Simulation of Collimation Performance in Colliders with Beam-Beam Effects

Frederik Van der Veken

with special thanks to R. De Maria, M. Hostettller, G. Iadarola, B. Lindström, K. Paraschou, S. Redaelli, and G. Sterbini

5/9/24 ***BB'24*** *EPFL, Lausanne (CH)*

Outline

Collimation at the LHC

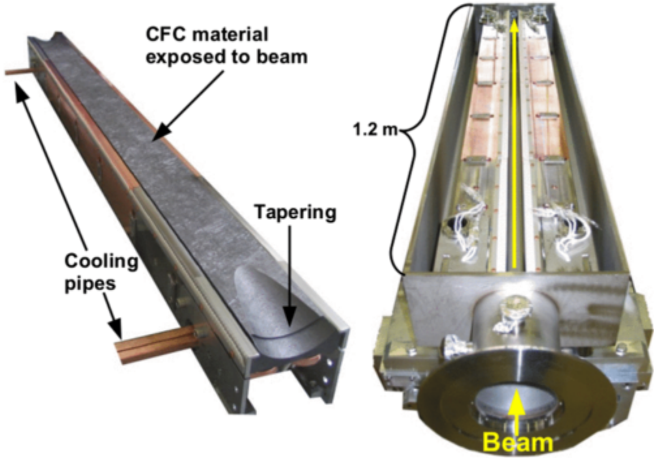
Hierarchy Breaking

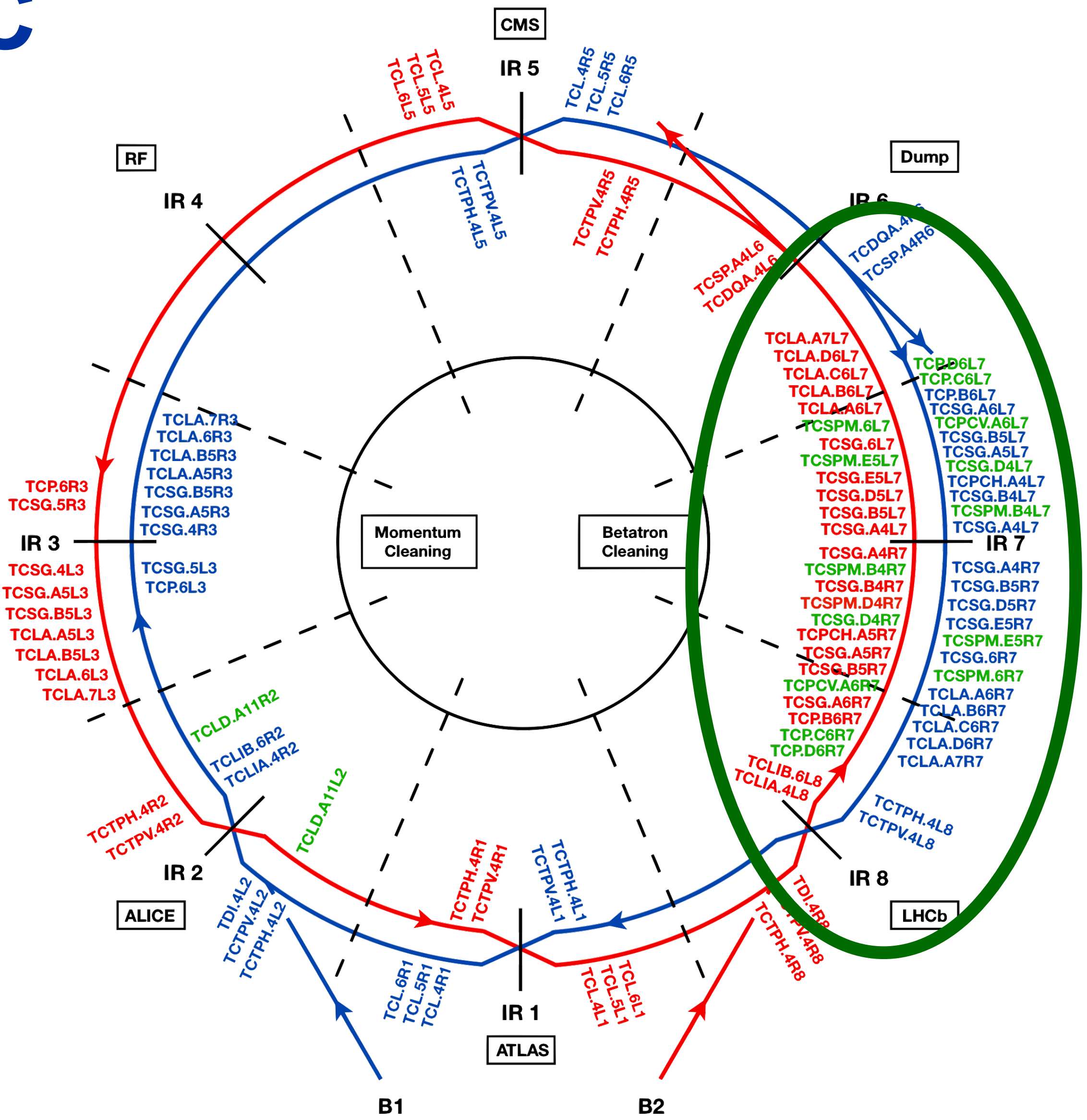
Simulations with Collimation and Beam-Beam

Simulation Results

Collimation System at the LHC

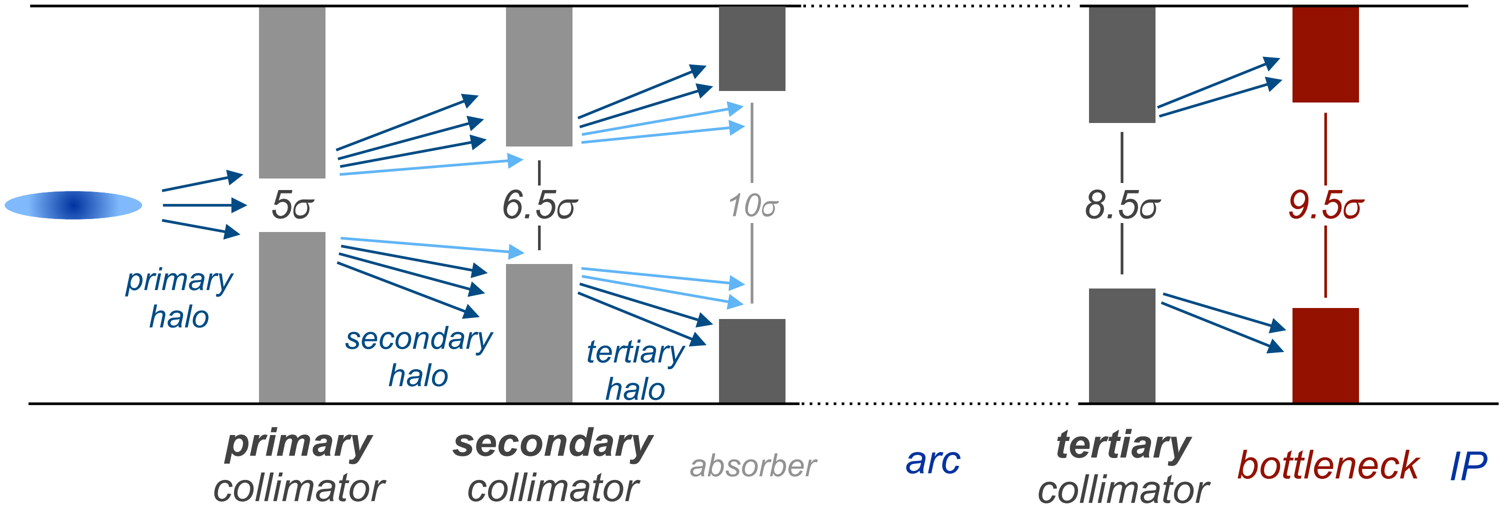
- More than 400MJ stored beam energy in LHC (up to 700MJ for HL)!
- 101 collimators to protect machine against quenches
- Multi-stage system, mainly in IR7:
    - Primary collimators closest to the beam
    - Secondary and tertiary collimators to intercept showers, protect the IPs, and reduce the background





Collimation Hierarchy

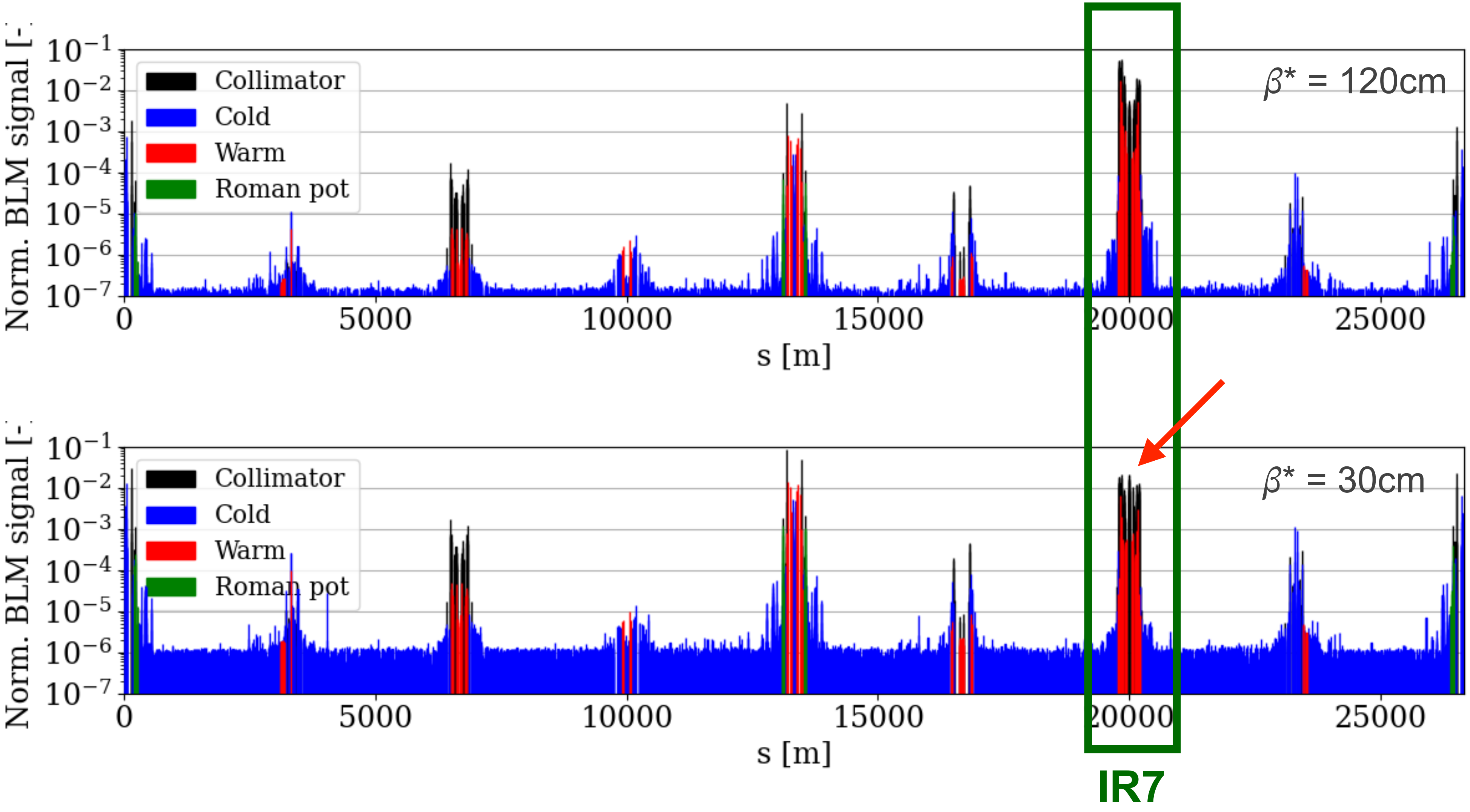
- Collimators follow **strict hierarchy**: primary - secondary - tertiary
  - *collimators layout is designed with optimal phase advances to ensure good hierarchy*
- **Aligned** around beam centre, opening defined in **beam size**
  - *bunch-dependent orbit shifts make each bunch see a different collimator cut!*



Collimation Simulations

- Collimation simulations are crucial to **validate collimation settings** before deployment and to spot issues
- Loss map simulations are typically done on commissioning setup:
  - low chromaticity and octupoles
  - no extra non-linearities
- Recent interest to include non-linearities into simulations: high chromaticity, high octupoles, beam-beam, ...
  - Emphasis on effect on orbit (alignment errors) and beta-beating (beam size)
  - Becomes even more important for future challenges like the High Luminosity LHC!
  - And more (many challenges related to high brightness beams)

Example: Hierarchy Breaking at the LHC



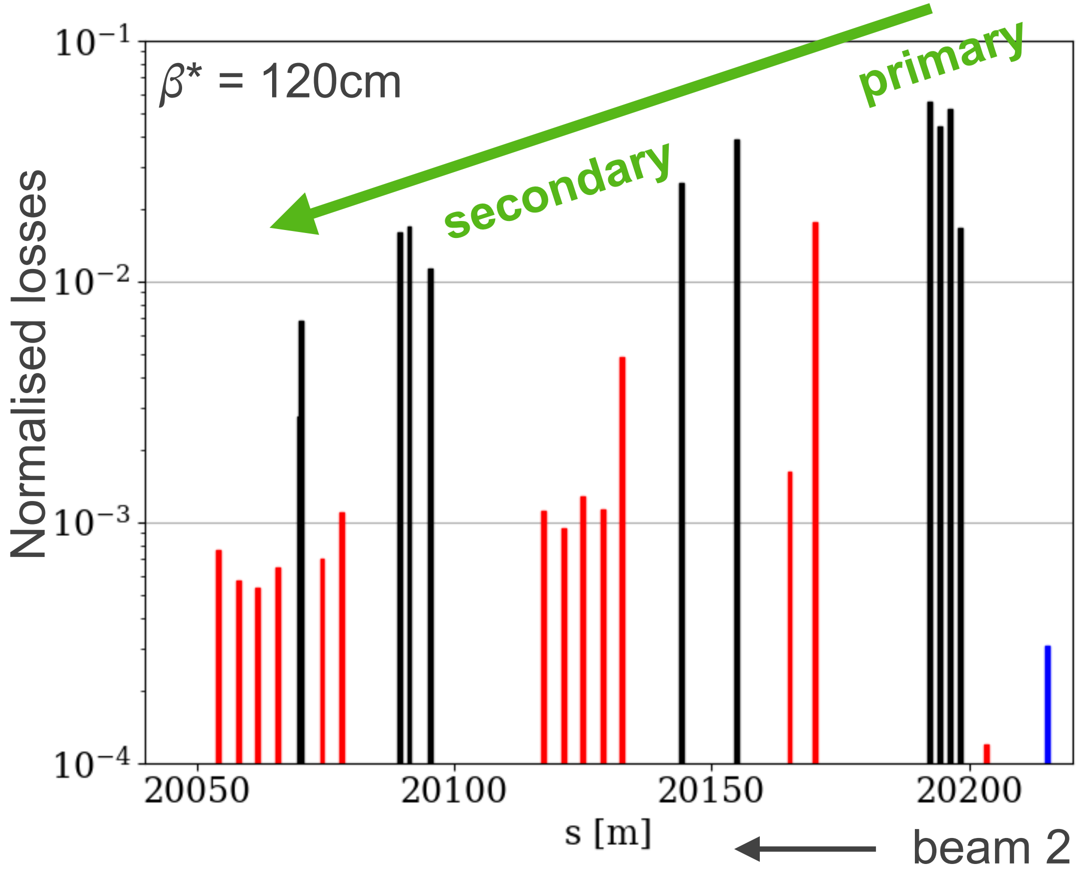
Good Hierarchy

Broken Hierarchy

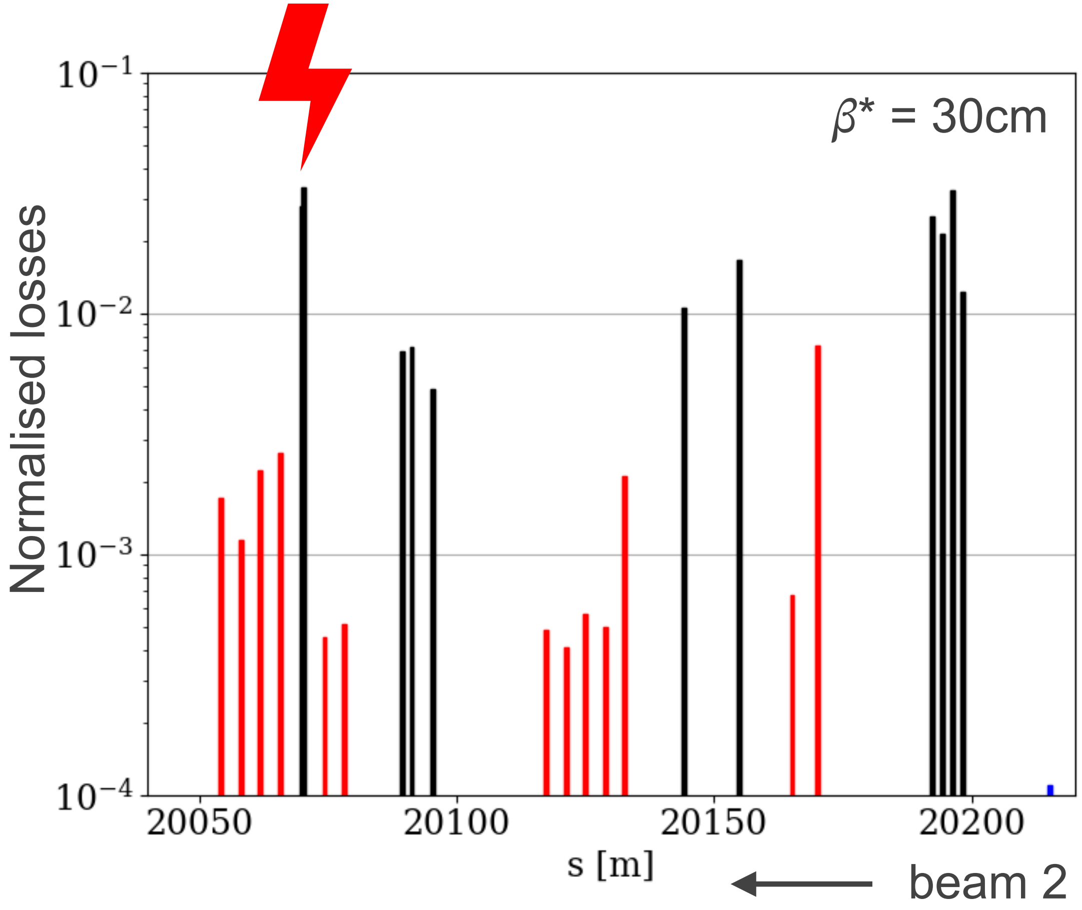
Example: Hierarchy Breaking at the LHC

April 2024

Good Hierarchy



Broken Hierarchy



Outline

Collimation at the LHC

Hierarchy Breaking

Simulations with Collimation and Beam-Beam

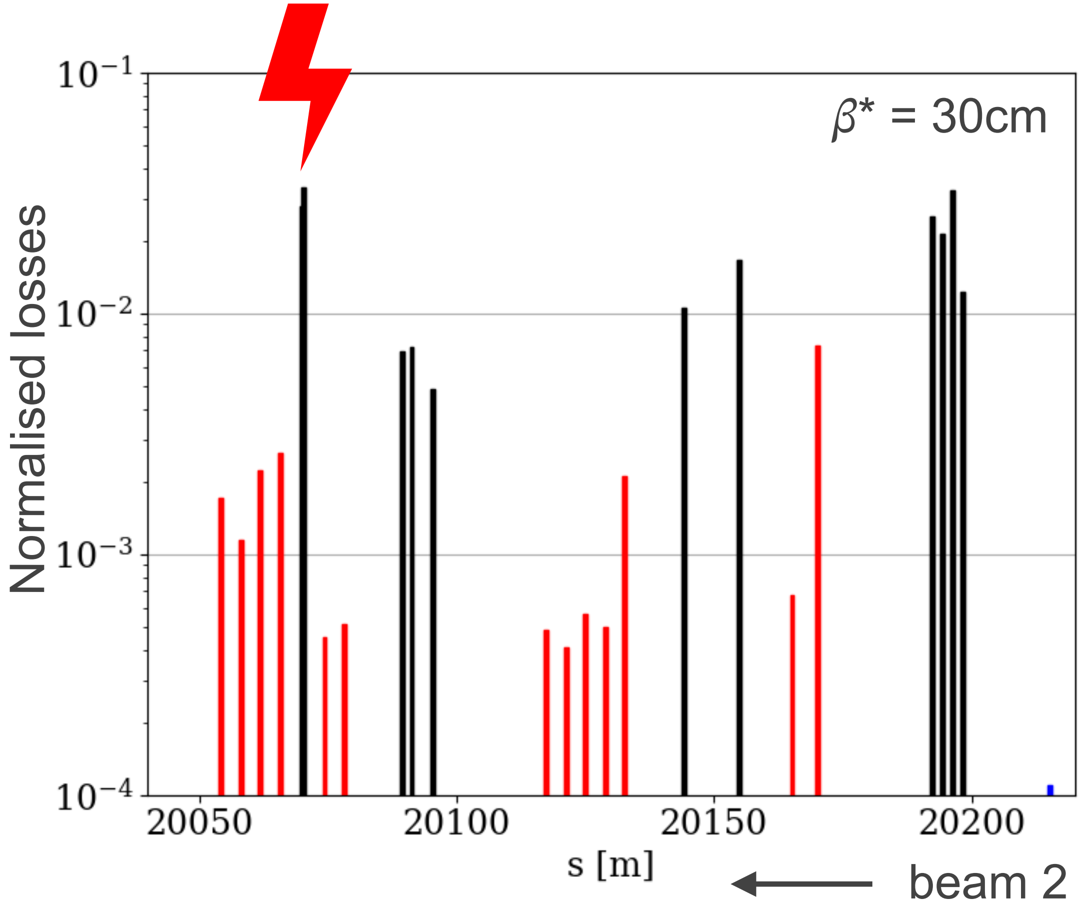
Simulation Results

Hierarchy Breaking at the LHC

April 2024

- Hierarchy breaking appeared in beam 2 during the last step of levelling *(see T. Persson's talk)*
- Not observed with single beam! => clear **beam-beam effect**
- Dedicated measurements have shown different contributions:
  - orbit errors and **orbit distortion** from beam-beam effects
  - beta-beating (has minimal impact $\sim \sqrt{10\%}$)
  - spurious **vertical dispersion**
  - 3Qy resonance from **a3** lattice inhomogenities
  - **long range beam-beam** enhances 3Qy

Broken Hierarchy



Hierarchy Breaking at the LHC - Mitigations

- Hierarchy breaking appeared in beam 2 during the last step of levelling *(see T. Persson's talk)*
- Not observed with single beam! => clear **beam-beam effect**
- Dedicated measurements have shown different contributions:
  - orbit errors and **orbit distortion** from beam-beam effects
  - beta-beating (has minimal impact $\sim \sqrt{10\%}$)
  - spurious **vertical dispersion** → overcompensated dispersion correction knob
  - 3Qy resonance from **a3** lattice inhomogenities
  - **long range beam-beam** enhances 3Qy

3Qy resonance / long range beam-beam → reduced chromaticity; a3 correction

Hierarchy Breaking at the LHC - In Simulation

- Hierarchy breaking appeared in beam 2 during the last step of levelling *(see T. Persson's talk)*
- Not observed with single beam! => clear **beam-beam effect**
- Dedicated measurements have shown different contributions:
  - orbit errors and **orbit distortion** from beam-beam effects → retain dipolar kicks
  - beta-beating (has minimal impact $\sim \sqrt{10\%}$) → BBLR & BBHO
  - spurious **vertical dispersion** → add manual dispersion
  - 3Qy resonance from **a3** lattice inhomogenities → add lattice inhomogenities (WIP)
  - **long range beam-beam** enhances 3Qy → BBLR & BBHO

Outline

Collimation at the LHC

Hierarchy Breaking

Simulations with Collimation and Beam-Beam

Simulation Results

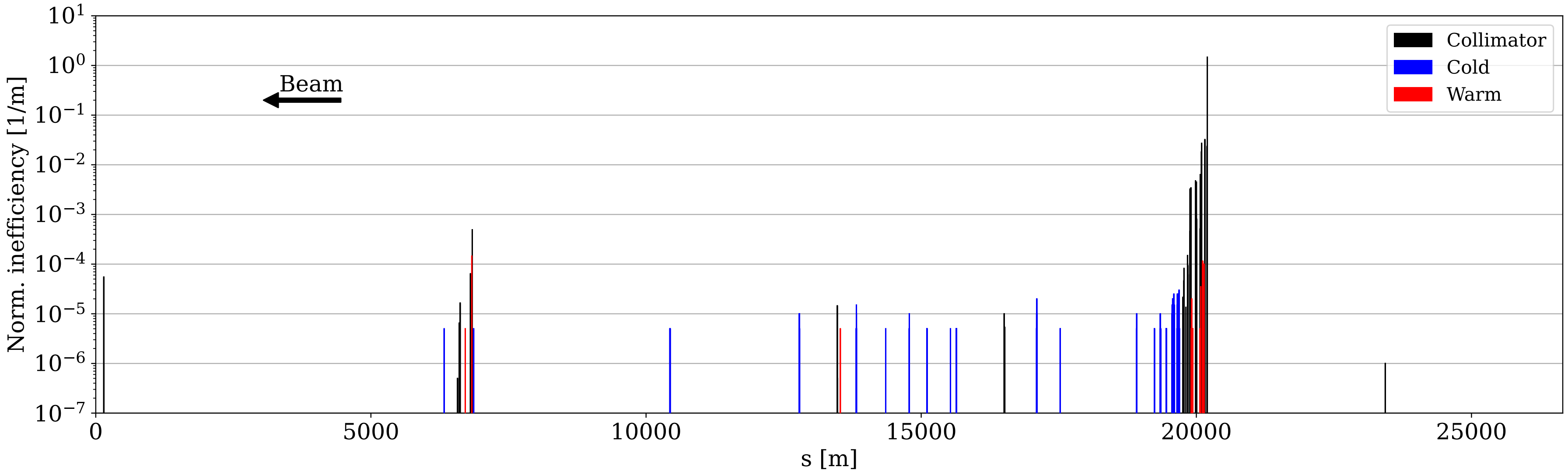
Combining Collimation with Beam-Beam

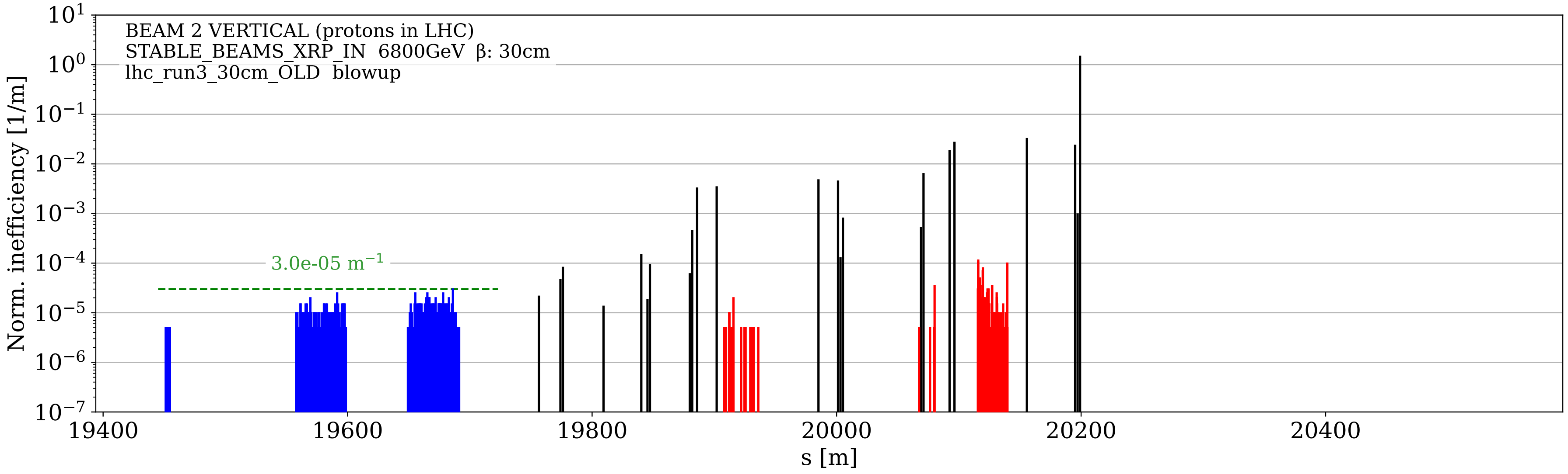
- Collimation simulations using Xsuite: **Xcoll**
  - with native scattering (Everest) ported from well-established SixTrack
  - possibility to use FLUKA and Geant4 *(see G. Broggi's talk)*
- Beam-beam simulations using Xsuite: **Xfields**
- Lattices used for collimation simulations include **aperture** markers
  - aperture scripts require a lot of **manual patching**, which does not work with the BB generation scripts!
    => **aperture patcher script** in post-processing
  - aperture **offsets** cannot be correctly reflected to B4 as the current implementation uses dedicated variables.
    => move the offset scripts to python (WIP)
  - collimator installations sometimes **clash with BB lenses**
    => injection protection hence not installed (patch)
    => redefine BB installation to avoid clashes (WIP)

Validation of Setup with Loss Maps

- Typical loss map simulations are done with a **pencil beam** which starts at the primary collimator
- In these simulations, this is not applicable (as hierarchy breaking would never manifest)
- Instead, use a matched particle distribution, and use a **blow-up** (new element in Xsuite) to send the beam to the collimators. This is also used to simulate aperture measurements *(see talk of C.E. Montanari)*
- Possibility to use strong blow-up to mimic measured loss map, or soft blow-up to stimulate diffusion

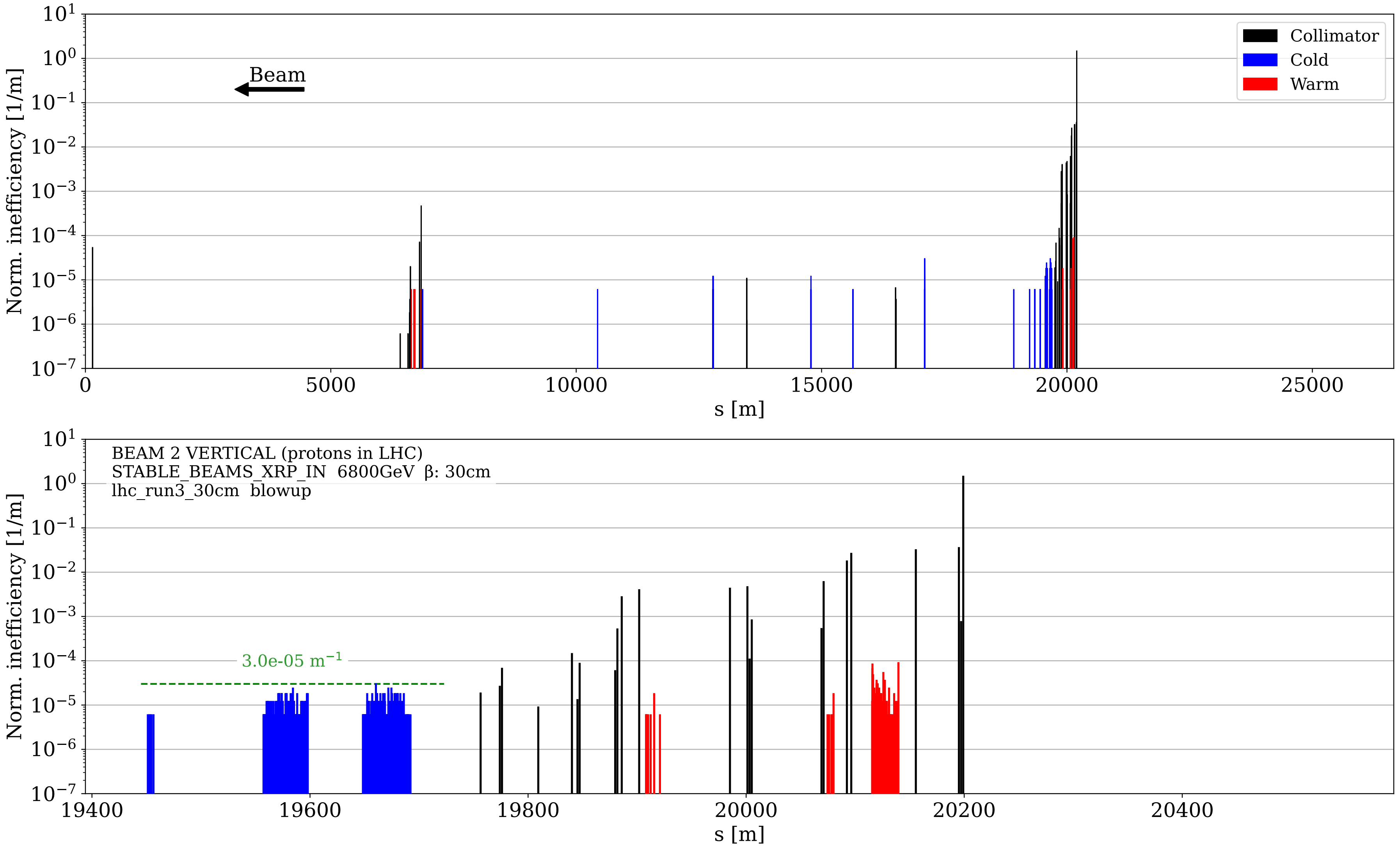
Validation of Setup with Loss Maps





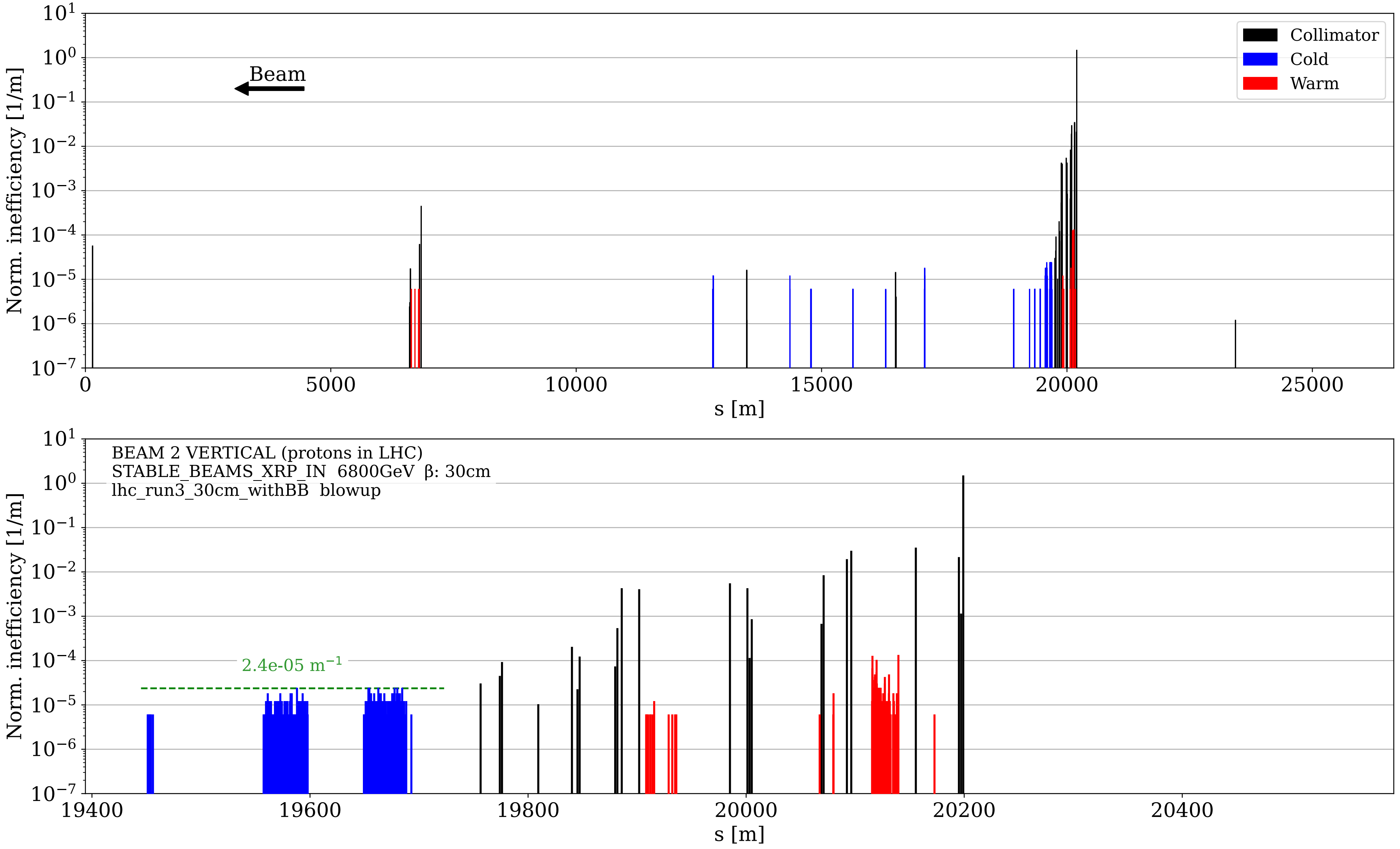
original setup

Validation of Setup with Loss Maps



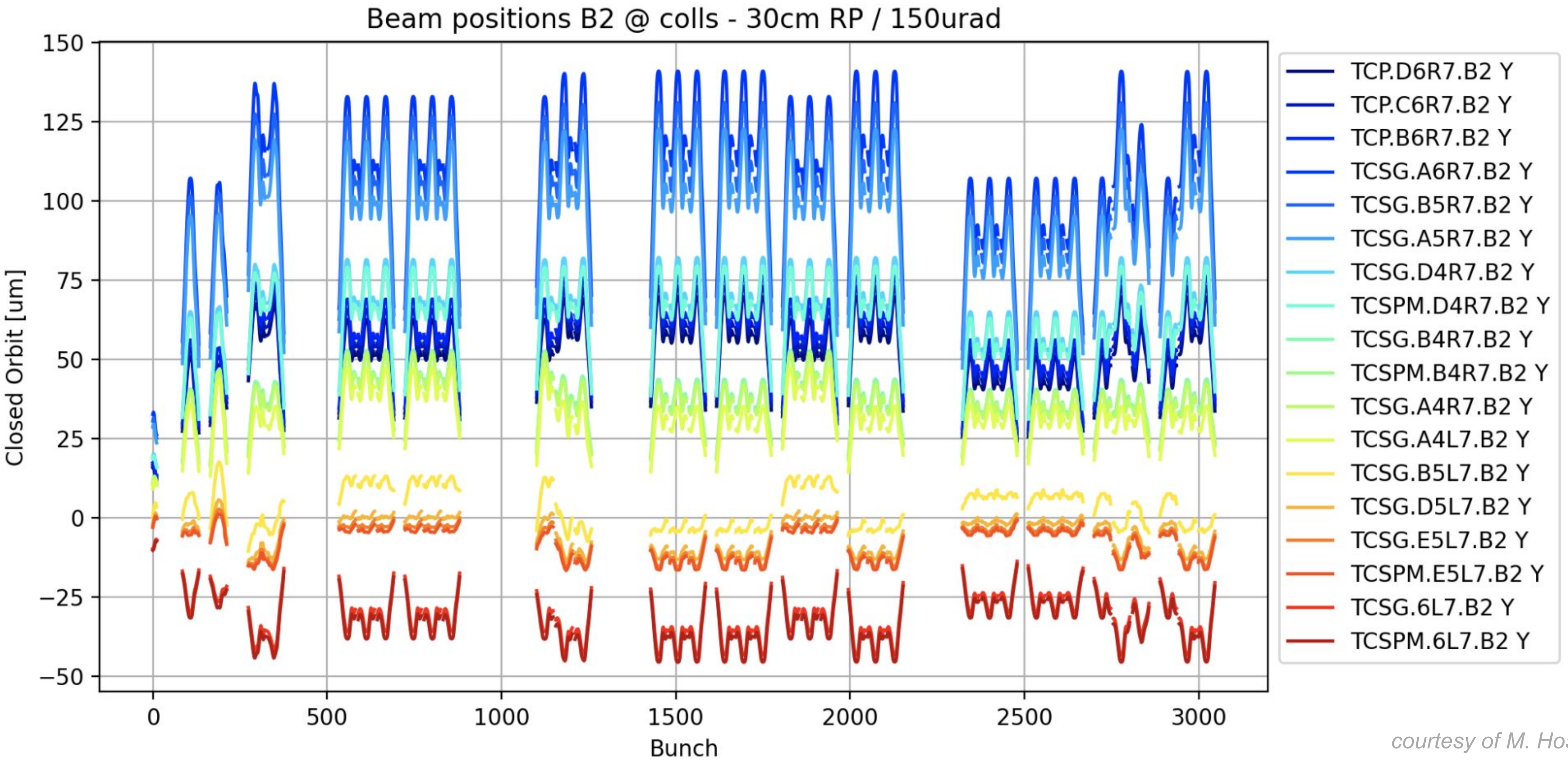
new setup
(no BB)

Validation of Setup with Loss Maps



new setup
(BB)

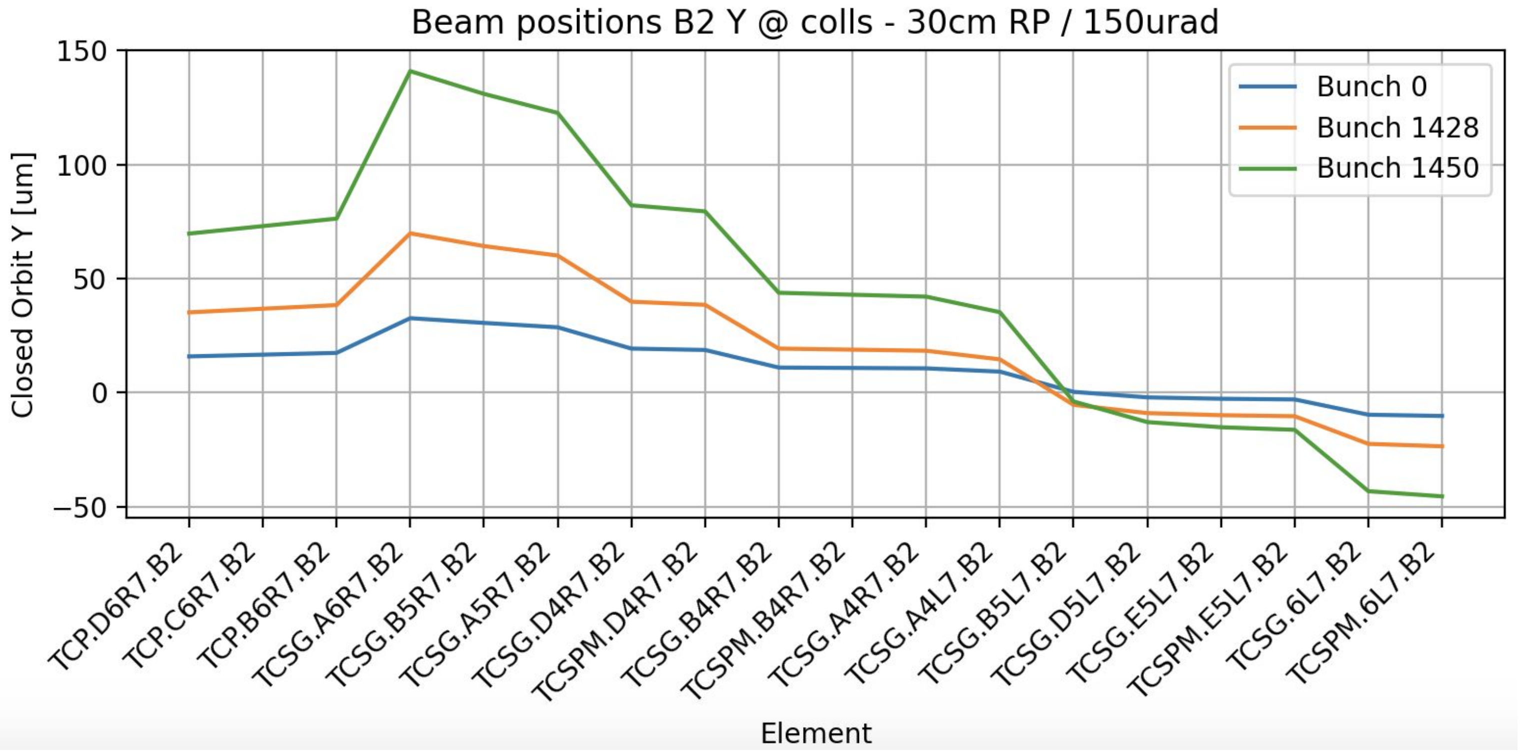
Orbit Distortion



courtesy of M. Hostettler

Orbit Distortion

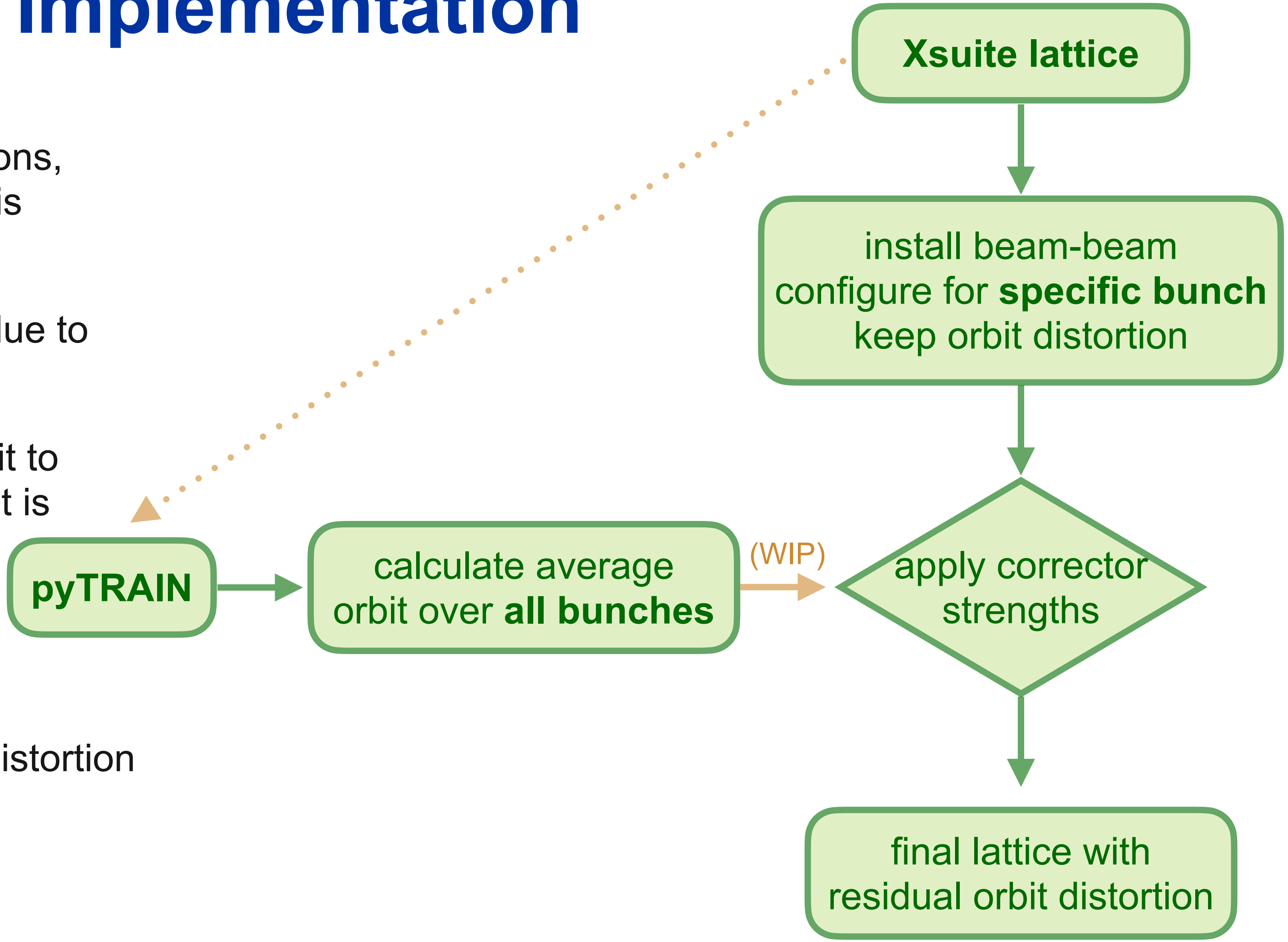
- Clear differences bunch-by-bunch
- Hierarchy becomes bunch-dependent
- This is the full effect on orbit; in practice the LHC has an **orbit feedback** system that corrects the average
- Still some orbit distortion left, up to 60um (0.25σ) between collimators



courtesy of M. Hostettler

Orbit Distortion - Implementation

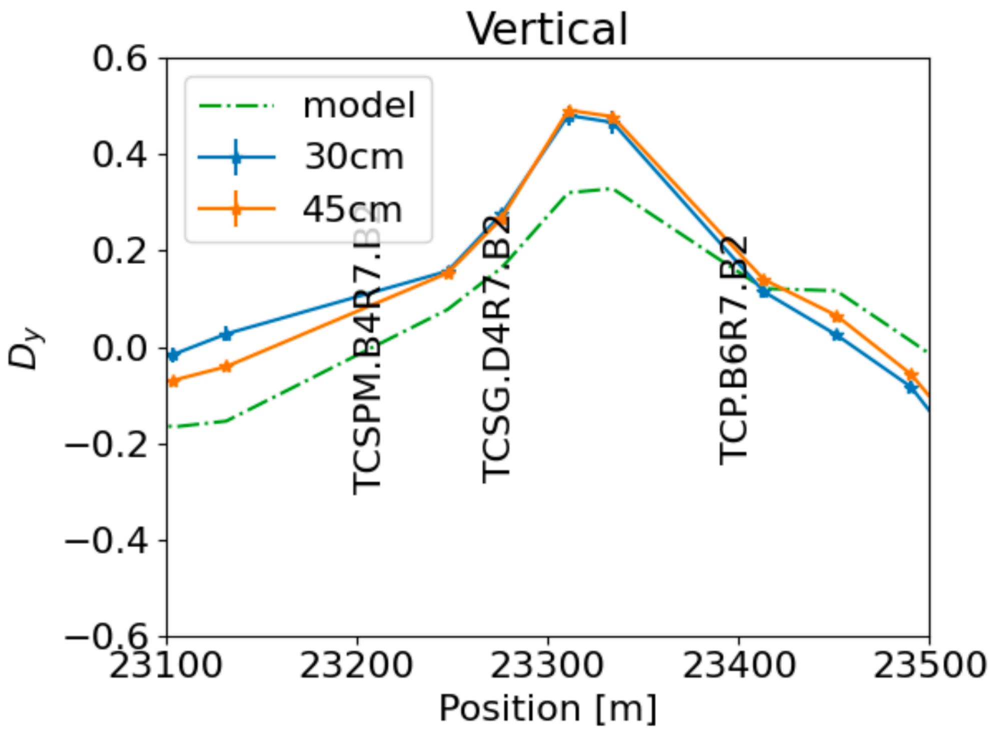
- In typical beam-beam tracking simulations, orbit distortion is **ignored** (dipolar kick is subtracted from the element)
- But full orbit distortion is **not realistic** due to orbit feedback system
- Individual bunch still sees distorted orbit to varying degree, depending on how far it is from the average
- WIP to implement a realistic orbit distortion including orbit feedback
- For now, use varying strength of orbit distortion



Spurious Vertical Dispersion

- Measured vertical dispersion in IR7 is higher than predicted from the MAD-X model, at the location of the secondary

- Mimic in simulation:
  - Installed vertical dipoles in IR7 to introduce spurious dispersion
  - Orbit is not affected, nor is dx
  - Limitation of model is that dy is affected everywhere around the ring
  - Implemented overcompensated knob



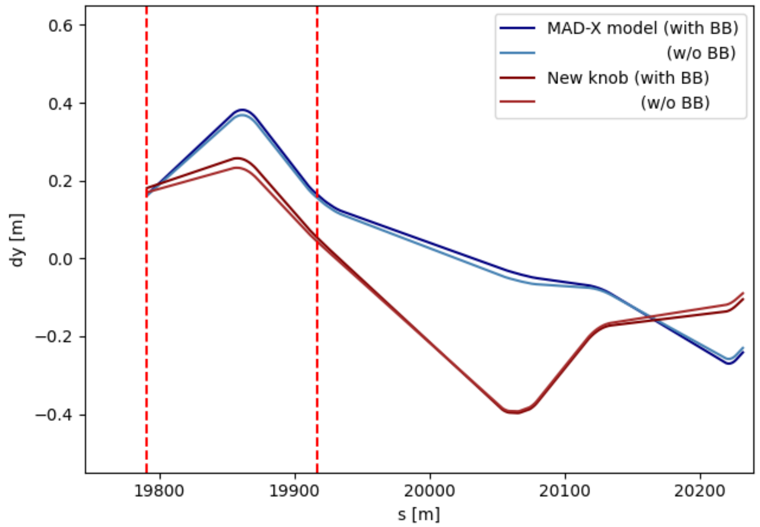
courtesy of T. Persson

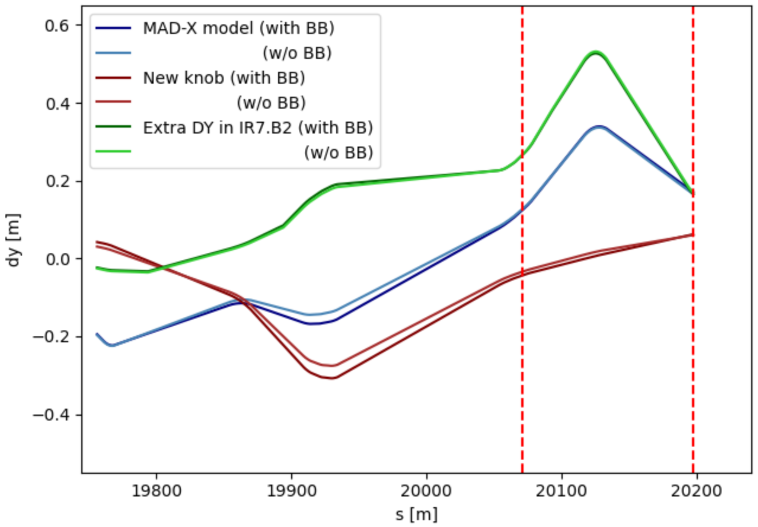
Spurious Vertical Dispersion

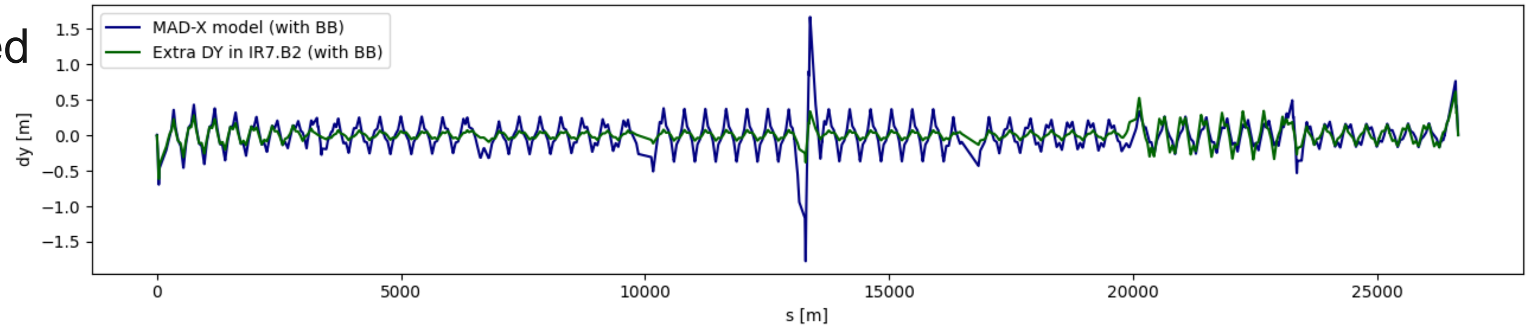
- Measured vertical dispersion in IR7 is higher than predicted from the MAD-X model, at the location of the secondary

- Mimic in simulation:
  - Installed vertical dipoles in IR7 to introduce spurious dispersion
  - Orbit is not affected, nor is dx
  - Limitation of model is that dy is affected everywhere around the ring
  - Implemented overcompensated knob

Vertical dispersion in IR7







Outline

Collimation at the LHC

Hierarchy Breaking

Simulations with Collimation and Beam-Beam

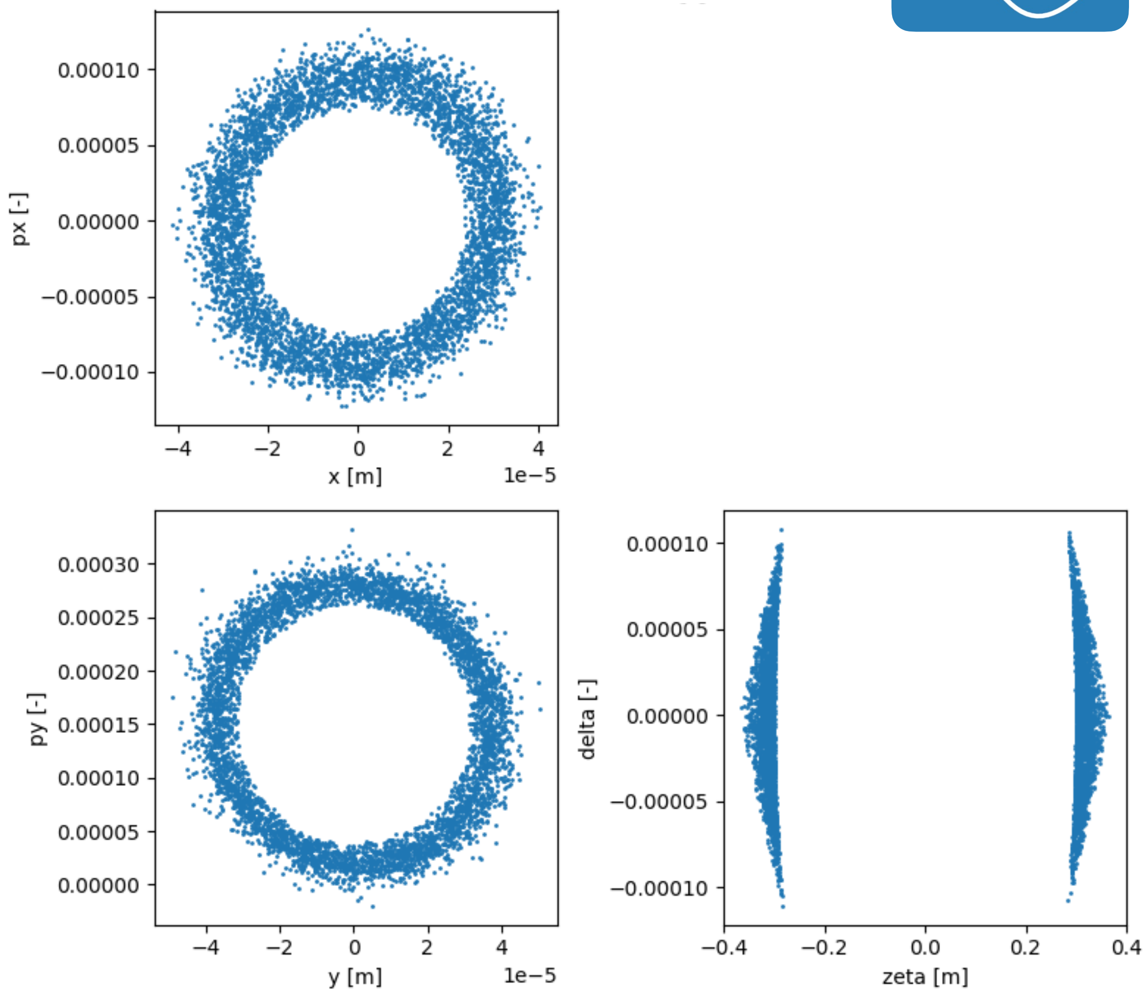
Simulation Results

Initial Particle Distribution

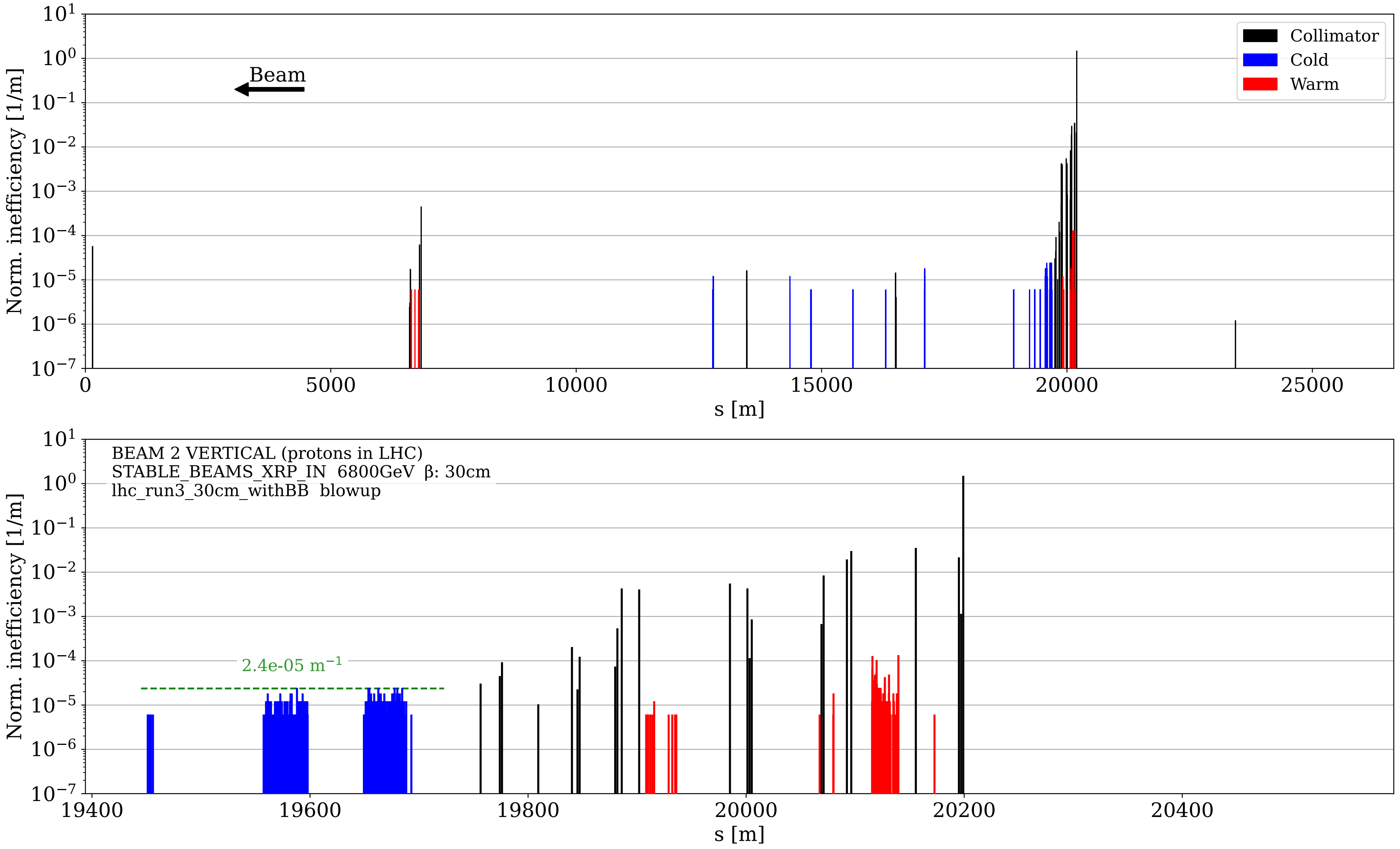
- Outer shell of particles:
  - Horizontal between 3 and 4 sigma (norm. amplitude)
  - Vertical > 4 sigma (norm. amplitude)
  - Zeta > 28cm (delta matched)

- Start with very soft (realistic-type) blow-up for 500 turns
  Let evolve for 9500 turns more

- Validate this setup with loss map simulation



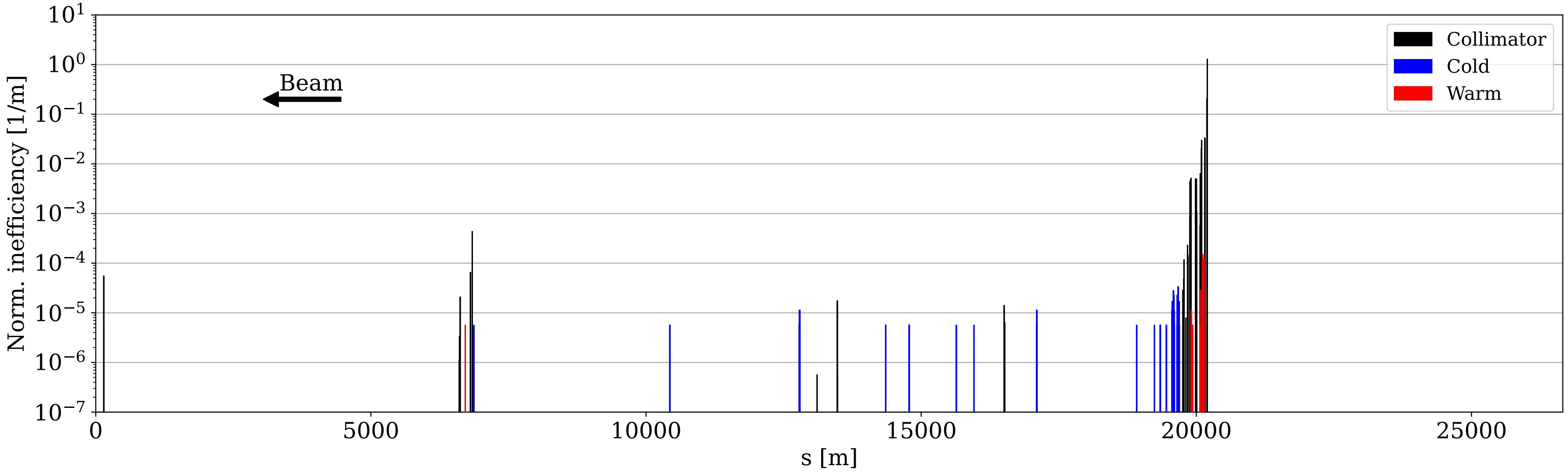
Validation of Initial Distribution with Loss Maps

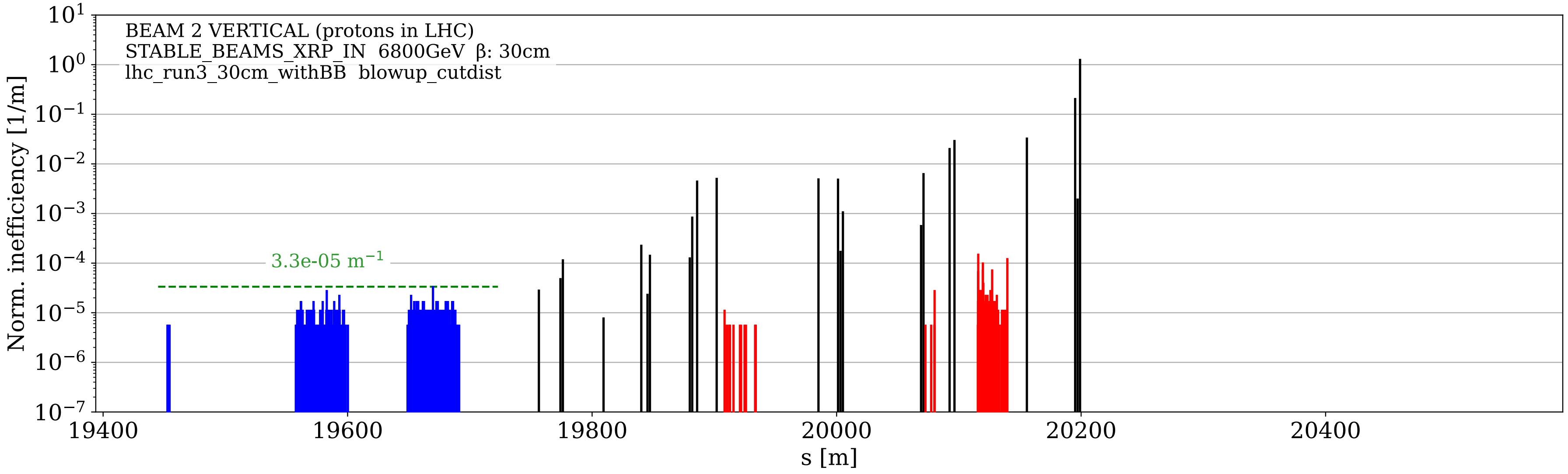


new lattice
(BB)

blow-up

Validation of Initial Distribution with Loss Maps





new lattice
(BB)

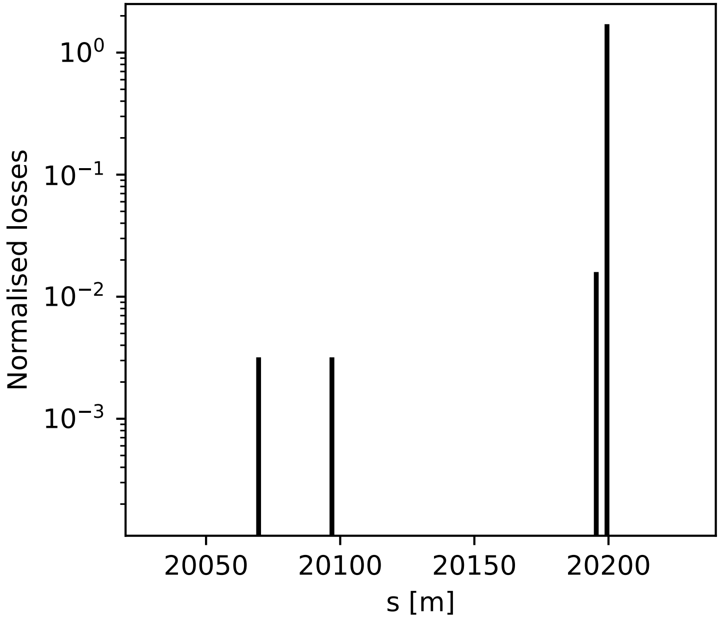
shell with blow-up

Simulation Setup

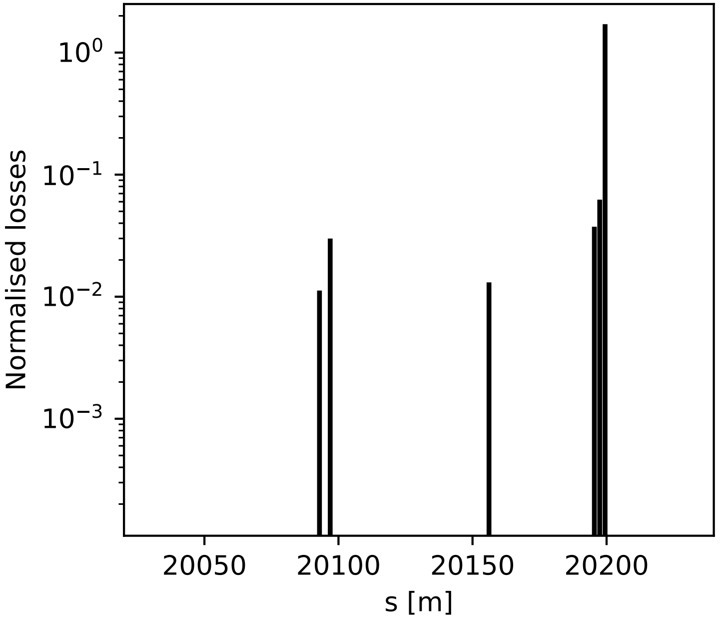
- 2024 optics, beta* = 30cm
- Bunch intensity as levelled (1.29 e11 p/b)
- Tunes: (62.315, 60.320)
- Cromaticity: 7 - 10 - 20
- Octupoles: 200A - 300A - 400A
- Residual uncorrected coupling Re[C-] = 0.001
- Vertical dispersion:
  - on_disp nominal, on_disp overcompensated by 100urad
  - with/without extra dispersion in IR7
- Beam-beam configured for worst bunch (beta-beating automatically taken into account)
- Beam-beam orbit distortion subtraction rescaled by: 1 (default) - 0.5 - 0.2 - 0 (full distortion)

Some preliminary results shown
(though low statistics)

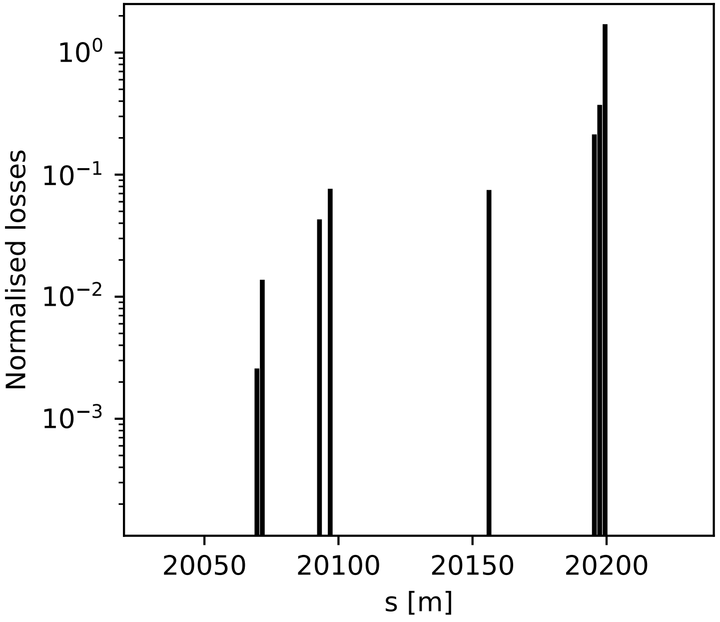
Results: Effect of Beam-Beam and Chroma



no beam-beam
chroma 7
octupoles 400

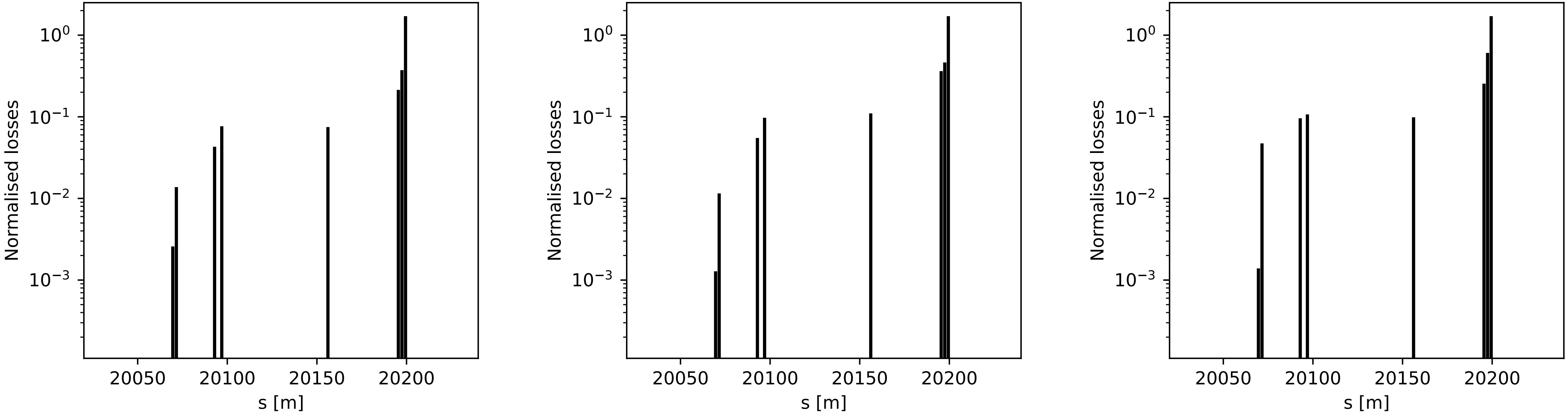


beam-beam
chroma 7
octupoles 400



beam-beam
chroma 20
octupoles 200

Results: Effect of Orbit Distortion

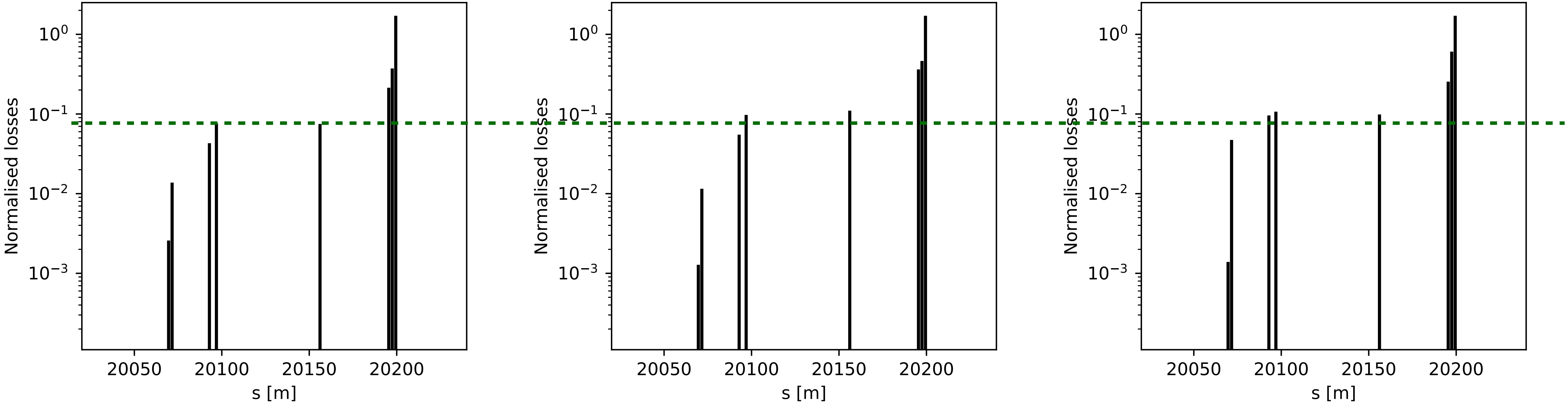


beam-beam
chroma 20
octupoles 200
orbit distortion rescaling 1

orbit distortion rescaling 0.5

orbit distortion rescaling 0.

Results: Effect of Orbit Distortion



beam-beam
chroma 20
octupoles 200
orbit distortion rescaling 1

orbit distortion rescaling 0.5

orbit distortion rescaling 0.

Conclusions and Outlook

- First setup for collimation simulations with beam-beam
- Lattice generation validated, orbit distortion (orbit feedback with pyTRAIN) is work in progress
- So far, not able to reproduce the hierarchy breaking, though clear hierarchy worsening
- Typical for simulations to have more losses on primary => investigations ongoing

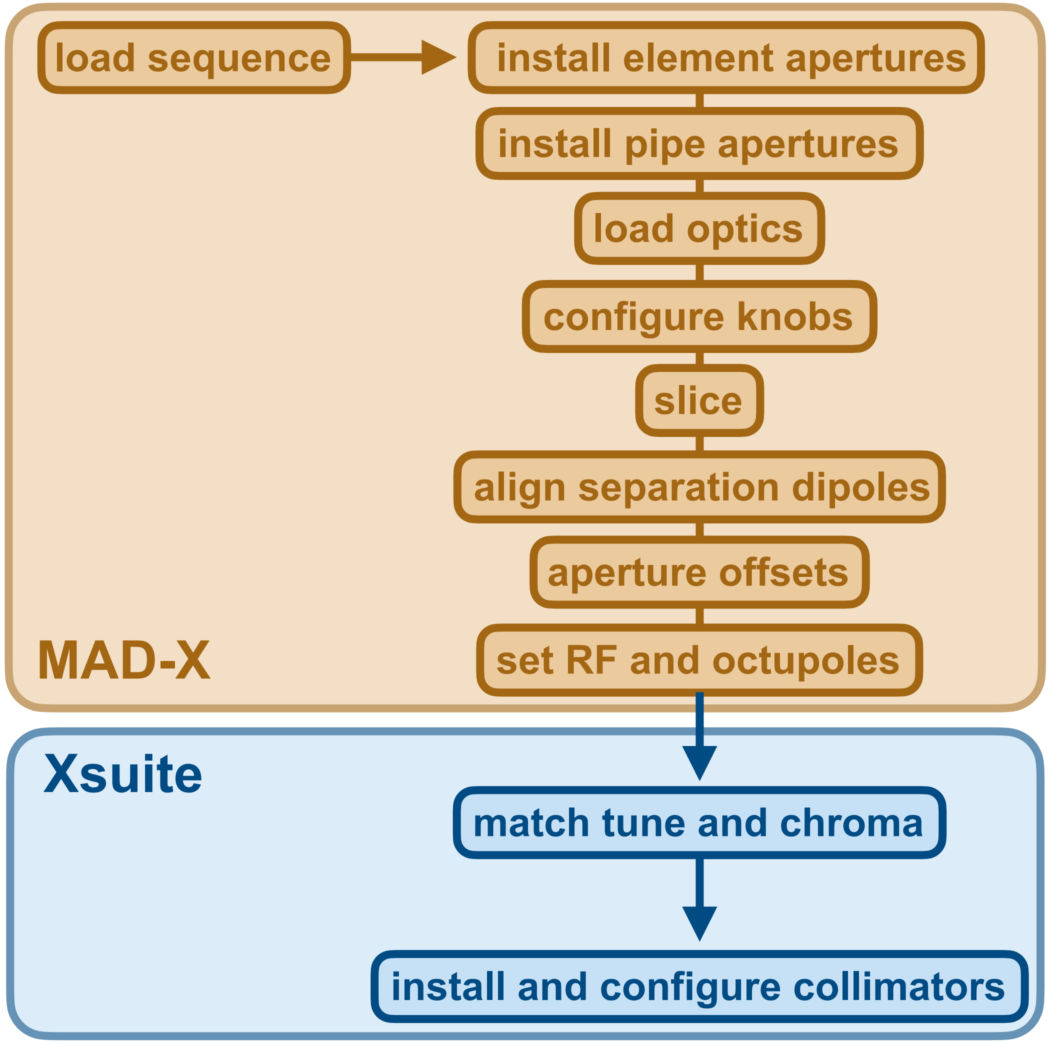
- **TODO:**
  - Finish orbit feedback implementation with pyTRAIN
  - Aperture scripts (offset and patches)
  - Explore parameter scan and different bunches, and increase statistics

home.cern

Backup Slides

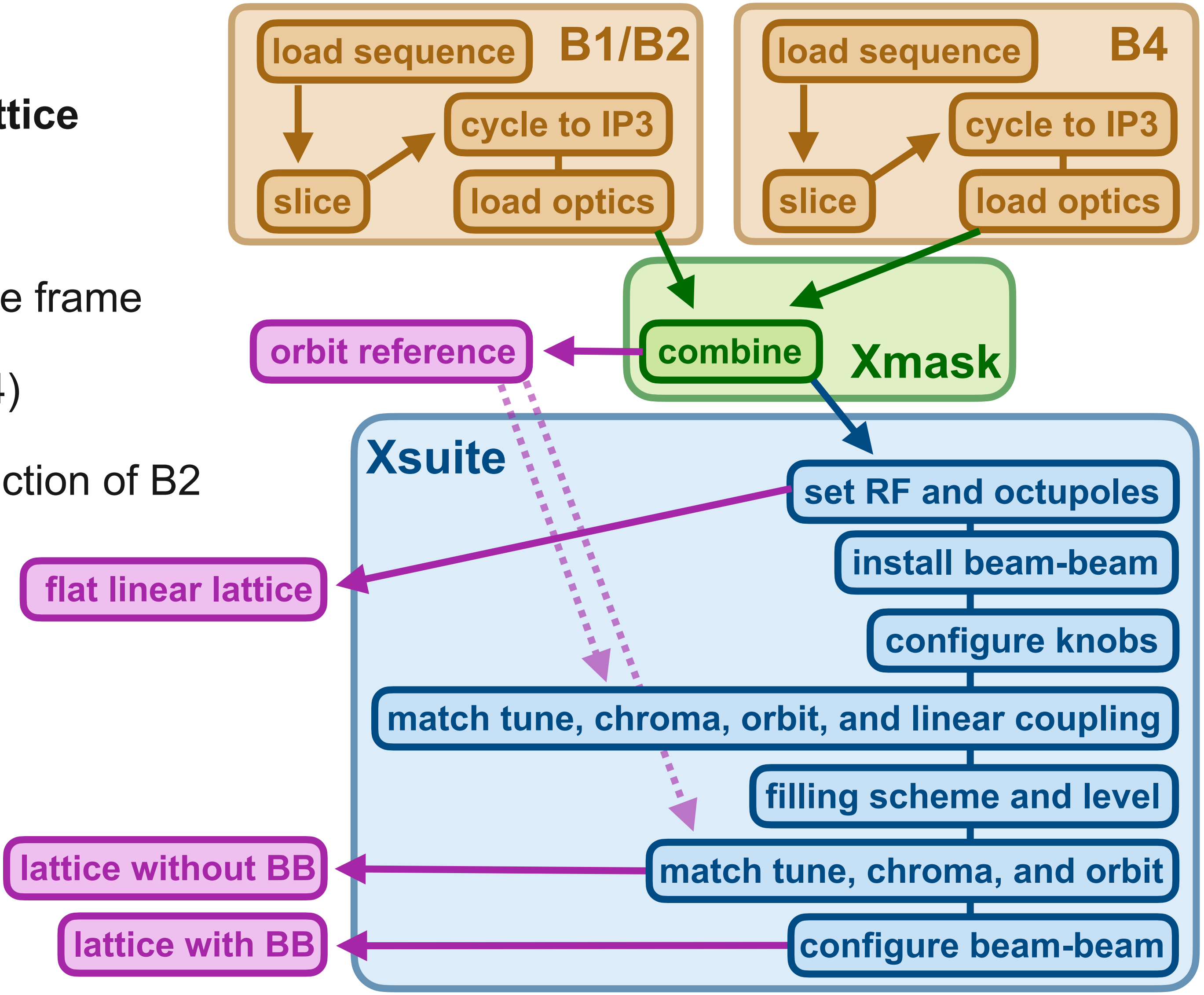
Tracking Simulations with Aperture and Collimation

- Collimation simulations use:
  - no magnet inhomogenities or other non-linearities
  - but allow non-zero chromaticity and octupoles
- When creating the lattice in MAD-X, care has to be taken to install apertures and align them (negative drifts etc)
- Lot of work goes into **maintenance of aperture models**
- Collimators are installed and configured at the last step, just before tracking
- Matching can be done in MAD-X or Xsuite



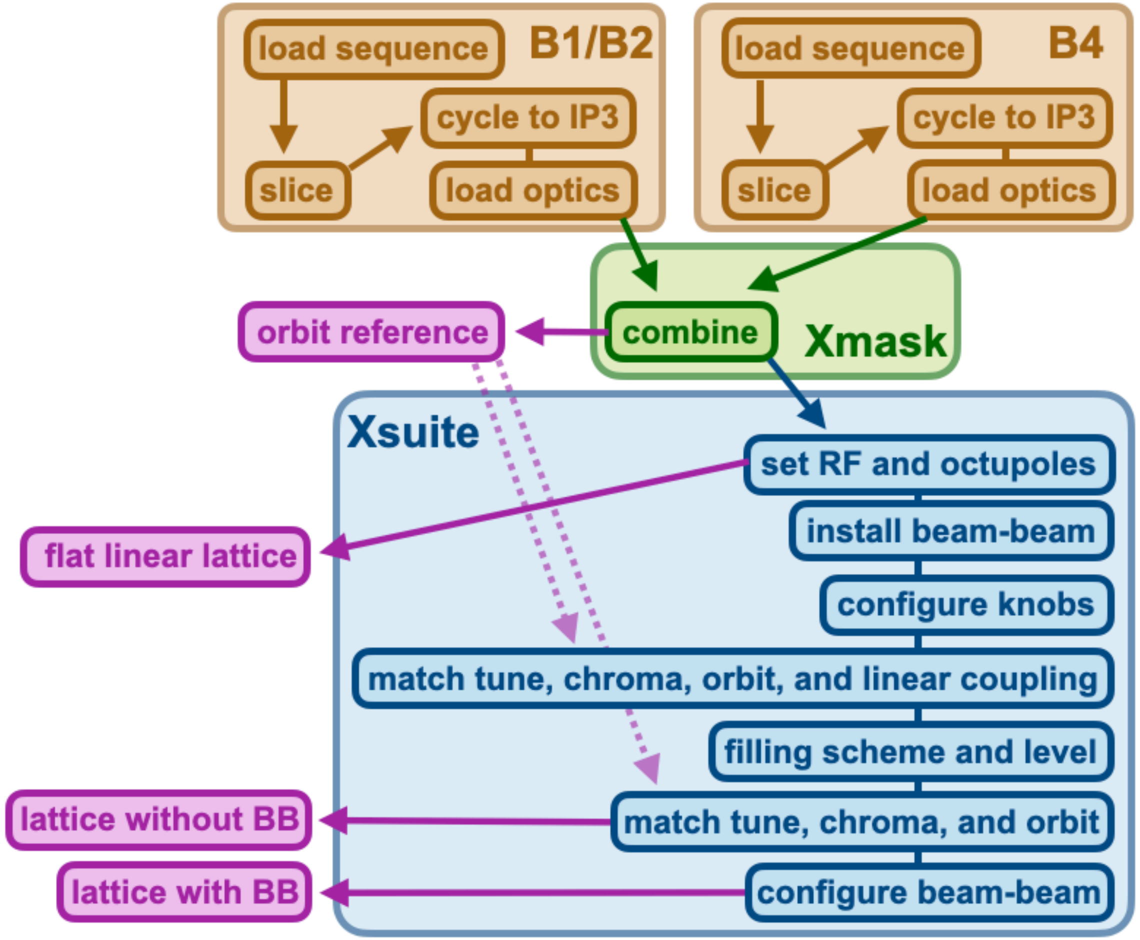
LHC Tracking Simulations with Beam-Beam

- Beam-beam simulations use a very **non-linear lattice**
- Need **two lattices** in parallel:
  - a lattice with both beams in the same reference frame
  - a lattice with beam 2 in the opposite frame (B4)
  - both lattices need to be in-sync: B4 exact reflection of B2 (this does not play well with aperture scripts)
- **Cycling to IP3** is necessary (to be able to install and configure beam-beam)
- **Orbit reference** is stored early-on



Tracking Simulations Combining Both

- Basic idea: replace MAD-X part in BB simulations by MAD-X part from collimation simulations, **but...**



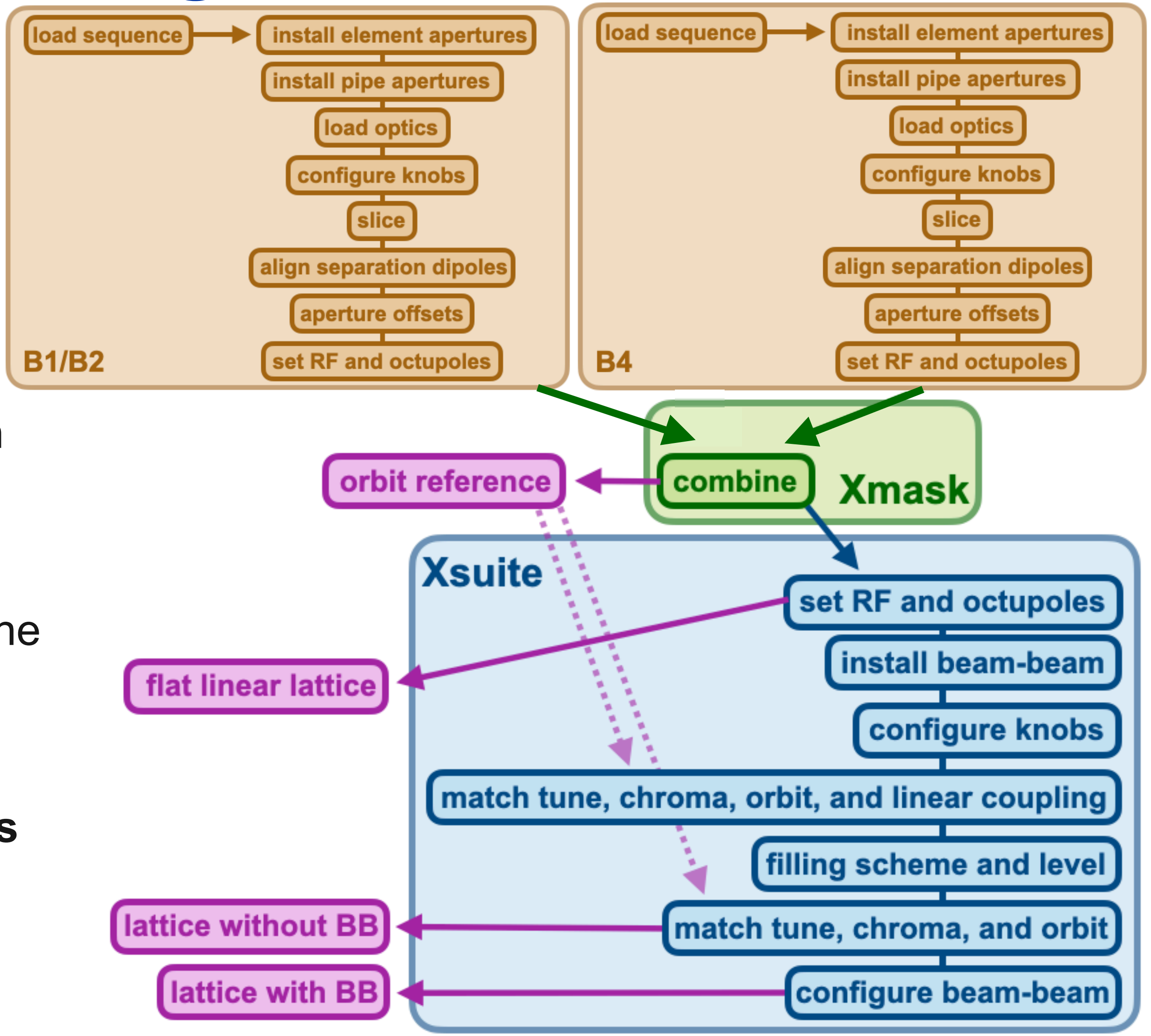
Tracking Simulations Combining Both

- Basic idea: replace MAD-X part in BB simulations by MAD-X part from collimation simulations, **but...**

- Aperture scripts require a lot of **manual patching**, which does not work with the BB scripts!
  => **aperture patcher script** in post-processing

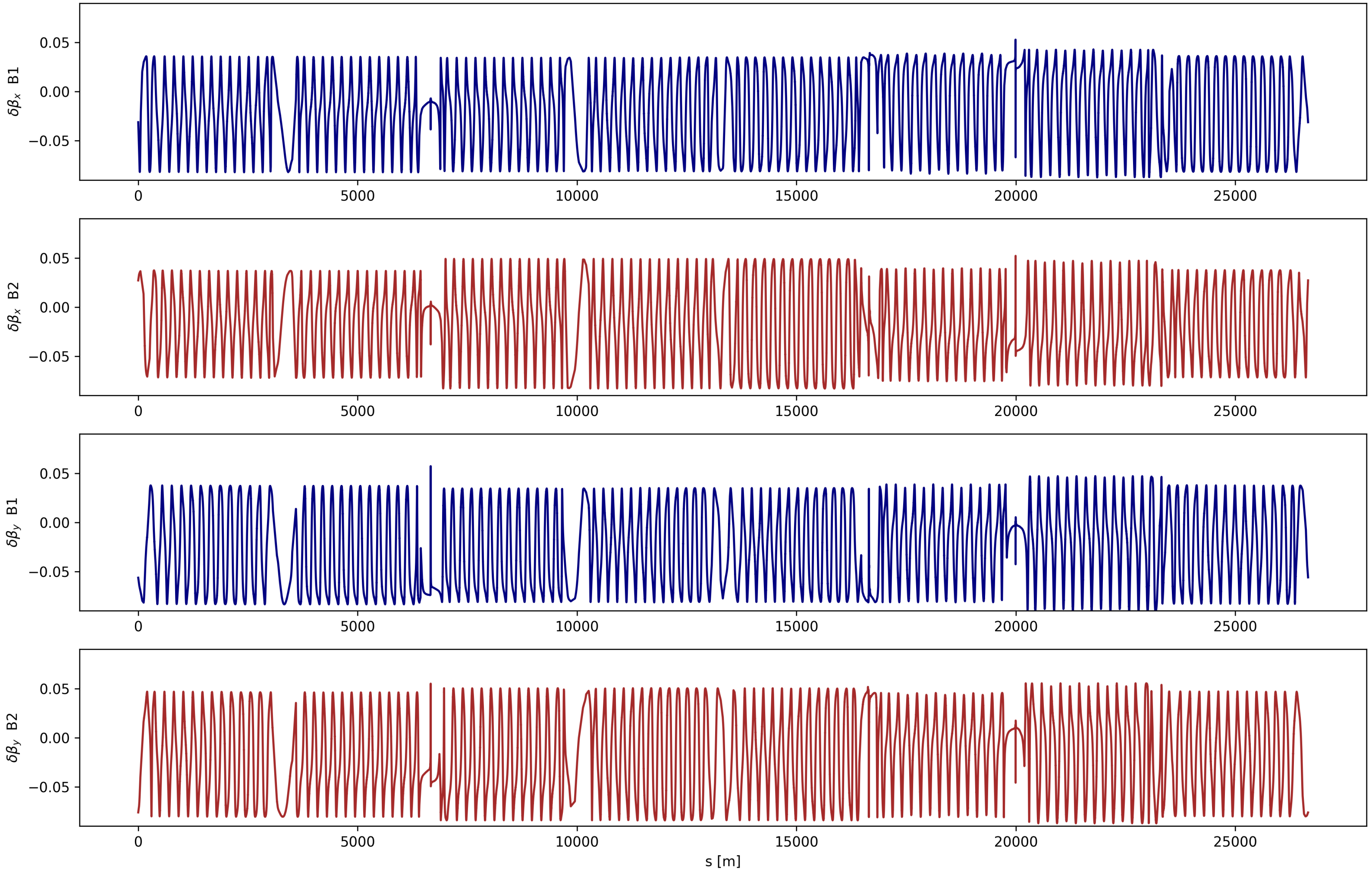
- Aperture **offsets** cannot be correctly reflected to B4 as the current implementation uses dedicated variables.
  => move the offset scripts to python (WIP)

- Collimator installations sometimes **clash with BB lenses**
  => injection protection hence not installed (patch)
  => redefine BB installation to avoid clashes (WIP)

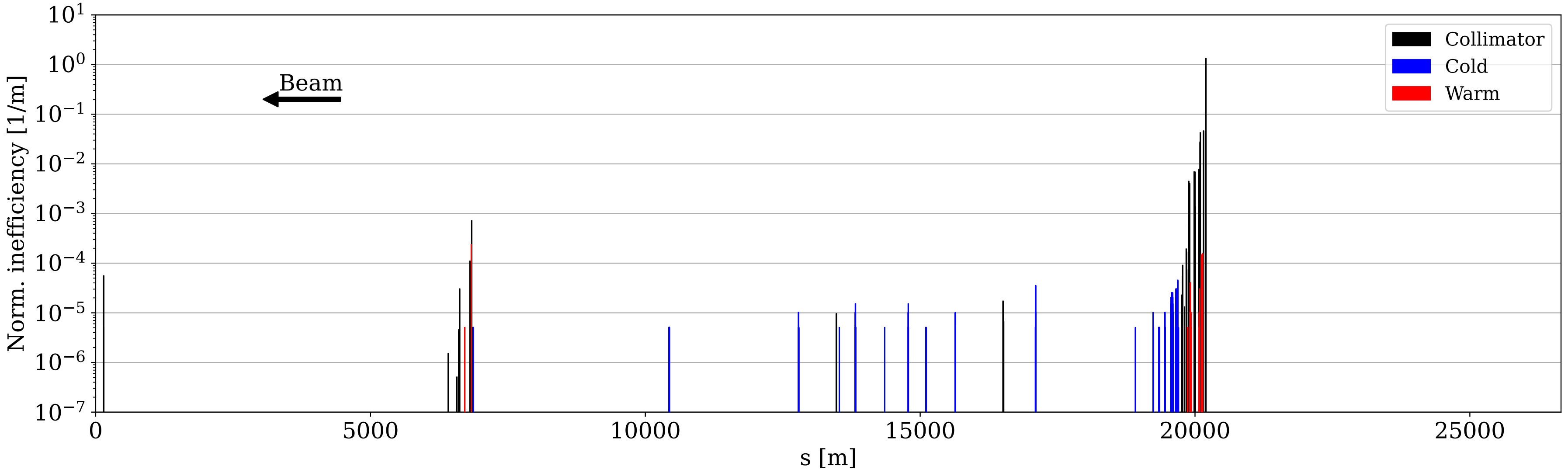


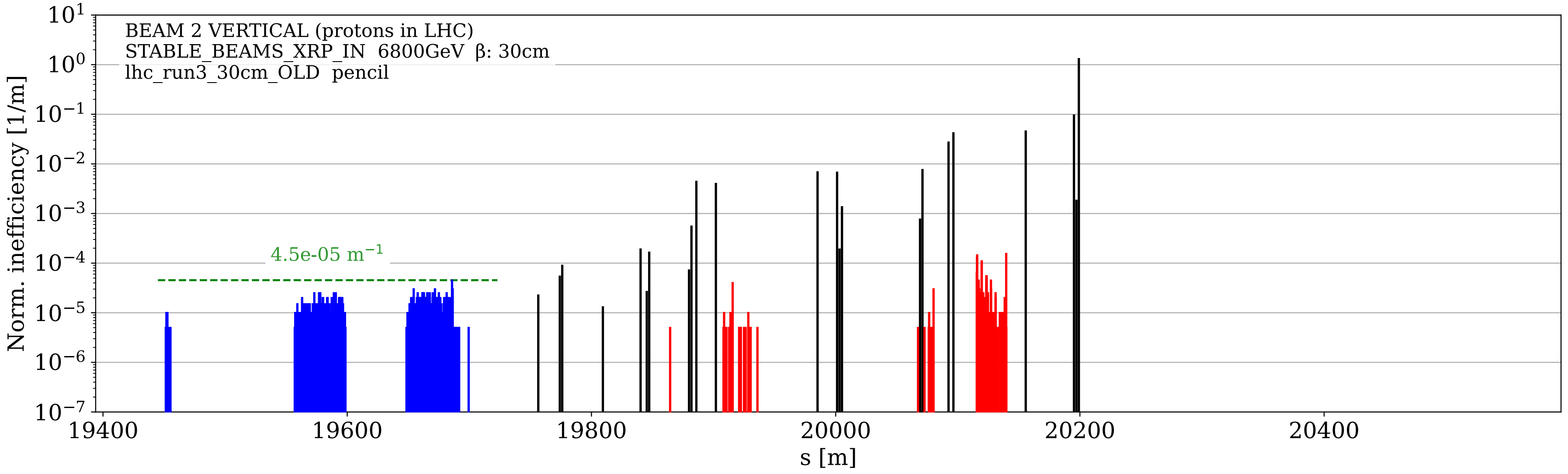
Validation of Lattice Generation

- **Orbit** is always verified at the lattice generation
- Similarily, the matching of **tune** and **chroma** is verified before finalisation of the lattice
- **Beta-beating** has been investigated and found compatible with expected values for beam-beam simulations



Validation of Setup with Loss Maps

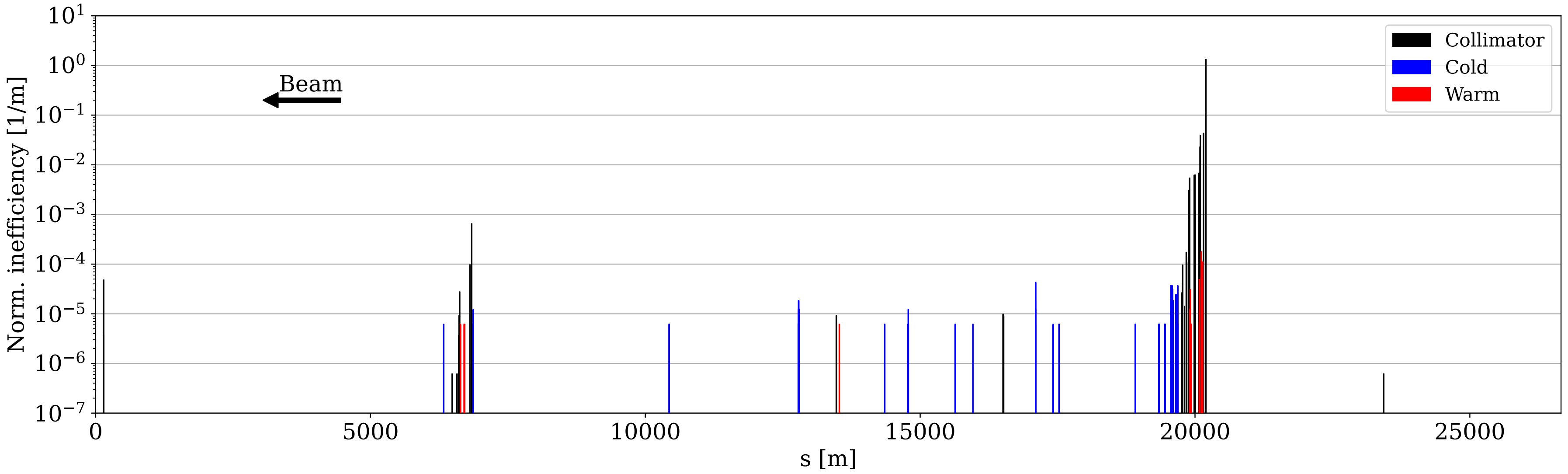


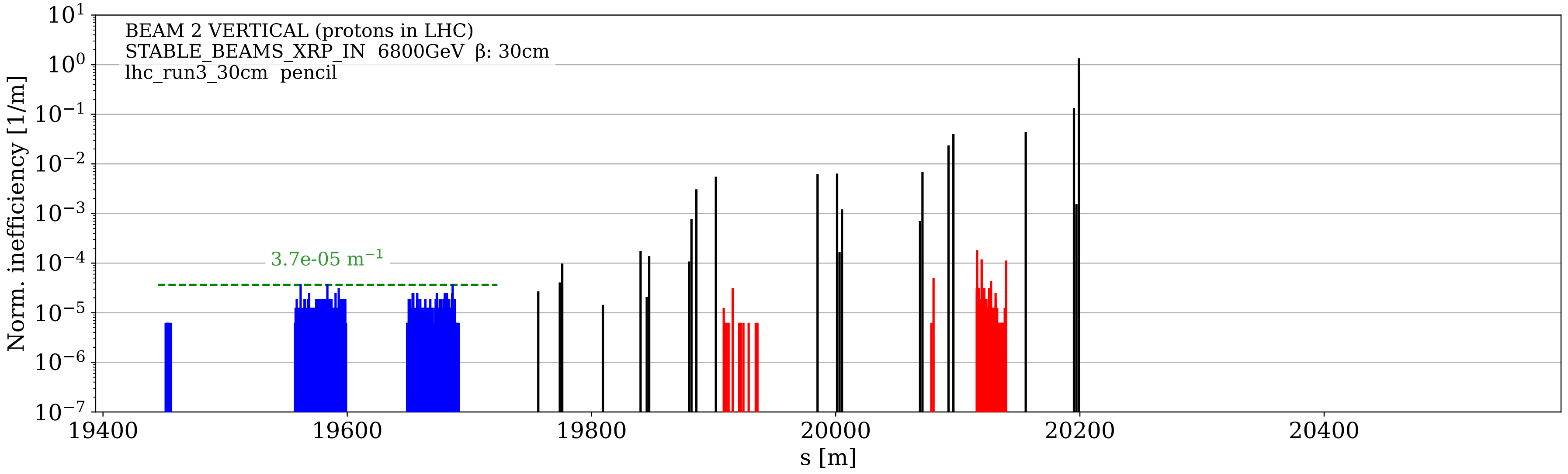


old lattice

pencil beam

Validation of Setup with Loss Maps

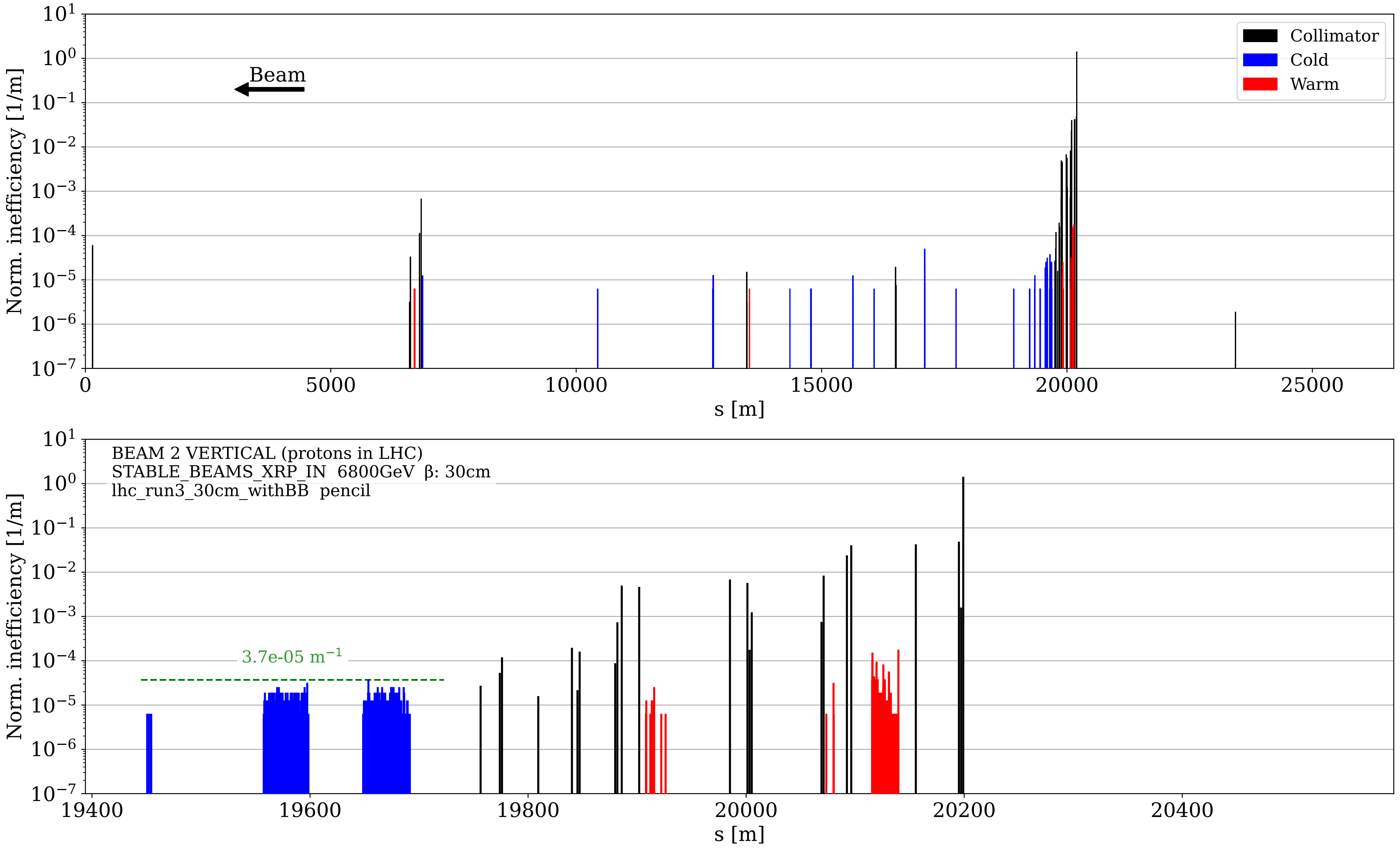




new lattice
(no BB)

pencil beam

Validation of Setup with Loss Maps



new lattice
(BB)

pencil beam

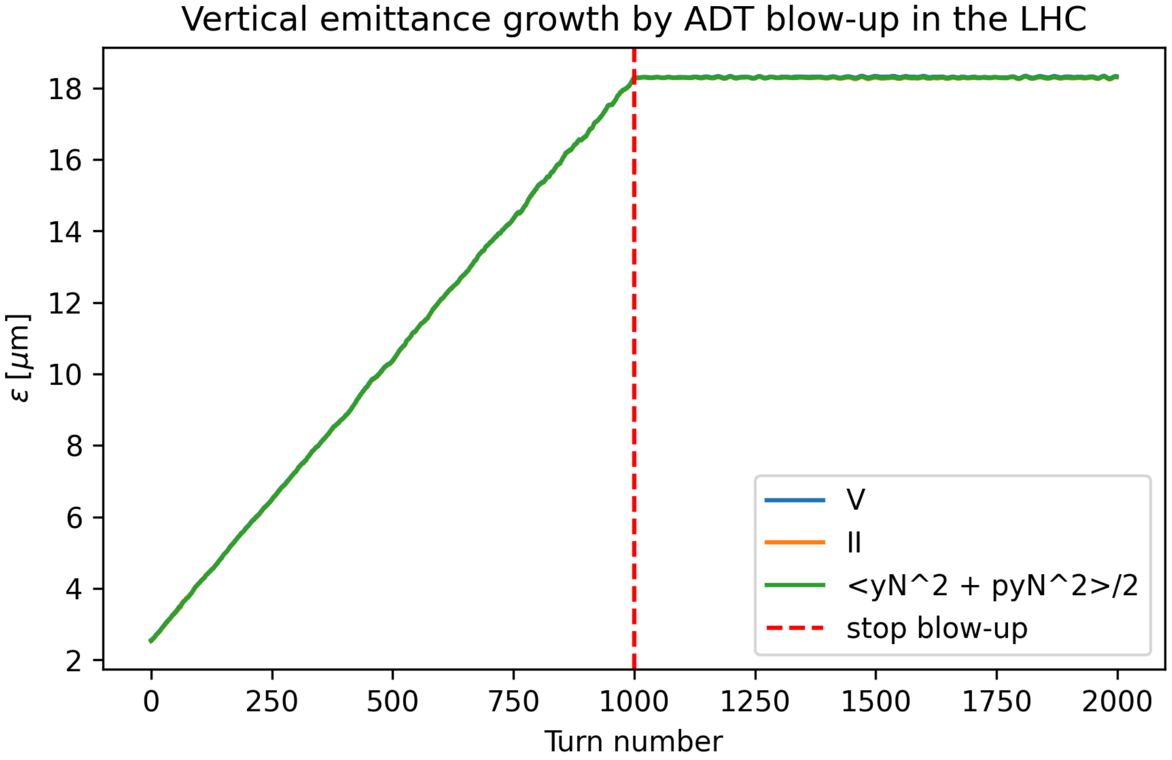
New Tools: EmittanceMonitor and BlowUp

- `EmittanceMonitor:`
  - Logs emittance per turn (geometric & normalised, plane-by-plane and orthogonal modes)
  - GPU-friendly

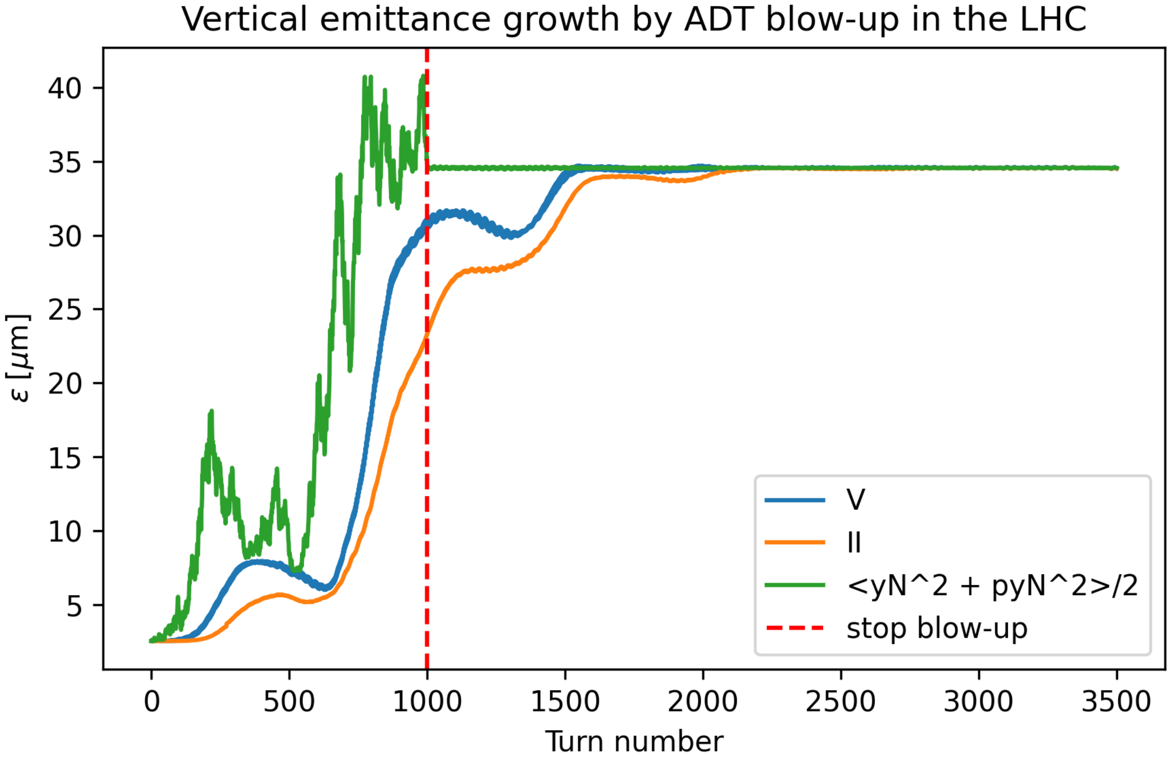
- `BlowUp:`
  - Adds random kicks to particles to induce emittance growth
  - Two modes:
    - *random kick per particle* (quick smooth blow-up)
    - *random kick per bunch* (more realistic)

New Tools: EmittanceMonitor and BlowUp

random kicks per particle



random kicks per bunch



New Tools: EmittanceMonitor and BlowUp

- The beam is shaken around and is no longer matched
- In other words: coordinate covariances do not relate to beam parameters anymore
- After blow-up, beam needs time to decohere again (1000 turns of blow-up; 1500 turns of relaxation time)
- Emittance calculation based on normalised coordinates is less correct for unmatched beam

random kicks per bunch