

Search for new physics with the Mu2e experiment at FERMILAB muon campus



S. Miscetti (LNF)

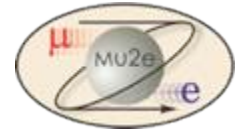
For the Mu2e Collaboration

MUSE outreach event

Tor Vergata University

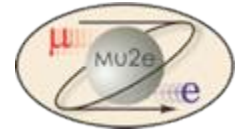
28/10/2019

MUSE



- The Physics
 - CLFV processes
 - BSM Reach of CLFV in muon sector
- Description of Muonic Atom processes
- Experimental technique
- Accelerator Complex
- Detector Layout
- Status of Mu2e experiment
- Conclusions

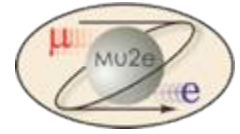
The Mu2e collaboration



Over 200 Scientists from 38 Institutions (six countries)

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

CLFV processes



- Muon-to-electron conversion is a **charged lepton flavor violating process** (CLFV) similar but complementary to other CLFV processes such as:

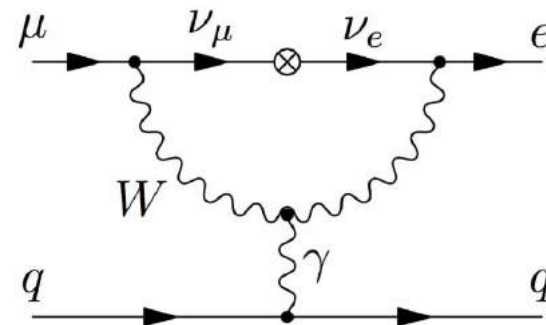
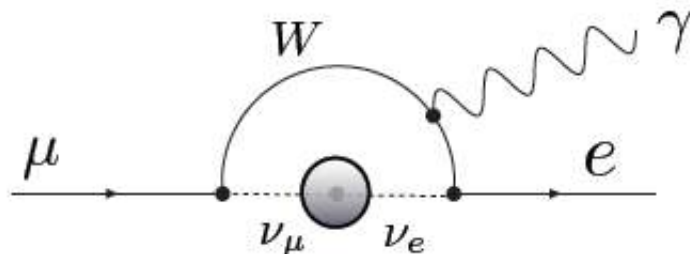
$$\mu^+ \rightarrow e^+ + \gamma, \mu^+ \rightarrow e^+ + e^+ + e^-, \tau \rightarrow e + \gamma, \tau \rightarrow \mu + \gamma, \tau \rightarrow 3e....$$

- The Mu2e experiment searches for **muon-to-electron conversion** in the coulomb field of a nucleus: $\mu^- Al \rightarrow e^- Al$

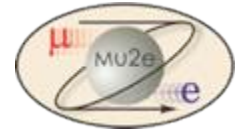
- **CLFV processes are forbidden in the Standard Model**

→ considering neutrino oscillations (LFV) they **are allowed but their BR is negligible 10^{-52}**

→ **New Physics could enhance CLFV rates to observable values**



Rates and discovery potential



- Most promising CLFV are based on muons:
 - clean topologies & large rates
 - the SM contribution is negligible: no SM background
- μ -e conversion covers the BSM on very broad range of models
 - Three stars signals Discovery potential
 - Sensitivity across the board

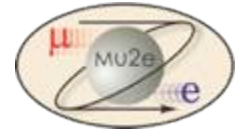
Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu \eta$	BR < 6.5 E-8	10 ⁻⁹ - 10 ⁻¹⁰ (Belle II)
$\tau \rightarrow \mu \gamma$	BR < 6.8 E-8	
$\tau \rightarrow \mu \mu \mu$	BR < 3.2 E-8	
$\tau \rightarrow e e e$	BR < 3.6 E-8	
$K_L \rightarrow e \mu$	BR < 4.7 E-12	
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \rightarrow e \mu$	BR < 7.8 E-8	
$B^+ \rightarrow K^+ e \mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+ \gamma$	BR < 4.2 E-13	10 ⁻¹⁴ (MEG)
$\mu^+ \rightarrow e^+ e^+ e^-$	BR < 1.0 E-12	10 ⁻¹⁶ (PSI)
$\mu N \rightarrow e N$	R _{μe} < 7.0 E-13	10 ⁻¹⁷ (Mu2e, COMET)

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

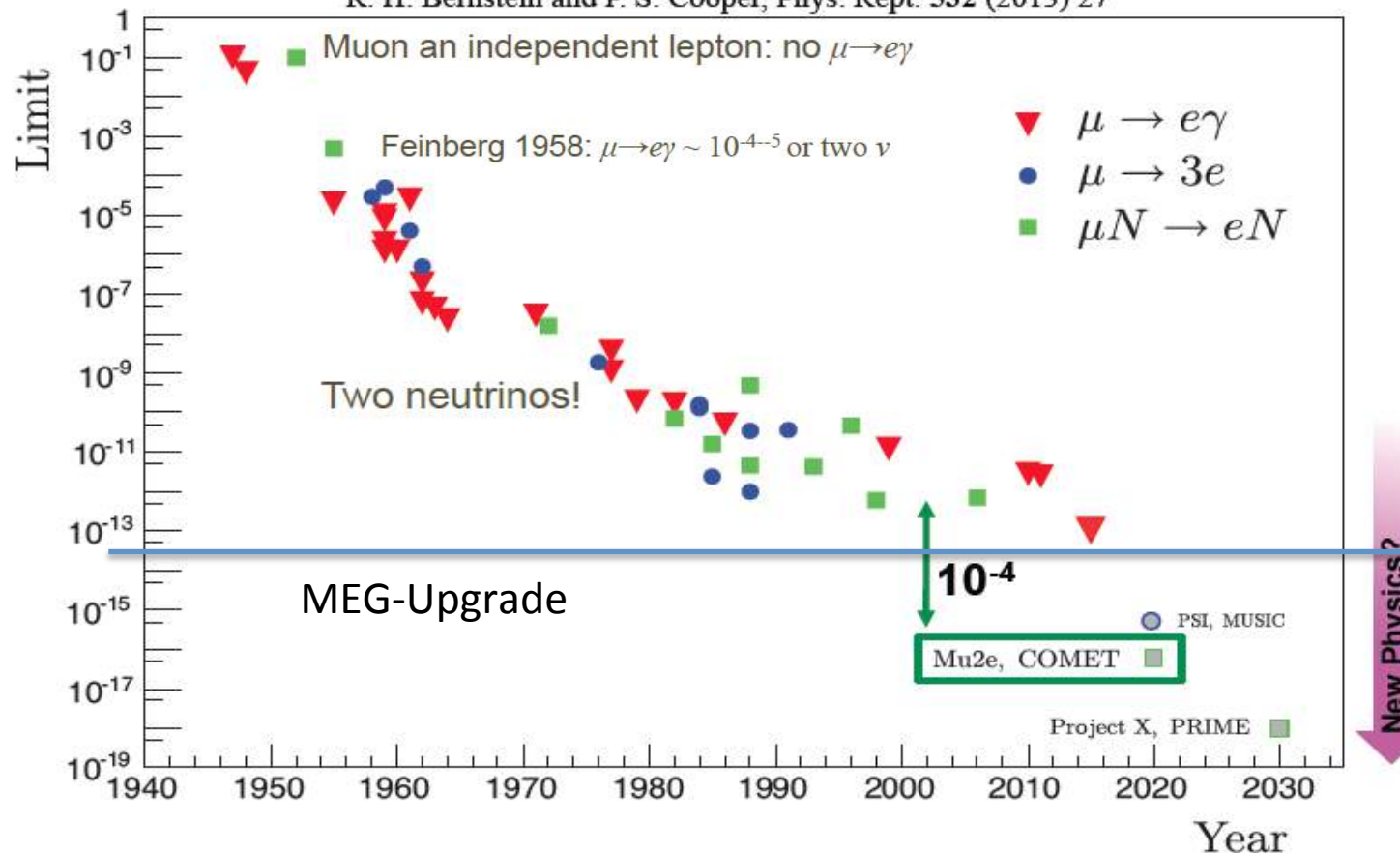
	AC	RVV2	AKM	δ LL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\psi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \rightarrow X_s \gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \rightarrow K^* \mu^+ \mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \rightarrow K^* \mu^+ \mu^-)$	★	★	★	★	★	★	?
$B \rightarrow K^{(*)} \nu \bar{\nu}$	★	★	★	★	★	★	★
$B_s \rightarrow \mu^+ \mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \rightarrow e \gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \rightarrow \mu \gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \rightarrow e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_x	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

CLFV history for muons



R. H. Bernstein and P. S. Cooper, Phys. Rept. 532 (2013) 27



Current best limits:

MEG-2016

$BR(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$

SINDRUM-1988

$BR(\mu \rightarrow 3e) < 1 \times 10^{-12}$

SINDRUM-II 2006

$R_{\mu e} < 6.1 \times 10^{-13}$

MU2E GOAL:

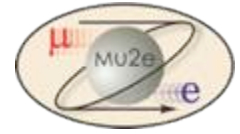
$R_{\mu e} = 8 \times 10^{-17}$

Mu2e (Fermilab) aims to improve by a factor 10^4 the present best limit

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

MUSE

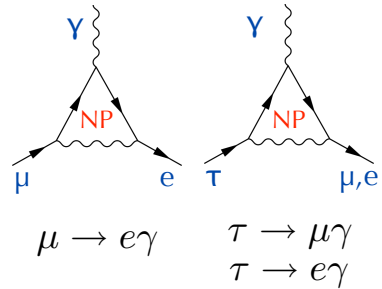
Mu2e vs MEG in the Λ/k plane



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

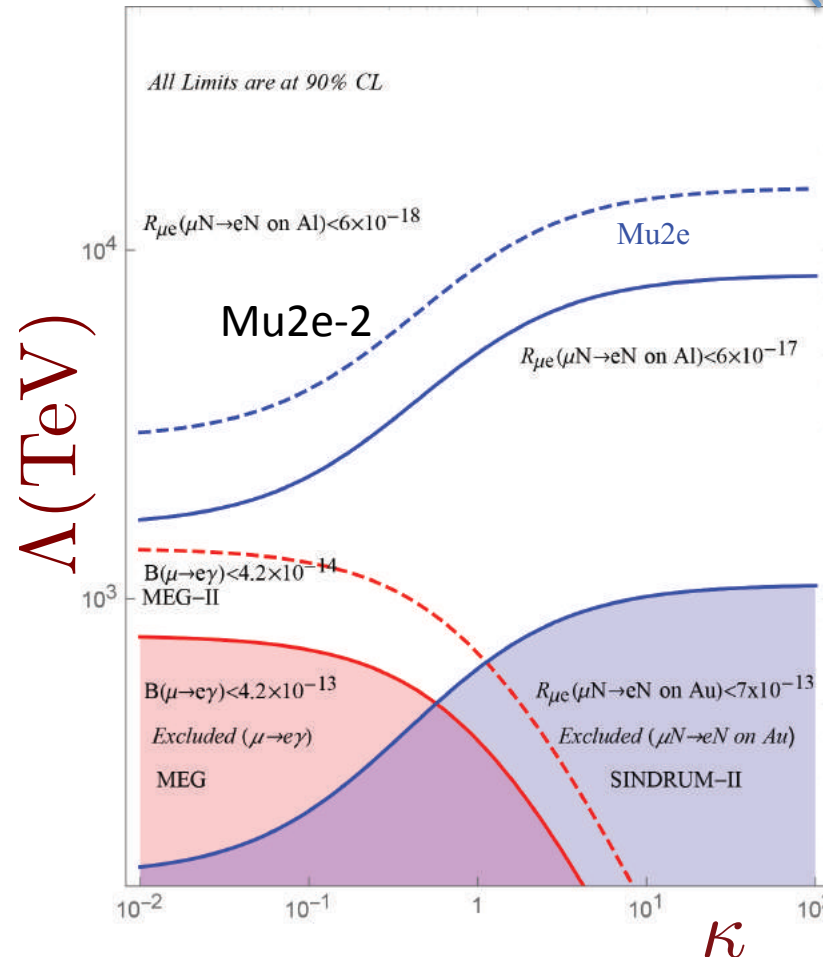
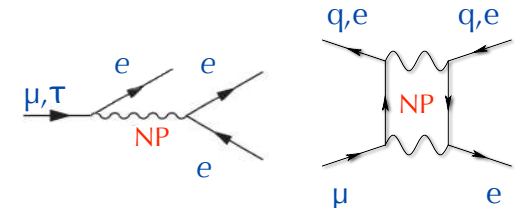
LOOP TERM

$$\kappa \ll 1$$



CONTACT TERM

$$\kappa \gg 1$$



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

Roughly equal to MEG upgrade
in loop-dominated physics

If SUSY seen @ LHC

→ rate ~10⁻¹⁵

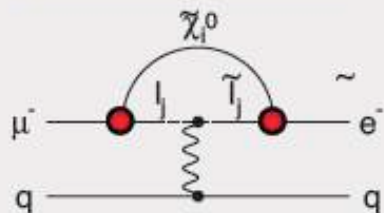
Implies **O(40) signal events**
with **negligible background**

Mu2e physics reach



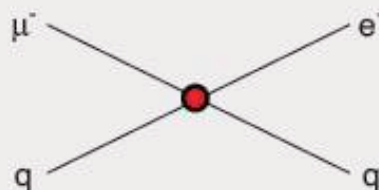
Supersymmetry

$$\text{rate} \sim 10^{-15}$$



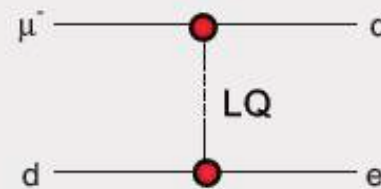
Compositeness

$$\Lambda_c \sim 3000 \text{ TeV}$$



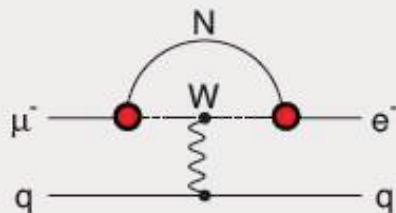
Leptoquark

$$M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{e d})^{1/2} \text{ TeV}/c^2$$



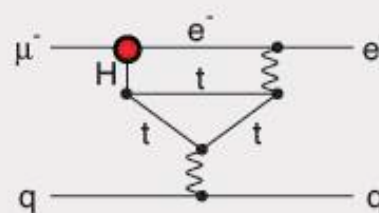
Heavy Neutrinos

$$|U_{\mu N} U_{e N}|^2 \sim 8 \times 10^{-13}$$



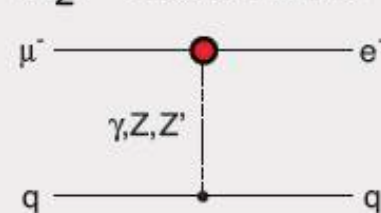
Second Higgs Doublet

$$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$$



Heavy Z' Anomal. Z Coupling

$$M_{Z'} = 3000 \text{ TeV}/c^2$$



Test of Physics BSM:

Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58
M. Raidal *et al*, Eur.Phys.J.C57:13-182,2008
A. de Gouvêa, P. Vogel, arXiv:1303.4097

SUSY benchmark points vs LHC

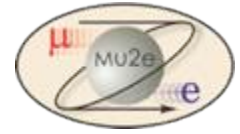
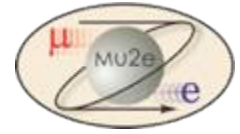


TABLE XII: LFV rates for points **SPS 1a** and **SPS 1b** in the CKM case and in the $U_{e3} = 0$ PMNS case. The processes that are within reach of the future experiments (MEG, SuperKEKB) have been highlighted in boldface. Those within reach of post-LHC era planned/discussed experiments (PRISM/PRIME, Super Flavour factory) highlighted in italics.

Process	SPS 1a		SPS 1b		SPS 2		SPS 3		Future Sensitivity
	CKM	$U_{e3} = 0$	CKM	$U_{e3} = 0$	CKM	$U_{e3} = 0$	CKM	$U_{e3} = 0$	
$\text{BR}(\mu \rightarrow e \gamma)$	$3.2 \cdot 10^{-14}$	$3.8 \cdot 10^{-13}$	$4.0 \cdot 10^{-13}$	$1.2 \cdot 10^{-12}$	$1.3 \cdot 10^{-15}$	$8.6 \cdot 10^{-15}$	$1.4 \cdot 10^{-15}$	$1.2 \cdot 10^{-14}$	$\mathcal{O}(10^{-14})$
$\text{BR}(\mu \rightarrow e e e)$	$2.3 \cdot 10^{-16}$	$2.7 \cdot 10^{-15}$	$2.9 \cdot 10^{-16}$	$8.6 \cdot 10^{-15}$	$9.4 \cdot 10^{-18}$	$6.2 \cdot 10^{-17}$	$1.0 \cdot 10^{-17}$	$8.9 \cdot 10^{-17}$	$\mathcal{O}(10^{-14})$
$\text{CR}(\mu \rightarrow e \text{ in Ti})$	$2.0 \cdot 10^{-15}$	$2.4 \cdot 10^{-14}$	$2.6 \cdot 10^{-15}$	$7.6 \cdot 10^{-14}$	$1.0 \cdot 10^{-16}$	$6.7 \cdot 10^{-16}$	$1.0 \cdot 10^{-16}$	$8.4 \cdot 10^{-16}$	$\mathcal{O}(10^{-18})$
$\text{BR}(\tau \rightarrow e \gamma)$	$2.3 \cdot 10^{-12}$	$6.0 \cdot 10^{-13}$	$3.5 \cdot 10^{-12}$	$1.7 \cdot 10^{-12}$	$1.4 \cdot 10^{-13}$	$4.8 \cdot 10^{-15}$	$1.2 \cdot 10^{-13}$	$4.1 \cdot 10^{-14}$	$\mathcal{O}(10^{-8})$
$\text{BR}(\tau \rightarrow e e e)$	$2.7 \cdot 10^{-14}$	$7.1 \cdot 10^{-15}$	$4.2 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$	$1.7 \cdot 10^{-15}$	$5.7 \cdot 10^{-17}$	$1.5 \cdot 10^{-15}$	$4.9 \cdot 10^{-16}$	$\mathcal{O}(10^{-8})$
$\text{BR}(\tau \rightarrow \mu \gamma)$	$5.0 \cdot 10^{-11}$	$1.1 \cdot 10^{-8}$	$7.3 \cdot 10^{-11}$	$1.3 \cdot 10^{-8}$	$2.9 \cdot 10^{-12}$	$7.8 \cdot 10^{-10}$	$2.7 \cdot 10^{-12}$	$6.0 \cdot 10^{-10}$	$\mathcal{O}(10^{-9})$
$\text{BR}(\tau \rightarrow \mu \mu \mu)$	$1.6 \cdot 10^{-13}$	$3.4 \cdot 10^{-11}$	$2.2 \cdot 10^{-13}$	$3.9 \cdot 10^{-11}$	$8.9 \cdot 10^{-15}$	$2.4 \cdot 10^{-12}$	$8.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-12}$	$\mathcal{O}(10^{-8})$

- These are SuSy benchmark points for which LHC has discovery sensitivity
- Some of these will be observable by MEG/Belle-2
- All of these will be observable by Mu2e

Other CLFV Predictions



M.Blanke, A.J.Buras, B.Duling, S.Recksiegel, C.Tarantino

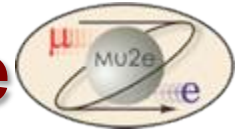
ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^- \rightarrow e^- e^+ e^-)}{Br(\mu \rightarrow e \gamma)}$	0.02...1	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \rightarrow e^- e^+ e^-)}{Br(\tau \rightarrow e \gamma)}$	0.04...0.4	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \rightarrow \mu^- \mu^+ \mu^-)}{Br(\tau \rightarrow \mu \gamma)}$	0.04...0.4	$\sim 2 \cdot 10^{-3}$	0.06...0.1
$\frac{Br(\tau^- \rightarrow e^- \mu^+ \mu^-)}{Br(\tau \rightarrow e \gamma)}$	0.04...0.3	$\sim 2 \cdot 10^{-3}$	0.02...0.04
$\frac{Br(\tau^- \rightarrow \mu^- e^+ e^-)}{Br(\tau \rightarrow \mu \gamma)}$	0.04...0.3	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \rightarrow e^- e^+ e^-)}{Br(\tau^- \rightarrow e^- \mu^+ \mu^-)}$	0.8...2.0	~ 5	0.3...0.5
$\frac{Br(\tau^- \rightarrow \mu^- \mu^+ \mu^-)}{Br(\tau^- \rightarrow \mu^- e^+ e^-)}$	0.7...1.6	~ 0.2	5...10
$\frac{R(\mu Ti \rightarrow e Ti)}{Br(\mu \rightarrow e \gamma)}$	$10^{-3} \dots 10^2$	$\sim 5 \cdot 10^{-3}$	0.08...0.15

arXiv:0909.5454v2[hep-ph]

Table 3: Comparison of various ratios of branching ratios in the LHT model ($f = 1$ TeV) and in the MSSM without [92,93] and with [96,97] significant Higgs contributions.

- Relative rates Conversions/MEG are model dependent
- Measure ratios to pin-down theory details

Muon to electron conversion is unique



Muon to electron conversion is a unique probe for BSM:

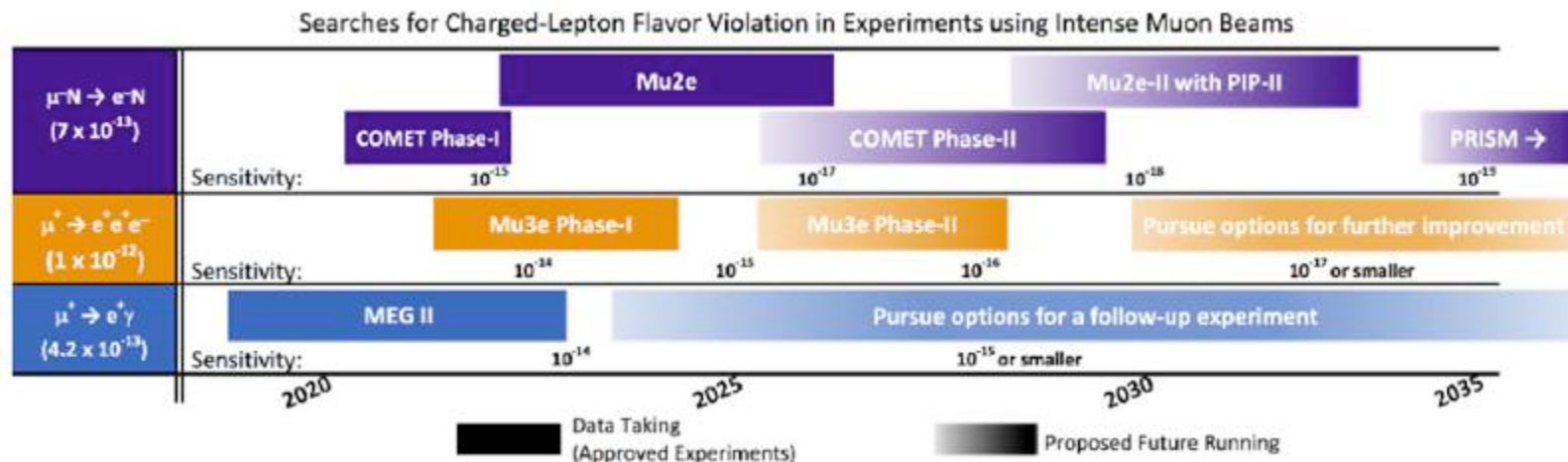
◆ **Broad discovery sensitivity across all models:**

- Sensitivity to the same physics of MEG/Mu3e with similar mass reach
- Sensitivity to physics that MEG/Mu3e are not
- If MEG/Mu3e observe a signal, Mu2e/COMET will see it also

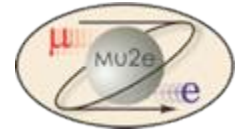
Ratio of the BR allows to pin-down physics model

- If MEG/Mu3e do not observe a signal, Mu2e/COMET have still a reach to do so.
In a long run, sensitivity can also further improve (Mu2e-II) with the proton improvement plan (PIP-2)

◆ **Sensitivity to Λ (mass scale) up to thousands of TeV beyond any current**



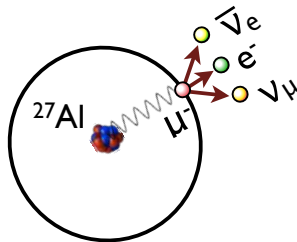
Experimental Technique



- ☐ Low momentum μ beam ($< 100 \text{ MeV}/c$)
- ☐ High intensity “pulsed” rate
 - $\rightarrow 10^{10}/s$ muon stop on Al. target
 - $\rightarrow 1.7 \mu\text{sec}$ micro-bunch
- ☐ Formation of muonic atoms that can make a:

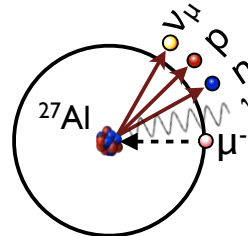
Decay in Orbit (DIO)

(BR=39%)



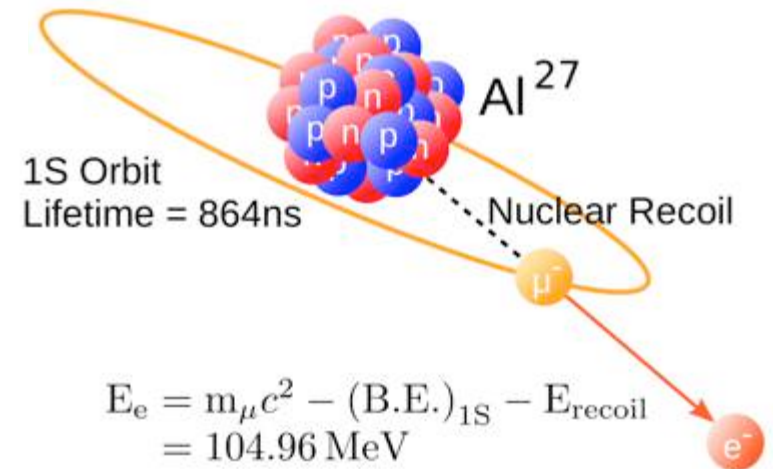
Muon Capture Process

(BR=61%)

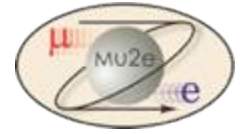


The conversion process results in a clear signature of a single electron, CE, with a mono-energetic spectrum close to the muon rest mass

Conversion Process

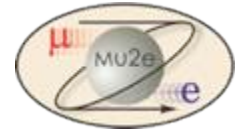


Mu2e sensitivity and rates



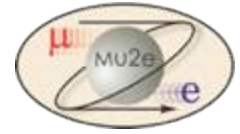
- **Design goal: single-event-sensitivity of 3×10^{-17}**
 - Requires about 10^{18} stopped muons
 - Requires about 10^{20} protons on target
 - Requires extreme suppression of backgrounds
- **Expected limit: $R_{\mu e} < 8 \times 10^{-17}$ @ 90% CL**
 - **Factor 10^4 improvement**
- **Discovery sensitivity: all $R_{\mu e} > 2 \times 10^{-16}$**
 - Covers broad range of new physics theories
- **High rate and large number of stopped muons 10^{18}**
 - Needs intense muon source and efficient transport to target

A search at extremely low probability



Prob of $10^{(-17)}$ → get in few weeks a meteorite and a lighting bold over your house

The need of a very large number of muons



Every 1 second Mu2e will

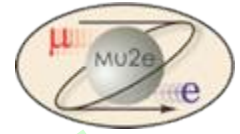
- Send 7,000,000,000,000 protons to the Production Solenoid
- Send 26,000,000,000 μ s through the Transport Solenoid
- Stop 13,000,000,000, μ s in the Detector Solenoid

Stop the muons in Al target

- Sensitivity goal requires $\sim 10^{18}$ stopped muons
- 10^{20} protons on target (2 year run - 2×10^7 s)



Need to fight a lot of backgrounds



- **Intrinsic – scale with number of stopped muons**

- μ Decay-in-Orbit (DIO)
- Radiative muon capture (RMC)

Precise Tracker

- **Late arriving – scale with number of late protons**

- **Radiative pion capture (RPC)**

$$\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+ e^- \text{ and } \pi^- N \rightarrow e^+ e^- N'$$

- **μ and π decay-in-flight (DIF)**

Pulsed Beam + extinction

- **Cosmic rays induced**

CRV+PID

- **Anti-proton induced**

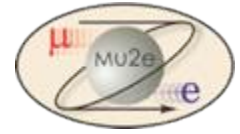
produce pions when they annihilate in the target ..
antiprotons are negative and they can be slow!

Proton Absorber

TO BE A DISCOVERY EXPERIMENT → Thumb Rule , keep N.bkg < 0.5 events

MUSE

The irreducible DIO background

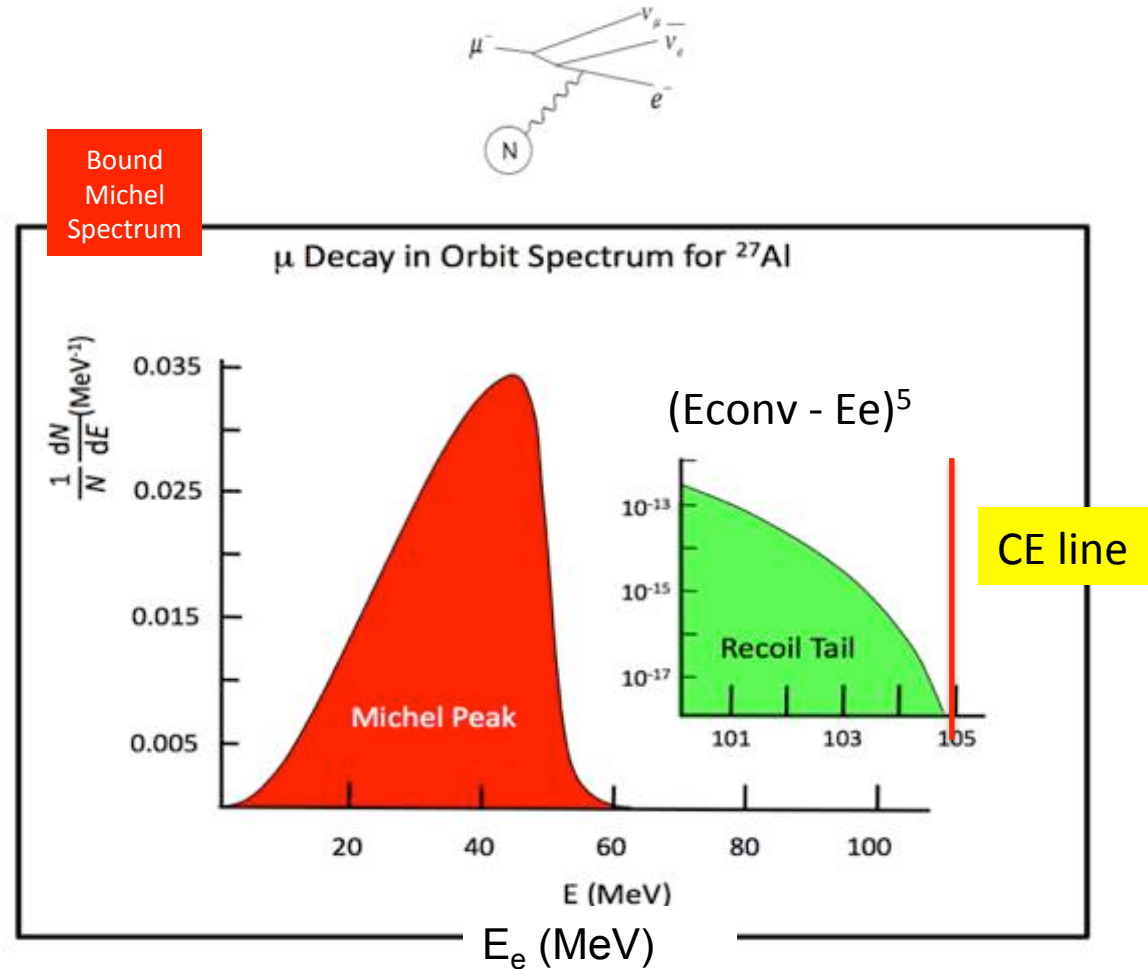


❑ The decay in orbit (DIO) is the most difficult background

❑ Electron energy distribution from the decay of bound muons is a (modified) Michel spectrum:

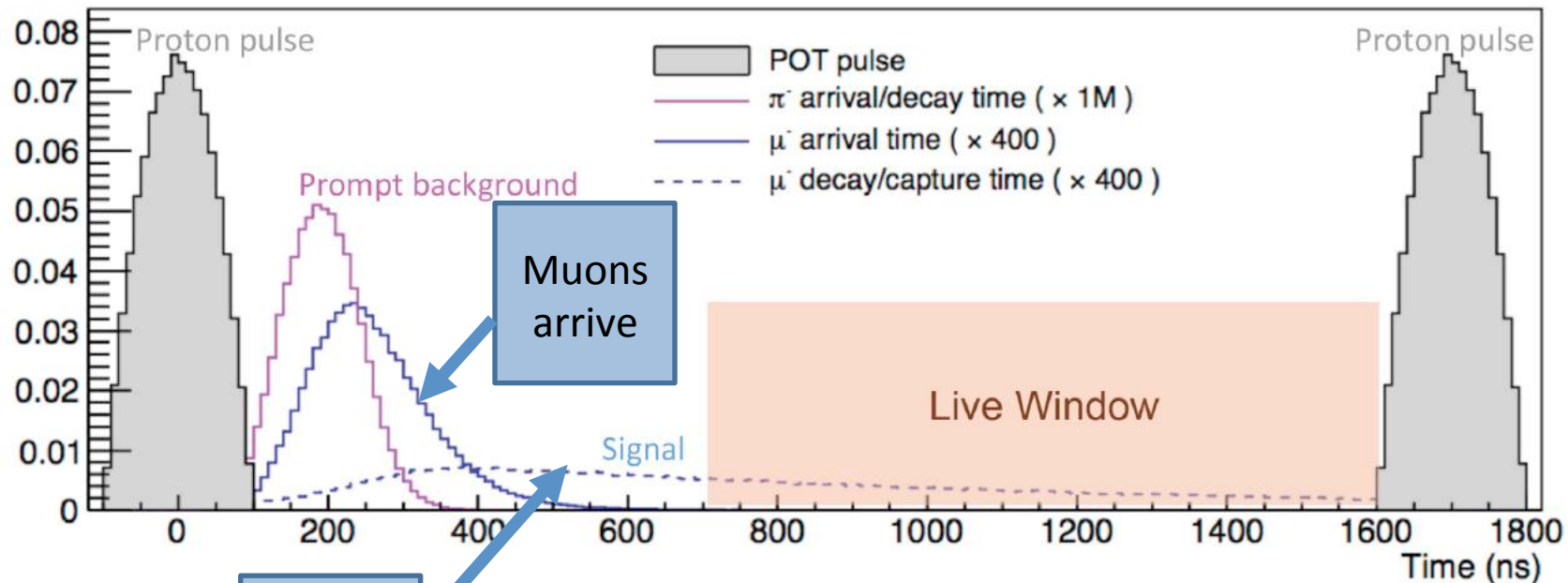
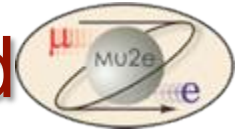
→ Presence of atomic nucleus and momentum transfer create a recoil tail with a fast falling slope close to the endpoint

→ 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

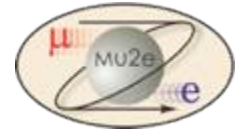
Beam structure → prompt background



- ❑ Pulsed proton beam (1695 ns peak-to-peak)
 - 700 ns delay before 1 ms live gate
 - prompt background dies away
- ❑ Extinction factor (rate of out-of-time protons) below 10^{-10} is required

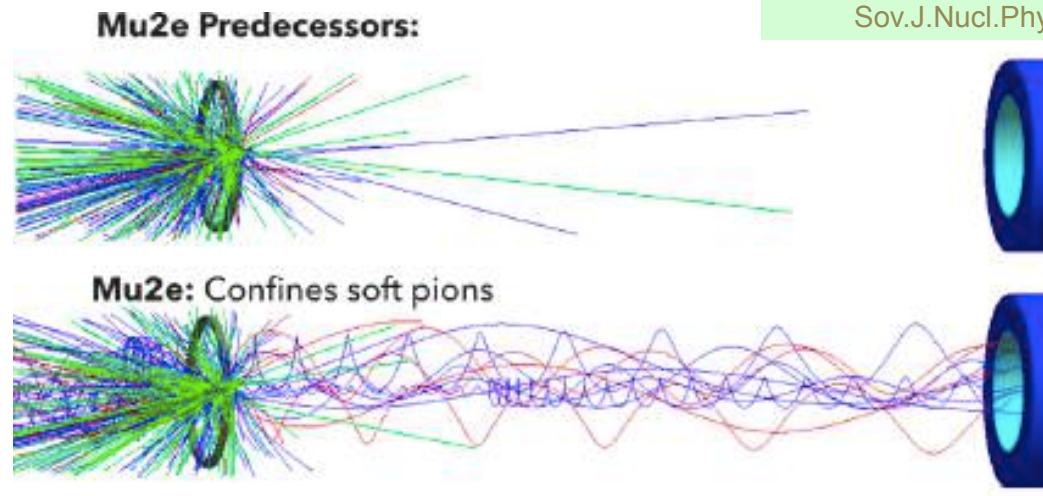
The trick here is ... muonic atomic lifetime
 $t(\mu)\text{Al} = 864 \text{ ns} \gg \text{prompt background}$

Summary: the keys to Mu2e Success



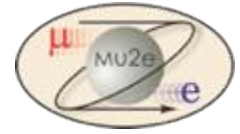
- ❑ **High intensity pulsed proton beam**
 - Narrow proton pulses ($< \pm 125$ ns)
 - Very few out-of-time protons ($< 10^{-10}$)
 - 3×10^7 proton/pulse.
- ❑ **High efficiency in transporting muon to Al target**
 - Need of a sophisticated magnet with gradient fields
- ❑ **Excellent detector for 100 MeV electrons**
 - Excellent momentum resolution (< 200 keV core)
 - Calorimeter for PID, triggering and track seeding
 - High Cosmic Ray Veto (CRV) efficiency ($> 99.99\%$)
 - Thin anti-proton annihilation window(s)

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



MUSE

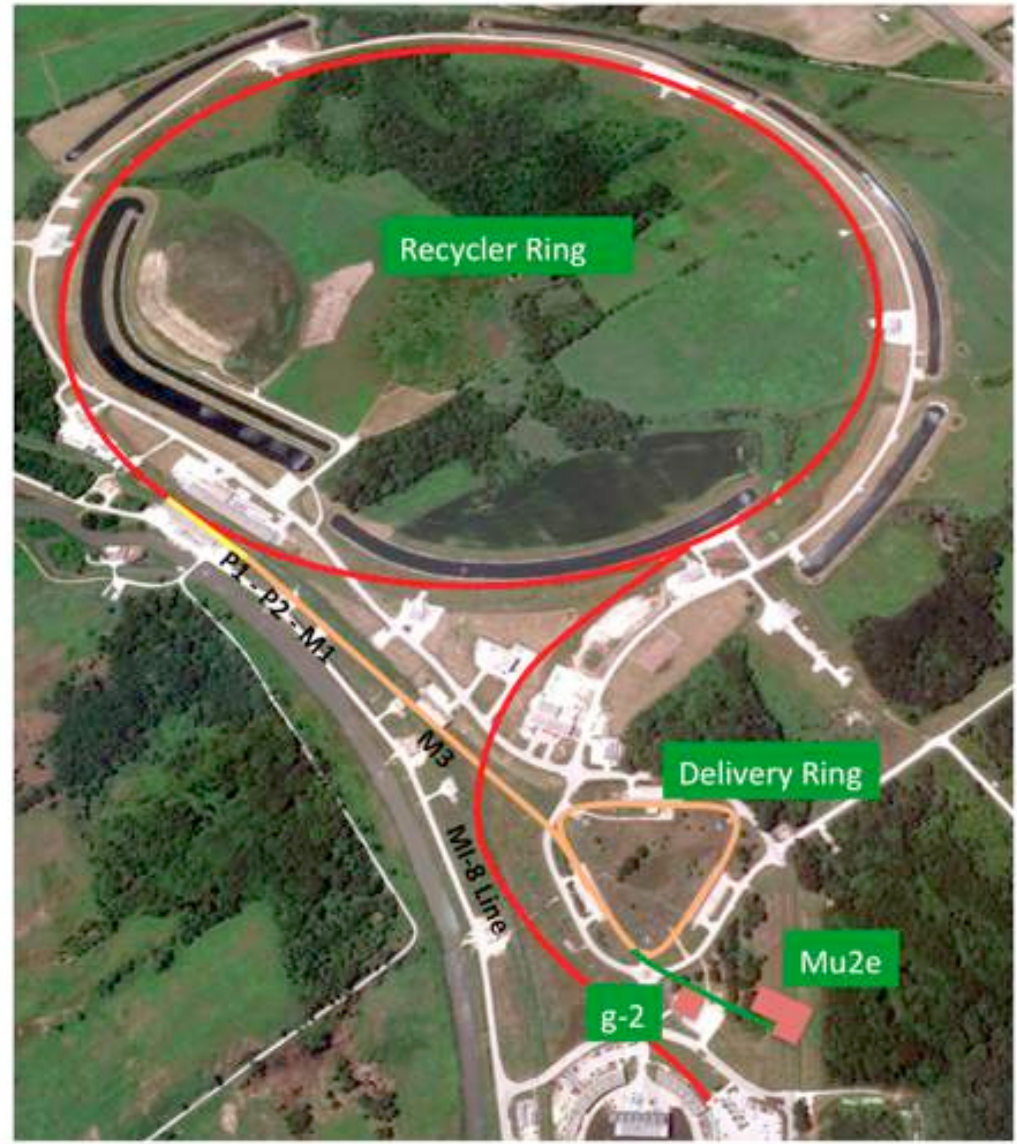
Accelerator Scheme for Mu2e beam



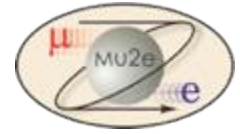
- ❑ Booster: batch of 4×10^{12} protons every 1/15th second (8 GeV, 8 kW)
- ❑ Booster “batch” is injected into the Recycler ring and re-bunched into 4 bunches
- ❑ These are extracted one at a time to the Delivery ring (ex Debuncher)
- ❑ As a bunch circulates, protons are resonantly extracted to produce the desired beam structure

→ **bunches of $\sim 3 \times 10^7$ protons each, separated by 1.7 μ s (delivery ring period) and then sent to the Mu2e Production Target**

- ❑ It runs together with neutrino beam for NOVA
- ❑ It cannot run together with Muon g-2.



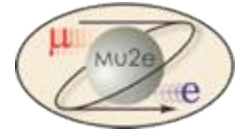
Muon campus & Mu2e Hall status



- Detector Hall Building
 - Broke Ground (April 2015)
 - Building Acceptance (March 2017)
- Infrastructure installation (still on going)
 - LCW pipes, Bus bar, Cable Trays
 - Interlocks, Networking, DAQ infrastructure
 - Cryo Distribution box ...

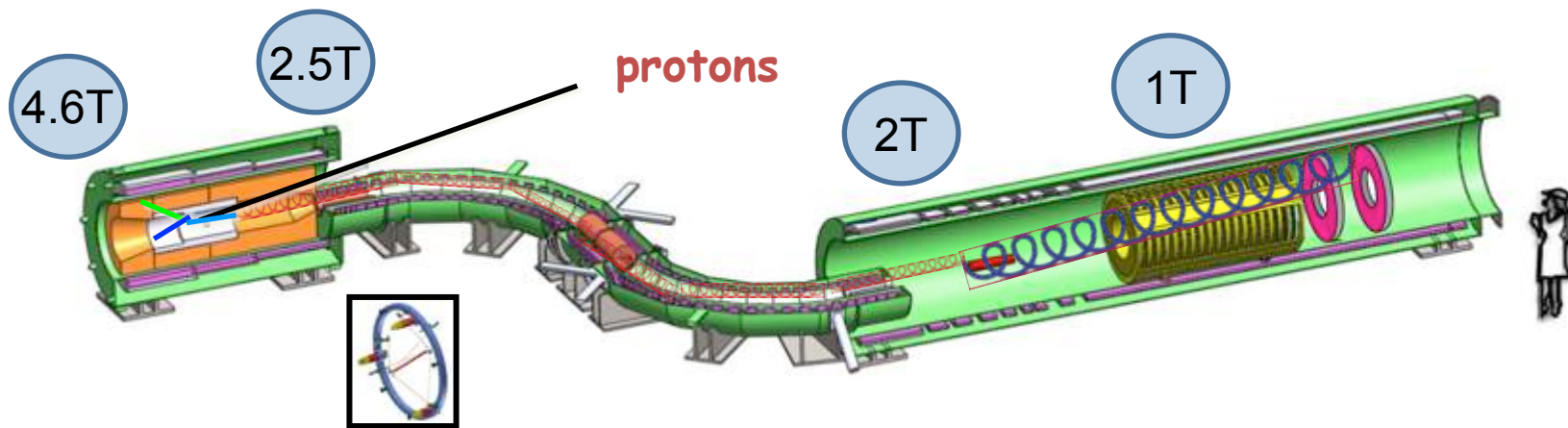


Muon Beam-line



Production Target / Solenoid (PS)

- 8 GeV Proton beam strikes target, producing mostly pions
- Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons → High Muon intensity



- Heat and radiation shielding
- Tungsten target.

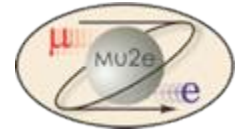
Target, Detector and Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- CRV to veto Cosmic Rays event

Transport Solenoid (TS)

Collimator selects low momentum, negative muons
Antiproton absorber in the mid-section
S-shape eliminates photons and neutrons

Detector Solenoid



Graded field "reflects" downstream a fraction of conversion electrons emitted upstream

Muon beam

Proton Absorber

Muon Beam Stop

muon stopping target

Tracker

EM Calorimeter

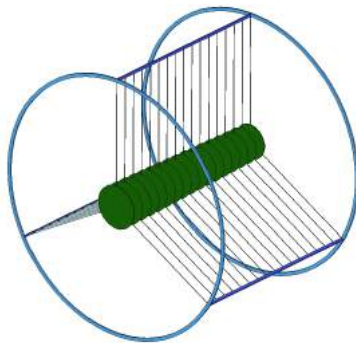
17 Al foils; Aluminum choice dictated by the bound muon lifetime (**864 ns**) that nicely matches the the Mu2e pulsed beam structure for prompts' separation

Sensitivity goal →

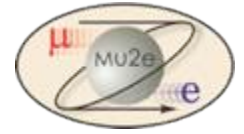
$\sim 6 \times 10^{17}$ stopped muons

3 year runs , 6×10^7 sec →

10^{10} stopped muon/sec



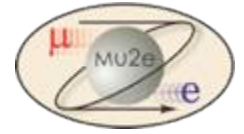
Status of PS/DS construction



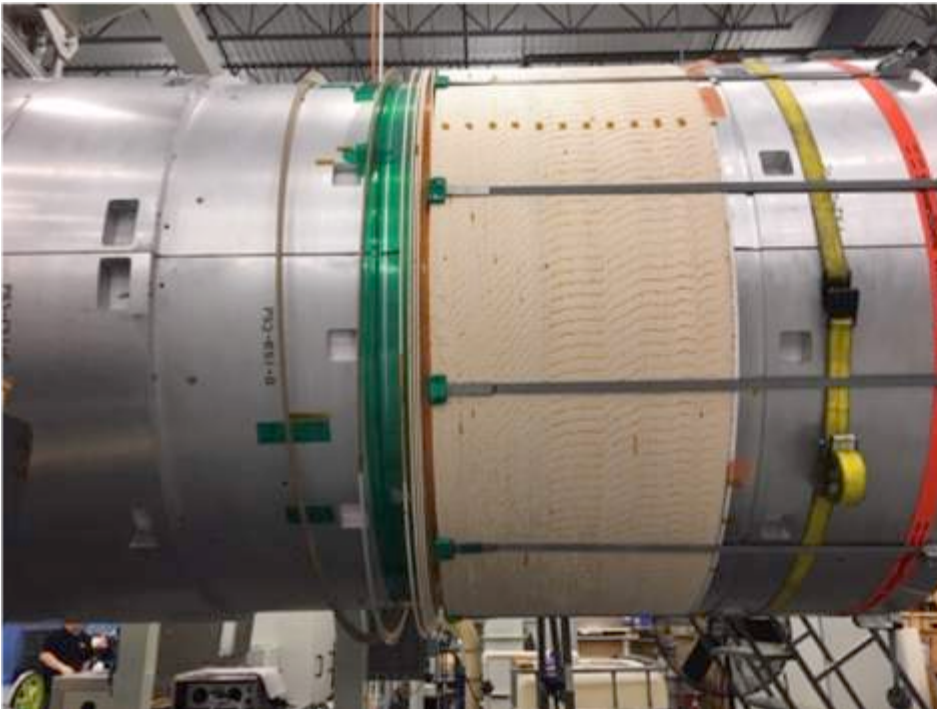
- PS/DS Cryostats being completed @ Joseph Oat (GA Subcontract)



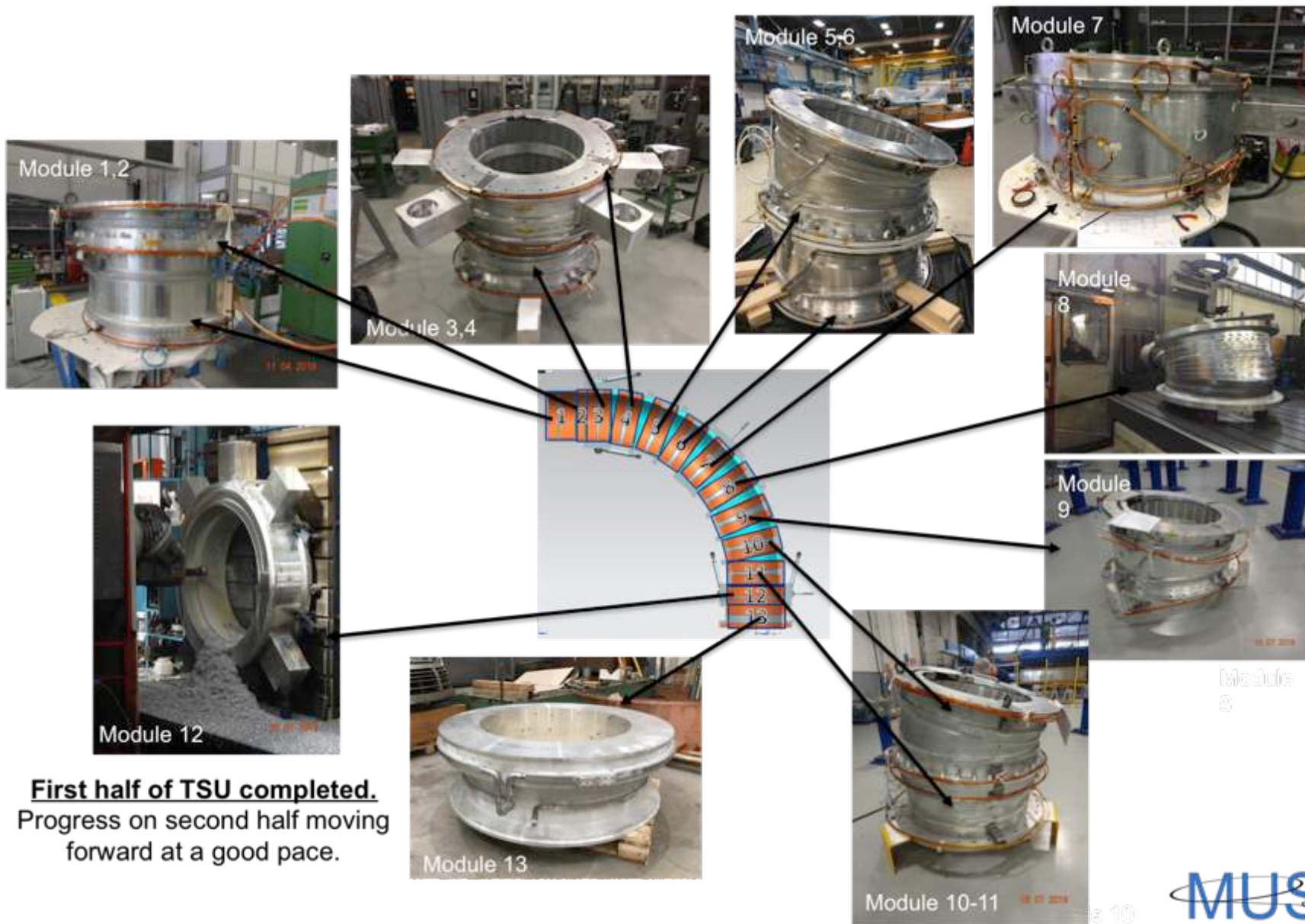
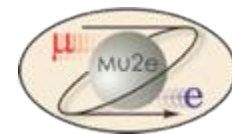
Status of PS/DS construction



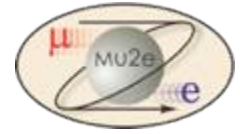
- Superconducting cable procured and tested
- PS/DS winding in progress at GA (Tupelo)



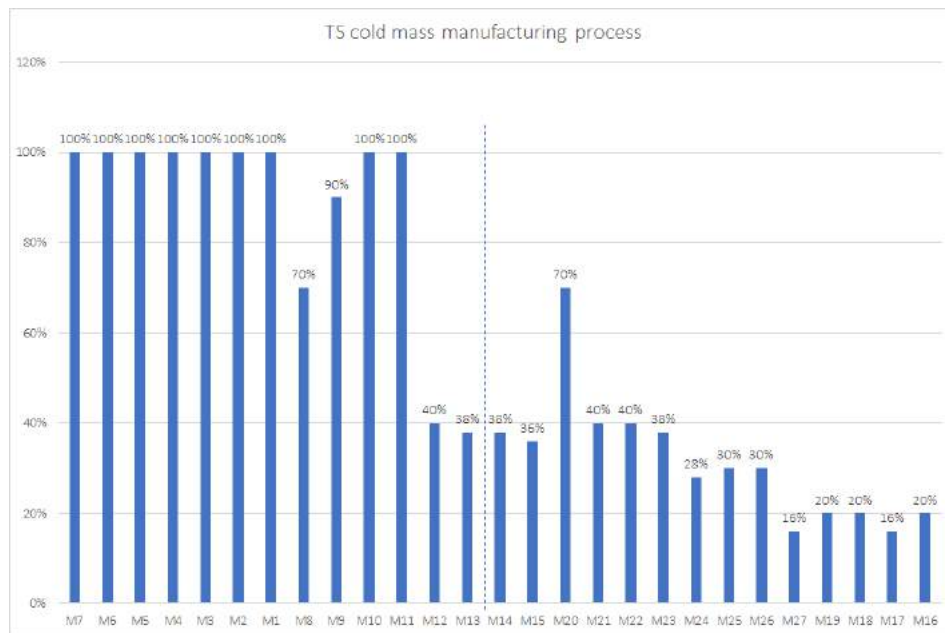
Status of TS construction



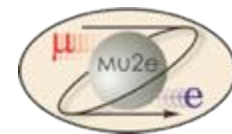
TS construction



- ❑ Construction of TSD also proceeds at full speed in ASG superconducting (Genoa)
- ❑ Overall TS modules construction better than 1/3 of total
- ❑ Second test unit (M5/M6) assembled on warm bore. Mated together perfectly. Alignment ongoing.

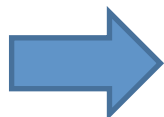


The Mu2e Tracker



Detector requirements:

1. Small amount of X_0
2. $\sigma_p < 180 \text{ keV @ } 105 \text{ MeV}$
3. Good rate capability:
 - 20 kHz/cm² in live window
 - Beam flash of 3 MHz/cm²
4. dE/dx capability to distinguish e^-/p
5. Operate in $B = 1 \text{ T}$, 10^{-4} Torr vacuum
6. Maximize/minimize acceptance for CE/DIO



Low mass straw drift tubes design: **straw**

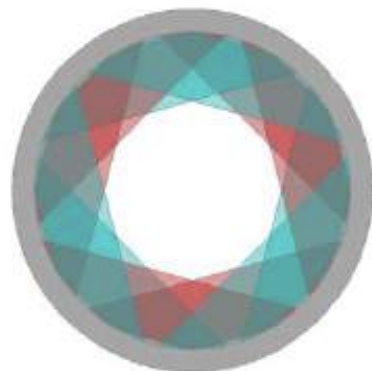
- 5 mm diameter, 33 – 117 cm length
- 15 μm Mylar wall, 25 μm Au-plated W wire
- 80:20 Ar:CO₂ @ 1 atm
- Dual-ended readout



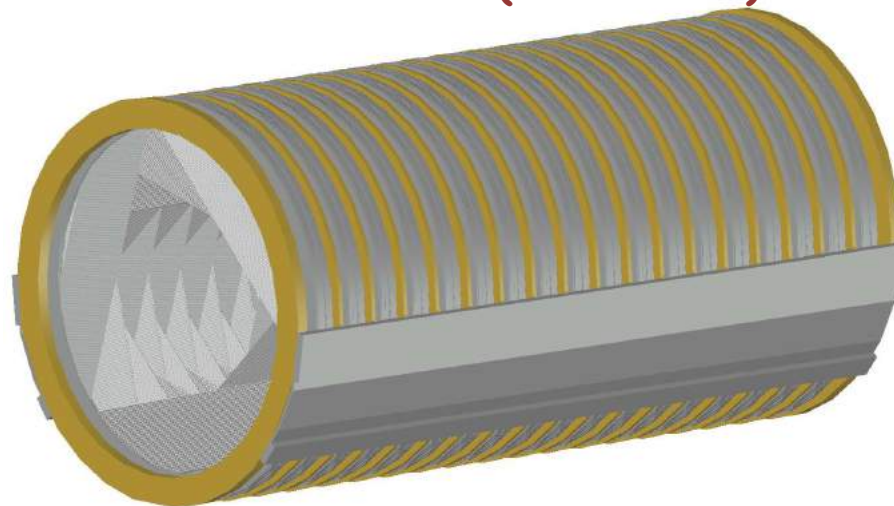
Tracker Plane



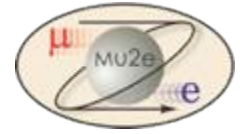
Tracker Station:
2 rotated planes



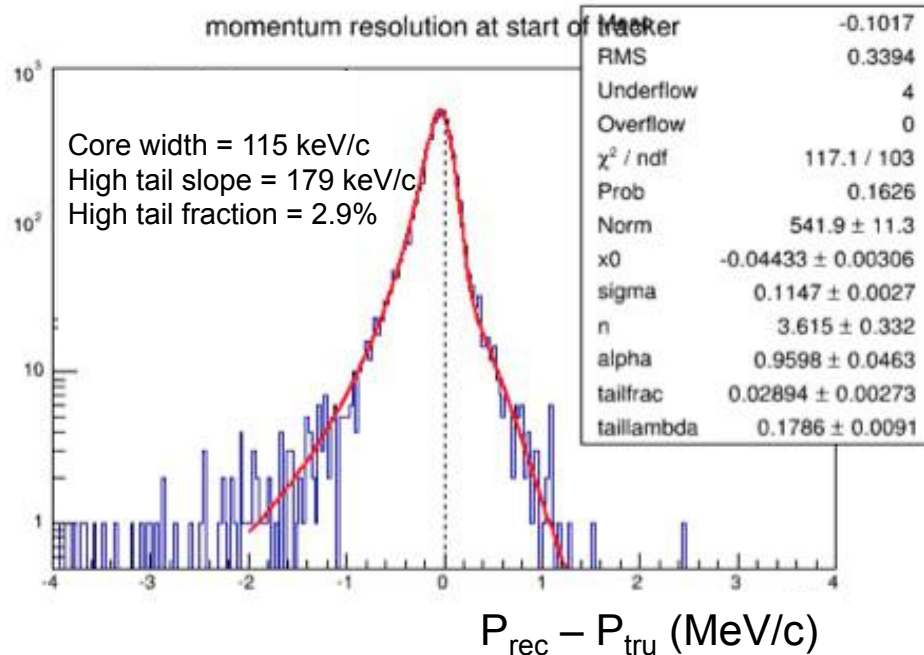
Tracker: 18 stations (>20k tubes)



Mu2e Tracker Performance

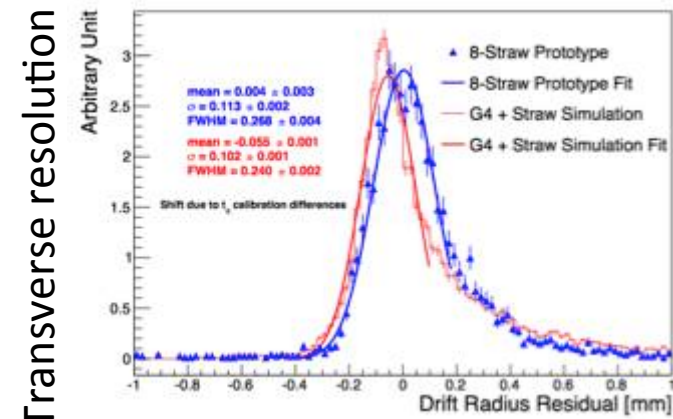


Full simulation



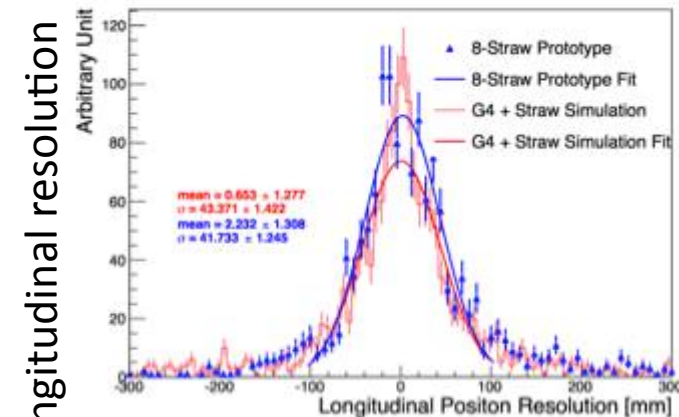
- ✗ Well within physics requirements
- ✗ Robust against increases in rate
- ✗ Inefficiency dominated by geometric acceptance

Cosmics, 8 channel prototype



$$\sigma_{\text{data}} = 0.133 \pm 0.022 \text{ mm}$$

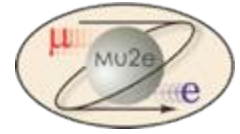
$$\sigma_{\text{MC}} = 0.102 \pm 0.001 \text{ mm}$$



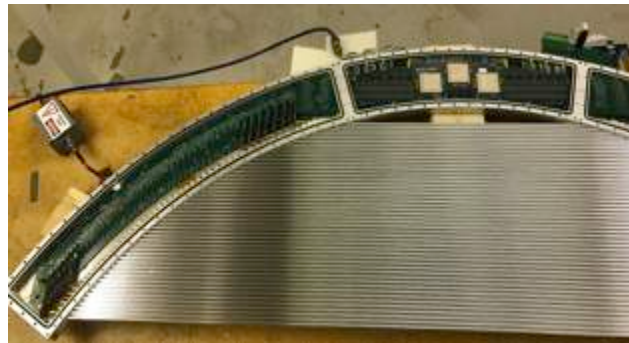
$$\sigma_{\text{data}} = 42 \pm 1 \text{ mm}$$

$$\sigma_{\text{MC}} = 43 \pm 1 \text{ mm}$$

Mu2e Tracker status



- Straw Procurement completed (30k straws)
- Straw production well progressed. Complete fixtures in May 2020
- **Panels**
 - Design Complete
 - Production assembly fixtures being fabricated
 - **UMN Panel Factory & QC Station set up**
 - Now working on the 11th pre-production panel.
 - Production will start after completing Pre-panel #12
- **Plane**
 - Plane assembly tooling fixture design nearly complete
- **Electronics**
 - Incorporation of rad hard FPGA in progress



Panel w/Front-End Electronics

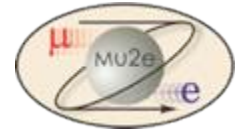


Three panels installed in plane



Panel: Straw Installation

Mu2e Calorimeter System



Calorimeter requirements:

- PID to distinguish e/μ
- Seed for track pattern recognition
- Tracking independent trigger
- Work in 1 T field and 10^{-4} Torr vacuum
- RadHard up to 100 krad, 10^{12} n/cm²/year

Calorimeter choice:

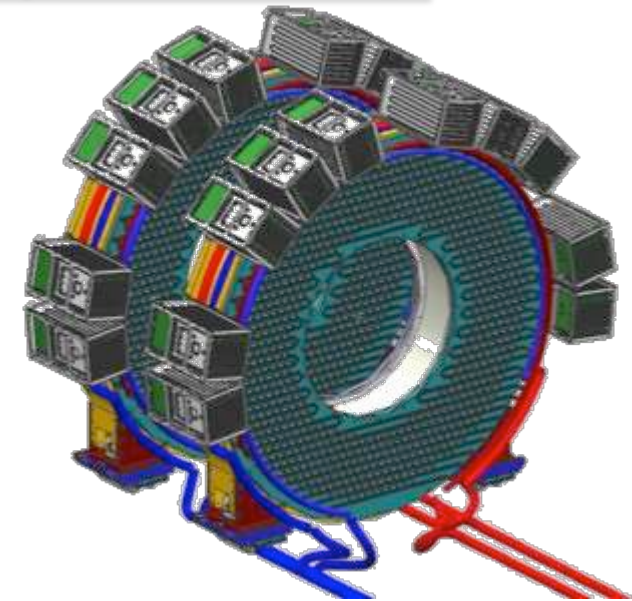
High granularity crystal calorimeter with
Large area custom UV extended SiPMs

- σ/E of O(10%) and Time resolution < 500 ps
- Position resolution of O(1 cm)
- High acceptance for CE signal @ 100 MeV
- FEE on SiPM pins, digital electronics on crates
- Calibration: 6 MeV source and Laser+MIPs

Annular disk geometry

- Square crystals 34x34x200 mm³
- Charge symmetric to measure

$$\mu^- N \rightarrow e^+ N$$



Basic Components:

- Undoped CsI crystals
- Mu2e SiPMs + FEE



MUSE

Mu2e Calorimeter performance

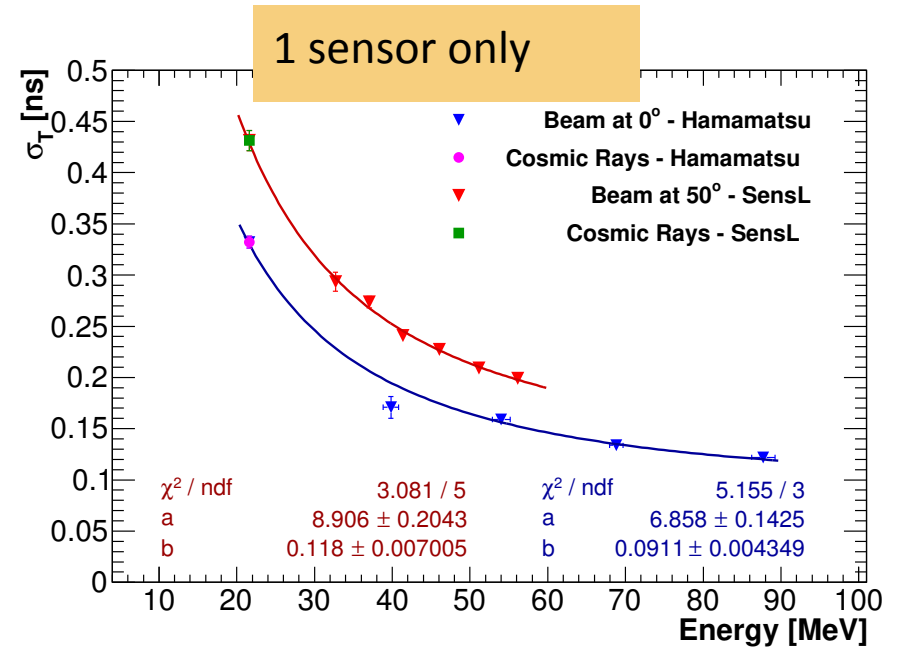
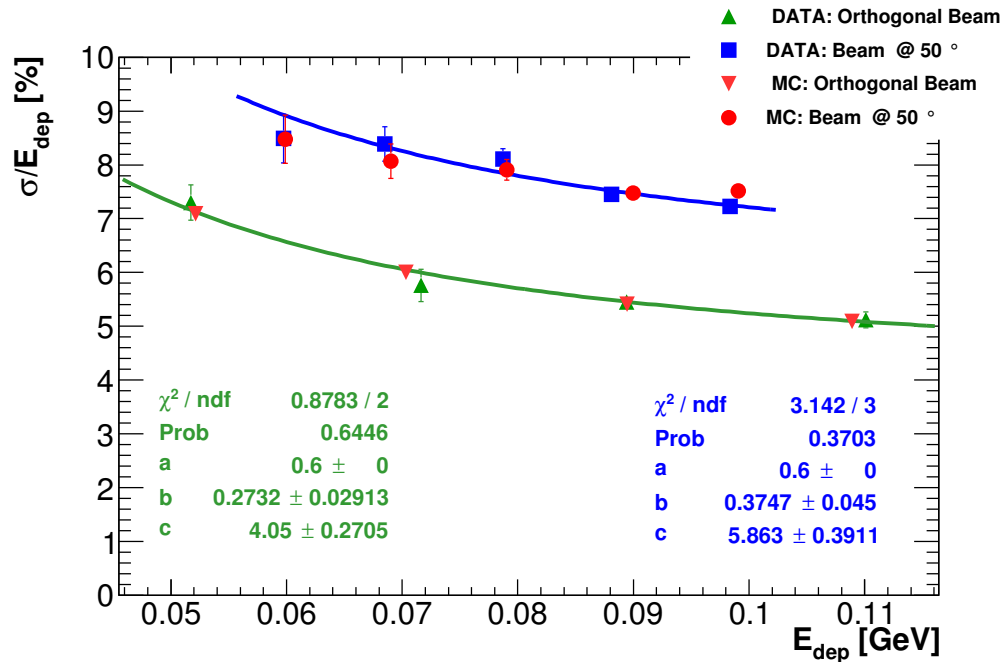
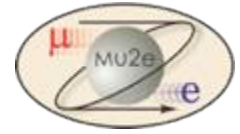
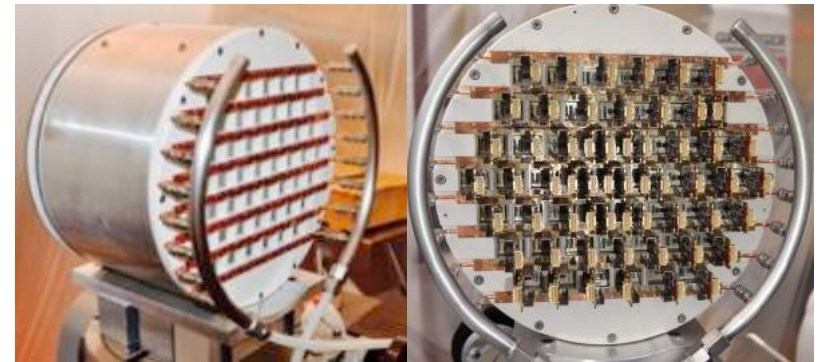
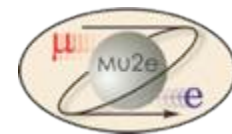


Figure 40: Energy resolution as a function of the energy deposit in the Module-0 in the orthogonal (blue) and tilted (green) configuration and comparison with the MC expectation.

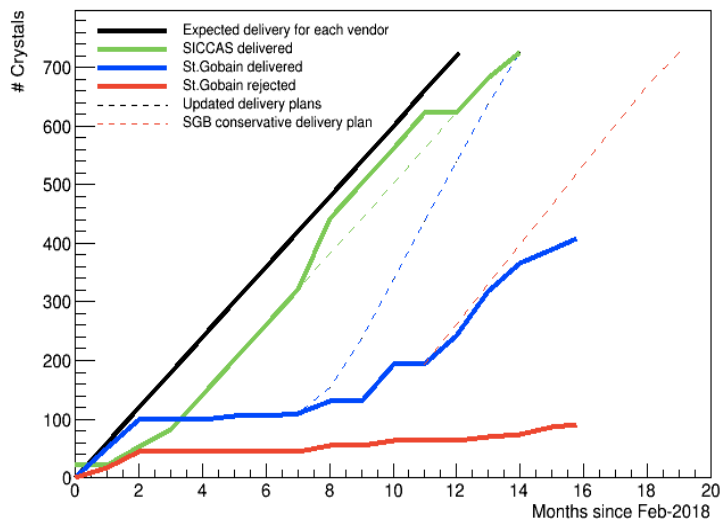
- Module-0 51 crystals, 102 SiPM/FEE channels:
- ➔ 5.4 % (7.3%) energy resolution @ 100 MeV for 0° (50°) impact angles with excellent data-MC agreement
 - ➔ Timing resolution better than 150 ps with one sensor
 - ➔ Mu2e requirements satisfied



Mu2e Calorimeter status

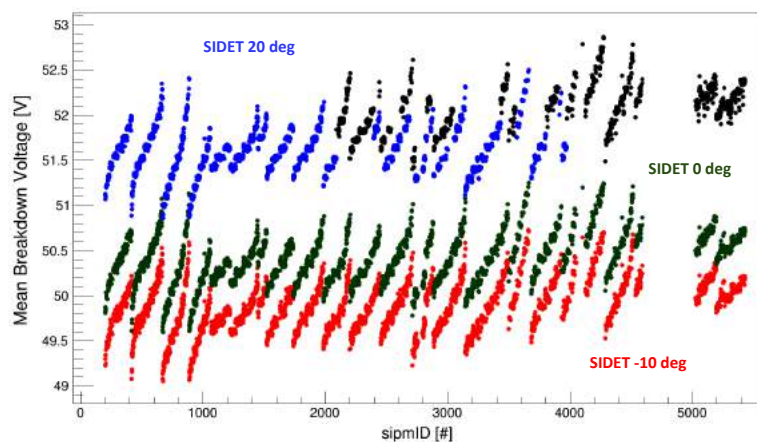


QA of crystal production



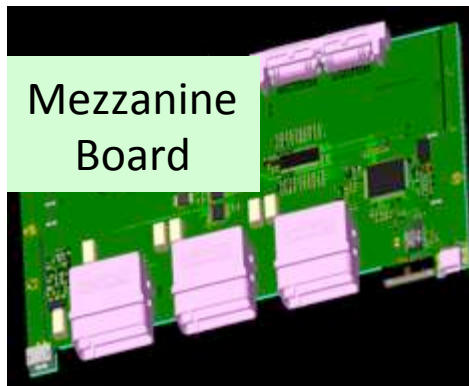
QA of SiPM production

- Results from the 5 tested batches confirmed the sipmID dependence of V_{br} :

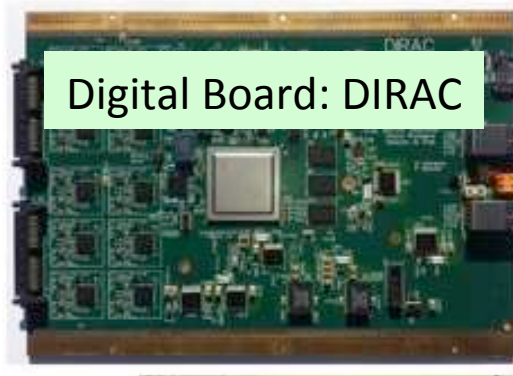


- 1100 out of 1450 crystals produced and tested
- 4000/4000 SiPMs produced and tested
- Radiation hardness test of DEE and DIRAC done
- Vertical slice test done
- Mechanics under construction in Italy

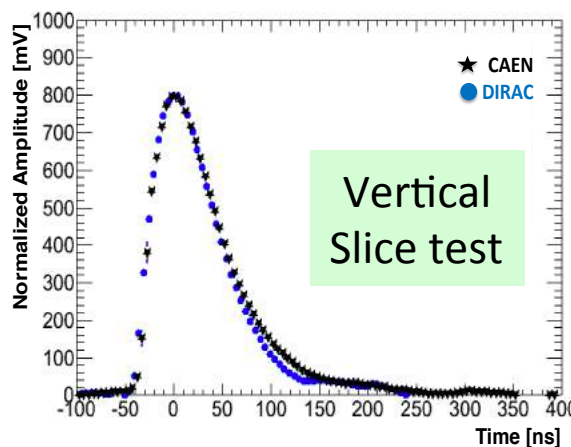
Mezzanine Board



Digital Board: DIRAC

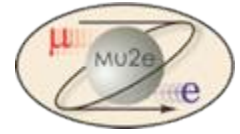


AI Disk Full Size proto

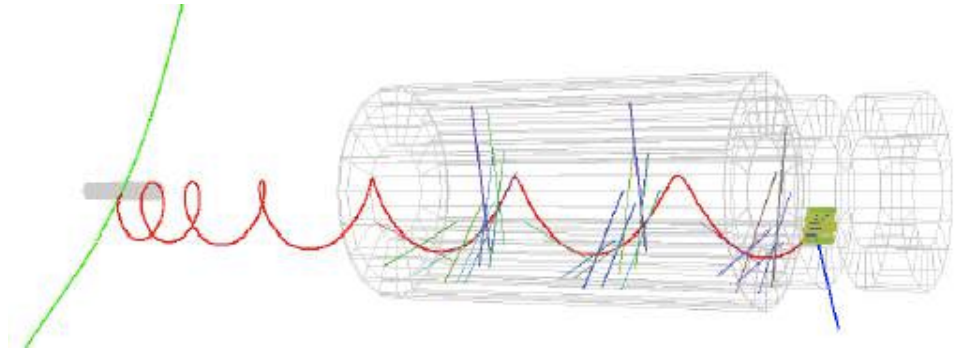


Vertical Slice test

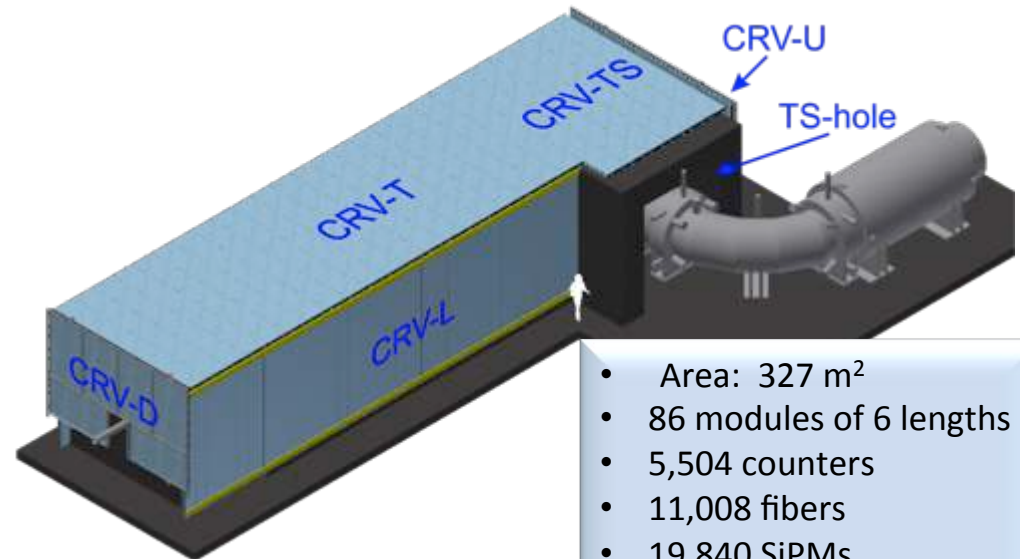
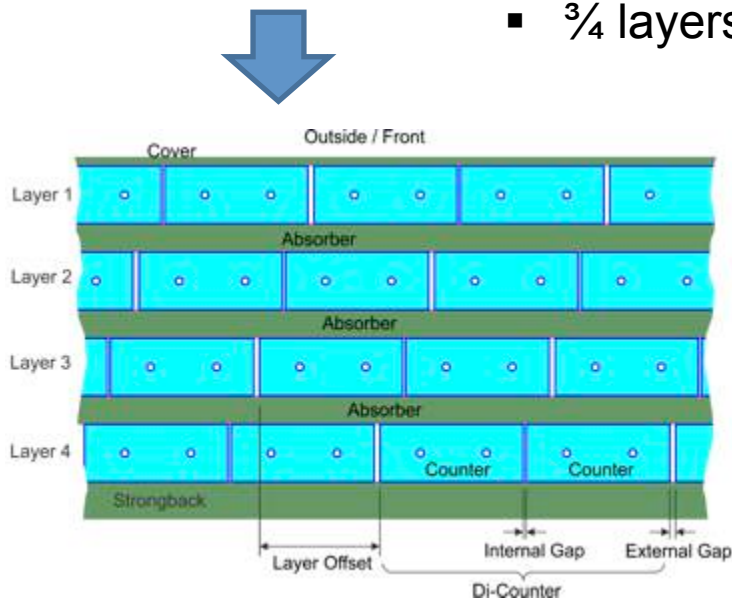
Mu2e Cosmic-Ray Veto



Cosmic ray muons will produce one fake signal event per day without a CRV. The muon itself can fake a 105 MeV e^- or it can knock out an e^-

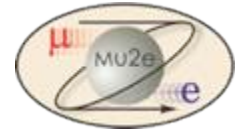


- **High efficiency (0.9999) veto needed**
- Four layers of extruded plastic scintillator, (5×2) cm²
- 2 WLS fibers (1.4 mm diameter) + (2×2) mm² SiPM readout
- $\frac{3}{4}$ layers hit: 125 ns veto



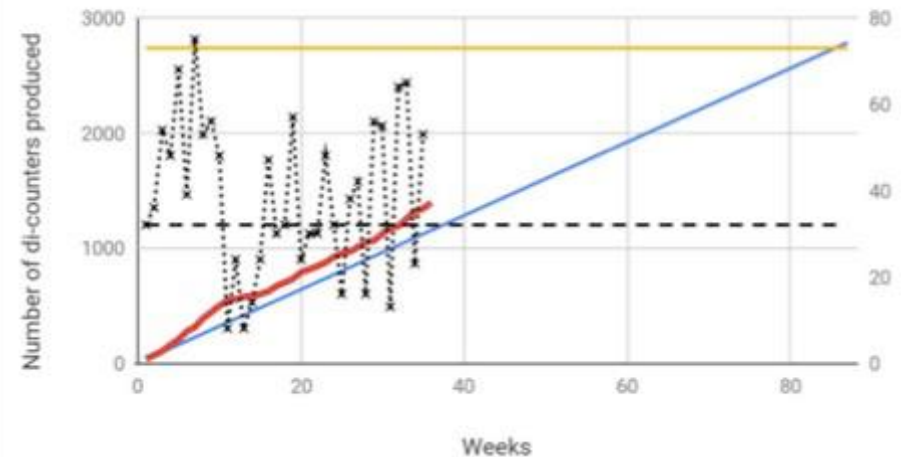
- Area: 327 m²
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards

CRV status



- 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
- Installation tests underway at ANL

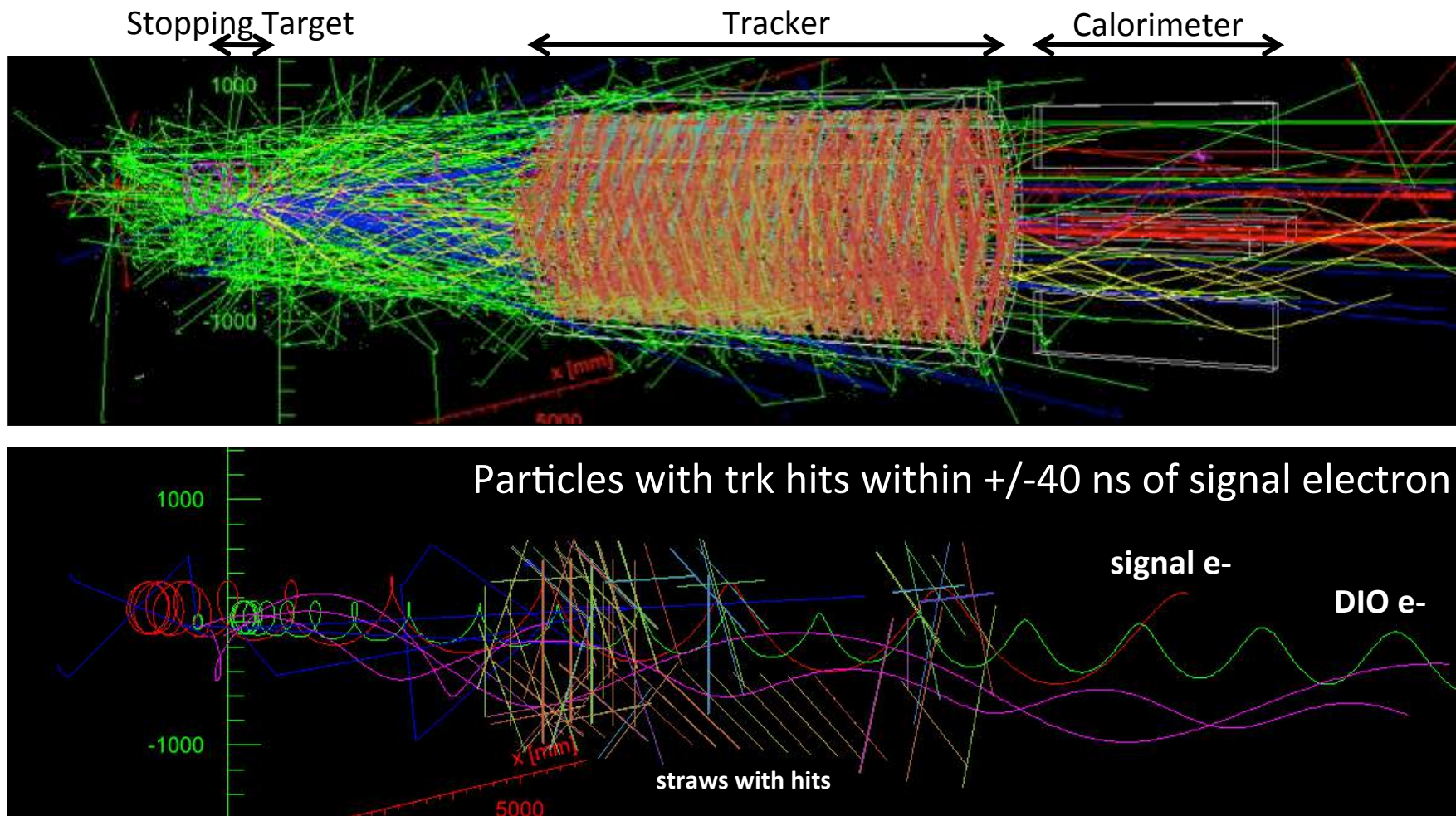
Weekly di-counter production (full production)



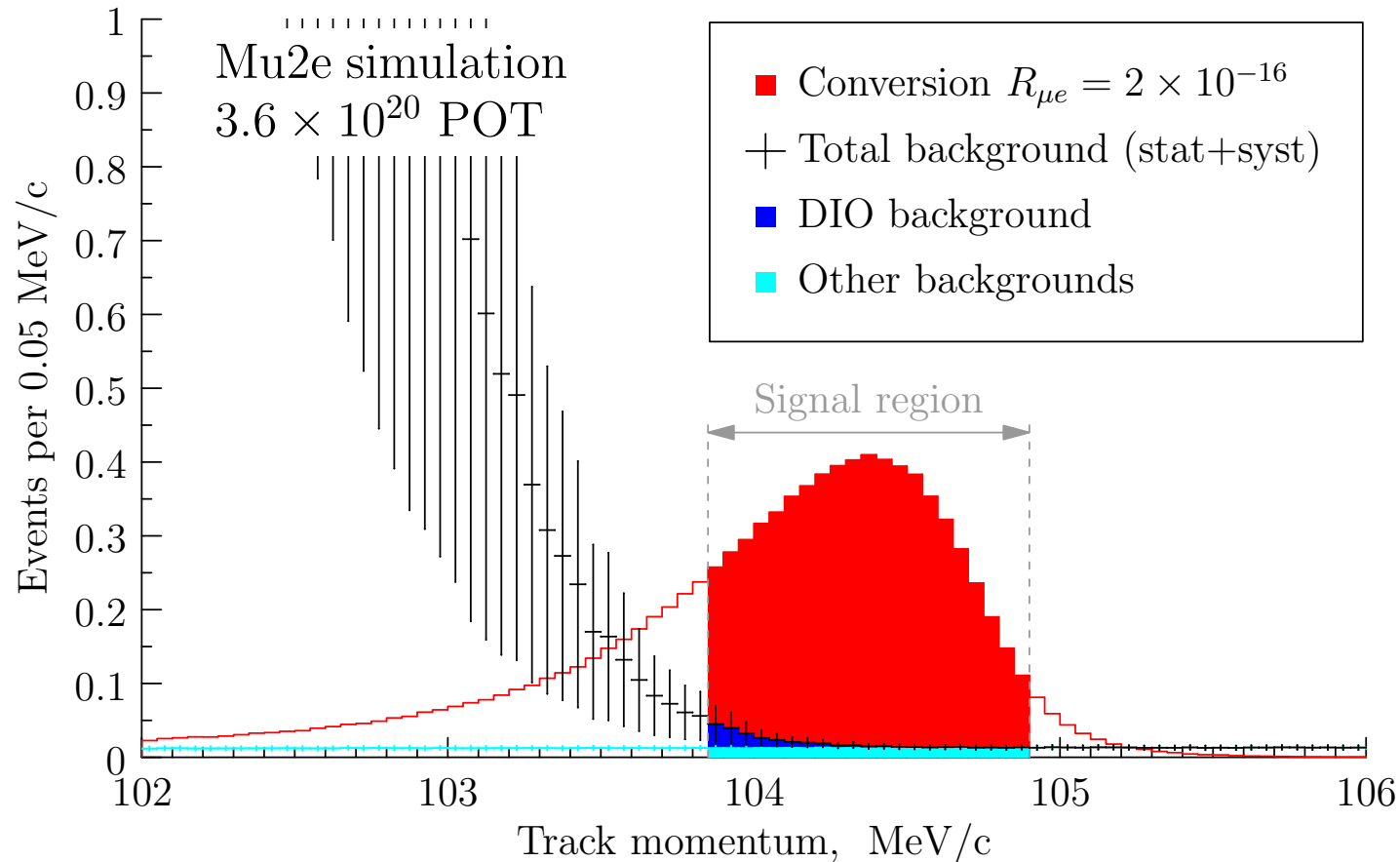
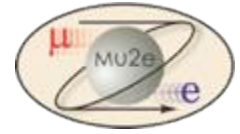
A typical Mu2e signal event



Signal electron, together with all the other hits/tracks occurring simultaneously, integrated over 500-1695 ns window

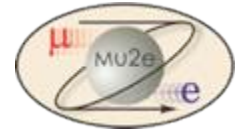


DIO/CE final count with simulation



Discovery sensitivity accomplished with three years of running and suppressing backgrounds to < 0.4 event total (50% cosmics, 35% DIOs)

Mu2e estimated Background

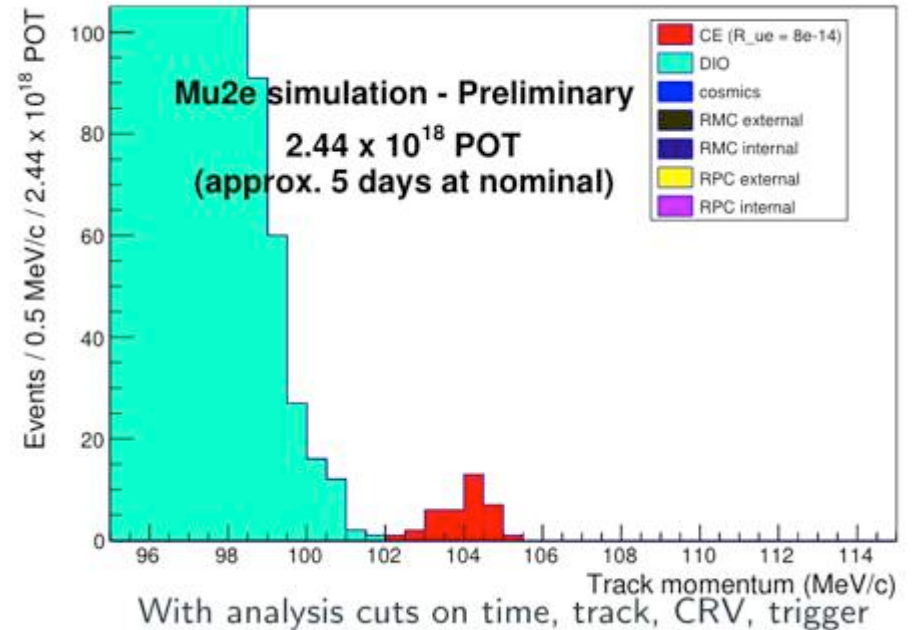
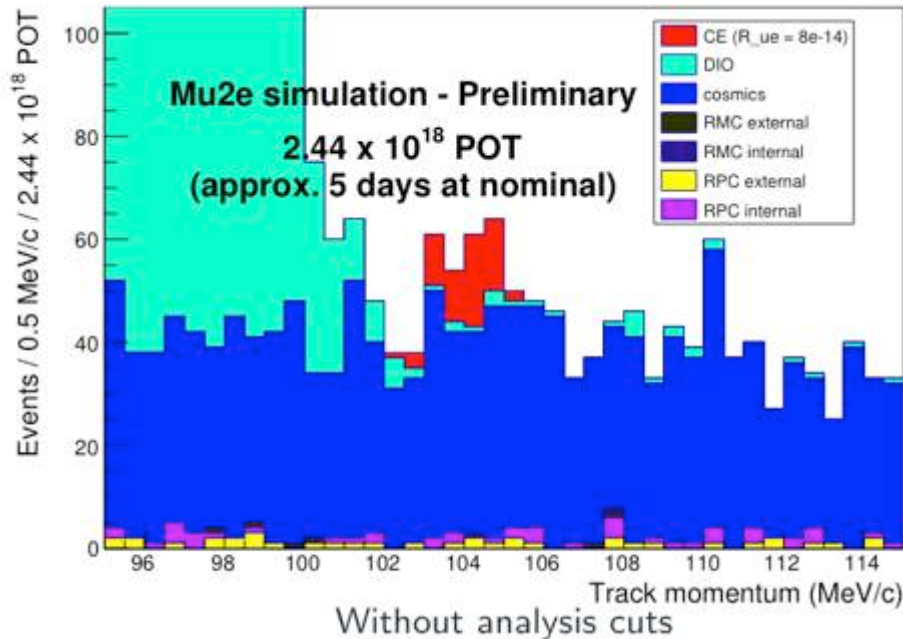
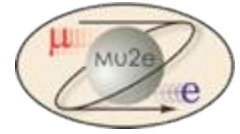


(assuming ~ 10 GHz muon stops, 6×10^{17} stopped muons in 6×10^7 s of beam time)

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

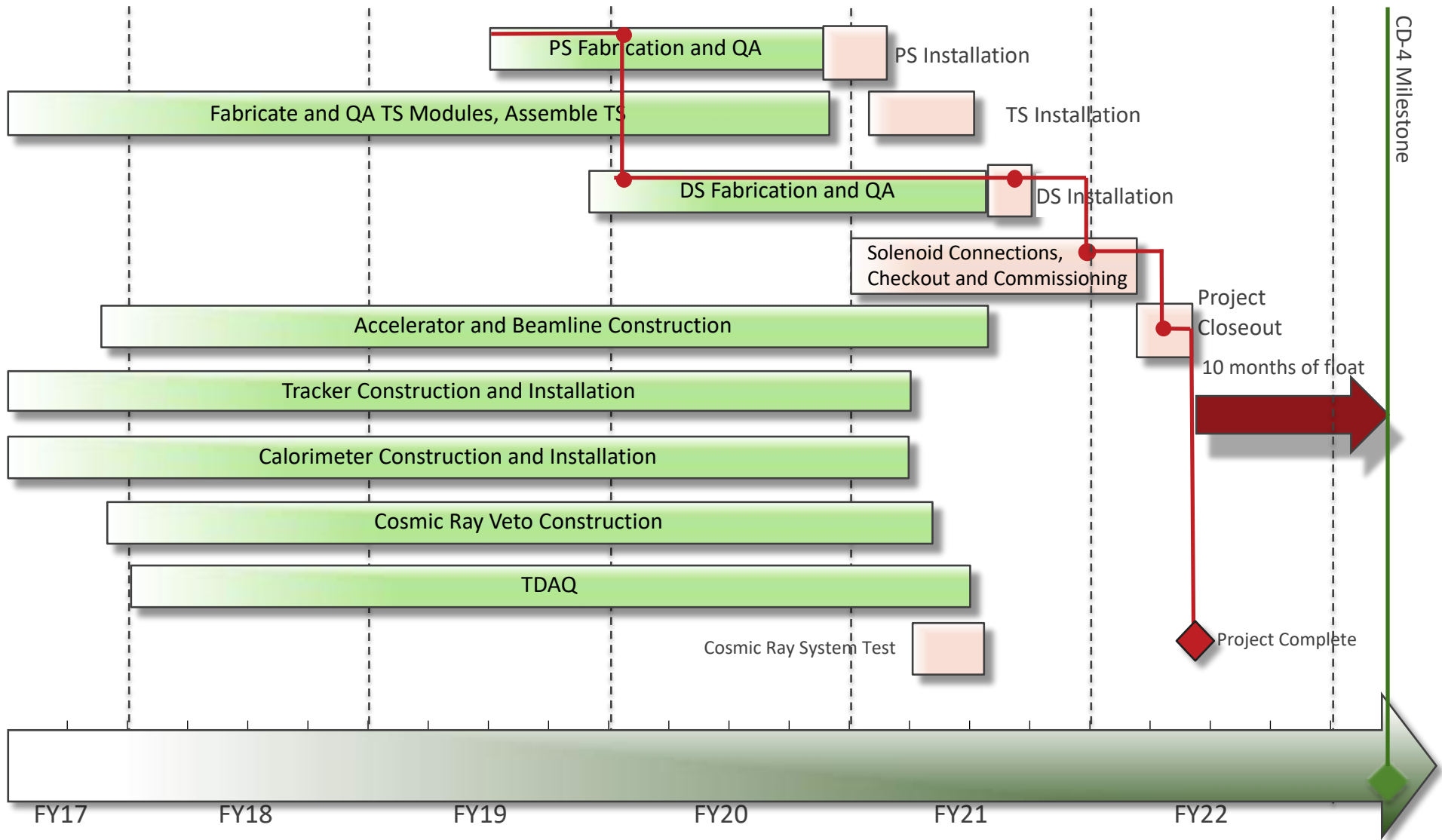
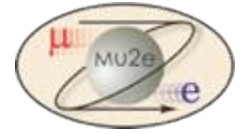
Upper Limit $< 8 \times 10^{-17}$ @ 90% C.L.

Mock Data Challenge (1% POT)



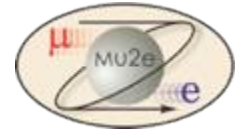
- 1 week of data taking simulated (< 1% of POT)
- Rue signal of 8×10^{-14} simulated. 1 order of magnitude below current limit
- Mixed samples created with randomized/hidden parameters to test analysis tools and reconstruction

Mu2e Project Schedule



Installation 2020-2021, Commissioning 2021-2022, Running 2023 →

Summary & conclusions

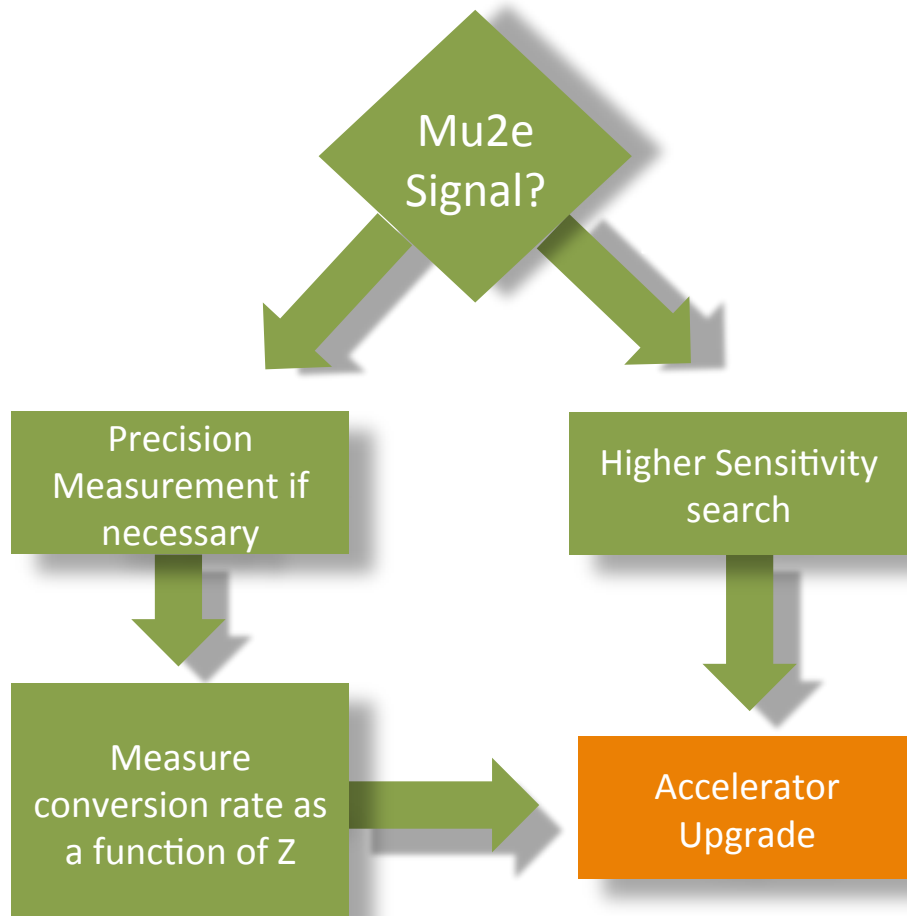
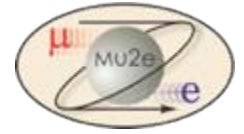


The Mu2e experiment will exploit the highest intensity muon beams of the Fermilab complex to search for CFLV

- Improves sensitivity on conversion exp. by a factor of 10^4
- Provides *discovery capability* over wide range of New Physics models
- It is complementary to LHC, heavy-flavor, dark matter, and neutrino experiments
- It will begin commissioning in 2021
- Physics running from 2023
- Start discussing about Mu2e-II

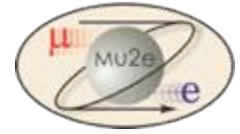
Additional Material

Do we need Mu2e-II ??



- 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

Mu2e-II EOI and problems



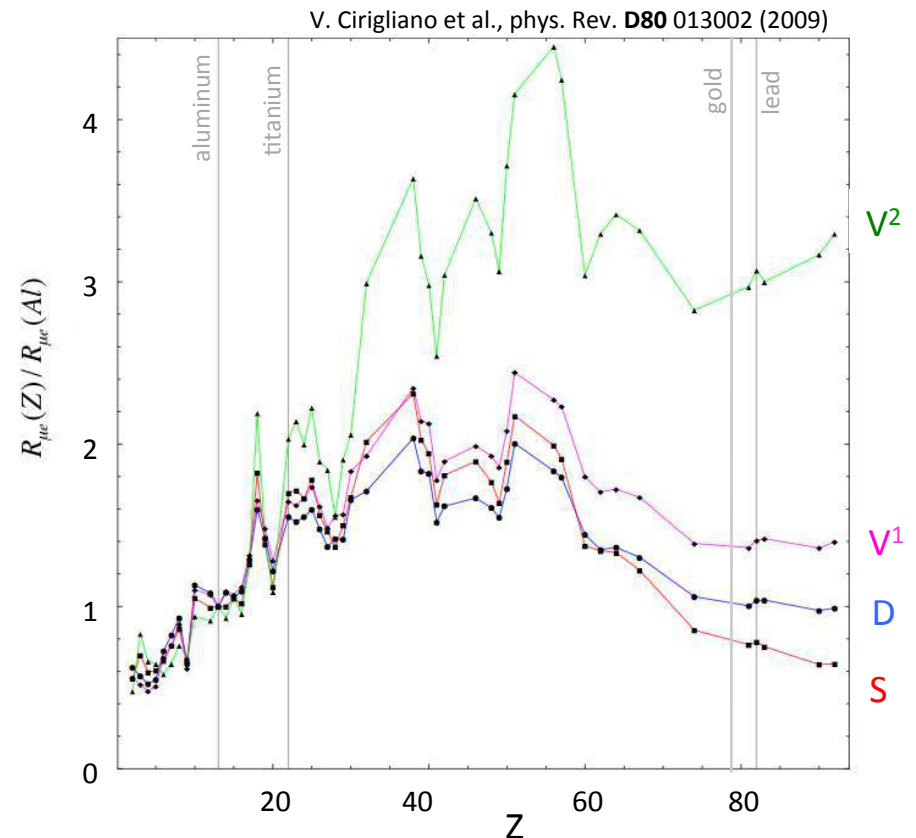
Studies for Mu2e-II (x10 reach) continuing

➔ EOI written (1307.1168 + 1802.02599)

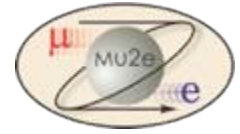
➔ Need for a large detector, accelerator and solenoid improvement

- 1) 800 MeV beam from PIP-II Linac
- 2) it may need a new PS and a radiatively cooled target to handle higher power and dose
- 3) radiation safety : needs more shieldings
- 4) Needs to improve detectors

➔ If CLFV discovered, it could help having runs with different targets to understand the dominant operator contribution



COMET vs Mu2e



- ☐ Similar capabilities in physics reach
- ☐ **COMET designed to operate at 56 kW, Mu2e 8 kW**
 - COMET will use all JPARC beam
 - Mu2e runs simultaneously with neutrino beam
- ☐ 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

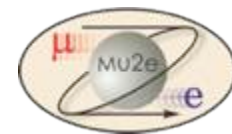
Phase-1 could be useful → if successful to study background rate

Phase-2 schedule → not yet approved

Mu2e → looking forward to Mu2e-II

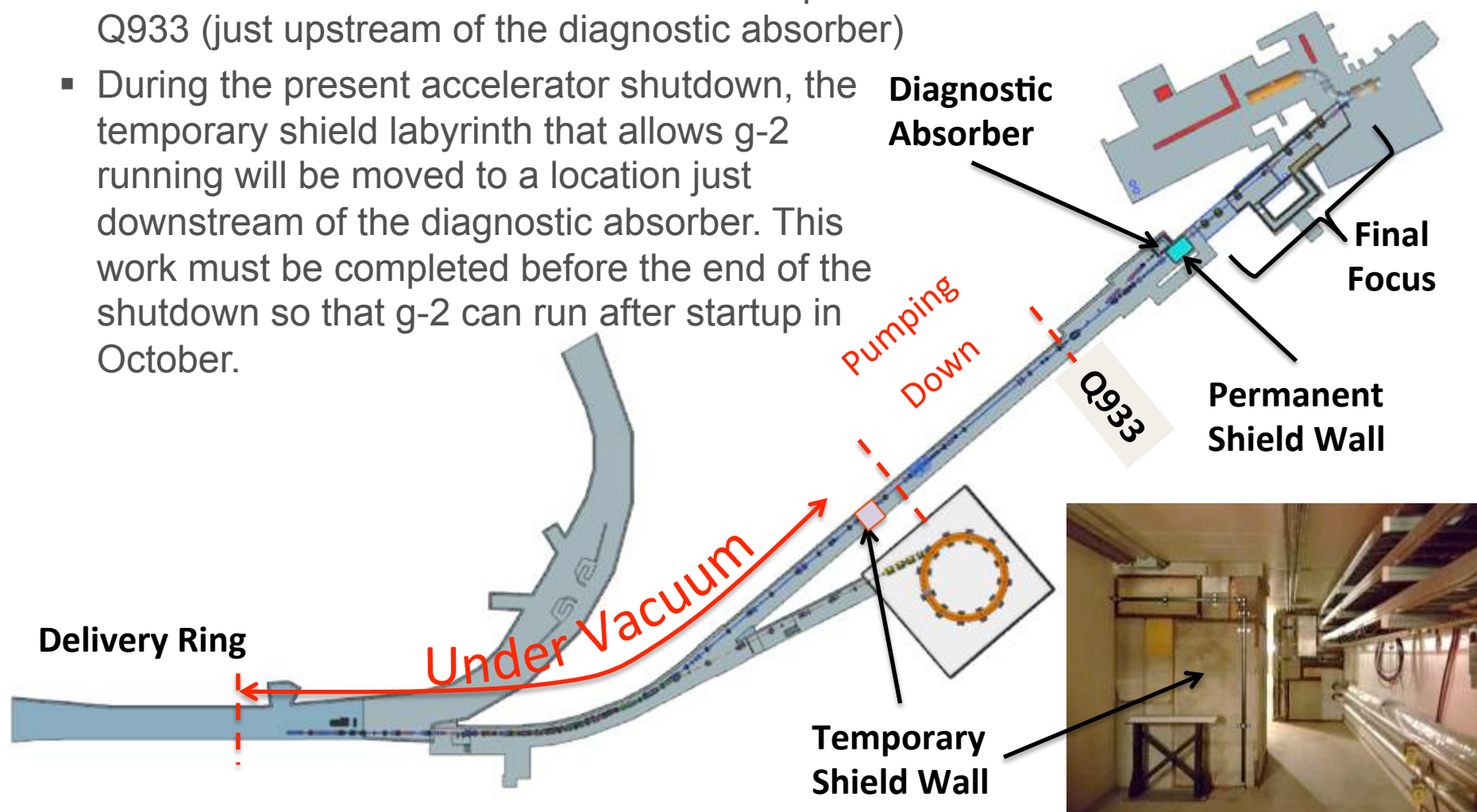
- ☐ Great competition/collaboration → ALCAP @ PSI

External Beamline

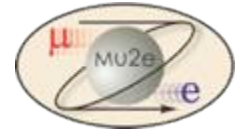


• M4 Beamline

- Beamline is installed and under vacuum up to Q933 (just upstream of the diagnostic absorber)
- During the present accelerator shutdown, the temporary shield labyrinth that allows g-2 running will be moved to a location just downstream of the diagnostic absorber. This work must be completed before the end of the shutdown so that g-2 can run after startup in October.

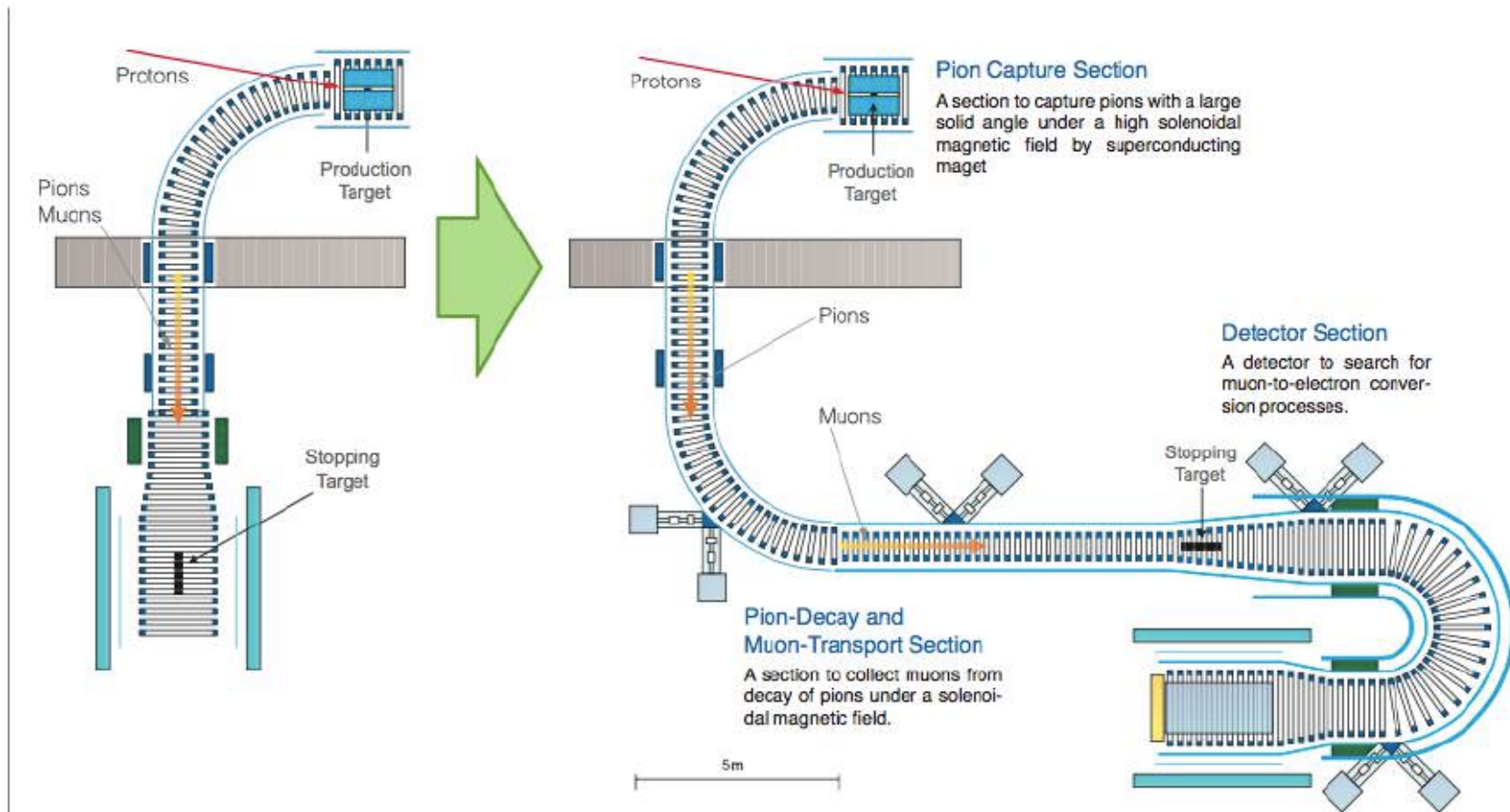


World program: COMET

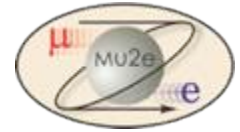


phase I

phase II



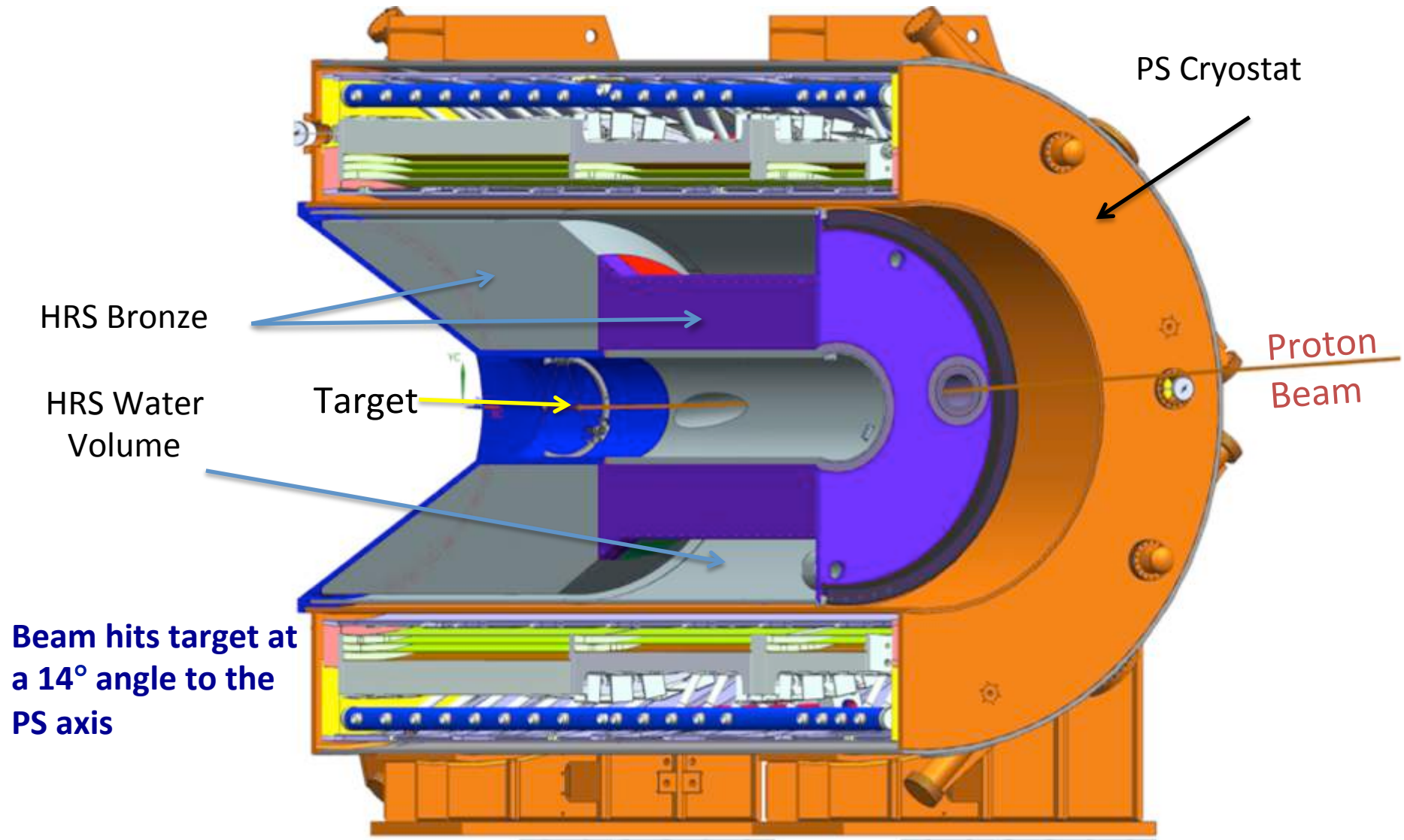
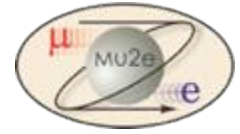
Status of Beamline



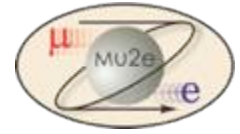
- Most beamline elements installed or being fabricated
- Prototype AC dipole for extinction fabricated
- Resonant extraction Sextupoles being fabricated
- M4 beamline under vacuum up to Q933
- Final focus section assembled



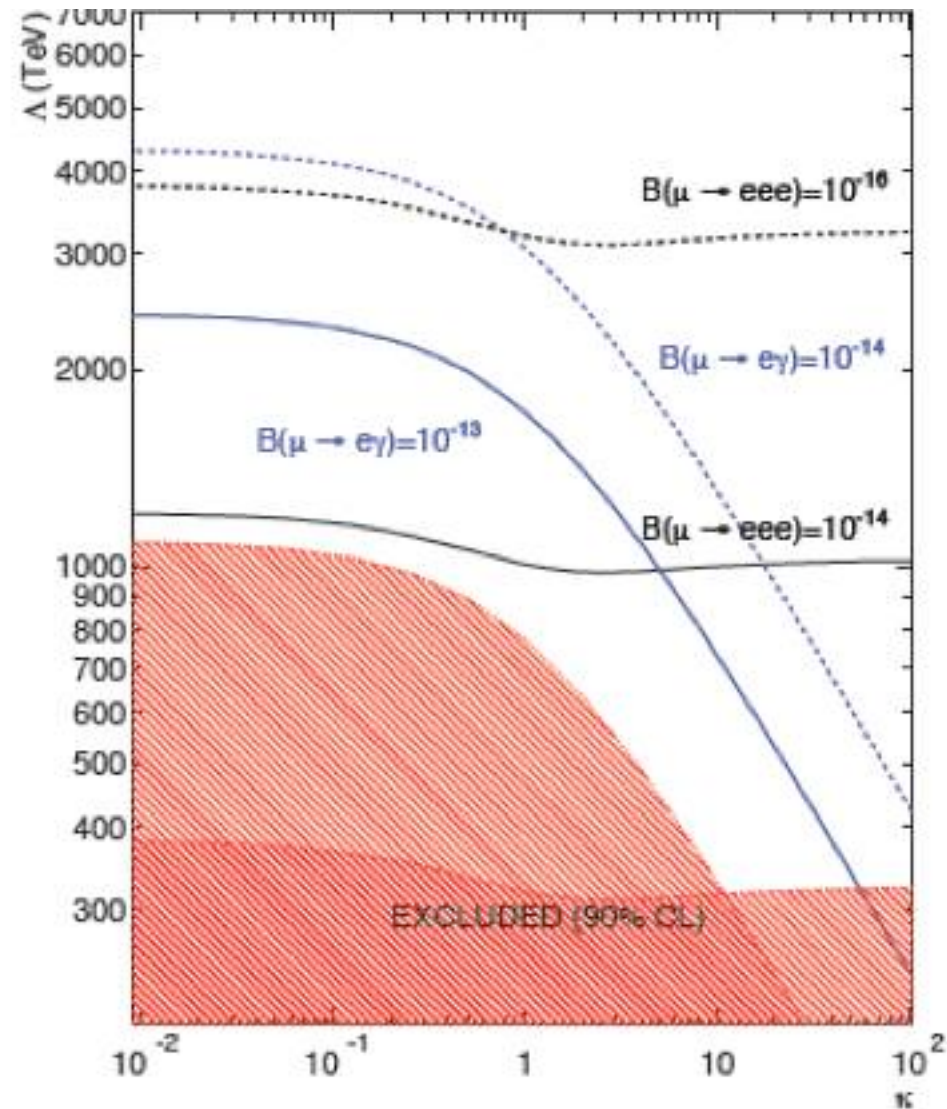
Heat and Radiation Shield (HRS)



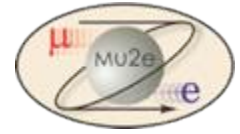
MEG vs Mu3e



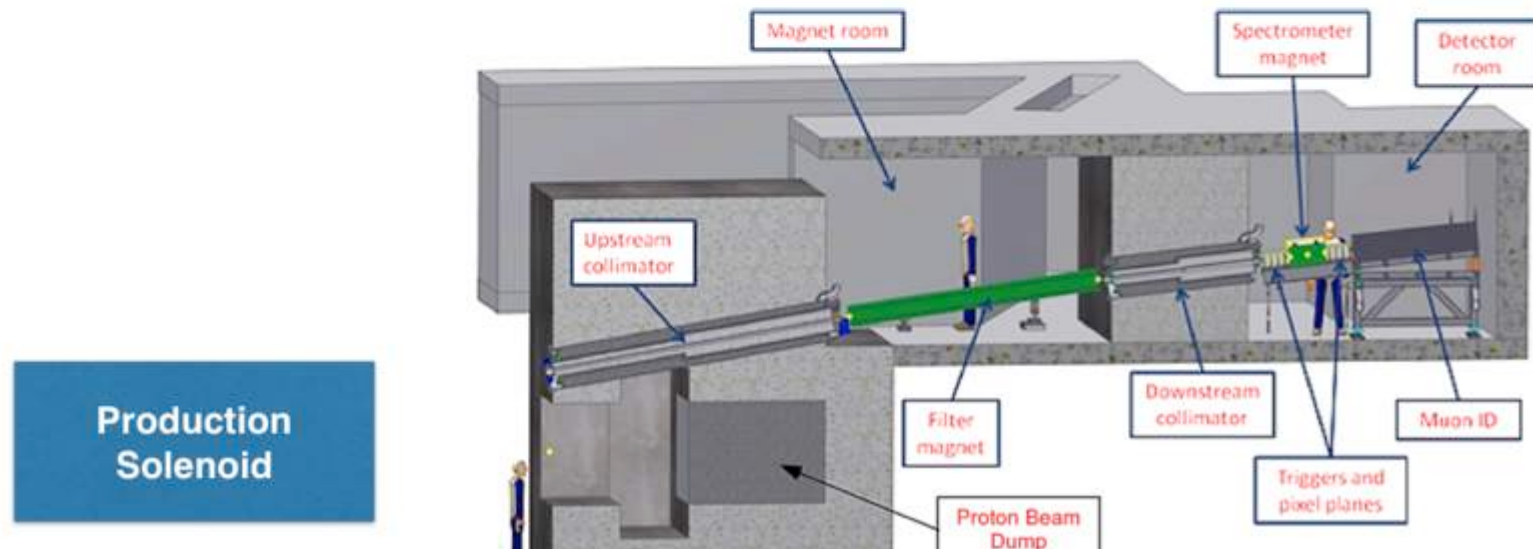
- Mu3e decays test also values of K larger than MEG but with different (reduced) sensitivity at large K with respect to Mu2e
- Phase 1 Mu3e at PSI aims to 10^{-15} (approved)
- Next phase aims to 10^{-16}
.. Schedule is not yet clear



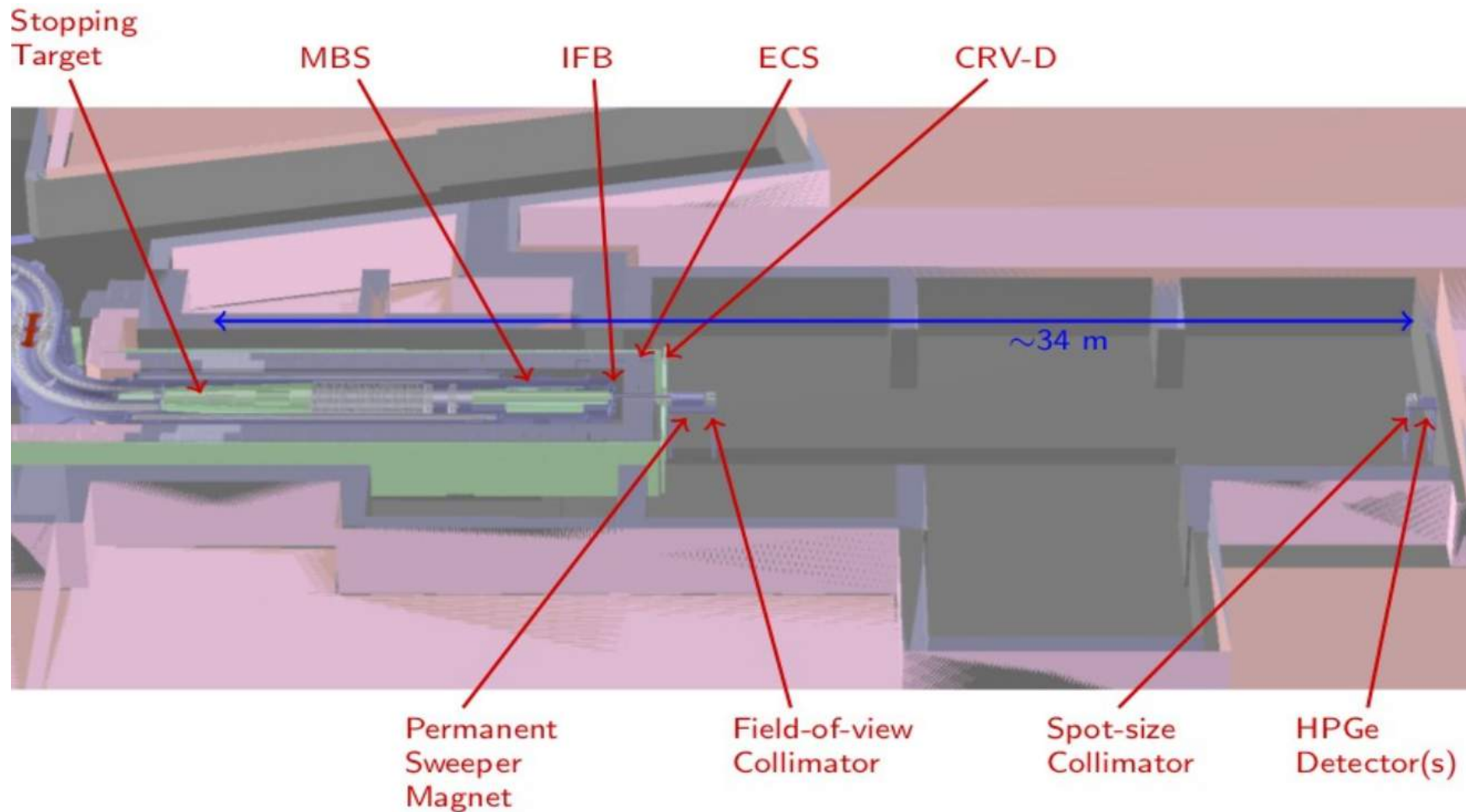
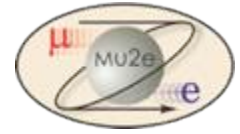
Extinction Monitor



- The RF structure of the Recycler provides some “intrinsic” extinction:
 - **Intrinsic extinction $\sim 10^{-5}$**
- A custom-made AC dipole placed just upstream of the PS provides additional extinction:
 - **AC dipole extinction $\sim 10^{-6} - 10^{-7}$**
- Together they provide a total extinction:
 - **Total extinction $\sim 10^{-11} - 10^{-12}$**
- Extinction measured using a detector system: Si-pixel + sampling EMC

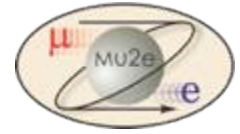


Stopping Monitor

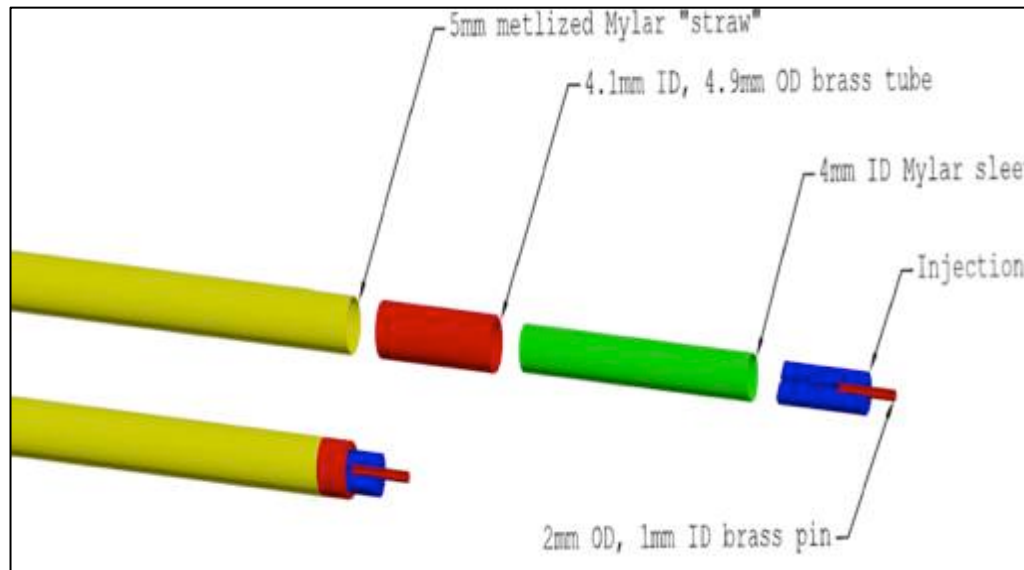


The STM will measure a variety of well understood gamma ray lines ... under a high-rate brehmstrahlung background

Straw Characteristics



Straw tube



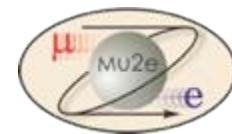
Characteristics:

- 5mm diameter and 334-1174 mm length
- 25 μm W sense wire (gold plated) at the center
- 15 microns Mylar wall
- Must operate in vacuum
- 80/20 Ar/CO₂ with HV < 1500 V

Straw tubes

- Proven technology
- Low mass $\rightarrow$ minimize scattering (track typically sees $\sim 0.25\%$ X_0)
- Modular, connections outside tracking volume
- **Challenge: straw wall thickness (15 μm) never done before**

Simulation results on tracker



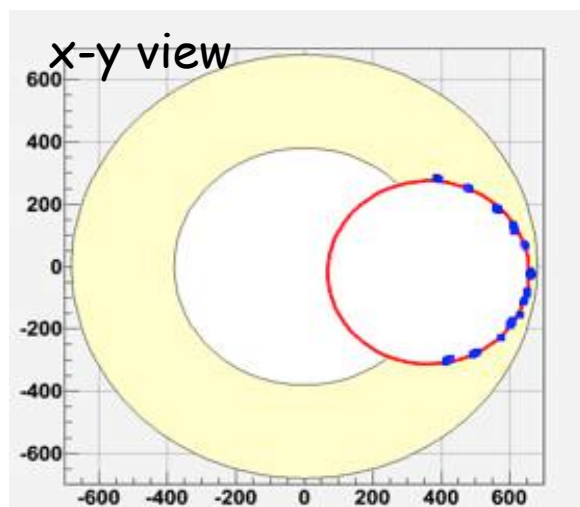
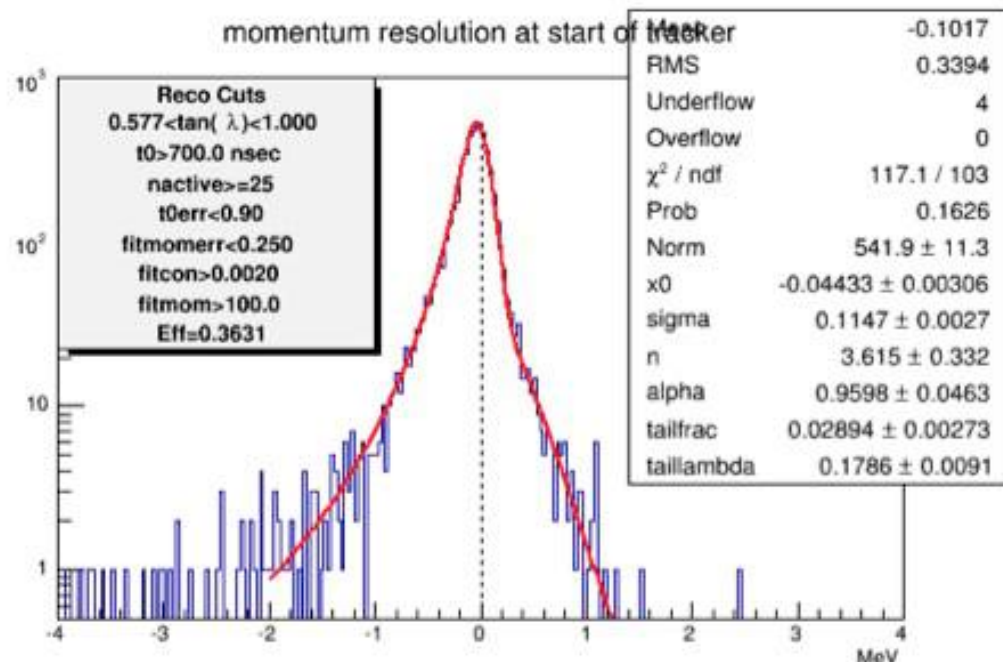
Pattern Recognition based on
BABAR Kalman Filter algorithm

No significant contribution of
mis-reconstructed background

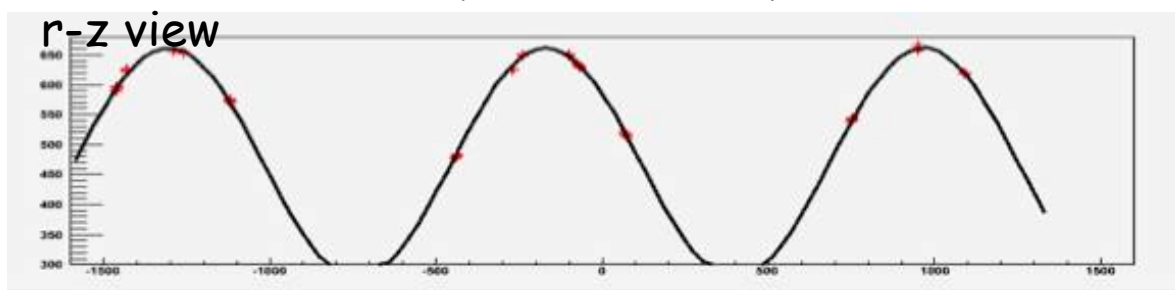
Momentum resolution

core $\sigma \sim 120$ keV

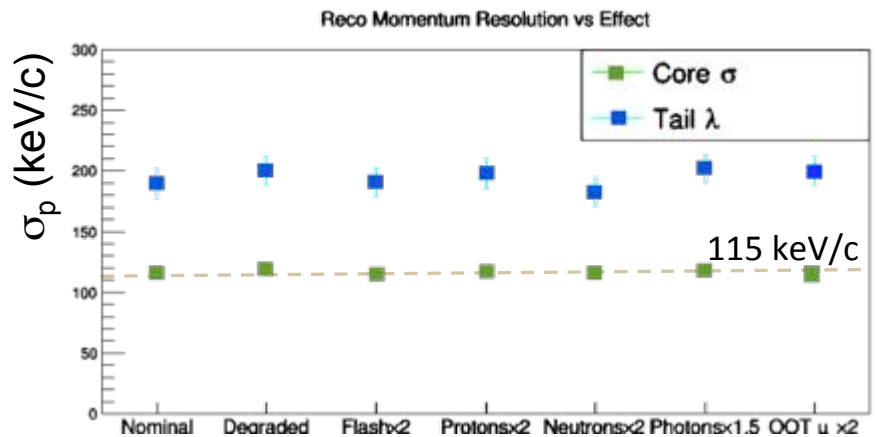
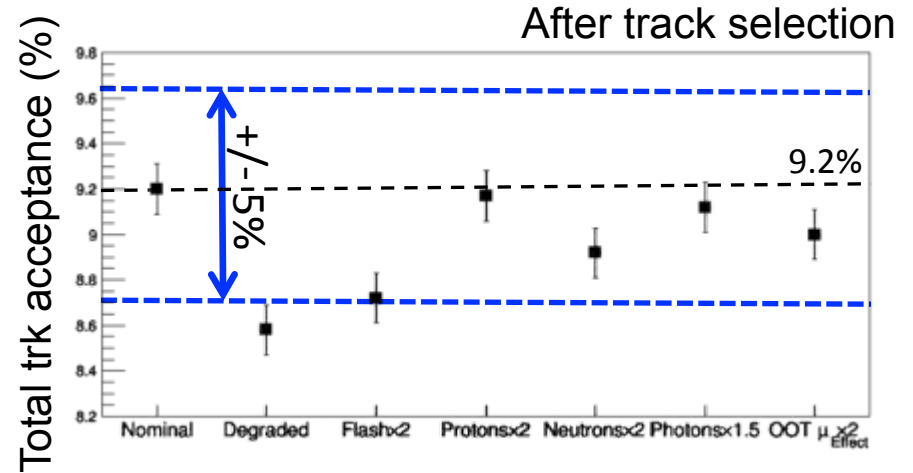
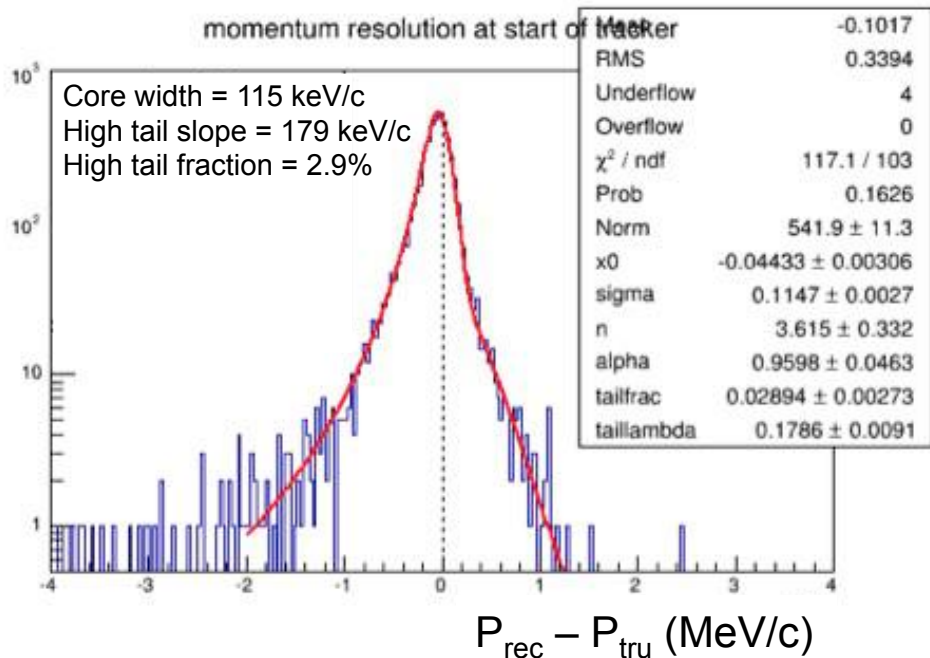
tail $\sigma \sim 180$ keV (2.5%)



Fit: Crystal Ball + exponential



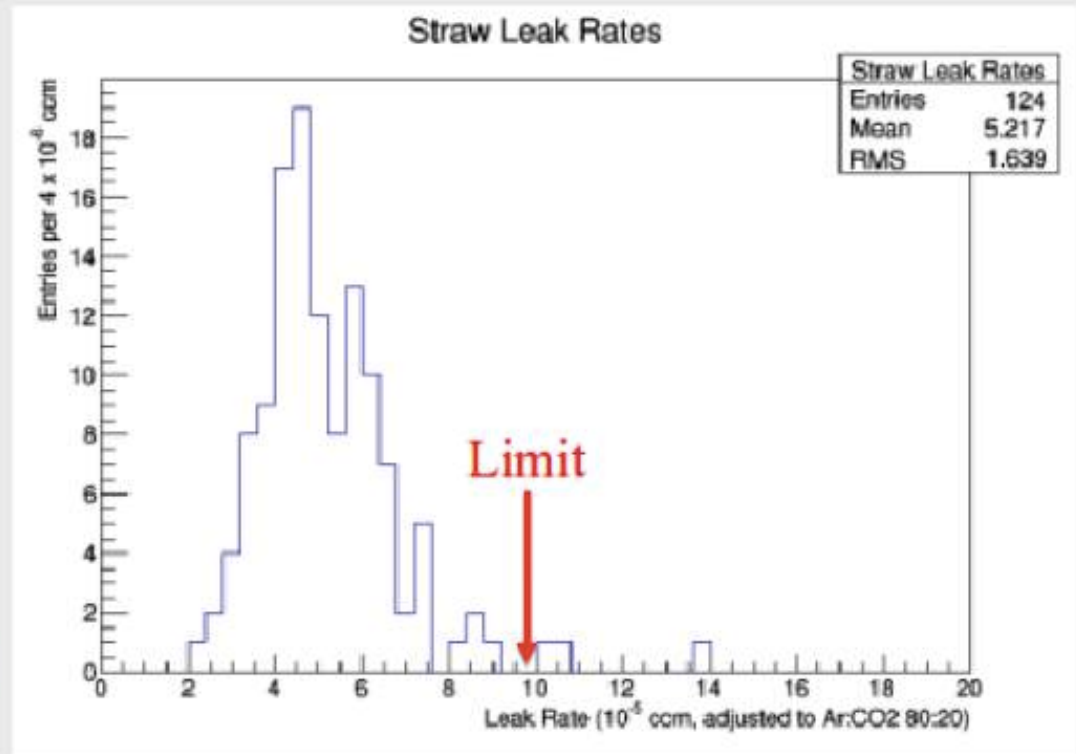
Expected tracker performances from full simulation



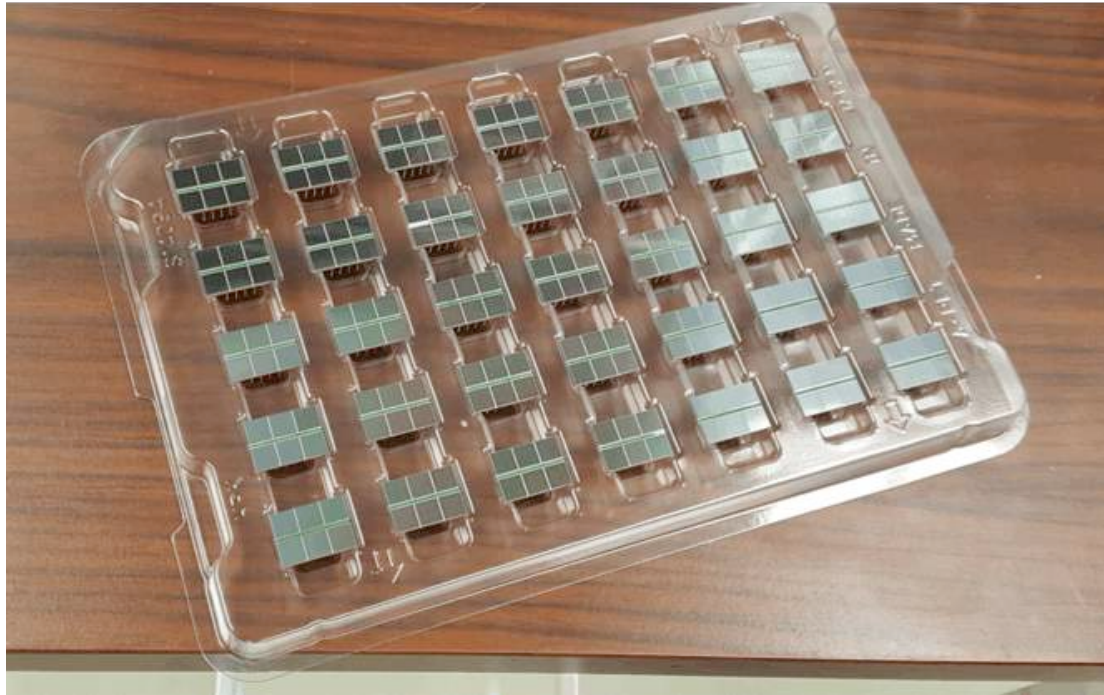
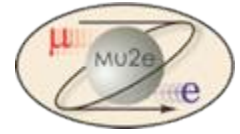
Variations in accidental hit rate

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

- The full tracker leak rate limit is $6 \text{ cm}^3/\text{min}$.
- many possible sources
- individual straw leak limit is $9.6 \times 10^{-5} \text{ cm}^3/\text{min}$
- 124 straws tested at FNAL last summer; 121 passed

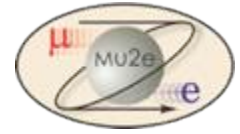


UV extended Mu2e SiPMs



- Large area array of 6x6 mm² UV extended SiPMs
- Mixed combination of series and parallel arrangement → 2x3
- Gain > 10⁶, PDE ~ 25% @ 315 nm, low spread btw cells in the array
- Resilience to neutron flux of up to 1.2 x 10¹² n_{1MeV}/cm² → I_{dark} increase
- **Need to cool them down to 0 °C**
- **MTTF of O(6x 10⁶ hours)**
- Pre-production phase underway: 3 producers being selected.

Tracking Design considerations



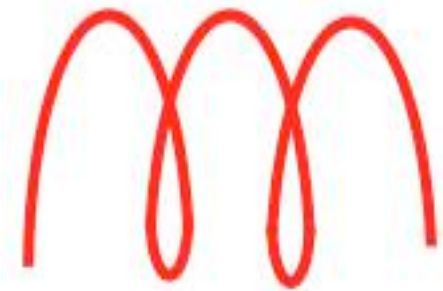
- High reconstruction efficiency for Conversion Electron (CE)
- High momentum resolution @ 100 MeV

In order to do so:

- Minimize multiple scattering (small material budget)
- High efficiency on single point
- Good single point space resolution
- Require many points/track (> 20)

- Axial B(field) = 10 kG = 1 T (uniform)
- Higher $P_T = 100$ MeV
- $\rho_{\max}$ (m) = $P_T / (0.3 \text{ B}) = 0.1 \text{ (GeV)} / 0.3 \times 1 \text{ (T)}$
→ 0.33 m = 33 cm

$$\frac{\sigma_{p_{\perp}}}{p_{\perp}} = \sqrt{\frac{720}{n+4}} \frac{\sigma_y p_{\perp}}{(0.3BL^2)} \text{ (m, GeV/c, T)}$$

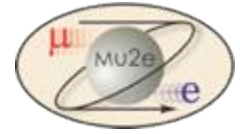


Larger p_T



Lower p_T

“back on the envelope” resolution



$$\frac{\sigma_{p_{\perp}}}{p_{\perp}} = \sqrt{\frac{720}{n+4}} \frac{\sigma_y p_{\perp}}{(0.3BL^2)} \text{ (m, GeV/c, T)}$$

(P_T example = 100 MeV = 0.1 GeV)

1) SPATIAL RESOLUTION CONTRIBUTION

- **N(hits) per track = 40, B(Field) = 1 T, L = 0.3 x 2π = 2 m, Sy = 200 μm**
- $\text{SQRT}(720/44) \times \sigma \text{ (point)} \times 0.1 / (0.3 \times 1 \times 4)$
 - $4 \times \sigma \text{ (point)} \times 0.1 \times 0.8 = 0.3 \times S_y \text{ (m)} \sim 60 \times 10^{-6} = 0.6 \times 10^{-4} = 0.06 \text{ permil}$
 - @ 100 MeV → $0.06 \times 100 \text{ keV} = 6 \text{ keV}$

2) MULTIPLE SCATTERING CONTRIBUTION

- $S_y \text{ (m.s.)} = L \sin\theta \times \text{Theta_rms} =$
- $\text{Theta_rms} = 13 \text{ MeV}/P(\text{MeV}) \times \text{SQRT}(L(X_0))$
 - @ 100 MeV and 1% X_0
 - $\text{Theta_rms} = 0.13 \times \text{SQRT}(10^{-2})$
 - $0.13 \times 0.1 = 0.013$
- **Sy (m.s.) = 1,3 cm**
50 times larger than space resolution
- **$\sigma(p)/p = 0.06 \times 50 \text{ permil} = 0.003$**

