Muon Flux Measurement
with Heavy Ion Runs

Attestation Seminar

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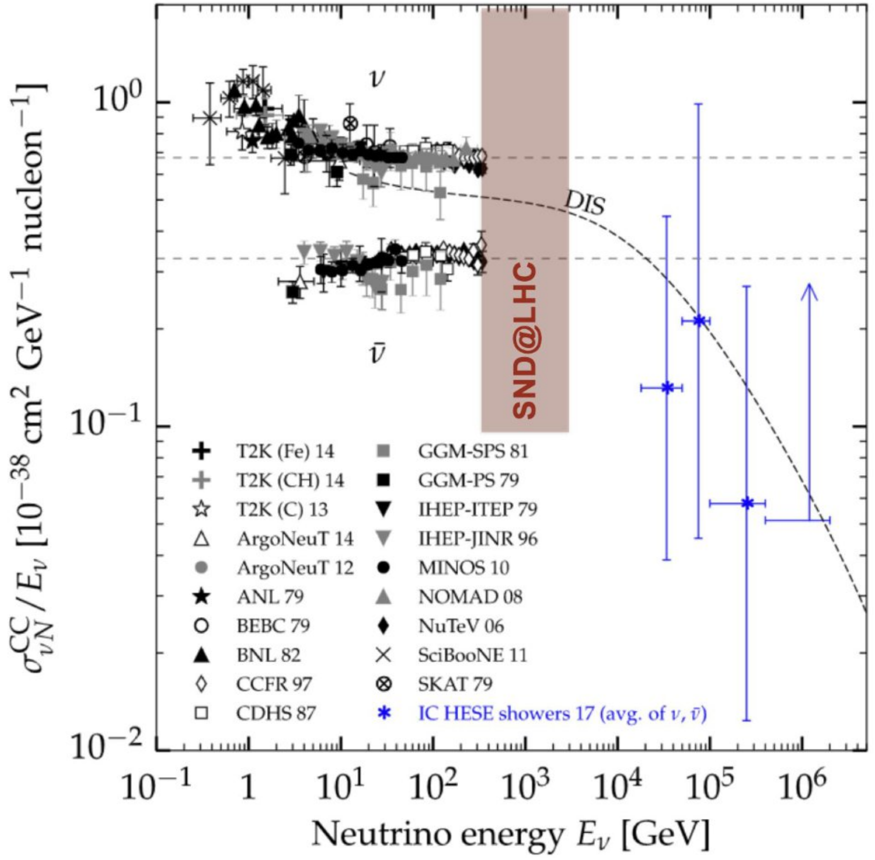
I) SND@LHC

Introduction and detector outline

SND@LHC

Physics Goals

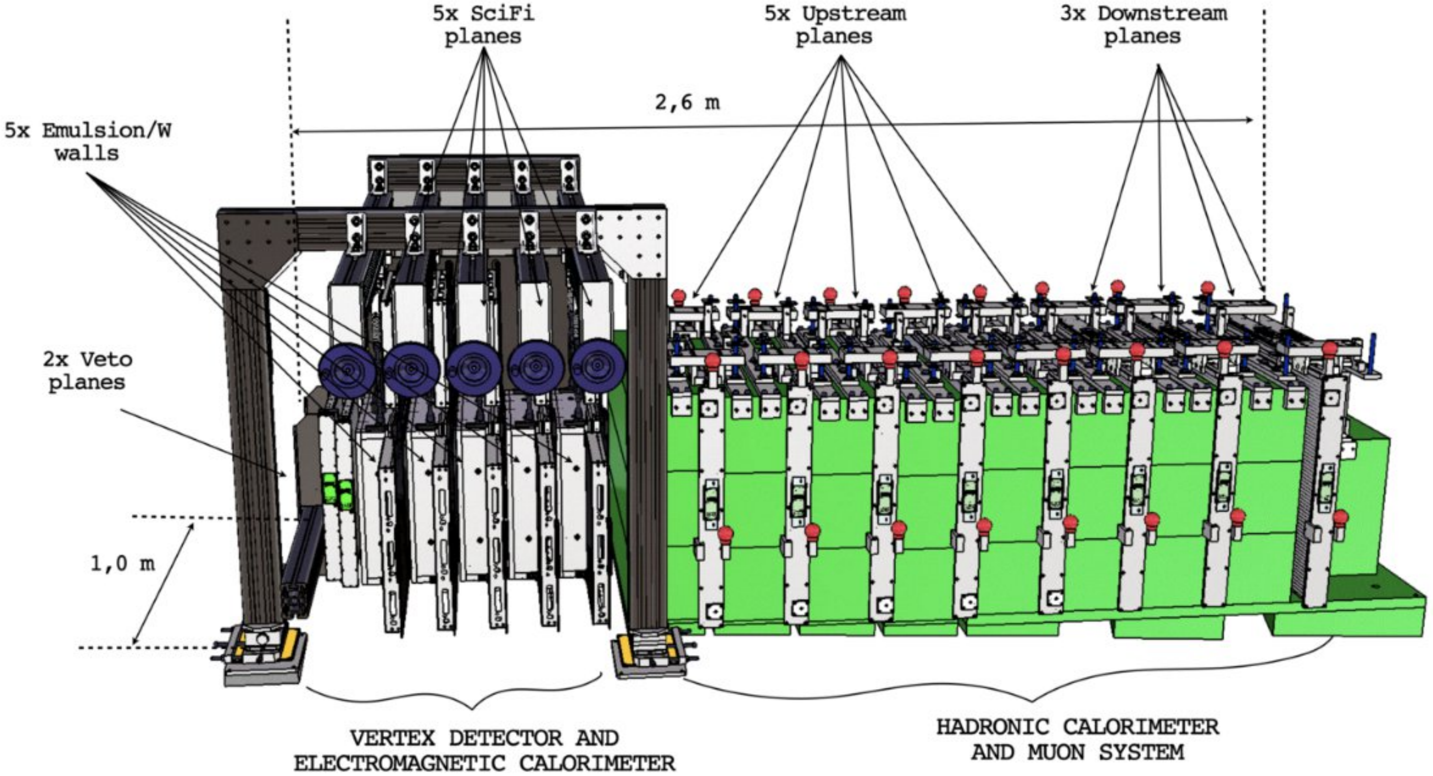
- ***Pave the way for future collider neutrino experiments:***
  - Study neutrinos of all flavours in the previously unexplored pseudorapidity range $7.2 < \eta < 8.6$.
  - Fill the gap in interaction cross section measurements of neutrinos between a few hundred GeV to a few TeV.
- ***Study heavy quark production***
  - In this η range, neutrinos are produced from the decay of heavy quarks such as charm decays ($c \rightarrow s + W^{\pm}$)
  - Constrain the gluon parton distribution function (*gPDF*) in the low Bjorken-x region.
- ***Search for feebly interacting particles (FIPs)***
  - Theorized to be produced in the proton-proton collisions.
  - More than the predicted number of elastic collisions will hint at light dark matter scattering events.



Detector Layout

Main components

- ***Veto system***
  - Three planes (two before 2023) of scintillator bars.
- ***Vertex detector (Scifi)***
  - Five walls of four emulsion cloud chambers (ECCs)
  - After each wall, there is plane of (horizontal and vertical) scintillating fibres for precise particle tracking.
- ***Muon system***
  - Eight iron blocks, each followed by a plane of scintillator bars.
  - ➢ ***Upstream (US)*** — First five pairs of Fe block and scintillator plane (Fe-Scint pairs).
  - ➢ ***Downstream (DS)*** — Last three Fe-Scint pairs (and additional fourth scintillator plane).



Muon Flux

- Muons are the main source of background to CC neutrino interactions.
- The emulsion films require regular replacements.
  - Informs the frequency at which the emulsions should be replaced if their use in ion runs is decided upon.
- It enables the study of muon production and propagation, as well as track reconstruction performance across a wide energy range and LHC optics.

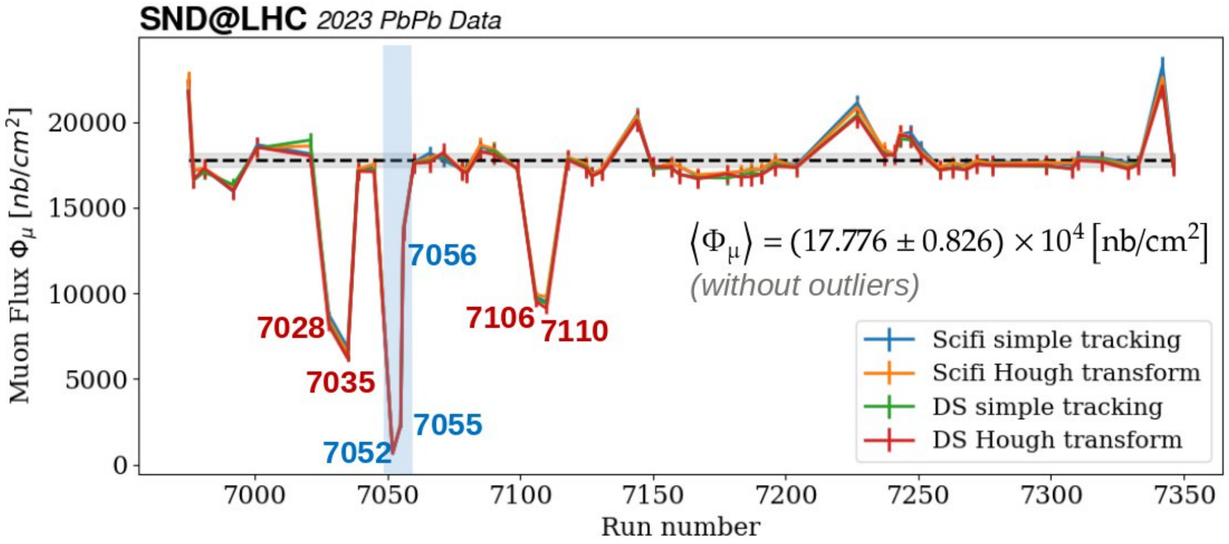
II) Initial Constraints and First Results

Strict track selection cuts and their suitability

Analysis with Tracks of Small Angles

Status from previous collaboration meeting

- Only ion runs from 2023 were analyzed.
- All angles constrained to 20 mrad
  - Both for efficiency calculation and track count.
- ***Overall consistent flux, but with presence of outlier runs with high or low flux.***



Issues:

- Limitation of 20 mrad leaves out a large fraction IP1 muon flux contribution.
- Outliers need to be explained and removed if that's appropriate.
- DS efficiencies are ~78%.

➢ *Luminosity differences between eos and LHC supertable.*

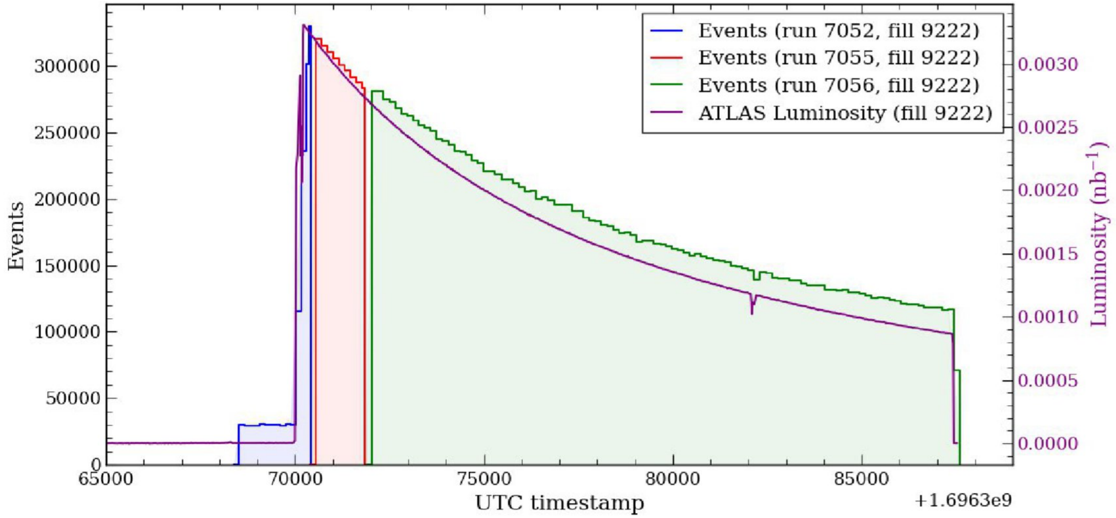
➢ *Luminosity uncertainty was still unknown.*

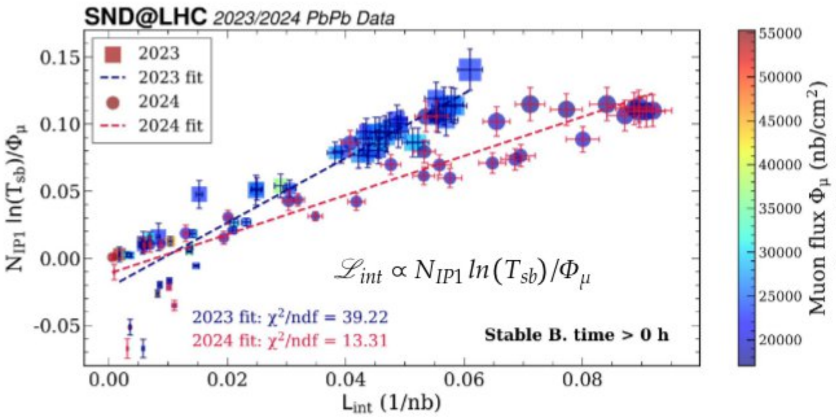
In order to equalize the muon flux across all measurements:

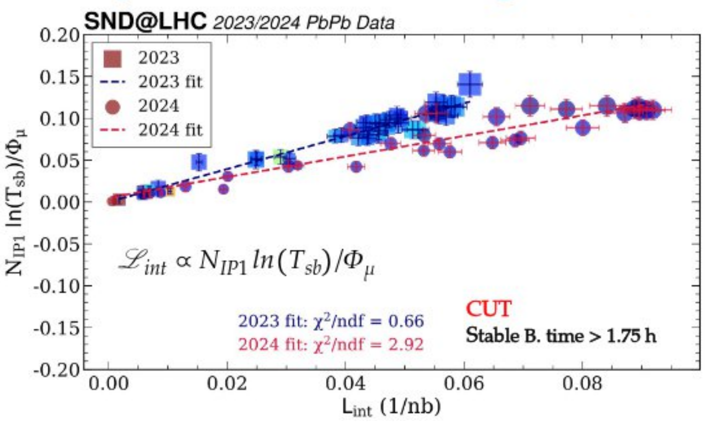
- *the set of constraints had to be very strict and finely tuned.*
- *equalization was achieved under circumstances of very low DS efficiency.*

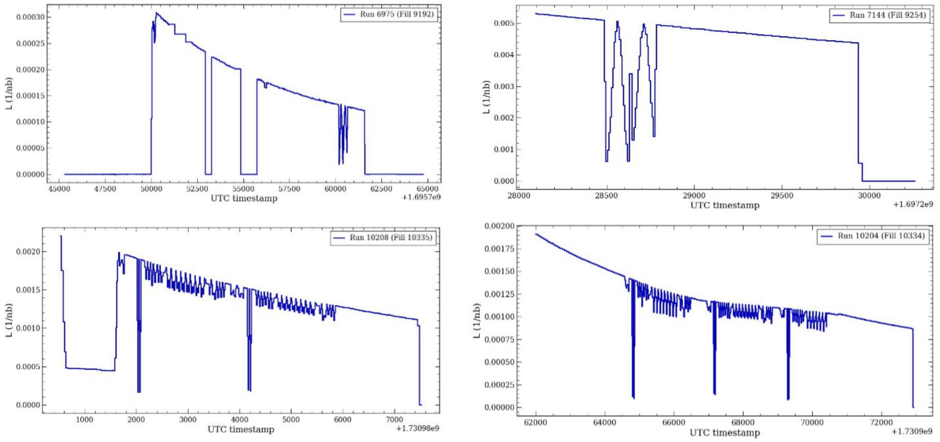
Outliers

- ***Some low-flux outliers*** corresponded to Van der Meer scan fills and were removed.
- ***Remaining three low-flux outliers*** had fluxes that summed to the expected value.
  - They were identified to correspond to the same fill and were combined.
- ***High-flux outliers*** were identified to deviate from the approximate relation $\mathscr{L}_{int} \propto \mathrm{N}_{\mathrm{IP1}} \ln(\mathrm{T}_{\mathrm{sb}})/\Phi_{\mu}$
  - Manual inspection of luminosity plots justifies their removal from the analysis
- ***No remaining outliers!***









Addition of 2024 PbPb Runs

First impression

✓ **Using the efficiencies calculated from 2023 data seems to work well!**

✗ Using independently calculated efficiency does not work!

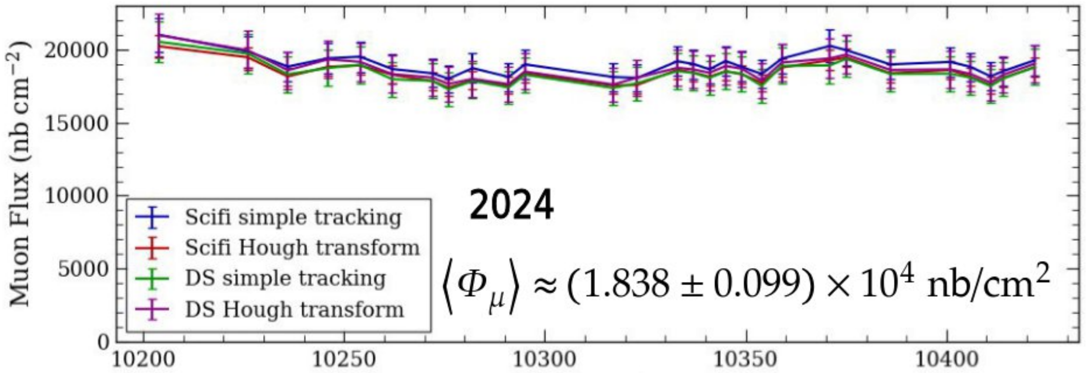
Efficiency calculation is highly sensitive to

– Angle constraint

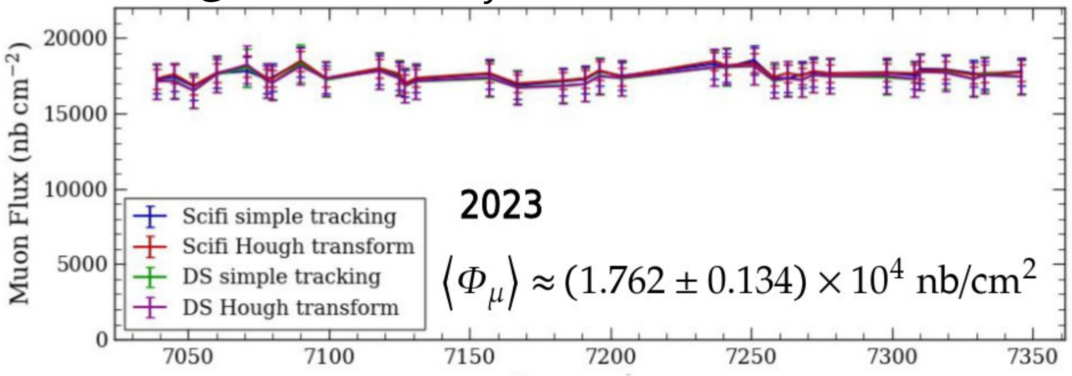
– Year of data collection

(in different ways for different track types!)

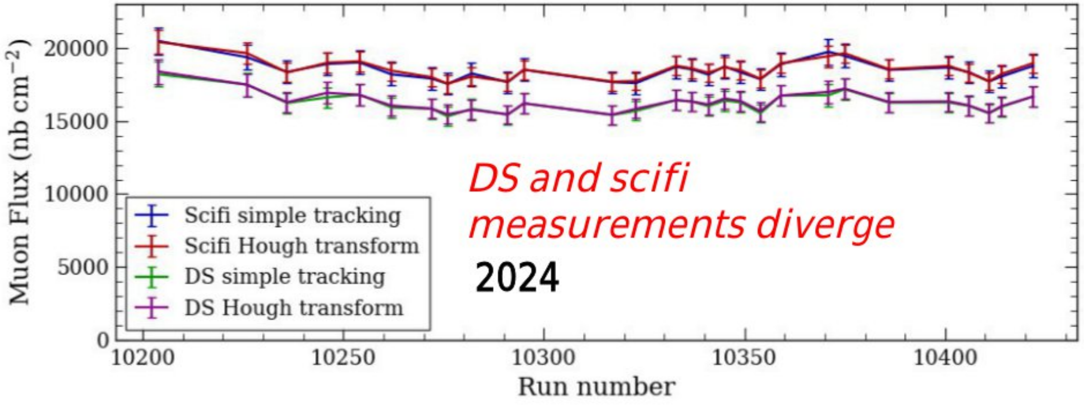
same efficiencies as in 2023



SND@LHC *Preliminary*



independently calculated efficiency for 2024



Key Takeaways so Far

- ***Constraints are too strict*** **—** Consistency between tracking methods can be established with a strict 20 mrad limit.
- ***Constraints are too ad hoc*** **—** They are tailored to specific LHC settings.
  Modifying the method to equalize the flux across system and tracking method require even more unreasonable angle cuts for 2024 runs.

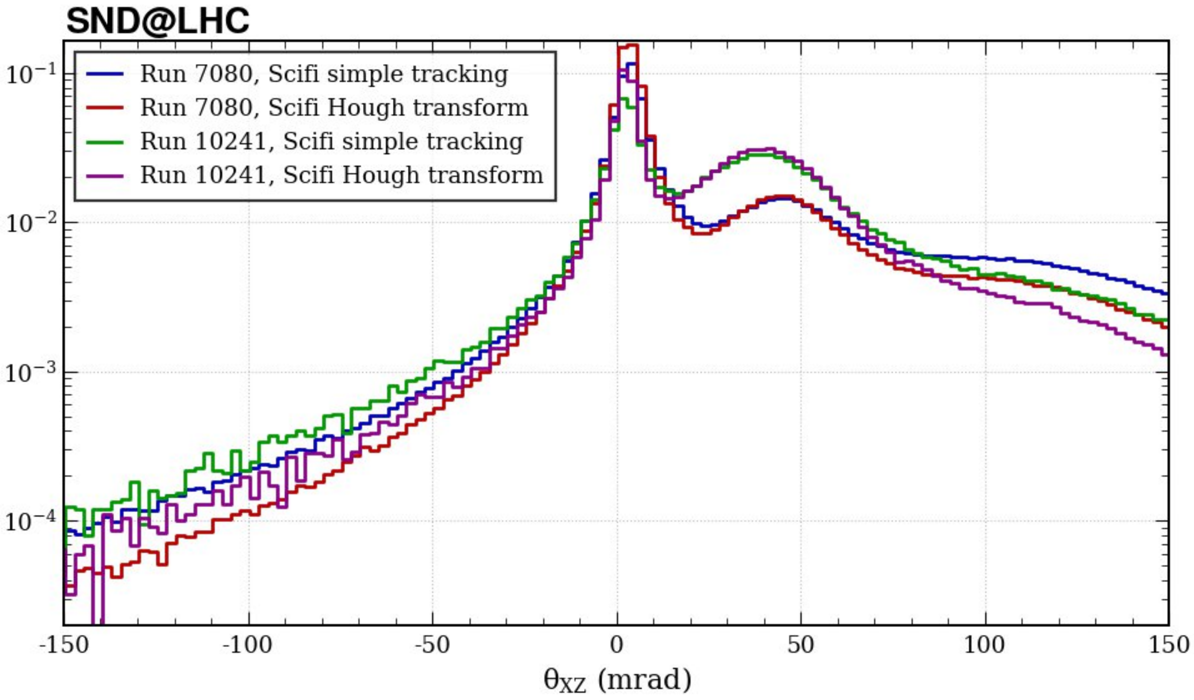
New approach

– Expand to angles of ±80 mrad.

– Address emerging discrepancies stemming from secondary muons not originating from IP1.

– Tune the method so the measured flux of different track types are as close as possible.

– Write any remaining differences as systematic uncertanties.



III) Expansion to Larger Angles (80 mrad)

Loosening constraints to include all IP1 Muons

Initial Setbacks

Concern 1 — Simple tracking finds more tracks than Hough transform, despite having lower reconstruction efficiency. Most prominent at higher angles.

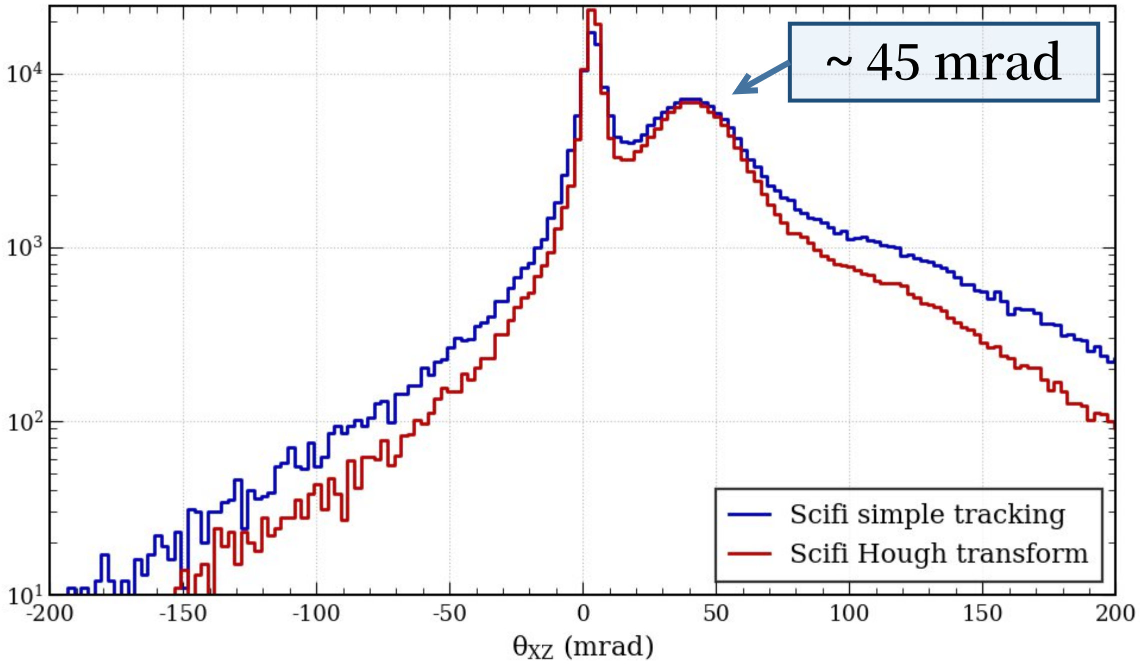
Possibilities

A. Simple tracking finds tracks that it should not.

B. Hough transform does not find tracks that it should.

Case A: *Should already be accounted for by introducing lower Hough tracking efficiency.*
Case B: *Might not have impact on efficiency, if "bad tracks" are not selected as tagging tracks.*

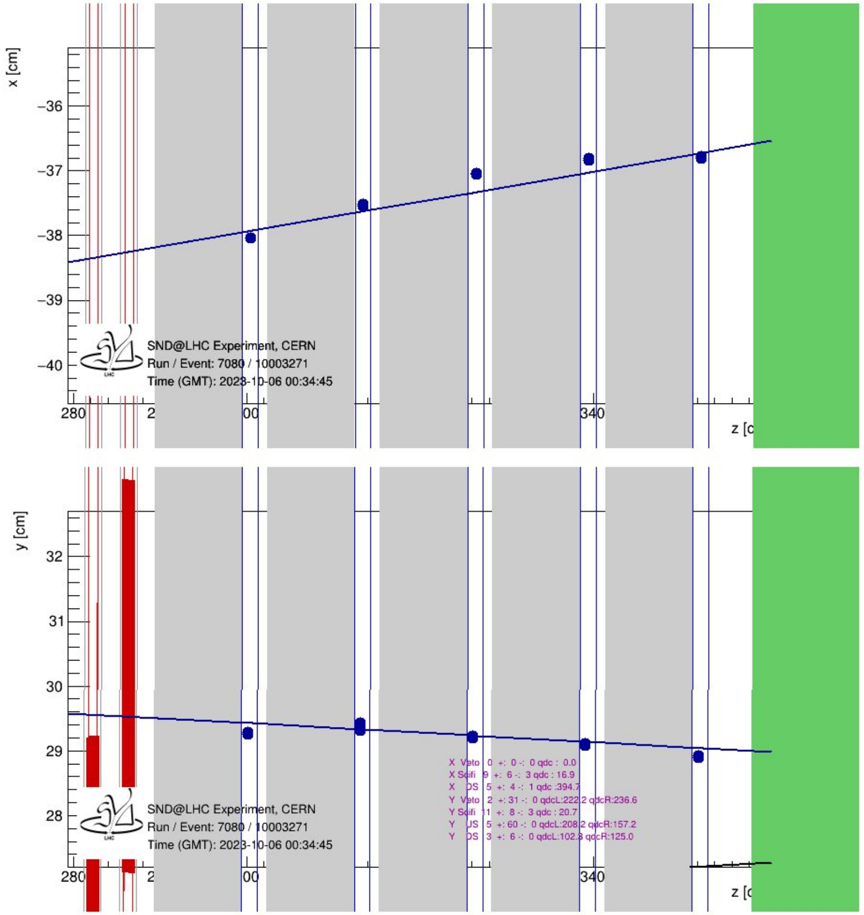
Concern 2 — Tracking efficiency results differ between 2023 and 2024 data
~ 4-6% higher in 2023 for all track types

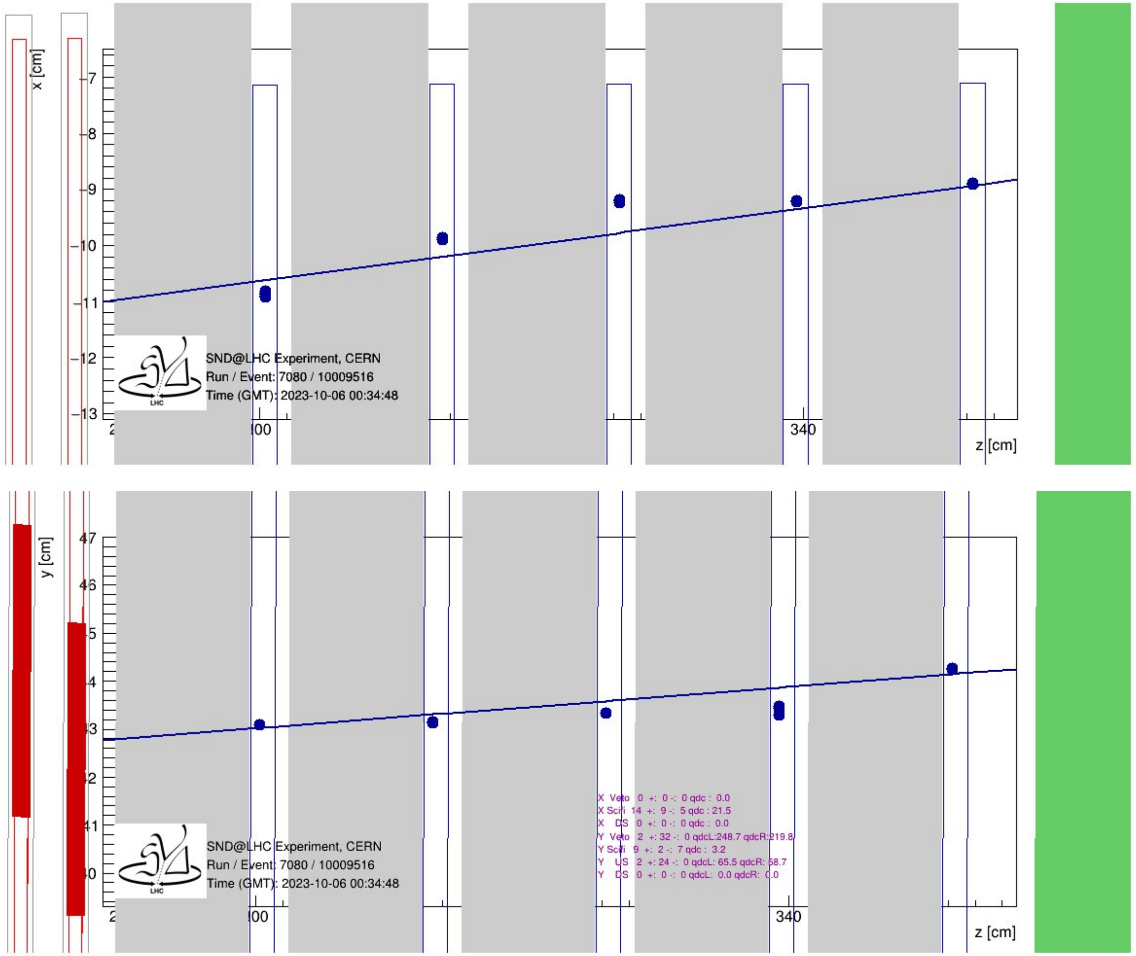


III.1) Excess of ST Tracks

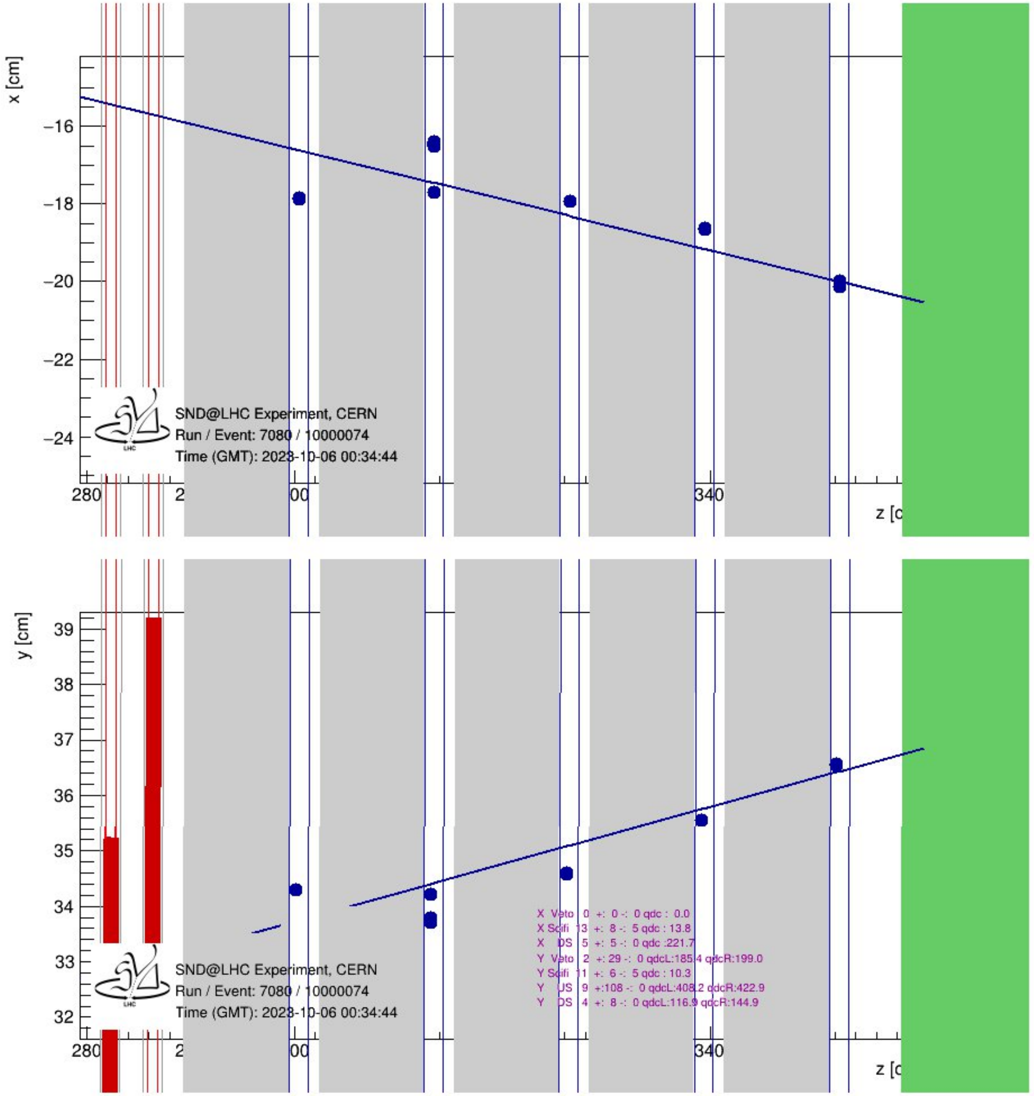
***Event Display* — Events *with a simple tracking track* and *without a Hough track*.**

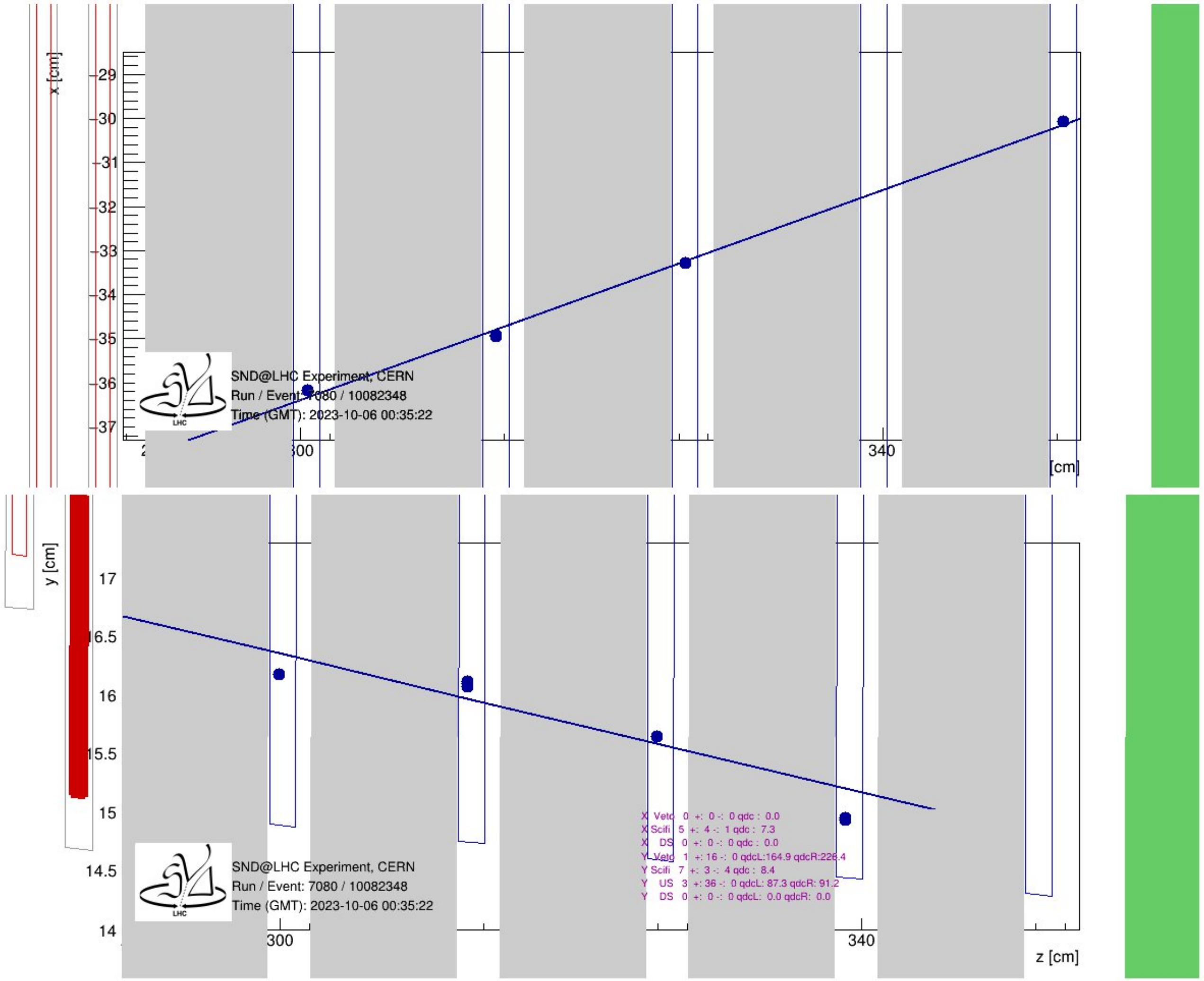
***Frequent Occurence* — Linear fit of curved trajectories (arcs) by simple tracking but not Hough transform.**



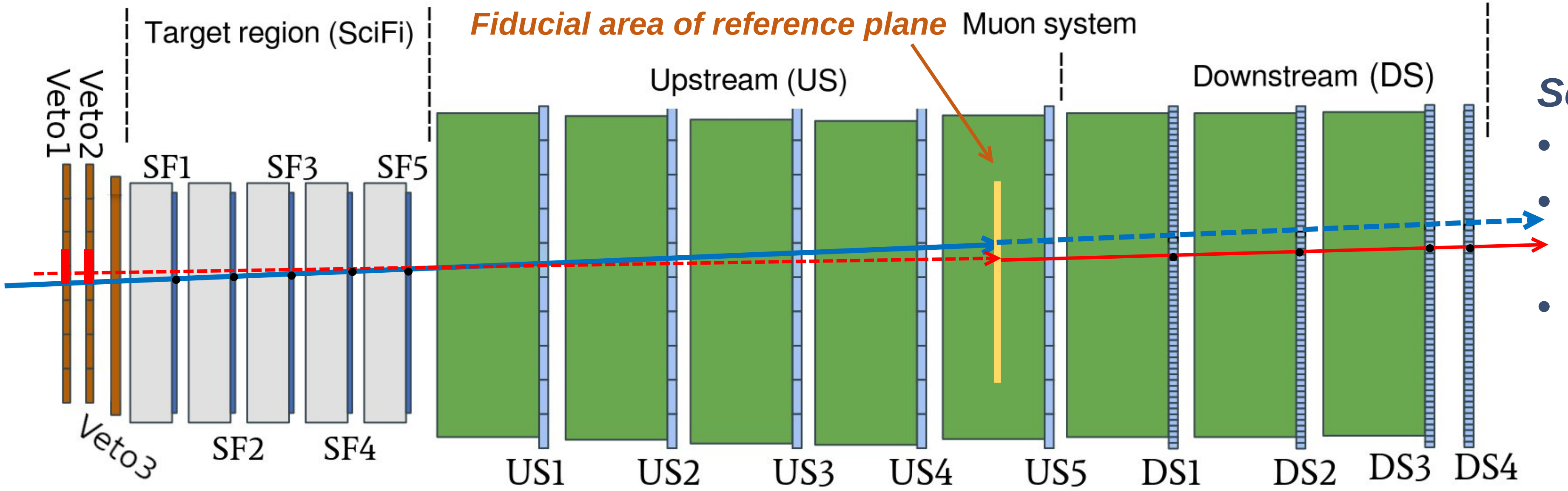


Excess of ST Tracks



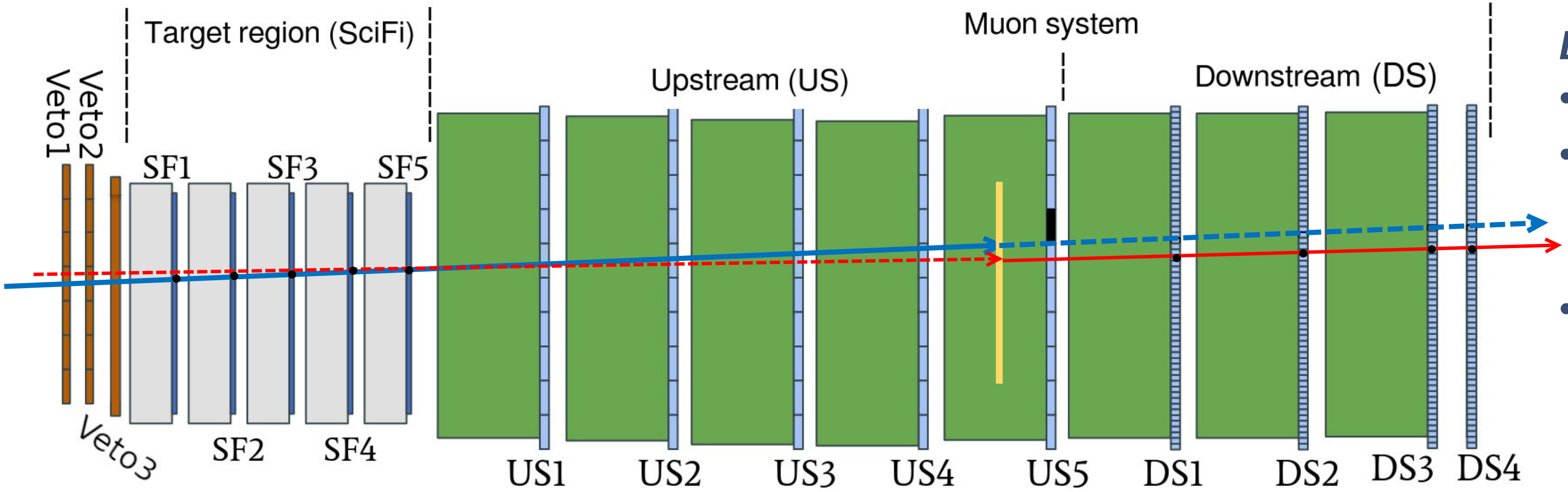


III.2) Measuring efficiency



Scifi efficiency

- DS tagging track $\overrightarrow{DS}$
- $\overrightarrow{DS}$ crosses within activated veto bar.
- A candidate scifi track $\overrightarrow{SF}$ and $\overrightarrow{DS}$ both cross a reference plane within 3 cm



DS efficiency

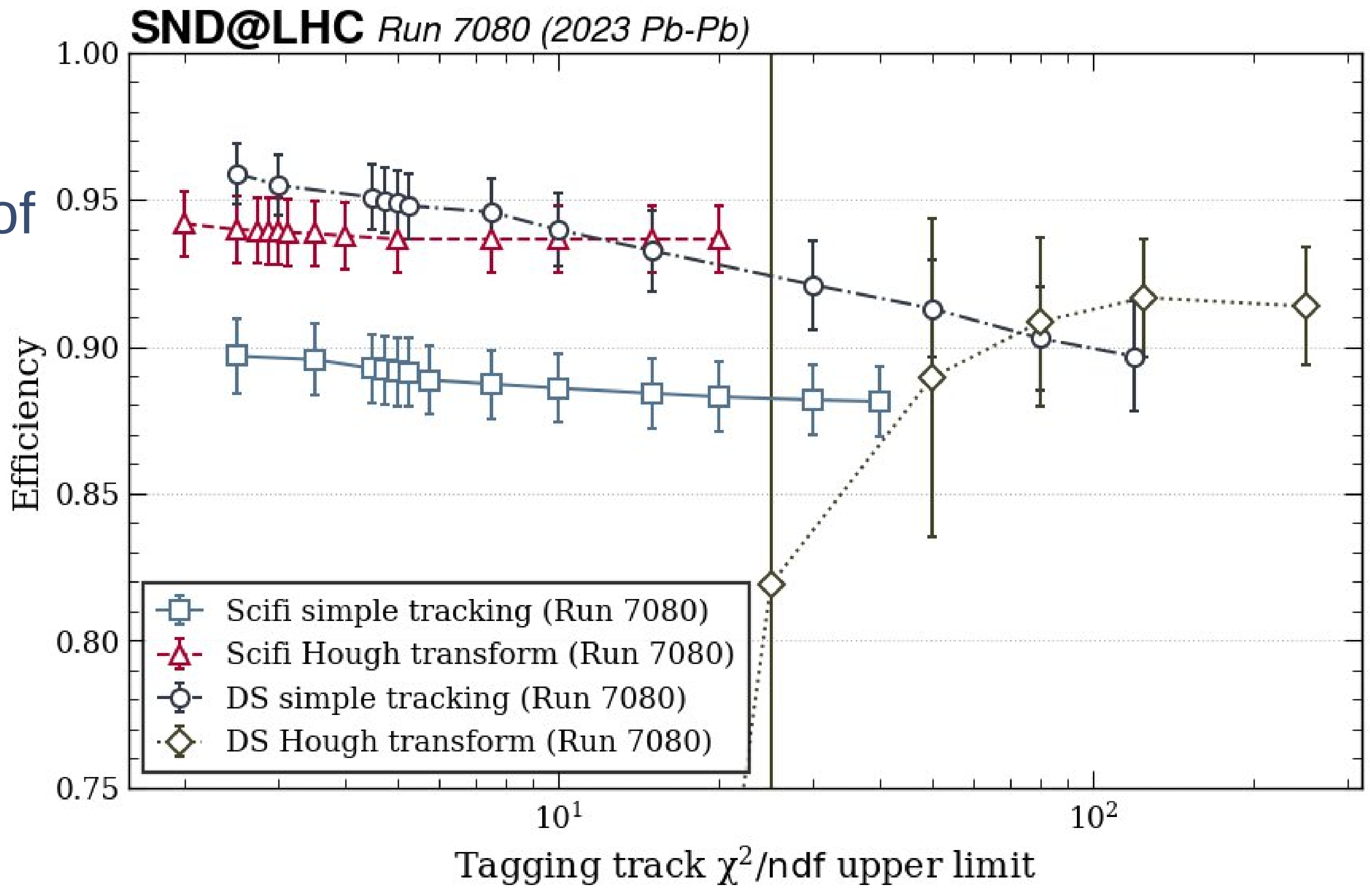
- Scifi tagging track $\overrightarrow{SF}$
- $\overrightarrow{SF}$ crosses within activated US5 bar and within DS4 acceptance.
- A candidate DS track $\overrightarrow{DS}$ and $\overrightarrow{SF}$ both cross a reference plane within 3 cm

χ^2/ndf constraint

Used in muon flux measurement for 2022 proton runs.

***Motivation* —** Ensure a reliable indication of the presence of a passing muon in the opposite detector system.

- Mostly unnecessary for Scifi tracking.
- Not well understood in DS tracking.
  - ***SF HT tracks of lower chi2ndf are worse at predicting a DS HT tracks?***
  - ***Strict constraints can deem DS ST more efficient than all other methods?***



***Conclusion* —** No chi-squared constraints are placed at this moment.

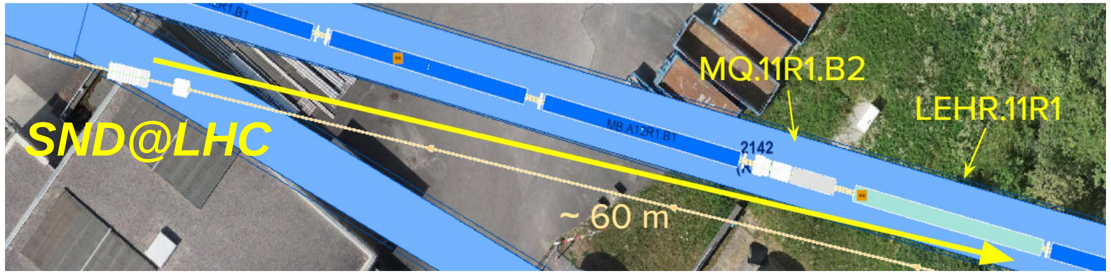
Interactions Along the Beamline

Different efficiencies for data of different years (calculated in identical way):

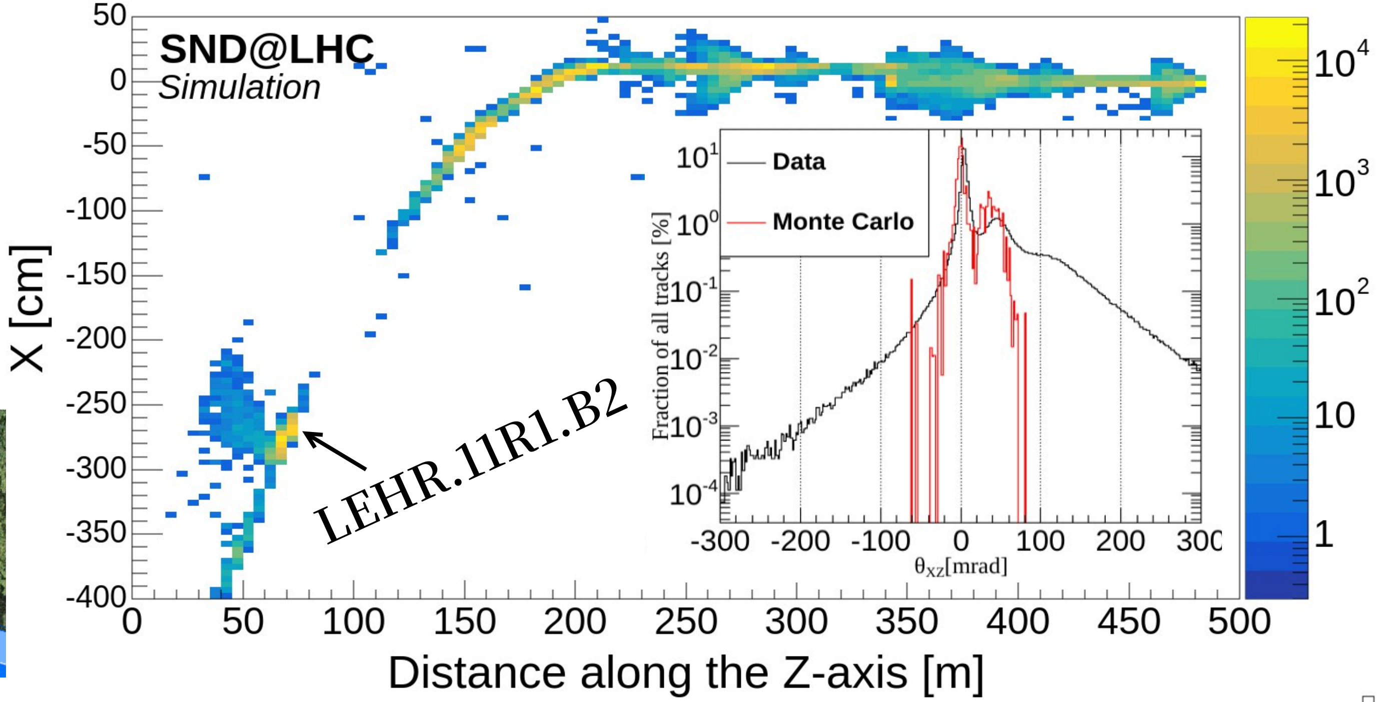
– ***Most probable reason —*** Changing the LHC settings introduces other muon production and deflection mechanisms.

– ***Known example —*** Interacting beams with collimator LEHR.11R1 produces mesons (kaons and pions) that decay to muons, which are then deflected by magnets towards the detector.

Track type	Run 5888 2023 p-p	Run 7080 2023 Pb-Pb	Run 8329 2024 p-p	Run 10241 2024 Pb-Pb
SF ST	0.887 ± 0.008	0.882 ± 0.009	0.887 ± 0.012	0.849 ± 0.008
SF HT	0.955 ± 0.006	0.937 ± 0.009	0.921 ± 0.009	0.877 ± 0.011
DS ST	0.913 ± 0.007	0.875 ± 0.020	0.896 ± 0.010	0.816 ± 0.022
DS HT	0.923 ± 0.011	0.890 ± 0.022	0.913 ± 0.015	0.841 ± 0.016



Distribution of beam interactions



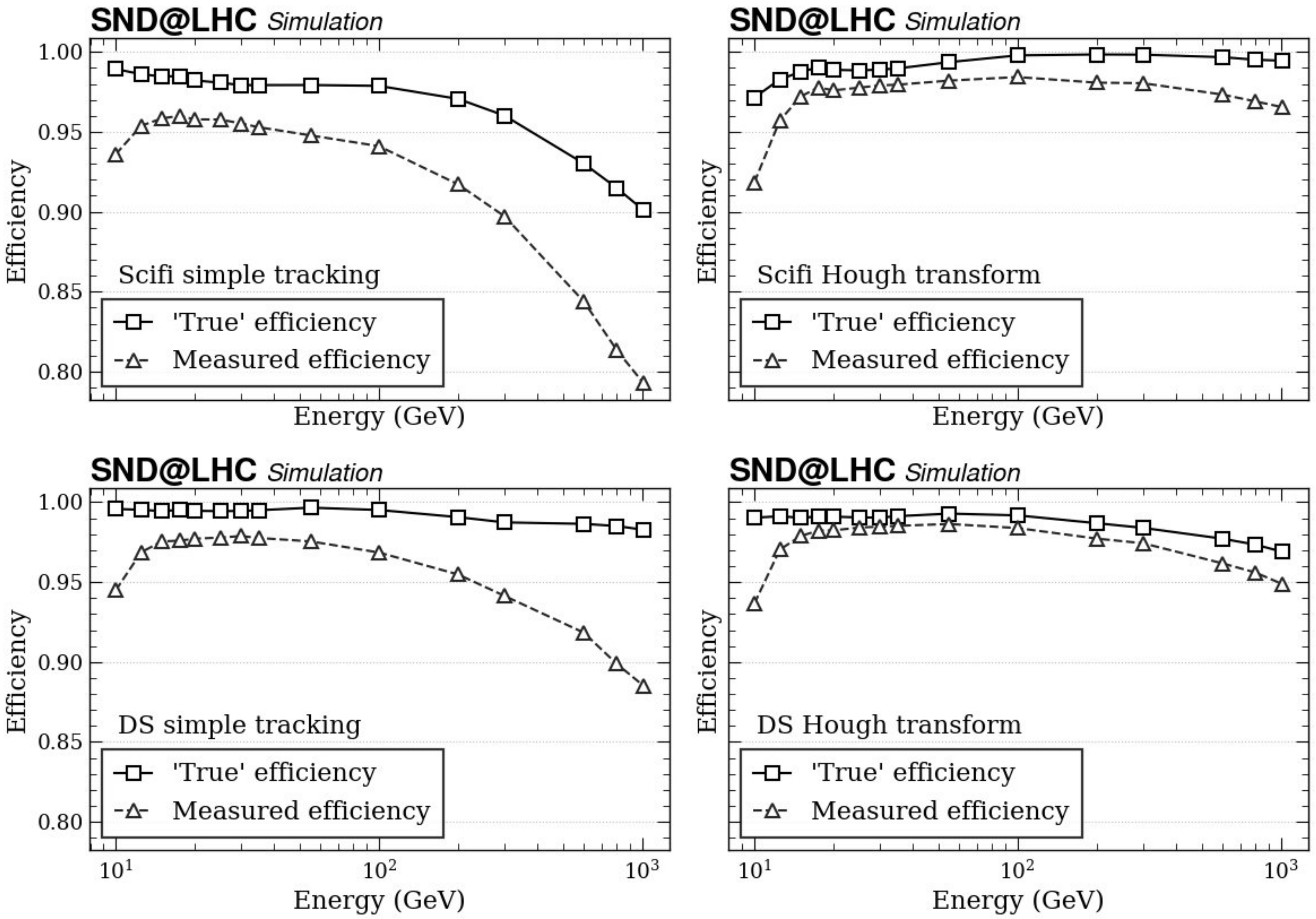
Measured vs 'True' Efficiency

Reminder

- ***True efficiency:*** *Calculated with the Monte Carlo method.* *(3H and 3V MC points)*
- **Measured efficiency:** *Calculated with tagging track method (applicable to data).*

Lower efficiencies at higher energies

➢ ***Possibility***: Higher concentration of low-energy muons in 2024 LHC configuration.

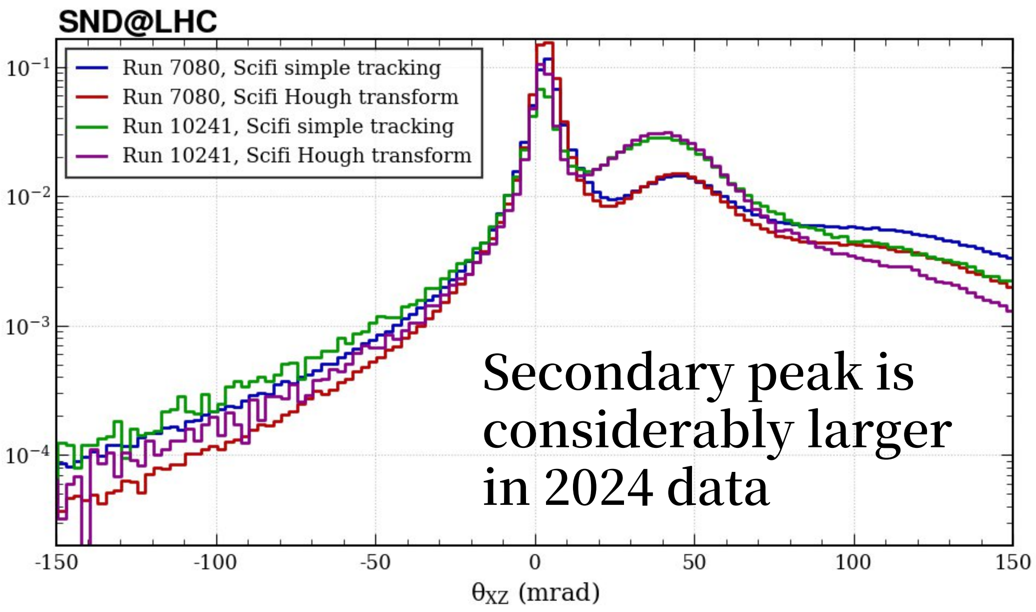


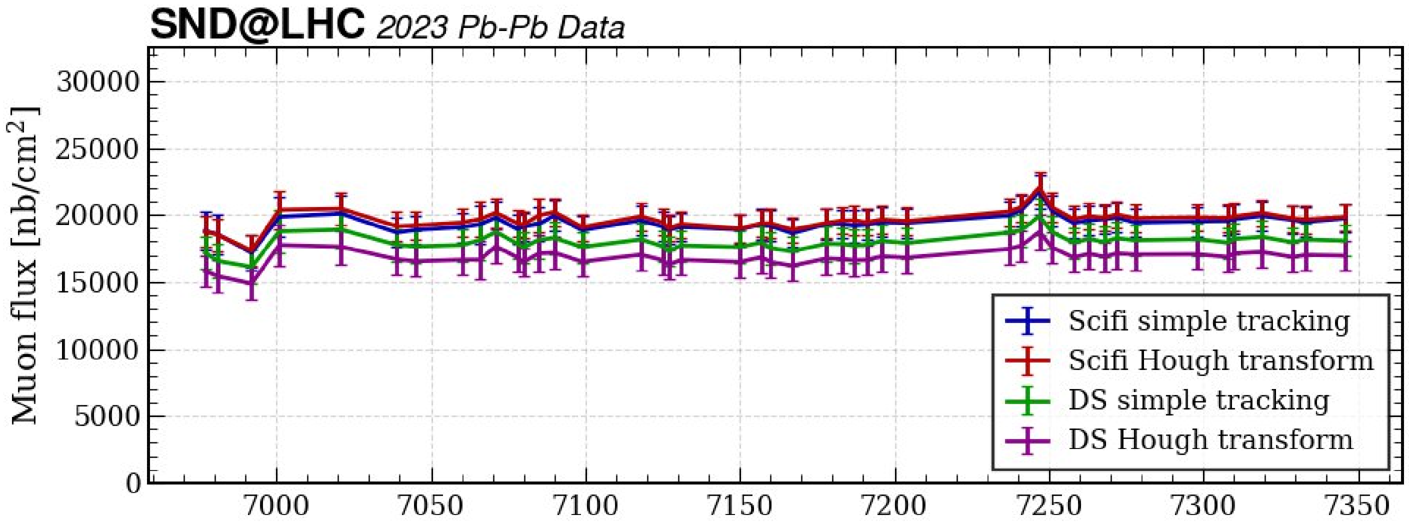
Muon Flux *(Tracks with up to 80 mrad)*

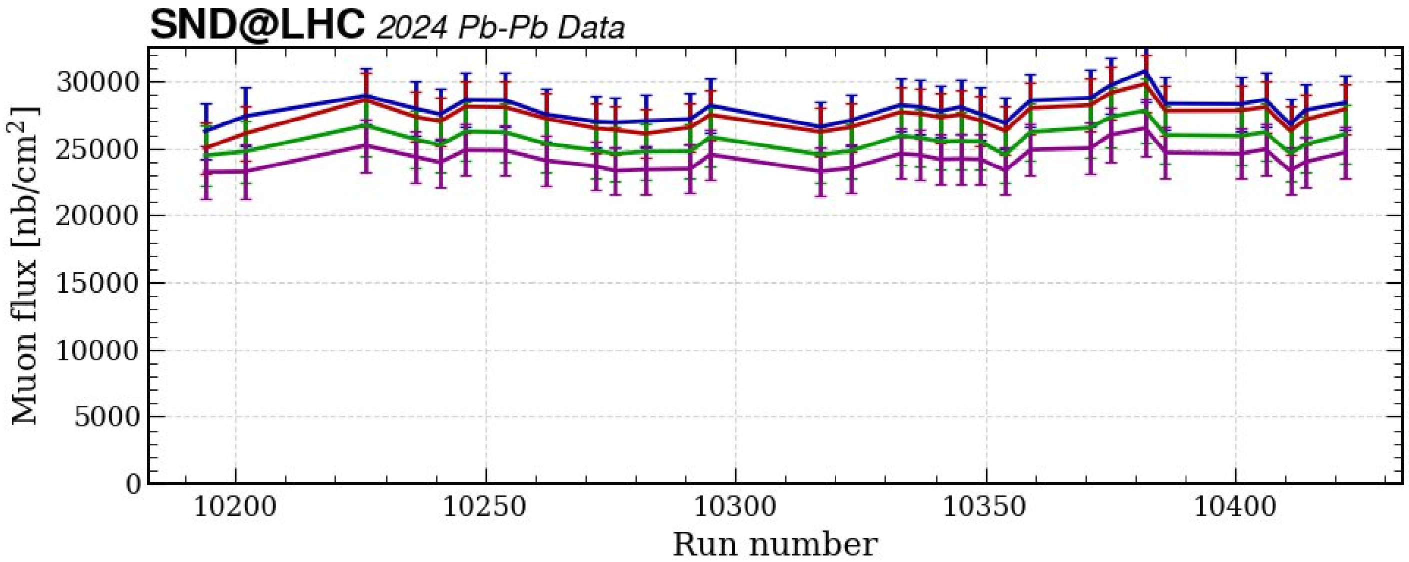
Factor of increase from 2023 to 2024 is ~1.85.

- It was much lower (~1.05) with a 20 mrad constraint.

Discrepancies between tracking algorithms still exist.







Summary and outlook

- Too many simple tracking tracks?
  - More ST tracks than HT tracks further away from central peak in angular distribution.
  - Many of them fit curved trajectories with a straight line, which Hough transform does not.
  - ➢ ***Should we include these curved muons to the flux (increase tolerance for Hough transform) or exclude them (reduce tolerance for simple tracking)?***
- Efficiencies differ between 2023 and 2024 data
  - ➢ Most likely related to different muon energy spectrum — not too worried about it at the moment.
- Non-IP1 contributions
  - ➢ Factoring out the LEHR.11R1 muons might be appropriate as we know for certain that they are not from Pb-Pb collisions.
  - ➢ ***Advice and suggestions are much appreciated!***

Hopeful outlook — *adjusting the tracking tolerance parameters will equalize the muon flux and the analysis note can be finalized within a few weeks.*

Other

Muon flux analysis

- Advanced stage, final adjustments before circulating as an internal note *(paper target EPJC)*

The experiment:

- Active participation in weekly analysis meetings and regular status updates on collaboration meetings.
- Multiple operation and emulsion development shifts.

University

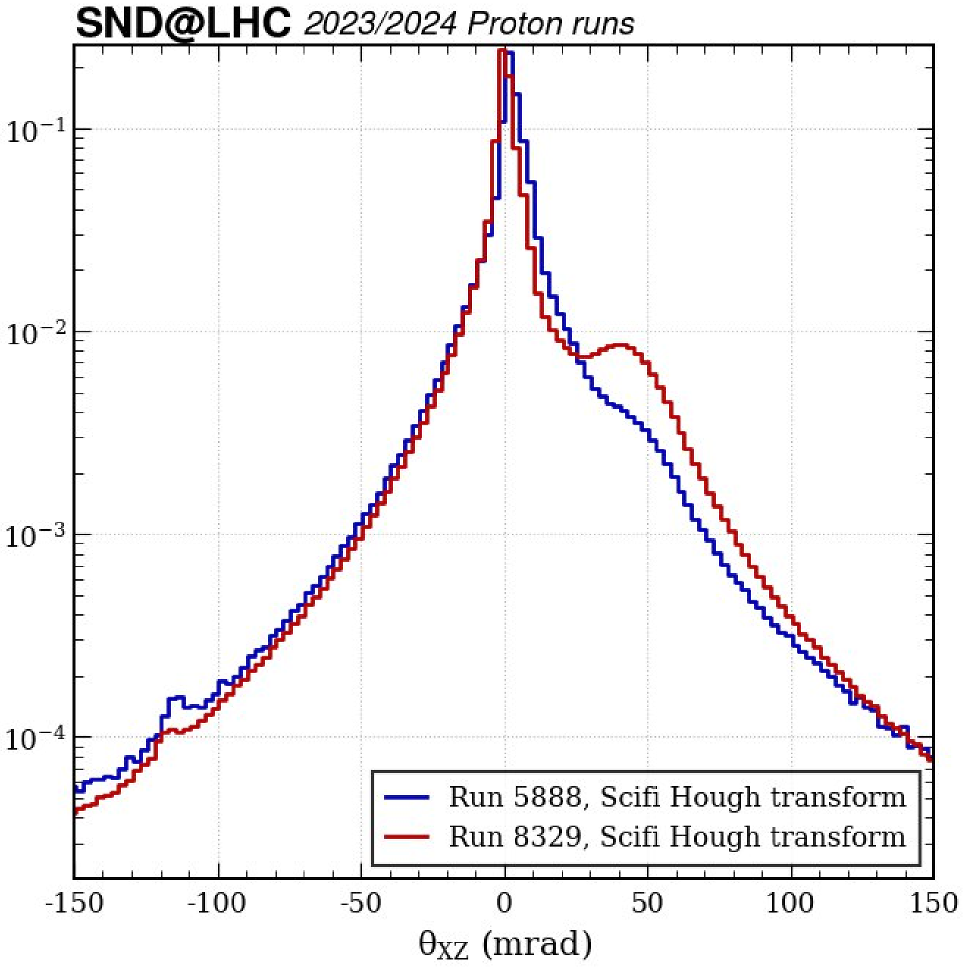
- Required physics PhD exam was successfully passed.
- Required course on particle cosmology was taken and successfully passed.
- Presented a lecture for the spring open door day.

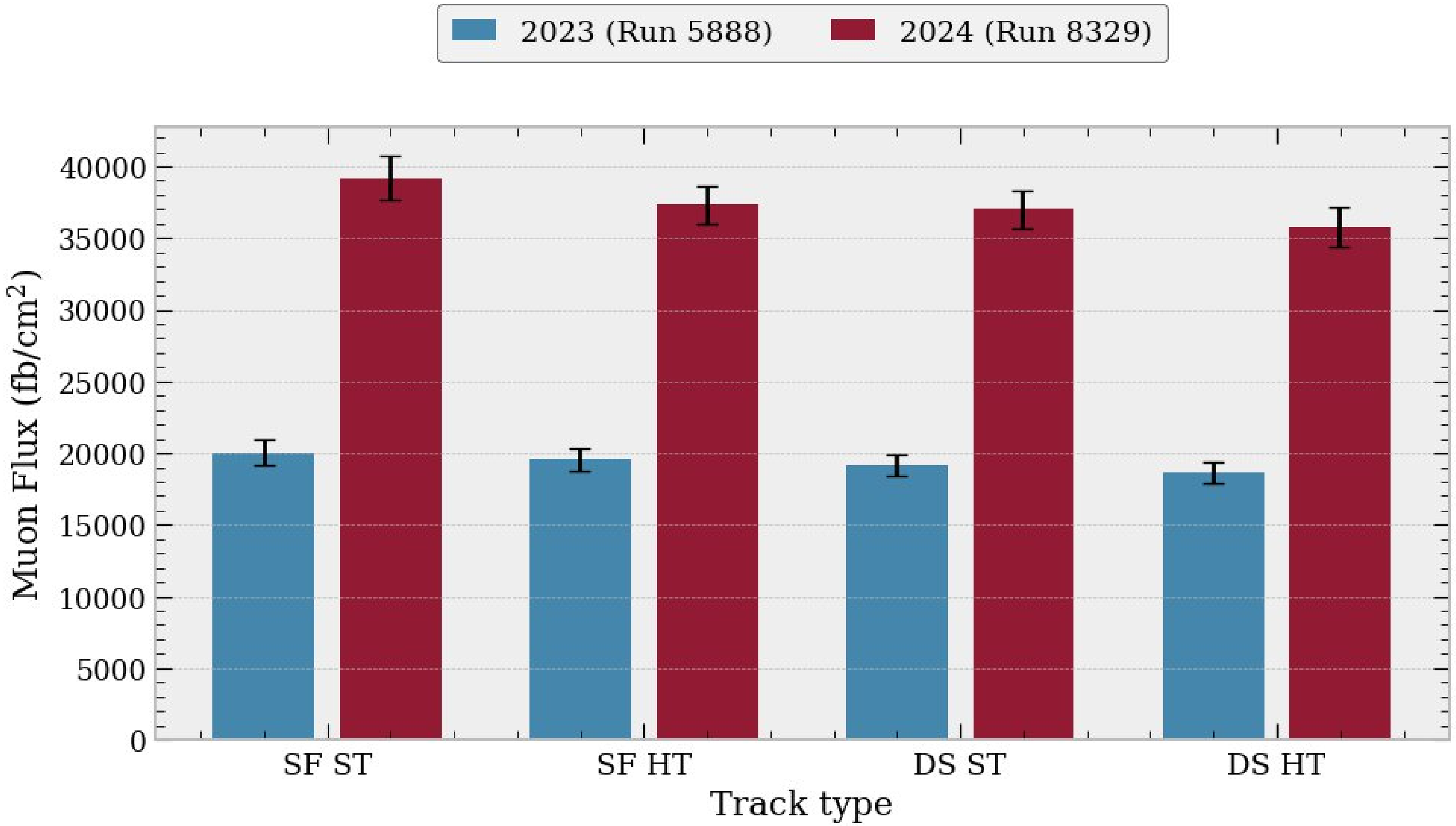
Backup Slides

Muon Flux in Proton Runs

Factor of increase from 2023 to 2024 is ~1.96.

- Secondary peak much more pronounced in 2024.





Contribution of Non-IP1 Muons

Secondary peak is formed of non-IP1 muons!

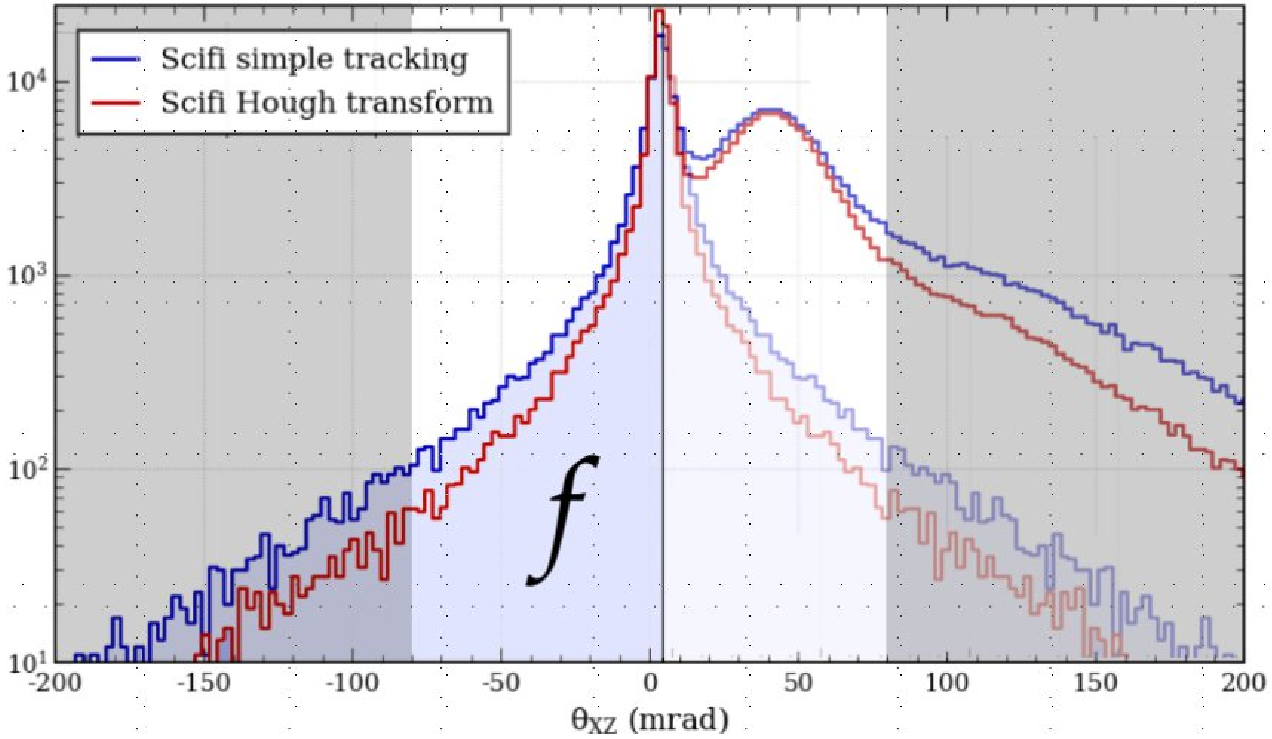
Naive approach:

– Get the fraction f of tracks on the left side of central maximum (where it's just IP1 muons).

– Assume we'd have the same number of IP1 tracks on the right side.

$$\mathbf{2}f \lesssim \mathbf{1}$$

– Correct the muon flux ($\Phi_\mu^{new} = \Phi_\mu^{old} \times 2f$)

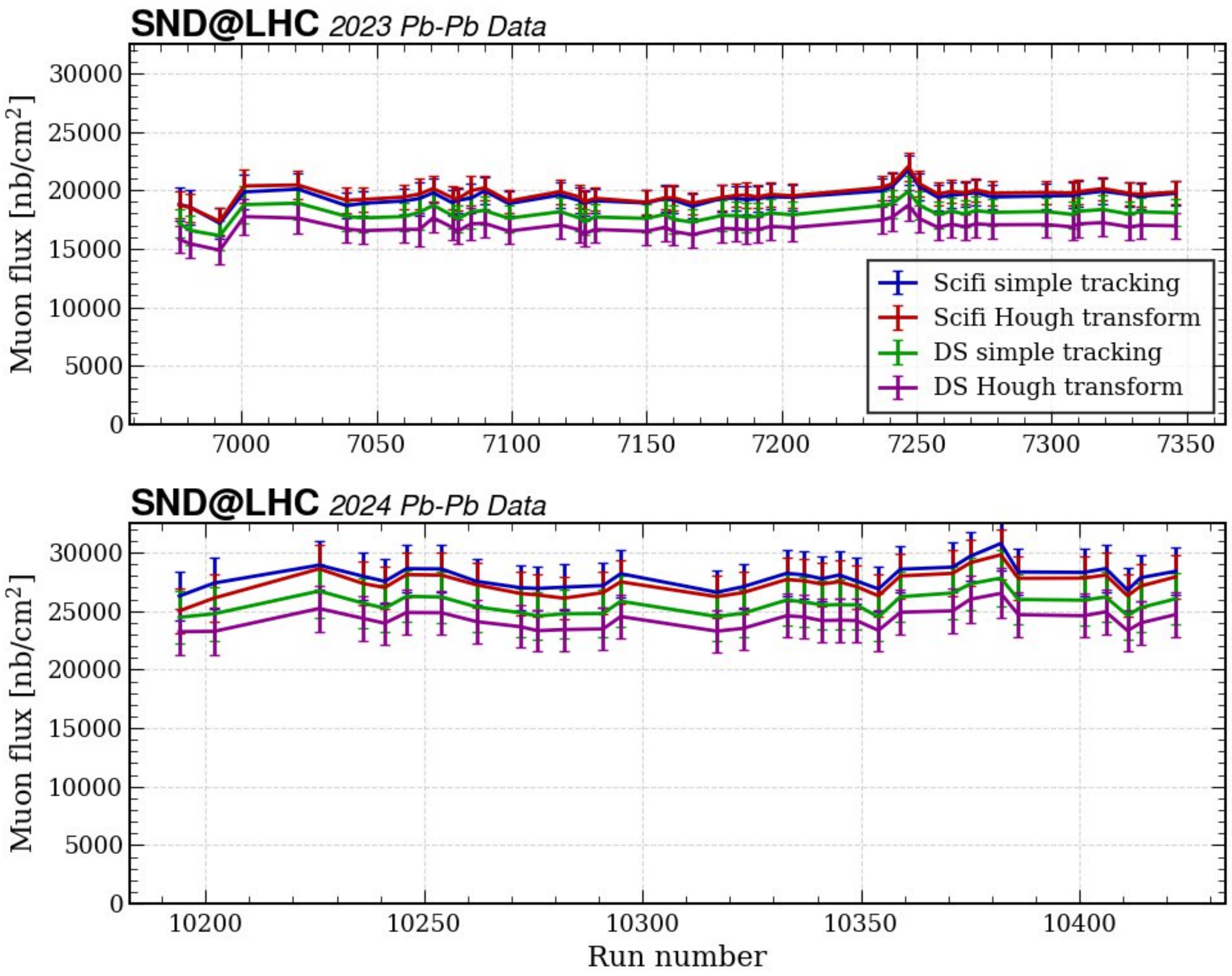


Contribution of Non-IP1 Muons

***The naive approach* suggests that ~32% of 2023 tracks and ~46% of 2024 tracks of angles below 80 mrad are from meson decay after beam interactions with LHC collimators!**

Corrected muon flux:

- ***Factor of increase from 2023 to 2024 down to ~1.45 (previously ~1.85)***



More sophisticated approach

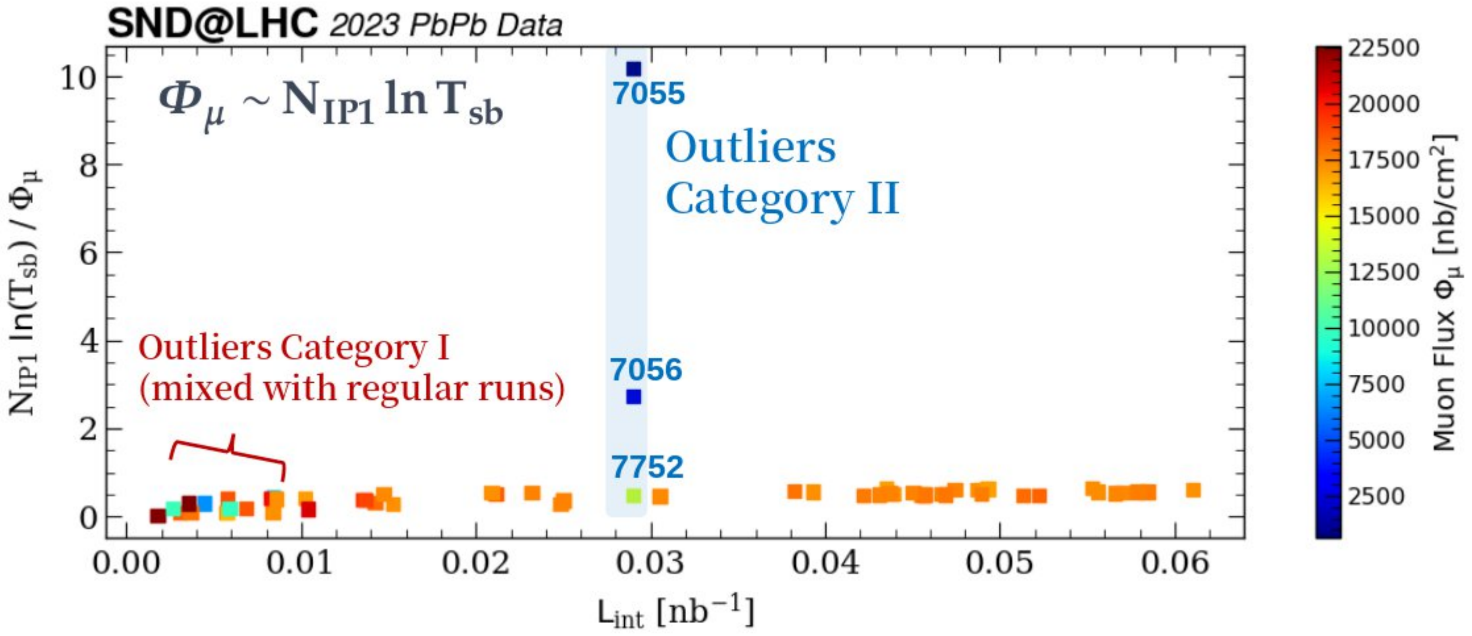
- Fit the histograms with an added gaussian for the secondary peak.
- Remove non-IP1 contributions.

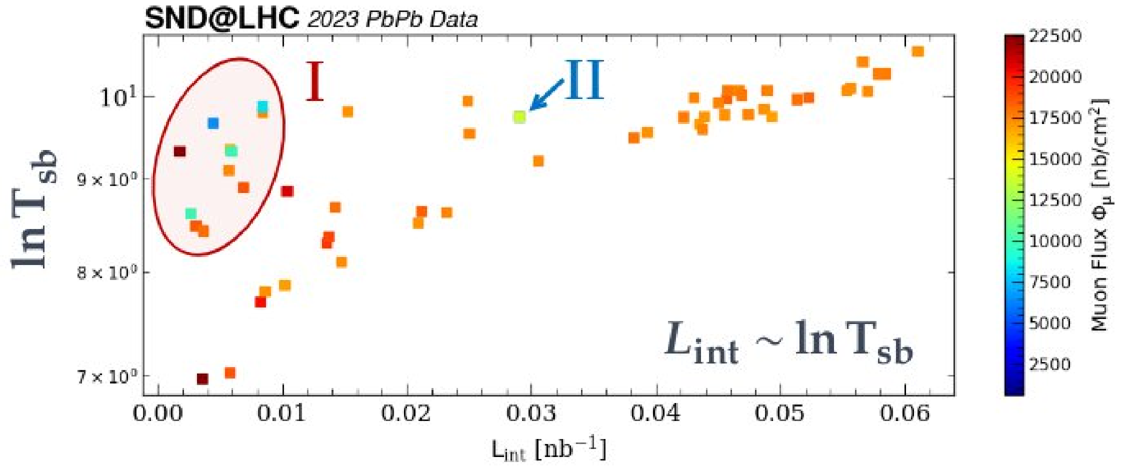
➢ ***Very difficult to fit such a steep central peak with wide tails.***

Categories of Low-Flux Outliers

Categories of low-flux outliers in 2023 data

- Seen to deviate from expected luminosity relationships in different ways.





Observation:

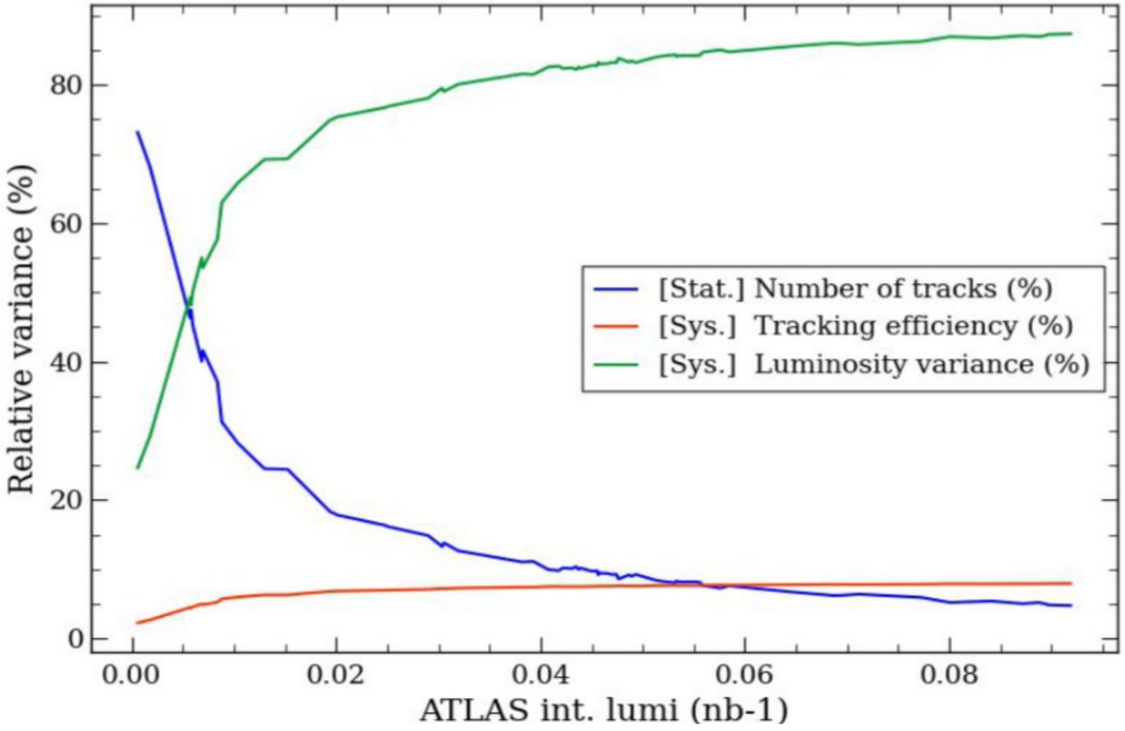
- *Low N_{IP1} and low L_{int} are necessary but insufficient condition for category I outliers*

ATLAS luminosity

Communication with ATLAS about what luminosity to use and its uncertainty.

- ***Current error is assigned 3.5%***
  (‘quick “best-guess” calibration’)
- Dominant systematic for the muon flux
  - *for most runs of reasonable statistics*
  - *with 20 mrad track angle constraint*.

➢ *It will take a while for them to release a public lumi uncertainty measurement.*

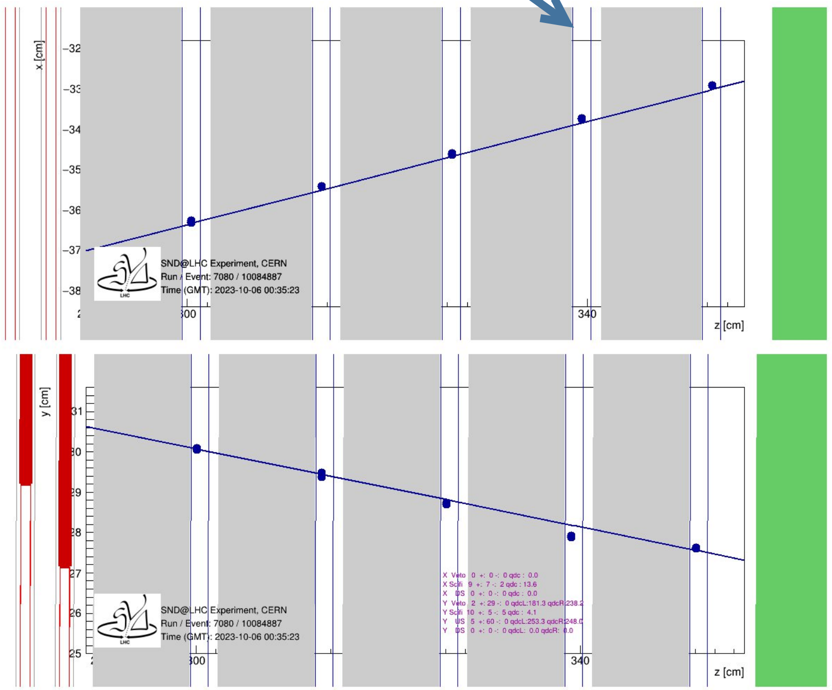


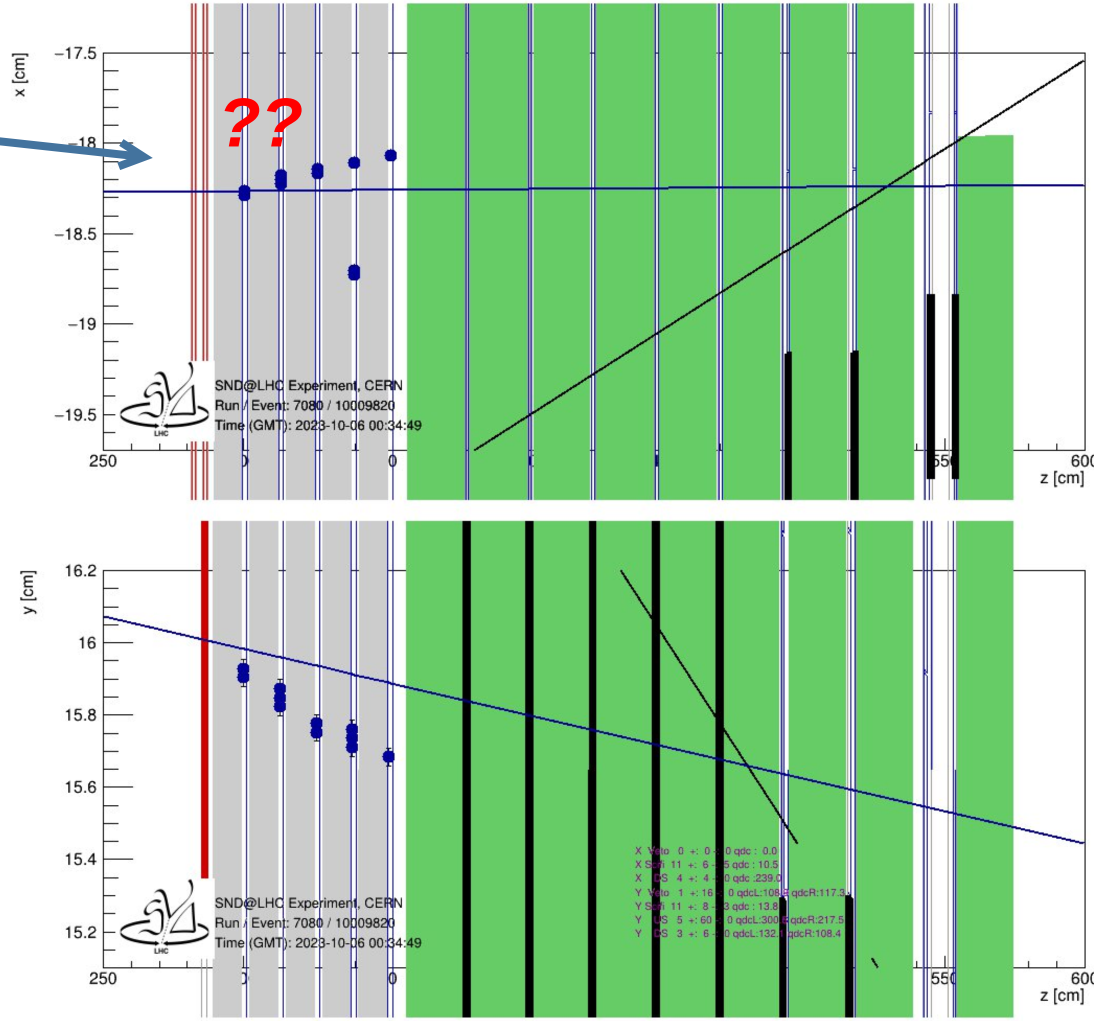
Excess of ST Tracks

Much less frequent occurences:

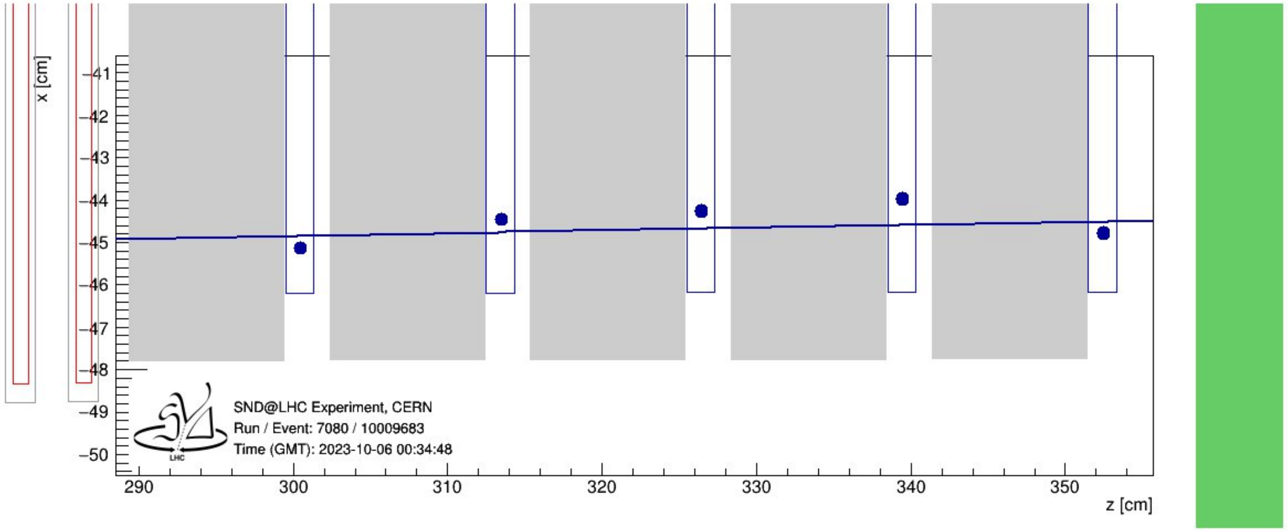
– Simple tracking build very questionable tracks.

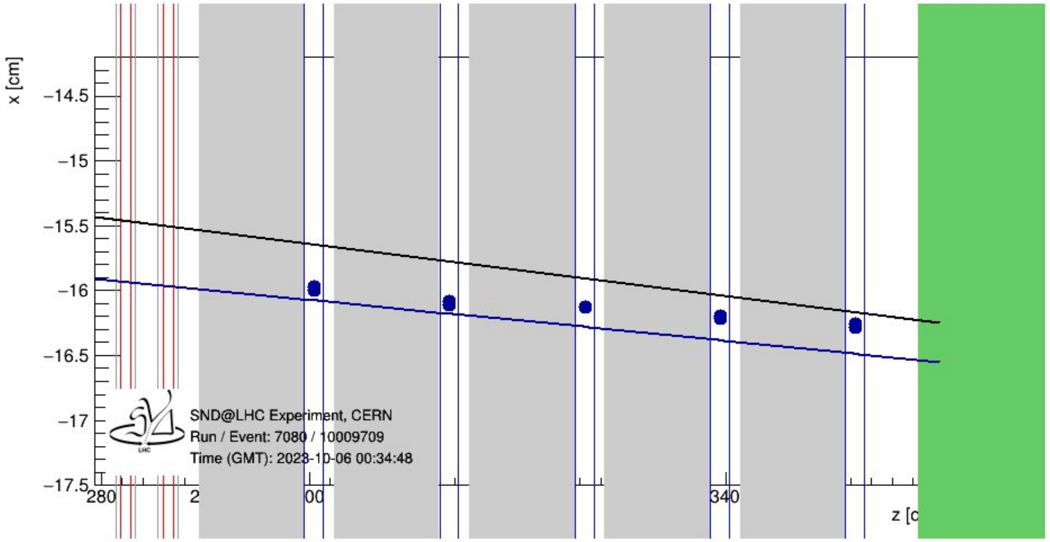
– Hough transform does not reconstruct a track that it probably should.

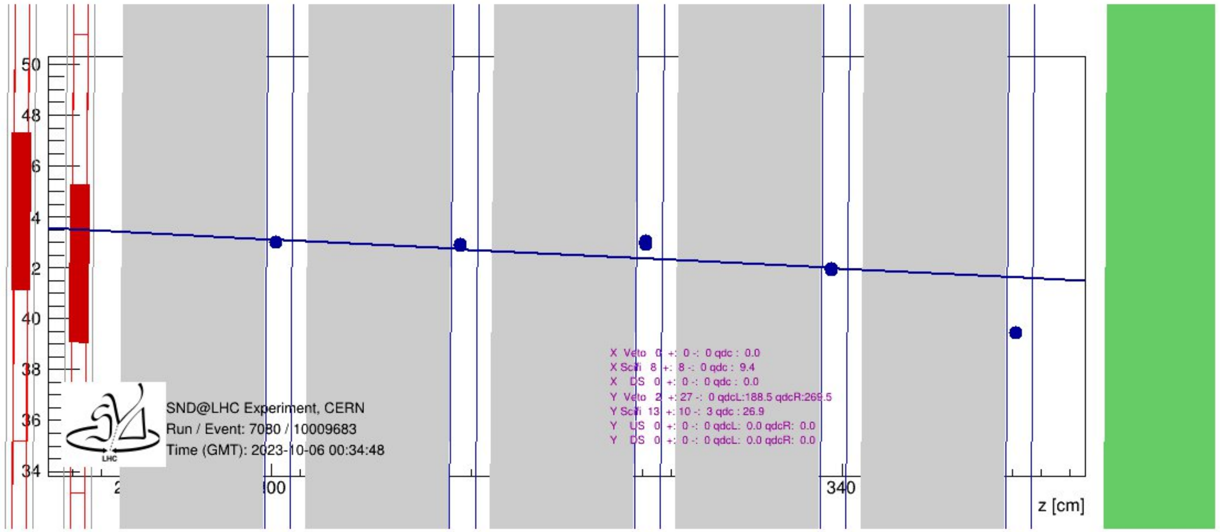


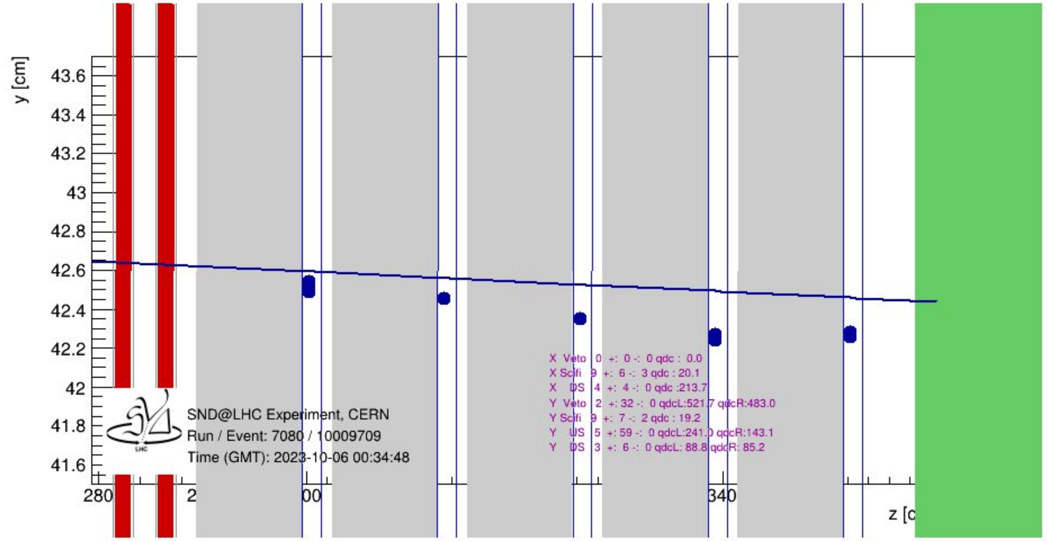


Excess of ST Tracks









Secondary Peak Composition