Searching CLFV and LNV processes with the Mu2e experiment at Fermilab

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LNF INFN & Tor Vergata University

LNF General Seminar

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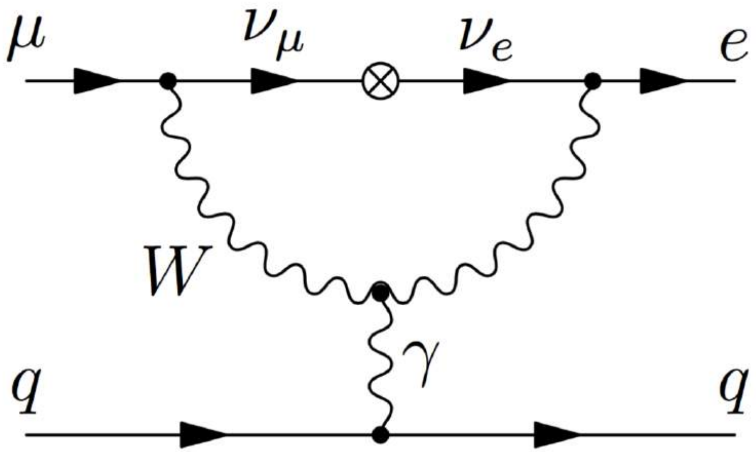
The Mu2e Collaboration

Over 200 Scientists from 40 Institutions (six countries)

Argonne National Laboratory Boston University Brookhaven National Laboratory University of California, Berkeley University of California, Davis University of California, Irvine California Institute of Technology City University of New York Joint Institute for Nuclear Research, Dubna Duke University Fermi National Accelerator Laboratory Laboratori Nazionali di Frascati INFN Genova Helmholtz-Zentrum Dresden-Rossendorf University of Houston Institute for High Energy Physics, Protvino Kansas State University Lawrence Berkeley National Laboratory INFN Lecce and Università del Salento Lewis University University of Liverpool University College London University of Louisville University of Manchester Università Marconi Roma University of Michigan University of Minnesota Institute for Nuclear Research, Moscow Muons Inc. Northern Illinois University Northwestern University Novosibirsk State University/Budker Institute of Nuclear Physics INFN Pisa Purdue University University of South Alabama Sun Yat Sen University INFN Trieste University of Virginia University of Washington Yale University

What is the μ^{-}-e^{-} process ?

- μ converts into an electron in the presence of a nucleus $\mu^{-}N \rightarrow e^{-}N$

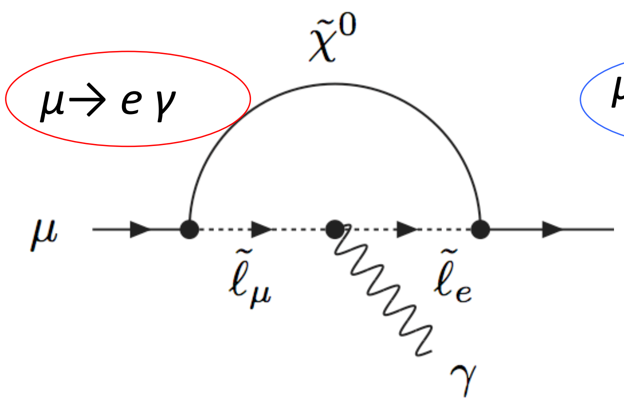


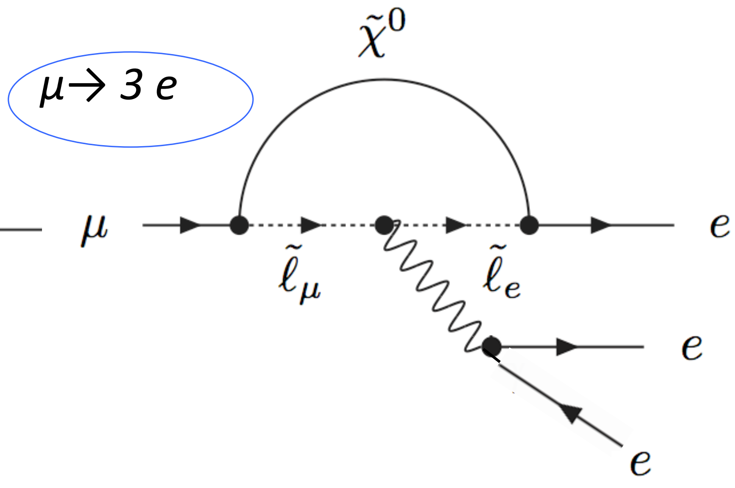
- μ-e process is an example of Charged Lepton Flavor Violating (CLFV) process.
- **CLFV processes are forbidden in the Standard Model!**
  - Assuming neutrino oscillation they are allowed **BUT negligible with BR ~ 10^{-50}**
- Many SM extensions enhance the rates to observable values
- **Any observation of a signal will be a clear evidence of New Physics**

CLFV

Process	Upper limit
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$
$\mu^+ \to e^+e^+e^-$	$< 1.0 \times 10^{-12}$
$\mu^- Ti \to e^- Ti$	$< 1.7 \times 10^{-12}$
$\mu^- Au \to e^- Au$	$< 6.1 \times 10^{-13}$
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$
$\tau^- \to \mu\gamma$	$< 4.4 \times 10^{-8}$
$\tau^- \to e^-e^+e^-$	$< 2.7 \times 10^{-8}$
$\tau^- \to \mu^-\mu + \mu^-$	$< 2.1 \times 10^{-8}$
$\tau^- \to e^-\mu^+\mu^-$	$< 2.7 \times 10^{-8}$
$\tau^- \to \mu^-e^+e^-$	$< 1.8 \times 10^{-8}$
$\tau^- \to e^+\mu^-\mu^-$	$< 1.7 \times 10^{-8}$
$\tau^- \to \mu^+e^-e^-$	$< 1.5 \times 10^{-8}$
$\pi^0 \to \mu e$	$< 3.6 \times 10^{-10}$
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$
$K_L^0 \to \pi^0\mu^+e^-$	$< 4.4 \times 10^{-10}$
$Z^0 \to \mu e$	$< 7.5 \times 10^{-7}$
$Z^0 \to \tau e$	$< 9.8 \times 10^{-6}$
$Z^0 \to \tau\mu$	$< 1.2 \times 10^{-6}$

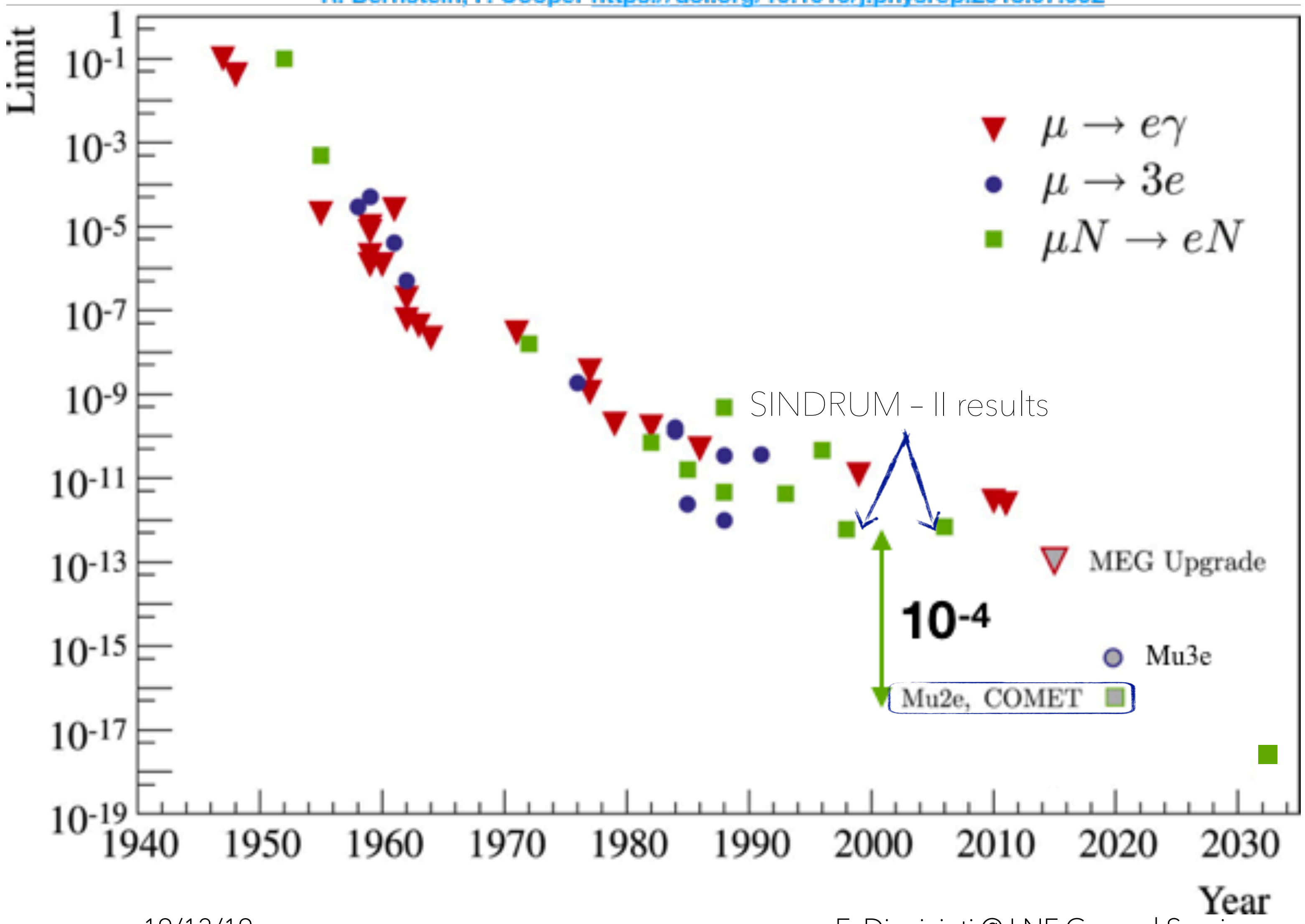
- Several searches involving different kind of particles
- **CLFV in μ sector represents the most sensitive probes:**
  - Clean topologies and large rate
  - No SM background
- Other muon processes complementary to μ-e conversion:
  - $\mu^+ \to e^+\gamma$
  - $\mu^+ \to e^+e^+e^-$





Muon CLFV – time line

R. Bernstein, P. Cooper https://doi.org/10.1016/j.physrep.2013.07.002



Current best limits:

BR(μ→eγ) < 4.2 x 10^{-13} MEG-2016

BR(μ→3e) < 1 x 10^{-12} SINDRUM-1988

$R_{\mu e}$ < 6.1 x 10^{-13} SINDRUM-II 2006

$R_{\mu e}$ < 8 x 10^{-17} Mu2e goal

COMET and DeeMee at JPARC(Japan)

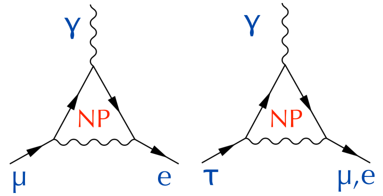
Mu2e Upgrade (MU2E-II)

"Effective" lagrangian

$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

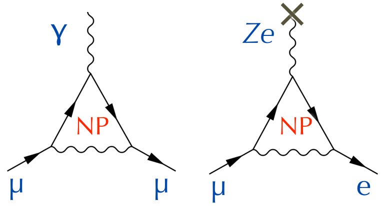
Loop term

$\kappa \ll 1$

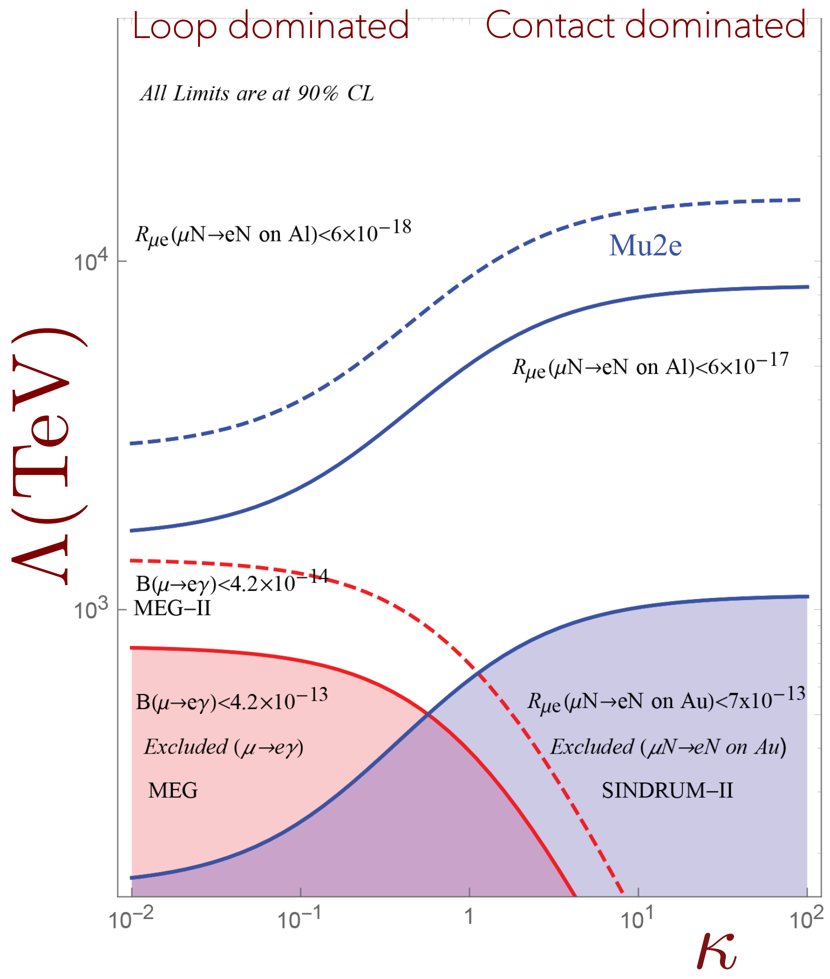


$\mu \to e\gamma$

$\tau \to \mu\gamma$
$\tau \to e\gamma$

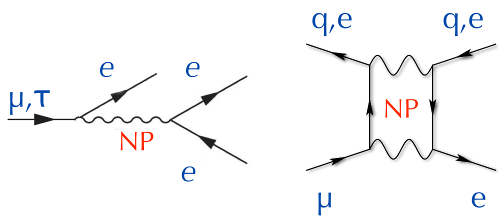


$(g-2)_\mu$ $\quad \mu^- \mathcal{N} \to e^- \mathcal{N}$



Contact term

$\kappa \gg 1$

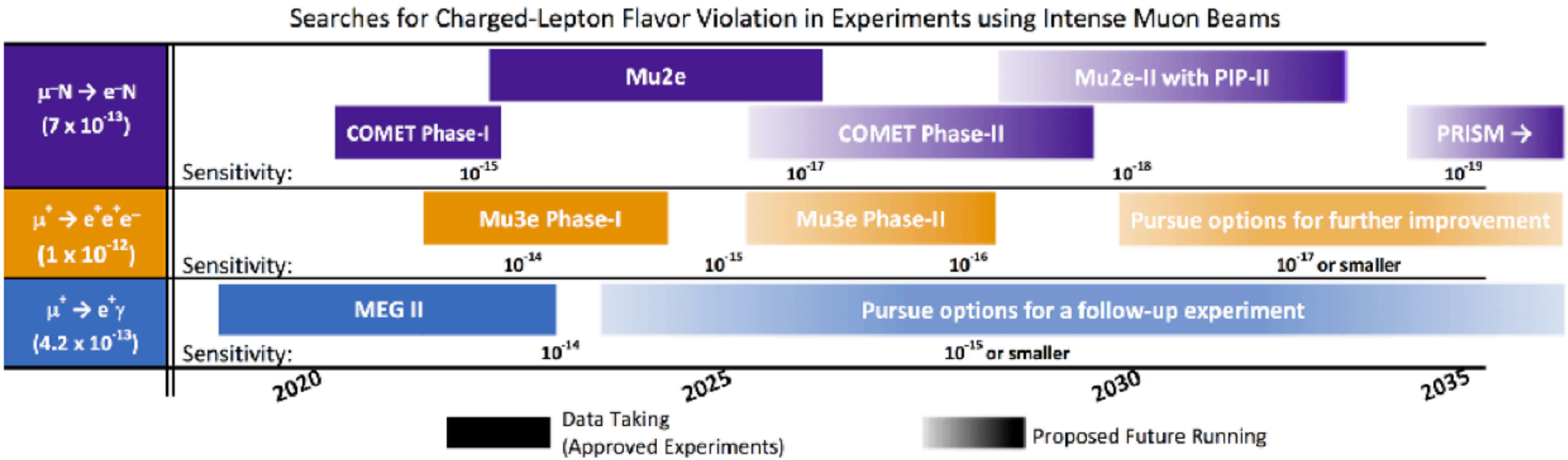


$\mu \to eee$
$\mu^- \mathcal{N} \to e^- \mathcal{N}$

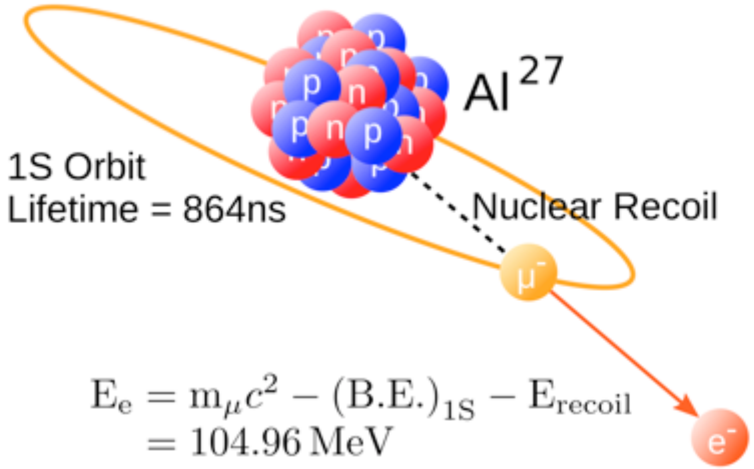
Mass scale discovery up to ~10^4 TeV, significantly above the direct LHC reach

Peculiarity of μ-e conversion

- μ-e conversion has a broad sensitivity across several alternative models:
  - Sensitivity to the same physics of MEG/Mu3e;
  - Sensitivity to physics that MEG/Mu3e are not;
  - If MEG/Mu3e observe a signal, Mu2e/COMET will see it also
  - If MEG/Mu3e do not observe a signal, Mu2e/COMET have still a reach to do so.



Mu2e Goal



$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} = 104.96\,\text{MeV}$$

- Mu2e measures the rate of μ-e conversion normalized to the μ captures in nuclei:

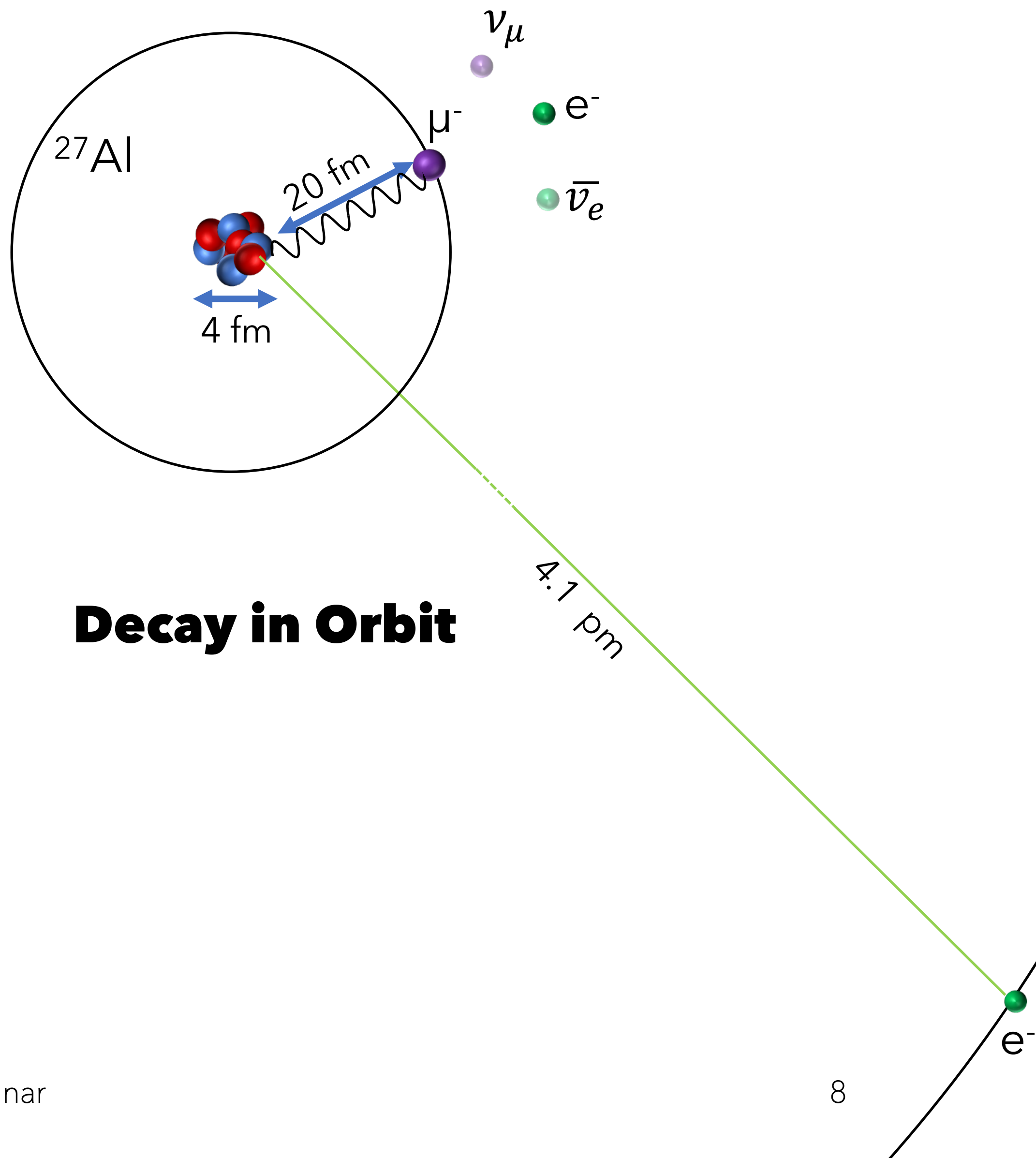
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1))} \leq 8 \times 10^{-17} (@\ 90\%\text{CL})$$

How to search for a μ-e conversion?

- Lots of μ's needed to reach the expected sensitivity **(10^{18})**
- High intensity μ beam in the target (10^{10} μ/s)
- Single line signal at ~105 MeV

Experimental technique

- Low momentum negative μ beam (<100 MeV/c)
- Stopped μ is trapped in the atomic orbit and quickly cascade in the 1s state
- μ undergoes 3 processes:
  - **Decay (39 %)** $\mu^- N \rightarrow e^- \nu_\mu \overline{\nu_e} N$ **(background)**
  - Capture (61%)
  - Conversion (<10^{-13})
- Look for excess at ~105 MeV/c



Decay in Orbit

Muonic atom lifetime : 826 ns

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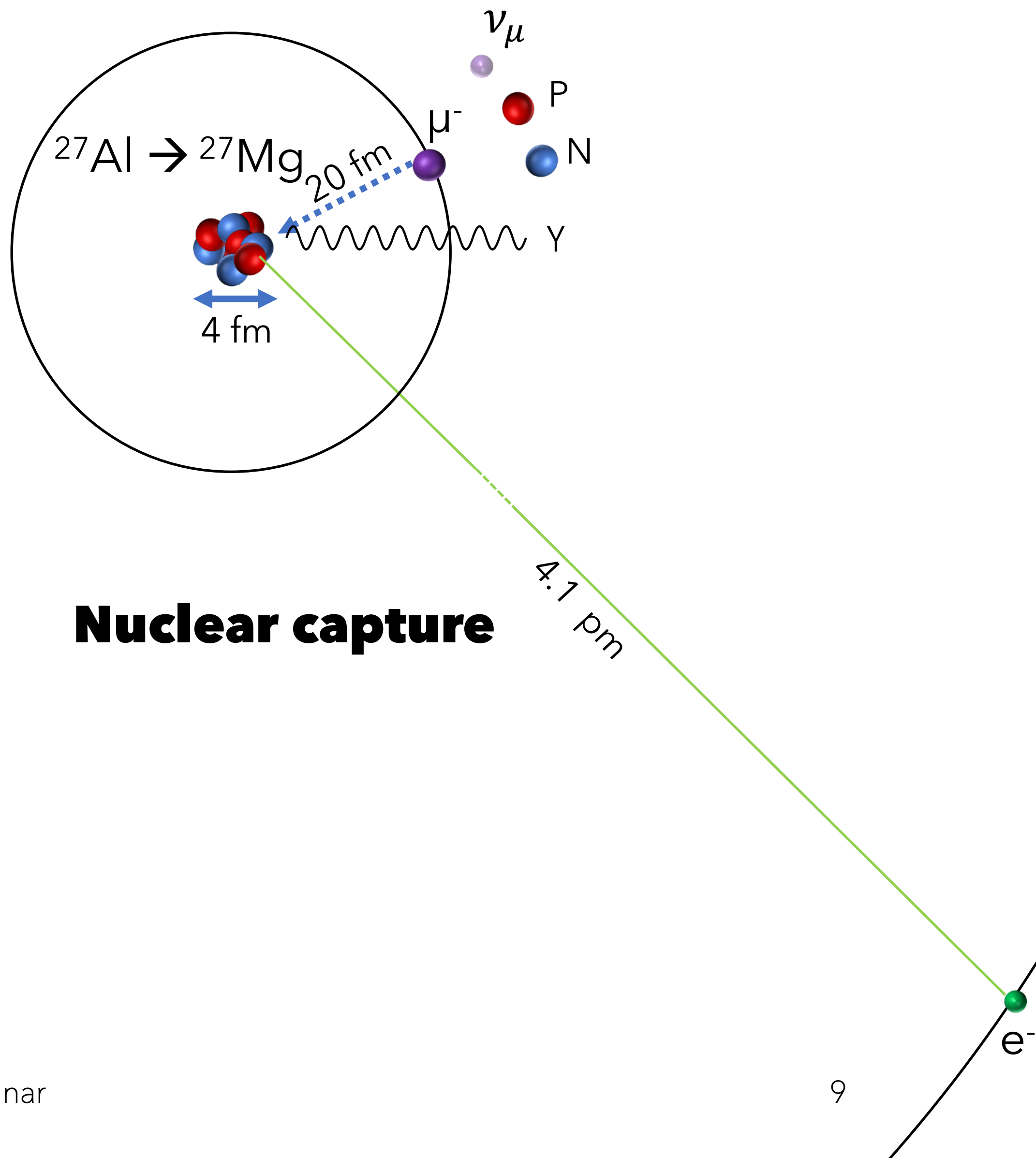
  - **Capture (61%)** $\mu^- N \to \nu_\mu N'$ **(Normalization)**
  - Conversion (<10^{-13})
- Look for excess at ~105 MeV

Muonic atom lifetime : 826 ns



Nuclear capture

Experimental technique

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- Stopped μ is trapped in the atomic orbit and quickly cascade in the 1s state
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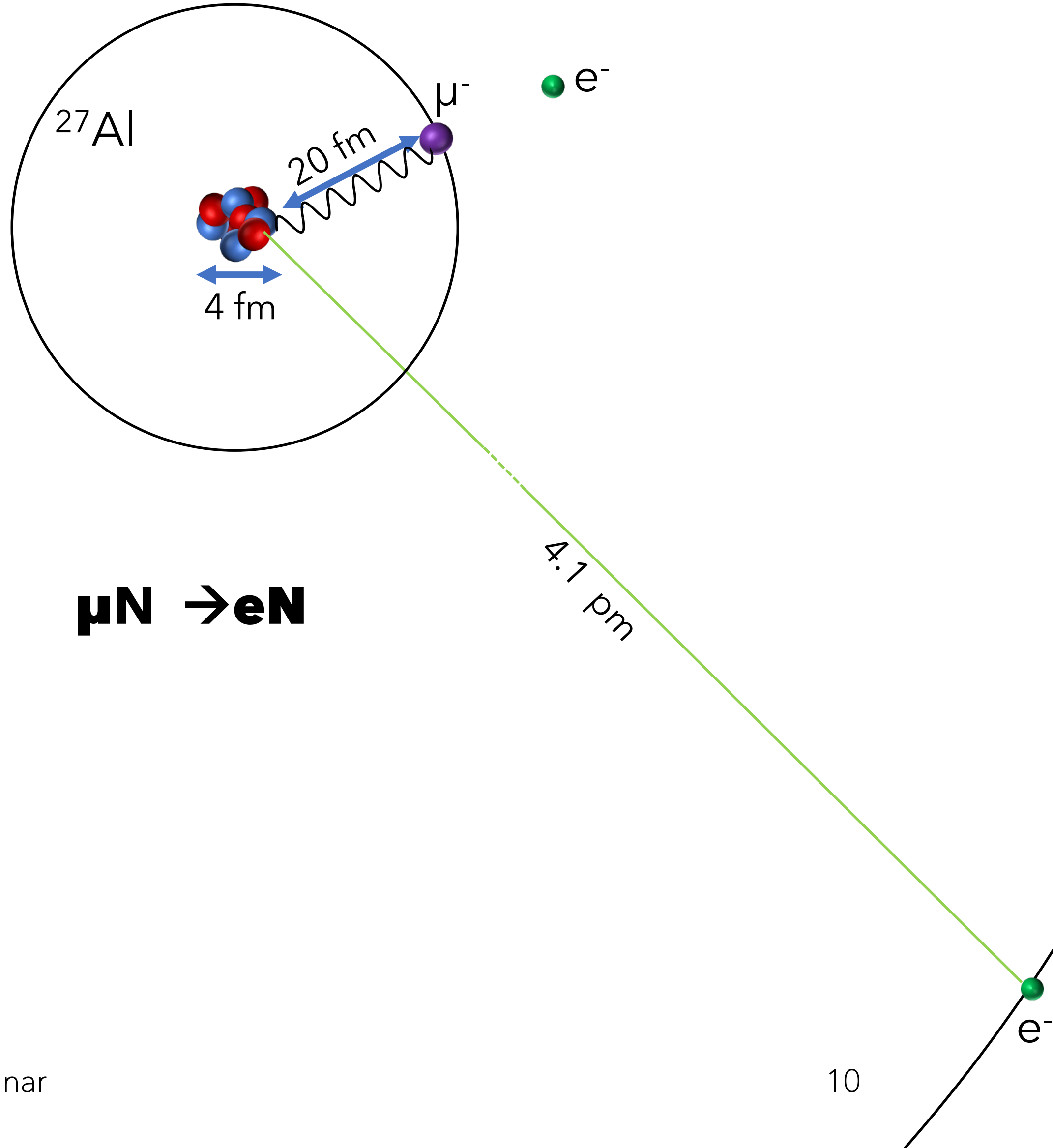
  - Capture (61%) $\mu^- N \rightarrow \nu_\mu N'$ (Normalization)
  - **Conversion (<10^{-13})** $\mu^- N \rightarrow e^- N$ **(Signal)**
- Look for excess at ~105 MeV



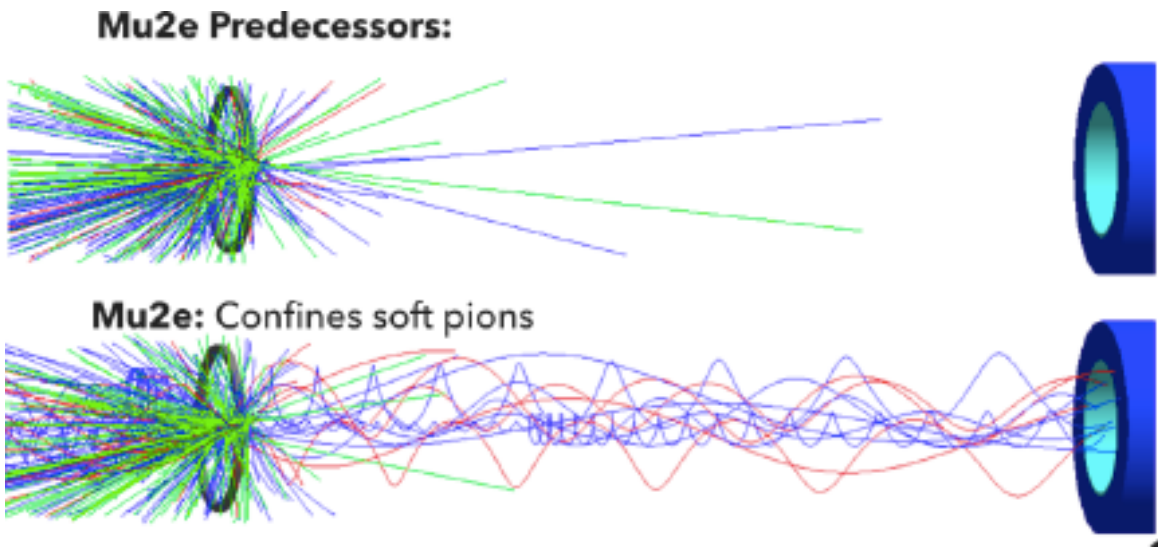
μN →eN

Muonic atom lifetime : 826 ns

Mu2e is cool

- **High intensity proton beam to produce pions → muons**

- **High efficiency in transporting muons from production to muon stopping target**
  - Soft pions confined with a solenoidal B field
  - Strong gradient to increase the yield through magnetic reflection



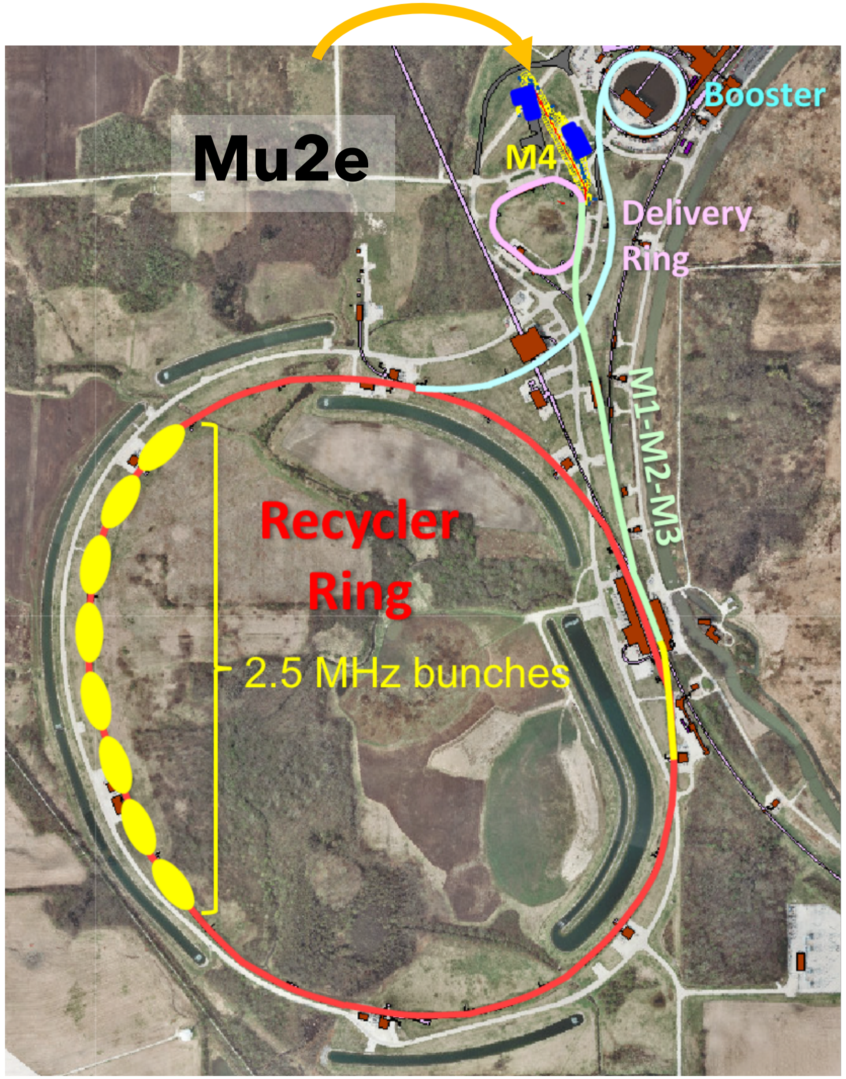
Lobashev and Djilkibaev Sov.J.Nucl.Phys. 49, 384 (1989)

- **Excellent detector for 100 MeV electrons**

Proton beam

- 8 GeV protons from the Booster
  - 4×10^{12} protons every 1/15th s
- collect data simultaneously with NOvA
- bunches of ~$3\text{x}10^7$ protons each, separated by 1.7 μs (delivery ring period) and then sent to the Mu2e Production Target

Mu2e cannot run together with Muon g-2



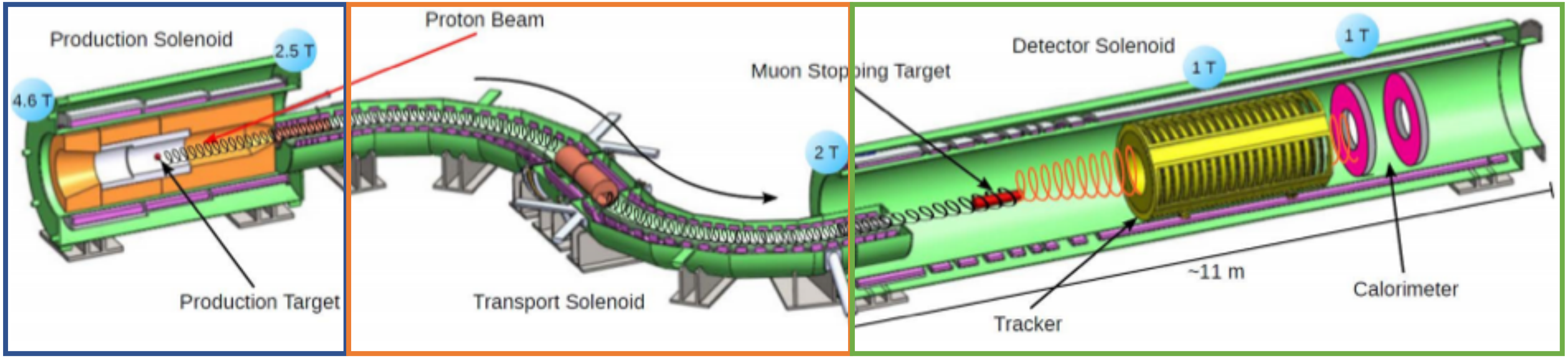
Mu2e design

PRODUCTION SOLENOID

- 8 GeV protons hit the target and produce mostly π
- Graded B field reflects slow forward π

DETECTOR SOLENOID

- Capture μ in the Al target
- Momentum measurement in the tracker and energy reconstruction with calorimeter
- CRV to veto cosmic ray events



TRANSPORT SOLENOID

- Selection and transport of low momentum μ^-
- Antiproton absorber in the mid-section

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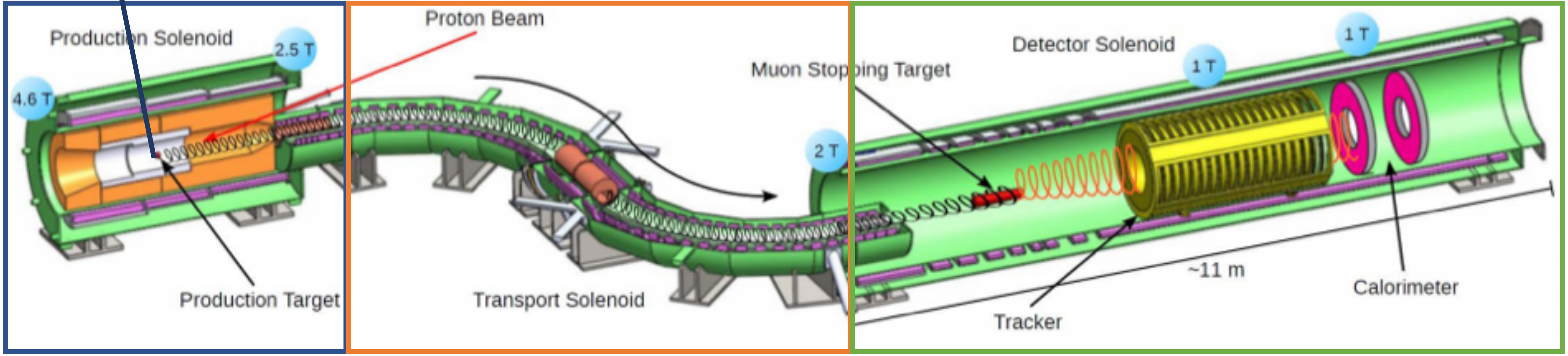

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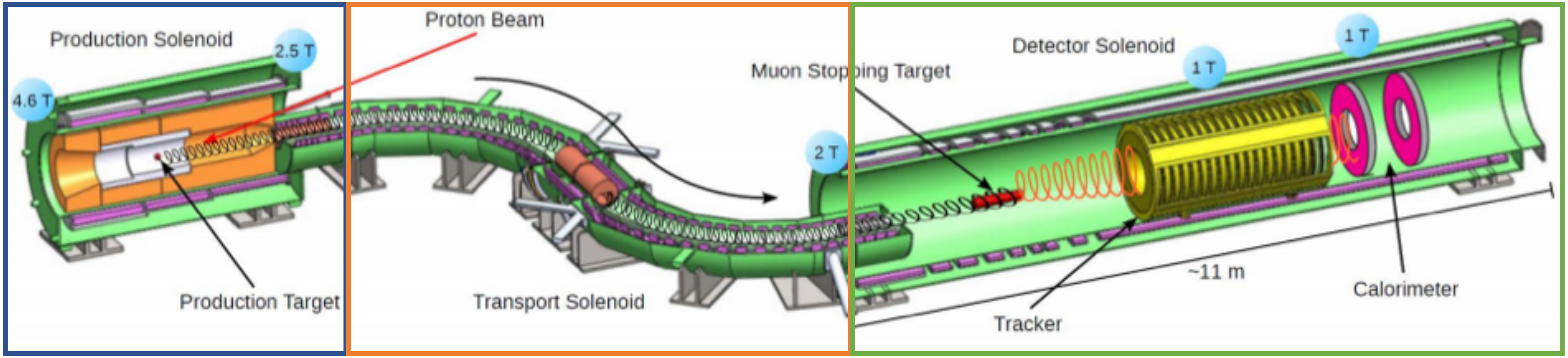

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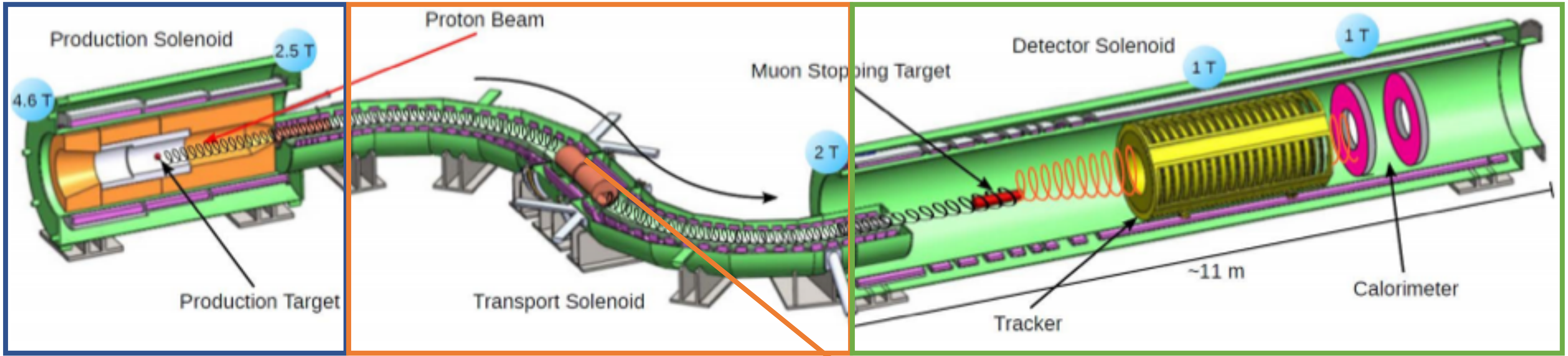

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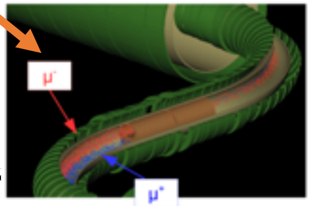

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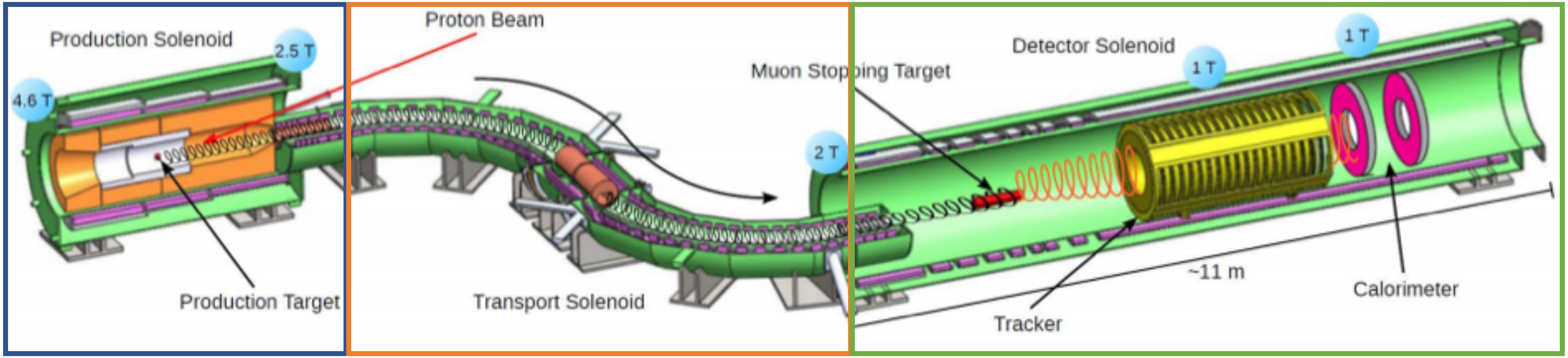

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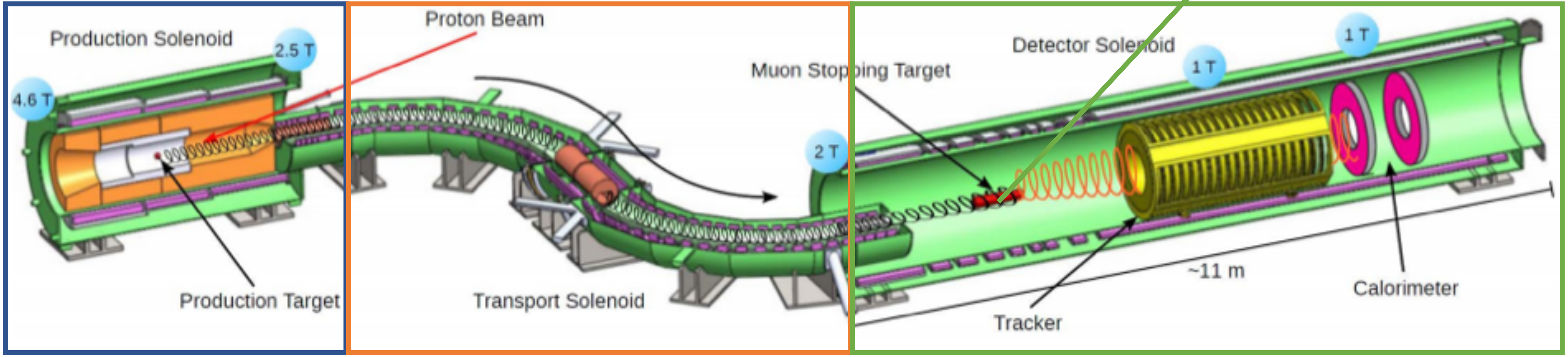

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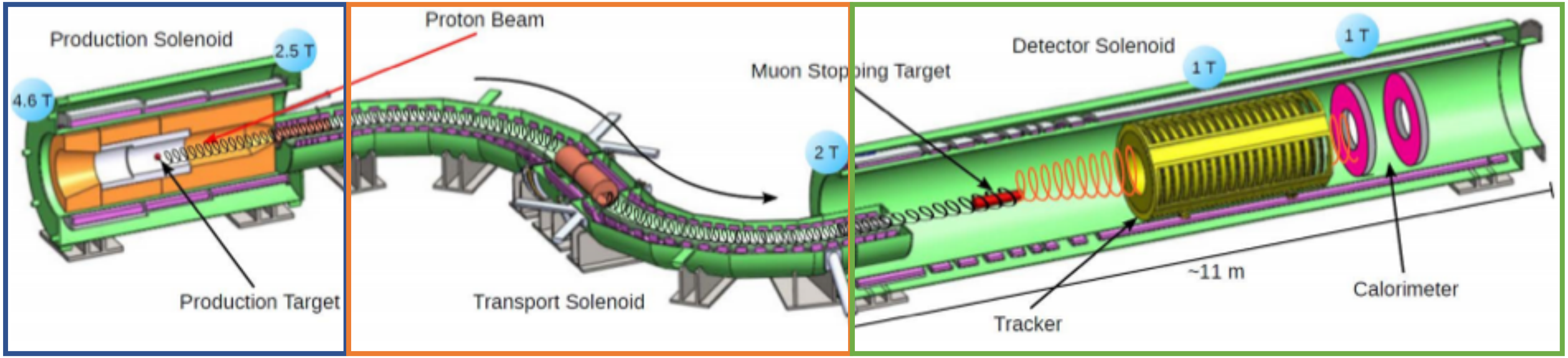

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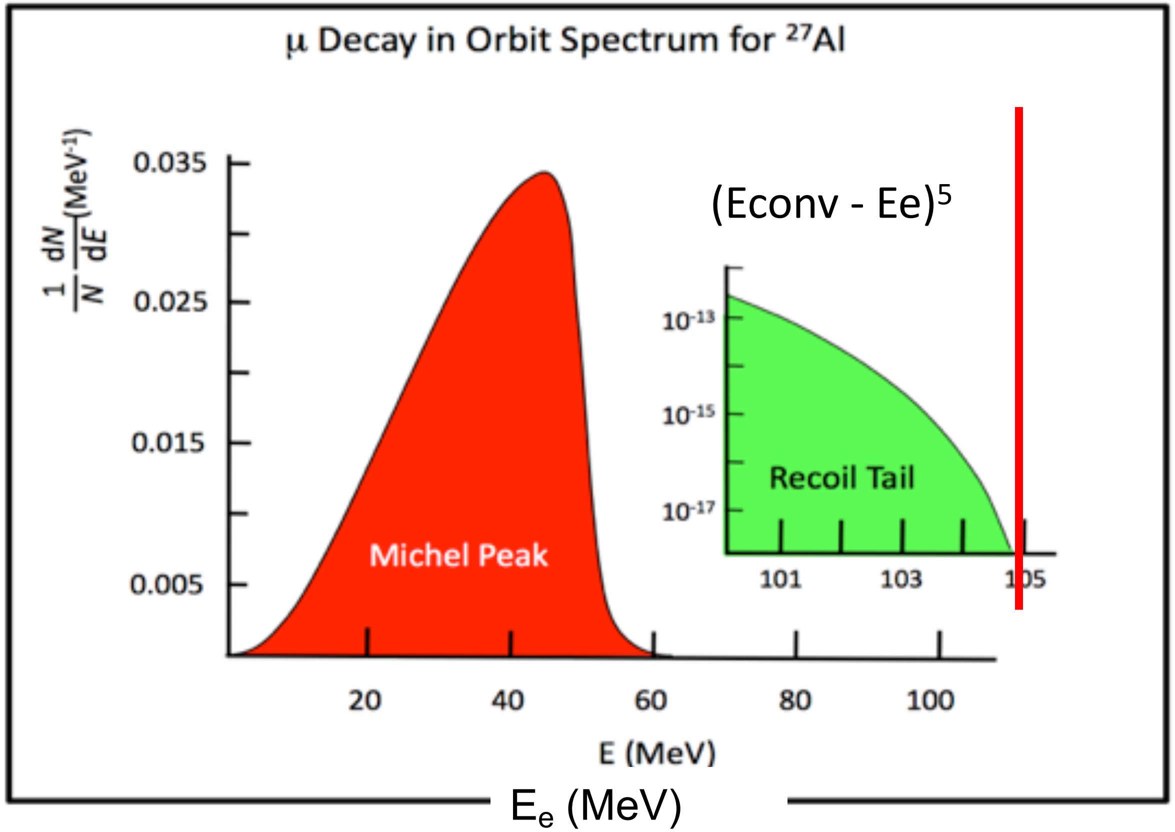
Backgrounds

- ***Intrinsic***
  - Decay In Orbit (DIO)
- ***Late arriving from prompt processes***
  - Radiative Pion capture
  - μ/π decay in flight
- ***Cosmic Rays***
- ***Antiproton annihilation***

DIO background

$$\mu^- N \rightarrow e^- \nu_\mu \overline{\nu_e} N$$

- Irreducible background
- Michel spectrum of electron from μ decay gets significantly modified by interaction with the nucleus
- Presence of a recoil tail with a fast falling slope close to the μ-e conversion endpoint.
- **To separate DIO endpoint from the CE line we need a high Resolution Spectrometer**



Czarnecki et al., Phys. Rev. D 84, 013006 (2011)
arXiv:1106.4756v2

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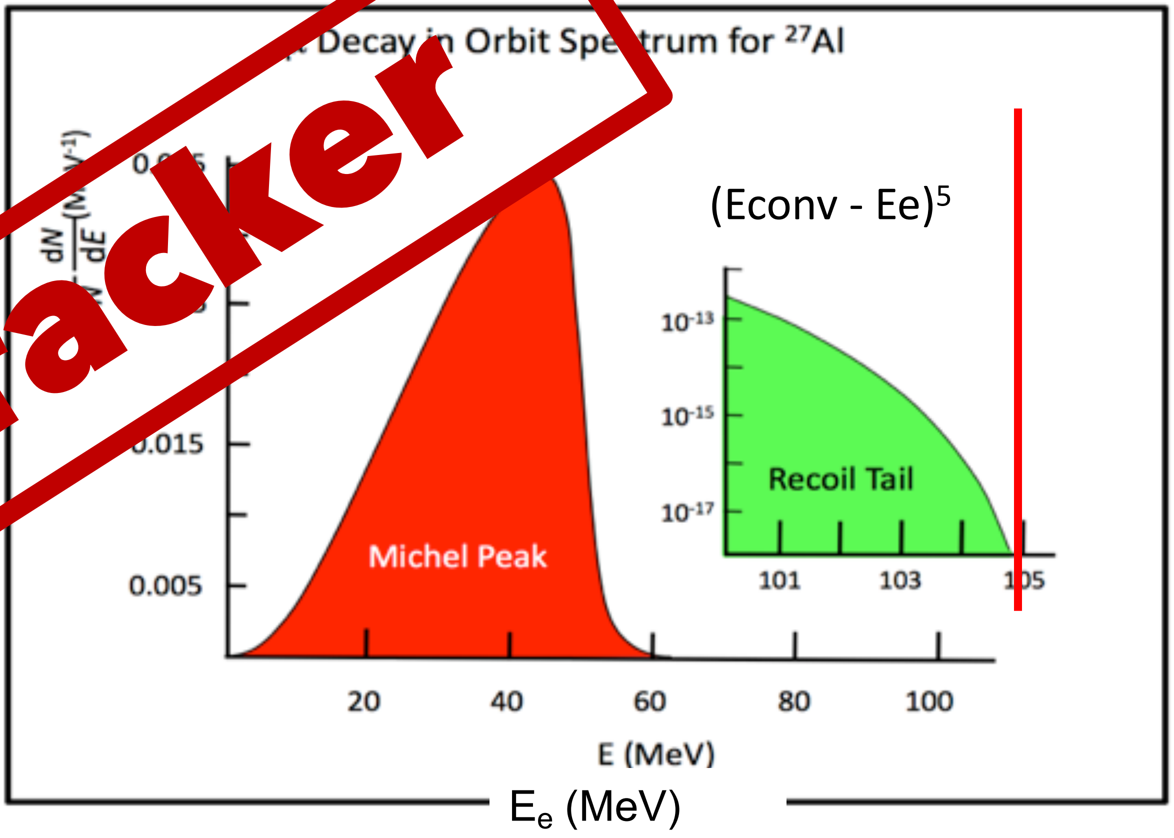
Precise Tracker



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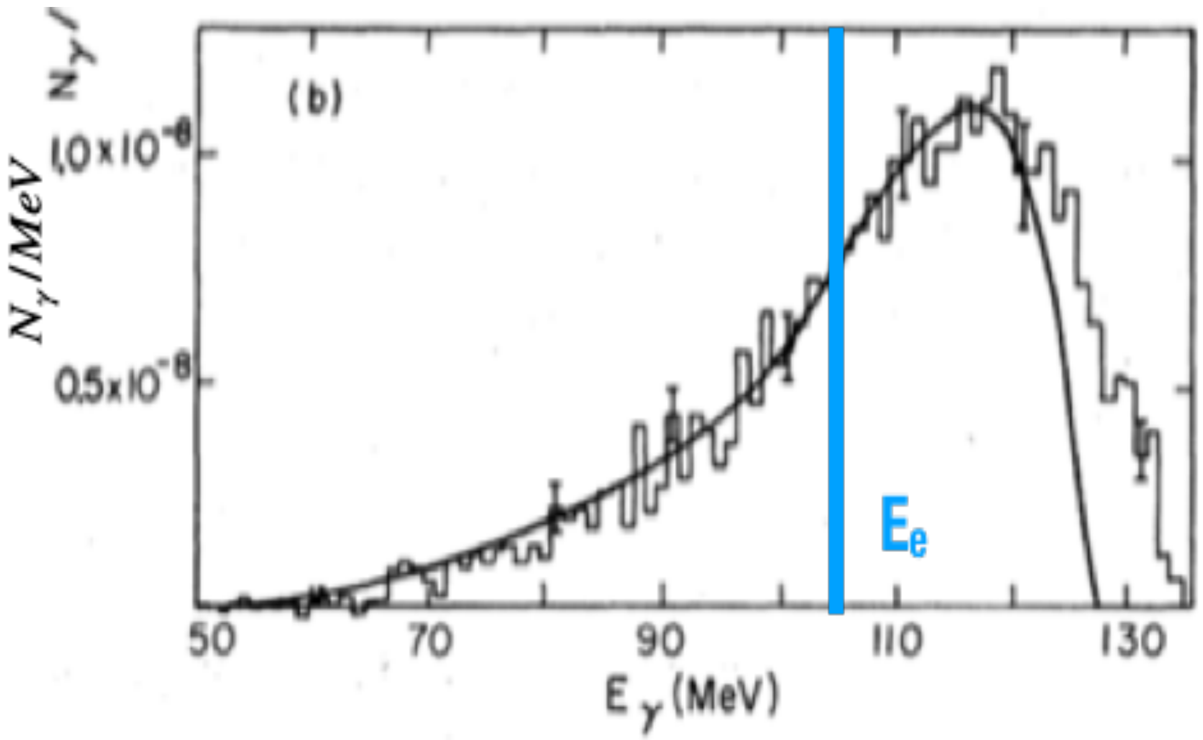
RPC background

$$\pi^- N \rightarrow \gamma N$$

- Non-decayed pions reach the stopping target and are radiatively captured;
- γ can convert (Dalitz or in material)
- Electrons can have the momentum in the signal window and mimic a conversion electron when positrons gets not reconstructed.
- The process is prompt:
  - ➔ Beam has to be "pulsed"
  - ➔ Beam has to have high extinction



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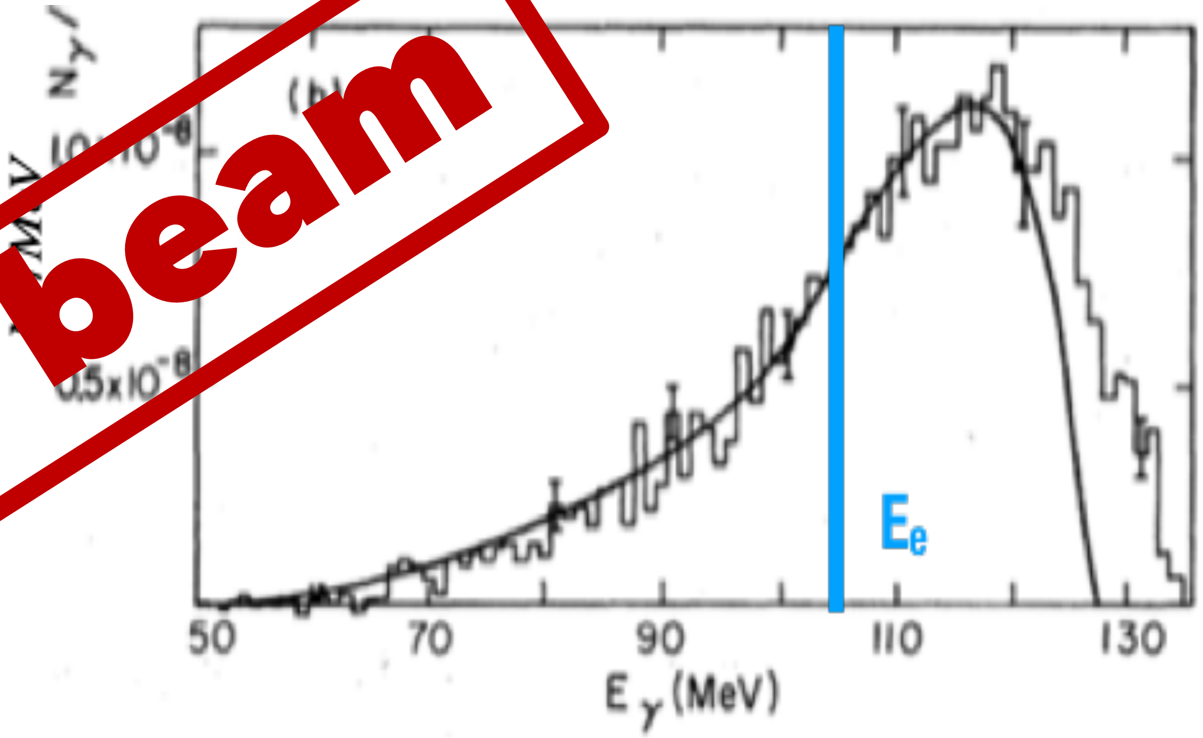
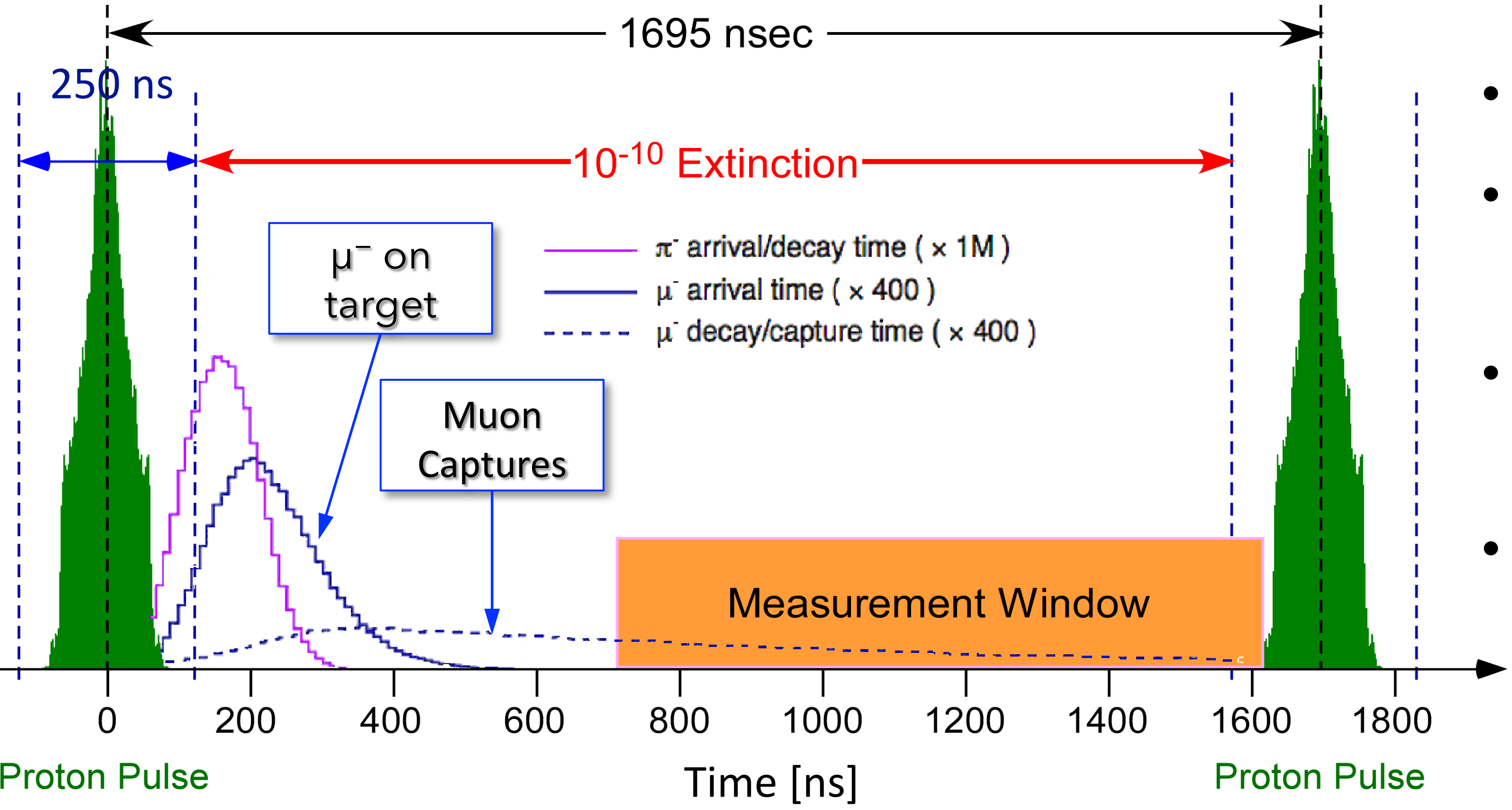
Pulsed beam



Beam structure

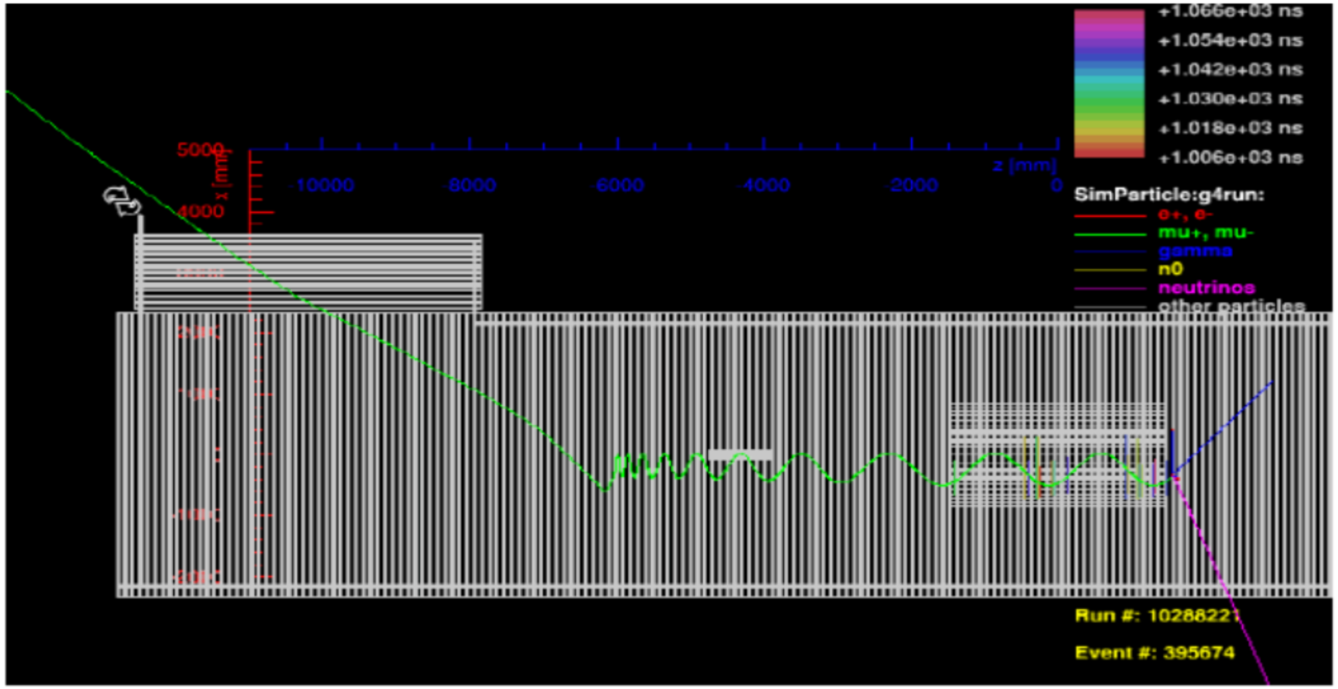


- Beam flash decays within 600 ns
- Live gate begins after prompt signal is gone
- **$\tau(\mu^-)$ in Al = 864 ns >> prompt background duration**
- Out-of-time backgrounds reduced by 10^{-10} extinction factor

Cosmic Rays

- Each day a cosmic ray event will mimic the signal of a conversion electron by:
  - producing *e* from decay in flight;
  - producing *e* via delta rays;
  - producing *e* from secondaries.

The parent muons cannot be stopped by shielding:
an active veto is needed to identify cosmic-ray muons.



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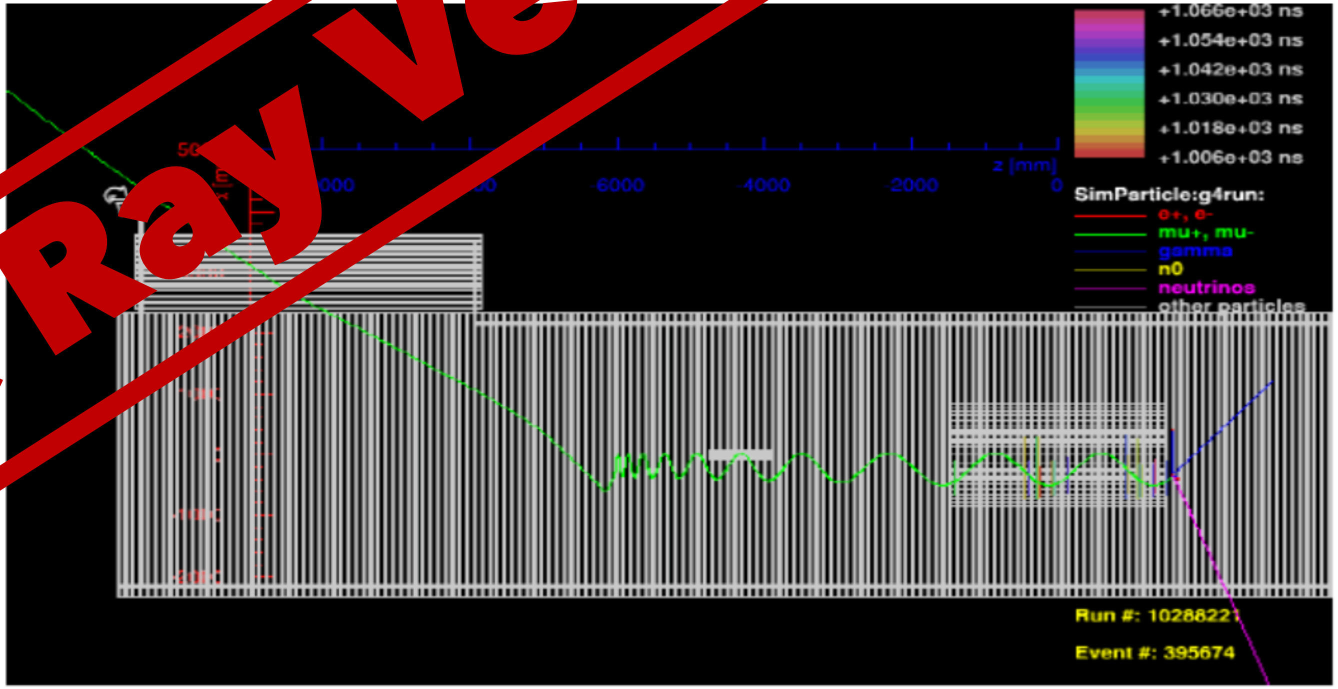

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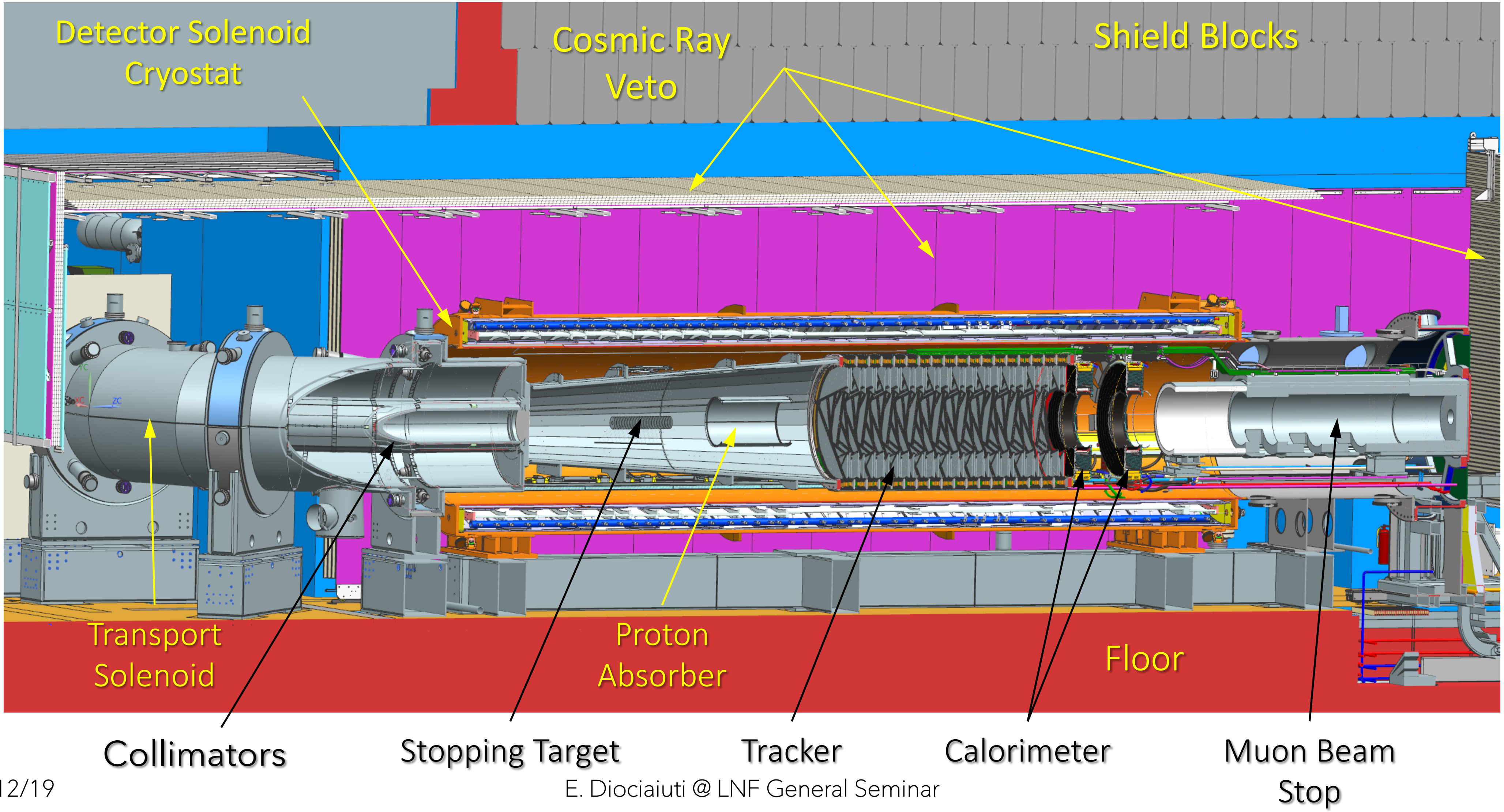
Cosmic Ray Veto

Muon campus

Detector Hall Building
- Ground Breaking (April 2015)
- Building Acceptance (March 2017)

Infrastructure installation (on going)
- LCW pipes, Bus bar, Cable Trays
- Interlocks, Networking, DAQ
- Cryo Distribution box …

DS layout


Detector Solenoid
Cryostat
Cosmic Ray
Veto
Shield Blocks
Transport
Solenoid
Proton
Absorber
Floor
Collimators
Stopping Target
Tracker
Calorimeter
Muon Beam
Stop

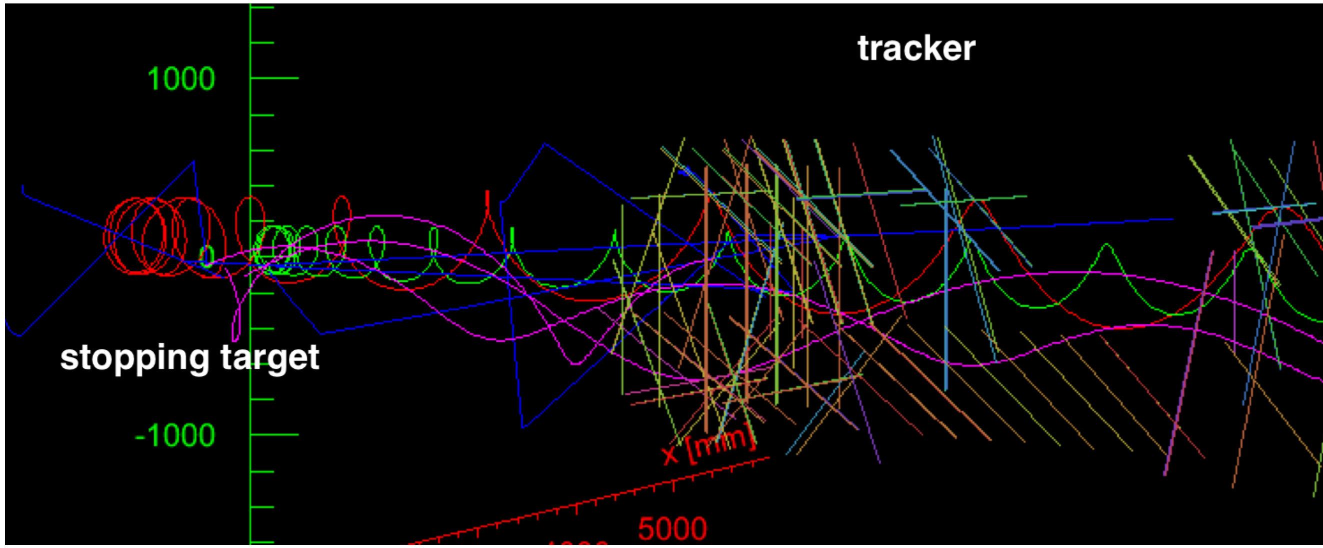
Tracker requirements

- **Provide a momentum resolution with core σ < 200 keV/c for a 105 MeV/c electron**

- Small amout of X_0 to reduce M.S.

- **Good rate capability:**
  - 20 kHz/cm^2 in live window
  - Beam flash of 3 MHz/cm^2

- **dE/dx capability to distinguish e$^-$/p**

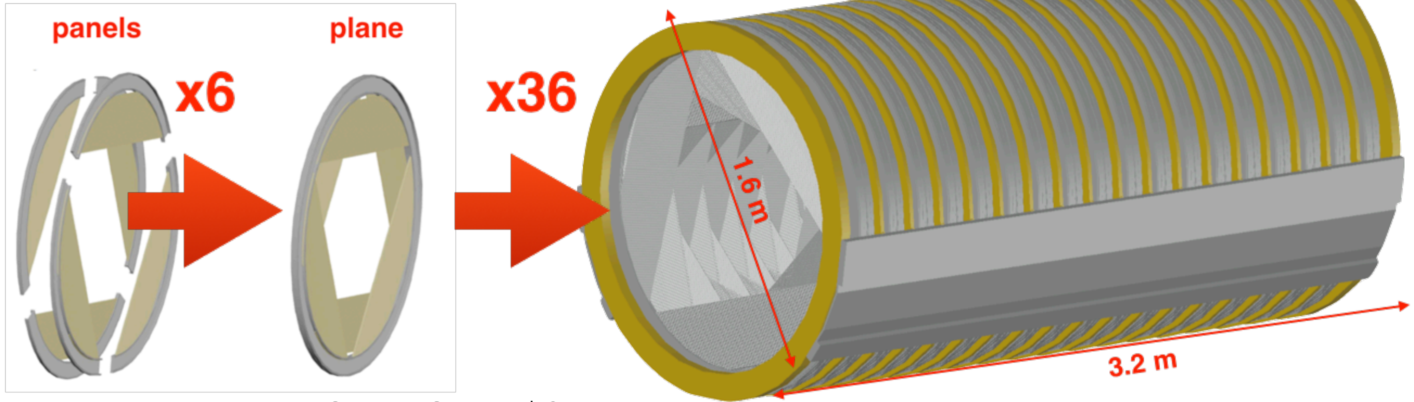


- Maximize/minimize acceptance for CE/DIO
- Work in 1 T field and 10^{-4} Torr vacuum

Tracker design

- 36 planes equally spaced with straw tubes oriented transversally to the beam
- Straw tubes : 5 mm diameter, 12 μm Mylar walls, 25 μm Au-plated W sense wire
- 80:20 $Ar:CO_2$ with HV ~ 1500 V
- Inner 38 cm un-instrumented
  - blind to beam flash
  - blind to **low** pT particles, only ~10^5 DIO remain

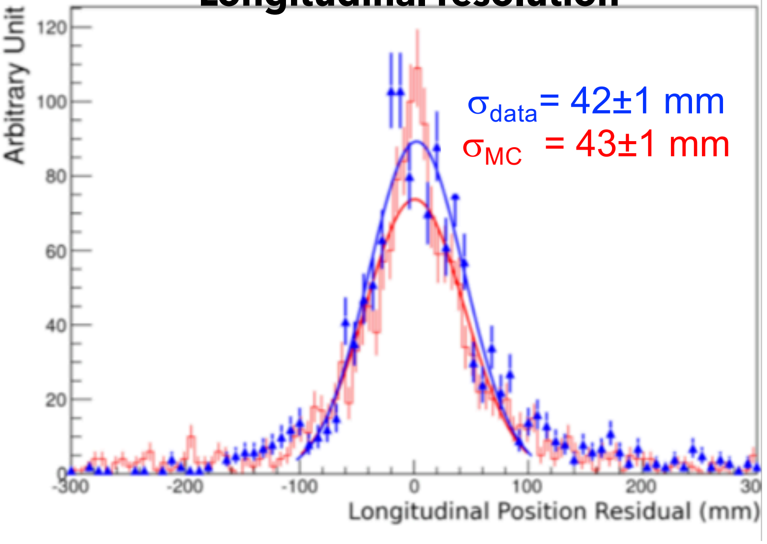
Straw-tube



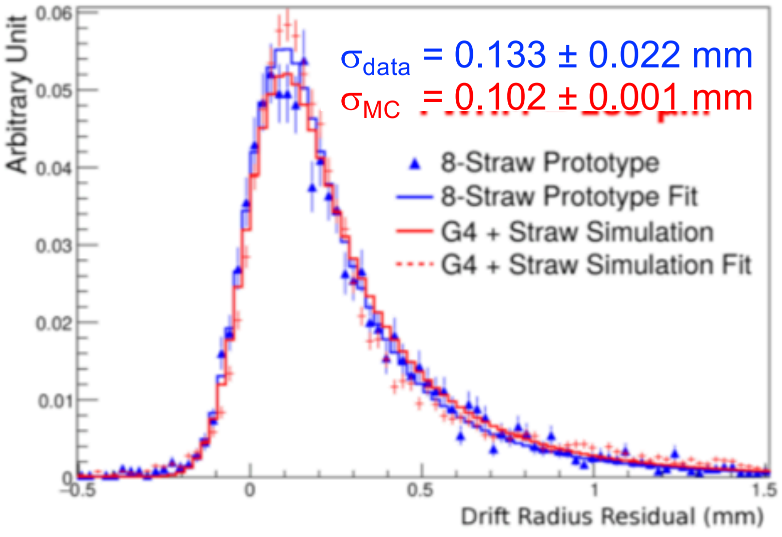
Tracker resolution

8-channels prototype test with comic rays:

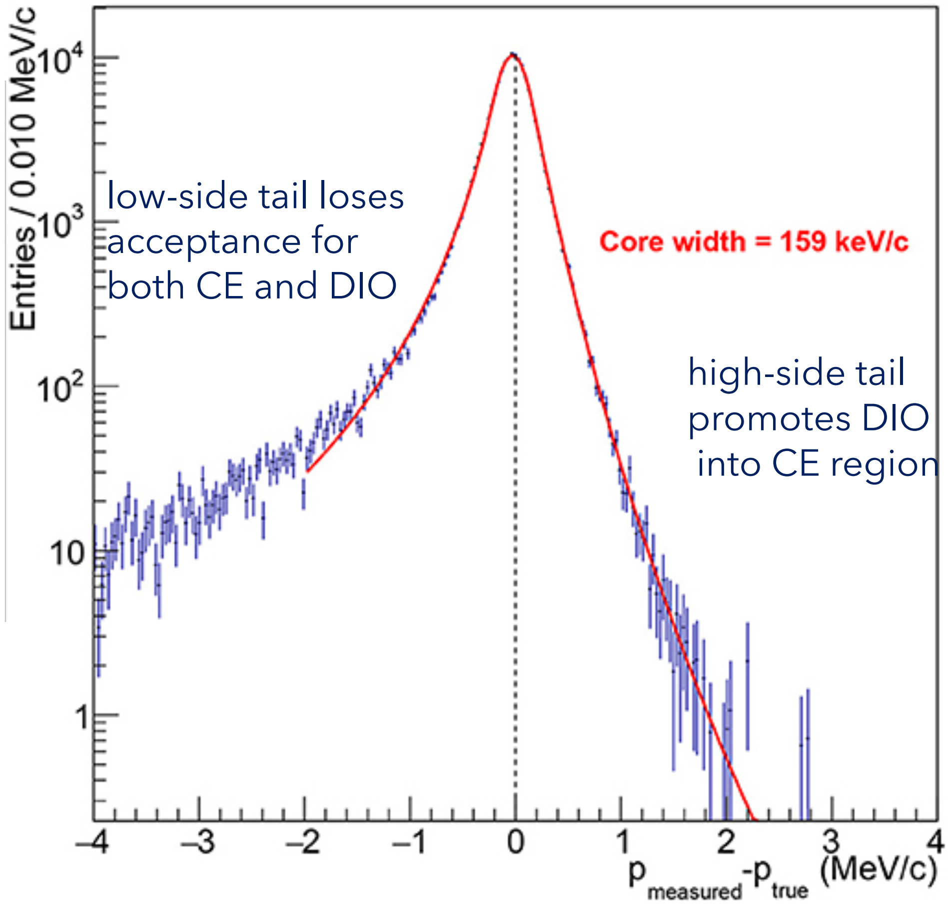
Longitudinal resolution



Transverse resolution



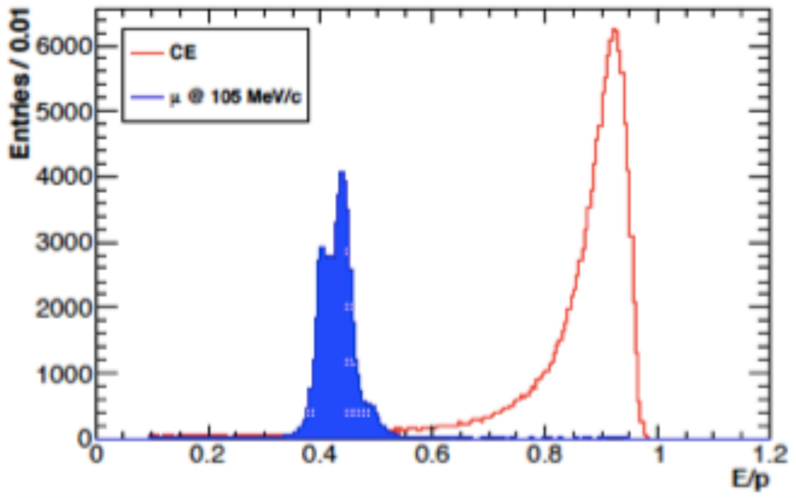
momentum resolution at start of tracker (simulation)

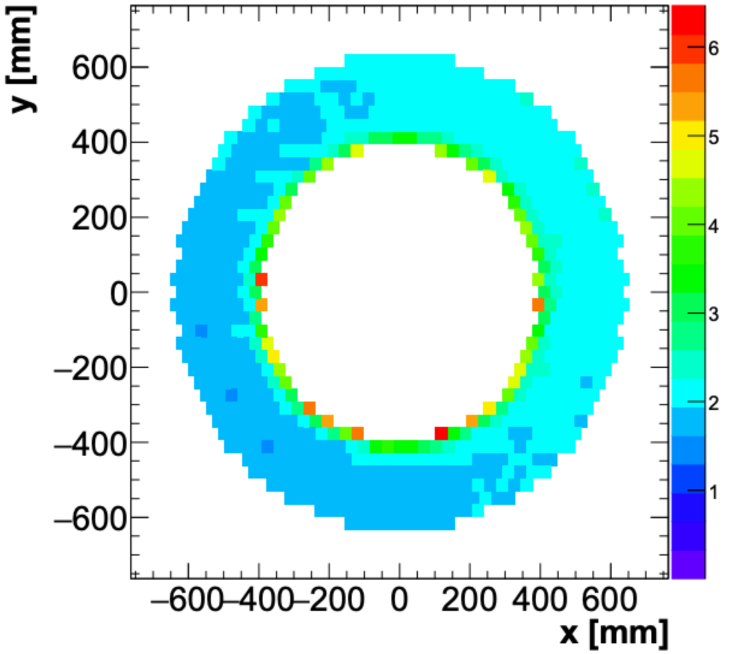


- Well within physics requirements
- Robust against increases in rate
- Inefficiency dominated by geometric acceptance

Calorimeter Requirements

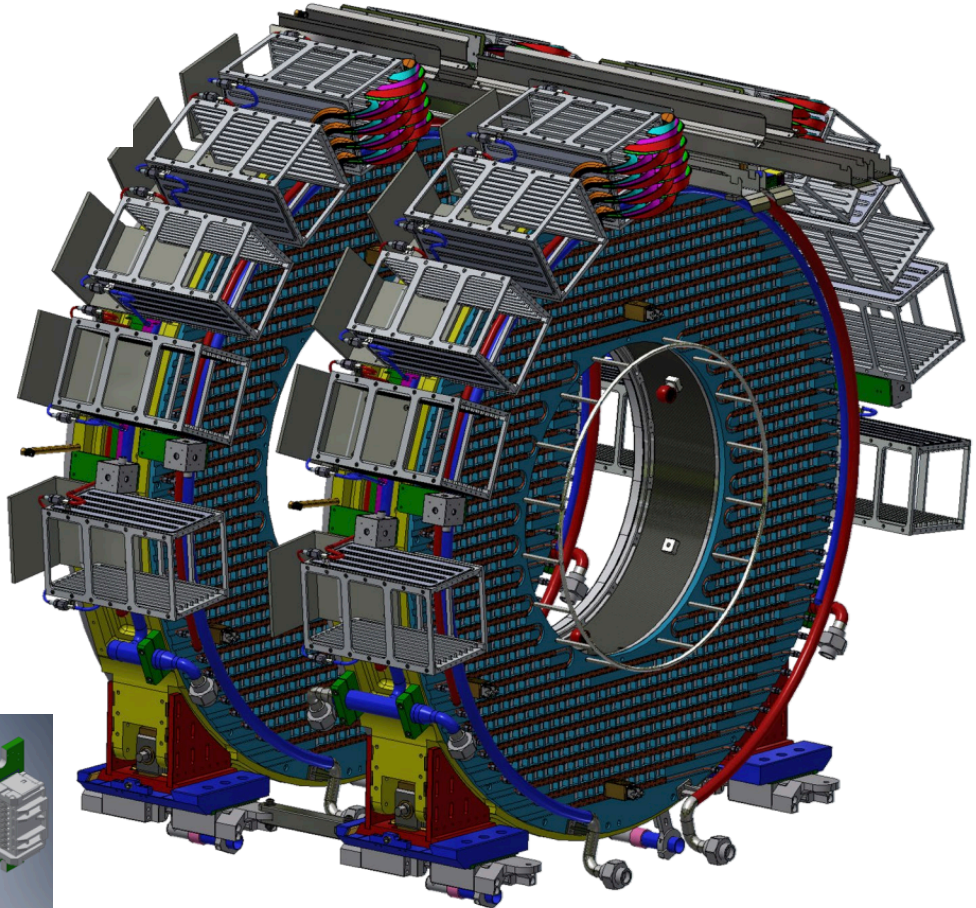
- **PID to distinguish e/μ**
- **Seed for track pattern recognition**
- **Independent trigger**
- Work in 1 T field and 10^{-4} Torr vacuum
- Withstand a very harsh radiation environment
  - Up to100 krad, 10^{12} n/cm^2/year
- **High acceptance for CE signal**
- $\sigma_E/E = \mathcal{O}(10\%)$ for CE
- $\sigma_T < 500$ ps for CE
- $\sigma_{X,Y} \leq 1$ cm

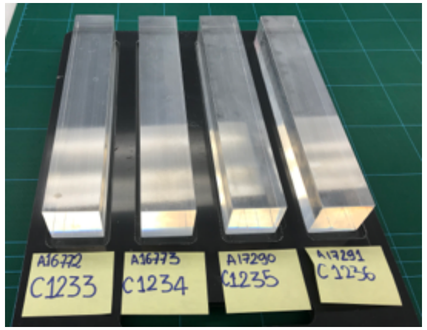


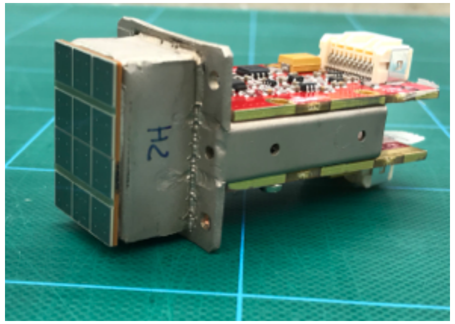


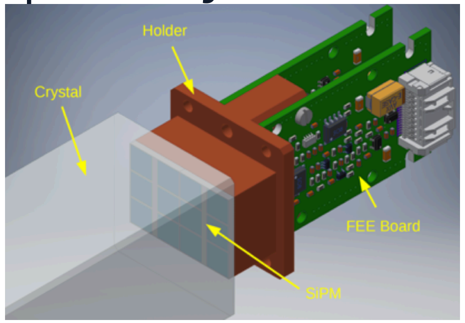
Calorimeter design

- 2 annular disks filled with 674 pure CsI crystals ($34x34x200\ mm^3$) each;
- Each crystal readout by 2 custom array of SiPMs
- R_{IN} =35.1 cm R_{OUT} = 66 cm
- Depth = 10 X_0 (200 mm), Disk separation ~ 75 cm
- 1 FEE / SiPM , Digital readout on crates
- Radioactive source and laser system provide absolute calibration and monitoring capability

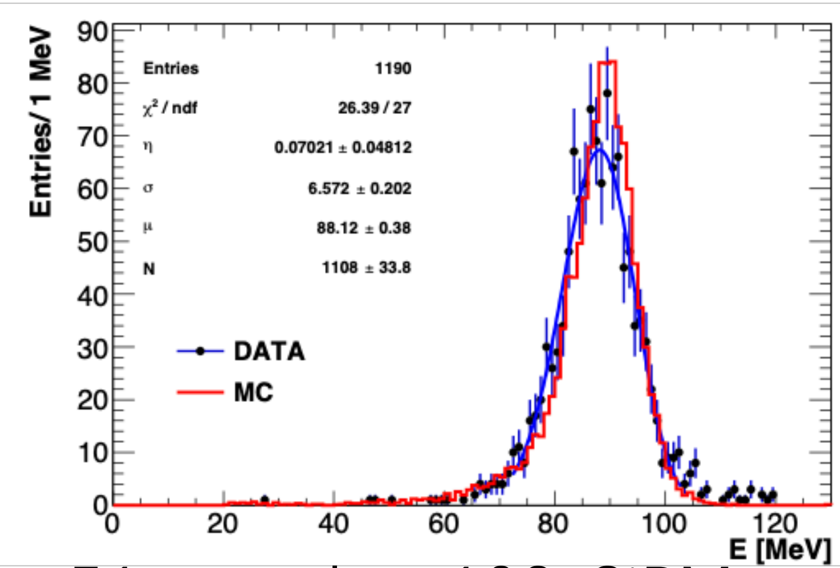


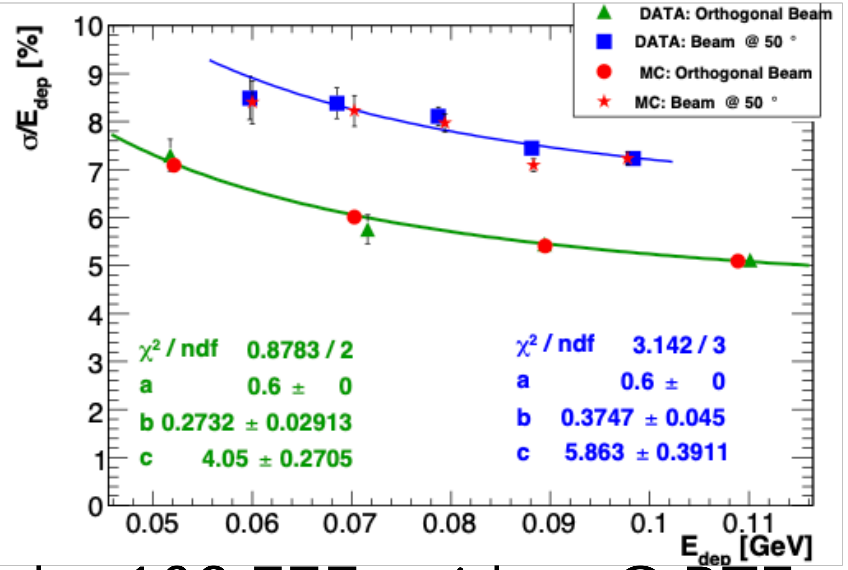


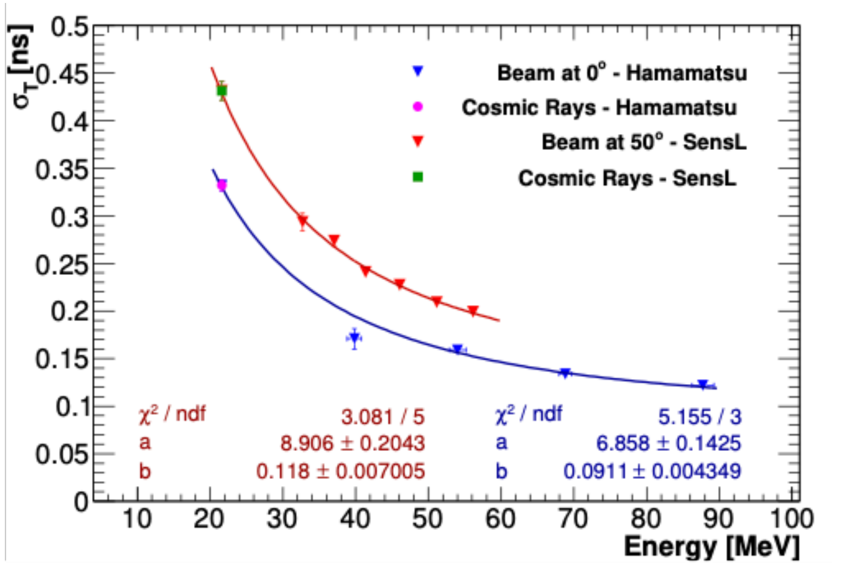




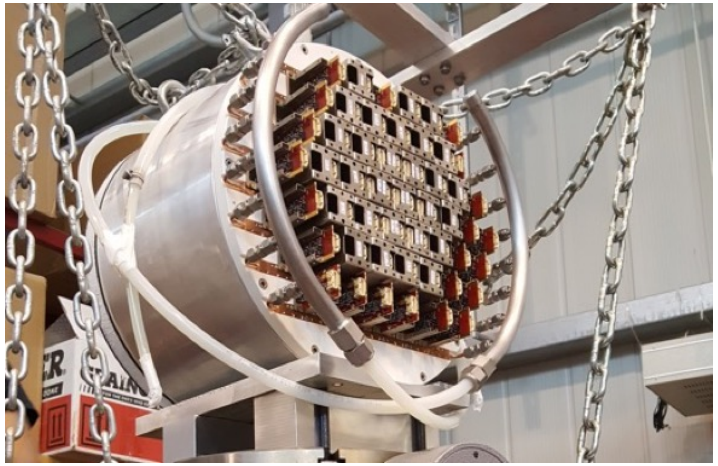
Calorimeter performances







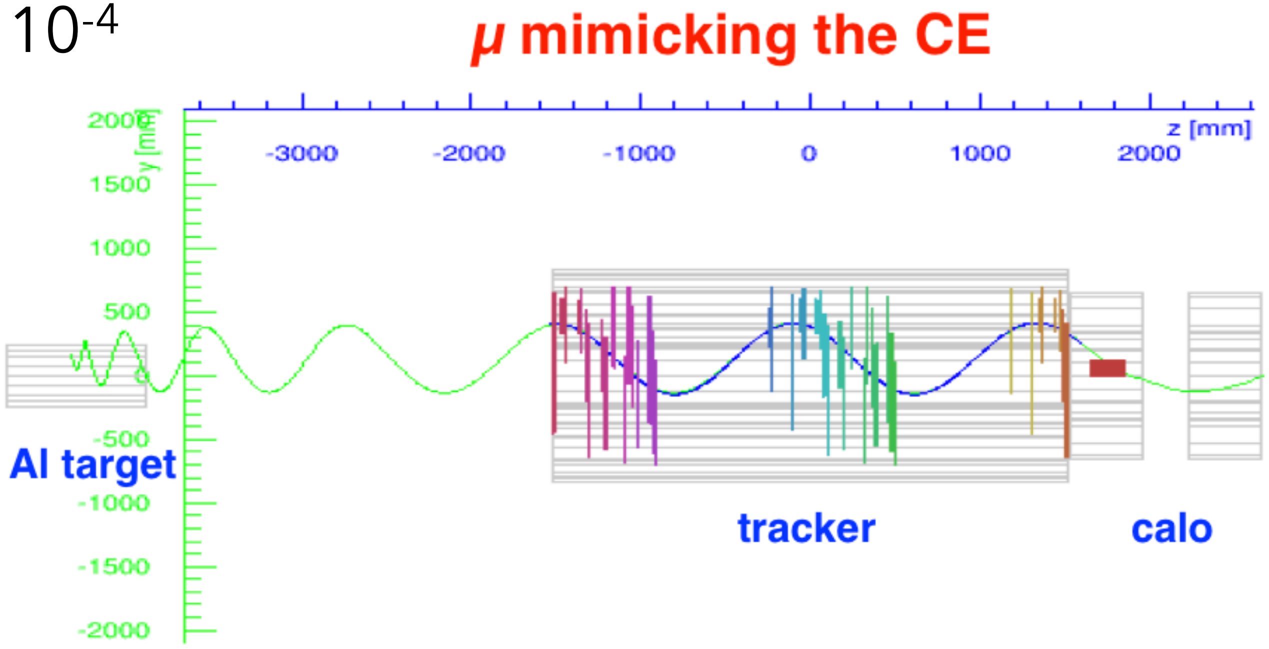
- 51 crystals + 102 SiPMs and + 102 FEEs with e^- @ BTF
- 5.4 % (7.3%) energy resolution @ 100 MeV for 0° (50°) impact angles. Excellent data-MC agreement
- Timing resolution < 150 ps with one sensor



Good agreement with the Mu2e requirements

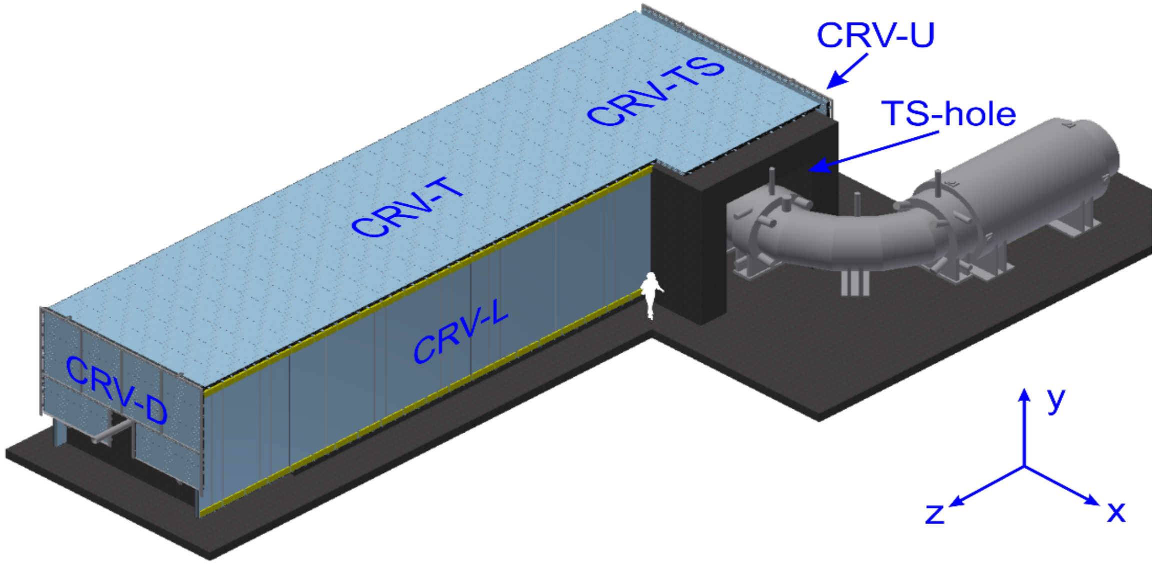
Cosmic Ray Veto requirements

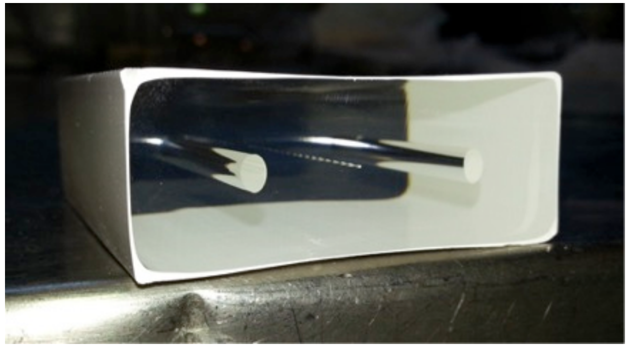
- **Limit the conversion-electron background due to Cosmic Rays to less than 0.2 events (at 90% CL) over the duration of the data taking run;**
- produce less than 10% dead time
- use less than 20% of the DAQ bandwidth
- Veto inefficiency < 10^{-4}

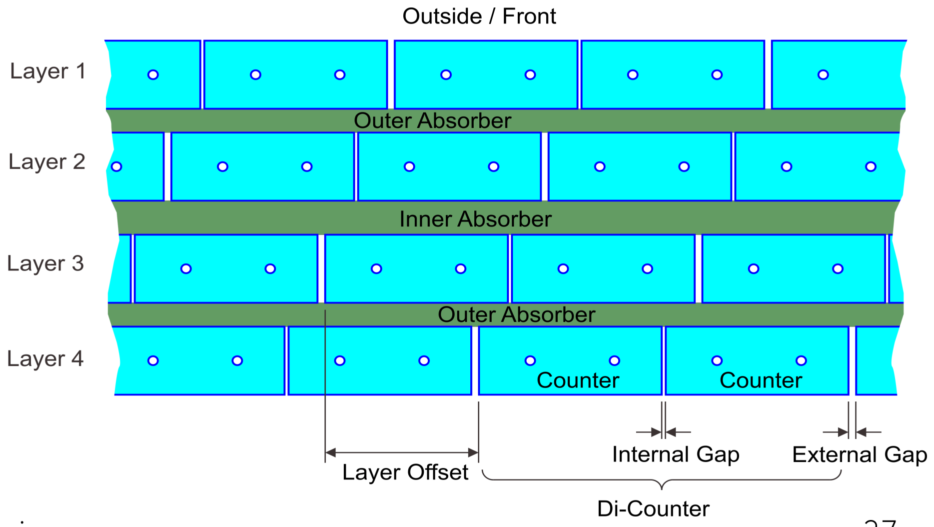


Cosmic Ray Veto design

- CRV system covers entire DS and half TS (surface of 327 m^2)
- 4 layers of scintillator counters
  - each bar is 50×20 mm^2 extruded scintillator counters of lengths ranging from 1m to 6.9 m.
  - 2 WLS fibers/bar
  - read out at both ends with SiPMs

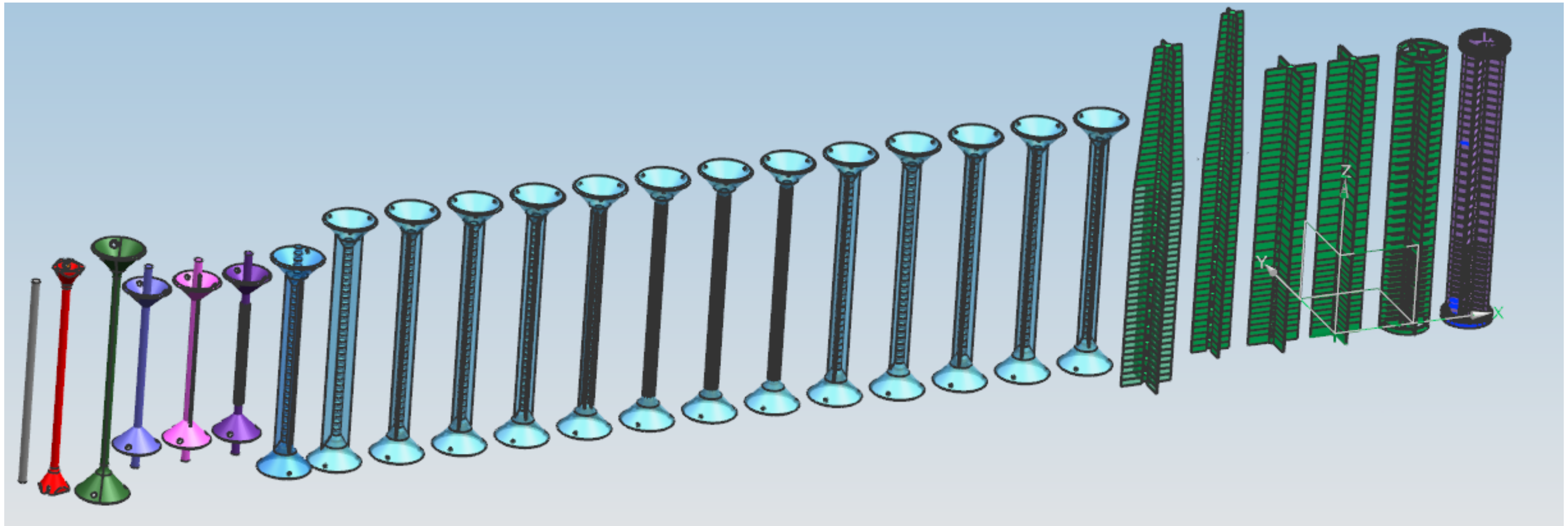


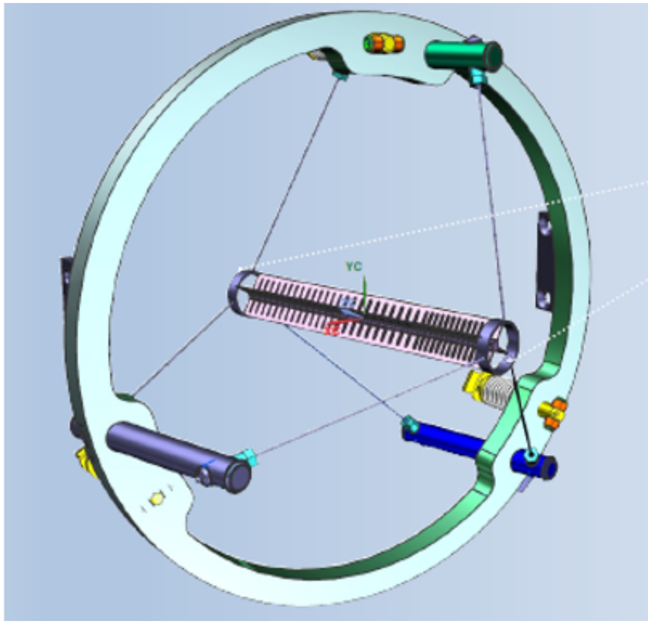




Production target

- Lots of work performed in the optimization of the Tungsten target
- 26th version is the final one: Hayman 2
  - circular rings at the end and core finned → better heat dispersion and temperature control

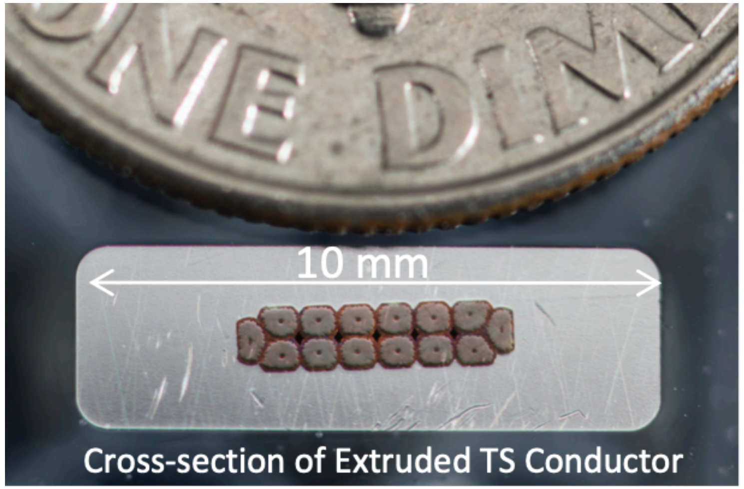




Solenoids: status and construction

	Production	Transport	Detector
Length (m)	4	13	11
Diameter (m)	1.7	0.4	1.9
Field @ start (T)	4.6	2.5	2.0
Field @ end (T)	2.5	2.0	1.0
Number of coils	3	52	11
Conductor (km)	14	44	17
Operating current (kA)	10	3	6
Stored energy (MJ)	80	20	30
Cold mass (tons)	11	26	8

- PS, DS built by **General Atomics** (USA)
- TS built by **ASG** (Italy)
- Superconducting cable procured and tested
- PS/DS winding in progress at GA (Tupelo)



TS status

- Series of wedge-shaped coil modules
- All 52 TS coils wound at cold mass vendor.
- 9 of 14 TS units completed, 5 remaining, all in fabrication
  - Significant improvement in vendor throughput
  - Vendor quality issues addressed by onsite presence and careful review of QC documents

Tracker status

- Straw Procurement completed (30k straws)
  - Straw production well progressed.
  - Complete fixtures in May 2020

Panels

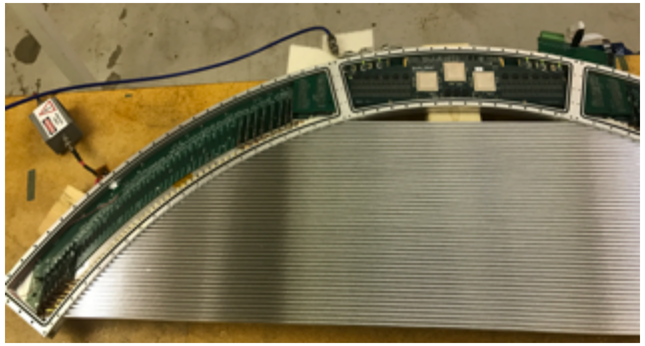
- Design Complete
- Production assembly fixtures fabricated
- UMN Panel Factory & QC Station set up
  - Now working on the 16th panel

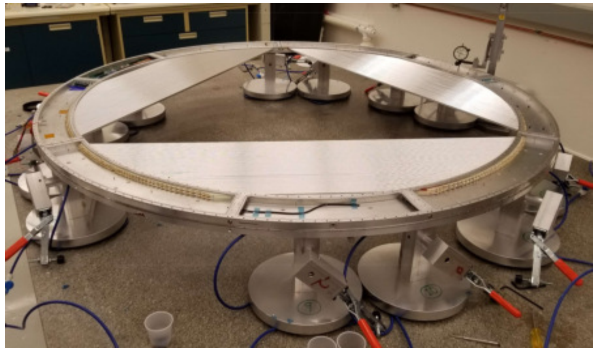
Plane

- Plane assembly tooling fixture design nearly complete

Electronics

- Incorporation of rad hard FPGA in progress


Panel w/Front-End Electronics


Three panels installed in plane

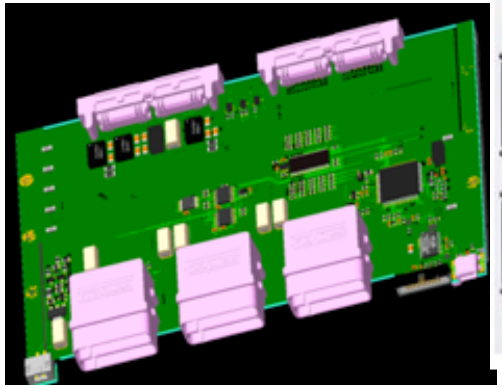

Panel: Straw Installation

Test beam under organization for the beginning of the next year

Calorimeter status

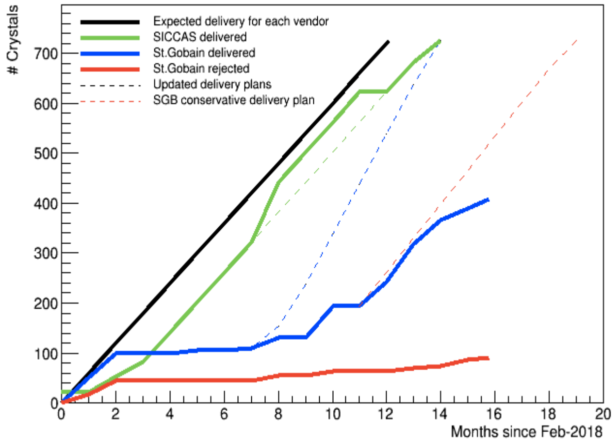
- 1100/1450 crystals produced and tested
- 4000/4000 SiPMs produced and tested
- Radiation hardness test of FEE and DIRAC done
- Vertical slice test done
- Mechanics under construction in Italy

Mezzanine Board

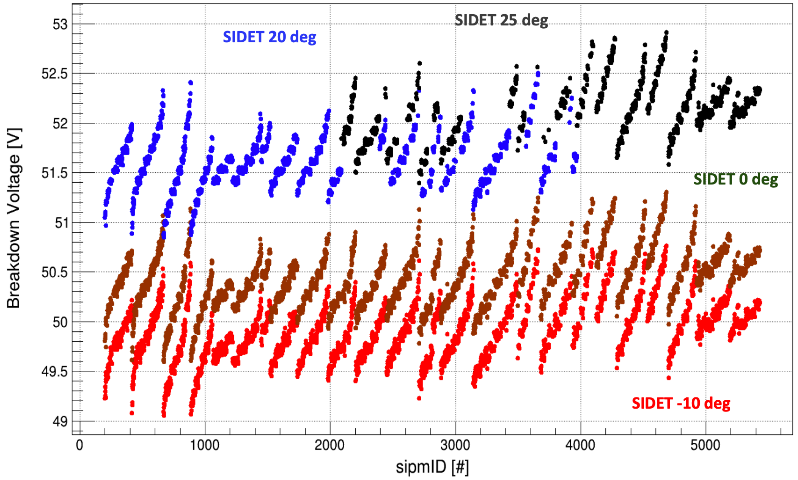


Digital Board: DIRAC

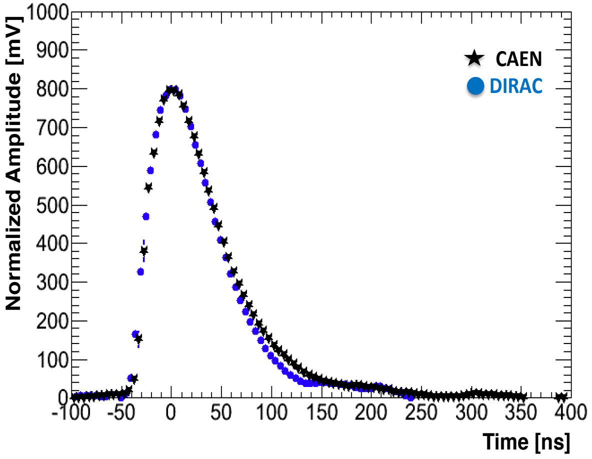
Crystal production



QA SiPMs production



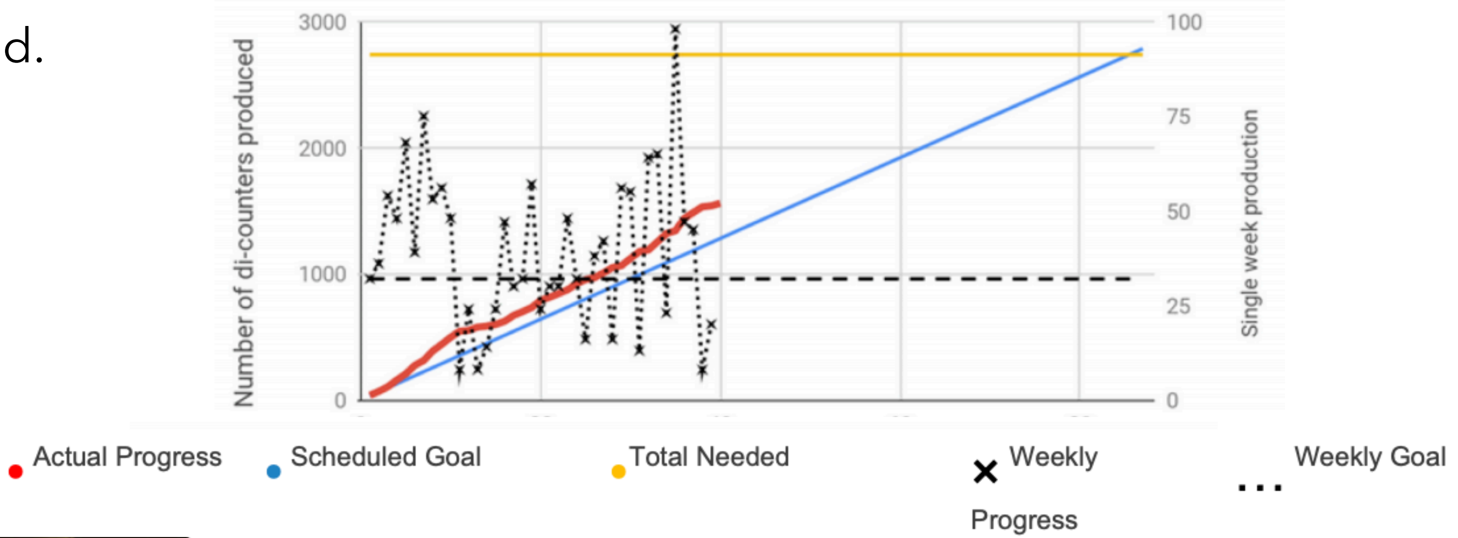
Vertical Slice test

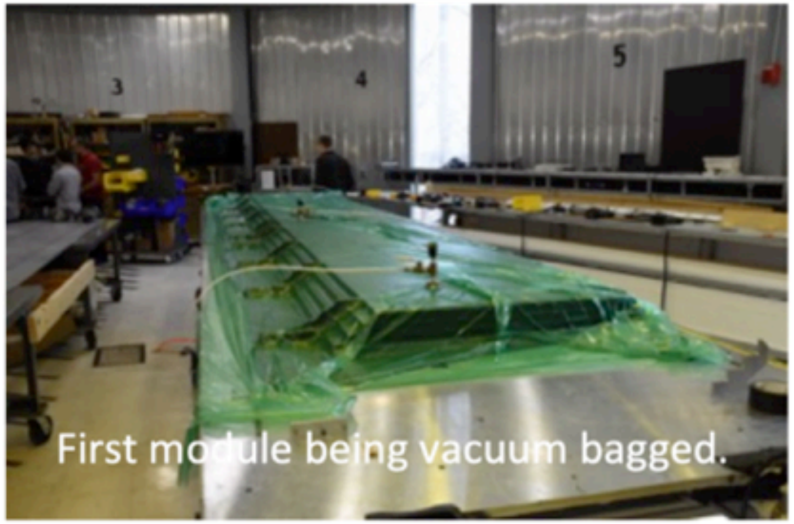


Al Disk Full Size proto

CRV

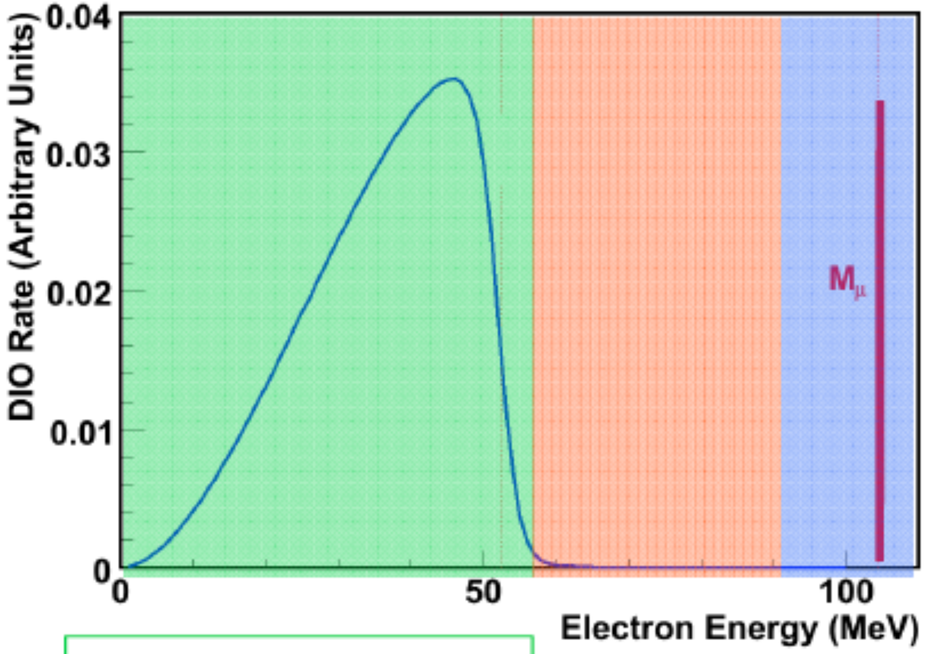
- CRV module and electronics design completed.
- Modules
  - Extrusion fabrication completed
  - Di-counter fabrication at UVA @ 50%
  - 6% of Module fabrication
- Electronics
  - Pre-production FEE Boards completed





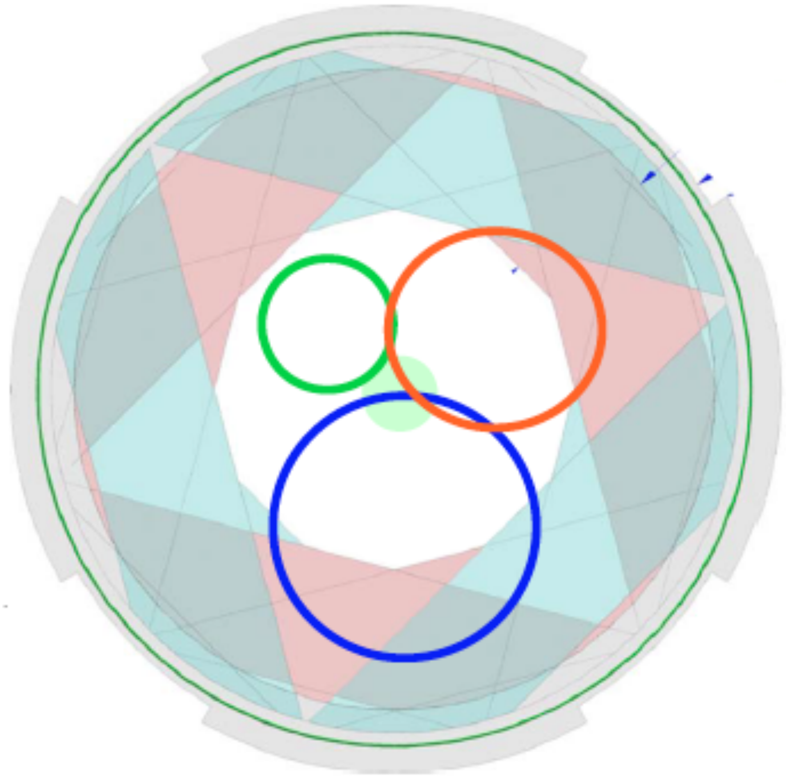
Reconstructing the momentum

reconstructable tracks



no hits in tracker

some hits tracker, tracks not reconstructable.

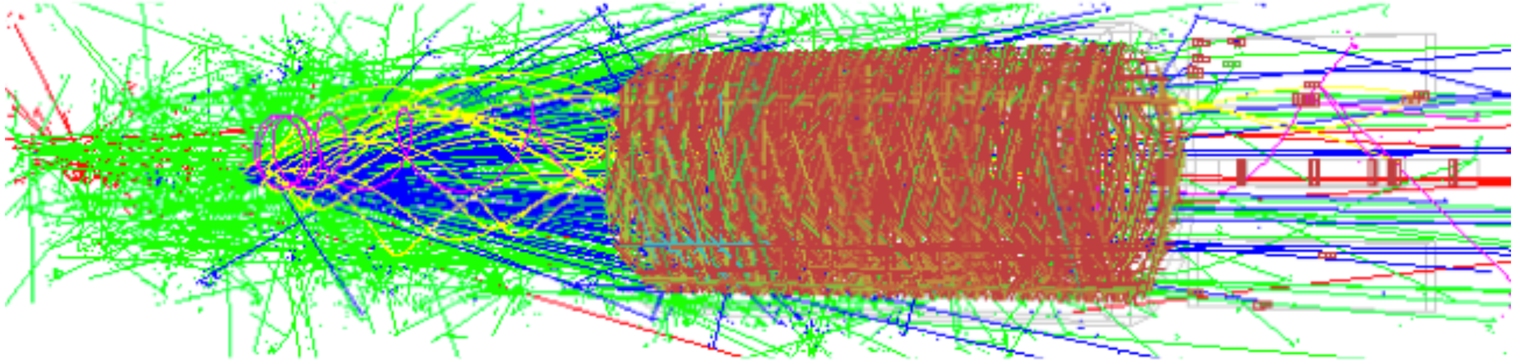


BLIND TO Beam Flash and > 99% DIO

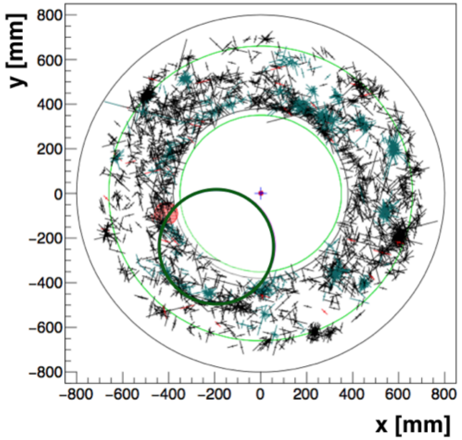
beam's-eye view of the tracker

A typical event…

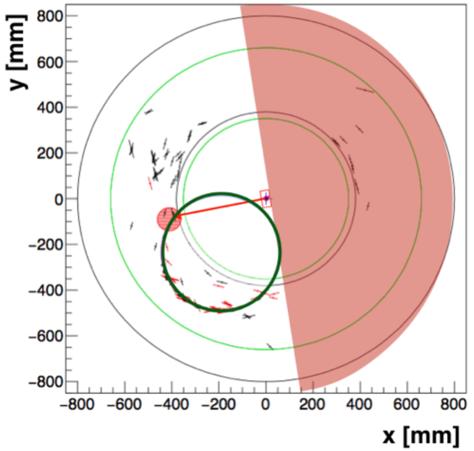
500 – 1695 ns window



no selection



calorimeter selection



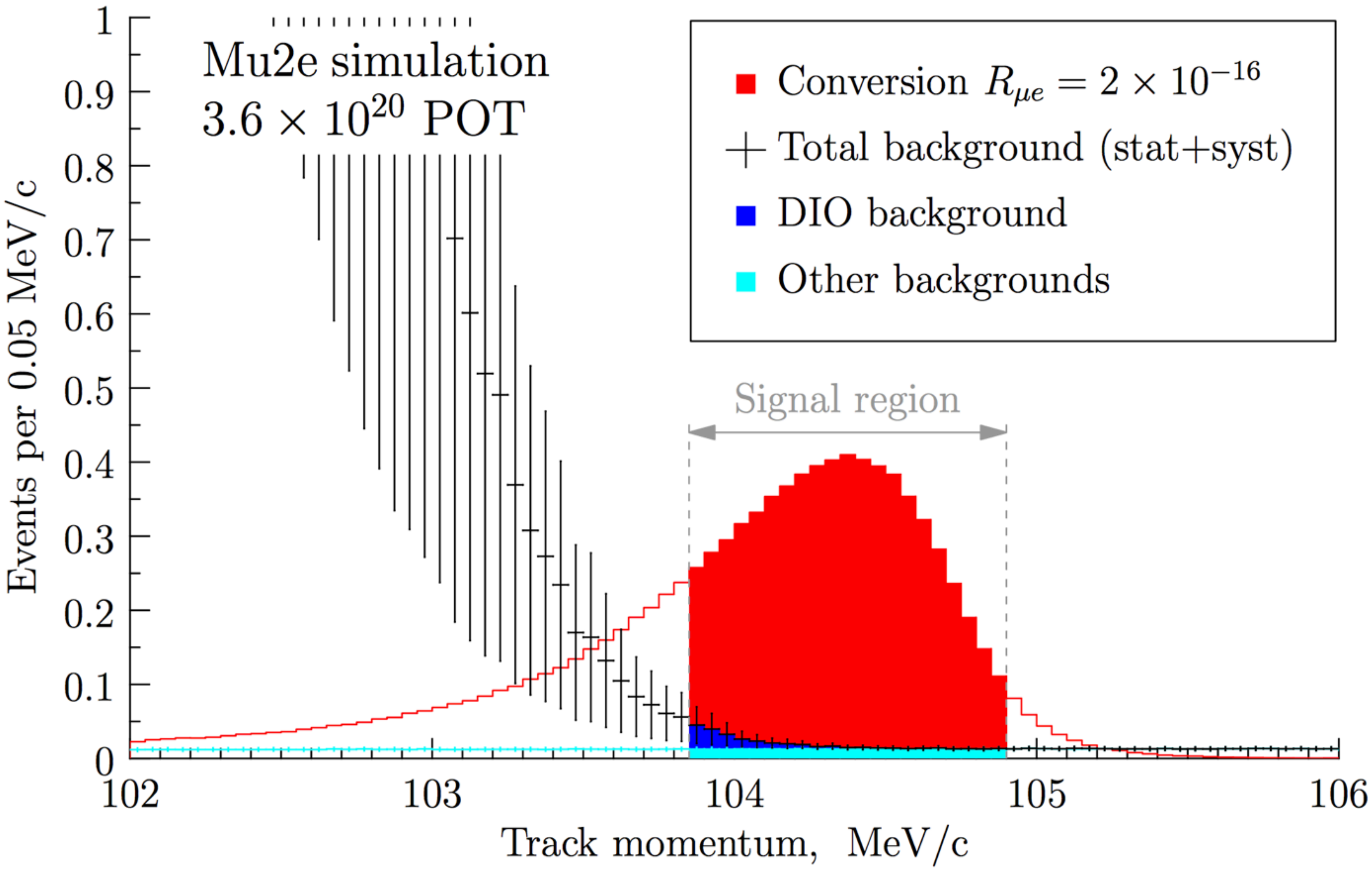
Track reconstruction workflow:

- pattern recognition: search for a group of hits correlated in time and forming a helicoidal trajectory
- global 3D track fit: uses B-field map and computes a unique chi2
- Kalman based fit: takes into account Energy loss and Multiple Scattering

Simulation of μ⁻-e⁻ conversion

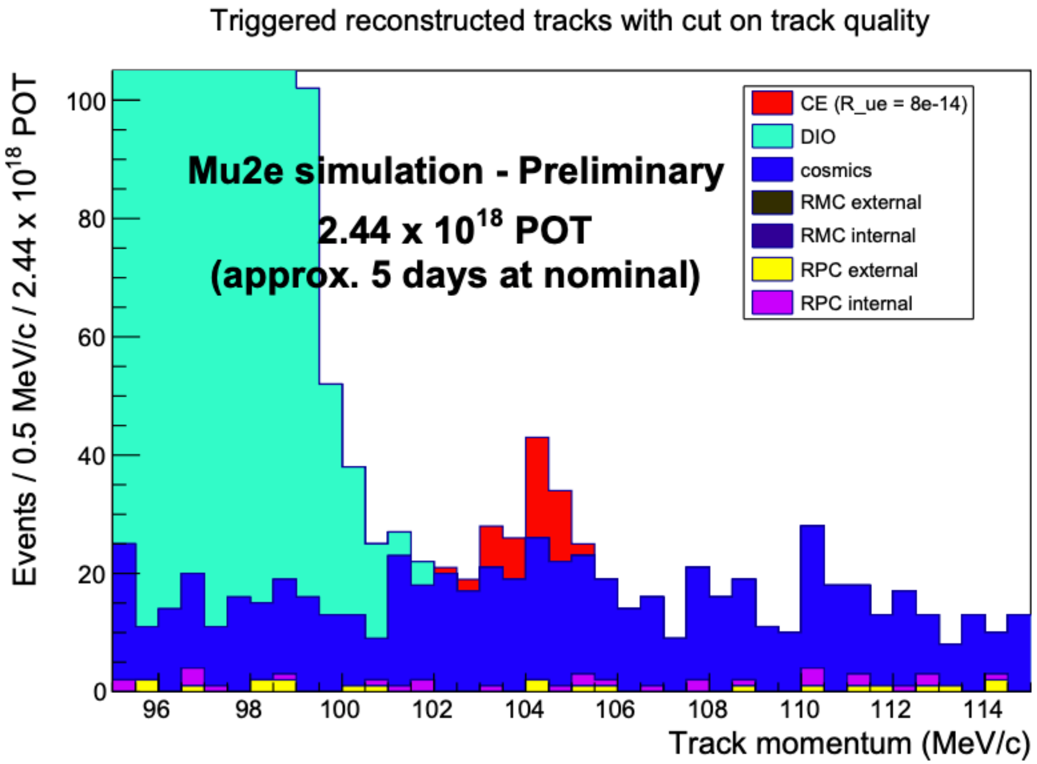
Discovery sensitivity **(7.5 events)** accomplished with three years of running and suppressing **backgrounds to < 0.4** event total

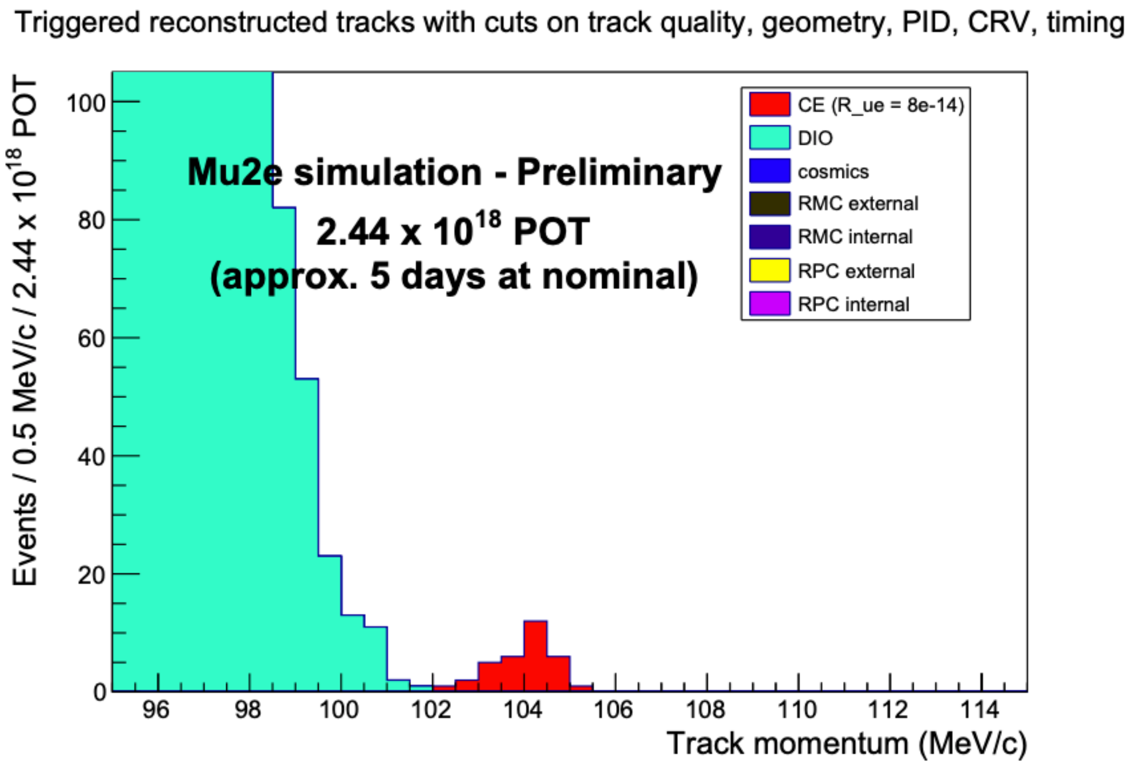
(50% cosmics, 35% DIOs)



Mock Data Challenge

- Simulated data ensemble mimicking a real dataset from the experiment
  - 1 week of data taking (<1% POT)
- $R_{\mu e} = 8 \times 10^{-14}$ simulated (10 times better than Sindrum-II)





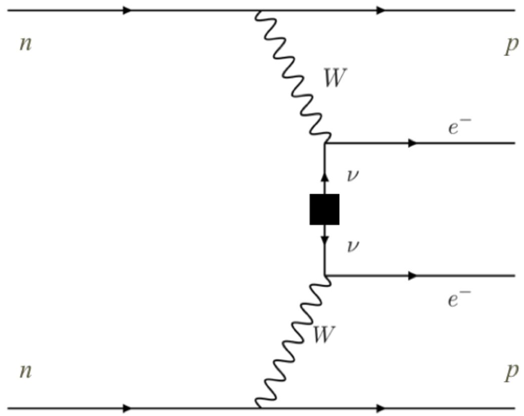
Additional searches?

- An additional channel that Mu2e can investigate is the μ^--e^+ conversion

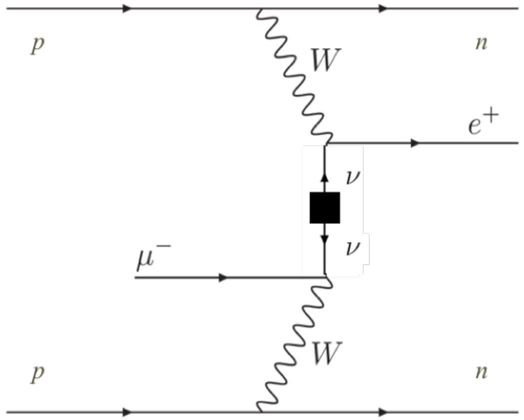
$$\mu^- + Al(27,13) \rightarrow e^+ + Na(27,11)$$

- This is an example both of Lepton number violation and CLFV

0νββ



μ^- N(A,Z) → e^+ N(A,Z-2)



- A recent study demonstrates that, while 0νββ has the greatest sensitivity to new ultraviolet energy scales, its rate might be suppressed by the new physics relationship to lepton flavor

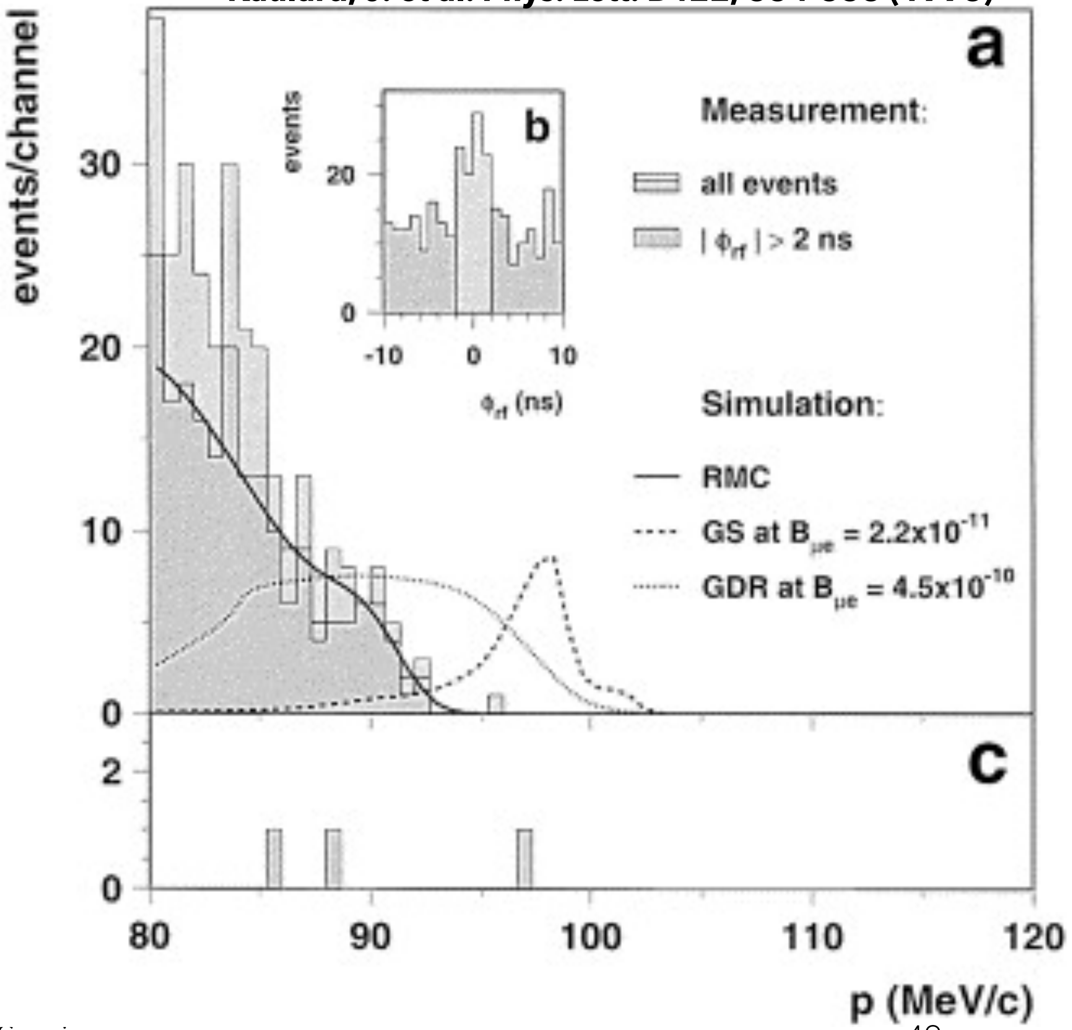
T. Geib, A. Merle, and K. Zuber. Phys. Lett. B 764,157 (2017).

μ^--e^+ conversion

- Need to occur at 2 nucleons (ΔQ =2)
- Conversion can undergo through Ground State Transition (40%**) and through Giant Dipole Resonance (60%)
  - $E_{e^+}^{GDR} = 83.9\ MeV$ --> completely dominated by backgrounds
  - $E_{e^+}^{GS} = 92.32\ MeV$

$$B^{GS}_{\mu^- e^+} < 1.7 \times 10^{-12} (90\% C.L)$$
$$B^{GDR}_{\mu^- e^+} < 3.6 \times 10^{-11} (90\% C.L)$$

Kaulard, J. et al. Phys. Lett. B422, 334-338 (1998)



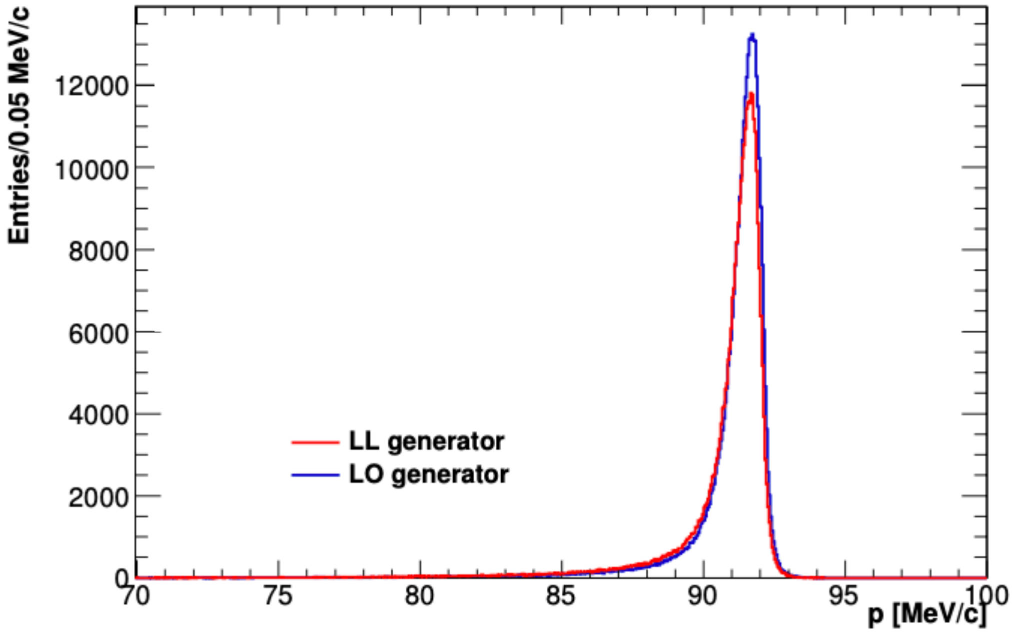
**Phys Rev C 70, 065501 (2004)

μ^--e^+ conversion in ^{27}Al (Signal)

- e^+ energy evaluated from the energy conservation of the process

$$E_{e^+} = m_\mu - B_\mu - E_{\rm recoil} - \Delta_{Z-2} = 92.32 \text{ MeV}$$

- Account of radiative correction in the full MC simulation



$$\frac{1}{\Gamma_0}\frac{\mathrm{d}\Gamma}{\mathrm{dE}_e} = \frac{1}{E_{max}}\left[\left(\ln\frac{4E_e^2}{m_e^2} - 2\right)\frac{E_e^2 + E_{max}}{E_{max}(E_{max} - E_e)} + P(E_e)\right]$$

Universal part

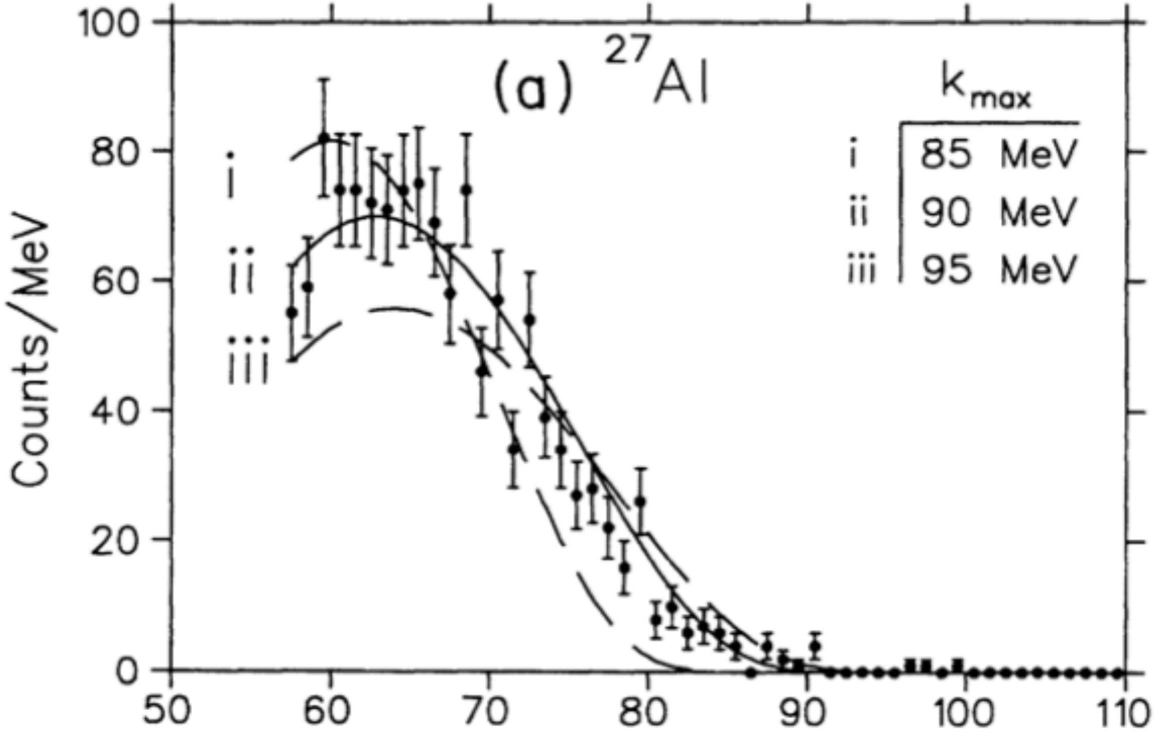
γ emission by a free e^+

Main background: RMC

$$\mu + N(A,Z) \rightarrow \gamma + \nu_\mu + N(A,Z-1)$$

- Asymmetric conversion of the γ
  - e^+ coming from pair production enter the signal region
- Measurements on light nuclei dominated by background DIO
- It is a rare process
  - $E_\gamma > 57$ MeV ~ 1.4×10^{-5}
  - Tails not well known
- Measured end point for ^{27}Al:
  - **k_{max} = (90.1 ± 2) MeV**

Eγ from RMC

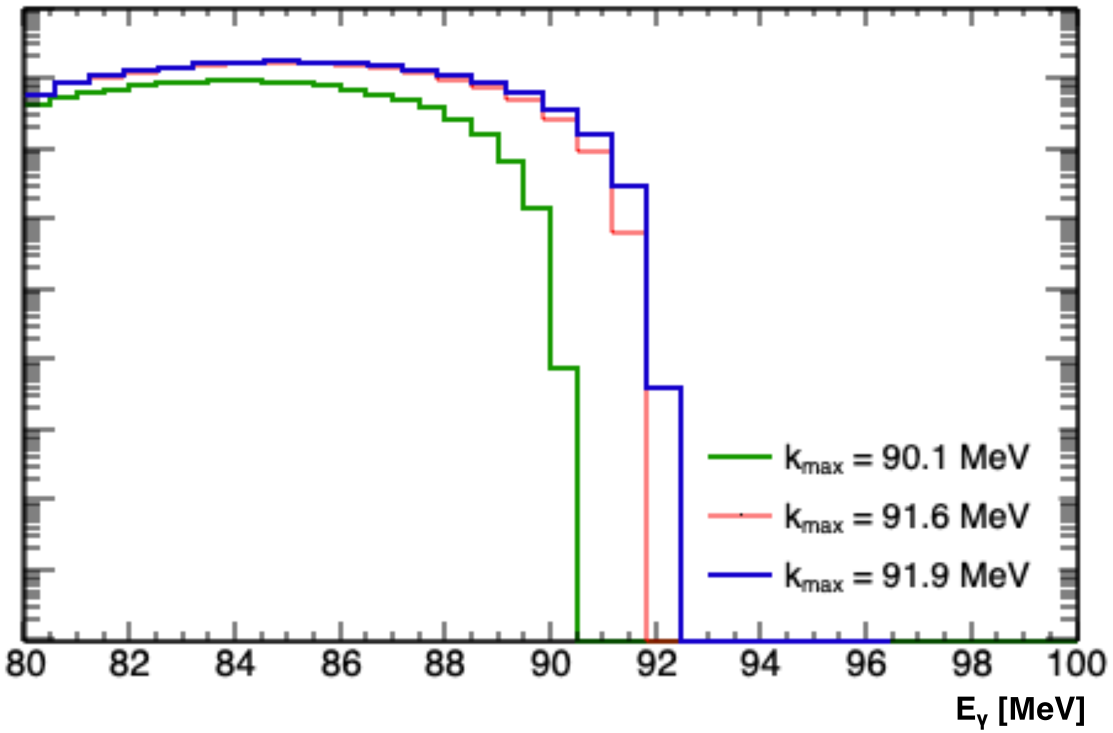


Triumf collaboration. *Physical Review C* 46.3 (1992): 1094

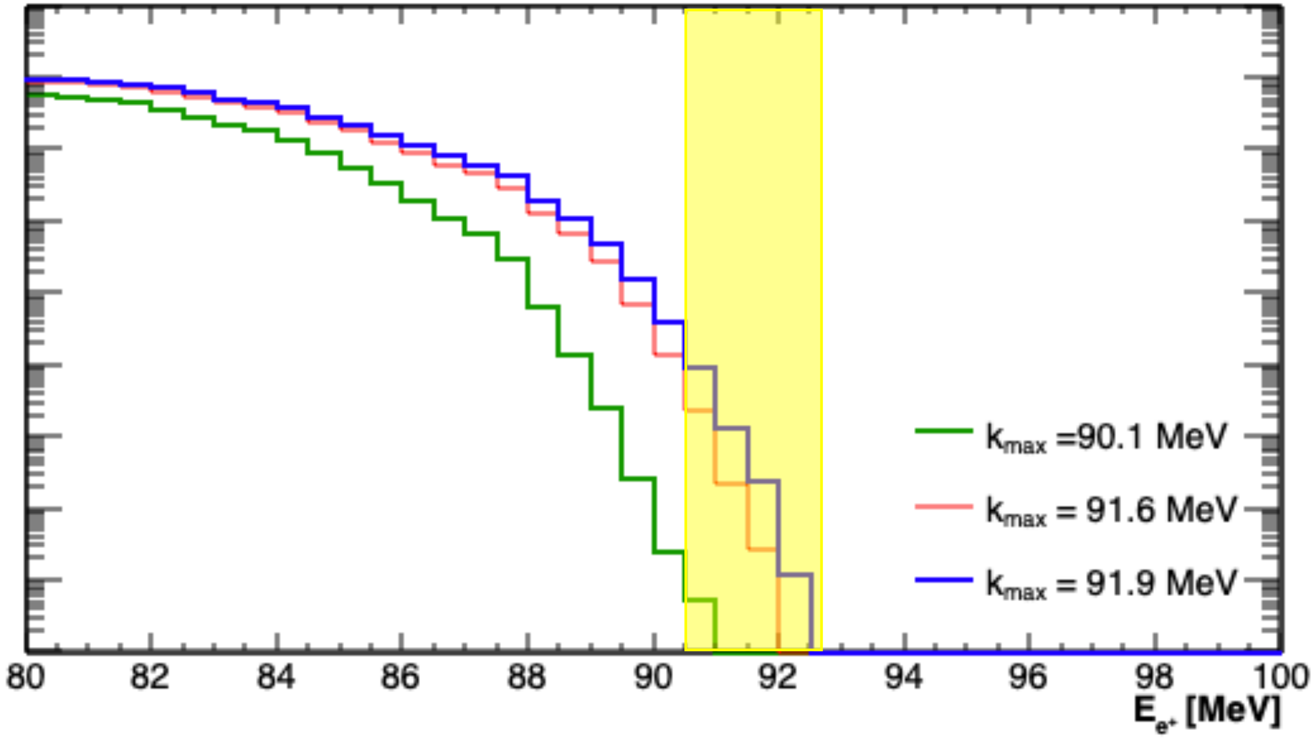
Modelling the RMC background

- First attempt to extract the RMC positron background from the RMC photon distribution
- Different k_{max} values tested

RMC photon distribution



RMC positron distribution



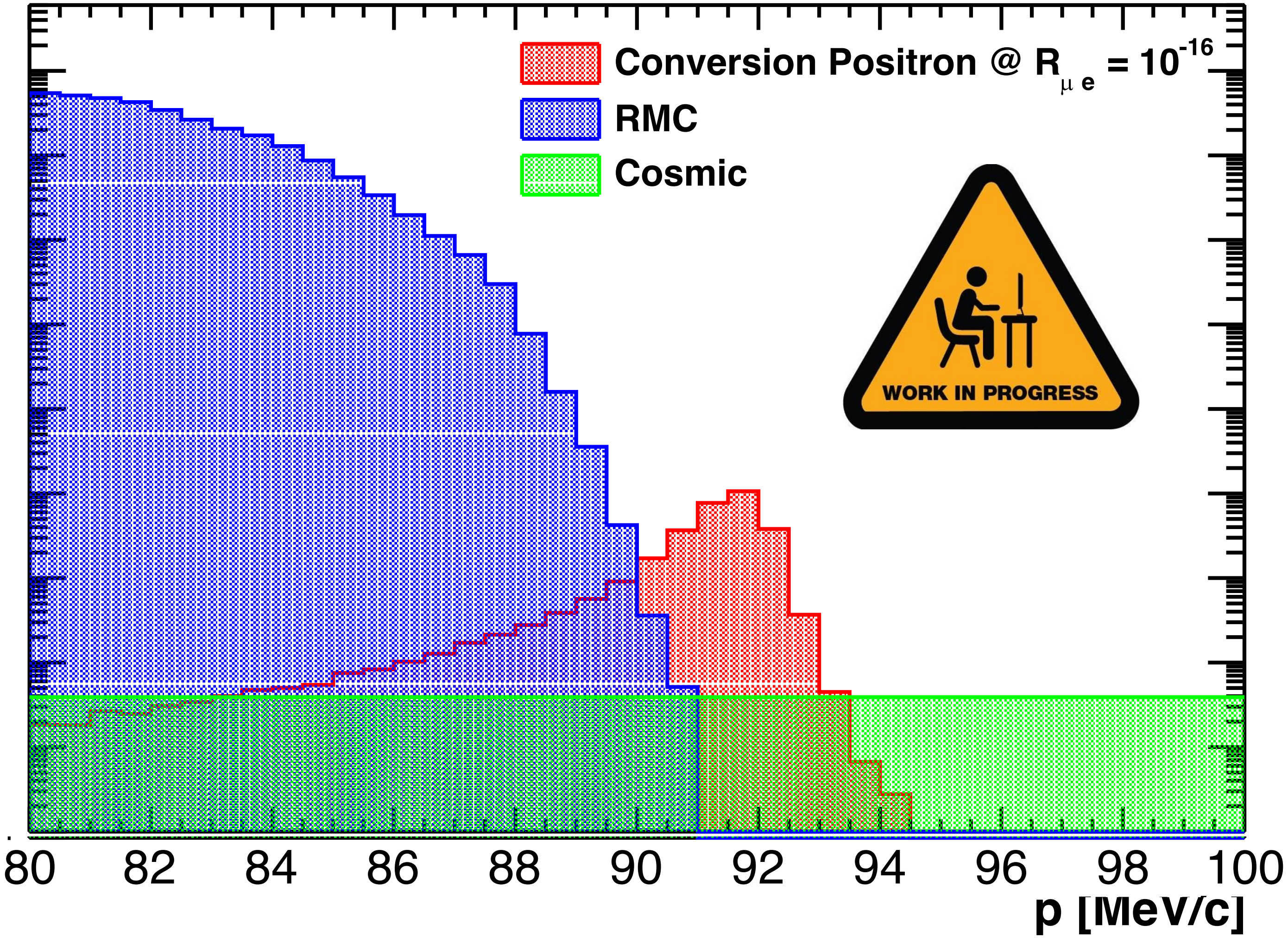
μ^{-}-e^{+} conversion .. First look

- Evaluation of the sensitivity for $\mu^{-}e^{+}$ conversion undergoing

- **For the moment only RMC (k_{max} = 90.1 MeV) and cosmic rays background considered**

➔ Sensitivity improvement w.r.t. Sindrum-II of almost 4 orders of magnitude

➔ Sensitivity strongly depends on k_{max}
It can worsen up to a factor of 20 changing the k_{max} value of few MeV

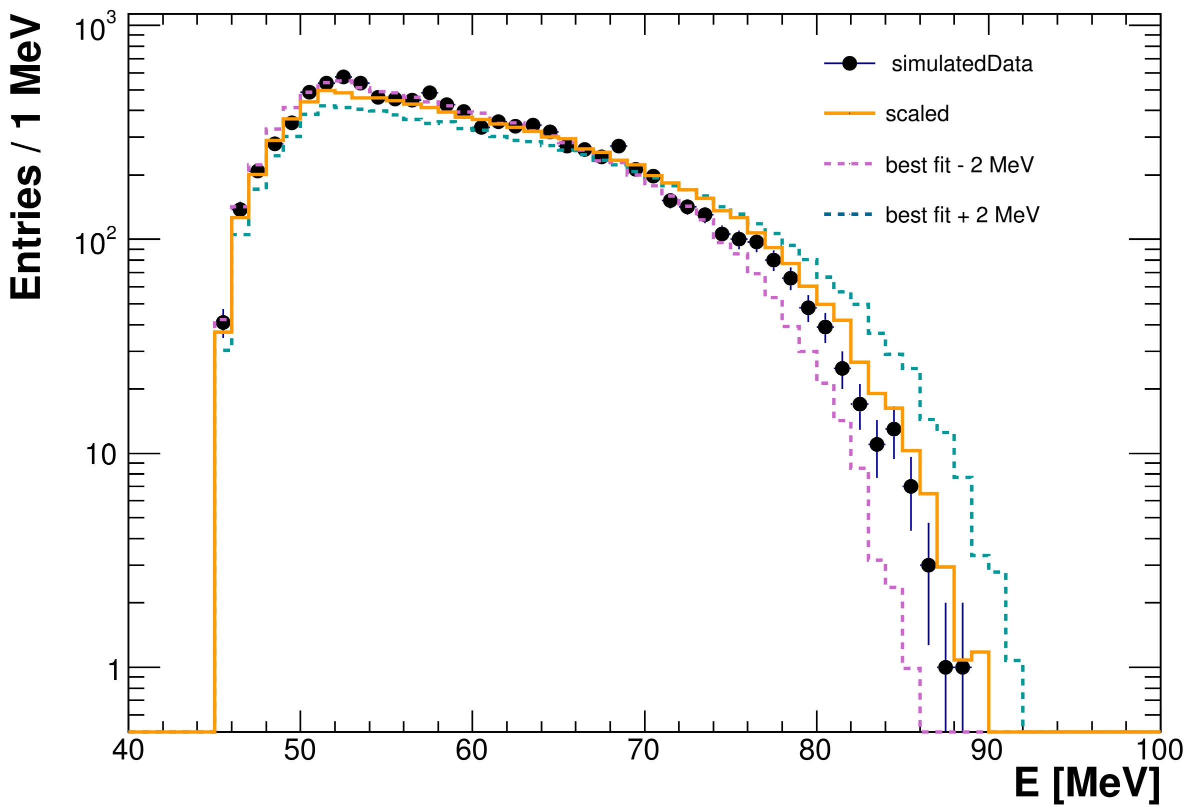


Calorimeter Contribution for RMC

- Know exactly the endpoint of the RMC distribution
  - calorimeter plays a central role!

$$\frac{\mathcal{R}_{RMC}}{\mu B} = \frac{N_{POT}}{\mu B} \times \frac{N_{\mu}^{stop}}{POT} \times F_{capt} \times P(RMC) \times \mathcal{R}(T_{gate}),$$

- Calorimeter able to reconstruct k_{max} within few 100 keV
- **After one week already possible to meausure the RMC distribution endpoint!**



Conclusions

The Mu2e experiment:

- Improves sensitivity on conversion experiment by a factor of 10^4
- Could largely improve sensitivity also for (LFV/CLFV) μ^--e^+ (still in progress)
- Provides *discovery capability* over wide range of New Physics models
  - Is complementary to LHC, heavy-flavor, dark matter, and neutrino experiments
- Will begin commissioning the detectors in 2021
- schedule dominated by the magnets delivery
- Will start physics data taking in 2023

Thank you!

Mu2e

LNF General Seminar, 19 December 2019

INFN LNF Istituto Nazionale di Fisica Nucleare

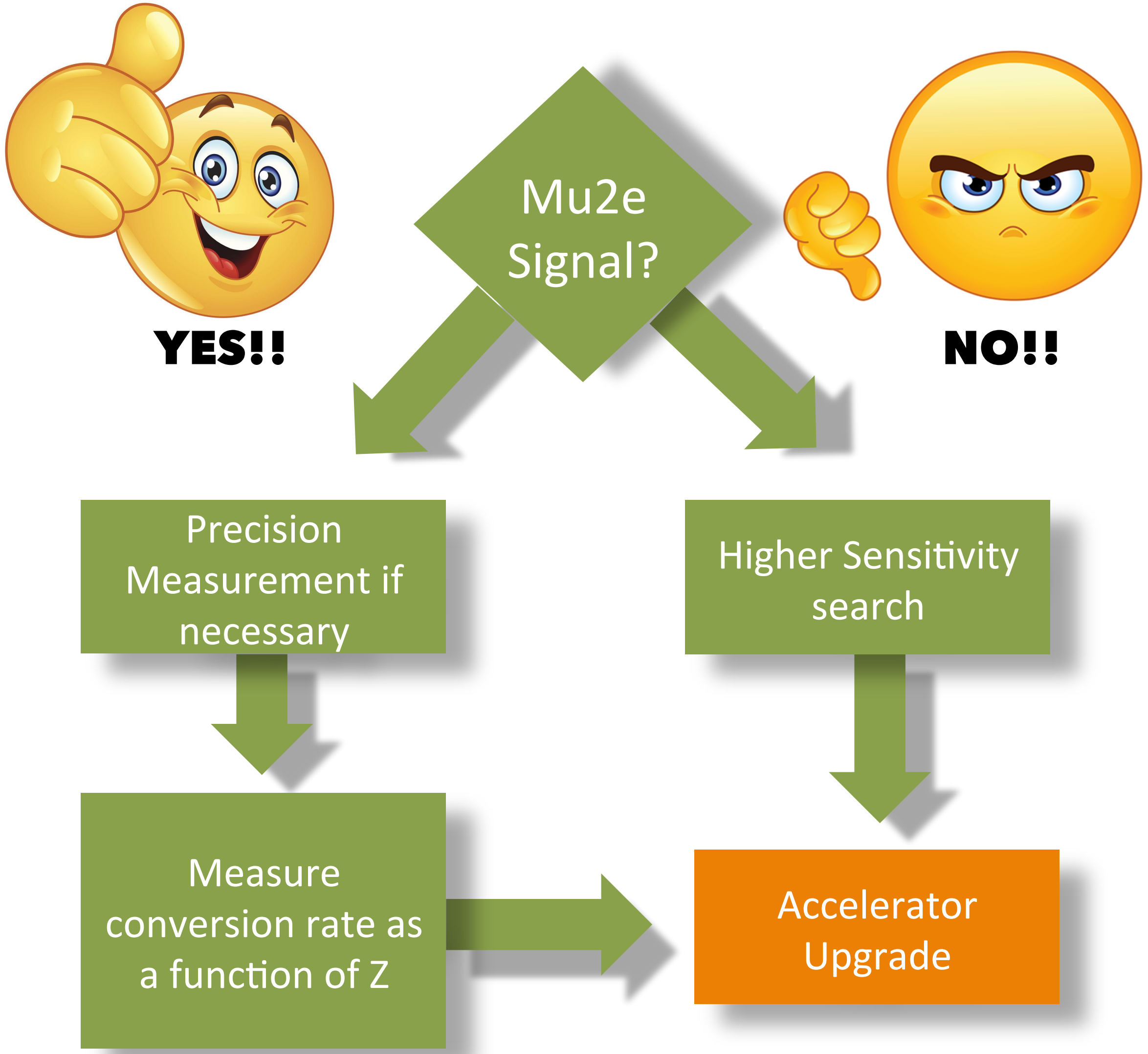
Fermilab

MUSE

Accelerator: status of construction

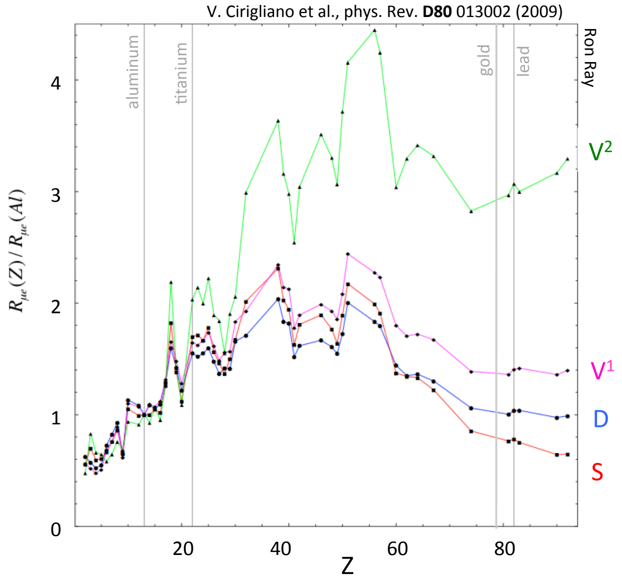
- Installation of beam magnets well along:
  - vacuum system
  - instrumentation upstream of the diagnostic absorber in progress

What if…

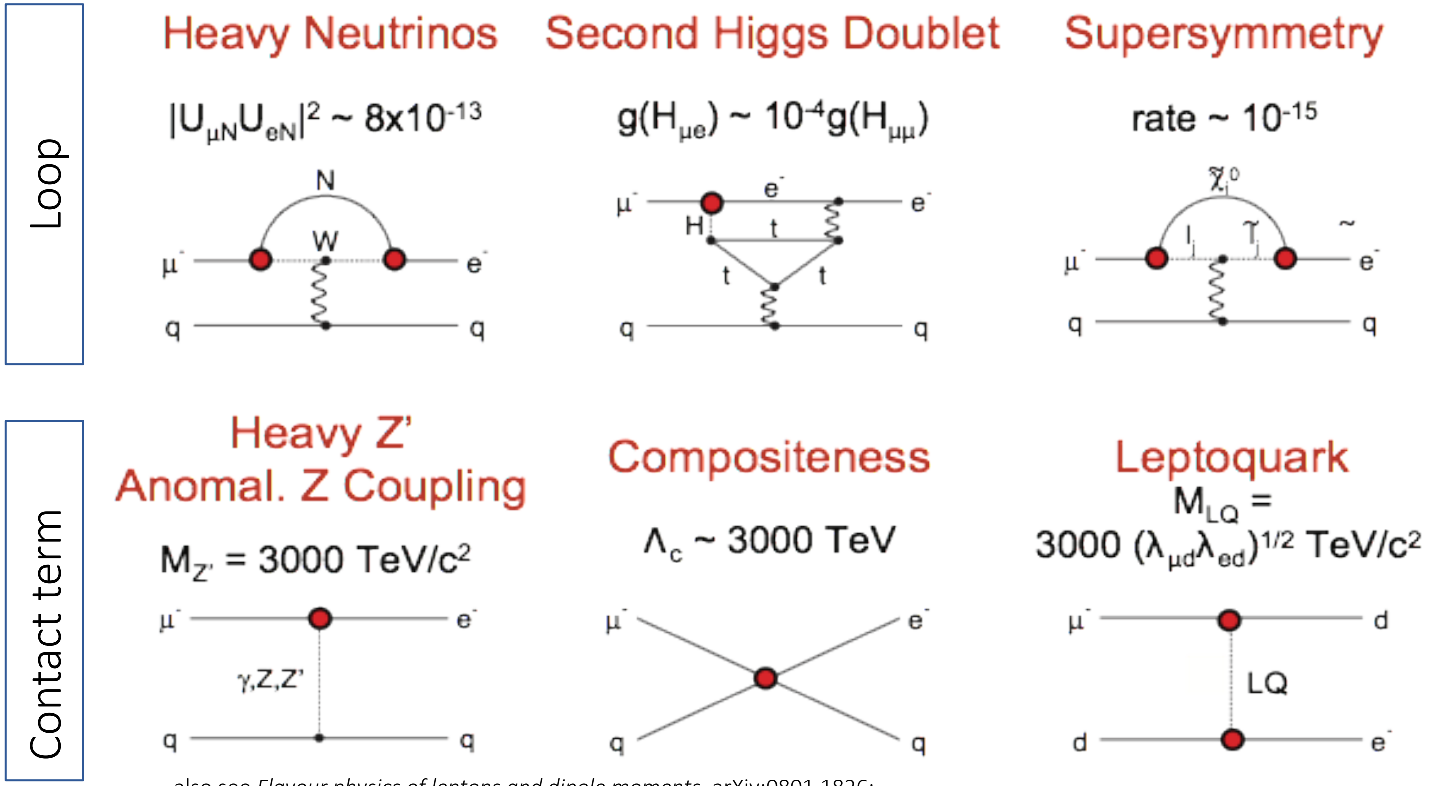


A next-generation Mu2e experiment makes sense in all scenarios:

- Push sensitivity or
- Study underlying new physics
- Will need more protons upgrade accelerator
- Snowmass white paper, arXiv:1802.02599



Muon CLFV



Models which can be probed also by $\mu \to e\gamma$ *searches*

Direct coupling between quarks and leptons, better accessed by $\mu N \to eN$

also see *Flavour physics of leptons and dipole moments*, arXiv:0801.1826;
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126

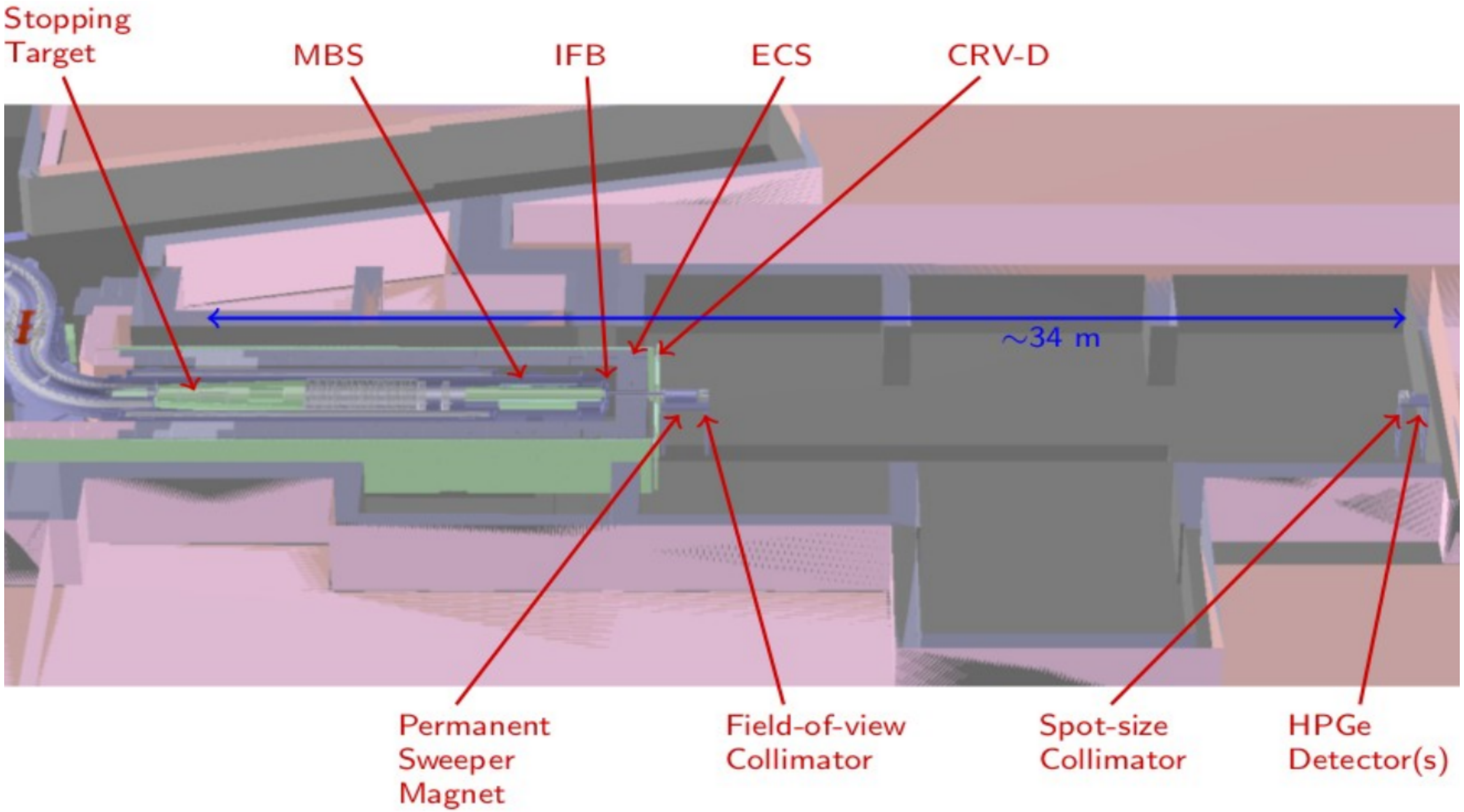
Probe mass scales λ 2000~10000 TeV significantly above the direct reach of LHC

Background estimate

assuming ~ 10 GHz muon stops, $6x10^{17}$ stopped muons in $6x10^{7}$ s of beam time

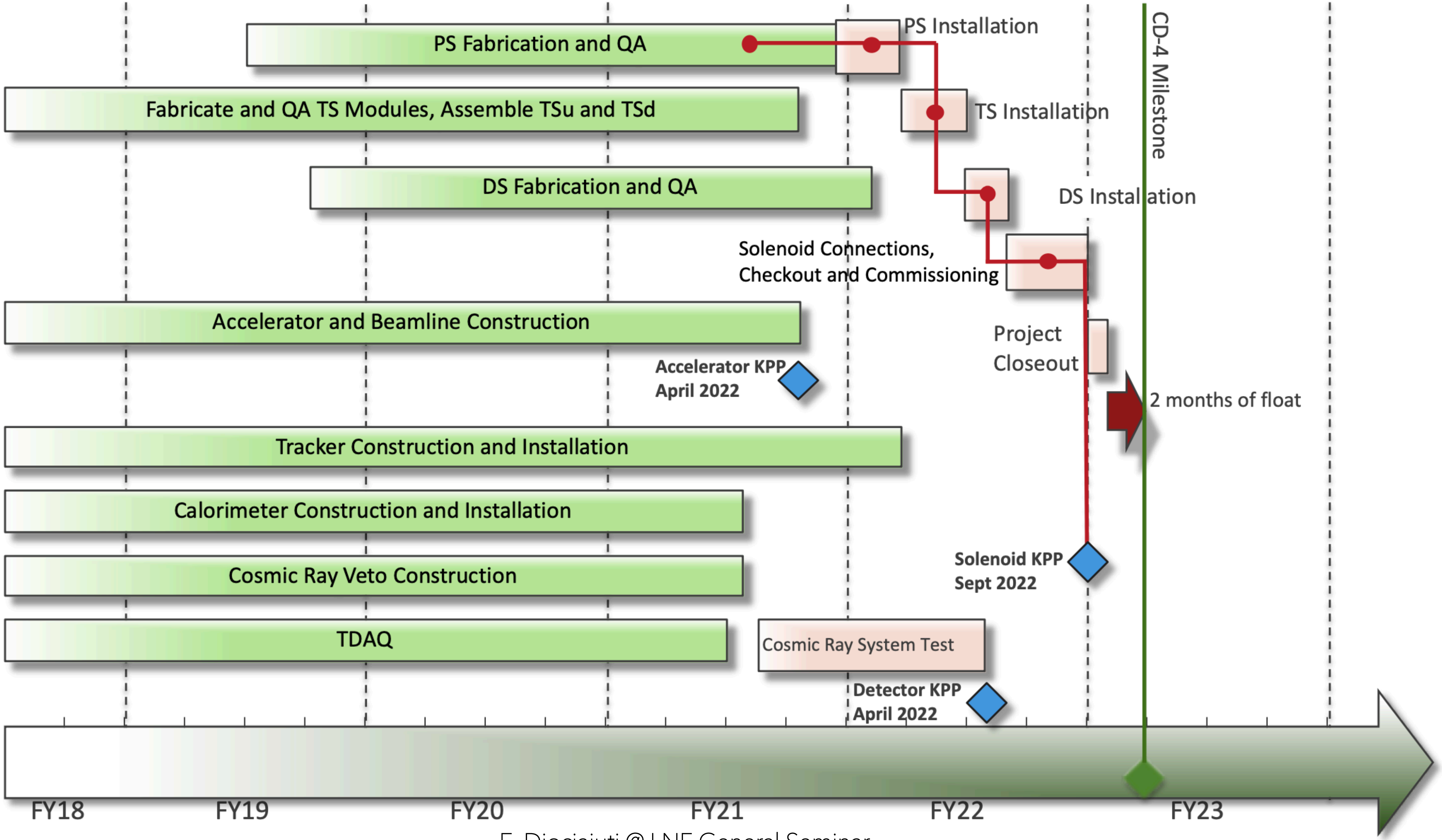
Category	Background Process	Estimated Yield
Intrinsic	Decay In Orbit (DIO)	0.144 ± 0.028(stat) ± 0.11(syst)
	Muon Capture (RMC)	0
Late Arriving	Pion Capture (RPC)	0.021 ± 0.001(stat) ± 0.002(syst)
	Muon Decay in Flight	< 0.003
	Pion Decay in Flight	0.001 ± <0.001
	Beam Electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Miscellaneous	Cosmic Ray Induced	0.209 ± 0.022(stat) ± 0.055(syst)
	Antiproton Induced	0.040 ± 0.001(stat) ± 0.020(syst)
Total		**0.41 ± 0.13(stat + syst)**

Stopping target monitor

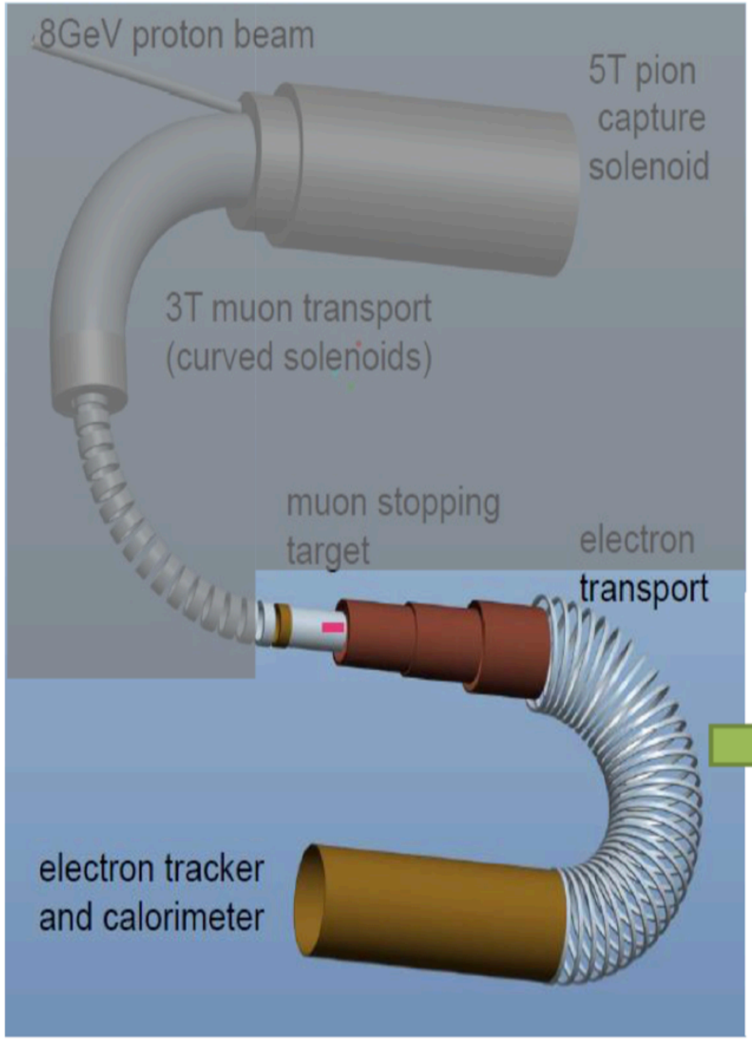


The STM will measure a variety of well understood gamma ray lines … under a high-rate brehmstrahlung background

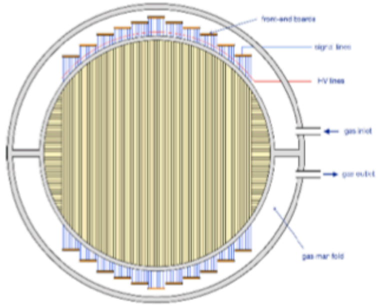
The schedule



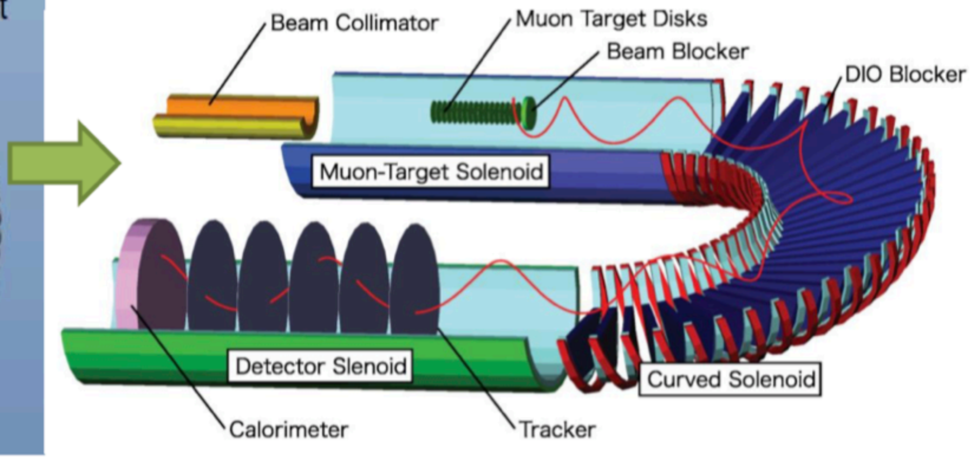
COMET



- Use straw tracker to measure the momentum
  - Really light: put in vacuum, 12 micro meter thin straw



- Electromagnetic calorimeter
  - Providing trigger, TOF and PID

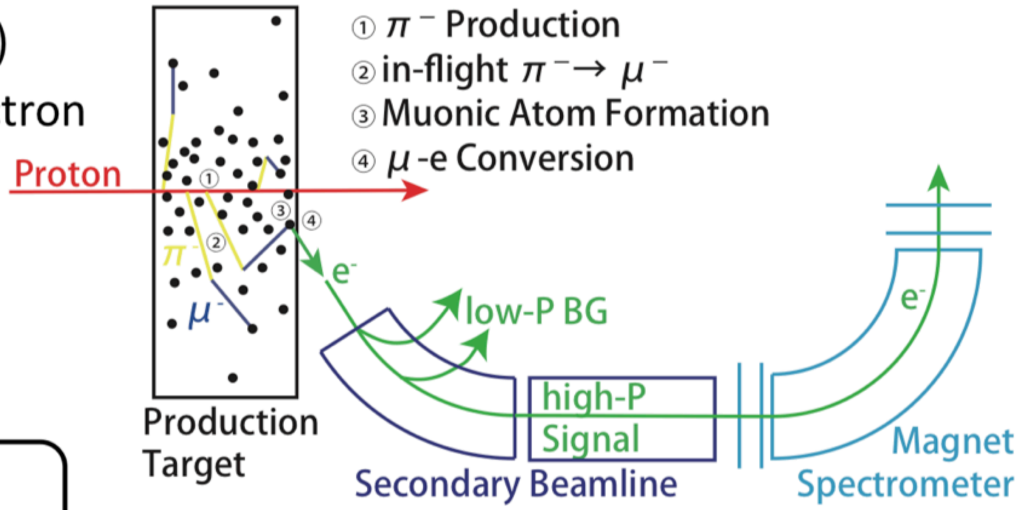


COMET vs Muqe

- ❑ Similar capabilities in physics reach
- ❑ **COMET designed to operate at 56 kW, Mu2e 8 kW**
- → COMET will use all JPARC beam
- → <u>Mu2e runs simultaneously with neutrino beam</u>
- ❑ Final bend after COMET stopping target efficiently transmits
- conversion e- and provides rate suppression in detector.
- ❑ **It does not transmit positrons (no $\mu^- N \rightarrow e^+ N$)**
- \- COMET solenoids ~ 10 m longer than Mu2e
- \- Higher beam → higher cost (solenoid shielding, neutron shielding)
- \- Longer solenoids carry "additional-cost" in operation
- Phase-1 could be useful → if successful to study background rate
- Phase-2 schedule → not yet approved
- Mu2e → looking forward to Mu2e-II
- ❑ Great competition/collaboration → ALCAP @ PSI

DeeMee

- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - 105 MeV
    - Delayed：~1µS
- No accidental backgrounds
- Physics backgrounds
  - Muon Decay in Orbit (DIO)
    - $E_e > 102.5$ MeV (BR:10^{-14})
    - $E_e > 103.5$ MeV (BR:10^{-16})
  - Beam Pion Capture
    - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$, $\gamma \rightarrow e^+ e^-$
    - Pulsed Proton beam
      - Prompt timing



- Low Energy main part: suppressed by the beamline.
- High Energy tail: Magnet Spectrometer ($\Delta p <$ 0.5%)

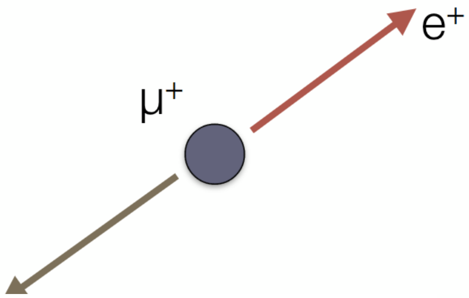
- Main pulse burst: State-of-the-art MWPC that becomes operational quickly after a burst.
- Delayed-protons: Suppressed owing to the extremely small after-protons from RCS -- $R_{DP} << 10^{-17}$.

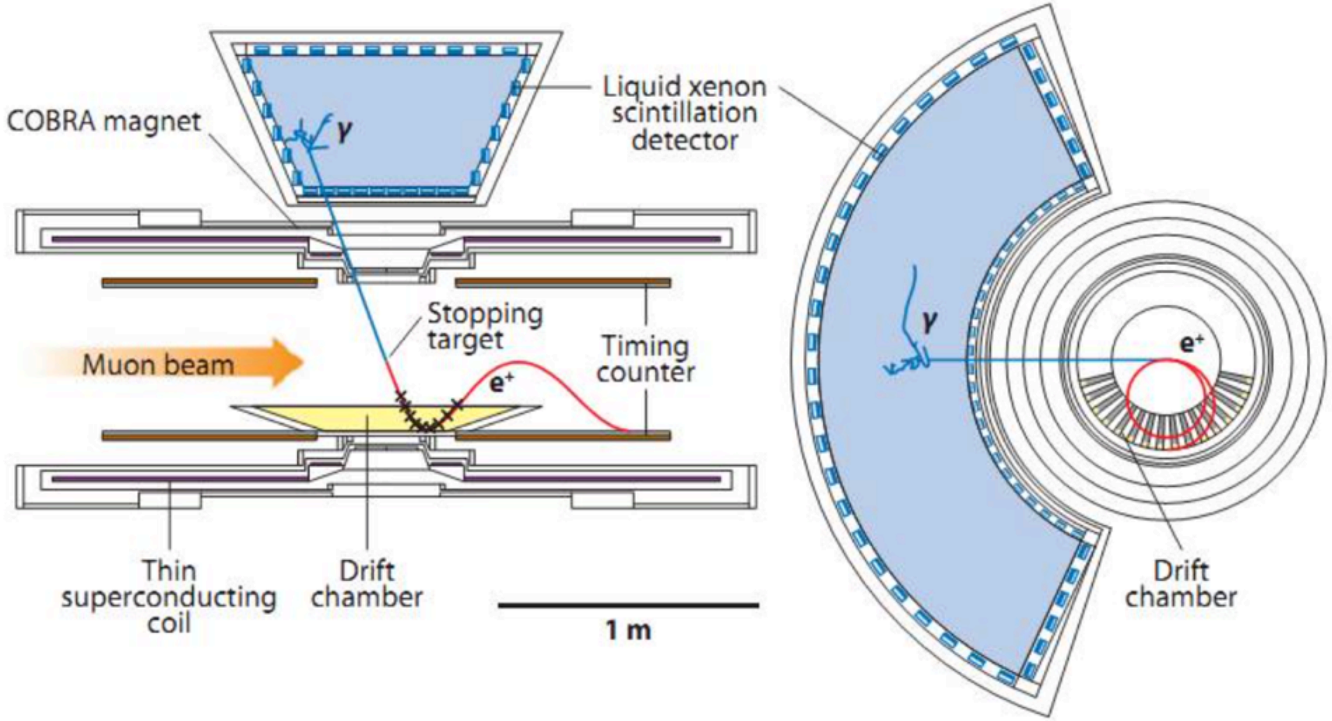
MEG

Experimental signature:

- Simultaneous back-to-back e^+ and γ

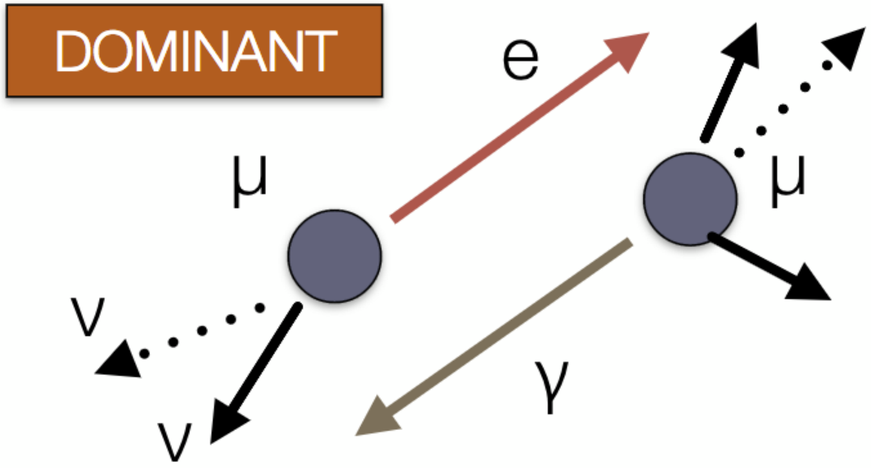
  $E_\gamma = E_{e+} = 52.8\text{MeV}$





MEG - Backgrounds

- **Accidental coincidence of e^+ and γ:**
  Proportional to I^2_μ (while signal proportional to I_μ)
  - Compromise between high intensity and low background



- **Radiative muon decay background**
  - Proportional to I_μ
  - Note: e^+ and γ simultaneous as for signal