Study of the impact of TS collimator misalignments on physics parameters of the Mu2e experiment

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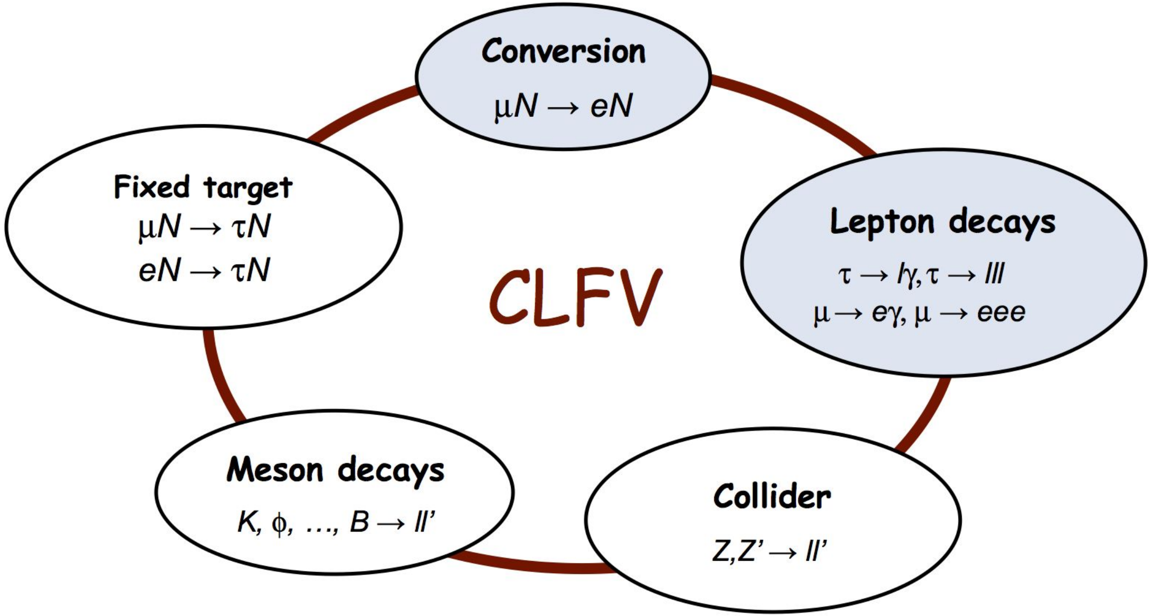
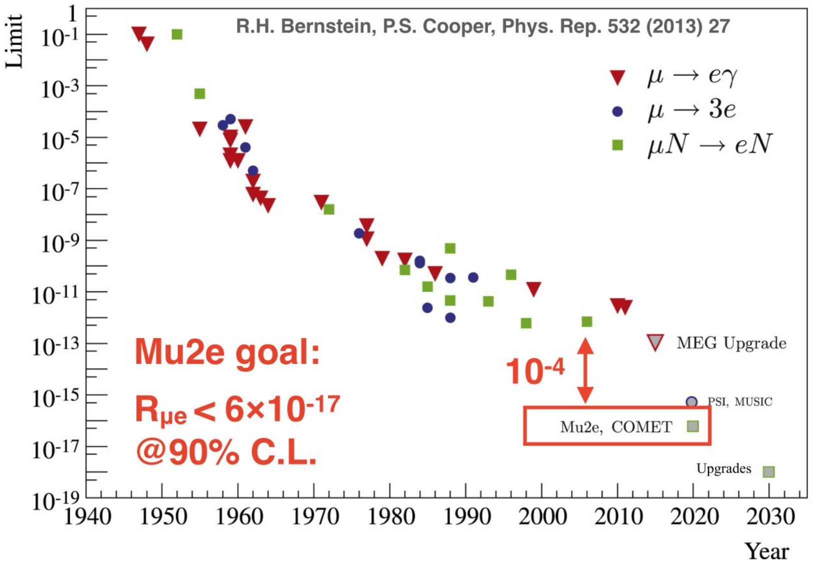
Charge Lepton Flavor Violation (CLFV)

- In the Standard Model (SM) neutrinoless charged lepton decays are extremely suppressed (<~ 10^{-52})
- Therefore observation of such decays is a signature of new physics



- Muons offer the best signatures because they are easily produced and weakly decaying, with a long τ

CLFV history



$$\mu \to e\gamma$$
$$(BR < 10^{-13})$$

Evidence of physics beyond the Standard Model

$$(BR < 10^{-52})$$

➢ Mu2e search process: conversion of muon into electron in a field of a nucleus, $\mu N \to eN$

Why?

- Muons are easy to produce and have a lifetime long enough to make muonic atoms
- Best combination of new physics reach and experimental sensitivity

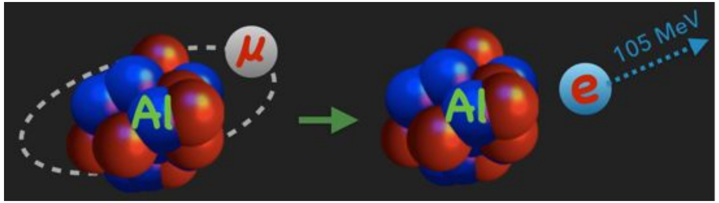
Mu2e in a nutshell

1. Produce 10^18 muonic Al atoms in the 1s state after 3 years of running
2. Count “muon conversion electrons” with tracking and calorimetry
   - Mono-energetic electrons emanating from the Al target

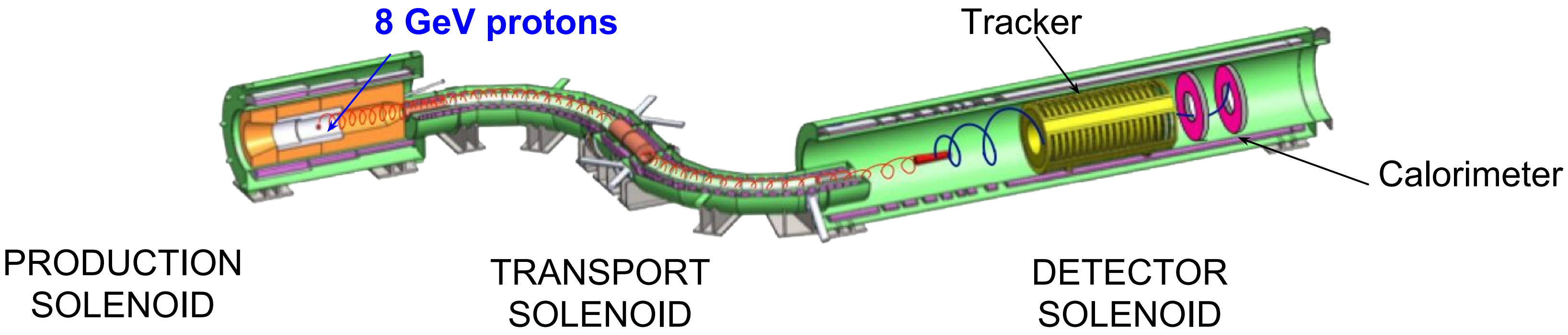
$$E_e = m_\mu - E_b - E_{recoil} = 104.96\ MeV$$

3. Suppress Background

➢ What happens to Muonic Al?
   - Nuclear capture (~61%) → **Normalization factor**
   - Muon decay in orbit (DIO) (~39%) → **Main Background**
   - Muon to electron conversion(< 10^{-13}) → **Signal**



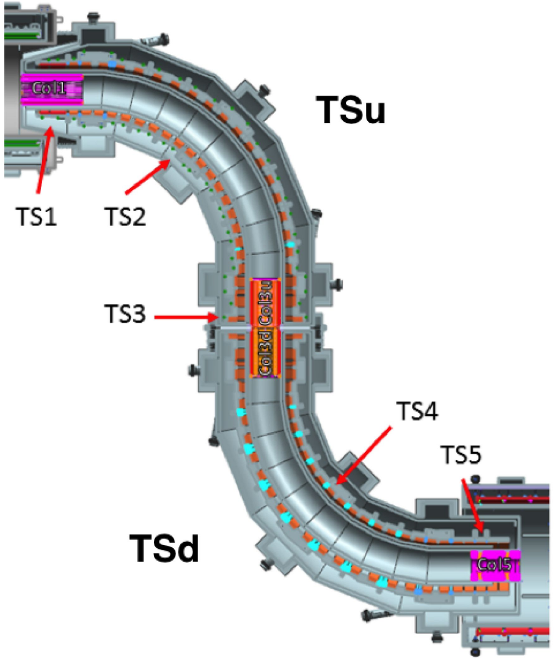
Mu2e outlook



- Pions are produced and decay into muons which spiral in the Transport Solenoid (TS)
- $3 * 10^{20}$ protons at the production target
- Single Event Sensitivity:

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \to e^- + A(Z,N)}{\mu^- + A(Z,N) \to \nu_\mu^- + A(Z-1,N)} \simeq 3 \cdot 10^{-17}$$

Transport Solenoid



- "S" shape → to select only charged particles
- 3 Collimators → TS3 selects negative particles because they drift above the horizontal plane

Studies of the physics effects of TS misalignments have already been made (F. Bradascio, MSc thesis Mu2e-doc-7808)

My work focuses on physics effects of the misalignments of the central collimator (TS3) along the TS beamline

Methodology and topics

- All the work presented here is done using the Mu2e default map: Mau10
- Physics simulation with GEANT4 in the framework of the Mu2e offline software
- Only the actual geometry is varied, not the field
- Analysis is conducted in ROOT

Topics examined

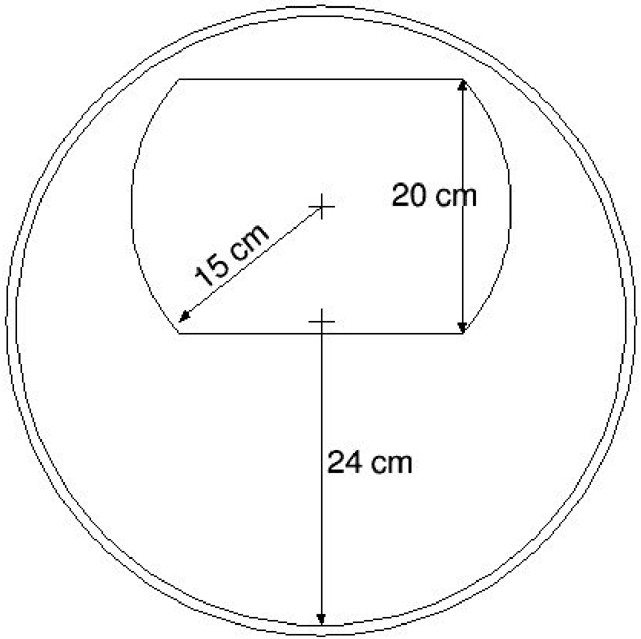
- Muon and Pion Stopping Rates
  - The muon capture and pion absorption probabilities at the stopping target depend on the direction of these particles, determined by the TS field
- Background from Beam Electrons
  - The scattering probability of beam electrons off the stopping target material depends on the direction of the electrons, determined by the TS field
- β Source Test
  - We can approximately trace the TS field lines by taking advantage of the small Larmor radius of low-momentum electrons injected into TS from a conventional β source

My work plan

Study only displacements and rotations of TS3 collimator:

Why is it important?

- ➢ Hole in the upper part selects negative particles with appropriate momentum → possible misalignment affects charge and momentum range selection
- ➢ What can happen to the physics of the experiment with slightly wrong momentum range and charge selection?

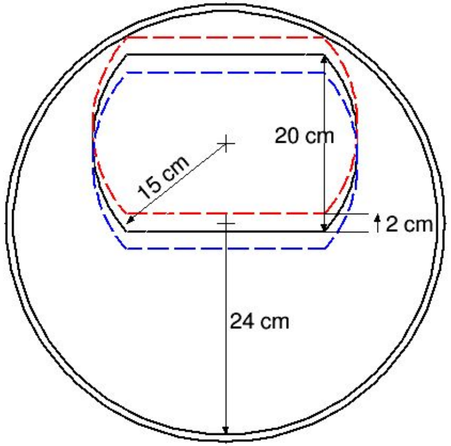


80+80 cm long Cu

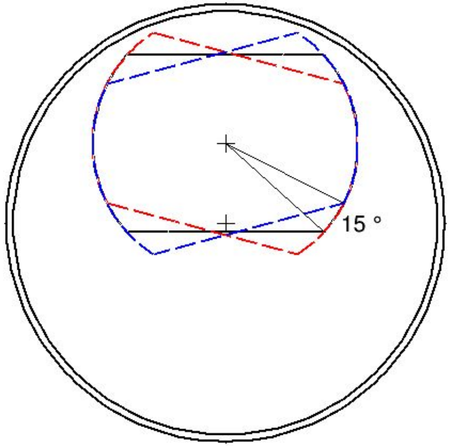
My work plan

Enormously exaggerated misalignments, to test the induced effects

Displacement:
2 cm up, 2 cm down



Rotation:
15° right, 15° left



Steps:

A. Shift up 2 cm
B. Shift down 2 cm
C. Rotation right 15°
D. Rotation left 15 °

Topics:

- Muons and Pions stopping rates
- Beam electrons
- Beta source test

Stopping Rates

Simulation provides the transport of muons and pions from the production target up to the stopping target

Protons on target: 10 M → muons can decay

→ pions are forced to be stable } Because of their shorter lifetime

- ➢ Estimation of background: Muon stopping rate: $\frac{N_\mu}{N_{POT}}$

  Pion stopping rate: $\frac{n_\pi}{N_{POT}}$

  n_π = number of pions weighted by $e^{-t/\tau}$

  τ = pion lifetime of 26 ns

- ➢ Deviation in rate between default case and rotated field maps
  - ○ Fractional yield factor:

$$\alpha = \frac{Y_{varied} - Y_{default}}{Y_{default}} \qquad \delta_\alpha = \sqrt{\frac{Y_{varied} \cdot (Y_{varied} - Y_{default})}{Y_{default}^3}}$$

$Y = N_\mu$ for muons

$Y = n_\pi$ for pions

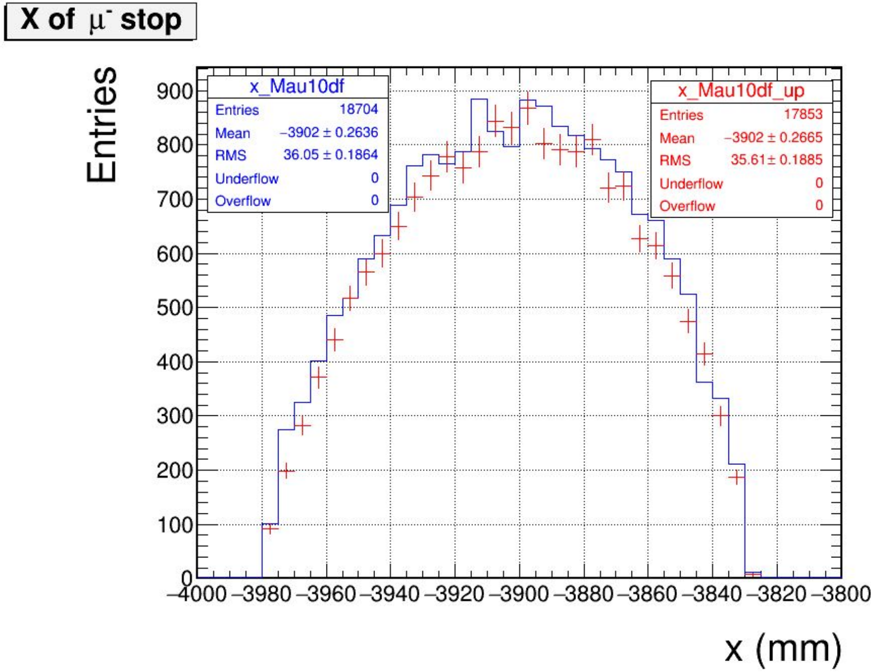
Muons and pions stopping rates

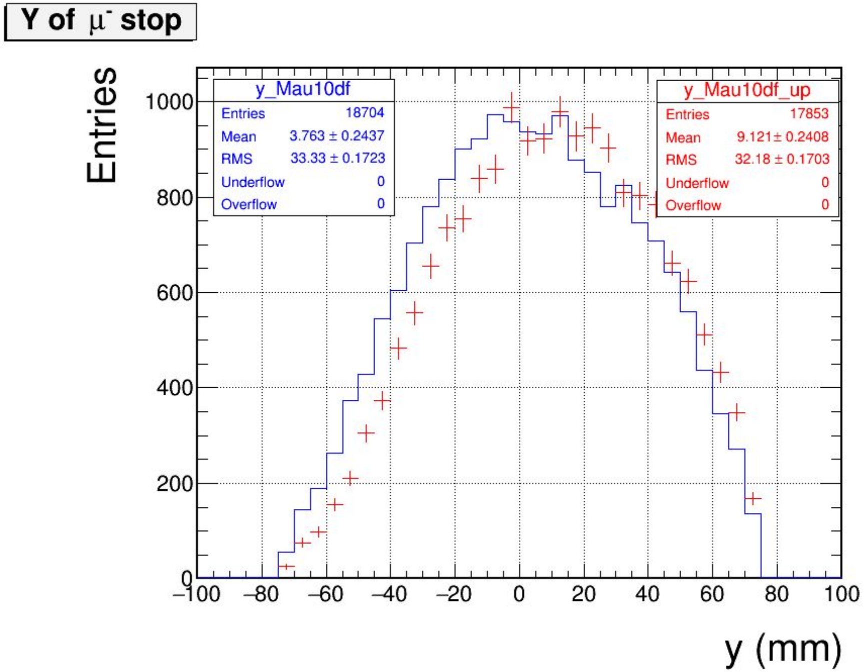
- Displacements:
  - Decrease of statistics moving the collimator: mainly a geometric effect
  - The weighed pion rate is very low (a few pions stopped) to allow significant conclusions
- Rotations:
  - Consistent results as we expected → rotation doesn't affect spiraling particles

→ Fractional yield differences: more sensitive to displacement down

	α_μ [%]	α_π [%]	N_μ/N_{POT} [10^{-3}]	n_π/N_{POT} [10^{-7}]
Default	----	----	1.87 ± 0.01	6.27 ± 0.08
UP (2cm)	-4.55 ± 1.00	12 ± 61	1.79 ± 0.01	7.01 ± 0.09
DOWN (2cm)	-7.18 ± 0.98	-17 ± 49	1.74 ± 0.01	5.18 ± 0.07
Right (-X 15°)	-0.98 ± 1.03	2 ± 57	1.85 ± 0.01	6.40 ± 0.08
Left (+X 15°)	-0.47 ± 1.03	4 ± 58	1.86 ± 0.01	6.53 ± 0.08

A) Muons shifted up

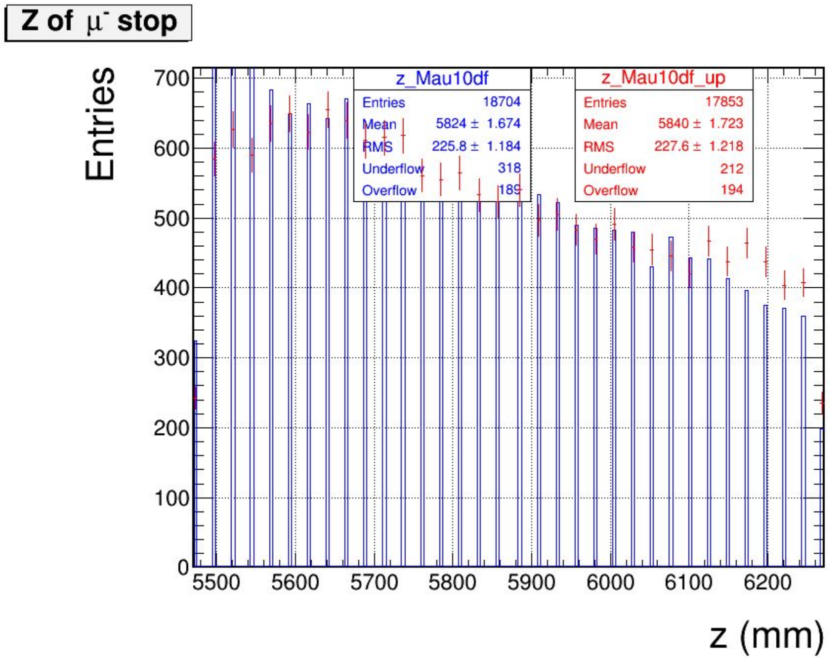


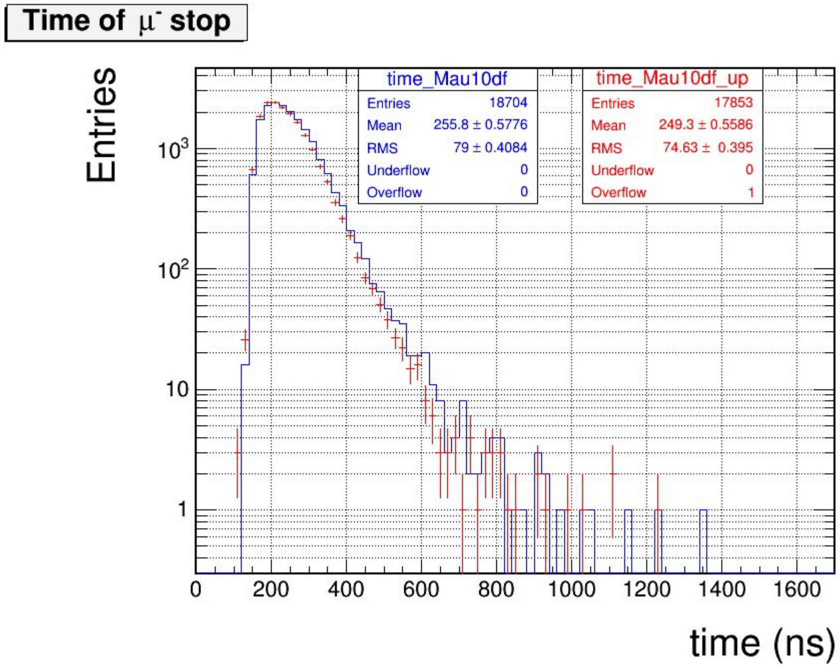


- Comparison with Federica results for the default case:
- Y distribution differs by many sigmas from the default case in accordance with the shift

Mean X	-3092 .0 ± 0.8
Mean Y	3.8 ± 0.8

A) Muons shifted up





- Comparison with Federica results:

Mean Z	5814 ± 5
Mean time	256 ± 1

Beam electrons background

- Proton Beam: $2 \cdot 10^9$ POT produces ~100 e^- arriving at the stopping target (VD9) $\rightarrow$ resampling needed to increase statistics (resampling factor = 10^6)
- A second stage simulation using the resampled e^- as input provides momenta and locations of e^- hits in the tracker volume

⟶ Results have big statistical fluctuation in number of e^- at the tracker

- crude approximation: could be done more efficiently by resampling over the cross section

Background Estimation:

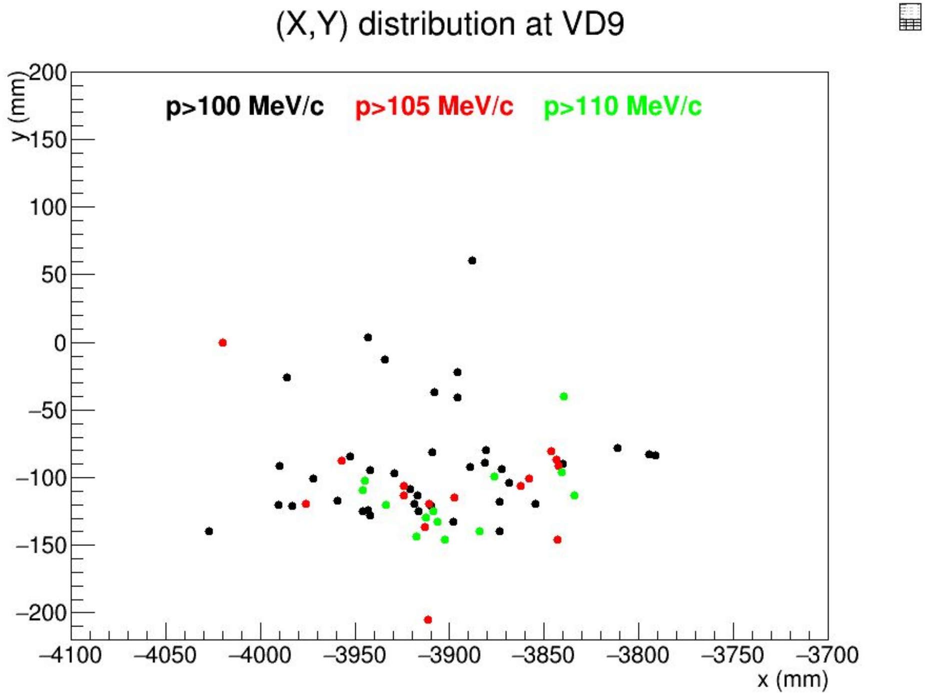
$$N_e = \frac{N}{N_{stat}} \times 3 \cdot 10^{20} \times 10^{-10} \times 0.5 = \boxed{(2.5 \pm 1.2) \times 10^{-4}}$$

By Federica Bradascio

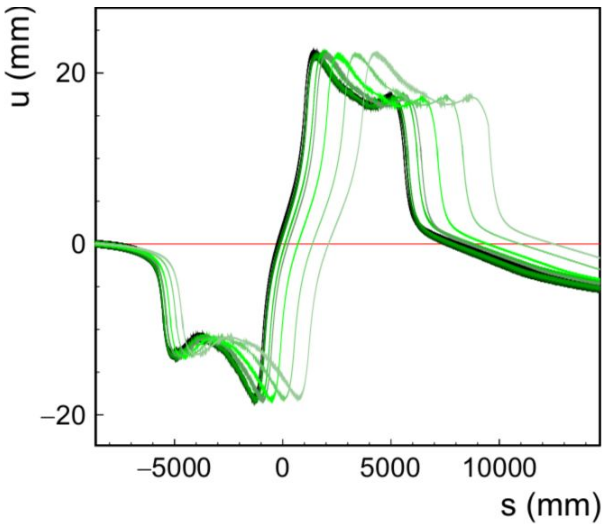
N	=	number of electrons in tracker that have $104<P<106$ MeV/c and $0.4 < P_z/P < 0.7$
N_{stat}	=	number of simulated POT times resampling factor (10^6)
3×10^{20}	=	expected number of POT in the experiment
10^{-10}	=	extinction factor
0.5	=	live time window

Default case: first stage

- ➢ Collect electrons at VD9 → POT: 2.0 M, e at VD9: 66
- ➢ Selected e^- with p>100 MeV

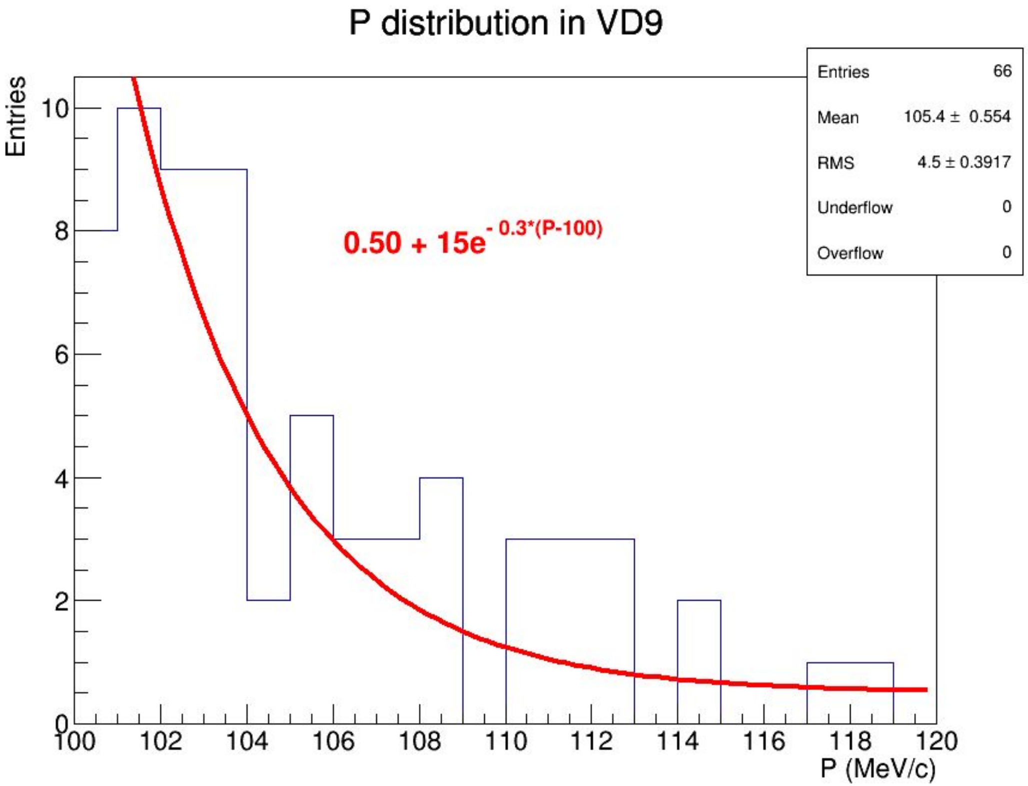


- hits in the downstream part because of the field lines:



Default case: Momentum distribution

- ➢ Fit the momentum distribution in order to do the resampling → particle momenta are randomized according to this fit
- ➢ Position and time distributions are randomized according to a gaussian distribution with σ=10 mm and σ=10 ns
- ➢ Momentum distribution: $f(p) = A\ e^{-k\,(p-p0)}$

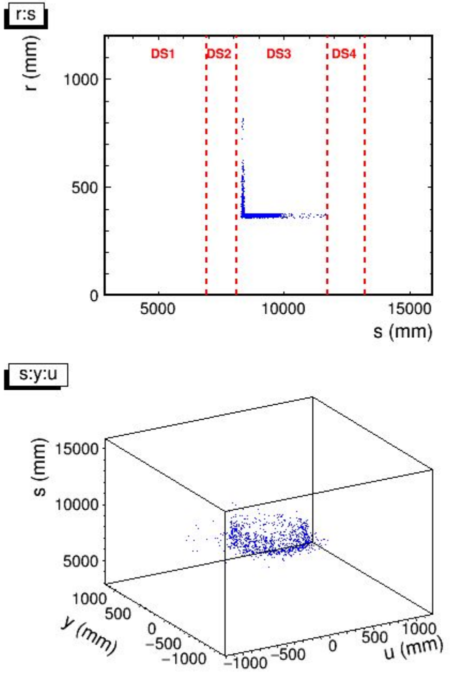


Federica's result: $(81 \pm 9)\ e^-$ at VD9

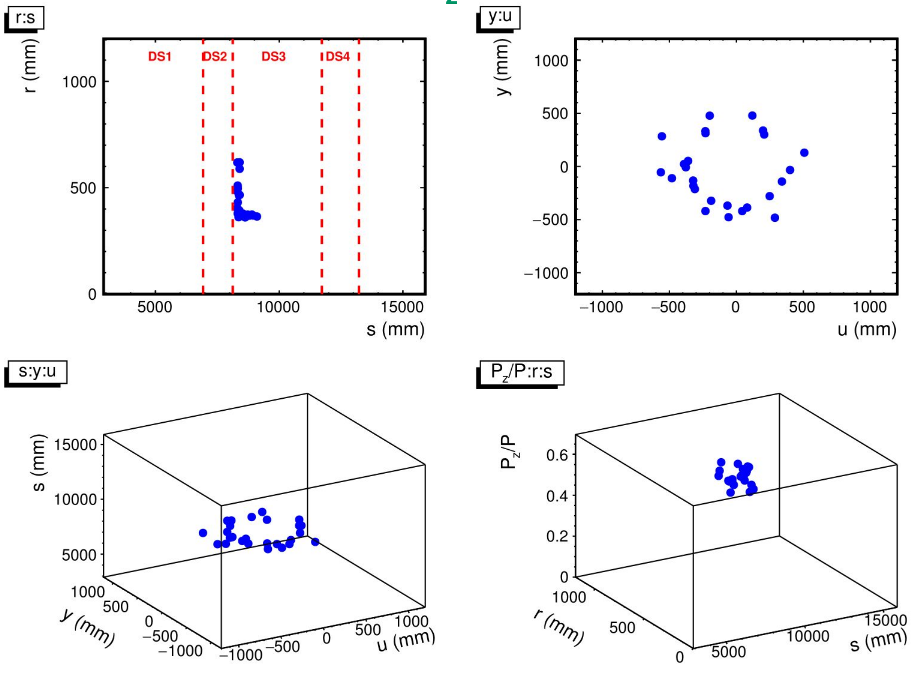
My result: $(66 \pm 8)\ e^-$ at VD9

Default case: Distribution of e⁻ hits in the tracker volume

Cut: p>95 MeV/c



After cuts:
104<p<106 MeV;
$0.4<p_z/p<0.7$



Comparisons and Background

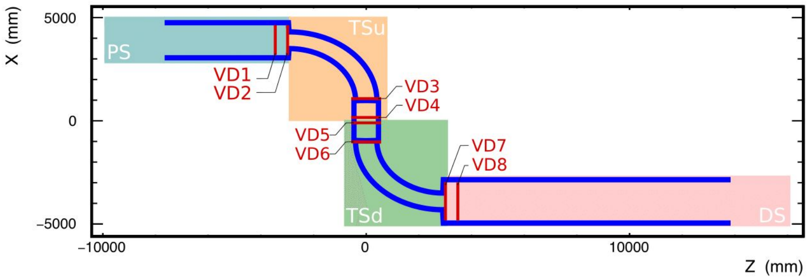
	original e^-	e^- VD9	e^- tracker before cuts	e^- tracker after cuts	Background
Default Mau10	1997 ± 45	66 ± 8	6717	26	$(2.0 \pm 0.6) \times 10^{-4}$
up	2000 ± 45	225 ±15	18531	118	$(9 \pm 1) \times 10^{-4}$
down	1996 ± 45	22 ± 5	4745	40	$(3.0 \pm 0.3) \times 10^{-4}$
Right 15°	2000 ± 45	90 ± 10	5548	25	$(1.9 \pm 0.7) \times 10^{-4}$

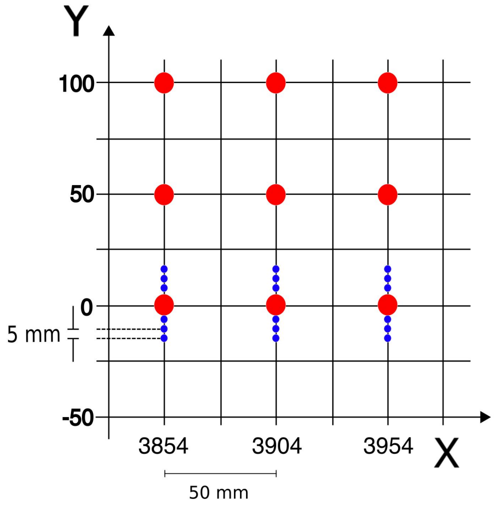
- ➢ Consistent results with previous studies for default case: → Federica's: $(1.9 \pm 0.1)\ 10^{-4}$
- ➢ The only case where the estimated background changes significantly is the displacement up
- ➢ This is expected because electrons drift higher up than muons in the TS3 region, due to a higher velocity distribution corresponding to the same momenta (→ same Larmor radii)

Beta source test

We cannot measure the field inside TS, so we need a sensitive test of TS misalignments: this can be done using low momentum electrons

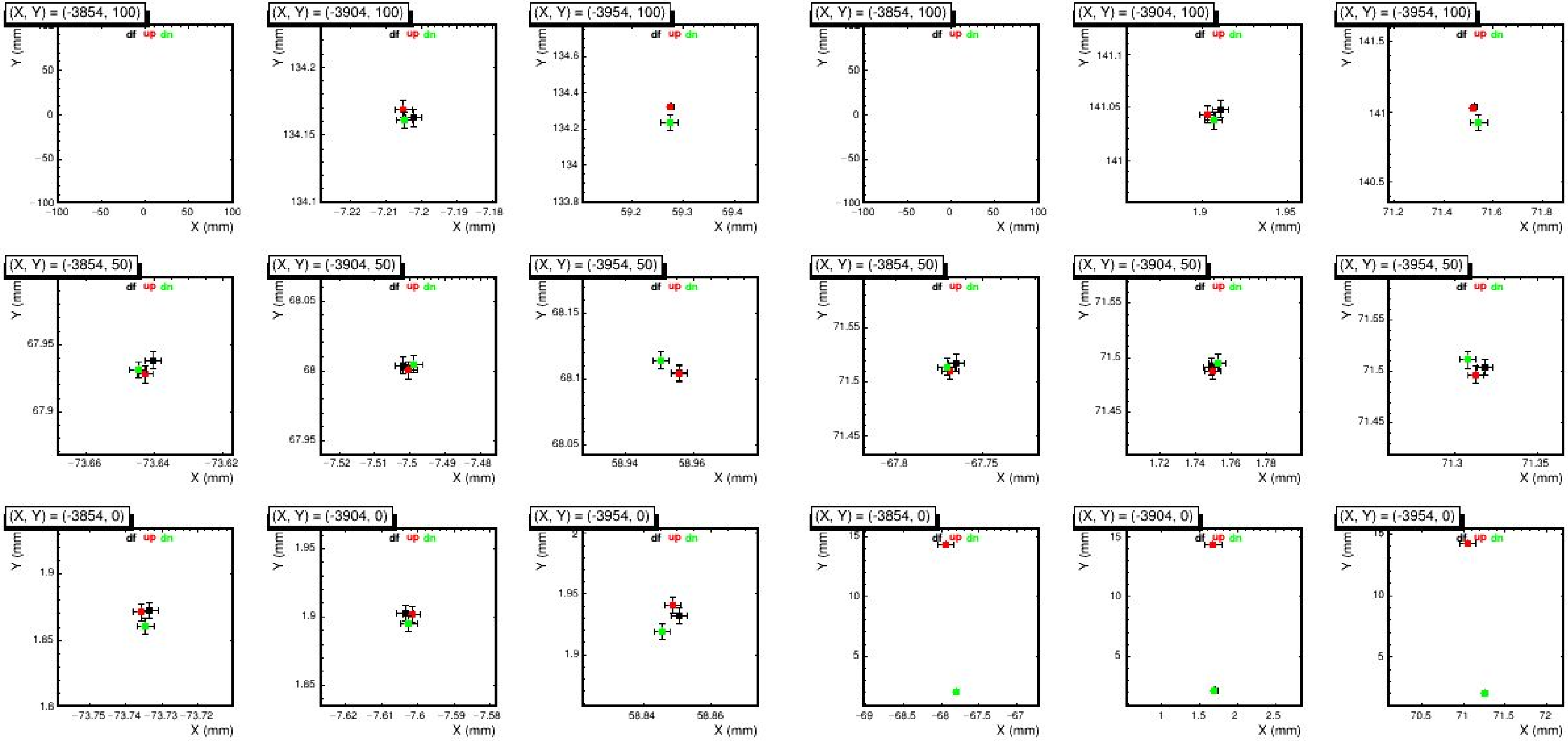
- Source: $^{90}Sr/^{90}Y$
  - No background
  - Good momentum range
- "Virtual detector":
  - (X,Y) resolution: ~300 μm
  - Momentum threshold: 200 keV/c
- 1 Torr air pressure is assumed in the beam line, to ensure that the electrons go through
- For each misalignment, 27 source positions are examined
- Look only at VD3 and VD4 because the TS3 cut is applied between them



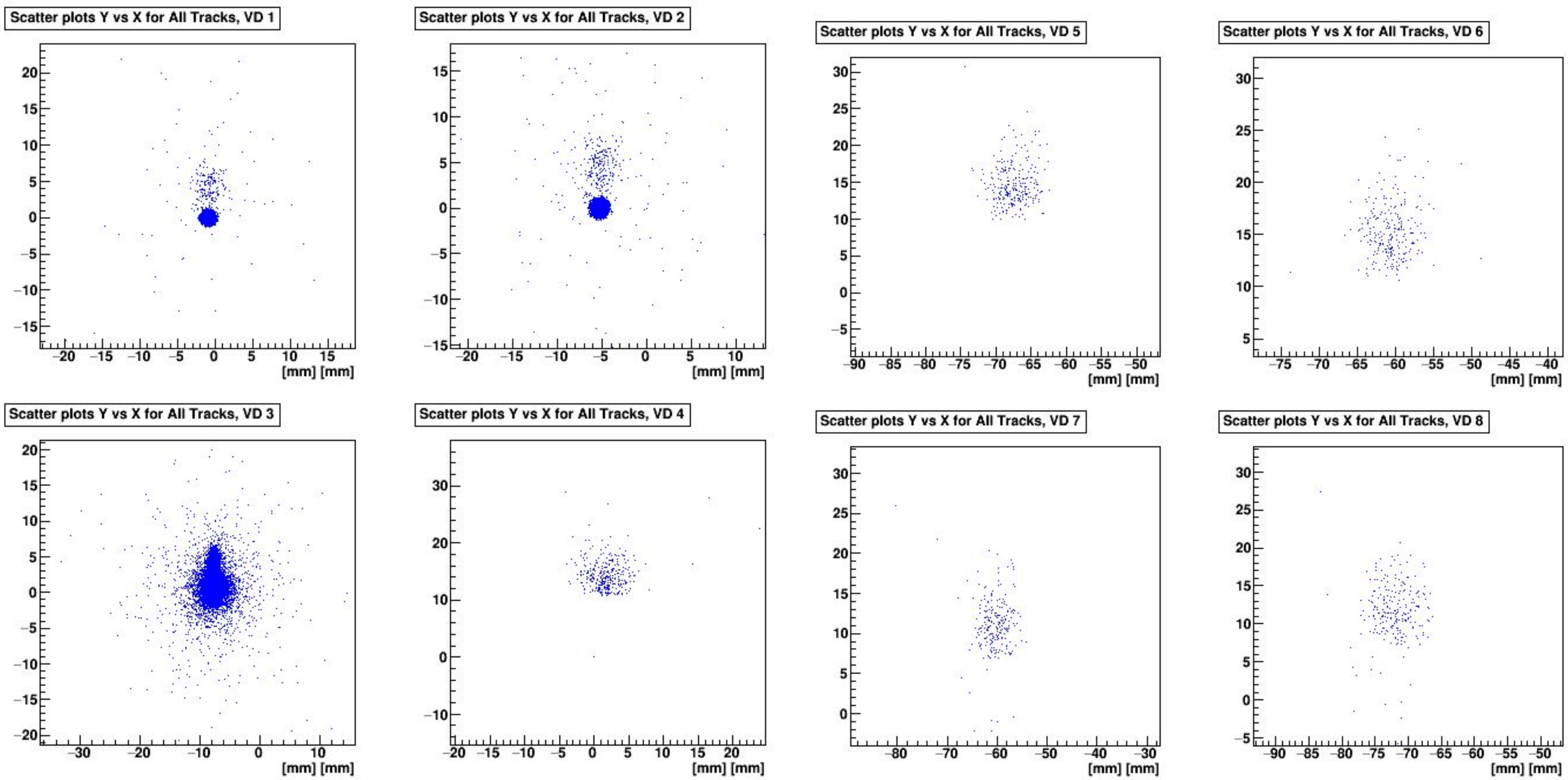


Comparison between default, up and down: steps of 50 mm

VD3 VD4



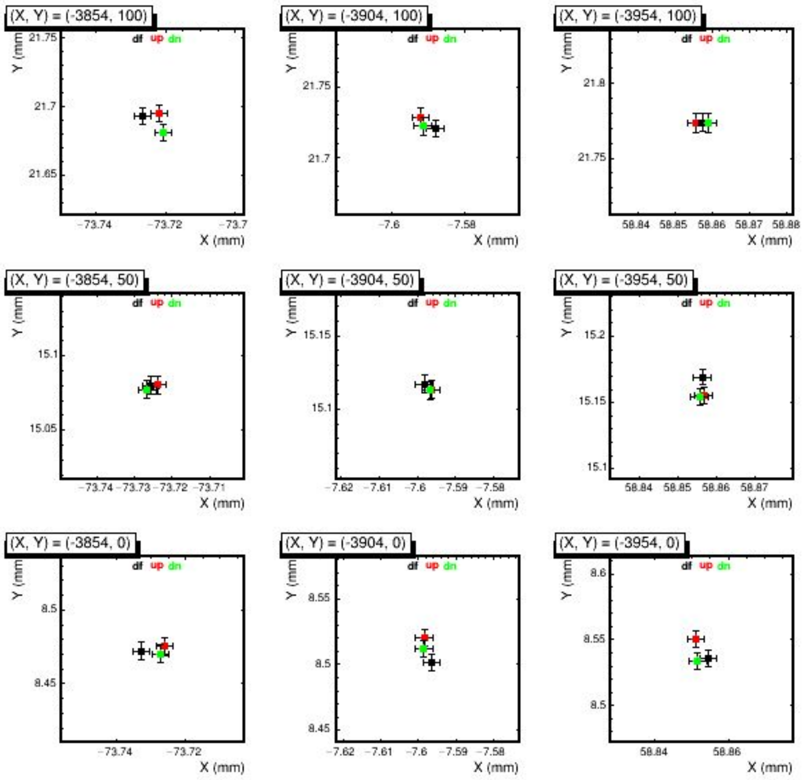
Source location on axis, collimator shifted up, statistics: 47832 @ VD3, 322 @ VD4



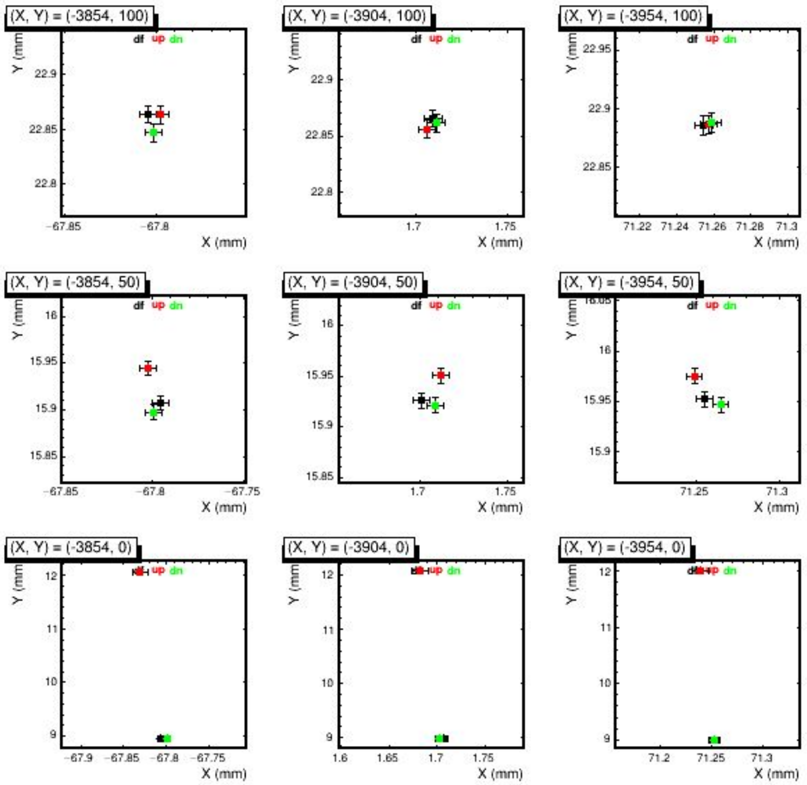
Comparison between default, up and down: steps of 5 mm

Steps above plane:

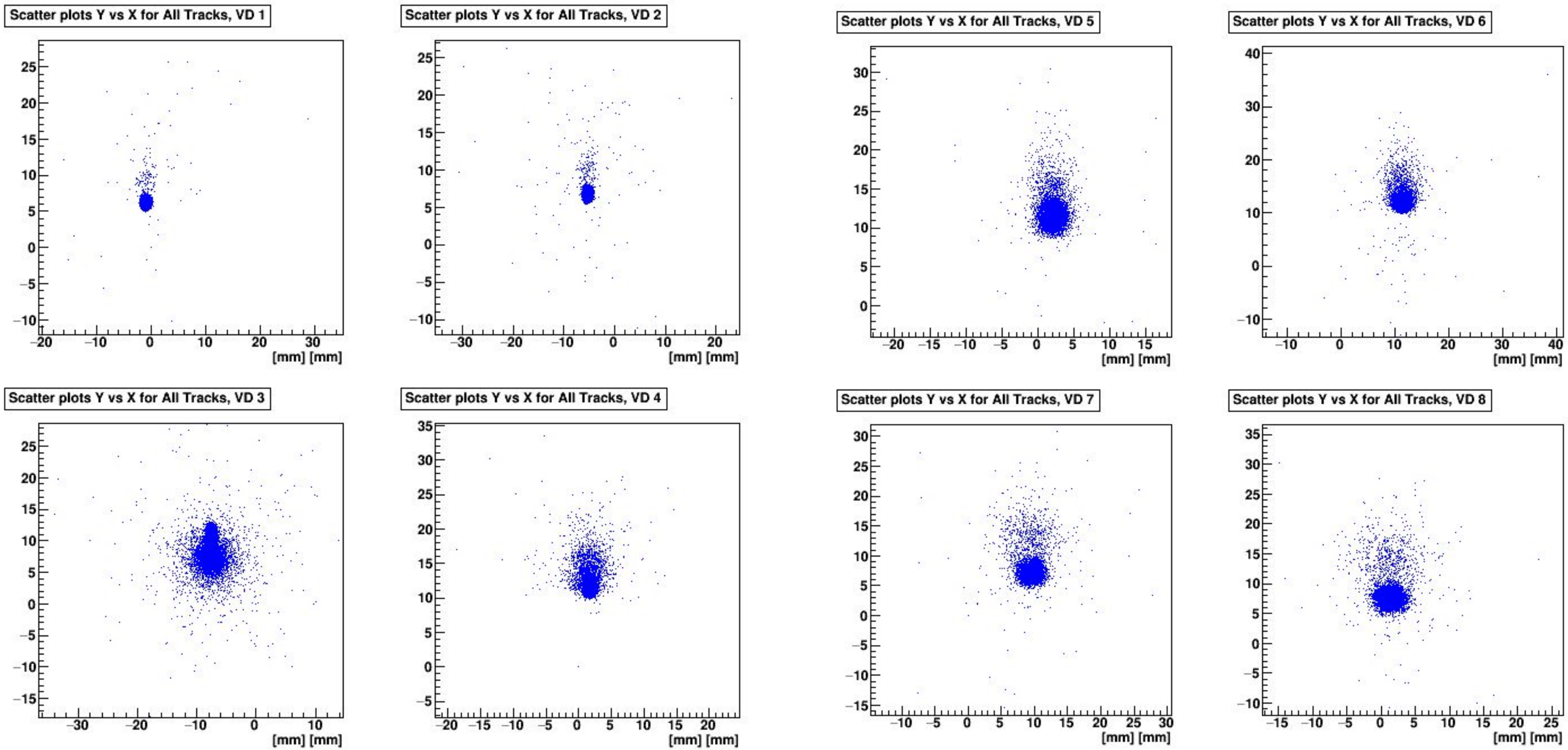
VD3



VD4



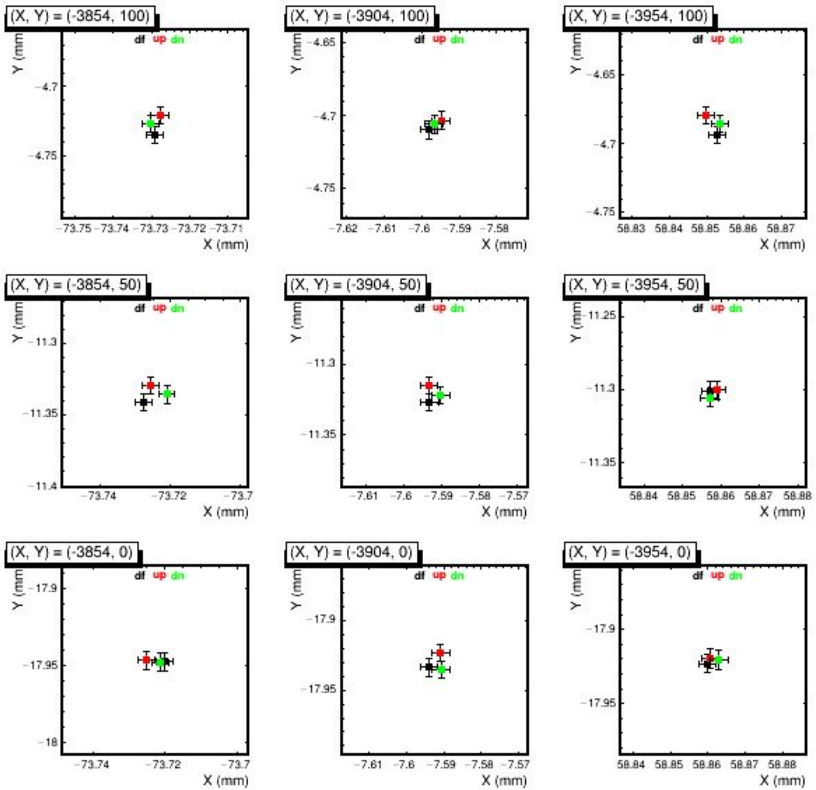
Source location on axis (small steps above plane), collimator shifted up, statistics: 47704 @ VD3, 8045 @ VD4



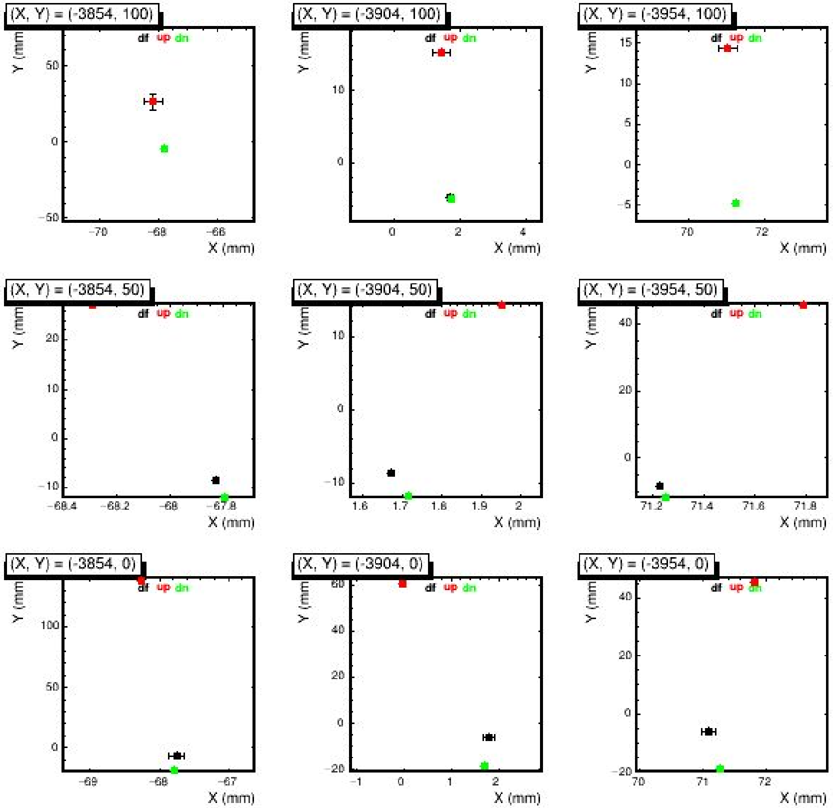
Comparison between default, up and down: steps of 5 mm

Steps below plane:

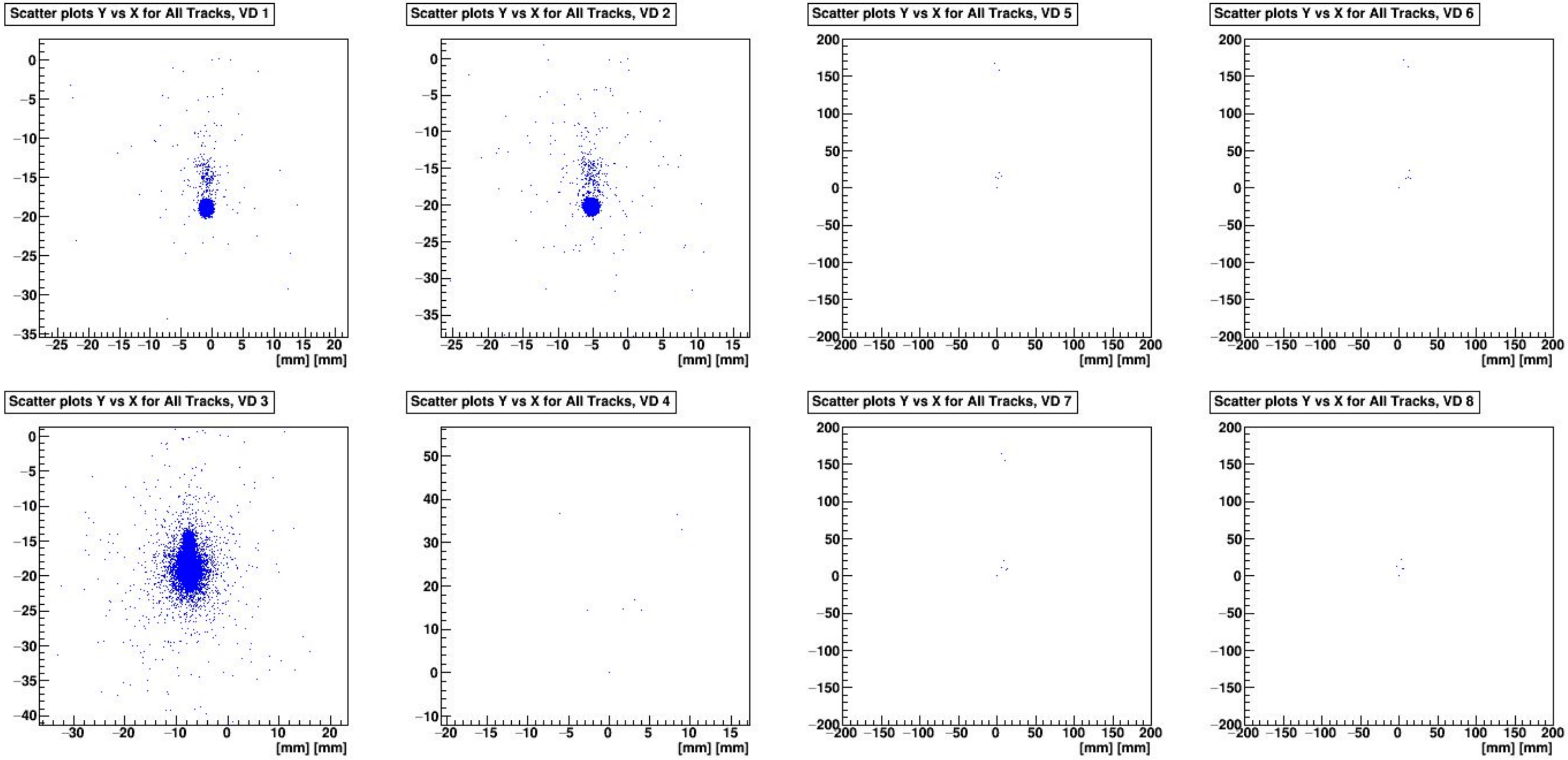
VD3



VD4



Source location on axis (small steps below plane), collimator shifted up, statistics: 47775 @ VD3, 9 @ VD4



Conclusions

- In general, only the up and down shifts and only in some cases can impact significantly the physics parameters of the experiment; rotations do not play an important role.
- Stopping rates: up and down shifts are important due to a geometric effect → the beam arriving at the stopping target is significantly displaced by the shifts.
- Beam electrons background: sensitive to collimator misalignments, increases as the collimator is shifted upwards → electrons drift higher up than muons in TS3.
- Beta source test: sensitive to collimator shift up → after the collimator the spots are cut and the corresponding <Y> is shifted up.
- The above findings for largely exaggerated misalignments of the TS3 collimator guarantee that the collimator design provides a safe operation point for the experiment.

Thank you for the attention