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Swiss Accelerator Research and Technology

Beam-beam tools and Weak-Strong Studies for the Future Circular Collider

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Background: Simulation Tools

- **Xsuite developments** allow detailed simulation of **FCC-ee**
  - See talk by G. Iadarola on Thursday
  - **Simulations** including:
    - Full description of **lattice** with **errors** and **radiation**
    - **Beam-beam effects**
  - **Beam-beam module** written by P. Kicsiny, talk yesterday
    - Used for **FCC studies** with full lattice description **without errors** e.g. for **dynamic aperture, emittance blow up**, **lifetimes**
- EPFL FCC **software framework**
  - Aim to enable comprehensive simulations with **multiple effects**
  - Understand and study their **interplay**
  - Introduce them **one at a time**

Background : FCC Tuning Studies

- FCC **tuning** studies[1]:
  - Simulations with different kinds of **lattice errors**
  - **Sensitivities**
  - **Corrections:**
    - **Optics** and **orbit corrections**
    - **Tuning knobs** to control **IP** optics functions
  - Very **limited** studies with **beam-beam** effects
- Significant achievements with **promising results**
  - Towards acceptable **dynamic aperture and optics** with realistic errors
  - Need to understand **impact of beam-beam effects**
- Studies shown today:
  - First studies on **interplay** of lattice **errors** and (WS) **beam-beam**
  - **Beam-beam perturbation** and **luminosity** with **IP parameter** scan

[1] 10.18429/JACoW-IPAC2024-WEPR02

Beam-beam and Lattice Errors

Towards comprehensive dynamic aperture studies

Target

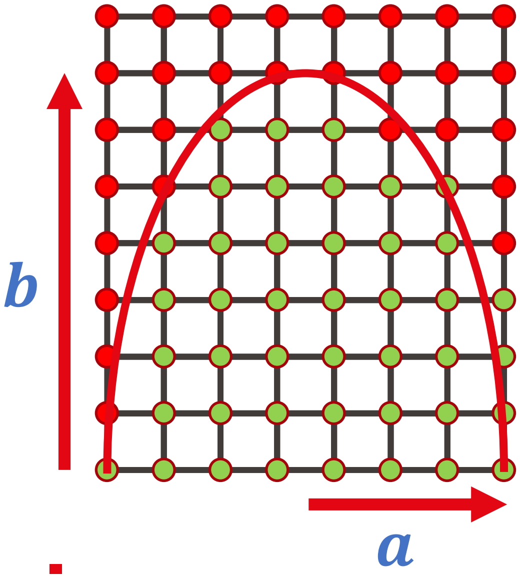
- First dynamic aperture studies including:
  - **Beam-beam**
  - **Full lattice with radiation**
  - **Lattice imperfections**
- Examining **one imperfection** at a time:
  - Excitation of different **multipoles**
  - Different **alignment errors**
- Studies done to
  - **Understand** how **different types of imperfections interact with beam-beam** and affect dynamic aperture
  - Aim to pinpoint behaviour and **target corrections**
- First iterations focuses on **transverse dynamic aperture**

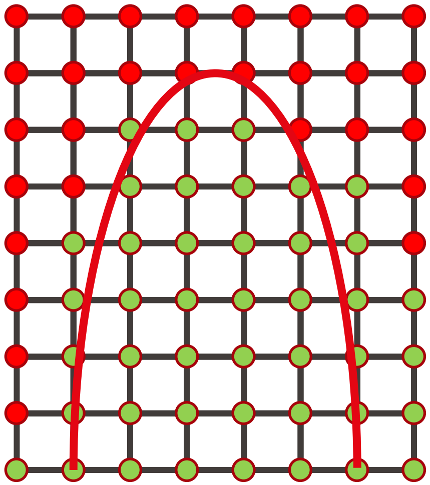
Simulation Set-up

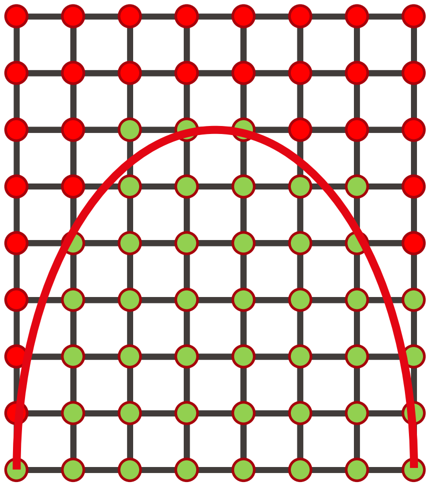
- Load **FCC-ee tt** lattice without perturbations from **MADX**
- **Perturb** lattice in MADX and **import** to **Xsuite**
- **Taper lattice** – adjust local magnet strength to match local beam energy
- Compute **6D Twiss** in Xsuite
- Install (**WS**) **beam-beam** elements in Xsuite
  - Two options: **B2 same/mirrored parameters** as B1, **B2 unperturbed**
- Compute **DA metric** – Largest Ellipse
- **Repeat without beam-beam**

Dynamic Aperture: Largest Ellipse

- Define dynamic aperture as **largest possible ellipse** (in X,Y plane) that only contains stable particles. Developed with A. Piveteau
- Allows get **quantifiable dynamic aperture** to **scan** parameters

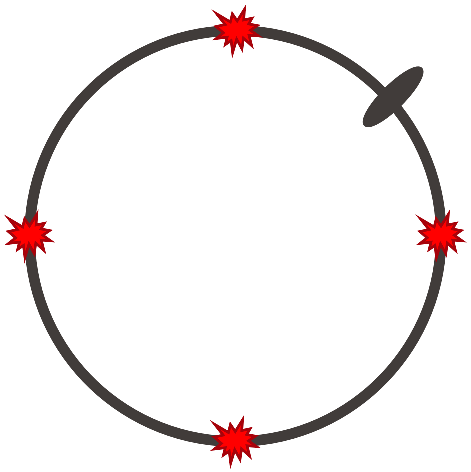


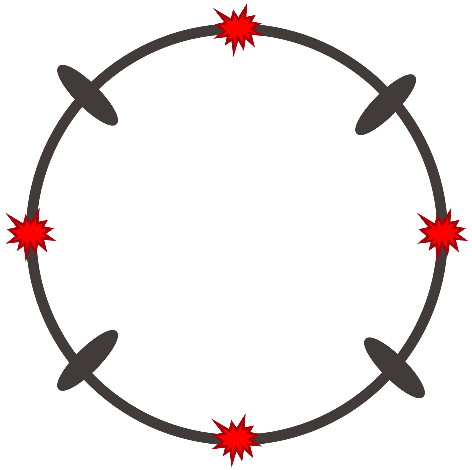




Controlled Excitation of Multipoles

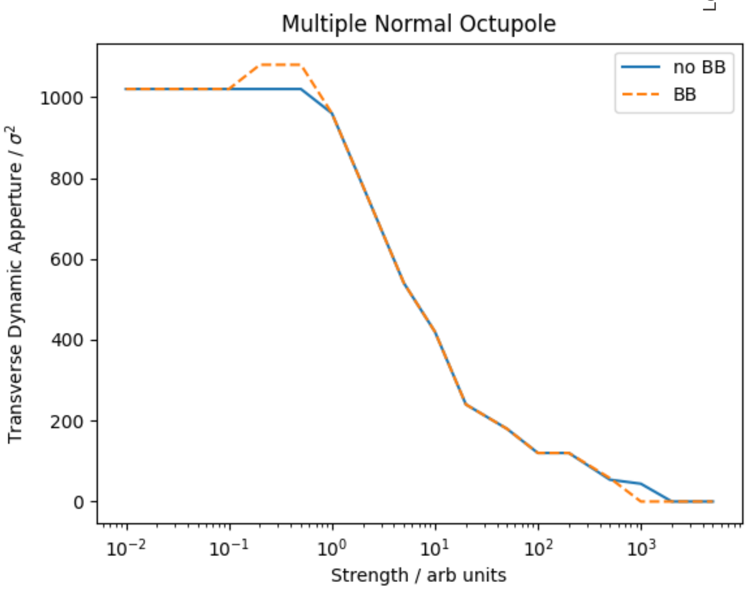
- Install **multipole** in “RF-insertions” of tt lattice
  - Separate studies:
    - In **one insertion**, in **all insertions**
    - **B2 mirror** B1, **B2 unperturbed**
- Separately **excite** dipole, quadrupole, sextupole and octupole fields
  - **Gradually increase** multipole strengths (arbitrary units)
  - Until dynamic aperture drops to **zero without beam-beam**
  - Repeat **with beam-beam**
  - Repeat with their **skew** equivalents





Findings

- Beam-beam shown to have a **very small impact** on transverse dynamic aperture
  - Largely follows the **same trends irrespective** of **beam-beam** element installed
  - True for **single perturbation** and **multiple** (rotationally symmetric) perturbations
- **Symmetric** and **unperturbed** B2 both have a very small impact
  - **No major difference** in behaviour

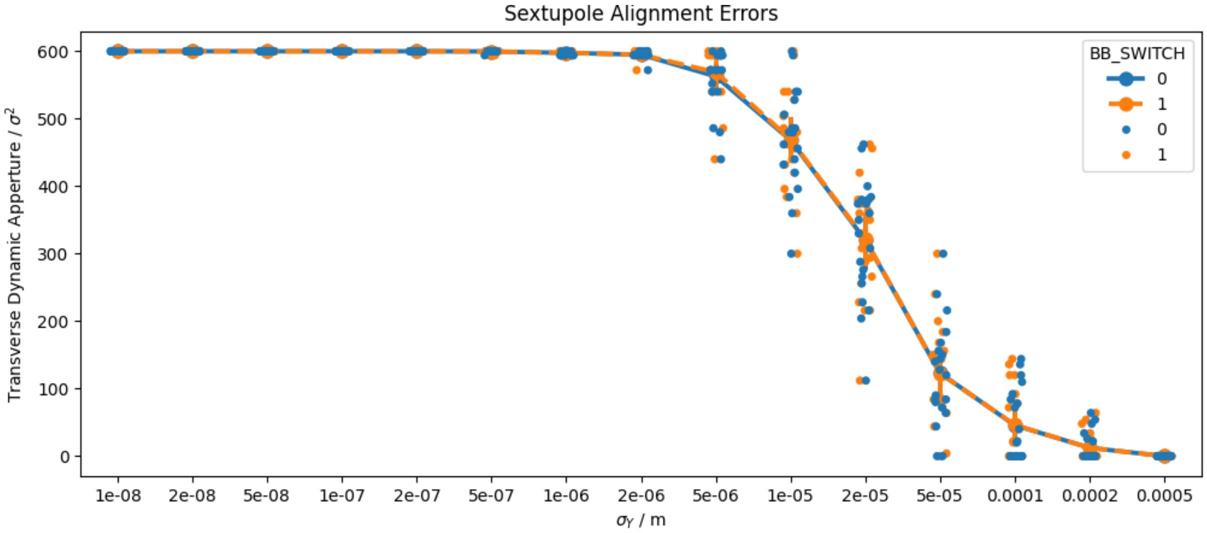


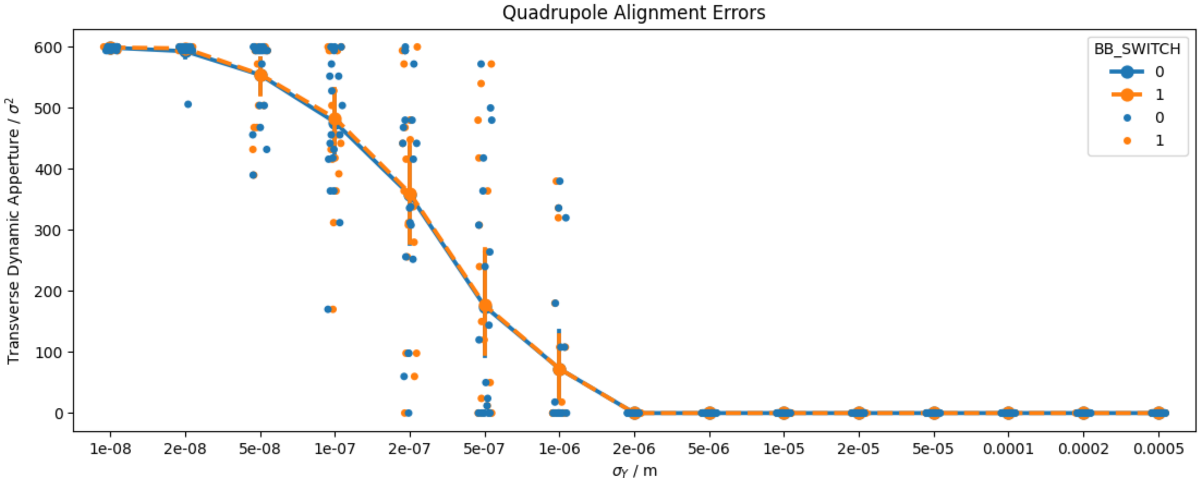
Example: plot for effect on DA with multiple octupoles

Alignment Errors

- Test impact of **alignment errors** on dynamic aperture
  - Focus on vertical alignment errors of:
    - **Sextupoles** - introduction of **coupling** and **optics beating**
    - **Quadrupoles** – same as sextupoles + introduction of **orbit + dispersion effects**
- Simulation **set up similar** as for multipoles
  - **Tapering** and **full radiation**
  - **B2** produced **symmetric** to B1
    - Ensure beams actually **interact** (**no orbit offsets**)
- **Random errors** with increasing **standard deviation**
  - Applied to quadrupoles **or** sextupoles
  - **20** identical errors **seeds** with and without **beam-beam**
  - Compute **average** and **standard deviation** of **dynamic aperture** for each error size
  - Compare **individual seeds** too

Results


Sextupole Alignment Errors
Transverse Dynamic Apperture / σ^2
600
500
400
300
200
100
0
1e-08
2e-08
5e-08
1e-07
2e-07
5e-07
1e-06
2e-06
5e-06
1e-05
2e-05
5e-05
0.0001
0.0002
0.0005
σ_Y / m
BB_SWITCH
0
1
0
1


Quadrupole Alignment Errors
Transverse Dynamic Apperture / σ^2
600
500
400
300
200
100
0
1e-08
2e-08
5e-08
1e-07
2e-07
5e-07
1e-06
2e-06
5e-06
1e-05
2e-05
5e-05
0.0001
0.0002
0.0005
σ_Y / m
BB_SWITCH
0
1
0
1

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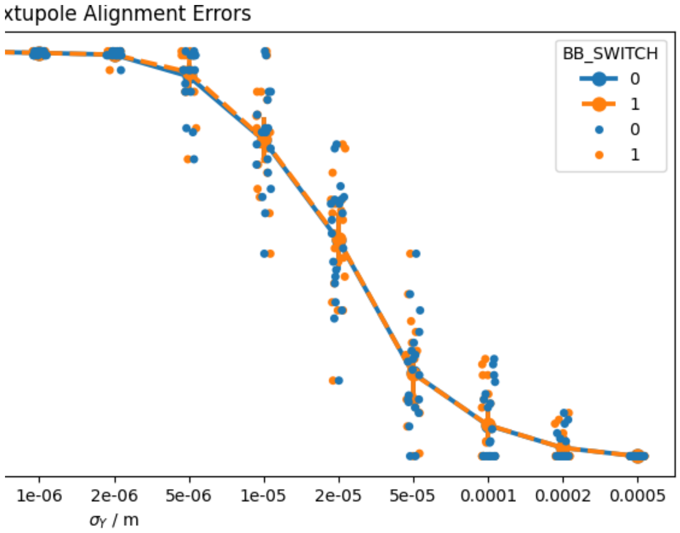
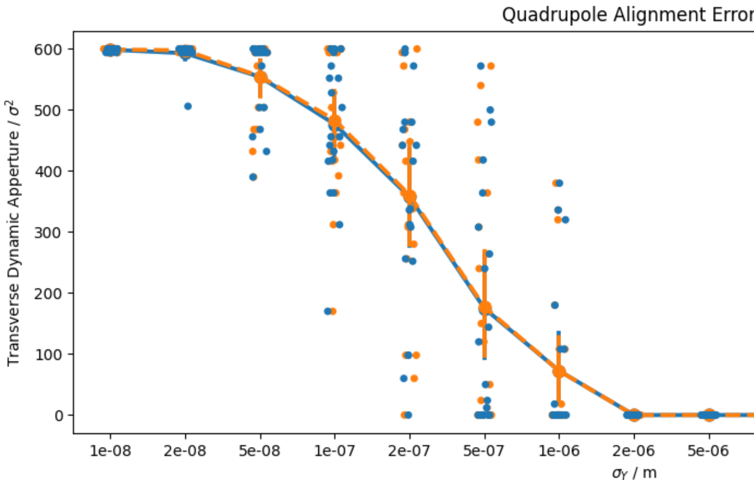
Results

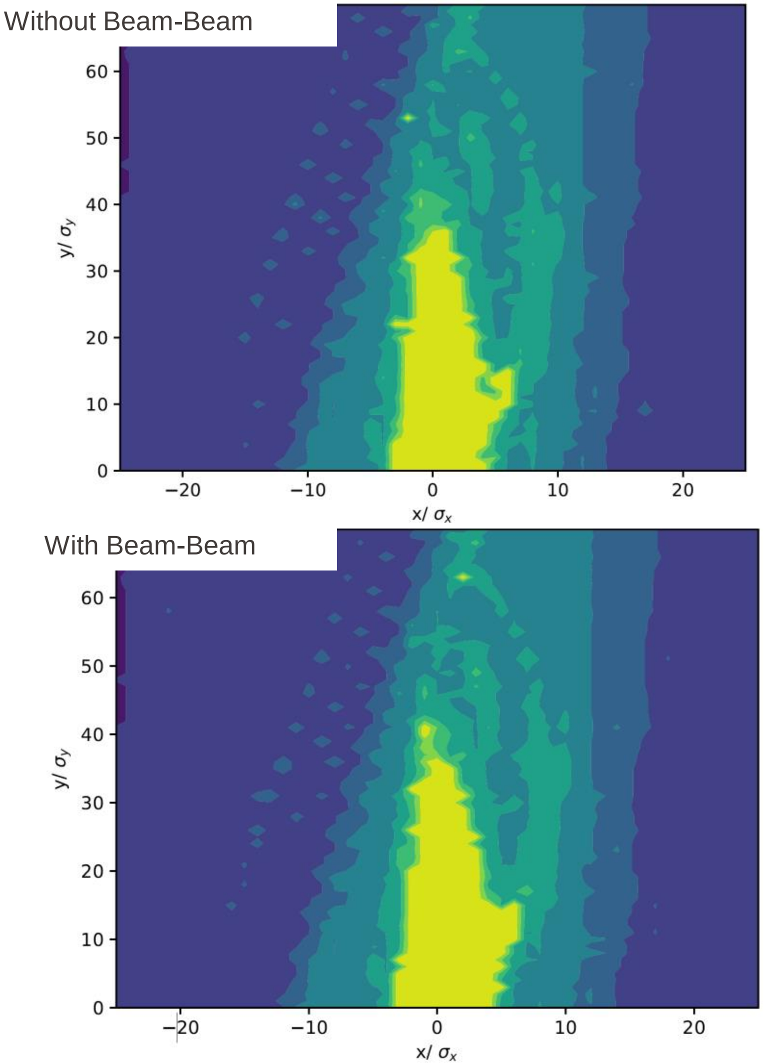
- Very **small impact** of beam-beam element on **average** dynamic aperture
- **Most** error **seeds** have very **similar** dynamic aperture in both cases
  - Shown **next to each** other in plot
  - **Few** cases with **differences**
    - Interesting to study these **behaviour of these seeds**
    - Need to **understand** how beam-beam **interacts** with these errors





Realistic Errors and Correction

- Lattice provided by **Yi Wu**
  - Z-lattice
  - **50 μm alignment errors** in arcs
  - **Orbit corrections** interleaved with **global tune** correction
- **Dynamic aperture** obtained
  - Tracked with **tapering** and **radiation** in arcs for 2500 turns
  - **with** and **without beam-beam** elements installed
    - (**B1 = B2 parameters**)



Conclusions on Errors and Beam-beam

- Observe that **WS beam-beam** perturbations have **small impact on transverse dynamic aperture**
  - **Magnetic errors**
  - **Alignment errors** – including realistic corrections
- Simulations consideration **average radiation damping** and **full lattice**
- **Promising first results** indicating low impact after **optics tuning**
- To get a fuller pictures also consider:
  - **Longitudinal** dynamic aperture
  - **Quantized radiation: synchrotron, beamstrahlung and bha-bha scattering**
  - **lifetime** – work towards making these simulations reliable
  - Study **correlating** dynamic aperture with lifetime

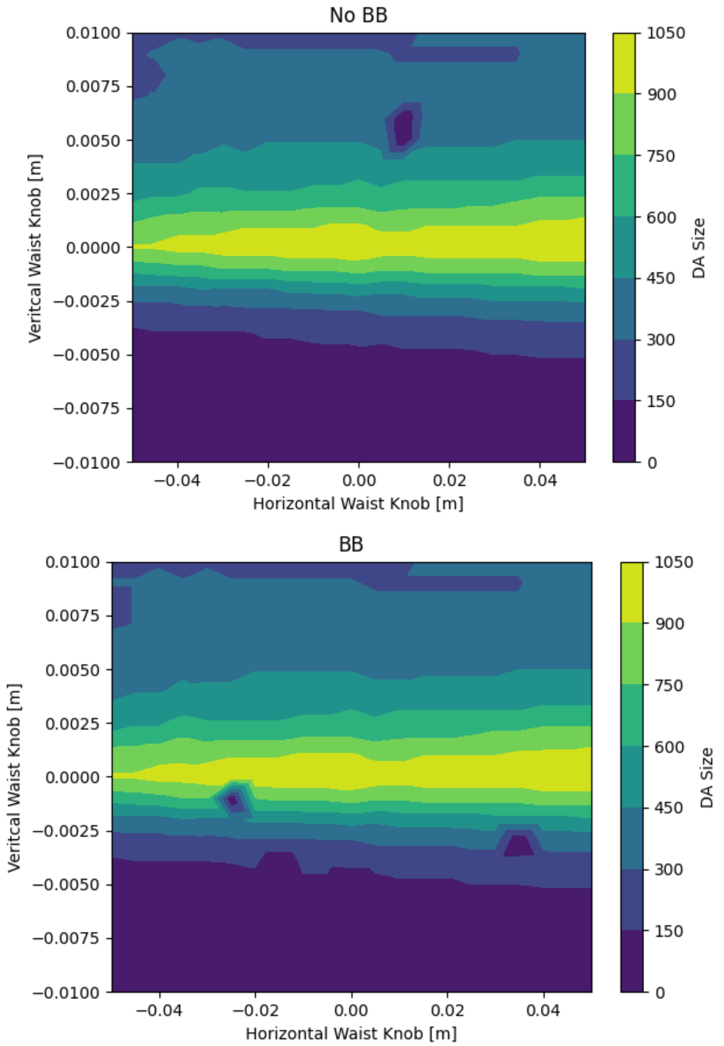
IP Parameters

Scanning IP Knobs

- FCC-ee **tuning knobs** exist to **control** the **IP** parameters
  - Including β **at waist** and **waist location**
- **Xsuite** can be used to study machine behaviour to when we scan these knobs in the presence of **(WS) beam-beam element**
  - Understand impact of optics perturbations in IP
    - Especially **critical** for **beam-beam**
  - Compute **luminosity** to see how IP perturbations could be **measured**
- Evaluate **availability** and **utility of knobs** e.g. as luminosity handle
  - Also understand impact on **other parameters** e.g. **emittance** - work done by A. Piveteau

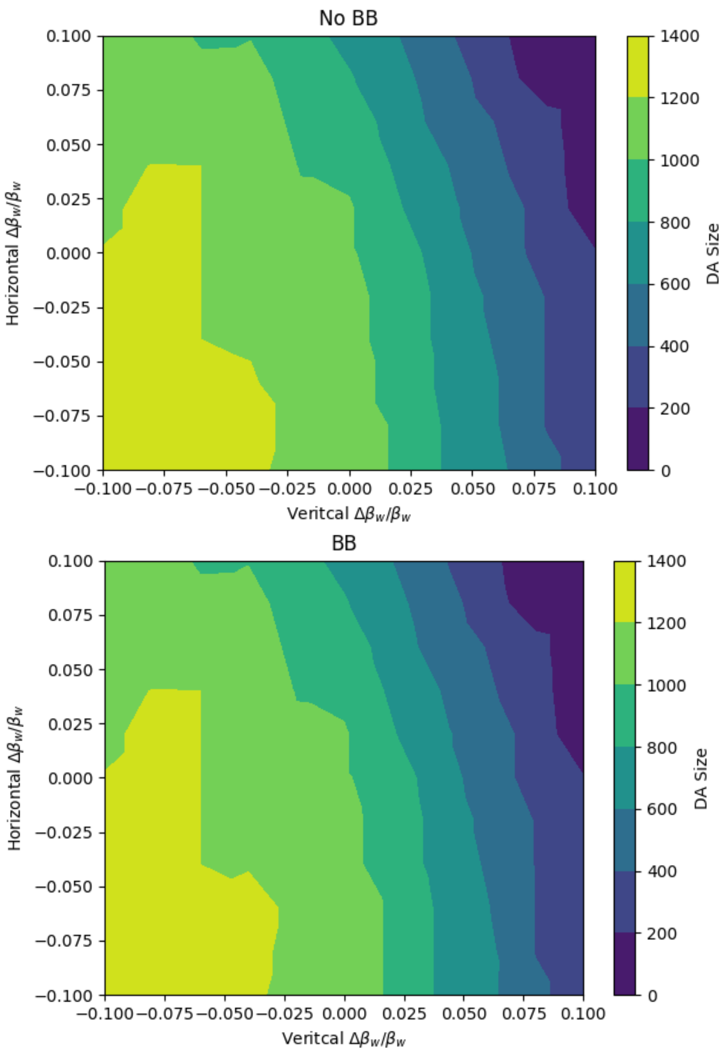
DA with IP Parameter Scan

- Change **waist location** in horizontal and vertical planes of tt lattice using **knobs**
  - In **all IPs simultaneously**
- **Radiating** lattice and install **beam-beam** elements in Xsuite
  - **B2 unperturbed**
- Scan each setting and track for 200 turns (tt) and establish **ellipse dynamic aperture**
- Repeat without beam-beam



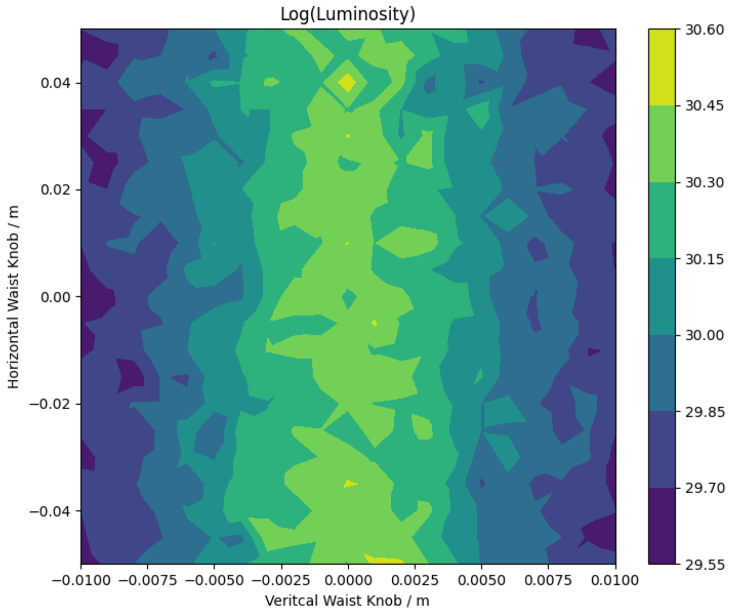
DA with IP Parameter Scan

- Change **waist location** in horizontal and vertical planes of tt lattice using **knobs**
  - In **all IPs simultaneously**
- **Radiating** lattice and install **beam-beam** elements in Xsuite
  - **B2 unperturbed**
- Scan each setting and track for 200 turns (tt) and establish **ellipse dynamic aperture**
- Repeat without beam-beam
- **Repeat for β_w**
- Again, **very small impact** on dynamic aperture



Luminosity Scans

- Change **waist location** in horizontal and vertical planes of tt lattice using **knobs**
  - In **single IP**
- **Radiating** lattice in Xsuite
- Install **single** beam-beam element in **modified IP**
- **Luminosity** computed using **Xsuite beam-beam**
  - Compute luminosity over 300 turns with 100,000 macro particles
- **Behavior as expected**
  - **Future** studies **with** (optics) **errors**
    - Use luminosity to **tune optics**



Conclusions

- **Xsuite** allows for **FCC-ee studies** with **full lattice** description, **radiation** and **beam-beam**
  - **Powerful** tool to **realistically** study FCC-ee in full detail
- **First studies** on the impact of **beam-beam** on dynamic aperture with **errors**
  - **Magnetic** errors and **alignments** errors
  - **Promising** first results towards demonstrating **feasibility**
  - Limited to **transverse dynamic aperture** – **more studies to follow**
- More focused studies on **IP parameters**
  - **Impact of knobs** on dynamic aperture with beam-beam
  - Beam-beam module for **luminosity scans**
  - Towards understanding **availability** and **utility of knobs**

Thank you!

Backup slides

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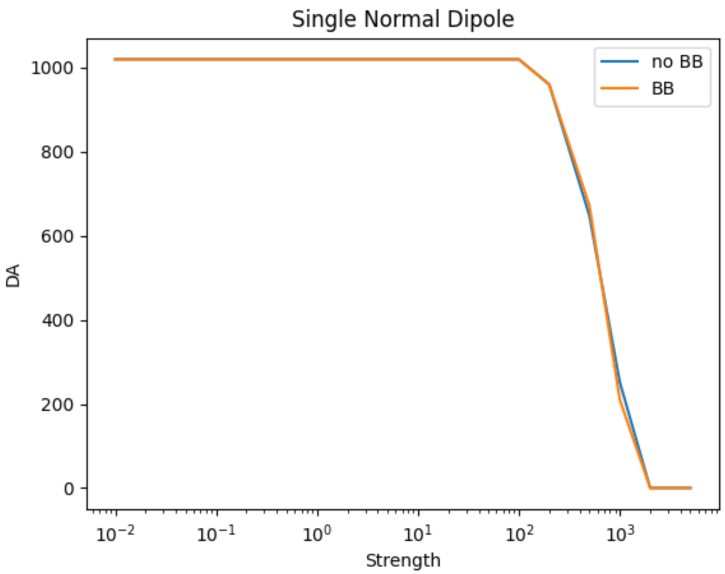
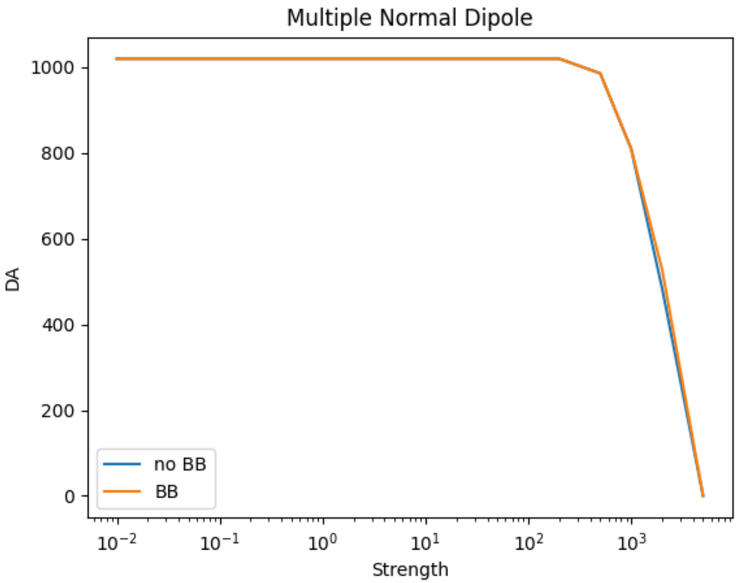
Dynamic Aperture: Largest Ellipse

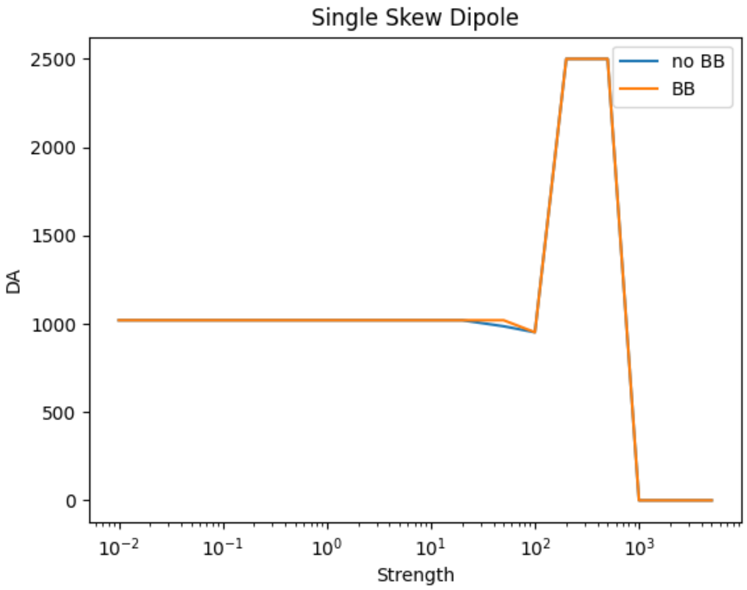
- **Scanning** parameters requires a systematic approach to **quantify dynamic aperture**
- Define dynamic aperture as **largest possible ellipse** (in X,Y plane) that only contains stable particles. Developed with A. Piveteau
- Algorithm as followed:
  - Generate particles on grid in **units of σ_x and σ_y**
  - **Track** for ~two lifetimes
  - Scan all possible ellipses with **axes** $a = [0, \sigma_{x_{MAX}}]$, $b = [0, \sigma_{y_{MAX}}]$
    - Using **same granularity** as grid
  - Accept ellipse if fully in stable region:
    - If **all particles** fulfil: **survived all turns** **OR** $\left(\frac{\sigma_x}{a}\right)^2 + \left(\frac{\sigma_y}{b}\right)^2 > 1$
  - DA defined as **maximum** $a \times b$ **accepted ellipse**

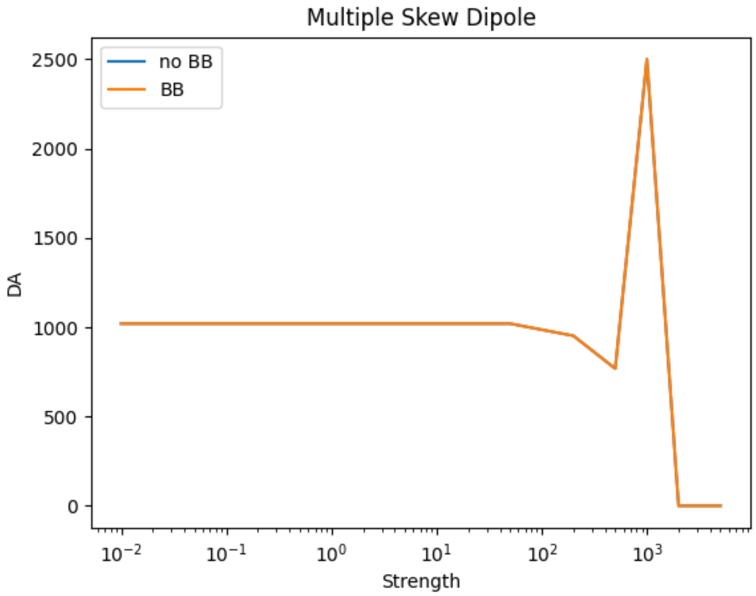
Dipole (Kicker)



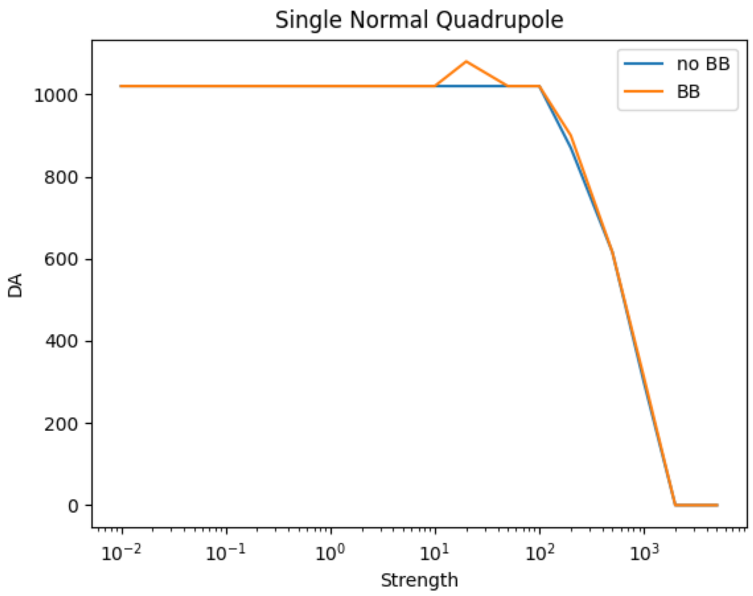


Skew Dipole (Kicker)





Quadrupole


Single Normal Quadrupole
no BB
BB
DA
Strength
0
200
400
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800
1000
10^{-2}
10^{-1}
10^{0}
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10^{2}
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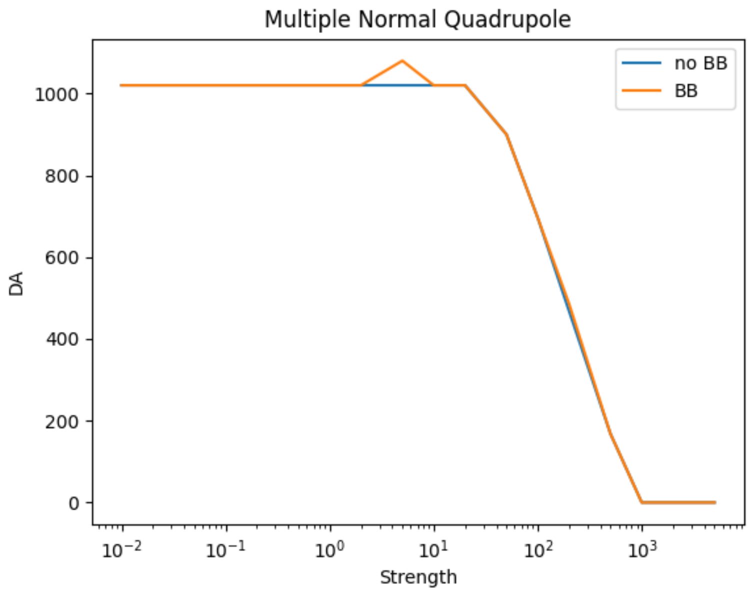
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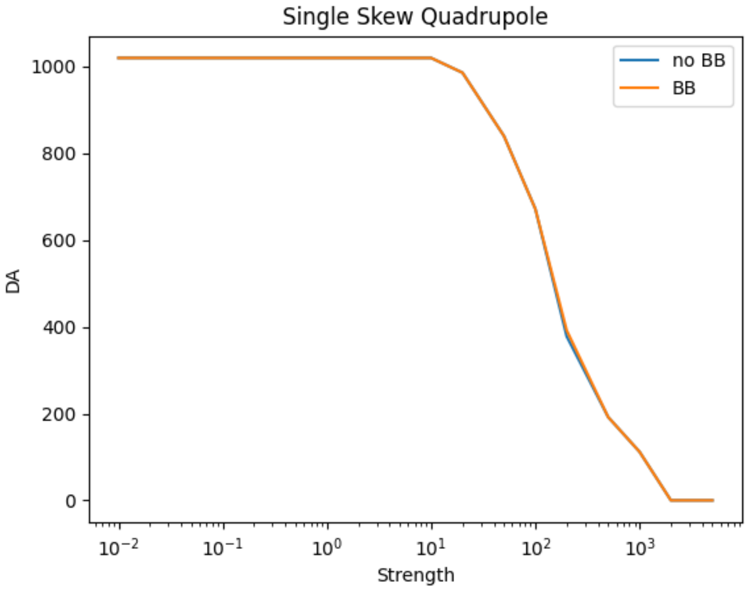
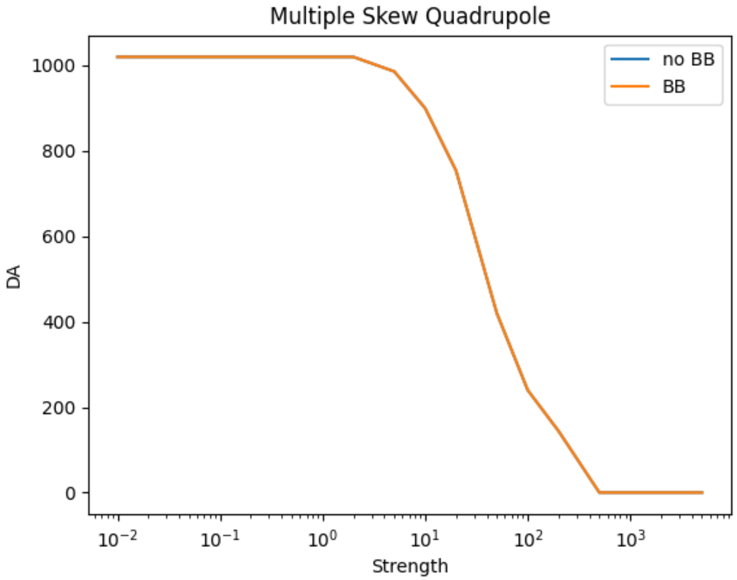
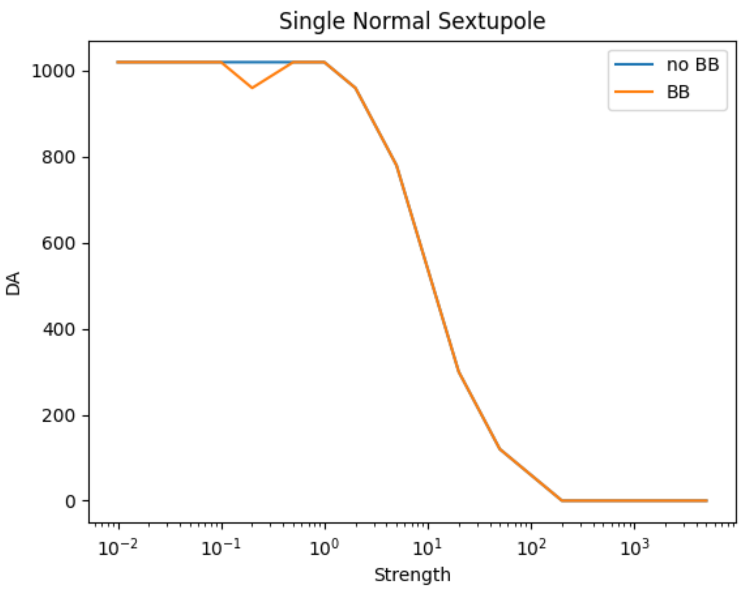
10^{0}
10^{1}
10^{2}
10^{3}

Skew Quadrupole





Sextupole


Single Normal Sextupole
no BB
BB
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10^{-2}
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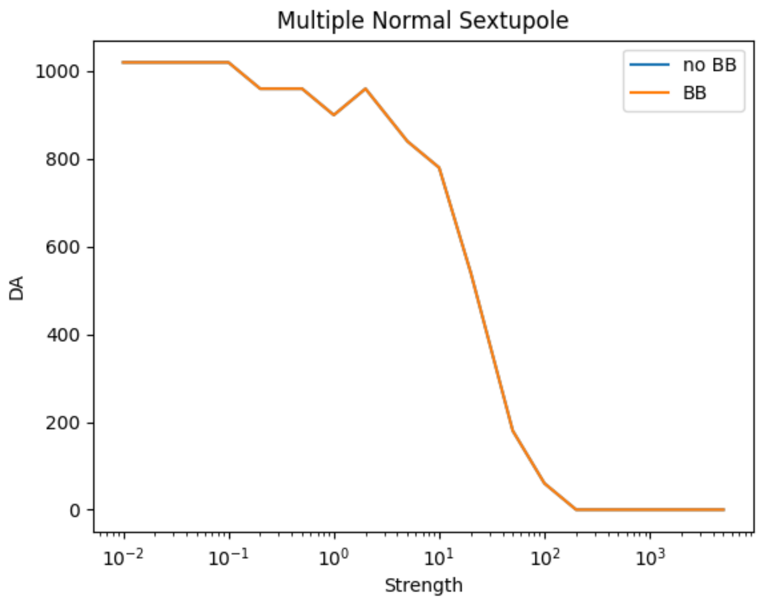
10^{1}
10^{2}
10^{3}
Strength


Multiple Normal Sextupole
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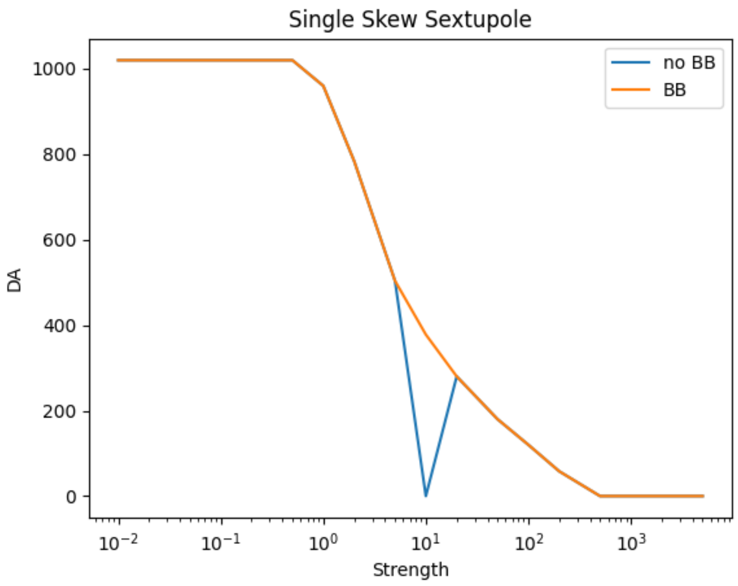
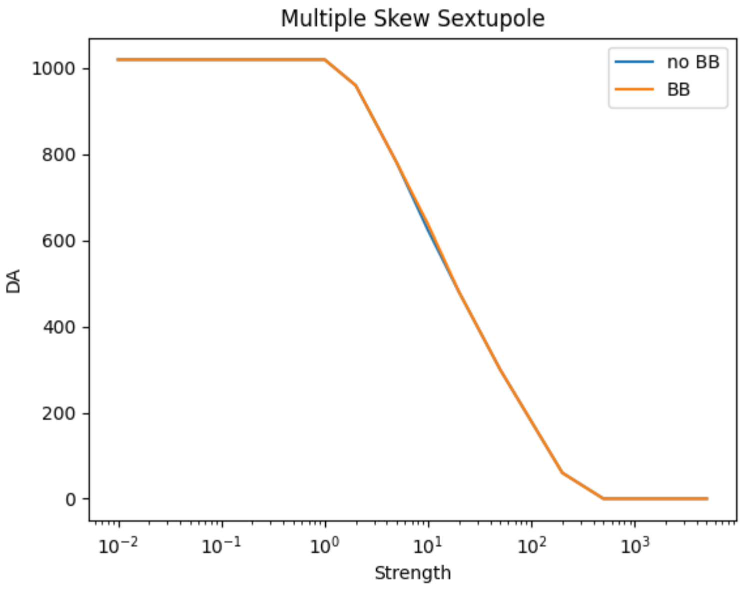
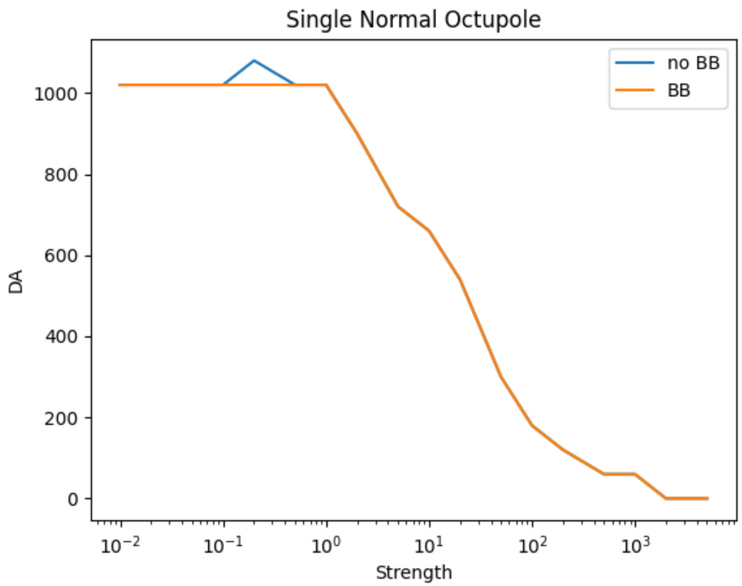
10^{3}
Strength

Skew Sextupole





Octupole



Single Normal Octupole
no BB
BB
DA
1000
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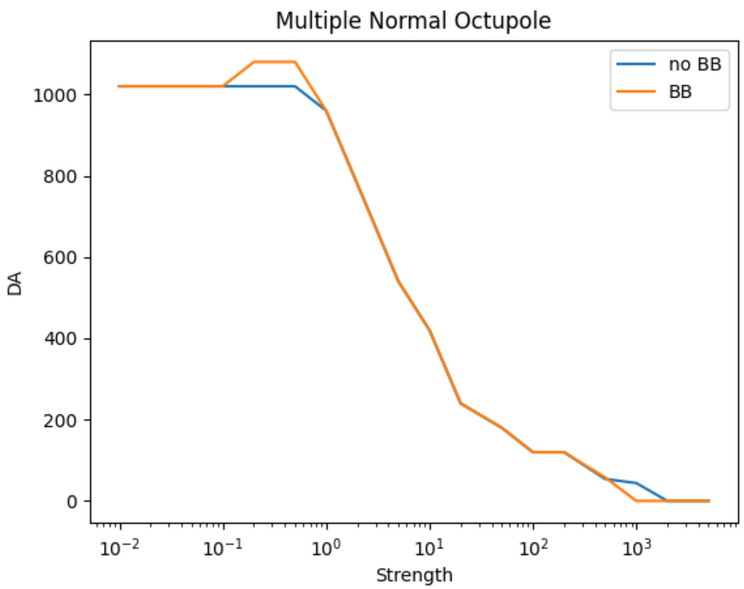
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Strength



Multiple Normal Octupole
no BB
BB
DA
1000
800
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0
10^{-2}
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10^{0}
10^{1}
10^{2}
10^{3}
Strength

Skew Octupole