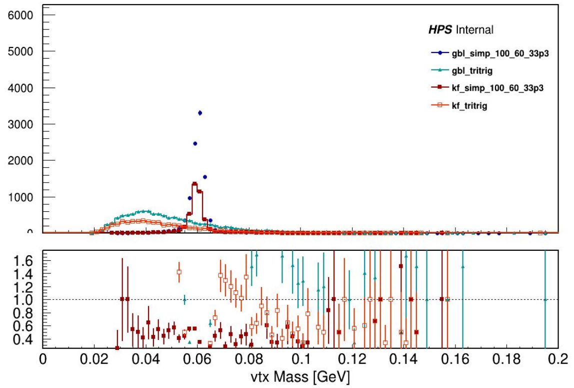
Vtx Preselection



L1L1



L2L2



Outlook

- While we are currently optimizing for a single $m_V : m_\pi : m_{A'}$ = 60: 33.3: 100, we will move towards studying different masses
  - SIMP MCs that have been produced ➔

m_V	m_π	$m_{A'}$
30	16.7	50
40	30	100
10	10	100
78	43.3	130
60	33.3	100

- Will study GBL/KF tracking performance on a per-track basis using truth information
  - SIMP signal purity
  - Background fake rates
  - Performance of reconstructed 2016 run data
- Determine if L1L1/L1L2/L2L2 categories are appropriate for SIMP analysis
- Sensitivity studies are needed moving forward