Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI

Landau damping studies for FCC-hh and beam-beam effects

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Acknowledgements: S. Arsenyev, L. Rivkin, D. Schulte, S. Antipov, O. Boine-Frankenheim, R. Tomas, A. Seryi, M. Schenk, D. Amorin, V. Schiltzev, B. Dalena, V. Kornilov, E. Métral, B. Salvant

HSC section meeting 4/06/2018

The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 654305. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

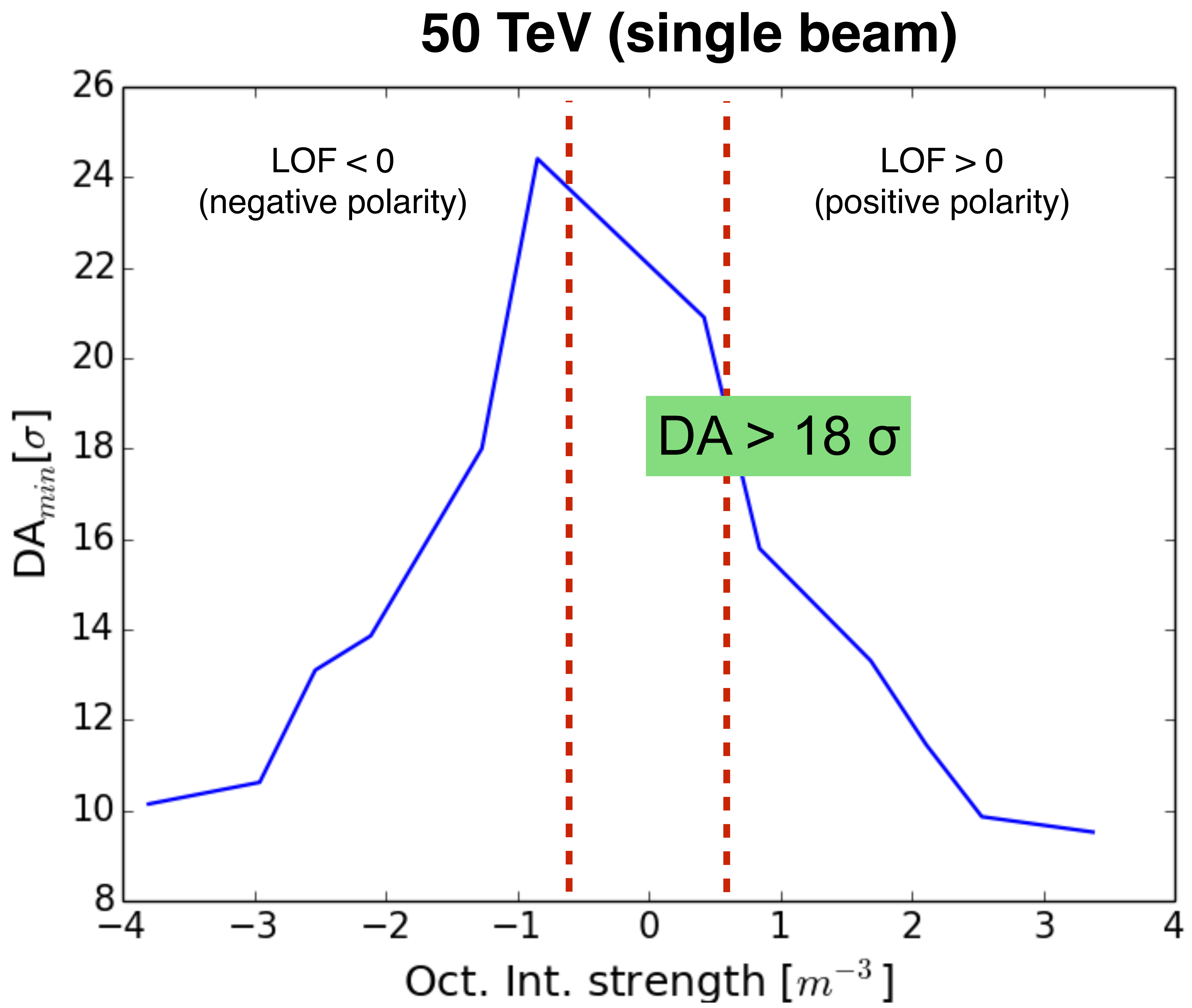
FCC-hh Octupoles for Landau damping (updated)

	LHC (7 TeV)	FCC (50 TeV)	FCC (3.3 TeV)
Gradient [T/m³]	63000	200000	200000
β-function [m]	100	200	200
Length [m]	0.32	0.5	0.5
Maximum Current [A]	550	720	720
Bρ [T · m]	23350	166783	11008
Oct int strength* [m⁻³] (single magnet)	0.863	0.600	9.085

$^* = G_{max}/(B\rho) \cdot (I_{oct}/I_{max}) \cdot L_{oct}$

Number of octupoles increased from 460 to 480
Increased octupole strength of 42 % w.r.t. previous octupole system

Impact of Landau octupoles on Dynamic Aperture (flat top energy)

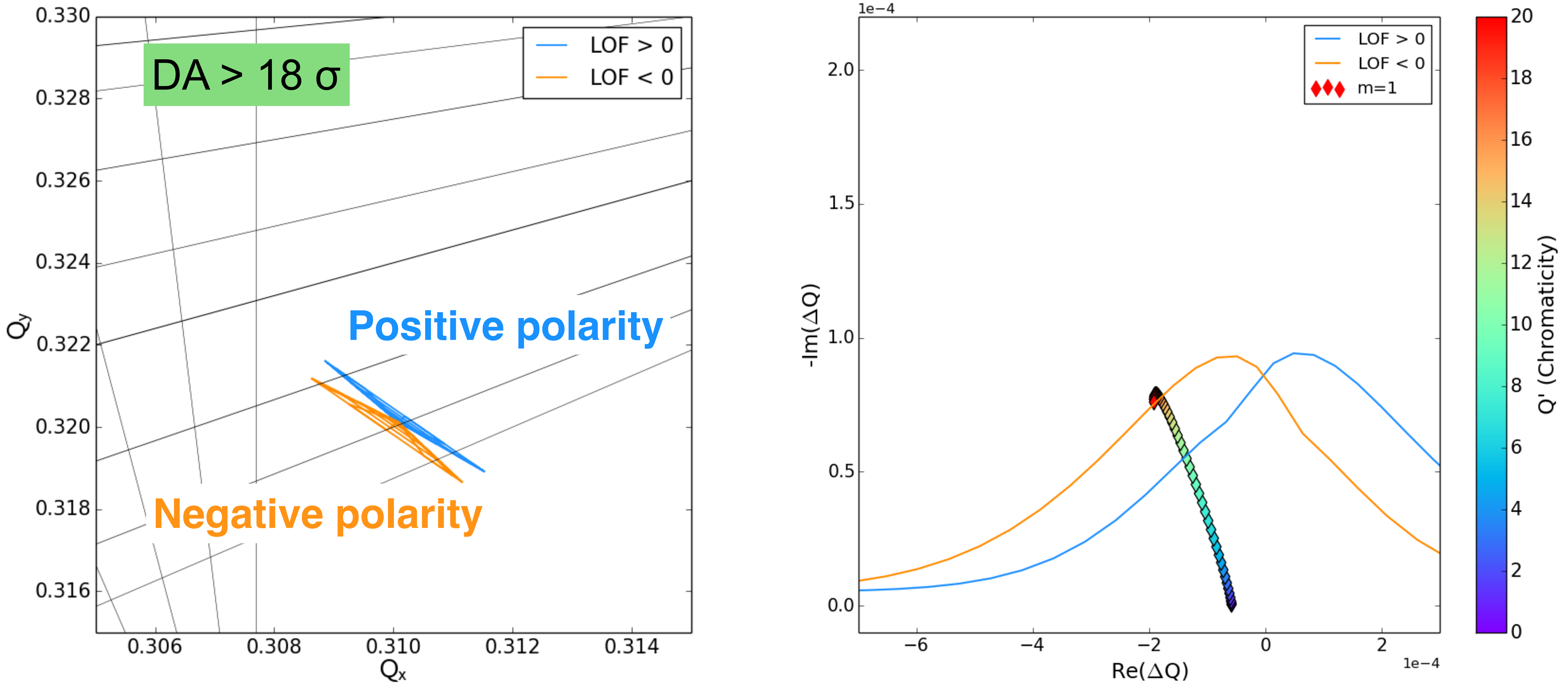


- DA decreases as a function of the octupole strength
- With the required octupole strength DA is above 18 σ for both octupole polarities

Landau damping for m≠ 0 and Q’≠ 0 at flat top energy

m=1 Coupled-bunch modes by S. Arsenyev

Flat top (no beam-beam)



DA > 18 σ

Positive polarity

Negative polarity

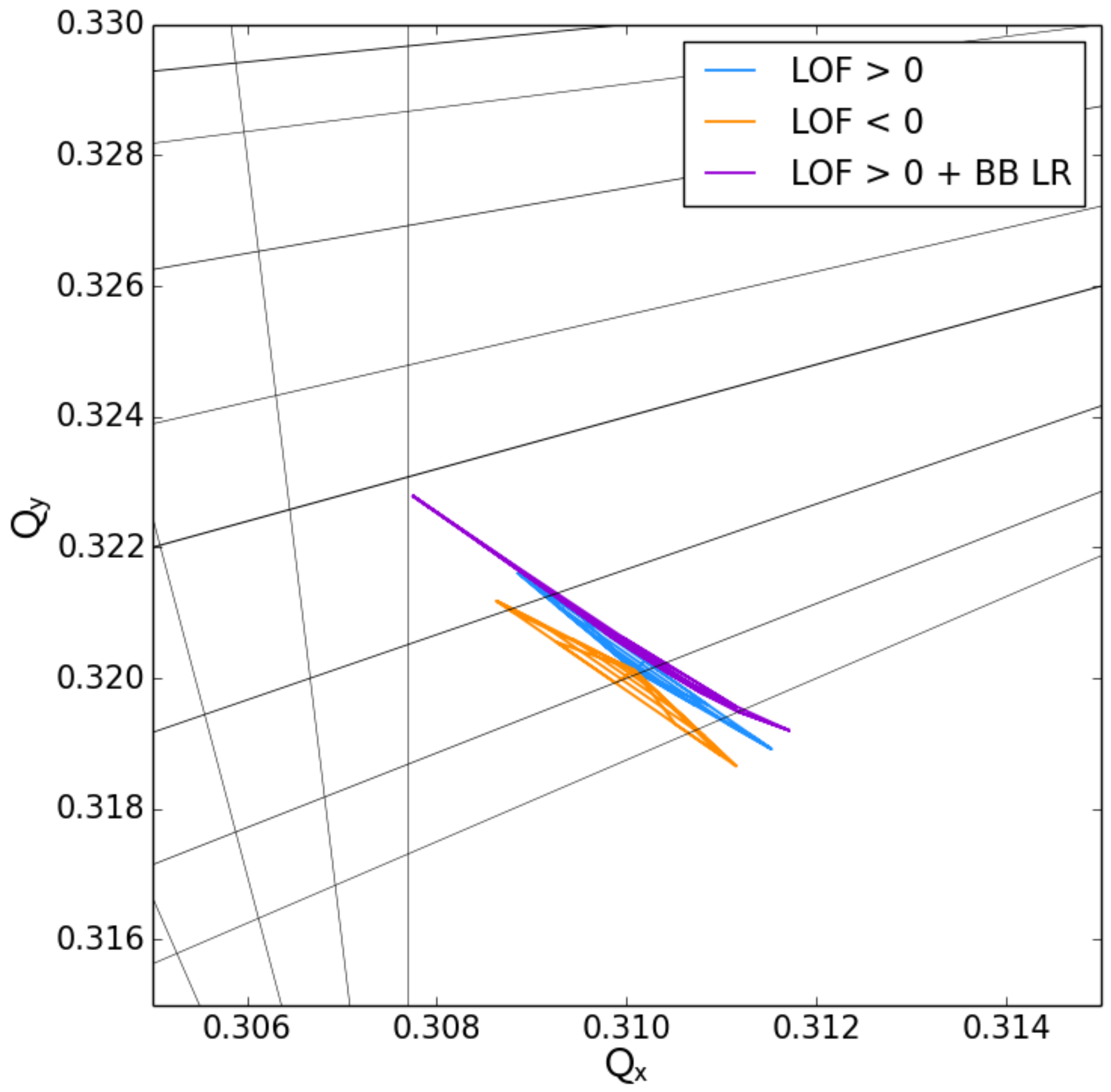
- m=0 damped by feedback
- stability diagrams obtained with available octupoles at their maximum strength

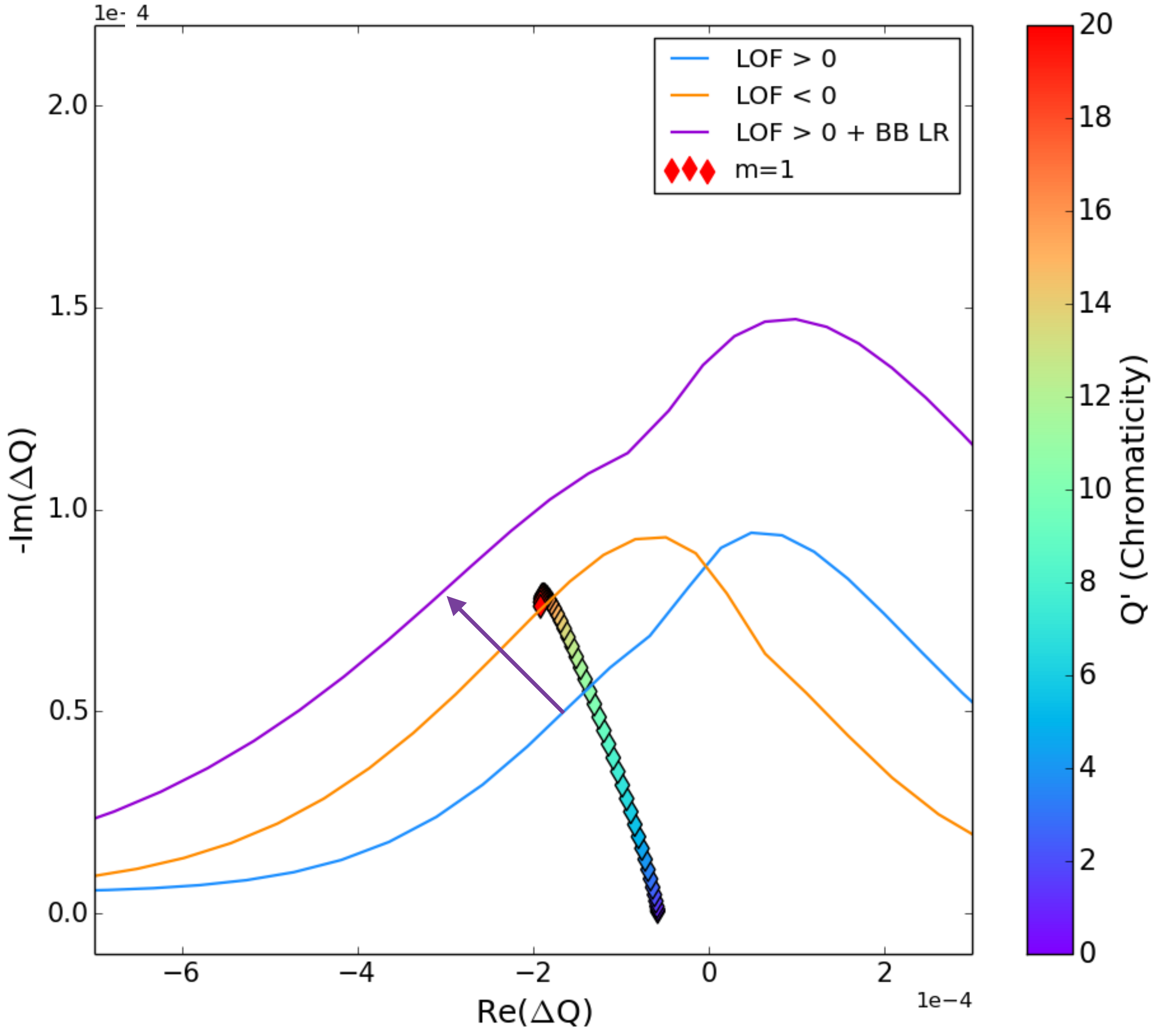
m ≥ 1 modes: octupoles sufficient up to Q’=20 units powered in negative octupole polarity (orange line)

Landau damping for m≠ 0 and Q’≠ 0
end of betatron squeeze

m=1 Coupled-bunch modes by S. Arsenyev

End of squeeze (beam-beam)



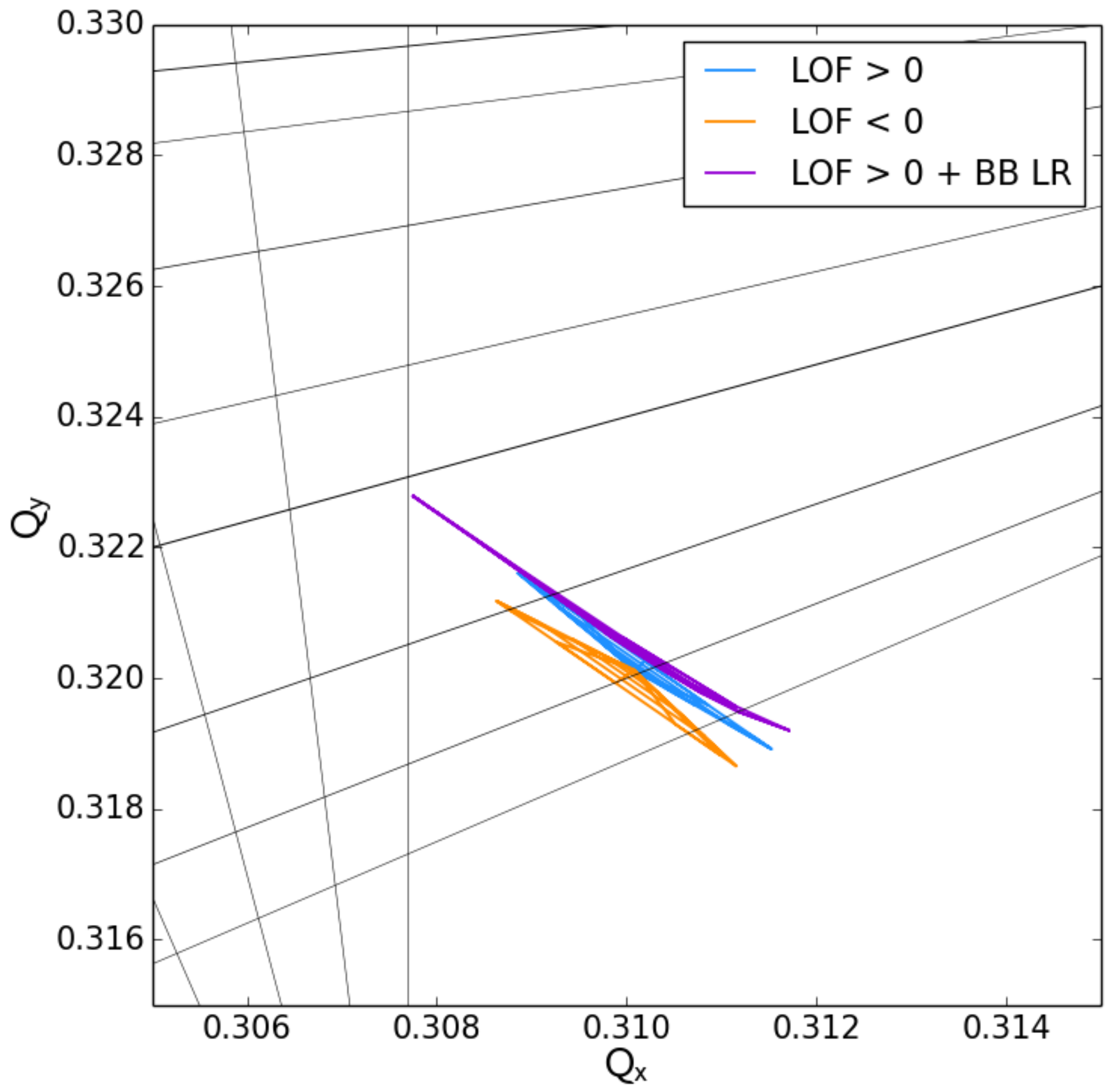


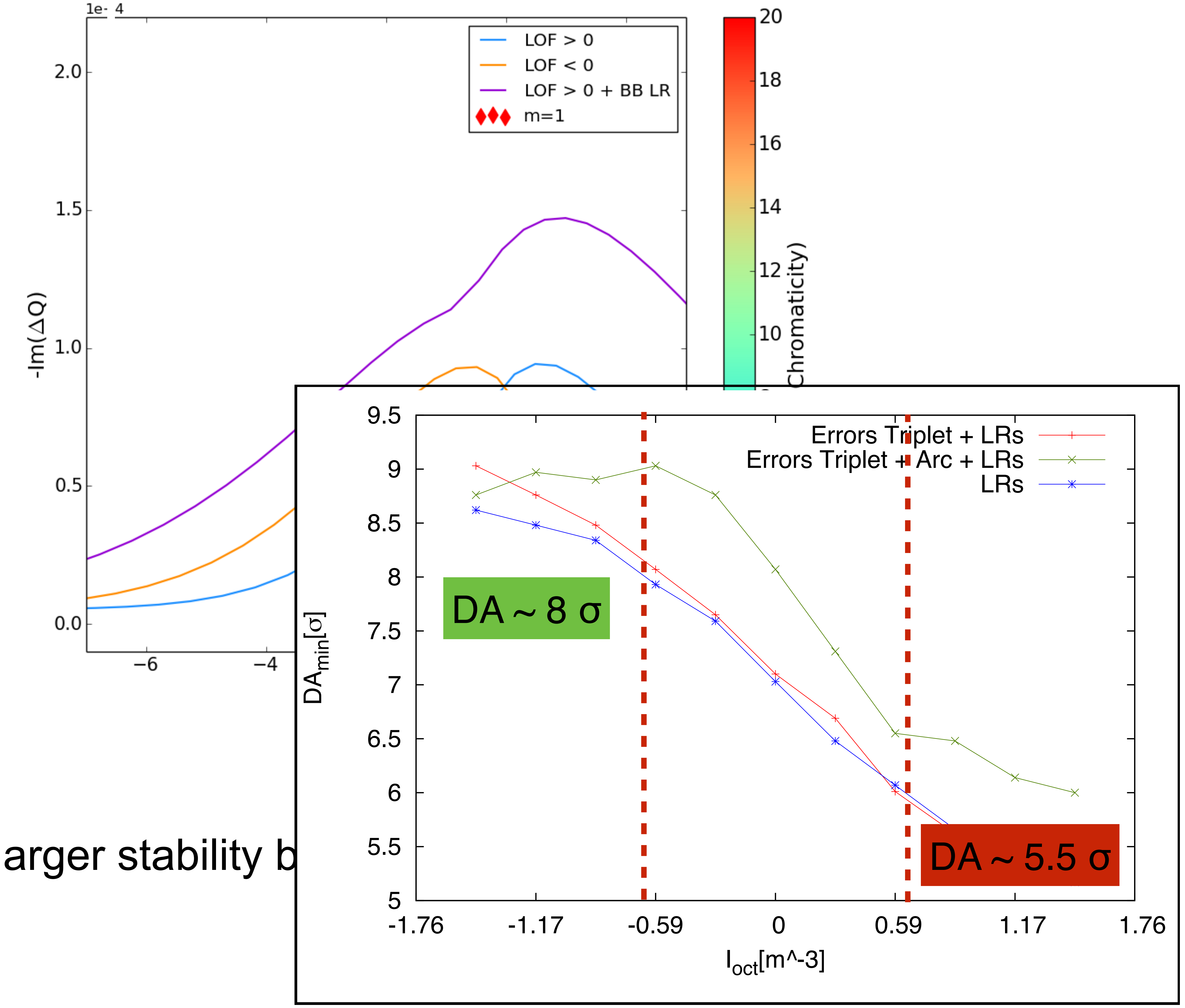
Tune spread from bb LR and positive octupoles adds up ➔ larger stability but smaller DA with respect to negative polarity (DA < 6 σ)

Landau damping for m≠ 0 and Q'≠ 0
end of betatron squeeze

m=1 Coupled-bunch modes by S. Arsenyev

End of squeeze (beam-beam)



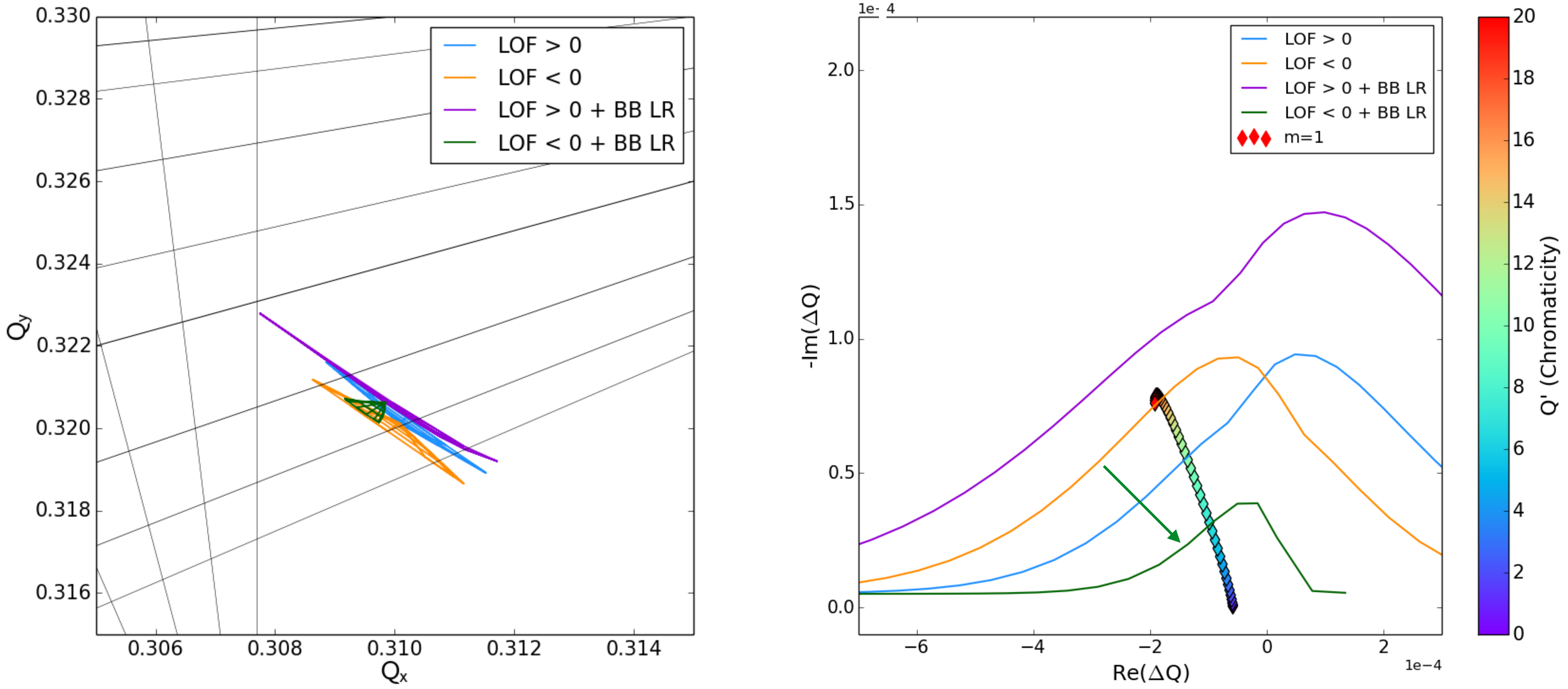


Tune spread from bb LR and positive octupoles adds up ➔ larger stability b
polarity (DA < 6 σ)

Landau damping for m≠ 0 and Q'≠ 0: end of betatron squeeze

m=1 Coupled-bunch modes by S. Arsenyev

End of squeeze (beam-beam)



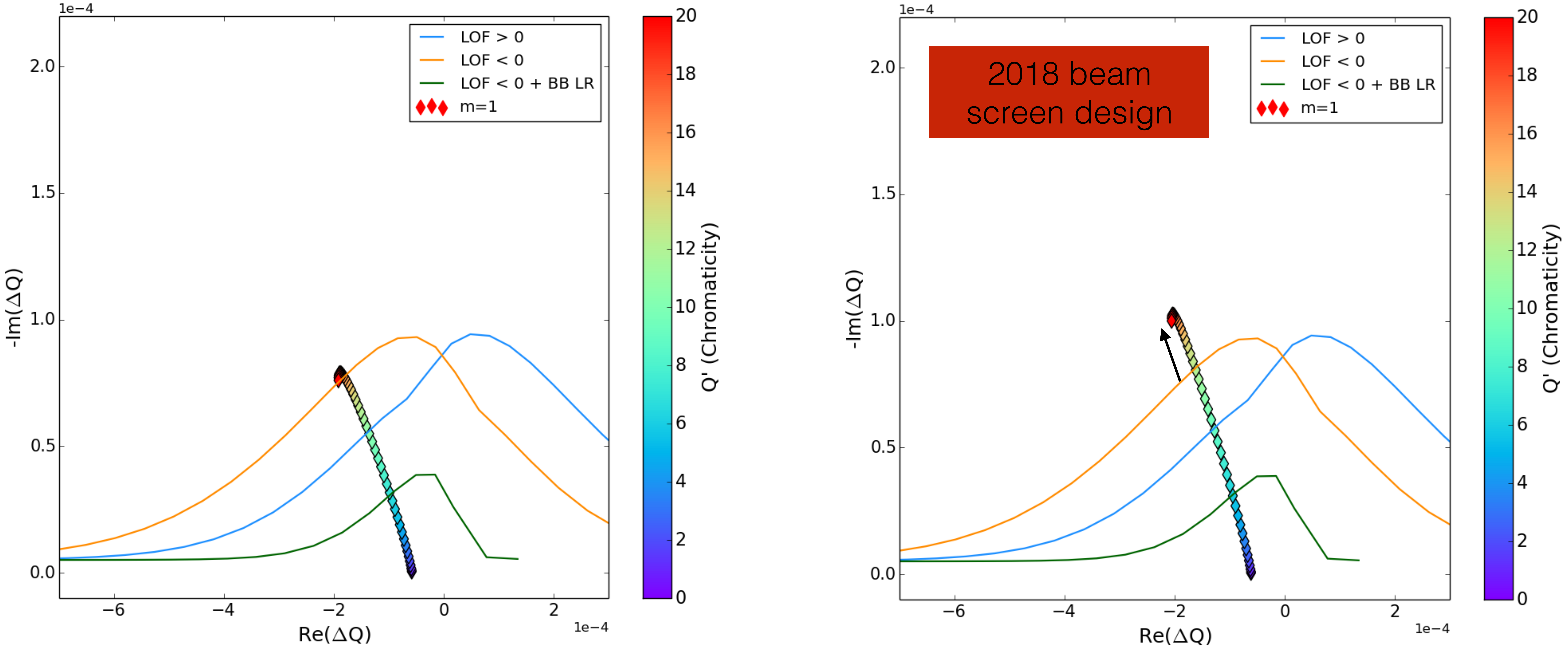
The stability diagram at flat top reduces at the end of the betatron squeeze with negative octupole polarity due to the interplay with long-range interactions (green line) **DA ~8.5 σ**

➔ The available octupole strength allows no margins at the end of the squeeze imposing a tight control on the chromaticity value without ADT!

Landau damping for m≠ 0 and Q’≠ 0 new beam pipe

m=1 Coupled-bunch modes by S. Arsenyev

Octupoles at their maximum strength



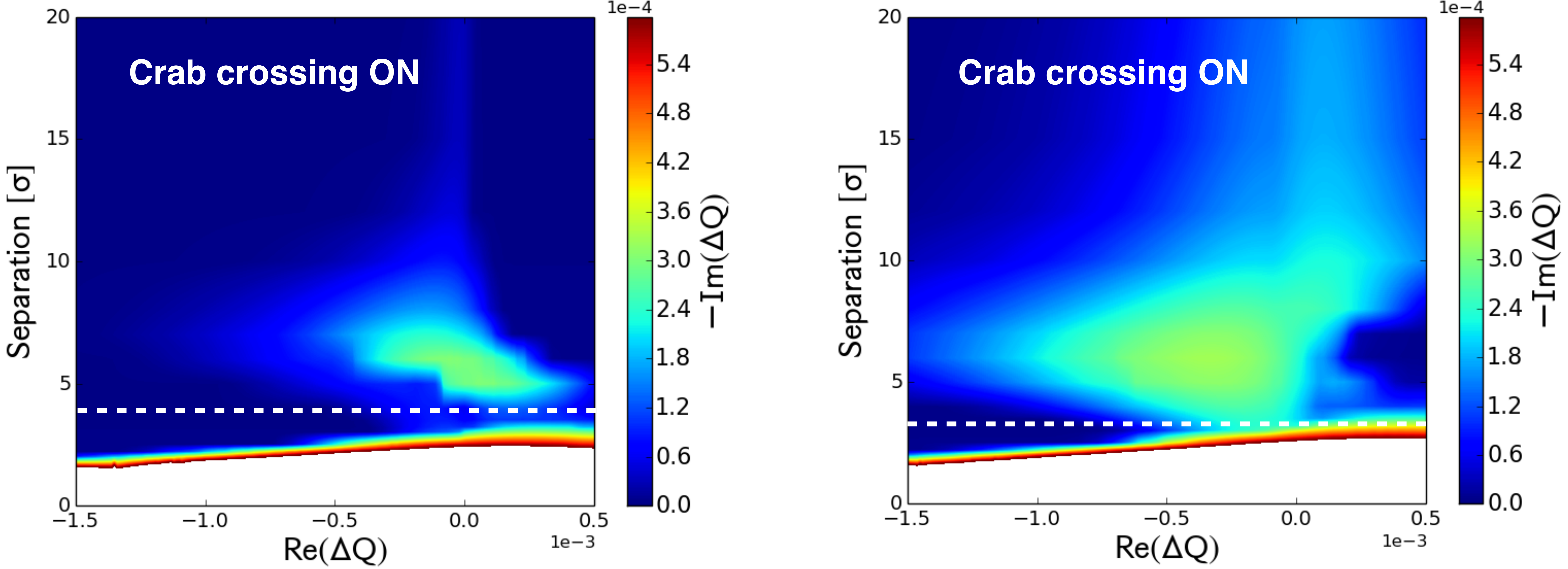
The new beam pipe increases imaginary part of m=1 up to 30%:

- An additional ~30% octupole strength is required to recover stability at flat top
- Constraints on chromaticity at the end of betatron squeeze tighter compared to previous design

Beam stability during the collapse of the separation bumps

Evolution of stability diagram during the collapse of the separation bump

Octupoles at their maximum strength

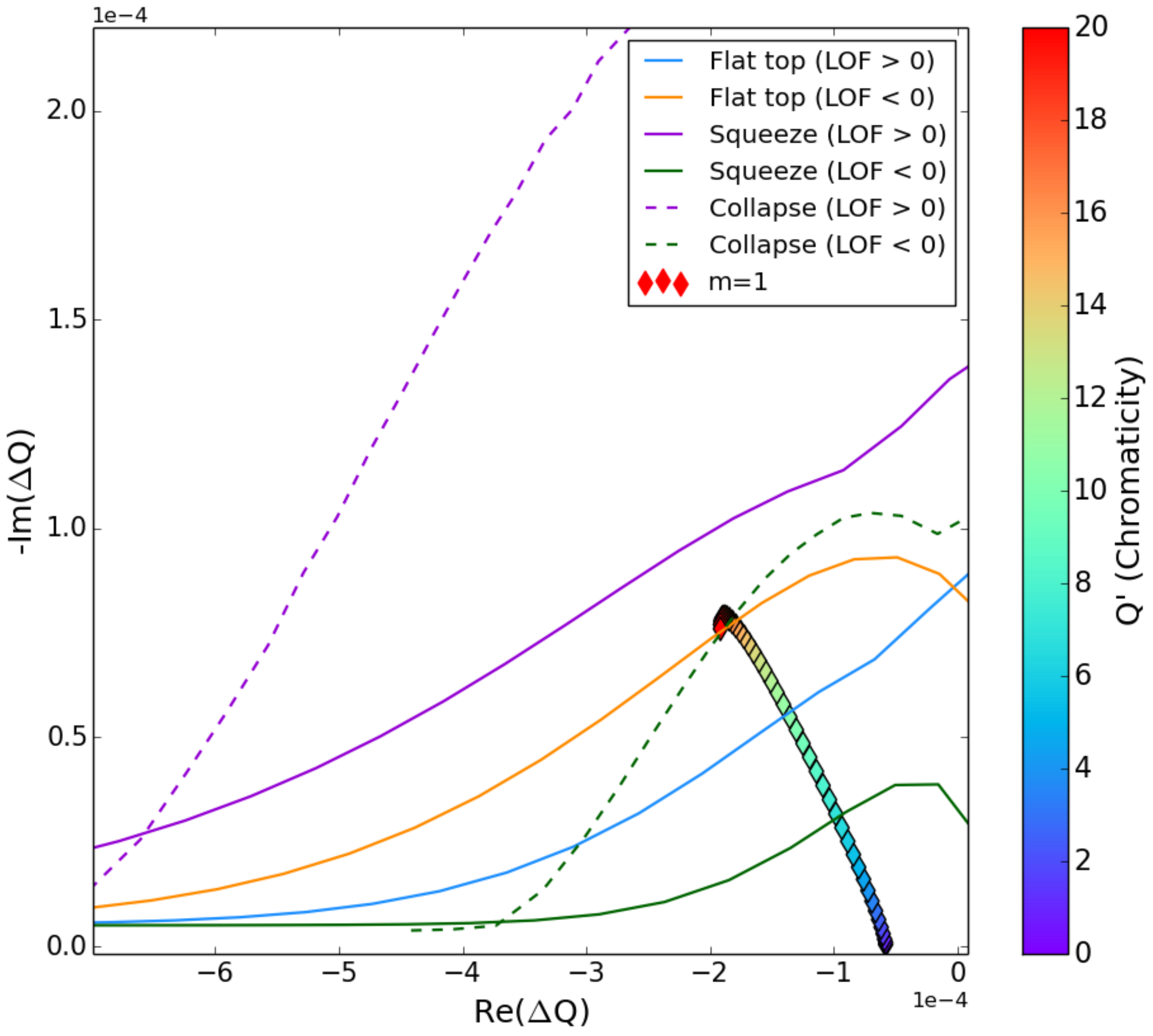

Negative oct. polarity

Positive oct. polarity

Minimum at 3 σ during the collapse, however SD at this minimum is larger or equivalent compared to end of betatron squeeze (see next slide)

Stability summary

Octupoles at their maximum strength



Flat top (single beam): larger stability with negative octupole polarity (orange line), m=1 Landau damped up to high Q' values (DA > 15 σ both polarities)

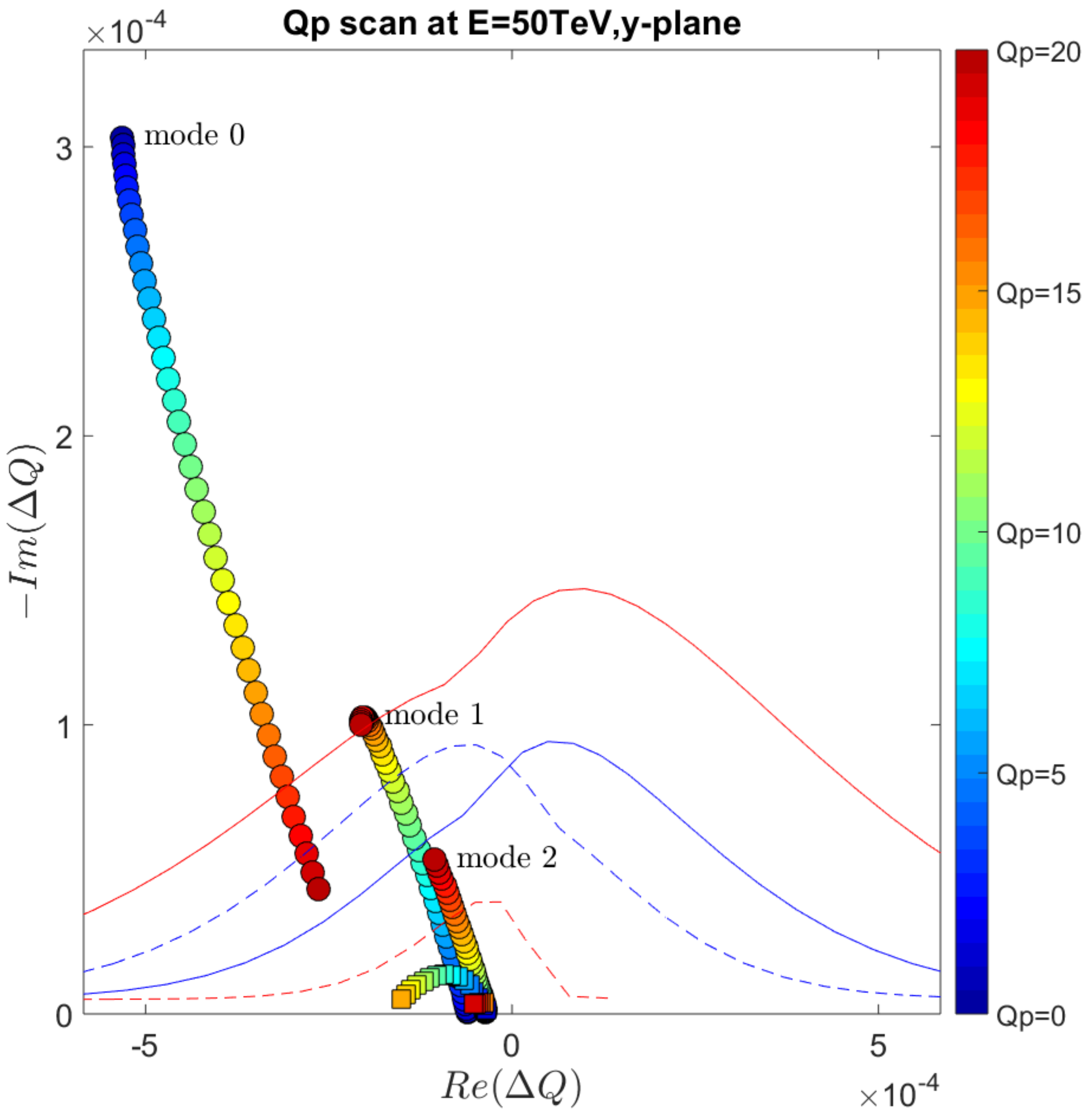
End of squeeze (beam-beam LR): strong reduction of stability with negative octupole polarity ➔ tight control on Q' values required, DA > 7.5 σ (DA < 6 σ for positive oct. polarity)

Collapse of sep. bumps (LR + HO crab on): stability increases during the collapse ➔ SD is larger or equivalent compared to end of betatron squeeze

Effect of ADT not included on coupled bunch modes!

Recent results including ADT effect on coupled bunch modes

Octupoles at their maximum strength

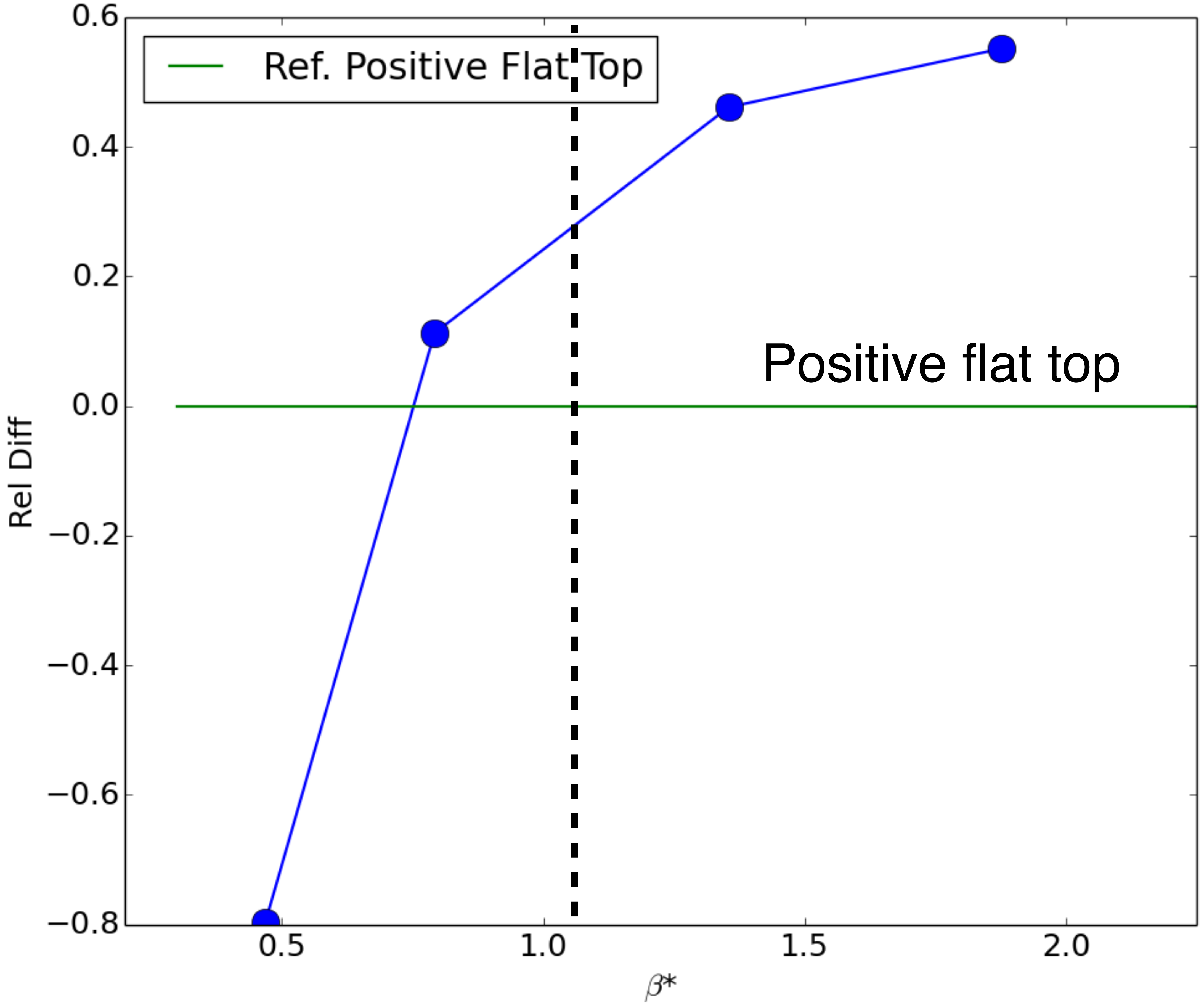


Coupled-bunch modes by S. Arsenyev and N. Klinkenberg

- Most unstable coupled bunch modes with ADT gain of 460 turns
- **Installed Landau octupoles provide enough stability, increase the ADT gain gives additional margins**

Stability and collide & squeeze

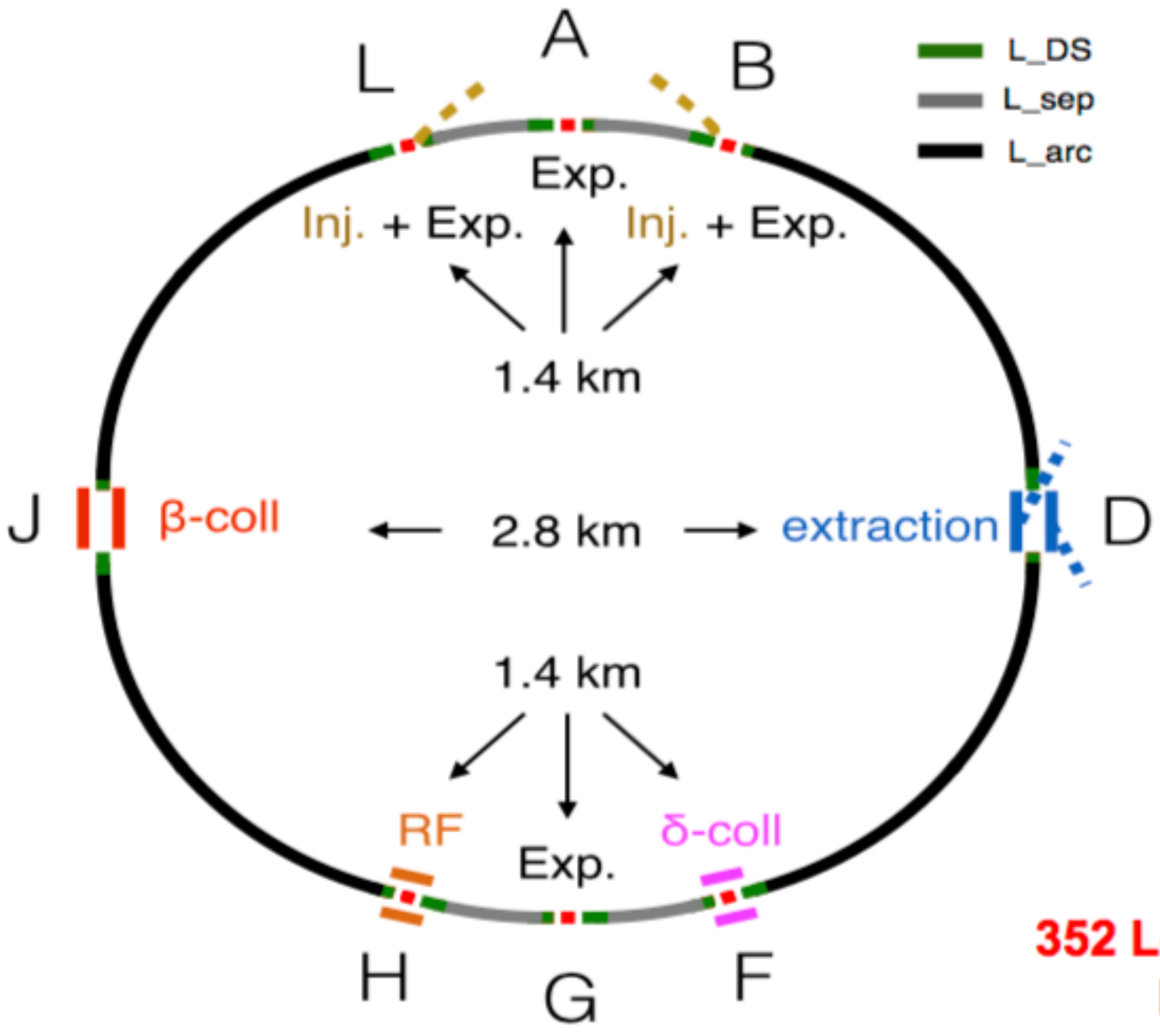
- Collide at around 2-1 meters tbd with detailed simulations
- Angles might be further reduced but to be defined → Need further checks due to a bug in the footprint calculations (on-going)



For β* > 80 cm the negative octupoles polarity is always above positive octupole polarity at flat top

- β* at injection 4.6 m
- Ramp and Squeeze to 2-1.2 m
- Collide and squeeze at reduced angle

Beam-beam effects

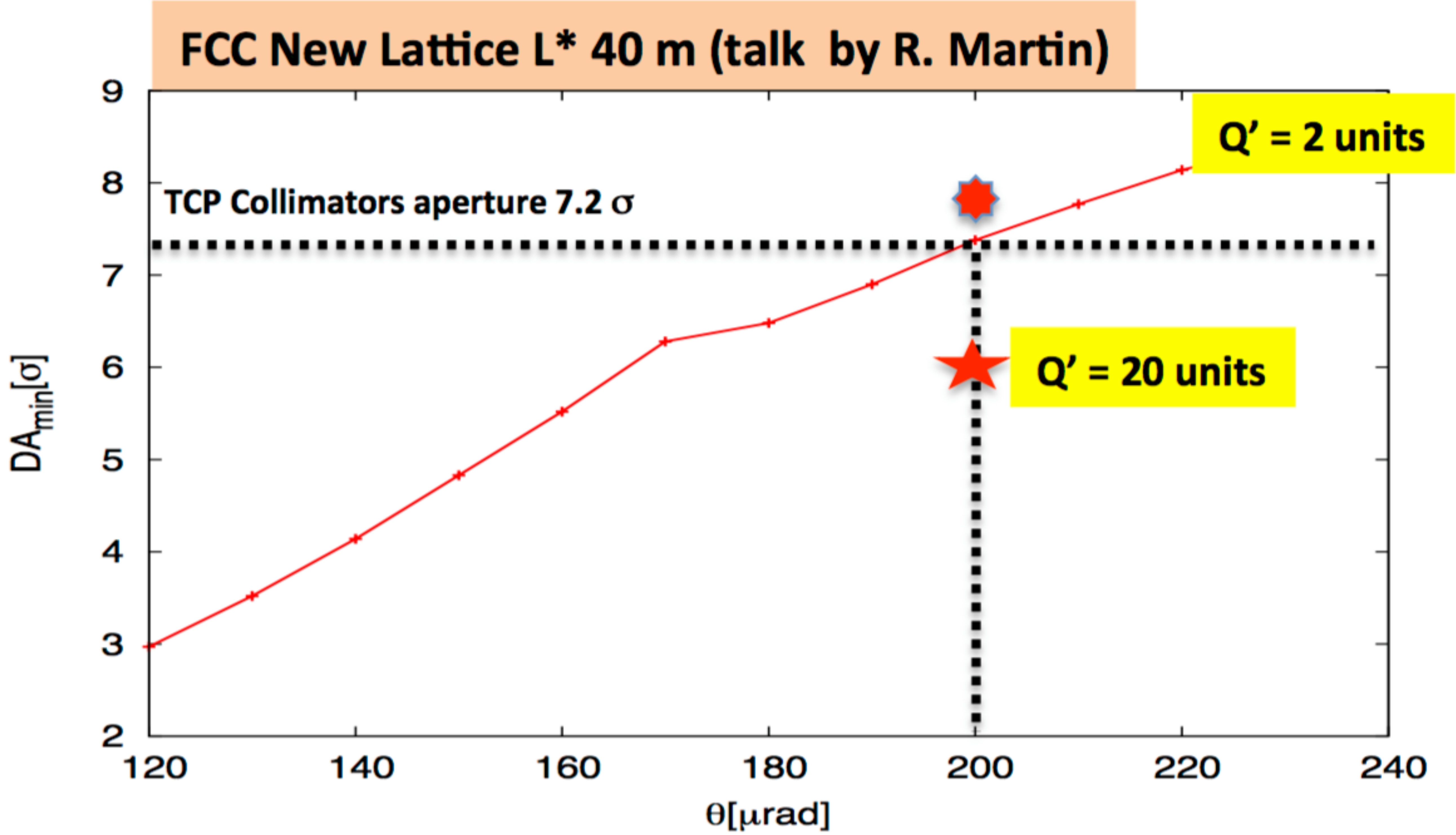


352 Long-Range interactions
For 4 Experiments

	FCC-hh Baseline	**FCC-hh Ultimate**
Luminosity L [10^{34}cm^{-2}s^{-1}]	5	20-30
Background events/bx	170 (34)	<1020 (204)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2(0.44)	
Max ΔQ_{bb} (for 2 IPs)	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ']	12	Crab. Cav.

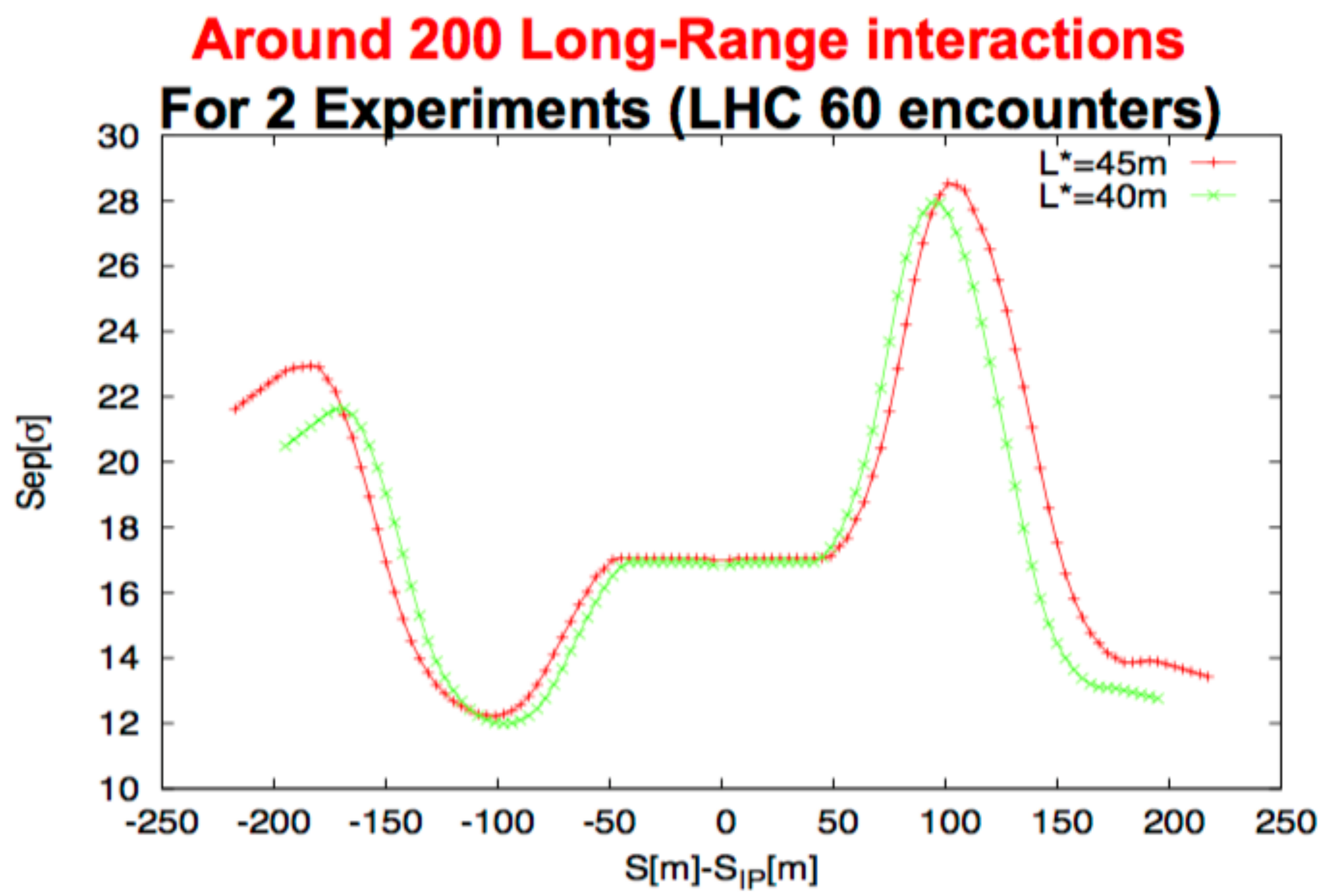
IPA and IPG: high luminosity experiments
IPL and IPB: low luminosity experiments
→ in shadow on main IPs where possible (defined luminosity operation)

Crossing angle choice: new optics



FCC New Lattice L* 40 m (talk by R. Martin)

- **New Interaction Region Layout L* 40 m optics**

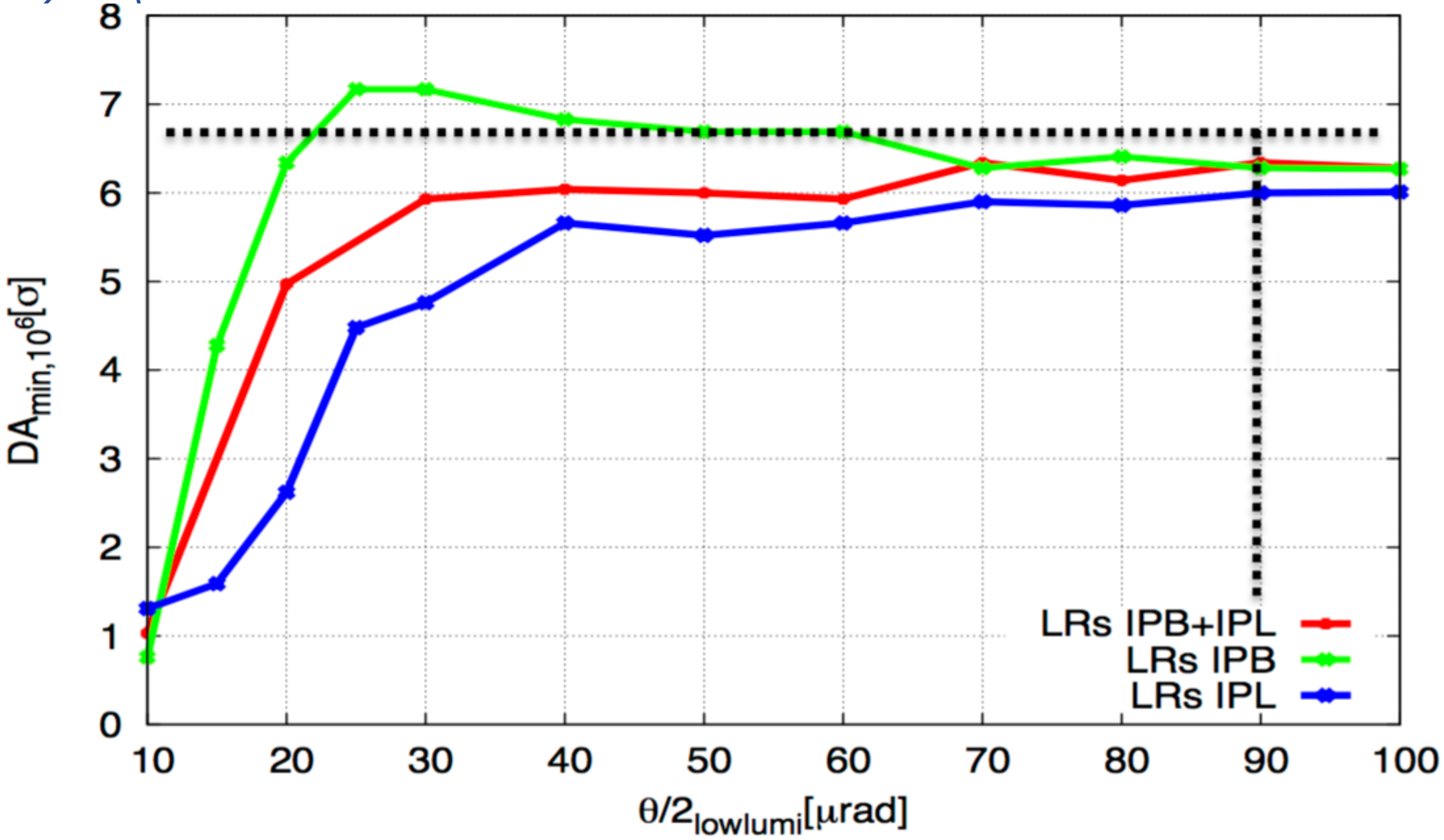


Around 200 Long-Range interactions

For 2 Experiments (LHC 60 encounters)

- New optics have reduced dynamic aperture →fewer encounters but smaller separations
- Crossing angle of **200 μrad at IPA and IPG** proposed allows for high chromaticity operation→ Still to be added :
  - → Landau Octupoles
  - → Magnets imperfections
  - → Tunability and low luminosity experiments

Low Luminosity Experiments: IPL and IPB



The long-range effects of IPL and B will impact bunches differently (**no passive compensation**)

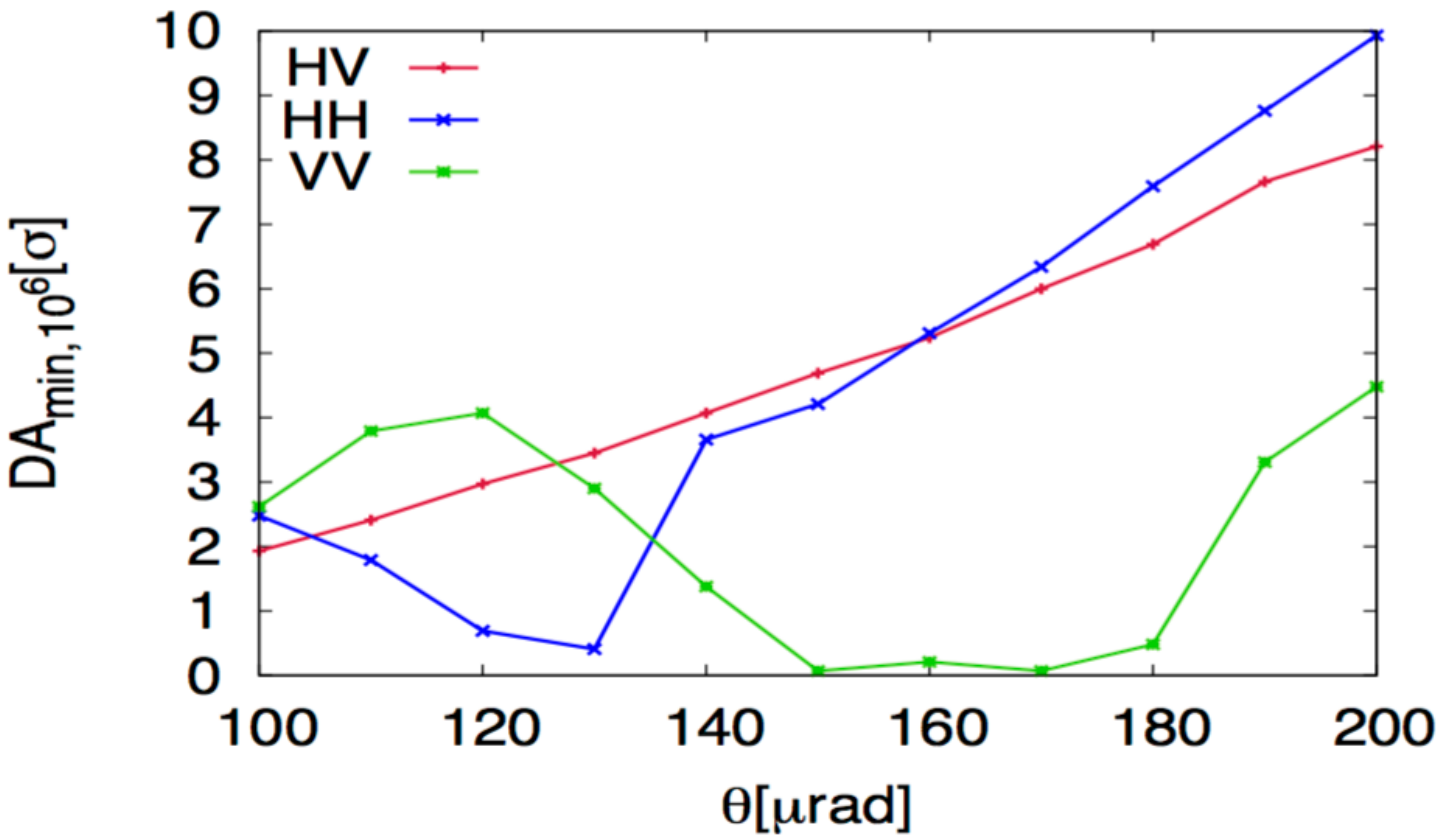
To have them not perturbing the high luminosity experiments should have **angles > 180 μrad**

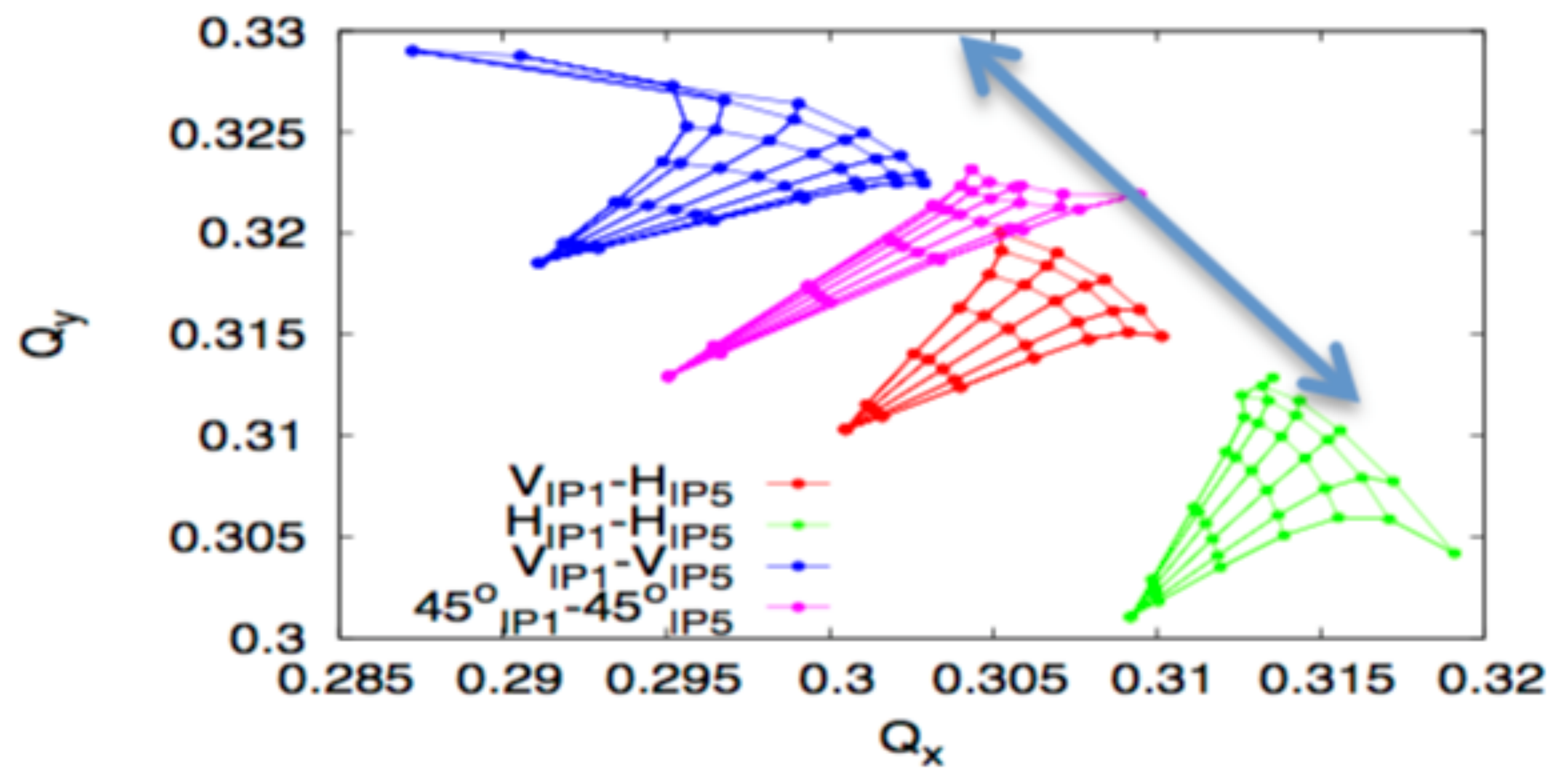
Level by separation the head-on collision to avoid strong tune shifts

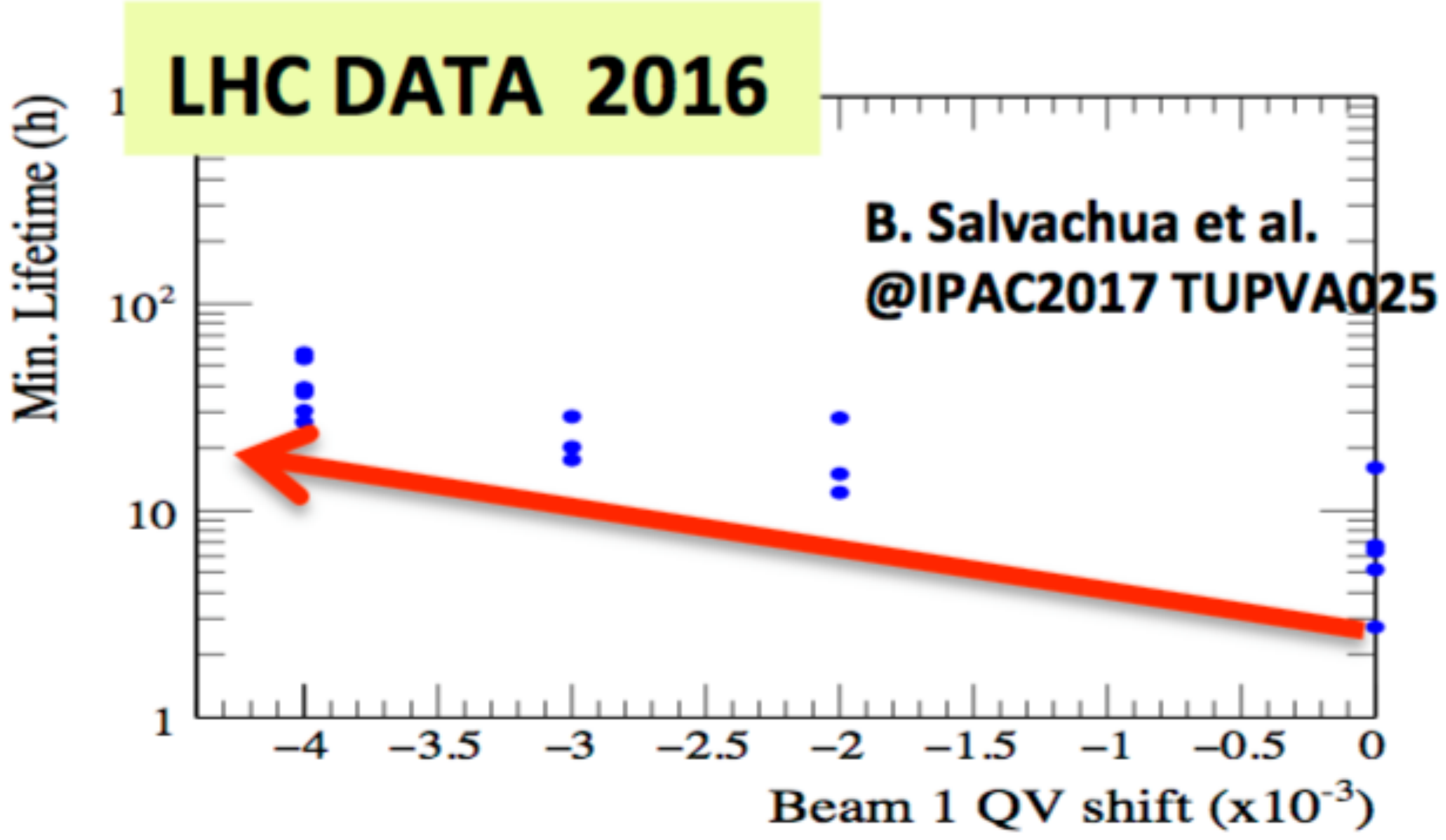
Same strategy as for in LHC and HL-LHC

- **Long-range:** crossing angles larger than 180 μrad (enough aperture from **M. Hofer**)
- **Head-on** apply separation leveling of luminosity = limit on integrated luminosity per year of run!
  To be defined with tune optimization!

Alternative Crossing scheme







LHC DATA 2016

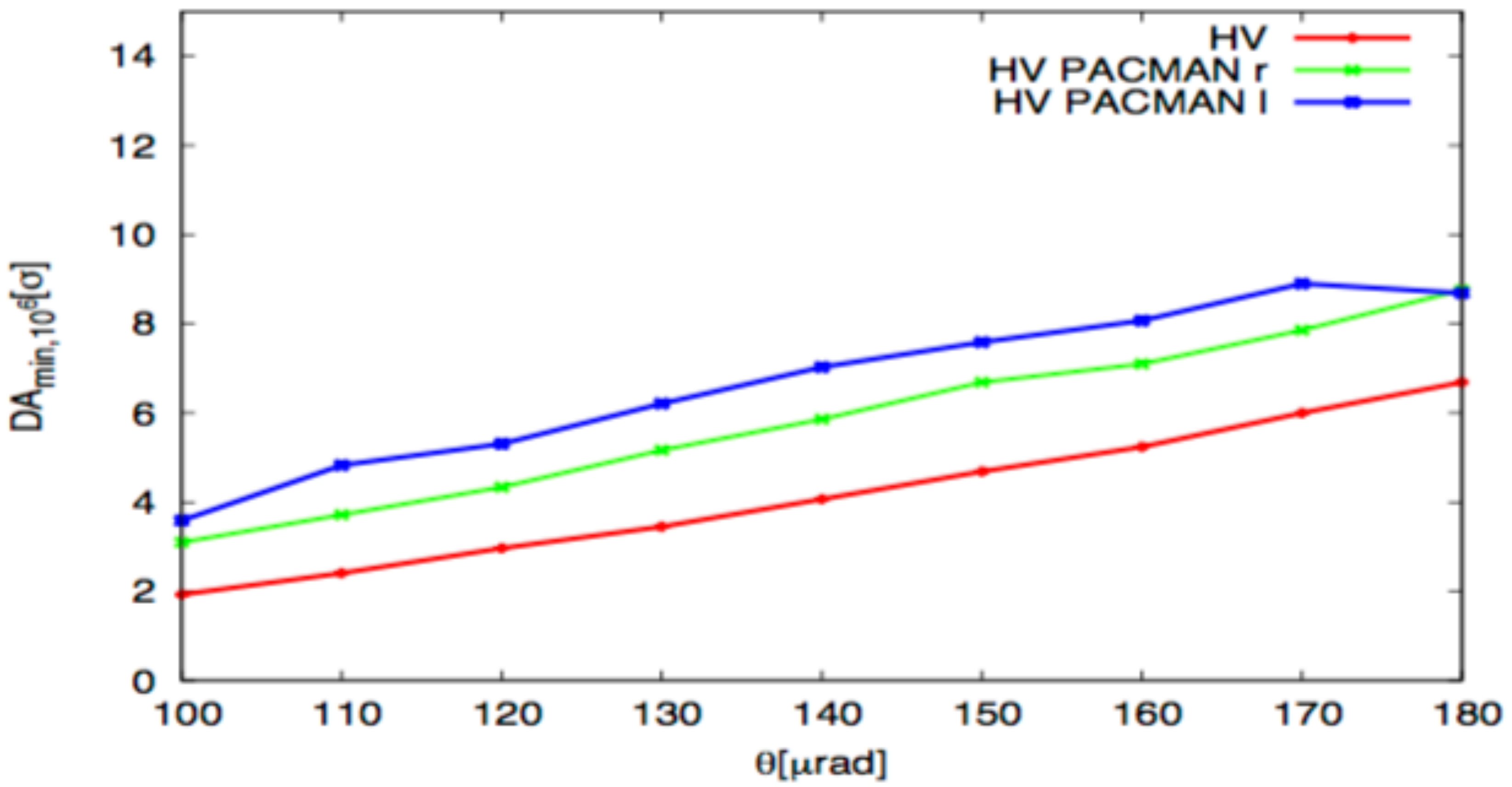
B. Salvachua et al. @IPAC2017 TUPVA025

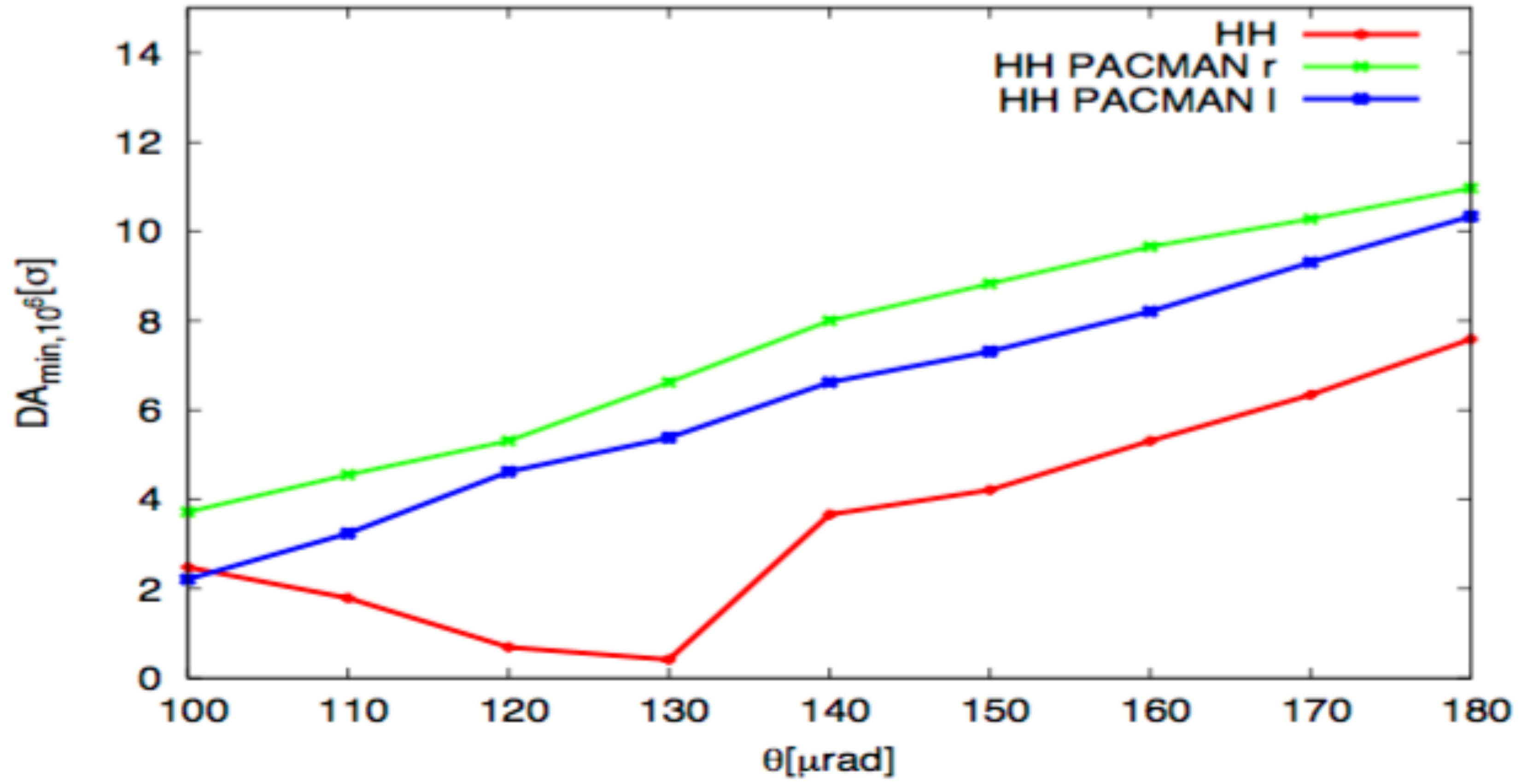
Pacman Bunches?

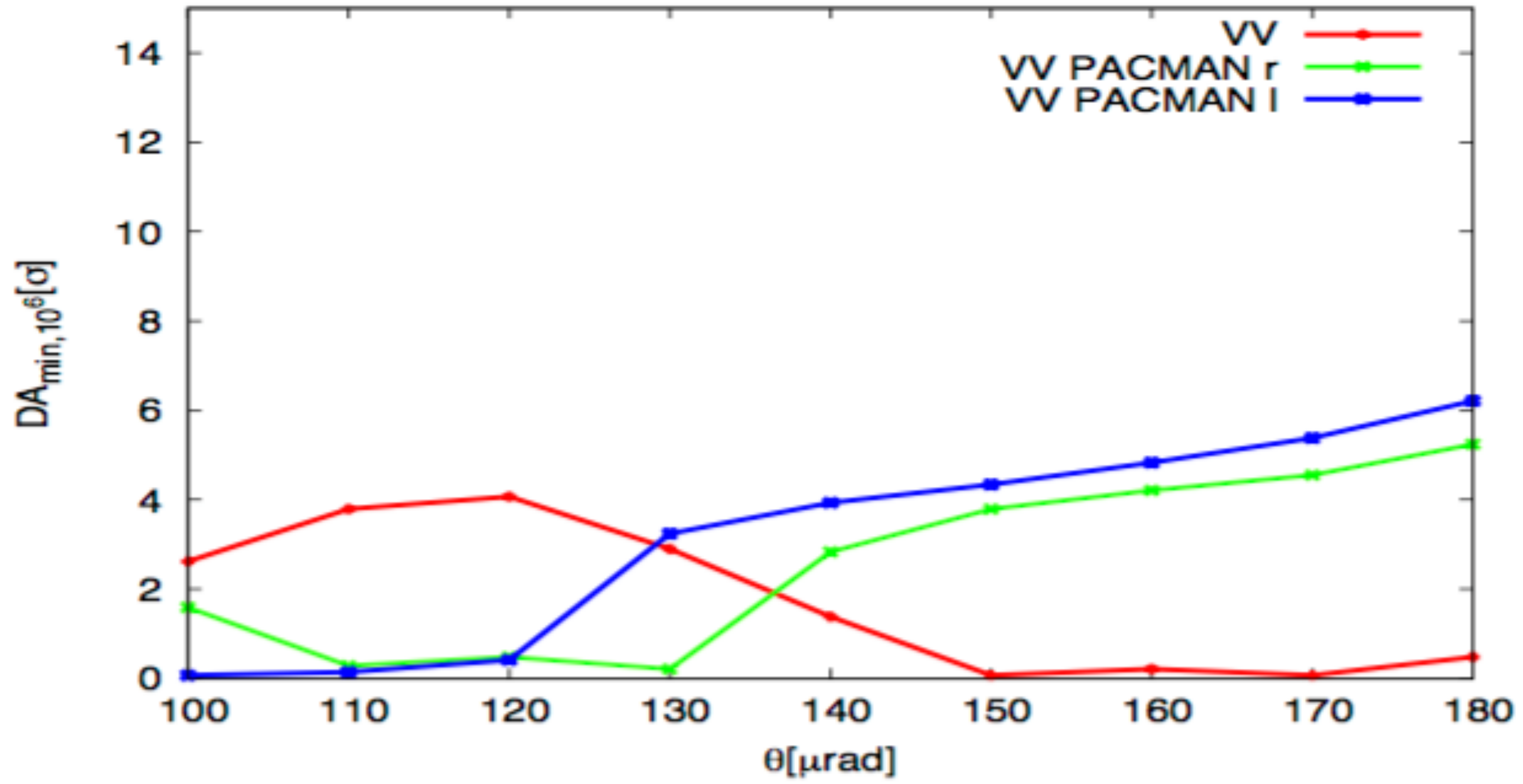
Alternative crossing schemes have been explored and show larger flexibility in terms of dynamic aperture with optimized tunes

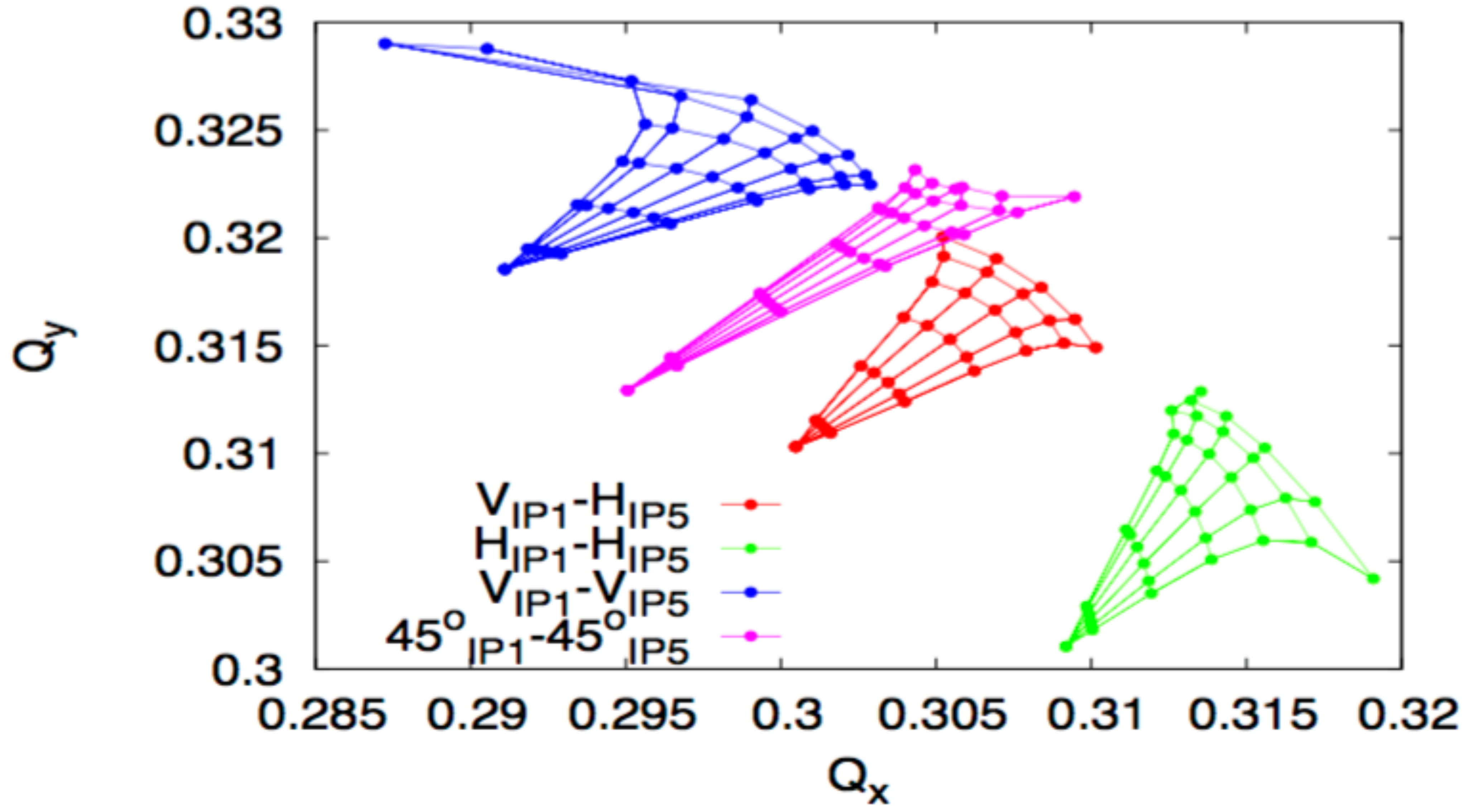
- HH Crossing is equivalent to HV
- VV not acceptable at the (0.31-0.32) working point due to strong impact of 3rd order resonance effect → Mirrored tune will solve the problem

Pacman Bunches







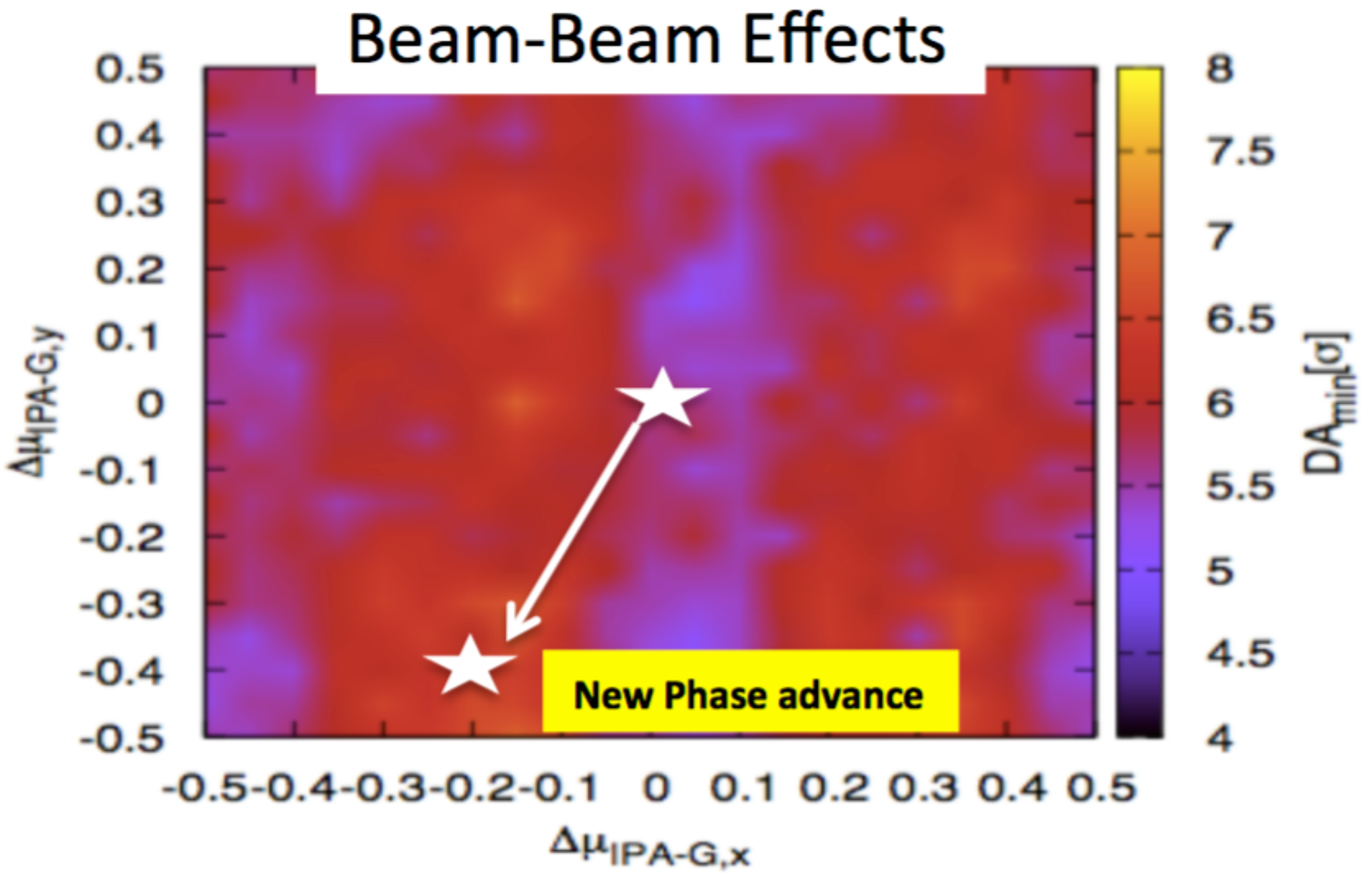


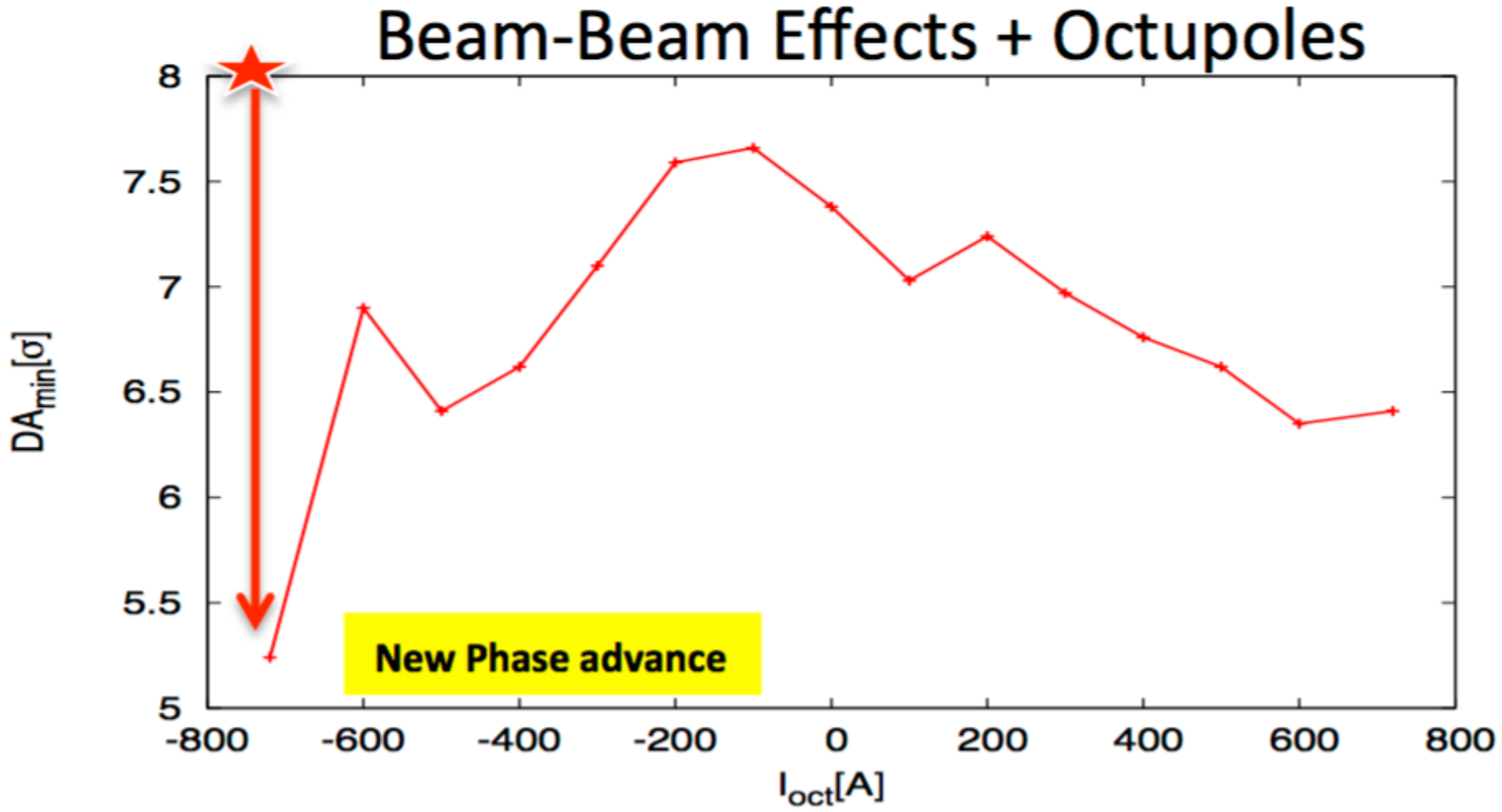
- For all crossing schemes the major impact of long-range effects are on the nominal bunches
- PACMAN bunches always show a better dynamic aperture, **DA is defined by nominal bunches**

Room for flexible configurations if needed by energy deposition studies
Tilted crossing schemes also under study

Optimization based on dynamic aperture scheme

Optimum phase advance for optics (E. Cruz talk) not always the best when other non-linearities are added

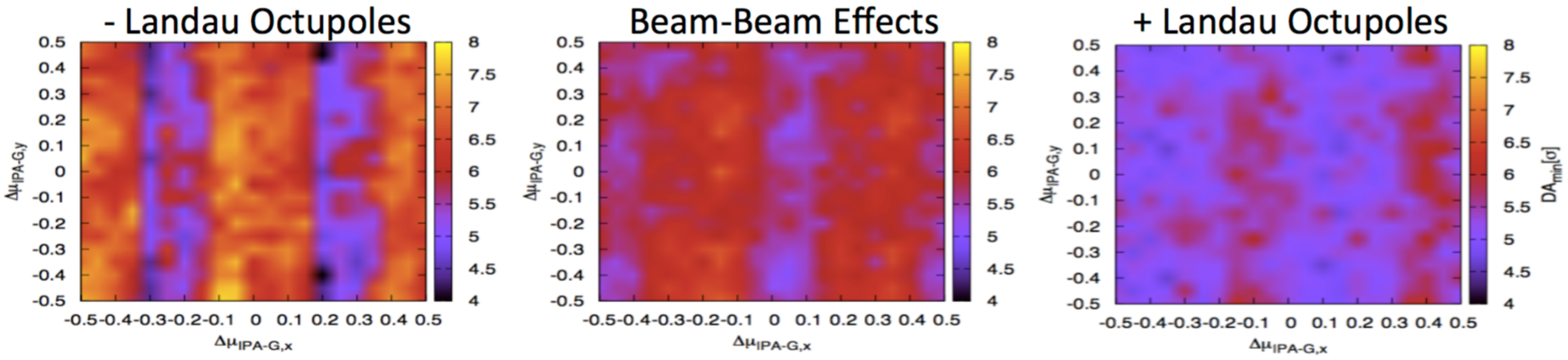

Beam-Beam Effects


Beam-Beam Effects + Octupoles

New Phase advance better for optics and beam-beam effects alone but breaks global compensation with octupole magnets (J. Barranco from Eurocircl 2017)

Optimized phase advance to have maximum Dynamic Aperture with beam-beam is not optimum in presence of Landau octupoles

Landau Octupoles and IP phase advance



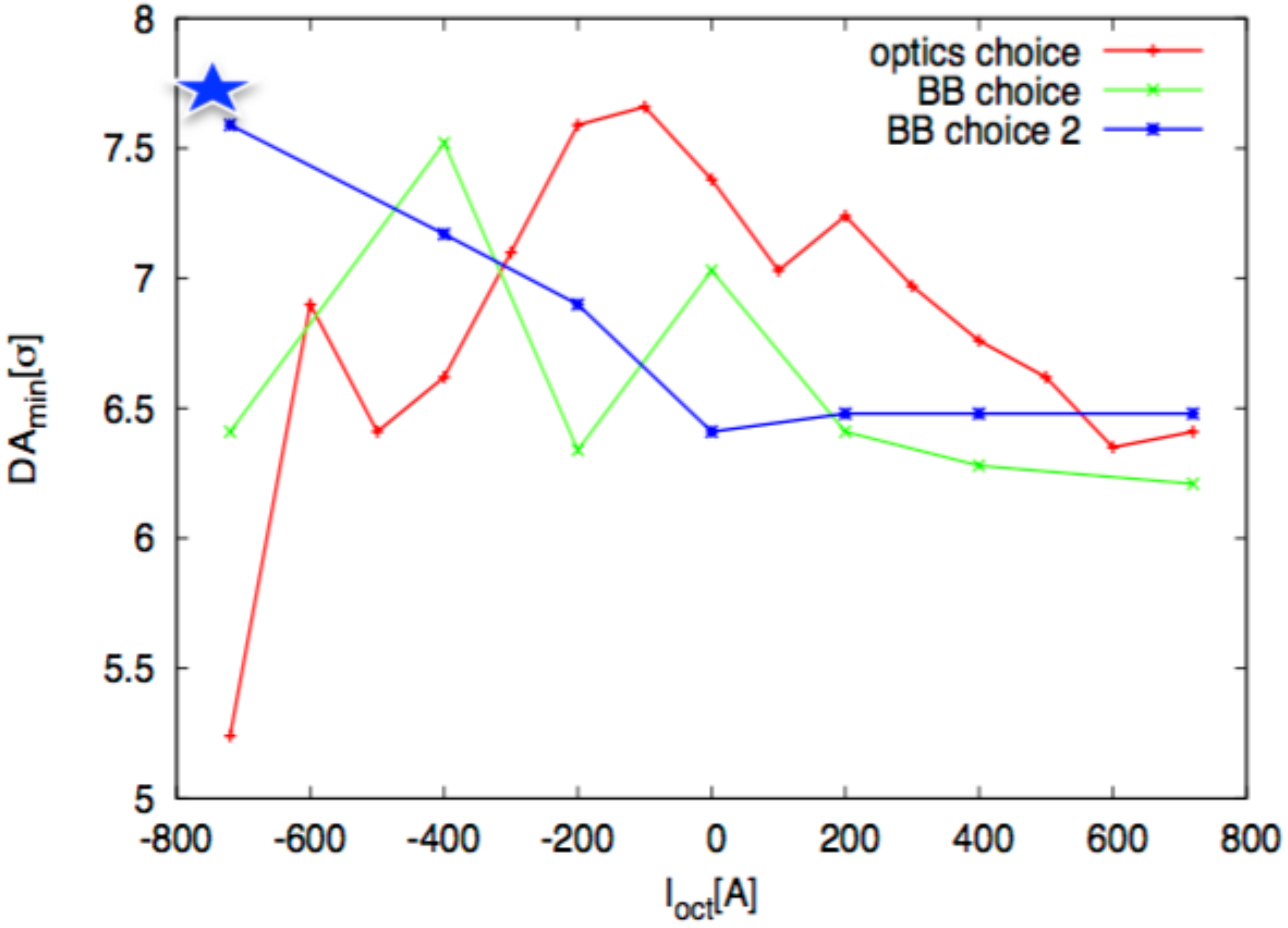
We choose to have Landau Octupoles powered in negative octupole polarity

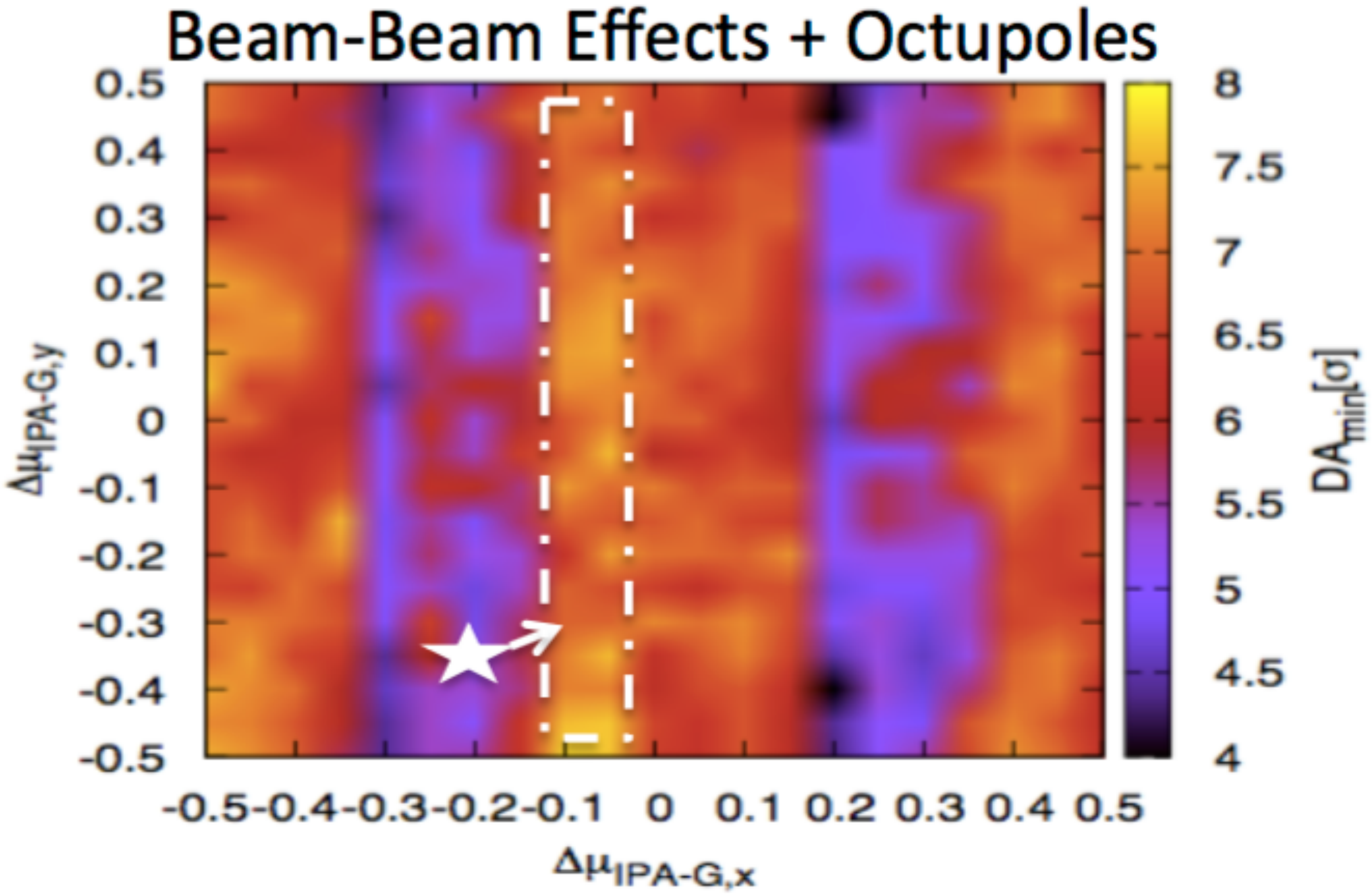
- → **provides larger stability for single beam (see C. Tambasco talk)**
- →**allows for larger DA with optimized phase advance thanks to compensation (J. Shi et al.,** CERN-ACC-NOTE-2017-036**) → large dynamic aperture margins**

Need to optimize the optics to keep compensation!

Different Phase advances at different stages of the operational cycle to maintain compensation

Optimization of optics based on dynamic aperture



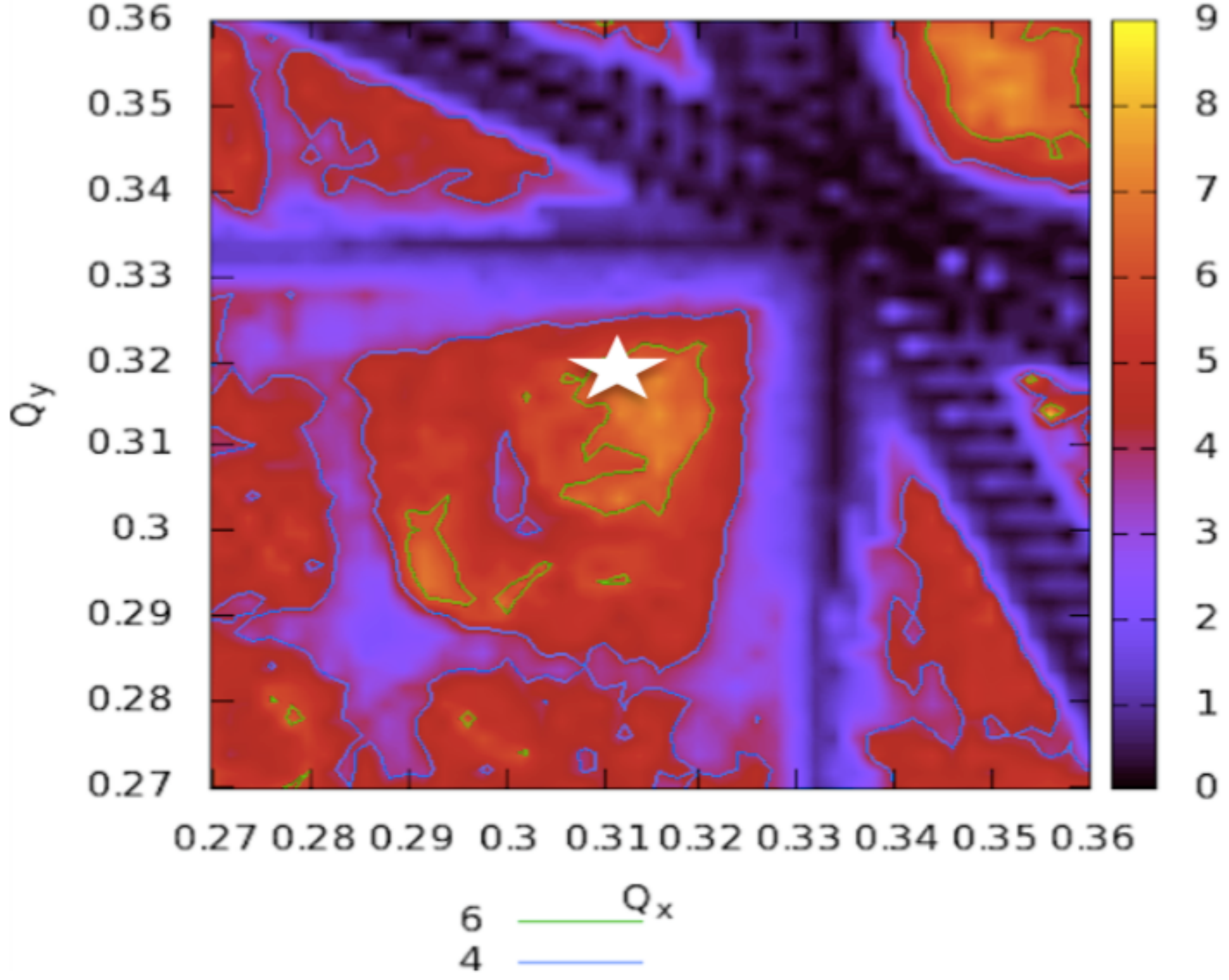


Further optimization of phase advance with beam-beam and octupoles compensation

→ Will further change with multipolar errors

Phase advance between IPs changes over the operational cycle of the collider to have maximum Dynamic Aperture

Dynamic Aperture dependency on tune



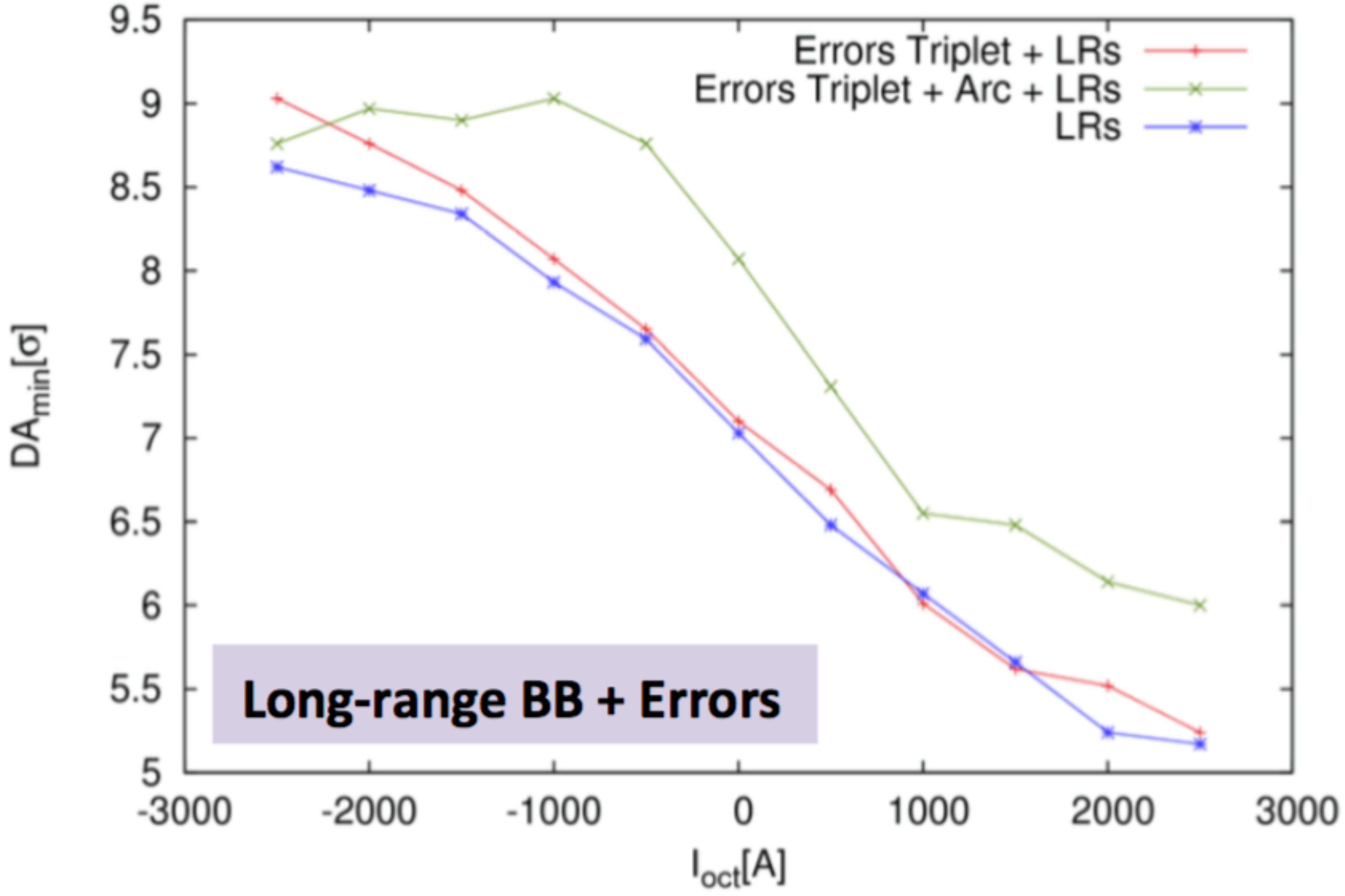
LHC@home
SixTrack

Define **robust baseline scenario with Dynamic Aperture above 6 σ** with all non-linearities (magnets errors, Landau octupoles, high chromaticity and beam-beam effects) and some margins for parameter fluctuations (10%)

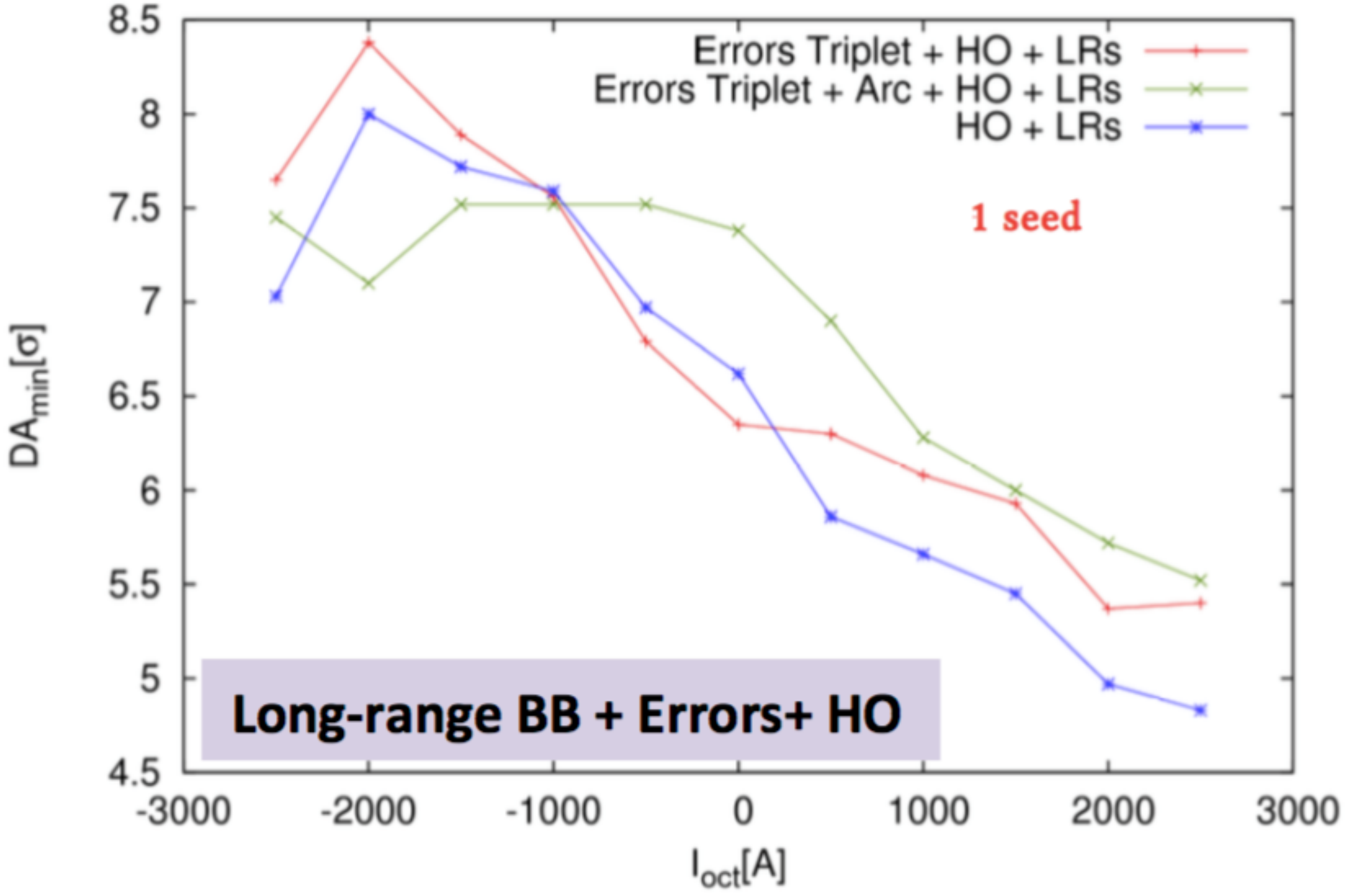
Tune optimization to find optimum and large area in tune diagram (on-going work)
→ host low luminosity experiments contributions (tune shifts) and multipolar errors

Dynamic Aperture with multipolar errors

FCC L* = 45 meter optics only one seed



Long-range BB + Errors



Long-range BB + Errors+ HO

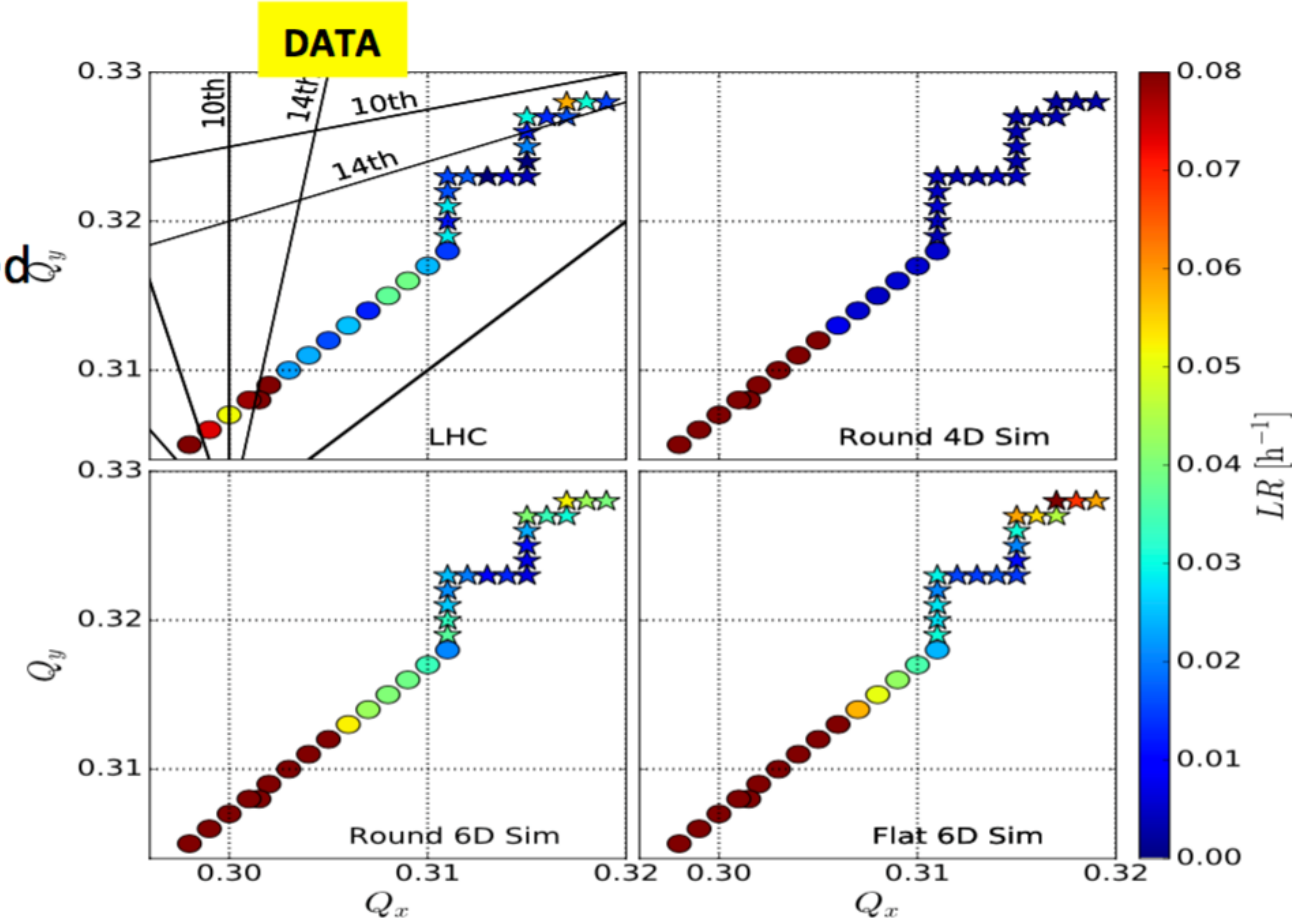
Break of long-range global compensation scheme in collision → need further studies and lattice optimization
L* 40 meter optics under study with full seed statistics

Head-on limit: losses and emittance growth

Model developed for FCC-hh of loss rates with 6D beam-beam and simplified lattice!

First comparisons to LHC losses data during dedicated experiment

- Total Beam-Beam tune shift of 0.02
- GPU accelerated 6D simulations (CABIN) compared to measured losses in the LHC.
- Clear impact of Piwinski angle to loss mechanism
- Good qualitative agreements
- Work on going on quantitative estimates (**magnets errors**)



Poster by S. Vik Furuseth
Strong Head-on Beam-Beam Interactions

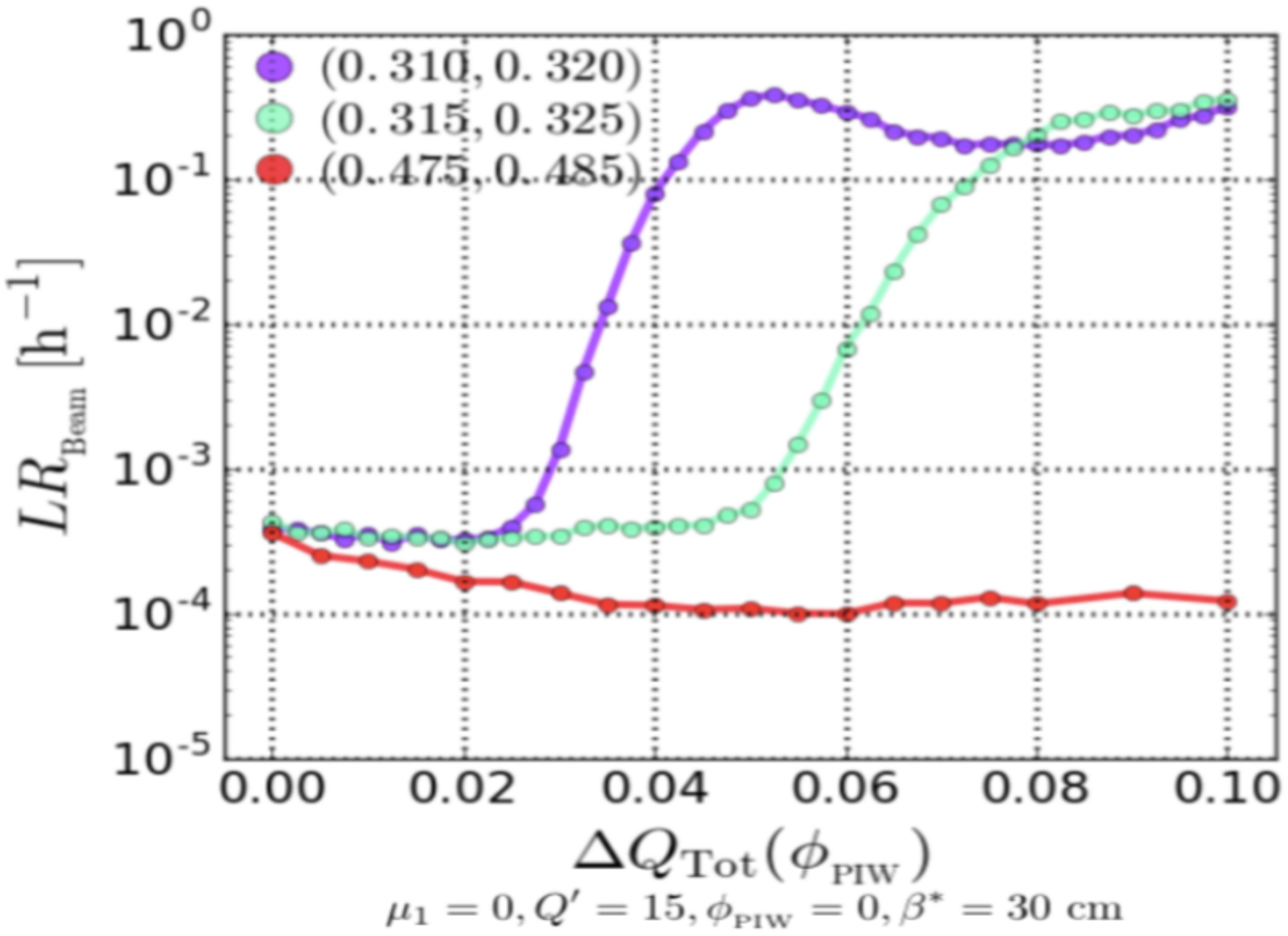
Head-on limit: losses and emittance growth

Baseline scenario (total beam-beam tune shift 0.02) shows no limitations

Ultimate (total beam-beam tune shift 0.03) is not given!

Working point optimization could increase the beam-beam maximum tune shift reach to 0.046

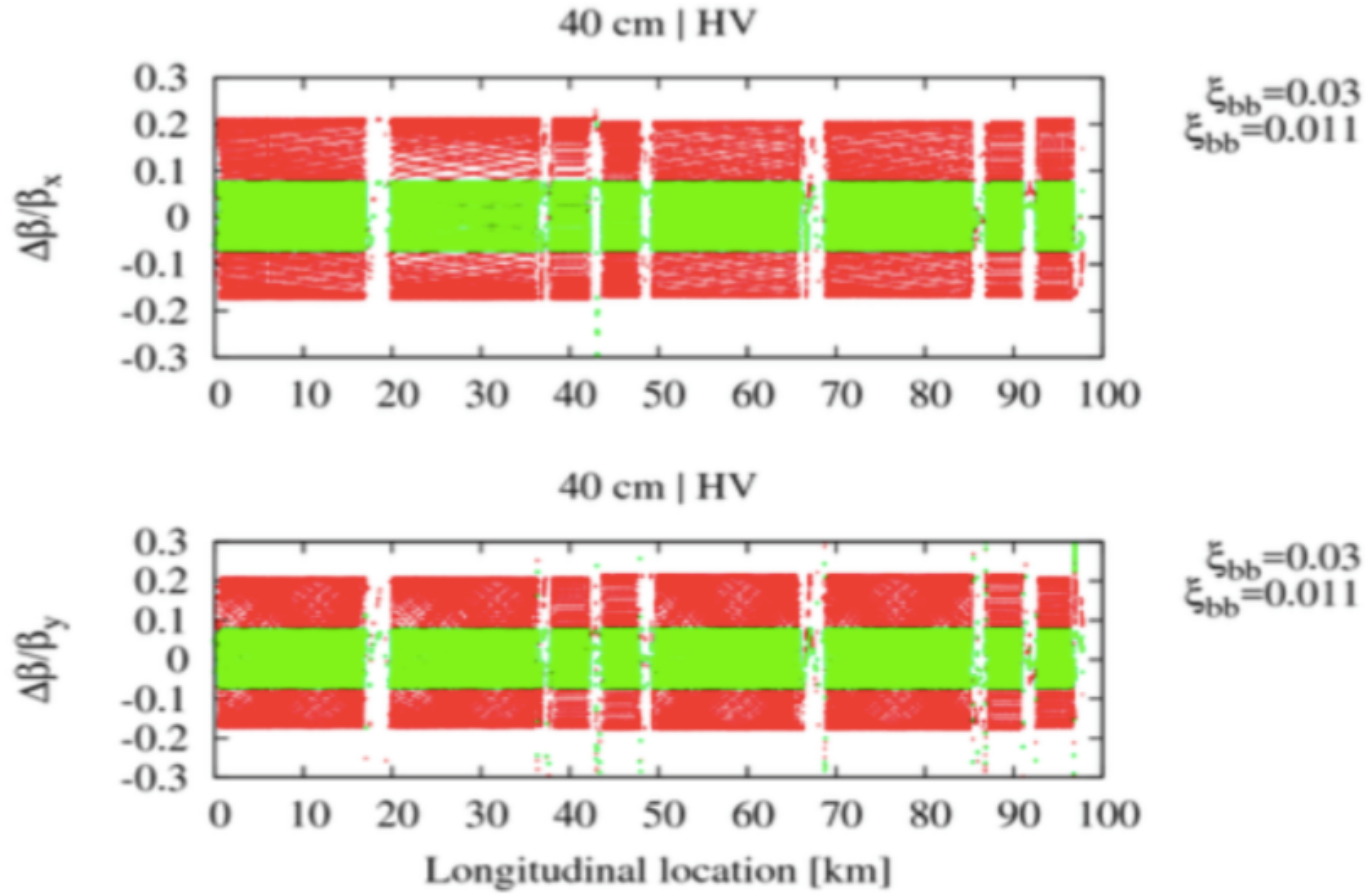
Further optimization between dynamic aperture studies and head-on studies are foreseen



Poster by S. Vik Furuseth
Strong Head-on Beam-Beam Interactions

Further studies needed to explore possible limitations linked to head-on beam-beam: LHC data benchmark fundamental!

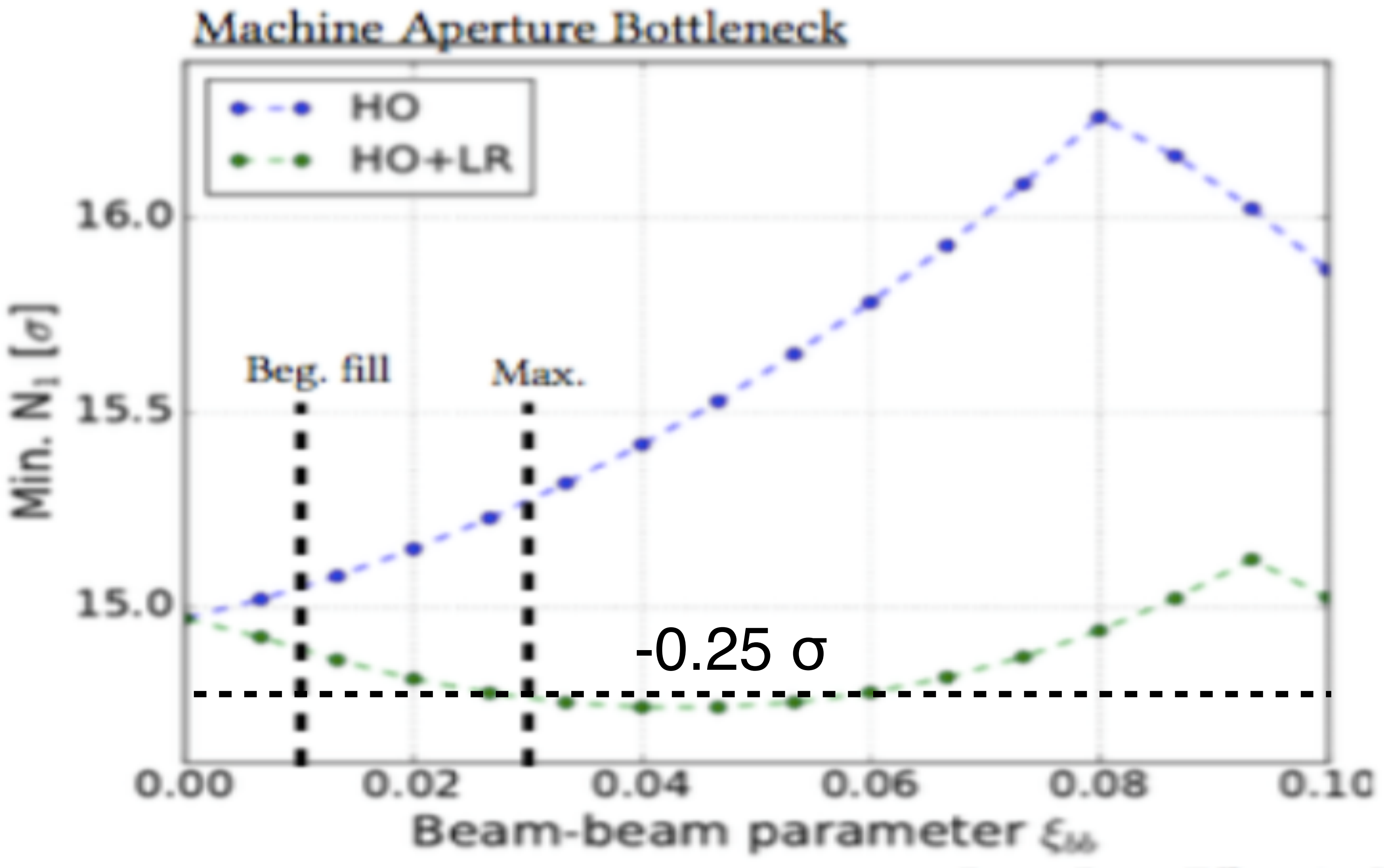
Head-on limit: beta beating

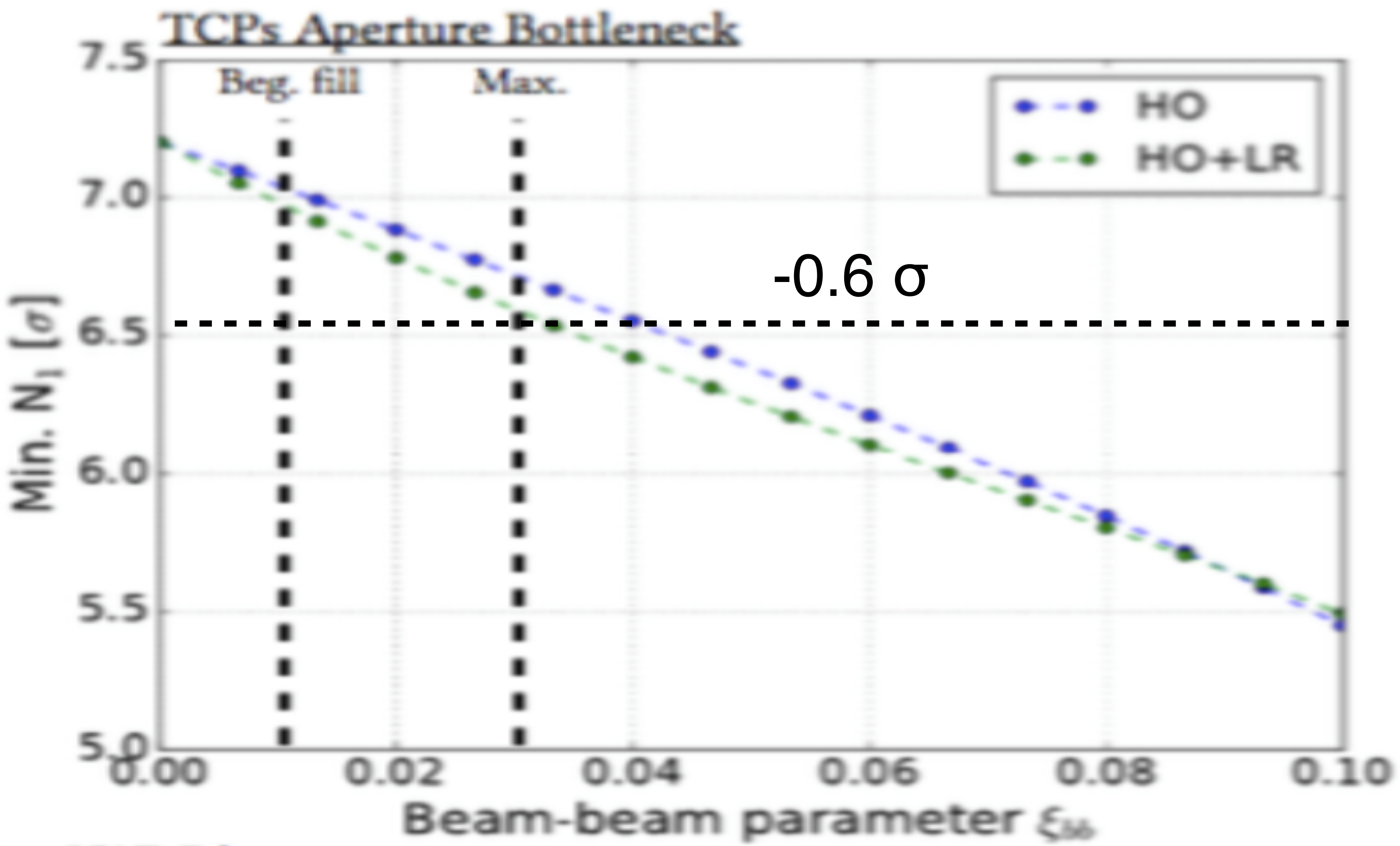


- Linear beating from MADX (0σ particles) with head on (HO) interactions in IPA and G and no lattice errors.
- Using L*=40m and β*=0.3m optics with full crab crossing.
- FCC adds new feature since the ξ_{bb} **changes over the fill** and so the beating.
  - $\xi_{bb,tot}$=0.011 (beg. Fill) - $\Delta\beta/\beta_{max}$=8 %
  - **$\xi_{bb,tot}$=0.03 (max)-$\Delta\beta/\beta_{max}$=22 %.**
- FCC is currently optimizing the phase advances between main experiments @ collision to maximize DA. This optics distortion becomes yet another parameter on the optimization (HO, octupoles,...).
- Collimation experts request $\Delta\beta/\beta_{max}$ <10 % as in the LHC.

Head-on limit: impact on aperture

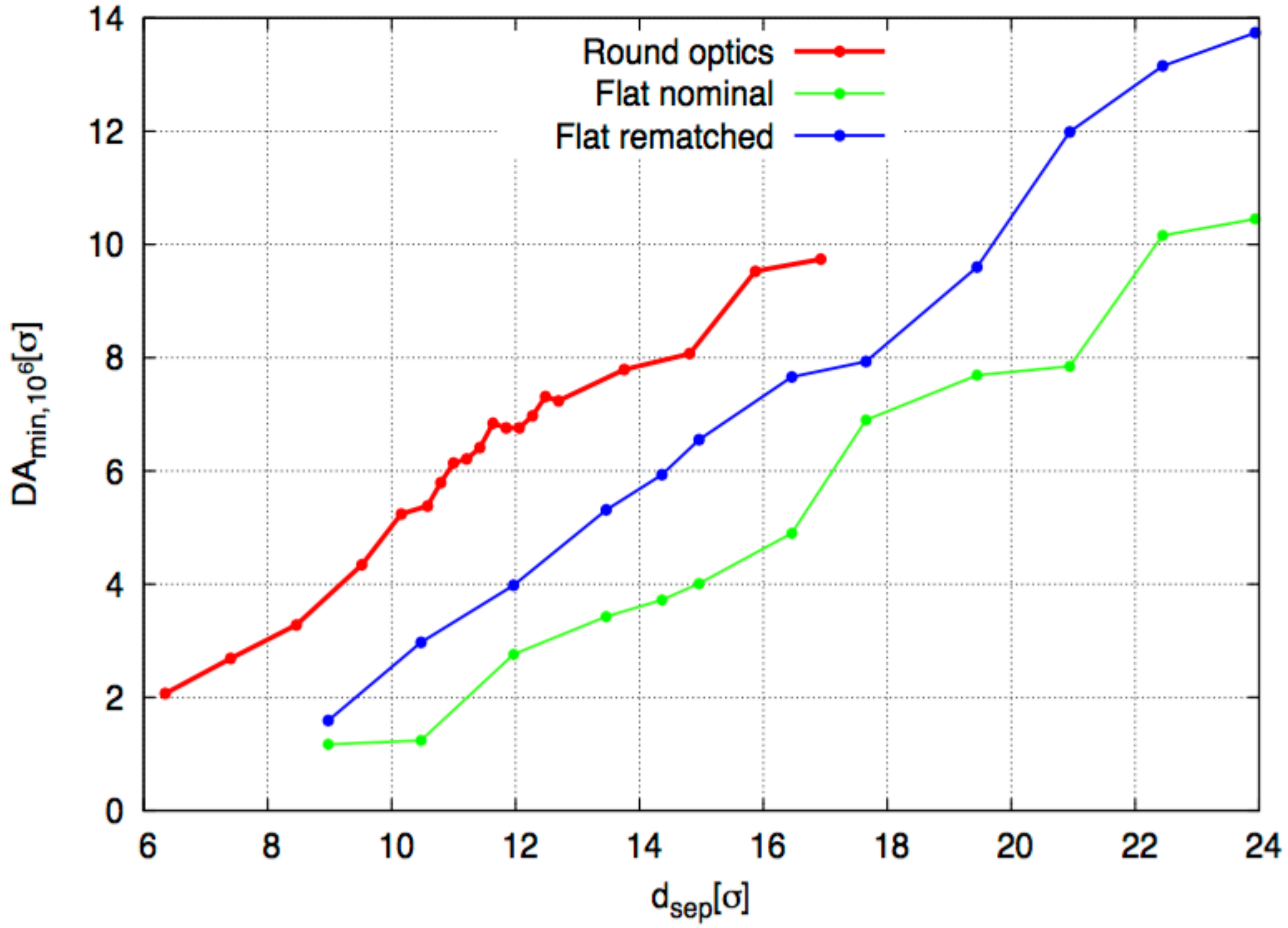
- We explore the impact on machine and collimator apertures for various ξ_{bb}. Only linear beating is considered (worst case).
- Machine aperture bottleneck in separation dipole MBRD.B4RA.H1.
  - For HO only no aperture decrease for expected ξ_{bb} FCC range [0.01-0.03].
  - For HO+LRs there is a decrease of ~0.25 σ for max ξ_{bb}=0.03.
- TCPs aperture bottleneck TCP.B6L2.B1 (for ξ_{bb}=0.01 HO, ξ_{bb}=0.016 HO+LRs) then TCP.A6L2.B1. For ξ_{bb}=0.03, a decrease of ~0.6 σ is observed.

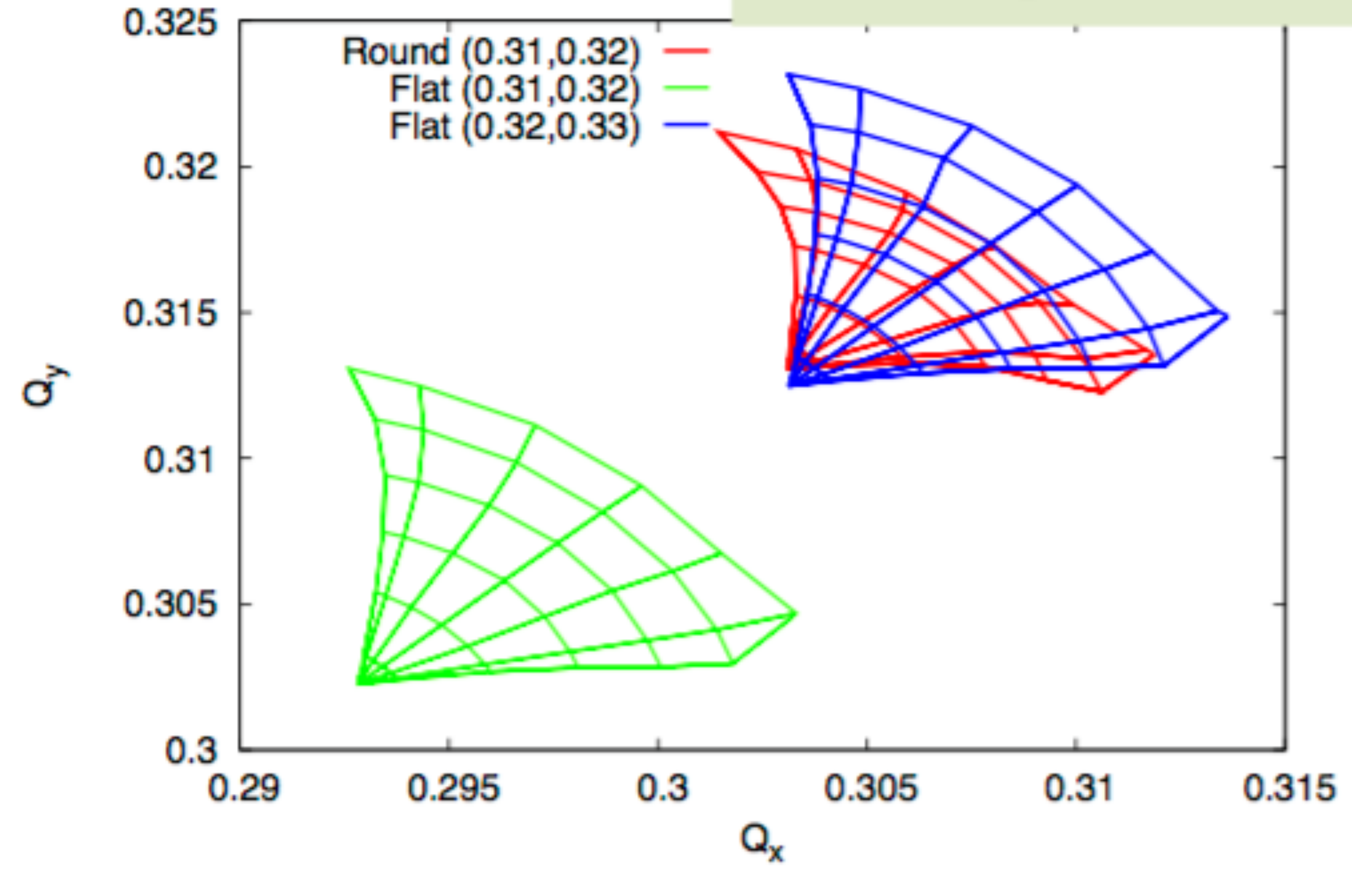




Impact on Collimation aperture of maximum 0.6 σ needs further study to address and identify possible limitations

Flat versus round optics: tune shift correction



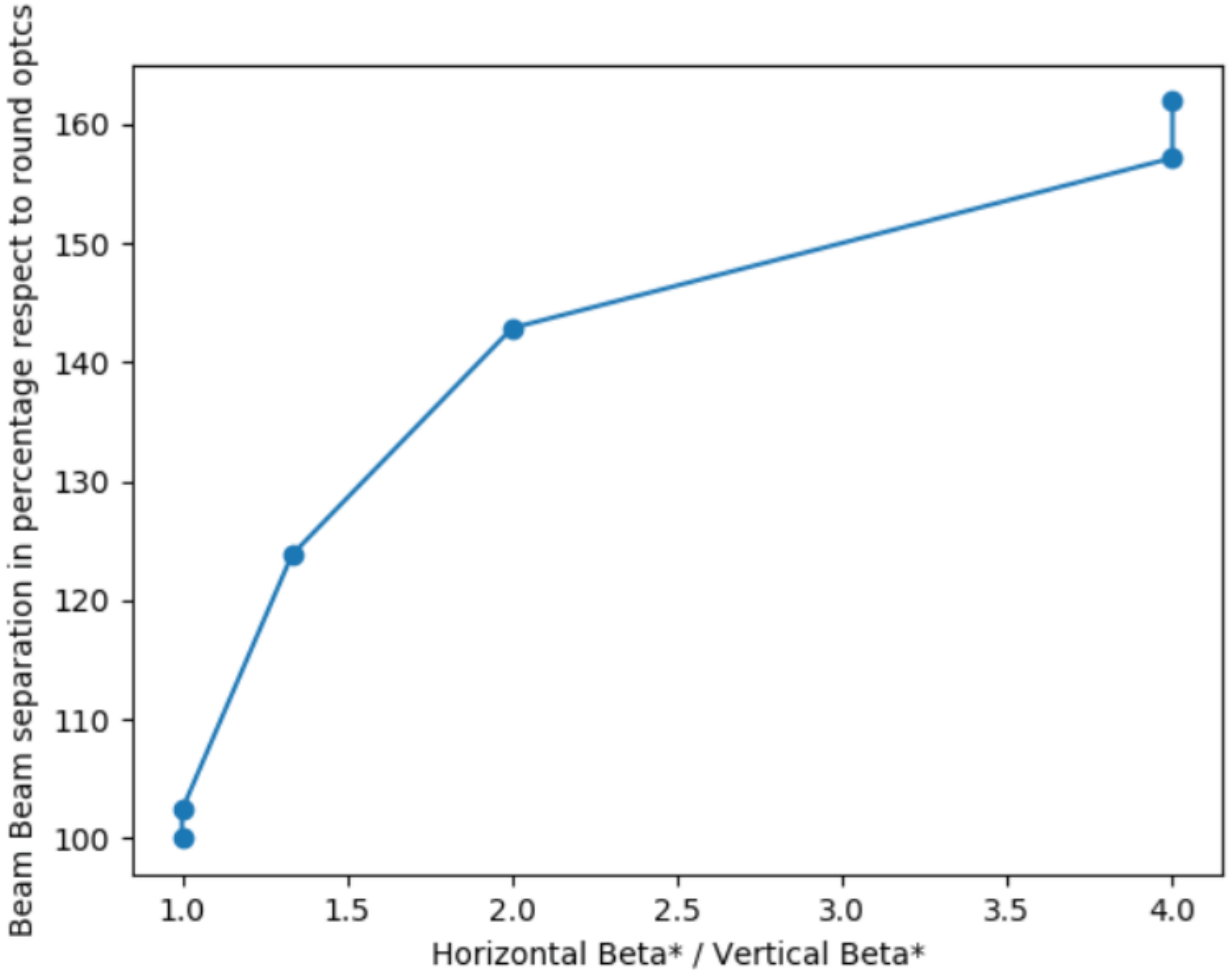


Flat optimized

Study case beta ratio of 4 and H-V crossing scheme:

- Flat optics will need **43%** more separation respect to round
- Correcting for the tune shift reduces the needs but still need **26%** larger separations
- **Larger aspects ratios of betas make things worse!**

Flat versus round optics: beta ratios



For H/V crossing schemes

The extra separation needed from dynamic aperture studies with a DA goal of 6 σ shows strong dependency on the beta* ratio at the IPs

Alternative crossing schemes become even more difficult→ separation up to factors 3-4 larger

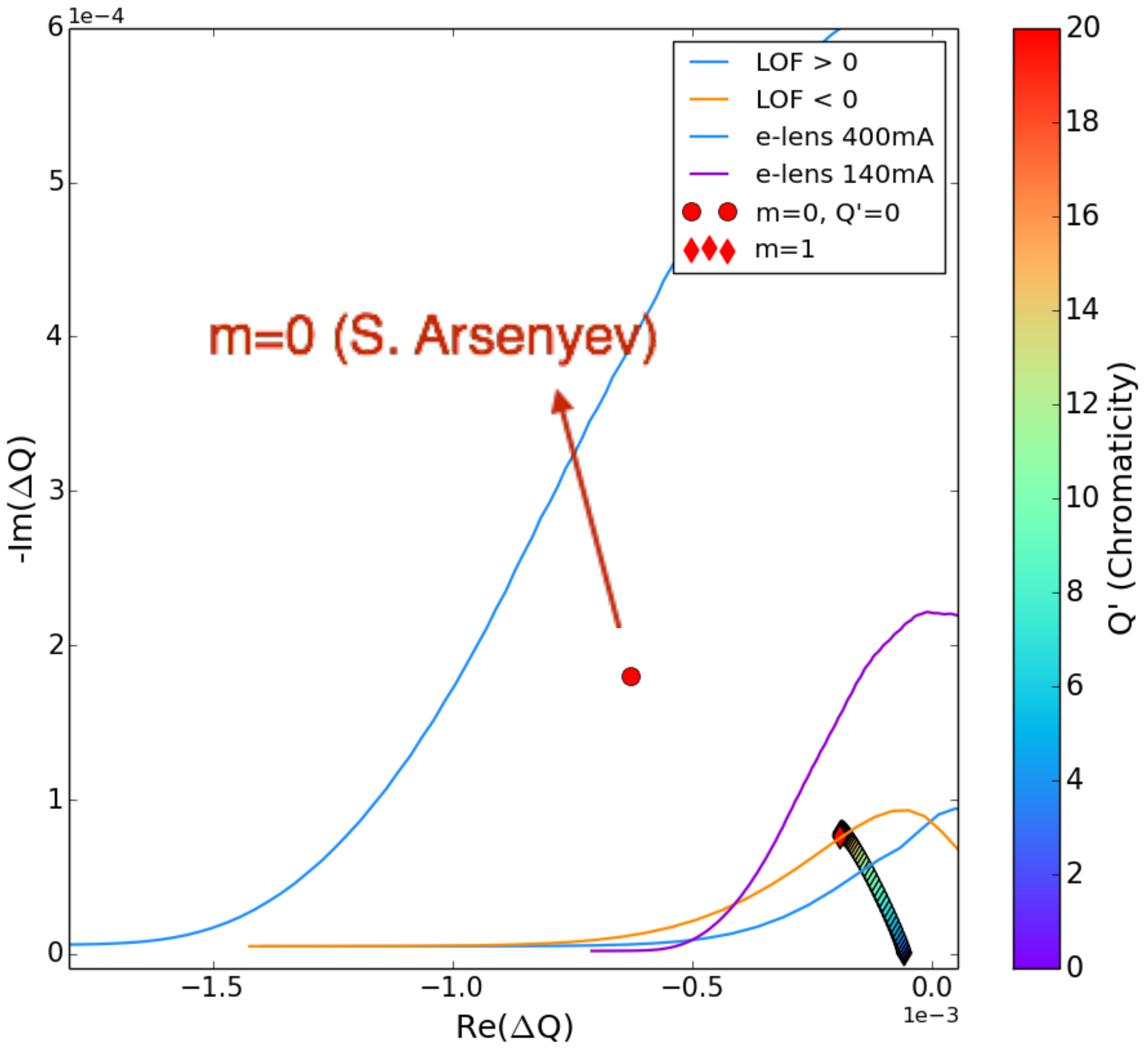
Studies on-going to propose a back up scenario for the CDR!

Summary

- Update octupole system→ **~42% more strength** + 4 % more n. octupoles
- **At flat top single beam stability ensured by octupole magnets (larger for negative polarity**) system (**DA > 18 σ both octupoles polarities)**
- Collapse sep. bumps (LR + HO crab on): **SD always larger or equivalent compared to the end of squeeze case**
- The new beam screen designs increase impedance of 30% → **recent results of ADT coupled bunch modes show sufficient stability at the end of the squeeze (ADT gain can be further reduced to have more margins)**
- **Collide & squeeze is a possible scenario with 1.1 < β*< 2 m** (**BB long range above 40σ**)
- **A robust baseline scenarios has been studied and beam-beam separation proposed based on dynamic aperture**
- **Optimized optics parameters have been shown to allow highest dynamic aperture** together with a global compensation scheme using Landau octupoles
- Newer optics **L* 40 m has to be optimized further with multipolar errors (on-going)**
- **Head-on beam-beam limit seem far away from chosen parameters but studies show optimized working points** in parallel to single particle dynamic aperture studies
- **Large beta-beating should be expected (30 %) and needs further understand of implications on loss maps and collimation system**
- **Alternative scenarios are explored to allow for flexibility** in the presence of other constrains
- Continuous benchmark to LHC data is fundamental to understand predictive power of simulations

Back-up

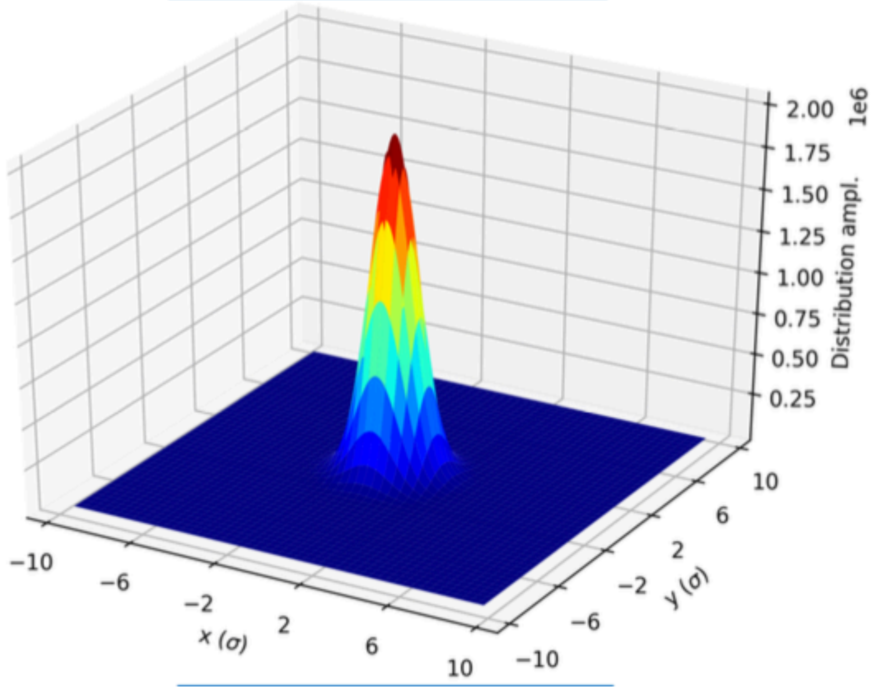
Electron lens for Landau damping: flat top energy



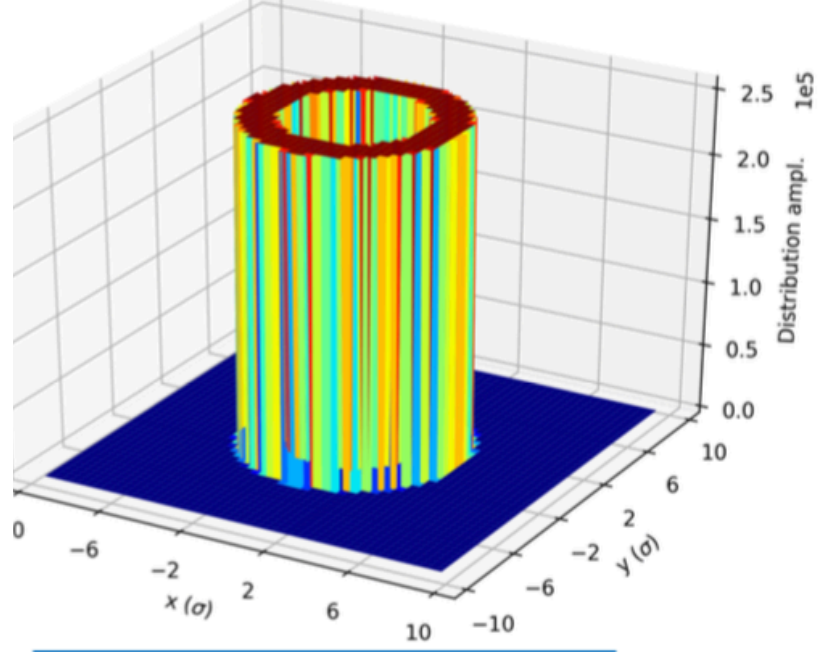
- 140 mA will be sufficient to provide enough Landau damping for m=1 (up tp Q’=20 units)
- 400 mA are required to damp m=0 at Q’=0

Different e-lens profiles have been implemented in COMBI (Project by EPFL Master student F. Barantani)

Gaussian profile

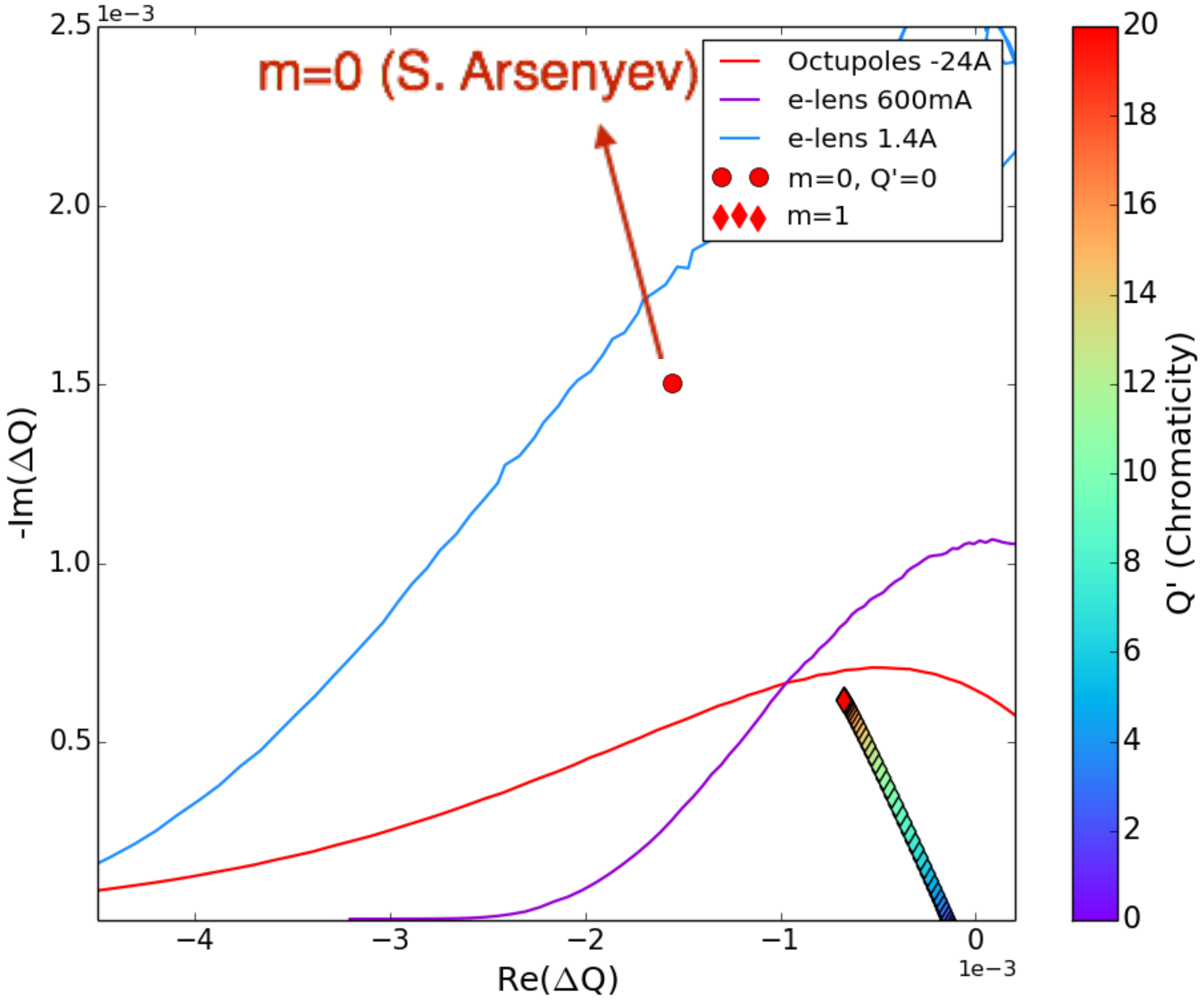


Cylindrical profile



[“Landau Damping of Beam Instabilities by Electron Lenses”, V. Shiltsev et al., 10.1103/PhysRevLett.119.134802]

Electron lens for Landau damping: injection energy



- 600 mA will be sufficient to provide enough Landau damping for m=1 (up to Q'=20 units)
- 1.4 A are required to damp m=0 at Q'=0

["Landau Damping of Beam Instabilities by Electron Lenses", V. Shiltsev et al., 10.1103/PhysRevLett.119.134802]