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Accelerating Science

PS-MU models' benchmarking with F8L-PFW harmonics and momentum computation corrections in the PS

Presenter: Vittorio Ferrentino

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Many thanks to:

Ewen Hamish Maclean, Alexander Huschauer, Denis Gerard Cotte and the whole OP-PS/PSB team, Tobias Hakan Bjorn Persson, the OMC team

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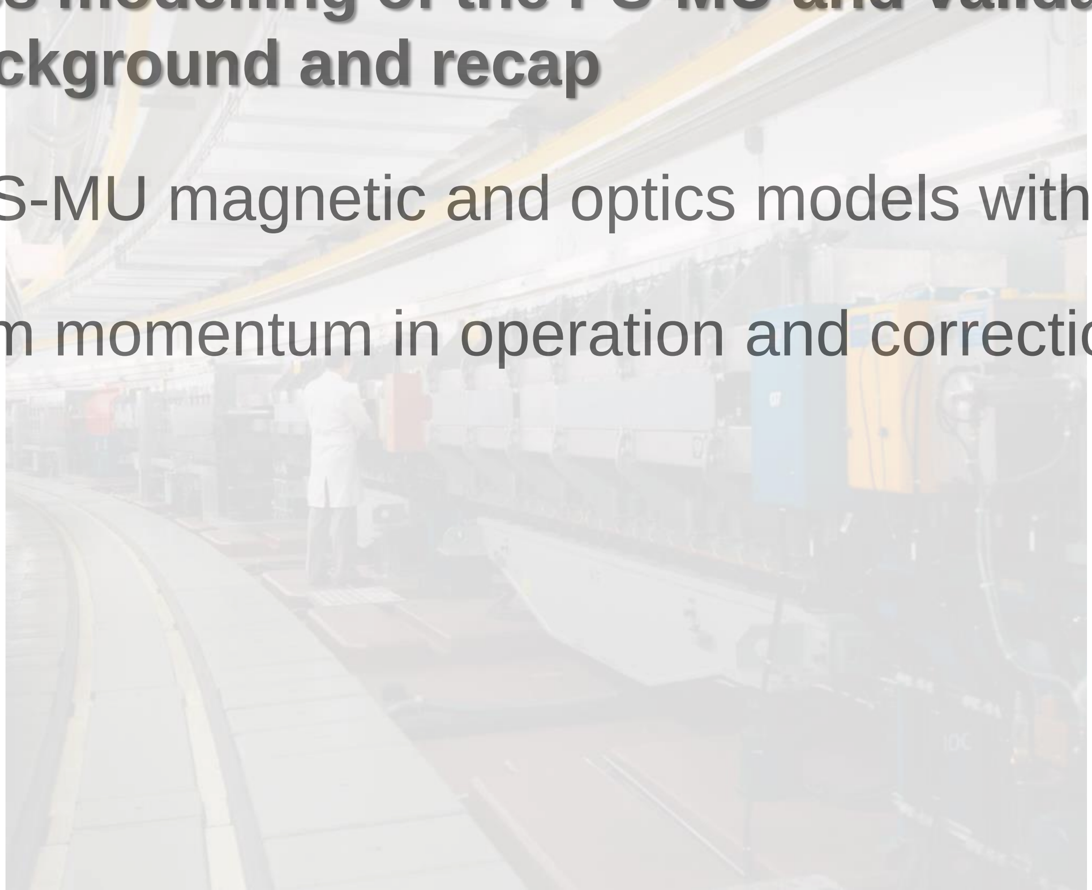
- **Magnetic and optics modelling of the PS-MU and validation via beam-based measurements: background and recap**
- Benchmark of the PS-MU magnetic and optics models with F8L-PFW
- Computation of beam momentum in operation and corrections driven by MU magnetic model
- Conclusions



PS-MU magnetic and optics modelling: background

- **Context and topic:** Magnetic and optics modelling of the CERN Proton Synchrotron (PS) Main Units (MUs) and their validation via beam-based measurements.

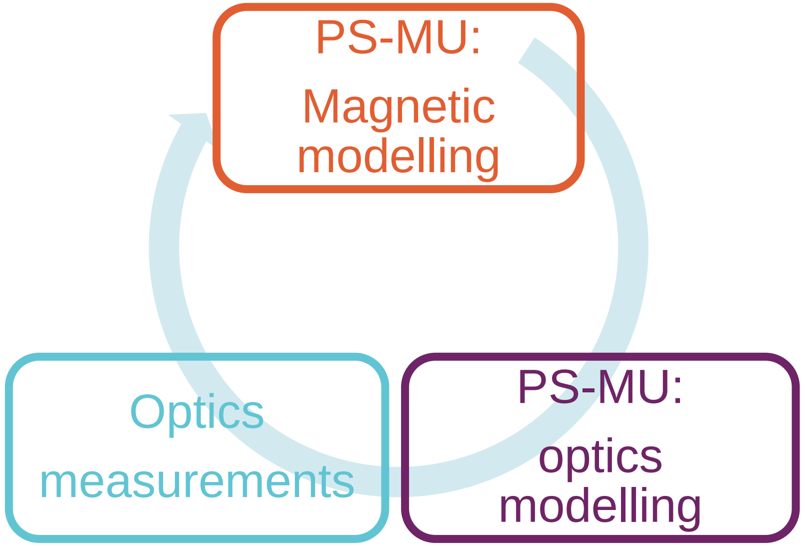
- **General problem:** although past efforts led to advancements in the modelling of the PS-MU, pre-existing models presented some limitations.
  - PS-MU finite-element pre-existing magnetic model presented mesh inconsistencies limiting its time-efficiency
  - PS-MU pre-existing optics model was an effected matched model →quadrupolar and sextupolar strengths (k_1 and k_2) in MAD-X matched to replicated measured or desired tunes and chromaticities

  → **pre-existing models did not provide a predictive, powerful tool to support and help operation.**

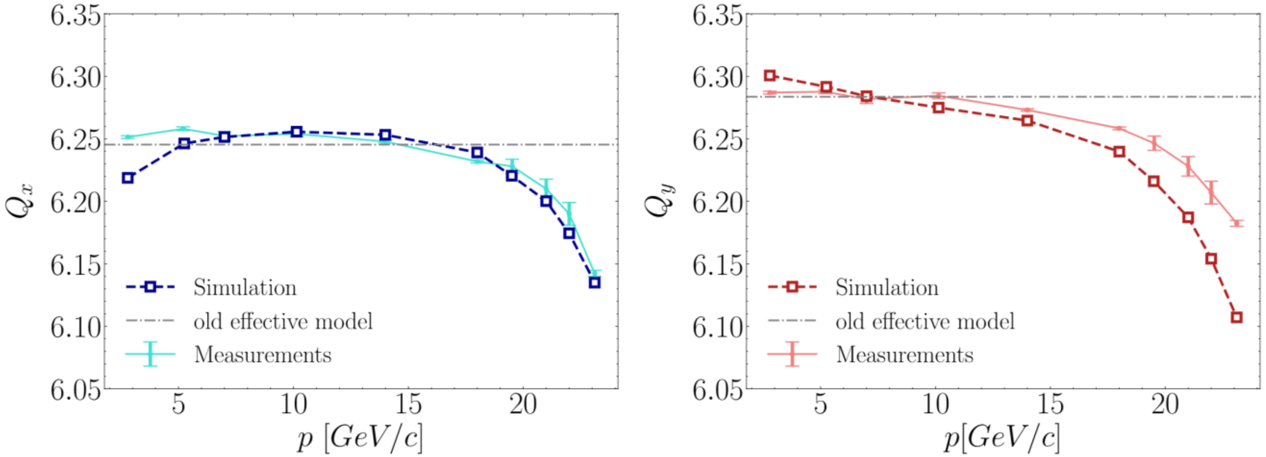
- **Objective:** overcome limitations of the pre-existing PS-MU magnetic and optics models to provide operation with a predictive tool which does not rely on empirical/measured data

PS-MU magnetic and optics modelling: recap

- **New magnetic and optics model of the PS-MU have been developed:**
  - Predicted harmonics from the new MU magnetic model are integrated in the MU MAD-X optics model
  - Predictions from the combined magnetic and optics models are validated against beam-based measurements



- **Initial studies were conducted for the bare-machine configuration (F8L and PFW off, presented at the 2024 IPP MD days).**
  - This benchmarking revealed a good agreement between simulated and measured points



Generally good agreement with major discrepancy on Q_y at high energy due to saturation and on Q_x at injection. Q_x matches better with simulation at high energies. Why?

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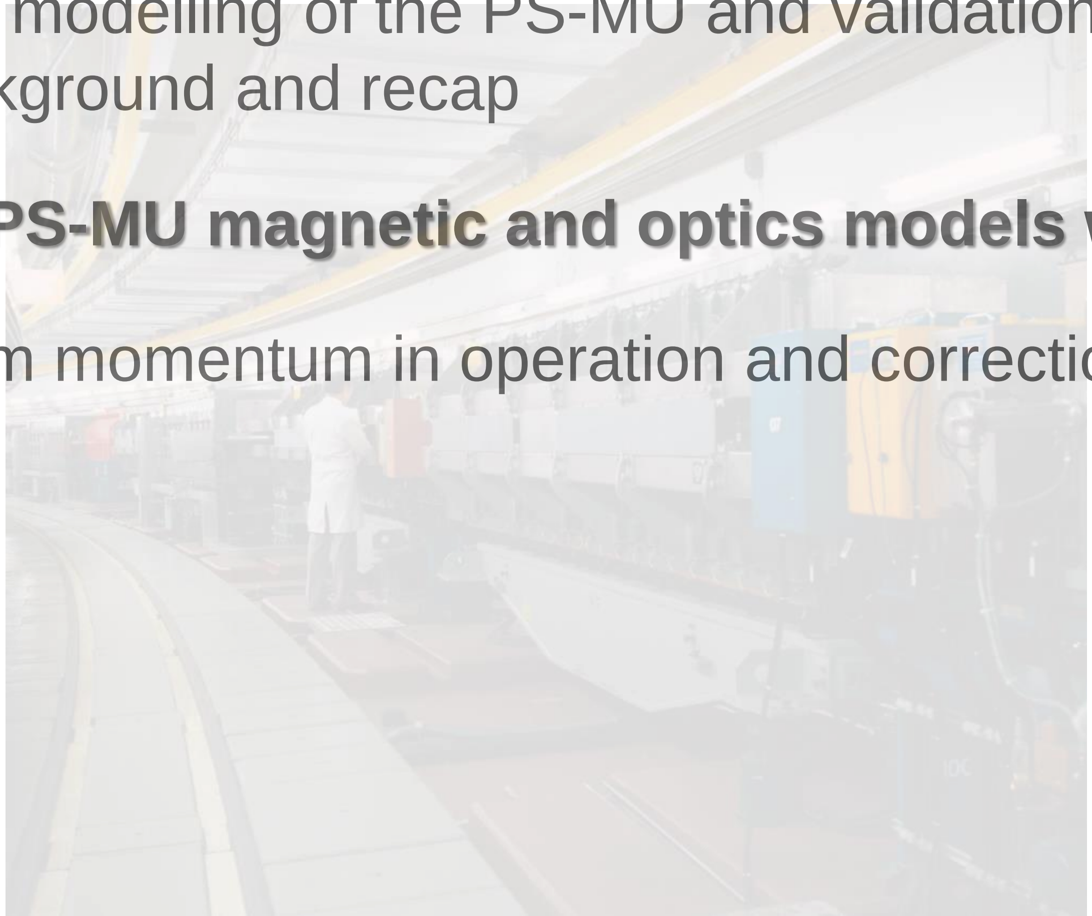
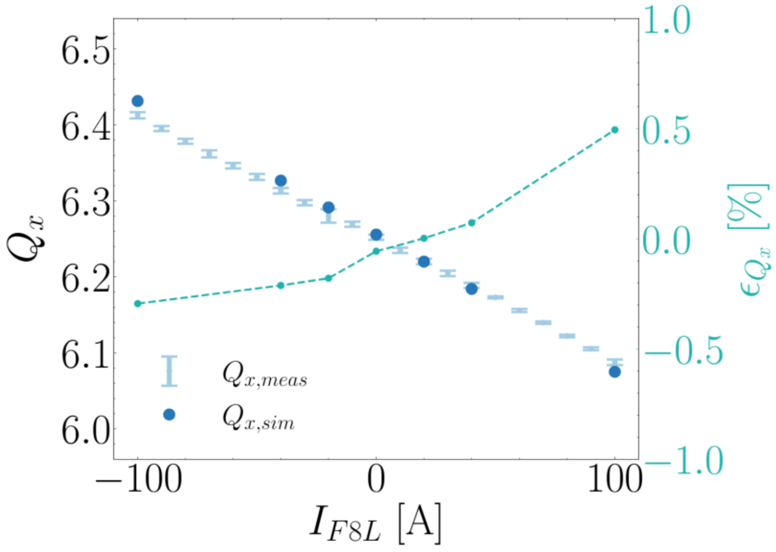
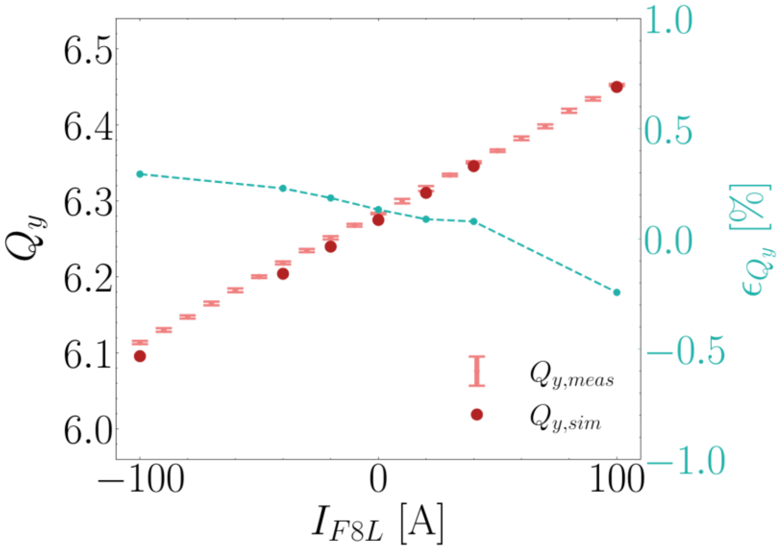


Models' benchmarking with additional circuits: F8L

- **Models including F8L were benchmarked at 3 different energy levels:**
  - 2.79 GeV/c (injection) → remanent field (not included in the model) plays a significant role in the measurements;
  - 10.14 GeV/c → intermediate energy → remanent field and iron saturation do not perturb the measurements;
  - 18.00 GeV/c → high energy → harmonics distortion from iron saturation is dominant
- **Example of benchmarking at 10.14 GeV/c ranging the I_{F8L} current:**





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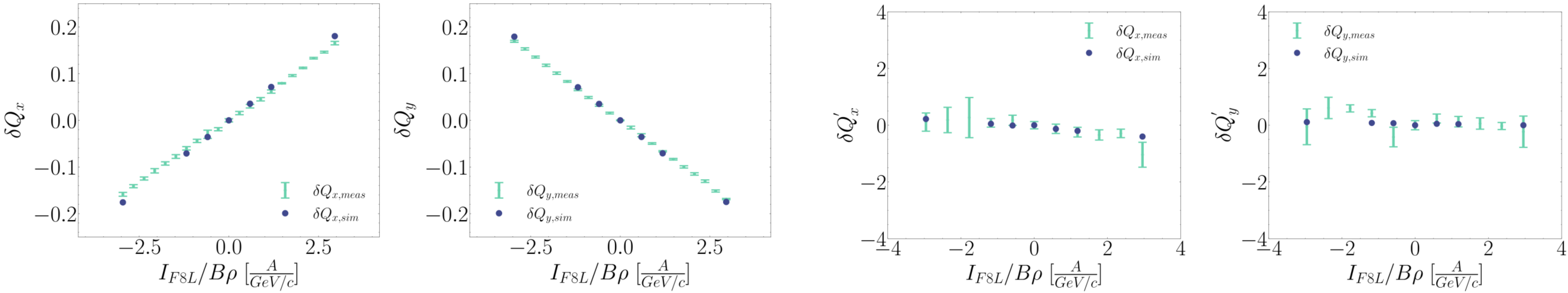
- **Example of benchmarking at 10.14 GeV/c ranging the I_{F8L} current:**
  - Tune-shift with respect to bare-machine: $\delta Q = Q_0 - Q(I_{F8L})$



Models' benchmarking with additional circuits: PFW

- **Models including PFW were benchmarked at 3 different energy levels:**
  - 2.79 GeV/c (injection) → remanent field (not included in the model) plays a significant role in the measurements;
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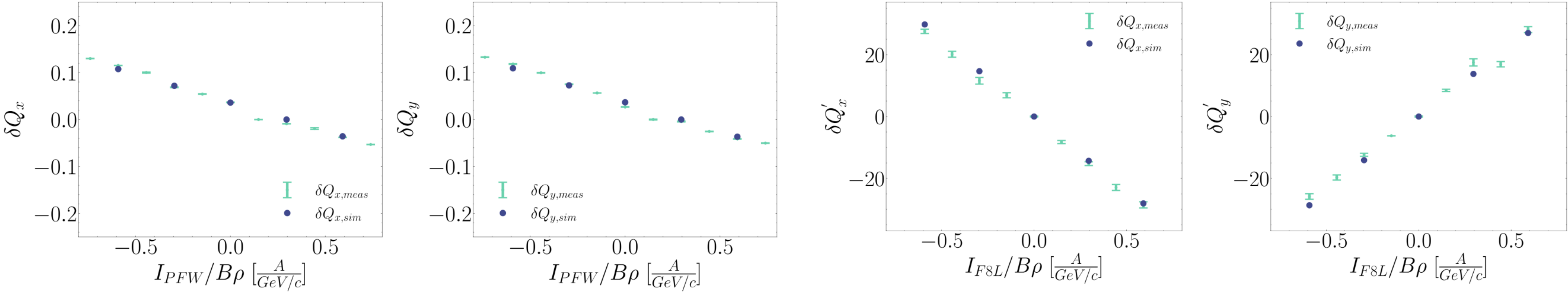

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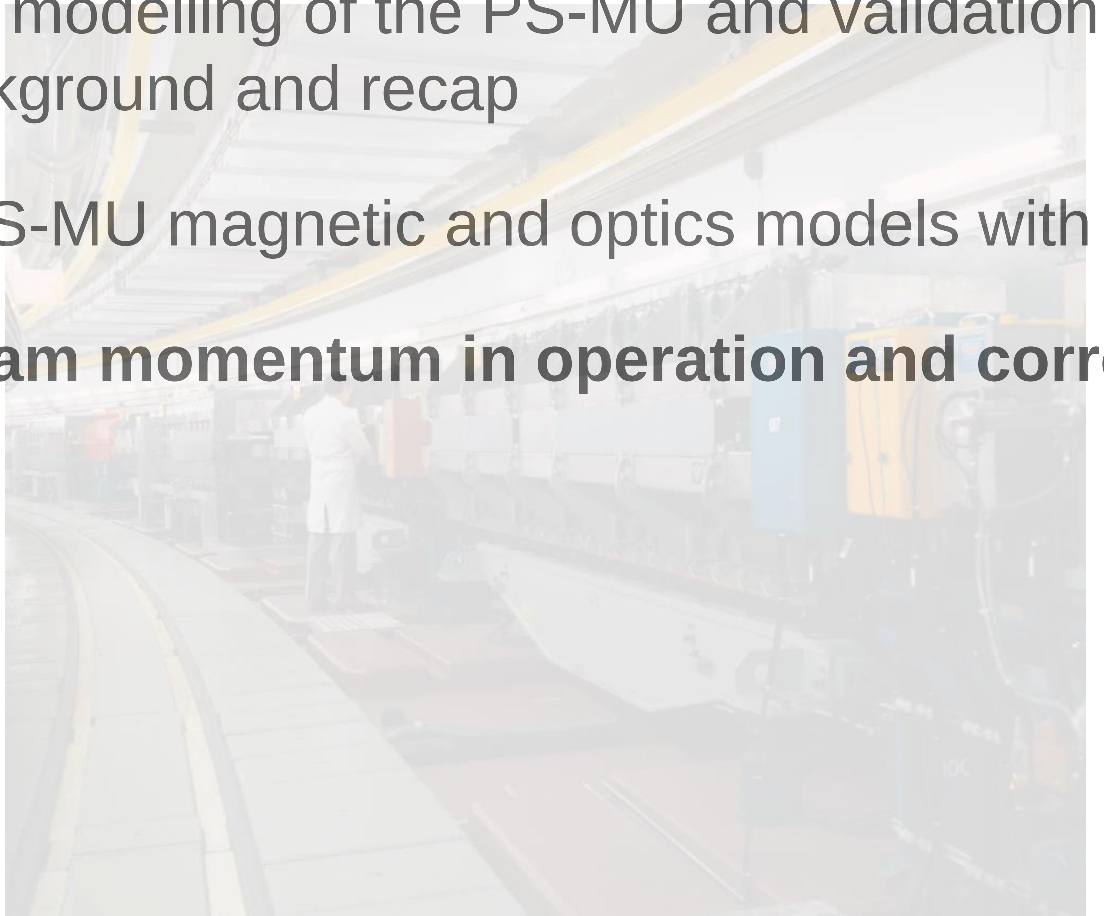


Momentum computation in operation

- **MAD-X optics simulations rely on the estimate of the beam momentum to convert the field harmonics computed in Opera (B_n) into magnet strengths (k_{n-1}). Beam momentum, accessible through LSA, is derived from the magnetic rigidity:**

$$k_{n-1}\,[m^{-n}] = \frac{1}{3.3356\,p}(n-1)!\,\frac{B_n}{R_{ref}^{n-1}} \qquad B\rho = 3.3356\,p$$

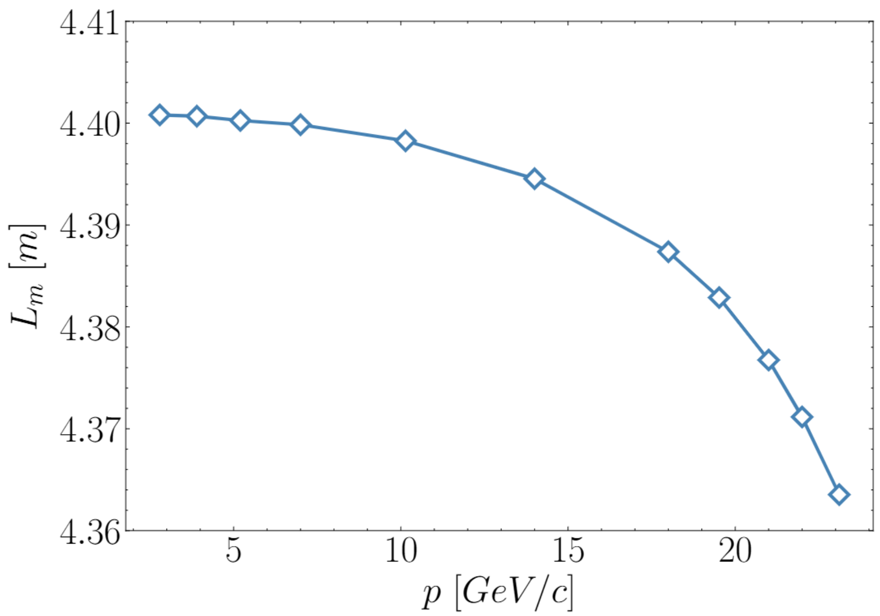
- **Field from the magnetic model was normalized using the programmed momentum of the specific cycle from LSA**
  - This designed momentum is regulated based on the B-train measurements, which ensure that the designed and the actual field in the machine matches.

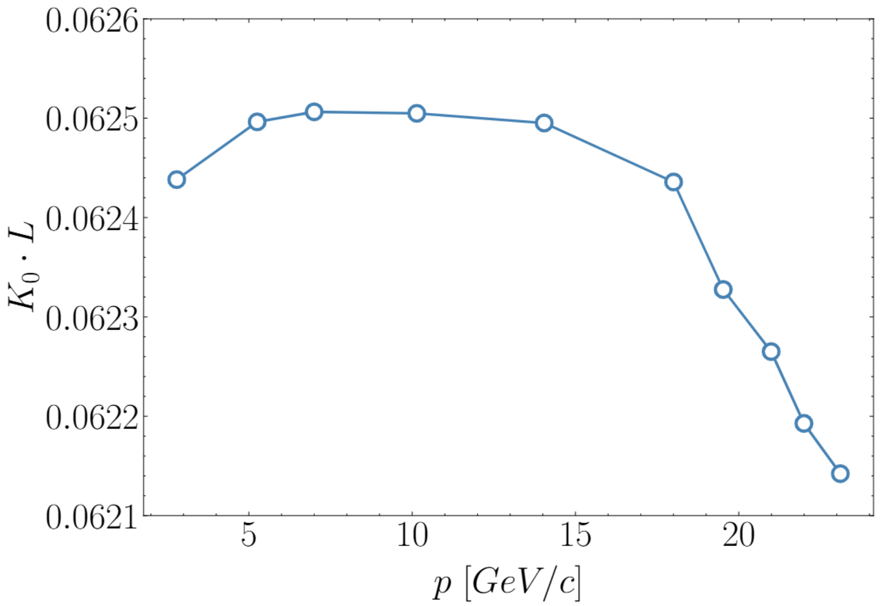
- **The nominal calculation used in the design of PS cycles assumes a constant magnetic length across the entire energy range, from injection to extraction, equal to the theoretical nominal magnetic length of the machine:**

$$L_m = \frac{C - n_{\substack{str\\sec}} L_{\substack{str\\sec}} - n_{\substack{sh\,str\\sec}} L_{\substack{sh\,str\\sec}}}{N_{MU}} = \frac{2\pi 100 - 20\cdot 3 - 80\cdot 1.6}{100} = 4.403\,m$$

Momentum computation in operation

- **Magnetic length was computed from the magnetic model:**





At injection, L_m matches with the theoretical value (slightly above 4.40 m).

At increasing energies, the MU gets shorter (L_m diminishes), with maximum variation of ~0.8% at 23.11 GeV/c.

The same effect is also evident from the simulation of the integrated dipole strengths k_0L. This also illustrates the problem with the programmed momentum computation because, with the machine circumference fixed and MRP forced to be constant, the k_0L should be constant.

Momentum computation in operation

- **Two distinct approaches followed to correct for the magnetic length saturation:**
  - Corrected momenta computation by flattening $k_0 L$ with the value it has at 10.14 GeV/c (no remanent field nor saturation effect):

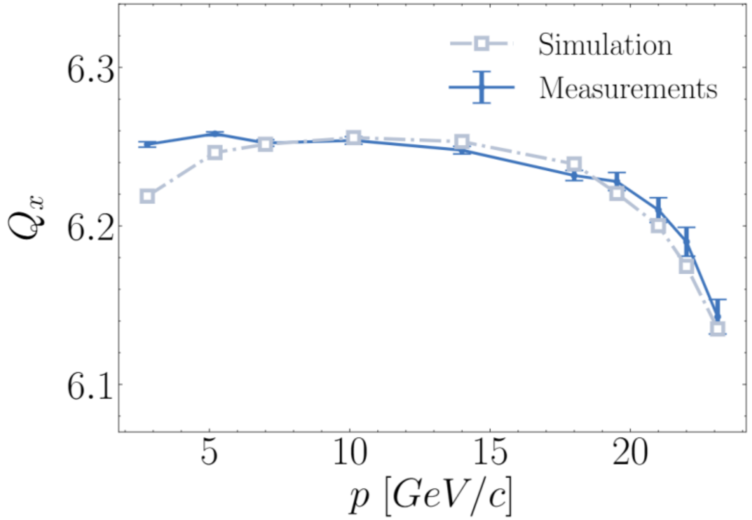
$$k_0(p) = \frac{1}{3.3356\,p} B_{1,i}(p) \;\rightarrow p_{corr} = \frac{B_{1,i}(p)}{3.3356\,k_0\left(10.14\,\frac{GeV}{c}\right)}$$

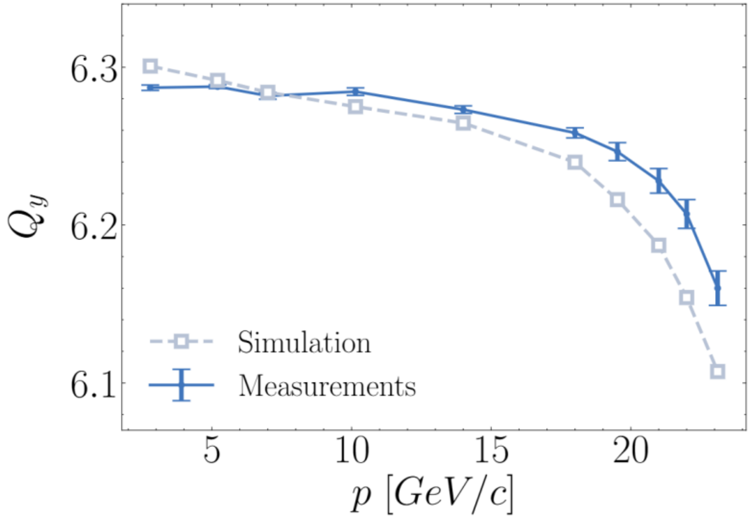
  - Corrected momentum computation via magnetic length predictions from the model:

$$L_m = \frac{2\pi\rho}{N_{MU}} \rightarrow \rho = \frac{N L_m}{2\pi}$$

$$B\rho = B\frac{N_{MU} L_m}{2\pi} = 3.3356\,p \;\rightarrow p = \frac{1}{2\pi}\frac{1}{3.3356} B N_{MU} L_m$$

- **With corrected momenta, magnet strengths were computed again and new optics simulations repeated**





Momentum computation in operation

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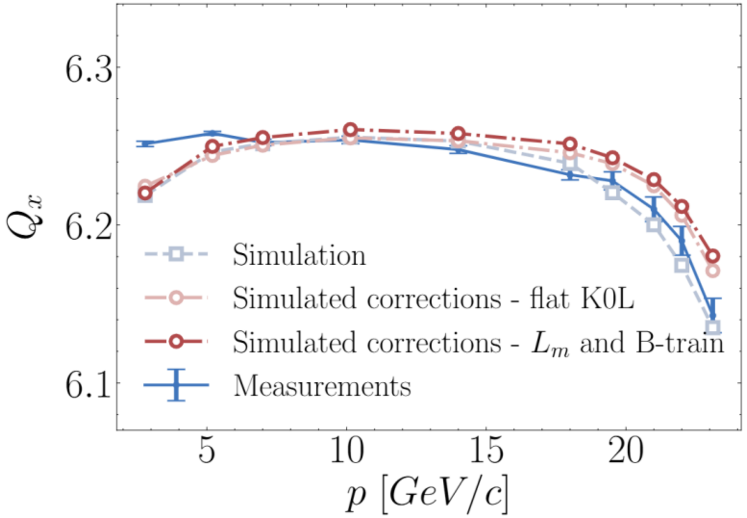
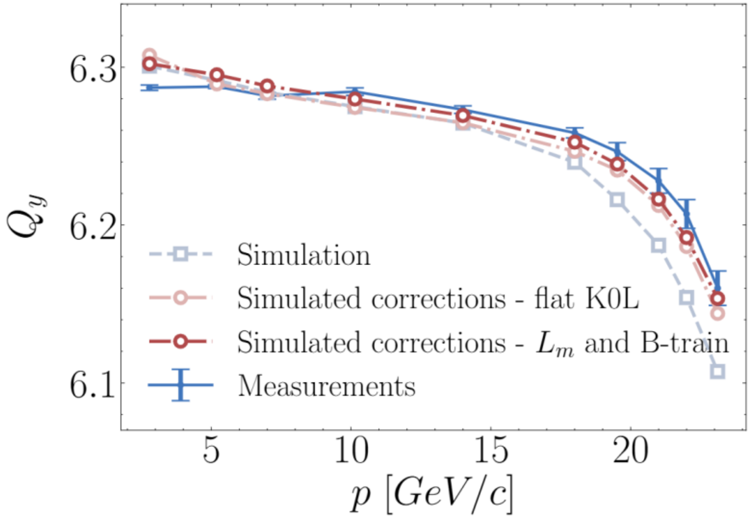
  - Corrected momentum computation via magnetic length predictions from the model:

$$L_m = \frac{2\pi\rho}{N_{MU}} \rightarrow \rho = \frac{NL_m}{2\pi}$$

$$B\rho = B\frac{N_{MU}L_m}{2\pi} = 3.3356\,p \rightarrow p = \frac{1}{2\pi}\frac{1}{3.3356}BN_{MU}L_m$$

- **With corrected momenta, magnet strengths were computed again and new optics simulations repeated**





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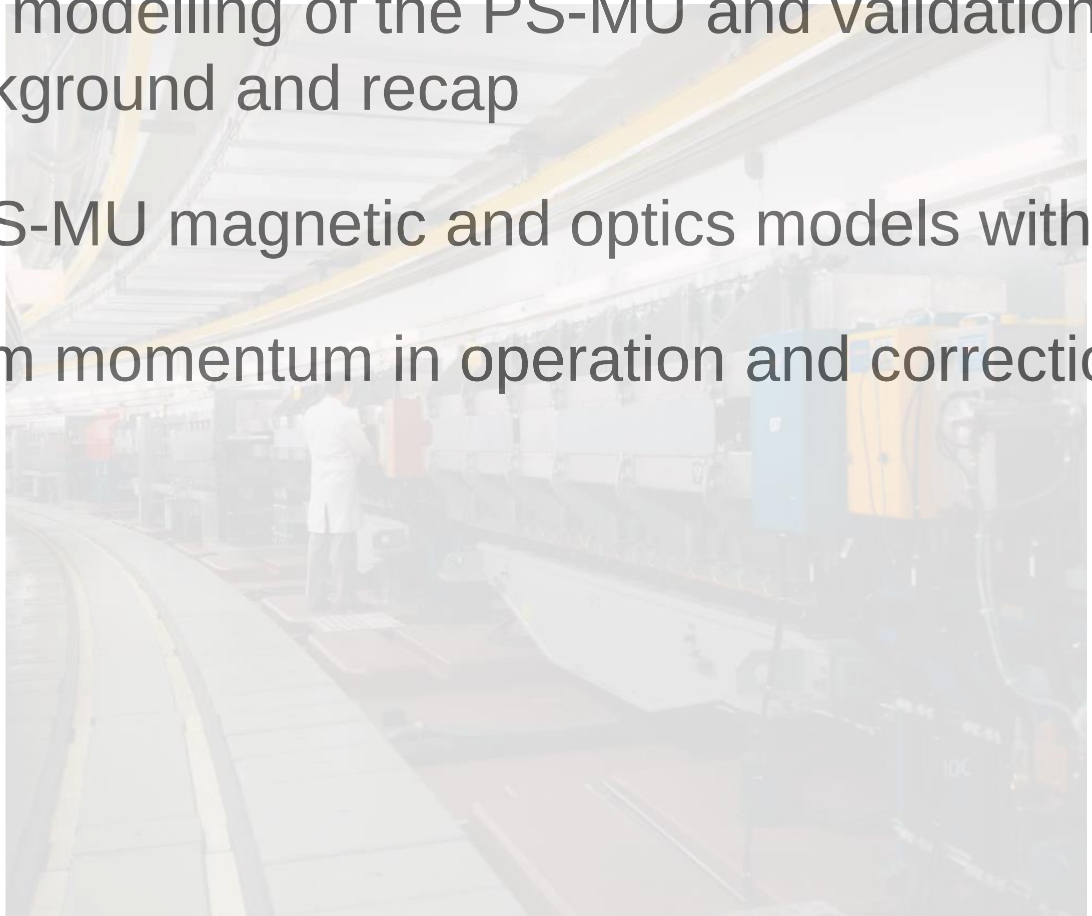

Conclusions

Bare-machine models' benchmarking showed a good agreement between measured and simulated data. Similarly for the chromaticity comparison, which inspired OP for bare-machine extraction at 15 GeV/c for some specific experimental areas.

Models' benchmarking against beam-based measurements including F8L and PFW showed excellent agreement in the tune and chromaticity shifts with respect to the bare-machine.

Models were also benchmarked in a more complex scenario which involves the simultaneous powering of all MU's circuits. The powering settings, taken from an operational LHC cycle, were applied on the 10.14 GeV/c and 18.00 GeV/c plateaus. Tunes and first order chromaticities showed very good agreement (*backup slides*).

Magnetic model helped identifying the impact of the magnetic length saturation on the estimate of the beam momentum in operation. With two distinct techniques, the momenta were corrected and tunes comparison improved further at high energies. Now, comparable discrepancies between Q_x and Q_y → OP is considering the introduction of a calibration factor to account for the saturation of the magnetic length.

After tripping POPS many times at 1am:

“Vittorio, we wish you a good night”

Thank you all for your attention

home.cern

Backup slides

Models' benchmarking with additional circuits: PFW

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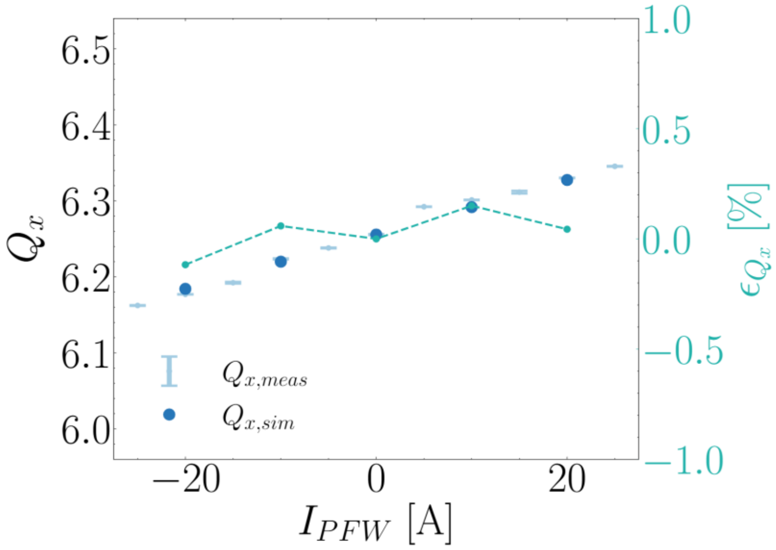

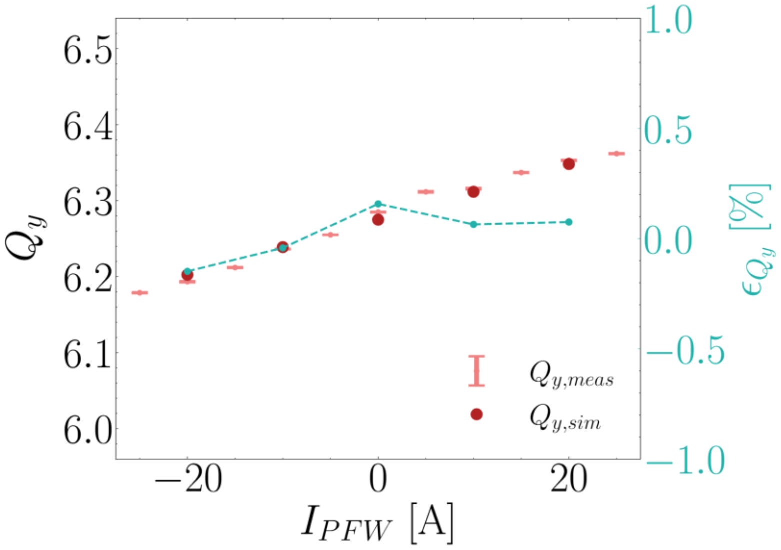

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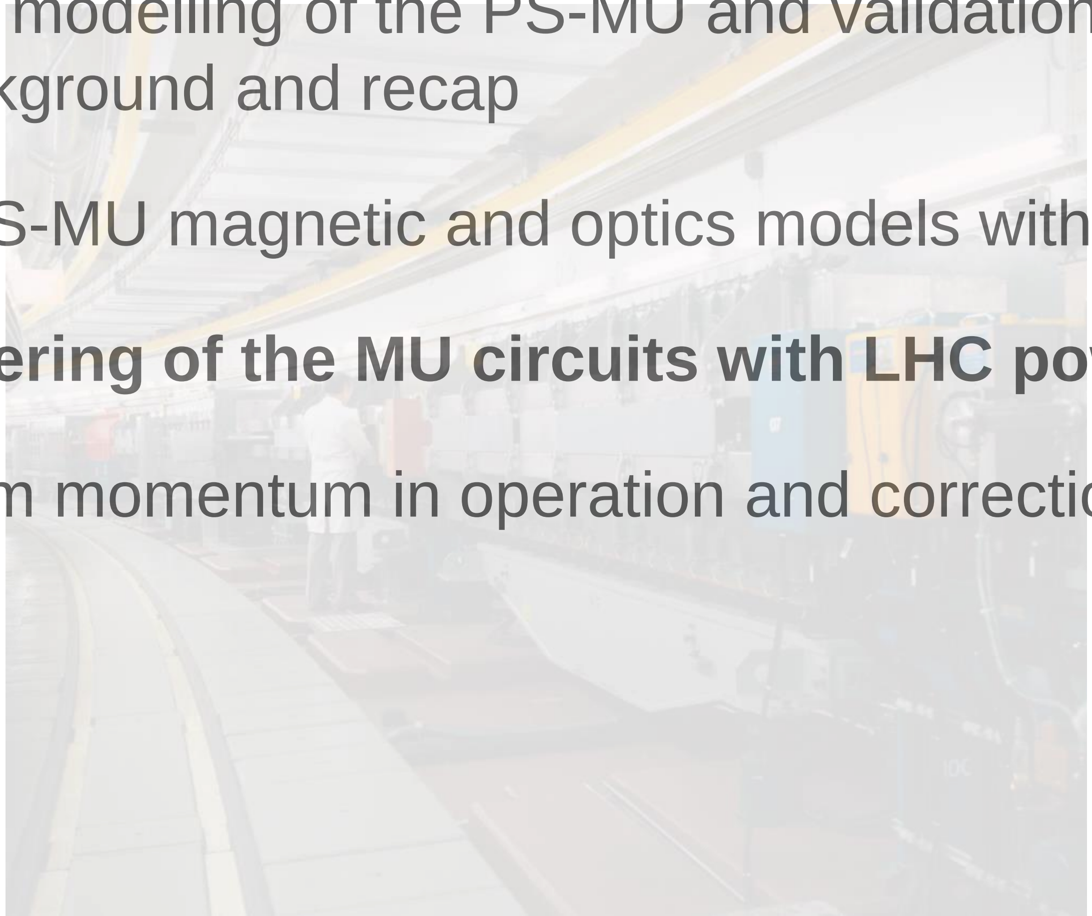

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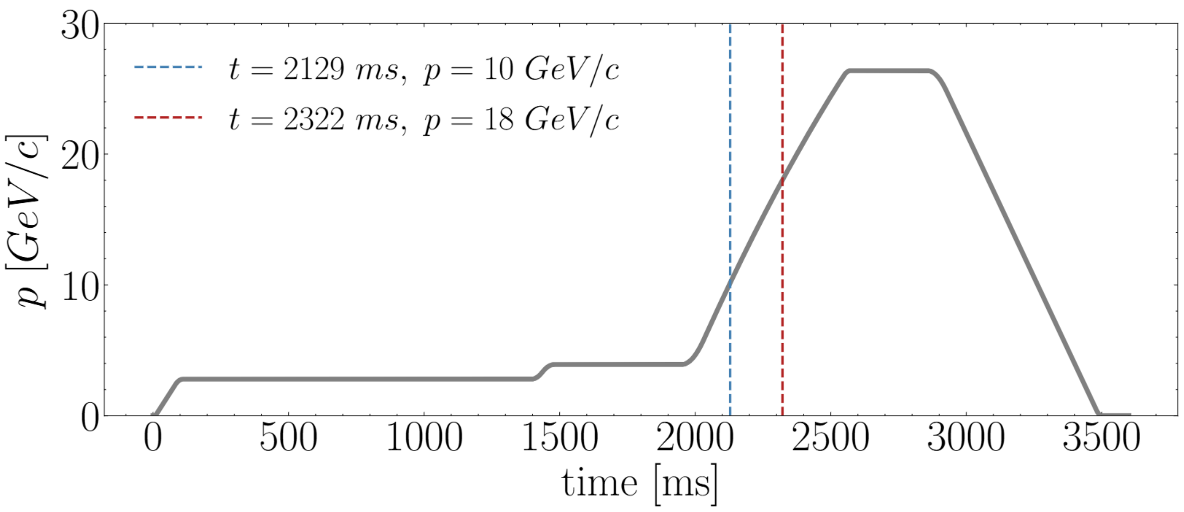
Simultaneous powering of all MU's circuits

- A more sophisticated scenario, including the simultaneous powering of Main Coil, F8L and PFW, was analyzed

- Powering settings from the operational LHC cycle LHC25\#48b-BCMS-LowTail-24 at 10.14 GeV/c and 18.00 GeV/c were applied on the corresponding plateaus

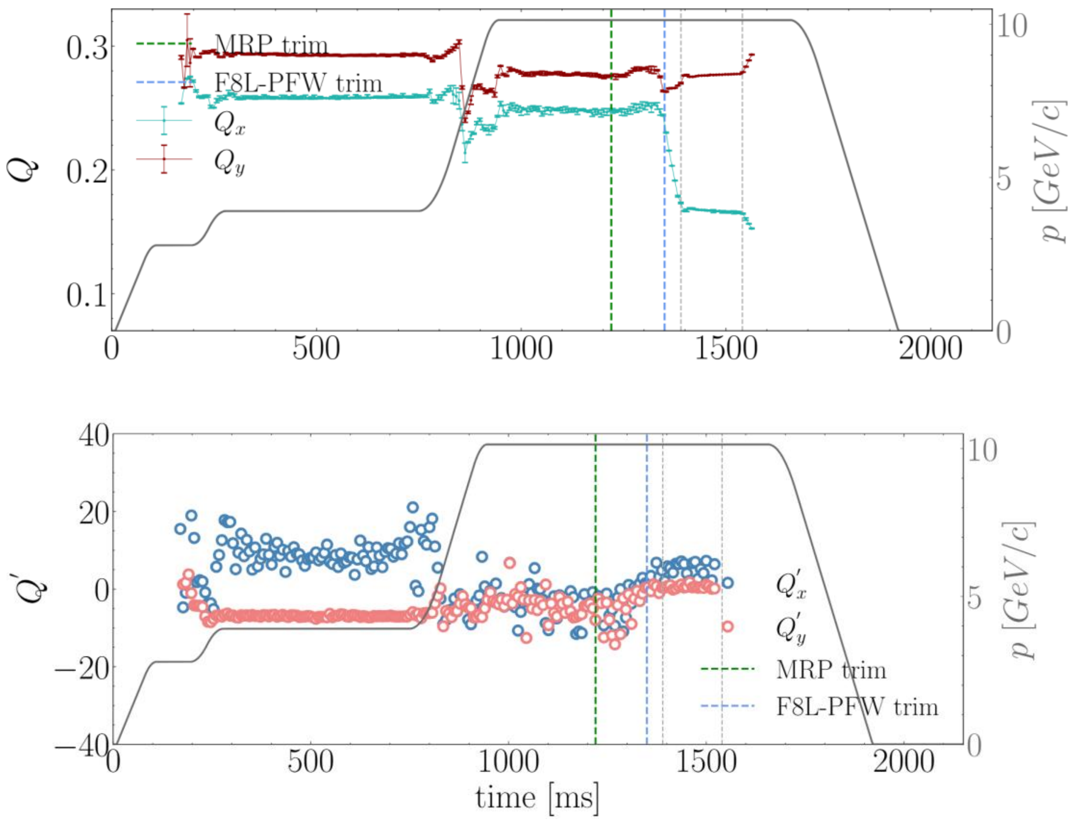


Circuit	I [A]	
	10.14 GeV/c	18.00 GeV/c
Main Coil	1925.30	3428.00
F8L	350.00	558.50
PFW – DN	-35.91	-54.60
PFW - DW	-47.86	-79.10
PFW – FN	23.53	42.80
PFW - FW	10.65	18.60

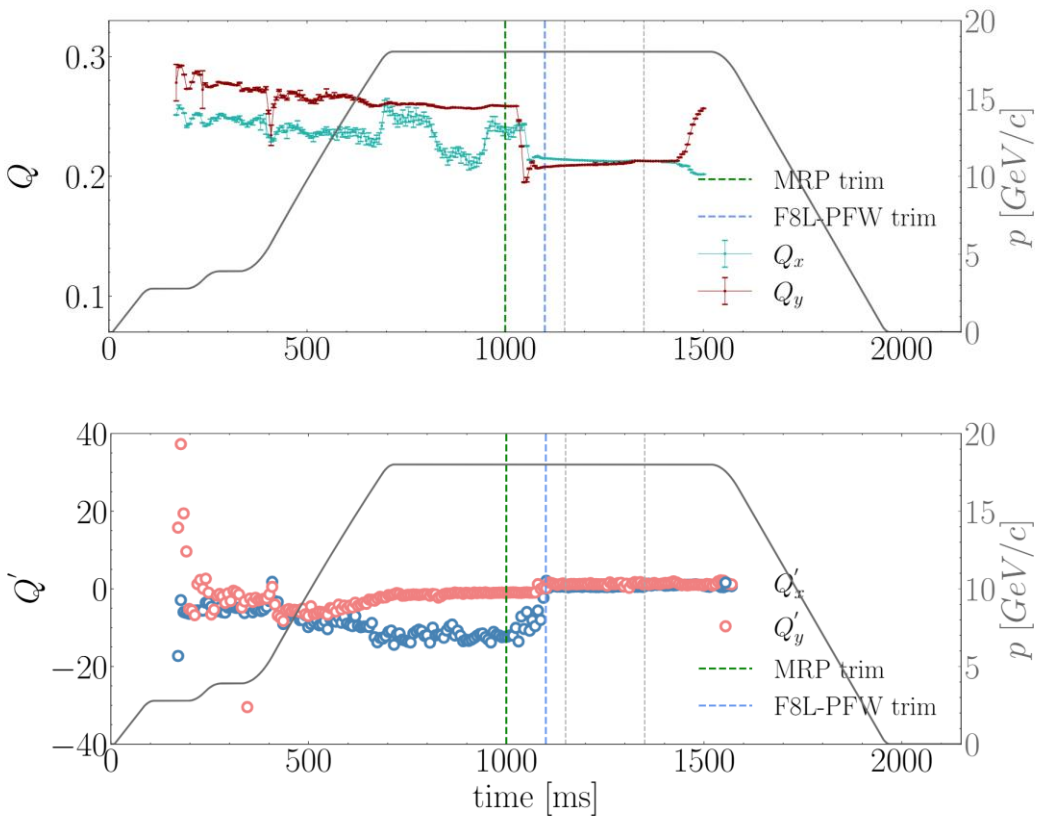
Simultaneous powering of all MU’s circuits

- **MRP measurements and corrections, tunes and first order chromaticity measurements:**

10.14 GeV/c

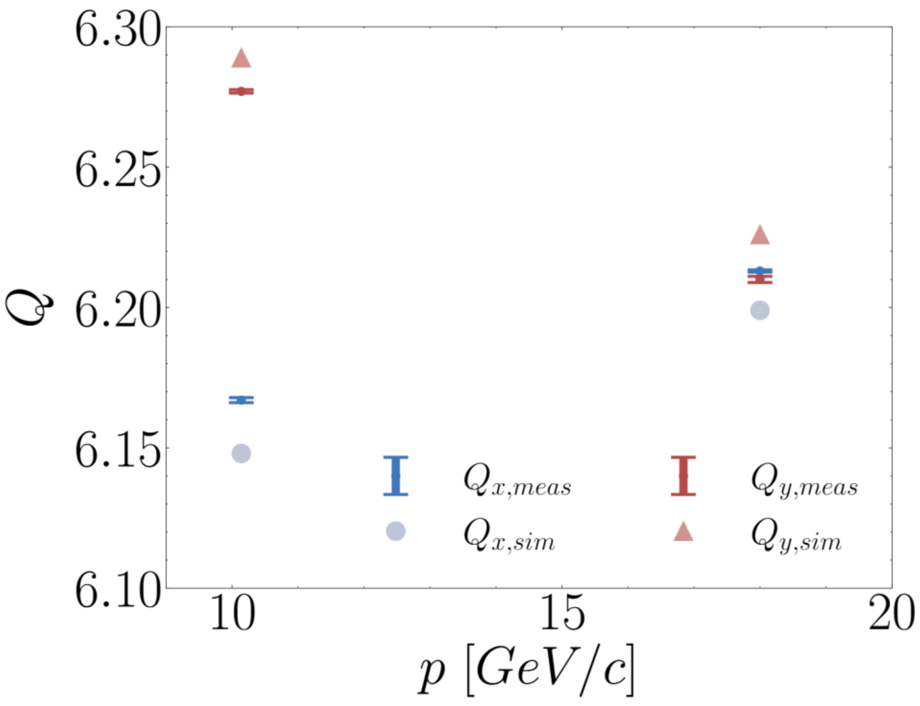


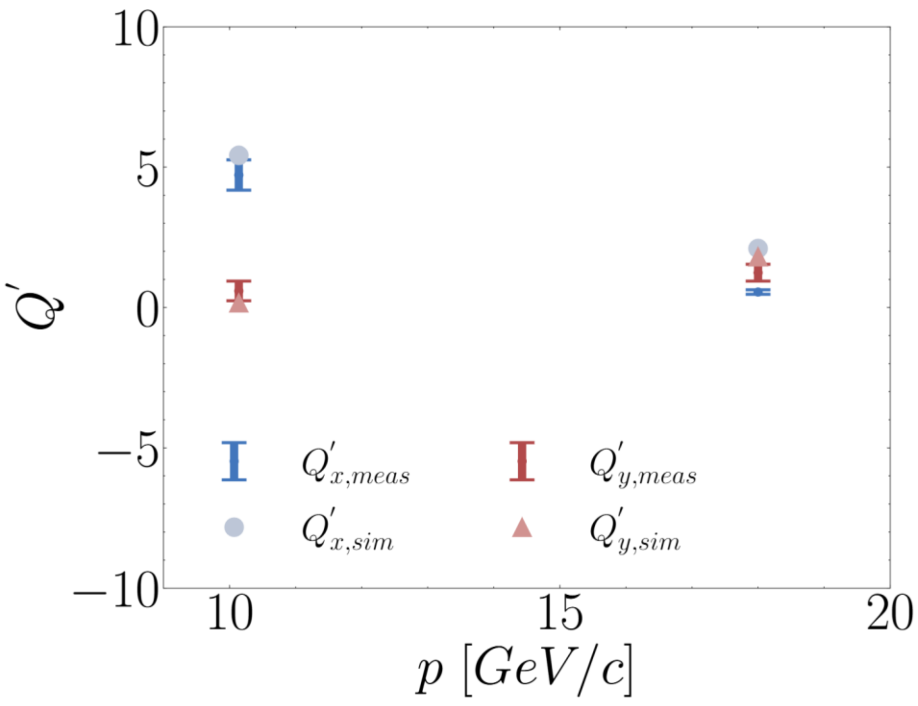
18.00 GeV/c



Simultaneous powering of all MU's circuits

- **Predicted tunes and chromaticity comparison against measurements:**





Tune discrepancy on the level below $2 \cdot 10^{-2}$, while measured and simulated tune-shifts are consistent.
Good agreement for the first chromaticity, mostly within the error bars.