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MUON Collider
Collaboration

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Current status of the 10 TeV collider

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

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Outline

- 10TeV Muon Collider
  - Final Focusing Scheme
  - Chromatic Correction & Matching Schemes
  - Arc
  - Tracking studies
- Summary - Outlook

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

10TeV Muon Collider - In a nutshell

1.5mm β^*

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

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

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

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

=> The CC generate significant positive momentum compaction factor (α_p) and should be controlled (keep the bunch length short) in the arcs among other parameters.

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 surface

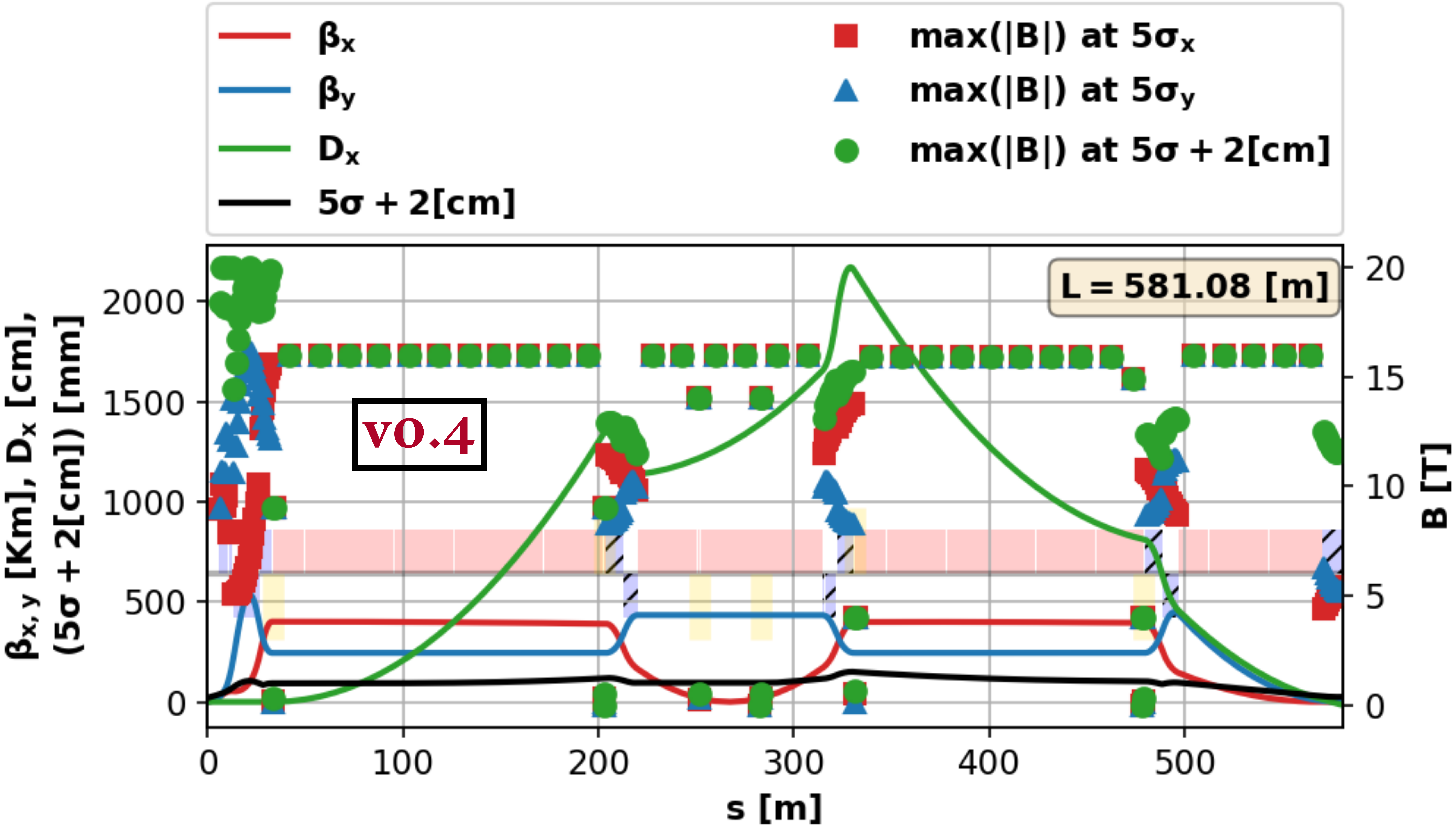
=> The planned shape of the collider is like a race track (2 straight sections for IPs)

=> Extensive use of dipoles and combined function magnets

10TeV Muon Collider **v0.4**
(Recap)

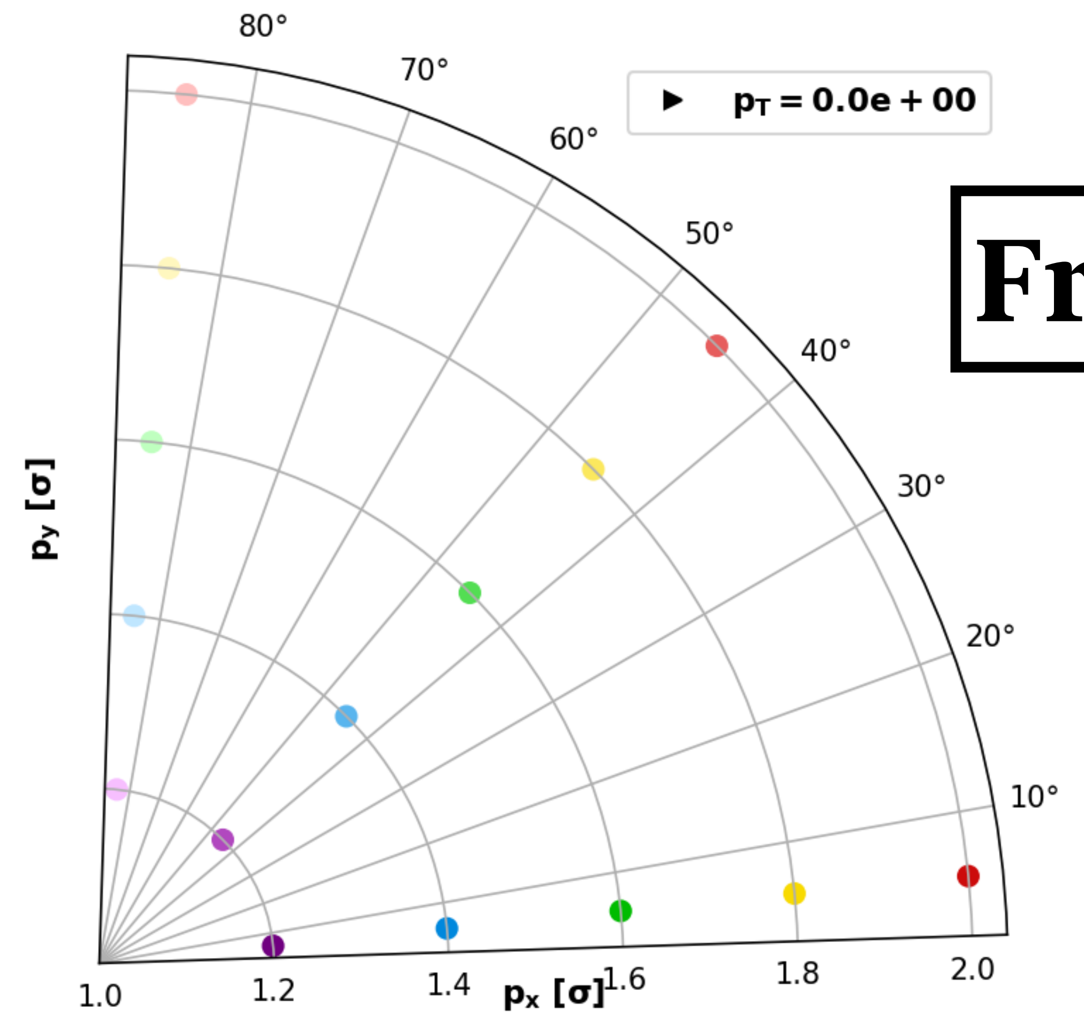
10TeV Muon Collider - Tracking Studies v0.4

- V0.4 CC with dipole-sextuple doublets incorporating an I or -I transform between the sextuples of a family.
- Every dipole-sextuple magnet is 1m long with sextupolar components weaker than 0.2T (increase of dispersion with the addition of dipoles between sextuples pairs of all sets).

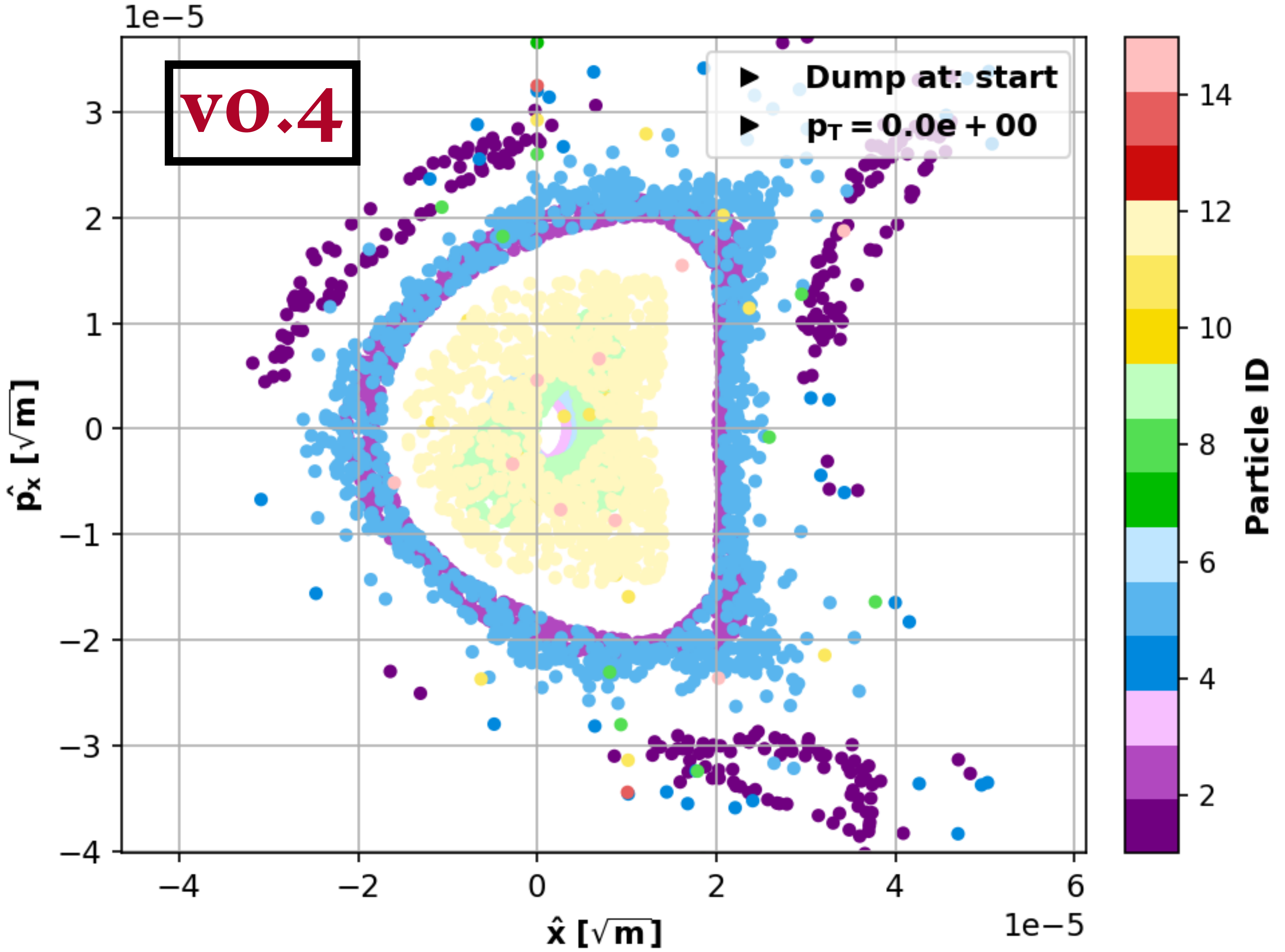


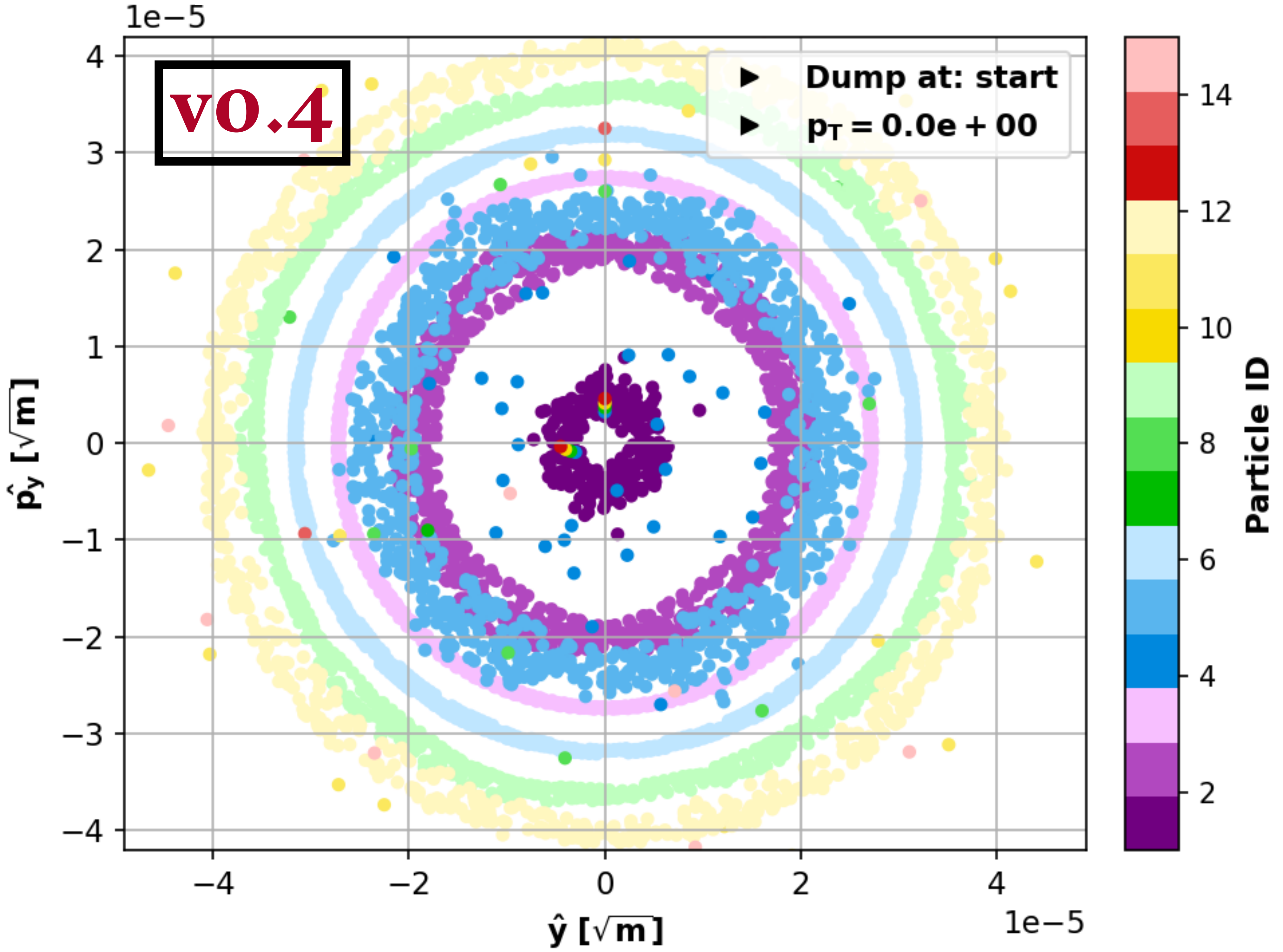
10TeV Muon Collider - Tracking Studies v0.4

- Due to small deviations from the I and -I transforms (of the order of $\Delta Q \sim 10^{-5}$), the DA even for particles with $\delta=0$ is quite weak (DA<2σ).



From 1 to 2σ



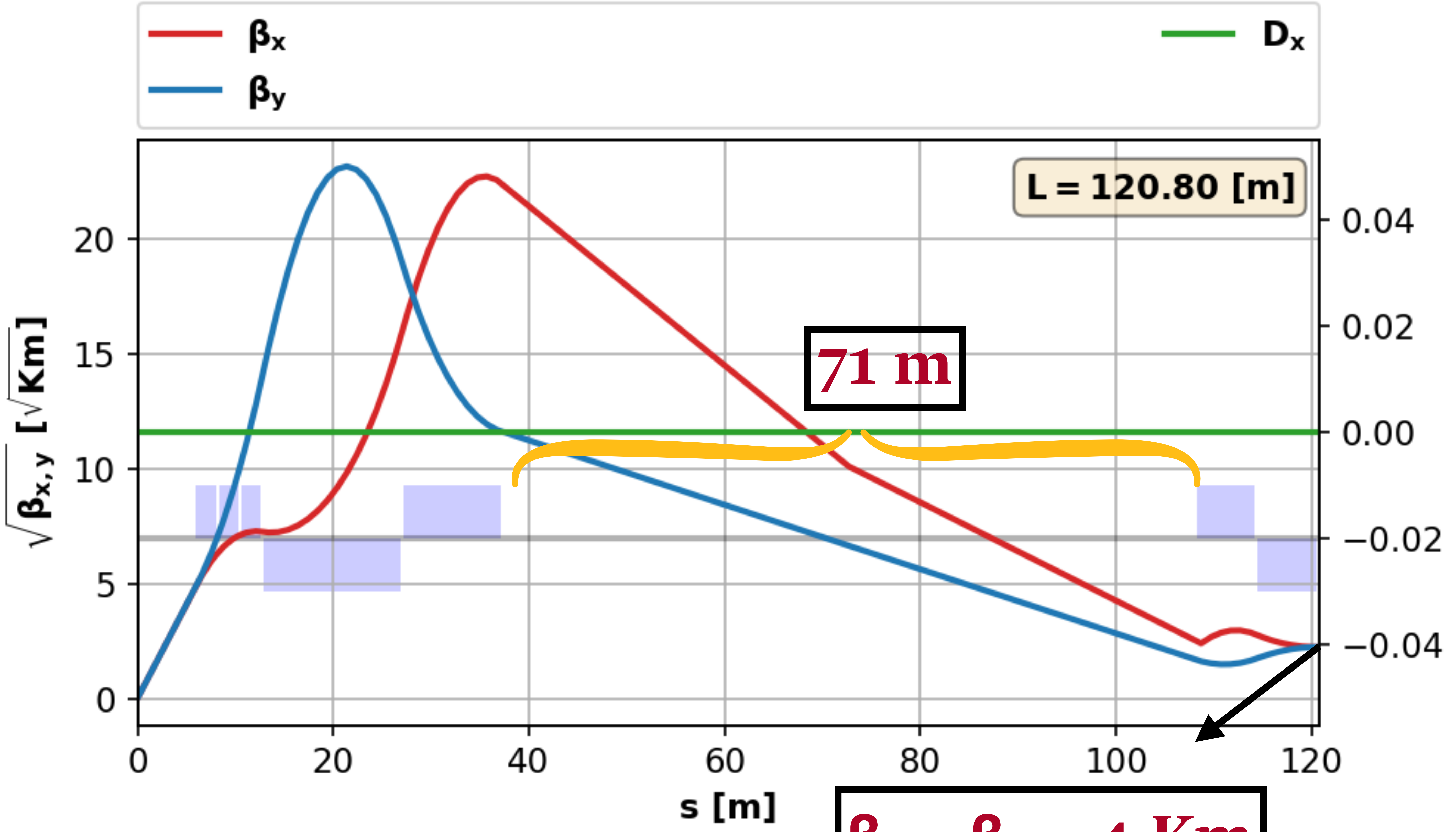


10TeV Muon Collider **v0.5**
(Current design)

10TeV Muon Collider - Final Focusing Scheme

- $L^* = 6$m and a triplet is used for the Final Focusing (FF).
- The maximum allowed magnetic field at the FF scheme is assumed to be the 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 quadrupoles in the FF scheme are used to control the β_x & β_y and to obtain a point to parallel matching ($\alpha_{x,y} = 0$) at the end of the FF scheme.
- 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 Scheme



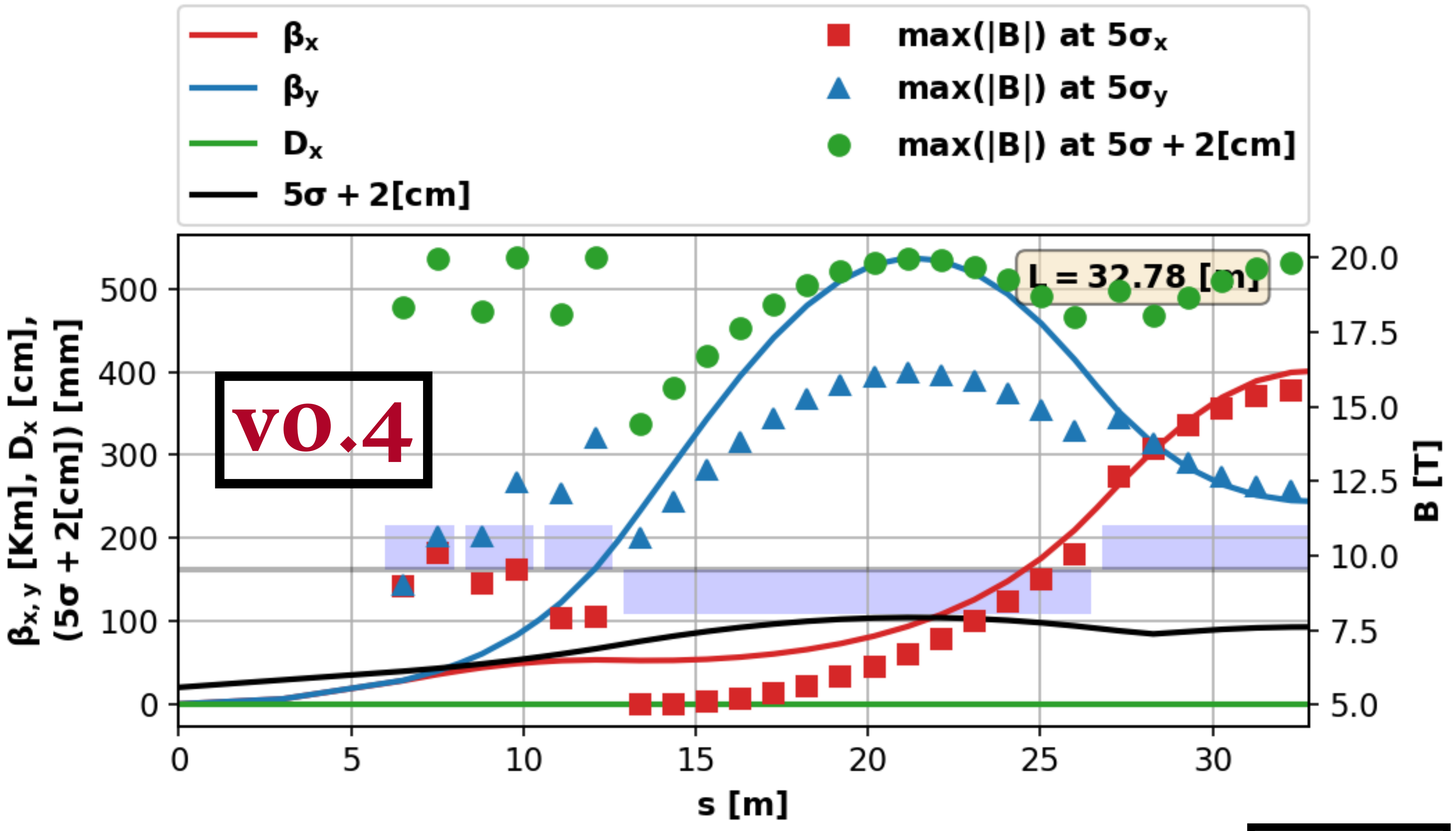
$\beta_x = \beta_y \sim 4$ Km

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

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

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

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

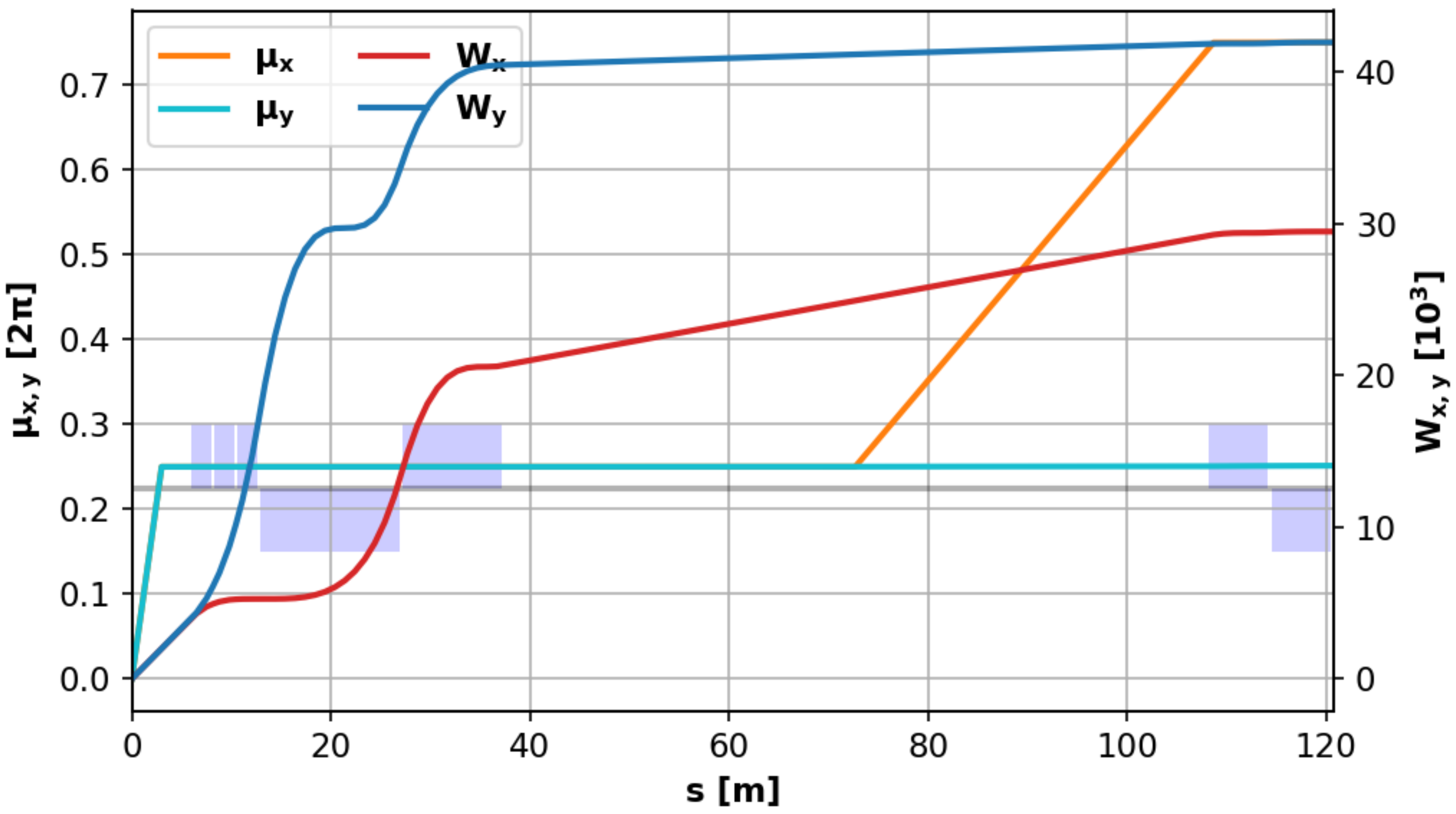


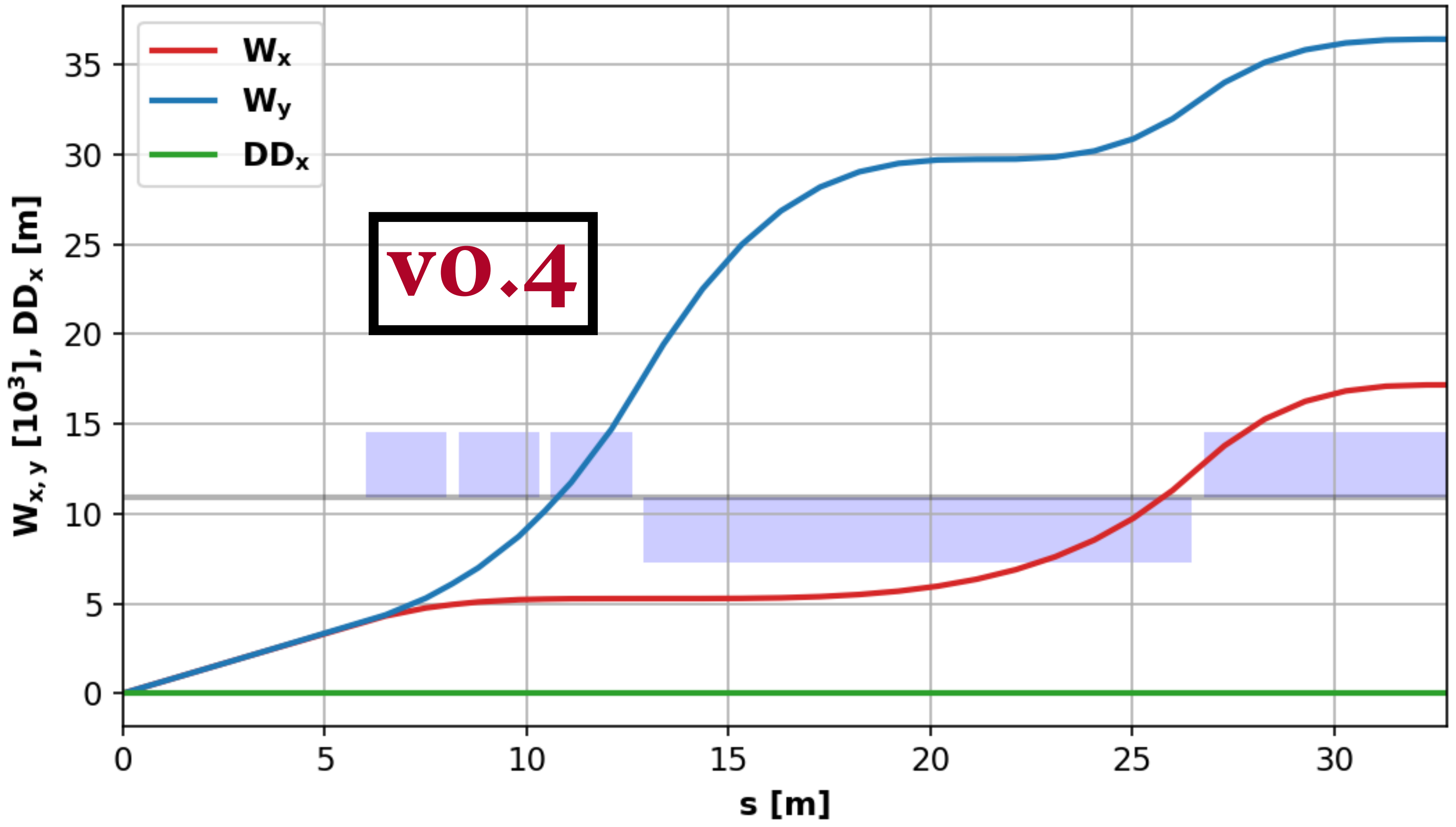
Entering the CC with small βs resulted in:
- Smaller aperture
- Smaller Ws
- Less impact from unwanted multipolar components
- Easier control of βs

10TeV Muon Collider - Final Focusing Scheme

- 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 ones become very large.

- Together with the large momentum spread ($\delta=10^{-3}$), these W values indicate large chromatic effects that have to be compensated carefully in order to avoid performance degradation.





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 and are separated by -I transform at x and y planes for the compensation of the RDTs excited by the sextupolar component.

Matching scheme (CC-Arc)

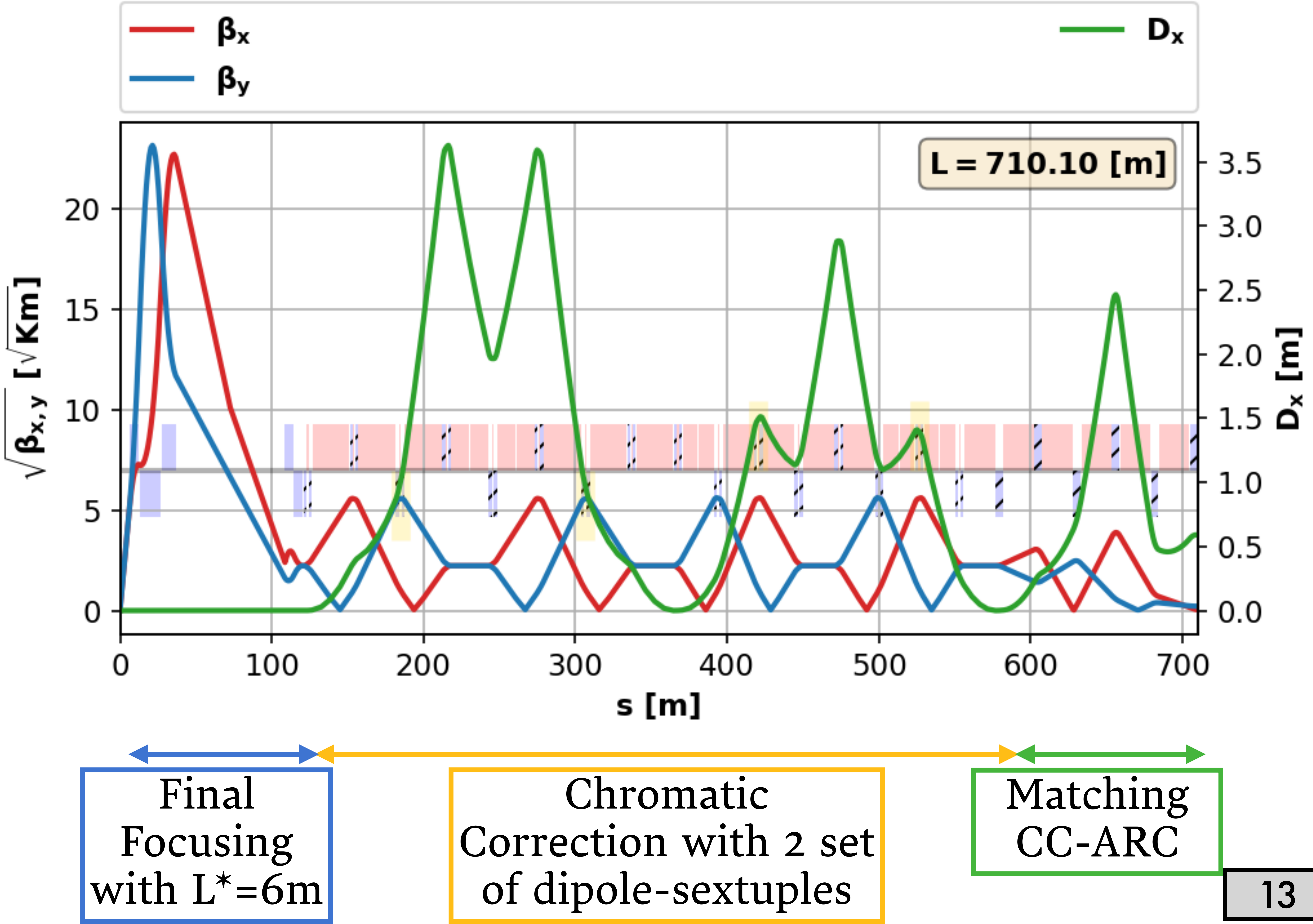
- The $\beta_{x,y}$, $\alpha_{x,y}$, D_x and D_{px} are matched by controlling the strength of six dipole-quadrupole and the dipole length separating the dipole-quadrupole magnets.

- The matching of the D_x and D_{px} is facilitated by controlling its value at the end of the CC scheme (keeping it to small values).

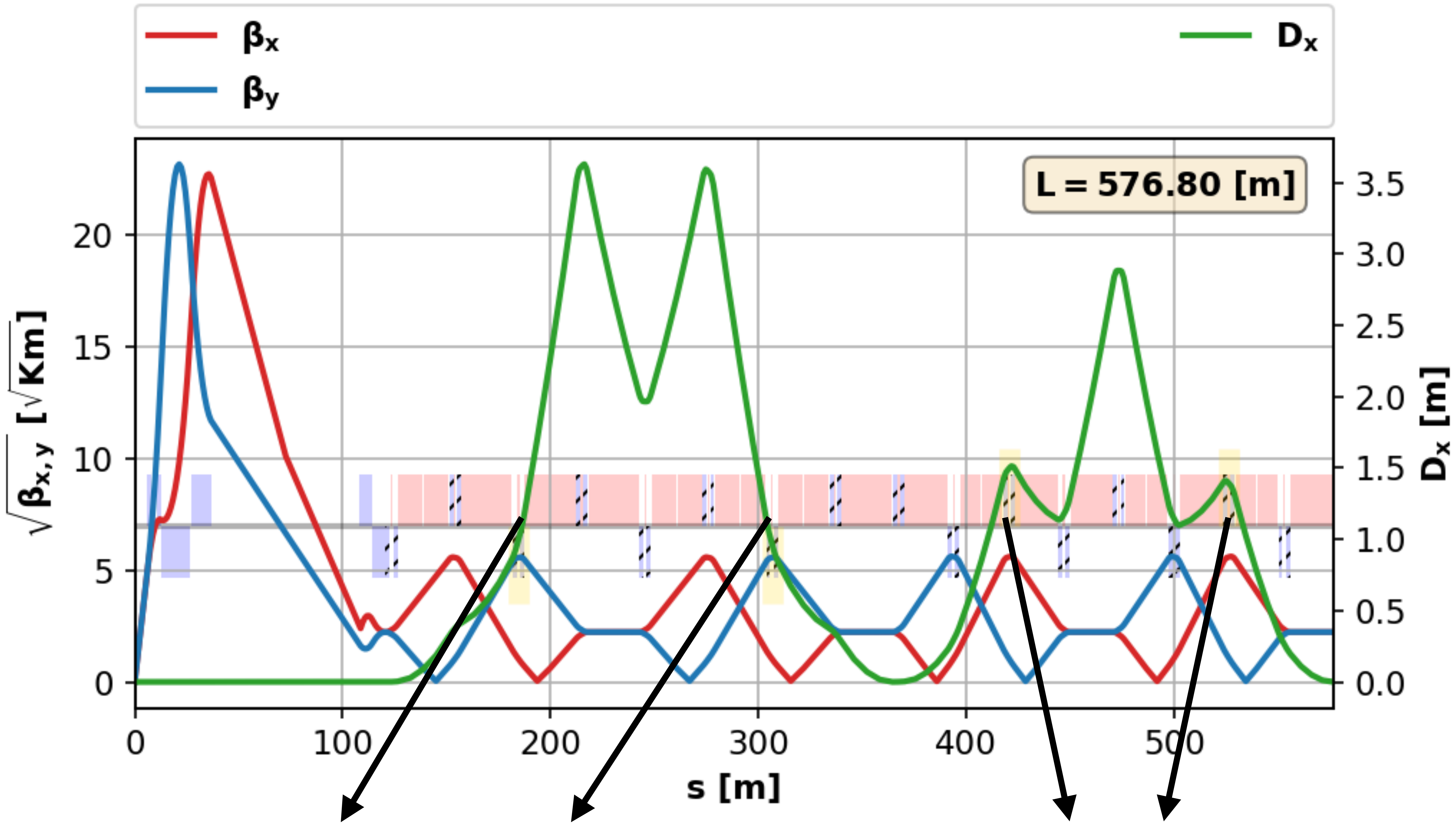
10TeV Muon Collider - Chromatic Correction & Matching Schemes

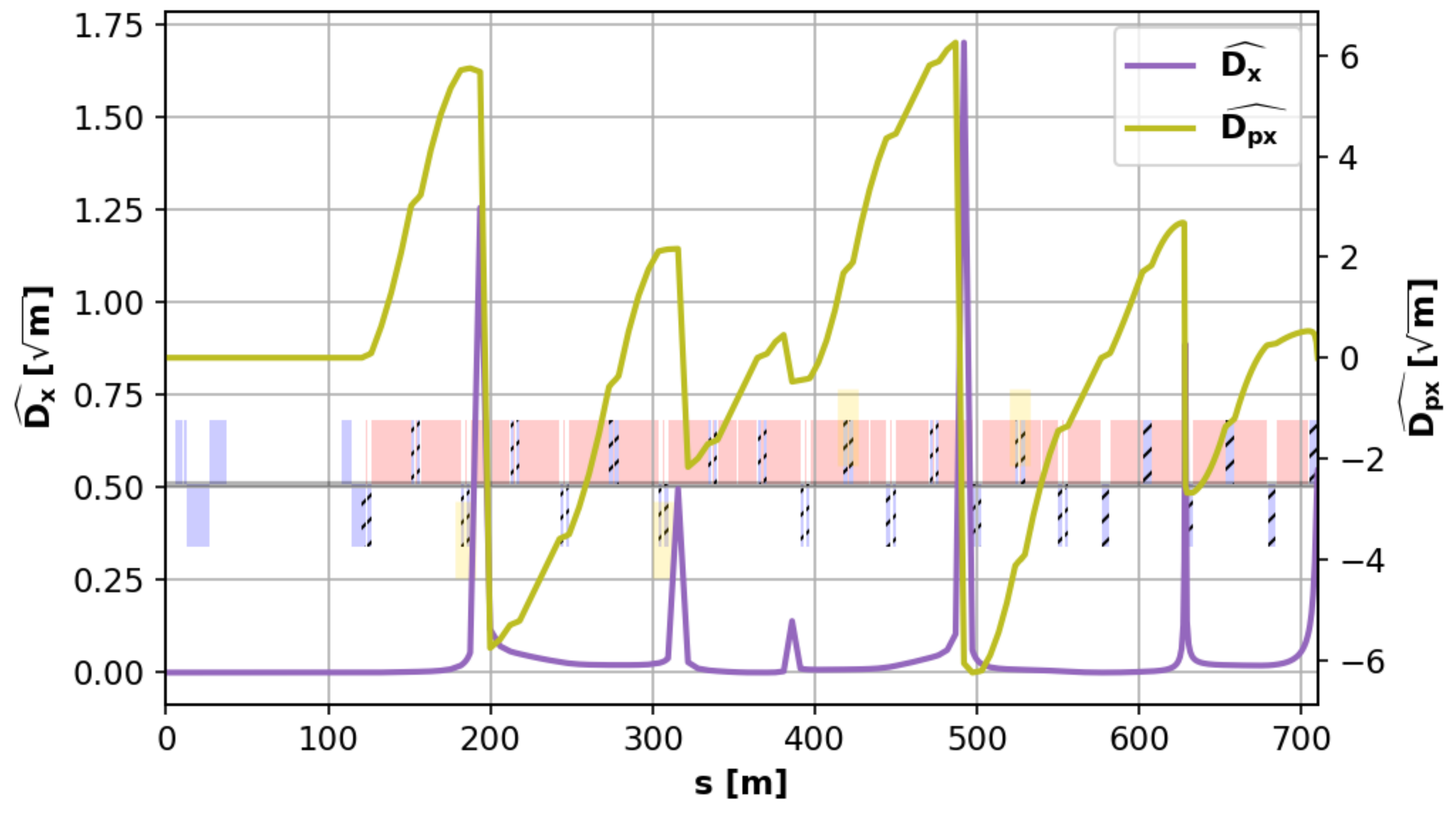
Colour code for lattice elements:

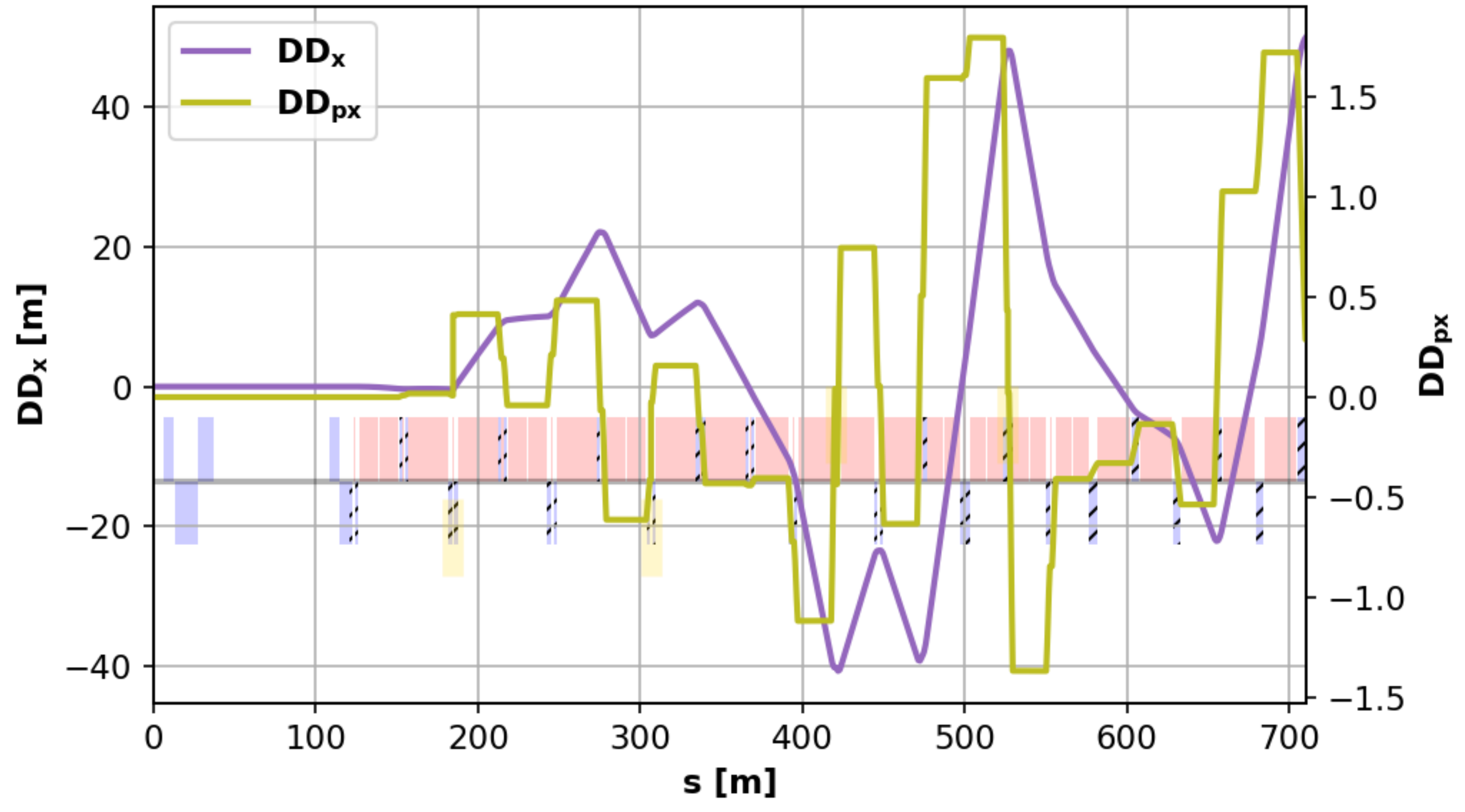
- Red dipoles
- Blue quadrupoles
- Hashed blue dipole-quadrupoles
- Red + Gold dipole-sextupoles (all 1m long)



10TeV Muon Collider - Chromatic Correction & Matching Schemes



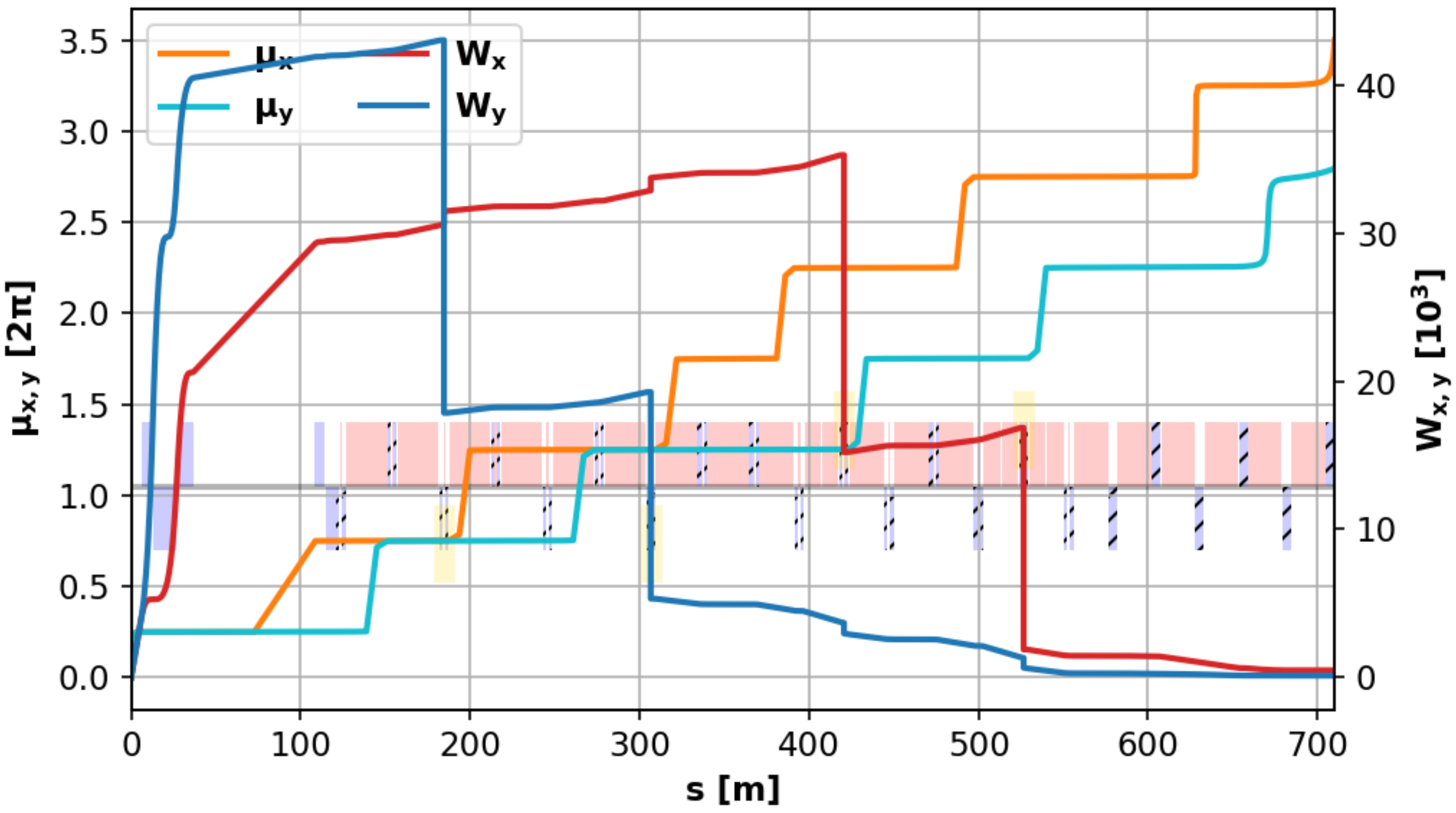


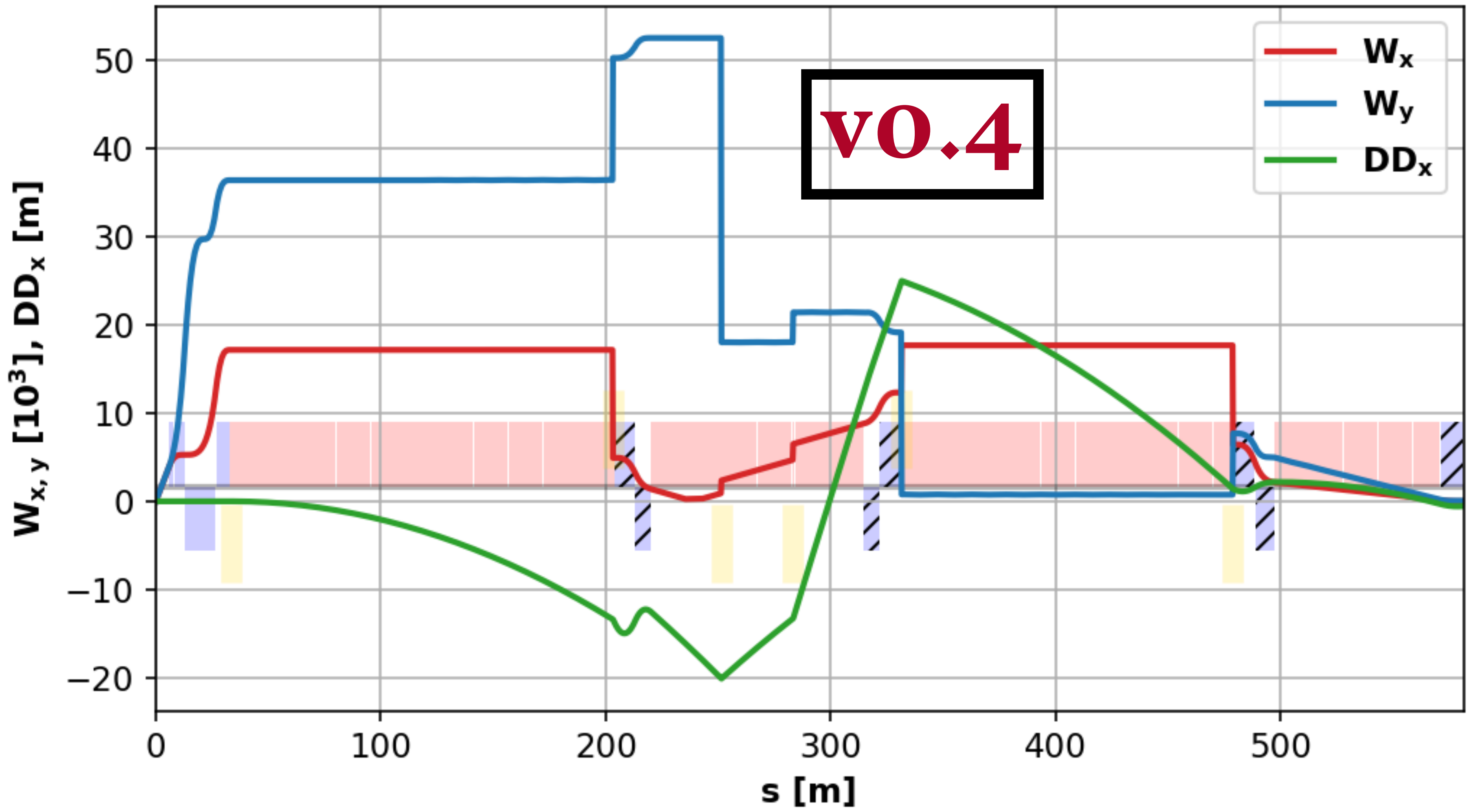


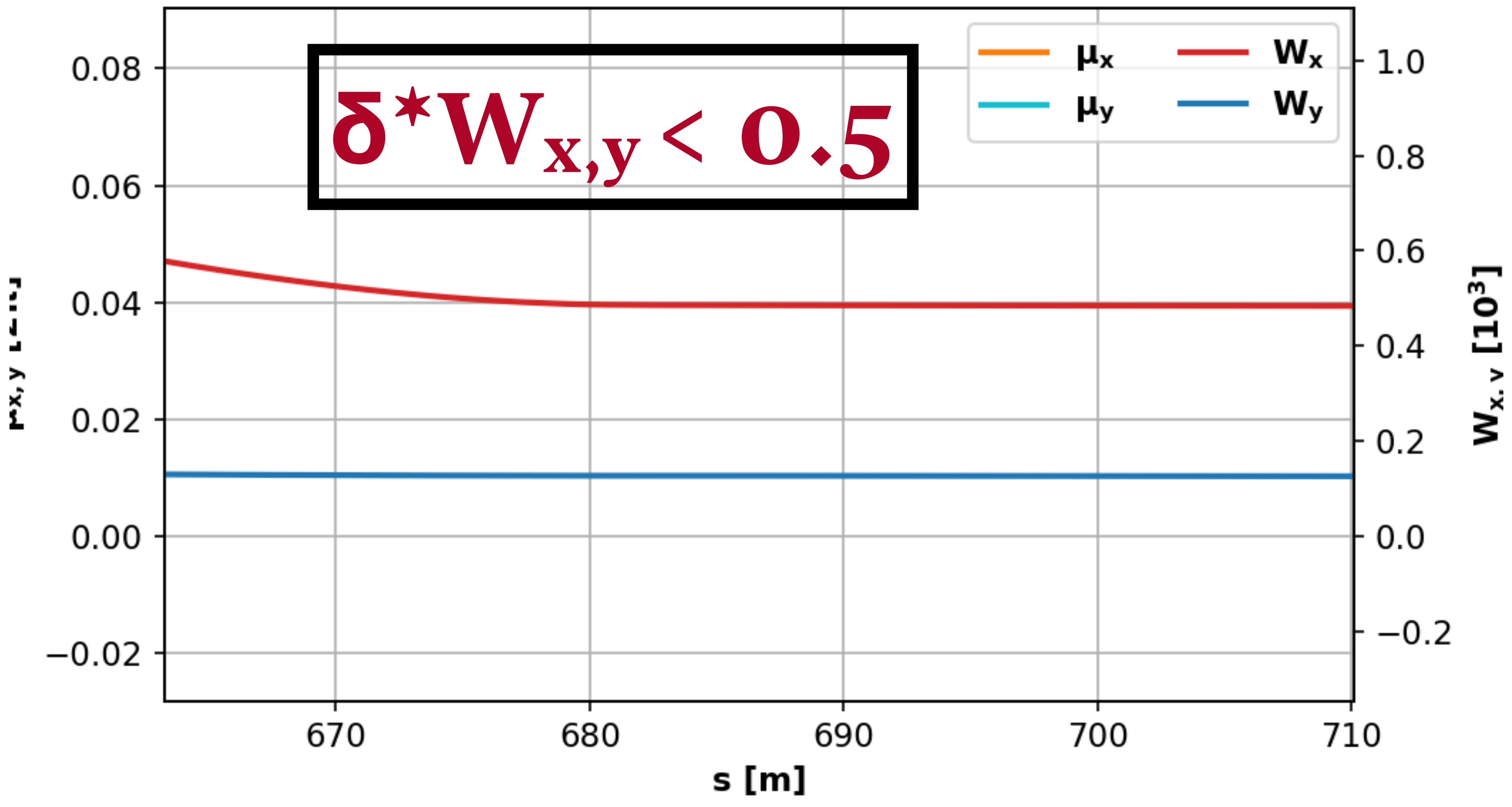
1st DS doublet for W_y
Large D_x, β_y and small β_x

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

10TeV Muon Collider - Chromatic Correction & Matching Schemes





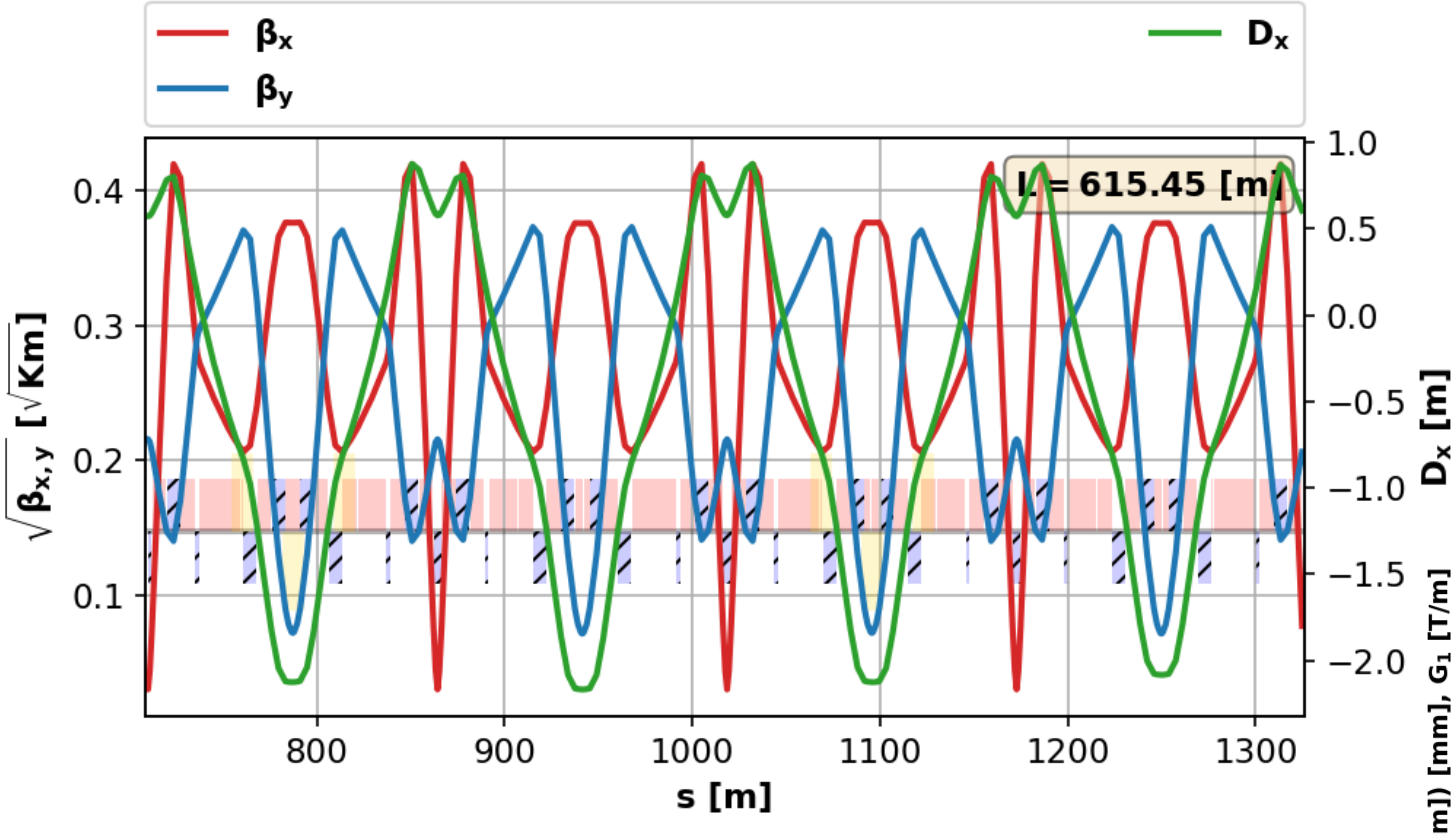


- The non zero $\delta^* W$ is improved in newer version.

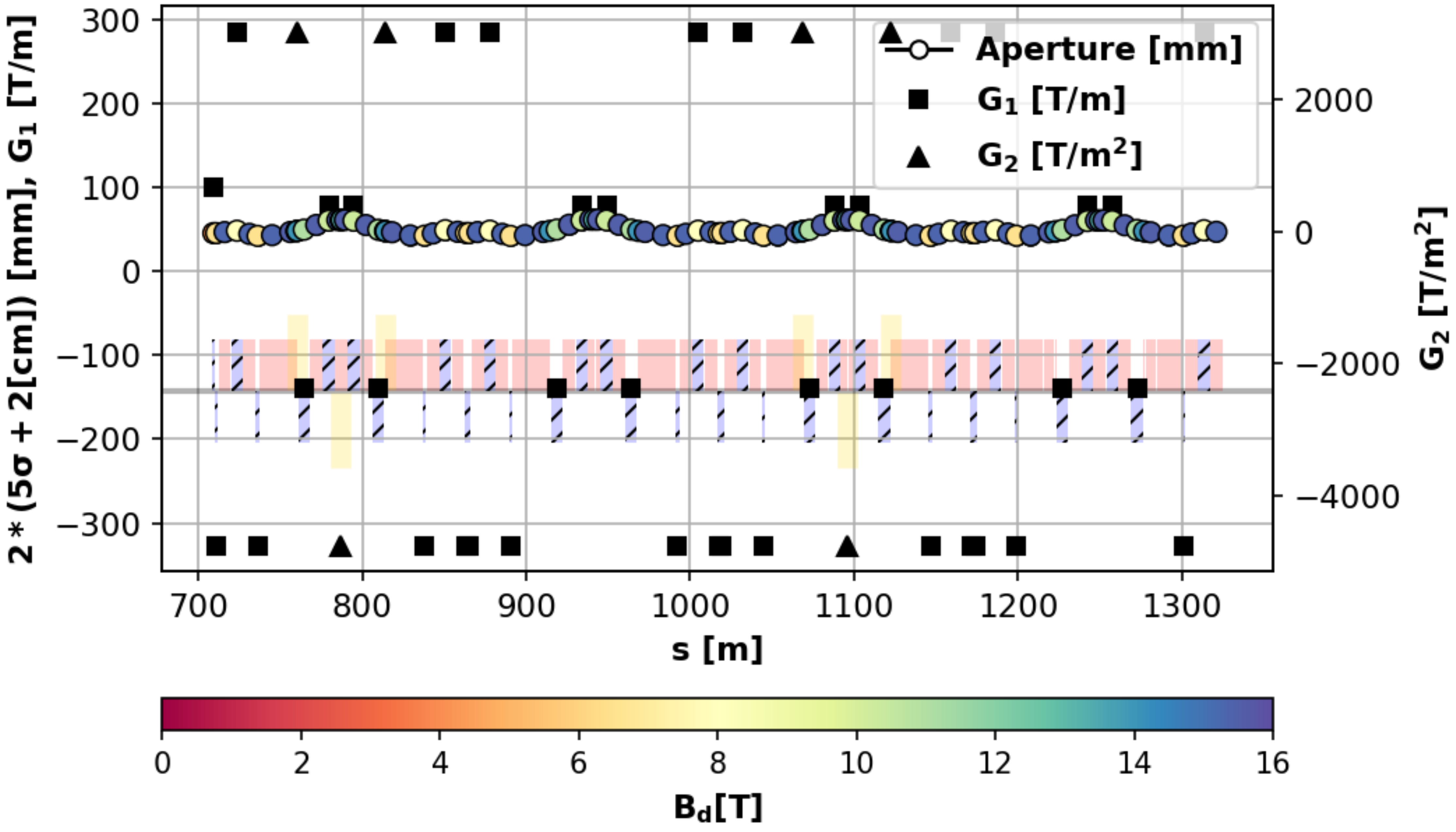
10TeV Muon Collider - Arc

- 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 in order to keep η_p small and stay below transition ($\eta_p, \alpha_p < 0$).
- 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).

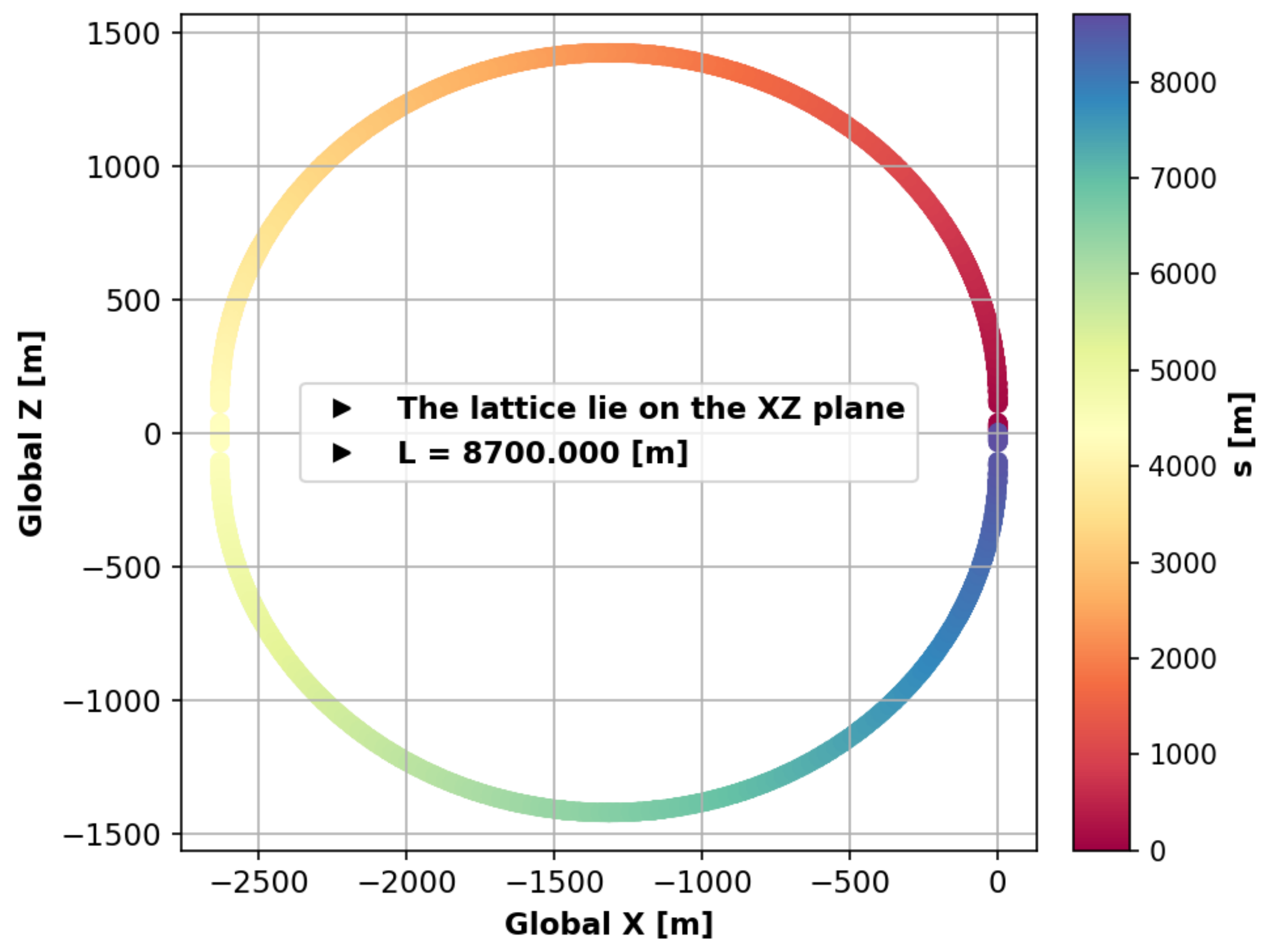
10TeV Muon Collider - Arc

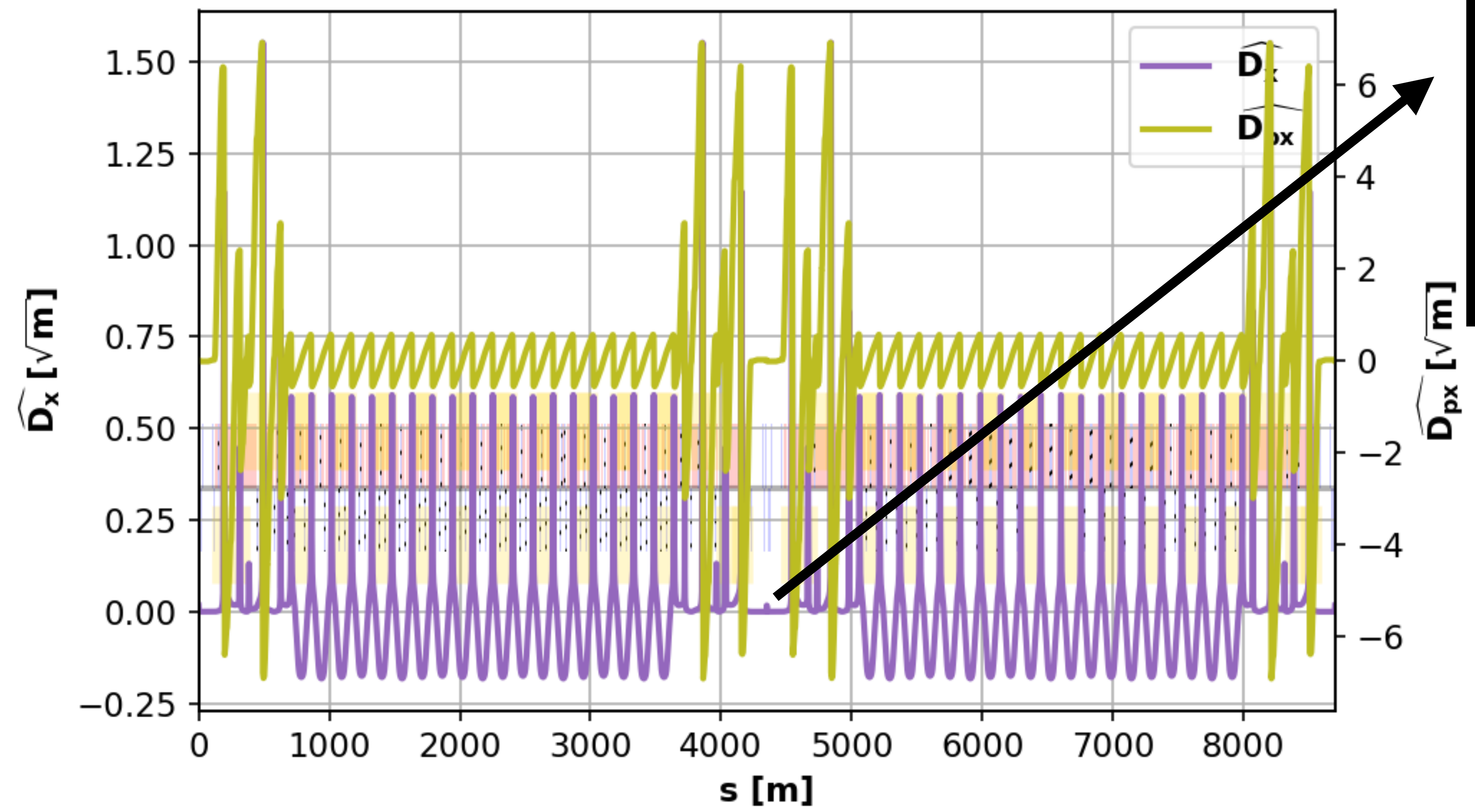


- Quite smaller betas and dispersion in version 0.5, reducing that way the magnets aperture by almost a facto 2.



10TeV Muon Collider - Full Lattice

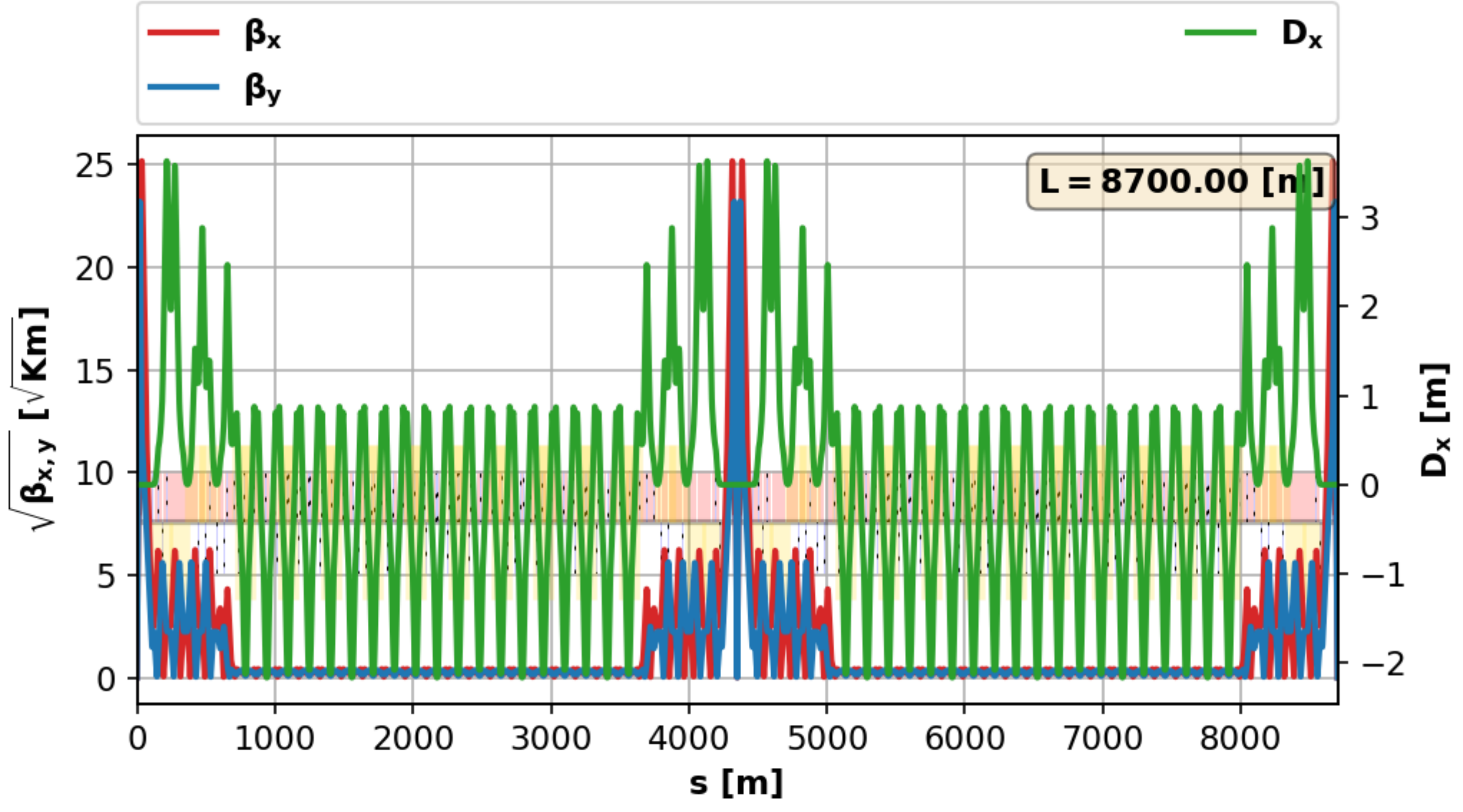


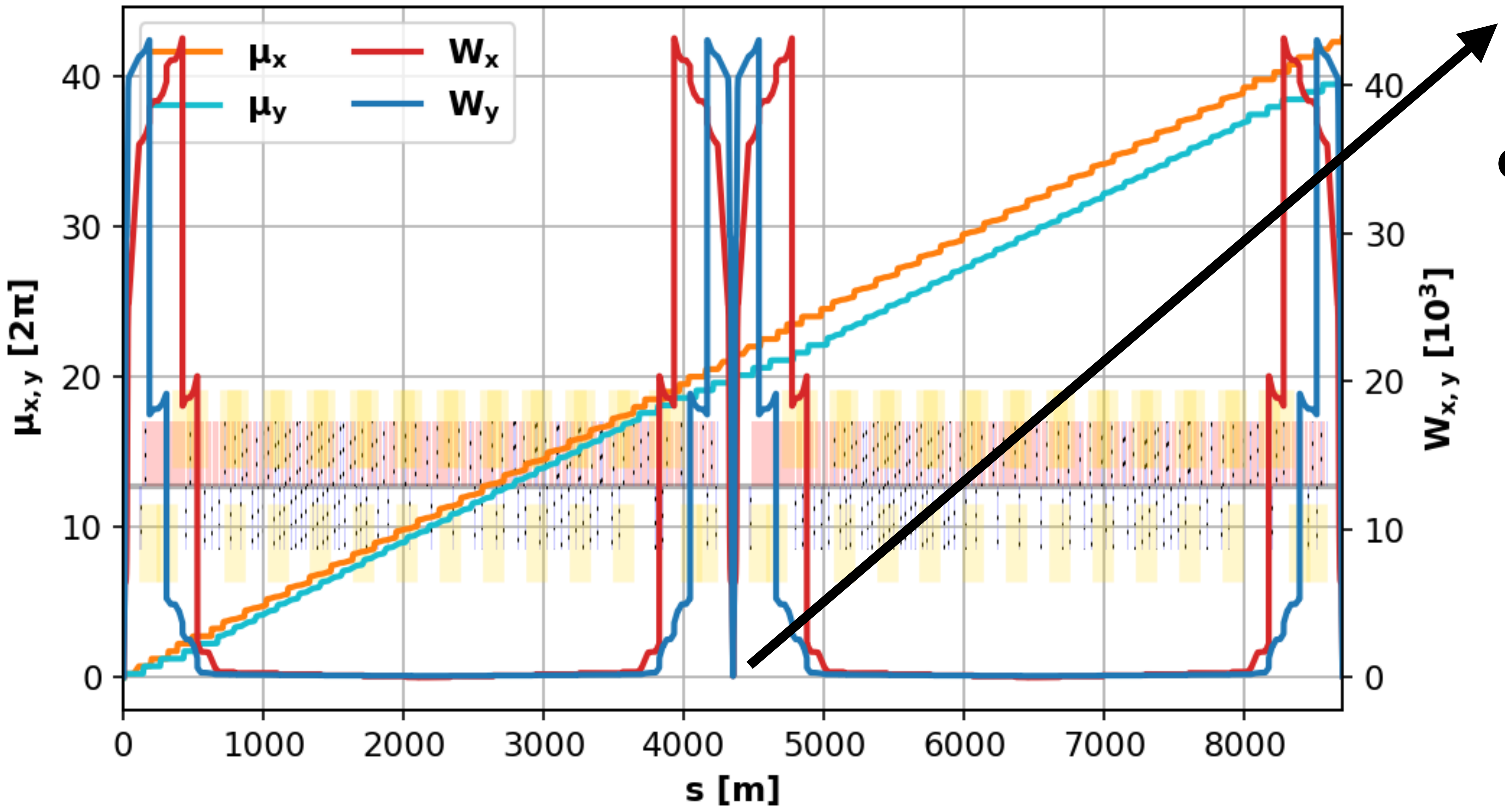


$D_{nx}, D_{npx} \neq 0$

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

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



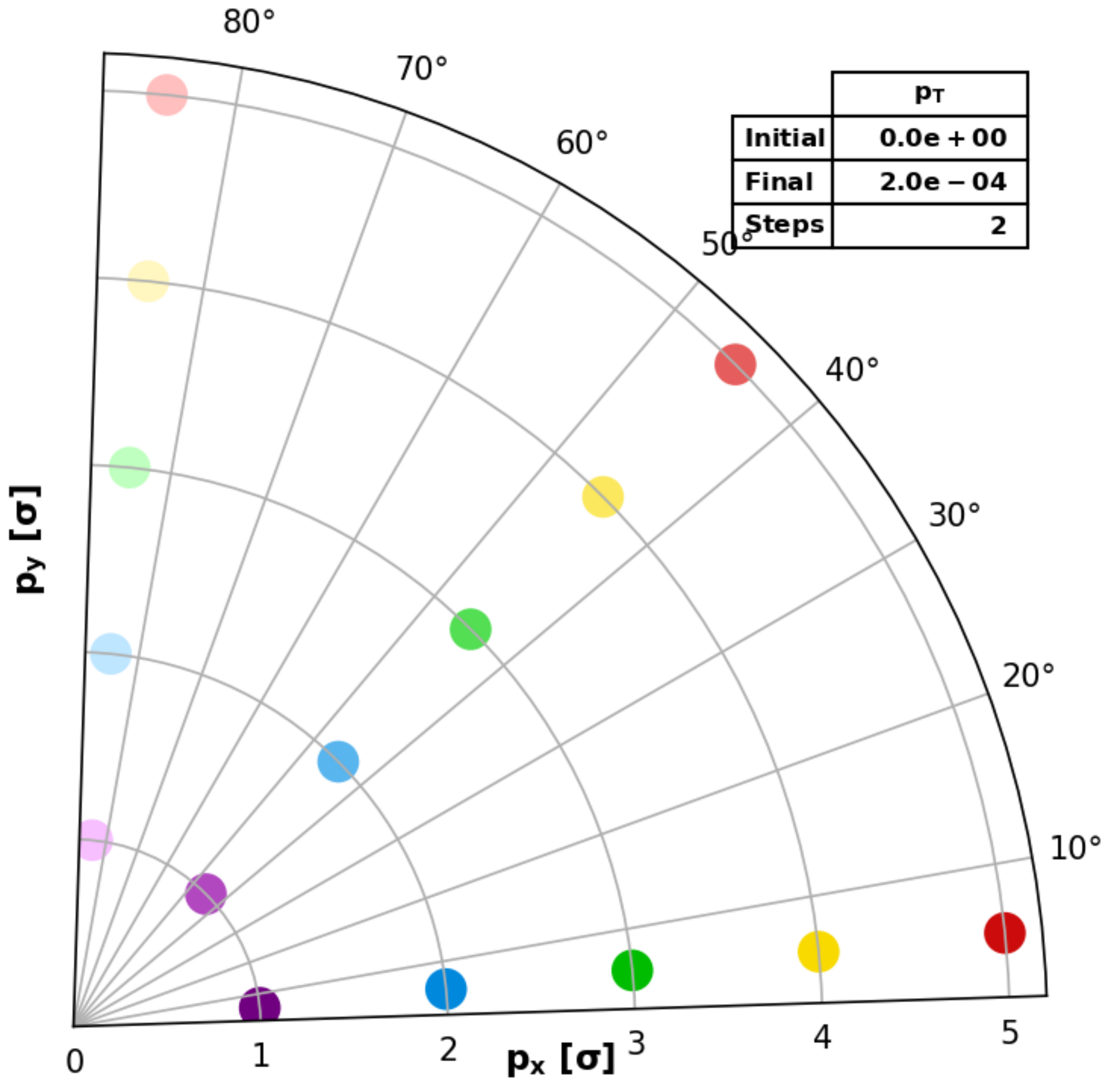


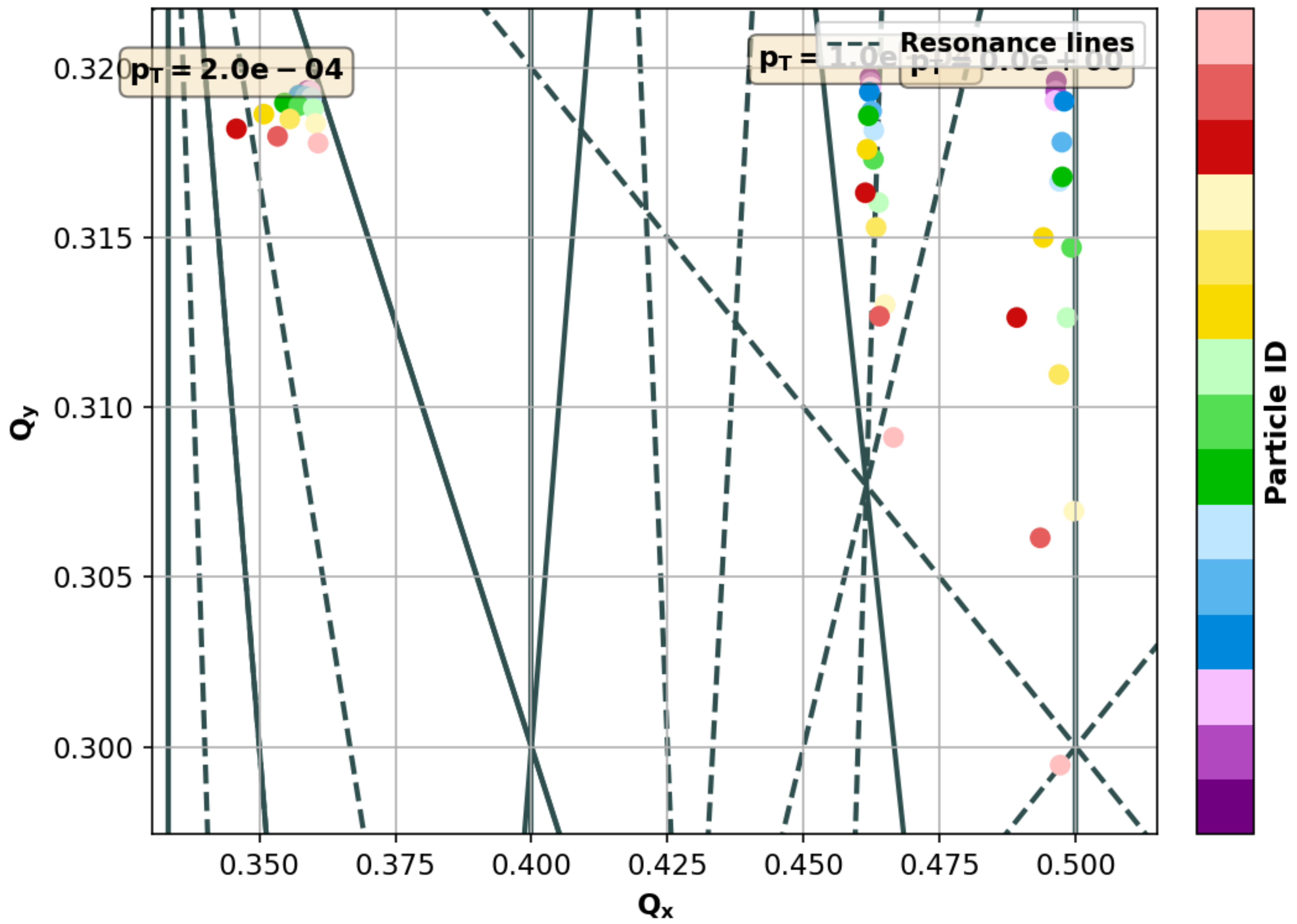
$\delta{*}W_{x,y} \simeq 0.1$

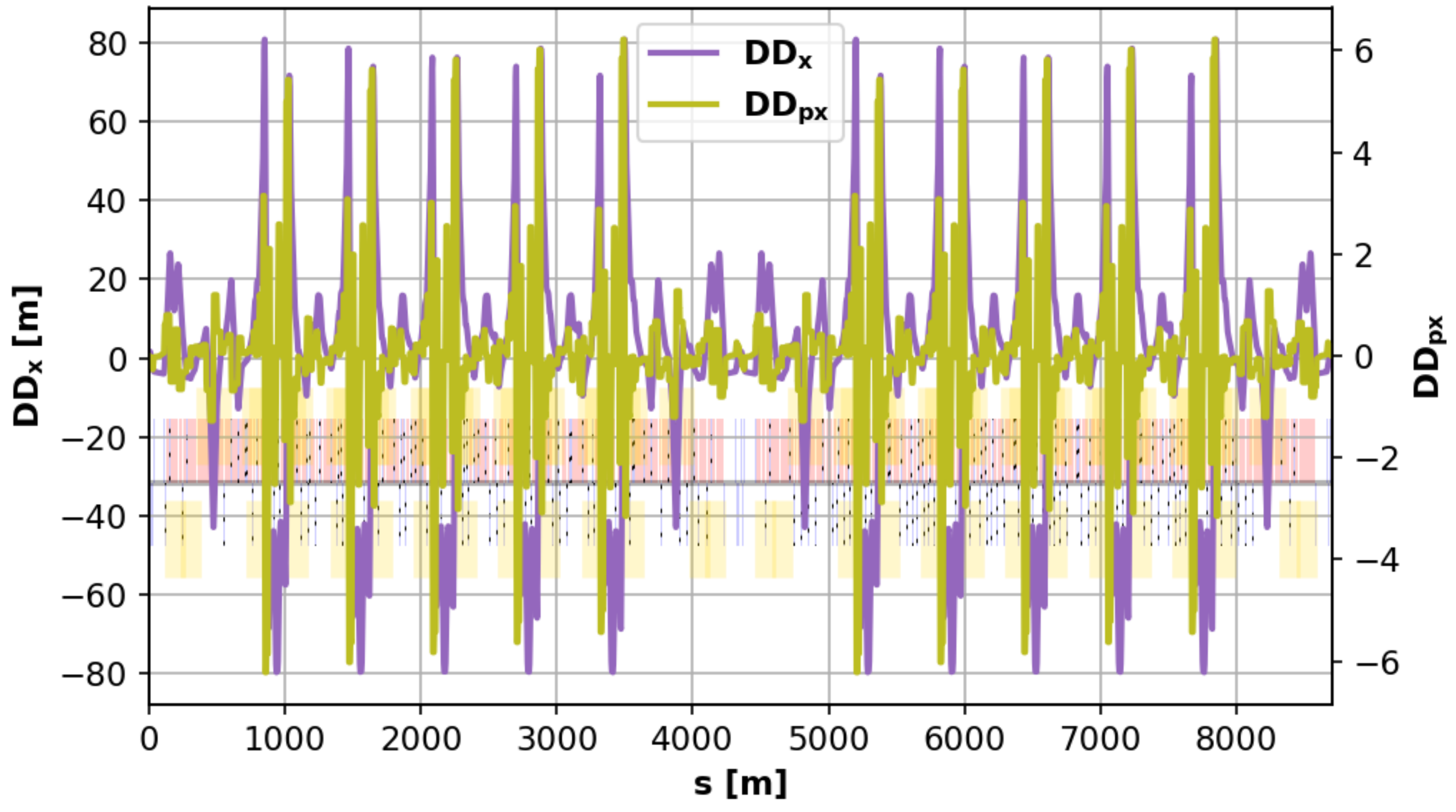
- The impact of the energy depended beta-beating, due to non zero δ*W, on the Luminosity should be assessed.

10TeV Muon Collider - Tracking Studies

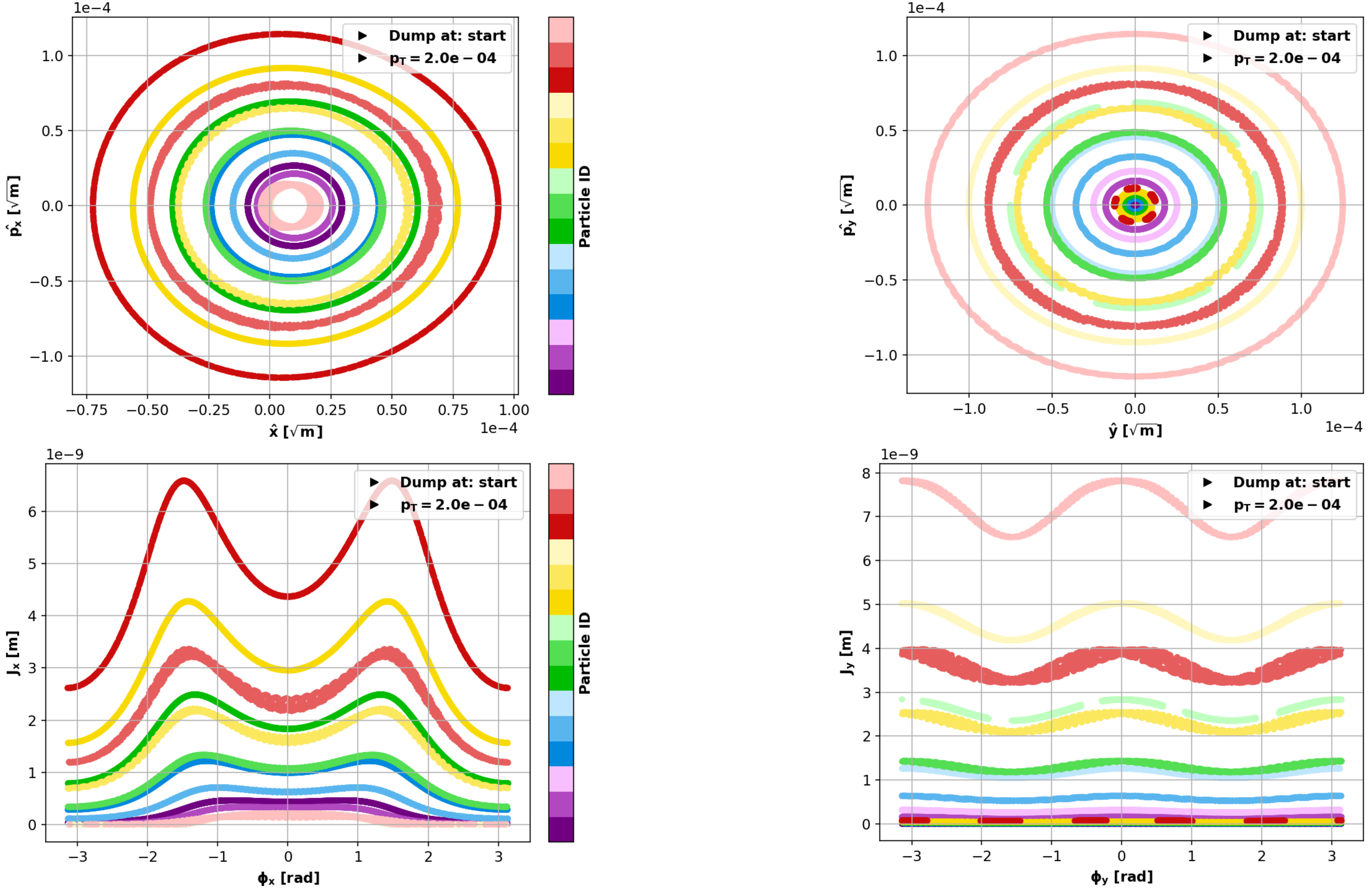
- Large higher order chromaticity, leads to insufficient momentum acceptance.
- Most probably, caused by slight betatron phase errors w.r.t. quads of inner triplet and sextuples in CC.
- Efforts to reduce these phase errors with next v0.6.



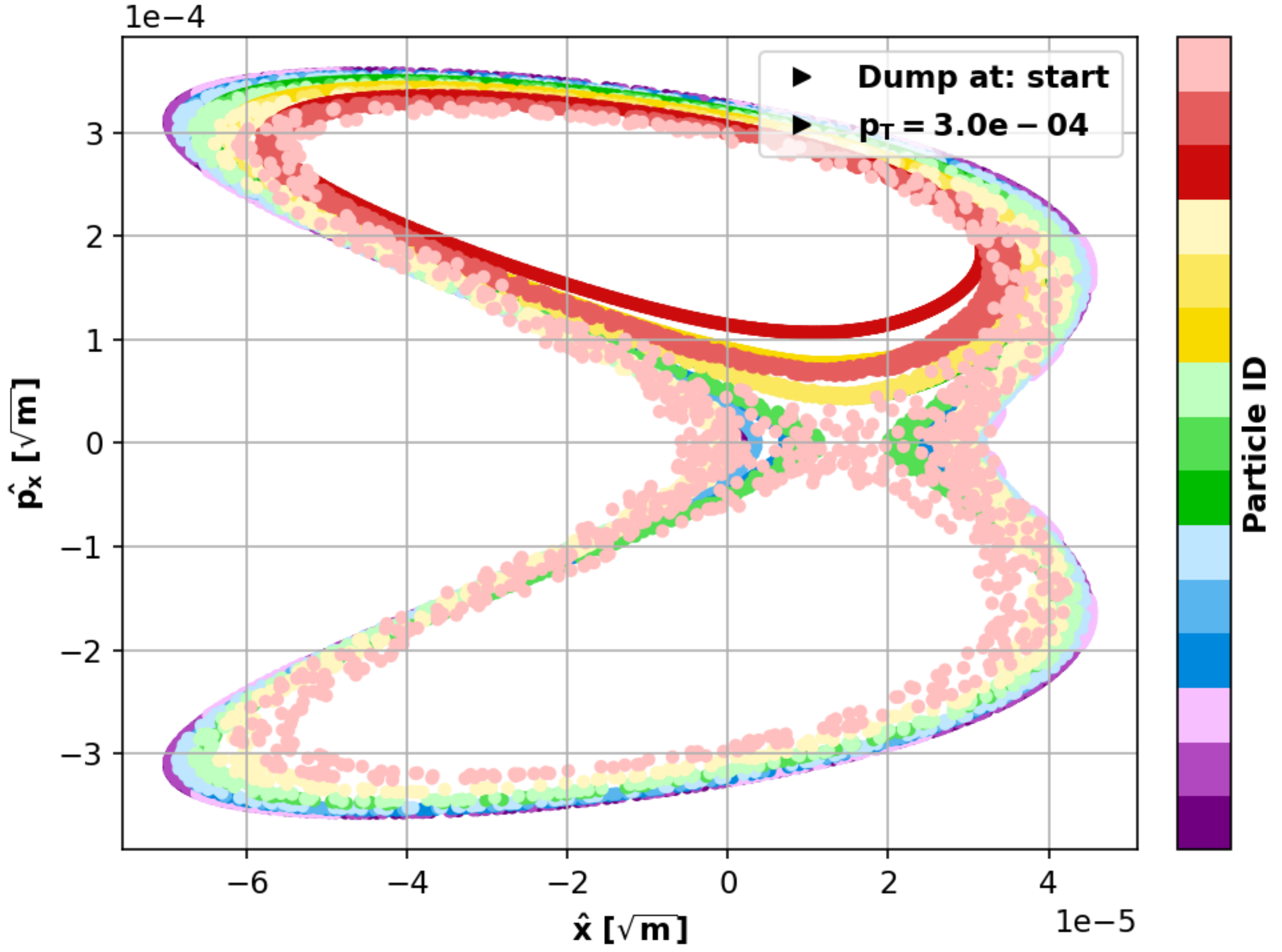


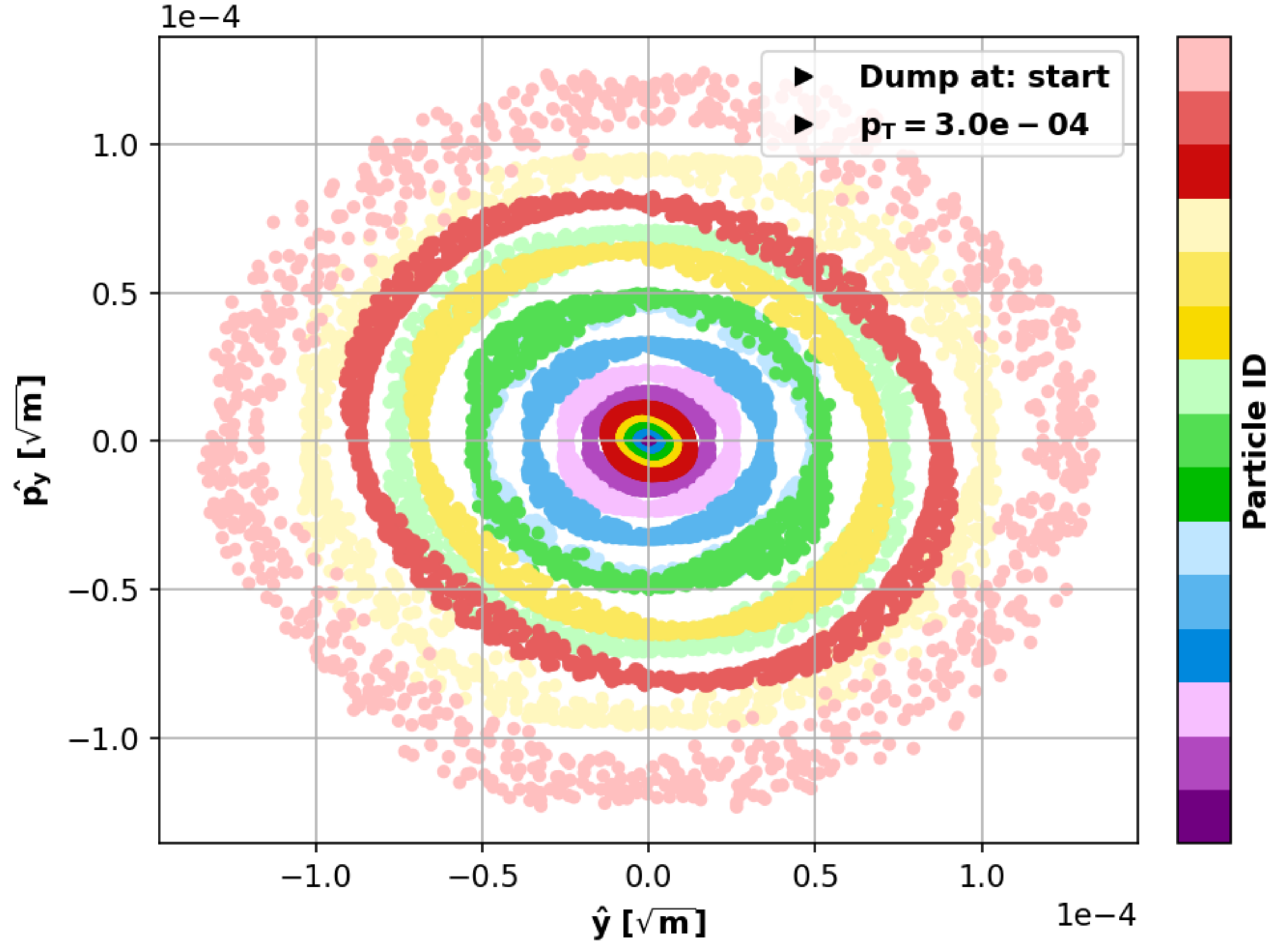


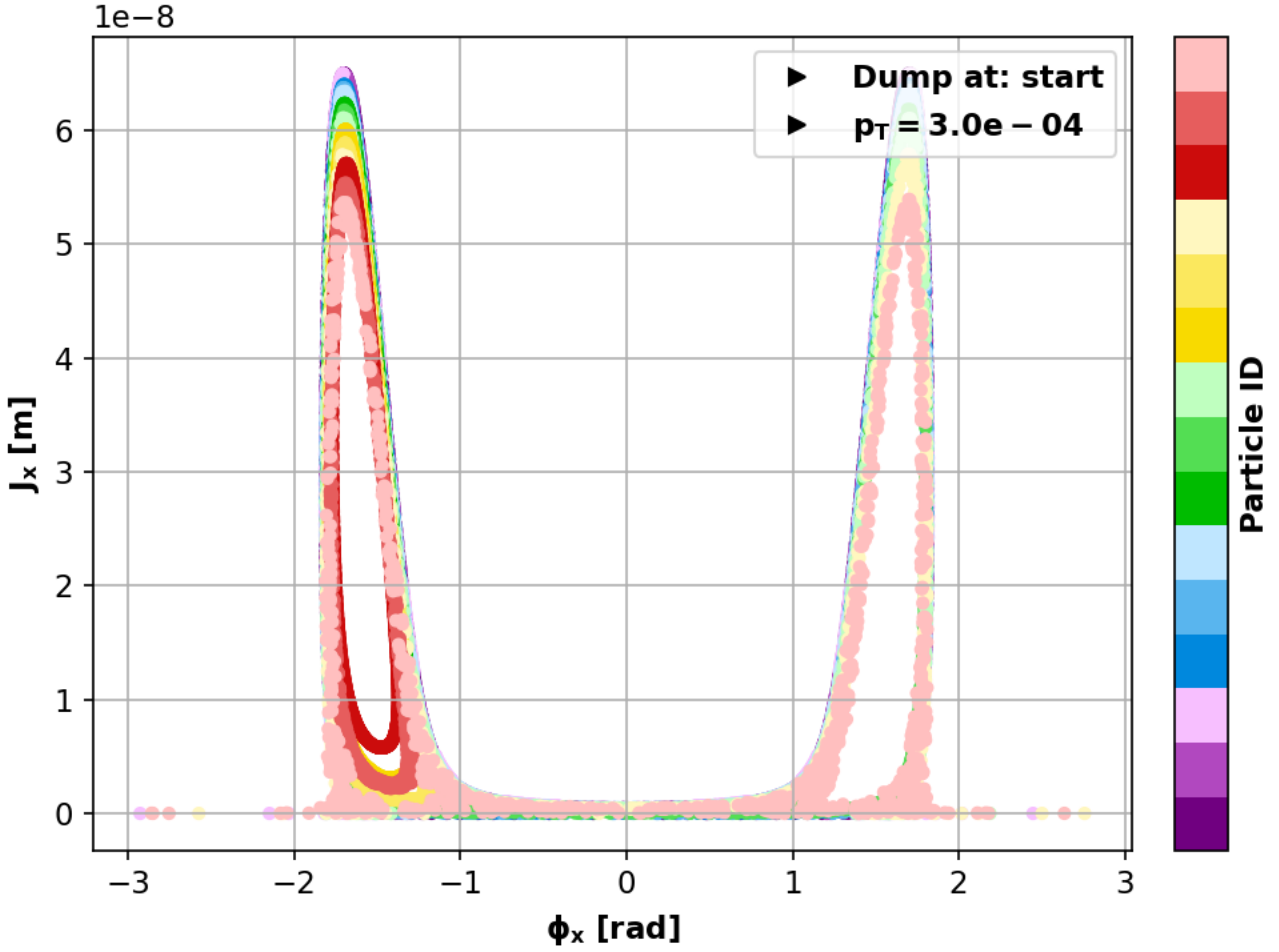
10TeV Muon Collider - Trackina Studies

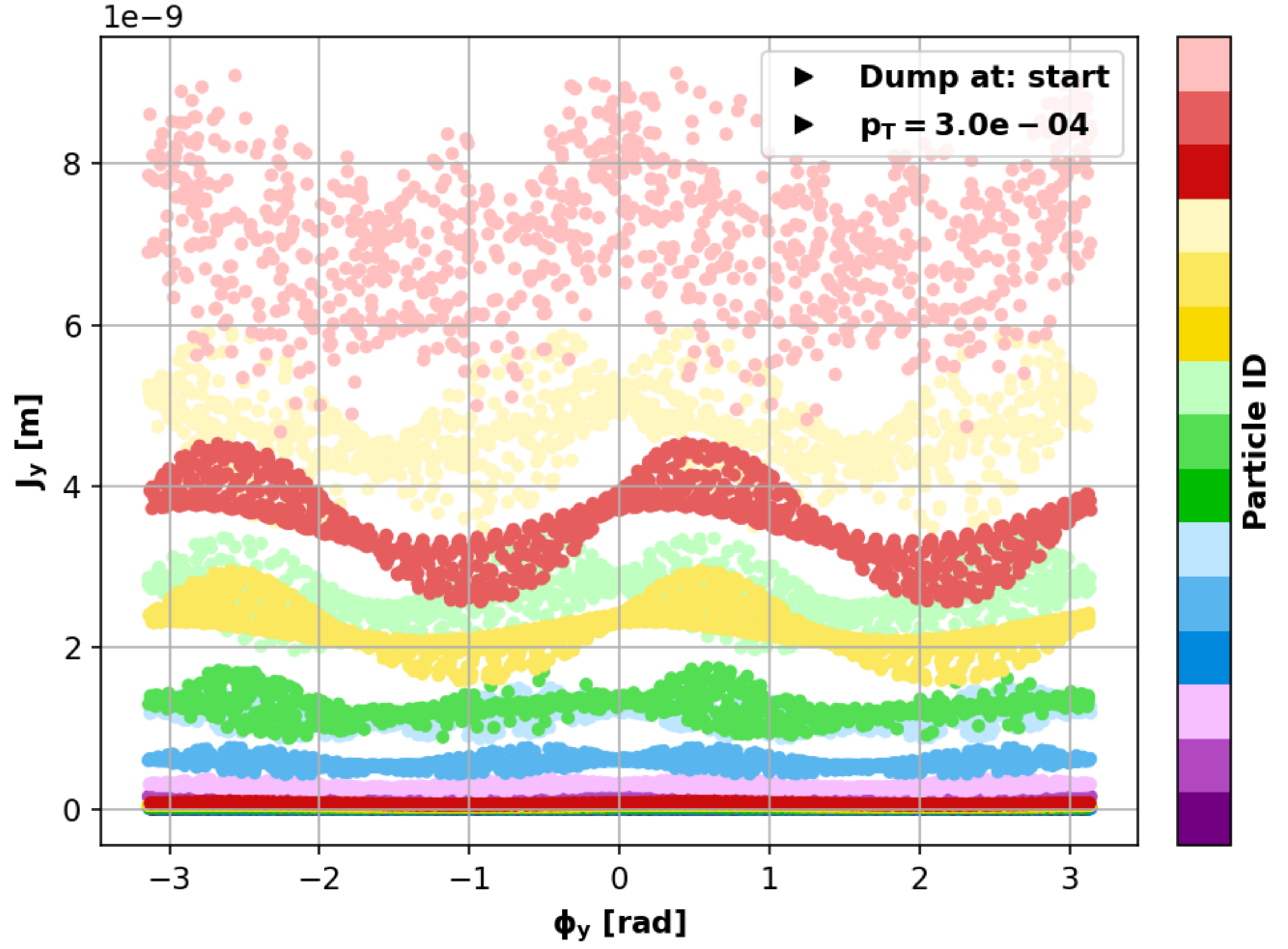


10TeV Muon Collider - Trackina Studies



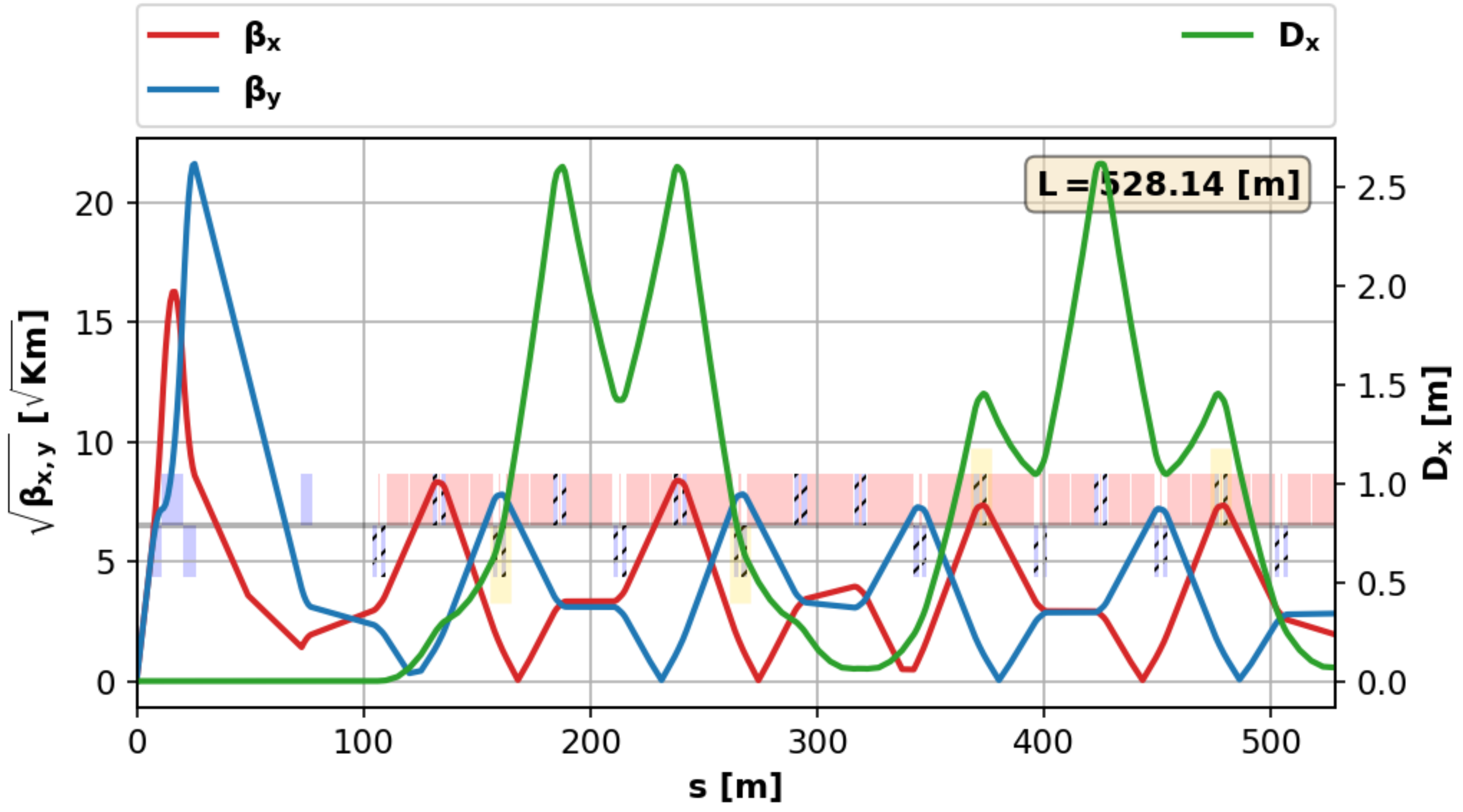






10TeV Muon Collider **v0.6**
(New design)

10TeV Muon Collider - Final Focusing



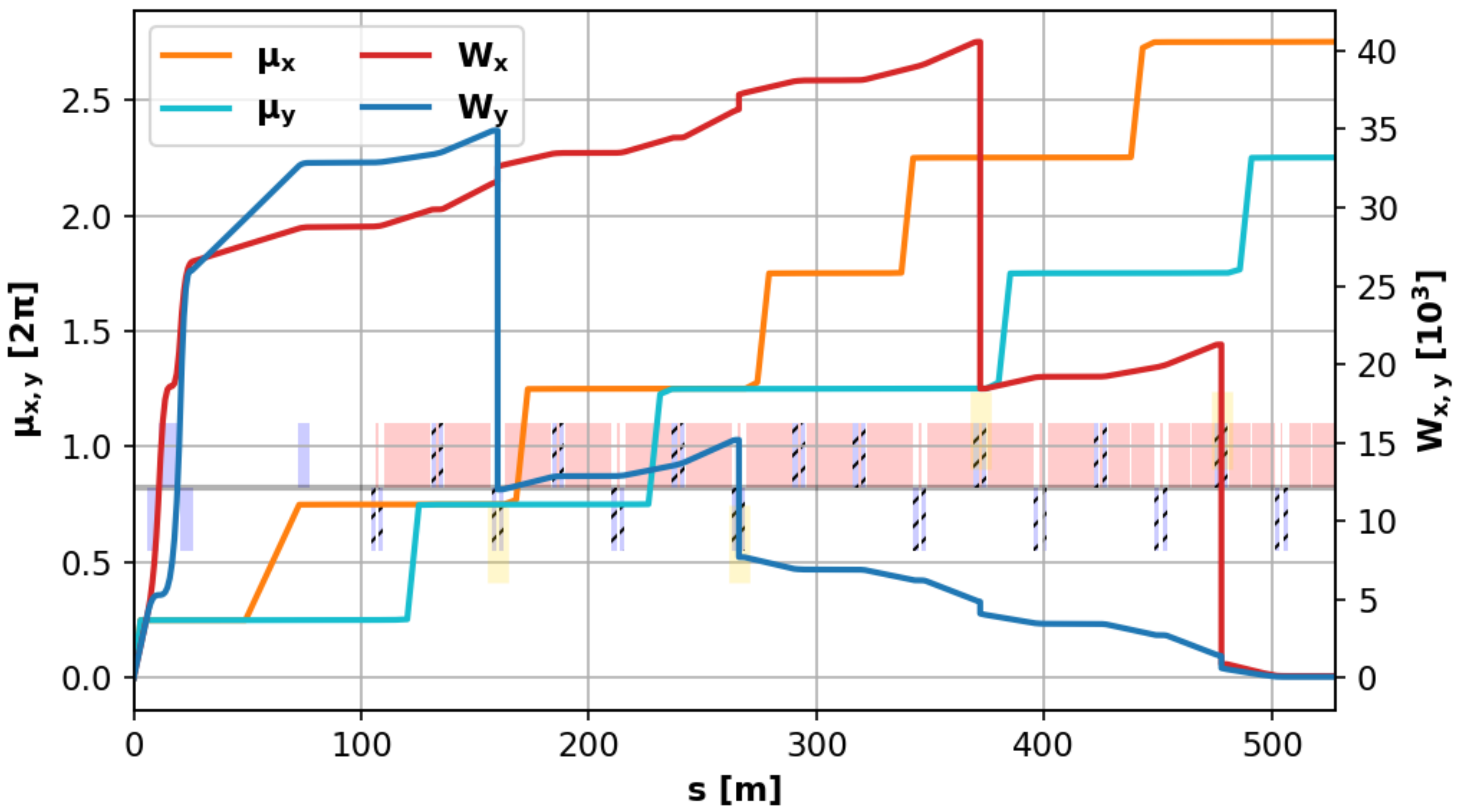
Pure quads and L*=6m

2 sets of dipole-sextuples

New Final Focussing

v0.6 FF include all the benefits of v0.5 (with similar design) and additional flexibilities for better control of the:

- W functions
- higher order chromatic effects



Summary

- Minimization of the areas without dipolar components in order to evenly distribute the muon decay products (mostly the neutrino flux) and to minimize the collider length.
- Extensive use of combined function magnets (dipole-quadrupole, dipole- sextupole, etc) with independent control of their multipolar components.
- The new final focusing controls the Montague chromatic functions and higher order chromatic effects.
- 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.

Outlook

- Complete lattice based on the improved CC sections.
- Study of non-linear dynamics and acceptances with this lattice -> non-linear momentum compaction.
- Proper modelling of combined function X-poles (higher order effects).
- Best location to include the straight sections.
- Estimation of the following parameters as well their tolerances:
  - minimum aperture (impedance, cold bore, coil insulation, thermal insulation between shielding and cold bore, ...)
  - maximum allowed magnetic fields - the strength of each multipole component in combined function, fringe field, power supply stability
  - maximum beta values (outside the IR) -> collider length -> Luminosity
  - chromatisity values (for stability), use of octuples
  - control of high order chromatic effects

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Thank you for your time!

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

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