Simulation studies of a pion production target for the Mu2e-II experiment

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for the Mu2e-II collaboration

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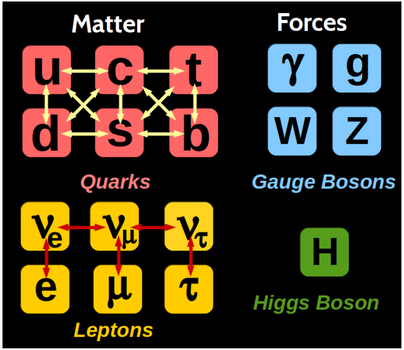
15th workshop on Shielding aspects of Accelerators, Targets, and Irradiation Facilities (SATIF-15), East Lansing, September 20-23, 2022

Motivation

The Standard Model of particle physics currently contains:

- Quark mixing
- Transitions between charged and neutral leptons of same flavor
- Neutrino oscillations

No charged lepton flavor violation (CLFV) observed so far!



Mu2e will search for the neutrinoless conversion of a muon into an electron in the coulomb field of a nucleus ($\mu N \rightarrow eN$) with a projected

upper limit of 6×10^{-17} (90% CL)

Current limit by SINDRUM-II (PSI): $BR(\mu Au \rightarrow eAu) < 7 \times 10^{-13}$(90% CL) [EPJ C47, 337 (2006)]

SM prediction via neutrino mixing is $\sim 10^{-54}$, but extensions of SM predict values up to $\sim 10^{-14}$ (Leptoquarks, heavy neutrinos, SUSY,...)

⇒ Unique possibility to test for New Physics

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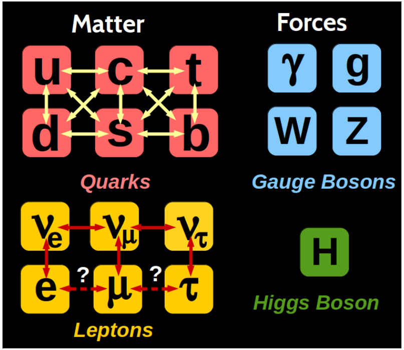

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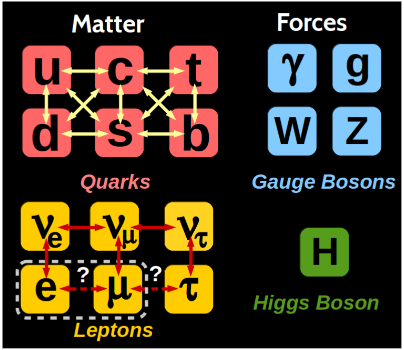

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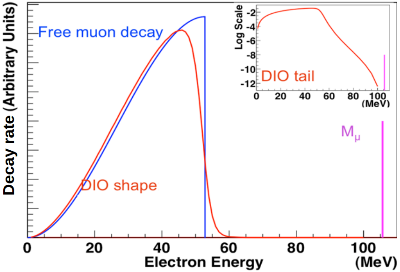
The Mu2e experiment

The **Mu2e** experiment will search for CLFV in the process ($\mu^- + \text{Al} \rightarrow e^- + \text{Al}$)

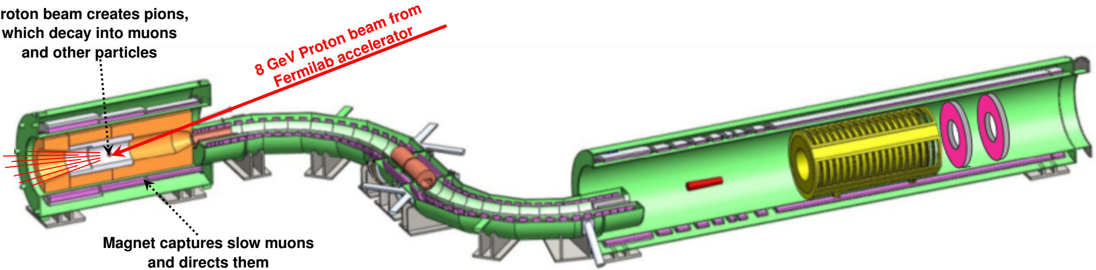
Stopped muons have a lifetime of 864 ns in the 1s-orbital of the Al nucleus

- about 60% of stopped muons undergo the muon capture reaction (e.g. $\mu^- + {}^{27}\text{Al} \rightarrow \nu_\mu + {}^{27}\text{Mg}$)
- $\sim$ 40% of stopped muons decay in orbit (DIO)
  - Michel spectrum of decay electrons dies around $M_\mu/2$
- CLFV signal for $\mu \rightarrow e$ conversion gives single mono-energetic electron
  - $E_e = 104.973\ \text{MeV} \simeq M_\mu$



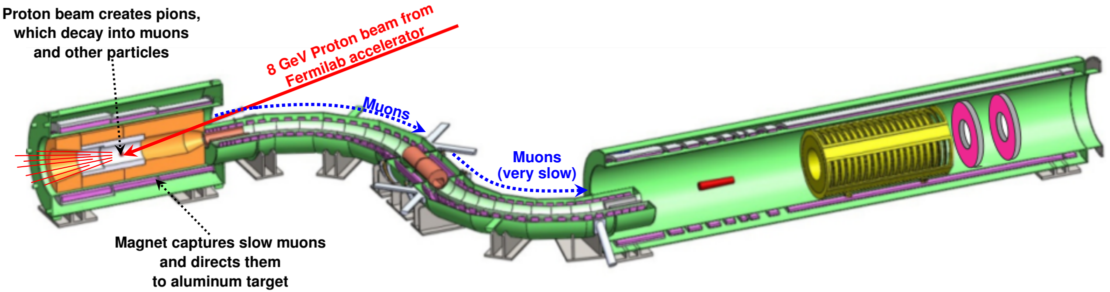
$$\text{Normalized ratio } R_{\mu e} = \frac{N(\mu^- + \text{Al} \rightarrow e^- + \text{Al})}{N(\mu^- + \text{Al} \rightarrow \text{nuclear capture})}$$

The Mu2e experiment



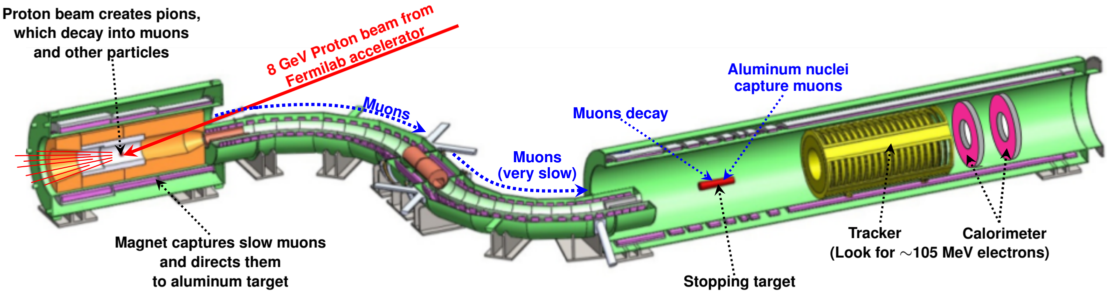
- Muons are obtained from 8 GeV proton beam on tungsten target
  - time-averaged beam power: 7.3 kW
  - 4×10^7 protons/pulse, pulse separation: 1695 ns
  - Magnetic field in Production Solenoid guides produced pions towards Transport Solenoid
  - Pions decay into muons

The Mu2e experiment



- Muons are transported in s-shaped Transport Solenoid
  - Absorber foils remove antiprotons
  - Solenoidal magnetic fields separate oppositely charged particles
  - Collimators select low-momentum negatively-charged muons.

The Mu2e experiment



- Muons are stopped on aluminum target foils in Detector Solenoid
  - stopped muons decay in orbit or are captured by the Al nucleus
  - decay electrons are detected by a tracking detector and a calorimeter

Mu2e-II vs. Mu2e

While the Mu2e experiment is currently under construction at FNAL (with physics data taking starting in 2026), a possible upgrade is discussed with the aim to improve the sensitvity to $\mu \rightarrow e$ conversion by at least one order of magnitude.

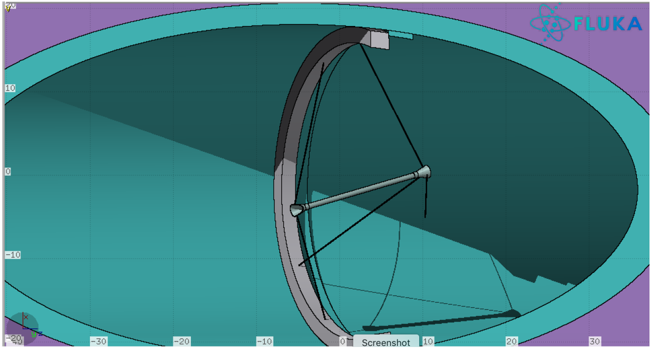
- more powerful proton source under construction at FNAL (PIP-II)
  - 800 MeV proton beam instead of 8 GeV proton beams
  - 100 kW beam power (respect to 7.3 kW at Mu2e)
  - 7.8×10^{14} protons/s (respect to 6.25×10^{12} protons/s at Mu2e)
  - $\sim$ 100 ns proton bunch width (respect to 250 ns at Mu2e)
- improved detector concepts
- Mu2e-II Snowmass White Paper: `https://arxiv.org/abs/2203.07569`

Higher beam intensity requires extensive simulation studies for radiation and particle yields in the pion production target region

- Ideally one would like to re-use as much as possible the existing shielding infrastructure

The Mu2e target design

The initial design for Mu2e's pion production target was a cylindrical tungsten rod with a length of 16 cm and a radius of 0.315 cm, held in place by a sophisticated holder structure (incoming beam is at 14^o angle to solenoid axis):



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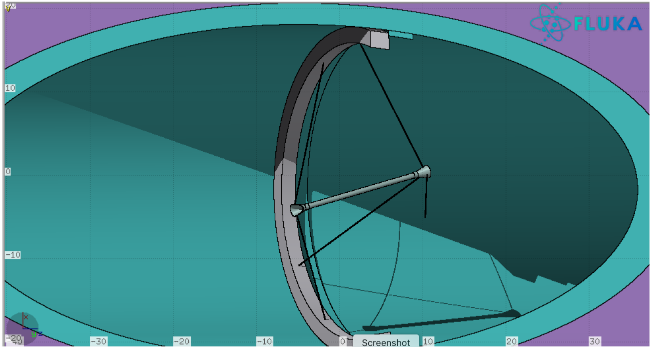
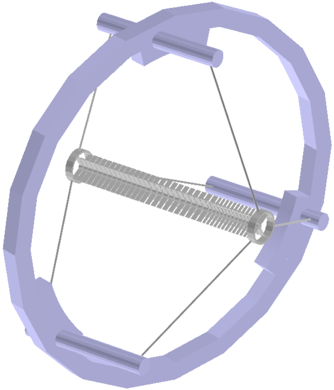


However, since about 10% of the 7.3 kW proton beam power are deposited into the target, a more sophisticated design was needed to allow for sufficient radiative cooling of the target, so that it survives a full year of Mu2e running.

The Mu2e target design

After several iterations, the final design was chosen, which preserves the number of muons per POT while increasing the capability to radiate away the energy.



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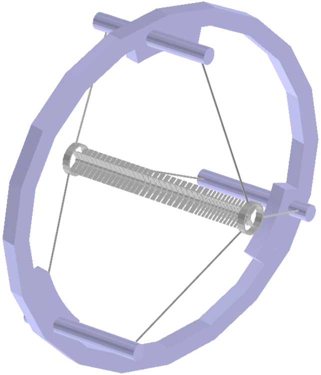

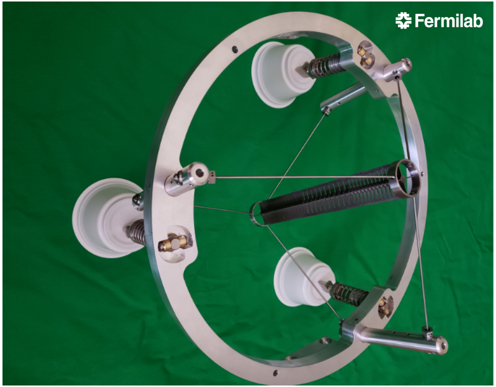

This target has now been constructed and assembled at FNAL.

The Mu2e-II target designs

Due to the higher proton beam intensity, Mu2e-II needs a pion production target which involves active cooling. The current target designs are based on a conveyor idea in which carbon or tungsten balls are circulated to and from the proton beam.

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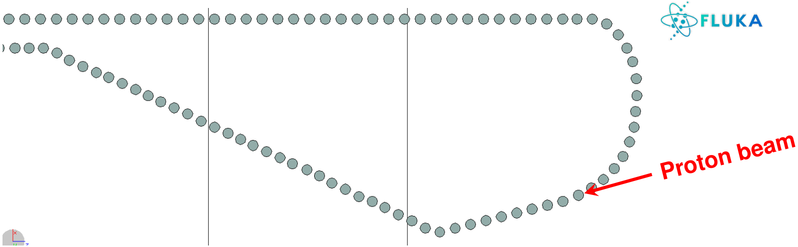
Target simulation with 285 tungsten balls:



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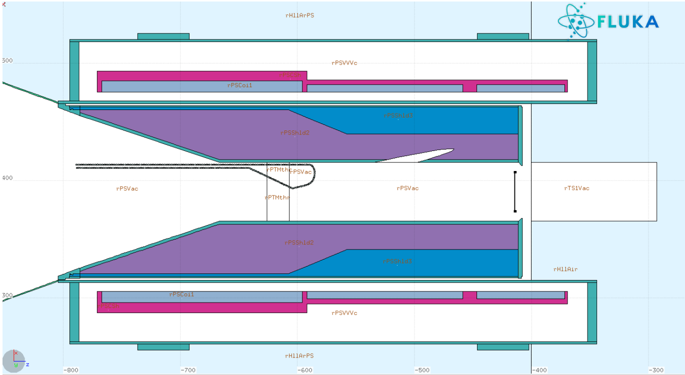

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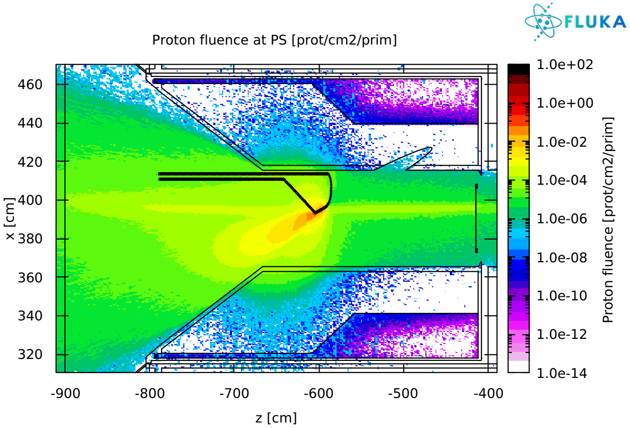

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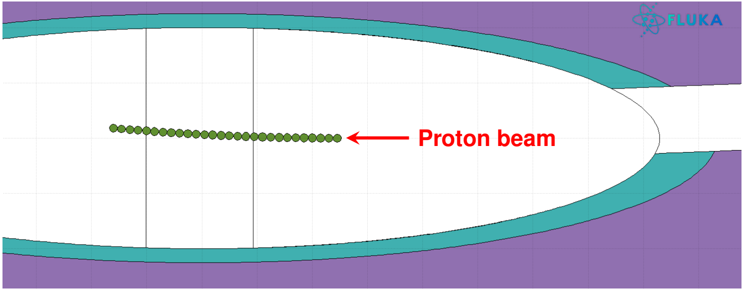
Target simulation with 28 carbon balls:



800 MeV proton beam gets deflected in Mu2e magnetic field when passing through the carbon balls.

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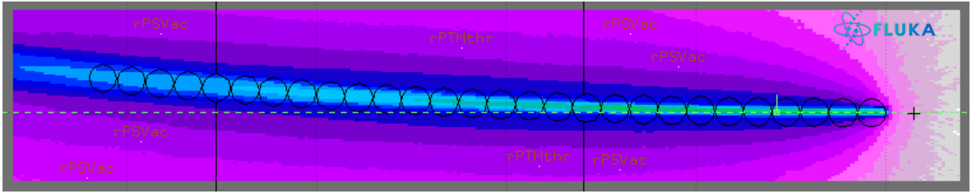

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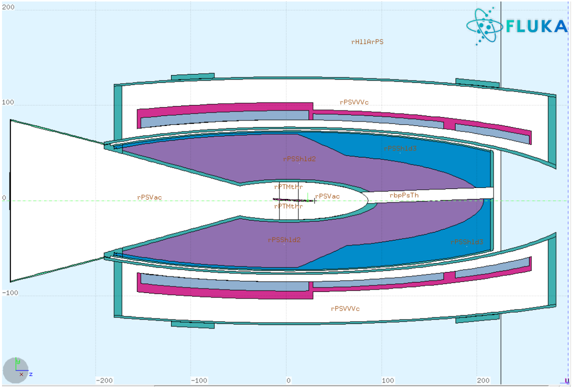


Simulation conditions

Simulations where carried out with **FLUKA2021.2.7** and **MARS15** using the following transport and production thresholds:

- 1 keV for everything **but**
- 10^{-5} eV for neutrons
- 10 keV for photons
- 100 keV for electrons
- 10^{-5} eV for electron and muon (anti-) neutrinos

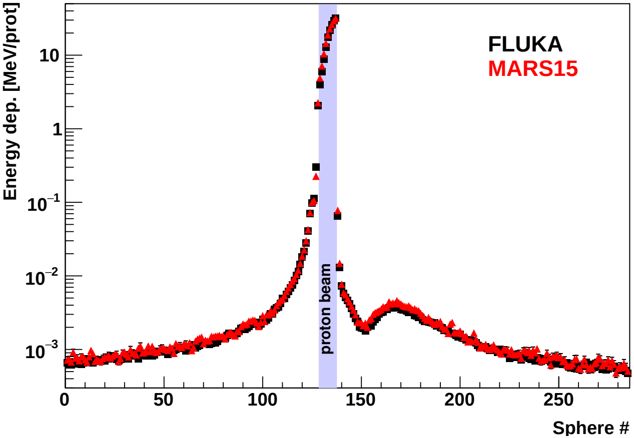
Some cross checks where also carried out using **MCNP6.2** and **PHITS 3.27** applying the same cuts.

Simulations within the Mu2e Offline framework were done using **GEANT4.10.07p02** with the `ShieldingM` physics list with a minimum range cut of 0.010 mm.

Carbon density was taken to be 1.86 g/cm^3, while for the tungsten density 19.3 g/cm^3 was used.

Energy deposition in the targets

800 MeV proton beam with a gaussian width of 1 mm on the conveyor target with tungsten balls:



Excellent agreement between the two codes!

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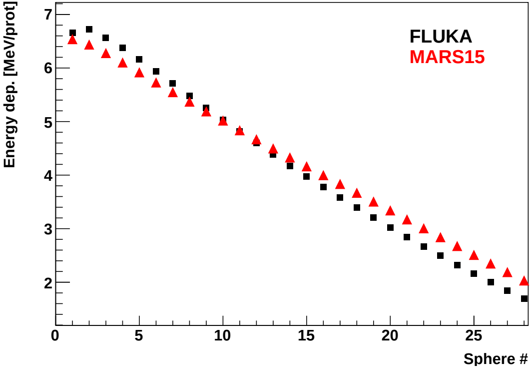

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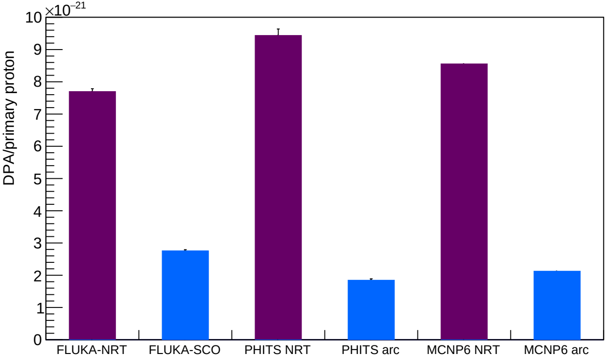
DPA studies

The comparison of DPA (“Displacements-per-Atom”) between **MARS** and **FLUKA** for the Mu2e-II target designs is not ready yet. Instead, the original Mu2e cylindrical tungsten target was used to compare the results for DPA using **FLUKA**, **PHITS** and **MCNP6** with an 800 MeV proton beam:



FLUKA: Progr. in Nucl. Science and Techn. 2, 769 (2011)

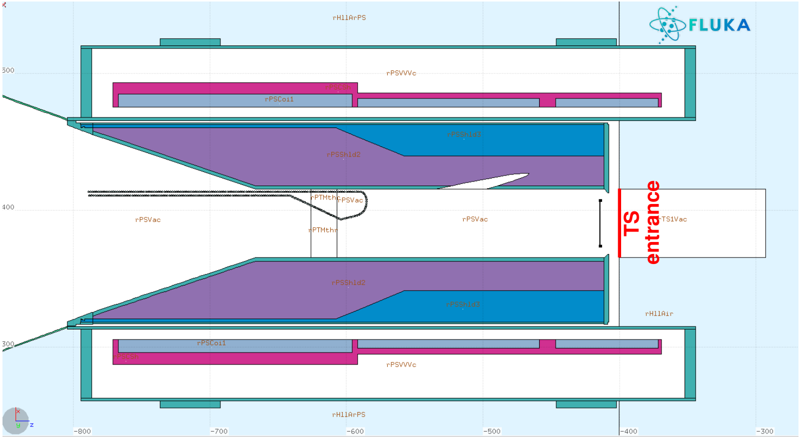
PHITS: J. of Nucl. Mat. 512, 450 (2018)

MCNP6: Nucl. Eng. and Techn. 51, 170 (2019)

The model by Norgert, Robinson and Torrens (NRT) overestimates the number of DPA because the athermal recombination (arc) is neglected. The default damage threshold energies E_D for tungsten for the different codes were used.

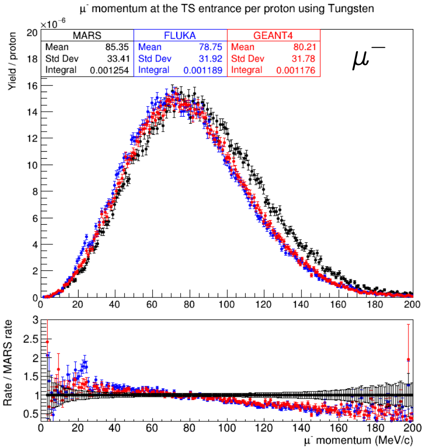
Particle yields entering Transport Solenoid

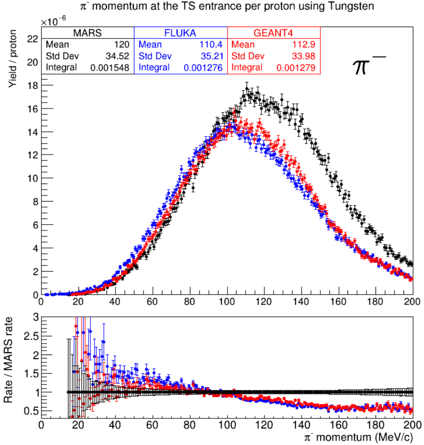
Particle yields for μ^- and π^- entering the Transport Solenoid were estimated with MARS15, FLUKA and GEANT4



Particle yields entering Transport Solenoid

μ^- and π^- particle yields estimated with MARS15, FLUKA and GEANT4 for the tungsten target design:





Particle yields entering Transport Solenoid

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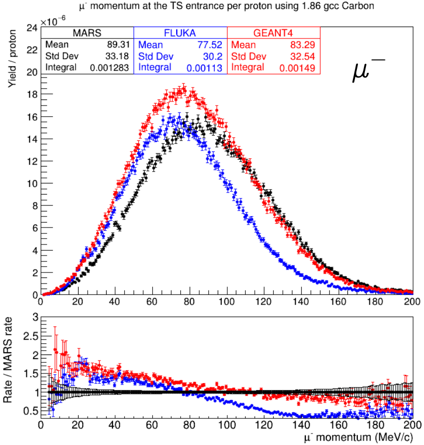
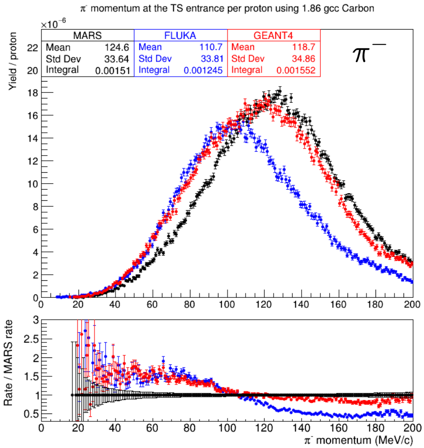
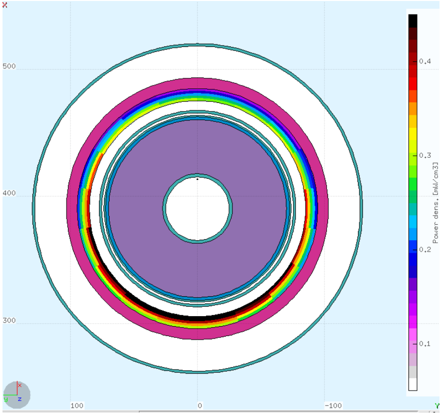
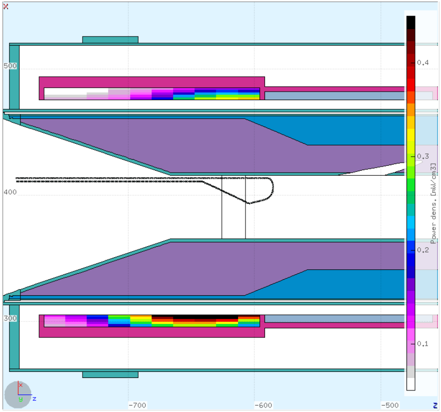




Simulations for the PS1 coil

Power density in coil 1 of the PS, using 800 MeV proton beam with 100kW beam power for the tungsten target design (FLUKA simulation):





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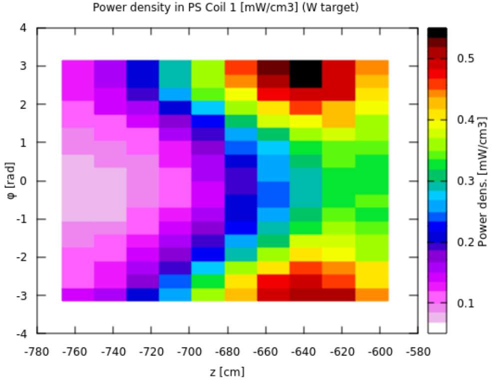


The peak power density in the PS1 coil for the tungsten target design is found to be 0.544 mW/cm3 $\pm 1.8\%$ or 0.138 mW/g $\pm 1.8\%$

Simulations for the PS1 coil

Results for deposited energy, DPA and dose for the tungsten target design:

Peak energy deposition [GeV/cm3/POT]:	$4.35 \times 10^{-9} \pm 1.8\%$
Peak power density [mW/cm3]:	$0.544 \pm 1.8\%$
Peak power density [mW/g]:	$0.138 \pm 1.8\%$
Peak DPA [DPA/POT] :	$8.67 \times 10^{-27} \pm 1.8\%$
Peak DPA [DPA/yr] :	$1 \times 10^{-4} \pm 1.8\%$
Peak Dose [GeV/g/POT]:	$1.10 \times 10^{-9} \pm 1.8\%$

Similarly, results for deposited energy, DPA and dose for the carbon target design:

Peak energy deposition [GeV/cm3/POT]:	$3.74 \times 10^{-9} \pm 2.4\%$
Peak power density [mW/cm3]:	$0.468 \pm 2.4\%$
Peak power density [mW/g]:	$0.118 \pm 2.4\%$
Peak DPA [DPA/POT] :	$7.68 \times 10^{-27} \pm 2.4\%$
Peak DPA [DPA/yr] :	$0.9 \times 10^{-4} \pm 2.4\%$
Peak Dose [GeV/g/POT]:	$0.95. \times 10^{-9} \pm 2.4\%$

Conclusions

- The pion production target designs for the Mu2e-II experiment have been simulated using **FLUKA2021**, **MARS15** and **GEANT4** radiation transport codes
  - good agreement between **MARS15** and **FLUKA2021** for energy deposition in both the tungsten- and carbon-based designs with 800 MeV proton beams
  - Comparison of DPA between **MARS** and **FLUKA** for the Mu2e-II target designs not yet ready, additional cross checks between **FLUKA**, **MCNP6** and **PHITS** using the Mu2e target design show reasonable agreement both for the NRT model and the models taking into account athermal recombination
- μ^- and π^- yields from the targets entering the Transportation solenoid were studied with **MARS**, **FLUKA** and **GEANT4**
  - Fair agreement between different codes, some local discrepancies still to be understood
- Simulations of radiation damage in the superconducting solenoid coils of the Production Solenoid (PS) have been started
  - this allows to understand whether the current shielding infrastructure of the Mu2e experiment could be reused

Spare Slides

New physics

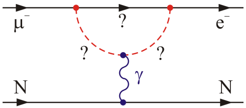
Model independent Lagrangian:

$$\mathcal{L}_{CLFV} = \underbrace{\frac{m_\mu}{(\kappa+1)\,\Lambda^2}\,\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu}}_{\text{“Dipole term”}} + \underbrace{\frac{\kappa}{(\kappa+1)\,\Lambda^2}\,\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)}_{\text{“Contact term”}}$$

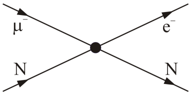
Λ: effective mass scale of New Physics

κ: relative contribution of contact term

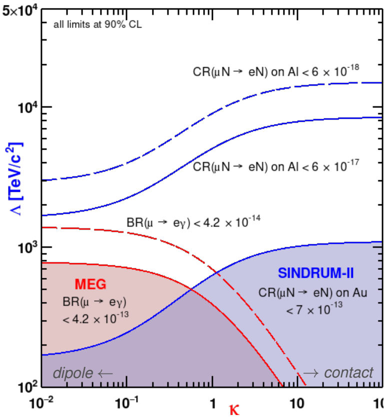
Dipole term: dominates for $\kappa \ll 1$



Contact term: dominates for $\kappa \gg 1$



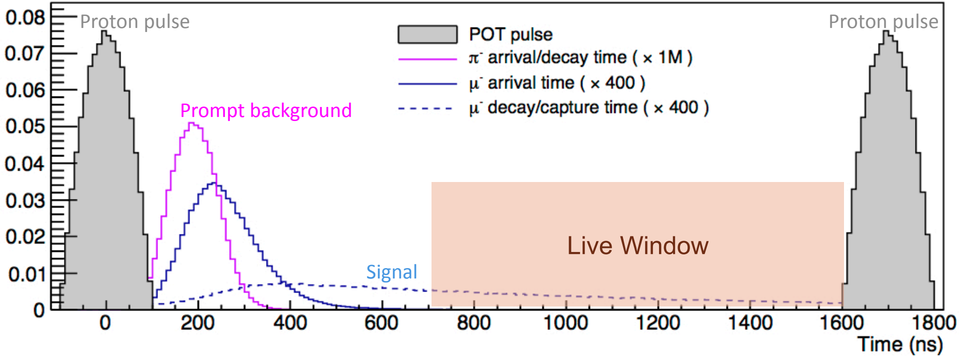
Mu2e will probe $\Lambda \sim O(10^3\text{ -}10^4)$ TeV/c^2



Derived from arXiv:1303.4097

The Mu2e experiment

Pulsed proton beam allows definition of a “Live Window” for the signal to suppress prompt background (1695 ns peak-to-peak):



- Fermilab accelerator complex provides optimal pulse spacing for Mu2e
- 700 ns delay allows to suppress prompt background from pions by $\sim 10^{-11}$
- Must achieve extinction (N_{p^+} out of bunch)/(N_{p^+} in bunch) $\leq 10^{-10}$