Mu2e : getting on mass shell

New Frontiers in Lepton Flavor, Pisa, 2023

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Fermions, mixing, flavor non-conservation

- flavor changing interactions of fermions are known for a long time
  - weak interactions of quarks are non-diagonal in flavor (i.e. V_{cd})
  - neutrinos also mix, interactions not known
- no observed mixing of charged leptons
- in SM, charged leptons do mix, but at a negligible level, $(\delta m_{\nu}^{2}/M_{W}^{2})^{2}$
- multiple models of physics beyond the SM allow potentially observable rates

Searches for lepton flavor/number violation

- multiple channels:
  - neutrino-less $\mu \rightarrow e$ conversion, $\mu \rightarrow e\gamma$, $\mu^+ \rightarrow e^+e^-e^+$
  - decays of $Z, J/\psi, \eta, H \rightarrow e\mu, e\tau$, ...
  - τ decays, i.e. $\tau^- \rightarrow -\mu^-\mu^+\mu^-$
  - $K \rightarrow pie\mu$, ..
- searches for CLFV $\mu \rightarrow e$ transitions stay apart: can make high intensity μ beams
- produce muons, stop them, [wait] and see what happens

CLFV searches with stopped muons and new physics mass scale

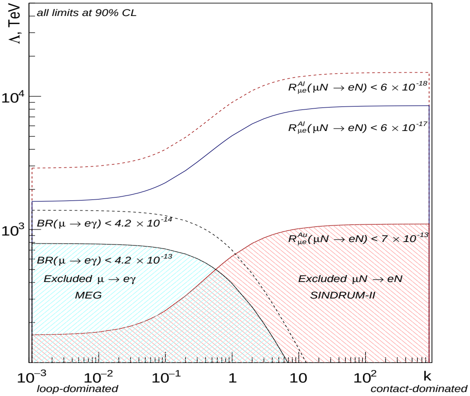
- CLFV lagrangian in EFT (de Gouvea, Fogel, 2013)-a model-independent "$\kappa - \Lambda$" view:

$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(k+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{k}{(k+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{q}_L\gamma_\mu q_L) + h.c.$$

- LHC probes mass scale of $\sim$ 10 TeV
- direct CLFV searches: $\Lambda \sim 10^3 - 10^4$ TeV
- $\mu \to e$ conversion, tree level:

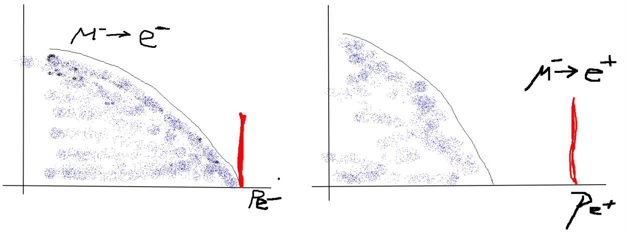
$$\frac{1}{\Lambda^2} \sim \frac{y_{new}^2}{M_{new}^2}$$

- for $y_{new} \sim 0.1$, $M_{new} \sim 10^2 - 10^3$ TeV



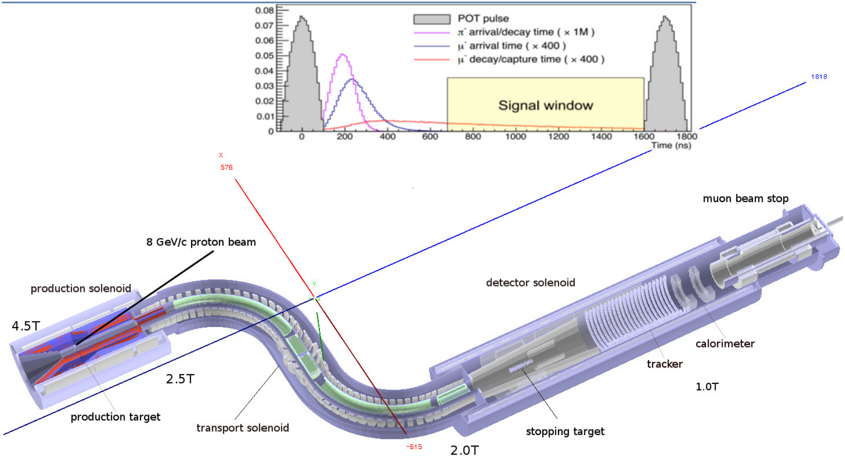
- **experiments with stopped muons probe mass scales higher than LHC**
- **search for the $\mu^- A \to e^- A$ conversion probes all types of interactions**

$\mu \to e$ conversion, on a nutshell



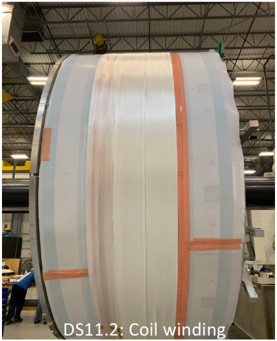
- $\mu^- A \to e^- A$ conversion is a coherent process
  - one of the experimental backgrounds (μ^- decays in orbit) has its endpoint exactly coinciding with the signal
- $\mu^- A \to e^+ A'$ conversion : no coherence
  - predicted rates orders of magnitude lower than the $\mu^- \to e^-$ conversion rates
  - a purely Majorana process, the 2nd best place (after $2\beta 0\nu$ decay) to search for such
  - signal separated from the dominant background - radiative muon capture (RMC) $\mu^- A \to \gamma(e^+ e^-) A' \nu$
  - separation is target-dependent

Mu2e experiment: idea by Lobashev and Dzhilkibaev, 1989



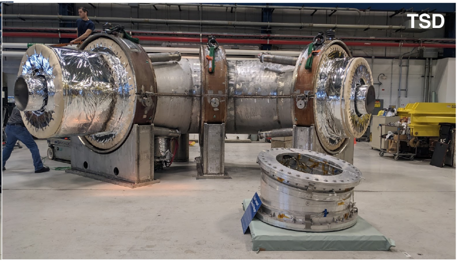
- three solenoids with graded field,
- pulsed proton beam p = 8.9 GeV/c, $\sim 10^{10}$ stopped muons/sec, beam extinction of 10^{-10}
- backwards extracted muons, delayed measurement, T(μAl) = 864 ns
- **in 3 yrs of running, reach SES $\sim 10^{-17}$ with the expected background < 1 event**

Production and detector solenoids



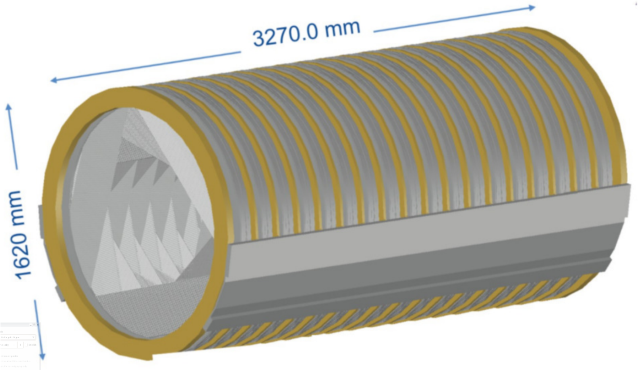
- production solenoid (PS): 3 coils, all produced, cold mass assembled
- detector solenoid (DS) : 11 coils, the last one is being wound

Transport solenoid



- SC coils (52) produced by Ansaldo Group, Genova, delivered to Fermilab before COVID
- the transport solenoid is on track to be installed in the fall of 2023

Tracker



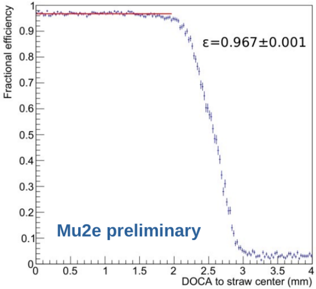
- 18 stations = 18x2 planes, based on D=5mm, L=40-110 cm straw tubes
- gas: Ar/CO2 (80/20), HV $\sim$ 1300 V
- resolution:
  - drift time: $\sim$ 2-3 ns (120-180 μ),
  - along the wire: $\sim$ 3-4 cm along the wire (time division)
- low-mass: $\sim$ 1% L_{rad}, momentum resolution $\sigma_P/P \sim 10^{-3}$
- will operate in vacuum at 10^{-4} torr , straws - at $\sim$ 1 atm

Tracker status

- 24 out of 36 planes produced , plan to complete end 2023 / early 2024 (need $\sim$ 6 mos)
- (2 planes –> 1 station) assembly will start in parallel in the fall
- integration testing with cosmics also in parallel, re-starting VST late summer/early fall

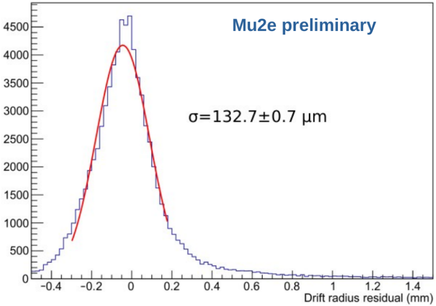
Tracker vertical slice test (VST)

Hit efficiency



VST straw efficiency

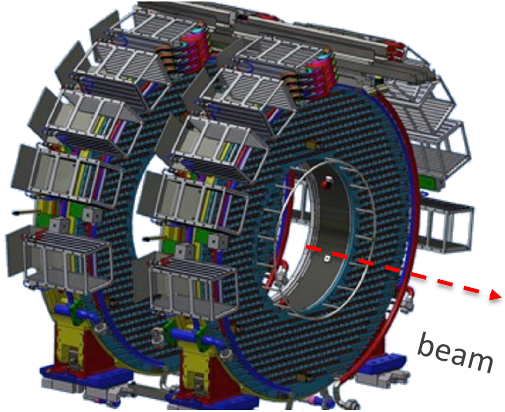
Transverse coordinate resolution



- one of the planes had electronics installed early and was tested with cosmics
- single straw efficiency above 95%, consistent with the readout thresholds
- observed drift resolution $\sigma_R \sim 130\mu$ –> $\sigma_T \sim 2$ ns

Calorimeter

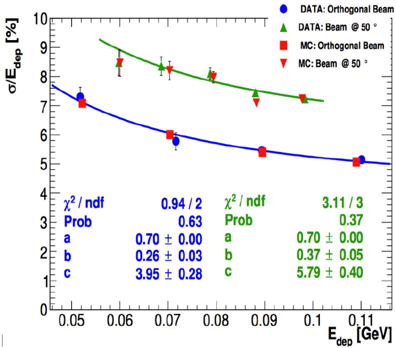
- undoped CsI crystals, 34x34x200 mm
- 2 disks, 674 crystals each
- 2 large area SiPMs per crystal
  - Hamamatsu, UV-extended
- requirements (@ 100 MeV):
  - $\sigma_E/E < 10\%$,
  - $\sigma_T < 500$ ps
- acceptance $\sim$ 95% wrt tracker

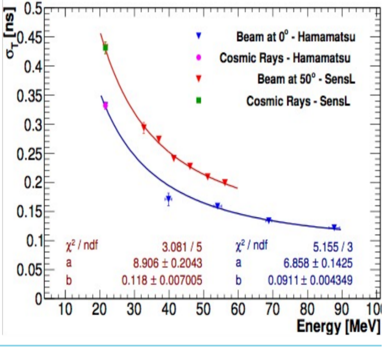


role

- particle identification = rejection of cosmic background
- standalone triggering

Calorimeter prototype beam test



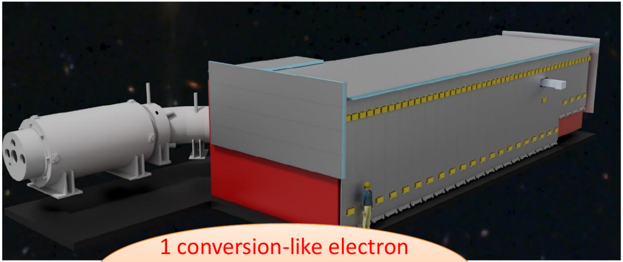


- 50 crystals large prototype successfully passed the test beam results (100 MeV e^-) :
  - $\sigma_E/E \sim 5-7\%$
  - $\sigma_T < 200$ ps

Calorimeter: status

- first disk fully assembled, assembly of the second disk to start shortly
- vertical slice tests to start in the fall

Cosmic Ray Veto System



1 conversion-like electron per day is produced by cosmic-ray muons

- total area: 335 m^2
- 83 modules, 10 types
- 5,344 counters
- 10,688 embedded fibers
- 19,392 SiPMs
- 4,848 counter MBs
- 339 front-end boards
- 17 readout controllers

- each side - 4 layers of scintillating counters,
- require 3 out of 4 hits to provide muon rejection $\sim 10^4$
- 99.4% efficiency per layer demonstrated in the test beam
- status:
  - 80/83 modules completed, the remaining three will be completed by the end of July
  - testing with cosmics and aging measurements in progress

Run Plan

- complete the project by the end of 2025
- commission and take data in 2026
- publish first results in 2027
- increase statistics by x10 after 2yr-long shutdown

$\mu^- \to e^-$ search: backgrounds and expected sensitivity in Run I

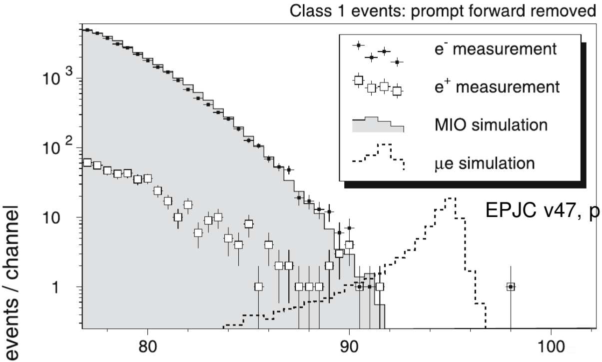
Assuming $6e^{16}$ stopped muons

- MDPI Universe 2023, 9(1), 54; https://doi.org/10.3390/universe9010054

Channel	Mu2e Run I
Cosmic rays	$0.046 \pm 0.010\ (\mathrm{stat}) \pm 0.009\ (\mathrm{syst})$
DIO	$0.038 \pm 0.002\ (\mathrm{stat})\ ^{+0.025}_{-0.015}\ (\mathrm{syst})$
Antiprotons	$0.010 \pm 0.003\ (\mathrm{stat}) \pm 0.010\ (\mathrm{syst})$
RPC in-time	$0.010 \pm 0.002\ (\mathrm{stat})\ ^{+0.001}_{-0.003}\ (\mathrm{syst})$
RPC out-of-time ($\zeta = 10^{-10}$)	$(1.2 \pm 0.1\ (\mathrm{stat})\ ^{+0.1}_{-0.3}\ (\mathrm{syst})) \times 10^{-3}$
RMC	$< 2.4 \times 10^{-3}$
Decays in flight	$< 2 \times 10^{-3}$
Beam electrons	$< 1 \times 10^{-3}$
Total	0.105 ± 0.032
SES	2.4×10^{-16}

- optimized 2D window: $103.60 < p < 104.90$ MeV/c and $640 < T_0 < 1650$ ns.
- expected sensitivity $R_{\mu e} < 6.2 \times 10^{-16}$ @ 90% CL (x 1000 of SINDRUM-II)
- expected "5 sigma" discovery sensitivity : 1.2×10^{-15} (need 5 events)

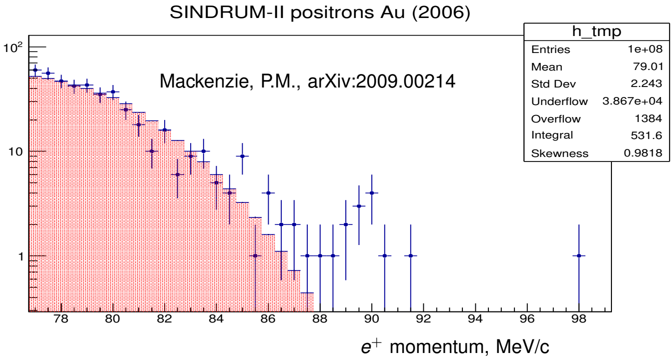
$\mu^- \to e^+$ conversion



EPJC v47, p 337 (2006)

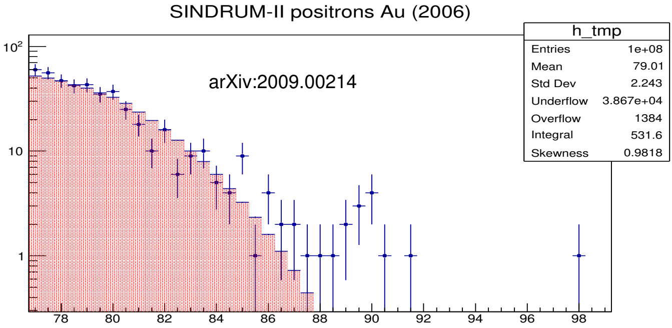
- Mu2e (and COMET) will also search for the $\mu^- A \to e^+ A'$ conversion
- SINDRUM-II data on Au:
  - good description of the e^- spectrum, no indication of a $\mu^- \to e^-$ signal
  - e^+ spectrum on (open squares) shows an interesting feature
- SINDRUM-II has two published results on $\mu^- \to e^+$ on Ti, no limit on Au

Model the SINDRUM-II e^+ background: RMC



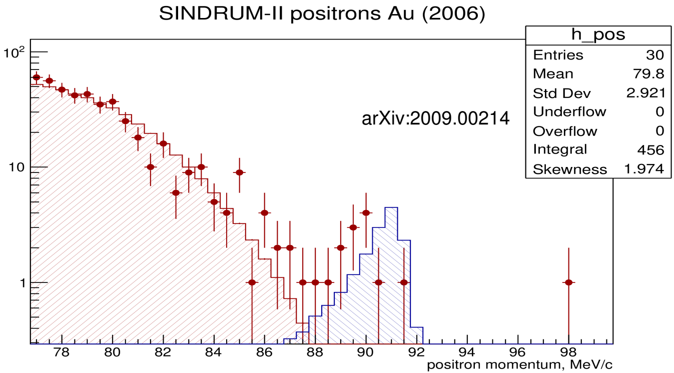
- backgrounds to the $\mu^- \to e^+$ search:
  - radiative muon capture(RMC, dominant), radiative pion capture(RPC), cosmics
- arXiv:2009.00214: an attempt to describe the SINDRUM-II e^+ spectrum
  - convolution of the RMC photon spectrum with the $\gamma \to e^+e^-$ energy sharing
- fit in the region p < 88 MeV/c gives $k_{max} = 88.6 \pm 0.6$ MeV,
  - consistent with existing RMC measurements ($k_{max} = 88.1 \pm 2.0$ MeV)

Eyeballing significance of the excess in e^+ spectrum



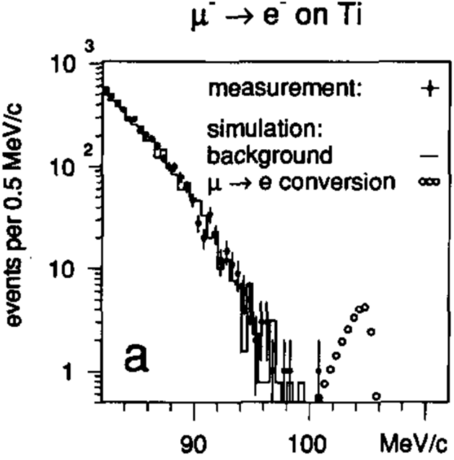
- “bump” region as 88-92 MeV/c, 13 events
- background : $\sim$ 0.5 events from RMC (integral of the closure approximation spectrum)
- cosmics+RPC flat, look above the excess : 1 event @ 98 MeV/c, sign unknown
- N(obs)=13, N(bgr)=2
- naive Poisson P(13/2) = 2.1 e-7, below "HEP 5-sigma" level, 2.8 e-7
- **the plot screams: double the statistics, plot me again !**

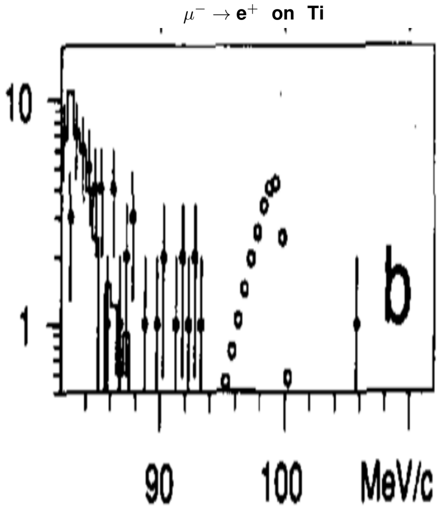
Did SINDRUM-II observe a $\mu^- \rightarrow e^+$ conversion peak on Au?



- the width of the excess consistent with the experimental resolution
- an expected signal from $\mu^- \rightarrow e^+$ conversion on Au is 1 MeV/c or $\sim 4\sigma$ higher
  - **1 MeV is a large discrepancy**, can't claim anything

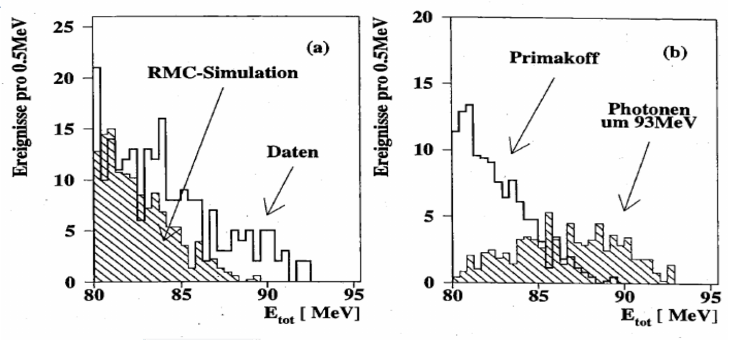
SINDRUM-II 1993: Phys Lett B317, p631 (1993)





- search for $\mu^- \to e^-$ and $\mu^- \to e^+$ conversion on Ti target (P signal = 99 MeV
- good description of the electron spectrum, excess in the positron spectrum at p > 90 MeV/c
- got around by observing that there was no e^+ events in the signal region

SINDRUM-II 1998: Ti target, Phys.Lett. B422 (1998) 334-338



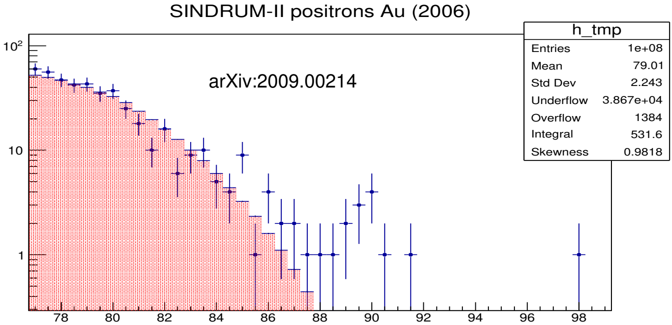
- publication which set the current best limit on $\mu^- \to e^+$ conversion
- Mu2e investigation lead to the PhD thesis of J.Kallard, underlying the publication
  - plots from the thesis
- to describe the data, introduced a LNV background process with a monochromatic photon:

$$\mu^- A \to A + \gamma$$

Thoughts on $\mu^- \to e^+$ conversion searches

- all recent searches for $\mu^- \to e^+$ conversion failed to describe the background
- show similar feature - significant excess of events over RMC prediction - near the endpoint
- perhaps we do not understand the endpoint of the RMC spectrum ?

More thoughts on $\mu^- \to e^+$ conversion



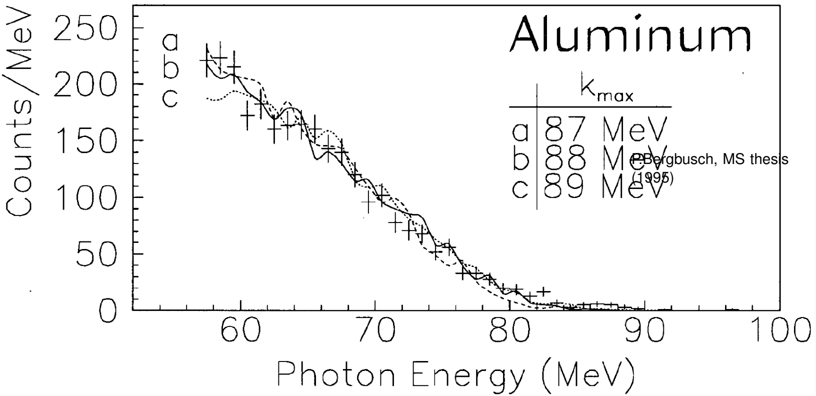
- expected energy of $\mu^- \to e+$ conversion positrons : E = 92.3 MeV,
- RMC endpoint : $k_{max} = 90.1 + 1.8$ MeV
- what do Mu2e/COMET do if with first two weeks of data we see a similar plot x100?
- improved theoretical understanding of the RMC endpoint is very much needed

Summary

- Mu2e is entering a very exciting time - getting on mass shell
- plan to take data in 2026
- $\mu^- \rightarrow e^+$ channel : need better theoretical understanding of the RMC

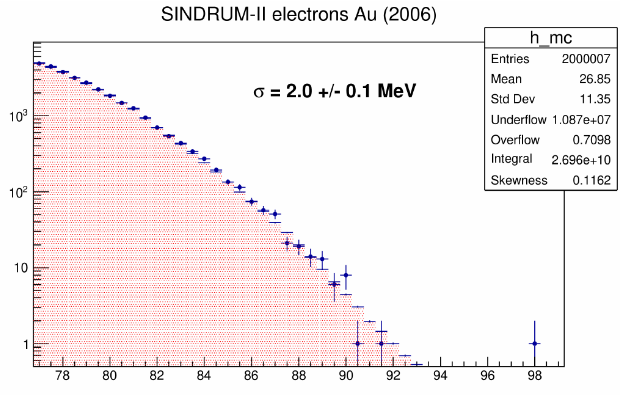
Backup

Radiative muon capture (RMC)



- a process similar to RPC, with mu- being captured instead of pi-
- kinematic endpoint at about 101.85 MeV, experimental measurements - 5-10 MeV lower
- experimentally : $k_{max} = 90.1 \pm 1.8$ MeV on Al (P.Bergbusch et al, PRC v59 p2853)
- expect neglible contribution to the search for $\mu^- \rightarrow e-$ conversion
- pero, RMC is the dominant background to the search for the $\mu^- \rightarrow e^+$ conversion on Al

Can SINDRUM-II e^- and e^+ spectra be described within the same assumptions



- use SINDRUM-II DIO spectrum to second guess the detector response (arXiv:2009.00214)
- two parameters: momentum resolution (gaussian), efficiency vs momentum (knee-shaped)
- good description overall, resolution parameter too large, as no RMC subtraction
- event at 98 MeV - momentum sign undefined