# Concurrent Operation of the LHeC and the High Luminosity -LHC

## Investigation of the Transversal Beam Dynamics of the Proton Beams

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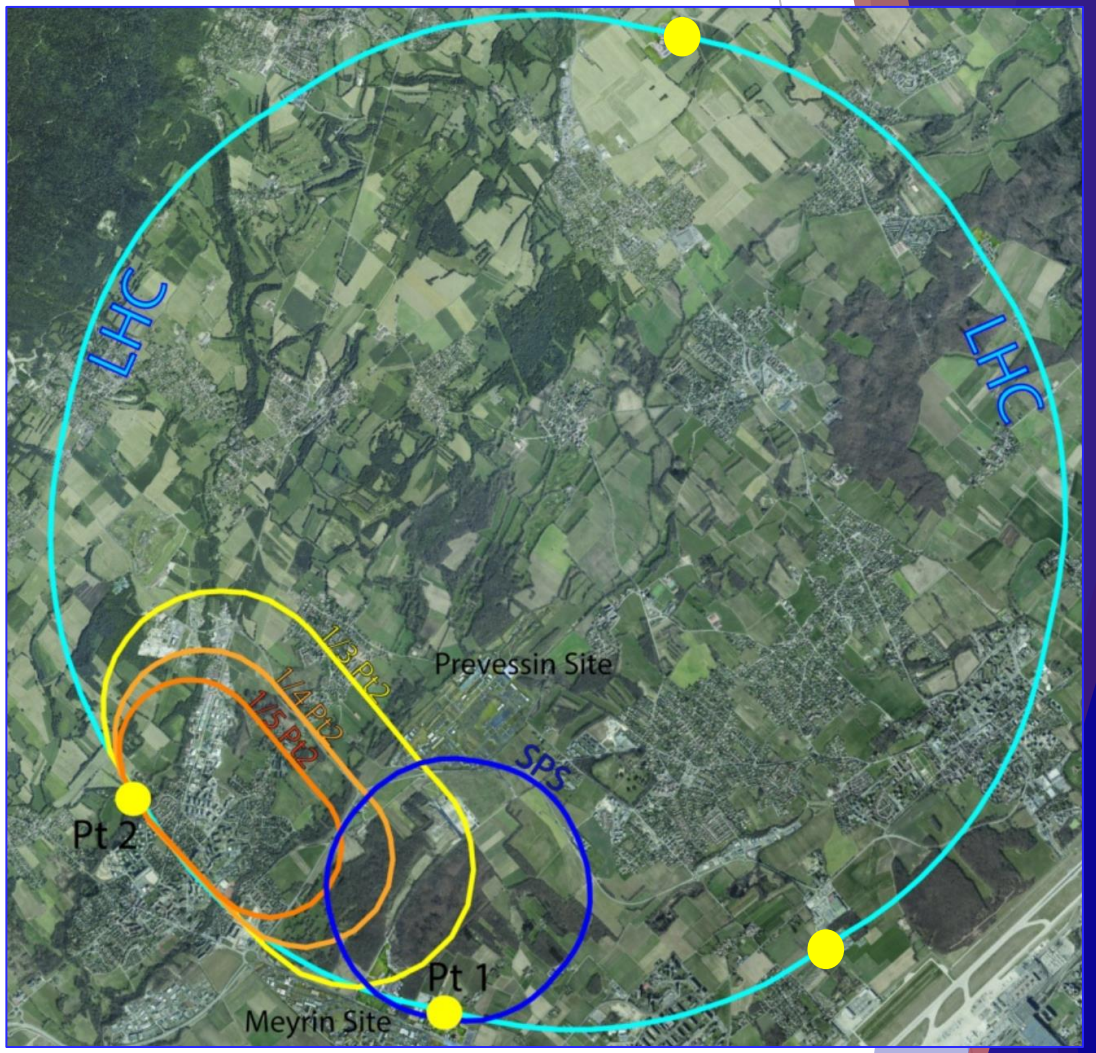
# LHeC in Concurrent Operation

- Equip the HL-LHC with a tangential energy recovery linac
- Realization of collisions of a 7 TeV proton beam with a 50 GeV electron beam -> $\sqrt{s} = 1.2$ TeV
- This would enable deep inelastic scattering experiments at IP2 with concurrent operation with the other experiments




Create a beam optics, enabling e-p collisions and one spectator proton beam passing by

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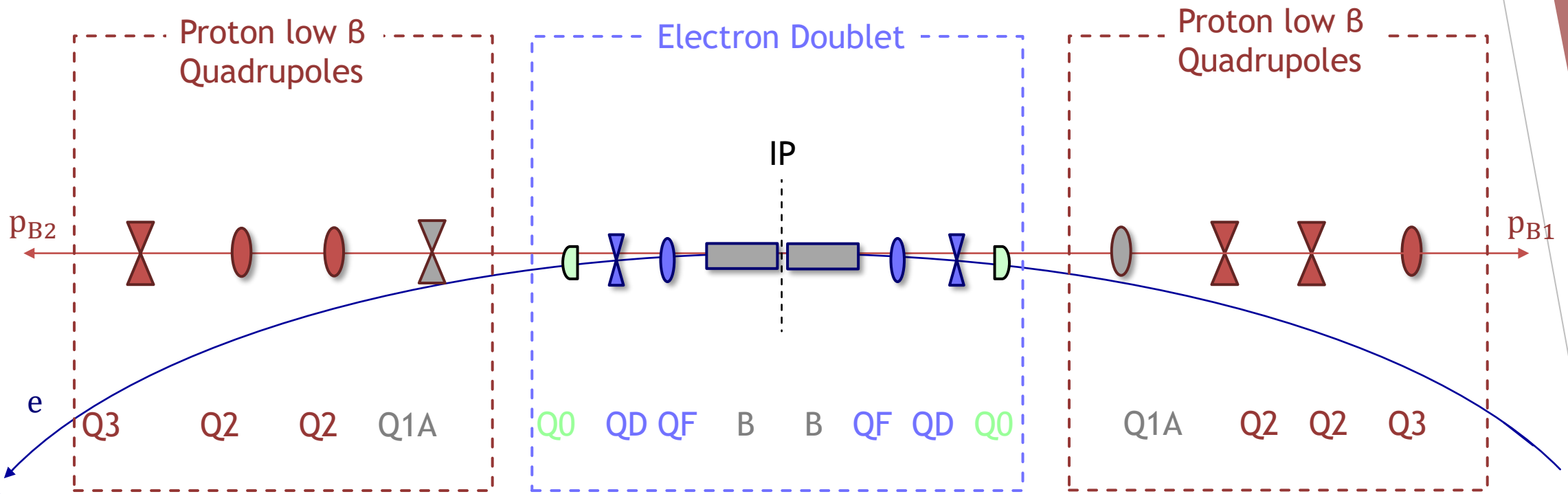
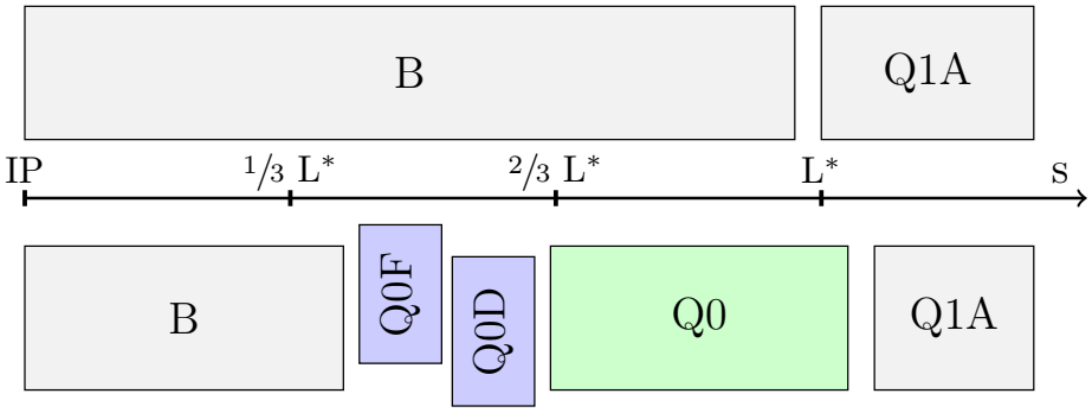
# Insertion of the Electron Doublet in the IR2 of the LHC




Doublet designed by K. André

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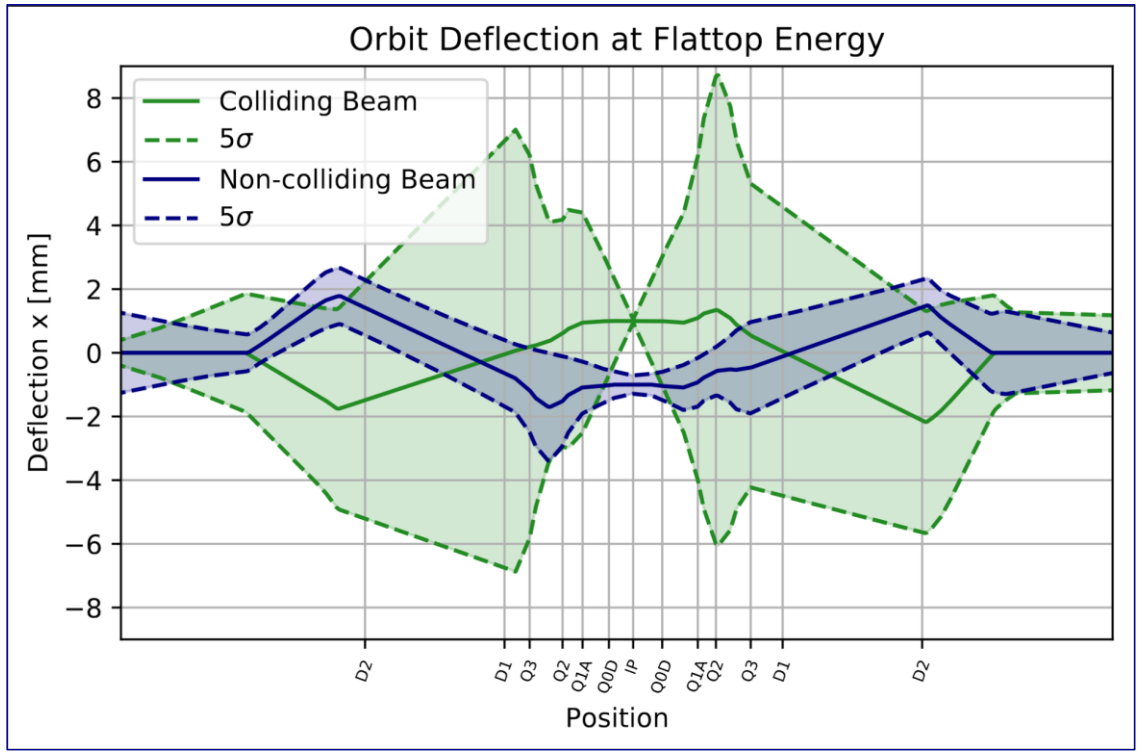
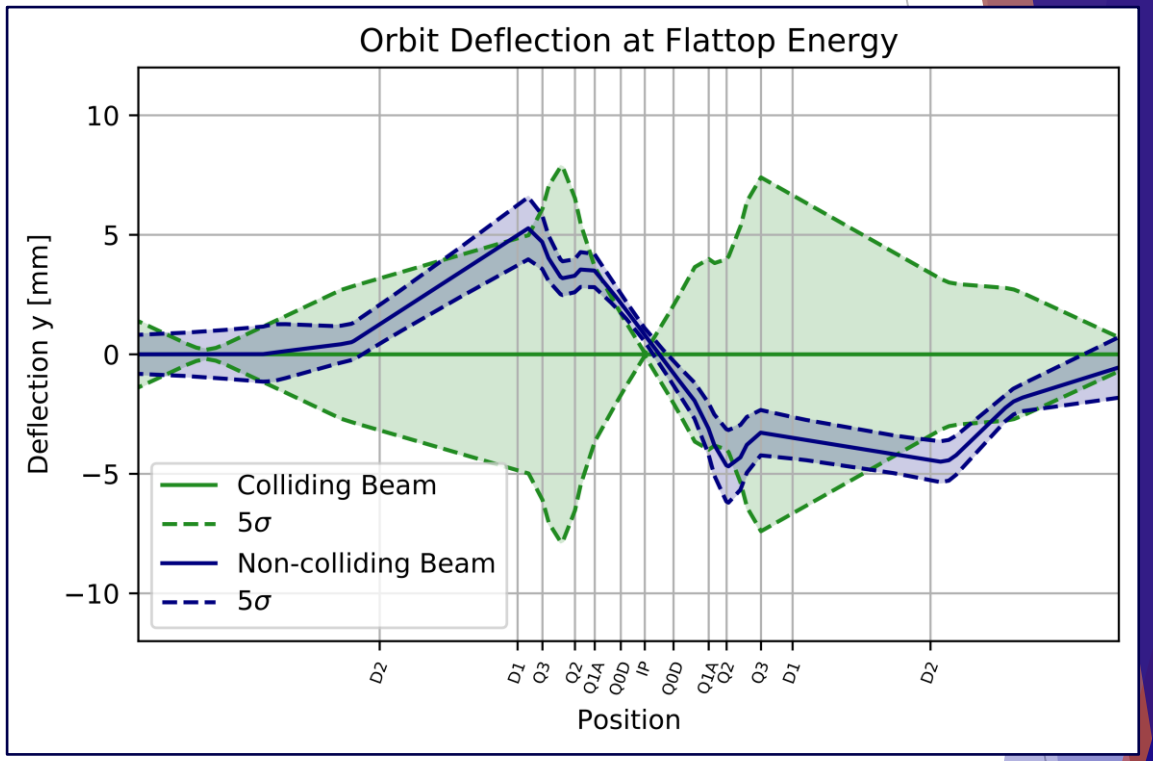
# Proton Beam Orbits and Optics

## x-plane




## y-plane




At the IP:

ß*= 0.35m Colliding Beam

ß*= 10m Non-colliding Beam

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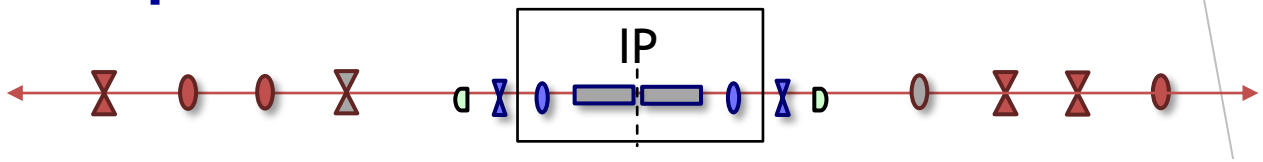
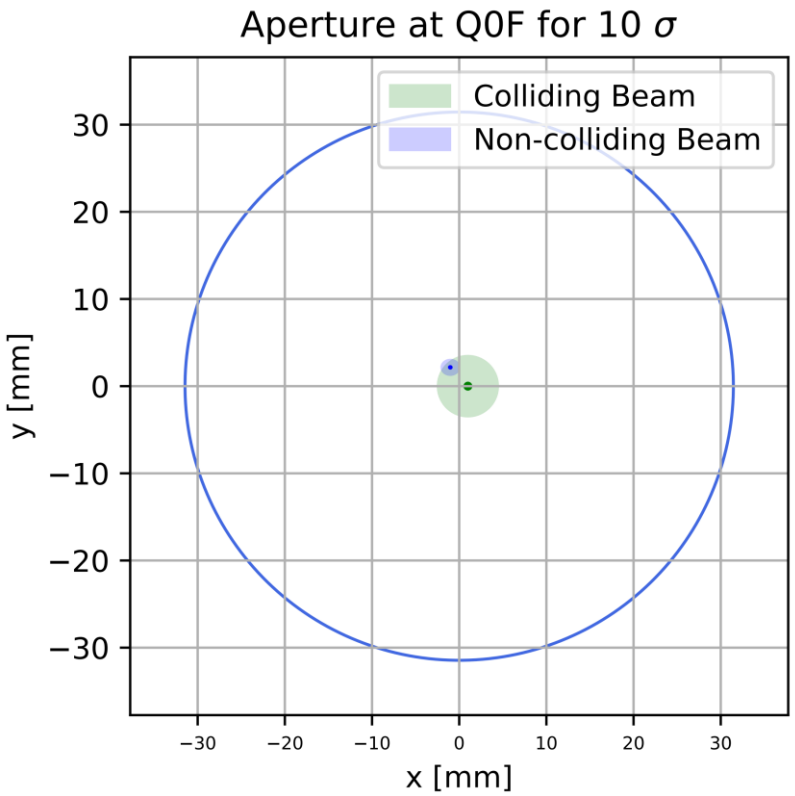
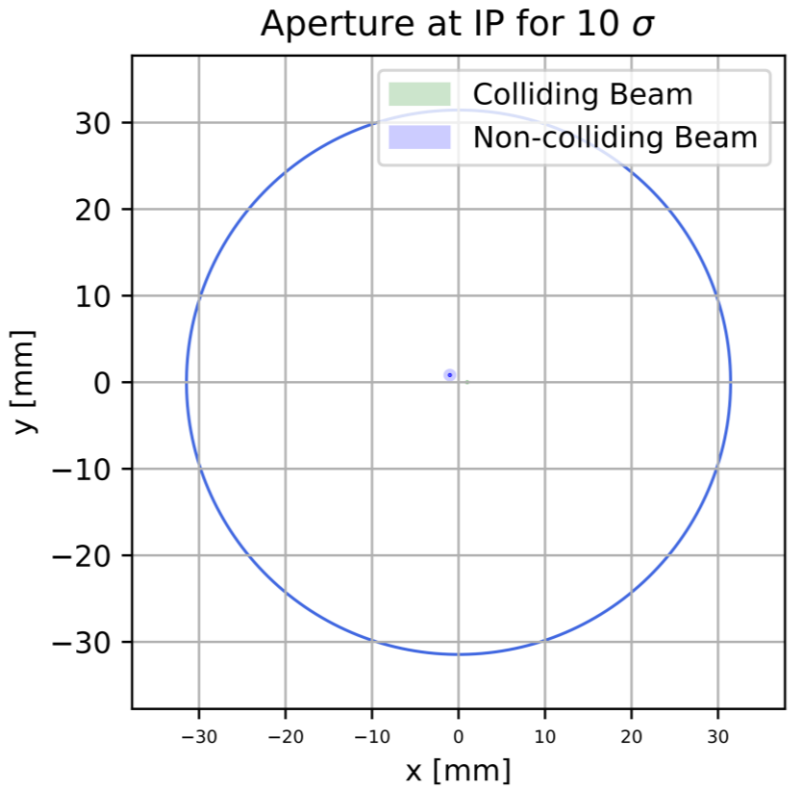
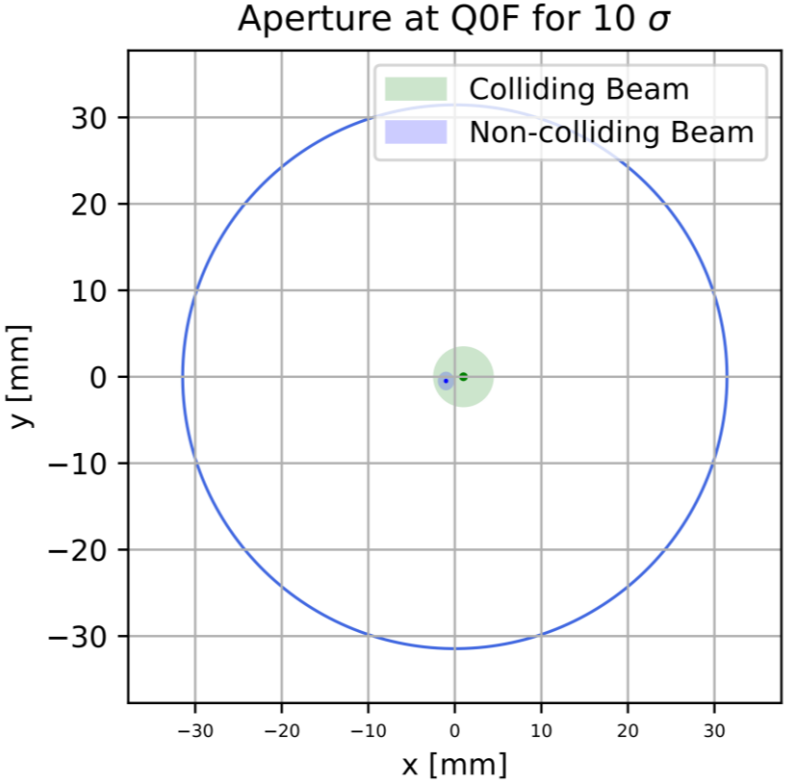
# Apertures in the Beam Pipe



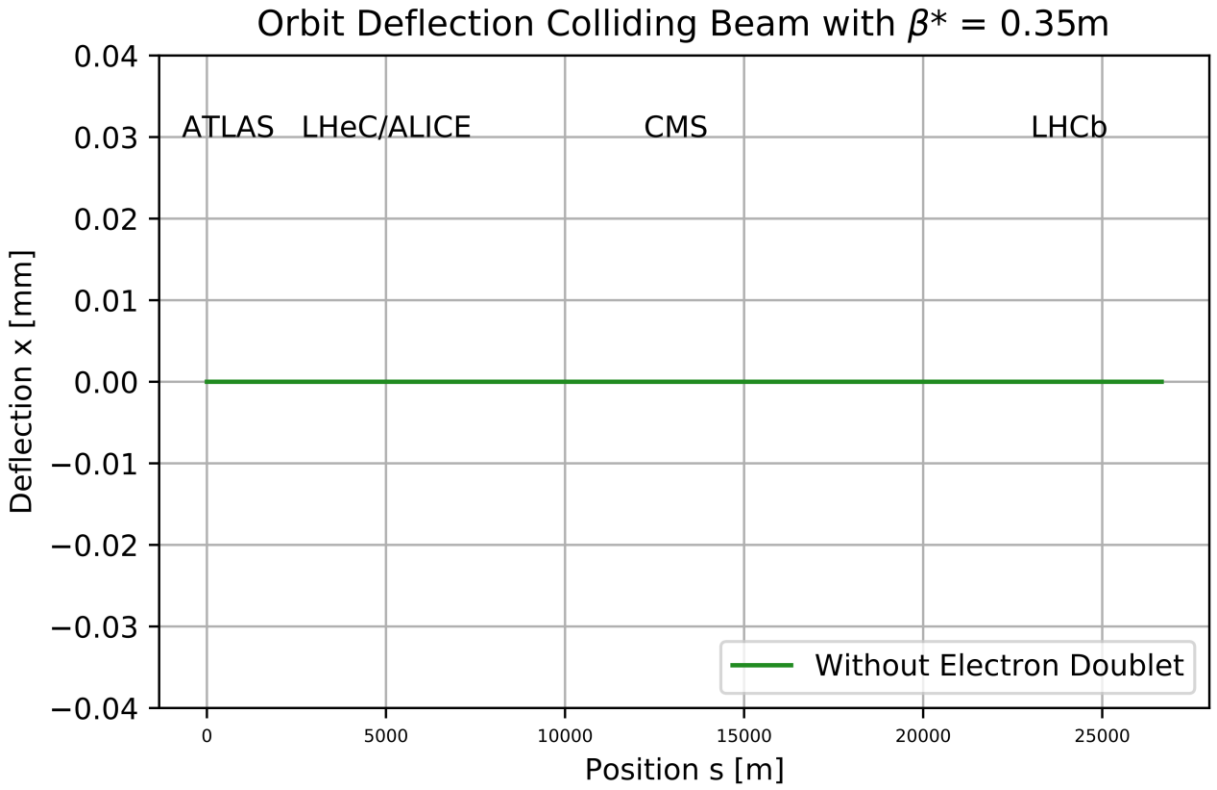




Cross section beam pipes

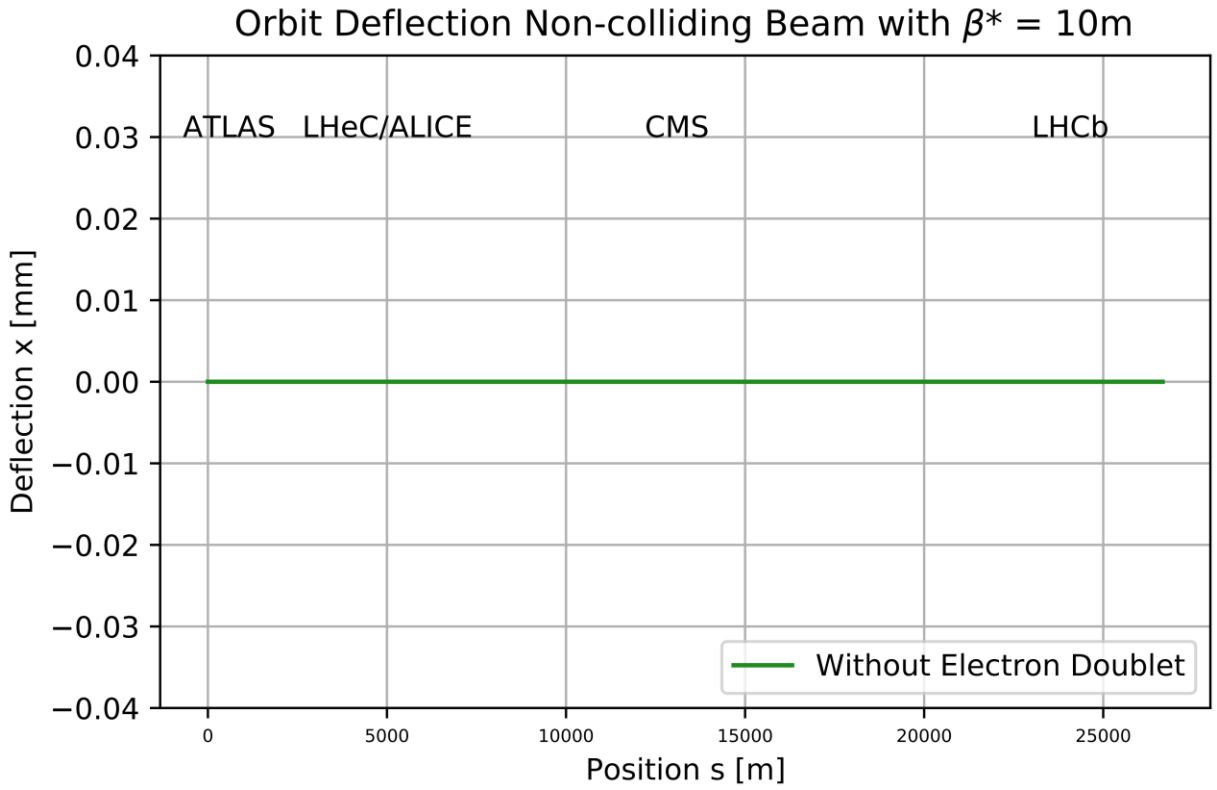
At the IP:
ß*= 0.35m Colliding Beam
ß*= 10m Non-colliding Beam

# Impact on the Proton Orbits x-plane

- Colliding Beam




- Non-colliding Beam

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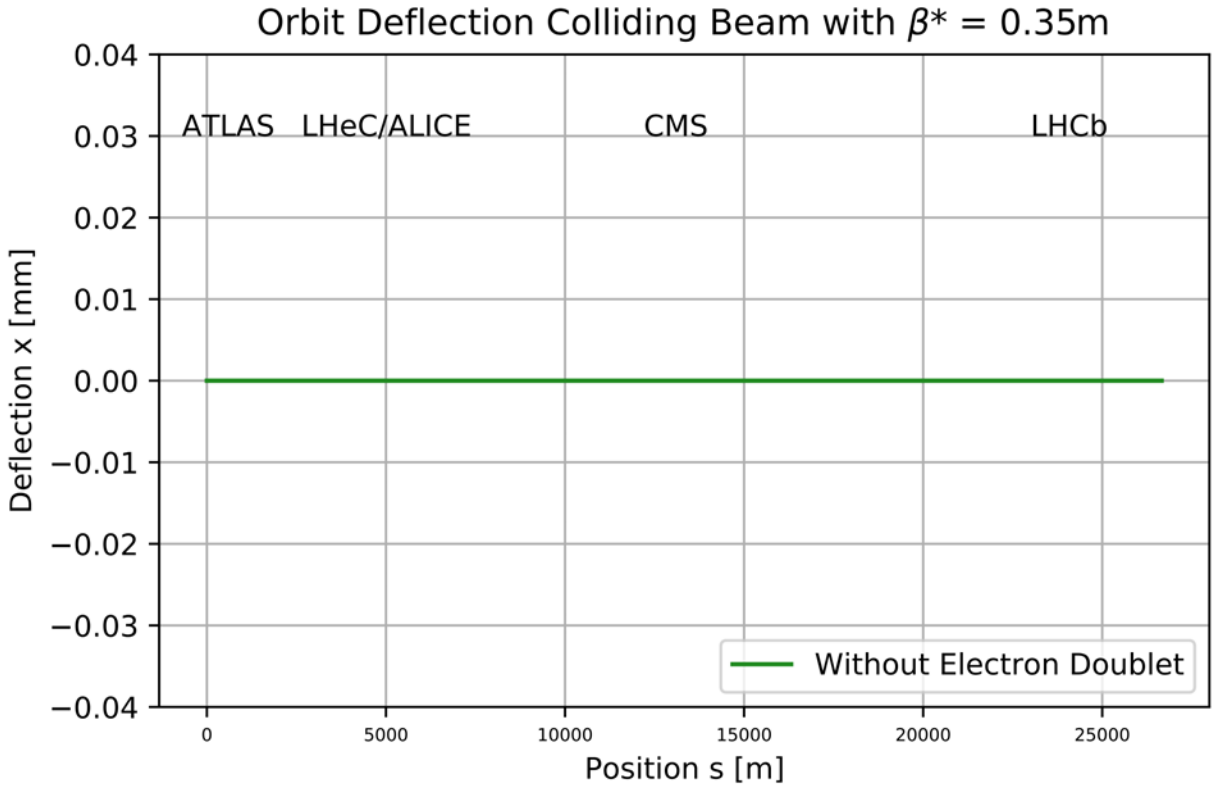
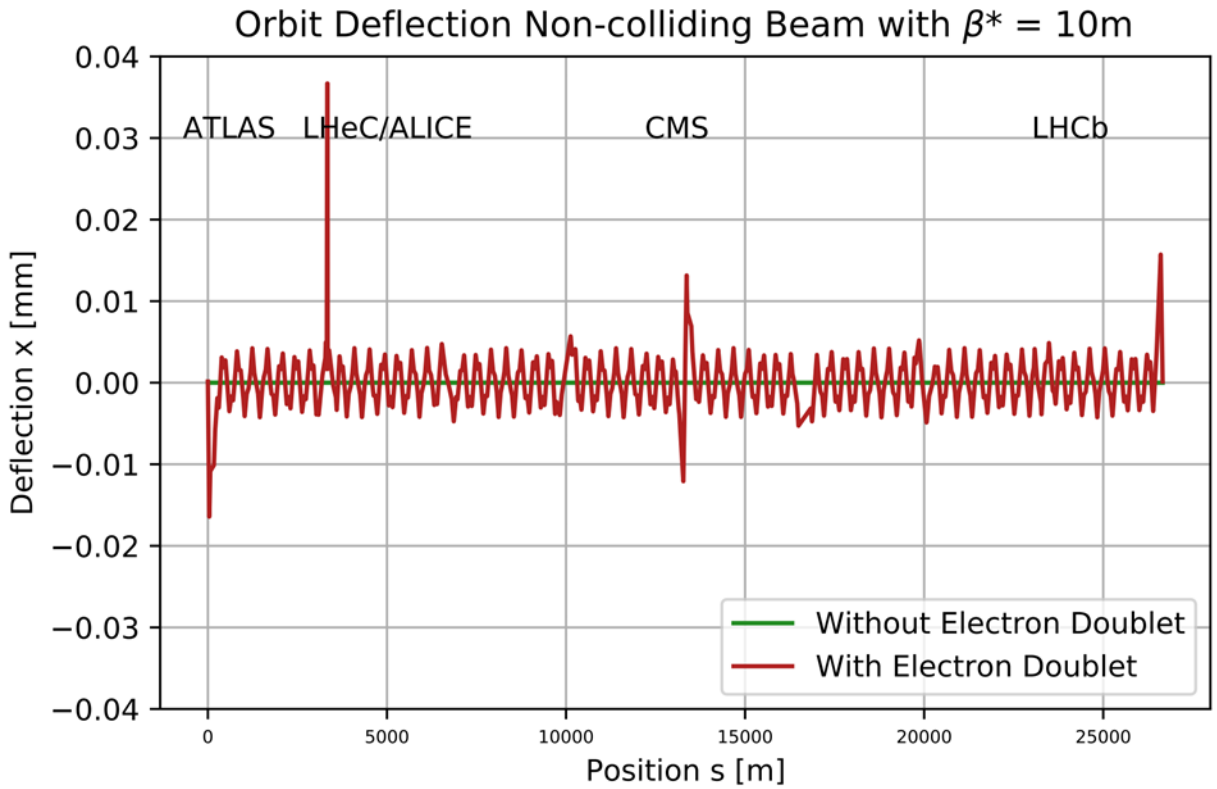
# Impact on the Proton Orbits x-plane

- Colliding Beam




- Non-colliding Beam

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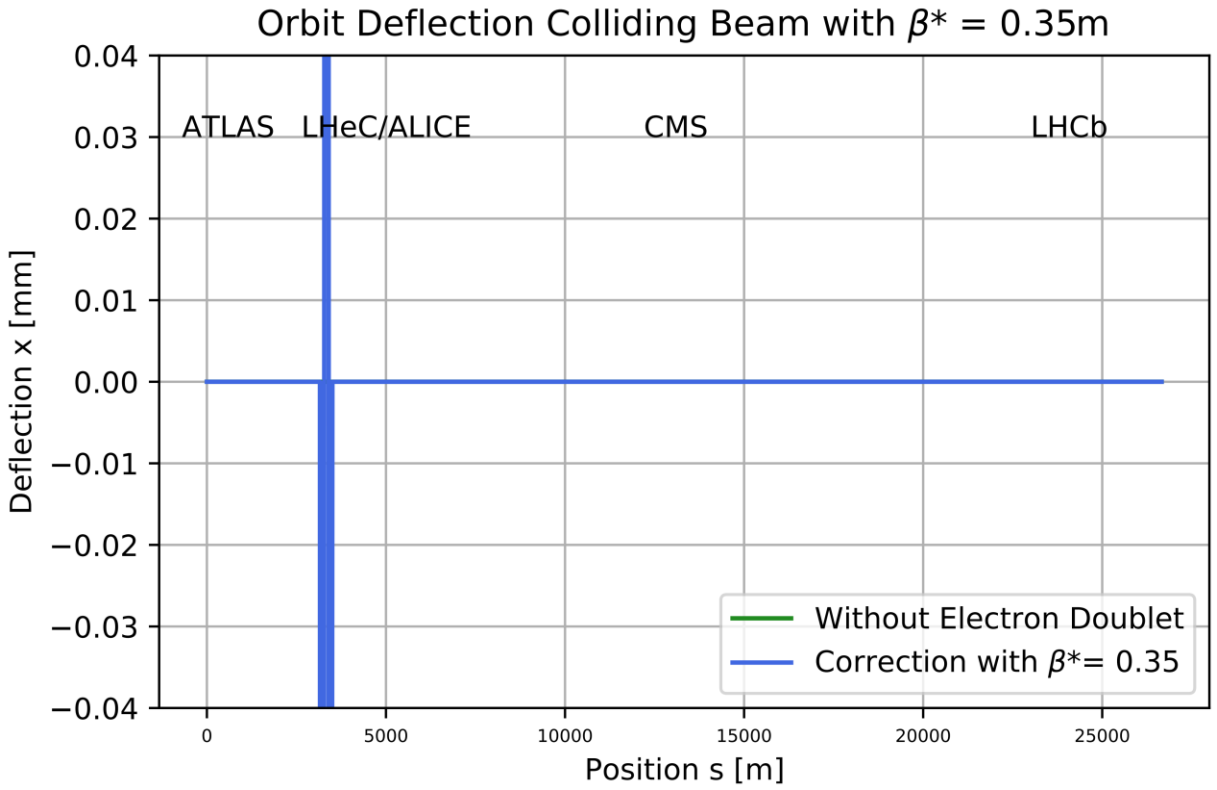
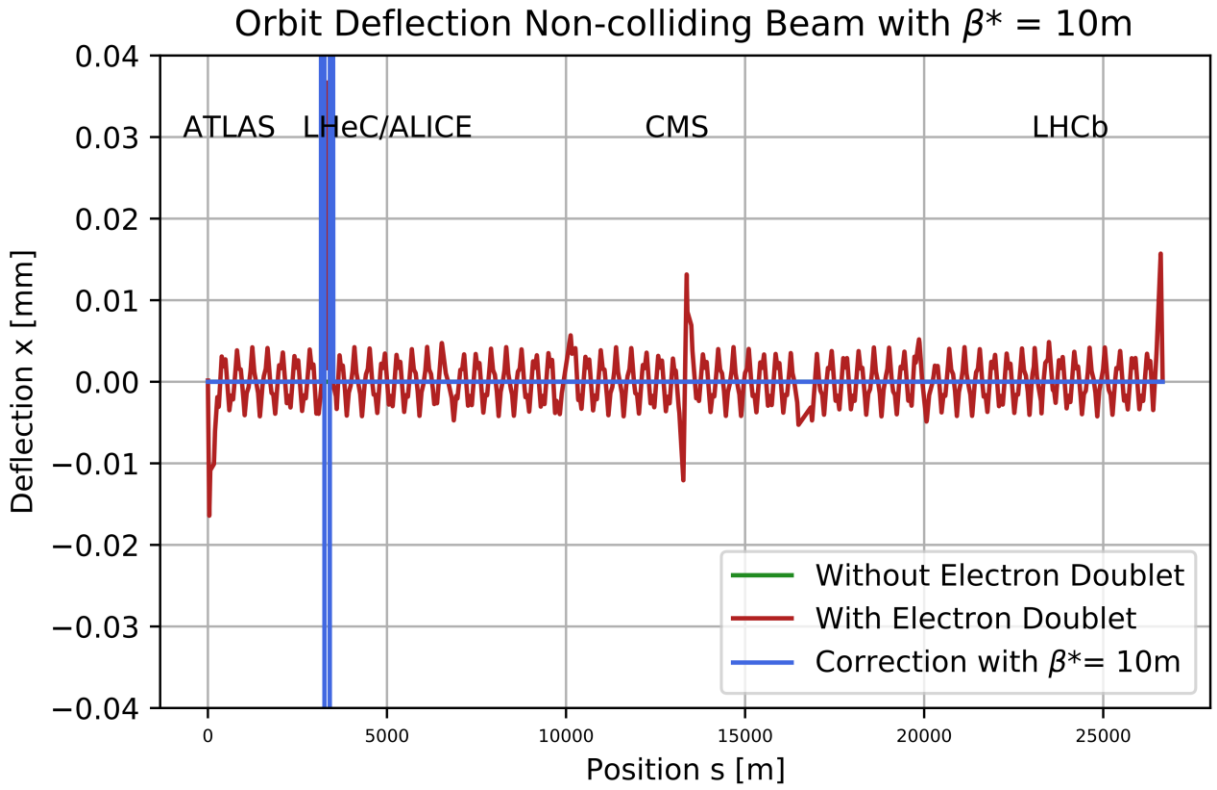
# Impact on the Proton Orbits x-plane

- Colliding Beam




- Non-colliding Beam

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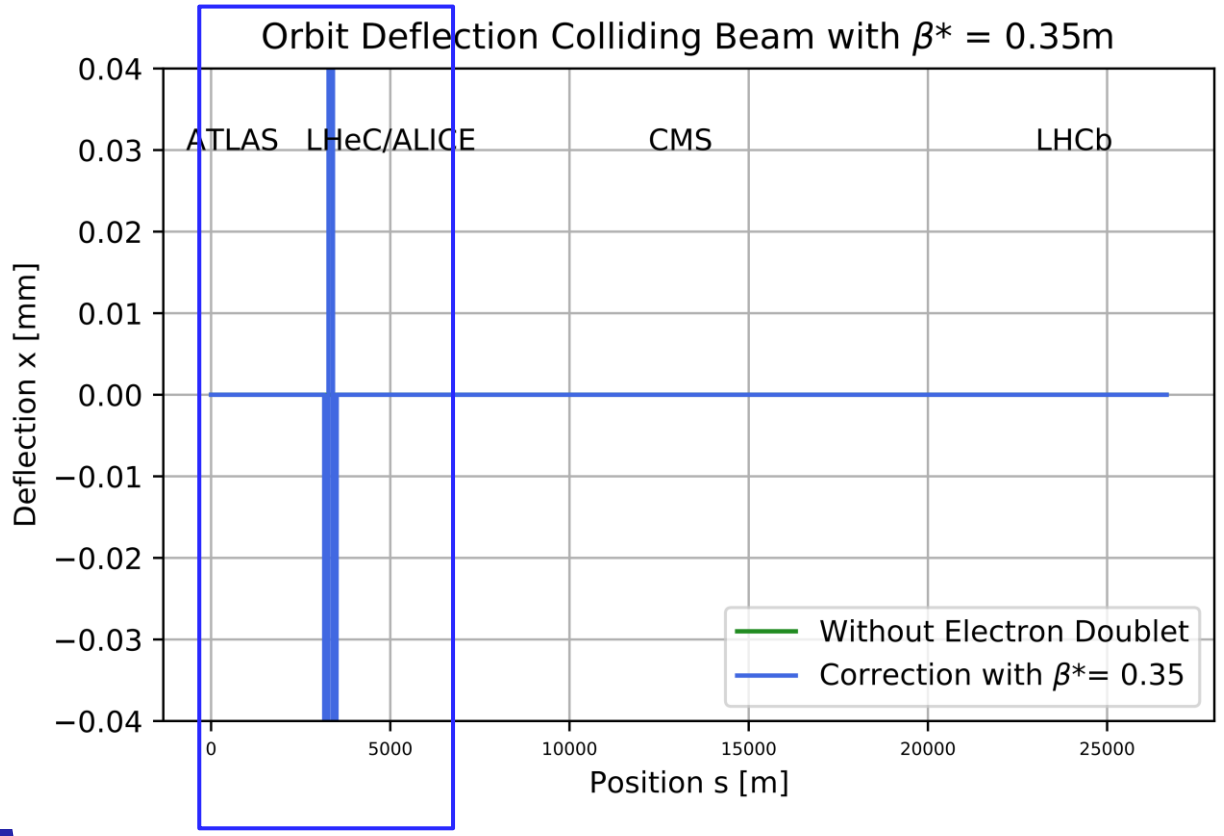
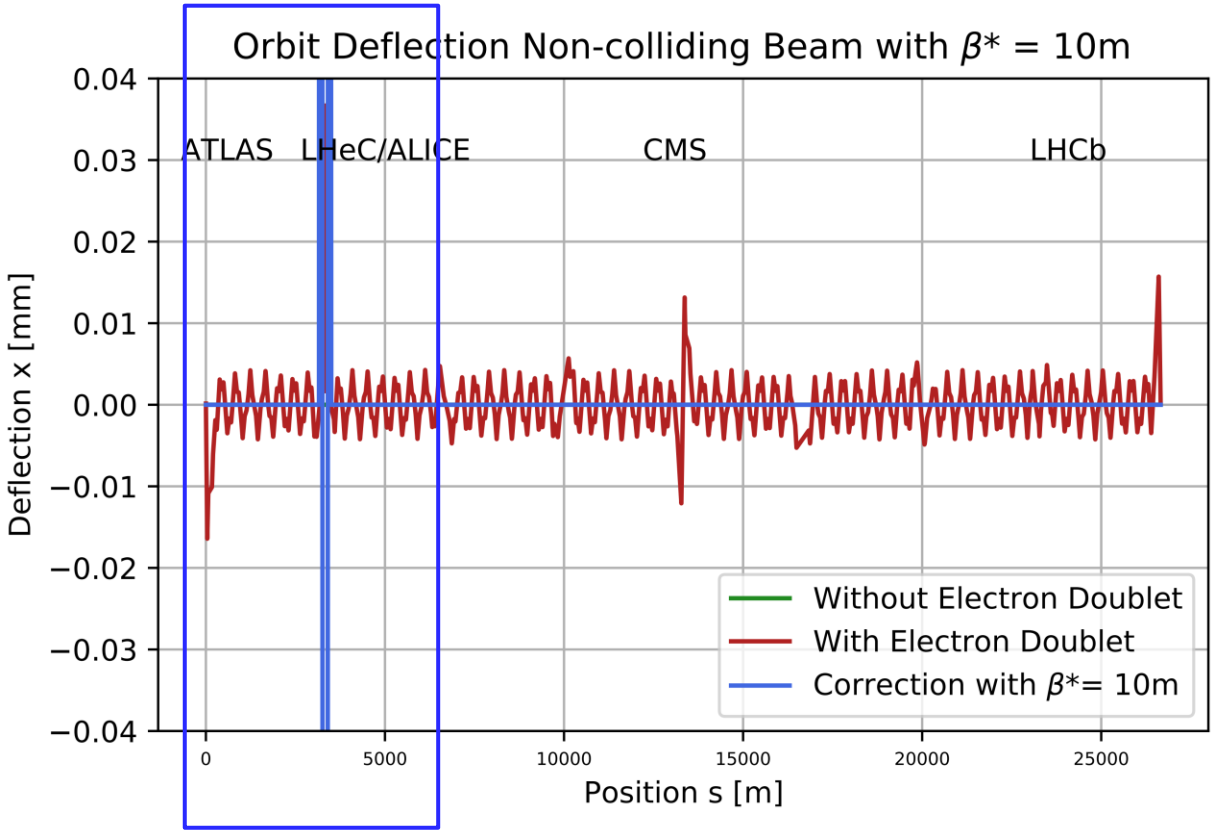
# Impact on the Proton Orbits x-plane

- Colliding Beam




- Non-colliding Beam

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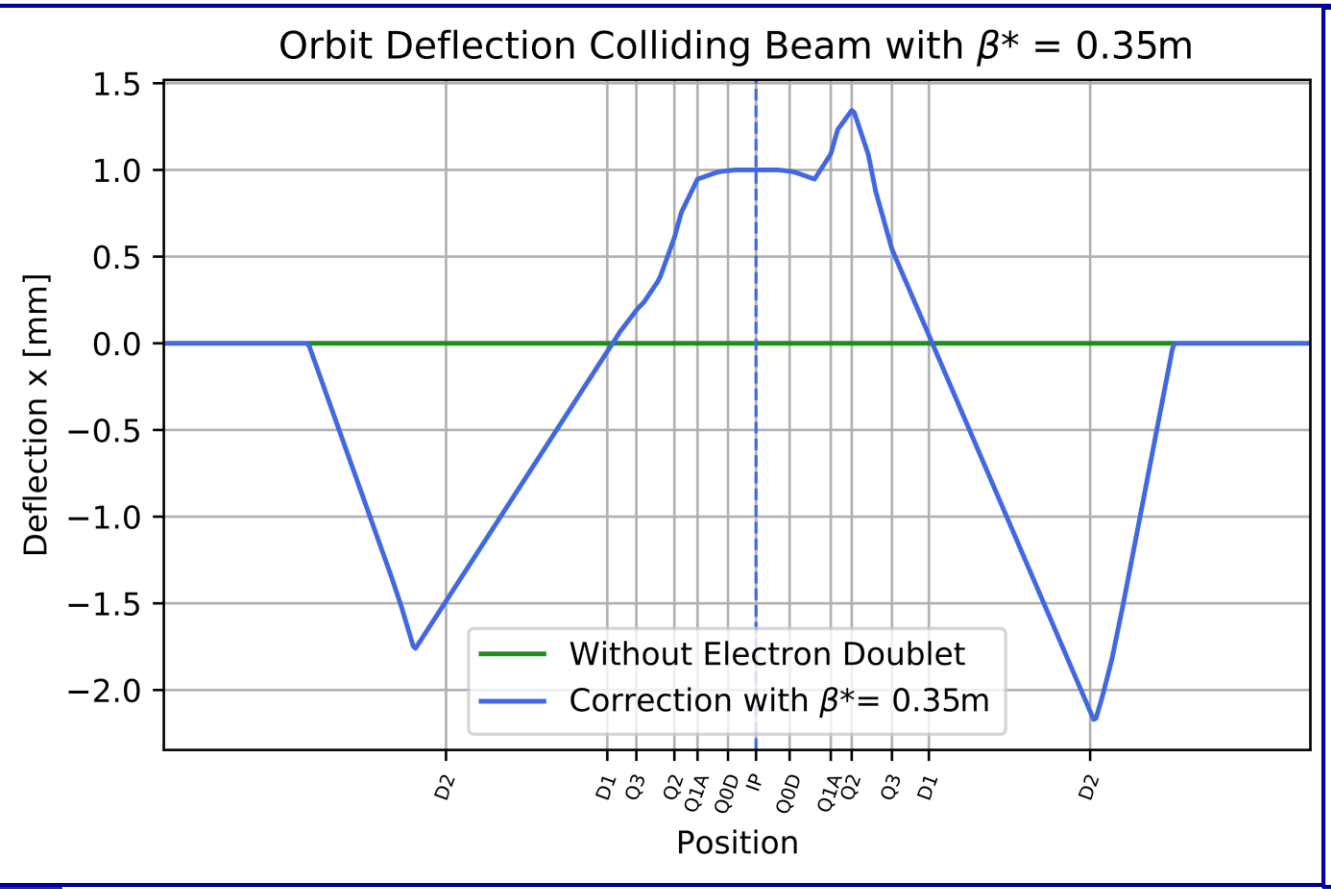
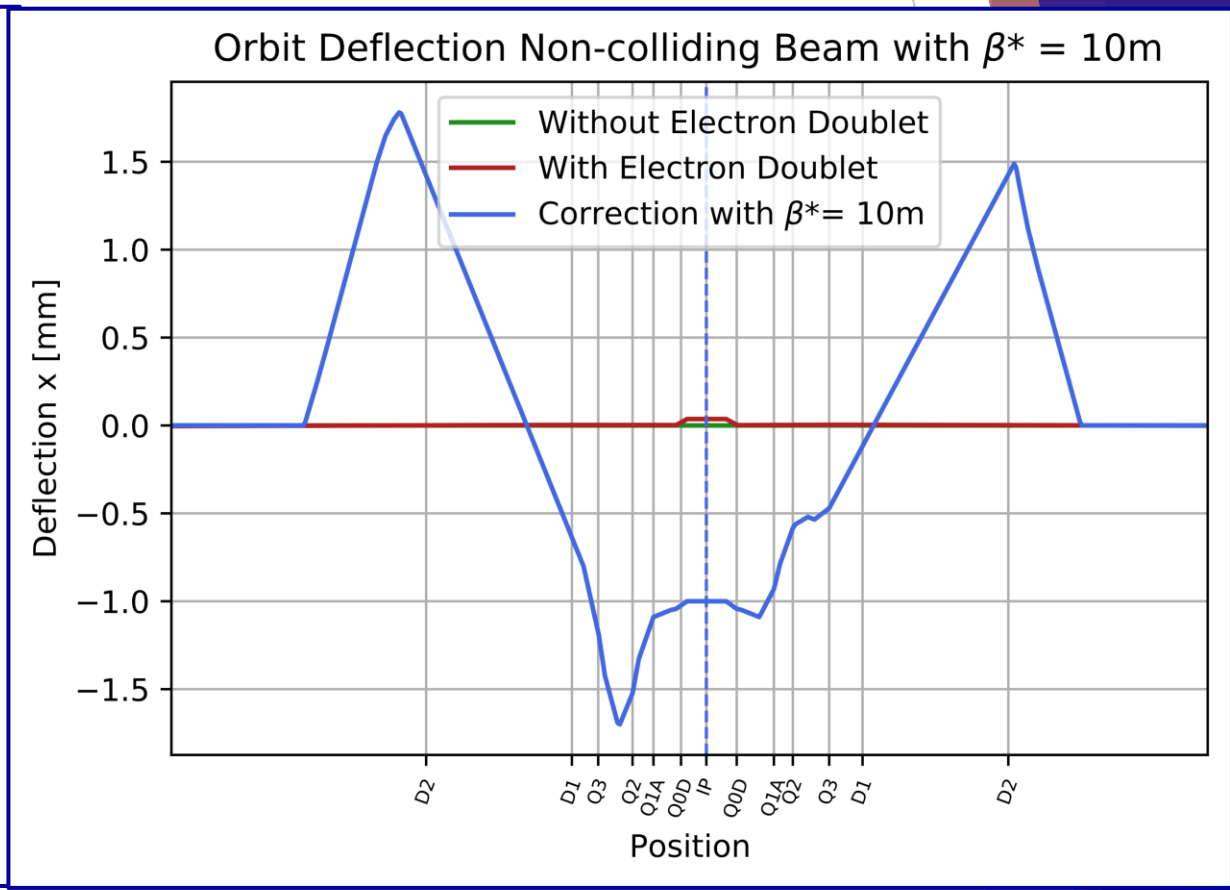
# Impact on the Proton Orbits x-plane

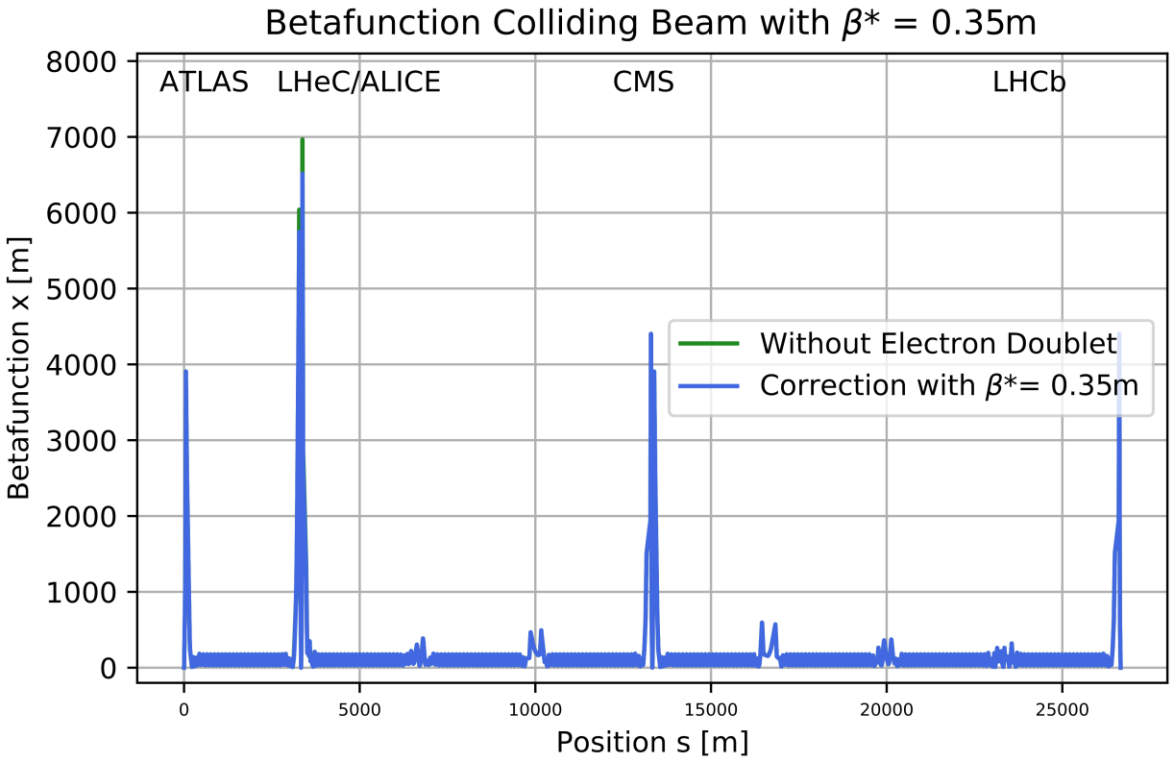
- Colliding Beam
- Non-colliding Beam



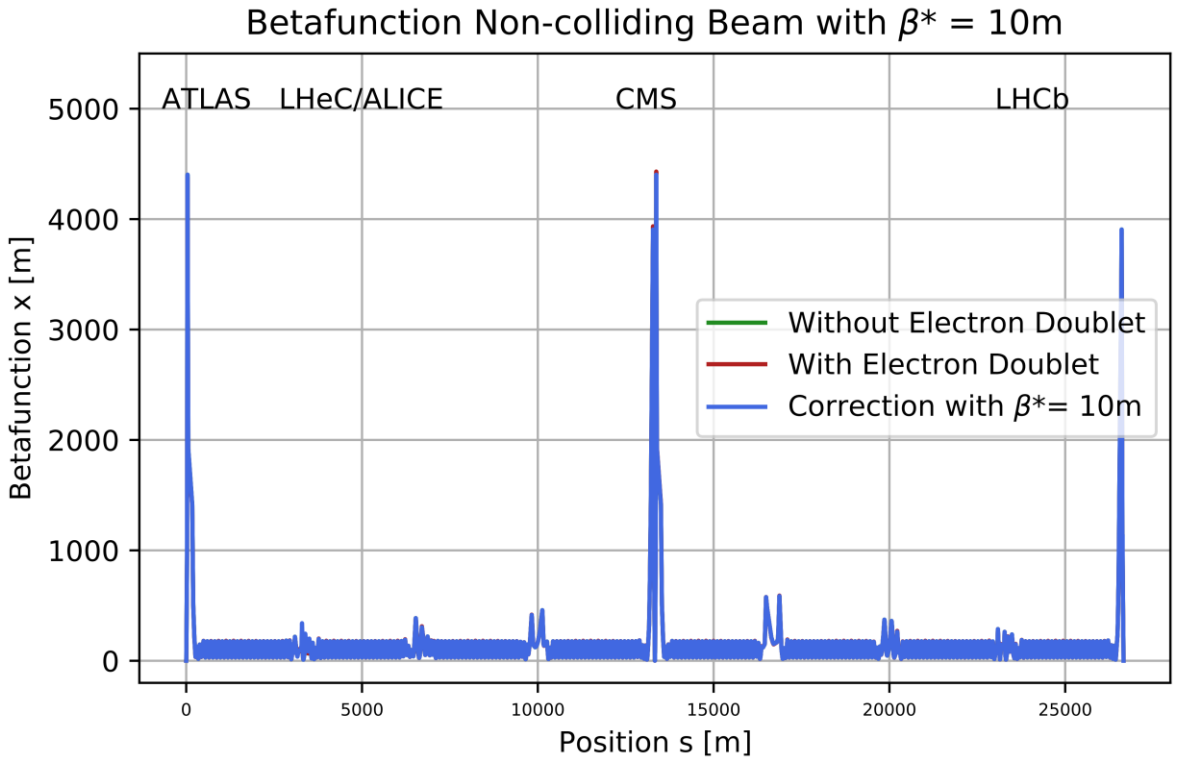



# Impact on the Proton Optics in the x-plane

- Colliding Beam




- Non-colliding Beam

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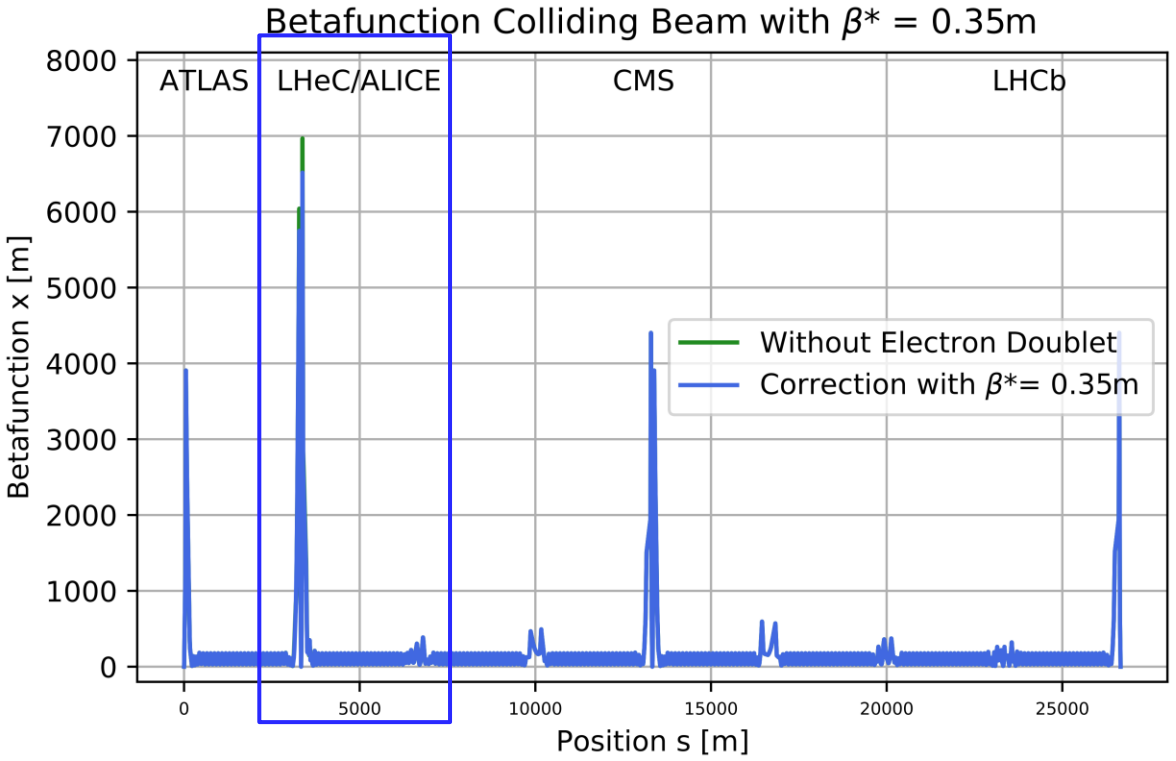
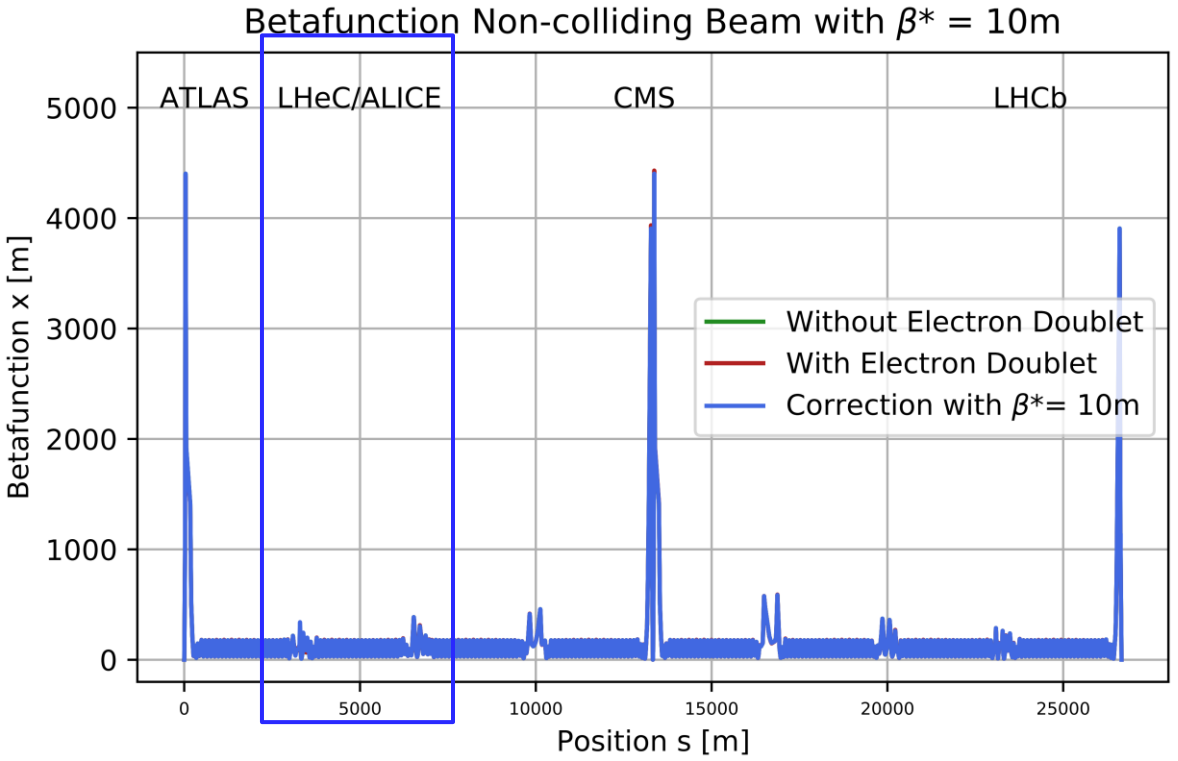
# Impact on the Proton Optics in the x-plane

- Colliding Beam




- Non-colliding Beam

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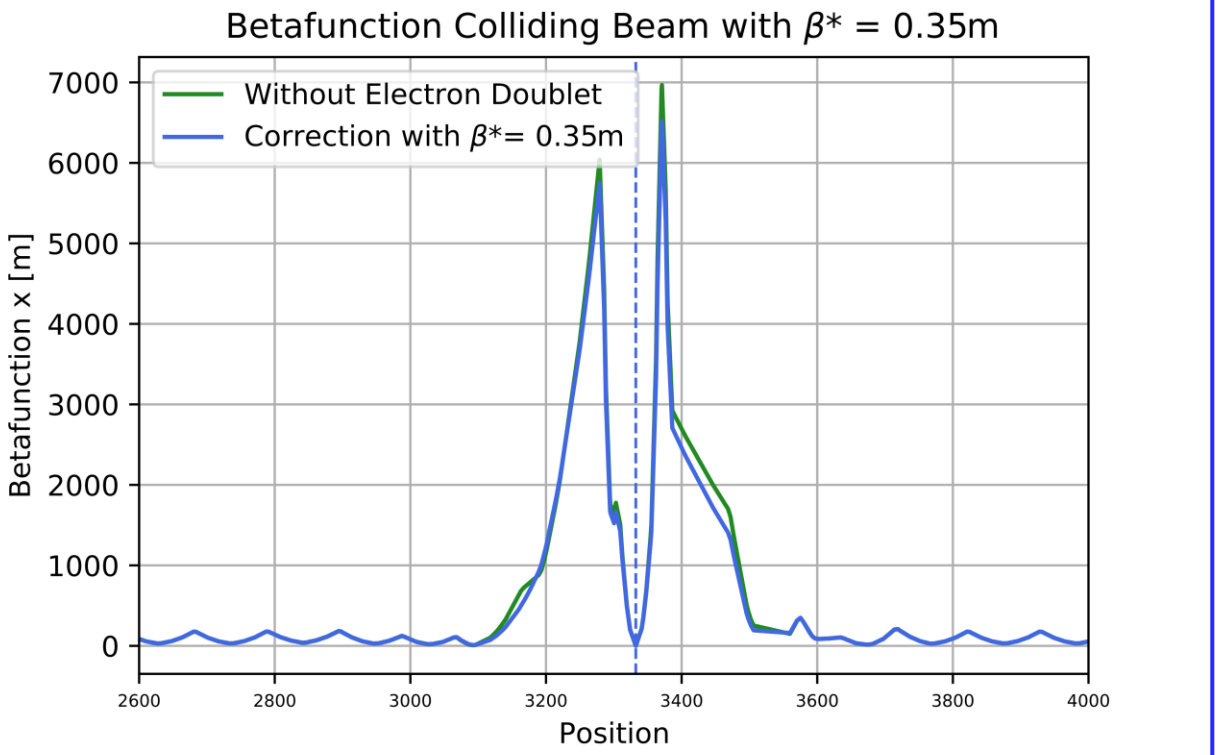


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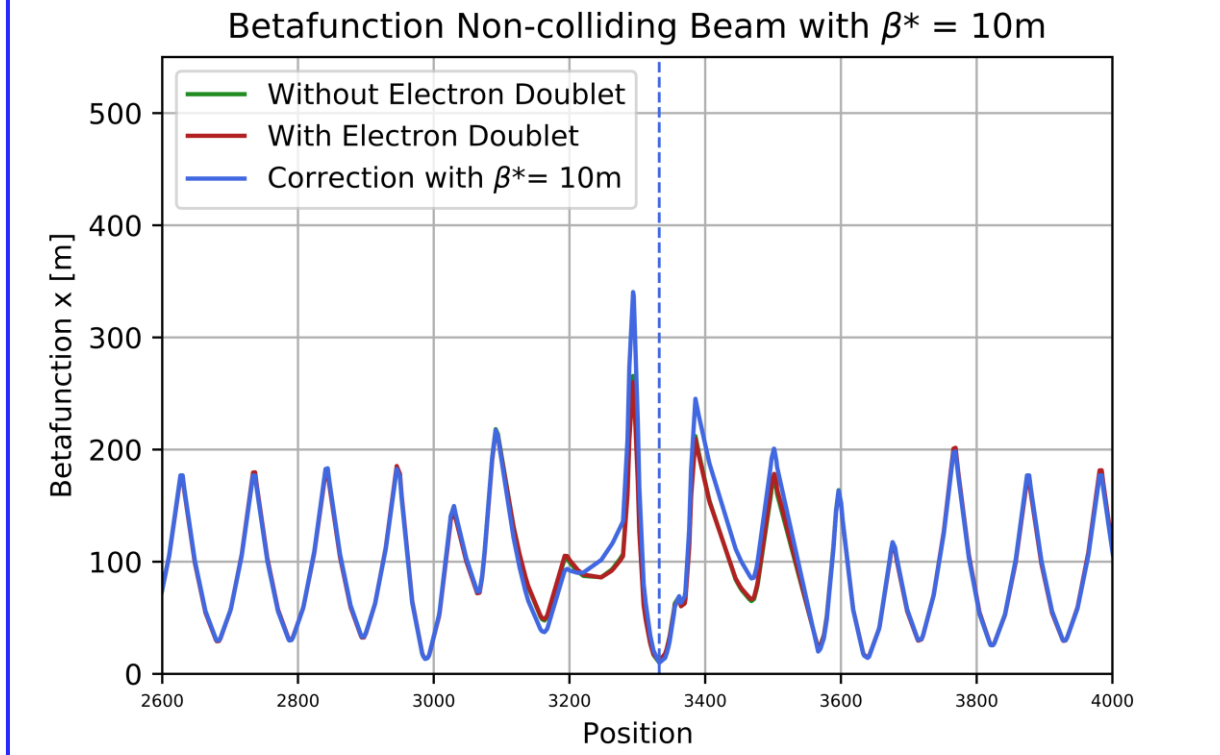


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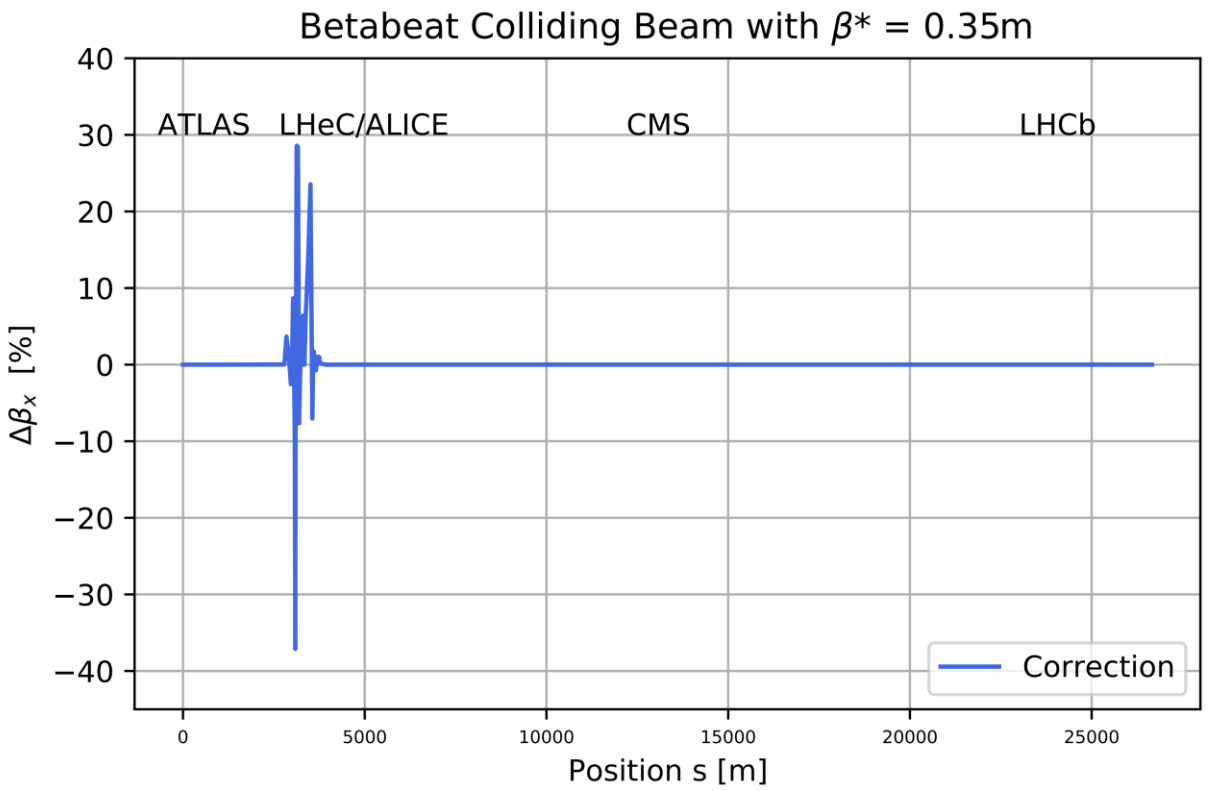
- Colliding Beam

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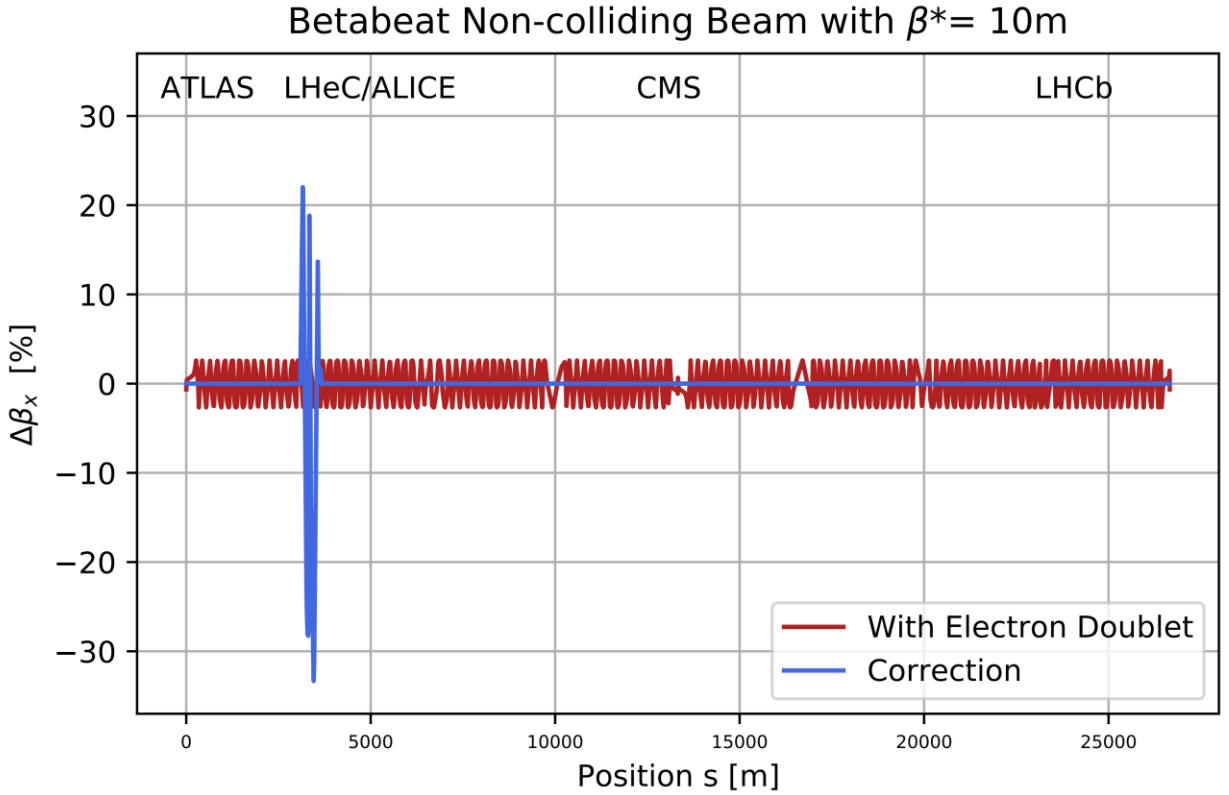


Betabeat:

$$\frac{\Delta\beta(s_0)}{\beta(s_0)} = \frac{\beta'(s_0) - \beta(s_0)}{\beta(s_0)}$$

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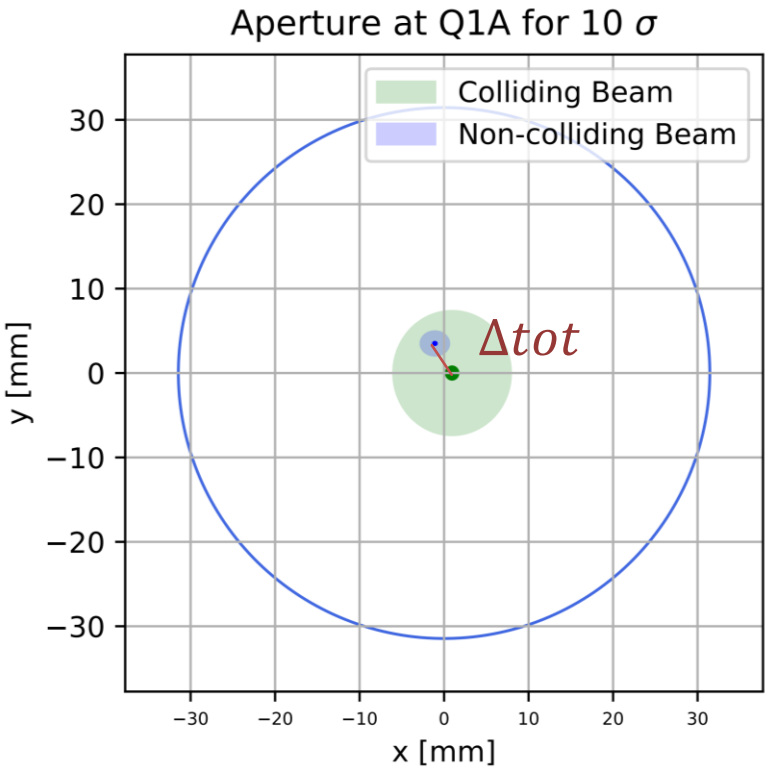
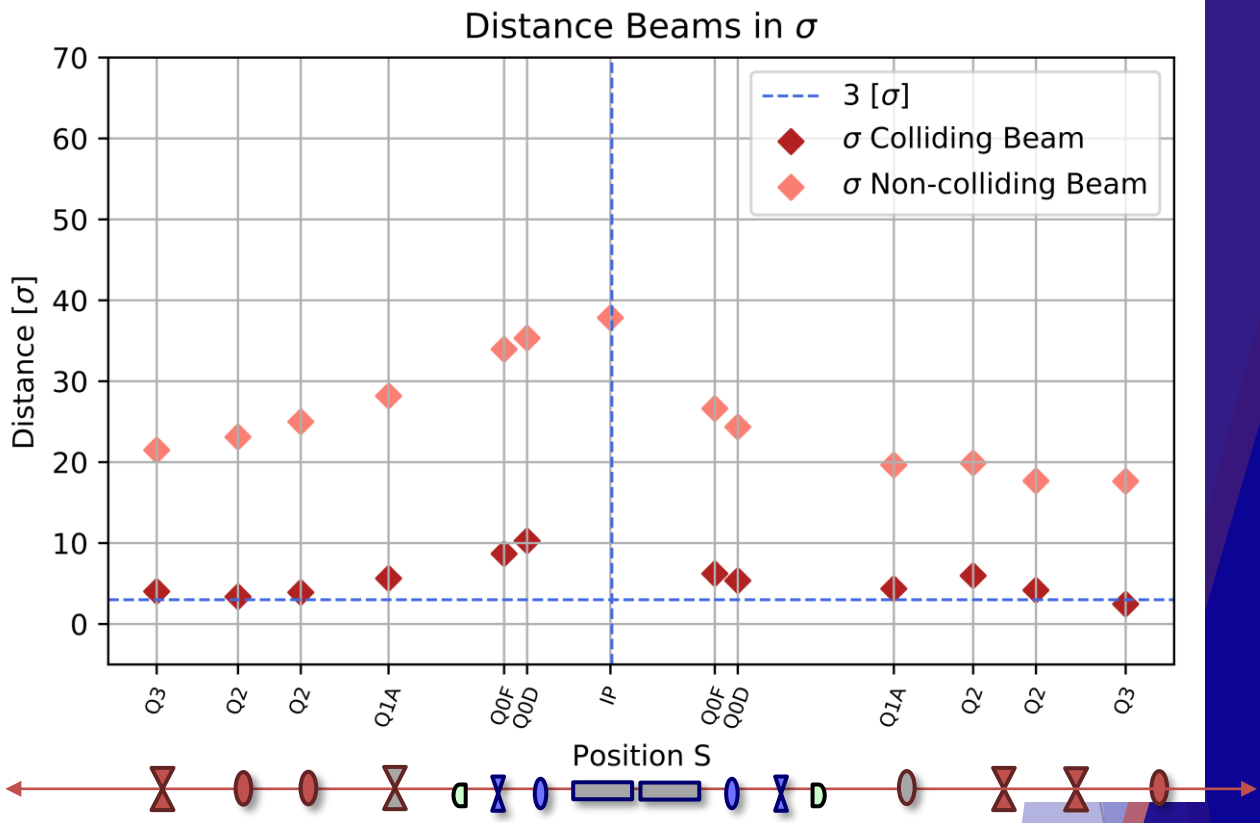
# Inter-beam Distance LHC

Total Distance between the beams in the shared interaction region in units of σ




$$\Delta tot\ [\sigma] = \frac{\Delta tot\ [m]}{\sigma_{B1,2}[m]}$$

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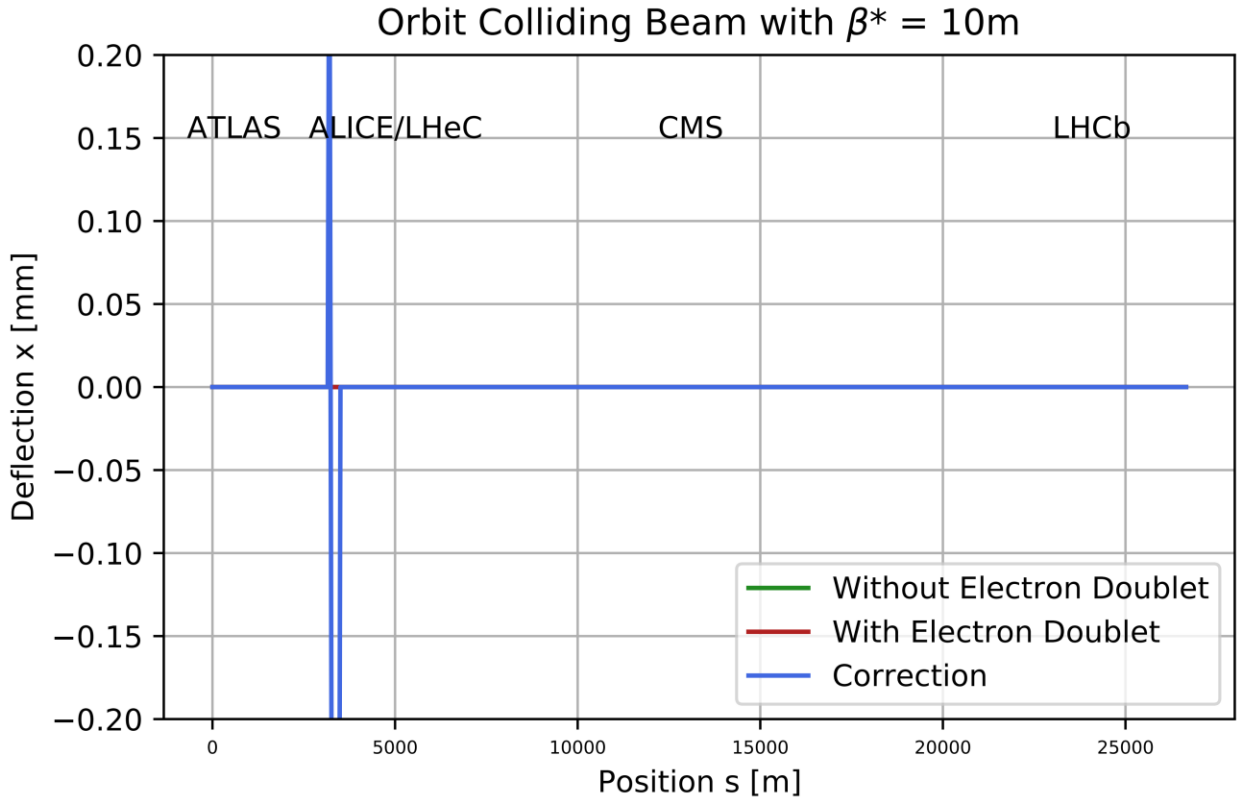
# High Luminosity -LHC Orbit Corrections

**HL-LHC**

- Implementation of stronger magnets with bigger apertures in the IRs
- Material change: Nb3Sn instead of NbTi

- Implementation of the electron IR of the HL-LHC
- Use of symmetric beams with a $\beta^*$ of 10m at the IP




preliminary results

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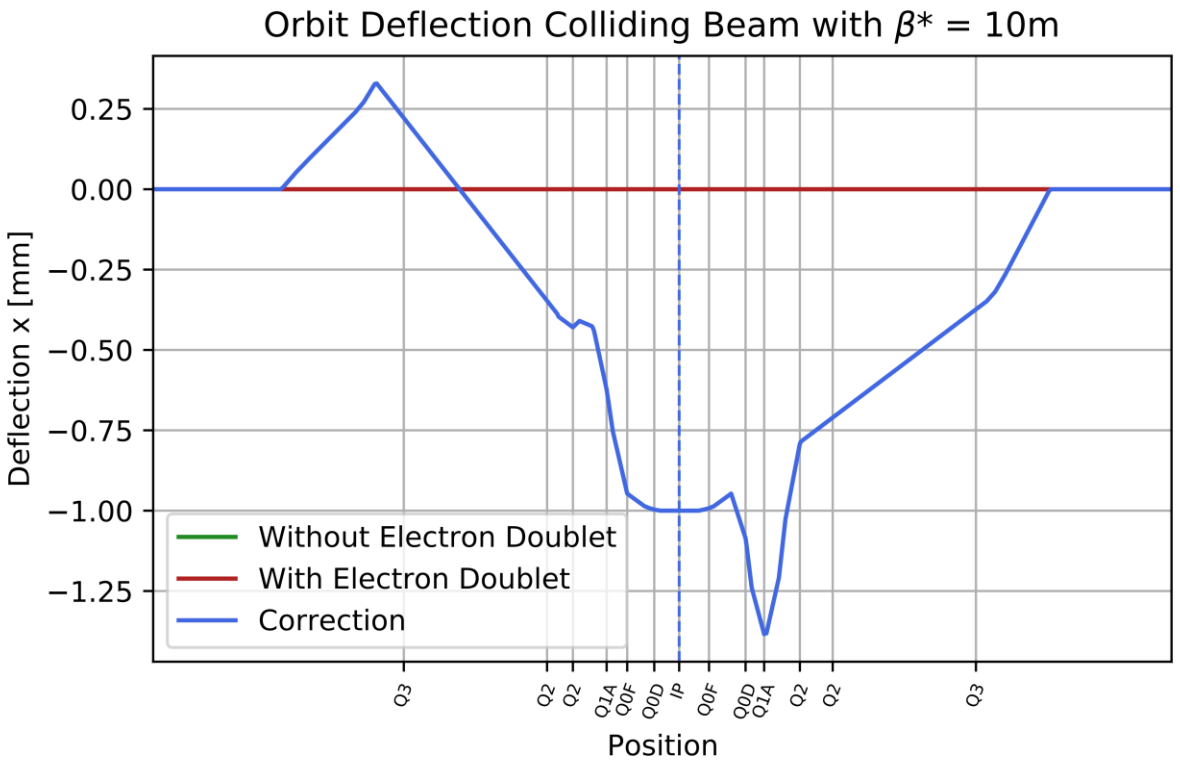
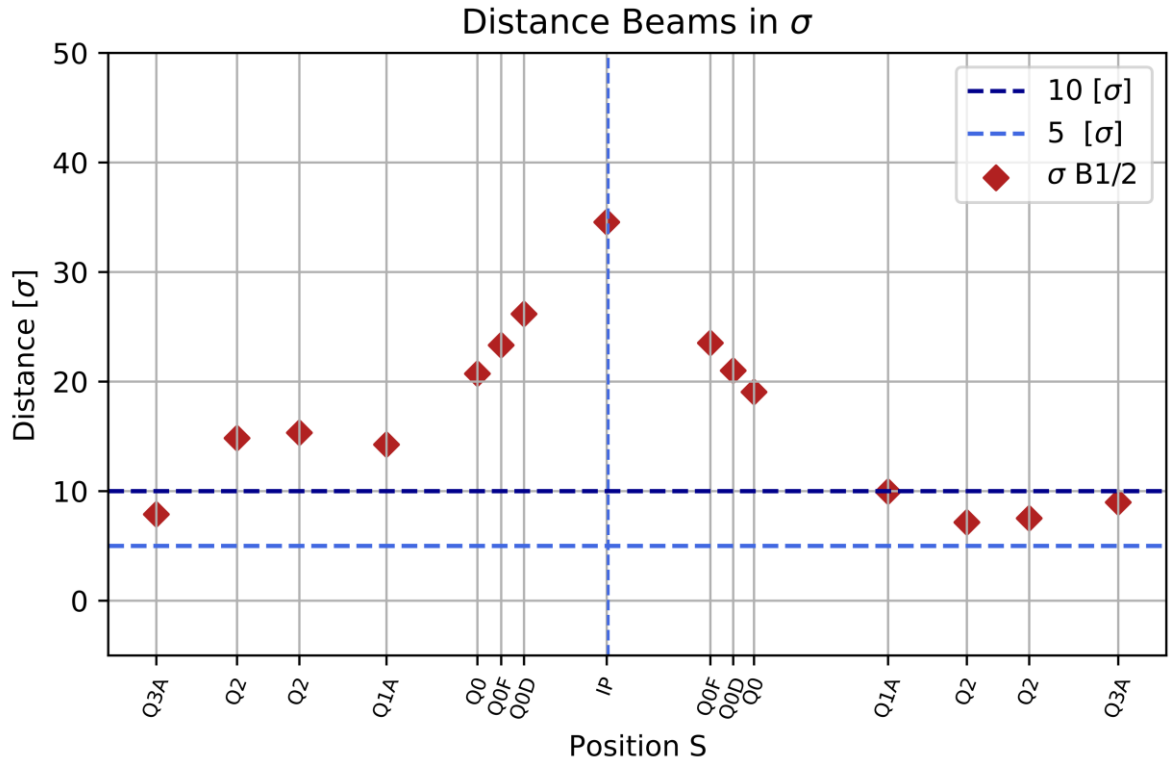
# High Luminosity -LHC Orbit Corrections

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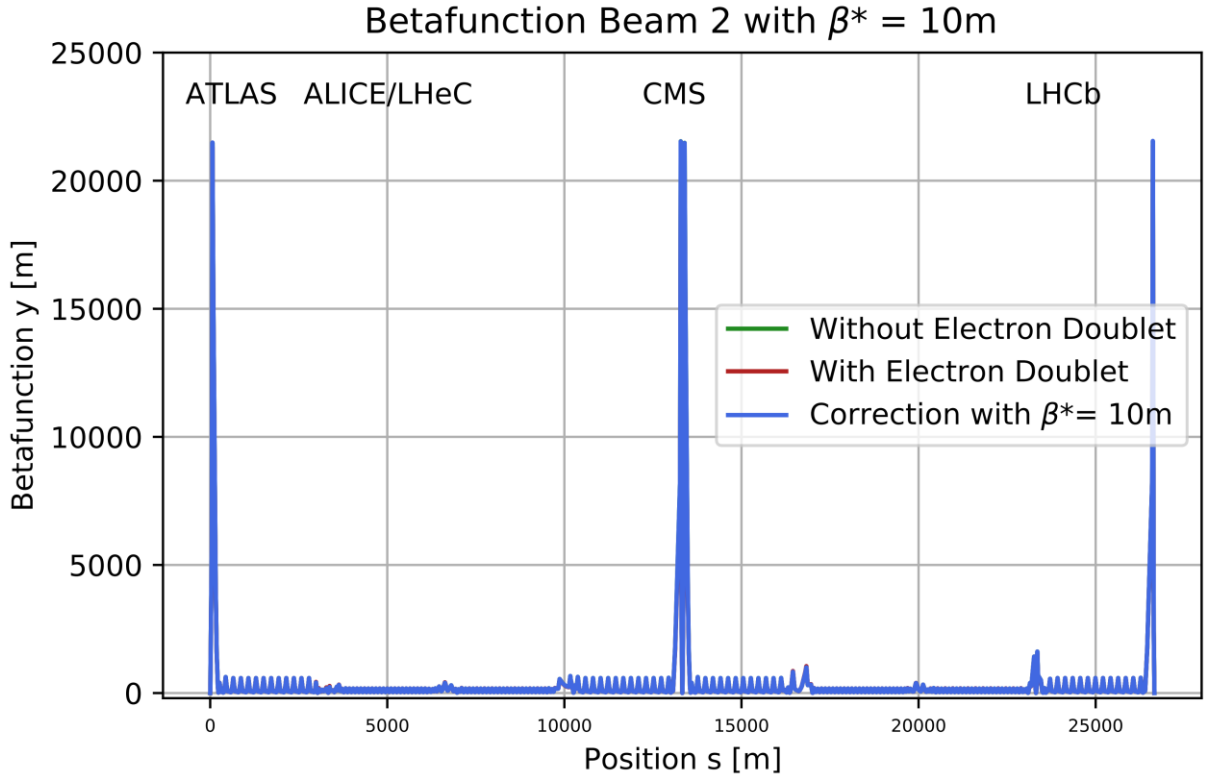
# Achromatic Telescopic Squeeze Optics

- The quadrupoles in their IRs reach their limits -> chromaticity rises
- Push the Luminosity further using the telescopic squeeze:

1. Squeeze to ß*=30cm in IP1 and IP5
2. Telescopic Squeeze from adjacent IRs to ß*=15cm

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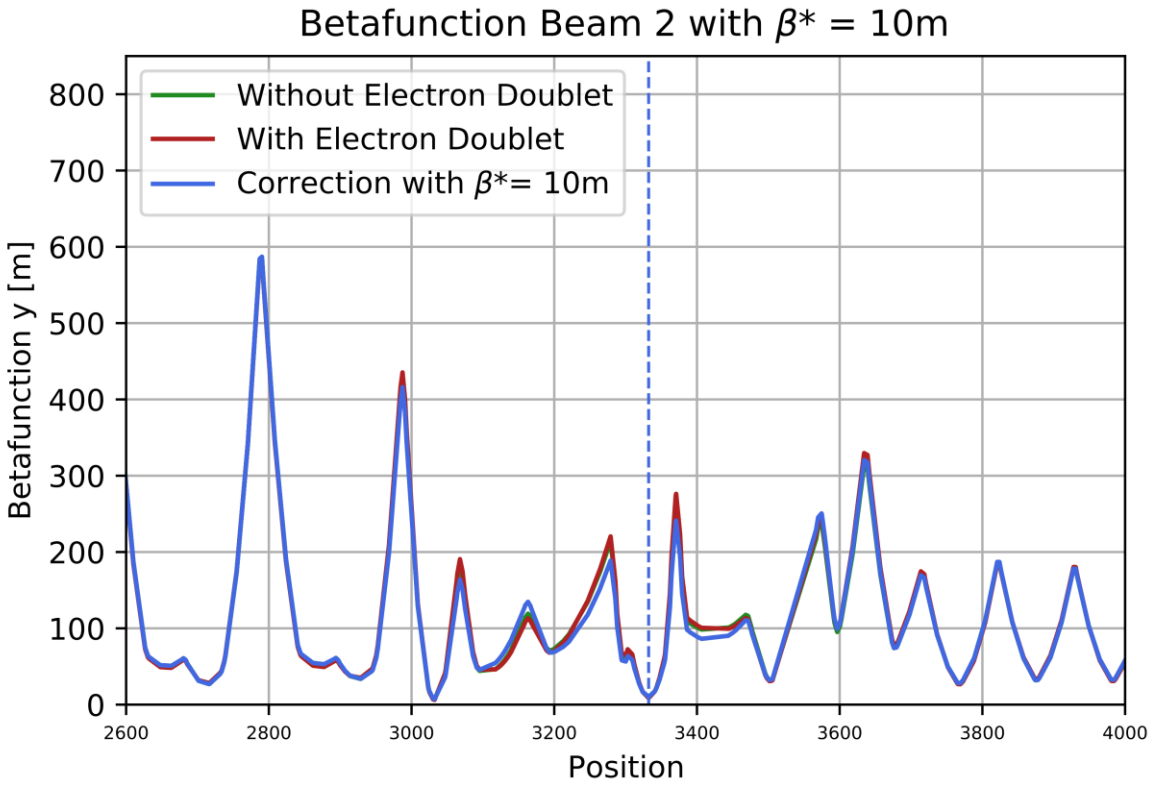


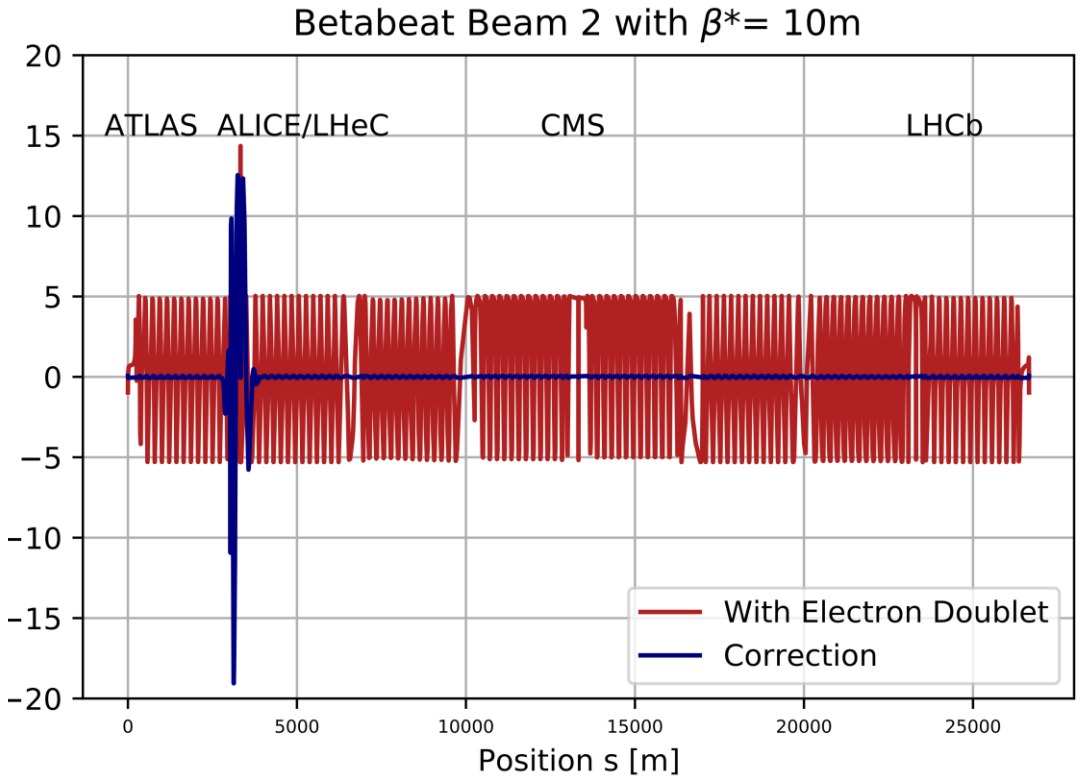


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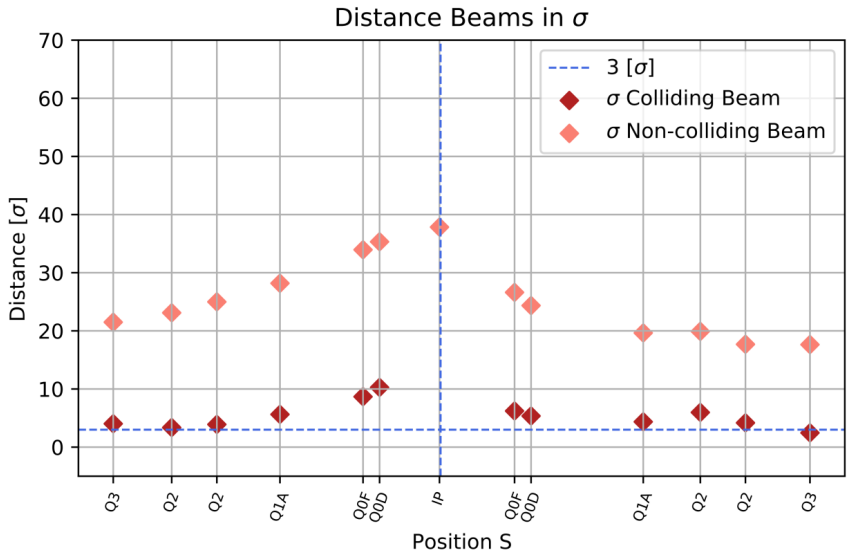
# Summary

- Successful implementation of the electron interaction region in the LHC and the HL-LHC lattice
- Optics and Orbit can be corrected for LHC and HL LHC
- Squeeze of the colliding beam down to 35cm for the LHC




# Outlook for the HL-LHC

- More aggressive ß* for the colliding beam to increase the luminosity
- Increase the inter-beam distance:

1. By using the orbit correctors to distance the non-colliding beam further from the orbit

2. By sweeping different ß* values for the non-colliding beam

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# Appendix

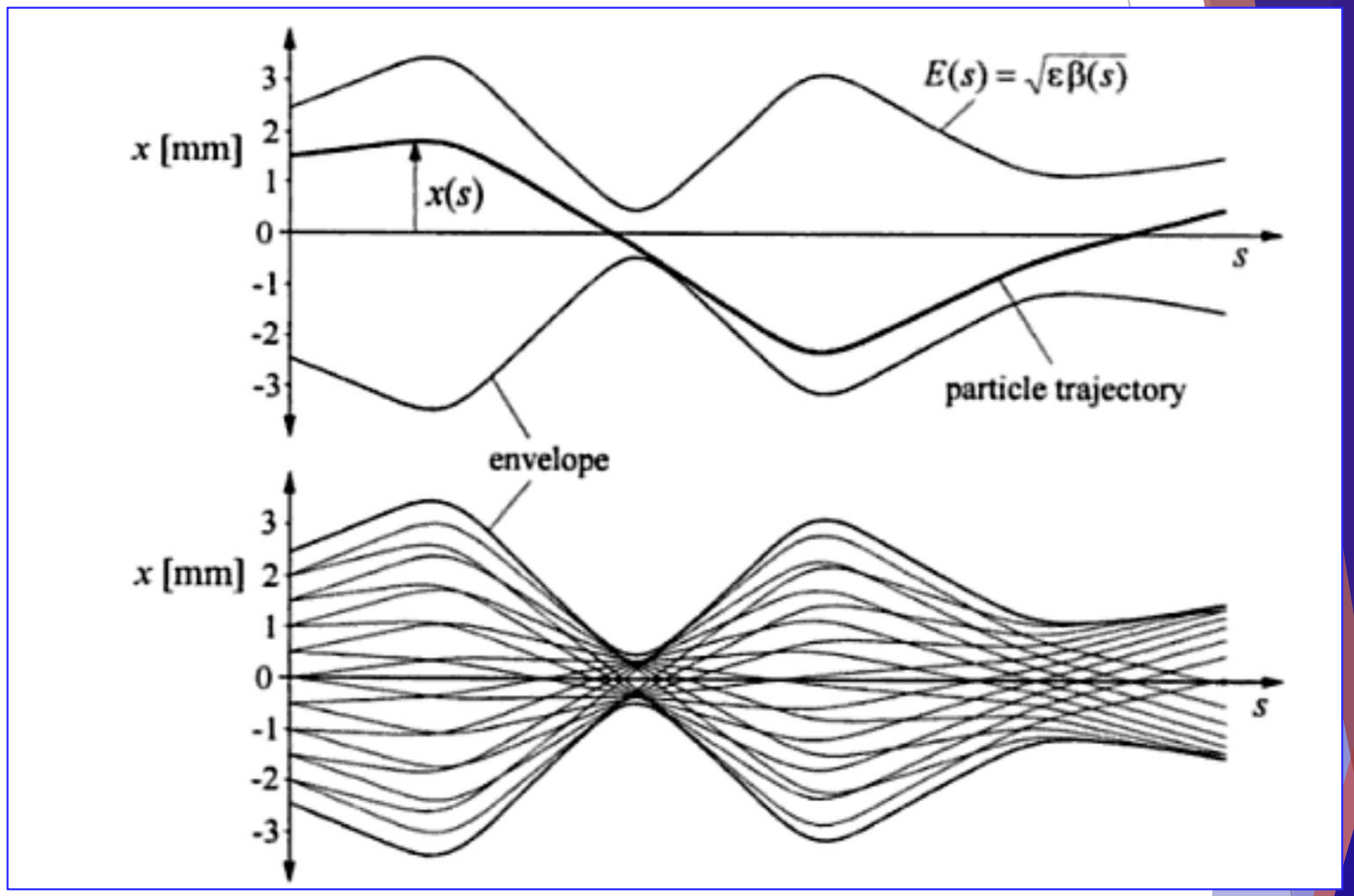
# Recap: Beam Envelope

$$L = \frac{N_1 \cdot N_2 \cdot n \cdot f}{4\pi\sigma_x\sigma_y}\,[cm^{-2}s^{-1}]$$

- During their travel on the trajectory s, the particles perform betatron oscillations
- The beam envelope for many particles and many turns is defined as:

$$E(s) = \sqrt{\varepsilon\beta(s)} = 1\sigma_u \qquad u = x, y$$

- $\varepsilon$ is the energy dependent emittance
- $\beta(s)$ defines the betafunction, which depends on the beam optics defining the beam size at a certain position s

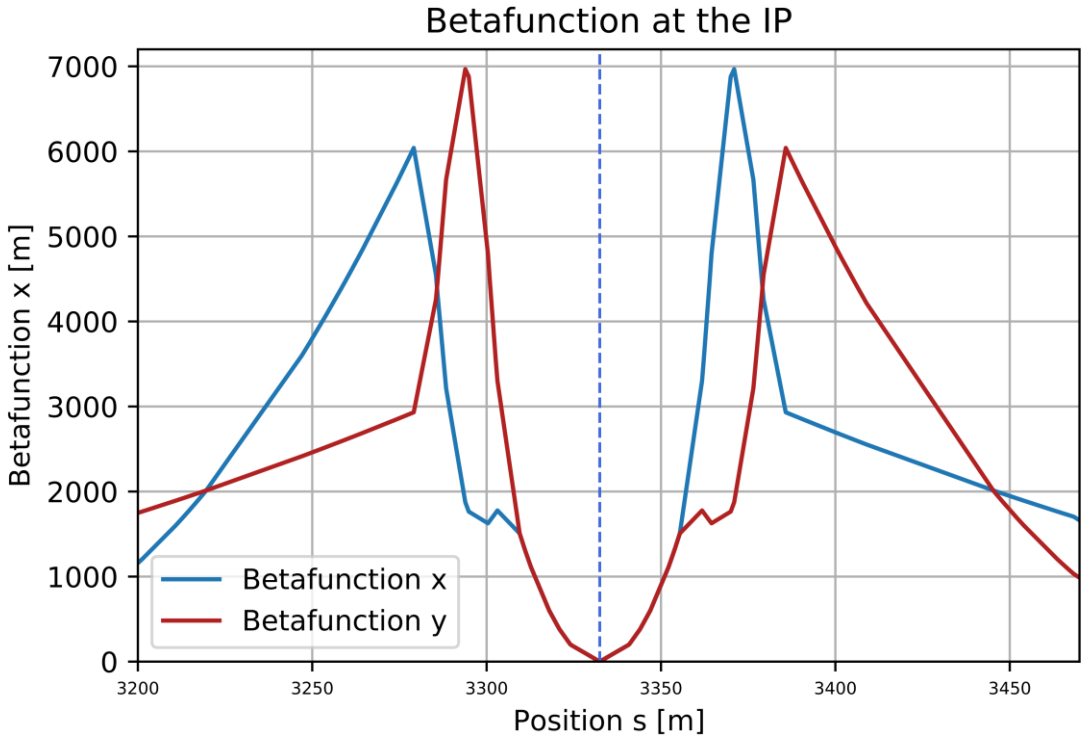


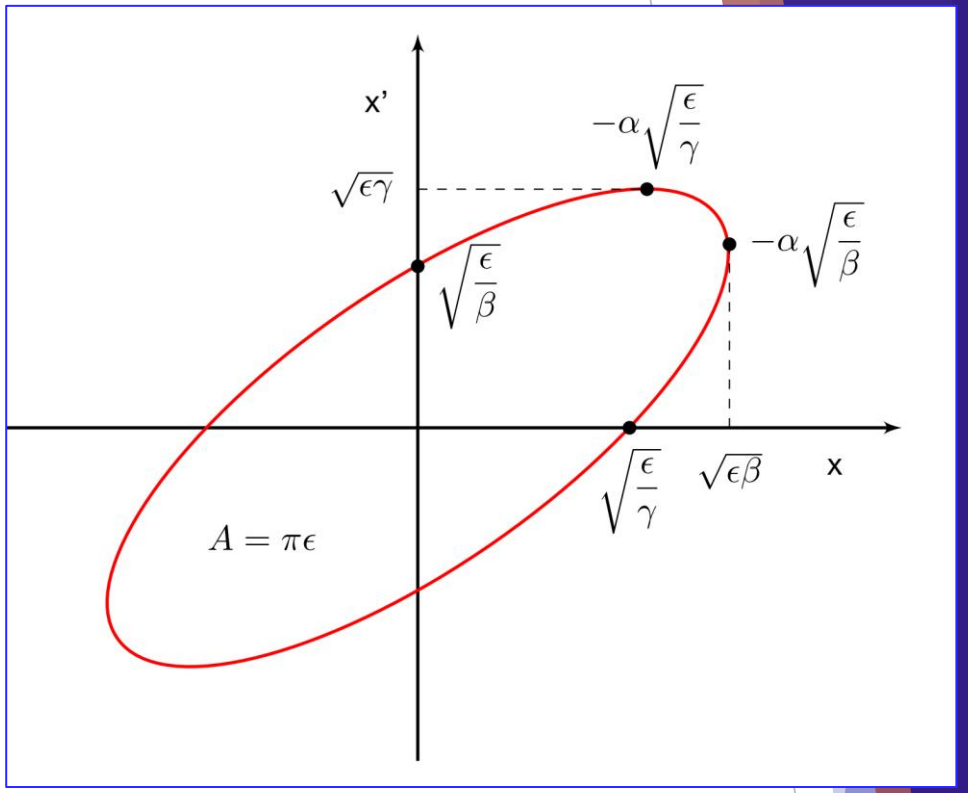

Beam envelope, K. Wille

# Phase Space Conservation and Liouville's Theorem

- *The phase-space distribution function is constant along the trajectories of the system*
- The area in the phase space is conserved

⇨ the smaller the beamsize, the bigger the divergence



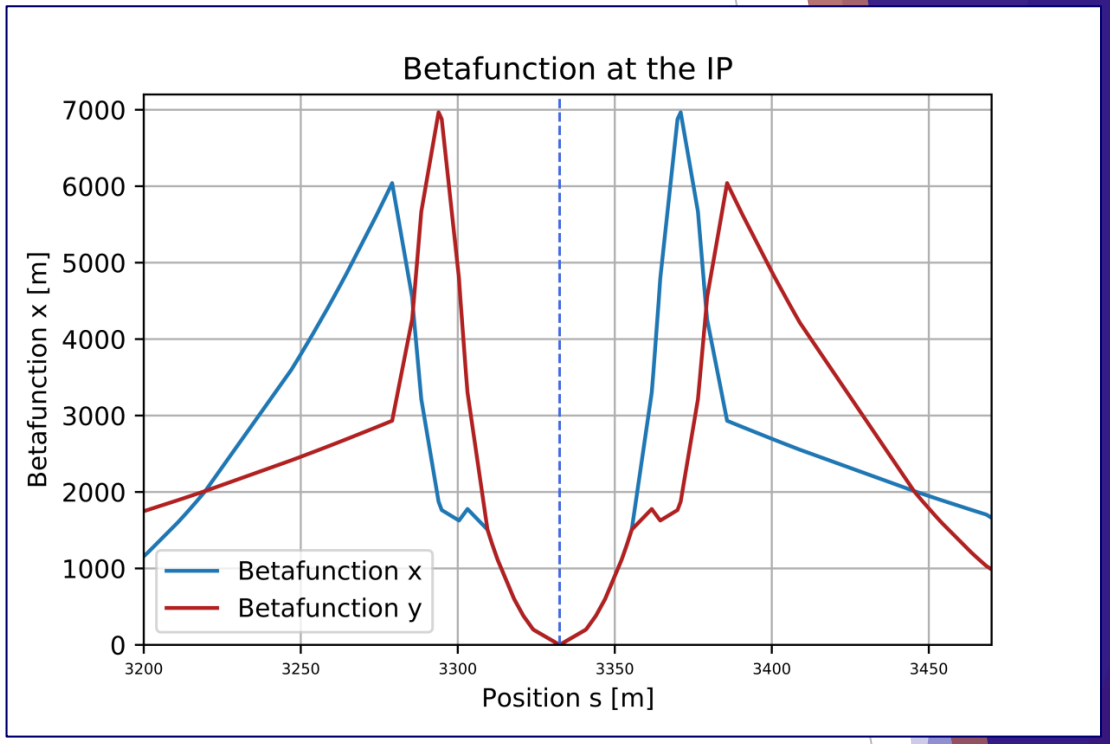




Phase Space Diagram

⇨ The Quadrupoles the closest to the IP need the biggest aperture

# Minibeta Optimization

- Betafunction in a drift space: $\beta(l) = \beta^* + \frac{l^2}{\beta^*}$
- Find optimal $\beta^*$: $\frac{d\beta(s)}{d\beta^*} = 1 - \frac{l^2}{\beta^{*2}} = 0$
- Smallest beta at the end of the drift for: $\beta^* = l$
- At ALICE the drift space has a length of 23m




An variation of the second beam between the design 10m and 23m could lead to optimized distances between the beams

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# How does this affect our collider?

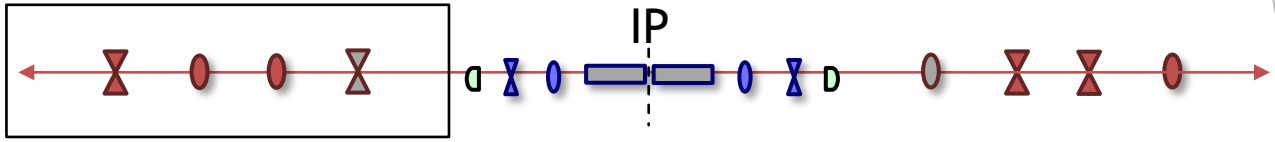
$$L = \frac{N_1 \cdot N_2 \cdot n \cdot f}{4\pi\sigma_x\sigma_y}\,[cm^{-2}s^{-1}]$$

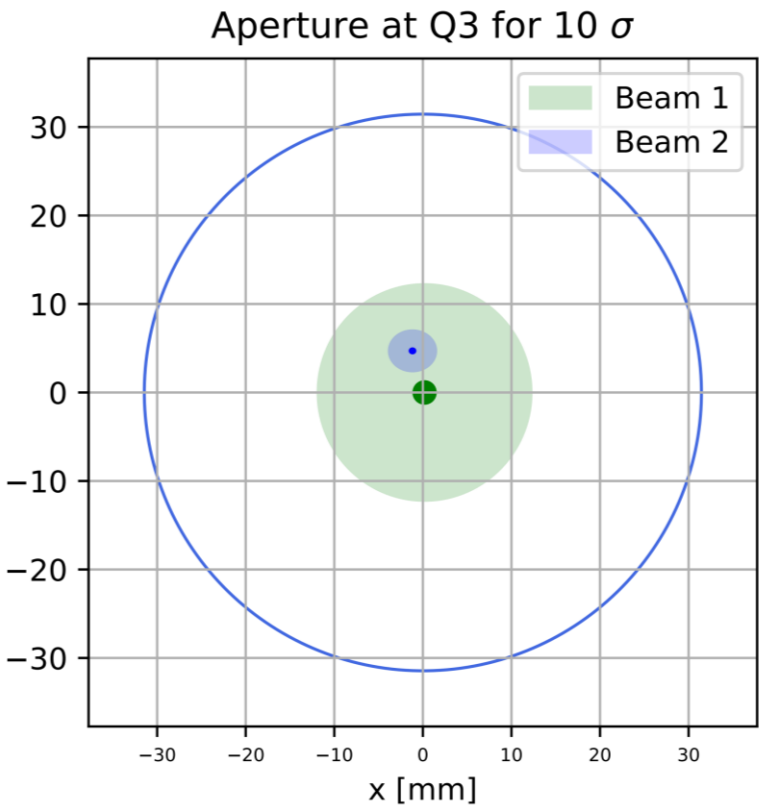
- Using the formula for beta in a drift: $\beta(l) = \beta^* + \frac{l^2}{\beta^*}$
- For the standard LHC this yields at ATLAS and CMS: $\beta(23) = 0.55m + \frac{23m^2}{0.55m} = 963\text{m}$
- How far can we go in betastar with a drift of 15m?

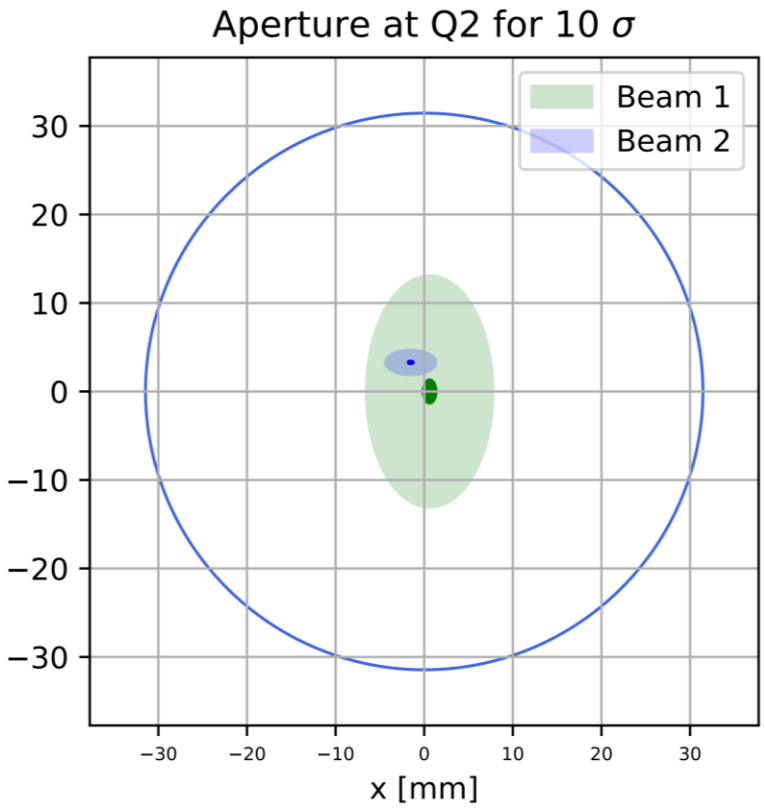
$$\beta(15) = x\,m + \frac{15m^2}{x\,m} = 963\text{m} \quad \Rightarrow \quad x = 0.234m$$

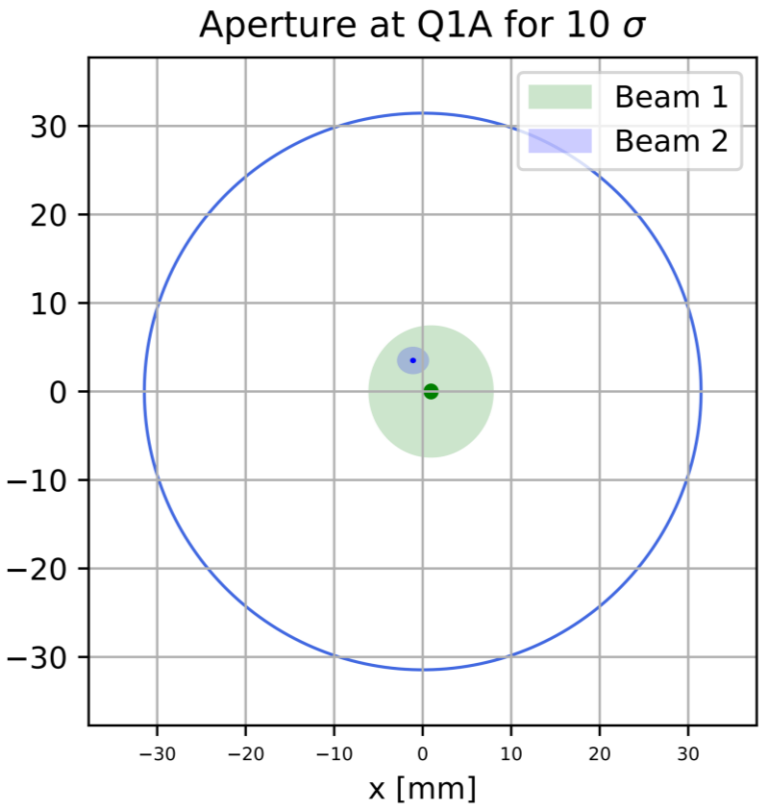
# LHC Data

# Apertures of the Proton Beams




Cross section beam pipes

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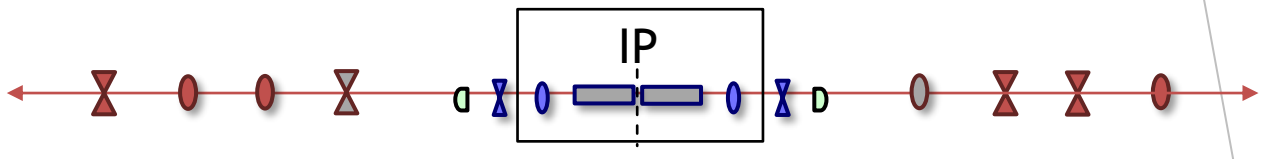
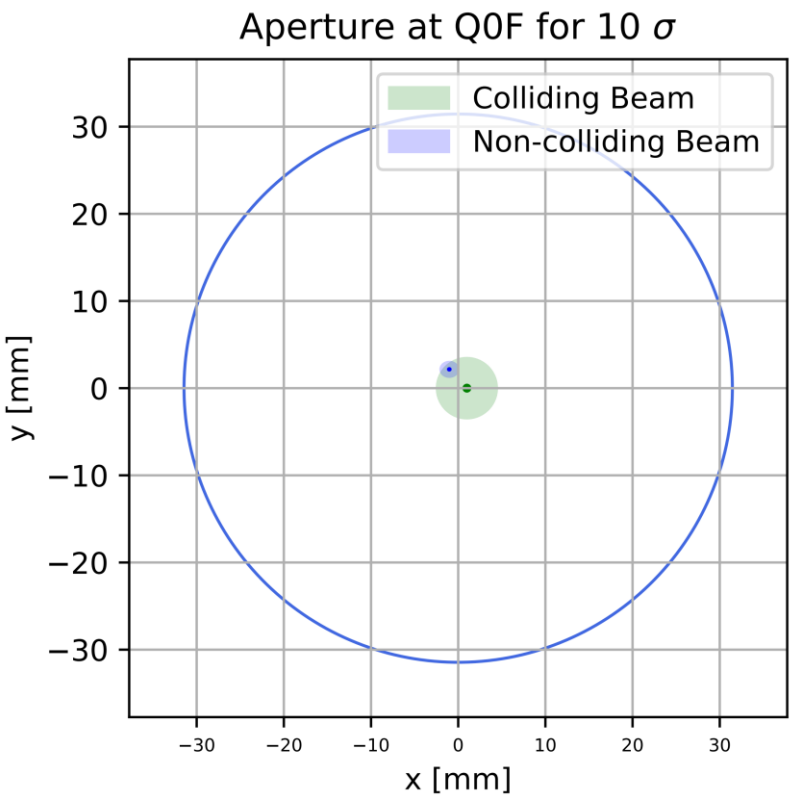
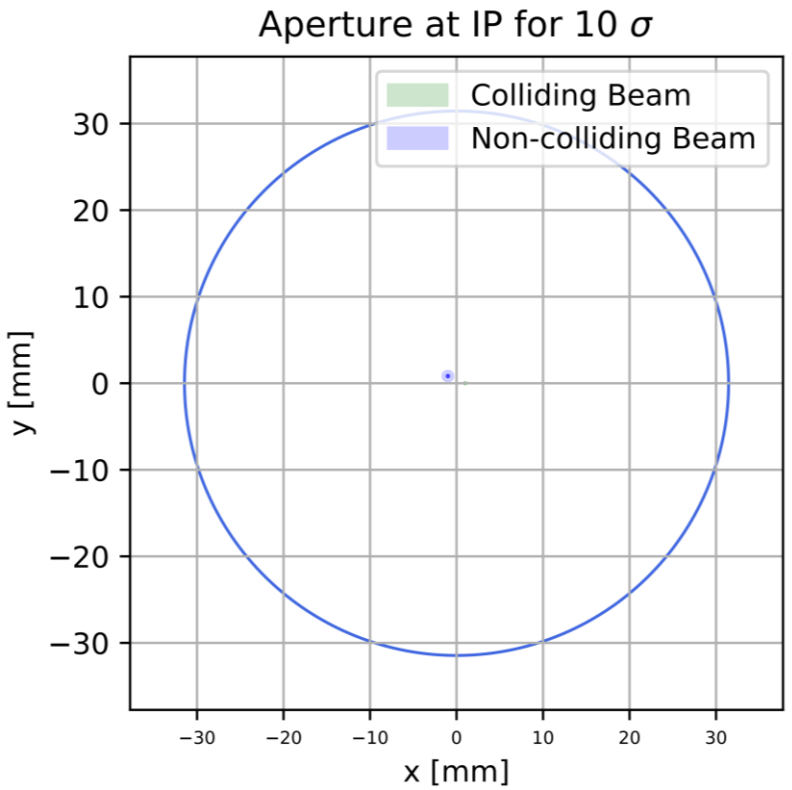
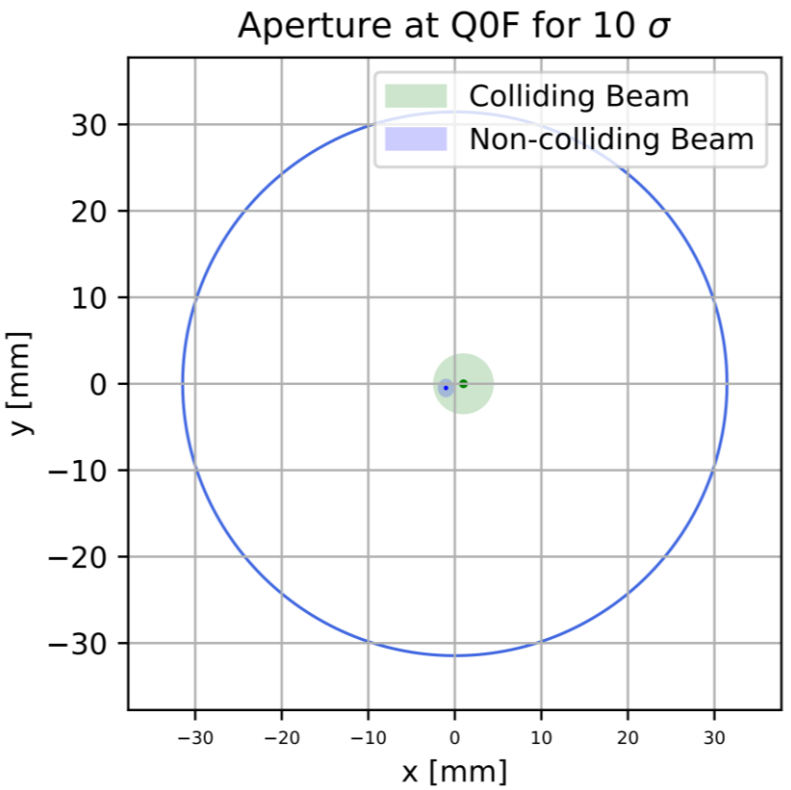


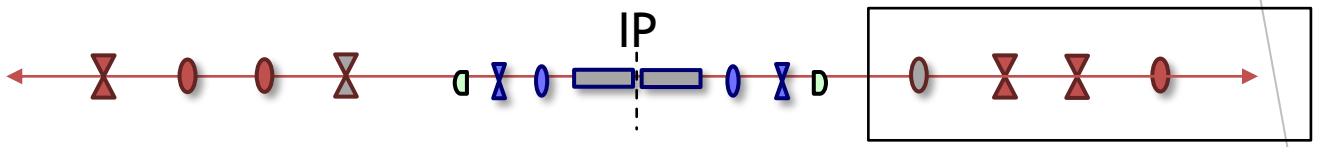



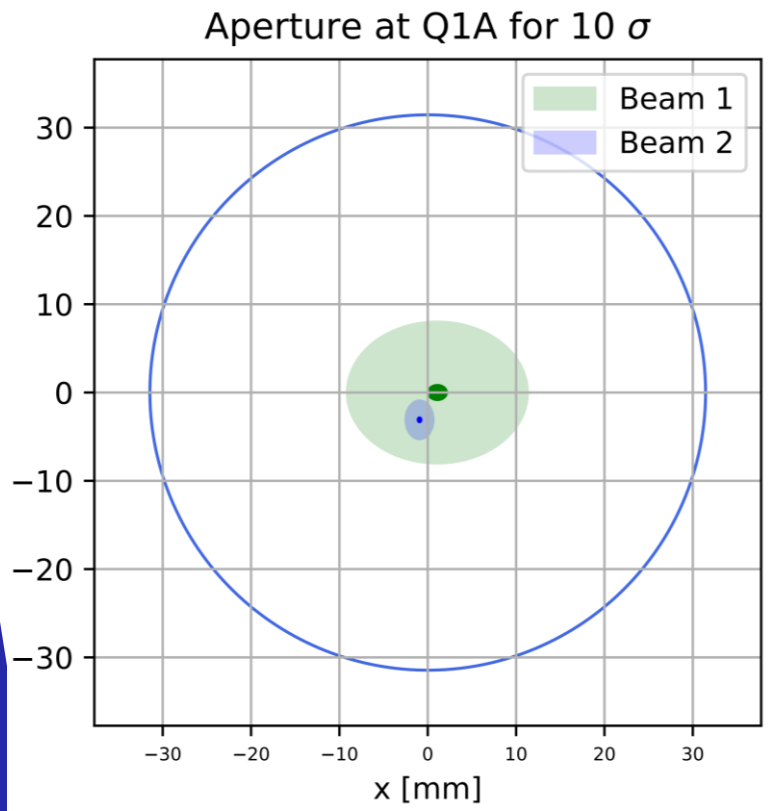



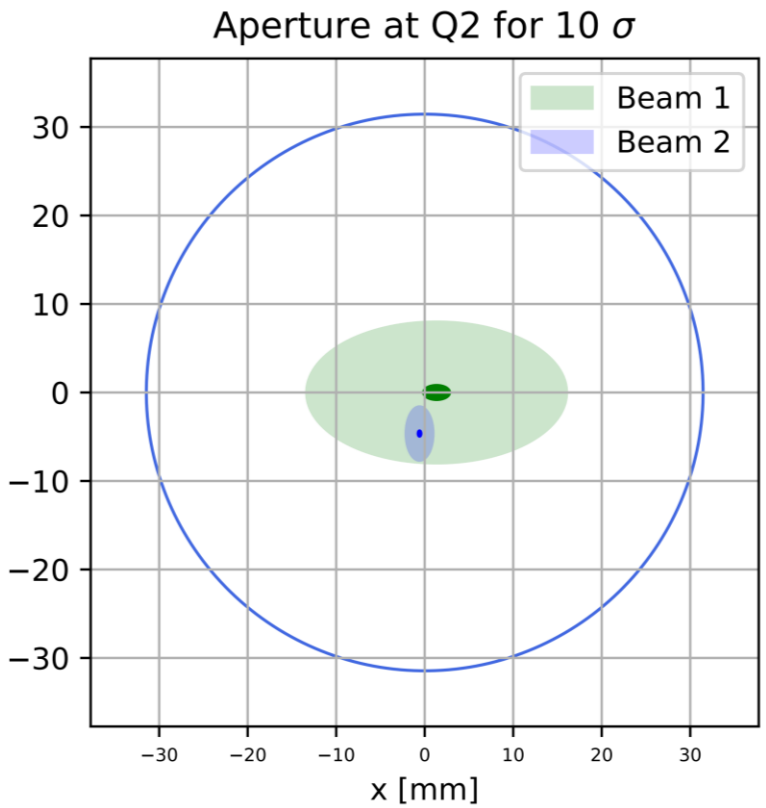

Cross section beam pipes

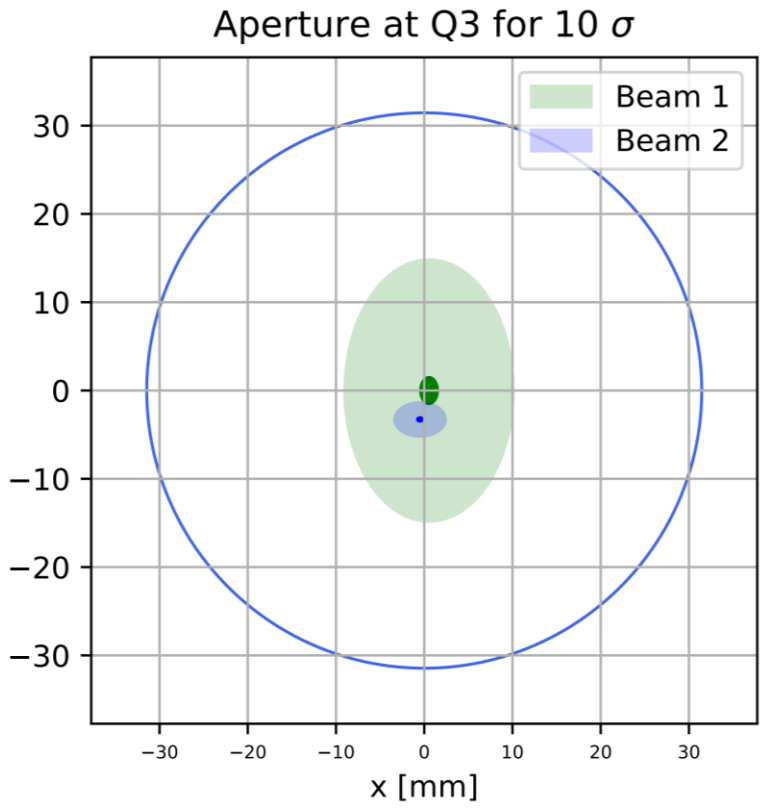
At the IP:
ß*= 0.35m Colliding Beam
ß*= 10m Non-colliding Beam

# Apertures of the Proton Beams




Cross section beam pipes

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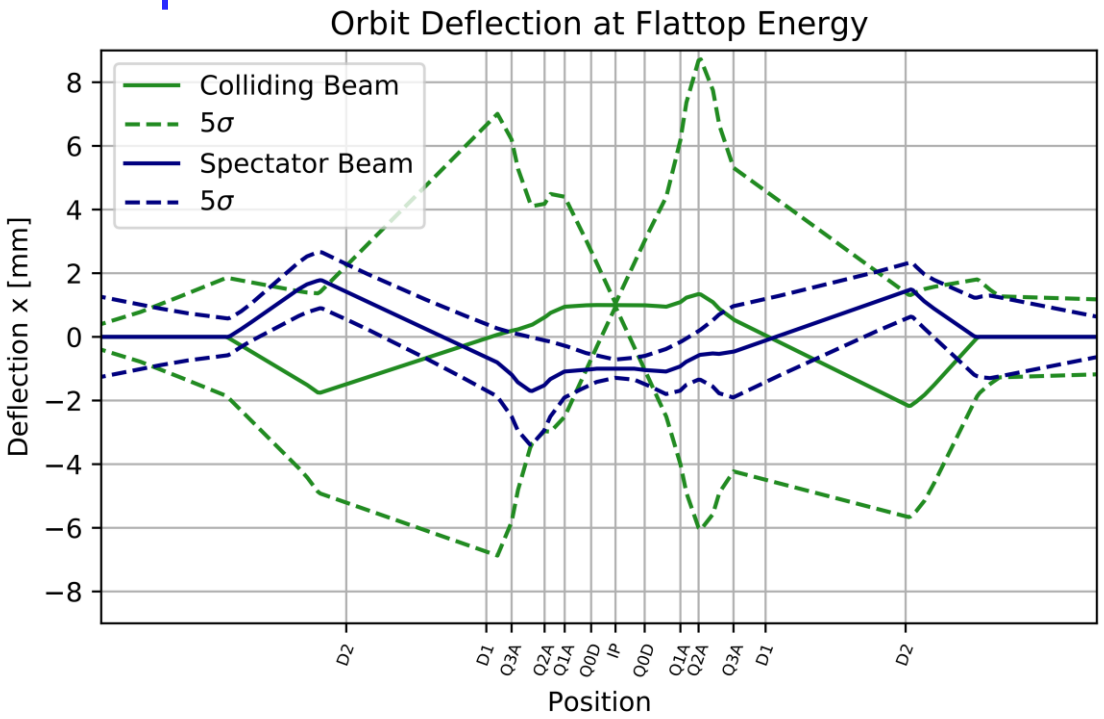
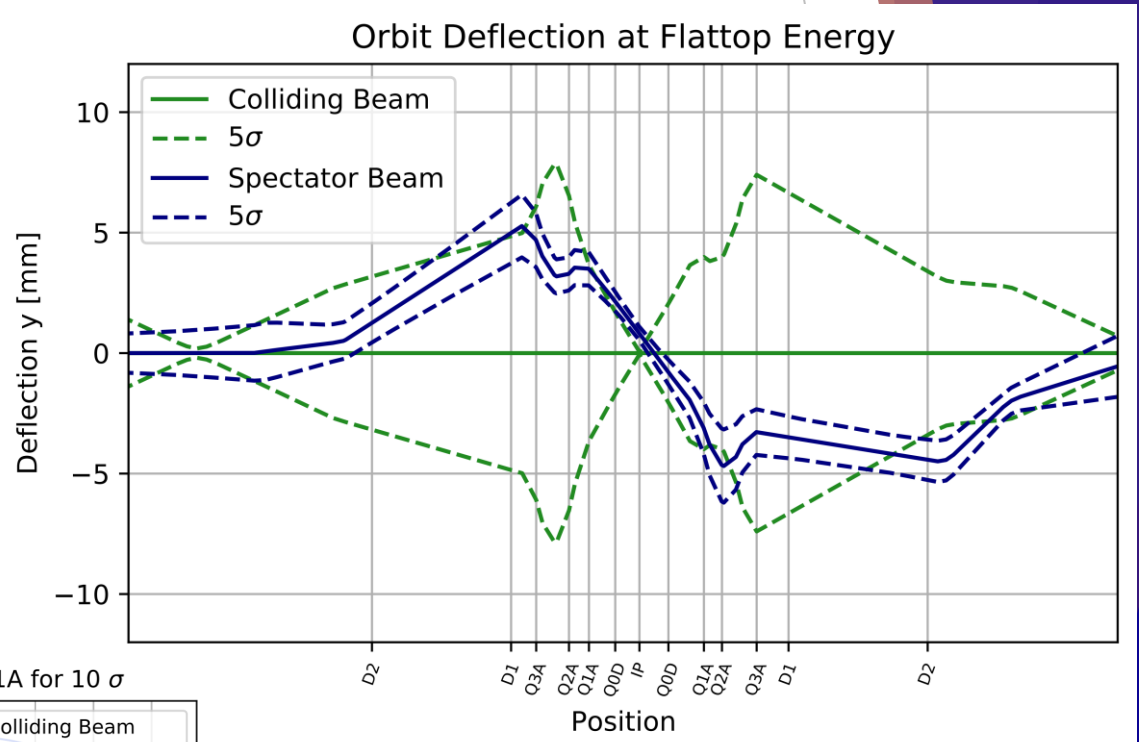
# Proton Optics and Orbit

## x-plane



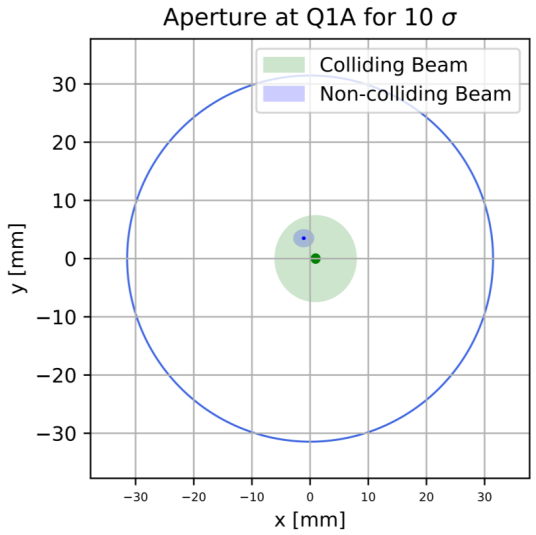

## y-plane




At the IP:

$\beta_1^*$= 0.35m

$\beta_2^*$= 10m … 23m

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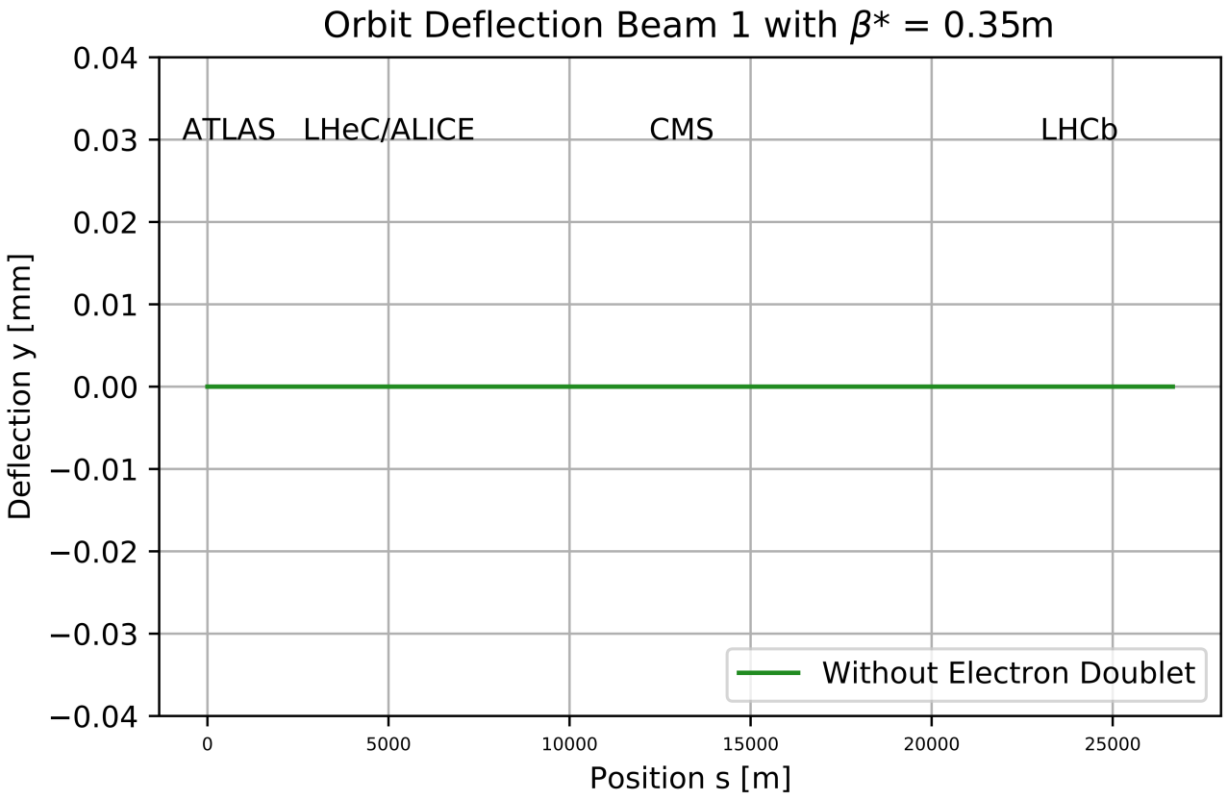
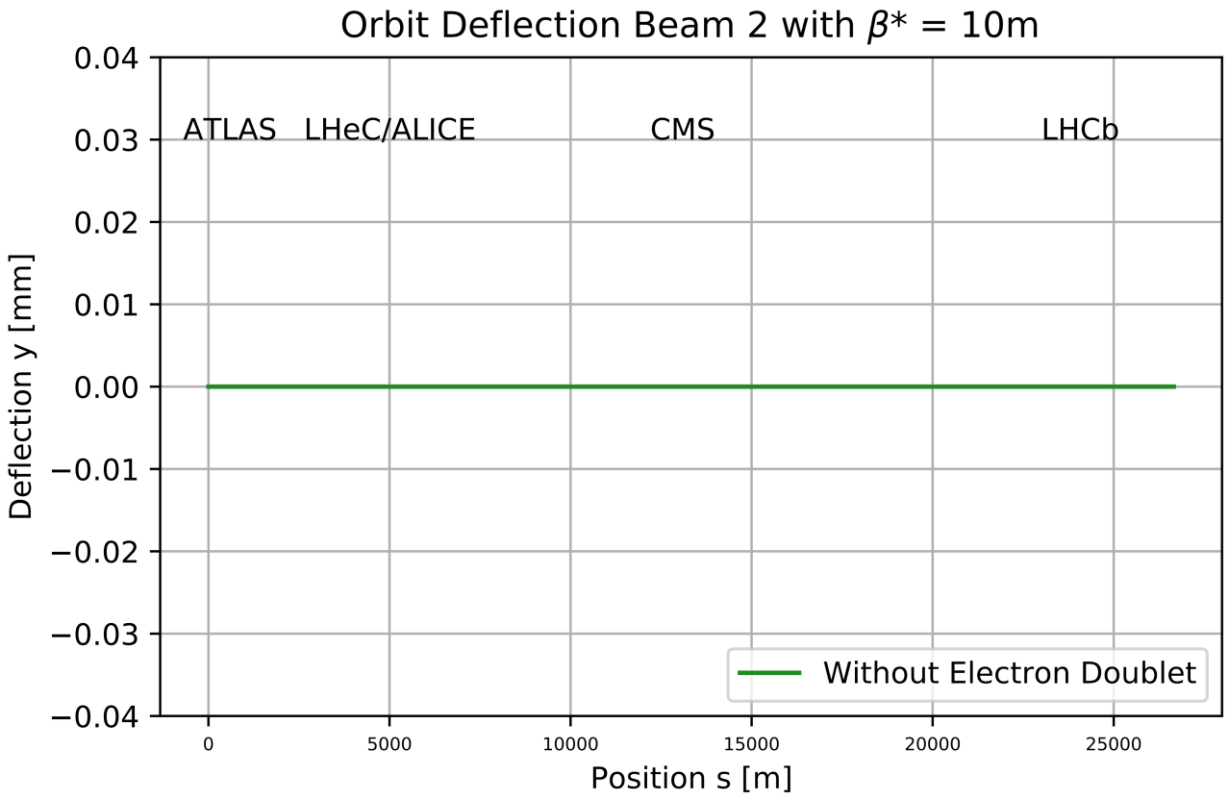
# Impact on the Proton Orbits y-plane

- Colliding Beam




- Spectator Beam

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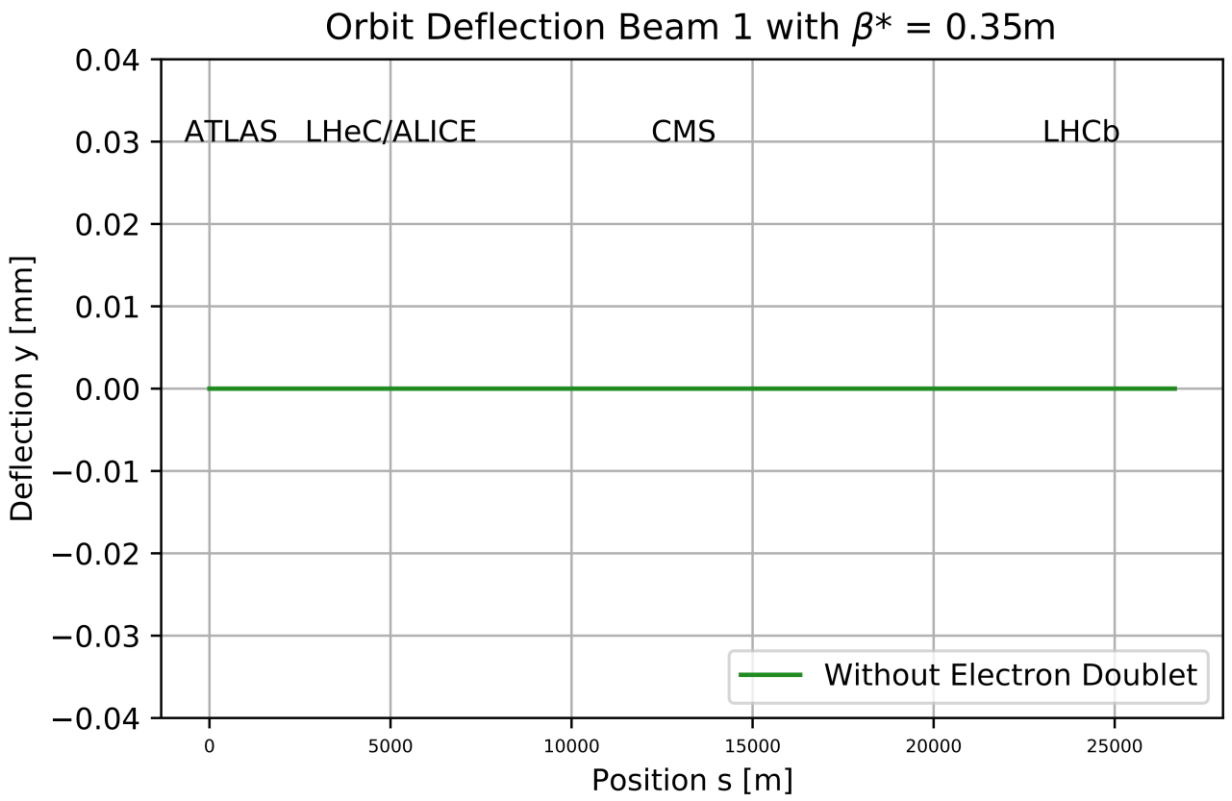
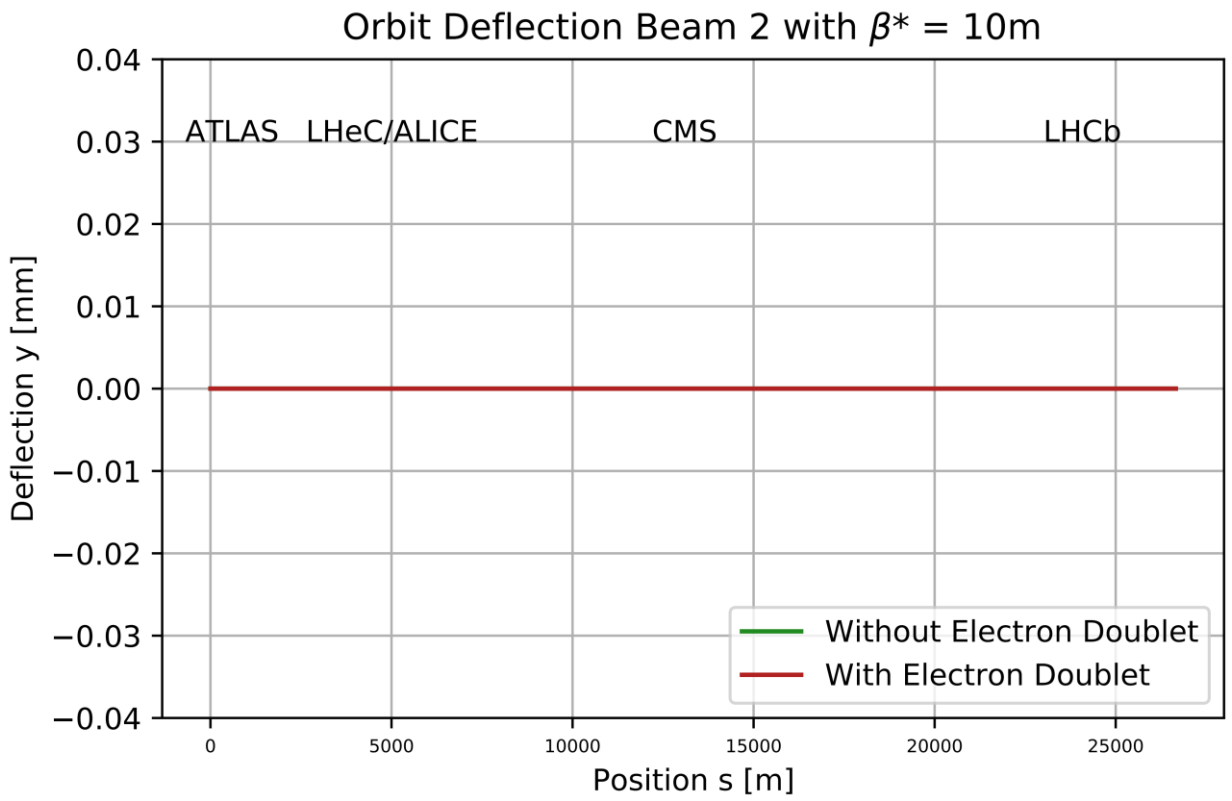
# Impact on the Proton Orbits y-plane

- Colliding Beam




- Spectator Beam

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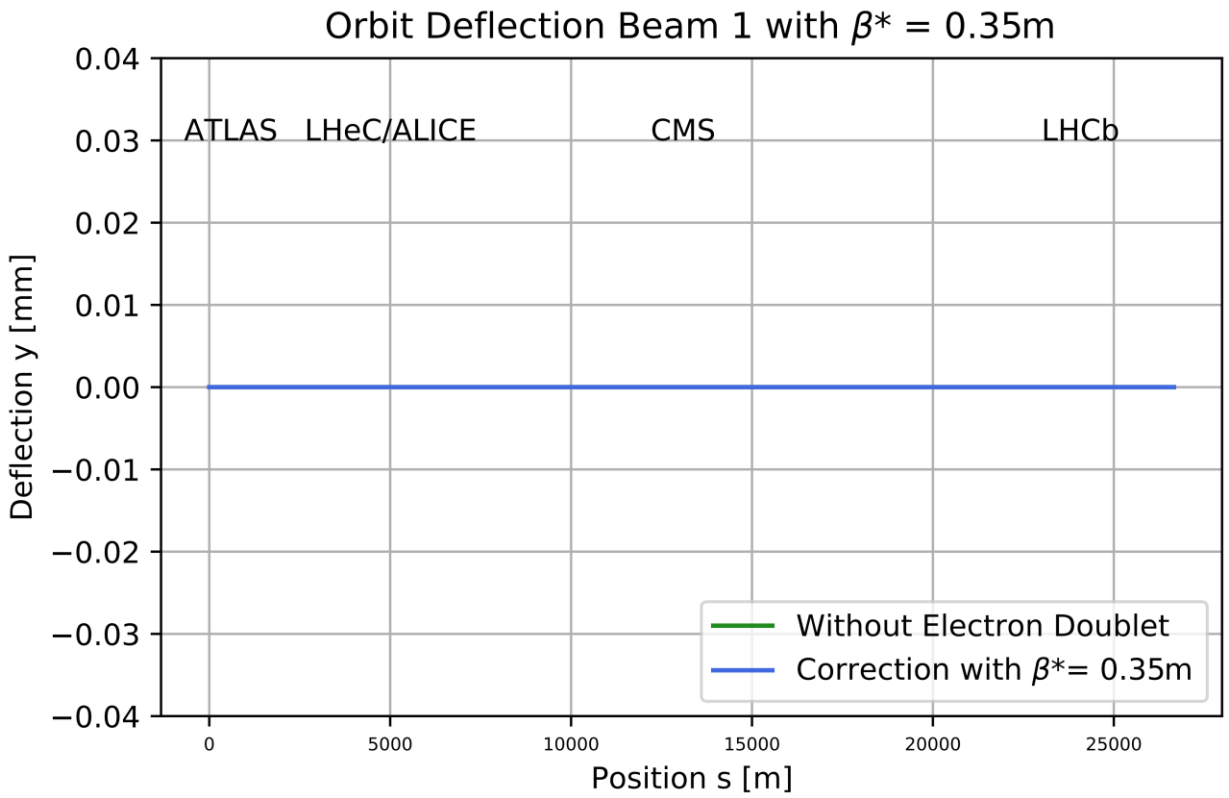
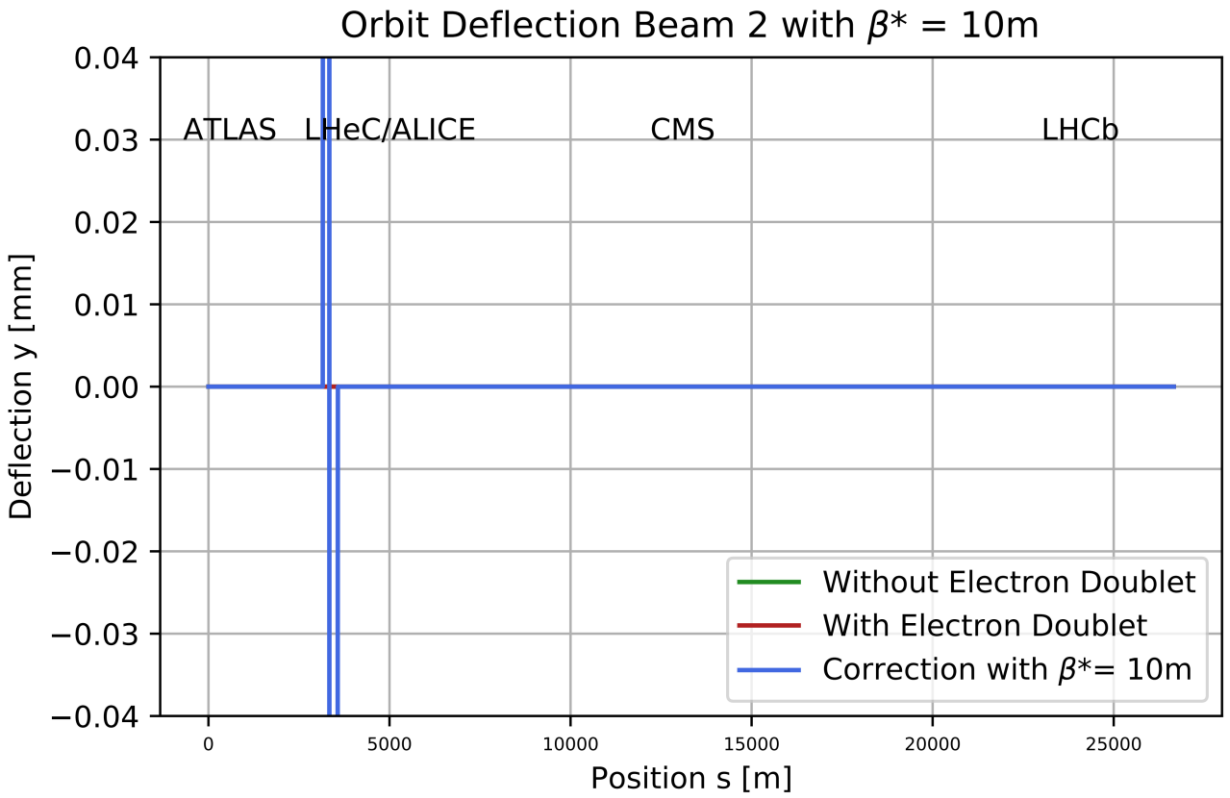
# Impact on the Proton Orbits y-plane

- Colliding Beam




- Spectator Beam

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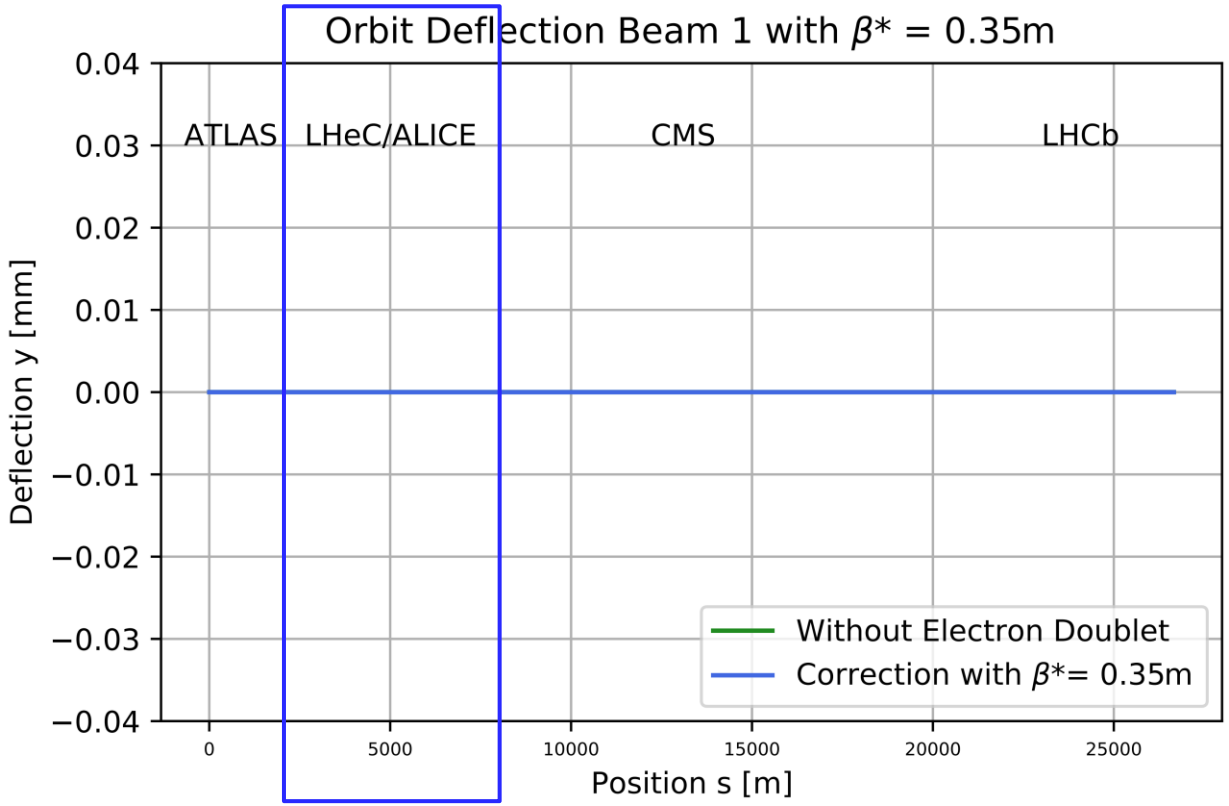
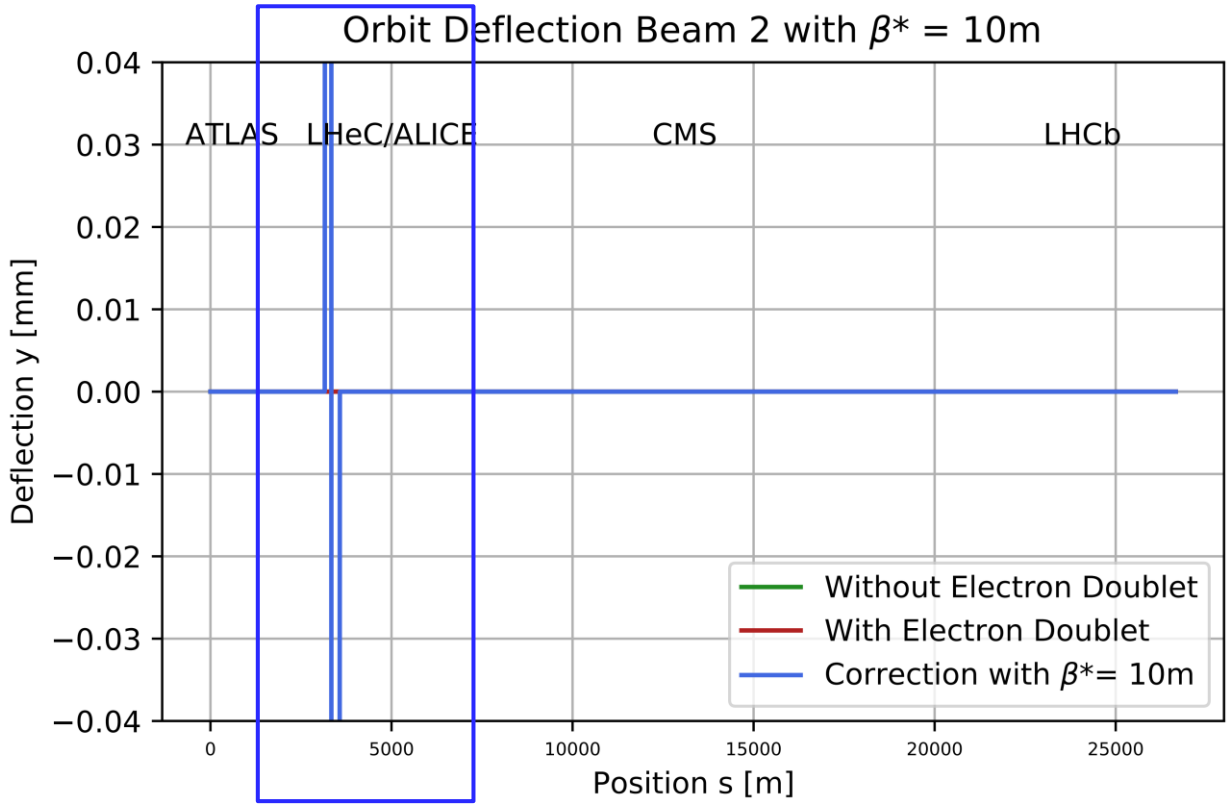
# Impact on the Proton Orbits y-plane

- Colliding Beam




- Spectator Beam

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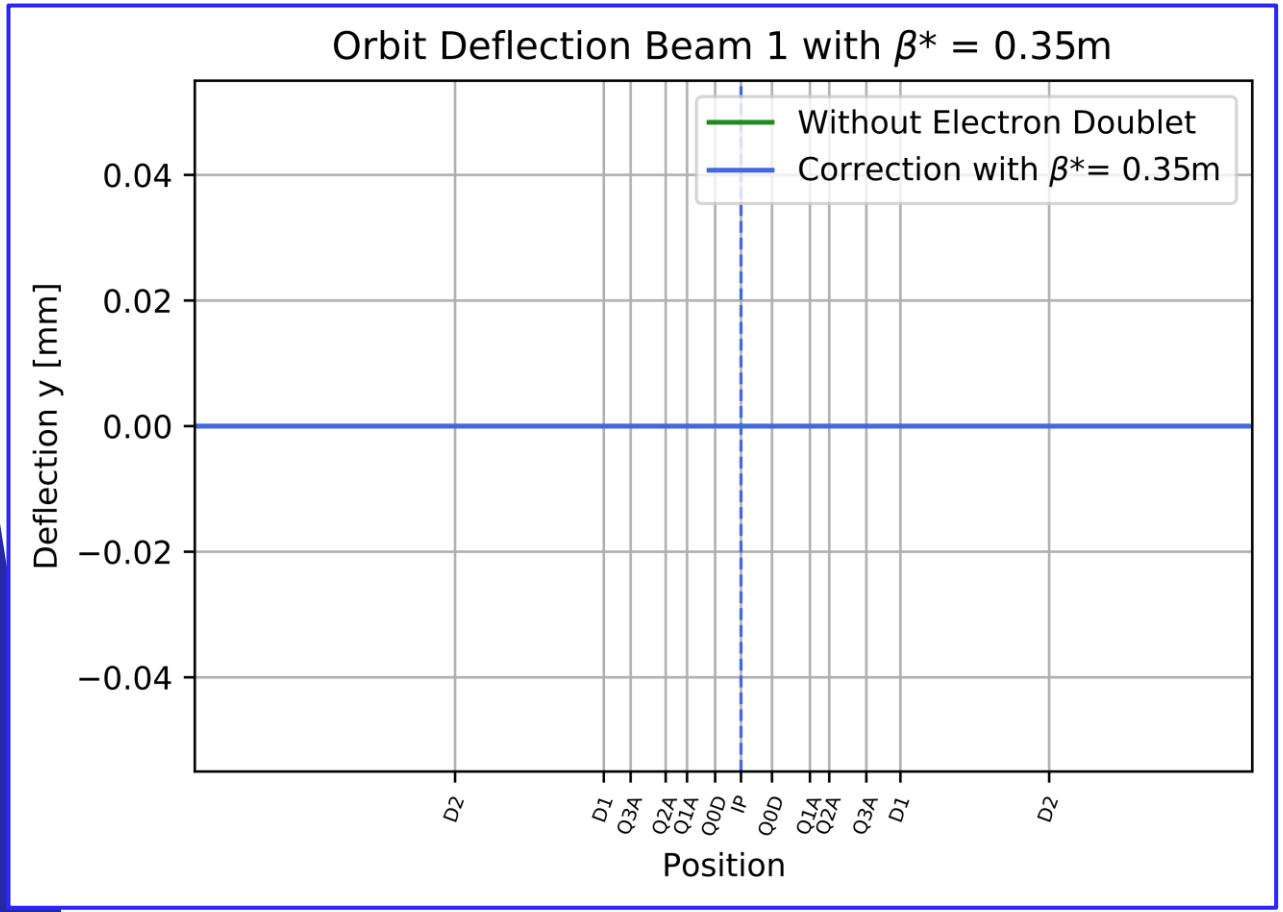
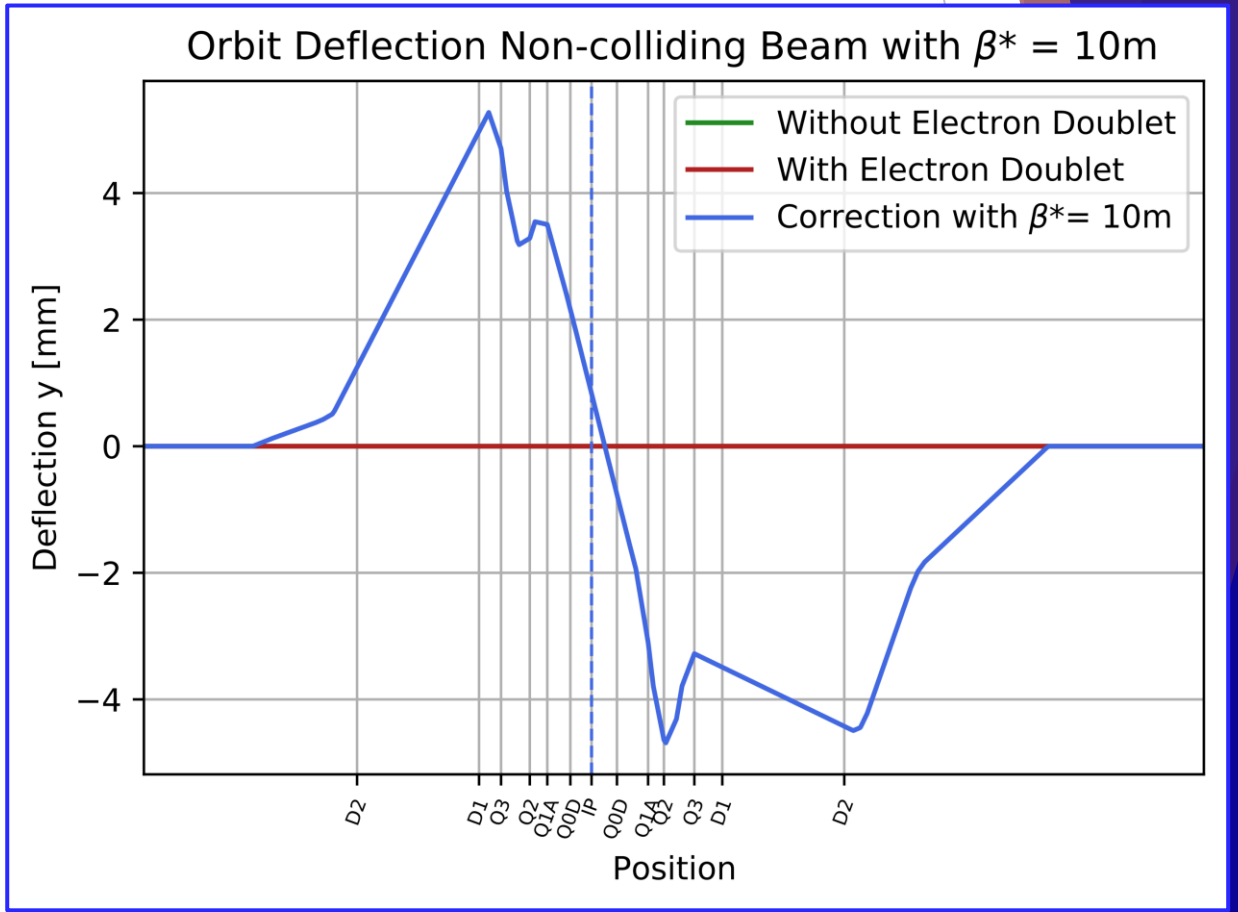
# Impact on the Proton Orbits y-plane

- Colliding Beam




- Spectator Beam

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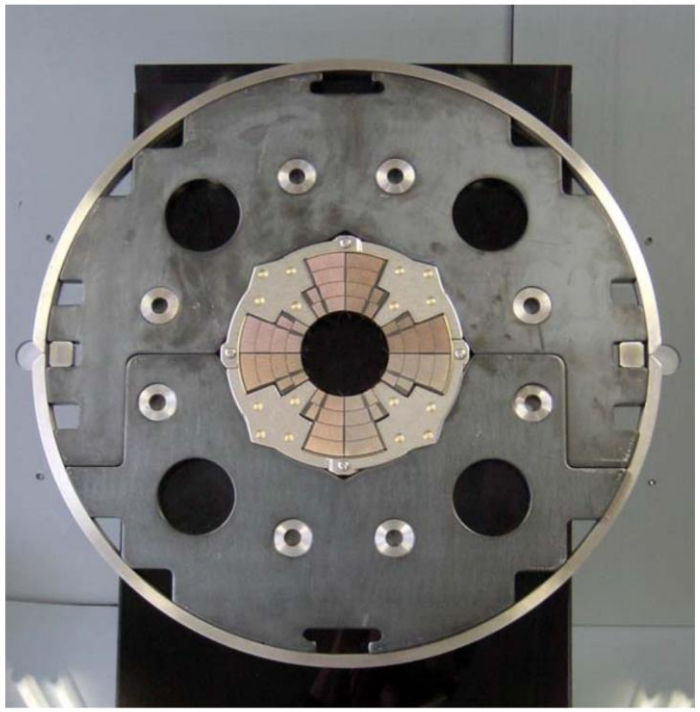
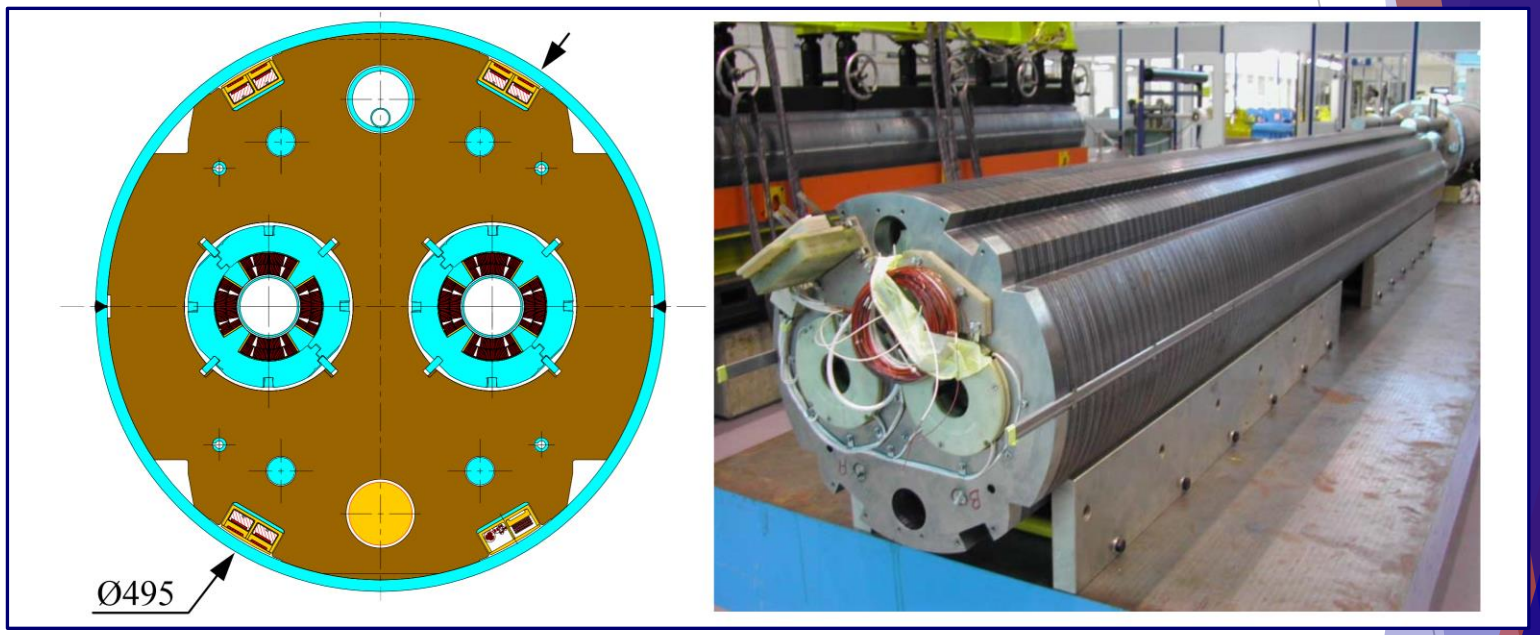
# Magnets constraints in the LHC IR



Inner Triplet Quadrupole

- On each side of the IP, there are 3 antisymmetric minibeta quadrupoles
- They are succeeded by 6 matching quadrupoles on each side




Matching Quadrupole

Both Beams see the same field in the Triplet

The Beams have their own Coils, they are however restricted in their difference through the yoke

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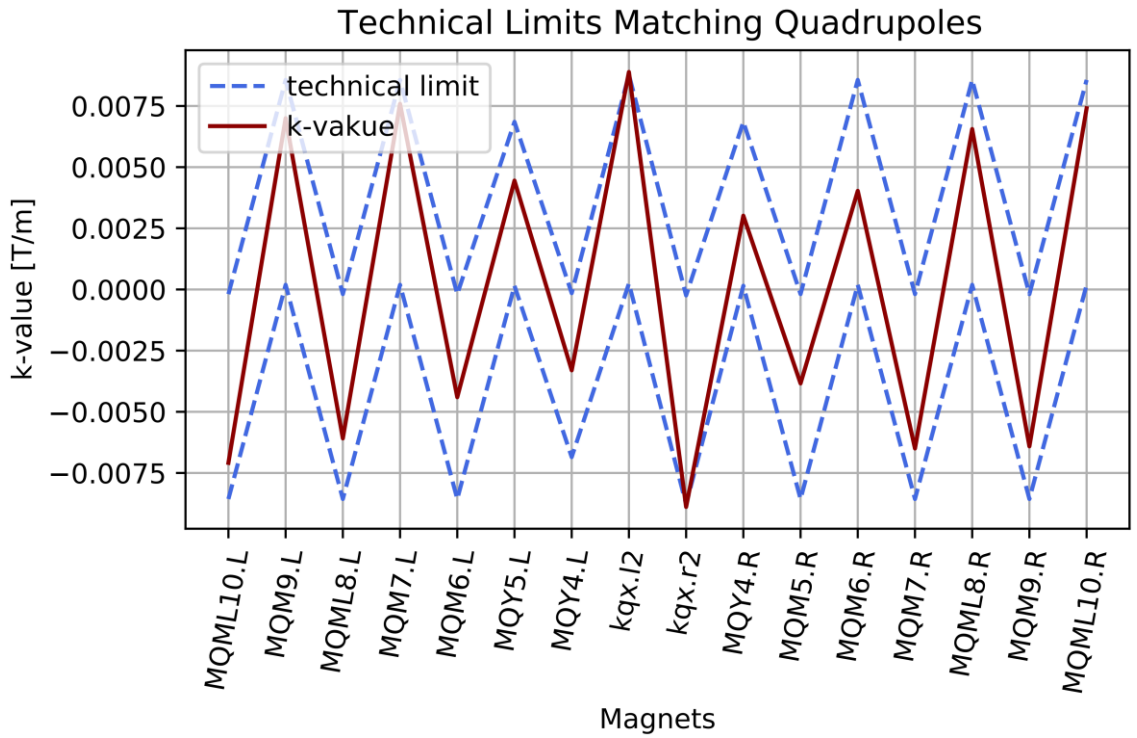
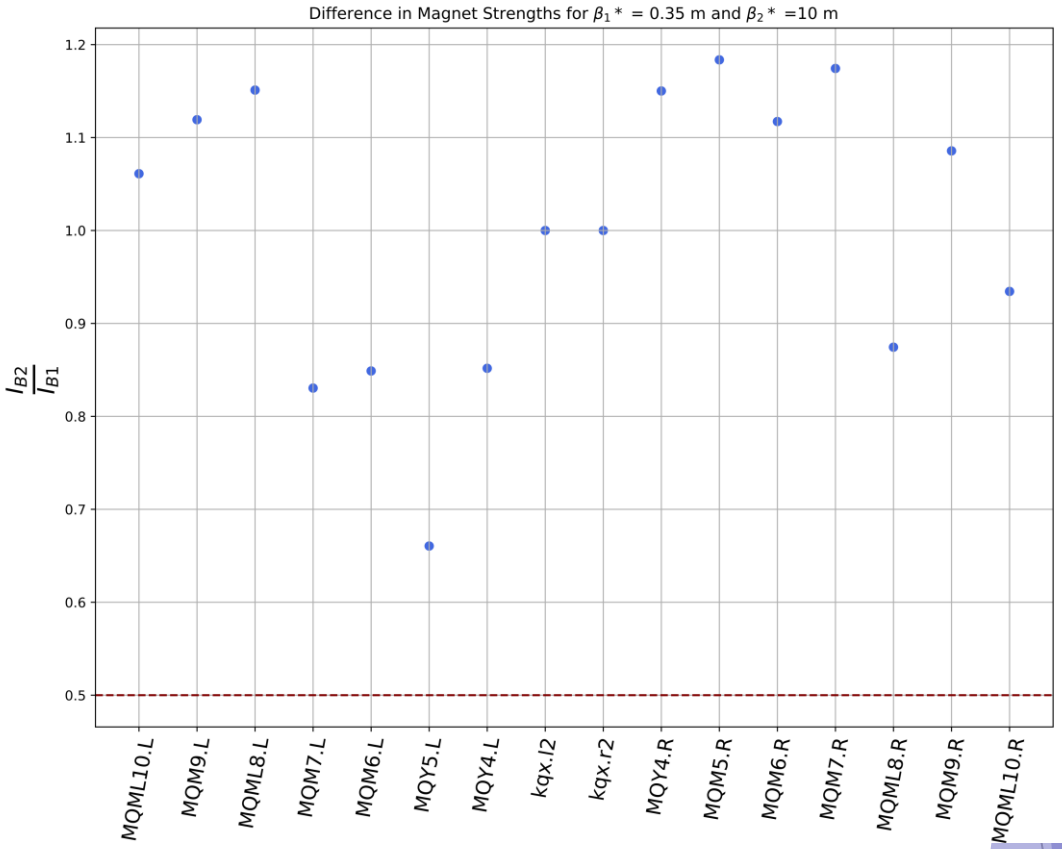
# Magnet Limitations

Gradient Limitations Beam 1
Matching Quadrupoles




Gradient Dependencies Beam 1
and Beam 2 Matching Quadrupoles

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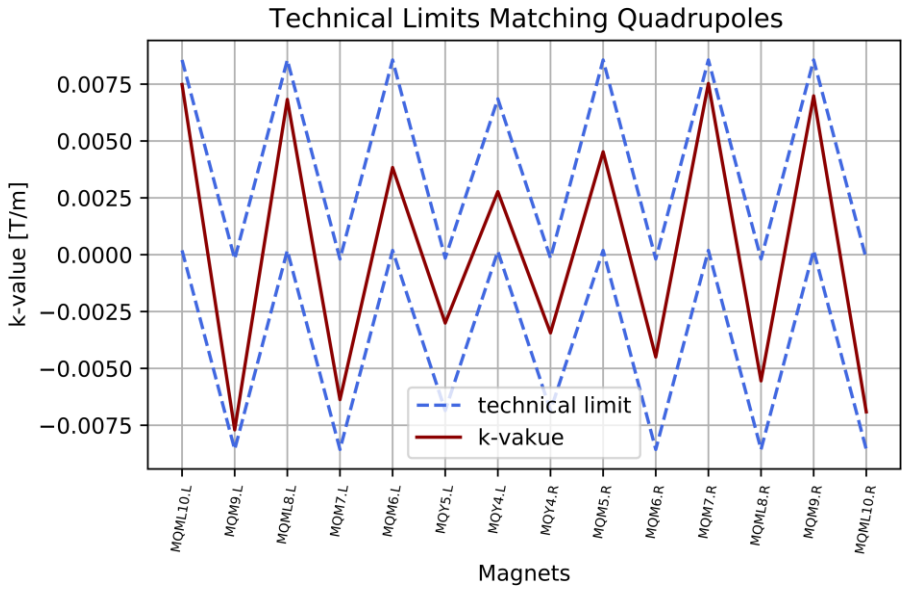
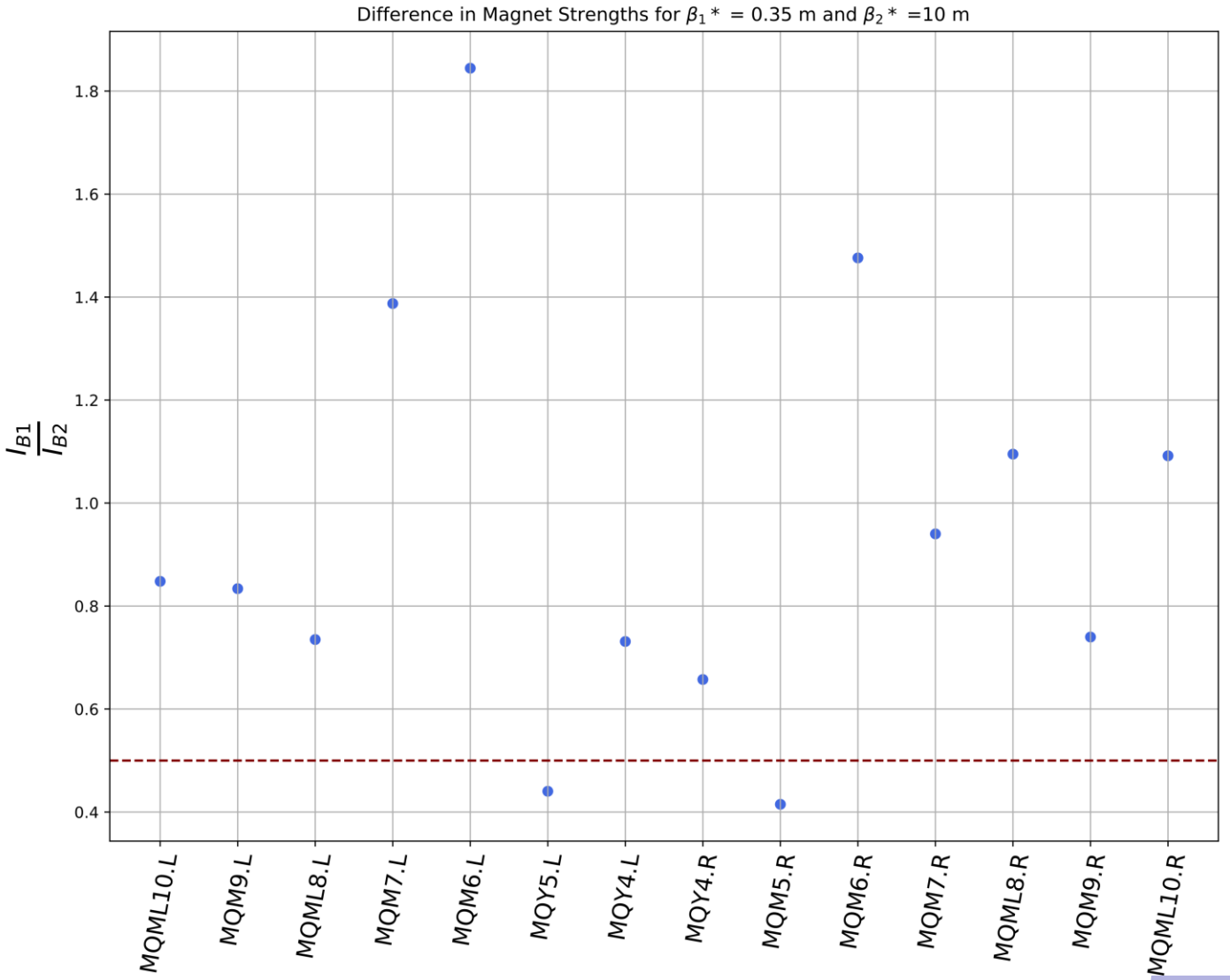
# Magnet Limitations

- Still necessary to change some copper wiring for the dependencies of the magnets for B1 and B2

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# Matching Quadrupoles Constraints

- The coils of the matching quadrupoles allow a difference in their strength of up to 50%