A Vision on $\pi e\nu$ Acceptance/Tail/Pile-up

-- Thoughts on relations between ATAR and CALO

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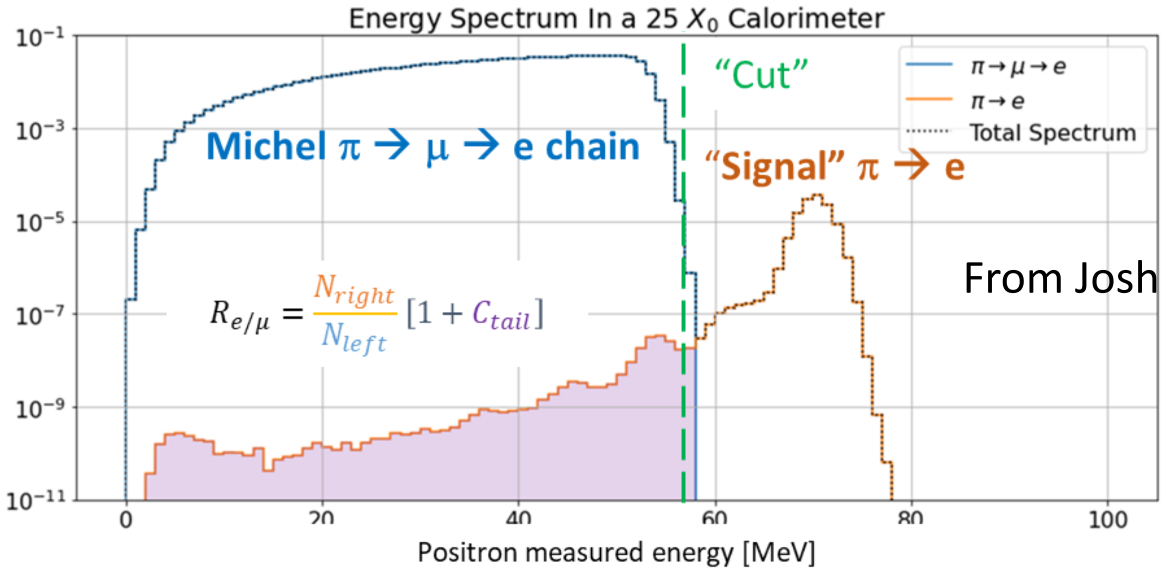
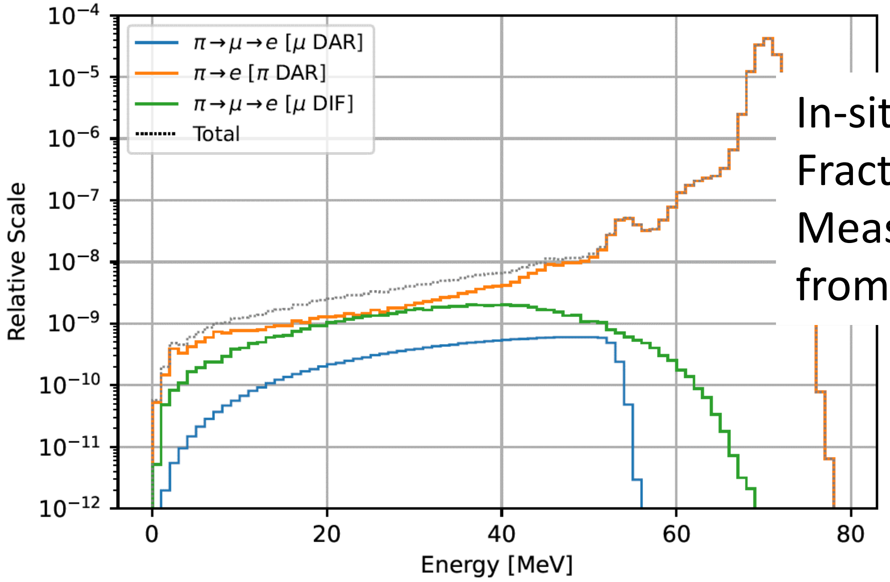
BNL

Measurement of $R^{\pi}_{e/\mu}$ in a Nutshell

- **Acceptance** difference between πeν and πμν must be known < 10^{-4}
  - 70 MeV vs. (0-52) MeV positron
  - 760 um or 4.2 MeV muon in πμν
- Absolute **tail correction** must be known < 10^{-4}
  - Better than 1% (0.5%) precision on a 1% (2%) tail fraction
- **Tail fraction** determined by energy separation between πeν and πμν, materials before CALO, and CALO acceptance (angular & depth)
  - Overall energy resolution
  - **Pileups**
- Sufficient event statistics → 300 kHz rate …



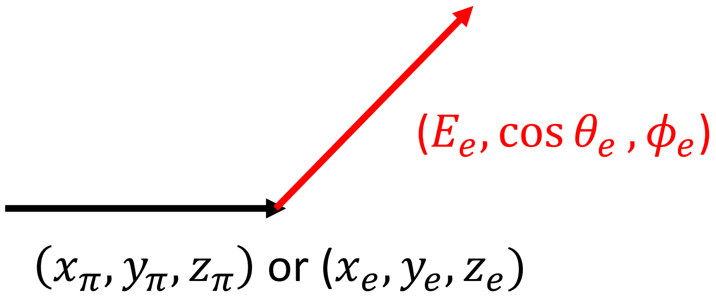
From Josh



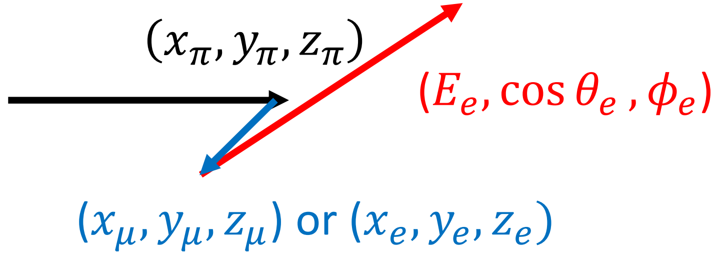
In-situ Tail Fraction Measurement from Vincent

Acceptance Difference between πeν and πμν

- πeν signal integrated over: $N_\pi(x_\pi, y_\pi, z_\pi) \times \epsilon(x_\pi, y_\pi, z_\pi, E_e, \cos\theta_e, \phi_e)$
  - (x_π, y_π, z_π): π decay location vector
  - $(E_e, \cos\theta_e, \phi_e)$: positron momentum vector
  - E_e ~ 70 MeV



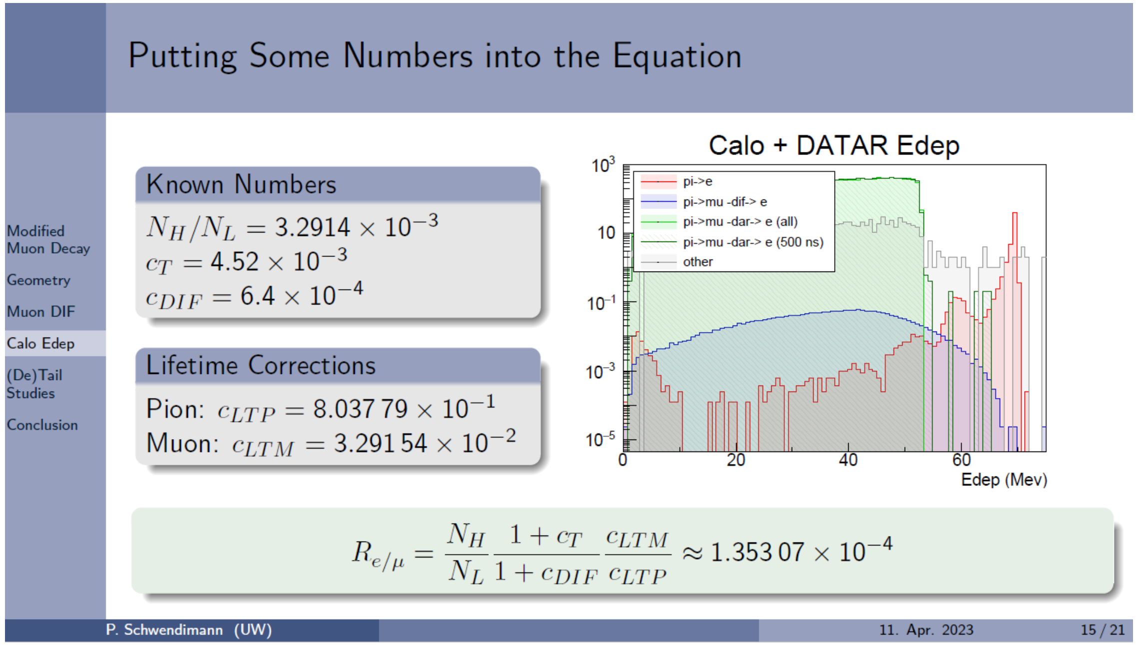
- πμν background integrated over: $N_\pi(x_\pi, y_\pi, z_\pi) \times \epsilon(x_\mu, y_\mu, z_\mu, E_e, \cos\theta_e, \phi_e)$
  - In addition, (x_μ, y_μ, z_μ): μ decay location vector
    - In average, (x_π, y_π, z_π) is separated from (x_μ, y_μ, z_μ) by about 760 um
  - E_e up to 52 MeV



- Define acceptance based on (x_π, y_π, z_π) and $(\cos\theta_e, \phi_e)$
  - Requiring the 'same' π decay location to minimize inaccuracy from beam profile
  - Requiring the same positron angle to minimize the difference in positron energies
  - No energy cut required

Impact on An Energy Cut

- Requiring CALO hit (i.e. energy cut) introduce a large (~10%) acceptance difference between πeν and πμν
  - <10^{-3} precision on this correction needed



- ATAR is an excellent tracking calorimeter,
  but big … → Define acceptance by ATAR only

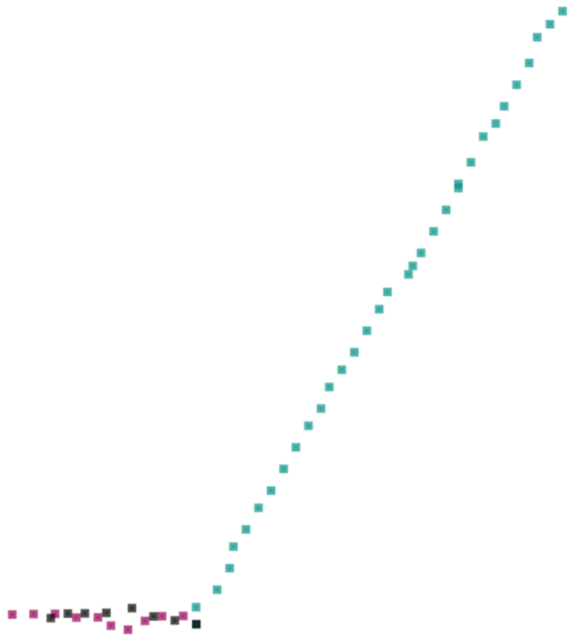
	Values	Uncertainties Stat	Uncertainties Syst
$R^{Raw}_{e/\mu}$ (10^{-4})	1.1972	0.0022	0.0005
π,μ lifetimes			0.0001
Other parameters			0.0003
Excluded components			0.0005
Corrections			
Acceptance	0.9991		0.0003
Low-energy tail	1.0316		0.0012
Other	1.0004		0.0008
$R^{Exp}_{e/\mu}$ (10^{-4})	1.2344	0.0023	0.0019

TABLE I: The table includes the raw branching ratio with its statistical and systematic uncertainties, the multiplicative corrections with their errors, and the result after applying corrections.

Pienu sys. Table PRL 115, 071801

Minimizing Acceptance Difference

- Define acceptance based on (x_π, y_π, z_π) and $(\cos\theta_e\,, \phi_e)$
  - Requiring 5 hits in reconstructing the positron track (up to 1000 um)
- What is the impact on acceptance w.r.t energy?
  - A positron's energy threshold ~ 0.5 MeV (940 um travel distance) → $\mathbf{2 \times 10^{-6}}$ **acceptance loss** considering Michel spectrum
- What is the impact on acceptance w.r.t angles?
  - > 15 degrees Bhabha scattering within 1000 um Si
    - πeν: 4.4×10^{-5} vs. πμν: 2.4×10^{-4}
    - Placing a cut on large-angle scattering or bear the correction → difference in acceptance ~ 10^{-4} level

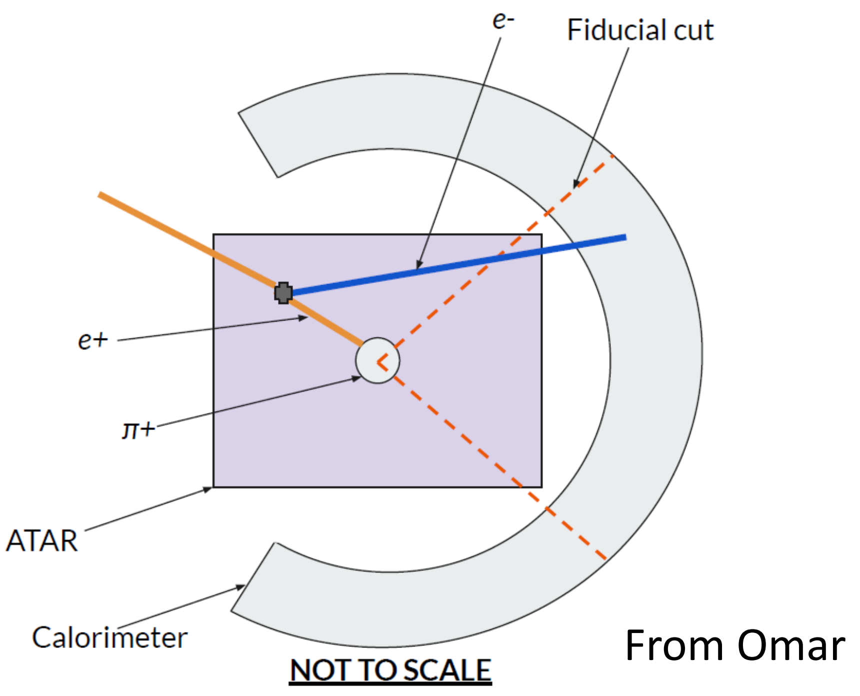


Taken from ν-Ar interaction in LArTPC, reconstructed by Wire-Cell

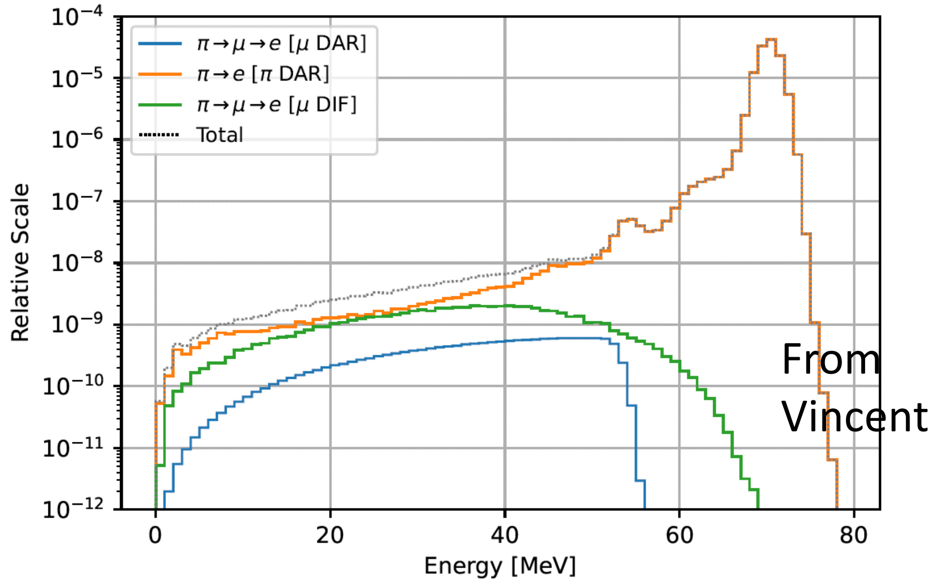
https://www.phy.bnl.gov/twister/bee/set/uboone/lee/2021/wire-cell-far/event/3/

Tail Fraction Measurement

- Given this definition of the acceptance, the πeν tail would be coming from
  - Energy loss in dead materials → minimizing dead materials
  - Large-angle Bhabha scattering leading to outside CALO acceptance → minimizing materials + enlarging CALO acceptance
  - Missing energies in the system (e.g. photo-disintegration) → some being irreducible
- Since ATAR is big & non-4π CALO, **it is critical to require in-situ tail fraction measurement in entire phase space (positron & angle)**
  - Cross-validation with tail fraction measurement of the positron beam at 0 degree

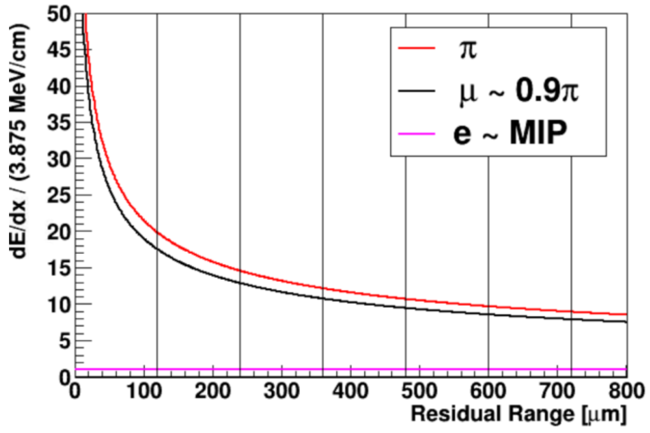


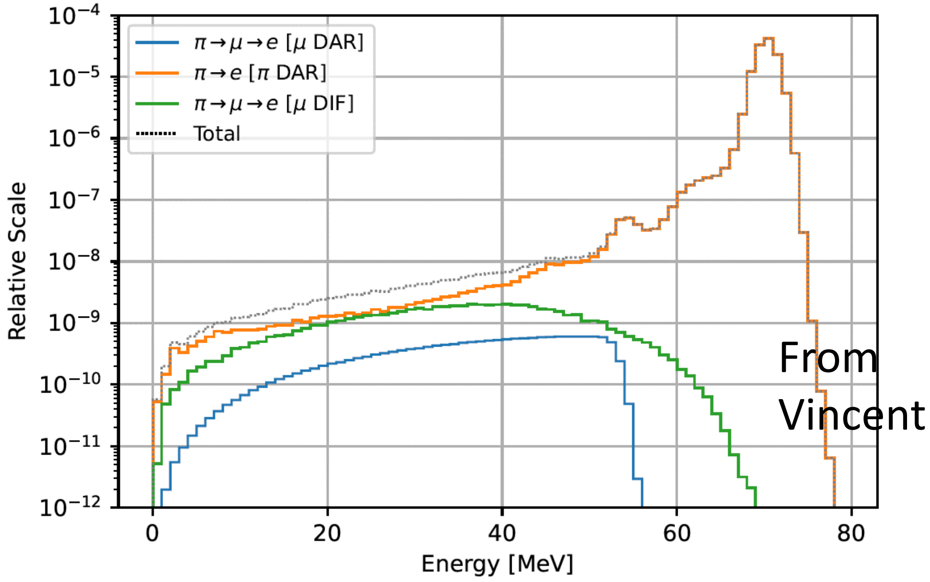
From Omar



Tail Fraction Measurement → ATAR Design

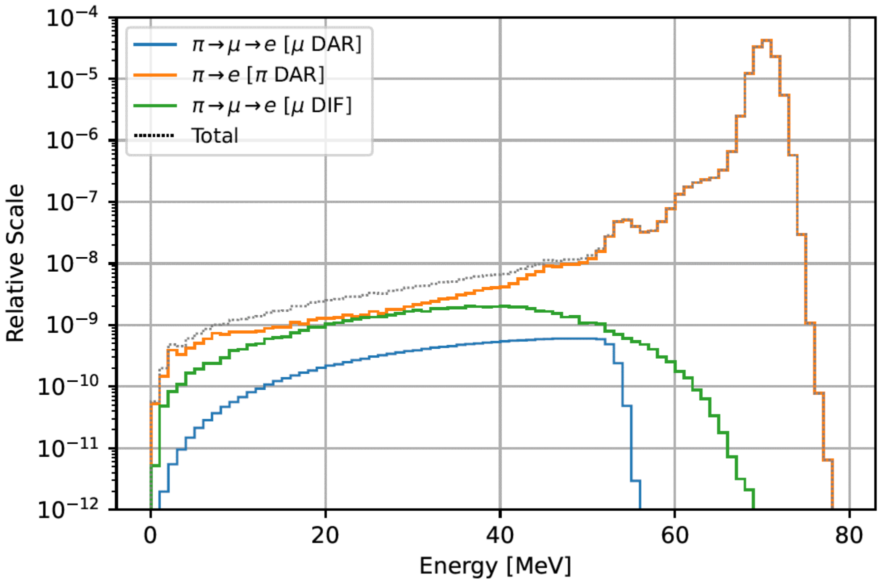
- The key to the tail fraction measurement is to identify the muon
  - πDAR-μDAR (π → μ → e): Timing and topology of three distinguished tracks and energy of the muon track
  - πDIF-μDAR (π/μ → e): Kink between π and μ, energy separation between π and μ
  - πDAR-μDIF (π→ μ/e): Energy of the muon, distance between pion and positron tracks
- Based on existing work, πDAR-μDIF is the most difficult (~5% of tail), improvements include
  - BDT instead of the simple energy cut
  - 2-sided readout to limit range of dE/dx
  - Energy resolution & minimizing gaps/dead regions





Comparison of Existing Studies → We need to do better!

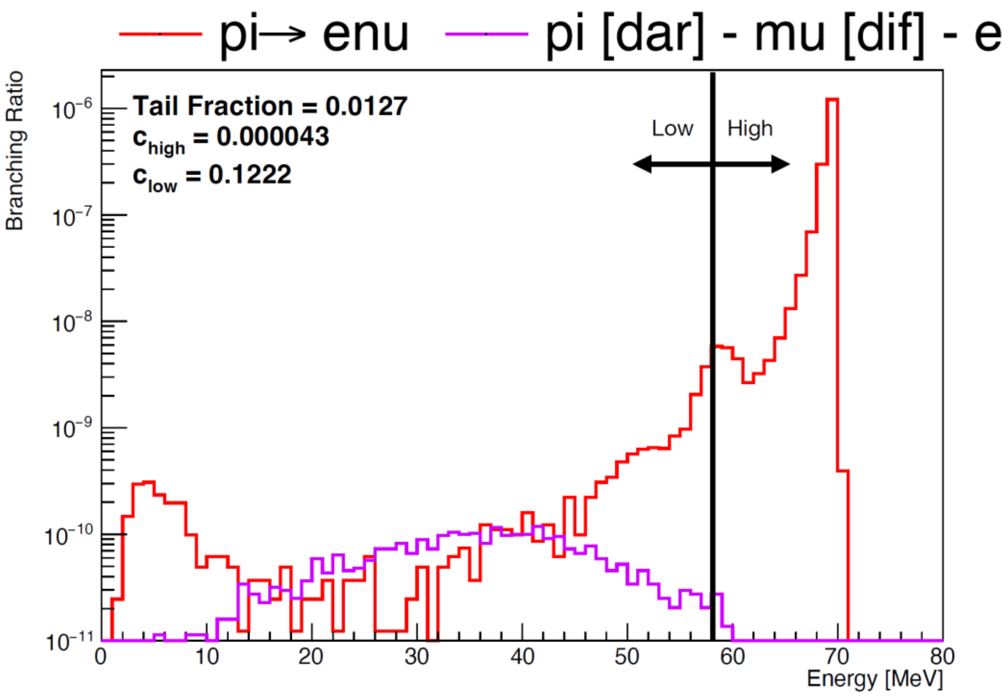
Simple Energy Cut from Vincent



Background @ ~5% of the πev tail, first proof-of-principle demonstration

Cons: bias in acceptance, x5 reduction in signal efficiency, also ideal geometry

dE/dx along z cut from Patrick/Quentin



Background @ ~12% of the πev tail with updated detector simulation (Goals @ 1%)

Room for improvements in 3D dE/dx in separating e vs. (e+μ), correlation in hits' dE/dx

Trigger Considerations

- Dedicated trigger to measure tail fractions does not have much room for any pre-scale for the consideration of sufficient statistical uncertainties
  - Dominated by the πμν events, (5,100) ns coincidence trigger → 3.3% of πμν events (~10 kHz)

- To suppress the massive amount of πμν and other background events
  - coincidence time (π-e/μ)
  - coincidence positron (π-e/μ)
  - energy cut on the delayed hit to suppress π-μ coincidence?
  - other ideas?

What is the requirement on the efficiency for the tail fraction measurement?

- Aim to collect 2×10^8 $\pi e \nu$ events
  - Statistics uncertainty: 0.7e-4 level
- @ 1% tail fraction for pienu events (or 2×10^6 events)
  - The tail correction will be about 1%, need to control the uncertainties of this correction to be < 0.7% (stat uncertainty)
  - Need at least 4×10^4 events
  - The overall efficiency for tail fraction measurement needs to be **more than 2%**
  - db-94 (Vincent) shows the current efficiency @ 5.4%
    - Can be significantly improved

```
== Creating output file: filtered_pienu_pidar.root
                     init: 1.17999e+06 (100%)
        e+ timing window: 740276 (62.7356%; 62.7356%)        -- in-ATAR pion DIF suppression
      central/tot energy: 671795 (56.9321%; 90.7493%)
               BDT score: 446241 (37.8172%; 66.4252%)
       post-stop energy: 63395 (5.37248%; 14.2064%)        -- muon DIF suppression
```

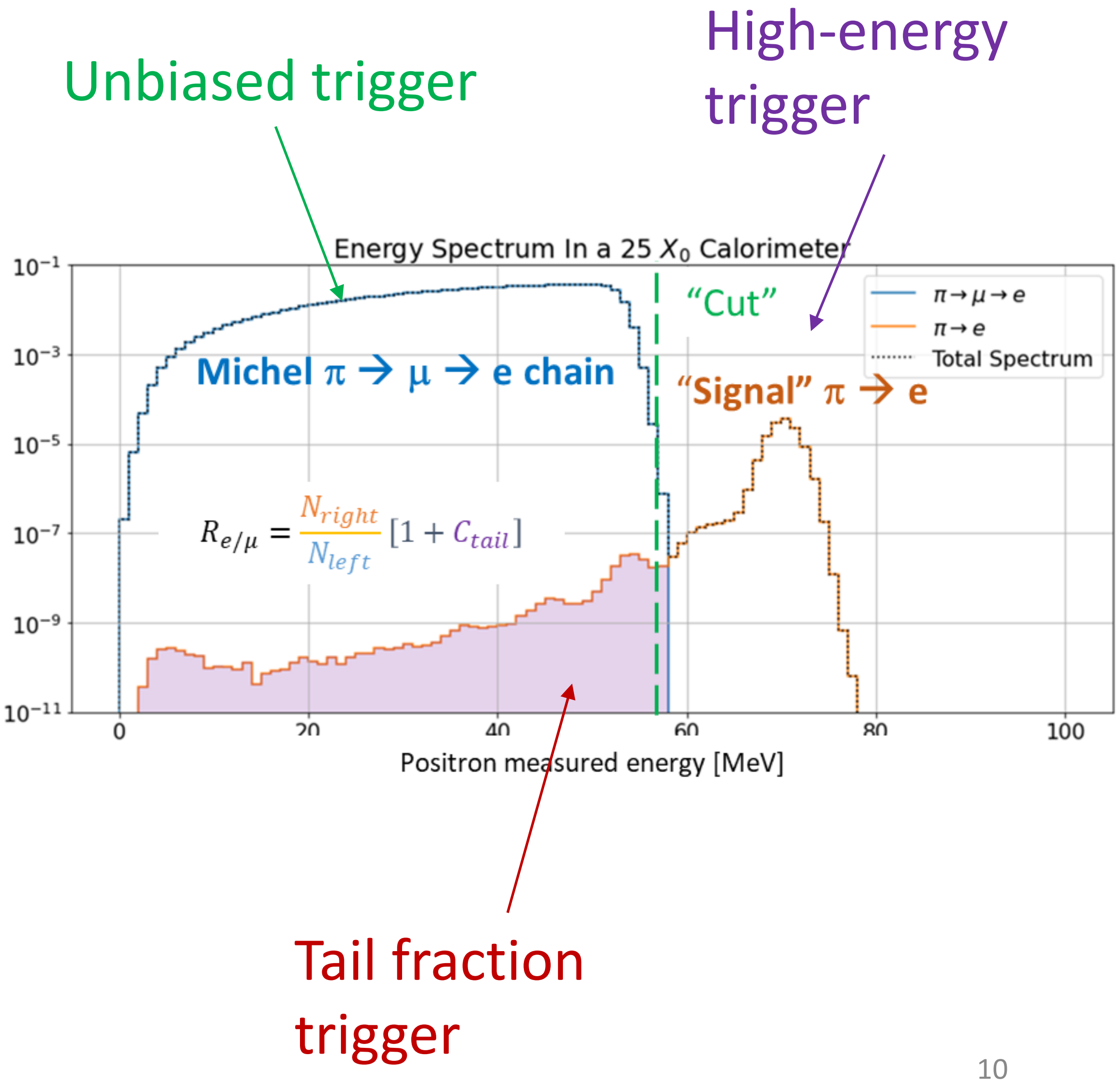
1

5-100 ns

- Pion lifetime correction: $\int_5^{100} e^{-t/t_\pi} dt$ =0.8038
- Pion-muon lifetime correction:
- $\int_5^{100}\int_x^{100} e^{-(y-x)/t_\mu} dy\, e^{-x/t_\pi} dx + \int_0^5 \int_5^{100} e^{-(y-x)/t_\mu} dy\, e^{-x/t_\pi} dx$
- =0.02570399 + 0.00738634 = 0.0330903
- Tmu = 2197.03 ns
- Tpi = 26.033 ns

Trigger Considerations

- High-Energy Trigger:
  - CALO + ATAR energy;   No pre-scale
  - Aim at high-energy πeν
- Tail fraction measurement:
  - ATAR-only; coincidence time & vertex & energy; No pre-scale
  - Aim at πeν
- Unbiased trigger: large pre-scale
  - Maybe with a coincidence timing?
  - Aim at πμe



ATAR Pileup Events

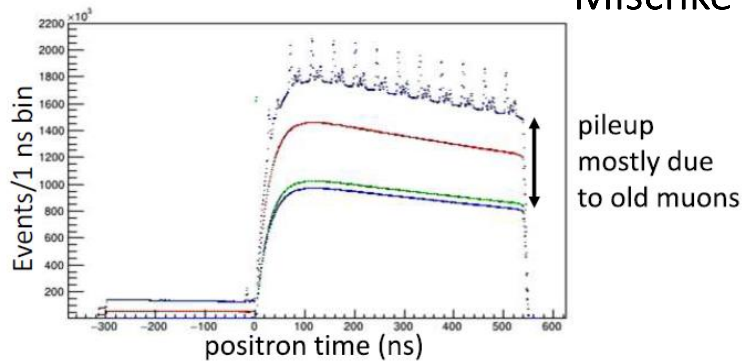
- Given the expected timing and position resolution of ATAR, pile-up is **NOT** an issue
  - 300 kHz rate → in-average 3.3 us separation between two events
  - ~5000 channels with O(100) um position resolutions
  - O(100) ps track timing resolution
  - Also track topology information

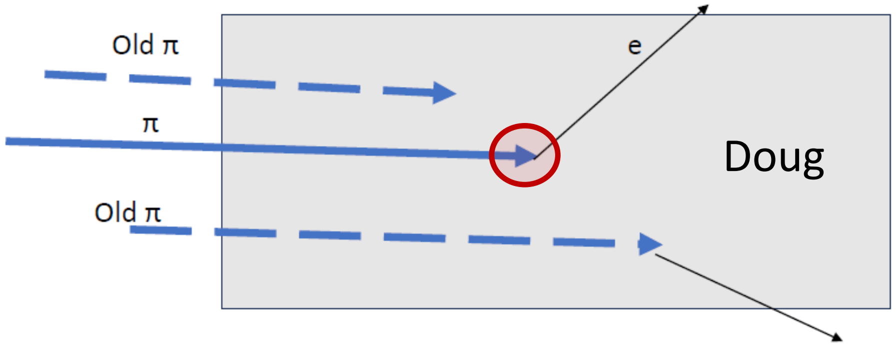
- Coincidence position requirement will eliminate old-muon-positron by O(100,000) level

Effect of pileup cuts on the time spectrum

- The pileup cuts are severe: ~35% of events pass
  - Black: after cuts to select incident pions
  - Red: after pileup cuts in scintillators
  - Green: after cuts for early-time pileup
  - Blue: after all selection cuts

Mischke





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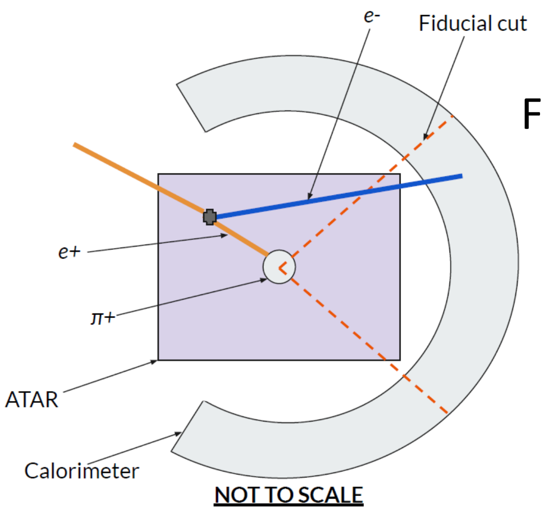


CALO Pileup Events

- Signals: positron or positron + electron from Bhabha scattering
  - Real coincidence for electrons from Bhabha scattering
- Pile-up background: positron + positron from old muons
  - Random coincidence

- With acceptance defined by ATAR only, only rely on the coincidence timing between ATAR and CALO hit cluster to deal with pile-up
  - O(100) ps timing resolution would be great
  - Advantage of XTal CALO option in separation

- With SiPM installed on the LXe CALO inner surface, the separation of pile-up events can be better, **worth it?**
  - Josh's study showed separation power with only outer-surface PMTs

Eur. Phys. J. C (2016) 76:434

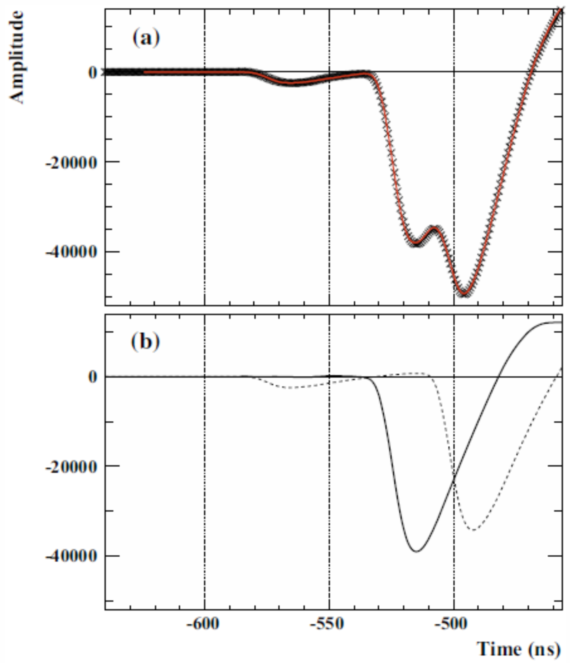
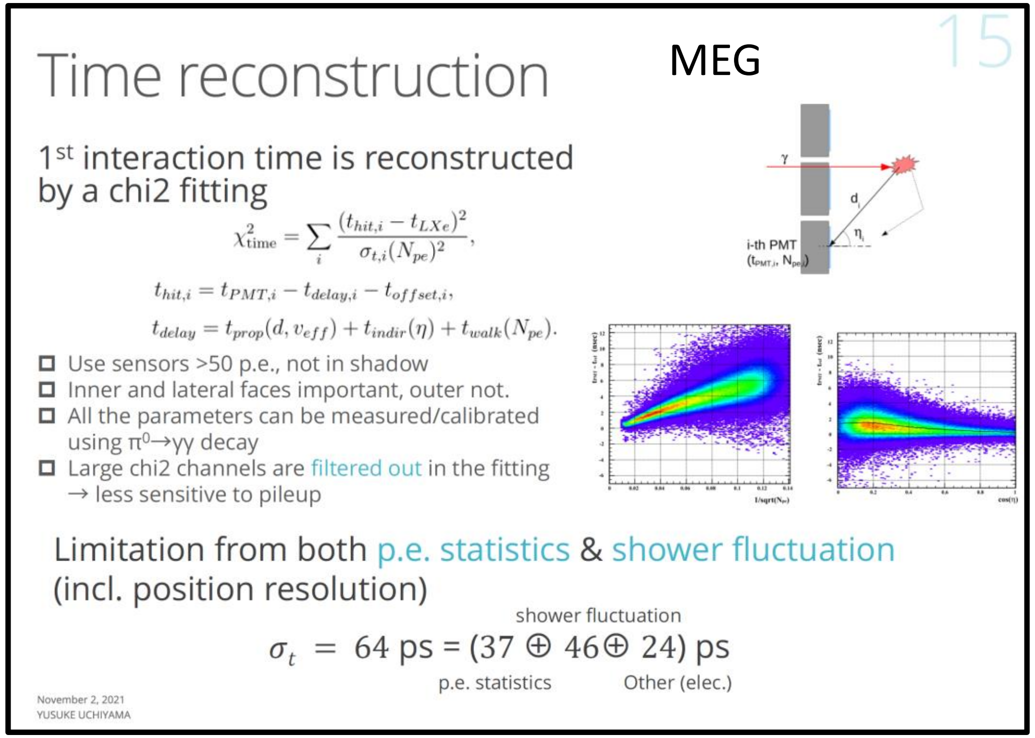
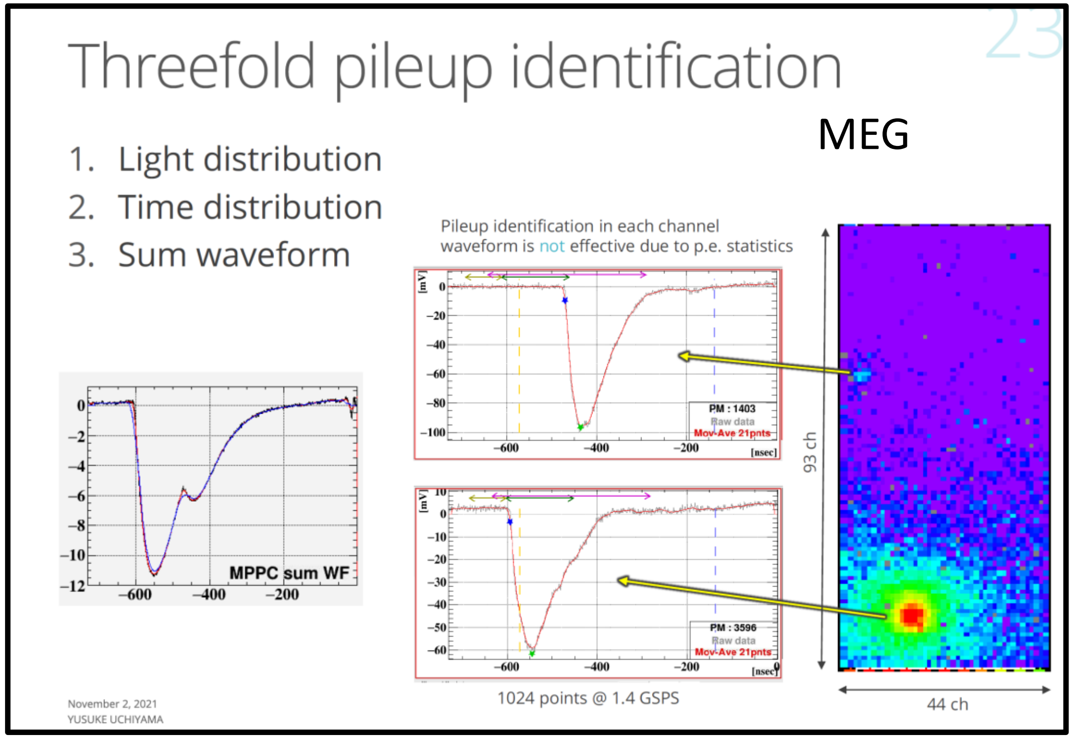


Fig. 10 **a** Example of a LXe detector waveform for an event with three photons (2.5, 40.1 and 36.1 MeV). The *cross markers* show the waveform (with the digital high-pass filter) summed over all PMTs with the coefficients defined in the text, and the *red line* shows the fitted superposition of three template waveforms. **b** The unfolded main pulse (*solid line*) and the pile-up pulses (*dashed*)

LXe CALO Event Reconstruction





- SiPM installed on the inner surface will allows for
  - Better timing information, good position separation
  - With a likelihood function, one can achieve a simultaneous fit of individual energies of pile-up events
- How to properly calibrate the light propagation models? ATAR-CALO or TPC?

Budget of Existing Dead Material

Detector	Description	Material/Radiation Length	Percentage
ATAR	Guard Ring (from Gabriele)	400 um Si /9.38 cm	0.45%
ATAR Cable	Up to 12 in each side (from Adam)	(100 um Kapton /28.6 cm + 50 um Copper / 1.43 cm)	Up to 4.6%
Tracker	From Josh From JaDeep*	2 mm Epoxy / 35 cm	0.57% 2%*
LXe Cryostat wall*	From Josh	2 mm Al/ (8.89 cm) Be will be better	2.2 %
LXe Cryostat wall	From Satoshi	Inner surface + honeycomb + outer surface	2.3%+1.8%+4.0% = 8.1%
SiPM inner Surface	From Satoshi	CFRP frame + PCB (and spacer) + MPPC	2.9%

Summary

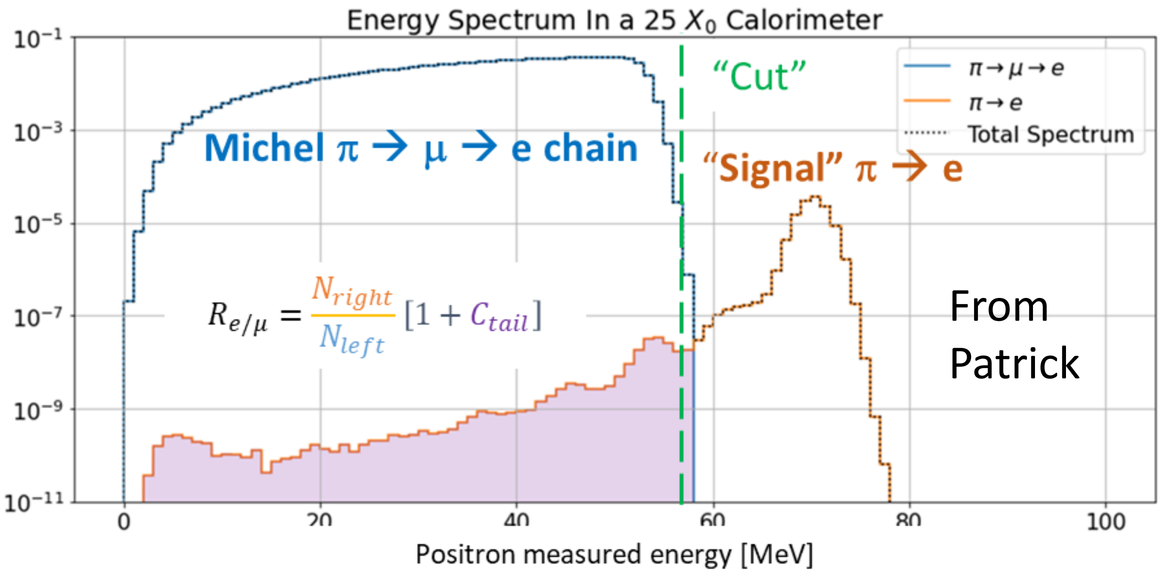
- ATAR-only πeν/ πμν acceptance definition can minimize difference to 10^{-4} level
  - Trigger scheme is the key R&D challenge

- In-situ πeν tail fraction measurement (at 10^{-4} level) in the entire phase space is critical
  - Cross-validation by a positron beam at 0 degree
  - Relax requirements on the precise knowledge of dead materials and geometry
  - ATAR design and analysis is the key R&D challenge

- CALO (ATAR) pile-up events can be (isn't) a challenge
  - Only rely on coincidence timing to separate signal (incl. Bhabha scattering) from background (pile-up)
    - Natural advantage of Xtal CALO option
    - Further studies will decide if inner-surface SiPMs are essential

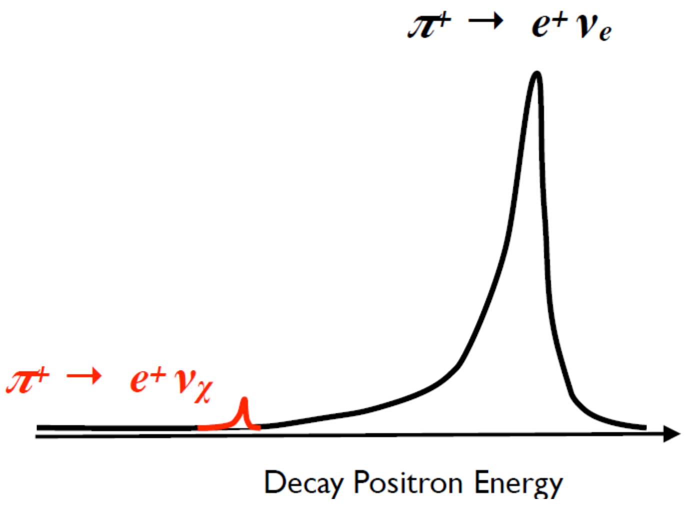
Energy Resolution

- Overall system energy resolution (CALO + ATAR) is crucial to PIONEER physics goals
  - Separation of πeν from πμν
  - Search for physics beyond SM in terms of exotic decays



- CALO energy resolution < ~2% @ 70 MeV

- ATAR energy deposition can in average range from 1.2 MeV to 10 MeV
  - Since ATAR is big, we need to include ATAR energy into the overall energy estimation
  - A good energy resolution is preferred



About dead materials

- ATAR
  - See Adam's talk, and
- ATAR Cable
  - 50 micron thick cables, 50% copper and 50% kapton
- Tracker
  - 1.6 mm epoxy backing and some thin gas, equivalent of 1 mm beam window, O(0.1) mm copper
- LXe Cryostat
  - 2 mm of Al/Be, maximum 0.5 cm?

- Xtal 35-50% smaller than LXe
- SiPM

	Values	Uncertainties	
		Stat	*Syst*
$R_{e/\mu}^{Raw}$ (10^{-4})	1.1972	0.0022	0.0005
π,μ lifetimes			0.0001
Other parameters			0.0003
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$R_{e/\mu}^{Exp}$ (10^{-4})	1.2344	0.0023	0.0019

TABLE I: The table includes the raw branching ratio with its statistical and systematic uncertainties, the multiplicative corrections with their errors, and the result after applying corrections.

Table 2.2 Material budget of the γ entrance window of the LXe detector. (left) MEG, (right) MEG II.

	Radiation thickness X_0
Outer cryostat wall	0.040
Honeycomb (Section 1.6.2)	0.018
Inner cryostat wall	0.023
Peek support or PMT	0.183
Total	0.264

	Radiation thickness X_0
Outer cryostat wall	0.040
Honeycomb (Section 1.6.2)	0.018
Inner cryostat wall	0.023
CFRP frame	0.003
PCB & Spacer	0.006
MPPC	0.020
Total	0.110

Figure 2.17 PCB used to align the MPPCs.

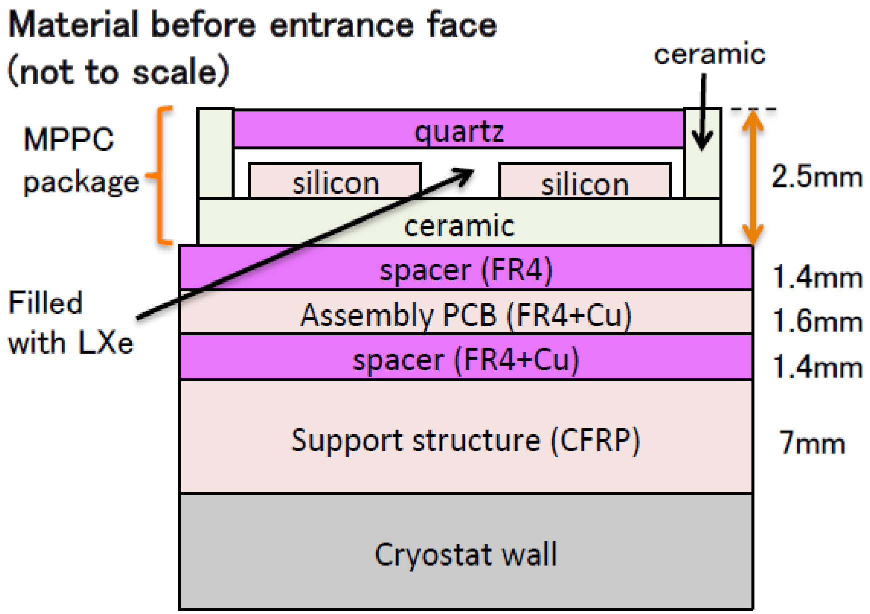

Figure 2.16 Material of the γ entrance window

https://meg.web.psi.ch/docs/theses/ogawa_phd.pdf

https://iopscience.iop.org/article/10.1088/1742-6596/308/1/012009