MERLIN for High Luminosity LHC Collimation

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In Collaboration with the MERLIN group:

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& In Collaboration with CERN:

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MANCHESTER 1824
The University of Manchester

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MERLIN

MERLIN

C++ Accelerator Physics Library (N. Walker @ DESY, storage ring functionality added by A. Wolksi)

User writes their own simulation containing:

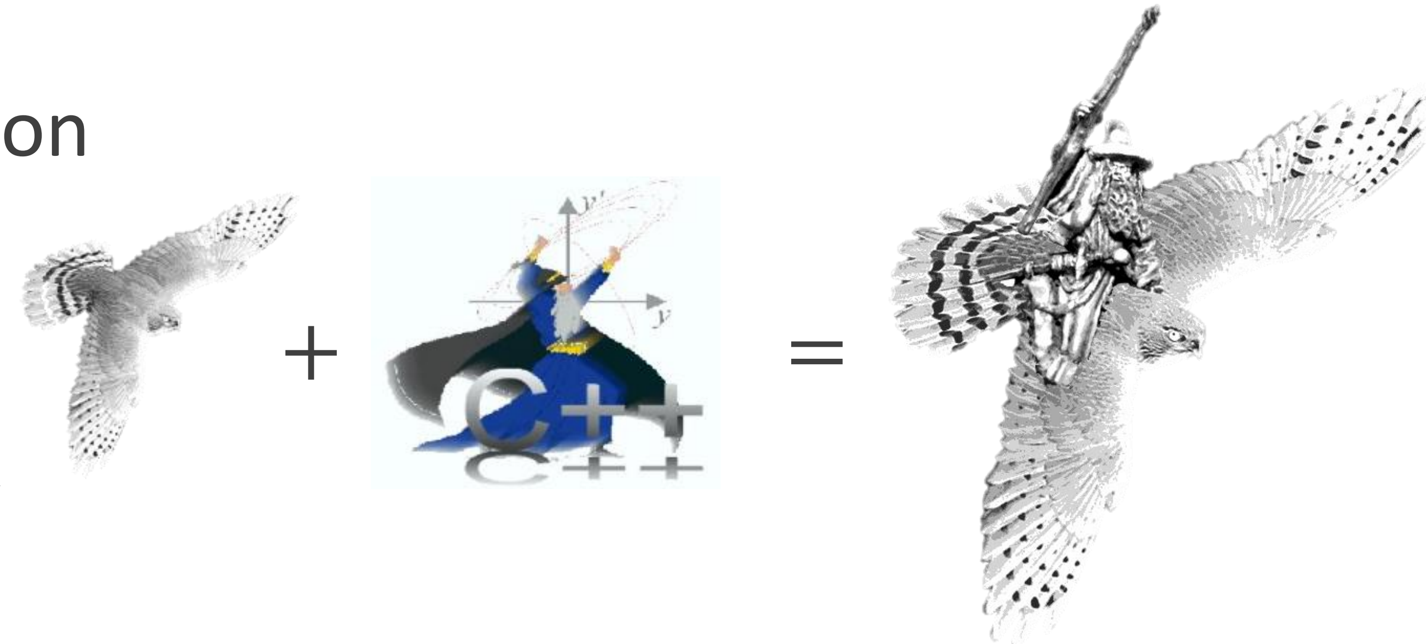
- Beam -> **Bunch**
- **Accelerator Model** (MAD .tfs table)
- **Tracker** (different integrators available)
- Physics Processes (user defined / pre existing)

Modular – **easier** to use

Extensible – if you have the physics, adding a process is trivial

Merge

- Consolidation of processes:
  - Collimation (scattering, binning, etc)
  - Hollow Electron Lens (HEL)
  - Crab Cavity Failure
- Clean up
- Optimisation
- Test suite
- Cmake
- Git history



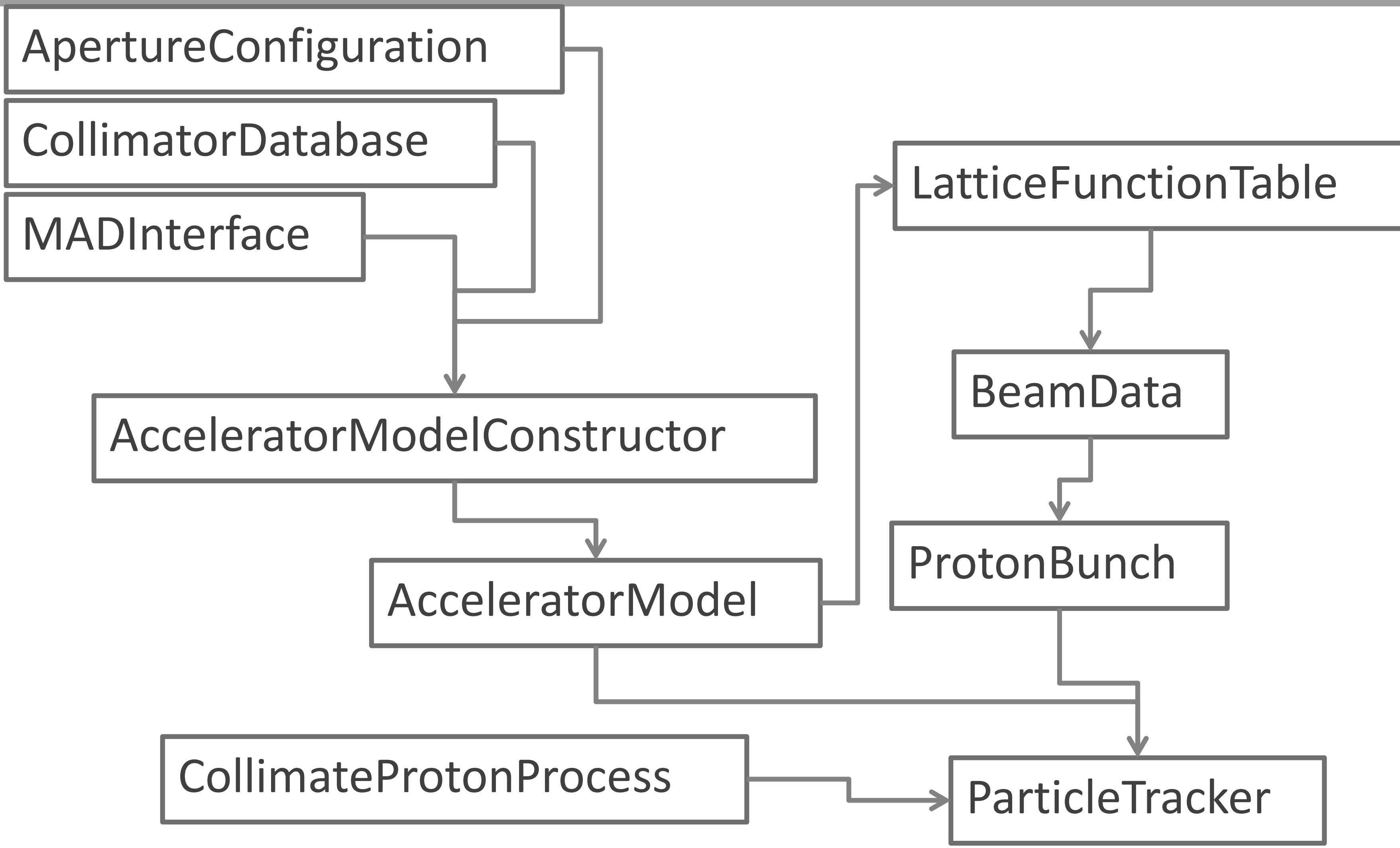
Former Developers

Thanks to all:

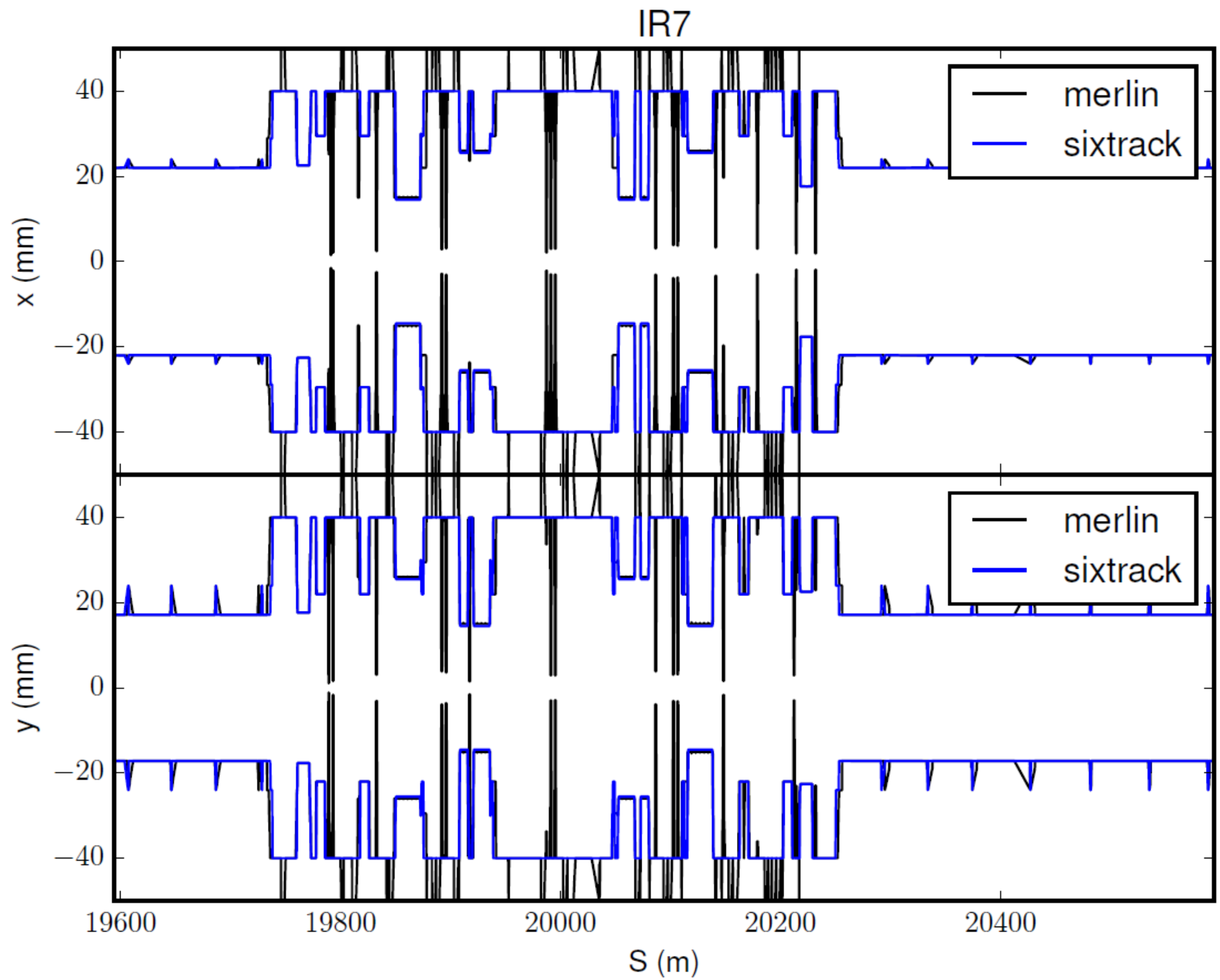
• James Molson	[Manchester]
• Maurizio Serluca	[Manchester]
• Adina Toader	[Manchester]
• Adriana Bungau	[Manchester]
• Andy Wolski	[Liverpool]
• Others …?	
• Dirk Krücker	[DESY]
• Nick Walker	[DESY]

COLLIMATION USING MERLIN

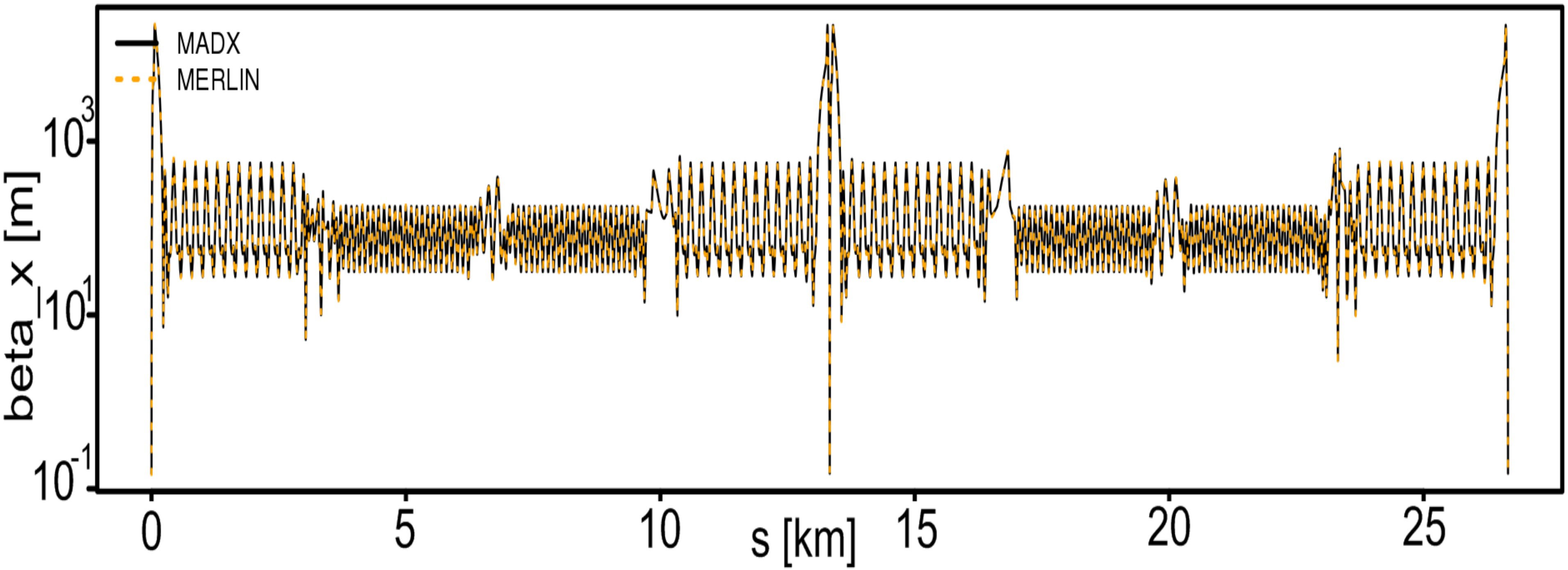
Typical User Code



Apertures


IR7
merlin
sixtrack
x (mm)
y (mm)
40
20
0
−20
−40
19600
19800
20000
20200
20400
S (m)

HL LHC Optics



Integrator

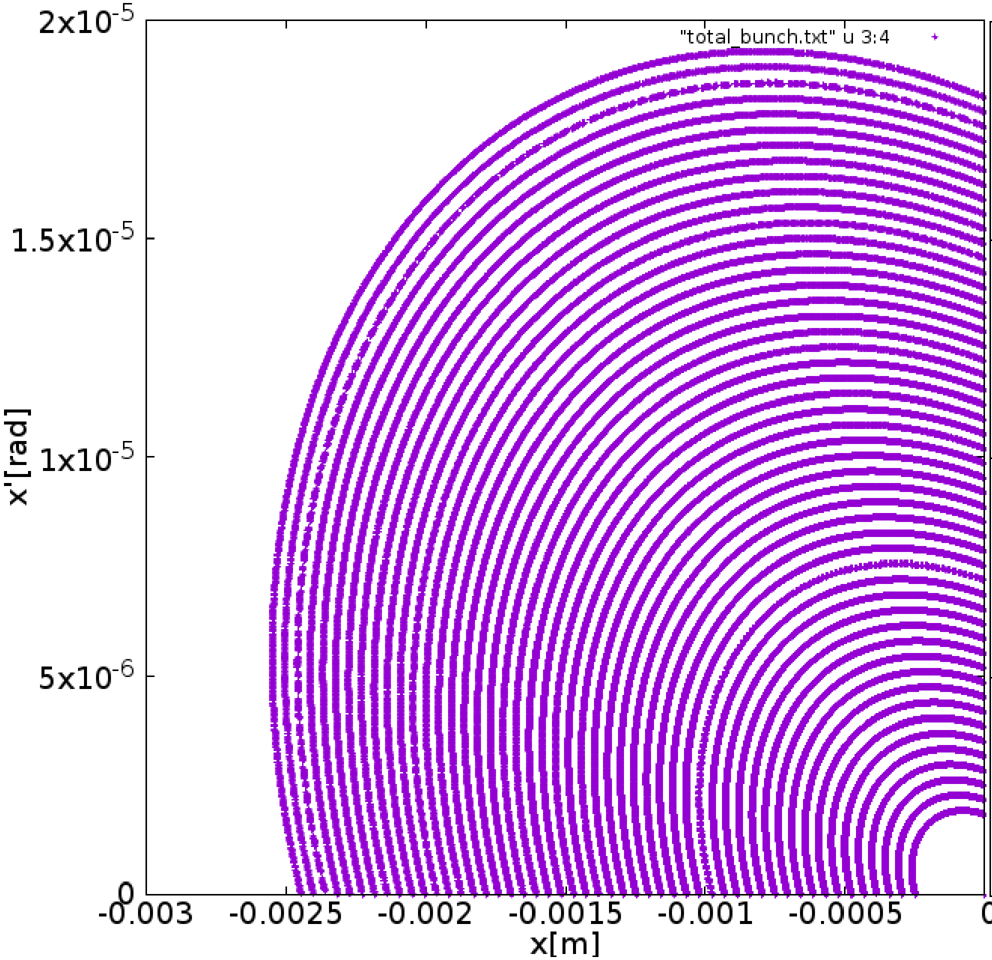
MERLIN includes 3 standard integrator sets:

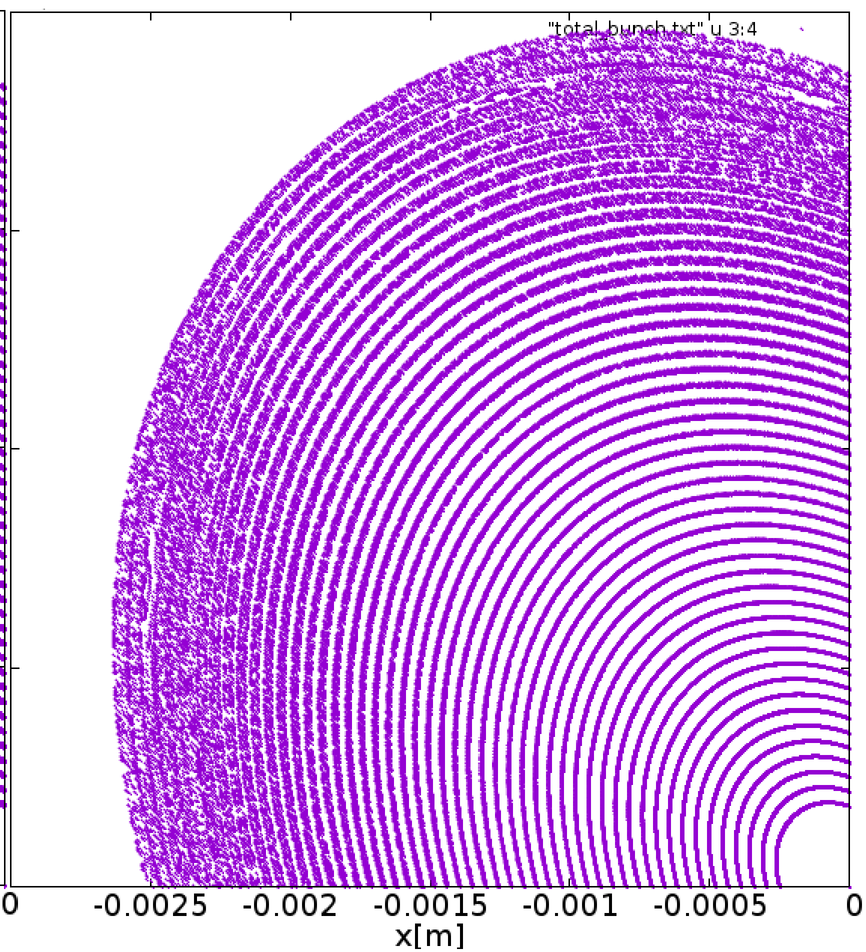
1. TRANSPORT
2. SYMPLECTIC
3. THIN_LENS

```
myParticleTracker->SetIntegratorSet (new ParticleTracking::SYMPLECTIC::StdISet());
myParticleTracker->SetIntegratorSet (new ParticleTracking::TRANSPORT::StdISet());
```

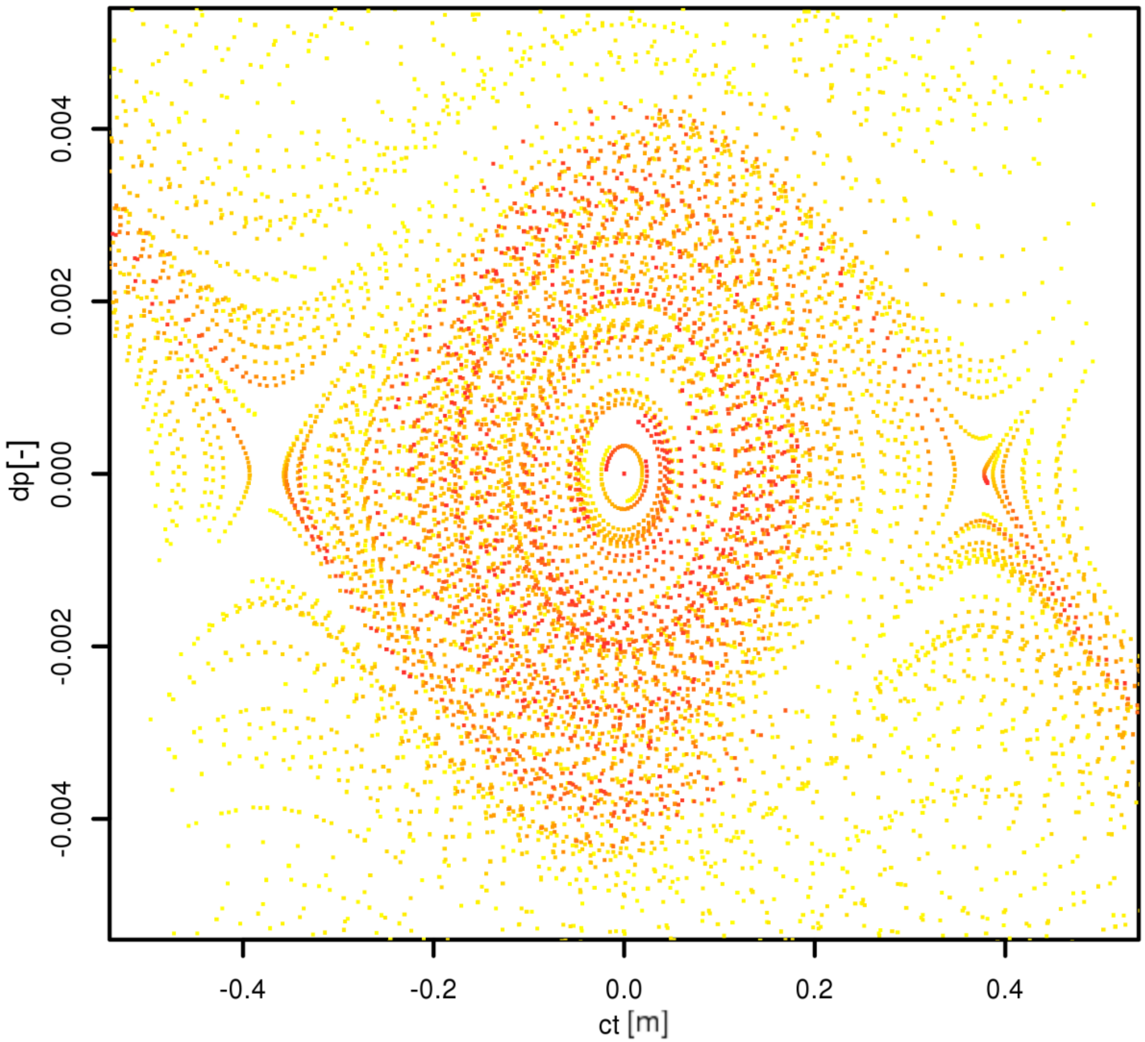
```
Legend:
Class
User object
Function
Variable
```

TRANPSORT vs SYMPLECTIC

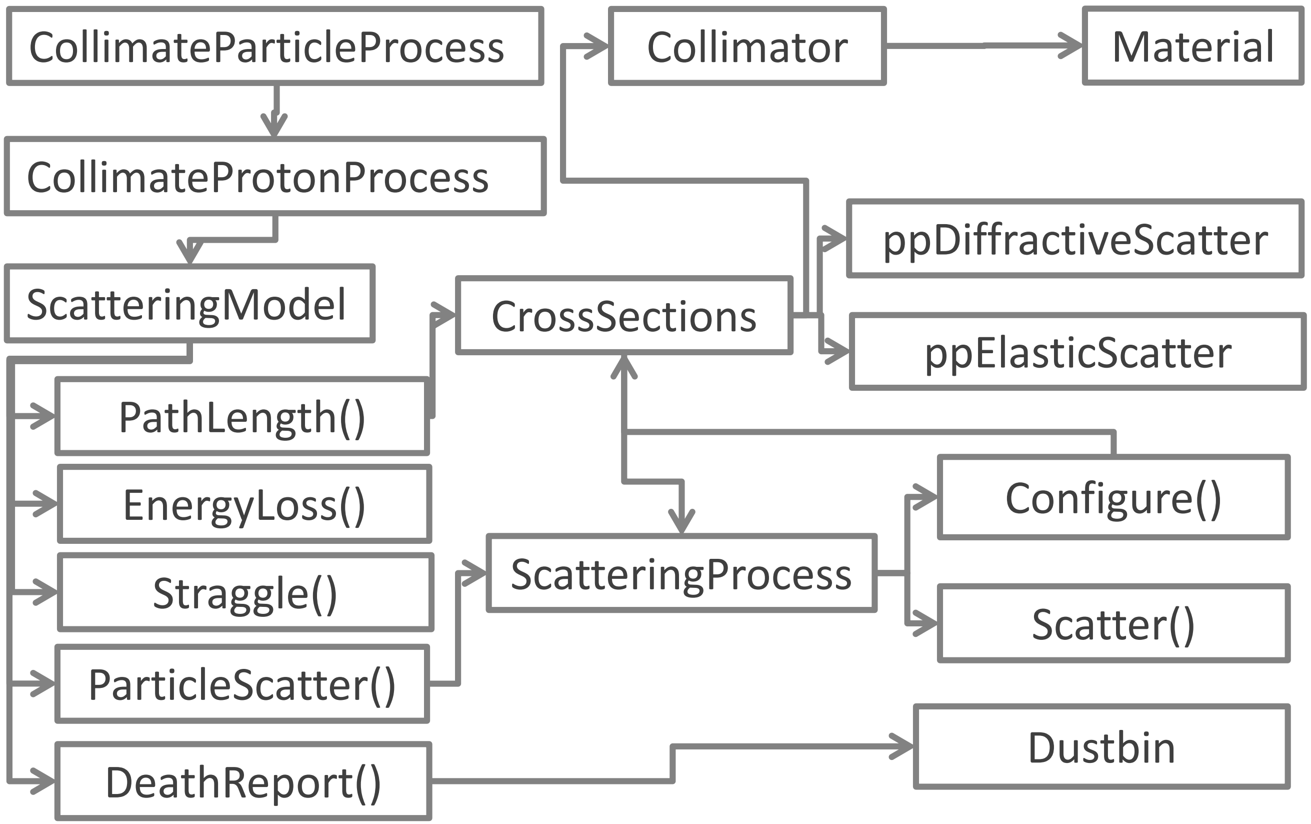




Synchrotron Motion



Collimation Process



Scattering Processes

SixTrack+K2 – like & MERLIN scattering for:

- Rutherford
- Elastic pn
- Elastic pN
- SD
- Inelastic

Merlin

- Rutherford
- Elastic pn
- Elastic pN
- SD
- Inelastic

SixTrack & ST + Ad. Ionisation

- ST Rutherford
- ST Elastic pn
- ST Elastic pN
- ST SD
- Inelastic

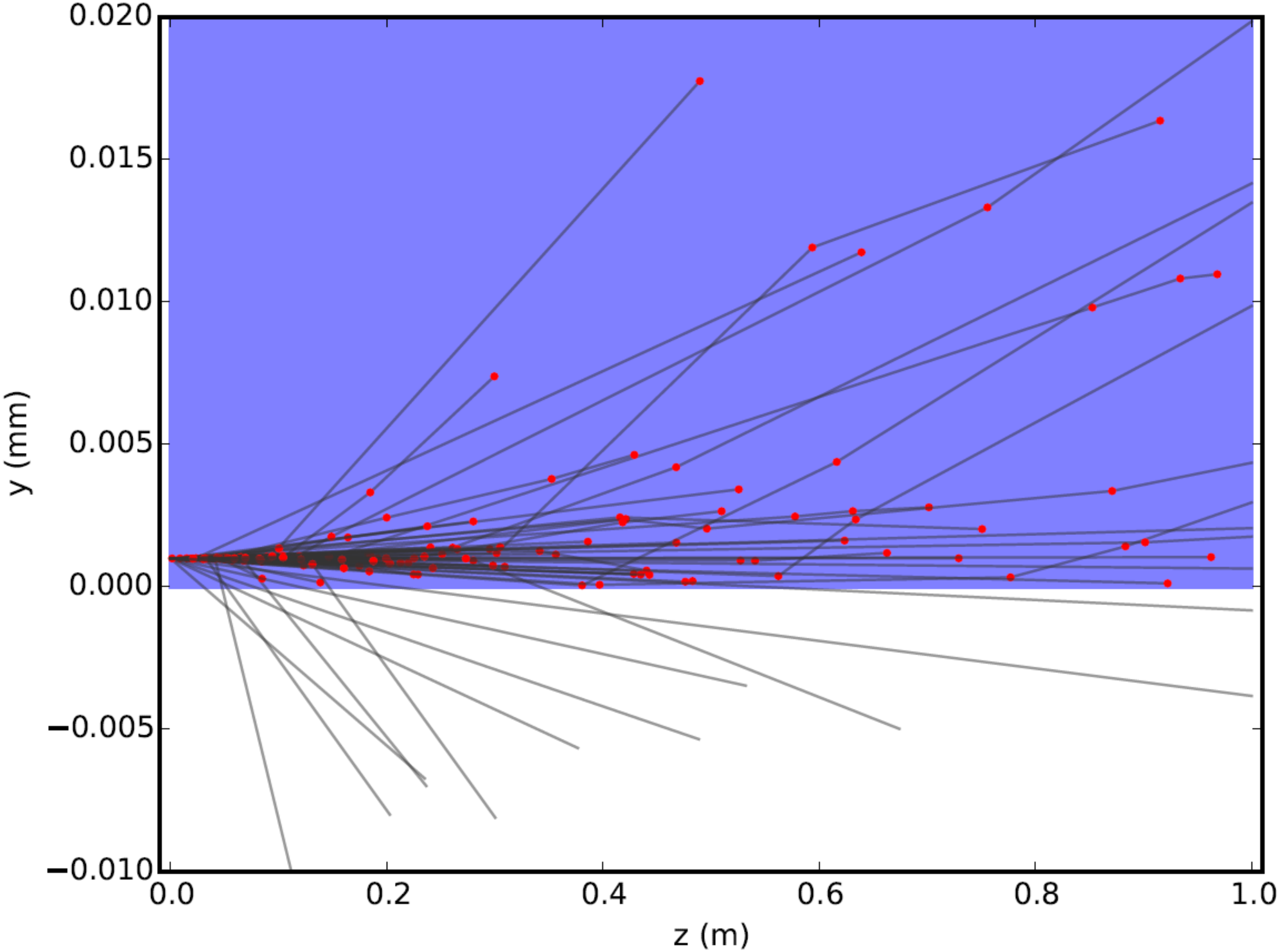
ST + Ad. Elastic

- ST Rutherford
- Elastic pn
- Elastic pN
- ST SD
- Inelastic

ST + Ad. SD

- ST Rutherford
- ST Elastic pn
- ST Elastic pN
- SD
- Inelastic

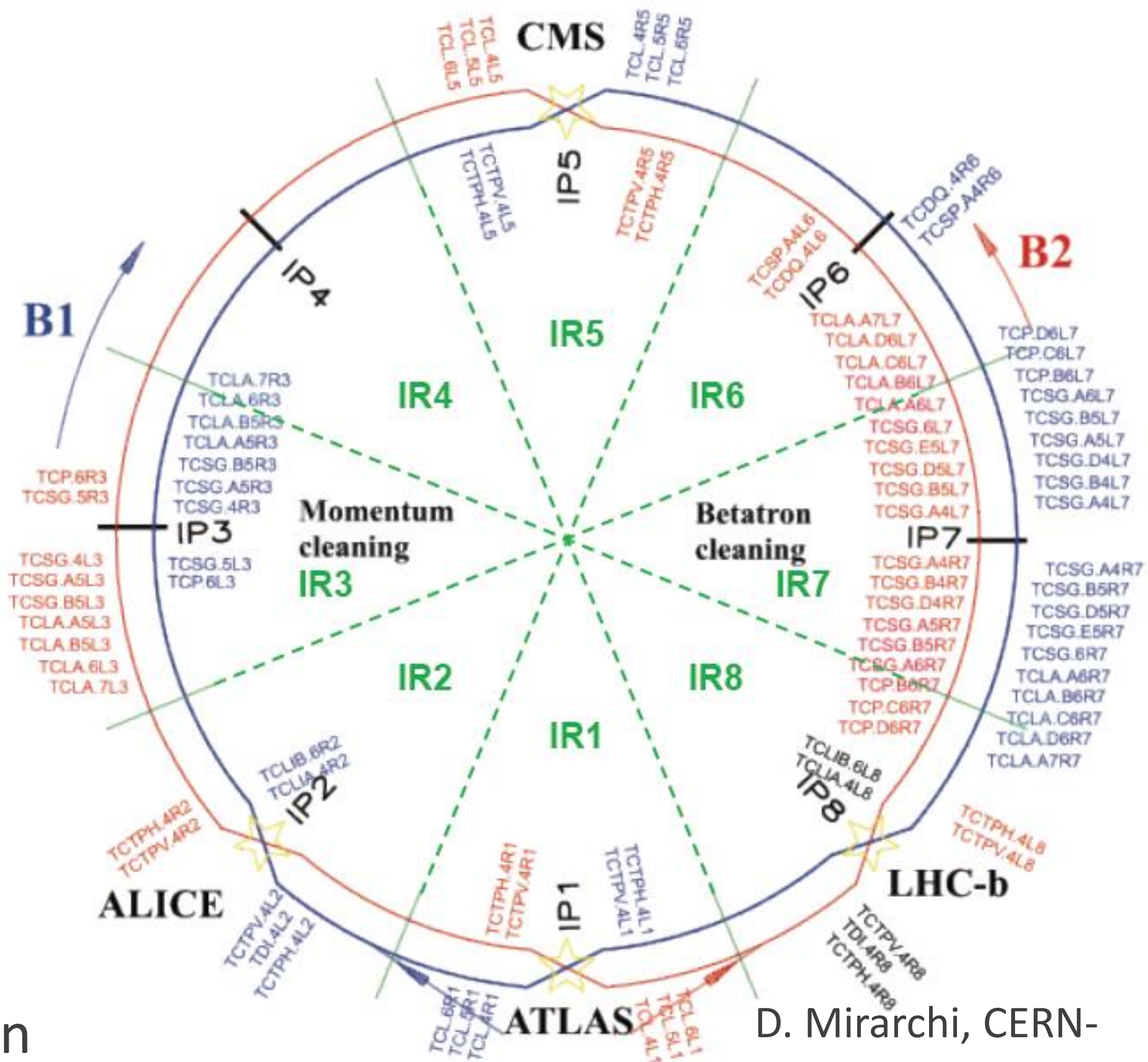
Scattering



LHC COLLIMATION

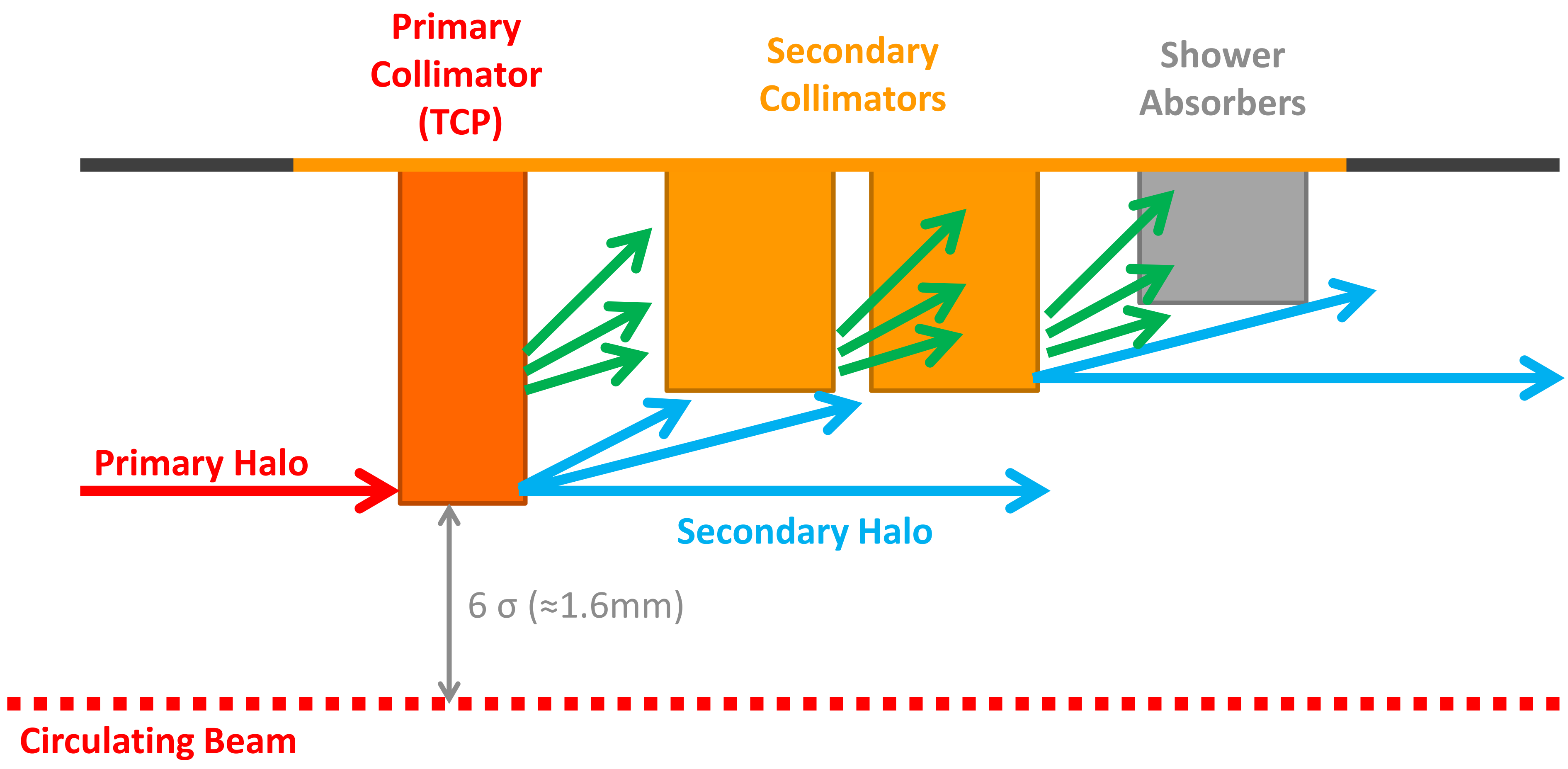
LHC Collimation System

- 108 Collimators (incl. transfer lines)
- 54 per beam
- 50 movable
- IR7: Betatron Cleaning
- IR3: Momentum Cleaning
- Injection & Extraction protection
- IP triplet protection
- IP background reduction



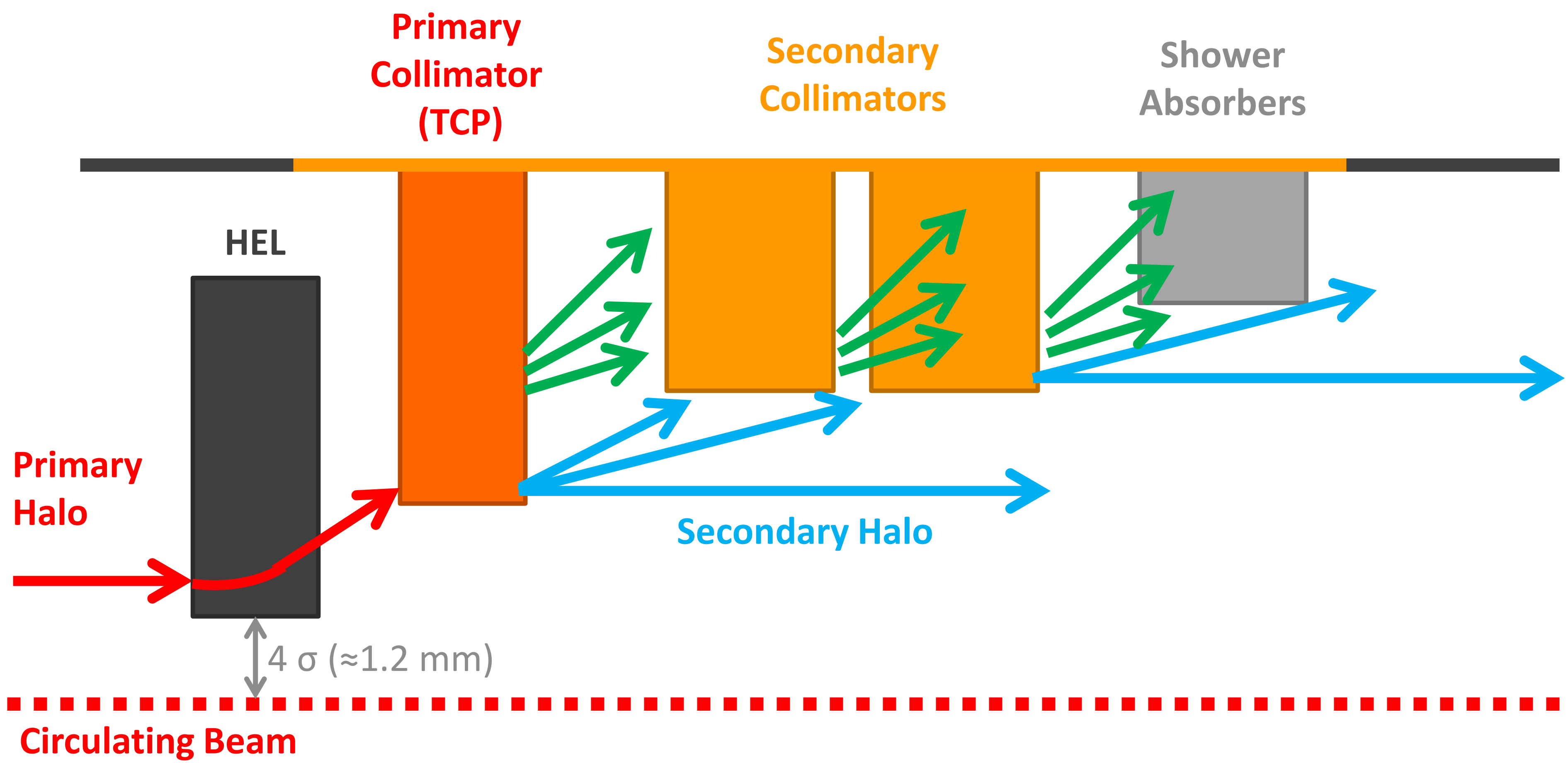
D. Mirarchi, CERN-THESIS-2015-099

LHC Collimation Hierarchy



HOLLOW ELECTRON LENS

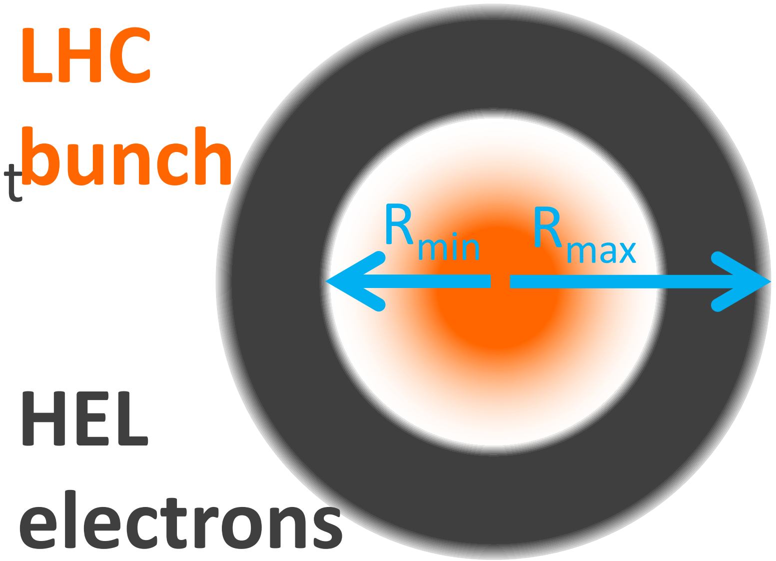
Hierarchy + HEL



Principle

LHC beam travels coaxially through hollow cylindrical beam of pulsed, magnetically confined, low energy e^-s

- Halo particles (transverse displacement > R_{min}) see e^- beam EM field ∝ transverse position
- Halo particles are kicked ~0.1 μrad



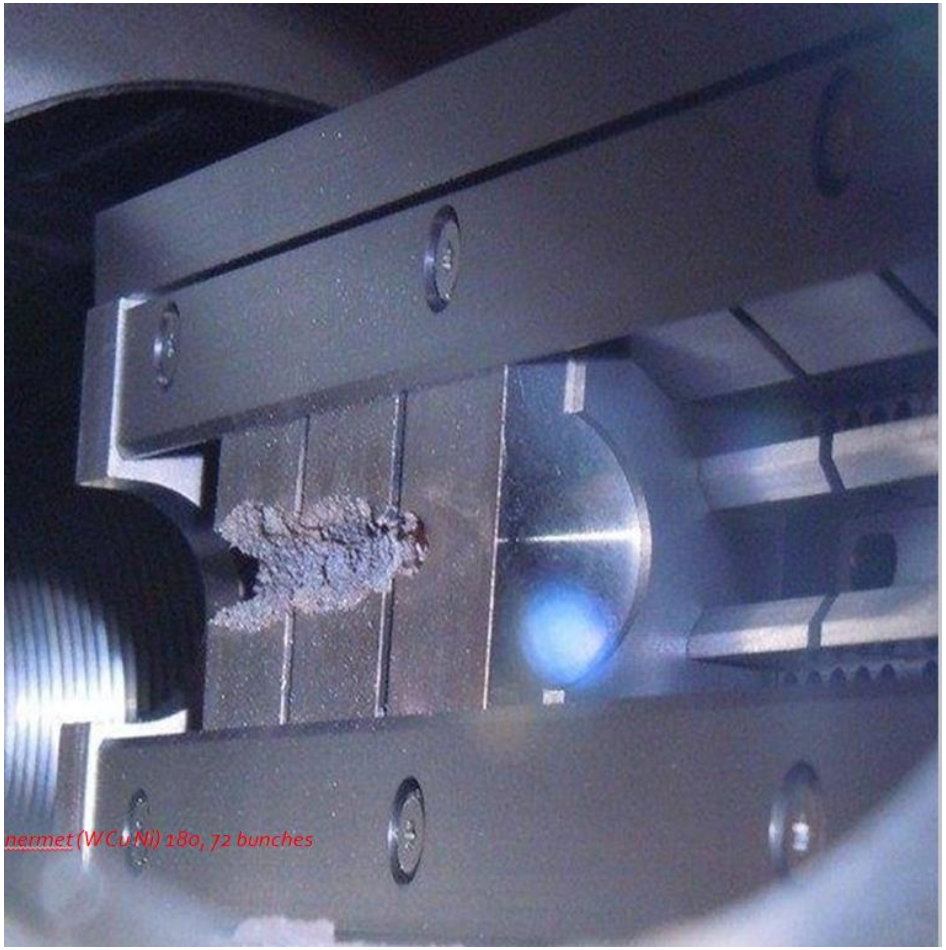
Transverse illustration of HEL beam operating outside the LHC proton beam.

Soft scraping device

- No absorption of halo particles
- Controlled increase in diffusion of halo particles on to **collimators**
- **Collimation enhancer**

Why a HEL?

Not solid ∴ no heat load to manage, cannot be damaged ∴ can operate close to the beam core



A. Bertarelli (CERN)
HiRadMat ColUSM

HOLLOW ELECTRON LENS PROCESS

Assumptions

- Fields from solenoid and dipole magnets in HEL are ignored
- e^- distribution is uniform and symmetric
- Kick derivation assumes infinitely long HEL
- Only active part of HEL is considered (not the overlapping region)

HEL Kick

$$\theta_{max}(r) = \frac{1}{4\pi\epsilon_0 c^2}\frac{2LI(1+\beta_e\beta_p)}{(B\rho)_p\beta_e\beta_p}\frac{1}{r}$$

$$\theta_{kick} = \begin{cases} 0, & r < R_{min} \\ \frac{r^2 - R_{min}^2}{R_{max}^2 - R_{min}^2}\theta_{max}, & R_{min} < r < R_{max} \\ \theta_{max}, & r > R_{max} \end{cases}$$

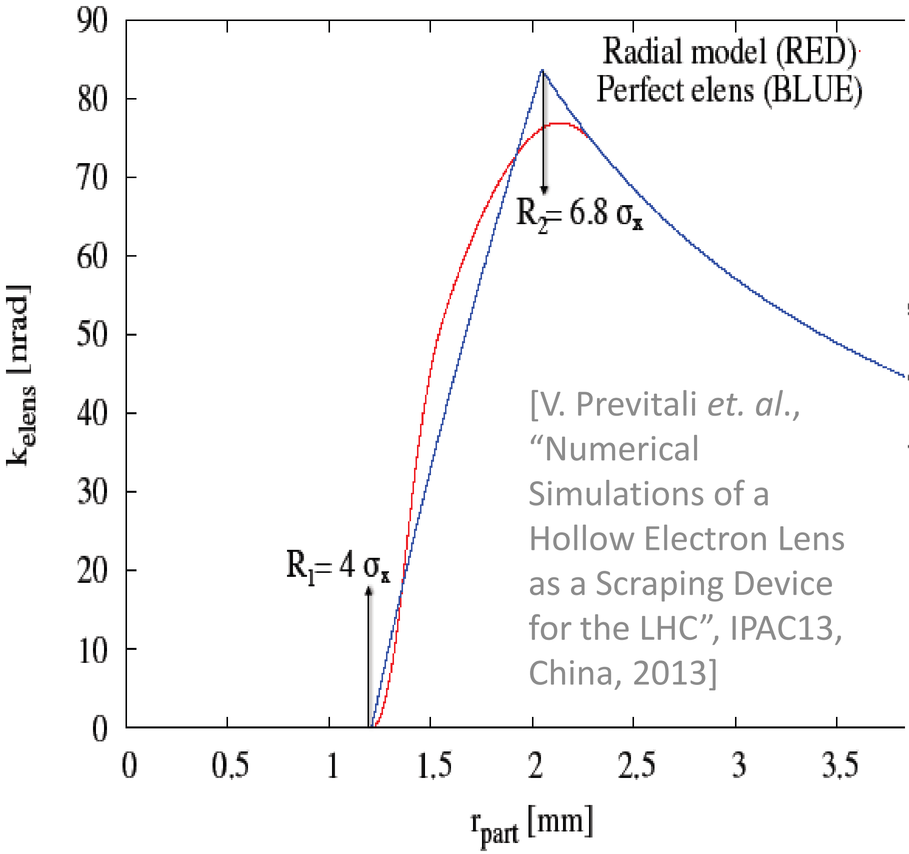
[V. Previtali *et. al*., "Numerical Simulations of a Hollow Electron Lens as a Scraping Device for the LHC", IPAC13, China, 2013]

Summary of HEL implementation:

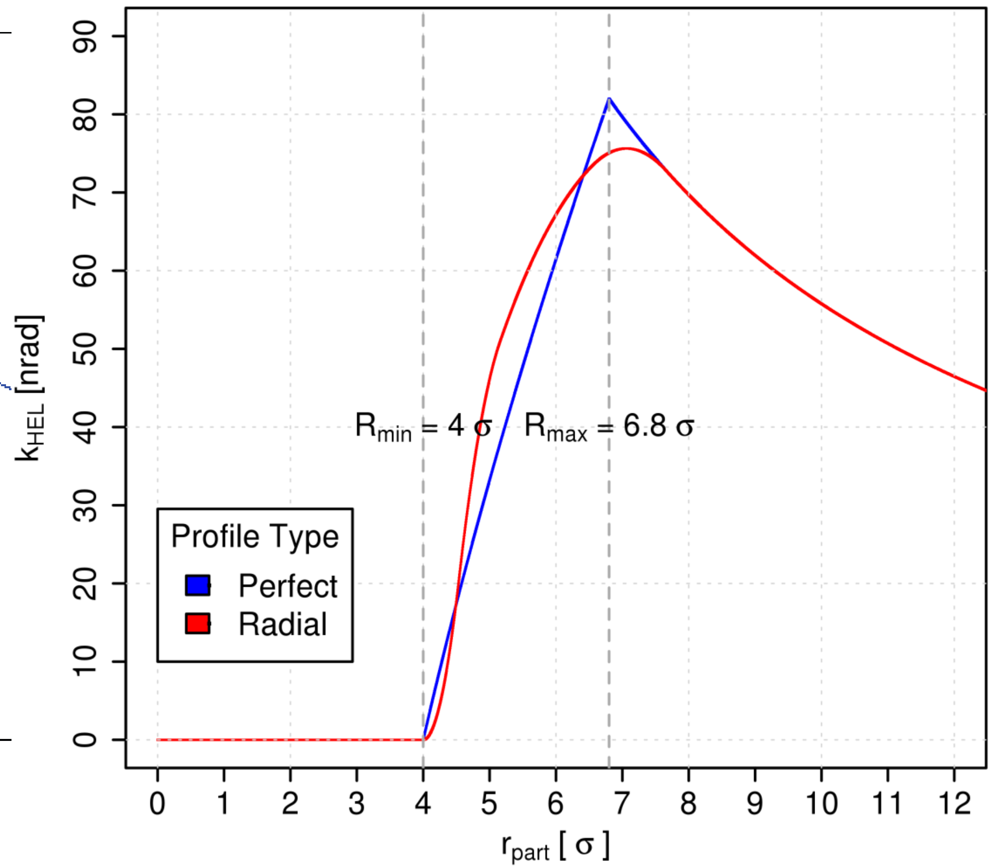
https://sites.google.com/site/hollowelens/home

Radial Profiles

SixTrack



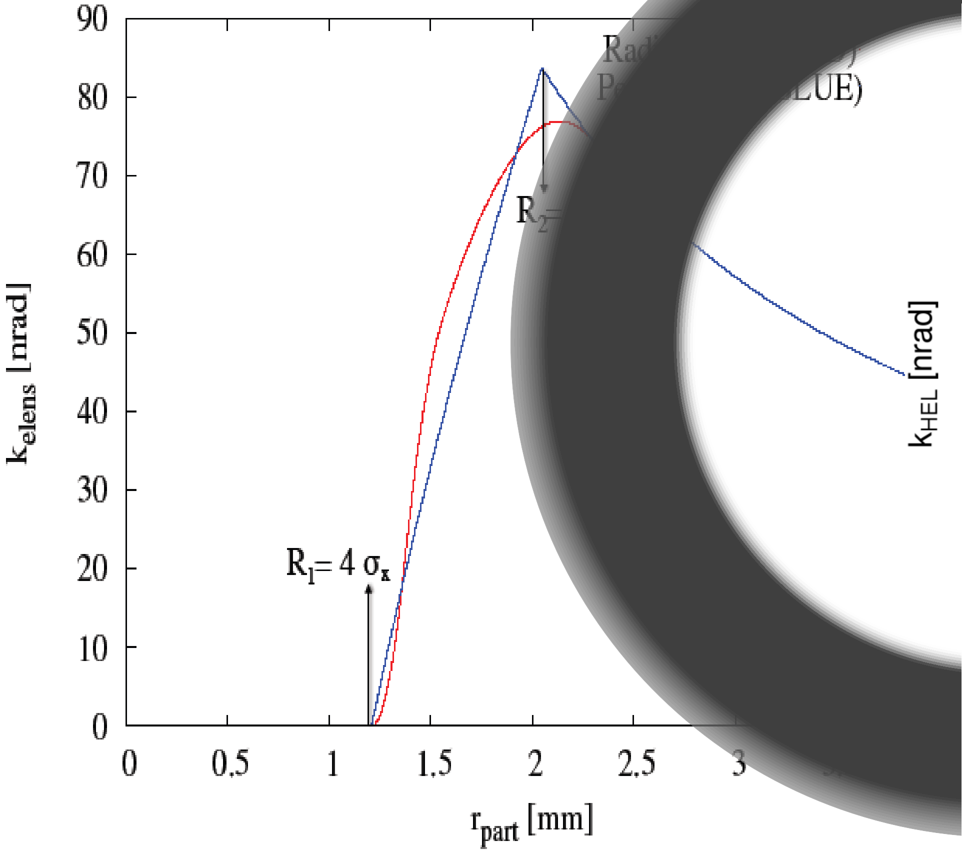
MERLIN



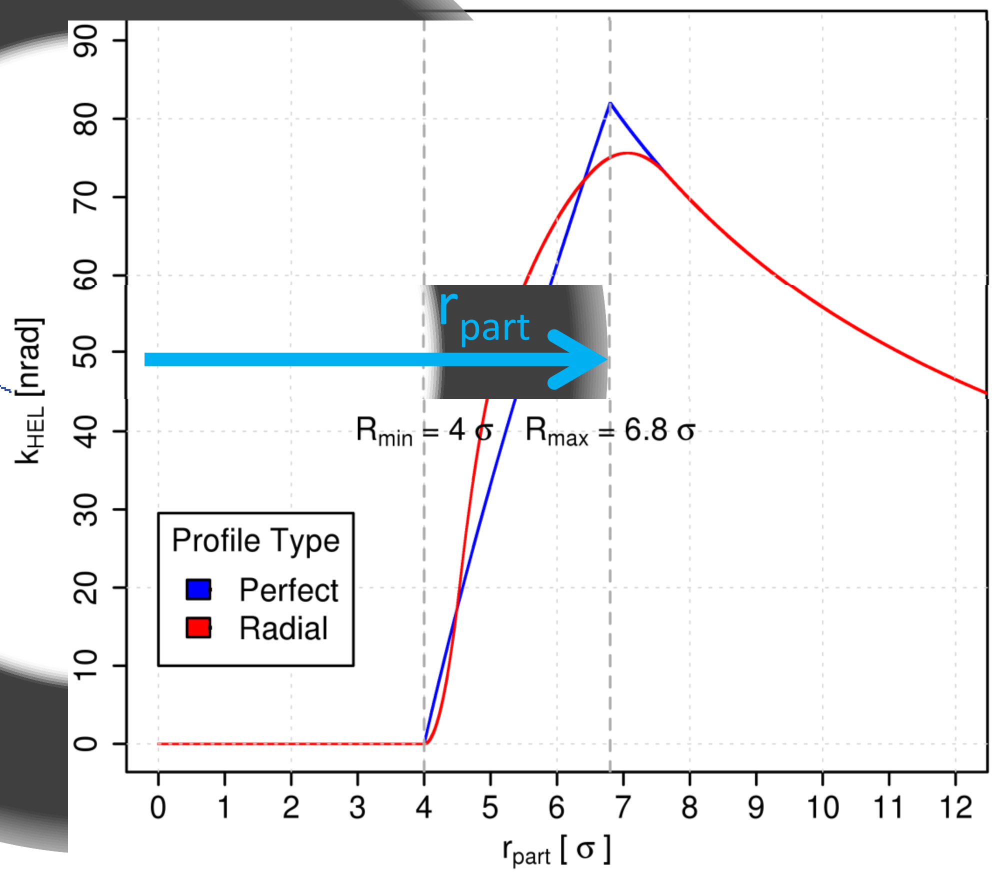
Standard 'Tevatron' HEL settings: L = 2 [m], I=1.2 [A], E_{e-} = 5 [KeV]

Radial Profiles

SixTrack



MERLIN



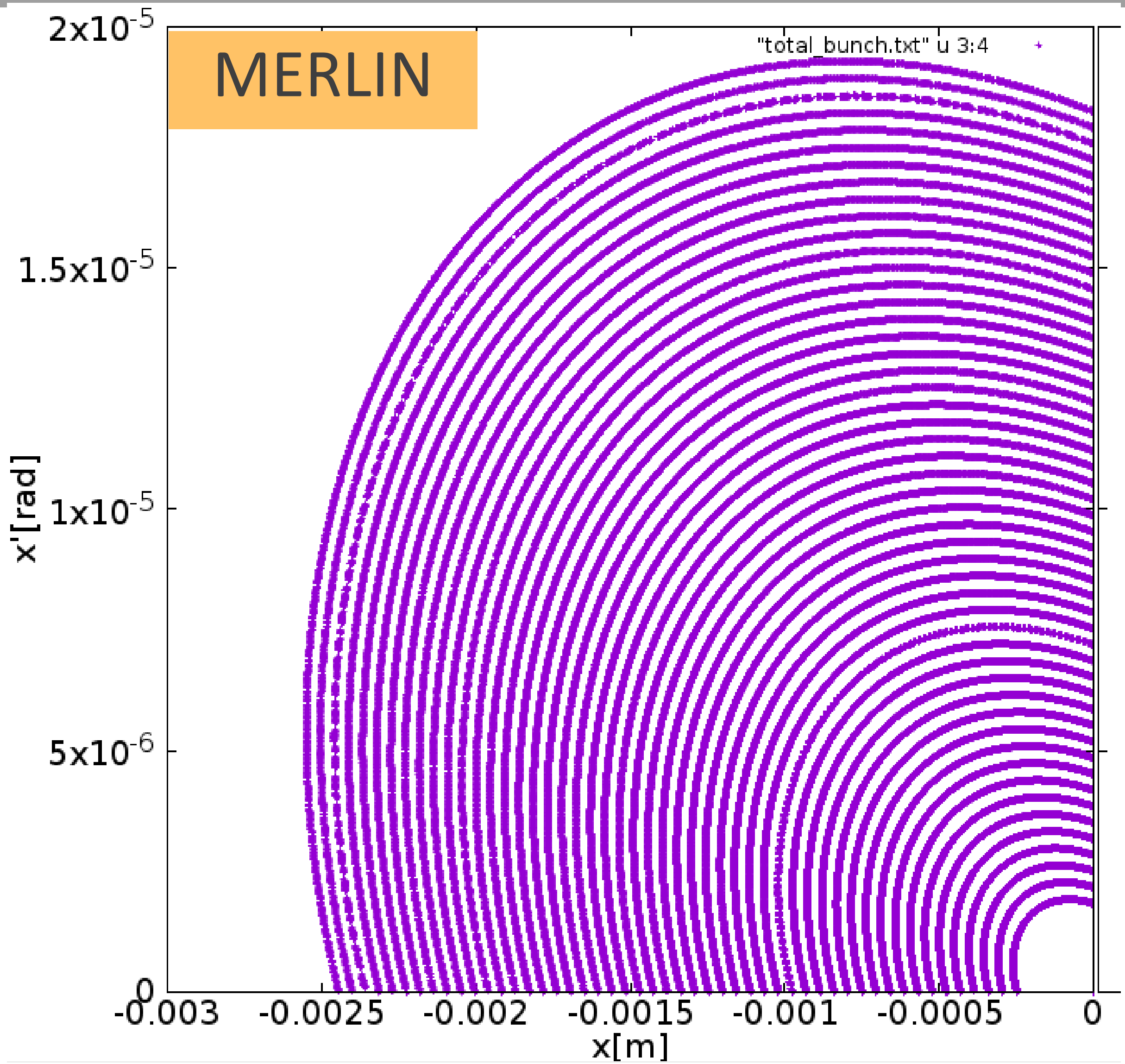
Standard ‘Tevatron’ HEL settings: L = 2 [m], I=1.2 [A], E_{e-} = 5 [KeV]

Poincaré Sections

- HEL @ s = 10037 m (40m downstream of IP4) in LHC lattice (RB46)
- 10^4 – 10^5 turns in the LHC
  - Nominal v6.503, HL v1.2
- Output particle data @HEL position every turn
- Plot *xx'* phase space to see effect

Nominal + Tevatron: No HEL

Parameter	Value
LHC lattice	Nominal
HEL hardware	Tevatron
Mode	NO HEL
I [A]	1.2
E_e [KeV]	5
L [m]	2
R_{min} [σ_x]	4
R_{max} [σ_x]	6.8
Dist^n	MERLIN 1-10 σ_x

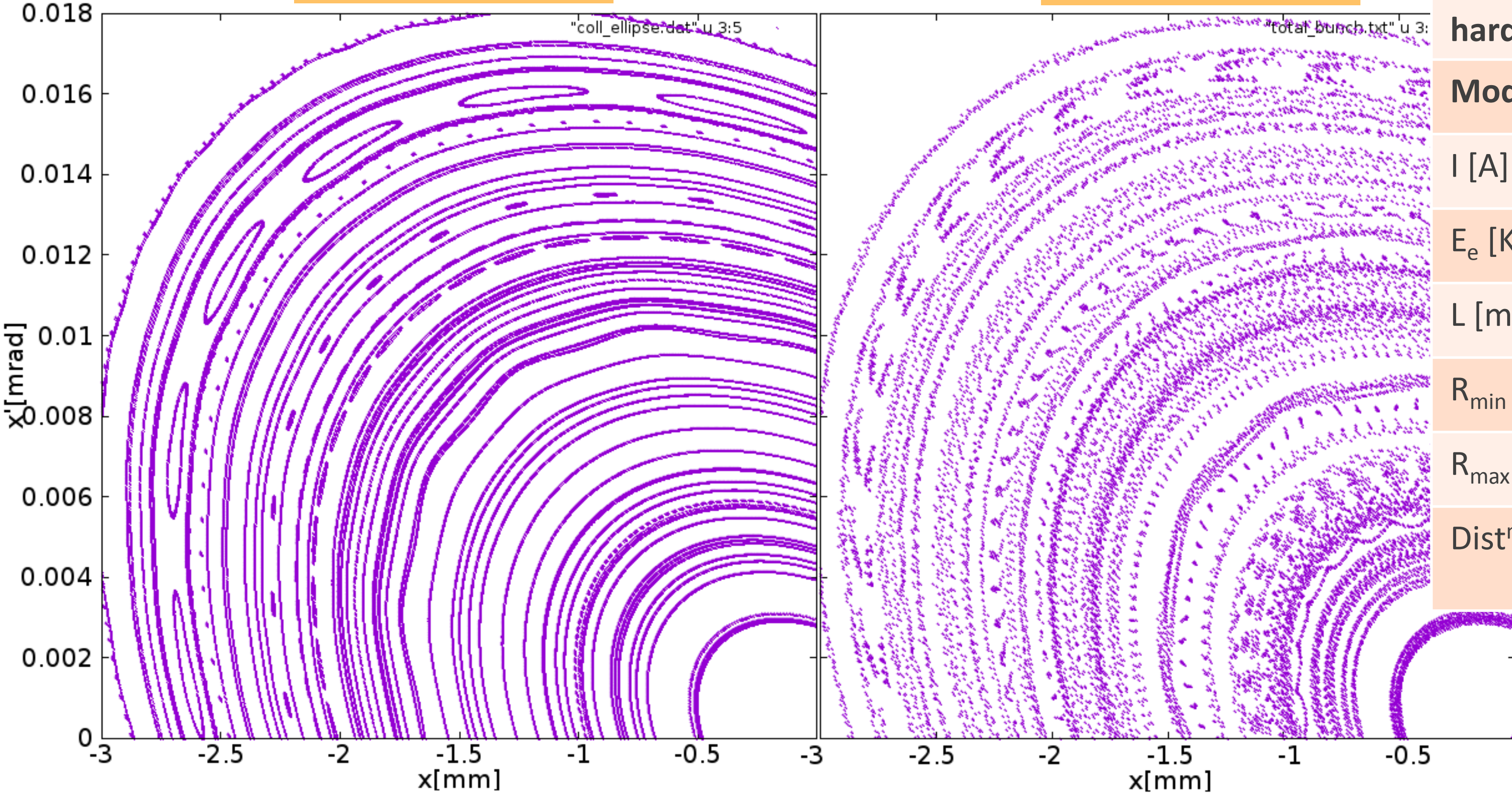


SixTrack vs MERLIN: DC

Identical SixTrack bunch

SixTrack

MERLIN



Parameter	Value
LHC lattice	Nominal
HEL hardware	Tevatron
Mode	DC
I [A]	1.2
E_e [KeV]	5
L [m]	2
R_{min} [σ_x]	4
R_{max} [σ_x]	6.8
Dist^n	SixTrack 1-10 σ_x

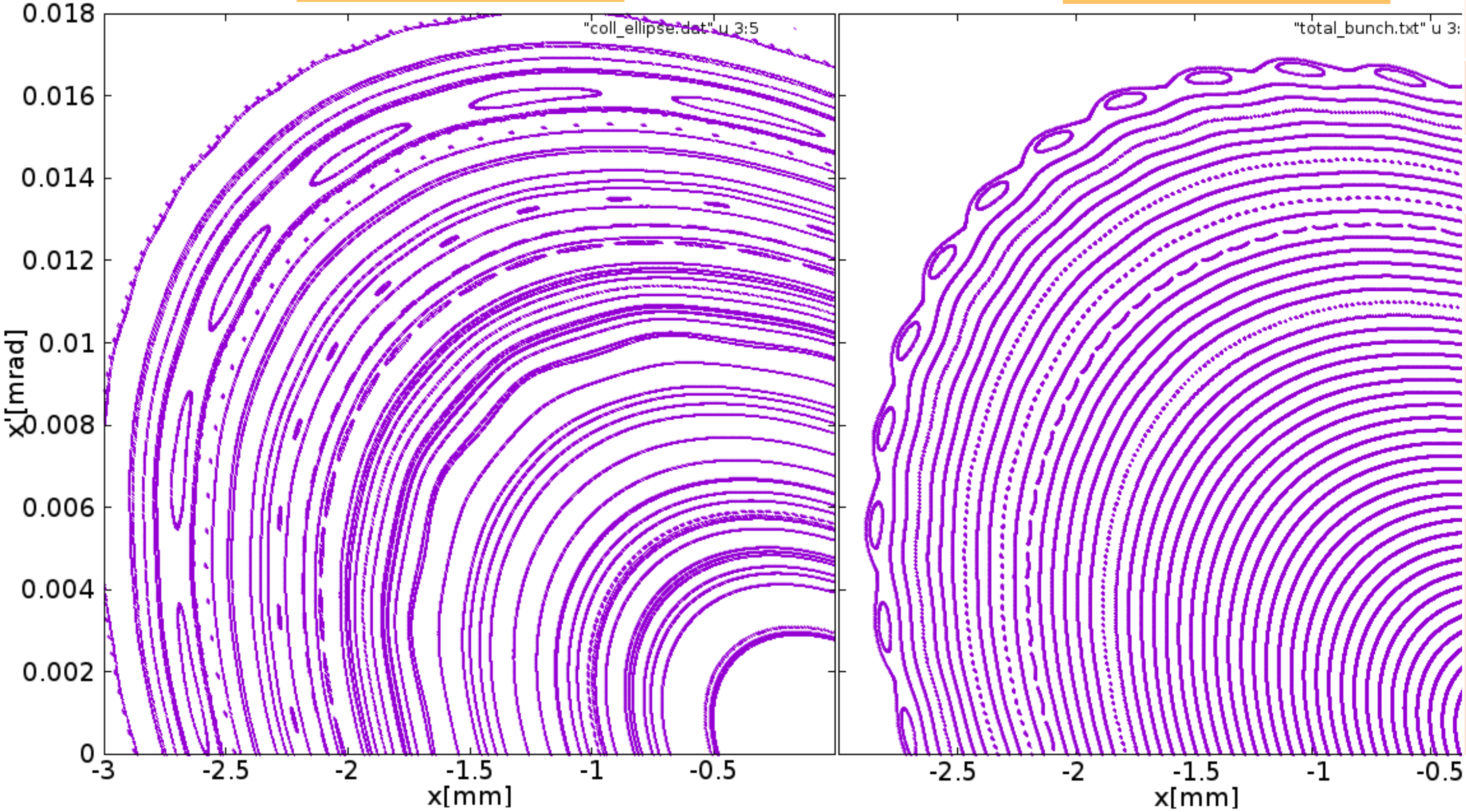
$4\sigma_x \approx 1.17$ mm

SixTrack vs MERLIN: DC

Different initial bunch for clarity

SixTrack (using SixTrack bunch)

MERLIN (using MERLIN bunch)



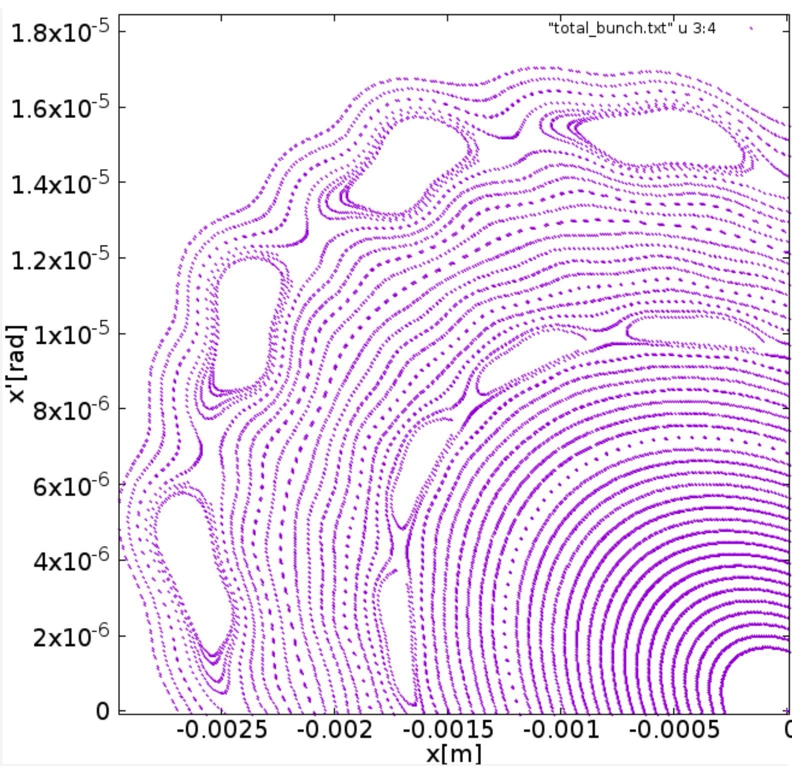
Parameter	Value
LHC lattice	**Nominal**
HEL hardware	**Tevatron**
Mode	**DC**
I [A]	1.2
E_e [KeV]	5
L [m]	2
R_{min} [σ_x]	4
R_{max} [σ_x]	6.8
$Dist^n$	SixTrack (Left) MERLIN (Right) 1-10 σ_x

$4\sigma_x \approx 1.17$ mm

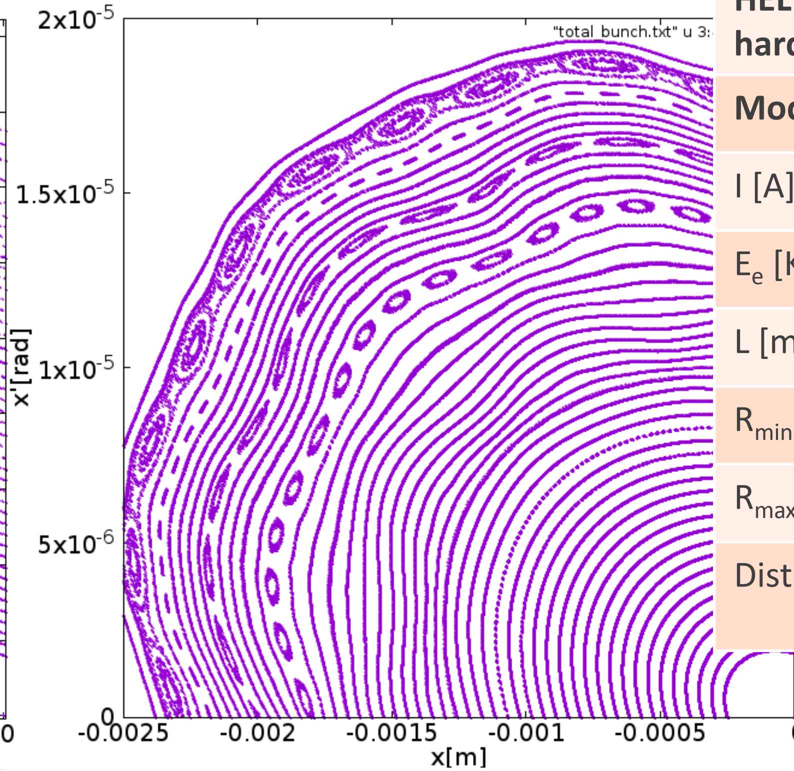
Nominal vs HL LHC: DC

Identical MERLIN bunch

MERLIN nominal



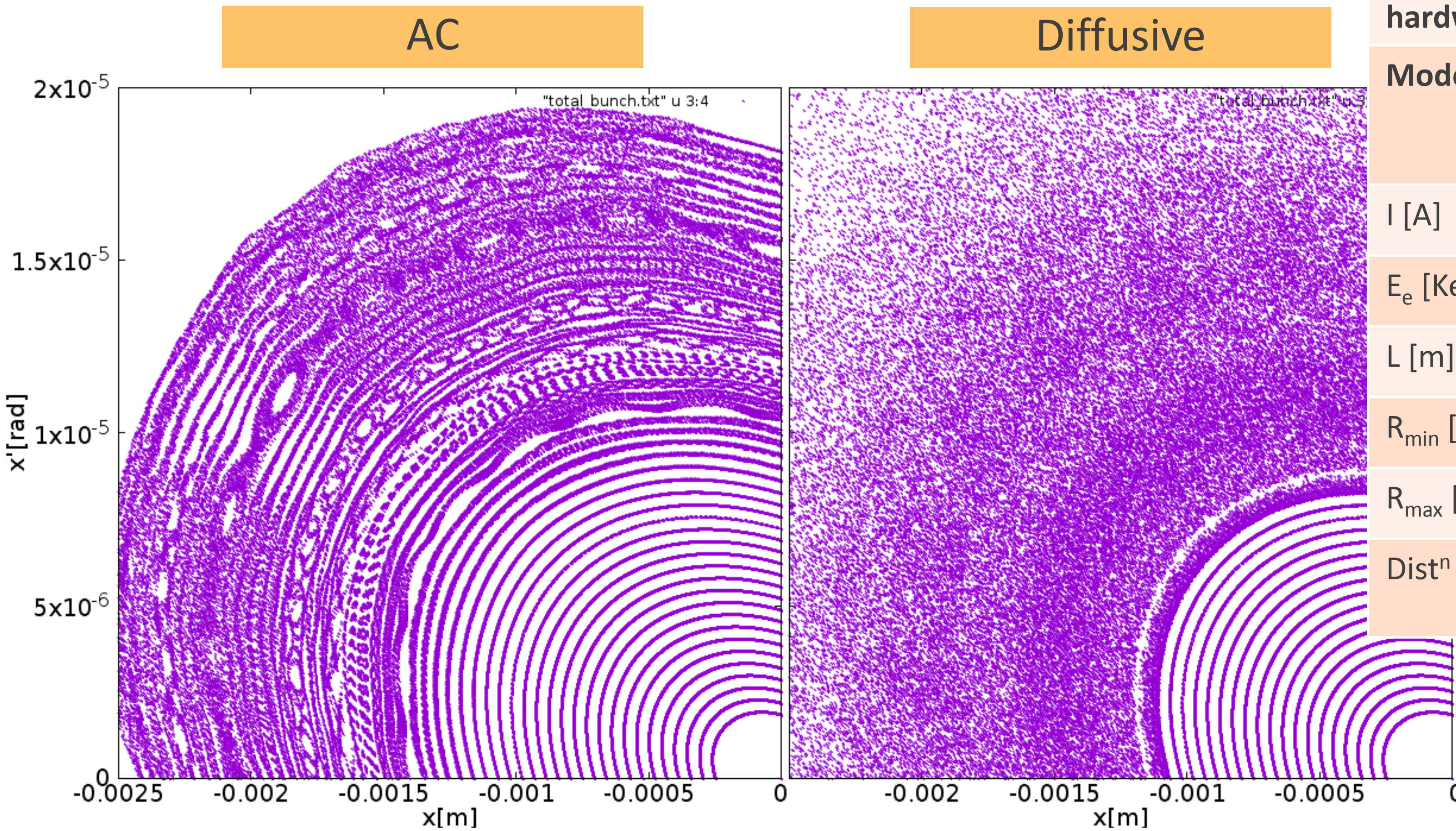
MERLIN HL



Parameter	Value
LHC lattice	Nominal (left) HL (right)
HEL hardware	LHC
Mode	DC
I [A]	5
E_e [KeV]	10
L [m]	3
R_{min} [σ_x]	4
R_{max} [σ_x]	8
Dist^n	MERLIN 1-10 σ_x

HL LHC: AC vs Diffusive

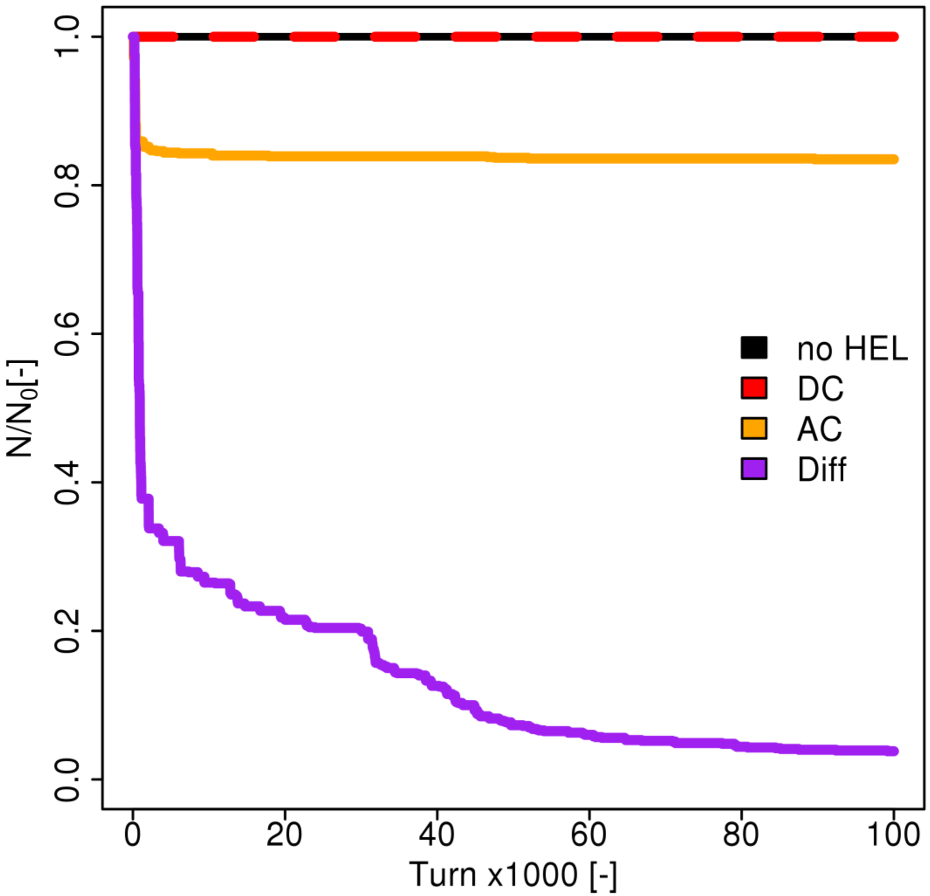
Identical MERLIN bunch



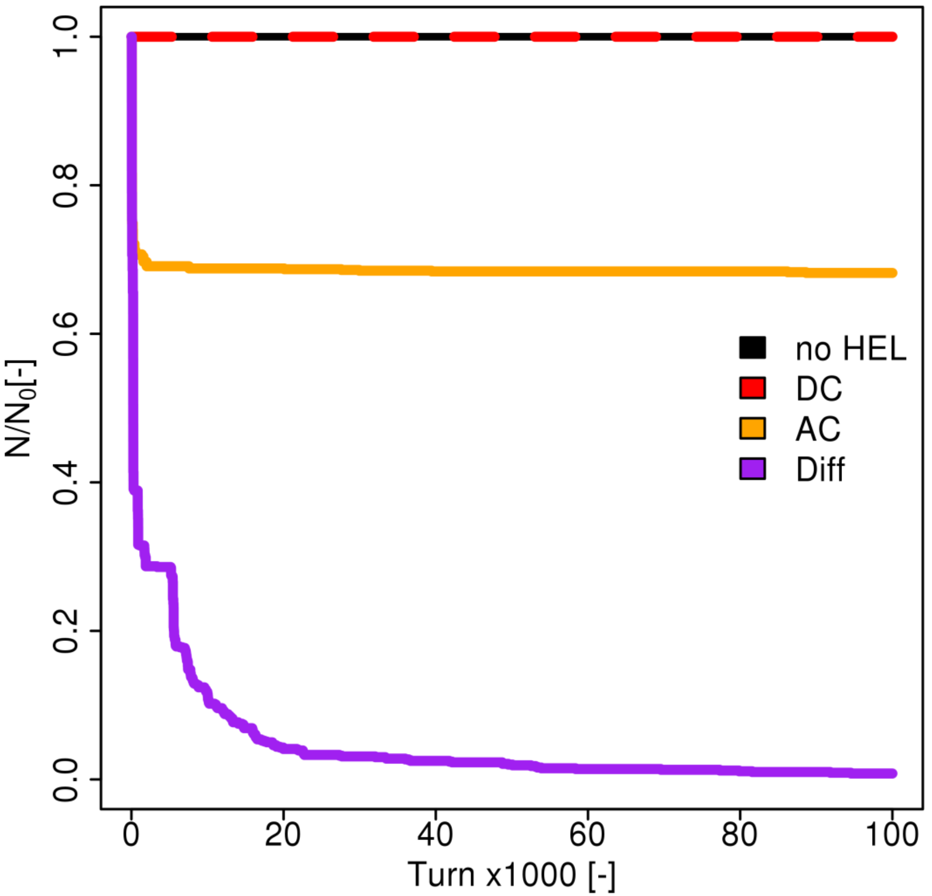
Parameter	Value
LHC lattice	HL
HEL hardware	LHC
Mode	AC (left) Diffusive (right)
I [A]	5
E_e [KeV]	10
L [m]	3
R_{min} [σ_x]	4
R_{max} [σ_x]	8
Dist^n	MERLIN 1-10 σ_x

Cleaning: nominal vs HL LHC

Nominal LHC

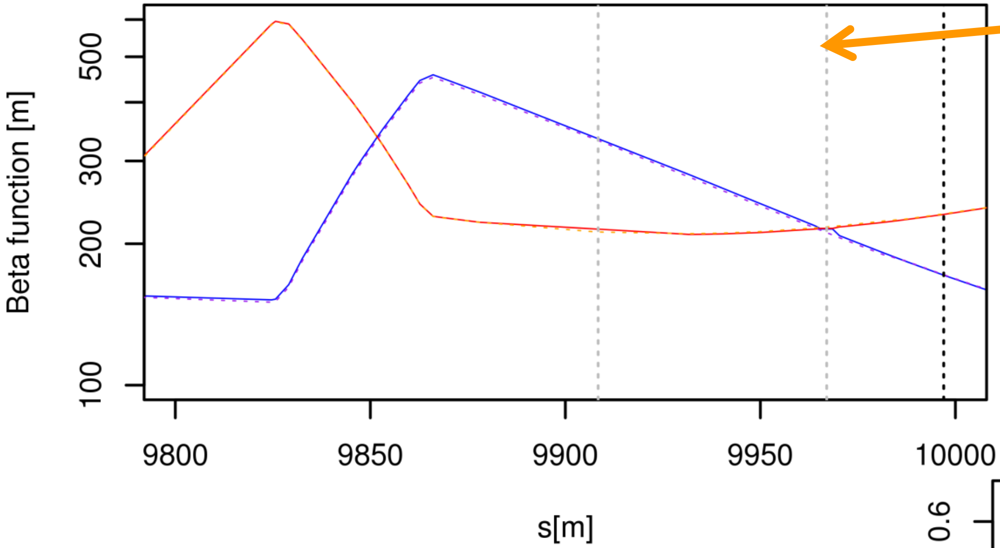


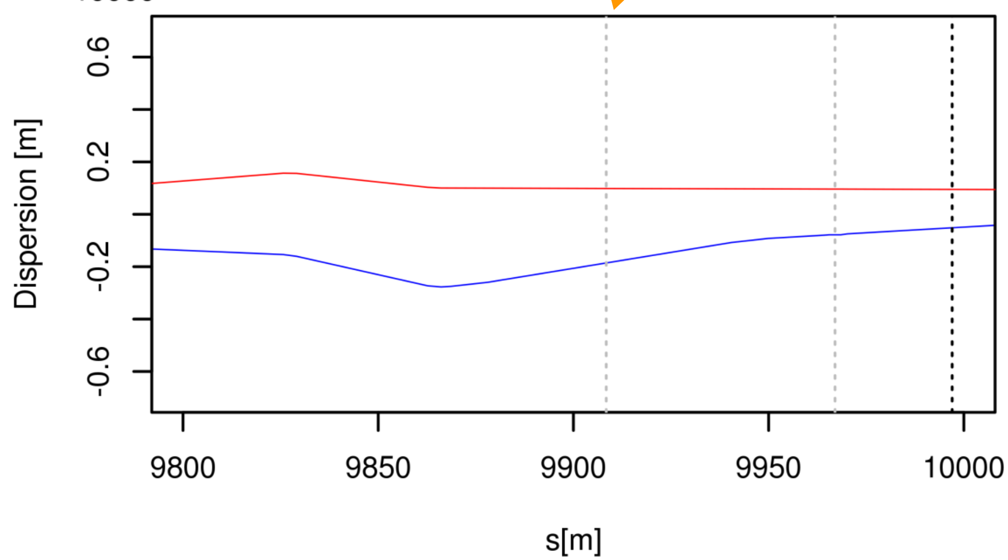
High Luminosity LHC



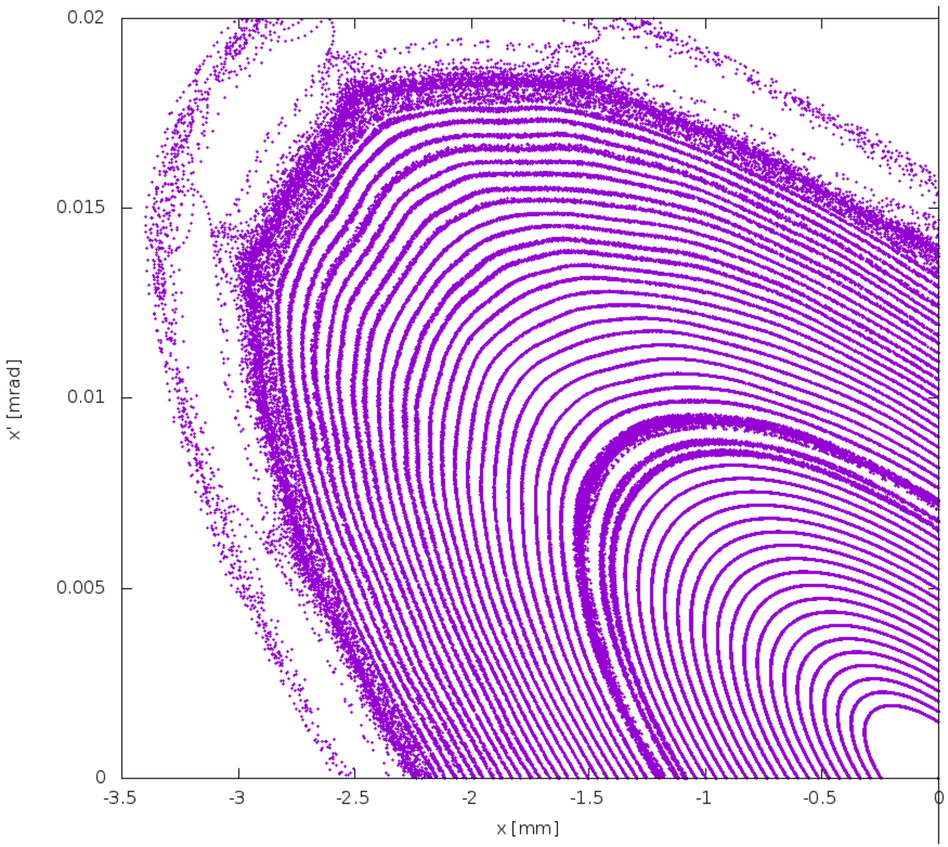
HEL Integration

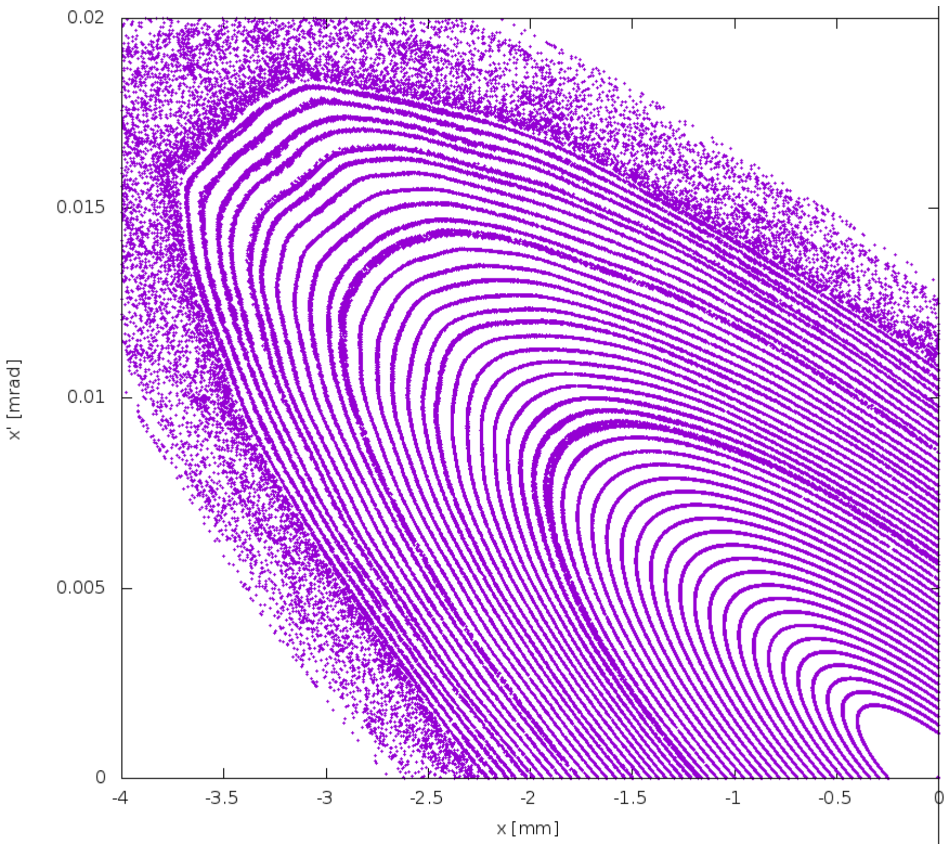
2 new candidate locations in IR4: ±30m, ±88.6m





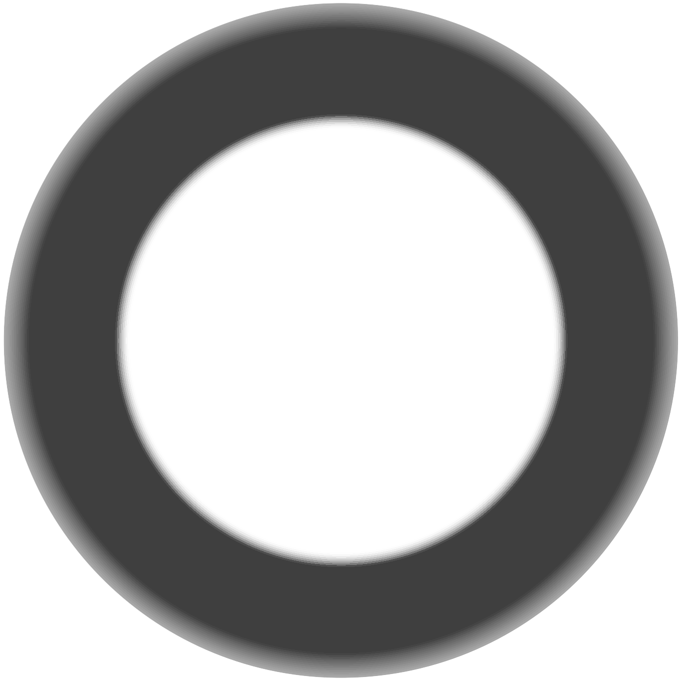
HEL Integration

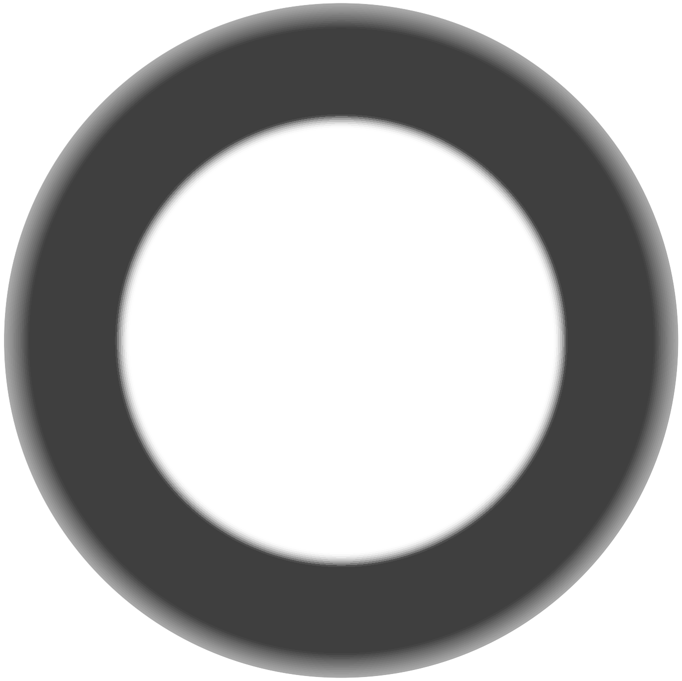




Future HEL Work

- Compare cleaning enhancement in each location
- Investigate cleaning of non round beam @±88.6m





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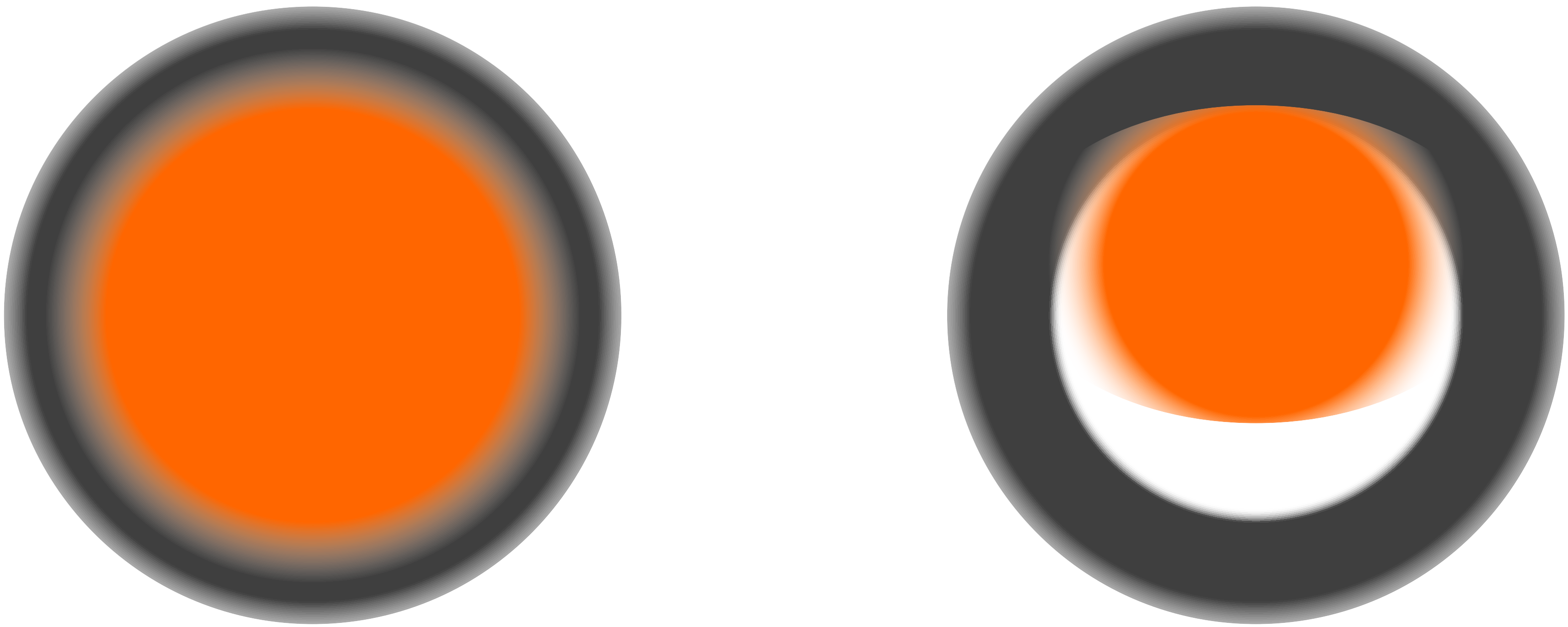
Future HEL Work

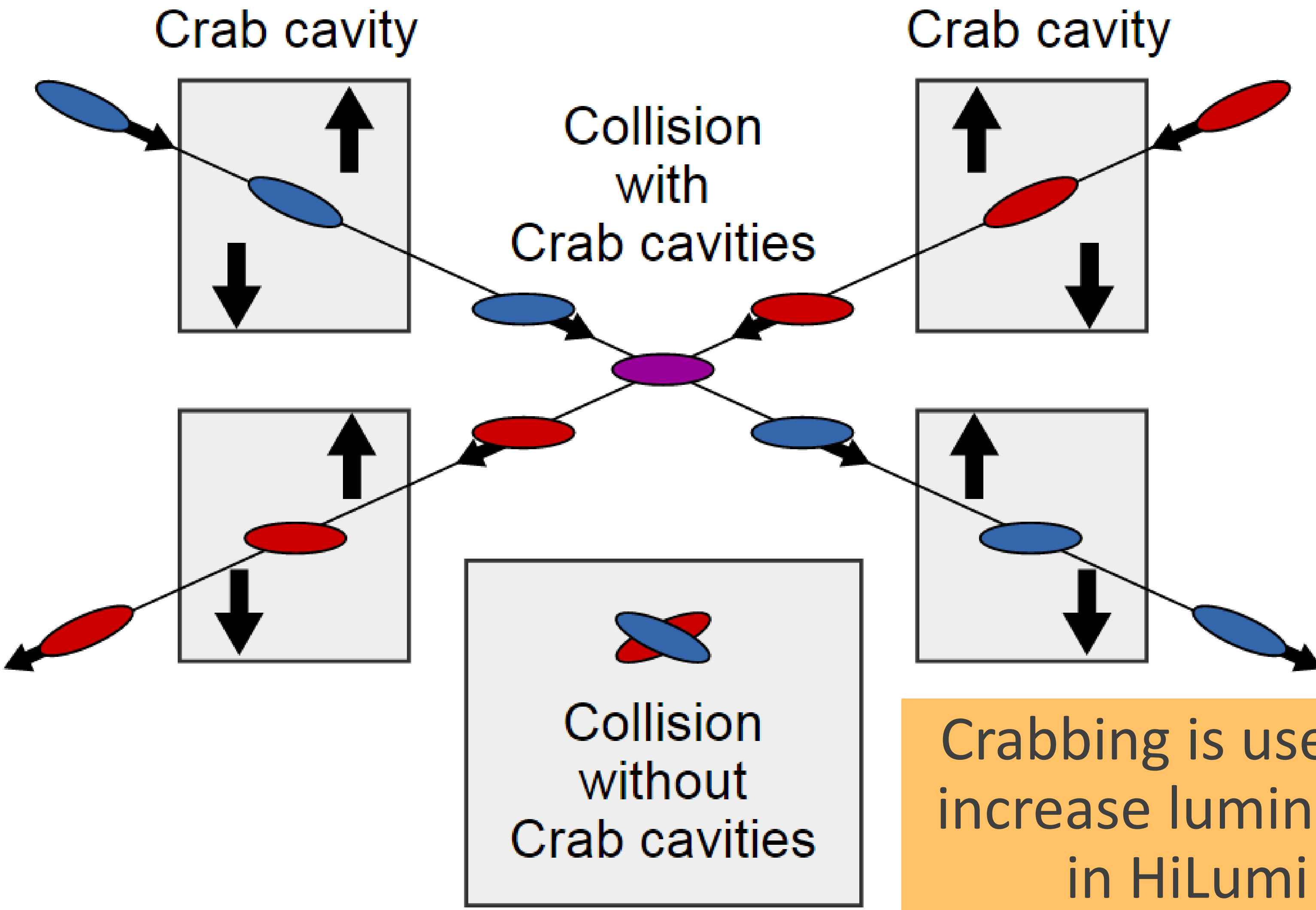
- Compare cleaning enhancement in each location
- Investigate cleaning of non round beam @±88.6m



CRAB CAVITY FAILURE PROCESS

HR & Andrea Santamaria Garcia @ CERN

Crabbing in HiLumi



Crabbing is used to increase luminosity in HiLumi

Why implement CCFailure?

- For HiLumi LHC – cases of crab cavity failures are catastrophic failures
  - Beam spread out to ~ 10 σ
  - Massive losses in magnets
  - Quenches
  - Permanent damage
  - Too fast to trigger a beam dump (< 3 turns)
- Can the HEL deplete the halo sufficiently, so that if CC failure occurs, losses can be handled by the proposed collimation system?

Simple Kick Model

Andrea Santamaría García

Crab cabity kick

The Hamiltonian to describe a thin horizontal CC is:

$$H_{crab} = \frac{qV}{p_s} \sin\left(\phi_s + \frac{\omega z}{c}\right) x$$

So that:

$$\Delta p_x = -\frac{\partial H_{crab}}{\partial x} = -\frac{qV}{p_s} sin\left(\phi_s + \frac{\omega z}{c}\right)$$

$$\Delta p_z = -\frac{\partial H_{crab}}{\partial z} = -\frac{qV}{p_s} cos\left(\phi_s + \frac{\omega z}{c}\right) \frac{\omega}{c} x$$

Derivation of the voltage

To translate the (y, y') vector between two arbitrary points of the machine we use the tran

$$\begin{pmatrix} y_2 \\ y_2' \end{pmatrix} = M_{1\to 2} \begin{pmatrix} y_1 \\ y_1' \end{pmatrix}$$

In terms of the Twiss paramenters and the phase advance between the points we have:

$$M_{1\to 2} = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos(\Delta\mu) + \alpha_1 \sin(\Delta\mu)) & \sqrt{\beta_1\beta_2} \sin(\Delta\mu) \\ -\frac{(1+\alpha_1\alpha_2)\sin(\Delta\mu)+(\alpha_2-\alpha_1)\cos(\Delta\mu)}{\sqrt{\beta_1\beta_2}} & \sqrt{\frac{\beta_1}{\beta_2}}(\cos(\Delta\mu) - \alpha_2 \sin(\Delta\mu)) \end{pmatrix}$$

So:

$$\begin{pmatrix} y_2 \\ y_2' \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} y_1 \\ y_1' \end{pmatrix} \rightarrow \begin{cases} y_2 = M_{11} y_1 + M \\ y_2' = M_{21} y_1 + M \end{cases}$$

We want to translate the particles from the begining of the crab cavity to the end. We can phase advance and beta functions is negligeable, so that $M_{11} = 1$. We then have:

$$y_2 = y_1 + M_{12} y_1'$$

where we can replace y_1' by the kick formula:

$$y_2 = y_1 + M_{12} \frac{qV \sin\left(\phi_s + \frac{\omega z}{c}\right)}{E}$$

We know that the voltage has to be chosen in order to compensate half the crossing angle θ. The slope is:

$$\tan(\theta) = \frac{\Delta y}{\Delta s} \approx \frac{dy}{ds} \rightarrow \tan(\theta) = \frac{d\left(y_1 + M_{12}\frac{qV \sin\left(\phi_s + \frac{\omega z}{c}\right)}{E}\right)}{ds}$$

$z = s - s_0$ where s_0 is the position in the center of the bunch. Assuming small angles the expression can be simplified into:

$$\tan(\theta) = \frac{M_{12} qV\omega}{cE} \Rightarrow V = \frac{cE\tan(\theta)}{q\omega M_{12}} = \frac{cE\tan(\theta)}{q\omega\sqrt{\beta_1\beta_2}\sin(\Delta\mu) n_{cc}}$$

The voltage to close the bump would then be:

$$V_2 = -M_{22} V$$

where M_{22} denotes the $(2, 2)$ element of the optical transfer matrix from the first CC to the second one downstream.

$$M_{22} = \sqrt{\frac{\beta_1}{\beta_2}}(\cos(\Delta\mu) - \alpha_2 \sin(\Delta\mu)) \approx \sqrt{\frac{\beta_1}{\beta_2}}(\cos(\Delta\mu))$$

where the subindex 1 denotes *upstream* and 2 denotes *downstream*. The phase advance between the CCs and the IP is optimized to be $\Delta\mu = \frac{\pi}{2}$.

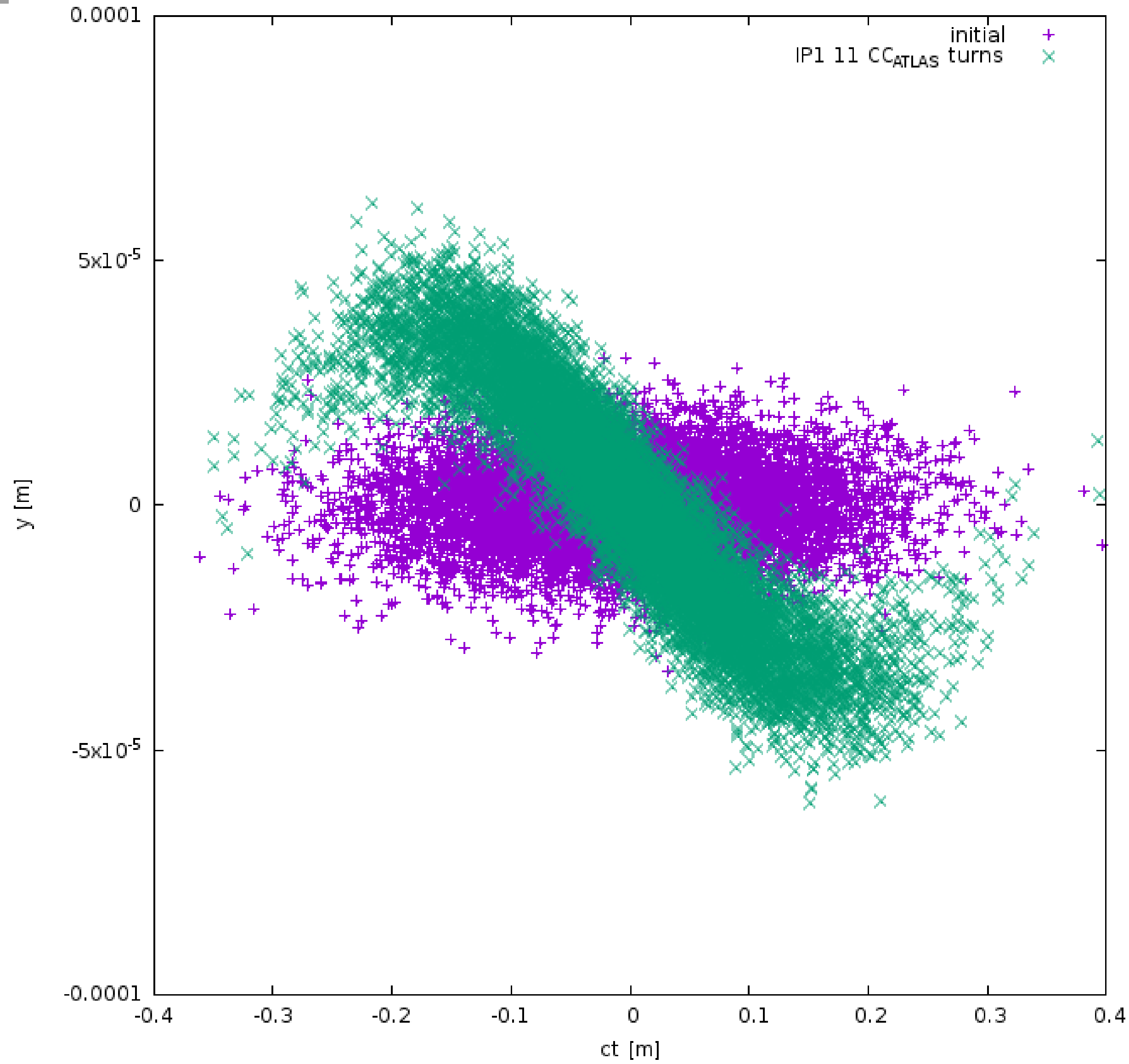
Derivation of the displacement

Coming back to the equation:

$$y_2 = y_1 + M_{12} \frac{qV \sin\left(\phi_s + \frac{\omega z}{c}\right)}{E}$$

Thin CC Kick

Vertical crabbing @ IP1 (ATLAS)



Closed Bump

Bunch at TCP after a full 'CC' turn

'Pre tracked'

IP1 -> First ATLAS CC

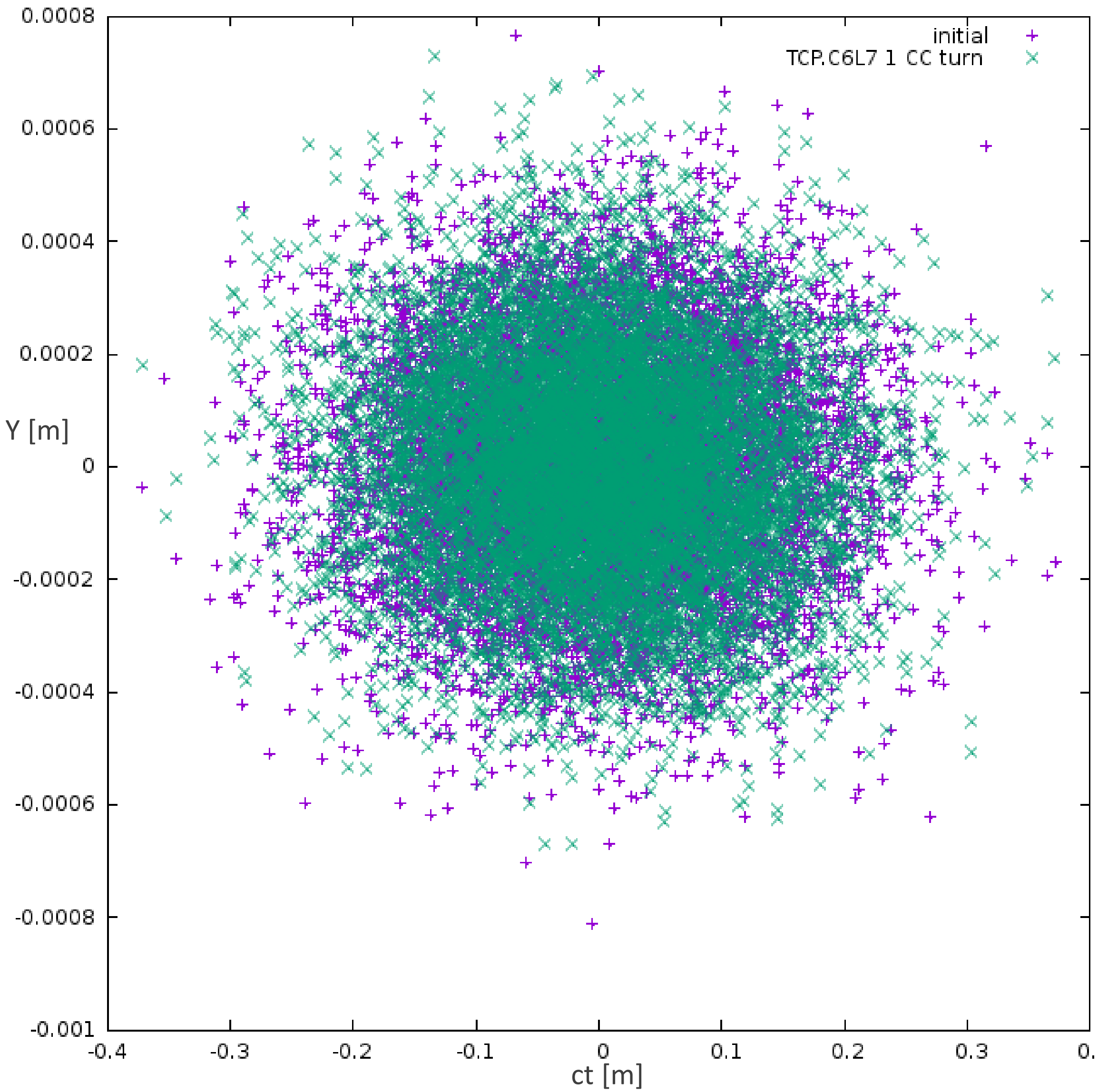
'Tracked + CCF Process'

First ATLAS CC -> 1 turn

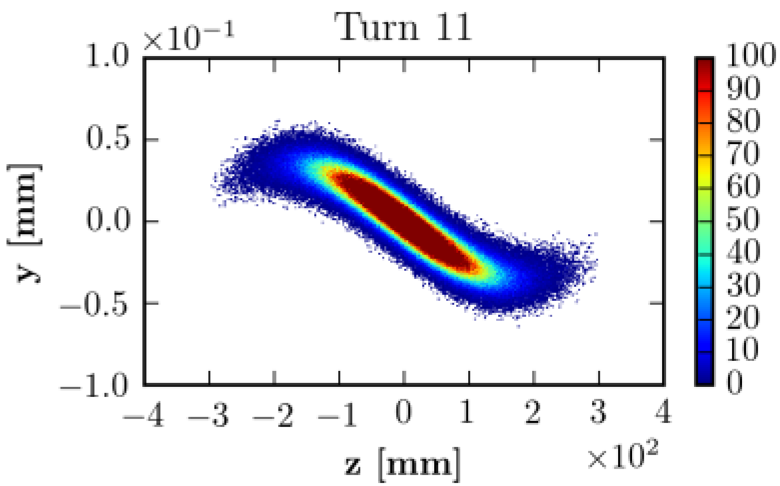
'Post tracked'

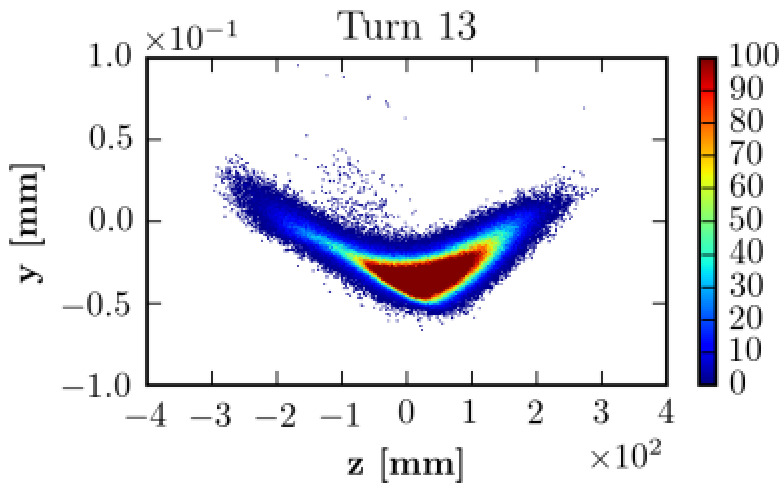
First ATLAS CC -> IP1

Holds for many turns

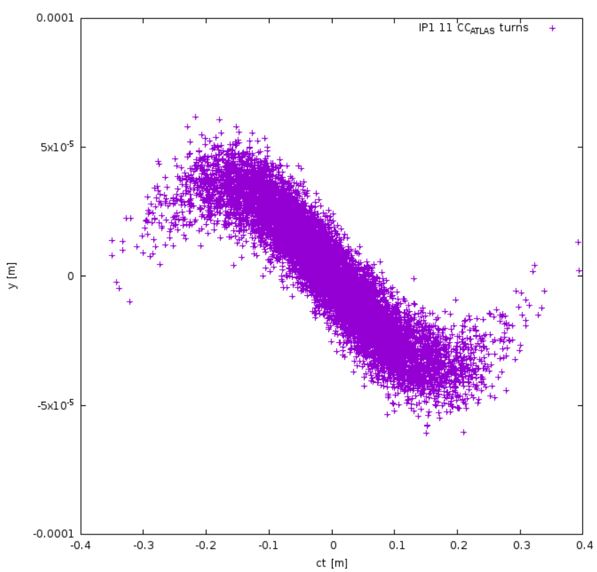


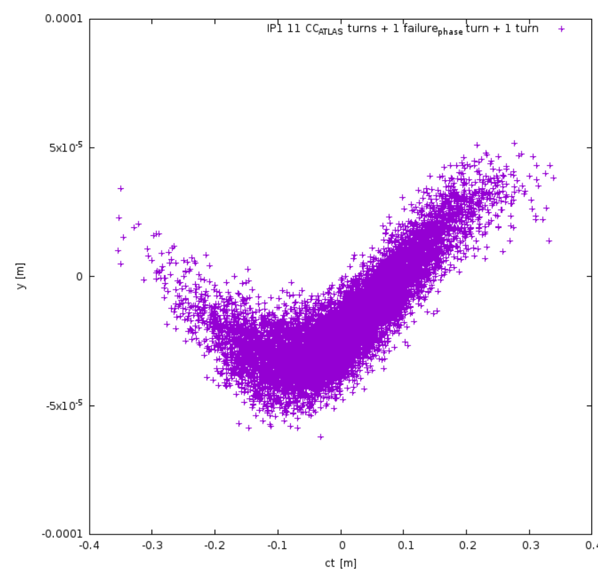
4 CC 90° Phase Failure





A. Santamaría (Wednesday)



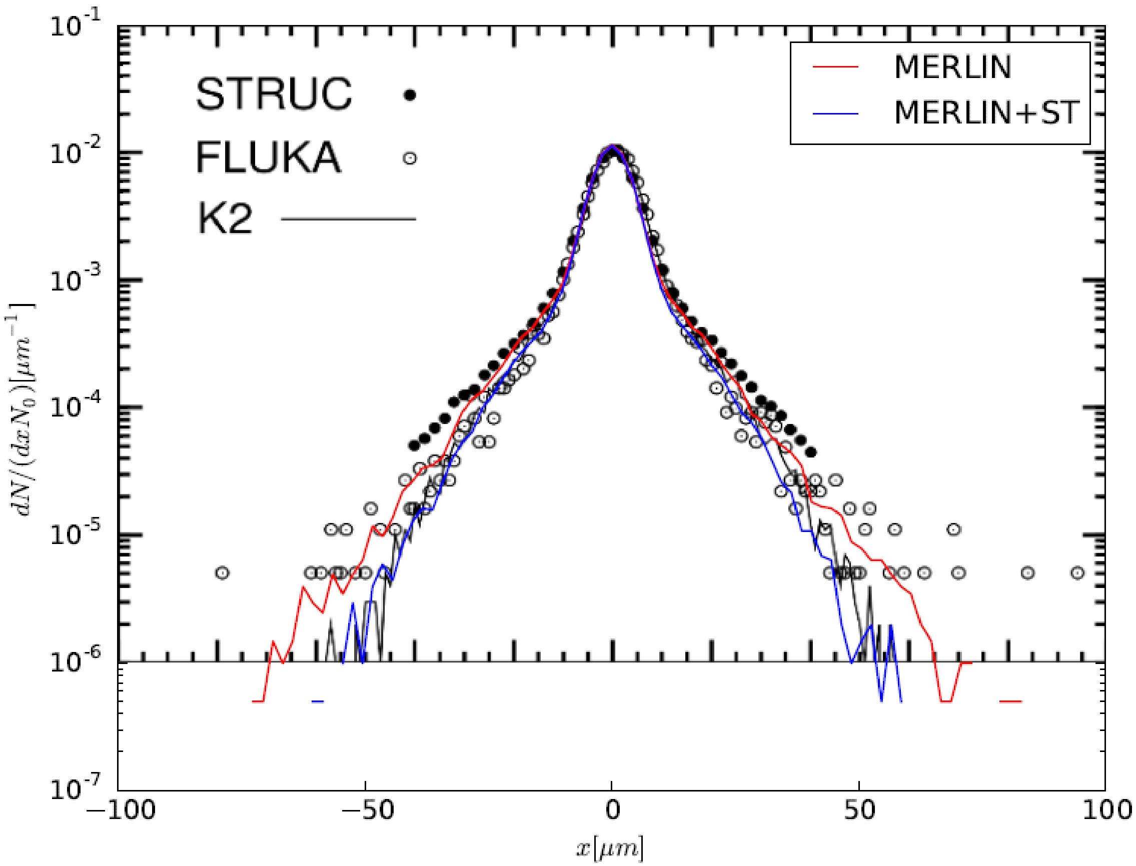


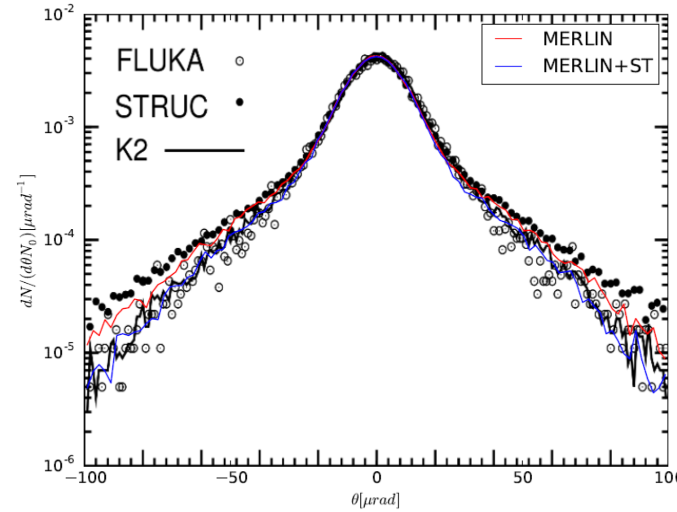
MERLIN (Thursday)

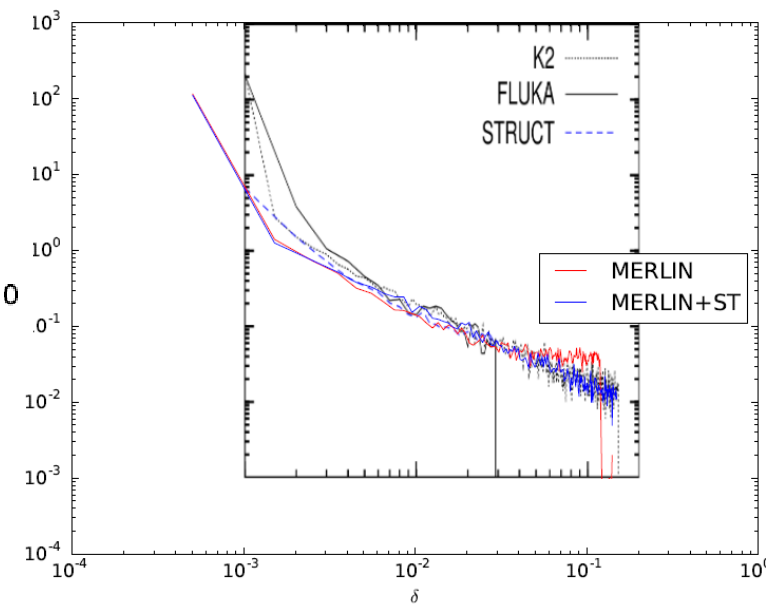
MATERIALS

Scattering Test Case

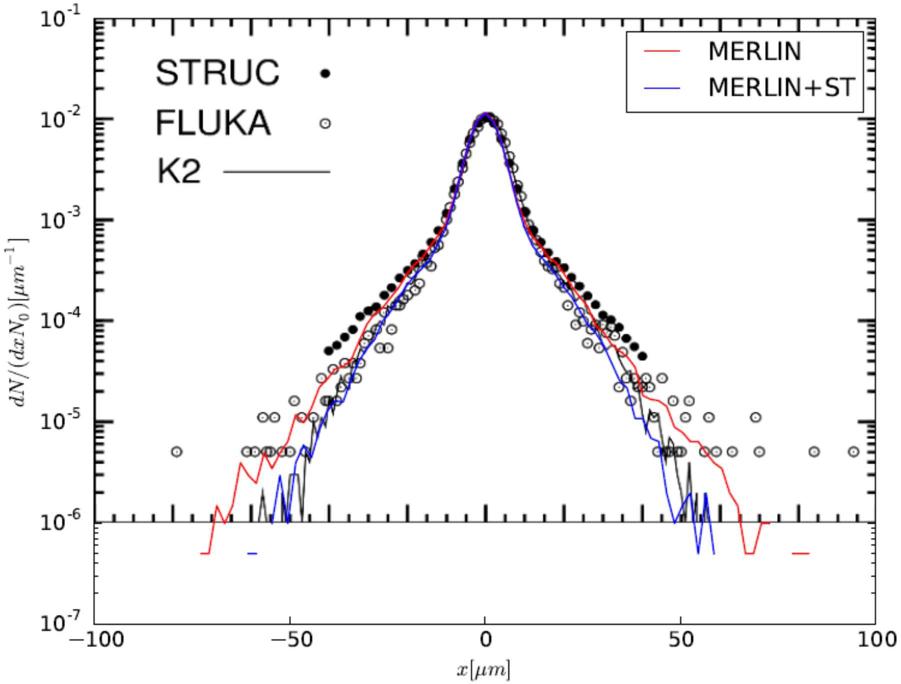
Assmann *et al.* Comparison

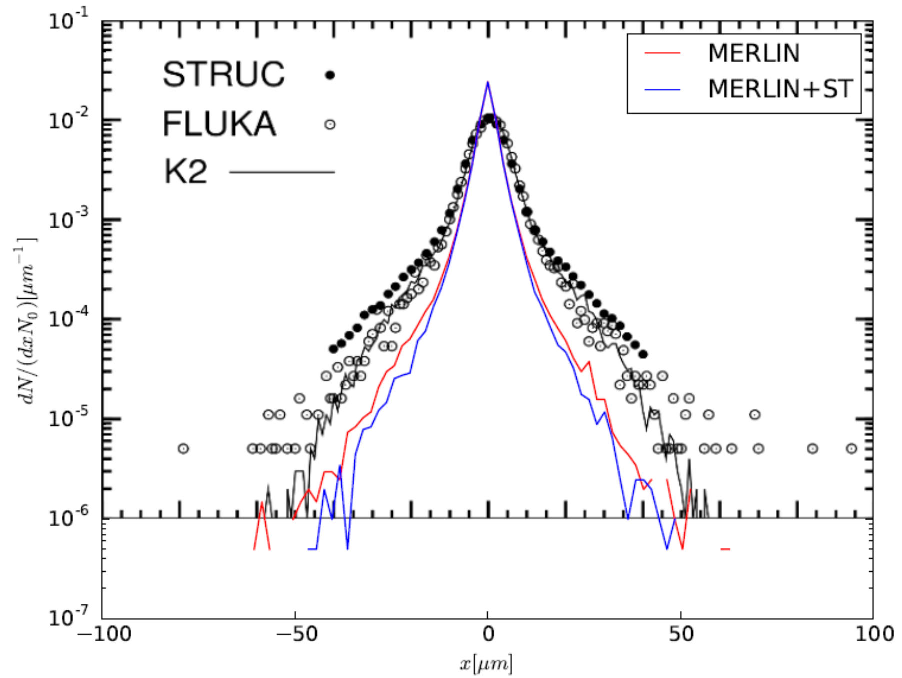




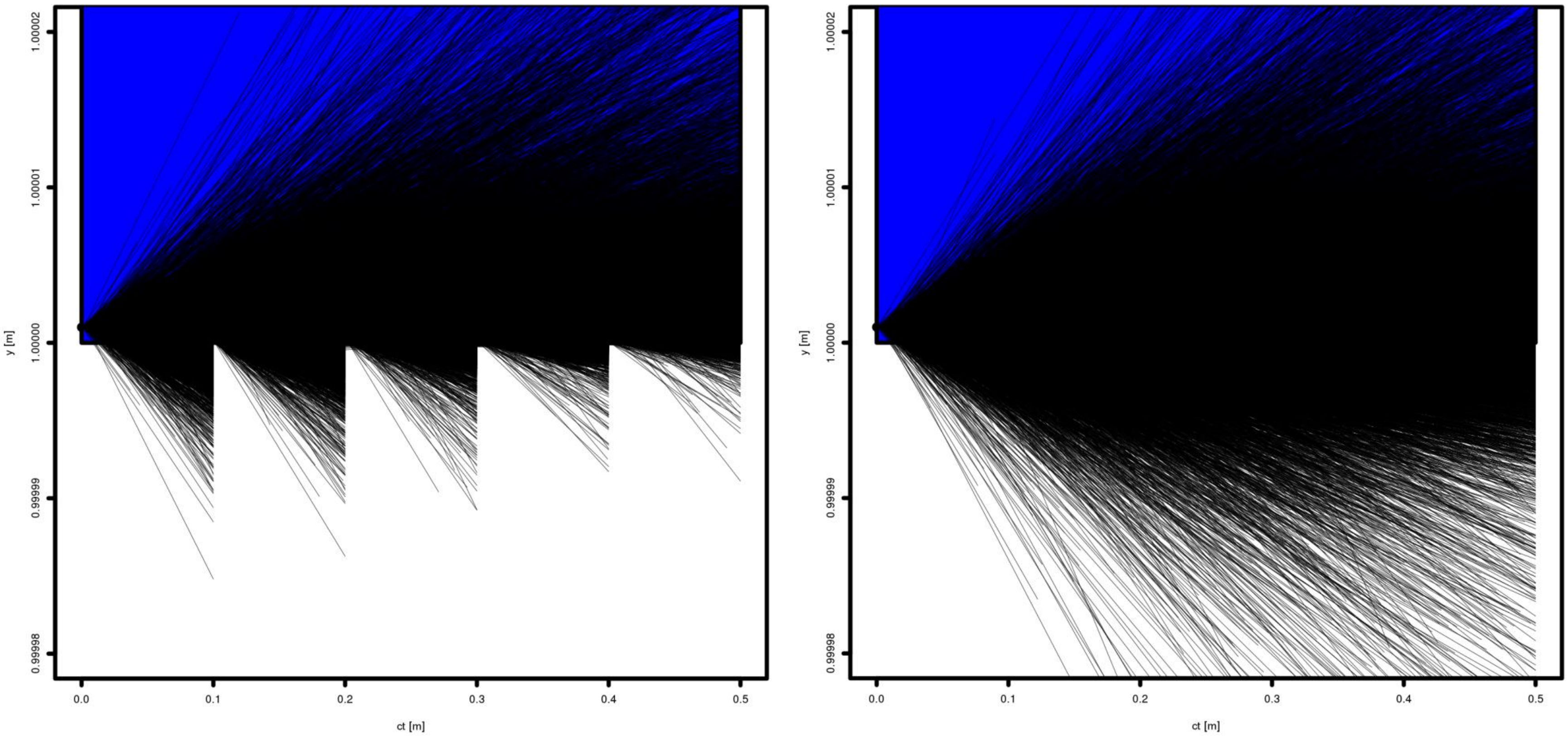


Dependence on bin size



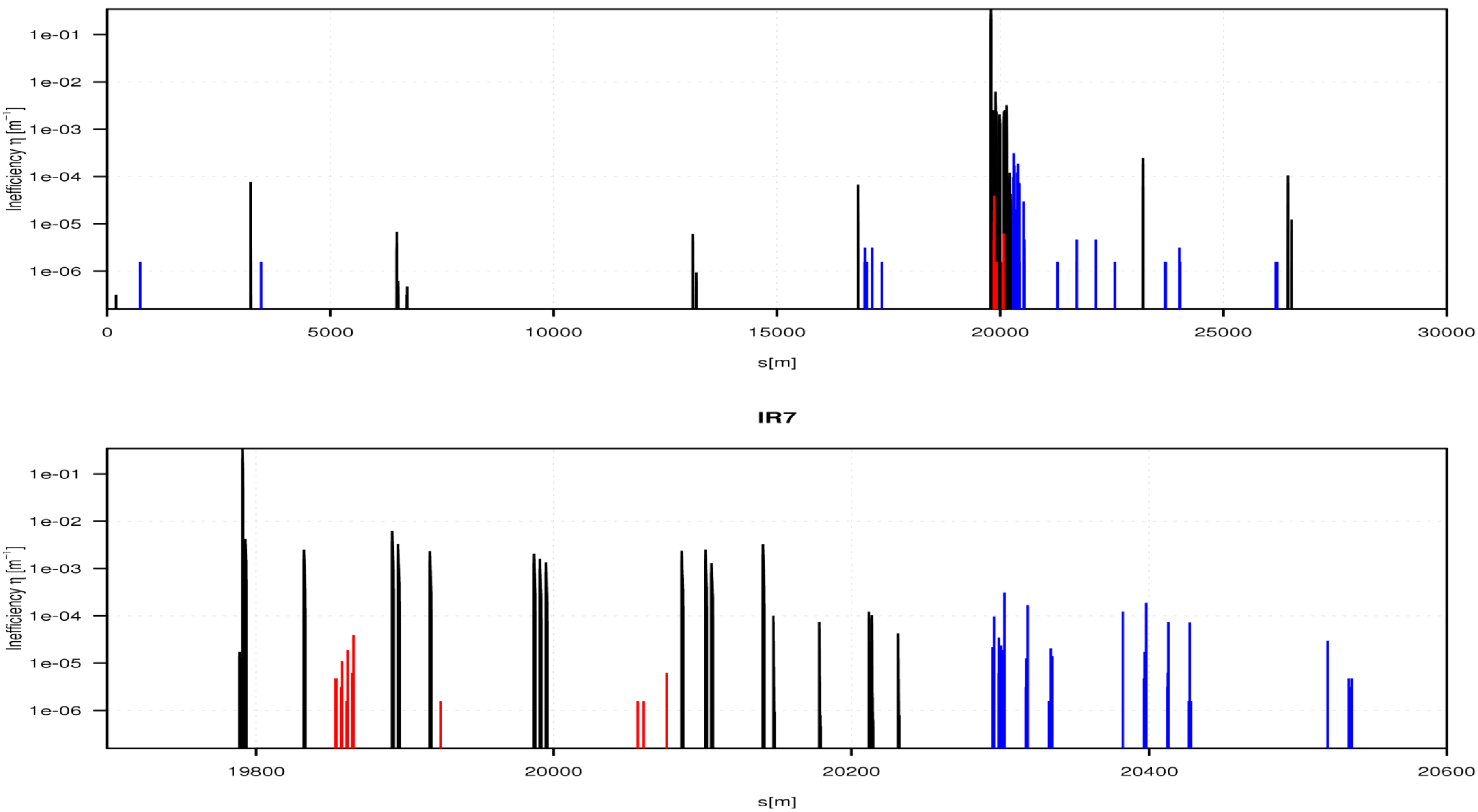


Scattering vs Bin Size



LOSS MAPS

HL v1.2.1 (Crossing On)



FUTURE

Documentation

- MERLIN is on GitHub
- HR merlin site: https://sites.google.com/site/haroonrafiquemerlin/
- HR HEL site: https://sites.google.com/site/hollowelens/home
- HR thesis – early 2016

Future Work

Run **side-by-side with, and use to improve SixTrack** HEL routine for HL LHC (J. Wagner @CERN)

Use of **CC failure** model and integrator (c.f. A. Santamaría @ CERN)

HEL integration study (A. Rossi & J. Wagner @ CERN)

Support of **MERLIN use @ CERN** (A. Valloni + many more)

CC failure + HEL + Loss Maps?

S. Tygier – **HL squeeze loss study**

J. Molson – **FCC Collimation**

Acknowledgements

J. Molson, M. Serluca, S. Tygier – MERLIN development
R. Bruce & S. Redaelli – Collimation
A. Santamaría – CC failure
D. Mirarchi & J. Wagner – HEL
A. Rossi – HL HEL integration
A. Valloni – Sanity check
R. Barlow – Supervision
NGACDT – Opportunities & funding etc

TIME FOR COFFEE (OR BEER)