Muon background studies for SND/FASER in IR1

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with input from S. Ilieva, B. Petersen

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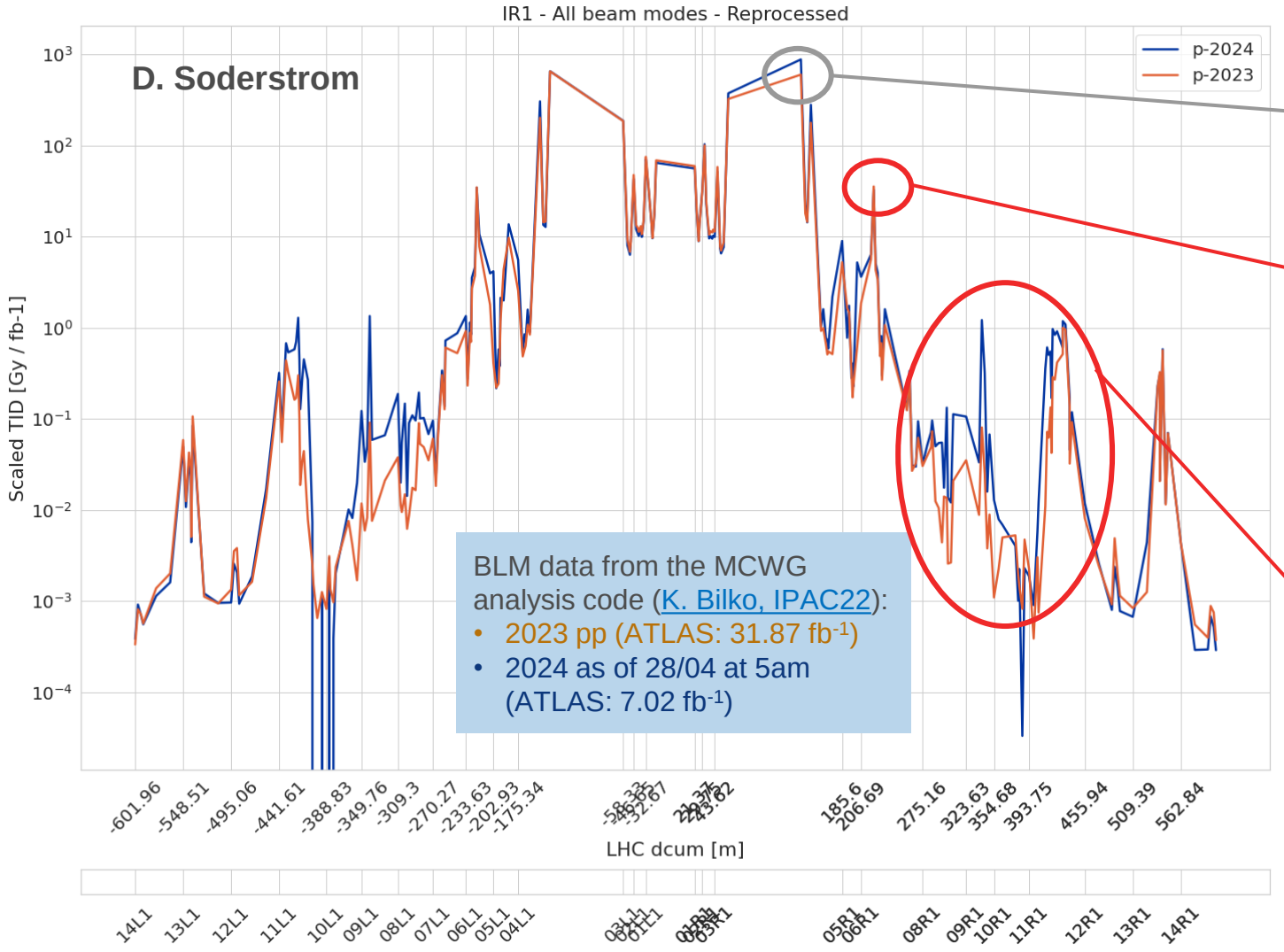
Introduction

- 2023 LHC configuration in IR1:
  - “Regular” optics, negative crossing angle (-160 µrad)
  - TCL6 @ 1.85mm
- 2024 configurations with RP optics, motivated by the need to extend the IT lifetime:
  - Reverse polarity optics, with Q4 off
  - Positive crossing angle (+160 µrad)
  - TCL6 @ 1.585mm
- Observed “side effects” of RP optics in 2024:
  - Higher radiation leakage to the DS for a fixed TCL6 setting
  - Higher muon background towards FASER and SND

BLMs in IR1: TID/fb^{-1} in 2023 vs 2024



Change in TID/fb^{-1} on the TAN on the right side, attributed to BLM displacement → can be ignored

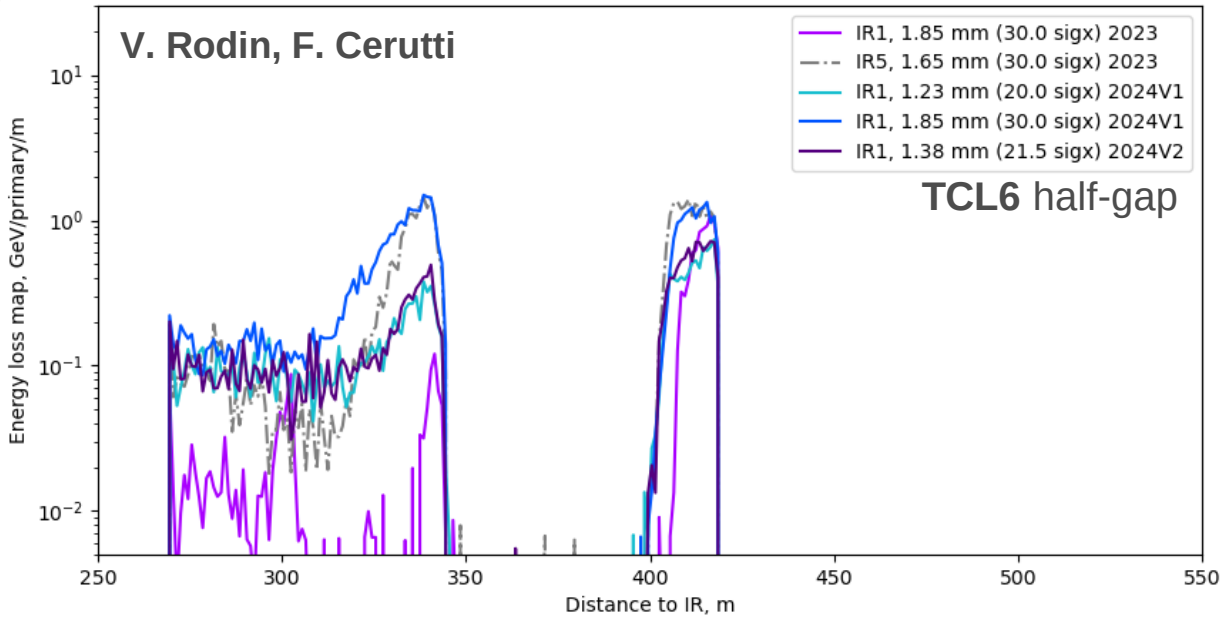
TCL6 TID/fb^{-1} (right side): 34.6 Gy/fb^{-1} in 2023, 35.4 Gy/fb^{-1} in 2024
→ same TID near the TCL6 despite the smaller gap (1.585 mm vs 1.83 mm)

More DS losses in 2024 despite the tighter TCL6 setting, which can be attributed to the RP optics (see next slide)

FLUKA studies of DS losses in IR1, Chamonix 2024

Evolution of Dispersion Suppressor losses

Cell 8-9 [GeV/coll]	Half-cell 11 [GeV/coll]
1.3	7.7
19	17
9.4	7.5
28	14.5

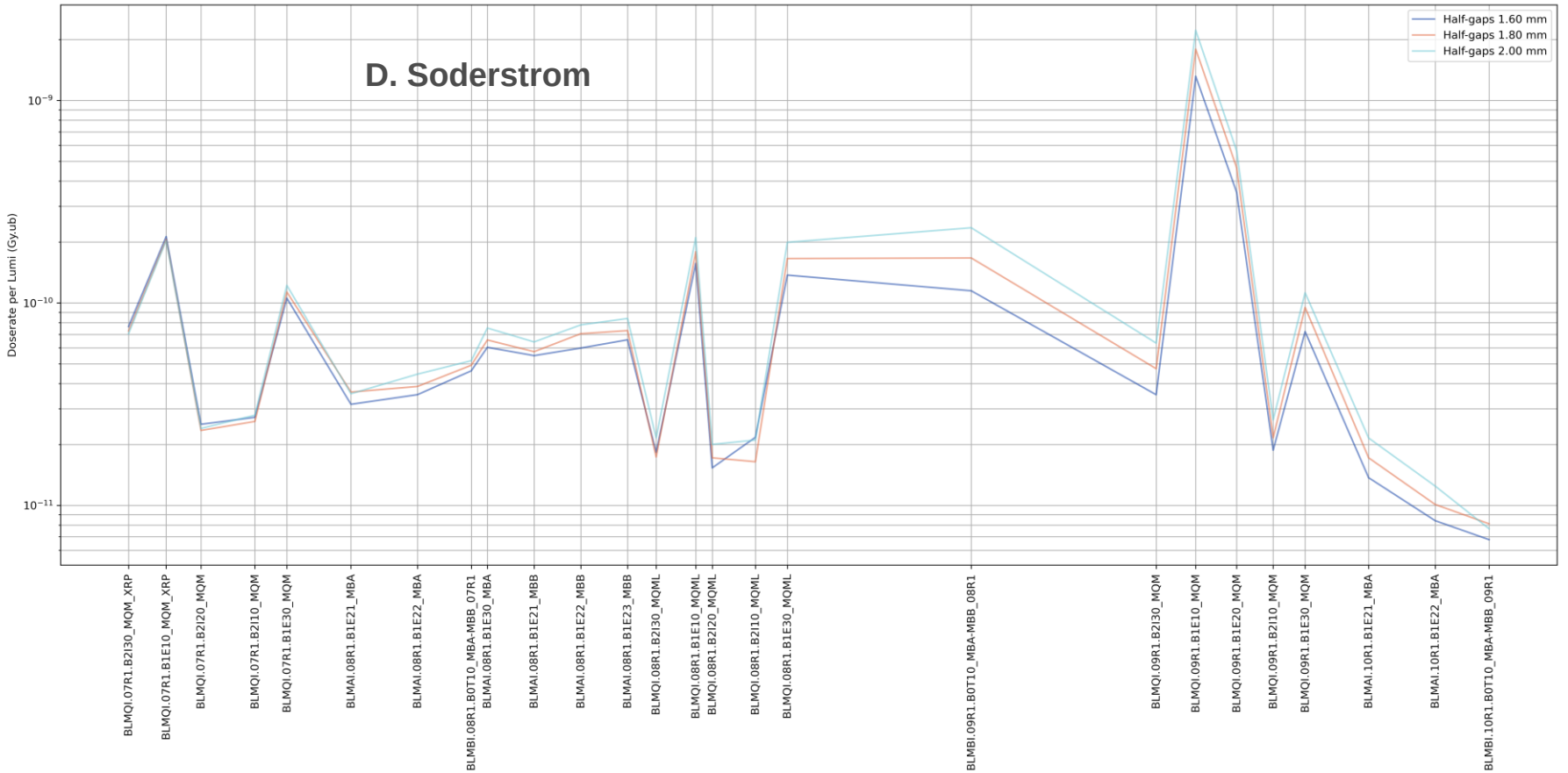


- Energy loss maps simulated with FLUKA for 2023 (IR1-IR5) and 2024 RP optics (IR1):
  - 2023 DS losses were lower in IR1 than IR5, but **the 2024 RP optics lead to an increase of IR1 losses for fixed TCL6 settings**
  - Among the two TCL6 settings studied for Chamonix, a 1.23 mm gap leads to lower losses compared to 2023-IR5, while a 1.85 mm gap leads to even higher DS losses compared to 2023-IR5, enhancing the risk of R2E-induced downtime
  - At Chamonix, F. Cerutti showed that a 2024 TCL6 half-gap of 1.2-1.4 mm is compatible with acceptable R2E losses, while the current setting (1.585 mm) can be regarded as a compromise solution

BLM studies of DS losses in IR1, TCL6 scan

Cell	Dose level increase (%)
11L1	11
10L1	41
9L1	60
8L1	31
8R1	29
9R1	69
10R1	39
11R1	7

- BLM TID rate per unit luminosity during a TCL6 scan on the night between May 2nd-3rd

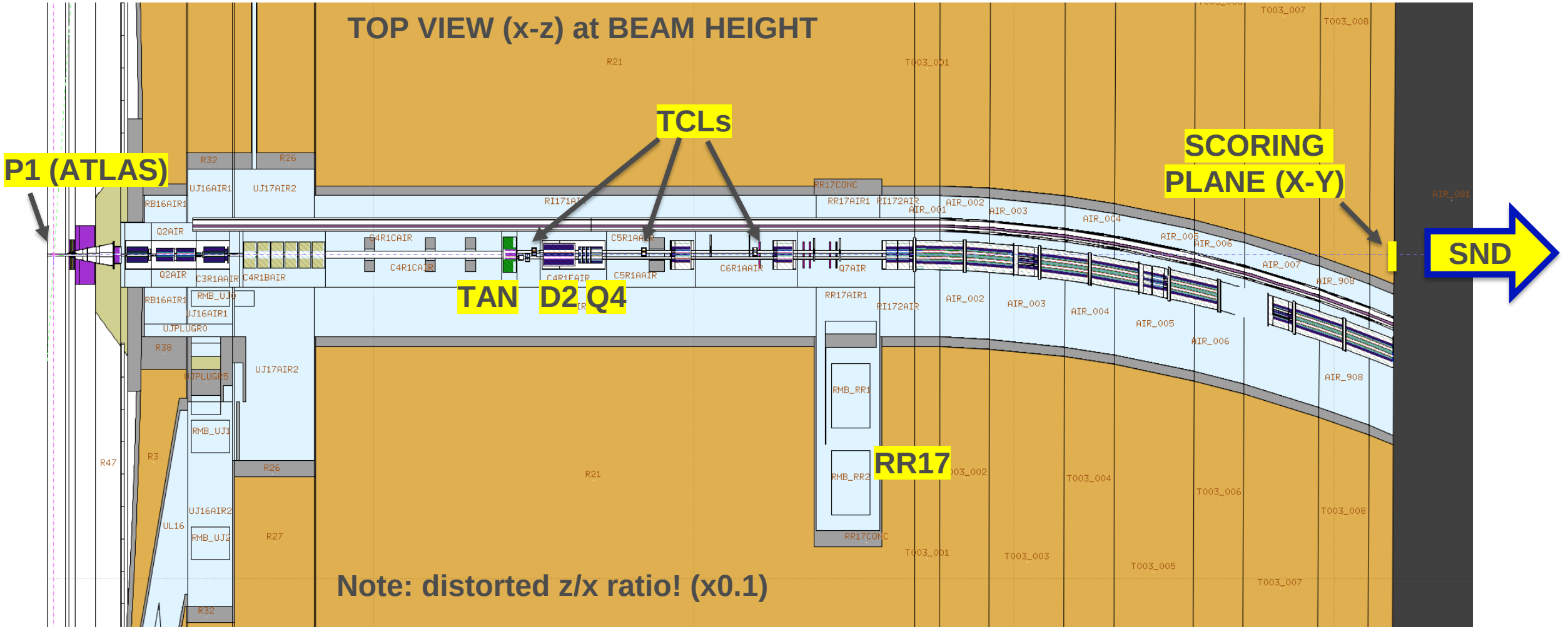


- Confirming that the DS losses are highly sensitive to the TCL6 setting (up to +69% in 9R1 when moving from ~1.6mm to ~2mm half-gap)

FASER-SND muon background studies

- FLUKA simulations of muon flux in a 1.8 m x 1.8 m plane at z=418.5 m from IP1 to evaluate the changes in background to FASER/SND from 2023 to 2024
- Many configurations have been simulated. Shown today:
  - **2023 optics, TCL6 @1.85mm**
  - **2024 RP optics**, **TCL6 @1.85mm**, **Q4 off**
  - **2024 RP optics, TCL6 @1.585mm, Q4 off**
  - **2024 RP optics, TCL6 open (25mm), Q4 off**
  - **2024 RP optics, TCL6 @1.585mm, Q4 on at 80 T/m** (NOT a viable optics configuration, but useful to assess the impact of Q4 on the muon flux caused by the collision debris)
- Unless stated otherwise, the results are referred to an ATLAS luminosity of 2e34 $cm^{-2}s^{-1}$

FLUKA geometry of IR1

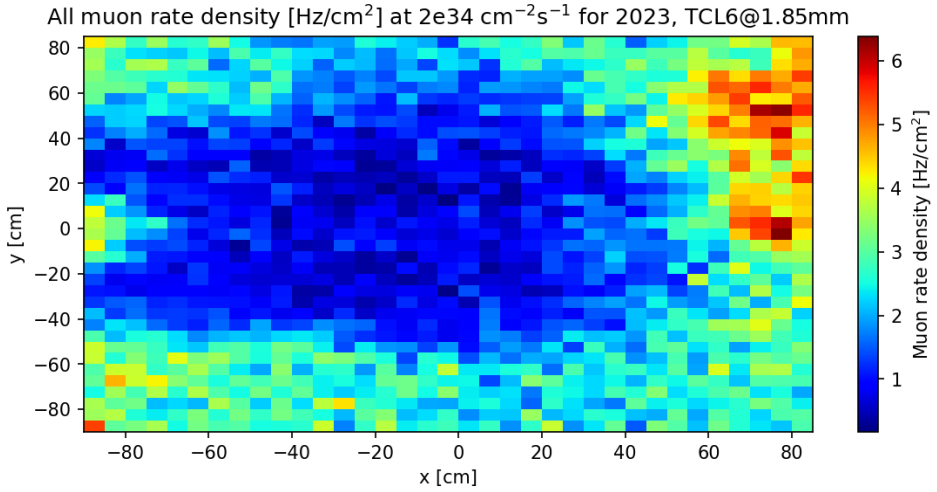


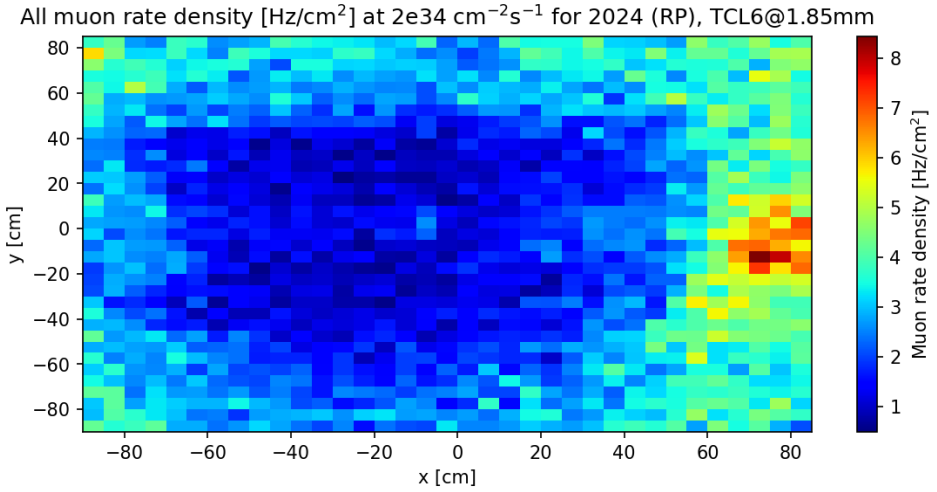
FLUKA output format

```
# Scoring particles entering Region No
# Col  1: FLUKA run number
# Col  2: primary event number
# -- Particle information --
# Col  3: FLUKA particle type ID
# Col  4: Generation number
# Col  5: Kinetic energy (GeV)
# Col  6: Statistical weight
# -- Crossing at scoring plane --
# Col  7: x coord (cm)
# Col  8: y coord (cm)
# Col  9: x dir cosine
# Col 10: y dir cosine
# Col 11: z coord (cm)
# Col 12: Particle age since primary event (sec)
# Col 13: Last decay x cooord (cm)
# Col 14: Last decay y cooord (cm)
# Col 15: Last decay z cooord (cm)
# Col 16: Last decay ID
# Col 17: Last interaction x cooord (cm)
# Col 18: Last interaction y cooord (cm)
# Col 19: Last interaction z cooord (cm)
# Col 20: Last interaction ID
```

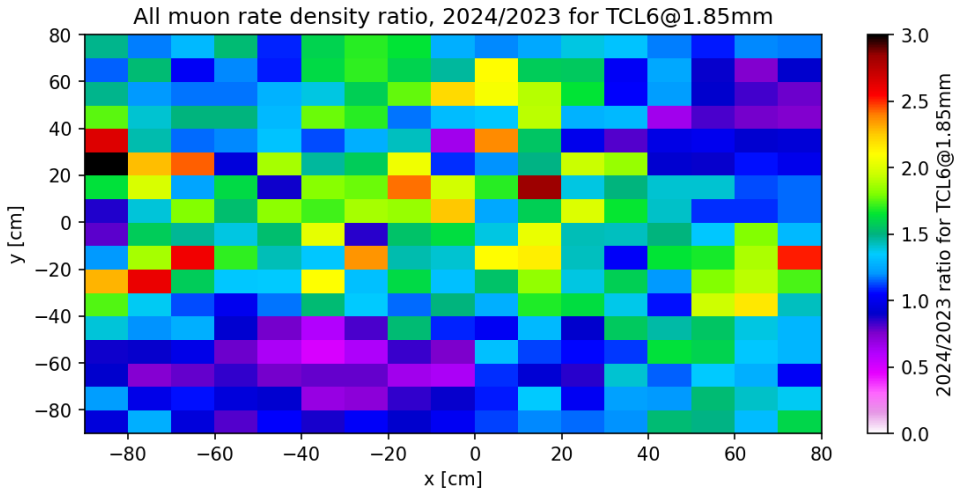
- All muons crossing a 1.8 m x 1.8 m plane at z=418.5 m from IP1 are recorded, allowing to study their properties (e.g., space distribution, energy spectra, and more)
- Important: the flux at FASER/SND may scale differently with respect to the selected plane (although correlations are expected). Full 2nd-step simulations by the experiments are required to compare the results with the measurements.

FLUKA results: all muons on plane at z@418.5 m for (|x|,|y|) in [-90,90] cm



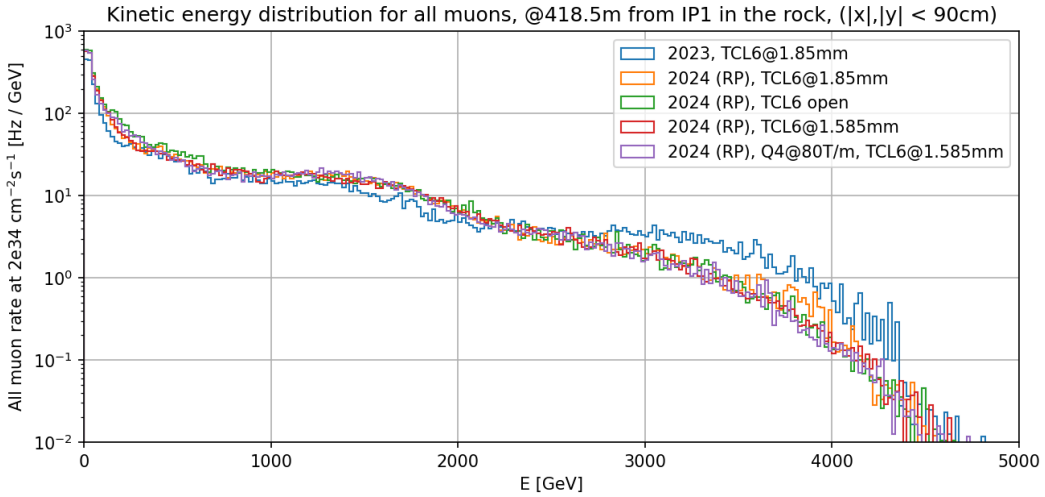


BOTH POSITIVE AND NEGATIVE MUONS ARE INCLUDED

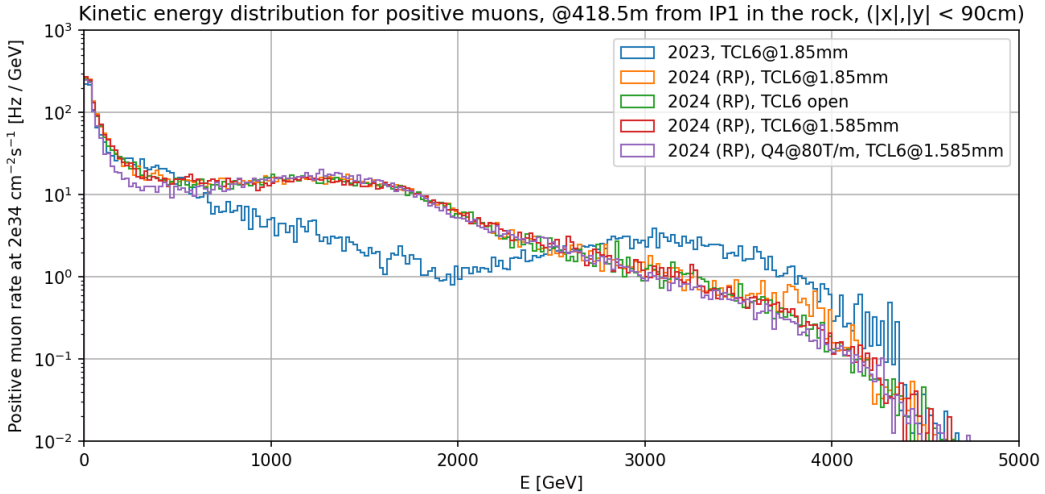


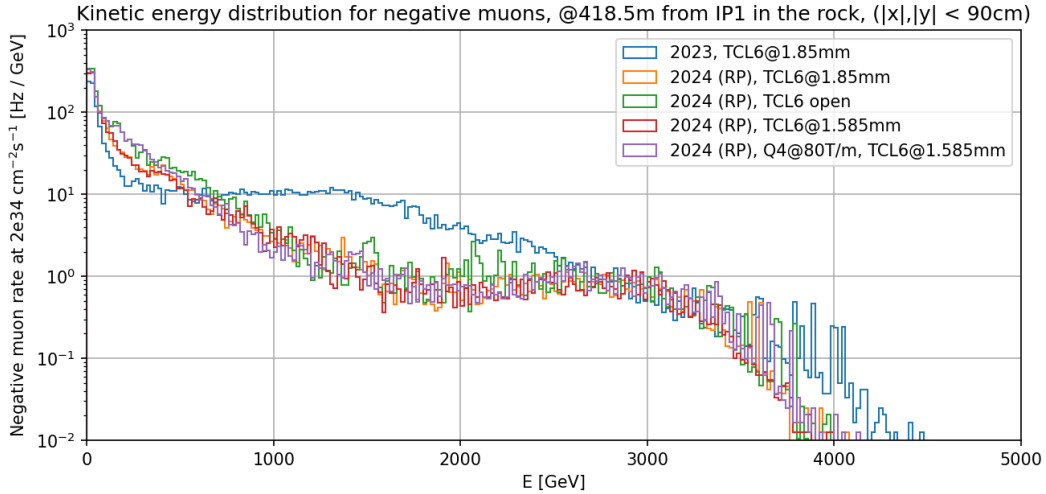
- Muon flux density in the scoring plane for 2023 optics and 2024 (RP) optics, with the same TCL6 setting (1.85mm).
- The ratio plot (left) shows that the flux increases and decreases in a non-uniform way within this plane
  → since only a small fraction of the muons in this plane reach FASER/SND, we can expect that the actual muon flux at FASER/SND scales differently compared to the total muon flux at this scoring plane

FLUKA simulations: energy spectra



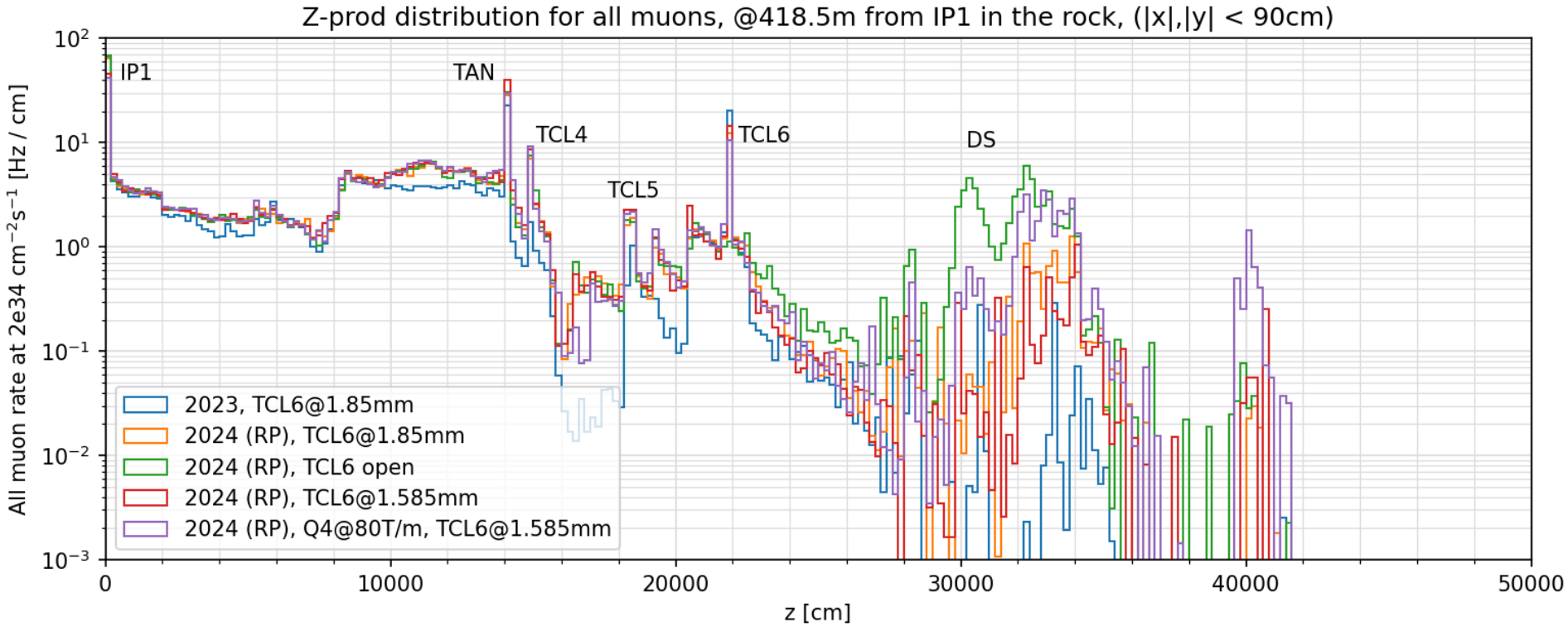
- 2024 (RP) vs 2023: significant differences in the energy spectra, with opposite behaviour for positive and negative muons
- Small impact of TCL6 on the spectra in 2024, and no significant difference even when switching the Q4 back on





FLUKA simulations: muon production point (both signs)

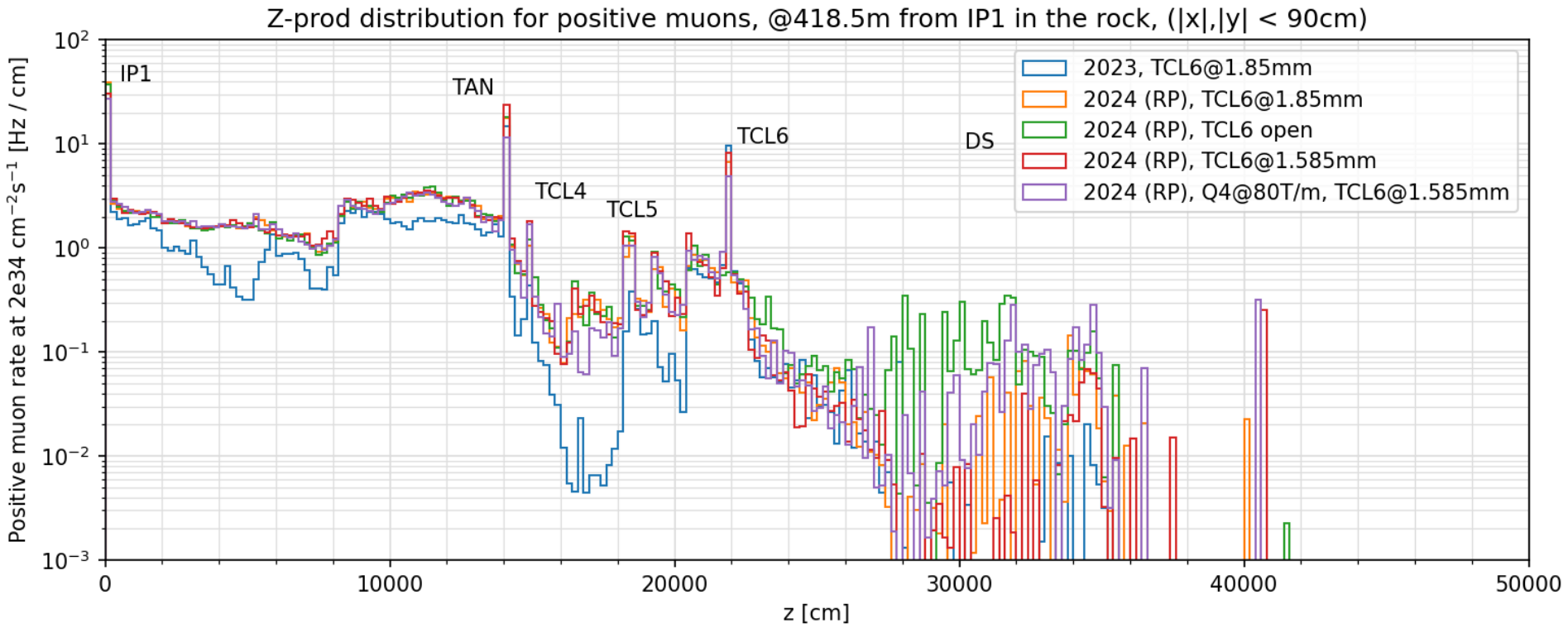
- Increase of muon flux from the straight section up to the TAN included, and also between TCL4 and TCL5 (but with a lower overall rate).
- For 2024 (RP optics), small difference between individual TCL6 settings, but higher flux from the DS when opening it
- Switching on the Q4 with 2024 optics yields some local differences, but doesn't change the overall picture



FLUKA simulations: positive muon production point

- The increase of muons from the inner triplet and up to the TAN is particularly visible when selecting only the positive ones

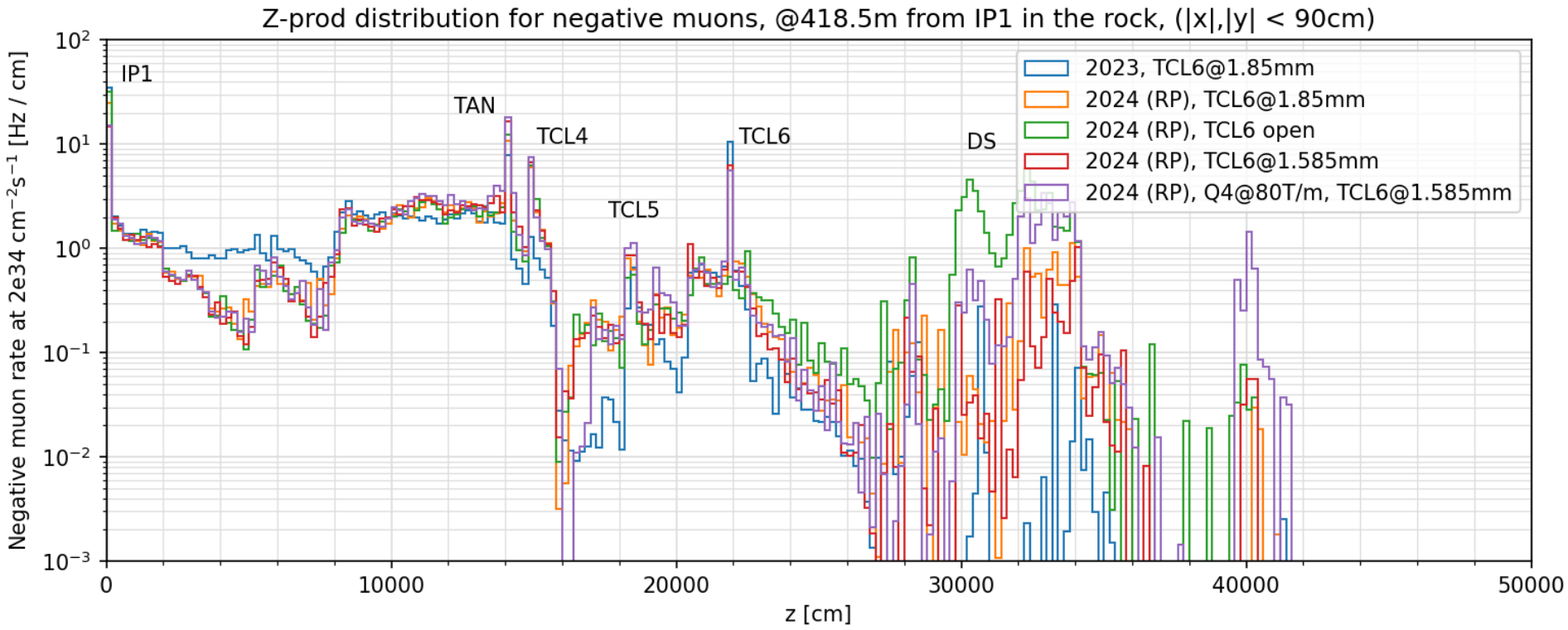
- The flux of positive muons from the DS remains low for all simulated configurations



FLUKA simulations: negative muon production point

- The flux of negative muons from the inner triplet is lower with the 2024 RP optics, although there is still an enhanced contribution from before the TAN (and from the TCL4-5 area)

- As expected, the muons coming from the DS are mostly negative



Integral muon fluxes: all muon rates in Hz for 2e34 $cm^{-2}s^{-1}$

Configuration	Total rate	From IP (first 3m)	Between 3m and TAN (incl.)	Between TCL4 and TCL6 (incl.)	Post-TCL6
2023 baseline, TCL6@1.85mm	**6.92e+04**	**1.76e+04**	**4.32e+04**	**7.42e+03**	**1.05e+03**
2024 (RP), Q4 off, TCL6@1.85mm	8.44e+04	1.83e+04	5.36e+04	9.37e+03	3.11e+03
2024 (RP) baseline, Q4 off, TCL6@1.585mm	**8.34e+04**	**1.34e+04**	**5.73e+04**	**1.05e+04**	**2.20e+03**
2024 (RP), Q4 off, TCL6 open	9.30e+04	1.85e+04	5.32e+04	7.36e+03	1.39e+04
2024 (RP), Q4@80T/m, TCL6@1.585mm,	8.49e+04	1.18e+04	5.58e+04	9.51e+03	7.88e+03

- Muon flux increase by **~20%*** from 2023 to 2024, mostly driven by muons from before the TAN (included)
- A fully opened TCL6 would yield a significant increase in muon flux from the DS
- The impact of Q4 on the fluxes is relatively limited, confirming that the increase in muon flux from 2023 to 2024 is mostly driven by the fields of the triplet magnets

***reminder: this is the simulated increase of the muon flux at the plane defined on slides 6-7. The rate at FASER/SND can (and does) scale differently**

Input from FASER and SND (S. Ilieva)

- The SND collaboration has further extended the muon flux simulations from the plane at 418.5m (defined on slides 6-7) to the SND position, computing the total instantaneous muon background in Hz at L_0 (10^{34} cm^{-2}/s)
- The rate has been compared to the measurements of the detector for 2022 (~similar to 2023) and 2024, confirming a total increase by approximately a factor of ~2-3

	FLUKA [Hz @ L_0]	Measurement [Hz @ L_0]
2022 (nom)	255	280
2024 (RP)	765	615

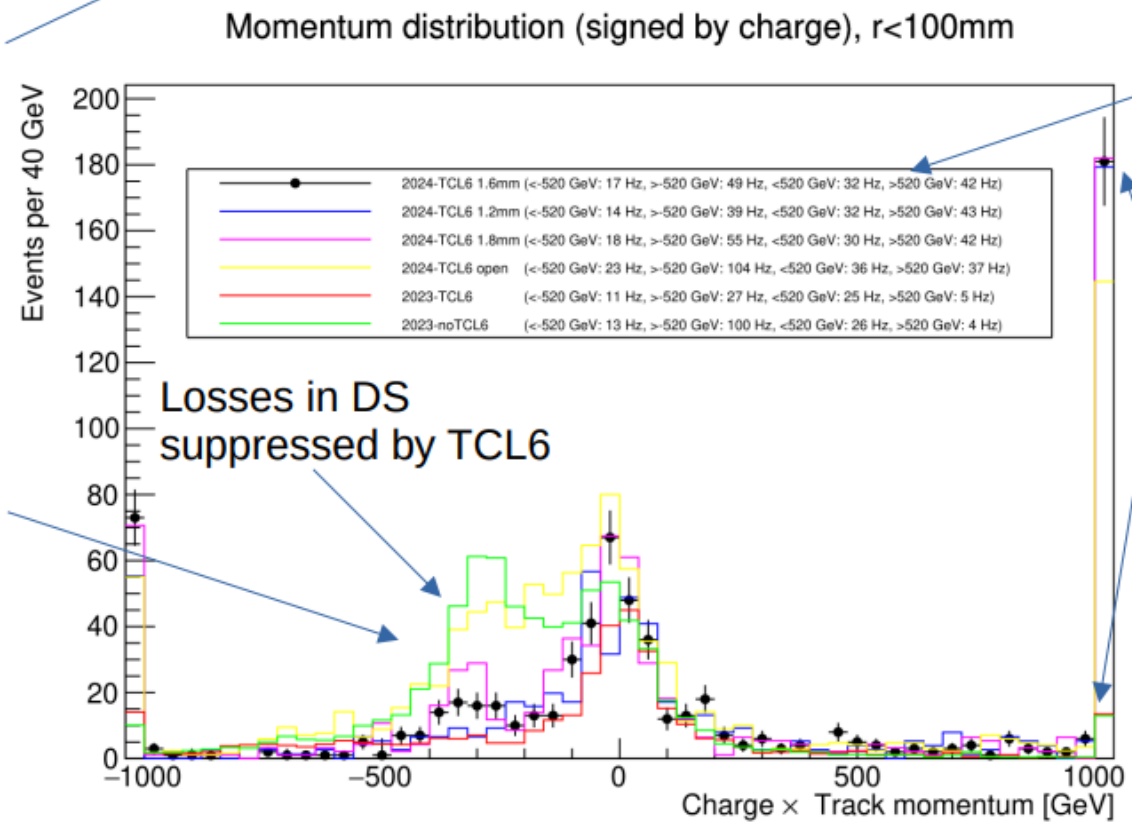
- Main message: the rate at the SND position increases by more than at the full scoring plane, as confirmed both with the simulations and experimentally.

Input from FASER (B. Petersen): 2024 flux and TCL6 scan

Date	30/3	30/3	28/3	31/3	28/3	3/4	4/4
TCL6 half-gap	1.2mm	1.6mm	1.6mm	1.8mm	3.3mm	1.6mm closer TCL4/5	Open TCL4/5/6
Coincidence trigger	538.1+- 12.7 Hz	566.5+- 11.7 Hz	552.0+- 35.9 Hz	577.0+- 13.0 Hz	666.1+- 32.3 Hz	594.4+-11.1 Hz	992.8+-12.5 Hz

Was ~280 Hz in 2022/23

Rates scaled to $2x10^{34}$ (different areas)



Having TCL6 quite closed still helps reduce negative muons from DS region

Main difference to 2022/23 is large increase in high momentum positively-charged muons

(note charge and momentum not well measured >1000 GeV)

B. Petersen, ColWG#279

Summary remarks

- We discussed the following implications of RP optics in IR1 in 2024:
  - Radiation leakage to the DS: increase confirmed by data and simulations, measurable but kept under control by a tighter TCL6 setting (1.585mm in 2024 vs 1.85mm in 2023)
  - Higher muon background towards FASER and SND (roughly 2x in both experiments)
- Our FLUKA results refer to a 1.8 m x 1.8 m plane 70m upstream of FASER/SND, where the rates are larger than the FASER/SND measurements. At this plane, the increase in flux is limited to ~20%, but we see portions of it where the increase is larger.
- When extended to SND, the simulations confirm an expected increase by a factor close to 3 (even slightly above the measurements).
- The simulations indicate that the increase in background is mostly driven by muons coming from the first portion of the LSS up to the TAN. Even by artificially switching on the Q4 we don't recover a 2023-like behaviour
  → the increase appears to be a feature of the RP optics, with no obvious mitigation measures for 2024
- Both experiments prefer tighter TCL6 settings (confirmed by both simulations 2024 TCL6 scans)
- Note: the fact that we see more muons coming from the triplet shall not be regarded as evidence of more overall losses in the triplet, as we are only focusing on a very limited phase space (i.e., the muons passing through the above 1.8 m x 1.8 m square).
- Next step: as suggested by S. Fartoukh, we will explore an optics version with horizontal crossing in IR1 (new twiss files already received)

Backup

Integral muon fluxes: positive muon rates in Hz for 2e34 $cm^{-2}s^{-1}$

Configuration	Total rate	From IP (first 3m)	Between 3m and TAN (incl.)	Between TCL4 and TCL6 (incl.)	Post-TCL6
2023 baseline, TCL6@1.85mm	**3.38e+04**	**8.88e+03**	**2.12e+04**	**3.26e+03**	**4.89e+02**
2024 (RP), Q4 off, TCL6@1.85mm	4.93e+04	1.13e+04	3.30e+04	4.30e+03	6.94e+02
2024 (RP) baseline, Q4 off, TCL6@1.585mm	**4.90e+04**	**8.84e+03**	**3.46e+04**	**4.99e+03**	**5.83e+02**
2024 (RP), Q4 off, TCL6 open	4.80e+04	1.02e+04	3.28e+04	3.31e+03	1.60e+03
2024 (RP), Q4@80T/m, TCL6@1.585mm,	4.36e+04	7.26e+03	3.12e+04	4.01e+03	1.05e+03

***reminder: this is the simulated increase of the muon flux at the plane defined on slides 6-7. The rate at FASER/SND can (and does) scale differently**

Integral muon fluxes: negative muon rates in Hz for 2e34 $cm^{-2}s^{-1}$

Configuration	Total rate	From IP (first 3m)	Between 3m and TAN (incl.)	Between TCL4 and TCL6 (incl.)	Post-TCL6
2023 baseline, TCL6@1.85mm	**3.55e+04**	**8.71e+03**	**2.20e+04**	**4.16e+03**	**5.56e+02**
2024 (RP), Q4 off, TCL6@1.85mm	3.51e+04	7.01e+03	2.06e+04	5.07e+03	2.41e+03
2024 (RP) baseline, Q4 off, TCL6@1.585mm	**3.44e+04**	**4.58e+03**	**2.27e+04**	**5.50e+03**	**1.62e+03**
2024 (RP), Q4 off, TCL6 open	4.50e+04	8.24e+03	2.04e+04	4.06e+03	1.23e+04
2024 (RP), Q4@80T/m, TCL6@1.585mm,	4.14e+04	4.51e+03	2.45e+04	5.50e+03	6.83e+03

***reminder: this is the simulated increase of the muon flux at the plane defined on slides 6-7. The rate at FASER/SND can (and does) scale differently**