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Sub-GeV particle identification and tagged photon beam for the Water Cherenkov Test Experiment

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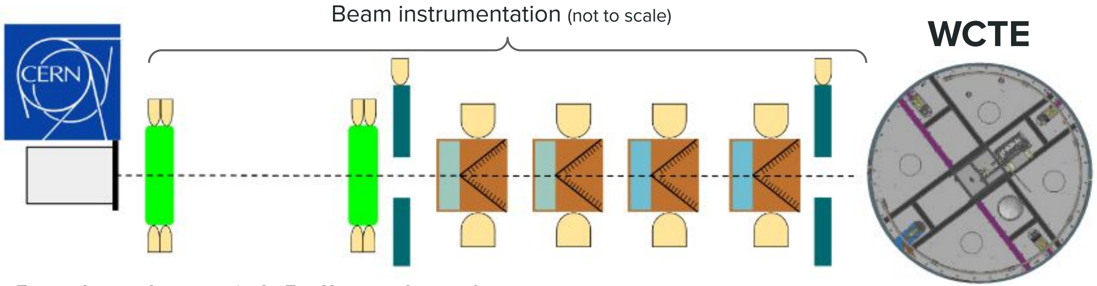
Contents

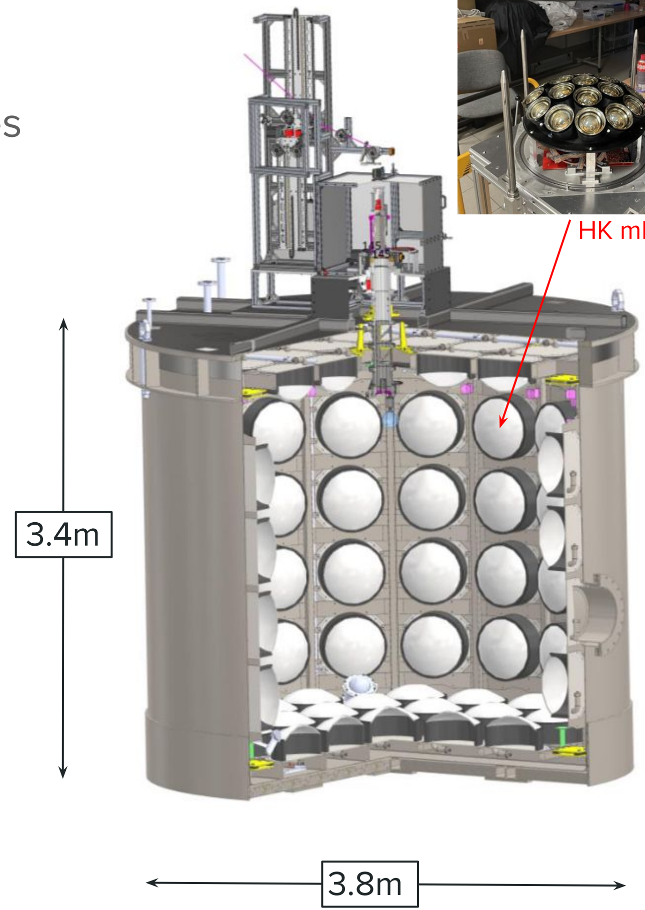
The Water Cherenkov Test experiment at CERN

- The Water Cherenkov Test Experiment (WCTE) will
  - develop and test hardware and calibration techniques
  - study the interaction of π, p, e, μ and γ in ultra-pure and Gd-doped water

  to help Hyper-Kamiokande reach its targeted precision.

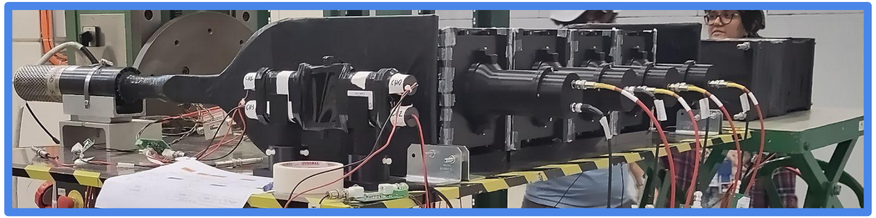
- WCTE be installed in summer 2024 at CERN in the newly refurbished T9 beamline (East Area) and receive a beam of charged particles (π, p, e, μ) with momenta 200 MeV/c to 2 GeV/c.





WCTE beamline and July 2023 beam test

- WCTE will use two beamline set-ups:
  - one low momentum set-up,
    - ID the charged particles
    - momentum measurement
  - one tagged photon set-up,
    - produce beam of photons of known energy



- Both of these set-ups have been tested at CERN in July 2023. During this 3-week long beam test, the collaboration was able to:
  - Test and calibrate the beam monitoring hardware
  - Develop DAQ, PID and energy measurement techniques
  - Demonstrate good pion/muon separation and good photon production rates
  - Make the first precise measurement of the beam composition

Low momentum charged particle setup

For studies of charged particle interactions in water Cherenkov detectors

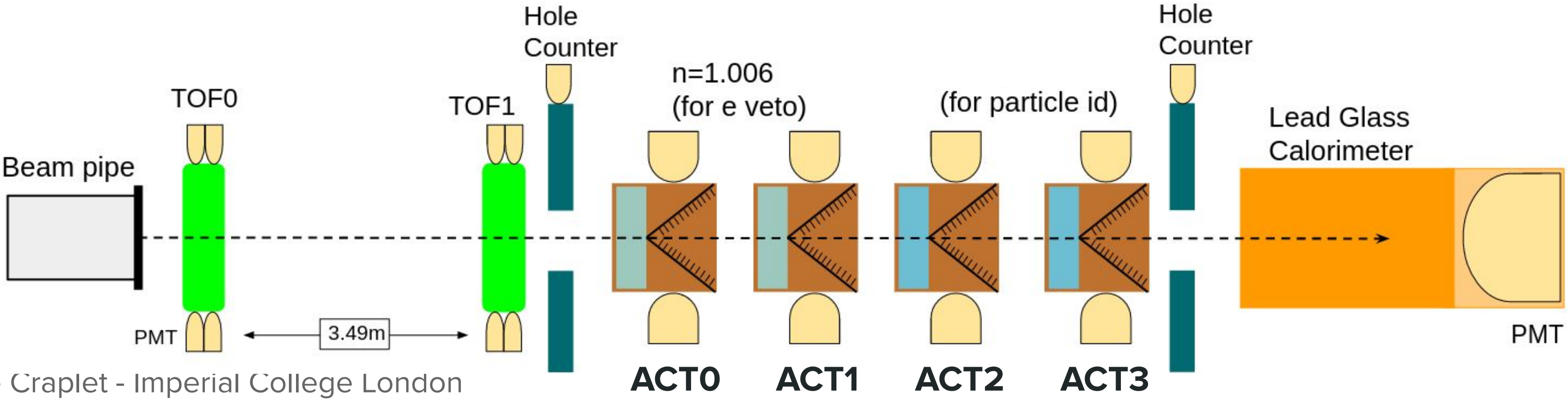
Set-up for Sub-GeV particle identification

Trigger scintillators : • provide time of flight and beam momentum measurement

Hole counters : • provide beam halo veto

Aerogel Cherenkov Threshold (ACTs) detectors: • upstream **ACTs** used for e veto • downstream **ACTs** refractive index tailored to the beam momentum • **e** and **μ** above Cherenkov threshold • **π** and **p** below threshold

Lead-glass calorimeter : • provides momentum measurement and additional particle ID information. • The water Cherenkov detector will replace the calorimeter in 2024

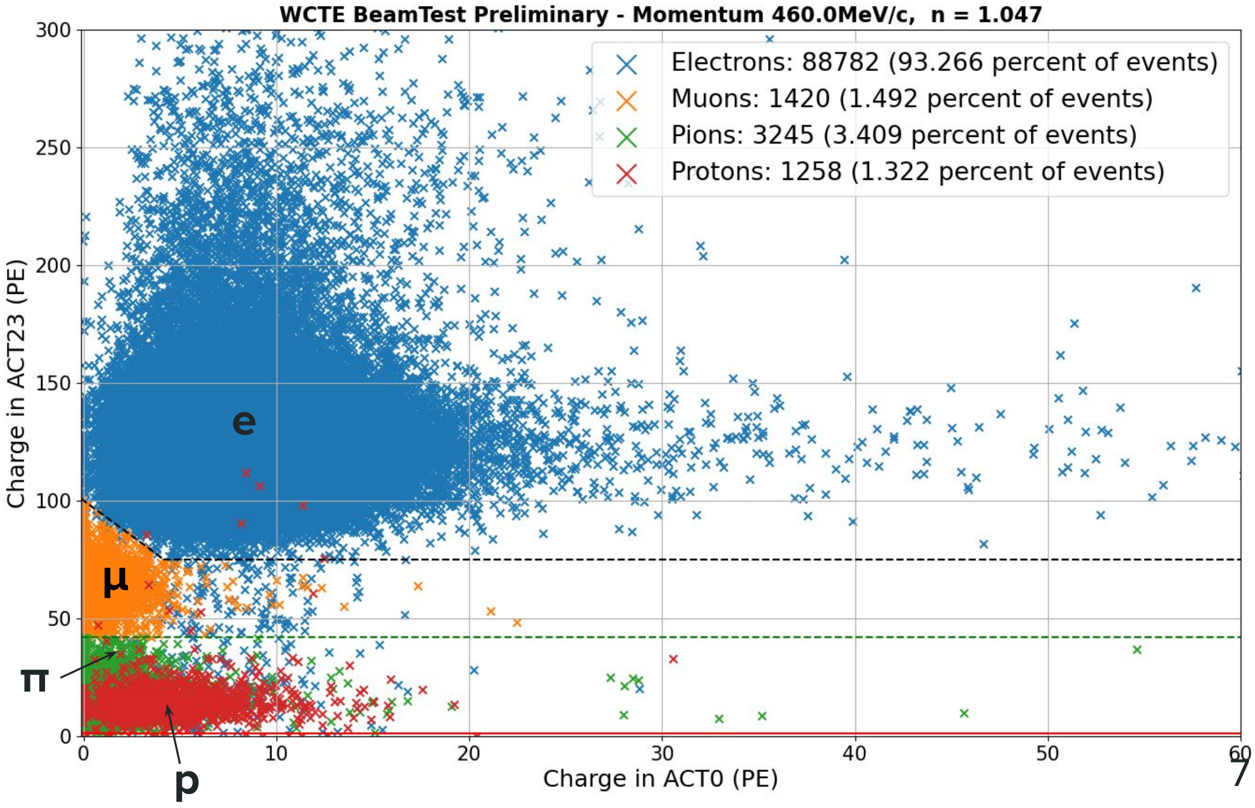


Method for Sub-GeV particle identification

- A peak finding algorithm gives charge and time of hits in all detectors.

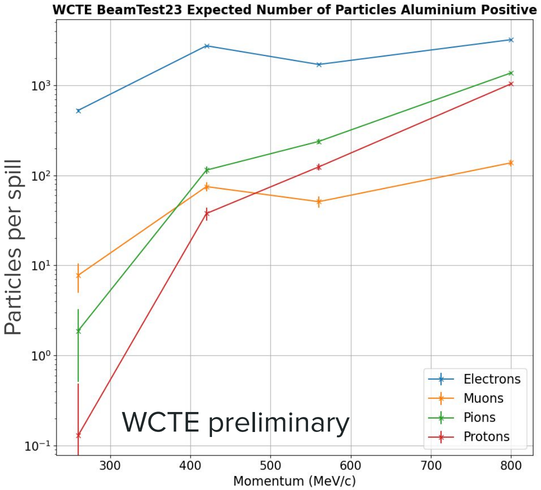
- **Protons** identified using time of flight cut.
- Cuts on ACTs is used to separate μ, π and **e**.
- Selection validated using calorimeter.

	Purity	Efficiency
μ	97.0%	97.1%
π	99.6%	93.5%



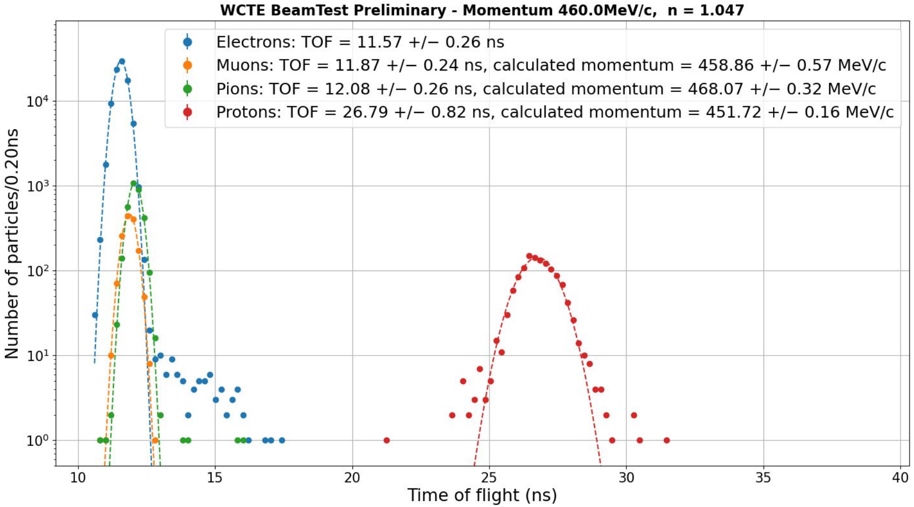
T9 beamline characterisation

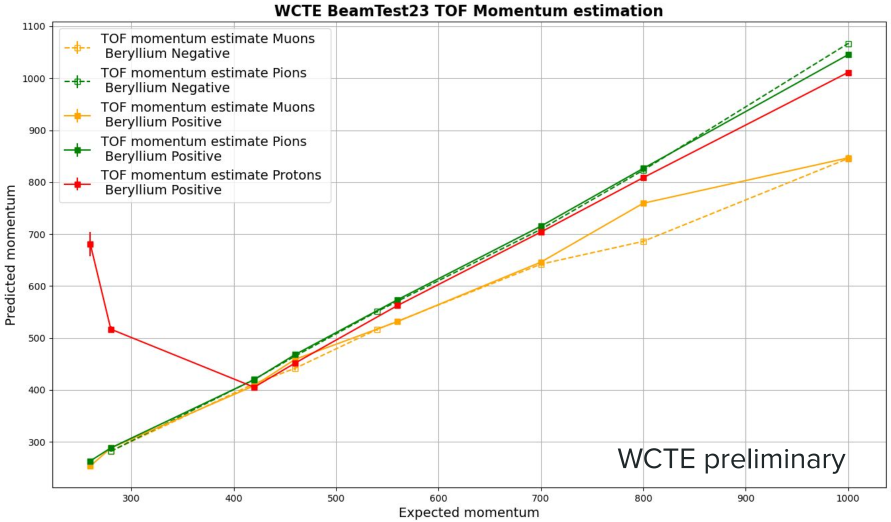
- WCTE performed the first characterisation of the upgraded T9 beam.
- Results agree with simulations.



Number of particle per spill, Al 200mm target (preliminary)

	μ	π	e	p
260 MeV/c	2	8	530	0
420 MeV/c	75	120	2.7k	40
800 MeV/c	140	1.3k	3k	1k



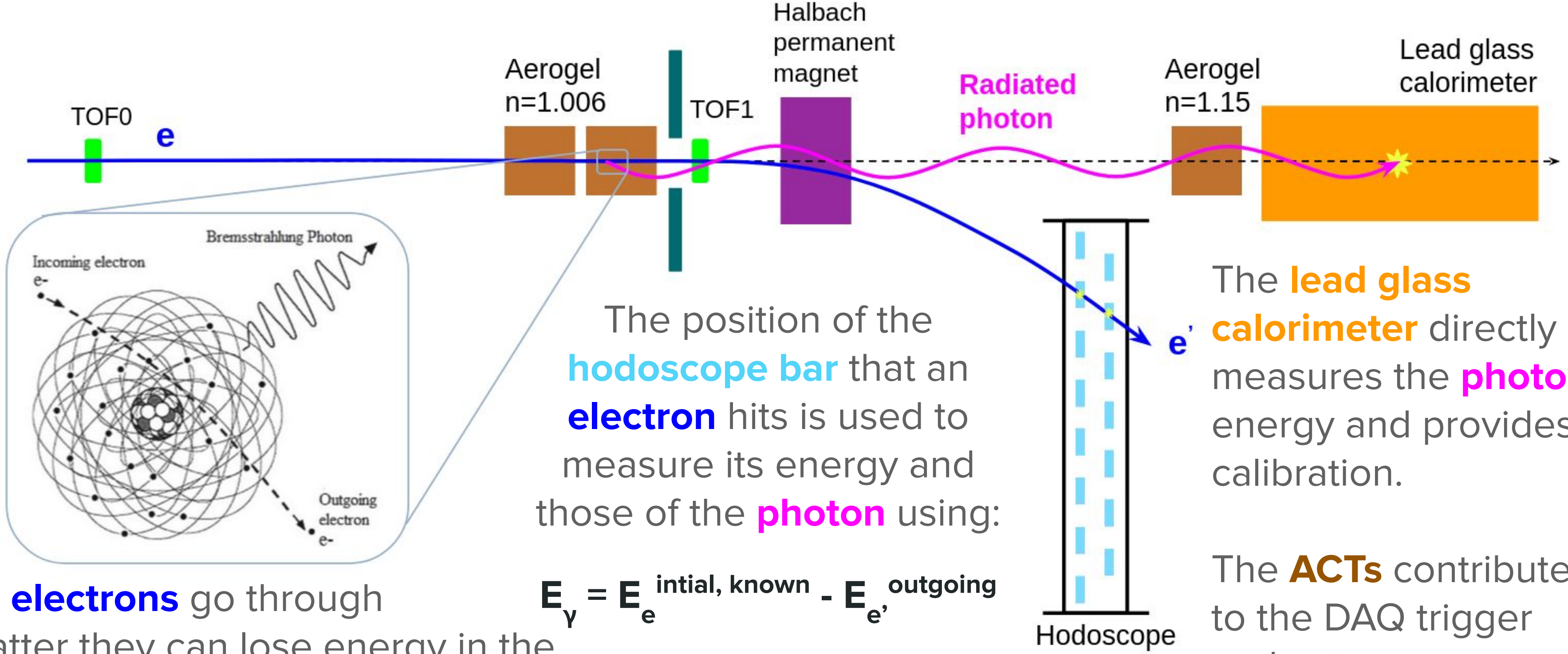


Tagged photon setup

For electron/gamma separation and photo–absorption studies in water Cherenkov detectors

Set-up for tagged photon production

Electrons are deflected by the **permanent magnet**, depending on their energy.



The position of the **hodoscope bar** that an **electron** hits is used to measure its energy and those of the **photon** using:

$$E_\gamma = E_e^{intial,\ known} - E_{e'}^{outgoing}$$

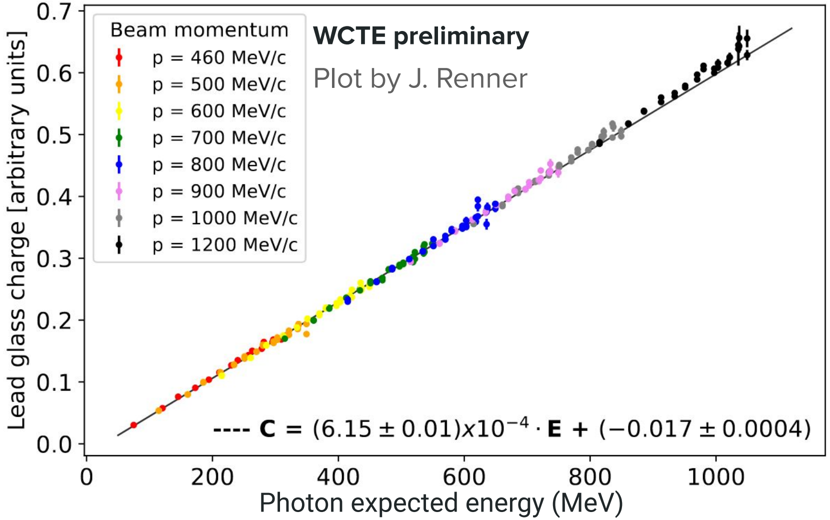
The **lead glass calorimeter** directly measures the **photon** energy and provides calibration.

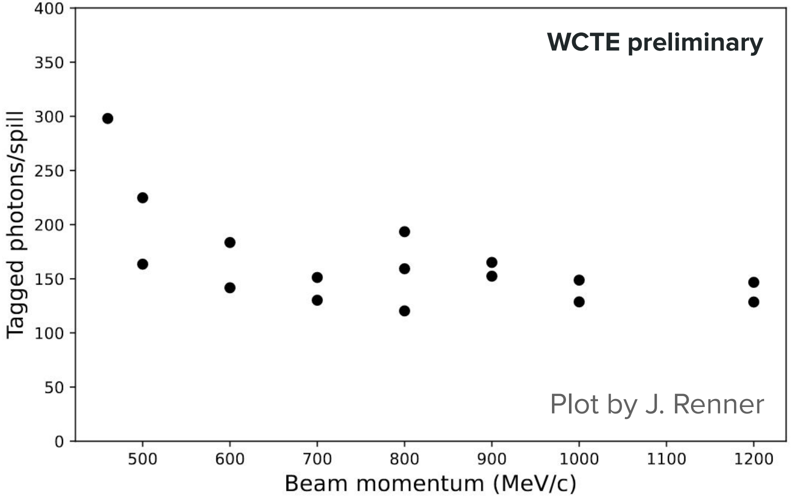
The **ACTs** contribute to the DAQ trigger and veto.

As **electrons** go through matter they can lose energy in the form of **Bremsstrahlung photons**.

Tagged photons results

- Electron beam of momentum 460 MeV/c to 1.2 GeV/c produces photons with energy from 100 MeV/c to 1 GeV/c.
- In July 2023 hundreds of tagged photons were produced per spill.
- Upcoming upgrades to hardware and analysis should bring further improvements.





Conclusions and outlook

- The WCTE will help Hyper−Kamiokande reach its Physics goals, thanks notably to its beamline instrumentation providing particle ID and momentum measurement.

- The 2023 beam test achieved:
  - Muon selection with 97 % purity at 97% efficiency
  - Pions selection with 99% purity at 93% efficiency
  - Production of hundreds of photon per spill with good energy resolution
  - First characterisation of the newly refurbished T9 beam

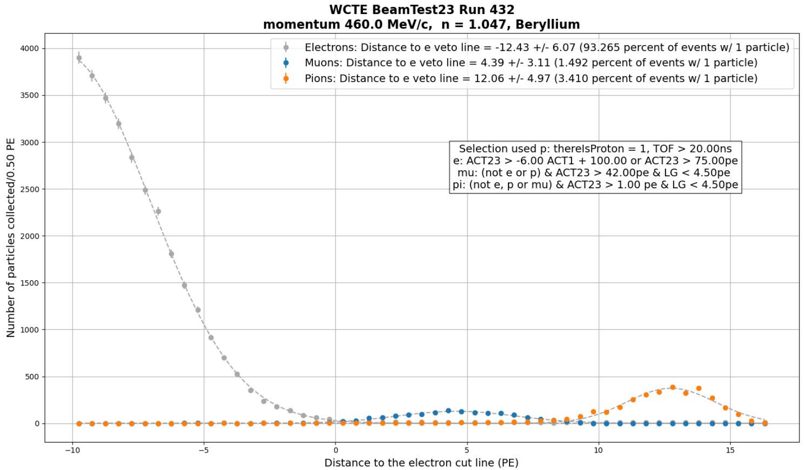
- Finalisation of the beam hardware and analysis is ongoing to prepare for WCTE operation this autumn.

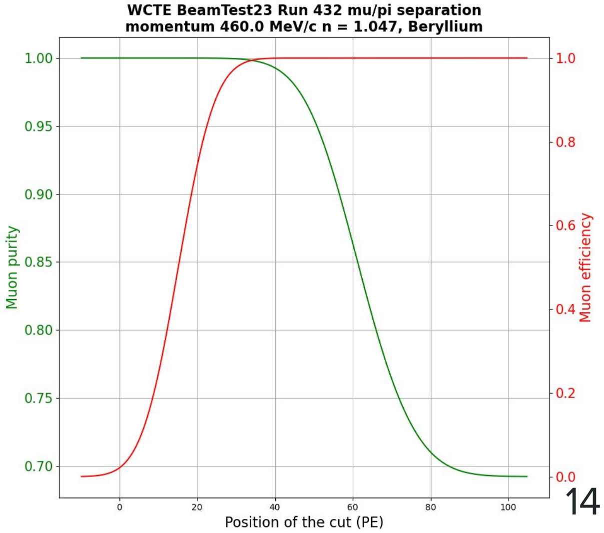
Back-up slides

Selection purity and limitations

- The efficiency and purity of the selection is calculated using gaussian fits to the distributions as a function of the cut variable.

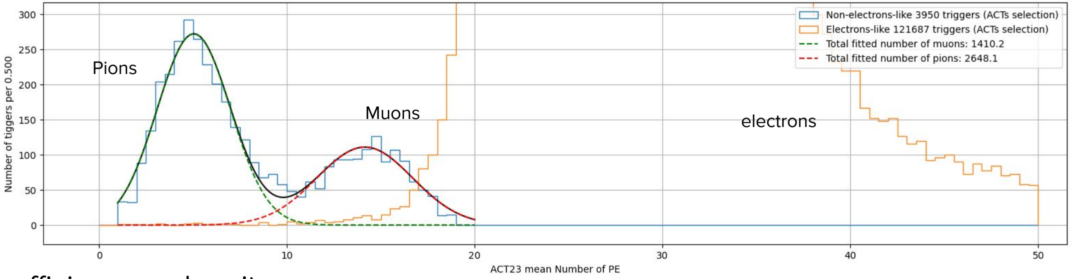
- For a run a 460MeV/c a preliminary selection yields a 97% (99.6%) purity for the muon (pion) sample with an efficiency of 97.1% (93.5%).





	Fraction of the sample			
460MeV/c	Muon-like	Pion-like	Electron-like	Efficiency
Muon sample	**97.0%**	0.3%	2.7%	**97.1%**
Pion sample	0.4%	**99.6%**	0%	**93.5%**

Optimal muon/pion separation



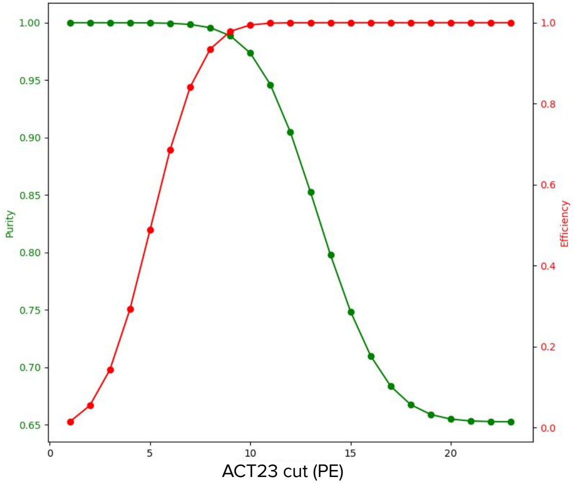
Motivation:

- Decide on the ACT23 cut that give the best purity to the muon and pion sample

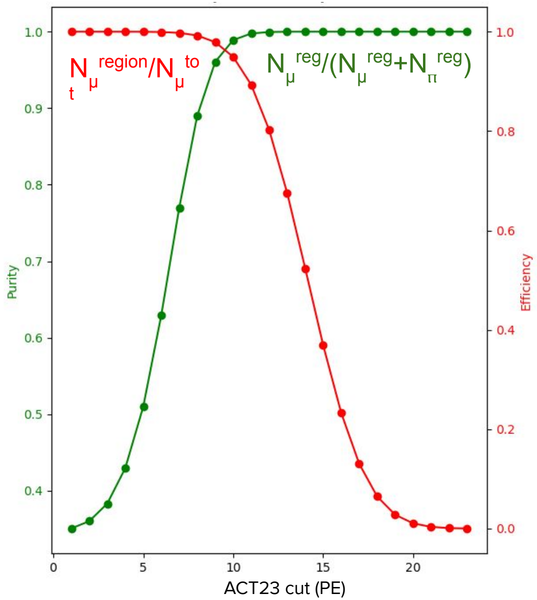
Method:

- Fit a sum of gaussian to the ACT23 signal
- Calculate the purity and efficiency of the samples as the position of the cut line is varied (from the overlap in the integral)

Pion efficiency and purity



Muon efficiency and purity



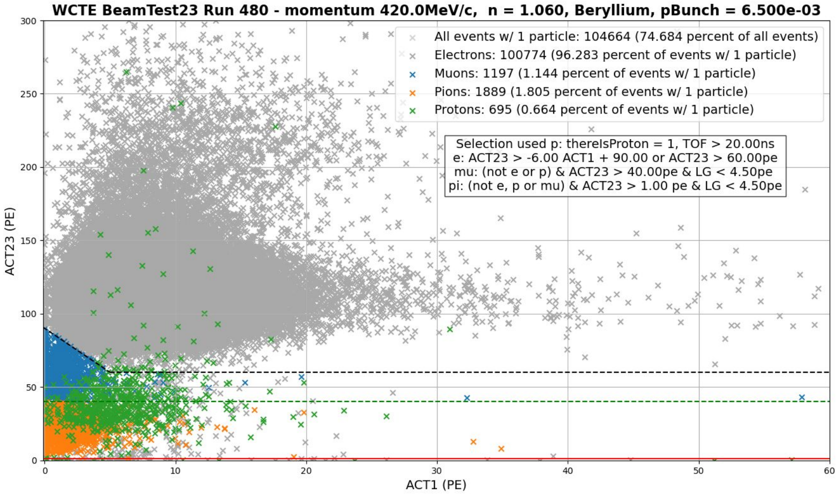
Cuts chosen: pion 8pe, muon 10pe

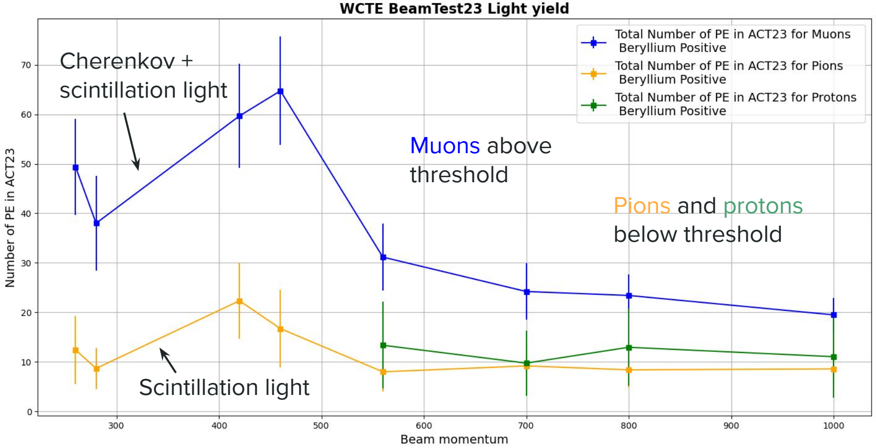
	Pions	Muons
Efficiency	**93.5%**	**94.9%**
Purity	**99.6%**	**98.9%***

* taking also the electron contamination into account brings muon purity down to 97.1%

Charged particle analysis summary

- The analysis framework now includes the developed by Arturo
- Particles are identified using a 2D selectic
- Scintillation light was identified in the A
- Final efficiency and purity of selection s





The Water Cherenkov Test experiment at CERN

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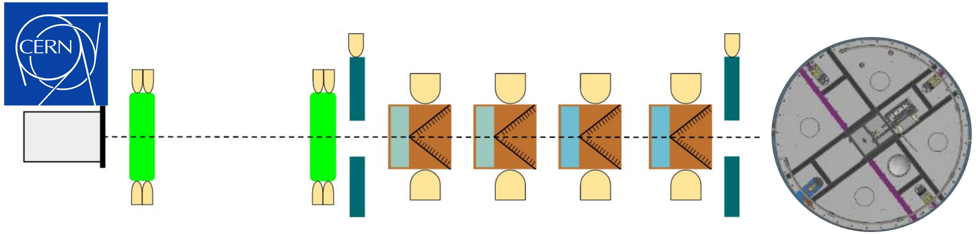
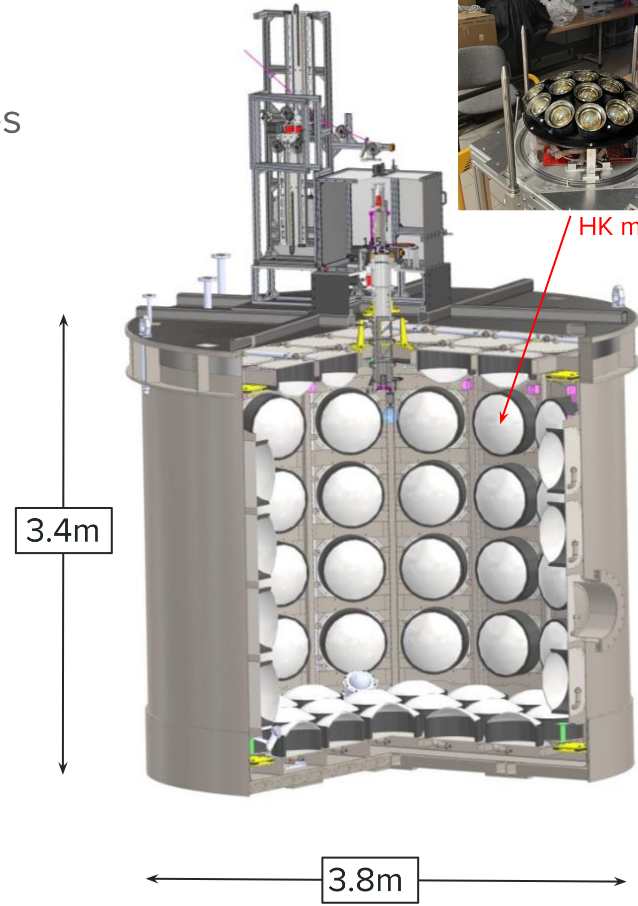
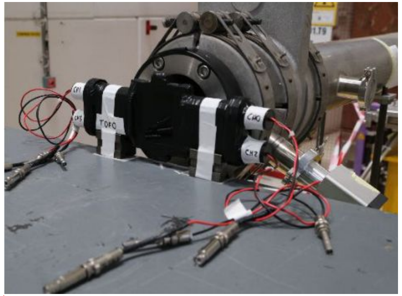
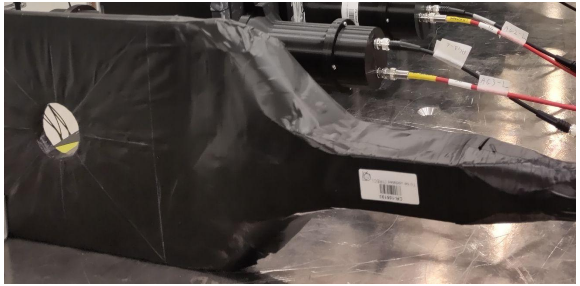


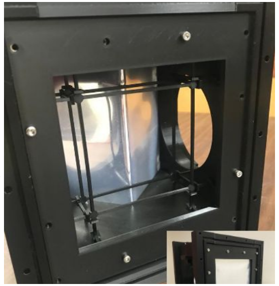


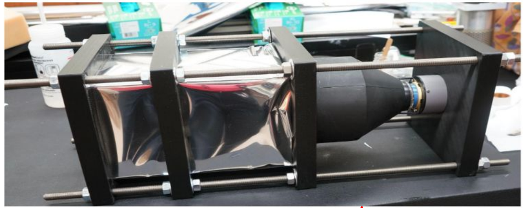
Plan

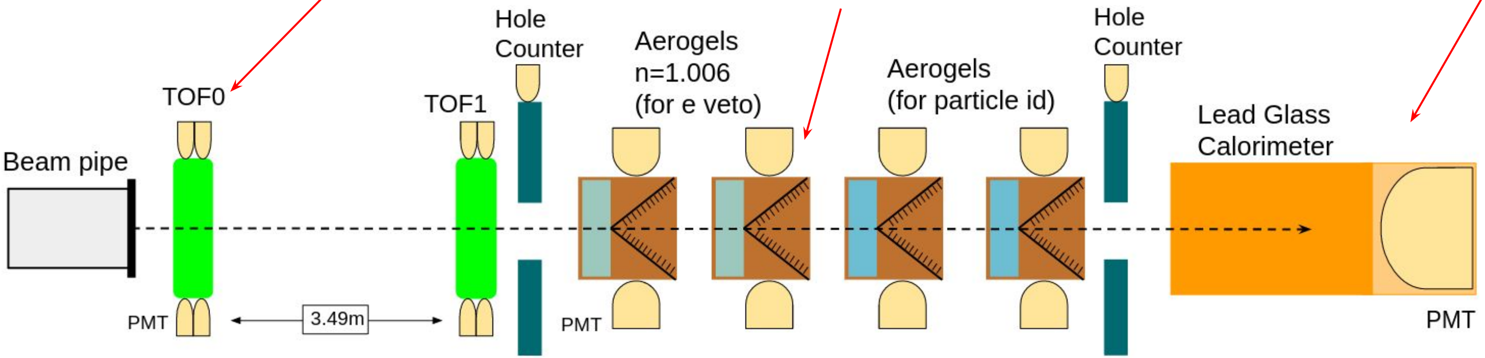
- Data processing tools
- Scintillation light
- Selection method
- Momentum estimate using TOF
- Particles selection purity and efficiency
- Number of particles











Multi-Peak analysis for the ACT boxes signal

Limitations of the charge estimation using peak integration:

- Scattering and reflections in the ACT box => long signal difficult to put bounds one
- Algorithm will always find **a** peak but not always the correct one => bias
- Peak integration dependent on which amplifier used (e.g. ACT0 shorter pulse => less likely to merge peaks)

Window integration method:

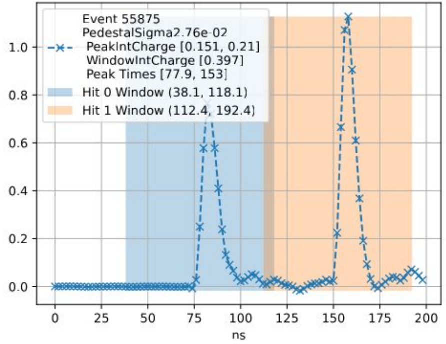
- Integrate the waveform over a fixed time duration (window)
- Position the integration window with respect to the expected arrival time of the particle in the ACT

Requires:

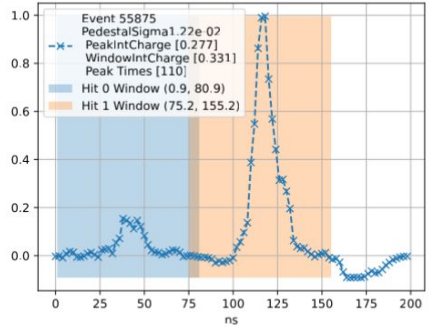
- Calibration of the timing offset between detectors (including particle-dependant time of flight, see this slide)
- An integration window of a size such that it collects only but all of the charge corresponding to a given particle

(see this slide)

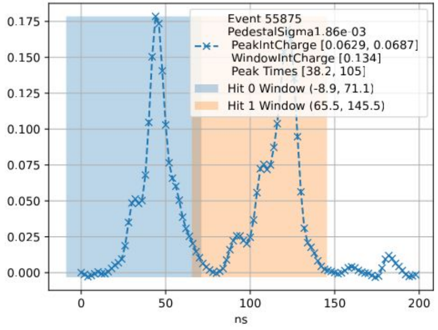
TOF01



ACT0R



ACT2L



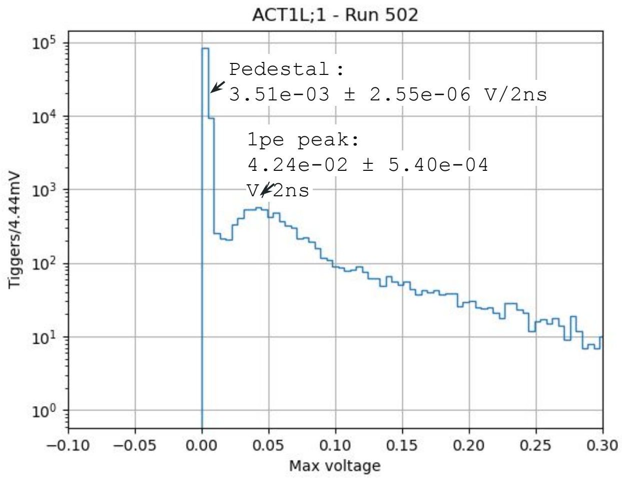
Signal conversion to 1pe

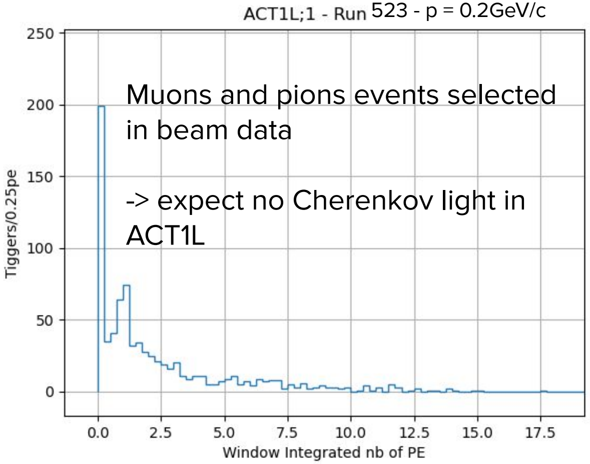
Motivation:

- The PMTs have different gain due to different voltage, inner structure…
- To compare them reliably -> need to convert the signal to units of photoelectrons

Method: (see backups)

- Collect the waveform's maximum amplitude for a run with random triggers (run 502, would have been useful to collect more)
- Fit a gaussian to the 1pe peak and use it to convert V/2ns into 1pe
- Fit the peak integrated charge and scale so that it lies at 1pe (to handle the non-zero width of 1pe)





See 1pe stability checks here

Scintillation light study

ACT light yield

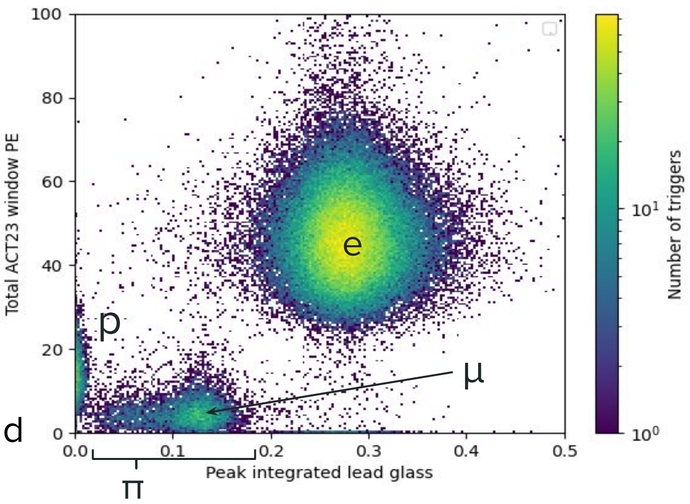
Motivation:

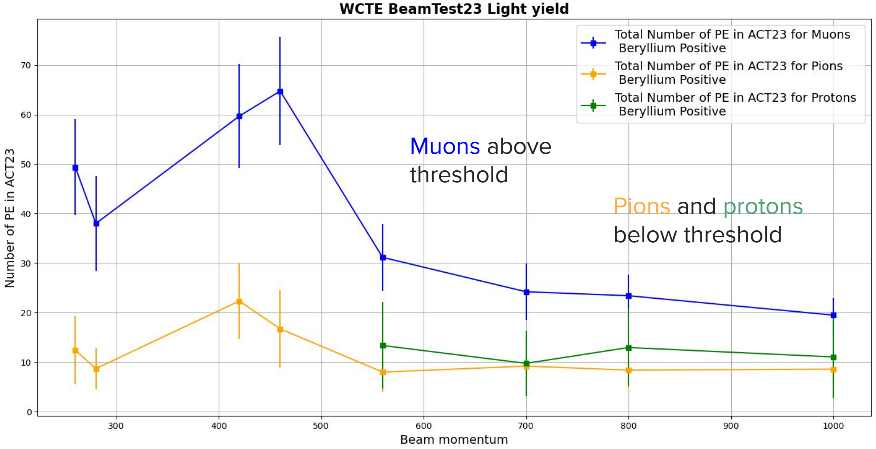
- Seen that we have light in the ACTs even for particles below threshold

Method:

- Verify the amount of light observed for pions and protons below threshold.
- Check the timing of the light when all particles are below threshold

Run 435 - 500MeV/c (pos) n = 1.02





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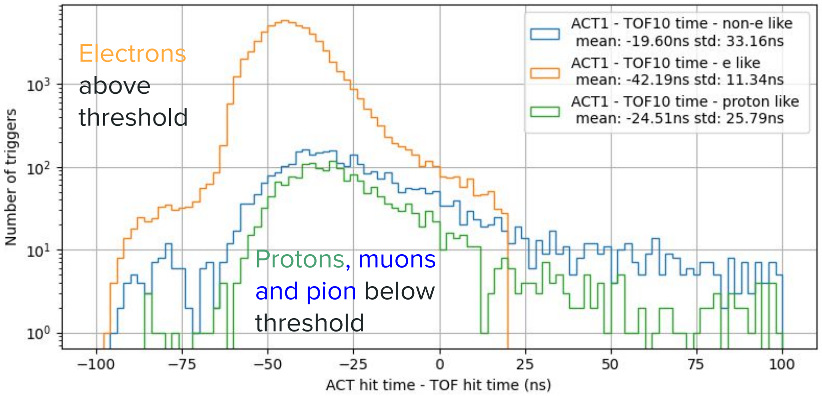


Scintillation light

- We observed light for pions and protons below threshold, up to 10PE per box, with more light for protons than pions. The amount of light depends on the box used.

- The light observed for particles below threshold is on average later than prompt Cherenkov light (seen for electrons) by about 15ns.

- This light is due to scintillation in the 3M reflective film inside of the ACT boxes.

> ground. To check the scintillation response of the 3M film, we have performed a test using a photomultiplier and a ^{238}Pu α source. The observed scintillation is at the level of 15–34% relatively to NE102A plastic scintillator (depending on the side of the film facing the photomultiplier).

E. Armengeaud et. al. (2017)

Selection method

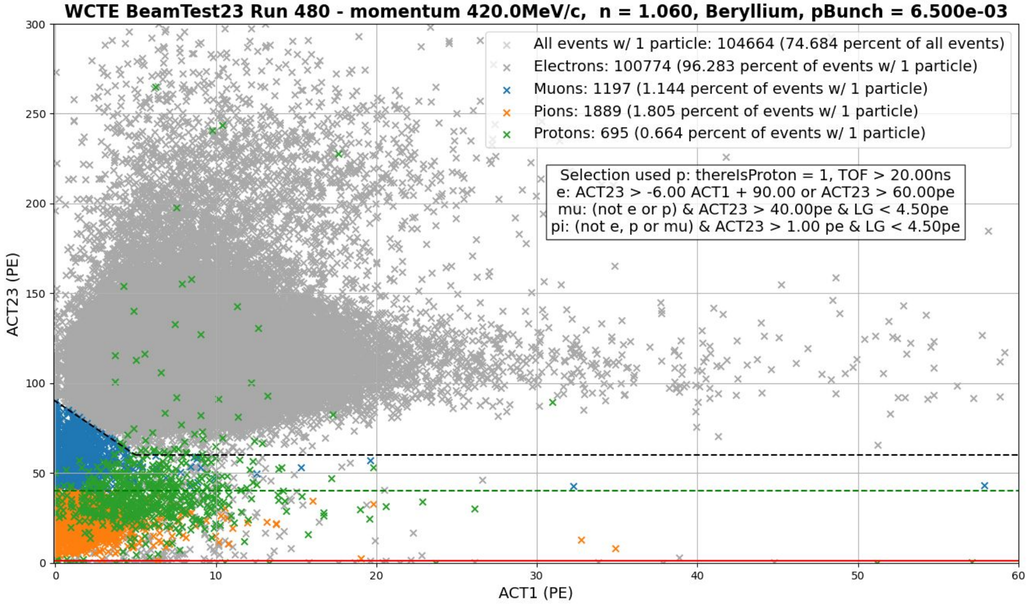
Selection rules

Motivation:

- Identify muons, pions and electrons
- Count the number of particles in the beam line

Method:

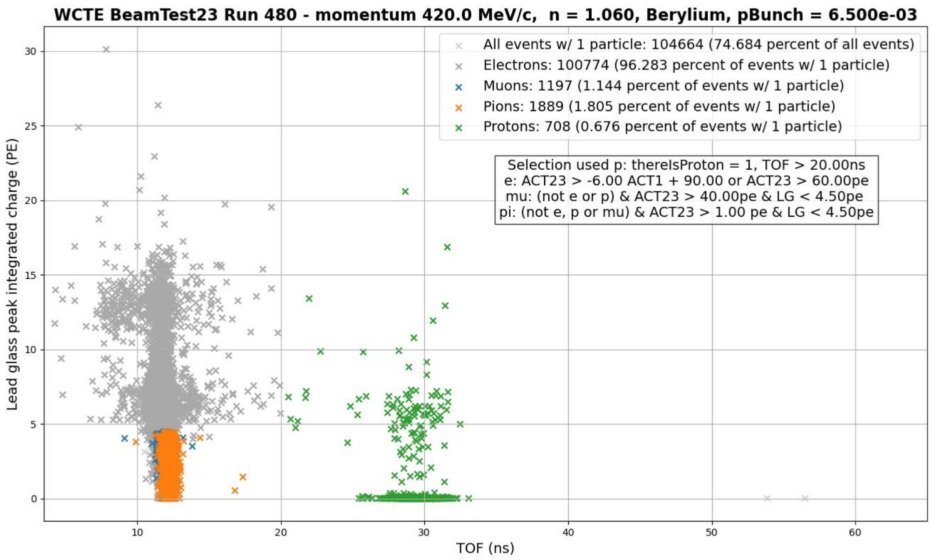
- Require only 1 particle in the 200ns analysis window
- Use a TOF cut to ID protons
- Use 2D cuts in ACT23 vs ACT1 to separate e, mu, pi
- Add a cut on Lead Glass charge to get rid of 'weird electrons' (see these backup slides)

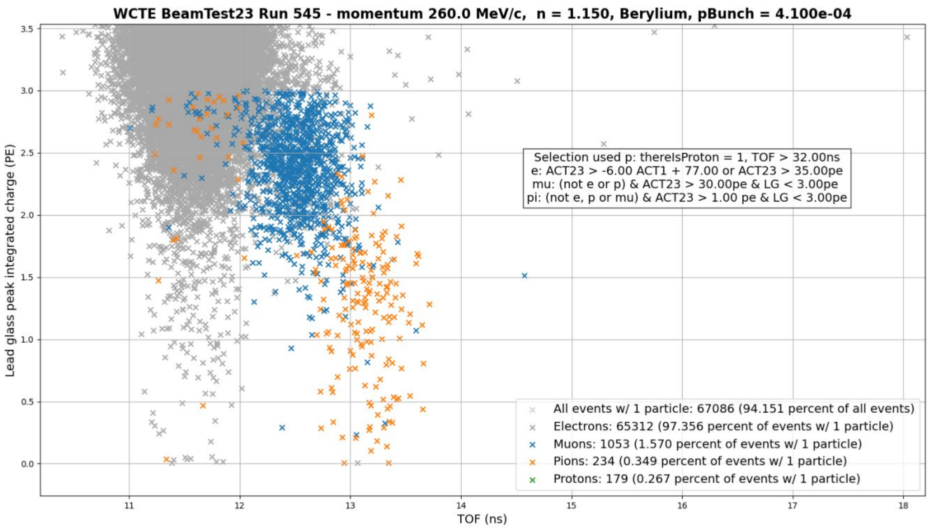


Verify selection

Motivation:

- Check that the selection behaves as expected
- Note any biais





Interesting points:

- Most protons get absorbed before they reach the Lead Glass
- At low momentum there is about 10% e contamination in mu and pi sample -> Lead Glass cut is not enough to remove them

Selection discussion

- We can identify particles using the ACT and TOF signals.
- The electron (and beam halo?) veto still needs some work. In particular, there are ‘weird electrons’ producing little to no light in any of the ACTs.
- To obtain accurate particle numbers, here I remove the ‘weird electrons’ by applying a cut on the Lead Glass.
- The particle identification has a ~90% purity for momenta between 400MeV/c and 700MeV/c.
- The purity is worse at lower momenta due to ‘weird electron’ contamination. The purity is worse at higher momenta due to scintillation light.

Momentum estimate using TOF

Momentum estimate using TOF

Motivation:

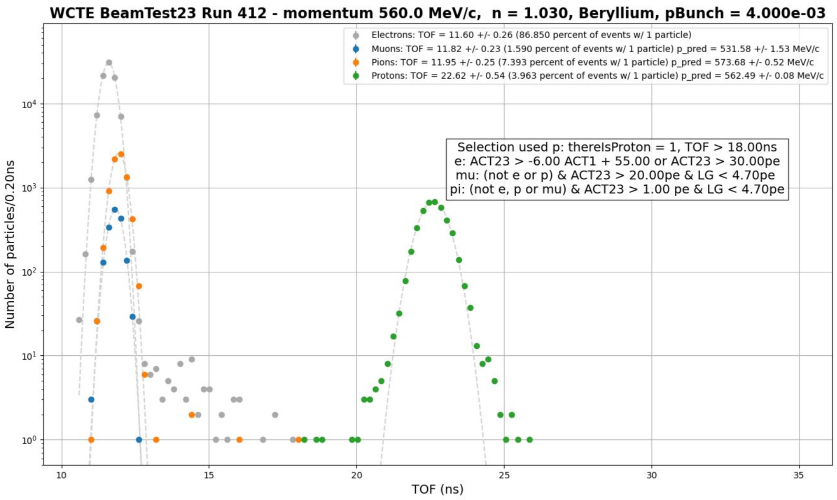
- Have a way to measure the beam momentum without using the Lead Glass information
- Check for any momentum biais

Method:

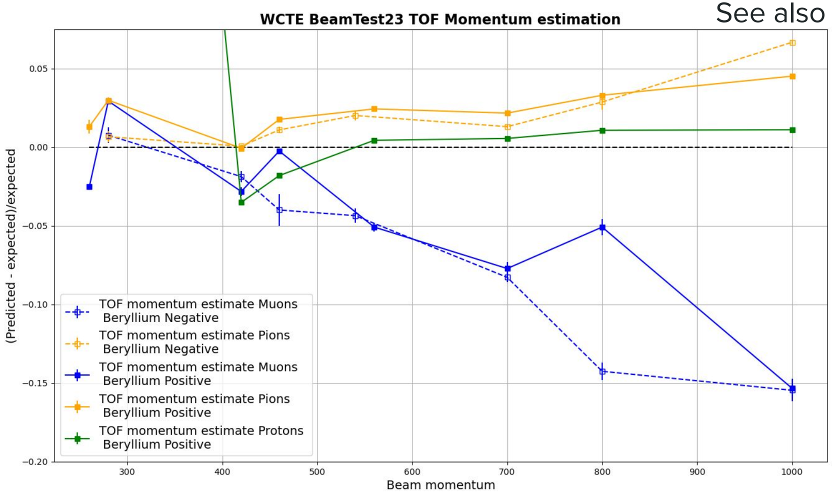
- Align the timing between the scintillator triggers using the e sample.
- Calculate and fit the TOF of each particle population
- Use the fitted position of the mean TOF and the particle mass to measure the momentum

Information:

- At high momentum, the muons are too fast -> poor momentum estimate
- At low momentum, there are no protons
- Less than 10% difference with expected momentum



See also this

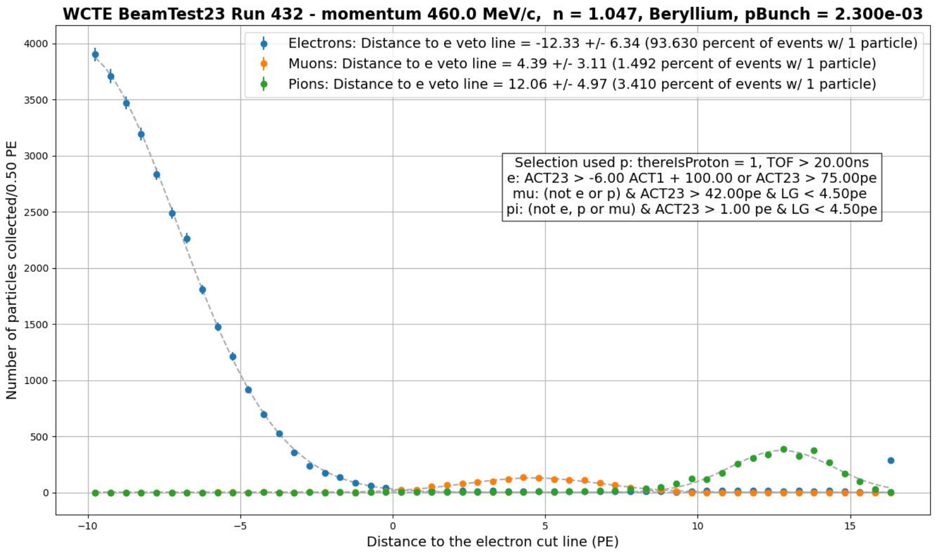


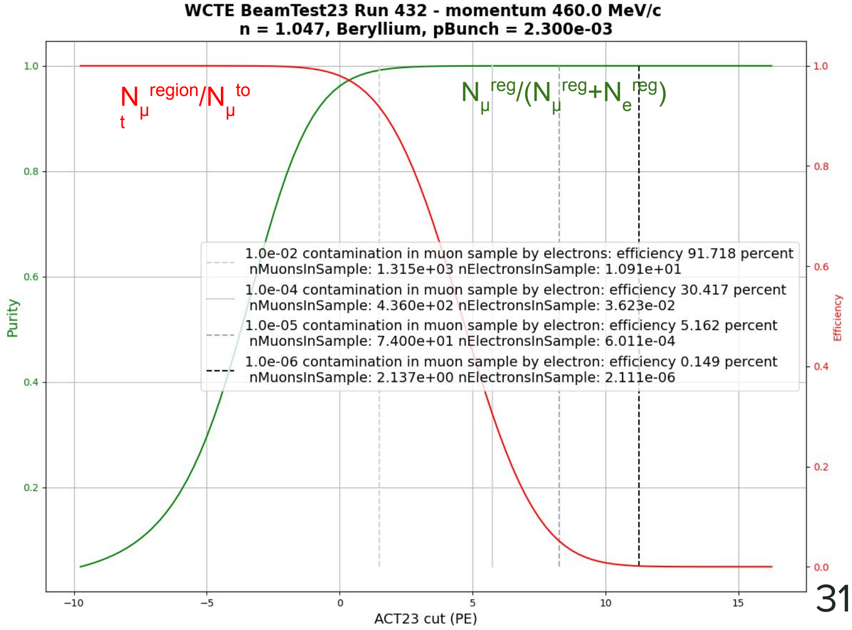
Selection purity

Electron/muon separation

Example: medium electron/muon separation from 2023 beam test

- Plot the distance to the cut line for each population, fit with a gaussian
- Use the gaussian overlap to derive efficiency and purity as a function of cut line position
- Can achieve 10^{-5} electron contamination in muon sample with a 5.2% efficiency.
- Can achieve 10^{-6} electron contamination in muon sample with a 0.15% efficiency.

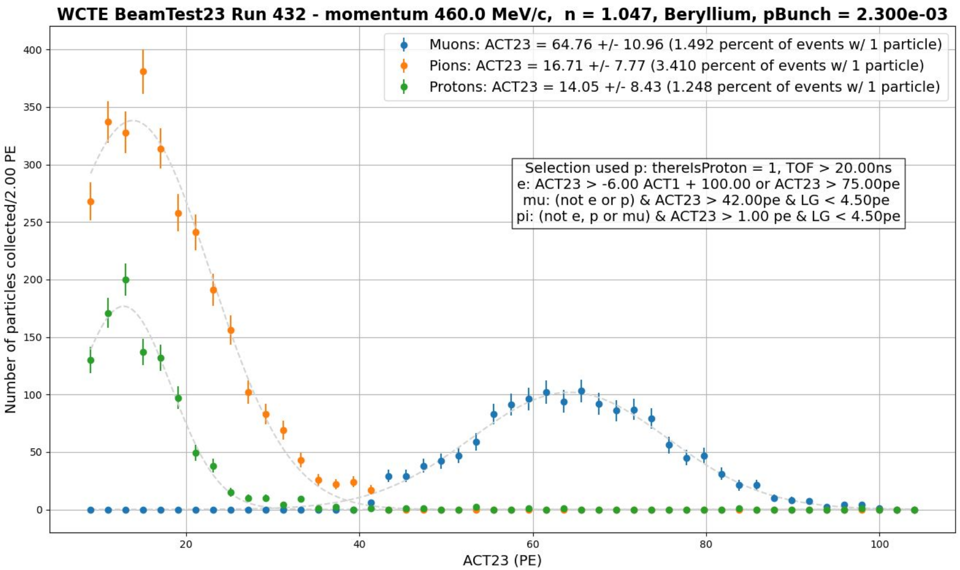


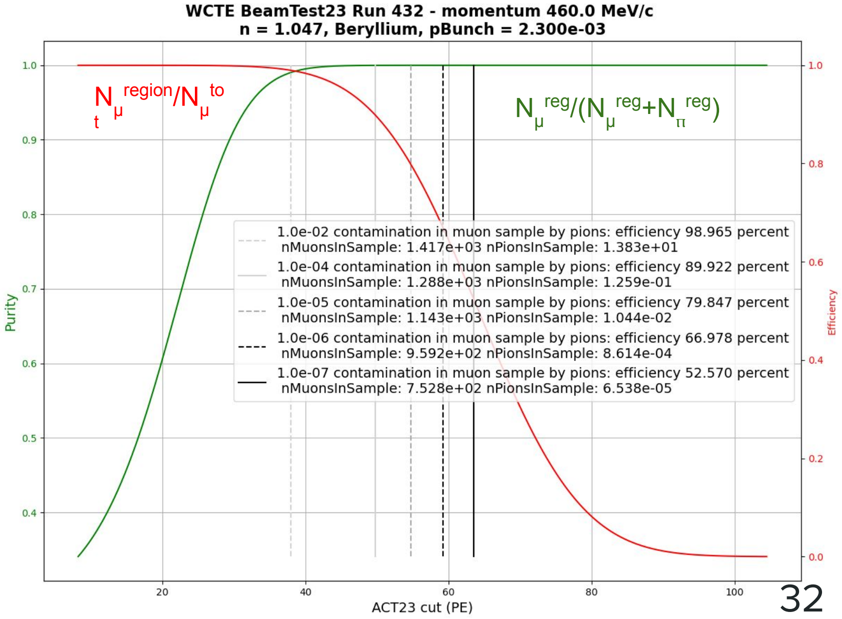


Pion/muon separation

Example: best pion/muon separation from 2023 beam test

- Plot the ACT23 signal of each population, fit with a gaussian
- Use the gaussian overlap to derive efficiency and purity as a function of cut line position
- Can achieve 10^{-6} pion contamination in muon sample with a 67% efficiency
- Can achieve 10^{-6} muon contamination in pion sample with a 33% efficiency (see this slide)



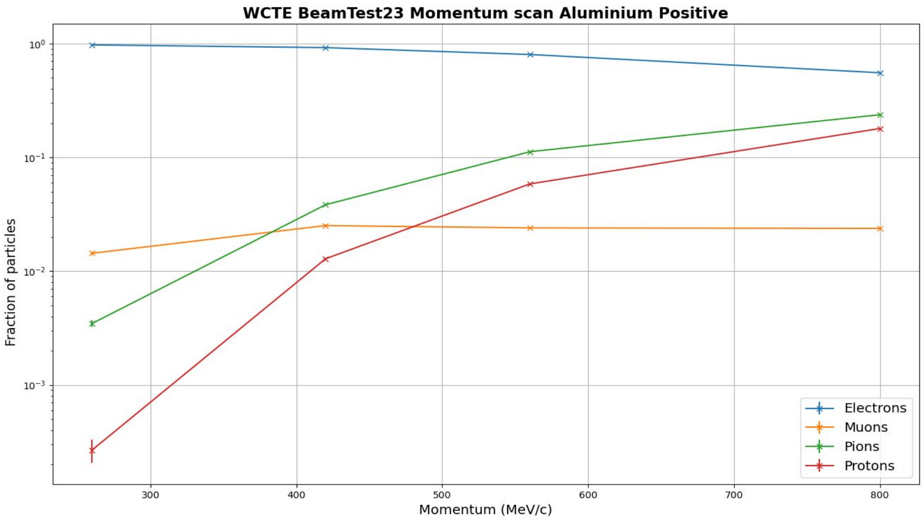


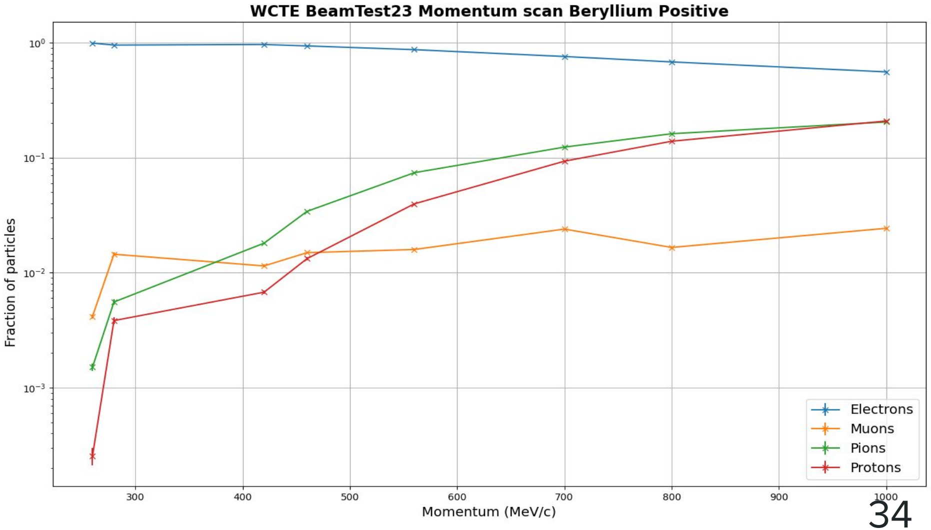
Particle counting

Fraction of particle collected during July 2023 Beam test

Motivation:

- Have a feel for proportion of muons, pions, proton and electrons in the beam
- Use particle selection previously derived
- Compare the target yields: Aluminium has a slightly better mu to e and pi to e ratio than Beryllium

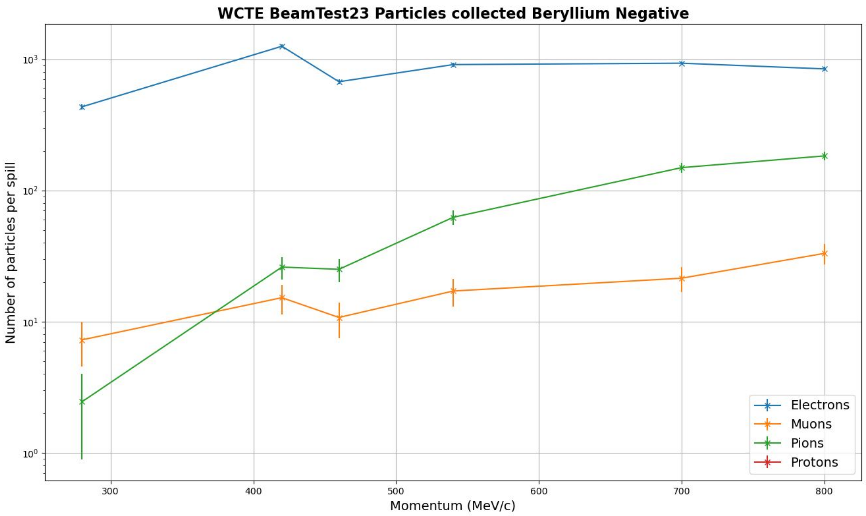


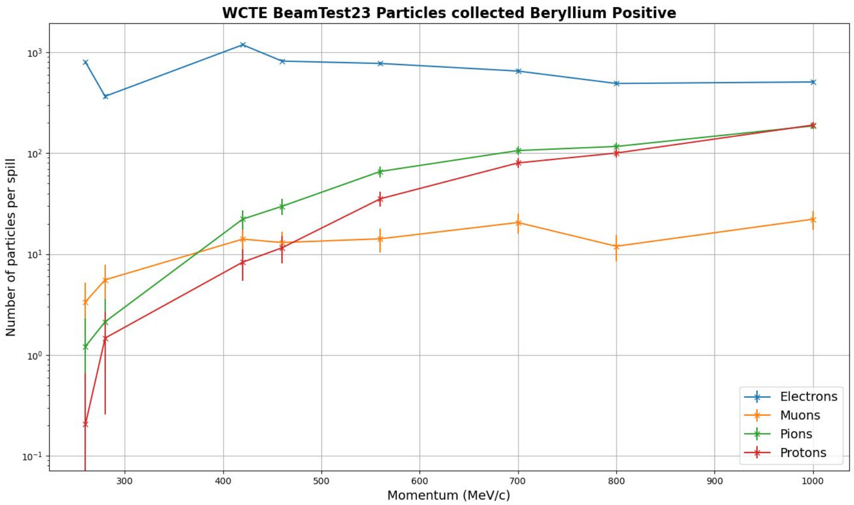


Total of particle collected during July 2023 Beam test

Caution: These numbers are below what we might expect for the 2024 run time

- There was a large dead time. Due to a faulty connection the deadtime was not always applied
- The condition that there is only 1 particle in all TOF removes up to 20% of the dataset
- Some events O(~0.1%) are discarded as noise





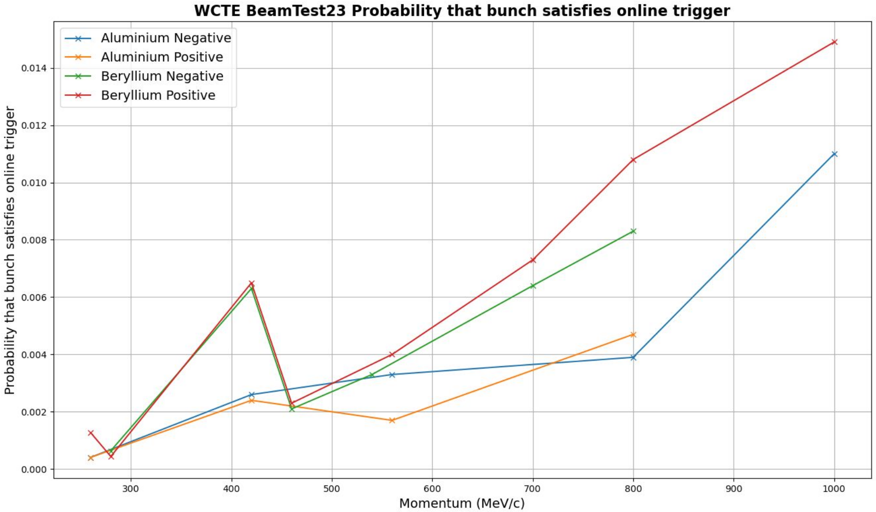
Prediction for number of particles

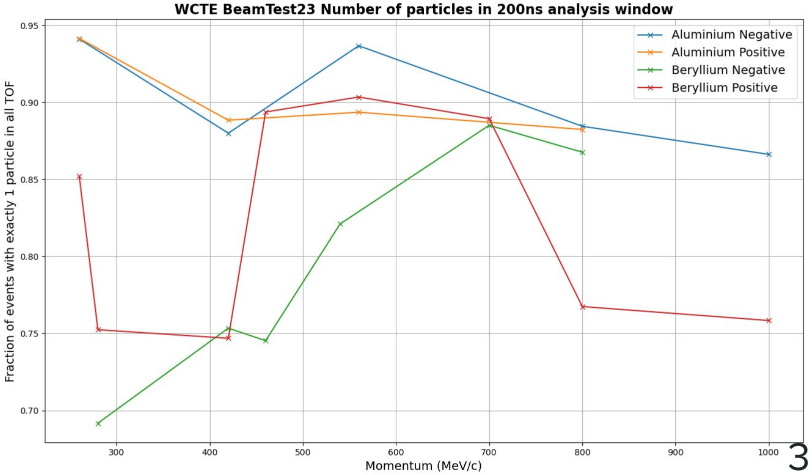
Motivation:

- Have numbers for making the WCTE run plan

Method:

- Account for the probability for a bunch to satisfy the July 2023 online trigger (see Dean's presentation)
  - For particle estimation: multiply by 3 to account for dead time failures
- Account for the probability to satisfy the offline trigger
  - Probability to have only 1 particle in the event (technically this is not necessary, just for higher precision)
  - Fraction of events that is identified as a certain particle type
- Multiply by the number of bunches in a spill (1.4M)





See also this estimate for run time

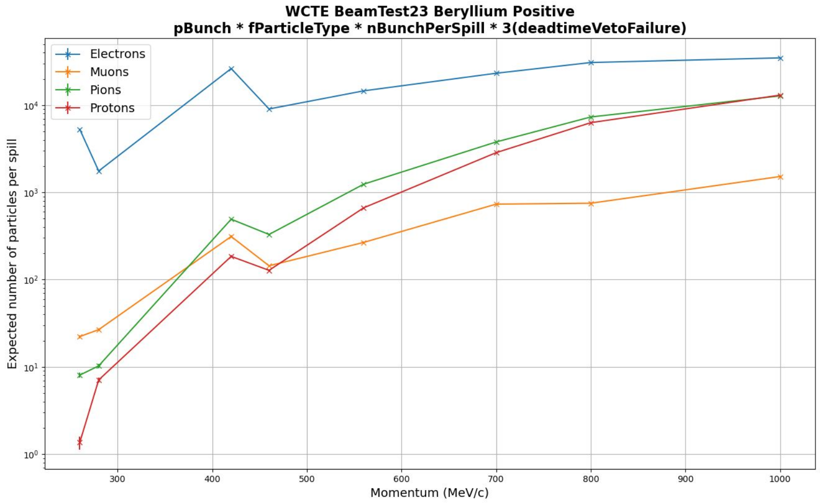
Prediction for number of particles

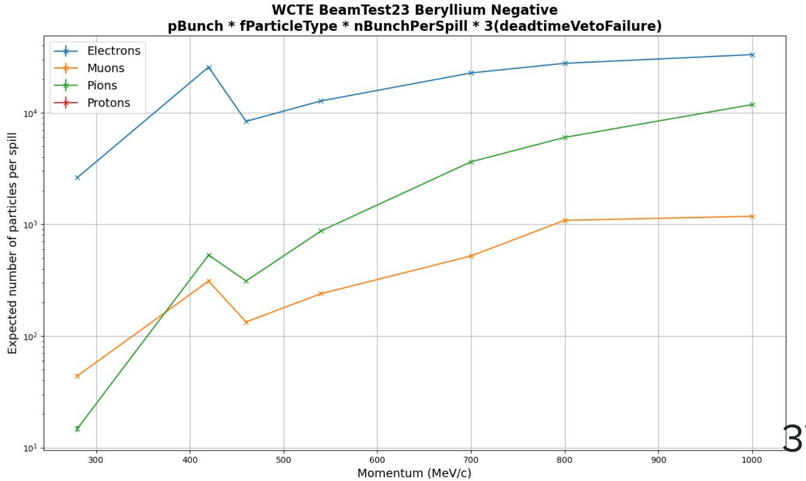
Discussion:

- According to this prediction we will get between 22.3 and 1 520 mu/spill and between 8.0 and 12 800 pi/spill

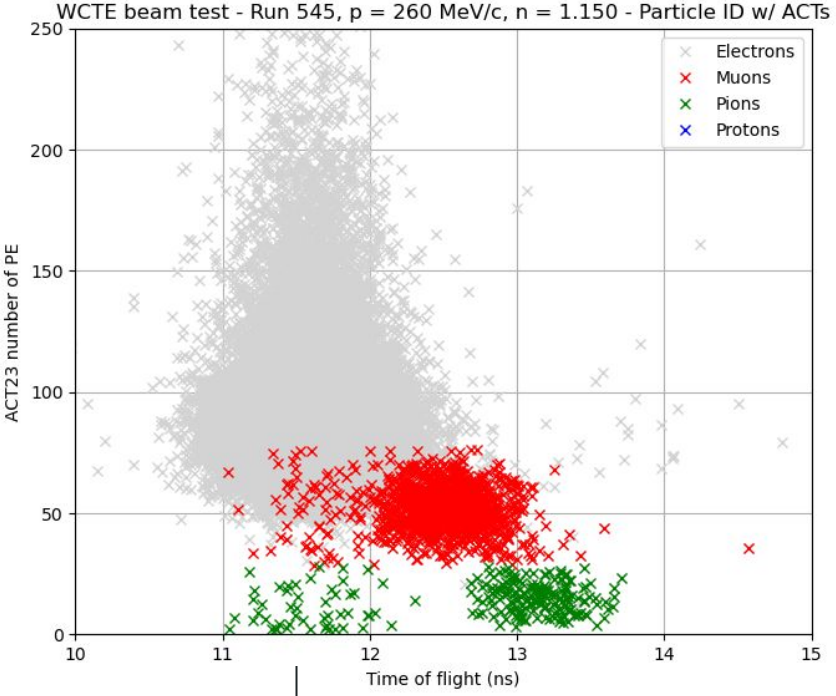
- Number of particles per spill, beryllium target, positive beam
  - **Assume** 100% efficiency, 100% purity
  - Assume same online e^- veto as during beam time

	Muons	Pions	Electrons
260MeV/c	22.2	8.0	5 281
420MeV/c	312	492	26 337
560MeV/c	266	1 242	14 606
700MeV/c	733	3 791	23 219
1000MeV/c	1 518	12 778	34 842





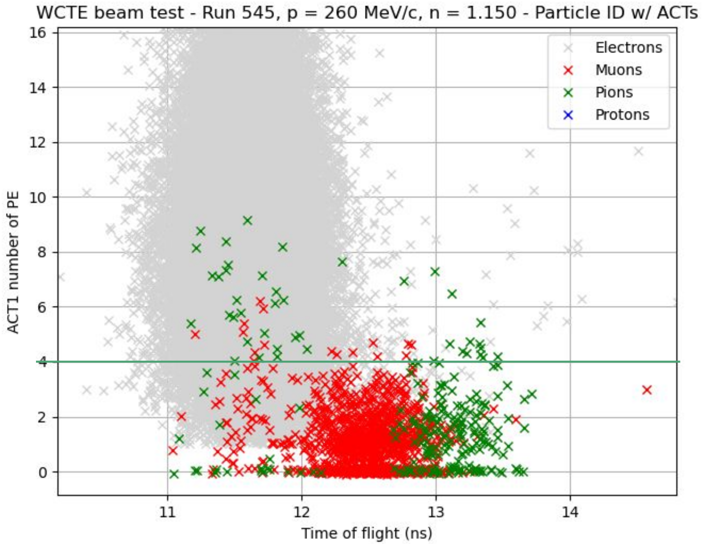
Issue: electrons not making any light in e veto

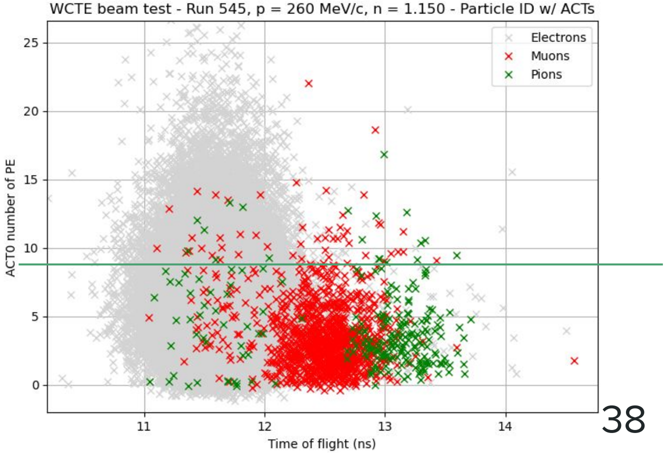


Electrons wrongly identified as pions/muons

Scintillation in ACT1 and ACT0 drops the e veto capabilities

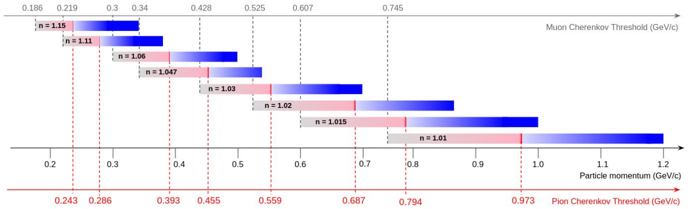
This background is fast light (faster than scintillation)





Scintillation light study

ACT light yield per cm of aerogel



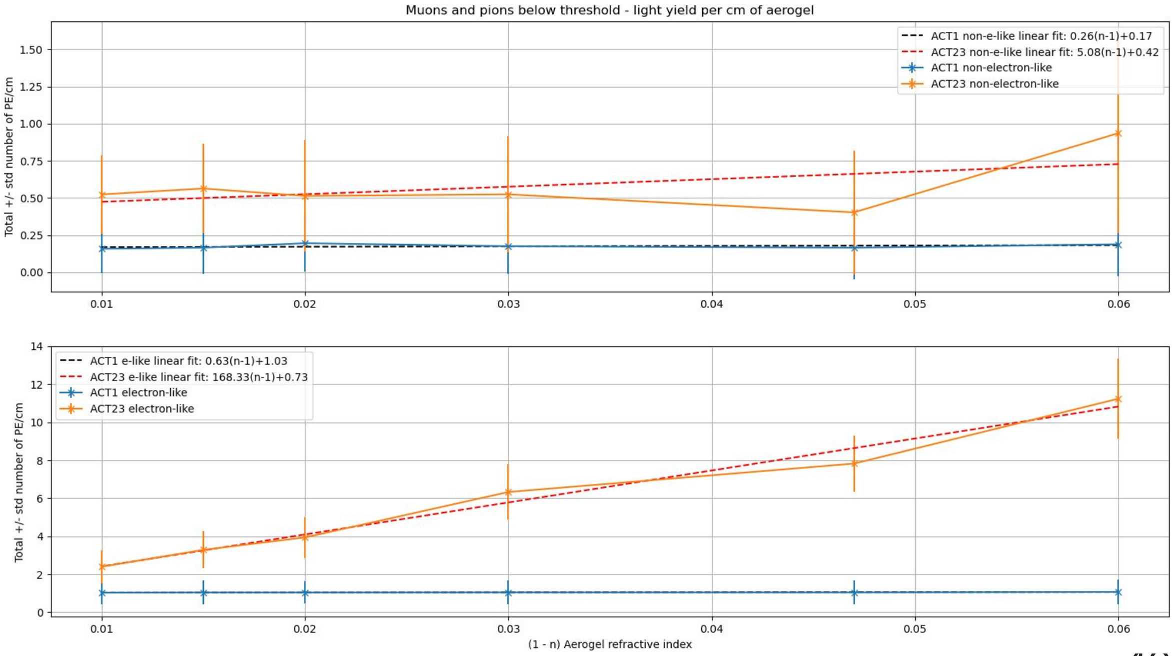
Run	Momentum (MeV/c)	refractive index
484, 475, 474	-300, 300, 300	1.06
460, 459	-600, 600	1.015
435	500	1.02
429, 430	340, -340	1.047
416, 415	-420, 420	1.03
391, 373, 372, 364	-700, -700, 700, 700	1.01

Thanks Sirous for the table!

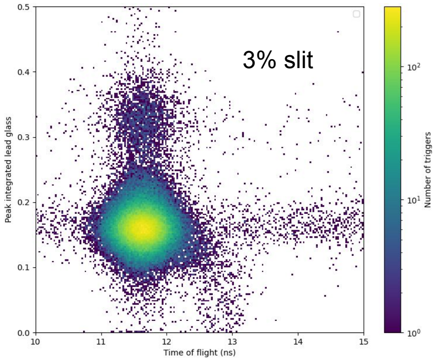
ACT box number	Index of Refraction	Thickness (cm)
1	1.15	2
2	1.15	2
3	1.13	2
4	1.13	2
5	1.11	2
6	1.11	2
7	1.03	4
8	1.03	6
9	1.06	4
10	1.06	6
11	1.047	8
12	1.047	8
13	1.015	6
14	1.015	6
15	1.006	8
16	1.006	8
17	1.02	6
18	1.02	6
19	1.01	6
20	1.01	6

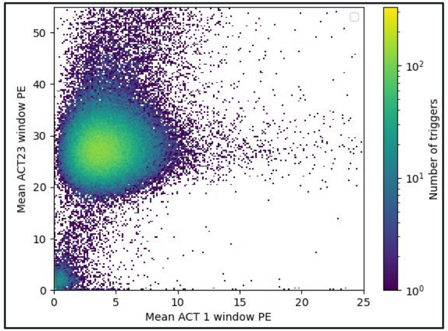
Notes:

- The light yield is stable for µ and πbelow threshold, in the ACT1 and ACT2+3 and above 1pe
- Constant amount of light for electrons in ACT1 and above 1pe (in total)
- Mean number of PE produced by electrons in ACT2&3 is proportional to (1-n)

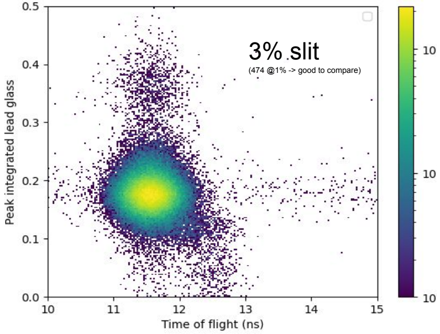


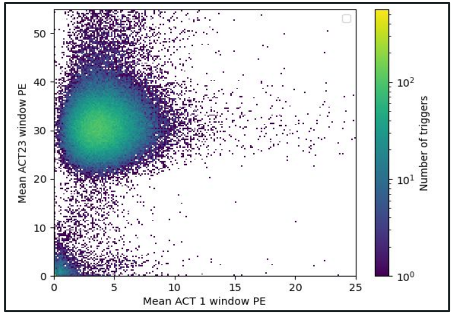
484 - n = 1.06



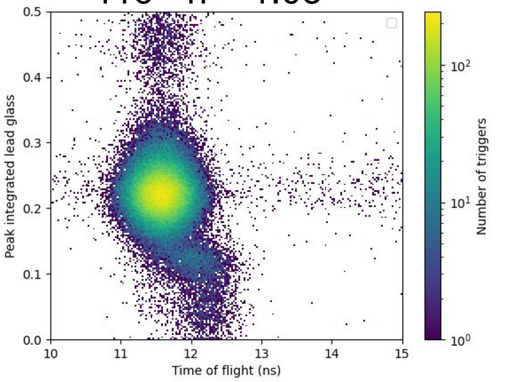


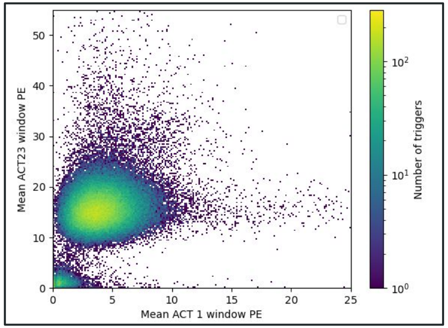
429 - n = 1.047



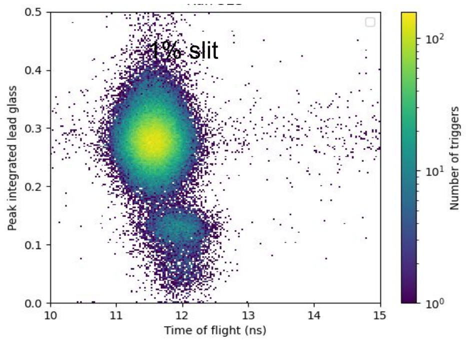


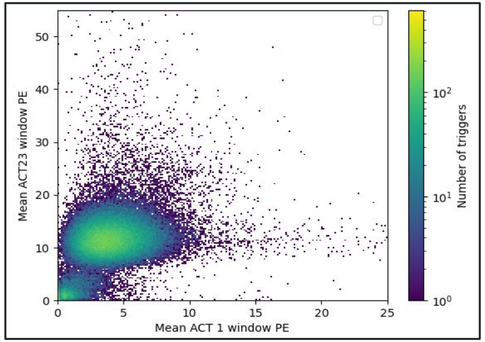
416 - n = 1.03





435 - n = 1.02





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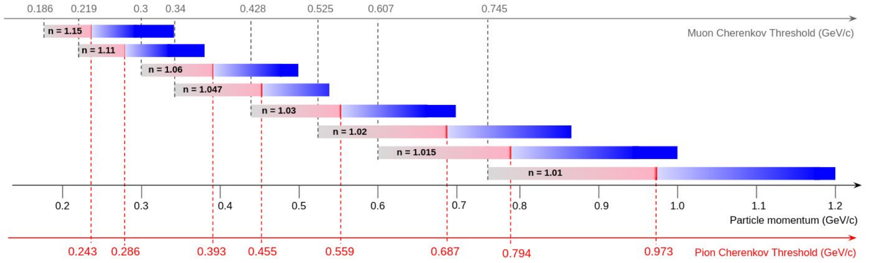
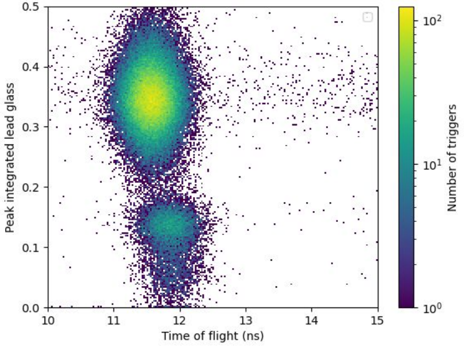
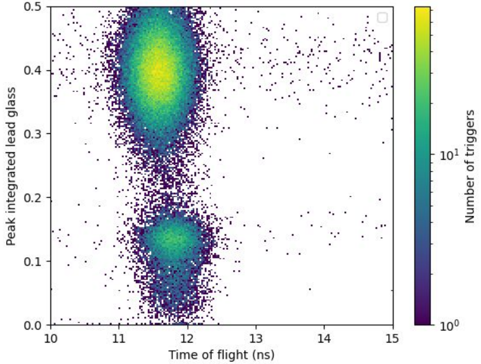


1 hit in tof only, no cut on nPeaks_Hole

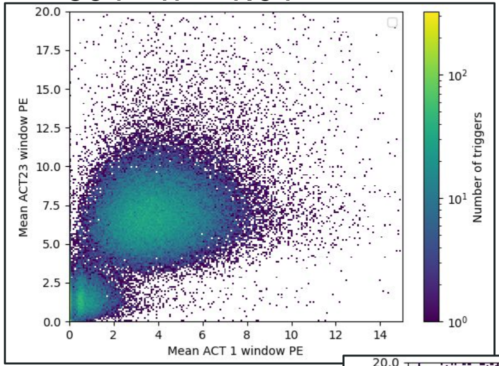
460 - n = 1.015



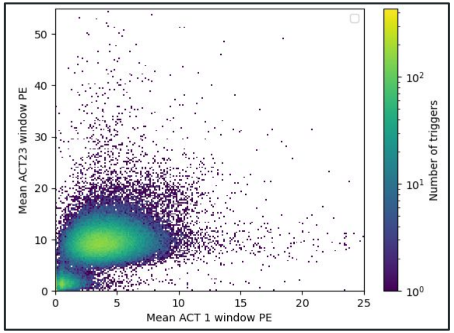
391 - n = 1.01

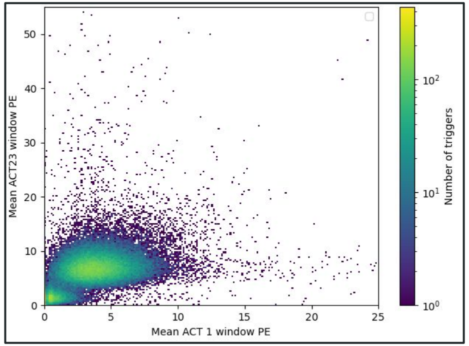


391 - n = 1.01

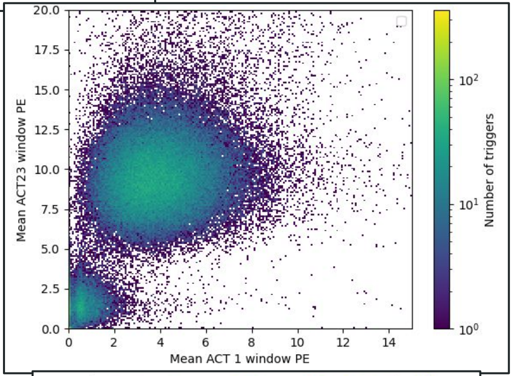


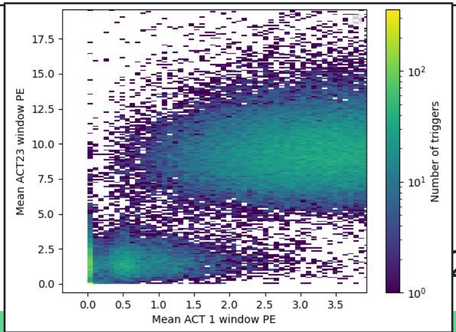
Zoomed in on photon yield at low refractive index





460- n = 1.015





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429, 430	340, -340	1.047
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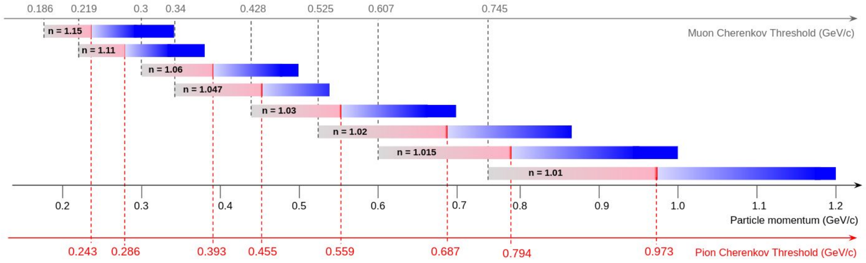
391, 373, 372, 364	-700, -700, 700, 700	1.01



Selection purity

Electron contamination

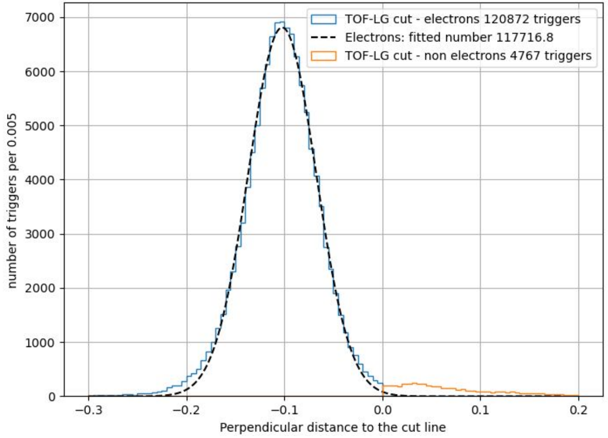
Motivation:

- Quantify how much electron contamination there is in the muons+pion sample

Method:

- Plot the perpendicular distance to the cut line
- Fit the distributions with a gaussian
- Integrate the fitted gaussian to count the number of contaminating electrons in the integration region
  - Purity = $N^{region}_{e} / (N^{region}_{\mu} + N^{region}_{\pi})$
  - Efficiency = $N^{region}_{\mu+\pi} / N^{total}_{\mu+\pi}$

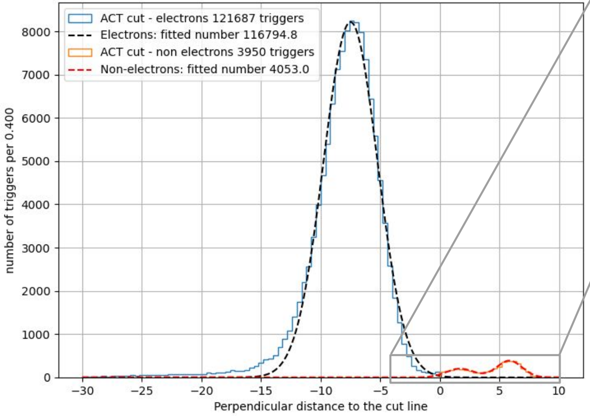
Selection 1 - Lead Glass vs TOF



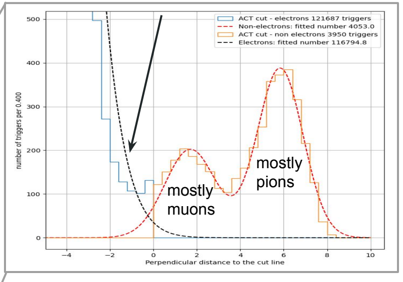
Lead glass vs TOF selection:
Electron efficiency = **99.8%**
MuonAndPion Purity = **96.2%**

Note: didn't manage to fit the muon+pion distribution, using the number of triggers instead

Selection 2 - ACT23 vs ACT1



Poor fit: overestimation of the contamination




```
Electron Purity: 0.999
Electron Efficiency: 1.000
MuonAndPion Purity: 0.986
MuonAndPion Efficiency: 0.973
```

Note: most of the electron contamination is in the muon sample

Muon/pion separation

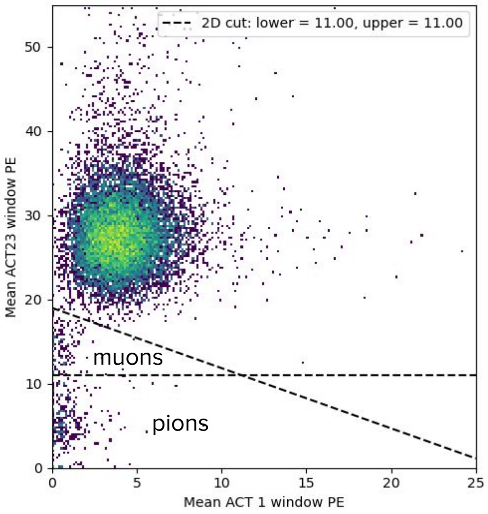
Visually, the populations behave as expected:
Constant energy in the lead glass for the muons,
Later TOF for the pions

Motivation:

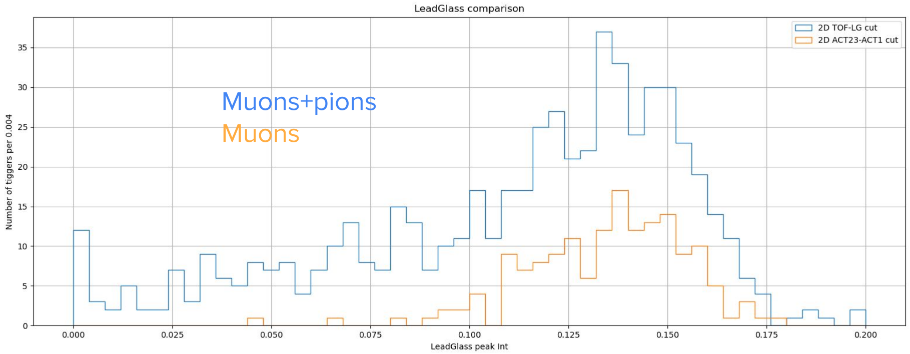
- Identify pions from muons

Method:

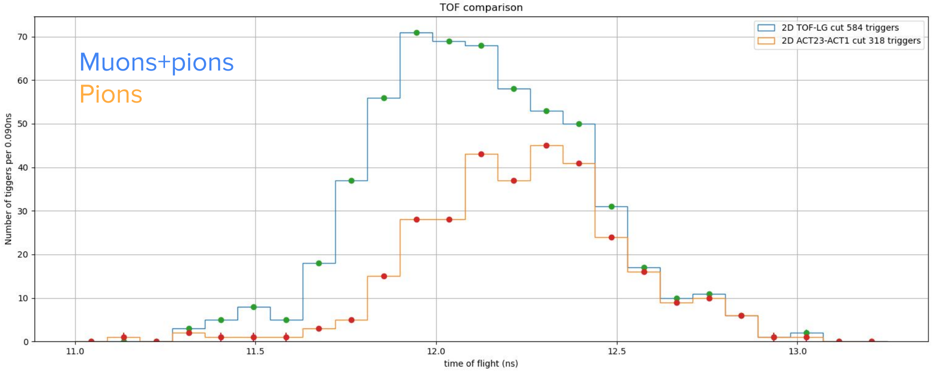
- Apply a cut on ACT23
- Check visually the behaviour of each sample in TOF and Lead-Glass



Lead glass



Time of flight



Particle counting

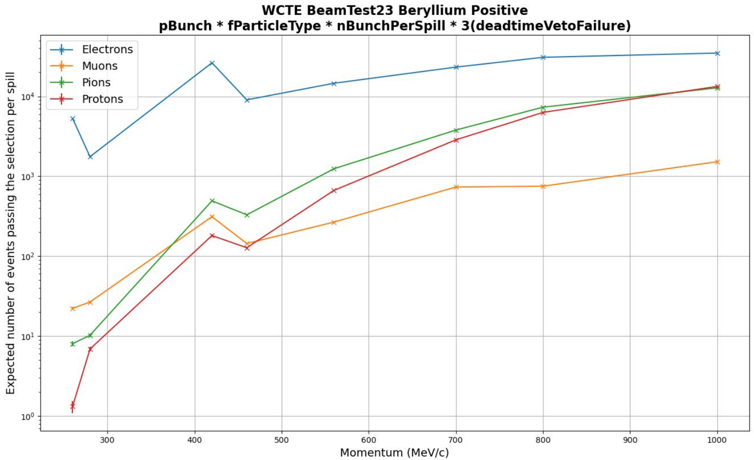
See also this

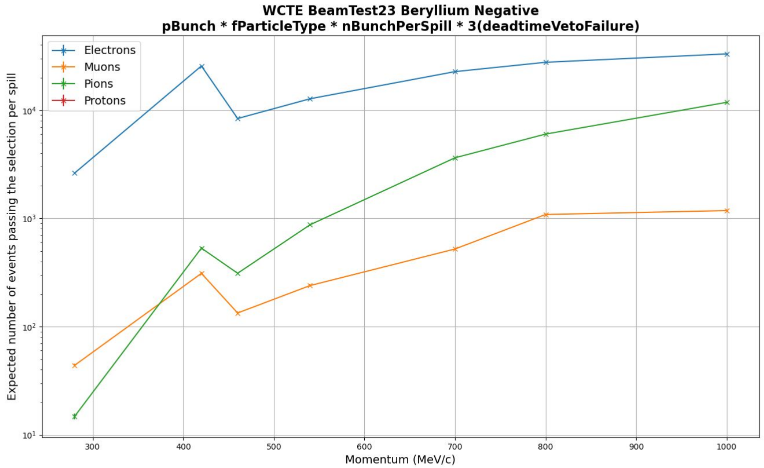
Prediction for number of particles

Discussion:

- According to this prediction we will get between 22.3 and 1 520 mu/spill and between 8.0 and 12 800 pi/spill
- Beam time necessary to **collect 1M** particles (Beryllium target)
  - **Assume** 2spill/minute, 24h days, no dead time, 100% efficiency

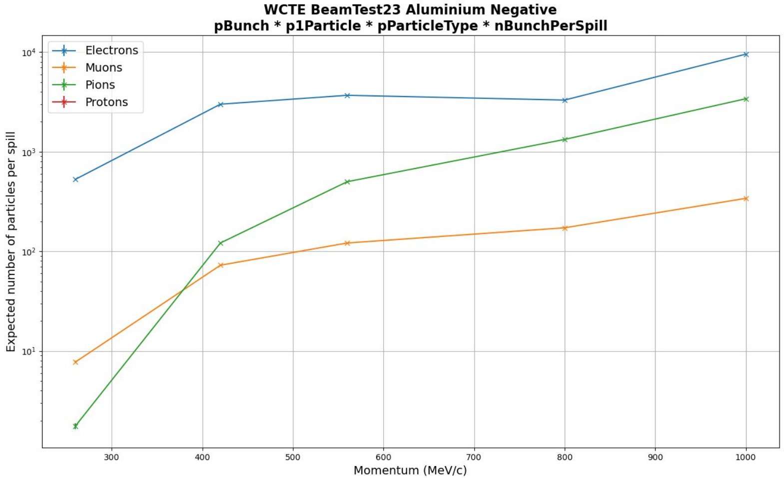
	Muons	Pions	Electrons
260MeV/c	15.6 days	43.4 days	1.5h
420MeV/c	26.7h	16.9h	19mins
560MeV/c	31.3h	6.7h	34mins
700MeV/c	11.4h	2.2h	21mins
1000MeV/c	5.5h	39mins	14mins

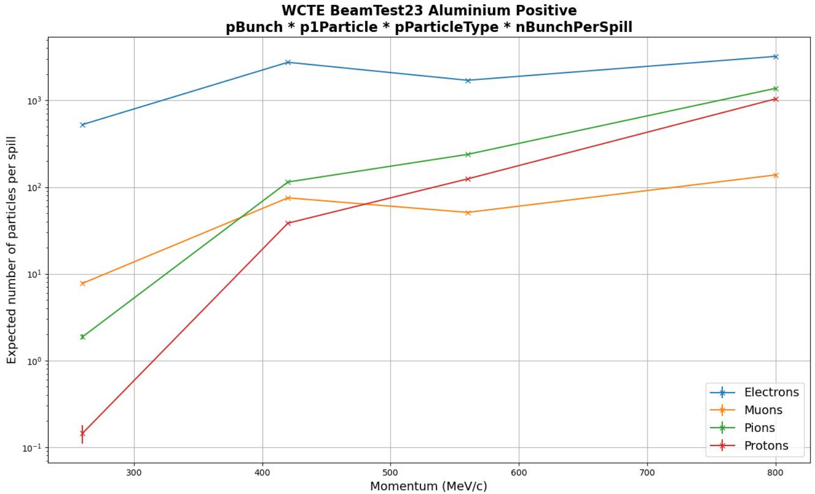


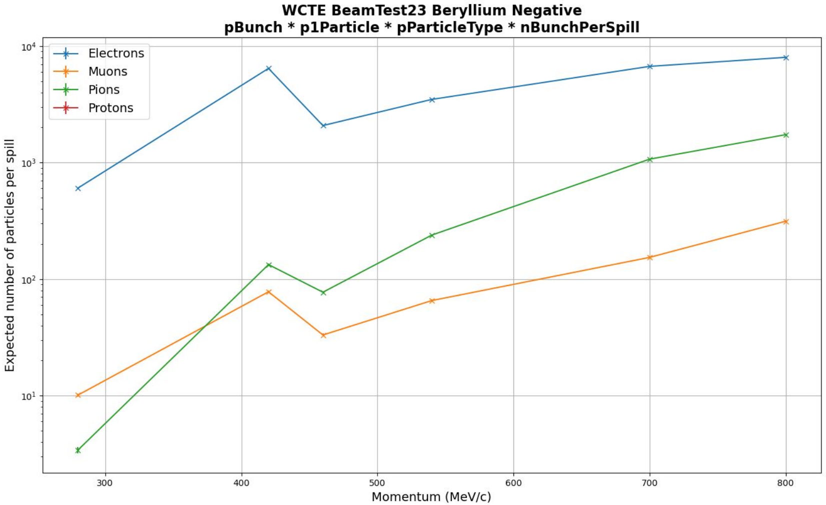


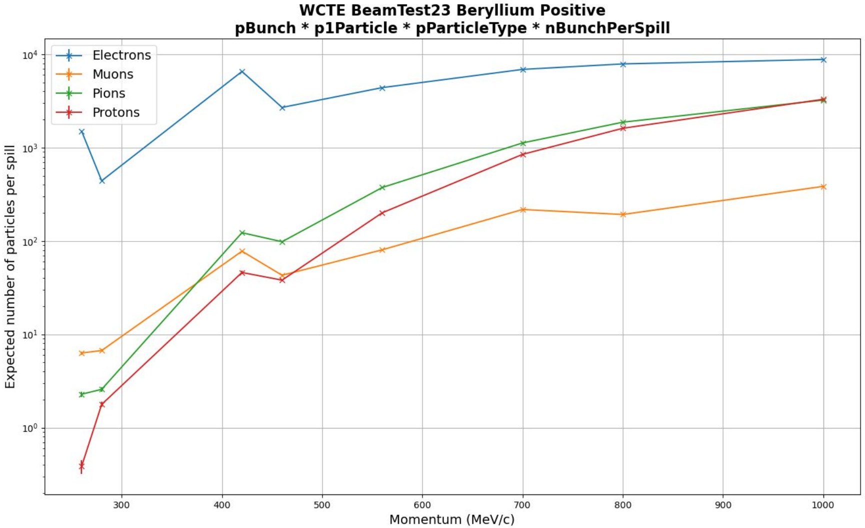
Number of particles per spill here

Take into account the 1 particle requirement









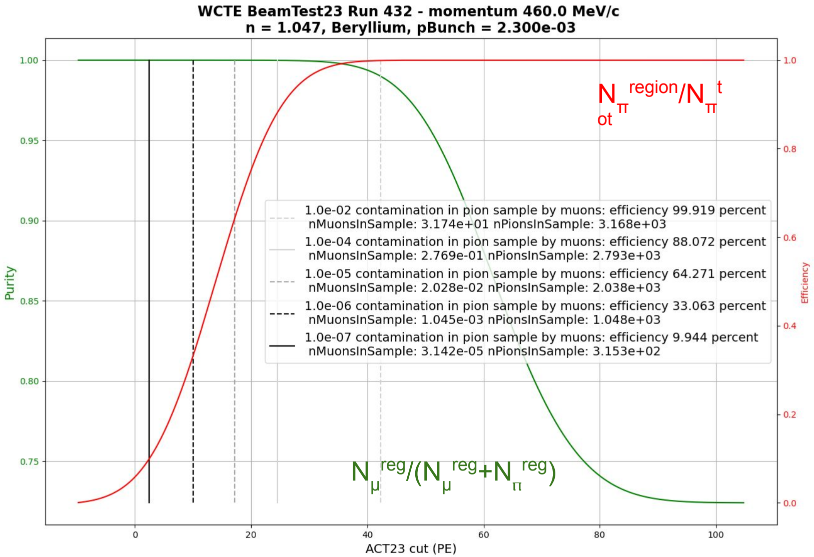
Alie (

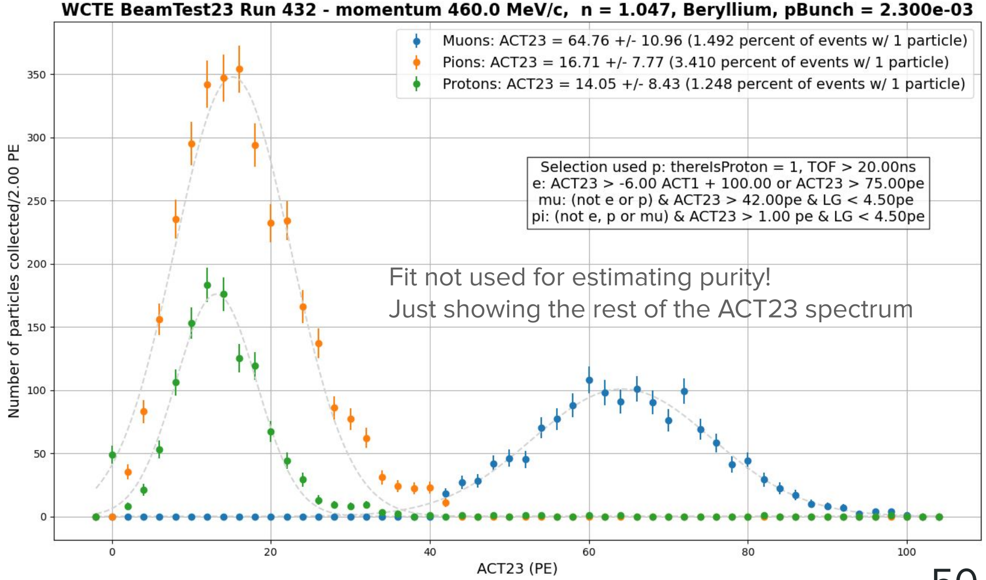
Selection

Muon/pion separation

Example: best pion/muon separation from 2023 beam test

- Plot the ACT23 signal of each population, fit with a gaussian
- Use the gaussian overlap to derive efficiency and purity as a function of cut line position
- Can achieve 10^{-6} pion contamination in muon sample with a 67% efficiency
- Can achieve 10^{-6} pion contamination in muon sample with a 33% efficiency

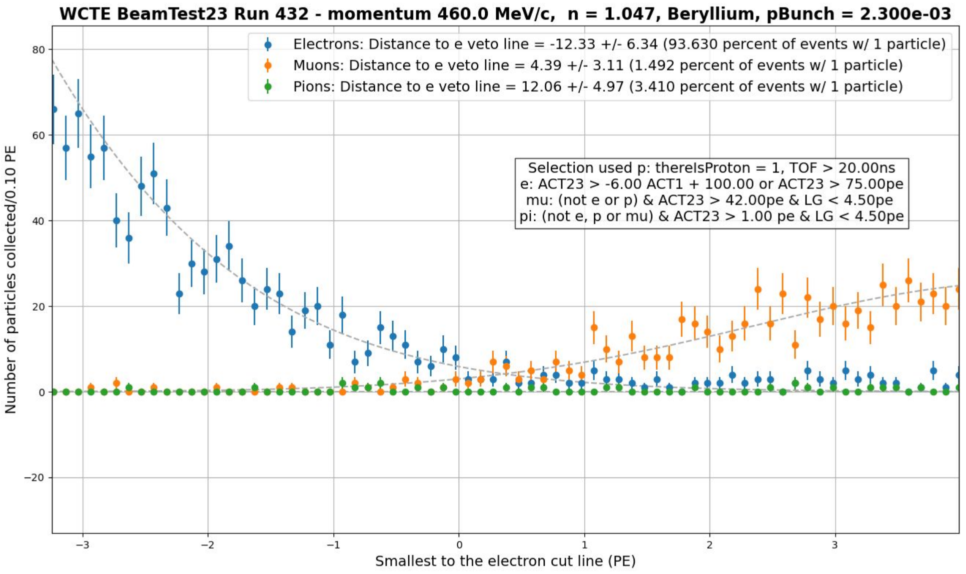


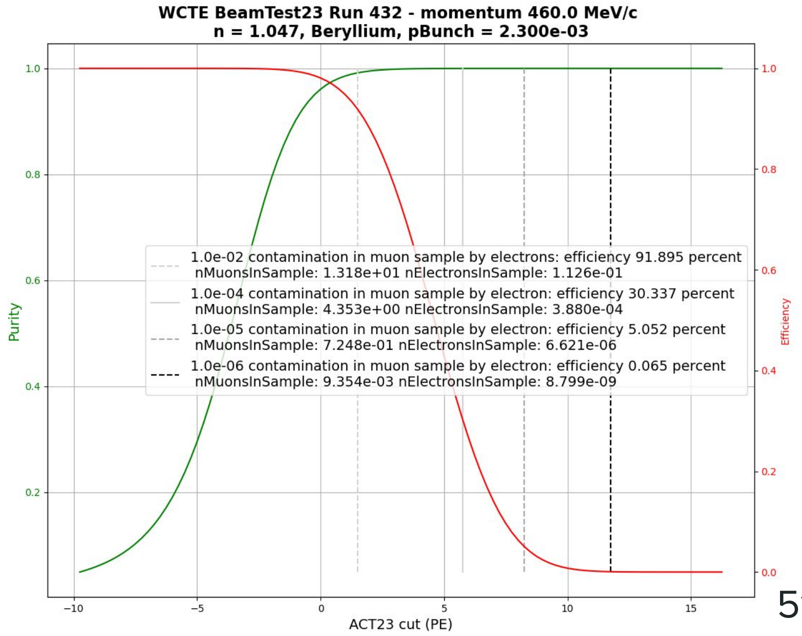


Electron/muon separation

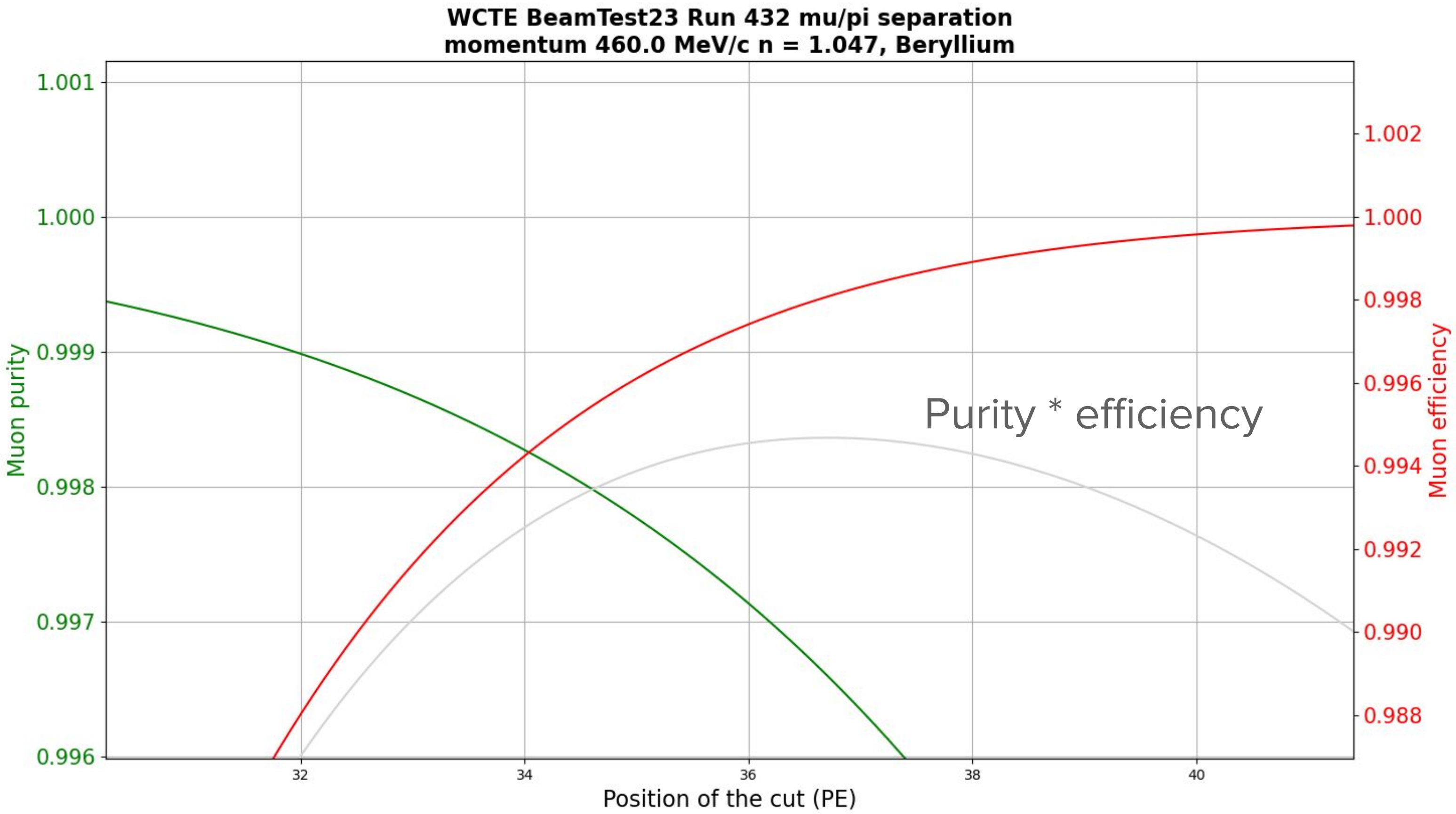
Example: medium electron/muon separation from 2023 beam test

- Plot the distance to the cut line for each population, fit with a gaussian
- Use the gaussian overlap to derive efficiency and purity as a function of cut line position
- Can achieve 10^{-5} electron contamination in muon sample with a 5.0% efficiency.
- Can achieve 10^{-6} electron contamination in muon sample with a 0.065% efficiency.





muon/pion separation



muon/electron separation