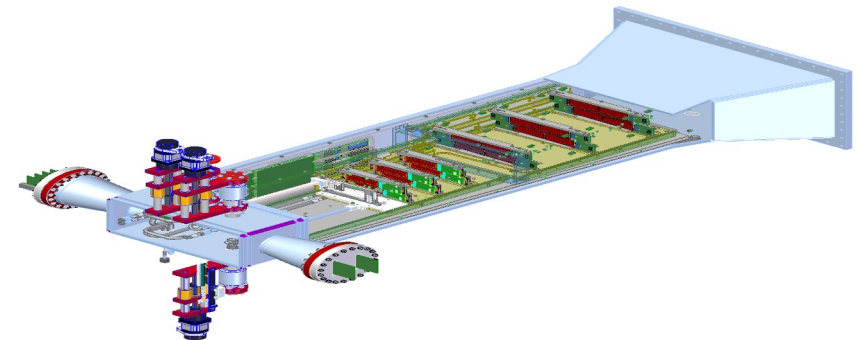


Status of the HPS Experiment

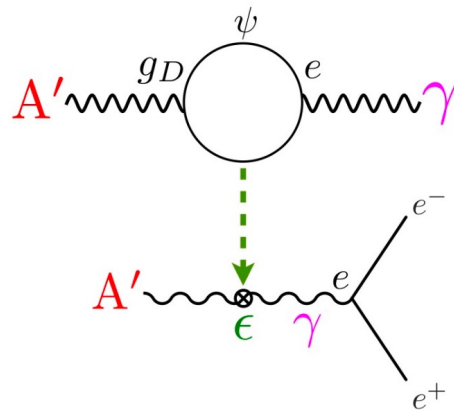
Tongtong Cao
Jefferson Lab

CLAS Collaboration Meeting
July 11— 14, 2023

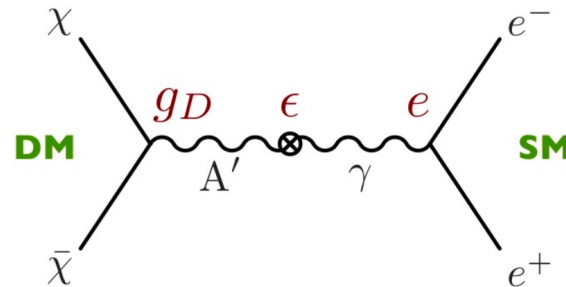


Dark photons A'

- There is strong evidence for the existence of Dark Matter (DM) from astronomical observations.
- While WIMPs remain of great interest, there is strong motivation to explore a broader set of DM candidates.
- Light DM (sub-GeV range) candidates are completely neutral under Standard Model forces, but interact through a new U(1) gauge bosons A' (a.k.a. heavy photon, dark photon, U boson, etc).
- The photon coupling to A' could provide a non-gravitational window into existence of light DM.



$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$



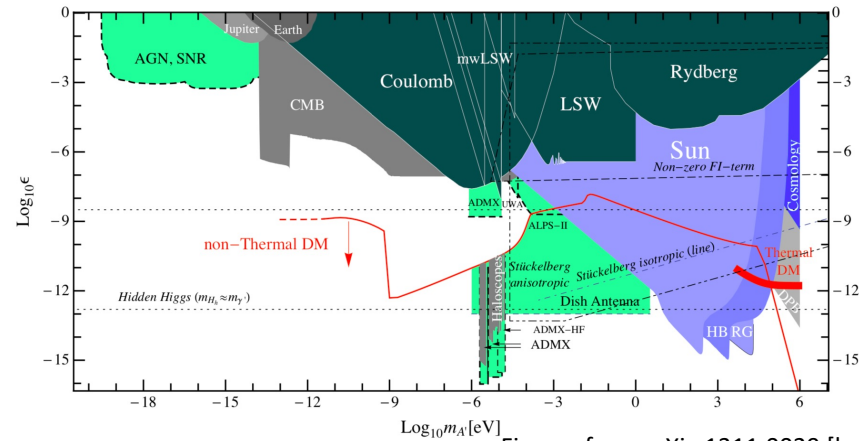
$$\alpha \equiv \frac{e^2}{4\pi}$$

$$\Delta\mathcal{L}_{kin.mix} = \frac{\epsilon}{2} F'_{\mu\nu} F_Y^{\mu\nu}$$

B. Holdom, Phys. Lett. B 166, 196 (1986)

Where Could A' Be?

Parameter space with $m_{A'} < 1 \text{ MeV}/c^2$



Figures from arXiv:1311.0029 [hep-ph]

Parameter space with $m_{A'} > 1 \text{ MeV}/c^2$

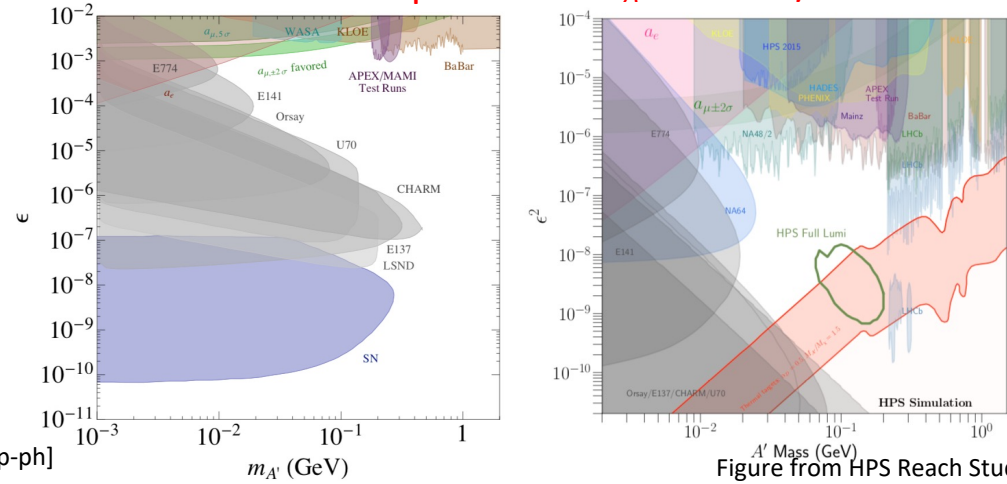
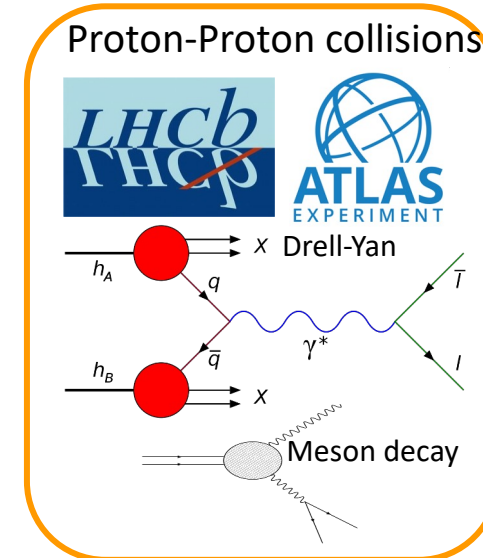
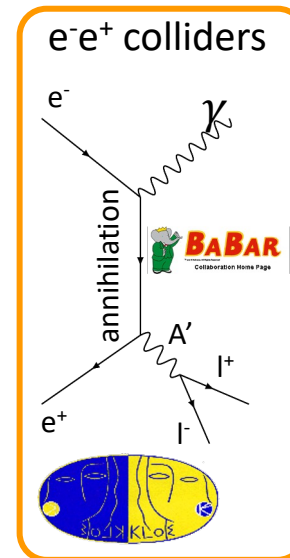
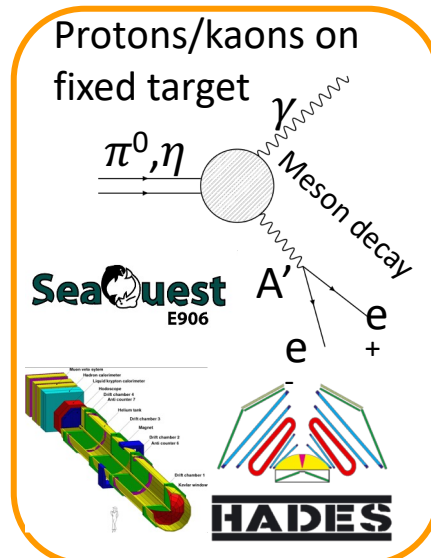
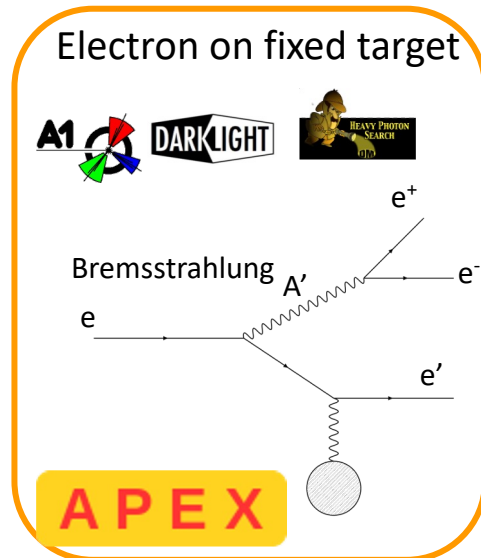


Figure from HPS Reach Study

For $m_{A'} > 1 \text{ MeV}/c^2$, A' can decay to charged particle pair.



Figures from Dr. R. Paremuzyan

A' Lifetime and HPS Signatures

$$\gamma_{c\tau} \approx \frac{0.8cm}{N_{eff}} \left(\frac{E_{beam}}{10GeV} \right) \left(\frac{10^{-4}}{\epsilon} \right)^2 \left(\frac{100MeV}{m_{A'}} \right)^2 \text{ for fixed-target experiments}$$

Phys. Rev. D 80, 075018 (2009)

- Two strategies to probe A' at different parameter space region:
 - Short-lived/prompt particles: search for resonance over a large background
 - Long-lived/displaced particles: search for displaced vertex of A'
- HPS can explore a wide range of heavy photon mass ($m_{A'} \sim 20 - 200 \text{ MeV}/c^2$) and couplings ($\epsilon^2 \sim 10^{-10} - 10^{-6}$) by both strategies.

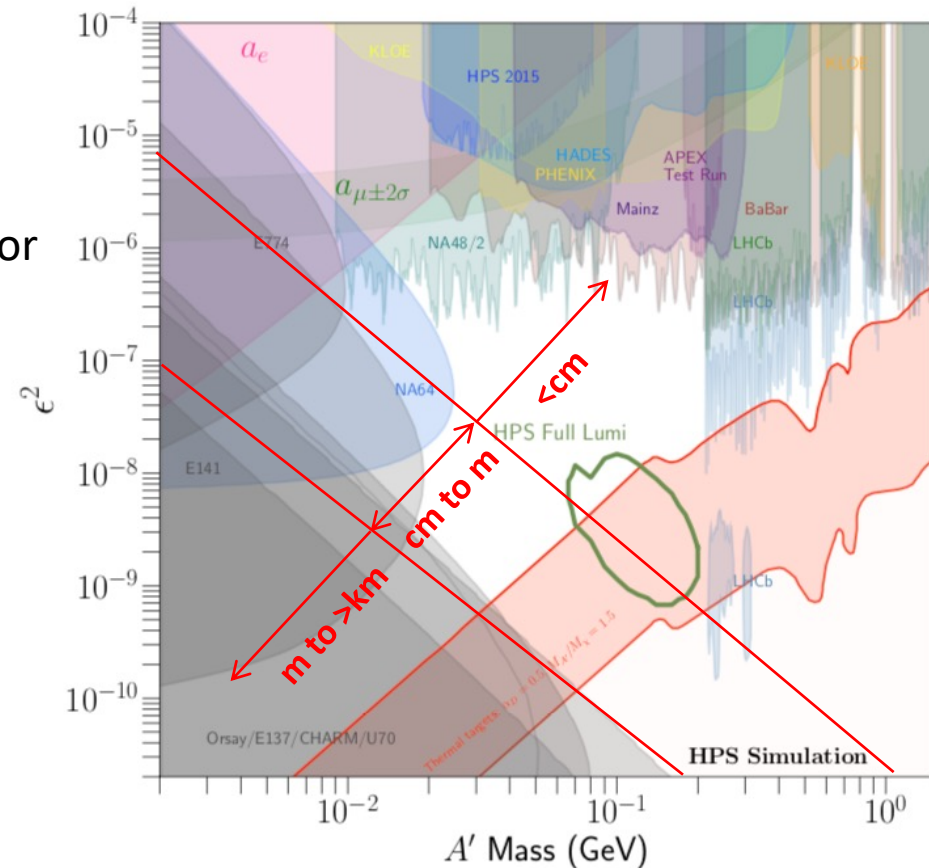
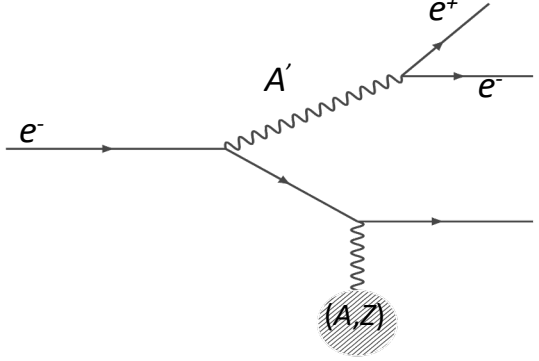
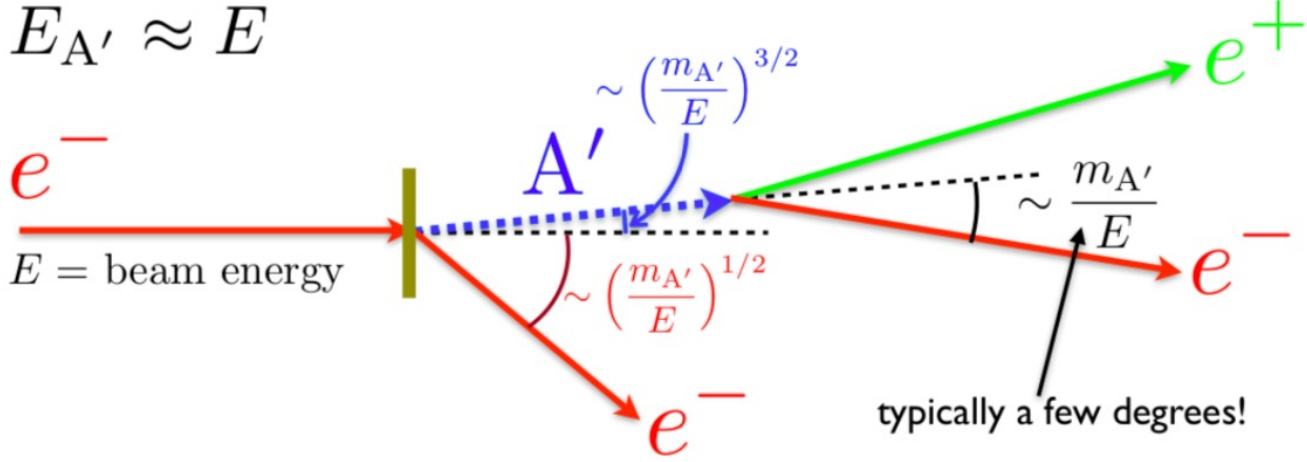


Figure from HPS Reach Study

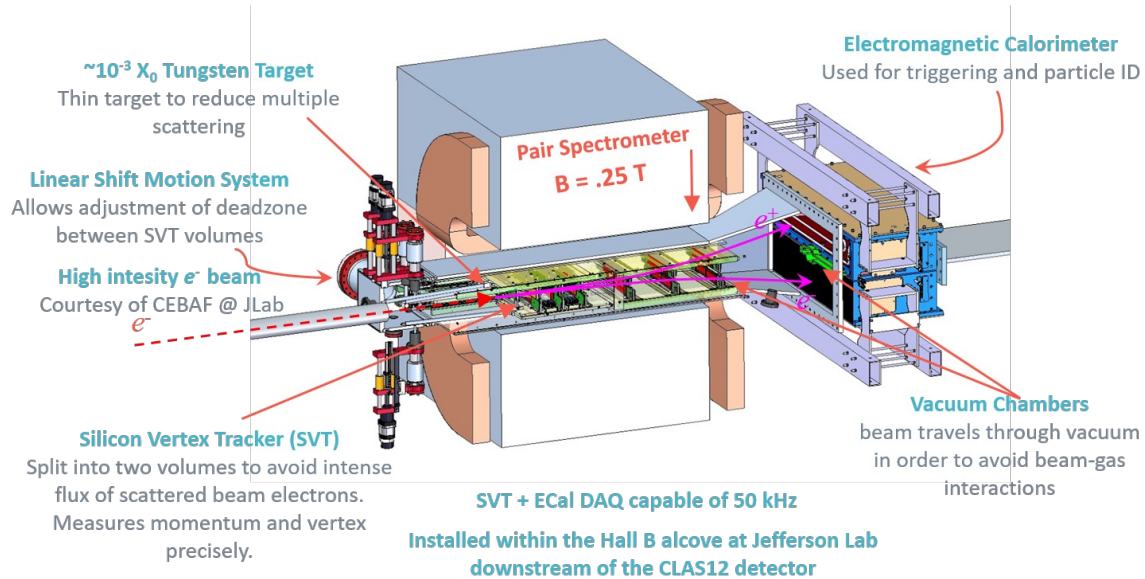
Kinematics of HPS



- A' takes almost all of beam energy and forward angle of A' is very small.
- Decay angles of lepton pair from A' are small, typically a few degrees.
- The experimental facility requires small angle detection of charged particle pair as well as good invariant mass resolution and high luminosity.

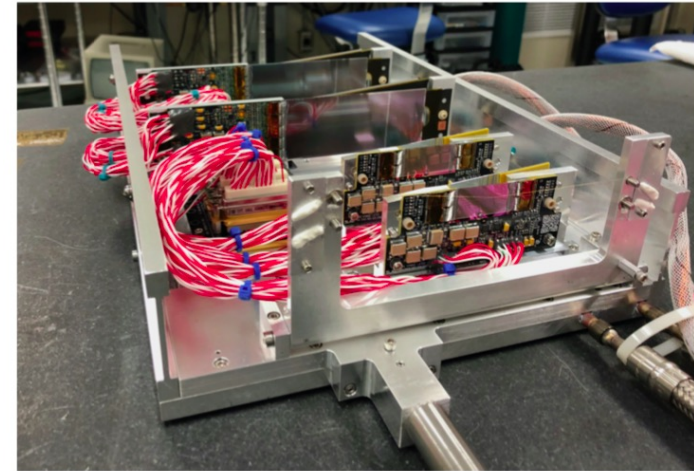
HPS Experimental Facility

Experimental setup



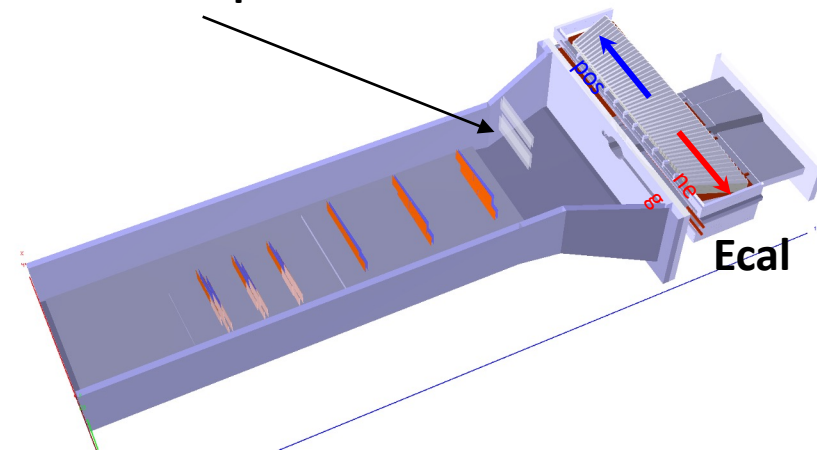
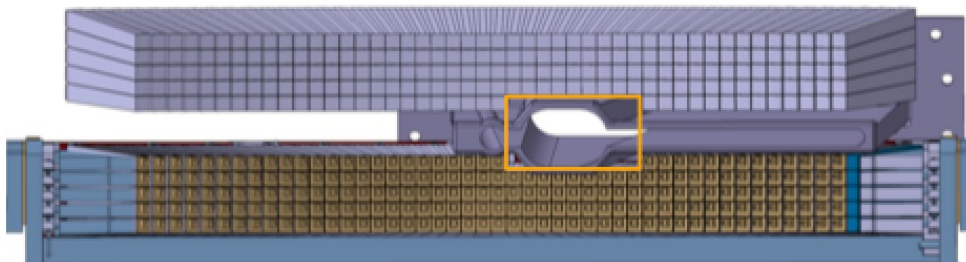
SVT

L0 layer was added before 2019 run

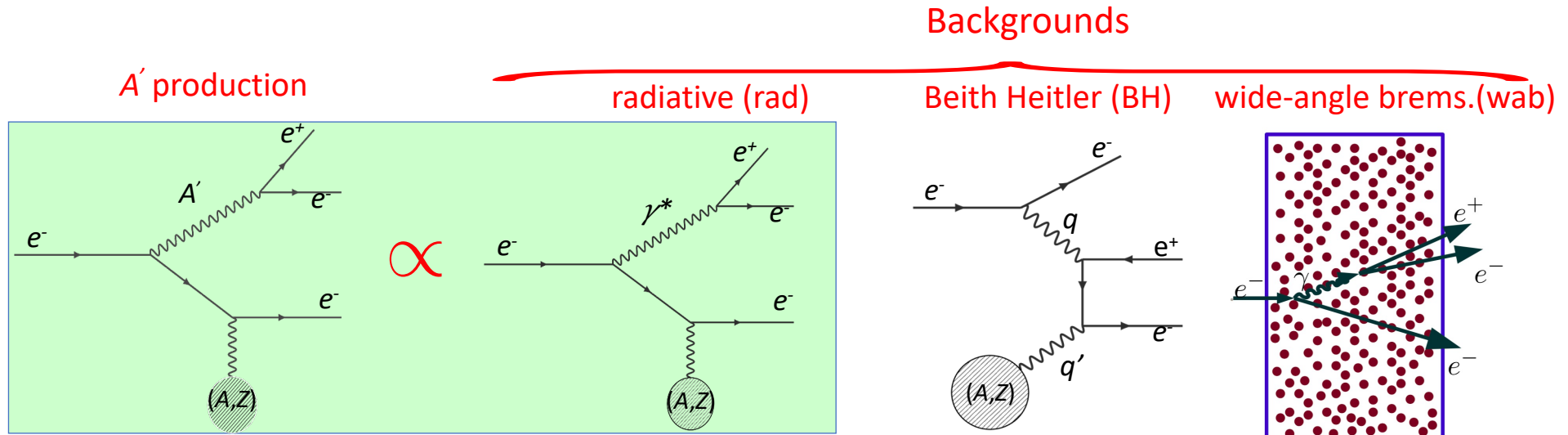


Hodoscope was added before 2019 run

Ecal



A' Search in HPS



trident = rad + BH + interference

$$\sigma_{A'} = \frac{3\pi m_{A'} \epsilon^2}{2N_{eff}\alpha} \frac{d\sigma_{\gamma^*}}{dm} \Big|_{m=m_{A'}}$$

Phys. Rev. D 80, 075018 (2009)

$$f_{rad}(m) = \frac{\frac{d\sigma_{\gamma^*}}{dm}}{\frac{d\sigma_{all}}{dm}} = \frac{\frac{d\sigma_{\gamma^*}}{dm}}{\frac{d\sigma_{trident}}{dm} + \frac{d\sigma_{wab}}{dm}}$$

- Expected **signal yield for prompt A'** in a mass bin with N_{bin} of e^+e^- pairs

$$S(m_{A'}, \epsilon^2) = N_{bin} f_{rad}(m_{A'}) \frac{3\pi m_{A'} \epsilon^2}{2N_{eff}\alpha}$$

- Expected **signal yield for displaced A'** in a mass bin with z cut:

$$S_{bin,zCut}(m_{A'}, \epsilon^2) = \underline{\epsilon_{bin}} S(m_{A'}, \epsilon^2) \times \int_{target}^{zMax} \frac{e^{-(z_{target}-z)/c\tau}}{\gamma c\tau} \epsilon_{vtx}(m_{A'}, \epsilon^2) dz$$

An efficiency factor to correct S in a finite mass bin

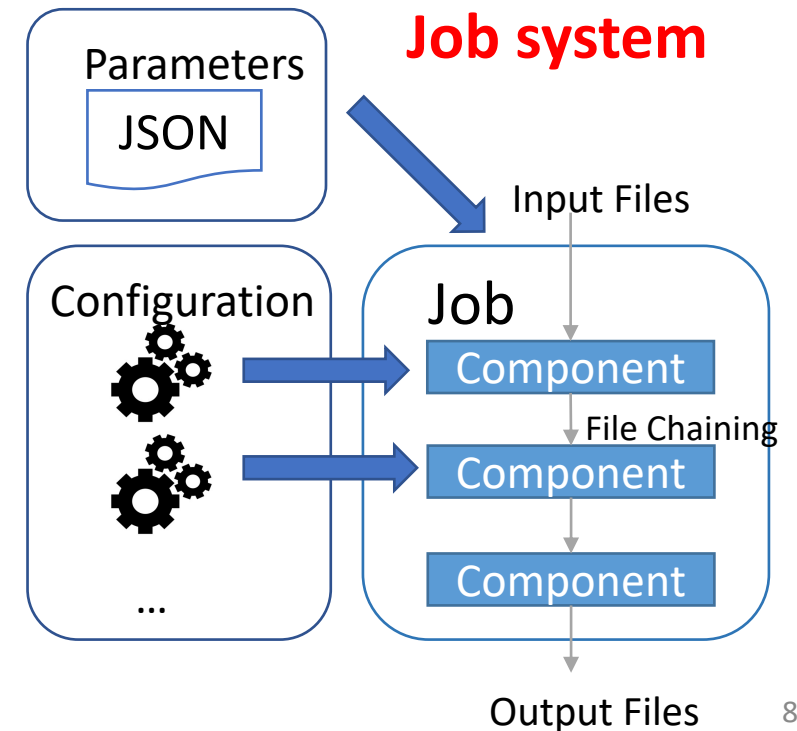
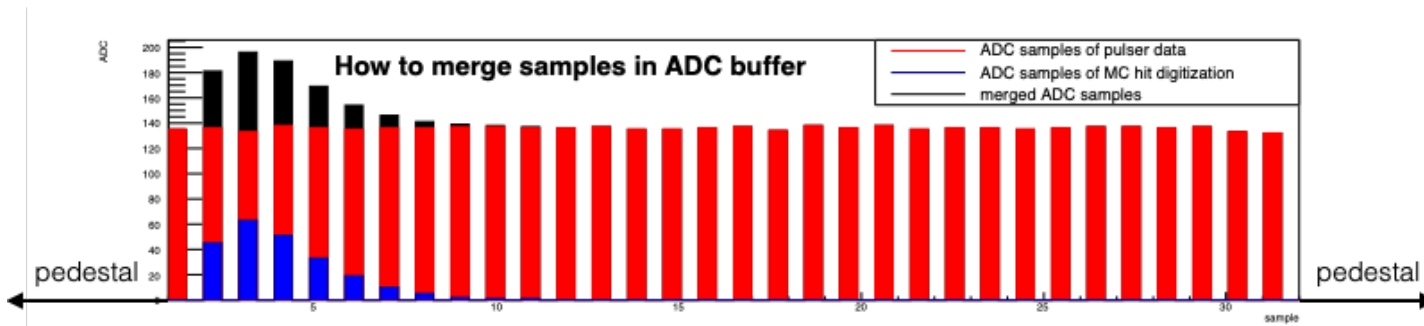
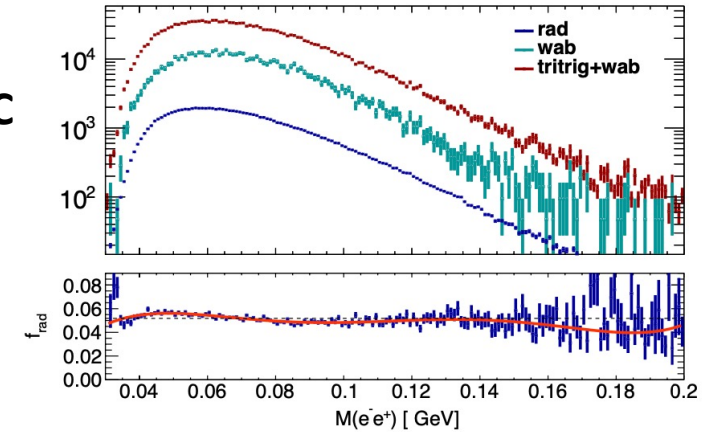
Normalized truth signal shape

Normalized efficiency including acceptance and effects of analysis and z cuts

HPS MC

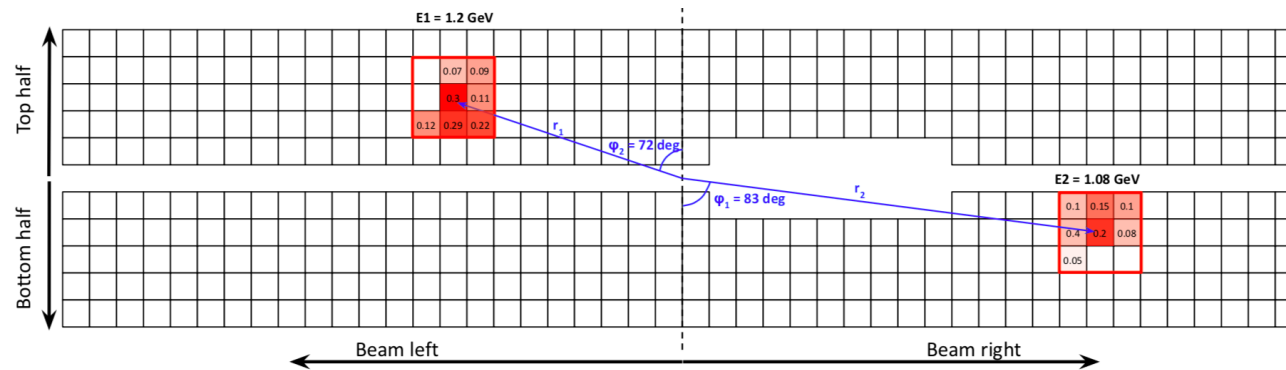
- A robust set of software packages are applied into realistic Monte Carlo simulations for calibration and analysis, including event generation (MadGraph), target processing (EGS5), detector simulation (SLIC), readout with digitization and trigger (hps-java), and some tools for support.
- Recently, a **job system** by Python was developed to build scripts for integration of MC chains and to provide commands for MC production in single/batch modes.
- Recently, an **alternative readout system** was developed to merge MC signals and random data at the digitization stage for improvement of production efficiency and better match between MC and data. It will be applied for analysis of 2019 & 2021 HPS runs.

f_{rad} by MC



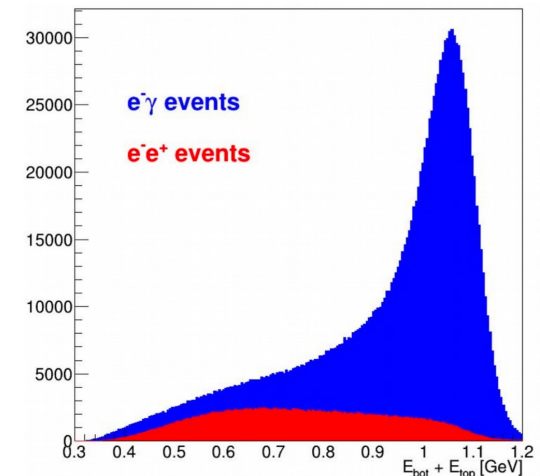
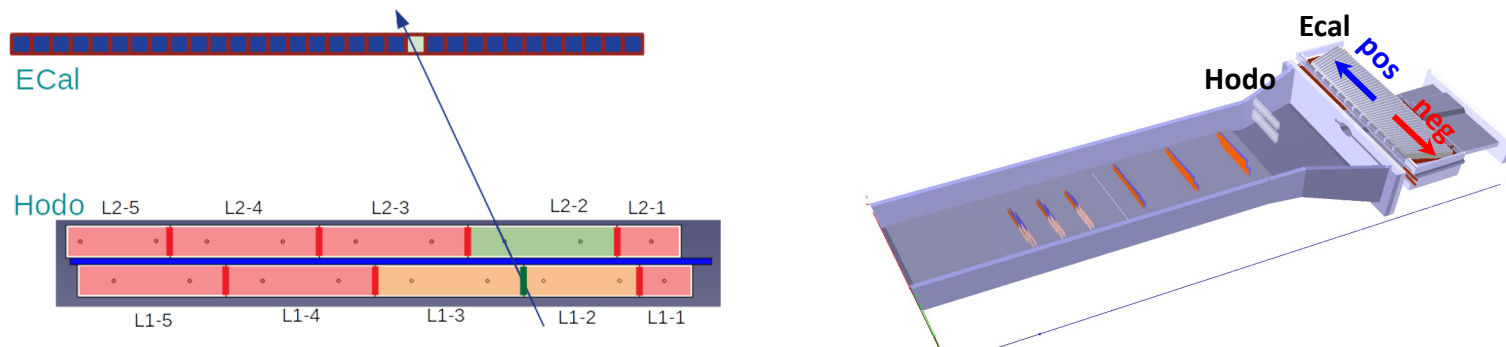
HPS Triggers

- Main triggers for HPS physics data with e^+e^- pair:
 - Pair triggers with Ecal top⊗bot coincidence for 2015 and 2016 engineer runs



- Fake rate from photons must be suppressed.
- Trigger on only positrons can increase acceptance

- Single triggers with Hodo⊗Ecal coincidence at positron side for 2019 and 2021 runs



- Other triggers: Møller trigger, Full Energy Electrons (FEE) trigger, random triggers, etc

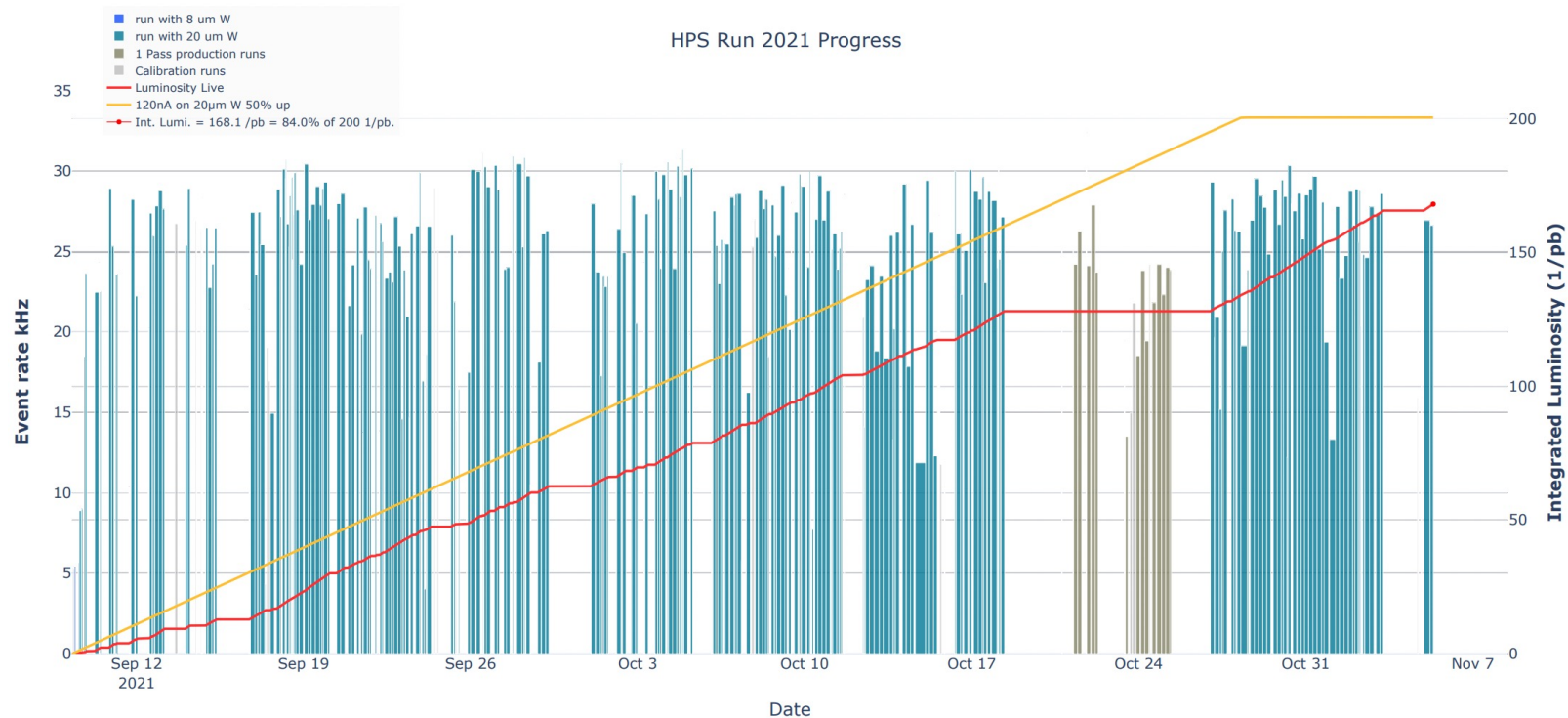
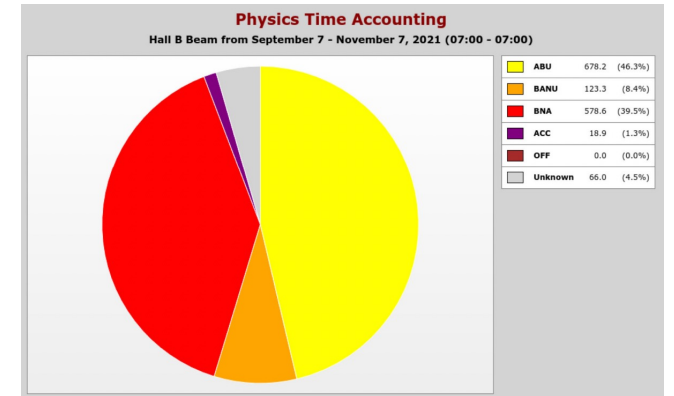
HPS Runs

- 2015 engineer run: a larger fraction of commissioning time; a small physics dataset
- 2016 engineer run: commissioned much more quickly; a significantly larger dataset
- 2019 production run: dedicated operation with facility upgrades; the first large physics dataset
- 2021 production run: the second large physics dataset
- HPS has 107 PAC-approved days remaining for data-taking

Run	Energy (GeV)	Target ($\% X_0 W$)	Beam Time Used	$\int \mathcal{L} \text{ pb}^{-1}$
2015	1.056	0.125	9.5 days	1.17
2016	2.30	0.125	5.5 days	10.75
2019	4.55	0.25/0.625	30 days	122
2021	3.74	0.625	28 days	168

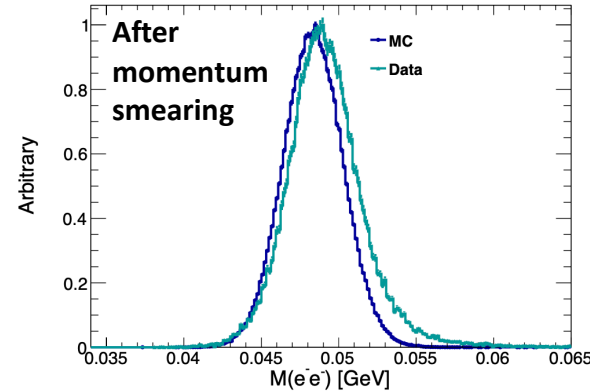
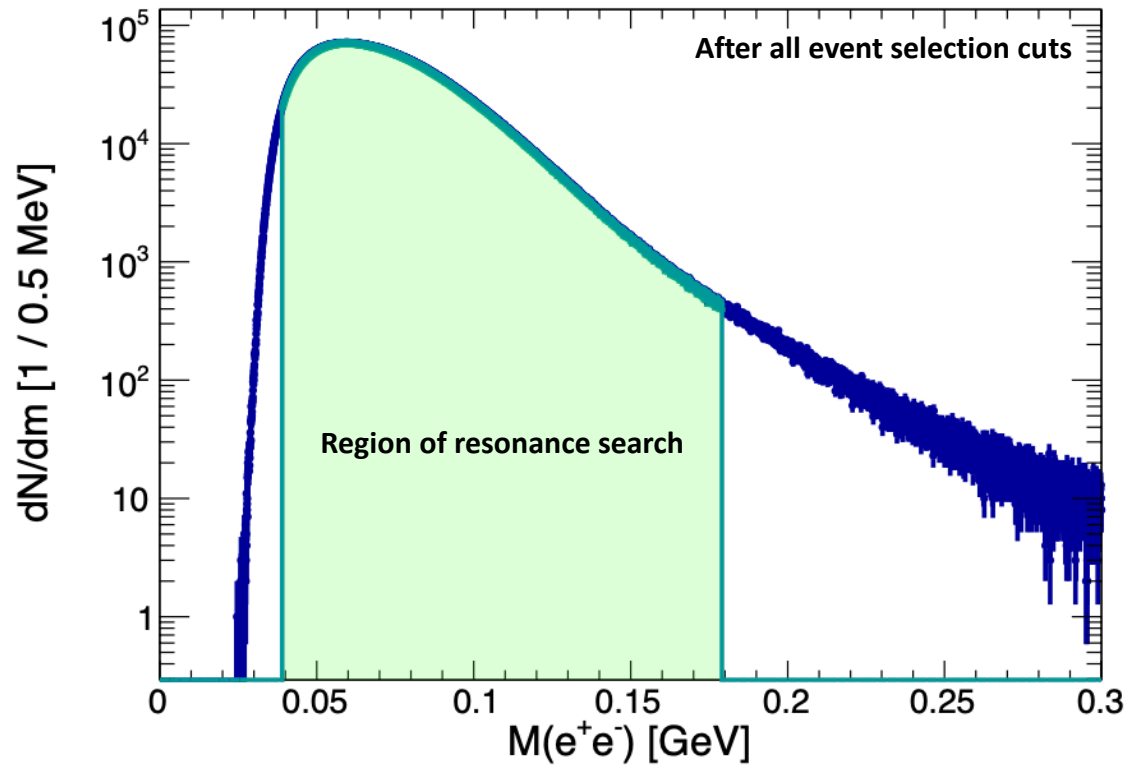
Latest 2021 Run

- Very successful run from Sep. 7 to Nov. 5, 2021
- Total luminosity is 168.1 pb^{-1} (84% of 200 pb^{-1} with a total of 222 mC of charge)
- Total number of events is 69 billion, 839 TB of data
- Hall Efficiency is 84.6% (ABU: 678.2 hours; BANU: 123.3 hours)

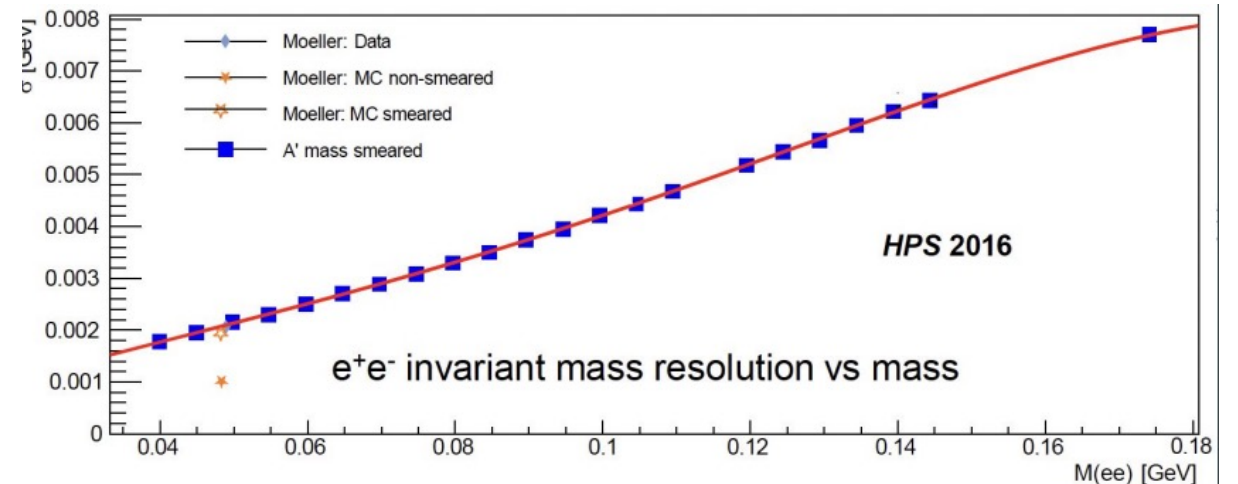


Study of Resonance Search for 2016 Run

HPS employs a resonance search over a mass range of 39-179 MeV/ c^2 for 2016 run.

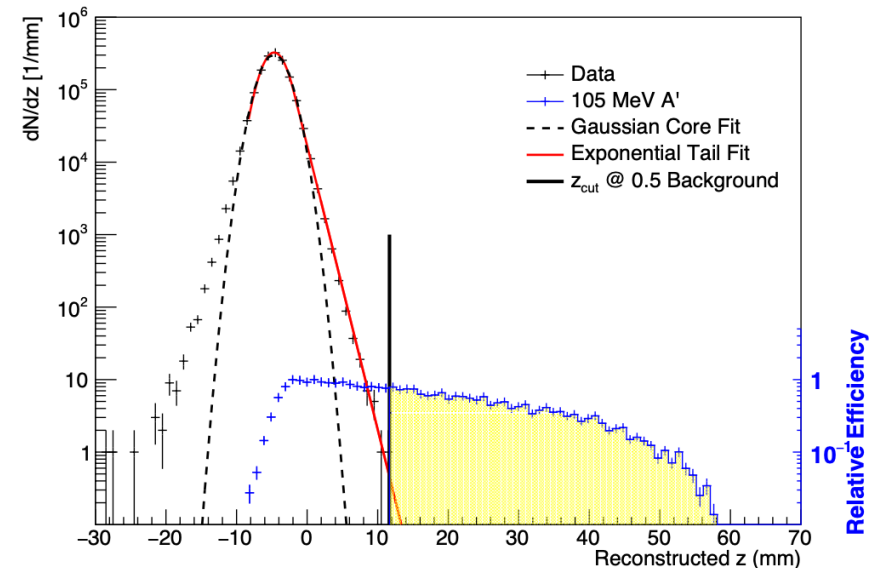
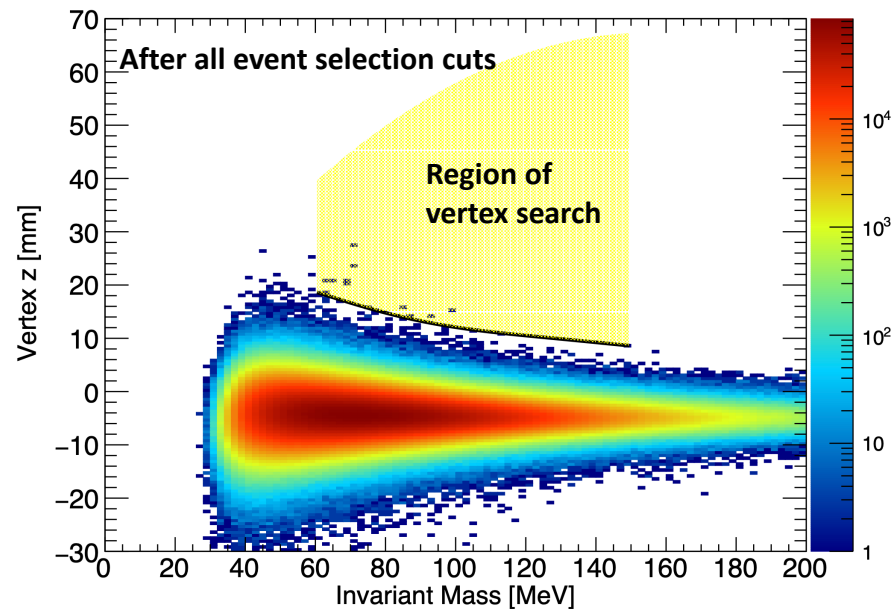


- Understanding A' mass resolution is critical for HPS analysis.
- Estimated A' mass resolution by MC needs to be scaled by ratio of data to MC.
- The Møller resonance is used to extract the ratio.



Study of Vertex Search for 2016 Run

- The displaced vertex analysis is to search for long-lived A' 's produced in the target that decay to e^+e^- pair in the range 1-10 cm downstream.
- Due to the low rate of the expected signal, a signal region must be defined such that very little background is expected. For each $m_{A'}$ bin, z cut is applied where the background model predicts 0.5 events.
- The vertex search explores A' masses in the range of 60-150 MeV/c^2 for 2016 run.

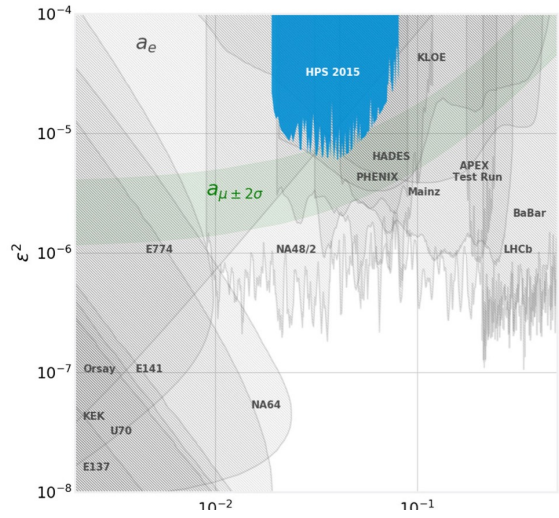


HPS Publications for 2015 & 2016 Runs

95% C.L. upper limit by **resonance search**

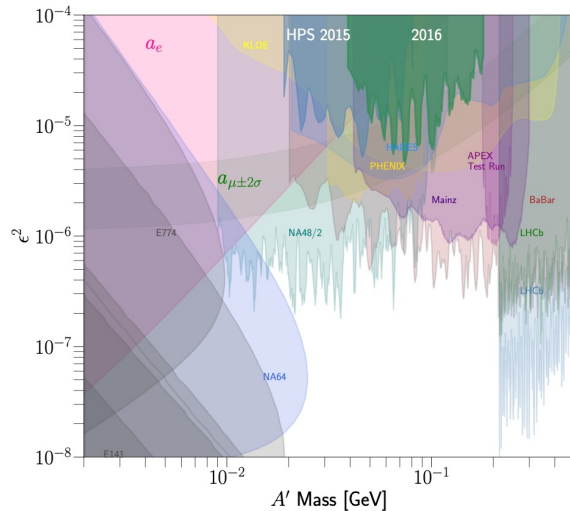
2015

Phys. Rev. D 98, 091101(R) (2018)

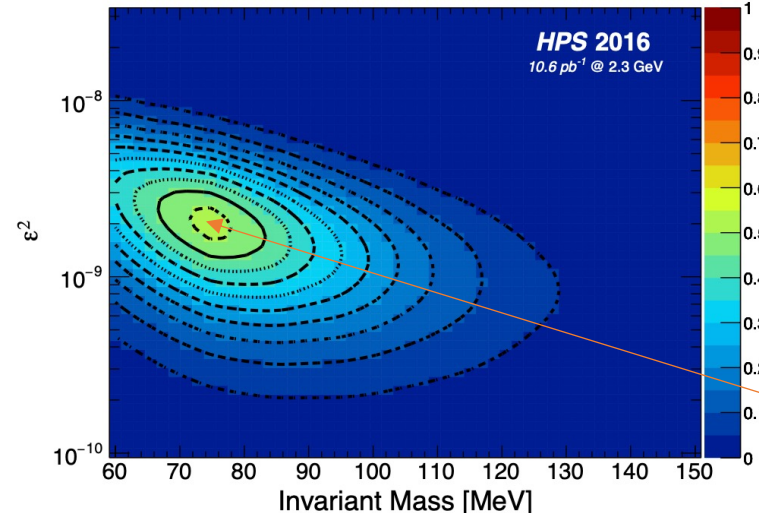


2016

- 2015 result is updated by a more modern statistical approach
- The resonance search results confirm the results from previous searches, but does not extend their sensitivity.

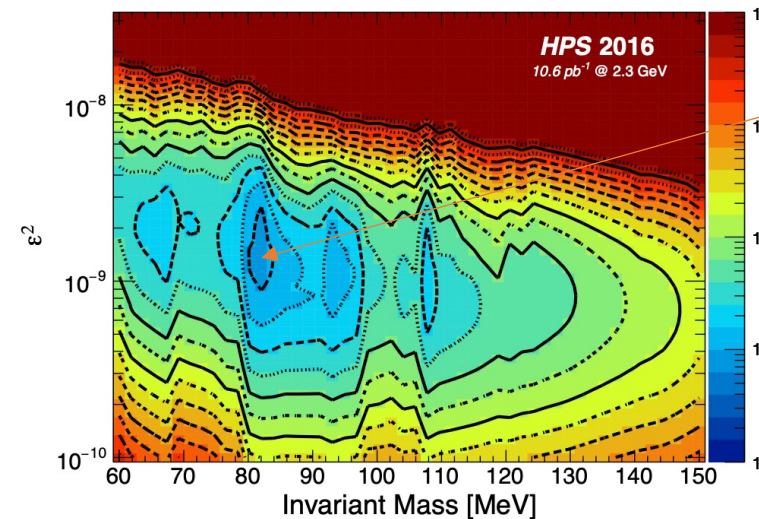


2016 displaced vertex search



2016 results have been accepted to be published by Phys. Rev. D recently.

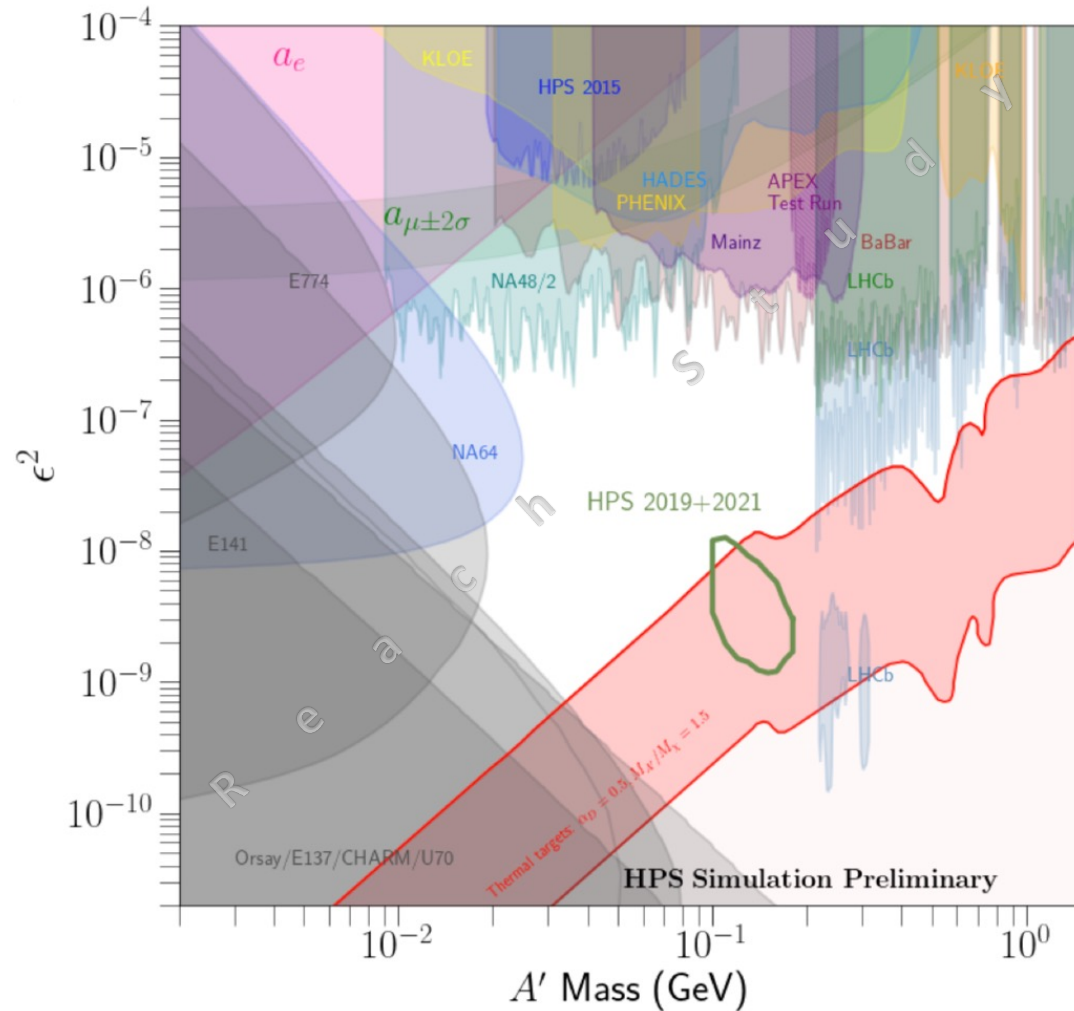
At maximum, $0.52 A'$ is expected at $m_{A'} = 75 \text{ MeV}/c^2$ and $\varepsilon^2 = 2.1 \times 10^{-9}$



• With optimum interval method, for an A' -like model with 7.9σ (c.s.), the limit is just given at $m_{A'} = 82.0 \text{ MeV}/c^2$ and $\varepsilon^2 = 1.7 \times 10^{-9}$ with 90% C.L.

• Can not set upper limit with 2016 luminosity

Reach Estimates for 2019 & 2021 Runs

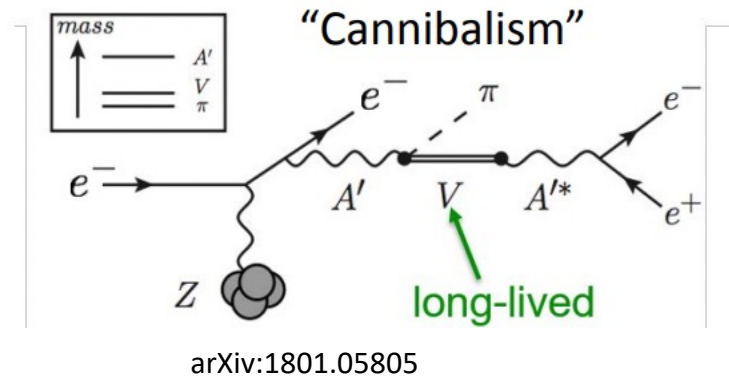


Very promising to yield new exclusions with facility upgrades and much higher luminosity

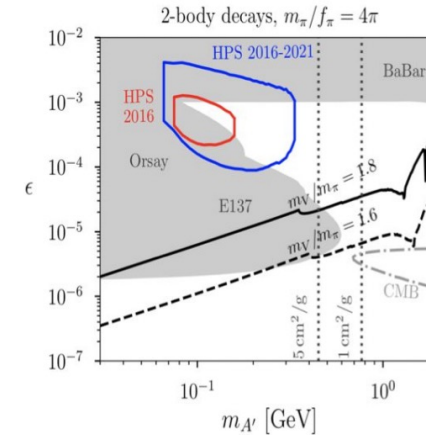
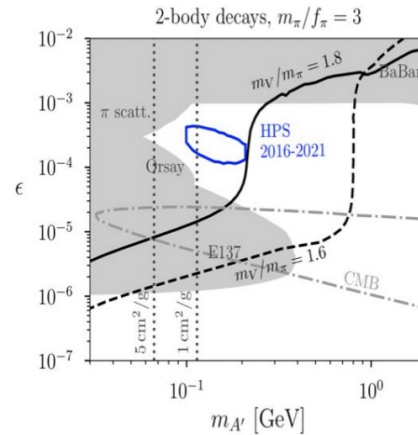
Other Models of Interest

Displaced vertices via electron-production on $\sim\text{cm}$ -scale allow new regions of the parameter space to be explored through further interaction models:

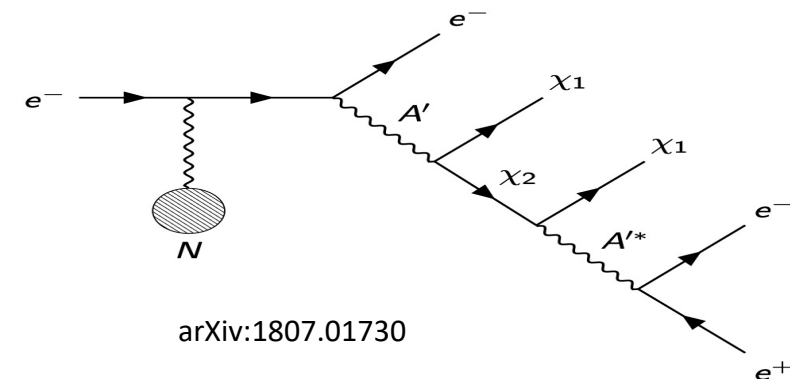
- Strongly Interactive Massive Particles (SIMPs)



Reach study by Alic Spellman



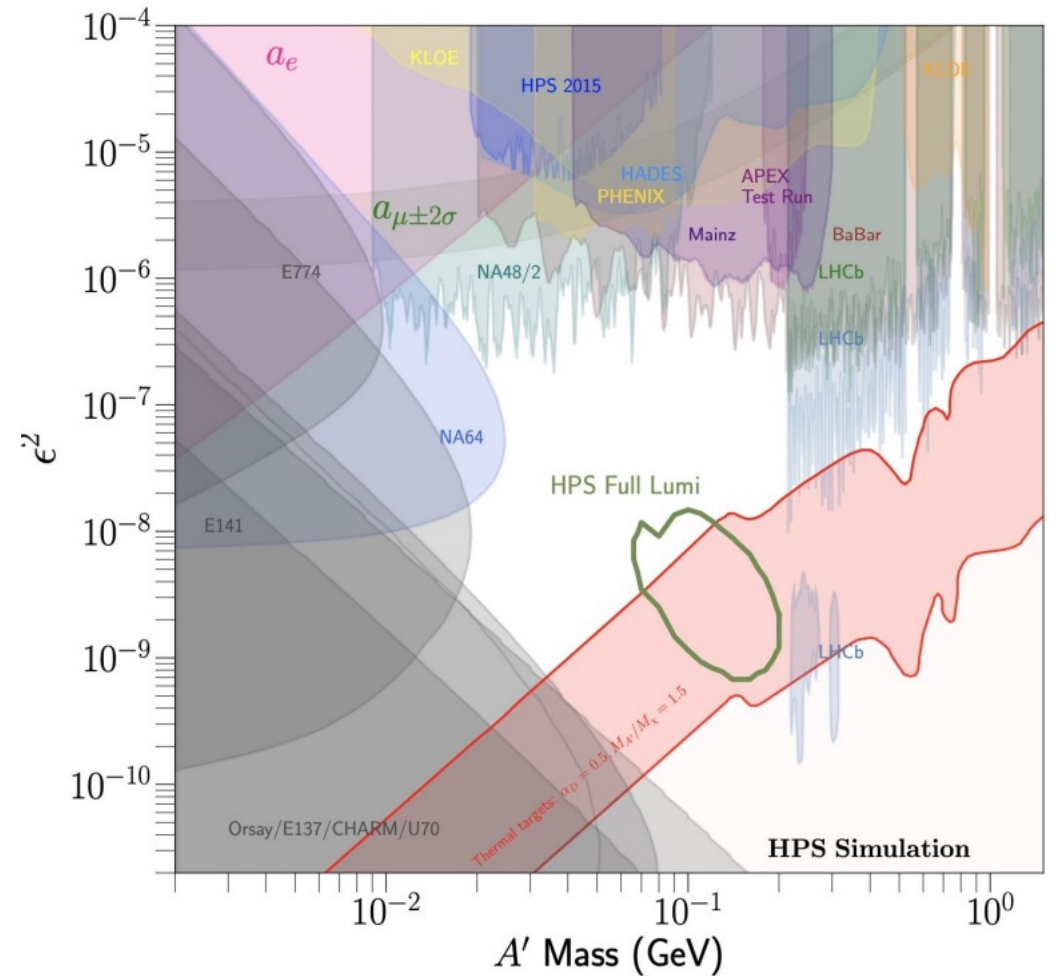
- inelastic Dark Matter (iDM)



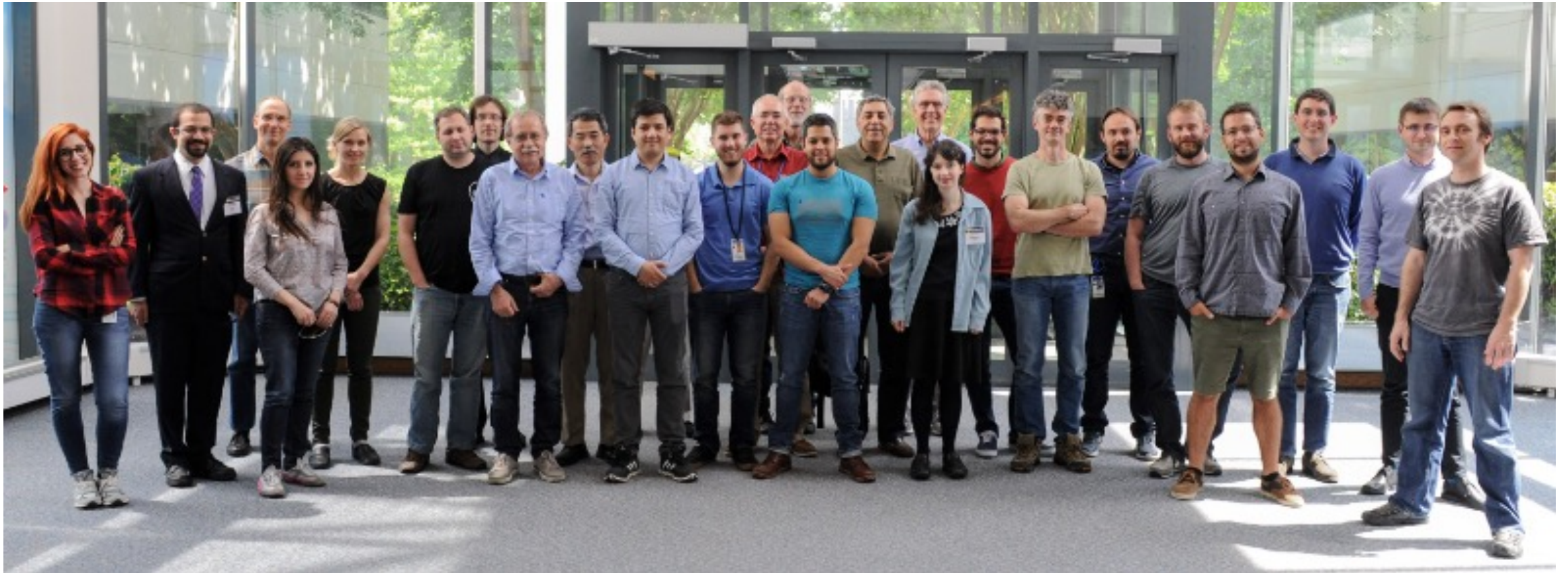
A generator with a MadGraph model is in development by Tom Eichlersmith

Summary

- HPS results from 2015 resonance search are published, and 2016 results have been accepted for publication.
- Analysis from 2019 & 2021 are expected to yield new exclusions and potential discovery of A' in a highly motivated region of parameter space.
- HPS has completed 73 days of running, and has 107 PAC-approved days remaining for future experiments.

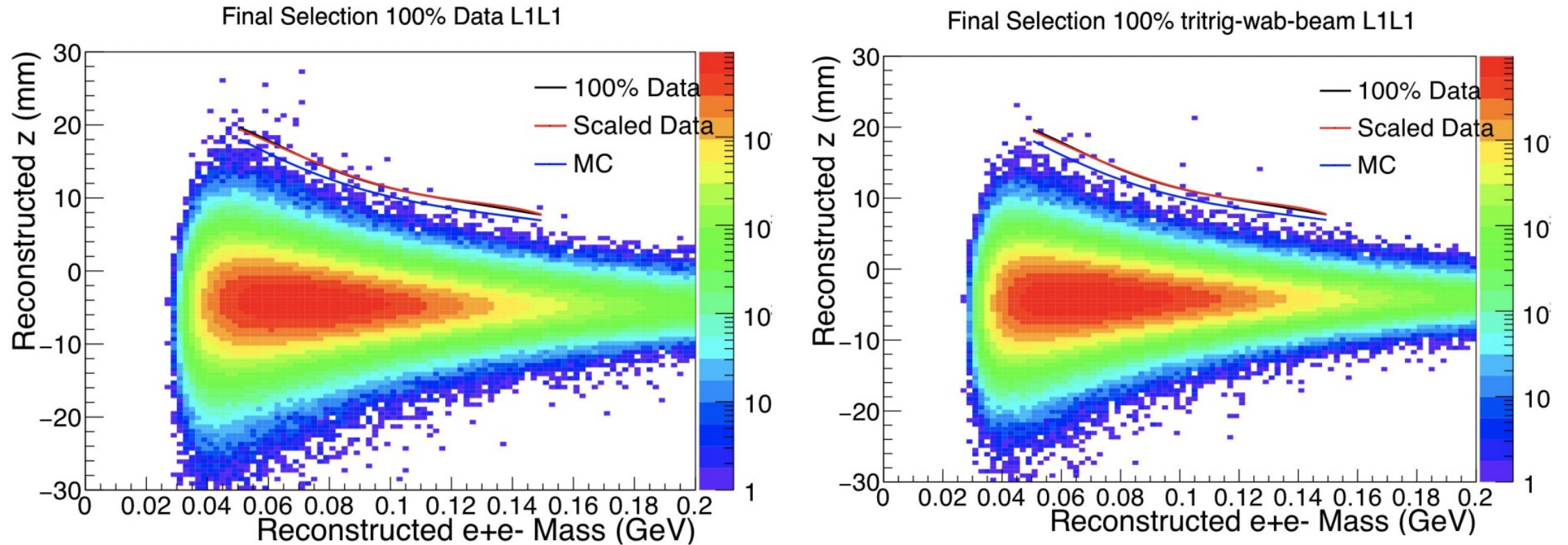


HPS Collaboration



Backup Slides

HPS L1L1 Data/MC Comparison



- In higher mass region, we have confidence that we achieved the expected level of background necessary (0.5) for a search.
- Still investigate lower mass region, most likely background.

Additional Backgrounds Beyond Zcut

- Measurement is limited by multiple scattering, but events past zcut are mainly due to rare double **large Coulomb scatters** (left) and picking up the **wrong L1 hit**

