SIMPs HPS analysis

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HPS Collaboration Meeting
05.13.2020

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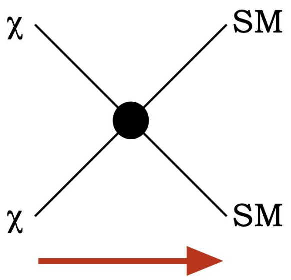
WIMP vs SIMP miracle

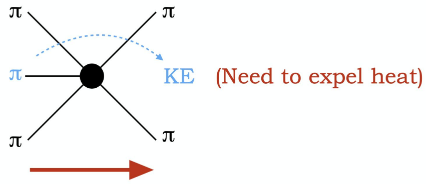
Relic abundance set by 2 → 2 annihilations



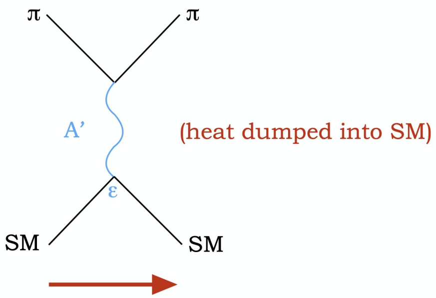
$$m_\chi \sim \alpha_\chi \ (T_{\rm eq} m_{\rm pl})^{1/2} \sim \alpha_\chi \times 10 \text{ TeV}$$

- DM mass ~ O(weak scale)
- alpha ~ O(weak coupling)

Relic abundance set thermally by freeze-out of a 3 → 2 process depleting number of DM particles in dark sector



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



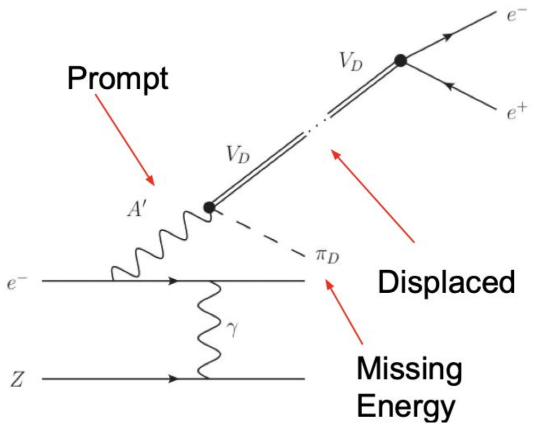
At t=$t_{\text{freeze-out}}$ DM ⟵⟶ SM kinetic equilibrium, meaning dark sector must couple to SM to maintain this: interactions are mediated by A'!

- DM mass ~ O(MeV-GeV)
- strong self-coupling

Brief refresher of SIMP theory

Strongly Interacting Massive Particles: arise from QCD-like dark sector based on SU(3) group containing 3 flavors of “dark” quarks w/ charges=+1,-1,-1

- $\boldsymbol{\pi}_D$ = dark pion comprises the DM
- A’ = couples dark sector to SM via kinetic mixing
- V_D = heavy dark vector meson (analogous to SM ϱ meson)
- $\boldsymbol{\varepsilon}$ = kinetic mixing parameter
- α_D = $U(1)_D$ gauge coupling constant
- $f\boldsymbol{\pi}_D$= dark sector pion decay constant

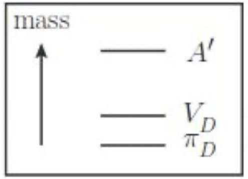


Most of the SIMP theory material is directly lifted from:

- Matt Solt’s talk
- SIMP rates at HPS whitepaper
- SIMP cosmology paper

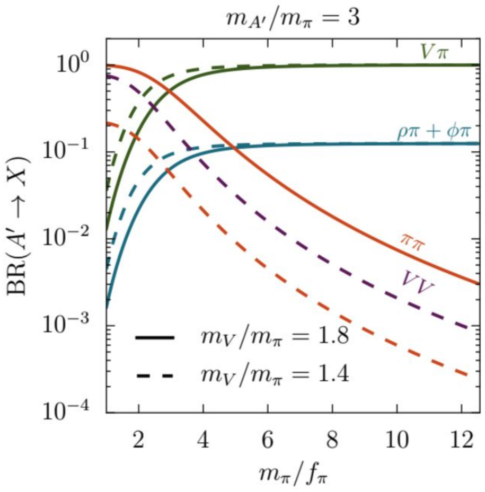
Constraints on the SIMP theory

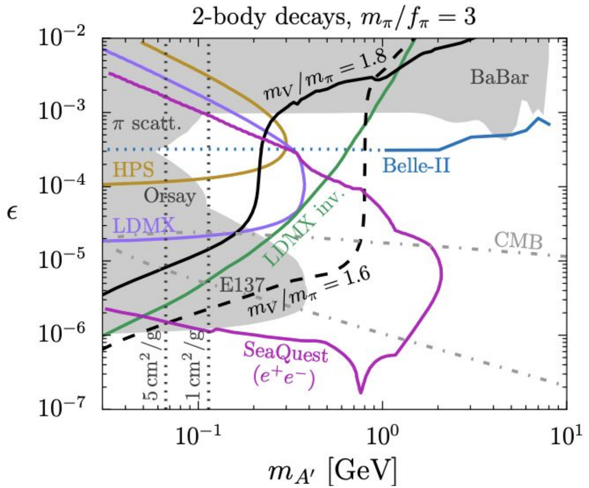
- $m\pi_D$, mV_D , and $f\pi_D$ govern the relic abundance, so **$m\pi_D/f\pi_D < 4\pi$** [~3-4 for wide range of masses]
- A' → SM in early Universe is suppressed by small kinetic mixing, so **$\varepsilon < 10^{-2}$**
  - SIMP cosmology sets small lower bound: **$\varepsilon > 10^{-6.3}$**
- α_D constrained by perturbativity to be <1, so take QED-like **$\alpha_D \sim 0.01$**
- Mass hierarchy:
  - SIMP cosmology requires suppression of standard annihilations & semi-annihilations, $\pi_D\pi_D \to A' \to SM\ SM$ **OR** $\pi_D\pi_D \to A'\pi_D$ so: **$mA' > 2m\pi_D$**
  - *Visible* HPS signals require: **$mV_D < 2m\pi_D$** and **$mA' > mV_D + m\pi_D$**

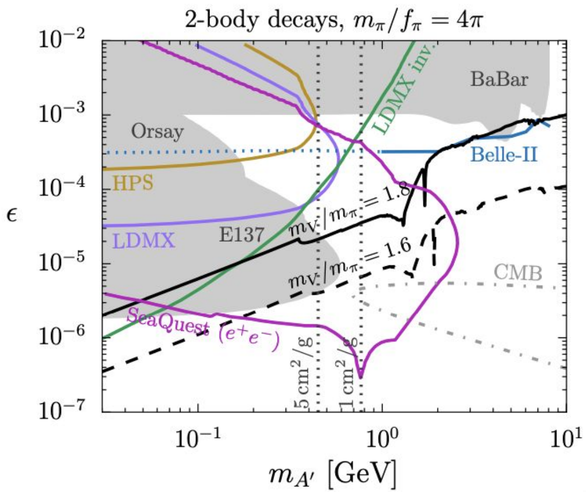


Choice of parameters

- 2-body decays of V_D are detectable at HPS
  - V^0 decays such as $\rho \rightarrow$ e+e- or $\varphi \rightarrow$ e+e-
- HPS projected sensitivity is largely unaffected by mV_D:$m\pi_D$ but relic abundance is extremely sensitive to splitting



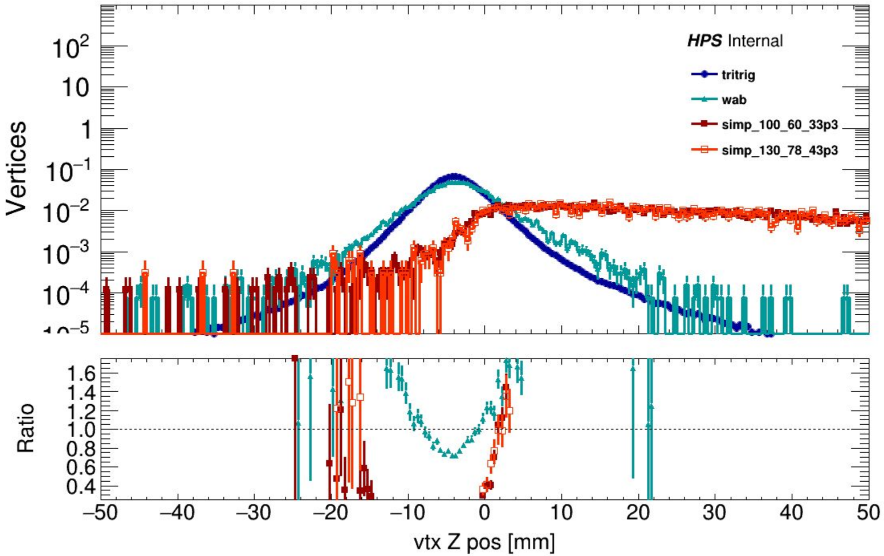


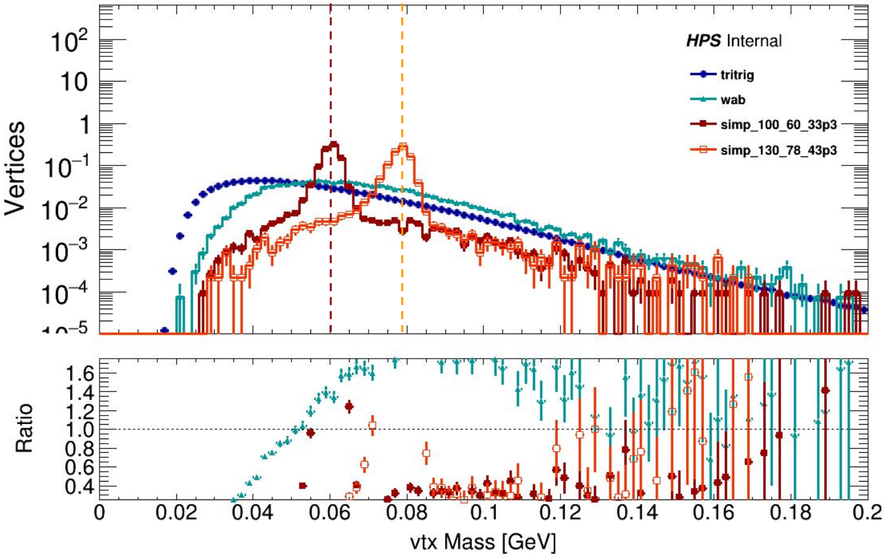


SIMPs MC for HPS

- Full MC production chain in place used to generate 2016 SIMP MC:
  - MG5 configurations integrated into hps-mc
    - LHEs validated against existing ones produced by Takashi some time ago (see backup)
  - V_D displacement handled by a separate tool: simp-lhe-to-stdhep
    - Signals in following slides are generated with ctau = 10 mm
  - Samples include beam overlay, rotation to beam coordinates, PU & trigger simulation, and full 2016 detector reconstruction
- Process LCIO outputs from hps-mc with hpstr to generate ROOT reco tuples
  - Includes MCParticle linking if desired

What does the signal look like?





We want to reconstruct an e+e- vertex displaced in Z peaking at mass values below the A' mass

SIMPs signal efficiency

Applying the 2016 vertexing analysis pre-selection yields ~73% SIMP signal efficiency
N.B. Normalization is not applied to these yields!

	$m_{A'} = 130$ MeV, $m_{\rho_D} = 78$ MeV, $m_{\pi_D} = 43.3$ MeV	ϵ_{tot}	$m_{A'} = 100$ MeV, $m_{\rho_D} = 60$ MeV, $m_{\pi_D} = 33.3$ MeV	ϵ_{tot}	WAB	ϵ_{tot}	Tritrig	ϵ_{tot}
Trigger Pair1	6377	–	15433	–	31840	–	7.95433e06	–
$e^-\Delta_d(trk, clu) < 10\sigma$	6326	0.992	15281	0.99	31621	0.993	7.86906e06	0.989
$e^+\Delta_d(trk, clu) < 10\sigma$	6317	0.991	15252	0.988	31392	0.986	7.85067e06	0.987
$\Delta_t(clu_{e^-}, clu_{e^+}) < 1.45$ns	6198	0.972	14956	0.969	30922	0.971	7.73721e06	0.973
$e^-\Delta_t(trk, clu) < 4$ns	6174	0.968	14882	0.964	30802	0.967	7.68891e06	0.967
$e^+\Delta_t(trk, clu) < 4$ns	6153	0.965	14816	0.96	30361	0.954	7.6686e06	0.964
$p_{e^-} < 1.75$ GeV	6144	0.963	14806	0.959	30305	0.952	7.66146e06	0.963
e^- track $\chi^2/\text{ndf} < 6$	5969	0.936	14320	0.928	29662	0.932	7.48835e06	0.941
e^+ track $\chi^2/\text{ndf} < 6$	5812	0.911	13802	0.894	27073	0.85	7.33095e06	0.922
$p_{e^-} > 0.4$ [GeV]	5502	0.863	13305	0.862	27002	0.848	7.24516e06	0.911
$p_{e^+} > 0.4$ [GeV]	5319	0.834	13016	0.843	26704	0.839	7.20846e06	0.906
$\chi^2_{unc} < 10$	4682	0.734	11166	0.724	13132	0.412	6.76432e06	0.85
$p_{vtx} < 2.4$ [GeV]	4682	0.734	11164	0.723	13087	0.411	6.76015e06	0.85

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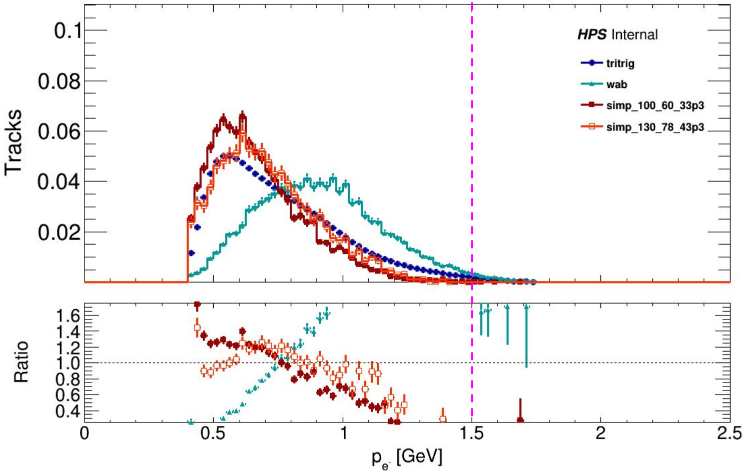
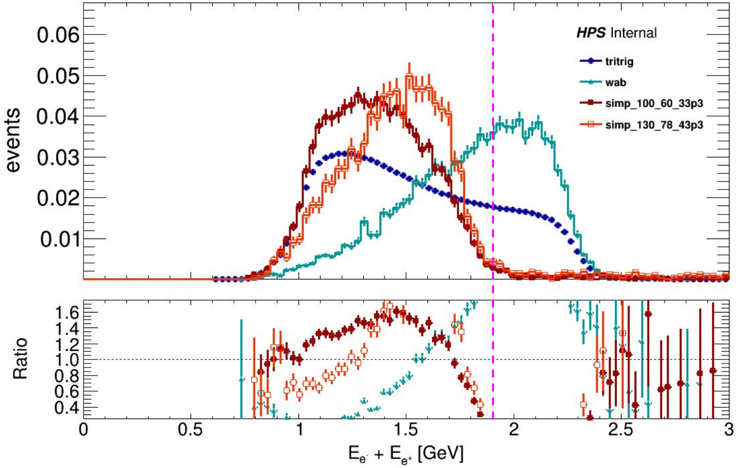
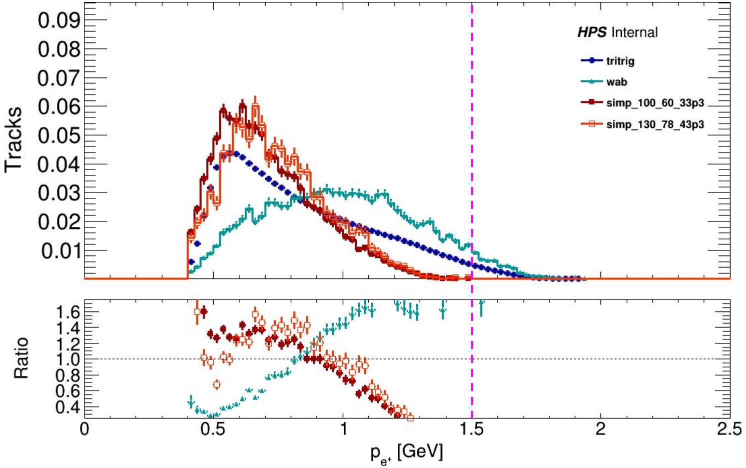
Signal kinematics of interest [I]

- Expect softer e+/e- momenta wrt tritrig/wab/nominal displaced A' signal, since π_D carries significant fraction of total momentum (as missing)
- In general, the heavier the mV_D the harder the resulting e+/e- decay product momenta
- [See gallery of distributions here]()

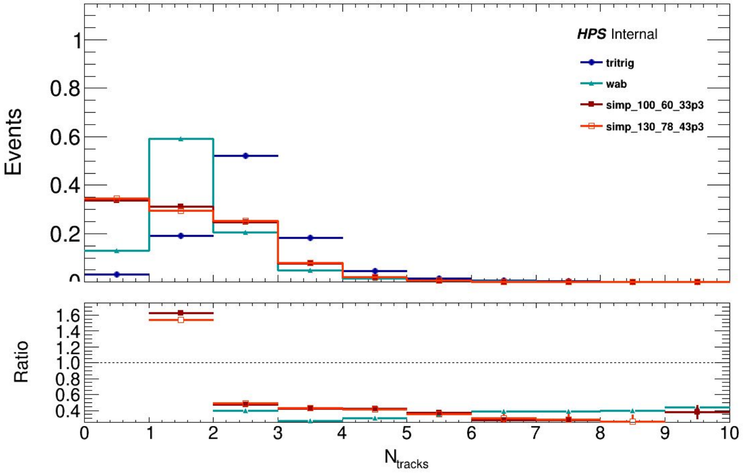


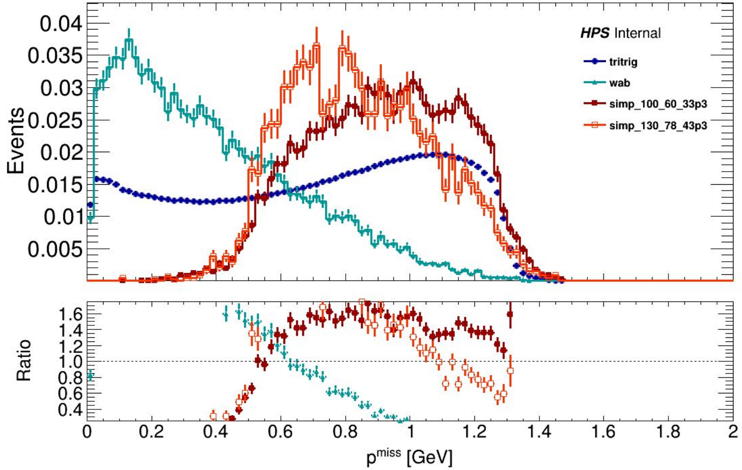


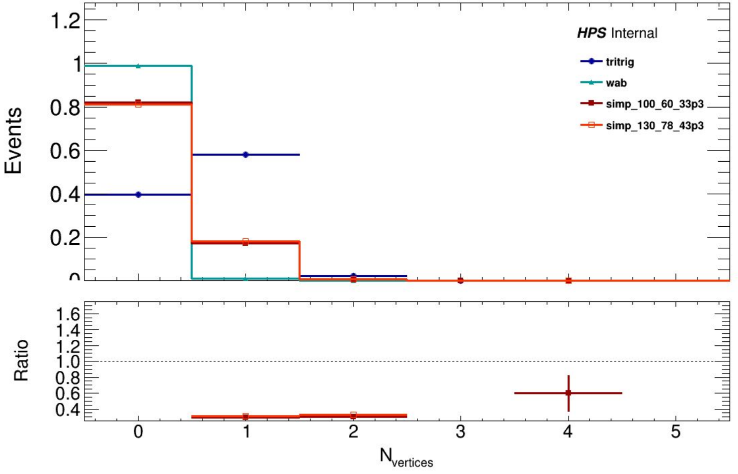


Signal kinematics of interest [II]

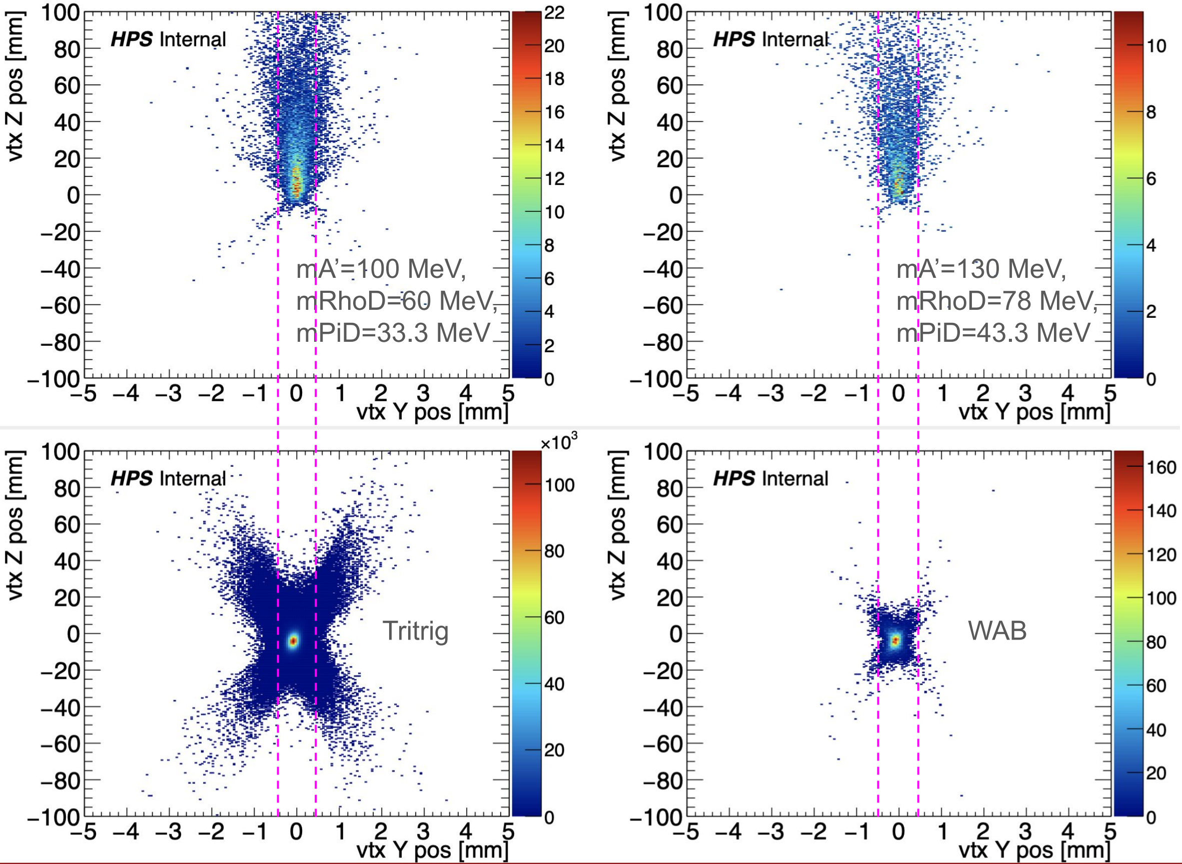
- Requiring single unconstrained V0 in the event significantly suppresses WAB bkg, but in turn reduces signal efficiency dramatically
- Pmiss (= Pbeam - Psum) expectedly strongly discriminating against WAB bkg, less so against tritrig
- See gallery of distributions here







SIMP signal vertex kinematics [vtx analysis preselection]



Vertex Z vs Y position:

V_D production is typically very forward, so we would expect the spread in the reconstructed vertex Y position to be relatively small for SIMP signals

- Would help to eliminate significant part of the high Z tail in tritrig events
- WAB events less affected

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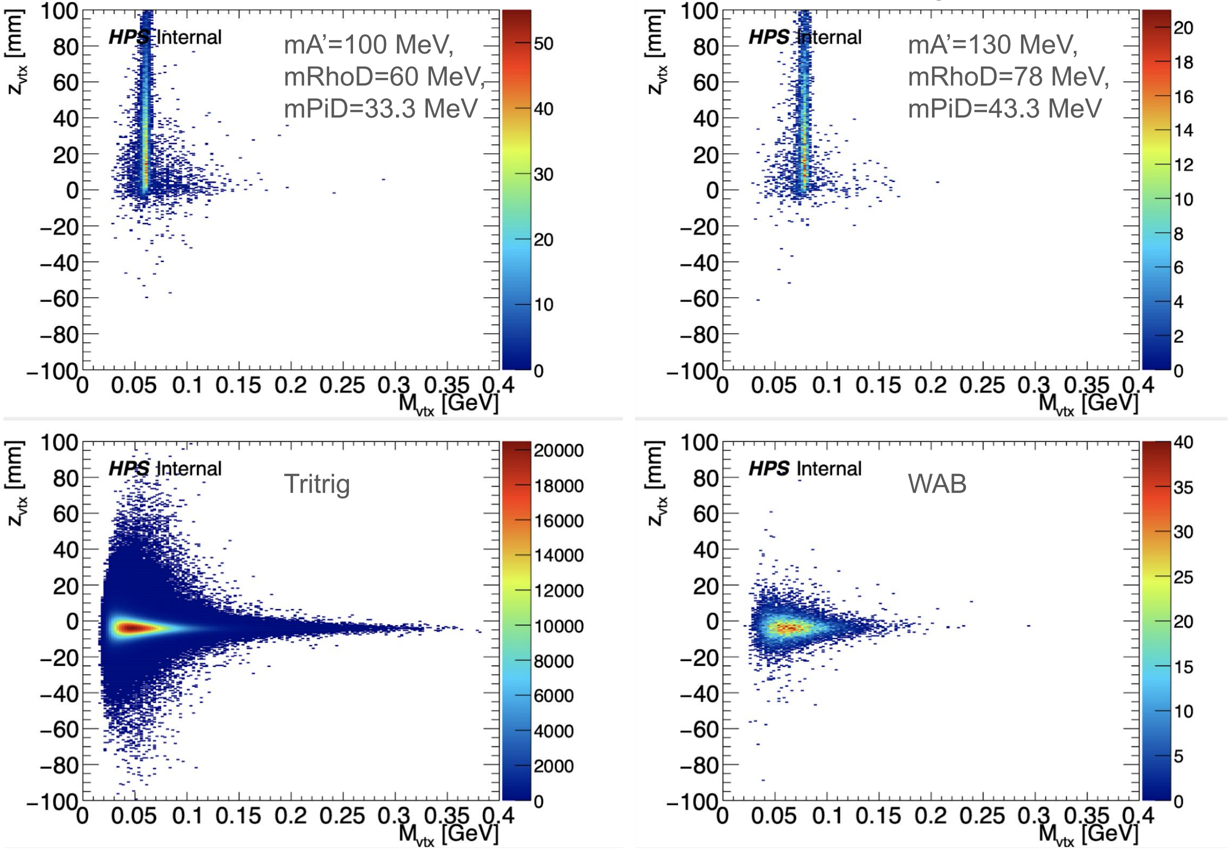
Towards “SIMP tight” cuts

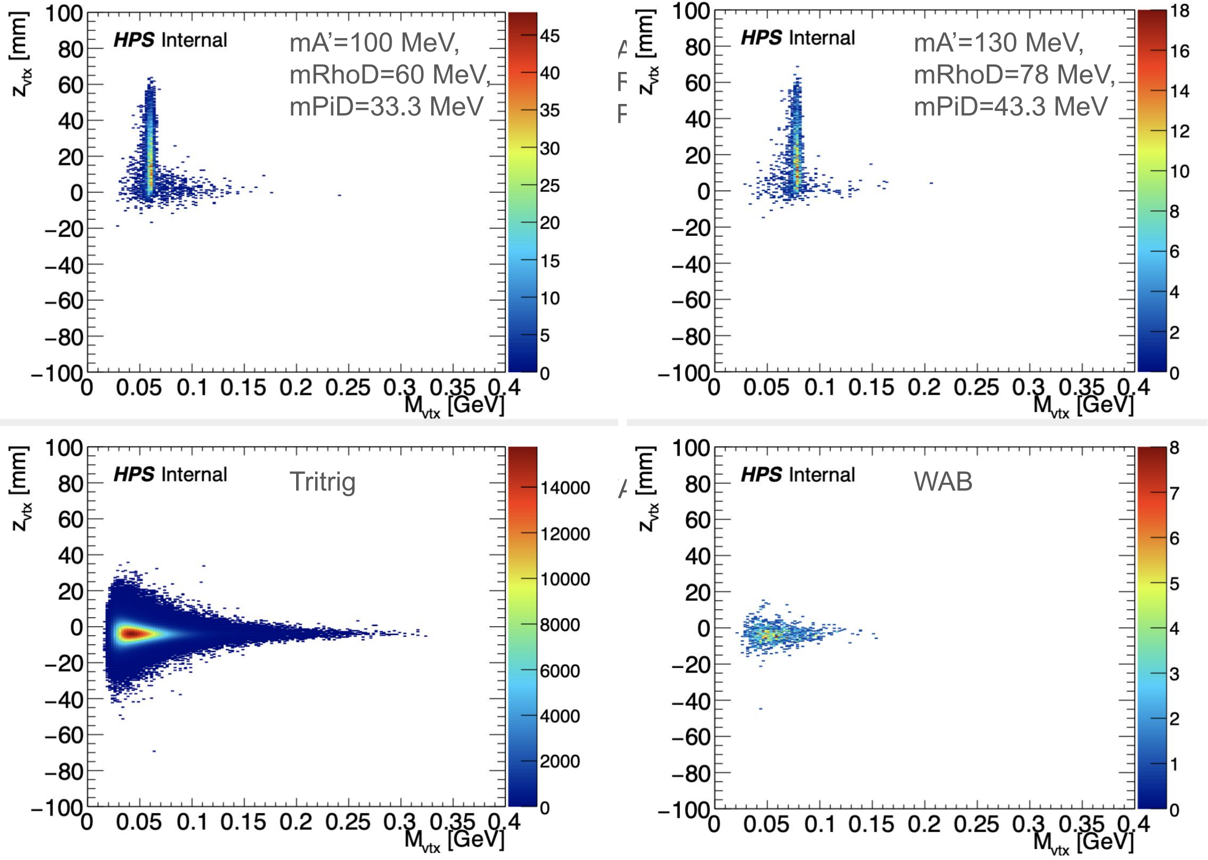
	$m_{A'} = 130$ MeV $m_{\rho_D} = 78$ MeV $m_{\pi_D} = 43.3$ MeV		$m_{A'} = 100$ MeV $m_{\rho_D} = 60$ MeV $m_{\pi_D} = 33.3$ MeV		WAB		Tritrig	
		ϵ_{tot}		ϵ_{tot}		ϵ_{tot}		ϵ_{tot}
Vtx analysis preselection	4682	–	11164	–	13087	–	6.76015e+06	–
pass L1L1	3062	0.654	7176	0.643	5200	0.397	6.49437e+06	0.961
$E_{e^-} + E_{e^+} < 0.83$Ebeam	2876	0.614	7011	0.628	2886	0.221	5.10391e+06	0.755
$p_e^- < 1.5$ GeV	2876	0.614	7009	0.628	2859	0.218	5.08178e+06	0.752
$p_e^+ < 1.5$ GeV	2876	0.614	7009	0.628	2811	0.215	5.05666e+06	0.748
$p_{vtx} < 2.0$ GeV	2876	0.614	7004	0.627	2423	0.185	4.8498e+06	0.717
$N^{e^-}_{\text{Shared}}$ L0=0	2762	0.59	6748	0.604	2347	0.179	4.67108e+06	0.691
$N^{e^+}_{\text{Shared}}$ L0=0	2686	0.574	6513	0.583	1128	0.086	4.50254e+06	0.666
N_{vtx}=1	2624	0.56	6355	0.569	1112	0.085	4.39421e+06	0.65
vtx Y> -0.4 mm	2508	0.536	6135	0.55	1098	0.084	4.36561e+06	0.646
vtx Y< 0.4 mm	2265	0.484	5758	0.516	1089	0.083	4.35818e+06	0.645

- L1L1 requirement removes ~35% of preselected SIMP signal events → likely possible to recover with L1L2 or L2L2 a la vertex analysis
- Esum & e+/e- momenta requirements help suppress tritrig
- No shared hits at L0 for e+ GBL track has 50% relative effect on WABs
- Lower/upper bounds on vtx Y position may be redundant for suppressing tritrig

Vertex invariant mass vs Z position [vtx analysis preselection]



Vertex invariant mass vs Z position ["SIMP tight" cuts]



Conclusions and outlook

- First look at the SIMPs 2-body signal at HPS
  - Integration of SIMP signal configurations into hps-mc
  - Full chain for 2016 MC reconstruction used to produce samples
    - In principle, this can be repeated for 2019 HPS detector settings, but will require re-running LHE generation step with updated Ebeam
- Preliminary investigation of vertex analysis preselection & some dedicated “SIMP tight” cuts
  - Worth exploring vertex impact parameter & isolation requirements from vertex search
    - Vertex analysis preselection plots
    - SIMP tight selection plots (WIP)

Back up

SIMP MC production

Link to updated google sheet

HPS_HOME=/gpfs/slac/atlas/fs1/d/ssevova/hps

mA'	mRhoD	mPiD	lhe	displaced stdhep	slcio	root
50	30	16.7	$HPS_HOME/hps-mc/production_v2/50_30_16p7	$HPS_HOME/hps-mc/displaced_stdhep/ctau10mm/50_30_16p7	$HPS_HOME/hps-mc/recon/ctau10mm/50_30_16p7	$HPS_HOME/hpstr/mc/simp/ctau10mm/50_30_16p7/simp_50_30_16p7_rec
100	40	30	$HPS_HOME/hps-mc/production_v2/100_40_30	$HPS_HOME/hps-mc/displaced_stdhep/ctau10mm/100_40_30	$HPS_HOME/hps-mc/recon/ctau10mm/100_40_30	$HPS_HOME/hpstr/mc/simp/ctau10mm/100_40_30/simp_100_40_30_recon
100	10	10	$HPS_HOME/hps-mc/production_v2/100_10_10	$HPS_HOME/hps-mc/displaced_stdhep/ctau10mm/100_10_10	$HPS_HOME/hps-mc/recon/ctau10mm/100_10_10	$HPS_HOME/hpstr/mc/simp/ctau10mm/100_10_10/simp_100_10_10_recon
130	78	43.3	$HPS_HOME/hps-mc/production_v2/130_78_43p3	$HPS_HOME/hps-mc/displaced_stdhep/ctau10mm/130_78_43p3	$HPS_HOME/hps-mc/recon/ctau10mm/130_78_43p3	$HPS_HOME/hpstr/mc/simp/ctau10mm/130_78_43p3/simp_130_78_43p3_r
100	60	33.3	$HPS_HOME/hps-mc/production_v2/100_60_33p3	$HPS_HOME/hps-mc/displaced_stdhep/ctau10mm/100_60_33p3	$HPS_HOME/hps-mc/recon/ctau10mm/100_60_33p3	$HPS_HOME/hpstr/mc/simp/ctau10mm/100_60_33p3/simp_100_60_33p3_r

hps-mc
and
lhe to root parser

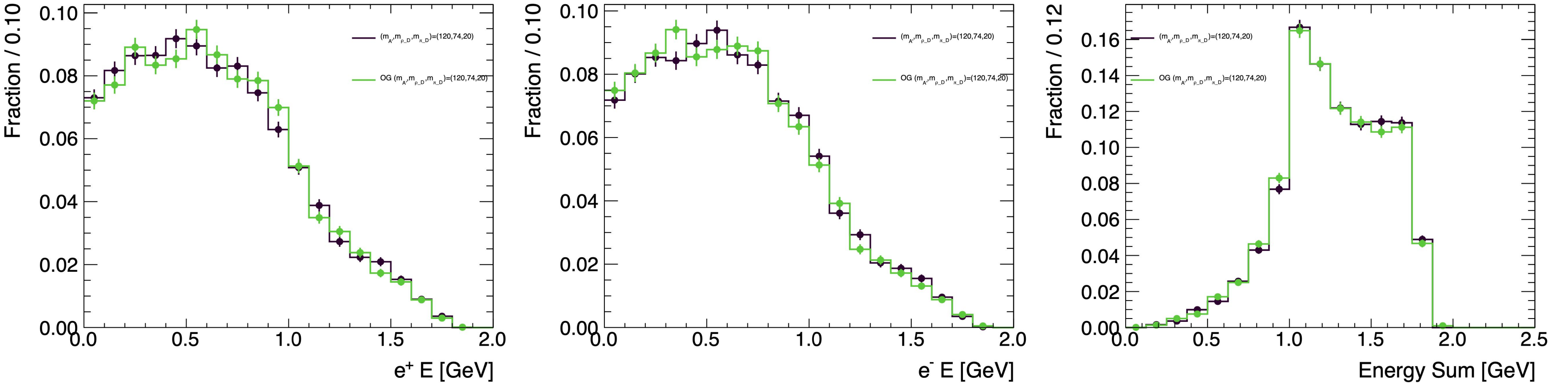
simp_lhe_to_stdhep

hps-mc (hps-java)

hpstr

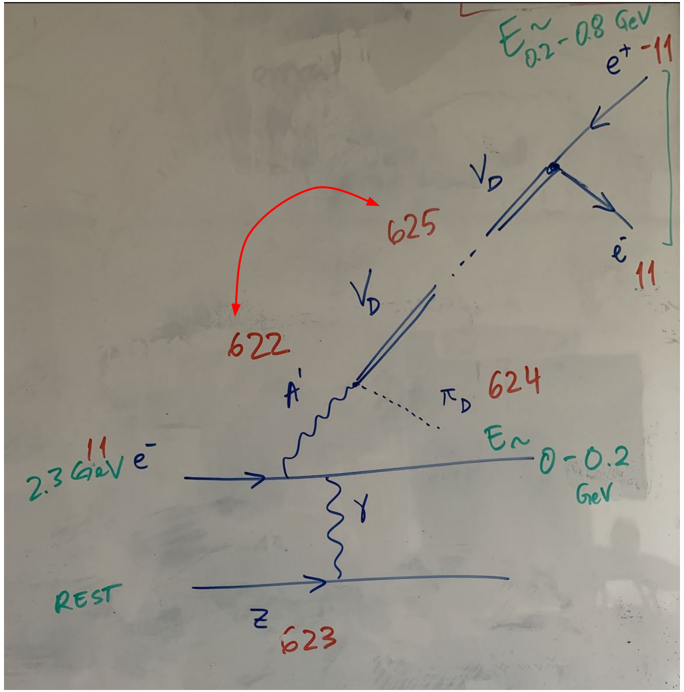
MC step 1: LHE

- Generated LHE files for a few mass points w/ SIMP model UFO from Nikita, Stefania, Natalia, et al
- Validated against existing LHE files from Takashi:
    - Compare basic kinematic quantities at particle-level using parser developed to translate LHE event to ROOT: hps-lhe-parsers (does tritrig, rad, WABs, A's too)
    - Kinematics from new and original LHEs agree well within stats uncertainties



MC step 2: STDHEP

- LHE files do not take into account the displacement of rhoD
- Displacement tool in hps-mc only displaces e+e- if mother PDG ID=622 (A')
  - simp lhe to stdhep: wrapper for Takashi's tool that takes in LHE, swaps 625 & 622 (including mother-daughter linking), displaces e+e-, and spits out STDHEP file
  - *N.B: for the plots that follow ctau=10 mm*



MC step 3: SLCIO

- Run displaced STDHEP files through the rest of the MC chain including normal readout and reconstruction for the 2016 HPS detector:
  - Rotate to beam coordinates
  - Generate events in SLIC
  - Insert empty bunches expected by PU simulation
  - Run simulated events in readout to generate Pairs1 trigger
  - Run 2016 MC reconstruction

```
        "target_z": -4.3,
        "detector": "HPS-PhysicsRun2016-Pass2",
             "run": 7984,
"readout_steering": "/org/hps/steering/readout/PhysicsRun2016TrigPairs1_LargeMC.lcsim",
  "recon_steering": "/org/hps/steering/recon/PhysicsRun2016FullReconMC.lcsim",
```

MC step 4: ROOT

A. Use hpstr to process SLCIO files & produce ROOT ntuples
   - Reco config: https://github.com/JeffersonLab/hpstr/blob/master/processors/config/recoTuple_cfg.py

B. Use VertexAnaProcessor (with some modifications) to process ntuples with cutflows to produce histos
   - https://github.com/ssevova/hpstr/blob/master/processors/src/VertexAnaProcessor.cxx
   - Vtx ana config: https://github.com/ssevova/hpstr/blob/master/processors/config/anaVtxTuple_cfg.py
   - SIMP region defs:
     https://github.com/ssevova/hpstr/blob/master/analysis/selections/vertexSelection.json
     https://github.com/ssevova/hpstr/blob/master/analysis/selections/simpTight.json
     https://github.com/ssevova/hpstr/blob/master/analysis/selections/simpTightL1L1.json
     https://github.com/ssevova/hpstr/blob/master/analysis/selections/simpTightL1L1NoSharedL0.json

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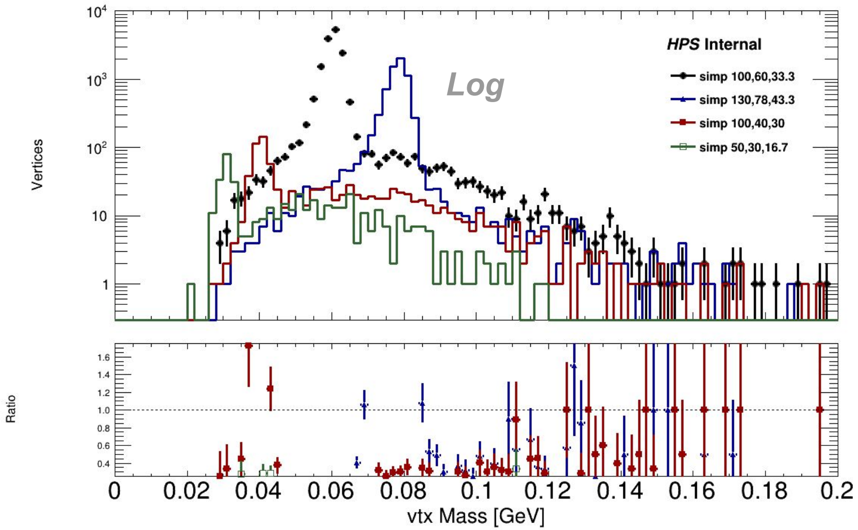
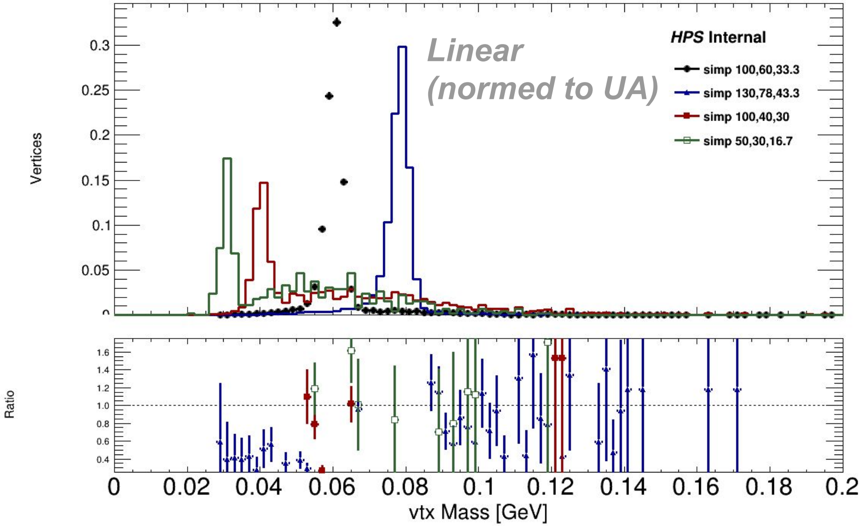
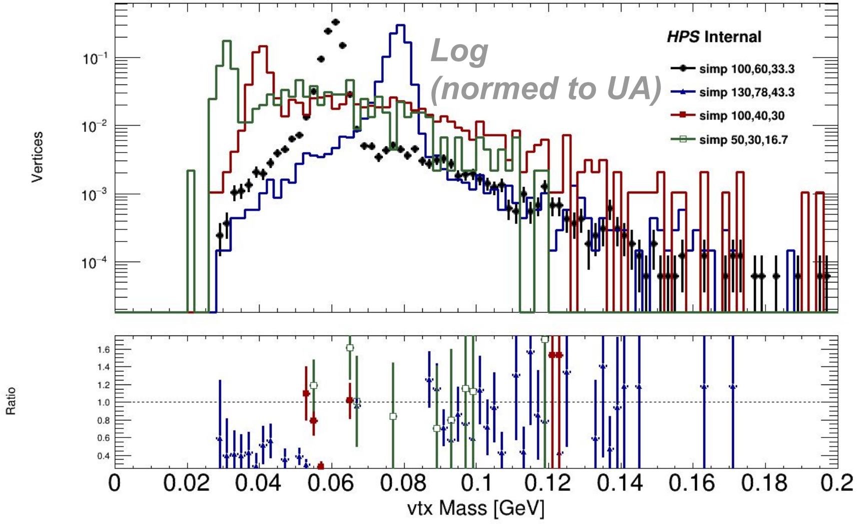
Vertex invariant mass [I]

- Observe a considerable shoulder/tail in vertex mass for signal points with low mass rho_D [e.g. A'=50, rhoD=30, piD=16.7 MeV]
- Effect is less pronounced for higher rho_D mass

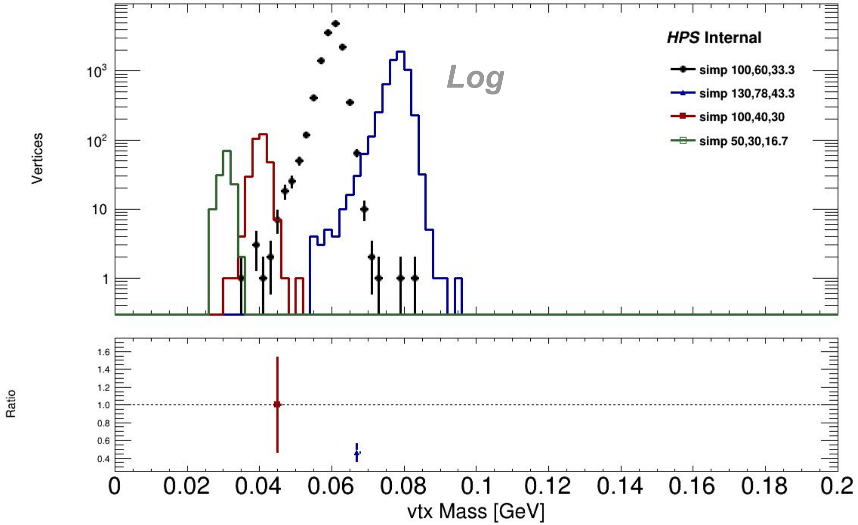


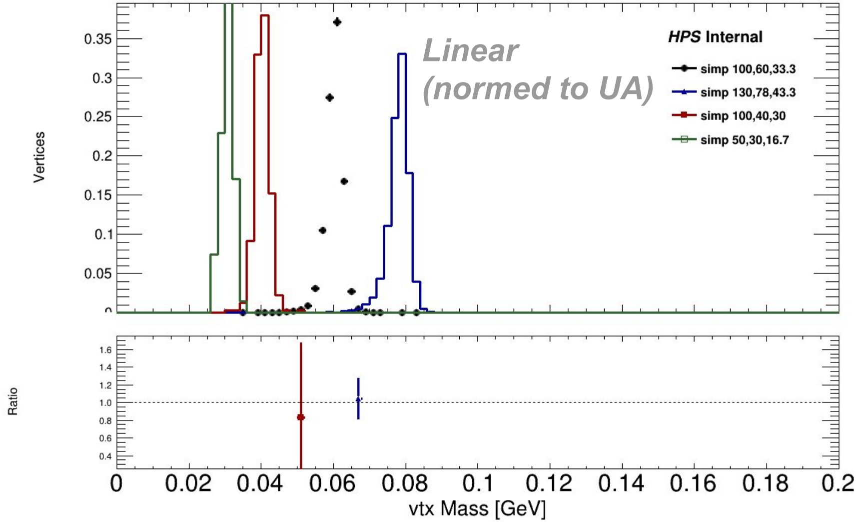


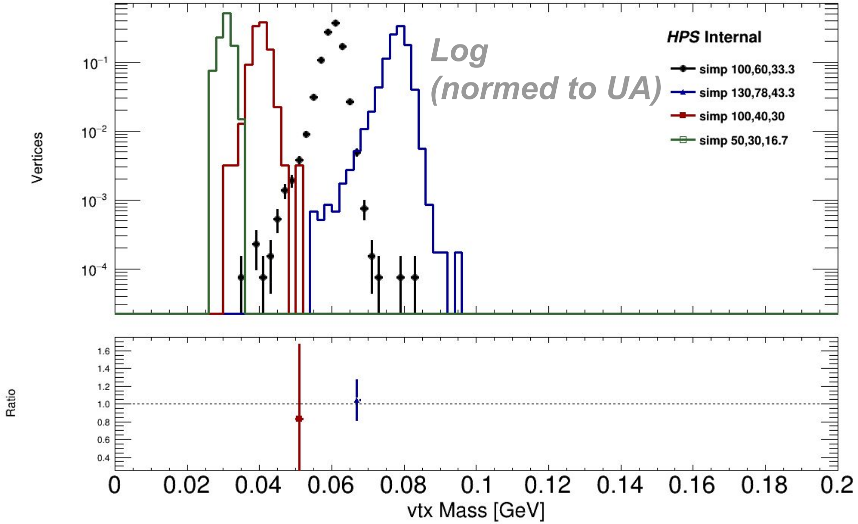


Vertex invariant mass [II]

- Check if track linked to e- with highest # hits on track is associated to truth radiated or recoil electron
- Demonstrates that large tail comes from vertices reconstructed using ***recoil*** electron track



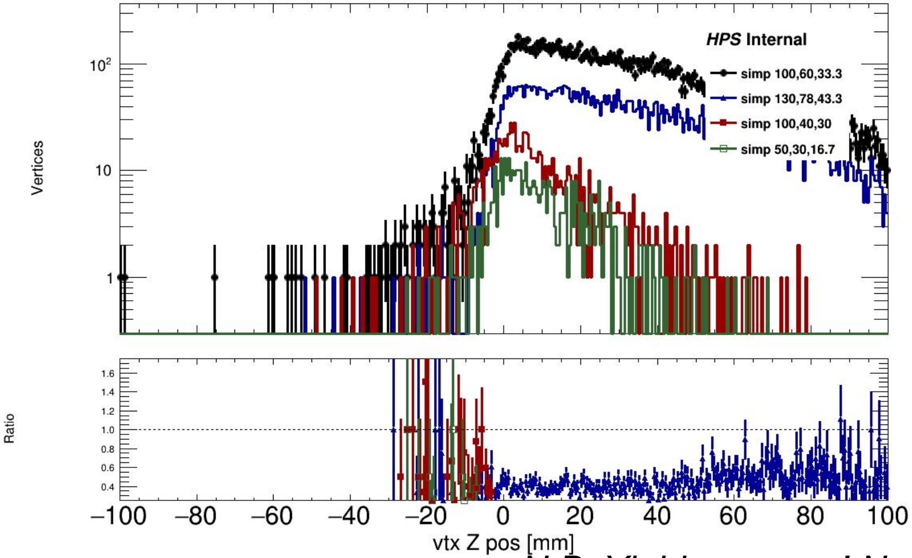




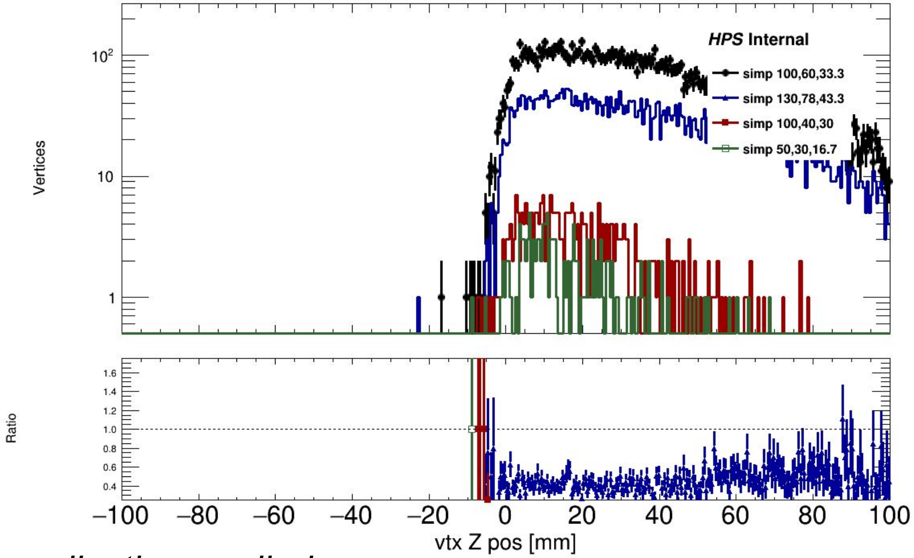
Vertex Z position

- e- tracks matched to truth recoil e- seem to contribute at low vtx z position

Vtx analysis pre-selection



Vtx analysis pre-selection
+ Tracks matched to truth rad e-

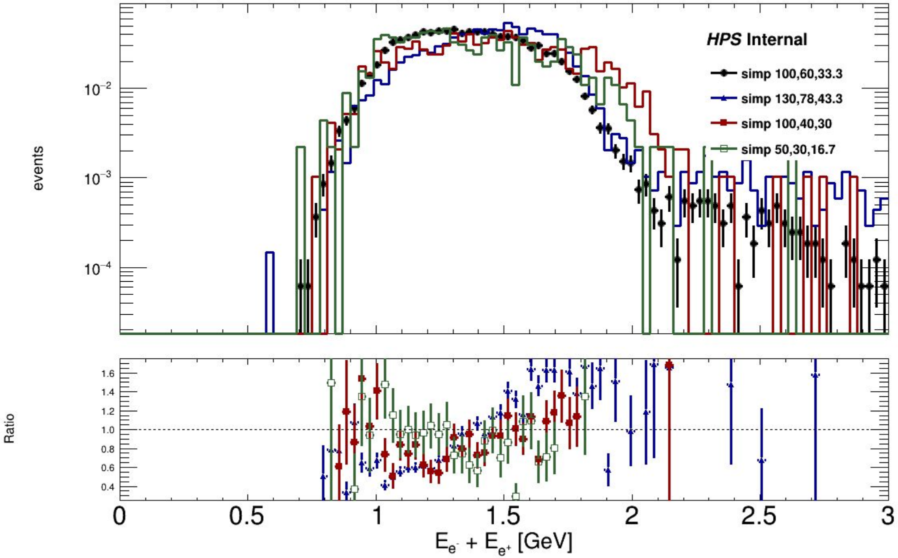


N.B: Yields are raw! No normalization applied

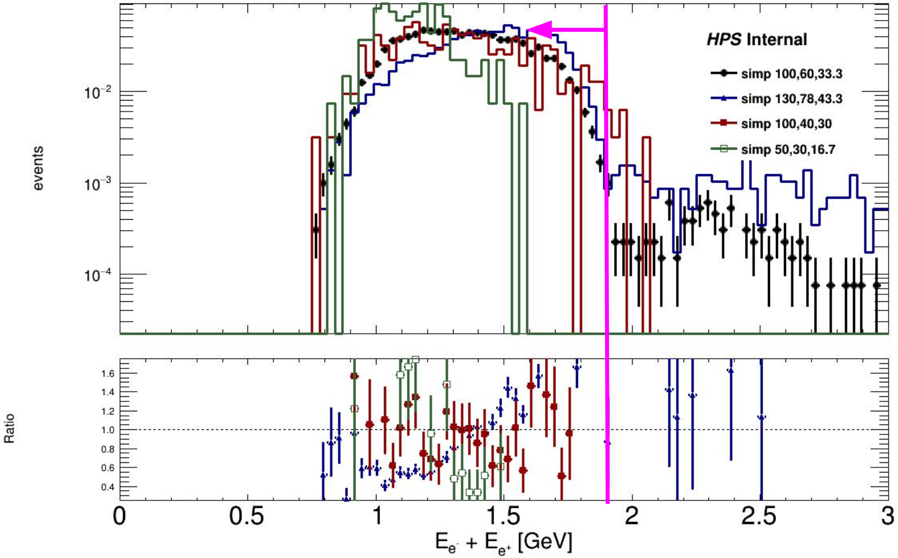
Esum

- Truth-matched Esum distribution suggests that Esum < 1.9 GeV could be useful in suppressing contribution from recoil e-: Esum/Ebeam < 0.83 (opposite from vertex analysis!)

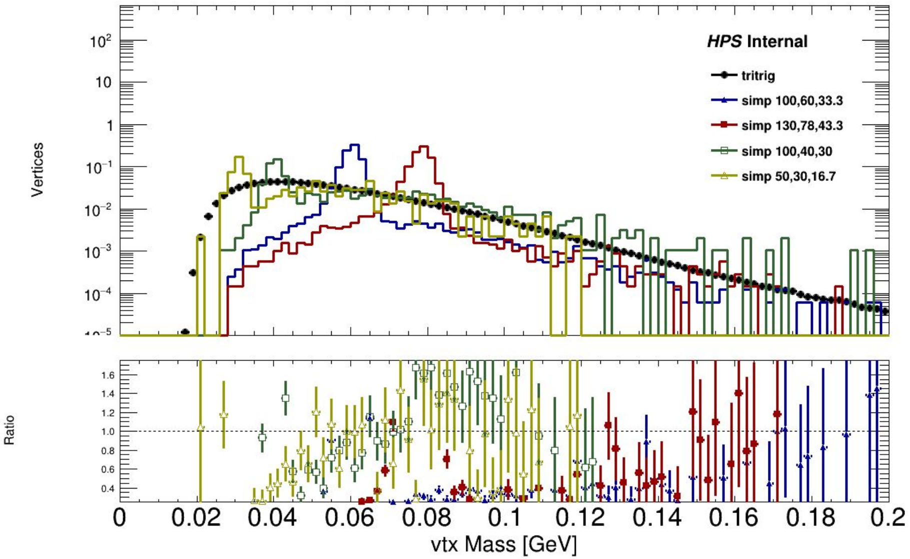
Vtx analysis pre-selection

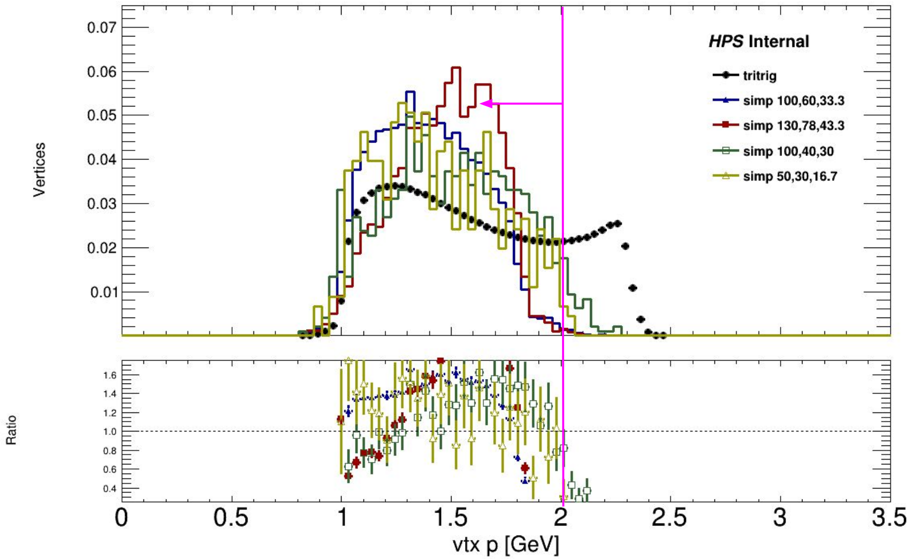


Vtx analysis pre-selection
+ Tracks matched to truth rad e-



Comparison with tritrig: vtx inv mass & momentum

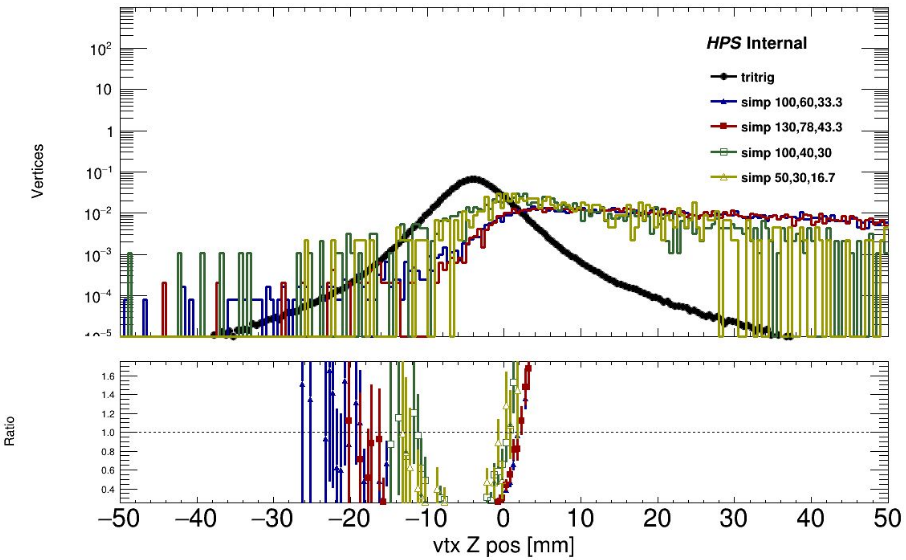


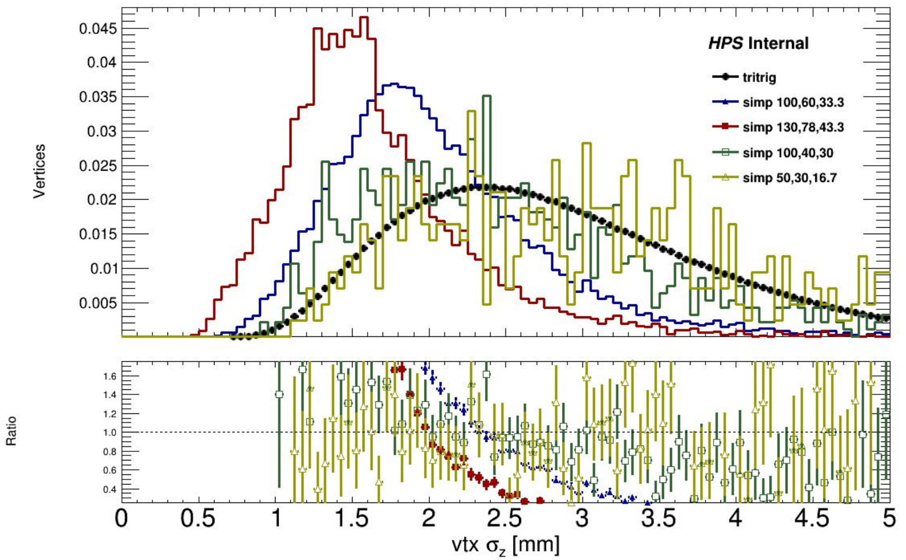


rhoD (displaced resonance) is generally softer than nominal displaced A', since some energy goes into producing piD which is undetected (missing energy)

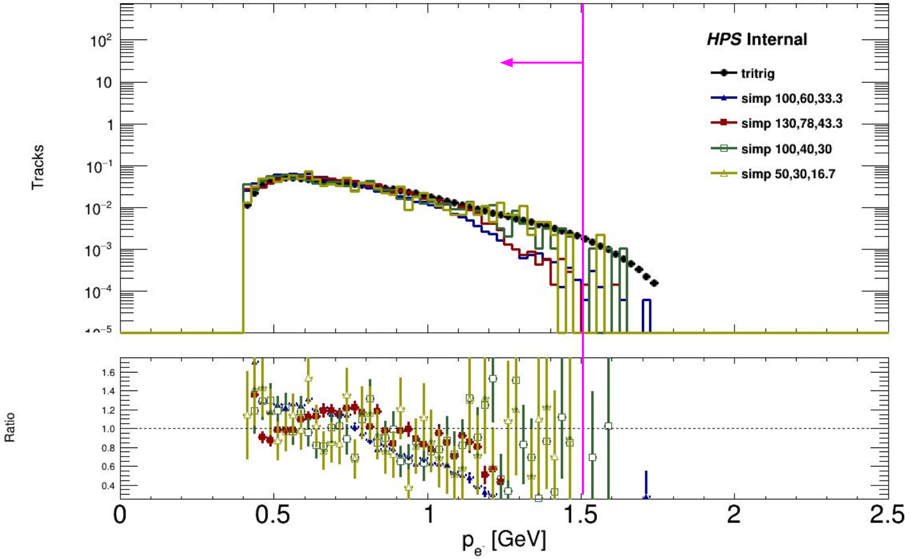
- Contrary to vertex analysis, V0 <u>will not</u> carry most of the beam energy
- V0 p < 2 GeV will make SIMPs orthogonal to vertex analysis *(What/if any is radiative cut for vtx?)*

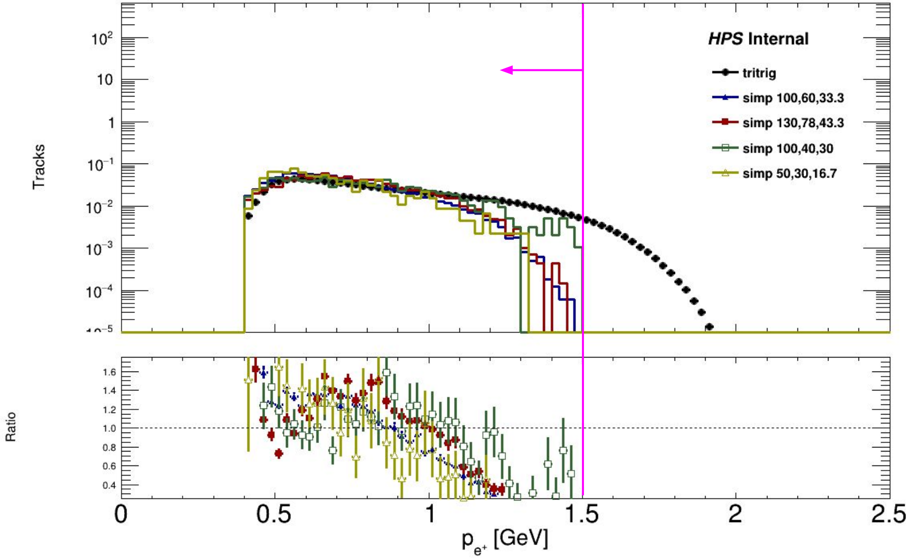
Comparison with tritrig: vtx Z position & σ_Z





Comparison with tritrig: e+ & e- momenta

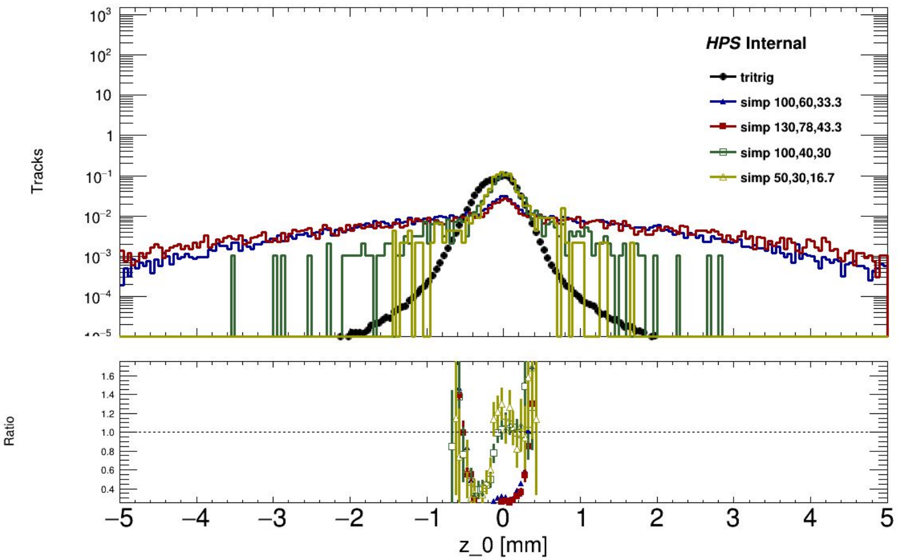


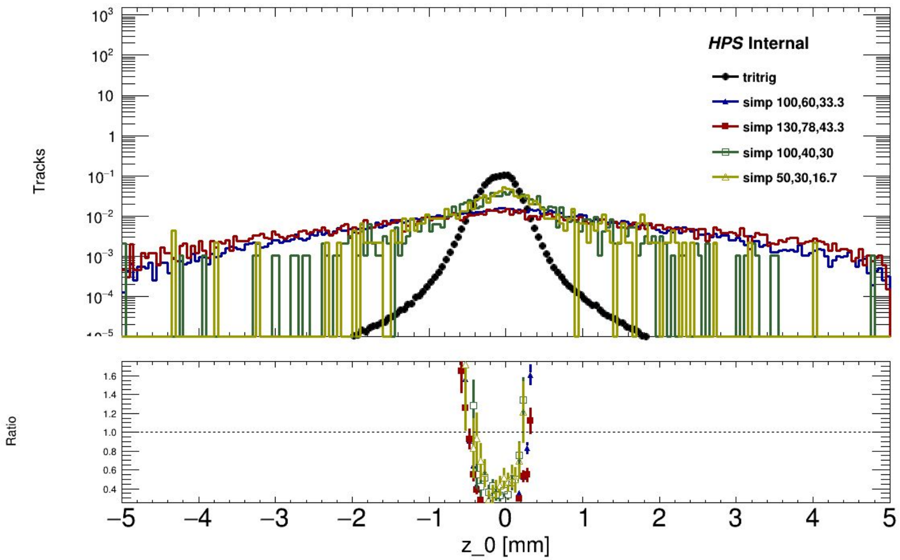


SIMP signal e+&e- are expected to be quite soft

- Tightening upper bound on e+&e- to $p < 1.5$ GeV could suppress tritrig w/o sacrificing signal

Comparison with tritrig: e+ & e- impact parameters

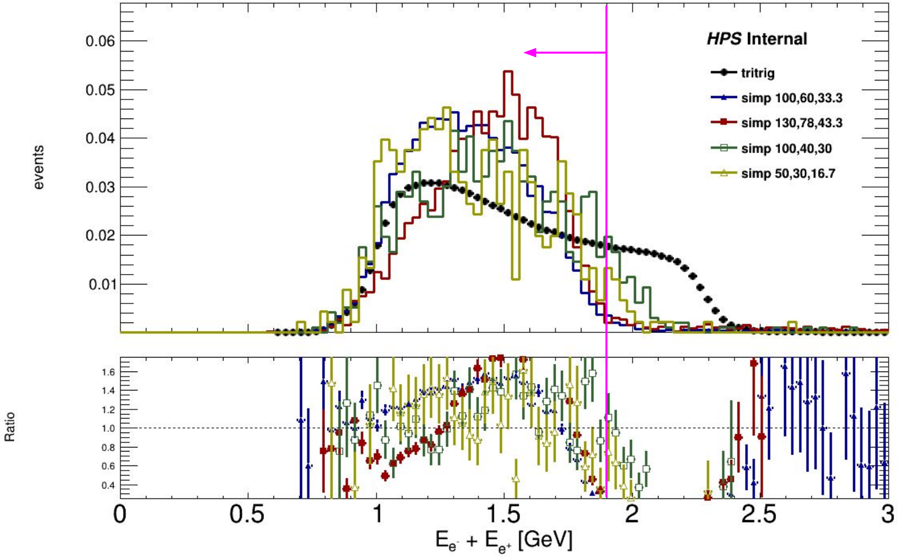


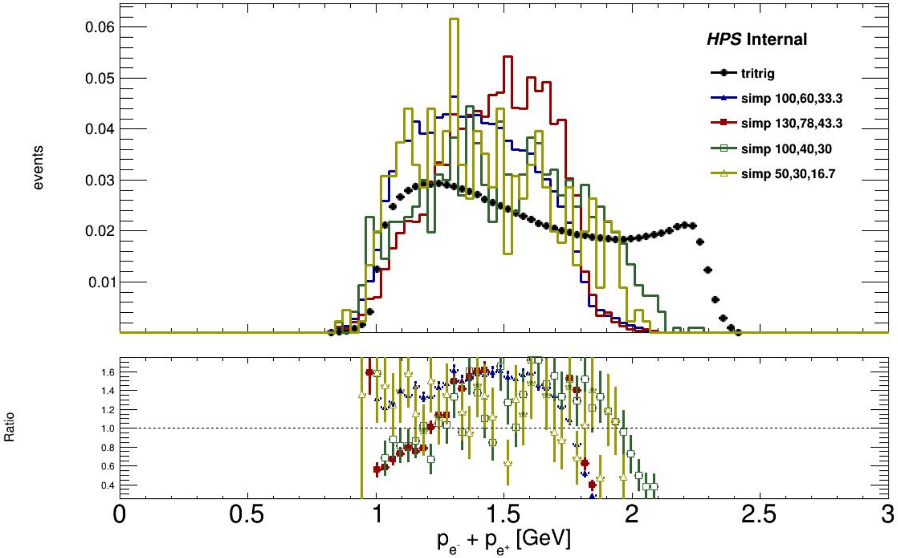


Impact parameters expected to increase as a function of rhoD mass and vtx z position

- z0 is broader for signals with rhoD>=60 MeV than for lower mass signals
- **AI:** Worth investigating impact parameters cuts used in vertex analysis

Comparison with tritrig: Esum & Psum





SIMP signal e+/e- are expected to be quite soft

- Tightening upper bound on Esum to < 1.9 GeV could suppress tritrig w/o sacrificing much signal
  - Basically inverse to cut applied in Tight L1L1 vtx selection

Vtx analysis pre-selection + SIMP “tight” selection (WIP)

Cut Description	Requirement
Trigger	Pair1
Track-cluster match	$\chi^2 < 10$
Cluster Time Difference	$\lvert t_{e+Cluster} - t_{e-Cluster} \rvert < 1.45$ ns
Track-Cluster Time Difference	$\lvert t_{e+Track} - t_{e+Cluster} -$ offset$\rvert < 4$ ns
Track-Cluster Time Difference	$\lvert t_{e-Track} - t_{e-Cluster} -$ offset$\rvert < 4$ ns
Beam electron cut	$p(e^-) < 1.75$ GeV
Track Quality	$\chi^2/dof < 6$
Vertex Quality	$\chi^2_{unc} < 10$
Minimum e^+ Momentum	$p(e^+) > 0.4$ GeV
Minimum e^- Momentum	$p(e^-) > 0.4$ GeV
Maximum Vertex Momentum	$V_{0p} < 2.4$ GeV

- e+&e- with hit in L1: pass L1L1
- Max sum energy: Esum/Ebeam < 0.83
- Maximum e- momentum: p(e-) < 1.5 GeV
- Maximum e+ momentum: p(e+) < 1.5 GeV
- Maximum vtx momentum: p(vtx) < 2.0 GeV
- No shared hits in L0 for e+&e-: Nshared=0
- One good V0: Nvtx = 1

Plots plots plots....

- Useful to flip between these histos normalized to unit area [linear on left; log on right]
  - Tritrig vs SIMP signals: vtx analysis preselection
  - Tritrig vs SIMP signals: vtx analysis preselection + SIMP “tight” selection

Next steps....

- Move the truth matching in VertexAnaProcessor.cxx to its own class in hpstr
- Investigate cluster-track distance and time matching
  - Get cluster timing info (already have track timing info)
- Study various cuts from TightL1L1 vtx analysis selection, e.g isolation & impact parameters
  - Quantitative optimizations of cuts based on e.g. significance Z=sqrt(2[S+B x log(1+S/B) -S])
- Include WAB & rad bkg samples
- Signal cross sections: use nb Nikita provided to tabulate production rates for given mass points

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