ALPS 2023 – ALpine Particle physics Symposium

The search for Charged Lepton Flavour Violation with the Mu2e experiment

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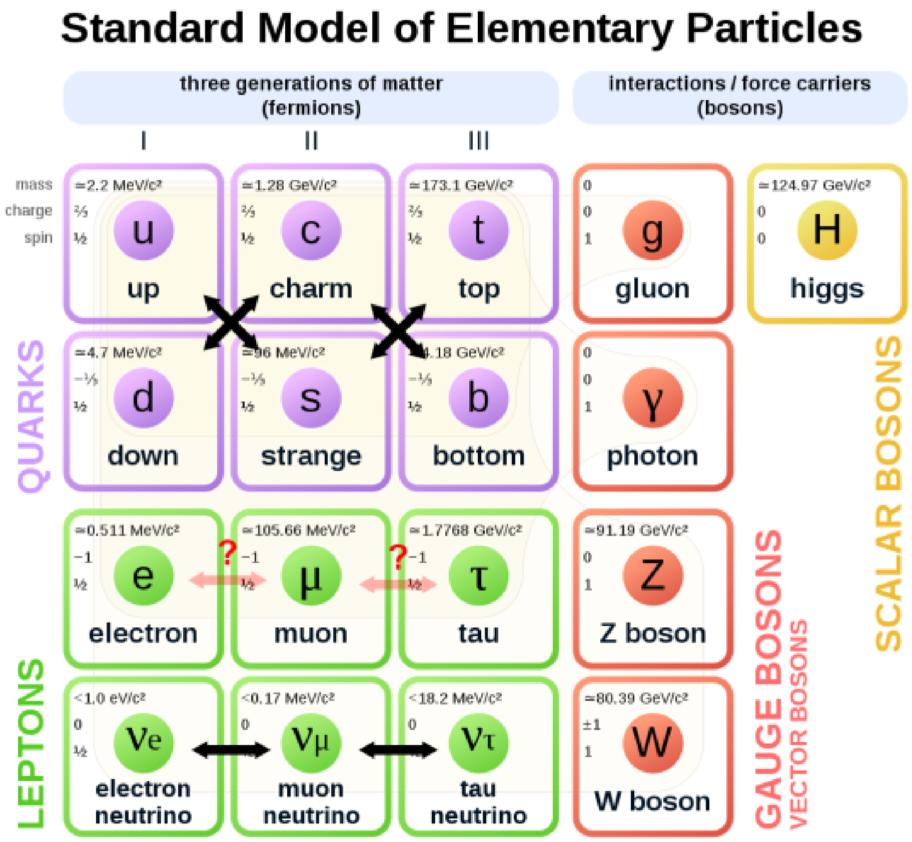
for the Mu2e Collaboration

Motivation of the experiment



The current Standard Model of particle physics contains:

- Quark Mixing
- Neutrino oscillations
- Transitions between charged and neutral leptons with same flavor

No flavor violation of charged leptons has been observed so far!

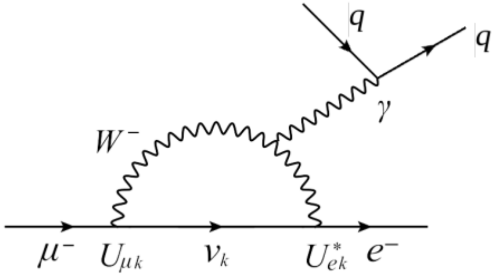
Charged Lepton Flavor Violation (CLFV)

The Standard Model with neutrino masses (νSM) says its unobservably rare...

...but many Beyond Standard Model (BSM) theories predict enhanced rates of CLFV

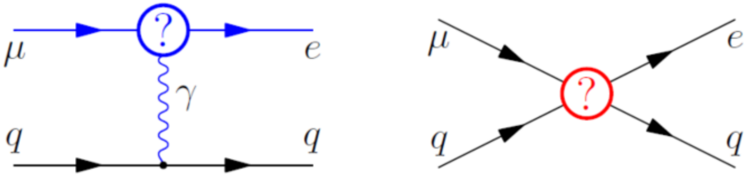
νSM Prediction

$$R_{\mu\to e} \propto \left(\frac{\Delta m_\nu^2}{M_W^2}\right)^2 < 10^{-52}$$



BSM Predictions

$$R_{\mu\to e} \sim 10^{-17} - 10^{-15}$$



Mu2e will search for neutrino-less Muon-to-Electron conversion in the Coulomb field of a nucleus: (μ^- + Al → e^- + Al) with a projected

upper limit of 8 x 10^{-17} (90% CL)

Current limit by SINDRUM-II at PSI (on Au): < 7 x 10^{-13} (90% CL)

Aim of the experiment is to reach a single event sensitivity of **3 x 10^{-17}** on the conversion rate

➡ **Unique possibility to test for New Physics**

The Mu2e experiment

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

Muons stopped in Al have a lifetime of 864 ns in the orbital 1s of the Al nucleus

- ~ 60% of stopped muons undergo muon capture reaction (i.e. $\mu^- + {}^{27}\mathrm{Al} \rightarrow \nu + {}^{27}\mathrm{Mg}$)
- ~ 40% of muons bound in the muonic Al decay decay in orbit (DIO) to an electron and two neutrinos:

$$(\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e)$$

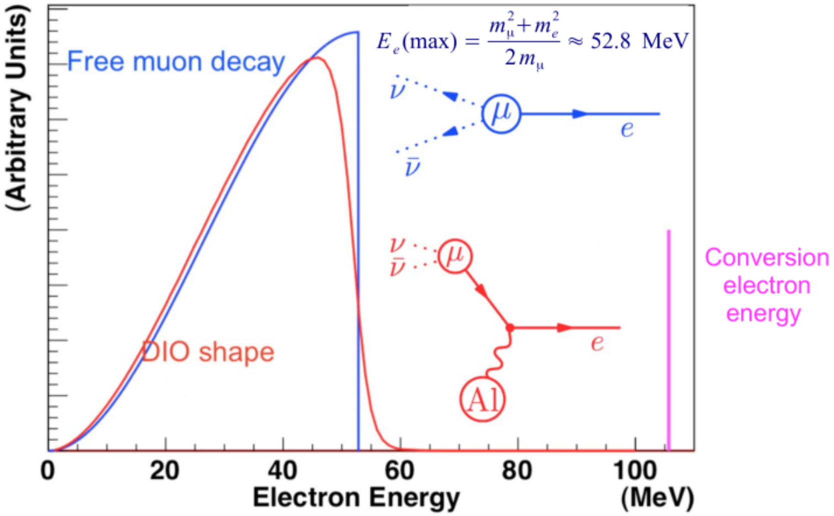
Nuclear recoil modifies energy spectrum:

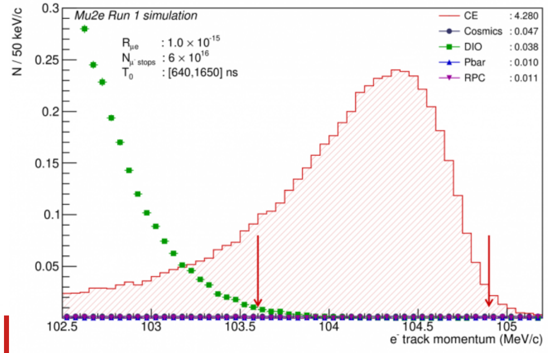
- peak still at ~ 50 MeV, but
- tail extends up to the conversion energy

- Signal of CLFV conversion process gives a single monochromatic electron with

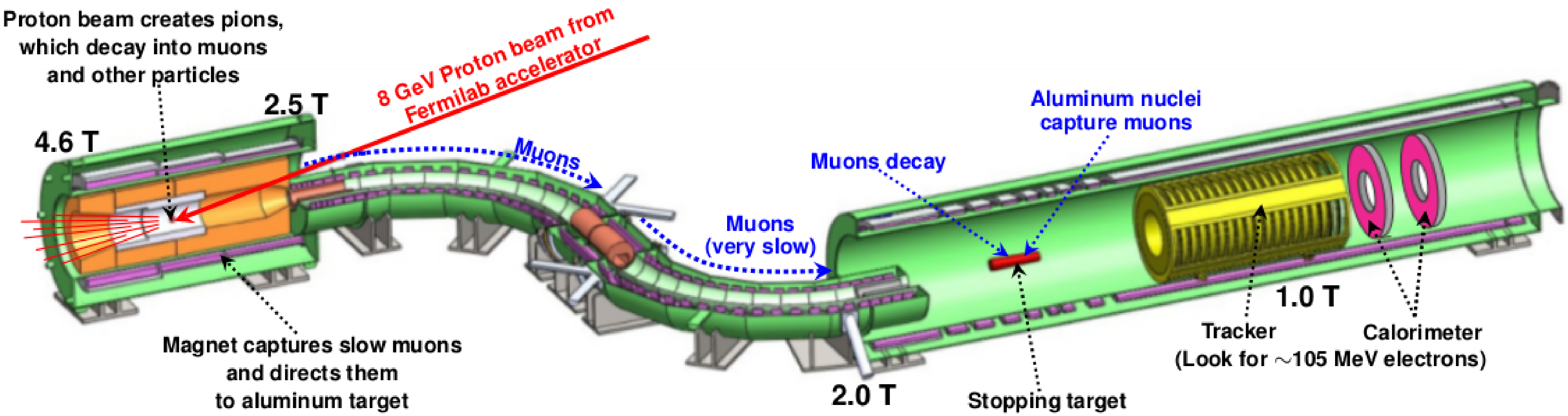
$$E_e = 104.973\ \mathrm{MeV} \simeq M_\mu$$

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





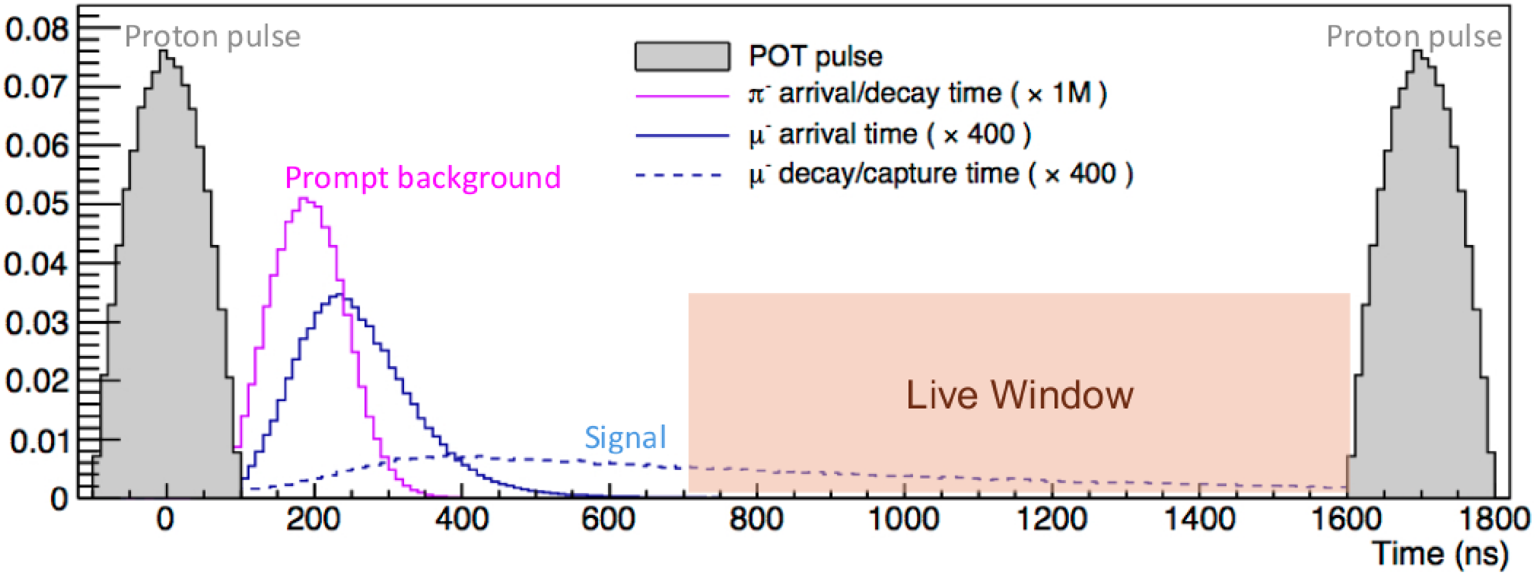
The Mu2e experiment



- 8 GeV proton beam hits tungsten target and produces pions
- Pions are transported in s-shaped Transport Solenoid where they decay into muons
- Muons are stopped on aluminum target foils in Detector Solenoid
- Detectors (tracker and calorimeter) search for 105 MeV conversion electrons

The Mu2e experiment

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



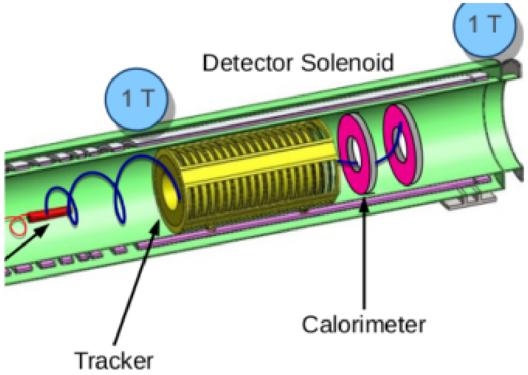
- Fermilab accelerator complex provides optimal pulse spacing for Mu2e
- 700 ns delay allows to suppress prompt background from pions by $\sim 10^{-11}$
- Must achieve extinction (N_{p^+} out of bunch)/(N_{p^+} in bunch) $\leq 10^{-10}$

The Mu2e tracker

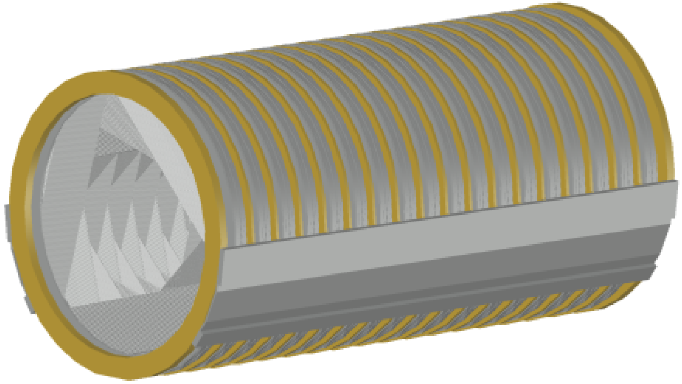
Goal: high-resolution momentum measurement

(< 180 keV/c @ 105 MeV/c)

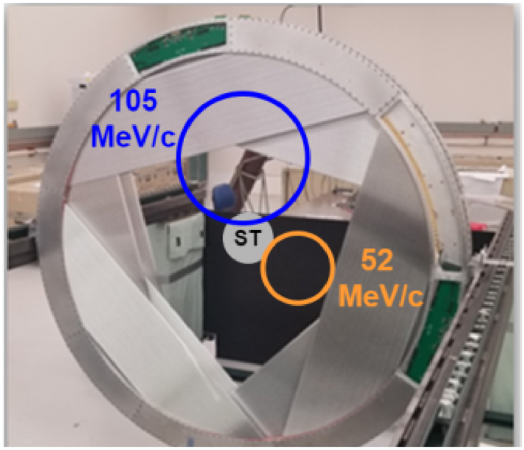
- minimize energy loss by operating in vacuum and using low mass straws
- extra hit position information with high-angle stereo overlaps and readout on both ends of straw
- reduce background hits with a central hole



5 mm diameter, 15 μm thick walls

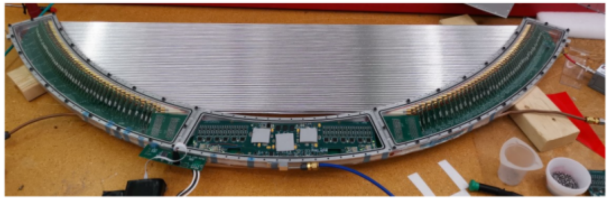


plane with central hole



- 96 straws per panel
- 6 panels per plane
- 36 planes

→ ***20736 straws***

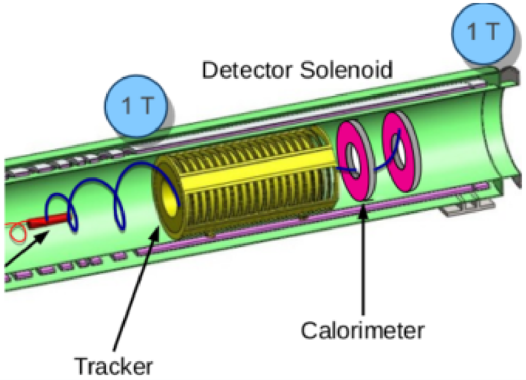


1 panel = 96 straws

The Mu2e calorimeter

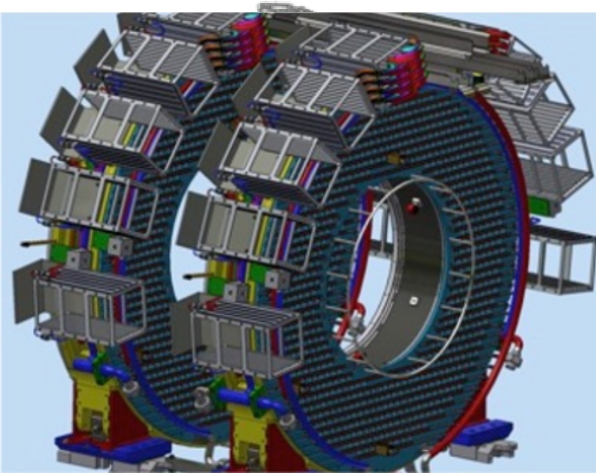
Goal: fast energy measurement

(Time resolution: < 150 ps @ 100 MeV)



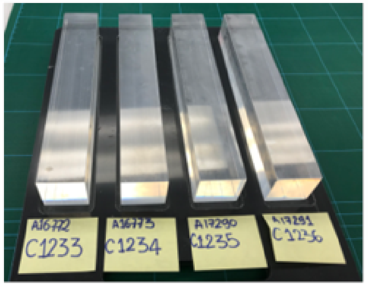
- can be used for the trigger
- combine with momentum measurement for e/μ separation
- energy clusters can also be used to seed the track fit

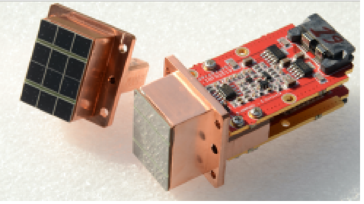
Two disks, each 674 crystals



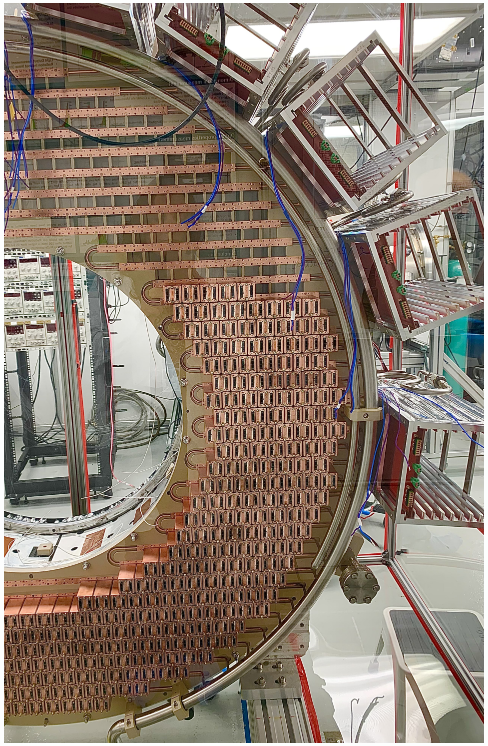
undoped CsI crystals

(20 x 3.4 x 3.4 cm^3)





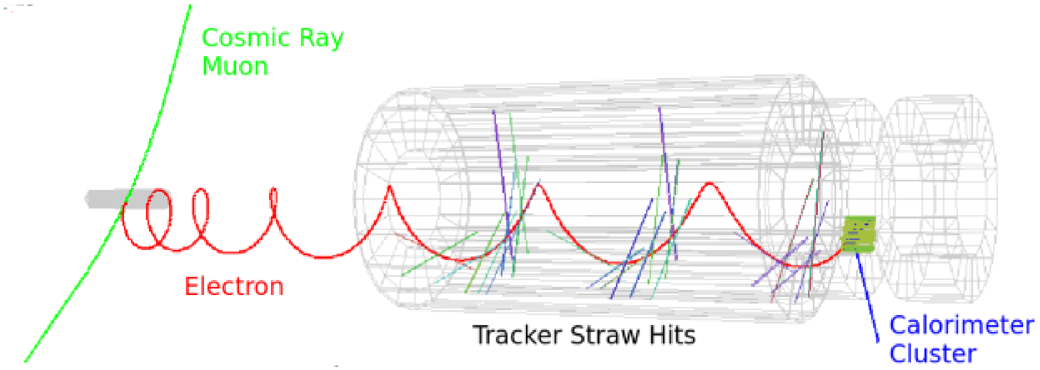
SiPM readout with FEE boards

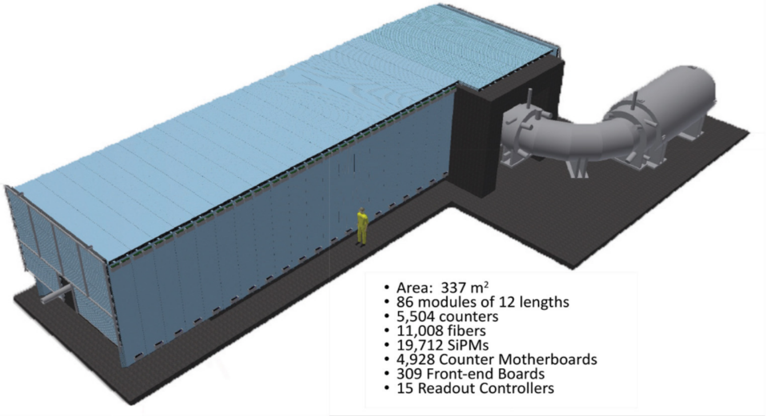


The Cosmic-Ray veto

A nearly hermetic cosmic ray veto suppresses the background due to the cosmic rays that could hit the Mu2e stopping target and knock out an electron with the conversion energy (this effect would result in **~1 background event per day**).

In addition, an electron from a cosmic muon with the conversion energy could be trapped in the field of the TS, propagate in the stopping target region and be reconstructed

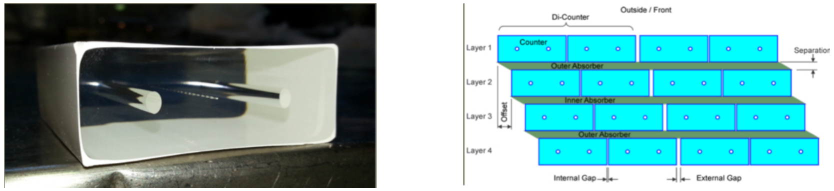




- Area: 337 m^2
- 86 modules of 12 lengths
- 5,504 counters
- 11,008 fibers
- 19,712 SiPMs
- 4,928 Counter Motherboards
- 309 Front-end Boards
- 15 Readout Controllers

The CRV must be **99.99% efficient**

It covers therefore entire Detector Solenoid and half of the Transport Solenoid



4 overlapping layers of scintillator bars, with 2 wavelength-shifting fibers/bar

Statistical sensitivity and Background studies

Goal: Single Event Sensitivity = 3 x $\mathbf{10^{-17}}$

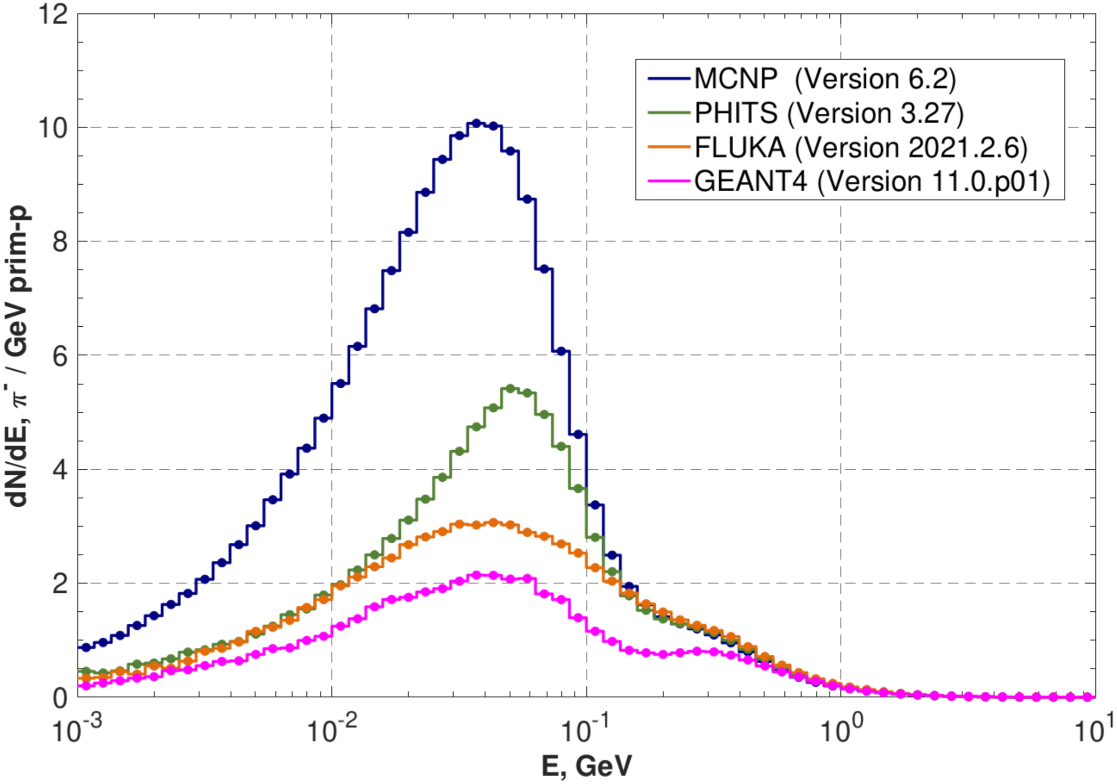
To reach this goal:

- reliable estimate of the relevant particle yields
- rigorous control of all backgrounds
  (both beam-related and cosmic-ray related)

→ **Need of very reliable Monte Carlo predictions**

Extensive code-code comparisons
between GEANT4, FLUKA 2021, MCNP6.1, MARS15 and PHITS

Yield of charged pions on Tungsten


All π- exiting the production target

Tungsten core elements

Radius: 3.15 mm

Length:

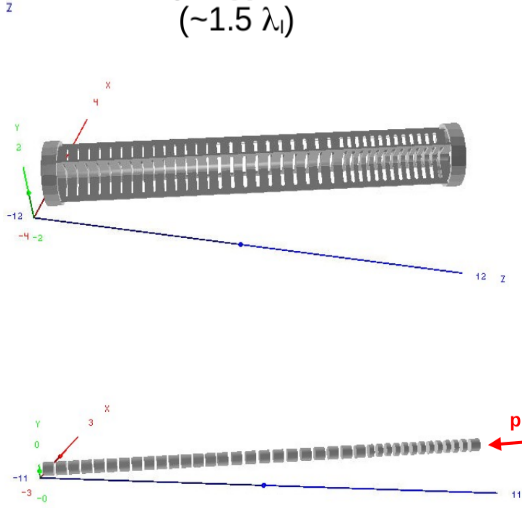
14 x 5 mm (0.5 mm gap)

12 x 5 mm (1 mm gap)

12 x 2.5 mm (1 mm gap)

Total Length (t): 16 cm

(~1.5 λ_I)



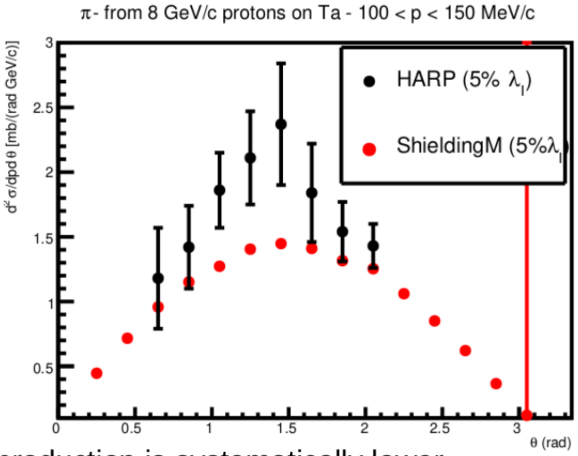
The number of π- produced in the PT and their angular and momentum distribution affects the expected rate of muons on target:

$$N^{\mu^-}_{POT} = 1.59\ 10^{-3}$$

The code-code comparison has been made describing the target as a full cylinder (no gaps, no fins, no magnetic field)

Pion producion on Ta

Geant4 vs HARP: π- from 8 GeV/c p on Ta (100<p<150 MeV/c

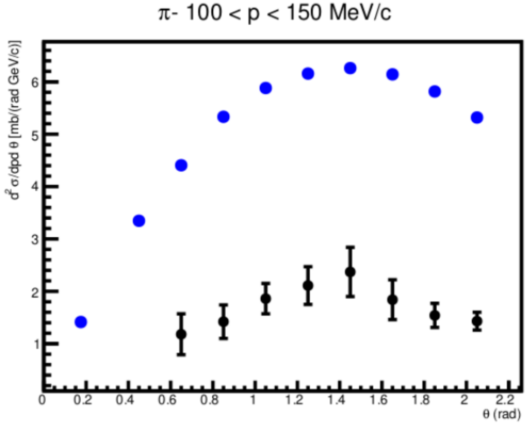


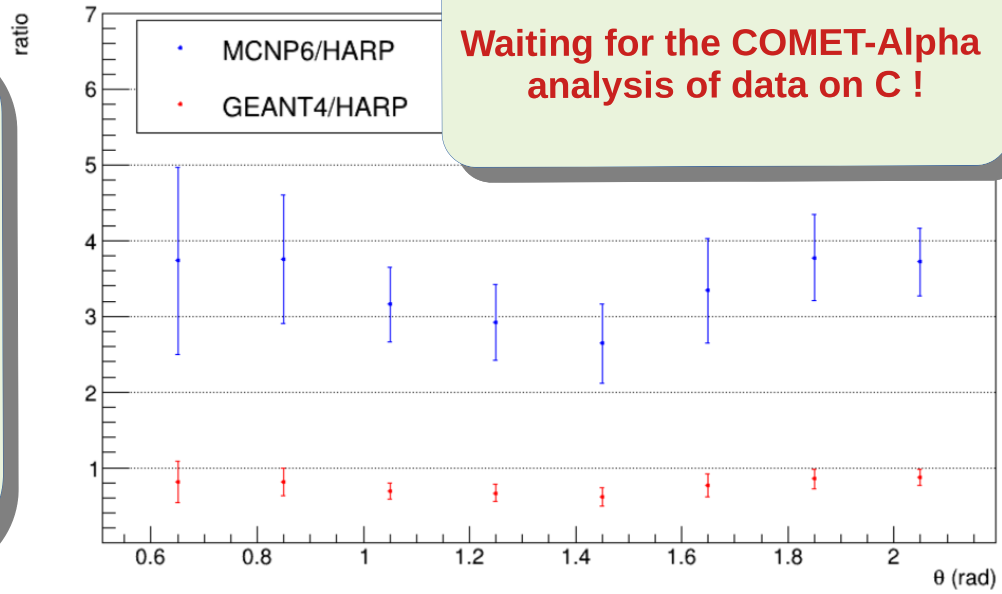
Geant4 π- production is systematically lower
Better agreement for backward production

Using the same Ta target used by HARP, at 100 MeV and large production angles **Geant4 (ShieldingM physics list) is in a much better agreement to experimental data.**

No proton data are available:
- for p <100 MeV/c
- for the most backward region cos θ < -0.5 where most of pions producing stopped muons in Mu2e are

MCNP vs HARP: π- from 8 GeV/c p on Ta (100<p<150 MeV/c)





Waiting for the COMET-Alpha analysis of data on C !

Background studies I: antiprotons

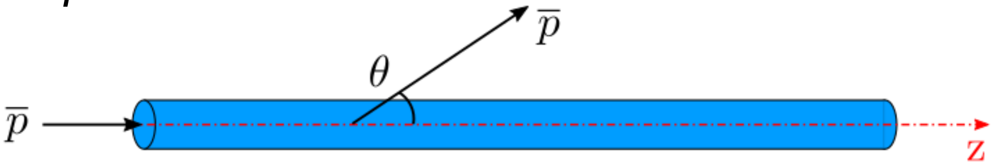
Problem:

Proton interactions in the Tungsten Production Target produce antiprotons that could reach the aluminum Stopping Target, annihilate and produce background electrons

In addition, pions created in TS by antiproton interactions can produce background electrons via Radiative Pion Capture (a part of this background can be rejected by a cut on the signal time window)

To control this background, it is crucial to correctly evaluate of the number of antiprotons <u>initially forward produced, and then backscattered towards the TS</u>

Simple MC model



- GEANT4 data are produced with the *ShieldingM* physics list

- MCNP simulation uses the LAQGSM03.03 model (as MARS15)

- FLUKA uses the default model For hadronic interactions

Based on the results of this study, a correction on the GEANT4 predicted fraction of antiprotons entering the TS has been evaluated

Comparison in [0° - 45°]

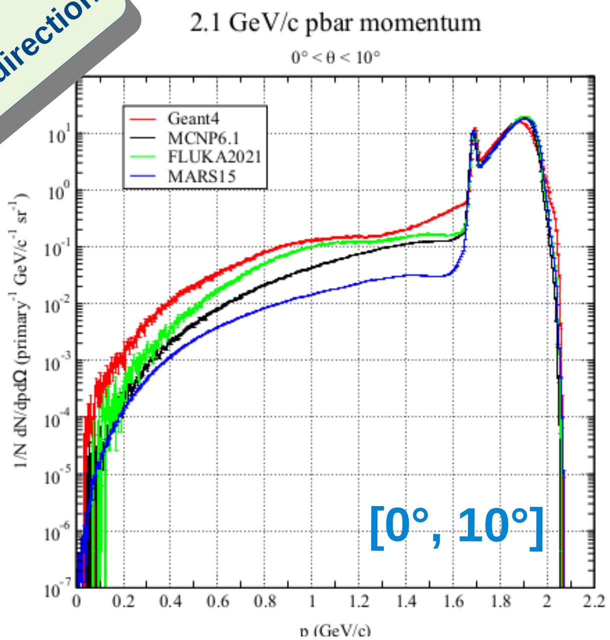
$\overline{p}$ beam momentum of 1.9 GeV/c

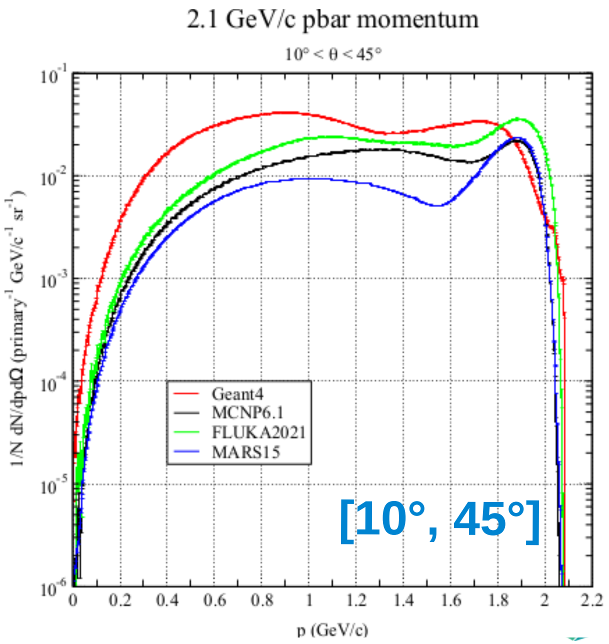
θ	Geant4	MCNP6	Δ	FLUKA	Δ	MARS15	Δ
$0° - 10°$	3.11	3.23	3.7%	3.38	8.5%	3.19	2.4%
$10° - 45°$	$5.38 \cdot 10^{-2}$	$2.28 \cdot 10^{-2}$	-57.5%	$2.52 \cdot 10^{-2}$	-53.2%	$1.47 \cdot 10^{-2}$	-72.6%

$\overline{p}$ beam momentum of 2.1 GeV/c

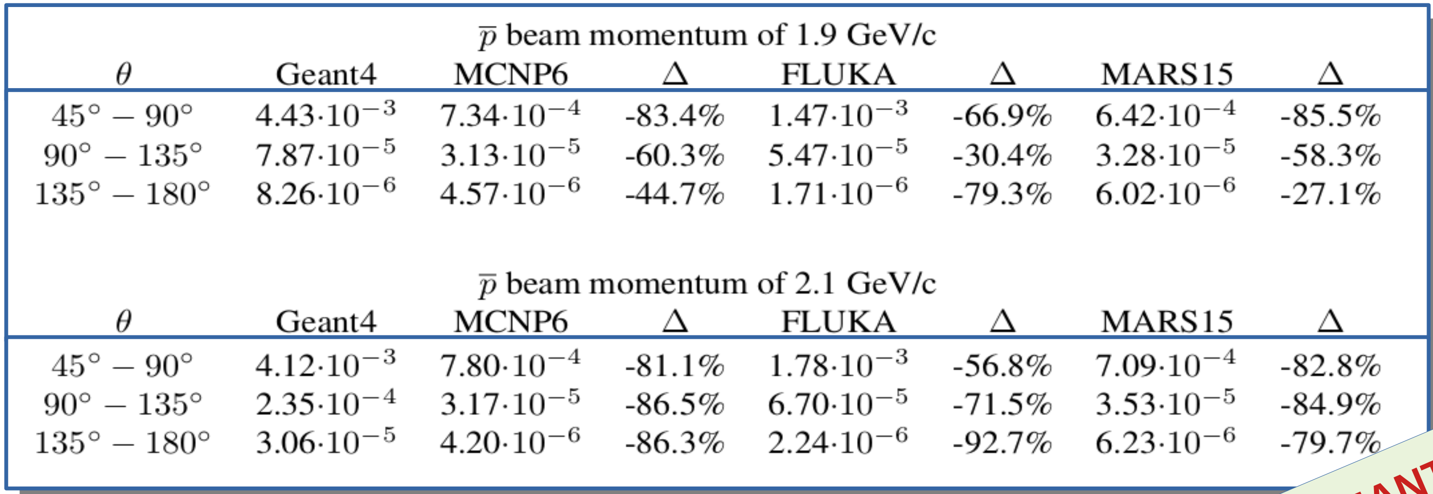
θ	Geant4	MCNP6	Δ	FLUKA	Δ	MARS15	Δ
$0° - 10°$	3.01	3.04	1.0%	3.22	7.1%	3.01	0.1%
$10° - 45°$	$5.03 \cdot 10^{-2}$	$2.27 \cdot 10^{-2}$	-55.0%	$3.30 \cdot 10^{-2}$	-34.4%	$1.46 \cdot 10^{-2}$	-70.9%

Good agreement in the very forward direction





Comparison at large angles



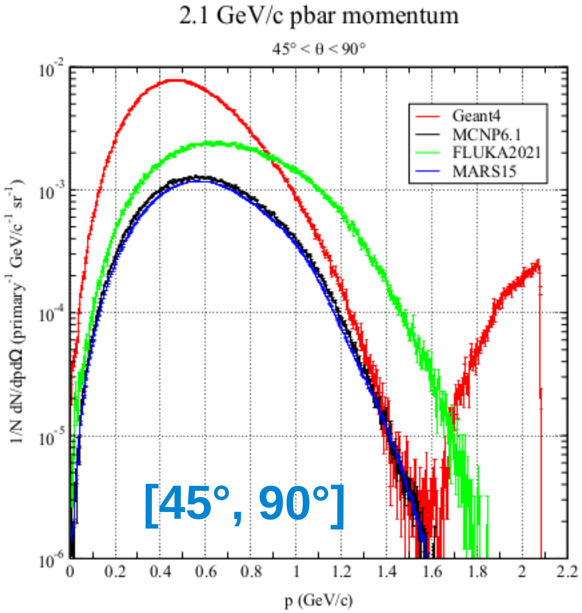
$\overline{p}$ beam momentum of 1.9 GeV/c

θ	Geant4	MCNP6	Δ	FLUKA	Δ	MARS15	Δ
45° – 90°	$4.43{\cdot}10^{-3}$	$7.34{\cdot}10^{-4}$	-83.4%	$1.47{\cdot}10^{-3}$	-66.9%	$6.42{\cdot}10^{-4}$	-85.5%
90° – 135°	$7.87{\cdot}10^{-5}$	$3.13{\cdot}10^{-5}$	-60.3%	$5.47{\cdot}10^{-5}$	-30.4%	$3.28{\cdot}10^{-5}$	-58.3%
135° – 180°	$8.26{\cdot}10^{-6}$	$4.57{\cdot}10^{-6}$	-44.7%	$1.71{\cdot}10^{-6}$	-79.3%	$6.02{\cdot}10^{-6}$	-27.1%

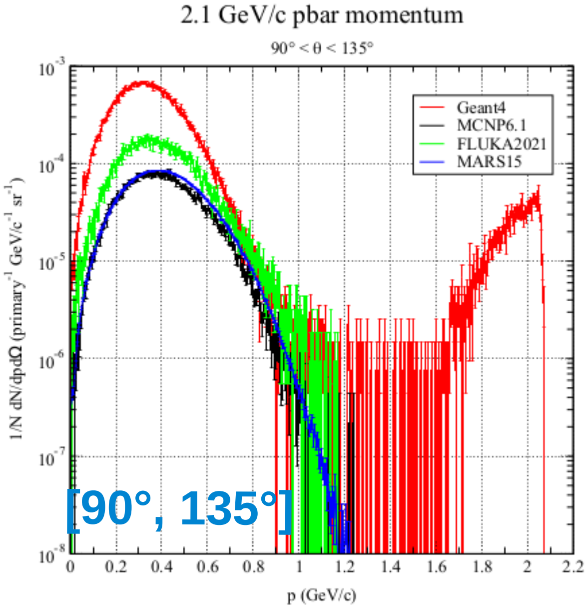
$\overline{p}$ beam momentum of 2.1 GeV/c

θ	Geant4	MCNP6	Δ	FLUKA	Δ	MARS15	Δ
45° – 90°	$4.12{\cdot}10^{-3}$	$7.80{\cdot}10^{-4}$	-81.1%	$1.78{\cdot}10^{-3}$	-56.8%	$7.09{\cdot}10^{-4}$	-82.8%
90° – 135°	$2.35{\cdot}10^{-4}$	$3.17{\cdot}10^{-5}$	-86.5%	$6.70{\cdot}10^{-5}$	-71.5%	$3.53{\cdot}10^{-5}$	-84.9%
135° – 180°	$3.06{\cdot}10^{-5}$	$4.20{\cdot}10^{-6}$	-86.3%	$2.24{\cdot}10^{-6}$	-92.7%	$6.23{\cdot}10^{-6}$	-79.7%

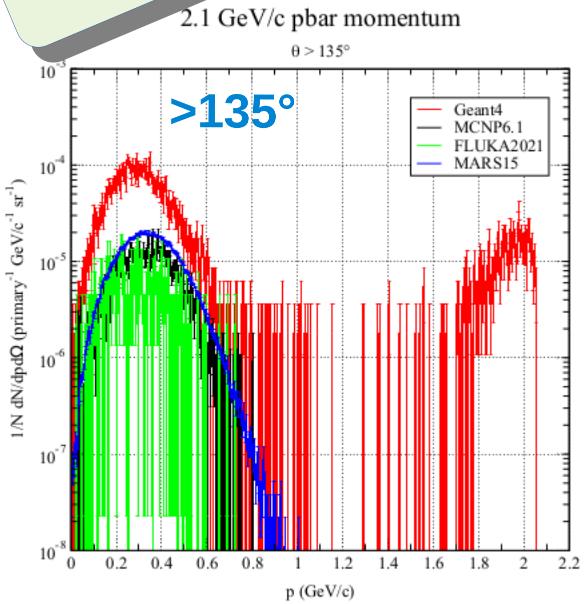
GEANT4 overestimate the $\overline{p}$ yield at large angles



2.1 GeV/c pbar momentum



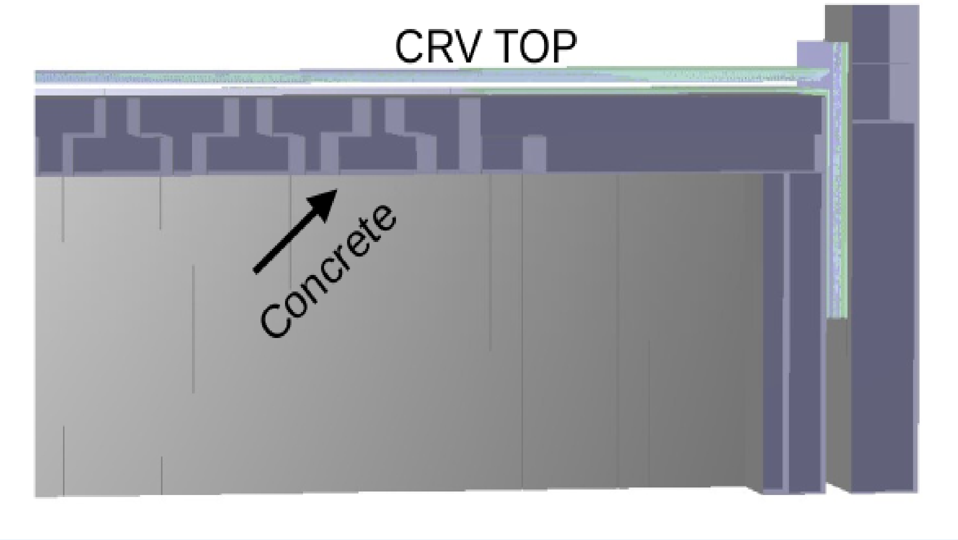
2.1 GeV/c pbar momentum



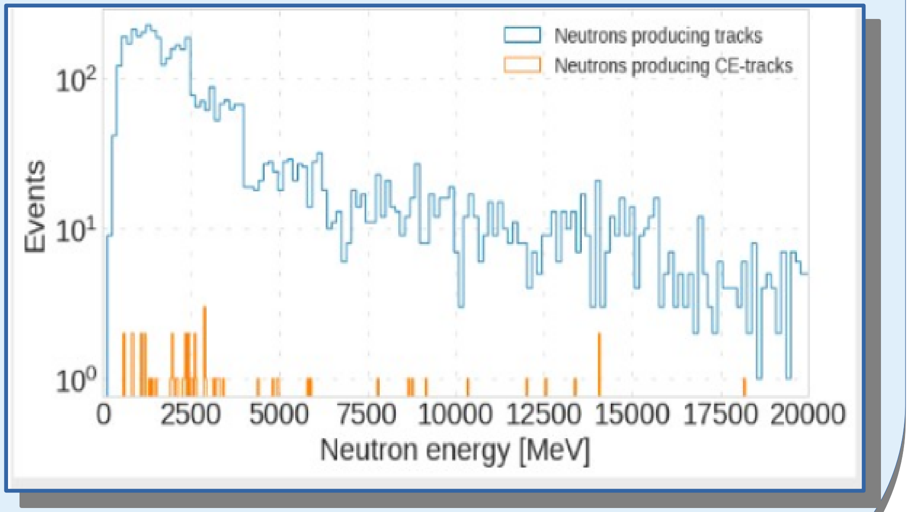
2.1 GeV/c pbar momentum

Background studies II: cosmic ray-related background

The CRV system is shielded by 1 m of (normal) concrete, to be protected from the neutrons coming from the upstream beamline



This concrete absorbs **cosmic neutrons** and **neutral kaons**, which form an additional possible source of background



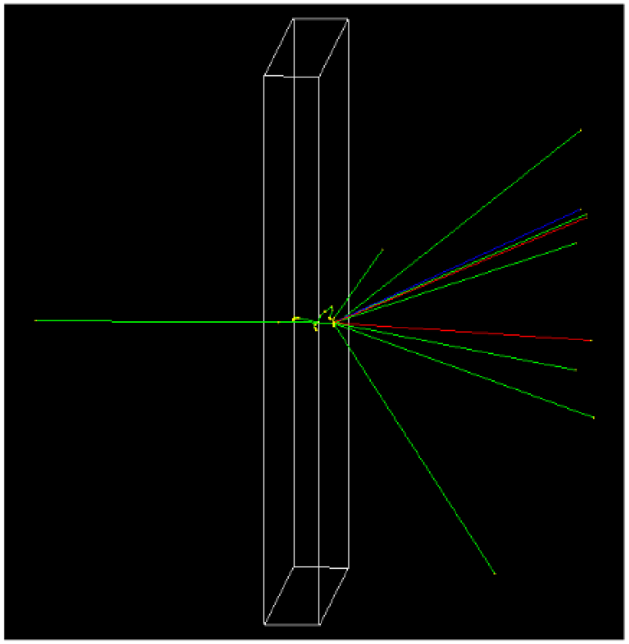
Cosmic neutrons arriving in the DS region

Most of the neutrons that are a possible CE background via production of secondaries have an energy of **~2.5 GeV**

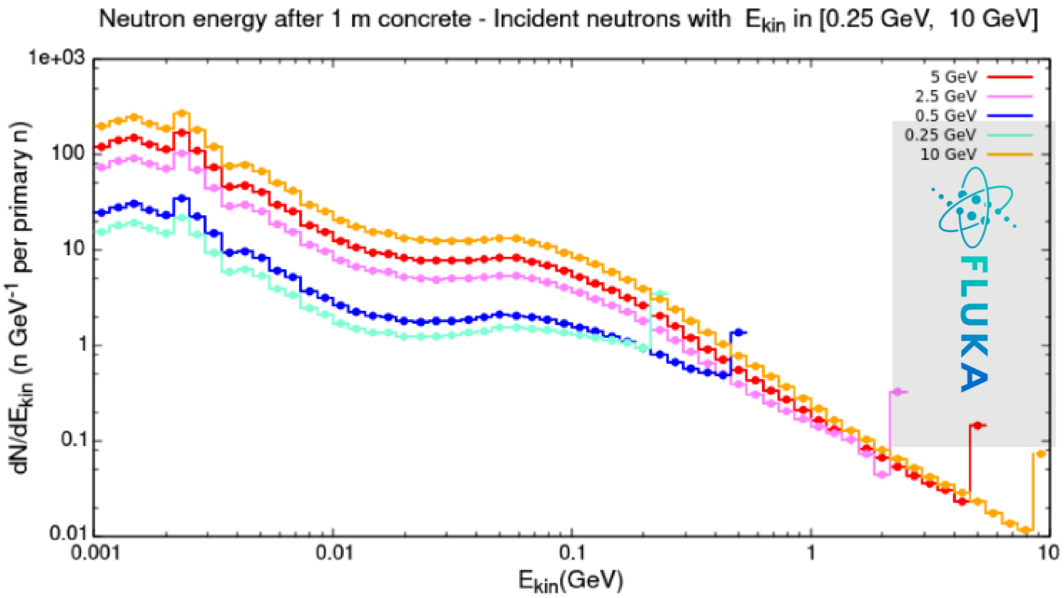
Neutron transmission in concrete

A simple model to check neutron absorption

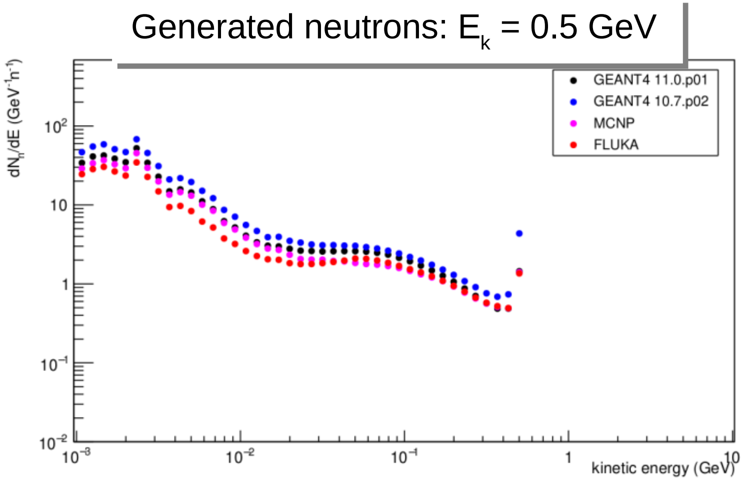
Shoot neutrons of fixed energies on a 1x10x10 m^3 block of concrete and see what reaches a Virtual Detector located just after the block



Interacting neutron

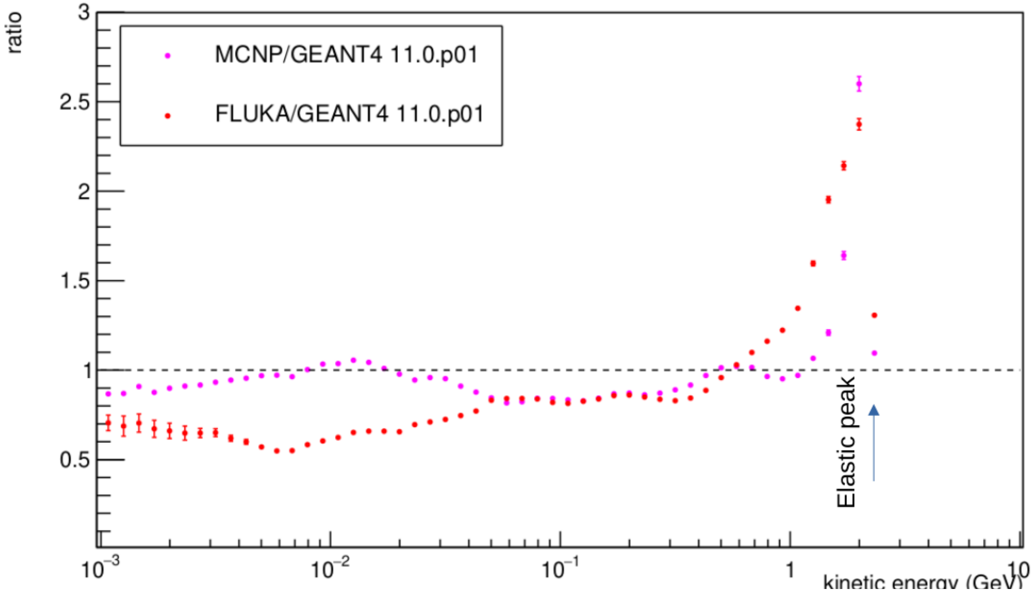


Neutron transmission in concrete


Generated neutrons: E_k = 0.5 GeV

The lower value of FLUKA in the low energy range is due to the fact that the coalescence machanism is taken into account

Neutrons after 1m of concrete (2.5 GeV n beam): ratio to G4



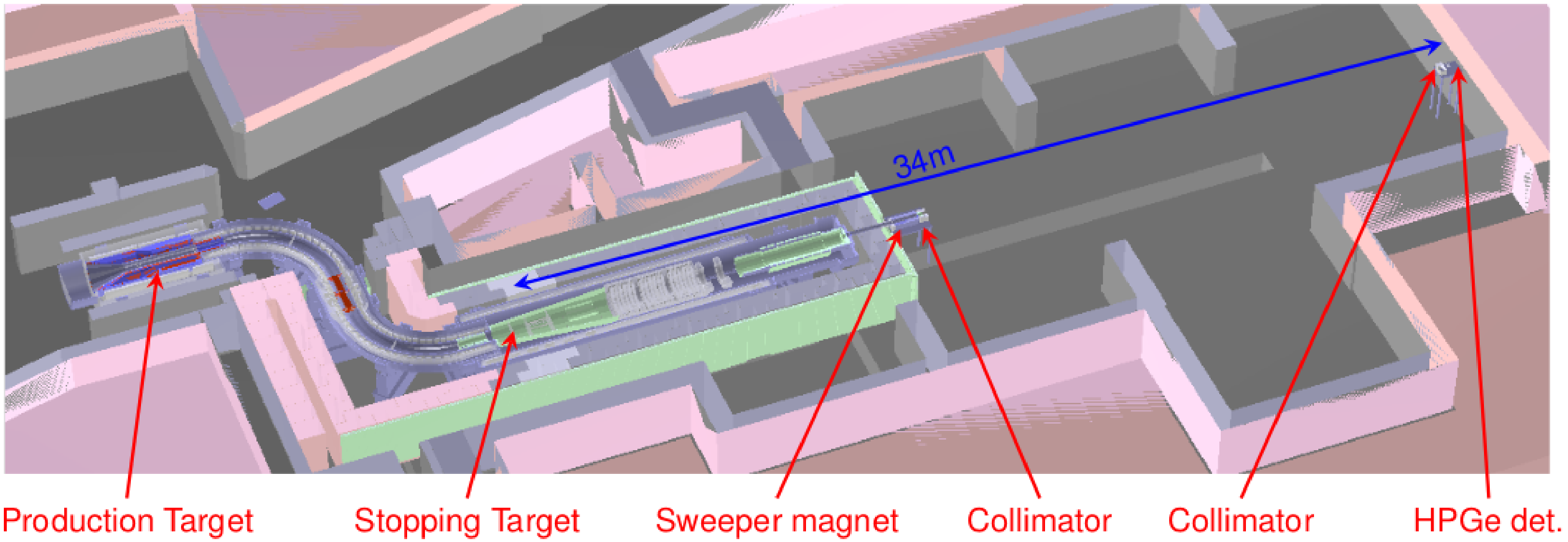
- Using a pencil beam of 2.5 GeV, the spectra of neutrons after 1 m concrete generally differ by **less than a factor 2**
- Close to neutron elastic peak the GEANT4 yield is **~2.5 lower** than MCNP and FLUKA ones.

This implies that the current uncertainty on the Mu2e cosmic background is underestimated

Normalization of signal events: the Stopping Target Monitor

Goal: measurement of the muon capture rate in Aluminum at the 10% level

Detector system: <u>High Purity Germanium detector</u> + <u>LaBr$_3$ detector</u>
LaB$_3$ has worse energy resolution, but can sustain higher rates

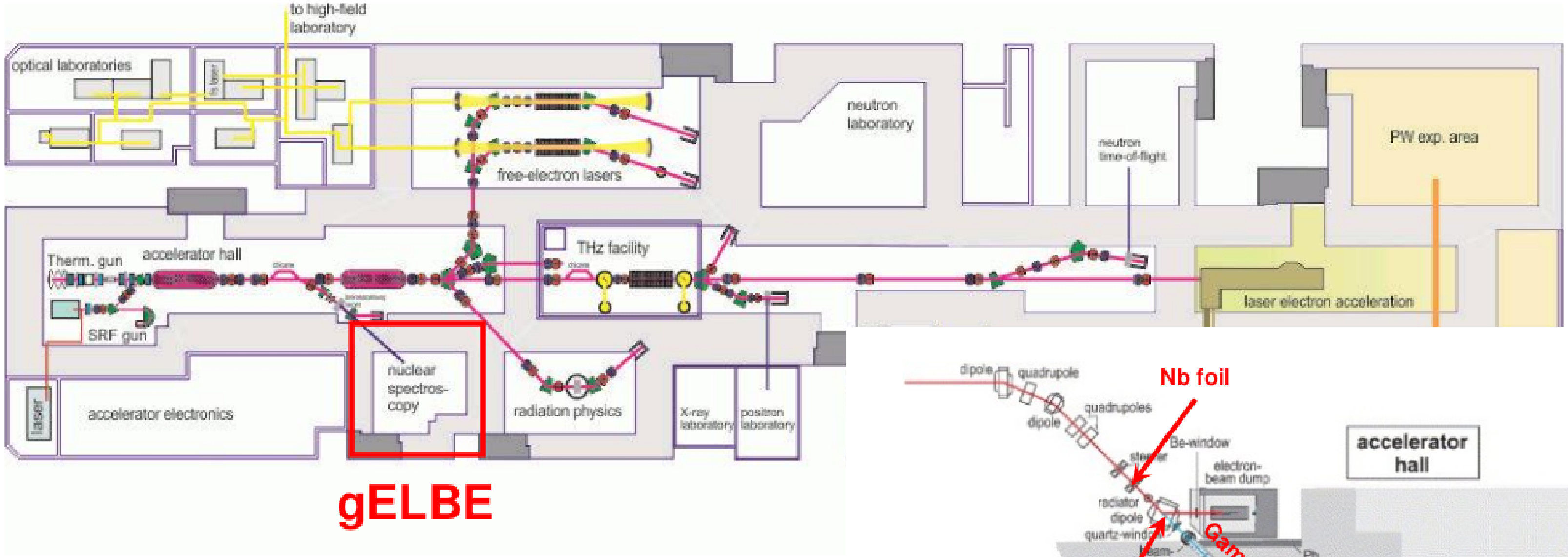


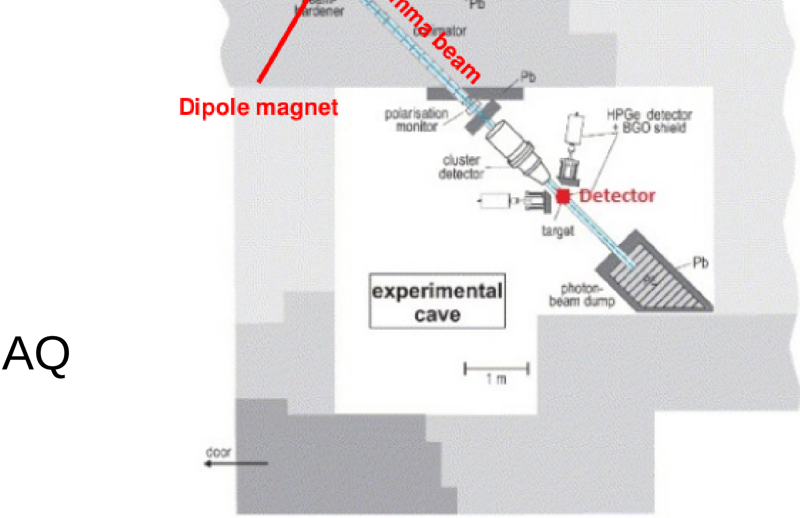
- measure X- and γ-rays from muonic Aluminum
  - 347 keV 2p-1s X-ray (80% of muon stops)
  - 844 keV delayed γ-ray (5% of muon stops)
  - **1809 keV** γ-ray (30% of muon stops)

- line-of-sight view of Muon Stopping Target
- behind tungsten collimator with 0.5 cm^2 holes
- sweeper magnet to reduce charged particle background and radiation damage to detector

Testing the STM detector system at the gELBE radiaton source

$E_e \leq 40$ MeV; $I_e \leq 1$ mA; Micropulse duration 10 ps $< \Delta t <$ 1 μs





3 Irradiation Campaigns:

- *August 2017:* HPGe test
- *September 2021:* $LaBr_3$ test
- *April 2022:* Test of full system with the FPGA-based DAQ

Testing the STM detector system at the gELBE radiaton source

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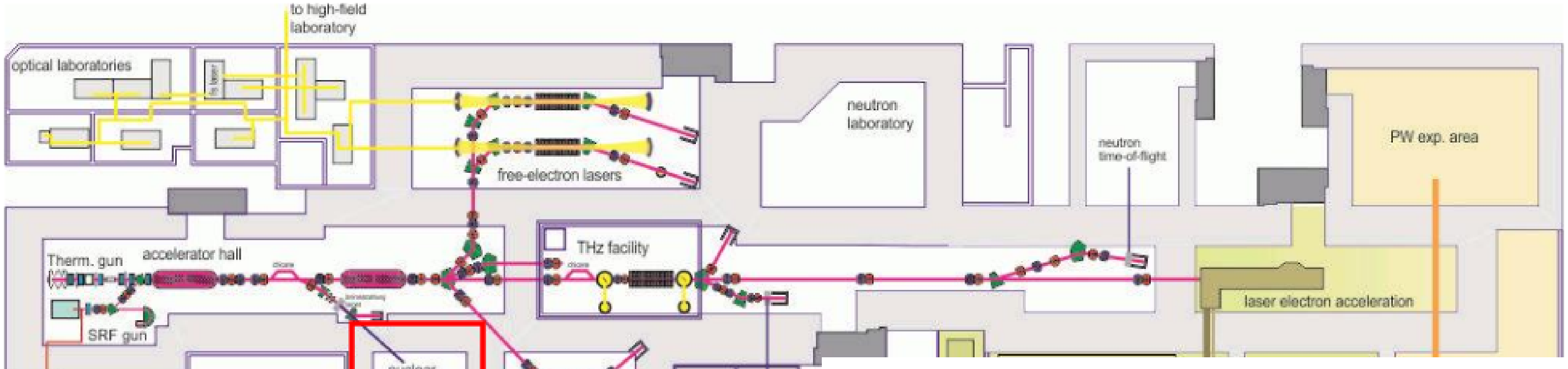

gELBE

3 Irradiation Campaigns:

- *August 2017:* HPGe test
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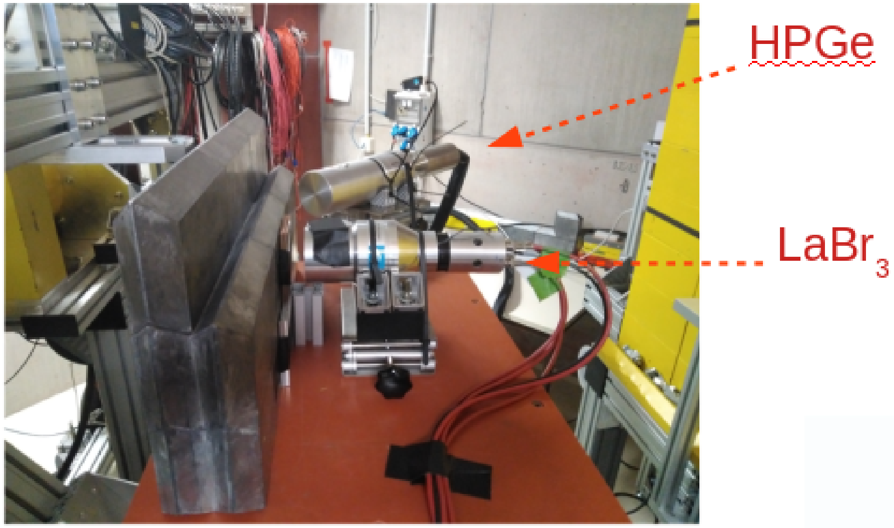
$LaBr_3$ and **HPGe** detectors in the **gELBE** cave:



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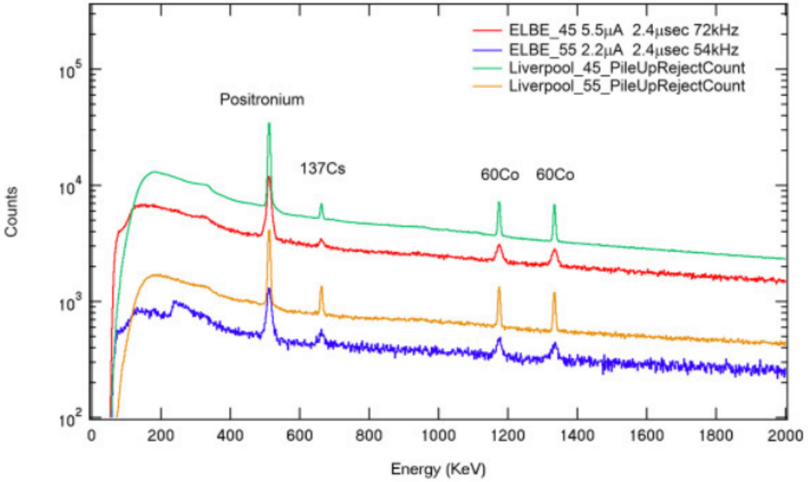


August 2017:

HPGe test of Energy resolution, radiation damage, sustained rate

Energy resolution between **3 keV** and **6 keV**

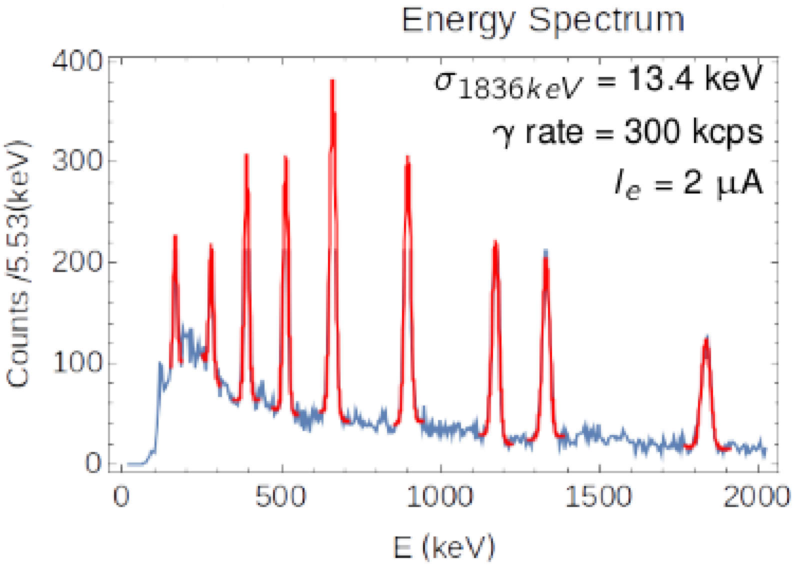
September 2021:

LaBr$_3$ can handle data taking at twice the expected photon rate

Pulse frequency: **813 kHz**

With this pulse frequency, "Nominal" expected Mu2e conditions were found with

1.1 uA electron current:
150 kcps with **3.8 MeV average photon energy**.



Conclusion

- The Mu2e experiment at FERMILAB will search for the neutrino-less conversion of a muon into an electron in the field of an Al nucleus,
  with a projected upper limit: 8×10^{-17} (90% CL)

- Detectors are currently being set up in Mu2e building

- Pion production yield and background studies are key points in order to reach the required sensitivity

- Normalization will be provided by measuring the total number of muon captures via the Stopping Target Monitor (STM), which will measure the rate of 1809 keV γ -rays emitted from the Stopping Target's aluminum discs when muons are captured

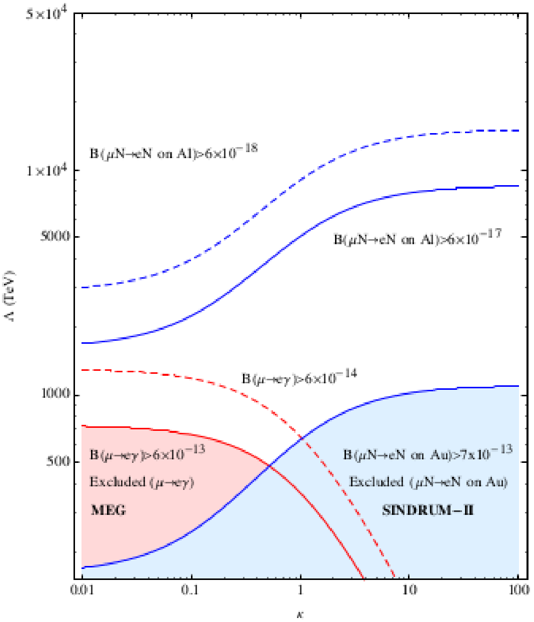
- With a first run of physics data taking starting in 2026,
  Mu2e will either unambiguously discover CLFV
  or push the limit on muon → electron conversion by nearly four orders of magnitude

Exciting next future !

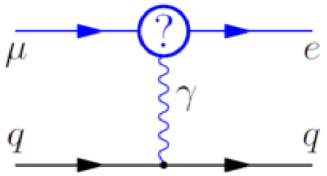
Backup

If we assume a toy Lagrangian of the form:

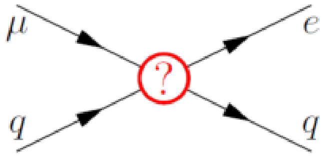
$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\overline{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\overline{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\overline{q_L}\gamma^\mu q_L\right)$$



Bernstein, de Gouvea



$\kappa << 1$
(loop term)



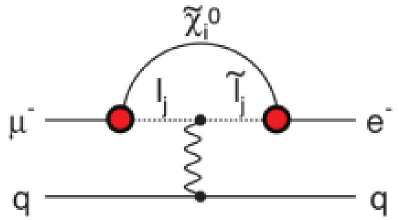
$\kappa >> 1$
(four-point contact term)

Complementary to the LHC

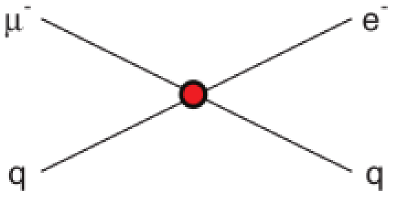
- can probe mass scales up to 10^4 TeV
- (assuming maximal mixing and unit coupling – $R_{\mu\rightarrow e} \sim \frac{g\theta_{e\mu}}{\Lambda^2}$)

A selection of BSM theories that predict enhanced rates of CLFV processes:

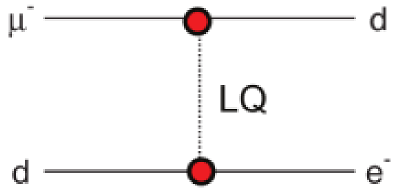
Supersymmetry



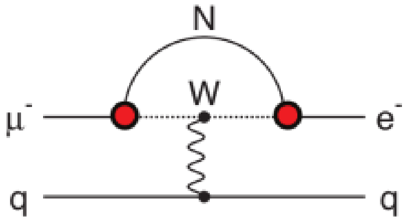
Compositeness



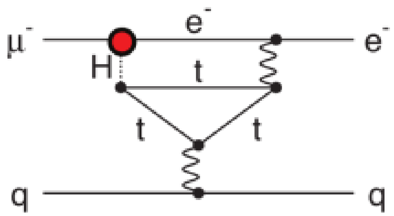
Leptoquark



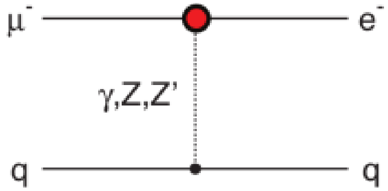
Heavy Neutrinos



Second Higgs Doublet

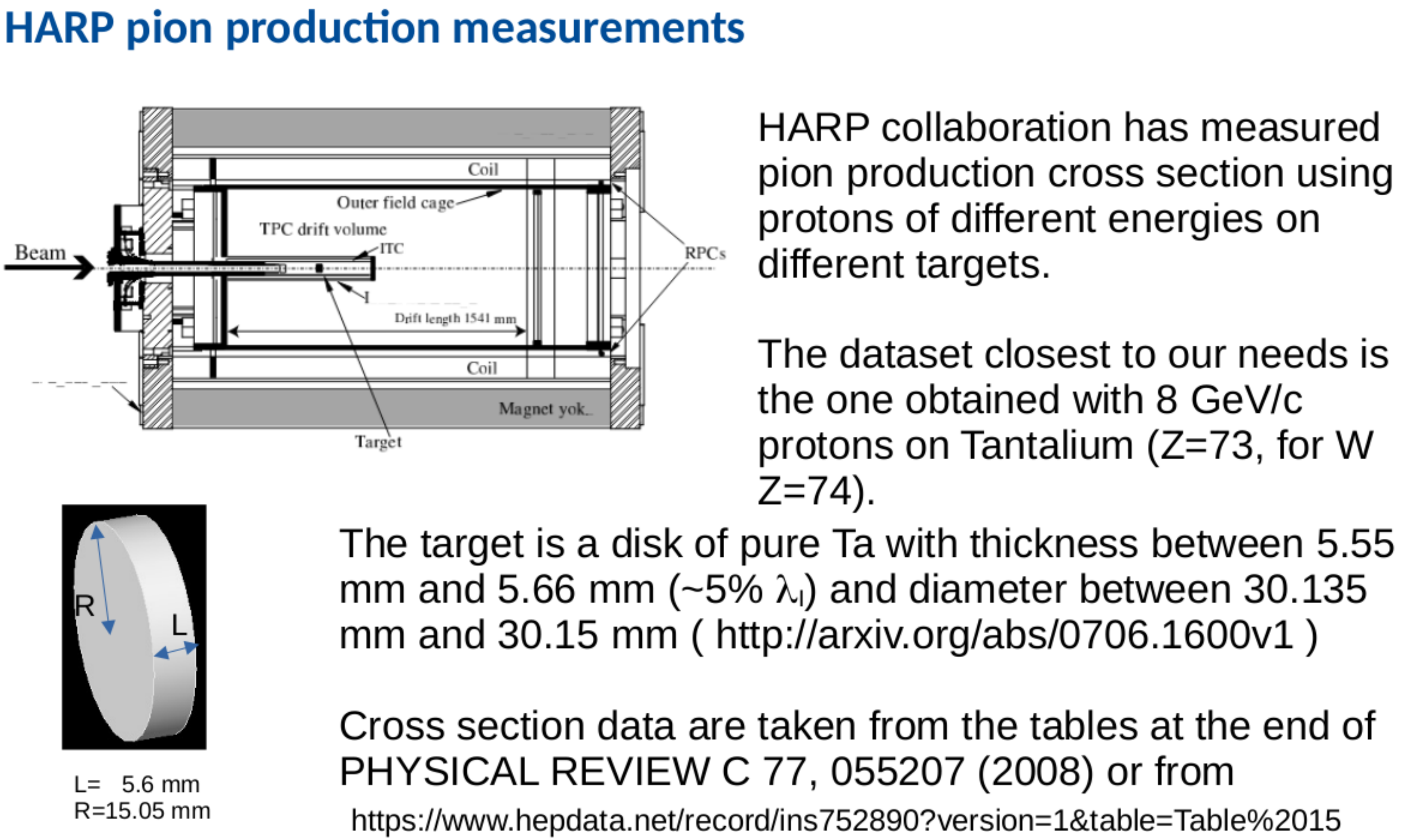


Heavy Z'
Anomal. Z Coupling



Comparison with HARP data:
Pion production cross section for 8 GeV/c Protons on Tantalum (Z=73)

From DocDB 42601



HARP pion production measurements

HARP collaboration has measured pion production cross section using protons of different energies on different targets.

The dataset closest to our needs is the one obtained with 8 GeV/c protons on Tantalium (Z=73, for W Z=74).

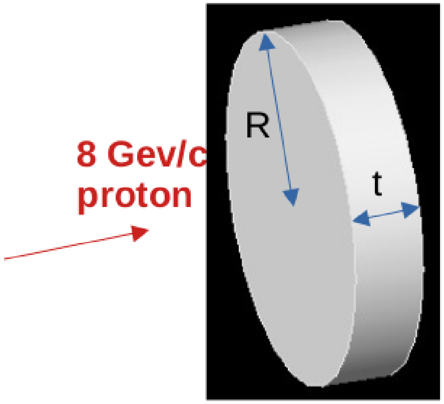
The target is a disk of pure Ta with thickness between 5.55 mm and 5.66 mm (~5% λ_I) and diameter between 30.135 mm and 30.15 mm (http://arxiv.org/abs/0706.1600v1)

L= 5.6 mm
R=15.05 mm

Cross section data are taken from the tables at the end of PHYSICAL REVIEW C 77, 055207 (2008) or from

https://www.hepdata.net/record/ins752890?version=1&table=Table%2015

Geant4 11.0.p01 simulation



Tantalium target (full cylinder)
Thickness: **t=6 mm** (~5% λ_I)
Radius: 15 mm

Material: G4_Ta
ρ: 16.654 g/cm3
RadL: 4.094 mm
Nucl.Int.Length: 11.887 cm

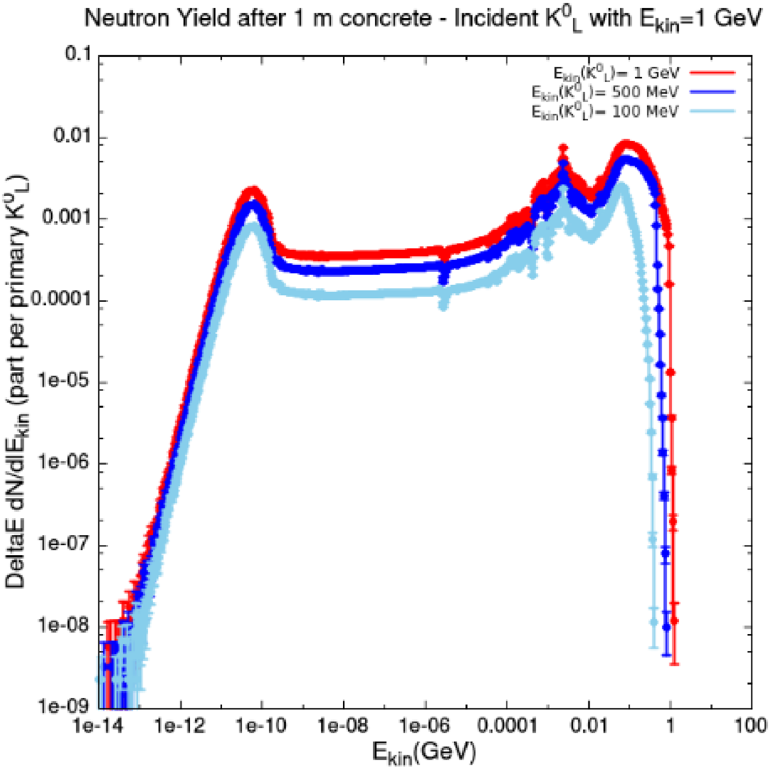
Element: Ta (Ta) Z = 73.0 N = 181 **A = 180.948 g/mole**
- Isotope:Ta180 Z = 73 N = 180 A = 179.95 g/mole 0.012%
- Isotope:Ta181 Z = 73 N = 181 A = 180.95 g/mole 99.988%

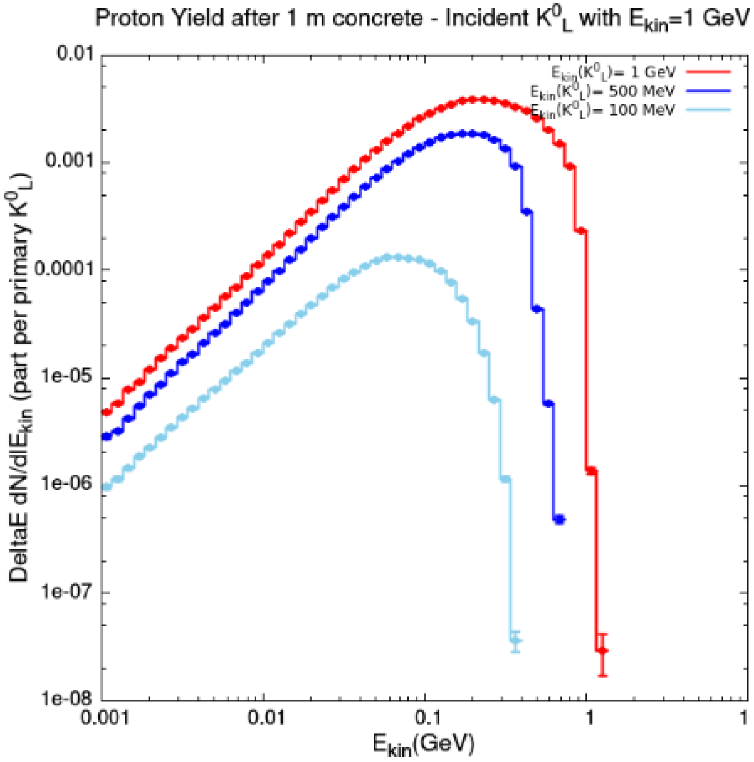
Physics list: ShieldingM (BertiniCascade: 0 eV → 9.9 GeV FTFP: 9.5 GeV → 100 TeV)

Cross section calculation: $$\frac{d^2\sigma}{dp_i d\theta_j} = \frac{N^{\pi}_{ij}}{N_{POT}} \frac{A}{N_A \rho t} \frac{1}{\Delta p_i \Delta\theta_j}$$

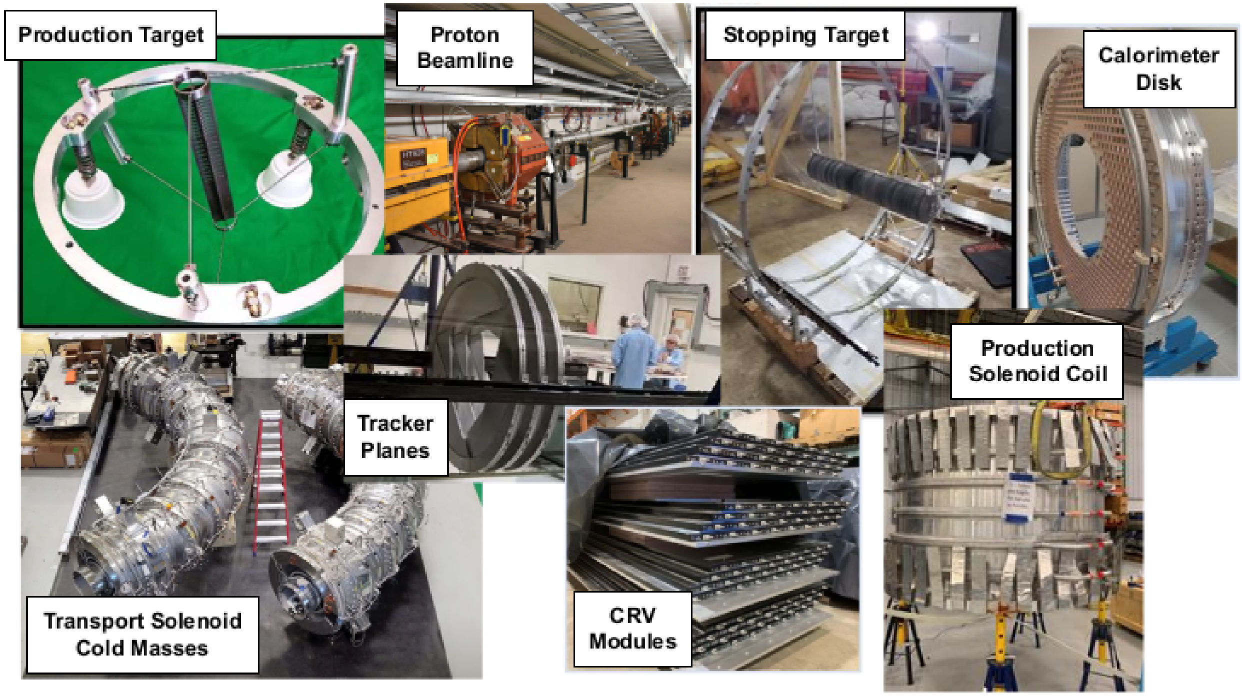
Pion p and θ at primary vertex (parent track ID=1 i.e. generated proton)

K^0_L transmission in concrete: secondaries (FLUKA results)


Neutron Yield after 1 m concrete - Incident K^0_L with E_{kin}=1 GeV


Proton Yield after 1 m concrete - Incident K^0_L with E_{kin}=1 GeV

Construction well underway!



- Detector commissioning through to end of 2024
- Take Run 1 data in 2025 and 2026 until LBNF/PIP-II shutdown
  - x1000 improvement over SINDRUM-II
- Resume data collection in 2029 after long shutdown
  - x10000 improvements over SINDRUM-II