Some beam-beam considerations on optics design of the low β insertions

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- Performance reach with small β*
  - Adaptive β*
  - Crab cavities
- Crossing scheme
- Conclusion

Luminosity and beam-beam tune shift

- Round beams

$$L_0 = \frac{n_b f_{rev} N^2}{4\pi\sigma^2}$$

$$\xi = \frac{r_0 N}{4\pi\epsilon}$$

$$\Rightarrow \quad L_0 = \frac{n_b f_{rev} \gamma}{r_0} \frac{N \xi}{\beta^*}$$

Cleaning
Machine protection
Power loss
Heating

(→ N)

Emittance growth
Beam loss
Dynamic effects
(Orbit, β_{beat})

(→ ξ)

(β^* →) Smallest β* ?

Critical β*

$$\frac{1}{N}\frac{dN}{dT}=\sigma_{tot}\frac{n_{IP}f_{rev}\gamma}{4\pi\beta^*}\frac{N}{\epsilon}$$

$$\frac{1}{\epsilon}\frac{d\epsilon}{dT}=-\frac{1}{\tau}$$

$$\frac{N}{\epsilon}=cst\Rightarrow\sigma_{tot}\frac{f_{rev}\gamma}{r_0\beta^*}\xi_{tot}=\frac{1}{\tau}$$

- The system reaches ultimately reaches a balance between burn-off and synchrotron damping
  - The beam brightness (i.e. the beam-beam parameter) becomes constant
- To achieve a constant beam-beam parameter of 0.01, one requires :

$$\beta_c^*=\sigma_{tot}\tau\frac{f_{rev}\gamma}{r_0}\xi_{tot}\approx 0.06\,m$$

→ One will need to either actively control the beam brightness or live with a non-constant beam-beam parameter

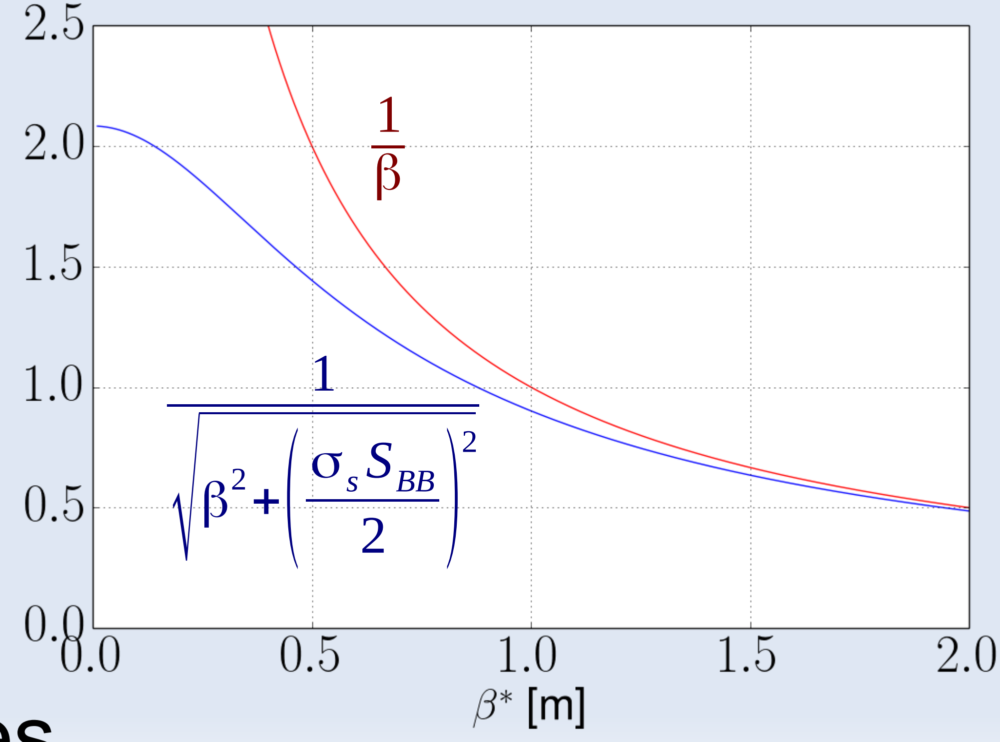
Crossing angle

- Crossing angle defined by long-range beam-beam interaction :

$$S_{BB} \approx \sqrt{\beta^* \frac{\gamma}{\epsilon_n}}\theta_{full} = 12$$ → Depends on the crossing scheme (L*, experimental spectrometer, …)

$$L = \frac{n_b f_{rev} N^2}{4\pi\sigma^2} \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\frac{\theta_{full}}{2}\right)^2}}$$

$$= \frac{n_b f_{rev} \gamma N^2}{4\pi\epsilon} \frac{1}{\sqrt{\beta^{*2}+\left(\frac{\sigma_s S_{BB}}{2}\right)^2}}$$



- β* <~0.3 m are not very interesting w/o crab cavities

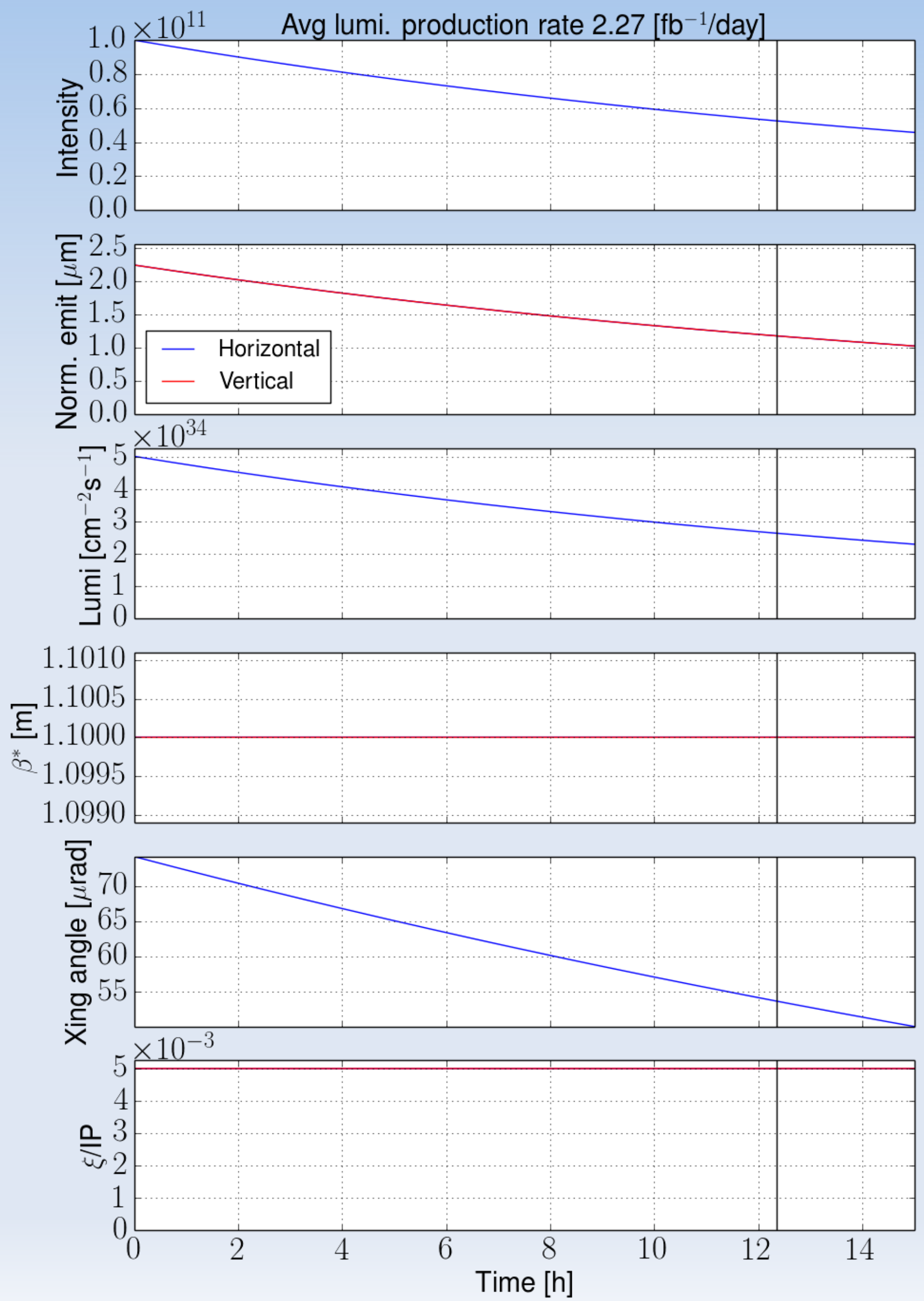
More elaborate luminosity model

$$\begin{cases} \frac{\partial I}{\partial t} &= -\frac{I(t)}{\tau_{lifetime}} - \mathcal{L}_{IP}(t)N_{IP}\sigma_{tot} \\ \frac{\partial \epsilon_x}{\partial t} &= -\frac{\epsilon_x(t)}{\tau_{rad,x}} + \alpha_{rad,x} + \frac{I(t)}{\epsilon_y(t)}\alpha_{IBS,x} \\ \frac{\partial \epsilon_y}{\partial t} &= -\frac{\epsilon_y(t)}{\tau_{rad,y}} \\ \frac{\partial \epsilon_s}{\partial t} &= 0 \\ \mathcal{L}_{IP} &= \frac{n_b f_{rev} N(t)^2 \gamma_r}{4\pi\beta^* \sqrt{\epsilon_x(t)\epsilon_y(t)}} \frac{cos(\phi(t))^2}{\sqrt{1+\frac{\sigma_s^2}{\sigma^2} tan(\phi(t))^2}} \end{cases}$$

- Still assume round beam (blow-up required in the vertical plane)
- Beam-beam parameter computed assuming two IPs with alternating crossing angle
- The crossing angle is adjusted during the fill to keep the same beam-beam separation at the long-range encounters

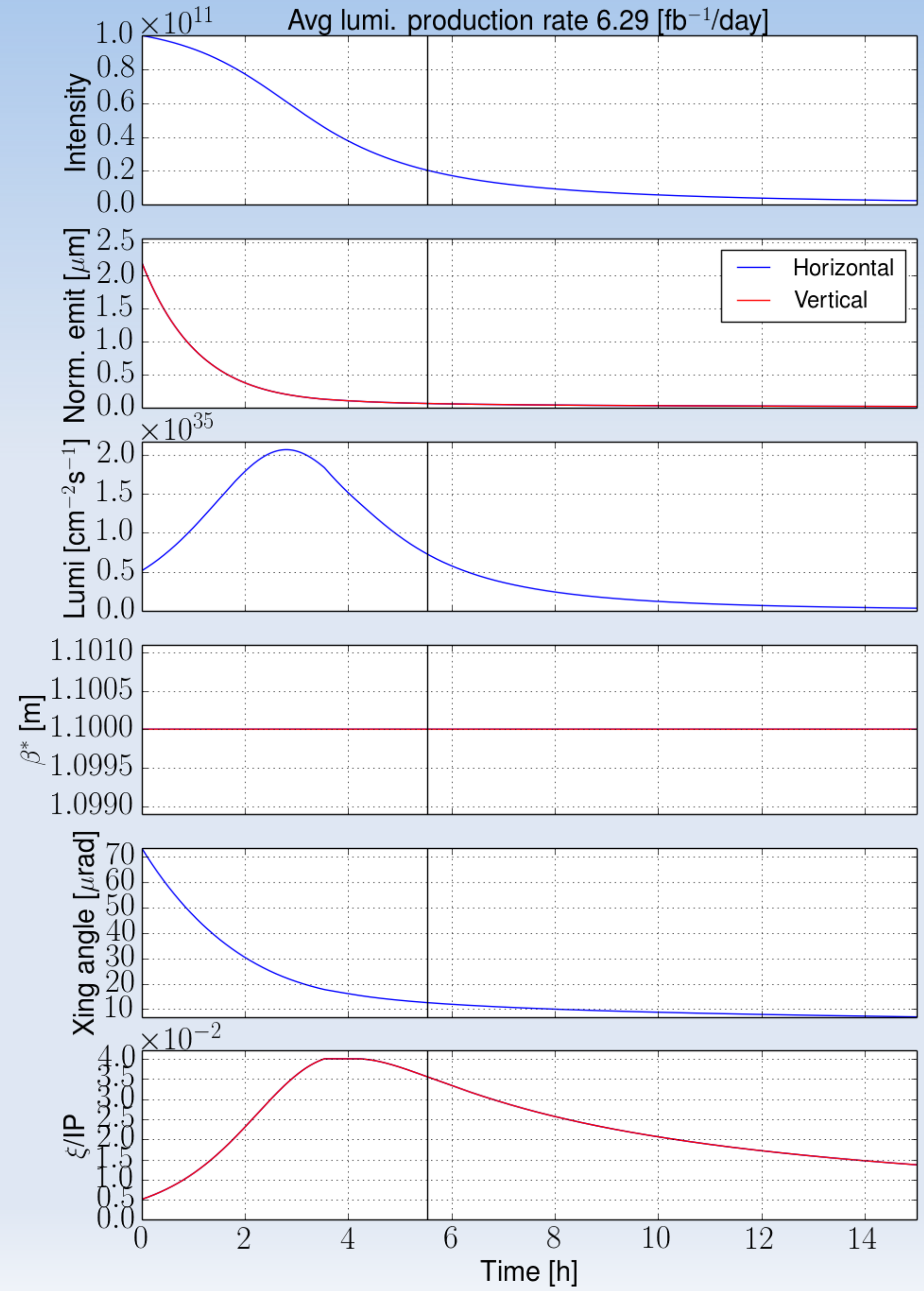
Beam parameter evolution

- The nominal configuration is limited by the small beam-beam tune shift



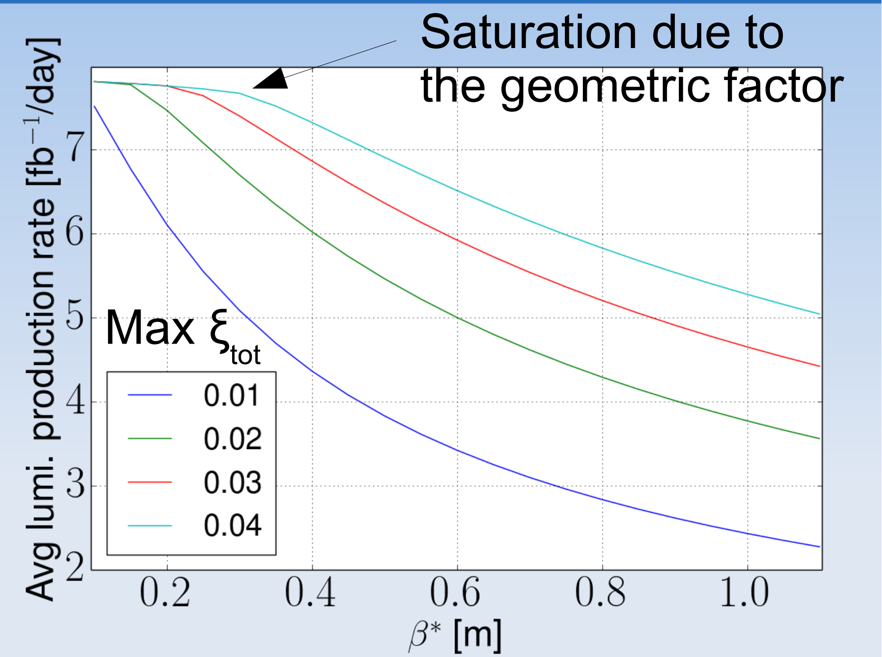
Beam parameter evolution

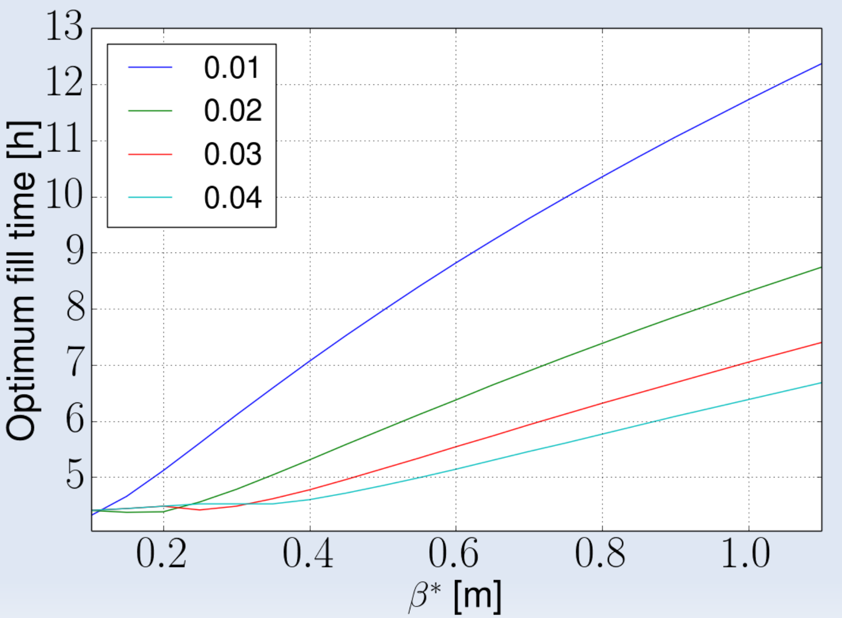
- The nominal configuration is limited by the small beam-beam tune shift
  - The beam parameter evolution is very different in configurations with larger beam-beam tune shift



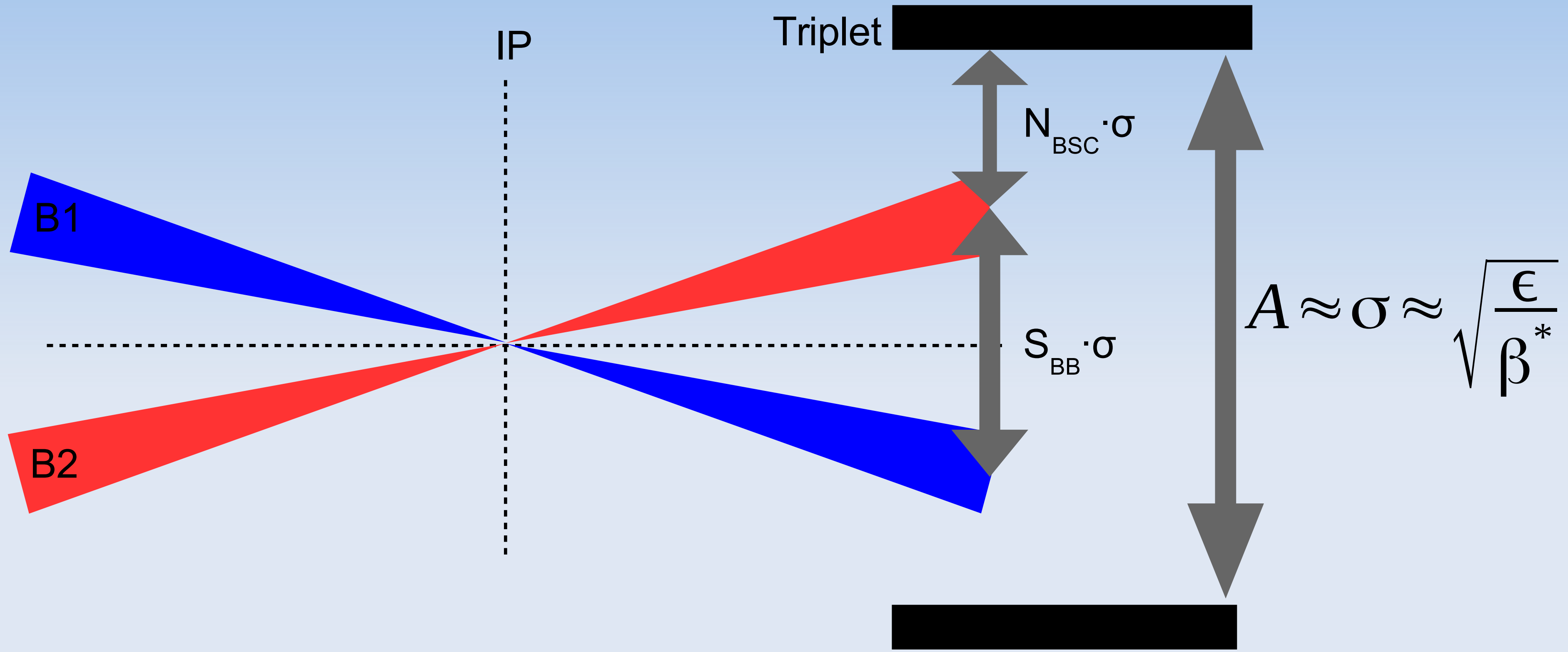
Beam parameter evolution

- The nominal configuration is limited by the small beam-beam tune shift
  - The beam parameter evolution is very different in configurations with larger beam-beam tune shift
- Reduced β* allows to achieve higher integrated luminosity within shorter fills





Adaptive optics

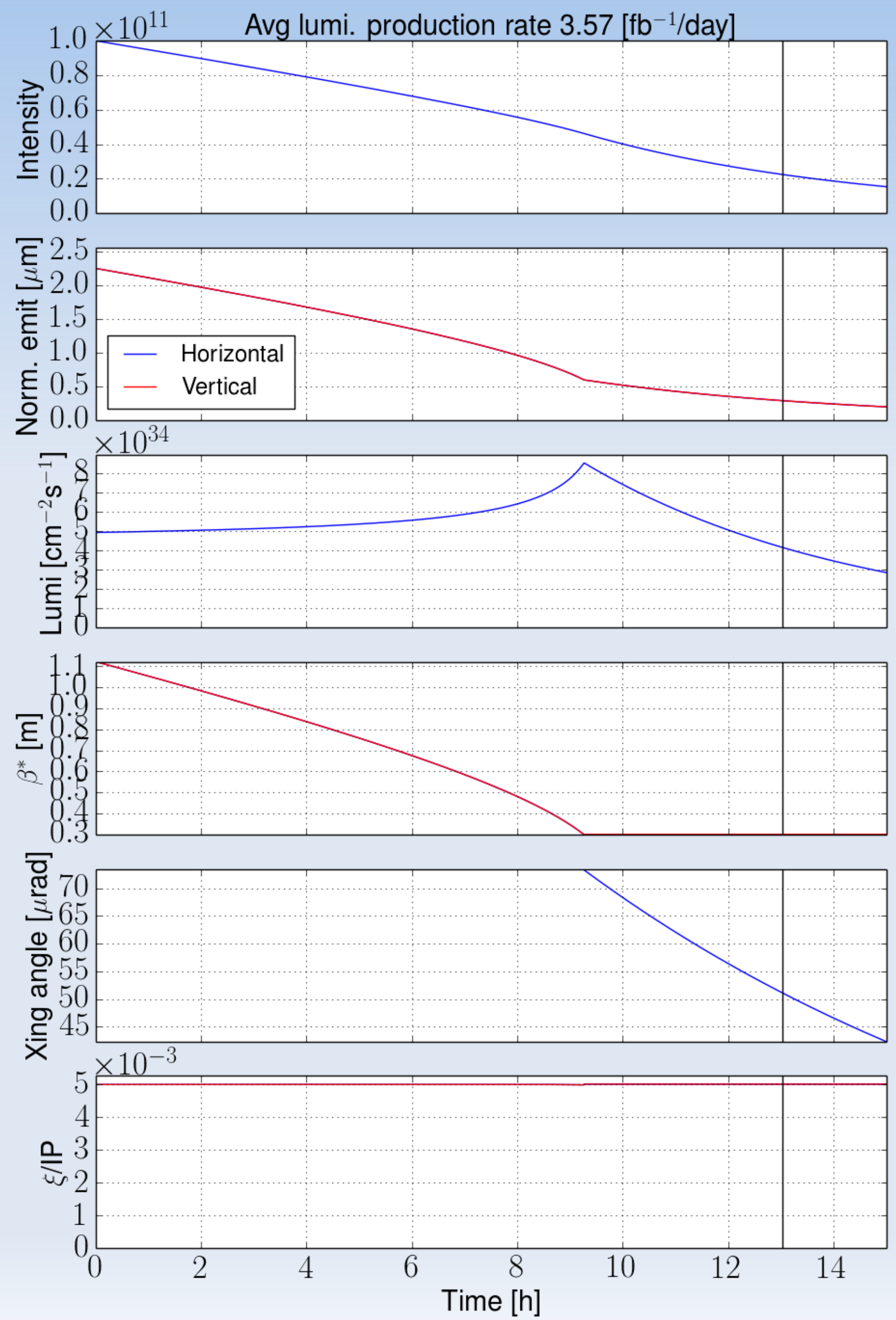


- β* can be reduced with the reduction of the emittance during the fill without increased aperture requirement by keeping the ratio ε/β* constant
  - The beam-stay-clear and the normalised beam-beam separation are kept constant

    → no change of crossing angle

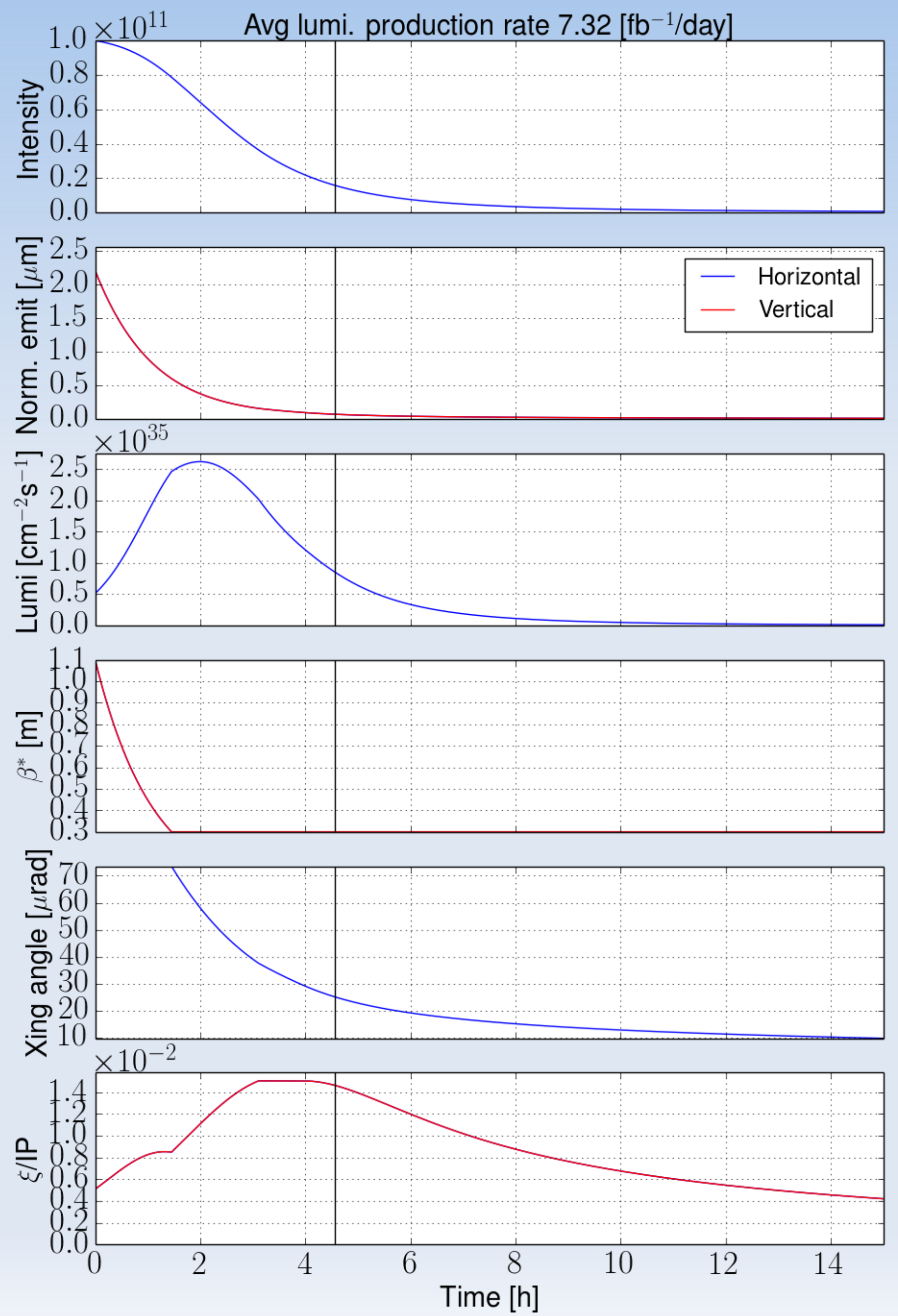
Beam parameter evolution

- Nominal configuration, with β* decreasing to 0.3 m during the fill
  - 1.5x performance increase, but at the cost of very long fills



Beam parameter evolution

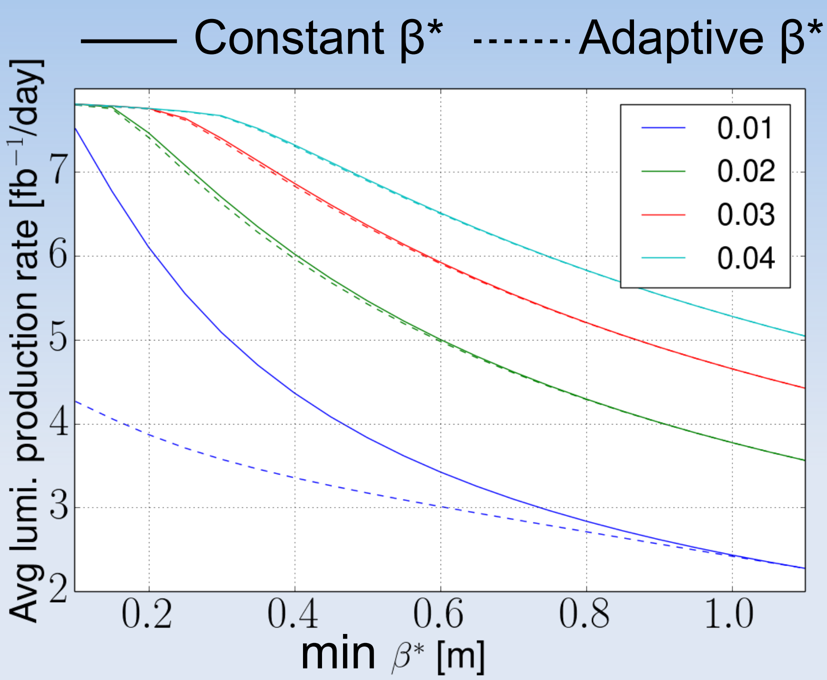
- Nominal configuration, with β* decreasing to 0.3 m during the fill
  - 1.5x performance increase, but at the cost of very long fills
- Large performance gain with slightly larger beam-beam tune shift

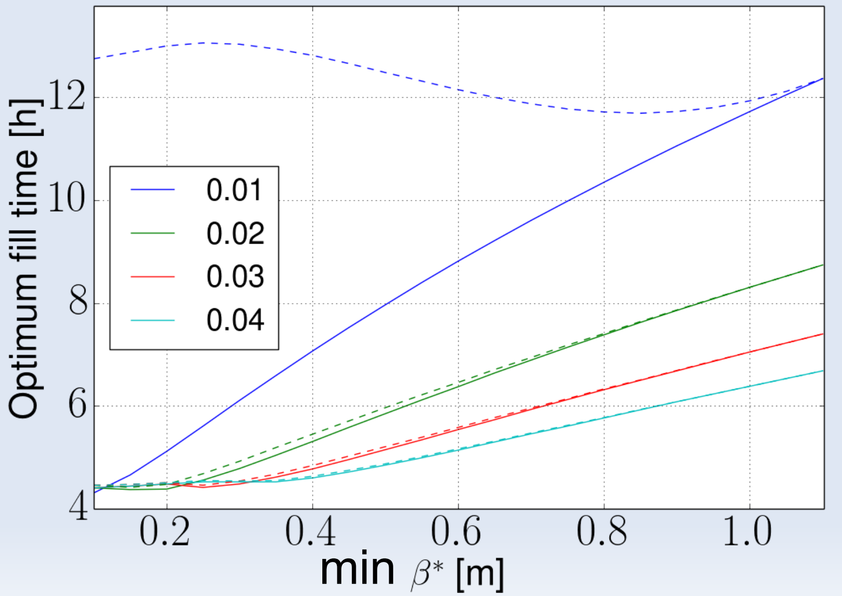


Beam parameter evolution

- Nominal configuration, with β* decreasing to 0.3 m during the fill
  - 1.5x performance increase, but at the cost of very long fills
- Large performance gain with slightly larger beam-beam tune shift
  - Similar to the configurations with constant β*
  - But the smallest β* is achieved with a small emittance

  → Relaxed aperture requirements

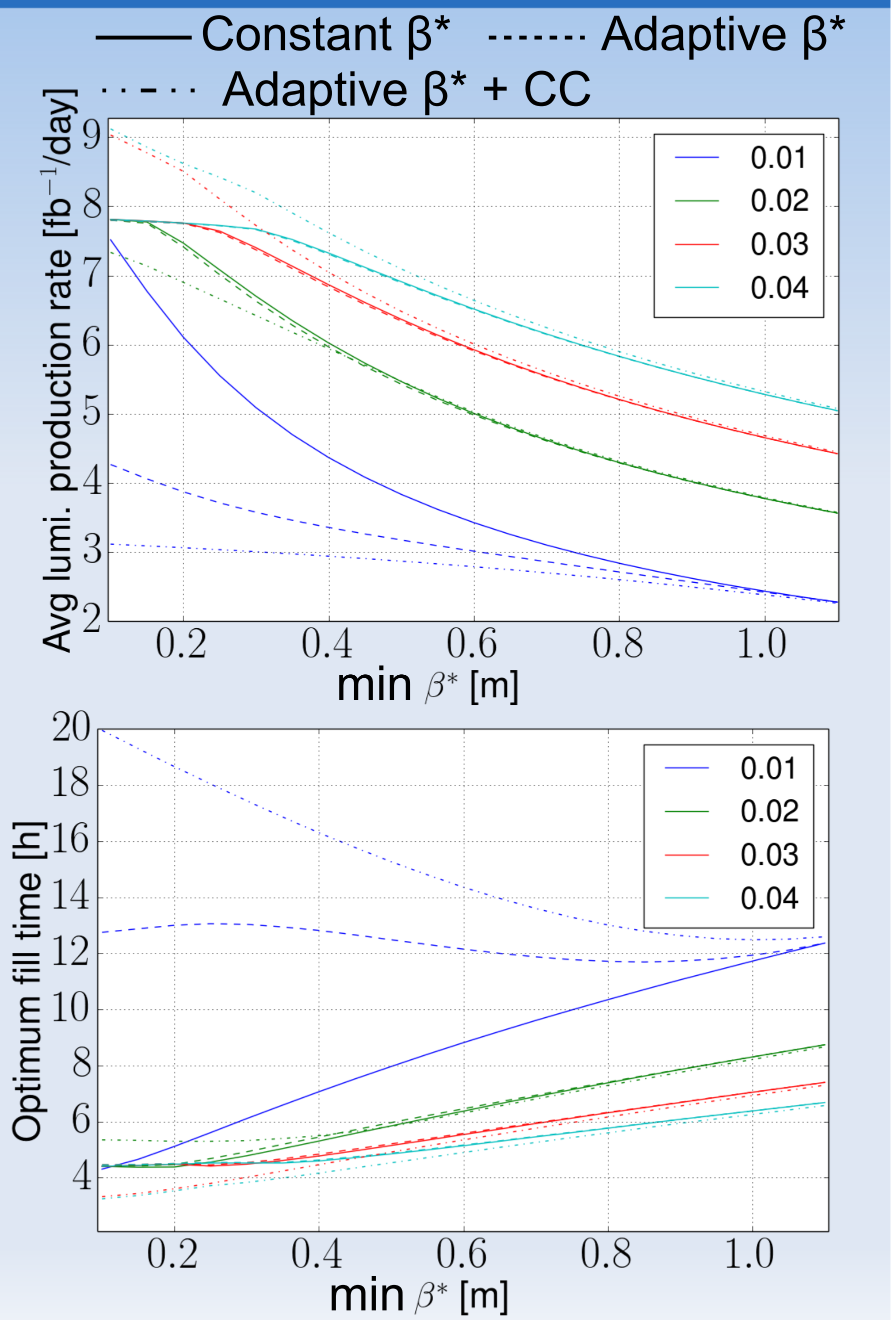


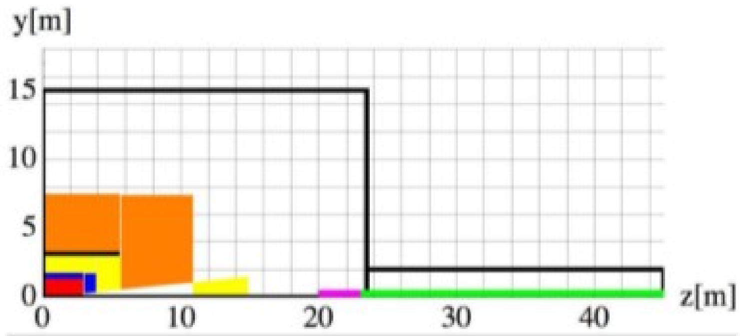


Crab cavity

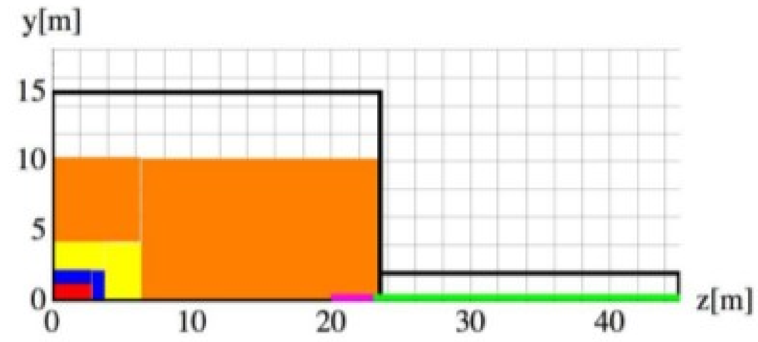
- Crab cavities are not helpful in configurations limited by the head-on beam-beam parameter
- Slight gain for β^*_{min} < 0.3 m

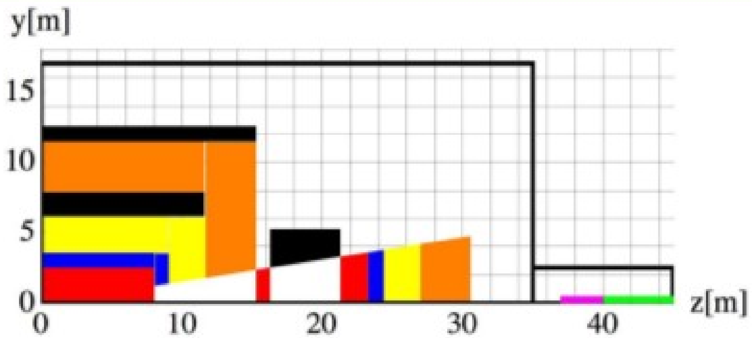
  → Adapting the β* allows to circumvent the needs for crab cavities, but the dynamics with large Piwinski angles has to be assessed





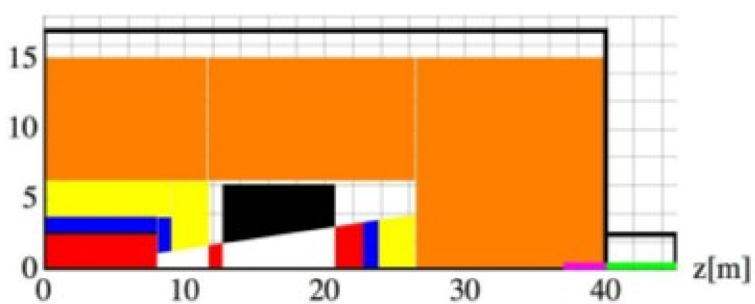
CMS & ATLAS





Twin Solenoid + Dipole, BL^2 scaled

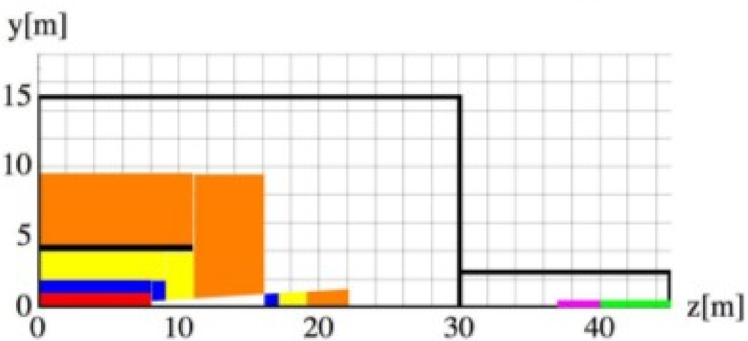
Tracker r=2.5m p_t reso 15% at 10TeV
12 lambda ECAL+HCAL =1m+2.5m
Coil R=6m, 6T, Shielding Coil
Forward Dipole 10Tm



Toroid + Dipole, BL^2 scaled

Tracker r=2.5m p_t reso 15% at 10TeV
Thin Coil R= 2.5m, B= 4T
12 lambda ECAL+HCAL =1m+2.5m
Muon Toroid
Forward Dipole 10Tm

Tracker
Emcal
Hcal
Muon
Coil
TAS
Triplet



CMS+, resolution scaled

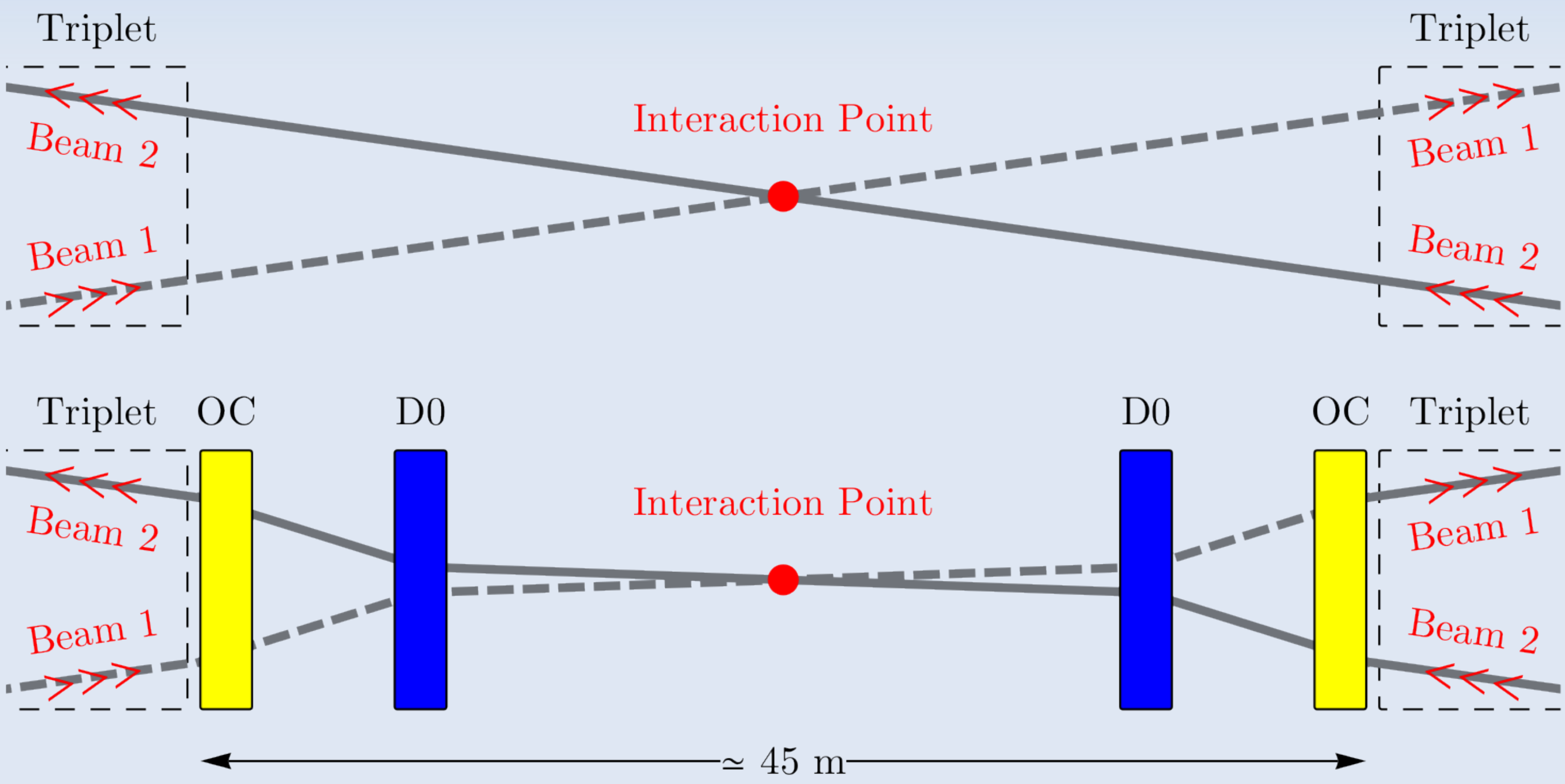
Tracker r=1.2m p_t reso 15% at 10TeV
12 lambda ECAL+HCAL =0.6m+2.2m
Coil R=4m
Iron Return Yoke
→ Extreme detector technology push

An early separation scheme for the LHC upgrade

- G. Sterbini, EPFL PhD thesis No 4574 (2010)

  → Place a dipole as close as possible to the IP in order to reduce the internal crossing angle keeping the same orbit in the triplet

  - D0 integrated strength : 10-15 Tm



An early separation scheme for the LHC upgrade

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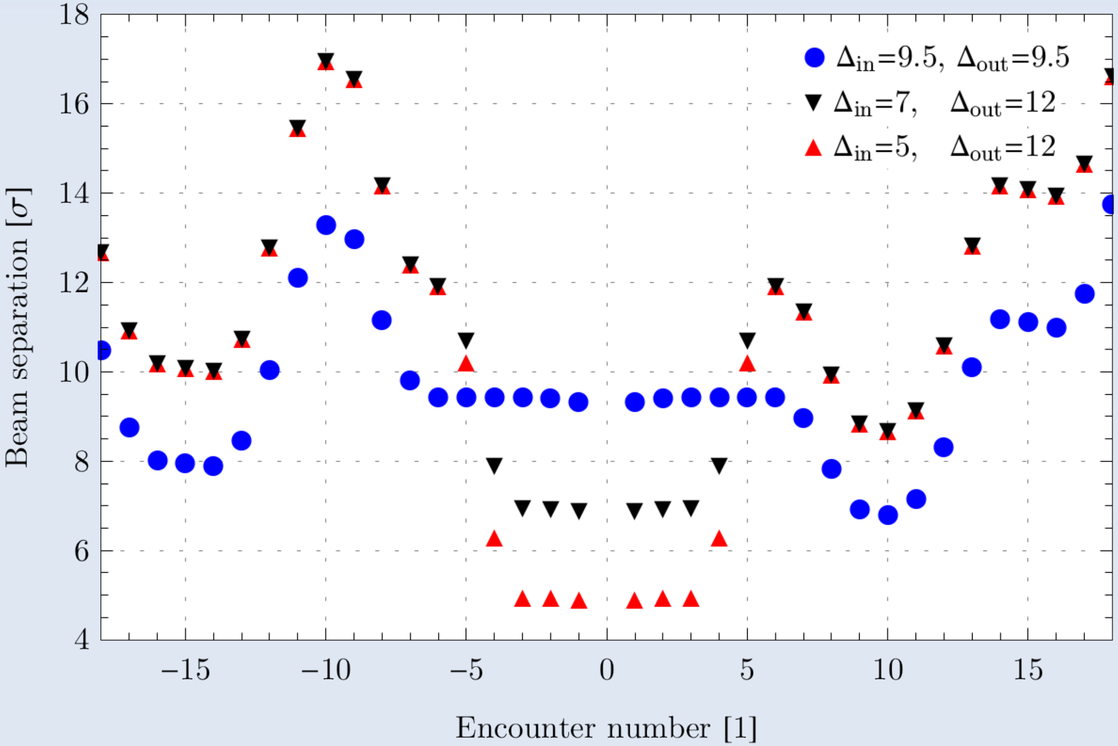
  → Place a dipole as close as possible to the IP in order to reduce the internal crossing angle keeping the same orbit in the triplet

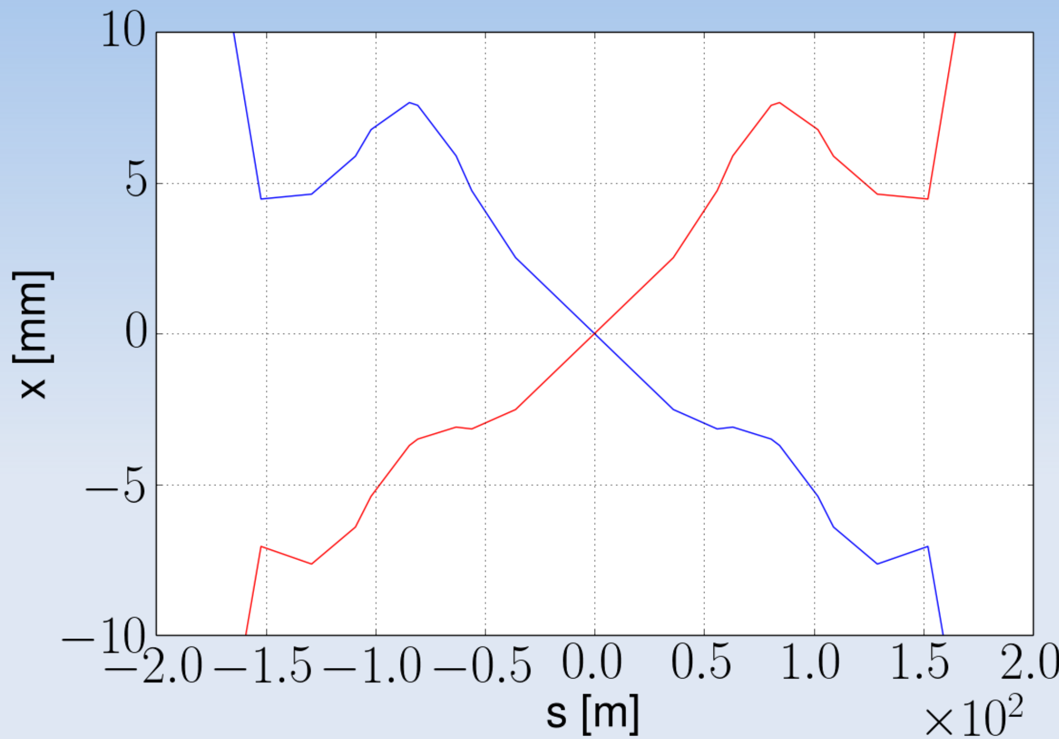
  - D0 integrated strength 10-15 Tm

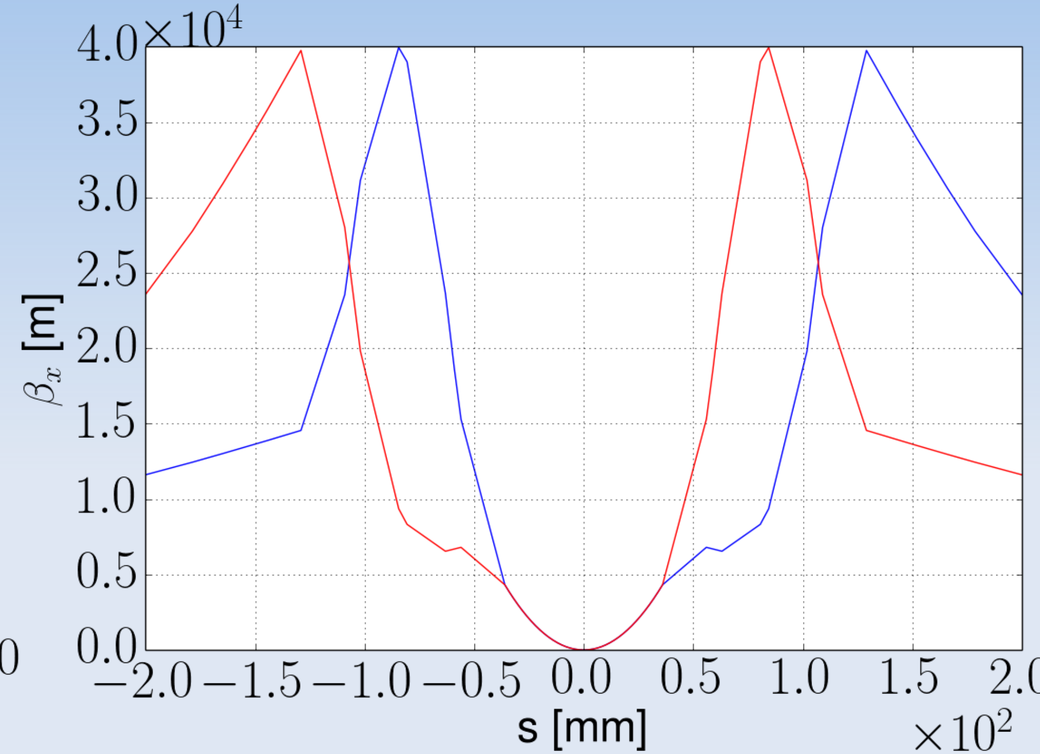
- Large impact on the separation between the beams

  → Similar long-range beam-beam 'strength' with lower geometric reduction factor



First try with the FCC IR

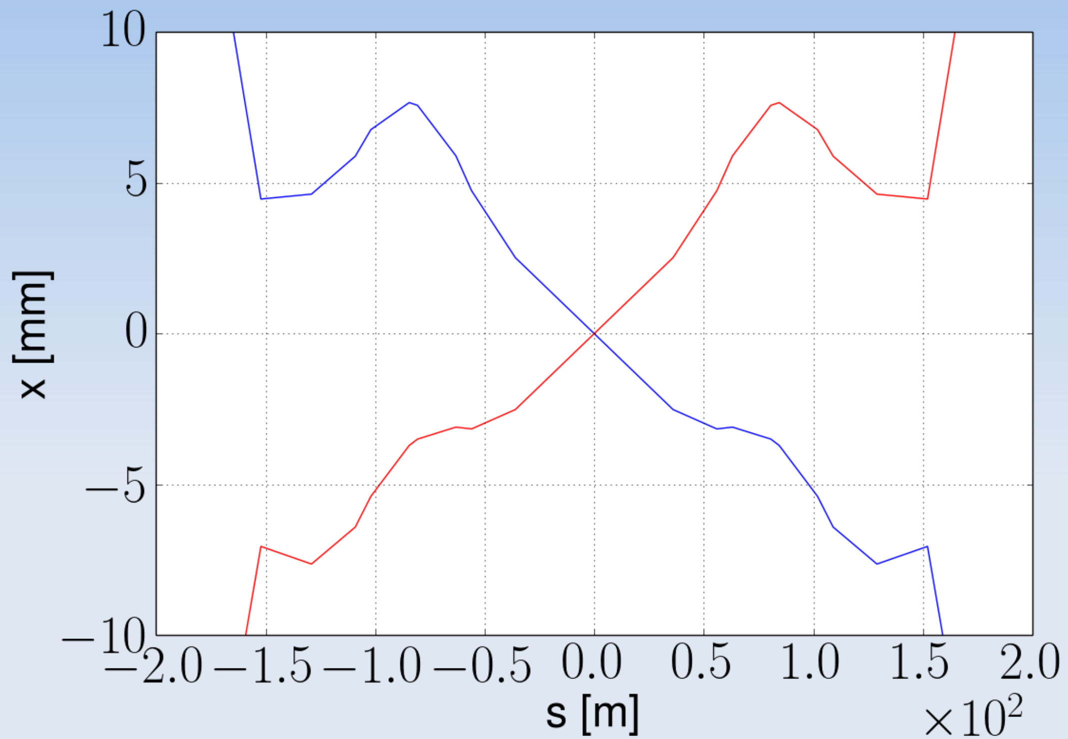


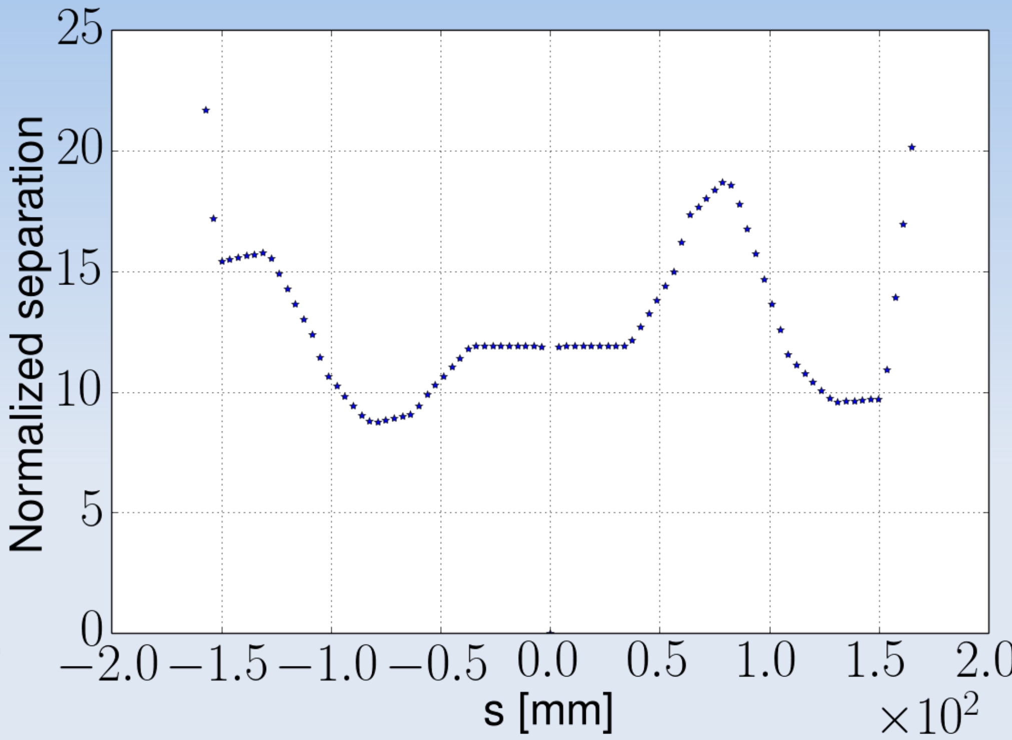


- Triplet first (scaled HL-LHC) β* = 0.3m, L* = 36m

  → θ_{full} = 70 μrad, such that S_{BB} = 12 σ

First try with the FCC IR





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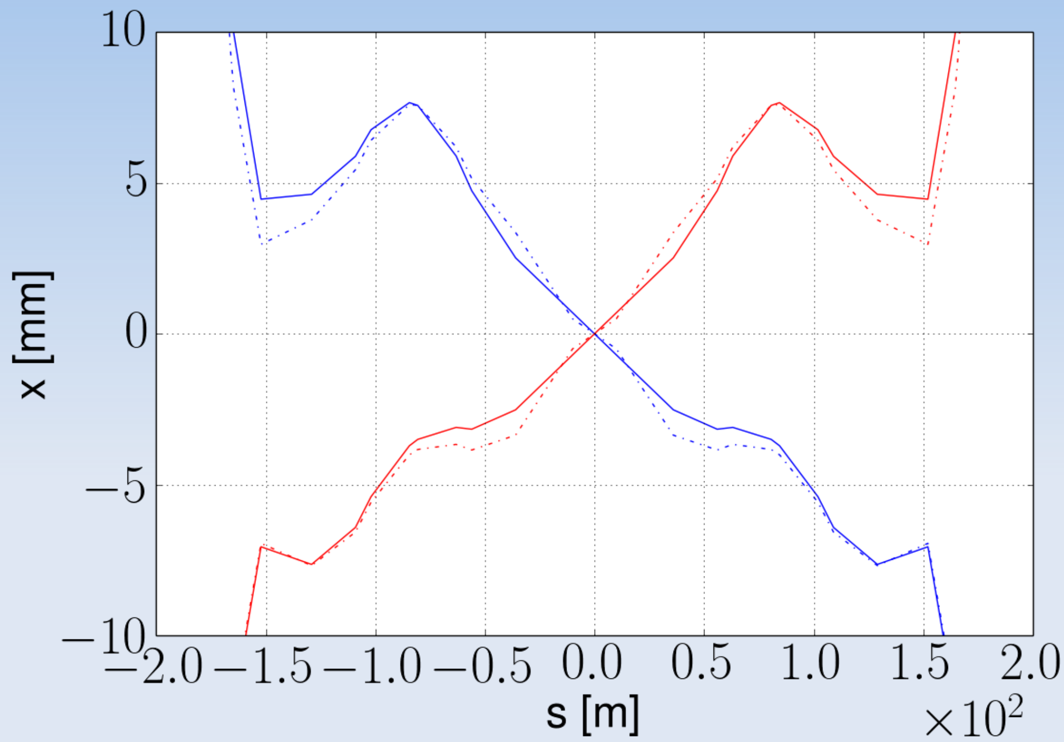

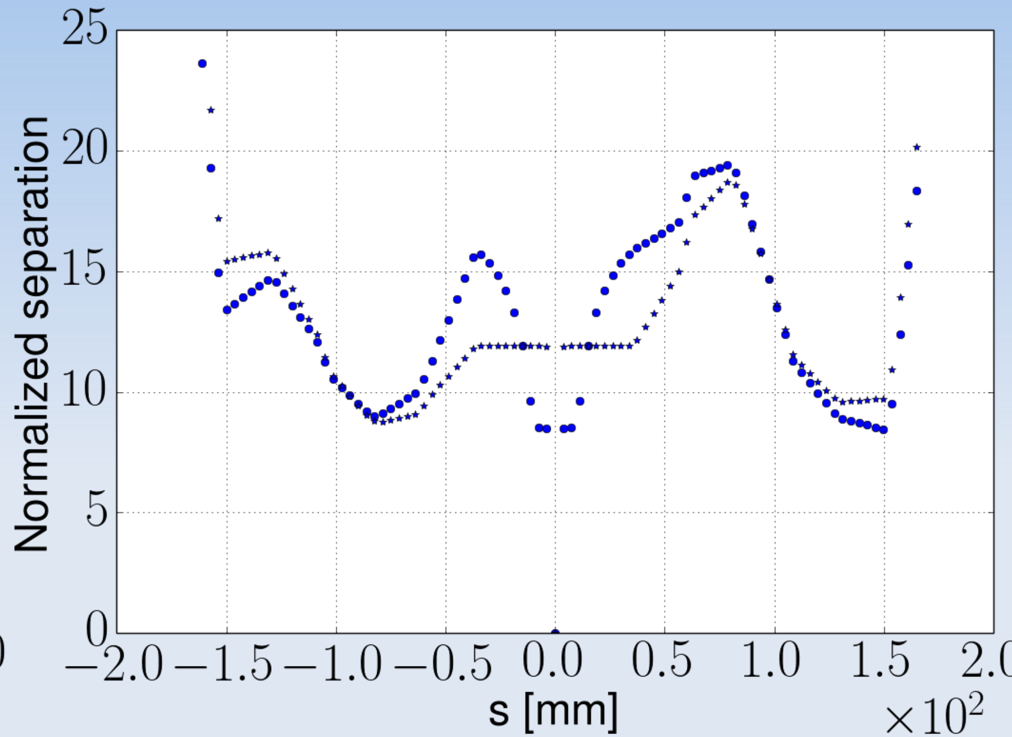

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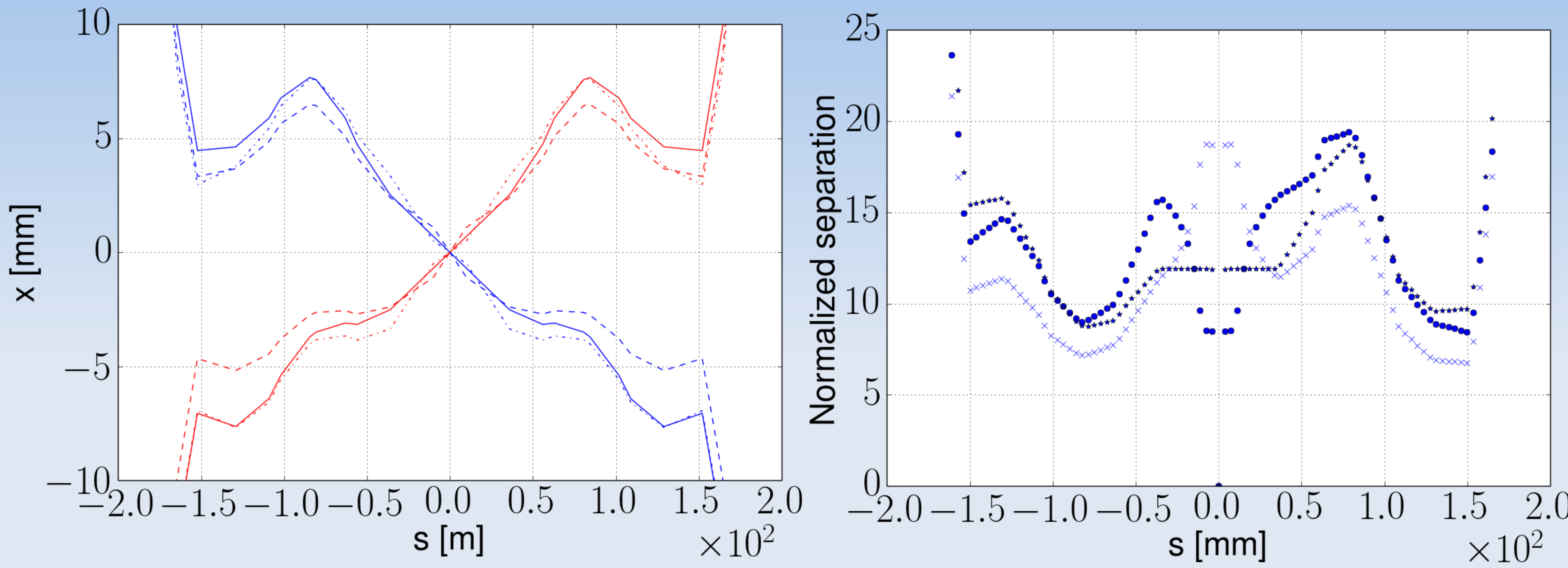
- A similar early separation scheme allows to reduce the internal Xing angle (10 Tm D0 at 10m from the IP)

First try with the FCC IR



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- A similar early separation scheme allows to reduce the internal Xing angle (10 Tm D0 at 10m from the IP)

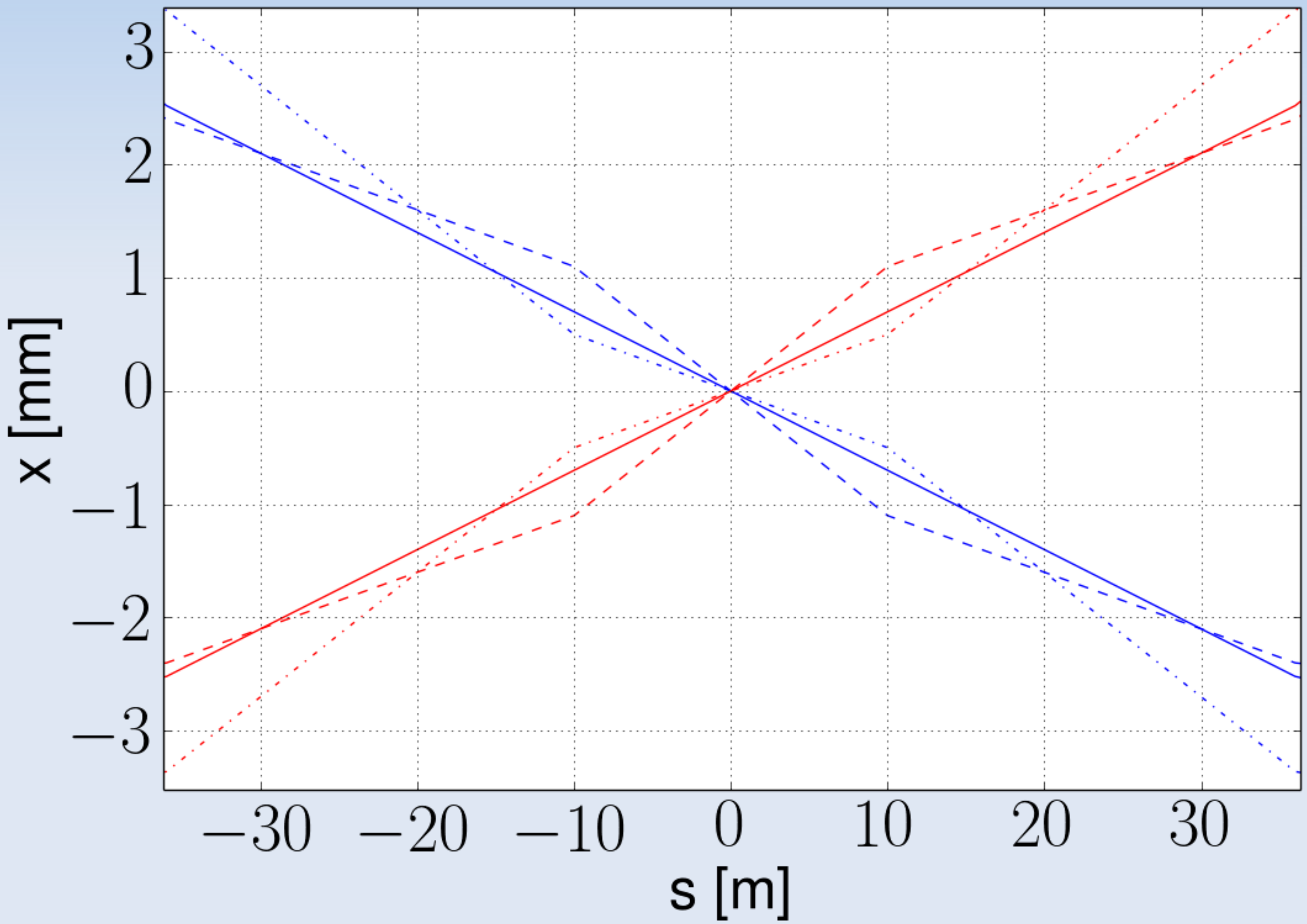
- The reversed scheme allows to reduce the external Xing angle

Conclusion

- Small β* is clearly a key for the luminosity performance
  - Adapting β* during the fill with a constant aperture requirements in the triplet offers a significant improvement
- Experimental spectrometers might be used to increase the performance
  - W/o crab cavity an early separation scheme could reduce the geometric reduction factor
  - With crab cavities, the reversed scheme might relax the aperture requirement in the triplet

    → The performance gain for both scheme should be quantified

BACKUP
Zoom on the drift space



BACKUP
Hourglass effect

- Hourglass is relevant for $\beta \sim \sigma_s = 0.08$ m

  → Only relevant for configurations with crab cavities

$$L_0 = \frac{n_b f_{rev} N^2}{4 \pi \epsilon \beta^*}$$

$$L = \frac{n_b f_{rev} \gamma N^2}{4 \pi \epsilon} \frac{\sqrt{\pi}}{\sigma_s} e^{\left(\frac{\beta^*}{\sigma_s}\right)^2} \int_{\frac{\beta^*}{\sigma_s}}^{\infty} e^{-x^2} dx$$