An LGAD-based fully active target for the PIENUX* experiment

Simone Mazza on behalf of the PIENUX* collaboration

12th workshop on picosecond timing detectors

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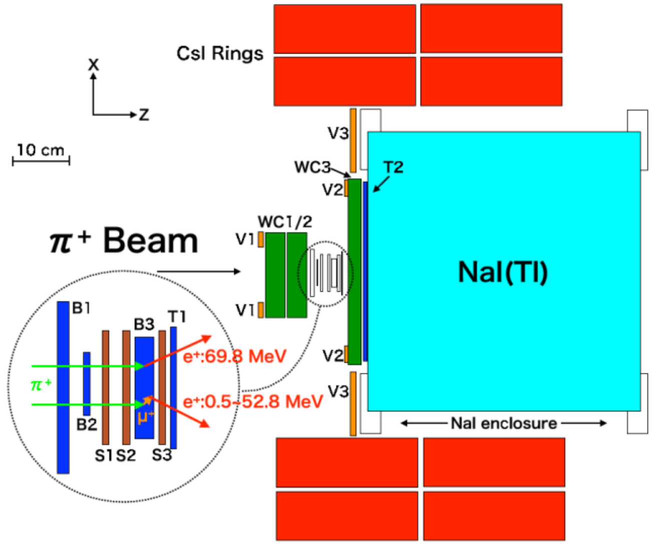
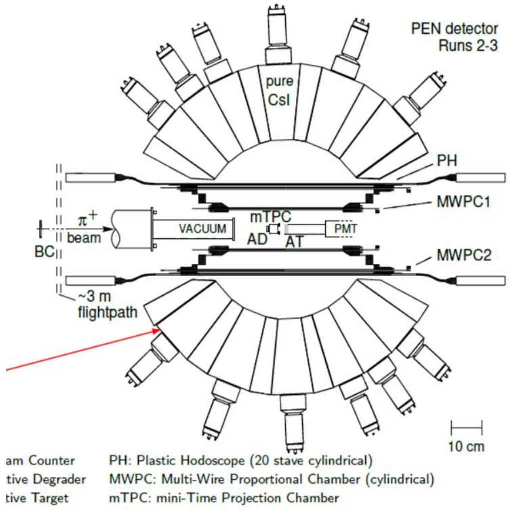
*Name to be updated

Past and future pion experiments

- Rare pion decay experiments showed significant results in the past decades
- **PIENU** (TRIUMF) has the best measurement up to date of $\mathbf{R_{e/\mu}}$ **electron/muon decay ratio in pion decay**
  - Precision measurement of lepton-flavor universality (LFU) for electron-muon
  - Foreseen final uncertainty (PEN/PIENU) < 0.1% (current 0.25%)
  - Located at the pion beam line at TRIUMF (https://pienu.triumf.ca/)
- Current best measurement of **Pion beta decay** $B(\pi^+ \rightarrow \pi^0 e^+ \nu)$ from **PiBeta** (PSI)
  - Final uncertainty 0.64%
  - Located at PSI (https://inspirehep.net/experiments/1108722)

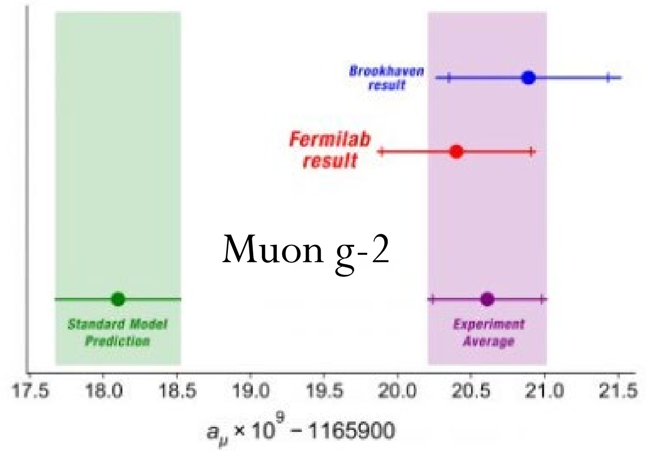
- **PIENUX***, a new generation pion decay experiment, plans to improve the $R_{e/\mu}$ and Pion beta decay branching fraction measurement
  - Plan to take place either at PSI or alternatively at TRIUMF (but a new beam line would need to be built at TRIUMF)

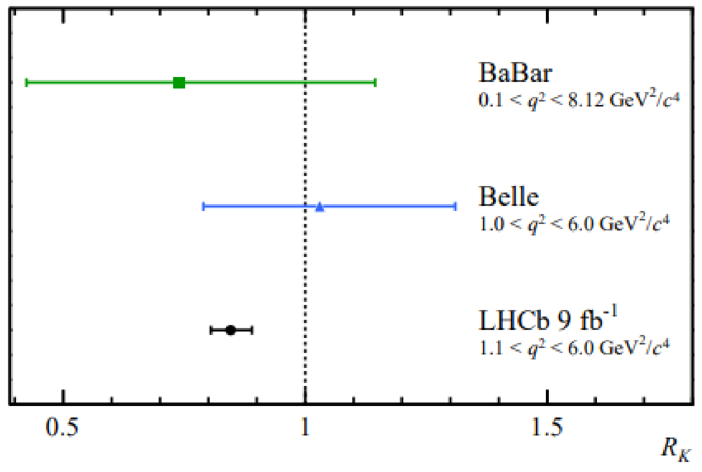




Recent results on Flavor universality tensions

- **Topic of Lepton flavor universality (LFU) violation is of great interest these days**
- Several high precision measurements of accurately predicted SM processes show possible indications of violating LFU and CKM unitarity
  - Muon g-2 recent result: 4.2 σ deviation from theory
    - https://news.fnal.gov/2021/04/first-results-from-fermilabs-muon-g-2-experiment-strengthen-evidence-of-new-physics/
  - B decays: $B \to D^*\tau\nu / B \to D^*\mu\nu$; $B \to K^*\mu\mu / B \to K^*ee$
    - R(D(*)),R (K*), R(K): (2-4 σ deviation); O(10%) deviations from universality.
    - (e.g. recent LHCb results on R(K) https://arxiv.org/abs/2103.11769)
  - Cabibbo-Angle anomaly (2-3 σ tension with unitarity): β and K decays
    - May be related to LFU violation
    - (Crivellin, Hofrichter: https://arxiv.org/abs/2002.07184)
  - Recent 4 σ excess shown by CMS (https://arxiv.org/pdf/2103.02708.pdf) in the e^+e^- spectrum for mass > 1.8 TeV
    - Together with CKM angle anomaly it can point to new physics in $R_{e/\mu}$
    - (Crivellin: https://arxiv.org/pdf/2103.12003.pdf)





PiENuX main physics goals

- **Need for extra precision in measurement of charged lepton flavor universality ($R_{e/\mu}$)**
- SM **theory** calculation is precise to **O(10E-4)**
- Current Theory precision is one order of magnitude better than experimental precision

Theory

$$R^{theory}_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = (1.2352 \pm 0.0002)x10^{-4}$$

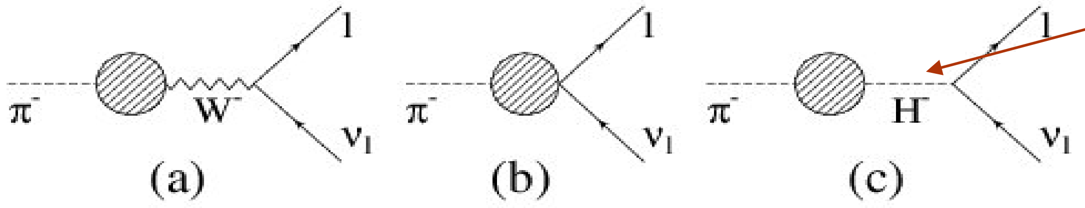
Current Result (PDG): $R^{exp}_{e/\mu} = 1.2327 \pm 0.0023x10^{-4}$ (±0.19%)

$$\frac{g_e}{g_\mu} = 0.9989 \pm 0.0009 \quad (\pm 0.09\%)$$

PEN, PIENU goals ($R^{exp}_{e/\mu} \leq \pm 0.1\%$)

PIENUX goals

- Measure $R_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)}$: $O(\pm 0.01\%)$



- **Process of π → eν** is helicity suppressed and **very sensitive to pseudo-scalar and scalar couplings that are absent in SM**
  - E.g. Charged Higgs BSM coupling (to 3000 TeV), but many others!
  - A disagreement between theory and experimental value for $R_{e/\mu}$ would be a clear indication of BSM
  - **Reach the same precision as the theory calculation**

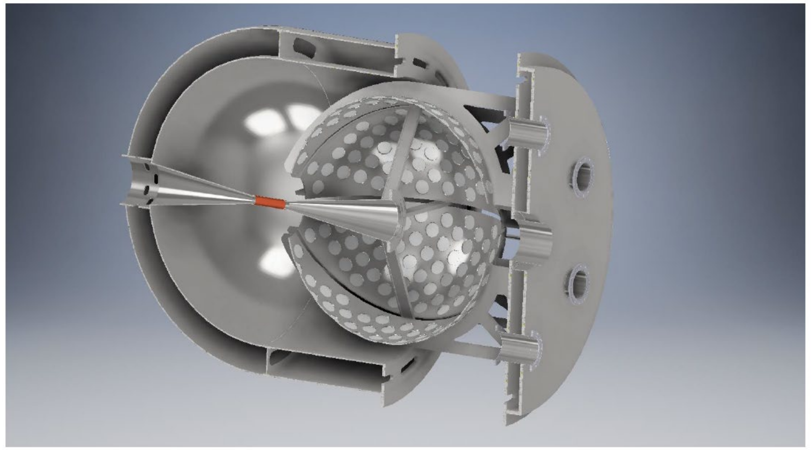
- Measure $R_{\pi\beta} = \frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\pi^+ \to all)}$: $O(\pm 0.05\%)$

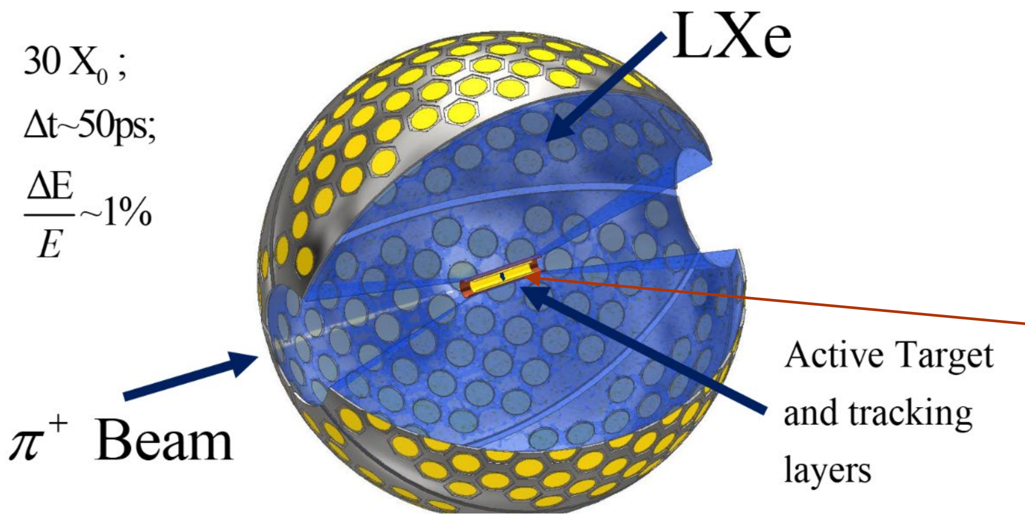
- **Precise measurement of Pion beta decay BF**
  - Important to test CKM unitarity (clean Vud measurement)
  - Current precision 0.6% (PIBETA)

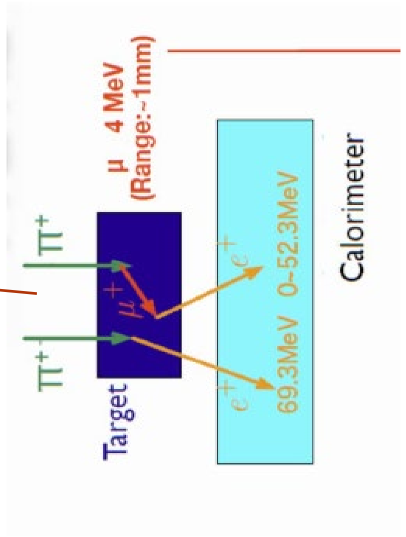
PIENUX* detector design

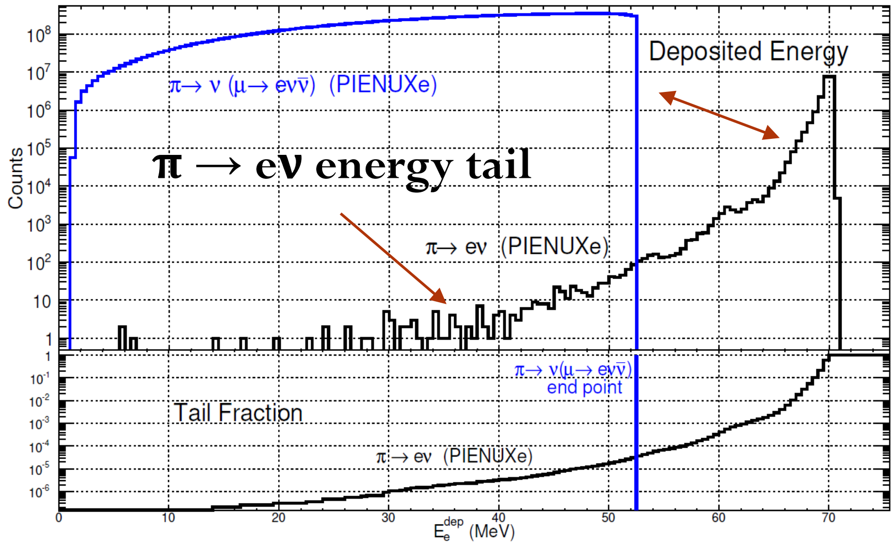
- PIENUX design is a ~1 m radius active sphere around a stopping target on a pion beam
- **Goal: Separation of energy spectra of $\pi \to e\nu$ and $\pi \to \mu\nu \to e\nu\nu$**
  - 2 vs 3 body decay, but 2-body energy tails overlaps with first spectrum
- **Two main detectors: a silicon active target (ATAR) and a 3π calorimeter**
- ATAR with fast timing allows to separate $\pi \to e\nu$ and $\pi \to \mu\nu \to e\nu\nu$ decays
  - Allow pileup reduction and suppresses the $\pi \to e\nu$ energy tail
  - Silicon strip tracker around ATAR to tag exiting positrons
- Segmented calorimeter (Liquid Xenon or LSO) measures the exiting positron energy and position with high precision
  - Allows the separation of the two energy distributions (much better than PIENU)

PiENuX mechanic support







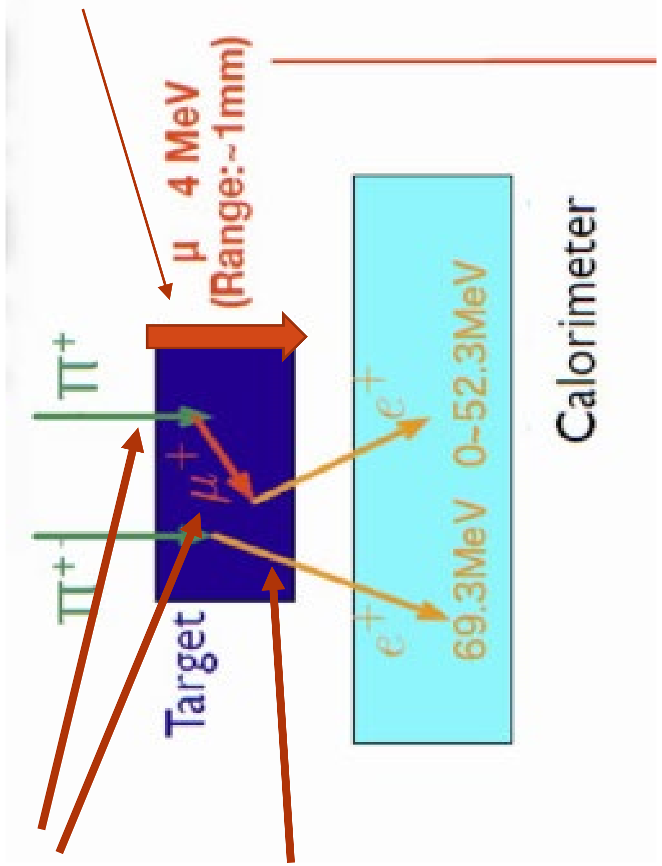


PiENuX ATAR requirements

- Full silicon active target
  - Compact ~2x2x1 cm block of active silicon to catch pion decay
  - Chosen technology: Low Gain Avalanche Detector (LGAD) strips
  - Since standard LGADs have granularity limitations (wide inter pad gap) a new high granularity LGAD technology is needed
  - Such as AC coupled LGADs (AC-LGADs)

- Requirements
  - **High longitudinal segmentation**: to detect the decay in flight of pions
  - **Compact**: less dead material (including air) as possible in between planes and around ATAR
  - **Fast collection time**: separate pulses that are close in time to reconstruct the pion decay
  - **Large Dynamic range**: detect energy deposition from positrons and slow pions/muons

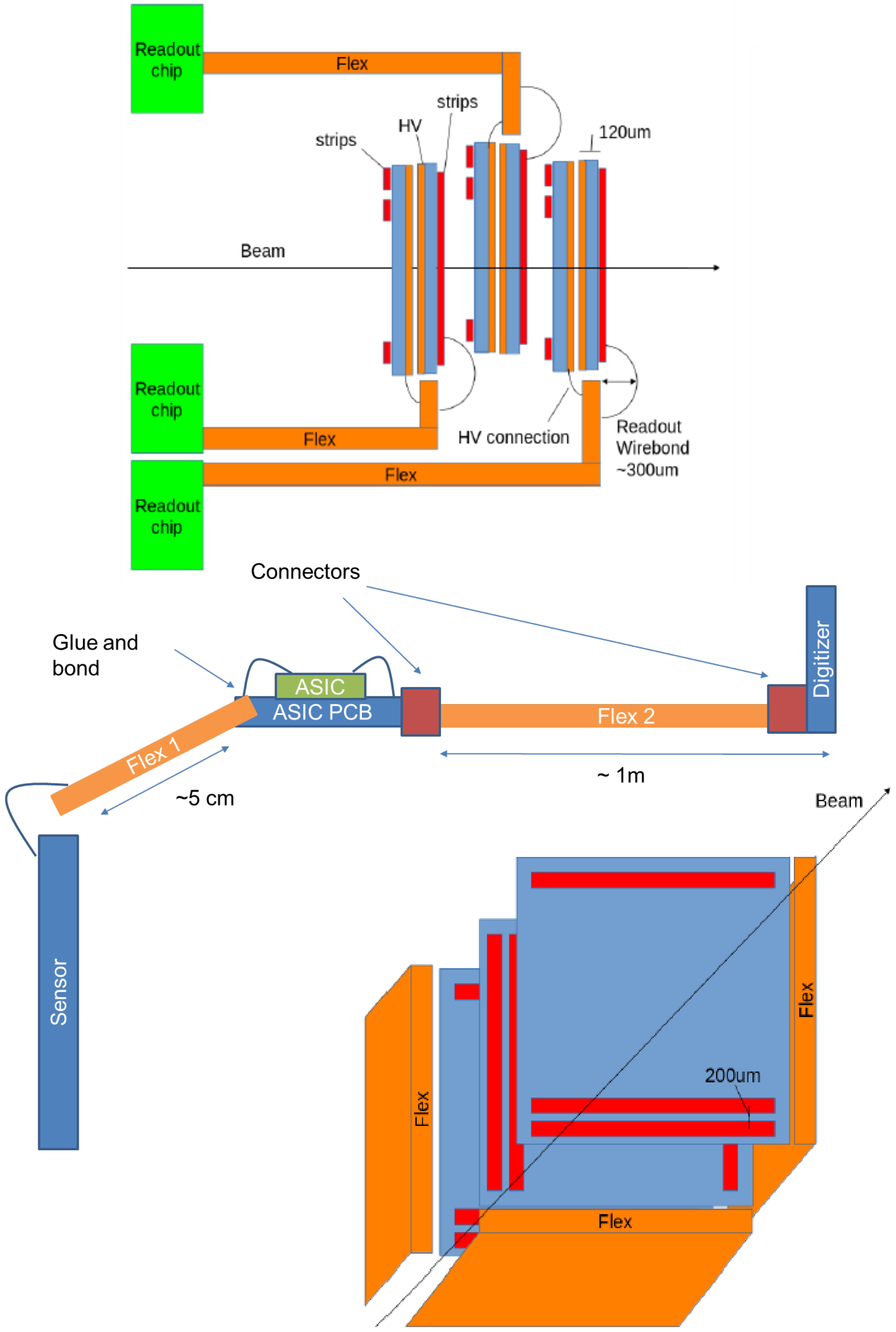
High segmentation, compact



Non-MiP MiP

PIENUX* ATAR design

- Tentative initial design
  - **48 layers of 120um thick AC-LGADs (or similar)**
  - 100 strips, 2 cm length, with 200 um pitch (2x2 cm area)
  - Compromise between granularity, total active area, timing and dead material
- Sensors are packed in stack of 2 with facing HV side and rotated by 90°
  - Strips are directly wire-bonded to a flex readout
- Readout flexes are on the four side alternating to allow space for the wire bonds
  - Flex is wire bonded to sensor and bent to exit at an angle
  - First short (5 cm) flex carries the un-amplified signal from sensor to ASIC with fast analog amplification
  - Amplified signal goes with another flex (~ 1 m) to a full digitizer on the back end (DRS4-like)
- Estimated (rough) total cost ~1 M$

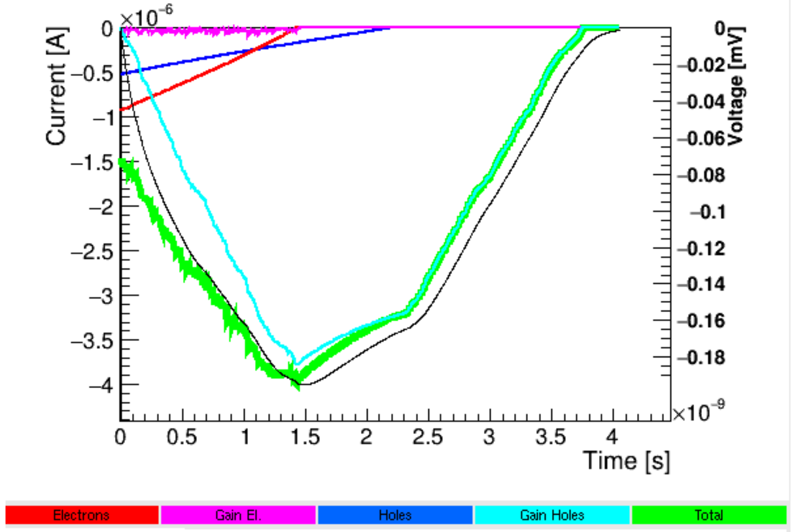


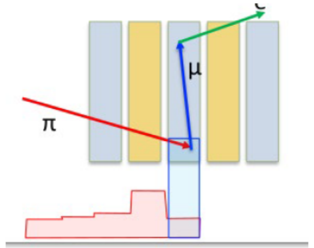
PiENuX ATAR challenges

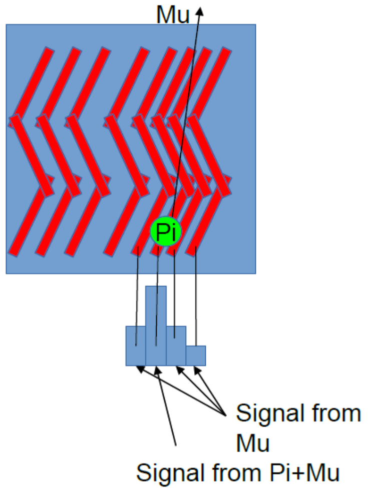
Several challenges ahead

- AC-LGAD is in current development and optimization
  - Might switch to other technologies such as TI-LGADs or DJ-LGADs
- **Recognize hits that are ~1 ns apart** with very different deposited energy
  - **Time separation to tag $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu\nu \rightarrow e\nu\nu$ decays**
  - Positron is a MiP, Muon/Pion are ~100 MiPs
  - Plan for full digitization of events and post-processing analysis
- **Amplifier with large dynamic range**
  - Defined as noise to max, ideally ~2000
- **Low material around ATAR** to reduce impact on positron energy
  - ASIC sitting on flex few cm away from ATAR, digitization outside of active area
  - Send un-amplified signal across a short flex (effect on signal to be studied)
- **Reduce cross talk** (DC-LGADs) and large area charge sharing (AC-LGADs) to avoid non-MiP events covering MiP events
- **Minimize blind regions**, when decayed Muon travels along one strip
  - E.g. plan for zig-zag strip design to have multiple hits from escaping muons

Simulated 120 um LGAD response

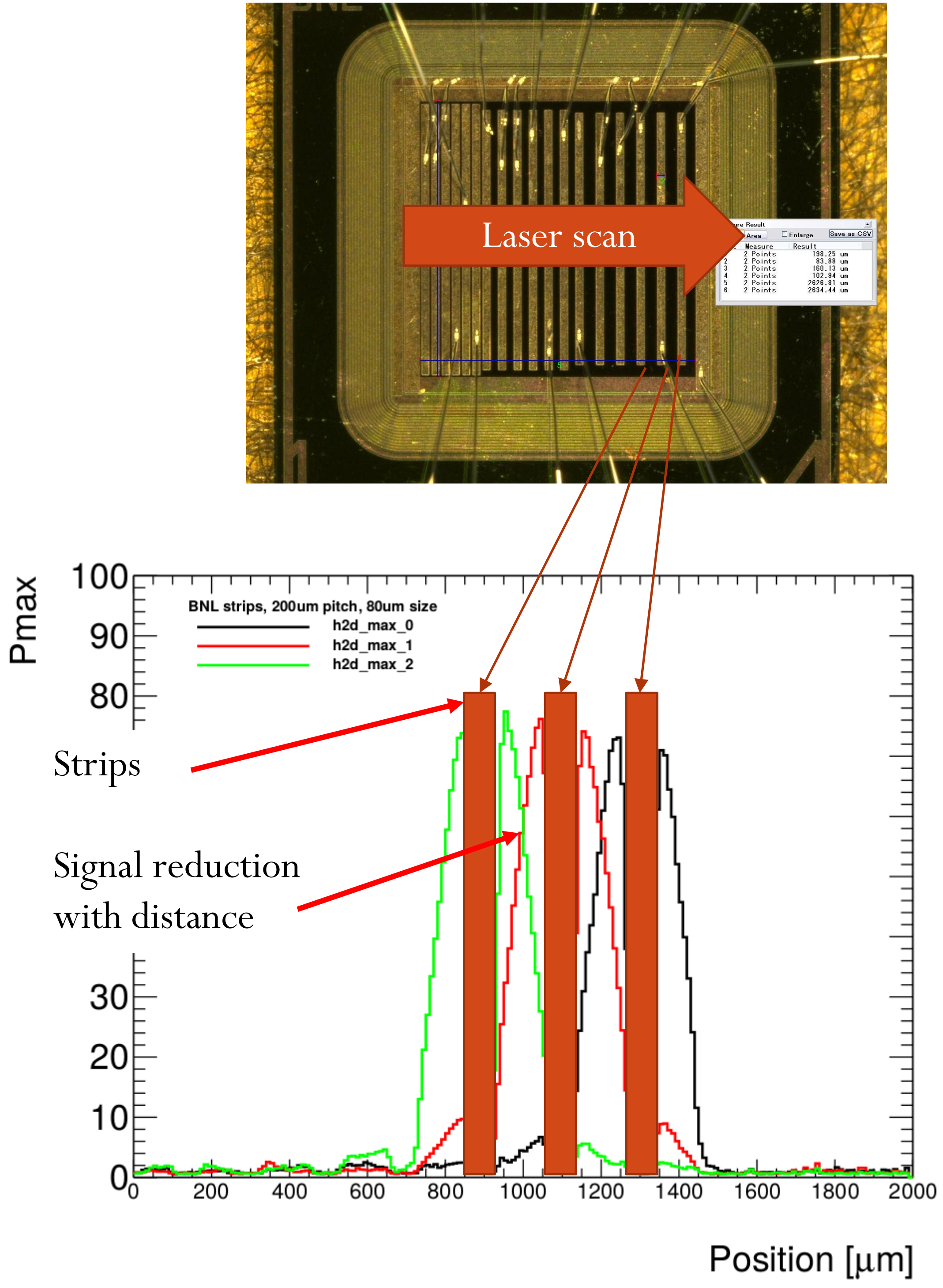




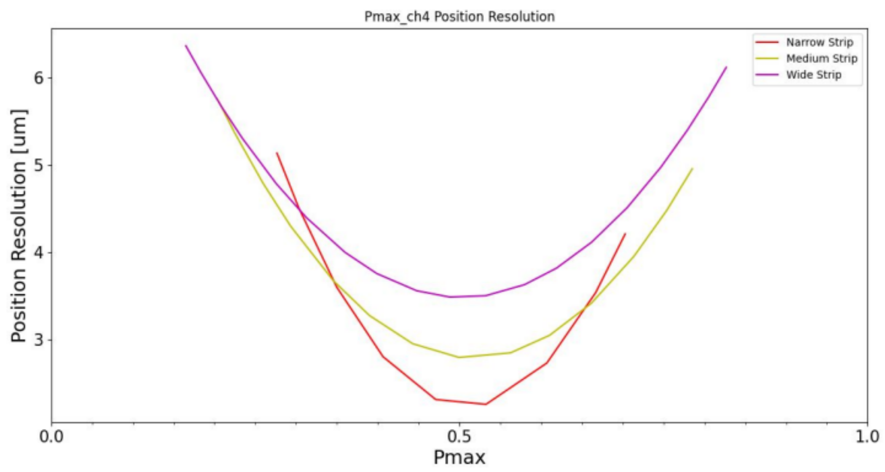


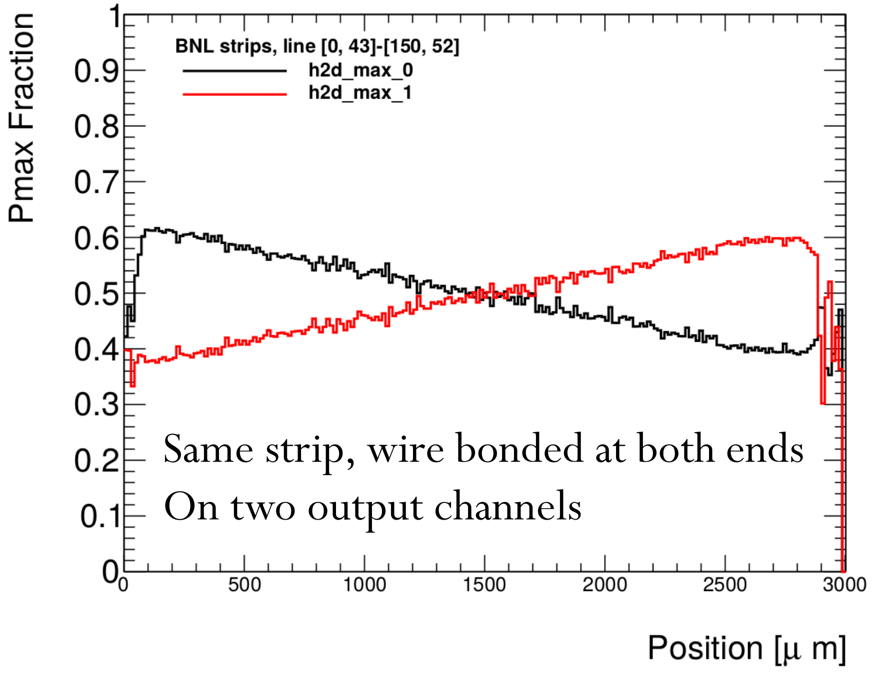
AC-LGAD studies

- Studies on BNL AC-LGAD 2x2 mm strip sensor (50 um)
  - Strip size 80 um, variable pitch: 200um, 150um, 100um (200 um same as design)
  - Same sensor in FNAL TB (results here)
- Sensor mounted on FNAL 16ch board, readout by fast scope
  - Tested with IR laser TCT
- Study the response of the strips vs position
  - AC-LGAD sensor with intrinsic charge sharing
  - Evaluate the reconstructed position resolution
  - Test the area of influence of charge sharing per strip
- Sensor response vs injected charge
  - Effect on charge sharing for ~100 MiPs of deposition
- Waveform shape
  - Undershoot might influence the ability to recognize close-by pulses



AC-LGAD resolution and strip double-sided readout



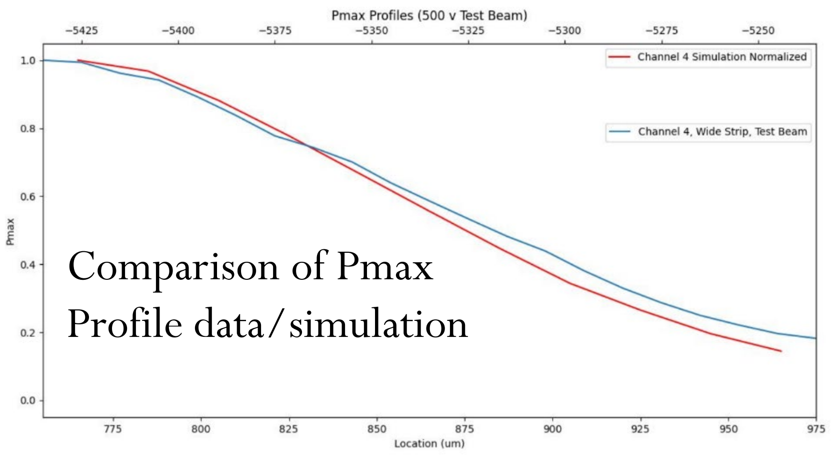


- Hit position resolution estimated from charge sharing function derivative
  - For a 80um strip with 200 um pitch we expect 5-10 um resolution in the direction perpendicular to the strip
- To achieve **hit detection in both X-Y** is possible to **readout the AC strip on both side**
  - Charge sharing between the two ends of the strip
  - Tested to work with TCT laser setup
- For a 2 mm strip the expected hit resolution parallel to the strip is few 100 um
  - For a 2 cm strip (final design) is ~mm
  - Can be extremely helpful in hit detection without increased readout overhead

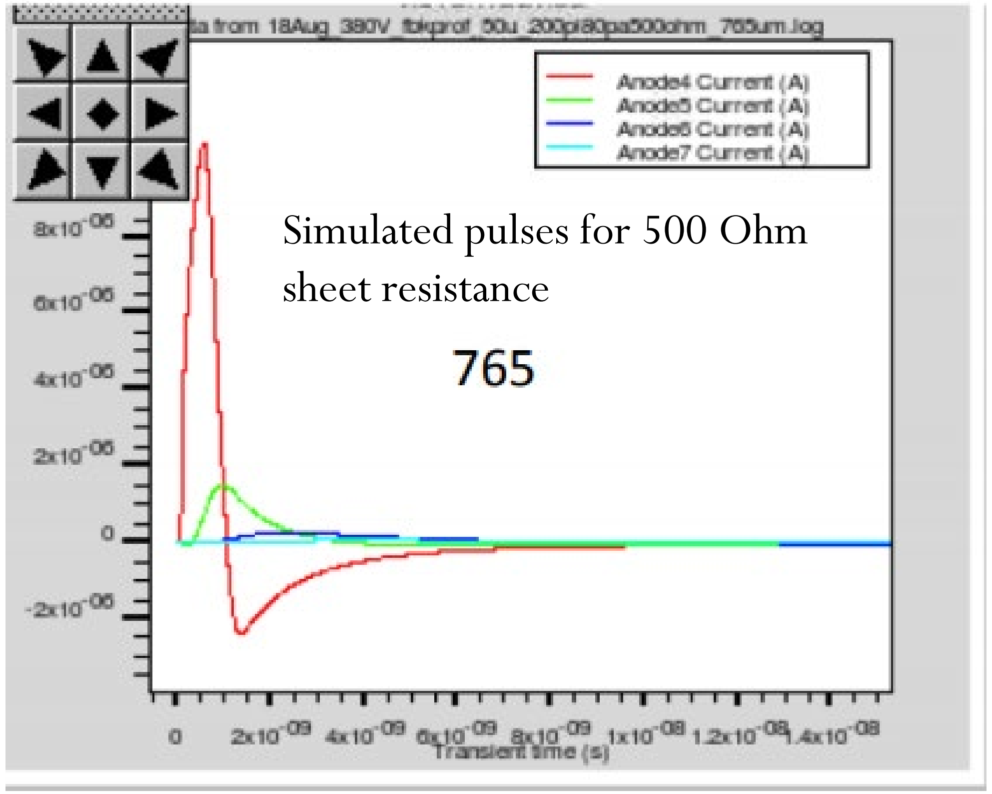
Many thanks to Marcus Wong!

TCAD Silvaco simulation

- AC-LGADs have different parameters that can be optimized for the application
  - Pad geometry, N+ sheet resistance, oxide thickness …
- **TCAD Silvaco simulations to study parameters variations**
  - Simulated strip sensor simulated with same geometry as the studied BNL sensor
  - Vary the N+ doping concentration to compare and match with the real sensor behavior
  - Optimize layout to minimize long range (after first neighbor) charge sharing and undershoot shape
- Predict the behavior of 120 um thick LGAD (final design)
  - Use results as input for prototype production



Comparison of Pmax Profile data/simulation

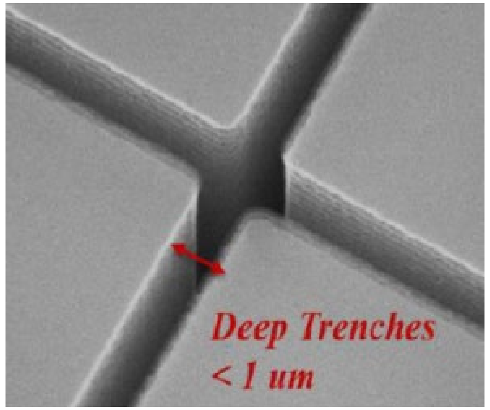


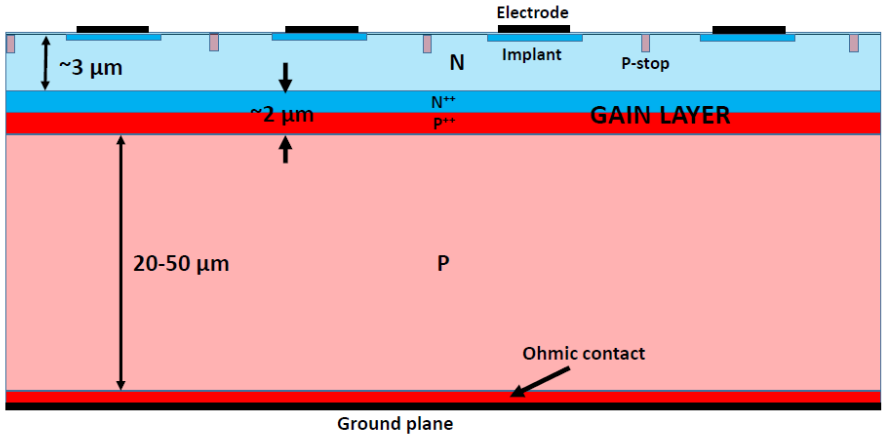
Simulated pulses for 500 Ohm sheet resistance

765

Many thanks to Mohammad Nizam And Marcus Wong!

Alternative higher granularity DC-LGAD prototypes





- Trench insulation of pads → TI-LGAD
  - Insulation between pads with trenches filled with insulator
  - First prototypes by FBK
  - https://doi.org/10.1109/LED.2020.2991351
- Deep junction → DJ-LGAD
  - Gain layer is buried and electric field near surface is low enough to allow standard silicon pixelation
  - First prototype produced at BNL with EPI growth
  - (Patent Application SC 2019-978 (UCSC))
  - https://arxiv.org/abs/2101.00511

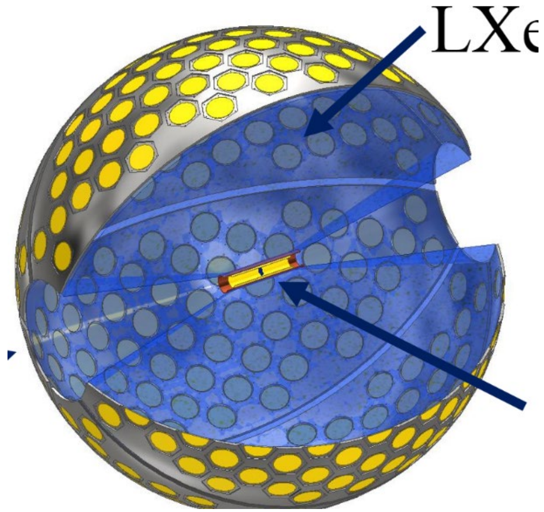
Gain suppression issue

- Recent results at TREDI and RD50 showed LGAD **gain suppression for high gain or large charge deposit**
  - https://indico.cern.ch/event/983068/contributions/4223231/, https://indico.cern.ch/event/1029124/contributions/4411287/, https://indico.cern.ch/event/1029124/contributions/4410381/
- Studied with TCT-laser and low energy ions
- Crucial parameter to be understood
  - Energy deposit can be as high as ~100 MiP in PIENUX
  - In extreme cases up to ~1000 MiP
- For pions it can be corrected (incident angle with sensor is known)
  - For decay muons it might be an issue
- However, it might reduce the dynamic range need of the amplifier
- Impact on hit reconstruction to be studied with simulation

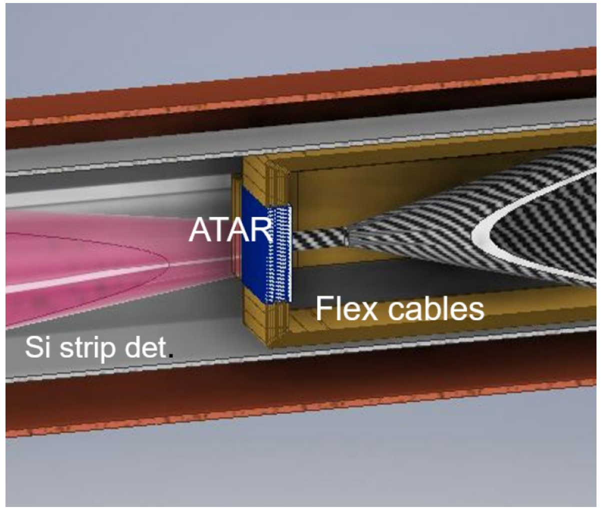
- **Plan to study the gain saturation effect on AC-LGAD strips in the next year at the University of Washington (CENPA) tunable energy ion beam**

Conclusions

- **PIENUX will provide precise measurement of $R_{e/\mu}$ reaching the same level of precision of the theory calculation**
  - This quantity is very sensitive to BSM processes of scalar and pseudo-scalar coupling
  - LFU violation is a topic of great interest these days
- Furthermore it will allow for **precision measurements of pion beta decay BF**
- Additional physics searches are also foreseen (such as ALPs and sterile neutrinos searches)



- PIENUX will feature an active target to separate $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu\nu \rightarrow e\nu\nu$ decays
  - Full silicon target of LGAD sensors (ATAR), crucial to suppress pion decay in flight
- **ATAR development will face many challenges**
  - Exploit for the first time high-density LGAD prototypes
  - Requires compactness and low inactive material all around
  - Development of readout ASIC with high dynamic range and trigger suitable for full digitization



- PIENUX is expected to start data taking in the **timescale of 5 year**
  - The PIENUX collaboration include experts from PIENU, PEN, NA62, MEG, Muon g-2, ATLAS and leading theorists

Abstract

PIENUX is a next-generation experiment to measure the charged-pion branching ratios to electrons vs muons, $R_{e/\mu}$ and pion beta decay (Pib) $\pi^+ \rightarrow \pi^0 e\nu$. $R_{e/\mu}$ provides the best test of e-μ universality and is extremely sensitive to new physics at high mass scales; Pib could provide a clean high precision value for V_{ud}. Order of magnitude improvements in precision to these reactions will probe lepton universality at an unprecedented level, determine V_{ud} in a theoretically pristine manner and test CKM unitarity at the quantum loop level. The pion to muon decay ($\pi \rightarrow \mu \rightarrow e$) has four orders of magnitude higher probability than the pion to electron decay ($\pi \rightarrow e\nu$). To achieve the necessary branching-ratio precision it is crucial to suppress the $\pi \rightarrow \mu \rightarrow e$ energy spectrum that overlaps with the low energy tail of $\pi \rightarrow e\nu$. The high-acceptance and high-resolution design of the PIENUX calorimeter allows to reduce the tail correction to be < 0.01%.

A high granularity active target (ATAR) is being designed to suppress the muon decay background sufficiently so that this tail can be directly measured. In addition, ATAR will provide detailed 4D tracking information to suppress other significant systematic uncertainties (pulse pile-up, decay in flight of slow pions) to < 0.01%, allowing the overall uncertainty in $R_{e/\mu}$ to be reduced to O(0.01%). The high precision 4D tracking would allow to separate the energy deposits of the pion decay products in both position and time. The chosen technology for the ATAR is Low Gain Avalanche Detector (LGAD). These are thin silicon detectors (down to 50 μm in thickness or less) with moderate internal signal amplification (up to a gain of ~50). LGADs are capable of providing measurements of minimum-ionizing particles (MiP) with time resolution as good as 17 ps. In addition, LGADs have fast rise time and short full charge collection time. The ATAR would be made of 48 planes of 2×2 cm strip LGADs with 120 μm of active thickness. To achieve a ~100% active region several technologies still under research are being evaluated, such as AC-LGADs and TI-LGADs. A dynamic range from MiP (positron) to several MeV (pion/muon) of deposited charge is expected, the detection and separation of close-by hits in such a wide dynamic range will be a main challenge. Furthermore the compactness and the requirement of low inactive material of the ATAR present challenges for the readout system, forcing the amplification chip and digitization to be positioned away from active region.

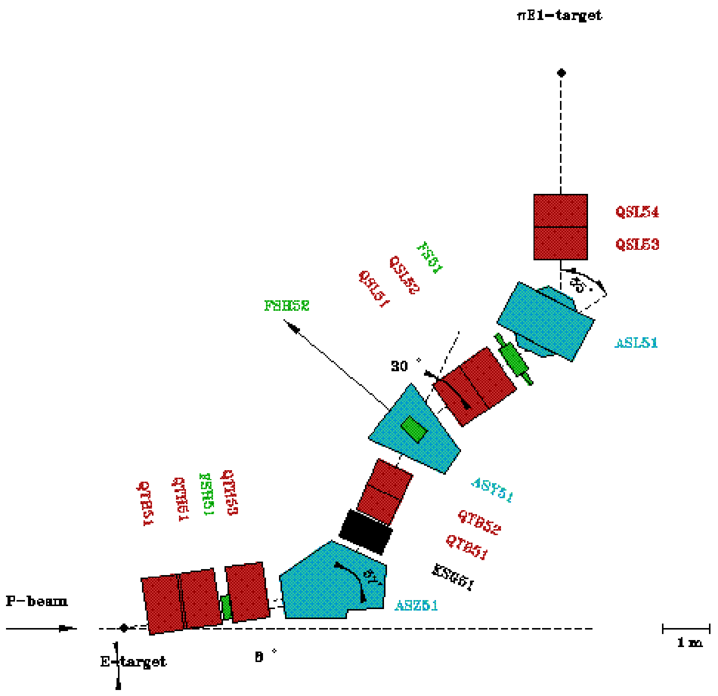
Pion beam requirements and PSI beam lines

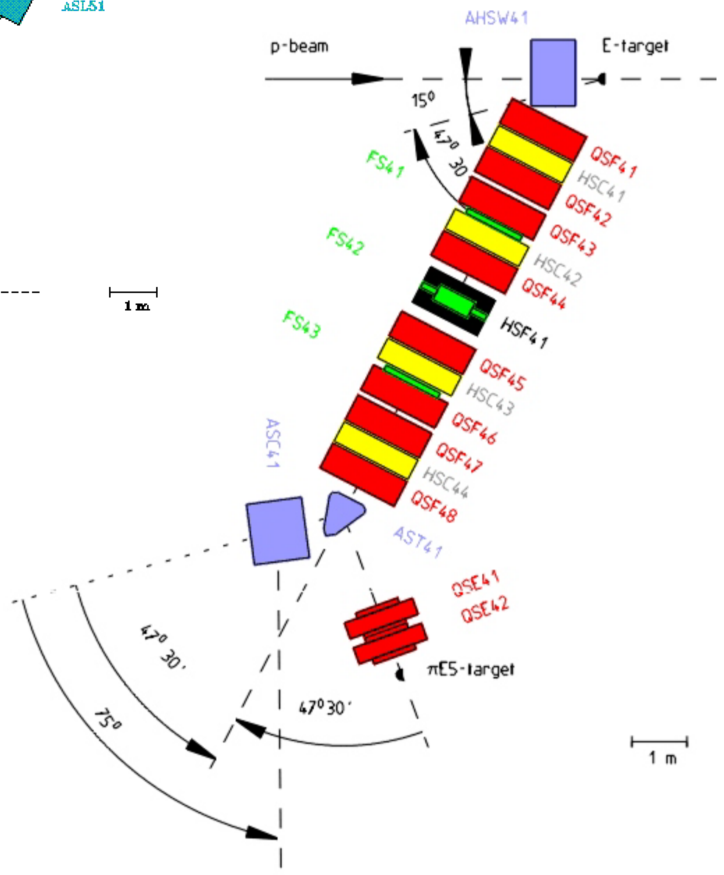
$\pi \rightarrow e\nu:$

- π^+ Beam: 75 MeV/c ; $\frac{\Delta p}{p} \sim 1\%$; $3\text{x}10^5$ Hz
- $3\text{ x}10^8$ events; $R_{e/\mu} \pm 0.01\%$ in 2 yrs

$\pi^+ \rightarrow \pi^0 e\nu:$

- π^+ Beam: 100 MeV/c ; $\frac{\Delta p}{p} \sim 3\%$; 10^7 Hz
- $7\text{ x}10^6$ events; $R_{\pi\beta} \pm 0.04\%$ in 4 yrs





- **piE1** is nominally agreed to be a 50:50 share of muSR and particle physics.
  - 1% dp/p, but low flux $\sim 10^7 (mA \cdot s)^{-1}$ (perhaps enough for pienu phase)
  - PIENUX would be in forward area and crane in-out
- **PiE5** is where MEG II sits and early Mu3e.
  - 2% dp/p, and higher flux $\sim 10^9 (mA \cdot s)^{-1}$(maybe enough for both pienu and pibeta phases)

$\pi \rightarrow e\,\nu$: Estimated Uncertainties

To be verified by simulations and prototype measurements.

PIENU (Current)		PIENUX	
Statistics	0.19%	0.006%	
Tail correction	0.12%	< 0.01%	(Calorimeter/ATAR)
t_0 correction	0.05%	--	*(ATAR timing)*
μ decay-in-flight correction	0.05%	*< 0.01%*	*(ATAR)*
Fitting parameters	0.05%	< *0.01%*	(Calorimeter/ATAR) *
Selection cuts	0.04%	< *0.01%*	(Calorimeter/ATAR) *
Acceptance correction	0.03%	*0.005%*	(Calorimeter)
Total	0.25%	**< 0.02%**	

* Reductions in uncertainties due to reduced pile-up effects.

$\pi^+ \rightarrow \pi^0 e^+ \nu$: Estimated Uncertainties

	PiBeta	**PIENUX**	
Statistics	0.4%	0.04%	
Systematics	0.4%	<0.04%	(ATAR (β), MC, Photonuclear, $\pi \rightarrow e\,\nu$)
Total	0.64%	**0.06%**	

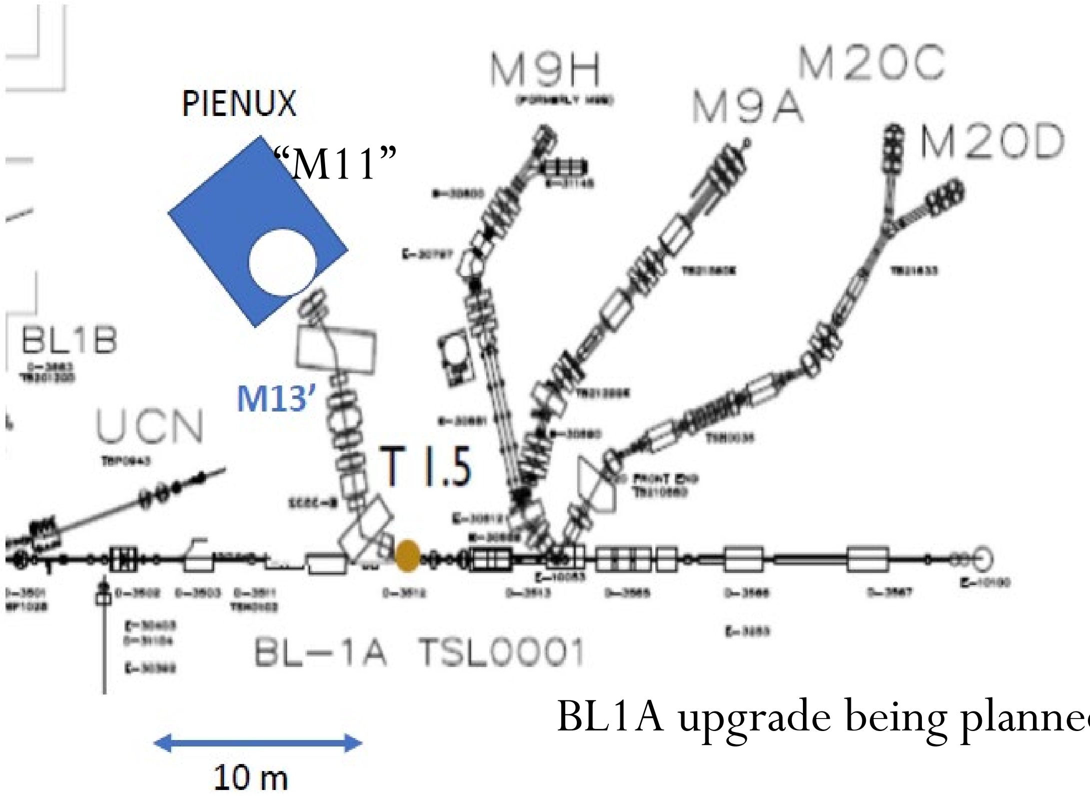
PIENUX: Beam Requirements and Possibilities at TRIUMF

$\pi \rightarrow e\nu$:

- π^{+}Beam: 75 MeV/c ; $\dfrac{\Delta p}{p}$~1%; $3\mathrm{x}10^{5}$ Hz
- 3 $\mathrm{x}10^{8}$ events; $R_{e/\mu}$ ±0.01% in 2 yrs

$\pi^{+} \rightarrow \pi^{0} e\nu$:

- π^{+}Beam: 100 MeV/c ; $\dfrac{\Delta p}{p}$~3%; 10^{7} Hz
- 7 $\mathrm{x}10^{6}$ events; $R_{\pi\beta}$ ±0.04% in 4 yrs



BL1A upgrade being planned.

TRIUMF

- M9A – only existing possibility
- New target station T1.5/beamline M13';
  PIENUX in current M11 area

A new large acceptance backward angle beamline (M13') viewing a 4 cm Be production target (T1.5) would satisfy the PIENUX requirements.