Status of the collider ring

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With special thanks to K. Oide, P. Raimondi, D. Schulte and R. Tomas

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Outline

- Earlier Versions Recap (v0.4 & v0.5)
- Current 10TeV Muon Collider (v0.6)
  - Final Focusing Quads
  - Chromatic Correction & Matching Sections
  - Arc
  - Tracking studies
- New Under Development Collider Ring (v0.7)
- Summary

10TeV Muon Collider

TABLE I. 10 TeV center of mass energy muon collider.

Parameters	Symbol	Unit	10TeV com mc
Particle energy	E	GeV	5000
Particle momentum	P_0	GeV c^{-1}	5000
Luminosity per IP	$\mathcal{L}$	10^{34} cm^{-2} s^{-1}	20
Bunch population	N_p	10^{12}	1.8
Transverse normalized rms emittance	$\varepsilon_{nx} = \varepsilon_{ny}$	μm	25
Transverse geometric rms emittance	$\varepsilon_{gx} = \varepsilon_{gy}$	nm	0.528
Longitudinal emittance ($4\pi\ \sigma_E\ \sigma_T$)	ε_l	eVs	0.314
Longitudinal geometric emittance ($\frac{\varepsilon_l c}{4\pi E_{0\mu}}$)	ε_{lg}	mm	70
Rms bunch length	σ_z	mm	1.5
Relative rms energy spread	δ	%	0.1
Beta function at IP	$\beta_x^\star = \beta_y^\star$	mm	1.5
Power per beam with 5 Hz repetition rate	P_{beam}	MW	7.2
Linear beam-beam tune shift per IP	ξ		0.078

10TeV Muon Collider - In a nutshell

Muon decay (short lifetime τ_0~2.2μs or τ_{5TeV}~0.1s)

=> The resulting neutrinos even from a short straight piece of collider generate a narrow "radiation cone" that is an issue at the location, where they reach the Earth's surface.

=> The planned shape of the collider is like a race track (2 straight sections for IPs).

=> Extensive use of dipoles and combined function magnets.

Very small β* at both planes β*=1.5mm

=> ~500Km βs in the Final Focusing (FF) quads (also large p_T=0.1%).

=> Enormous chromatic aberrations at the optical functions (described by Montague functions).

=> Necessity for a local Chromatic Correction (CC) scheme right after the FF quads.

=> Use of dipole-sextupol kicks at areas with large betas and dispersion.

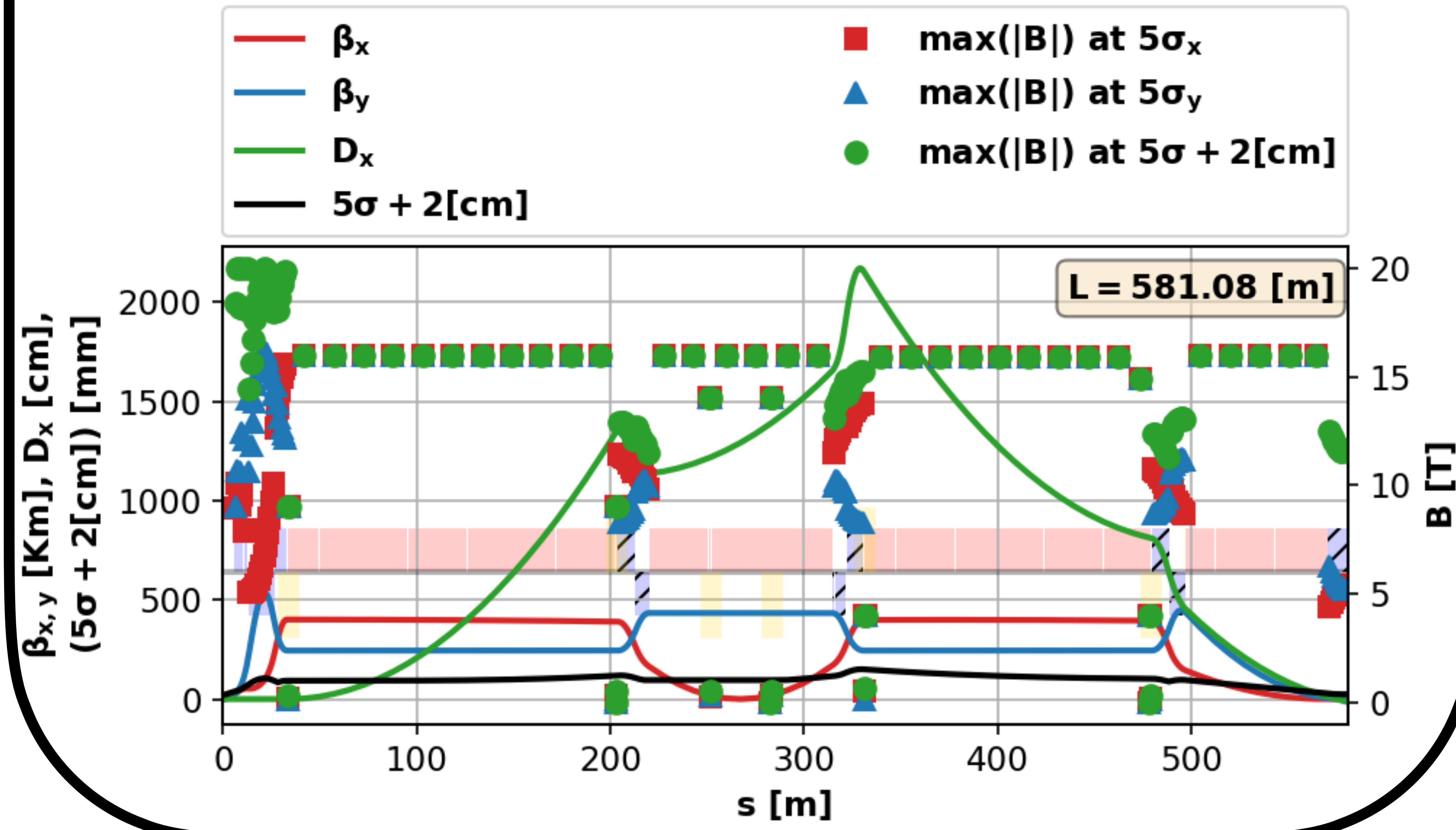
=> The CC generates significant positive momentum compaction factor (α_p) that has to be compensated (keep the bunch length short) in the arcs.

10TeV Muon Collider **v0.4**
(Earlier designs)

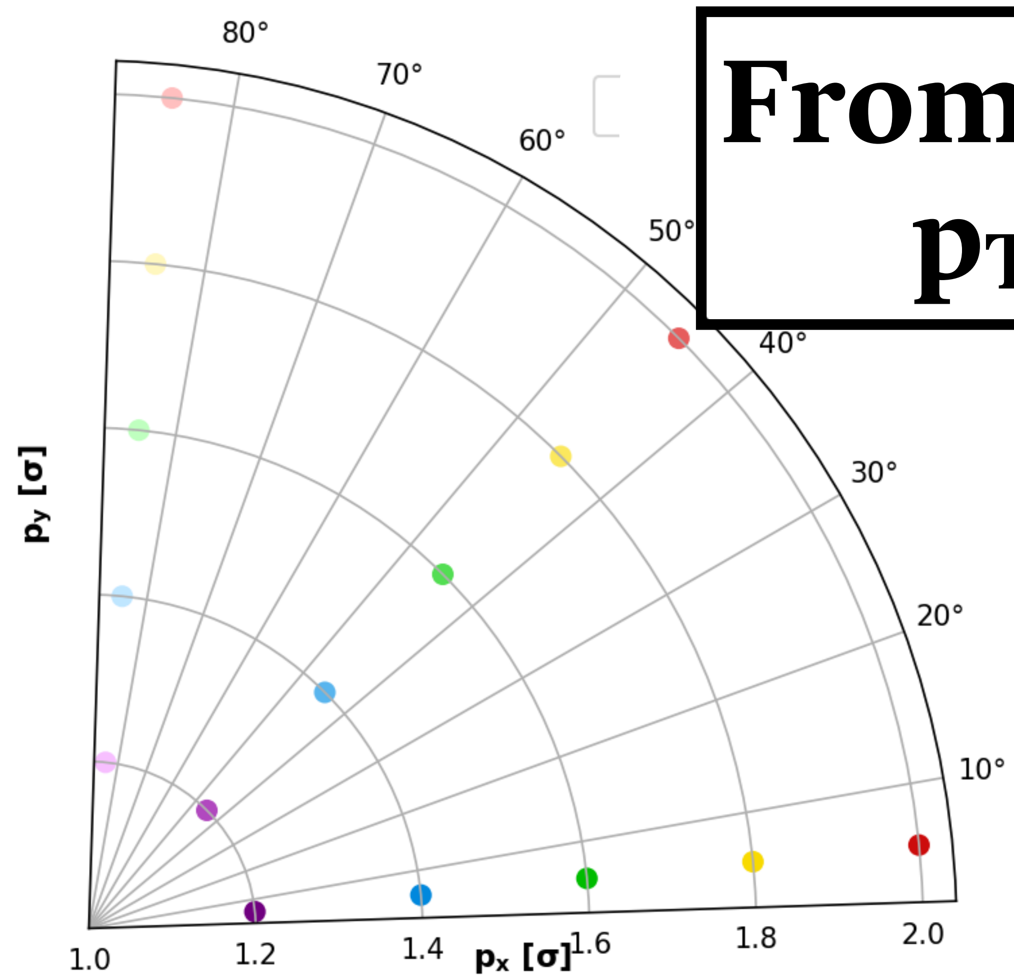
10TeV Muon Collider - Extended Final Focusing

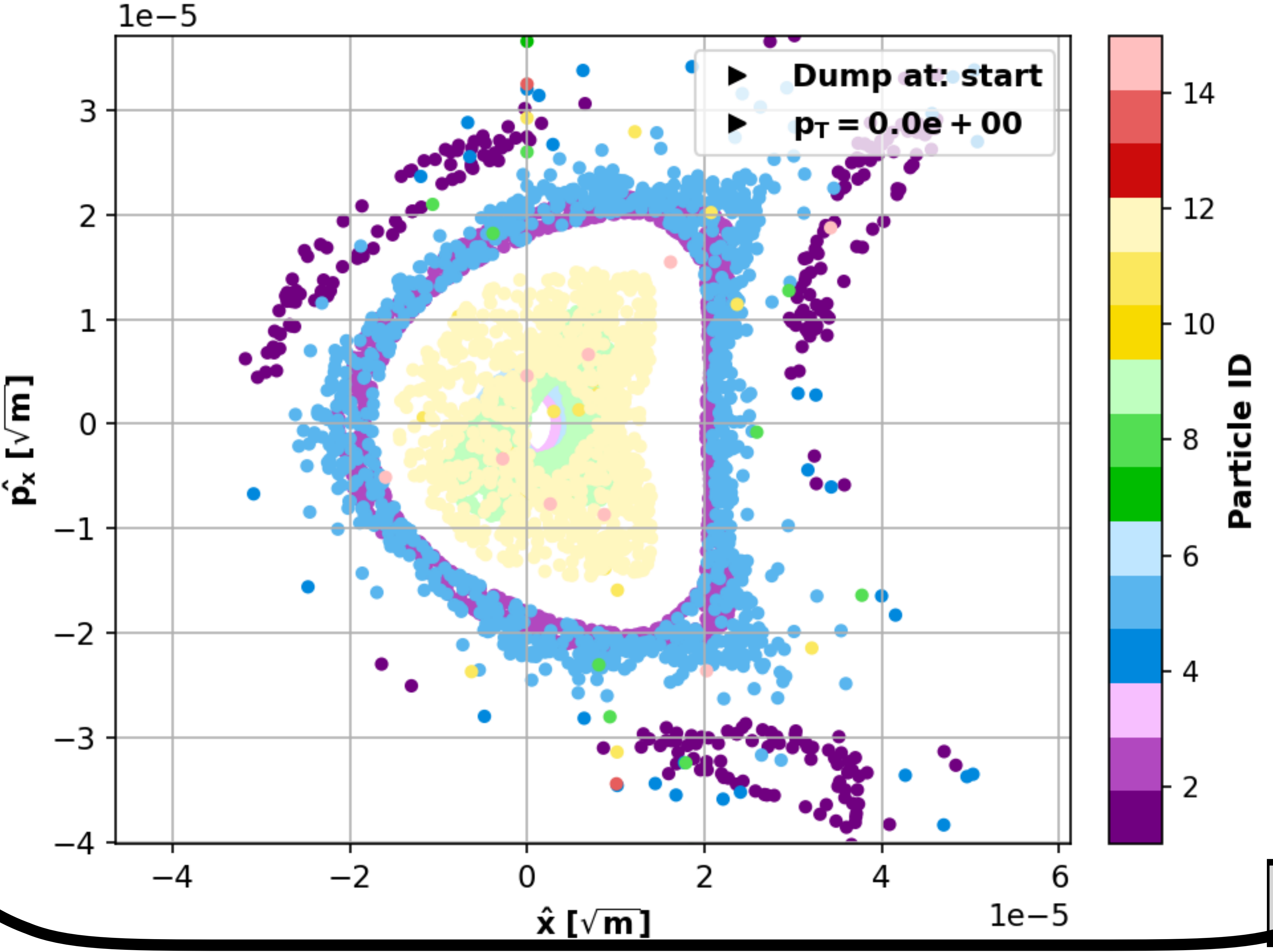
v0.4

- 3 doublets of dipole-sextuples
- use of I and -I transform between sextupoles of a given doublet
- 1m long dipole-sextupole with sextupolar components weaker than 0.2T



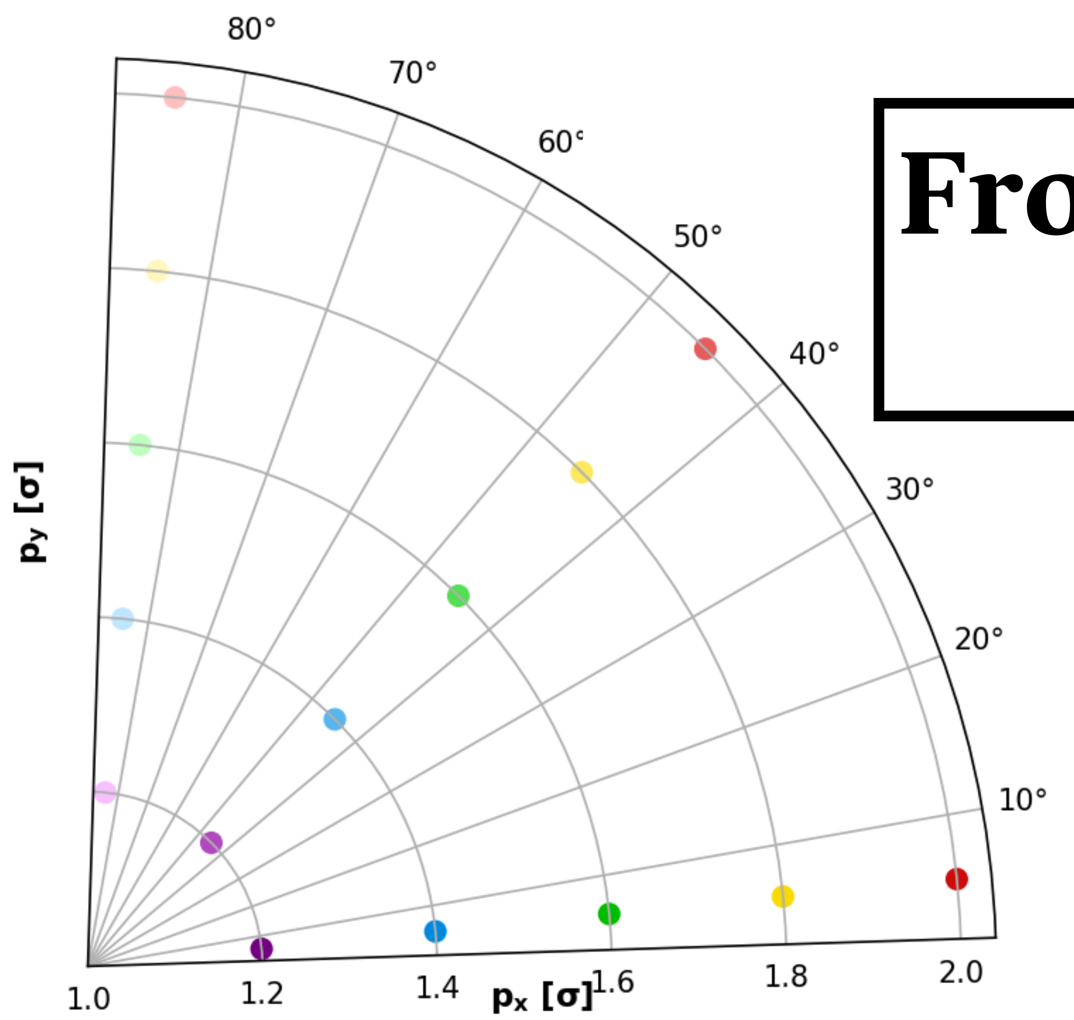
From 1 to 2σ
$p_T = 0$





10TeV Muon Collider - Tracking Studies

v0.4



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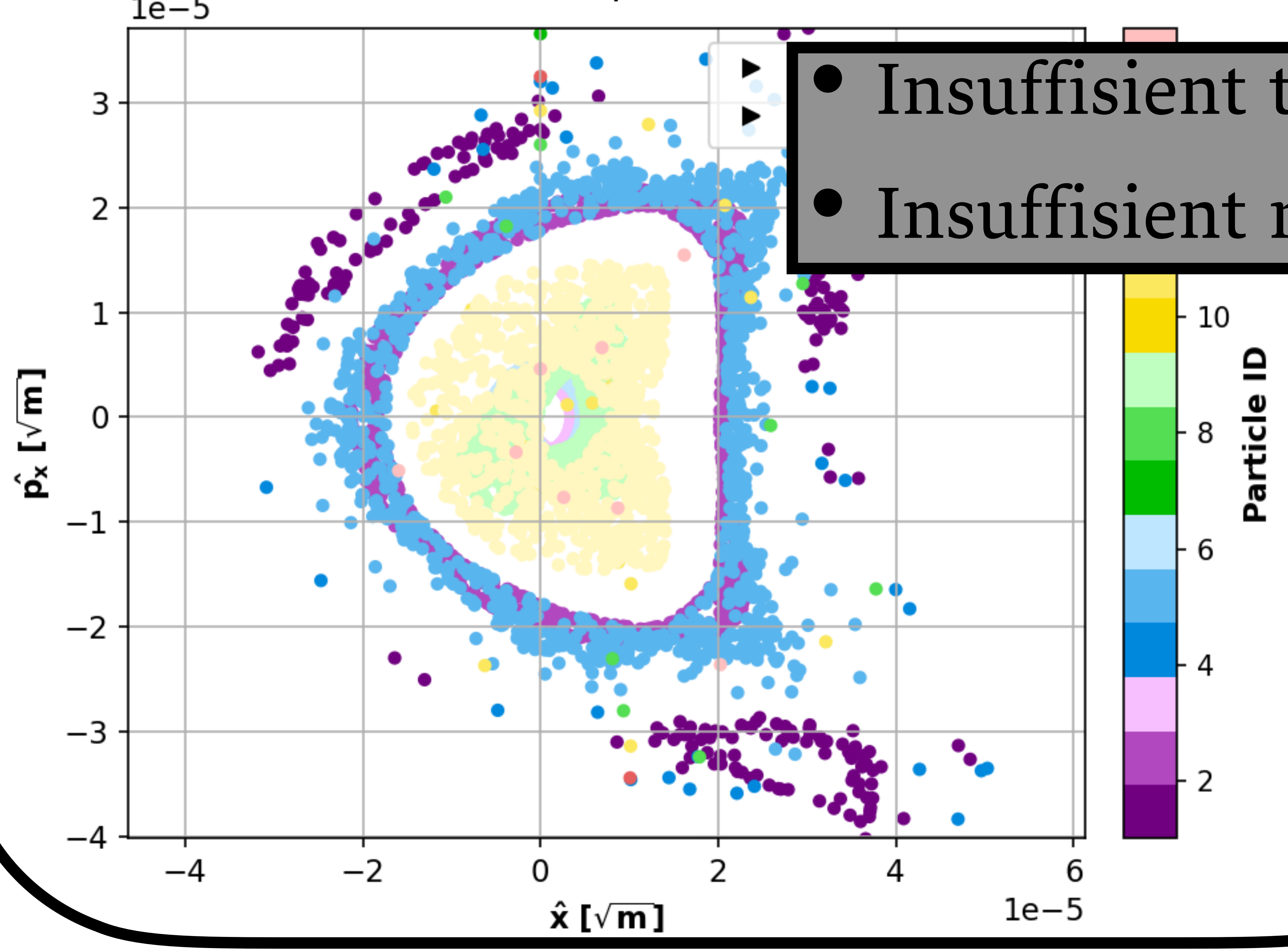
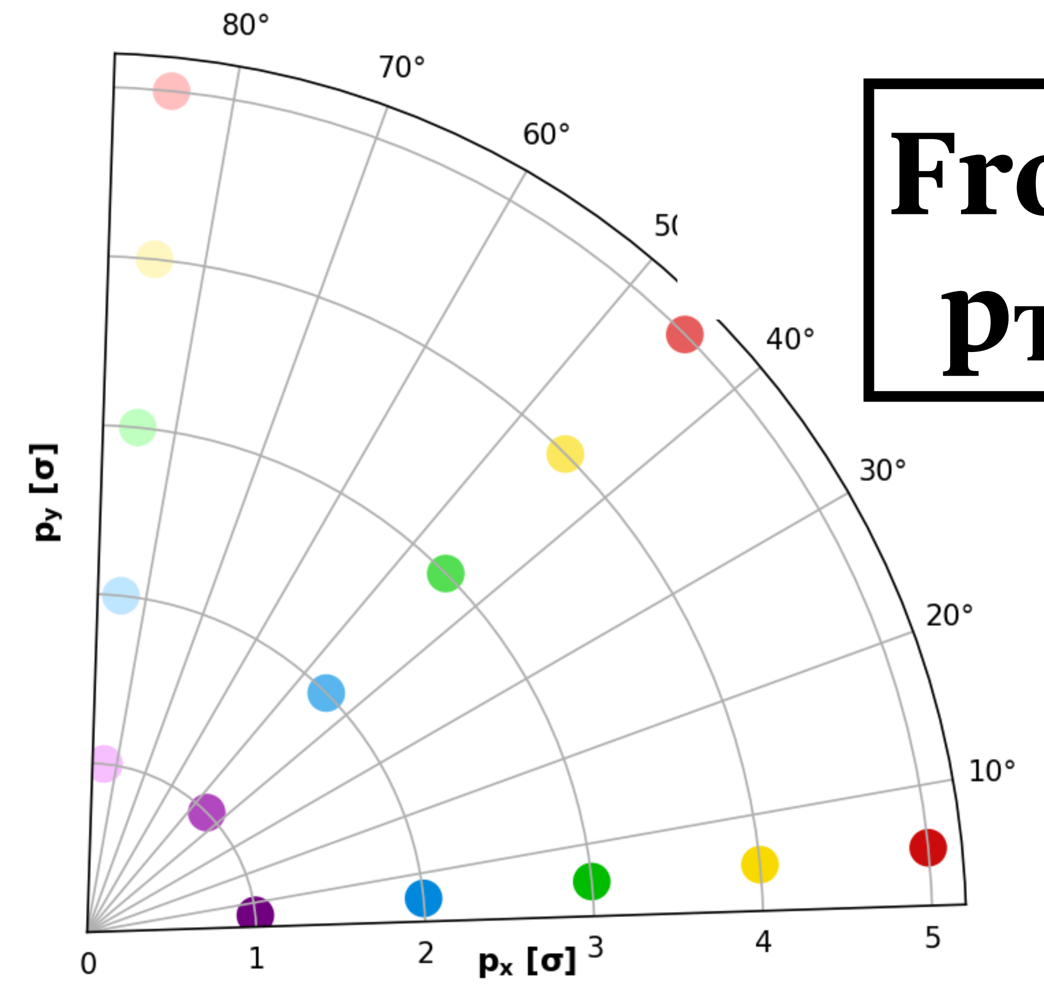
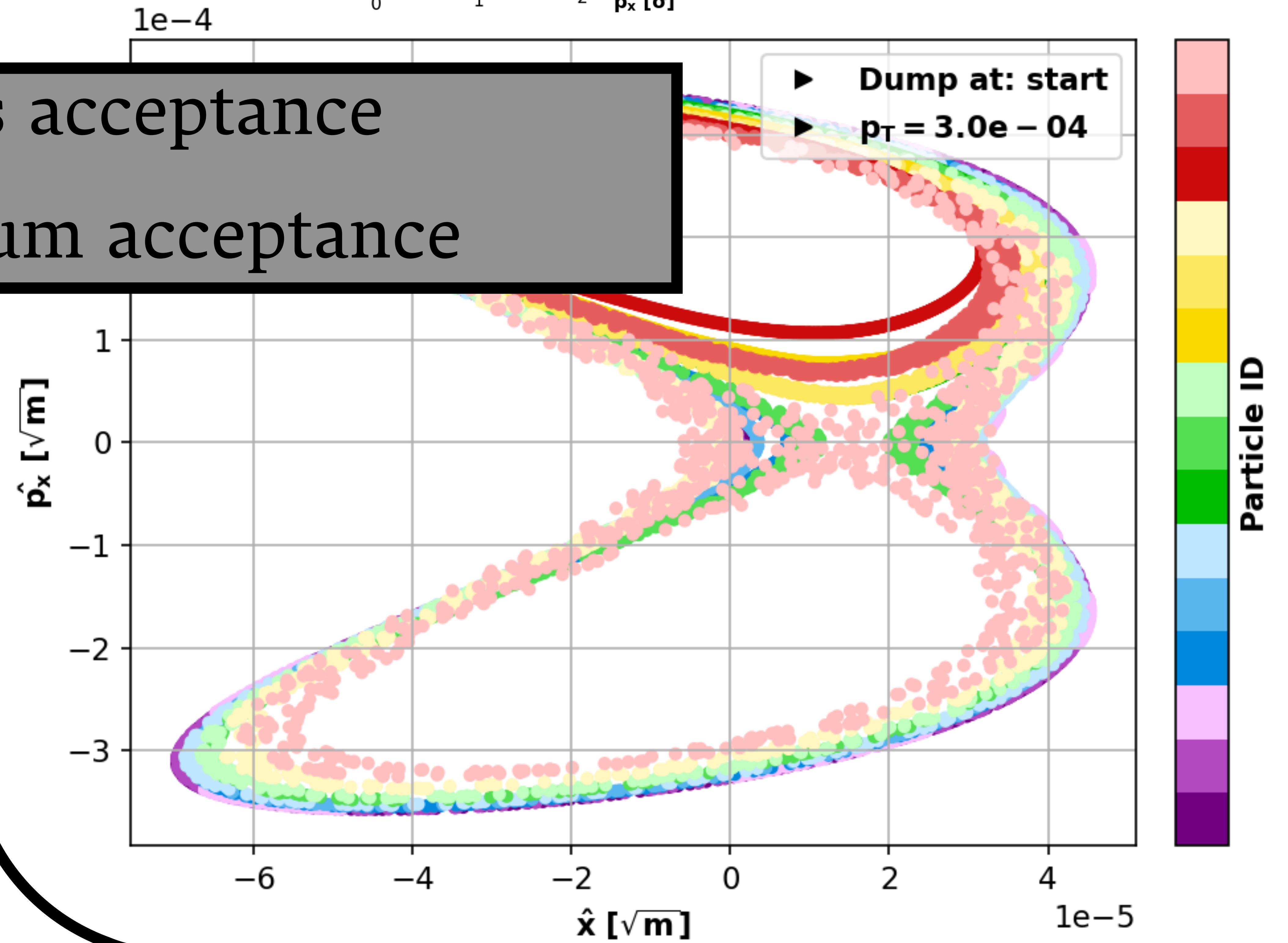


- Insuffisient transvers acceptance
- Insuffisient momentum acceptance

v0.5



From 1 to 5σ
p_T = 0.03%

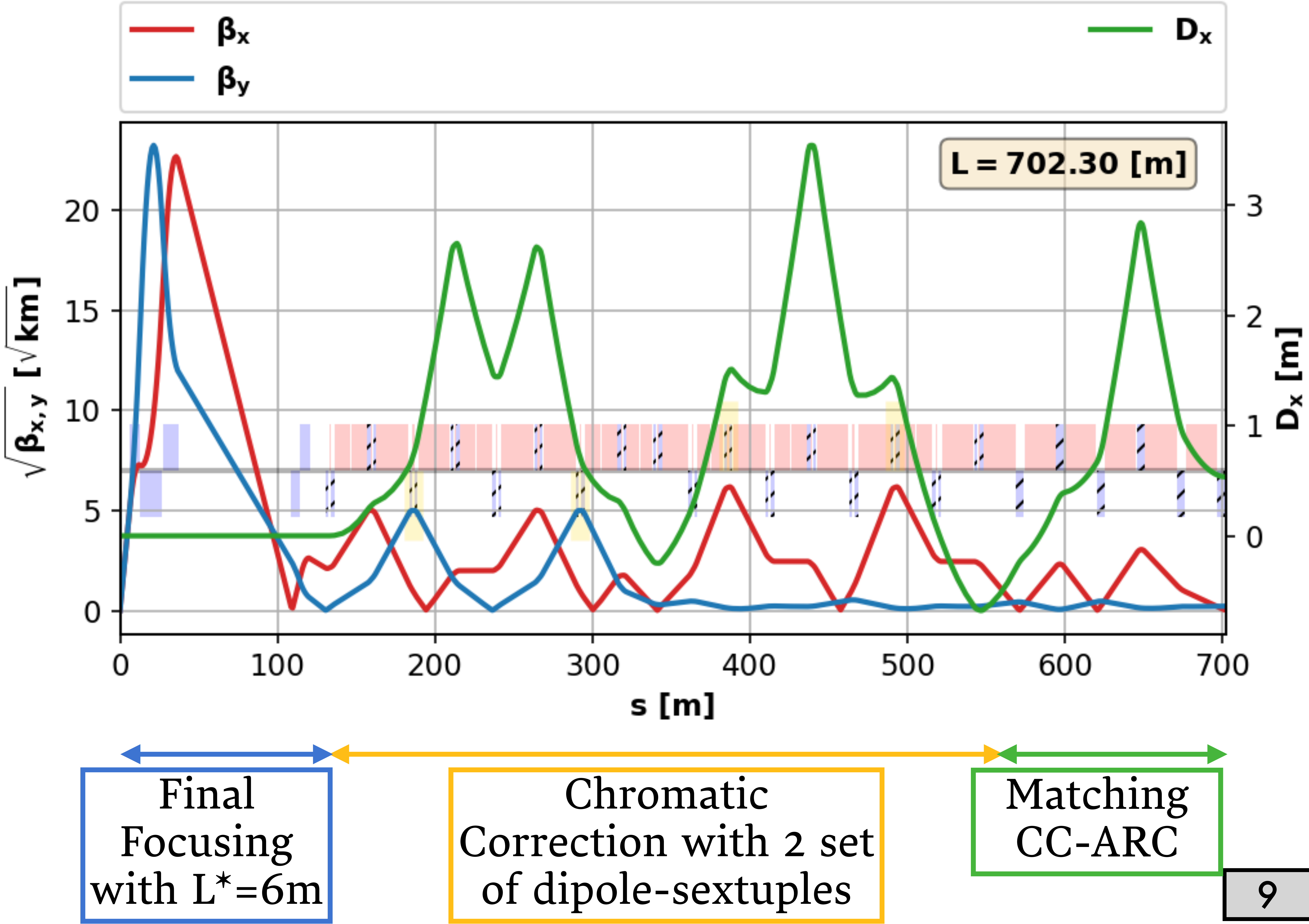


10TeV Muon Collider **v0.6**
(Current design)

10TeV Muon Collider - Extended Final Focusing

Colour code for lattice elements:

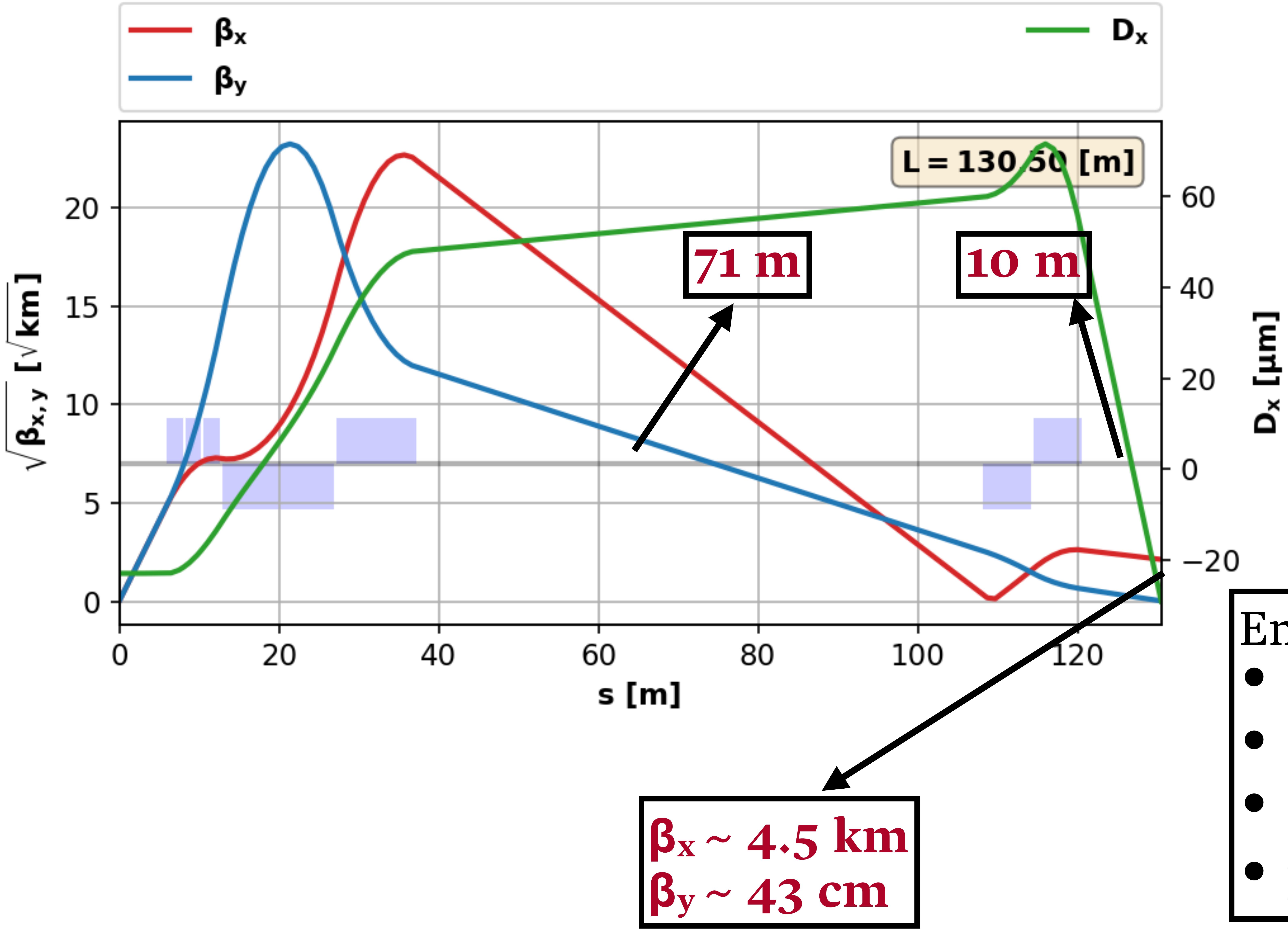
- Red dipoles
- Blue quadrupoles
- Hashed blue dipole-quadrupoles
- Red + Gold dipole-sextupoles (all 1m long)



10TeV Muon Collider - Final Focusing Quads

- L^* = 6m and five quadrupoles are used.
- The maximum magnetic field at the magnet aperture is set to 20T.
- Due to the fast increase (decrease) of the β functions right after the IP, the first magnet is split in shorter ones with different gradient, reducing that way the length of the FF scheme.
- The $\beta_{x,y}$ are reduced by two order of magnitude at the end of the FF quads while the last four quadrupoles are used to control the $\beta_{x,y}$ and $\alpha_{x,y}$ in the chromatic correction section.
- Inclusion of a drift section for a smoother reduction/control of the beta values (β_x,β_y) at the end of the FF scheme. This help to keep the Montague chromatic functions at smaller values in the chromatic correction section.

10TeV Muon Collider - Final Focusing Quads



$$B\rho = 16678.205 \ [Tm]$$

$$Aperture = 2(5\sigma + 0.02) \ [m]$$

$$\sigma_j = \sqrt{\frac{\beta_j \varepsilon_{nj}}{\beta_r \gamma_r} + (D_j \delta_p)^2} \ [m] \ with \ j = x, y$$

$$\sigma = max(\sigma_x, \sigma_y) \ [m]$$

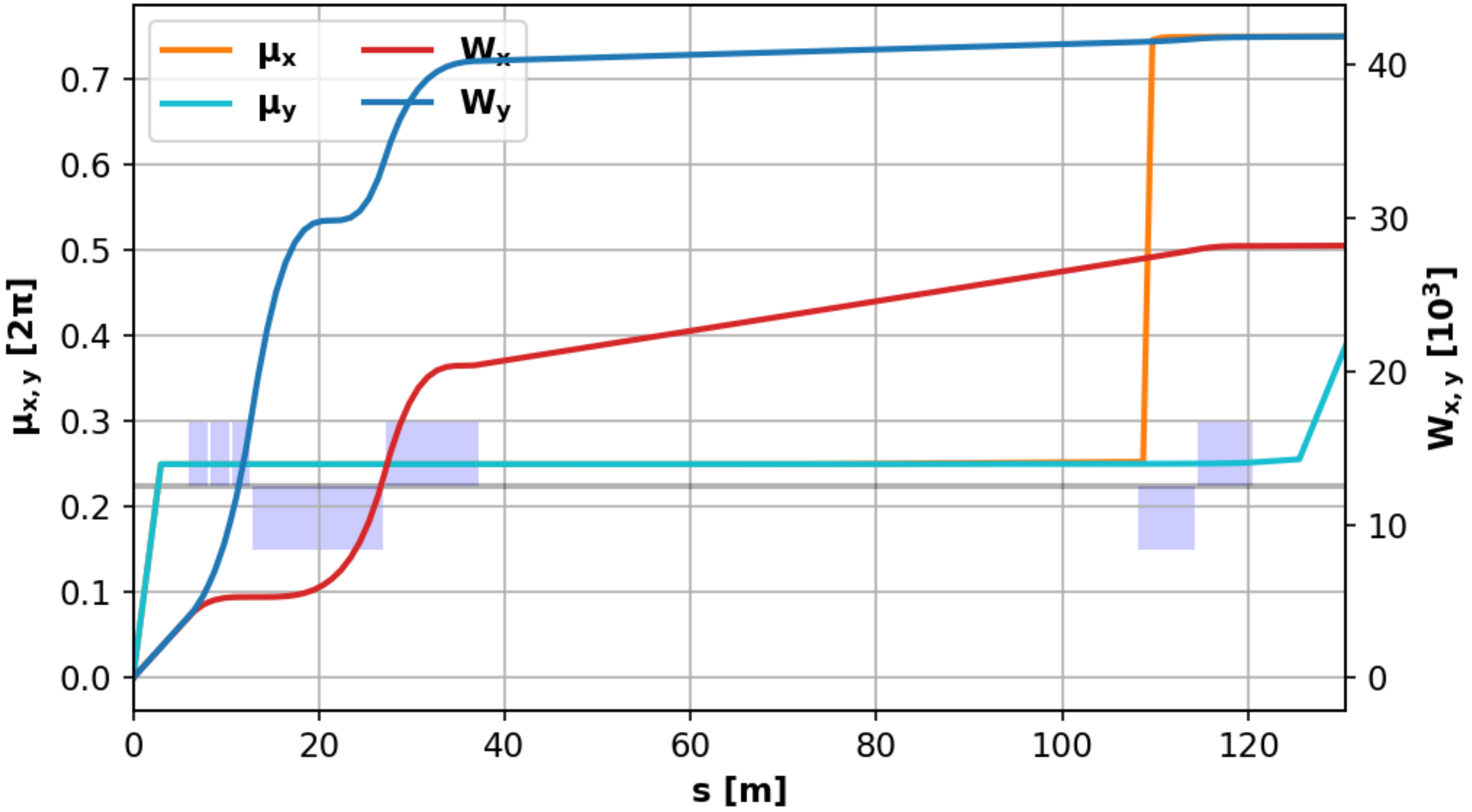
Entering the CC with small βs:

- Smaller aperture
- Smaller Ws
- Smaller unwanted multipolar kicks
- Easier control of βs

10TeV Muon Collider - Final Focusing Quads

- Due to strong focusing quadrupoles (β^*=1.5mm), the Montague chromatic functions ($W_{x,y}$) that describe the optics perturbation for off-momentum particles w.r.t on-momentum one become very large.

- Together with the large momentum spread ($p_T=10^{-3}$), these W values indicate enormous chromatic effects that must be compensated, otherwise momentum acceptance orders of magnitude smaller than momentum spread.



10TeV Muon Collider - Chromatic Correction & Matching Schemes

- The maximum allowed magnetic field is assumed to be the 16T.

Chromatic Correction (CC) scheme

- The CC scheme include 2 sets (doublets) of combined function dipole-sextupole magnets and each set is placed at positions with large β_q, where q=x or y, for the correction of the W_q at the end of CC scheme.

- Each set include a pair of dipole-sextupole magnets with the same k_2 separated by -I transform at x and y planes for the compensation of the RDTs excited by the sextupolar component.

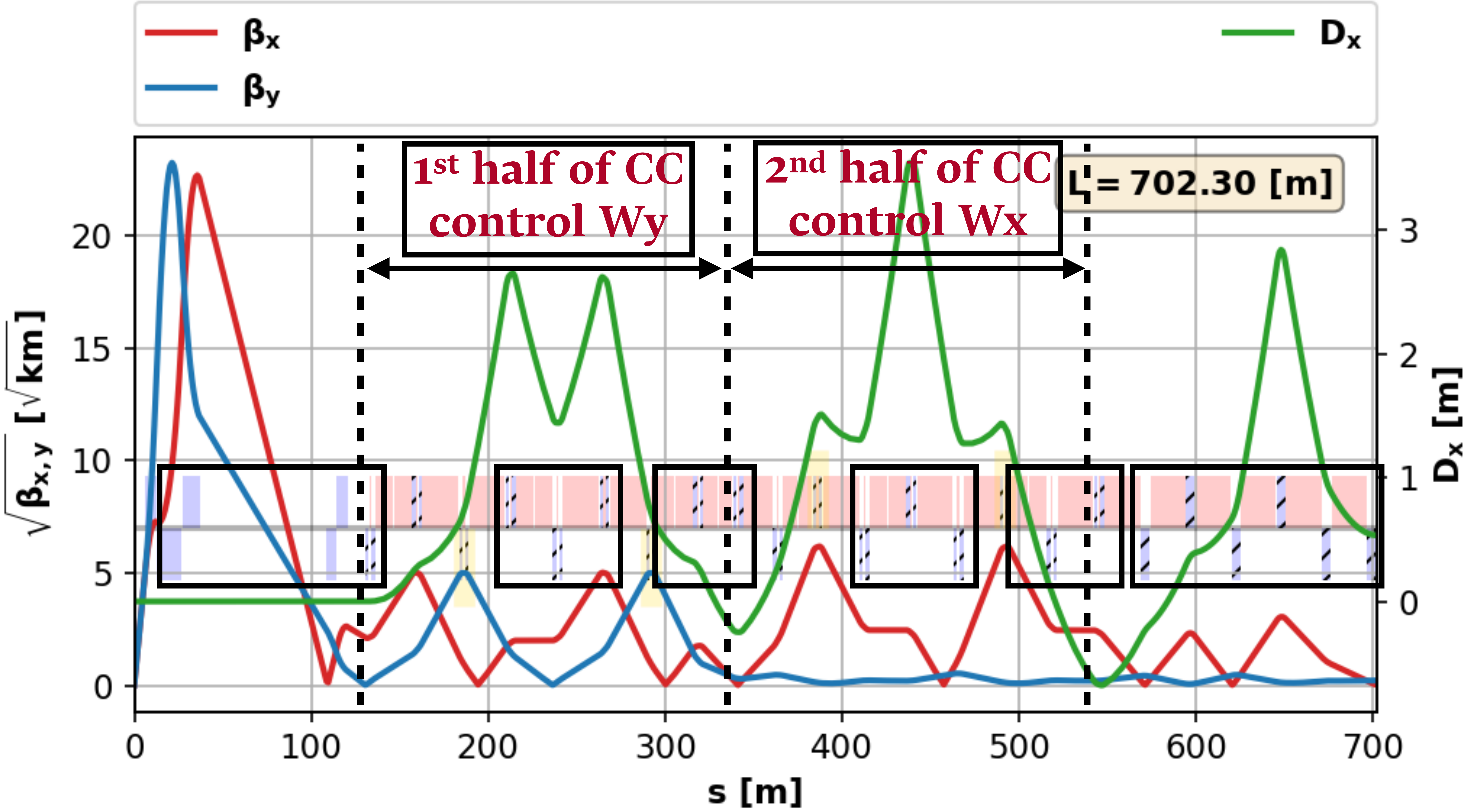
- The phase advance $\mu_y(\mu_x)$ between the IP and the first (third) dipole-sextupole magnets can be adjusted for a better control of higher order chromatic effects.

Matching scheme (CC-Arc)

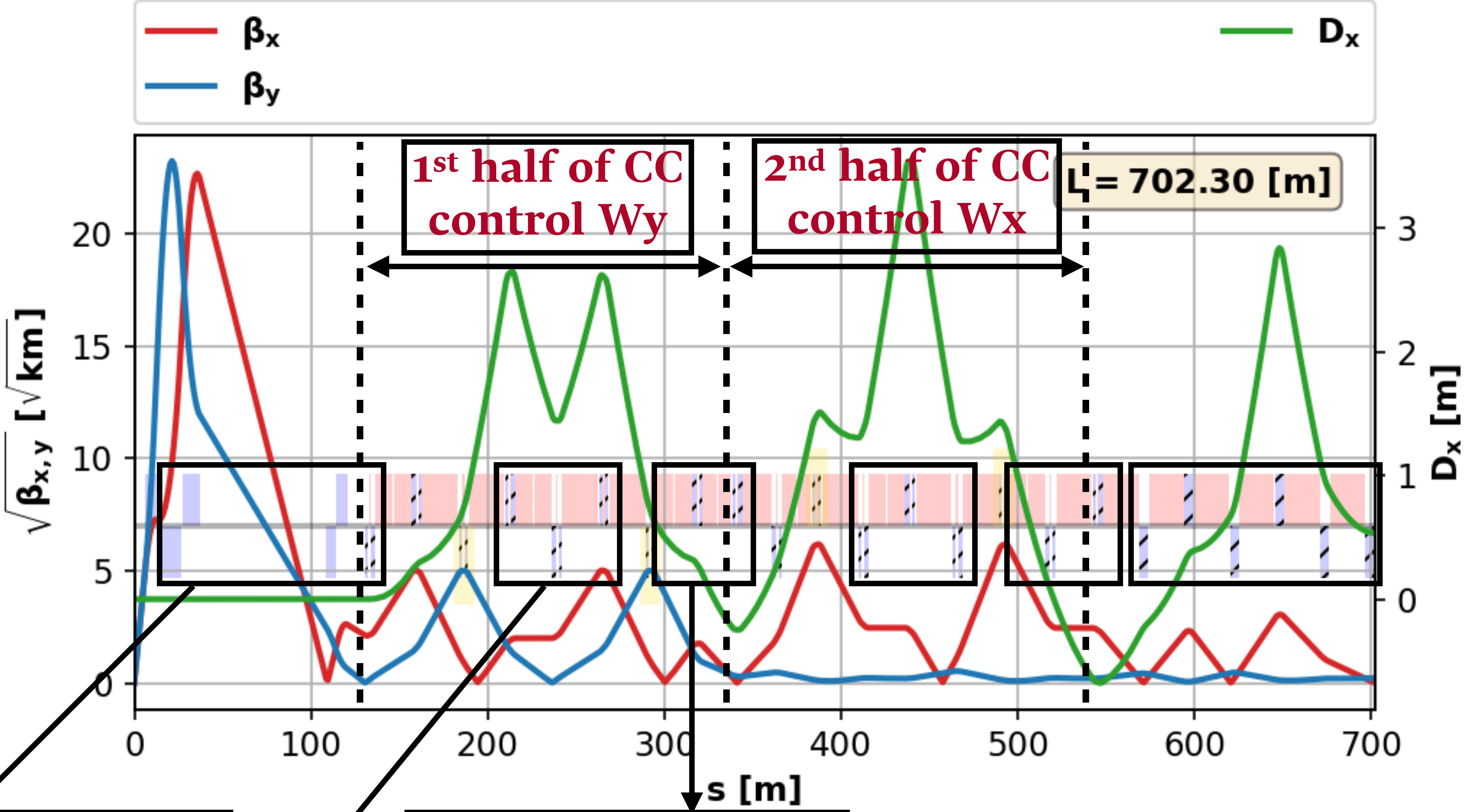
- The $\beta_{x,y}$, $\alpha_{x,y}$, D_x and D_{px} are matched by controlling the strength of six dipole-quadrupole and the dipole length separating the dipole-quadrupole magnets.

- The matching of the optical functions is facilitated by controlling its value at the end of the CC scheme (keeping it to small values).

10TeV Muon Collider - Extended Final Focusing Scheme



10TeV Muon Collider - Extended Final Focusing Scheme

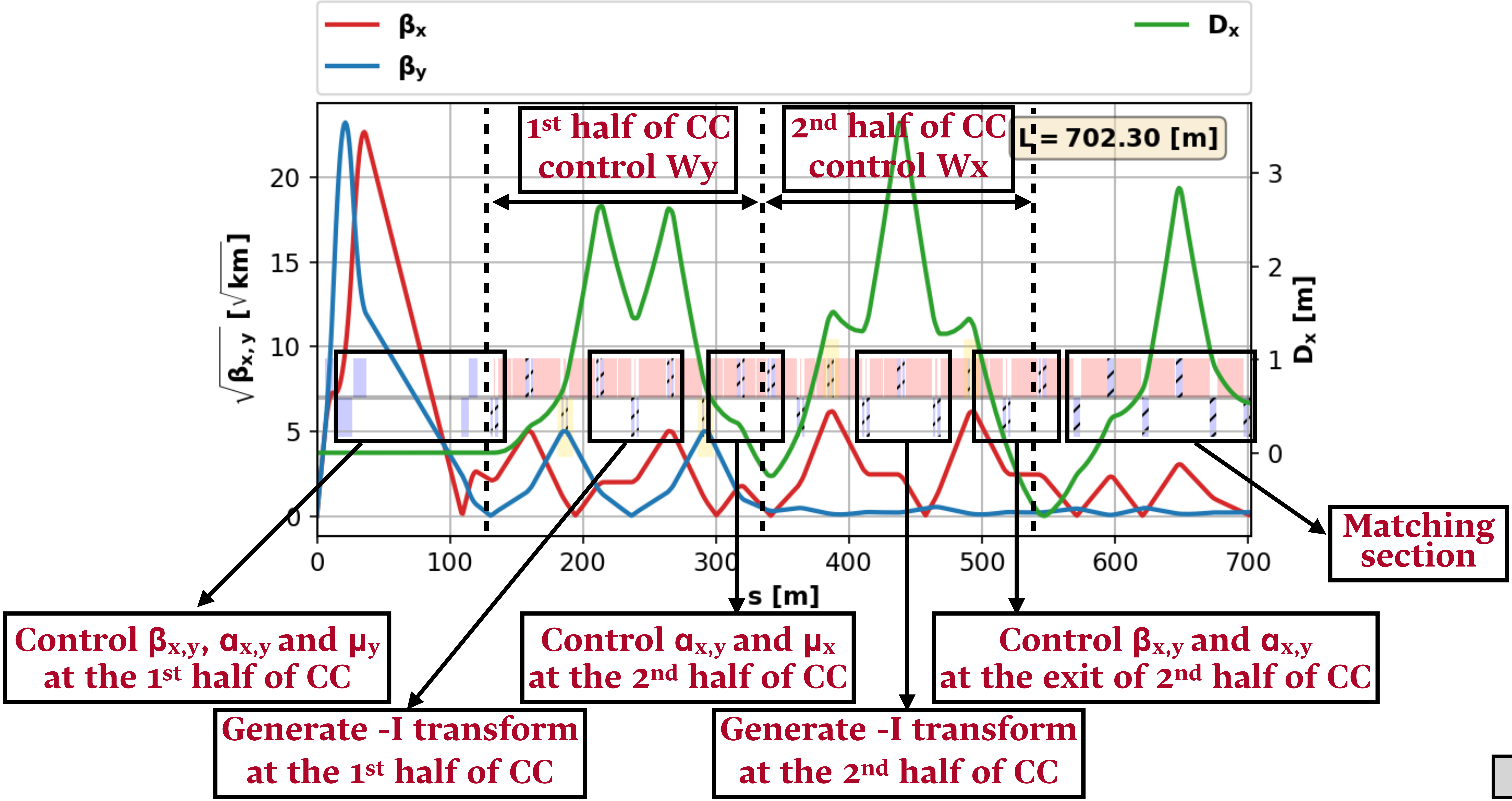


Control $\beta_{x,y}$, $\alpha_{x,y}$ and μ_y at the 1st half of CC

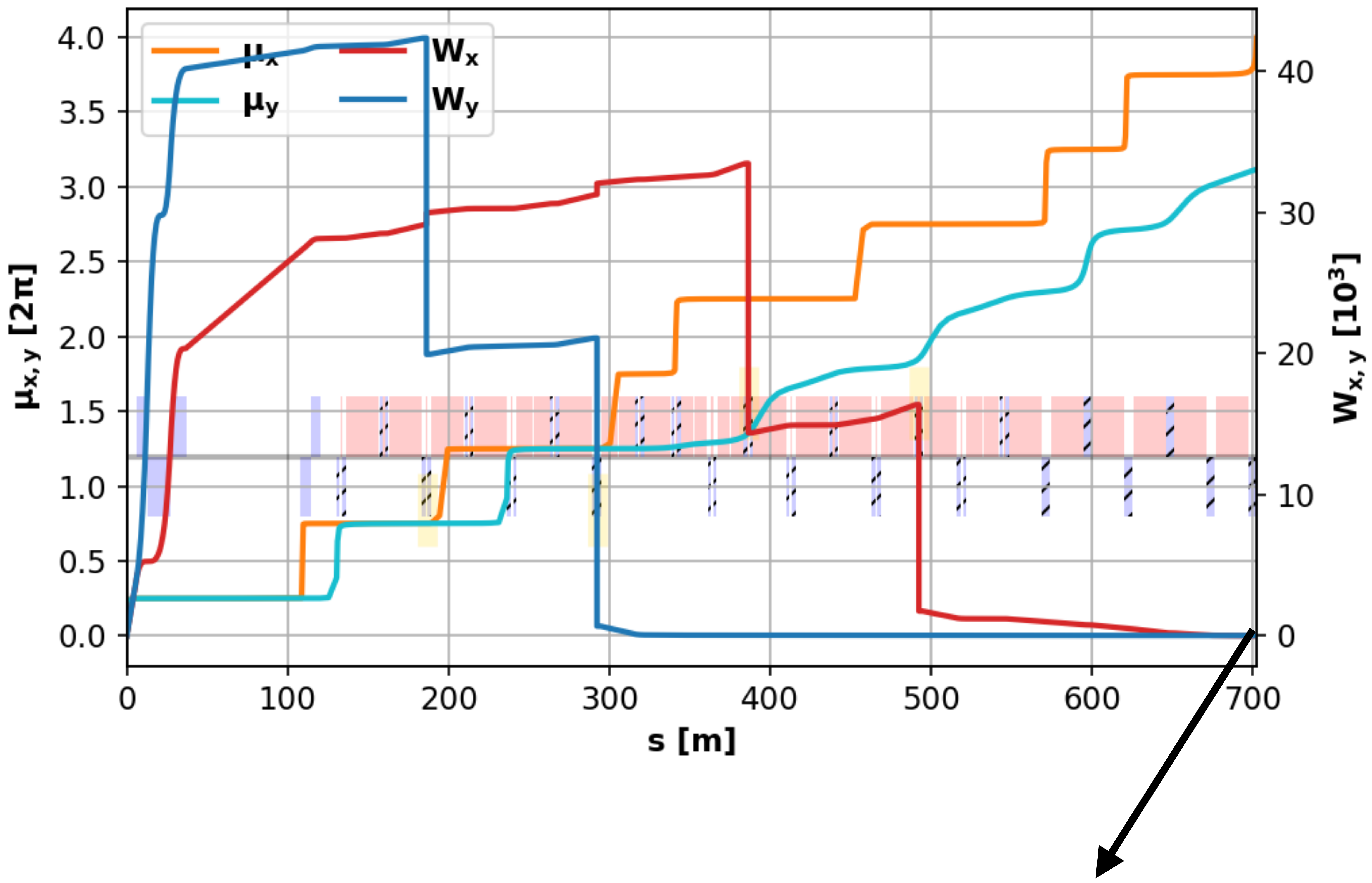
Control $\alpha_{x,y}$ and μ_x at the 2nd half of CC

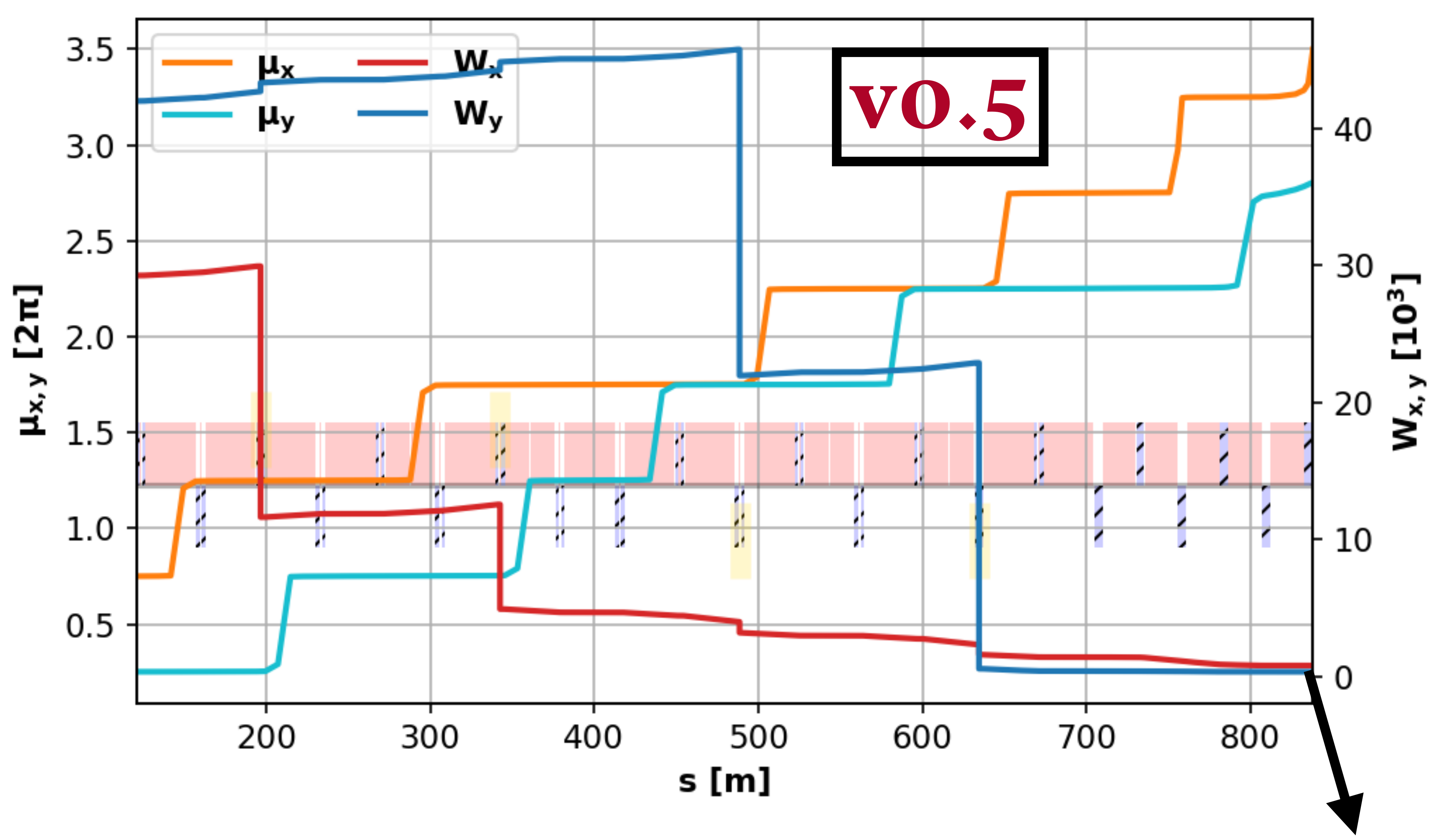
Generate -I transform at the 1st half of CC

10TeV Muon Collider - Extended Final Focusing Scheme



10TeV Muon Collider - Chromatic Correction & Matching Scheme





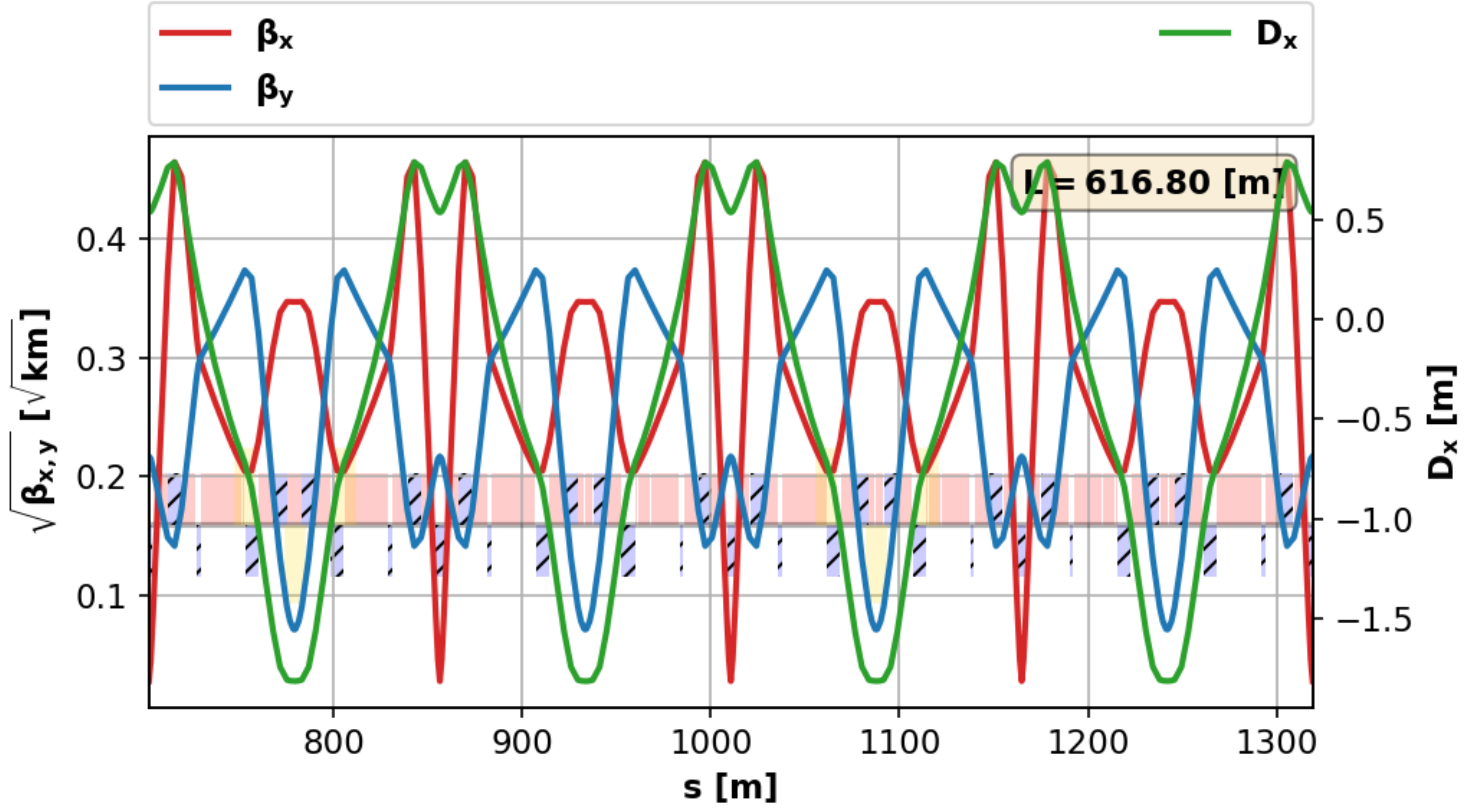
$\delta^* W_{x,y} < 0.02$

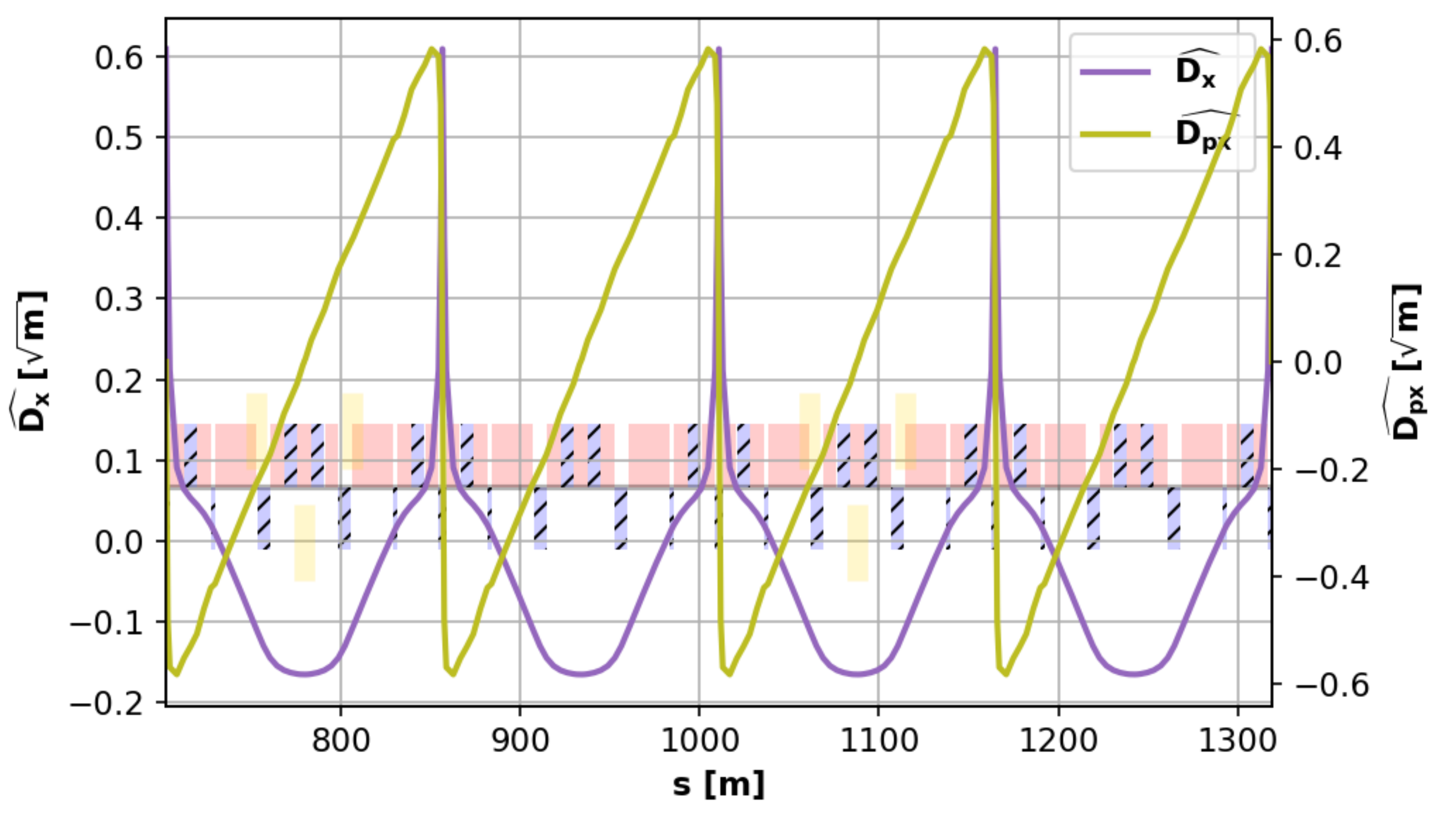
$\delta^* W_{x,y} < 1$

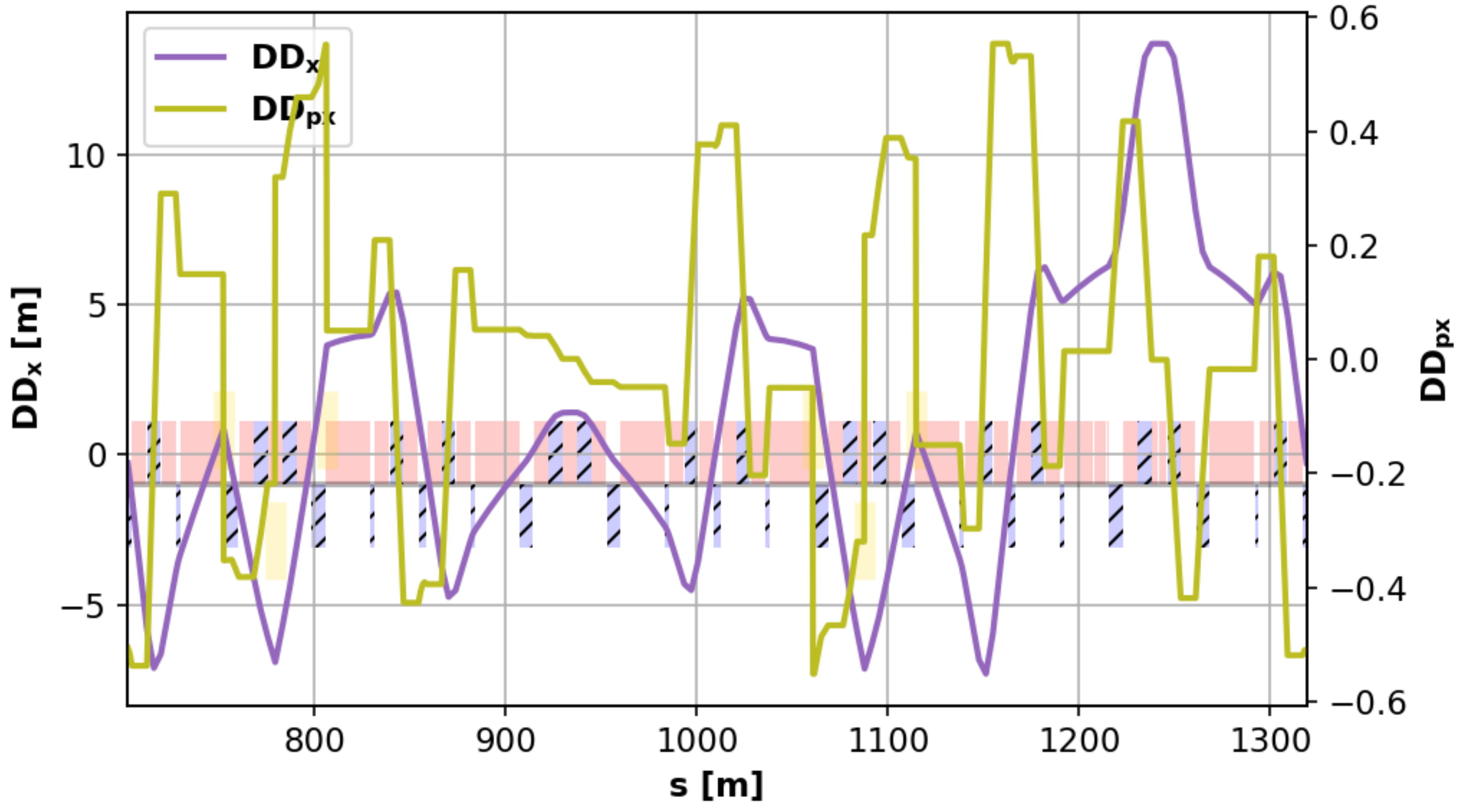
10TeV Muon Collider - Arc

- The CC scheme produces a large positive contribution to the momentum compaction factor (α_p) and phase slip ($\eta_p \sim \alpha_p - 4.5 \times 10^{-10}$) thus, a negative contribution from the arcs is generated with ability for to very precisely control α_p in order to keep η_p small.
- The maximum allowed magnetic field is assumed to be the 16T.
- Each arc section consist of repeated Flexible Momentum Compaction (FMC) cells (each one is made out of 2 FODO cells).
- The integrated strength of a set of dipoles located at areas with negative dispersion controls the α_p while with another set of dipoles, the 2π closing of the trajectory is controlled.
- The linear chromaticity at x and y planes is controlled with a set of combined function dipole-sextupole magnets separated by a -I transform.
- The phase advance per FMC cell is $3\pi/2$ (-I transform every second cell).

10TeV Muon Collider - Arc





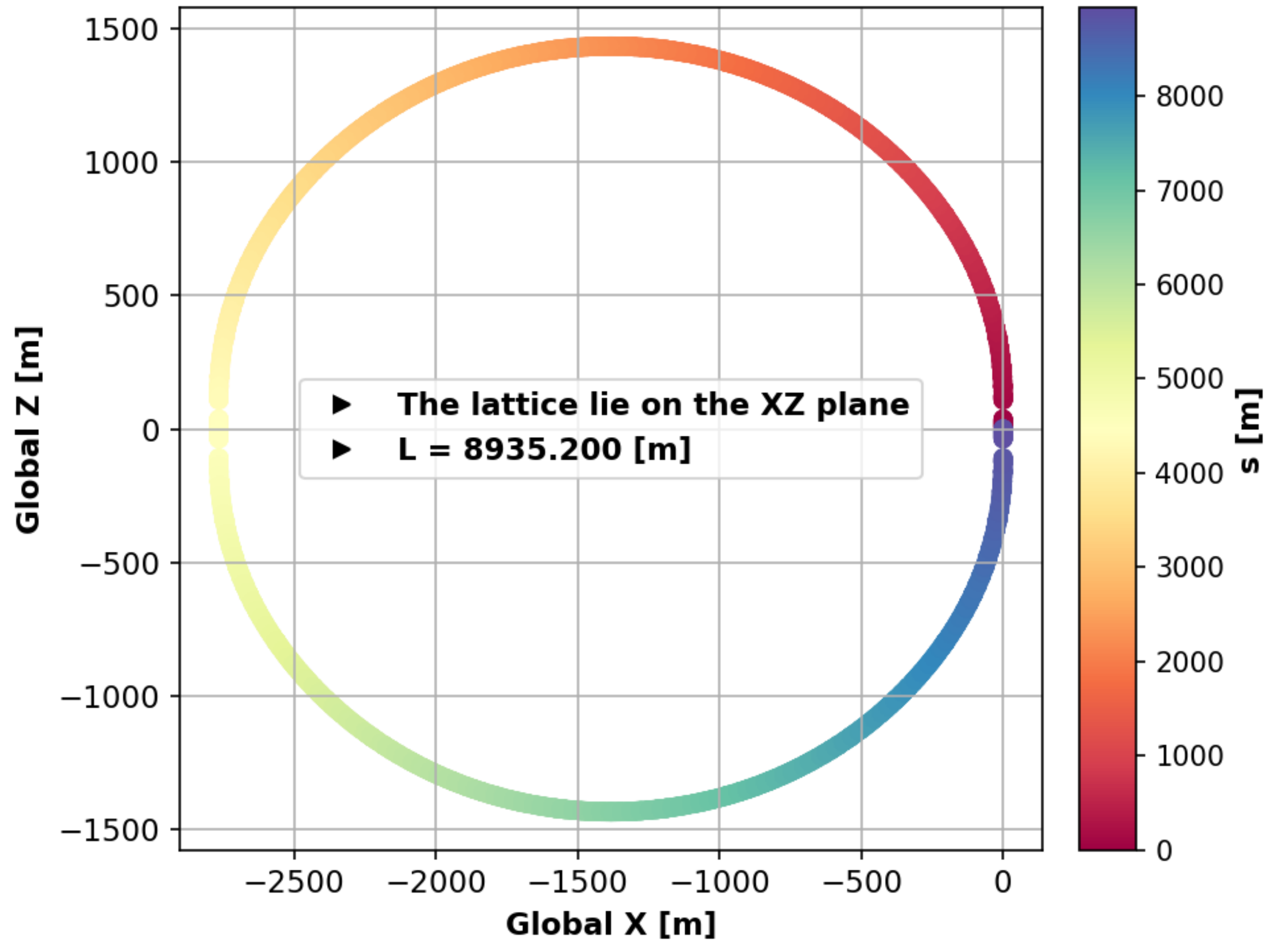


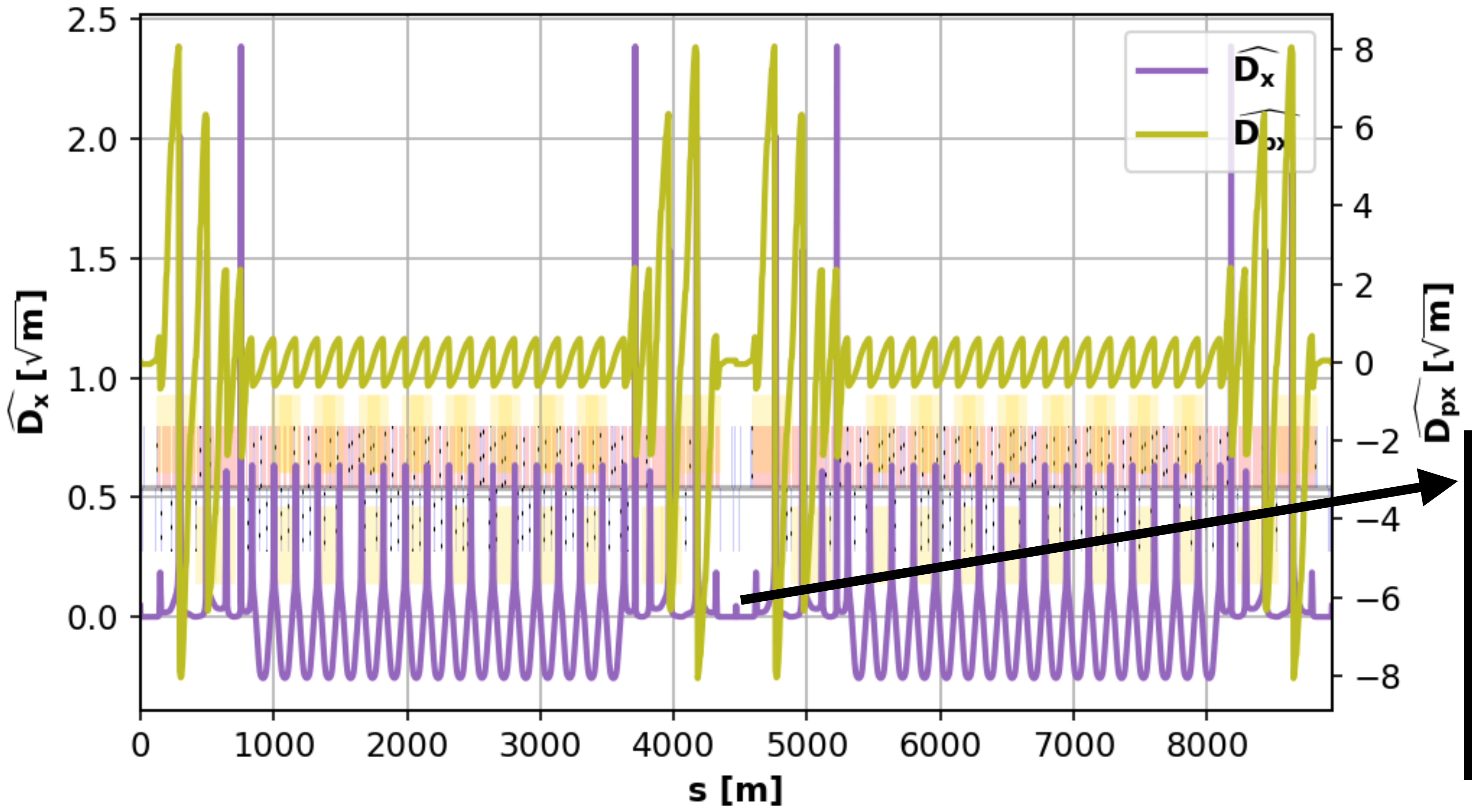
	v0.4	v0.6
5σ	~23.45mm	~9.15mm

May increase significantly in newer versions.

Significantly smaller than the 5σ in EFF.

10TeV Muon Collider - Full Lattice v0.5

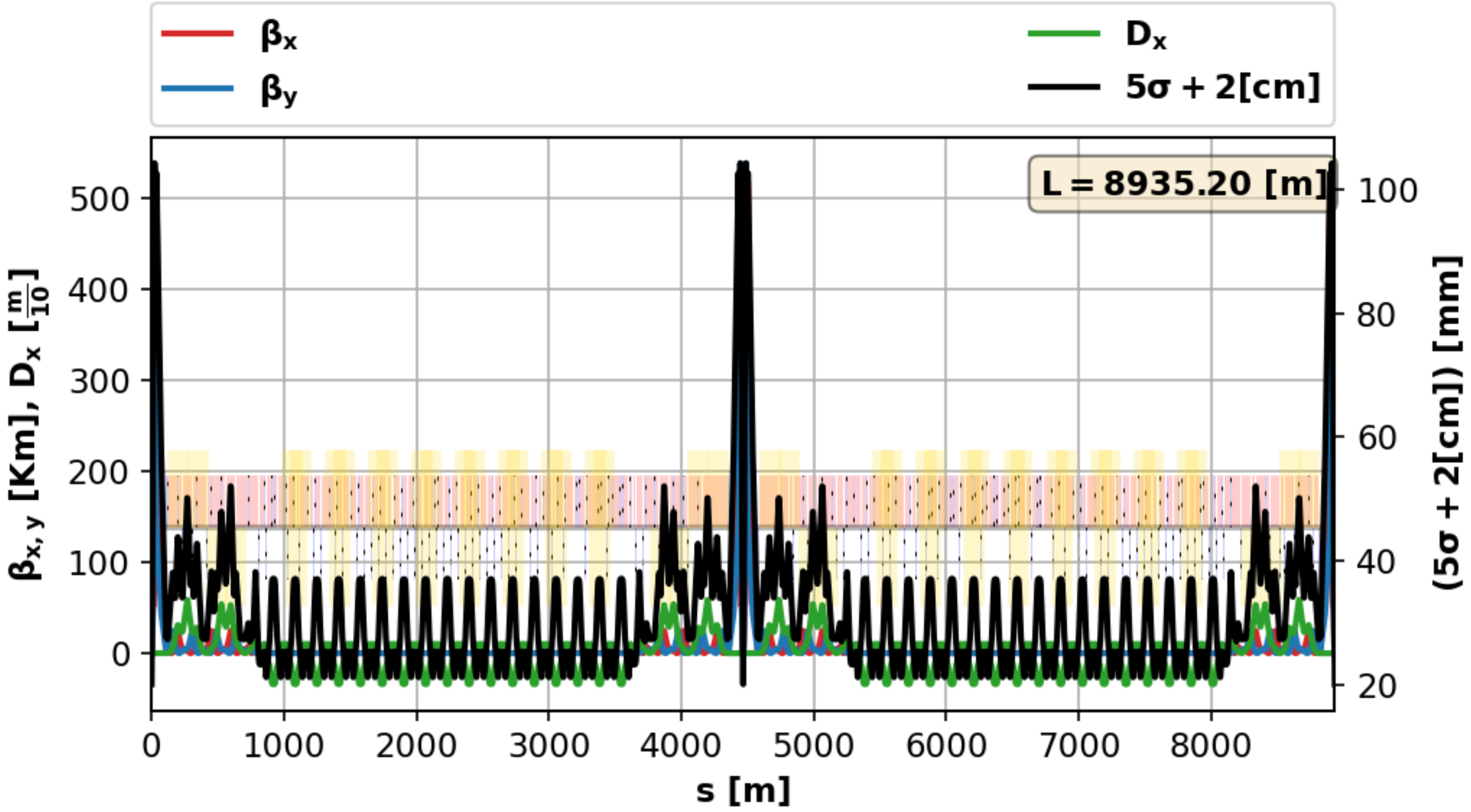


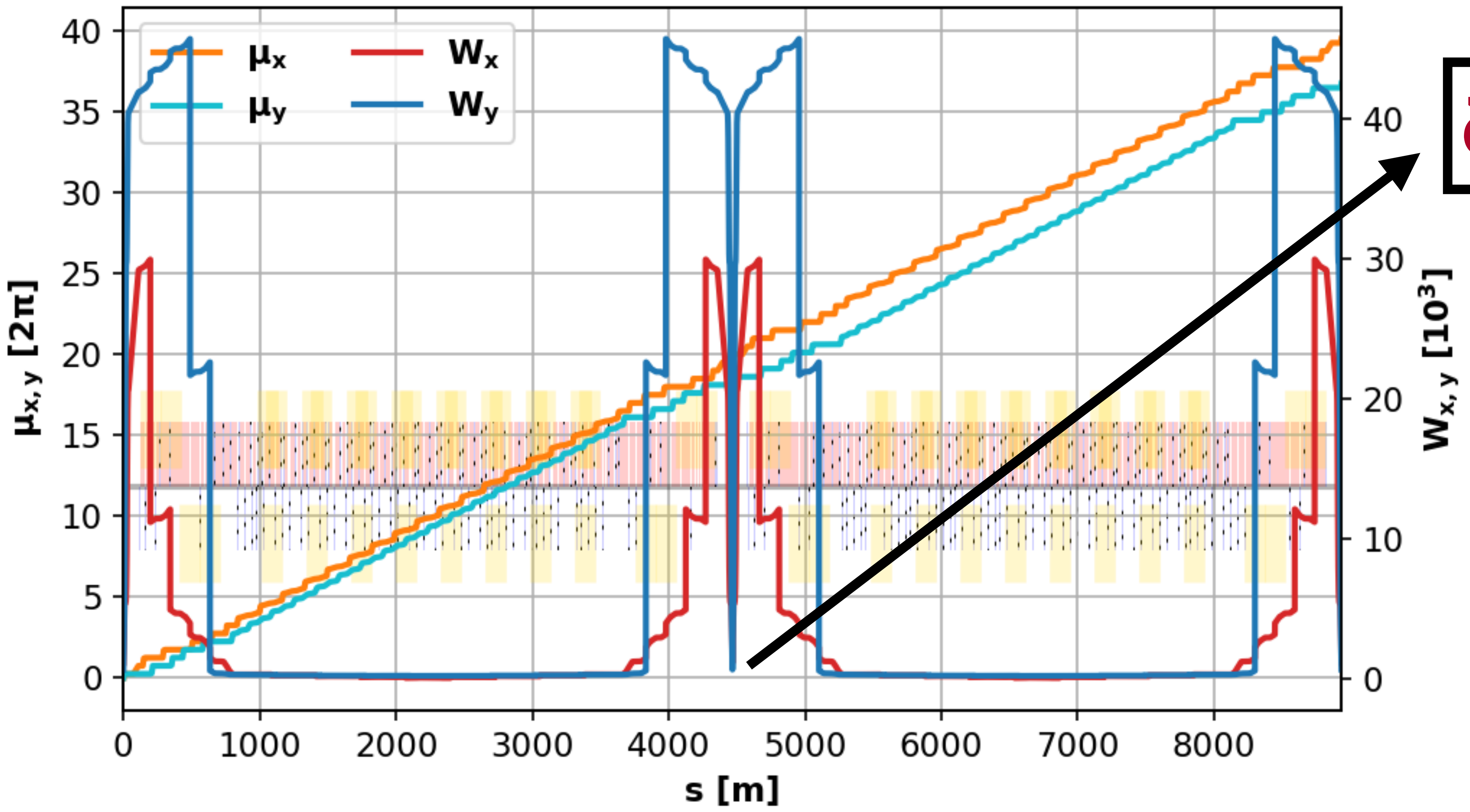


D_{nx}, $D_{npx} \neq 0$

$(D_x{*}\delta)^2 \simeq 4{*}(\varepsilon_g{*}\beta_x)$

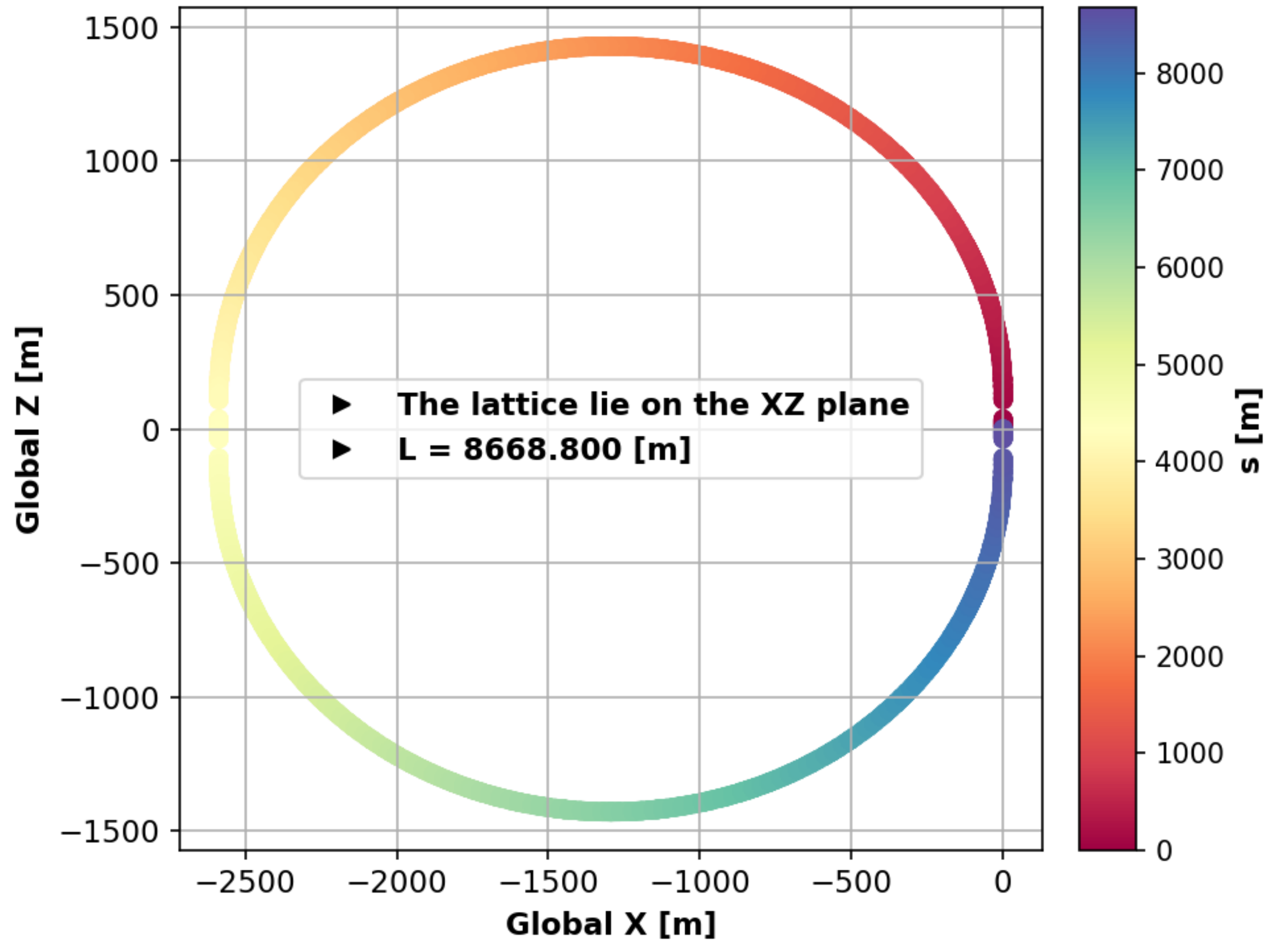
$\sigma_x \simeq \sqrt{5}\sigma_{\beta x}$

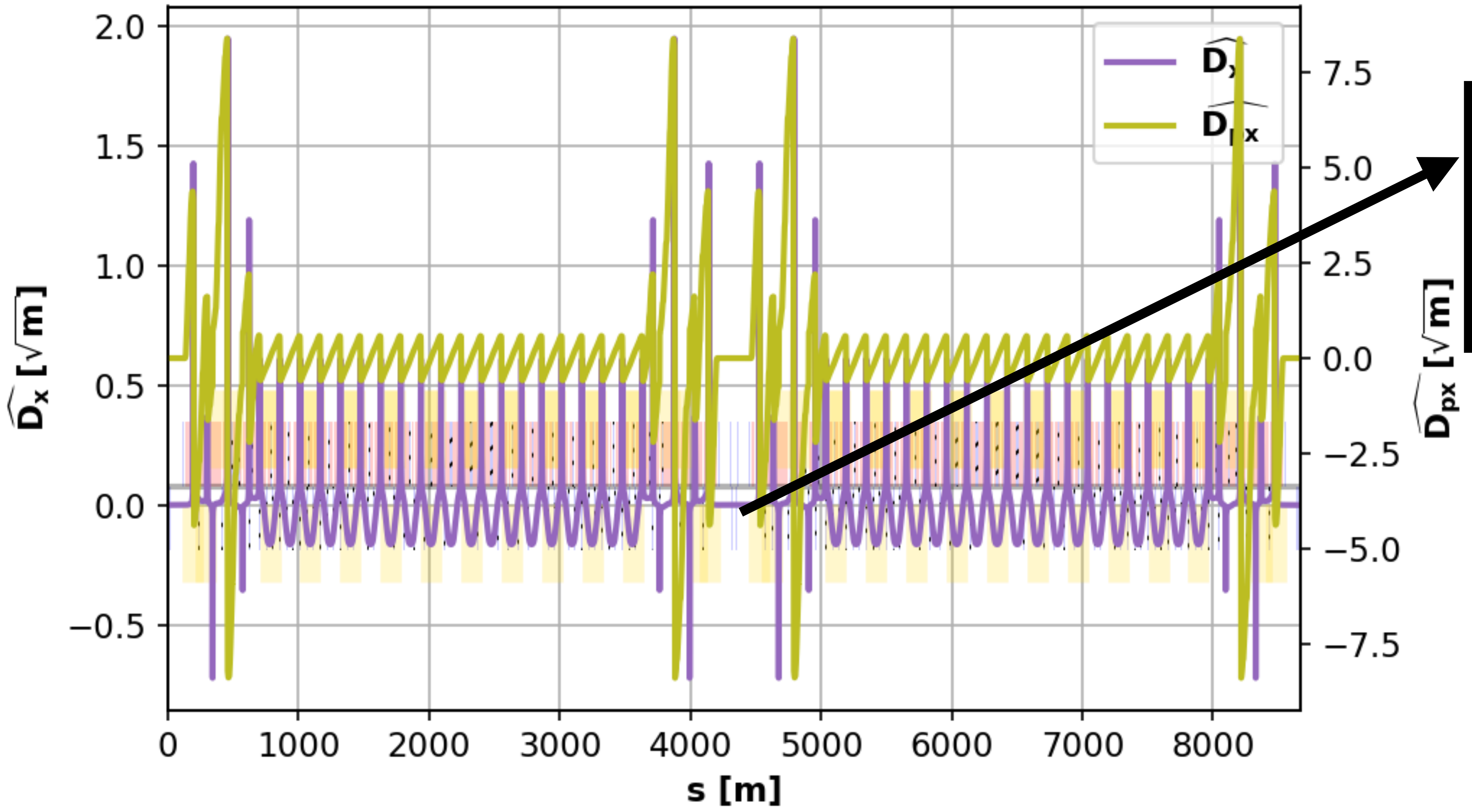




$\delta{*}W_{x,y} \simeq 1$

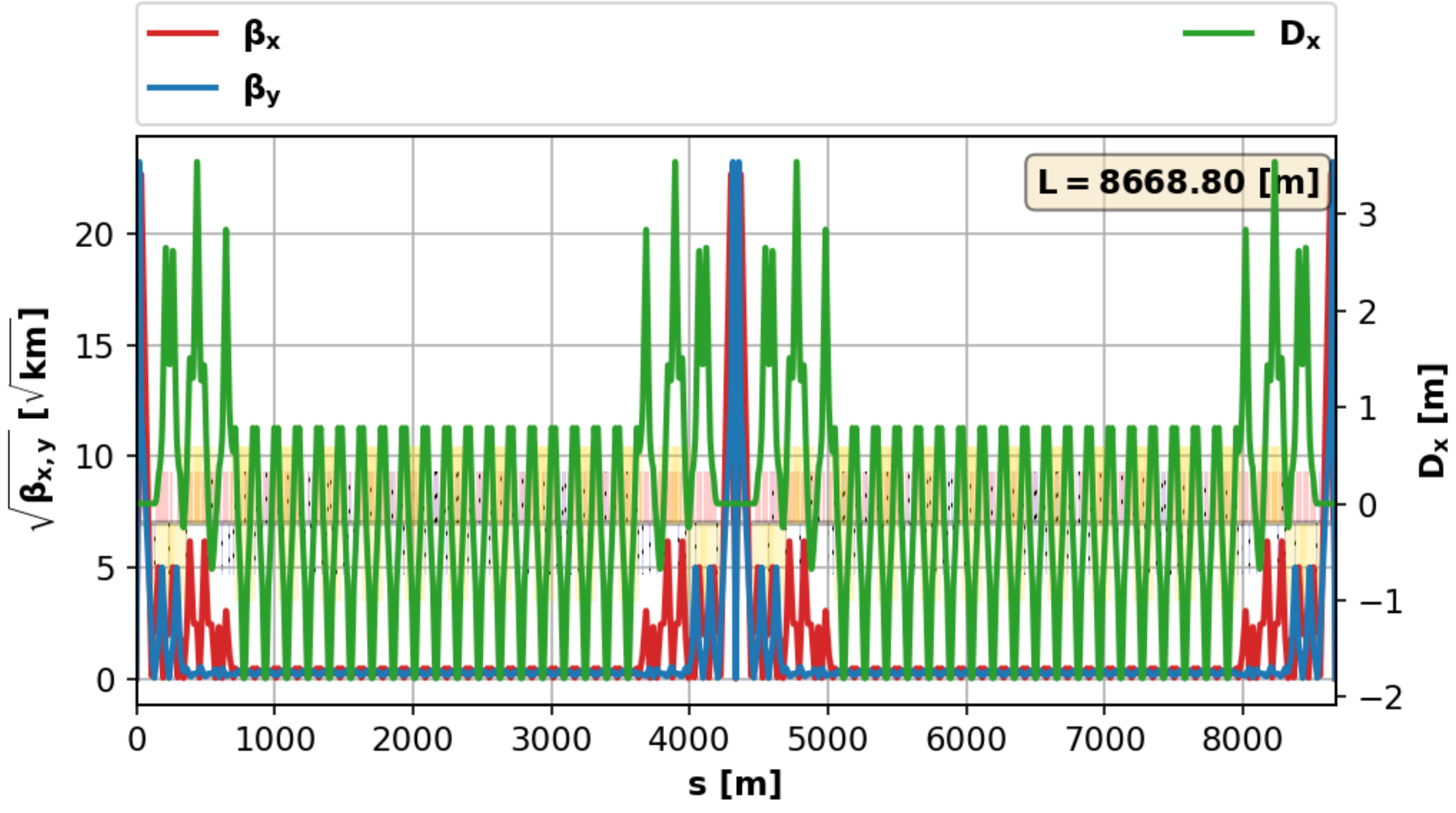
10TeV Muon Collider - Full Lattice

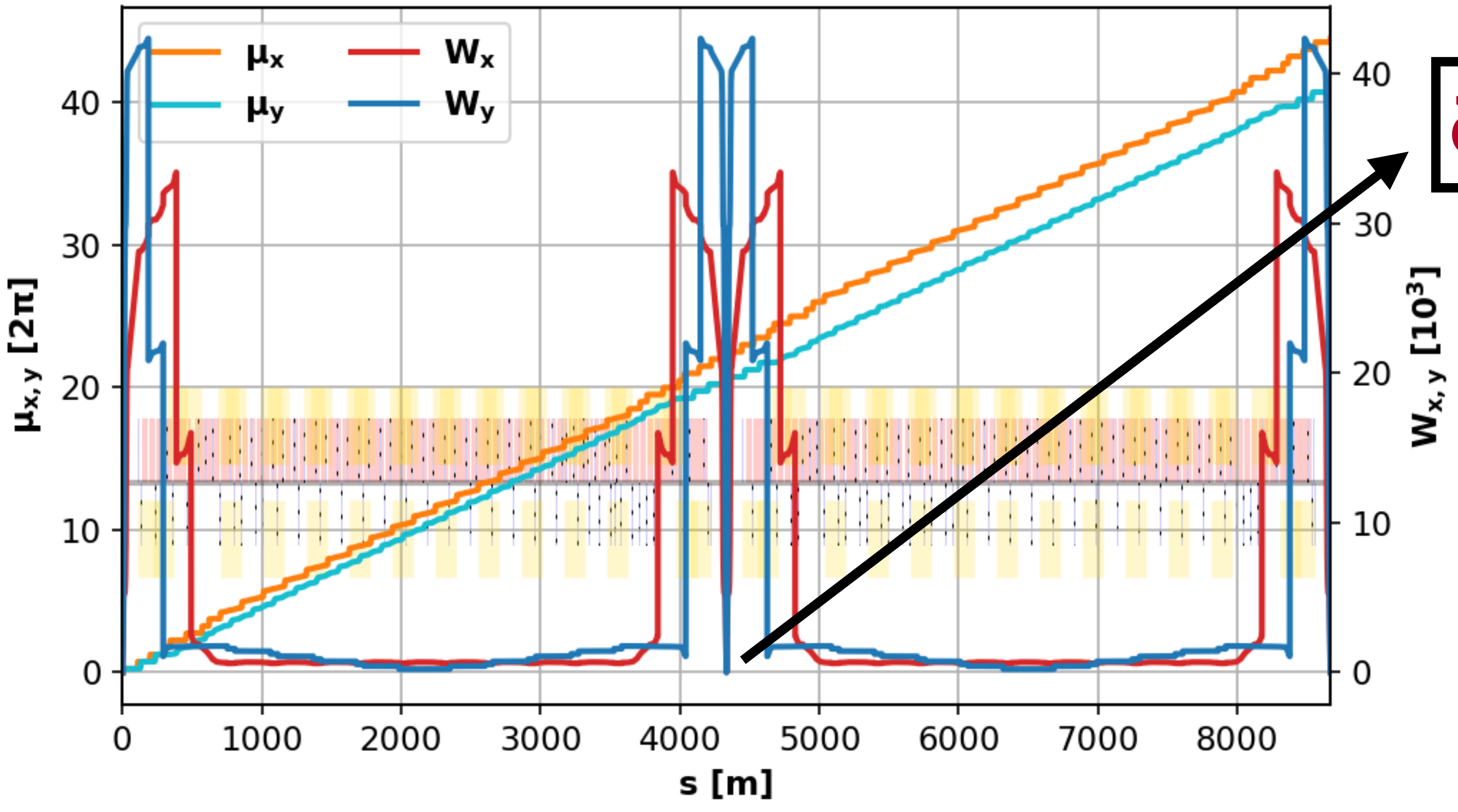




$D_{nx}, D_{npx} \sim 0$

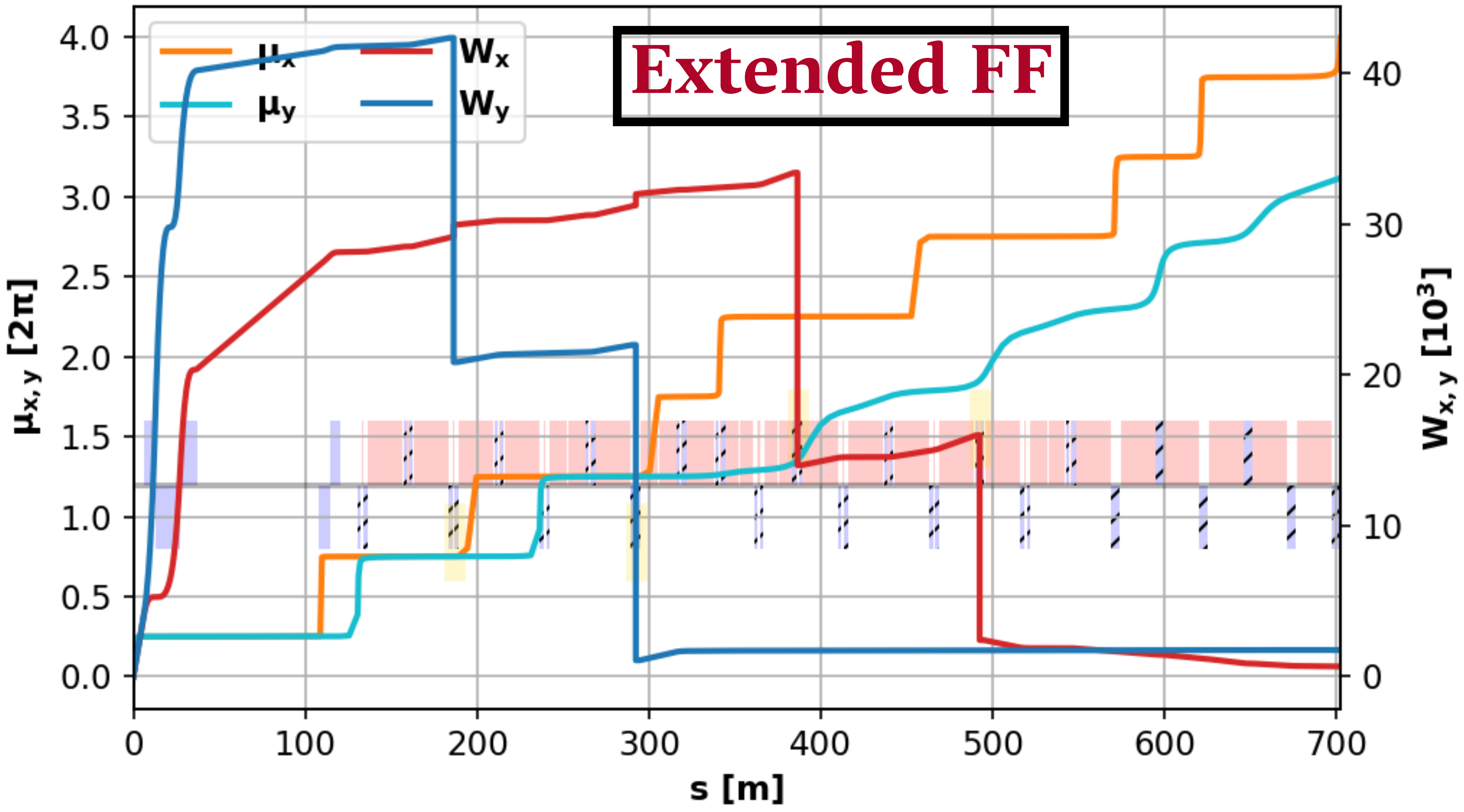
$\sigma_x \simeq \sigma_{\beta x}$

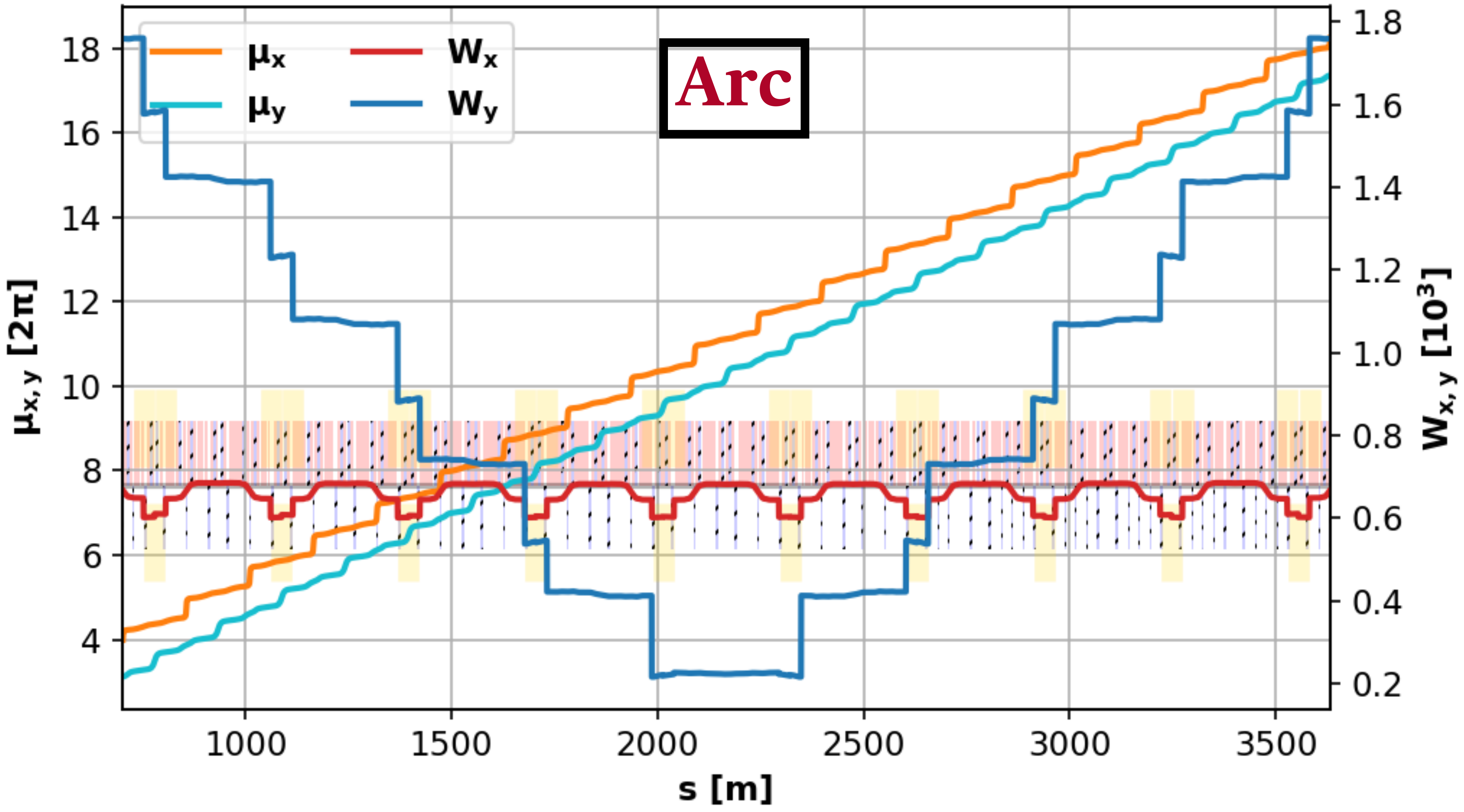




$\delta^* W_{x,y} \sim 0$

10TeV Muon Collider - Full Lattice





Match of linear chromaticity with arc dipole-sextuples.

↓

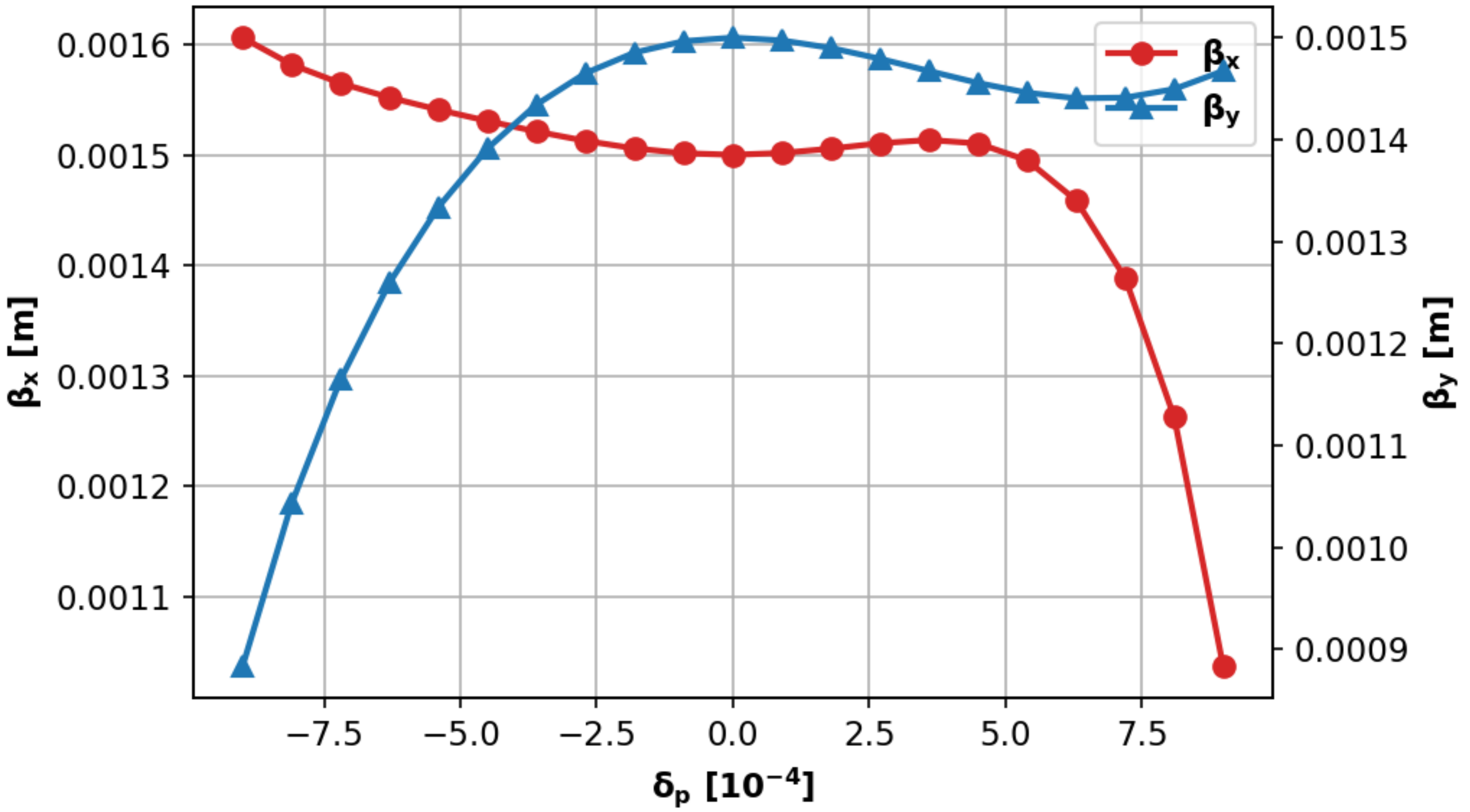
The $W_{x,y}$ at the IP are perturbed thus, the dipole-sextuples at the CC are know used to correct $W_{x,y}$ at IP.

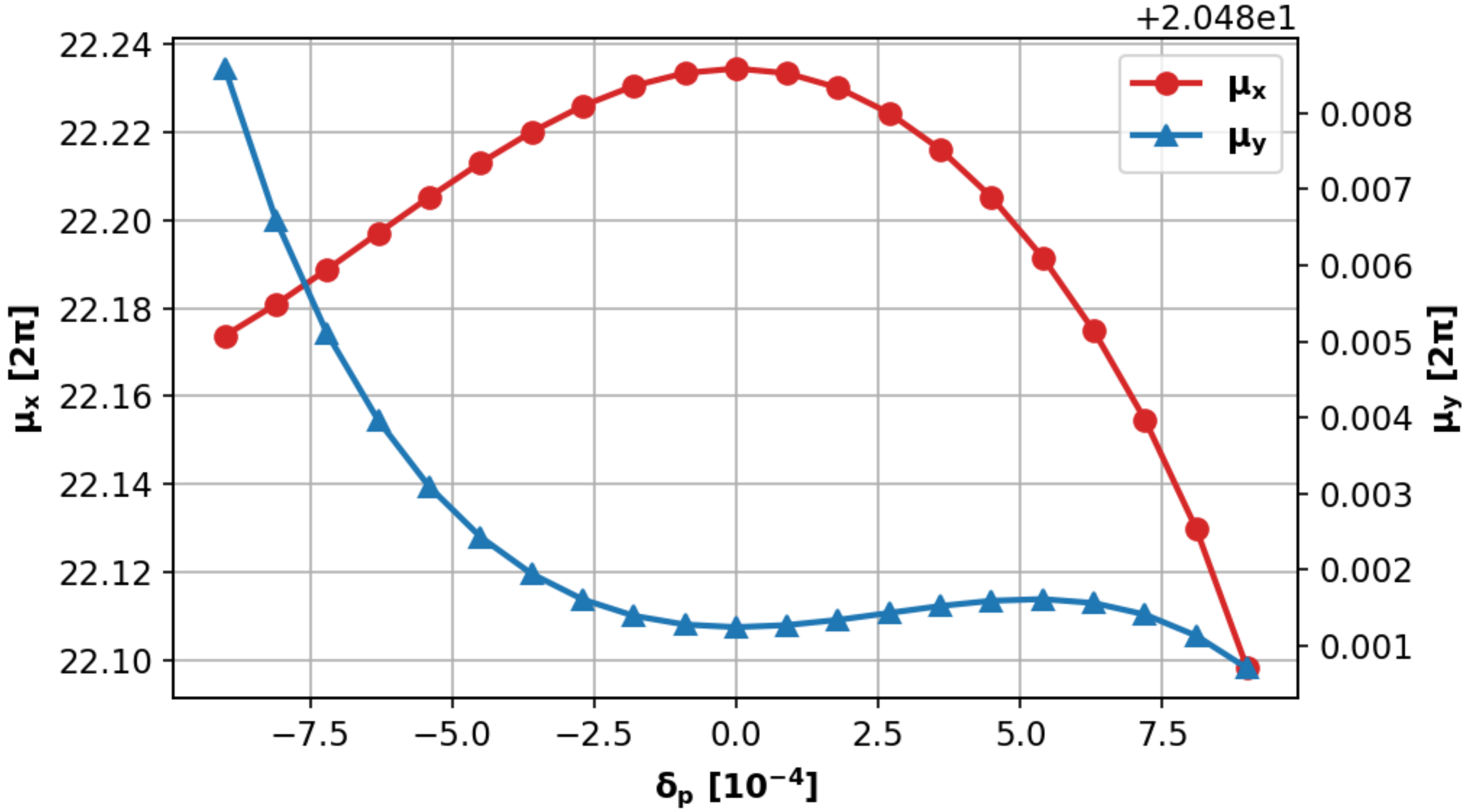
↓

The $W_{x,y}$ at the end of the EFF is not zero.

10TeV Muon Collider - Full Lattice

- In order to keep the $\beta^*_{x,y}$ unchanged for different δs, the μ_y from the IP to the 1st dipole-sextupole of the CC as well as the μ_x from the IP to the 3rd dipole-sextupole of the CC are controlled.

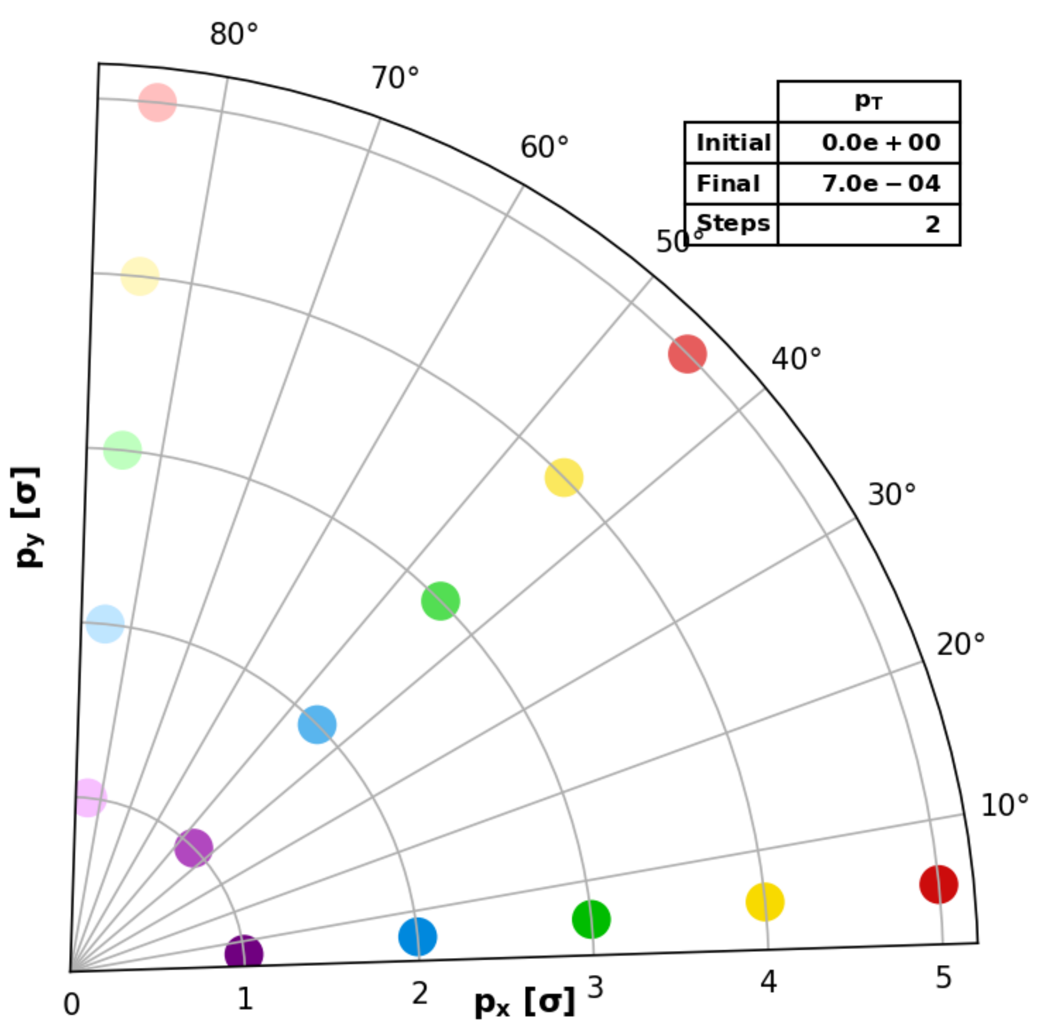


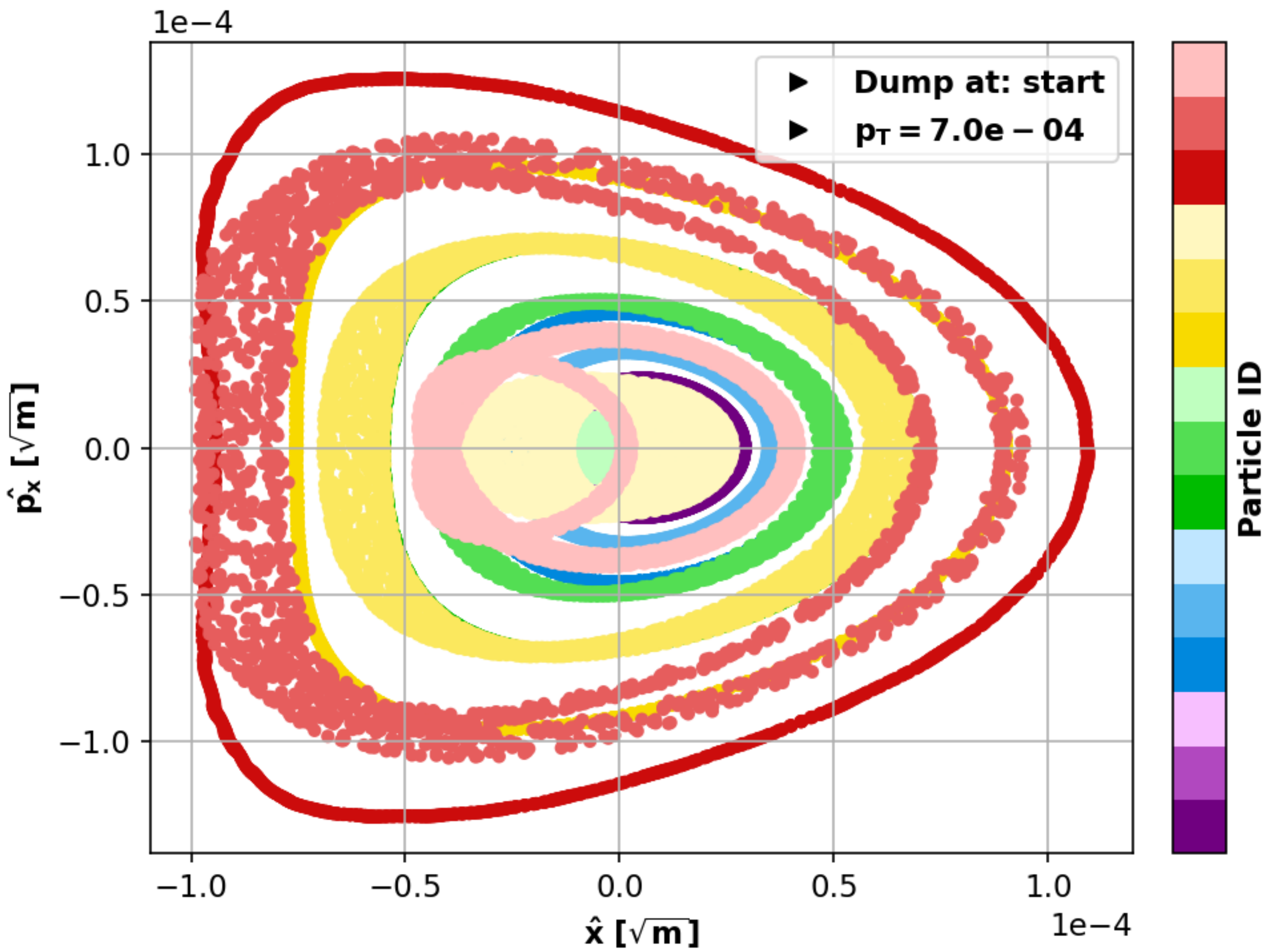


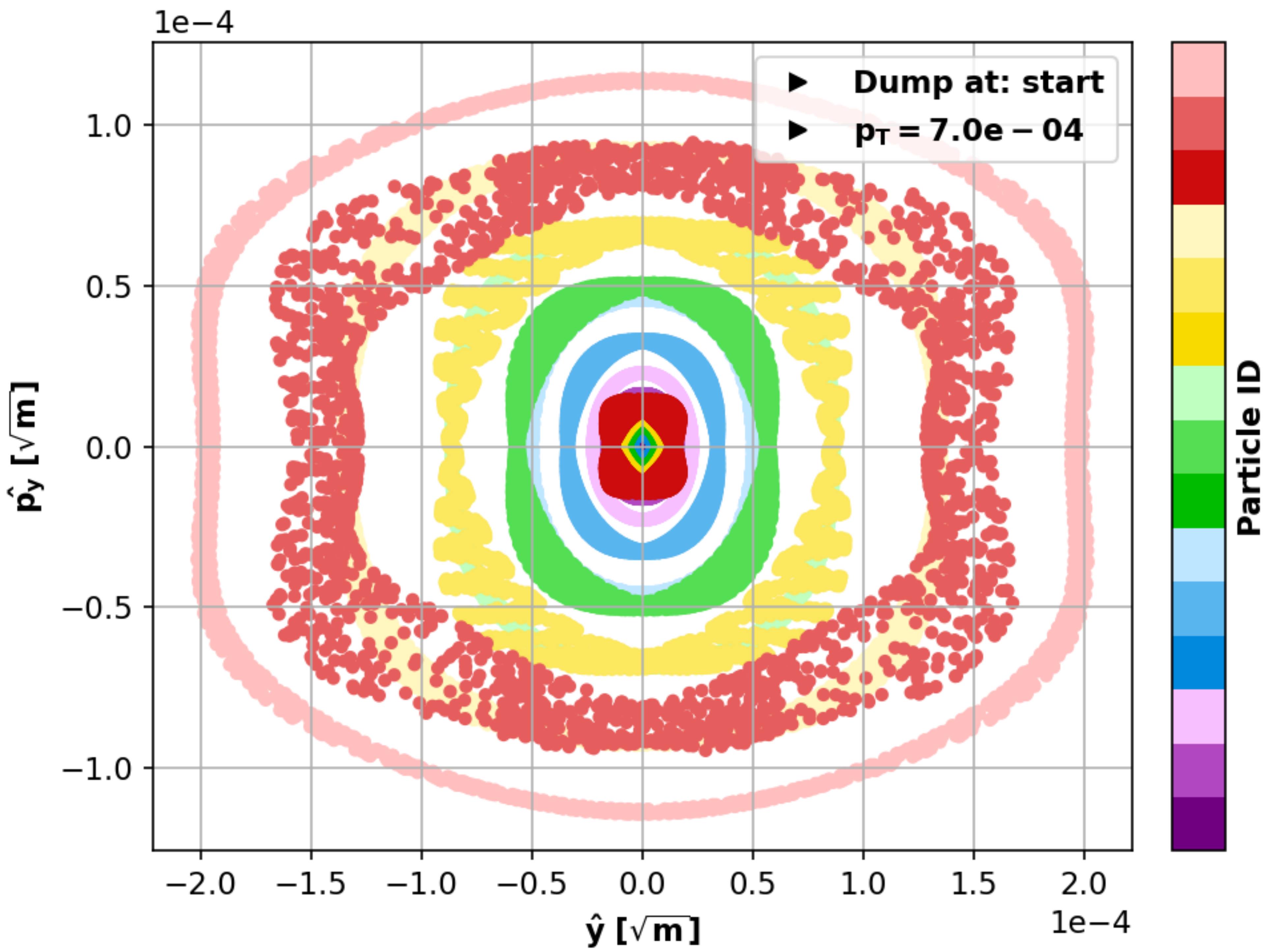
10TeV Muon Collider - Tracking Studies

- Off momentum transverse DA is significantly improved since earlier iterations (v0.4) and is getting closer to required performances.
- The working points obtained after putting all pieces together and is not very favourable (thus will be controlled in later versions).

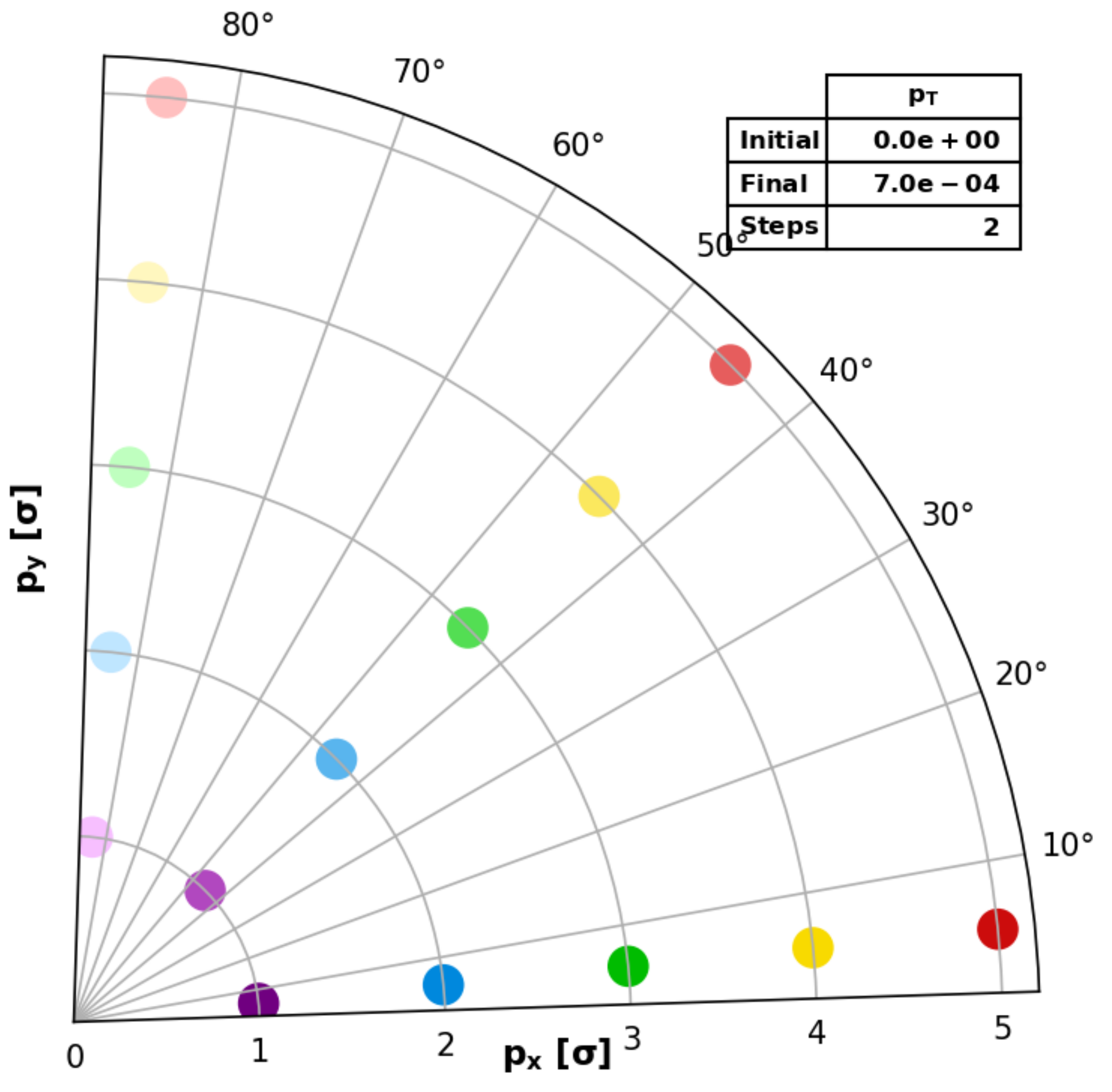
p_T [%]	DA_{min} [σ]
0.07	5
0.08	4
0.09	3
0.1	<1

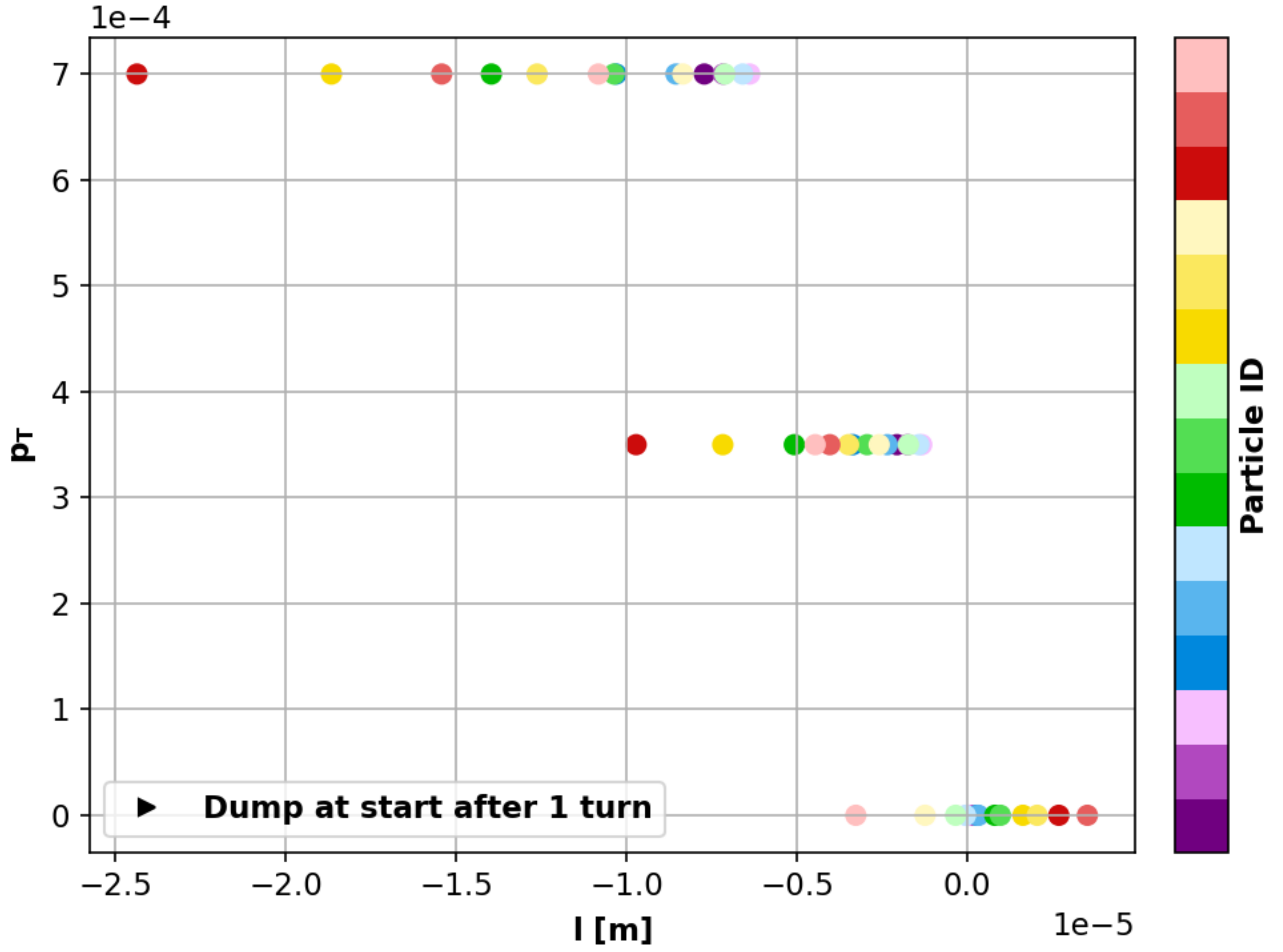






10TeV Muon Collider - Tracking Studies





Q_x=44.46902

ξ_x=0.02452

Q_y=40.96249

ξ_y=-0.57673

α_p=-1.97061e-07

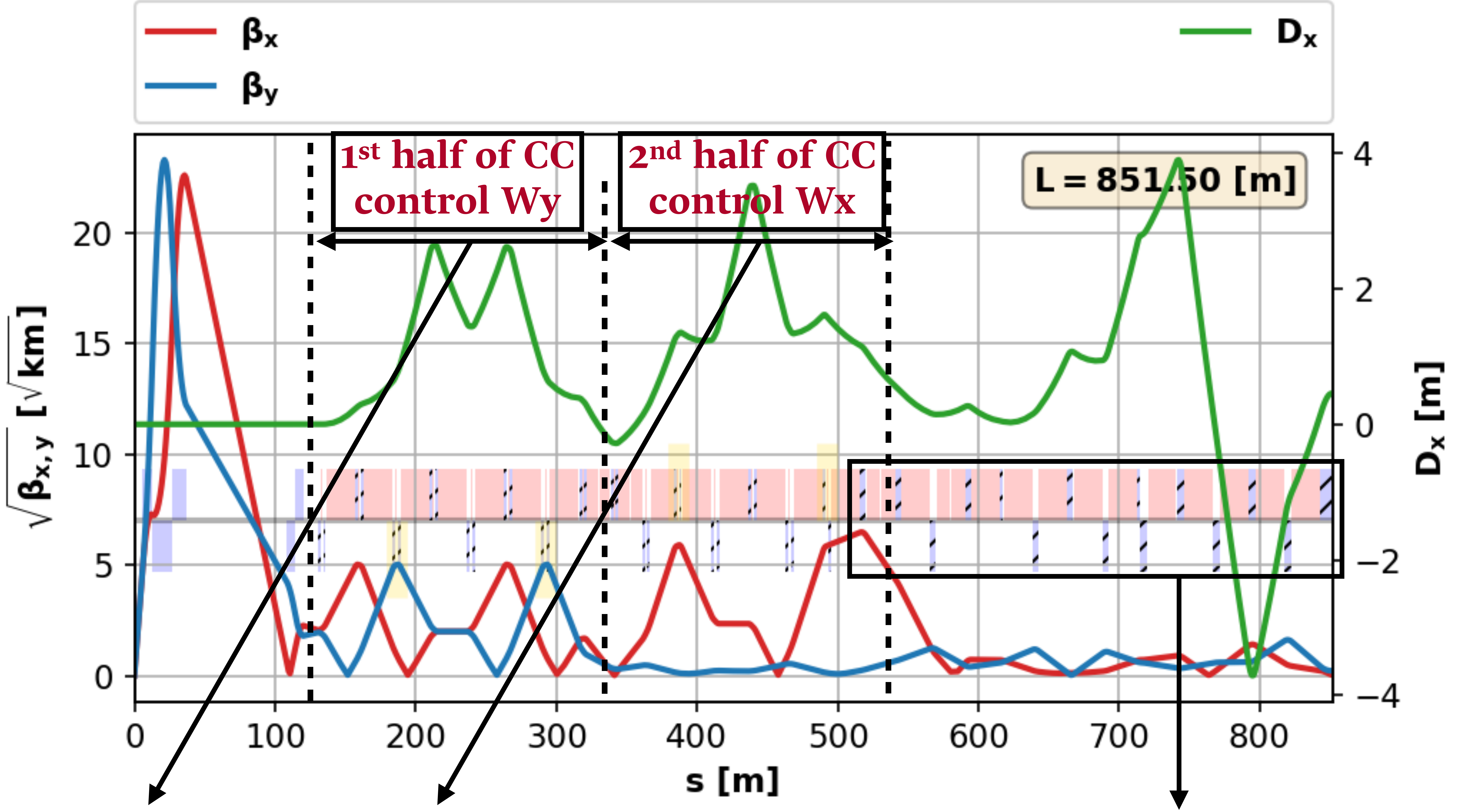
$$\frac{C}{C_0} = 1 + \alpha_p \delta_p + \alpha_p^{(2)} \delta_p^2 + \alpha_p^{(3)} \delta_p^3 + \cdots$$

C/C_o = 1 - 1.5e-5 / 8668.5 = 1 - 1.73e-9

$1+\alpha_p\delta_p$ = 1 - 1.97e-7 * 7e-4 = 1 - 1.38e-10

10TeV Muon Collider **v0.7**
(New design - work in progress)

10TeV Muon Collider - Extended Final Focusing Scheme



Compensate the energy aberrations of β^* with the 2 dipole-sextuple families and the phase advance from IP

Control of working point and matching section

Summary

- Minimisation of the areas without dipolar components in order to evenly distribute the muon decay products (mostly the neutrino flux) and to minimise the collider length.
- Extensive use of combined function magnets (dipole-quadrupole, dipole- sextupole, etc) with independent control of their multipolar components.
- The Extended Final Focusing section controls the Montague chromatic functions, the optics matching with the arc ones and the optics aberrations at the IP.
- Arc design with Flexible Momentum Compaction cells that control the momentum compaction factor, the linear chromaticity and the 2π closing of the trajectory with independent knobs.
- After several iterations, momentum acceptance significantly increased and now is of the same order of magnitude than the required one.
- Precise adjustment of betatron phases at location of CC sextupoles is improved.

To be addressed

- Control the working point.
- Better control of the optics aberrations at the IP and in the arcs.
- Improve the DA.
- Compensate additional BIB generated by the longer FFQ section ?
- Estimation of key parameters as well their tolerances for the:
  - minimum aperture
  - maximum allowed magnetic fields
  - beam-beam effects
  - ...

Thank you for your time!

All the **presented studies** are **work in progress** thus, any input is very welcome.

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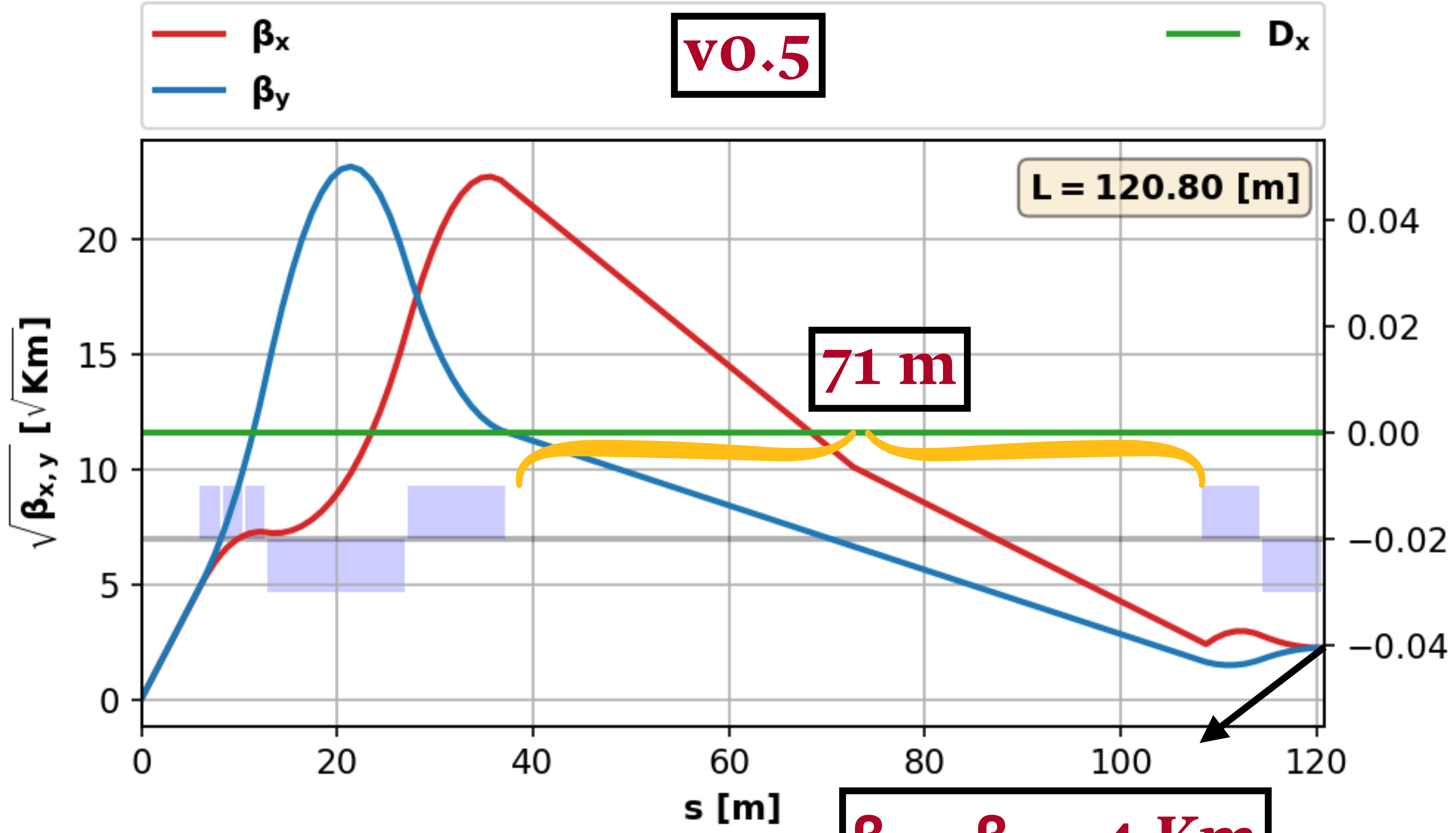
Backup

10TeV Muon Collider - Earlier Final Focusing Schemes



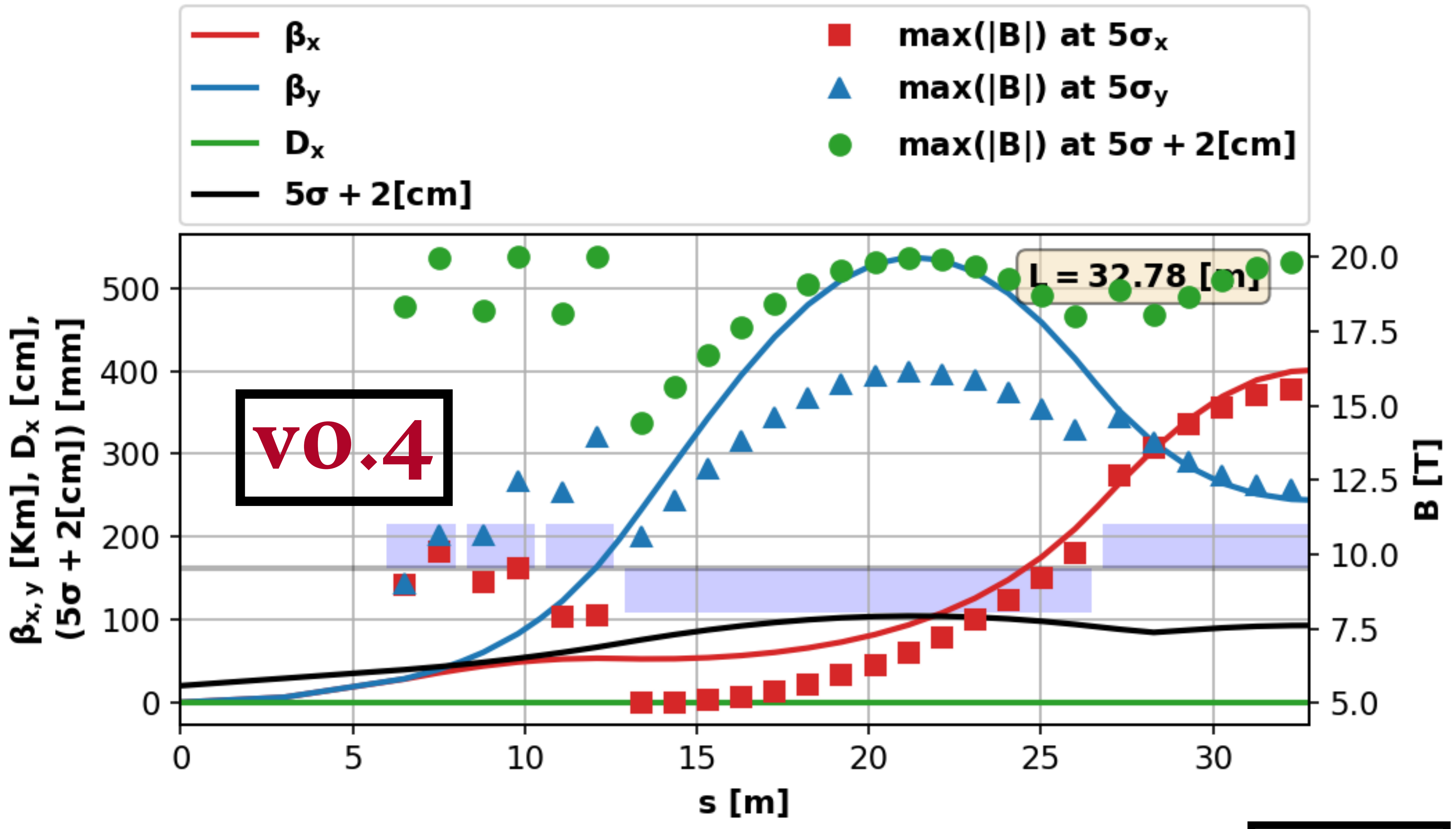
$\beta_x = \beta_y \sim 4$ Km

$$B\rho = 16678.205\ [Tm]$$

$$Aperture = 2(5\sigma + 0.02)\ [m]$$

$$\sigma_j = \sqrt{\frac{\beta_j \varepsilon_{nj}}{\beta_r \gamma_r} + (D_j \delta_p)^2}\ [m]\ with\ j = x, y$$

$$\sigma = max(\sigma_x, \sigma_y)\ [m]$$

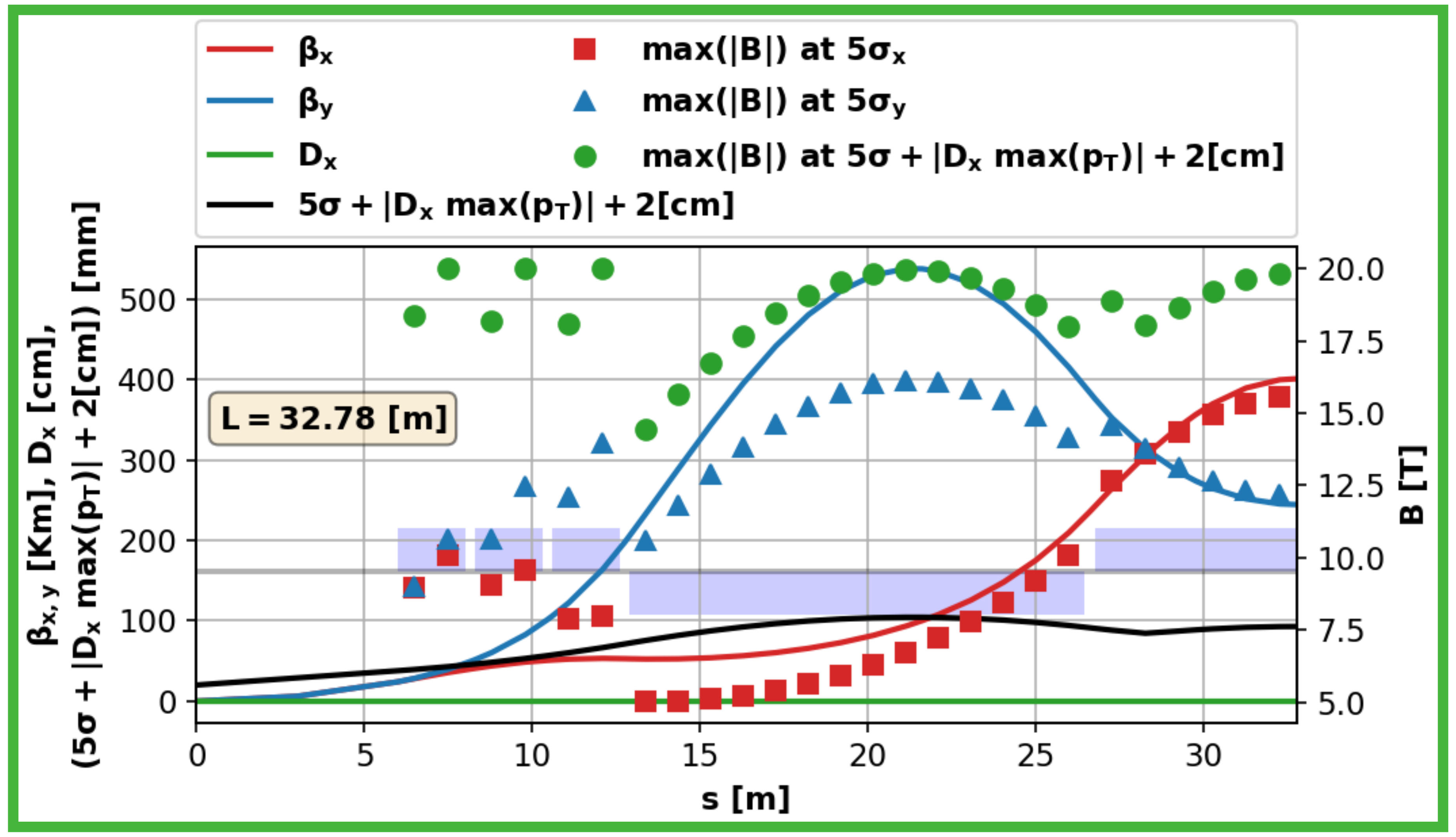


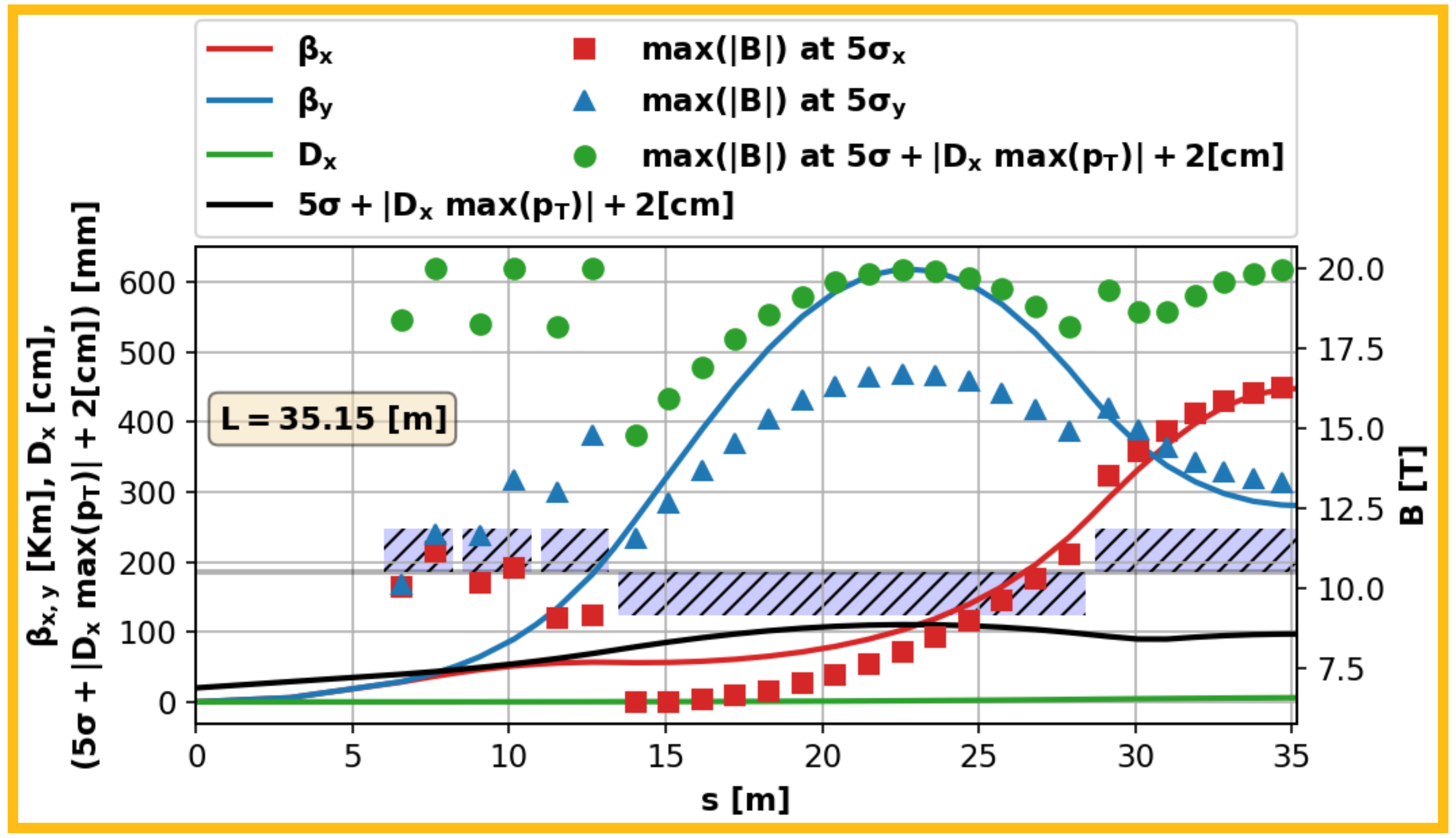
Entering the CC with small βs resulted in:

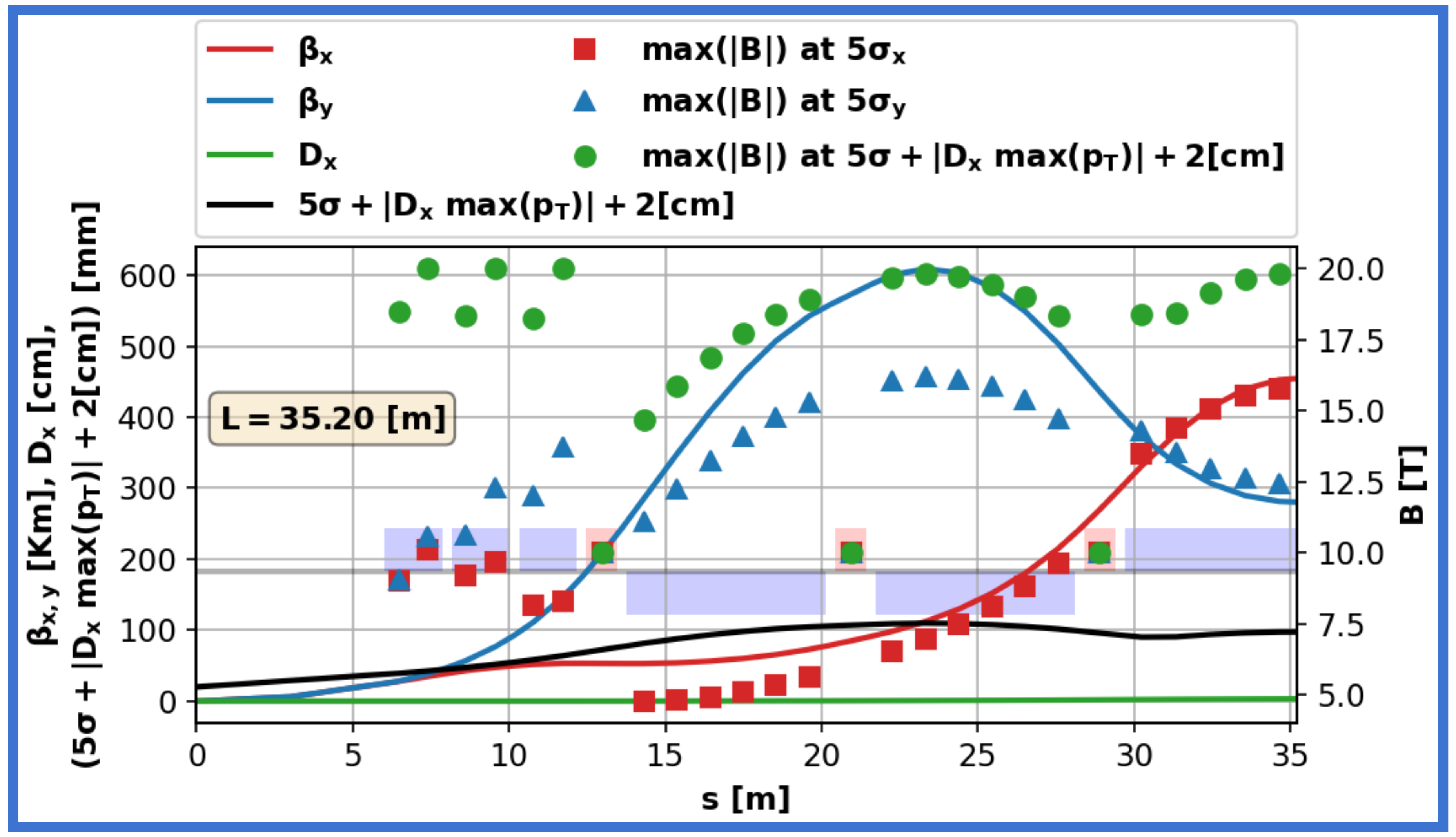
- Smaller aperture
- Smaller Ws
- Less impact from unwanted multipolar components
- Easier control of βs

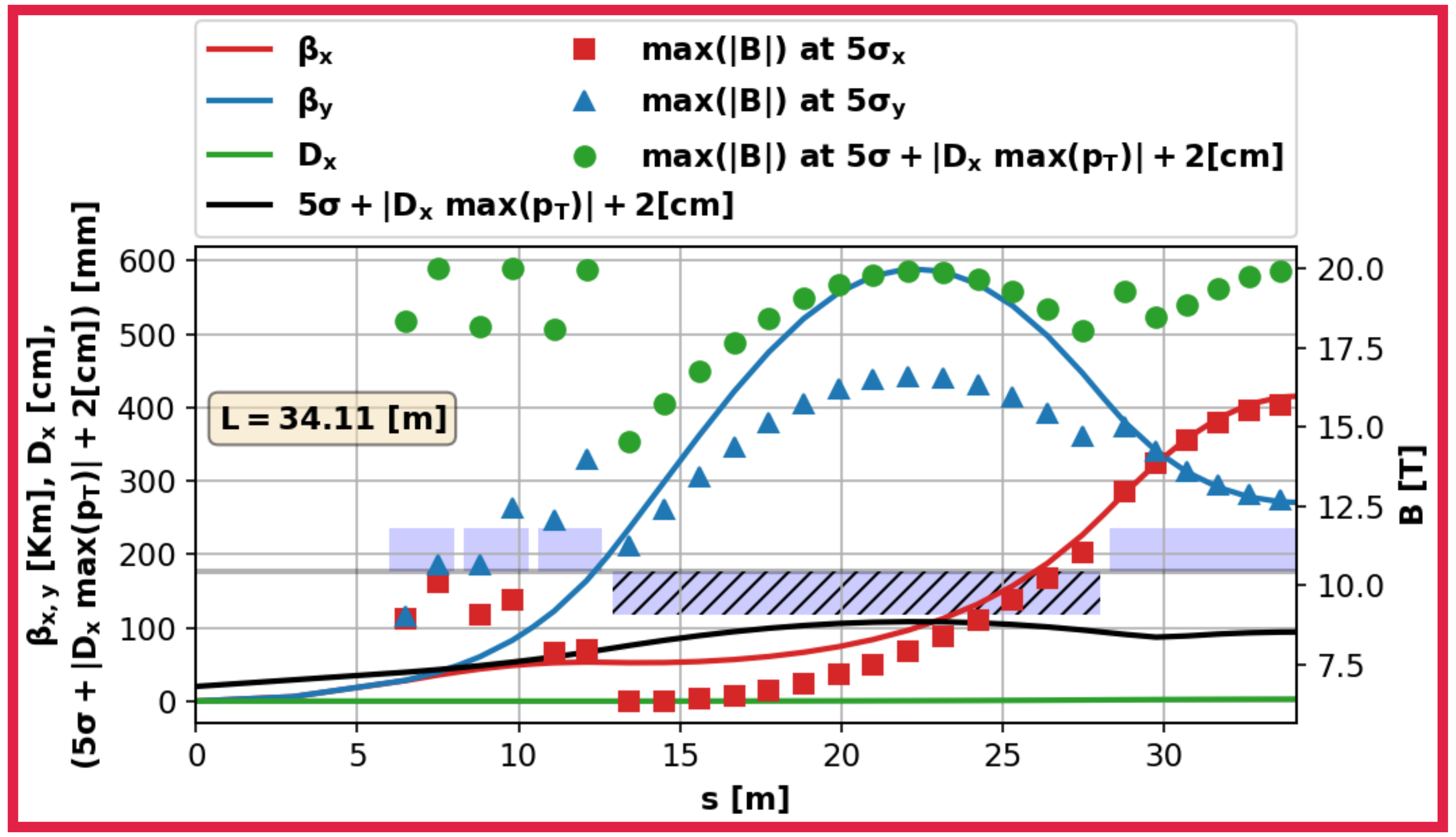
10TeV Muon Collider - Final Focusing Scheme v0.4

Due to muon decay along the interaction region, the Beam Induced Background (BIB) at the detectors area is significant thus in collaboration with the FLUKA team, the impact on BIB from the addition of dipolar components in the FF scheme is studied.









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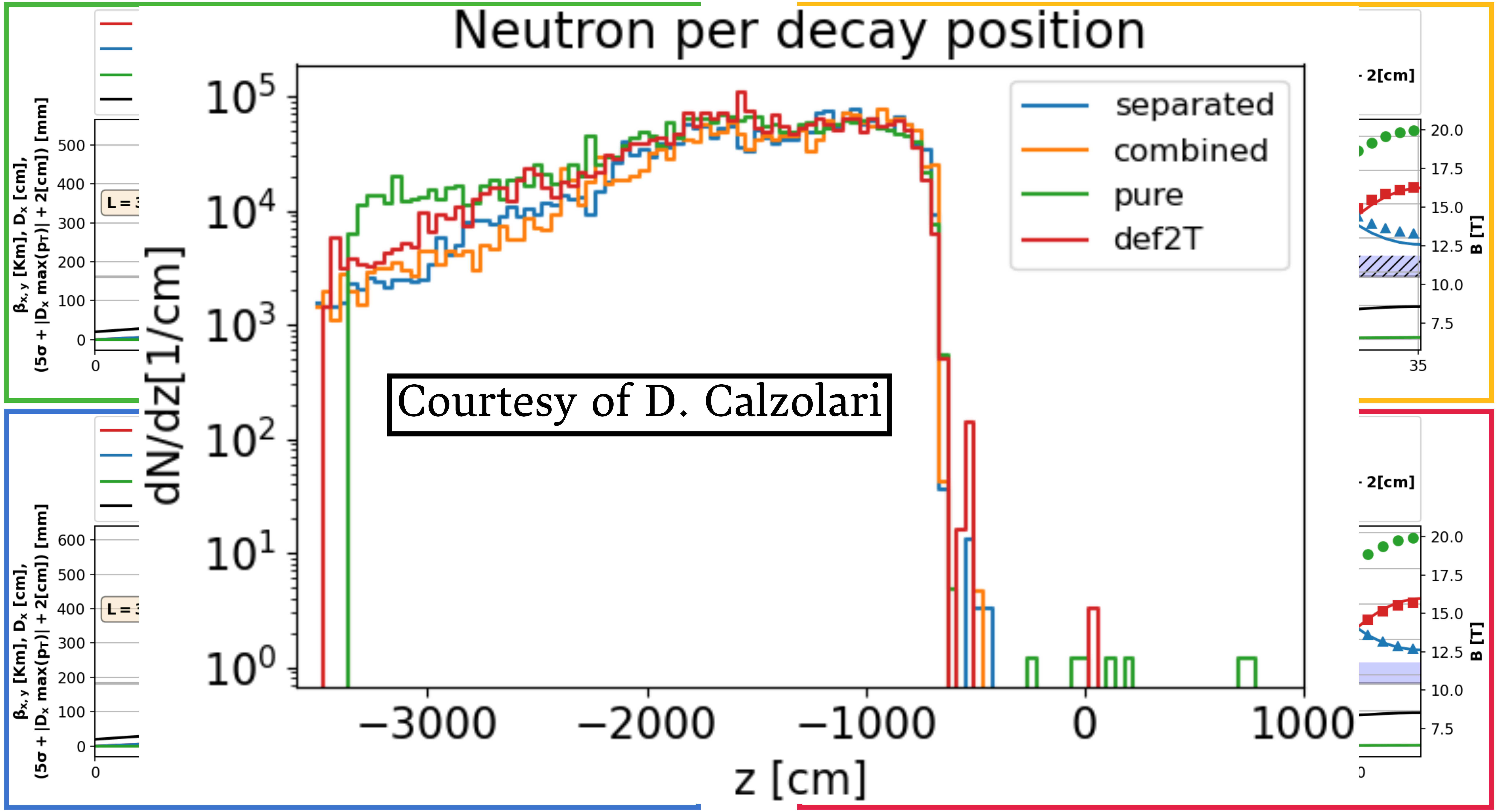
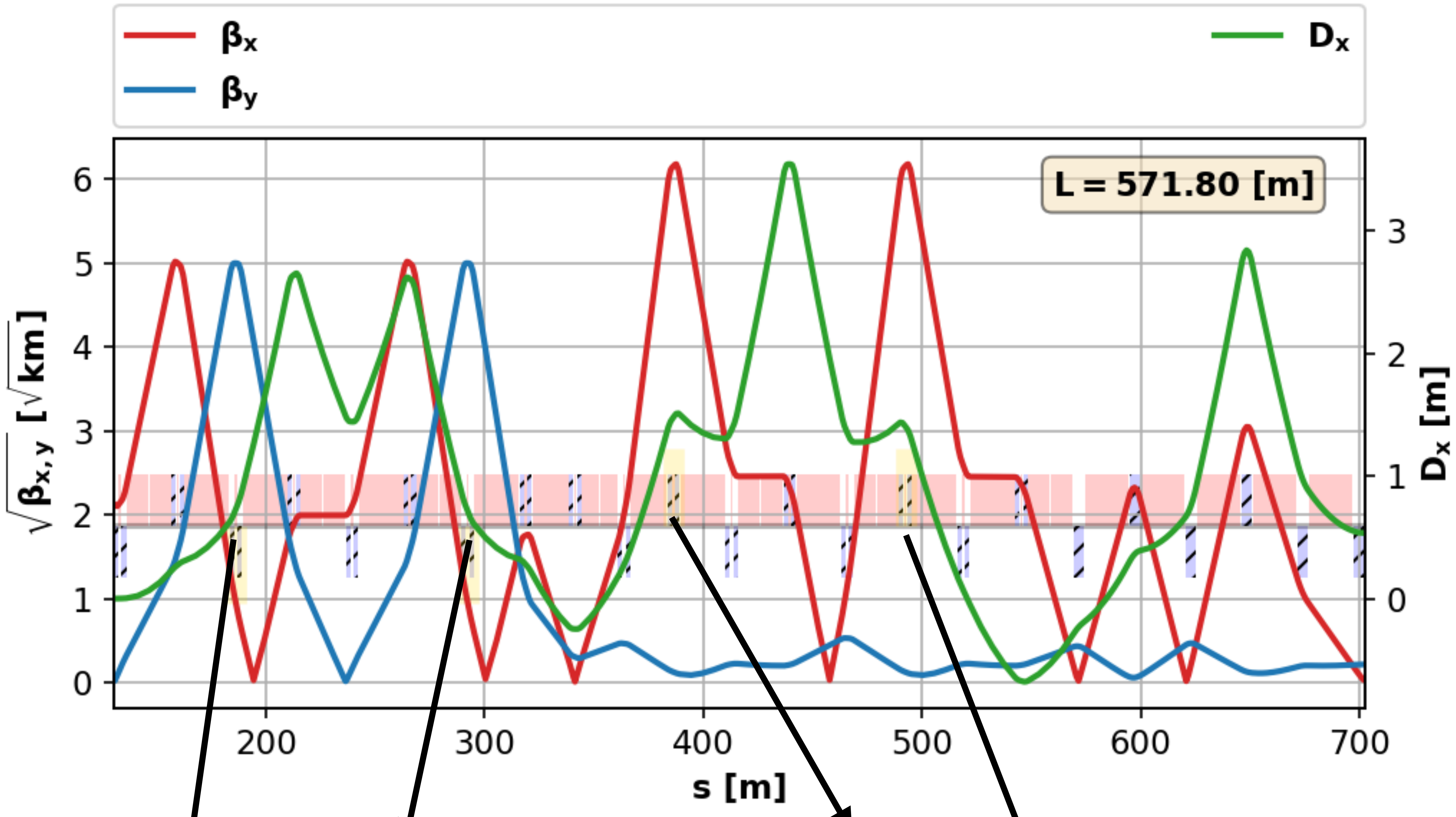
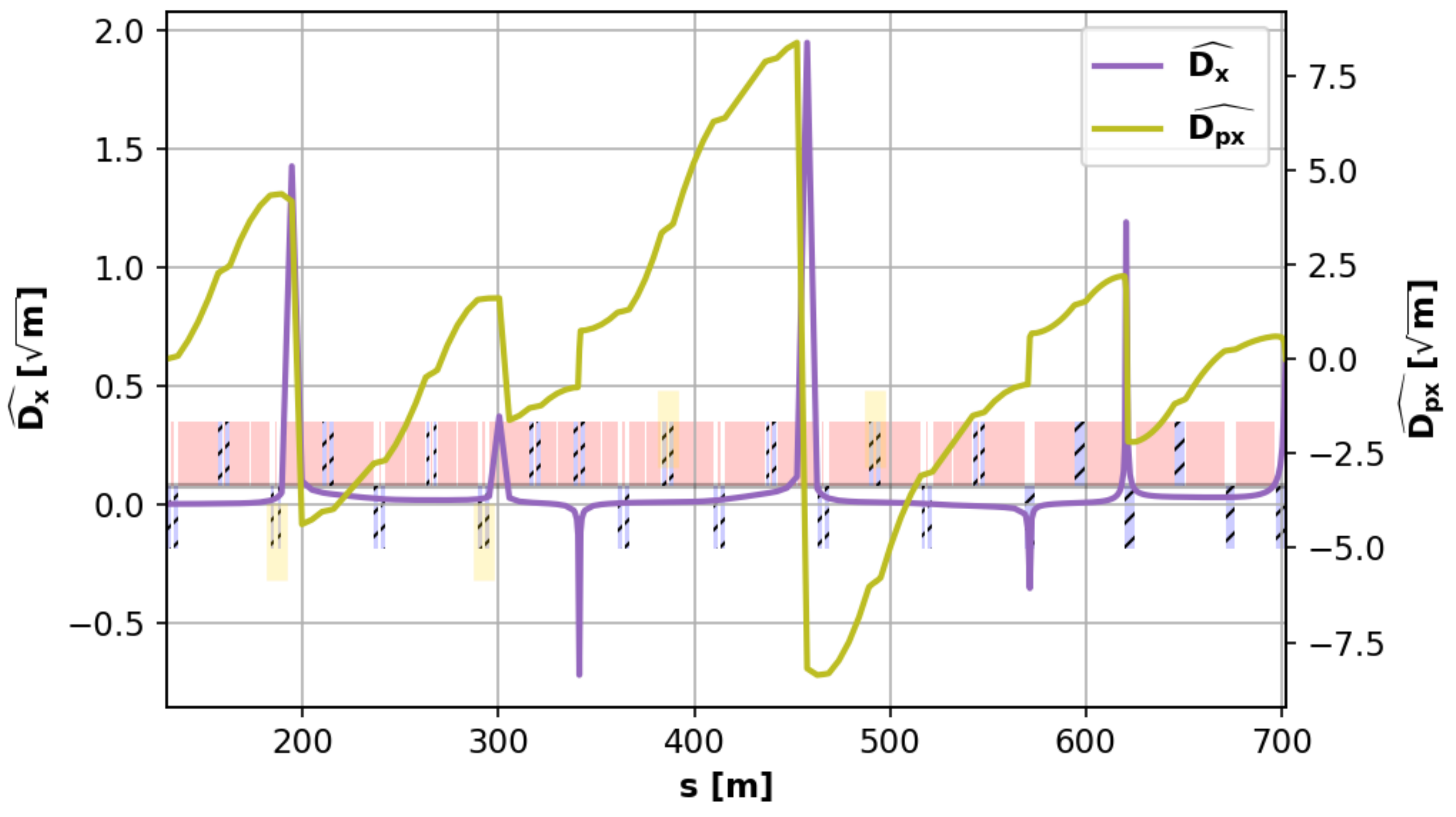


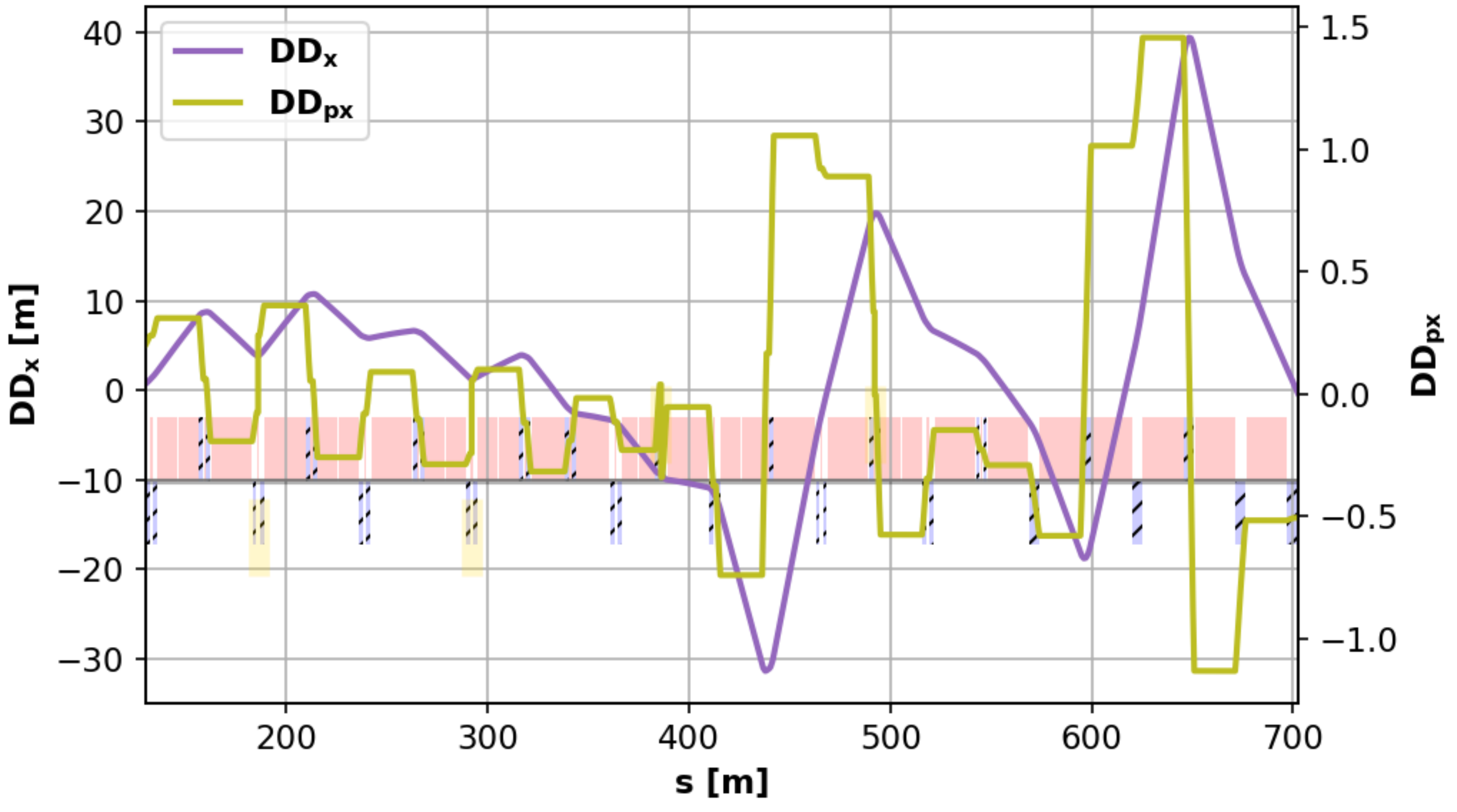
10TeV Muon Collider - Chromatic Correction & Matching Schemes



1st DS doublet for W_y
Large D_x, β_y and small β_x

2nd DS doublet for W_x
Large D_x, β_x and small β_y

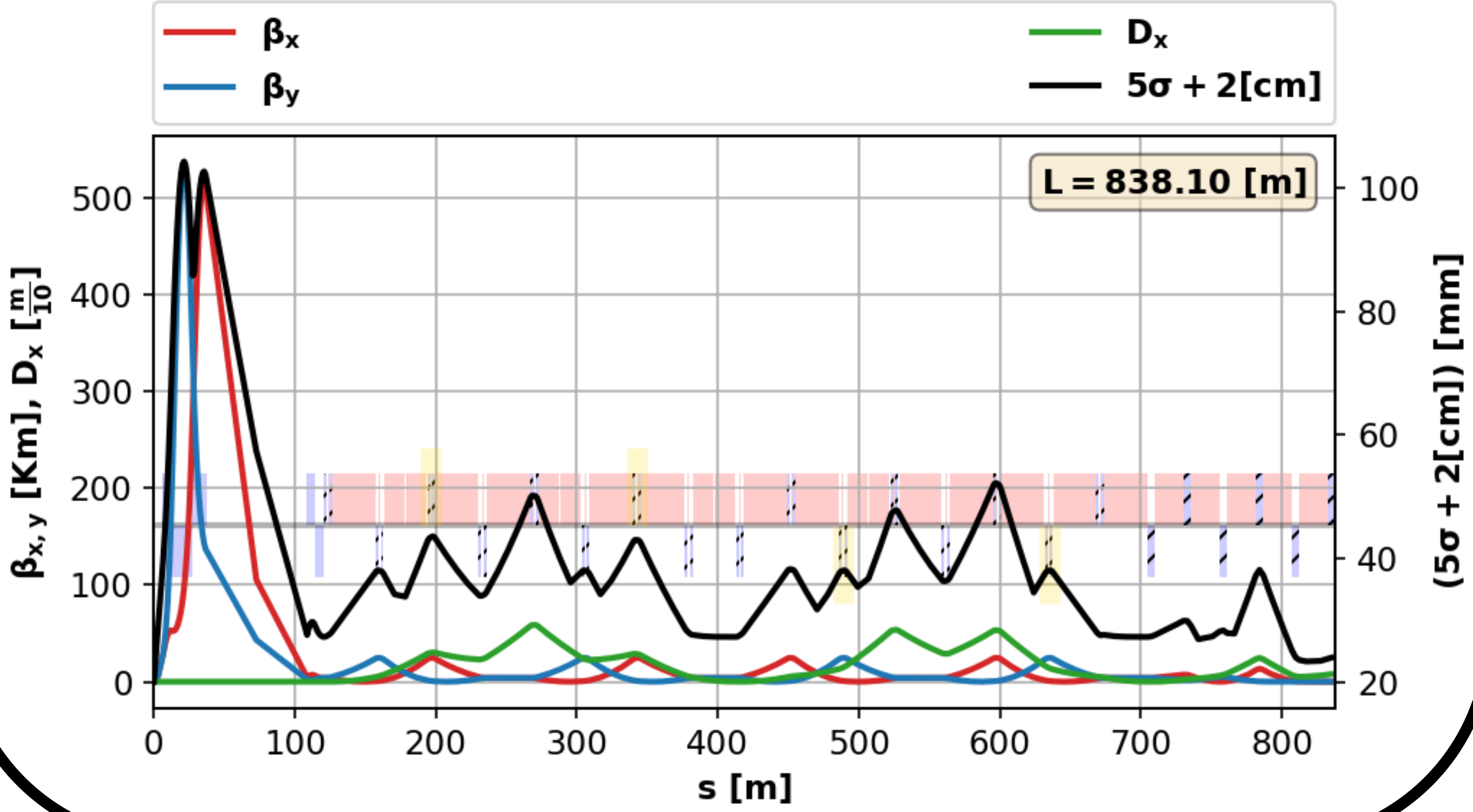




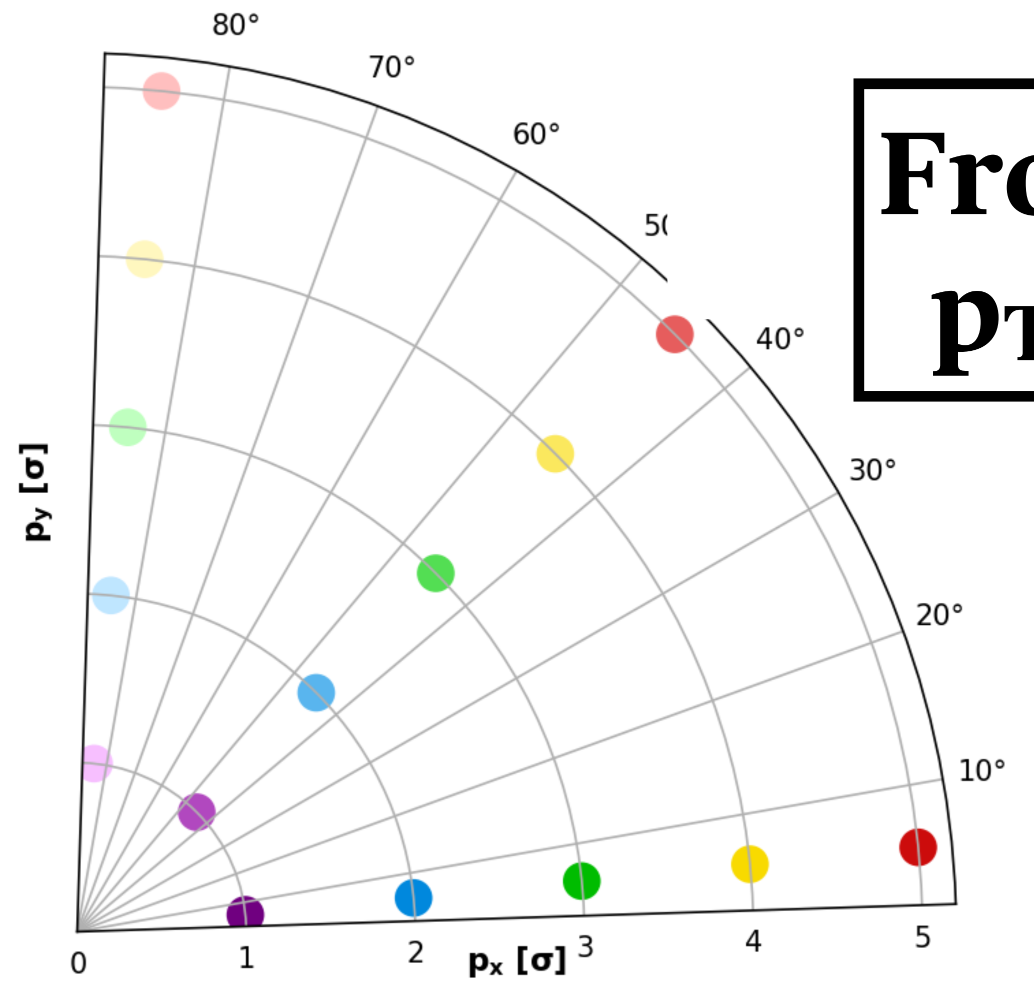
10TeV Muon Collider - Extended Final Focusing

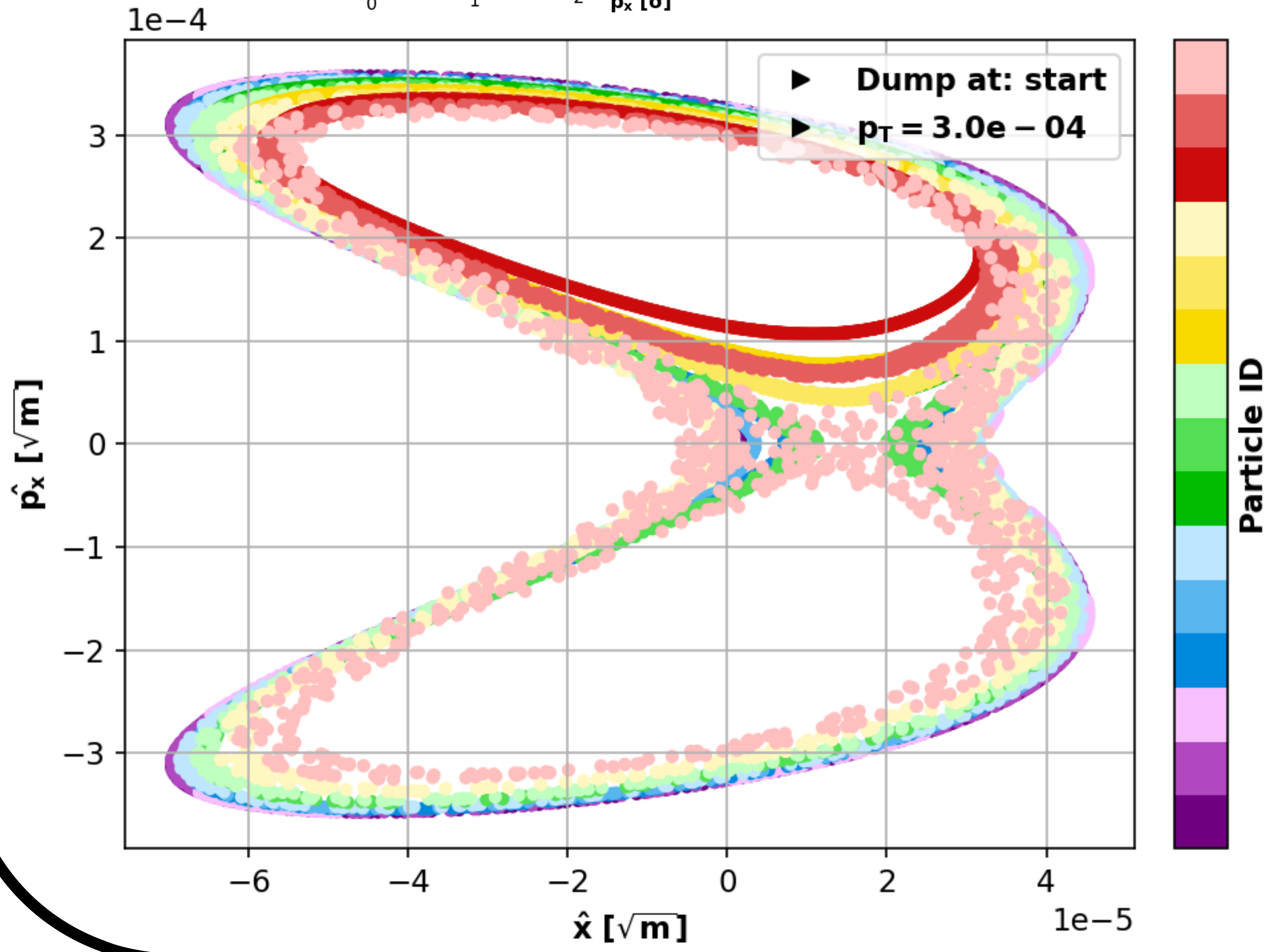
v0.5

- 2 doublets of dipole-sextuples
- use of -I transform between sextupoles of a given doublet
- 1m long dipole-sextupole with dipolar components larger than 4T



From 1 to 5σ
p_T = 0.03%

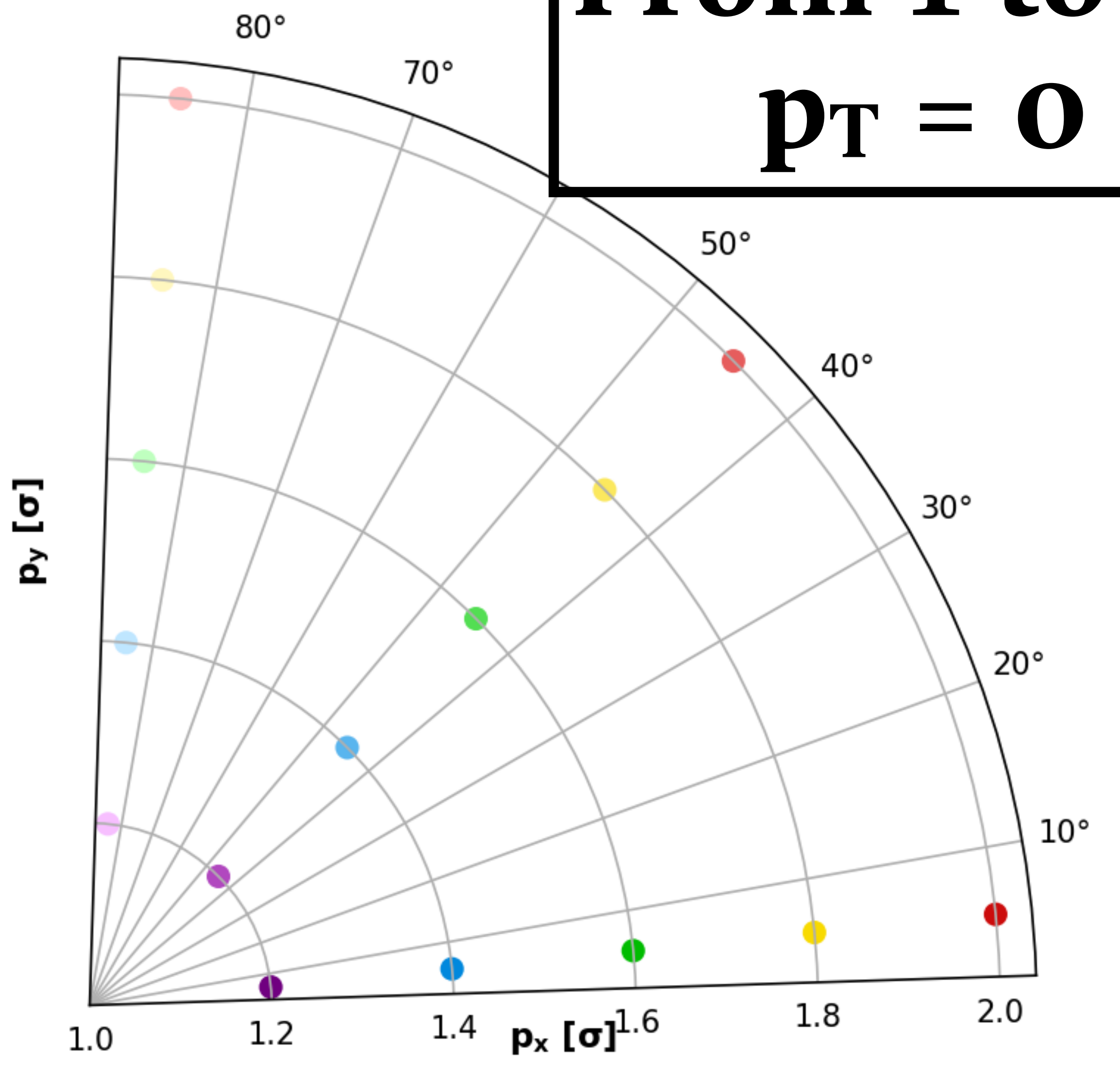


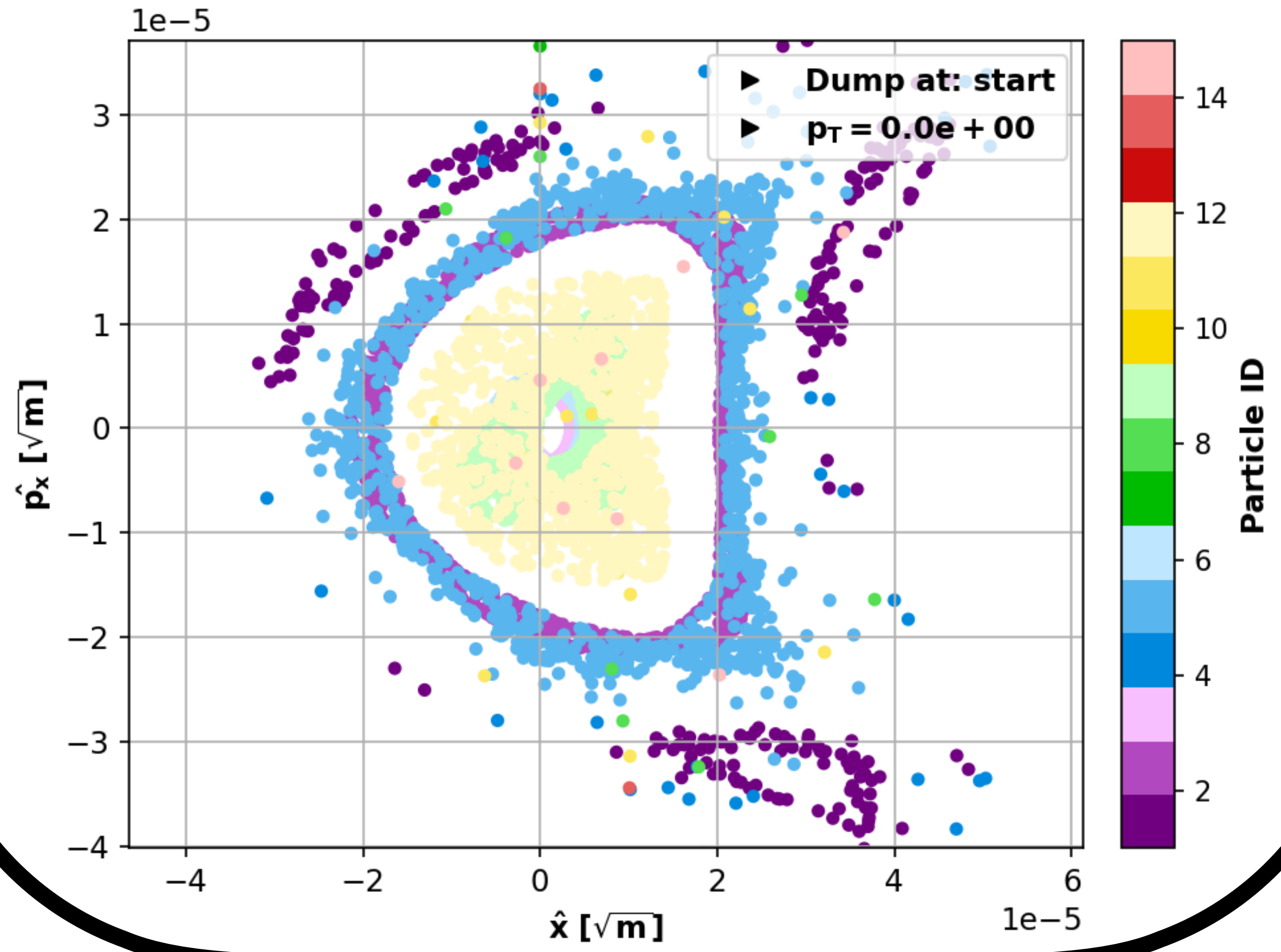


10TeV Muon Collider - Tracking Studies v0.4 - v0.6

v0.4

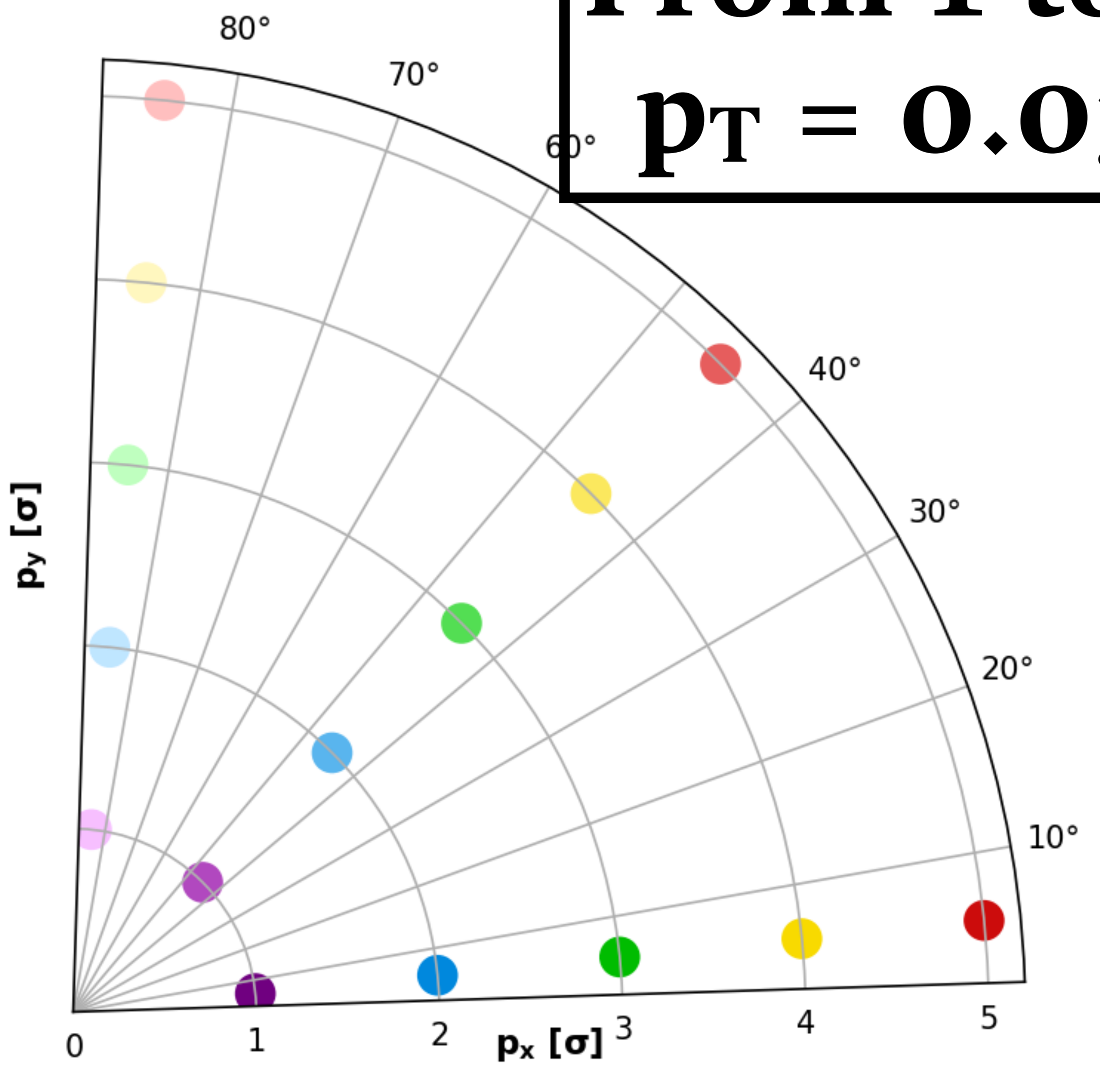
From 1 to 2σ
p_T = 0

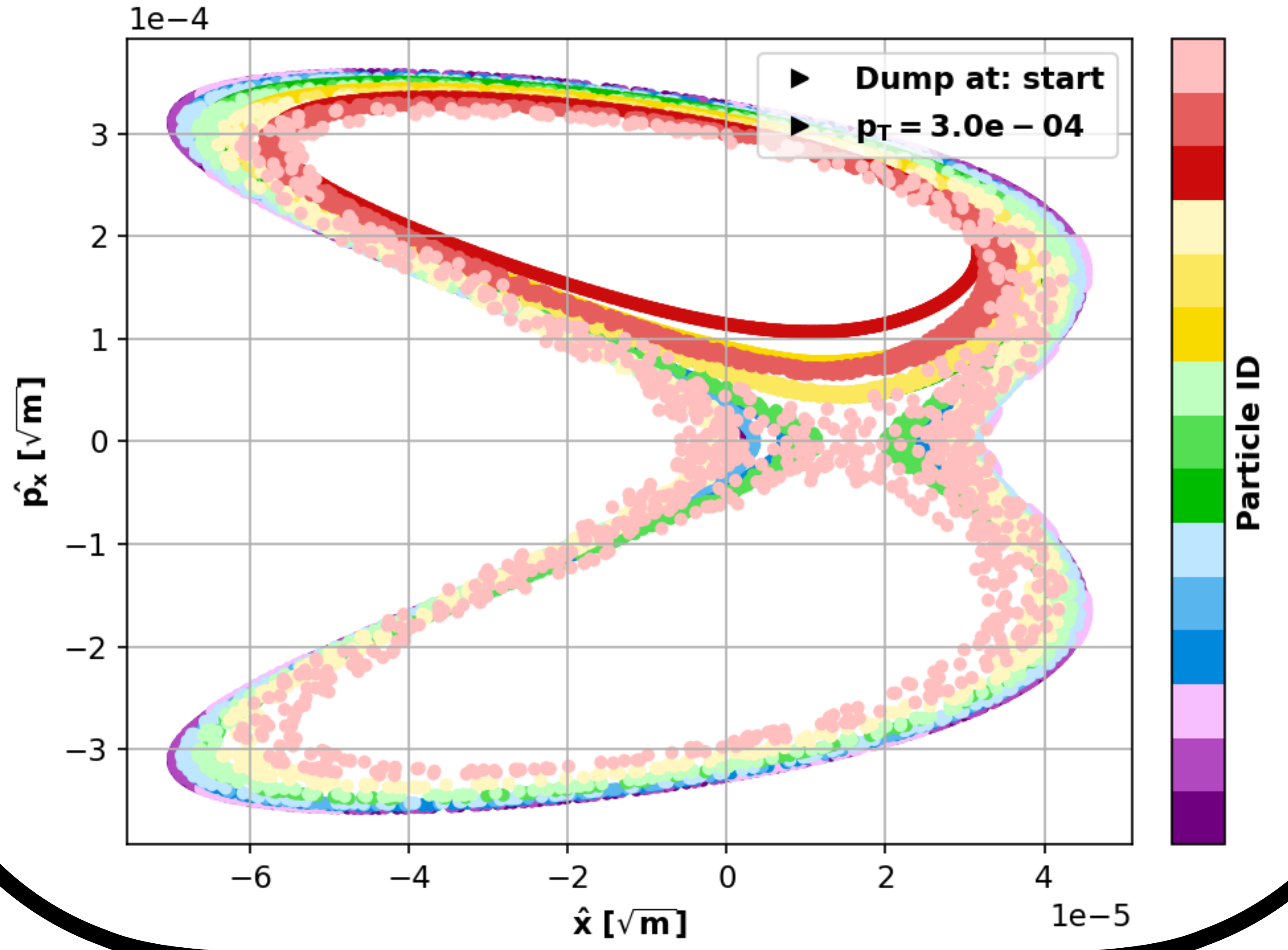




v0.5

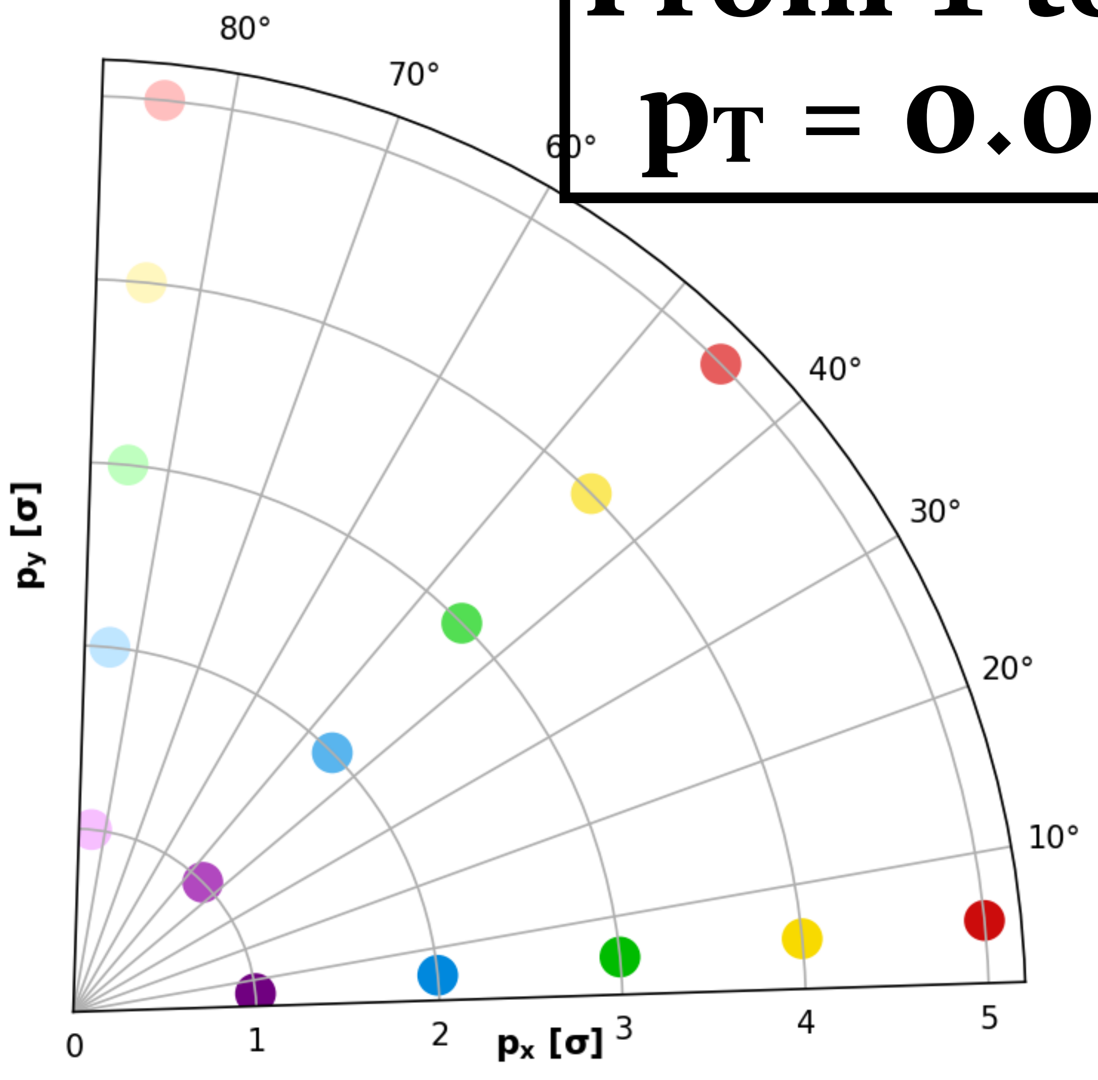
From 1 to 5σ
p_T = 0.03%

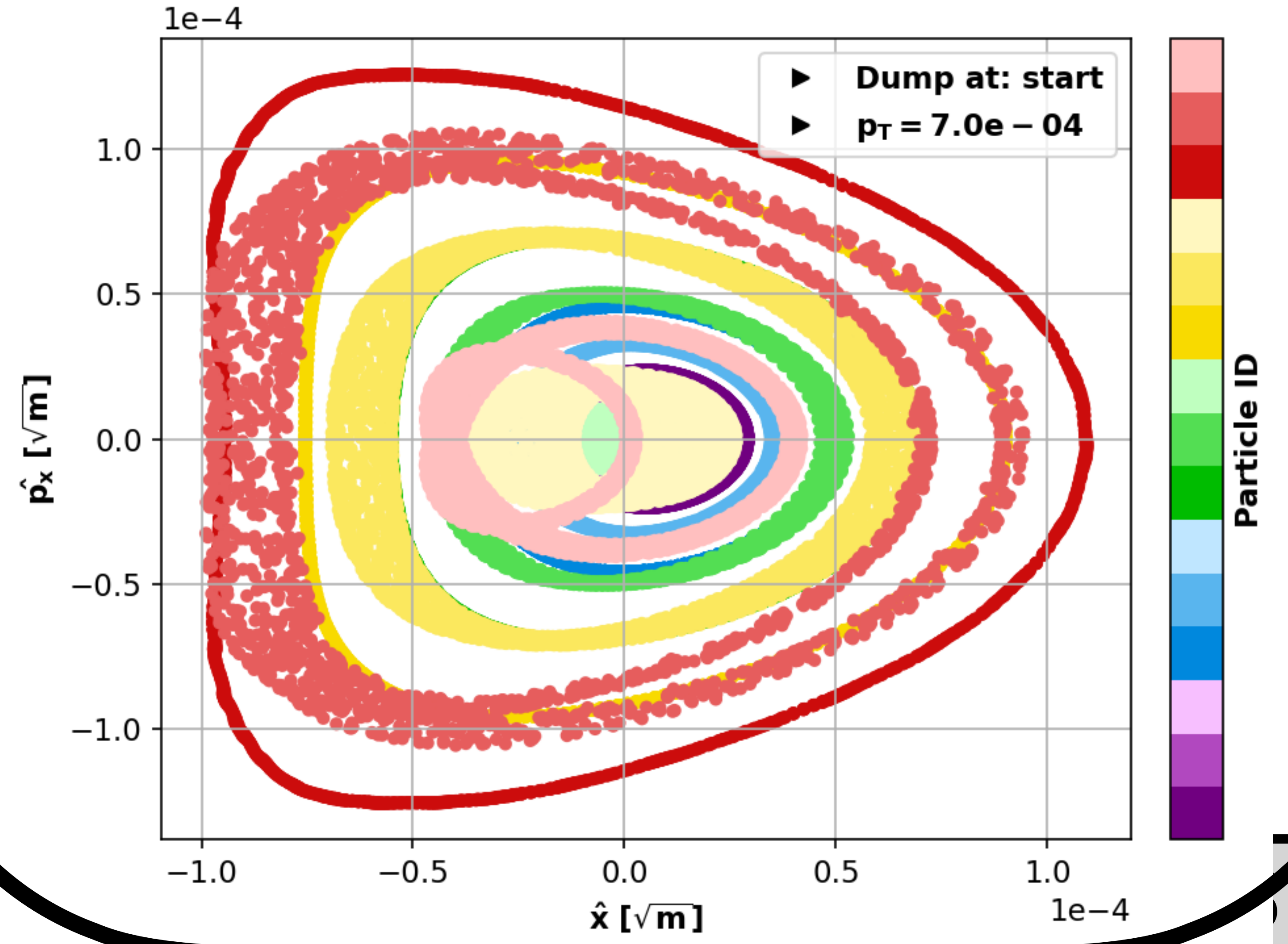




v0.6

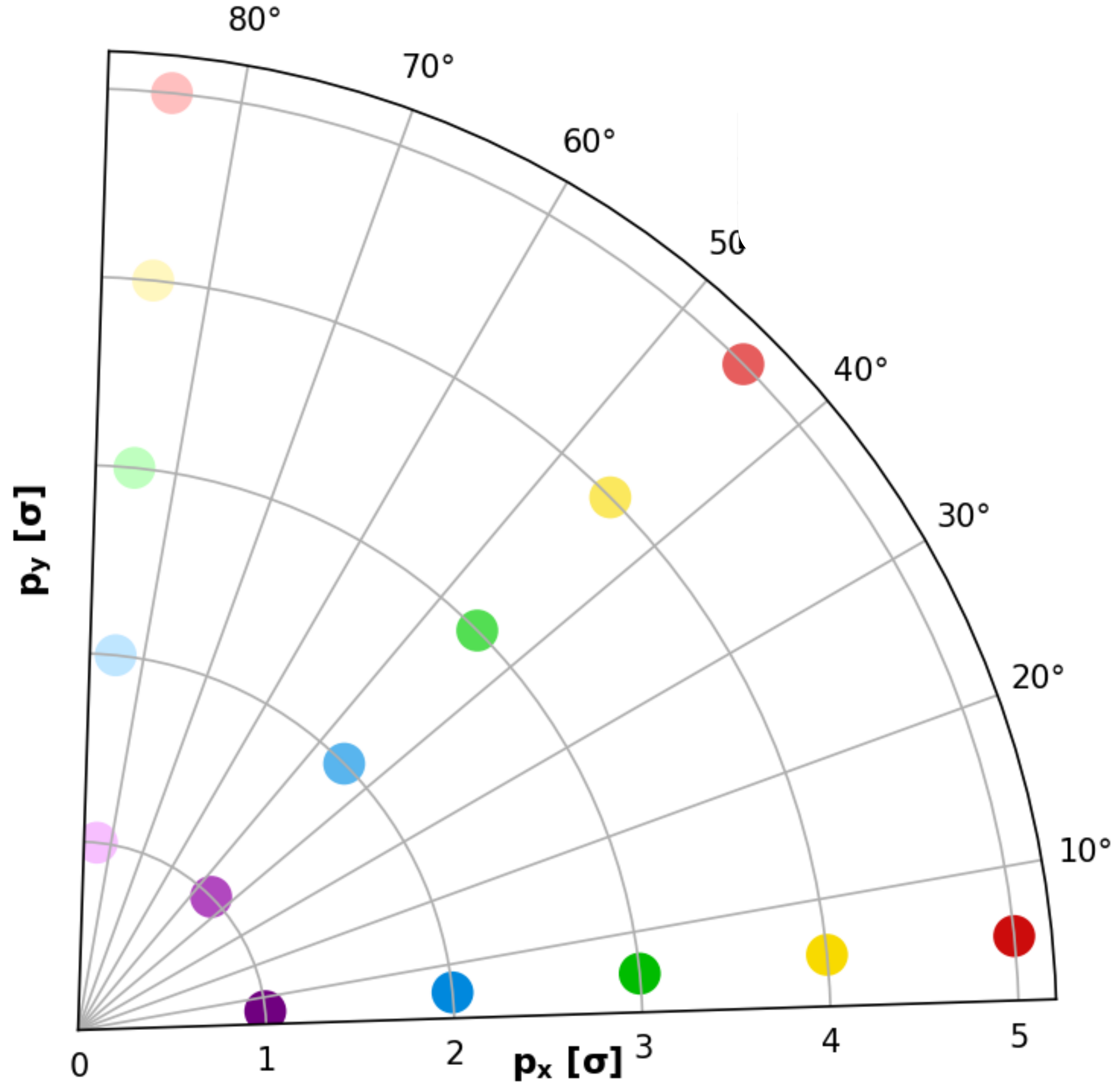
From 1 to 5σ
p_T = 0.07%



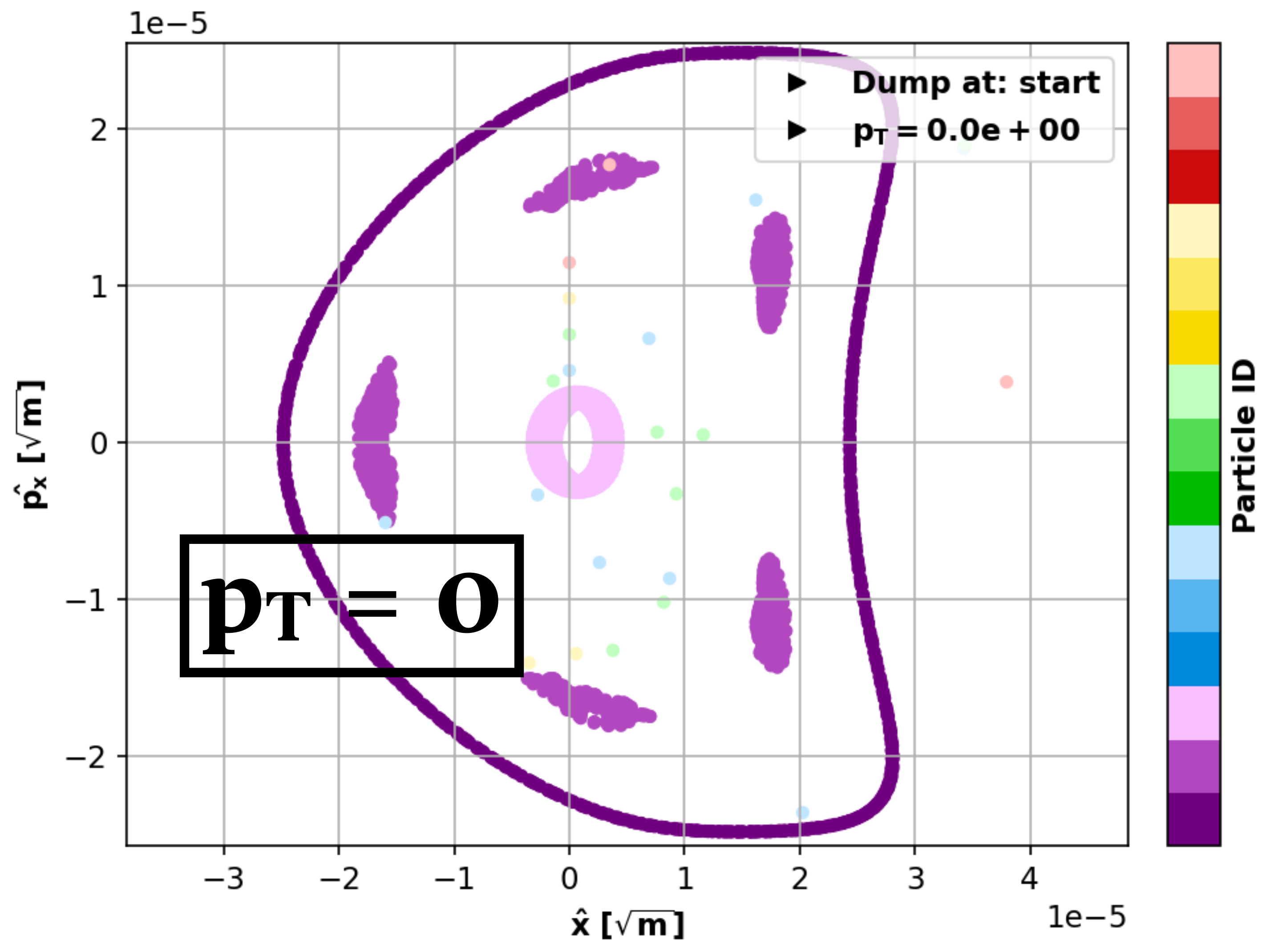


10TeV Muon Collider - Tracking Studies v0.4 - v0.6

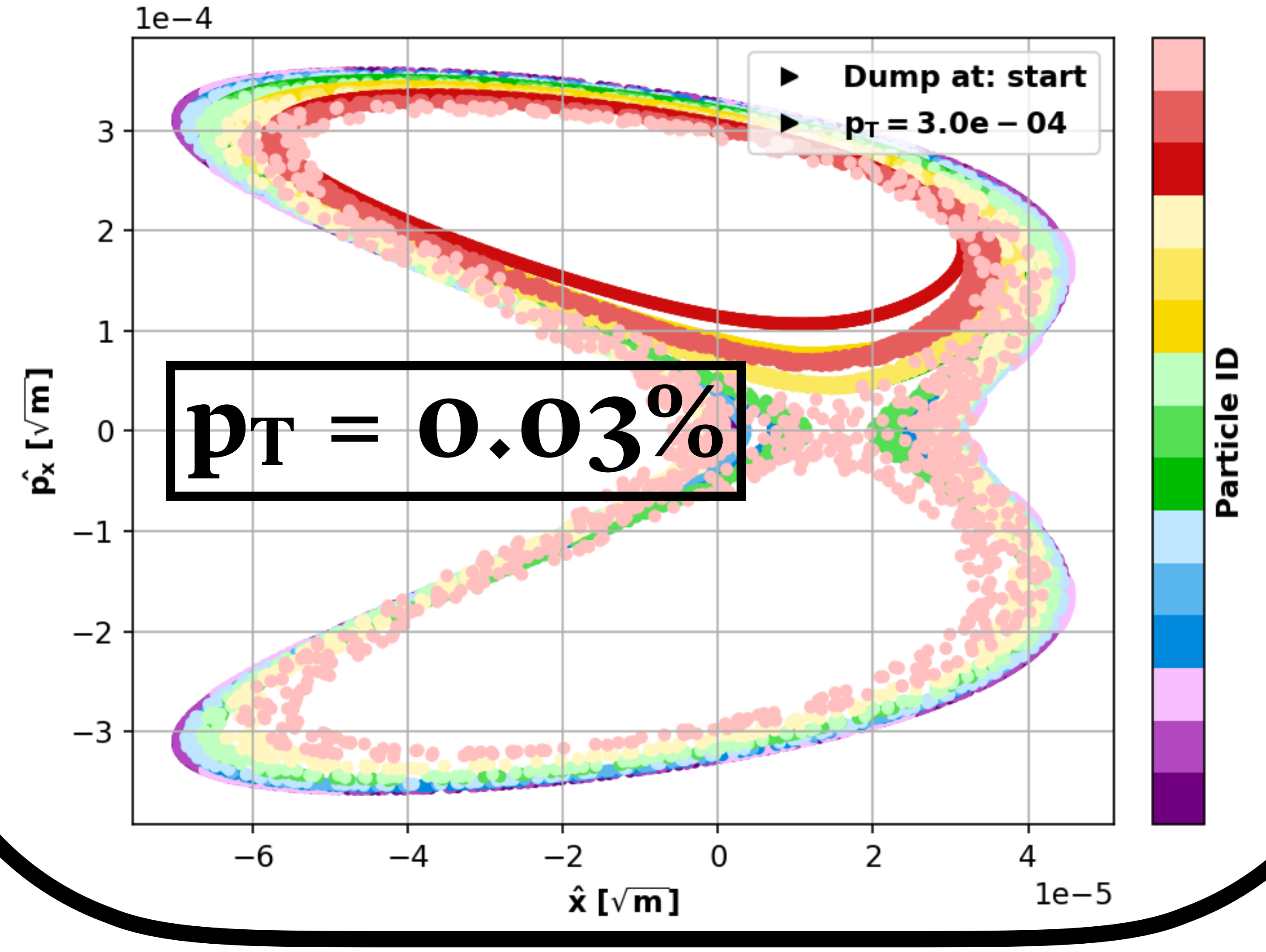
Initial conditions from 1 to 5σ (Particle ID)



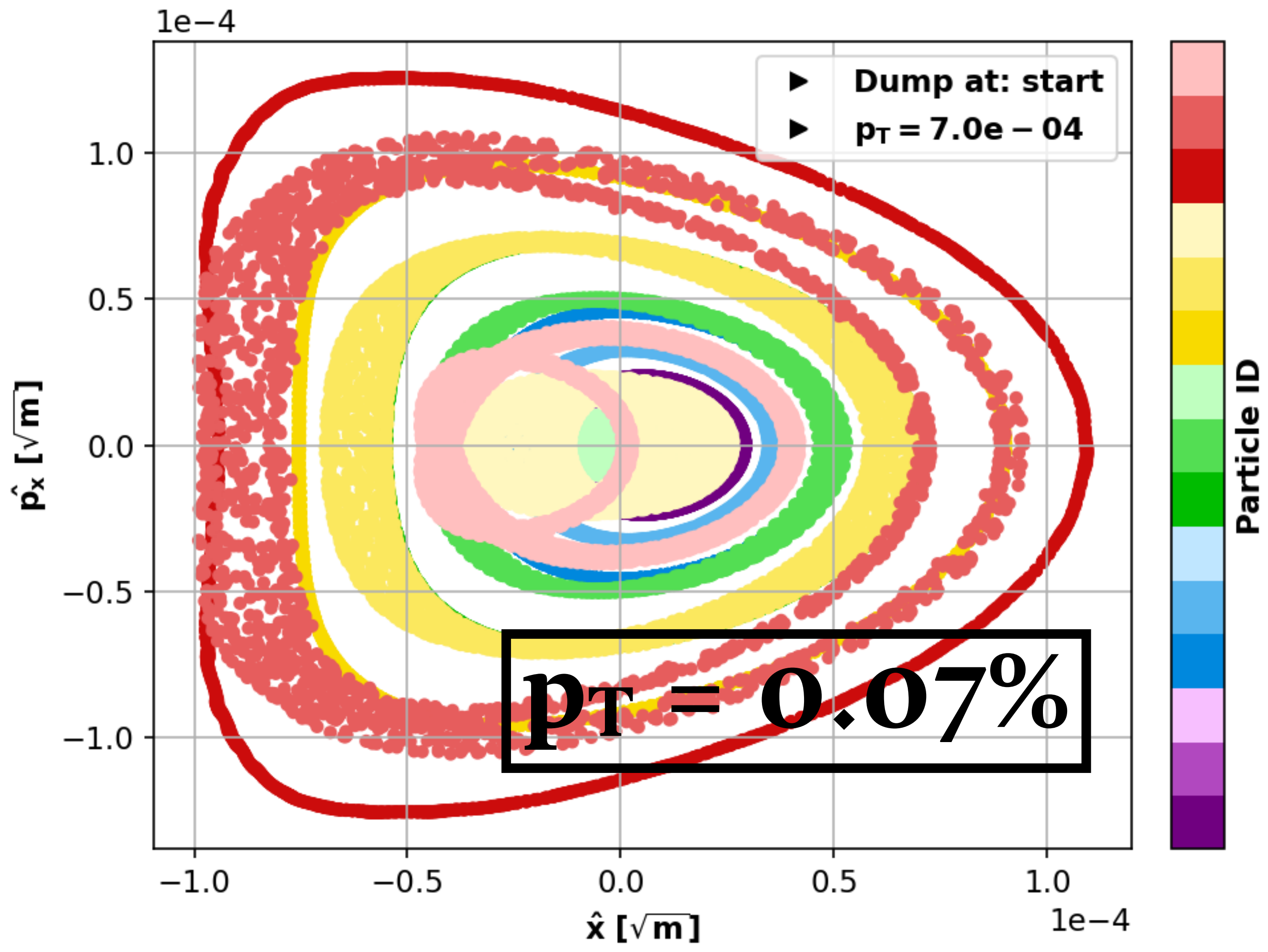
v0.4



v0.5

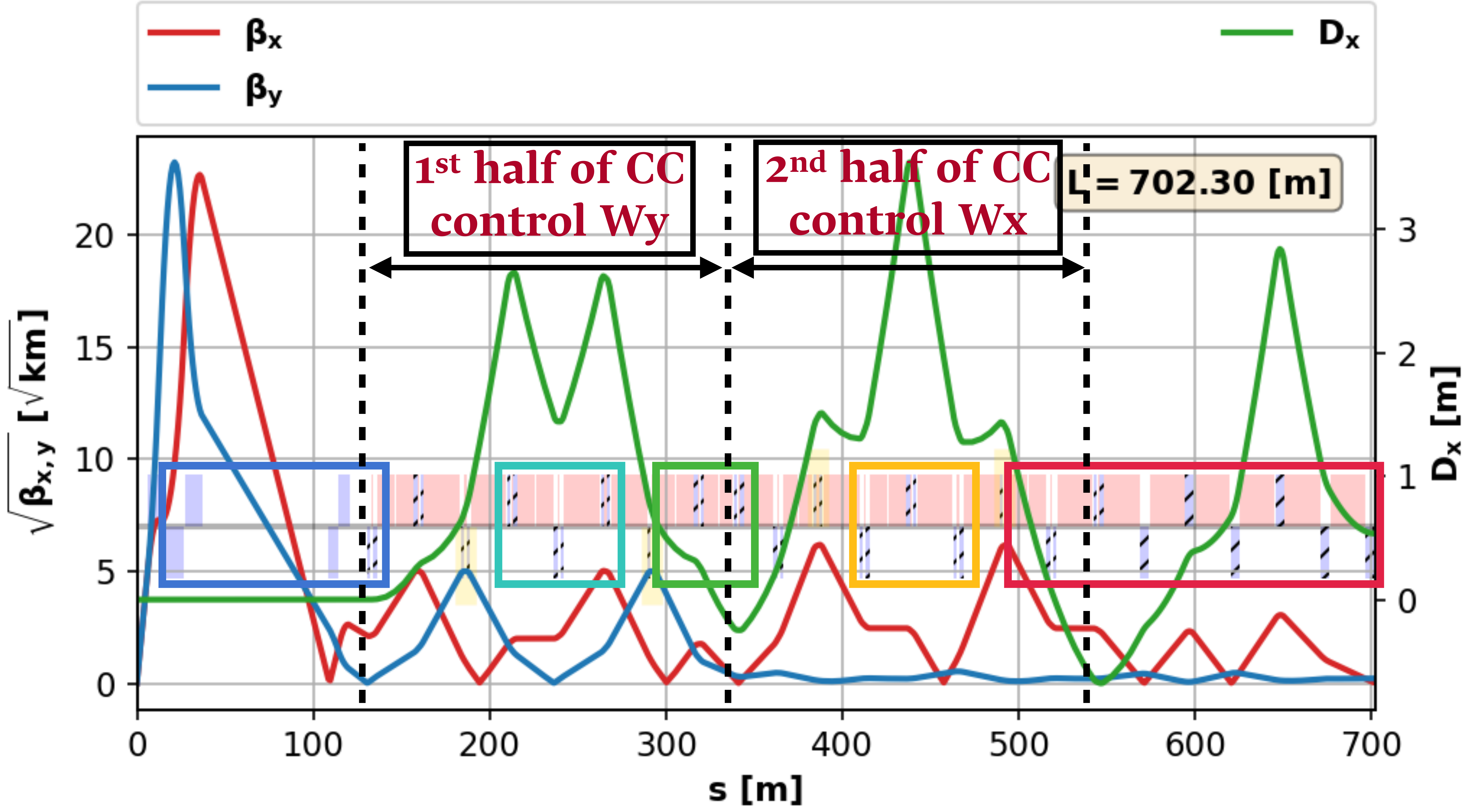


v0.6



p_T [%]	DA_{min} [σ]
0.07	5
0.08	4
0.09	3
0.1	<1

10TeV Muon Collider - Extended Final Focusing Schemes v0.7



Control $\beta_{x,y}$, $\alpha_{x,y}$ and μ_y at the 1st half of CC

Generate -I transform at the 1st half of CC

Control $\alpha_{x,y}$ and μ_x at the 2nd half of CC

Generate -I transform at the 2nd half of CC

Control of working point and matching with arc

10TeV Muon Collider - Arc magnet radial build

Muon collider arc (radial magnet build)

	Thickness (mm)	Min. radius (mm)	Max. radius (mm)
Beam aperture (5 sigma)	23.49	0	23.49
Cu layer	0.01	23.49	23.5
Tungsten absorber	40	23.5	63.5
Support/thermal insulation	11	63.5	74.5
Cold bore	3	74.5	77.5
Kapton insulation	0.5	77.5	78
Clearance	1	78	79
Coils		79	