1)  
Good evening,   
I’m Bastiano Vitali and today I will present to you the results of the work I have been doing with Prof. Donati and Dr. Murat at the Mu2e experiment. The focus has been the development of a monitor system for the Mu2e experiment.  
  
2)  
The violation of the lepton flavor is neither forced nor forbidden by the standard model.  
After the discovery and introduction of the neutrino oscillation, we expect violation in the charge sector too. In the extended SM these violations scale with (Delta massa nu)^2/M\_W^2 and have extremely low rates (below any experimental sensitivity).  
The different theories are quite flexible and predict different rates, some way higher. Experimental constraint are needed.

3)  
This is an   
In the last few decades many improvements lead to today’s stringent limits for the various processes.  
Specifically a great effort has been dedicated to the searches using muon, related to the development of high intensity muon beams. Leading structures in endeavour are Fermilab PSI and JPARC.

4)   
The Mu2e experiment (Fermilab) in particular searches for the neutrinoless coherent conversion in the field of a nucleus. The signature of this process is a monoenergetic electron. Aside for the binding energy and the nuclear recoil the electron’s energy is equal to the muon mass.  
The rate of this process is often normalized to the muon capture.  
The current limit on this process was set by SINDRUM II at PSI using a gold target  
Mu2e goal is to improve the limit by 4 orders of magnitude

5)  
This is a challenging sensitivity and the contribution from the various background needs to be minimize and fully understood.  
The highest contribution comes from background induced by cosmic rays. To reduce this contribution the collaboration developed a Cosmic Ray Veto system enclosing all the detectors.  
The second contribution comes from the muon decay in orbit. While in vacuum the end point of the spectrum is a 53 MeV, the interaction with the nucleus creates a long tail which reach the signal region. An excellent momentum resolution is needed to deal with this background.  
Antiprotons can be collected from the production target and annihilate in the stopping target. To reduce this contribution one can insert material in the beamline to make the antiproton interact before reaching the stopping target.  
The last contribution is from pions. The capture of pions can generate a photon which can convert asymmetrically in a high energy electron. To reduce this background Mu2e decided to use a pulsed beam (in a next slide we will see the timing structure)  
  
6)  
The apparatus is in three sections: production, transport and detector solenoid.  
The PS contains the Tungsten production target and a graded magnetic field to aid the collection of backward produced particles.  
The TS allows the pi to decay and applies a selection in charge and momentum. In particular in a curved solenoid the particles of different charge sign drift in different direction, allowing for the selection of negative particles.  
the DS contains the aluminum stopping target, a proton absorber and the detectors (tracker and calorimeter)  
  
7)  
As we anticipated a good momentum resolution is needed to identify DIO and conversion electrons and the tracker needs to be a ‘low mass’ detector. Mu2e chose a straw-tube tracker. The straws are organized in panels which are used to create a hollow cylinder. The bore makes the detector blind o low transverse momentum particles. The straws are read at both ends and are self supporting.  
The expected resolution is <200 KeV for 105 particles and is met by simulation and a small prototype.

8)  
The calorimeter plays a fundamental role in the identification and triggering. It is made by two disks of CsI cristals set at 70 cm apart: if a 105MeV partciel travels trough the hole of one of the two disks, will be detected from the other.  
Each crystal is read by two photomultipliers. The required resolutions have been met by the working prototype and the simulations.  
  
9)   
As anticipated, the beam is pulsed to reduce the background from pi (in the figure we can see the distribution for the arrival of pions and mu at the stopping target).  
An event is everything between two pulses of protons and these pulses, organized in spills, are obtained to a process called resonant extraction.  
Simply put the bunch in the delivery ring is pushed slightly out of orbit and the external portion is kicked by electrostatic septa out of the ring.  
  
10)  
The resonant extraction is a complicated process and significant intensity variation are expected in the same spill. The simulations indicate variations on the timescale of milliseconds.  
(we can see in the plot few peaks at 3 or 4 times the nominal intensity)

11)   
Why are we interested in these fluctuations? Both the reconstruction efficiency and the response of the Cosmic ray veto system are dependent on the proton pulse intensity: the efficiency decrease with the occupancy of the tracker and the veto can be triggered by neutron produced by the protons arrival  
  
12)  
What processes could we use to monitor these fluctuations?   
Given the photons emetted from the stopping target are going to be used to measure the normalization of the conversion process is reasonable to try and use the same detectors (a germanium detector to mesure the X photons from the muonic atom deecitation and a cesium lanthanum bromide to measure the 1.8 MeV photon fro the Mg after muon nuclear capture).  
Neither of the two systems can reach the time scale we are interested in  
The solution might be to count charged particles coming from the muon nuclear capture.  
We expect thousands of protons per event (1.7 mus) so the rate is not the problem.  
Question is if we can reconstruct these particels.  
Key aspects are the low beta and the presence of the proton absorber between the stopping target and the tracker.  
  
13)  
But how does the reconstruction work?  
The first step is to collect the information from the detectors:  
in the tracker the straws are read at both ends and the Delta t gives us the position alogn the wire. On top we have a deposit energy and a time of the hit. Hits which could have been produced by the same particle are grouped in time clusters.  
In the calorimeter crystals with energy deposit higher than a given threshold which are close in time and position are grouped in a cluster.  
(The information of the calorimetr is crucial in the triggering of the and seeding of the procedure)  
  
14)  
Once the hits are grouped we need to find the helix.  
projecting in XY we can use triplets of hits to find the axis of the helix and then the radius.  
In phi and Z is a simple linear fit, but first the ‘2 pi’ ambiguity needs to be resolved. After a full rotation the angle starts back at zero and we need to translate the hits at the right phi.   
  
15)  
The last step in the reconstruction accounts for the more complex effects like the energy loss, the non uniformity of the field and multiple scattering. If we consider a track to be a vector of parameter this vector is position-dependet and the values we found earlier are “averaged”.   
The Kalman Filter is a iterative procedure which allows to have the best possible estimate in any given point and it is a simple and fast way to include these effects in the fitting procedure.

16)  
Now that we have the starting structure we can tailor the reconstruction, developed and used for electrons, to our protons.  
  
17)  
Let’s start by generating protons with a flat distribution in momentum to check the reconstruction and understand the geometry.  
If we look at the number of hits in the tracker as a function of the generated momentum we find a non trivial distribution. At low momentum the particles are either stopped by the absorber or travel in the bore. For higher momentum the number of hits increase but then we have a dip. Why?

18)  
If we look at the distribution for the first and last hit in the tracker we can see that there is a pattern. The first and last hits at the energy we are interested in have a discontinuity. Thy jump from the last stations to the first.  
  
19)  
This depiction helps us to understand that for a given momentum instead of having an arch in the tracker we start having two short sections which are quite distant.

20)  
This structure is preserved when we perform the reconstruction because the particles in the momentum range of the change in topology are harder to reconstruct.   
Aside from this glaring dip the efficiency of the algorithm is quite good and the reconstruction works.  
(Efficiency here is evaluated with at the denominator particles which we could have reasonably reconstructed: having more than 5 straw hits)  
  
21)  
If we look at the number of full rotation the particle performs in the tracker we see that high momentum particles perform less than a full rotation.  
In order to reconstruct them they need to be forward enough not to get stucked in the cryostat and they are emitted forward.

22)  
The reconstructed momentum is consistent with what expected and we also can see the effects of the proton absorber in the lower part of the spectrum   
  
23)  
Of course the particles we are interested in are not uniformly uniformly in momentum.  
  
24)  
The AlCap and Twist collaborations continued the work done for example by Sobotkka and wills on the measurement of particles from muon nuclear capures.  
Without entering in details, there are two parameterization used today in the collaboration.   
The comparison between the two is here shown for both protons and deuterons and we generated samples for both parameterization.

25)   
For protons we see no significant change in the number of reconstructed tracks (per 1k particles generated). At the bottom we can see that the efficiency are compatible, as they should because the different spectra are both at the numerator and denominator of this histograms.

26)  
Doing something similar for deuterons we still find the efficiency to be compatible but the number of reconstructed tracks is increased with the more recent parameterization.  
This is expected because the previous parameterization used the same kinetic energy spectrum from protons and deuterons (given no other information was available) while the more recent is based on the last measurements.

27)  
Until now we looked at single particles event. What happens when dealing with a full event (everything in a 1.7 mus between two proton pusles)

28)  
The necessary step is to perform a selection on the hits. If we look at the distribution in energy deposit we can see that protons and deuterons hits have higher energy deposit (due to lower beta). As result we can apply a cut and reduce the ‘bacgkrund’ for our search (all electrons hits.)  
The value used for this study is 2 keV which could be further optimize but the new simulations will have a different distribution because of a different simulation of the readout electronics.

29)  
Applying the cut we can notice that the number of reconstructed tracks per event increase. We now reconstruct roughly 4.5 protons per event.

30)  
But how many of these tracks are actually NOT protons or deuterons? We can use the monte carlo truth and we can see that after the cut on the depsited charge we have virtually no tracks other than protons and deuterons.  
  
31)  
Now of course the question is what can we learn about the beam intensity from this measurement

32)  
If we make a scatter-plot fort he number of protons on target and the number of reconstructed tracks we can see there is a dependence. The distribution is quite wide but this is for 1 event = 1.7 mus while we are interested in 1 ms.   
So what we need is to know within 1ms how much we expect the proton beam to fluctuate.  
A reasonable approximation is a 10% variation.   
We can then slice this scatter-plot in horizontal bands of 10% height and take the mean for the distribution of the number of reconstructed tracks per slice.

33)   
what we obtain is a curve which gives the number of protons on target for a given average of tracks measured in one millisecond.  
We can perform a polynomial fit to give a rough estimate on the uncertainty that we would associate to this value.

34)  
assuming n tracks as average in 1 ms the relative uncertainty associated to the beam intensity is less then 15% which is a remarkable result given we are repurposing an already developed detector and adapting an already developed fitting procedure.

35)  
To recap:

The searches for CLFV processes are cardinal in the current effort of testing the standard model and the possible extensions.  
In this environment Mu2e is a pioneering experiment with a challenging goal.  
The current understanding of the delivering system indicates the presence of fluctuations on the timescale of milliseconds and this work is a study of feasibility for a monitoring system of these flucutations.  
We adapted the reconstruction procedure developed by the collaboration to reconstruct charged particles coming from the nuclear capture of stopped muon and a made a first estimate of the uncertainty associate to this method.  
The next step will be to update the result with the new simulations (expected in 2020)