The MUSE Experiment

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For the MUSE Collaboration

New Vistas in Low Energy Precision Physics
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Missing Piece of the Puzzle?
(The one slide motivation)

r_p (fm)	ep	μp
atom	0.877±0.007	0.841±0.0004
scattering	0.875±0.006	?

- World's most powerful separated mu/e/pi beam.
- Why μp scattering?
- Are μp and ep scattering are consistent or different? and, if different, if the difference is from novel physics or 2γ mechanisms:
  - If the μp and ep radii really differ by 4%, then the form factor slopes differ by 8% and cross section slopes differ by 16% – this should be relatively easy to measure.
  - 2γ affects e^+ and e^-, or μ^+ and μ^-, with opposite sign – the cross section difference is twice the 2γ correction, the average is the cross section without a 2γ effect.

MUSE Collaboration

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MUSE - PSI R12-01.1 Technique

r_p (fm)	ep	μp
atom	0.877±0.007	0.841±0.0004
scattering	0.875±0.006	?

$d\sigma/d\Omega(Q^2)$ = counts / ($\Delta\,\Omega$ N_{beam} $N_{target/area}$ x corrections x efficiencies)

$$\left[\frac{d\sigma}{d\Omega}\right] = \left[\frac{d\sigma}{d\Omega}\right]_{ns} \times \left[\frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau} + \left(2\tau - \frac{m^2}{M^2}\right) G_M^2(Q^2)\frac{\eta}{1-\eta}\right]$$

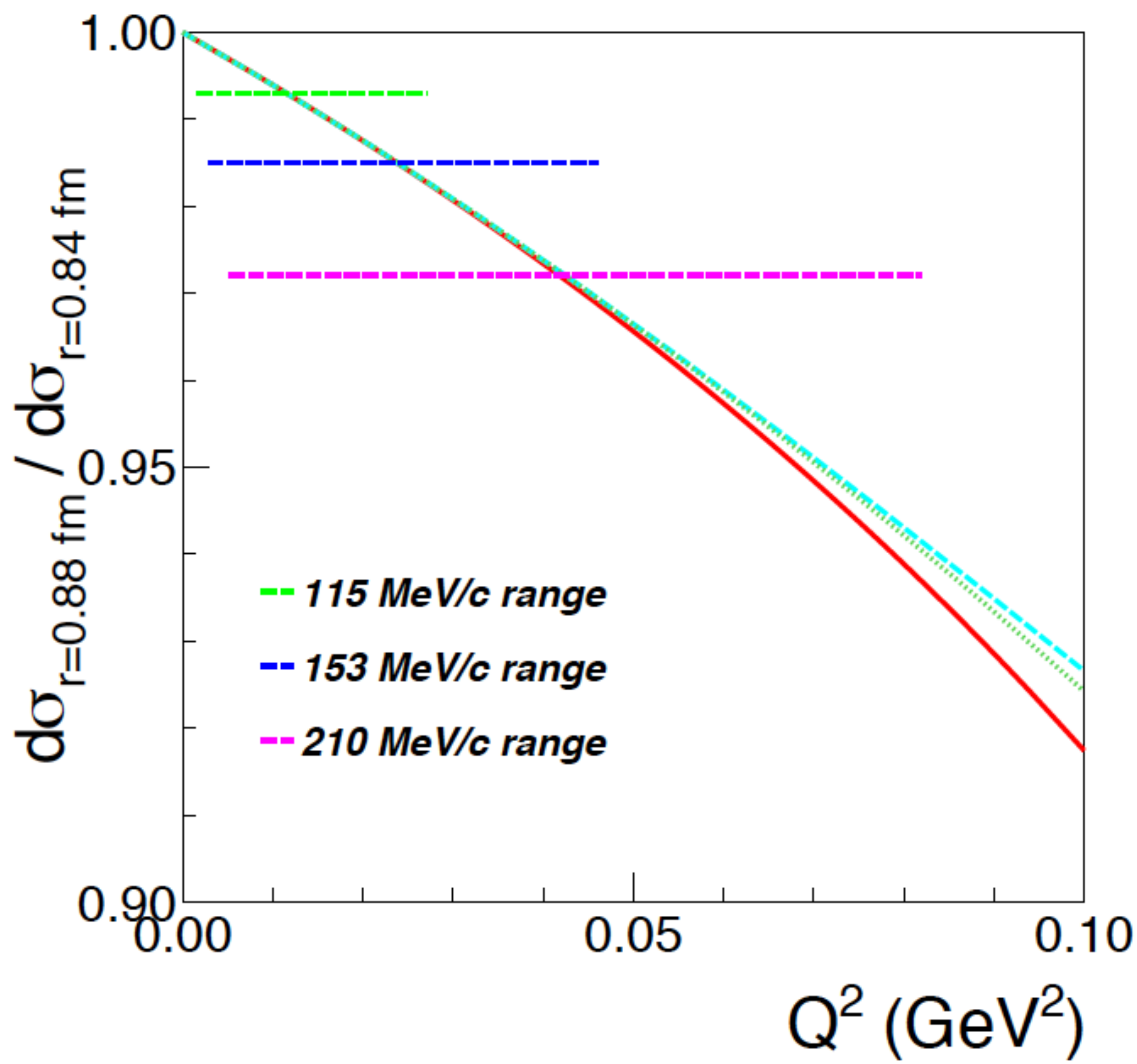
$$\left[\frac{d\sigma}{d\Omega}\right]_{ns} = \frac{\alpha^2}{4E^2}\frac{1-\eta}{\eta^2}\frac{1/d}{\left[1+\frac{2Ed}{M}\sin^2\frac{\theta}{2}+\frac{E}{M}(1-d)\right]} \qquad d = \frac{\left[1-\frac{m^2}{E^2}\right]^{1/2}}{\left[1-\frac{m^2}{E'^2}\right]^{1/2}}$$

$$\eta = Q^2/4EE'$$

following Preedom & Tegen, PRC36, 2466 (1987)

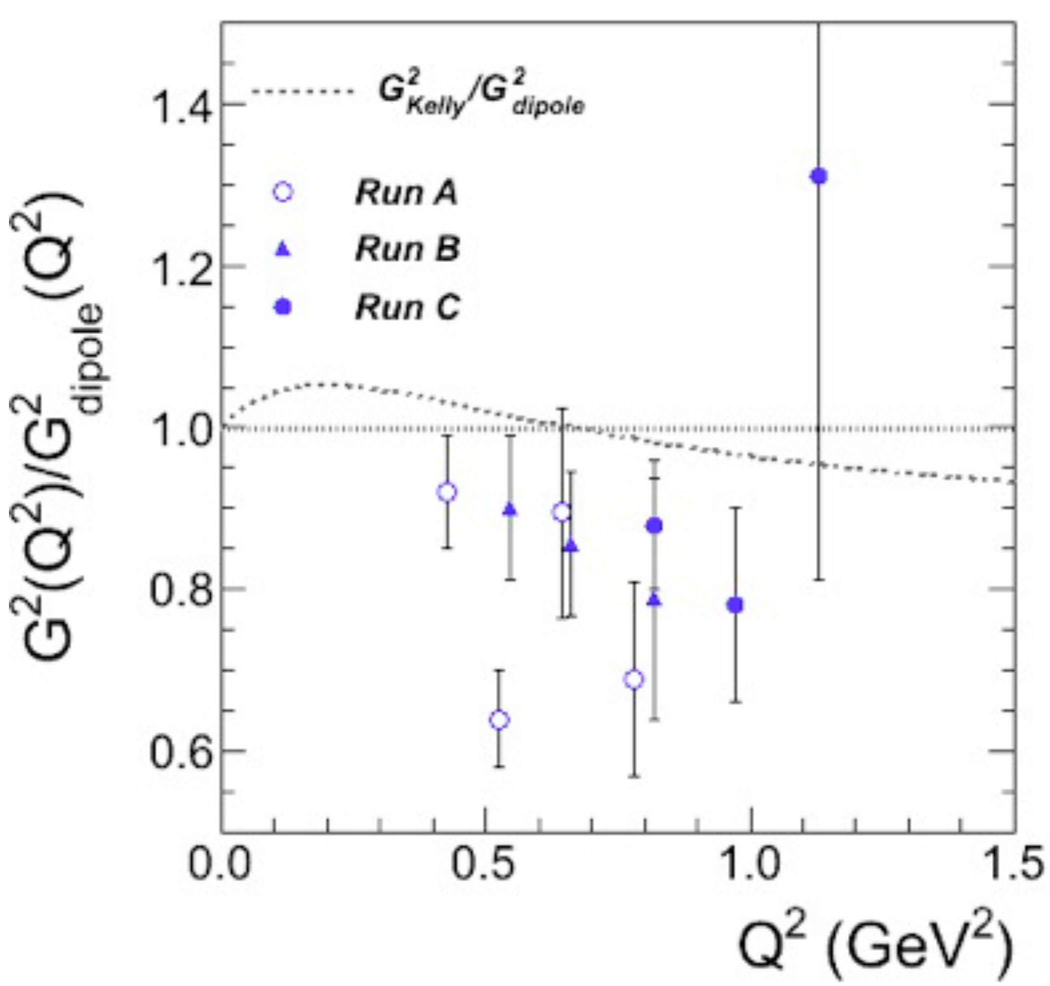
The effect of the radius on the cross section

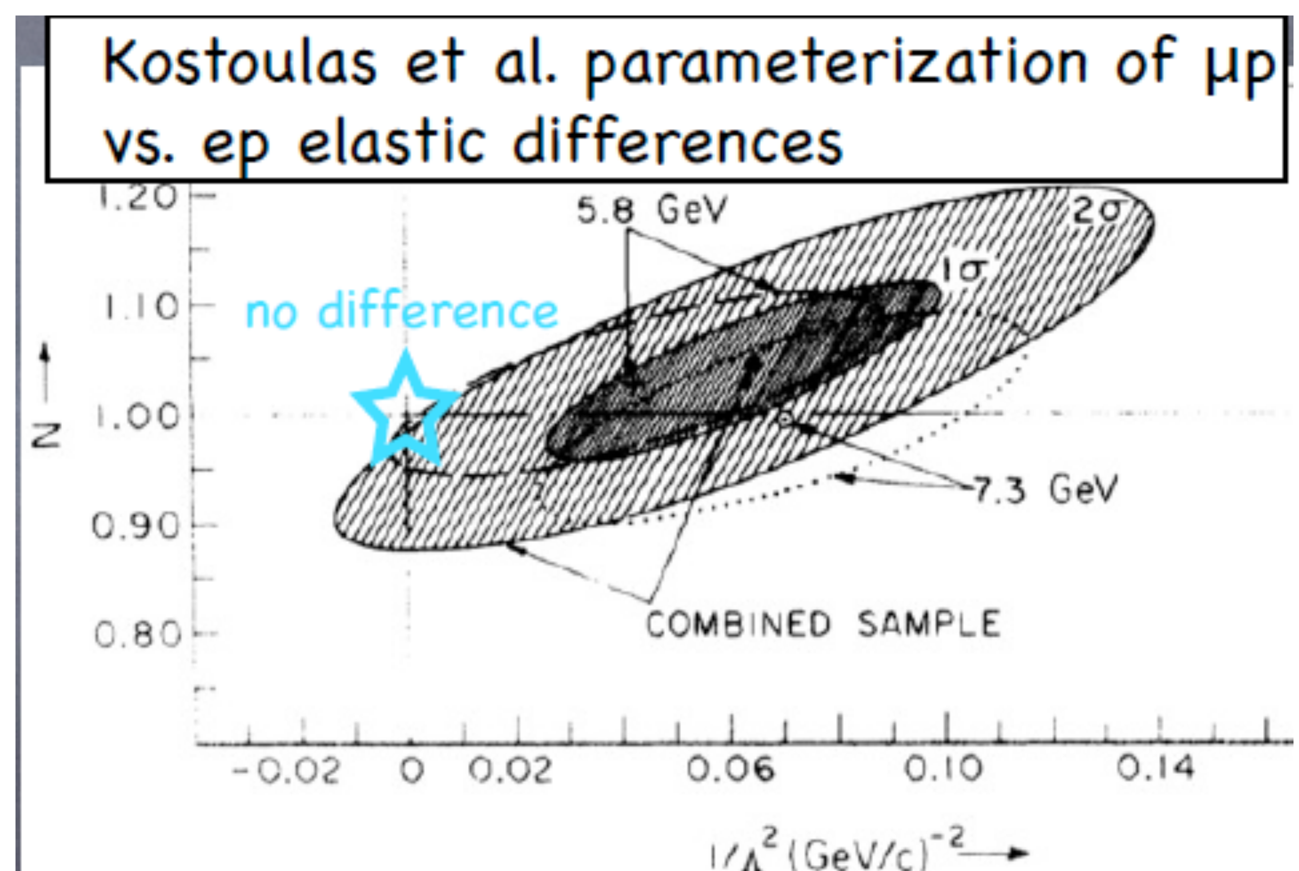
Plot shows ratio of cross section assuming a charge radius of 0.88fm to that assuming a radius of 0.84fm.
MUSE kinematics are indicated.



e-μ Universality

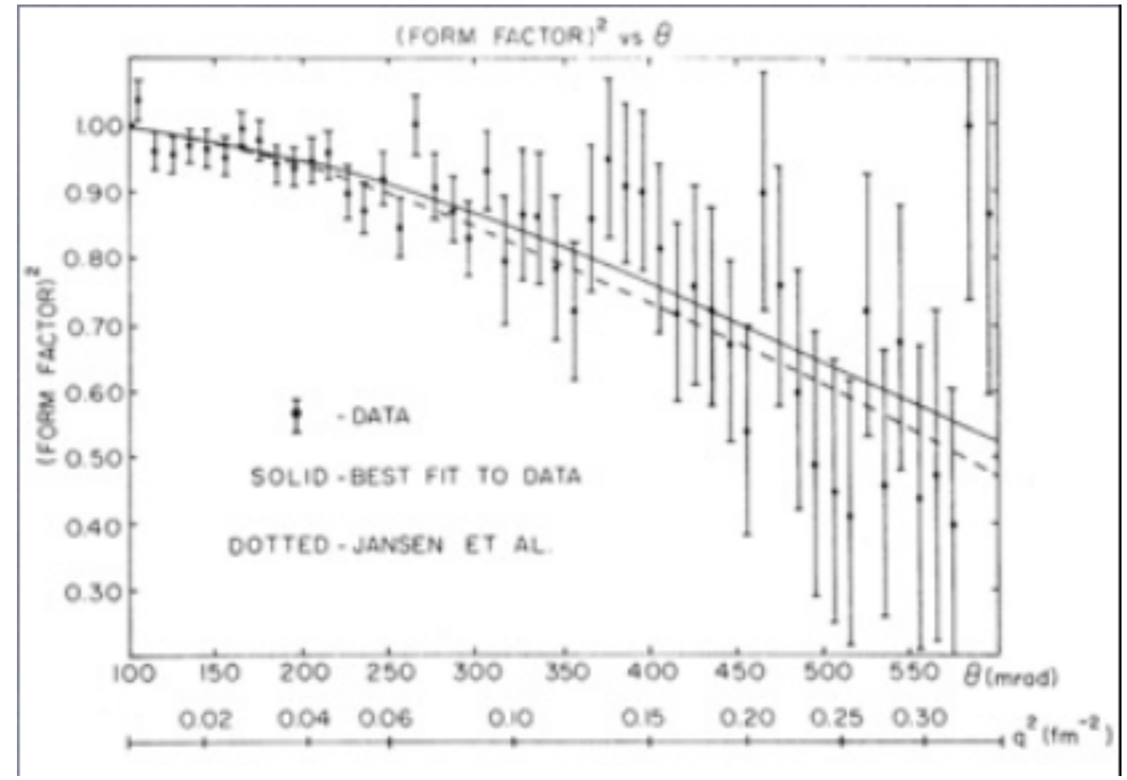
In the 1970s / 1980s, there were several experiments that tested whether the ep and μp interactions are equal. They found no convincing differences, once the μp data are renormalized up about 10%. In light of the proton ``radius'' puzzle, the experiments are not as good as one would like.





e-μ Universality

The 12C radius was determined with ep scattering and μC atoms.



The results agree:
Cardman et al. eC: 2.472 ± 0.015 fm
Offermann et al. eC: 2.478 ± 0.009 fm
Schaller et al. μC X rays: 2.4715 ± 0.016 fm
Ruckstuhl et al. μC X rays: 2.483 ± 0.002 fm
Sanford et al. μC elastic: 2.32 ± 0.13 fm

Perhaps carbon is right, e's and μ's are the same.
Perhaps hydrogen is right, e's and μ's are different.
Perhaps both are right - opposite effects for proton and neutron cancel with carbon.
But perhaps the carbon radius is insensitive to the nucleon radius, and μd or μHe would be a better choice.

MUSE IS NOT YOUR GARDEN VARIETY SCATTERING EXPERIMENT

Low beam flux

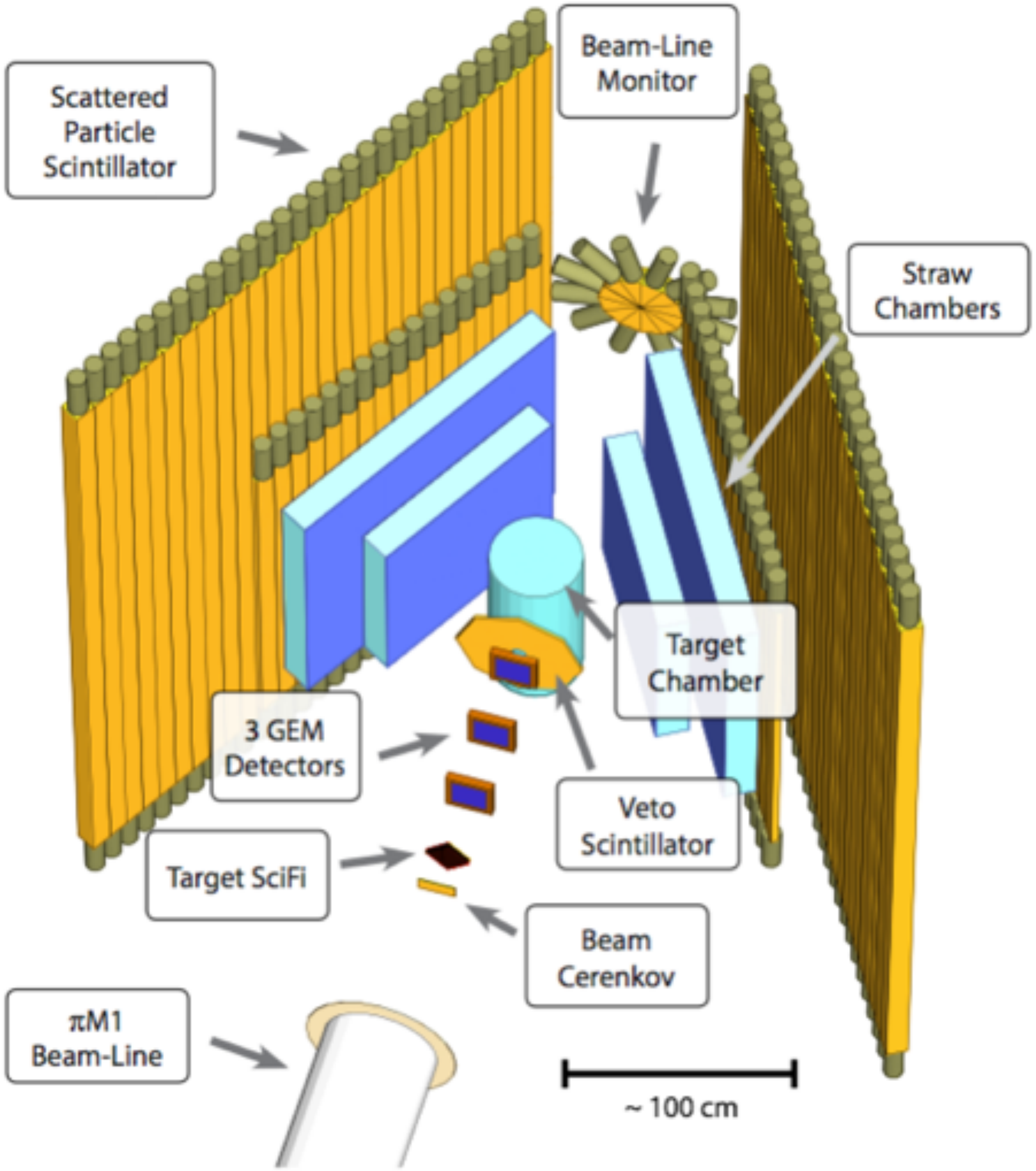
- Large angle, non-magnetic detectors.

Secondary beam (large emittance)

- Tracking of beam particles to target.

Mixed beam

- Identification of beam particle in trigger.



Experiment Overview

PSI πM1 channel

≈115, 153, 210 MeV/c mixed beams of $e^{\pm}$, $\mu^{\pm}$ and $\pi^{\pm}$

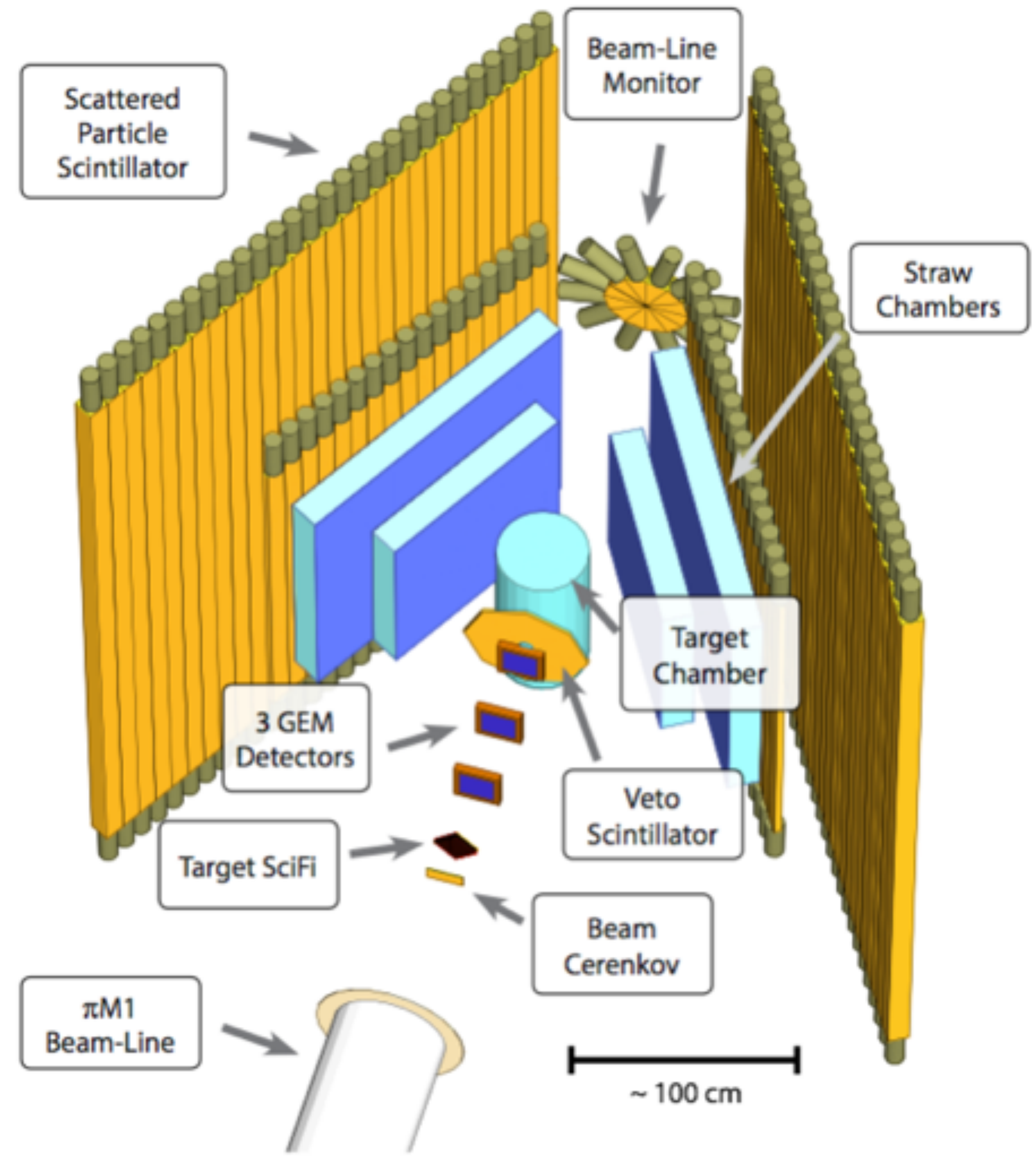
$\theta \approx 20^{o} - 100^{o}$

$Q^2 \approx 0.002 - 0.07\ GeV^2$

About 5 MHz total beam flux, ≈2-15% μ's, 10-98% e's, 0-80% π's

Beam monitored with SciFi, beam Cerenkov, GEMs

Scattered particles detected with straw chambers and scintillators



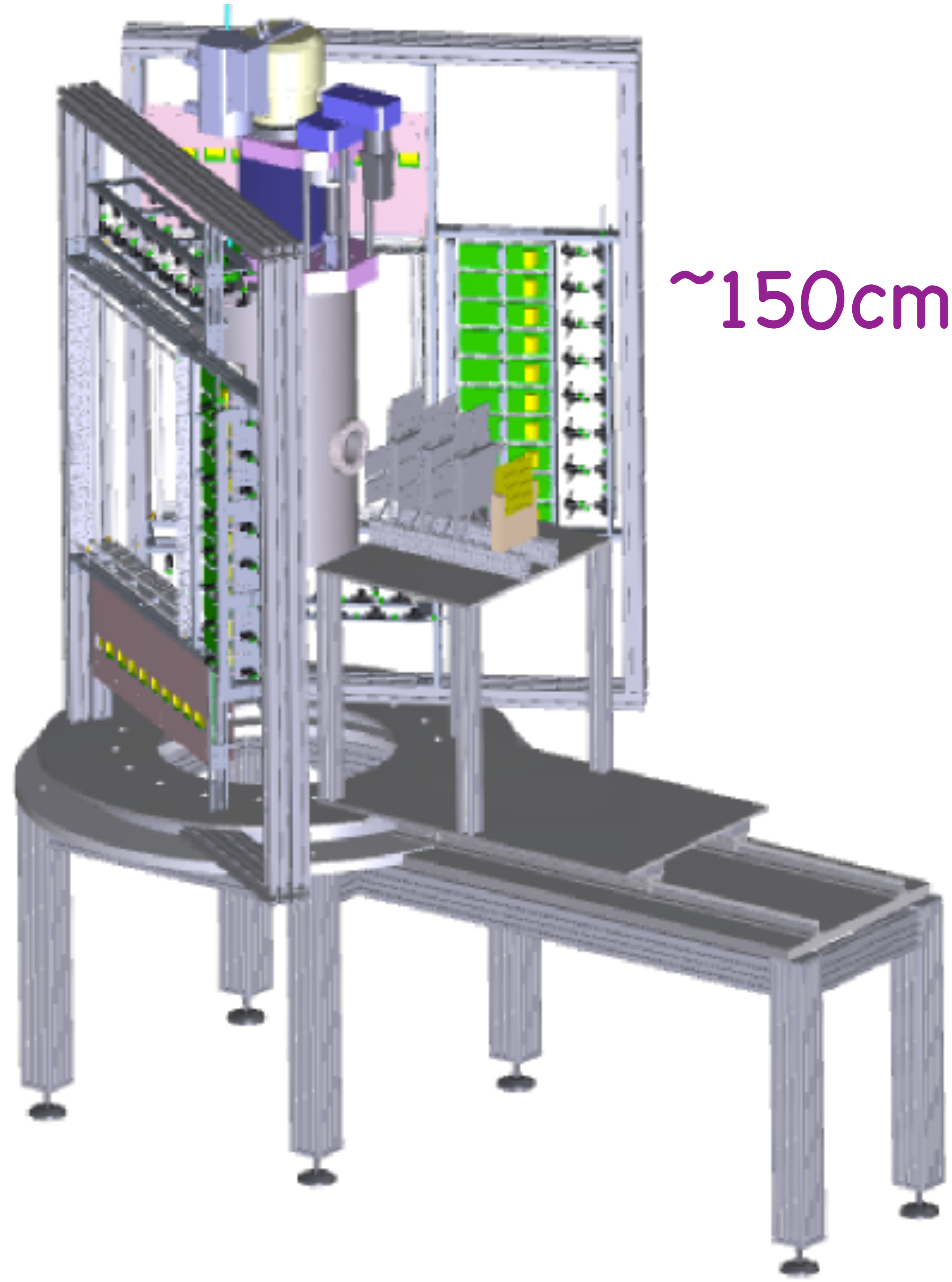
Not run like a normal cross section experiment - 7-8 orders of magnitude lower luminosity.

But there are some benefits: count every beam particle, no beam heating of target, low rates in detectors, ...

Experiment Overview (Trigger scintillators not shown)

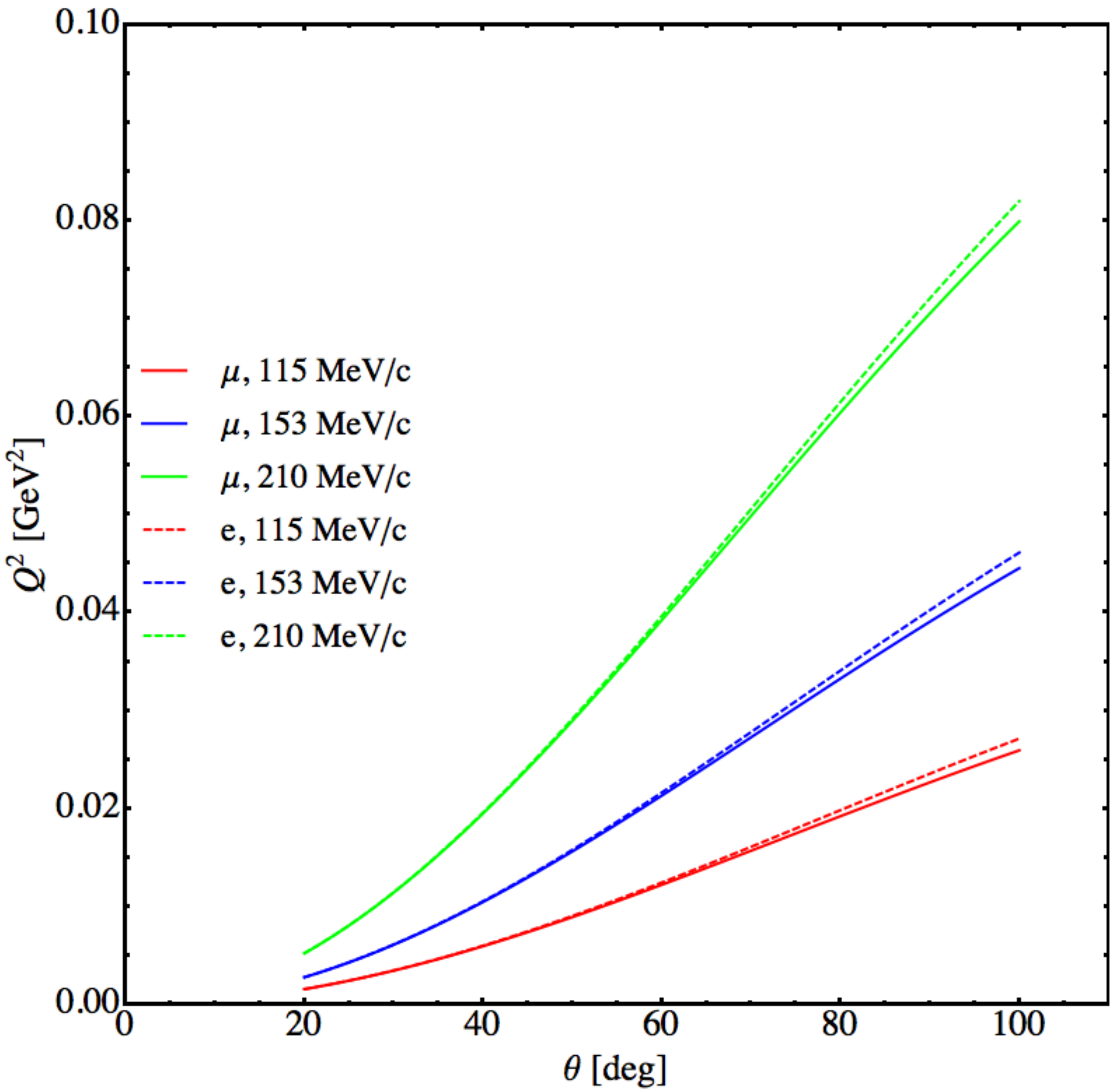
Beam and scattered particles each have timing detectors and tracking detectors.

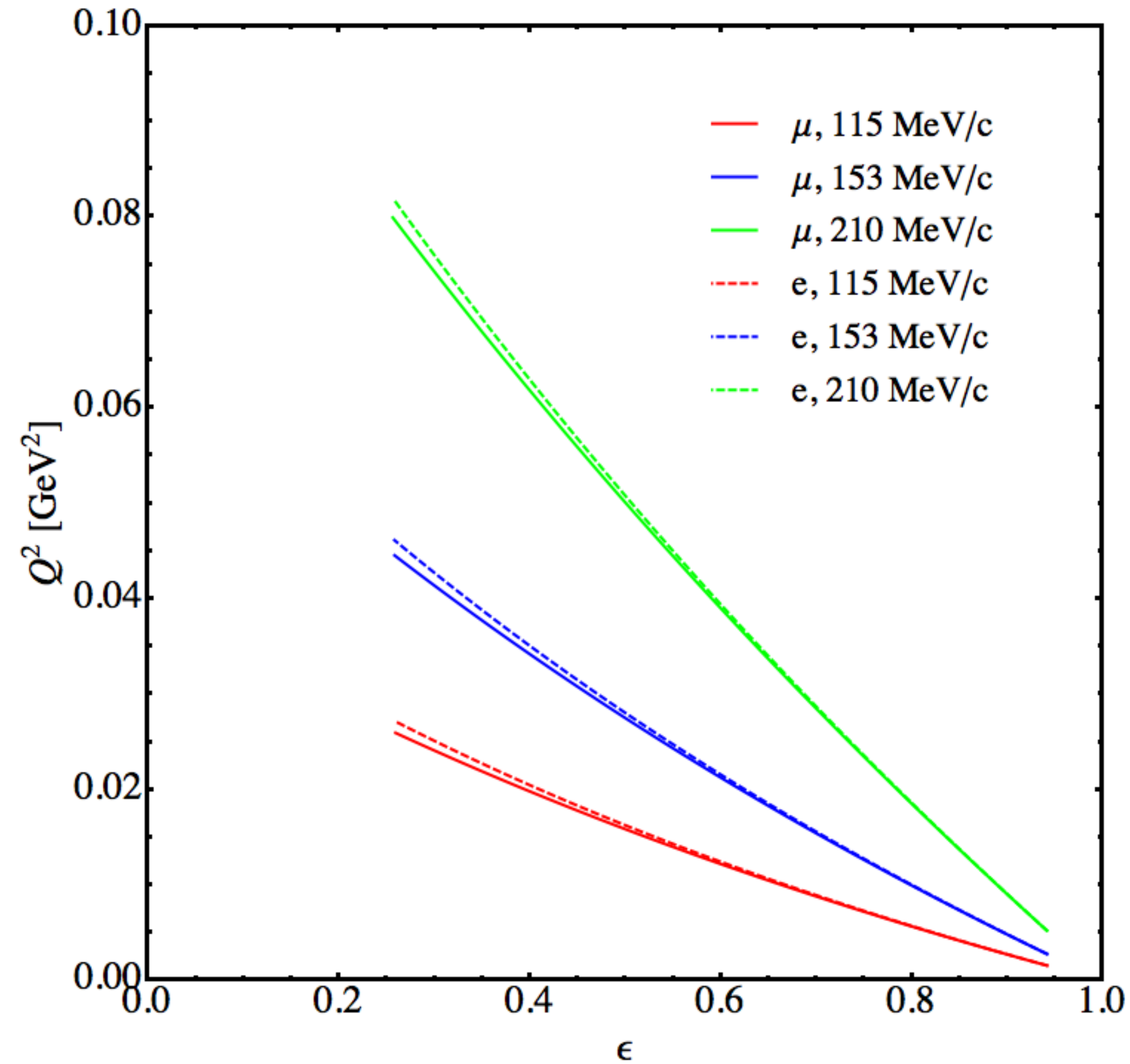
Complex alignment procedure with rotating and moving table.



~150cm

Experiment Overview





$\theta \approx 20^o - 100^o$

$Q^2 \approx 0.0015 - 0.08$ GeV^2

$\varepsilon \approx 0.256 - 0.94$

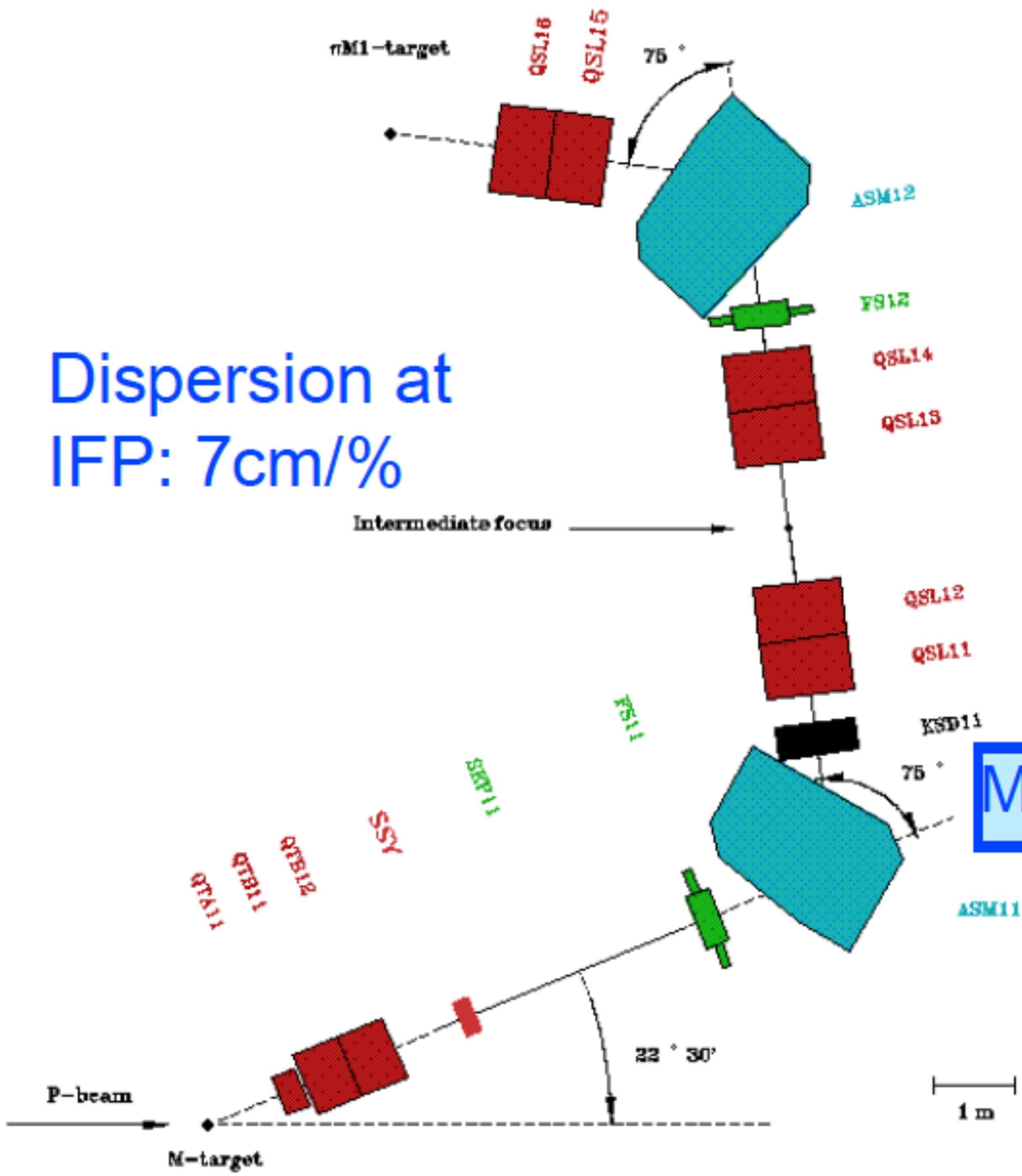
Allows Rosenbluth separation for some values of Q^2.

Important for controlling G_M

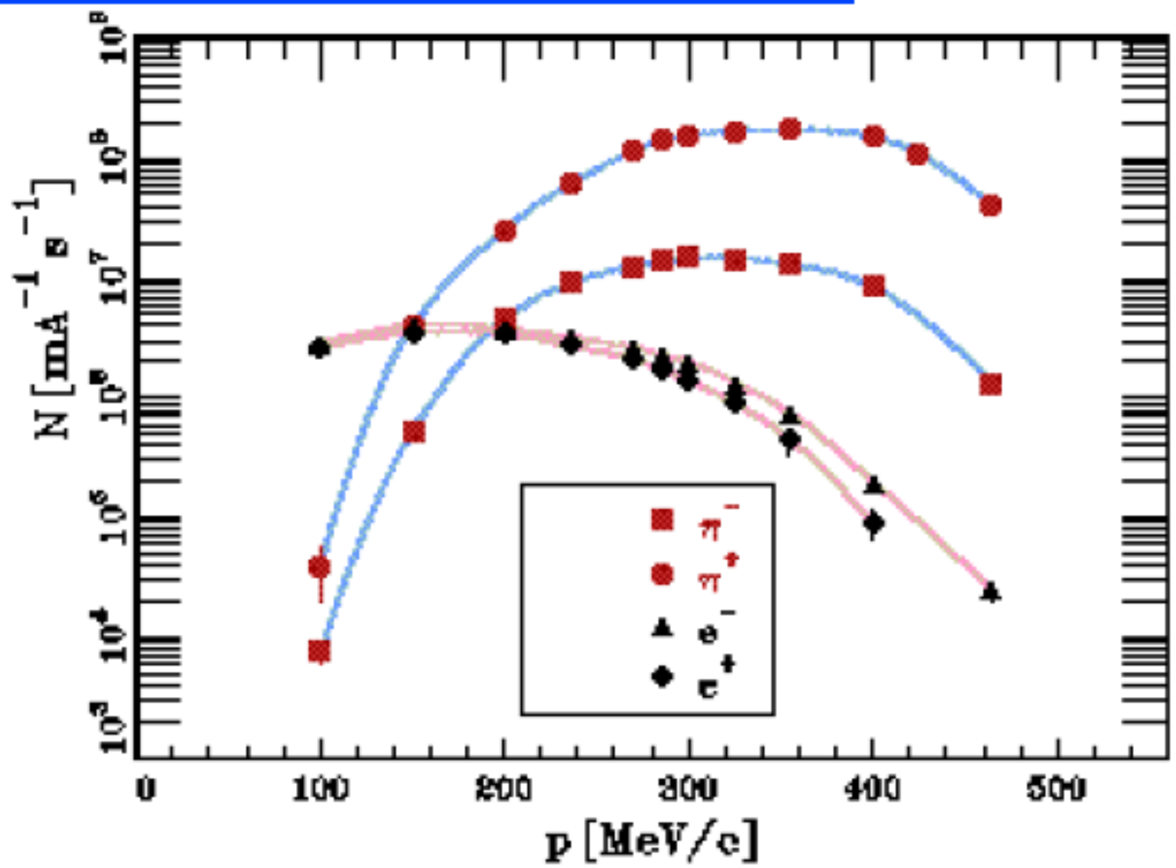
Essentially same coverage for all beam particles.

PSI πM1 Channel Characteristics

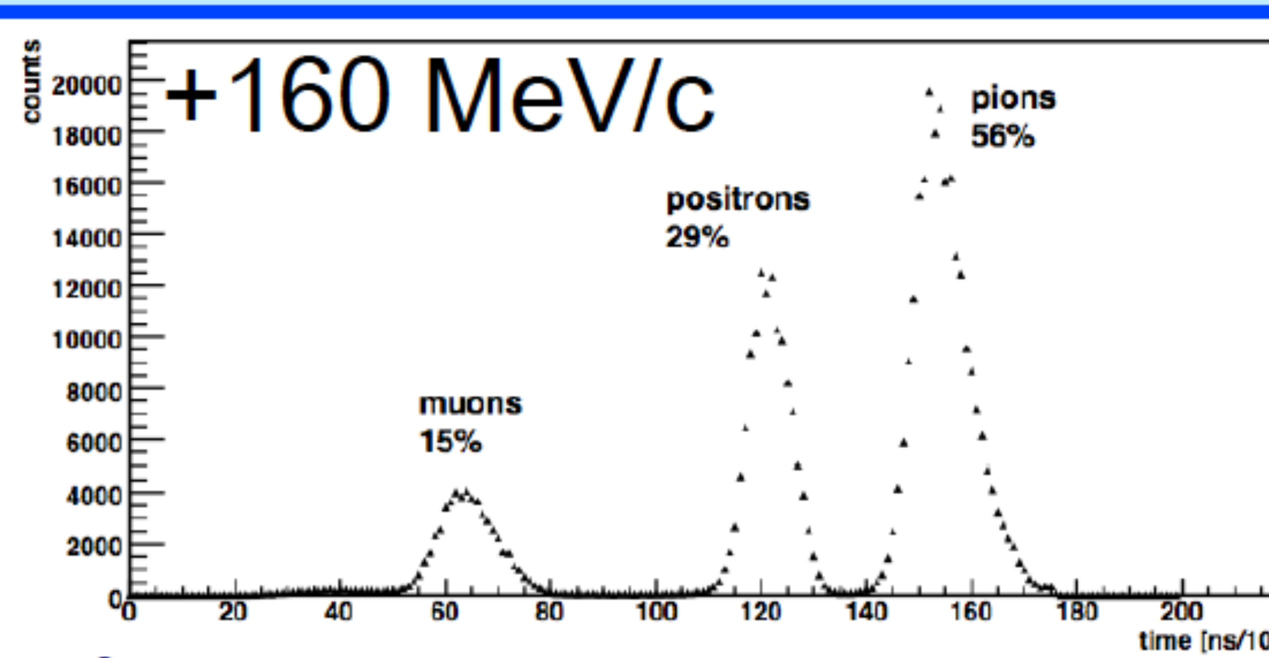
≈100 - 500 MeV/c mixed beam of μ's + e's + π's



Dispersion at IFP: 7cm/%



Momentum acceptance: 3% resolution: 0.1%



Beam spot (nominal): 1.5 cm X x 1 cm Y, 35 mr X' x 75 mr Y'

Spots from 0.7x0.9 cm^2 up to 16x10 cm^2, $\Delta p/p$ from 0.1-3.0%, used previously.

MUSE Design Choices

- Minimal R&D.
- Use existing designs as much as possible.
- Reuse equipment whenever possible.
- Maximal cost reduction.
- Modular construction (can run dress rehearsal with fewer components).

Performance Requirements

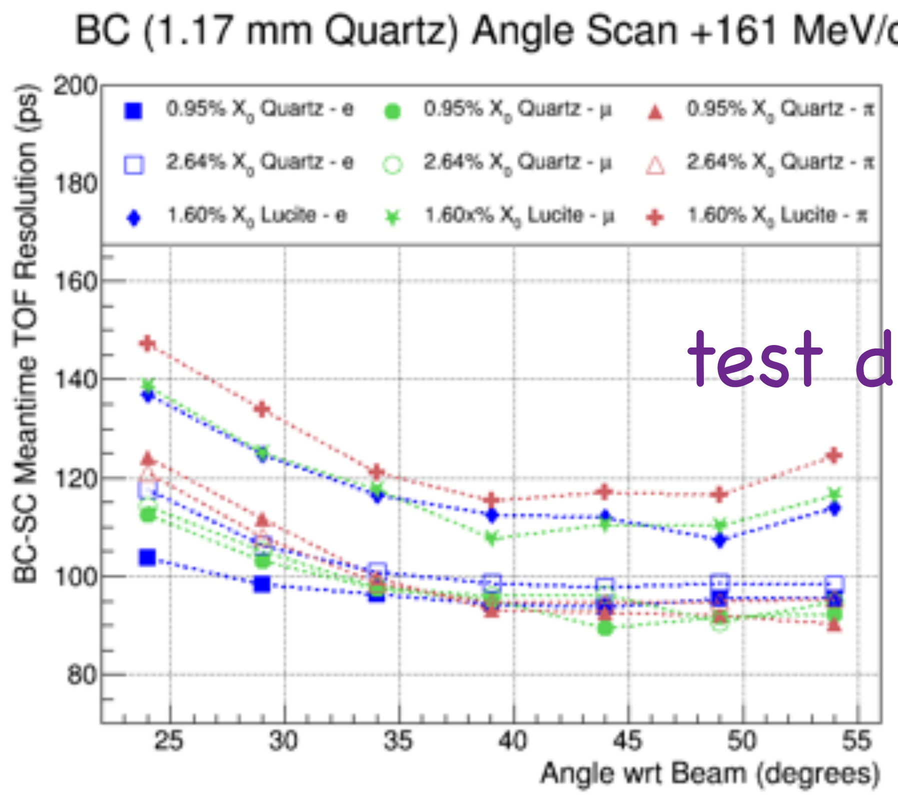
- Angle reconstruction to few mr (limited by multiple scattering).
- Reduce multiple scattering as much as possible.
- Mostly timing used for PID - O(50ps) time resolution.
- 99% or better online π rejection.

MUSE Test Runs

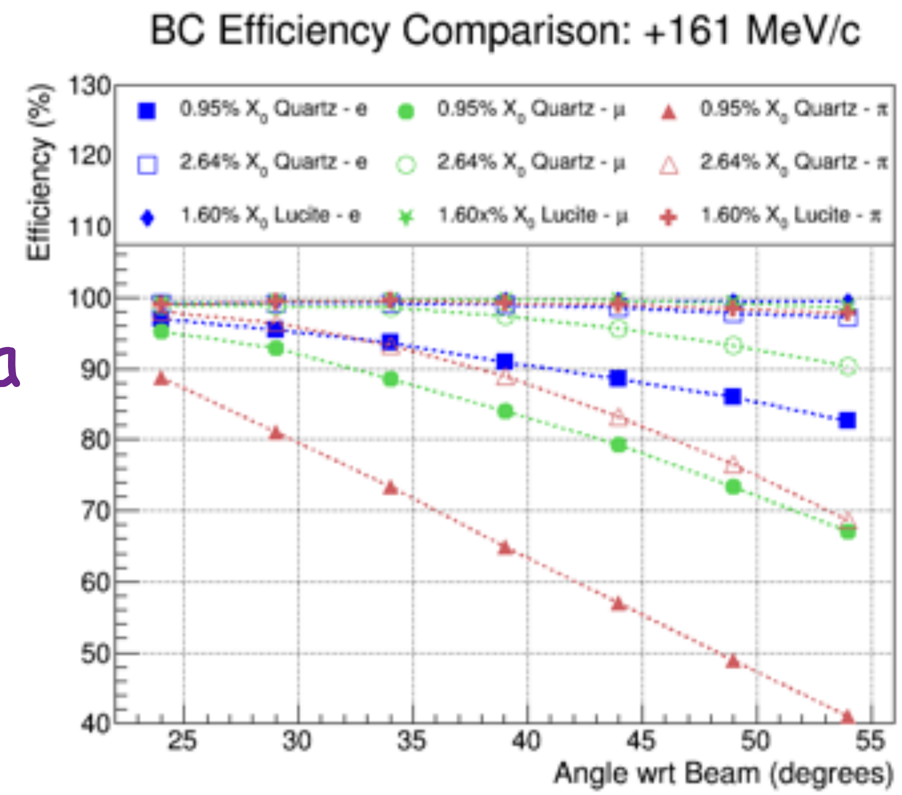
- 9 MUSE Test Runs
  - Oct 2012
  - May-June 2013
  - Oct 2013 (Cosmics)
  - Dec 2013
  - June 2014
  - Dec 2014
  - Feb 2015 (Cosmics)
  - June-July 2015
  - Dec 2015
  - Representation from 13 institutions.
- 9th run scheduled for May-June 2016

Beam Cerenkov (RU)

Used with RF signal for beam PID and triggering, and with scintillators (+tracks) for muon decay rejection



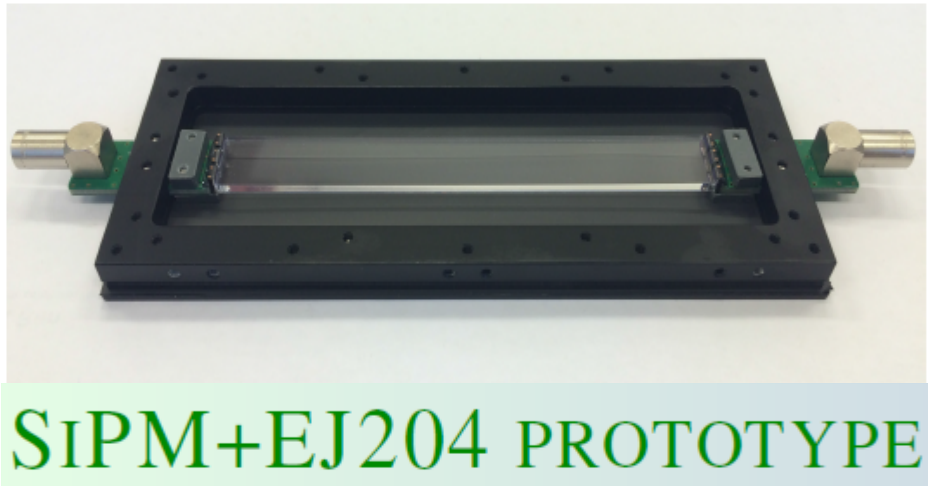
test data



Dec 14 + June 15 test configuration - mount will be different for experiment

Copying Albrow et al Fermilab design with quartz radiator mounted on Photek PMT240 MCP, Ortec 9327 readout.
Studying various radiators.
System (BC-scintillator) resolutions of 80 - 120 ps (σ) obtained.

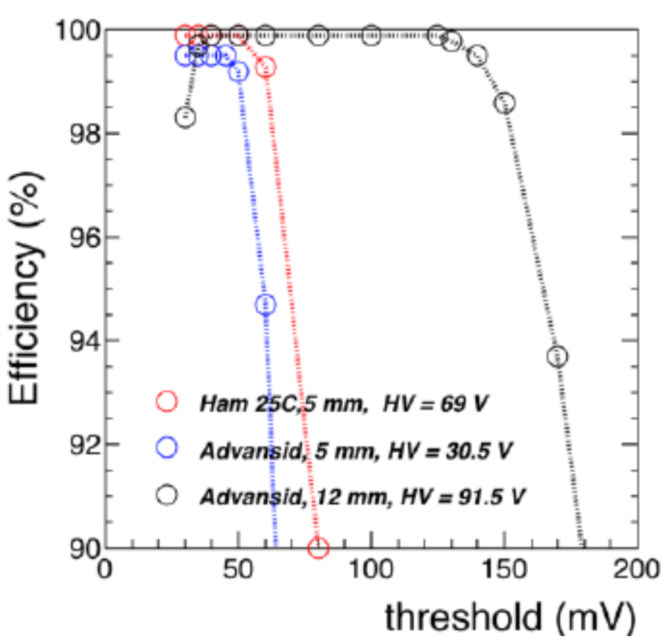
SiPM (TAU/Rutgers)

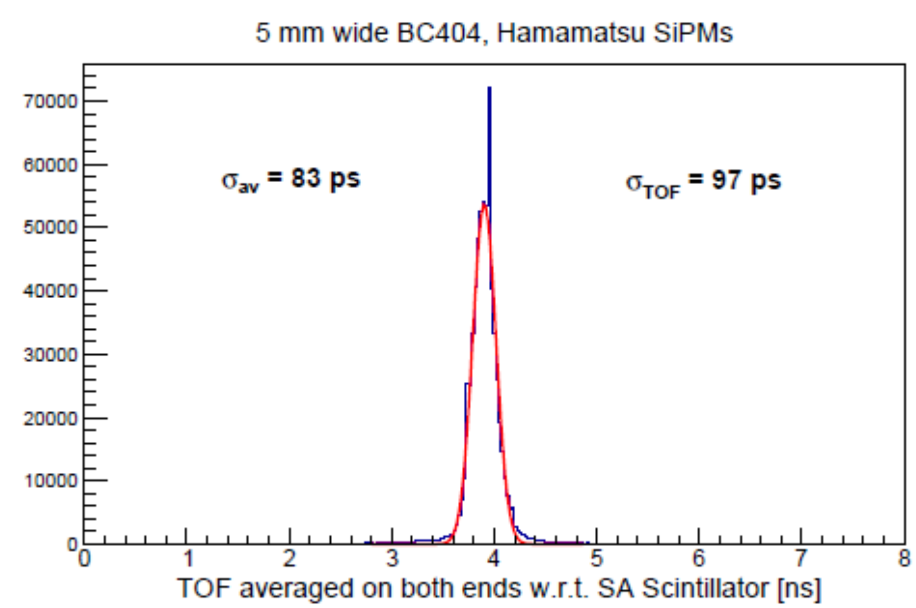


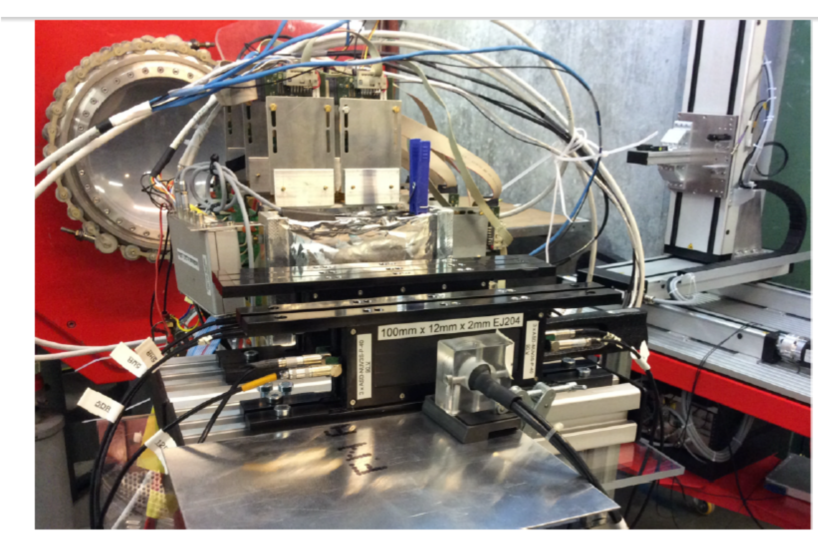
Used with RF signal for beam PID and triggering and with scintillators for muon decay rejection.

Used with GEMs for multiple track events, to determine triggering particle.

Tested at PSI (Dec 2015)

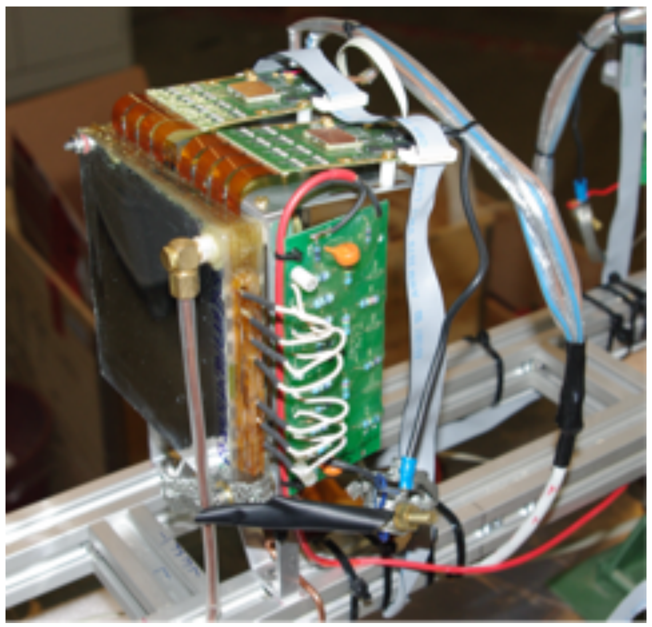




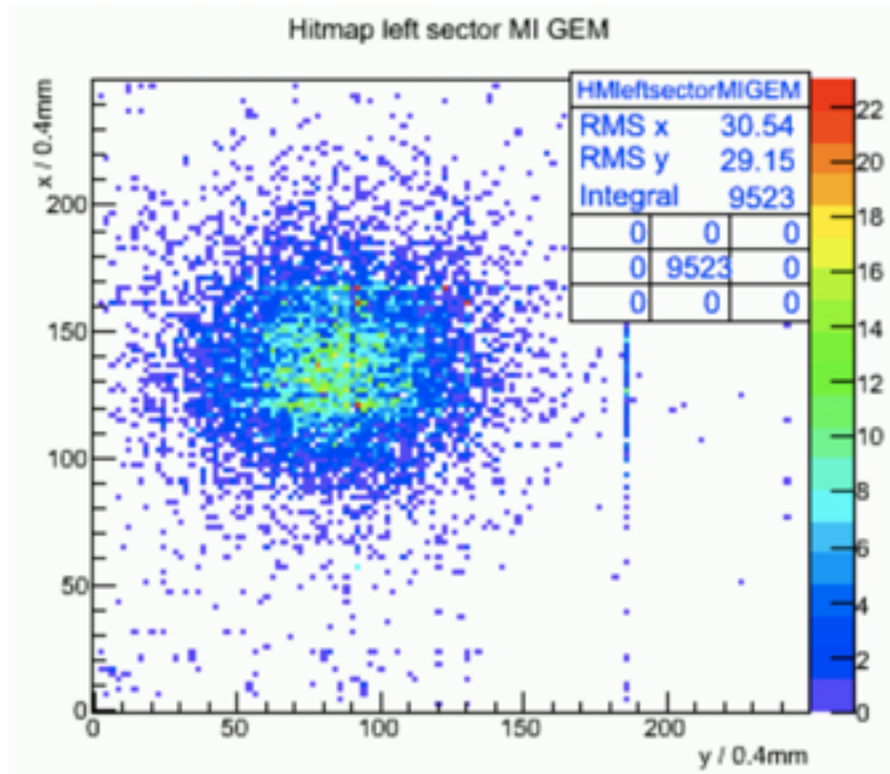


GEMs (HU)

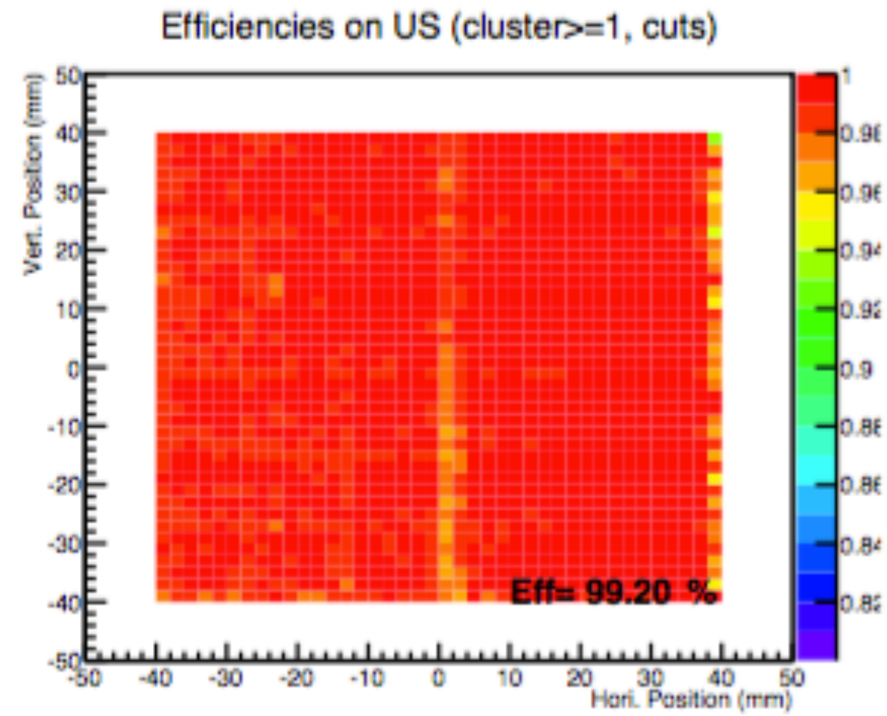
Used to track beam particles into the target



Existing GEM in MUSE test



Beam distribution measured by GEM



Measured efficiency map of a GEM

Using pre-existing OLYMPUS GEMs.
Upgrading DAQ rate capability.
(About 1 ms readout at OLYMPUS.)

VETO (SC)

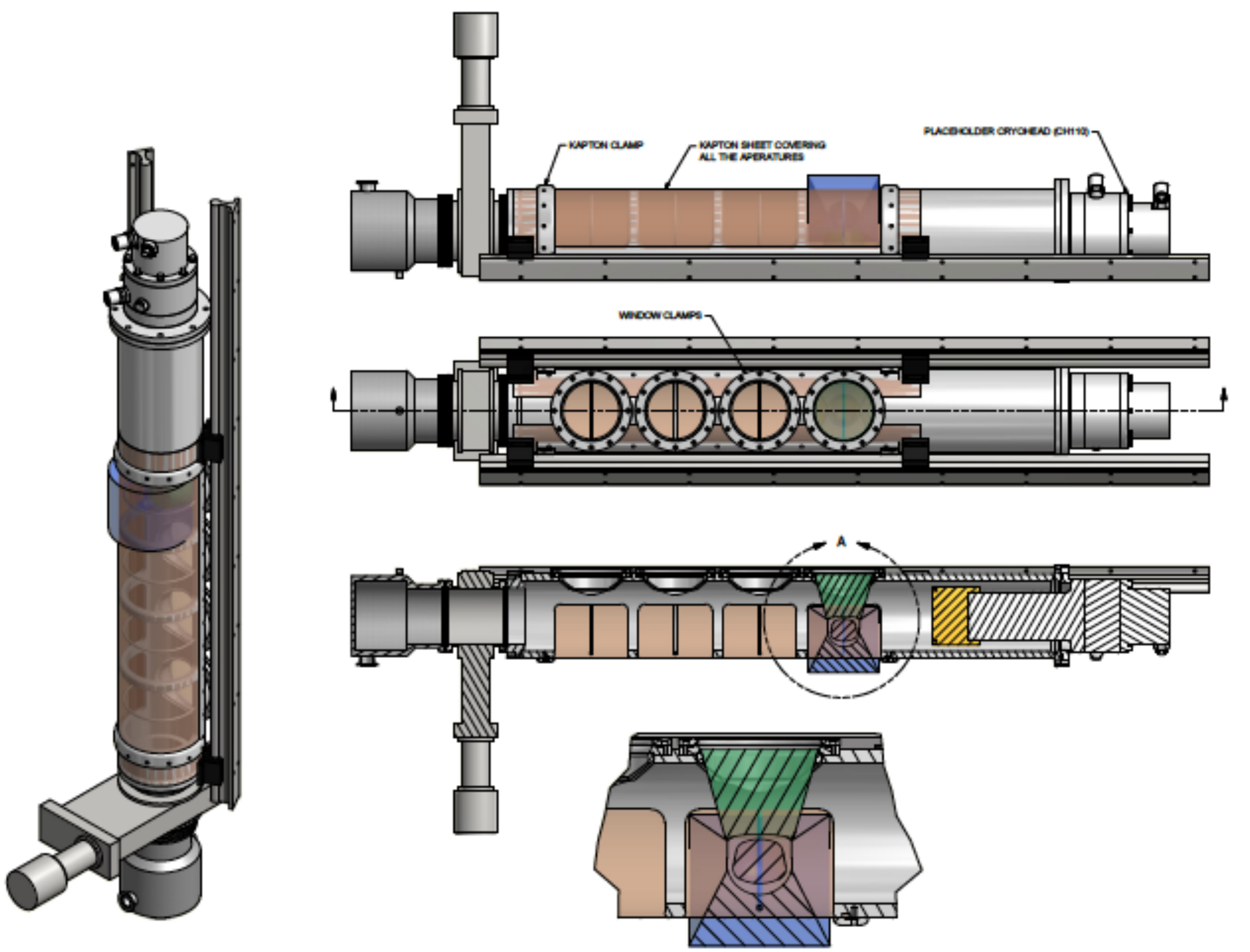
Used to avoid triggering on particles not headed into the target

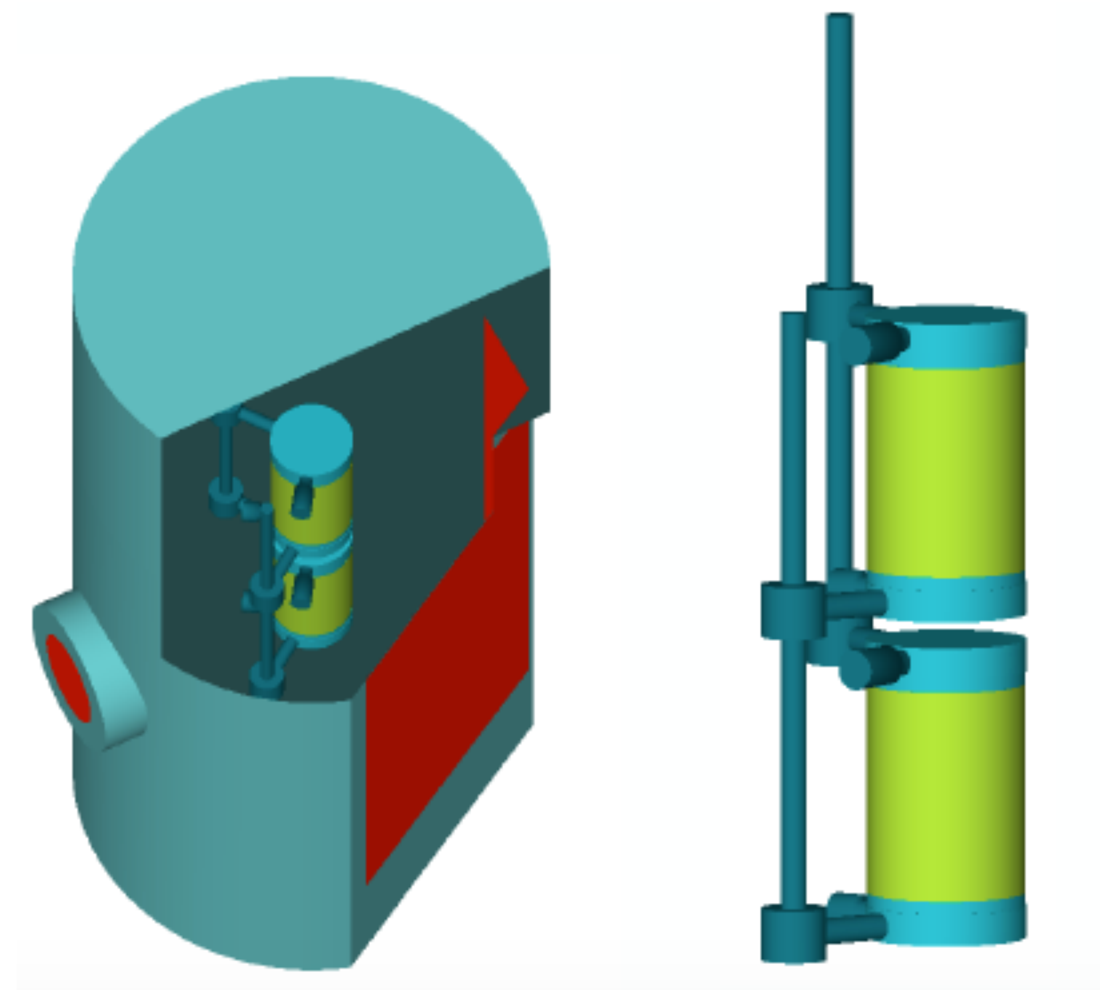
No veto elements produced yet.
Different geometry of scintillator paddle from standard SC paddles.

Note that use of thick scintillators allows high threshold, so triggering well above PMT noise.

Target (GW)

Low power cryotarget. Currently in advanced conceptual design.





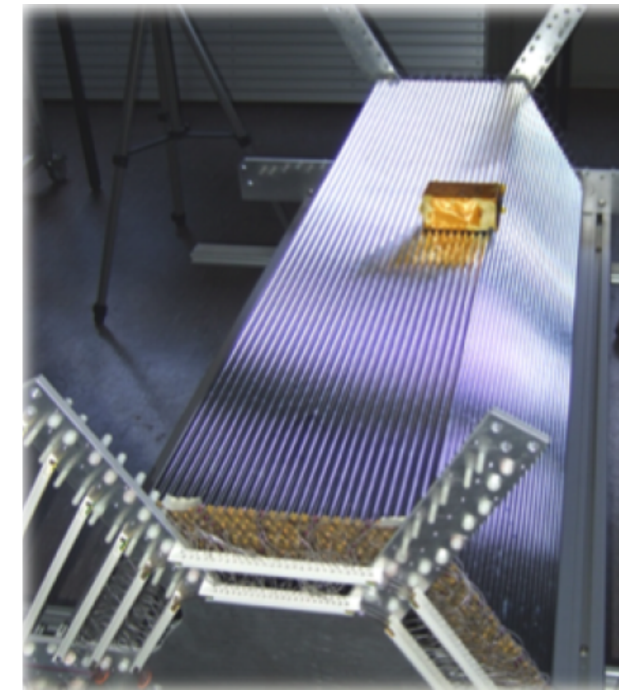
GEANT4 target simulation

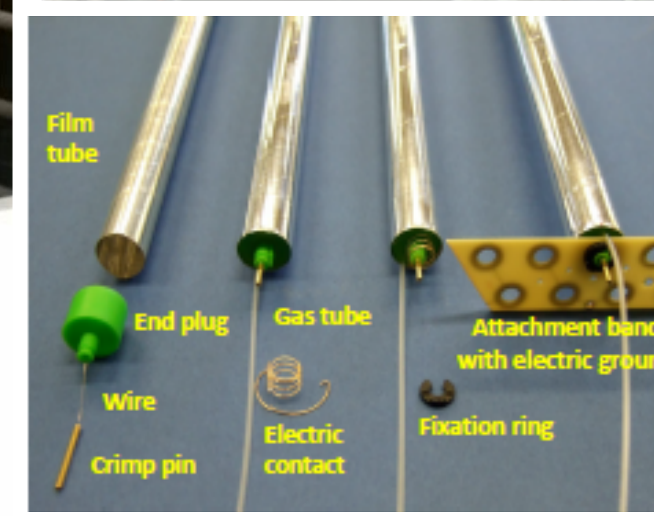
Straw Tube Tracker (HUJI + Temple)

- Resolution on the order of ~1 mr for scattered particles
- Sustain rates of ~a few kHz/cm.
- Very low material budget.
- Design based on PANDA Straw Tube Tracker.
- Low materials straws over pressured (2 bar absolute) for rigidity.
- 5X/5Y planes per chamber.
- Readout using standard TRB3/PADIWA.

- Close packed straws, w/ minimal gaps.
- ~30 um thick straws -> low material budget.
- 90/10 Ar/CO_2

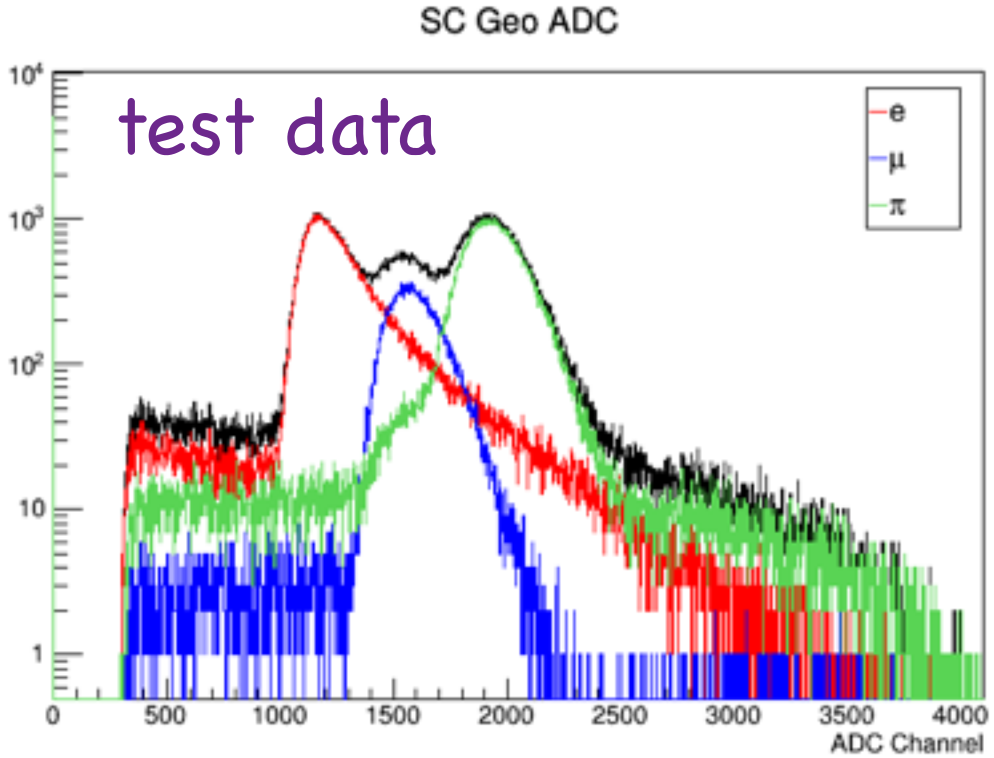
Element	Material	$X[mm]$	$X_0\ [cm]$	X/X_0
Film Tube	Mylar, 27 μm	0.085	28.7	3.0×10^{-4}
Coating	Al, $2\times0.03\,\mu$m	2×10^{-4}	8.9	2.2×10^{-6}
Gas	$Ar/CO_2(10\,\%)$	7.85	6131	1.3×10^{-4}
Wire	W/Re, 20 μm	3×10^{-5}	0.35	8.6×10^{-6}
			$\sum_{straw}$	4.4×10^{-4}

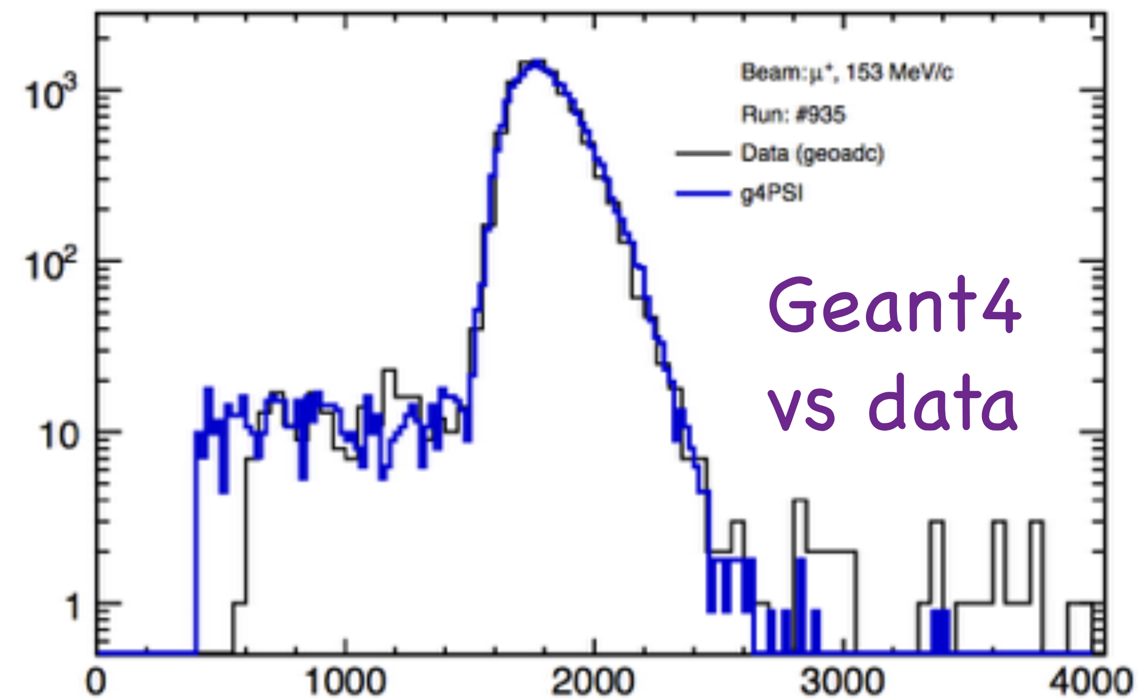




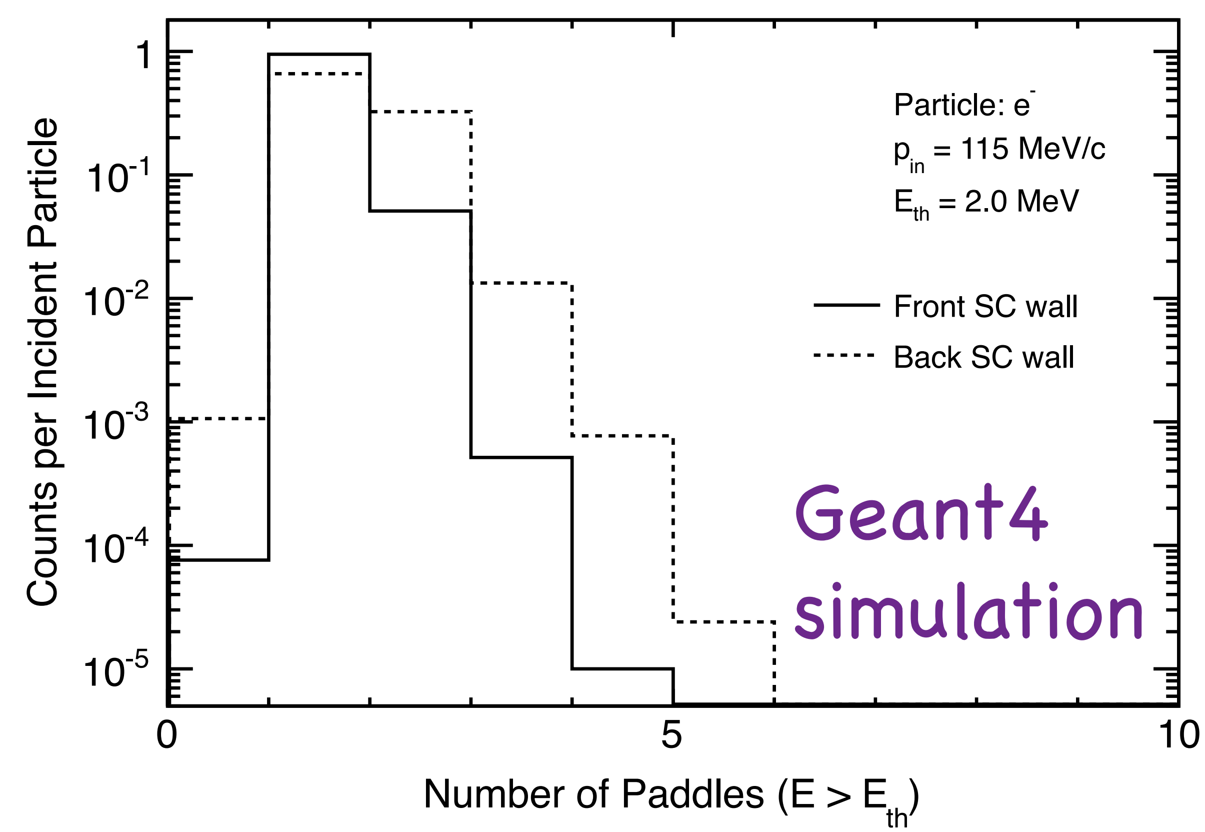
Scintillators (SC)

Used to detect scattered particles, time then, trigger with them





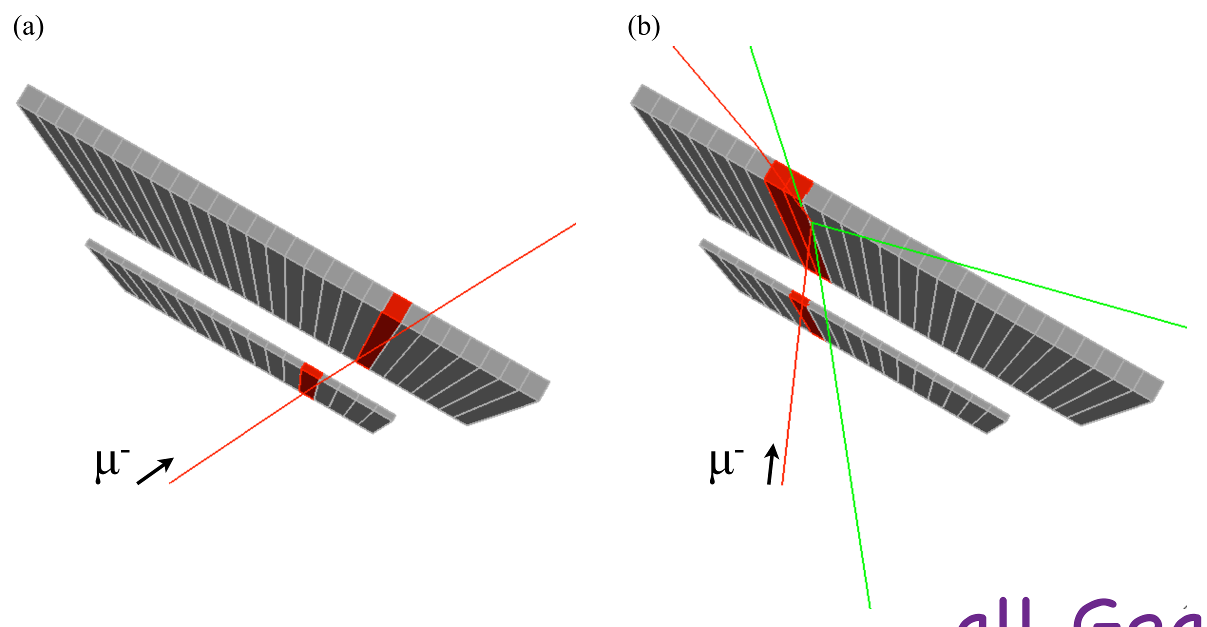
Particles lose several MeV on average in thick scintillator paddles. Low energy tail from particles that hit, but quickly scatter out of a paddle - which generally give large energy in neighboring paddle.

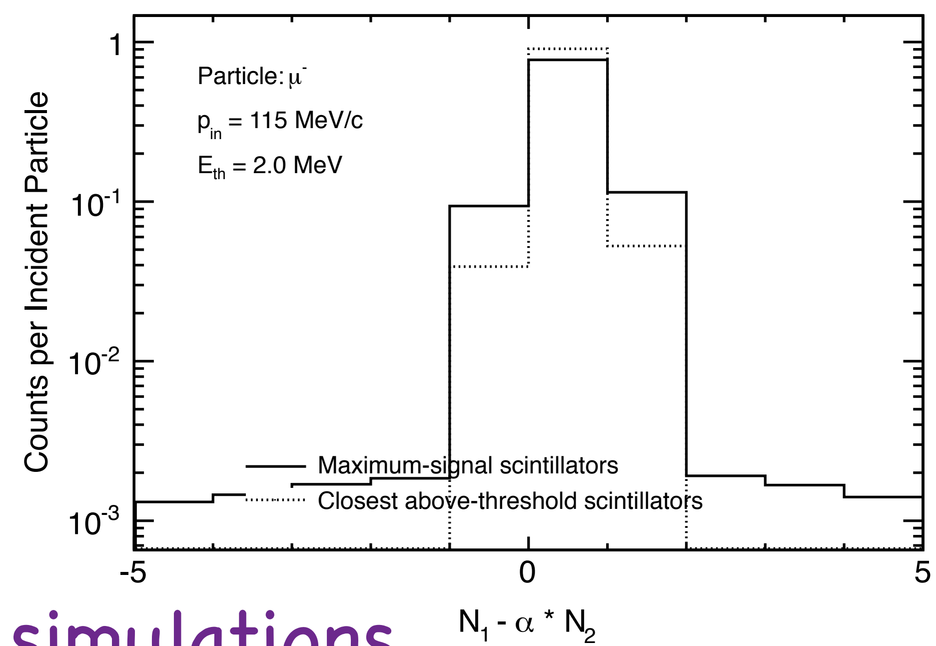


Scintillators (SC)

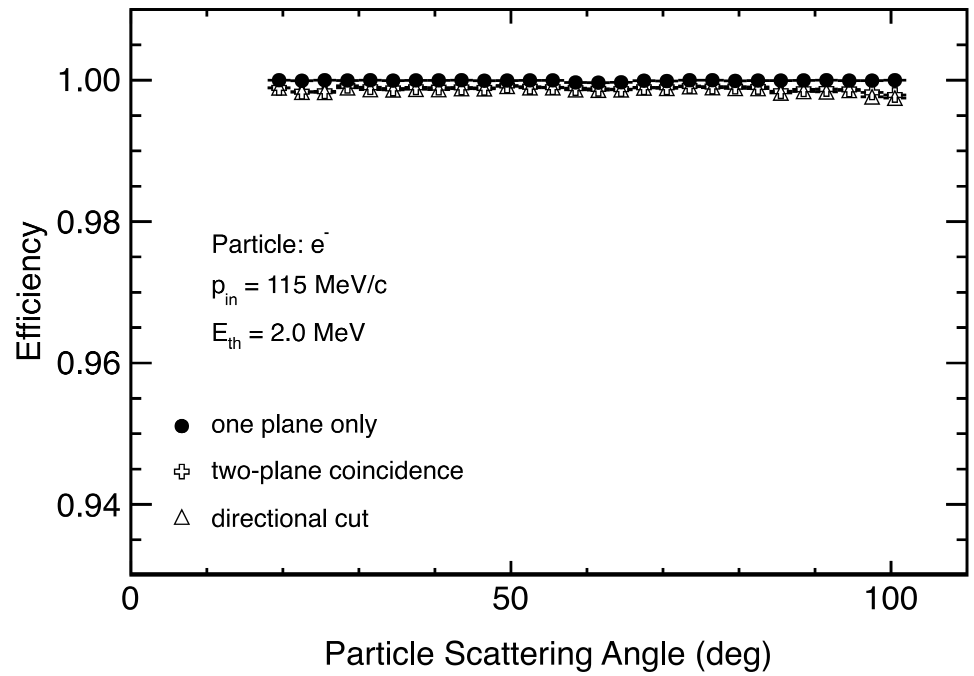
Individual paddles highly efficient

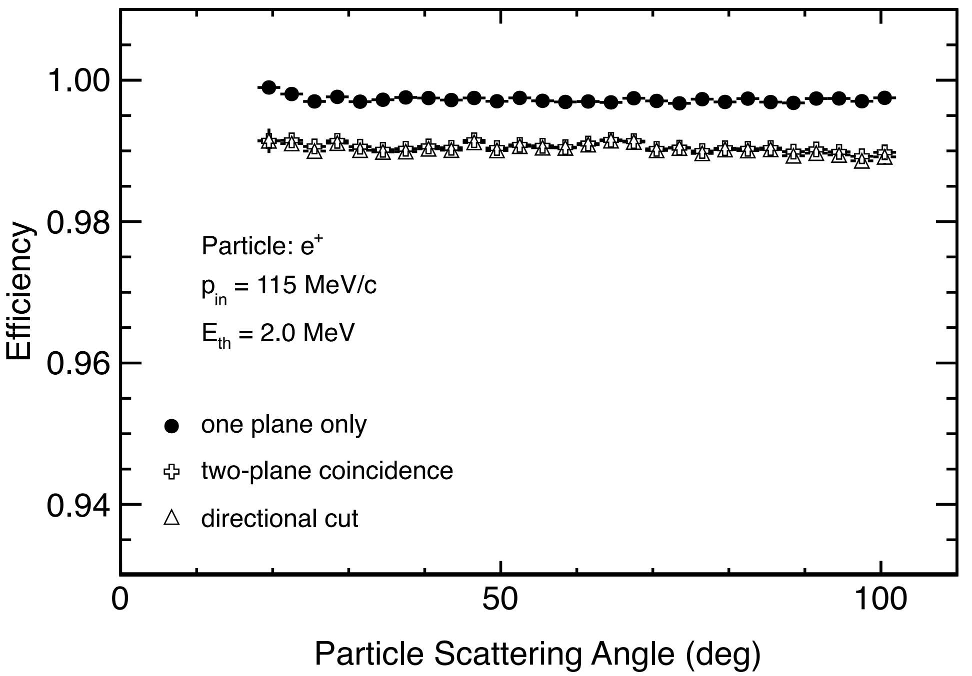
Two issues - two plane triggering, and e^+ annihilation





all Geant4 simulations



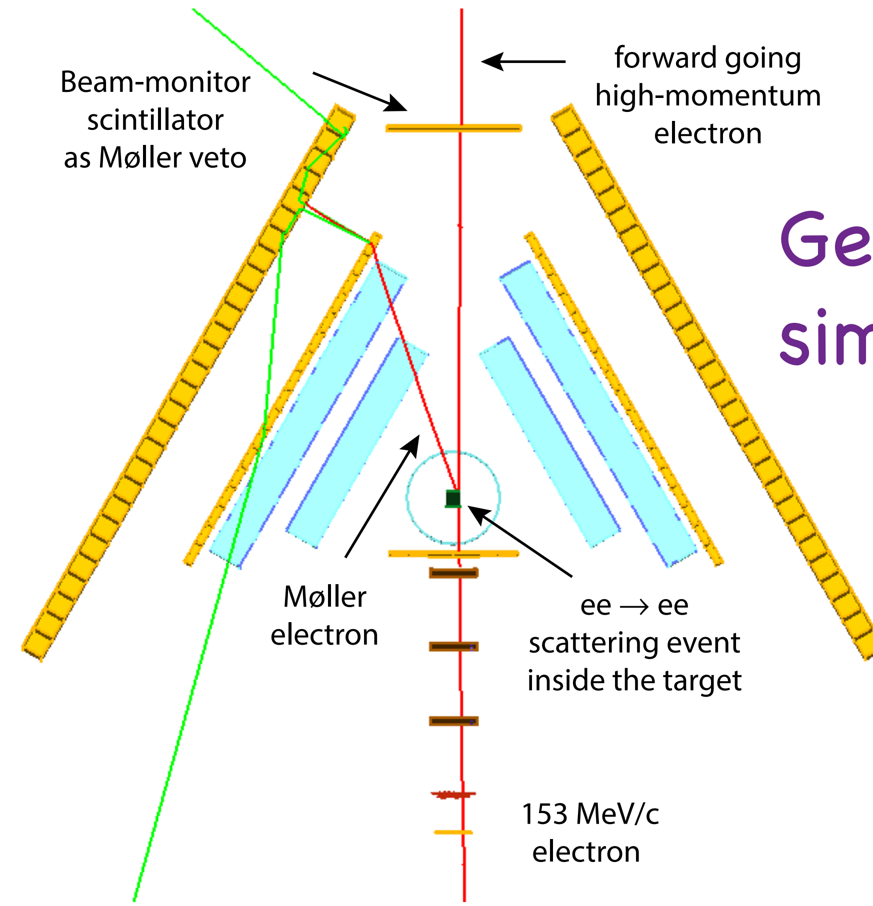


Efficiencies have been generated for all particles and beam momenta.

Beam Monitor

The beam monitor provides a continuous high resolution monitor of the stability of the RF time of randomly coincident beam particles.

It also provides the opportunity to veto events from Moller scattering or with higher momentum forward δ rays. Cutting these events reduces the statistical+systematic uncertainty from subtractions, while adding a systematic uncertainty from the beam monitor, and whether it introduces angle dependences.



Geant4 simulation

PLAN: study this possibility with Geant4 verified by data. Will test with 0° calorimetry at low beam rate.

Electronics (GW)

TRB3 for TDCs:

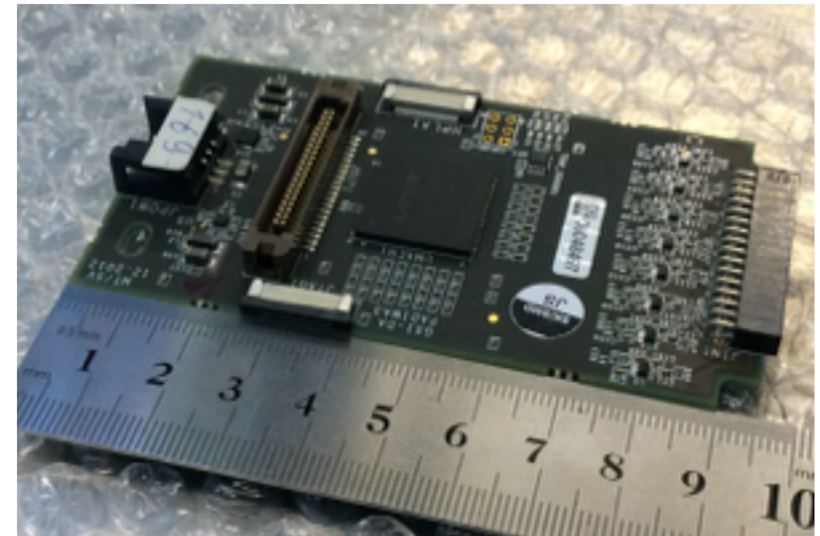
- around 10 ps resolution
- custom GSI board
- 192 channels/board
- AD with PADIWA level disc

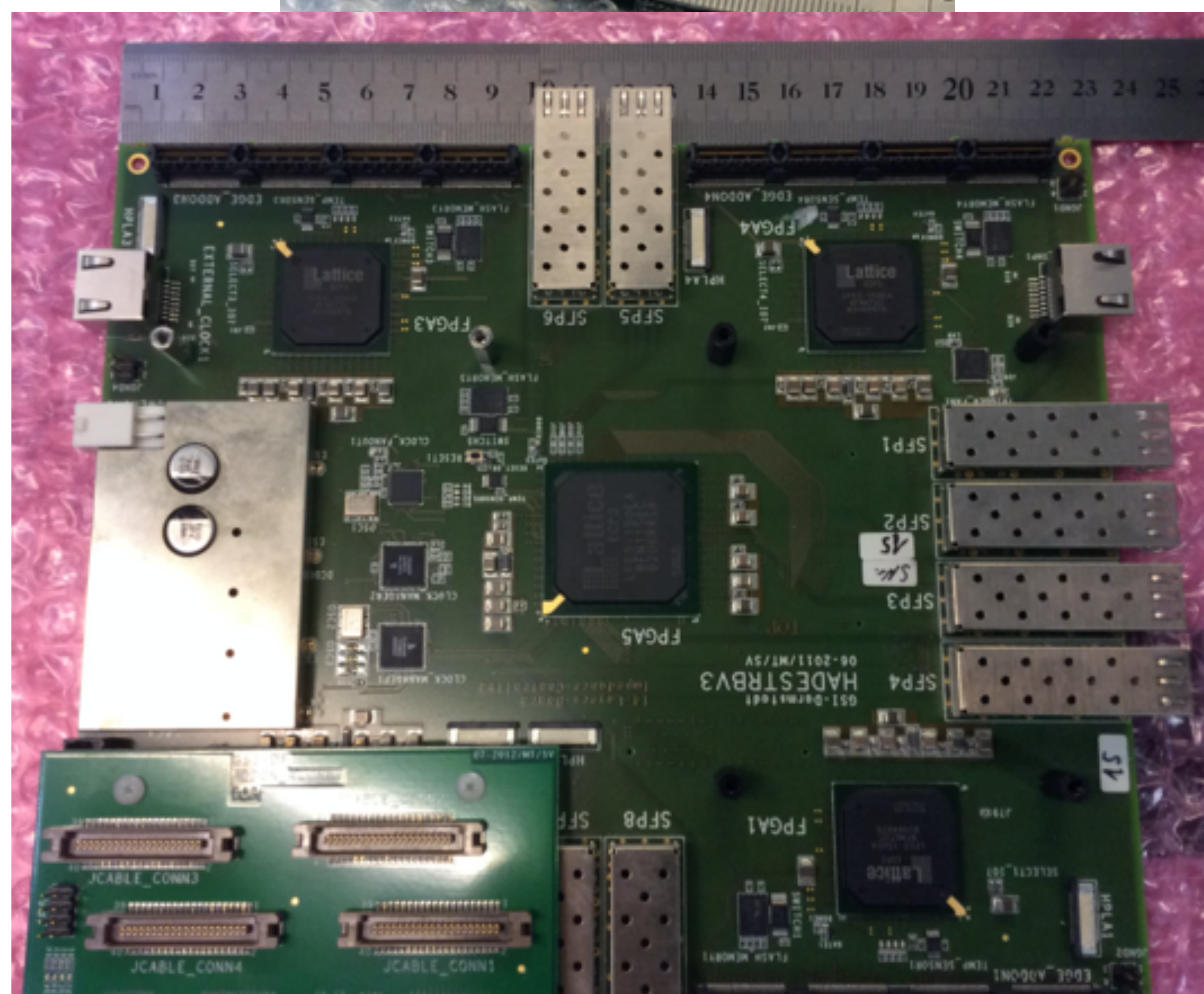
VME QDCs for charge

- Improve level disc timing to CFD level
- MESYTEC - individual channel gates

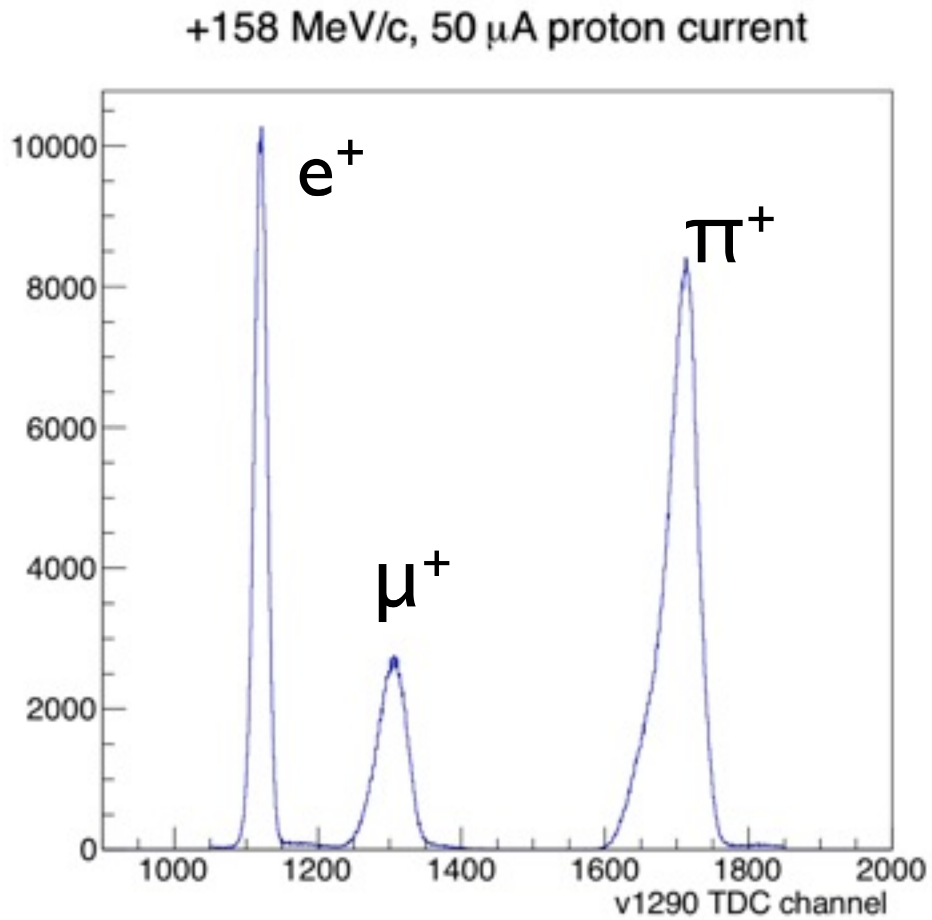
TRBs include 32-bit scalers

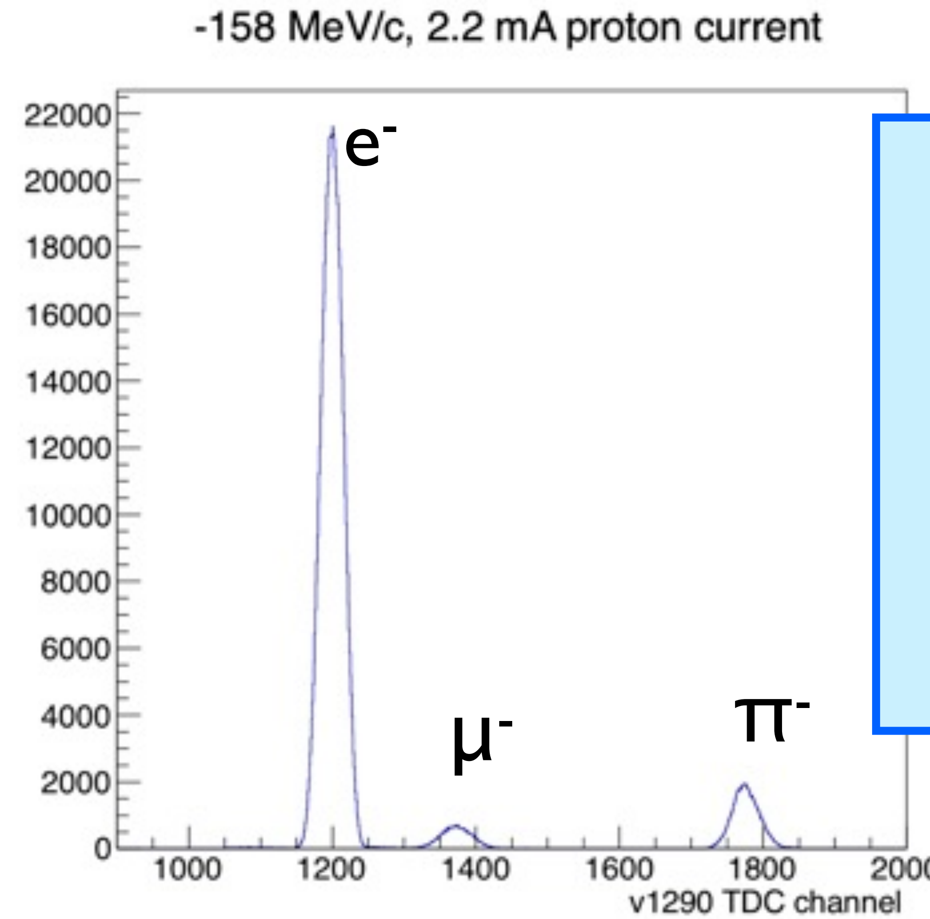
Trigger implemented on TRB FPGAs





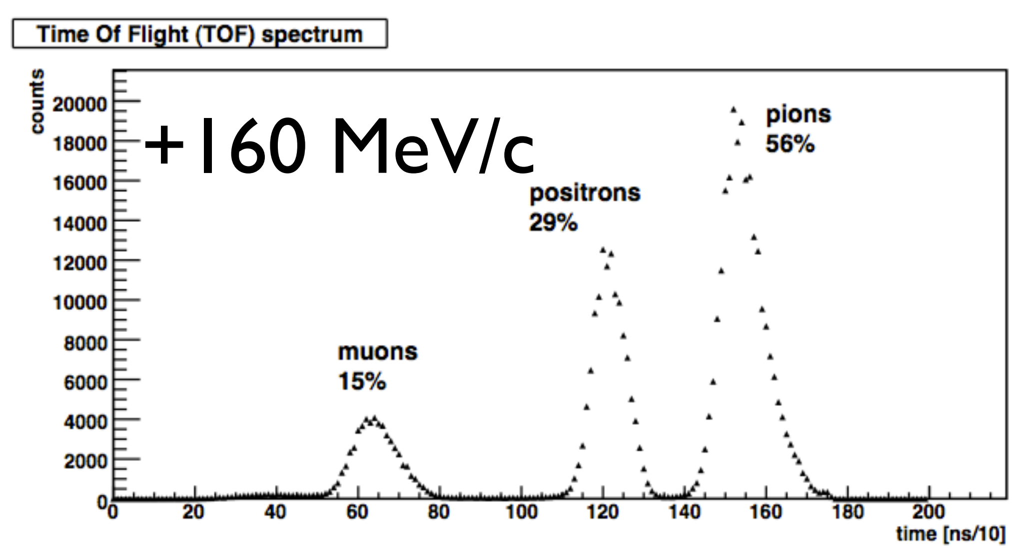
πM1 Channel - RF time in target region





RF peaks broader with 2.2 mA protons, ≈350 ps (σ) for e's and 400 - 500 ps (σ) for µ's and π's

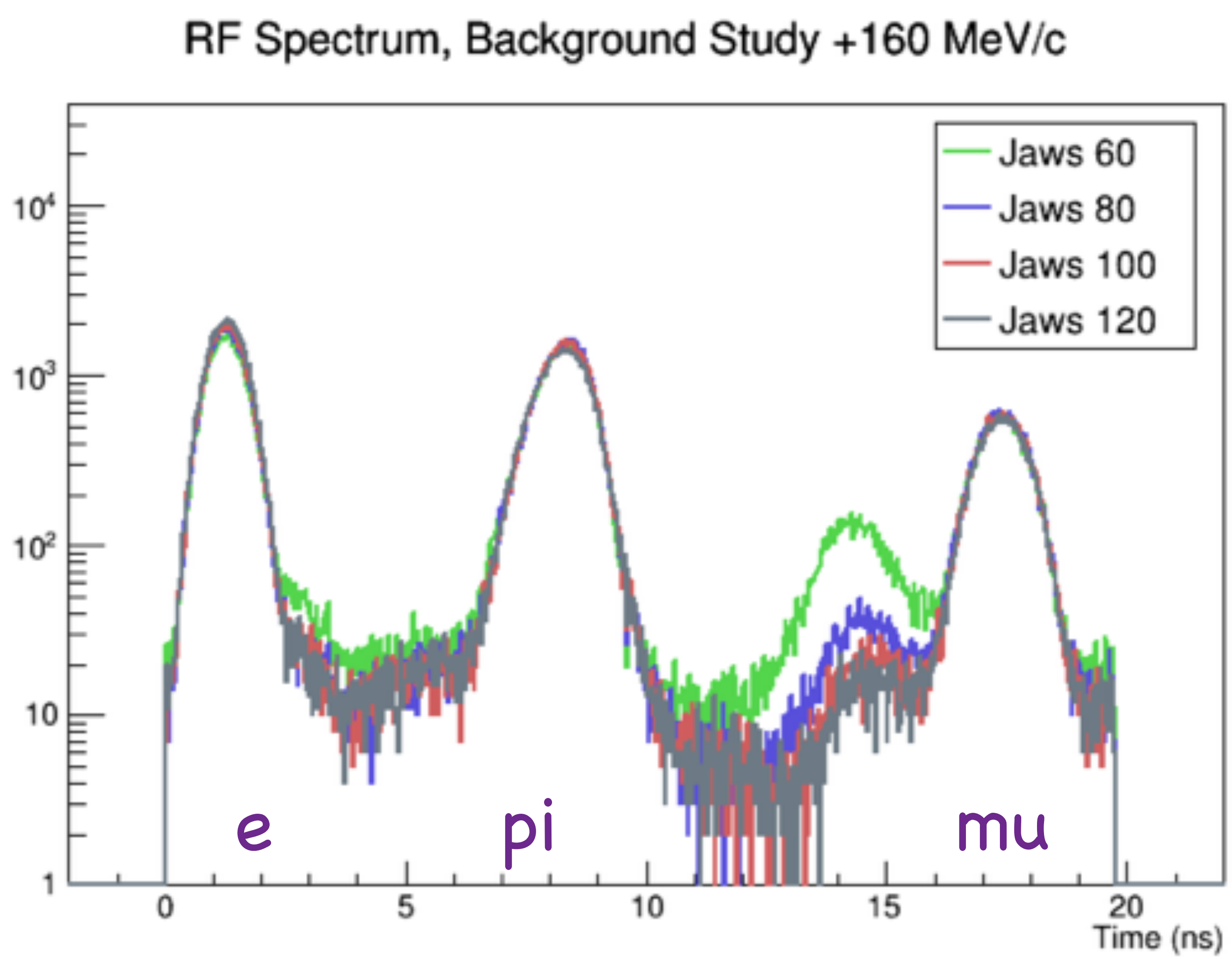
Obtained RF time spectra for several momenta from ≈110 to 225 MeV/c, and used these to determine relative particle fluxes



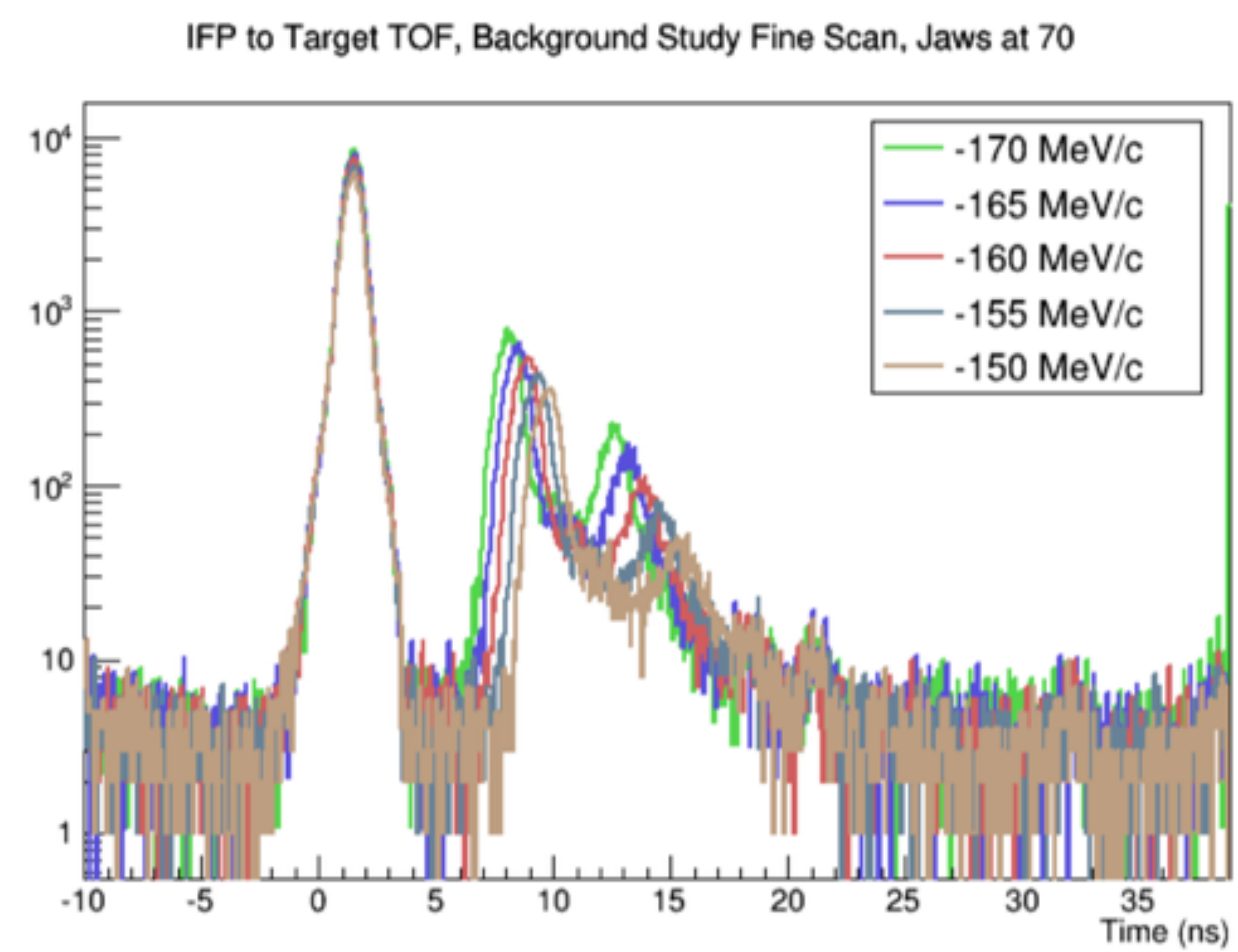
Old spectra, for comparison

Trigger

- e or mu beam particle + scattered particle + no veto hits
- Each implemented on TRB3 peripheral FPGAs
- Central FPGA needs to correlate information, include multiple trigger types with pre-scaling, latch, and output trigger and trigger-no-latch



test data

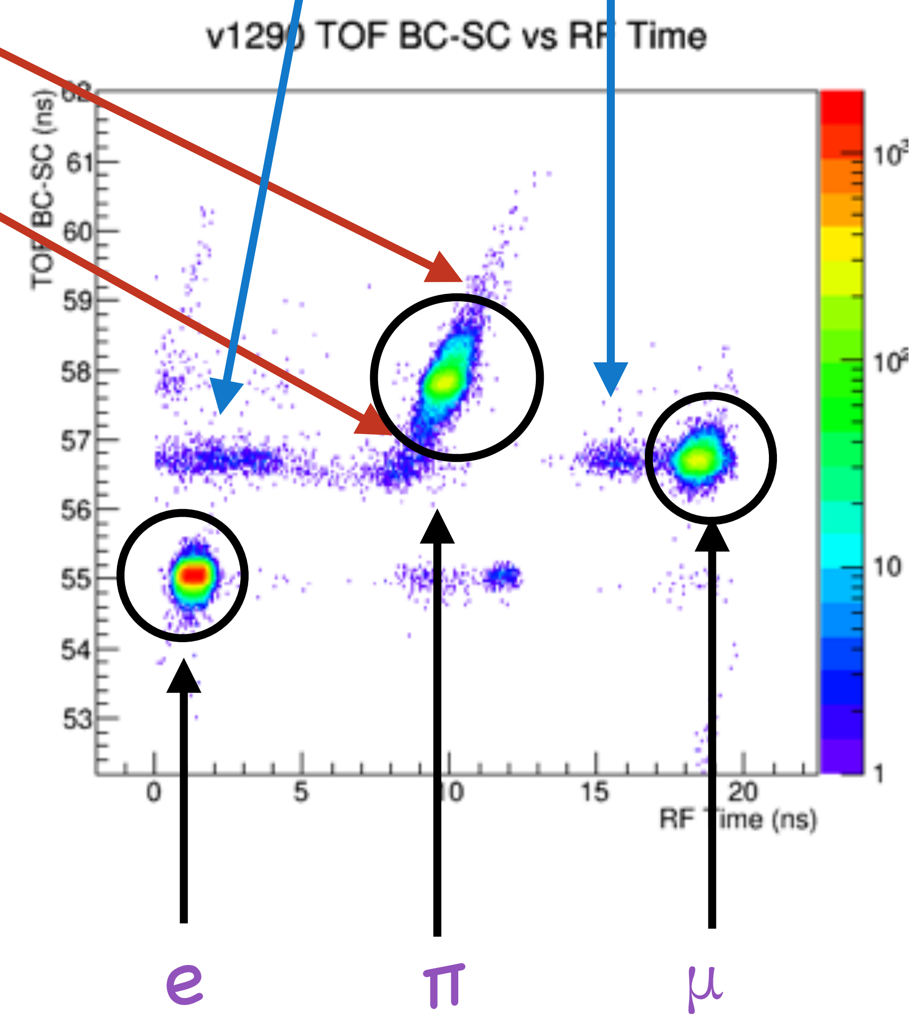


Trigger

Backgrounds underlying peaks can be better understood and removed in analysis using RF + TOF.

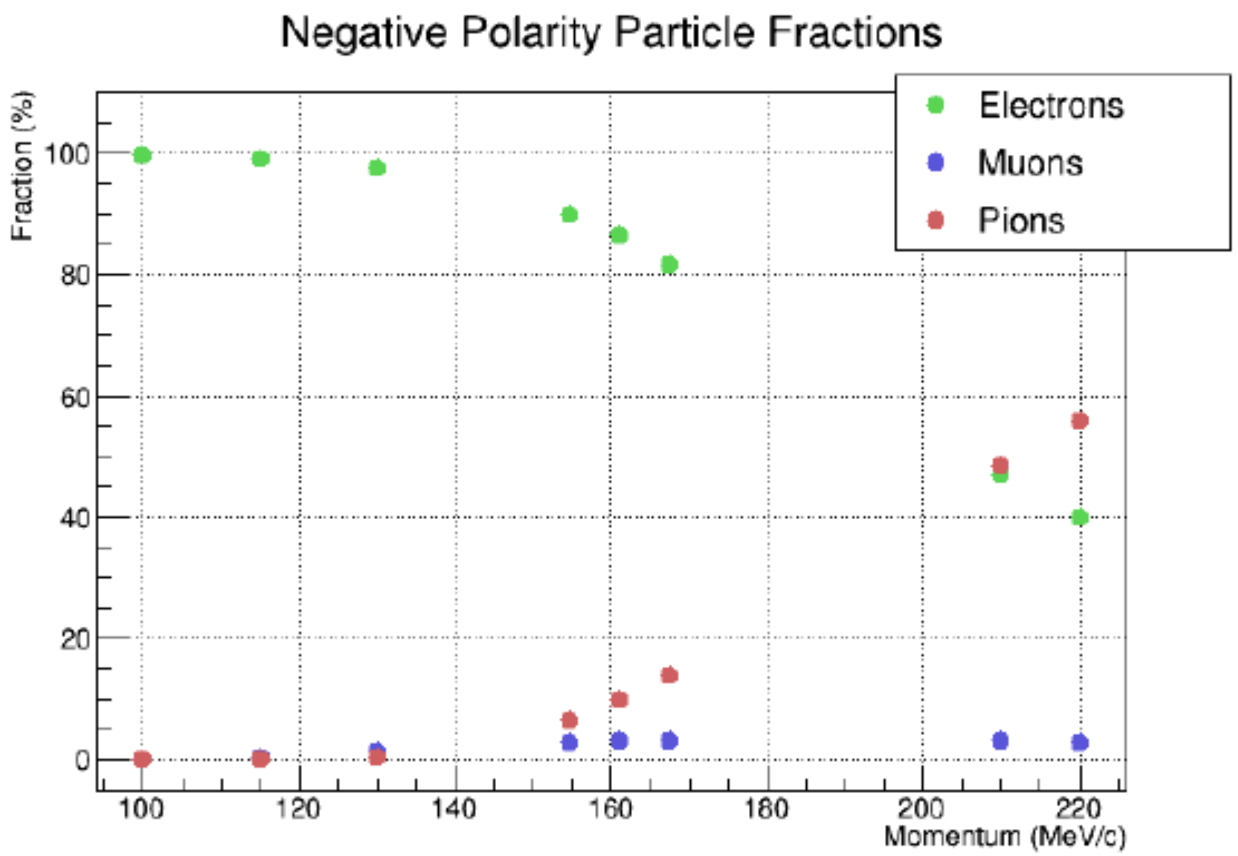
π decays before beam line, not at production target

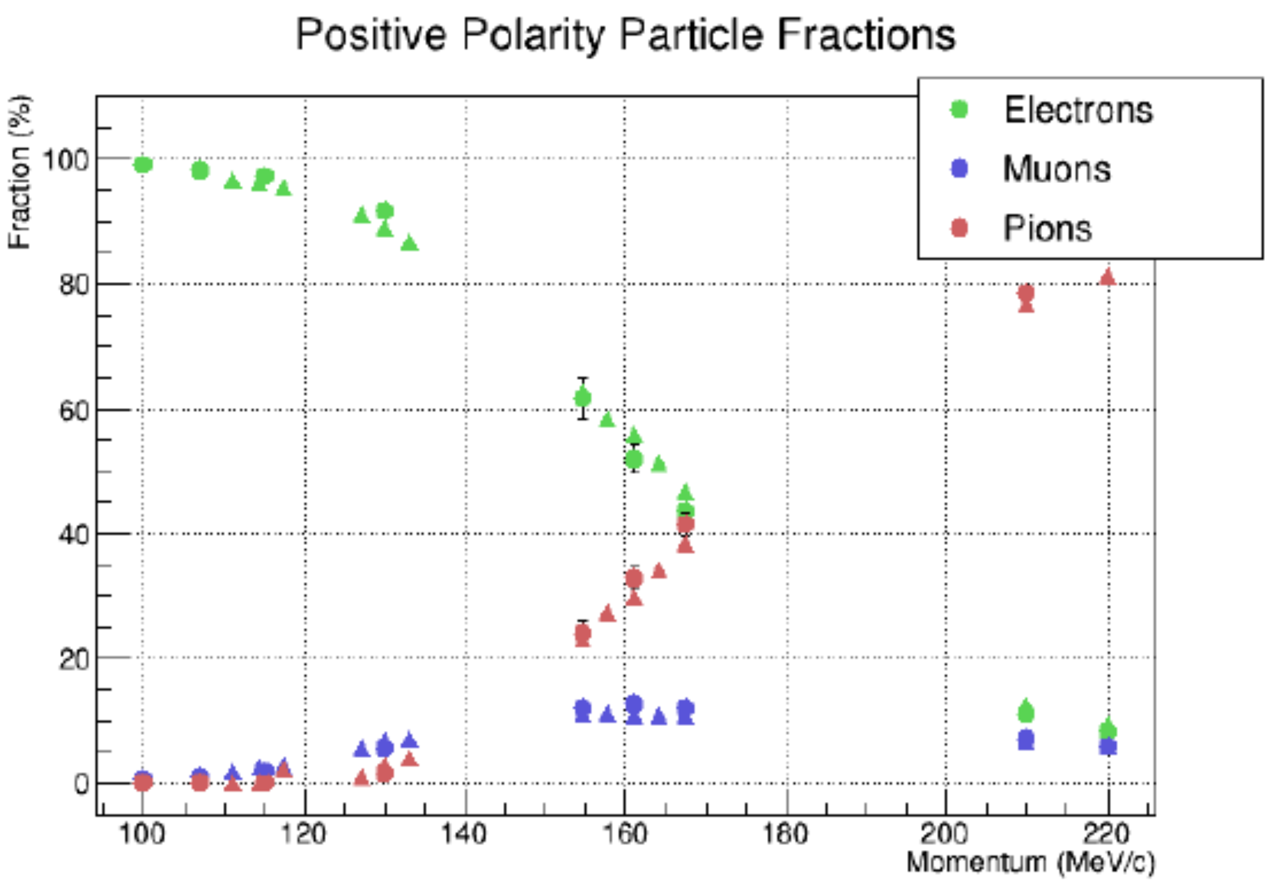
π decays near / between detectors



test data

MUSE Test Runs





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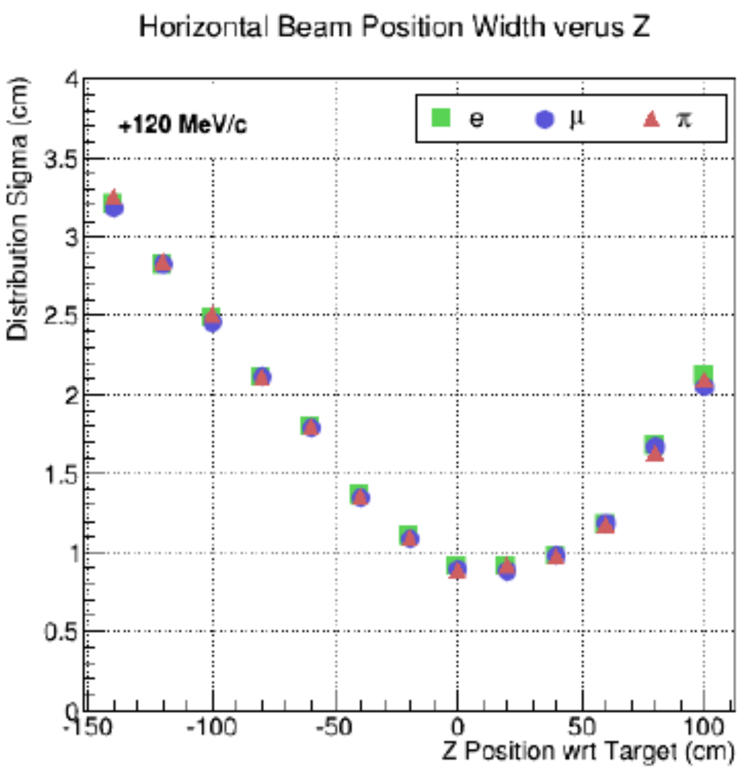
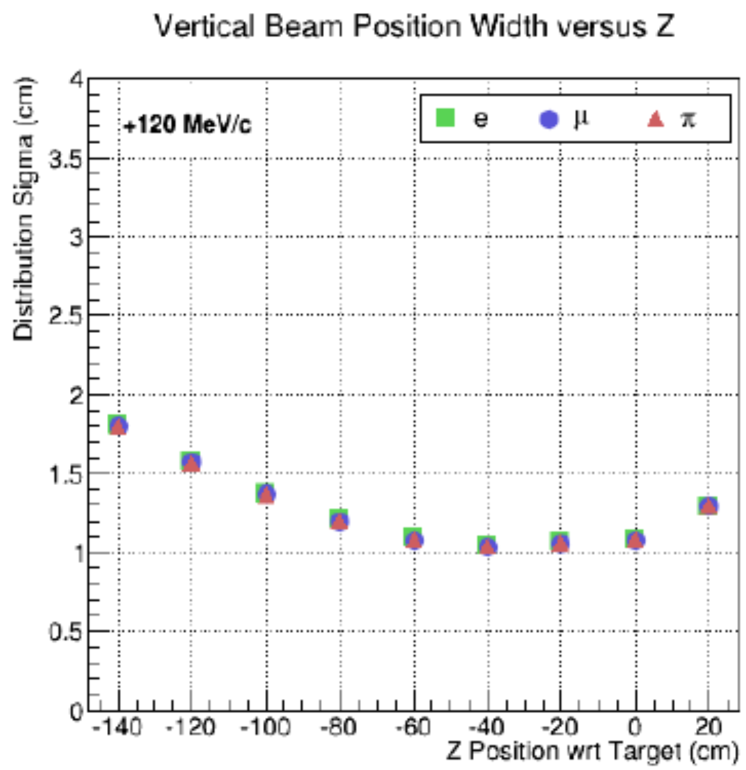
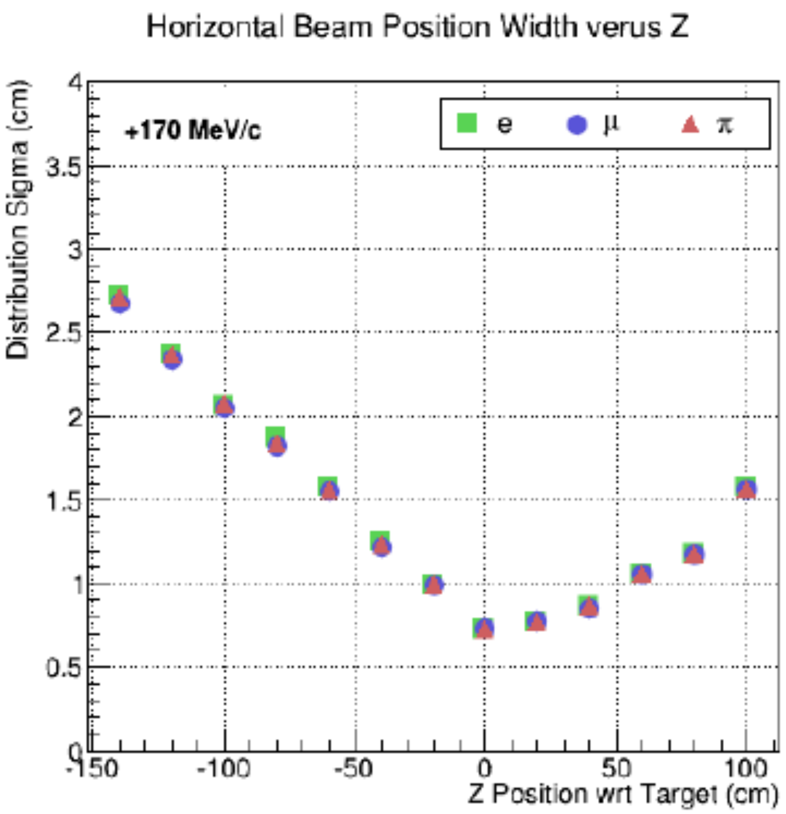
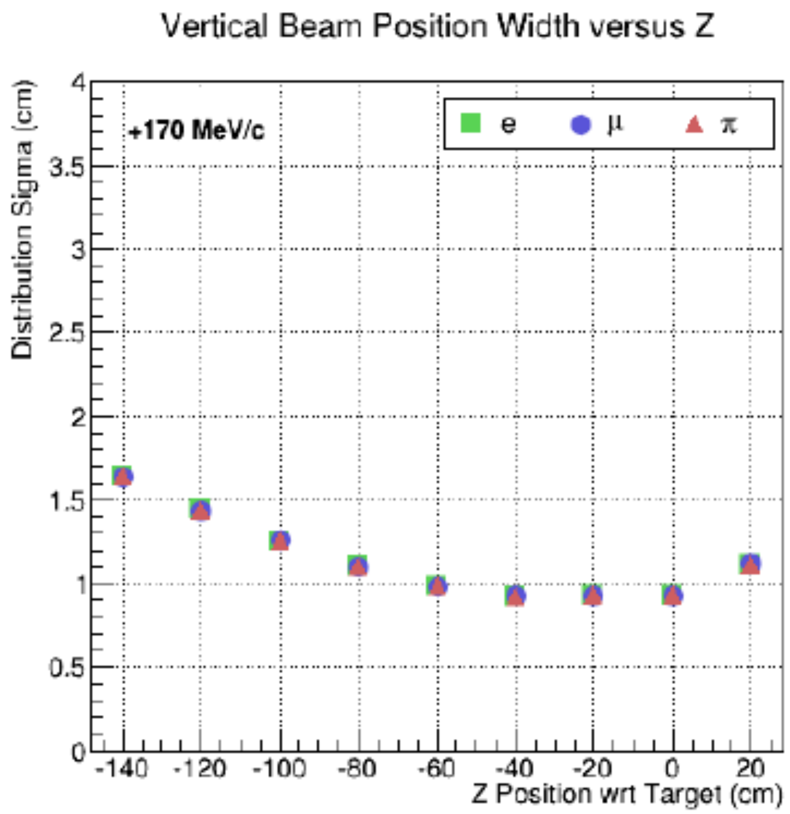








Experiment Status

PSI:

Approved, but must pass technical review to be awarded significant beam time.

NSF:

Has (with DOE) provided 750k + 150k soon to come for prototyping.

Issues: satisfy PSI, good project management

BSF:

Has awarded 100k for second stage prototyping

Note: Ultimately need around 6M for experiment - equipment + people + travel

The Case for MUSE

Why are the scattering results inconsistent?
Measures limiting uncertainty in radius extraction from muonic hydrogen.
Tests new low mass force carriers.

	Spectroscopy	eP Scattering	MUSE
State (sensitive to new low mass particle)	bound	unbound	unbound
Q^2 range	limited	large	large
charge state	-	-/+ (+ not in relevant range)	-/+
lepton	e/μ	e	e/μ
Sensitivity to 2γ	Theory Only	Theory Only	Measurement
Control of systematics in e/μ comparison	no	no	yes

Next Few Years for MUSE

Feb 2012	First PAC presentation
July 2012	PAC/PSI Technical Review
fall 2012	1st test run in πM1 beamline
Jan 2013	PAC approval
summer 2013	2nd test run in πM1 beamline
fall 2013	funding requests
Mar 2014	Funding review @ NSF (allocated design money)
June 2014	Test Run
Sep-Oct 2014	R&D Money
summer 2015	Proof of Concept Test Run (+R&D funds)
late 2015	New NSF Proposal
Dec 2015	Test Run
Feb 2016	NSF Review / PSI BVR
May 2016	NSF Management Review
Late 2017	set up and have dress rehearsal
2018 - 2019	production runs

The Bottom Line for MUSE

Will extract several observables:

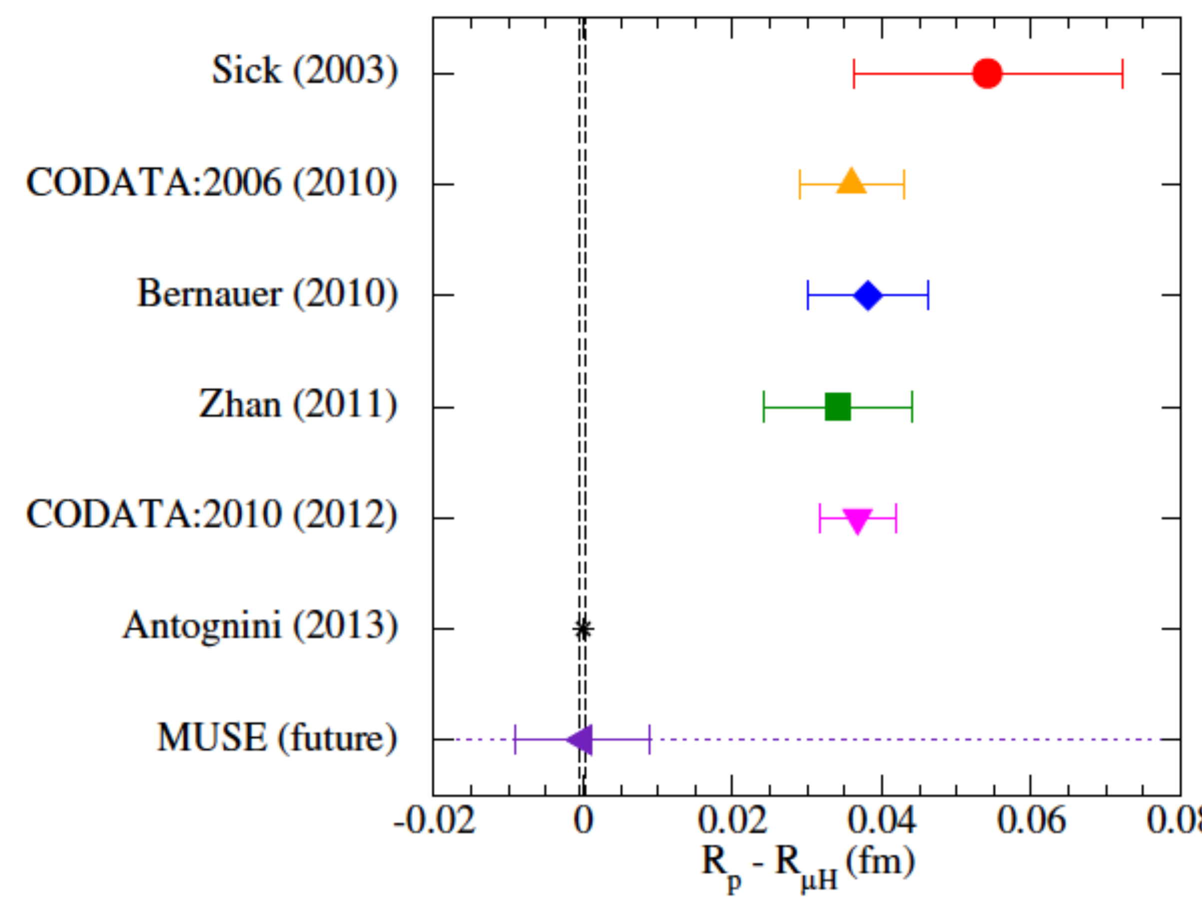
- Cross sections
- Charge averaged XS
- XS ratio

Gets rid of most of the systematic uncertainties.

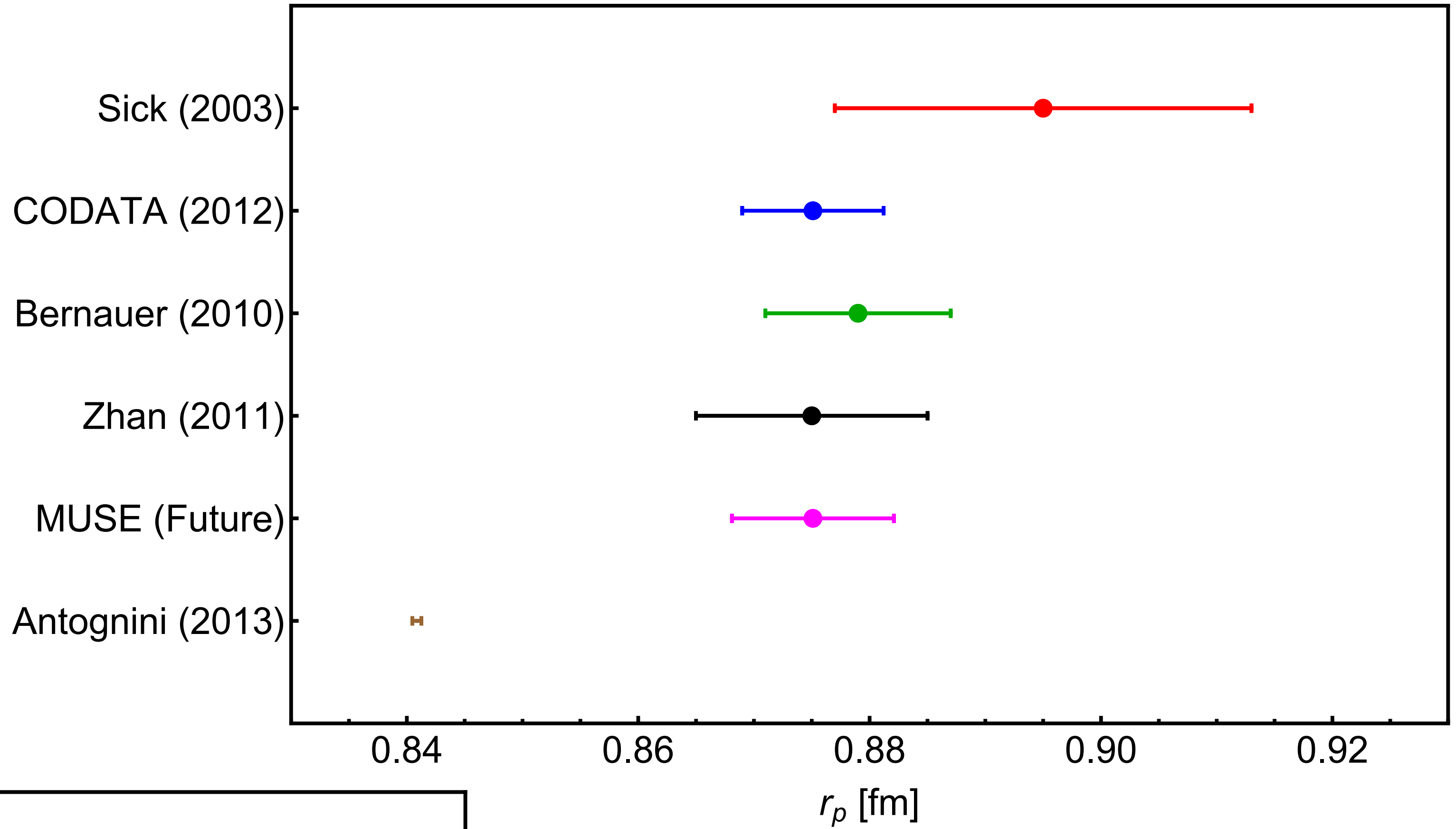
Translates to:

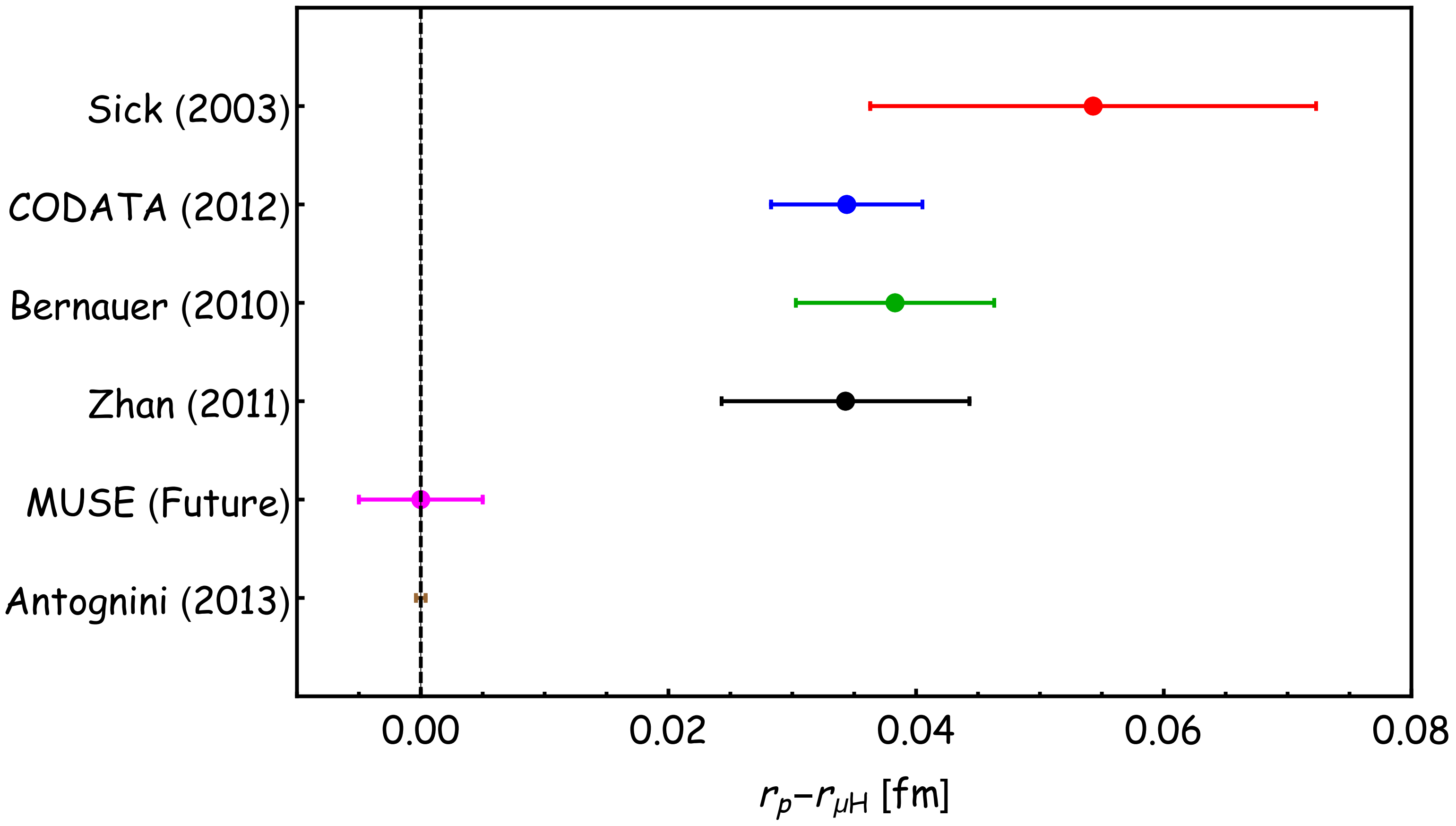
- e/mu difference
- 2-gamma effects
- Radii extraction

Test the e/mu radii difference to the 8 sigma level



The Bottom Line





How do we Resolve the Radius Puzzle

- New data needed to test that the e and μ are really different, and the implications of novel BSM and hadronic physics
  - BSM: scattering modified for Q^2 up to m^2_{BSM} , enhanced parity violation
  - Hadronic: enhanced 2γ exchange effects
- Experiments include:
  - Redoing atomic hydrogen
  - Light muonic atoms for radius comparison in heavier systems
  - Redoing electron scattering at lower Q^2
  - Muon scattering on nuclei.
  - **Muon scattering!**

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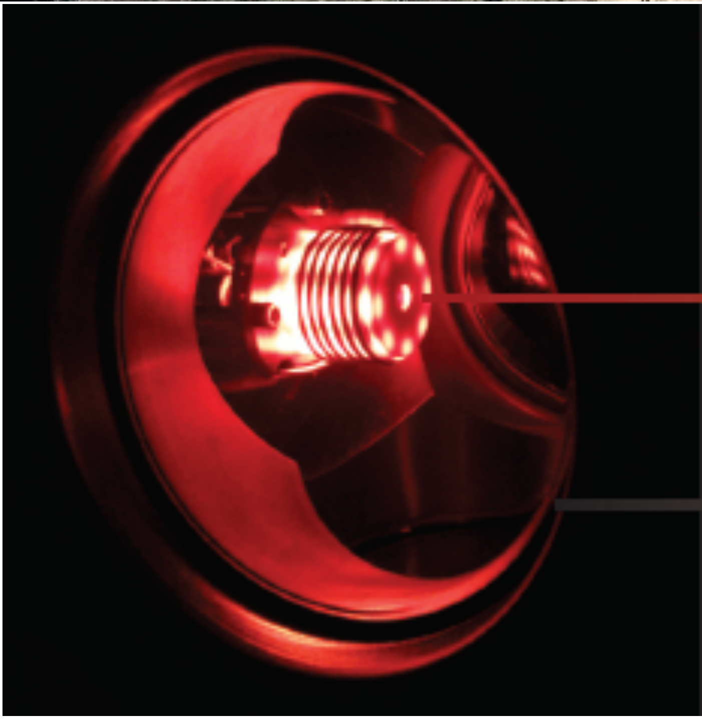
MUSE tests these

Possible next Gen.

Other planned Experiments

The next few years
(in lieu of a summary)

r_p (fm)	ep	μp
atom	Several new efforts	Heavier light nuclei
scattering	Mainz ISR JLab PRAD LEDEX@JLab	**MUSE**



PSAS'2016

International Conference on
Precision Physics of Simple Atomic Systems

PSAS2016
in Jerusalem
22-27/5/2016

Registration is now open

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THE HEBREW UNIVERSITY OF JERUSALEM