Simulating the Impacts of Space Charge Effects on the LHC Beam Halo

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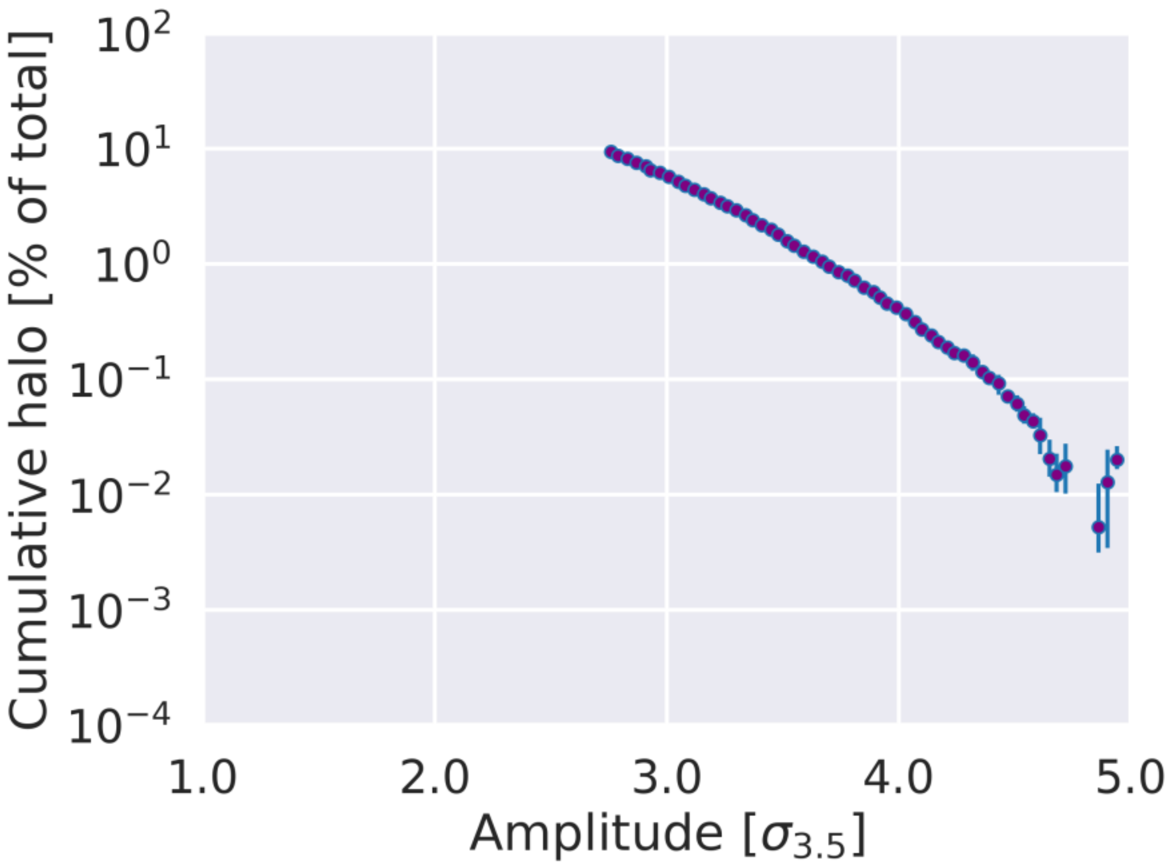
Outline

I. Introduction

The Beam Halo

- A halo particle is defined as a particle with **a large amplitude in either transverse plane**.
- Particle action in x: $J_x[\sigma_x^2] = \frac{\hat{x}^2 + \widehat{p_x}^2}{2}$.
- Particles with a transverse amplitude above 3σ in either plane considered halo particles – definition can vary.
- We consider a particle to be in the halo if $(\boldsymbol{2J_x > 9\sigma_x^2}) \vee (\boldsymbol{2J_y > 9\sigma_y^2})$.
- The beam halo in the LHC is **overpopulated** relative to the expected Gaussian.



$\sigma_{3.5}$: transverse beam size with an emittance $\varepsilon = 3.5\ \mu m$.

Figure: M. Rakic (EPFL PhD Thesis)

Halo Overpopulation and Scaling with Emittance

- Halo particles are of particular concern for machine protection.
- Measurements show that bunches with smaller emittances exhibit larger halo populations, and vice versa.
- In other words, there is an anti-correlation between halo content and emittance.
- Collective effects depend on intensity over emittance (“brightness”). Space charge is the main candidate among the collective effects that could be responsible.

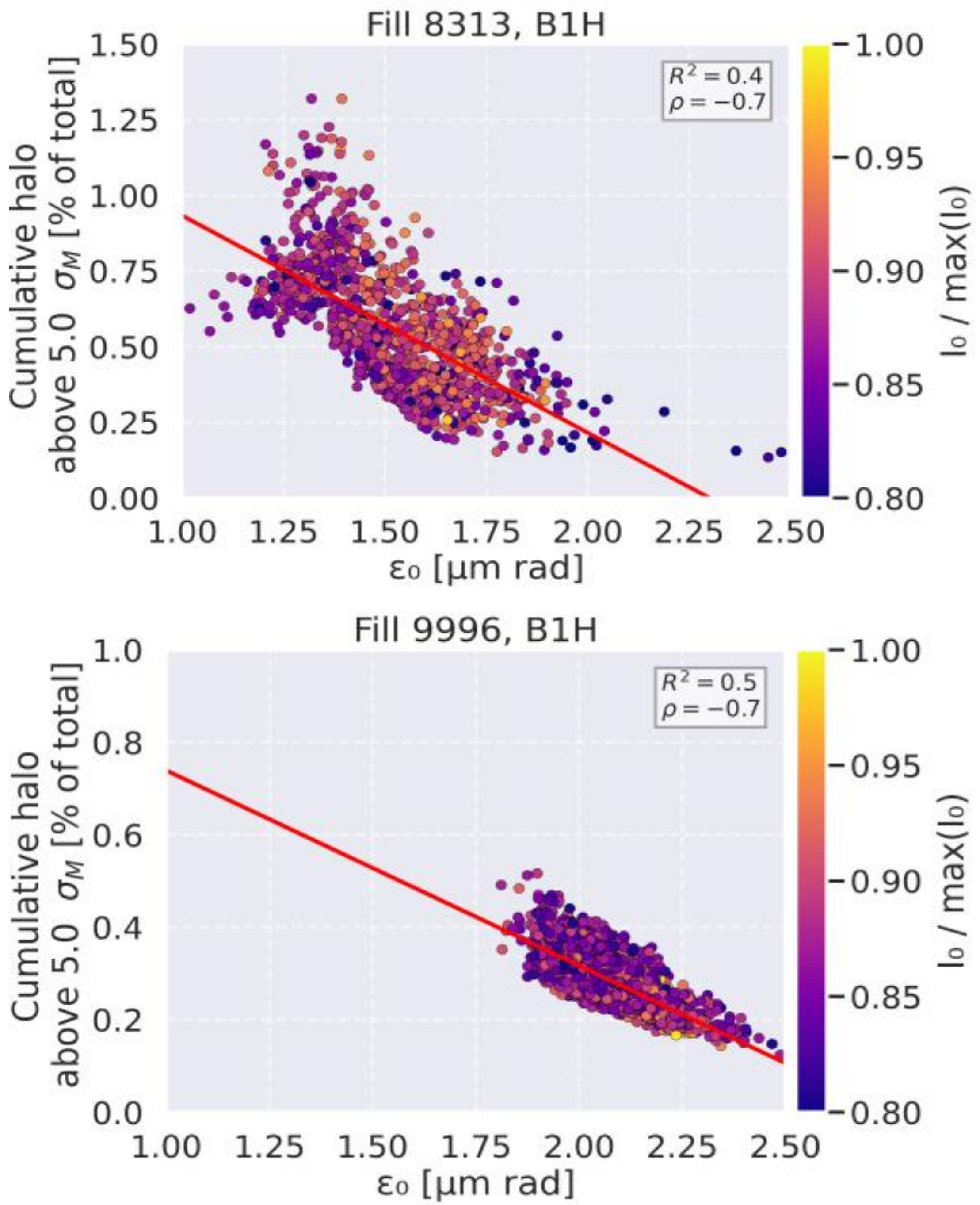
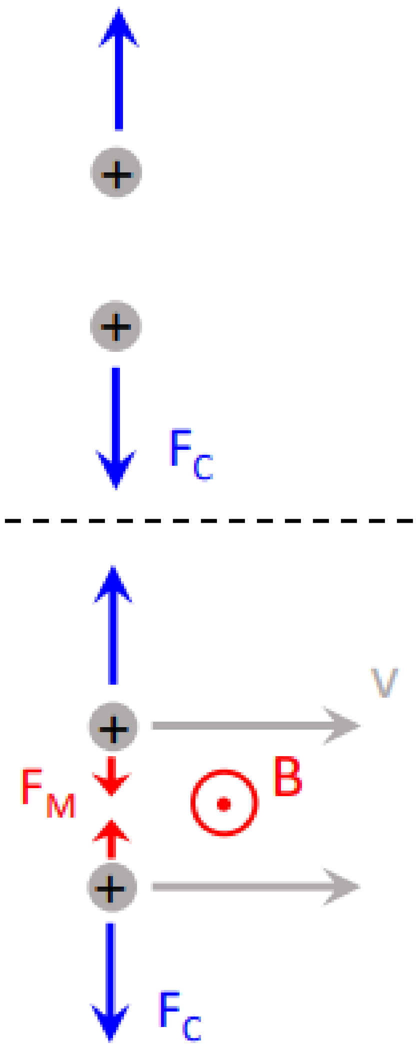


Figure: M. Rakic

Space Charge

- **The Coulomb repulsion between like charges with magnetic attraction given by their movement.**
- Begins to play a role in high-luminosity and high-intensity accelerators, such as the LHC and SPS.
- Space charge forces are created by the overlap of Coulomb repulsion and magnetic attraction between the ensemble of charged particles that constitutes a beam.

Consider two positively charged particles in free space:



At rest: particles only experience a repulsive Coulomb force F_c.

Moving at v: particles experience a repulsive Coulomb force F_c and an attractive magnetic force F_m.

Figure adapted from T. Pieloni

Space Charge Forces

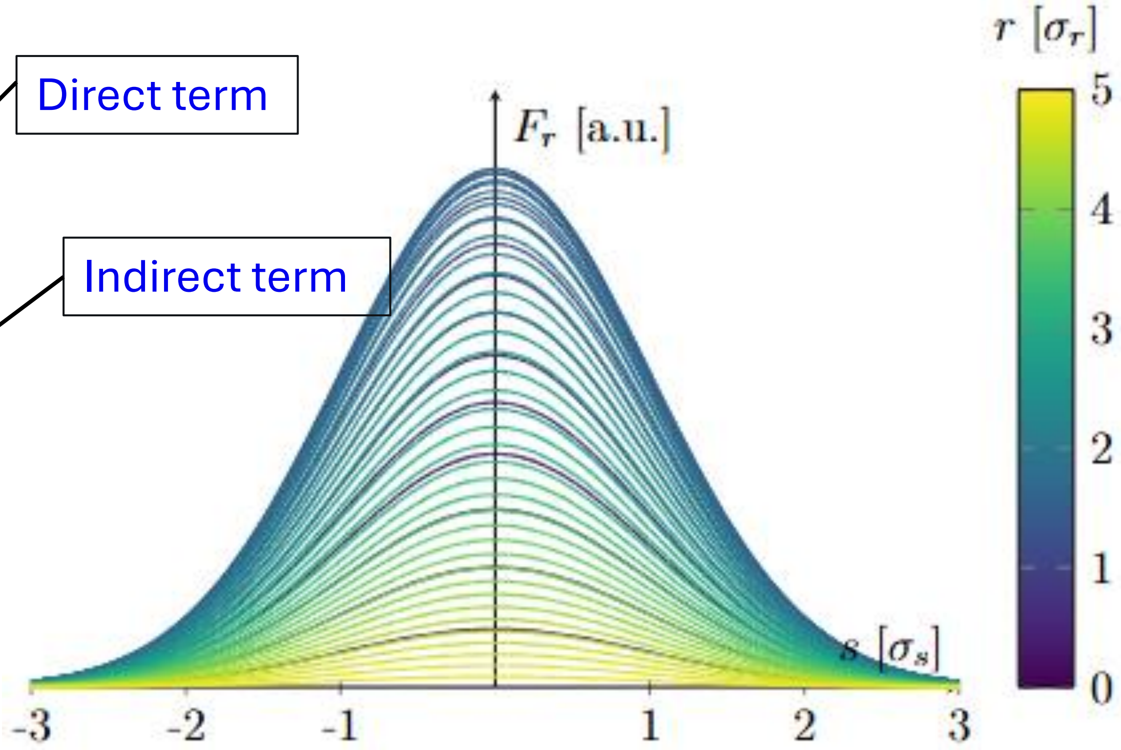
- Two forces experienced by a particle due to space charge: direct and indirect. Indirect space charge forces consider the effects of the beam pipe.
- Total transverse space charge force:

$$F_r(r,s) = \frac{Nq^2}{(2\pi)^{3/2}\varepsilon_0\gamma^2\sigma_s} e^{-\frac{s^2}{2\sigma_s^2}} \left[\frac{1}{r}\left(1 - e^{-\frac{r^2}{2\sigma_r^2}}\right) - \frac{r}{b^2}\right]$$

Direct term

Indirect term

- Weaker in the LHC due to strong inverse energy dependence – will show results for LHC and SPS regimes.
- Core particles experience strongest space charge force.
- Space charge forces produce an amplitude-dependent tune shift which can cross resonances.



II. Methodology

Methods for Calculating $\varepsilon_{x,y}$ in Simulations

Equation relating emittance to beam size $\sigma_{x,y}$, dispersion $D_{x,y}$ and longitudinal spread σ_δ :

$$\varepsilon_{x,y} = \frac{\sigma_{x,y}^2}{\beta_{x,y}} - \frac{D_{x,y}^2}{\beta_{x,y}} \sigma_\delta^2$$

- Constant emittance $\varepsilon_{x,y}^c$ – emittance is assumed to be constant with time. Physically: no diffusive mechanisms, constant of motion.

Realistic methods:

- Profile emittance $\varepsilon_{x,y}^p$ – calculated statistically from beam profile only.
- Gaussian emittance $\varepsilon_{x,y}^G$ – $\sigma_{x,y}^G$ is extracted from a Gaussian fitted to the beam profile.

Most accurate method (but physically impossible):

- Distribution emittance $\varepsilon_{x,y}^d$ – position of every particle known. Beam size = standard deviation of full positional distribution.

Calculating Halo Content from Full Distribution

- Positions and momenta of all particles known in normalised coordinates.
- Action computed directly for each particle.
- Scraping measurements involve moving collimator jaws inwards in small steps towards the beam core, removing beam tails.
- This method is evidently destructive to the beam.

Scraping Measurement Setup

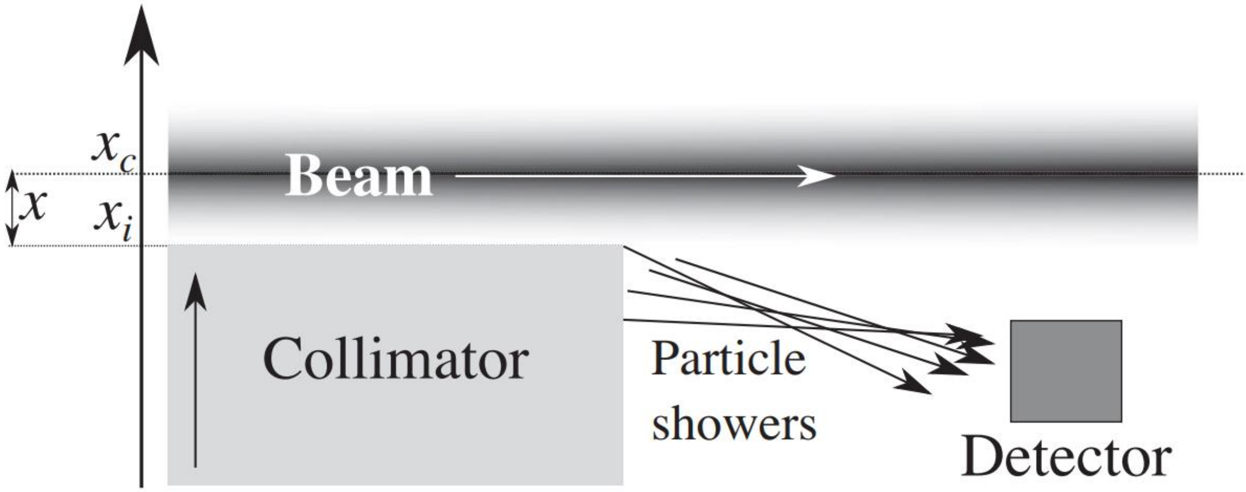
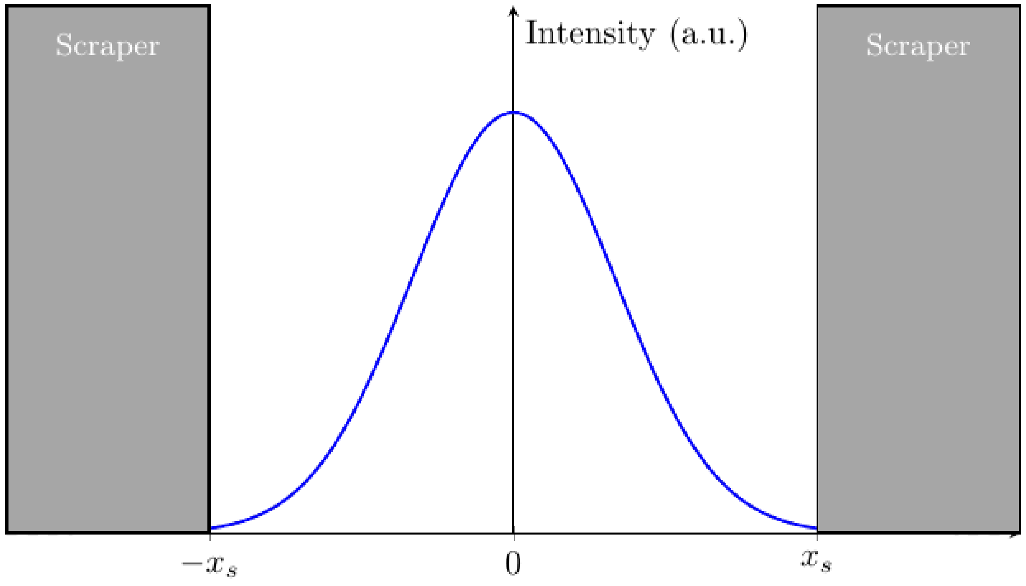


Figure: A. Gorzawski et al.

Beam Profile Scraped at 3σ



Calculating Halo Content from Profile

- Knowledge of only the horizontal and vertical beam profiles is assumed – this method is **non-destructive**.
- Inverse Abel transform of beam profile reconstructs particle distribution.
- Underlying assumption: circularly symmetric 2D distribution – **not always guaranteed**.
- Fraction of halo particles calculated by integrating the action distribution above the halo limit and dividing by the total area.
- This mirrors profile measurements taken using Beam Wire Scanners (BWS) or Beam Synchrotron Radiation Telescopes (BSRT).

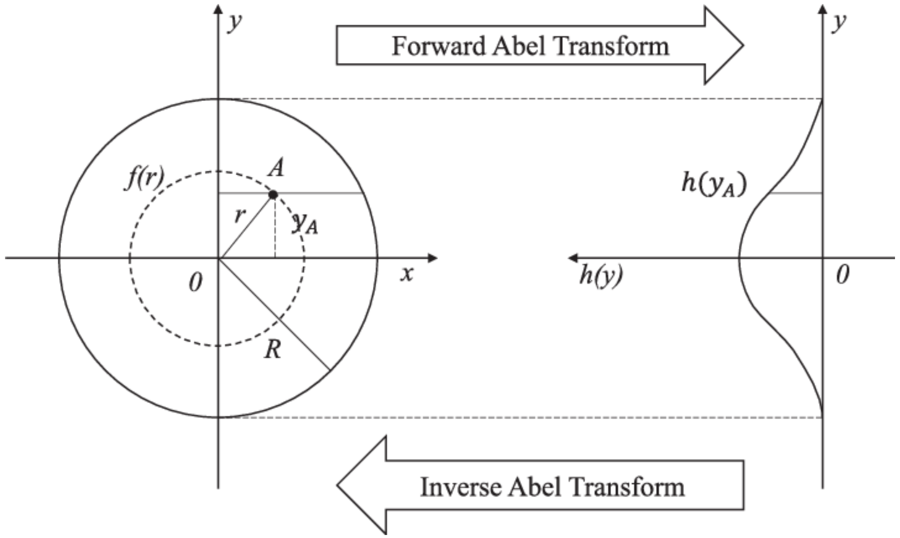


Figure: Y. Zhang et al.

$$f_t = f_x + f_y - f_x f_y$$

Simulation Setup

- Long-term, multi-particle tracking simulations were performed using ***XSuite***.
- Frozen space charge model used.
- Particle-in-cell (PIC) model may have produced more accurate results.
- **100,000 particles** for each case presented – on computationally feasible and operationally relevant timescales.
- 10^5 particles is statistically significant in order to observe effects in the tails of the distribution.

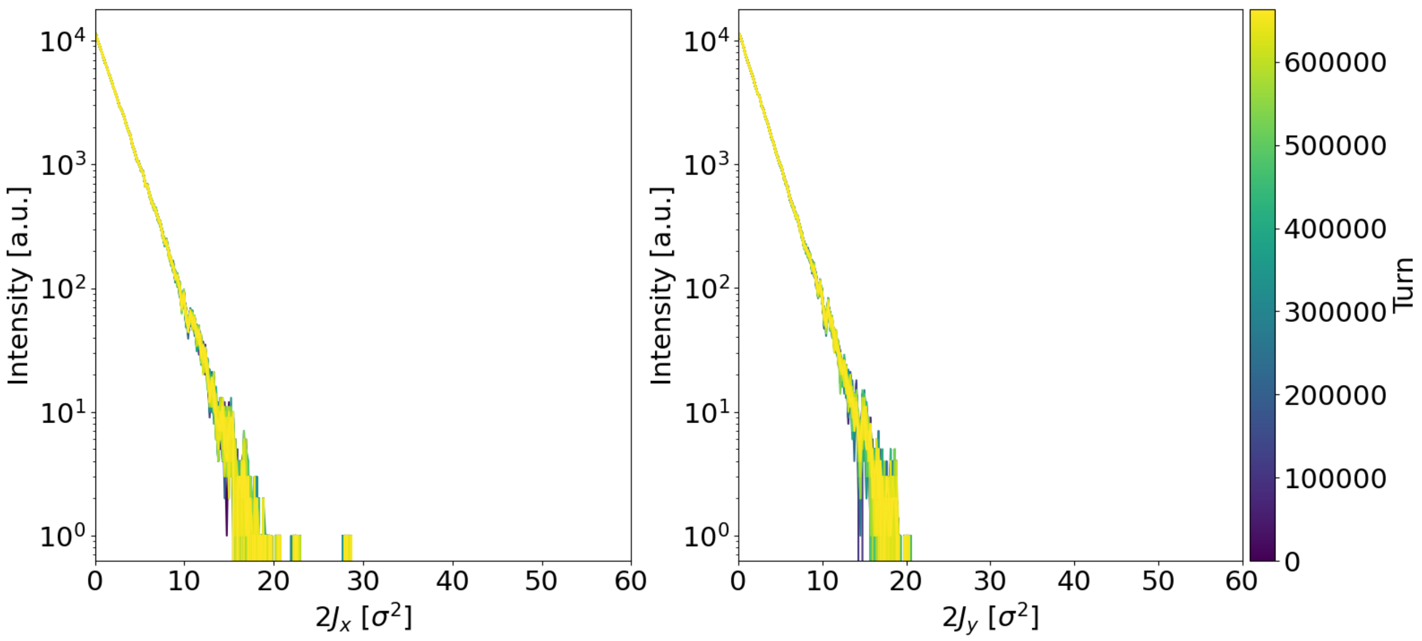
Frozen Model	PIC Model
▪ Uses a fixed Gaussian bunch distribution to compute space charge forces. ▪ Assumes that initially computed space charge forces are constant throughout tracking. ▪ May not hold if particle distribution significantly diverges from a Gaussian. ▪ Fastest and least computationally intensive.	▪ No assumptions made on bunch shape. ▪ Uses average momenta to recompute space charge forces. ▪ Space charge forces recomputed throughout tracking. ▪ Highly computationally intensive.

III. Simulations of Space Charge Effects on the Beam Halo in the LHC

Initial LHC Simulations: Results and Parameters

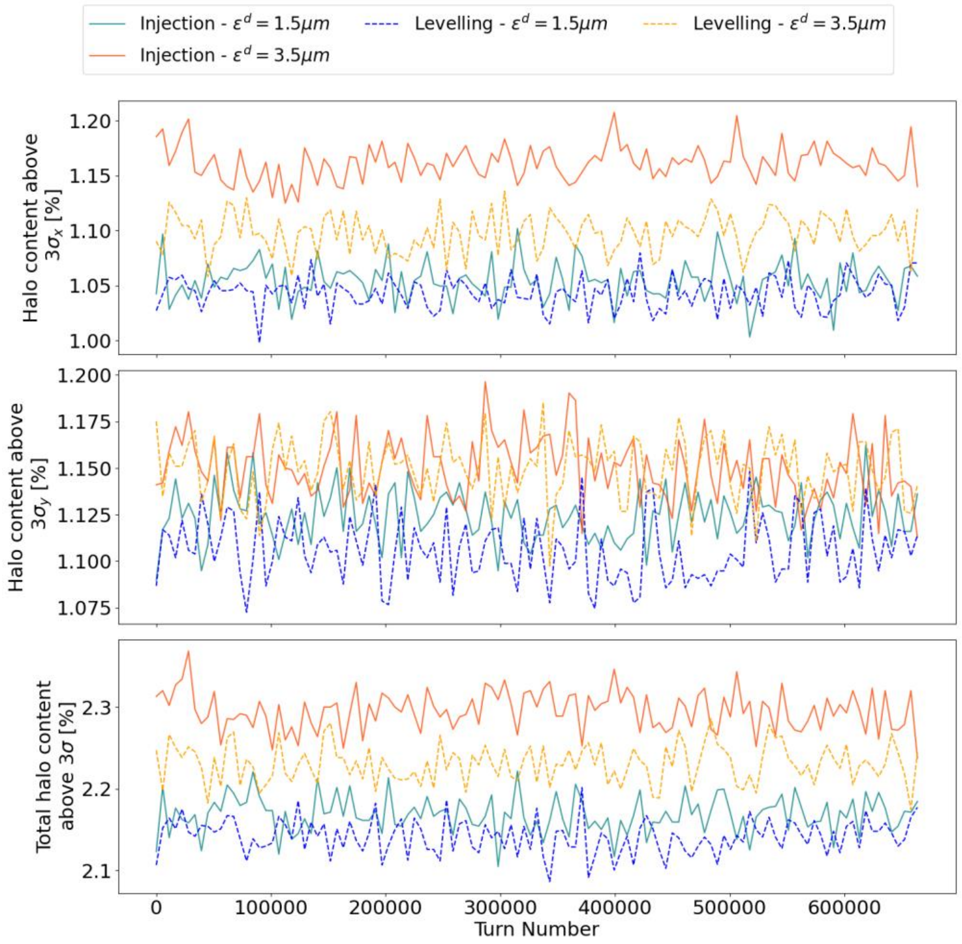
- Initial emittances at both ends of the realistic LHC working range ($\varepsilon_{x,y}$ = 1.5μm and 3.5μm).
- Injection (450GeV) and top (6.8TeV) energies simulated.
- Intensity follows a negative exponential distribution with respect to action.
- Only ε^d is used in this section.
- Even in the regime most optimal for space charge effects to occur ($\varepsilon_{x,y}$ = 1.5μm at 450GeV) – no discernible effects were observed.

Action Distribution (at injection, $\varepsilon^d = 1.5\mu m$):



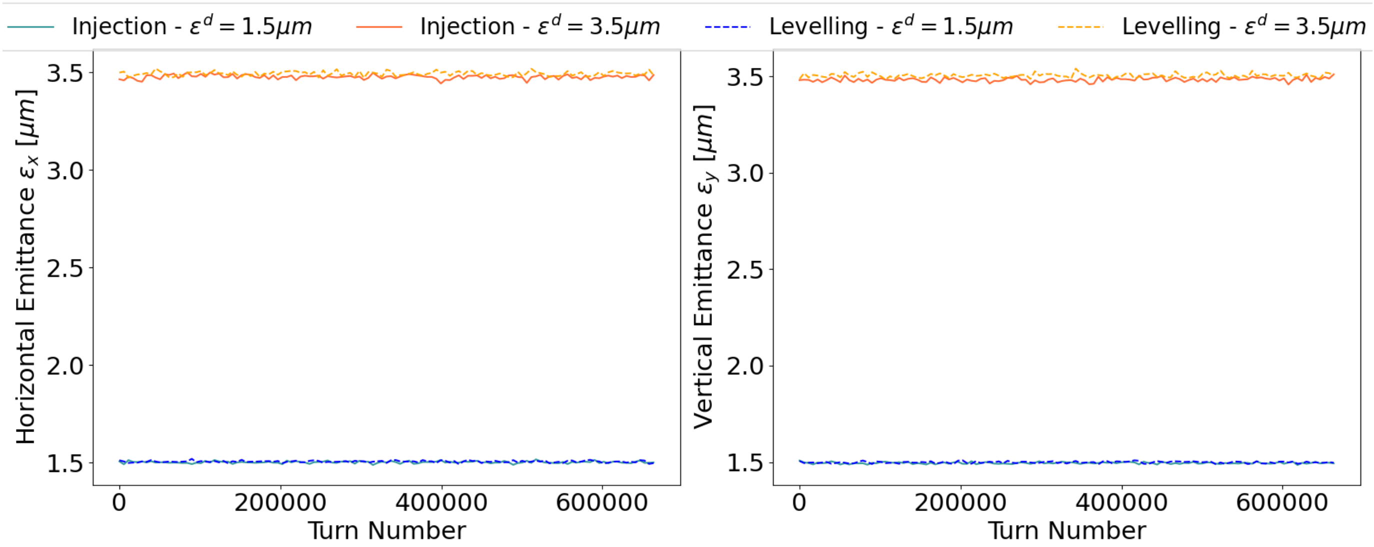
Results of Initial LHC Simulations (cont.)

Halo Content Evolution



Halo content and emittance do not increase or decrease significantly with time.

Emittance Evolution



Two extreme regimes were explored to make space charge relevant with unrealistic parameters (backup slides).

III. Simulations of Space Charge Effects on the Beam Halo in the LHC

IV. Simulations of Space Charge Effects on the Beam Halo in the SPS

Introduction to SPS Simulations

- Even the injection energy in the LHC is far too low for space charge effects to occur with realistic intensities and emittances.
- The SPS is known to exhibit strong space charge effects.
- If the halo develops during the SPS flat-bottom, then it is conserved if not enhanced during the energy ramp and injection into the LHC.
- Initial emittances between 0.6 and 2.0μm inclusive were simulated, in increments of 0.2μm.
- Two different tune working points covered.

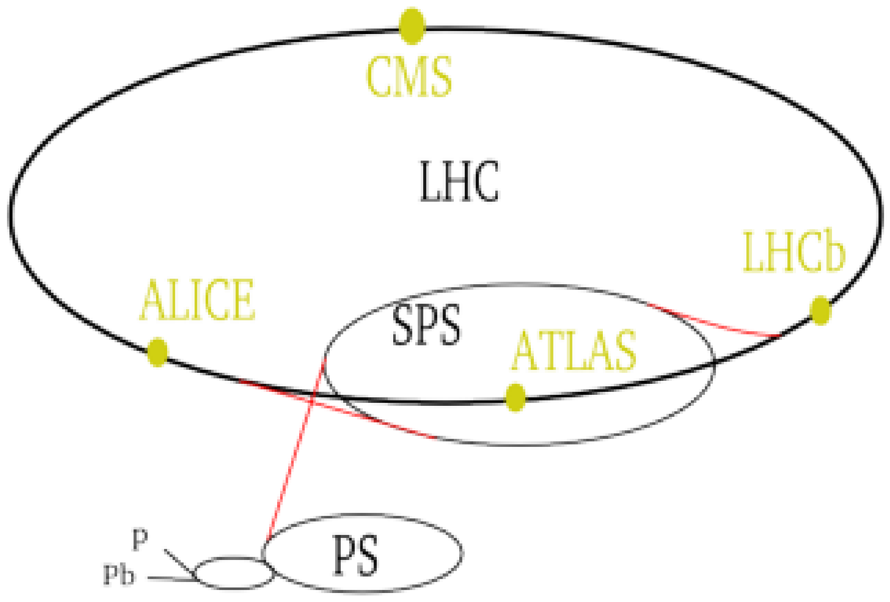


Figure: A. Horvath

Working Points and Field Errors

Old vs. New Working Point

- The first working point (WP1), with $Q_x/Q_y = 20.13/20.18$, showed significant emittance growth.
- Large tune shift spread crossing of the $Q_x + 3Q_y$ resonance.
- A new working point (WP2) was introduced in 2025 to reduce emittance growth, with $Q_x/Q_y = 20.16/20.21$.
- Most examples are presented using WP1.

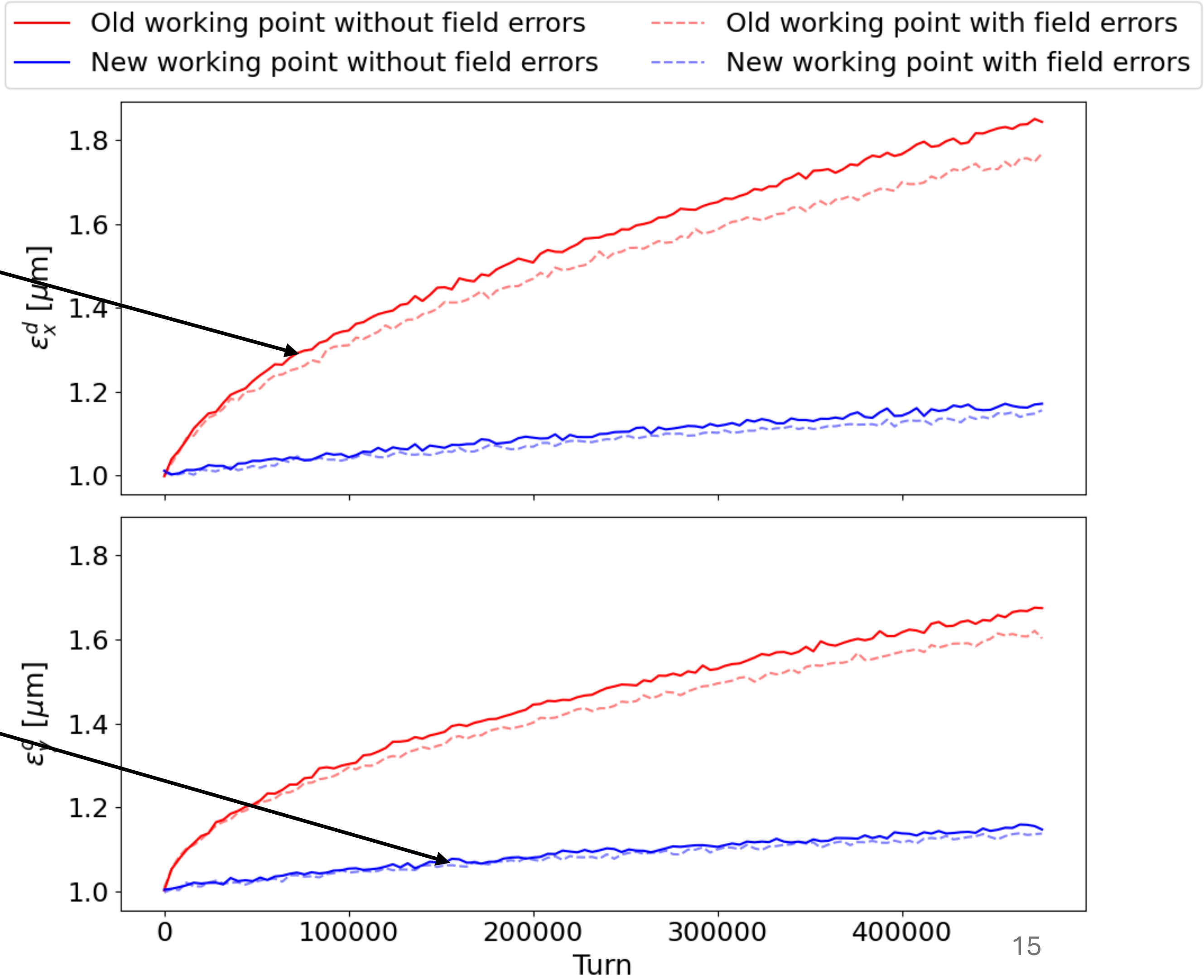
Field Errors

- Higher-order multipolar field errors can be present in magnets due to their inherent manufacturing imperfections.
- Field errors can excite resonances – worsening emittance blow-up and losses.
- Two models of the machine used: one ideal, and one introducing field errors based on past measurements.

Emittance Growth at Both Working Points – With and Without Field Errors ($\varepsilon_0 = 1.0\mu m$)

WP1 exhibits significant emittance blow-up compared to WP2 – the tunes in the latter were successfully optimised to reduce this phenomenon.

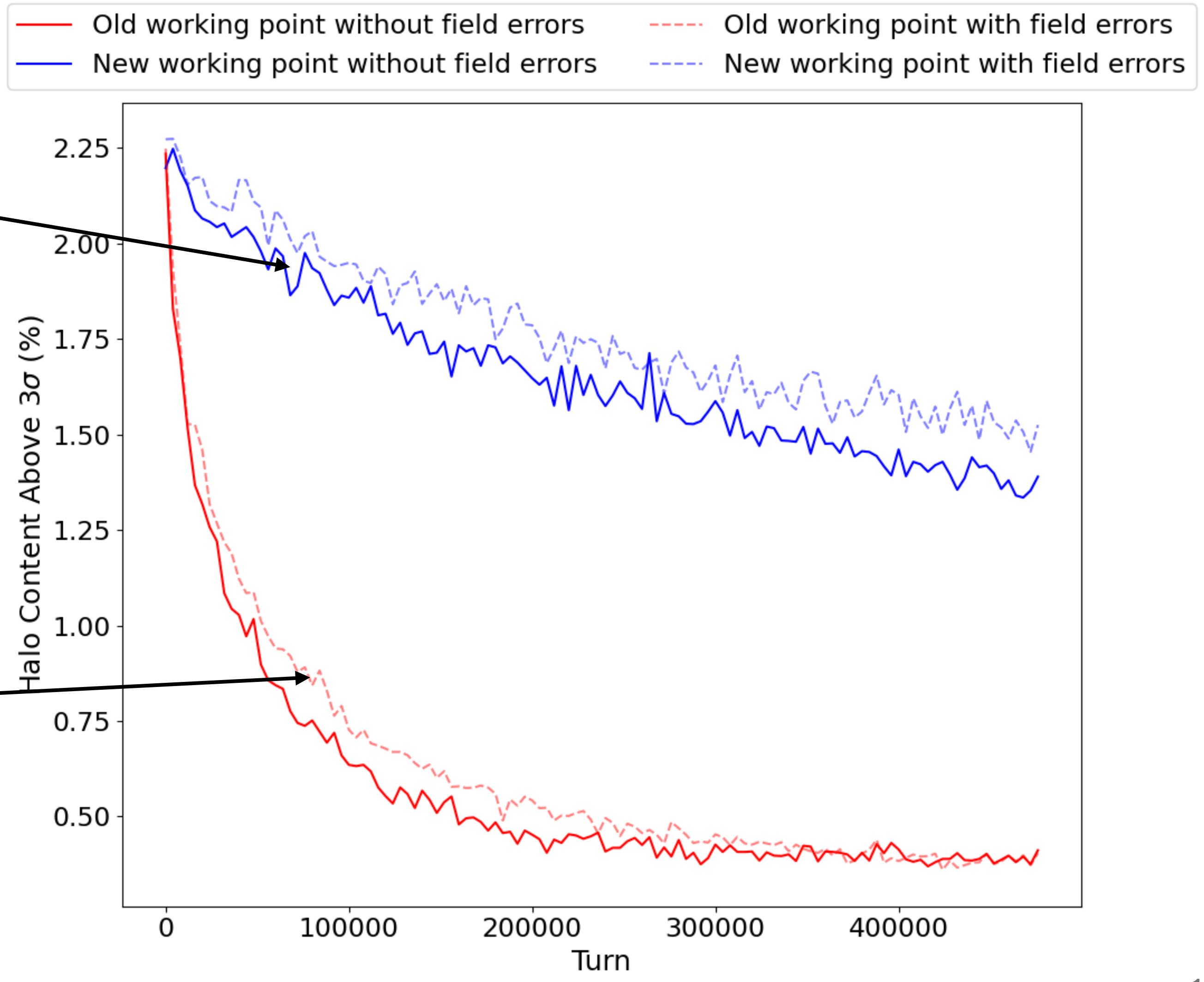
Field errors do not have a major effect on emittance growth – particularly at WP2.



Halo Content Evolution at Both Working Points – With and Without Field Errors ($\varepsilon_0 = 1.0\mu m$)

Much larger halo content despite lower emittance growth in WP2.

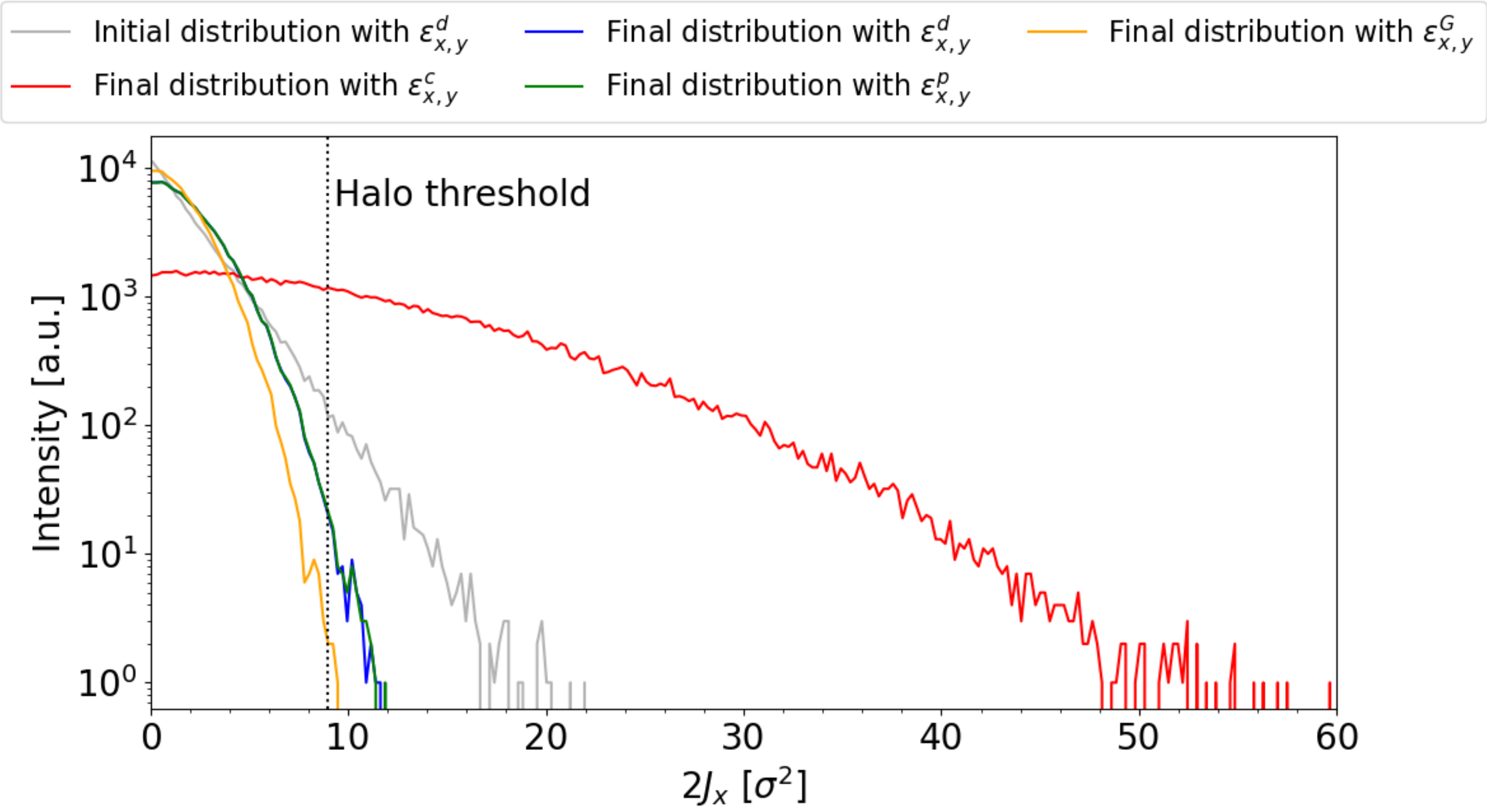
Field errors did not have a significant effect on halo content either. Ideal models used exclusively from now on.



Emittance Calculation Method Comparison

- **Emittance calculation methods have a significant effect on the final action distribution.**
- The constant emittance ($\varepsilon_{x,y}{}^{c}$) greatly overestimates halo content due to failing to account for emittance growth.
- The profile emittance ($\varepsilon_{x,y}{}^{p}$) closely approximates the distribution emittance ($\varepsilon_{x,y}{}^{d}$).
- The emittance taken from a Gaussian fit of the profile ($\varepsilon_{x,y}{}^{G}$) underestimates halo content – it does not account for tails being flattened by space charge effects.

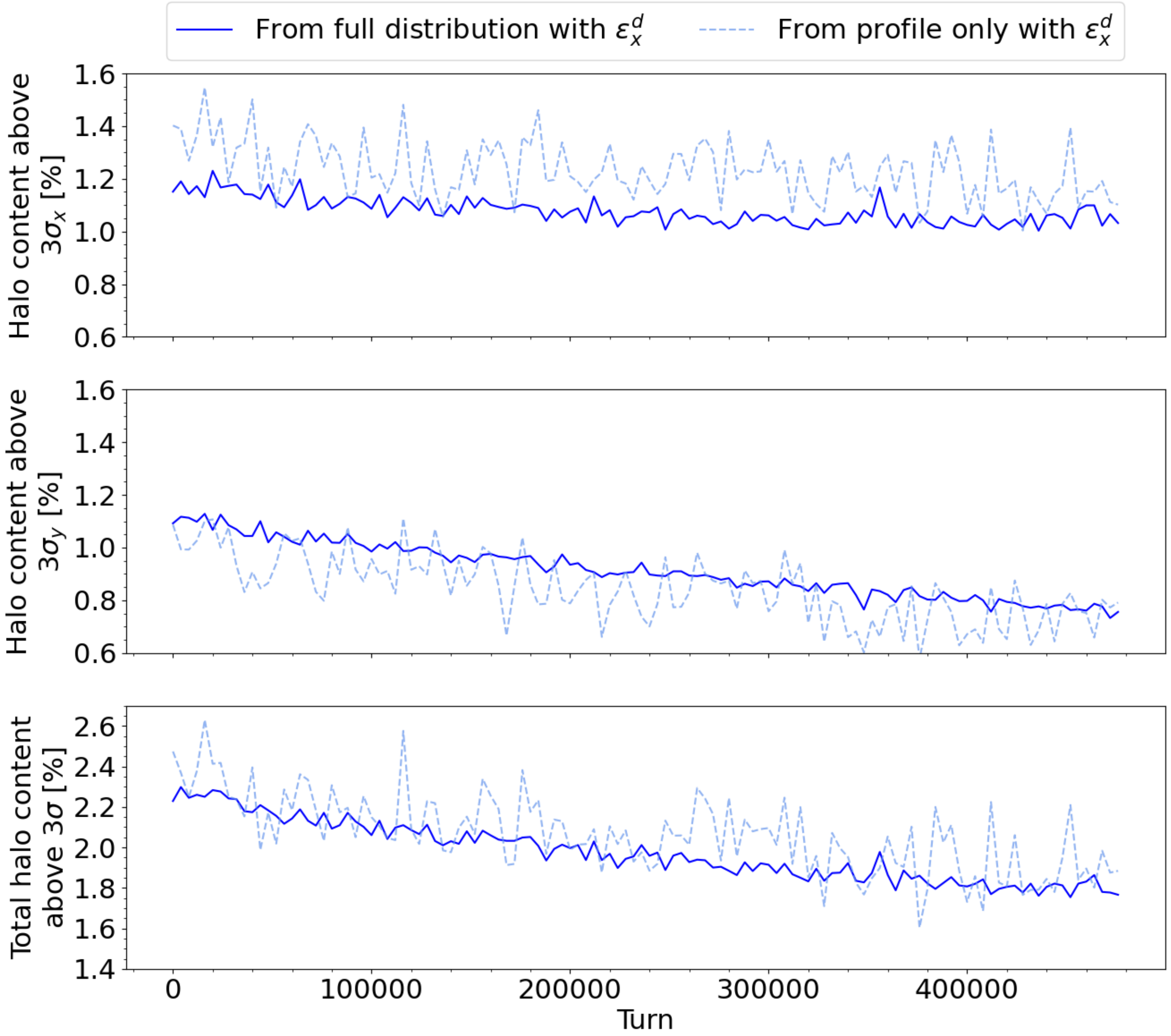
Action Distributions at End of Tracking (ε_0= 0.6μm):



Same phenomena in y-plane.

Halo Content Evolution – Full Distribution vs. Profile Only (ε_x^d with ε_{x0}= 1.4 μm)

- The agreement between the two methods is strong.
- While halo content from the beam profile only is noisy, it can reproduce true halo content well in most cases.
- Although the agreement decreases in cases where halo content is very low, the trends are captured correctly.
- Different regimes are visible in x and y – this could be due to model input, different tunes, errors, etc.

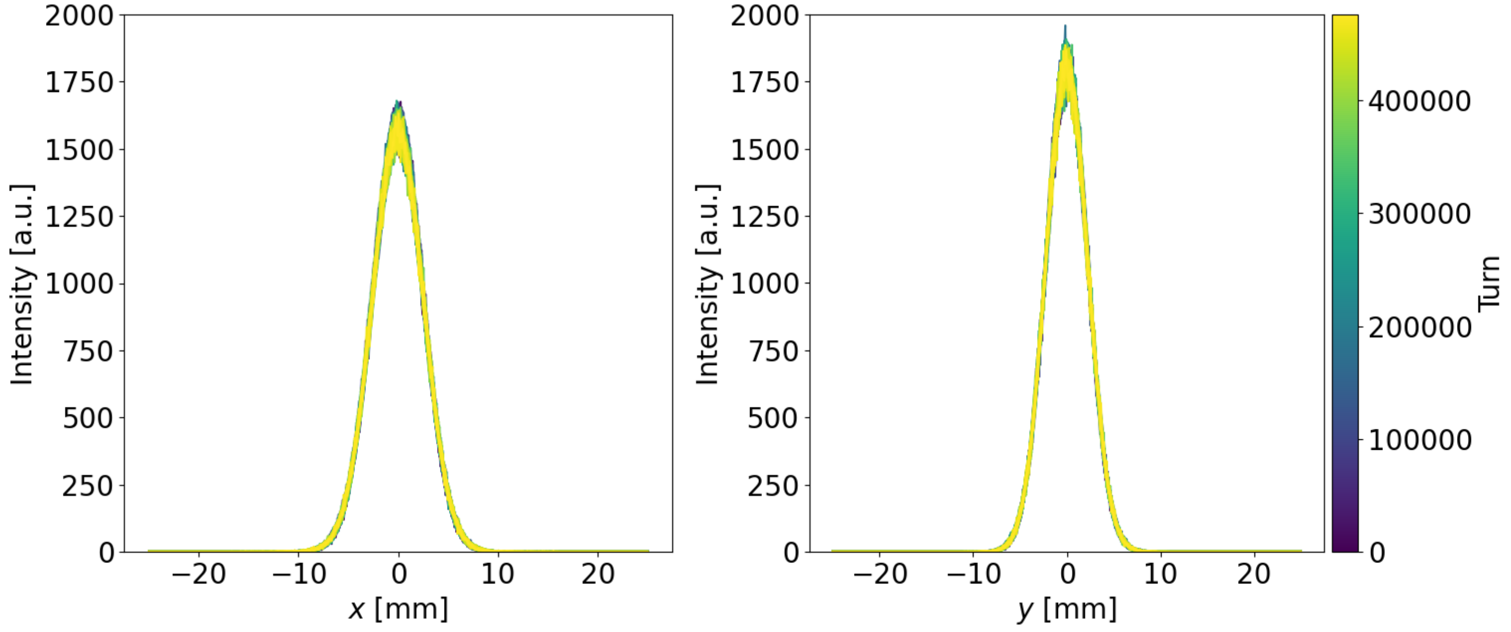


IV. Simulations of Space Charge Effects on the Beam Halo in the SPS

Beam Profile Evolution (I)

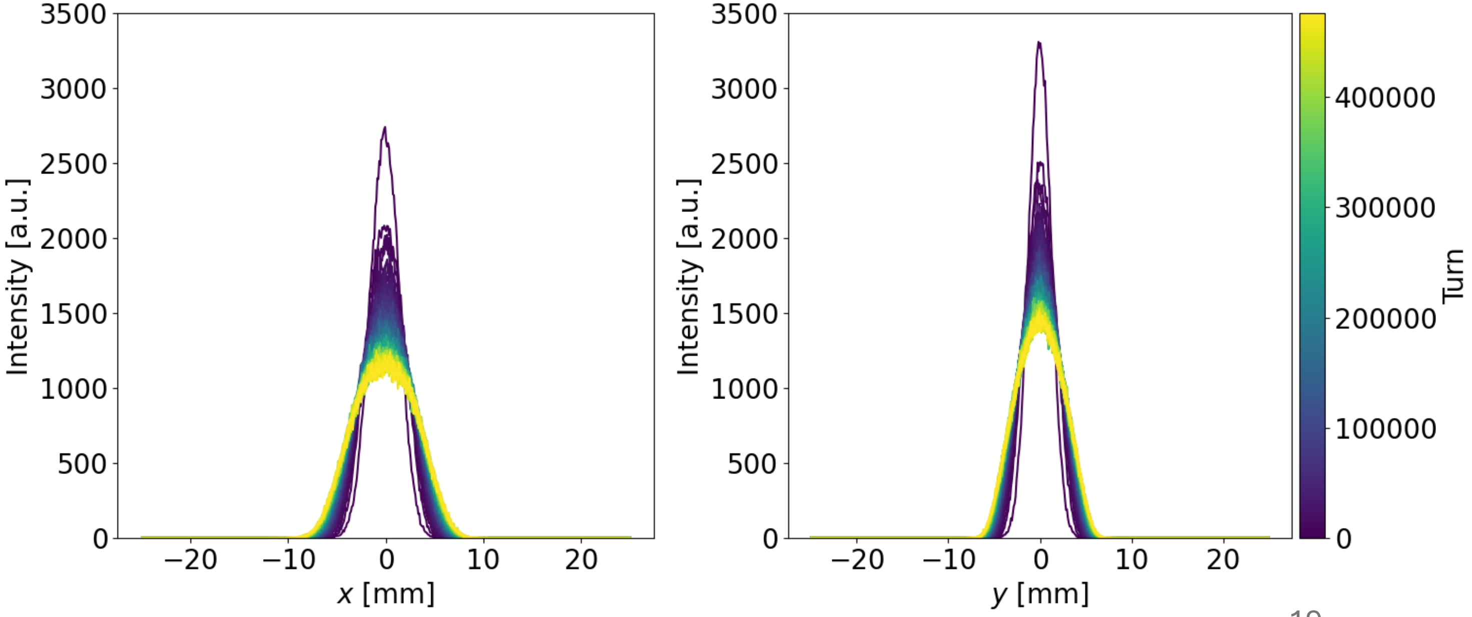
ε_0 = 2.0 µm

- For larger initial emittances, space charge effects are negligible, and the distribution does not change much with time.



ε_0 = 0.6 µm

- Space charge effects are clearly very strong for small initial emittances, so the distortion of the distribution is significant.

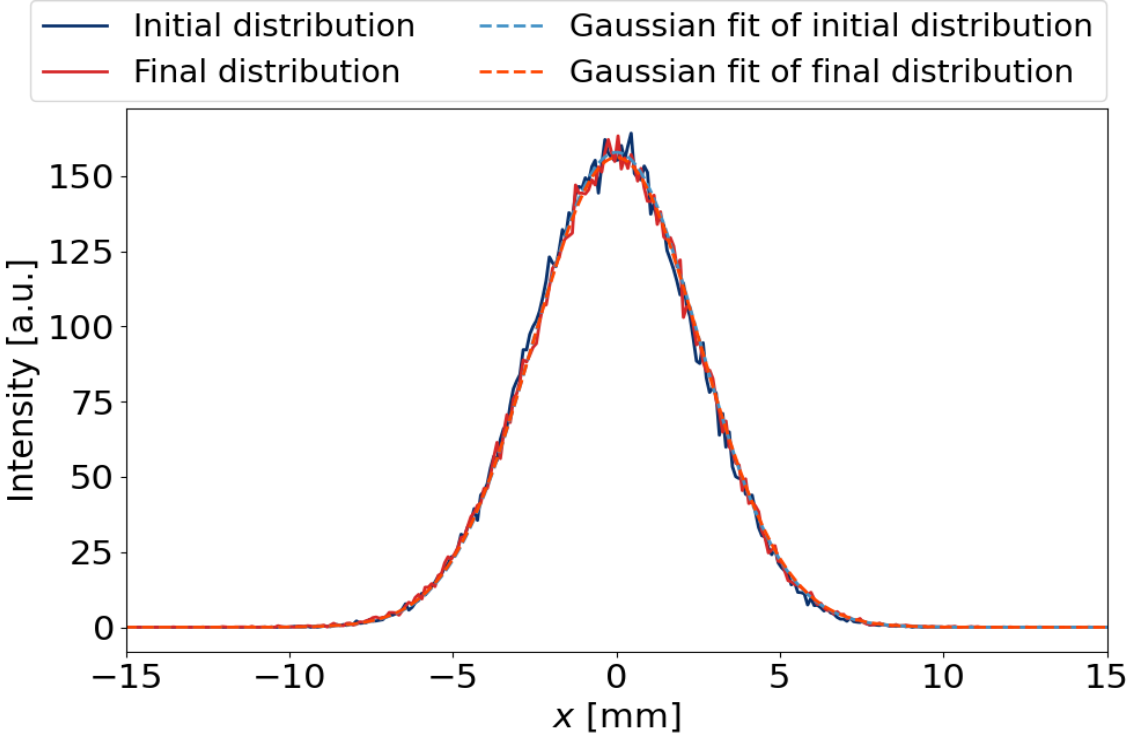


Beam Profile Evolution (II)

ε_{0x} [μm]	Initial q_x	Final q_x
0.6	0.986	0.780
2.0	0.982	1.005

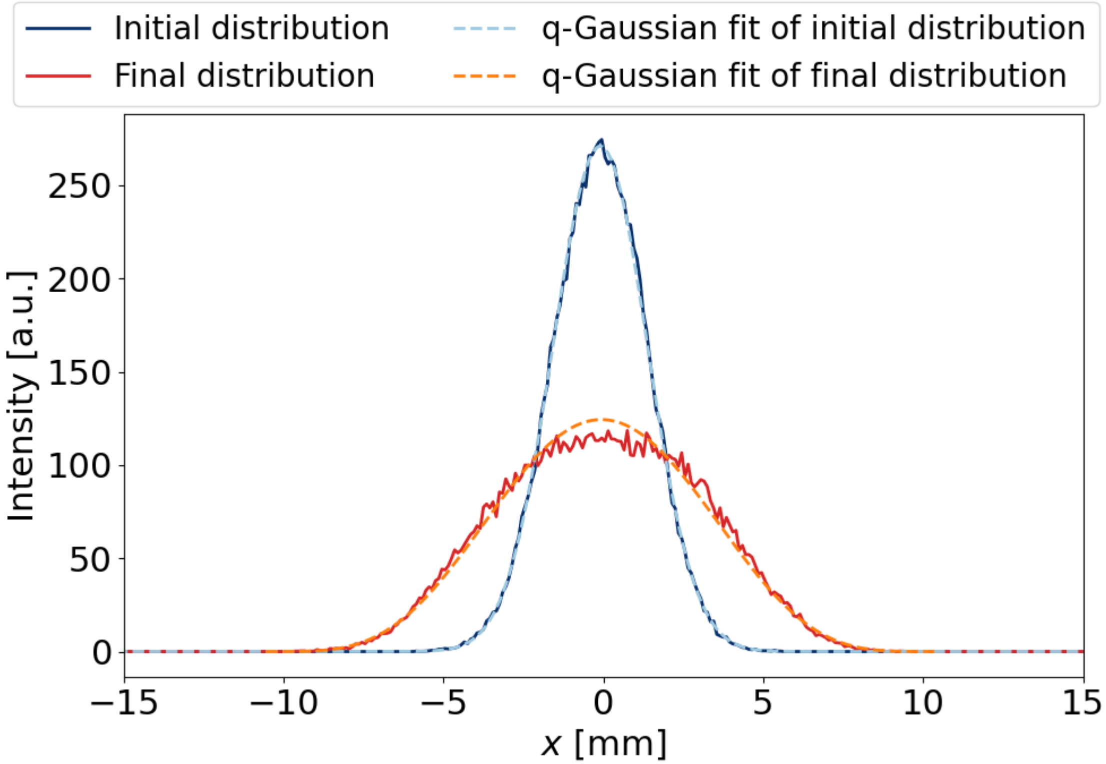
ε_0 = 2.0 μm:

- Distribution is Gaussian throughout.
- Emittance and halo content undergo far smaller perturbations w.r.t. time.



ε_0 = 0.6 μm:

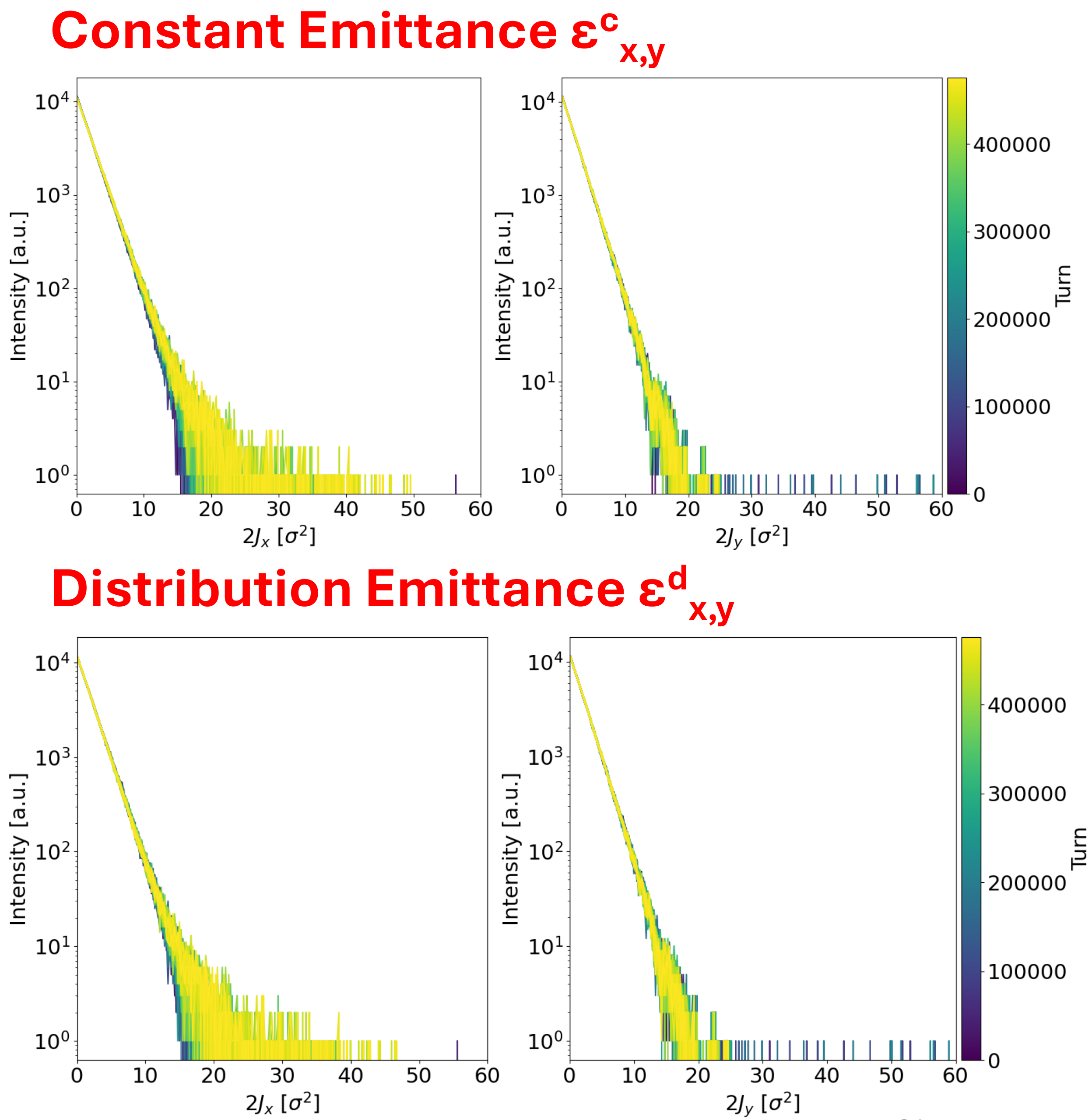
- Initial distribution is Gaussian (q ≈ 1).
- Final distribution is better parameterised as a q-Gaussian with q < 1.
- Lower q-value → lighter tails → lower halo content.
- Wider profile → larger emittance.



IV. Simulations of Space Charge Effects on the Beam Halo in the SPS

Action Distribution: $\varepsilon_0 = 2.0\ \mu m$

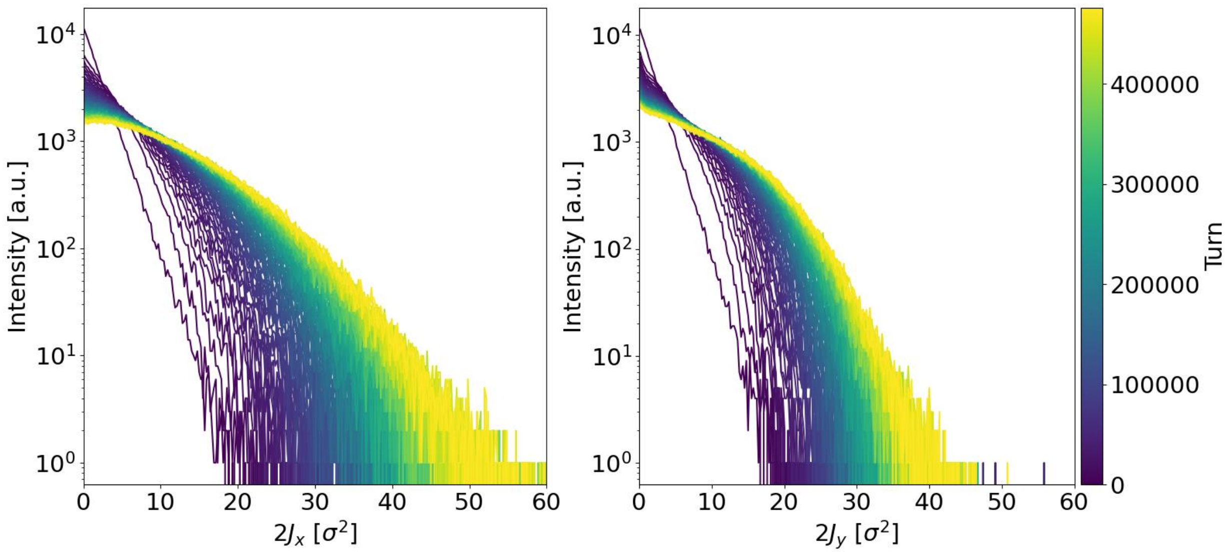
- **Very little emittance growth** - ε_c is a sufficient approximation in this case.
- The **beam profile is largely constant** – which implies that the beam size is too.
- Action distribution does not undergo major changes throughout tracking.
- ε^d is the true emittance.



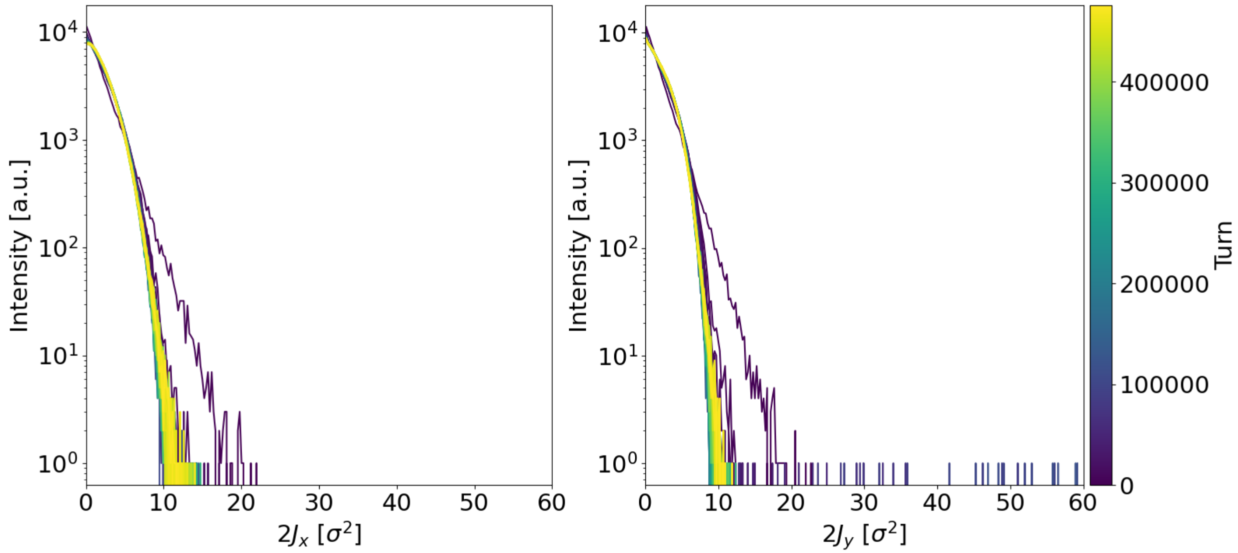
Action Distribution: $\varepsilon_0 = 0.6$ μm

- ***ε^c* is a poor approximation.**
- There is **significant emittance growth** in this case - ε^c fails to account for this.
- The **beam profile is significantly perturbed** – this shows up on the action distribution (fewer halo particles over time).

Constant Emittance $\varepsilon^c_{x,y}$



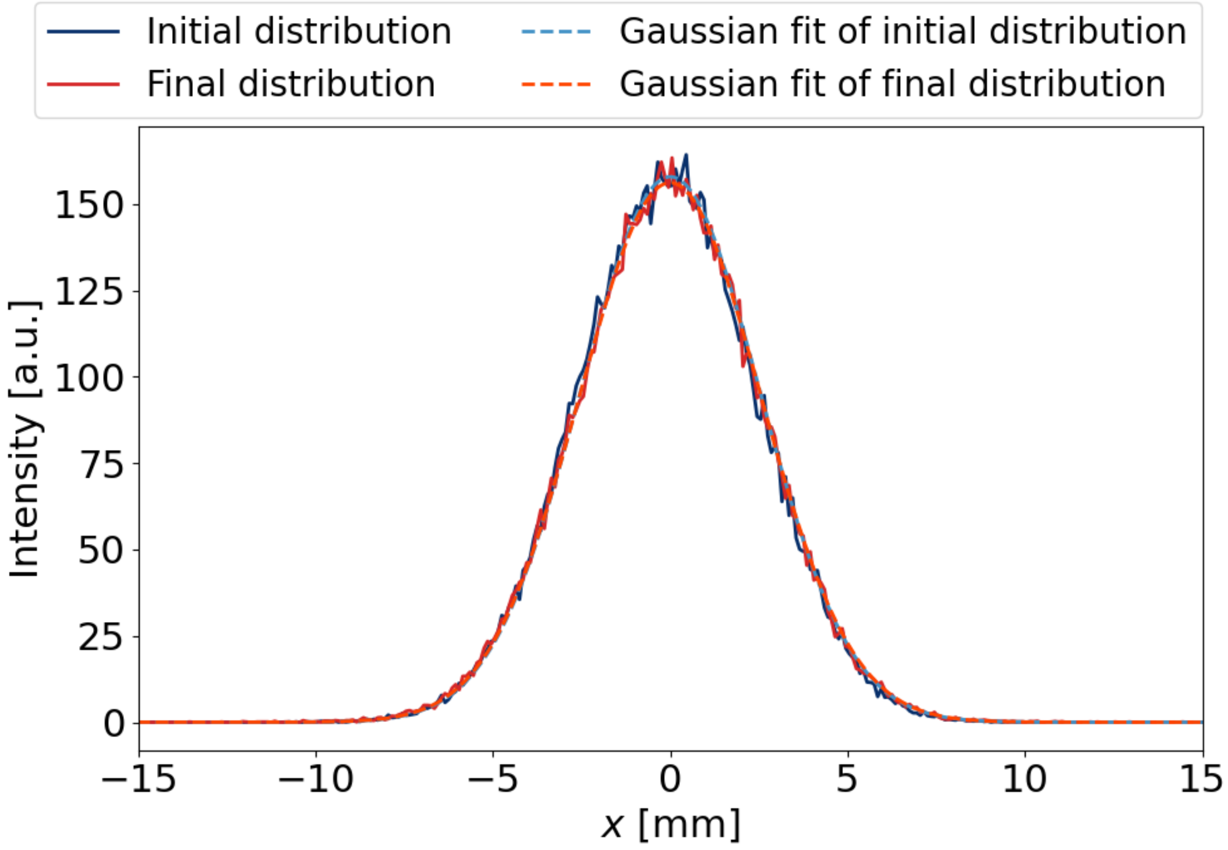
Distribution Emittance $\varepsilon^d_{x,y}$



Gaussian Fit of Profile

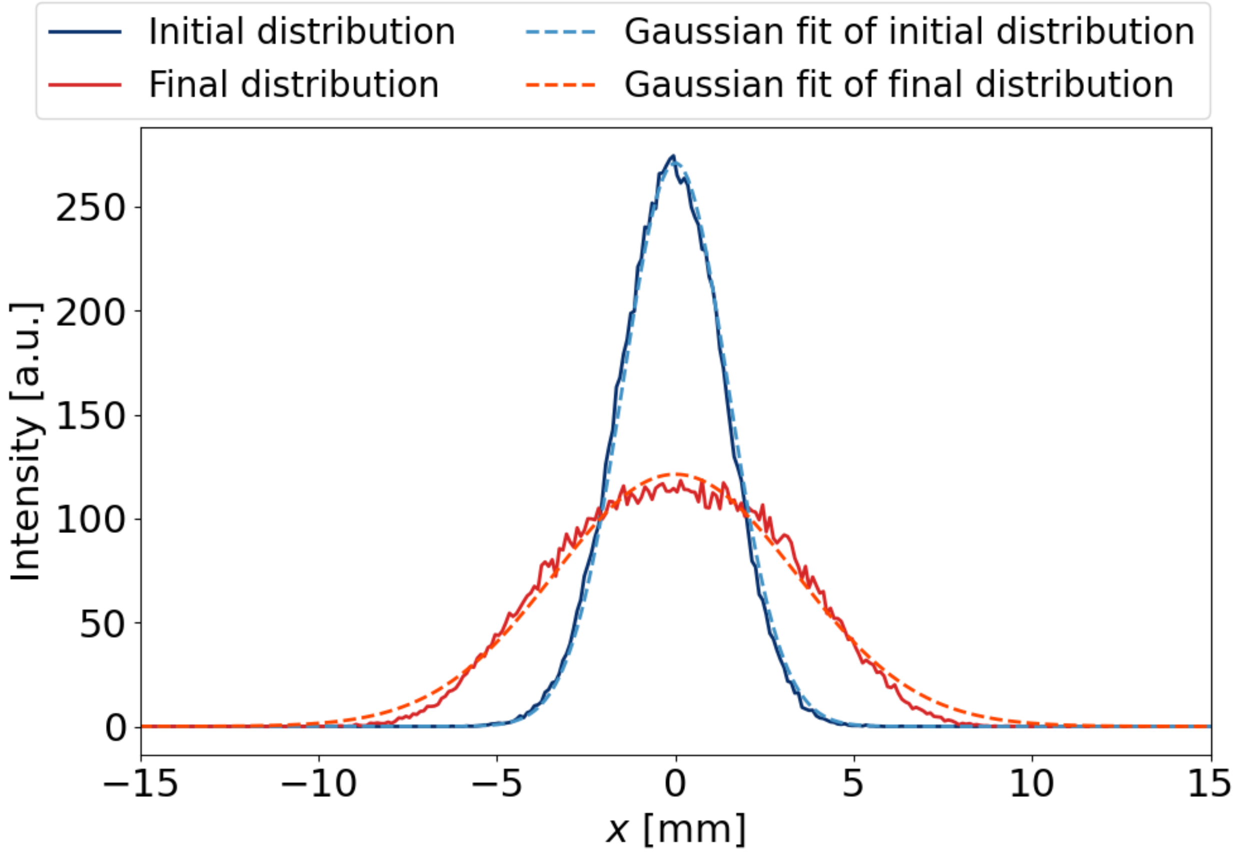
ε_0 = 2.0 μm

- Good fit throughout particle tracking.
- Sufficient approximation due to almost negligible emittance growth.



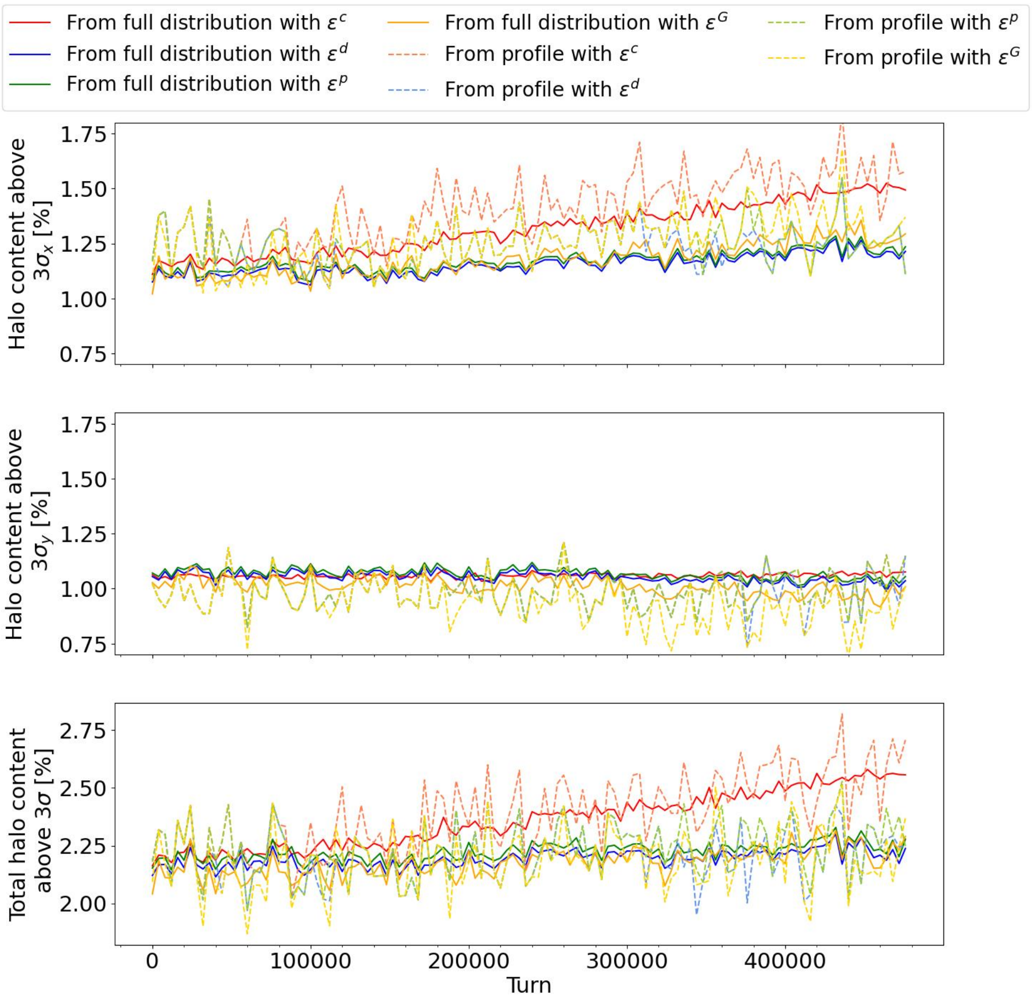
ε_0 = 0.6 μm

- Poor fit for final distribution.
- Not ideal for calculating emittance evolution – emittance is overestimated.



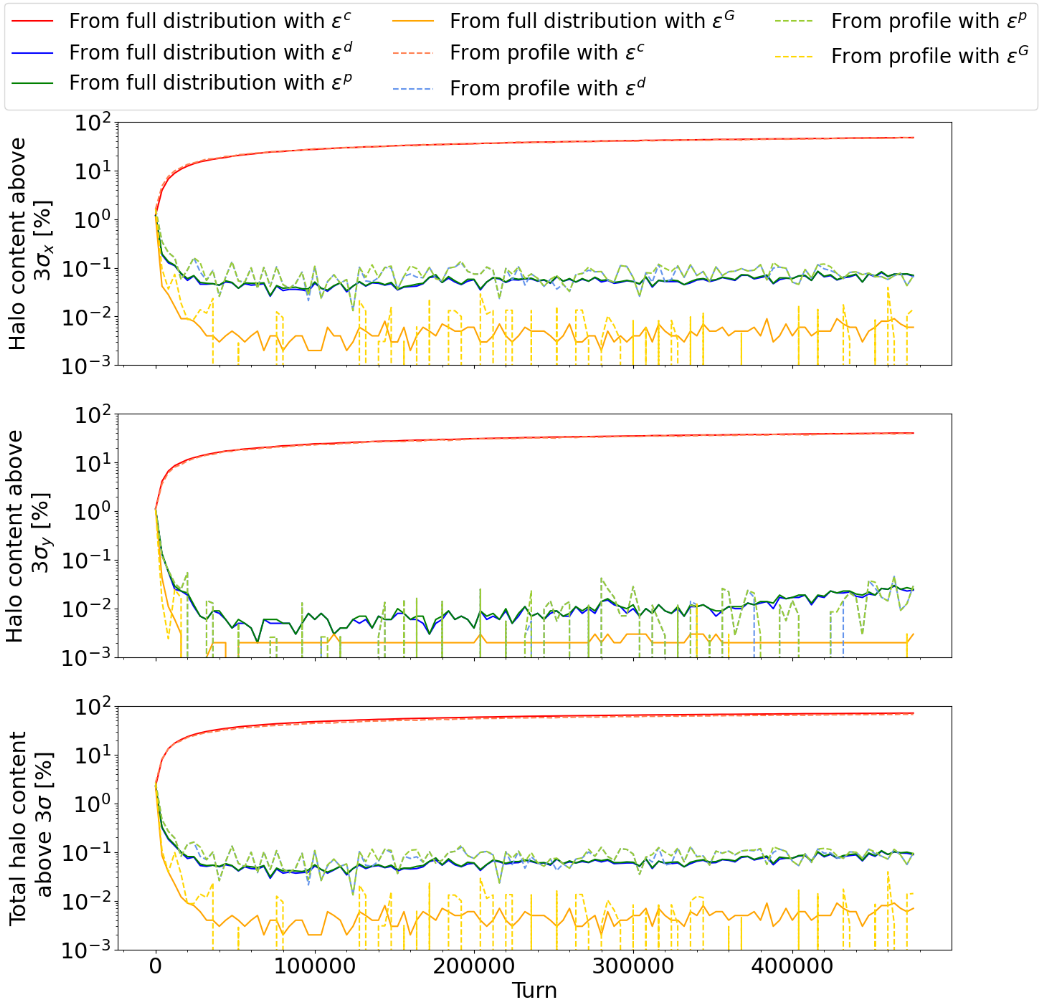
Halo Content Evolution

2.0 μm



- Halo is either approximately constant or slightly increases over time due to weak space charge effects.

0.6 μm

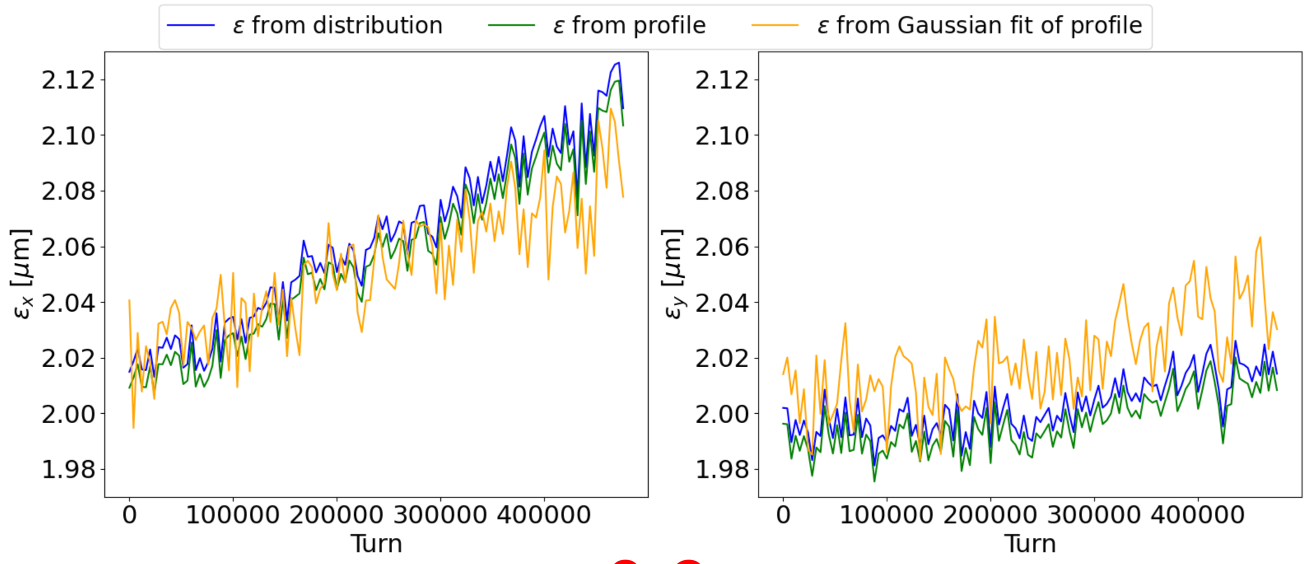


- Halo decreases over time due to significant space charge effects.

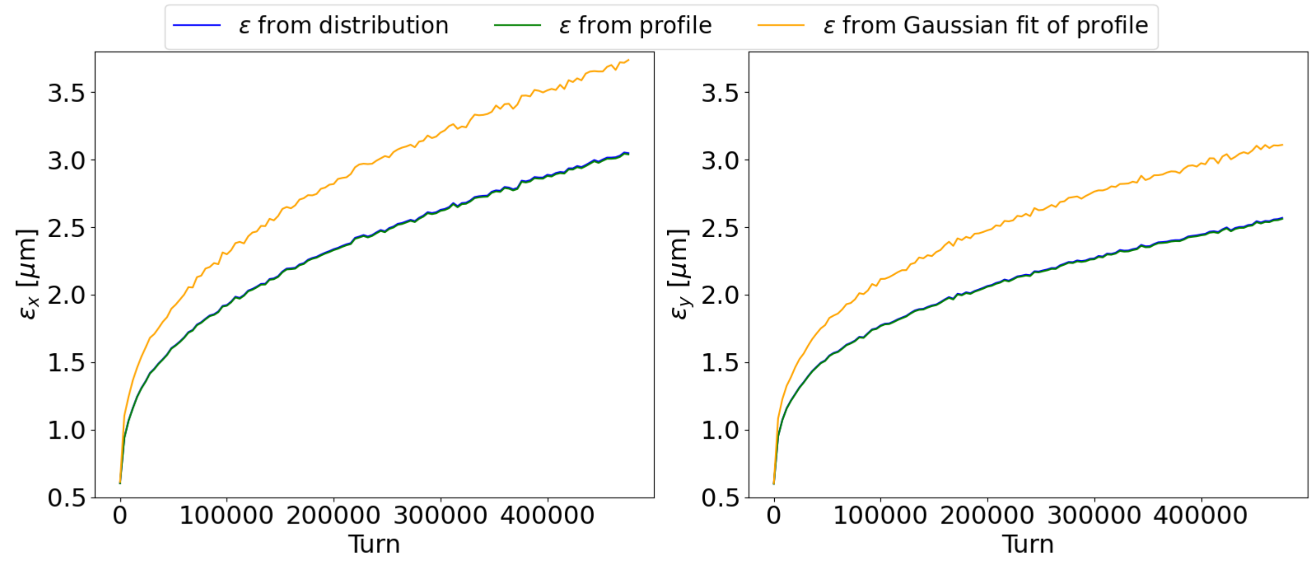
Emittance Growth

- Emittance growth from profile epsilon $\varepsilon^{p}_{x,y}$ almost identical to true emittance growth from $\varepsilon^{d}_{x,y}$.
- $\varepsilon^{G}_{x,y}$ overestimates emittance growth for ε_0 = 0.6μm, but approximates $\varepsilon^{d}_{x,y}$ much better for 2.0μm.
- Space charge effects are weak at ε_0 = 2.0μm.

2.0 μm

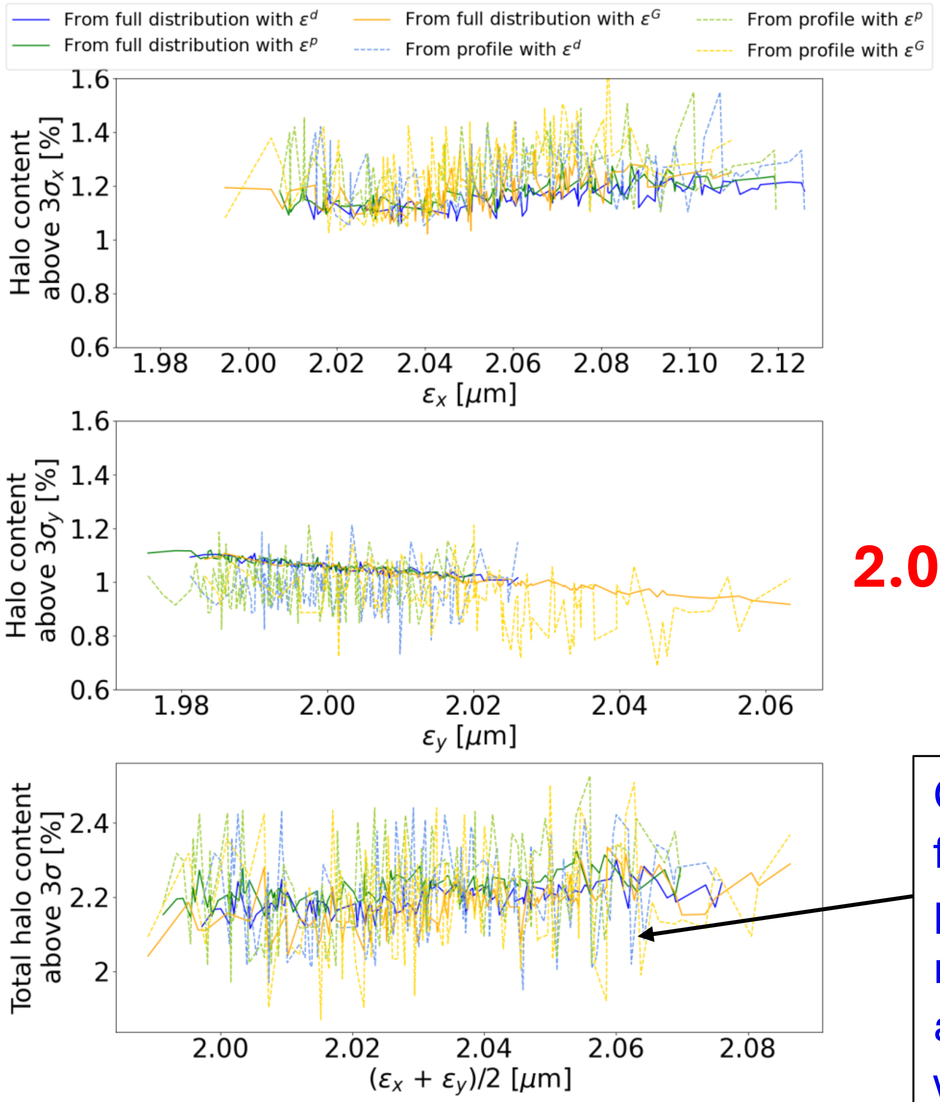


0.6 μm



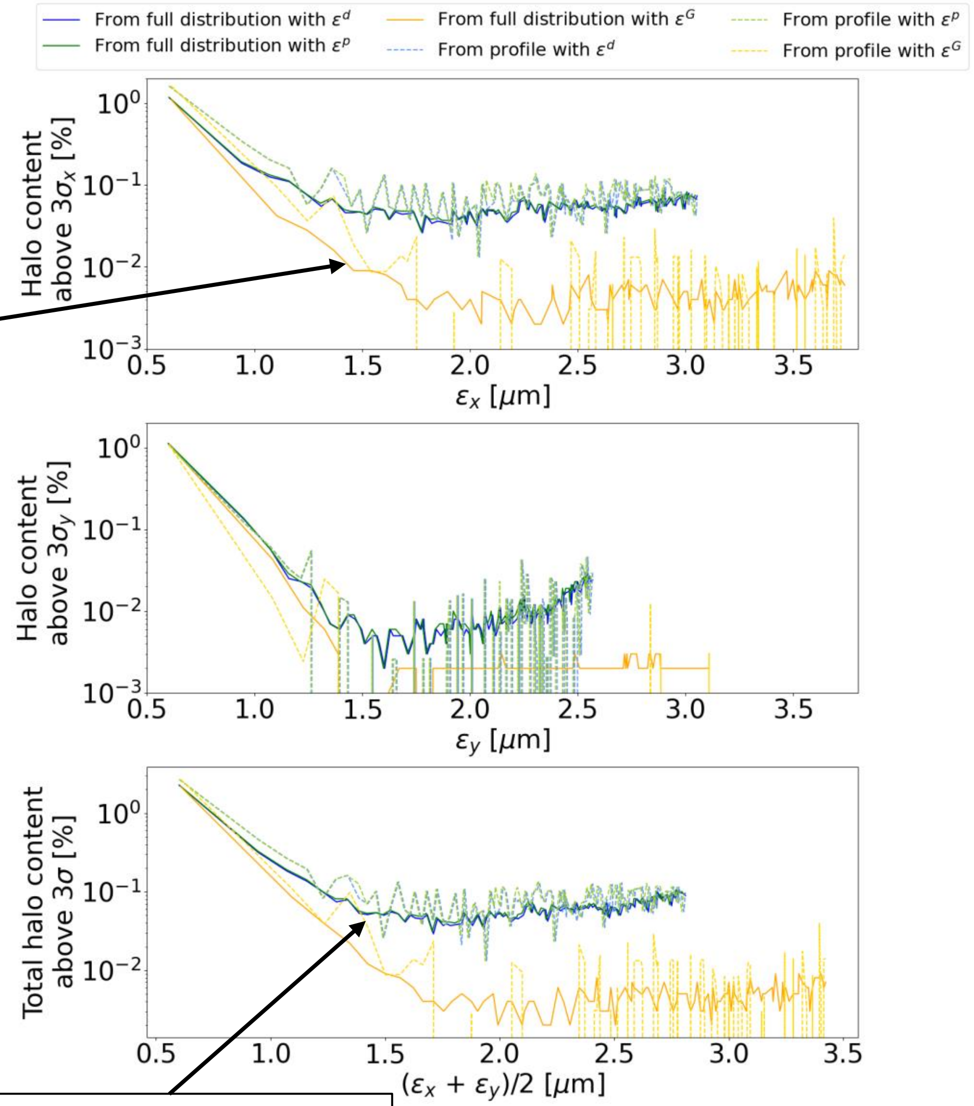
IV. Simulations of Space Charge Effects on the Beam Halo in the SPS

Halo Evolution with Emittance



2.0 μm

0.6 μm



ε^G underestimates halo content evolution.

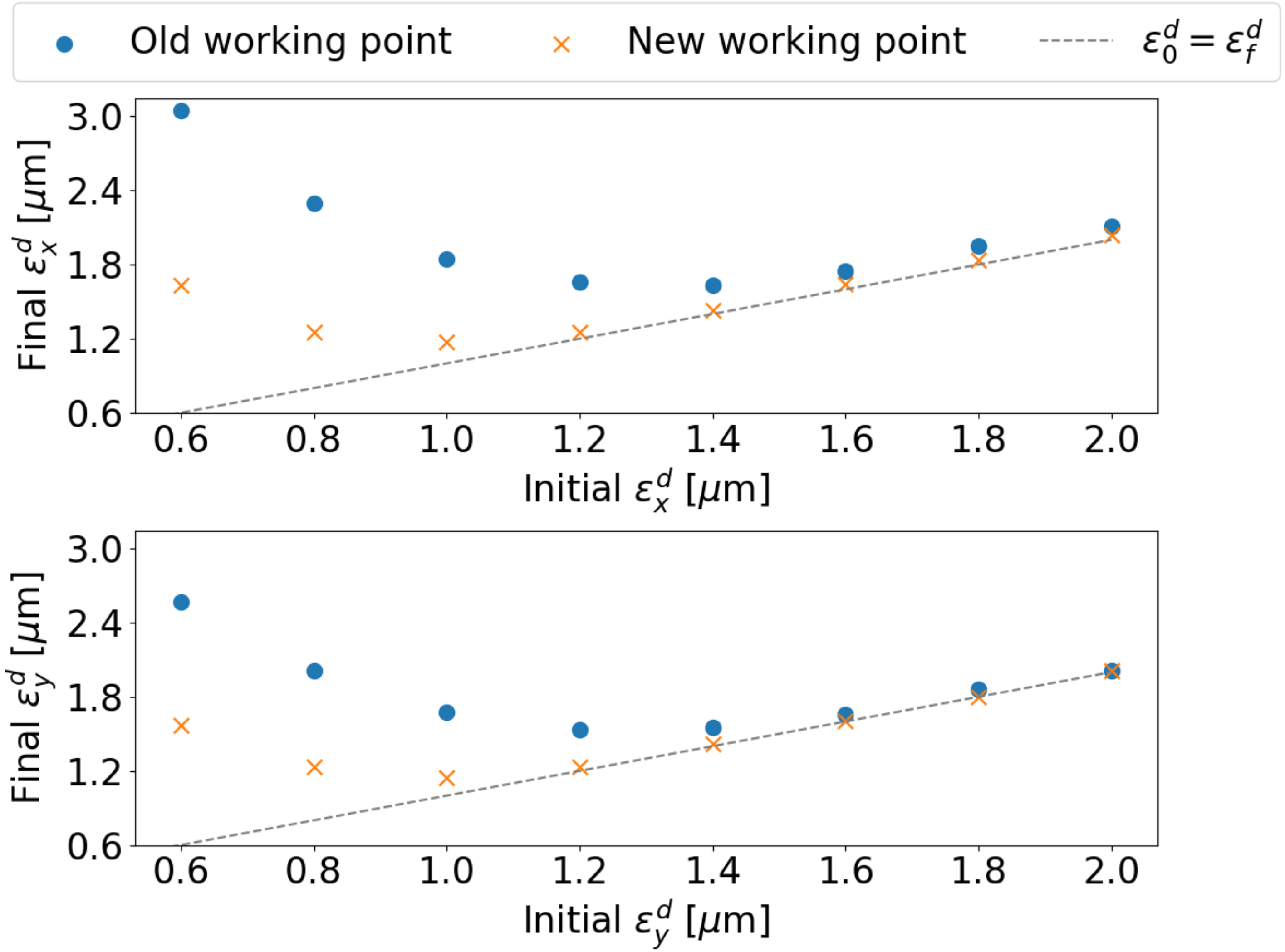
Calculations from profile are particularly noisy – but both approximations work well.

Horizontal plane dominates

IV. Simulations of Space Charge Effects on the Beam Halo in the SPS

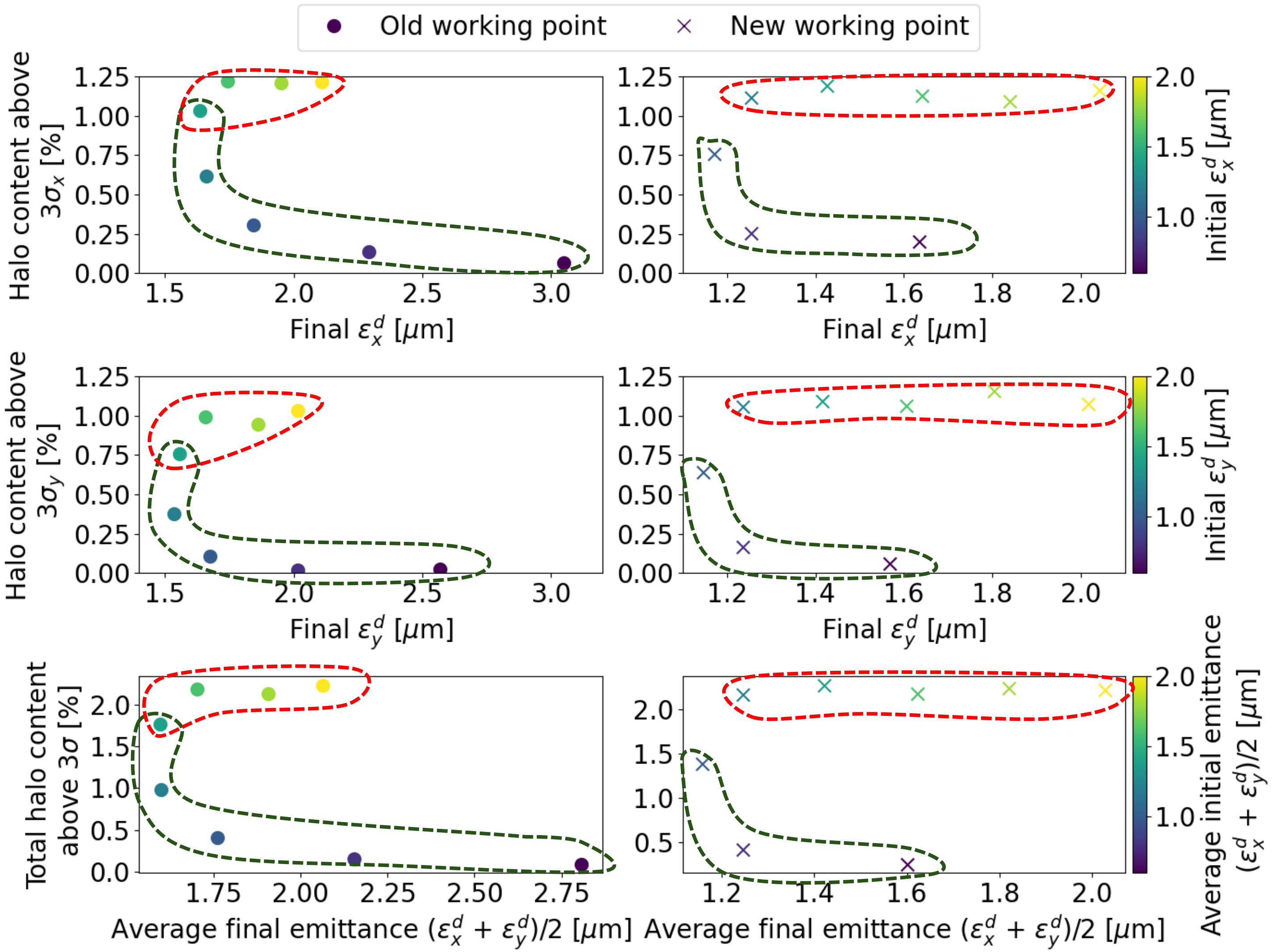
Emittance Growth – Old and New Working Points

- Lower initial emittances exhibit much higher emittance growth, as before.
- WP2 shows lower emittance growth throughout.
- Emittance growth becomes roughly negligible around $\varepsilon_0 = 1.6\mu m$ at both working points.



Halo Content – Old and New Working Points

- **Two regimes** of increasing and decreasing halo content against final emittance.
- Smaller ε_0: **anti-correlation** between halo content and final emittance. Could be a source of LHC halo formation.
- Larger ε_0: halo content approximately constant or slightly increasing.
- Former regime *could be a source of halo formation*.

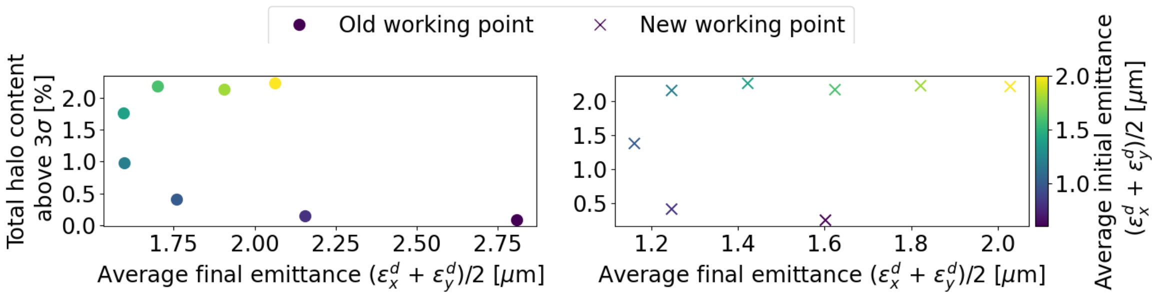


V. Conclusions

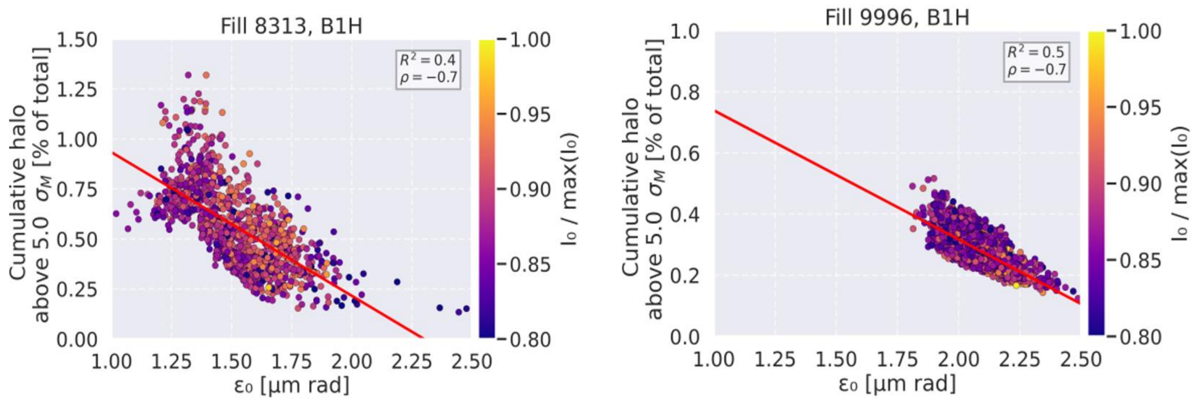
Conclusions

- This investigation involved simulating space charge effects using models of the LHC - and its injector, the SPS – using the frozen space charge model (fixed Gaussian bunch distribution).
- Space charge effects are negligible in the LHC due to even its injection energy being too high. Therefore, space charge effects in the LHC cannot have contributed to the formation of the beam halo.
- The second part of the investigation focused on the SPS, which has a low enough energy for space charge effects to be exhibited.
- Space charge effects in the SPS could be a source of the observed halo, assuming the halo forms at the flat-bottom energy (26 GeV); and is conserved during ramping to 450GeV, extraction & injection into the LHC, and ramping to 6.8TeV.

Simulated (SPS)



Measured (LHC, M. Rakic)



Backup and References

Contents:

- Space Charge Tune Shift (I)
- LHC Simulations – Extreme Cases (10x higher intensity and 3x lower emittance). Action distributions, Gaussian fits, halo content and emittance against time, and halo content vs. emittance. (III)
- Beam Profile Evolution (q-Gaussian): both planes (IV)
- Gaussian Fit of Profile: both planes (IV)
- Outlook (V)
- References

Space Charge Tune Shift

- Tune shift of zero-amplitude particle in the centre due to transverse space charge effects:

$$\Delta Q_{x,y} = -\frac{\rho^2 e\lambda_0}{8\pi\varepsilon_0\beta^2\gamma^2 E_0 Q_{x0,y0}\sigma_{x,y}^2}$$

- Tune shift also depends on longitudinal charge density.
- Resulting spread in betatron tunes can result in some values being close to rational numbers – resulting in the crossing of resonances, where the tune shift decreases.
- **Resonant conditions:** $\boldsymbol{mQ_x + nQ_y = l}$**, where** $\boldsymbol{m, n, l} \in \mathbb{Z}$**, and** $|\boldsymbol{m}| + |\boldsymbol{n}|$ **is the order of the resonance**.
- Crossing of resonances results in the beam losing particles or blowing up.

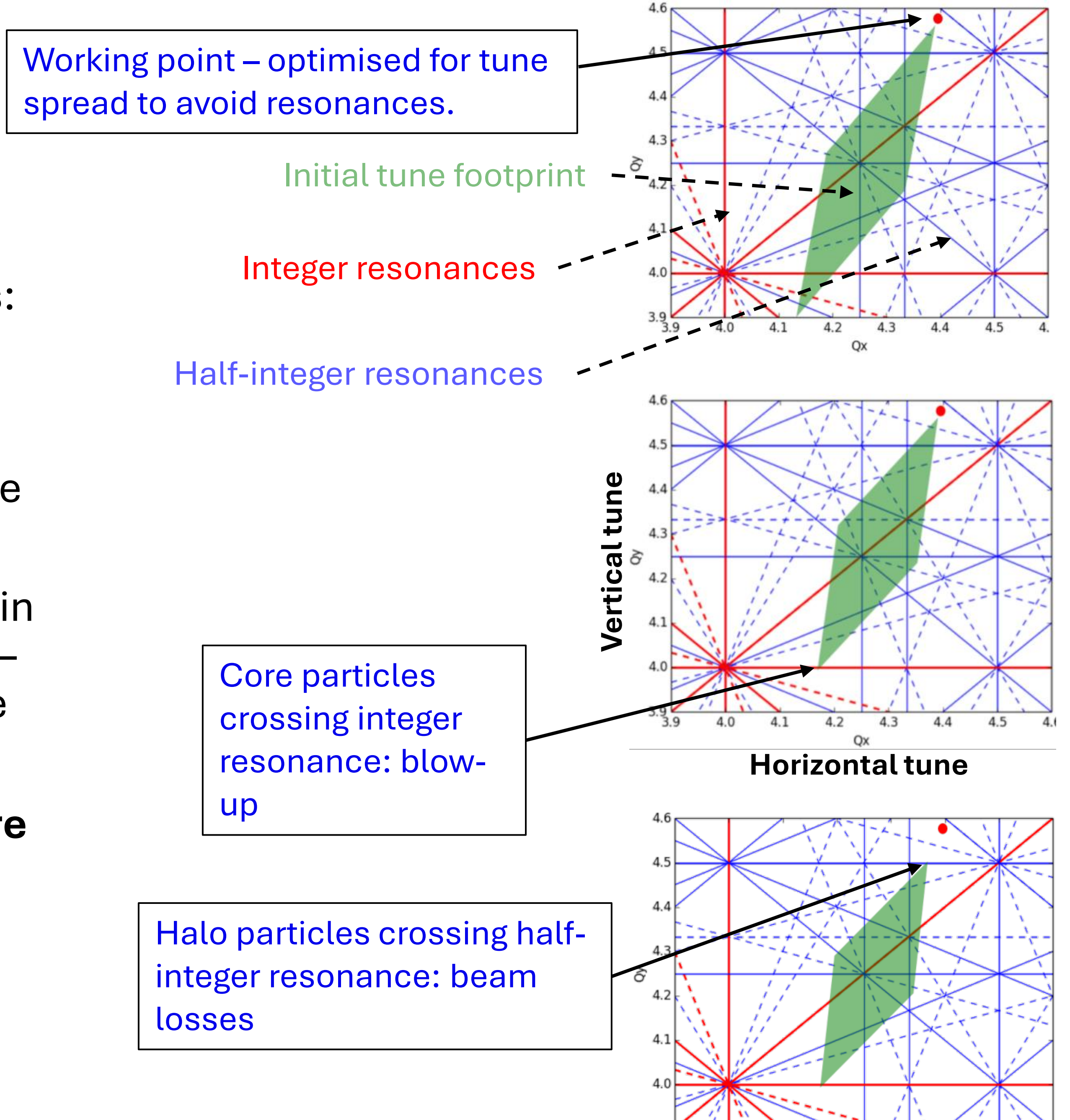


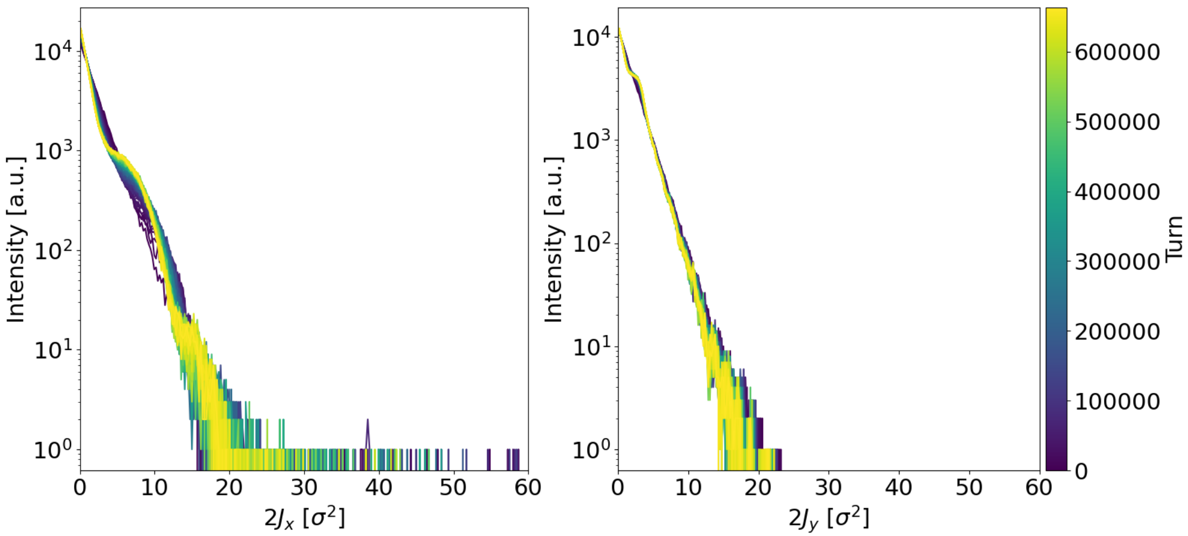
Figure adapted from K. Li

LHC Simulations: Extreme Cases

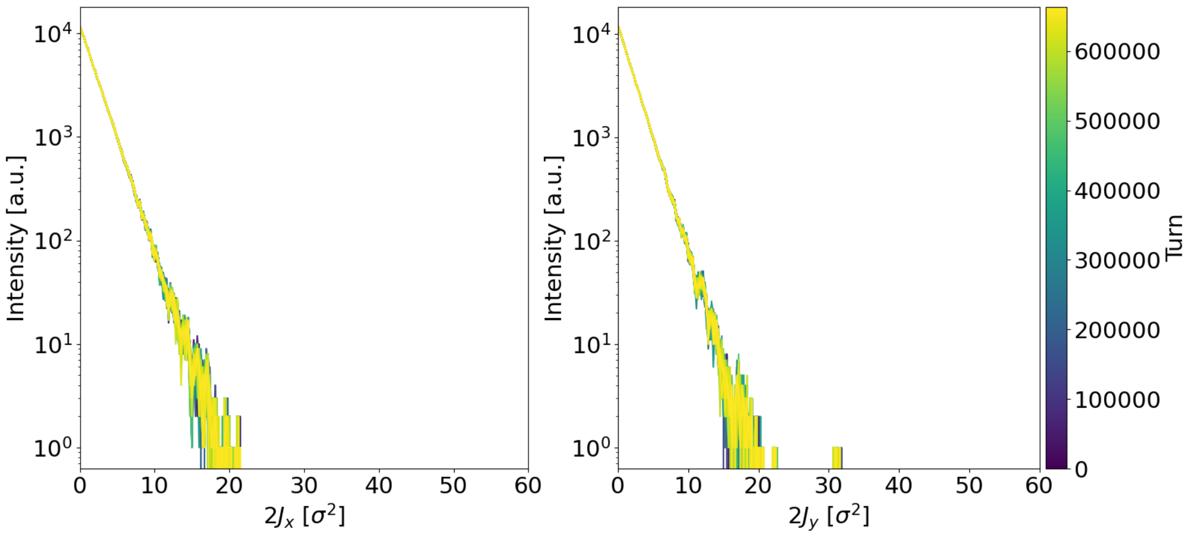
- First extreme case: increasing the intensity by an order of magnitude ($N = 2.1 \times 10^{11} \rightarrow 2.1 \times 10^{12}$ particles).
- Second extreme case: decreasing the emittances to below the operational range of the LHC ($\varepsilon_{x,y} = 1.5 \rightarrow 0.5\mu m$).
- Increasing the intensity distorted the action distribution – there is a visible perturbation around $2J_x = 8 - 11\sigma_x^2$.
- Decreasing the emittances had no visible effect on the action distribution.
- No major particle losses were observed in either case – only ~1% for the higher intensity.

Action Distributions (at injection)

$\varepsilon^d = 1.5\mu m, N = 2.1 \times 10^{12}$



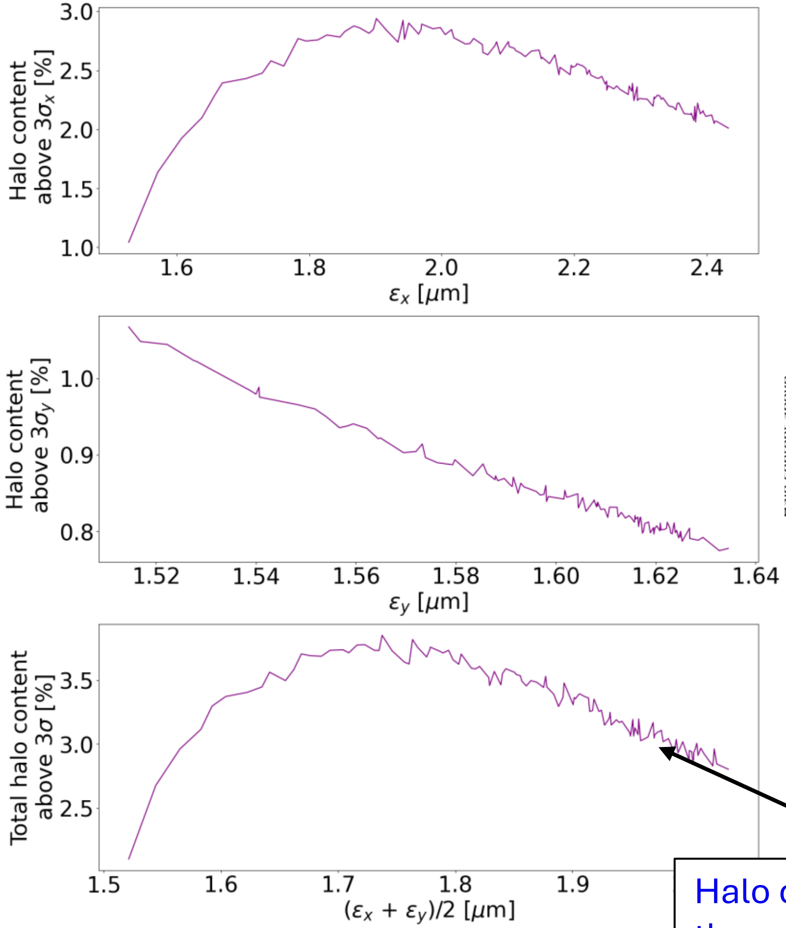
$\varepsilon^d = 0.5\mu m, N = 2.1 \times 10^{11}$



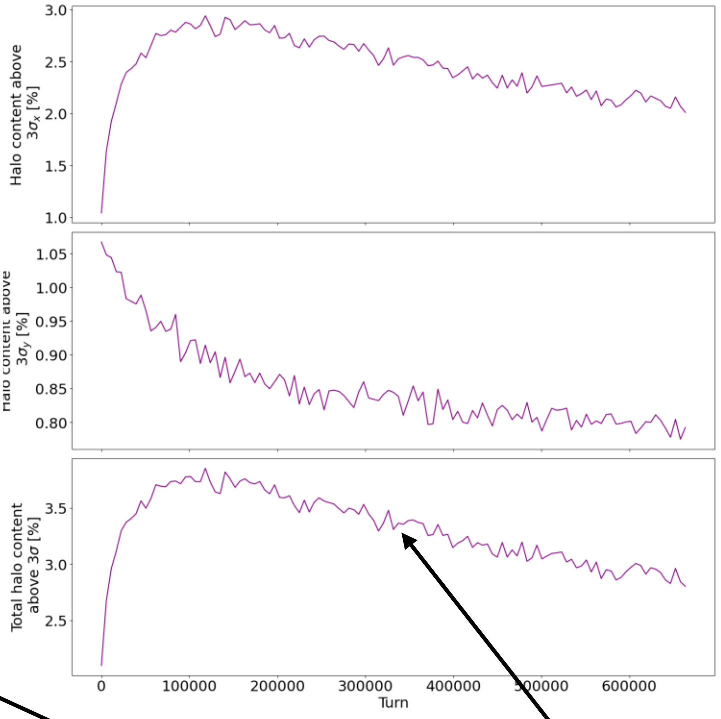
Results of LHC Simulations in Extreme Cases (cont.): $N = 2.1 \times 10^{12}$

Far more particles in tail than expected Gaussian.

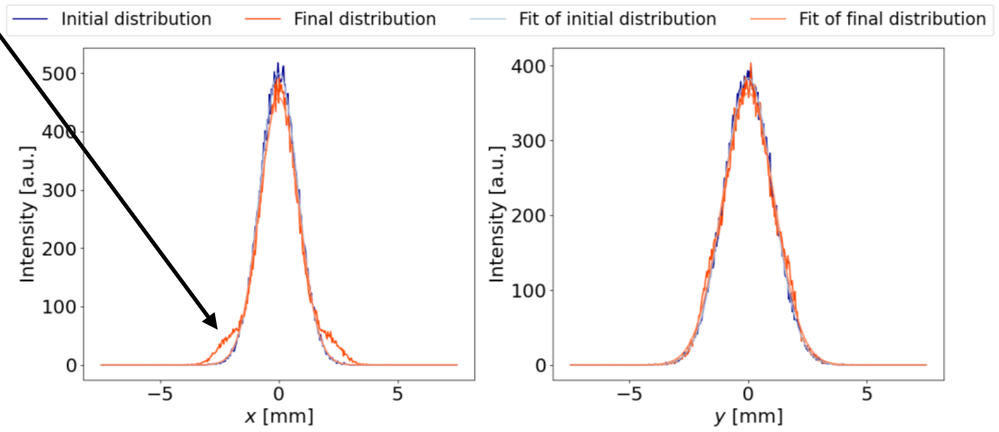
Halo Content vs. Emittance



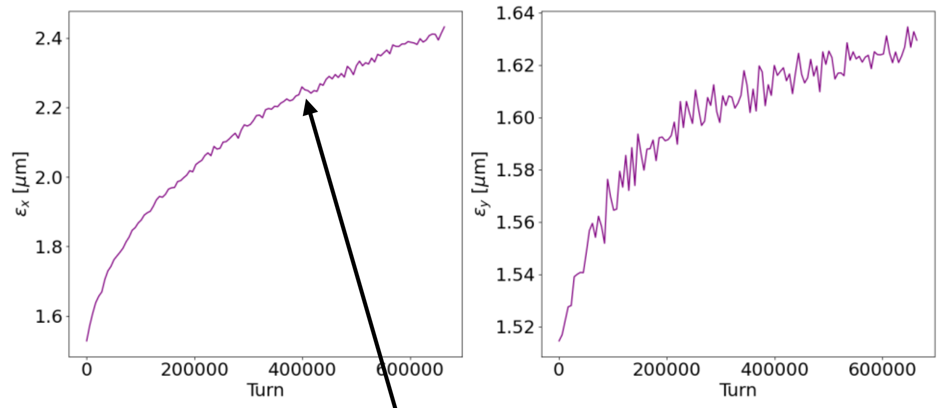
Halo Content vs. Time



Gaussian Fit of Beam



Emittance Evolution



Halo content increases then slowly decreases with emittance.

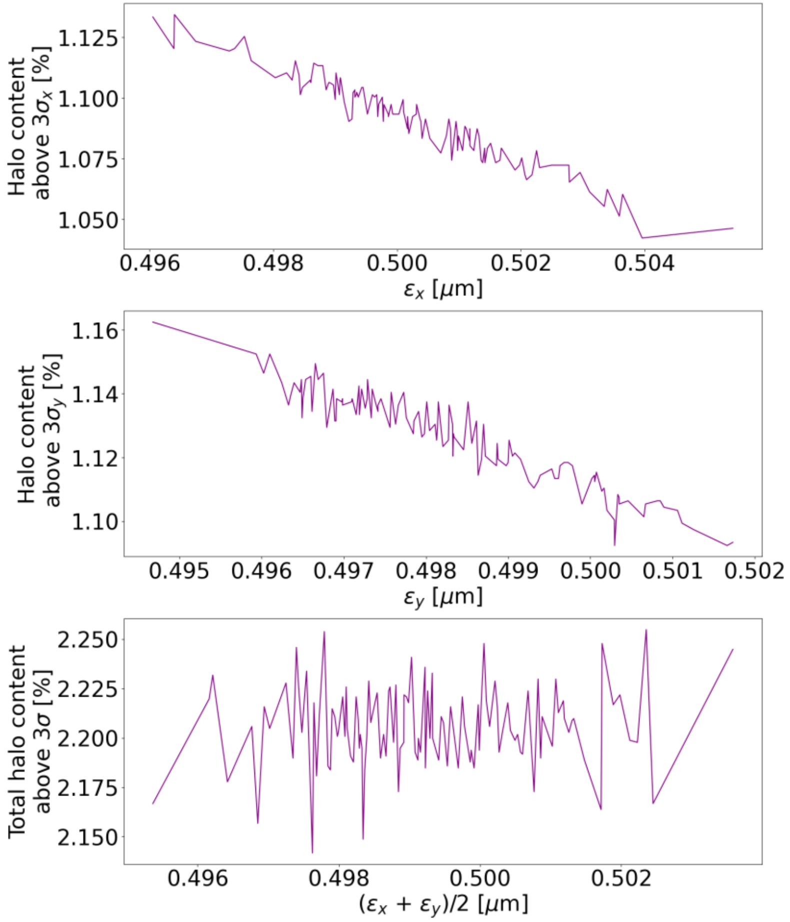
Halo content also increases then slowly decreases with time.

Significant emittance growth.

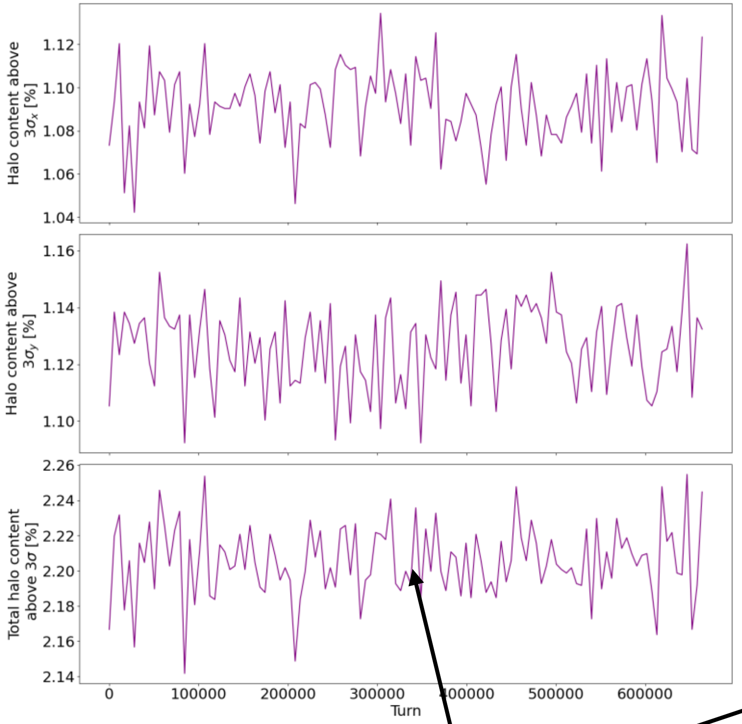
III. Simulations of Space Charge Effects on the Beam Halo in the LHC

Results of LHC Simulations in Extreme Cases (cont.): $\varepsilon_0 = 0.5\ \mu m$

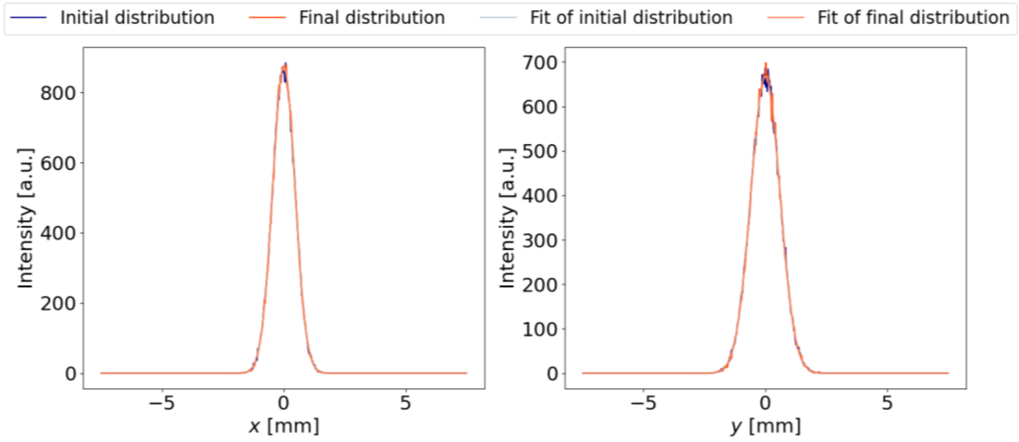
Halo Content vs. Emittance



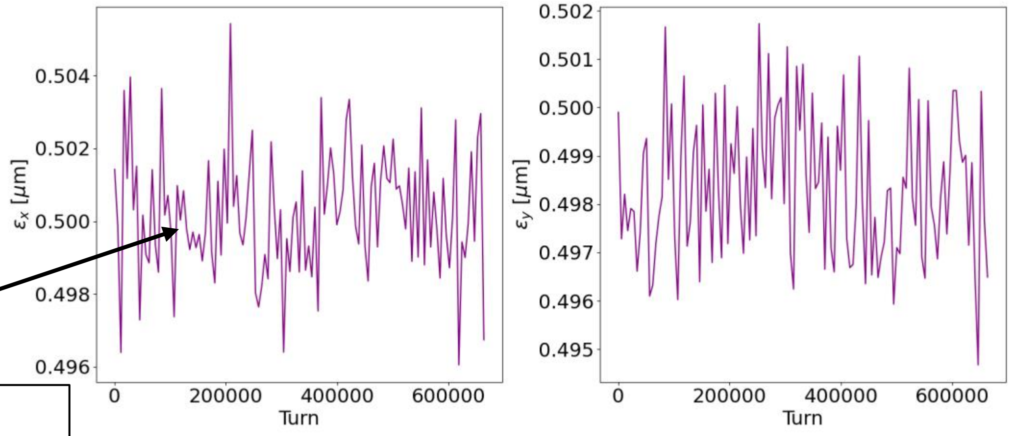
Halo Content vs. Time



Gaussian Fit of Beam Profile



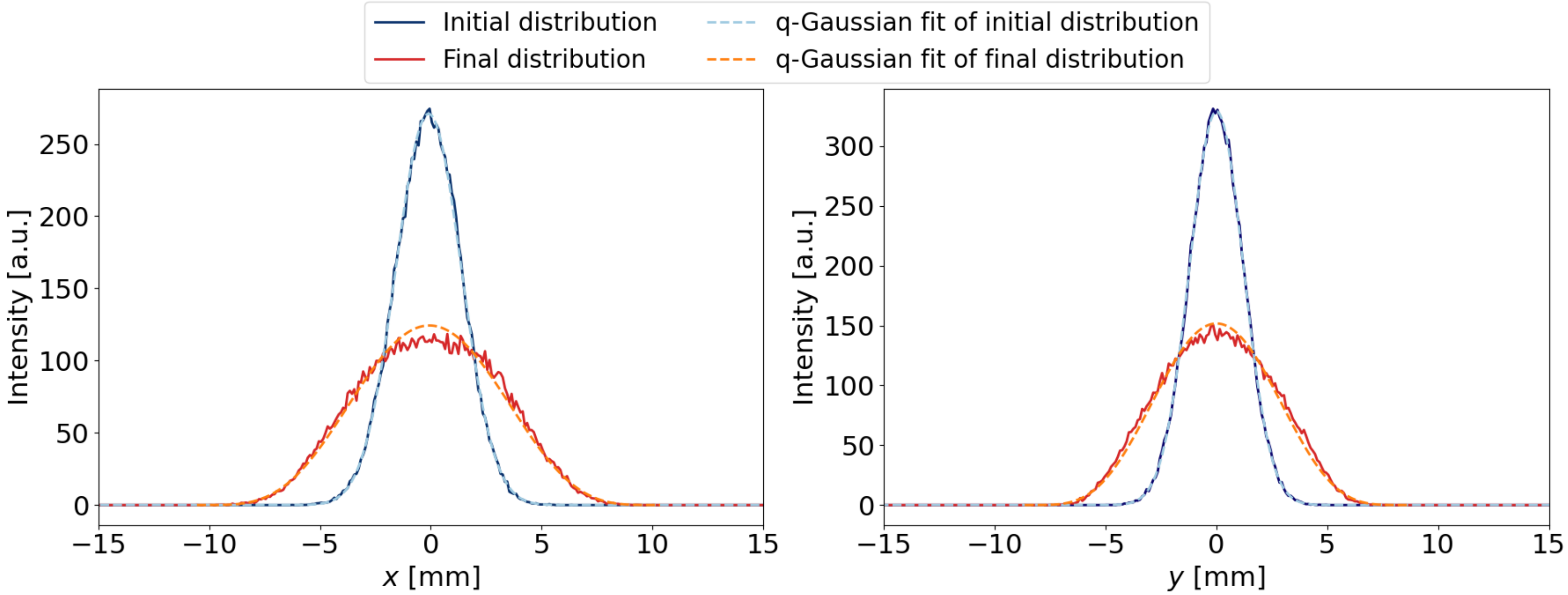
Emittance Evolution



Halo content and emittance largely constant with time – no halo growth with emittance.

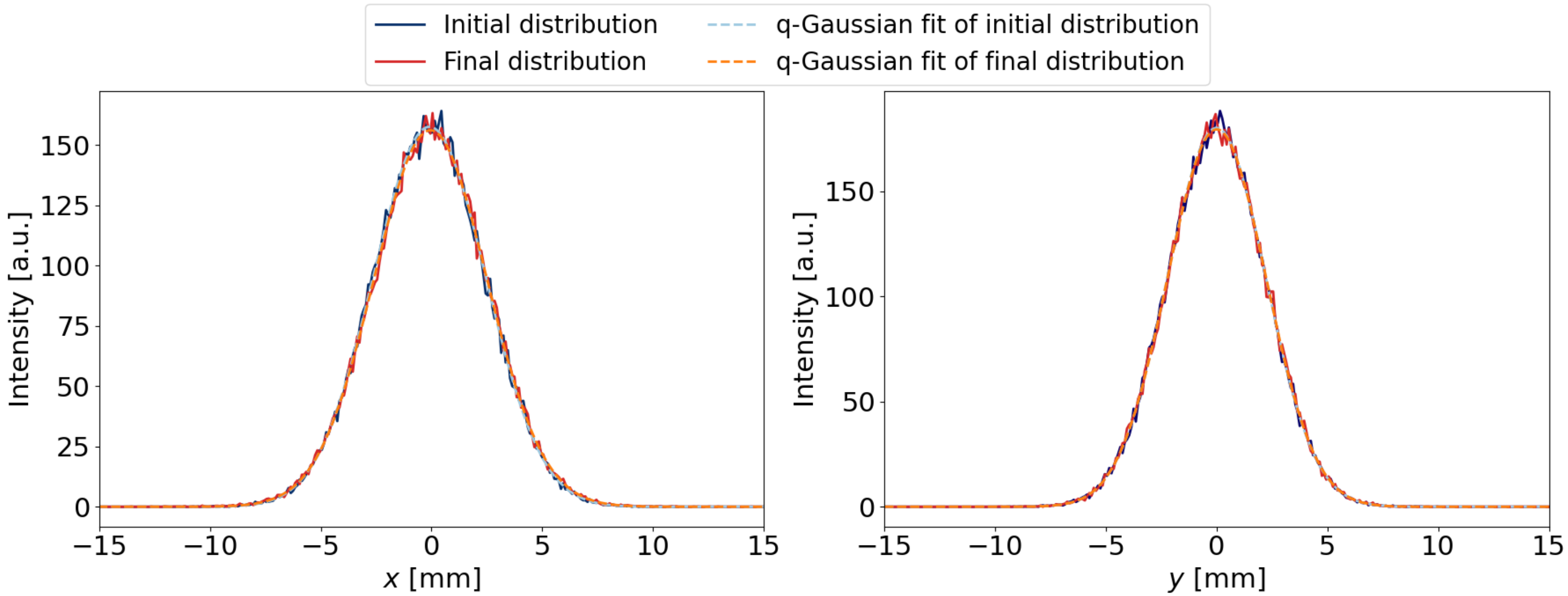
III. Simulations of Space Charge Effects on the Beam Halo in the LHC

Beam Profile Evolution (II)



ε_0 = 0.6 μm:

- Initial distribution is Gaussian (q ≈ 1).
- Final distribution is better parameterised as a q-Gaussian with q < 1.
- Lower q-value → lighter tails → lower halo content.
- Wider profile → higher emittance.



ε_0 = 2.0 μm:

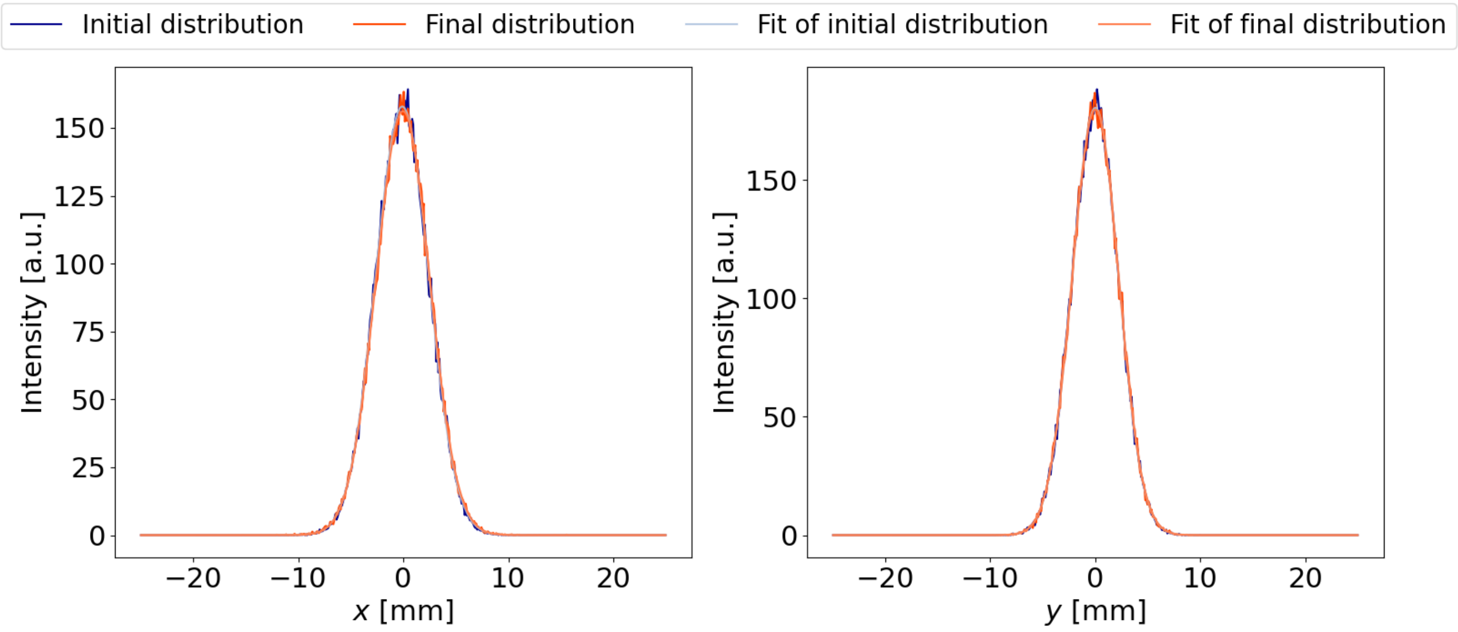
- Distribution is Gaussian throughout.
- Emittance and halo content undergo far smaller perturbations w.r.t. time.

	Initial	Final
q_x: 0.6μm	0.986	0.780
q_y: 0.6μm	0.993	0.790
q_x: 2.0μm	0.982	1.005
q_y: 2.0μm	0.988	0.986

Gaussian Fit of Profile

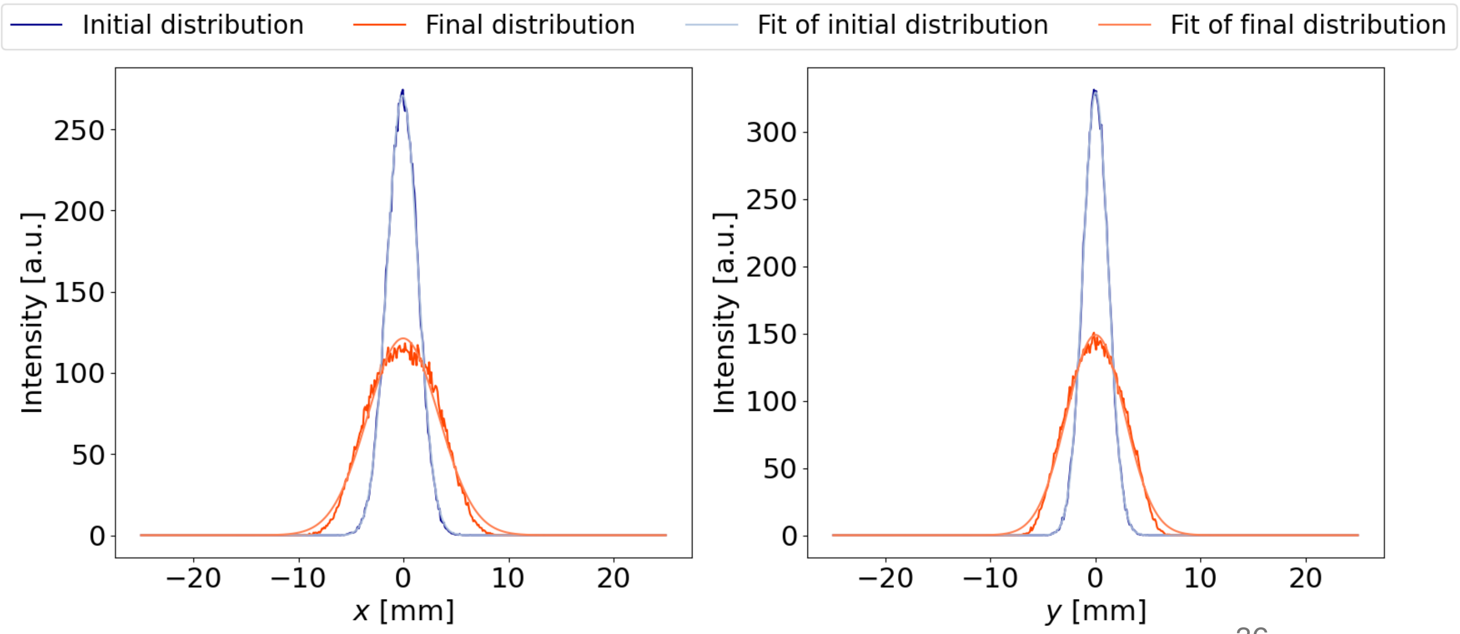
ε_0 = 2.0 μm

- Good fit throughout particle tracking.
- Sufficient approximation due to almost negligible emittance growth.



ε_0 = 0.6 μm

- Good fit for initial distribution, but poor fit for final distribution.
- Not ideal for calculating emittance evolution.



Outlook

- Space charge effects in the SPS could be a source of the observed halo in the LHC.
- However, there are quantitative disparities between the measurements and simulations.
- Errors in the SPS-LHC transfer could have contributed.
- Effects in the SPS: noise (e.g. power supply ripple in main quadrupoles and dipoles)
- Effects in the LHC: β-beating, intra-beam scattering (IBS) and beam-beam effects.
- Simulations of these effects should be considered, in addition to the use of the more accurate particle-in-cell (PIC) model in lieu of the frozen model for the computation of space charge forces.

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