Accelerator Physics Studies for Future Neutrino Projects

Androula Alekou
CERN

Outline

- Neutrino Oscillations Theory
- Neutrino Factory (NF)
    - Muon ionization cooling
    - Reference NF cooling lattice
    - Bucked Coils Lattice
    - Results
- LAGUNA-LBNO
    - High Power Proton Synchrotron (HP-PS)
    - Orbit Correction
    - Collimation
    - Results and future optimizations
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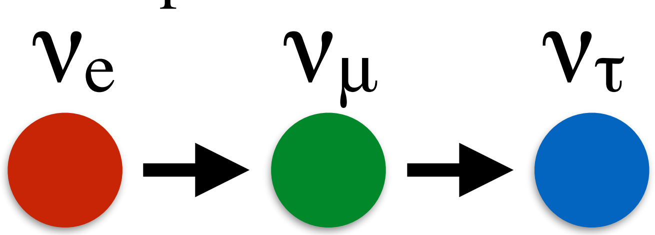

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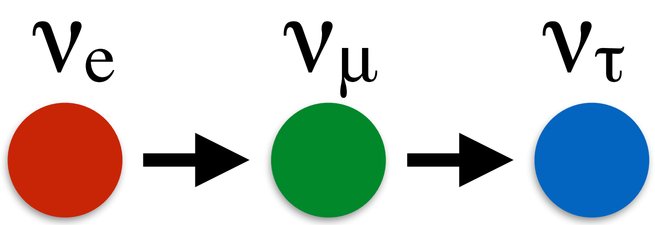

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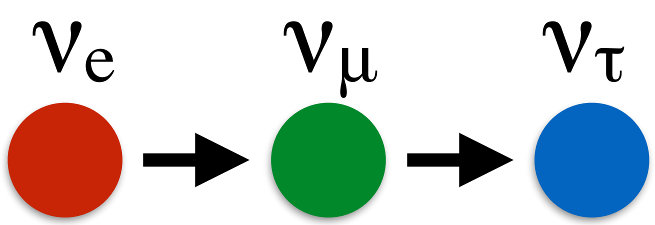

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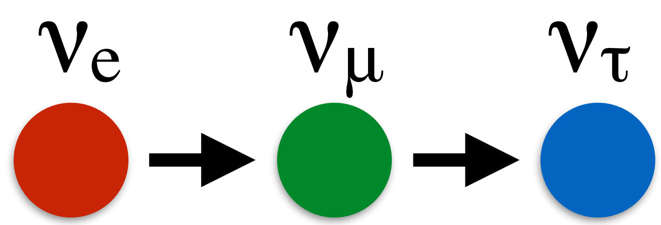

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- Neutrinos oscillate because their flavor eigenstates α (α=e, μ, τ) are superpositions of mass eigenstates (i=1, 2, 3): $|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$

L: distance neutrinos travel

E: neutrino energy

U_{ai}: PMNS mixing matrix

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We don't know: $\Delta m^2_{23}>0$ or $\Delta m^2_{23}<0$

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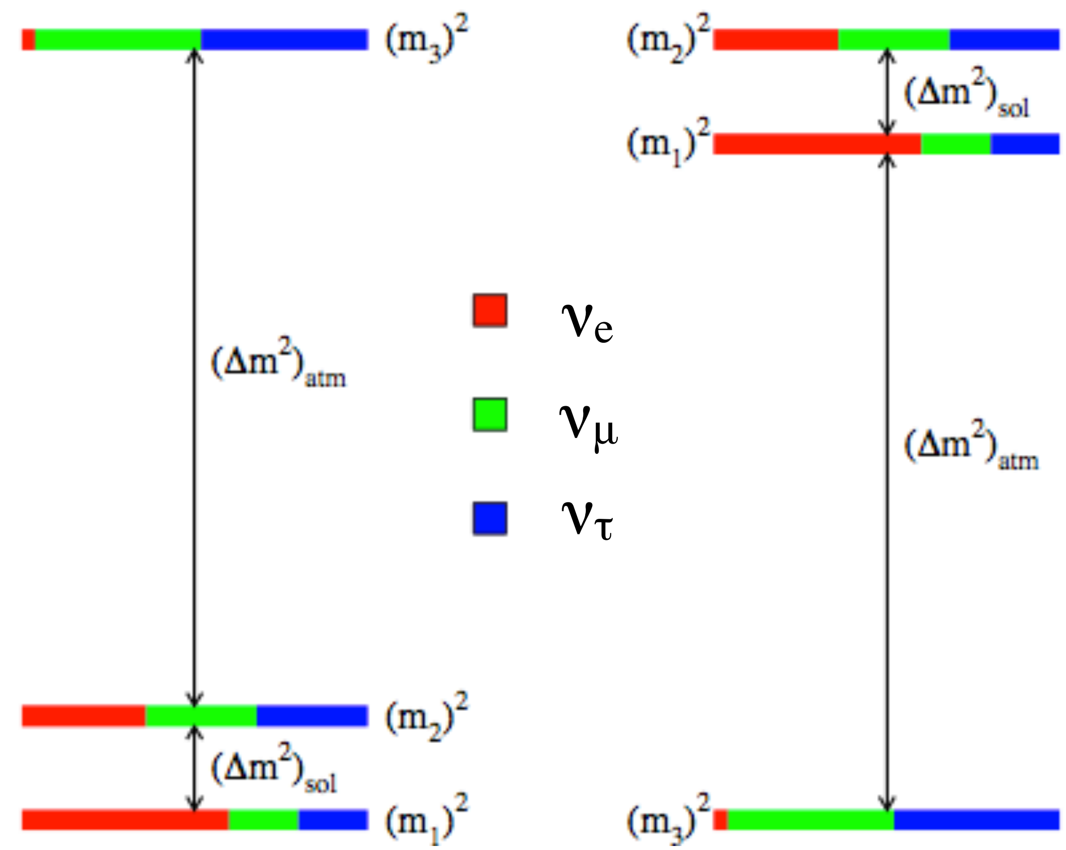
- if $(m_2)^2>(m_1)^2>(m_3)^2$: inverted hierarchy



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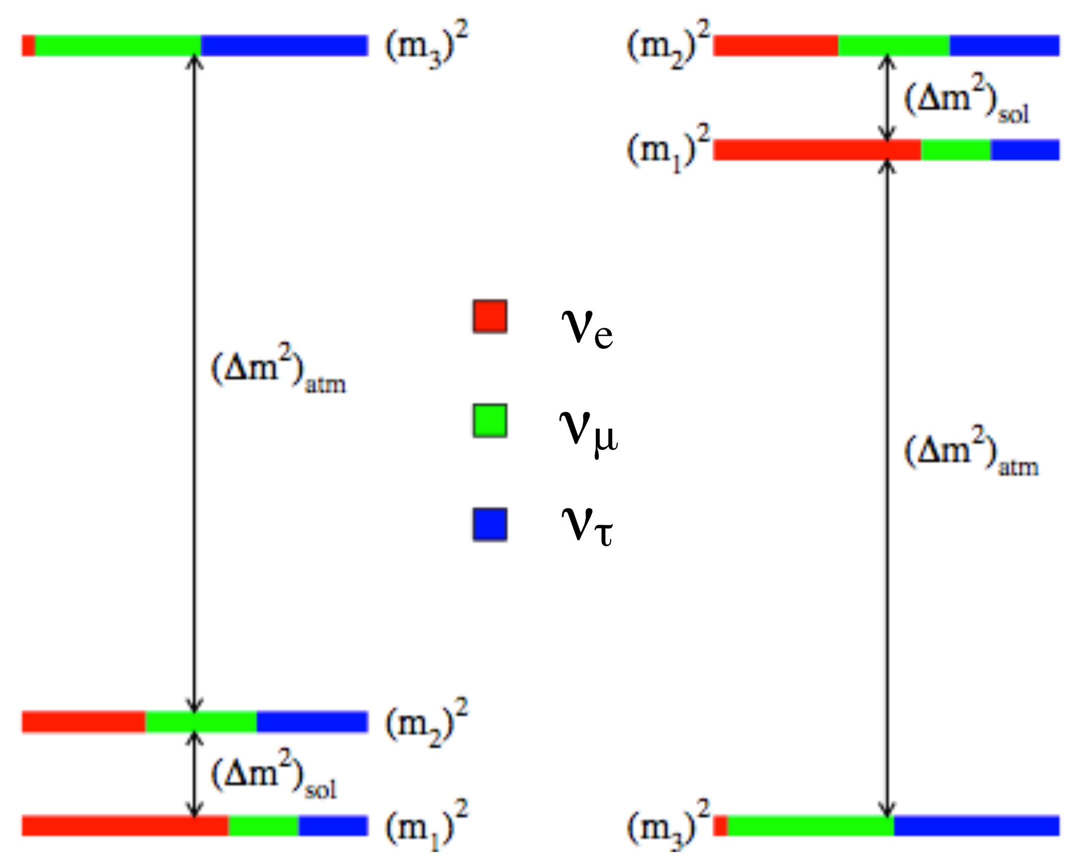

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What still needs to be determined:
δ and mass hierarchy (sign of Δm^2_{23})

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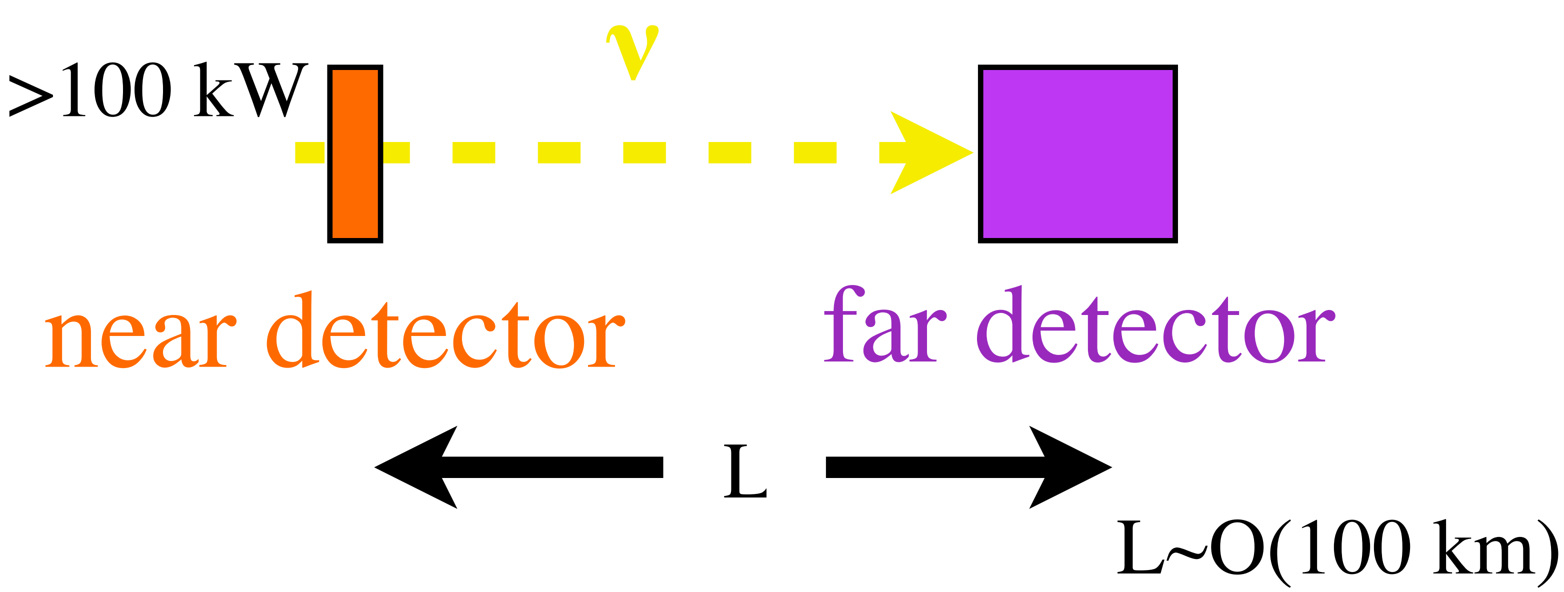

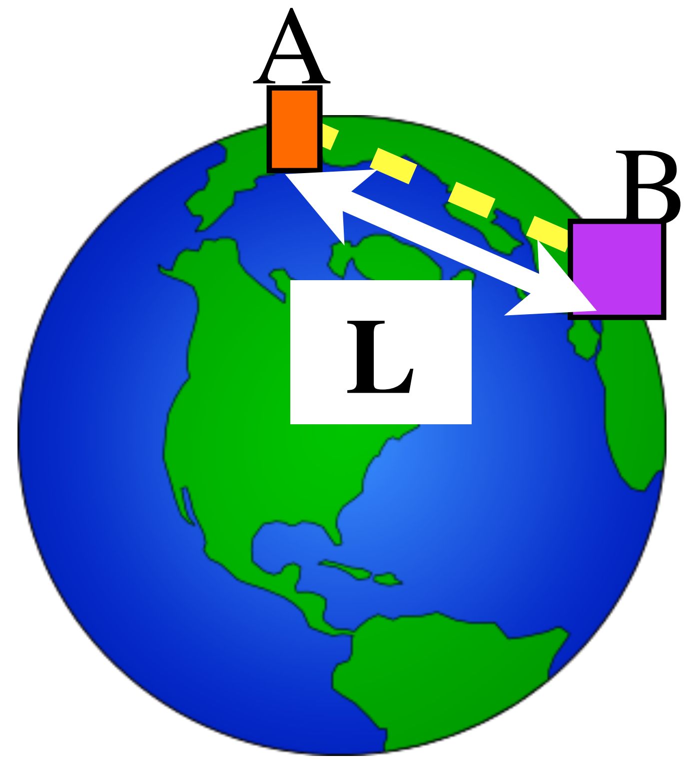

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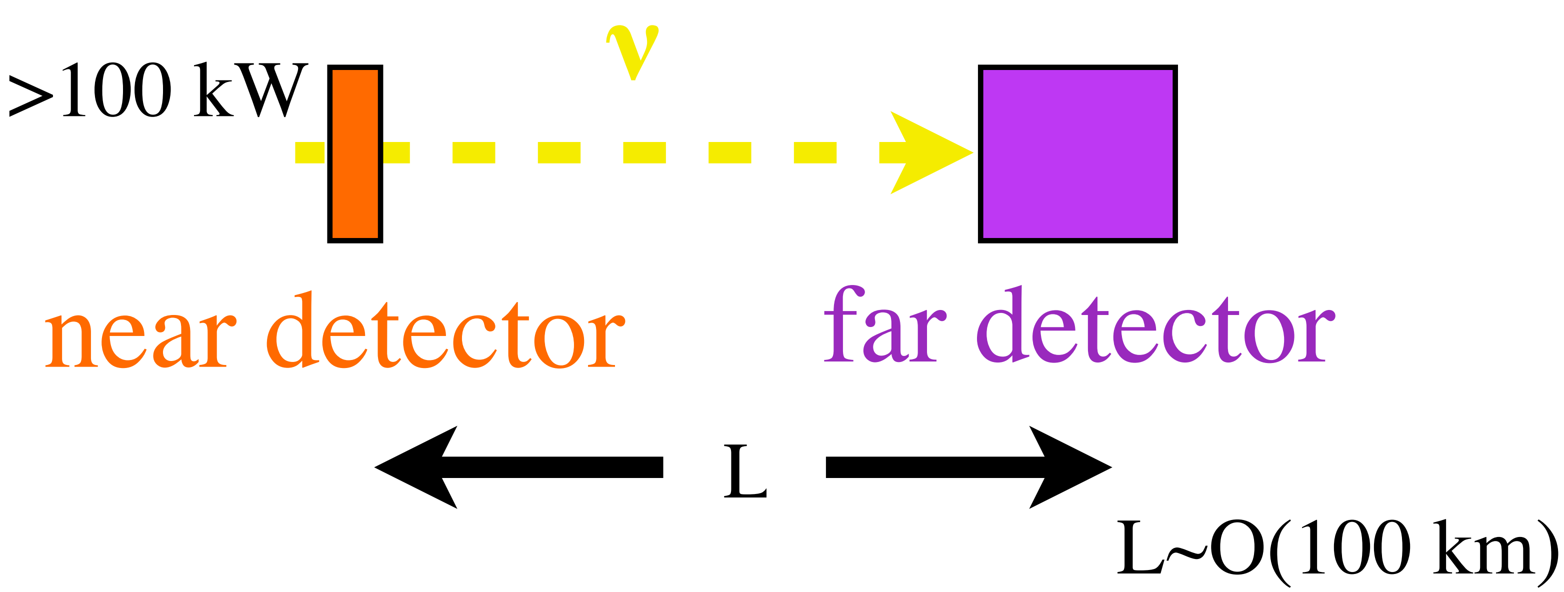

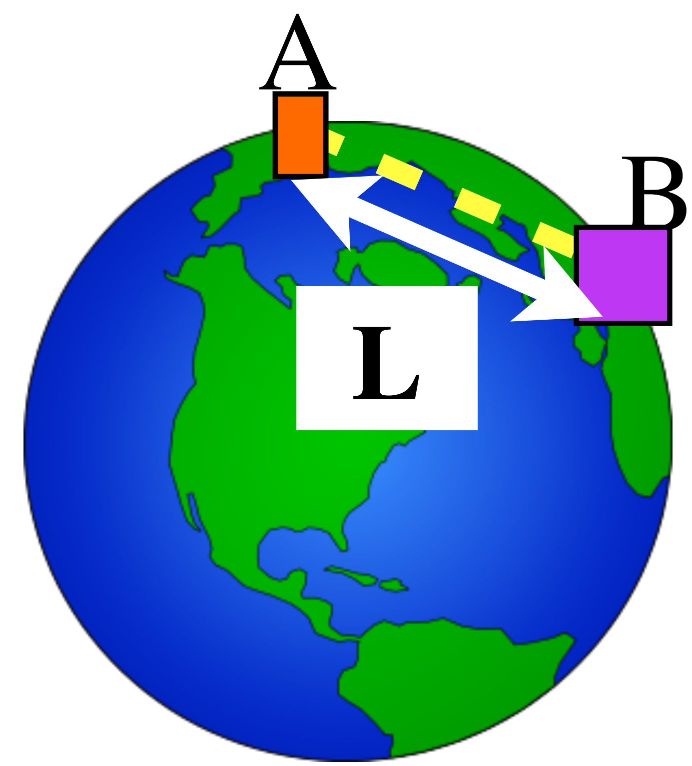

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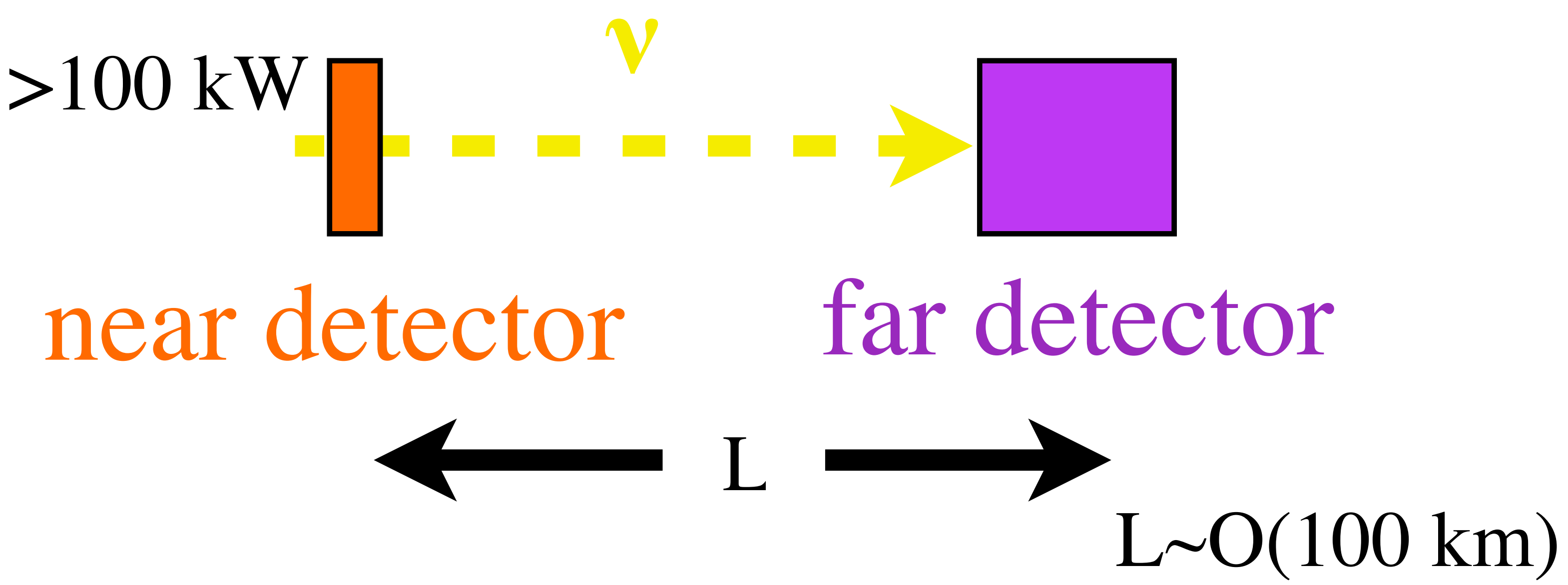

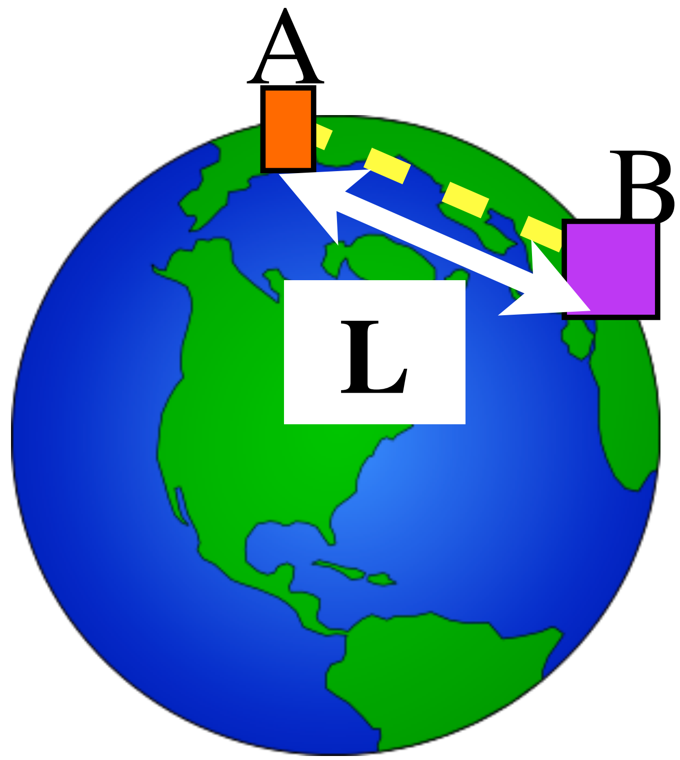

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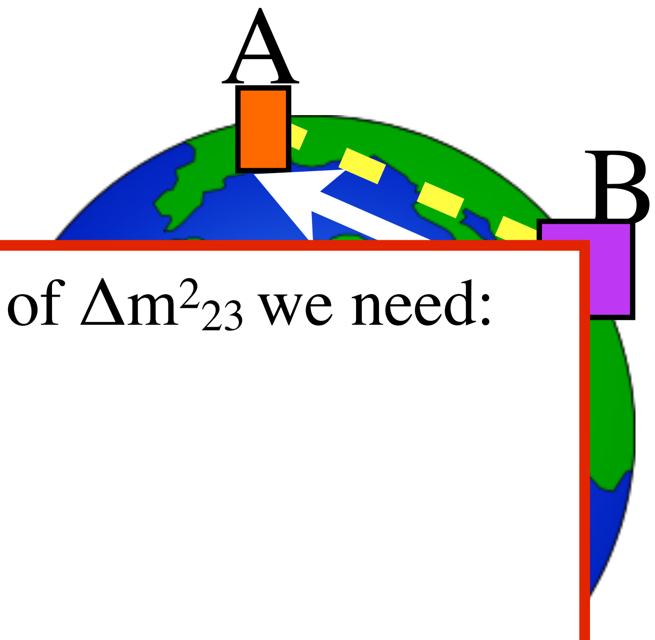

- For full determination and precise measurement of δ and sign of Δm^2_{23} we need:
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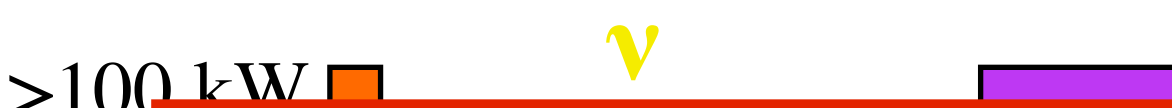

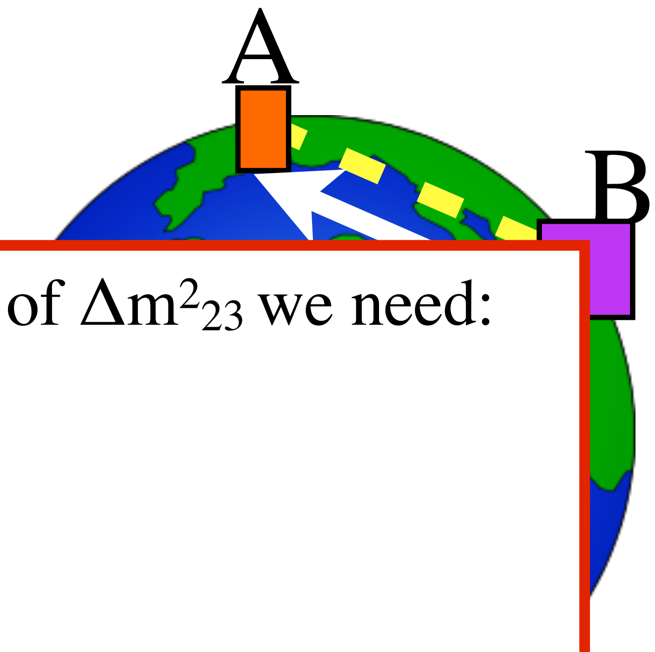

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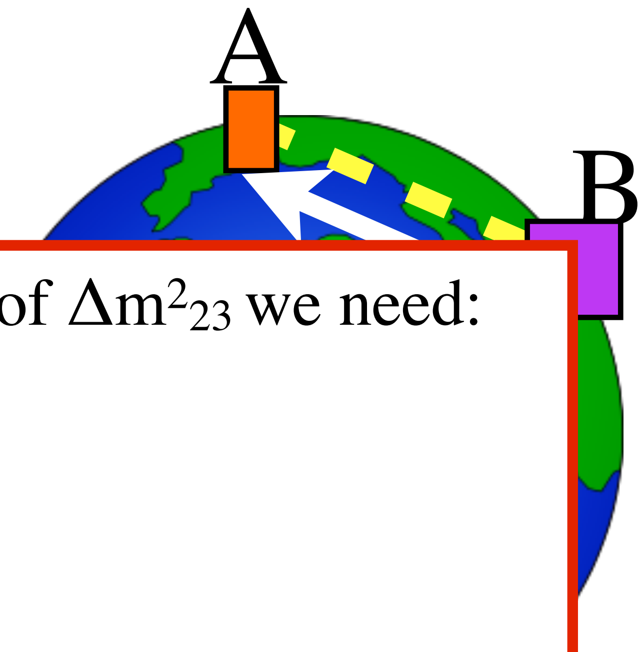

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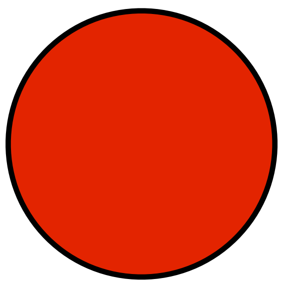

p^+ accelerator

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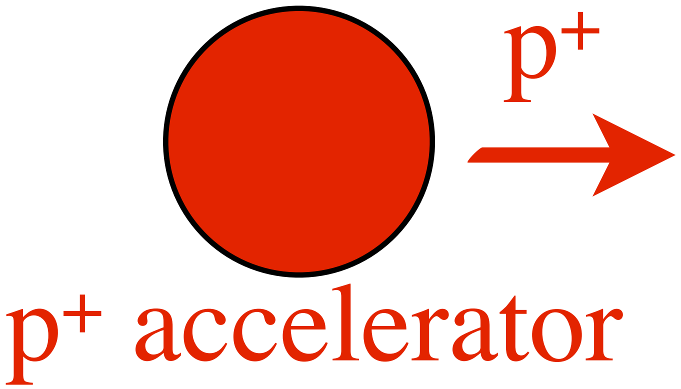

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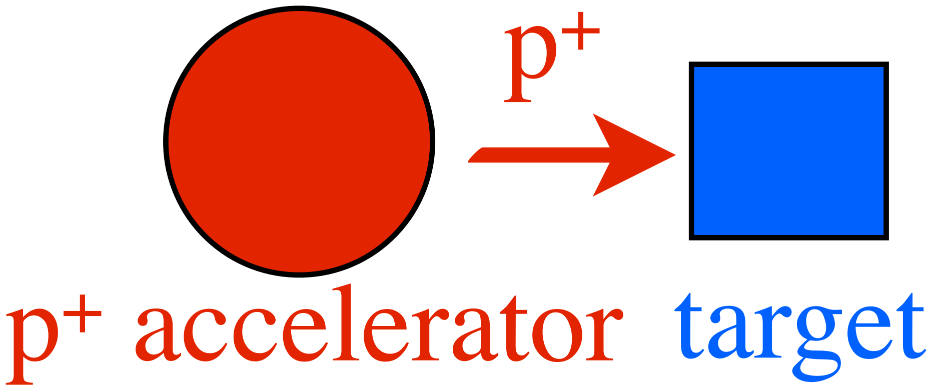

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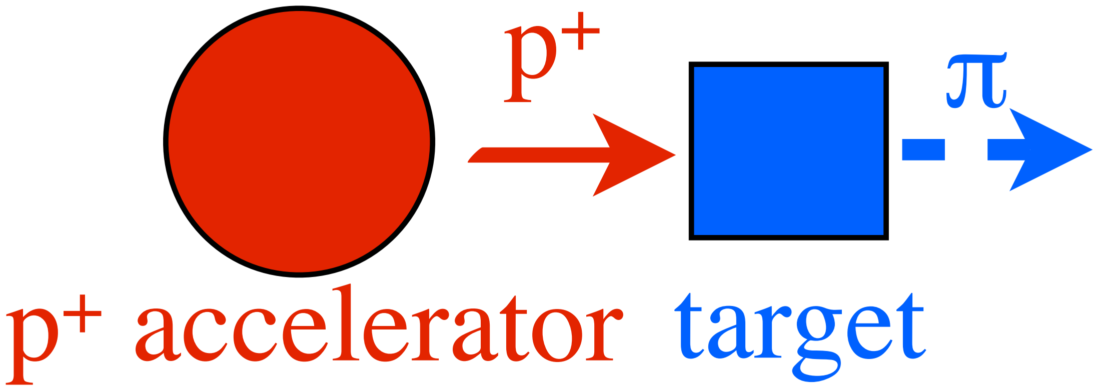

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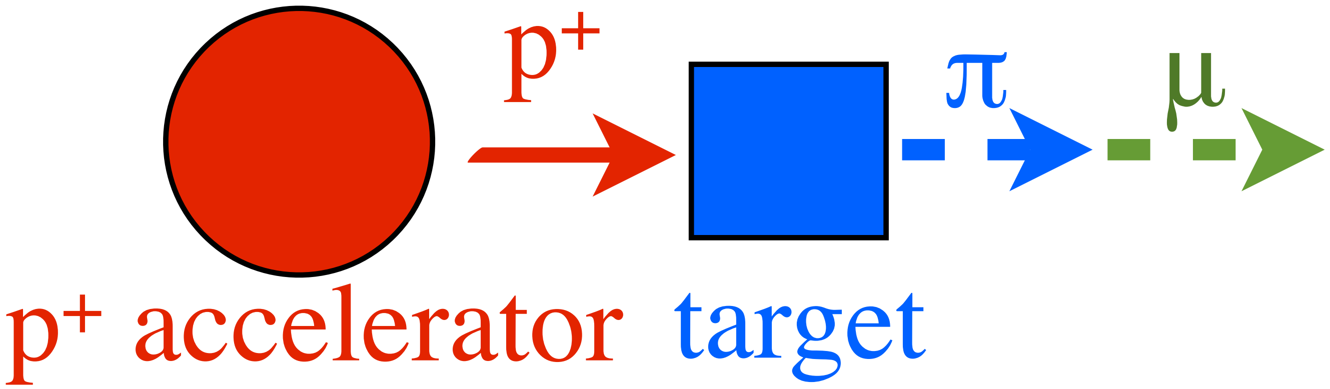

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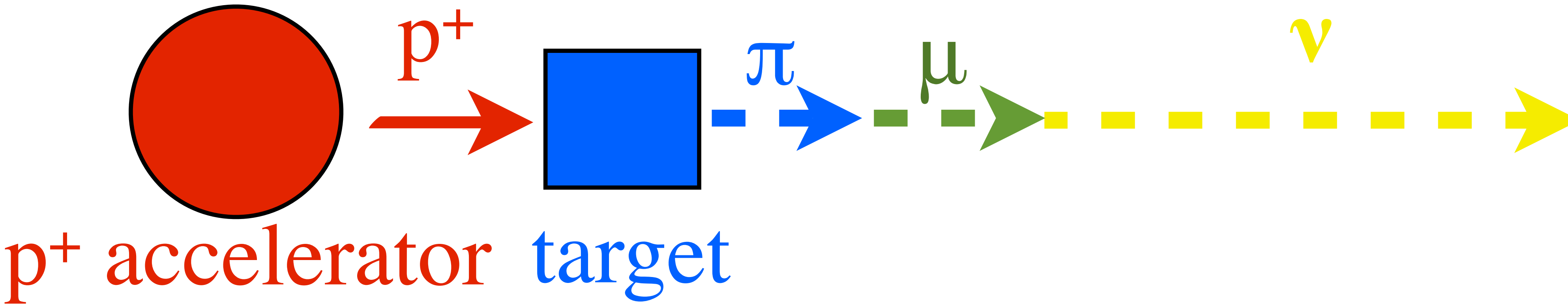

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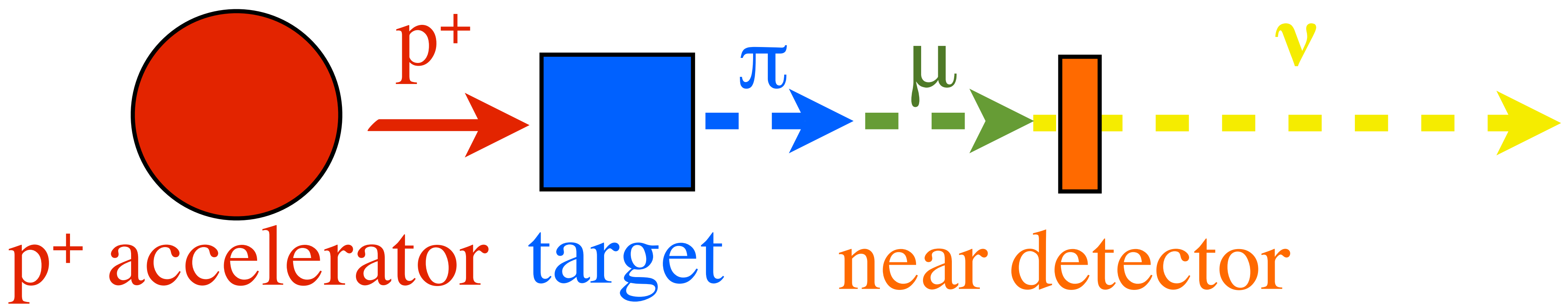

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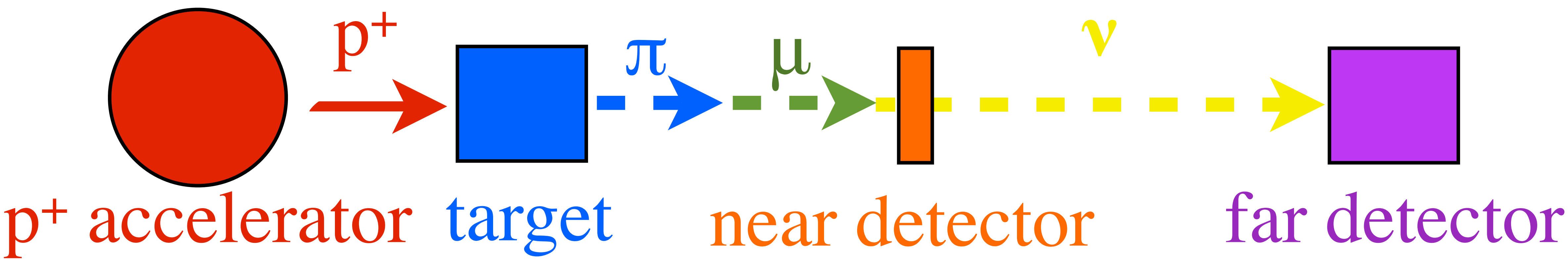

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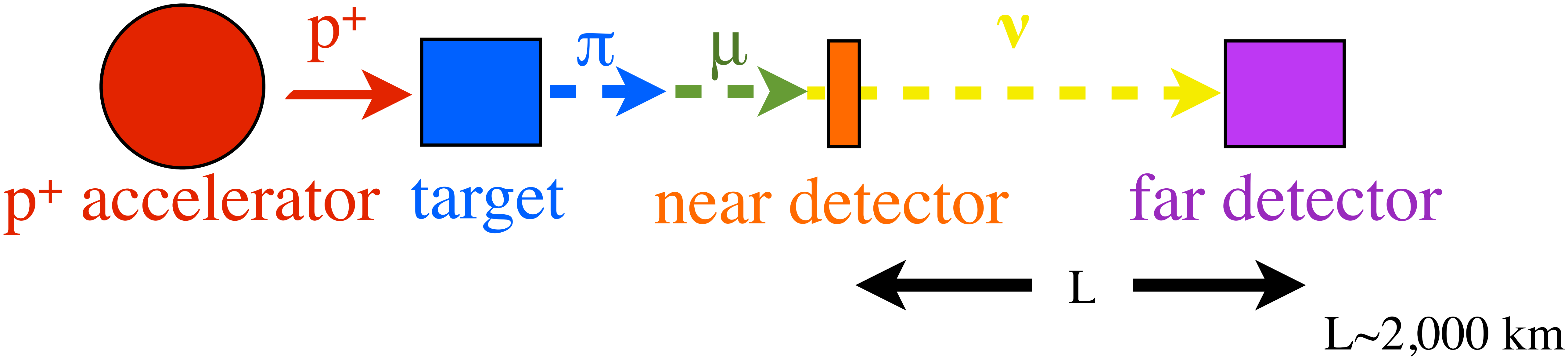

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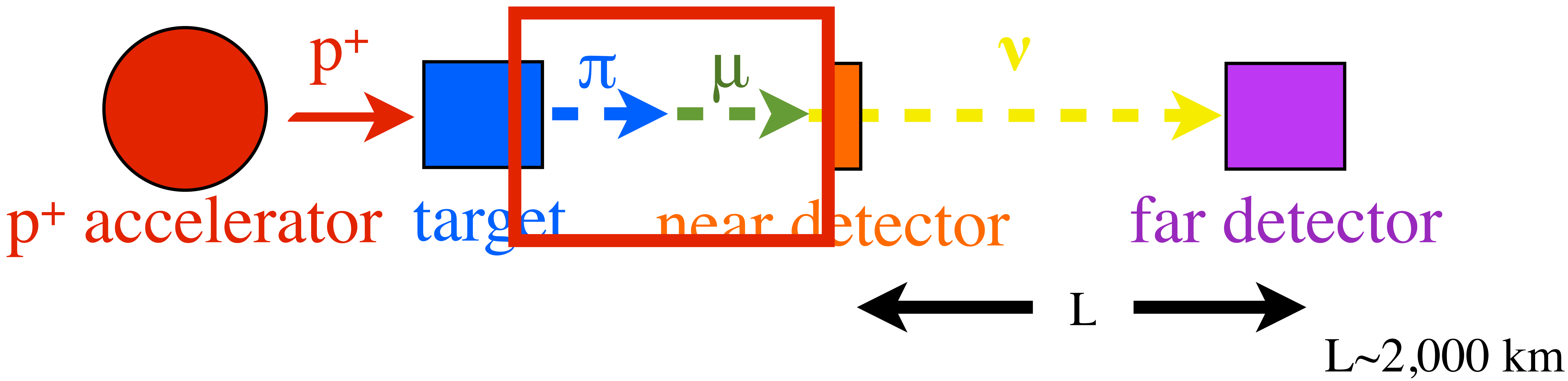

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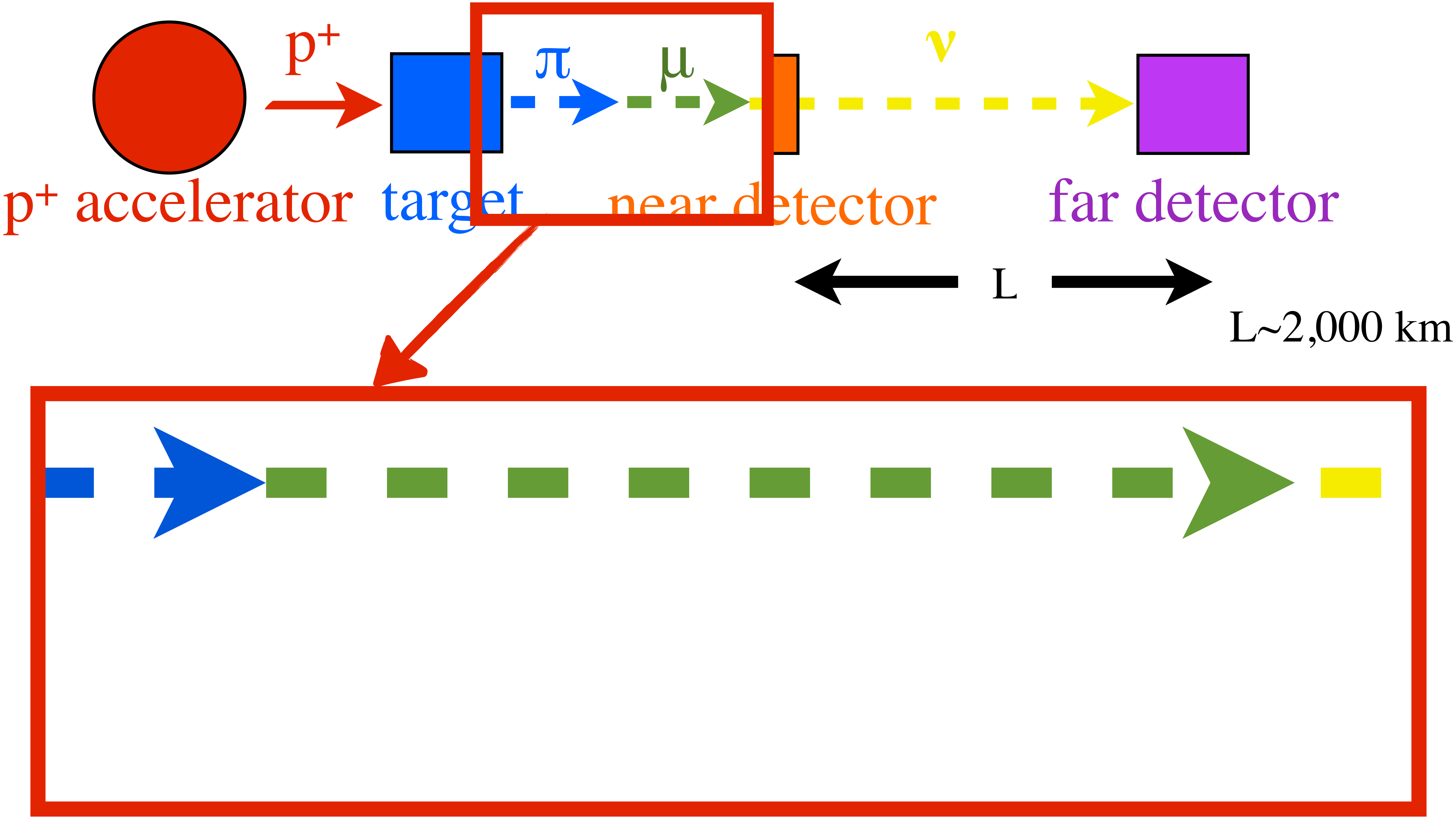

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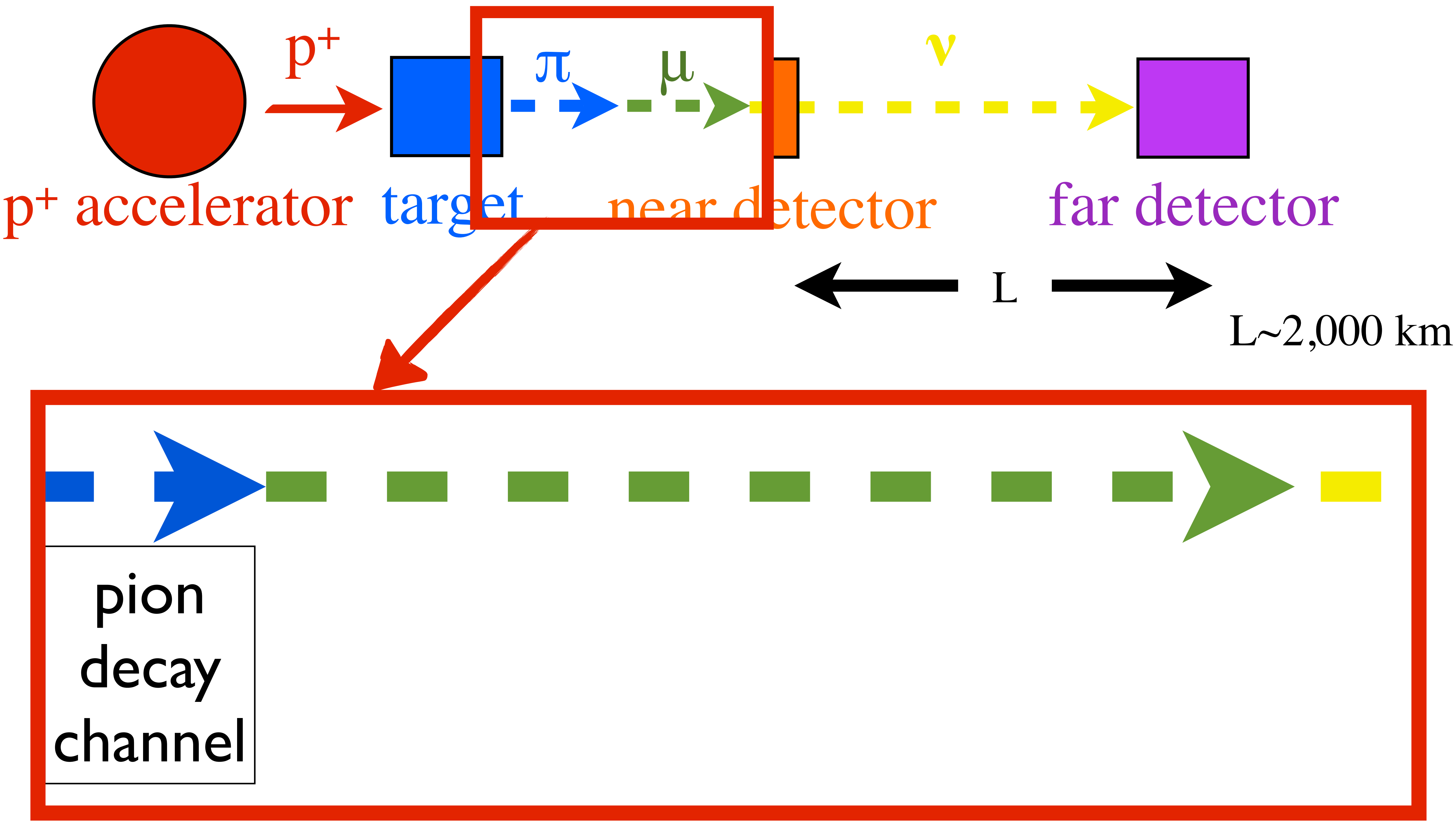

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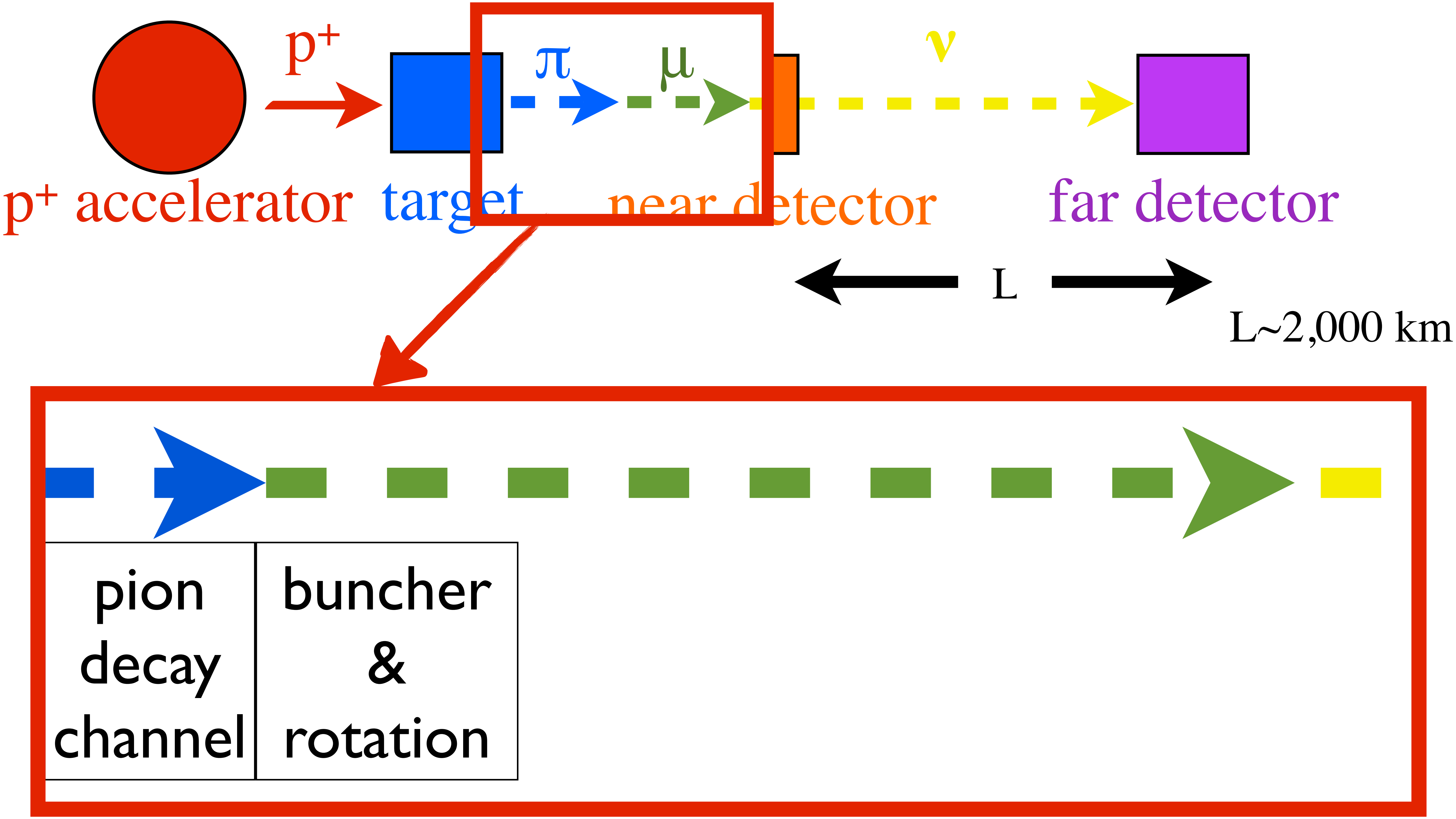

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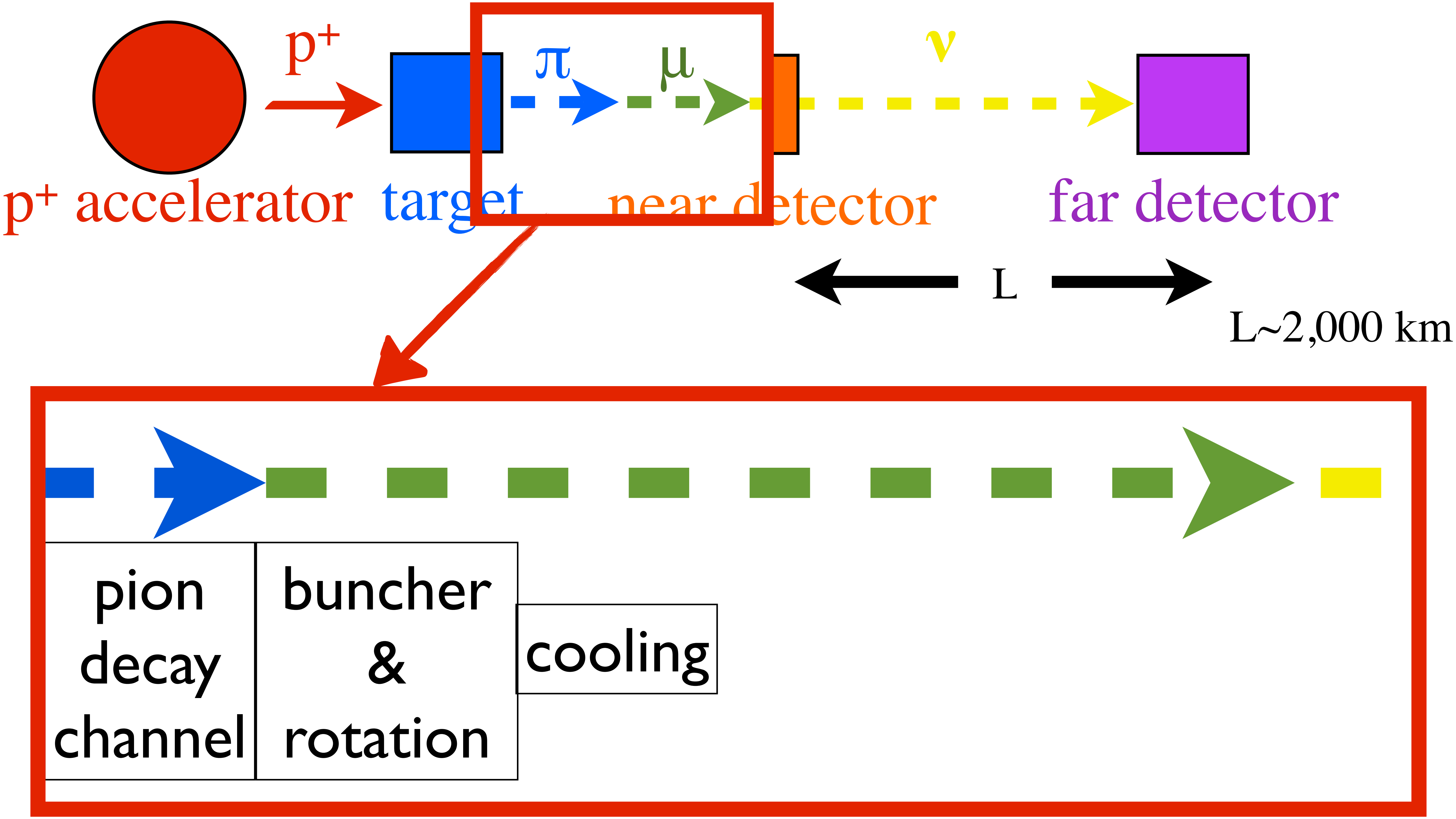

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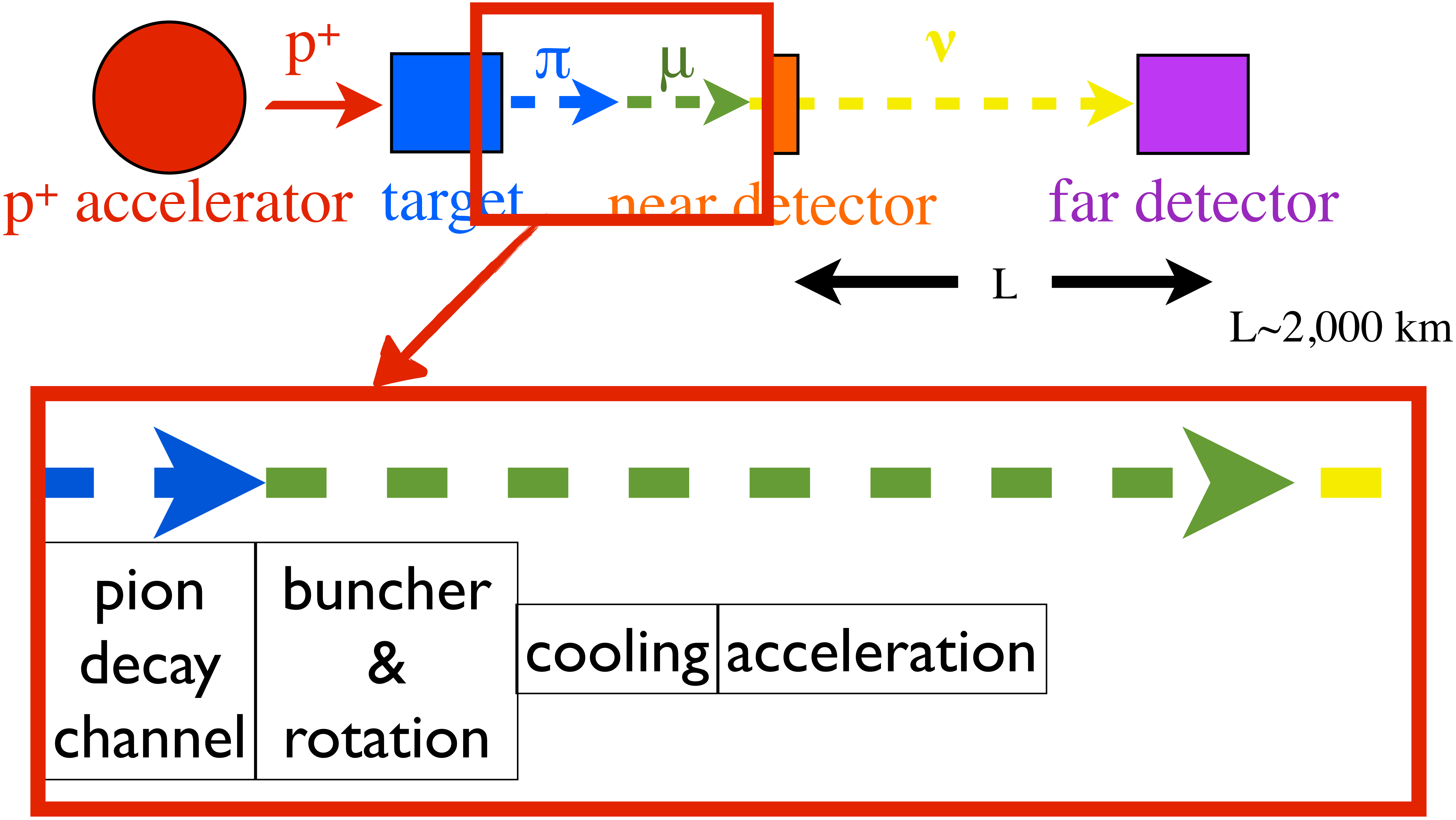

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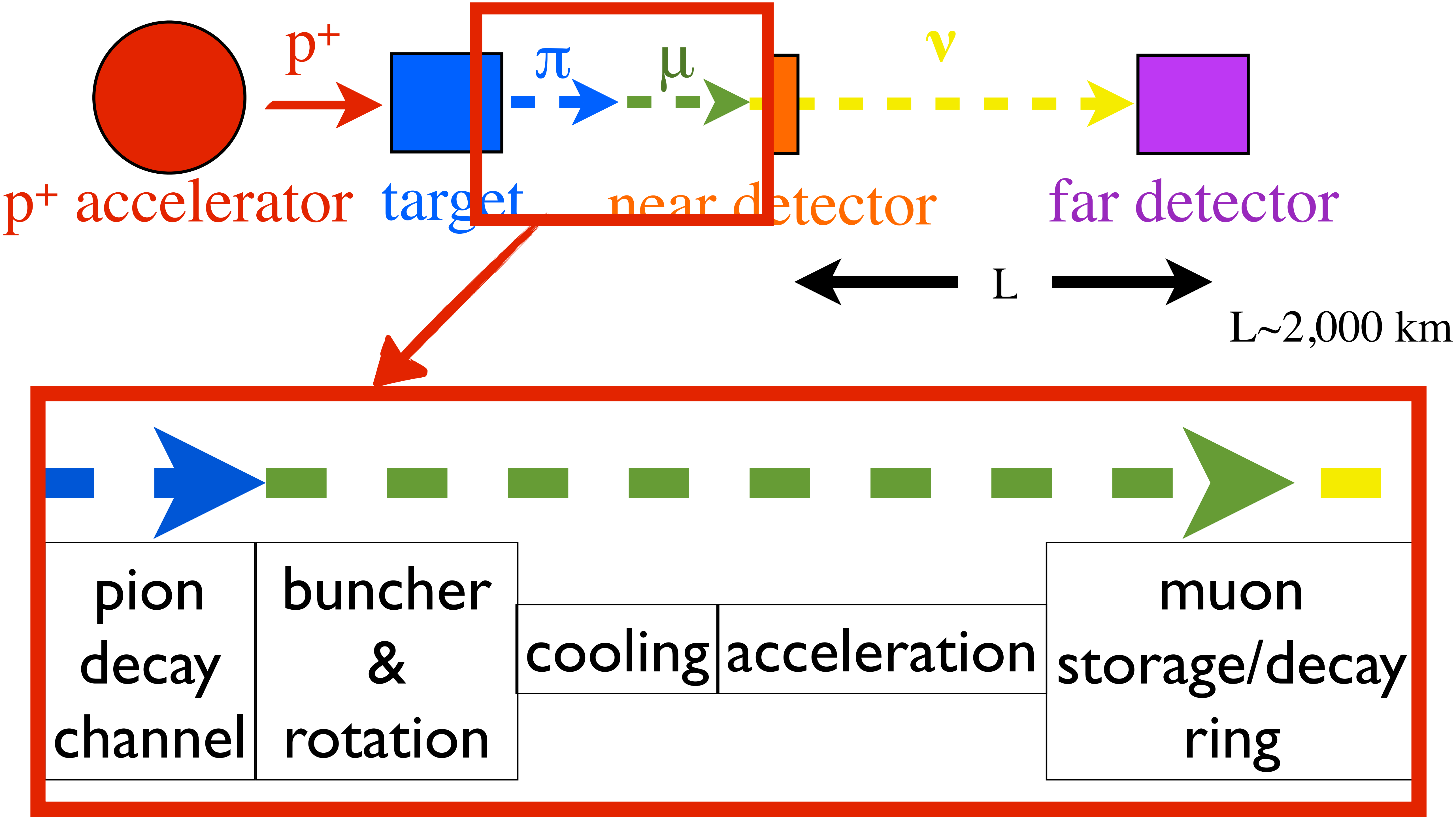

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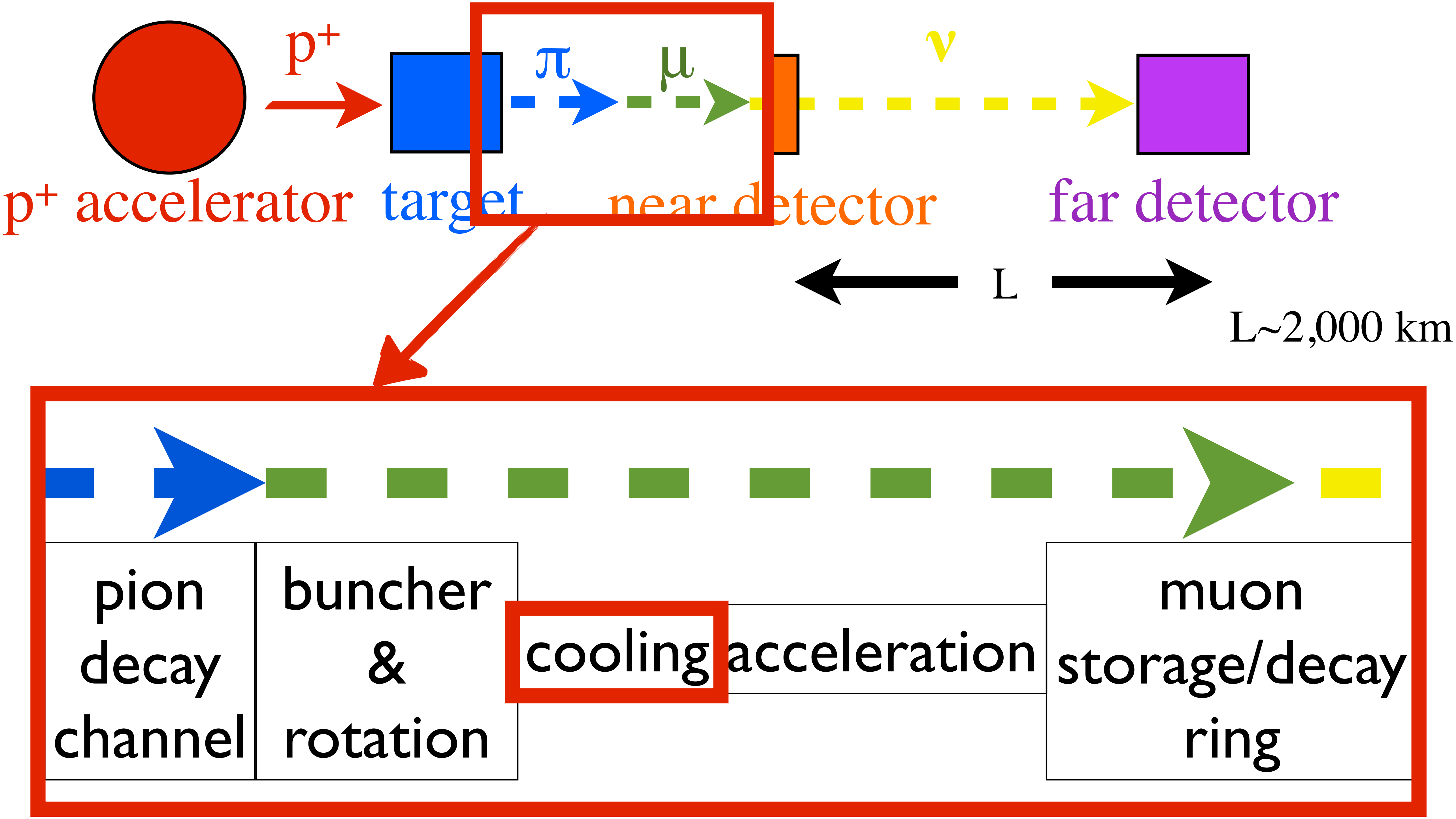

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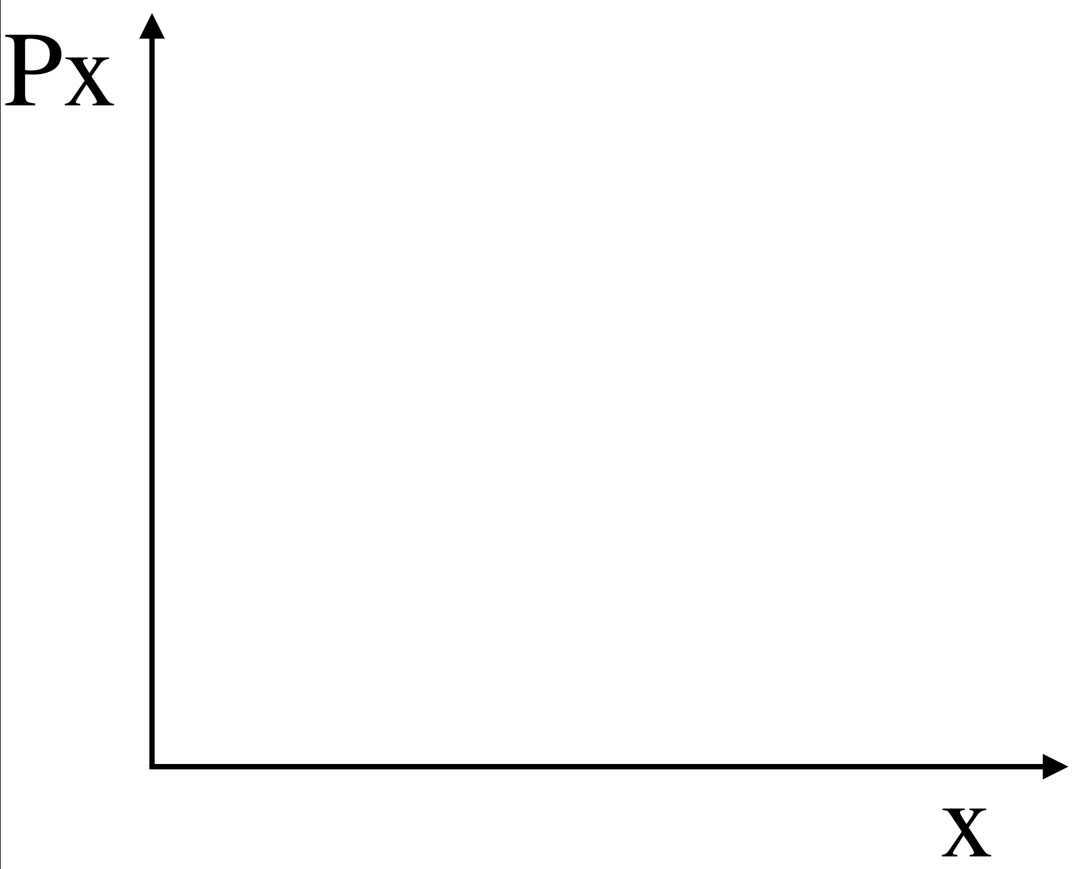

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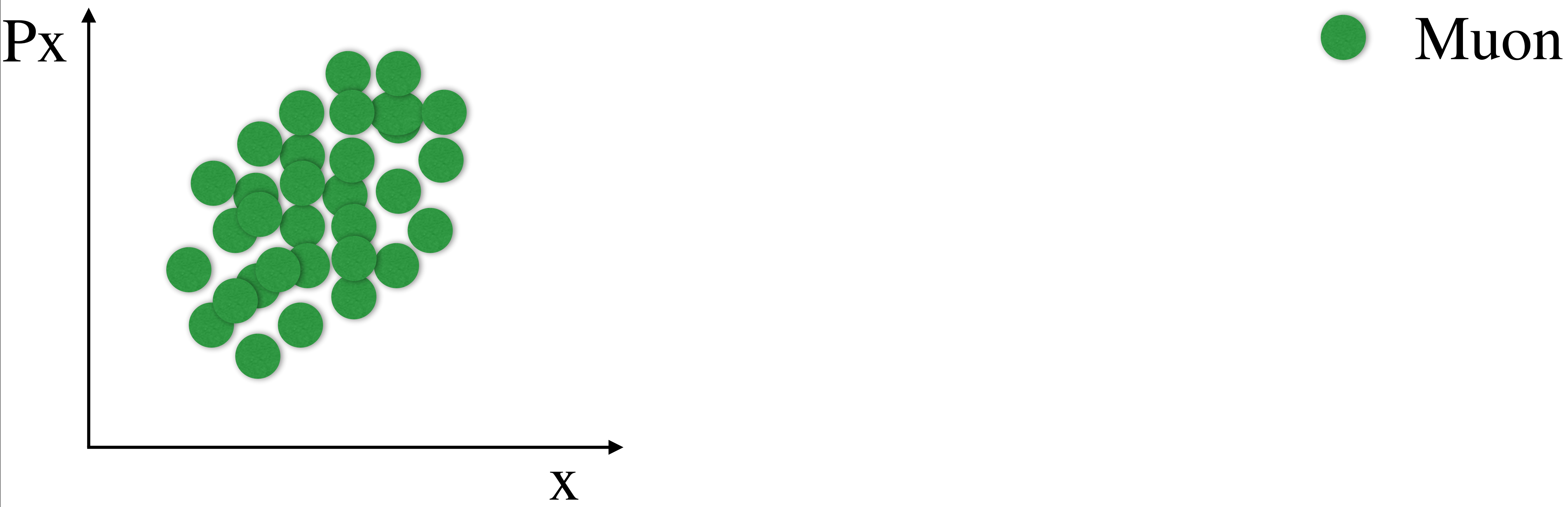

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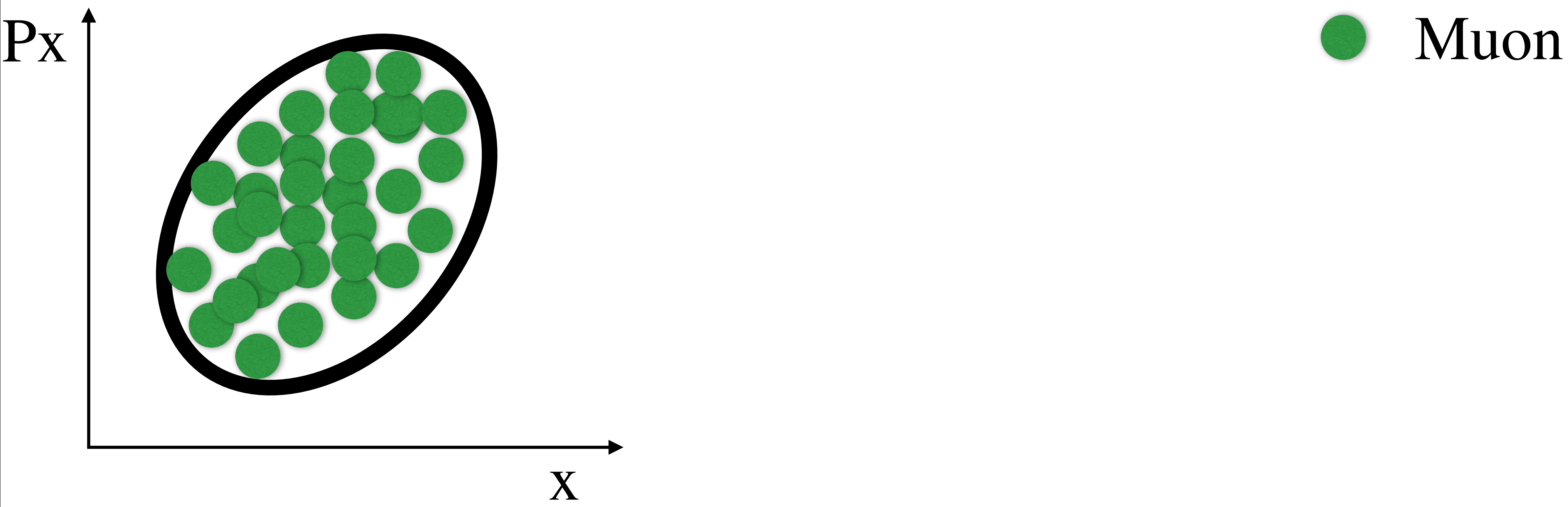

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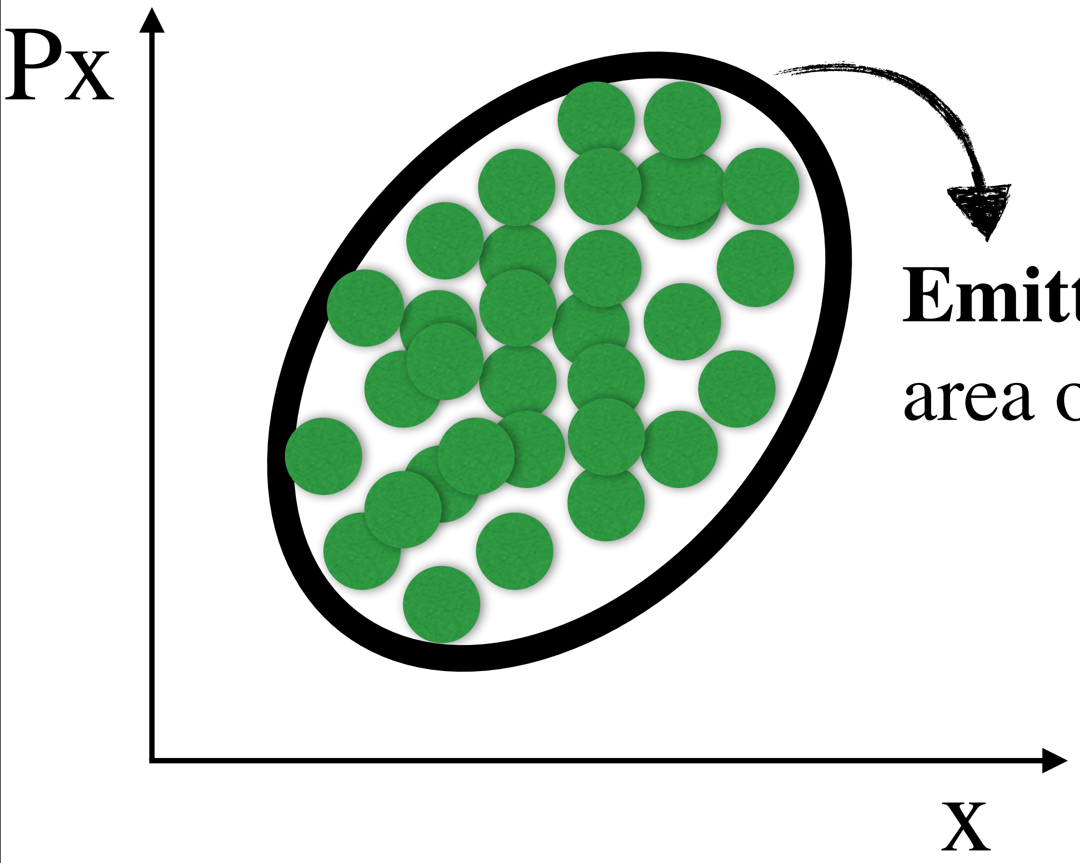

Emittance, ε:
area of ellipse

Ionization Cooling (1/2)

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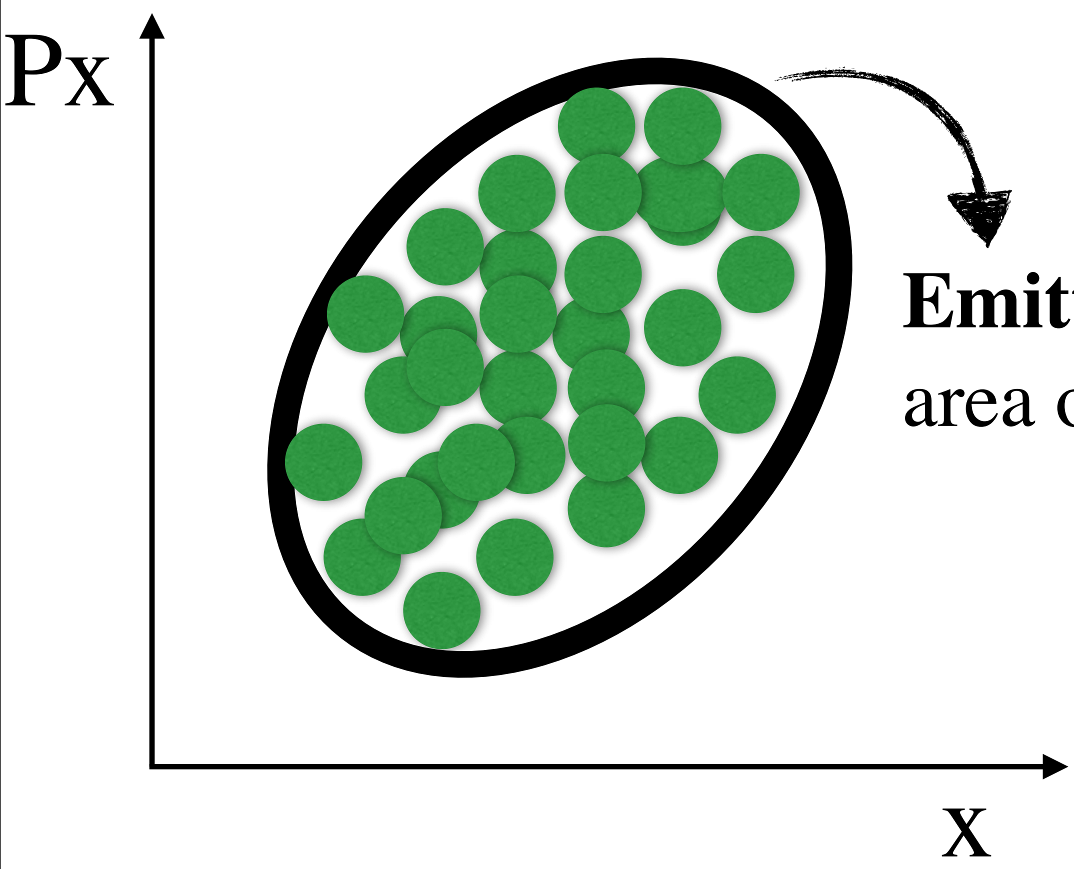

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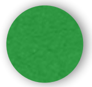

Muon

Size of beam depends on emittance

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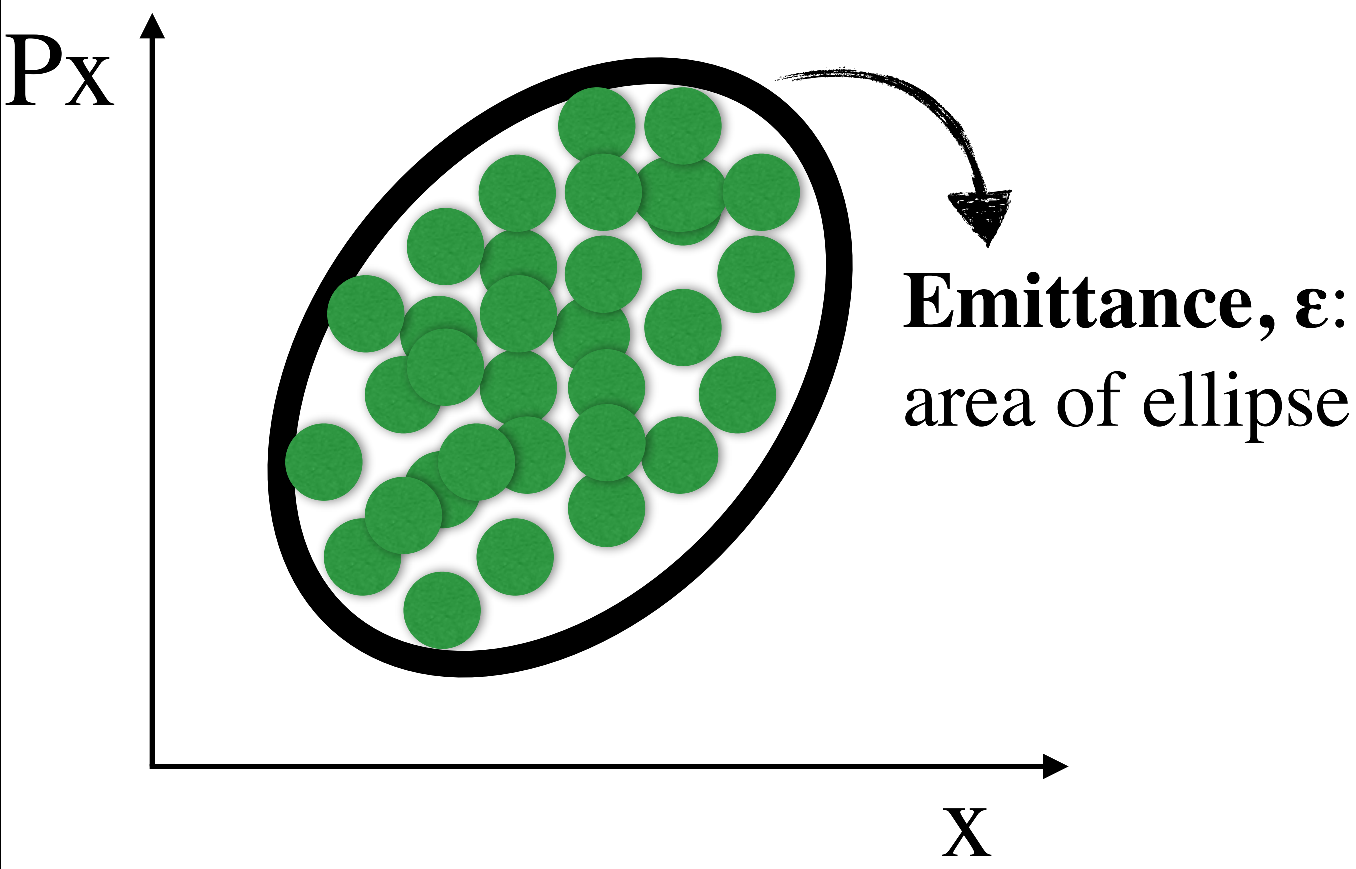

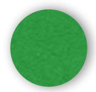

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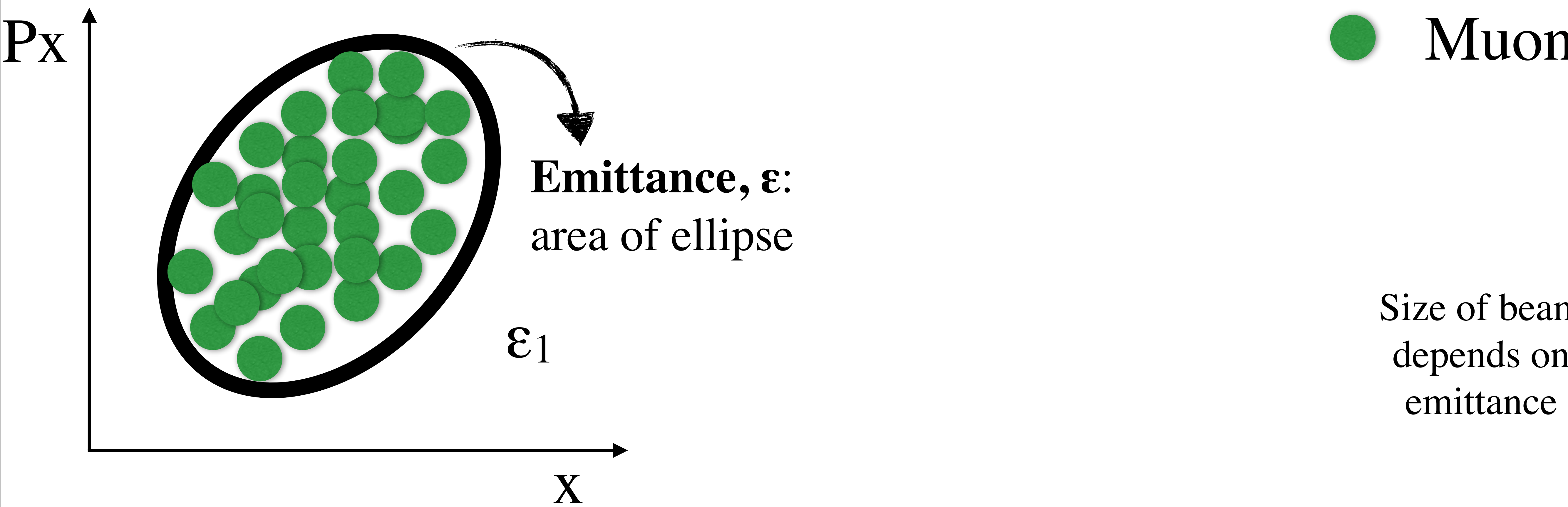

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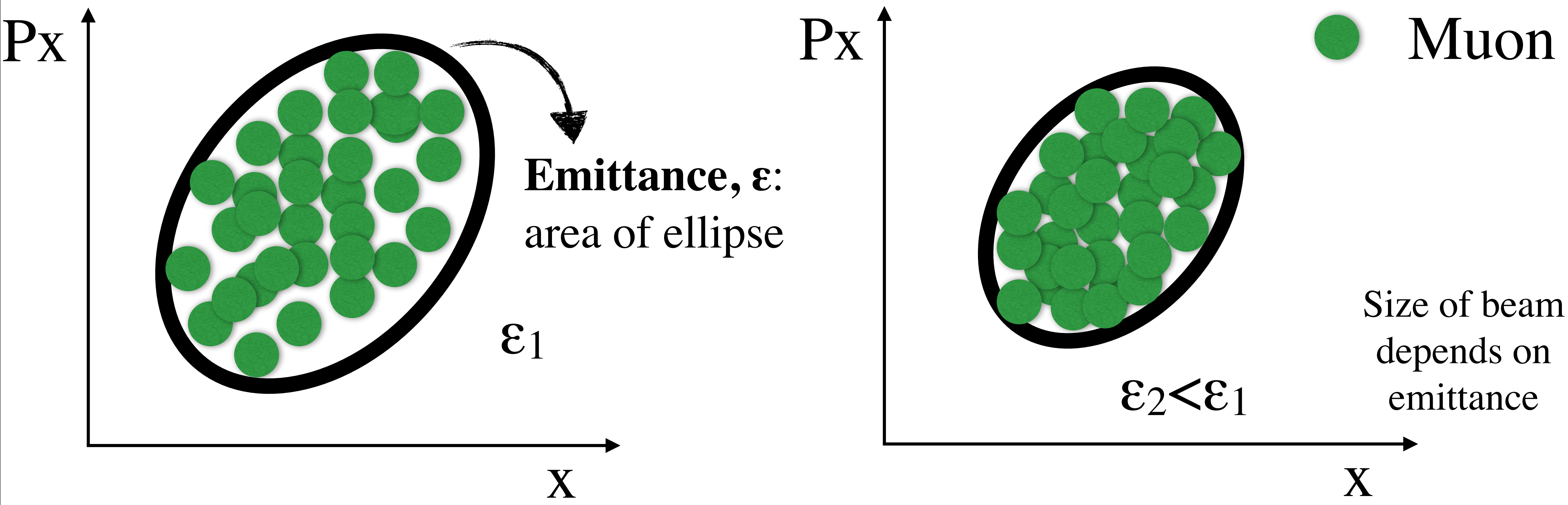

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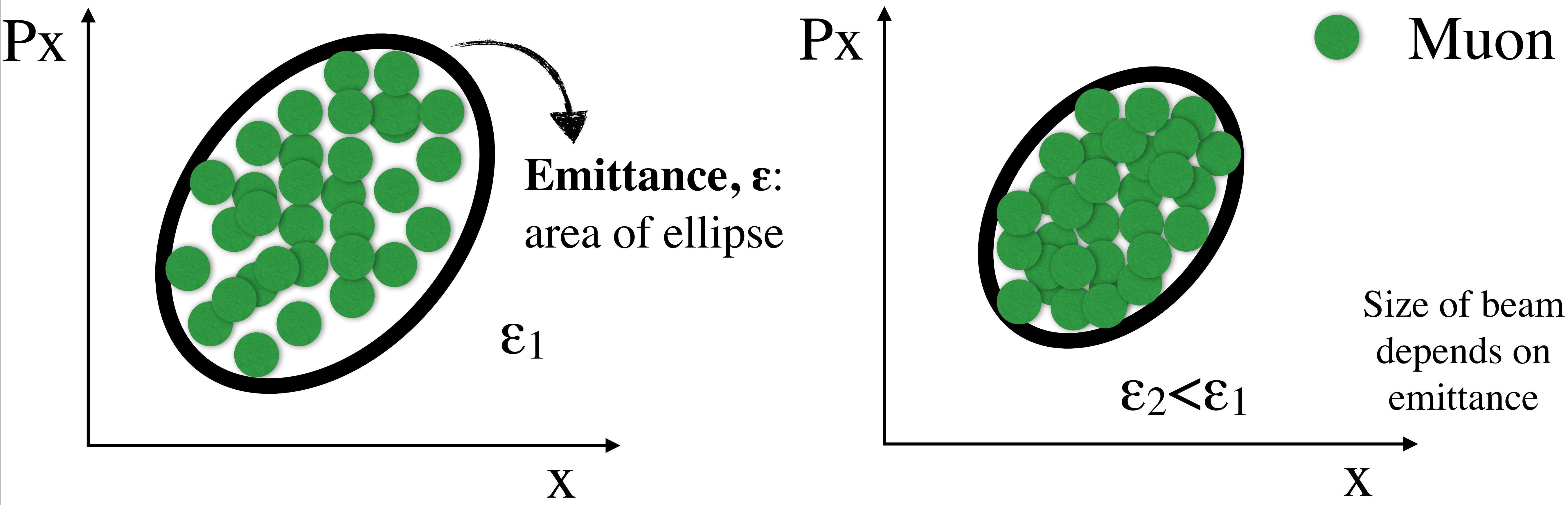

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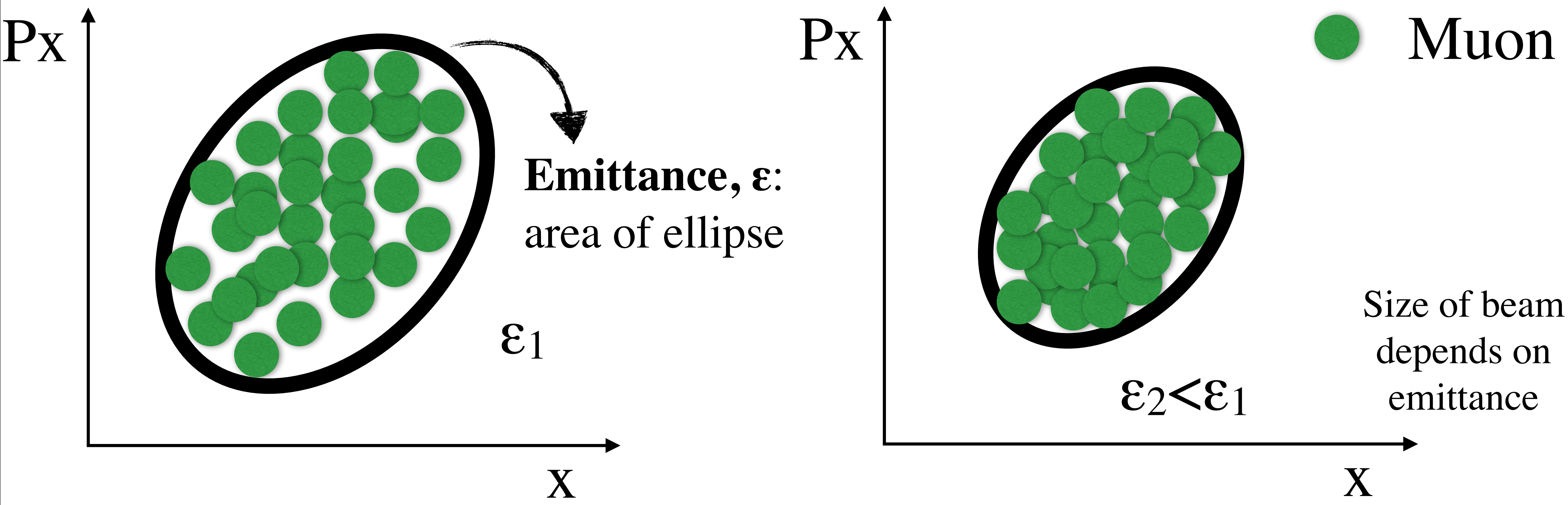

- For efficient muon transfer to downstream accelerators, transverse emittance needs to decrease (muon cooling)
- But...muons decay very fast (~2.2 μs at rest) so traditional cooling techniques can't be applied on muons
- So: only viable cooling technique for muons is *ionization cooling*

Ionization Cooling (2/2)

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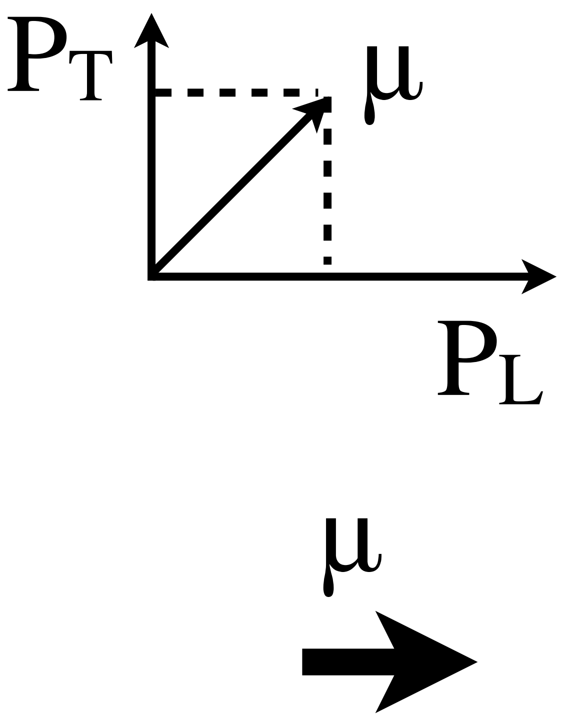

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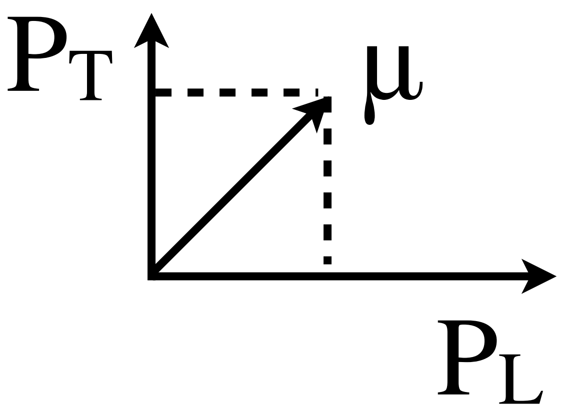

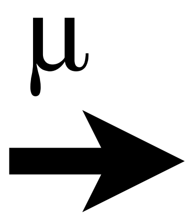

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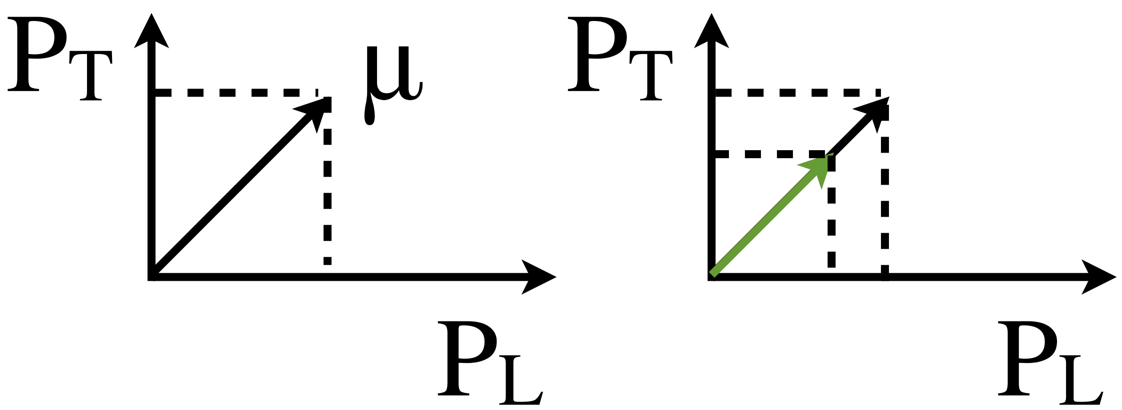

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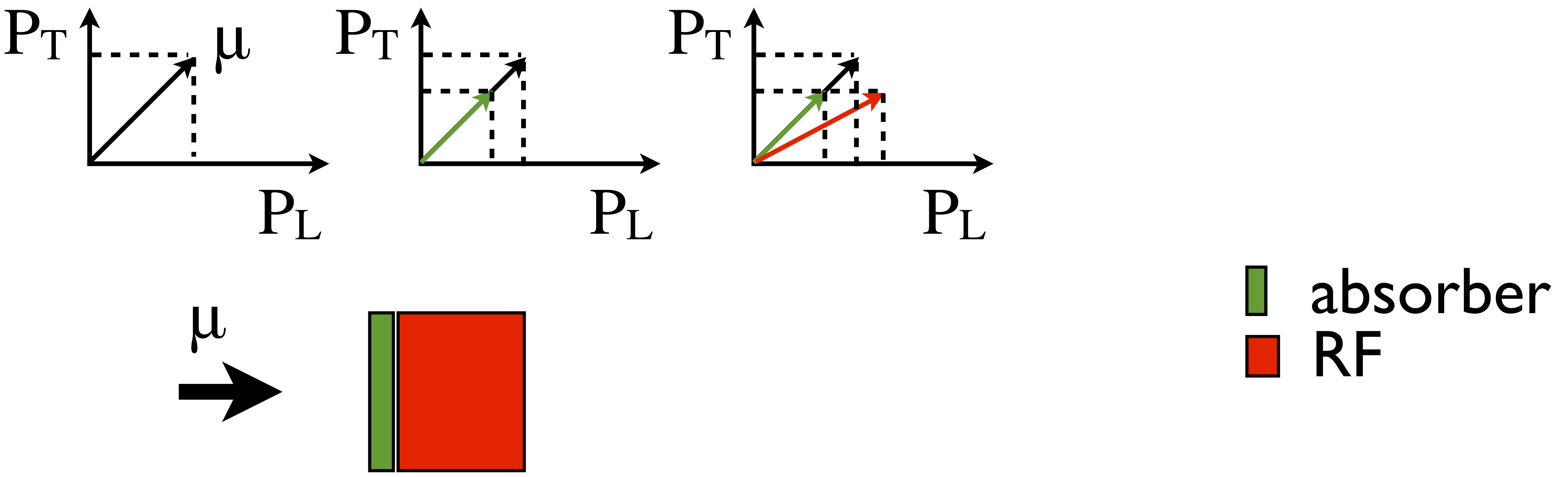

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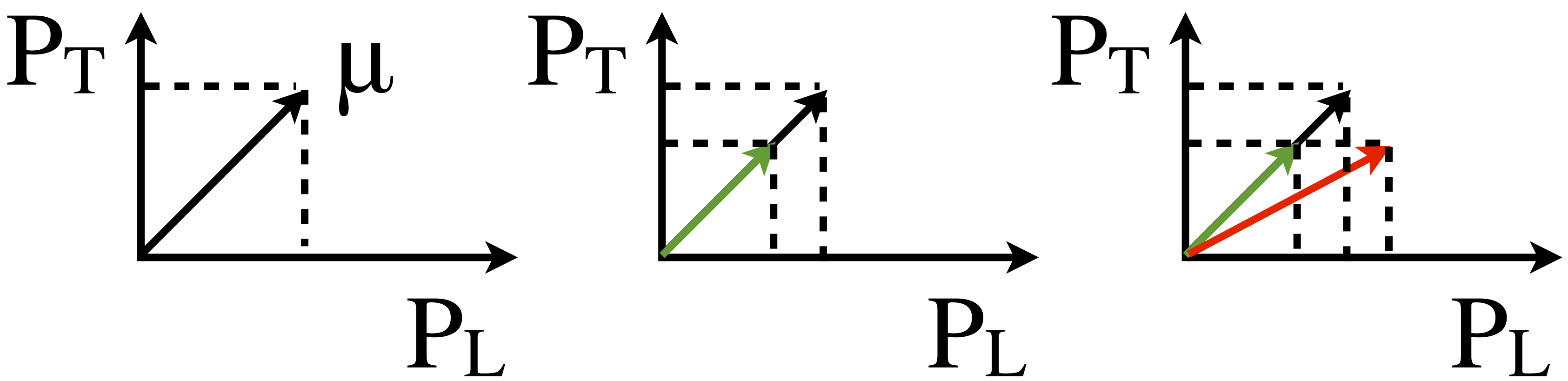

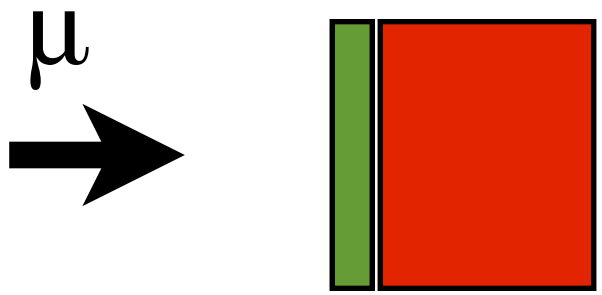

...repeat as necessary

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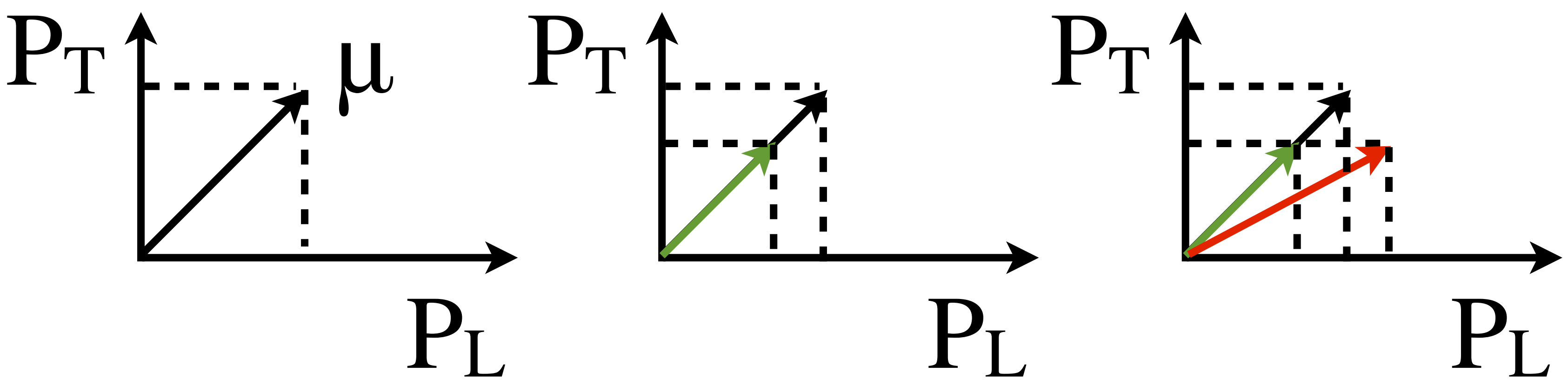

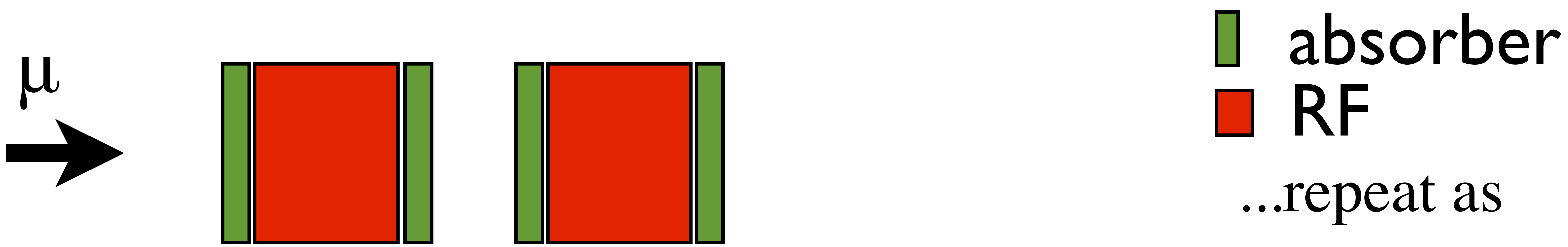

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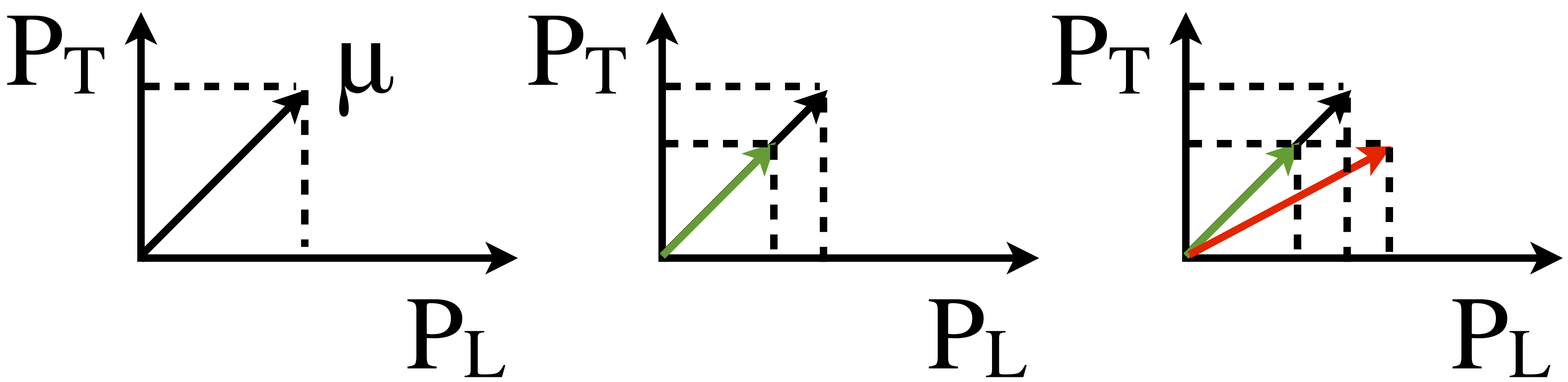

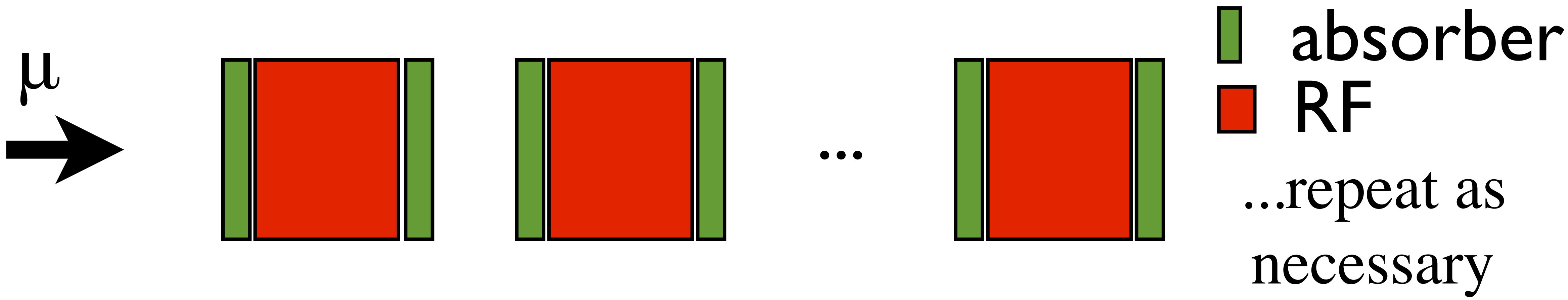

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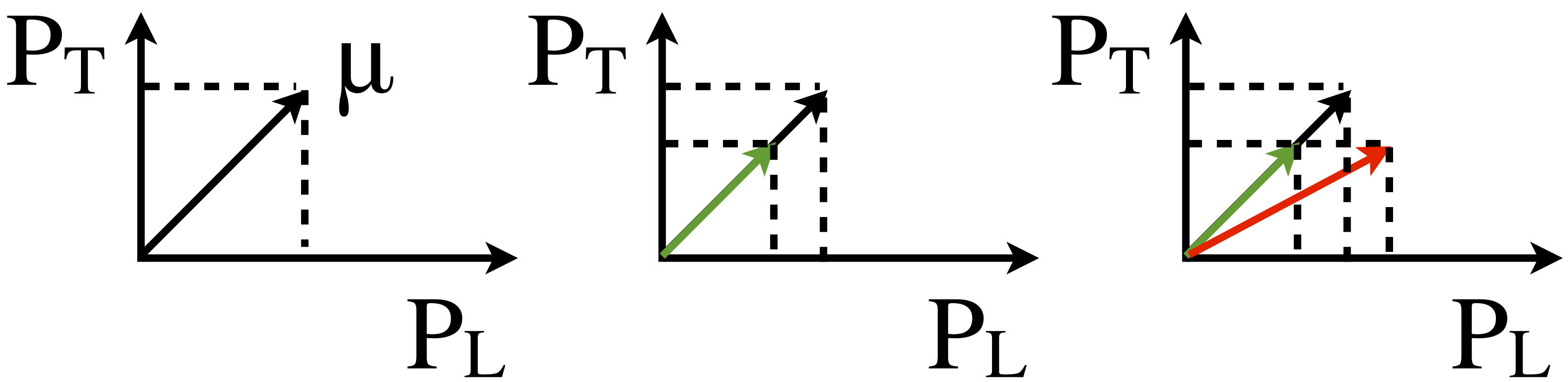
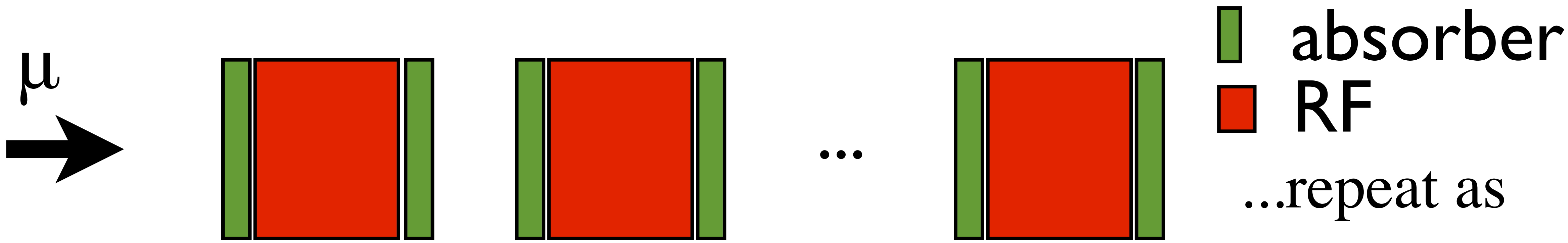


net effect: transverse emittance reduction



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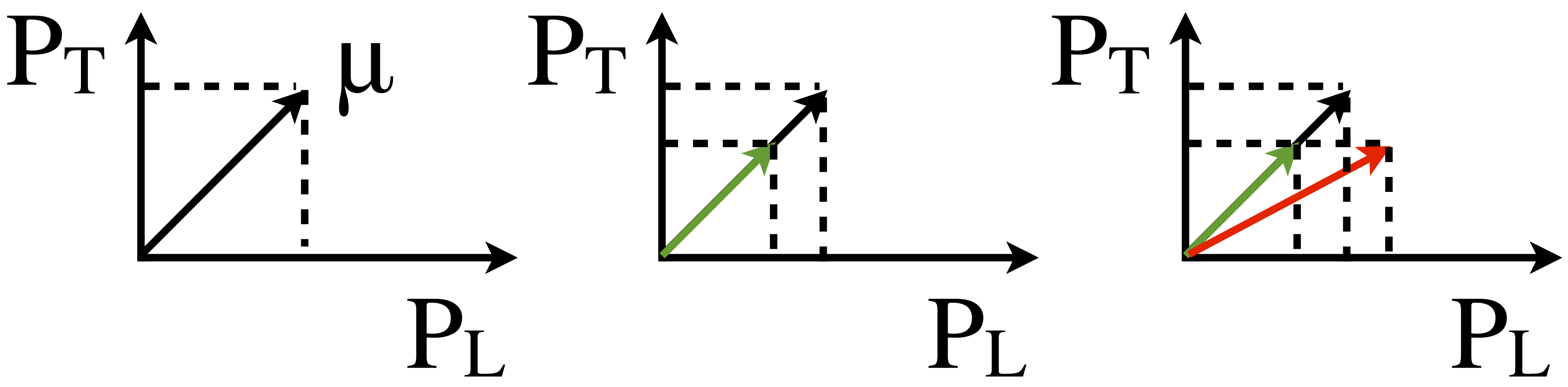

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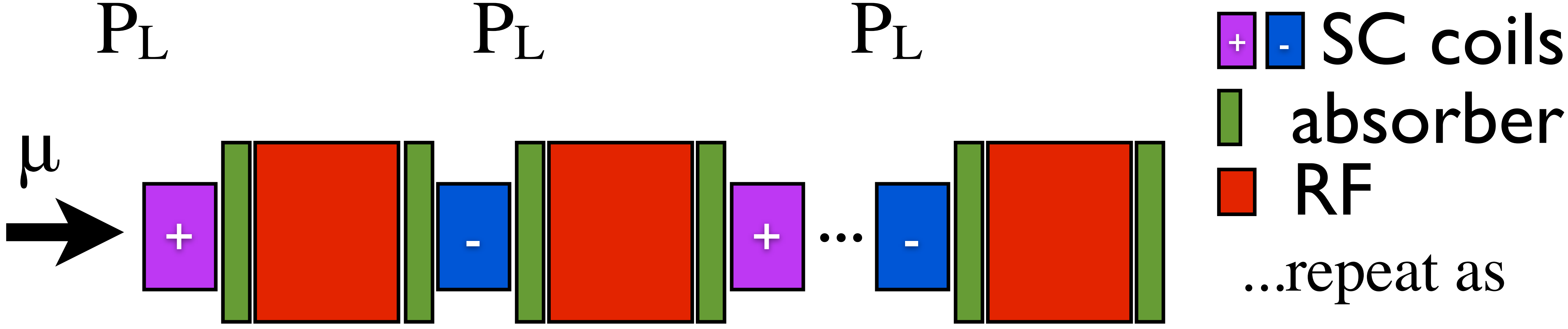

...repeat as necessary

MICE

- Ionization Cooling is straightforward in theory but has never been experimentally demonstrated yet
- **M**uon **I**onisation **C**ooling **E**xperiment (MICE):
  - based at the Rutherford Appleton Laboratory (RAL), UK
  - will be the first experiment to demonstrate muon ionization cooling [2]
- Participated in beam commissioning shifts


Working hard in the MICE control room


In the MICE hall

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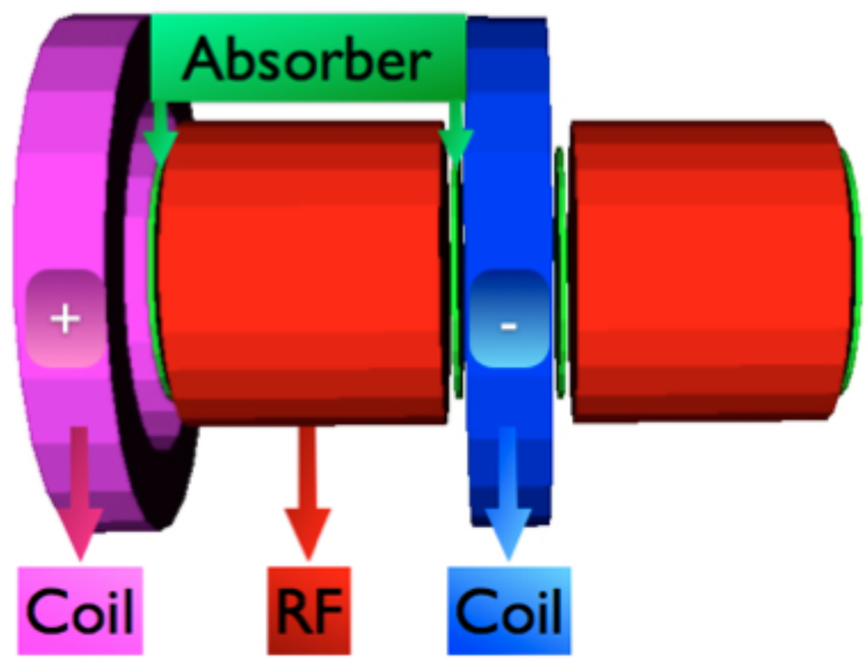
that's me :)

In the MICE hall

FSIIA

FSIIA*: reference ionization cooling lattice of NF successfully reduces transverse emittance



*FSIIA: Feasibility Study IIA

FSIIA

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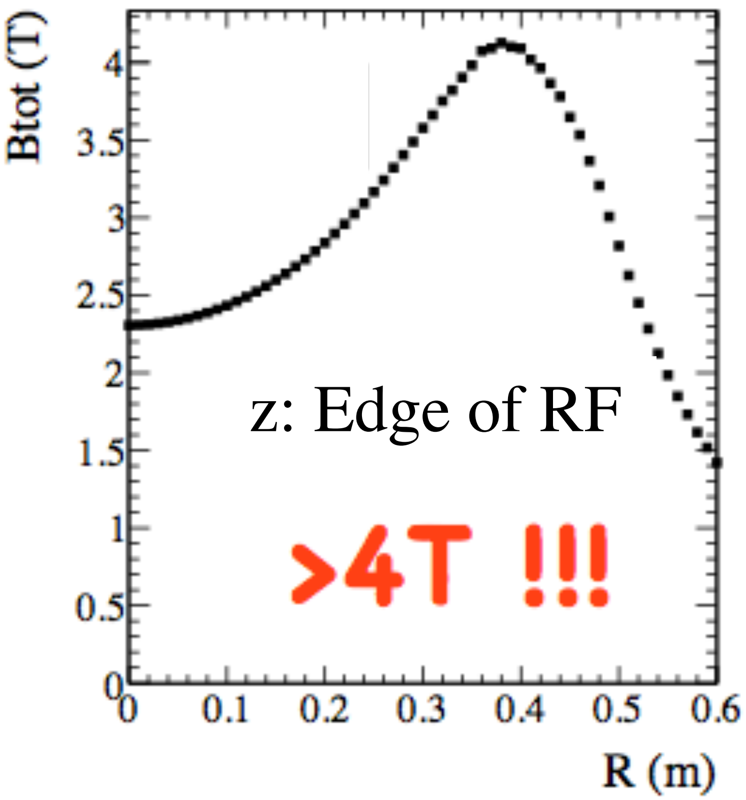
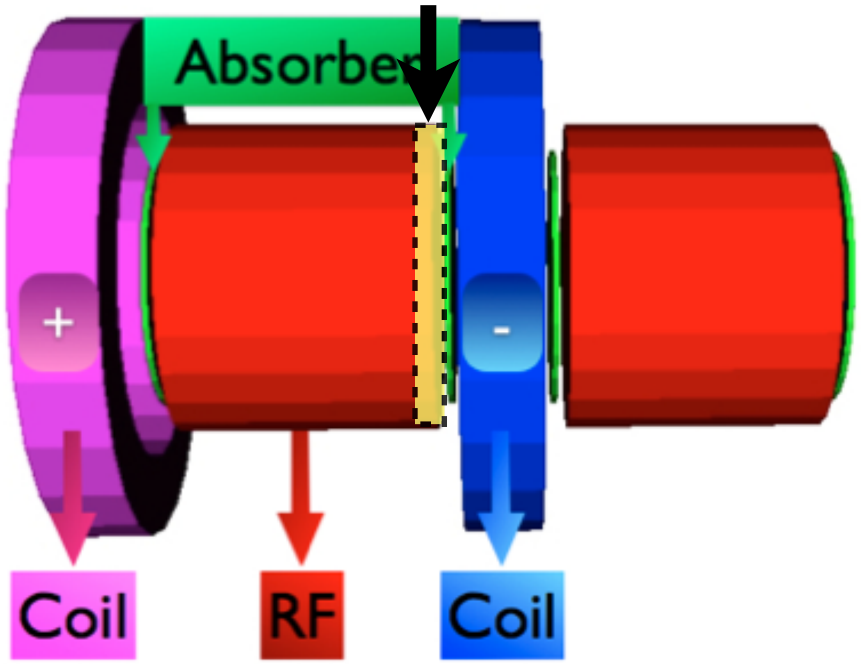
...but has very large magnetic field at edge of RF cavities





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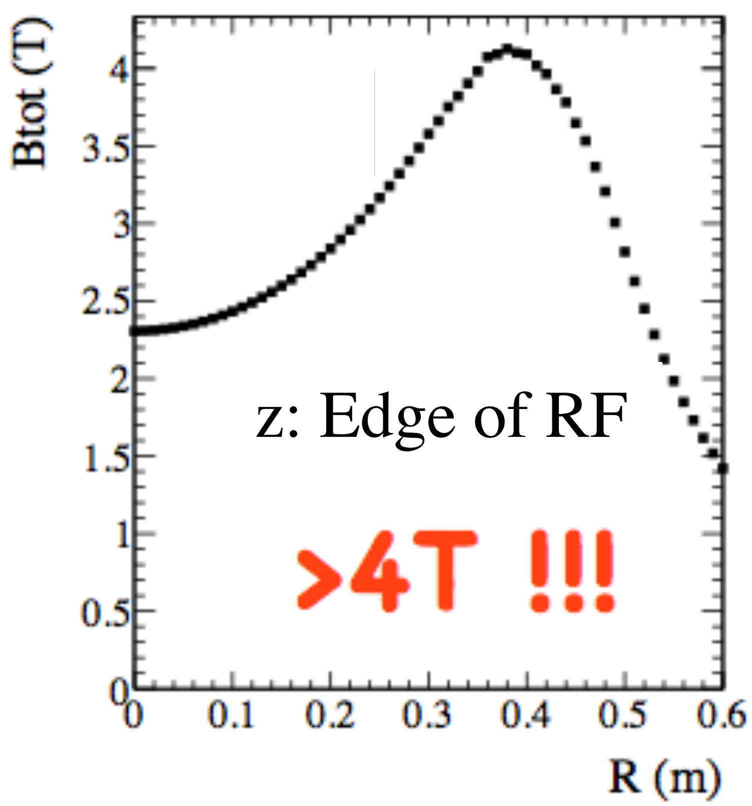

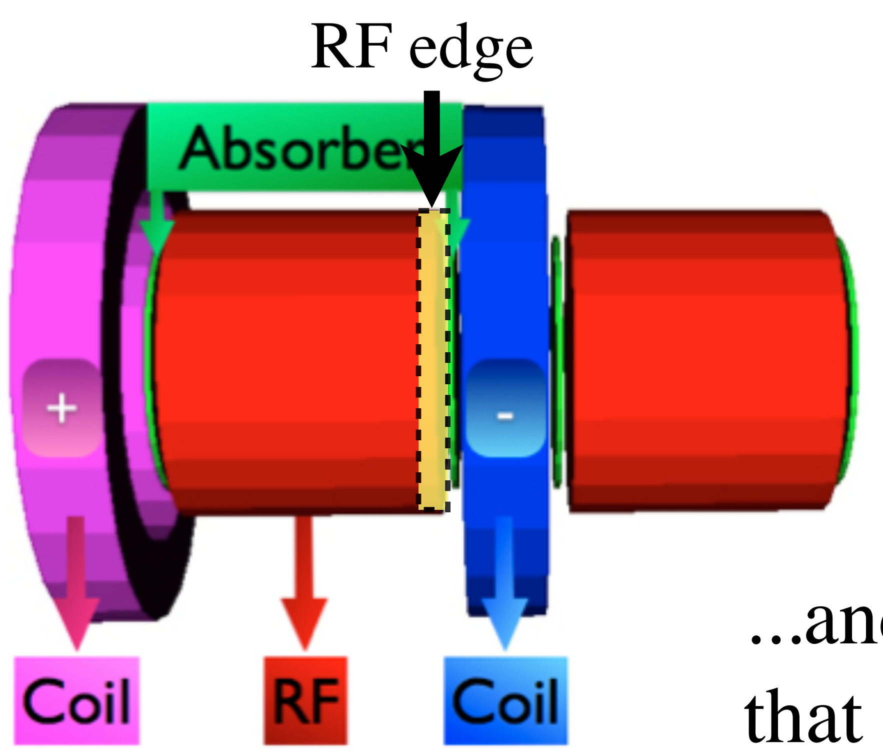

...and recent studies indicated that high magnetic field at end of RF cavities can lead to RF breakdown [3]

*FSIIA: Feasibility Study IIA

RF breakdown

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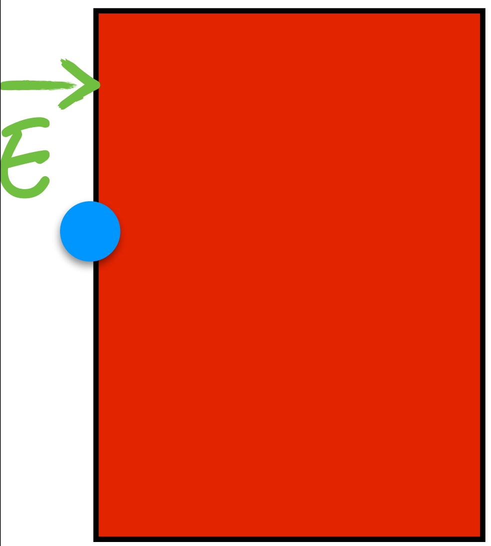

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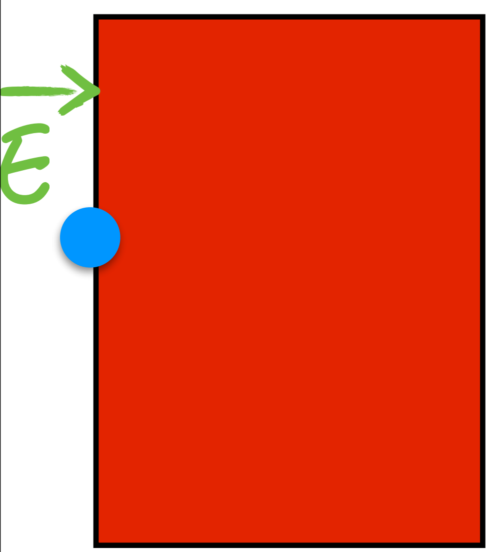

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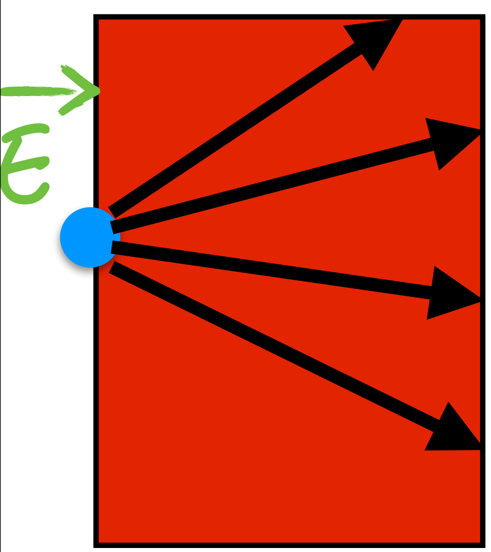

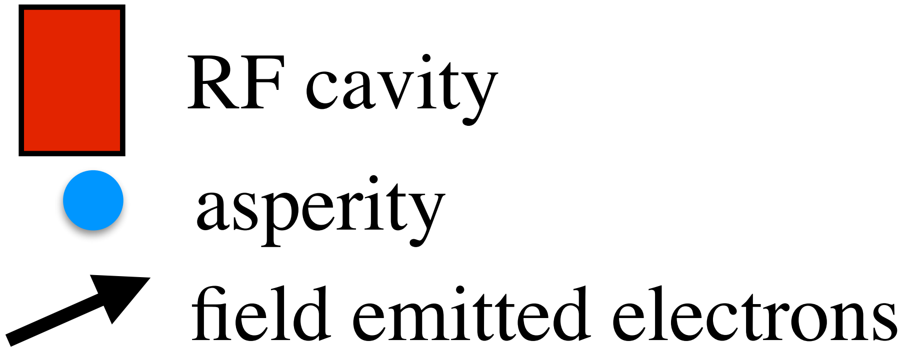

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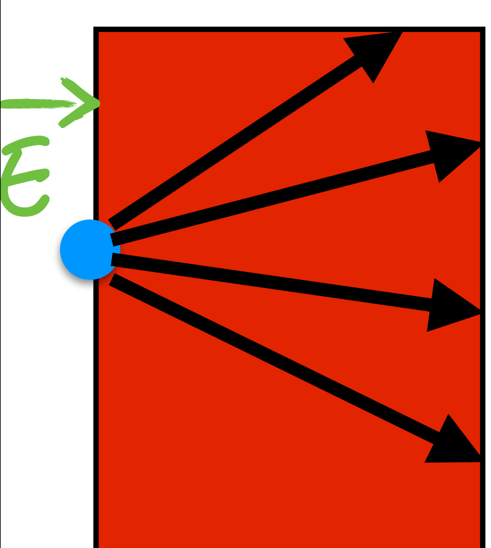

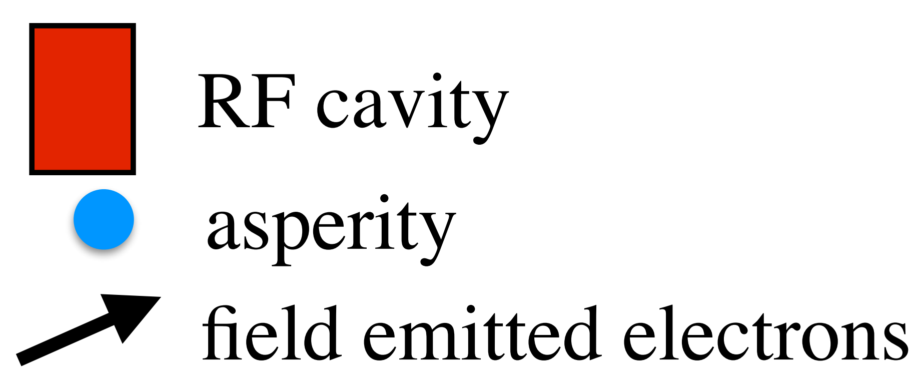

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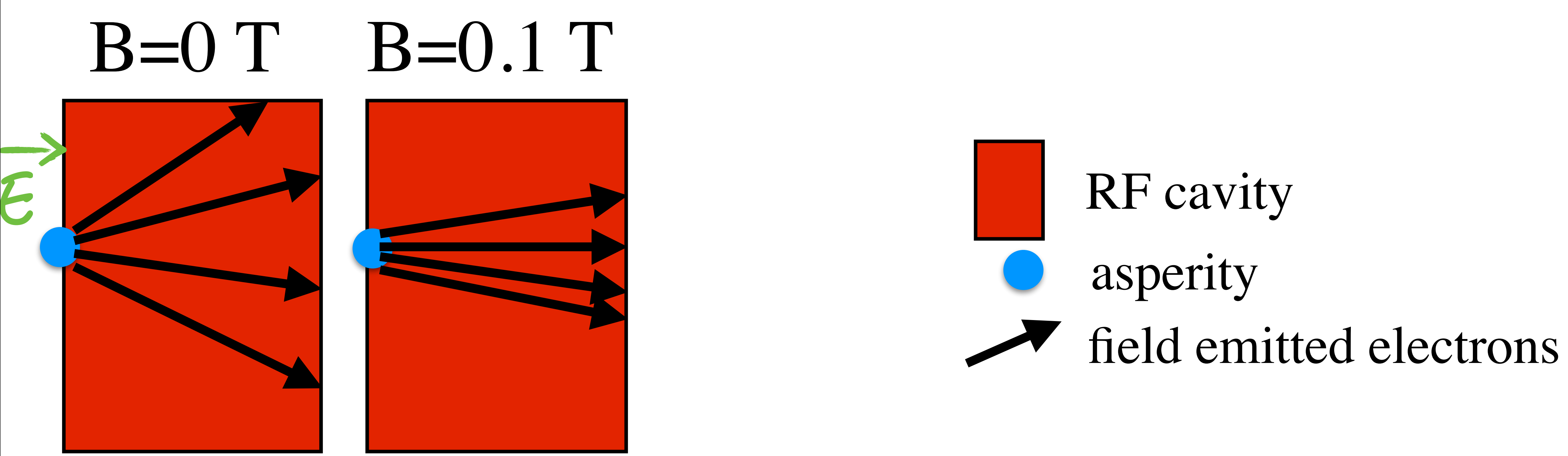

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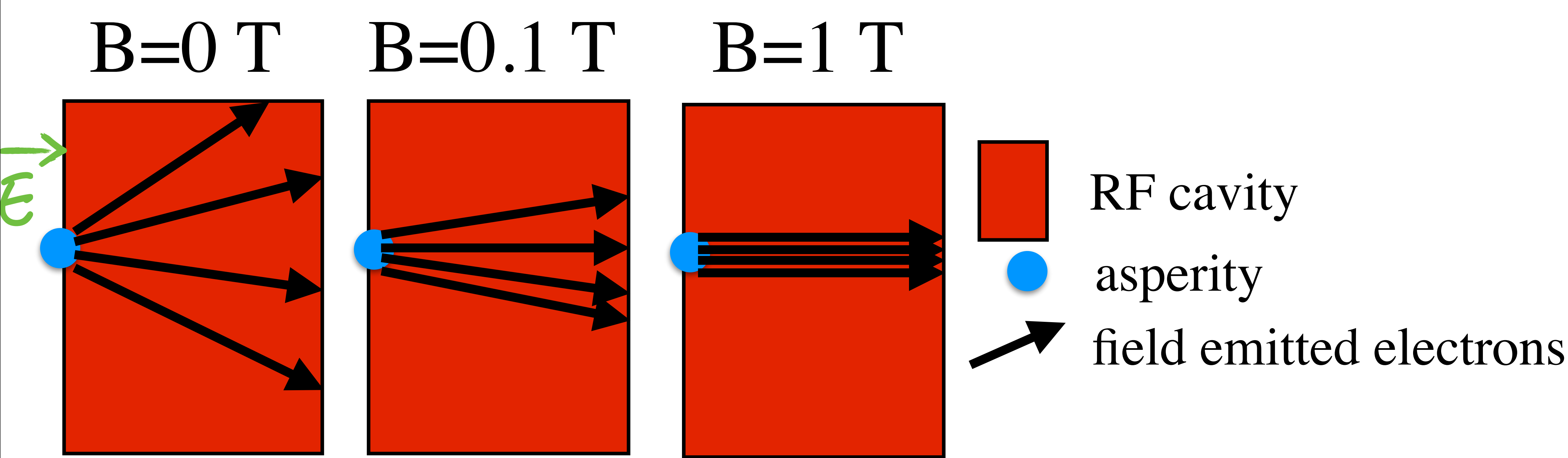

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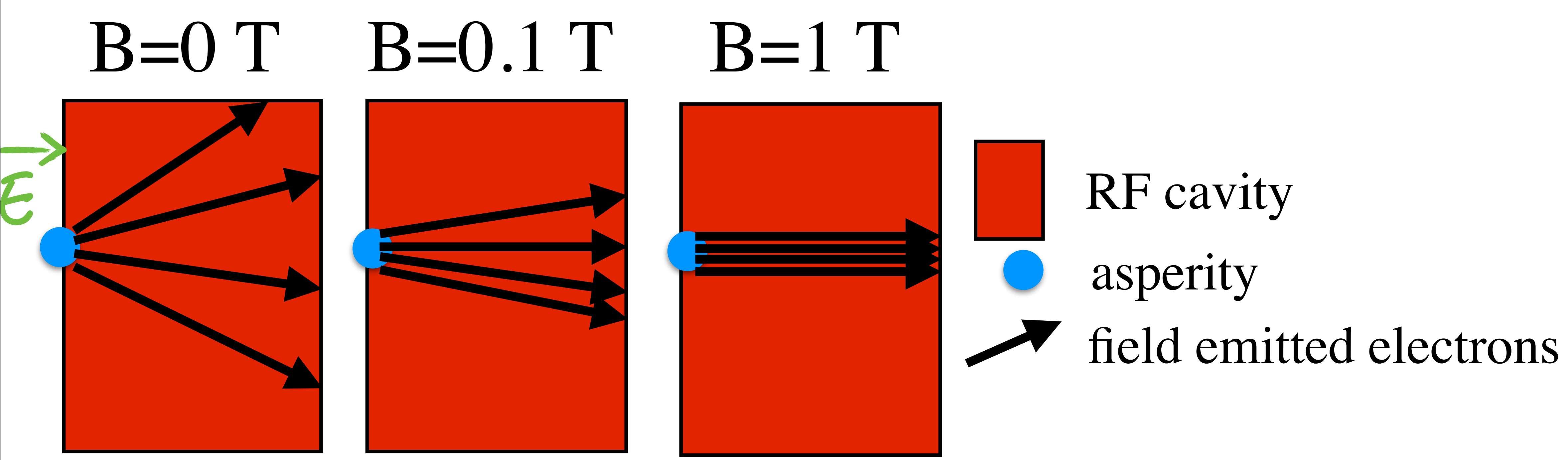

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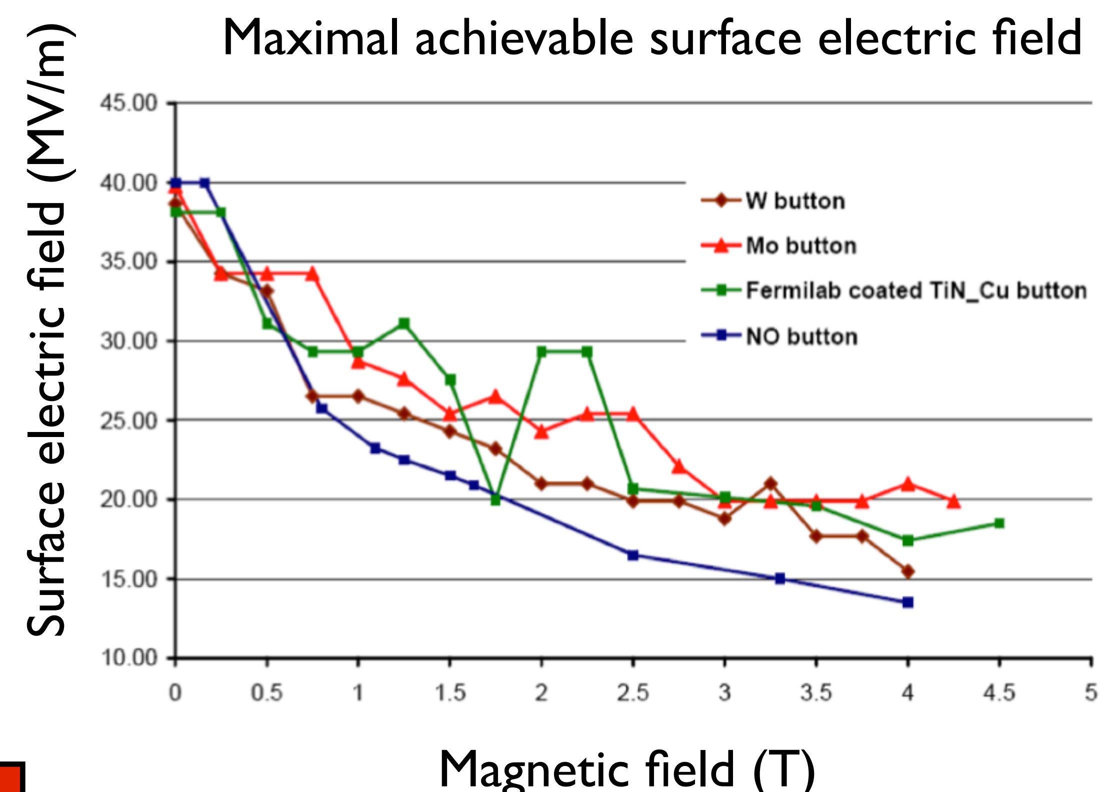

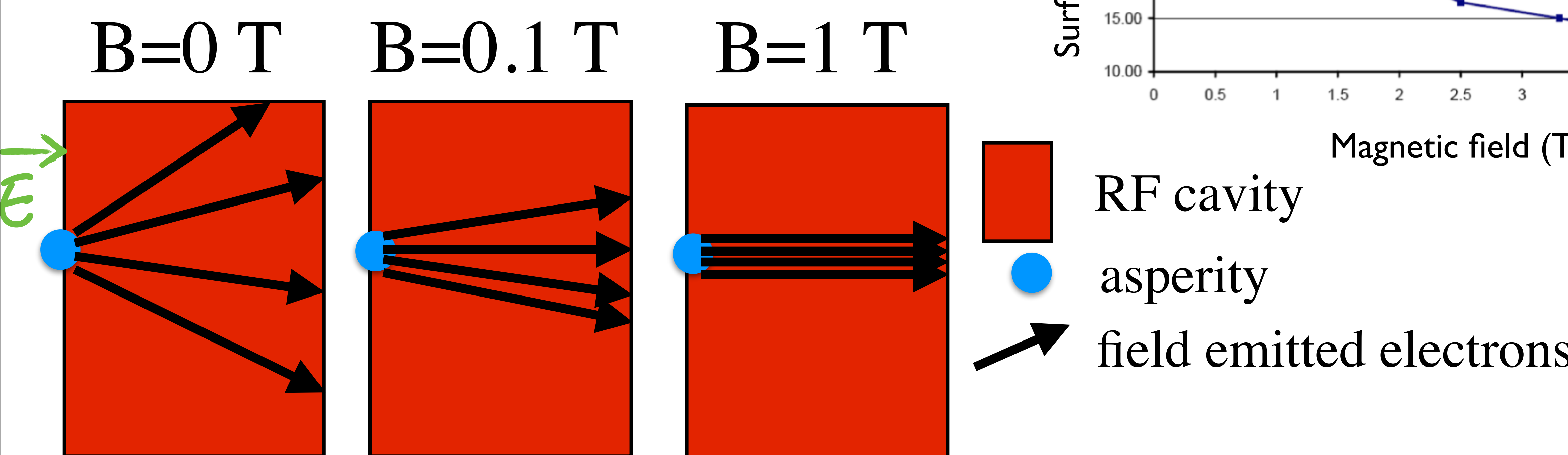

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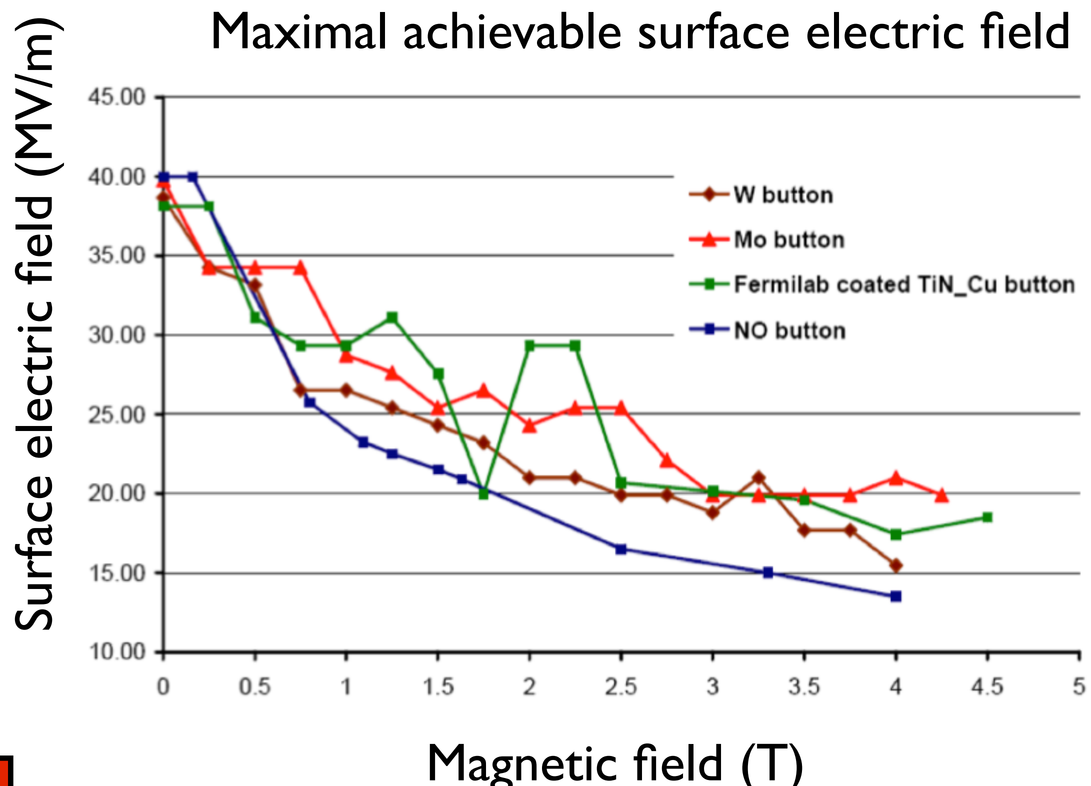
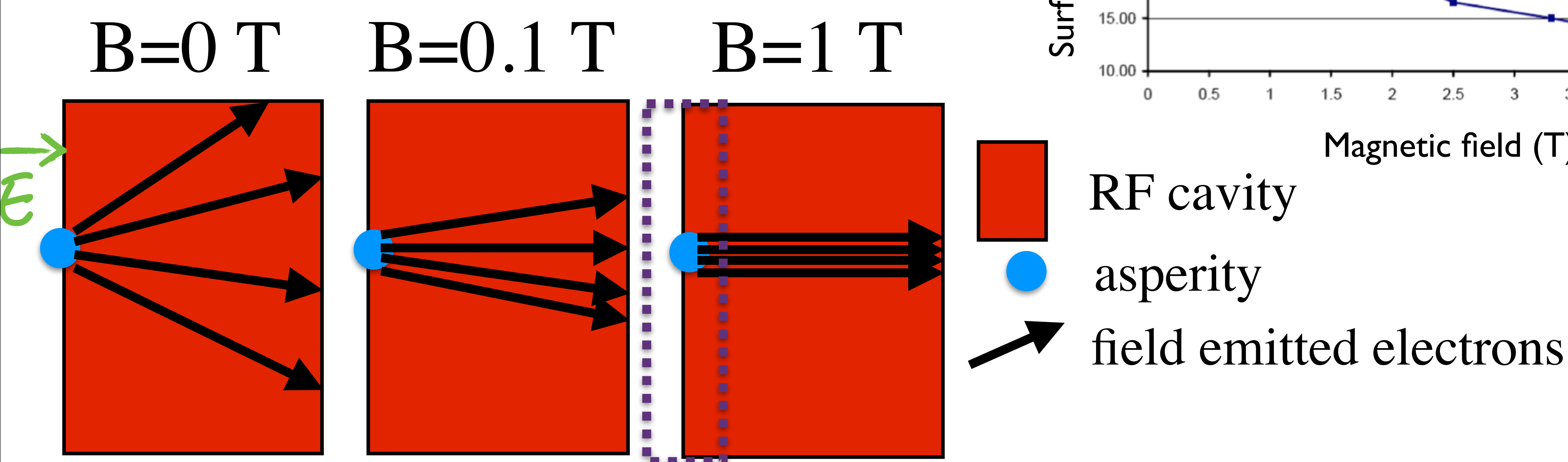
- Edge of RF: most sensitive z-position wrt RF breakdown (especially the iris, i.e. ~30 cm radius)





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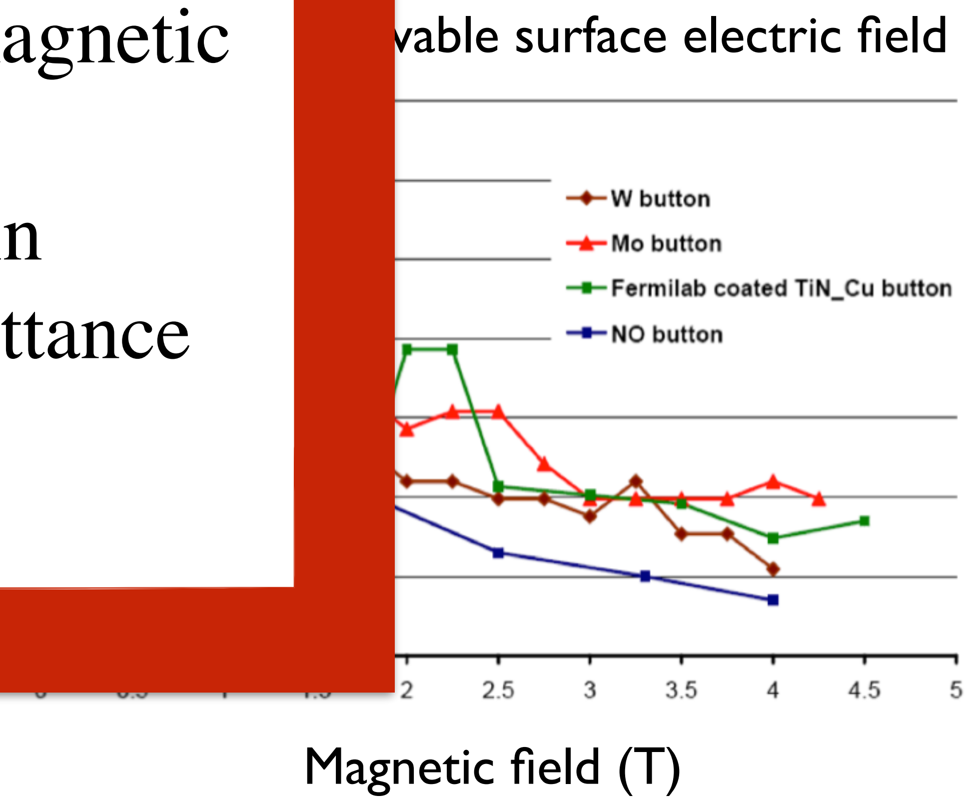
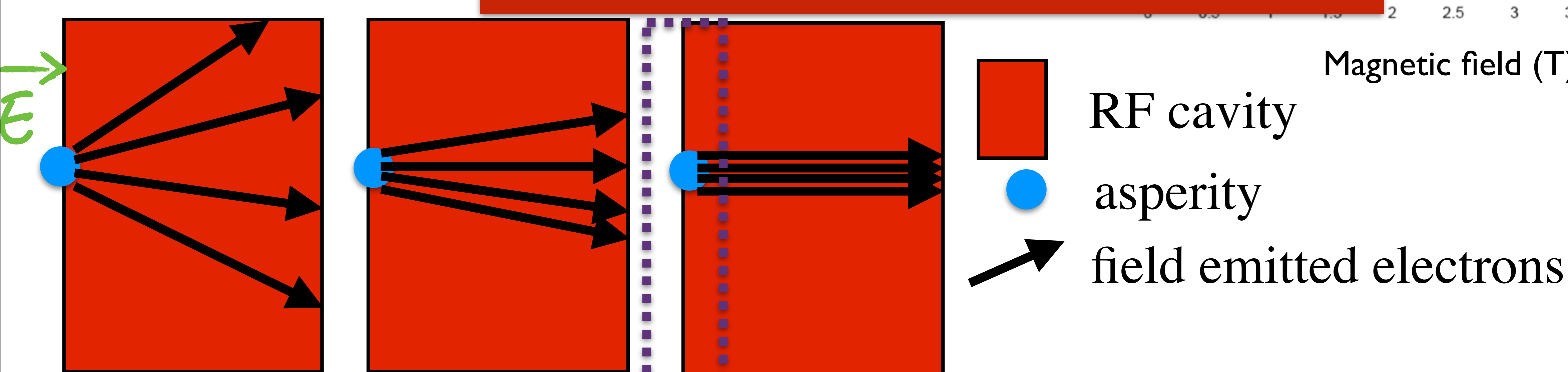
Since reference lattice of Neutrino Factory, FSIIA, has large B at end of RF cavities an alternative lattice needs to be found that:

a) significantly reduces magnetic field at RF cavities
b) performs equally well in cooling efficiency (emittance reduction and muon transmission)



B=0 T B=0…



Bucked Coils Lattice

- Proposed and designed a new lattice that uses a pair of homocentric and opposite polarity coils, called Bucked Coils (BC), rather than a single one

Ref: [4], [5], [6]

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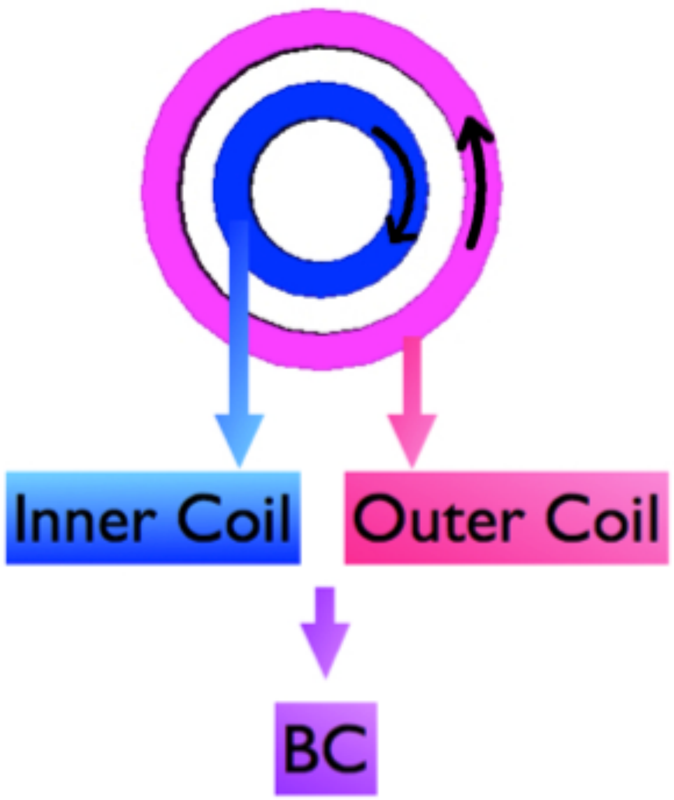

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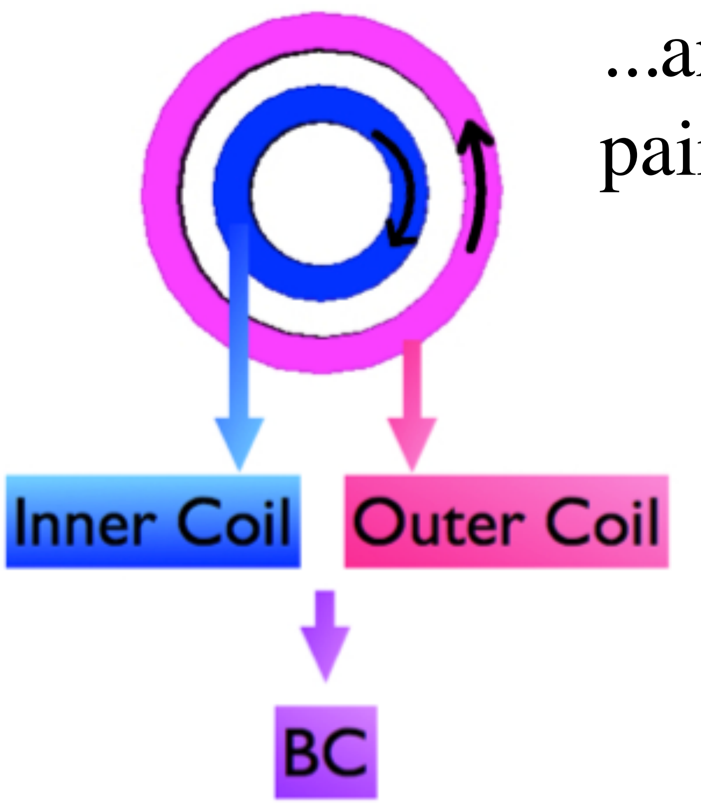

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...and with every repetition of the BC pair alternate the polarity of the coils

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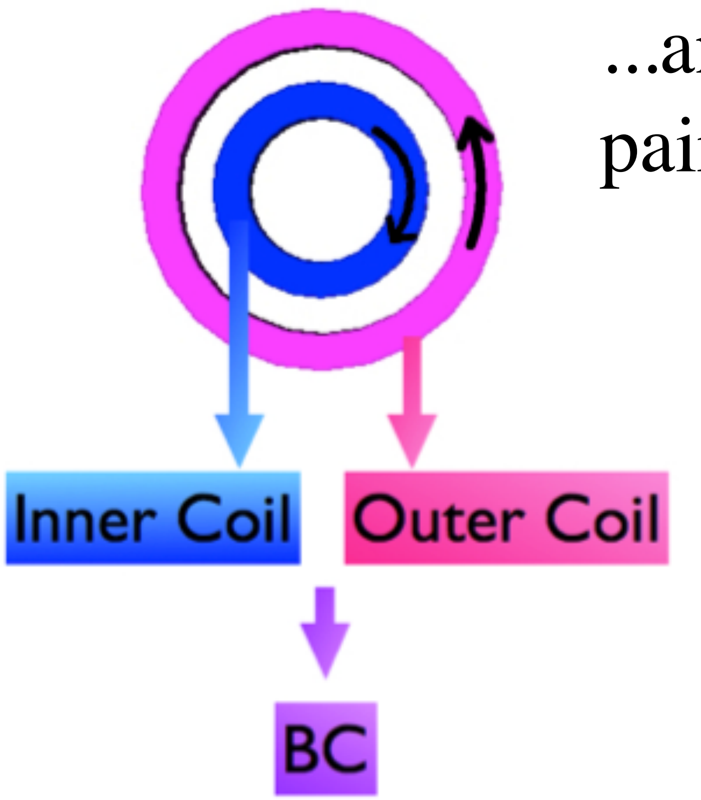

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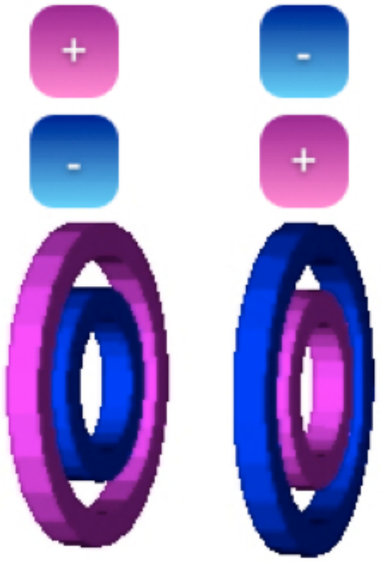

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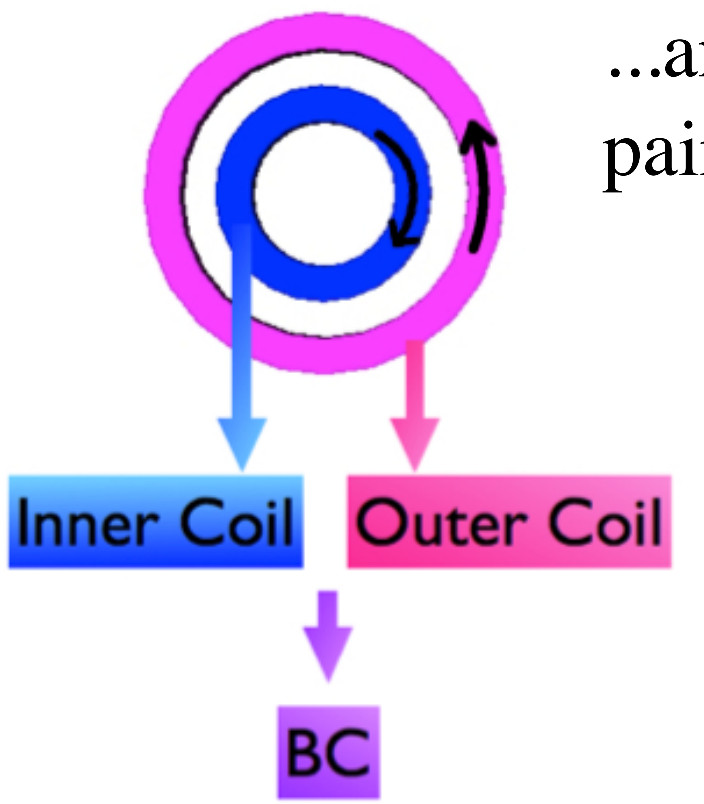

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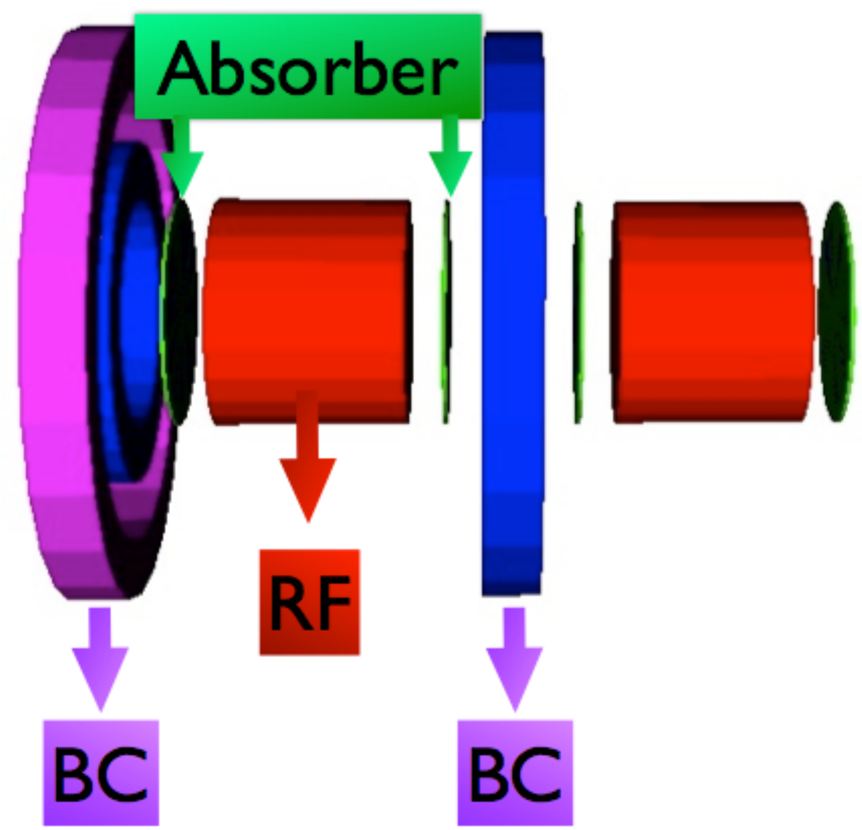
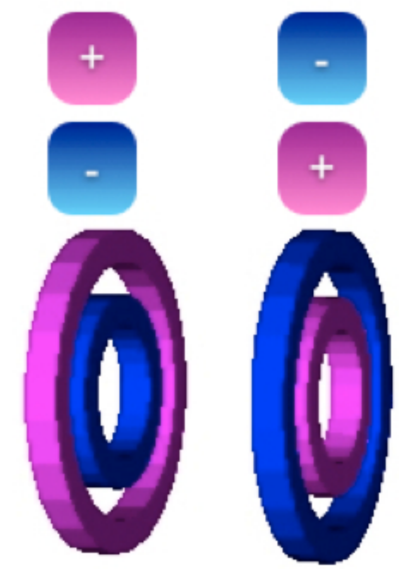


1 full-cell of the Bucked Coils Lattice



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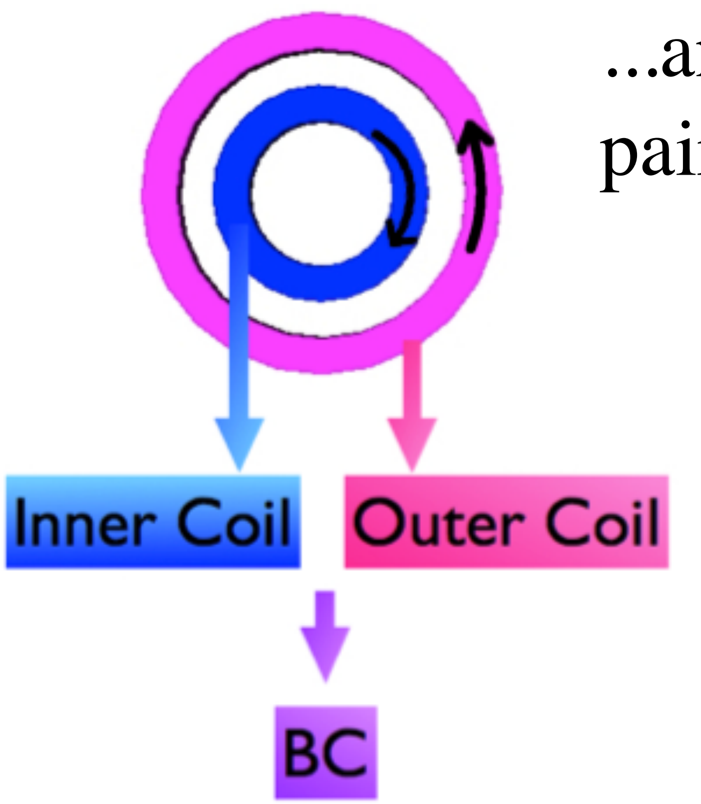

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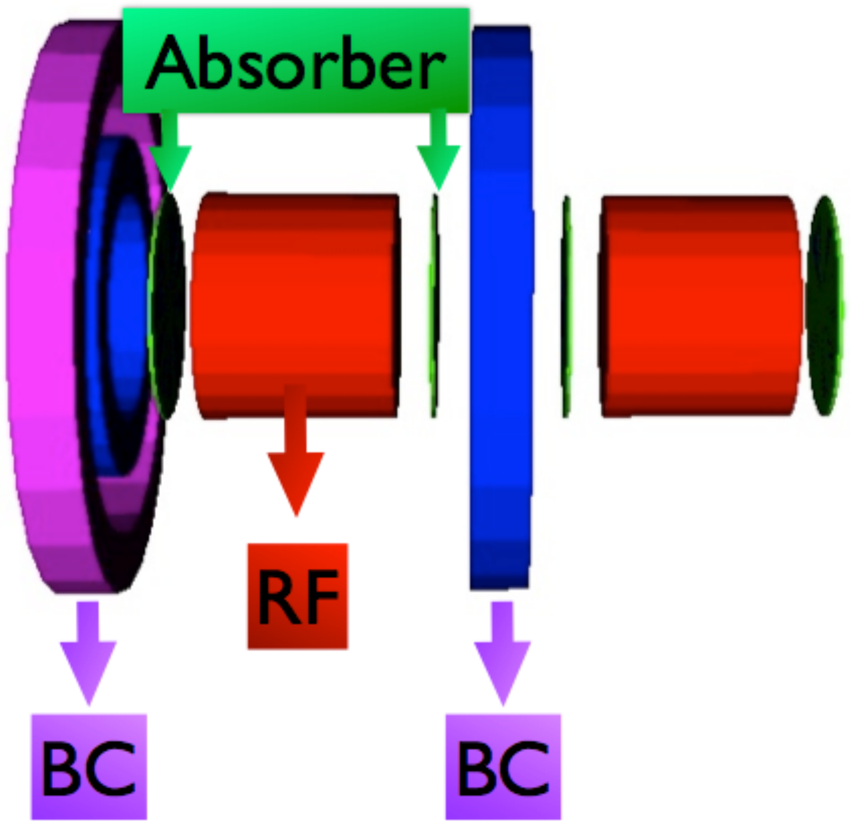

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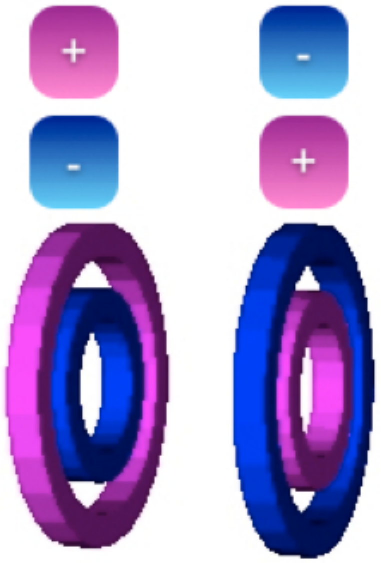
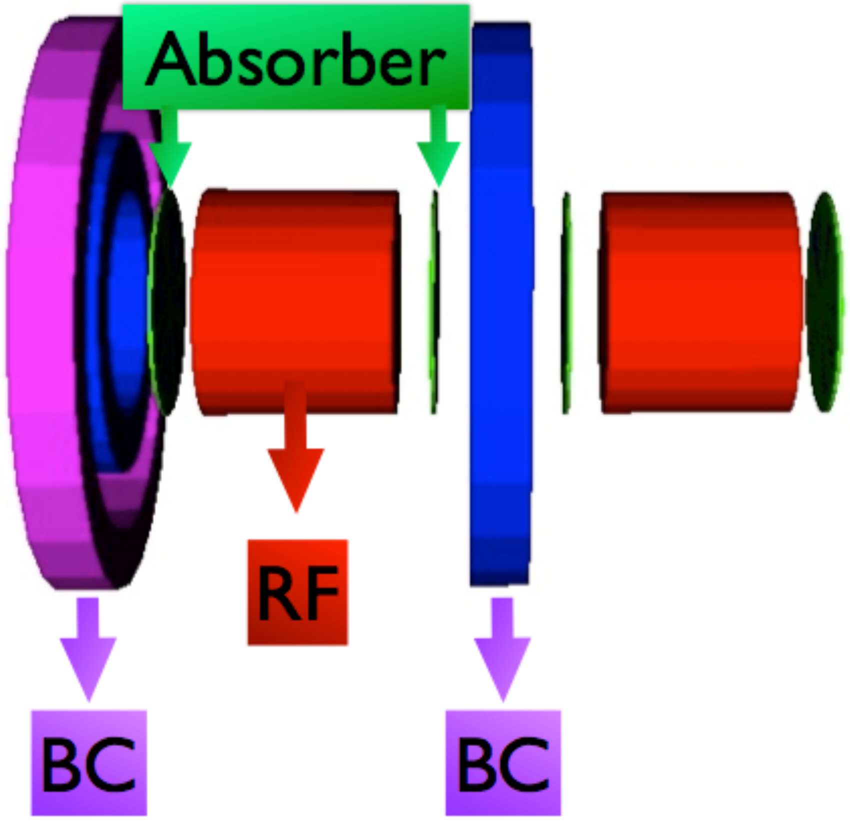


With every repeat of BC the coils' polarity alternates

Ref: [4], [5], [6]

Bucked Coils Lattice

...and with every repetition of the BC pair alternate the polarity of the coils



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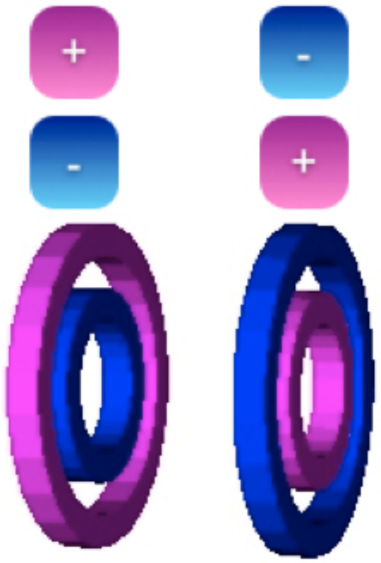

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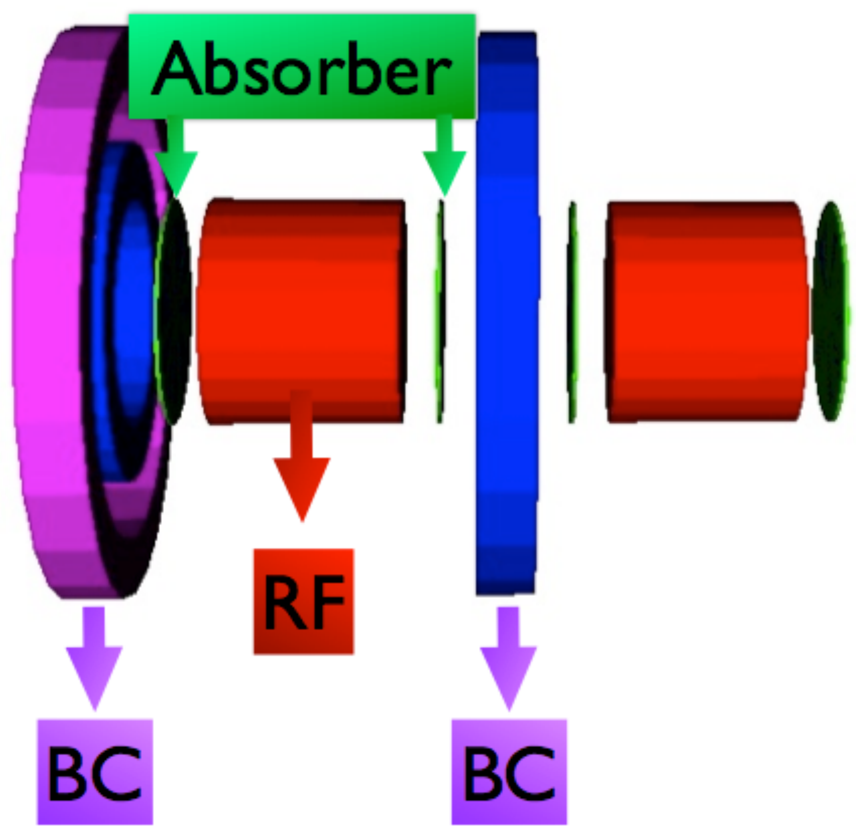

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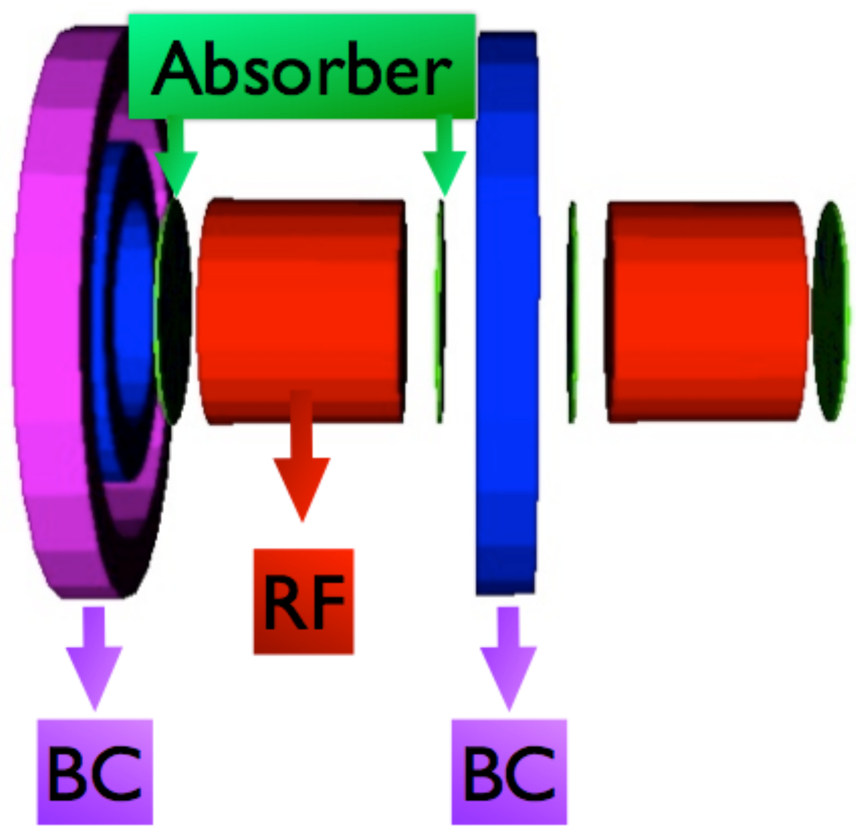

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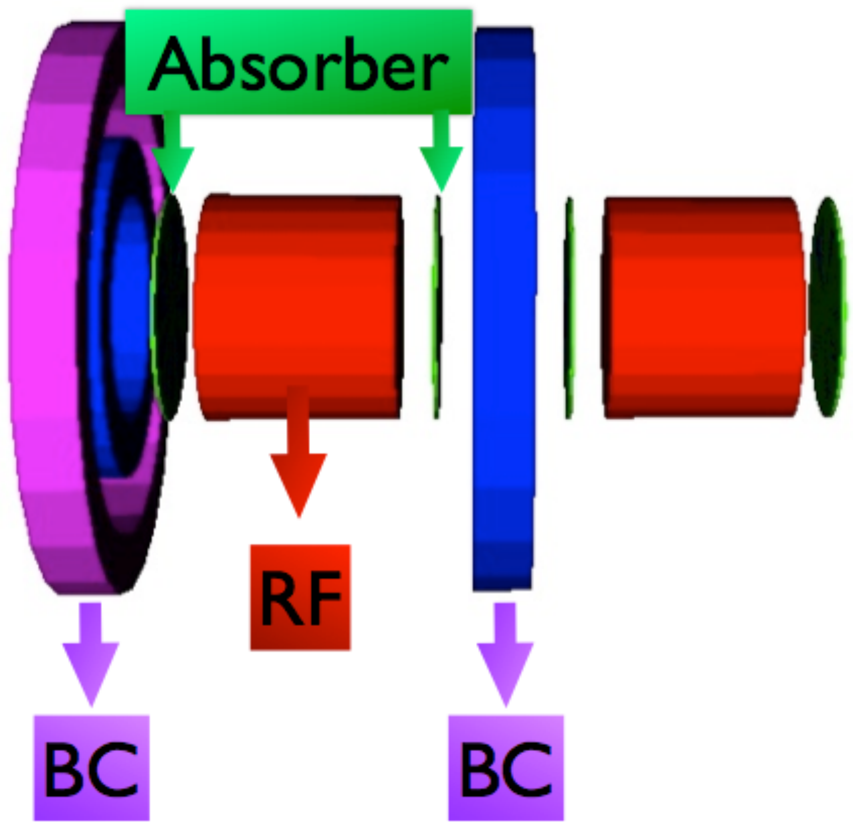

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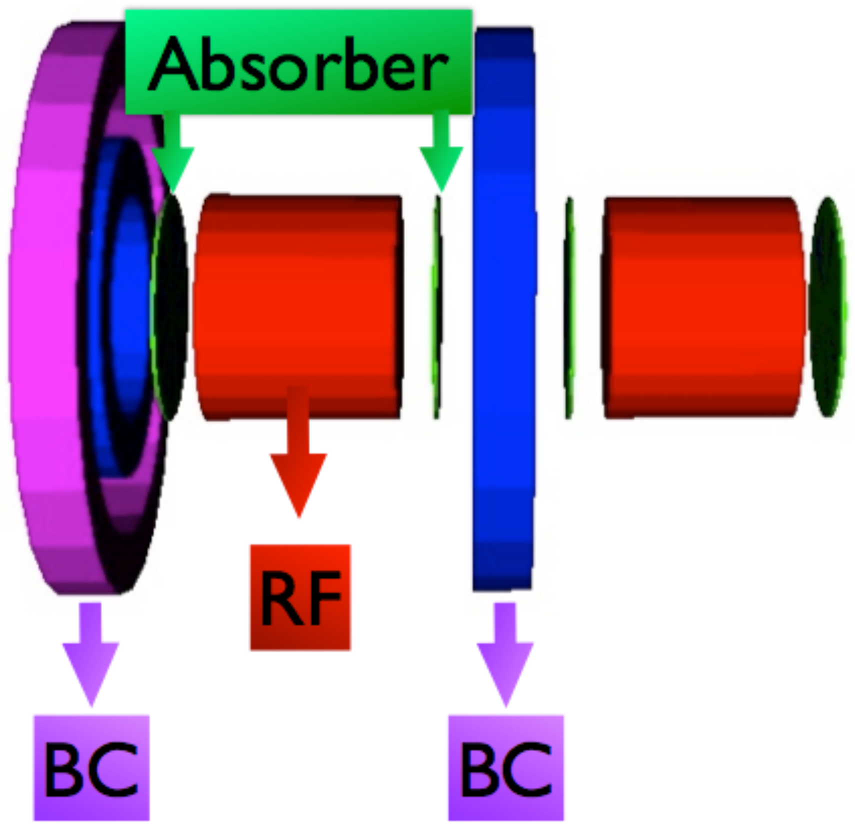
Bucked Coils Lattice

- 6 different BC versions will be presented
- Only differ in full cell-length and current densities



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Bucked Coils Lattice

Lattice	FSIIA	BC-I	BC-II	BC-III	BC-IV	BC-V	BC-VI
Full cell-length (L) [m]	1.5	2.1	2.1	2.1	1.8	1.8	1.8
IC [A/mm	106.667	120	97.2	87.48	132	120	87.48
OC [A/mm	N/A	90.24	77.14	66.73	99.26	90	66.73

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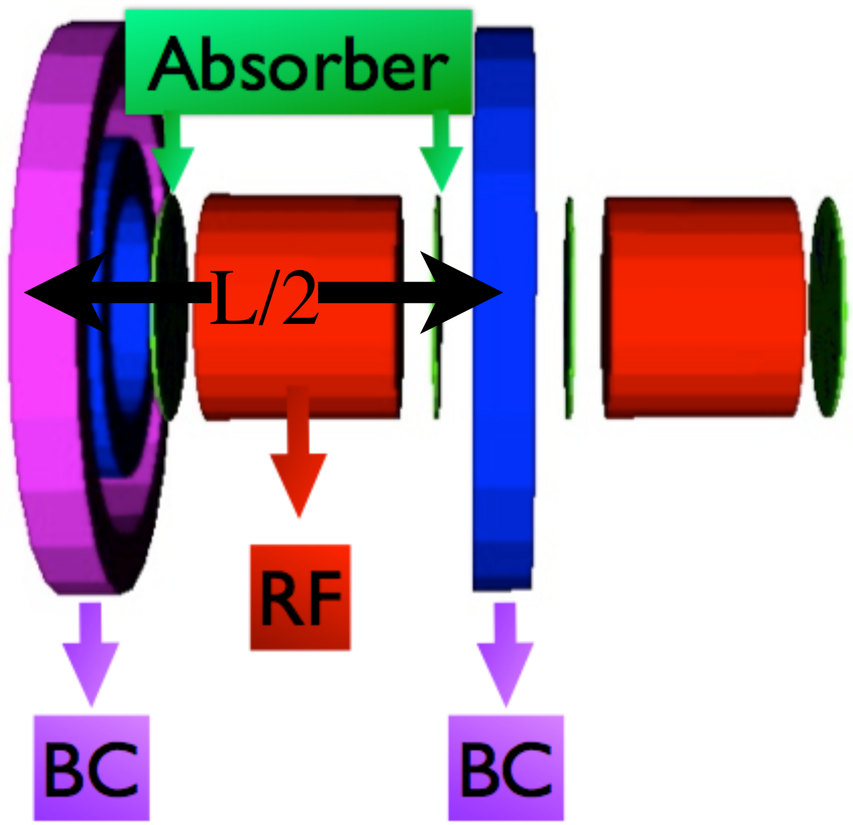

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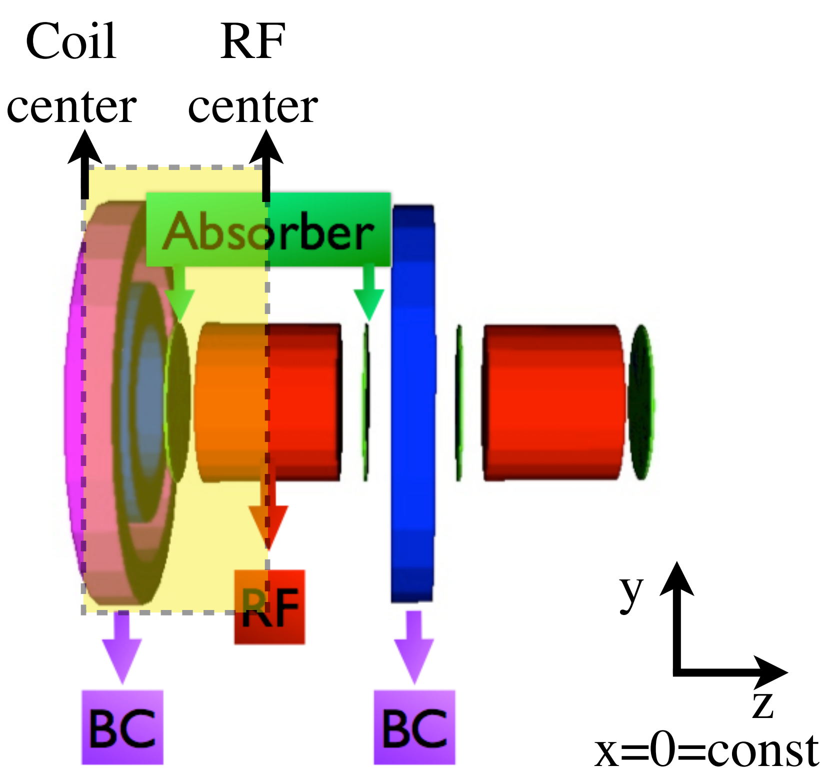
Magnetic field

Magnetic field



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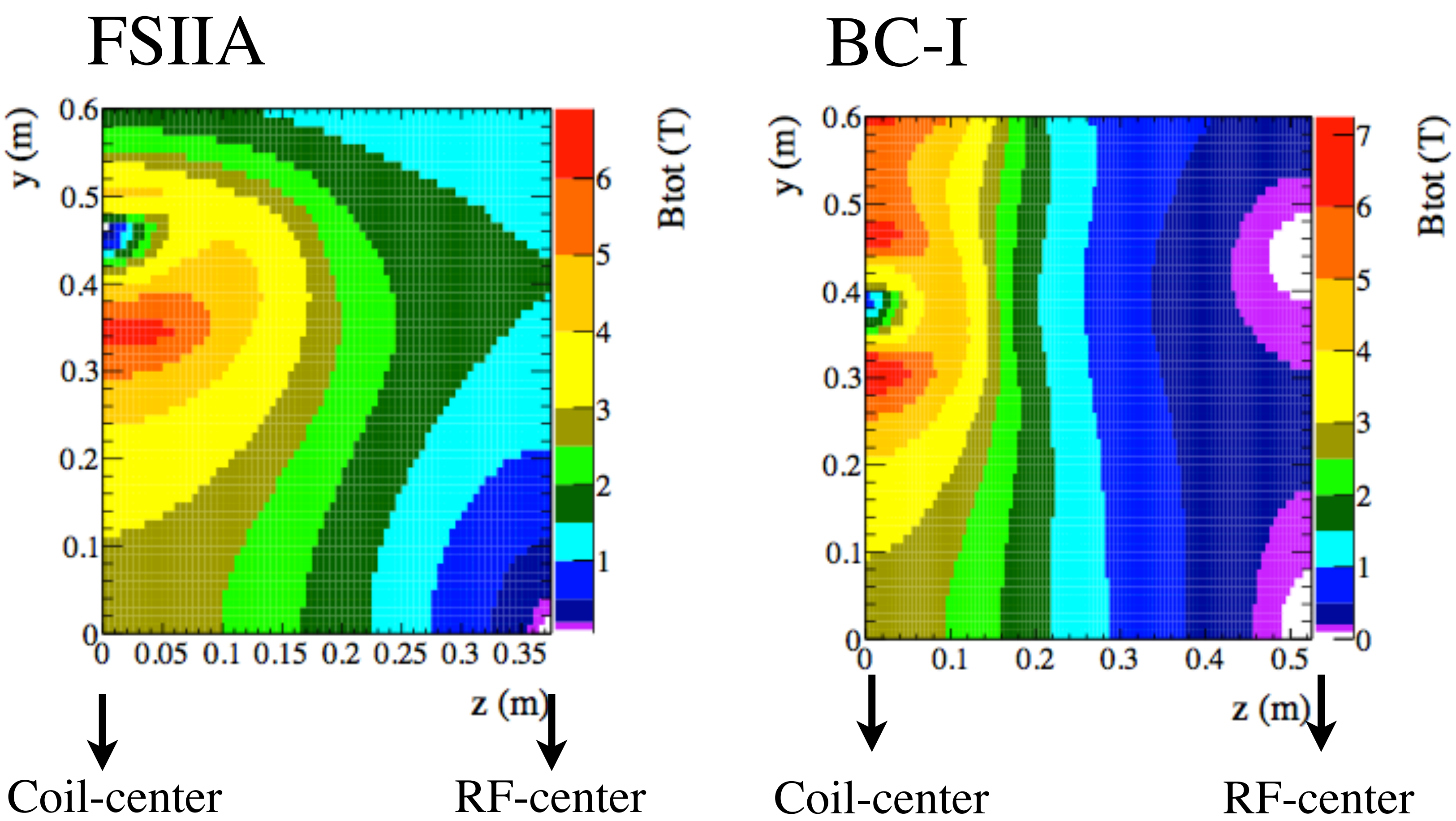

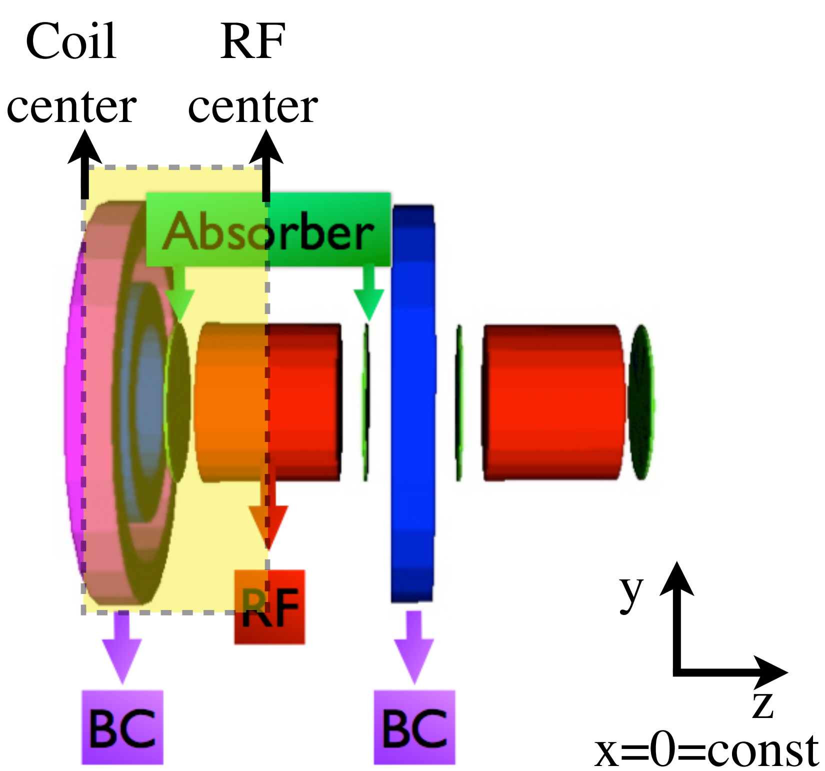

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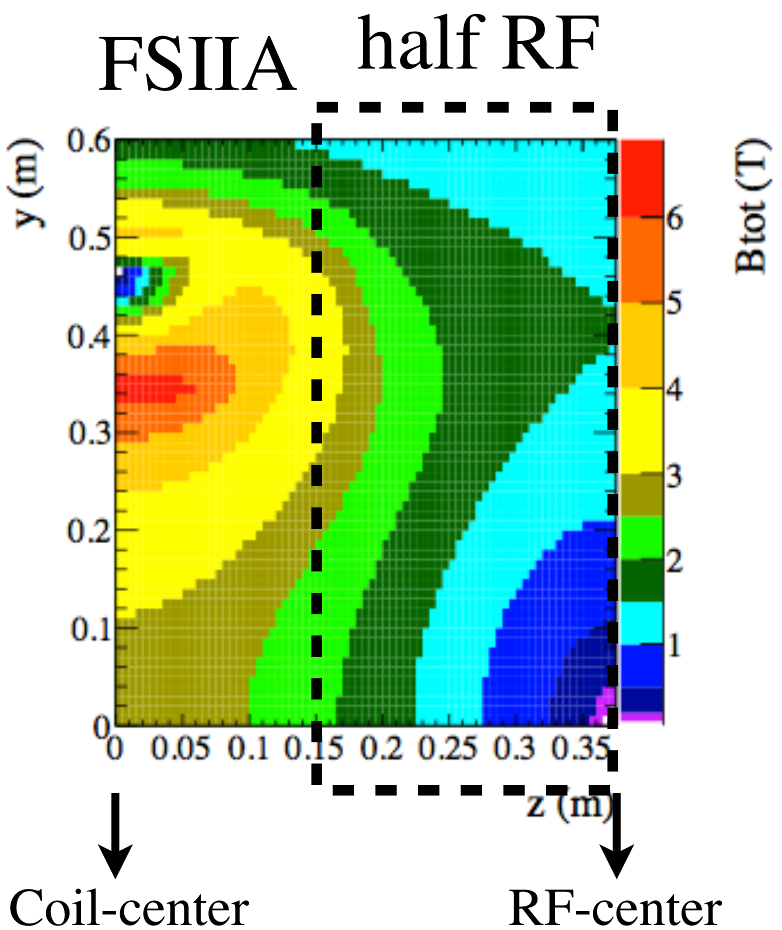

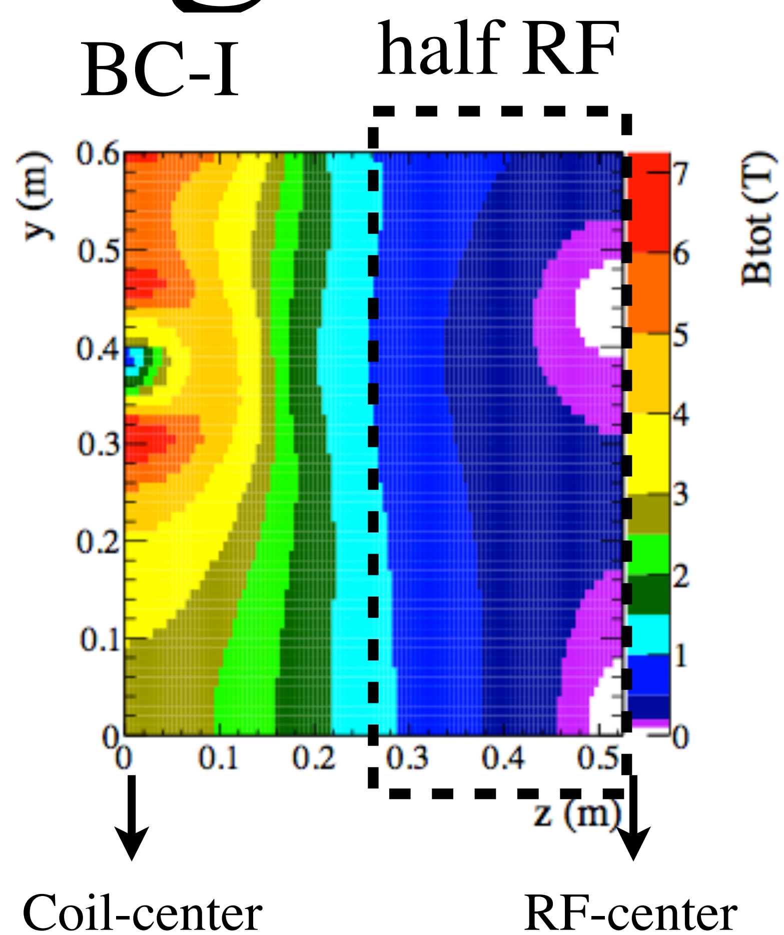

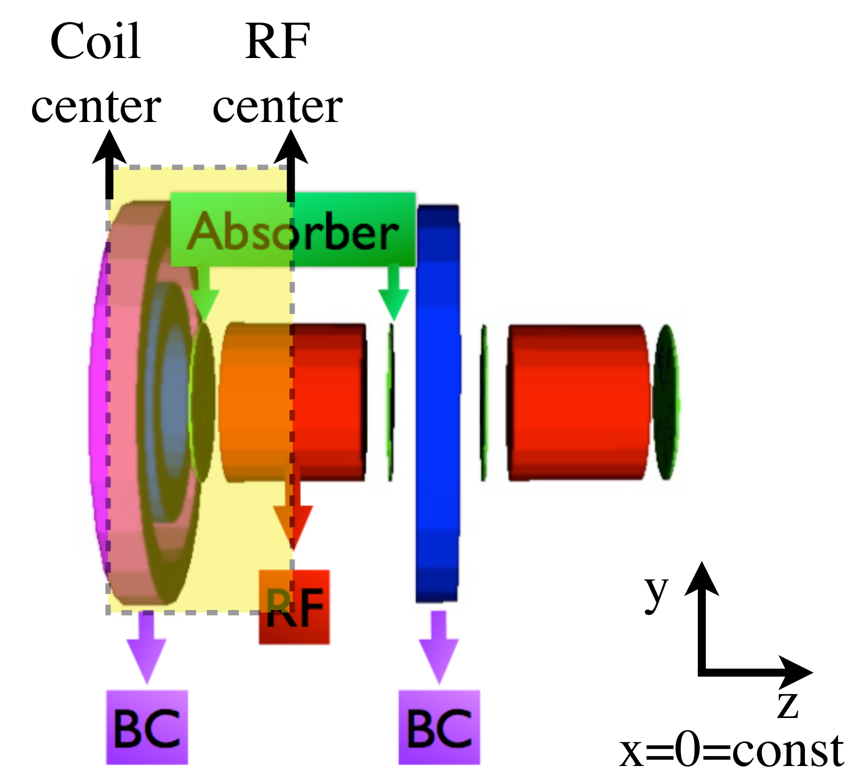

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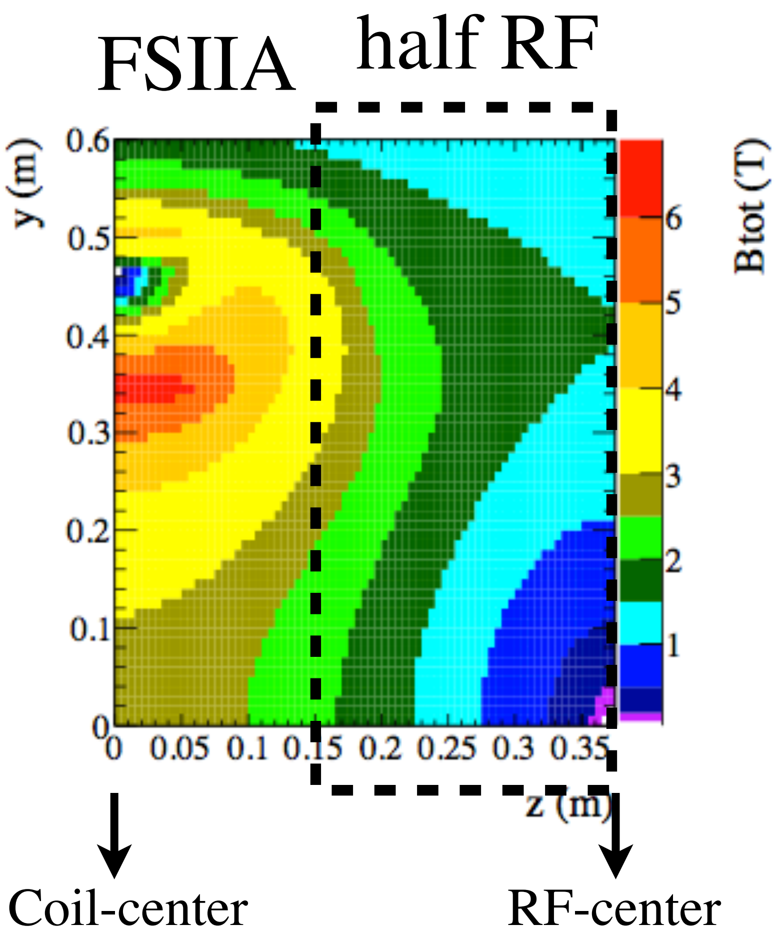
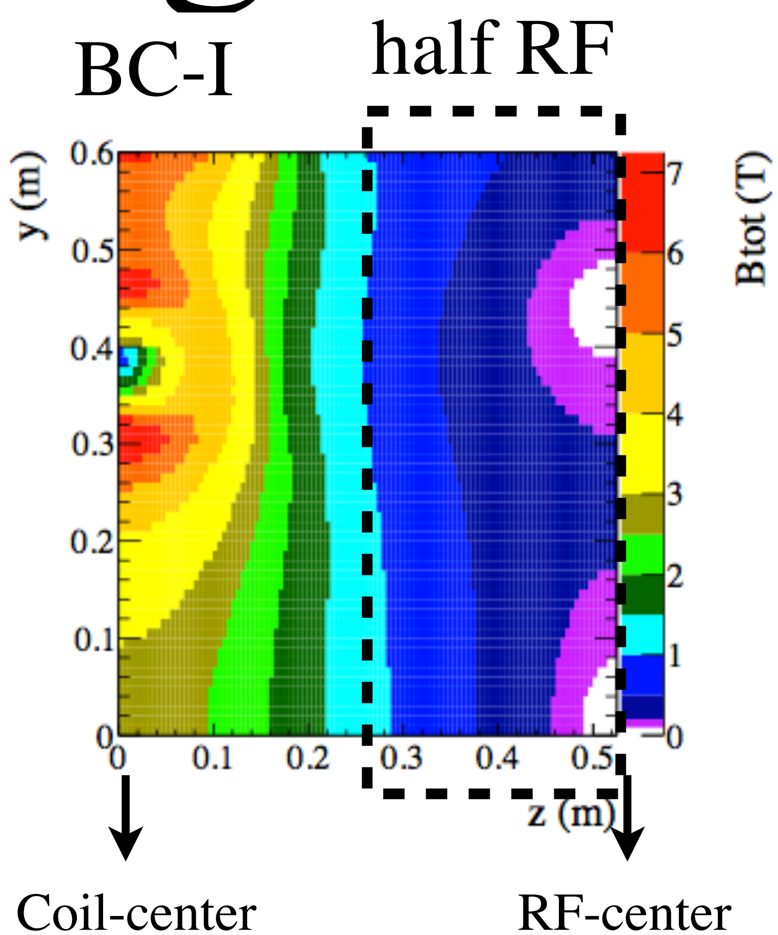
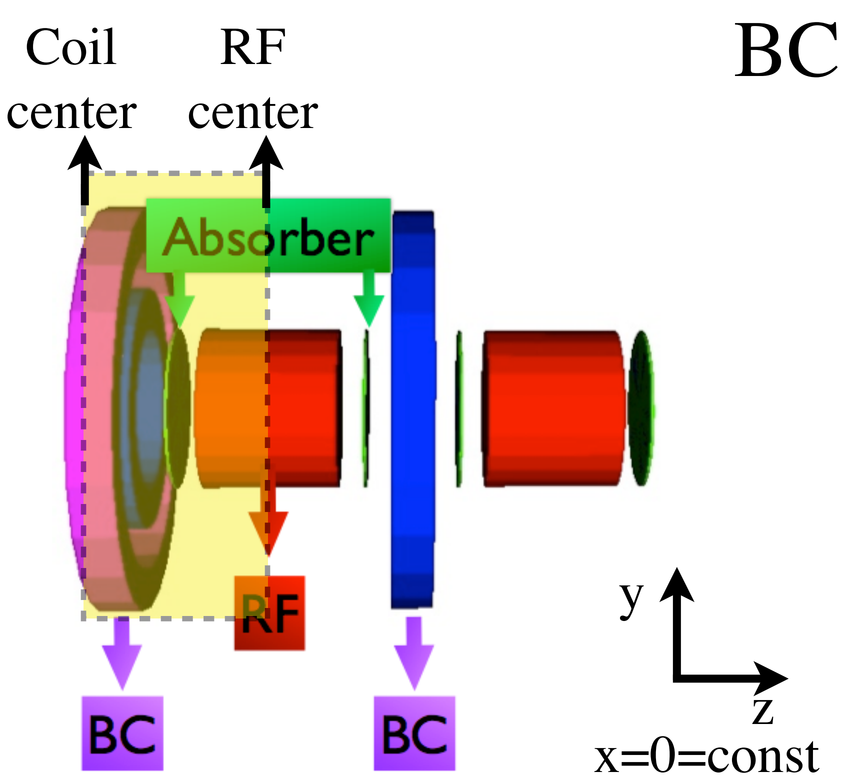




BC: Larger area within RF cavity with $B<1$ T



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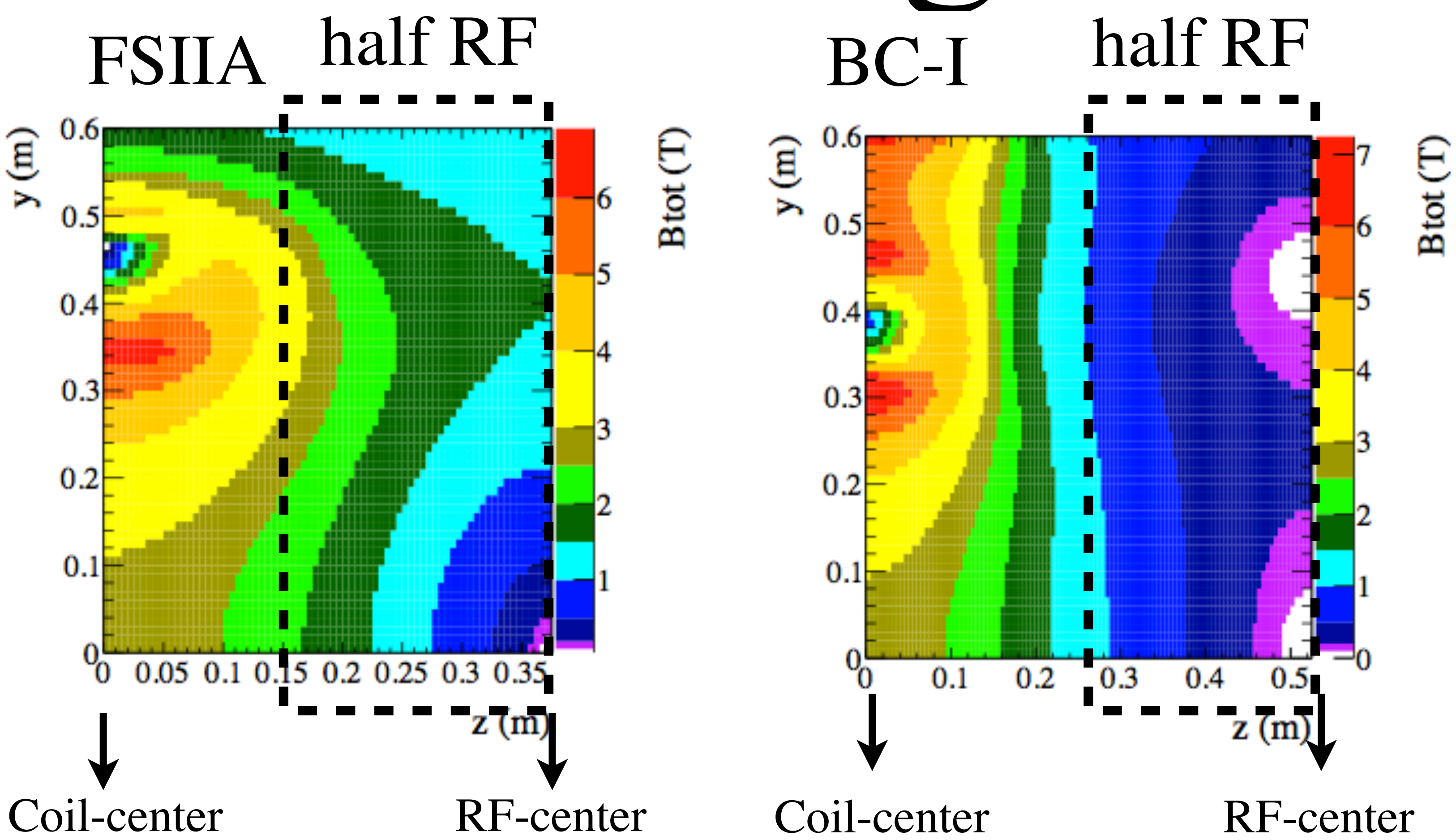

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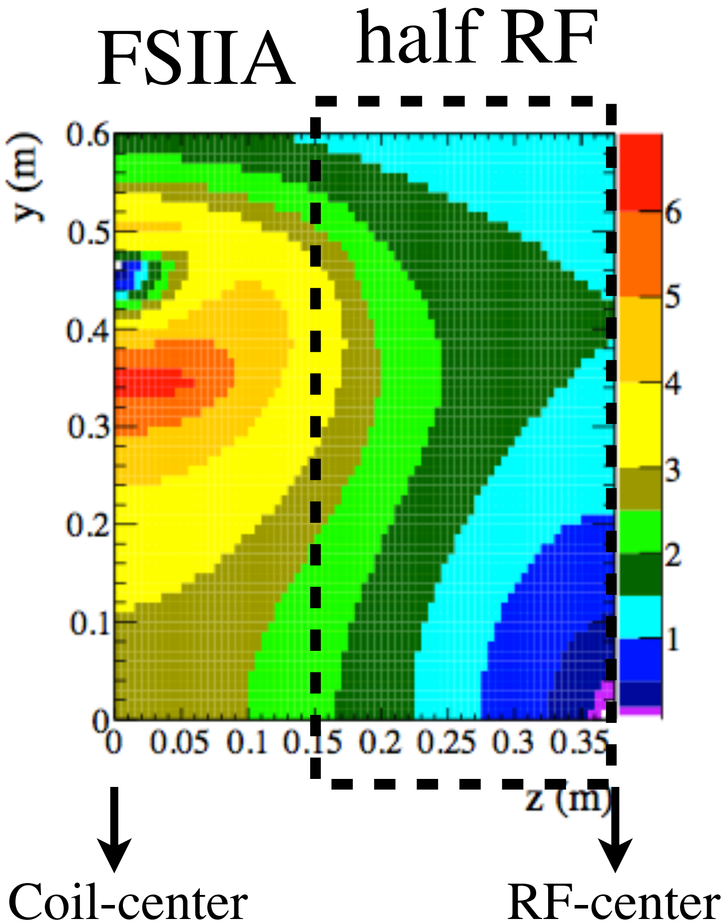

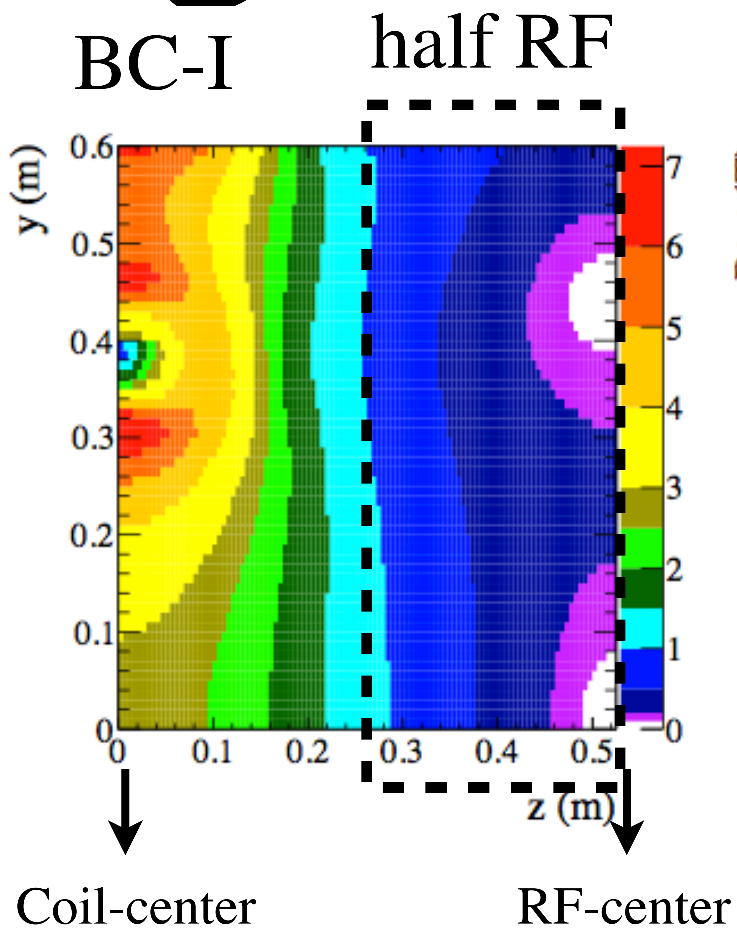

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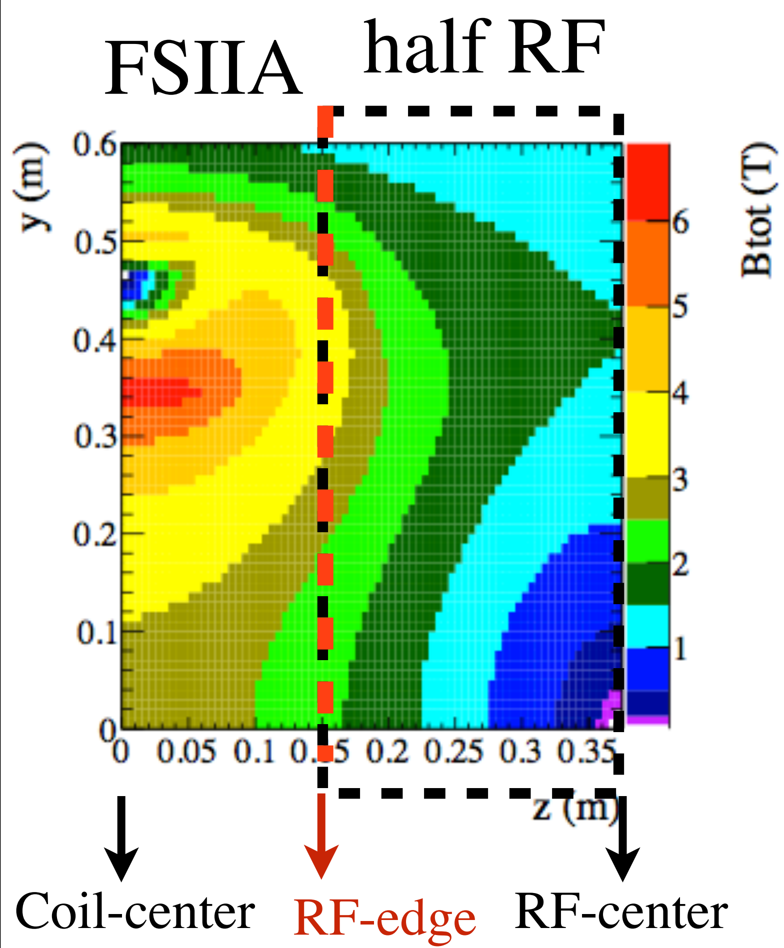
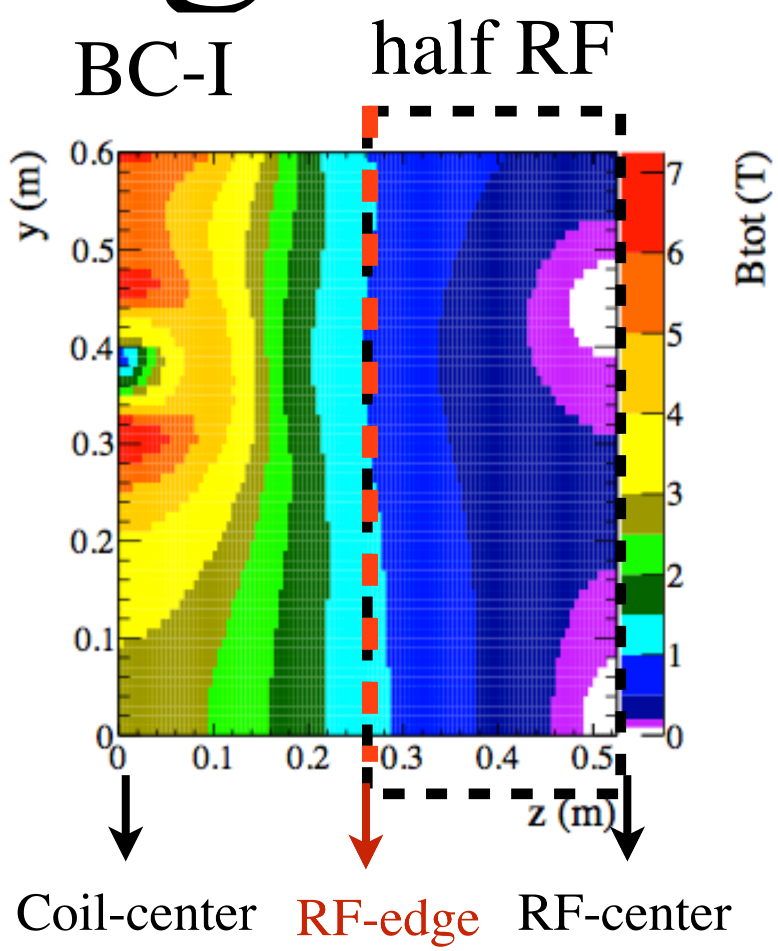
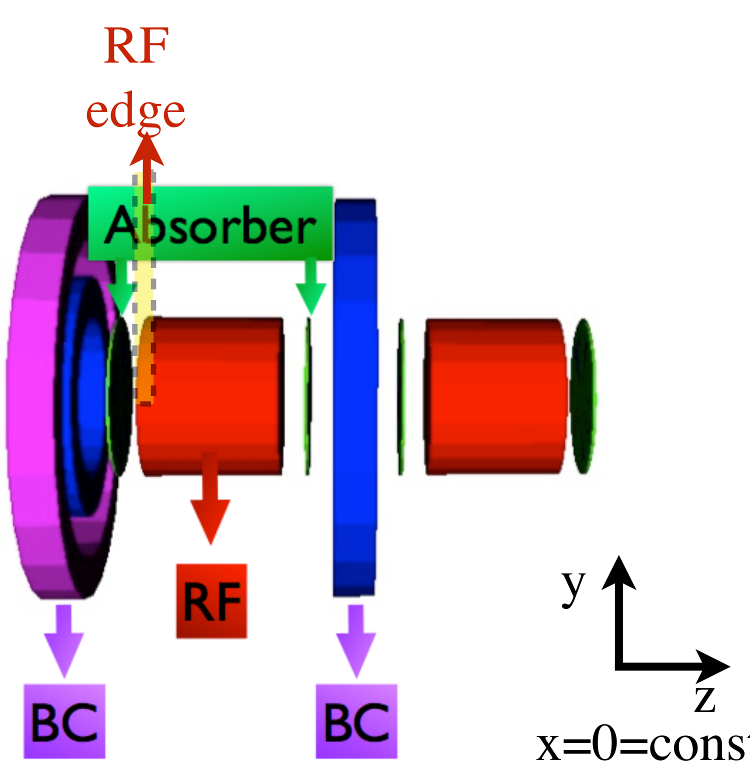




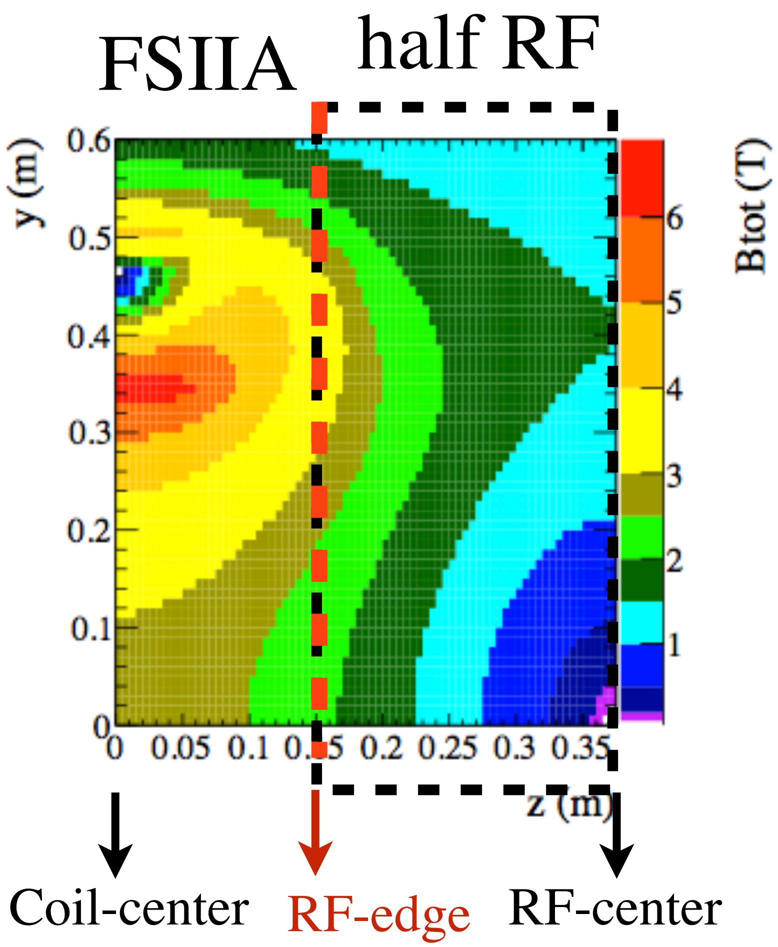


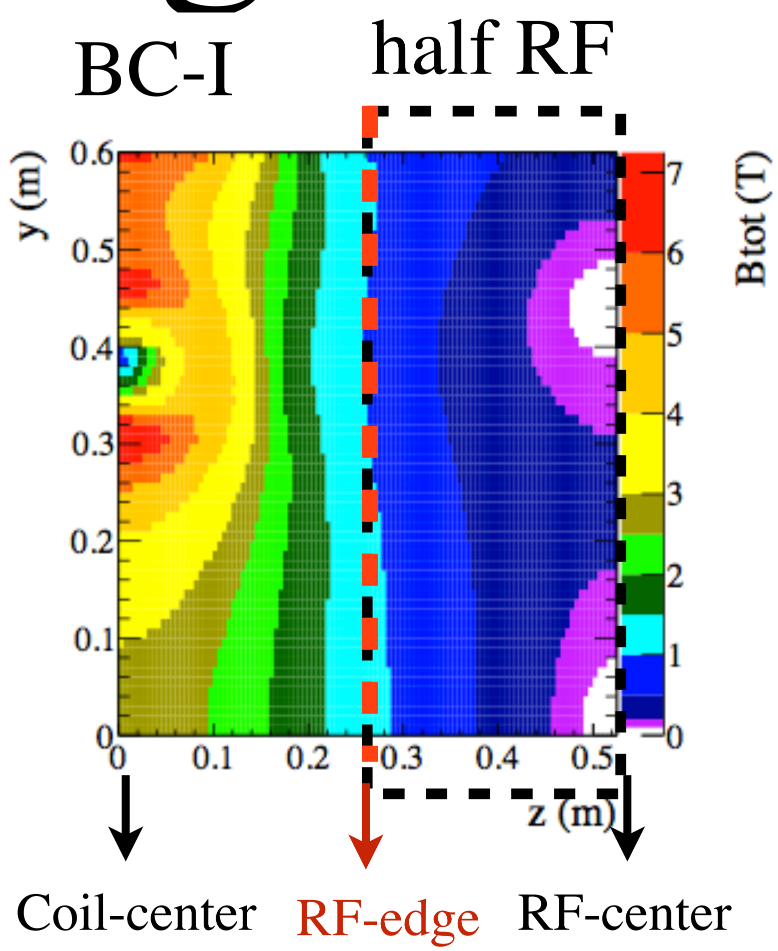
**

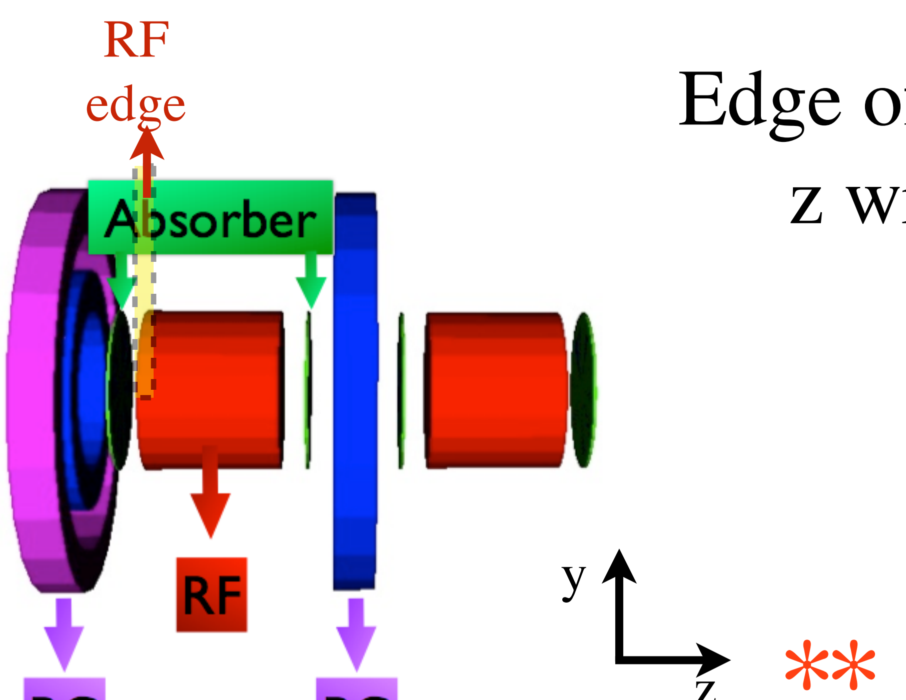
x=0=const

z=end of RFs=constant

Magnetic field







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Edge of RFs: most sensitive

z wrt RF breakdown:

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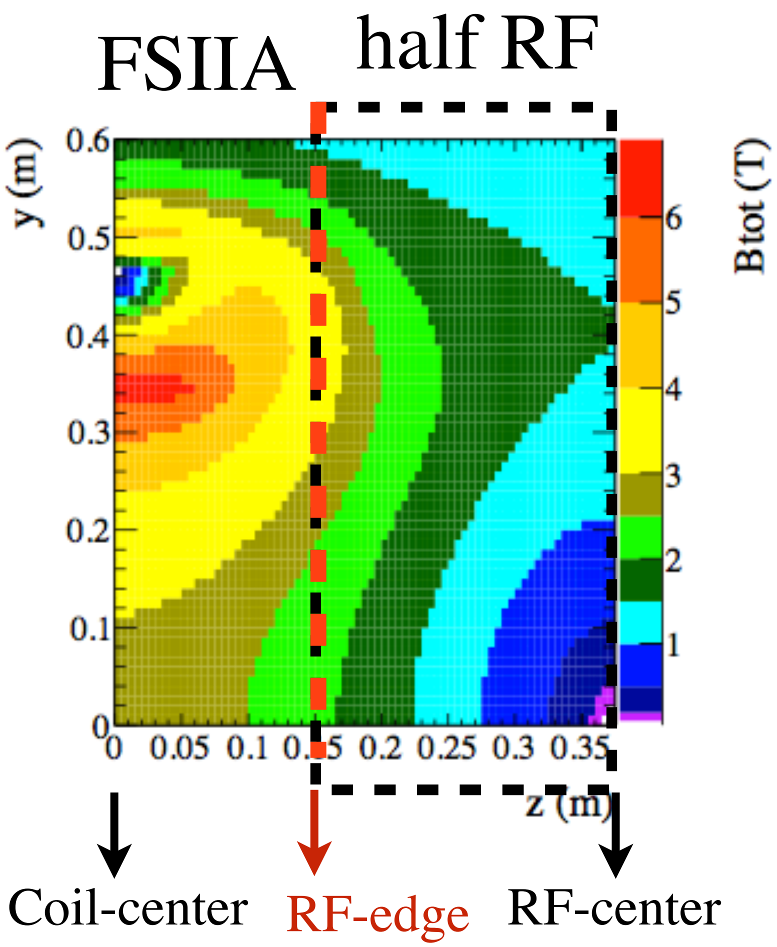

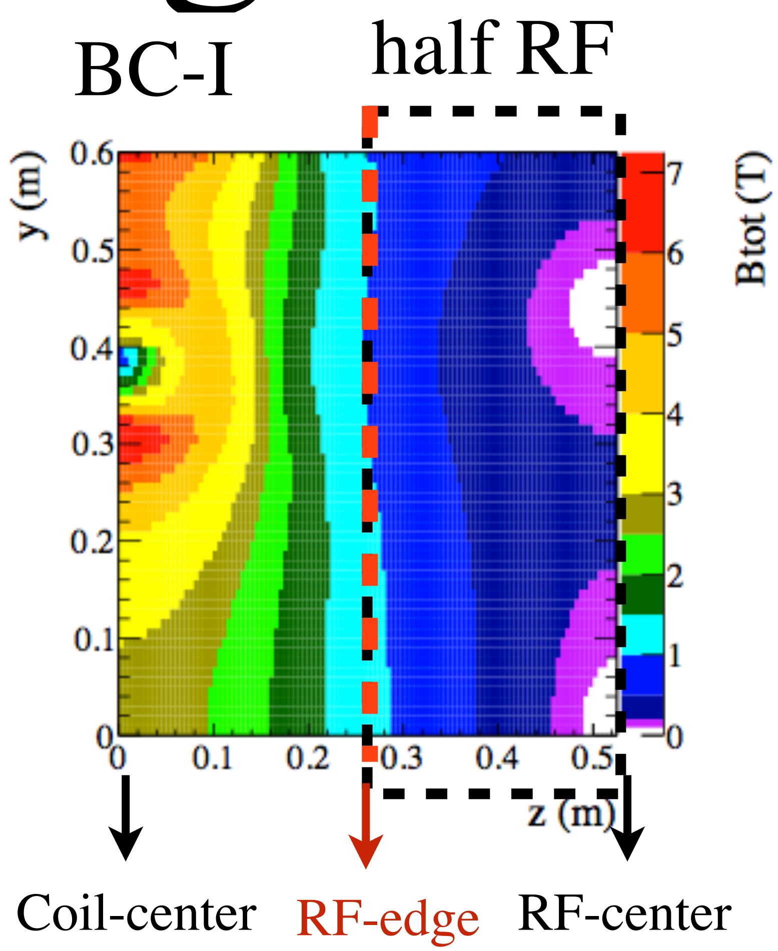

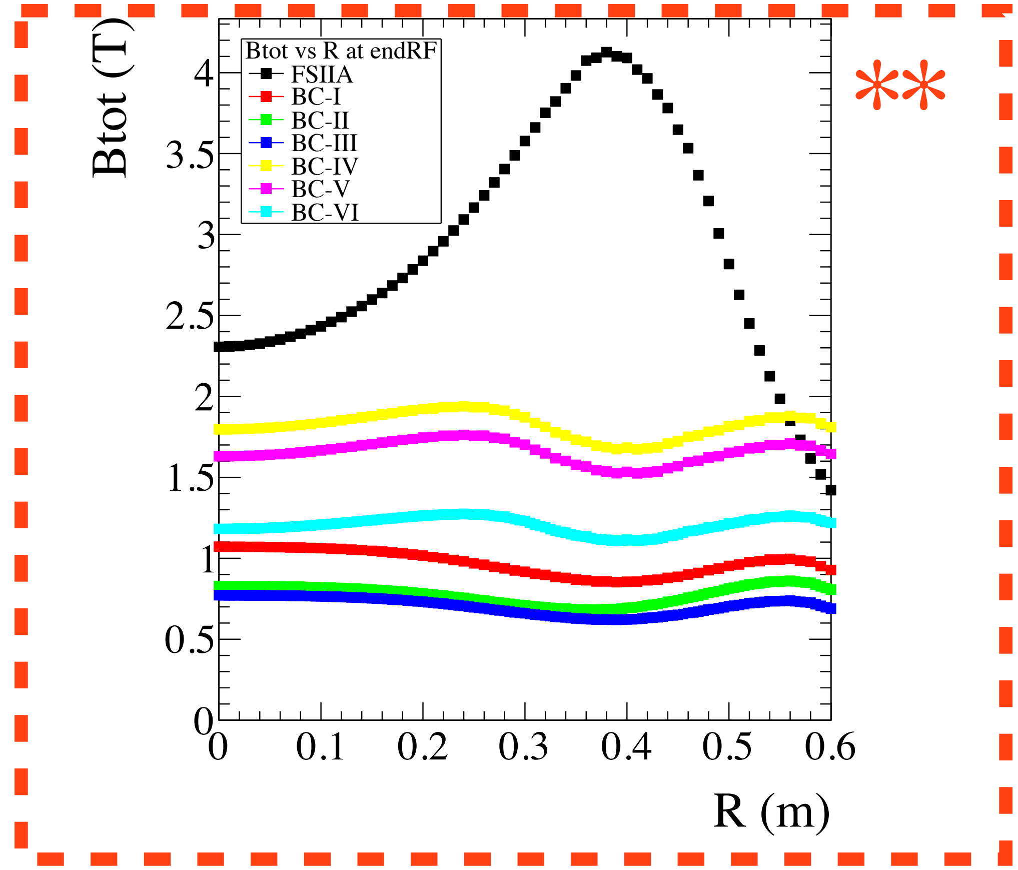

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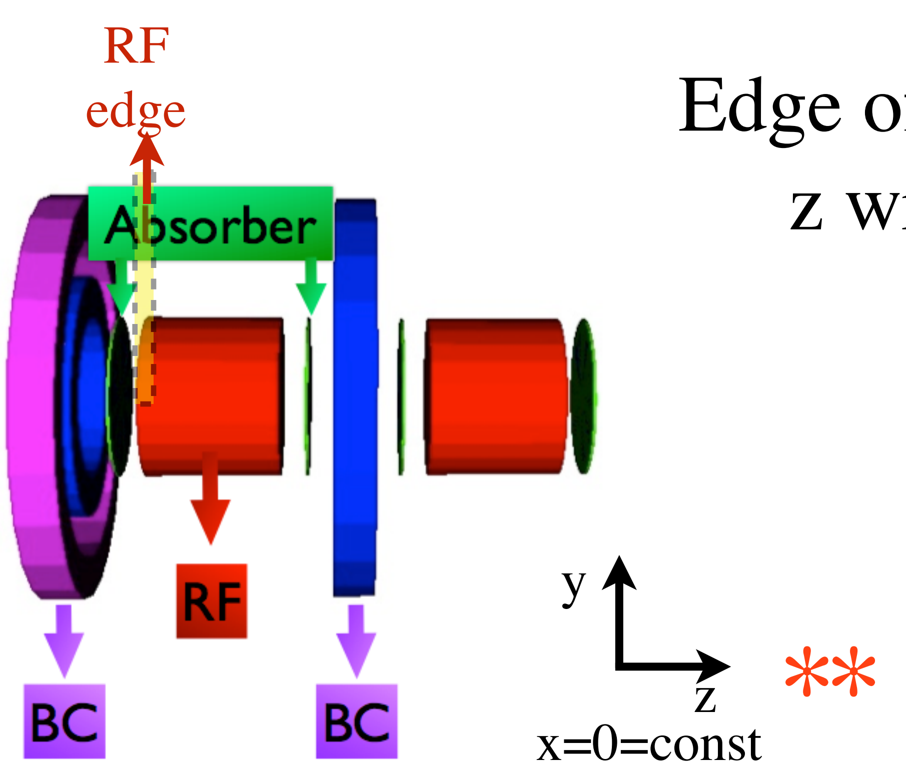

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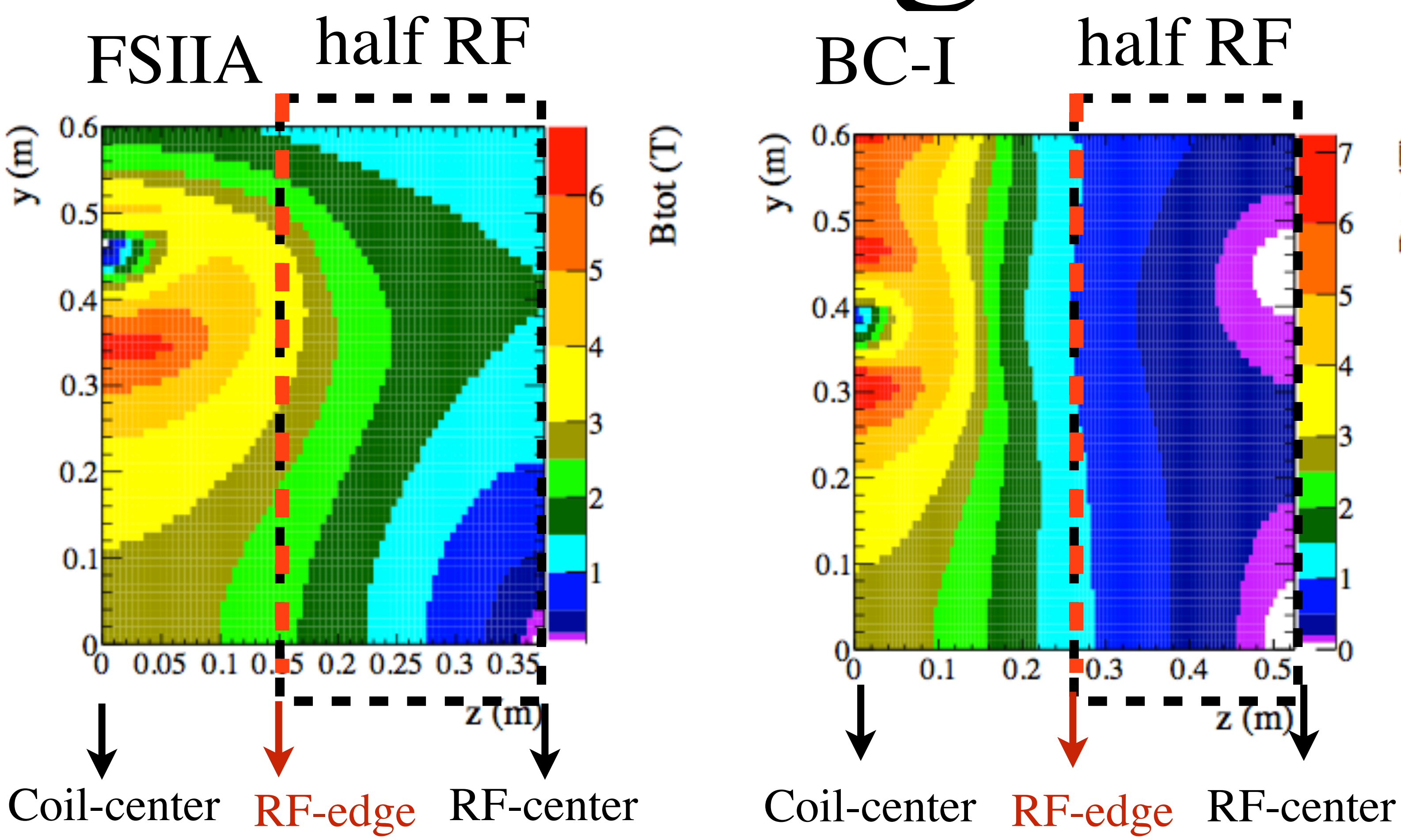

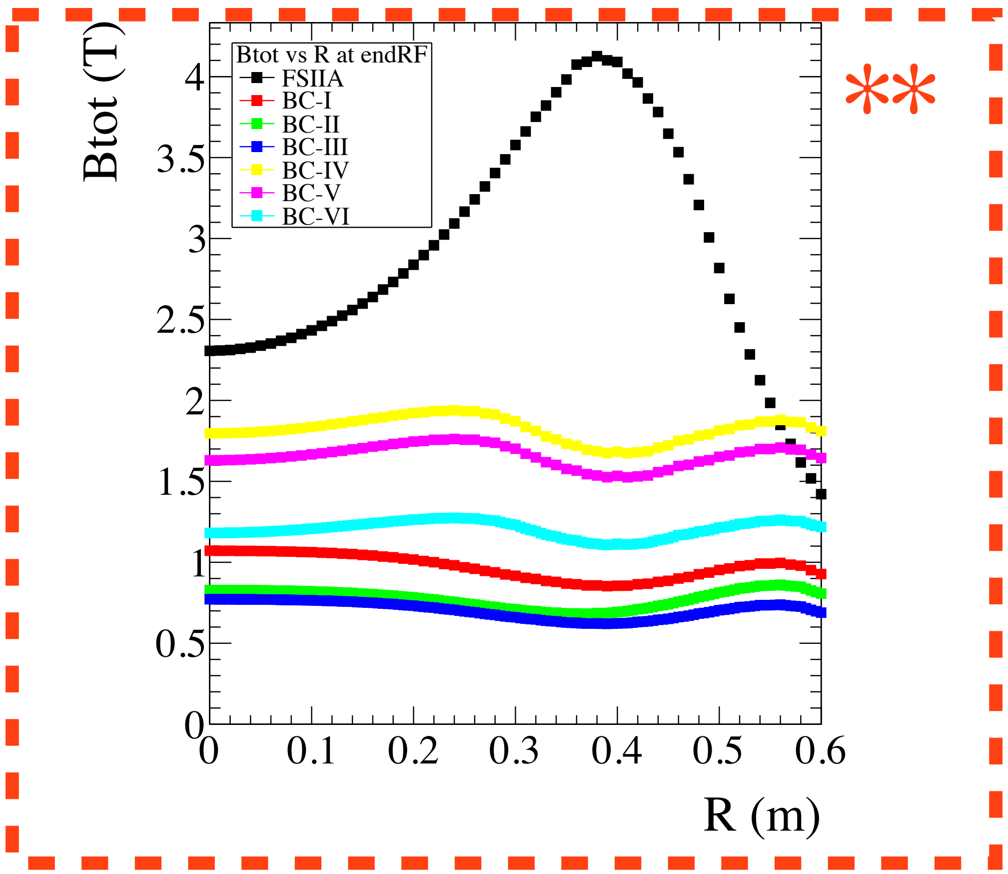

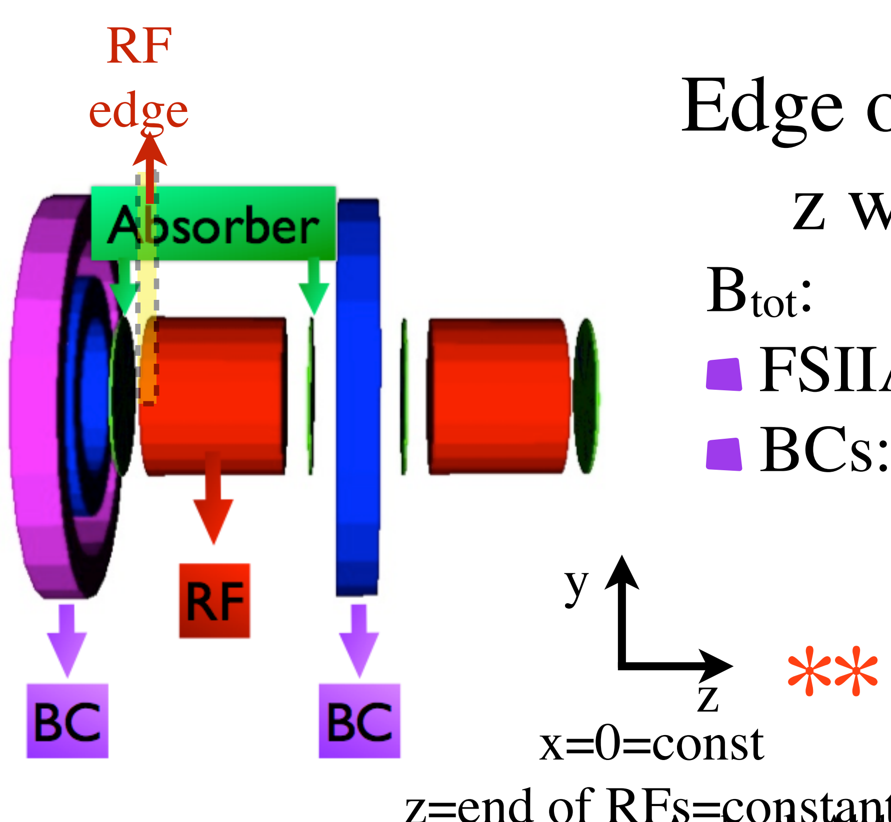

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- BCs: x2-5 lower

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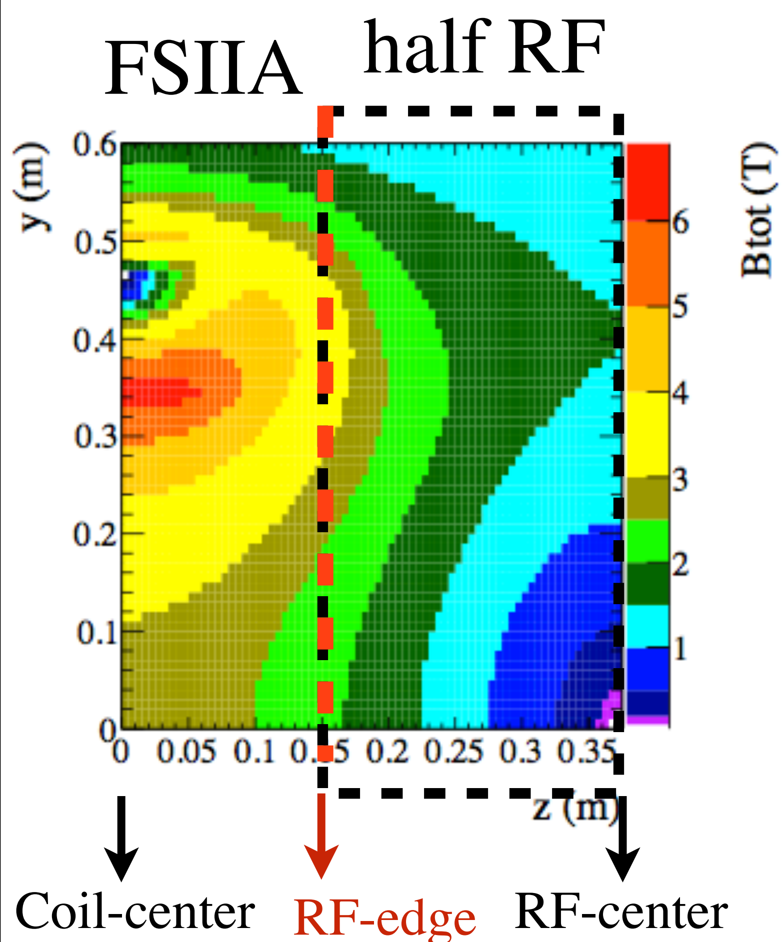

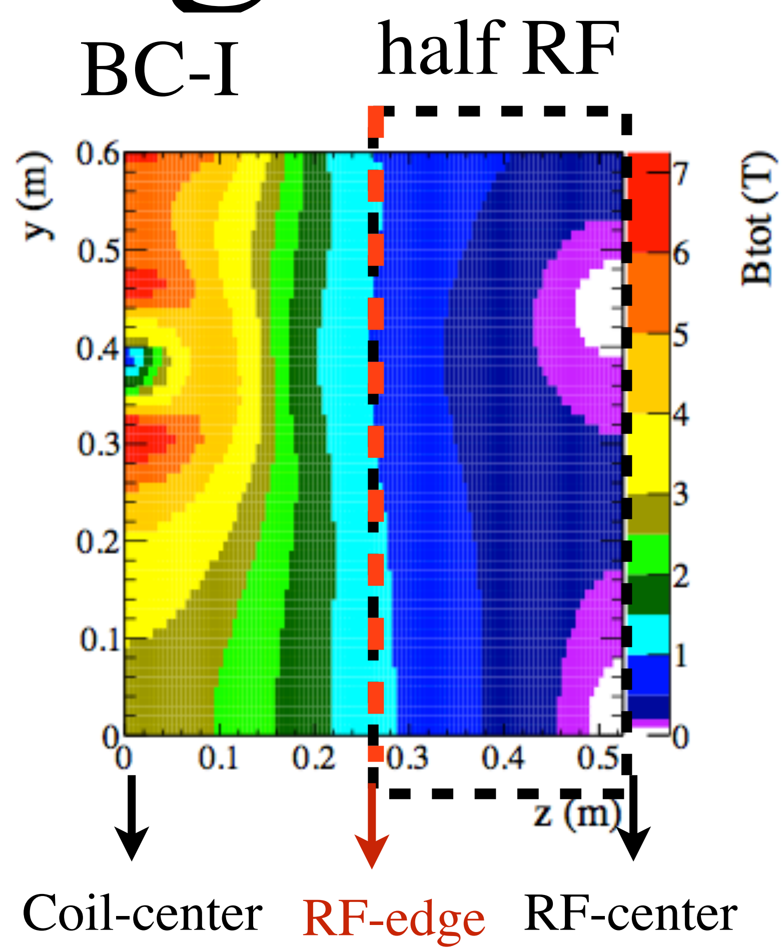

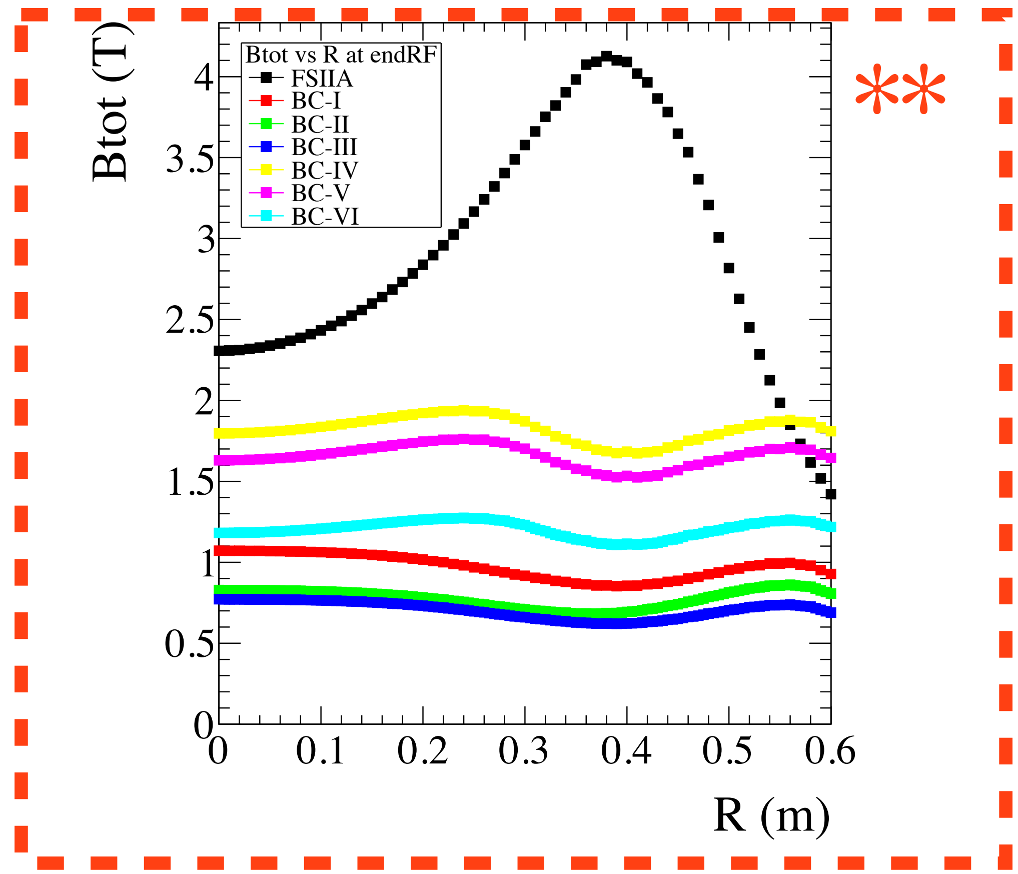

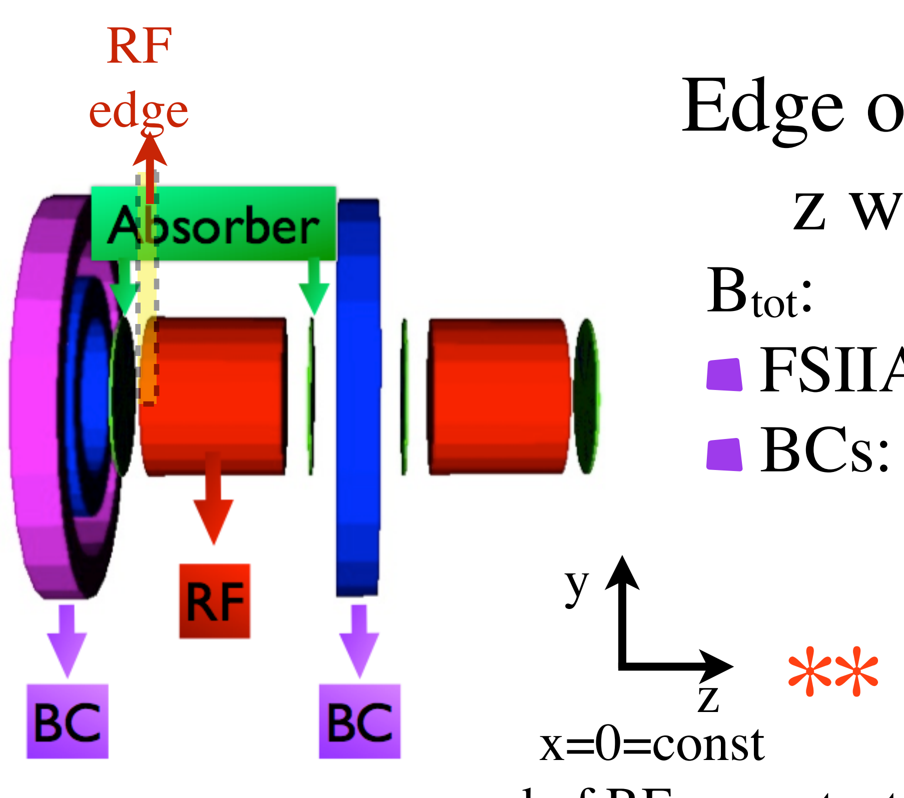

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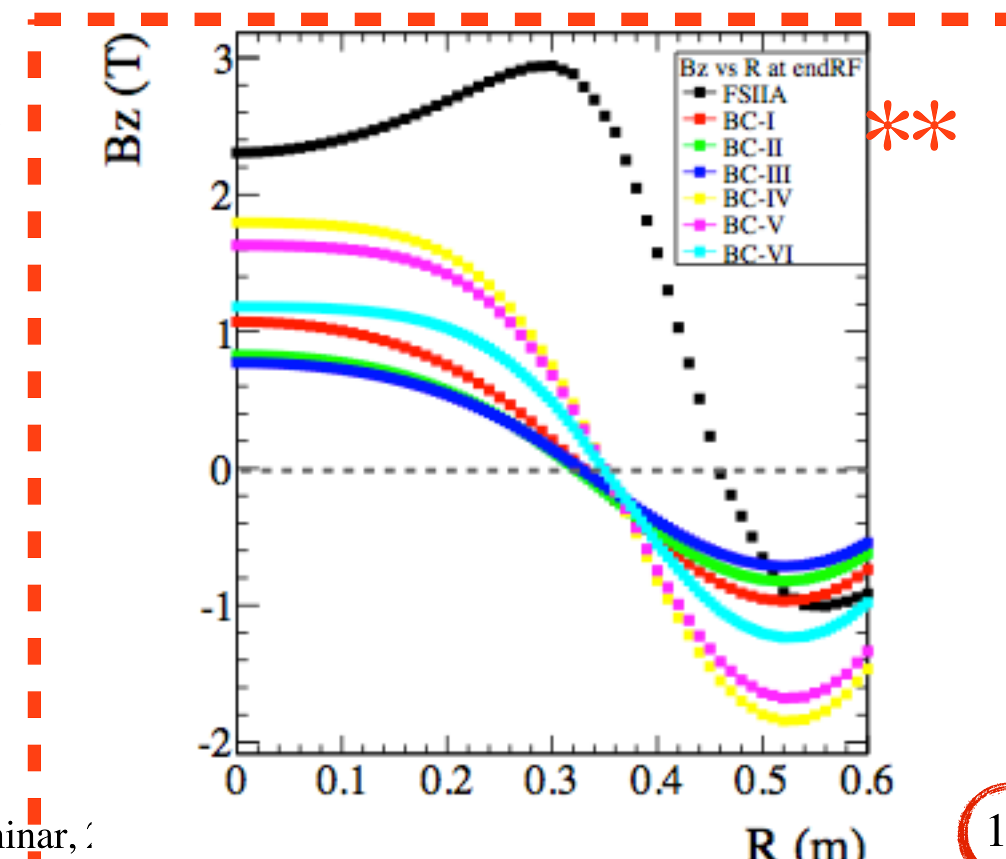

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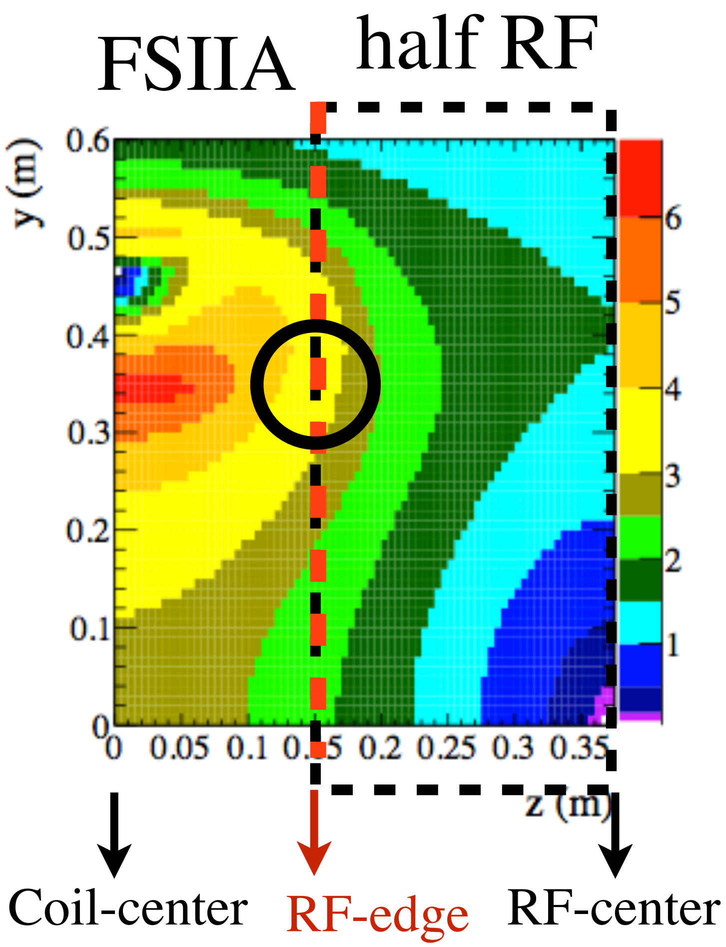

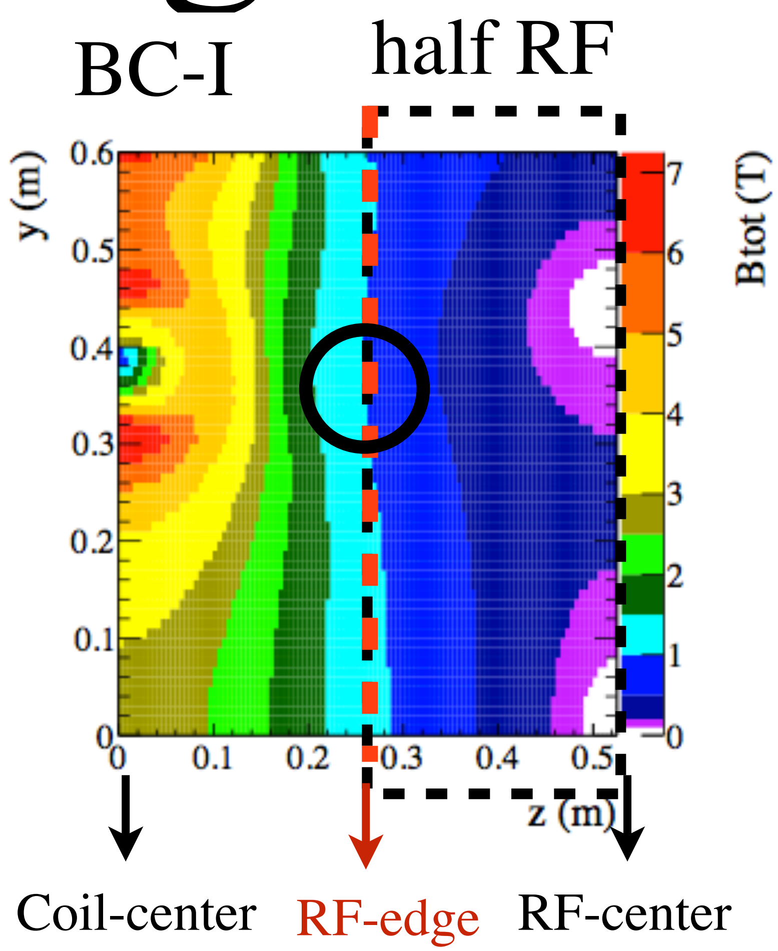

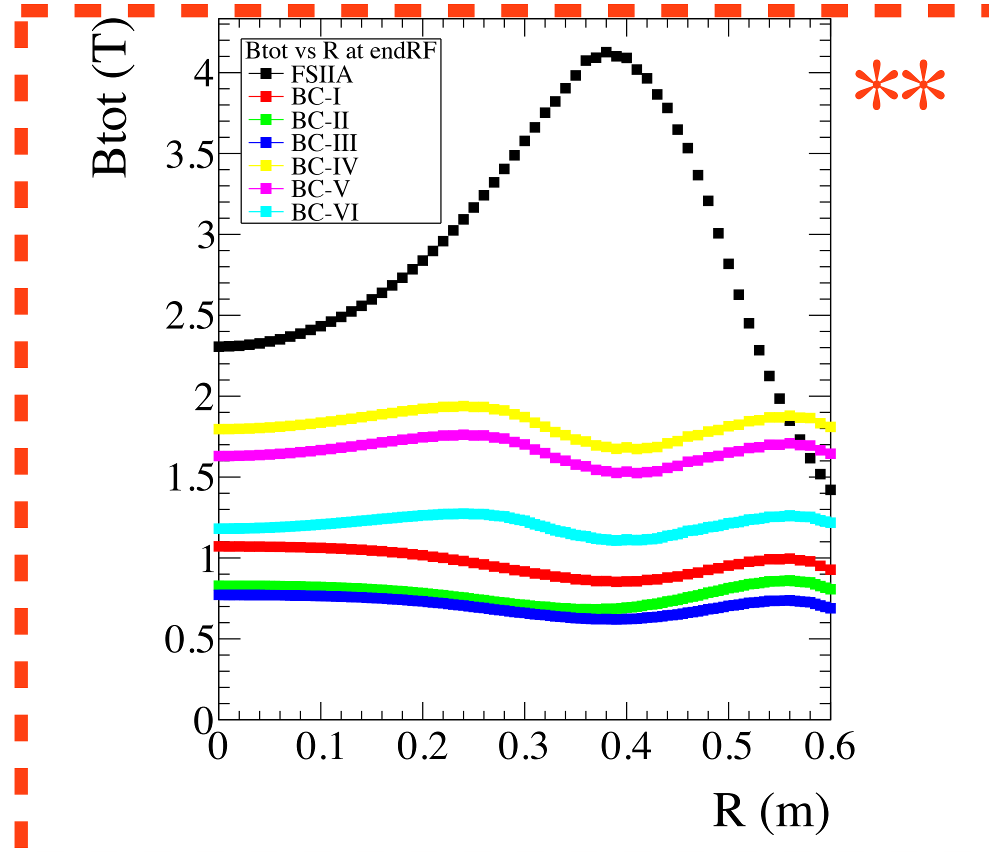

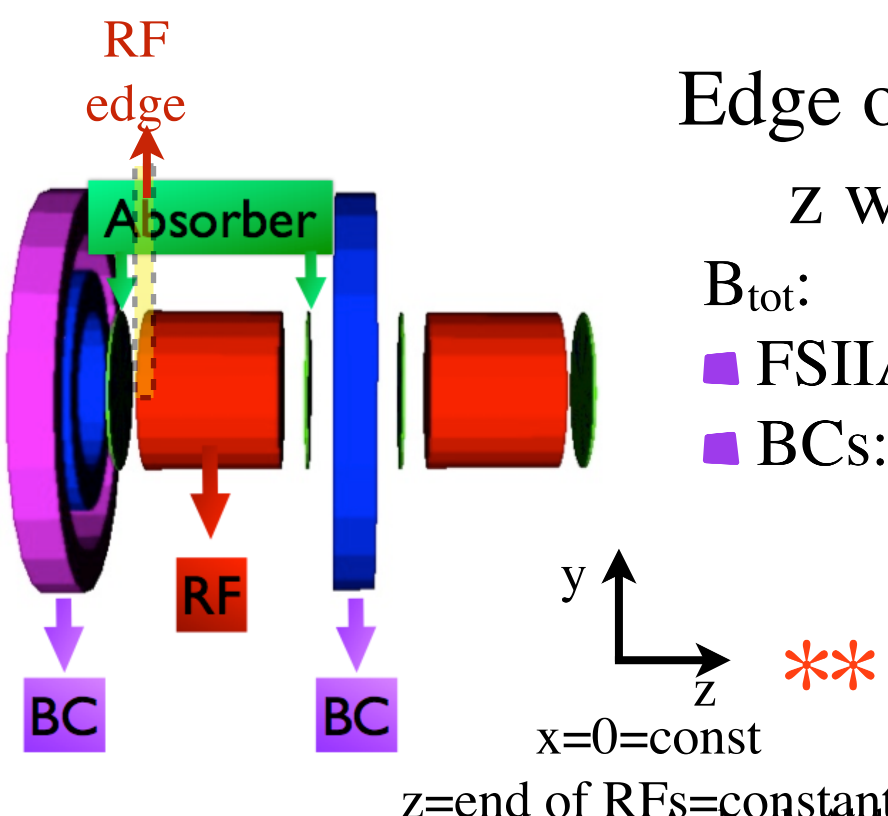

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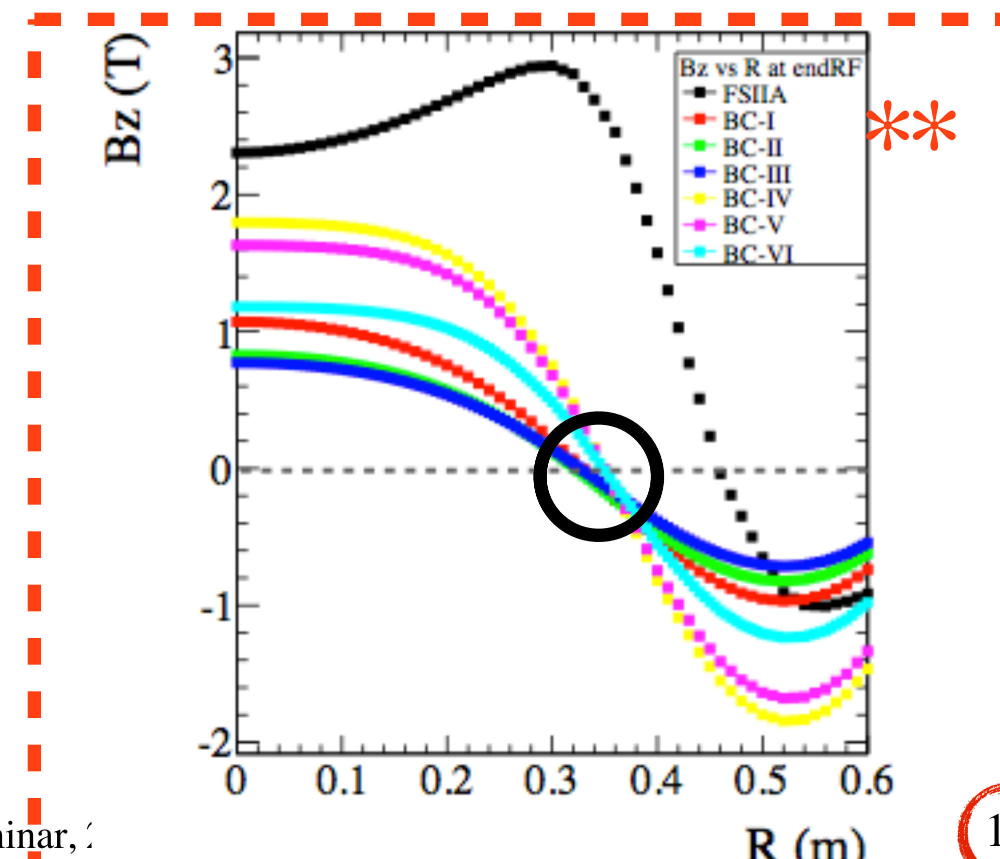
B_z at 35 cm, **iris**:

- FSIIA~2.5 T
- BCs~0 T



Cooling efficiency

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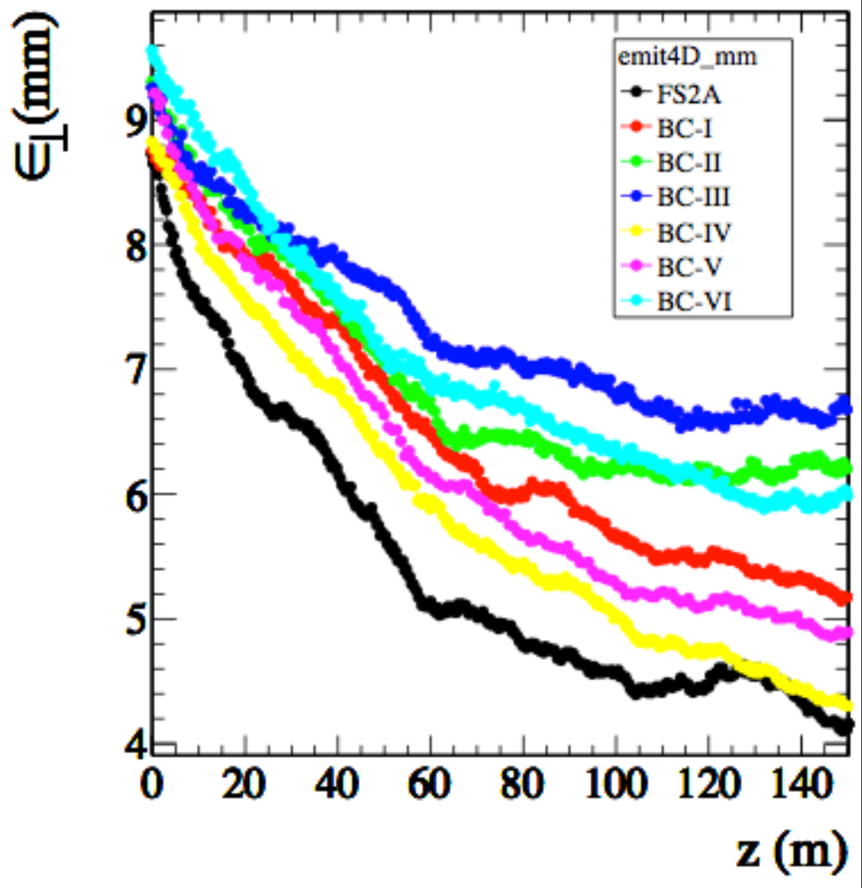
- Emittance reduction: better cooling for FSIIA and BC-IV



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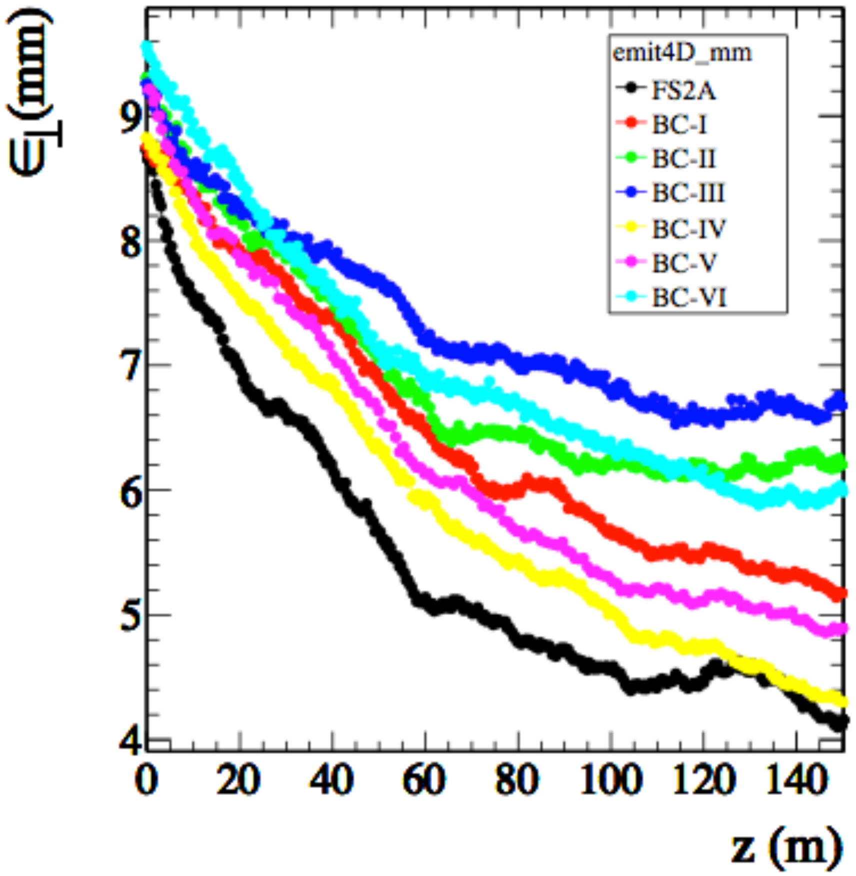

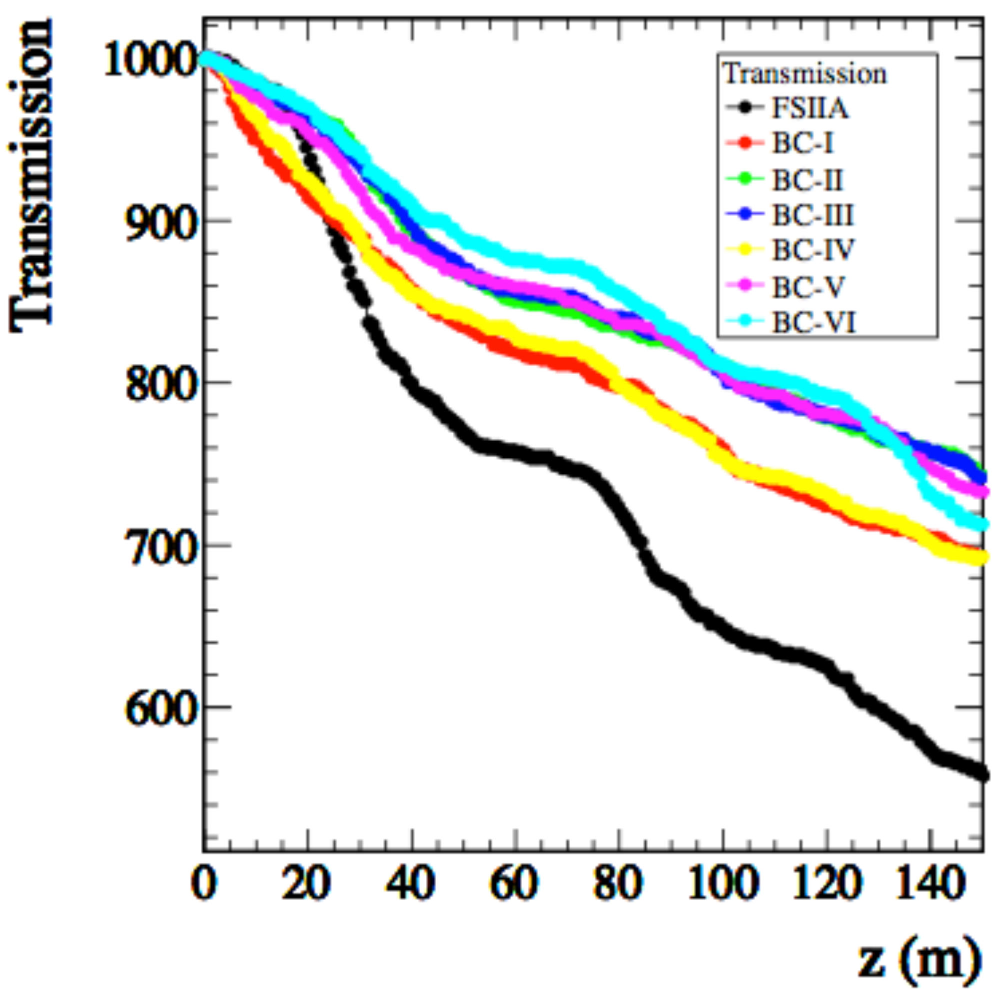

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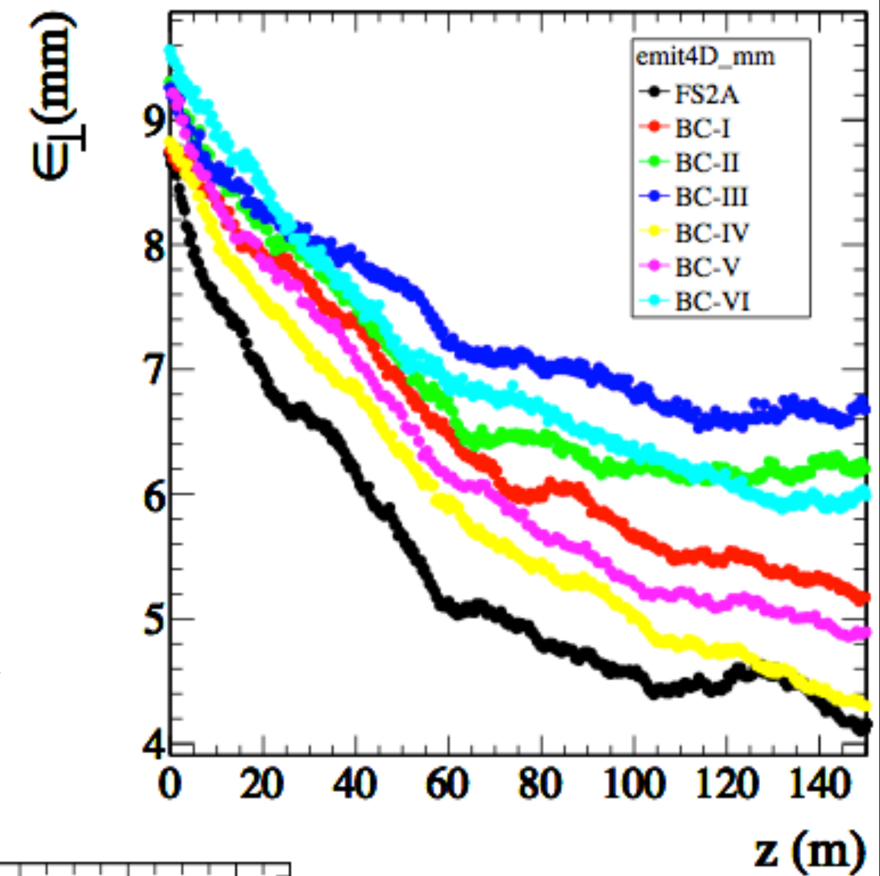
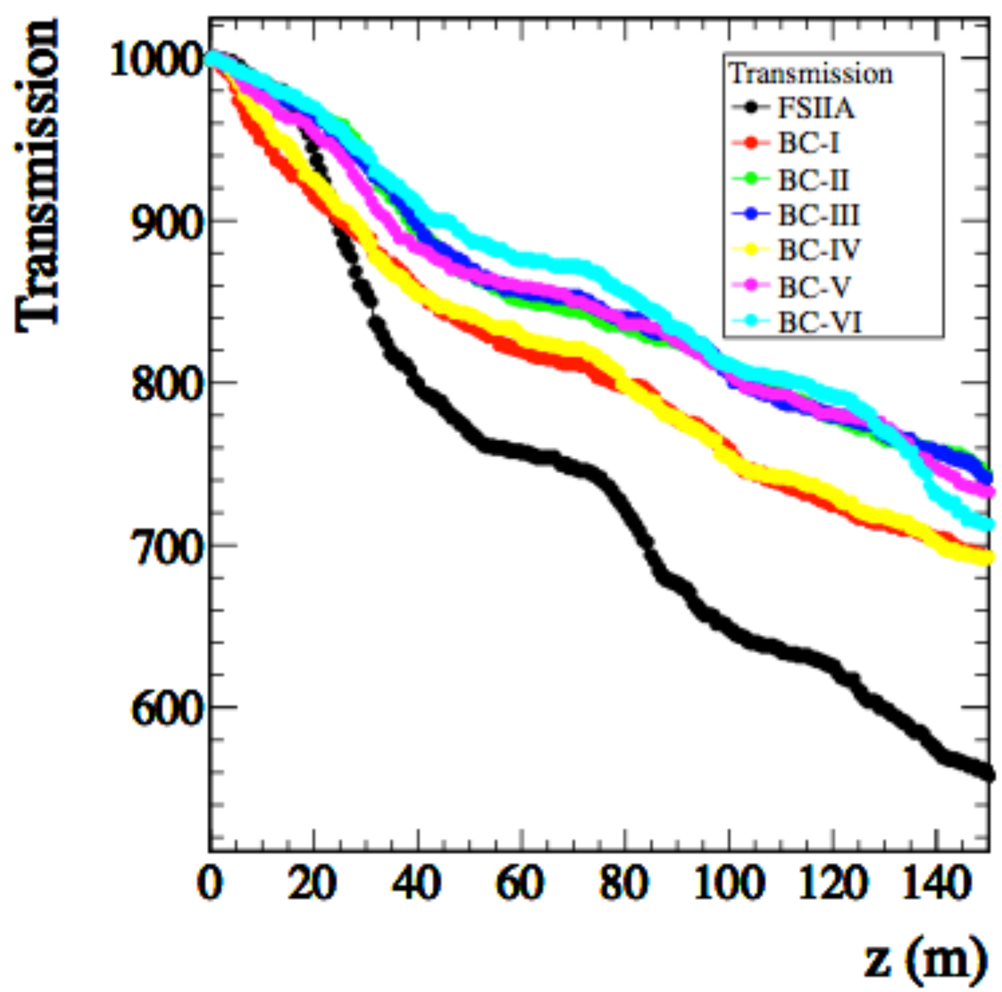
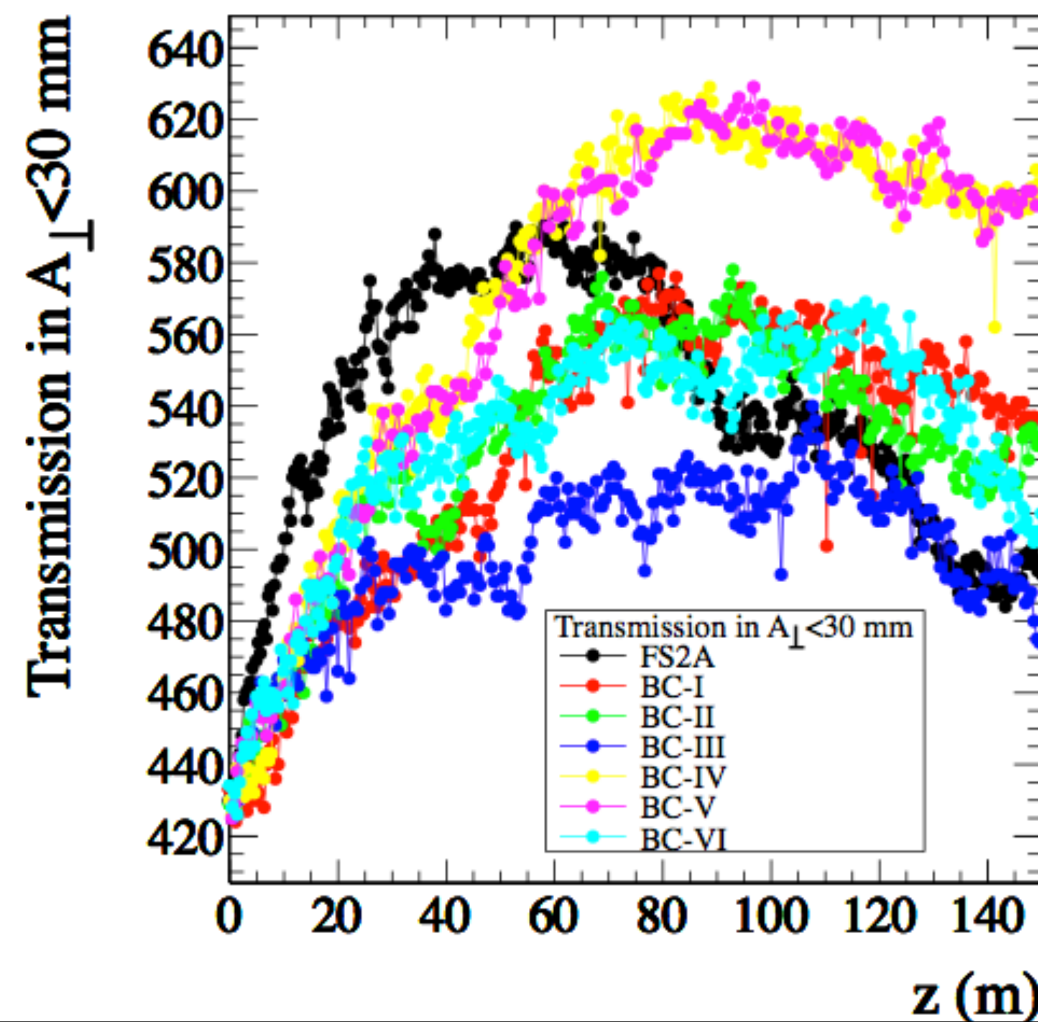
- BC-IV, -V: best transmission (z=90 m)
- At z=70 m, where FSIIA achieves max transmission, BCs achieve equal or insignificantly lower transmission than FSIIA







Feasibility

- All BC versions and FSIIA require strong solenoidal magnets which can only be constructed as Superconductors (SC)
- Lorentz force acting on solenoid has a radial and axial component
- Radial component generates hoop stress, σ=JBR (approximation)
- Typical hoop stress limit for Nb-Ti SC coils: ~200 MPa

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Lattice	Hoop stress [MPa]
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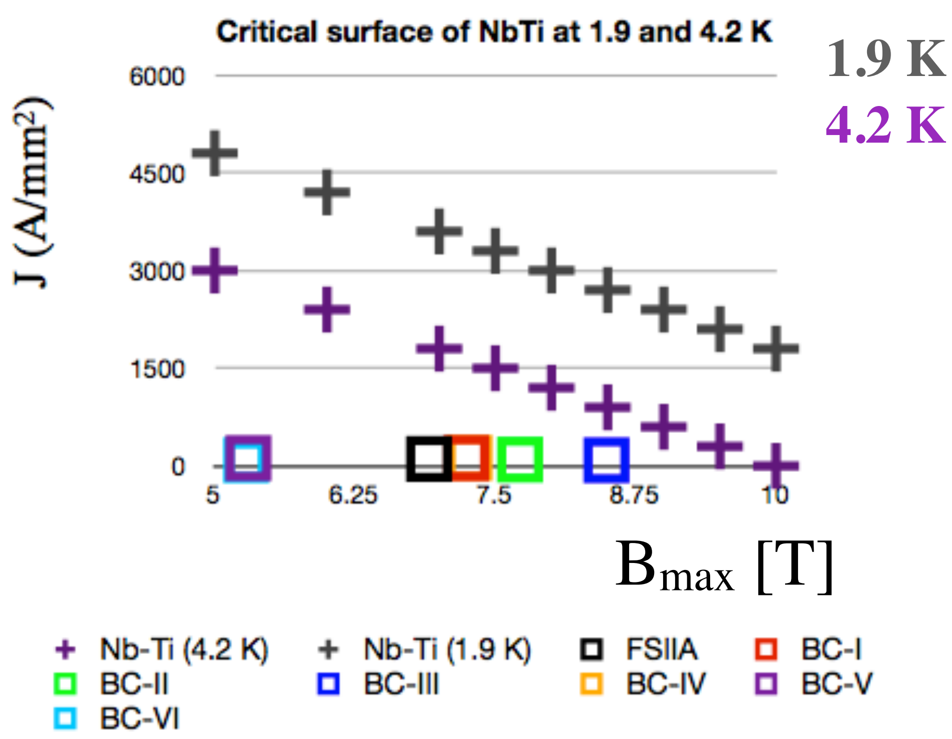

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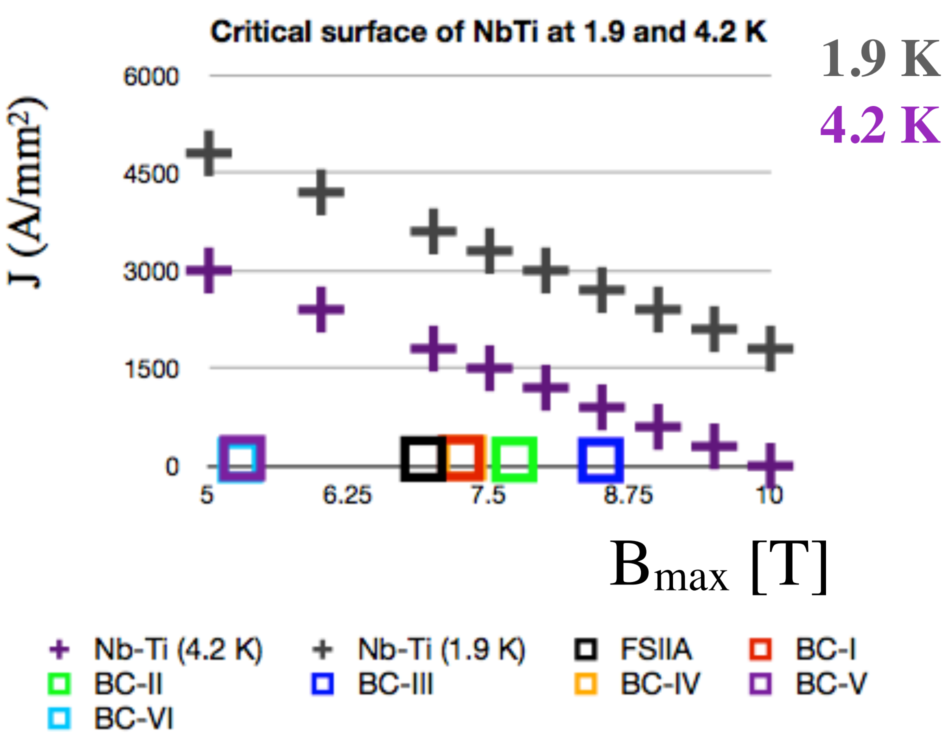

All lattices within limits of SC operation

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Lattice	
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BC-II	
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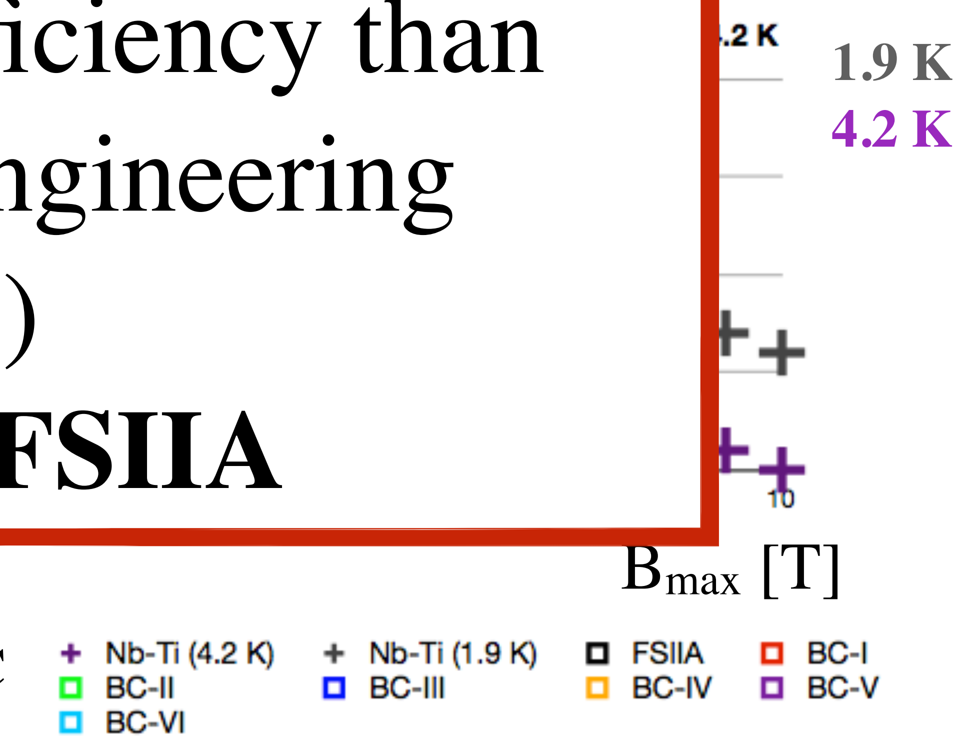
The Bucked Coils Lattice successfully reduces B at positions of RF cavities and also results in equal or better cooling efficiency than FSIIA (and is within the engineering feasibility limits!)

Main alternative for FSIIA

critical surface: at a particular temperature, T and current density, J, there is specific field that transforms SC to normal-conducting magnet



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Outline

- Neutrino Oscillations Theory
- Neutrino Factory (NF)
  - Muon ionization cooling
  - Reference NF cooling lattice
  - Bucked Coils Lattice
  - Results
- LAGUNA-LBNO
  - High Power Proton Synchrotron (HP-PS)
  - Orbit Correction
  - Collimation
  - Results and future optimizations
- Summary and Conclusions

LAGUNA-LBNO

Pan-European Infrastructure for **Large Apparatus** Studying **Grand Unification, Neutrino Astrophysics** and **Long Baseline Neutrino Oscillations** [7]

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Amongst other things, the LAGUNA observatory will:

- study matter-antimatter asymmetry using neutrinos produced at CERN

LAGUNA-LBNO

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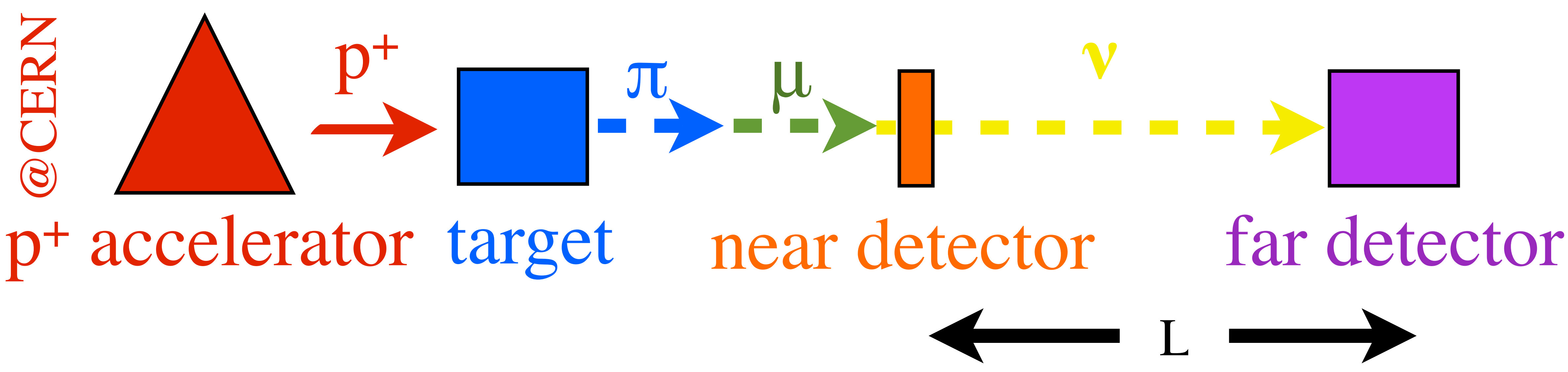

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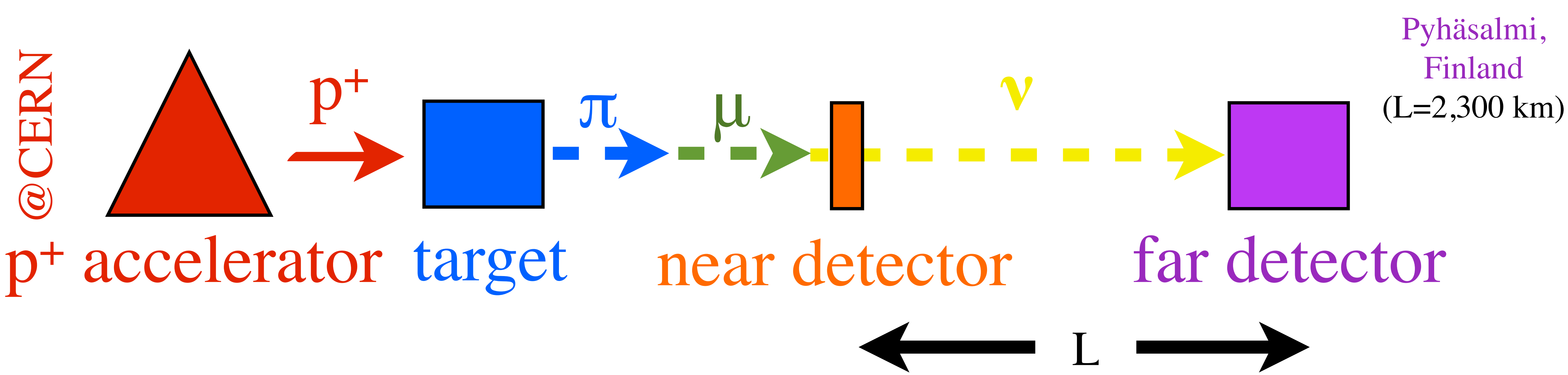
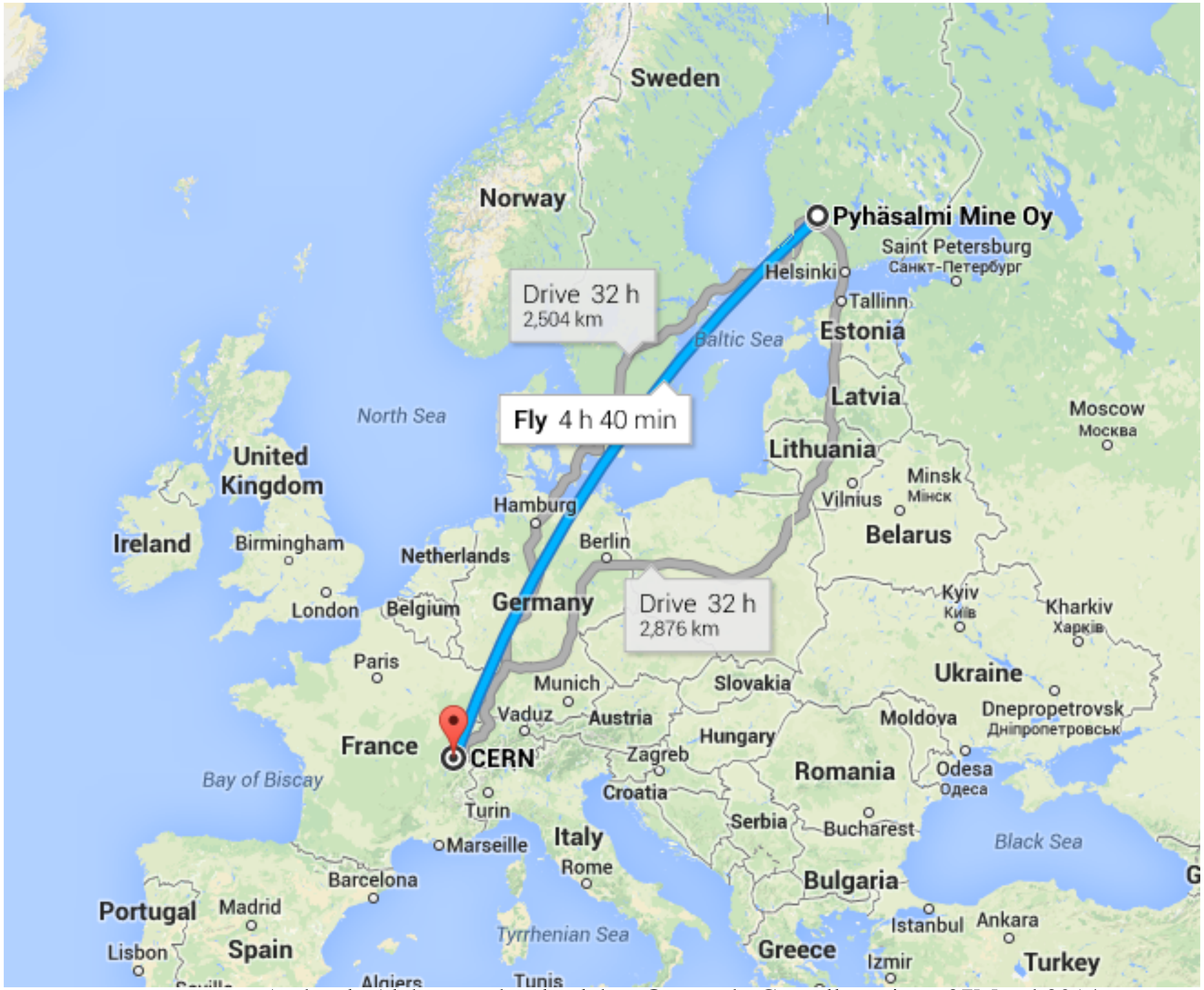


The Pyhäsalmi mine



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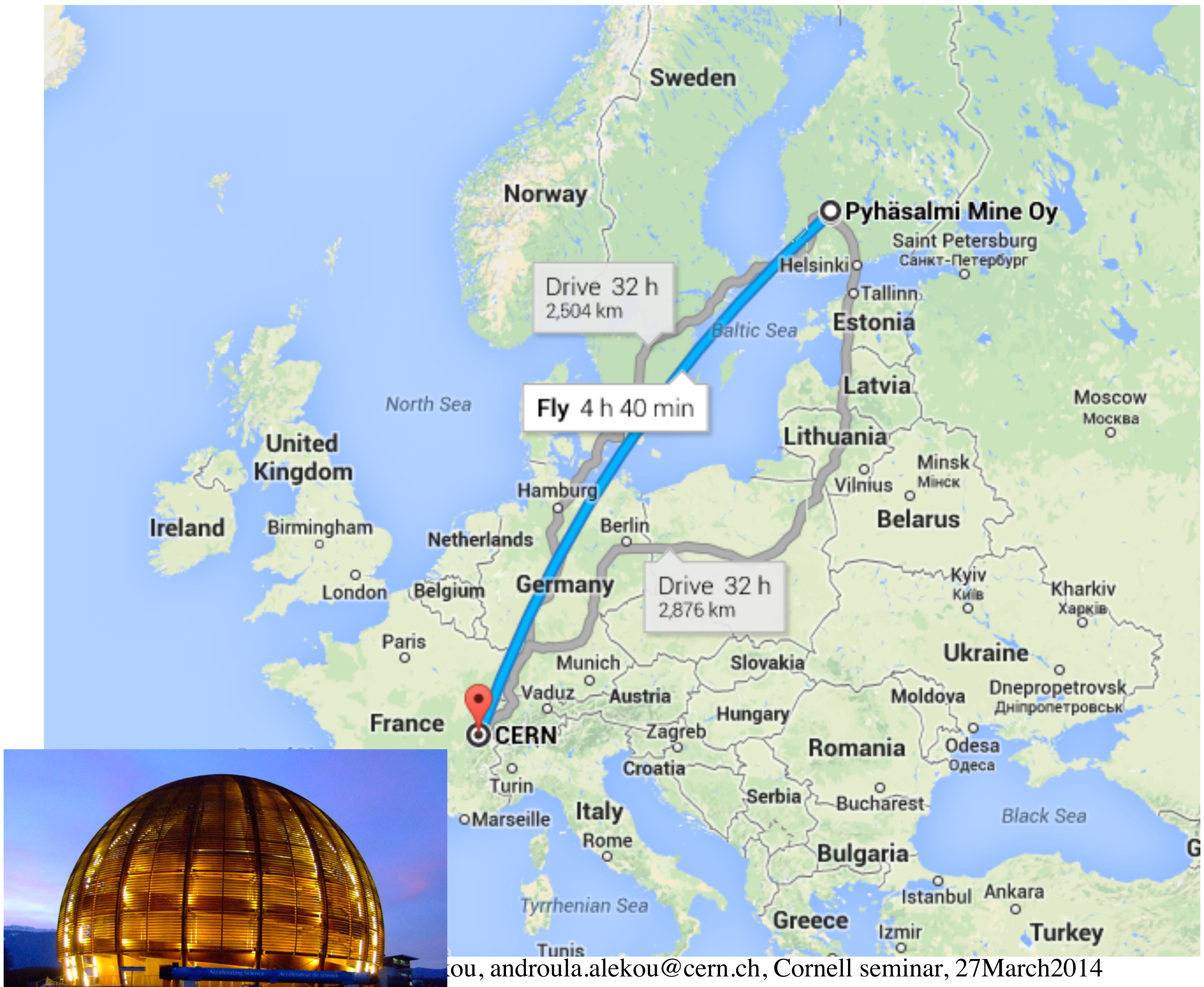

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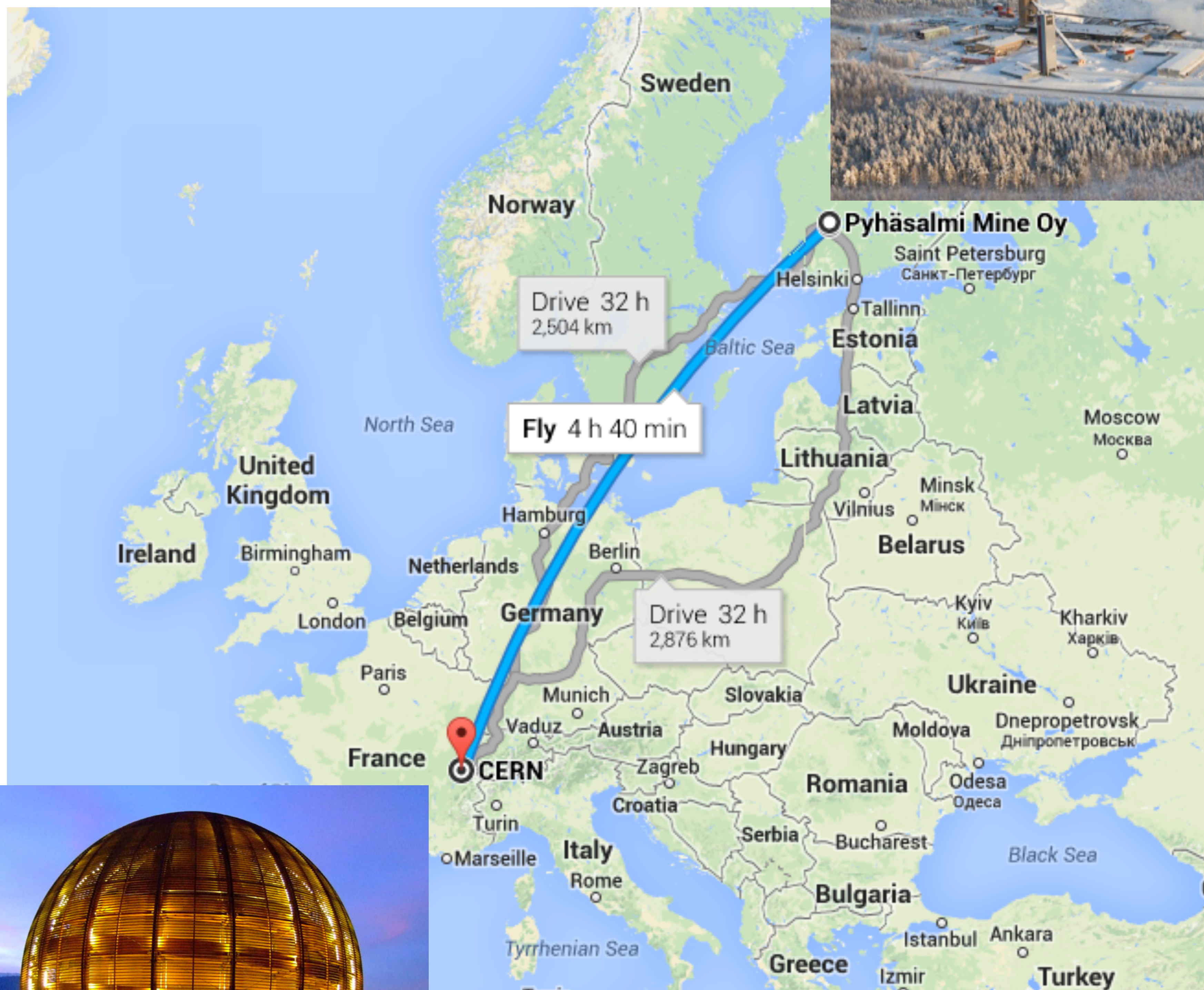

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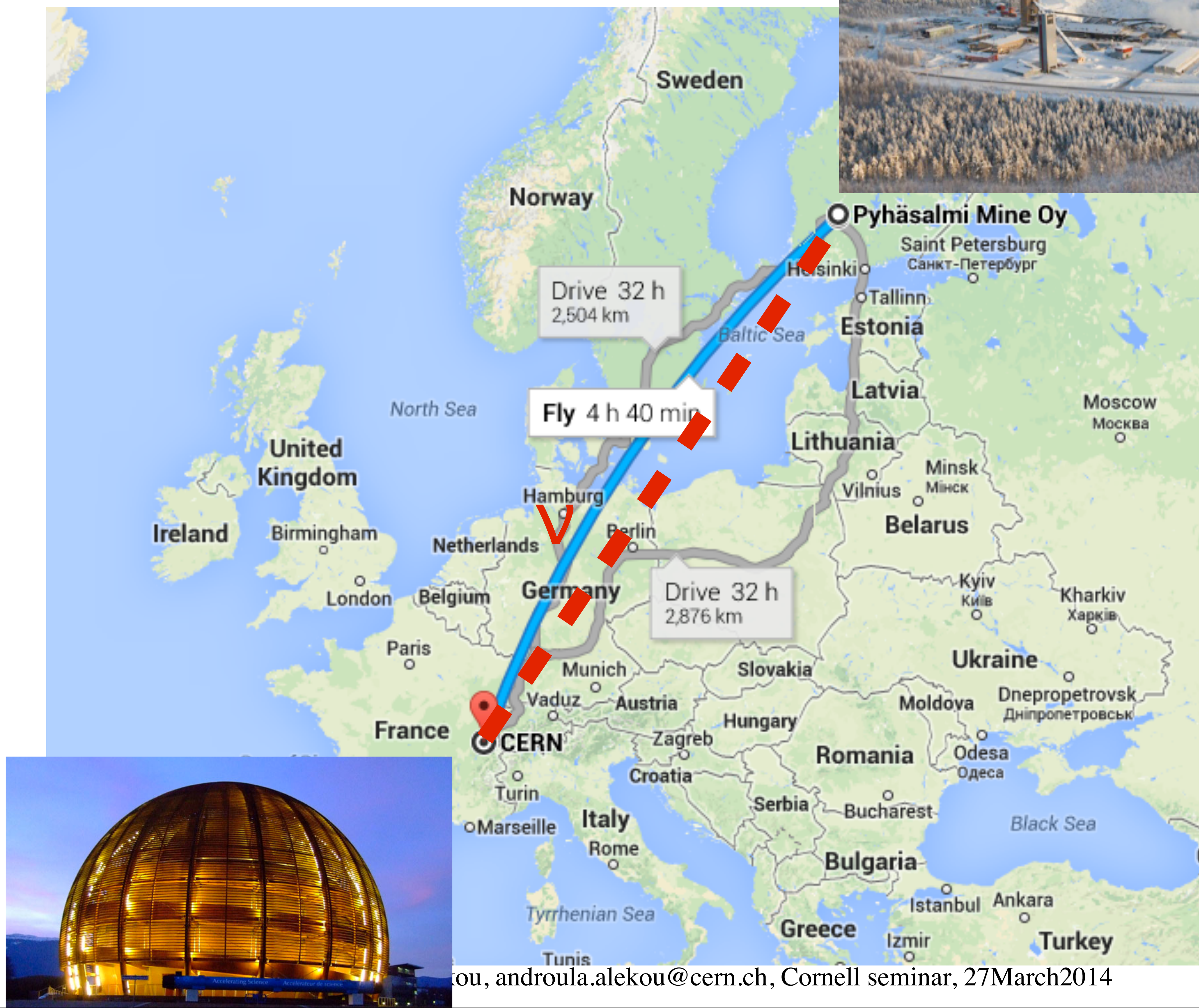

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Baseline: 2,300 km

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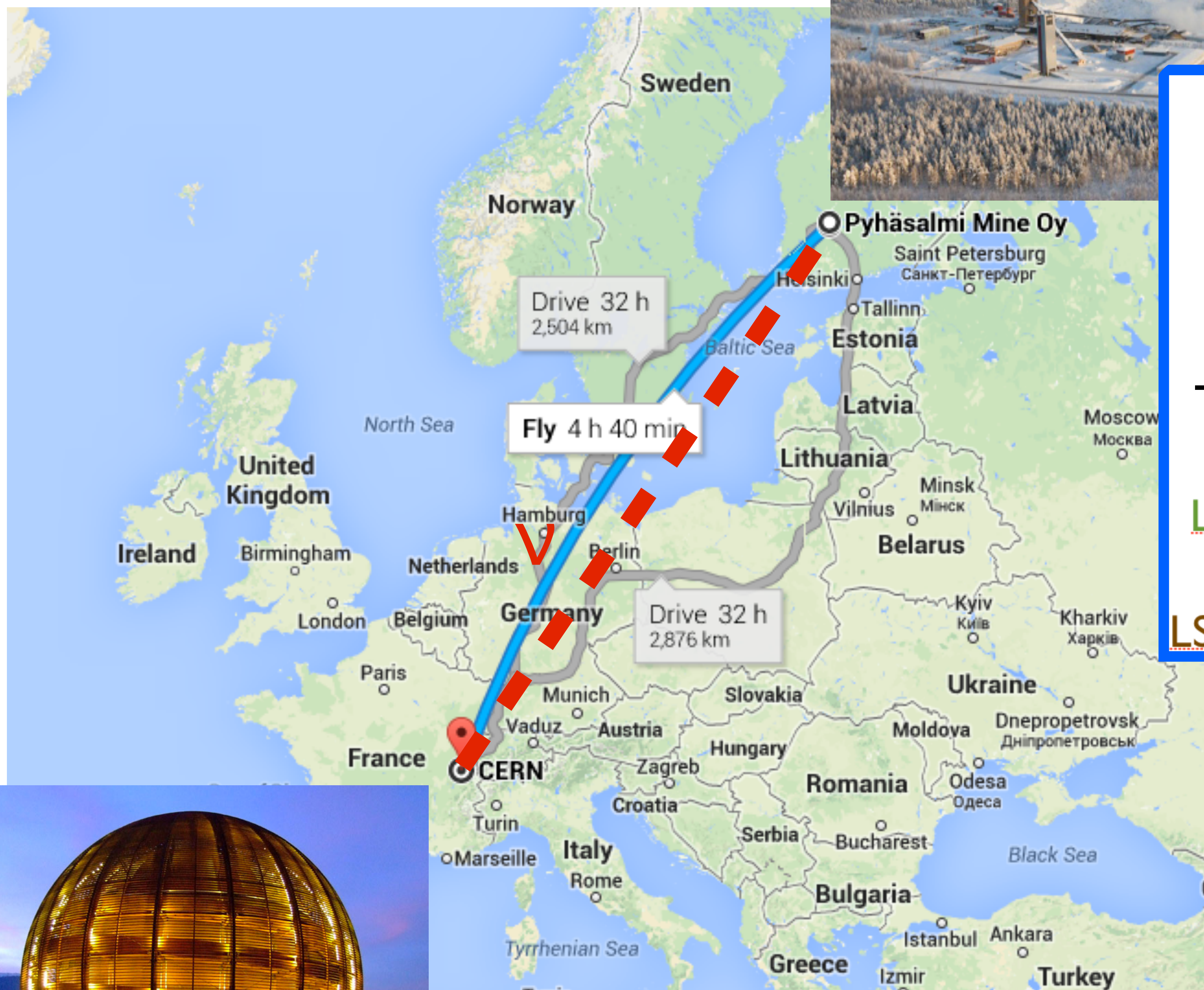

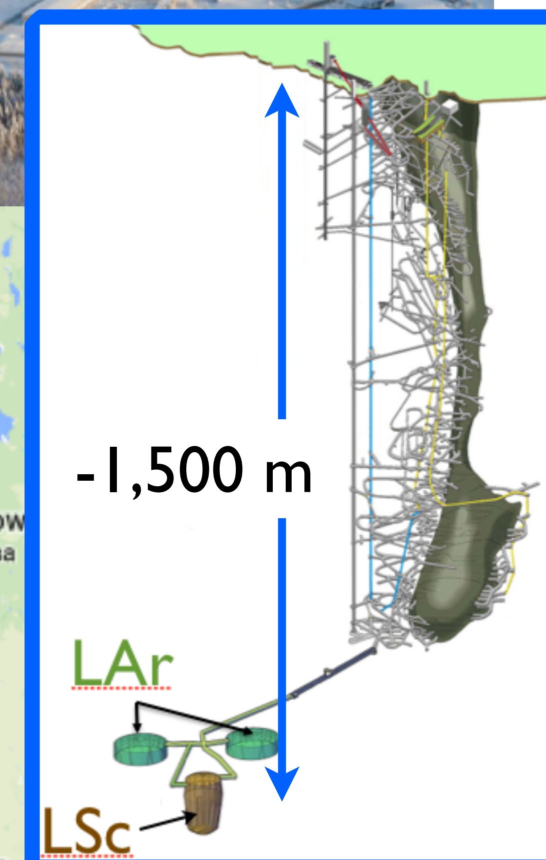

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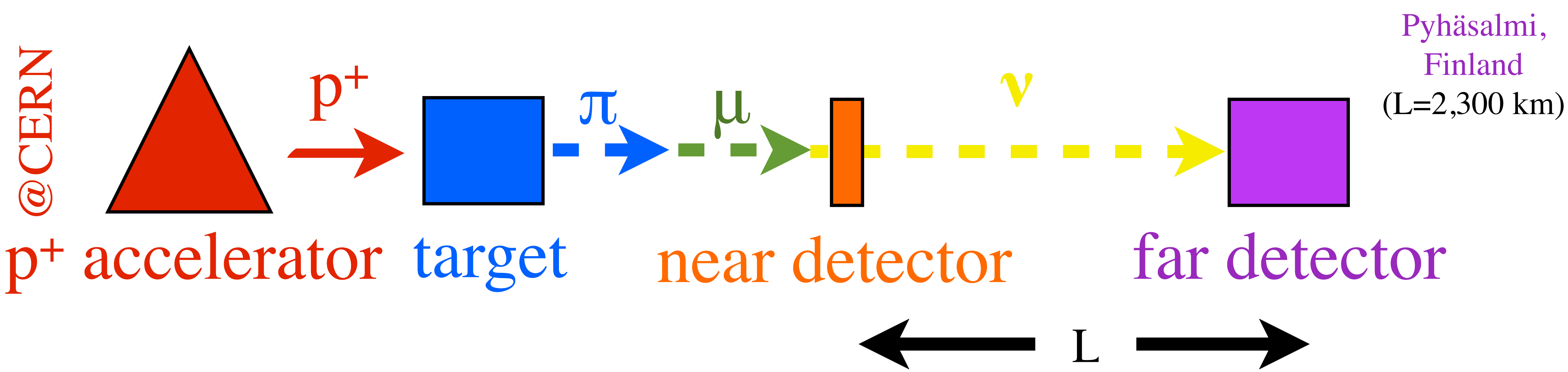

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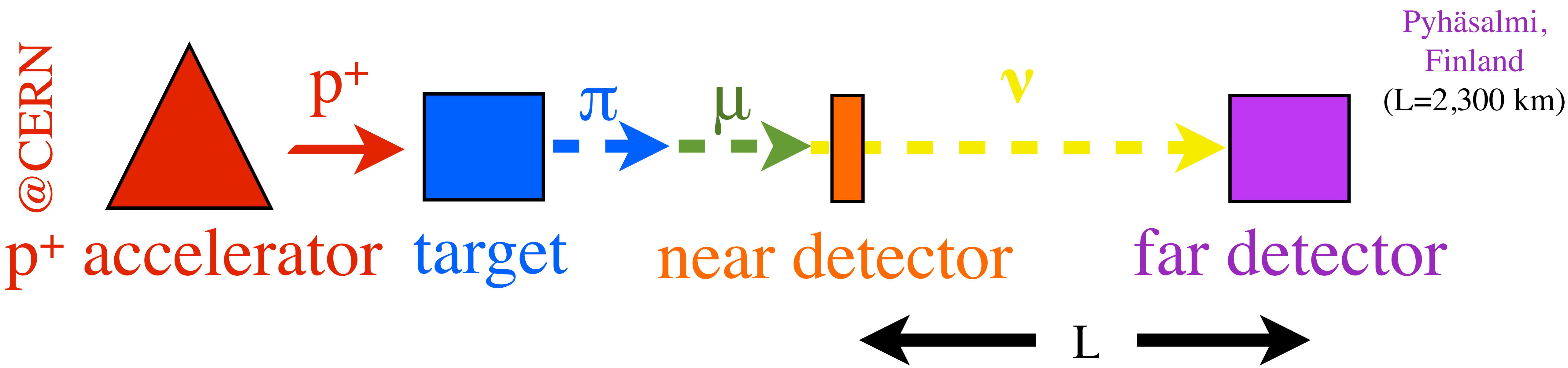

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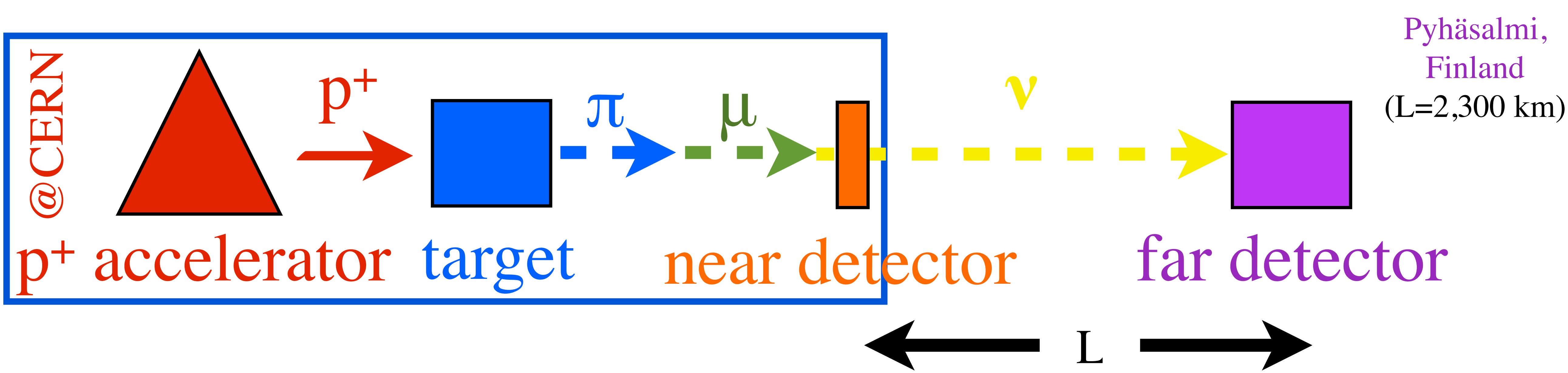

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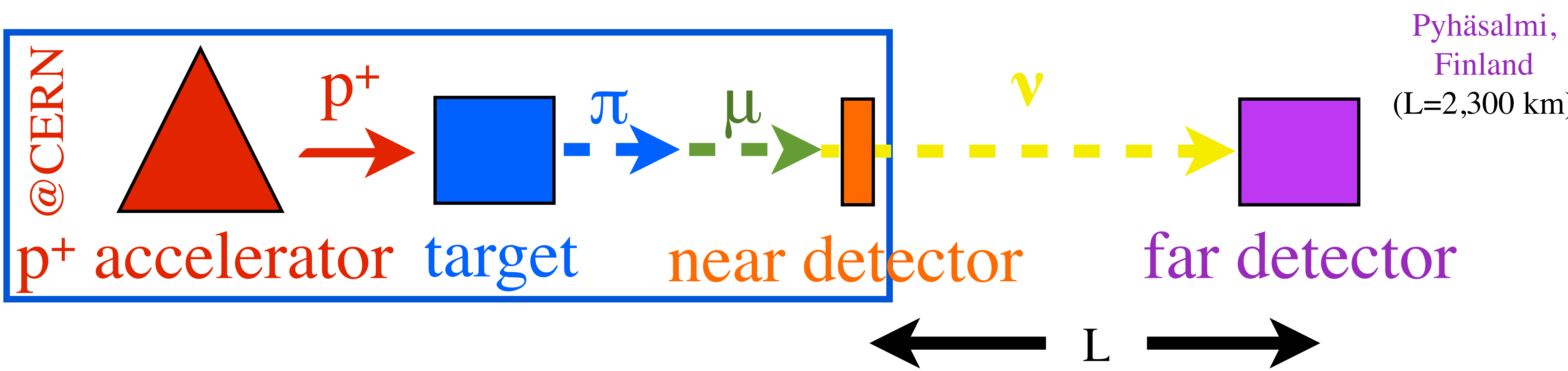

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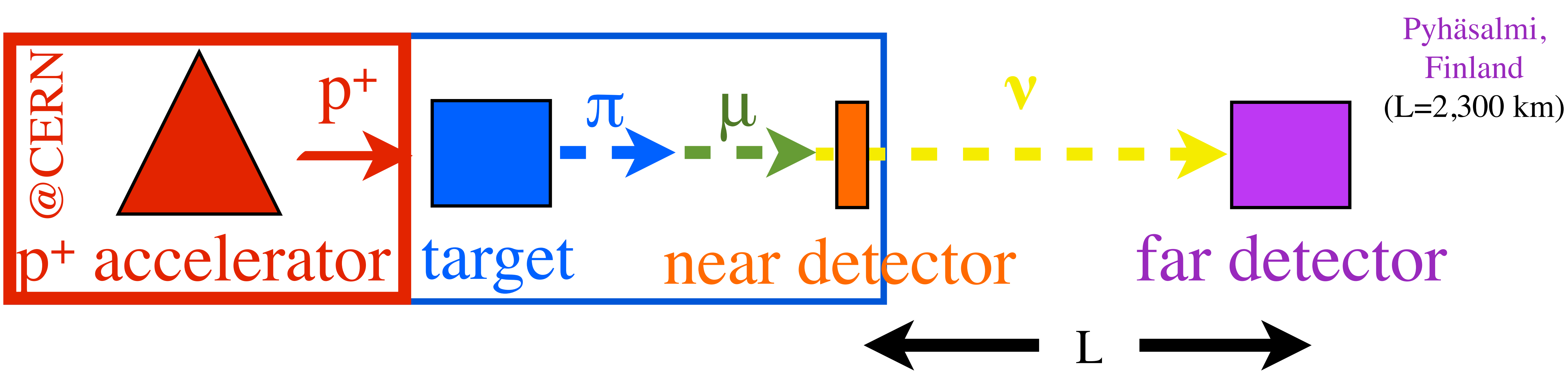

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HP-PS

- 3-fold symmetry
- 3 Long Straight Sections (LSS):
  - a) injection/extraction
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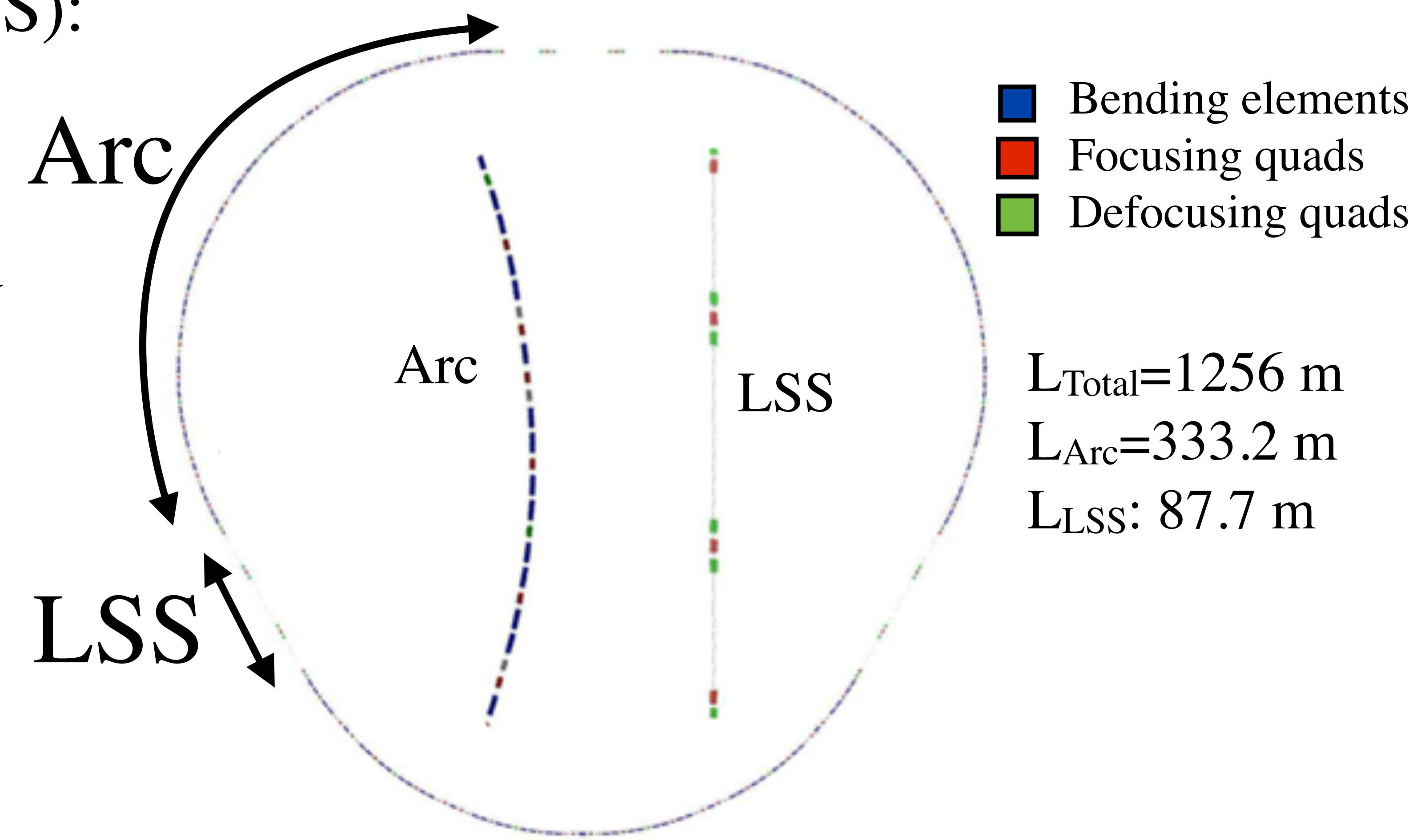
  - c) RF cavities
- Protons final energy: 50 GeV



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L_{Arc}=333.2 m
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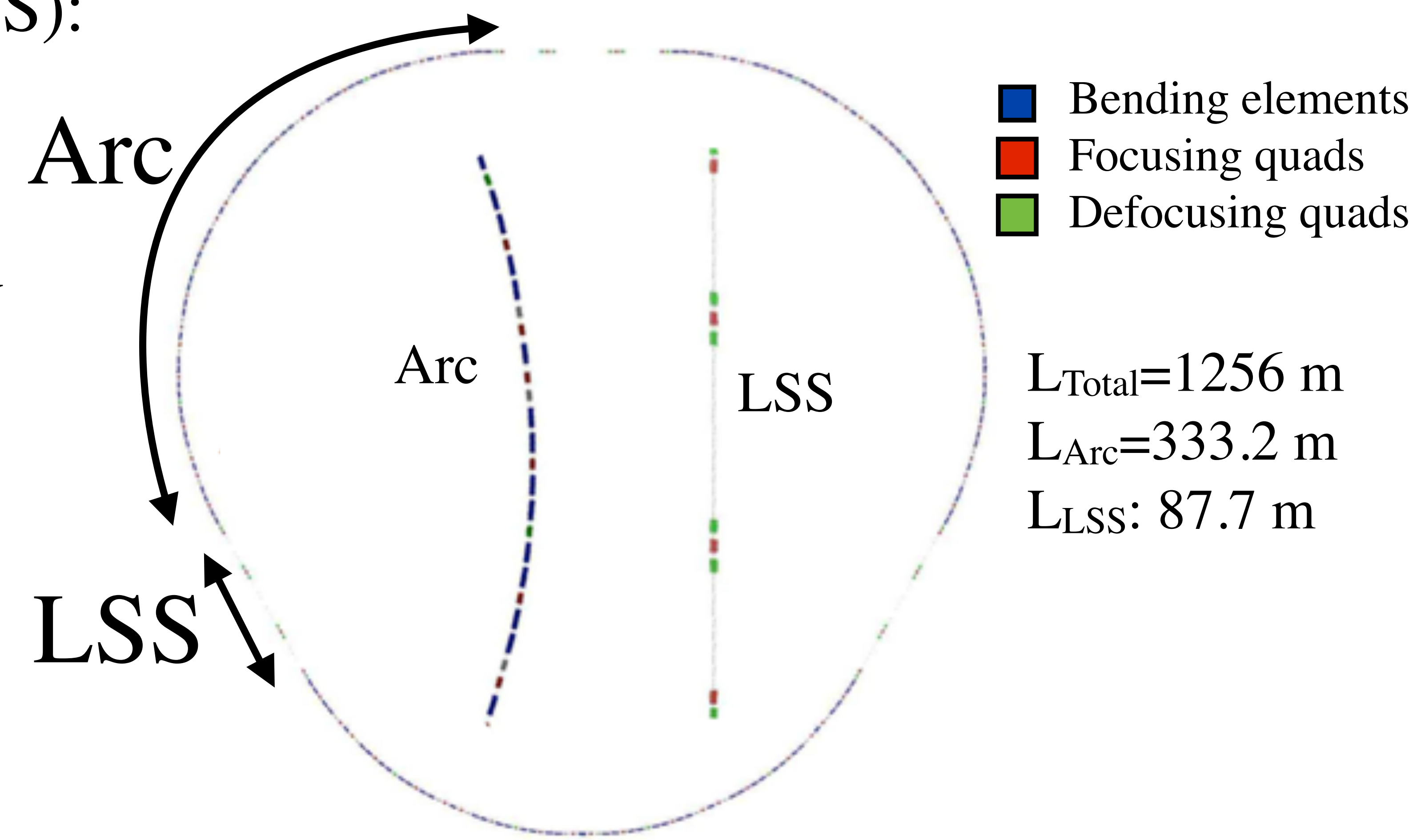

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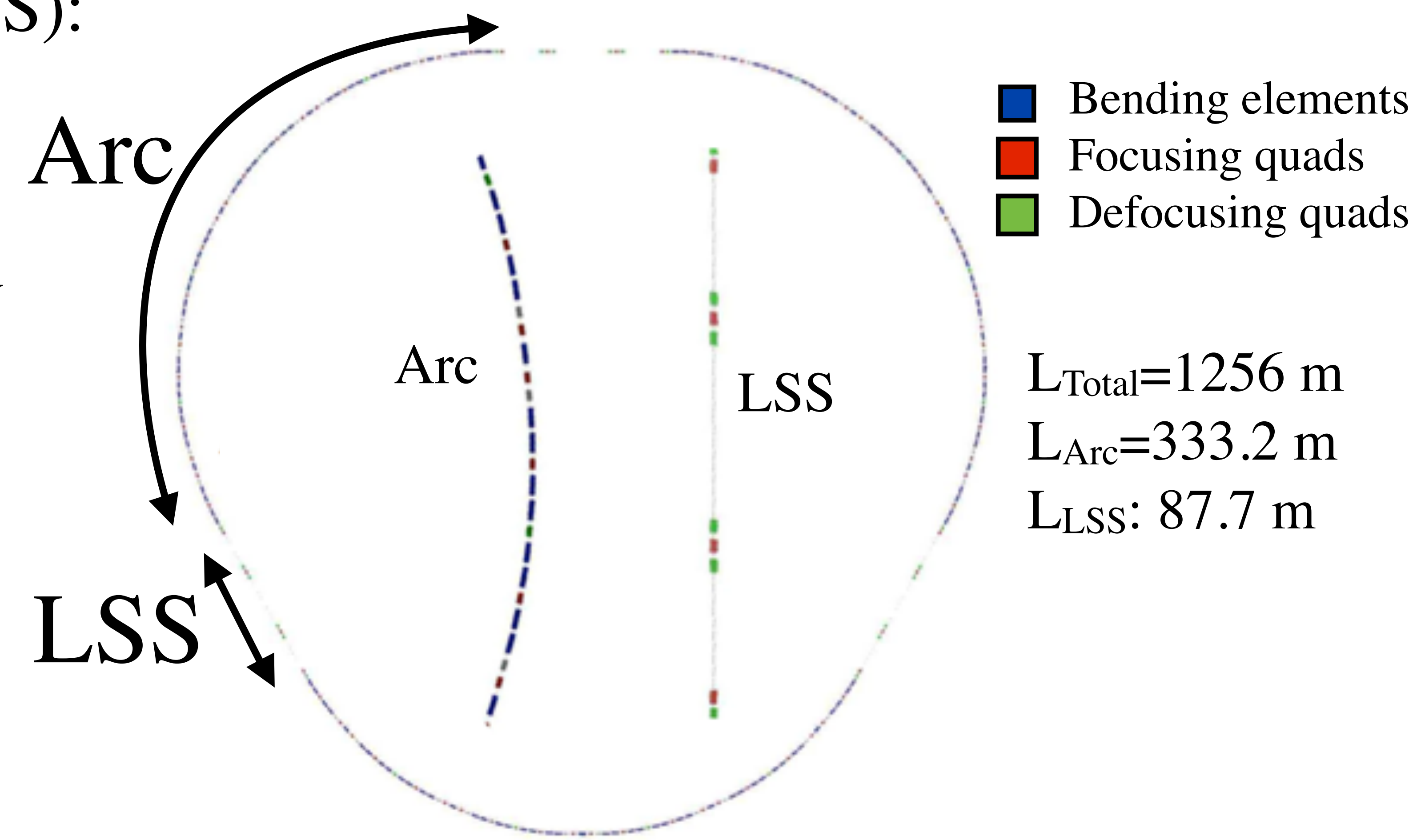

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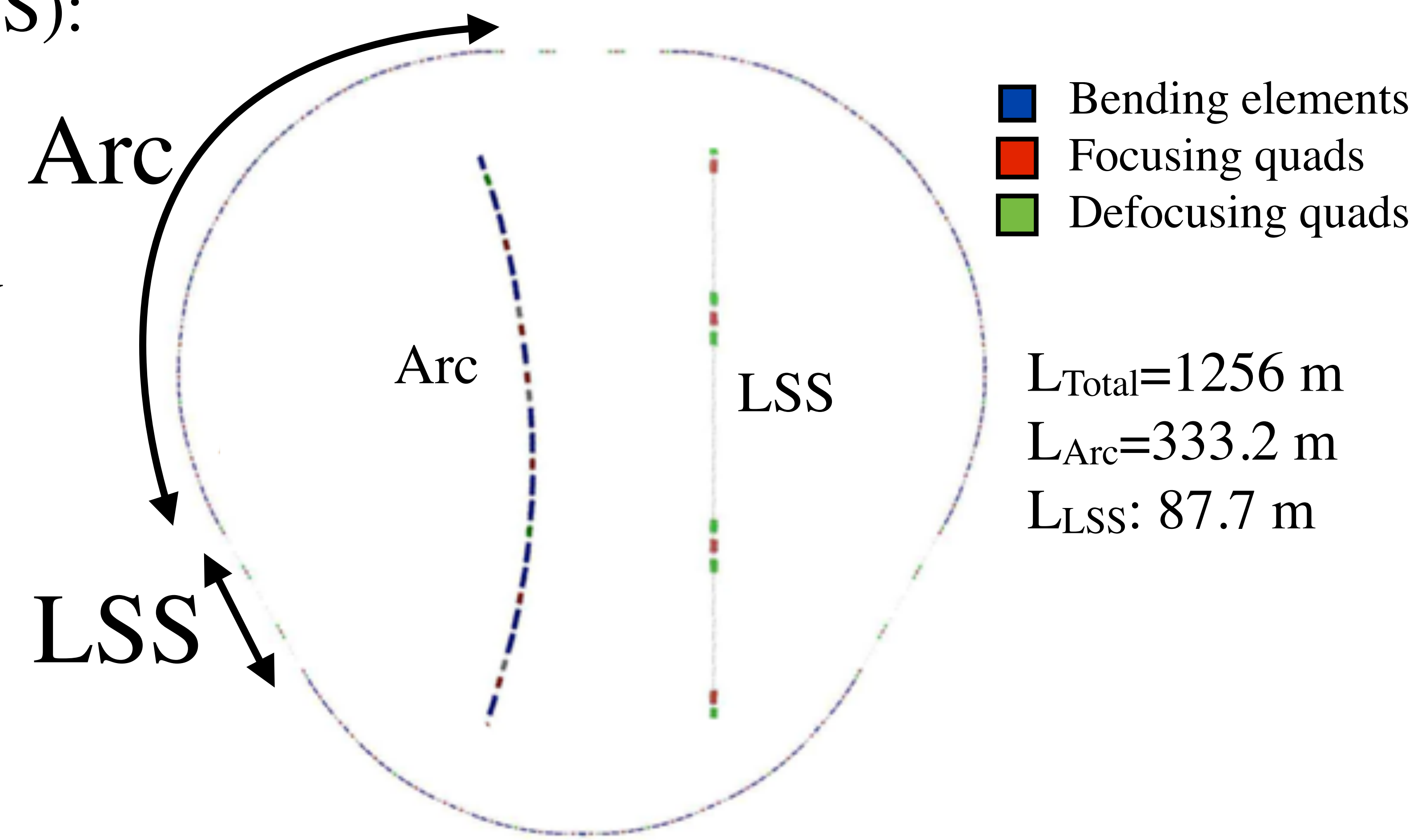

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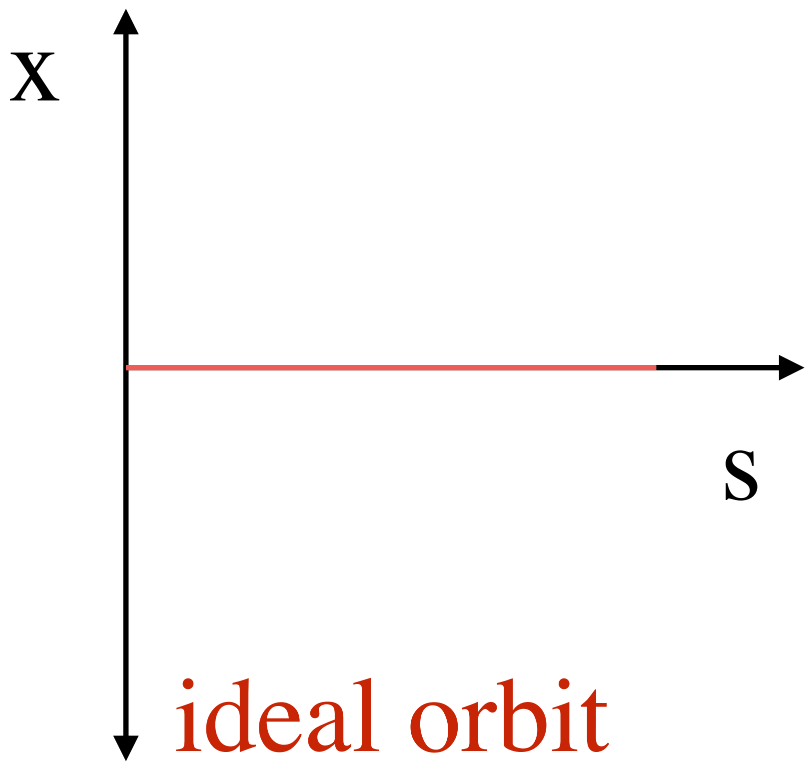

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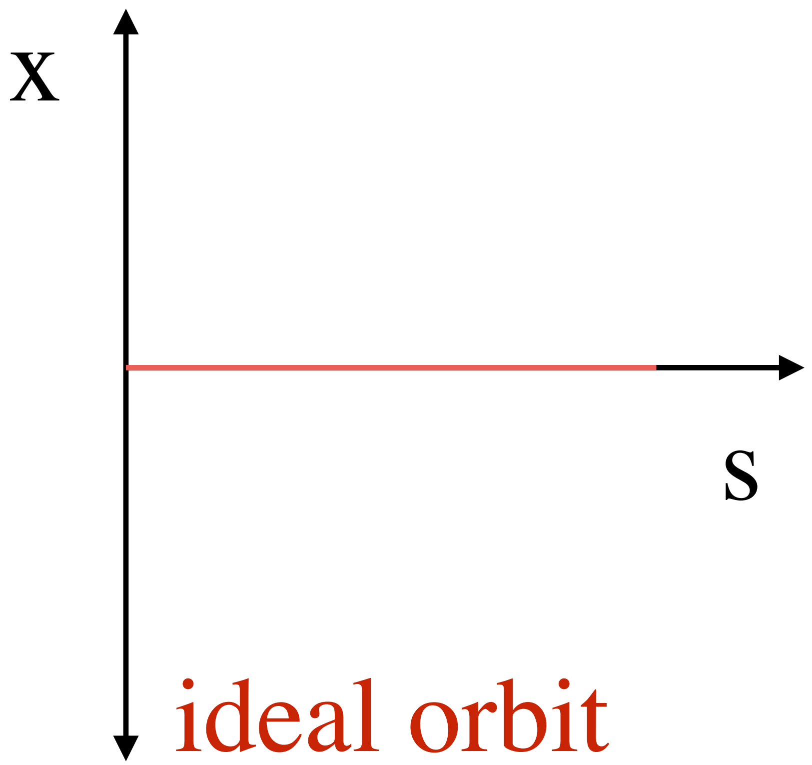

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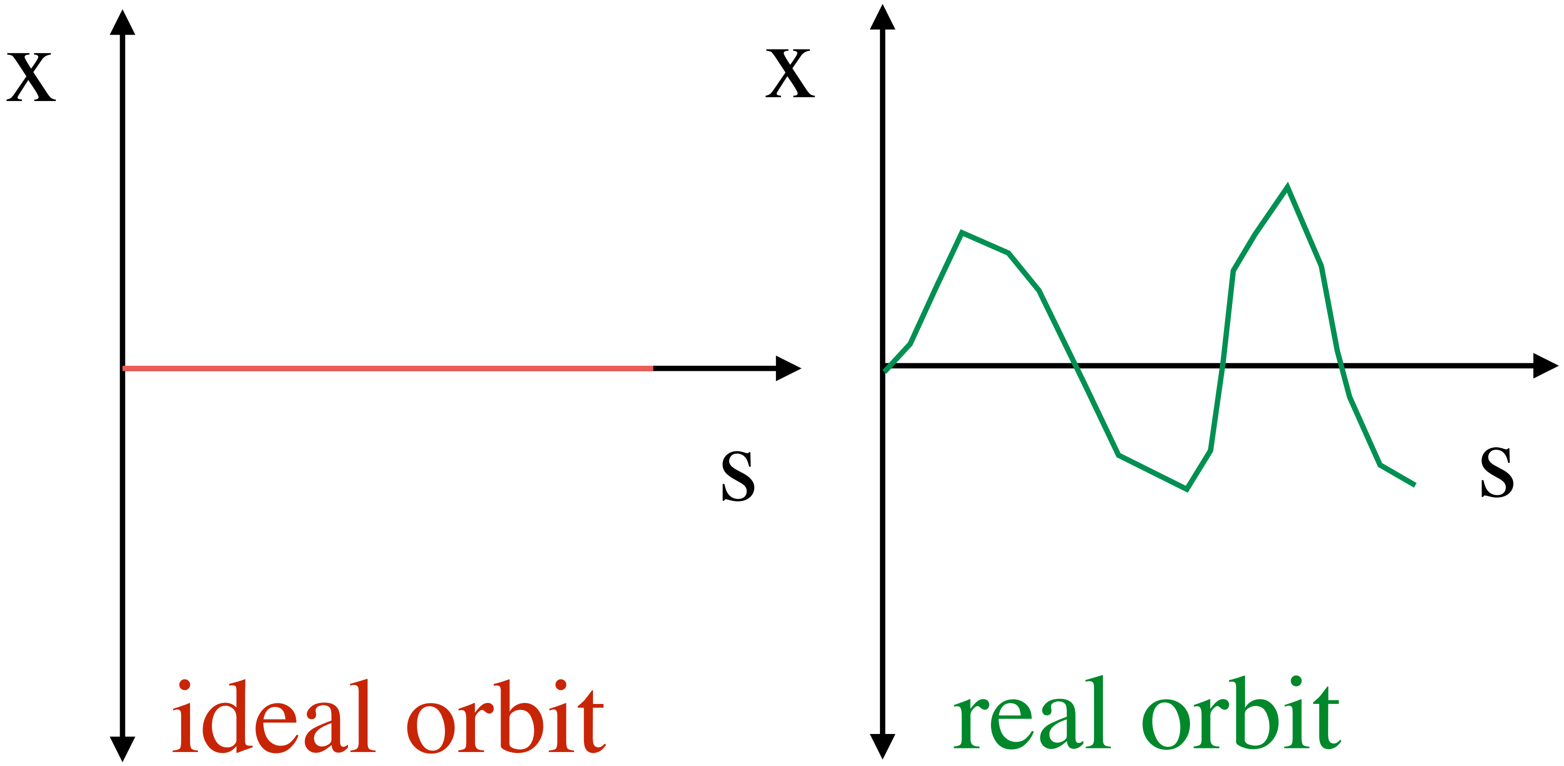

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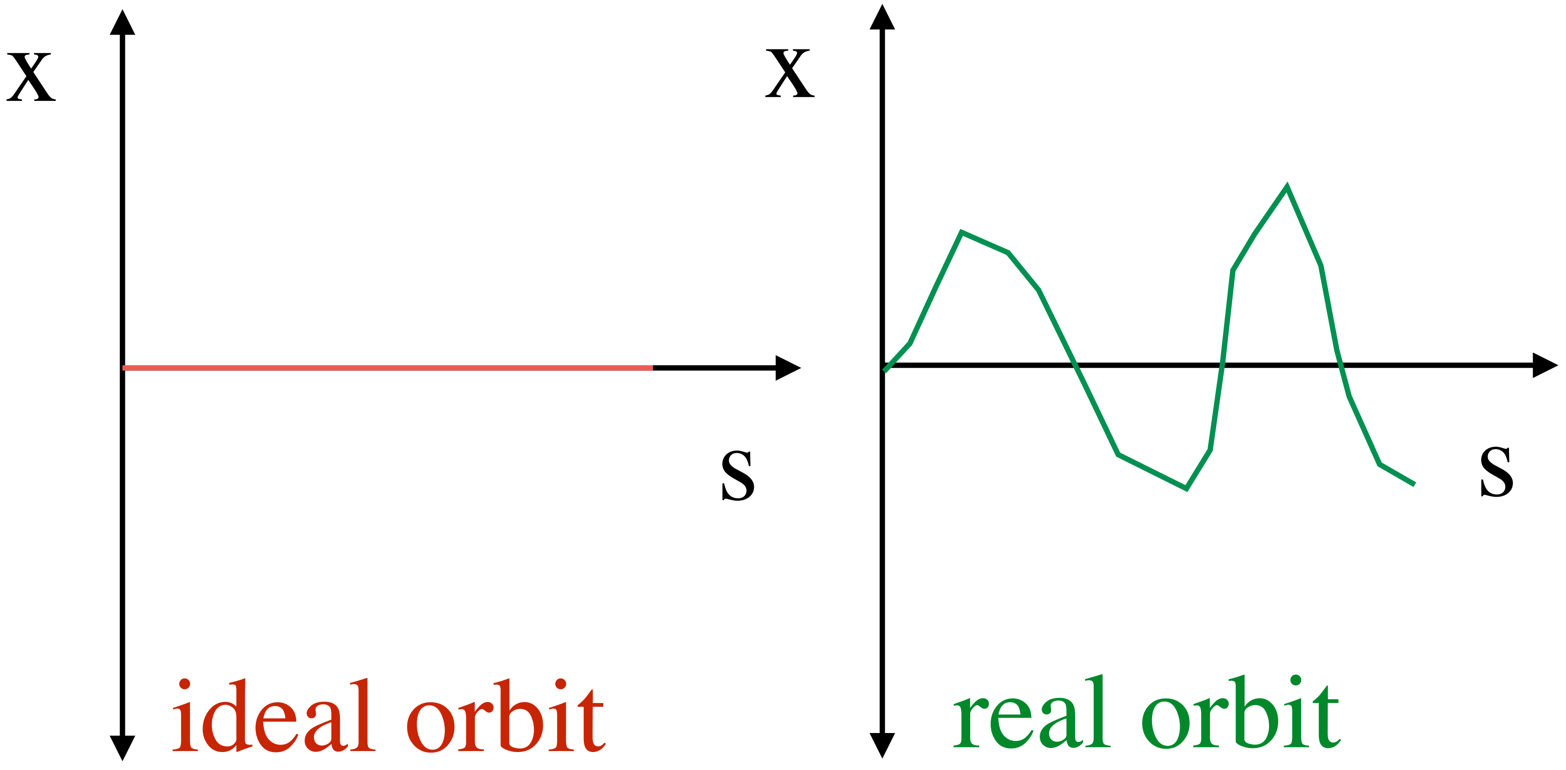

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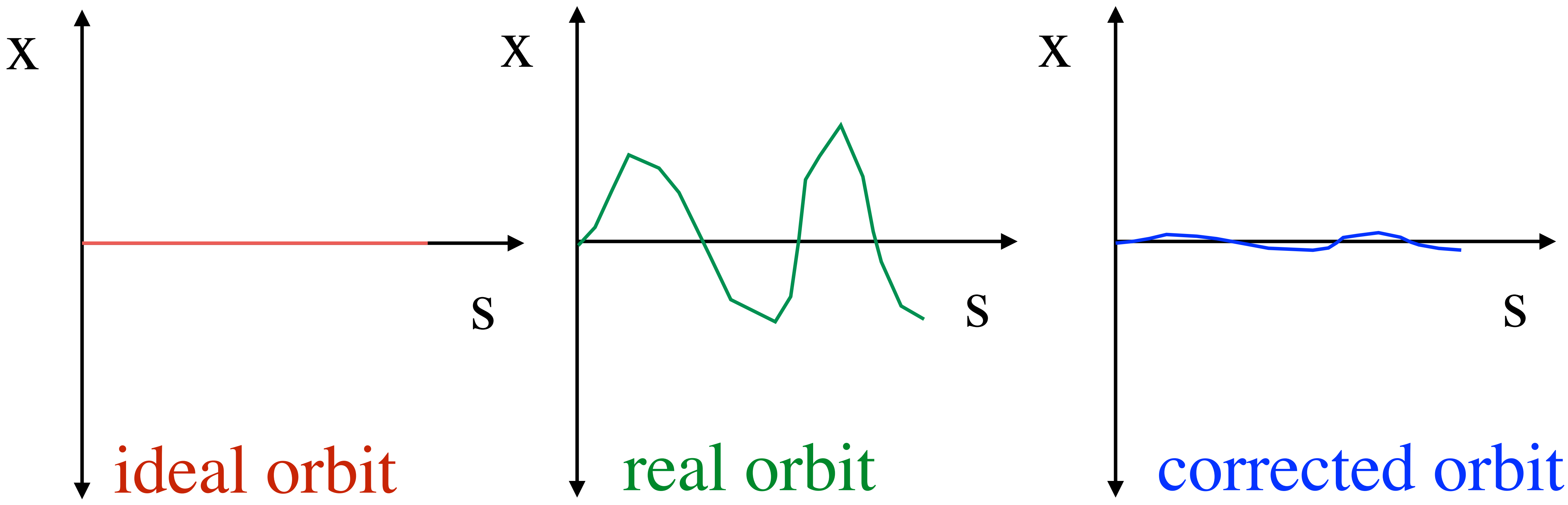

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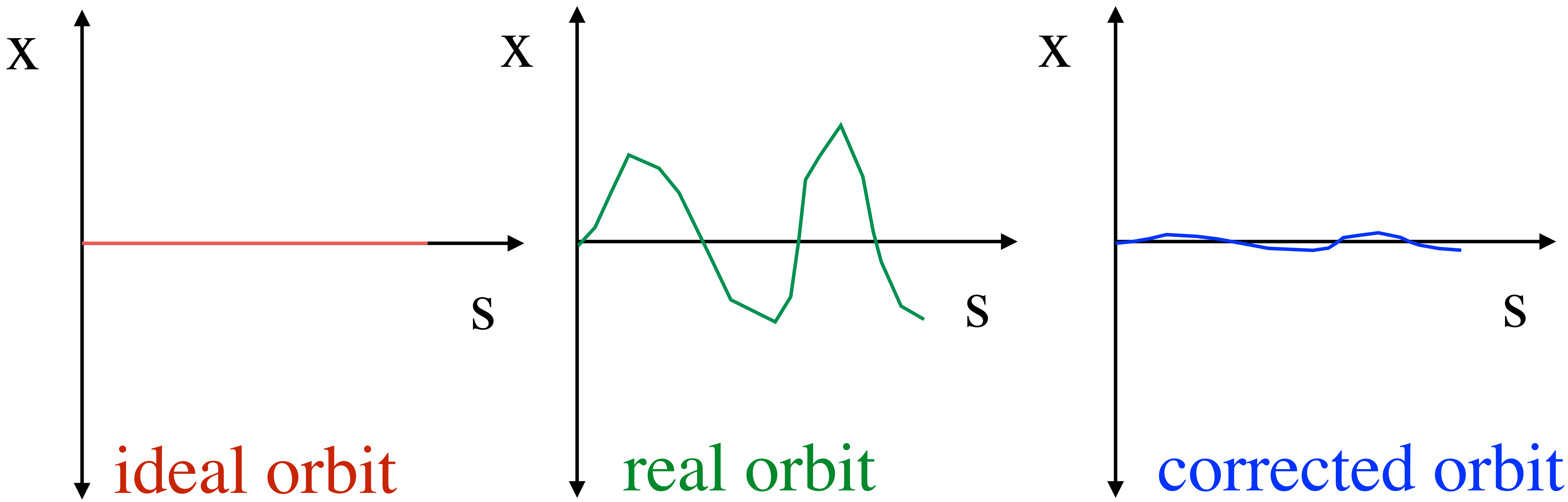

- Corrector magnets needed to reduce orbit distortion magnitude
- Need to check if correctors strengths needed for HP-PS are within limit

Orbit correction (2/2)

To evaluate efficiency and performance of orbit correction system:

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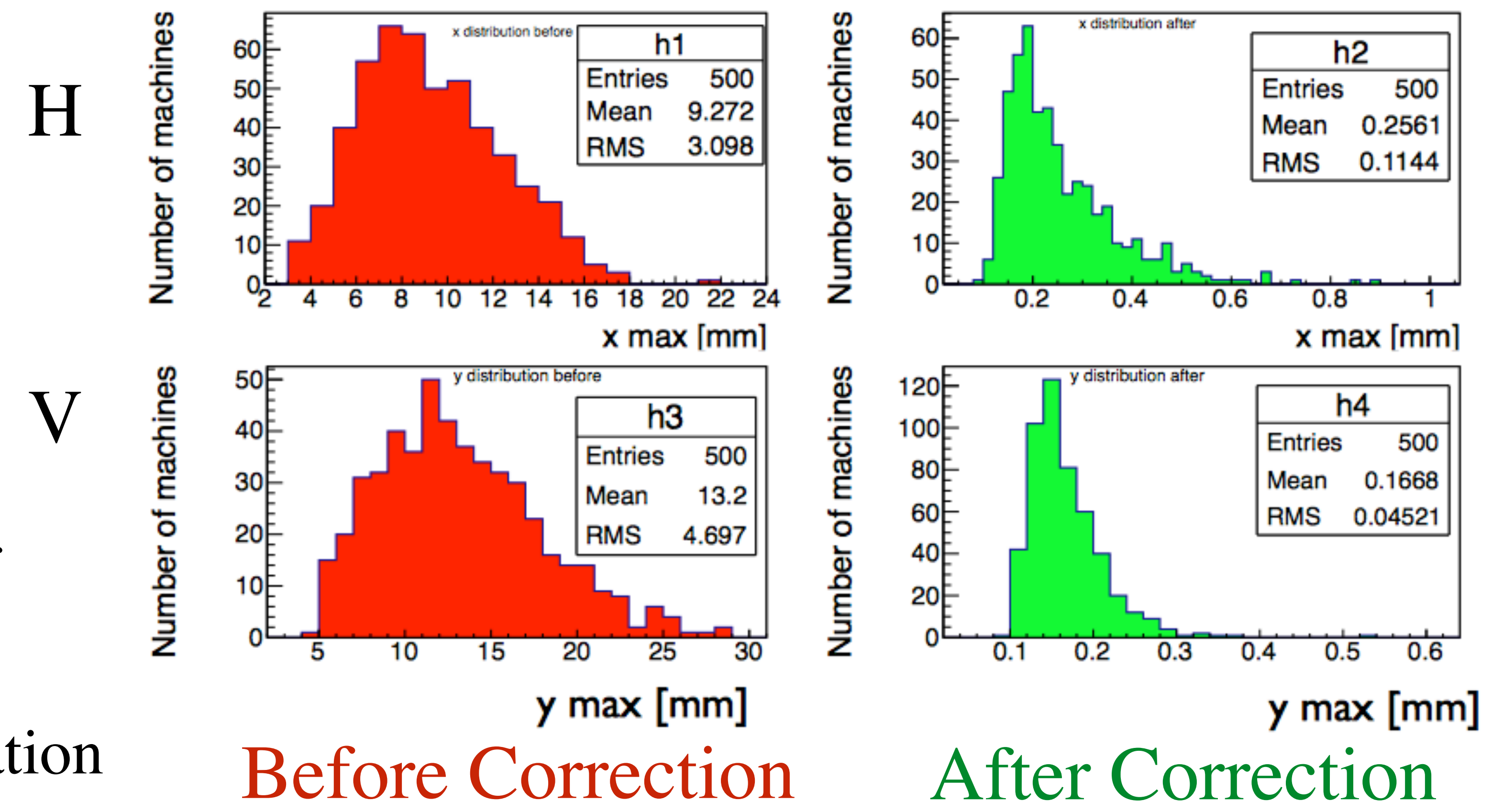
Distribution of max H and V orbit deviation **before** and **after** correction



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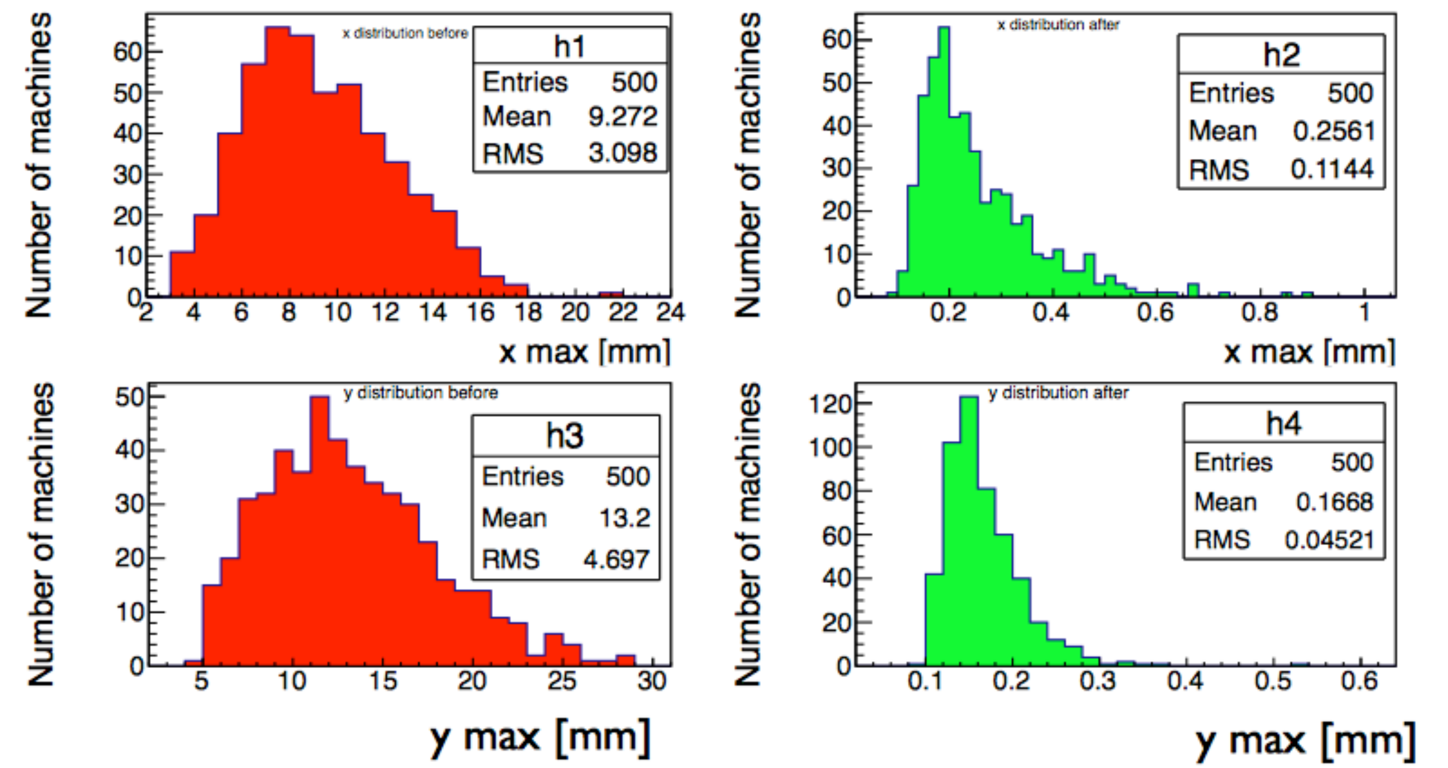

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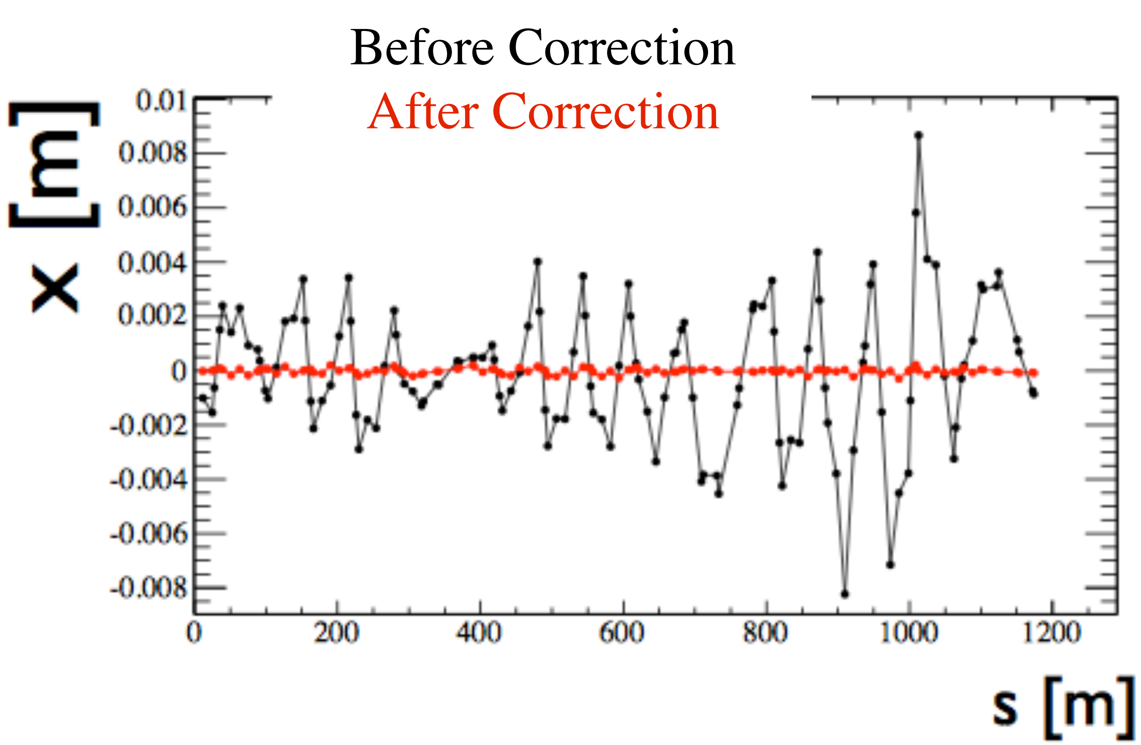

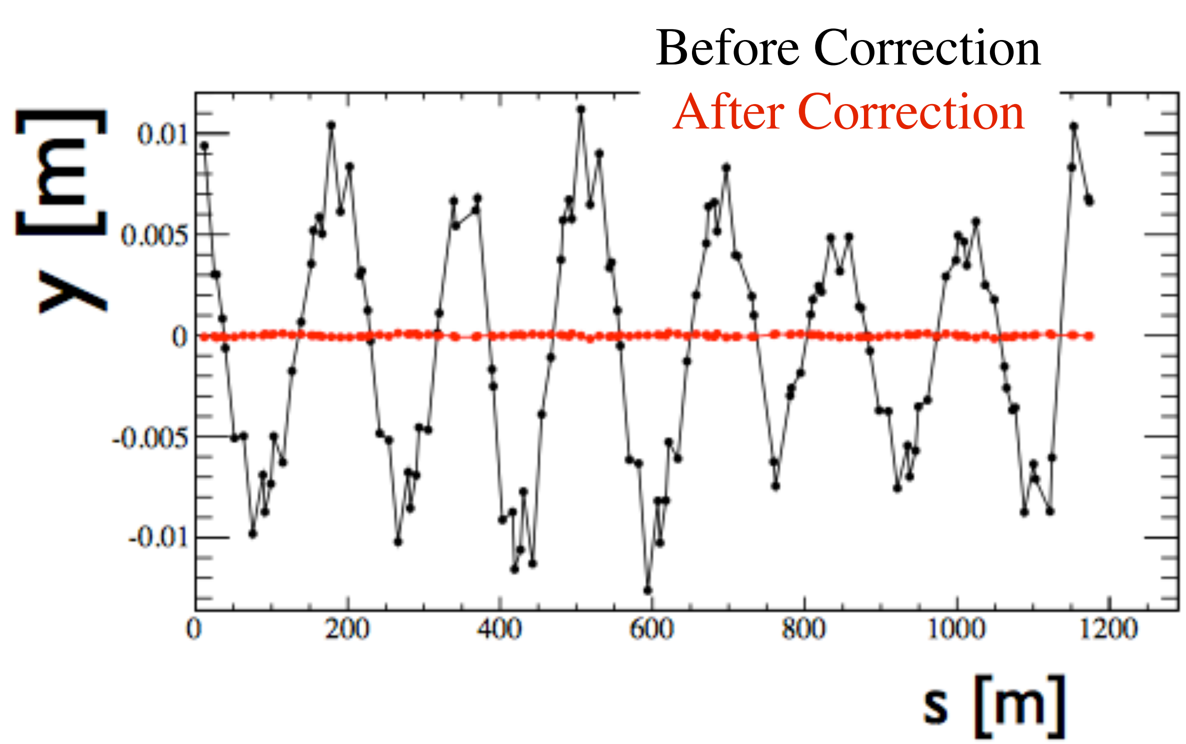

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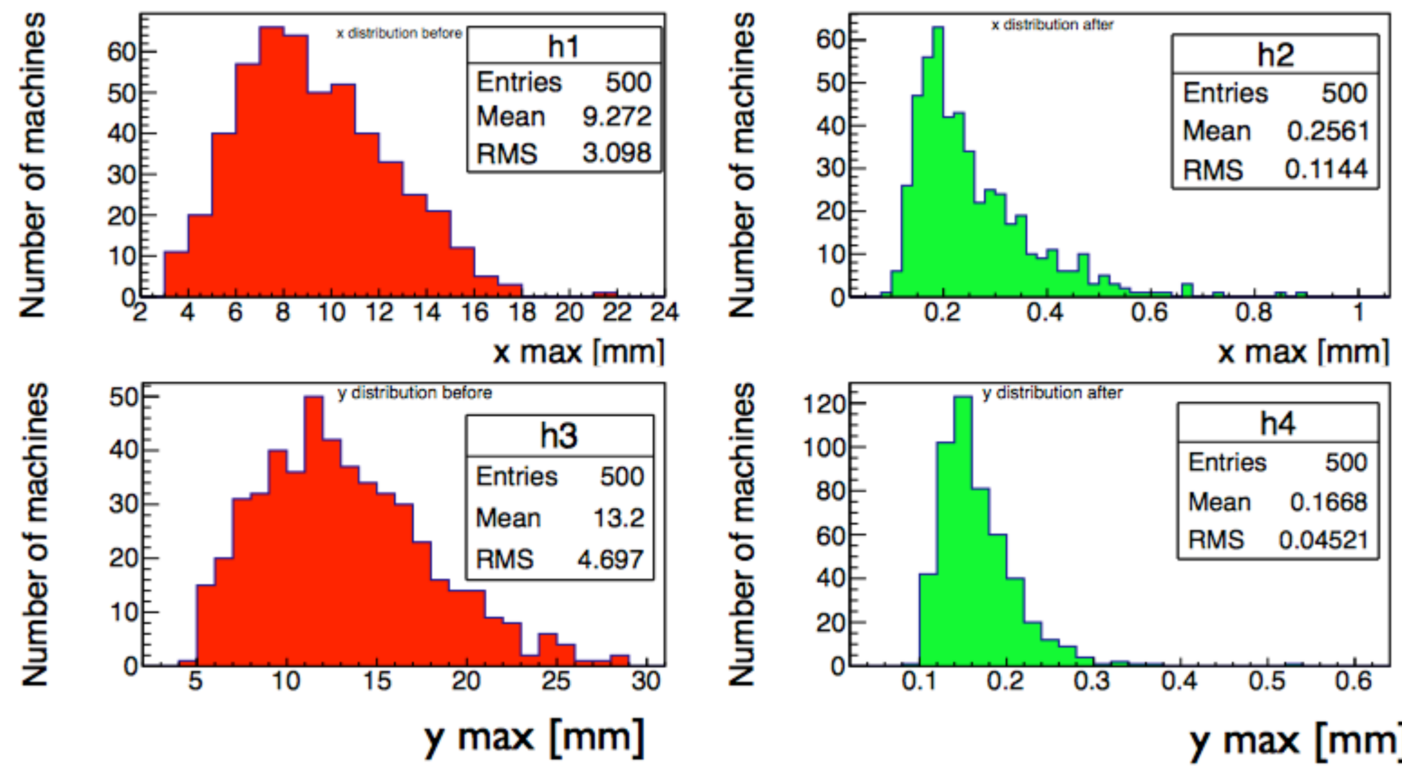

Before Correction

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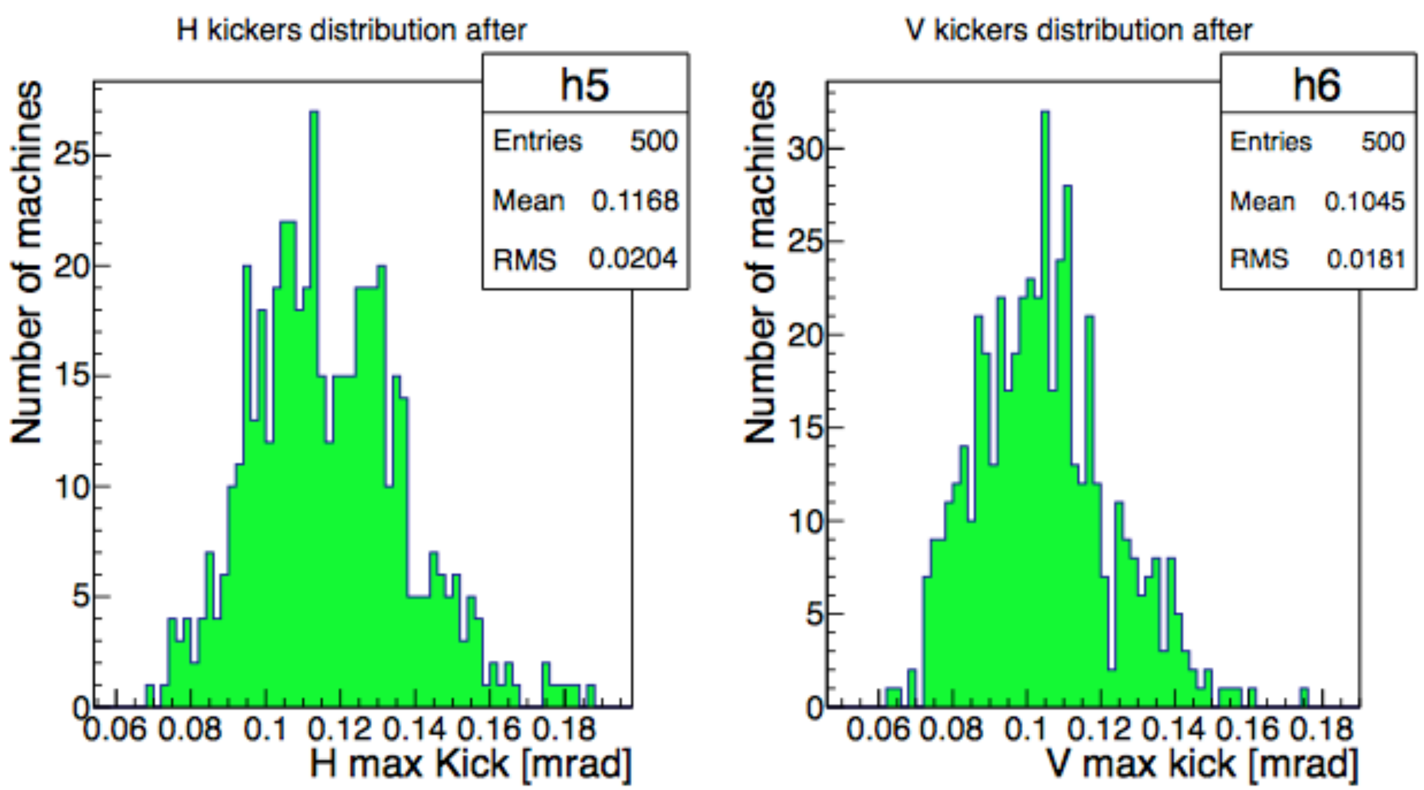
Distribution of max H and V kicker strength



Correctors' strength needed <0.2 mrad (~0.05 T for E=50 GeV), i.e. **well within the limits**

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- Why do we need collimators?

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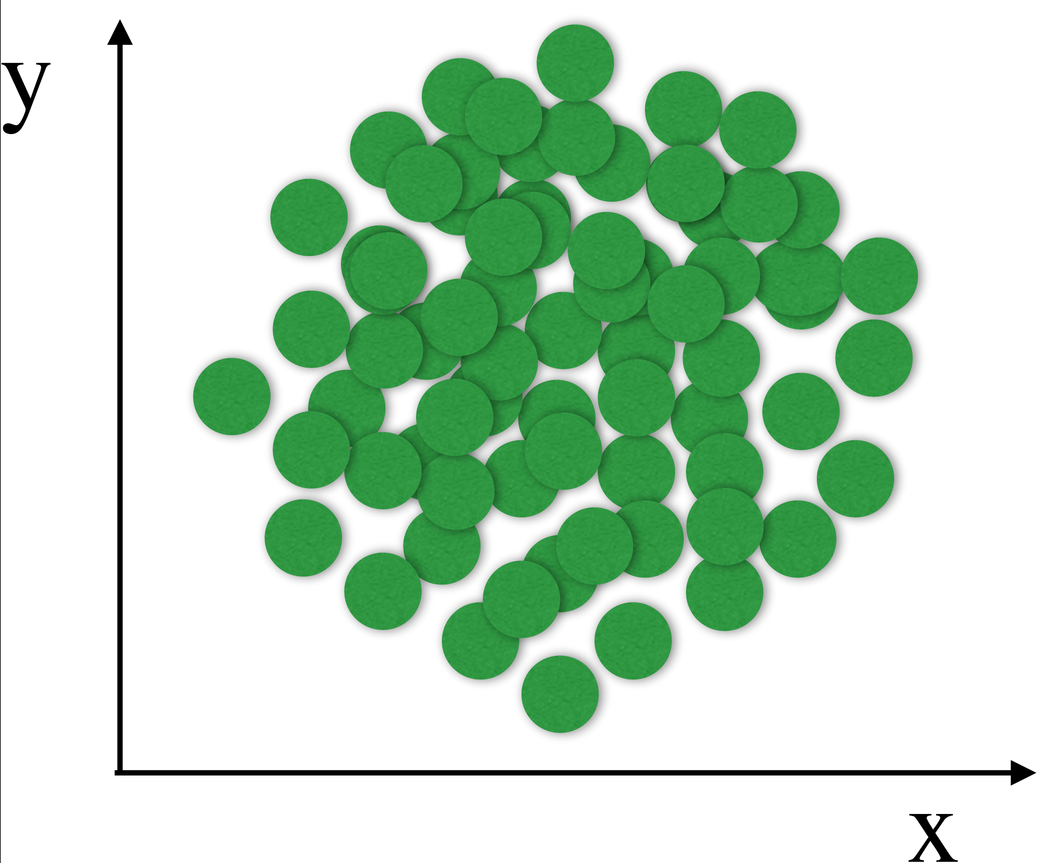

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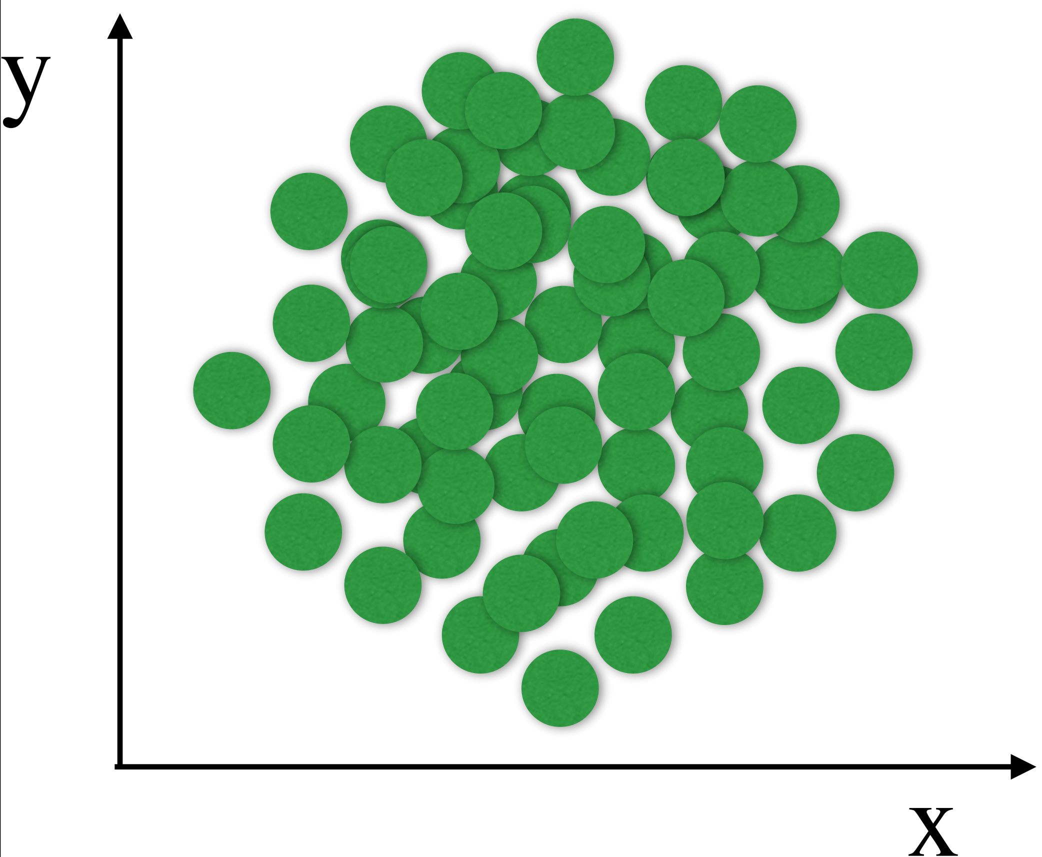

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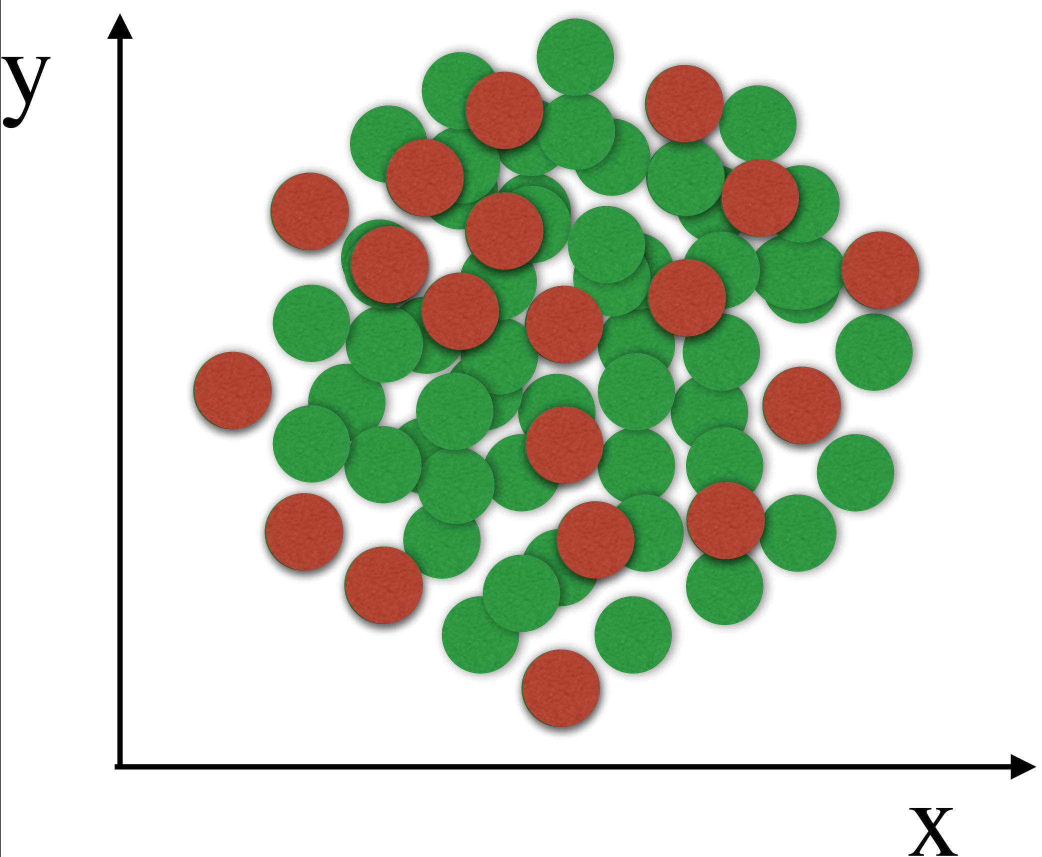

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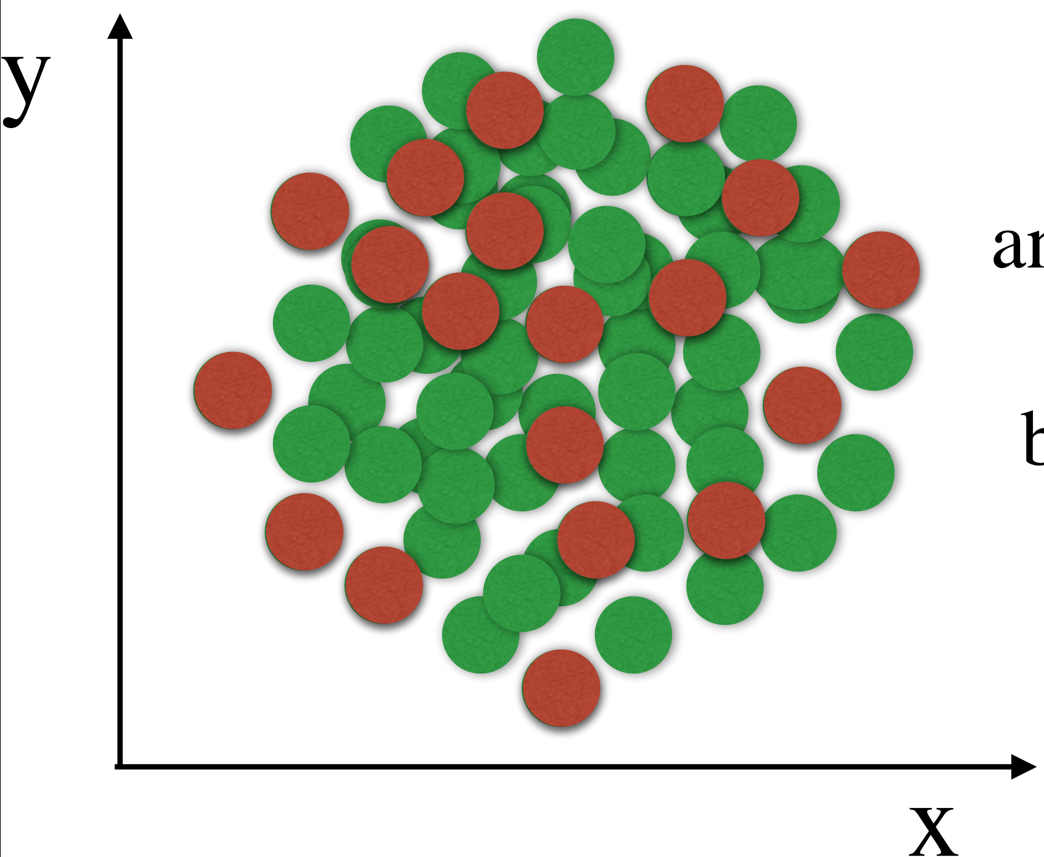

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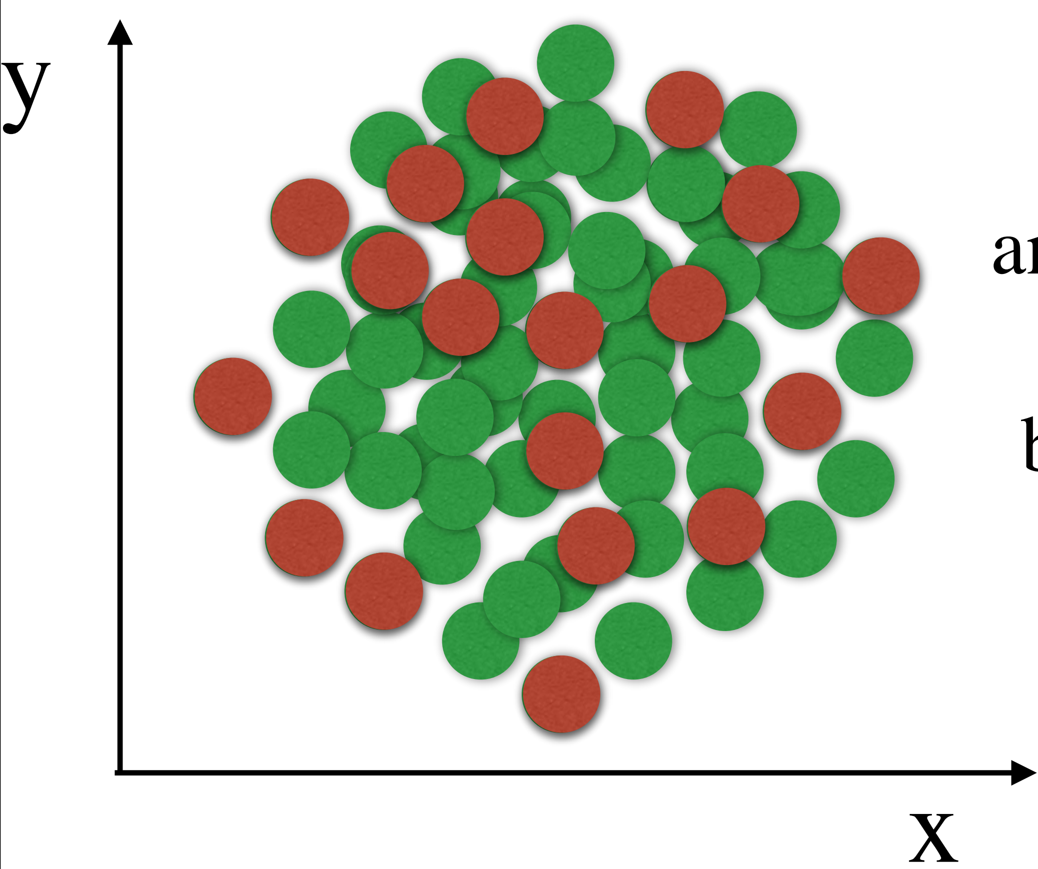

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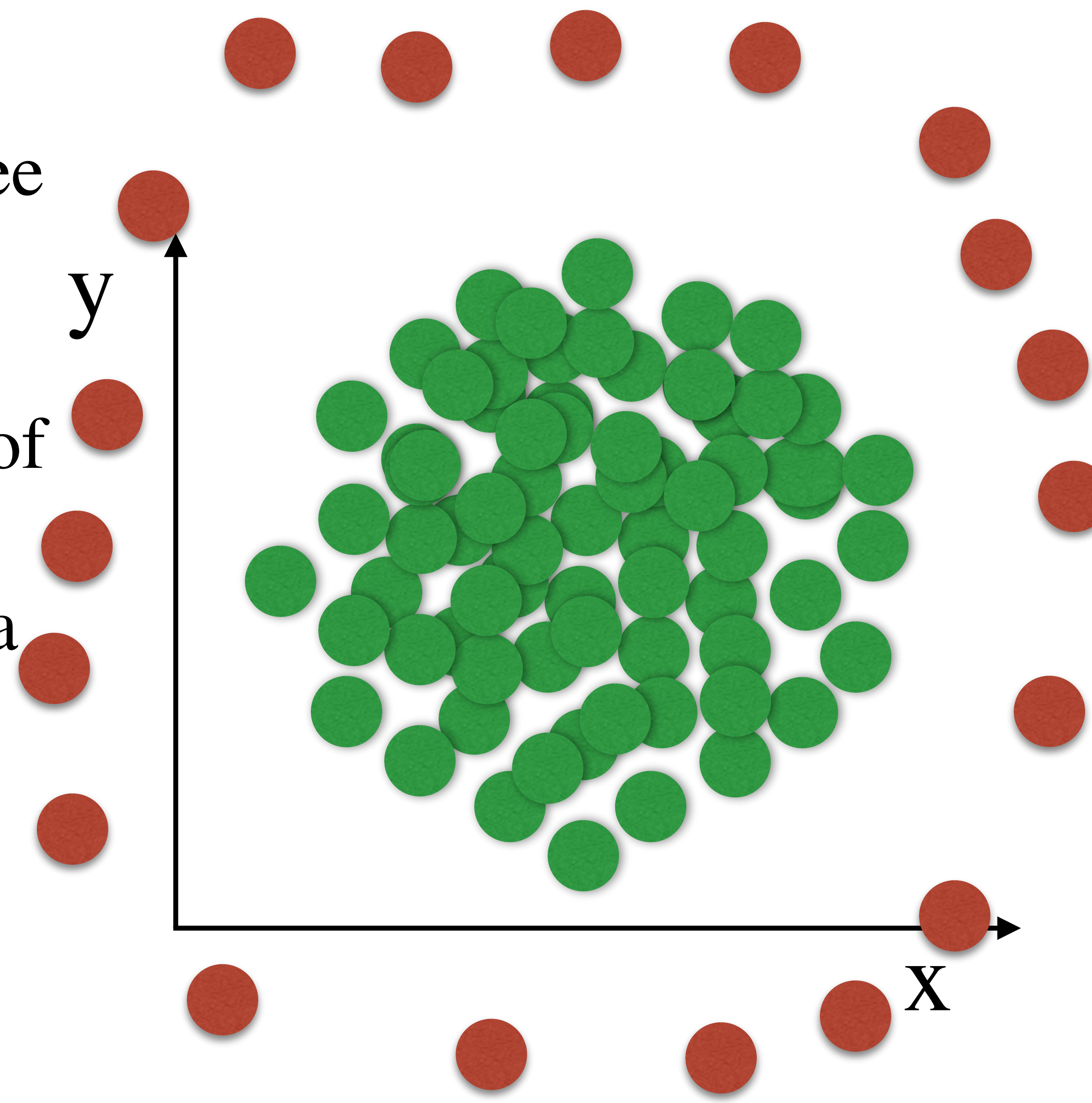

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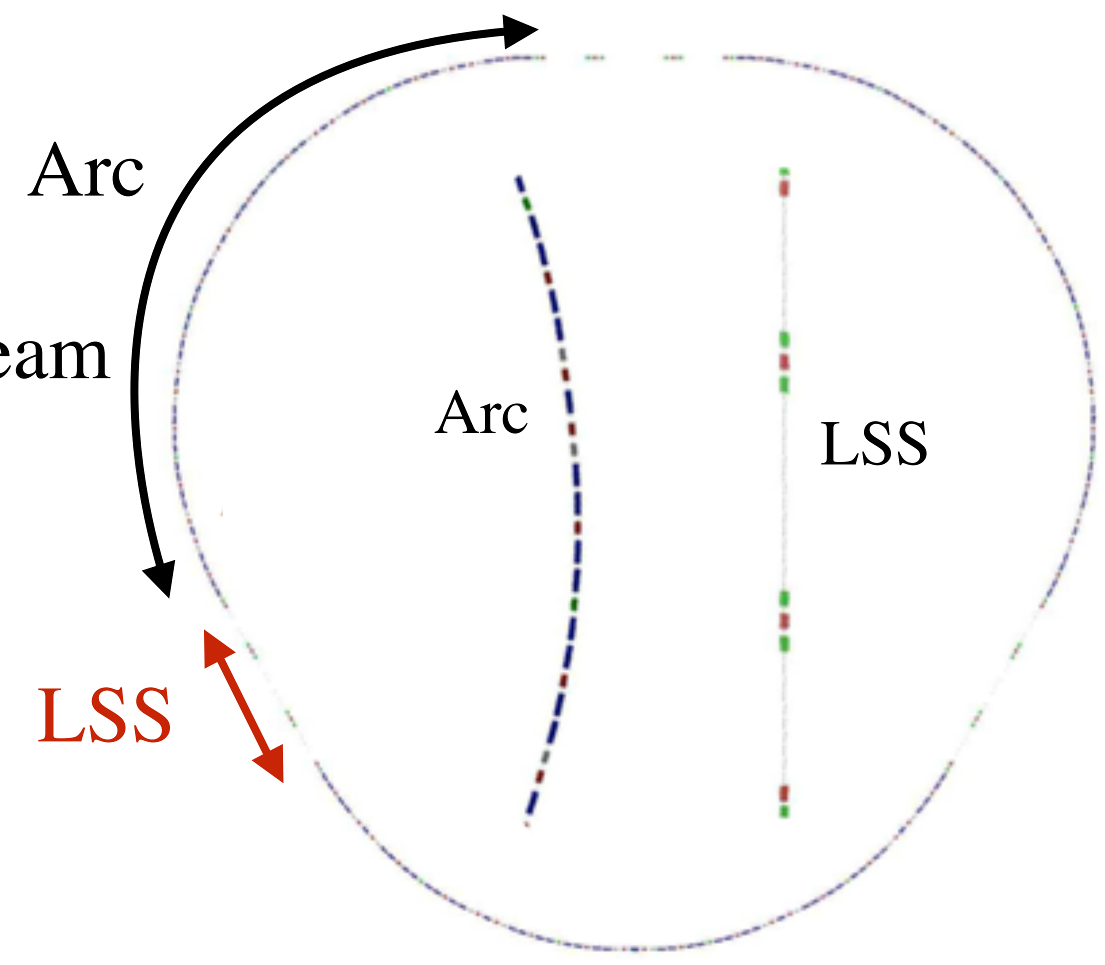
  - to localize slow losses in controlled way in properly equipped locations: dedicated LSS (Long Straight Section) for transverse collimation



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There are equal numbers of H and V collimators; here only H are shown

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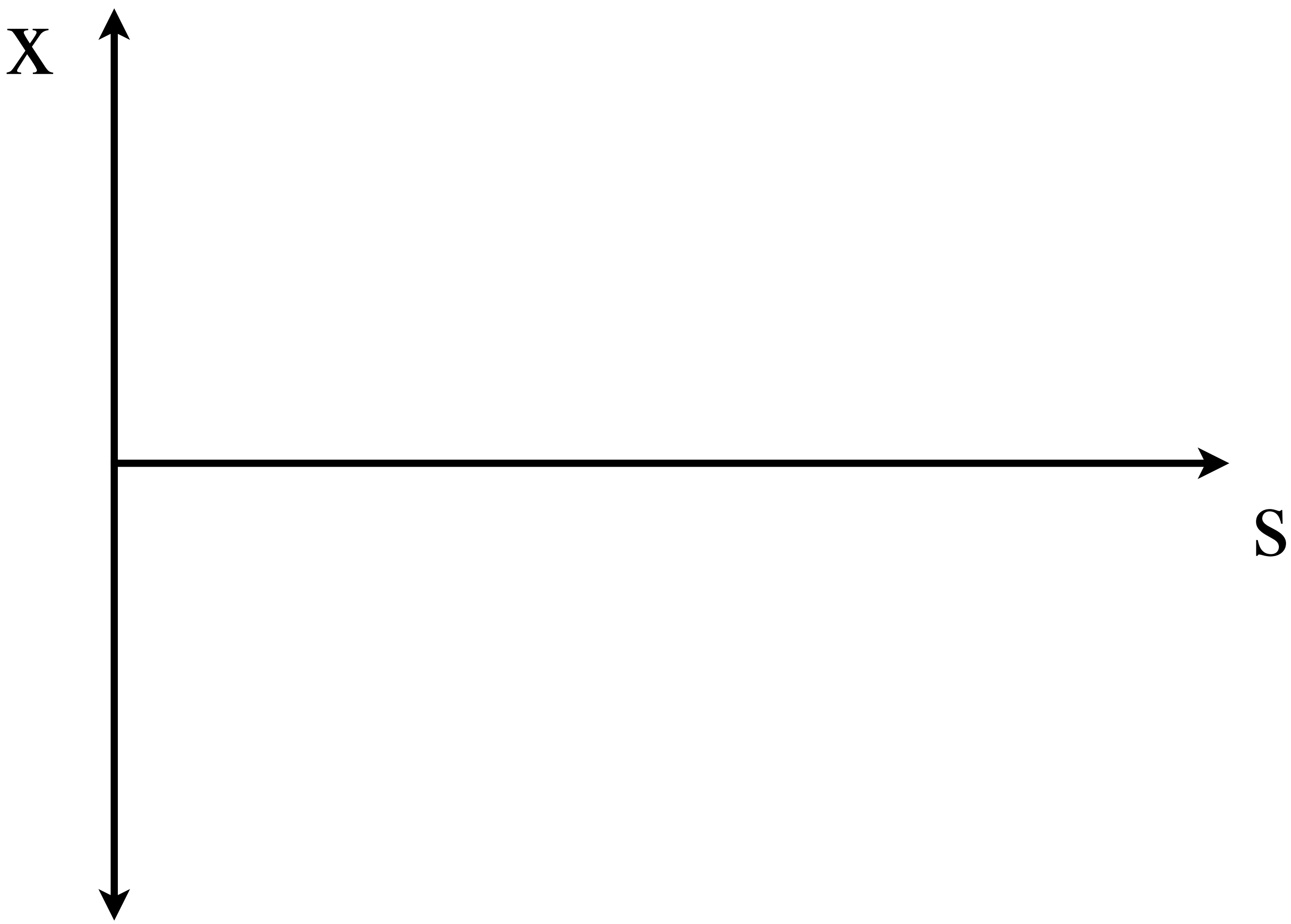

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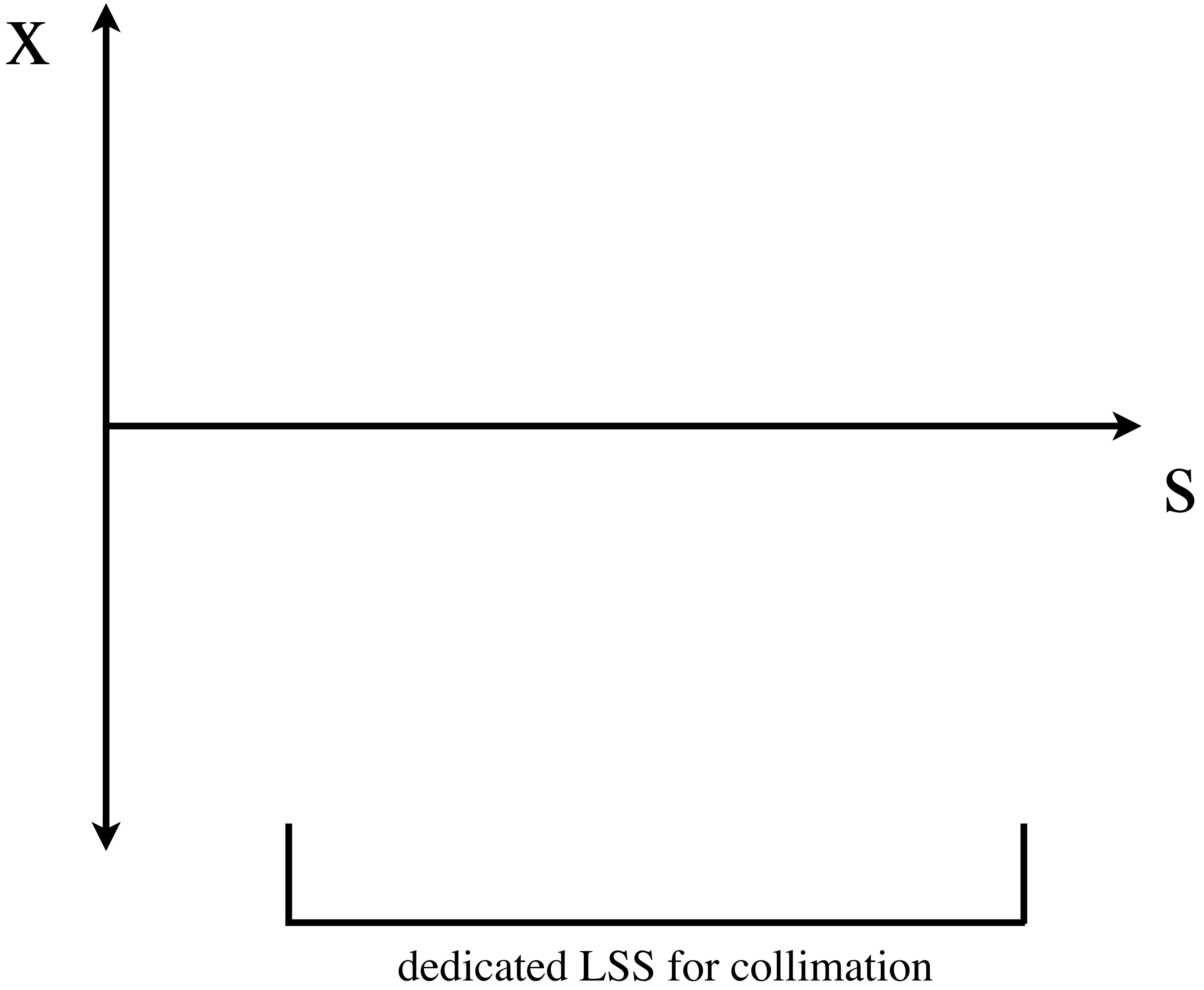

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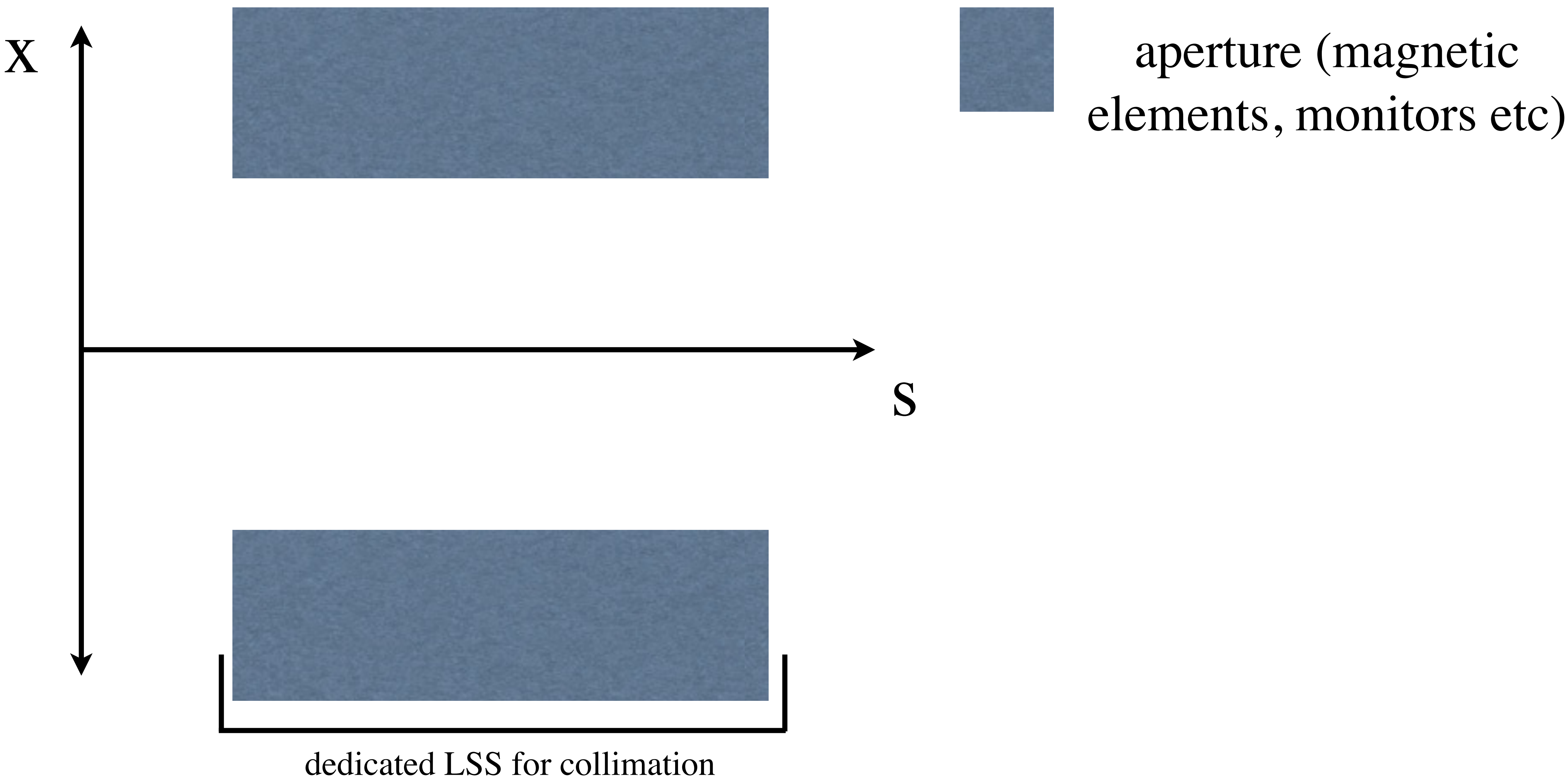

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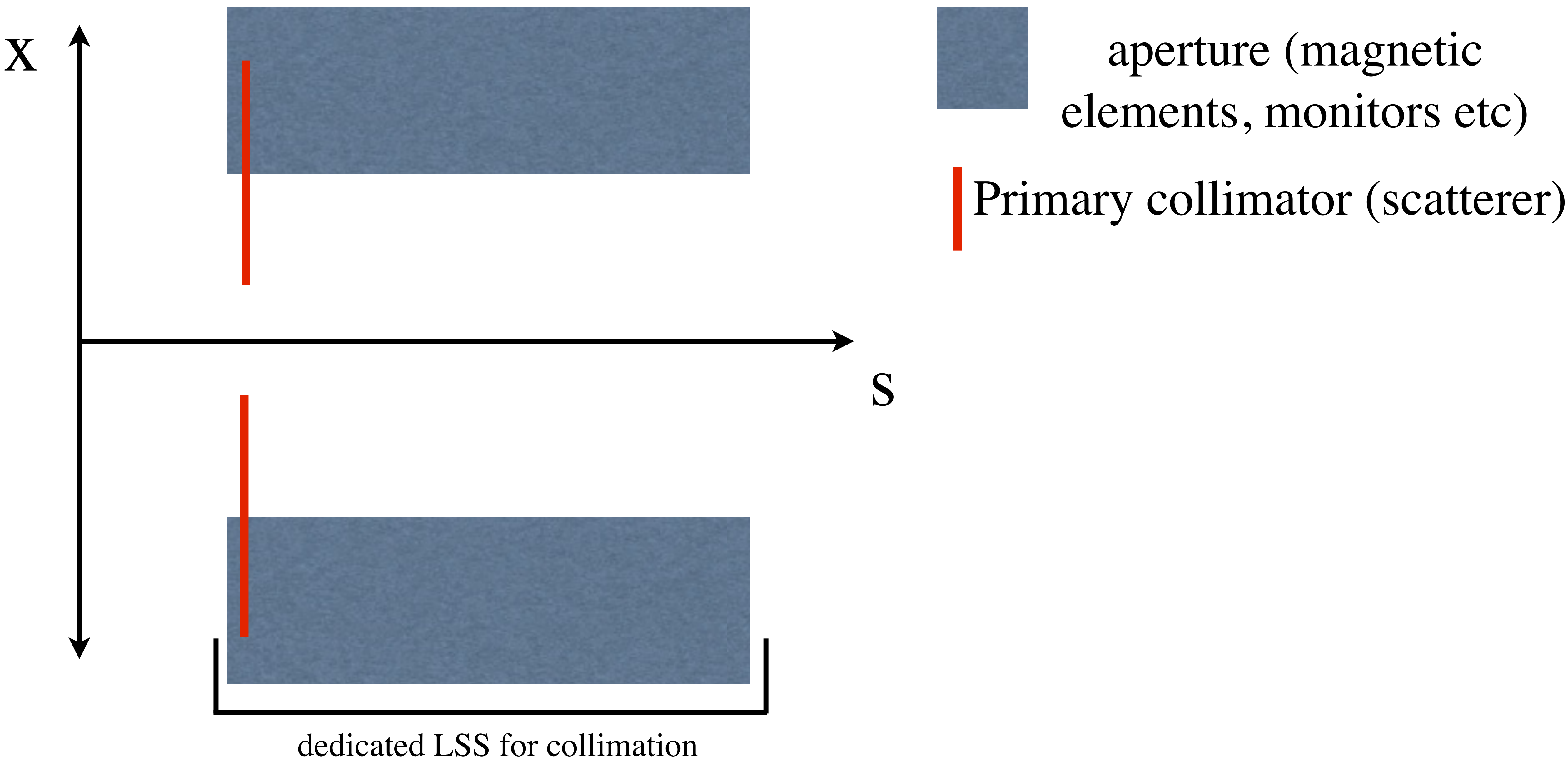

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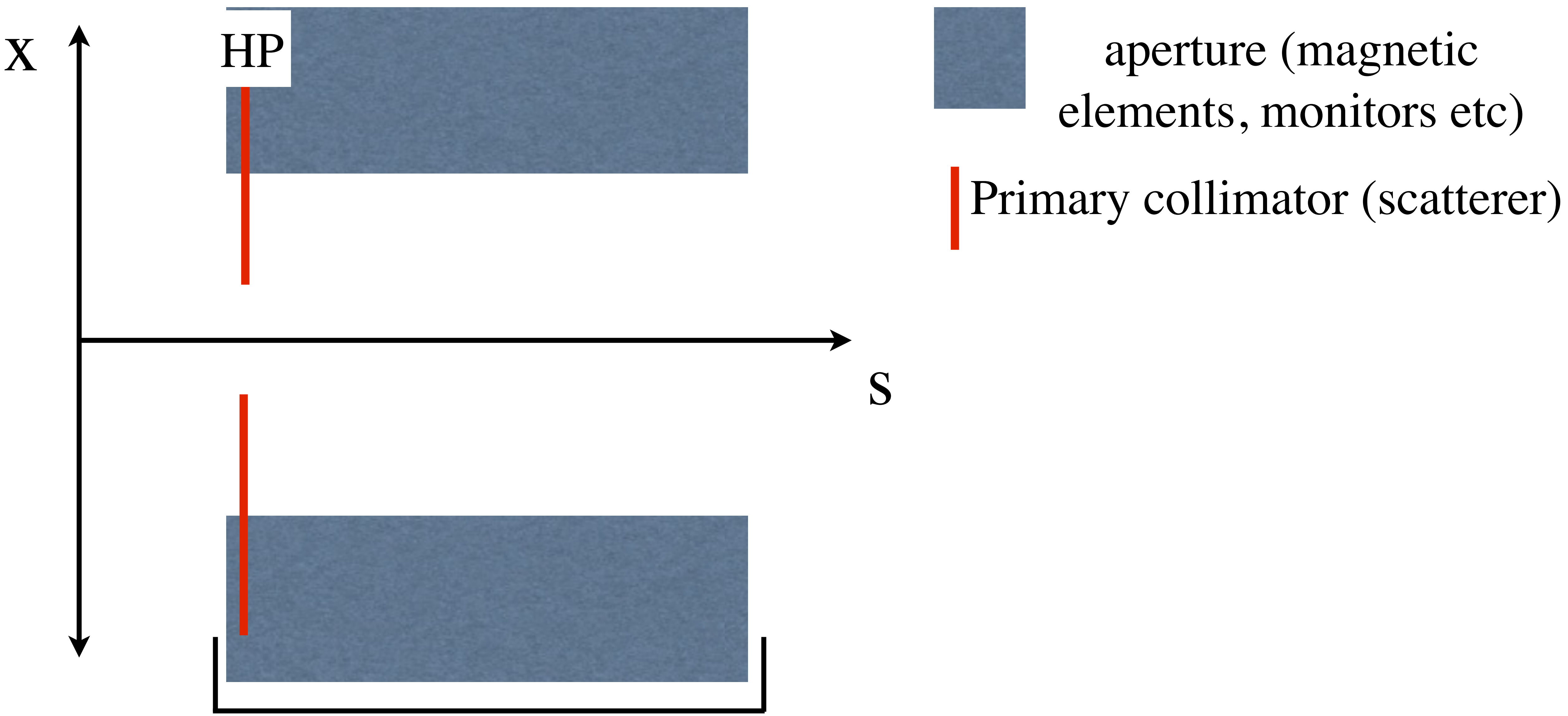

dedicated LSS for collimation

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- **P**rimaries/scrapers/scatterers (H**P**): increase chance that halo particles will be absorbed later on by secondary collimators
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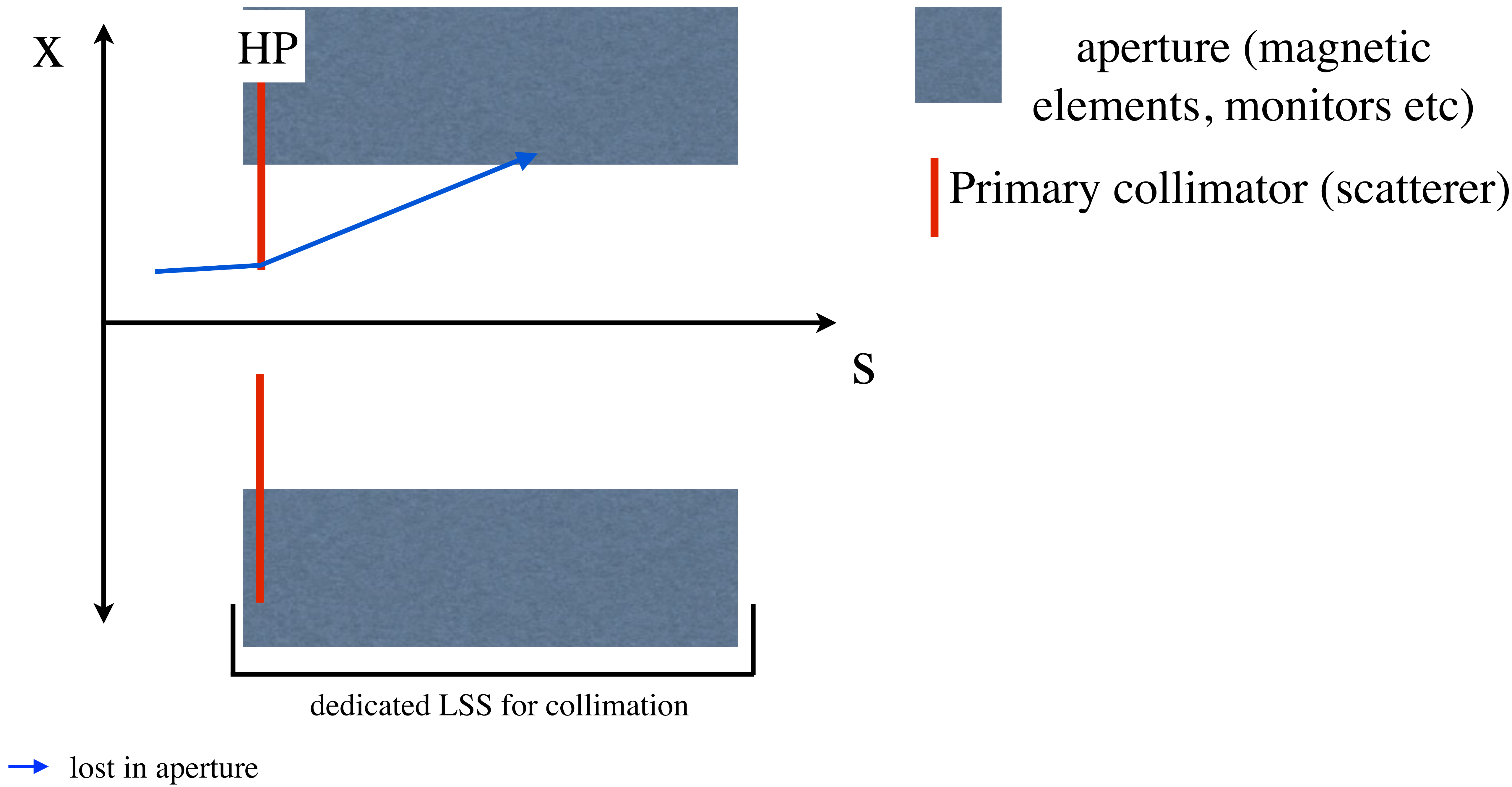

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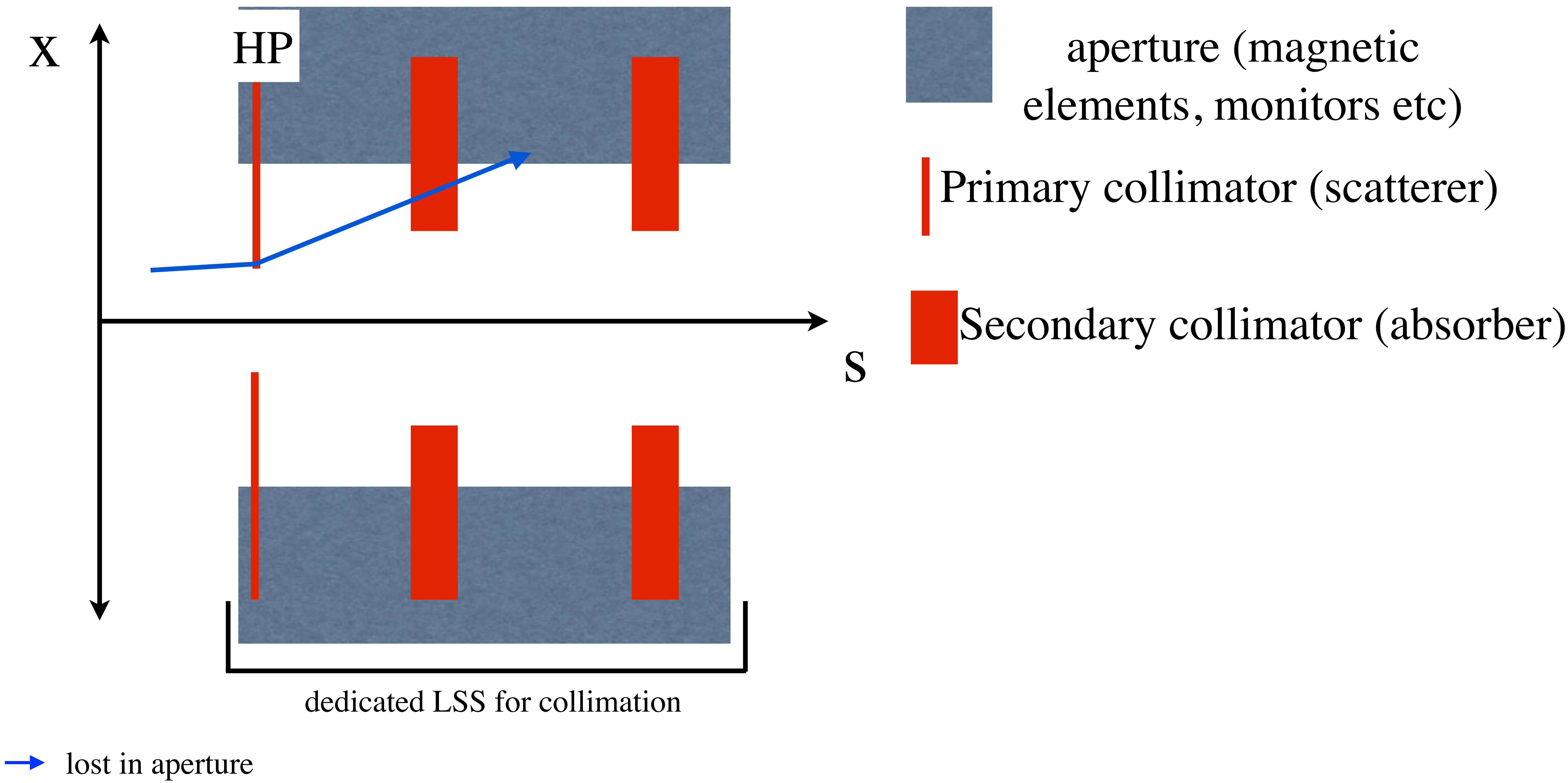

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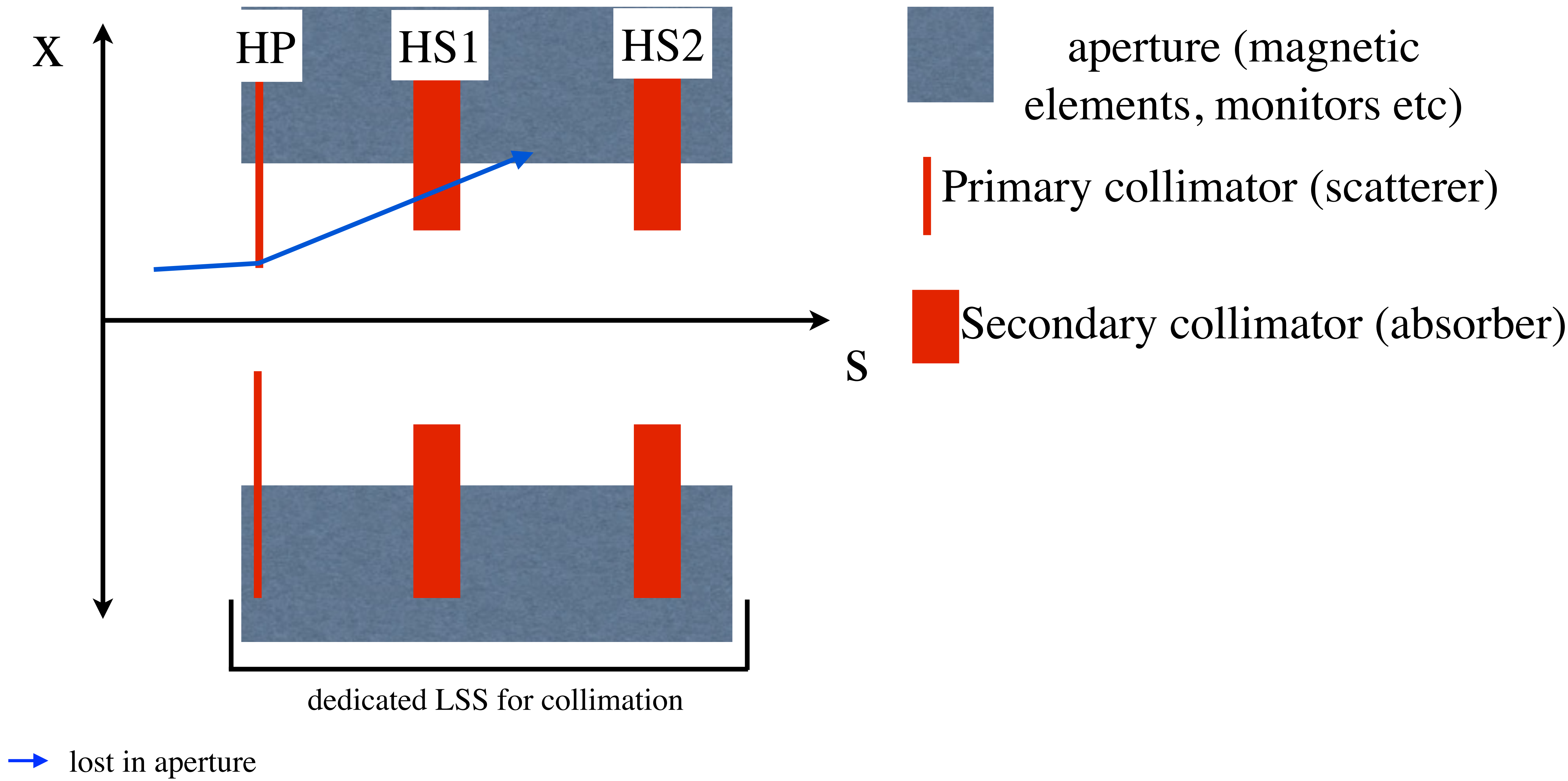

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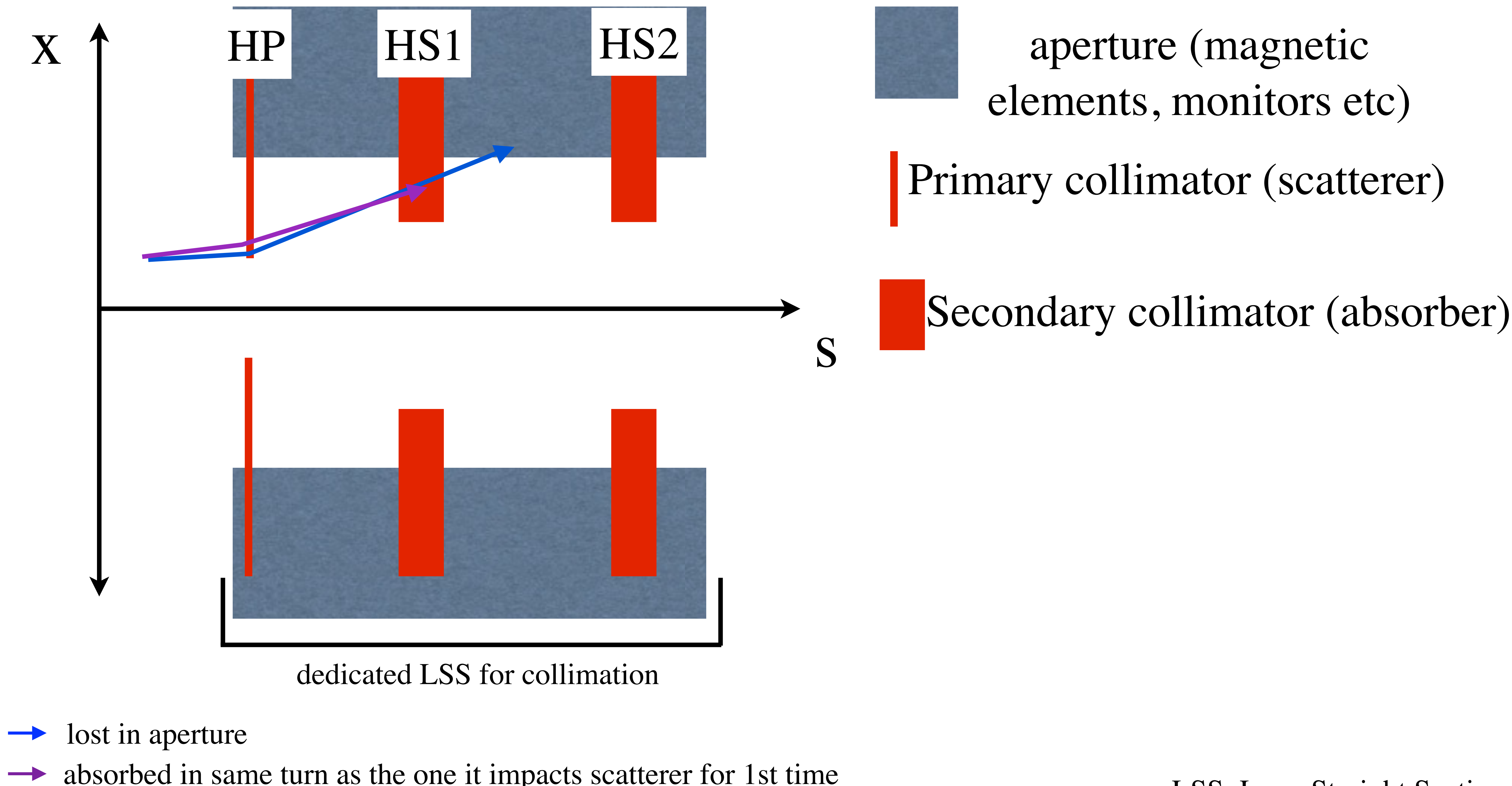

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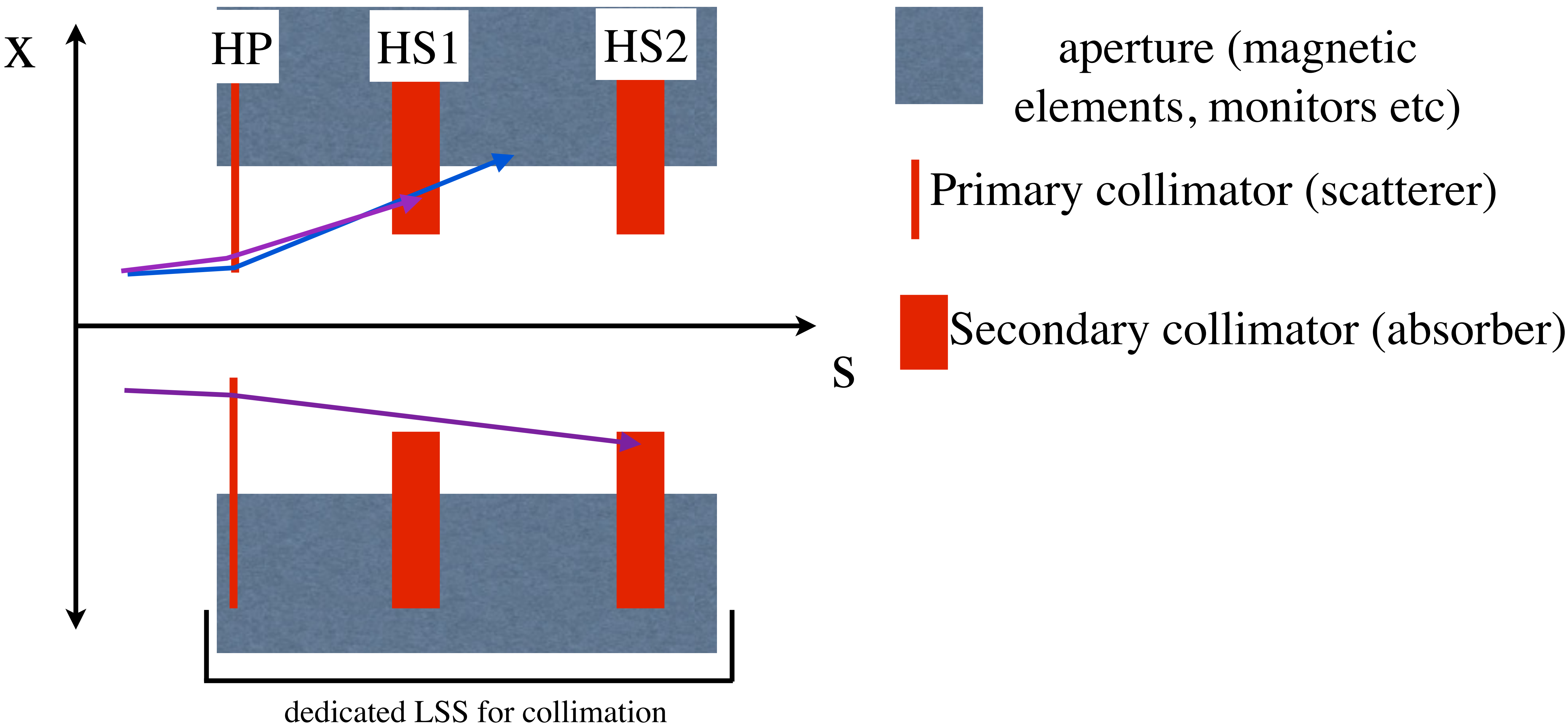

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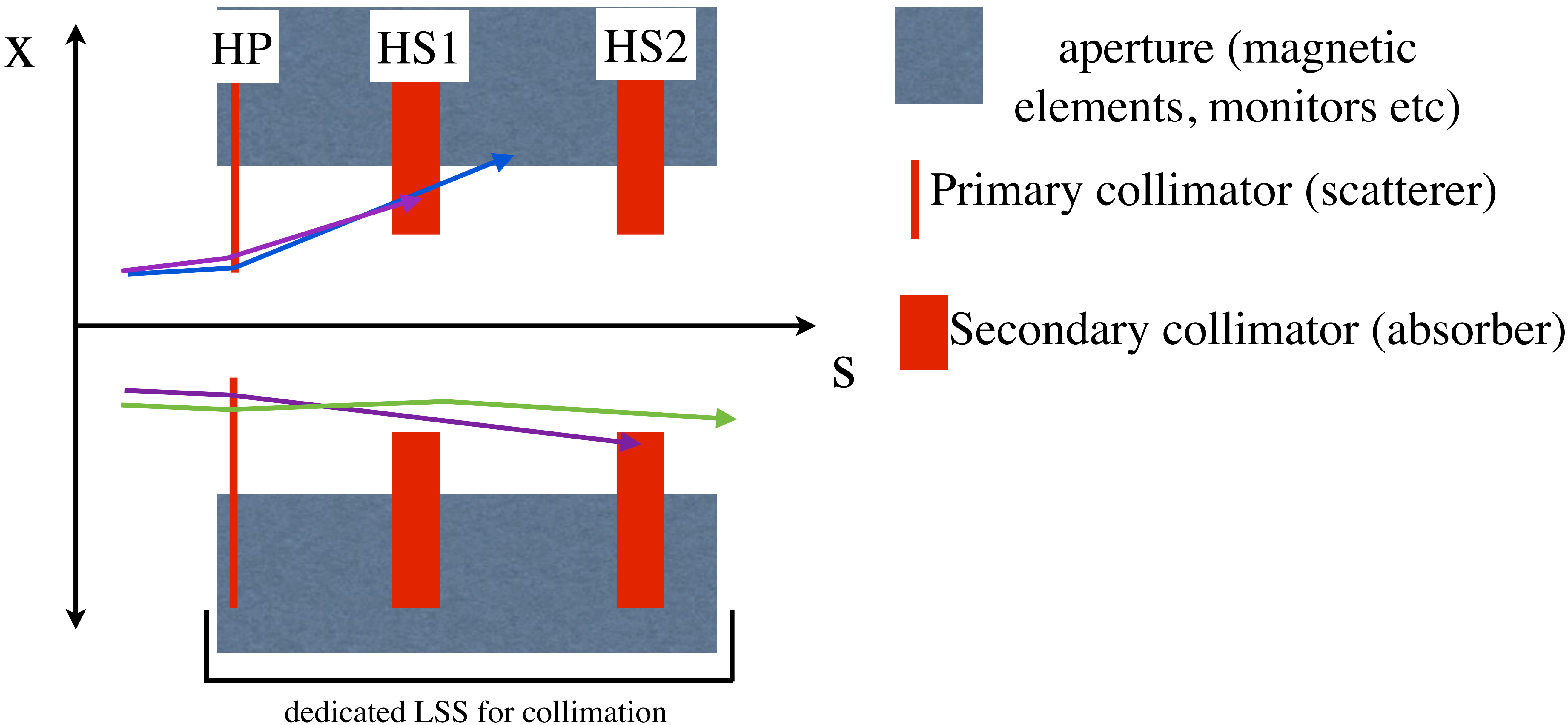

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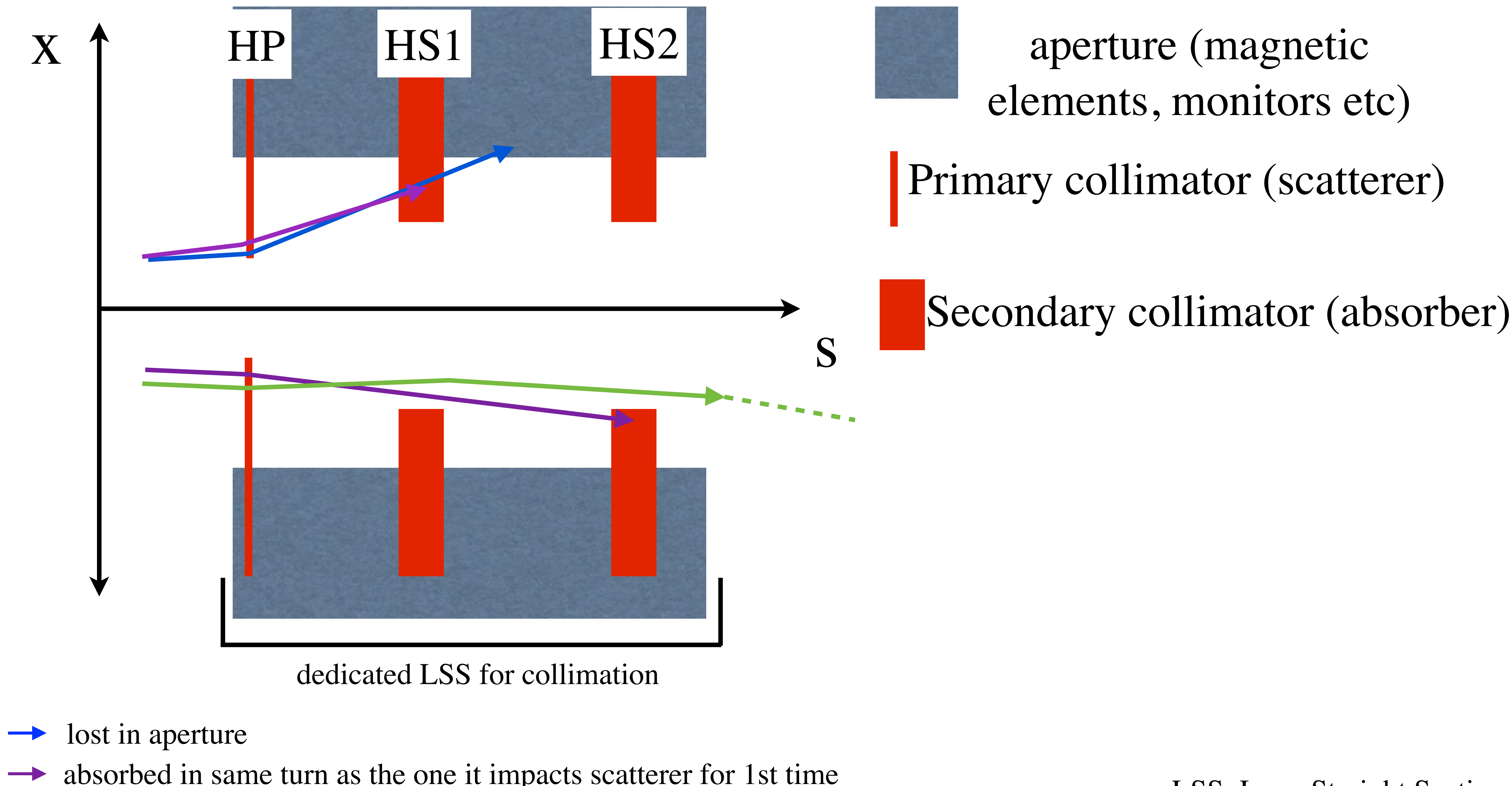

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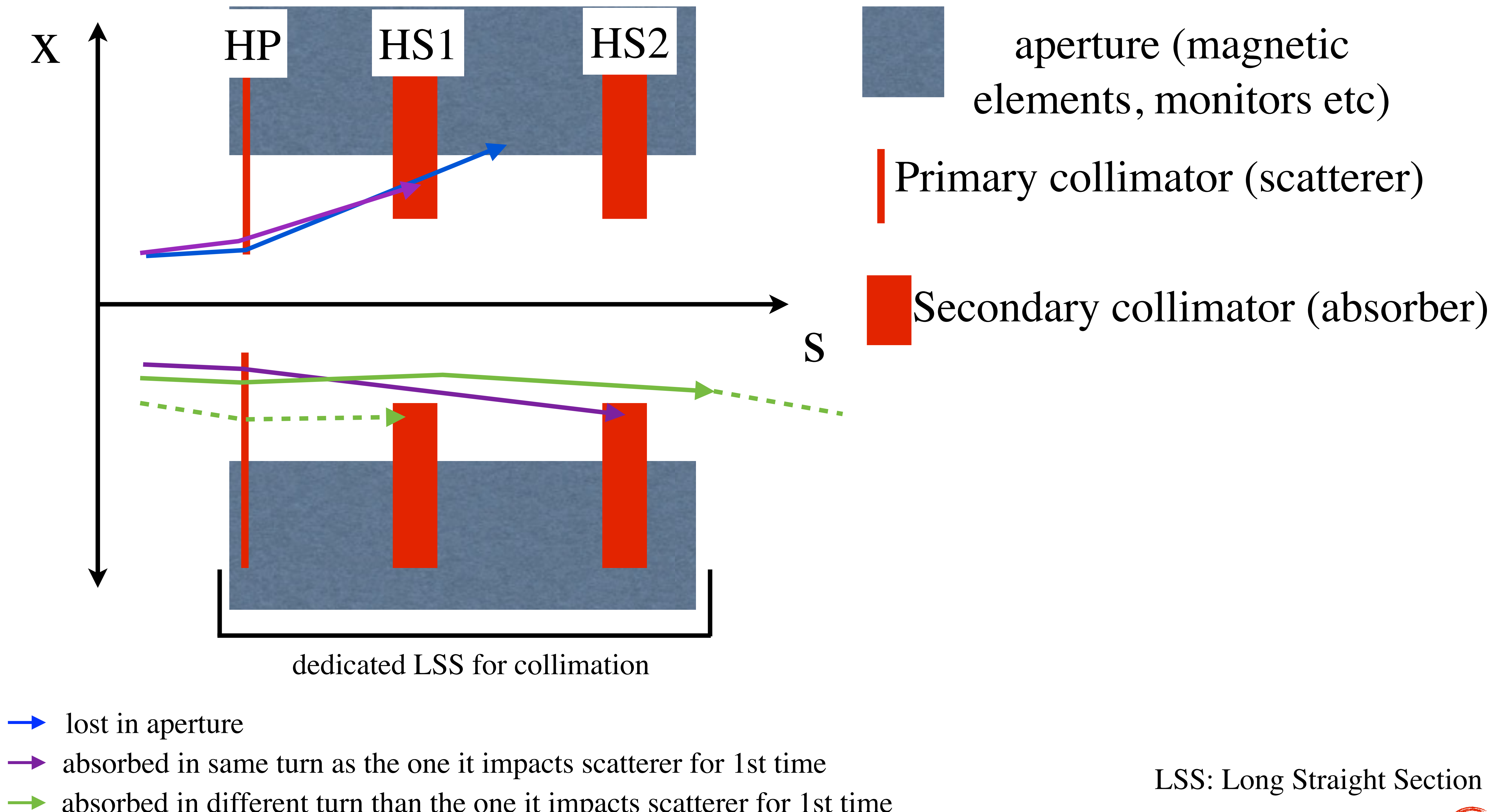

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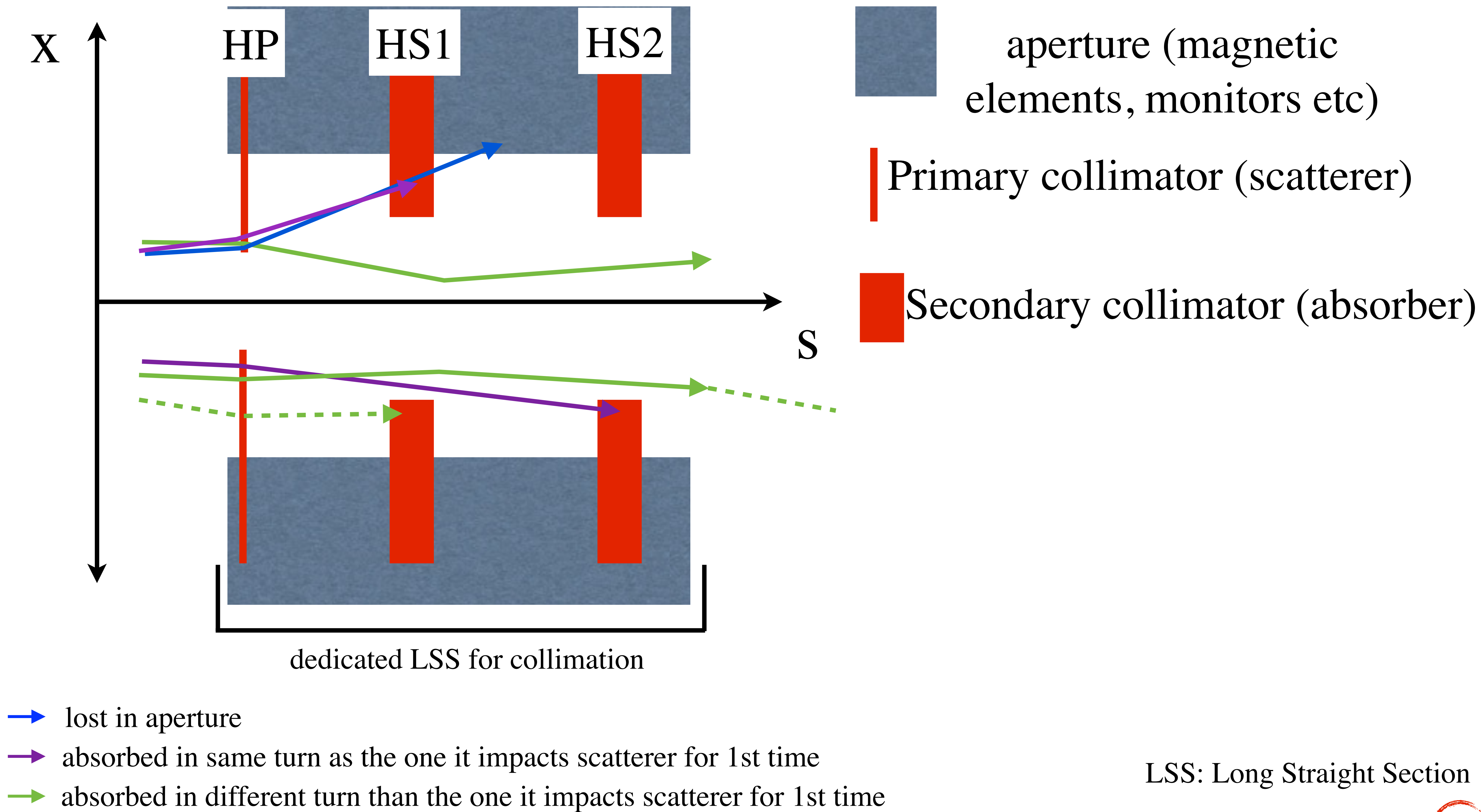

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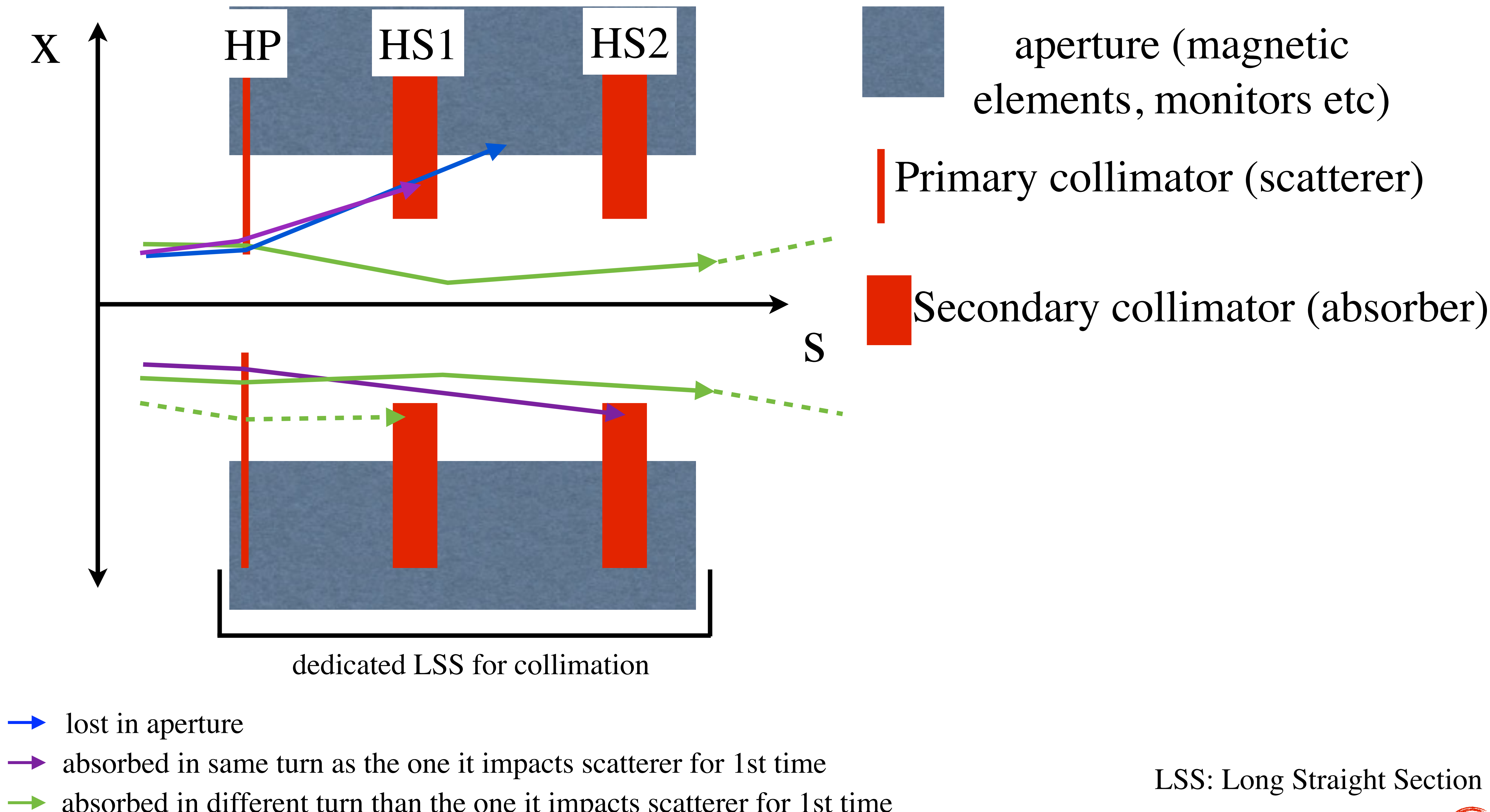

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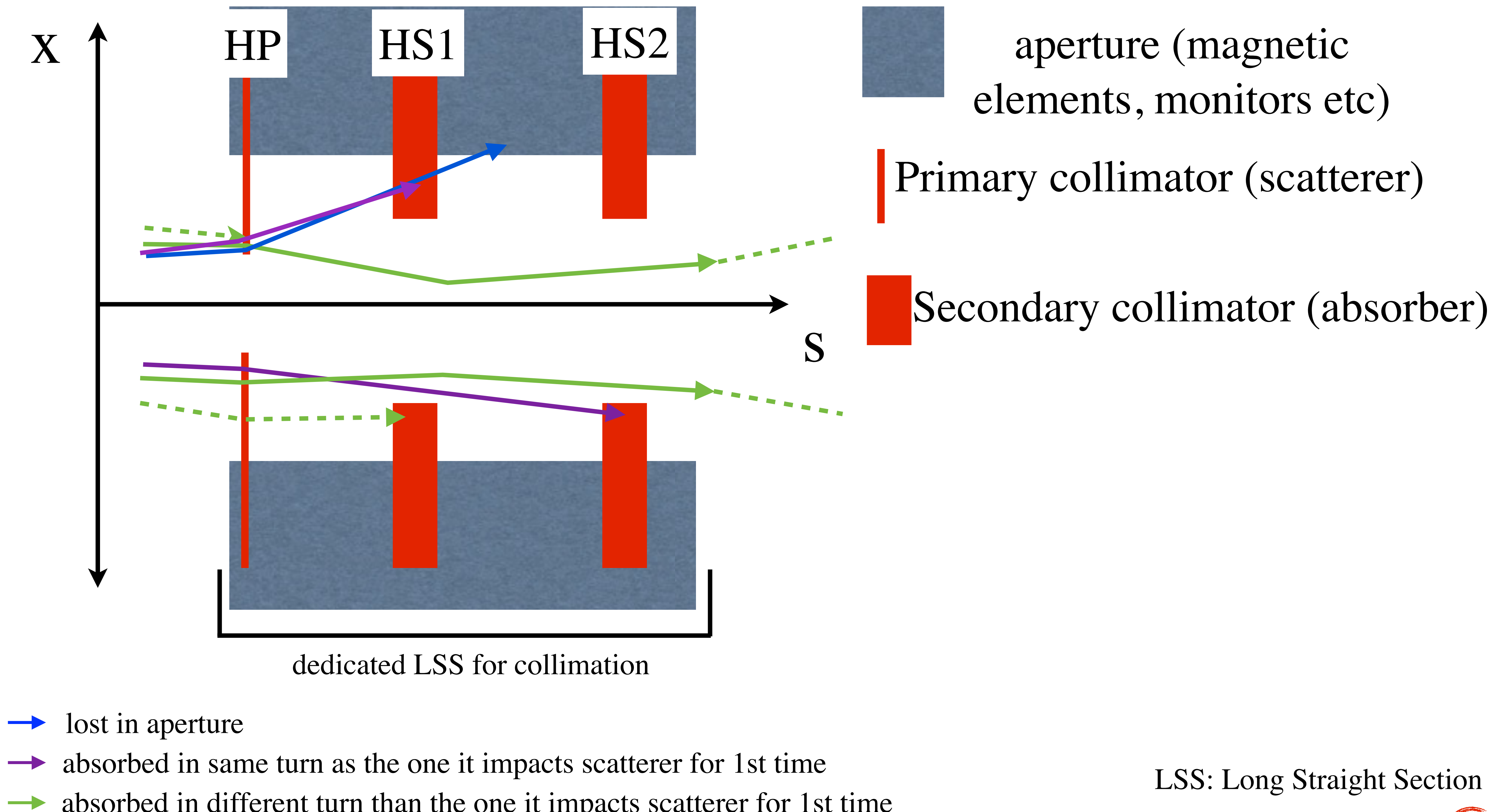

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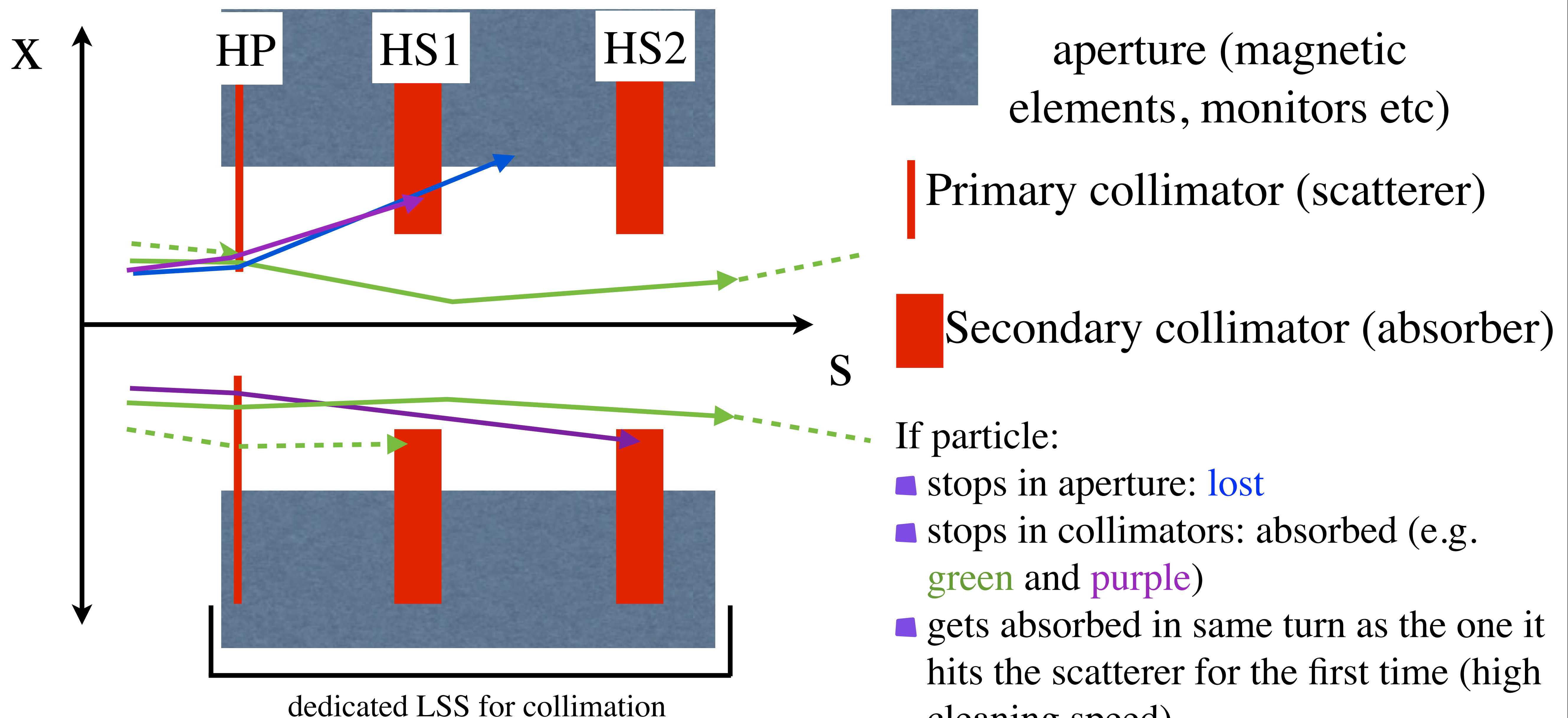
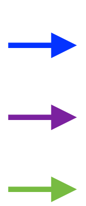


If particle:

- stops in aperture: lost
- stops in collimators: absorbed (e.g. green and purple)
- gets absorbed in same turn as the one it hits the scatterer for the first time (high cleaning speed)



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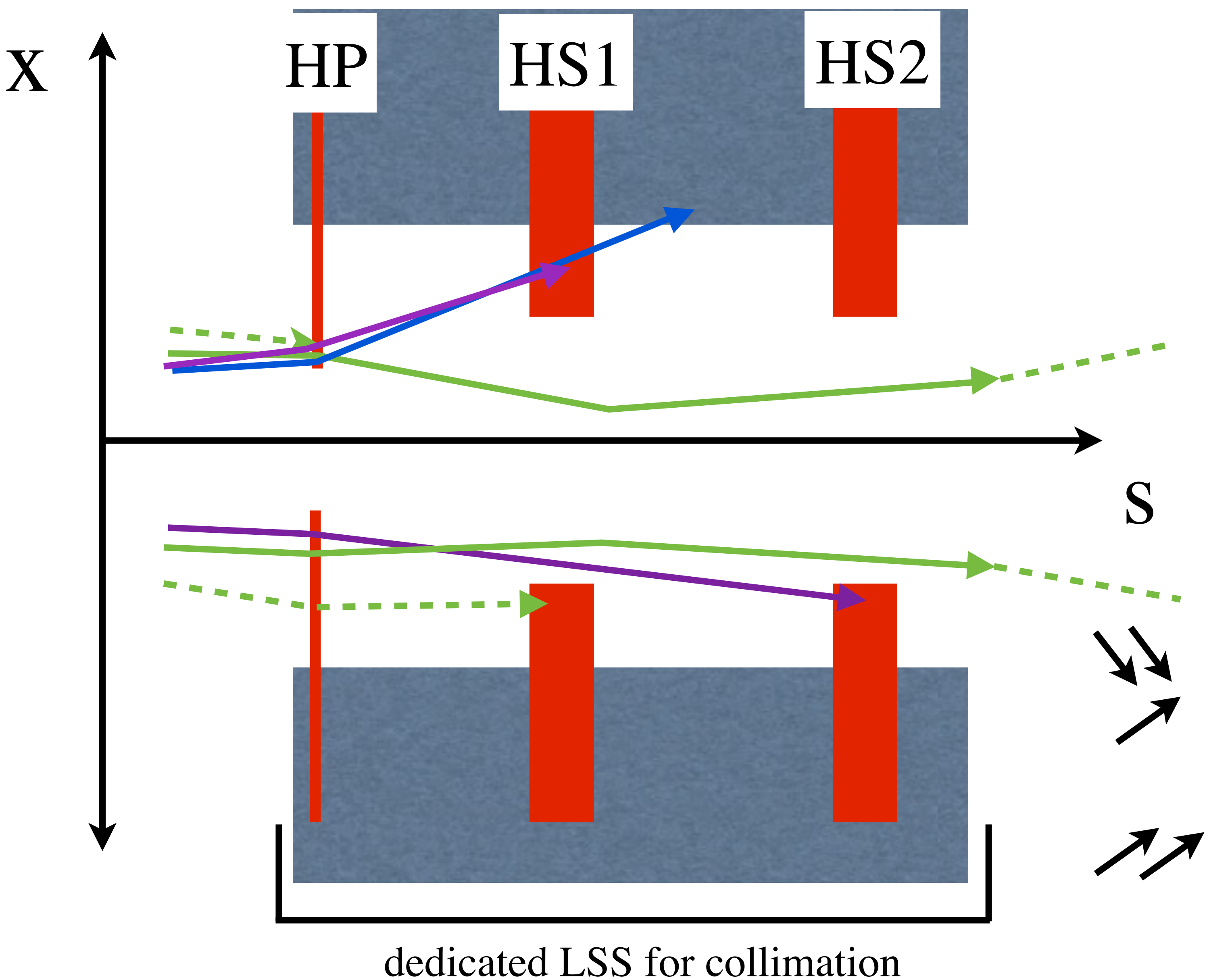

aperture (magnetic elements, monitors etc)

Primary collimator (scatterer)

Secondary collimator (absorber)

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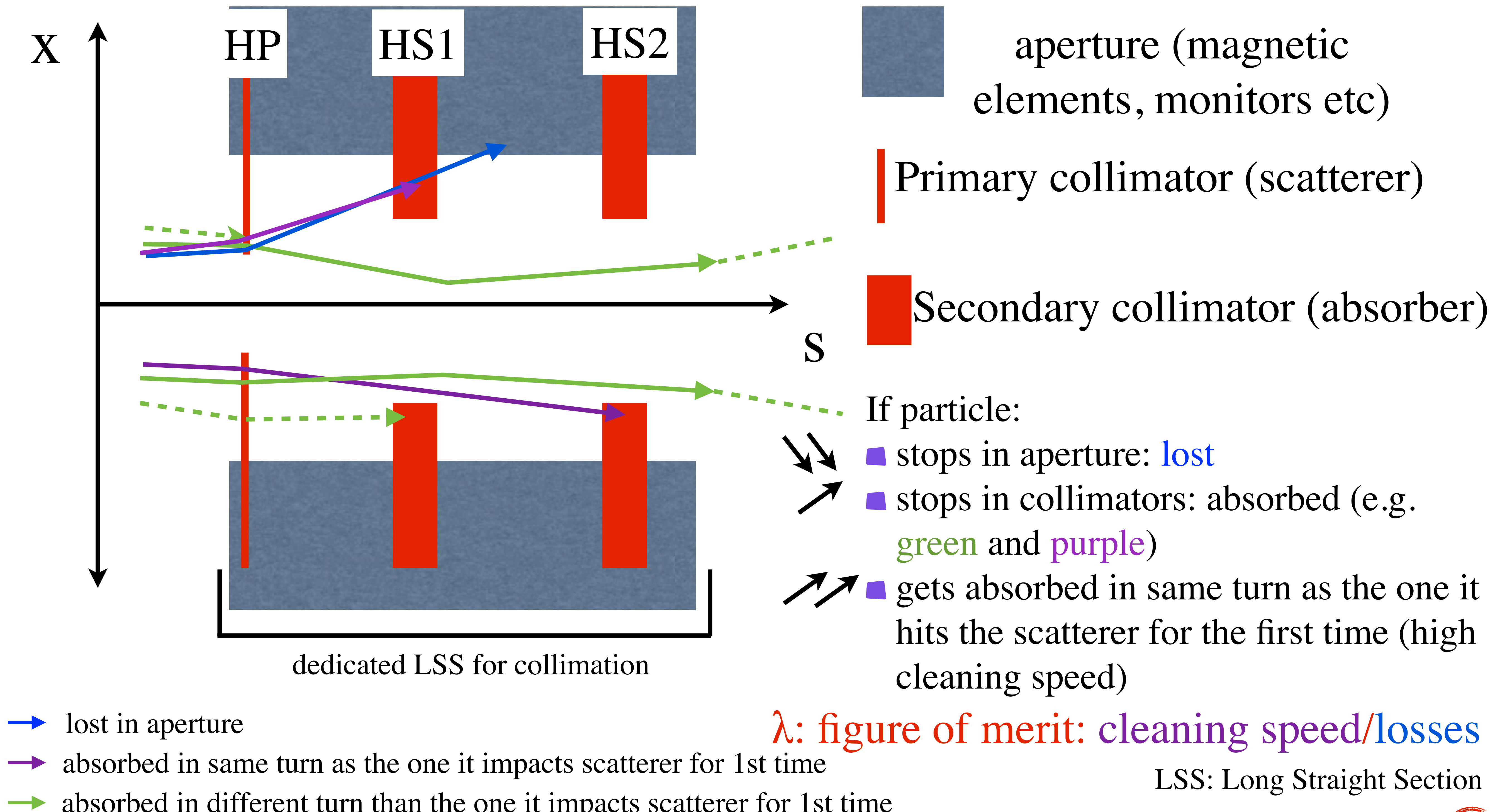

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λ: figure of merit: cleaning speed/losses

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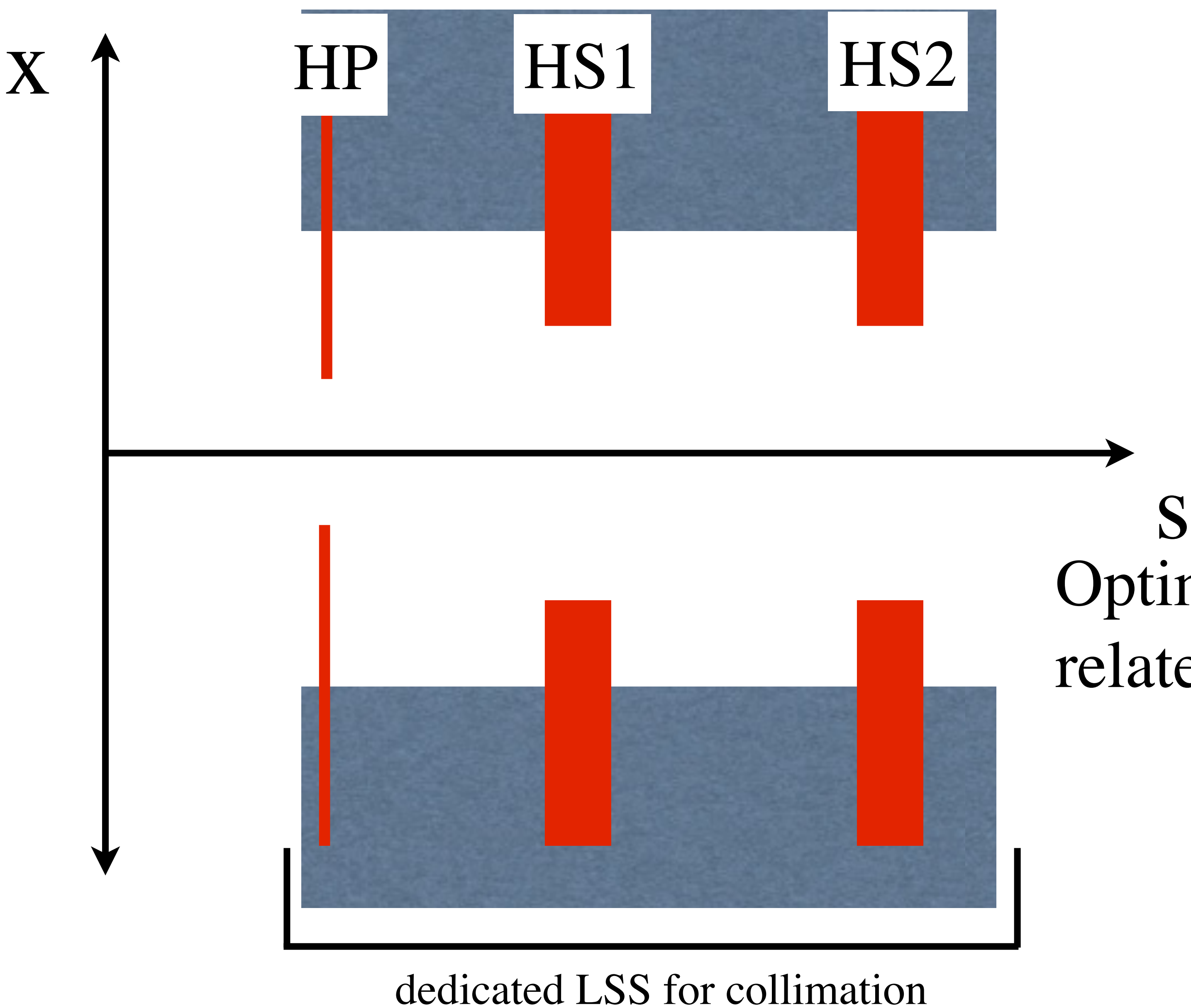
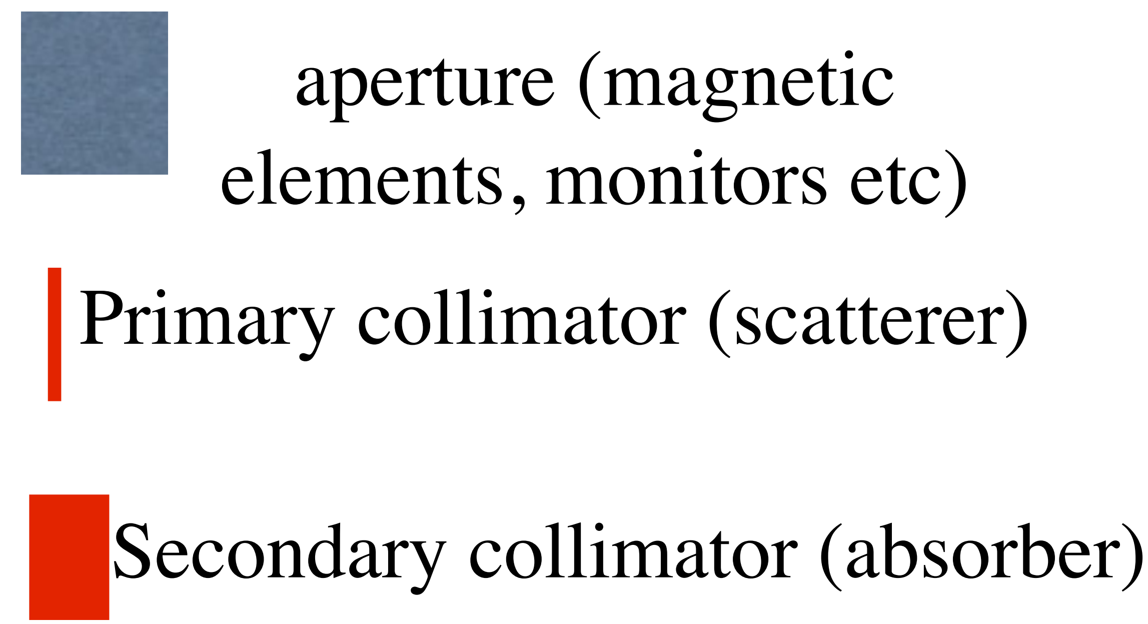
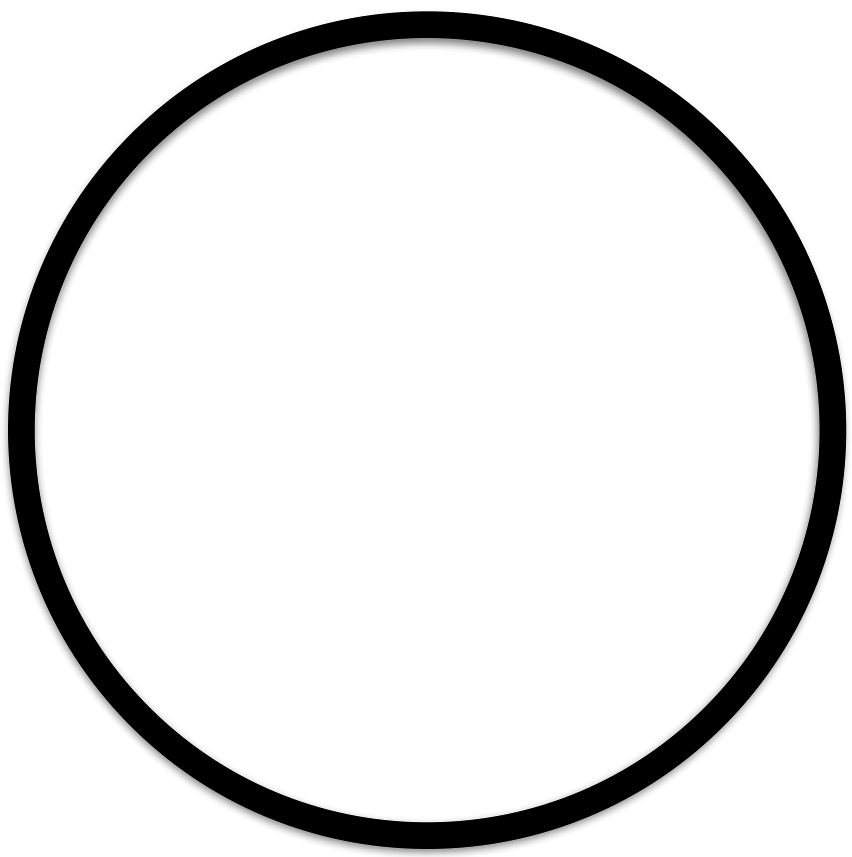




Optimum s-positioning is related to phase advance:

LSS: Long Straight Section

Phase advance



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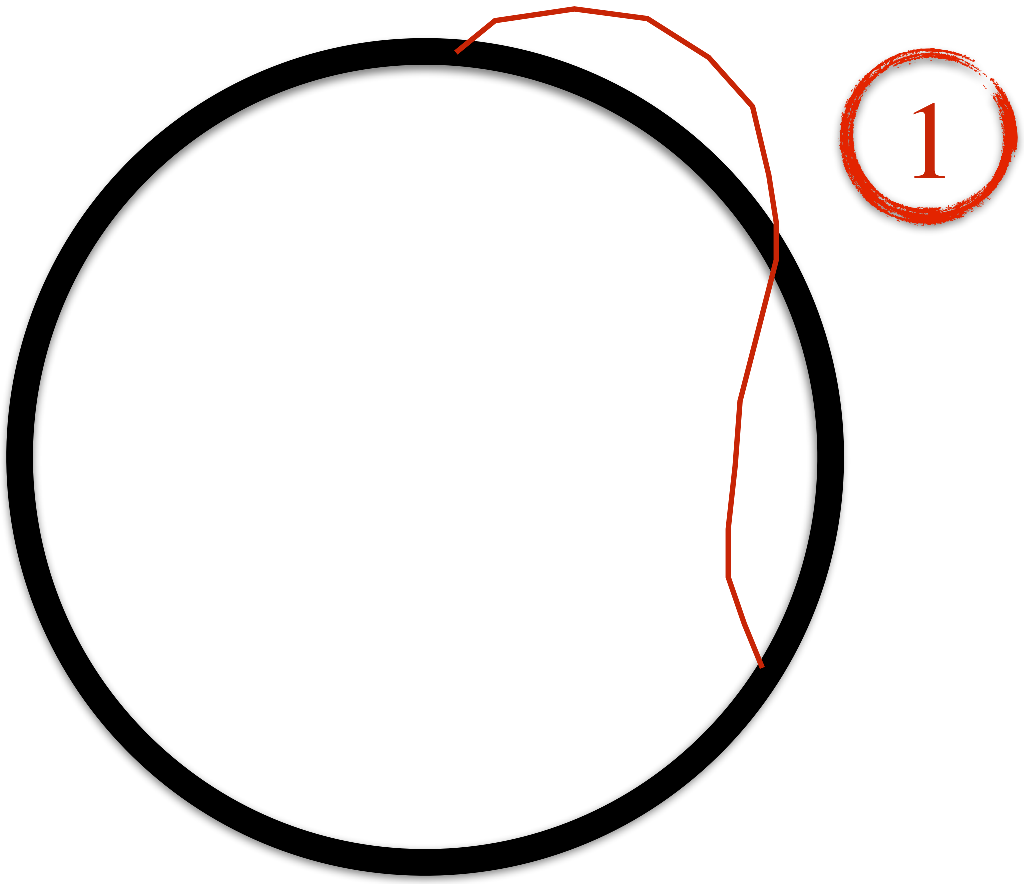

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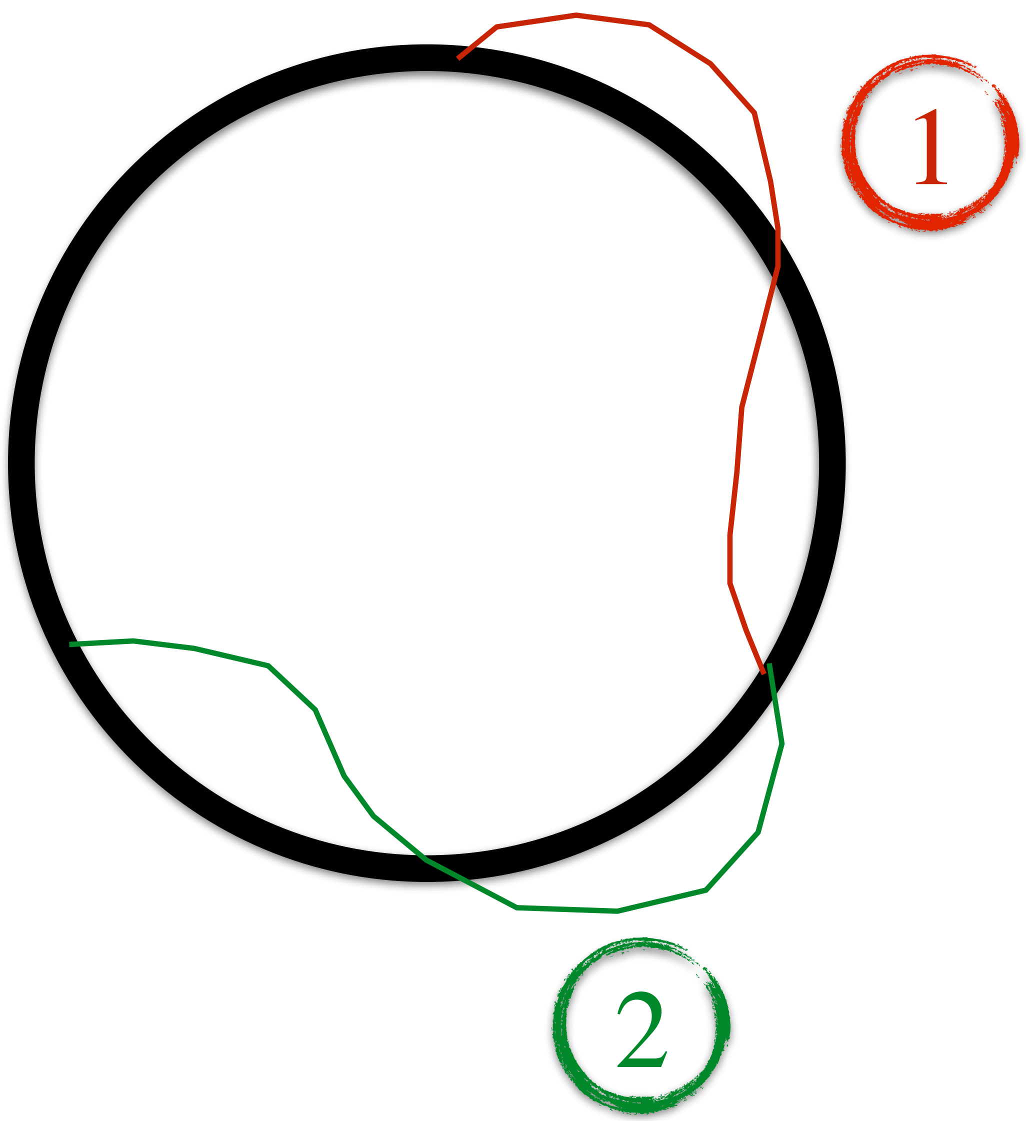

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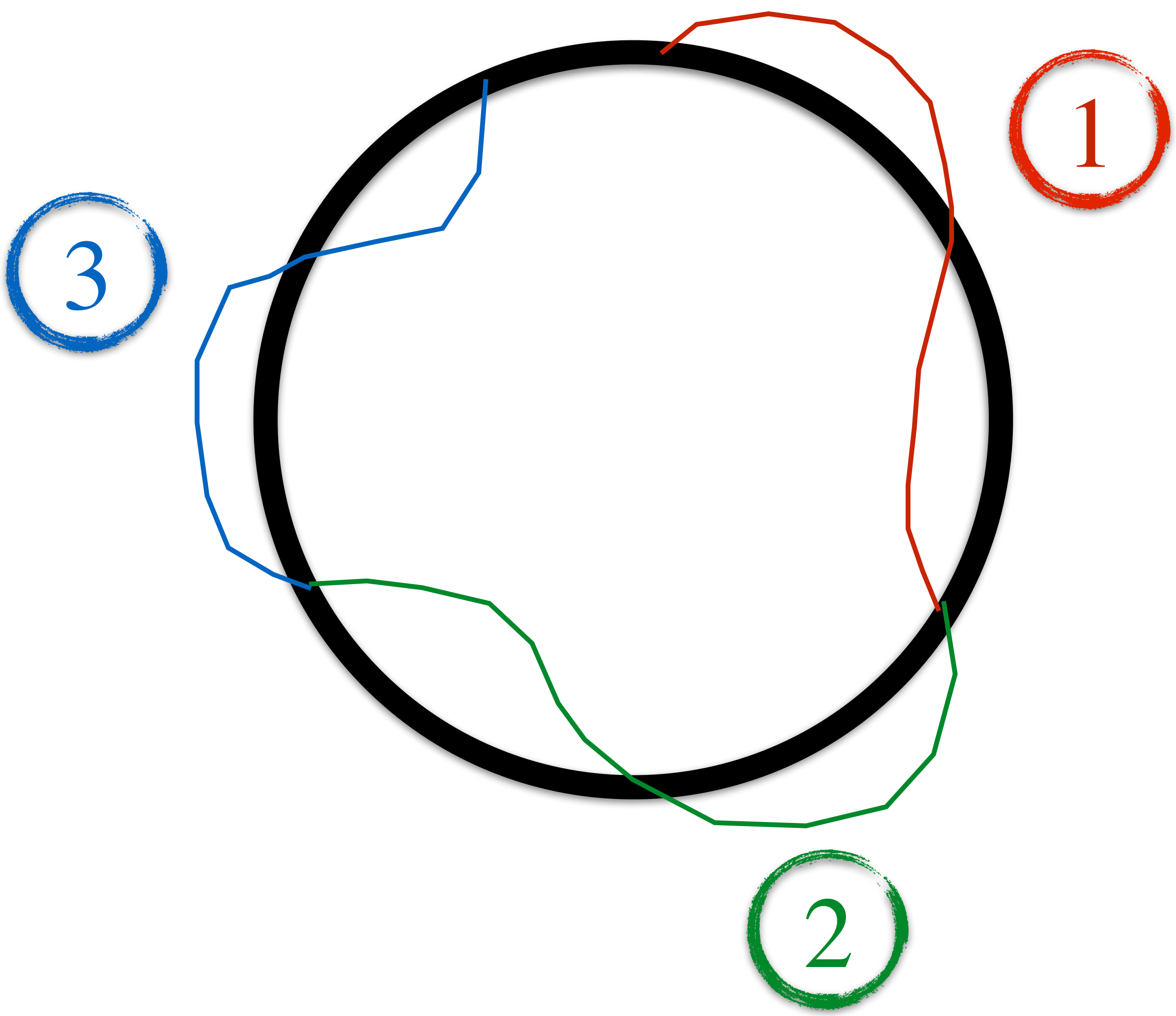

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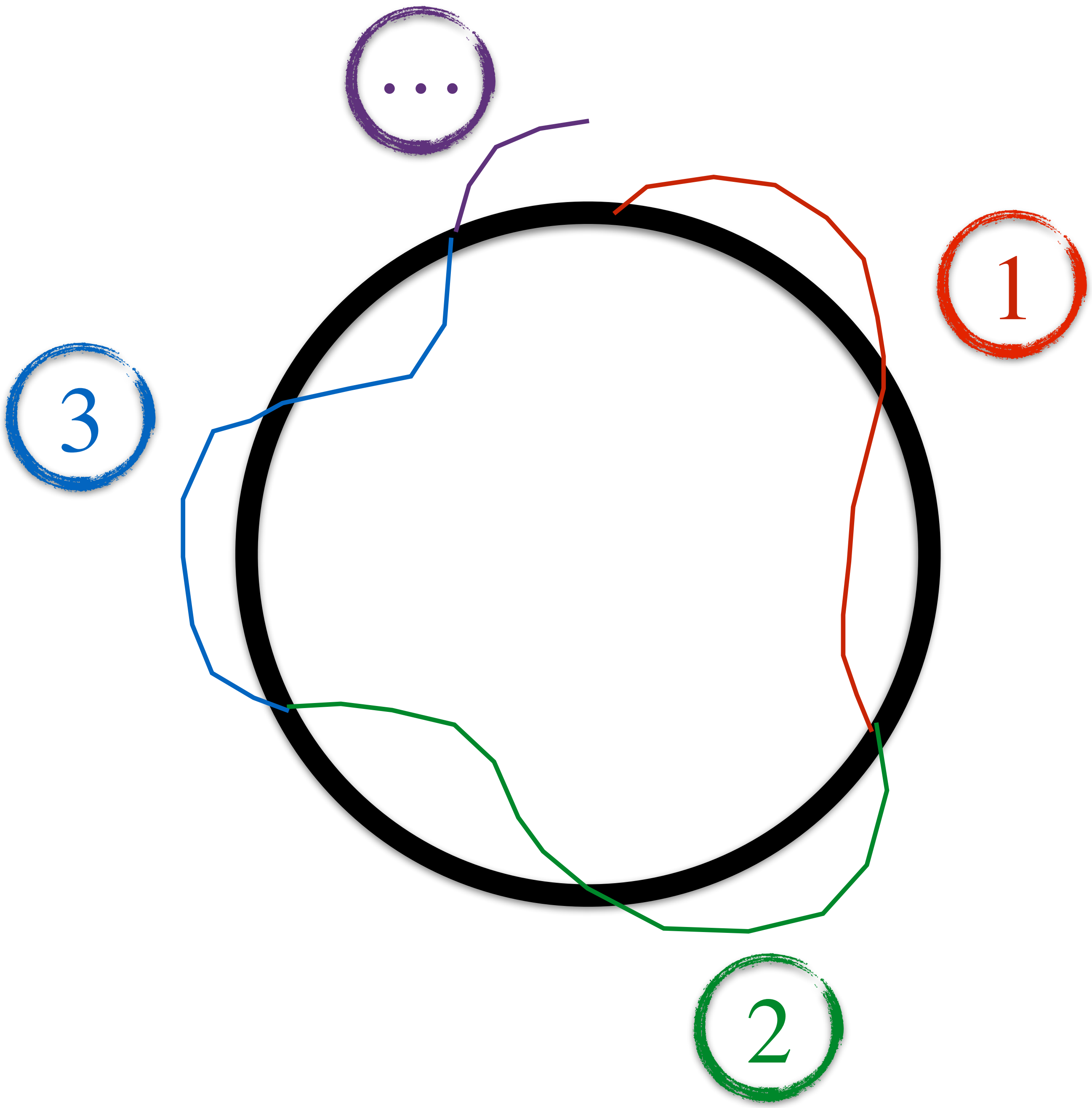

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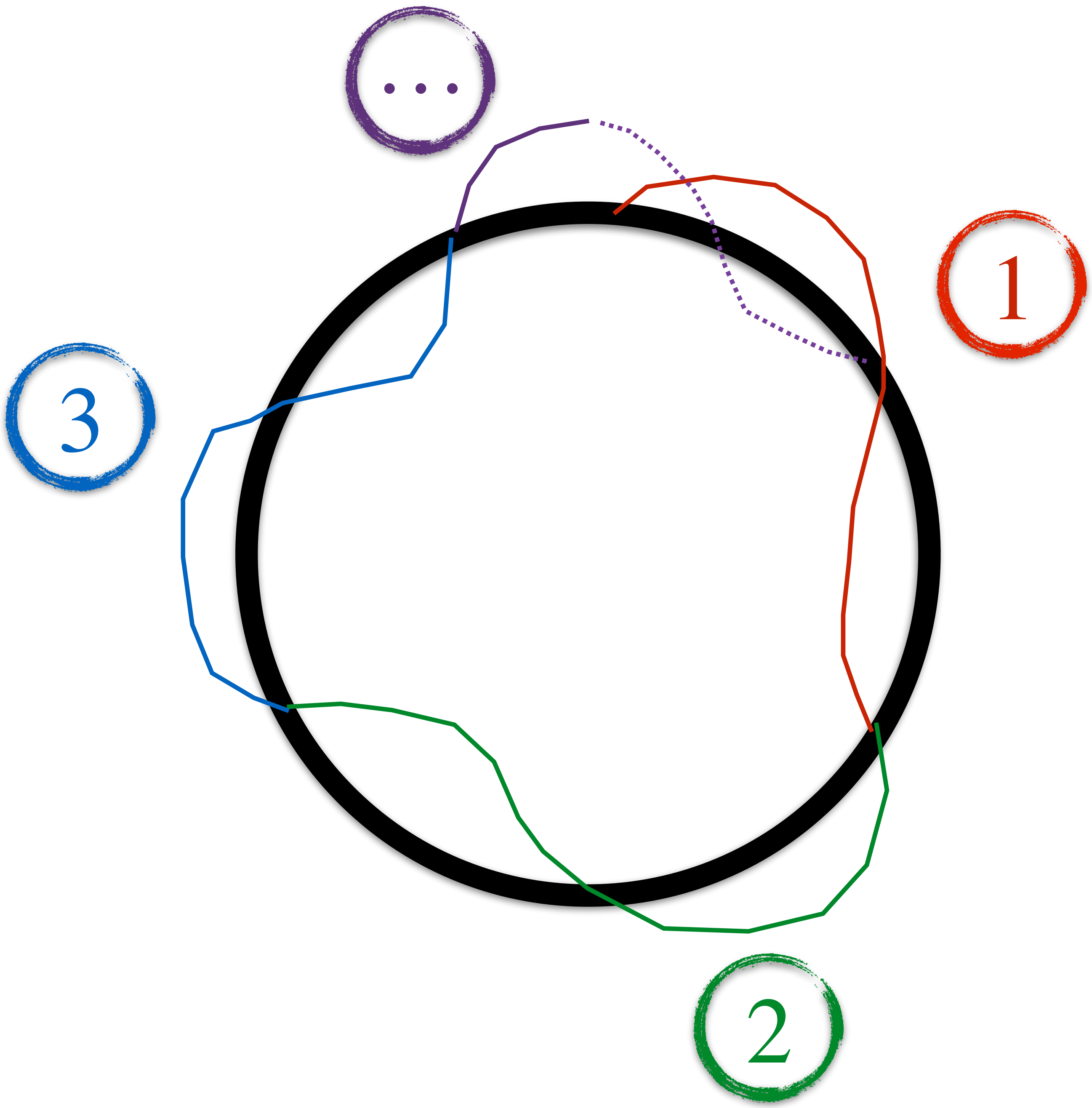

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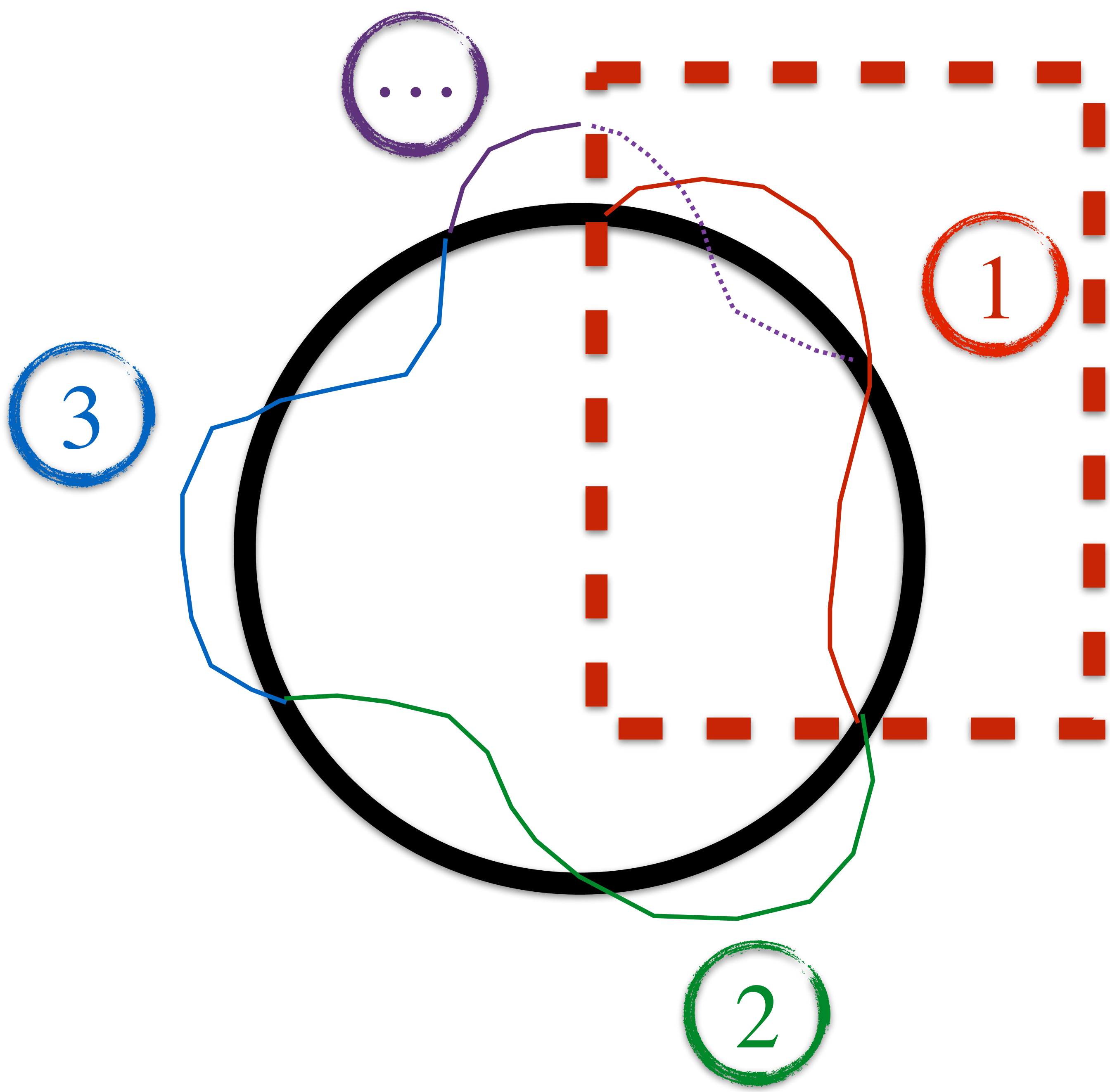

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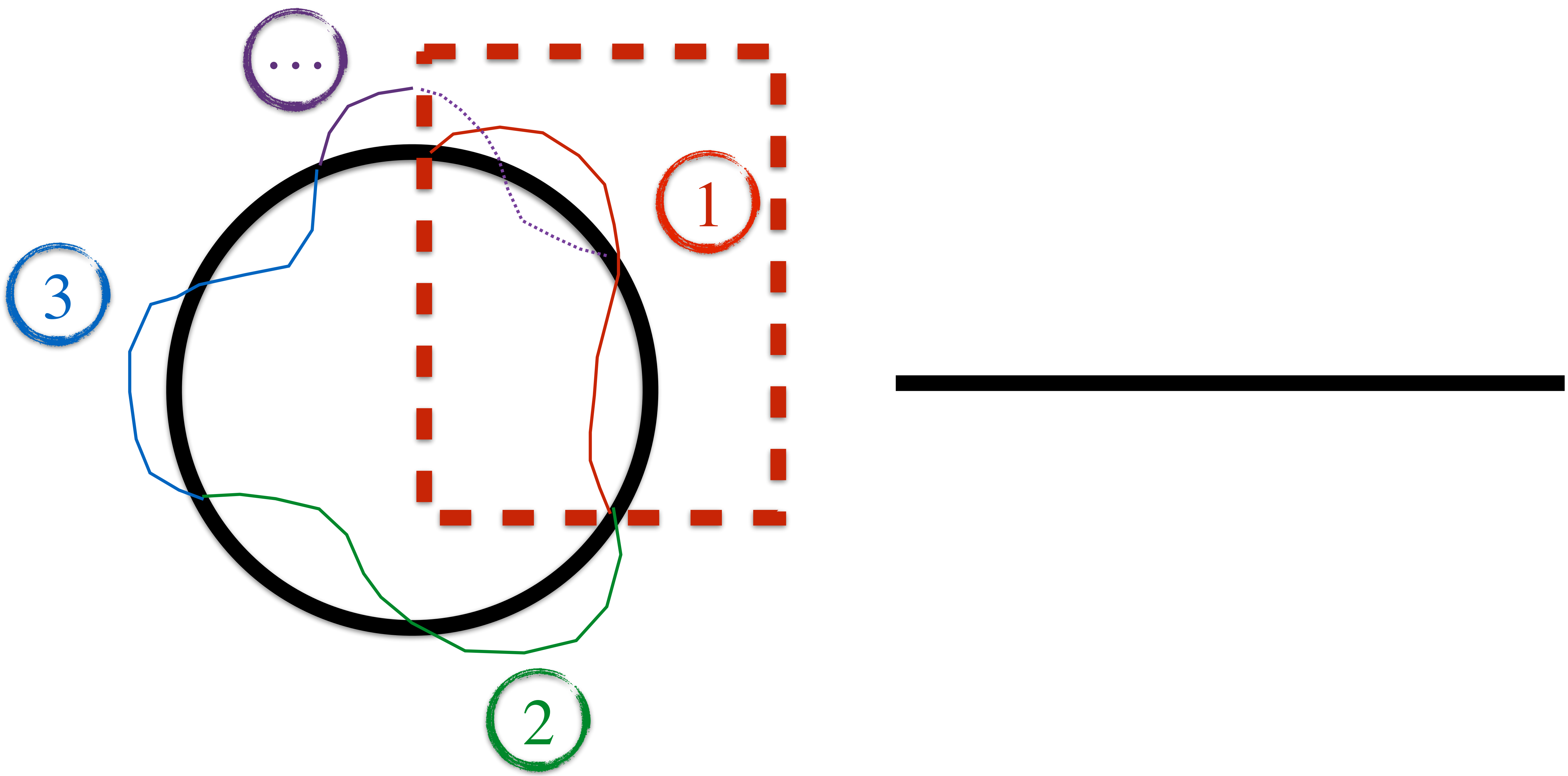

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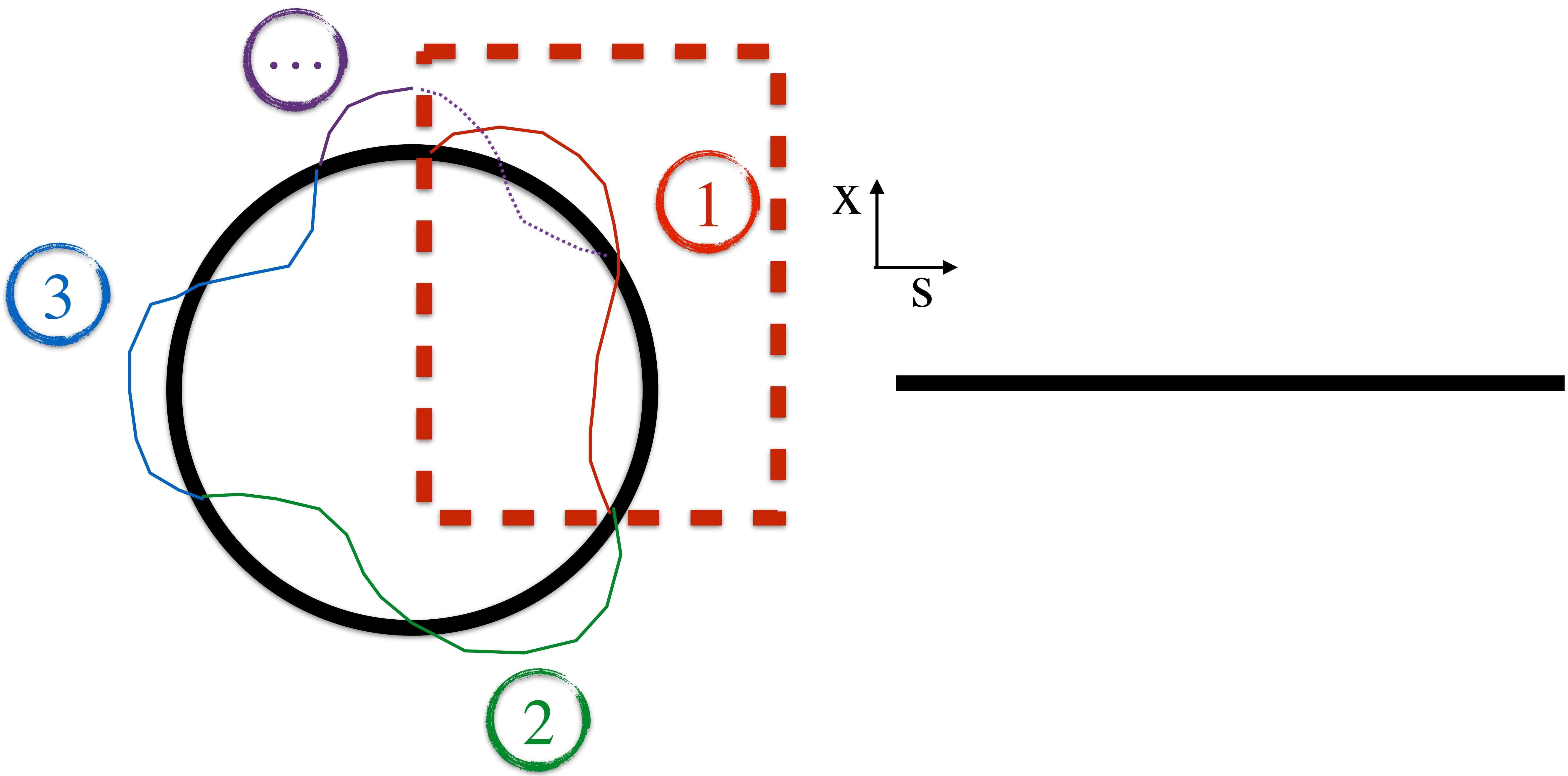

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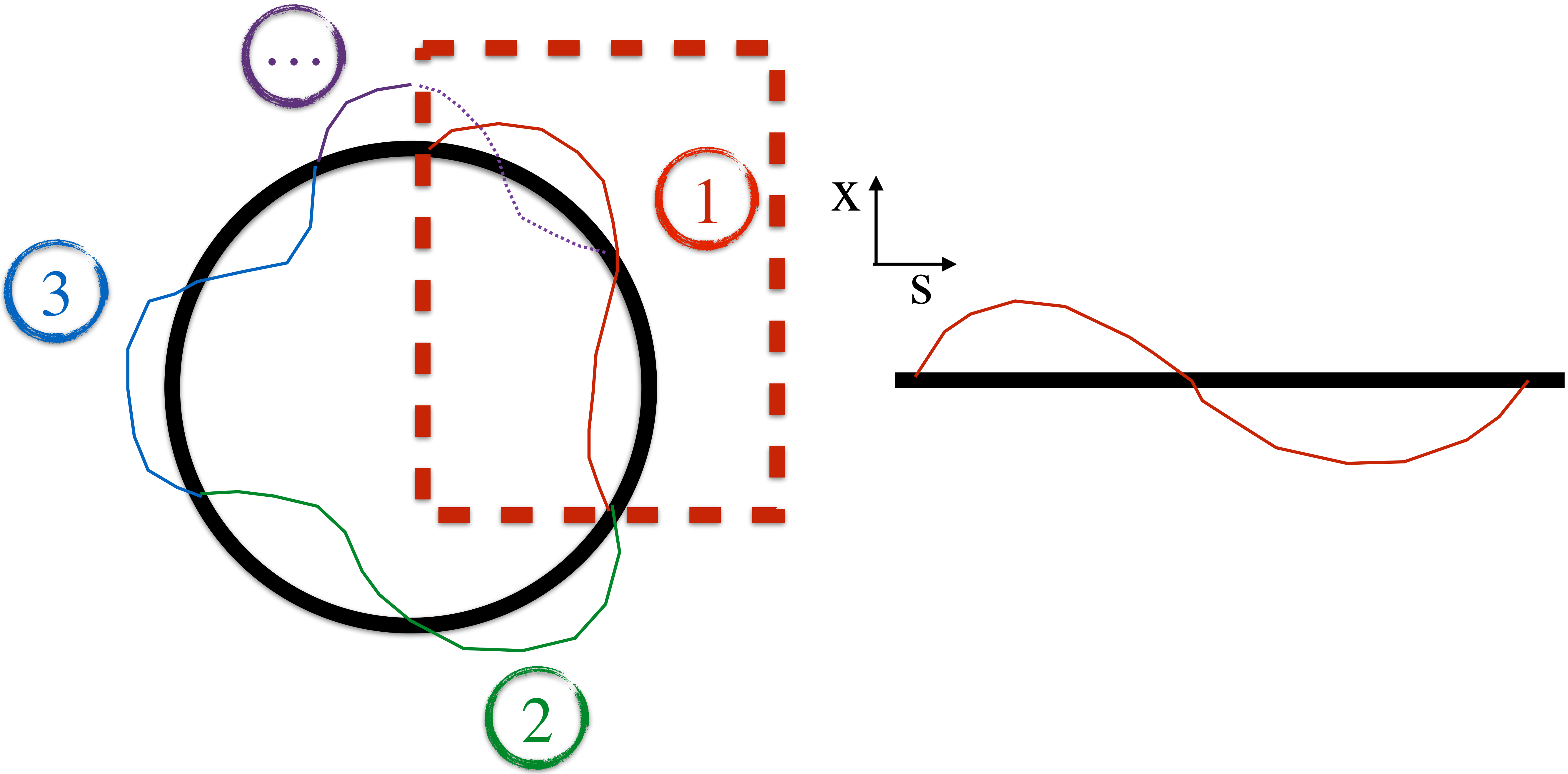

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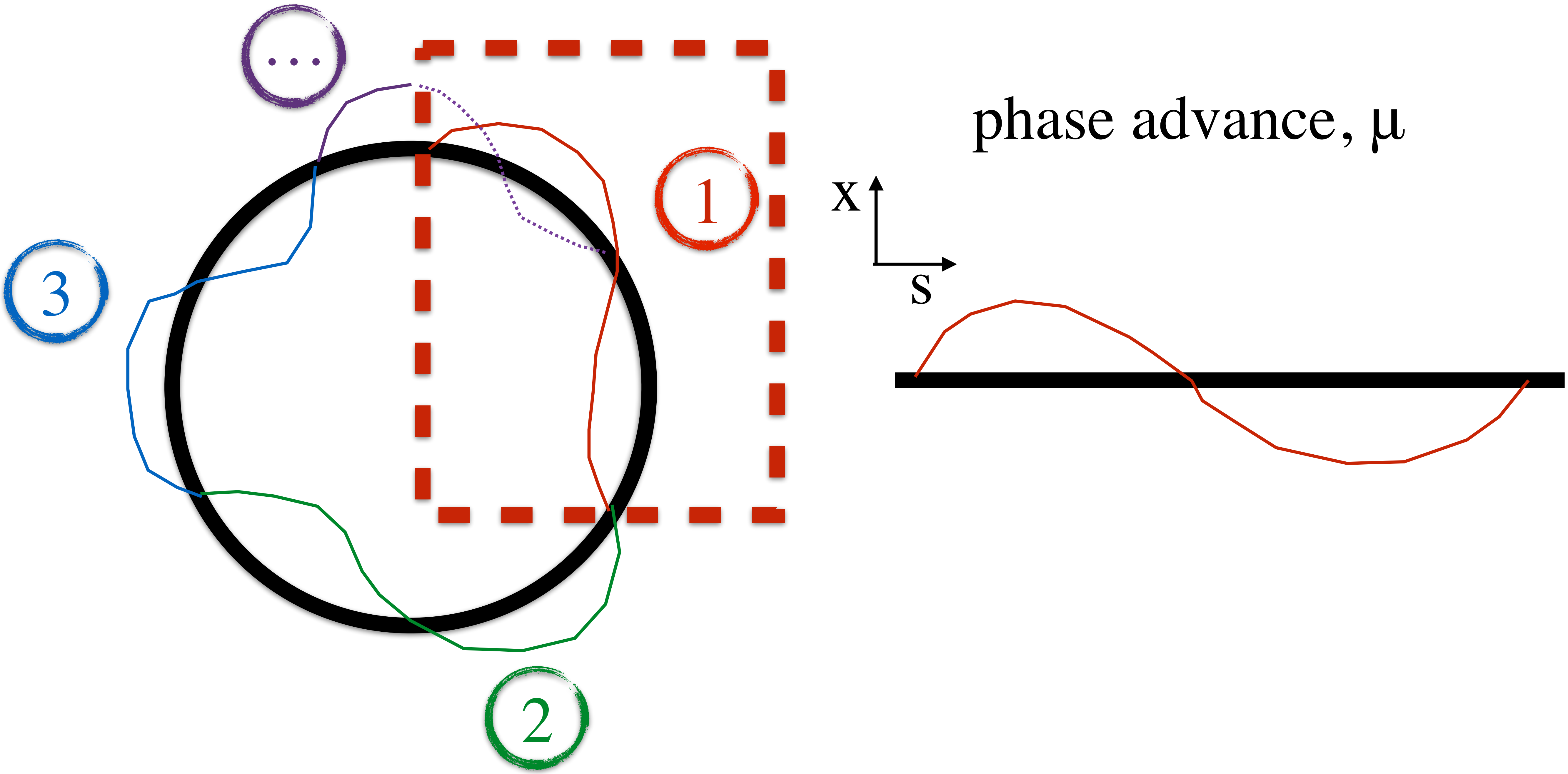

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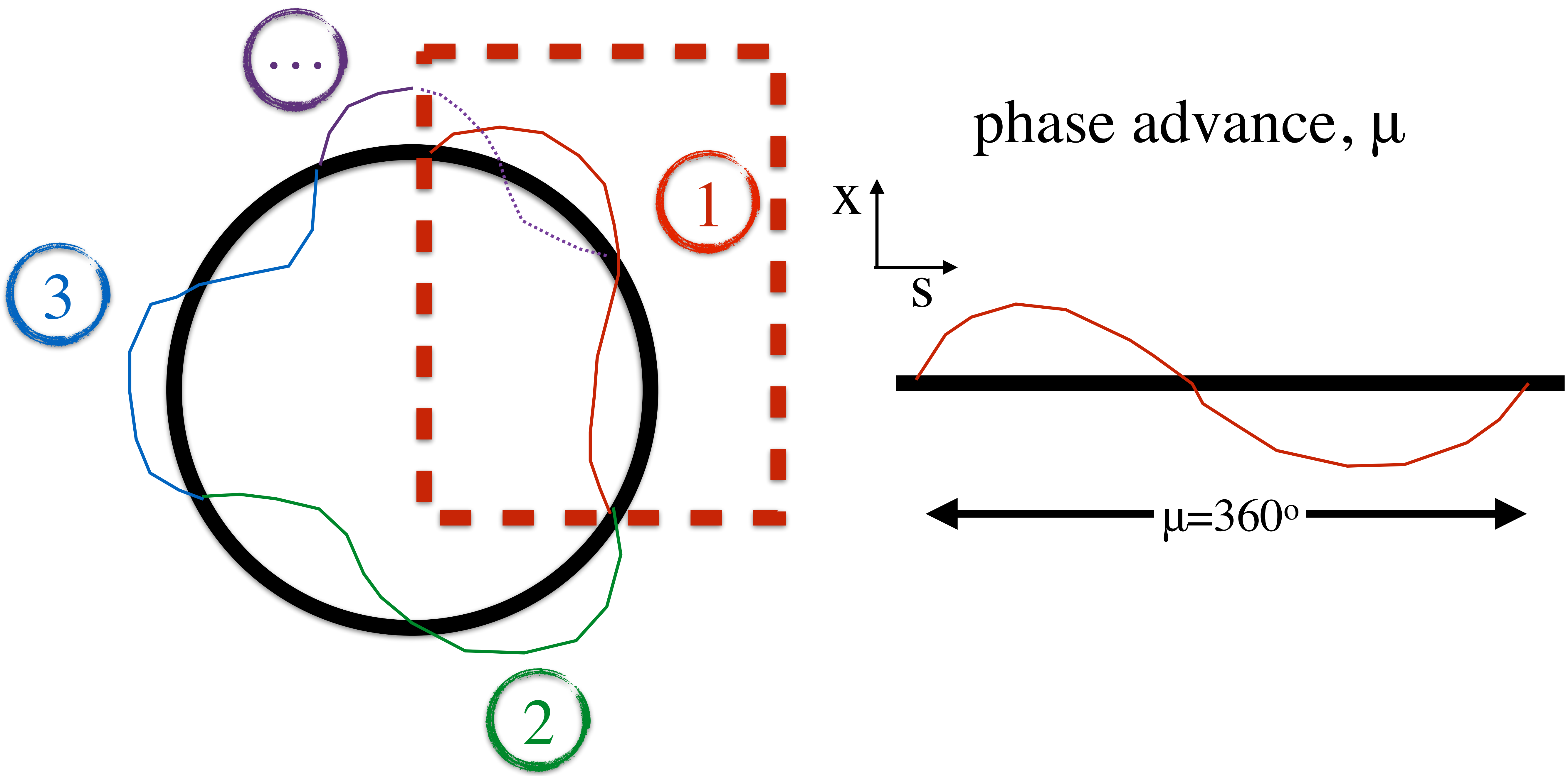

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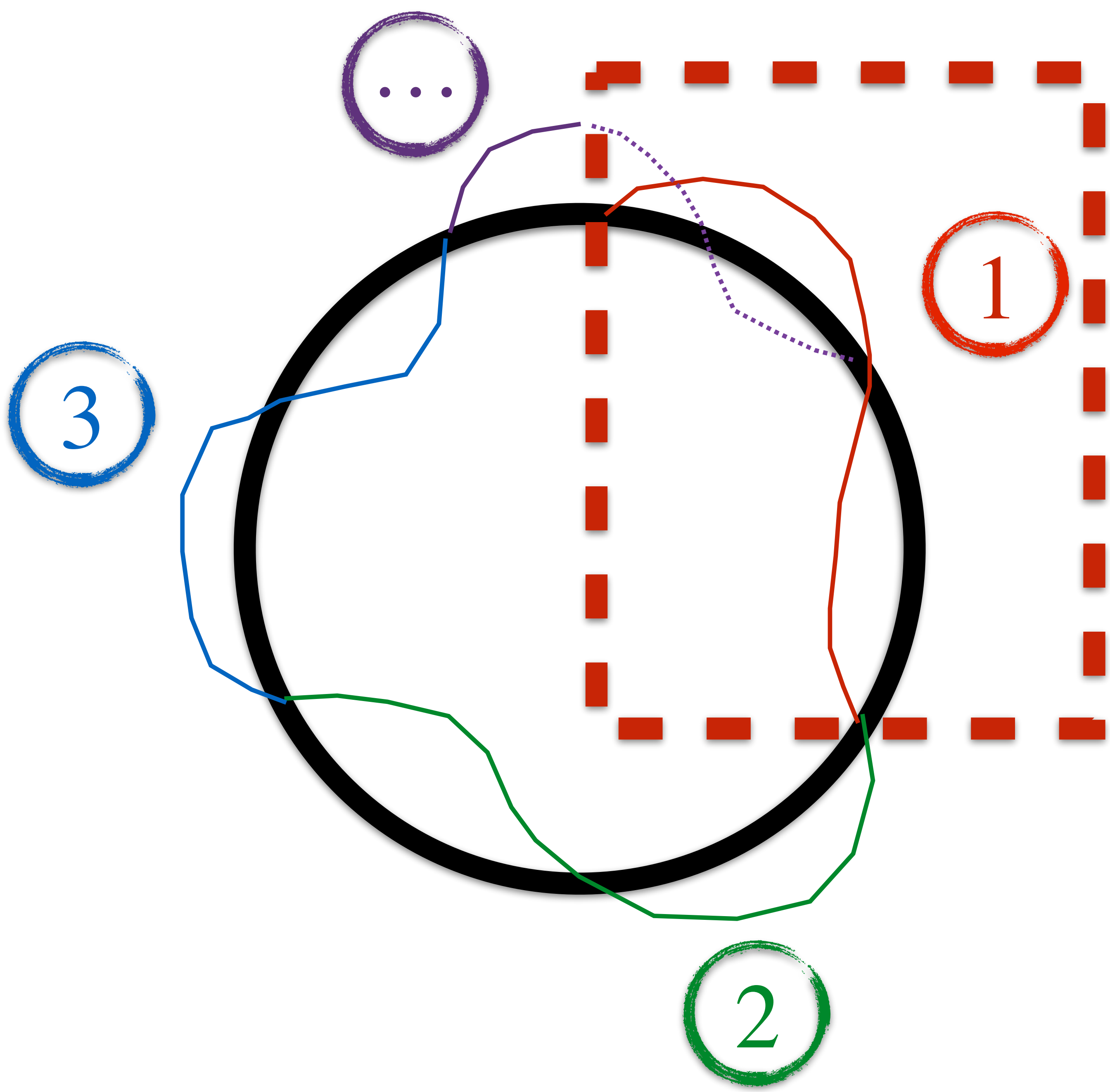
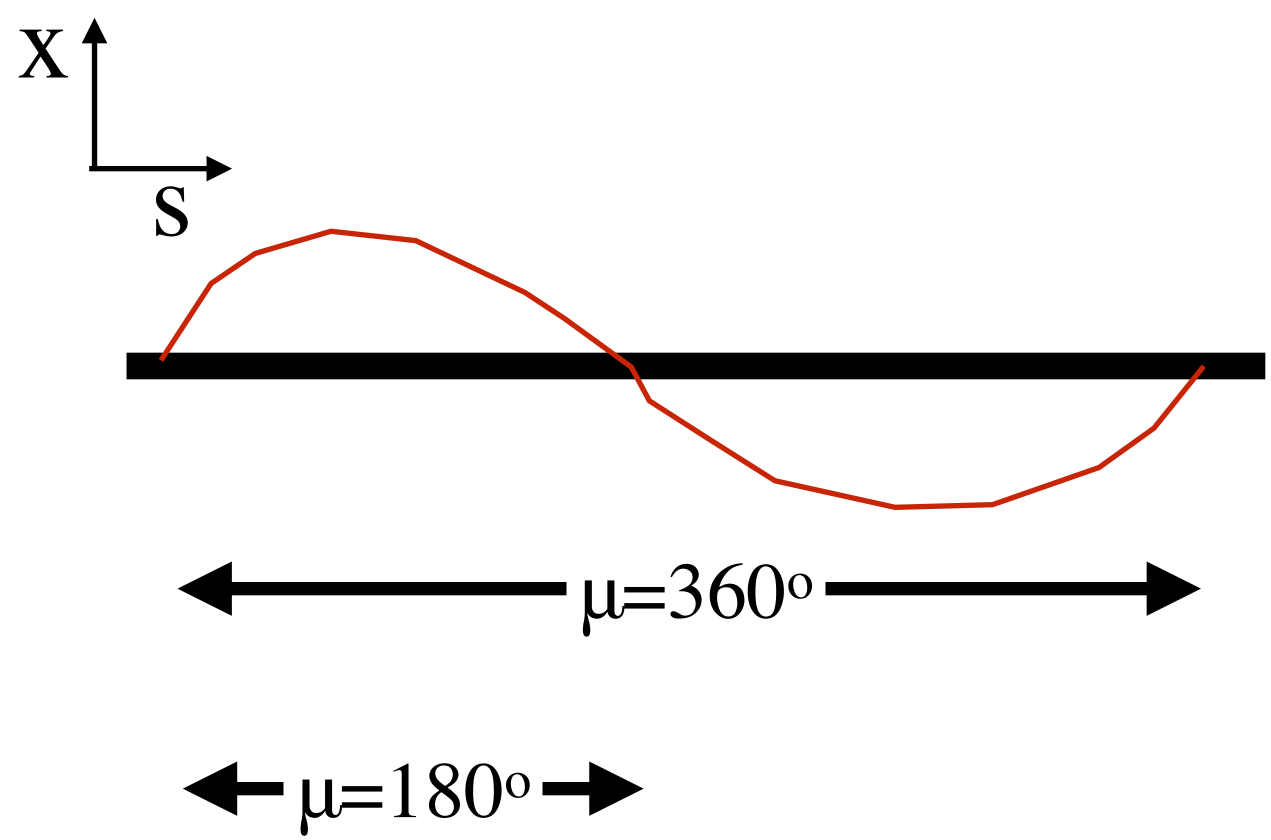


phase advance, μ



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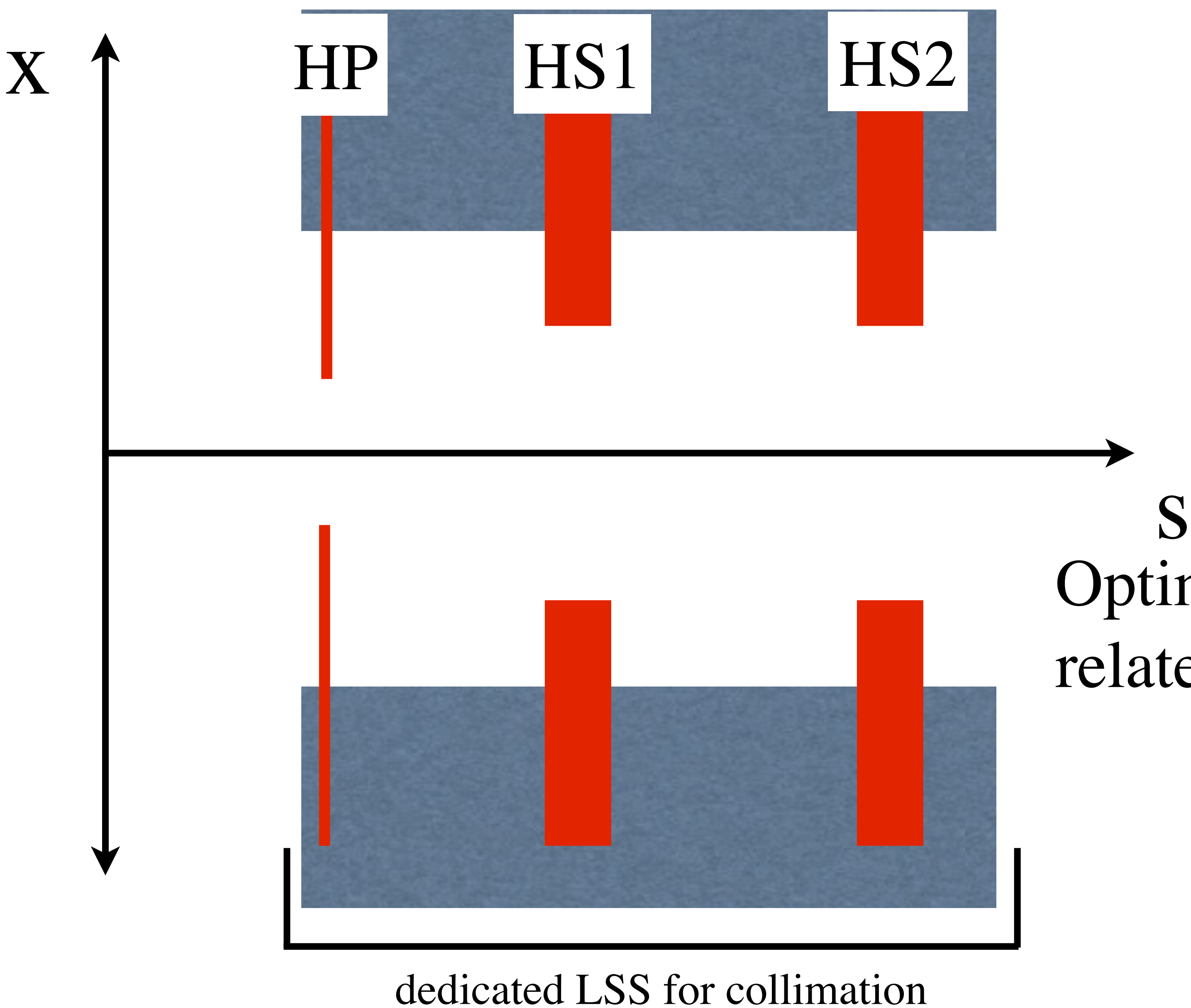

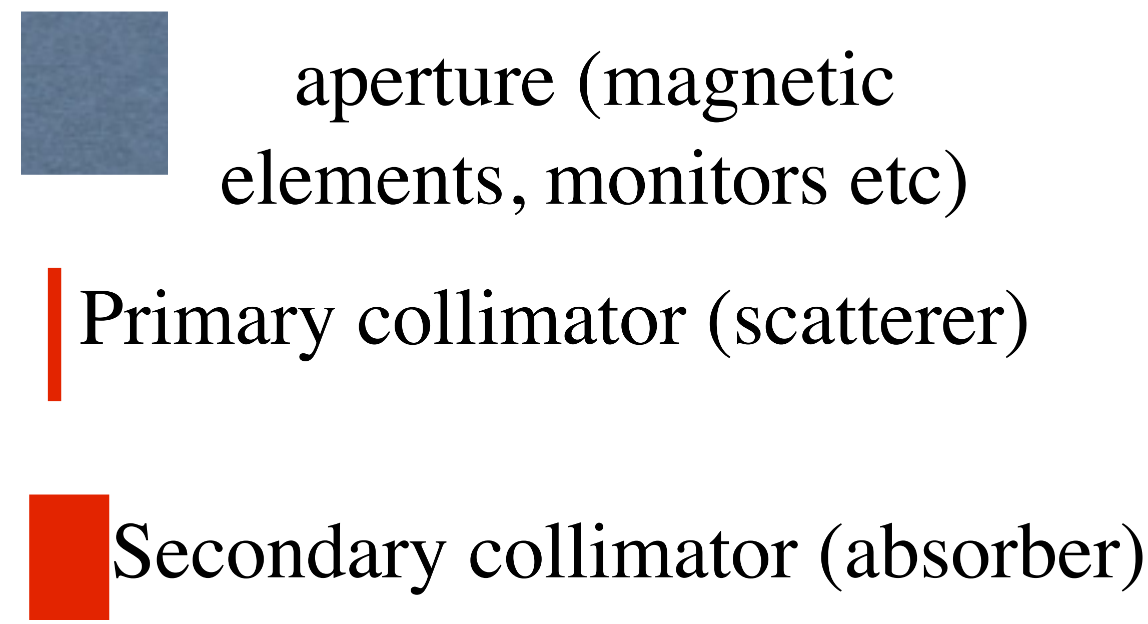

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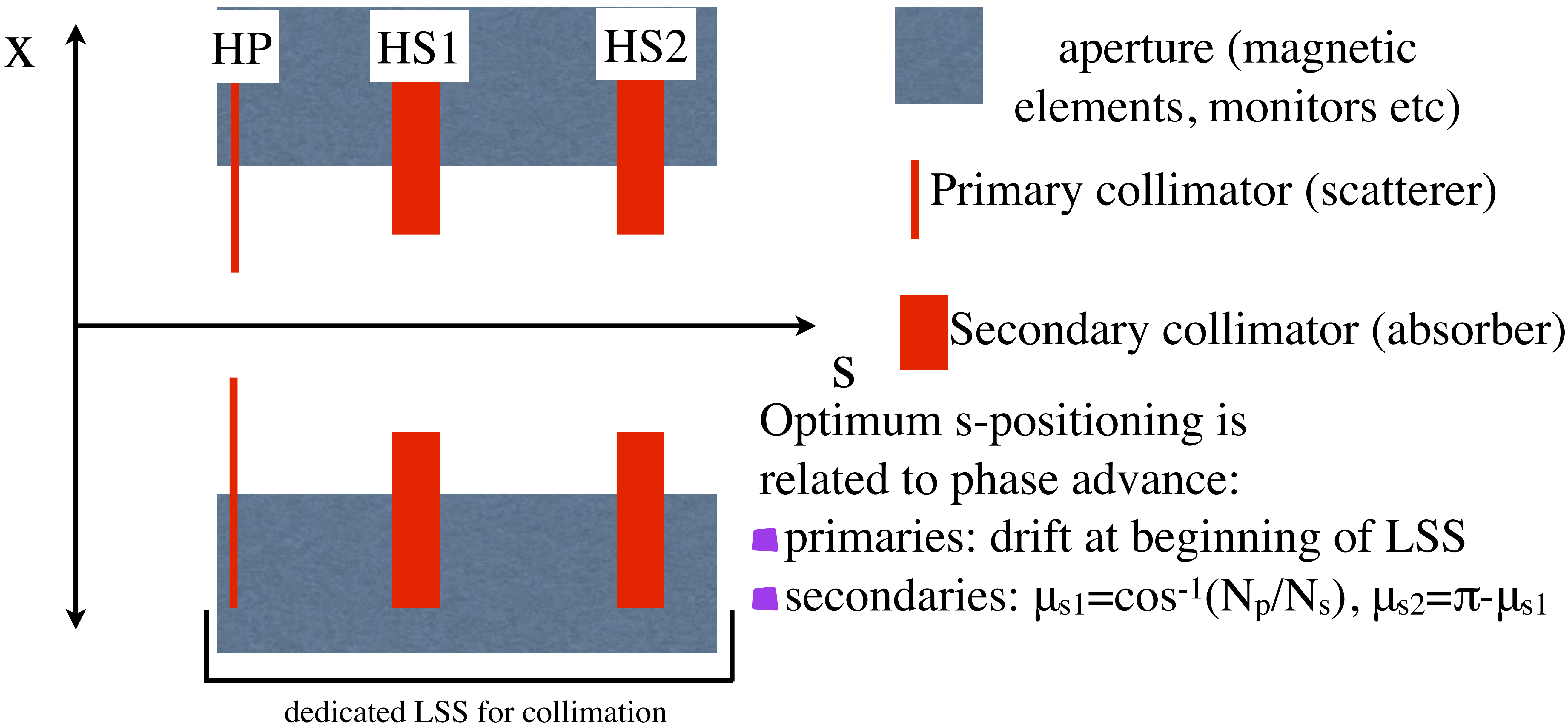

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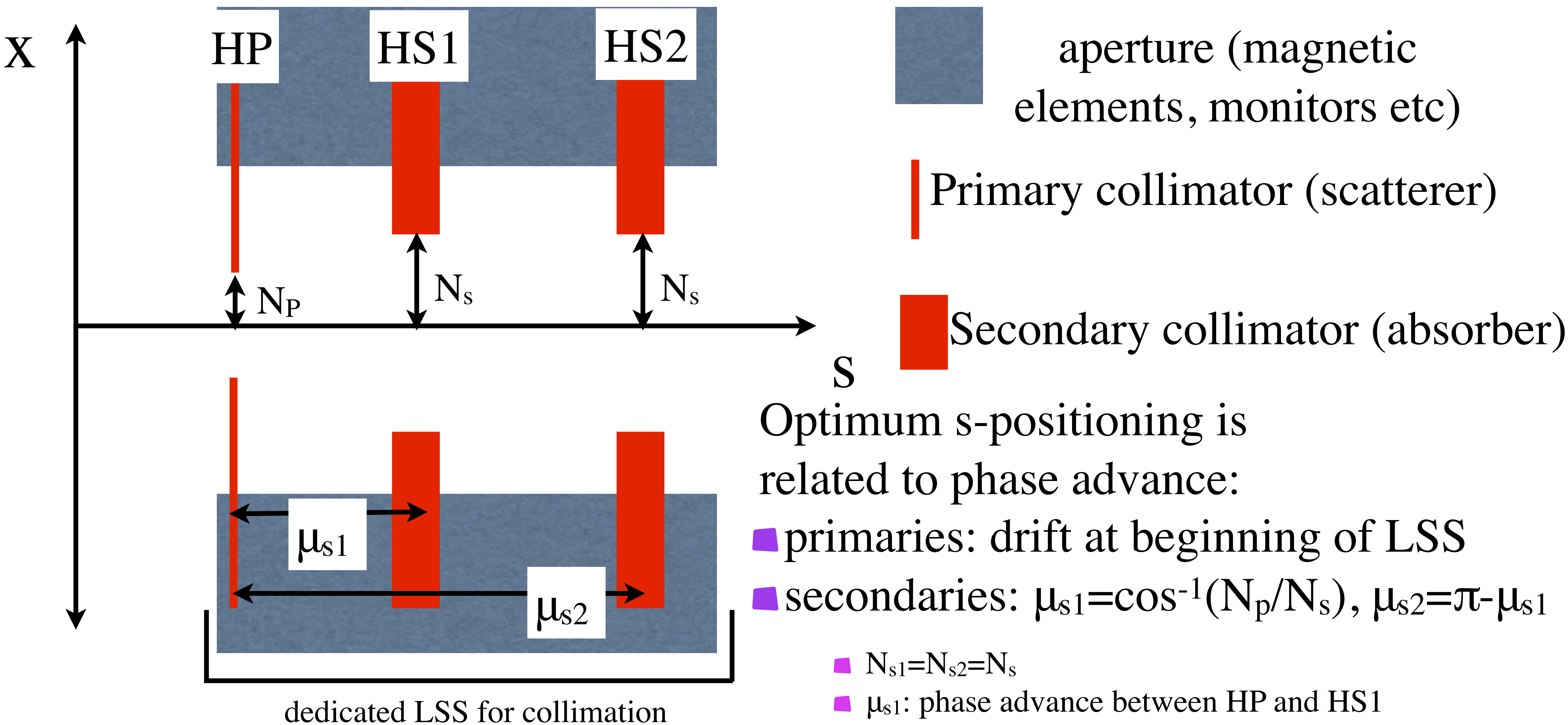

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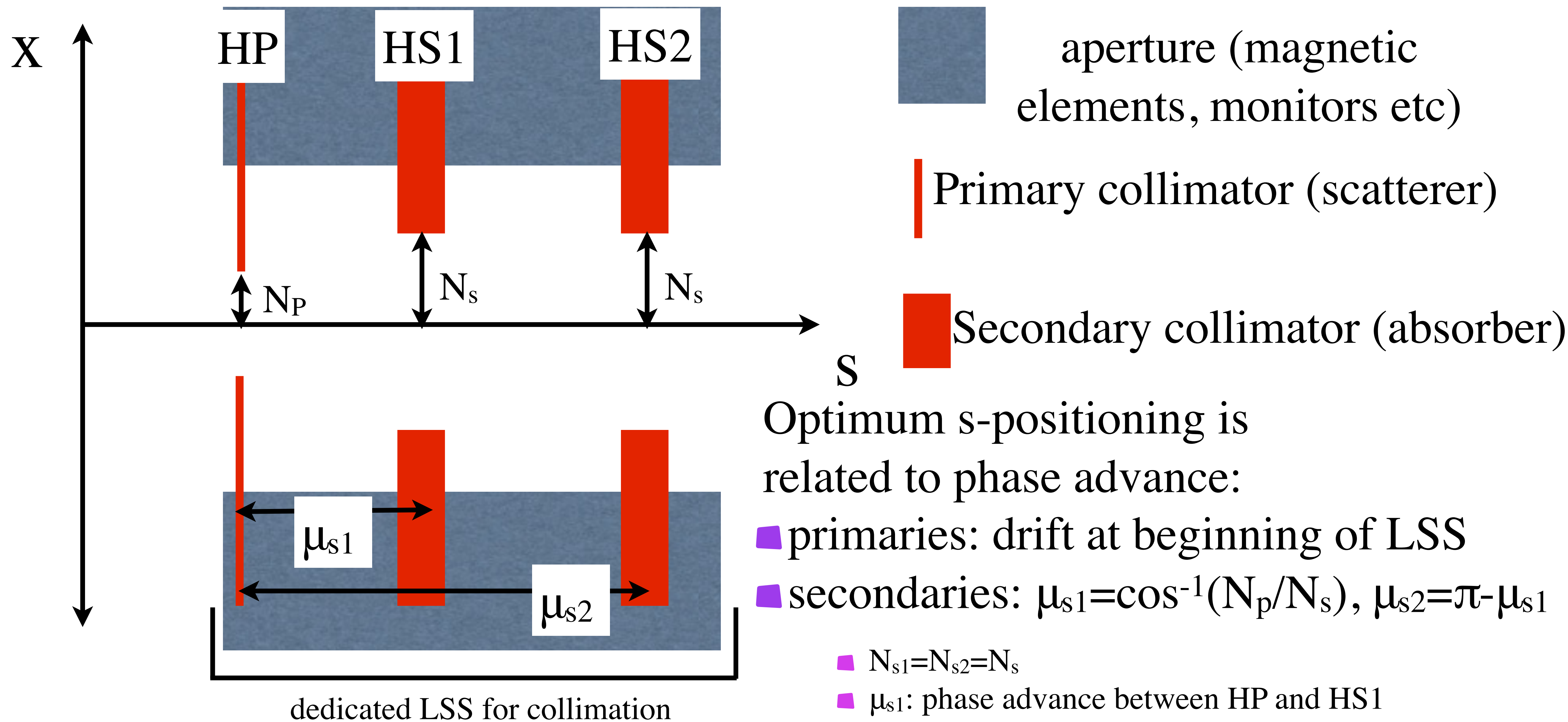

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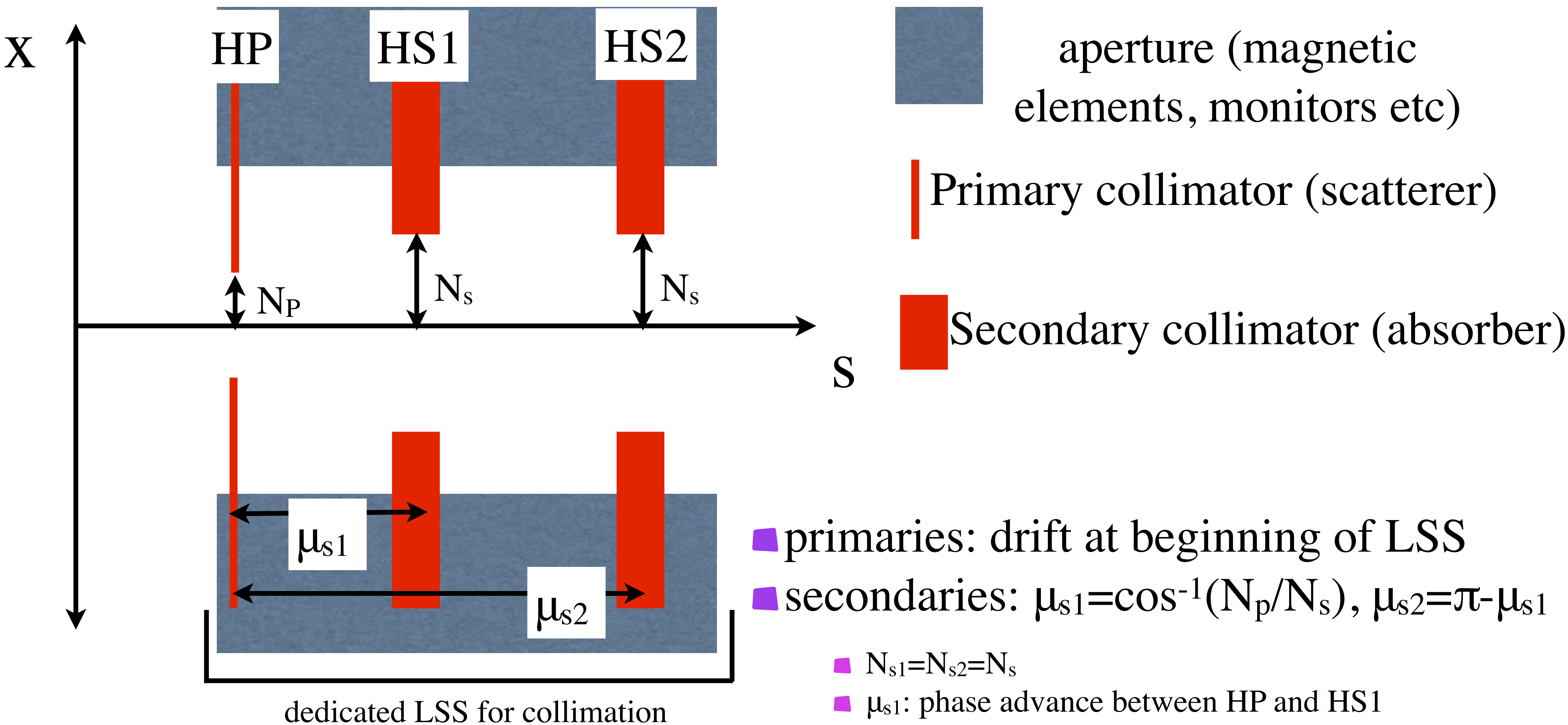

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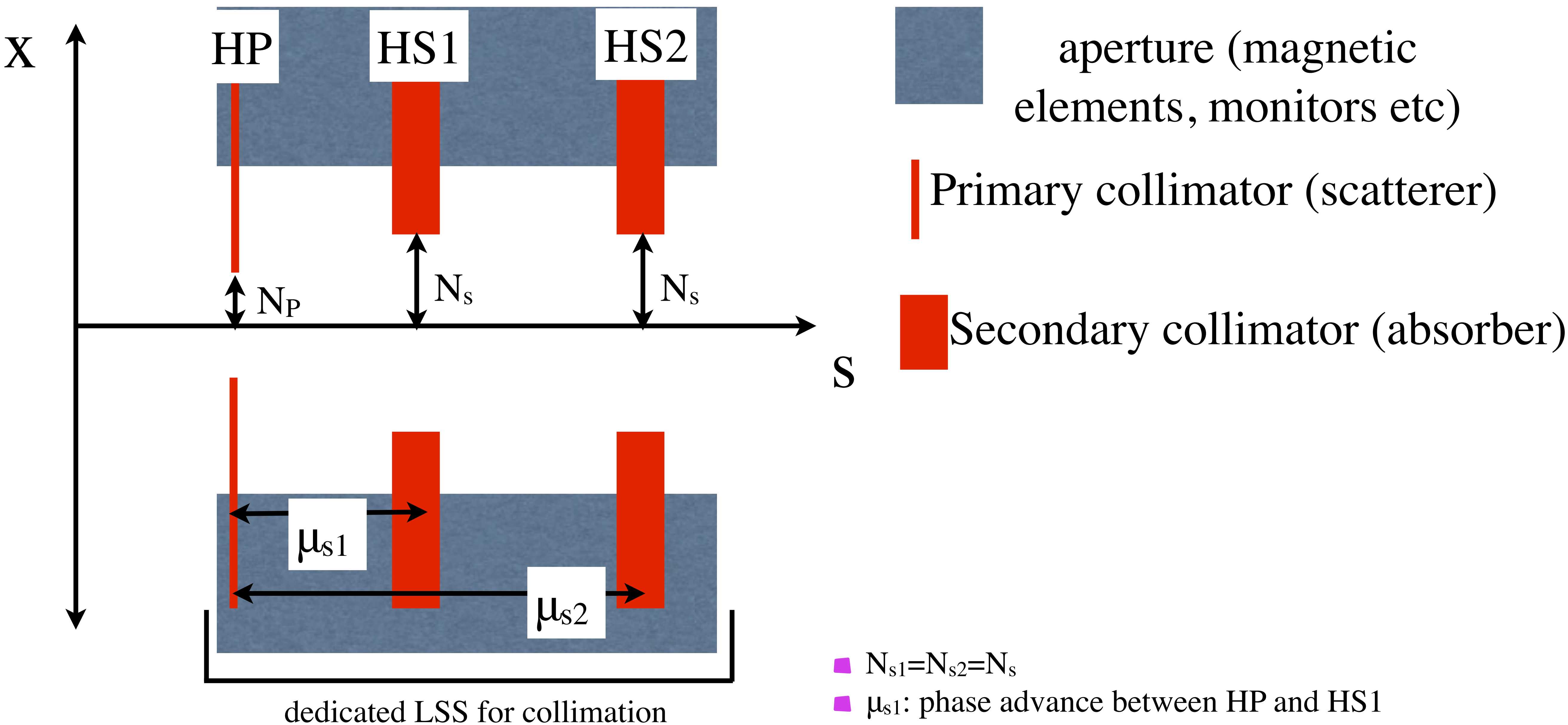

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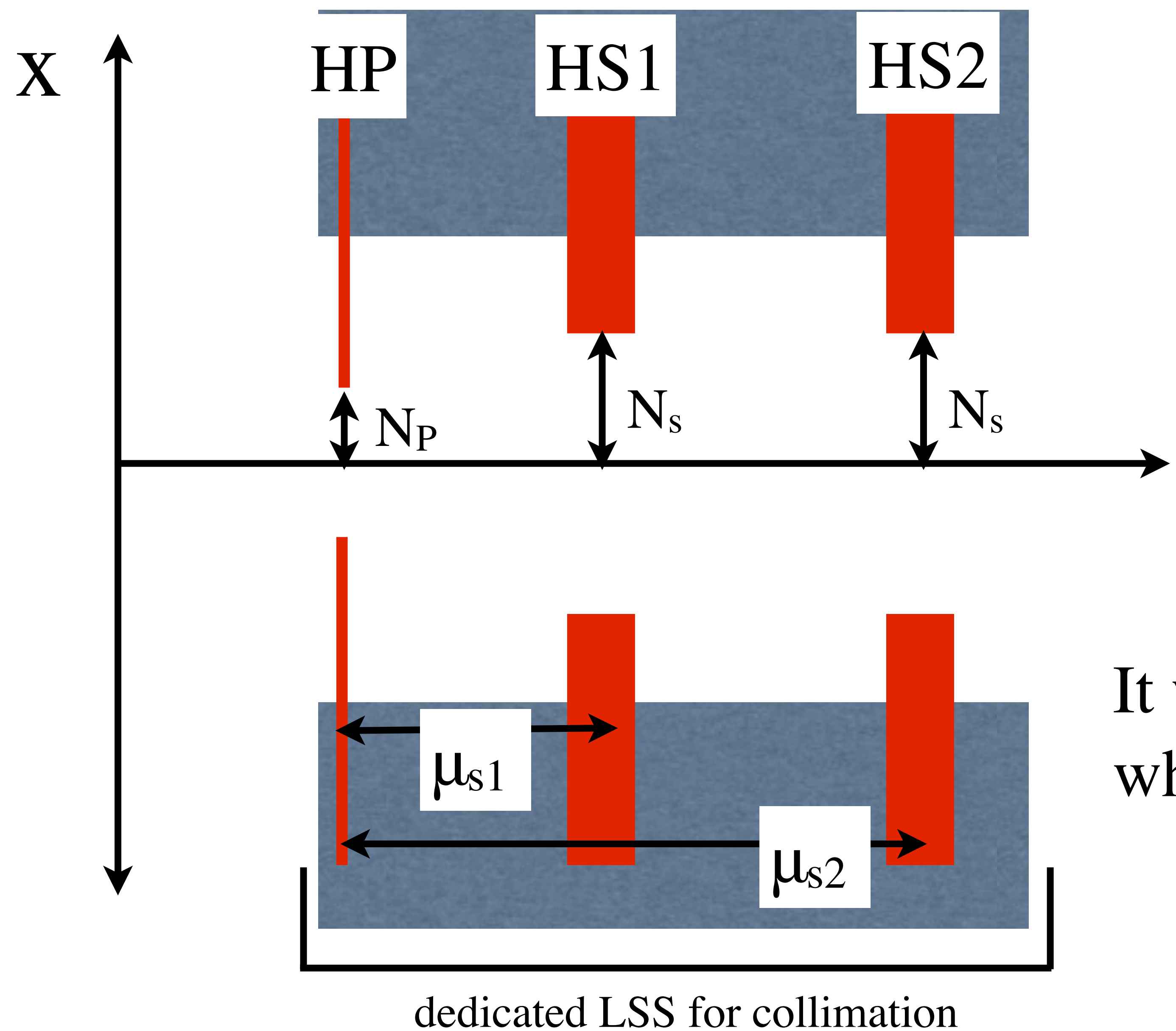

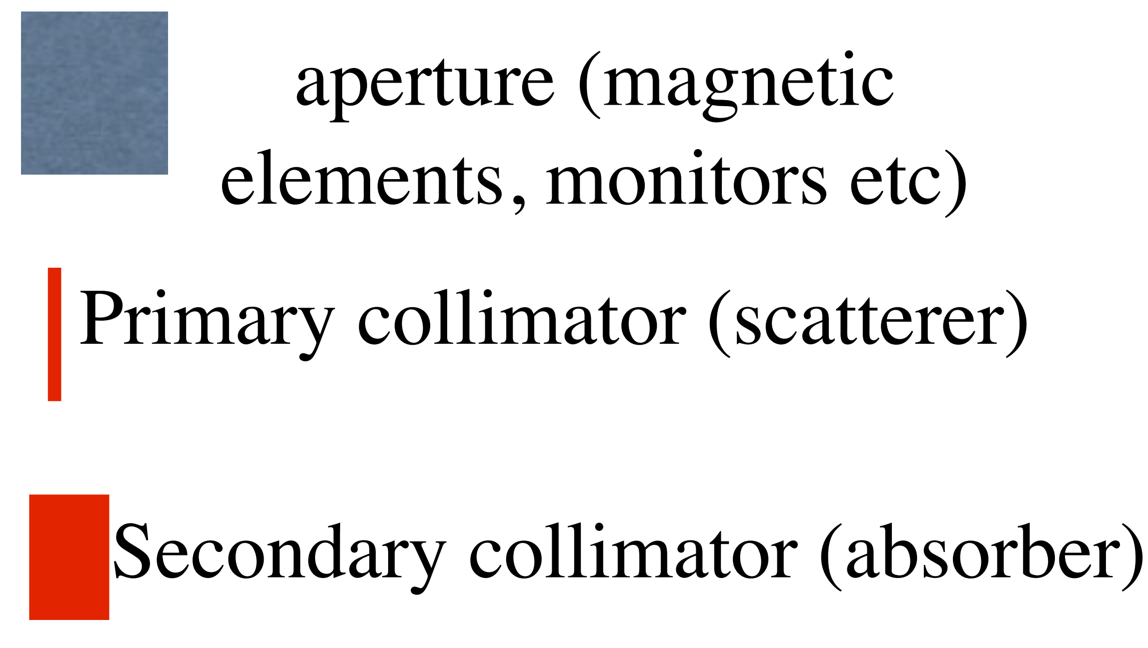

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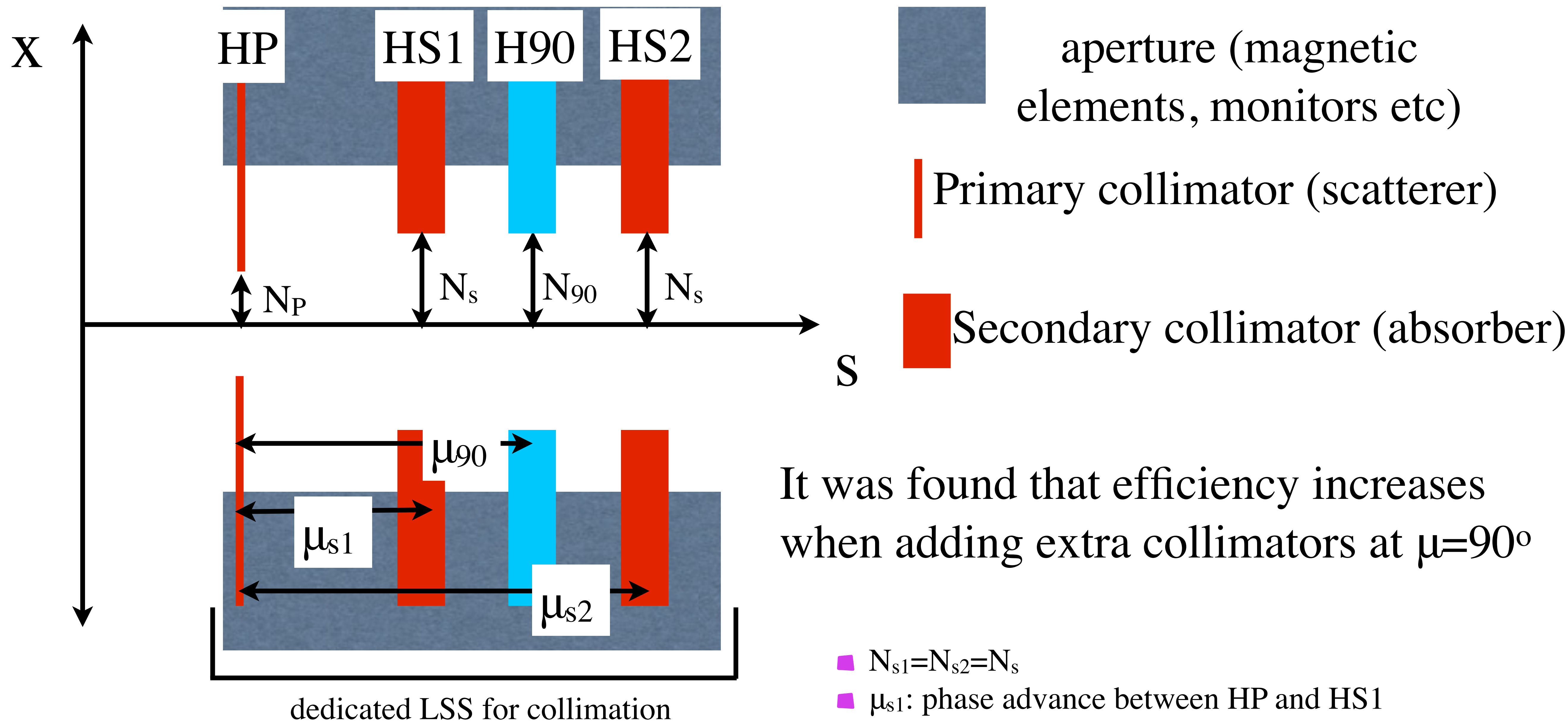

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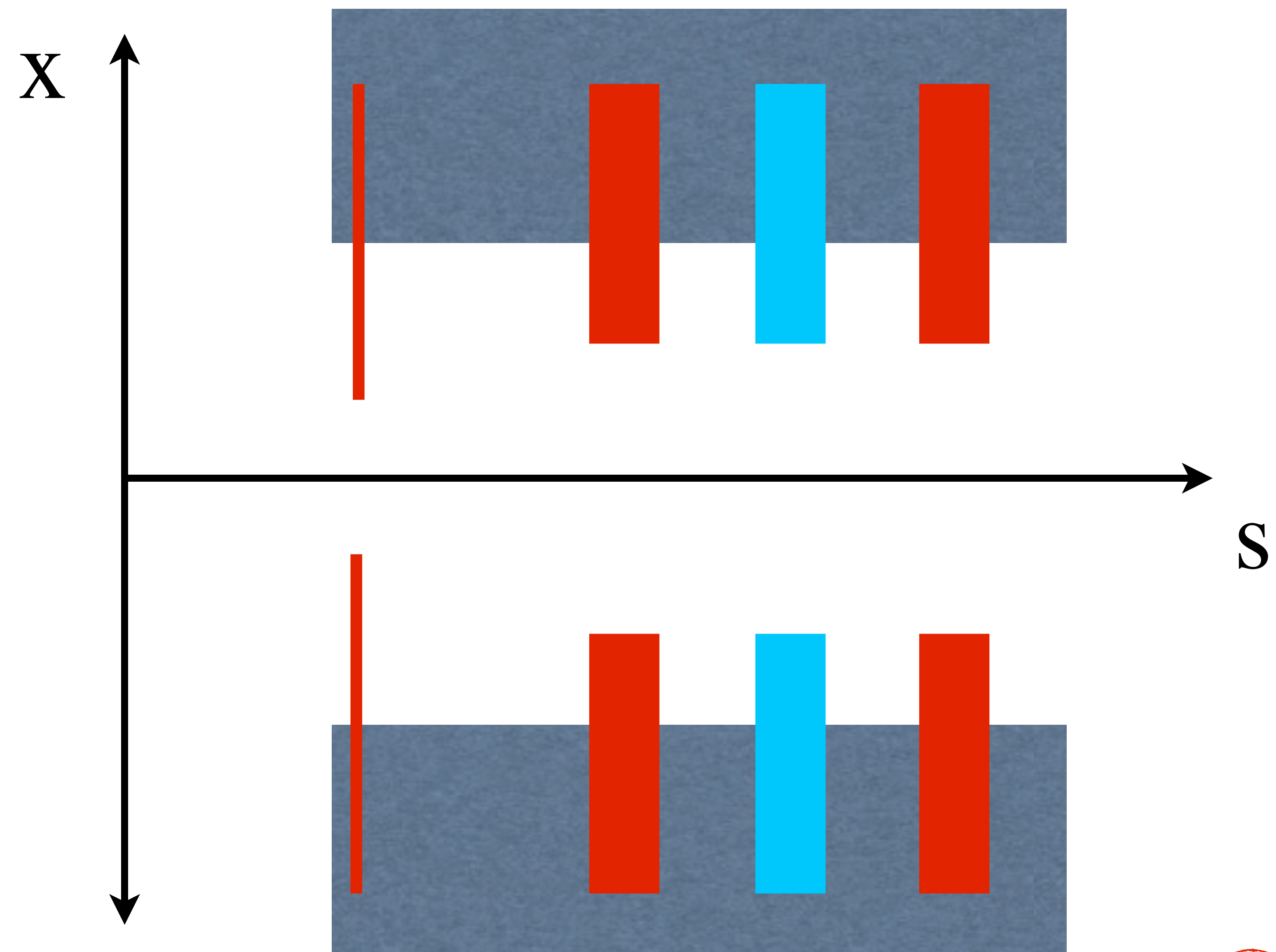
Optimizing Collimation Efficiency

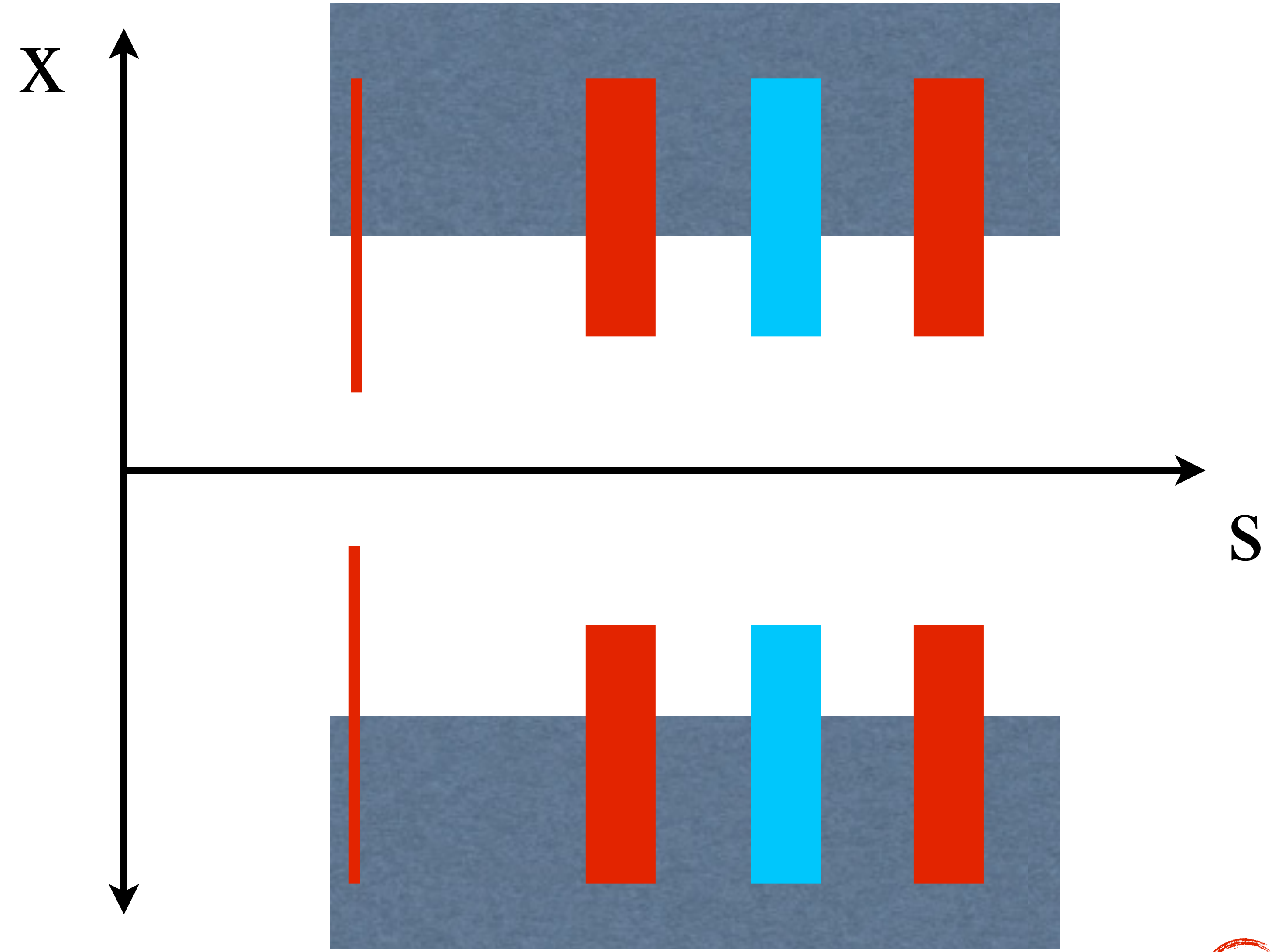
Parameters:



Optimizing Collimation Efficiency

Parameters:

- collimators thickness



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Parameters:

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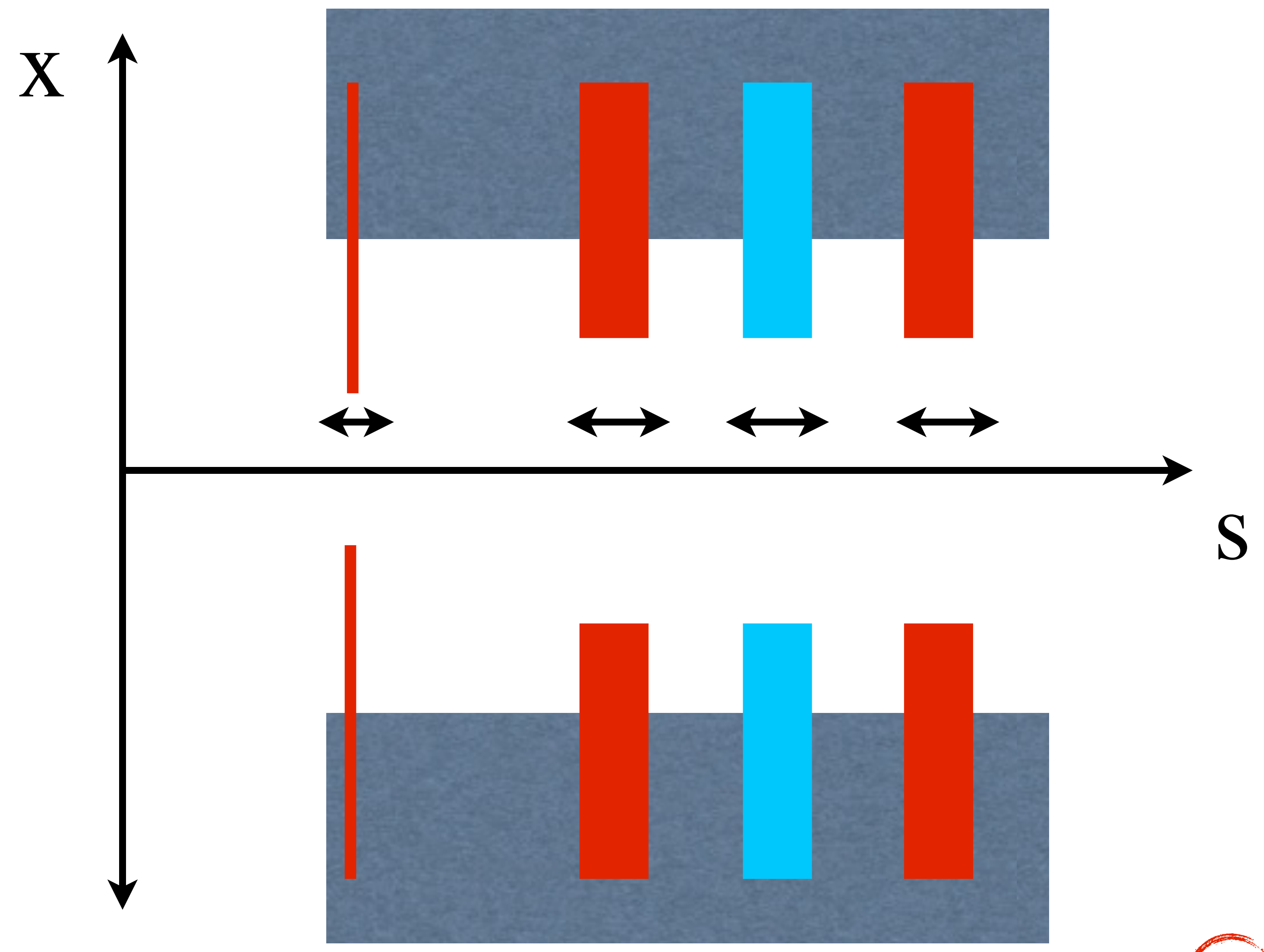
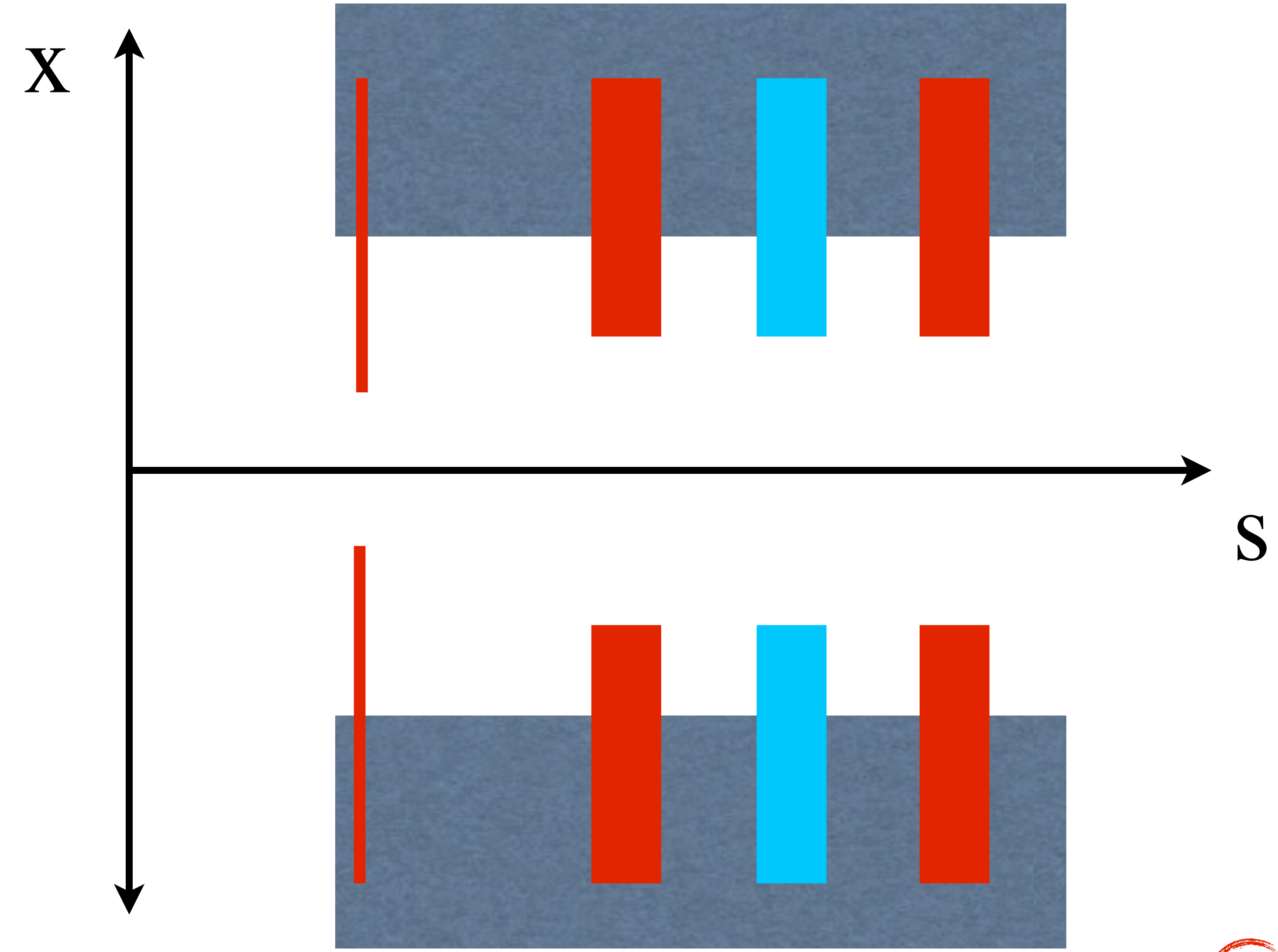


Optimizing Collimation Efficiency

Parameters:

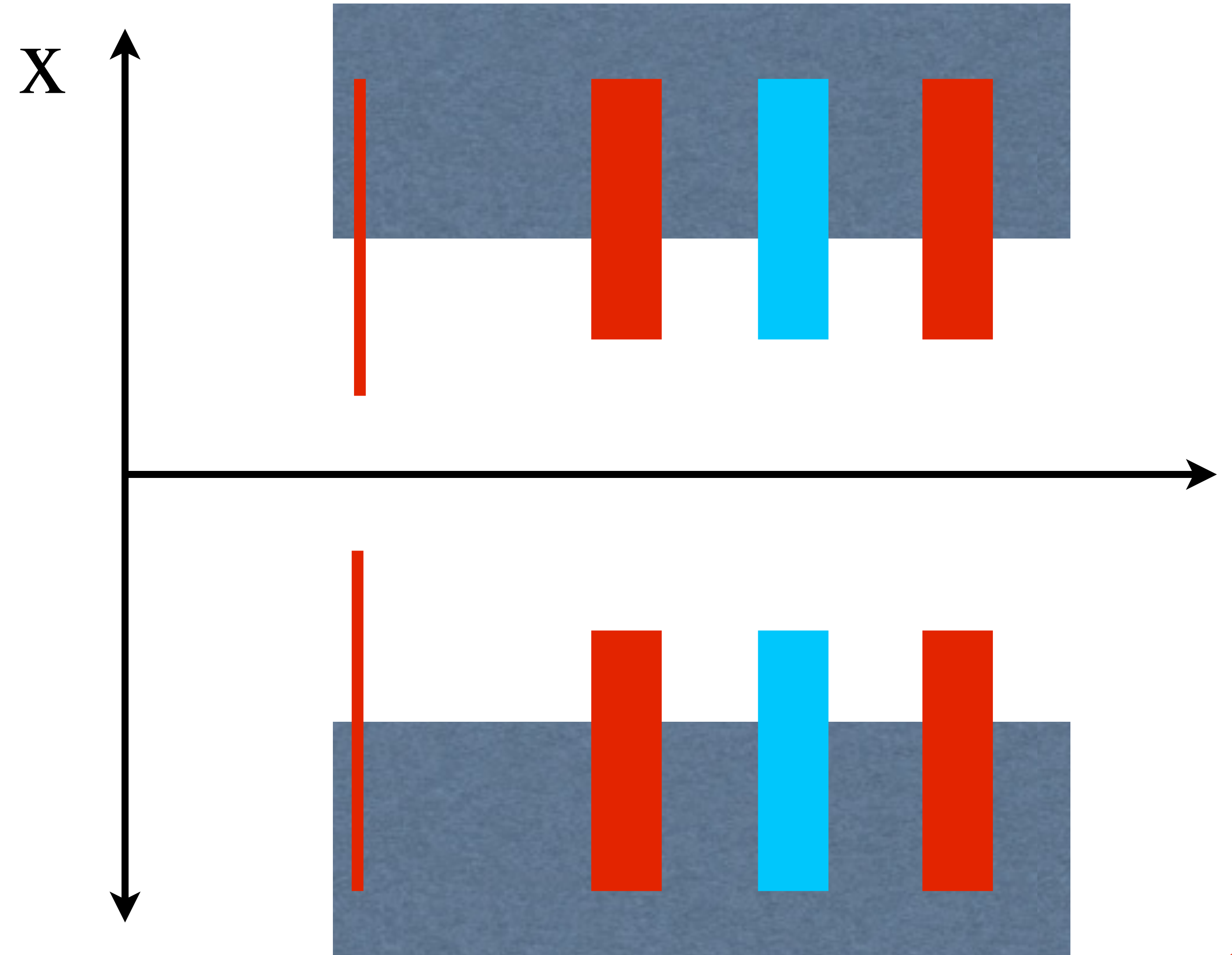
- collimators thickness



Optimizing Collimation Efficiency

Parameters:

- collimators thickness
- collimators material (e.g. graphite (C), tungsten (W))



Optimizing Collimation Efficiency

Parameters:

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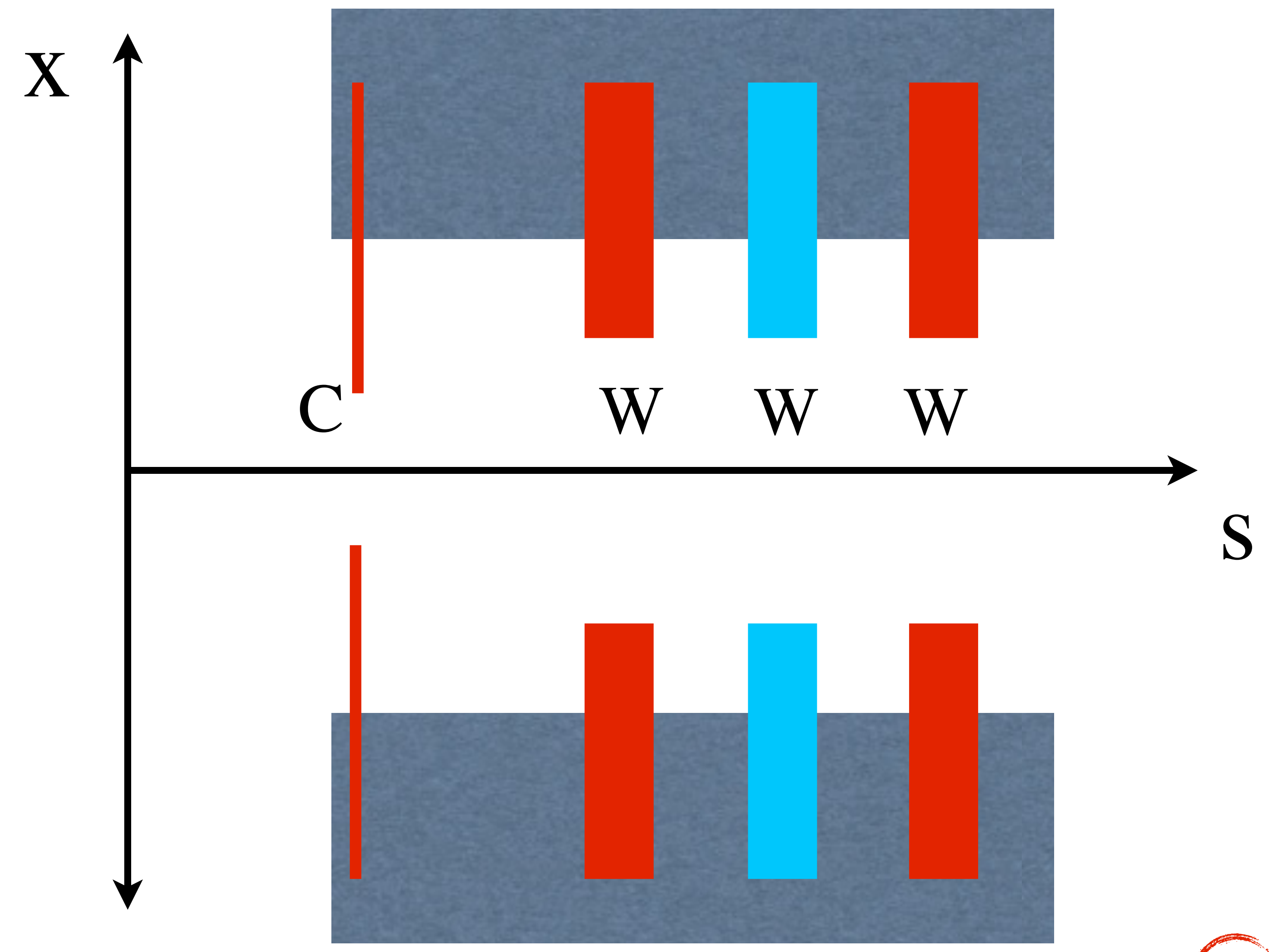
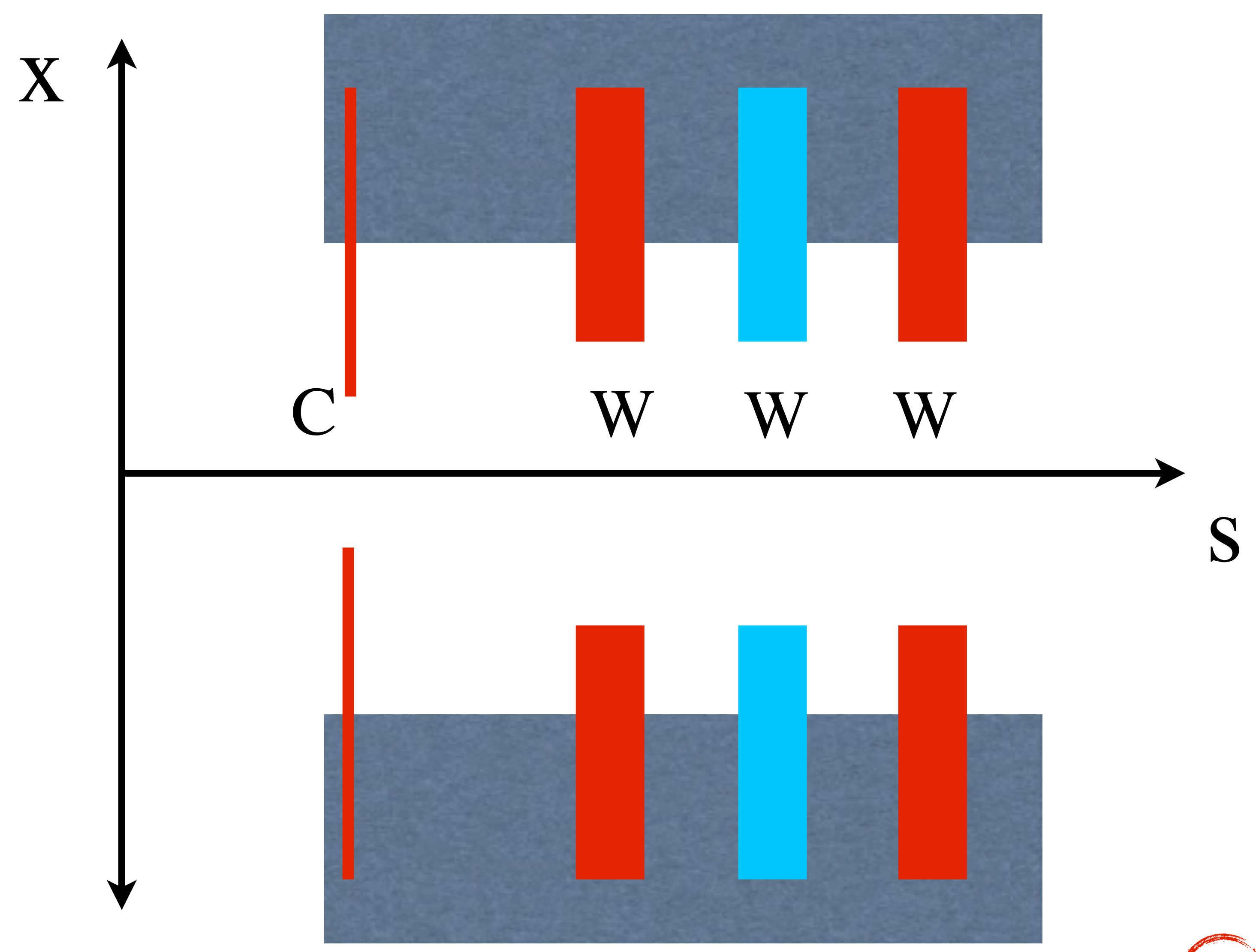


Optimizing Collimation Efficiency

Parameters:

- collimators thickness
- collimators material (e.g. graphite (C), tungsten (W))
- jaw opening



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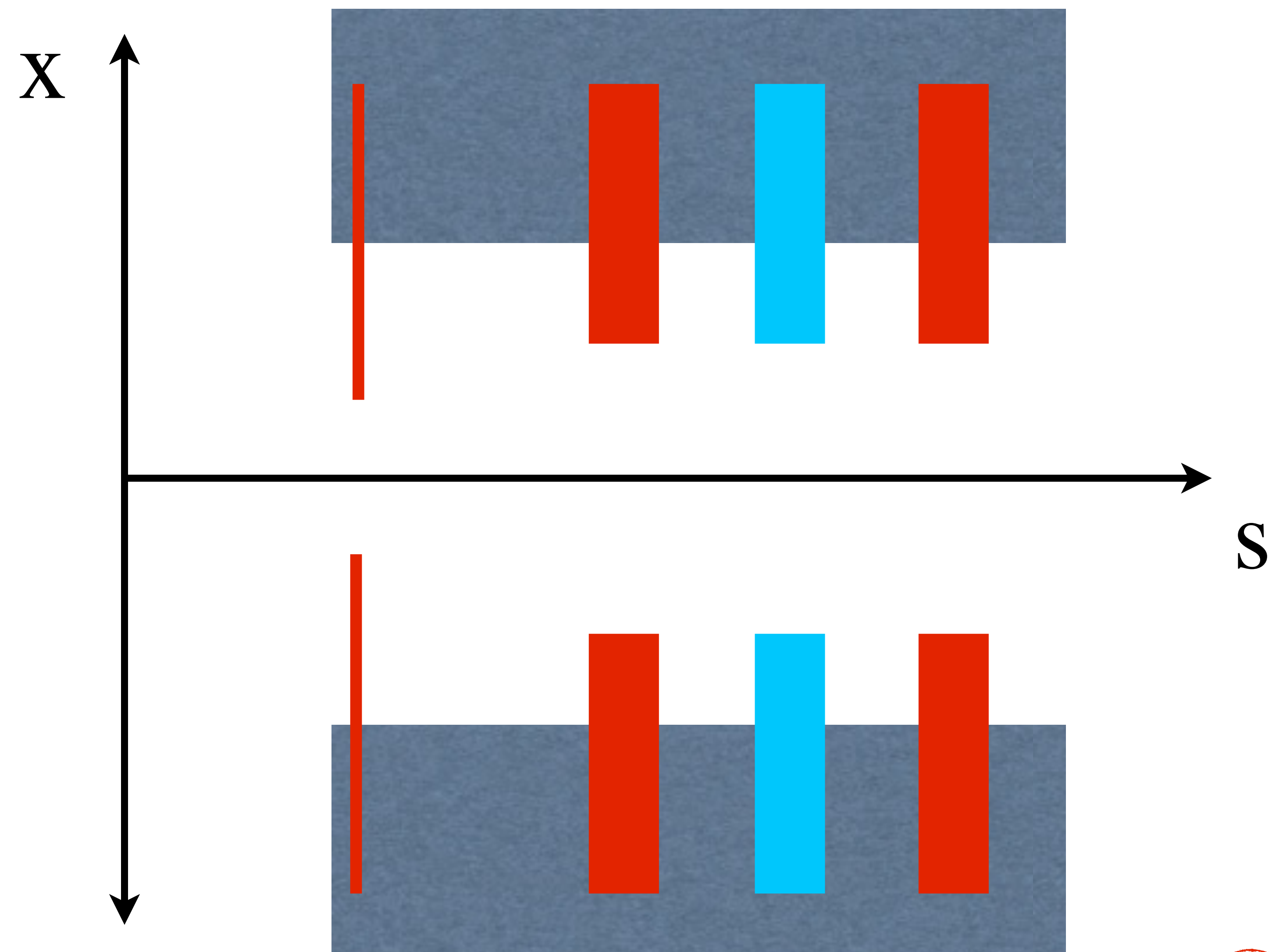
- jaw opening



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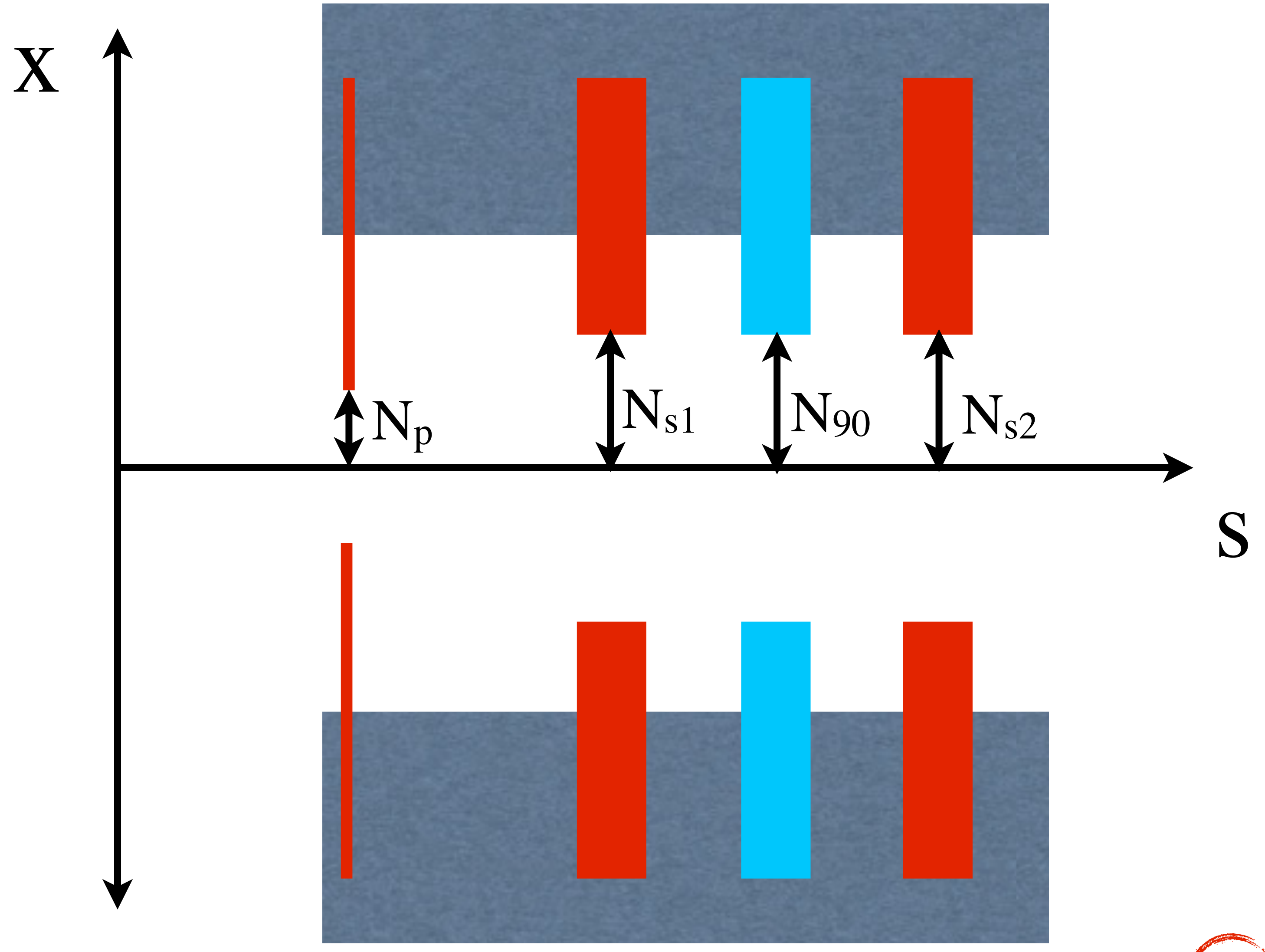

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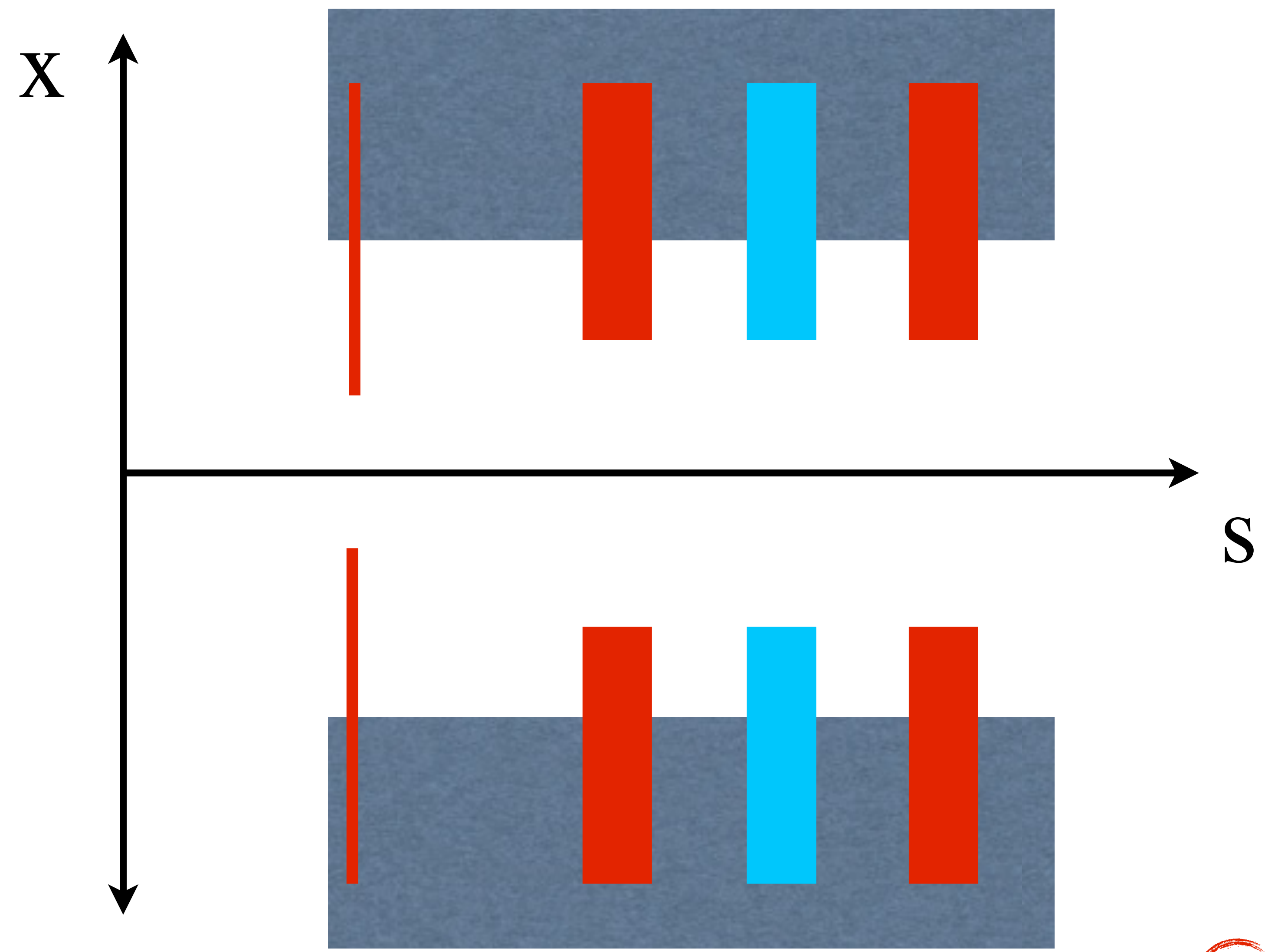

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Optimizing Collimation Efficiency

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For different:

Optimizing Collimation Efficiency

Parameters:

- collimators thickness
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For different:

- beam halo type (H or V)

Optimizing Collimation Efficiency

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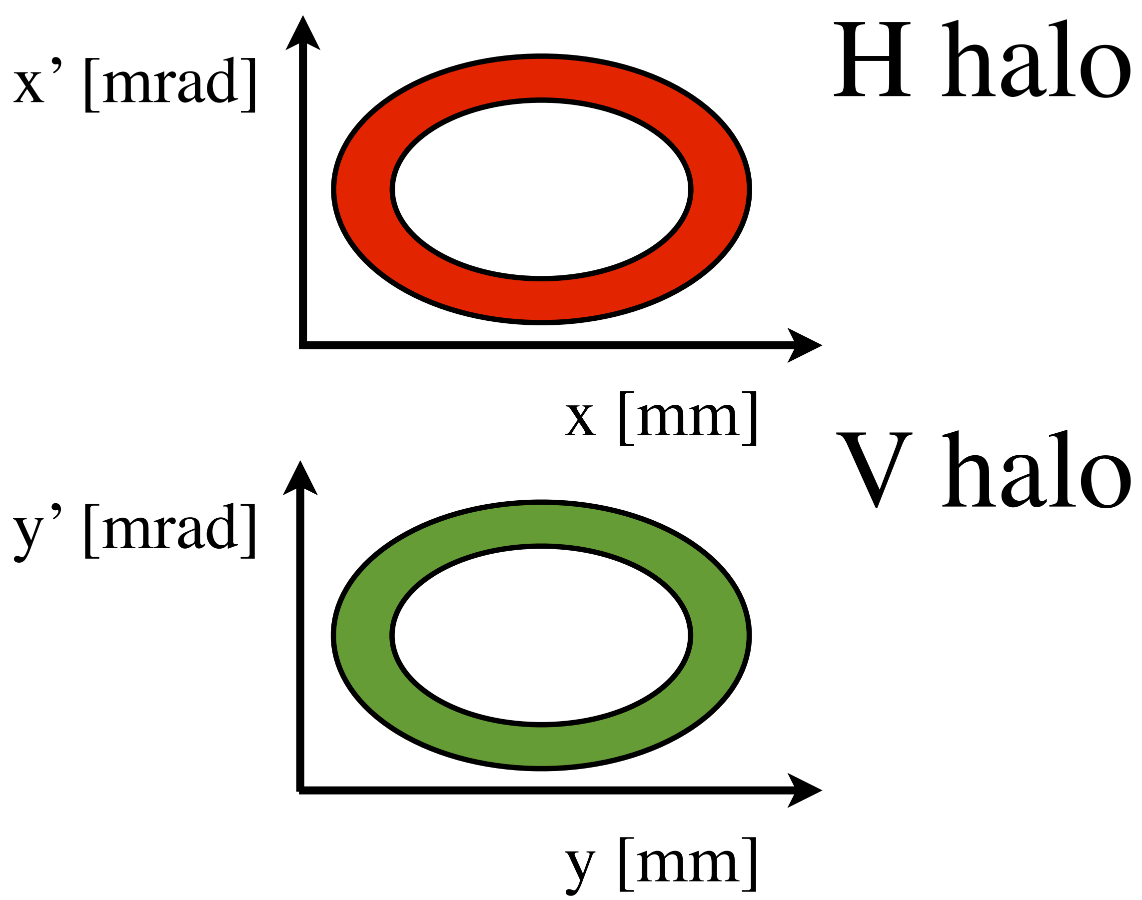

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- jaw opening

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- beam halo size (N_σ)/impact parameter (b_x)*

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For different:

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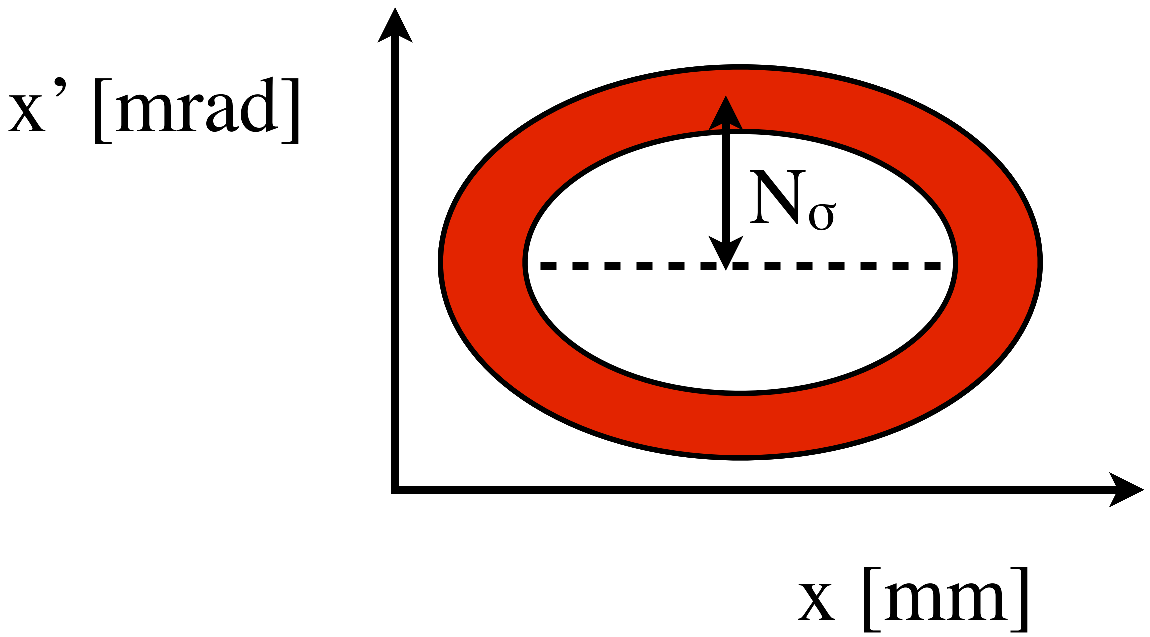
H halo



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- jaw opening

For different:

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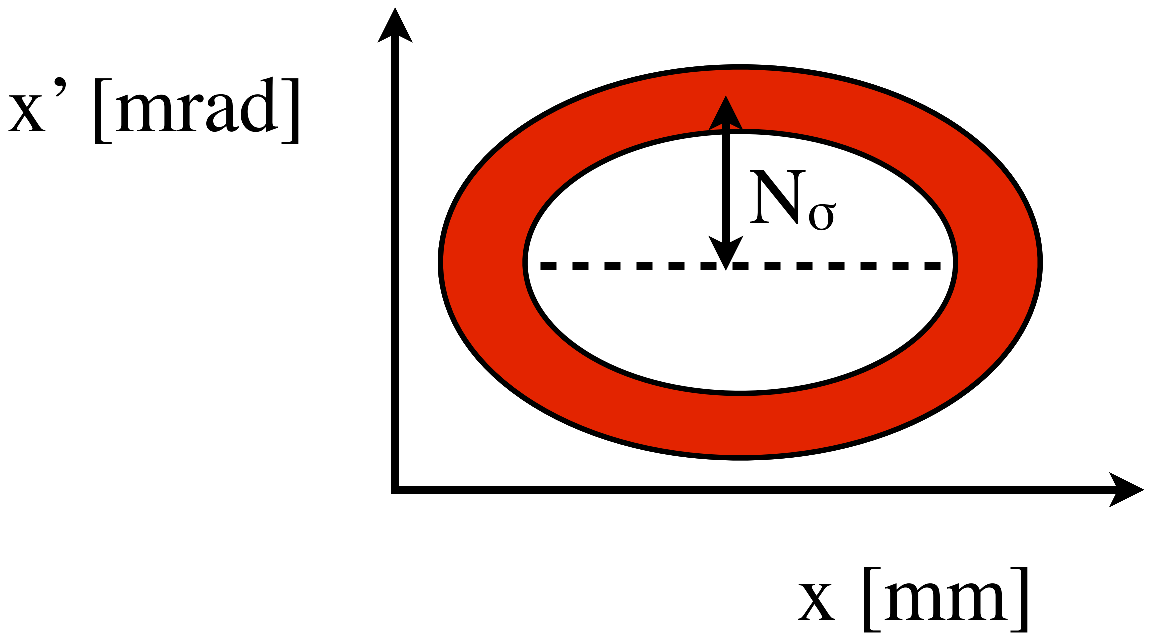
H halo



*Impact parameter, b_x: The transverse offset between the impact location and the edge of the jaw

Optimizing Collimation Efficiency

Parameters:

- collimators thickness
- collimators material (e.g. graphite (C), tungsten (W))
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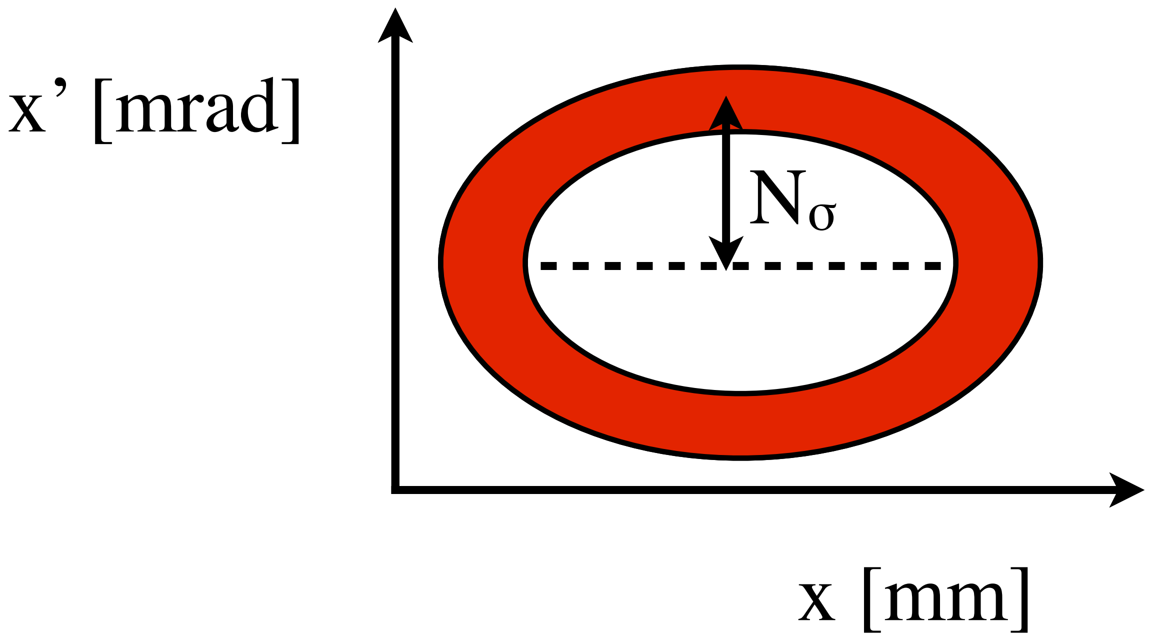
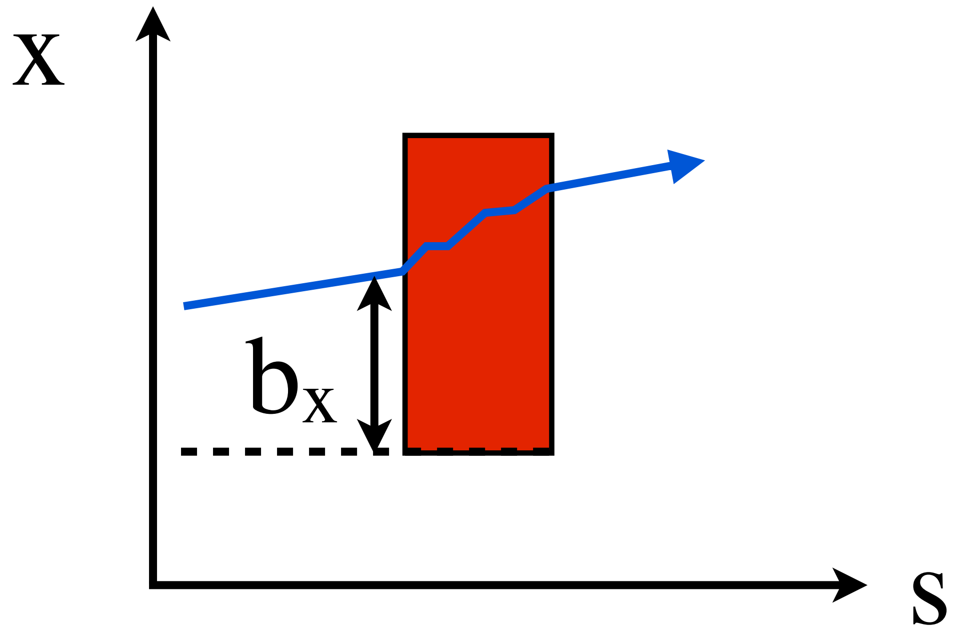
H halo





*Impact parameter, b_x: The transverse offset between the impact location and the edge of the jaw

Change thickness of primary collimators

Halo size [σ]	2.5
Halo type	H/V
Primary material	C/W
Primary thickness	changing
Secondary material	W
Secondary thickness	1 m
Jaw opening Np_Ns [σ]	2.5_3.0

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Secondary thickness	1 m
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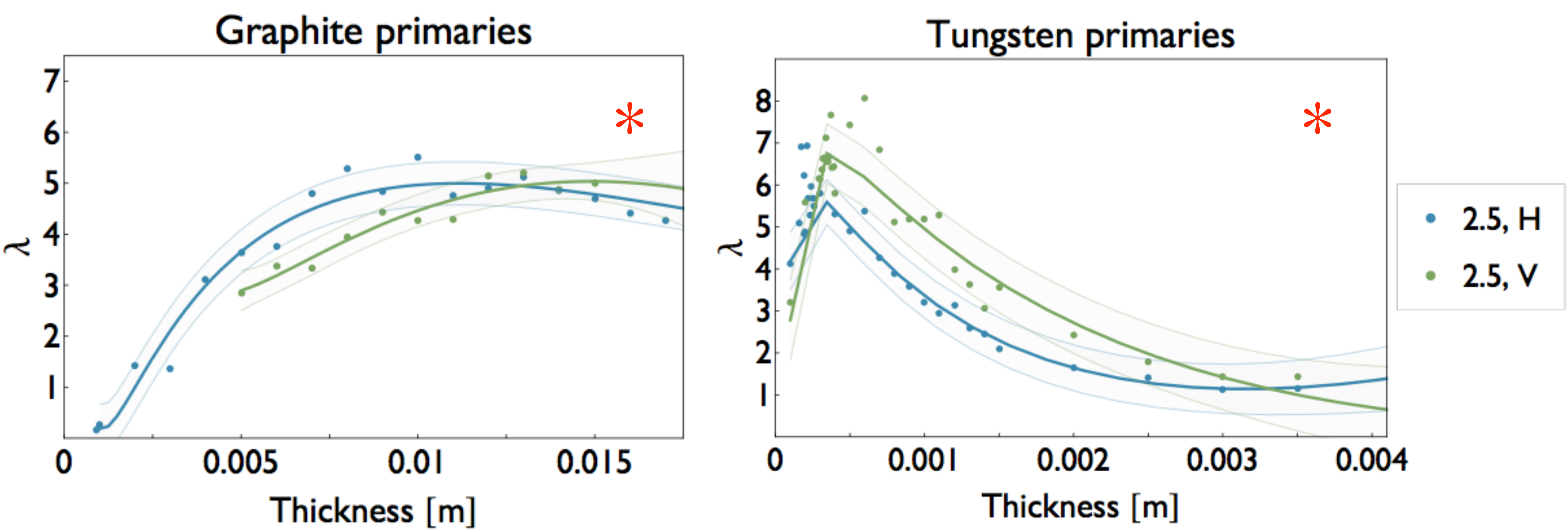


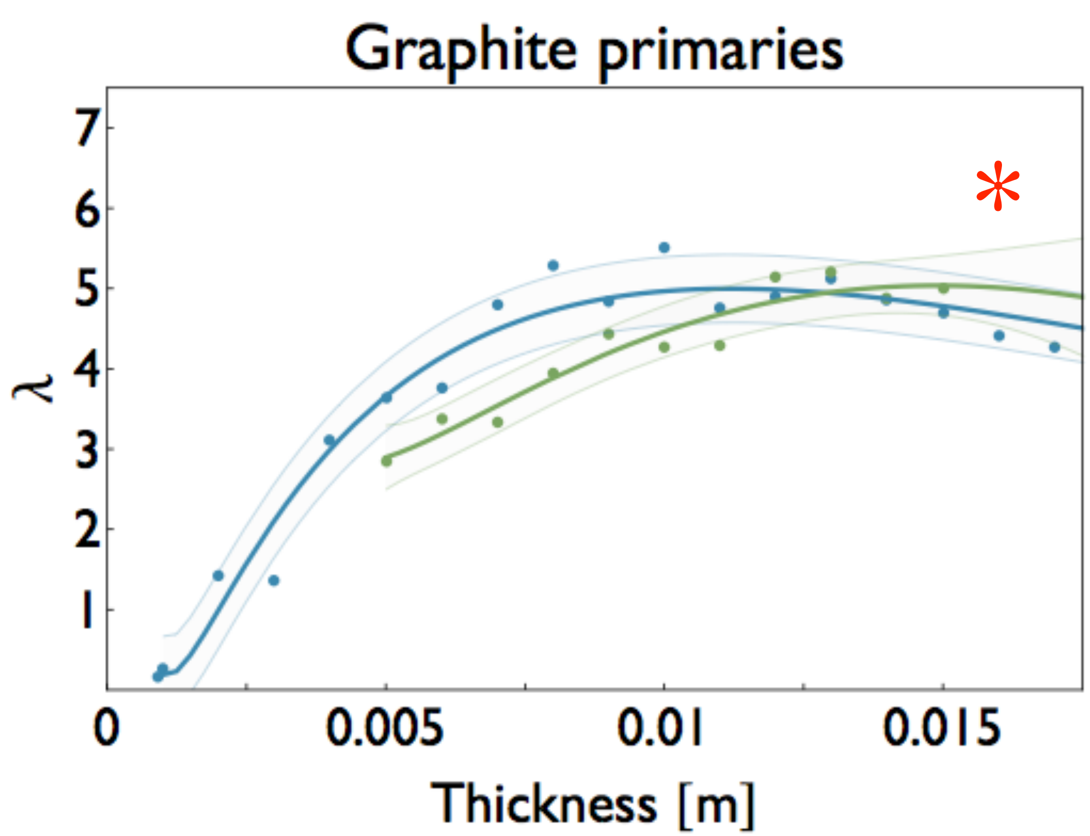
*In collaboration with Daniel Spitzbart

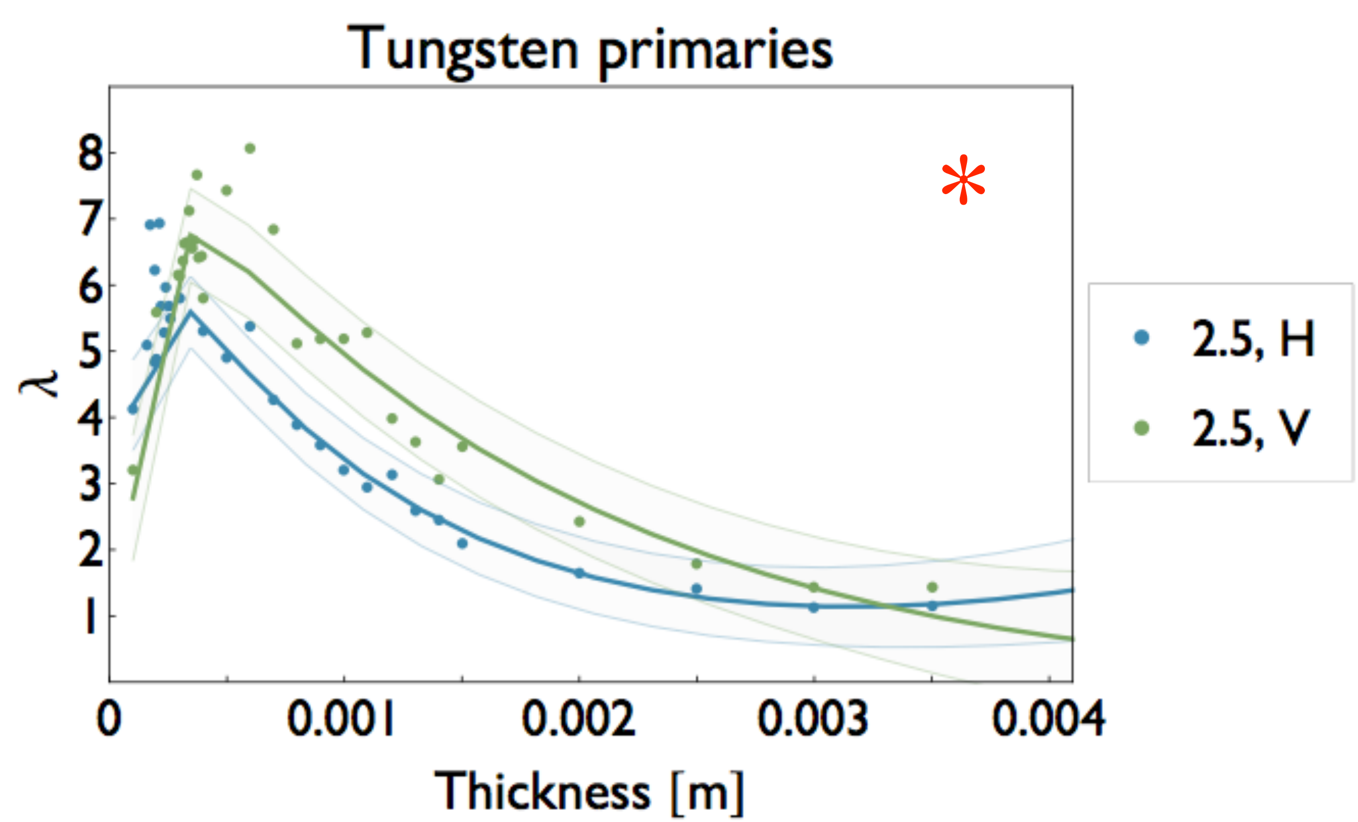
Change thickness of primary collimators

λ: figure of merit: cleaning speed/losses

Material	Halo	Thickness [mm]	λ
C	H	10	5.52
C	V	13	5.2
W	H	0.21	6.92
W	V	0.6	8.08

Halo size [σ]	2.5
Halo type	H/V
Primary material	C/W
Primary thickness	changing
Secondary material	W
Secondary thickness	1 m
Jaw opening Np_Ns [σ]	2.5_3.0





*In collaboration with Daniel Spitzbart

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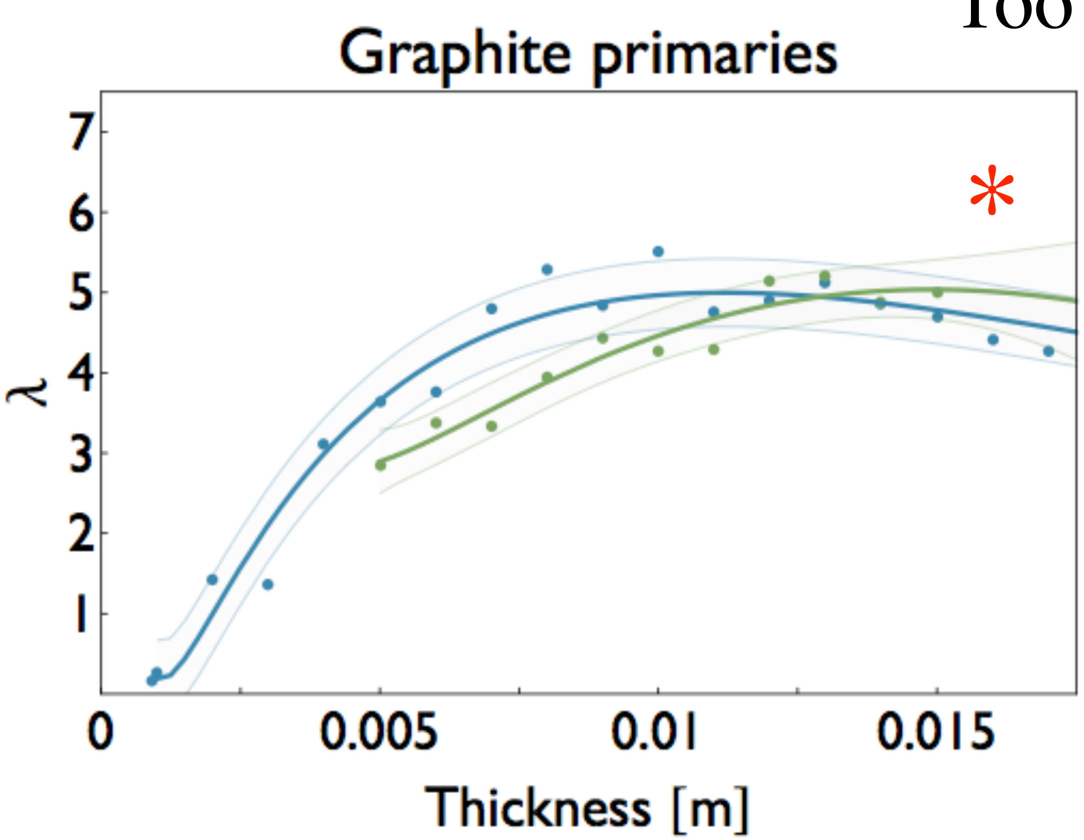
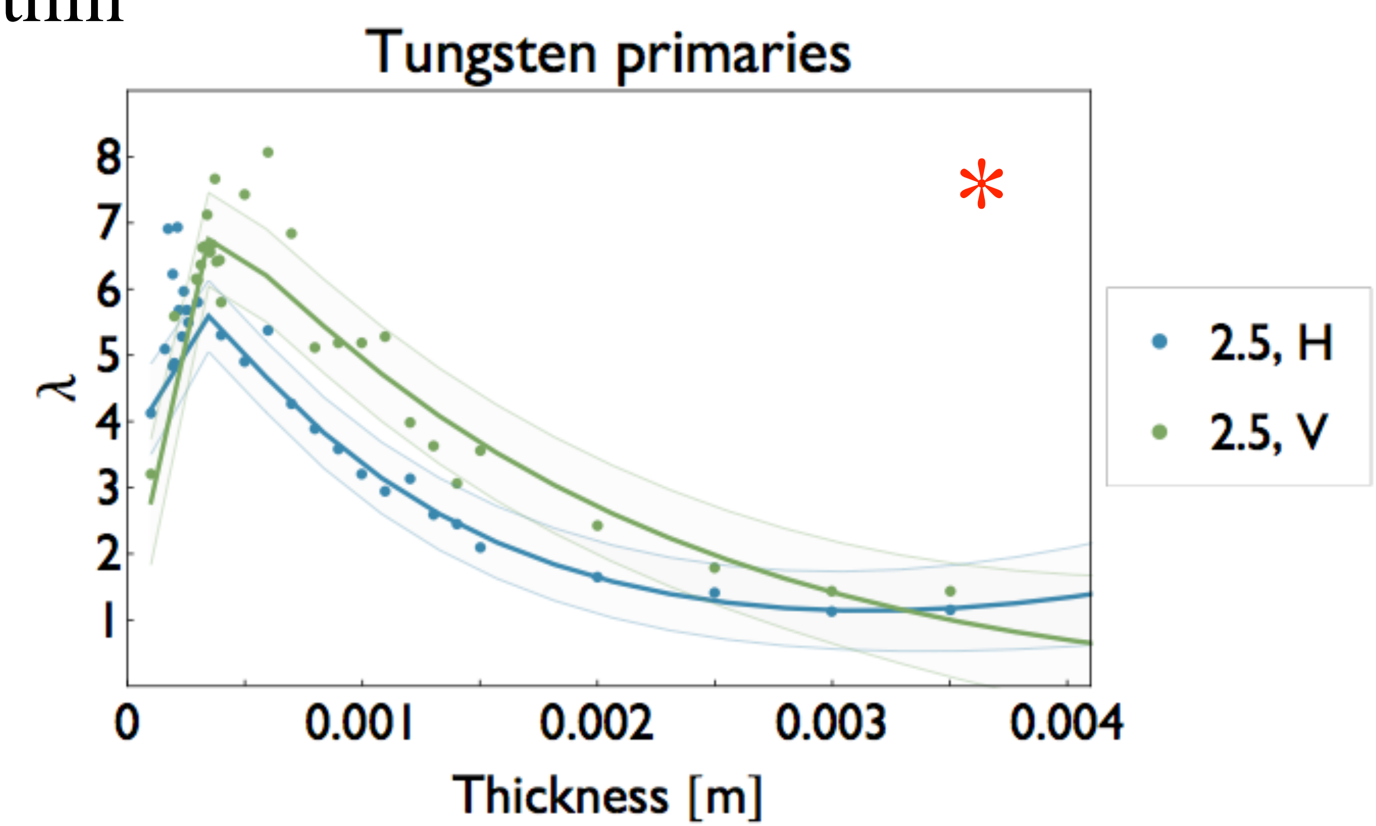
Material	Halo	Thickness [mm]	λ
C	H	10	5.52
C	V	13	5.2
W	H	0.21	6.92
W	V	0.6	8.08

Too thin

Halo size [σ]	2.5
Halo type	H/V
Primary material	C/W
Primary thickness	changing
Secondary material	W
Secondary thickness	1 m
Jaw opening Np_Ns [σ]	2.5_3.0





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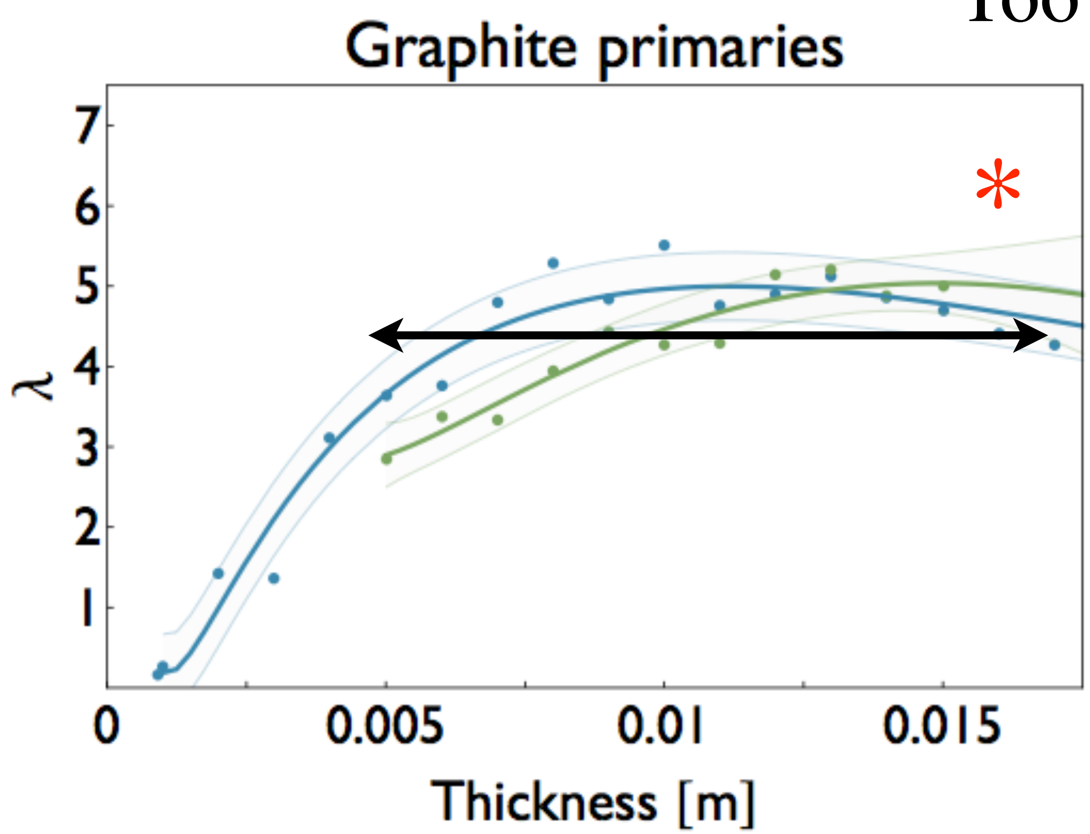
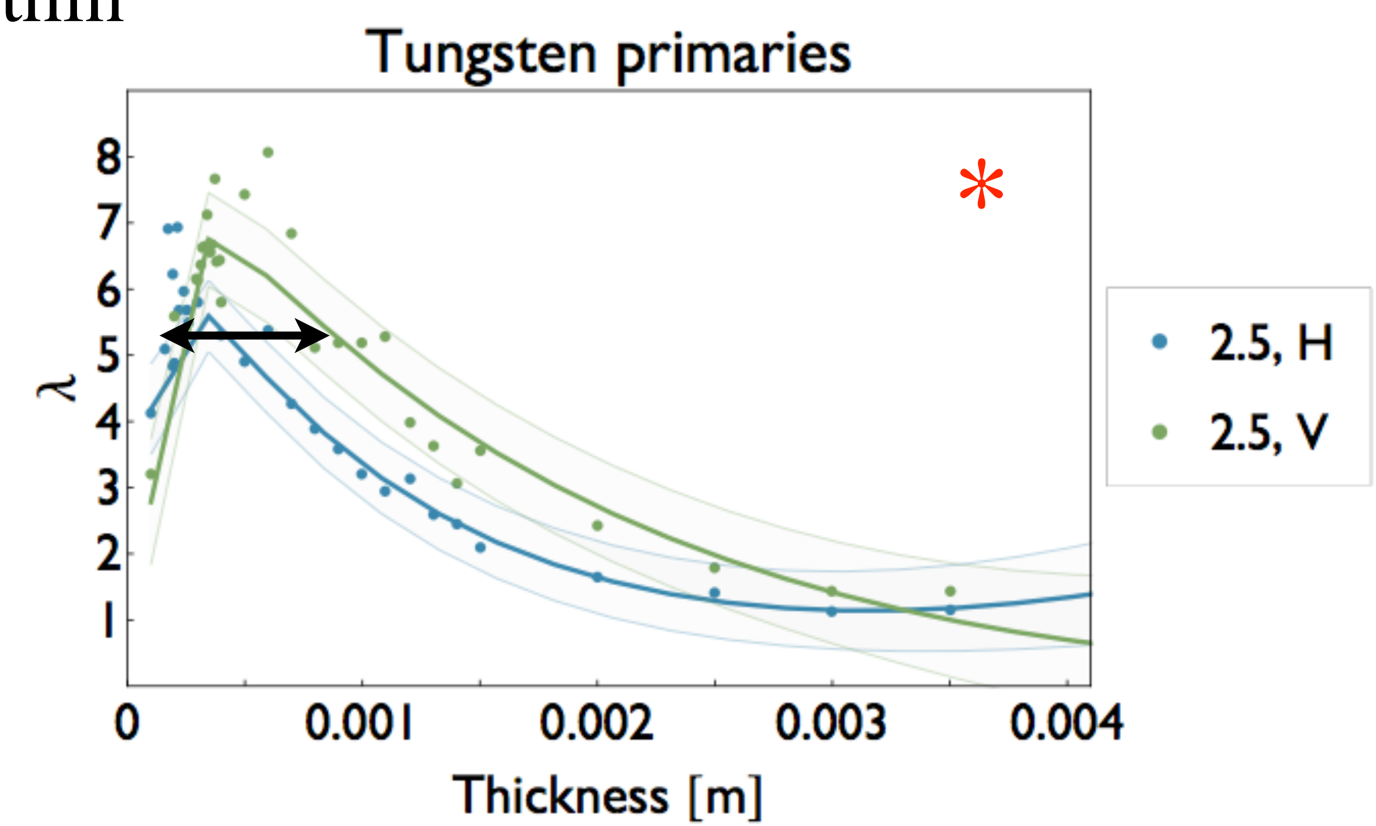




*In collaboration with Daniel Spitzbart

Graphite primaries: better λ for larger thickness range

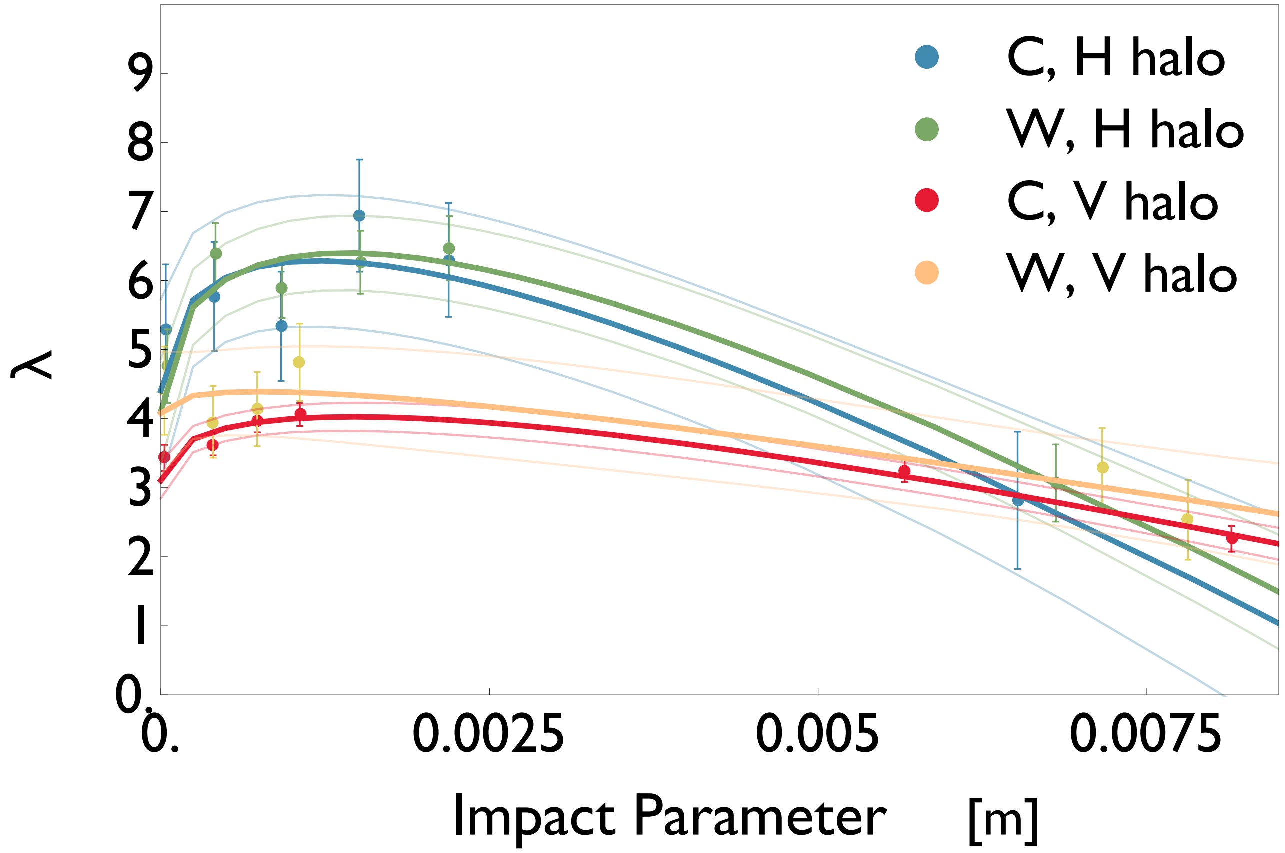
Change size of input beam

Halo size [σ]	changing
Halo type	H/V
Primary material	C/W
Primary thickness*	constant
Secondary material	W
Secondary thickness	1 m
Jaw opening Np_Ns [σ]	2.5_3.0

*Thickness of primaries: optimum, shown in previous slide

Change size of input beam

λ: figure of merit: cleaning speed/losses



Halo size [σ]	changing
Halo type	H/V
Primary material	C/W
Primary thickness*	constant
Secondary material	W
Secondary thickness	1 m
Jaw opening Np_Ns [σ]	2.5_3.0

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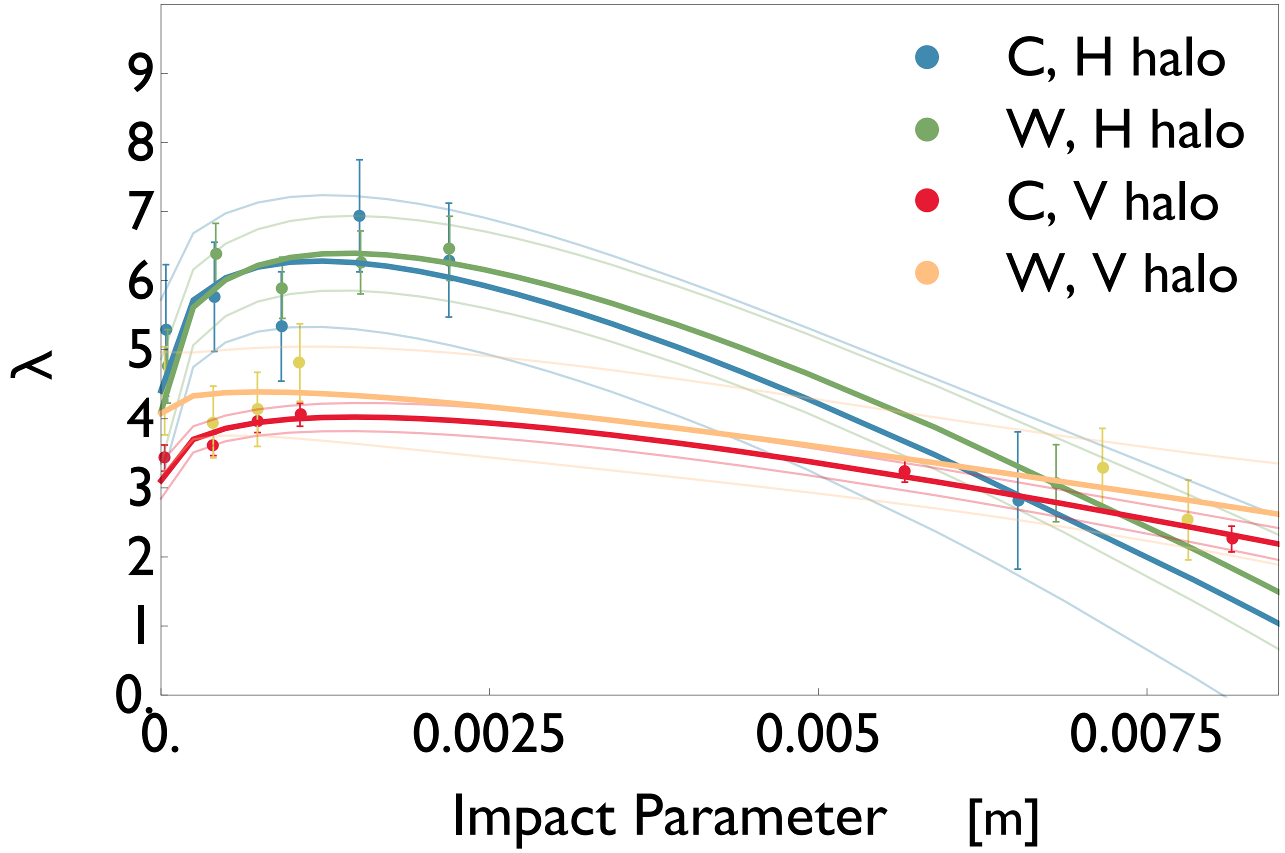
Change size of input beam

λ: figure of merit: cleaning speed/losses

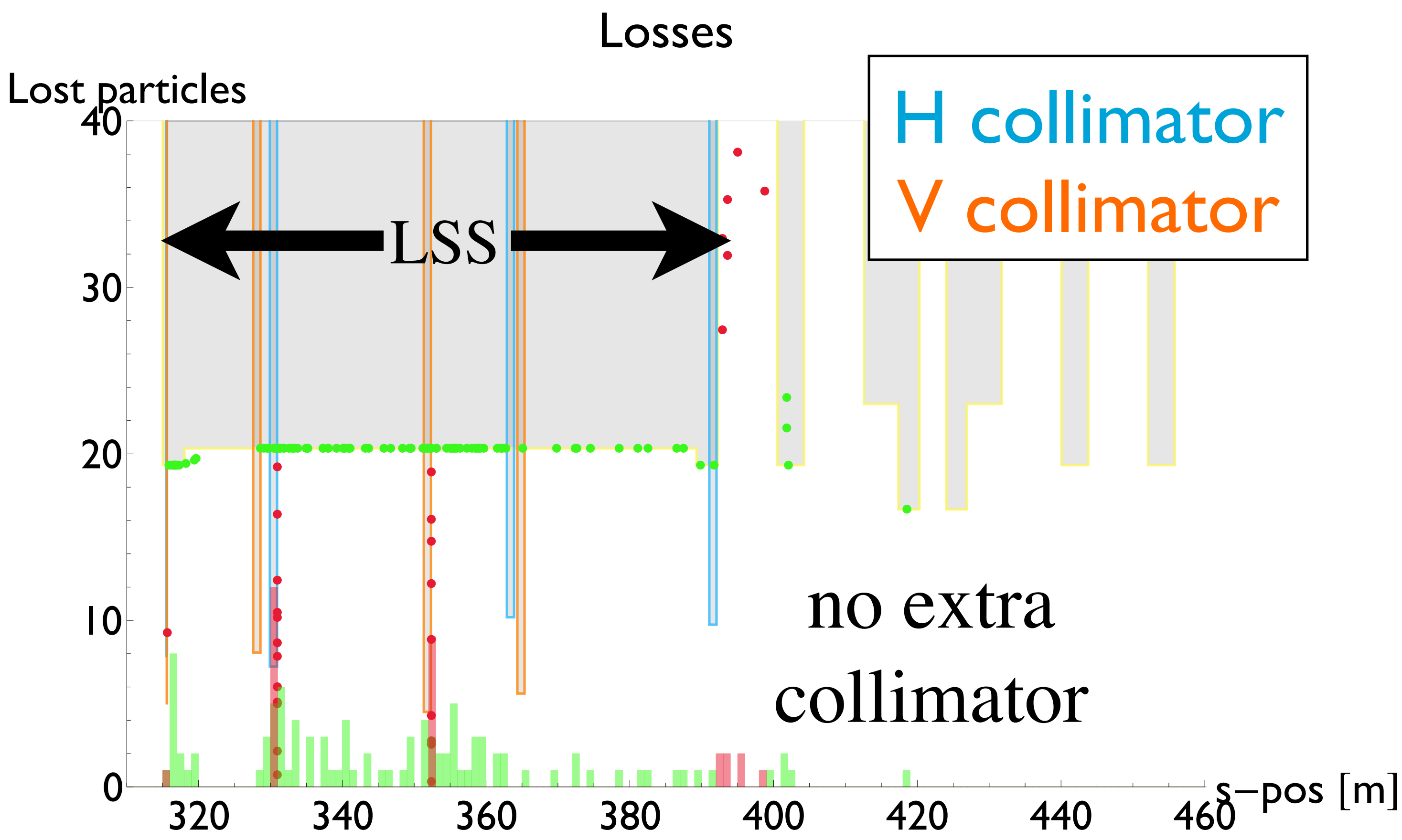


Halo size [σ]	changing
Halo type	H/V
Primary material	C/W
Primary thickness*	constant
Secondary material	W
Secondary thickness	1 m
Jaw opening Np_Ns [σ]	2.5_3.0

- Similar behavior between C and W for different impact parameters
- H halo better than V halo

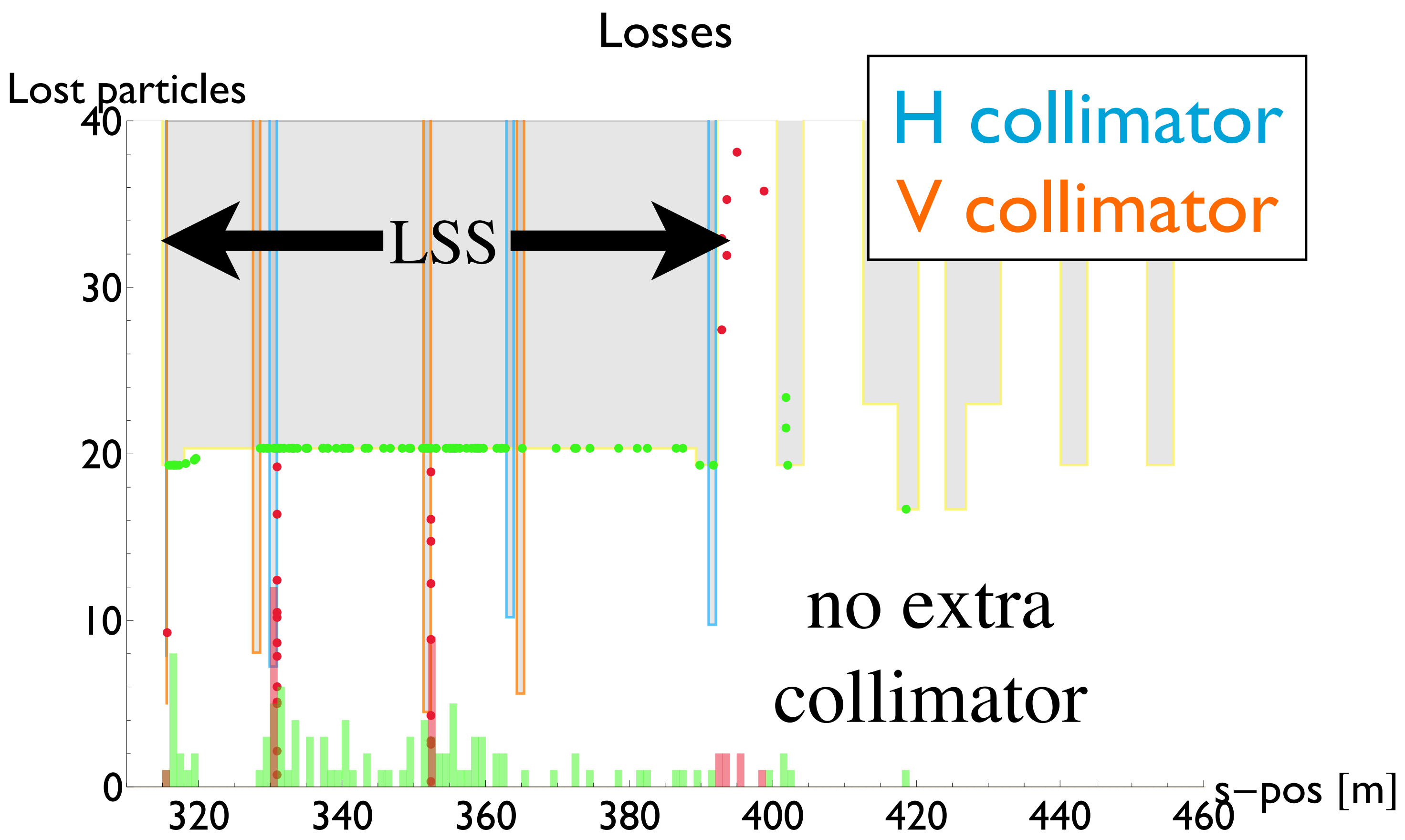
*Thickness of primaries: optimum, shown in previous slide

Adding more collimators



Halo size [σ]	2.5
Halo type	H
Primary material	C
Primary thickness [m]	0.01
Secondary material	W
Secondary thickness [m]	1
Jaw opening Np_Ns [σ]	2.5_3.0

Adding more collimators

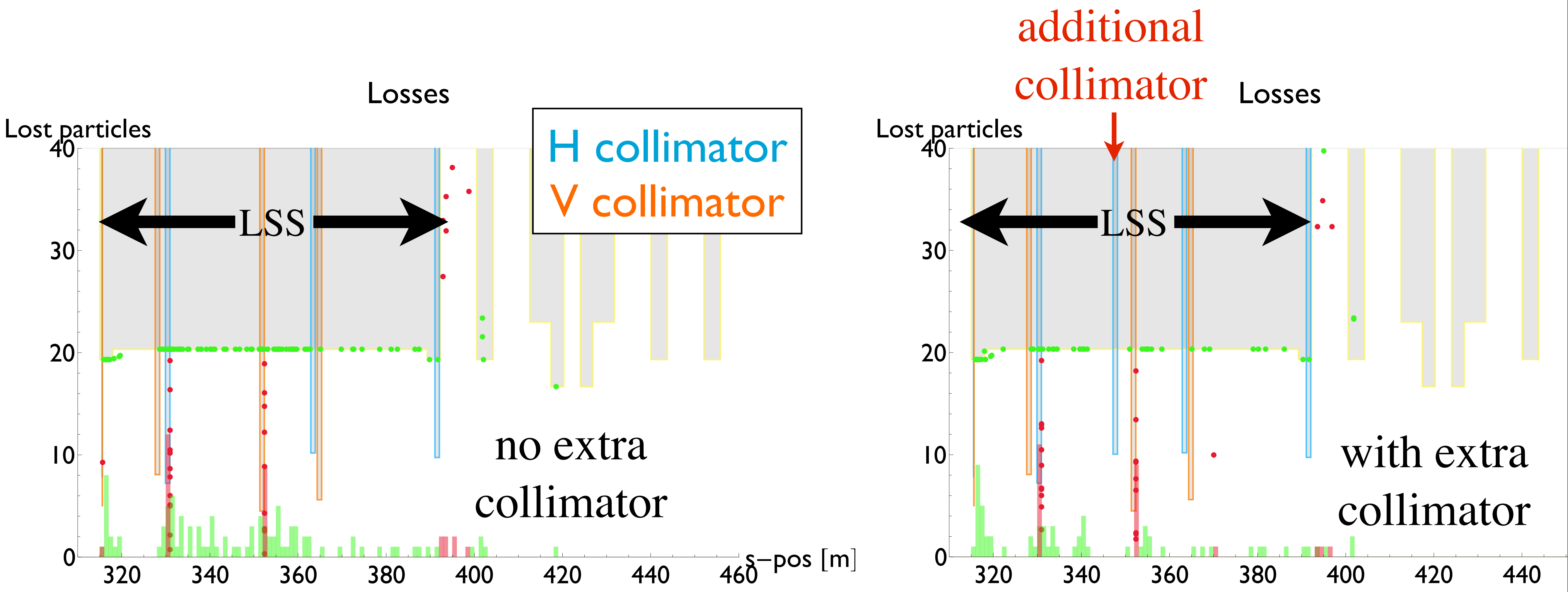


Halo size [σ]	2.5
Halo type	H
Primary material	C
Primary thickness [m]	0.01
Secondary material	W
Secondary thickness [m]	1
Jaw opening Np_Ns [σ]	2.5_3.0

Power deposition

- Assuming 1% halo and injection power (500 kW) then 20 lost particles within 10 m correspond to 5 W/m > 1 W/m limit
- Necessary to further reduce losses!

Adding more collimators



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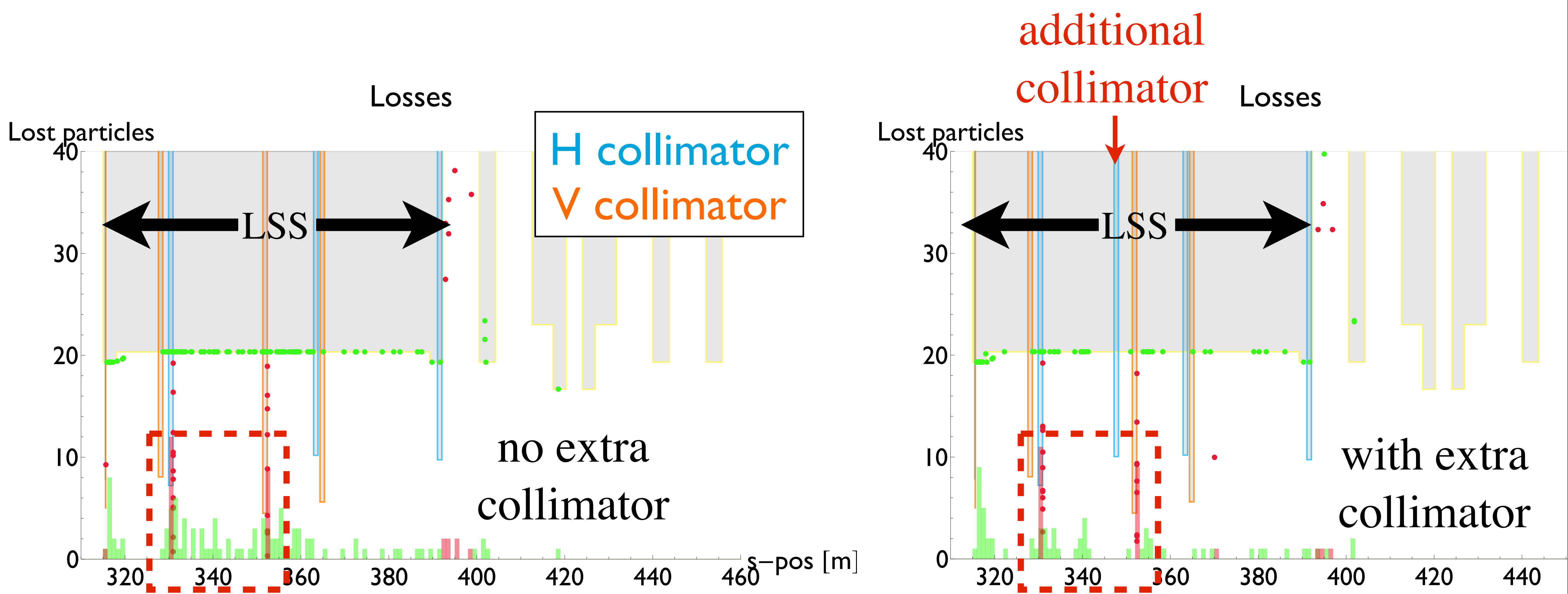

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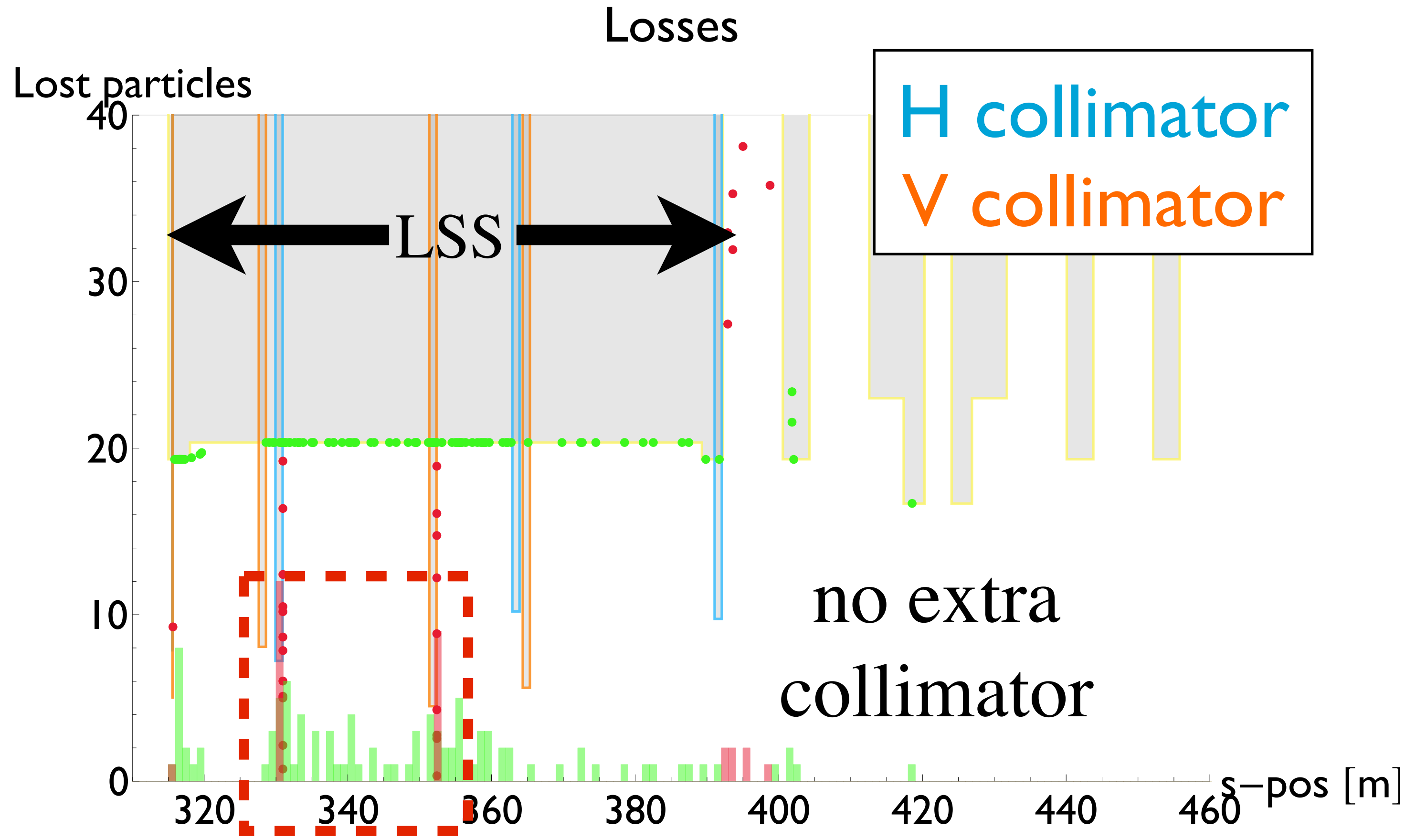
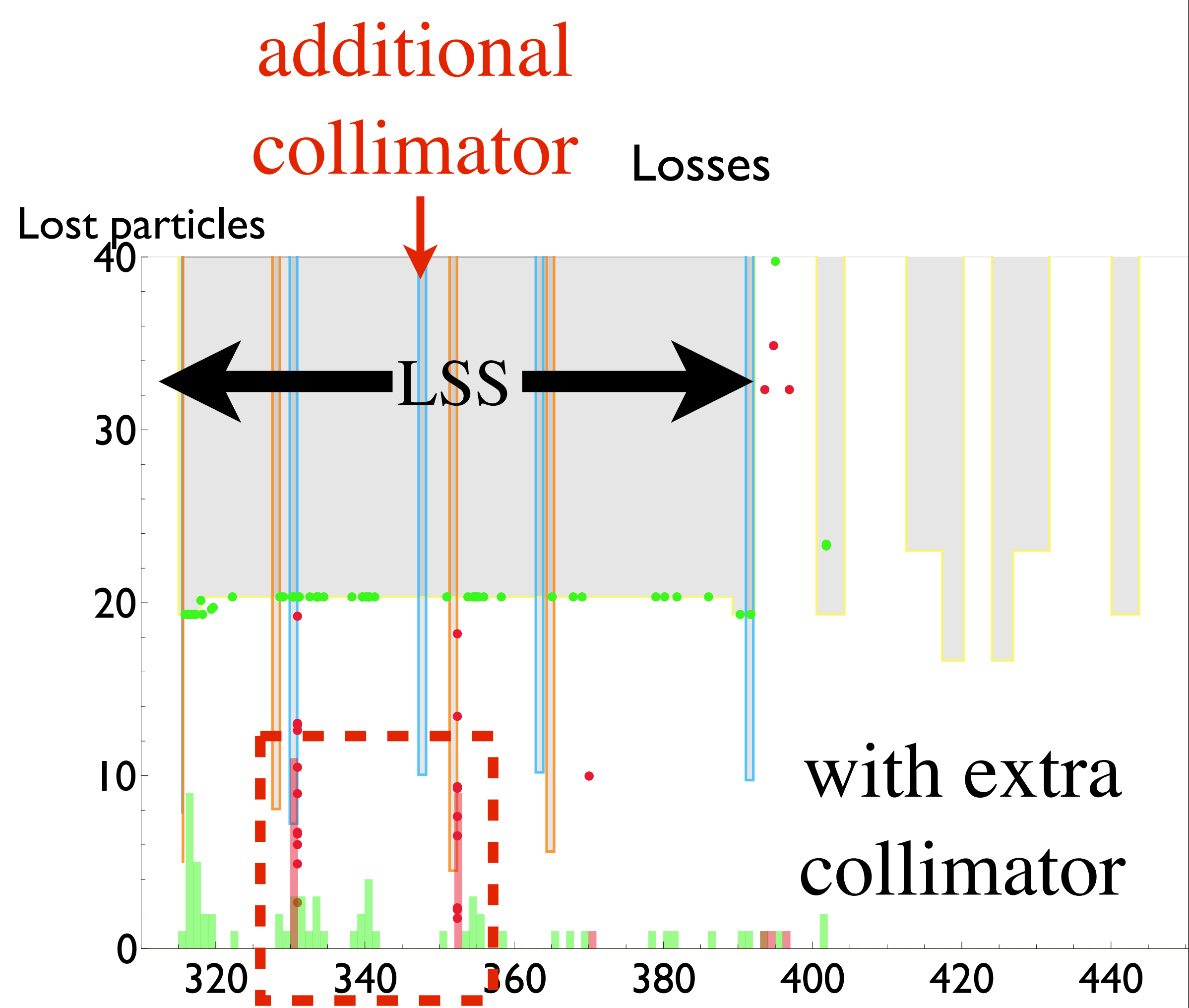




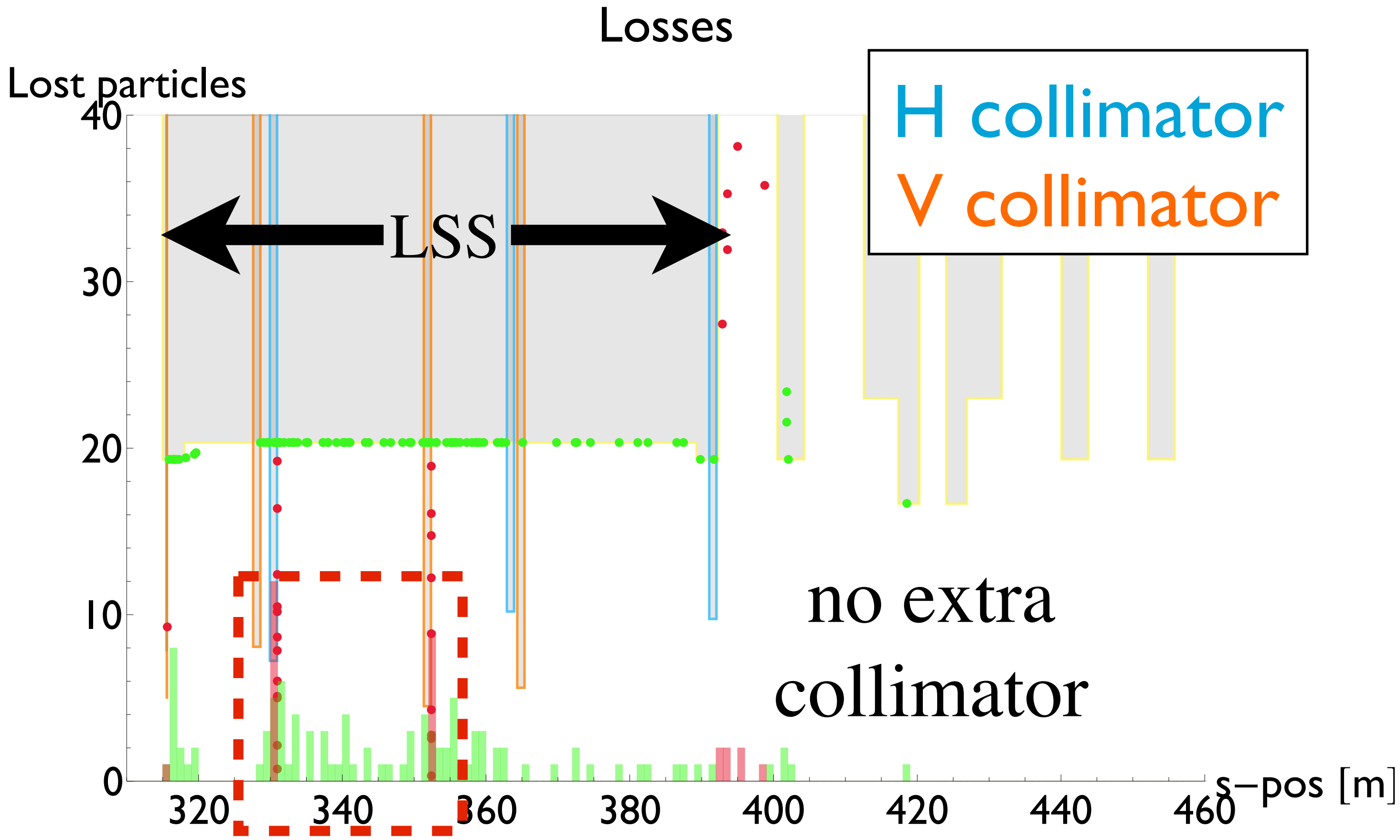
Power deposition

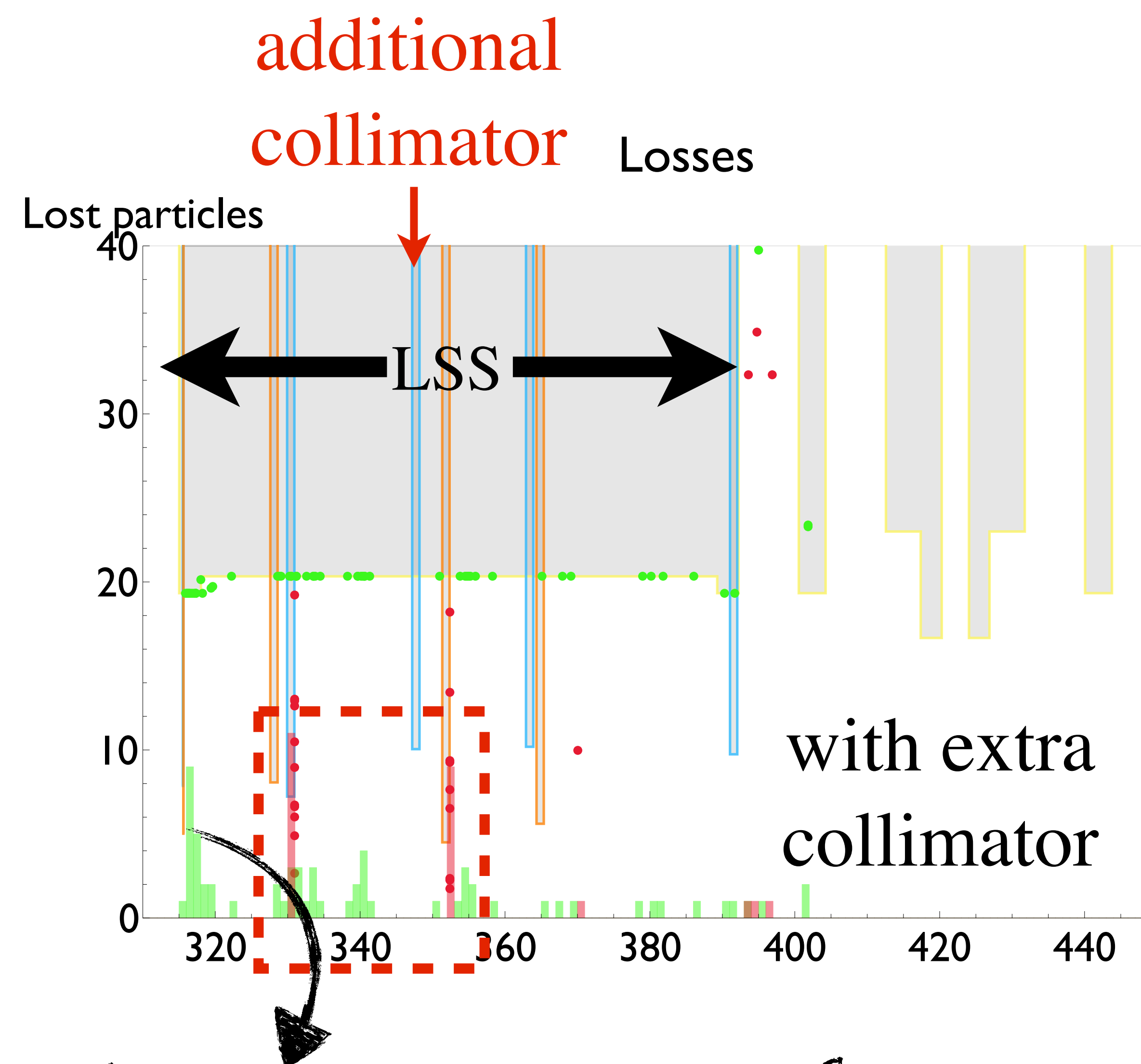
- Assuming 1% halo and injection power (500 kW) then 20 lost particles within 10 m correspond to 5 W/m > 1 W/m limit
- Necessary to further reduce losses!

Parameter	without extra	with extra
Inefficiency [%]	0.13	0.08
Cleaning Speed [%]	0.59	0.59
λ	4.68	7.17
absorptions	1017	1052
losses	100	63

Additional collimator has a positive impact

Adding more collimators





need to remove peak of losses

Power deposition

- Assuming 1% halo and injection power (500 kW) then 20 lost particles within 10 m correspond to 5 W/m > 1 W/m limit
- Necessary to further reduce losses!

Parameter	without extra	with extra
Inefficiency [%]	0.13	0.08
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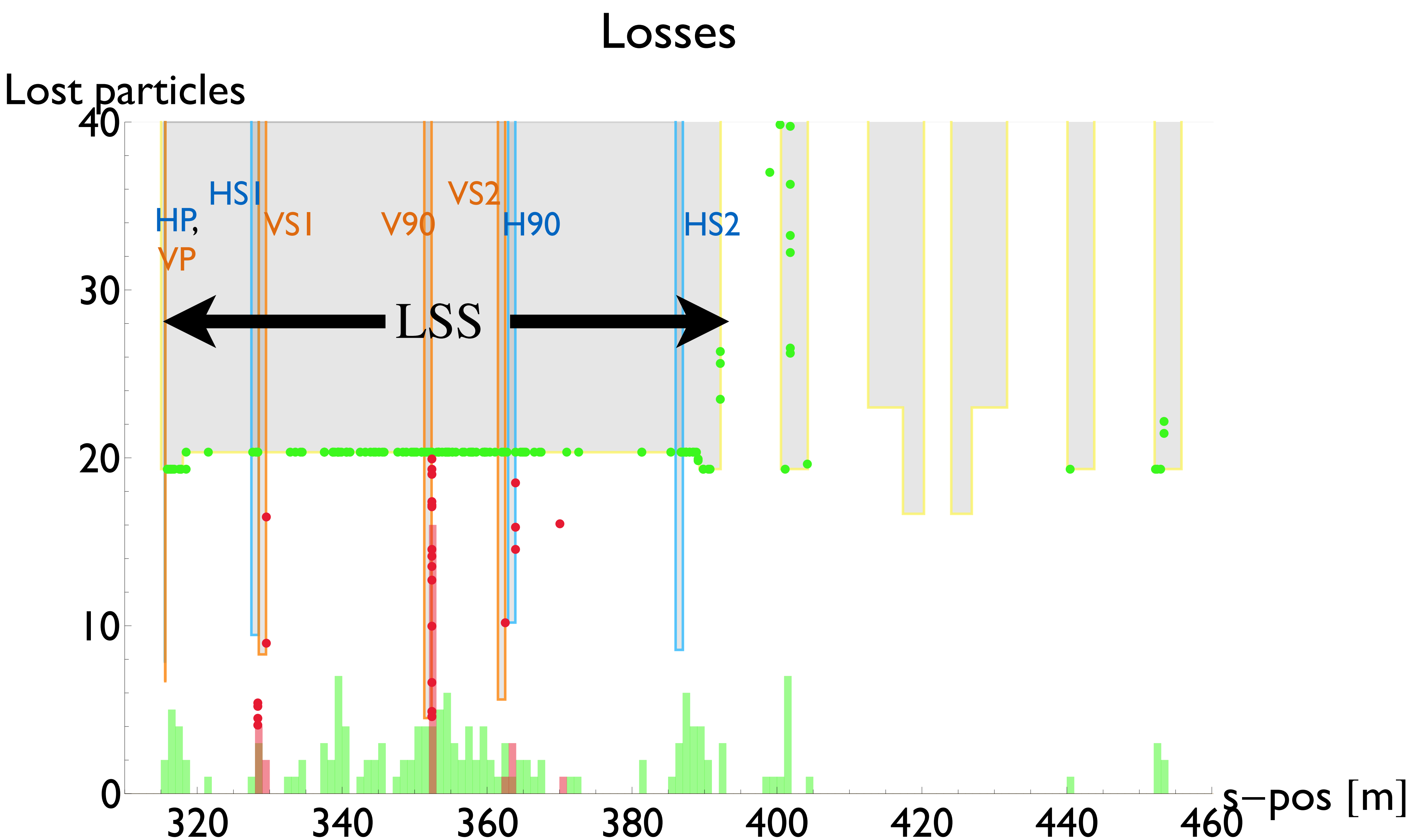
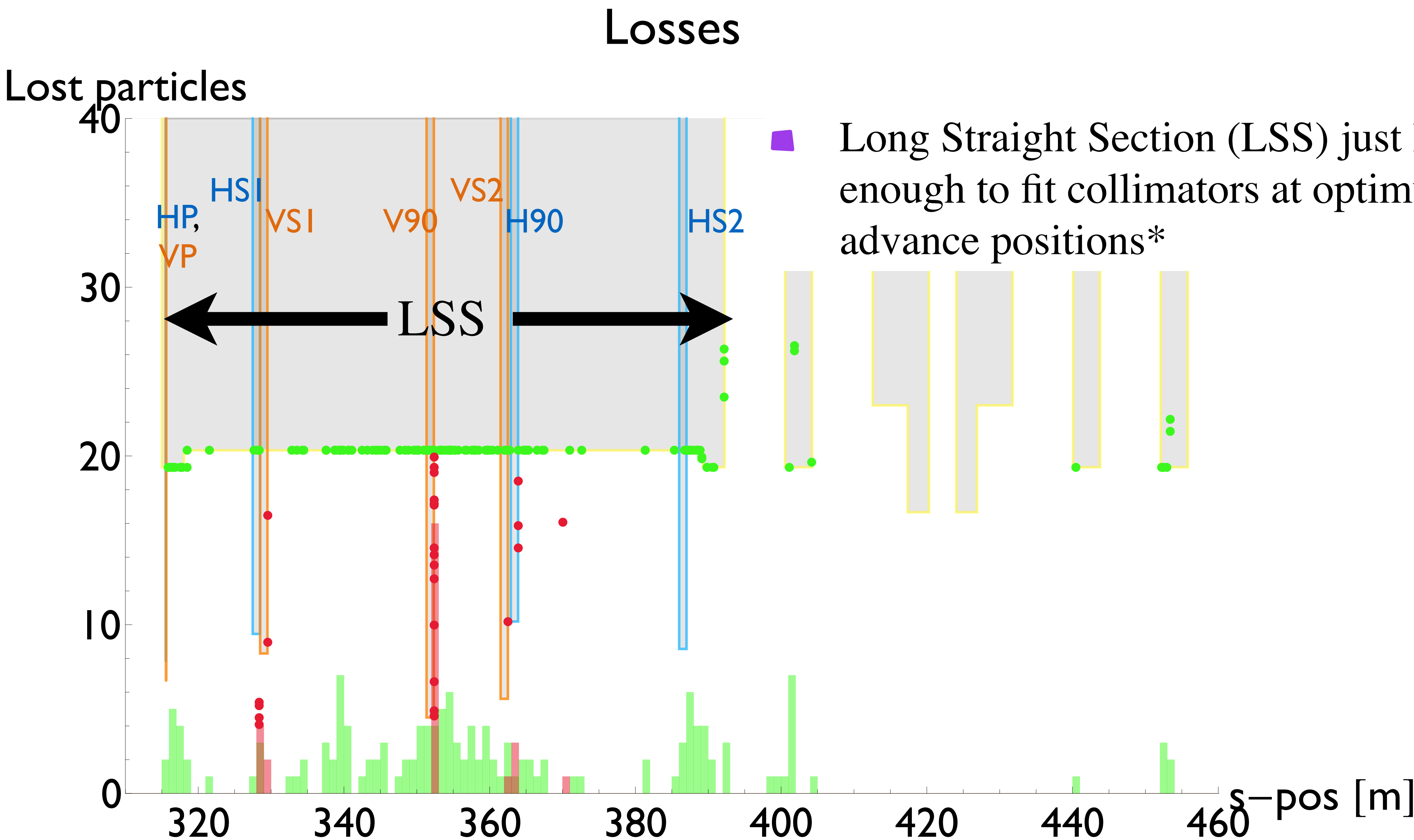
Additional collimator has a positive impact

Moving collimators (1/3)



LSS: Long Straight Section

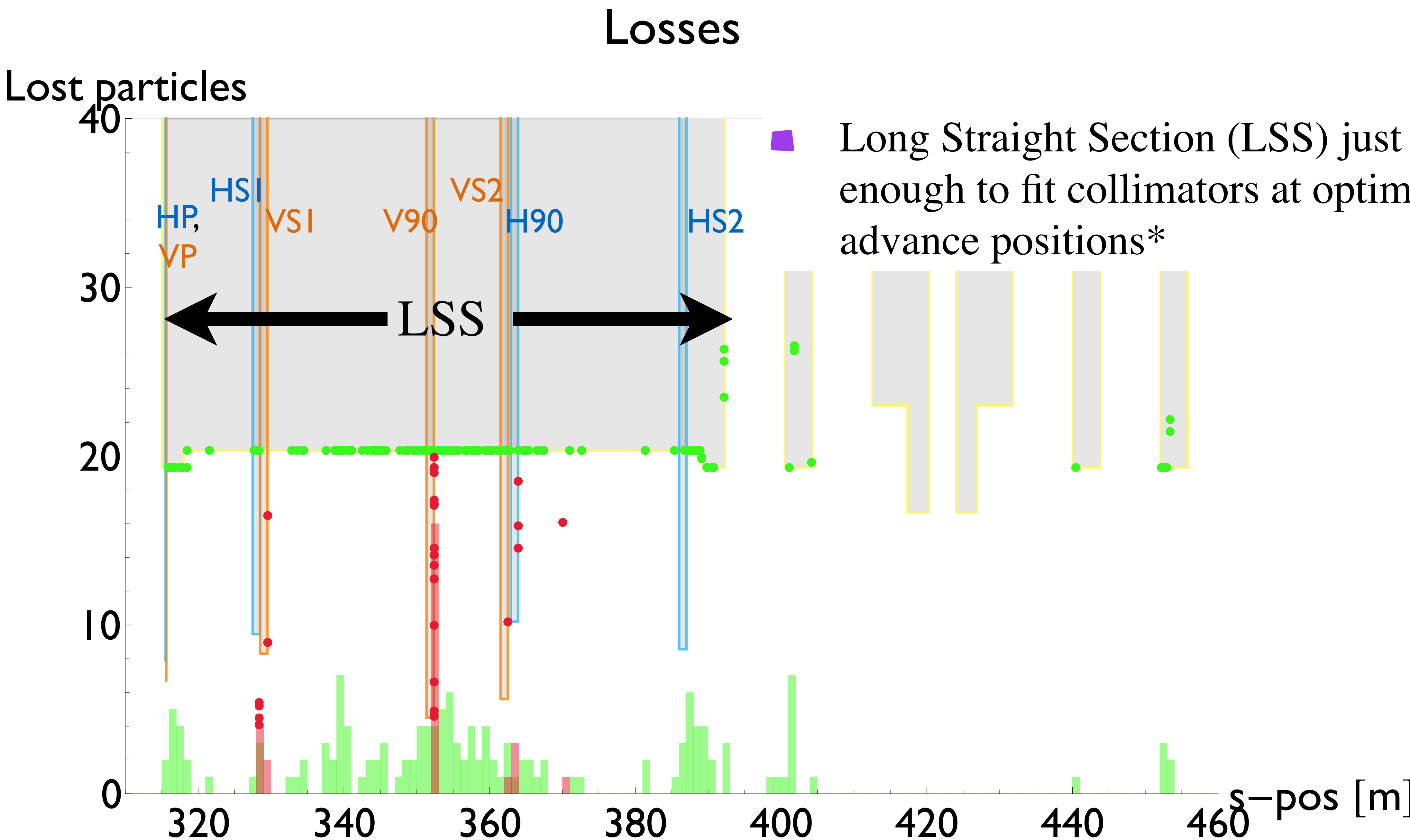
Moving collimators (1/3)



- Long Straight Section (LSS) just long enough to fit collimators at optimum phase advance positions*

LSS: Long Straight Section

Moving collimators (1/3)



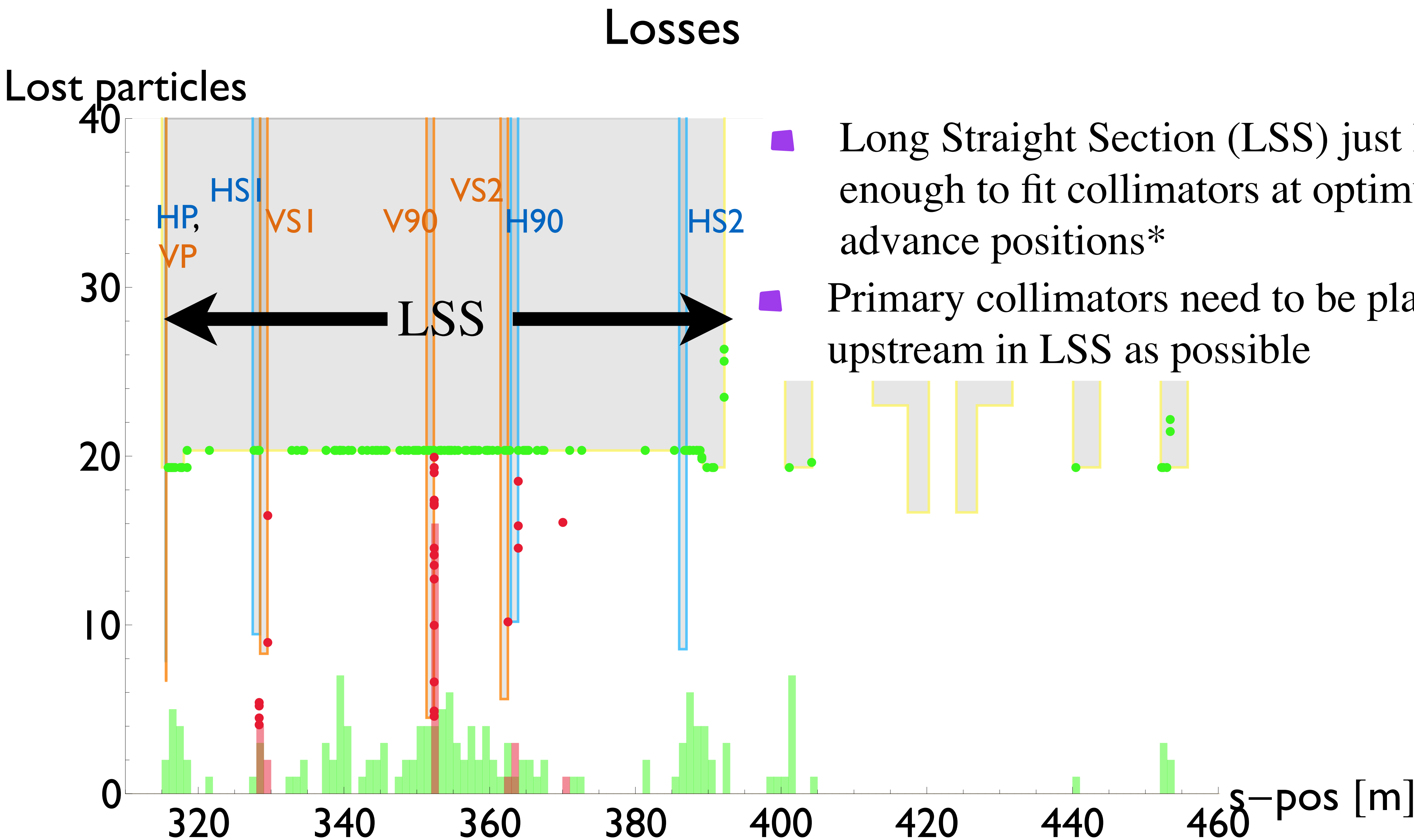
- Long Straight Section (LSS) just long enough to fit collimators at optimum phase advance positions*

**Remember: optimum s-location of secondary collimators is related to phase-advance wrt primary collimator:*

- $\mu_{s1}=acos(N_p/N_s)$, $\mu_{s2}=\pi-\mu_{s1}$
- *for* $N_p=2.5\sigma$ *and* $N_s=3.0\sigma$: $\mu_{s1}\sim 34^o$ *and* $\mu_{s2}\sim 146^o$
- μ_{LSS}*:152*^{o} *(H)*

LSS: Long Straight Section

Moving collimators (1/3)



- Long Straight Section (LSS) just long enough to fit collimators at optimum phase advance positions*
- Primary collimators need to be placed as upstream in LSS as possible

**Remember: optimum s-location of secondary collimators is related to phase-advance wrt primary collimator:*

- $\mu_{s1}=acos(N_p/N_s)$, $\mu_{s2}=\pi-\mu_{s1}$
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- μ_{LSS}: 152^o (H)

LSS: Long Straight Section

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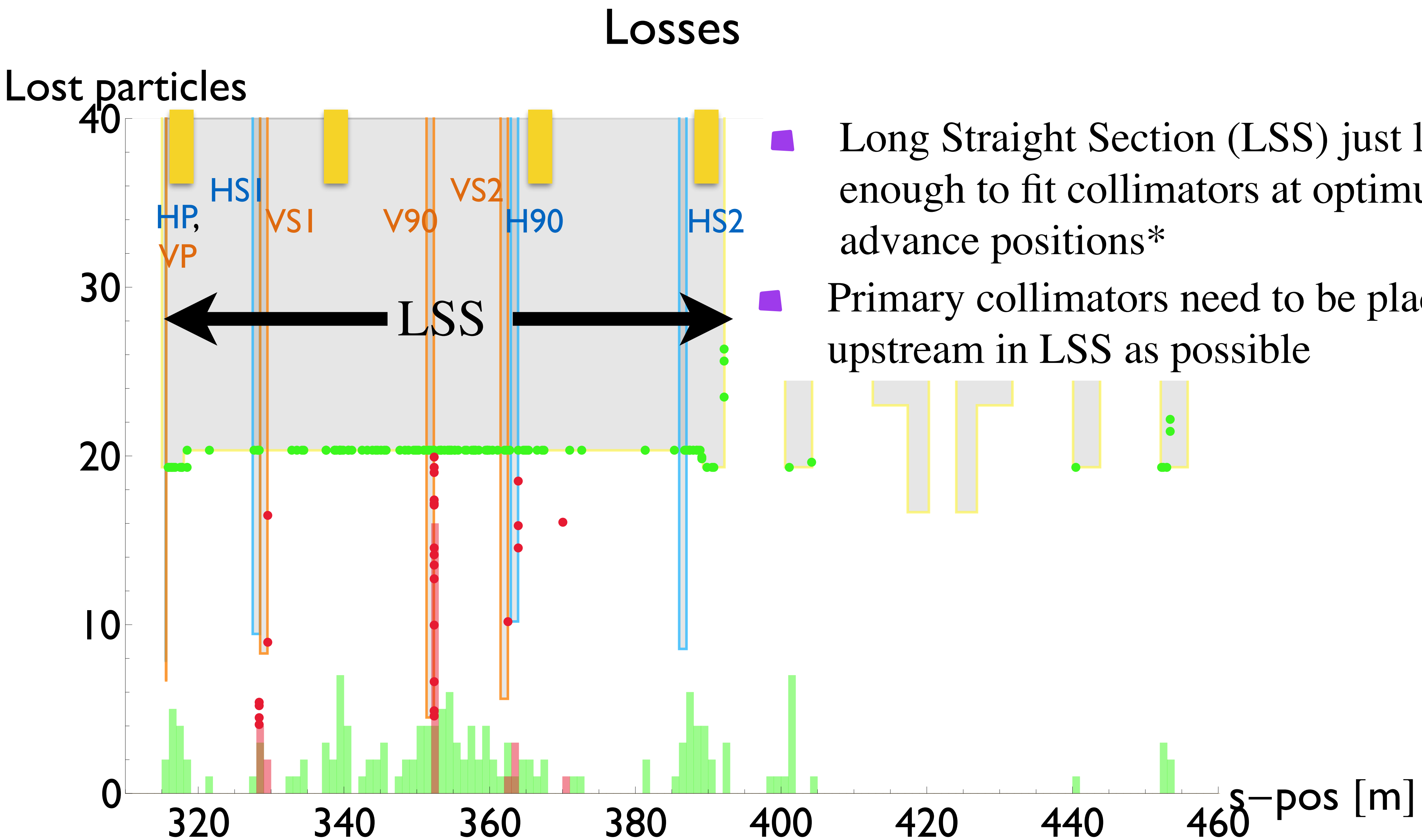

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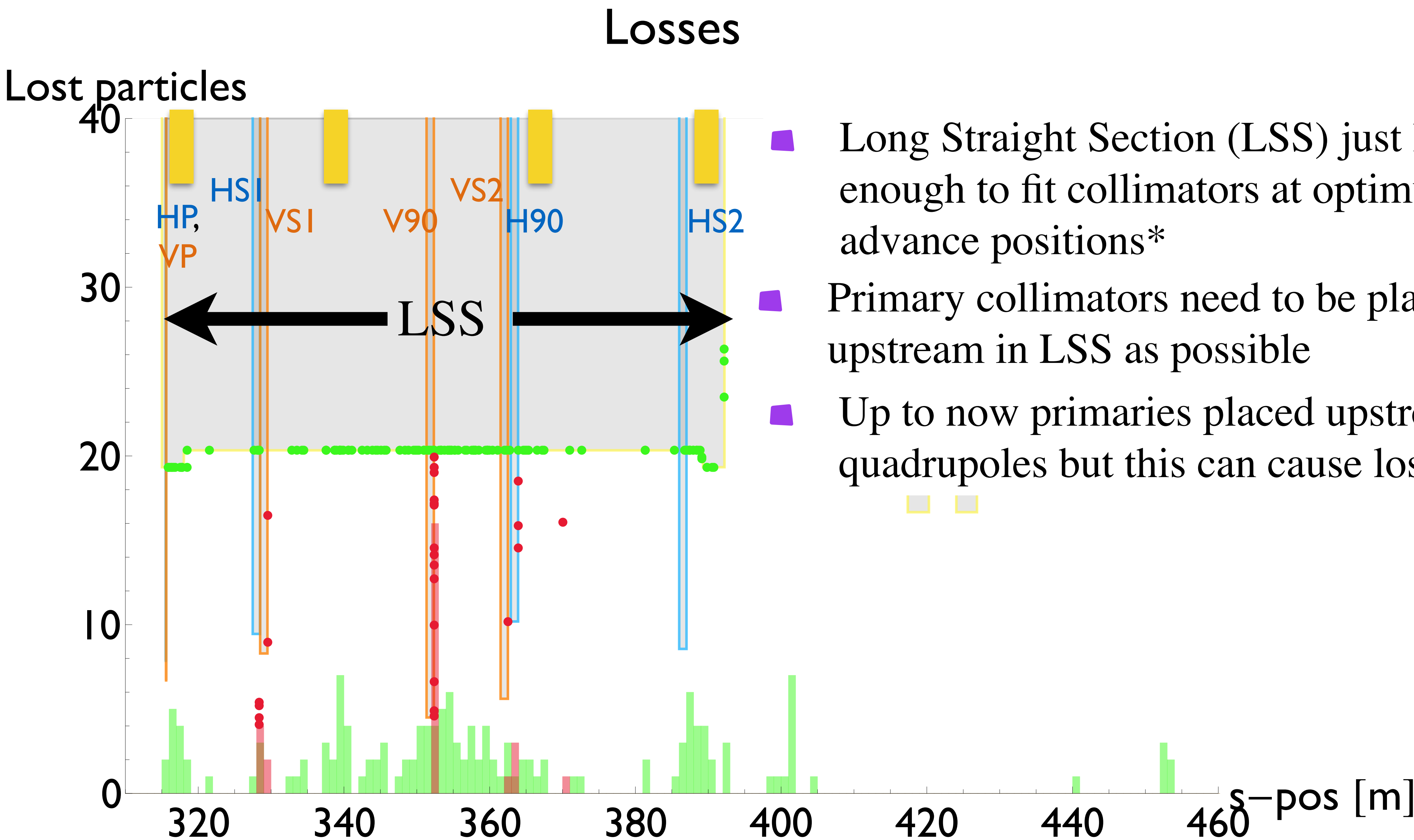
LSS: Long Straight Section

Quadrupoles

Moving collimators (1/3)



- Long Straight Section (LSS) just long enough to fit collimators at optimum phase advance positions*
- Primary collimators need to be placed as upstream in LSS as possible
- Up to now primaries placed upstream of quadrupoles but this can cause losses

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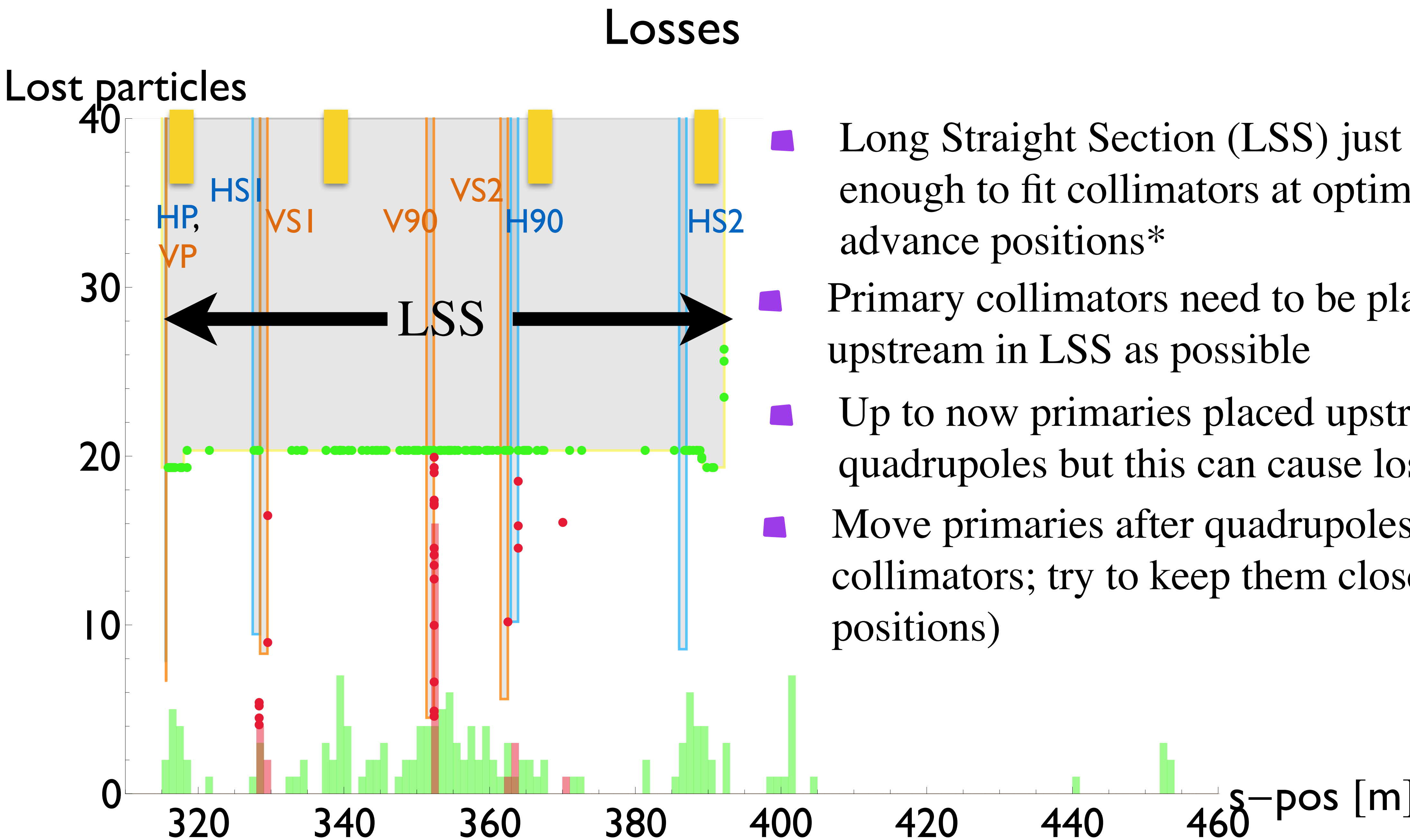
Quadrupoles

Moving collimators (1/3)



- Long Straight Section (LSS) just long enough to fit collimators at optimum phase advance positions*
- Primary collimators need to be placed as upstream in LSS as possible
- Up to now primaries placed upstream of quadrupoles but this can cause losses
- Move primaries after quadrupoles (shift secondary collimators; try to keep them close to optimum positions)

**Remember: optimum s-location of secondary collimators is related to phase-advance wrt primary collimator:*

- $\mu_{s1}=acos(N_p/N_s)$, $\mu_{s2}=\pi-\mu_{s1}$
- *for* $N_p=2.5\sigma$ *and* $N_s=3.0\sigma$: $\mu_{s1}\sim 34^o$ *and* $\mu_{s2}\sim 146^o$
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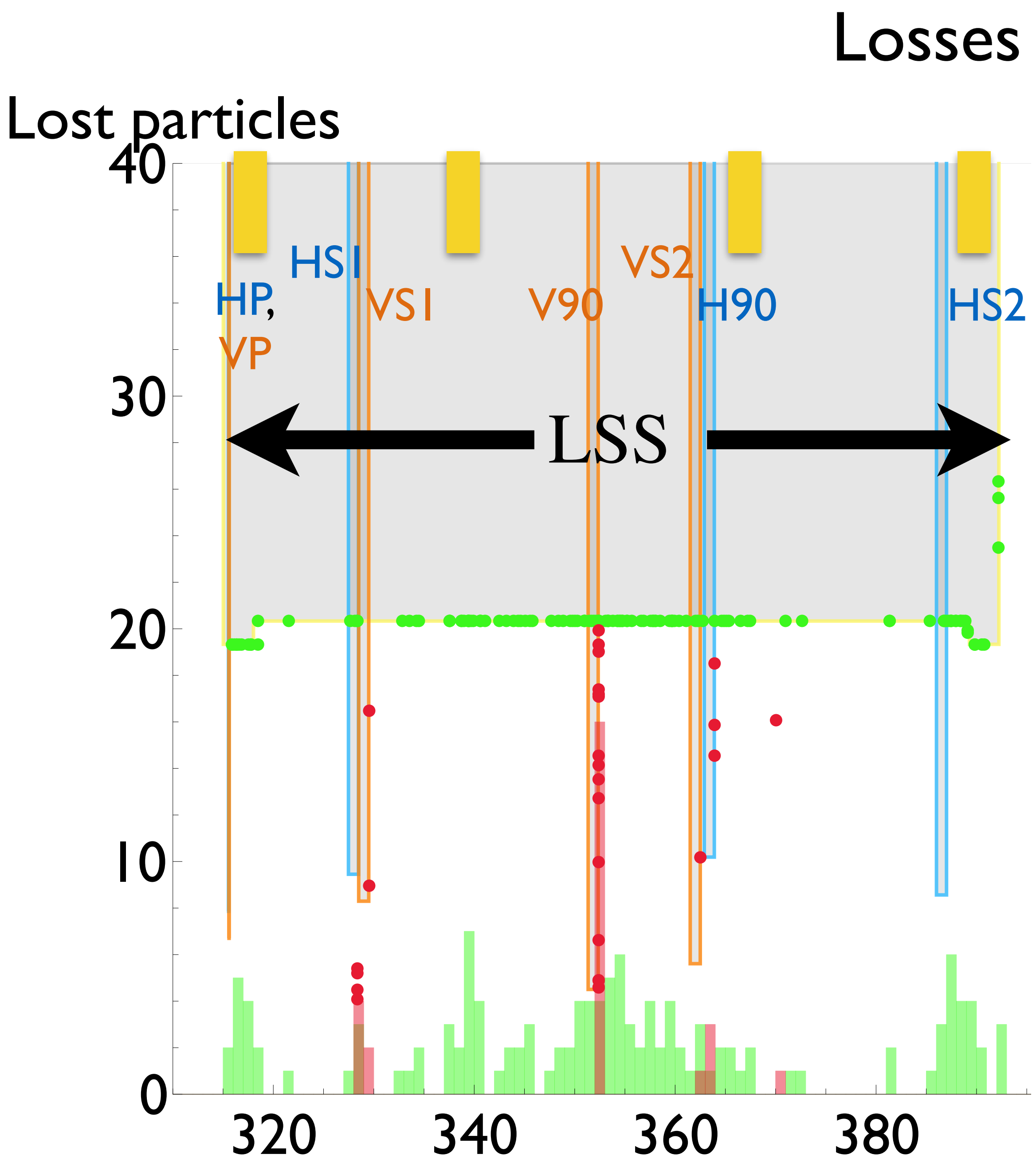
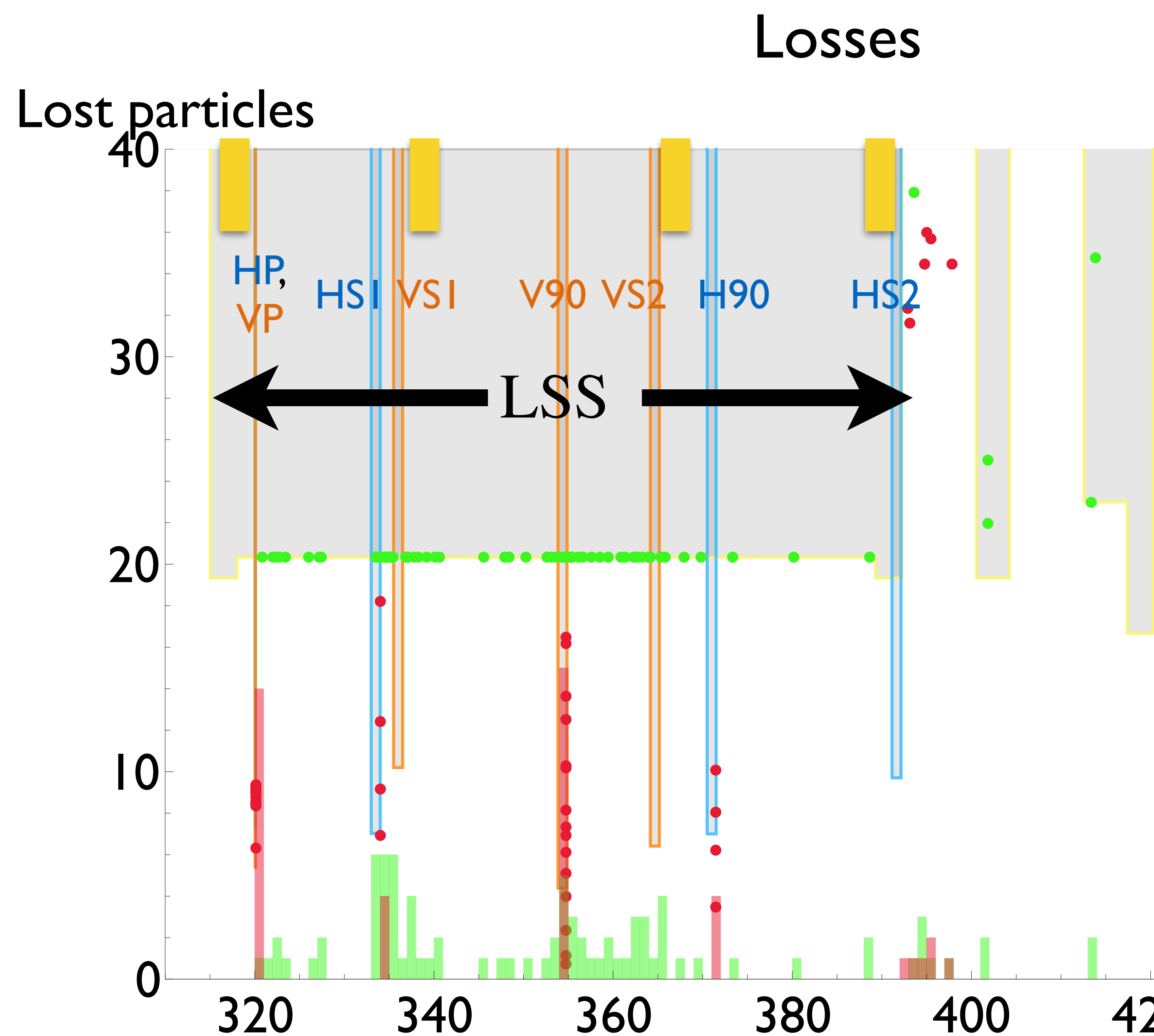
LSS: Long Straight Section

Quadrupoles

Moving collimators (1/3)





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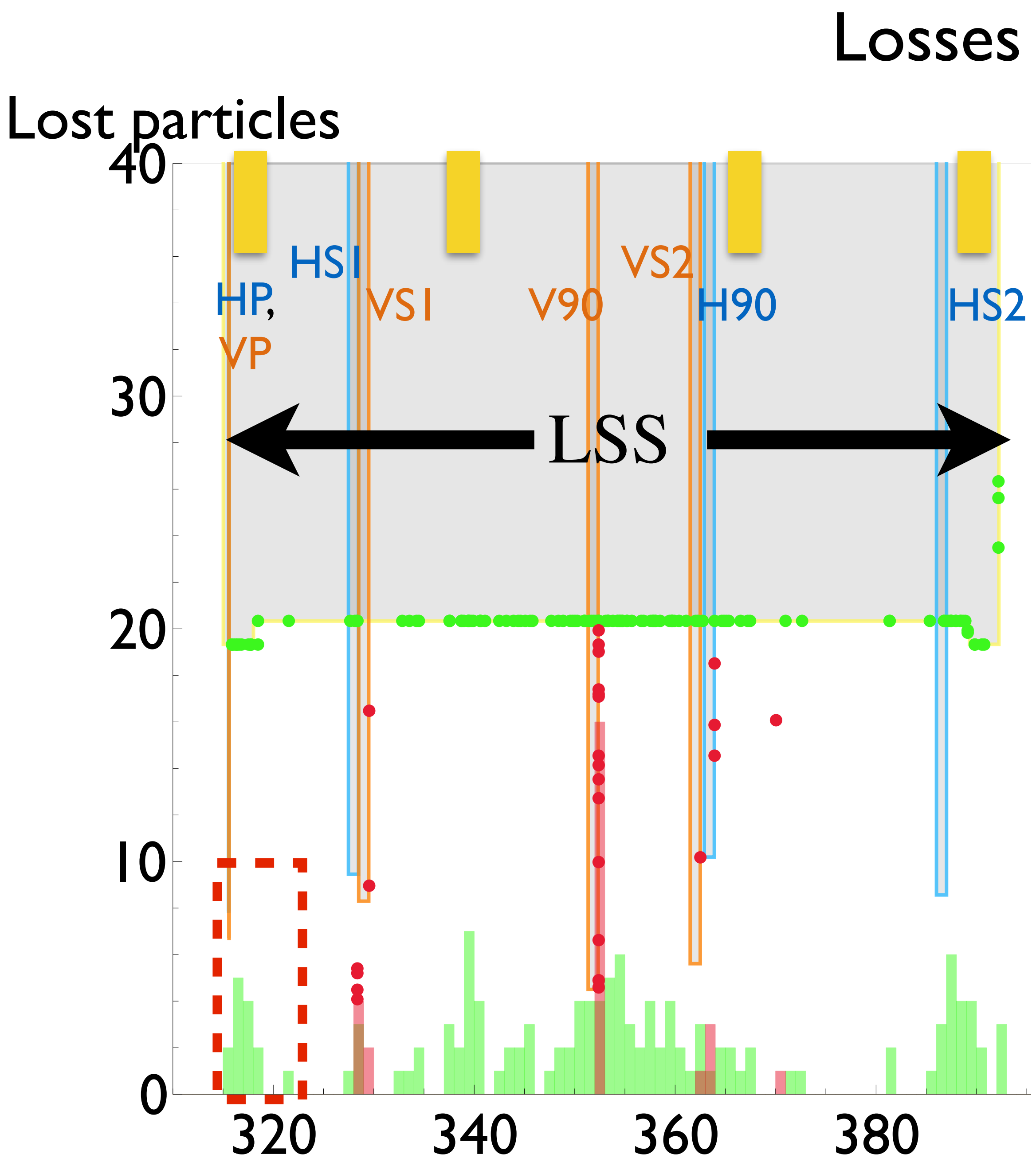
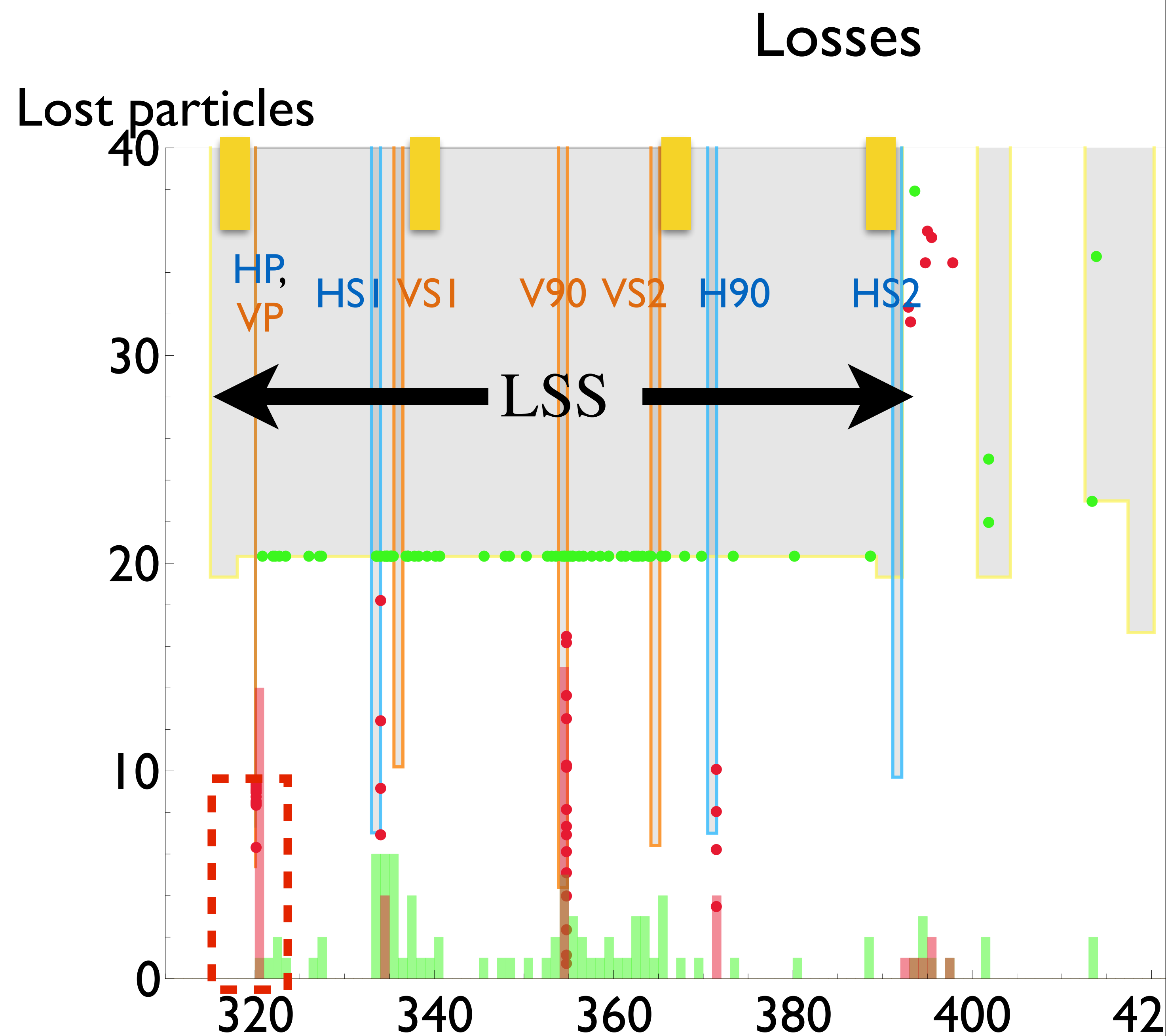
Quadrupoles

Moving collimators (1/3)





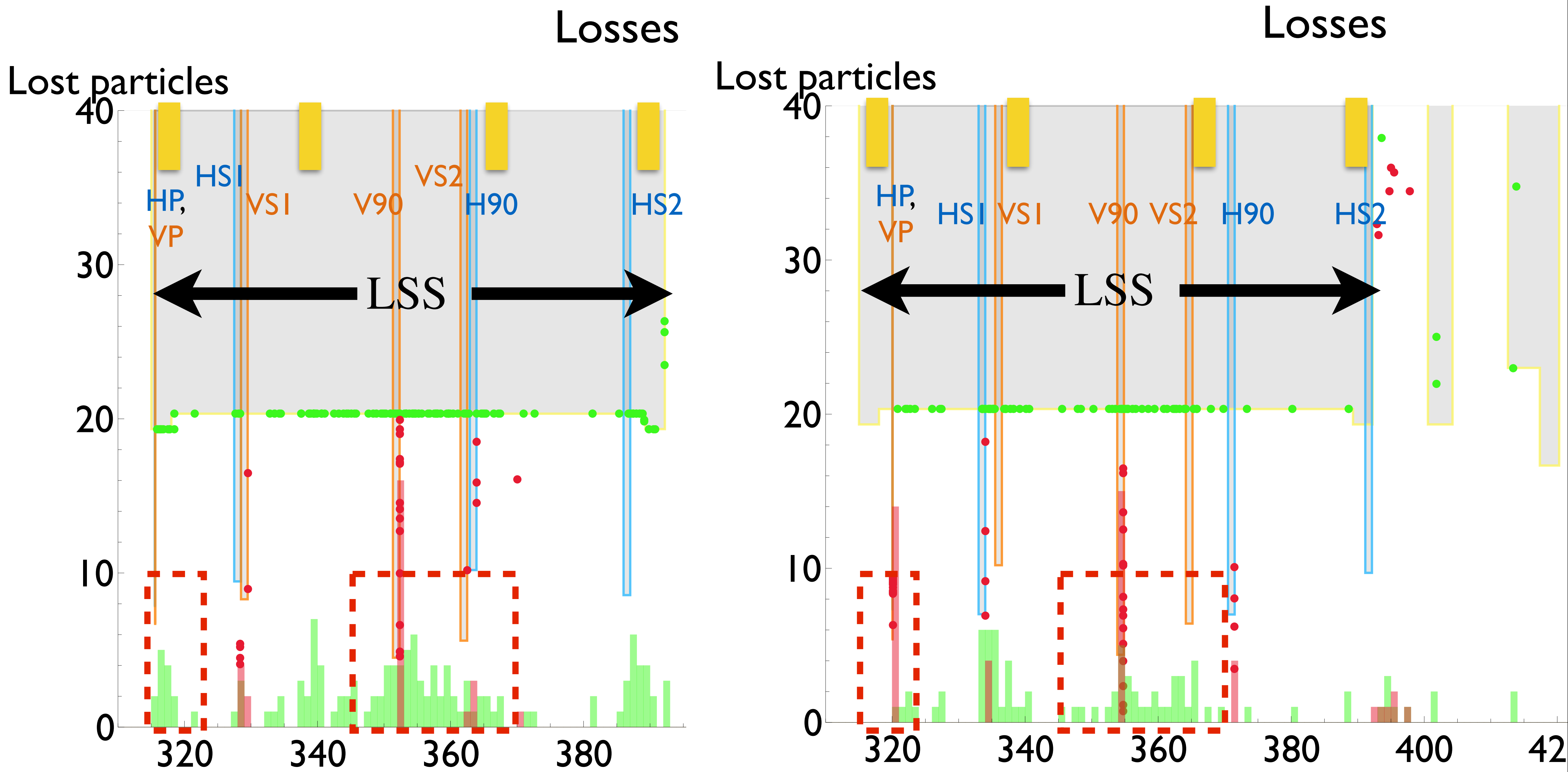
**Remember: optimum s-location of secondary collimators is related to phase-advance wrt primary collimator:*

- $\mu_{s1}=acos(N_p/N_s)$, $\mu_{s2}=\pi-\mu_{s1}$
- *for* $N_p=2.5\sigma$ *and* $N_s=3.0\sigma$: $\mu_{s1}\sim34^o$ *and* $\mu_{s2}\sim146^o$
- μ_{LSS}*:152º (H)*

LSS: Long Straight Section

Quadrupoles

Moving collimators (1/3)



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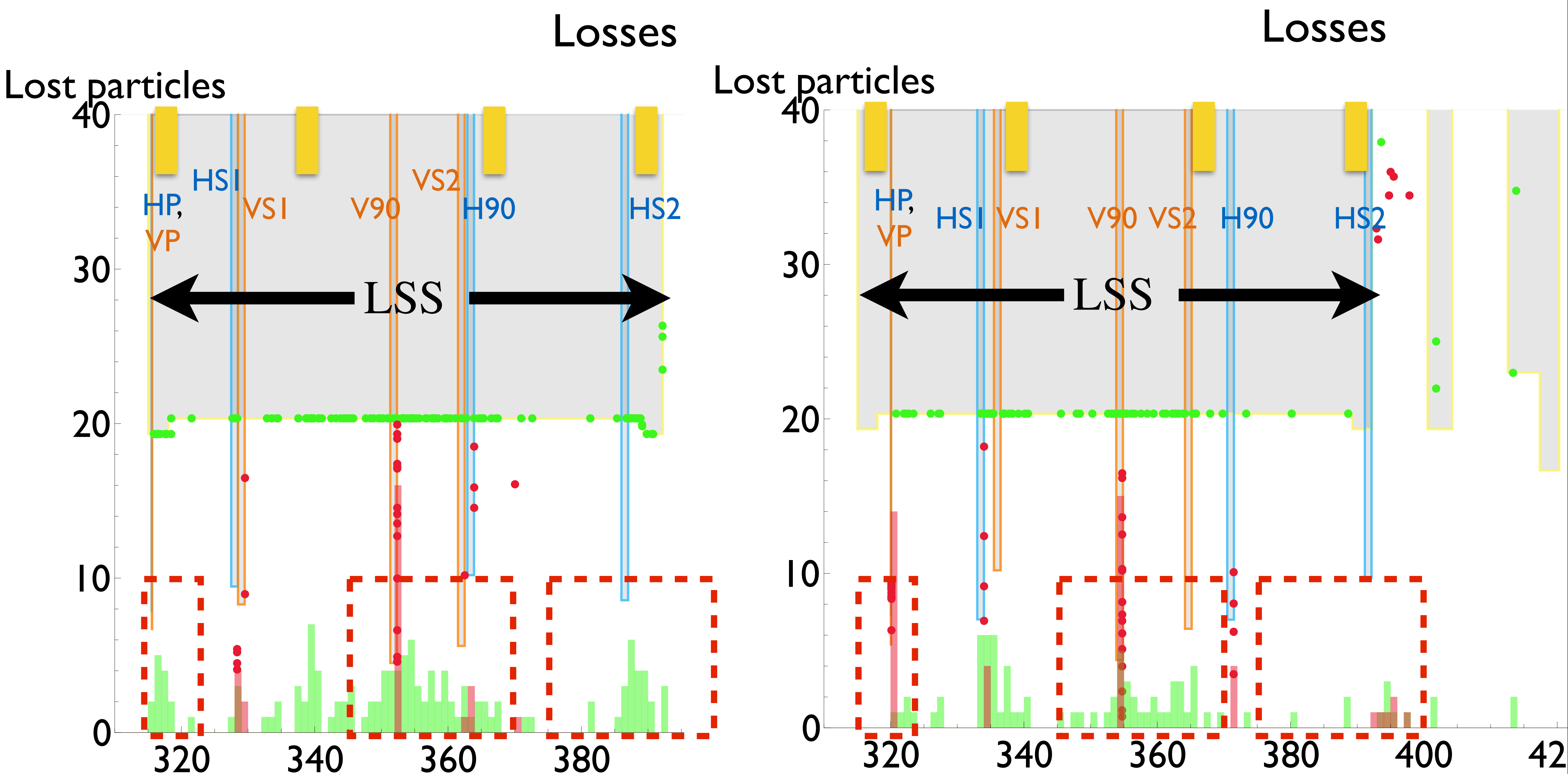

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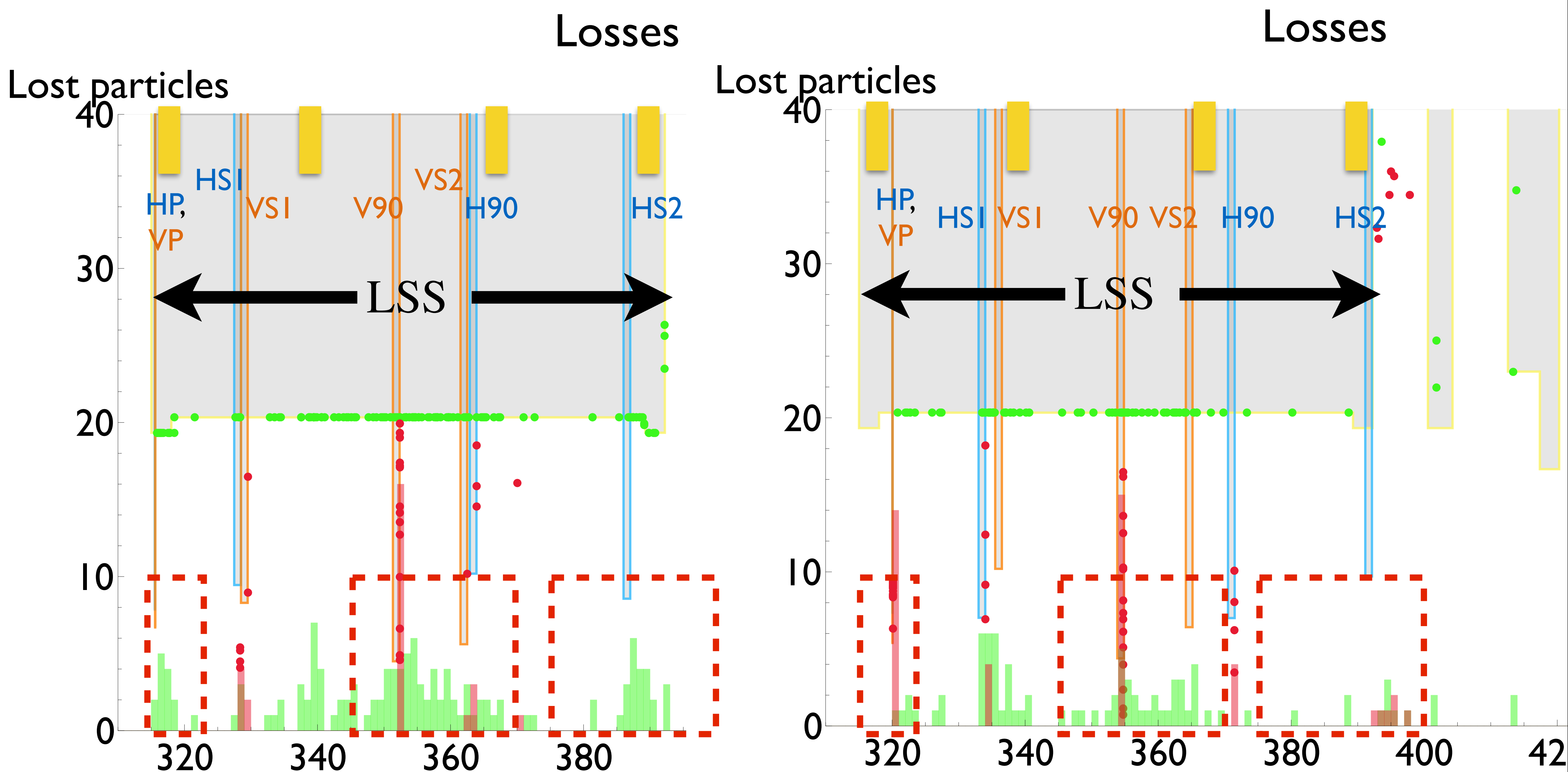
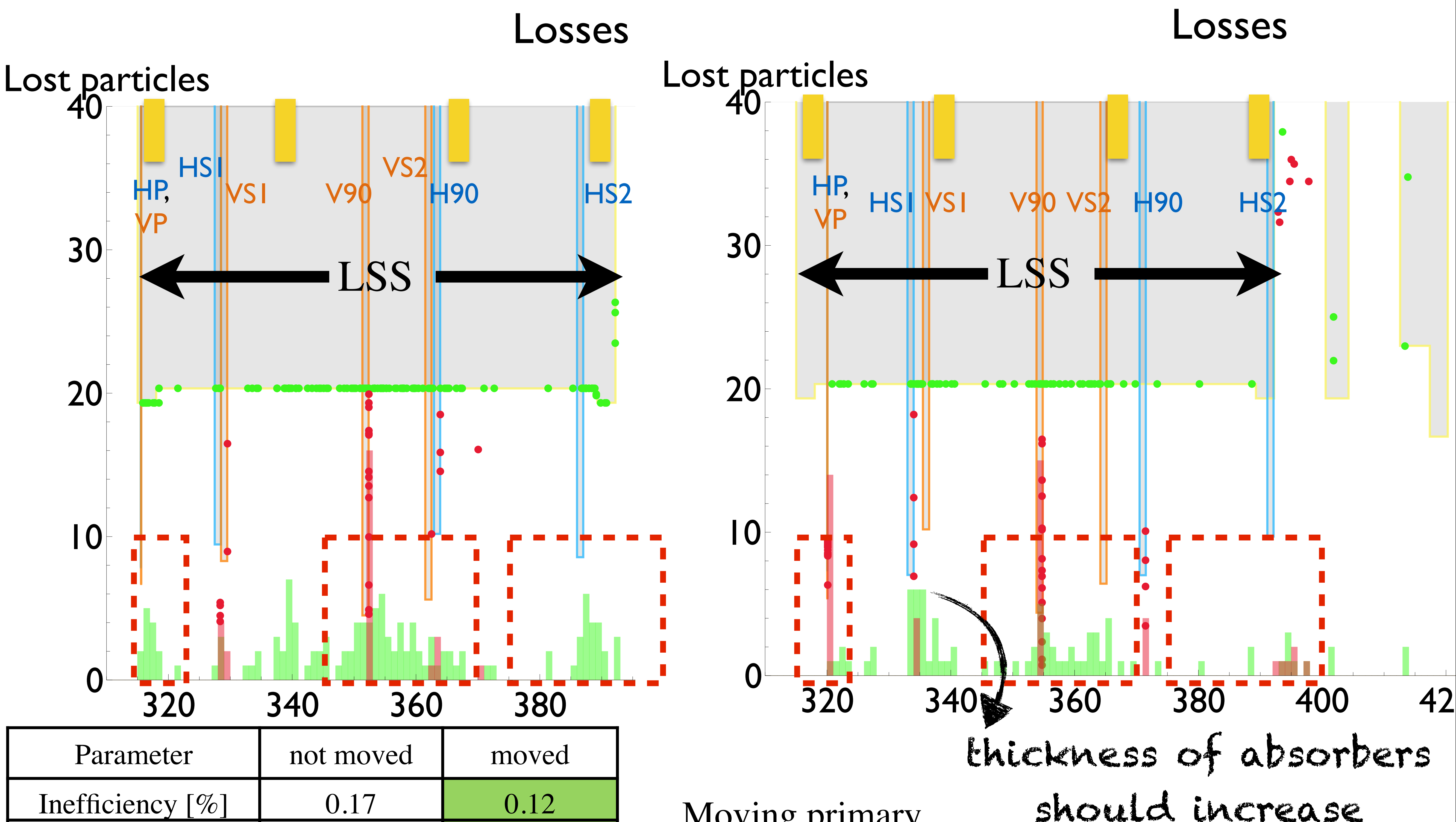


Parameter	not moved	moved
Inefficiency [%]	0.17	0.12
Cleaning Speed [%]	0.50	0.61
λ	2.94	5.08
absorptions	1067	1060
losses	150	86

Moving primary collimators after quadrupoles has a positive impact

Moving collimators (1/3)



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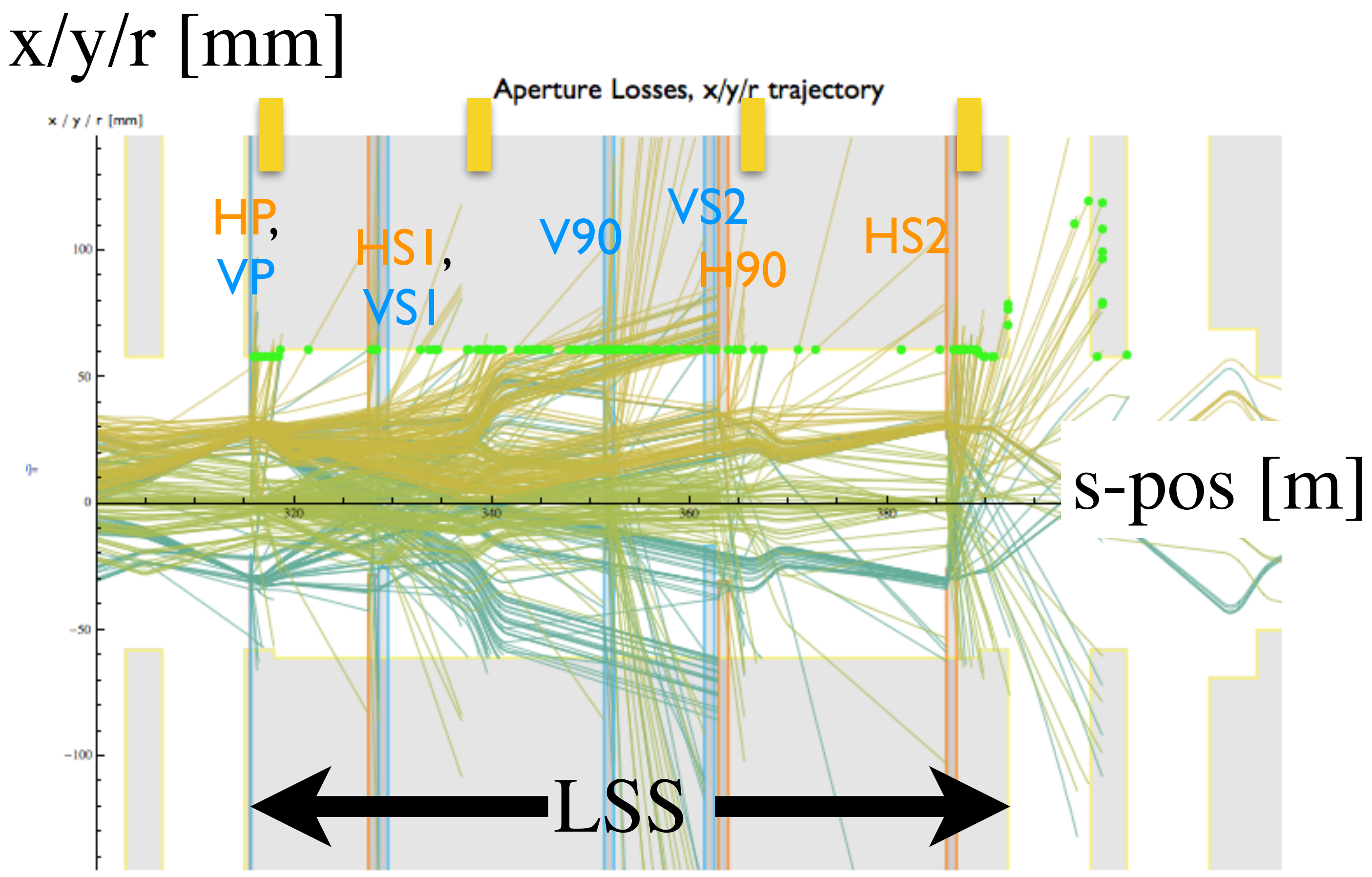
Moving primary collimators after quadrupoles has a positive impact

Moving collimators (2/3)

Losses in aperture (x-, y-trajectories)

Before moving the primaries



s-position of x/y losses

*different trajectory colors only to distinguish amongst lines

Moving collimators (2/3)

Losses in aperture (x-, y-trajectories)

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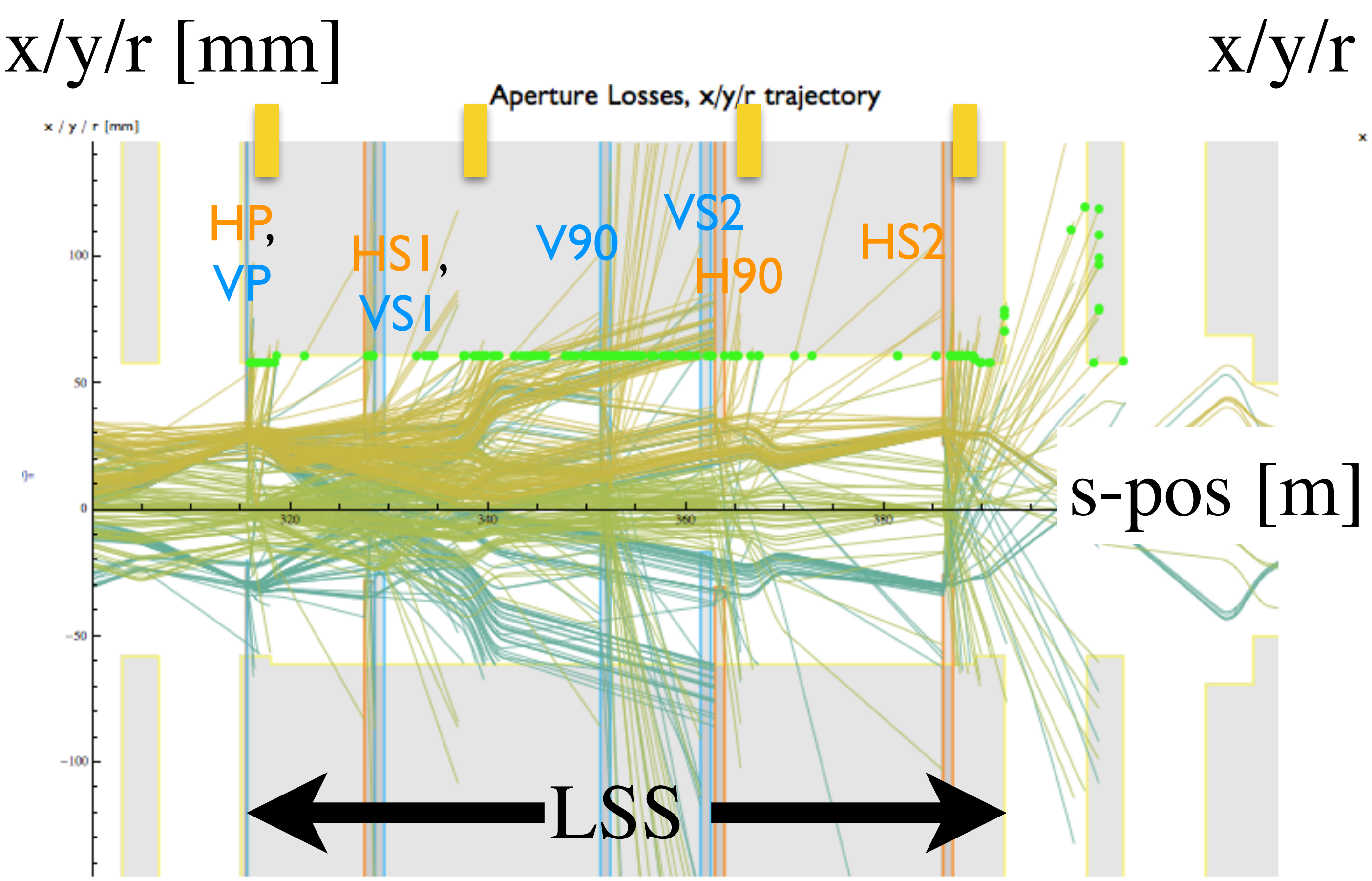
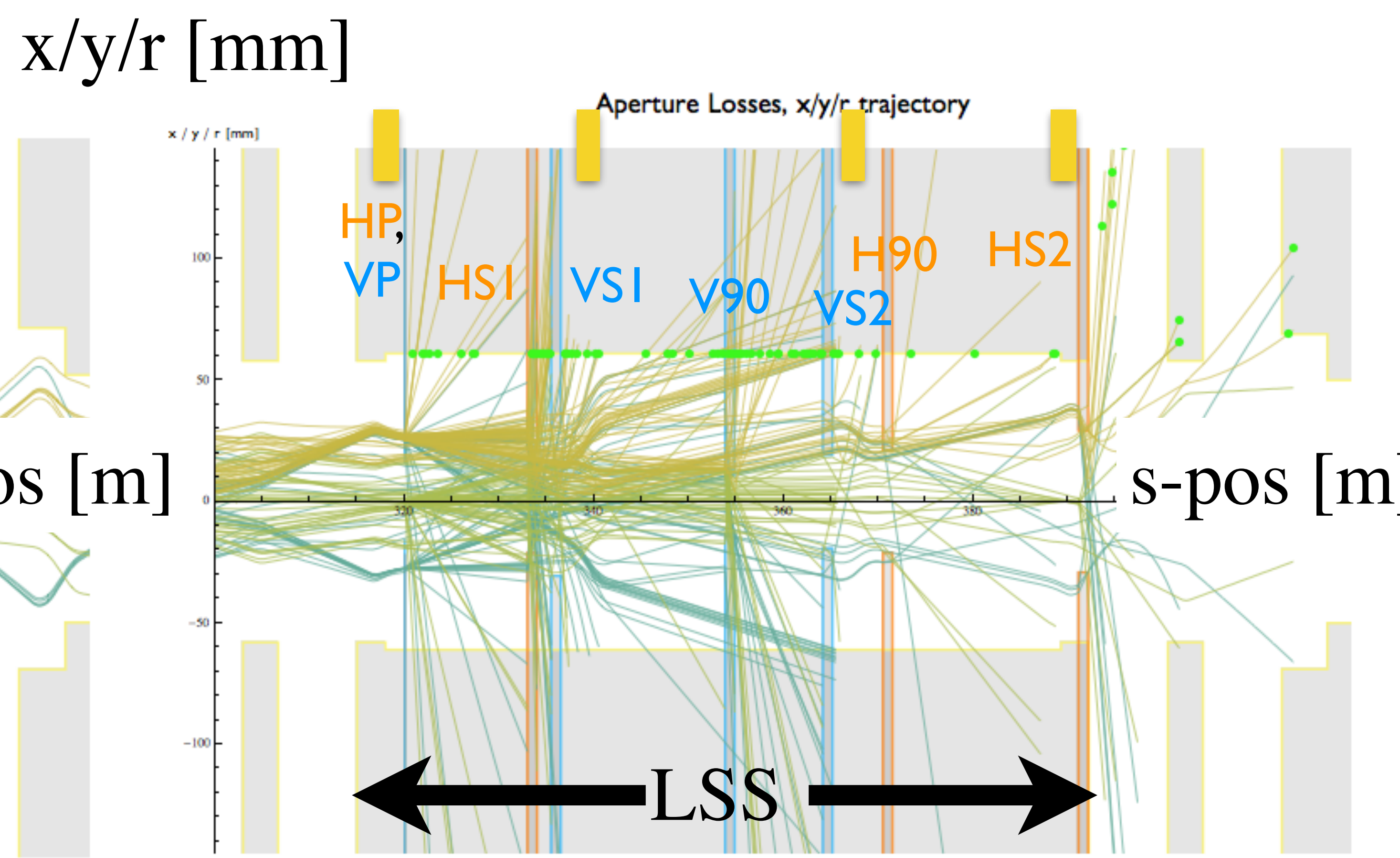


After moving the primaries



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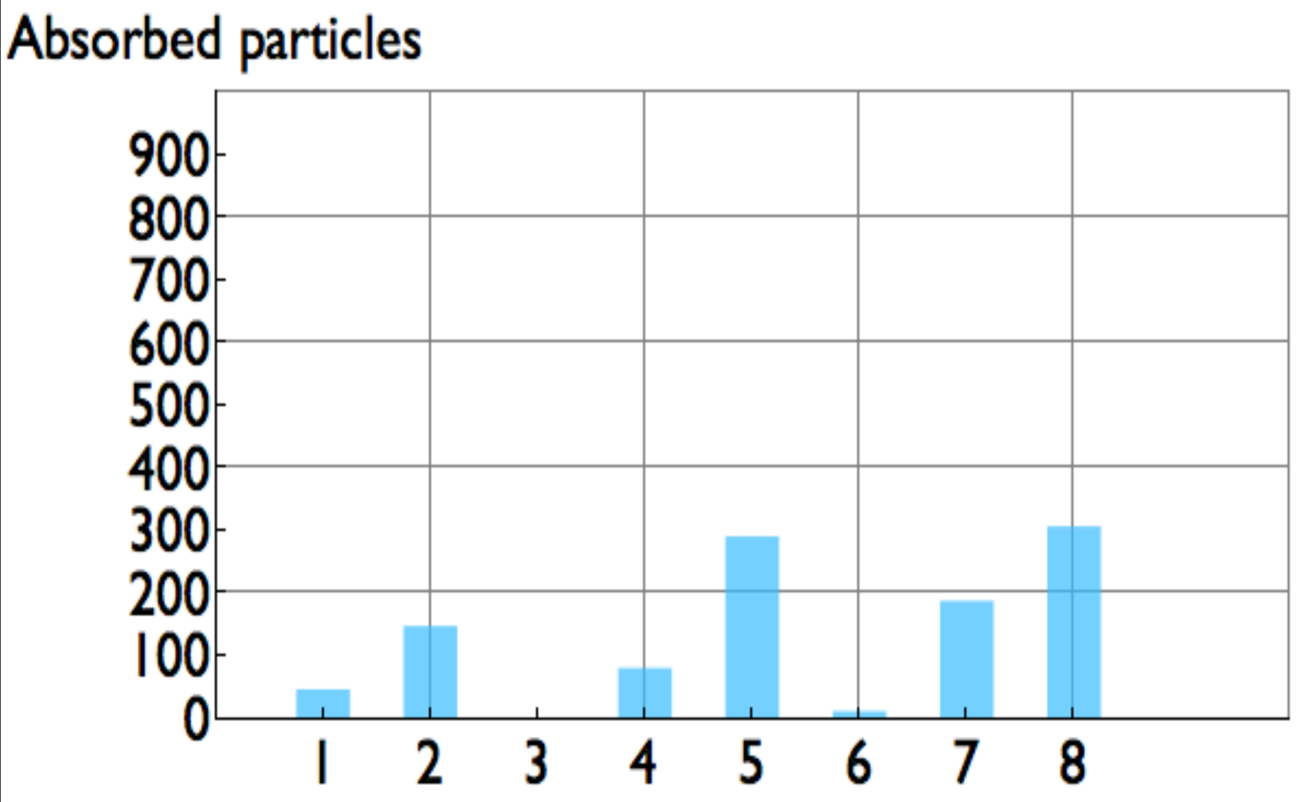
Moving collimators (3/3)

Particles absorbed in collimators

Before moving primaries



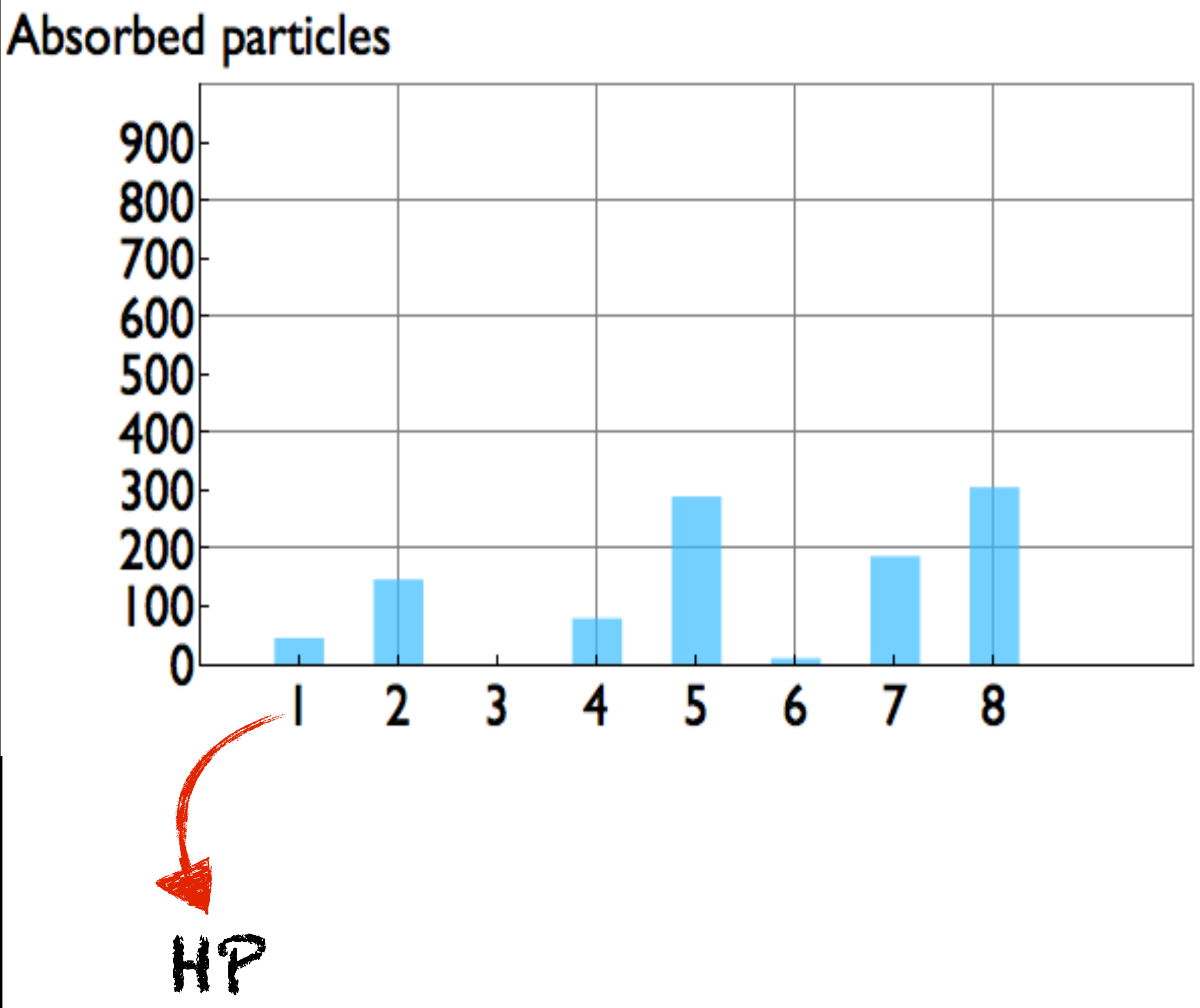
1-HP
2-HS1
3-VP
4-VS1
5-HS2
6-VS2
7-H90
8-V90

**Remember: input halo in this case was H*

Moving collimators (3/3)

Particles absorbed in collimators

Before moving primaries



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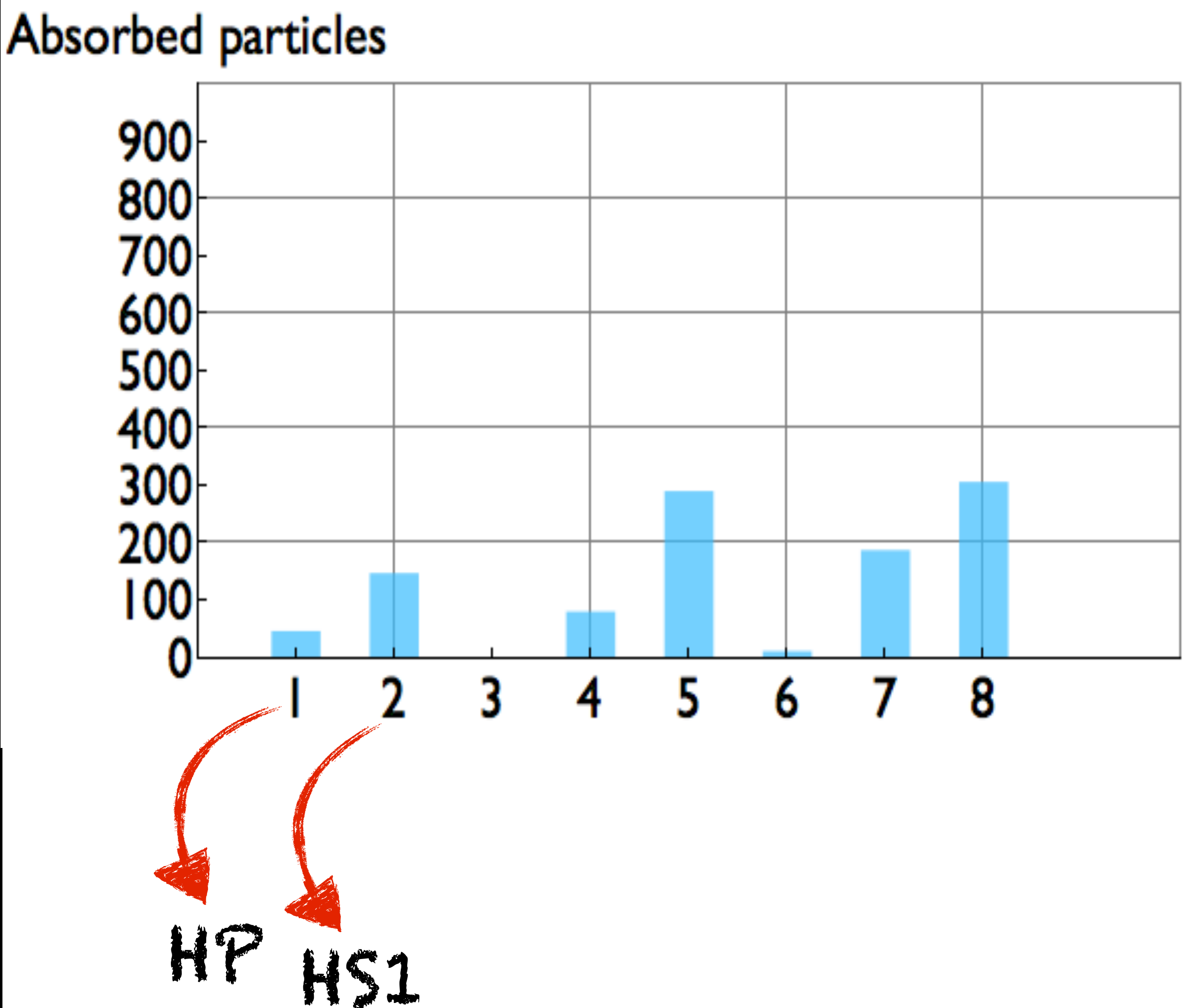

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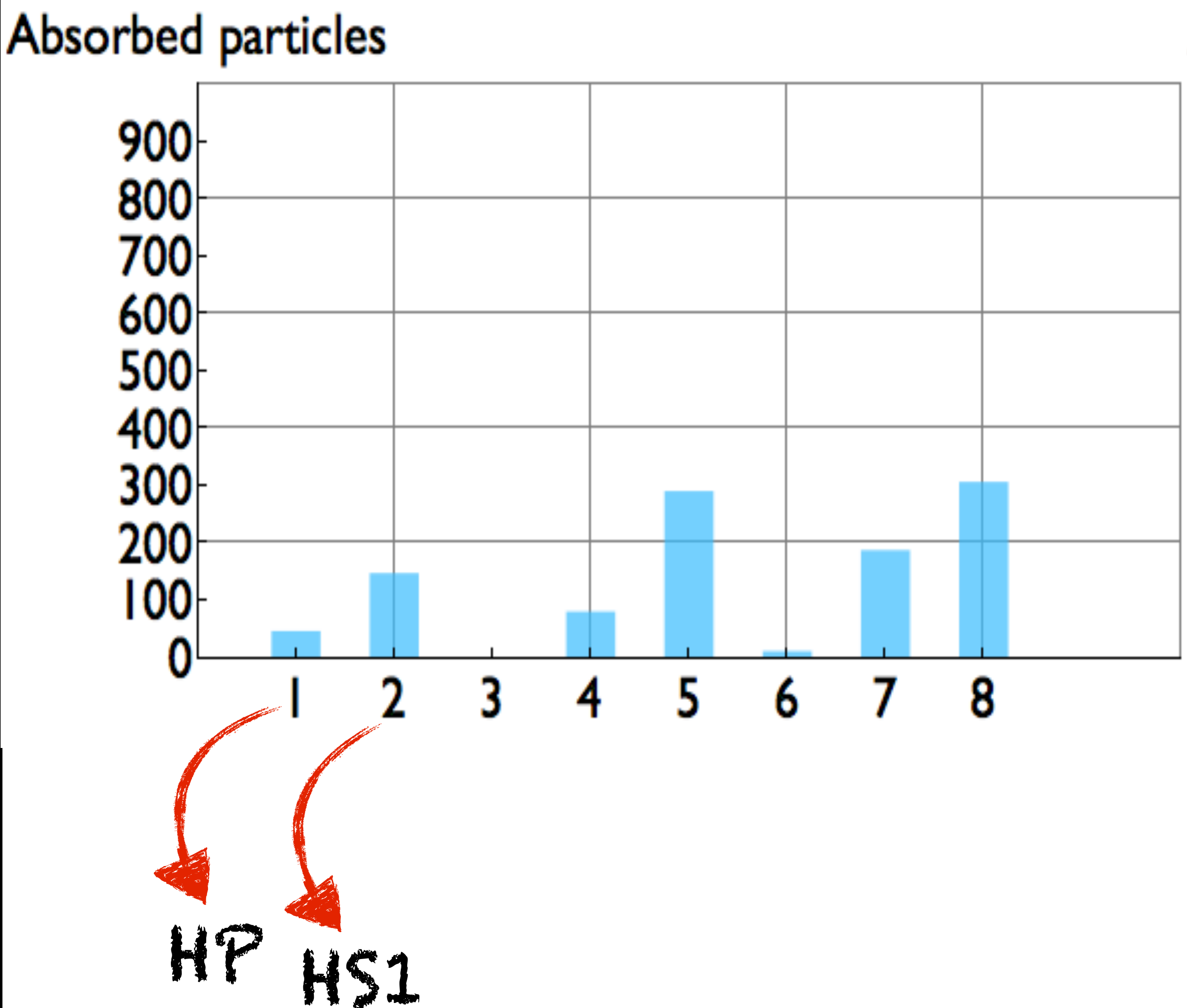
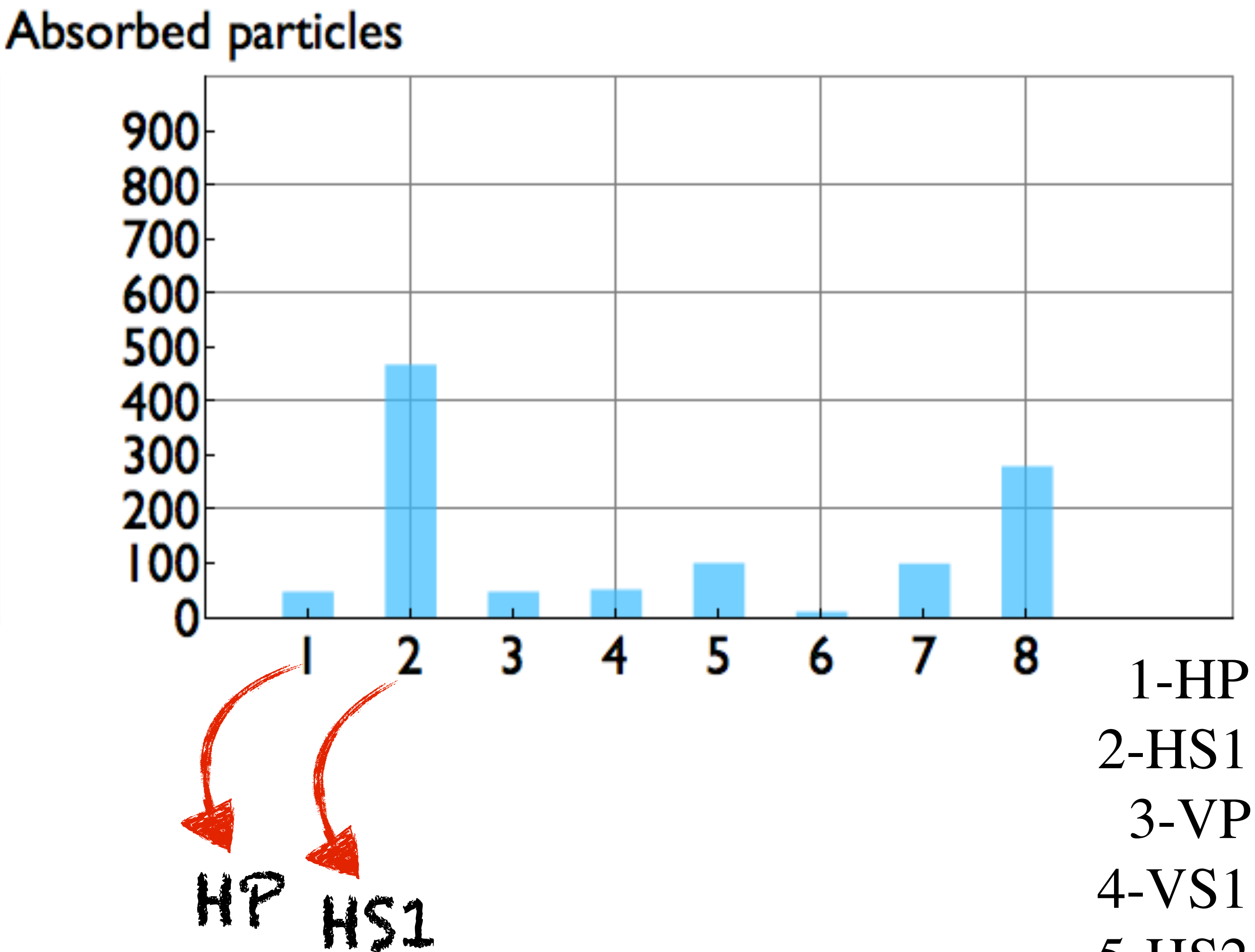


After moving primaries



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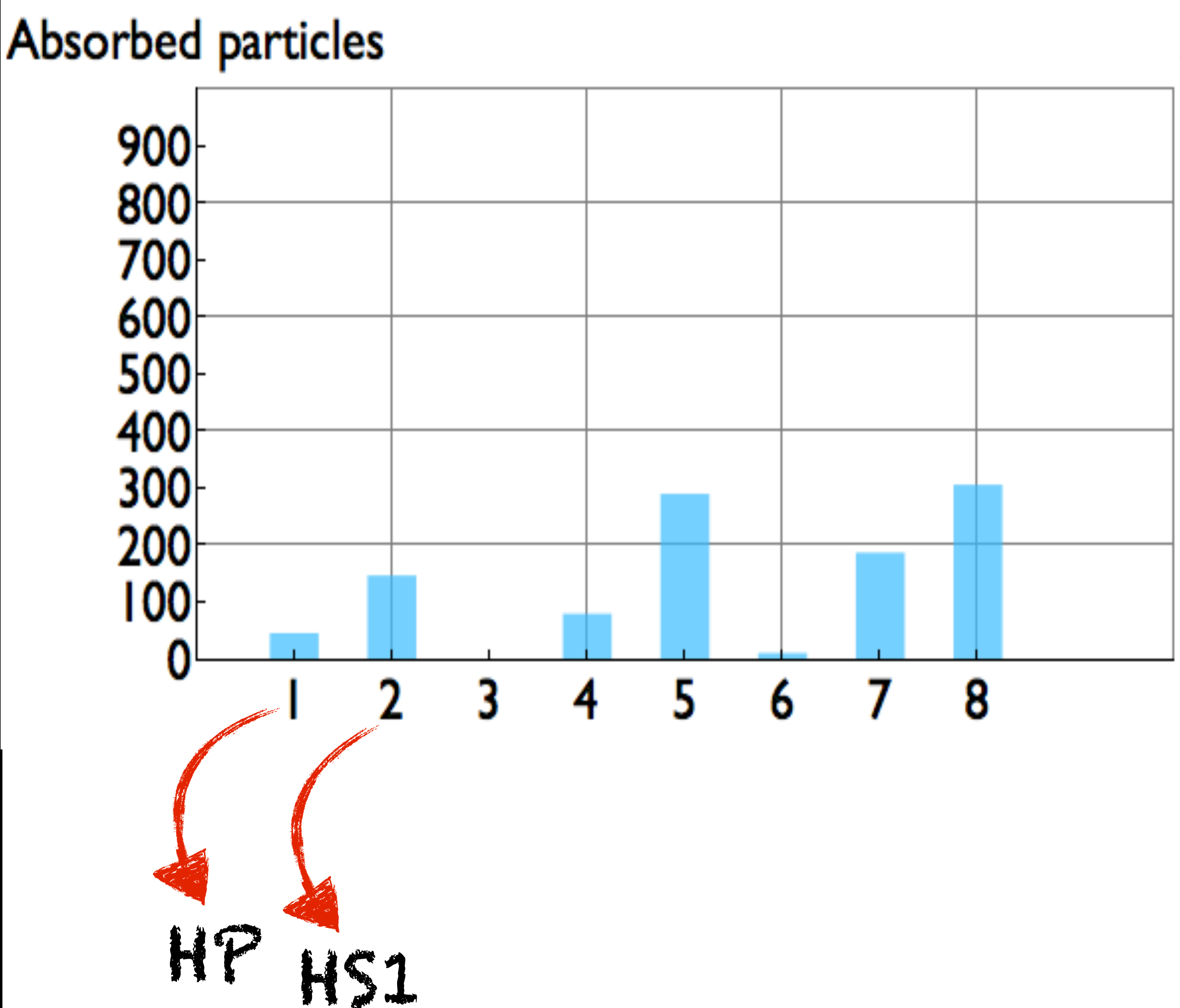

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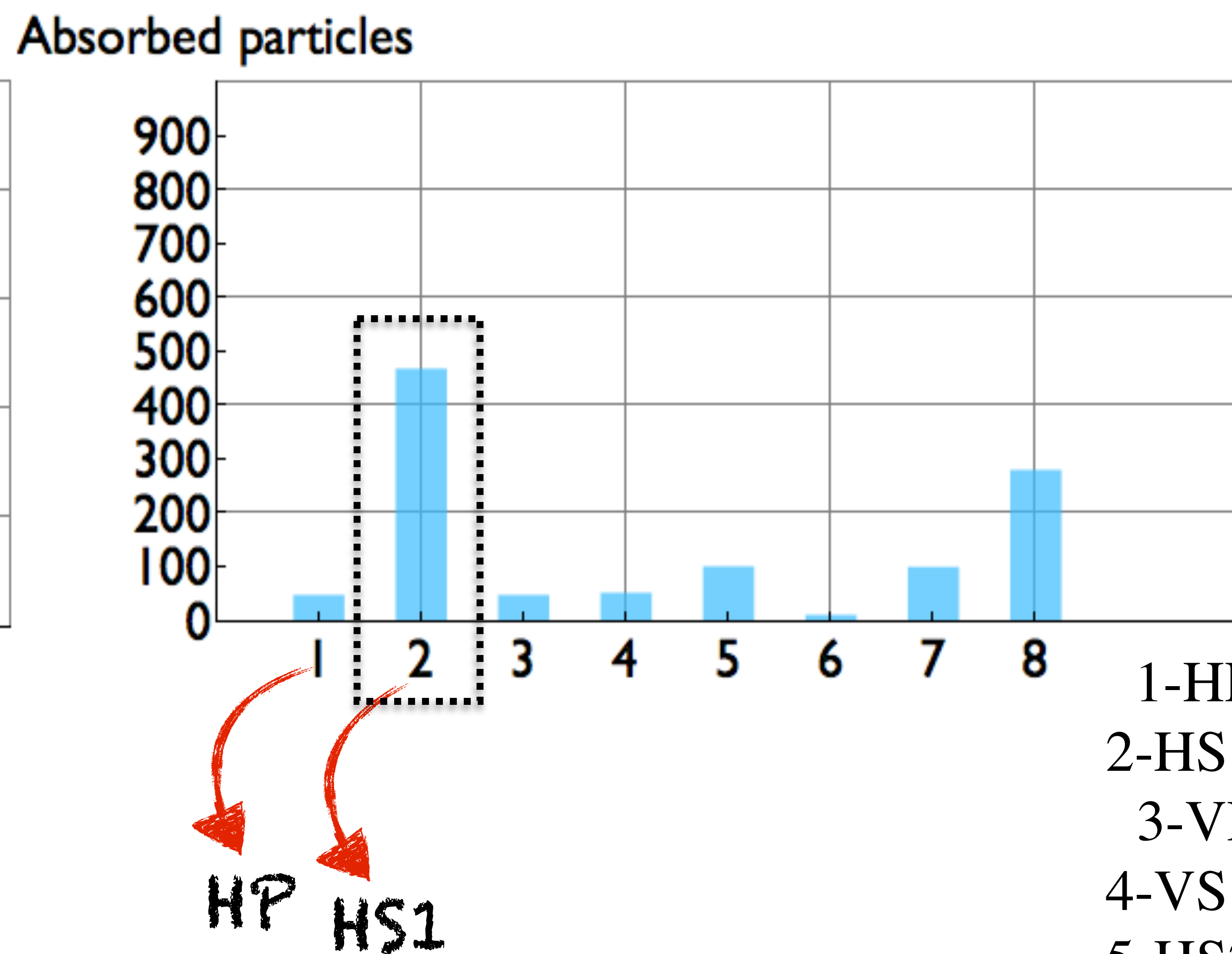

1-HP
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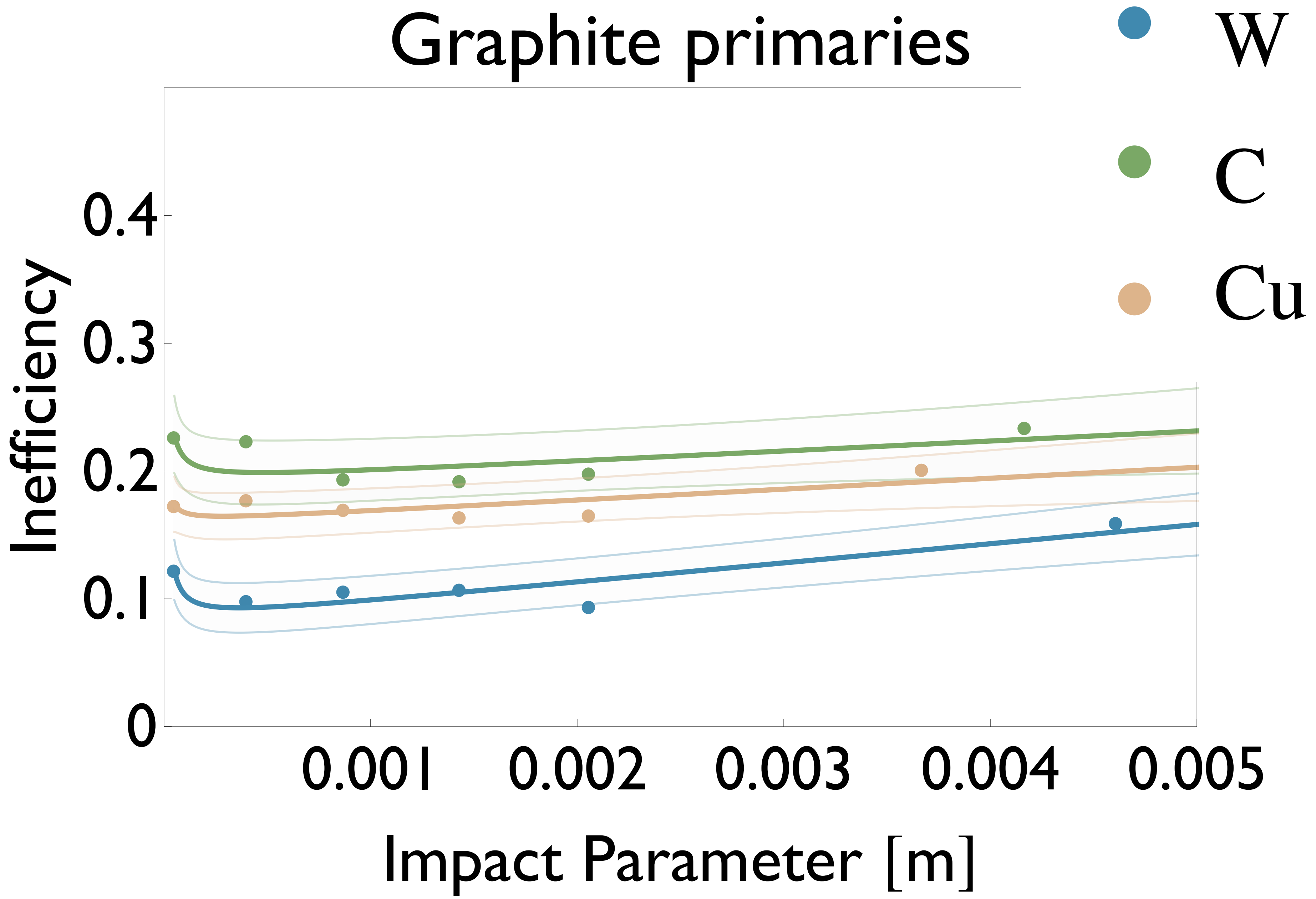
Absorptions from HS1* increase ~x3

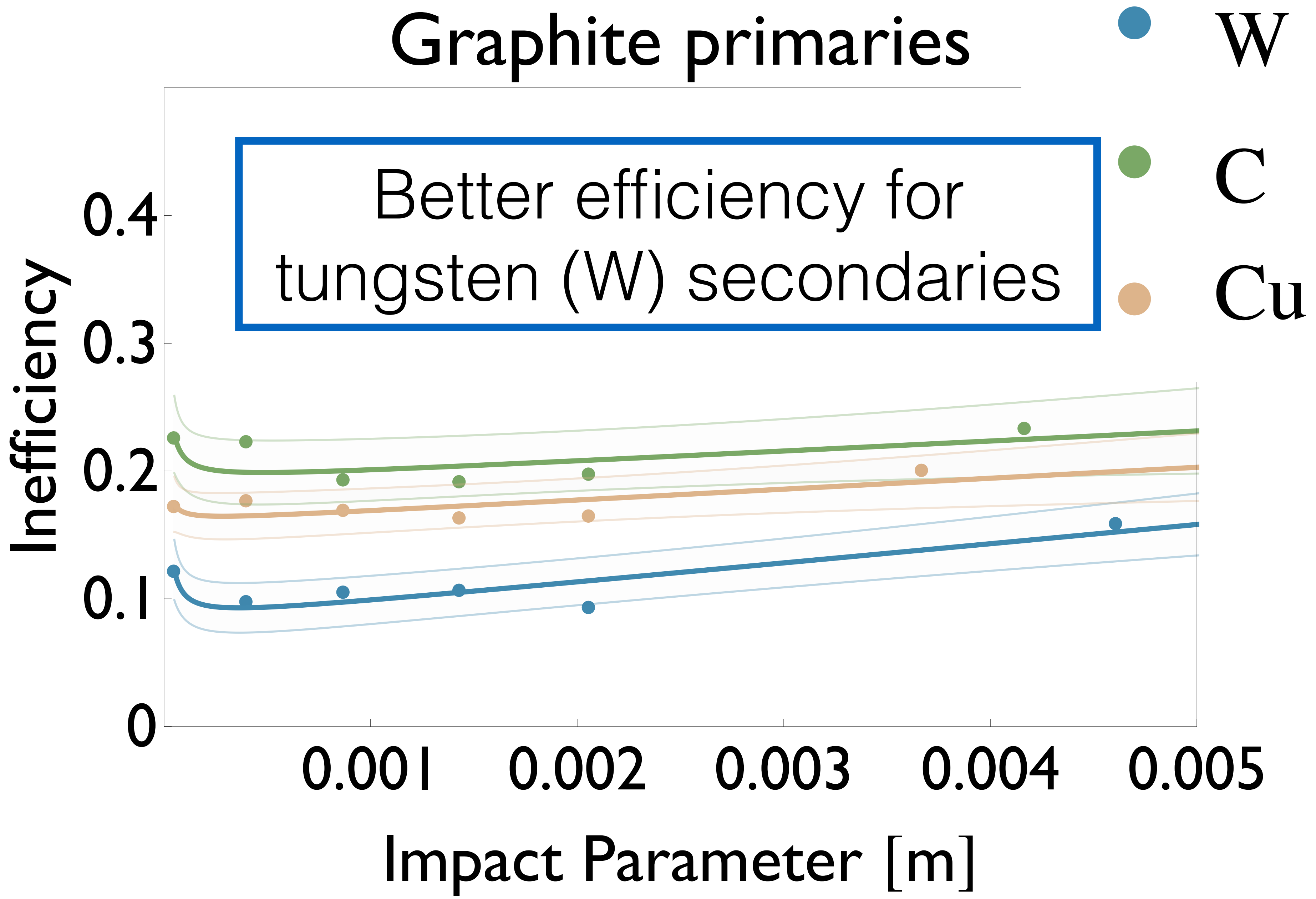
**Remember: input halo in this case was H*

Changing Secondary Material



Primaries: C

Changing Secondary Material



Primaries: C

Further optimisations

Goal: achieve <1 W/m power deposition

Further optimisations

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- Add more collimators
- Change location of secondary collimators (taking into account quadrupoles' location)
- Increase thickness of secondary collimators
- Change size of jaw opening

For different:

- beam halo type (H or V)
- beam halo size/impact parameter

Outline

- Neutrino Oscillations Theory
- Neutrino Factory (NF)
    - Muon ionization cooling
    - Reference NF cooling lattice
    - Bucked Coils Lattice
    - Results
- LAGUNA-LBNO
    - High Power Proton Synchrotron (HP-PS)
    - Orbit Correction
    - Collimation
    - Results and future optimizations
- Summary and Conclusions

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- Energy deposition and longitudinal collimation studies will soon follow

References

- [1] "Interim Design Report", The IDS-NF Collaboration, arXiv: 1112.2853 [hep-ex], Dec 2011
- [2] "Ionisation Cooling Lattices for the Neutrino Factory", Androula Alekou, PhD Thesis, MAP-DOC-4334, Mar 2012
- [3] "rf breakdown with external magnetic fields in 201 and 805 MHz cavities", R.B. Palmer et al., Phys. Rev. ST Accel. Beams 12 (2009) 031002, Mar 2009
- [4] "Bucked coils lattice: A novel ionisation cooling lattice for the neutrino factory", A. Alekou, J. Pasternak, JINST 7 (2012) P08017, Aug 2012
- [5] "Conceptual design and modeling of particle-matter interaction cooling systems for muon based applications", D. Stratakis and H. Sayed et al. (awaiting for approval)
- [6] "The MICE Muon Beam on ISIS and the beam-line instrumentation of the Muon Ionization Cooling Experiment", MICE Collaboration, JINST 7 (2012) P05009, arXiv:1203.4089 [physics.acc-ph], Mar 2012
- [7] "The mass-hierarchy and CP-violation discovery reach of the LBNO long-baseline neutrino experiment", LAGUNA-LBNO Collaboration, arXiv:1312.6520 [hep-ph], Jan 2014
- [8] "Design Options of a High-Power Proton Synchrotron for LAGUNA-LBNO", A. Alekou et al., IPAC-2013-THPWO081, May 2013

Thank you very much!

Any questions?

Extra Slides

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\beta i}U_{\alpha i}U_{\beta j}U^*_{\alpha j}) \sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} \Im(U^*_{\beta i}U_{\alpha i}U_{\beta j}U^*_{\alpha j}) \sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

Parameter	Value
Δm^2_{21} $[10^{-5}]$ eV^2	7.59 ± 0.21
$\lvert\Delta m^2_{32}\rvert$ $[10^{-3}]$ eV^2	$2.32^{+0.12}_{-0.08}$
$\sin^2(2\theta_{12})$	$0.861^{+0.026}_{-0.022}$
$\sin^2(2\theta_{23})$	> 0.90, 90% C.L.
$\sin^2(2\theta_{13})$	$0.092\pm0.016(\text{stat.})\pm0.005(\text{syst.})$

$$\Delta P^{CP}_{\alpha\beta} = \Delta P^{T}_{\alpha\beta} = -16 J_{\alpha\beta} \sin\left(\frac{\Delta m^2_{12}L}{4E}\right) \sin\left(\frac{\Delta m^2_{23}L}{4E}\right) \sin\left(\frac{\Delta m^2_{13}L}{4E}\right)$$

$\neq 0$ $\neq 0$ $\neq 0$

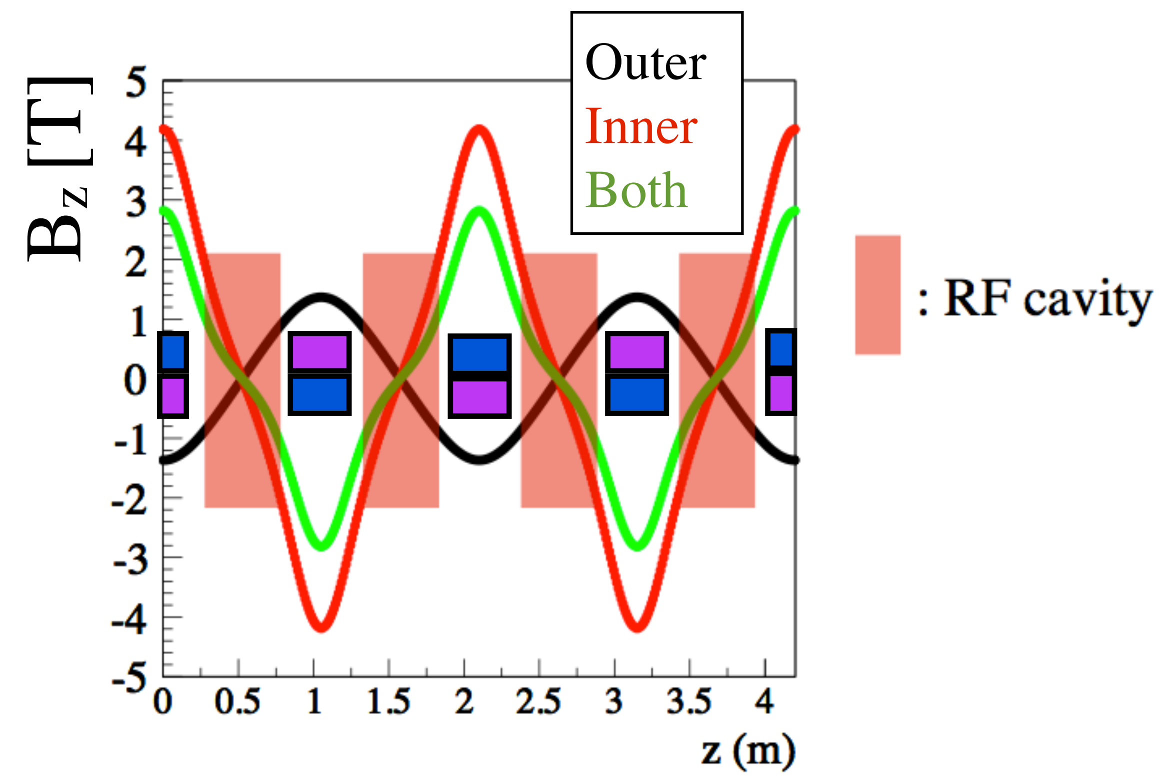
$$J_{\alpha\beta} \equiv \Im(U_{\alpha 1}U^*_{\alpha 2}U^*_{\beta 1}U_{\beta 2}) = \pm c_{12}s_{12}c_{23}s_{23}c^2_{13}s_{13}\sin\delta$$

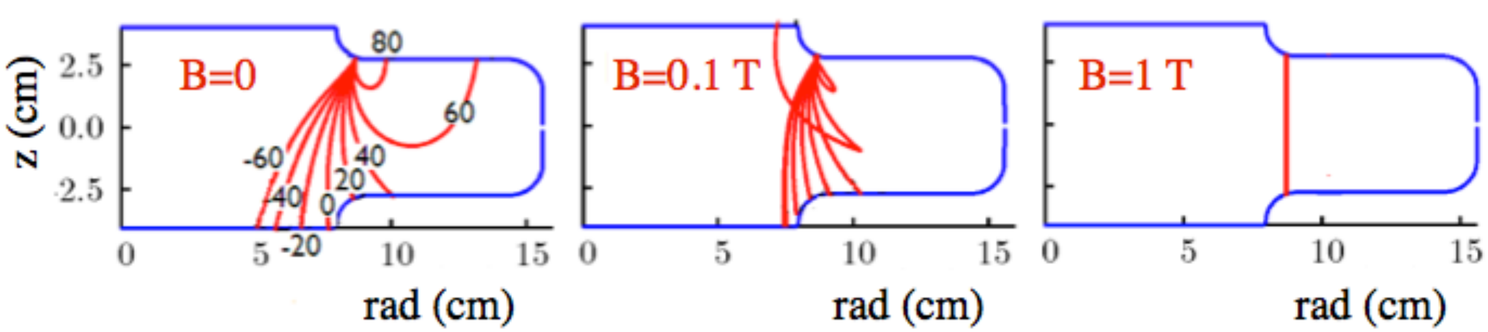
$\neq 0$

U_{ai}: PMNS mixing matrix

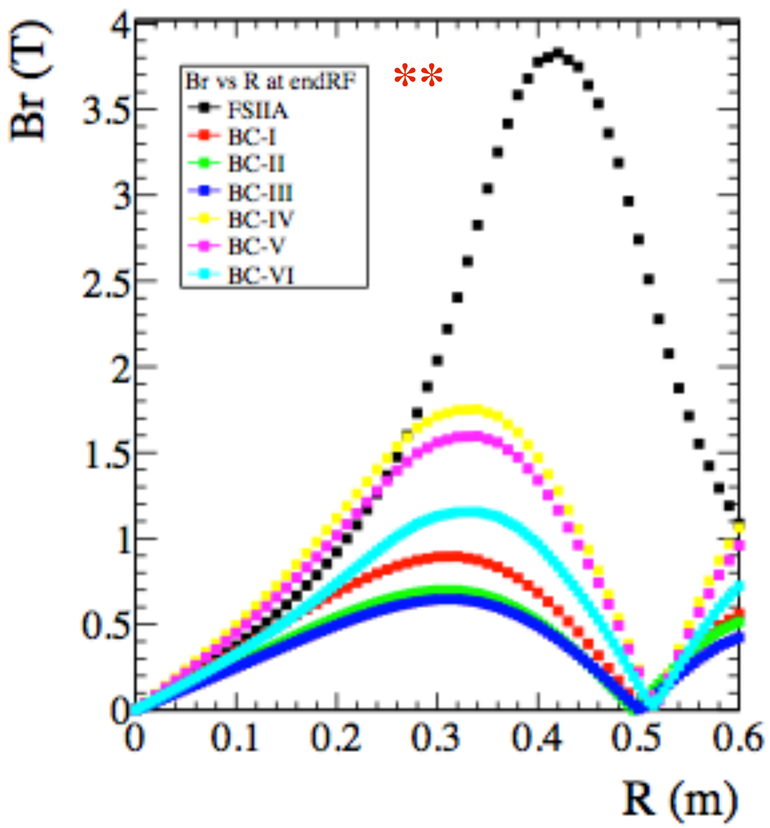
$s_{ij}=\sin\theta_{ij}$
$c_{ij}=\cos\theta_{ij}$
mixing angles: θ_{12}, θ_{23}, θ_{13}
δ: CP-violation phase

RF breakdown: worse at high gradient locations: electrostatic forces will pull the molten metal out and away from the surface. As the metal leaves the now damaged location, it will be exposed to field emitted electrons from the damaged area, and will be vaporised and ionised. This will lead to a local plasma and a subsequent breakdown





- G4MICE
- 1,000 muons
- Gaussian P distribution centered at 232 MeV/c
- 10 mm transverse emittance
- 0.07 ns longitudinal emittance
- Muon decays, MCS, straggling: ON



FSIIA>4 T

BC-I, BC-II, -III, -VI~x3.5-5 lower
BC-IV, -V~x2-3 lower

Lattice	FSIIA	BC-I
Full-cell Length [m]	1.5	2.1
Number of RF cavities	2	2
Number of Absorbers	4	4
Number of Coils	2	4 (2 pairs)
RF Cavities		
Peak Electric Field [MV/m]	15.000	16.585
Phase [degrees]	40	30
Length [m]	0.5	0.5
Radius [m]	0.3	0.3
Absorbers		
Length [m]	0.0115	0.0100
Radius [m]	0.25	0.30
Coils		
Current Density [A/mm^2]	106.667	IC: 120.000;
	N/A	OC: 90.240
Inner Radius [m]	0.35	IC: 0.30;
	N/A	OC: 0.60
Thickness [m]	0.15	IC: 0.15;
	N/A	OC: 0.15
Length [m]	0.15	IC: 0.15;
	N/A	OC: 0.15

LAGUNA observatory will:

- search for proton decay: direct evidence for unification of elementary forces
- allow detection of neutrinos from distant galactic supernovae: understand their explosion mechanism
- perform precision study of terrestrial, solar and atmospheric neutrinos
- study matter-antimatter asymmetry using neutrinos produced at CERN

Sixtrack tracking

Proton scattering in various collimator materials, including:

- Multiple Coulomb scattering,
- Ionization of the collimator material,
- Elastic proton-proton (*pp*) scattering, and inelastic diffractive *pp* scattering (single diffractive scattering),
- Inelastic proton-nucleon scattering,
- Elastic and inelastic proton-nucleus scattering,
- Rutherford scattering.

Detector options:

GLACIER: LAr; 1,424 m deep; 2x50 kt
LENA: LSc; 1,500 m deep; 50 kt

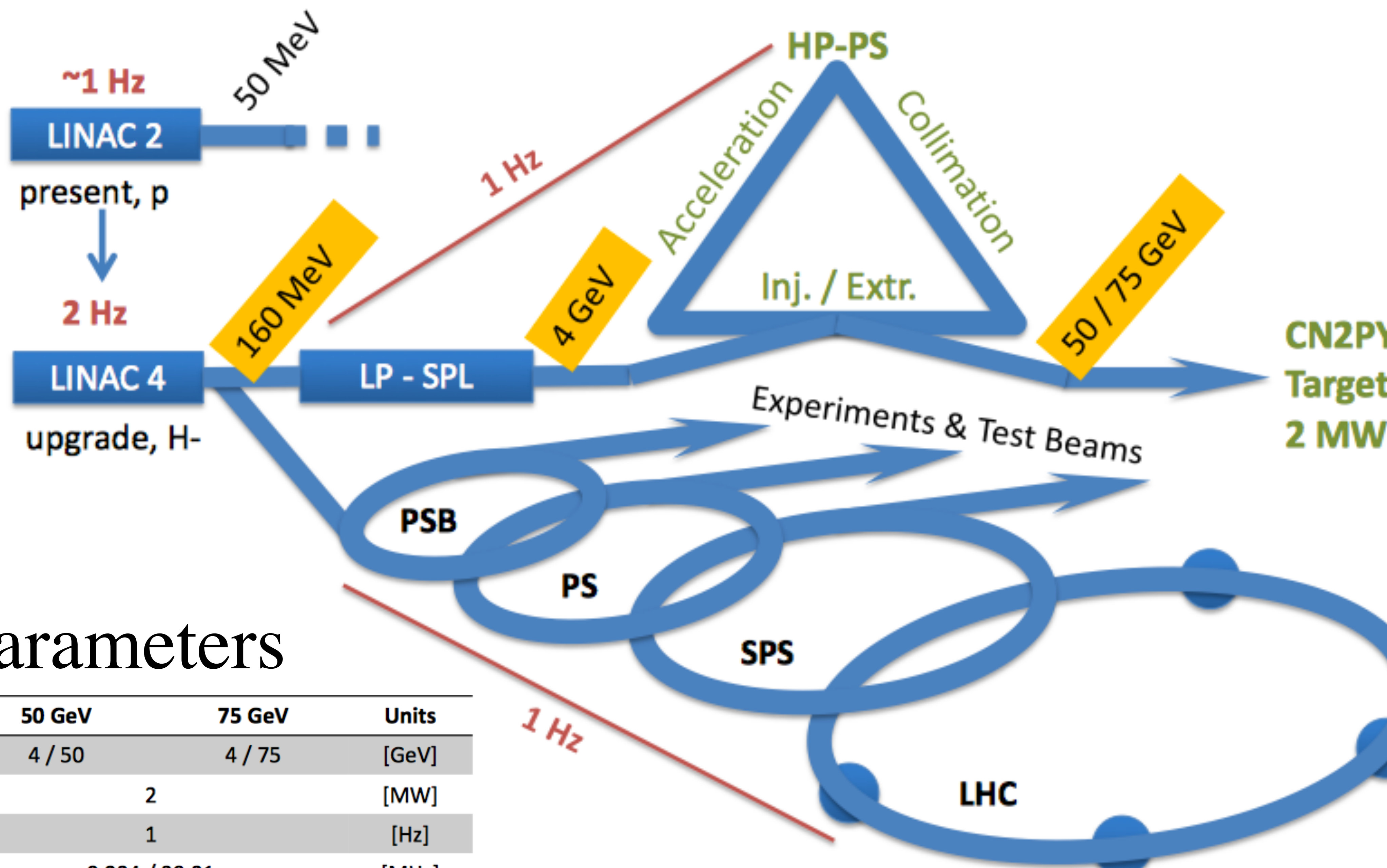
MEMPHYS: Water Cherenkov;
1,700 m deep; 500 kt

MEMPHYS: MEgatonMassPHYSics
GLACIER (Giant Liquid Argon Charge Imaging ExpeRiment)
LENA (Low Energy Neutrino Astronomy)
LAr: Liquid Argon
LSc: Liquid scintillator

Phase advance before moving collimators: 150 H and 200 V
After moving collimators: 145 H and 185 V

Applied random errors (Gaussian cut @ 3σ)	RMS*
Relative dipole field error	5.00E-04
Transverse quadrupole shift	0.2 mm
Longitudinal dipole shift	0.3 mm
Dipole tilt	0.3 mrad

Accelerator complex layout at CERN



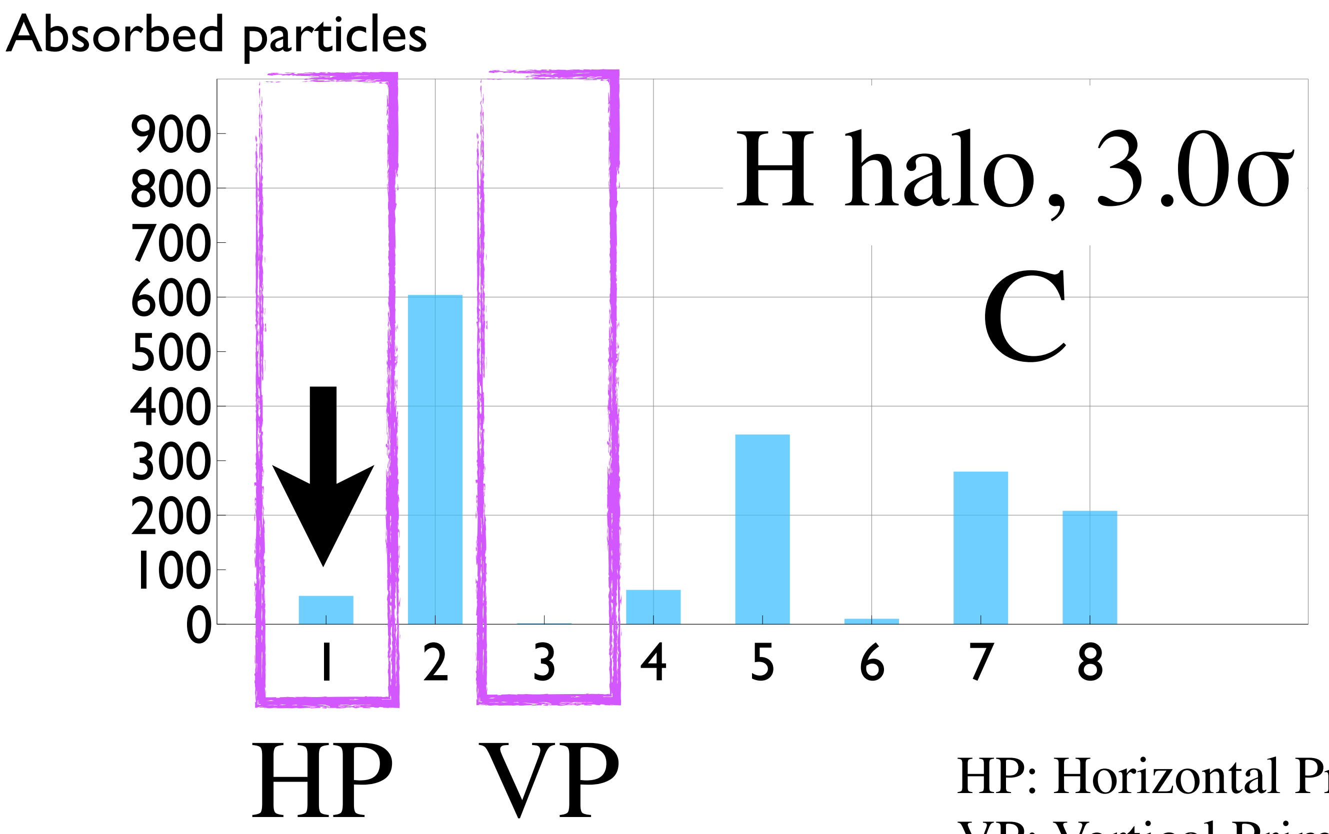
HP-PS parameters

Parameter	50 GeV	75 GeV	Units
Inj. / Extr. Kinetic Energy	4 / 50	4 / 75	[GeV]
Beam power	2		[MW]
Repetition rate	1		[Hz]
f_{rev} / f_{RF} @ inj.	0.234 / 39.31		[MHz]
RF harmonic	168		-
f_{rev} / f_{RF} @ extr.	0.238 / 40.08	0.238 / 40.08	[MHz]
Bunch spacing @ extr.	25		[ns]
Intensity per pulse	2.5×10^{14}	1.7×10^{14}	-
Number of bunches	157		-
Intensity per bunch	1.6×10^{12}	1.1×10^{12}	-
Main dipole field inj. / extr.	0.19 / 2.1	0.19 / 3.1	[T]

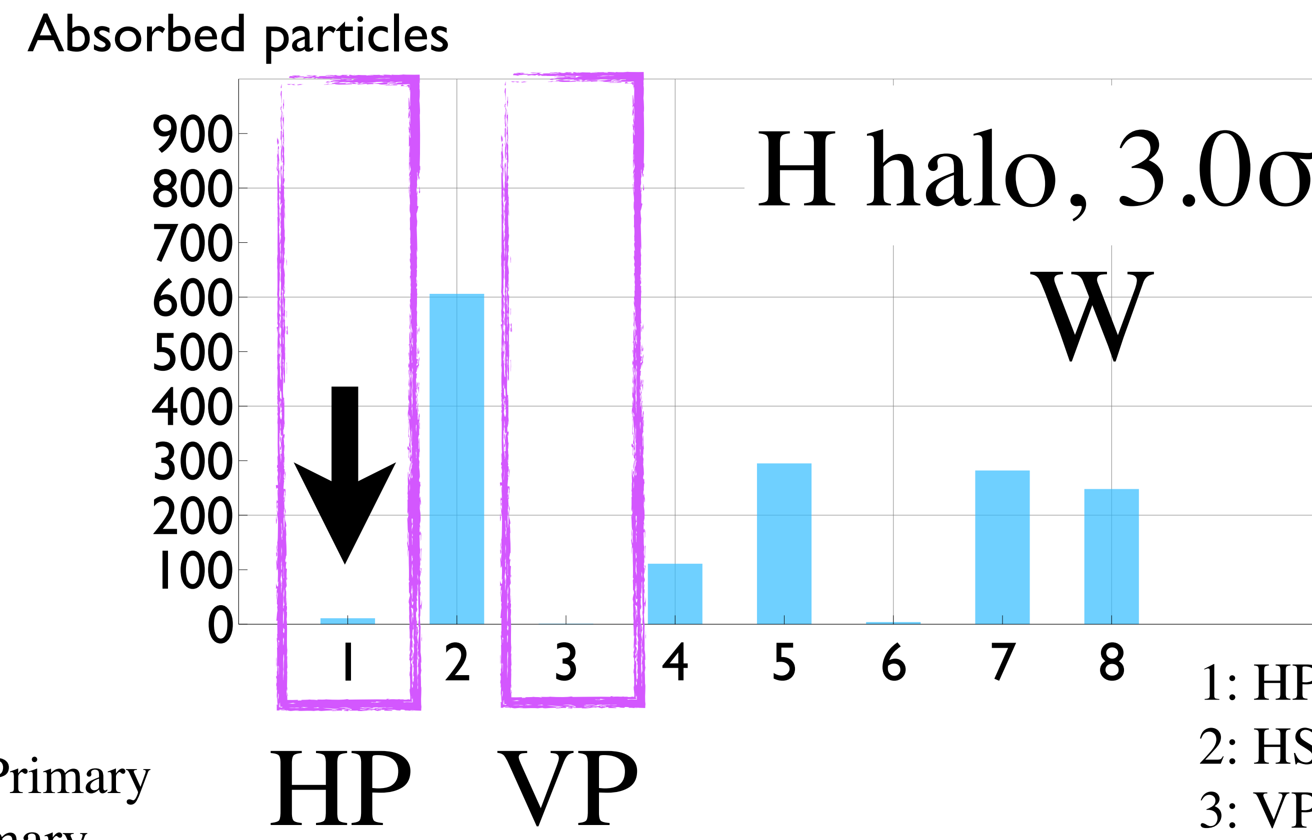
Tune and working point of HP-PS

```
@ Q1      %le    13.23595626
@ Q2      %le    7.208353731
@ DQ1     %le    -0.0004728116762
@ DQ2     %le    -0.001804231898
```

Absorptions in primary collimators



HP: Horizontal Primary
VP: Vertical Primary



1: HP
2: HS1
3: VP
4: VS1
5: HS2
6: VS2
7: H90
8: V90

λ: figure of merit
N_p: primary aperture
$N_s=N_{s1}=N_{s2}=N_{90}$: secondary aperture

- **W: less absorptions in primaries (for all beam sizes)**

Halo size	changing
Halo type	H/V
Primary material	W
Primary thickness	constant
Secondary material	W
Secondary thickness	1 m
Jaw opening Np_Ns [σ]	changing

Np_Ns	Halo	<λ>
2.5_3.0	H	5.48
2.5_3.0	V	3.86
2.5_2.8	H	6.24
2.5_2.8	V	4.09
3.0_3.5	H	6.5
3.0_3.5	V	5.34