High β*-optics for ALICE

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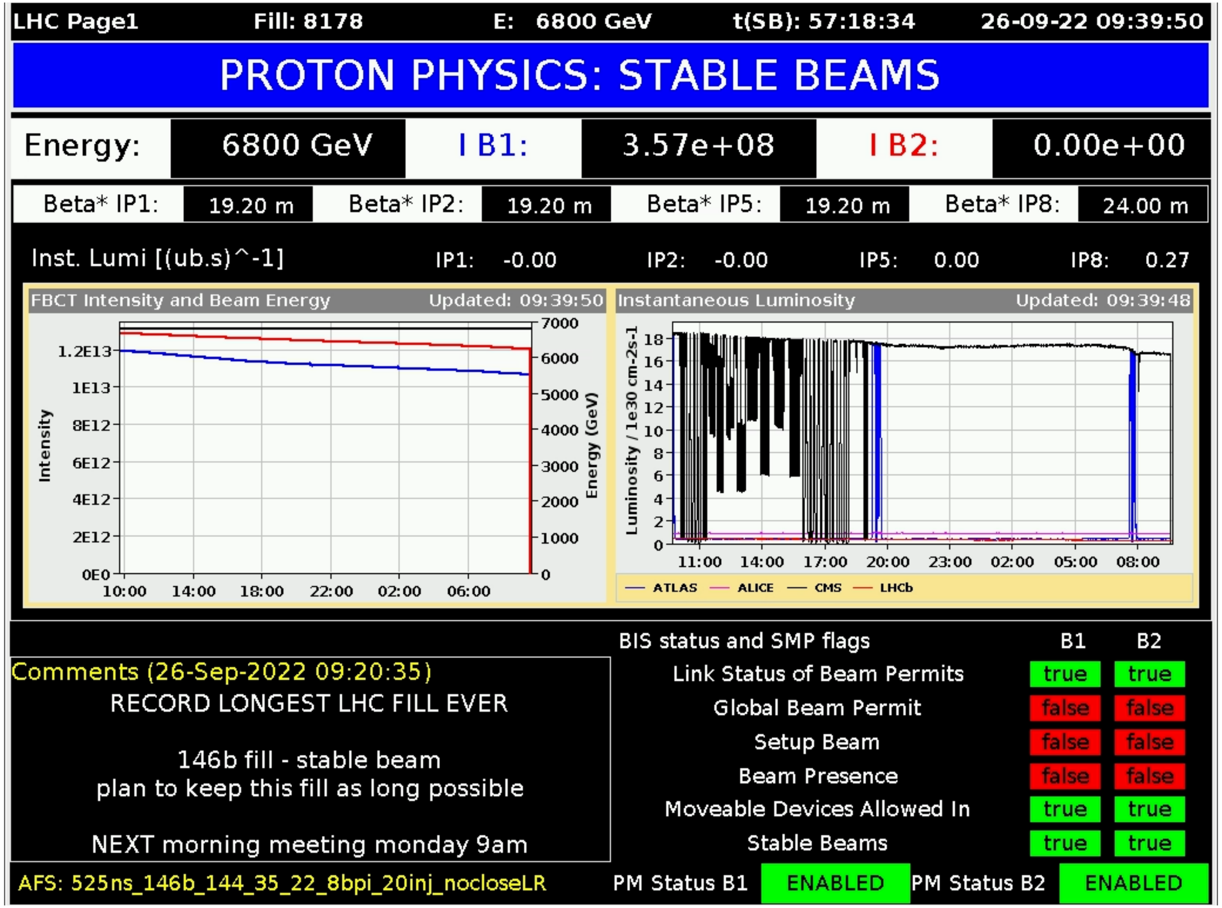
EMMI workshop on Forward Physics in ALICE 3
19.10.2023

- Longest LHC fill ever: **54.7 hours**
- Protons travelled **6.2 × 10^{13} m** in the LHC
- Beams confined by SC magnets with precision of **~ 10^{-4}m**
- Achieved by thousands of dipoles (guidance) and **quadrupoles** (focusing)
- **This talk: How quadrupole configuration can be optimized for forward physics in ALICE**

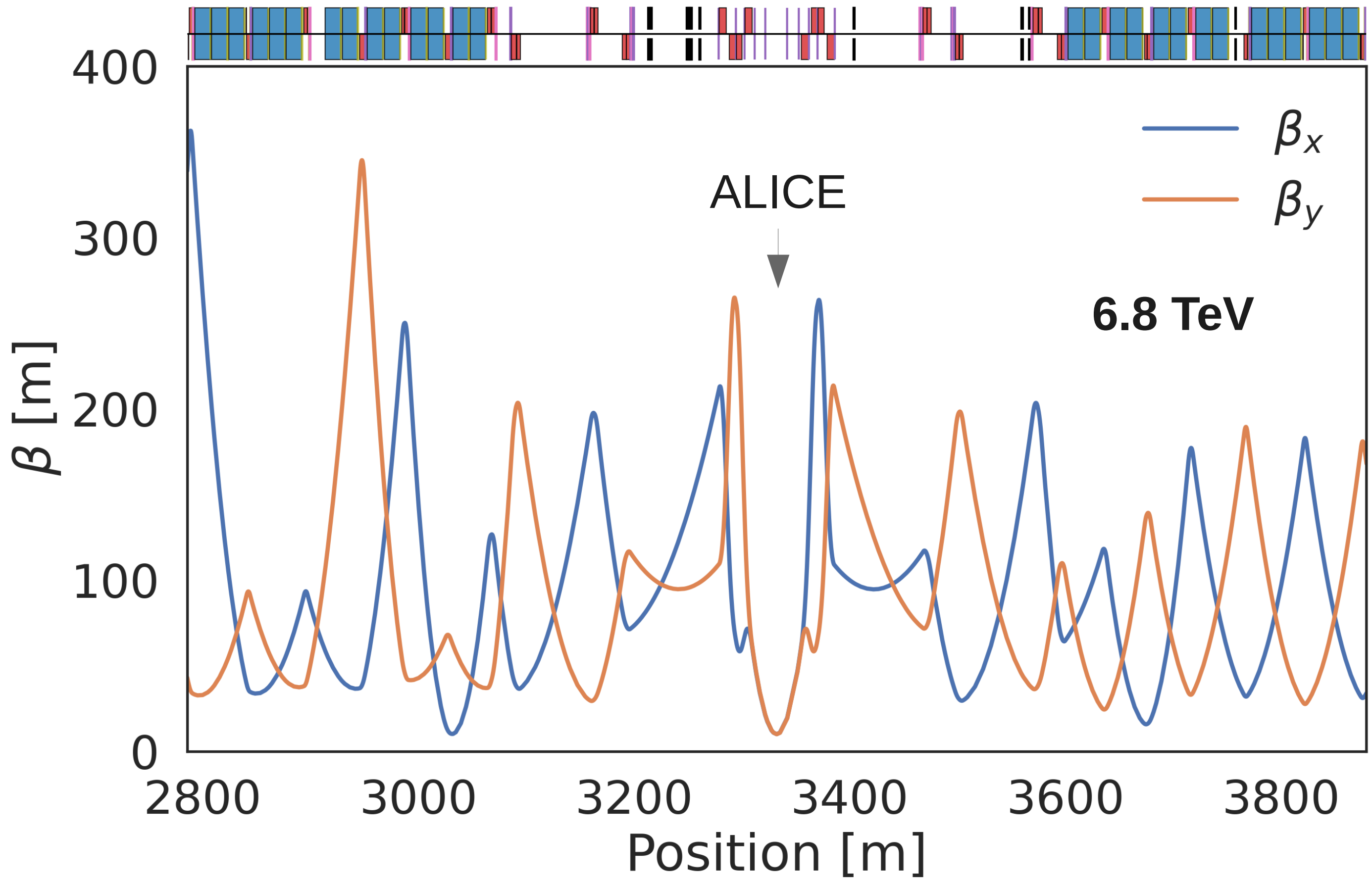


What to expect from this contribution

- Beam dynamics: how are **beams guided and focused** in the LHC?
- How is the **final focus for the experiments** done?
- How can it be **optimized for forward physics**?
- What is unique about **ALICE & forward physics**?
- Which **constraints** do we have to respect?
- What are **concrete and reasonable options** that could be applied?

Content

Some definitions



RMS beam size:

$$x_{\mathrm{RMS}}, y_{\mathrm{RMS}} = \sqrt{\epsilon\, \beta_{x,y}}$$

IP betatron function: β*

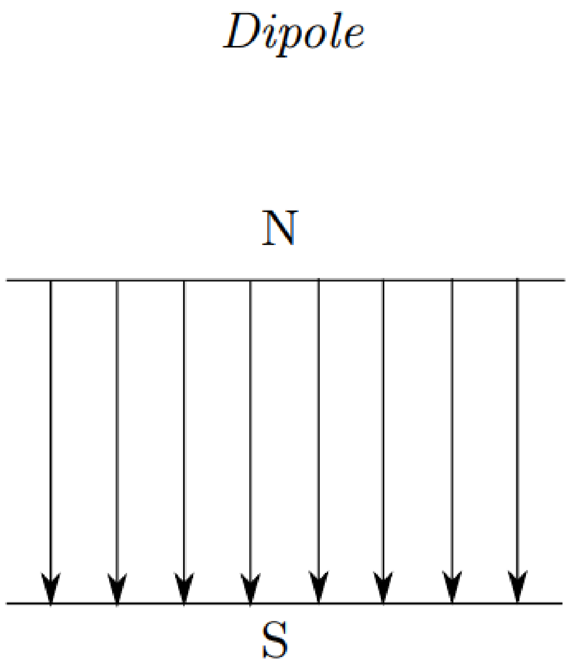
RMS beam divergence at IP:

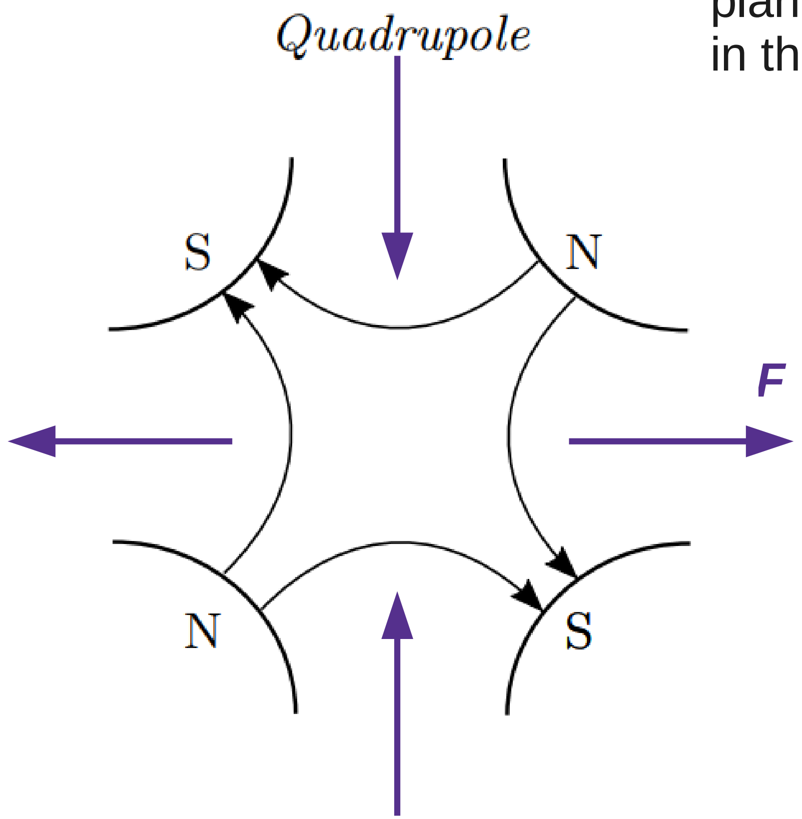
$$x'^{*}_{\mathrm{RMS}}, y'^{*}_{\mathrm{RMS}} = \sqrt{\frac{\epsilon}{\beta^{*}_{x,y}}}$$

Emittance ε : constant

Position : s

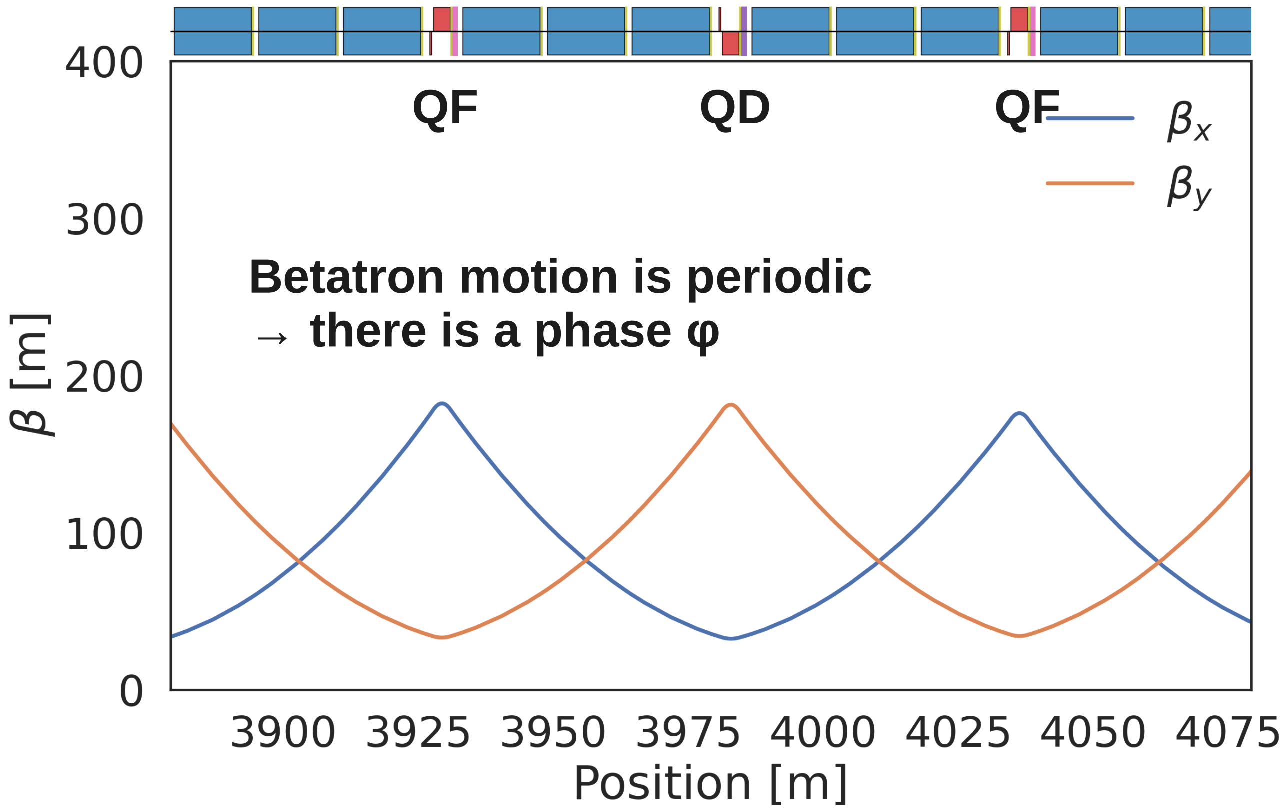
Quadrupoles and Dipoles





Quadrupoles:
Focusing in one plane & defocusing in the other

Periodic structure in arcs

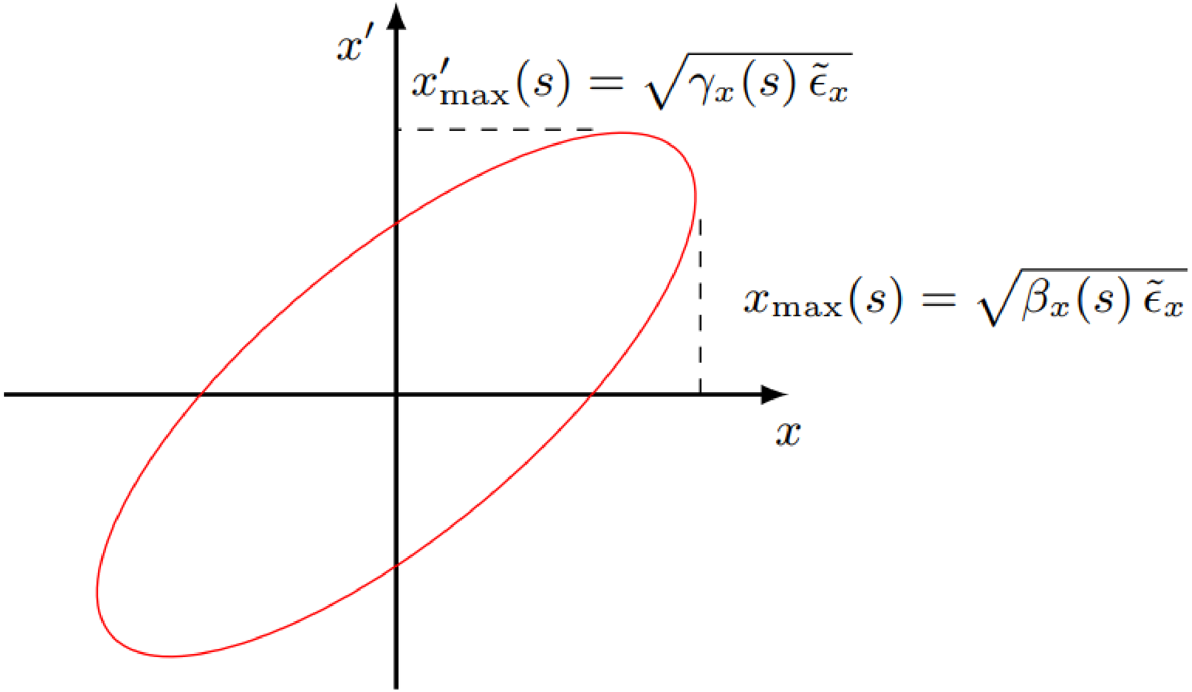


Quadrupoles: Focusing in one plane & defocusing in the other

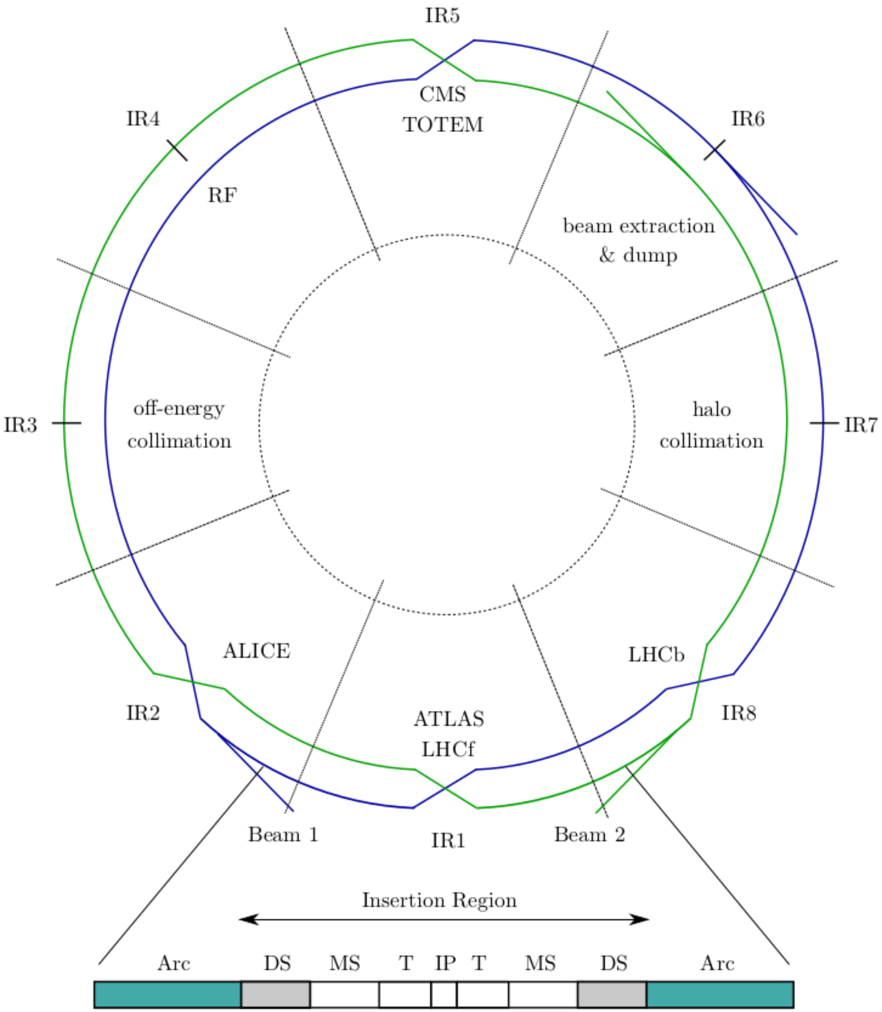
Solution: **periodic lattice for beam transport in LHC arc regions**

Phase space

- Phase space for given particle at given position
- Shape changes with β
- Phase space volume: particle action
- Entire beam: RMS emittance



LHC Layout



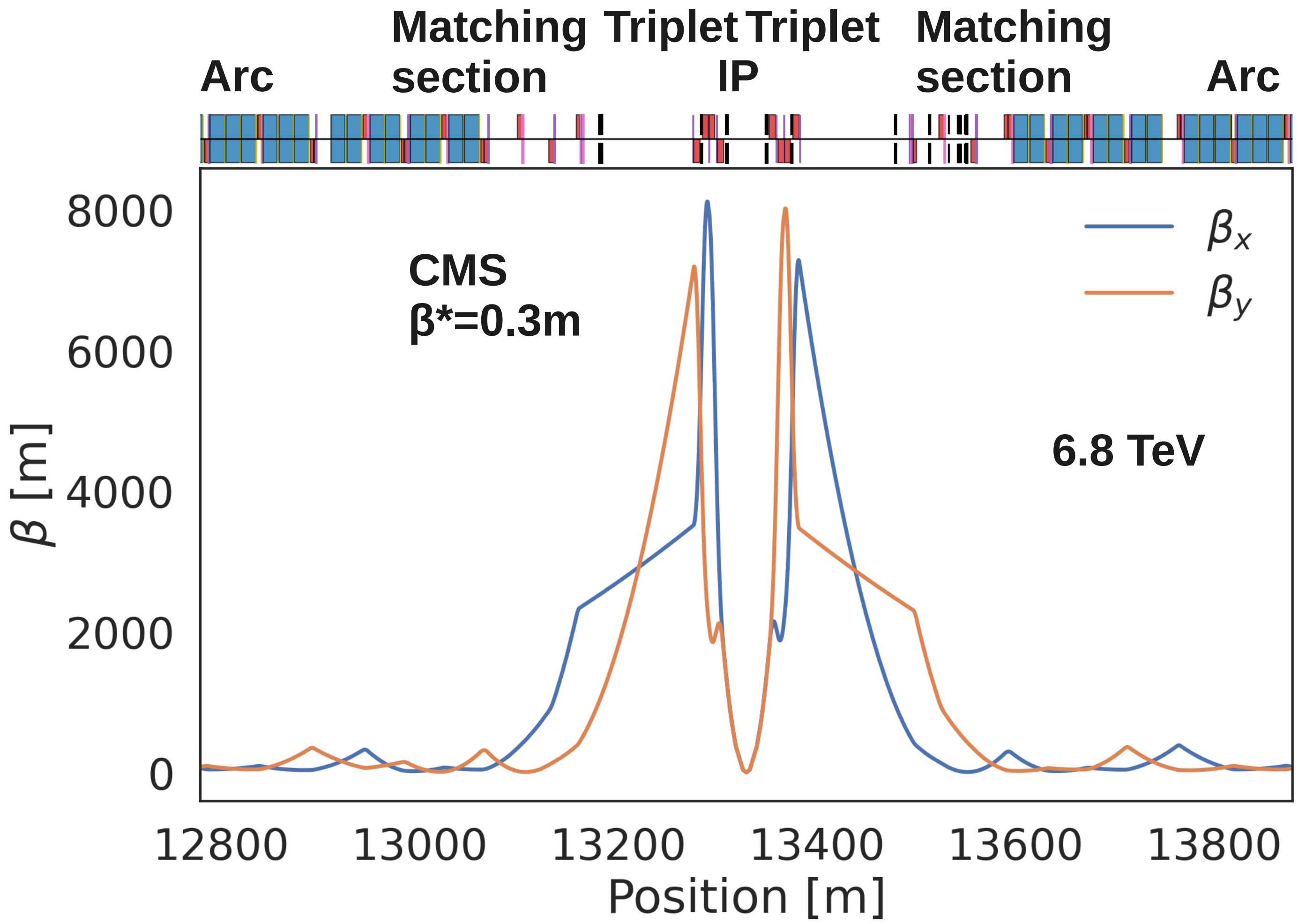
Quadrupole structure and setting **outside arcs more complicated!**

CMS Optics '23

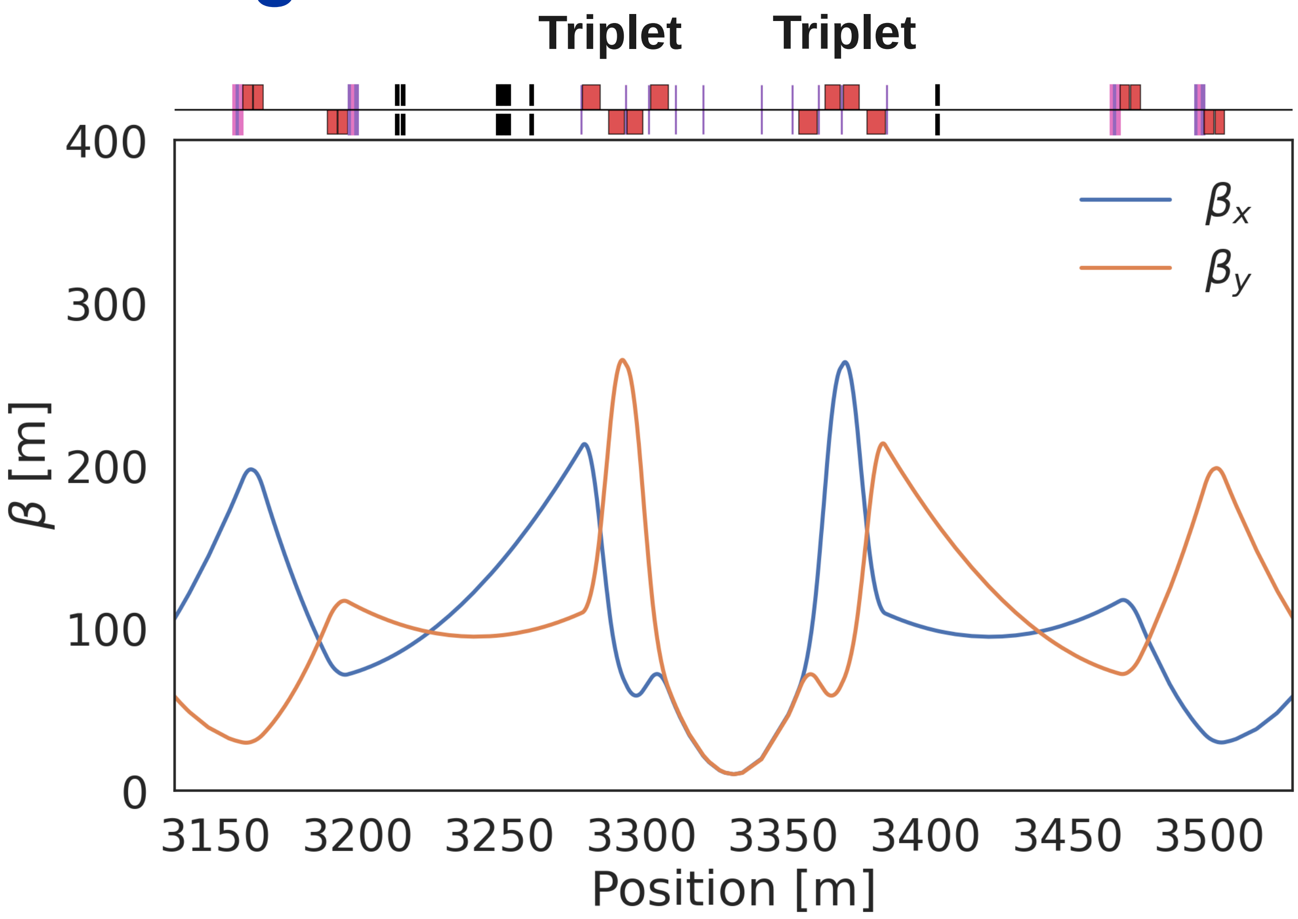
High luminosity operation – ATLAS and CMS with small β* → small beam size high divergence

$$x'_{RMS}, y'_{RMS} = \sqrt{\epsilon \frac{1+\alpha^2_{x,y}}{\beta_{x,y}}}$$

$$x'^*_{RMS}, y'^*_{RMS} = \sqrt{\frac{\epsilon}{\beta^*_{x,y}}}$$

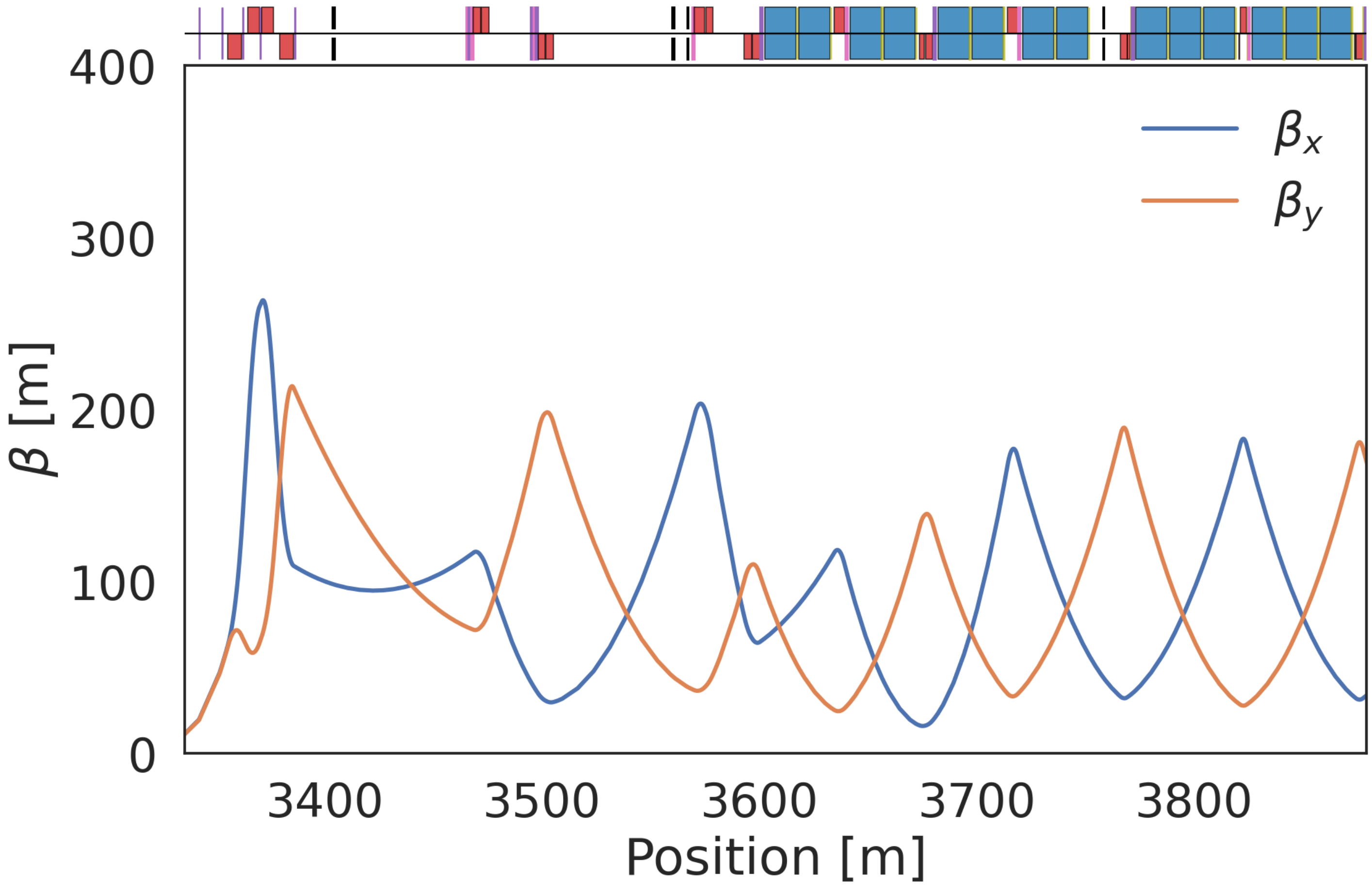


Final focusing



Quadrupole triplet: focus in both planes for IP!

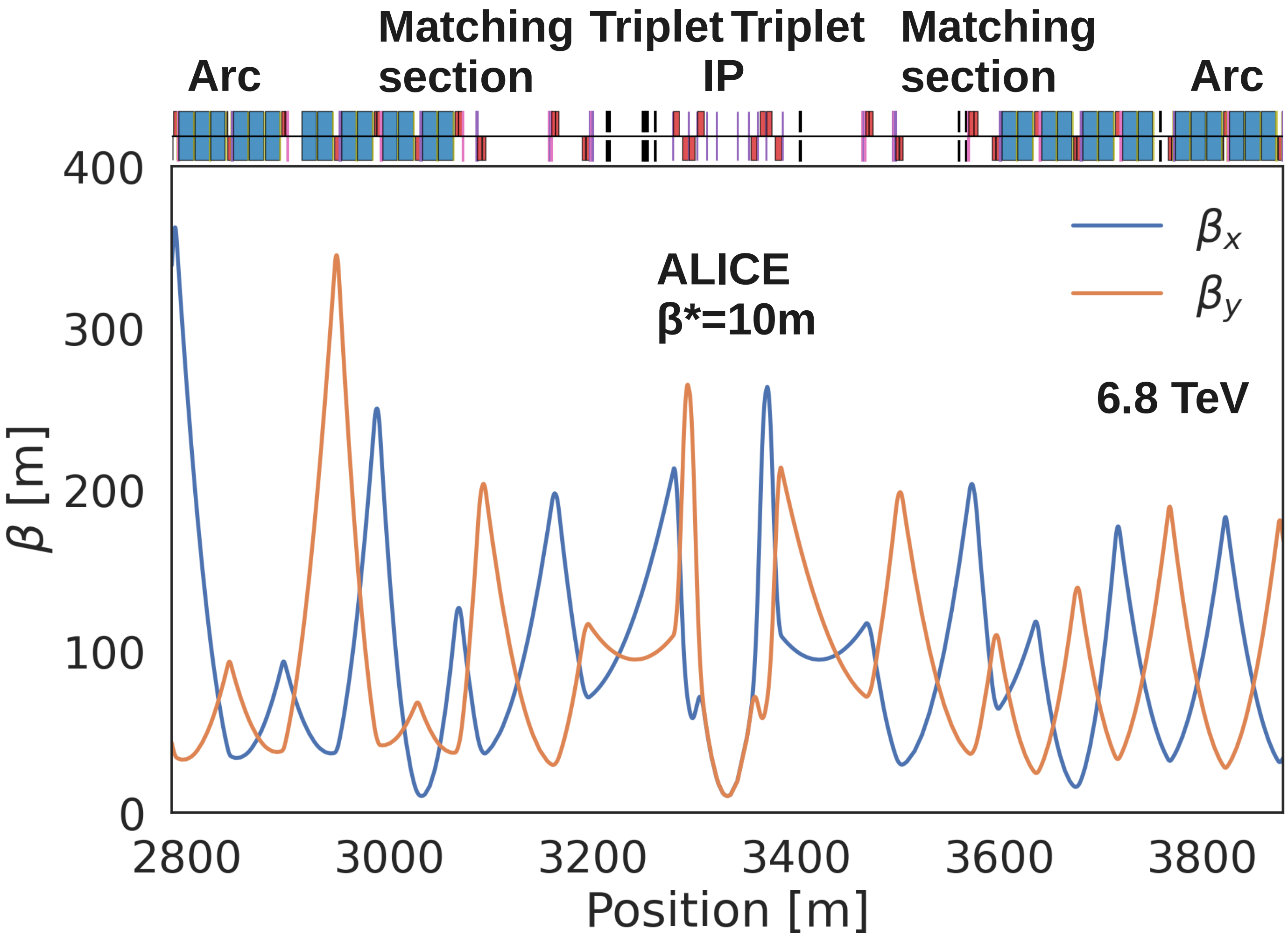
Matching section



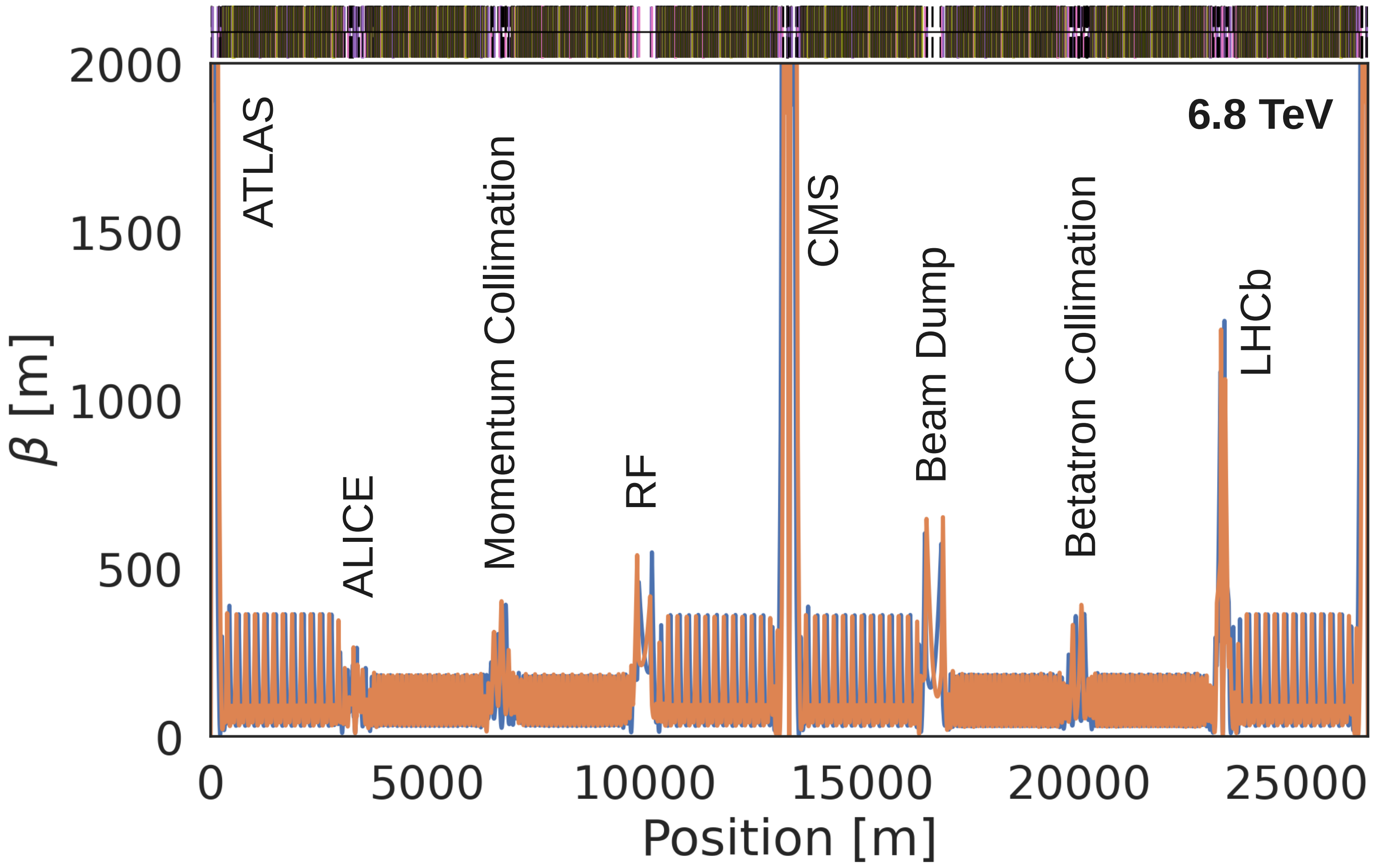
Provides appropriate transition between IP/triplet/arc

ALICE Optics ‘23

Upper proton luminosity limit in **ALICE: small β* not needed** (even luminosity levelling)



Global LHC Optics 2023



Beam Optics for Forward Physics

Forward physics – beam requirements

Divergence

$$x'^*_{RMS}, y'^*_{RMS} = \sqrt{\frac{\epsilon}{\beta^*_{x,y}}}$$

- Goal: measure very small momentum transfer
- Needs beam with small divergence → largest possible β*
- Special beam optics developed for TOTEM (CMS) and ATLAS-ALFA
- 2023 special high-β* run

2023 Nominal

Experiment	β* [m]
ATLAS	0.3
ALICE	10
CMS	0.3
LHCb	1.5

2023 Special High-β run

Experiment	β* [m]
ATLAS	3000/6000
ALICE	10
CMS	3000/6000
LHCb	

Perspective for ALICE

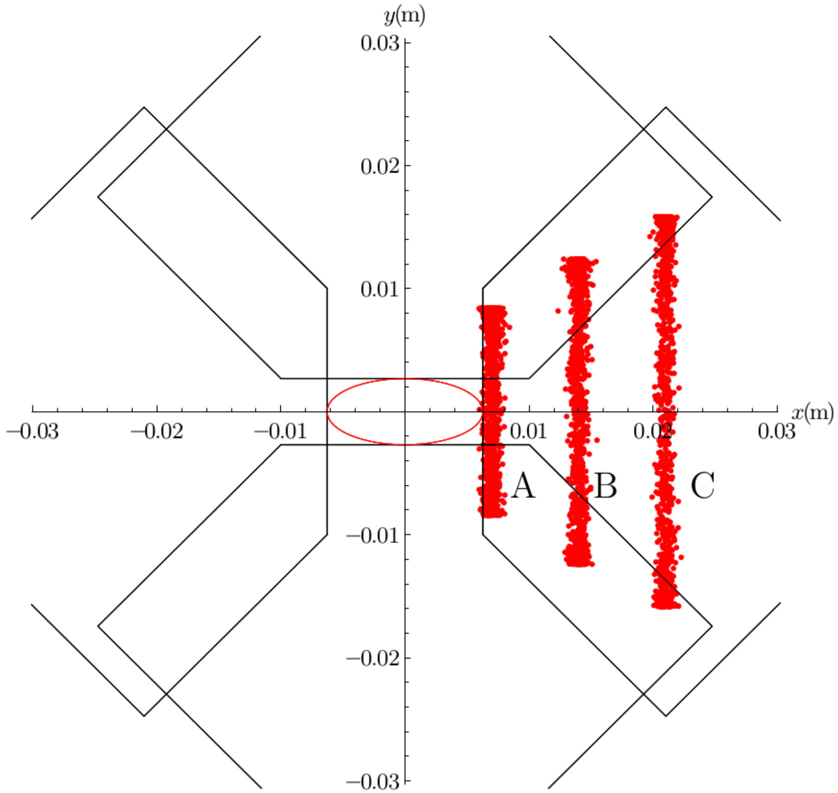
$$\mathcal{L} = \frac{n_B N_B^2 f_{\mathrm{rev}} \gamma}{4\pi \epsilon_N \beta^*} F$$

- ATLAS & CMS: high luminosity experiments
  - Main operational mode with squeezed beams (lowest possible β*)
  - Very limited beam time available with large β* to exploit forward detectors
- ALICE luminosity is levelled: no need for small β*
  - If forward detectors were installed could operate nominally at larger β*
  - What optics and β* could be envisaged?

Assumptions and Constraints

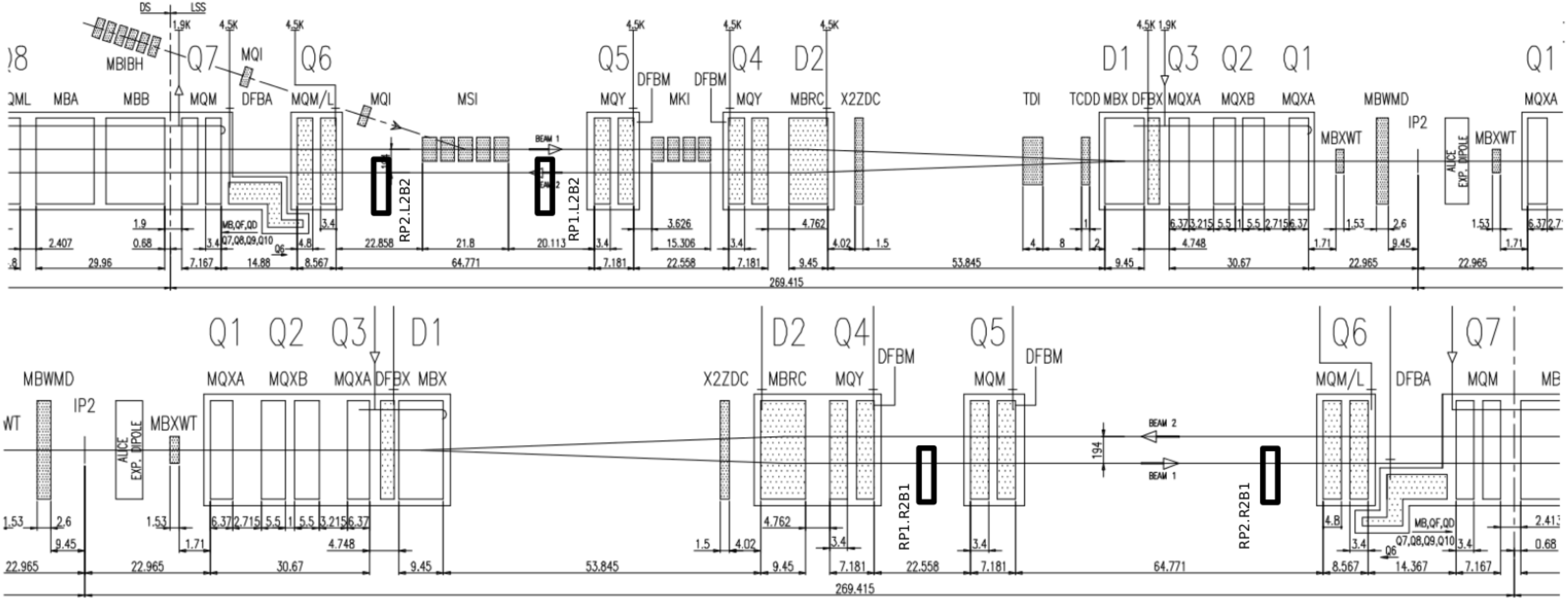
Assumptions

- Detection carried out with detectors that can be moved close to the beam
- Currently done with silicon detectors in Roman Pots for ALFA and TOTEM



Assumed Roman Pot Positions

-220m -180m



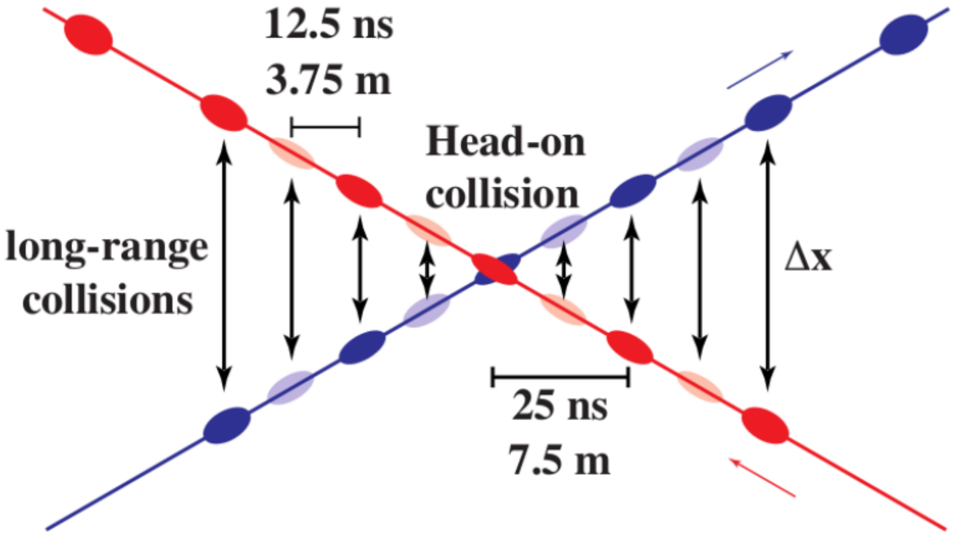
150m 220m

Optics constraints

- Largest possible β* in ALICE **compatible with high intensity operation**
- **Optical functions** at edges of insertion **must be matched** to arcs
- **Quadrupole currents** must be in certain range: $\mathbf{0.03 \leq k/k_{max} \leq 0.90}$
- **Symmetry** between B1 and B2 optics (double bore magnets with coupled circuits)
- **Tune** (number of betatron oscillations per turn) must be unchanged
- **Phase advance** between IP and second RP station close to π/2
- Enough **beam-beam separation** with the larger beams (25ns bunch spacing)
- **Aperture constraints** must be respected

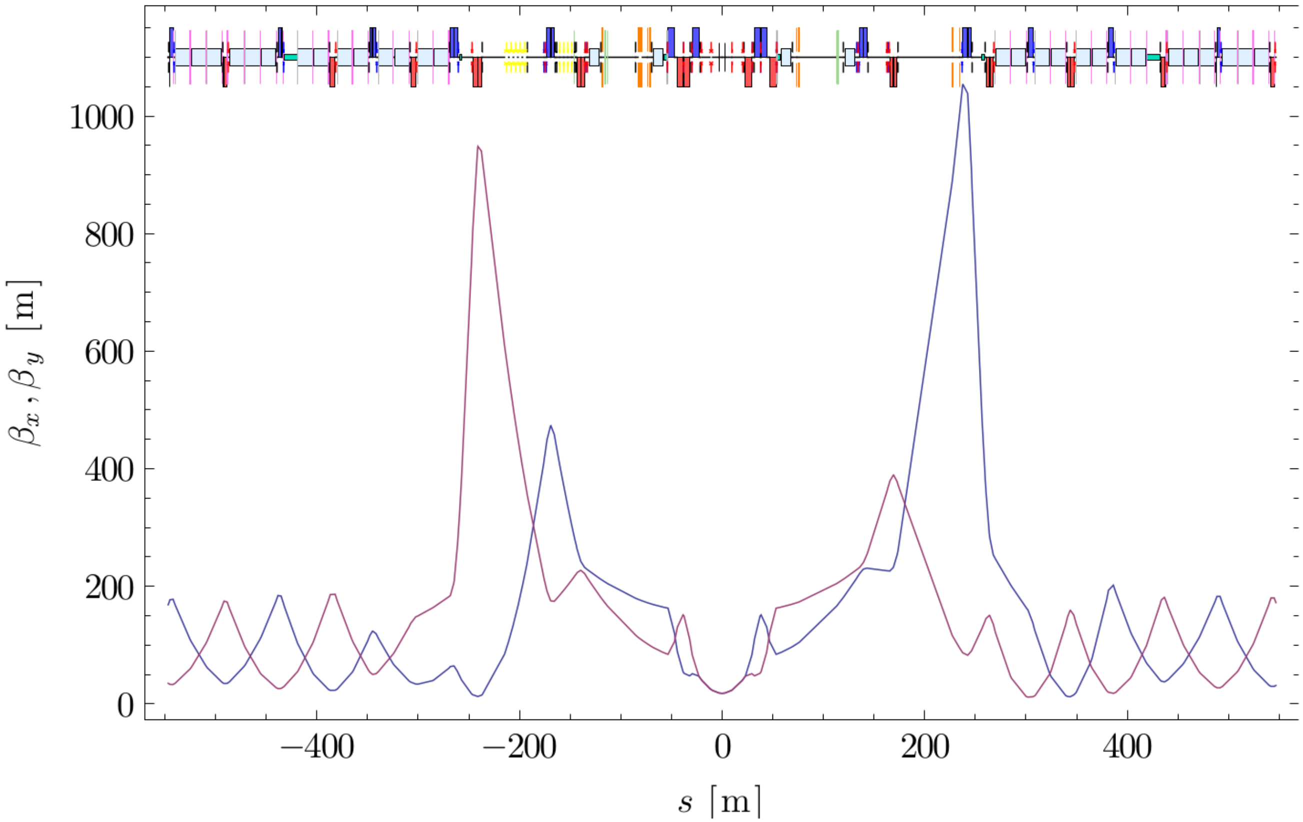
Optics design

Maximum β* reach



- Long range beam-beam encounters outside of IP
- Sufficient **bunch-bunch separation** needed**: 12σ**
- Can **calculate analytically** the maximum permitted assuming max. reachable crossing angle 300μrad
- 2013 (LHC) assuming ε_N=3.75μmrad: **Max. β*=18m**
- HL-LHC: ε_N=2.5μmrad **Max. β*=28m**

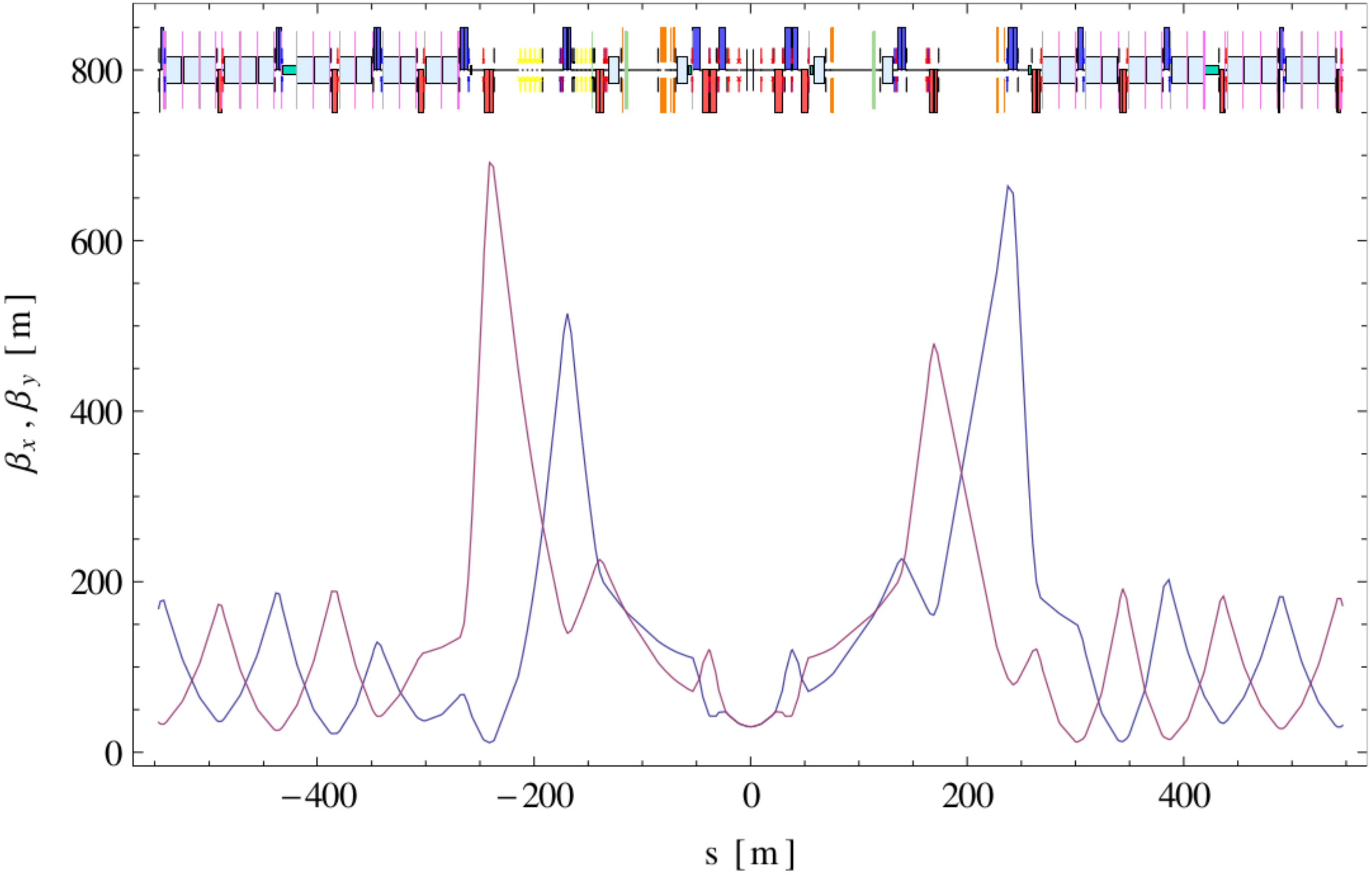
The β*=18m optics



- Matched for LHC (2013 study)
- Global HL-LHC optics will be different
- Likely similar matching can be done but not available so far

The β*=30m optics

- Not considered for LHC due to bunch separation
- With lower emittances in HL-LHC this optics is in reach
- Also here: re-matching required for HL optics



Optics parameters

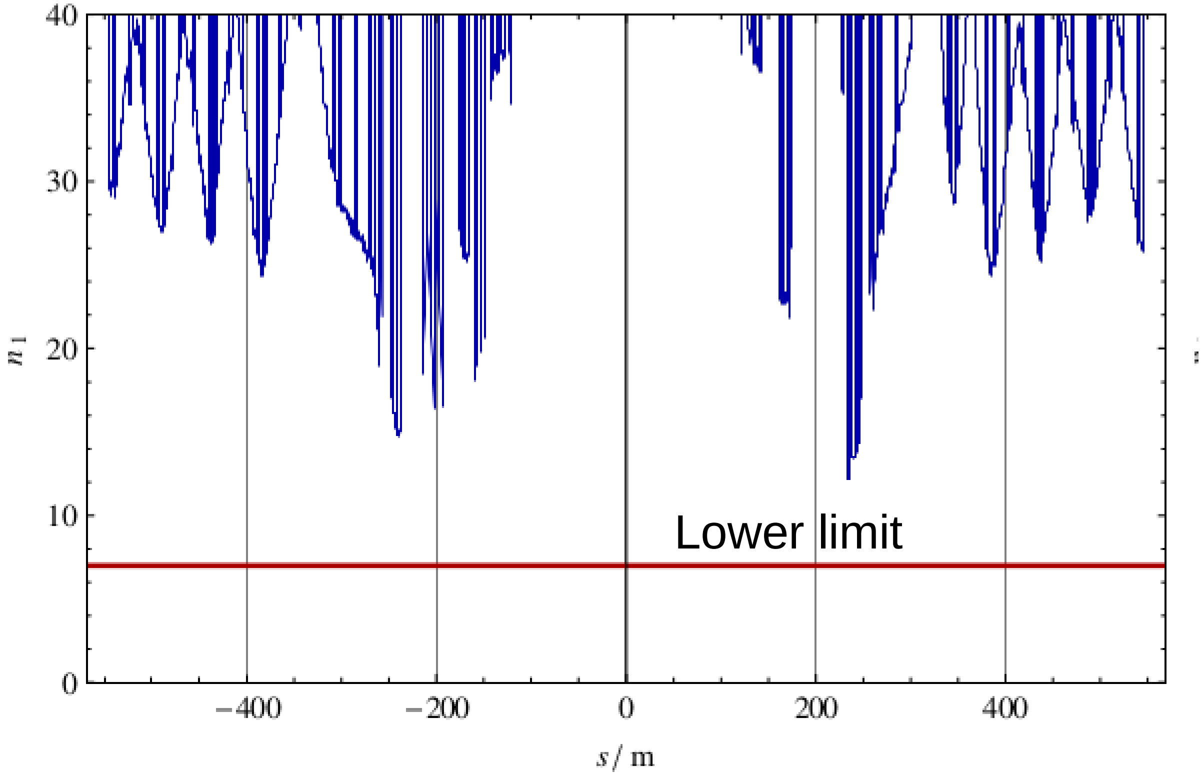
- Quadrupole current constraints: phase advance to RP can't be fully optimized
- Reduces angular acceptance
- Phase advance across IR can't be maintained – can possibly be compensated outside

		Beam 1		Beam 2	
Quantity	Unit	x	y	x	y
β^*	m	18.0	18.0	18.0	18.0
β_{RP1}	m	229.0	289.9	314.5	333.3
β_{RP2}	m	781.2	141.0	781.2	141.0
α_{RP1}		0.12	-2.64	-4.48	3.00
α_{RP2}		-7.17	1.80	-7.17	1.80
ΔQ_{IR}		0.4754	0.4567	0.4676	0.4534
$\Delta\psi_{\mathrm{RP1}}$		0.3073	0.2968	0.3271	0.3104
$\Delta\psi_{\mathrm{RP2}}$		0.3400	0.3400	0.3400	0.3400

18m optics

Aperture constraints

- Larger betatron functions and crossing angle
- Reduces normalized aperture
- With all tolerances & emittance 3.75µmrad: aperture okay for 18m and 30m optics
- Even less critical with HL-LHC beam emittance!



Acceptance

Particle traces at detector stations

Position and angle of scattered particle at detectors 1 & 2

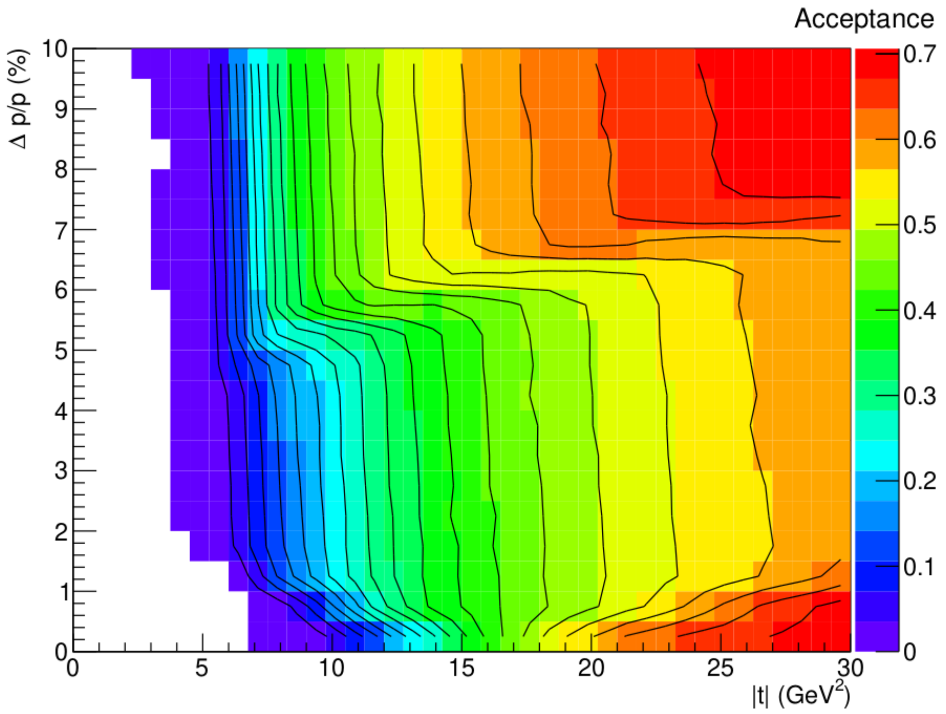
$$\begin{pmatrix} x_1 \\ \theta_{x1} \\ y_1 \\ \theta_{y1} \\ x_2 \\ \theta_{x2} \\ y_2 \\ \theta_{y2} \end{pmatrix} = \begin{pmatrix} v_{x1} & L_{x1} & 0 & 0 & D^{loc}_{x1} \\ v'_{x1} & L'_{x1} & 0 & 0 & D^{loc'}_{x1} \\ 0 & 0 & v_{y1} & L_{y1} & D^{loc}_{y1} \\ 0 & 0 & v'_{y1} & L'_{y1} & D^{loc'}_{y1} \\ v_{x2} & L_{x2} & 0 & 0 & D^{loc}_{x2} \\ v'_{x2} & L'_{x2} & 0 & 0 & D^{loc'}_{x2} \\ 0 & 0 & v_{y2} & L_{y2} & D^{loc}_{y2} \\ & 0 & v'_{y2} & L'_{y2} & D^{loc'}_{y2} \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_x \\ y_0 \\ \theta_y \\ \xi \end{pmatrix}$$

Position and angle at IP

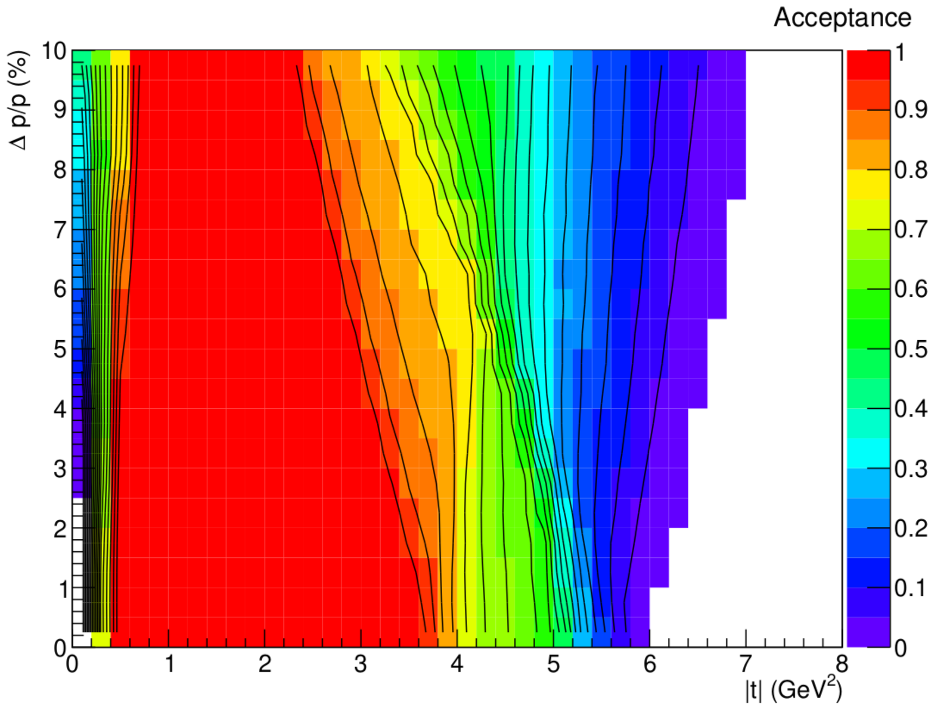
Transfer matrix derived from beam optics

$$L_{ij} = \sqrt{\beta^* \beta_{ij}} \sin(2\pi \Delta\mu_{ij})$$

Sim. Acceptance, ALICE A-Side (2013, LHC)

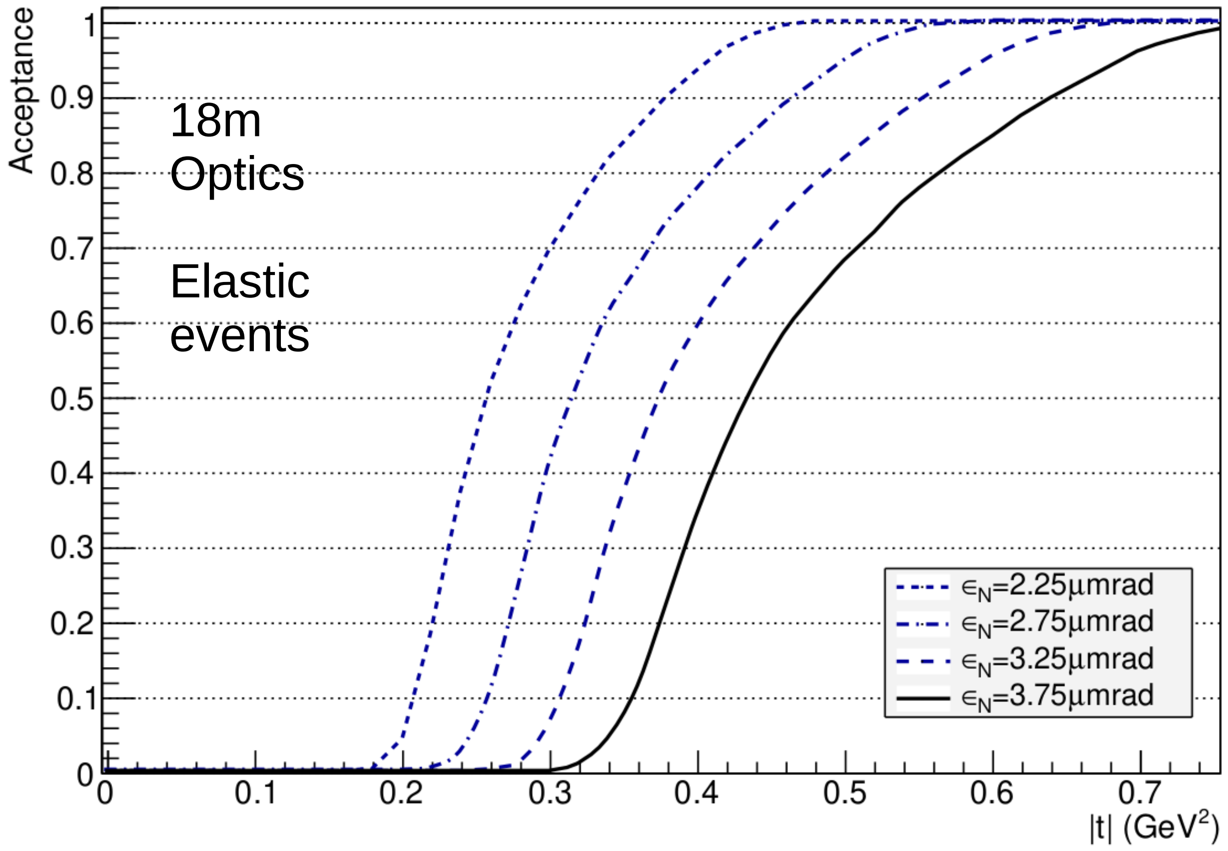


Nominal Optics (10m)



Optimized Optics (30m)

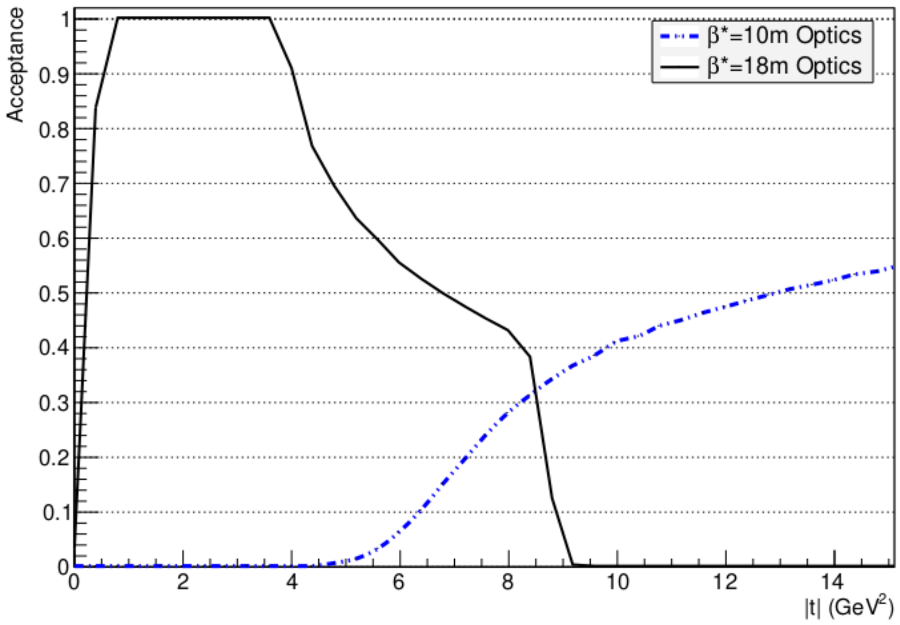
Evolution with emittance (2013 study, LHC)



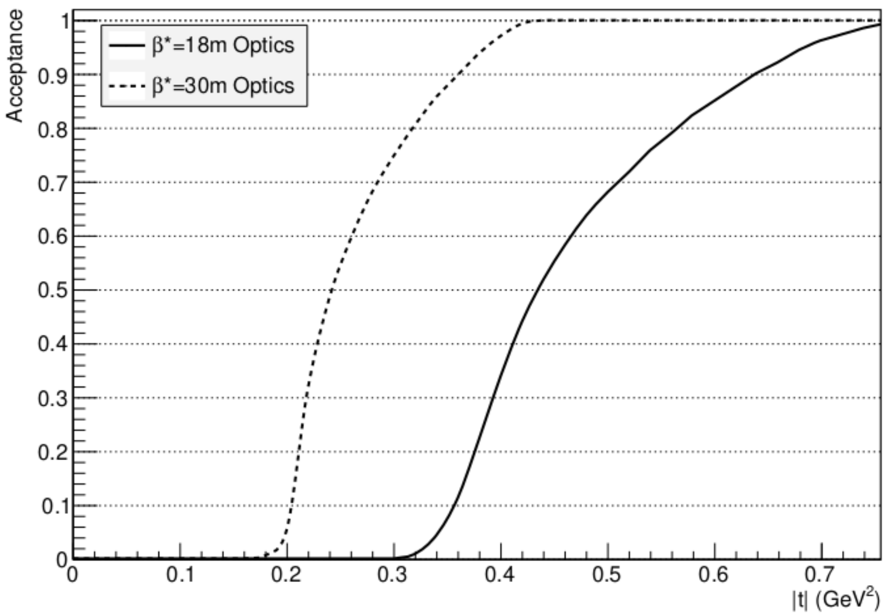
HL-LHC nominal
2.5μmrad

Evolution with beta (2013 study, LHC)

Elastic events



Elastic events



Conclusions

Conclusions

- **Higher β* optics could be feasible in ALICE**
- Advantage: **parallel** to **nominal** proton **operation**
- Disadvantage: Much lower β* reachable than in dedicated runs
- 2013 studies for **LHC**: **18m reachable** simulation indicates gain in acceptance
- **HL-LHC** smaller emittances maybe slightly higher values **could be in reach**
- More details only possible by **dedicated studies for HL-LHC**
  - Repeat matching with HL-LHC optics
  - Verify compatibility with telescopic squeeze
  - Work out compensation for phase advance

Literature

Tagging of very forward protons in ALICE
P. Hermes, R. Schicker, CERN-ATS-2013-001

Development of high-β* optics for ALICE
P. Hermes, Master’s thesis, 2013, University of Muenster