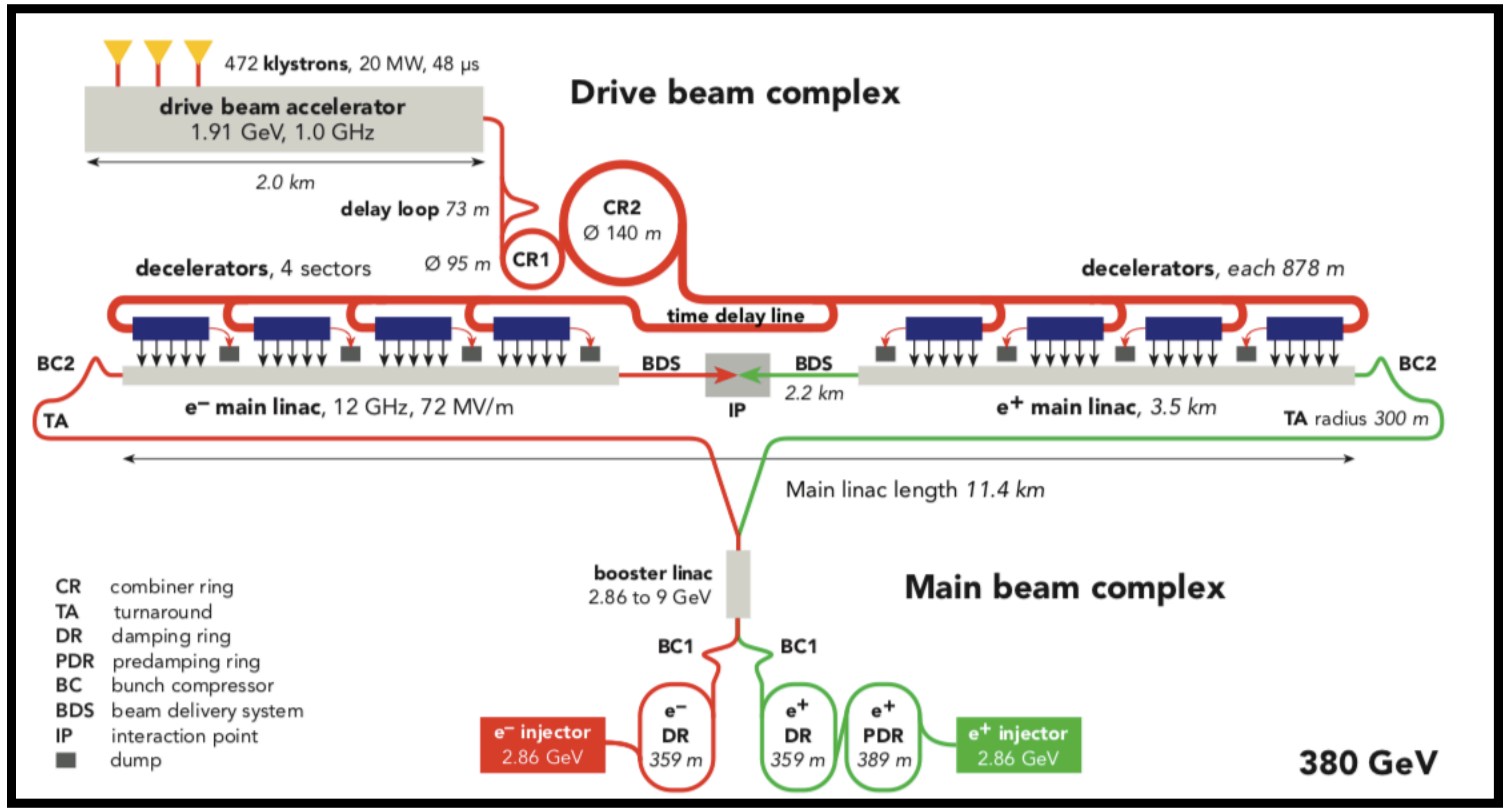
Completion of the two-beam luminosity tuning for the Compact Linear Collider

Jim Ögren

International Workshop on Future Linear Colliders (LCWS19)
October 28—November 1, 2019
Sendai, Japan

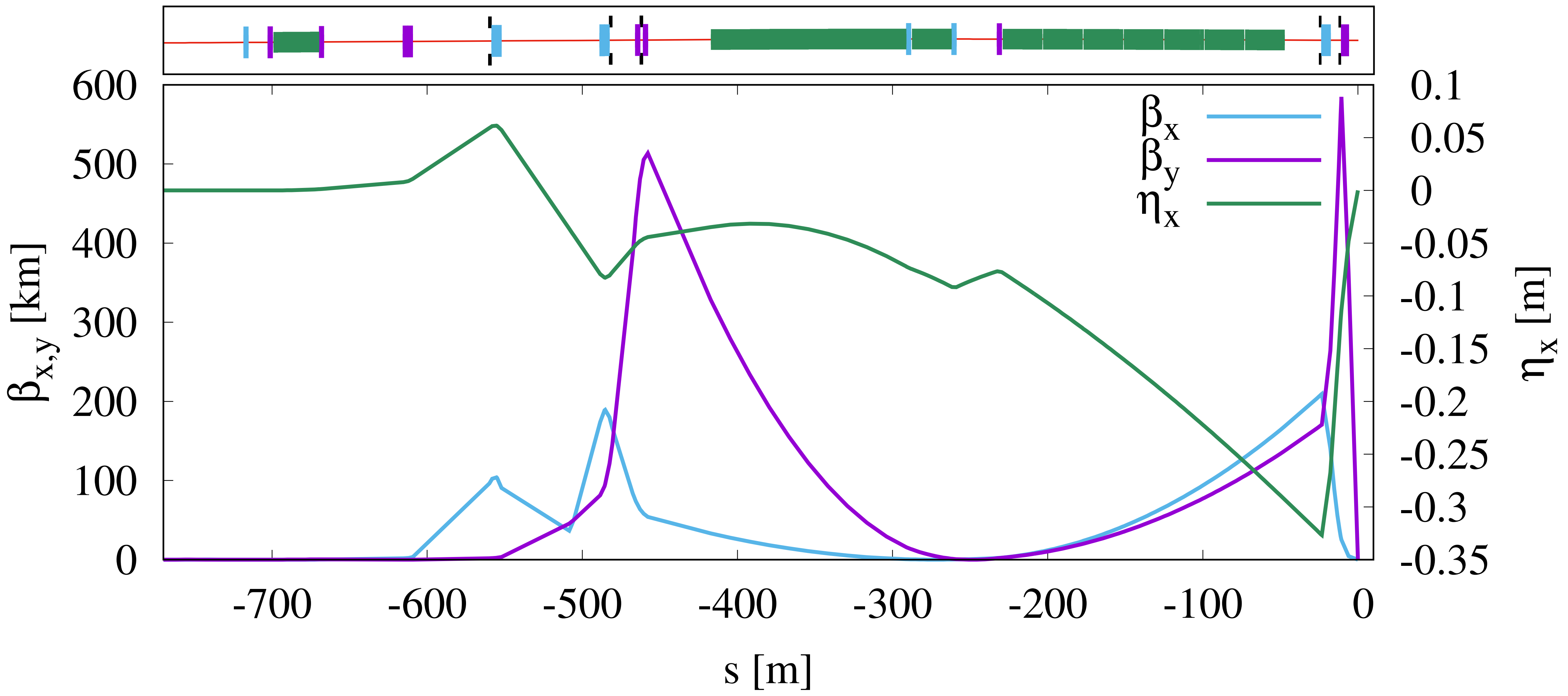
Acknowledgements:
Rogelio Tomás, Andrea Latina, Daniel Schulte

380 GeV final-focus system

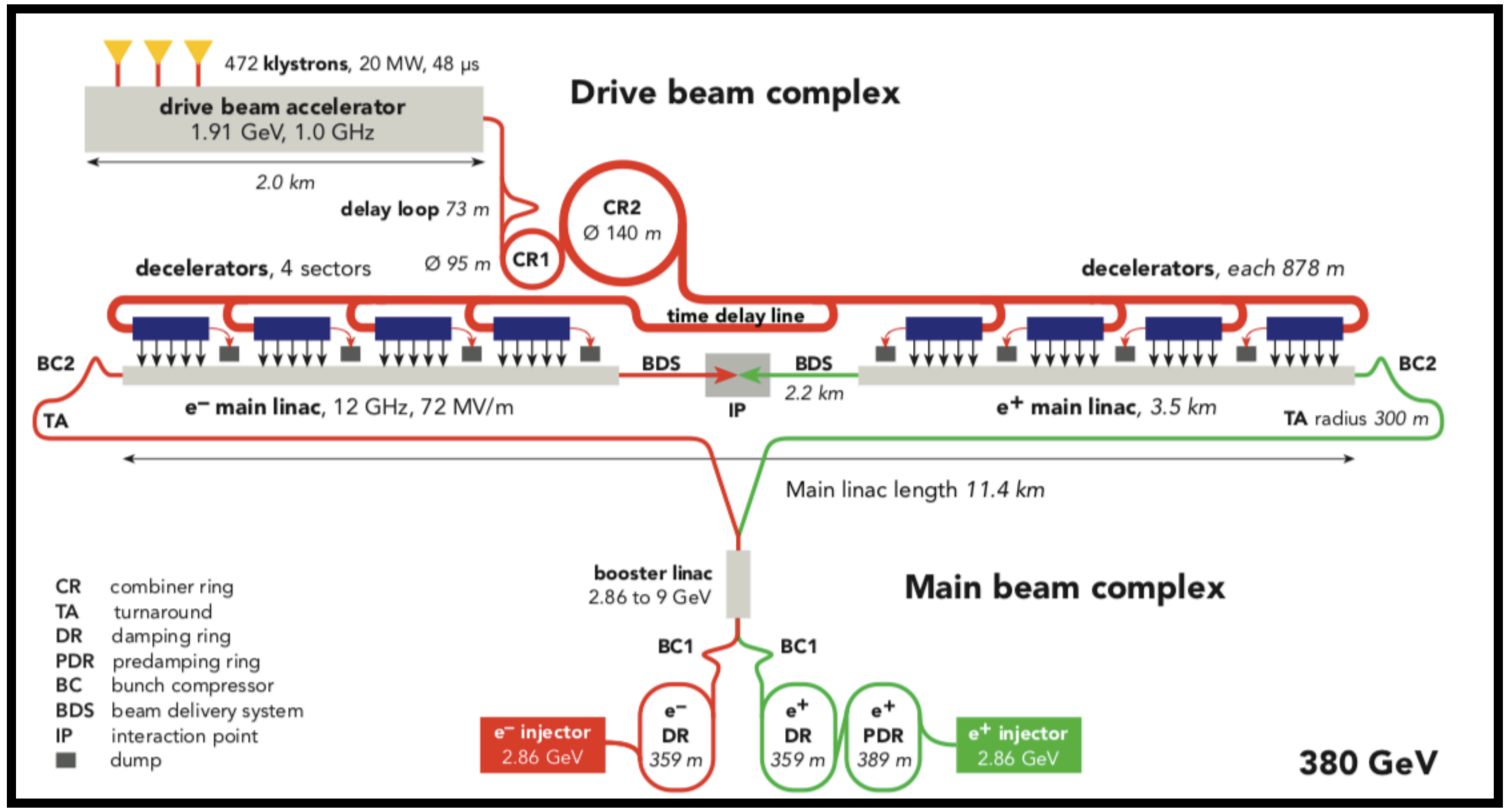


- Local chromaticity scheme
- 780 m long
- 20 quads, 6 sextupoles and 2 octupoles
- 385 m bending magnets
- $L^* = 6$ m

Norm. emittance (end of linac) $\gamma\epsilon_x/\gamma\epsilon_y$	[nm]	900 / 20
Norm. emittance (IP) $\gamma\epsilon_x/\gamma\epsilon_y$	[nm]	950 / 30
Beta function (IP) β_x^*/β_y^*	[mm]	8.2 / 0.1
Target IP beam size σ_x^*/σ_y^*	[nm]	149 / 2.9
Bunch length σ_z	[μm]	70
rms energy spread δ_p	[%]	0.35
Bunch population N_e	[10^9]	5.2
Number of bunches n_b		352
Repetition rate f_{rep}	[Hz]	50
Luminosity $\mathcal{L}_{total}$	[10^{34}cm^{-2}s^{-1}]	1.5
Peak luminosity $\mathcal{L}_{1\%}$	[10^{34}cm^{-2}s^{-1}]	0.9

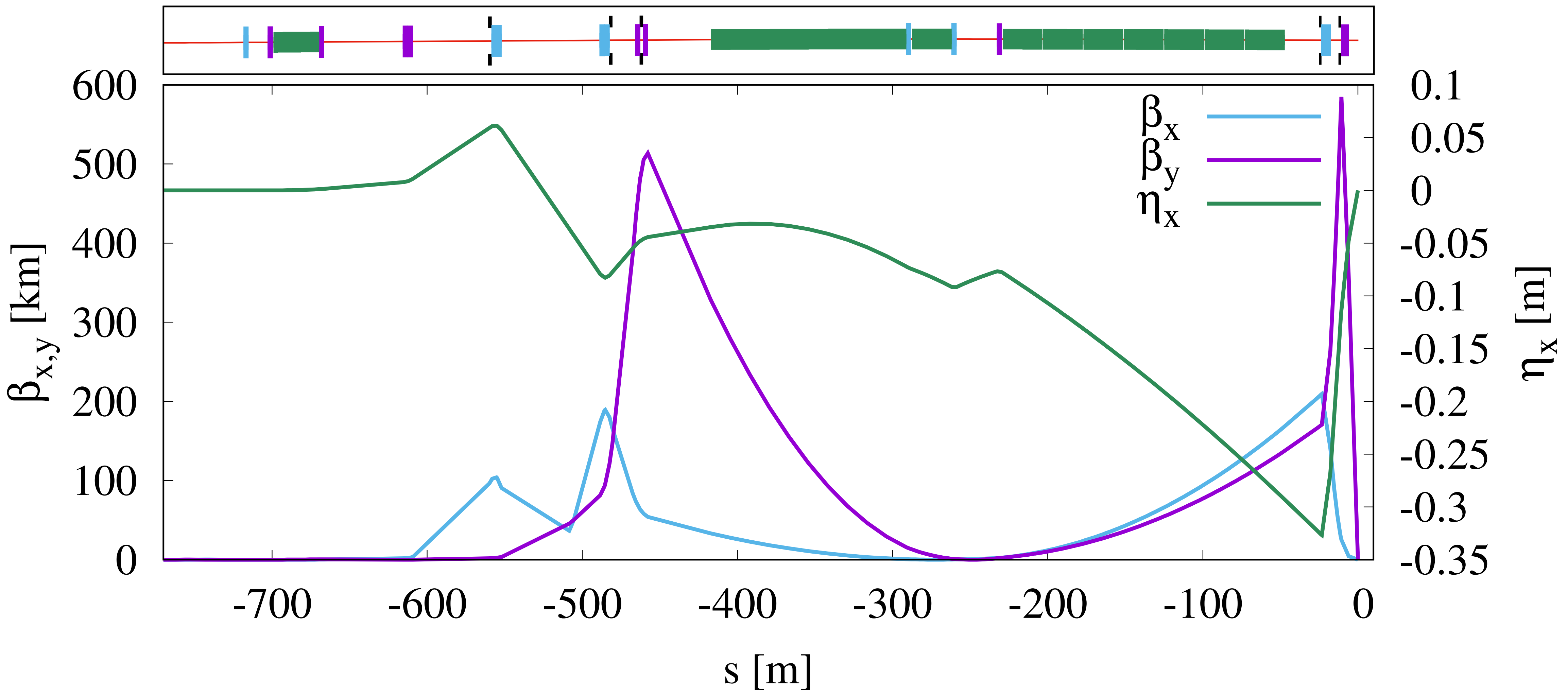


380 GeV final-focus system



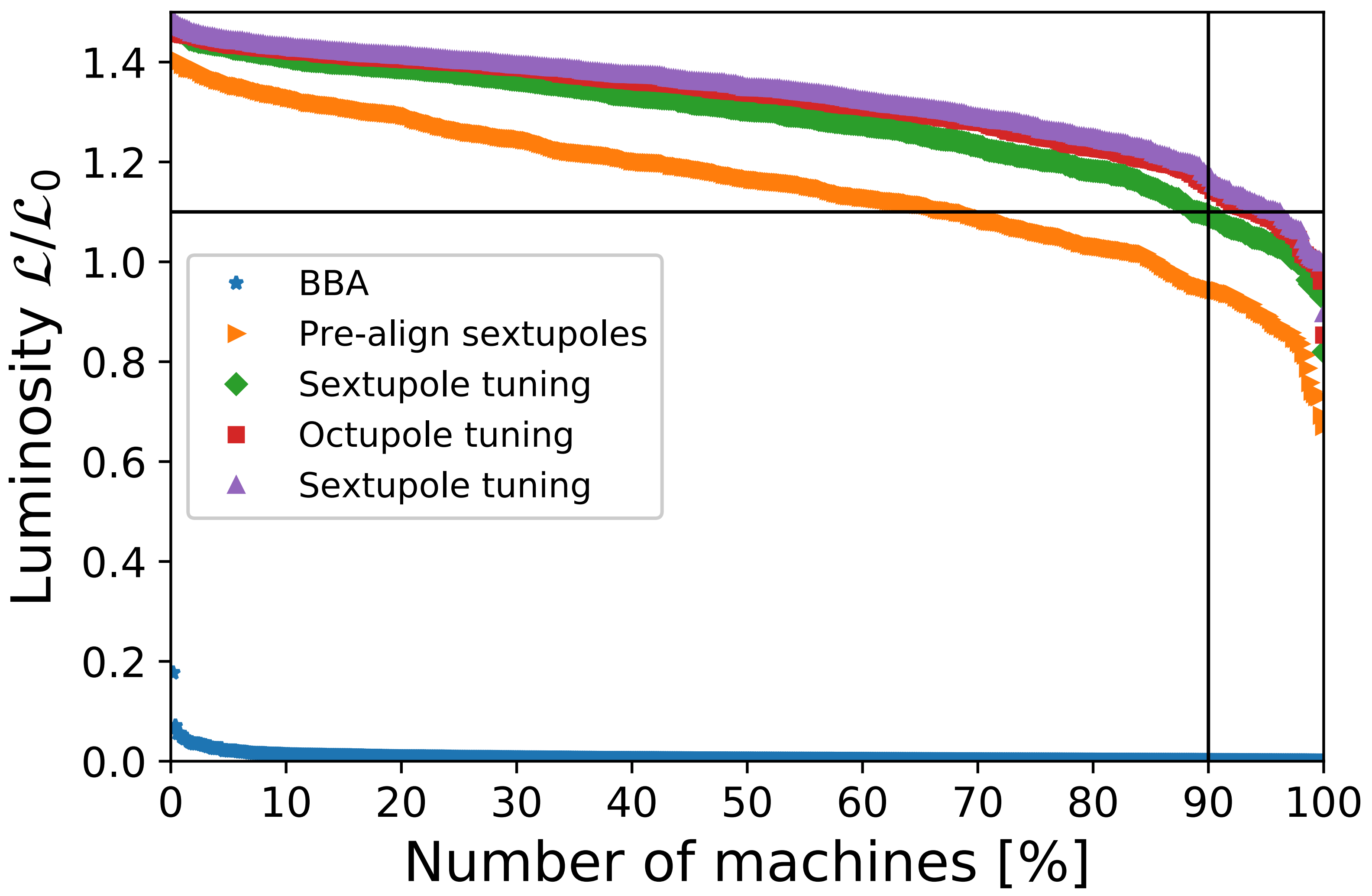
- Local chromaticity scheme
- 780 m long
- 20 quads, 6 sextupoles and 2 octupoles
- 385 m bending magnets
- $L^* = 6$ m

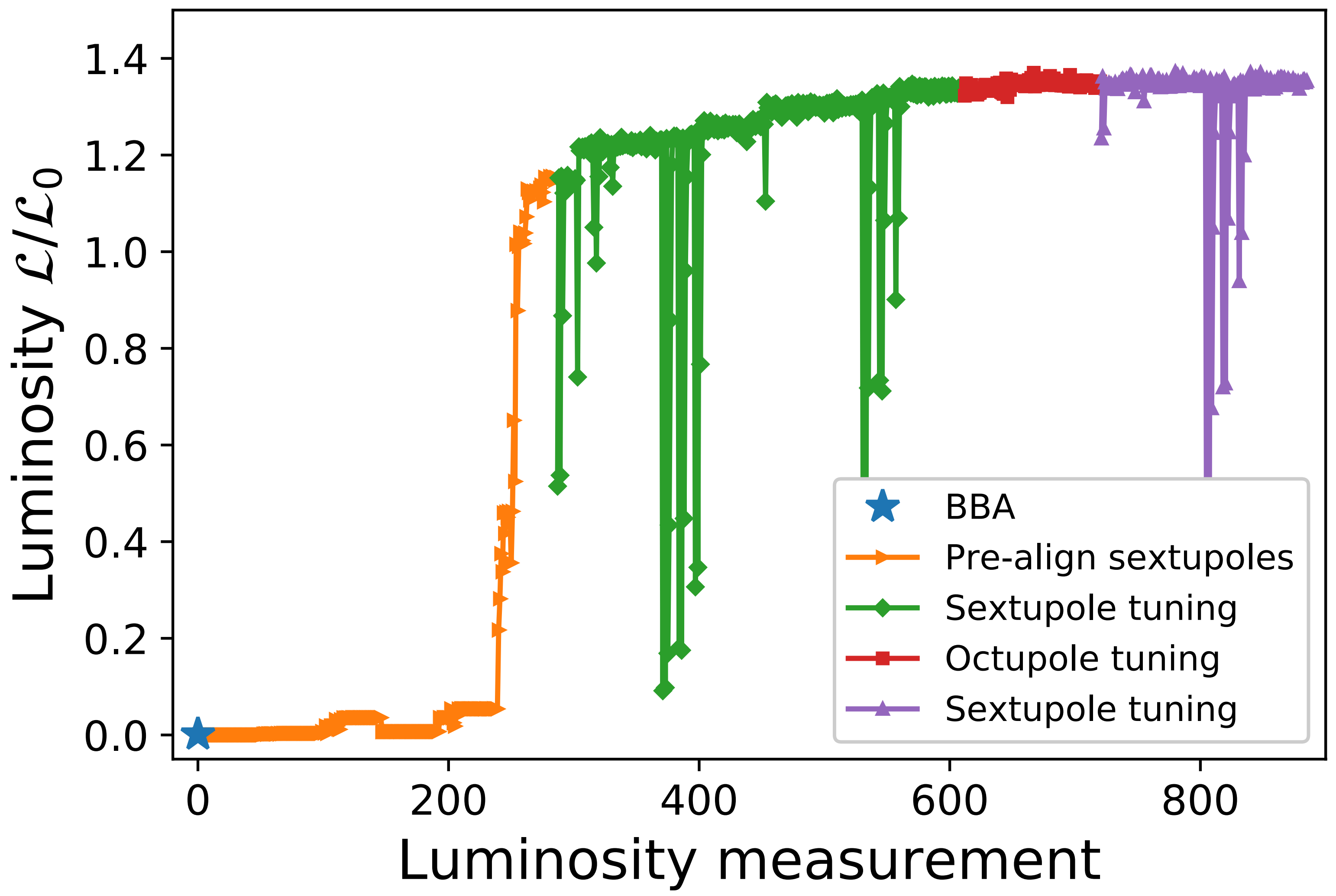
Norm. emittance (end of linac) $\gamma\epsilon_x/\gamma\epsilon_y$	[nm]	900 / 20
Norm. emittance (IP) $\gamma\epsilon_x/\gamma\epsilon_y$	[nm]	950 / 30
Beta function (IP) β_x^*/β_y^*	[mm]	8.2 / 0.1
Target IP beam size σ_x^*/σ_y^*	[nm]	149 / 2.9
Bunch length σ_z	[μm]	70
rms energy spread δ_p	[%]	0.35
Bunch population N_e	[10^9]	5.2
Number of bunches n_b		352
Repetition rate f_{rep}	[Hz]	50
Luminosity $\mathcal{L}_{total}$	[10^{34}cm^{-2}s^{-1}]	1.5
Peak luminosity $\mathcal{L}_{1\%}$	[10^{34}cm^{-2}s^{-1}]	0.9



Previous CLIC 380 GeV FFS Tuning Studies

- One-beam: only half of FFS, beam mirrored at IP
- Tracking in PLACET, beam-beam simulation in GUINEA-PIG
- Static imperfections
- Used luminosity as tuning signal
- Monte Carlo simulation with 500 machines
- 95% was successfully tuned using about 900 luminosity measurements

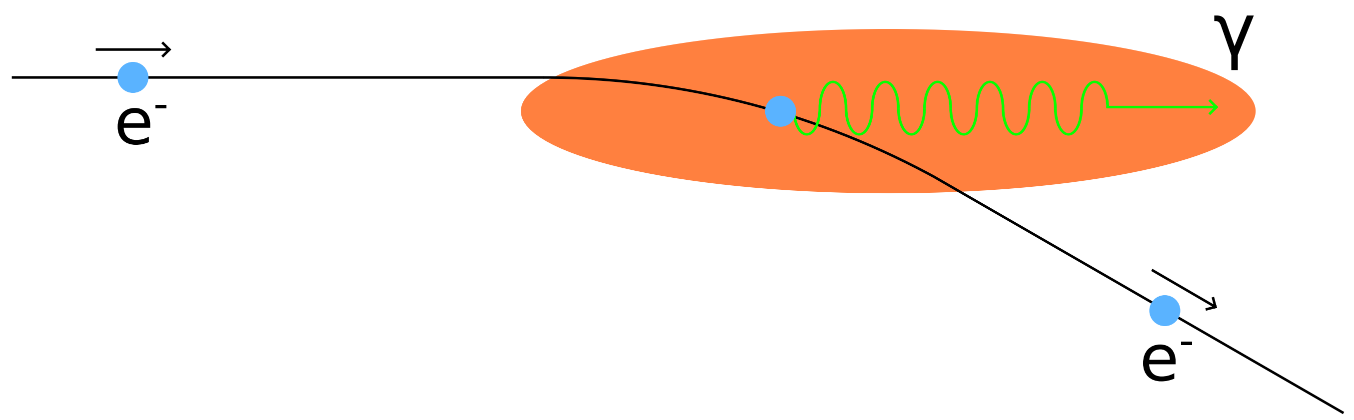




In this study:
- Two-beam tuning
- Using realistic tuning signals

For more information:
J. Ogren, A. Latina, R. Tomas and D. Schulte, *Tuning of the CLIC 380 GeV Final-Focus System with Static Imperfections*, CERN-ACC-2018-0055, CLIC-Note-1141.

Beamstrahlung

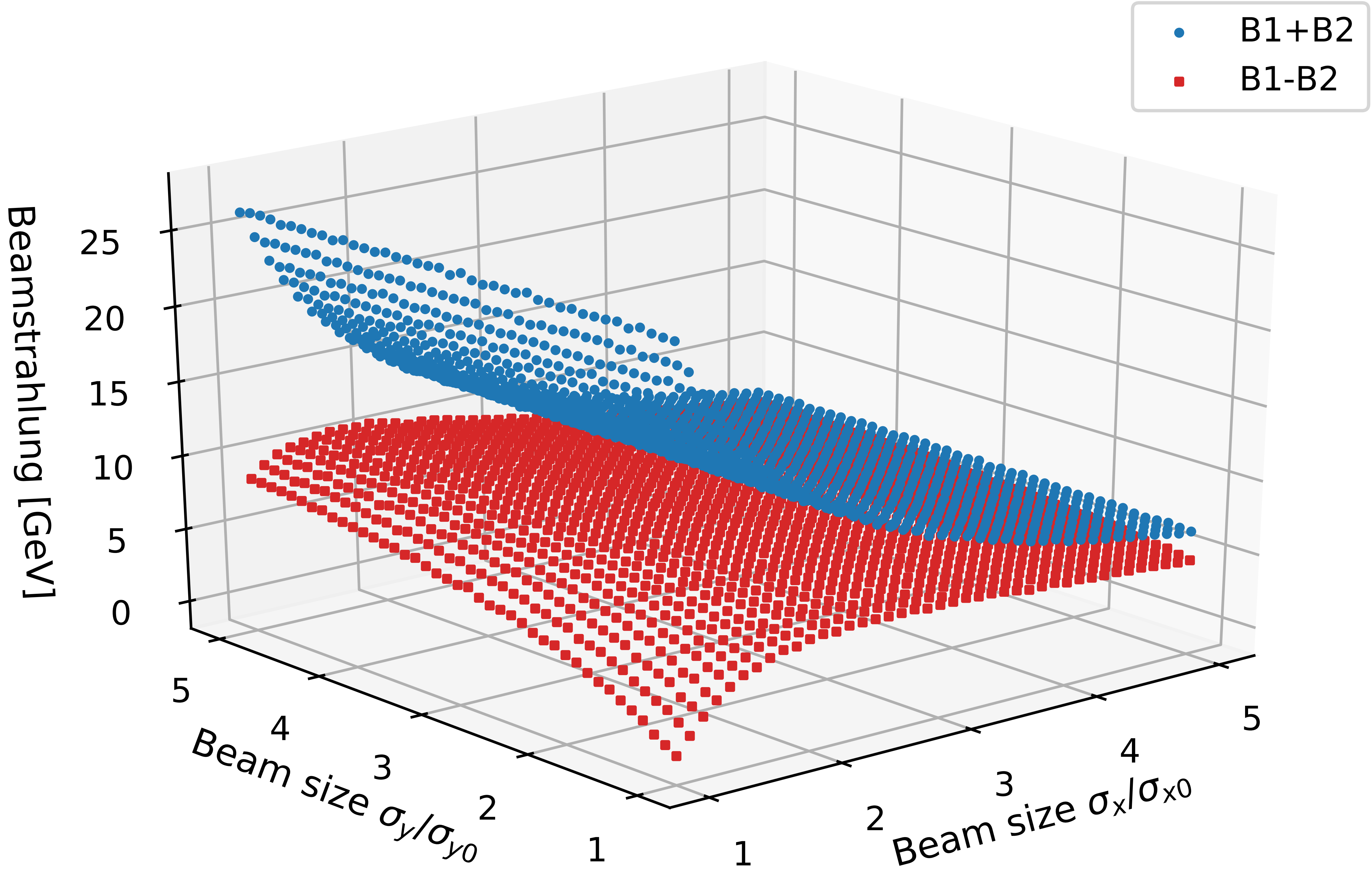


Particles in the one beam are bent by the EM fields from the other beam during collision and emits synchrotron radiation.

$$n_\gamma \propto \frac{N}{\sigma_x + \sigma_y}$$

$$E_\gamma \propto \frac{N}{(\sigma_x + \sigma_y)\sigma_z}$$

$$\mathcal{L} \propto \frac{N^2}{\sigma_x \sigma_y}$$



Number of photons and photon energy is proportional to $1/(\sigma_x + \sigma_y)$ and Luminosity $1/\sigma_x\sigma_y$

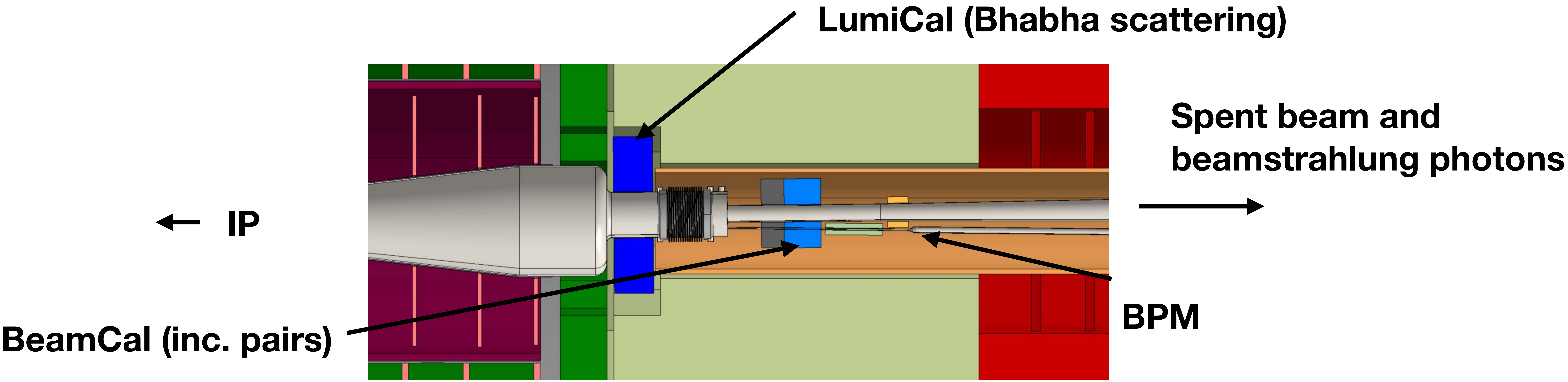
Total beamstrahlung power: good signal for horizontal beam size

Power asymmetry can give information about beam size differences

Cherenkov detectors: measure muons generated from photon interactions in the water dump

The BeamCal

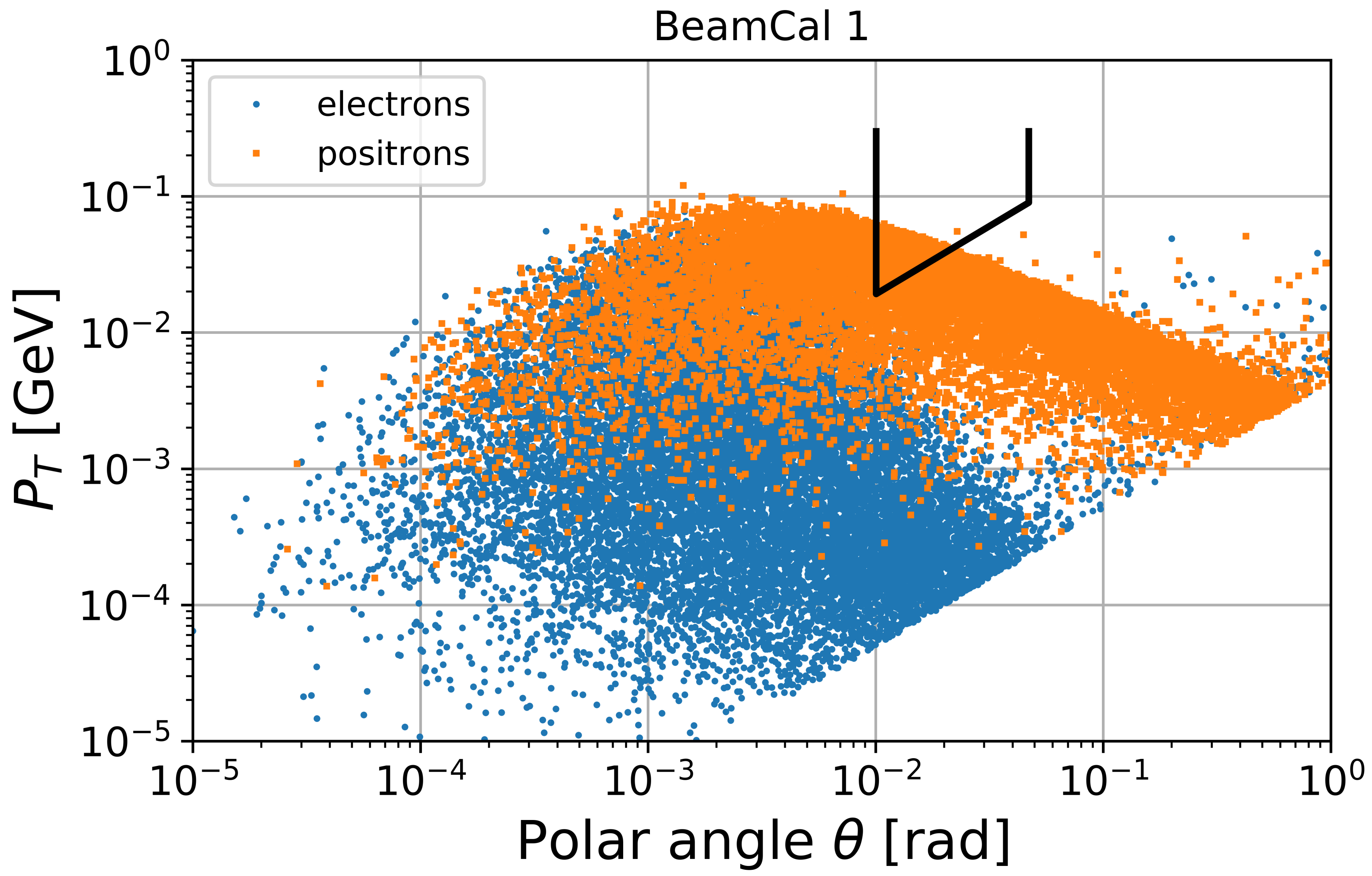
Incoherent e^-e^+ pairs:
In the beam-beam interaction e^-e^+ pairs are produced via scattering of beam particles and/or beamstrahlung photons

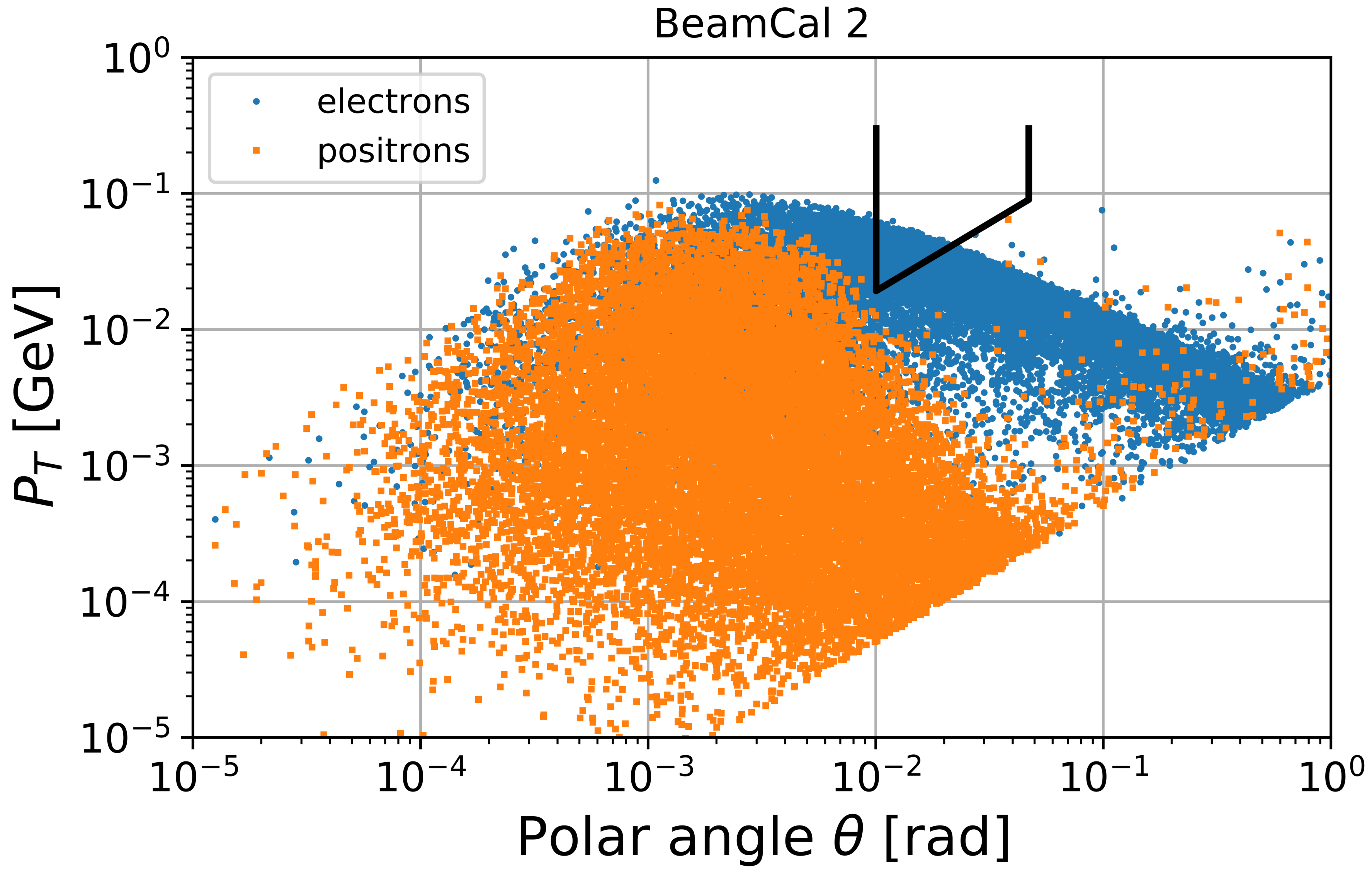


	Z_{start} [mm]	Z_{end} [mm]	R_{in} [mm]	R_{out} [mm]	θ_{min} [mrad]	θ_{max} [mrad]
LumiCal	2539	2710	100	340	39	134
BeamCal	3181	3441	32	150	10	46

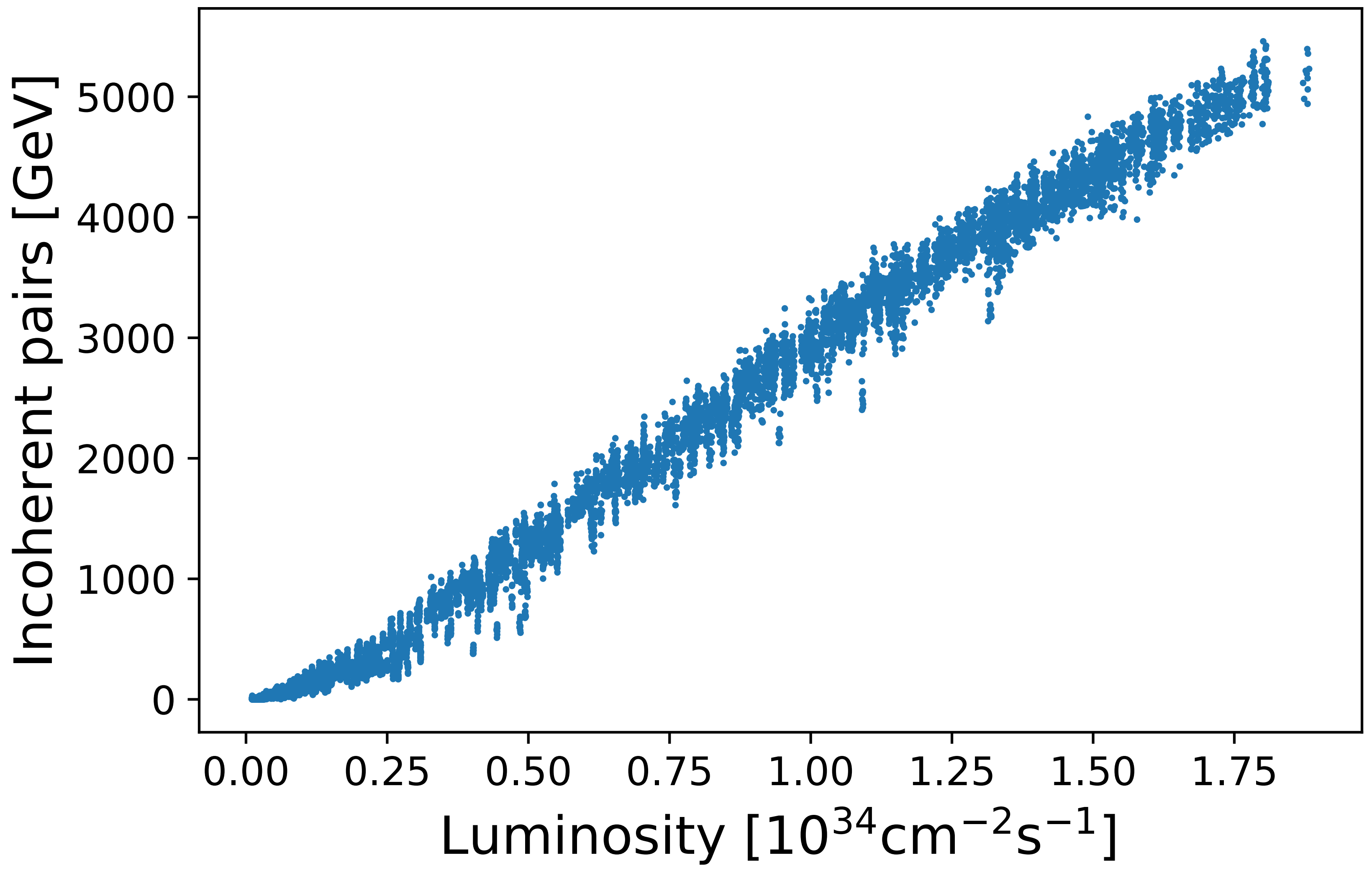
Incoherent pairs in BeamCal

- Compute and track pairs in GUINEA-PIG
  - deflection from EM fields of beam, use 7 grids
  - Computationally intensive
- Make cut in p_T—θ plane
  - Particles with correct angles and high enough energy
  - Total energy of ~6000 GeV/bunch-crossing



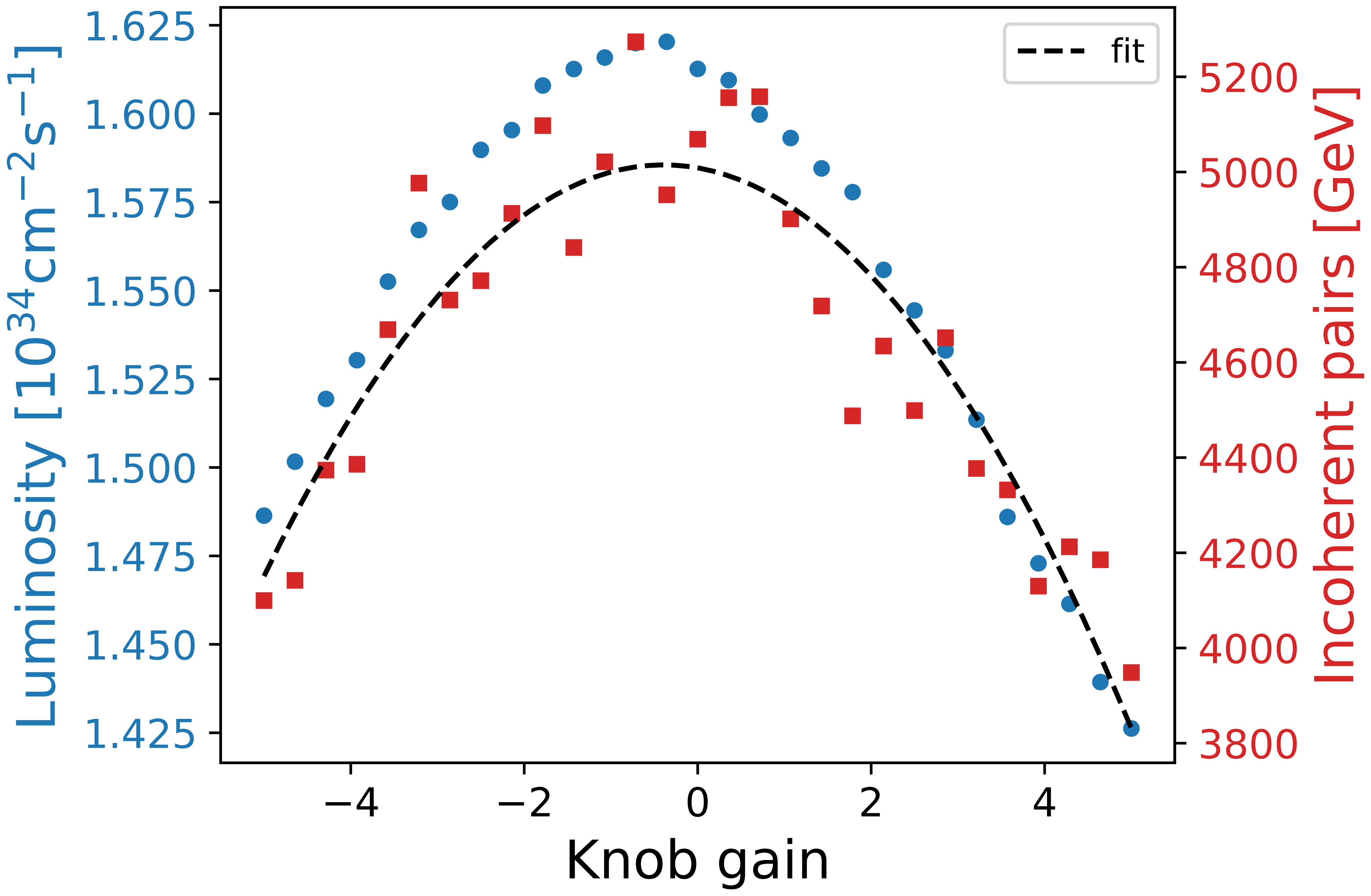


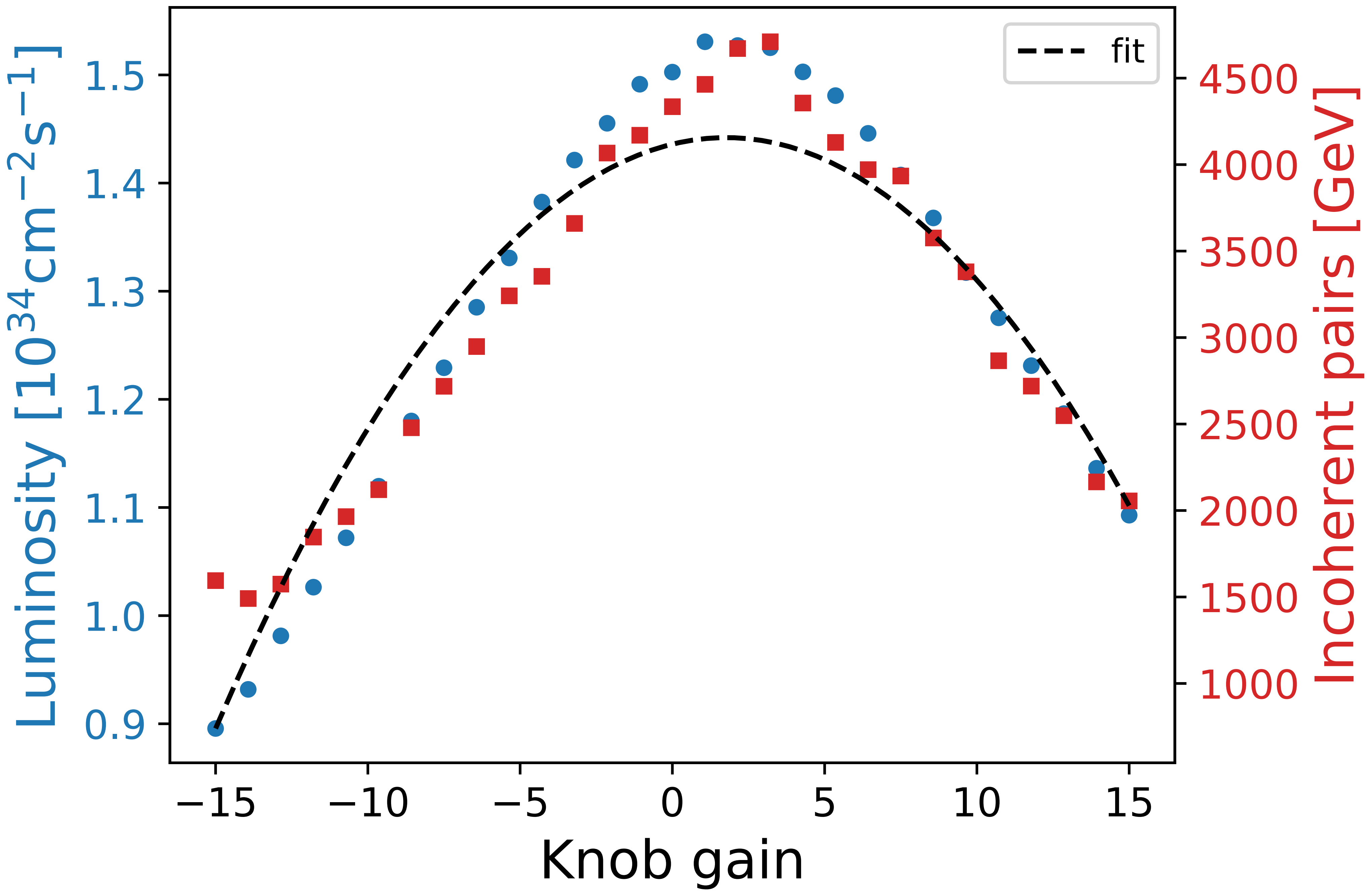
- Luminosity vs. inc. pairs
  - 1000 cases, 10 simulation per case
  - Linear correlation but noisy



Dealing with noise

Example scan of sextupole knobs





- Use mainy points (29 in this case) and make single parabolic fit
  - Previously parabolic minimizer on luminosity signal
  - Computationally beneficial: generate the points in parallel
- Scan over a sufficient range
- Seems robust

Simulation: tuning with static imperfections

Imperfection	Specified tolerance (rms error)	Elements
Resolution	20 nm	BPMs
Transverse misalignments	10 μm (20 μm)	BPMs, all magnets (multipoles)
Roll errors	100 μrad	BPMs, all magnets
Relative strength error	10^{-4}	All magnets

In this study:

- Seed of 500 machines
- Use tolerances as rms
- Assume ideal feedback and head-on collisions

Monte Carlo simulations:

- Generate machines with random imperfections
- Luminosity goal: 110% of $L_0 = 1.5e34\ cm^{-2}s^{-1}$
- Tuning goal: 90% of machines to be successfully tuned

Simulation: tuning with realistic signals

1) Beam-based alignment

- Treat electron and positron beamlines independently
- Correct trajectory and dispersion simultaneously

2) Maximize beamstrahlung power

- Maximize total beamstrahlung power (sum of two beamlines)
- Sextupole transverse position, random walk
- Tunes mainly horizontal beam size

3) Maximize total energy in inc. pairs

- Sextupole transverse position, random walk
- Tunes mainly vertical beam size

4) Sextupole knobs

- Scan sextupole knobs (transverse position)
- Maximize energy deposited from inc. pairs in BeamCal
- Use 2e4 particles and then 1e5 particles for fine tuning

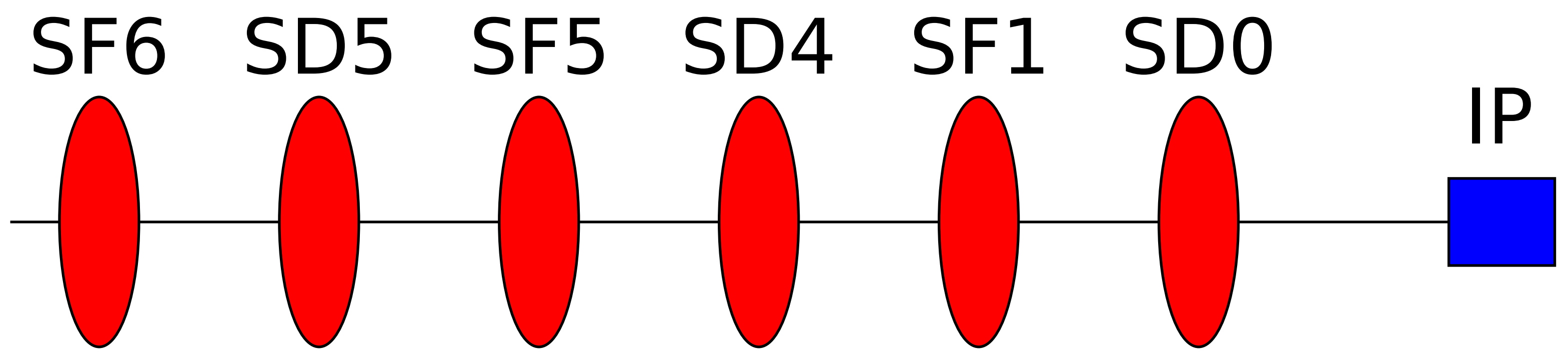
5) Quadrupole and Sextupole tuning

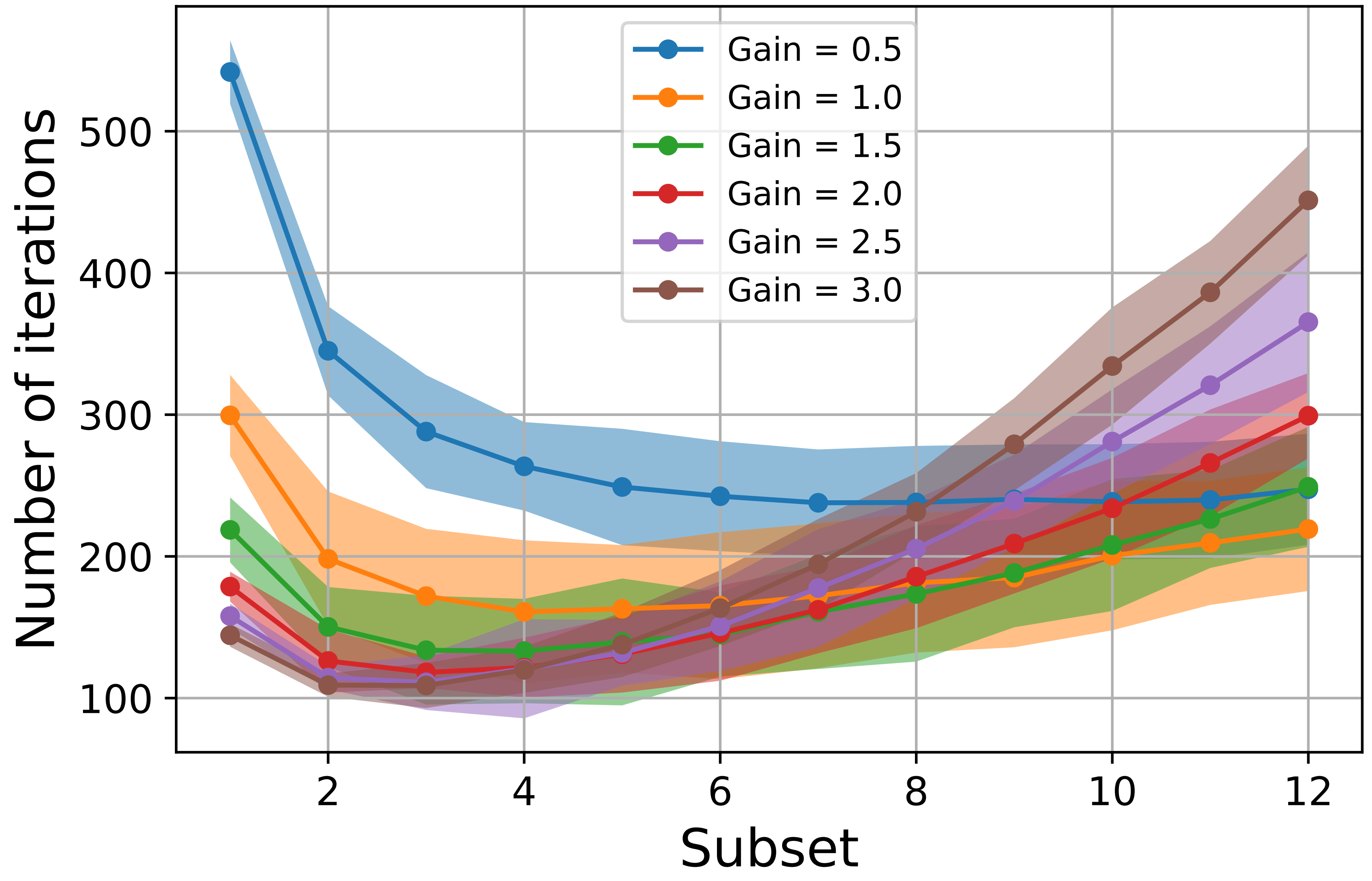
- Random walk moving quadrupoles and sextupoles together (if needed)
- Followed by sextupole knob scan

Random walk

Random walk algorithm for sextupole transverse position

- Randomly select which beamline to tune
- Select a random subset (e.g. 6 out of 12 DOF)
- Select a random direction for that subset
- Perform a short scan: 7 points, single parabolic fit (parallel execution)
- Select point that optimizes signal
- Iterate

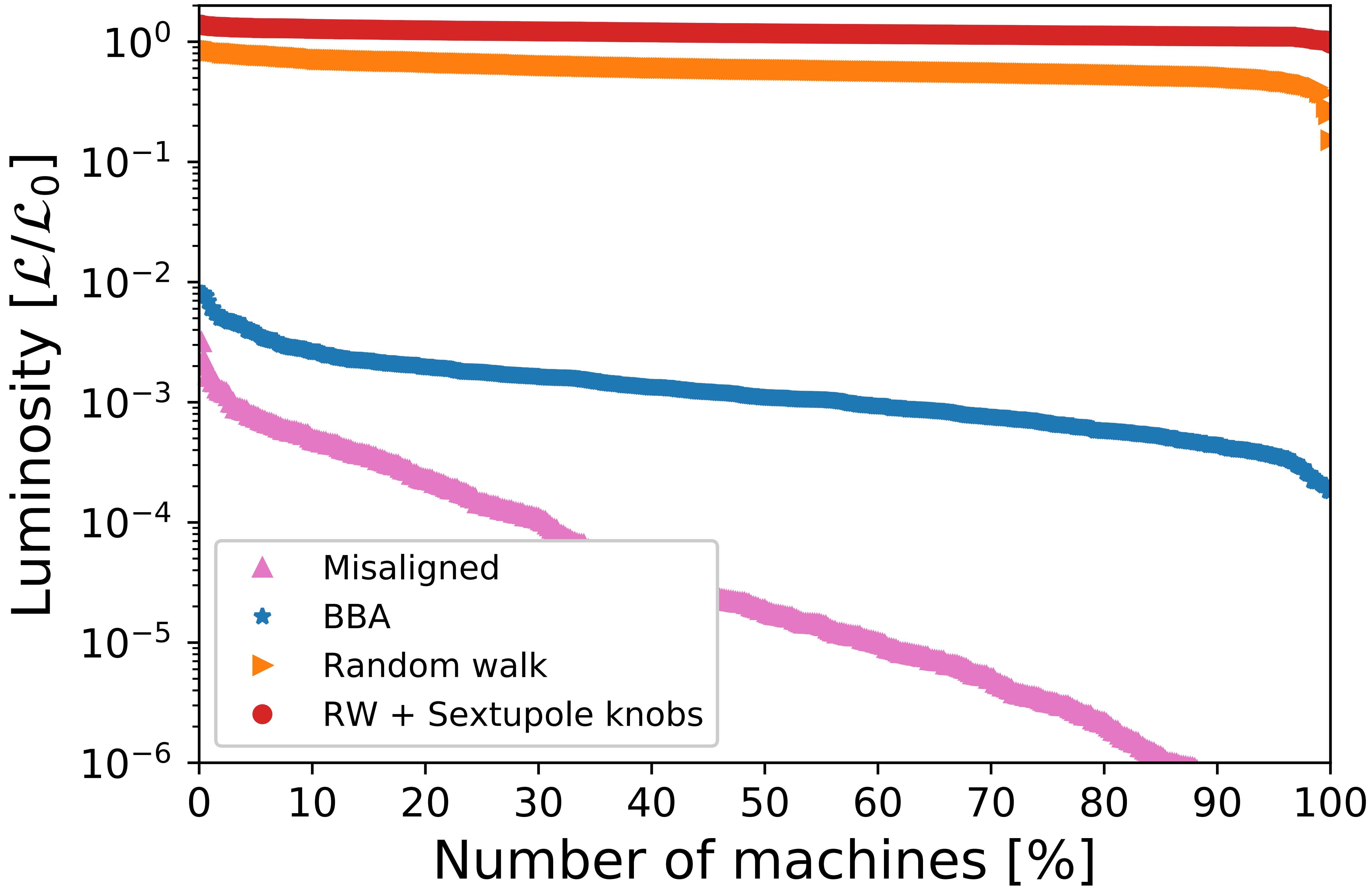




Optimizing hyperparameters using Machine Learning.

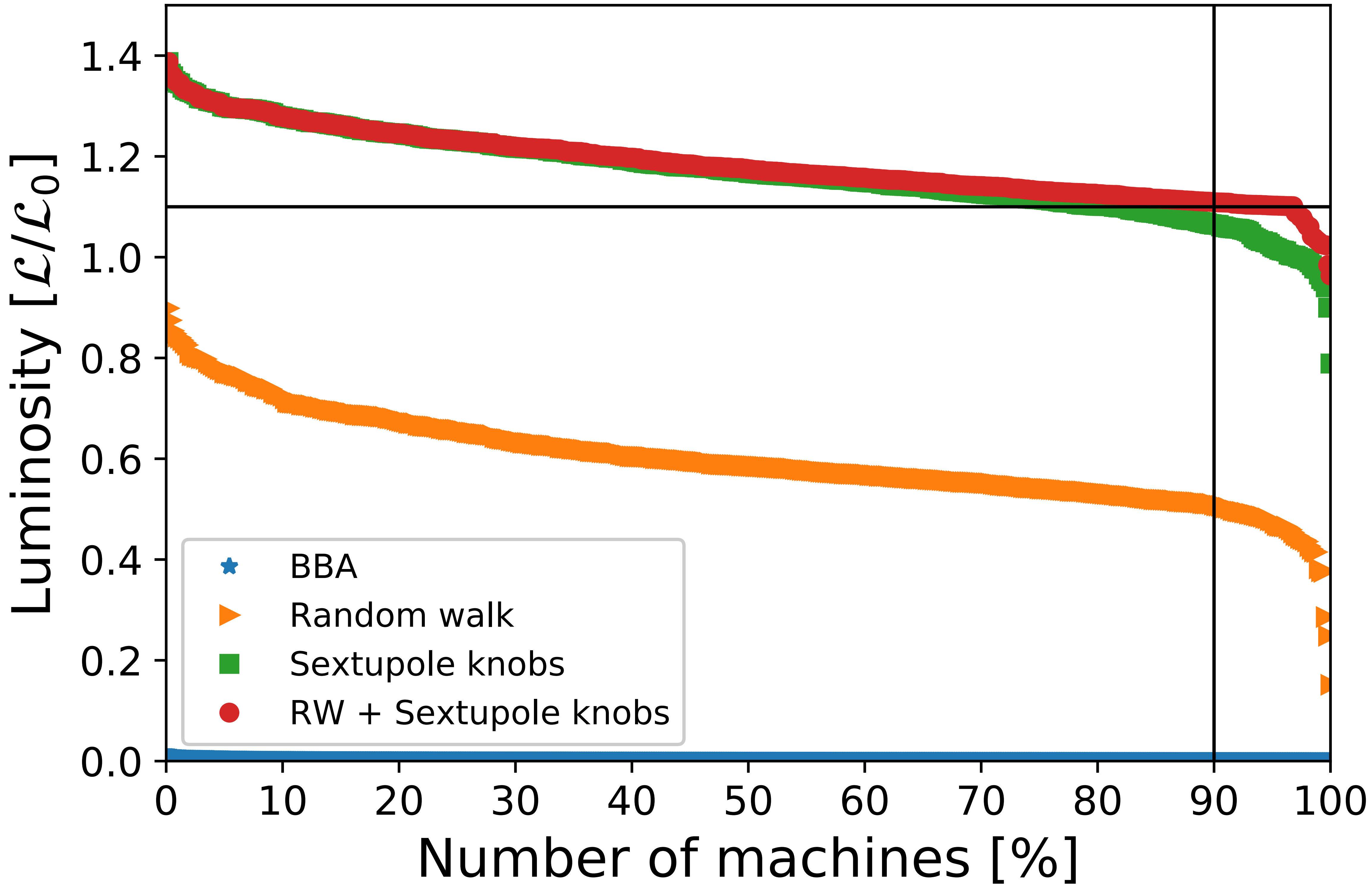
See talk on Wed

Results: Luminosity histogram



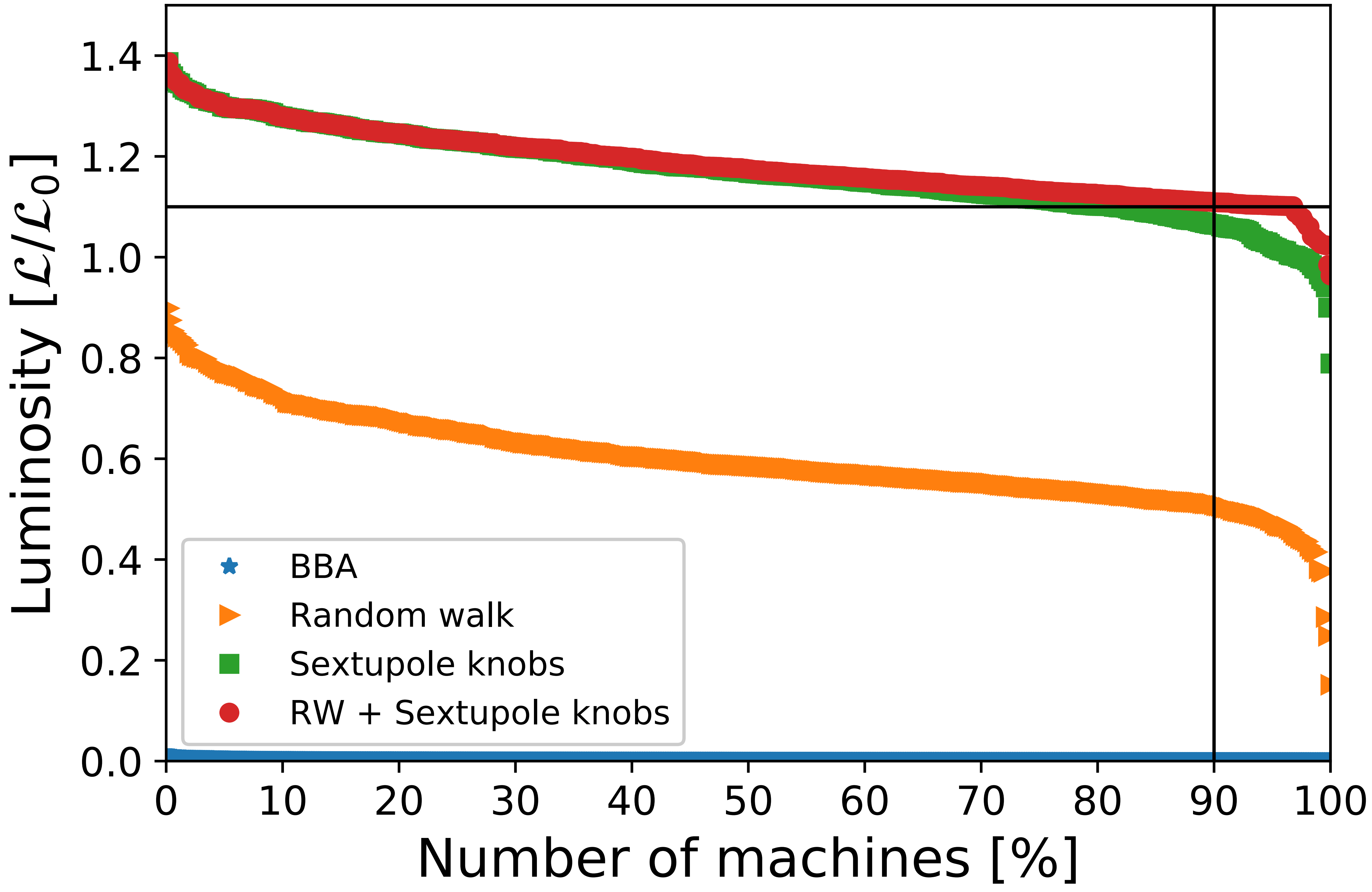
- Misaligned machine: 3-8 orders of magnitude from nominal luminosity
- After BBA: 2-4 orders of magnitude
- Random walk (beamstrahlung and pairs): within 10% of nominal luminosity

Results



- 500 machines
- After sextupole knobs: 406 machines reached target
- Untuned machines. Repeated scans of sextupole knobs unsuccessful
- Solution: Quadrupole and sextupole random walk tuning followed by sextupole knobs

Results



- 500 machines
- After sextupole knobs: 406 machines reached target
- Untuned machines. Repeated scans of sextupole knobs unsuccessful
- Solution: Quadrupole and sextupole random walk tuning followed by sextupole knobs

Final results: 484 machines successfully tuned

484/500 = **96.8% success rate**

Quadrupole and sextupole random walk

The problem:

- Quadrupoles influences the linear optics: e.g. phase advances between sextupoles and dispersion at sextupole locations
- For a given linear optics sextupole offsets can compensate many effects
- What if the linear optics is not corrected well enough?
- Scanning sextupole knobs gives same (sub-) optimum
- Moving quadrupoles will only worsen luminosity
- Solution: quadrupoles and sextupoles together: **achieve similar but different scenario**

Quadrupole and sextupole random walk

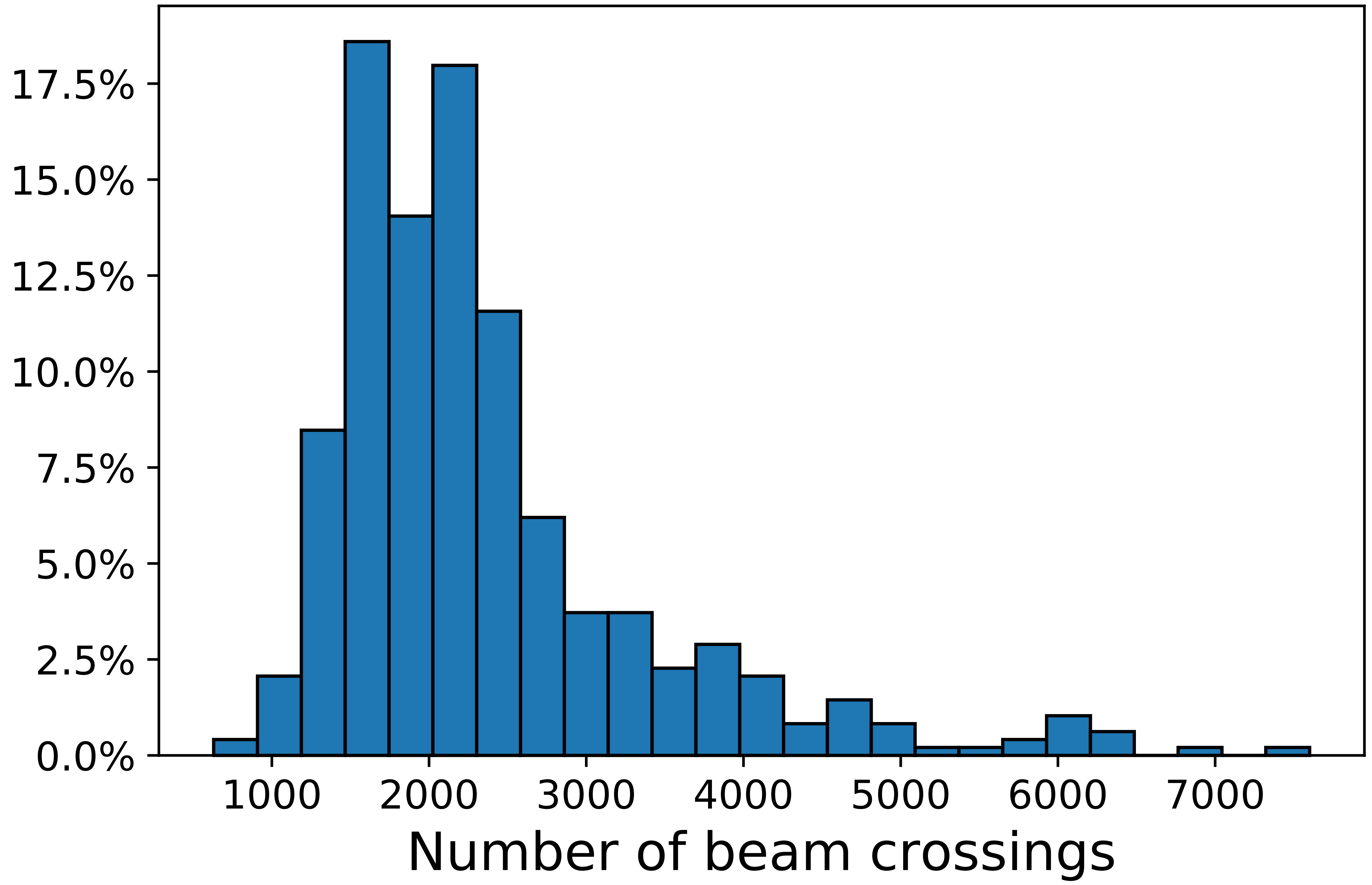
The problem:

- Quadrupoles influences the linear optics: e.g. phase advances between sextupoles and dispersion at sextupole locations
- For a given linear optics sextupole offsets can compensate many effects
- What if the linear optics is not corrected well enough?
- Scanning sextupole knobs gives same (sub-) optimum
- Moving quadrupoles will only worsen luminosity
- Solution: quadrupoles and sextupoles together: **achieve similar but different scenario**

Random walk algorithm quadrupoles and sextupoles

- Randomly select beamline to tune
- Select a random subset (e.g. 30 out of 52 DOF)
- Select a random direction for that subset
- Perform a short scan: 7 points, single parabolic fit (parallel execution)
- Select point that optimizes signal
- Iterate

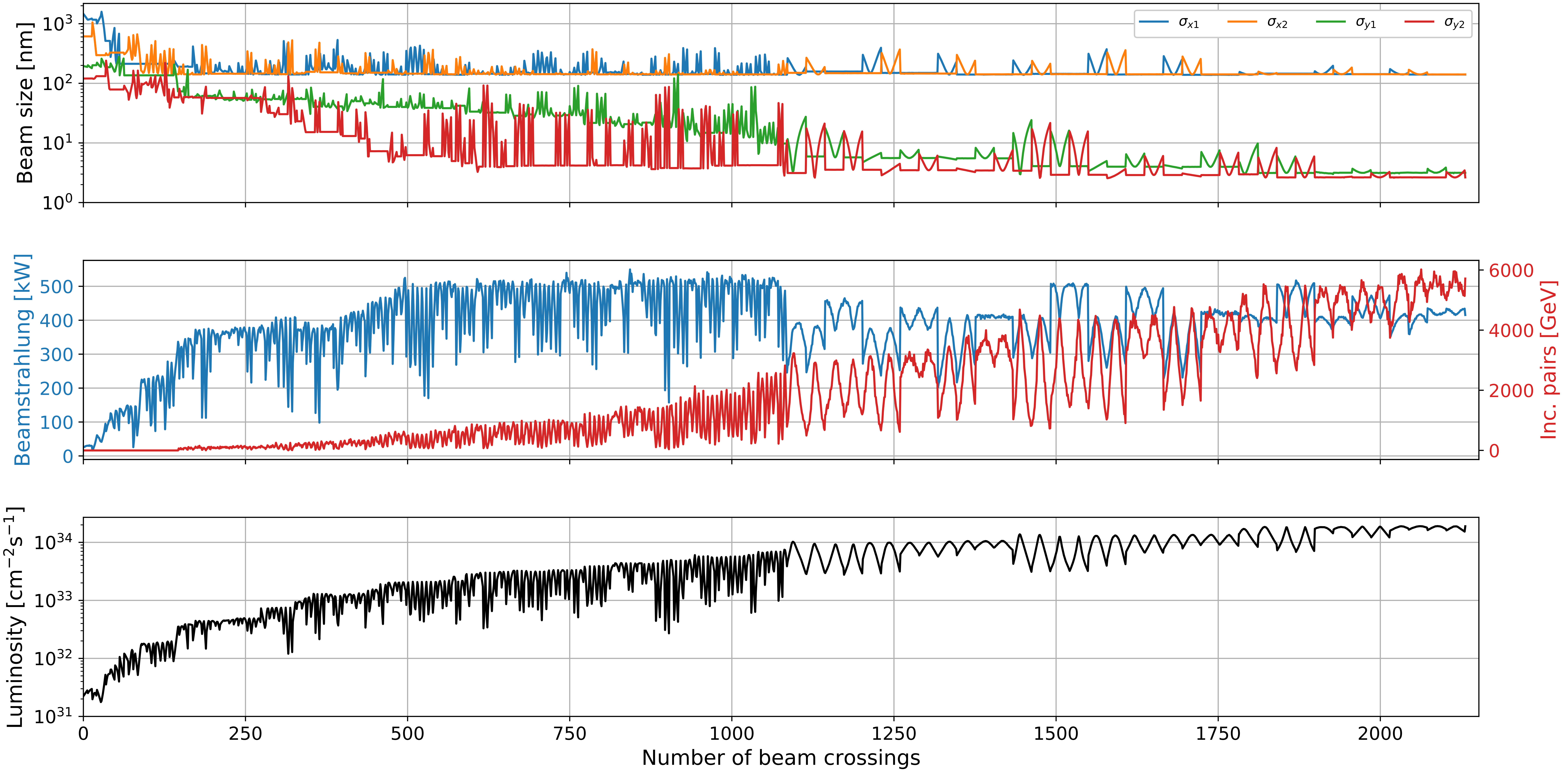
Tuning time



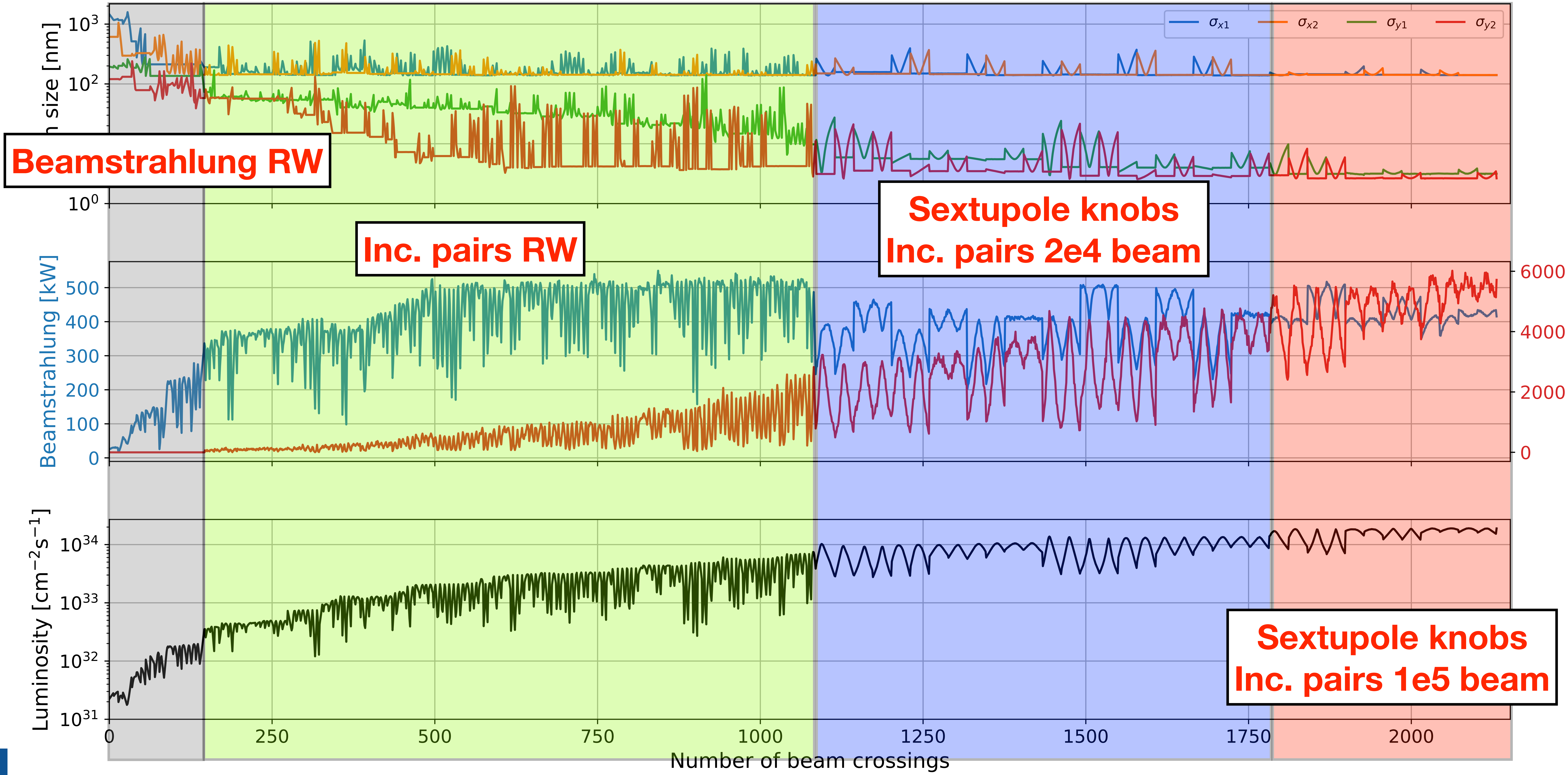
N_{min}	630
N_{max}	7601
N_{mean}	2371
N_{median}	2104

- Median number of iterations = 2104
- Close to 2x900 (one-beam tuning)
- Room for improvement

Tuning evolution of median machine



Tuning evolution of median machine



Low β_y lattice

Updated lattice for the CLIC 380 GeV

- Vertical beta function at IP was reduced from 100 μm to 70 μm
- See: A. Pastushenko: "A New FFS at CLIC 380 GeV," *this workshop.*

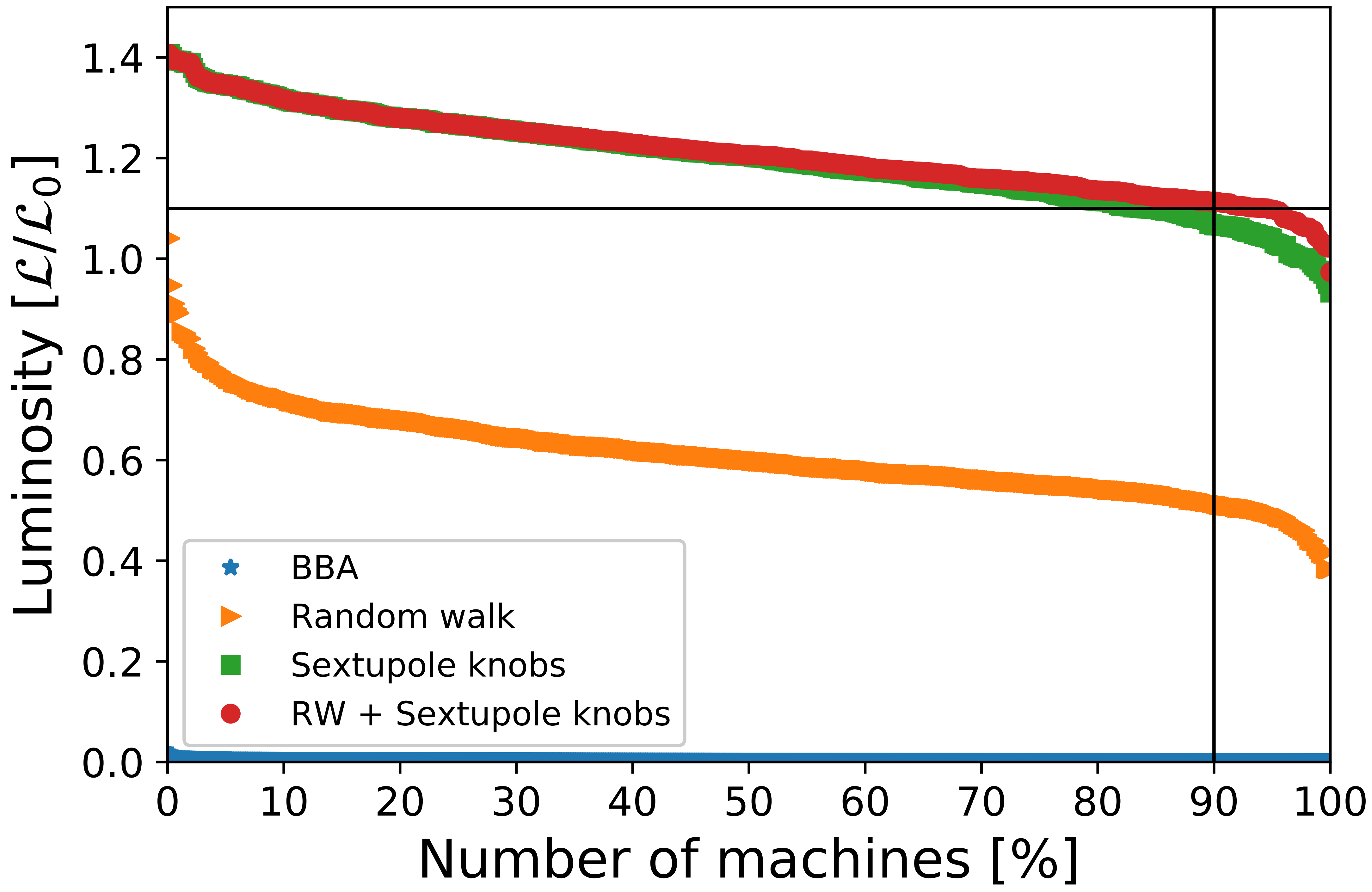
Tested same tuning procedure on new lattice

Low β_y lattice

Updated lattice for the CLIC 380 GeV

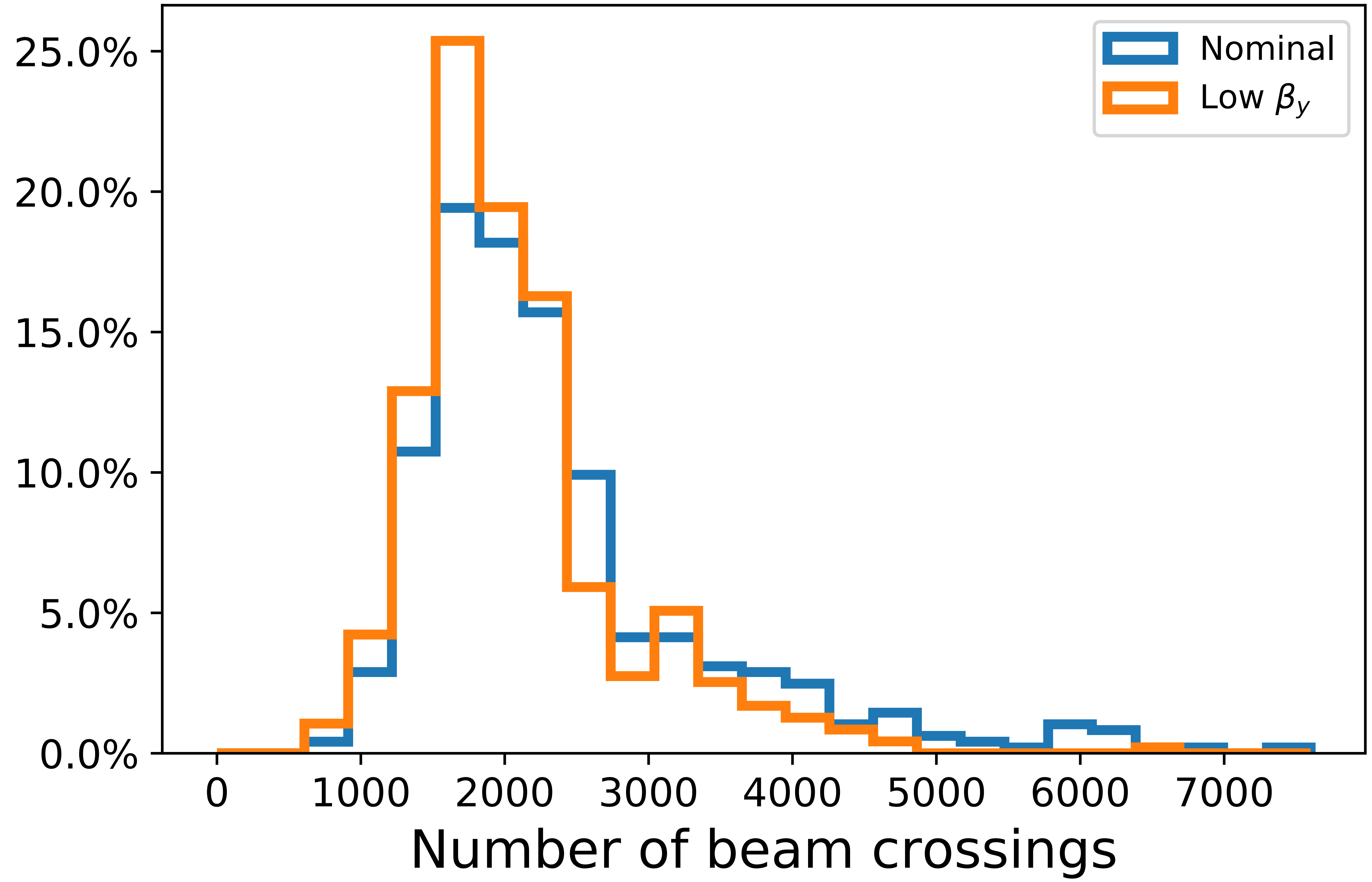
- Vertical beta function at IP was reduced from 100 µm to 70 µm
- See: A. Pastushenko: ”A New FFS at CLIC 380 GeV,” *this workshop.*

Tested same tuning procedure on new lattice



- Results very similar to nominal lattice
- Final result: **94.6 % successfully tuned**
- But tuning time was slightly lower

Comparing tuning times



	Nominal	Low βy
N_{min}	630	686
N_{max}	7601	6392
N_{mean}	2371	2081
N_{median}	2104	1900

- Low *βy* tunes slightly faster
- More luminosity overhead
- Random walk, limited sample size

Effects of ground motion

Apply ATL ground motion to both beamlines of a tuned machine

Recover luminosity

1-2-1 steering:

- Restore previous beam trajectory
- About 120 shots per beamline

Sextupole knob scan:

- 2 iterations
- 90 beam crossings per beamline and iteration

Effects of ground motion

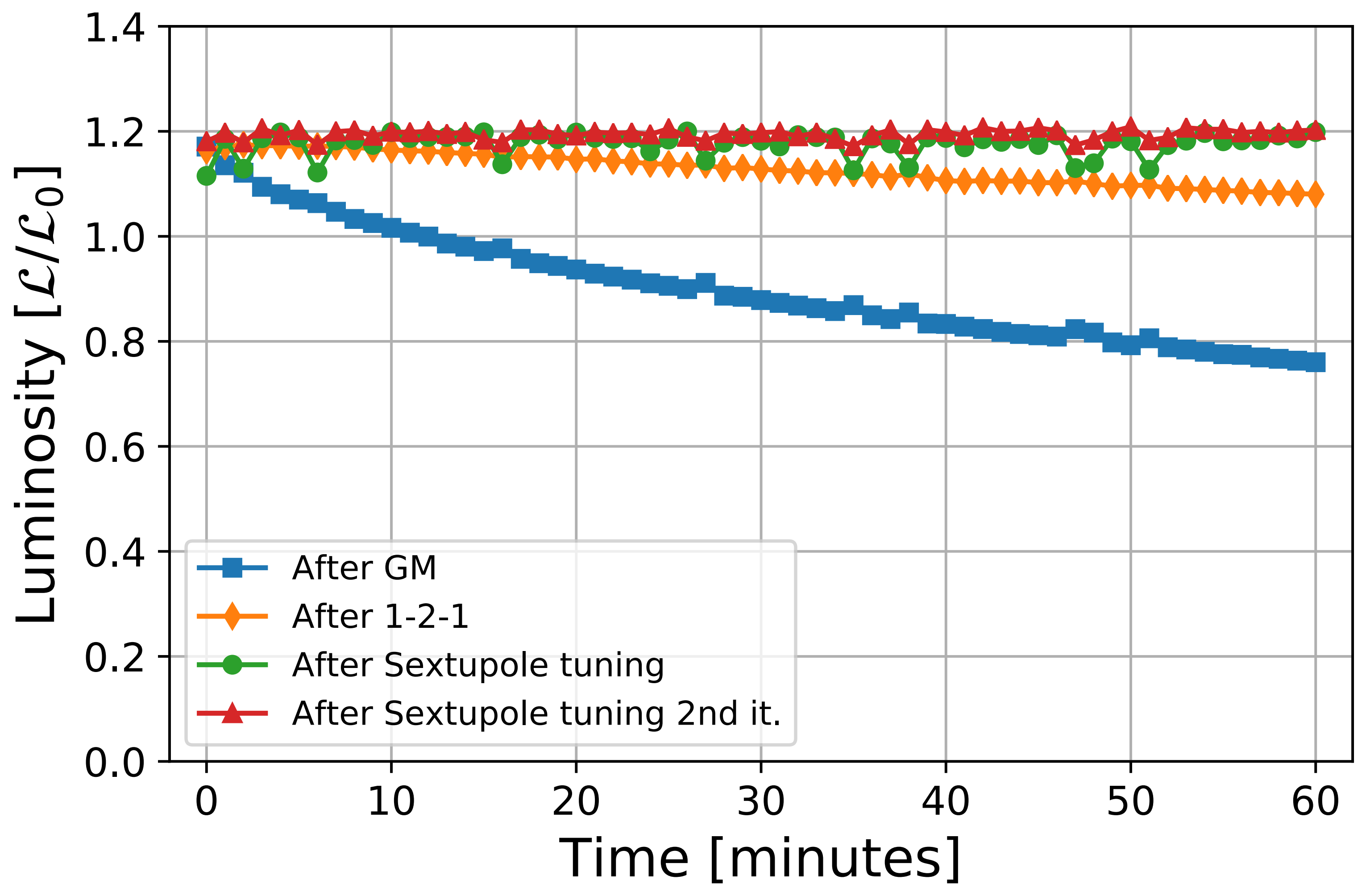
Apply ATL ground motion to both beamlines of a tuned machine

Recover luminosity

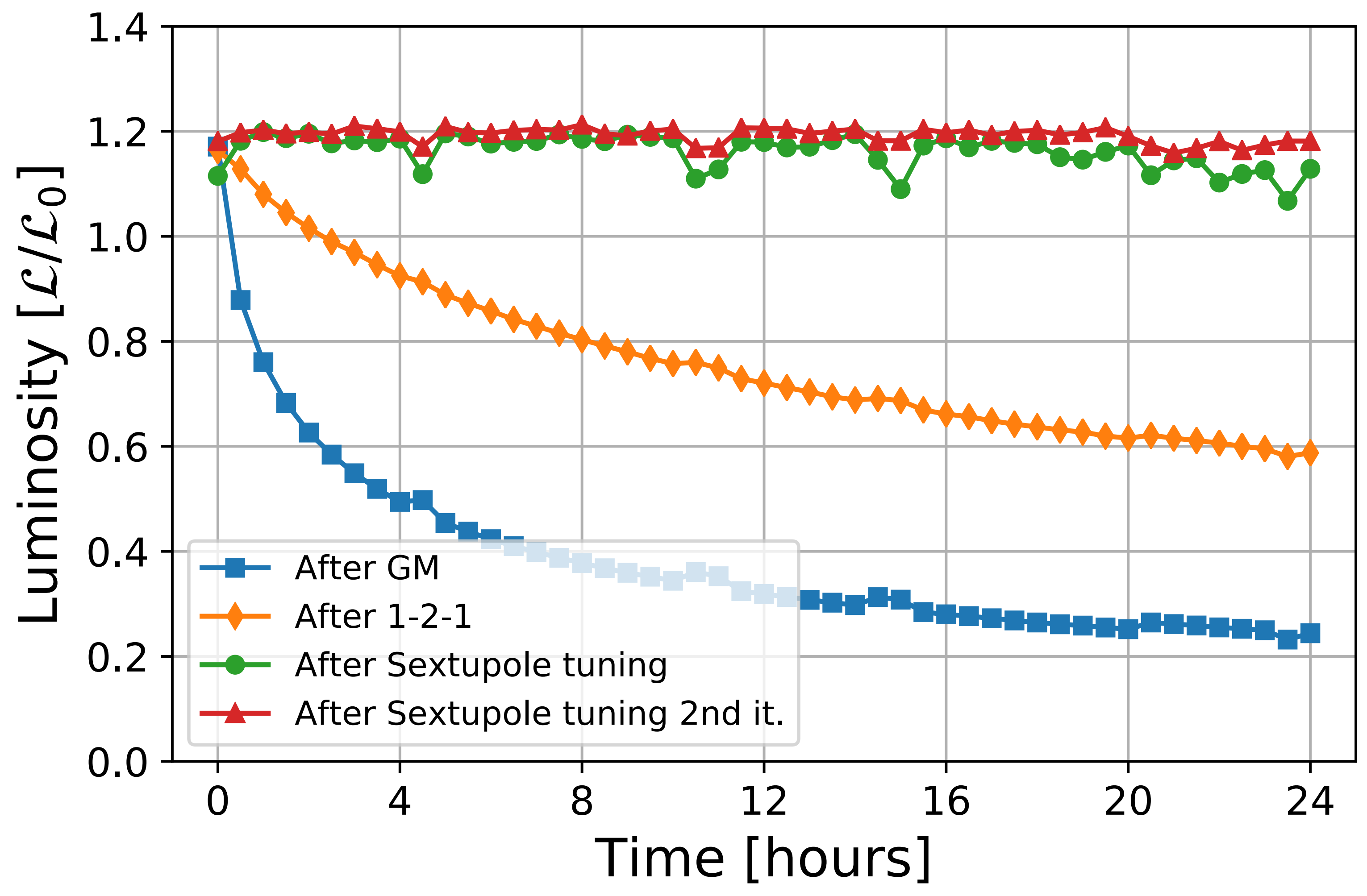
1-2-1 steering:
- Restore previous beam trajectory
- About 120 shots per beamline

Sextupole knob scan:
- 2 iterations
- 90 beam crossings per beamline and iteration

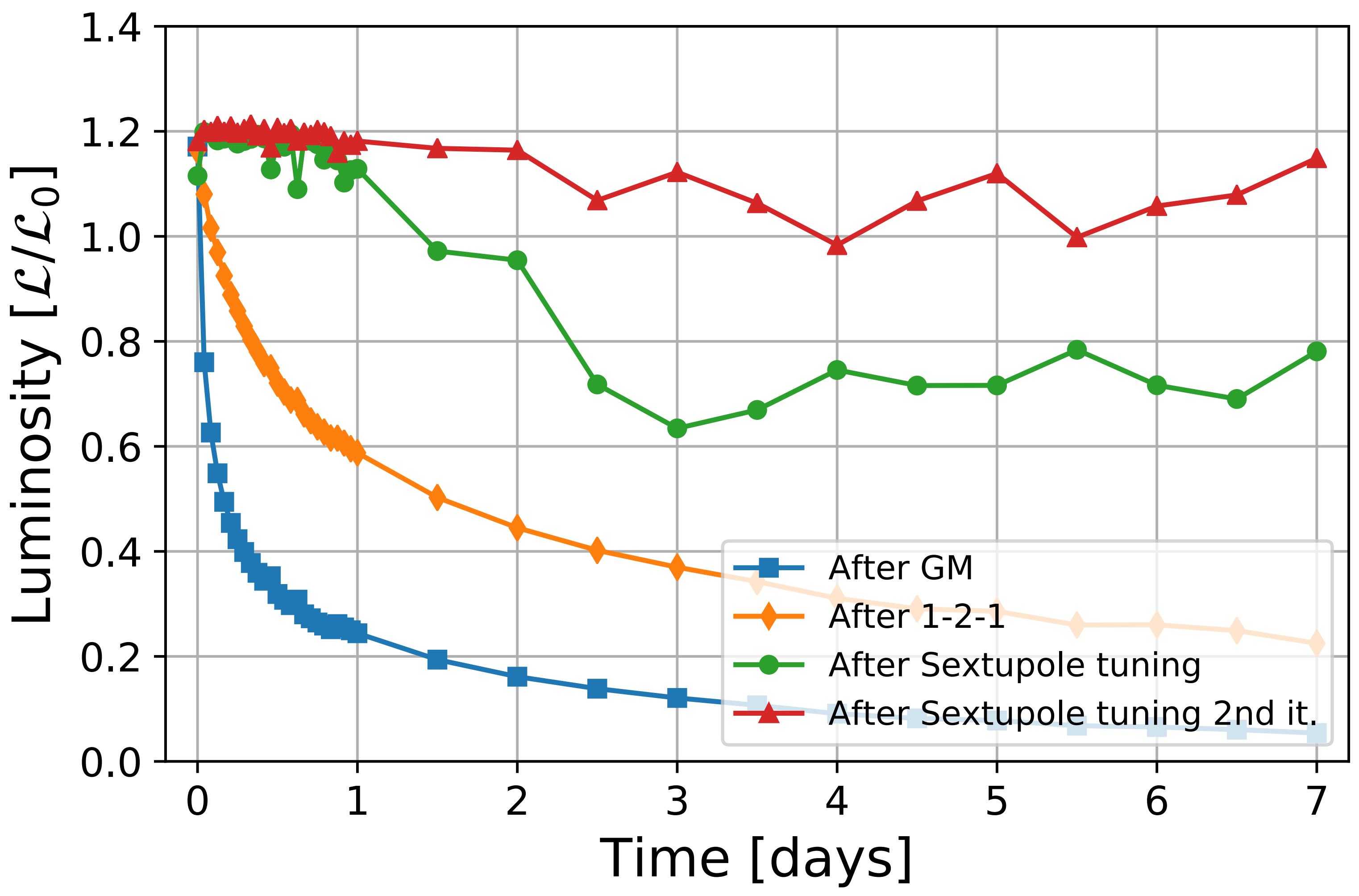
First hour



First day



First week



Quick recovery for downtime as long as 24 hours

Conclusions

- Successful two-beam tuning with realistic signals
  - We have a good handle on tuning of the FFS with static imperfections
  - Random walks with beamstrahlung and incoherent pairs
  - Knob scans maximizing inc. pairs signal
  - Combined quadrupole and sextupole random walk for machines that did not reach goal
- Simpler is better
  - Single parabolic fit is more noise-robust than e.g. a parabolic minimizer
  - Beamstrahlung asymmetry to determine larger beam works only in certain ranges
- We use single-bunch in simulation
  - Noise should be reduced when integrating over a full bunch train
- Imperfections that are not yet included
  - Dynamic imperfections
  - Beam jitter, beam energy jitter
  - Incoming beam with coupling
  - Crab cavity imperfections
  - Solenoid imperfections
  - Longitudinal misalignments
  - Realistic beam-beam feedback
  - Multipole magnetic errors