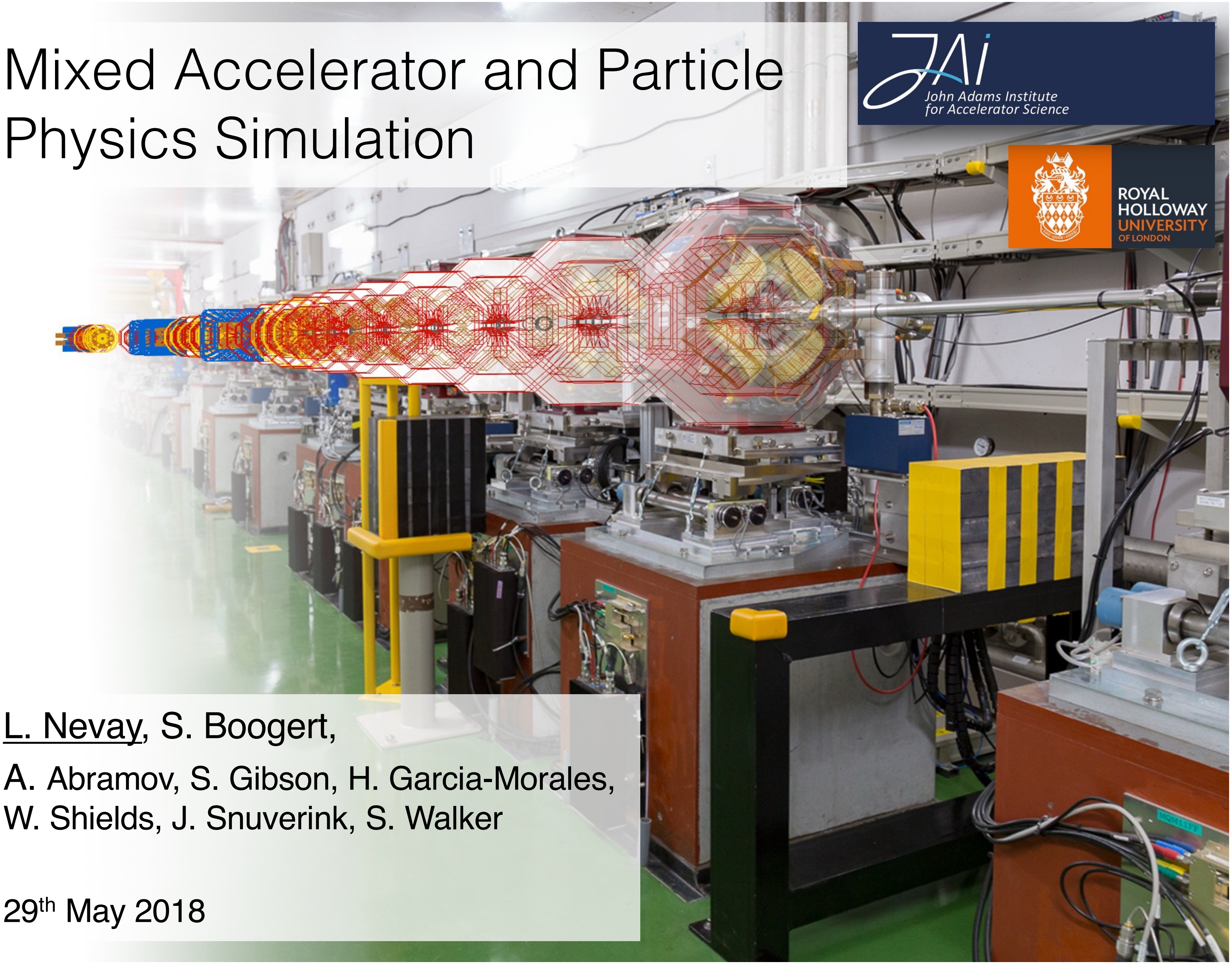
Mixed Accelerator and Particle Physics Simulation



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ROYAL HOLLOWAY UNIVERSITY OF LONDON

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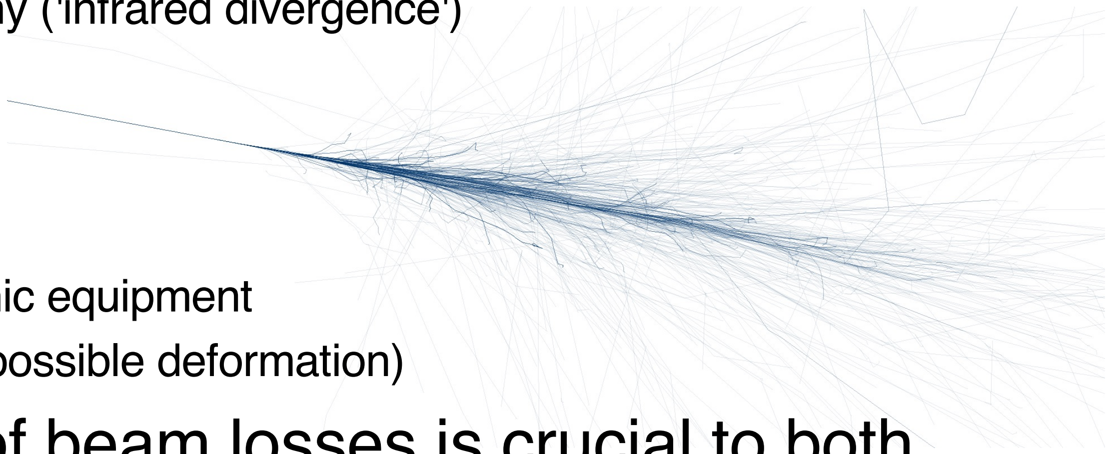
Outline

1) Introduction to problem
   - Beam induced backgrounds in accelerators
2) Our solution
   - Beam Delivery Simulation
3) Examples
   - International Linear Collider
   - Large Hadron Collider
   - PSI proton gantry

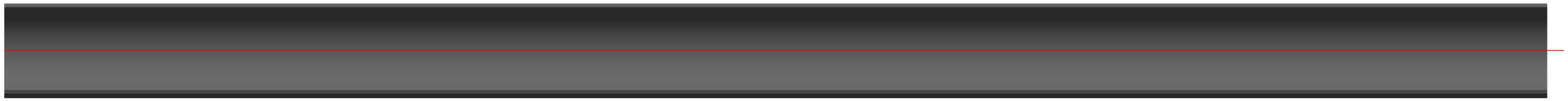
Introduction

- No accelerator perfectly contains all particles
  - either by design tolerance (certain capture %)
  - via stochastic processes (intra-beam scattering, beam-beam, collective effects)
- High energy particles lead to many secondary particles
  - photons, e^-, e^+, nuclear fragments, exotic unstable particles, etc.
  - one initial particle leads to many ('infrared divergence')
- Beam loss leads to:
  - detector background
  - energy deposition
  - heat loads, possibly in cryogenic equipment
  - radio-activation and damage (possible deformation)
- Prediction and control of beam losses is crucial to both the accelerator and experiment operation

1x 10 GeV e^- in Cu

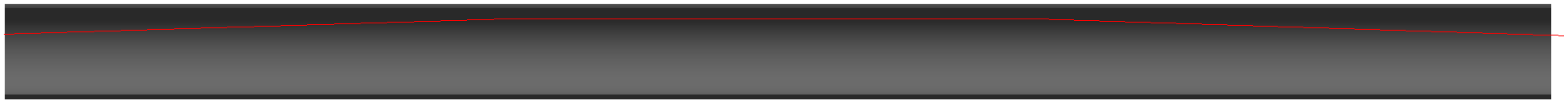


Beam Loss



particle in pipe

Beam Loss



+ field

Beam Loss

escape!

Beam Loss

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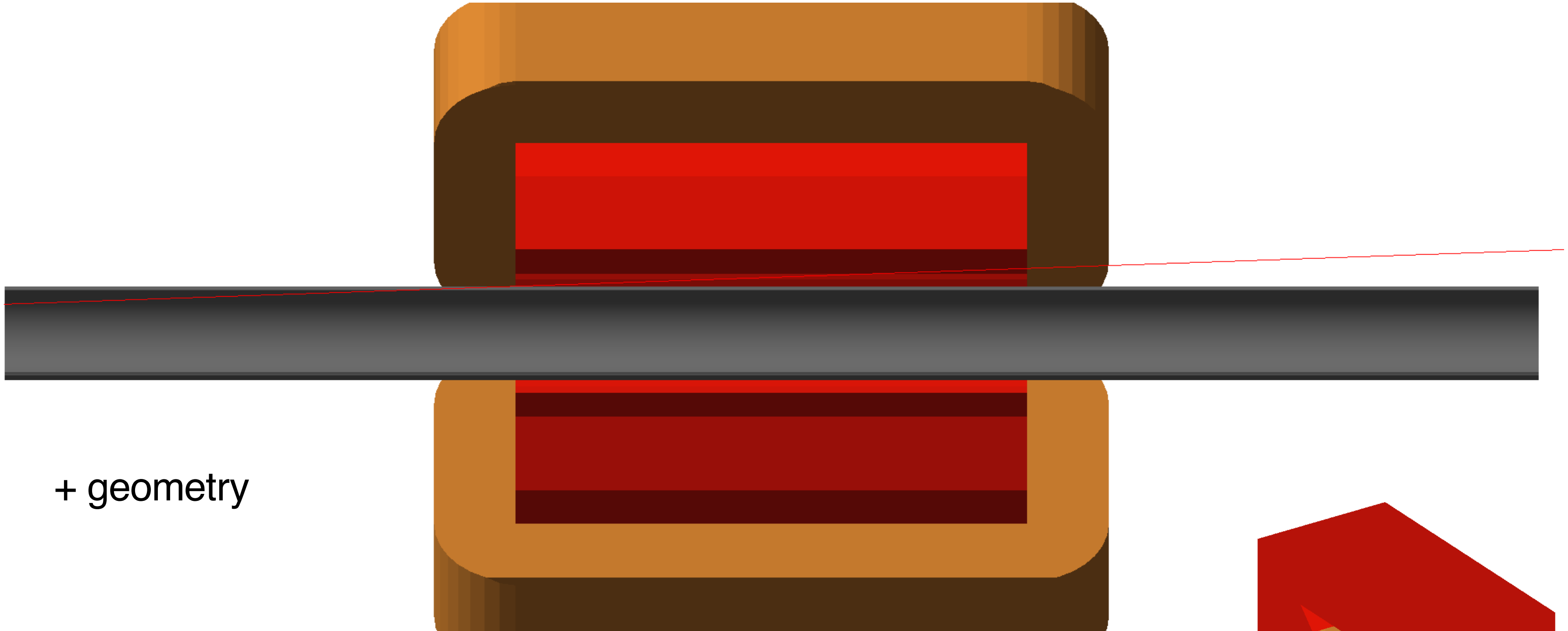
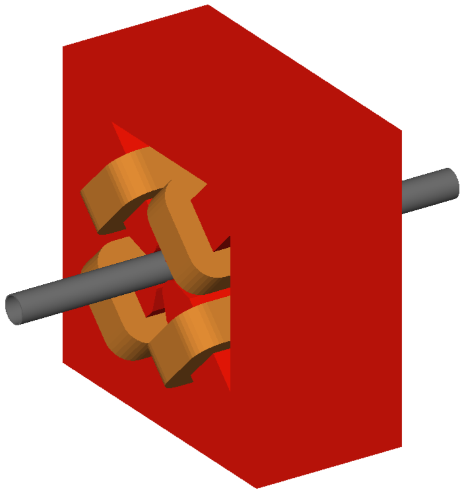
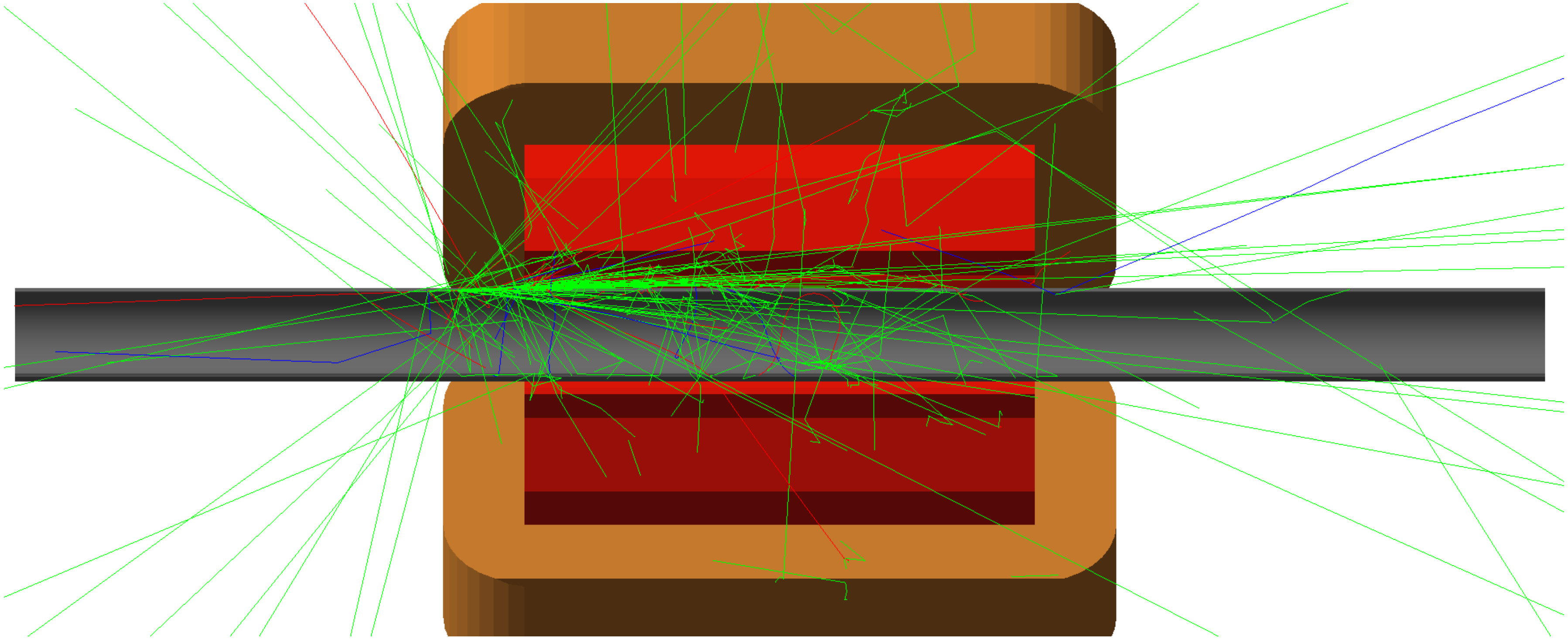


+ geometry

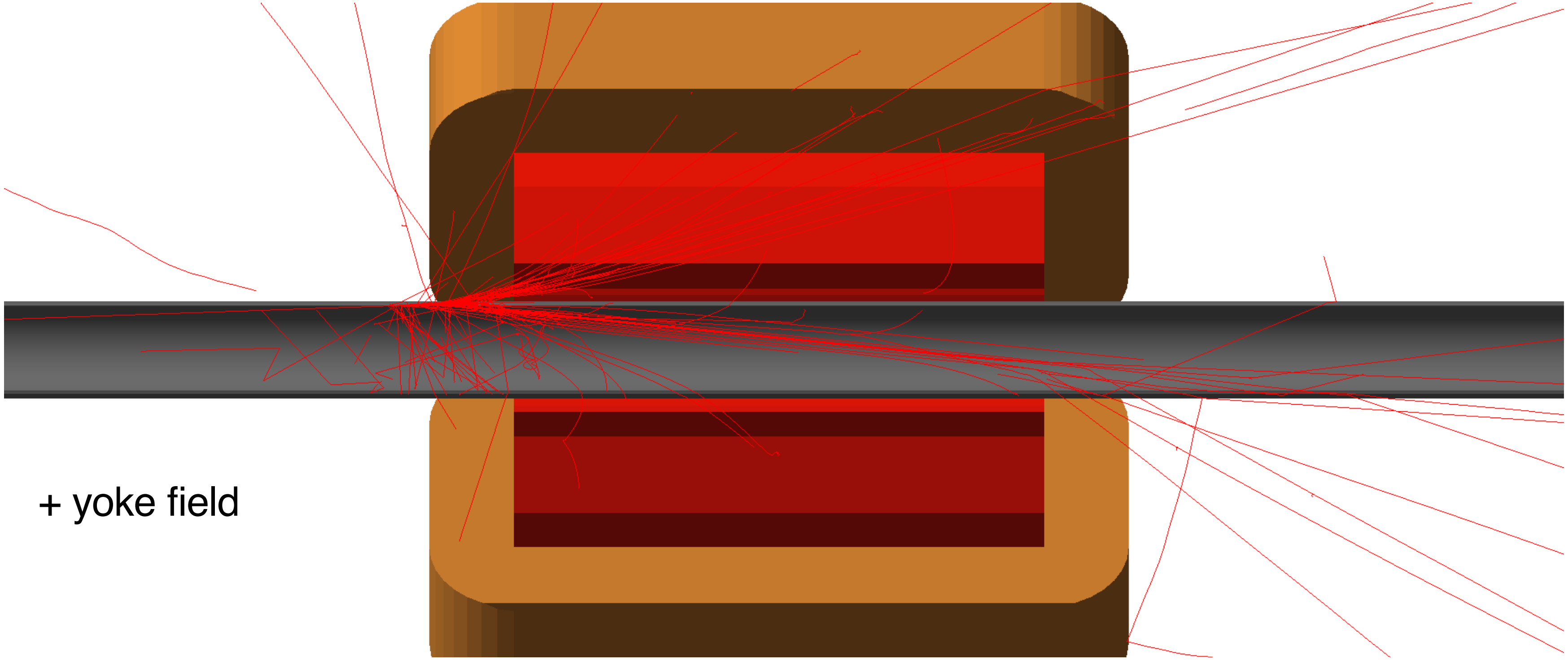


Beam Loss



+ physics

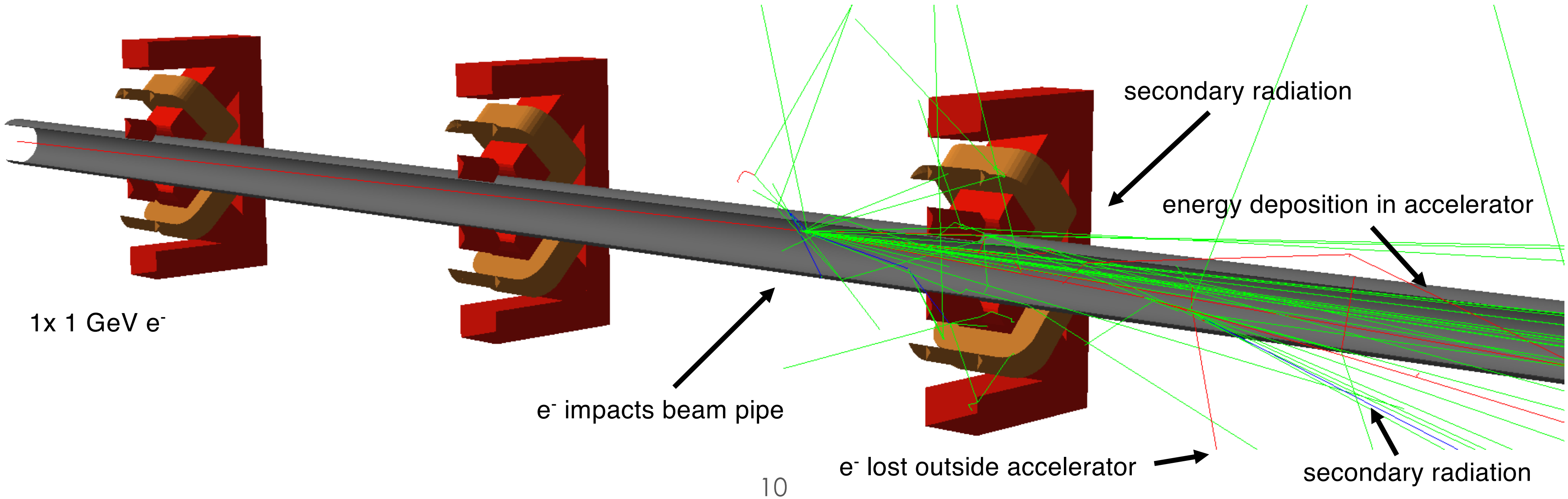
Beam Loss



+ yoke field

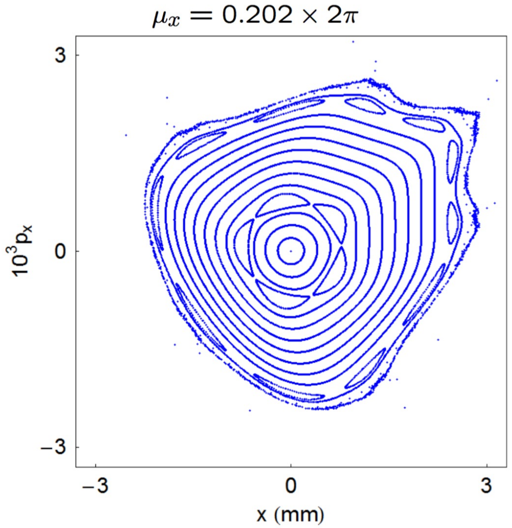
Simulating Beam Loss

- Simulate motion of particles in accelerator
- Predict where particle is 'lost'
  - what do we mean by lost here? impact? absorption?
- Simulate interaction with accelerator
- Motion in fields non-trivial
  - variety of fields in an accelerator
- Interaction also non-trivial

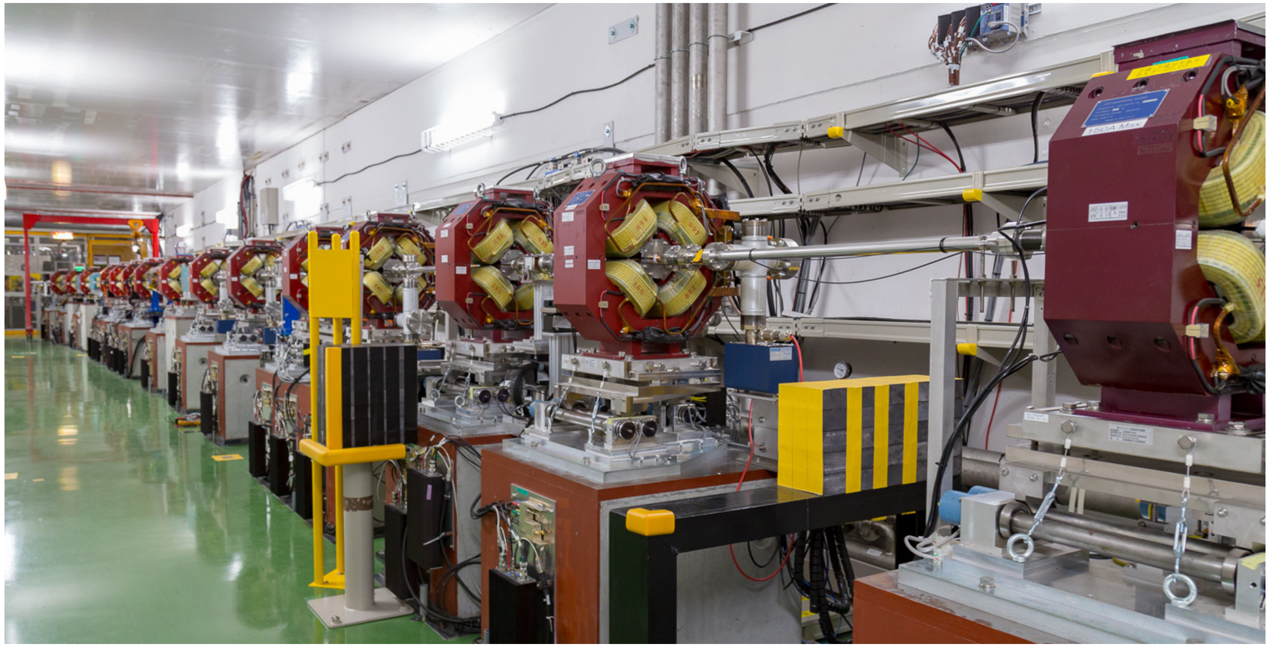


Accelerator Tracking

- Electromagnets used to guide particles
  - variety of types, each with different strengths
- For non-uniform B / E field use numerical integration
  - however, slow and limited accuracy
  - not useful for many thousands of operations - error increases
- Specific fields can have specific solutions
- Require physical accuracy and strict energy conservation

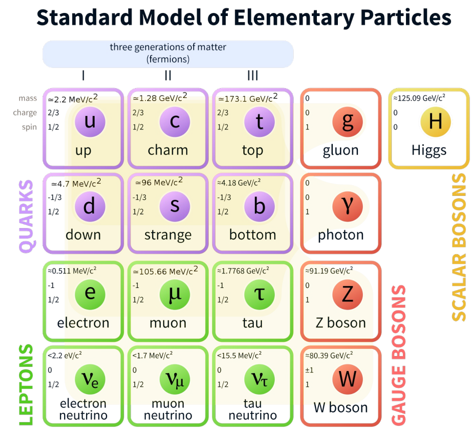


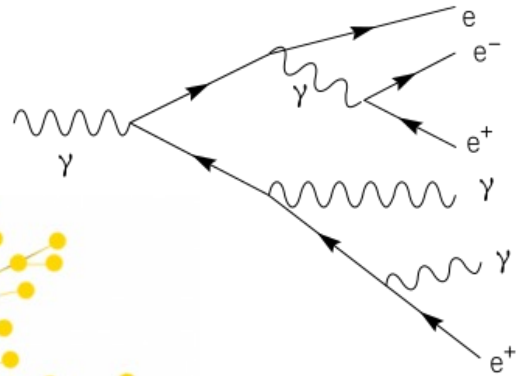
Example nonlinear fields
A. Wolski Lectures at Cockcroft

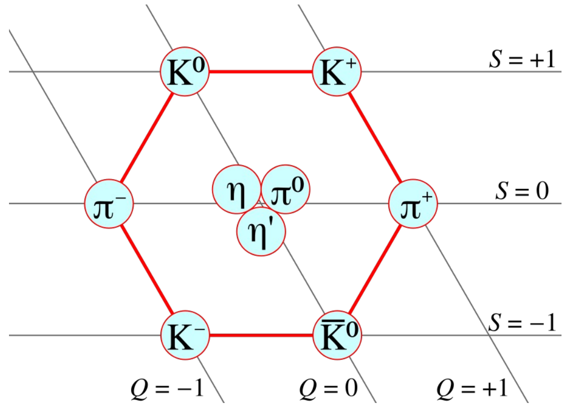


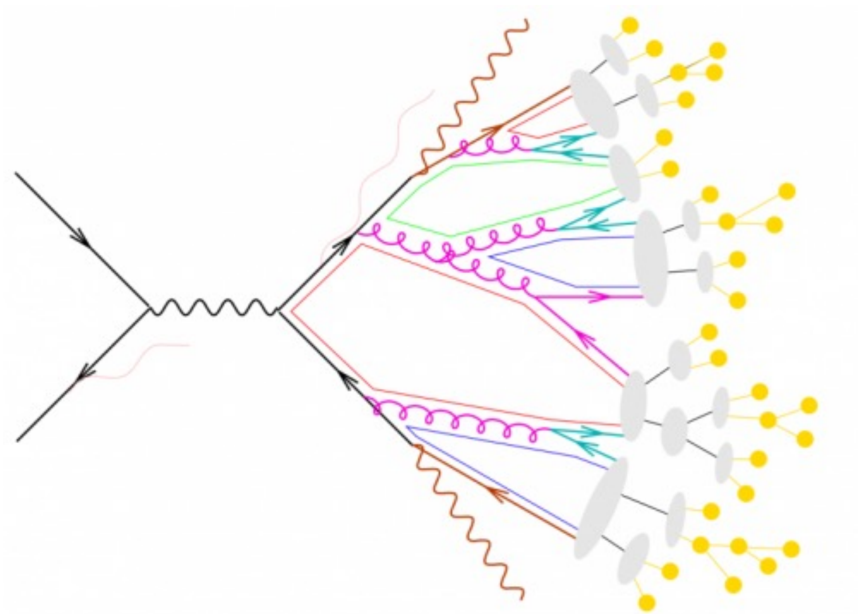
Particle Physics Processes

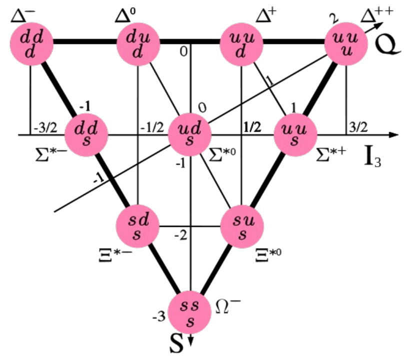
- Large variety of particles
- Large variety of processes & models
  - some data based, some pure model based, some mixed
  - different models for different energy ranges
- Available libraries - FLUKA, Geant4, MARS











Existing Solutions

- Specialised codes for accelerator tracking or radiation transport models
- Current solutions use a variety of approaches:
  - track up to impact on aperture
  - simulate most relevant parts separately - pass between codes

Accelerator Tracking

- SixTrack
- PTC / MADX
- Transport
- Lucretia

Radiation Transport

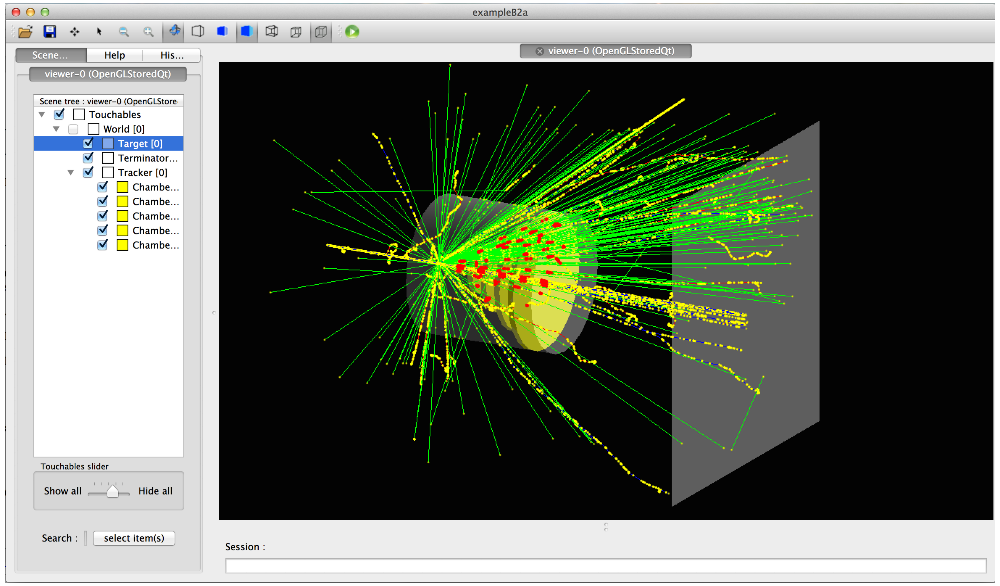
- FLUKA
- Geant4
- MARS
- MCNPX

Which Physics Package?

- Geant4
  - open source C++ class library for 3D particle physics Monte-Carlo models
  - conceived to simulate particle detector response
  - extensive particle physics models
  - regularly updated ~ every 6 months
  - used by detector community

- FLUKA
  - closed source Fortran
  - highly restrictive licence
  - ASCII input
  - also extensive particle physics models
  - used by radiation shielding community

http://geant4.web.cern.ch



Geant4 example of proton hitting calorimeter

Complexity…

- Creating 3D model of an accelerator is laborious
- Many people many years work
- Hard coded to that application
- Complex to create and validate

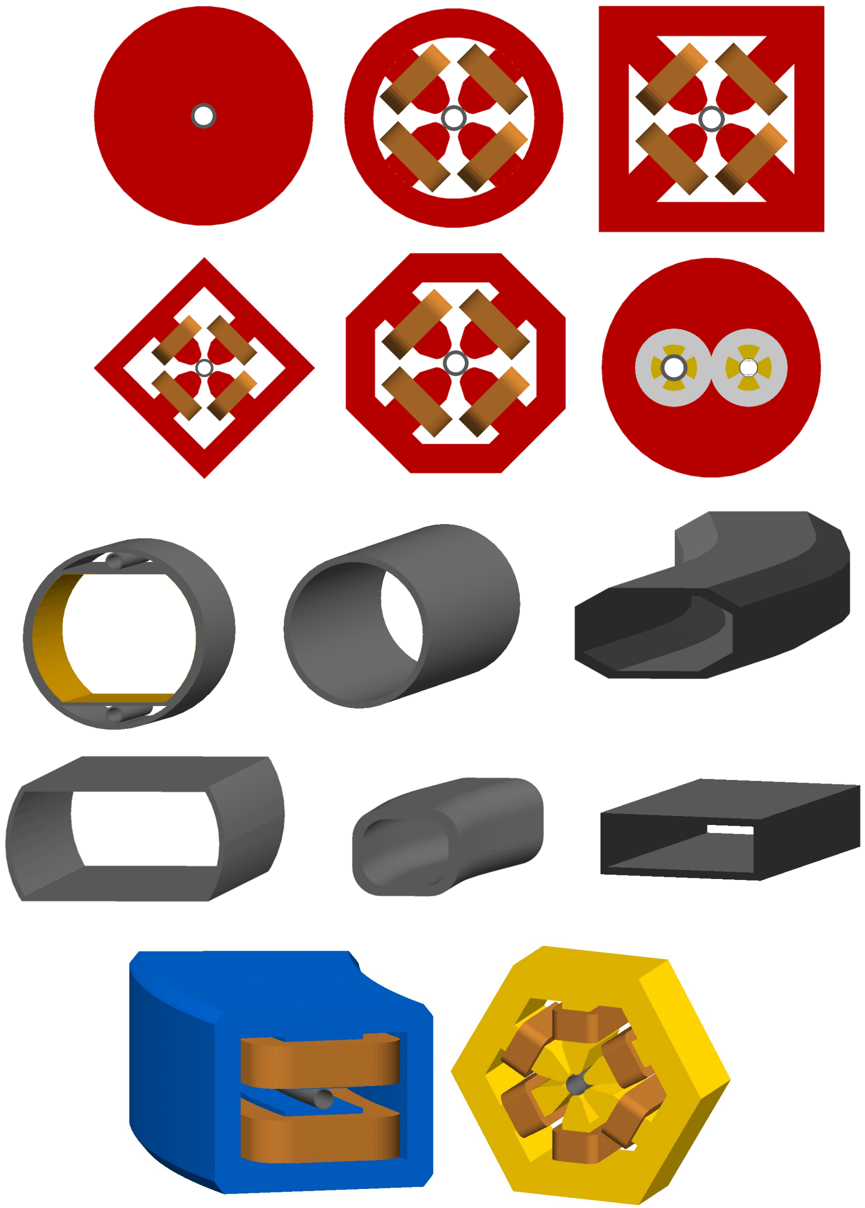
- Tracking codes complex in implementation
- Speciality can vary depending on application

- rarely do people therefore make such a model…

Beam Delivery Simulation (BDSIM)

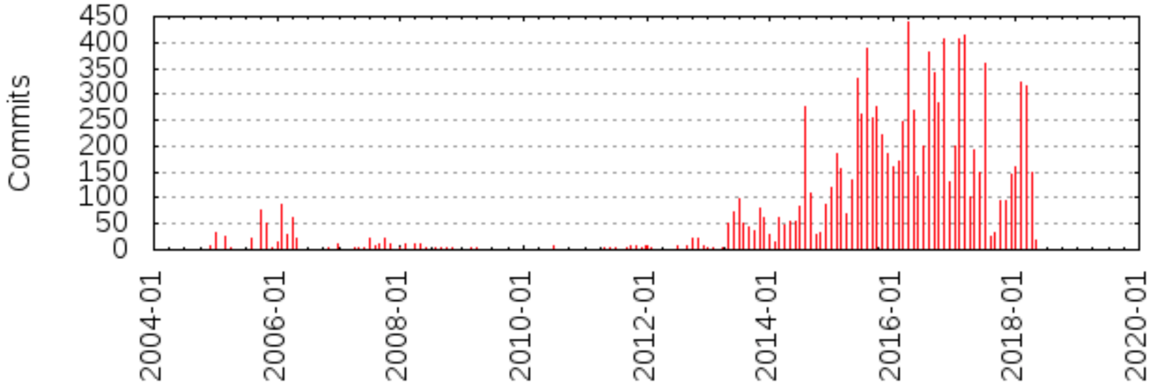
BDSIM - Beam Delivery Simulation

- Our solution…
- Library of generic accelerator geometry in Geant4 C++
  - you can learn a lot with generic geometry
  - scalable and safe
- MADX style input syntax in ASCII
- Can overlay other geometry and fields for more detail
- Thick lens tracking used for in-vacuum
  - replaces Geant4's 4th order Runge-Kutta
- 8 different beam pipe styles
- 8 different magnet yoke styles
  - All work together dynamically

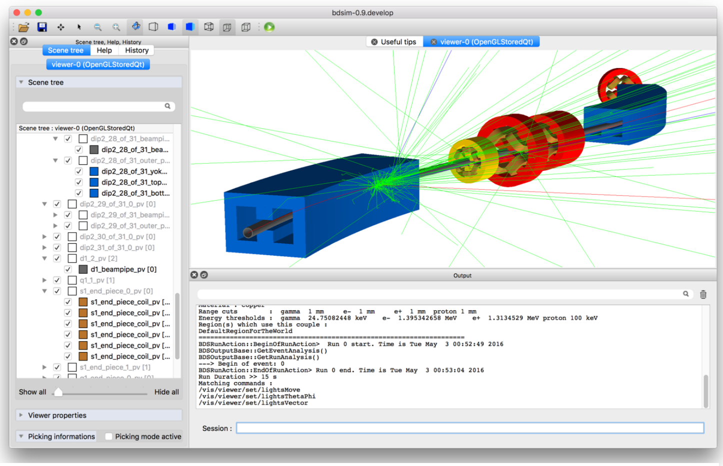


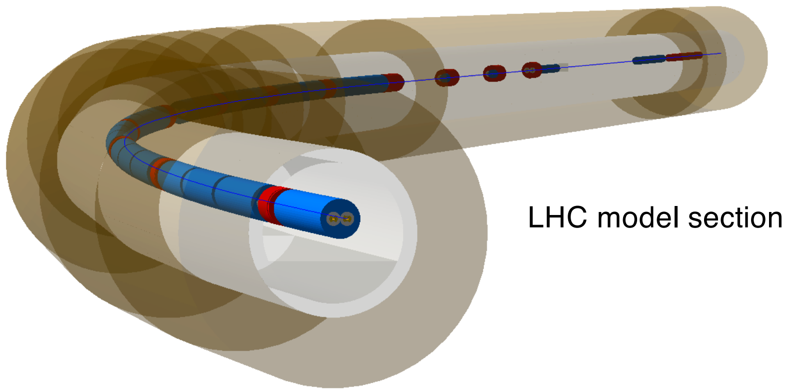
BDSIM History

- Started by Graham Blair in 2004 at Royal Holloway
- Developed by:
  - I. Agapov, L. Deacon, J. Carter, S. Malton, Y. Levinson, O. Dadoun
- Recently redeveloped for circular machines and low energy applications

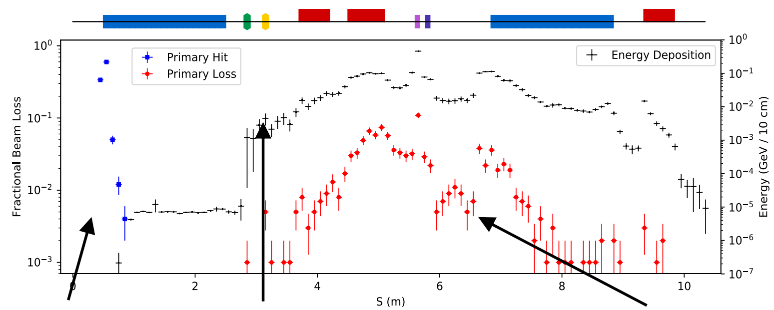


interactive visualiser





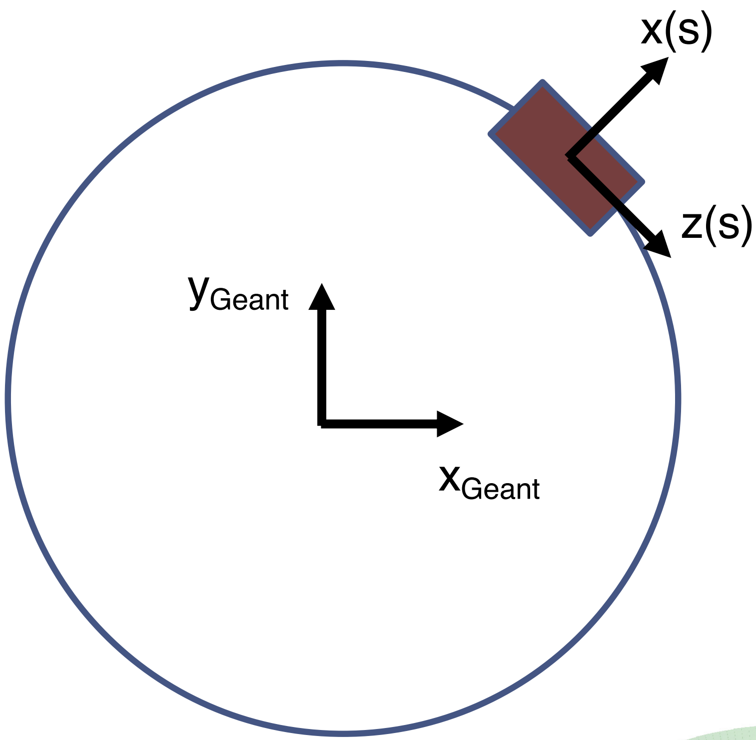
LHC model section

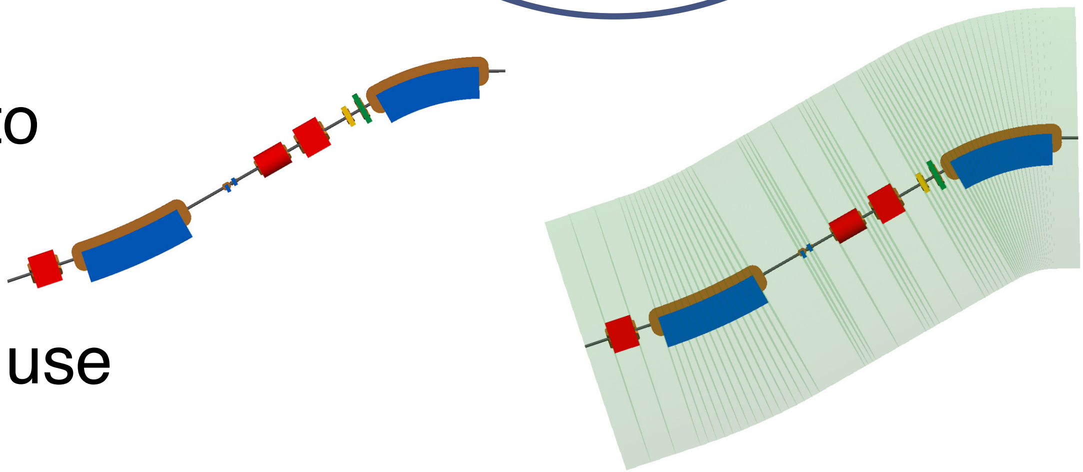


primary impact energy deposition primary loss

Coordinate Transforms

- Accelerator tracking uses a curvilinear system
- Geant4 uses 3D Cartesian coordinates
- Can look up transform from one volume to another
  - ie current to world (outermost)
  - level of hierarchy unknown and can vary
  - geometry may not be aligned to coordinate system
- Use parallel geometry to overcome this
  - different representation
- Matrix style integrators use transforms

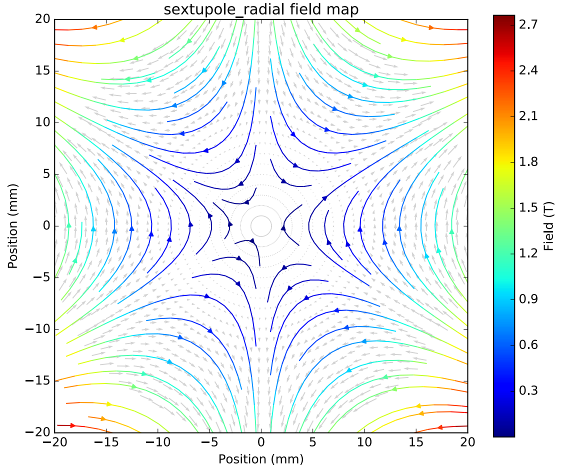




General Fields

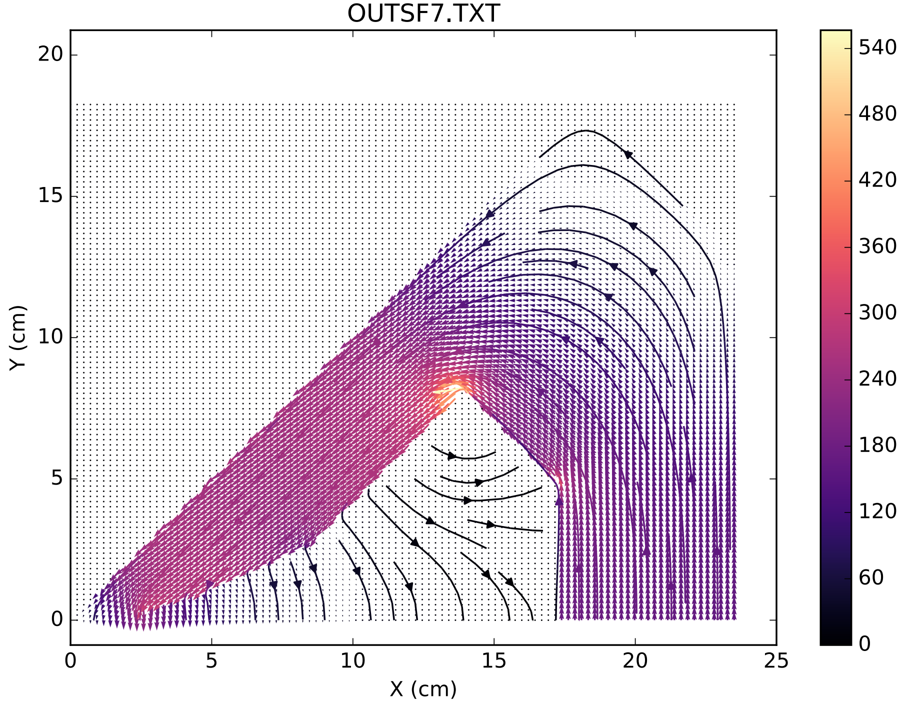
- Equations describe pure fields
- EM Solvers produce field maps
  - for real magnet designs
- Maps are grids of points
  - must be interpolated

sextupole field



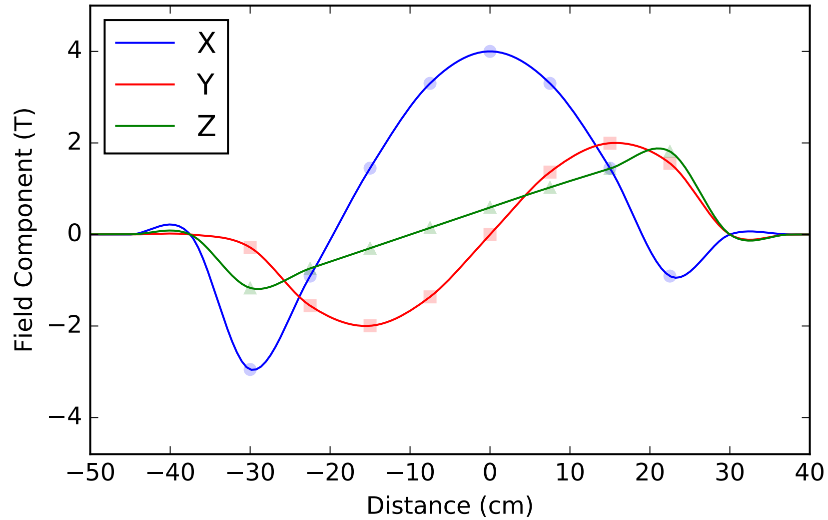
$$B_x = \frac{1}{2!}\frac{\partial^2 B_y}{\partial x^2}2xy$$
$$B_y = \frac{1}{2!}\frac{\partial^2 B_y}{\partial x^2}(x^2 - y^2)$$

$$k_2 = \frac{1}{B\rho}\frac{\partial^2 B_y}{\partial x^2}$$



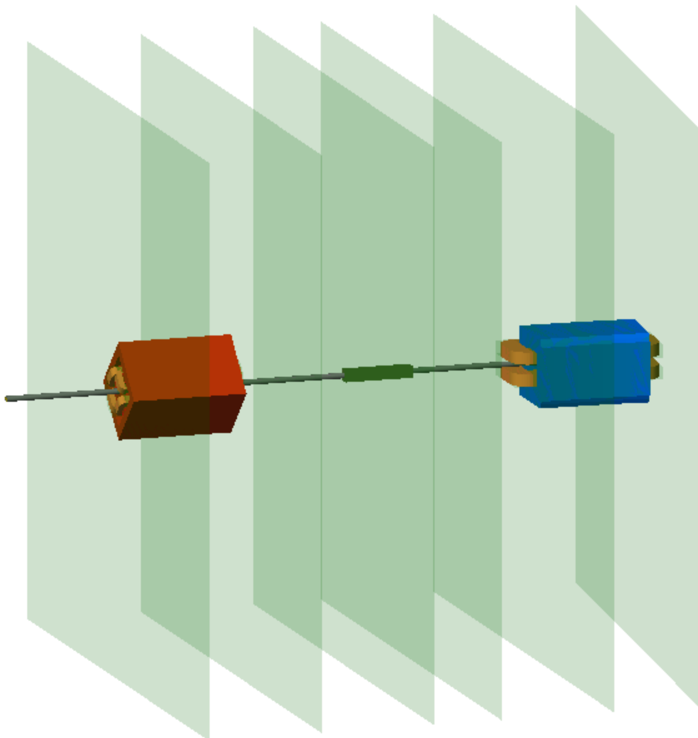
example field map from Poisson 2D

example interpolation



Information Reduction

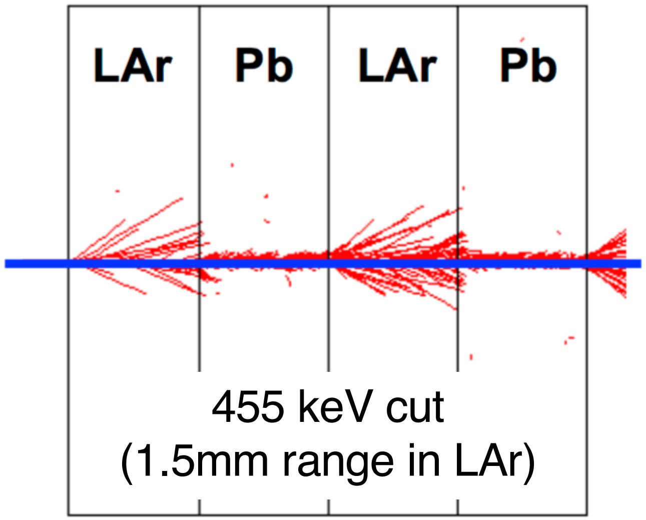
- particle physics simulation produces huge potential amount of information
  - coordinates of every step of every particle…
- Record what's key
- Control simulation level of detail…
- Energy deposition
  - optional samplers and optional trajectories
- Event by event storage
  - unlike tracking code, not 1 particle : 1 event



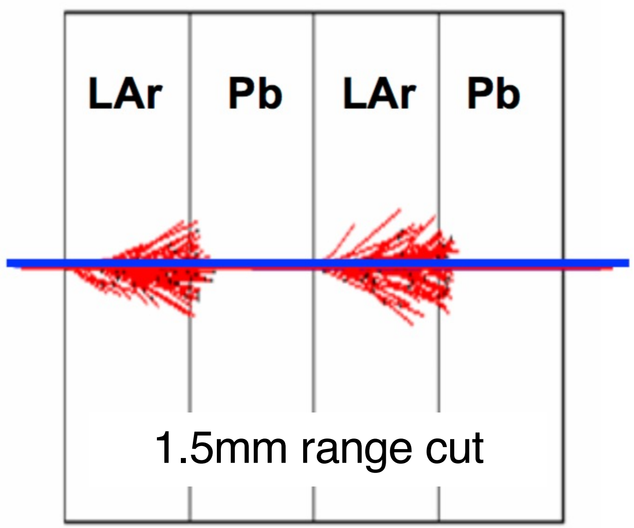
sampling planes after each element (normally invisible)

Control Over Simulation

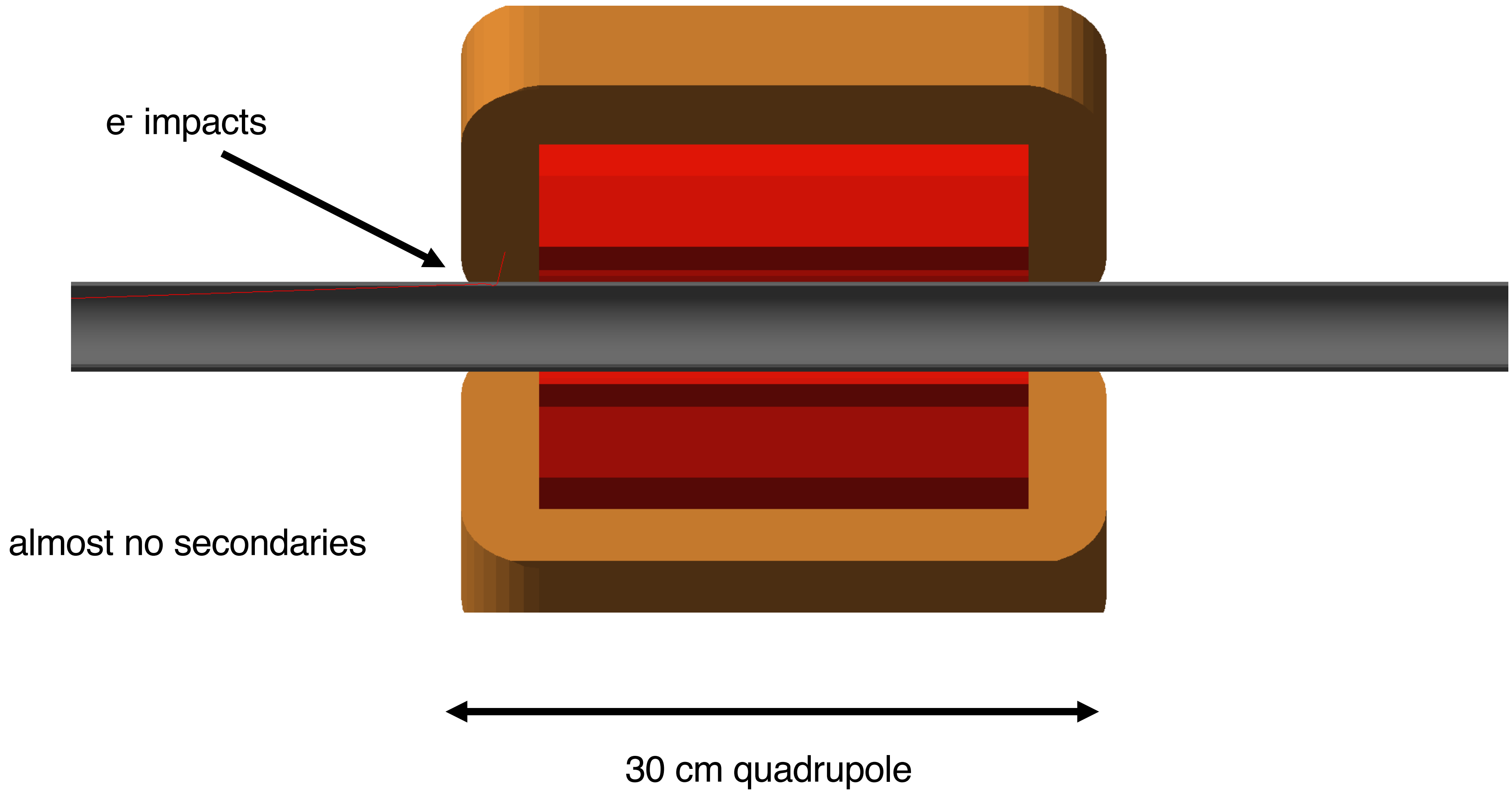
- Huge number of secondaries
  - e.g. 10^4 secondaries / event
- 'Infrared divergence'
- Necessary but can dominate tracking time
- Control through production 'range' cuts
- Roughly distance secondary would have to travel
  - corresponds to a different energy / particle / material



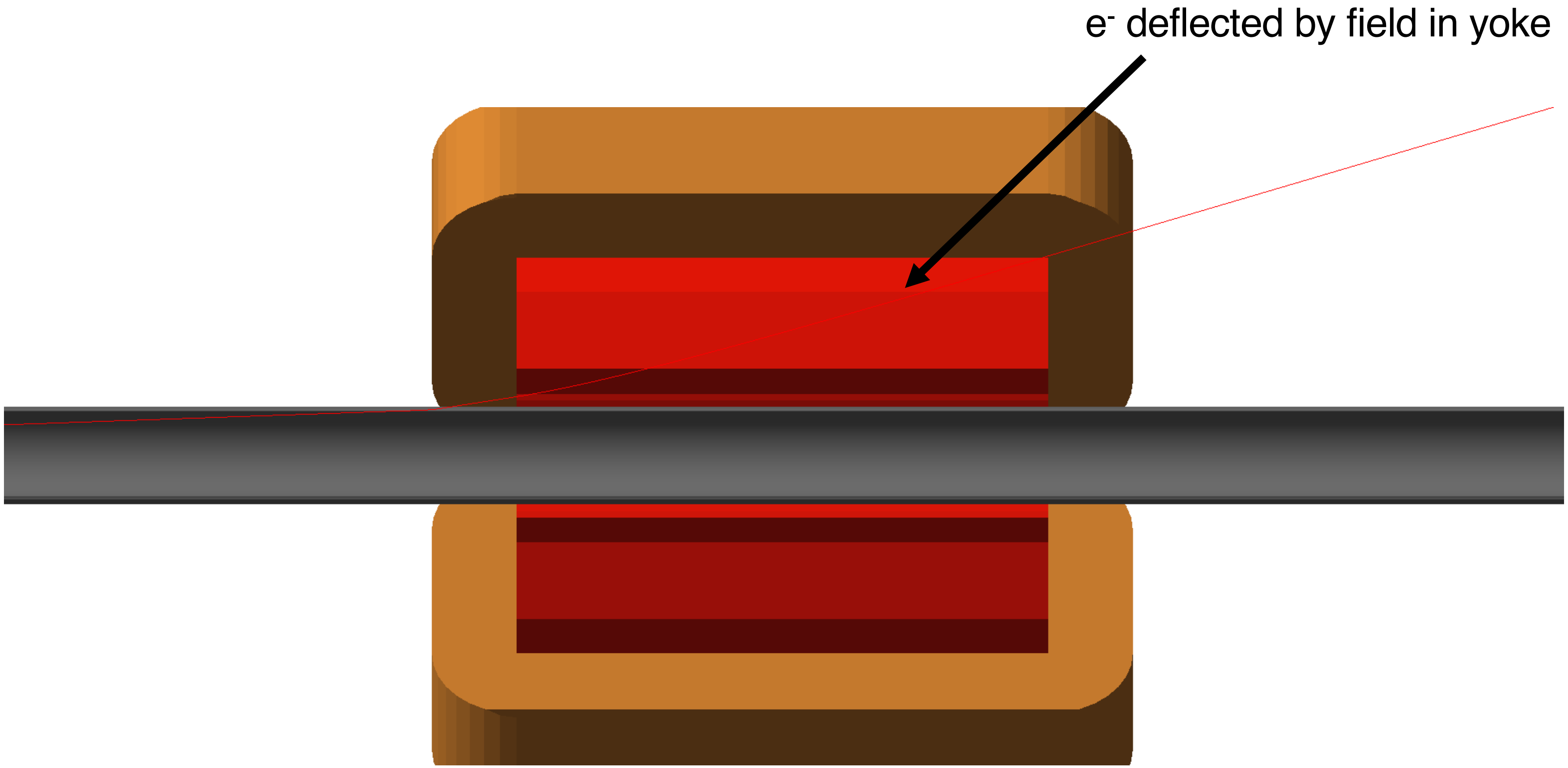
Geant4 example:
500 MeV p in
Lead sampling
calorimeter



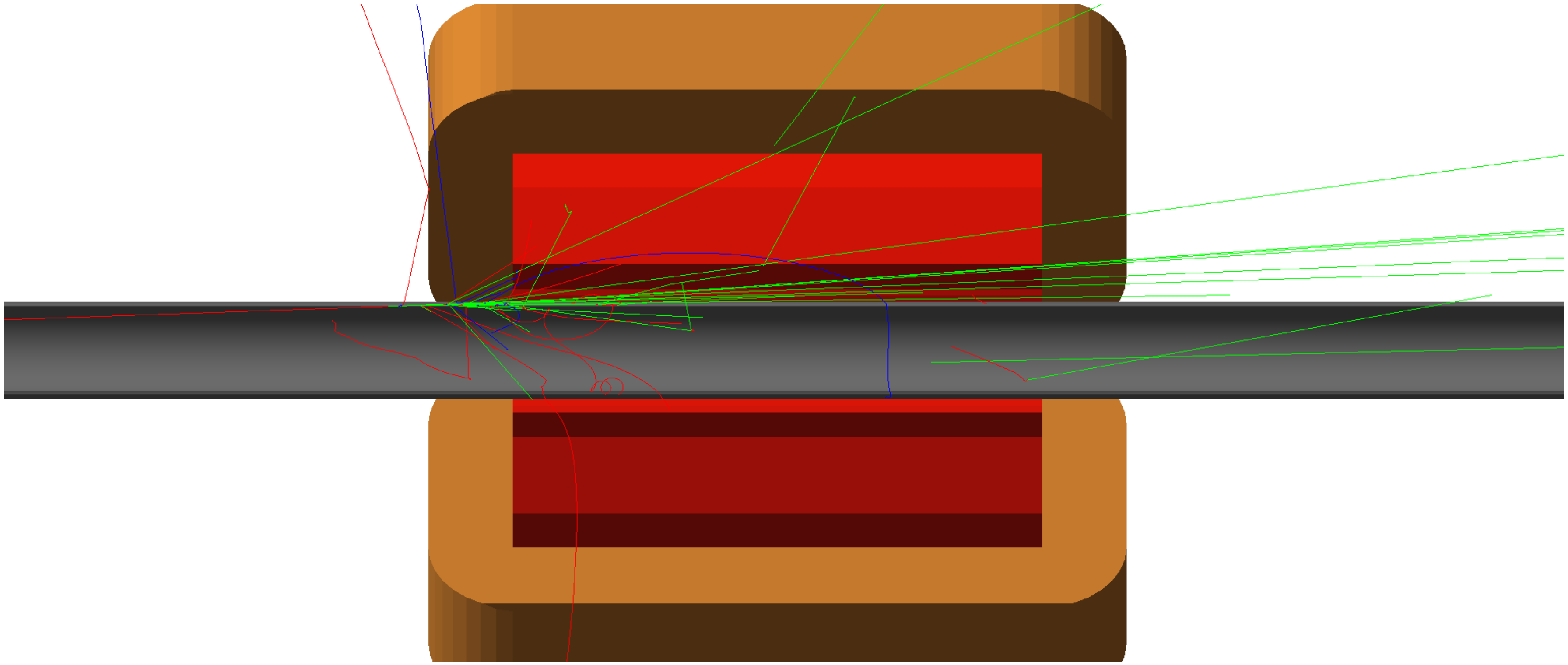
Range cuts (30 cm)



Range cuts (25 cm)

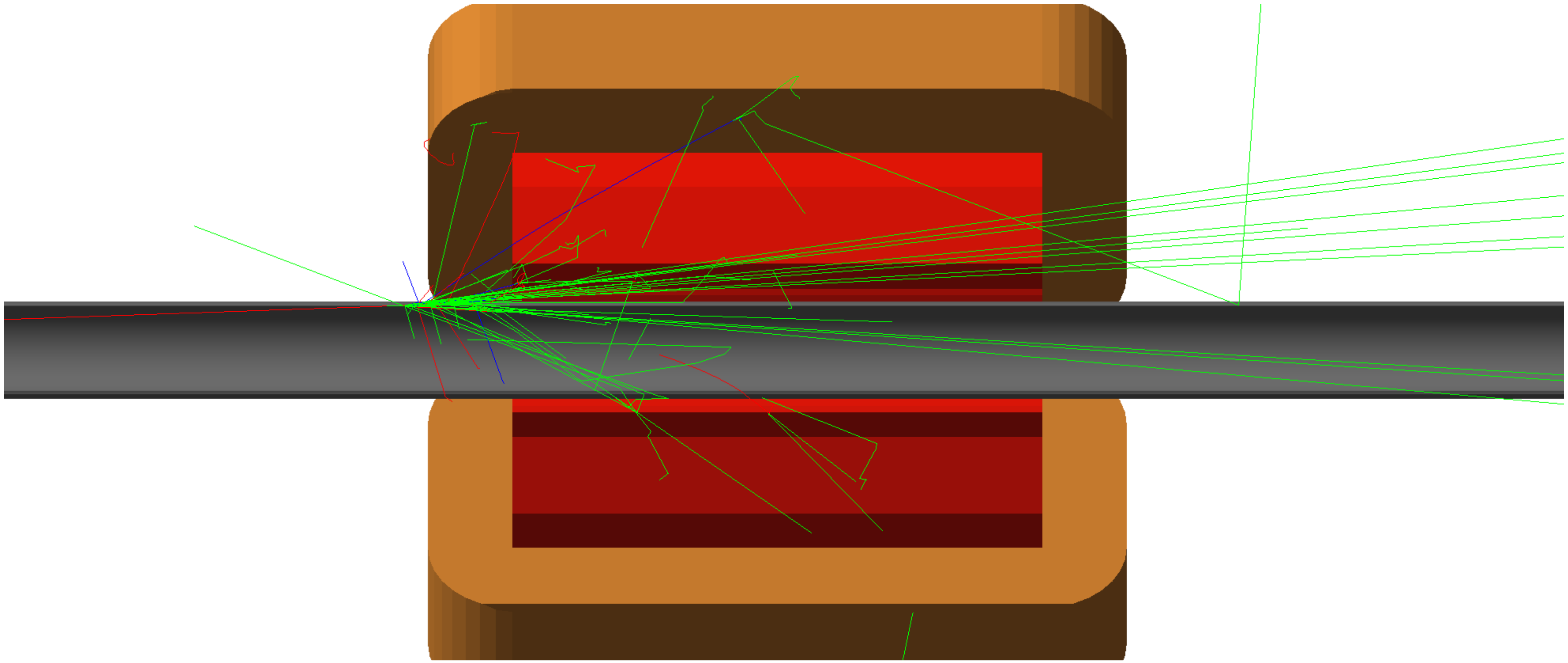


Range cuts (20 cm)

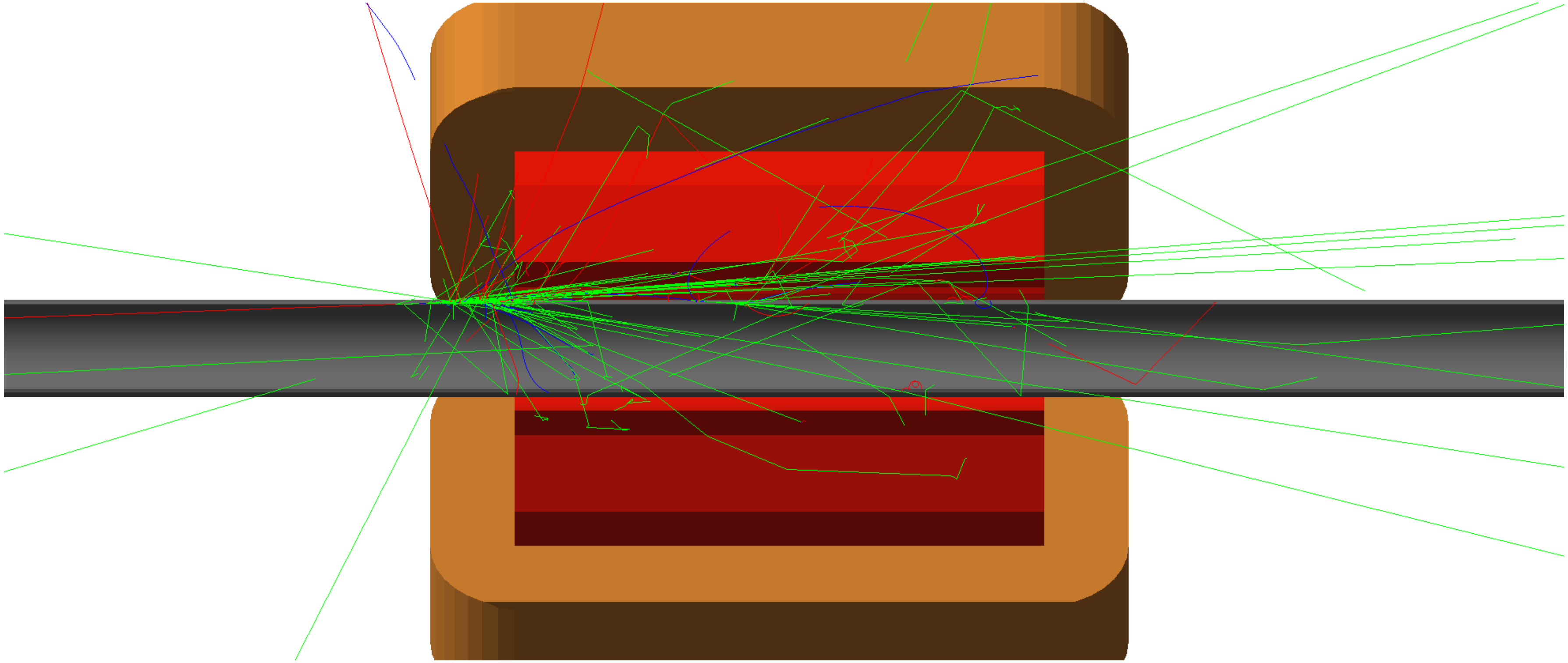


red : -ve
blue : +ve
green : neutral

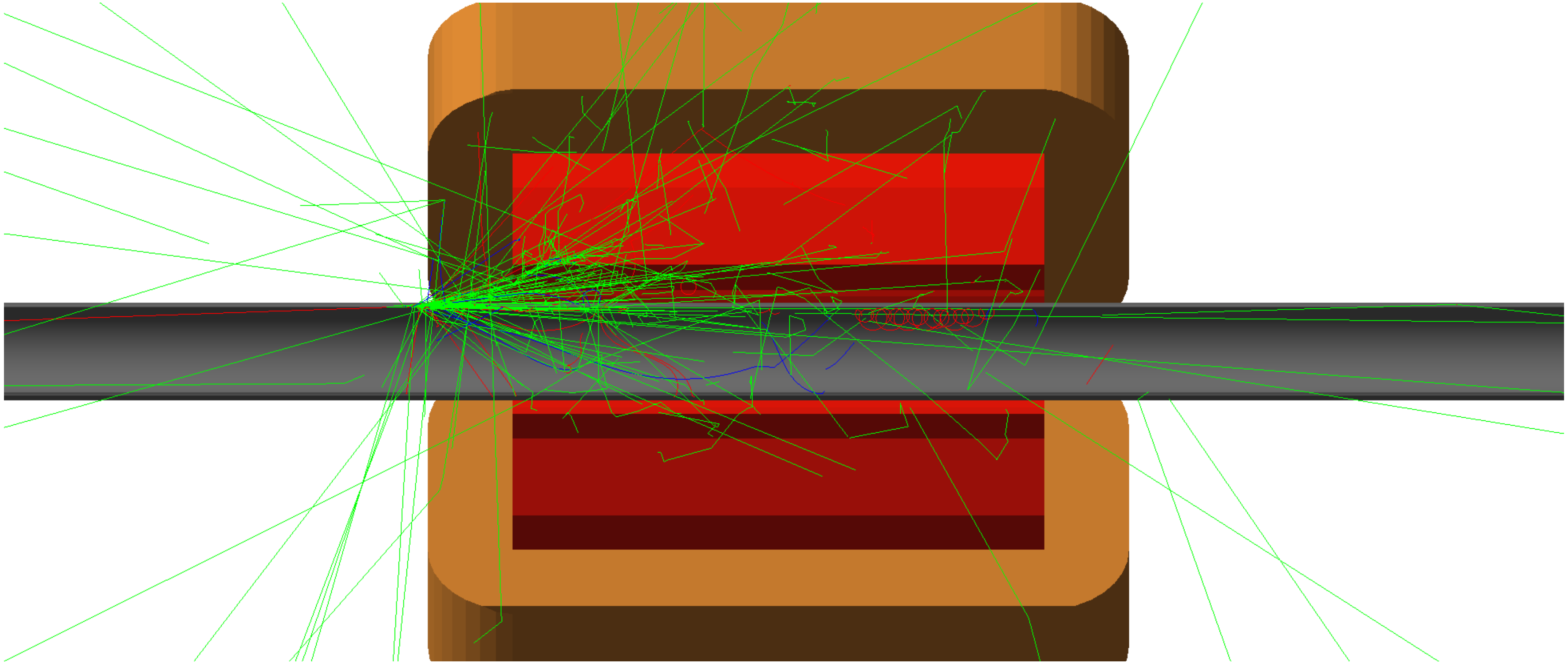
Range cuts (10 cm)



Range cuts (1cm)



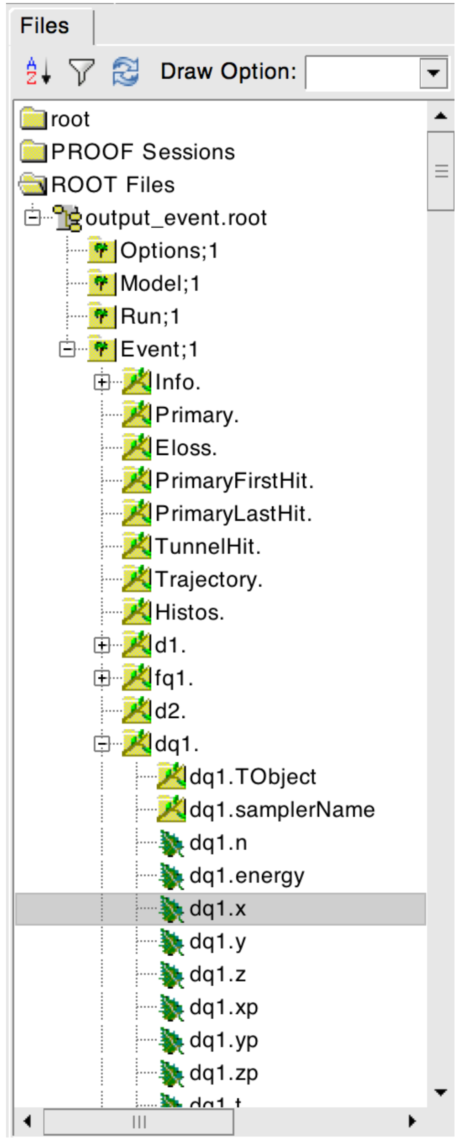
Range cuts (1 mm)

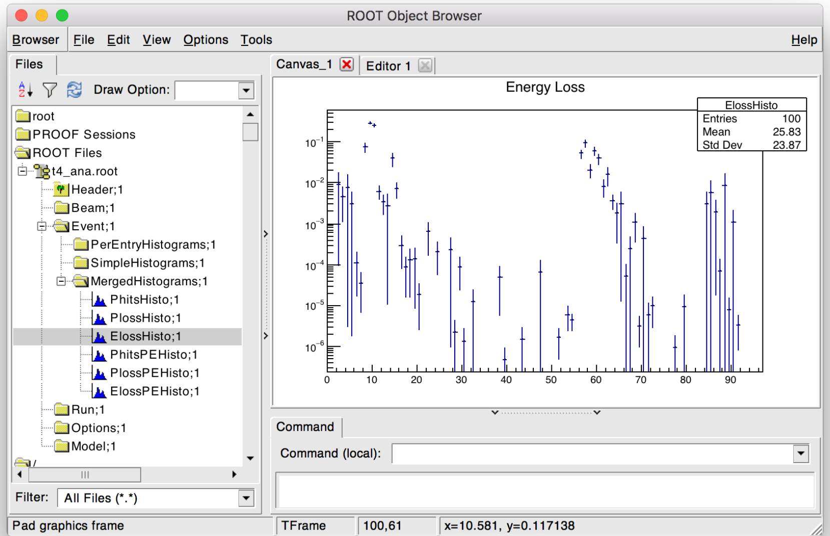


Output

- Use ROOT format for data
  - highly suited to particle physics event by event storage and analysis
- Well documented and widely used
  - support + community
- Scales well to large / parallel data sets
- BDSIM is strongly reproducible
  - all seeds and settings stored

structure of output file



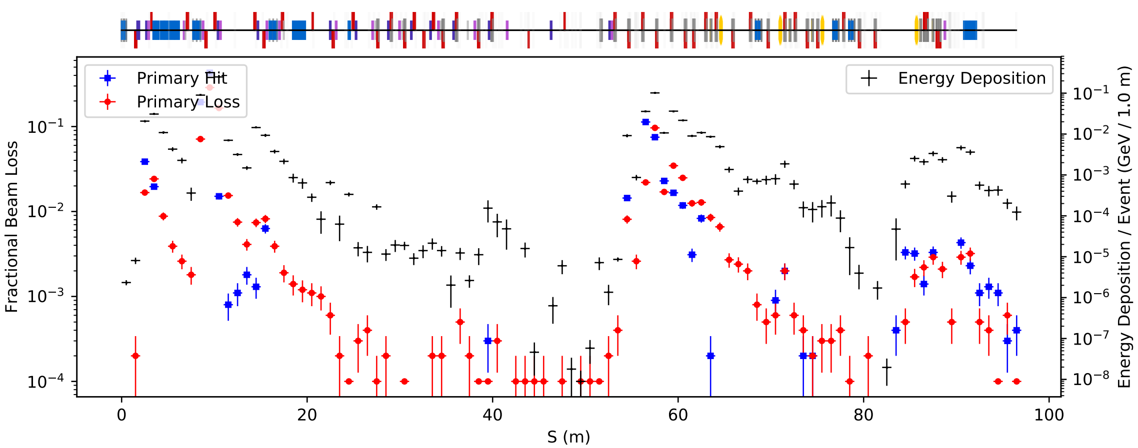


Analysis

- Analysis tool 'rebdsim' (root event BDSIM)
- Event by event analysis
- e.g. all neutrons over 20GeV that interact with collimator
  - no problem!
- Simple text input for 1,2,3D histograms

analysisConfig.txt

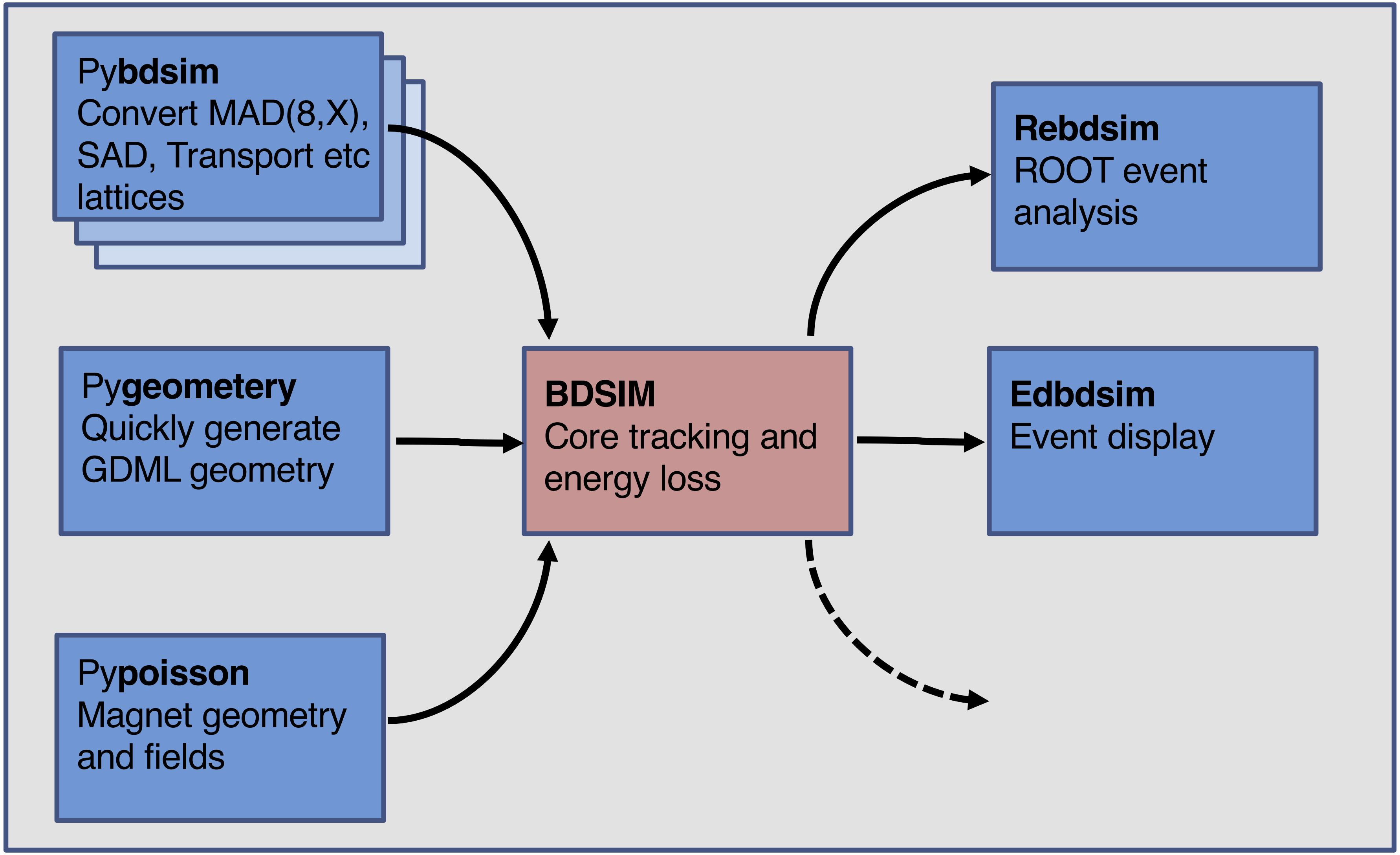
```
InputFilePath       ../../data/sample1.root
OutputFileName      ./ana1.root
# Object        treeName    Histogram Name       # Bins      Binning                    Variable                Selection
Histogram1D     Event.      EnergyLoss           {22}        {0:22}                     Eloss.S                 Eloss.energy*Eloss.weight
Histogram2D     Event.      Flux                 {30,30}     {-2.5:2.5,-2.5:2.5}        fq1.y:fq1.x             fq1.energy*fq1.weight
Histogram3D     Event.      Flux3D               {30,30,100} {-2.5:2.5,-2.5:2.5,0:1}    fq1.x:fq1.y:fq1.energy  1
Histogram2D     Event.      Neutrons             {50,50}     {-2:2,-2:2}                fq1.y:fq2.x             fq1.weight*(fq1.partID==2212)
```



'selection' is weighting
can be boolean and or numerical

basic impact, loss and
energy deposition analysis

BDSIM ecosystem



Model Conversion

- BDSIM uses MAD(8,X) style syntax
- Can write manually, but can also convert easily
- Prepare 'flat' optical description of lattice
  - here prepare MADX TFS format Twiss table

```
select,flag=twiss, clear;
twiss,sequence=SEQUENCENAME, file=twiss.tfs;
```

- Convert using pybdsim Python utility

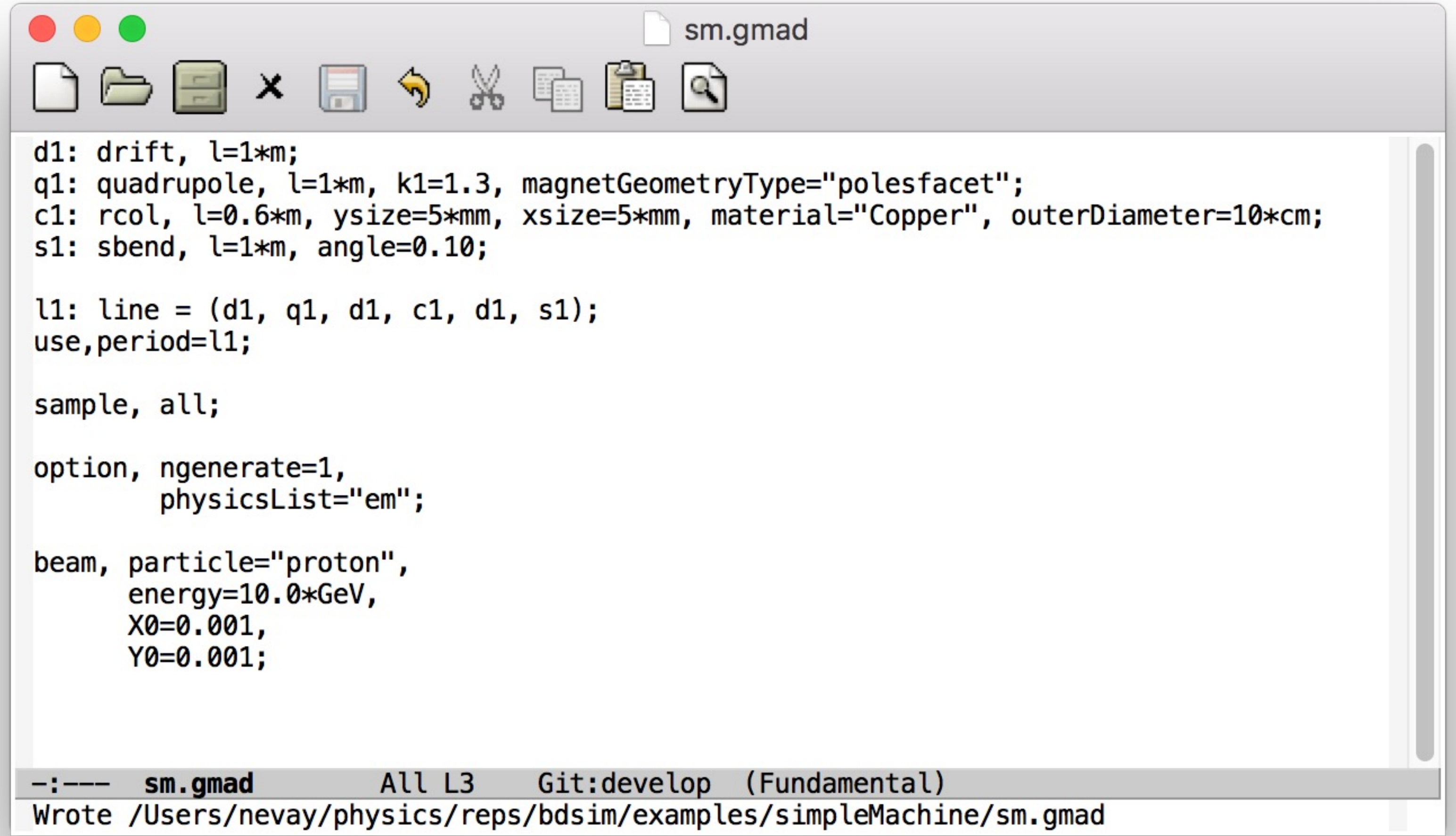
```
>>> a,b,c = pybdsim.Convert.MadxTfs2Gmad('inputfile.tfs', 'latticev1')
```

- Fold in information by name - Python dictionaries
  - up to user to how this information is sourced

```
>>> drift123dict = {'aper1':0.03, 'aper2':0.05, 'apertureType':'rectangular'}
>>> quaddict = {'magnetGeometryType':'polesfacetcrop}
>>> d = {'drift123':drift123dict, 'qf1x':quaddict}
>>> a,o = pybdsim.Convert.MadxTfs2Gmad('inputfile.tfs', 'latticev1', userdict=d)
```

Example Syntax

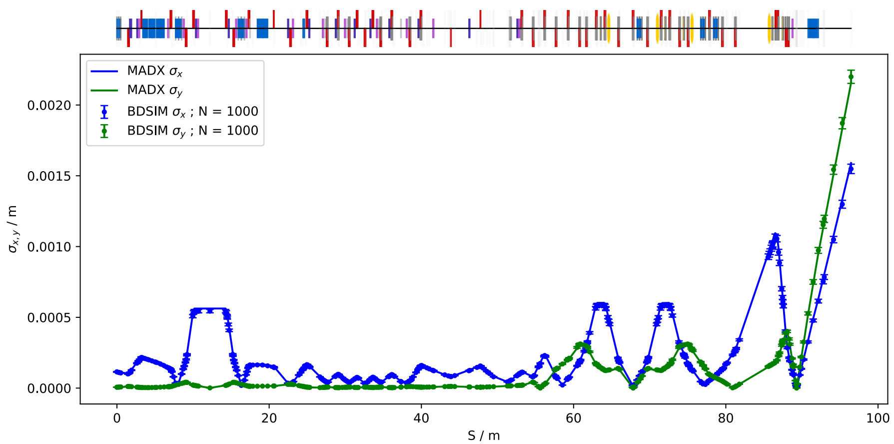
- "GMAD" - Geant4 + MAD

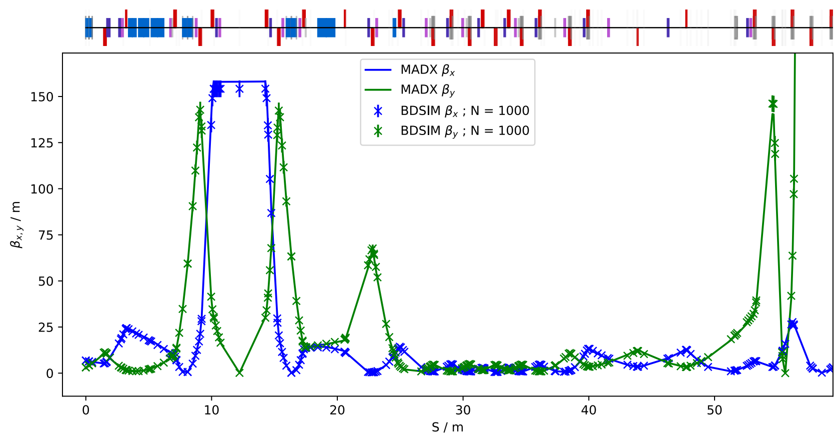


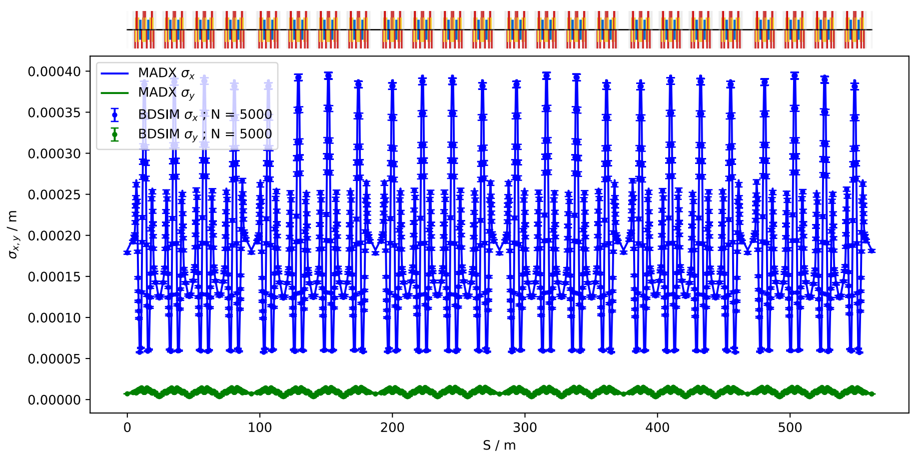

```
d1: drift, l=1*m;
q1: quadrupole, l=1*m, k1=1.3, magnetGeometryType="polesfacet";
c1: rcol, l=0.6*m, ysize=5*mm, xsize=5*mm, material="Copper", outerDiameter=10*cm;
s1: sbend, l=1*m, angle=0.10;

l1: line = (d1, q1, d1, c1, d1, s1);
use,period=l1;

sample, all;

option, ngenerate=1,
        physicsList="em";

beam, particle="proton",
      energy=10.0*GeV,
      X0=0.001,
      Y0=0.001;
```

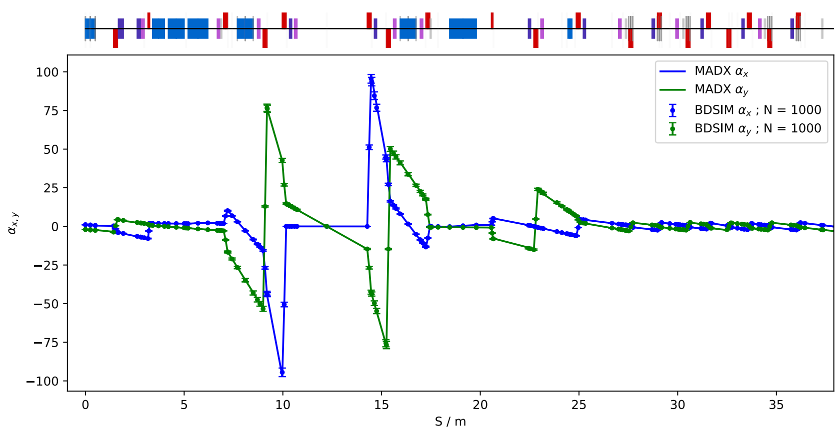
Optical Function Comparison

- Particle distribution recorded after each element
- Calculate optical functions from particle distribution
  - using (up to) 4th order moments
  - full statistical uncertainty calculated too



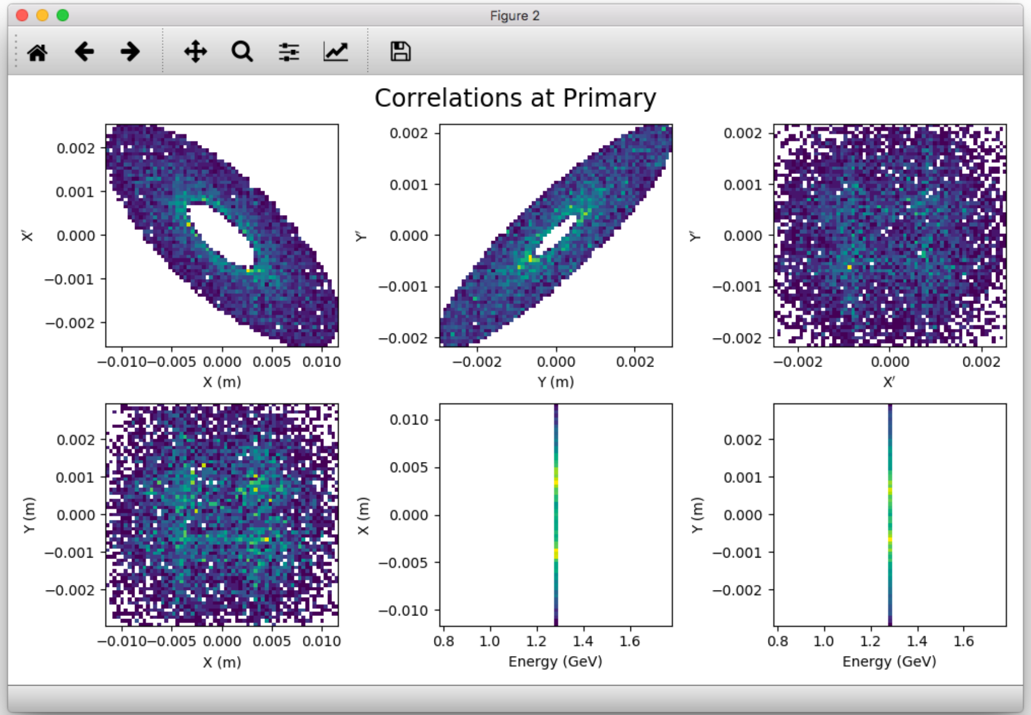


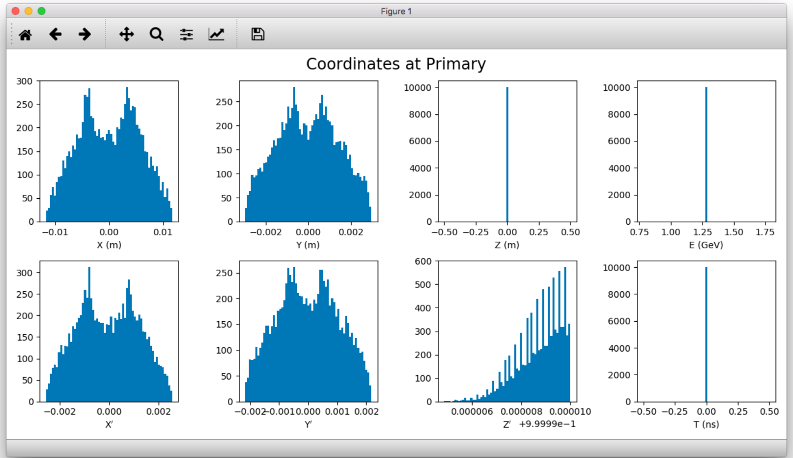




Beam Distribution

- Beam interaction rare - need more efficient simulation
- Interaction at 50 sigma?
- Efficiently generate required distribution





variety of distributions included using CLHEP pseudo-random number generator

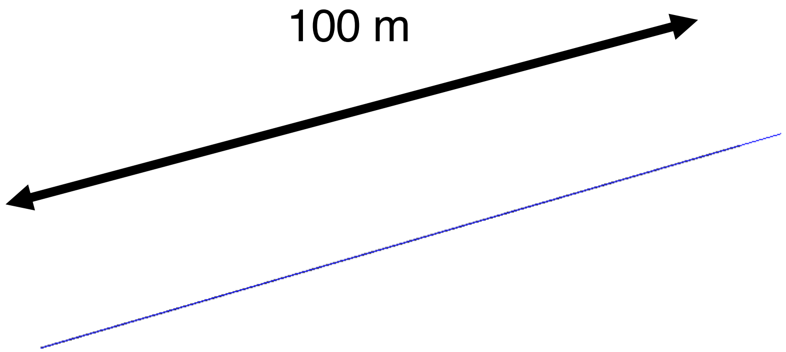
Physics Processes

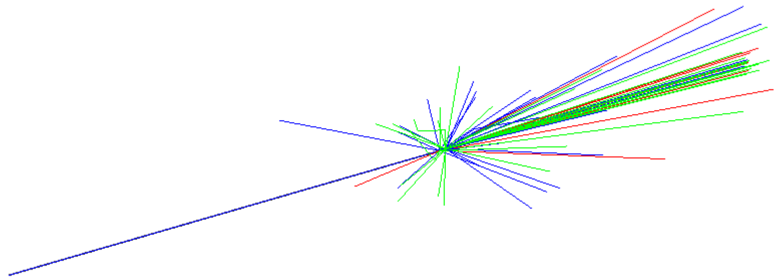
- Huge number of physics processes in Geant4
- Use physics 'lists'
  - standard set of processes for application / energy range
- "G4EmStandardPhysics" for example -> electromagnetic
- hadronic, decay, muon-specific, synchrotron radiation etc.
- Only use physics required
  - more processes = slower simulation
  - only selection of physics processes relevant for any application
  - possibility of different models for different energy ranges

```
option, physicsList = "em ftfp_bert decay muon hadronic_elastic em_extra"
```

Variance Reduction - Biasing

- Even with efficient choice of beam distribution events of interest may be rare
- Perhaps a particle physics outcome given an interaction
- Despite range in energies, want same error bars ⇒ variance reduction
- Classic example beam gas (interaction per event)





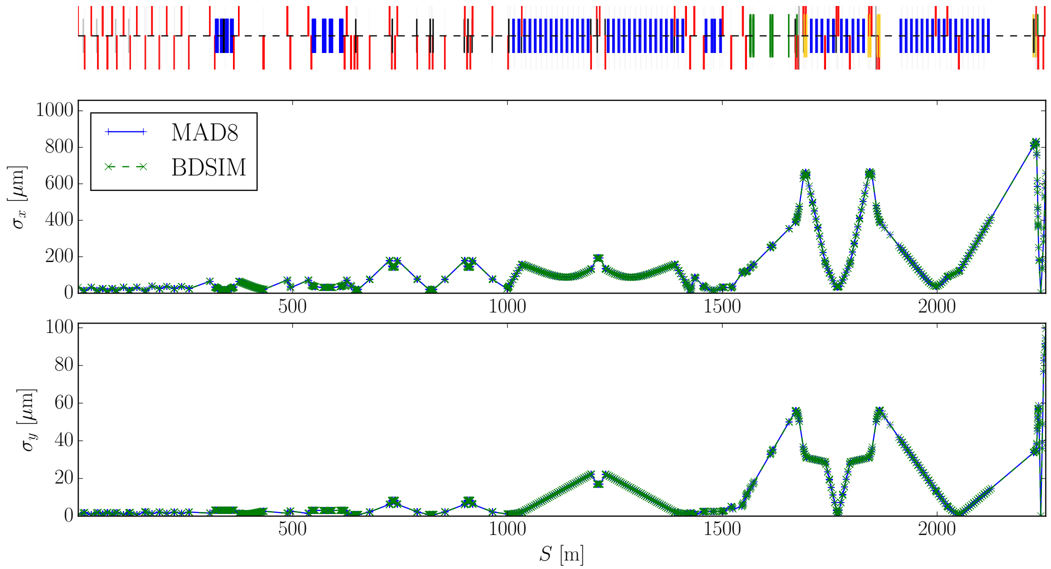
P=1×10^{-7} bar, Nitrogen @300K

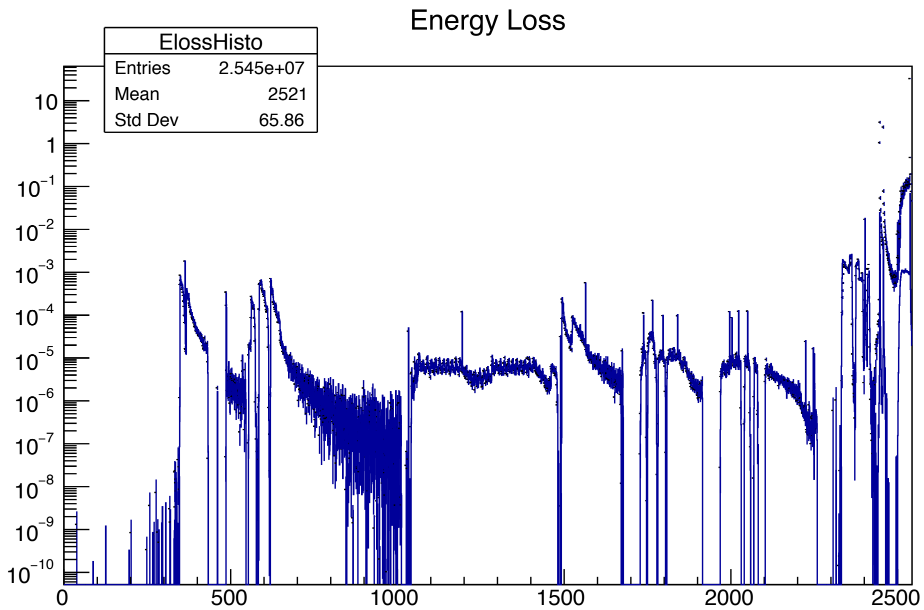
Primary interaction cross section only scaled by 1×10^{13}

Examples

ILC 250 GeV Model

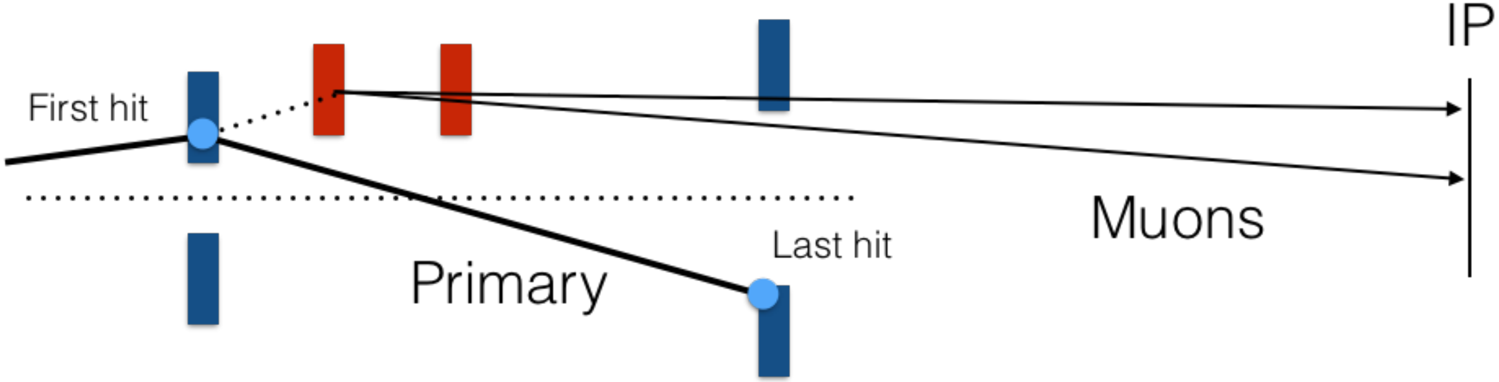
- Beam delivery system from BSY to IP
  - Linear optics agree well
  - Collimation defined by *no synchrotron radiation hitting final doublets*
  - What about all the losses long the BDS
- Synchrotron radiation
  - Simple test of photon emission from all magnetic elements
  - Uses well tested and built in Geant4 SR model

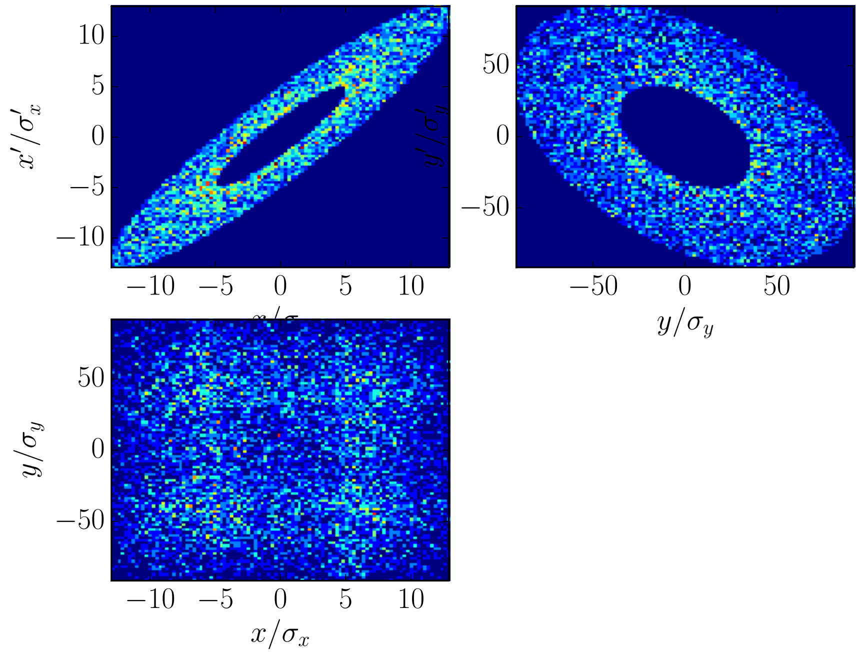




S. Boogert

ILC Muon Production Example



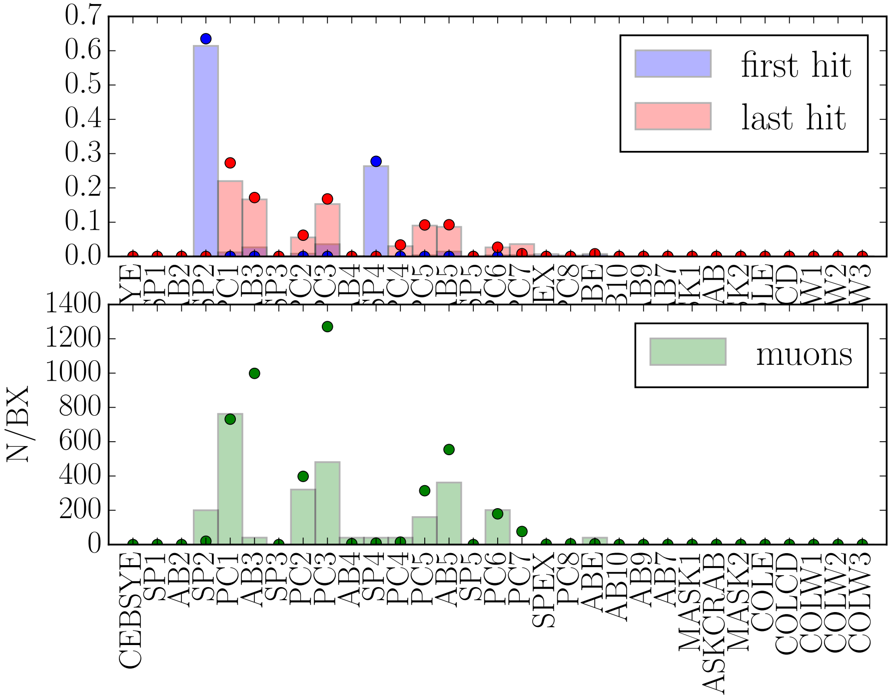


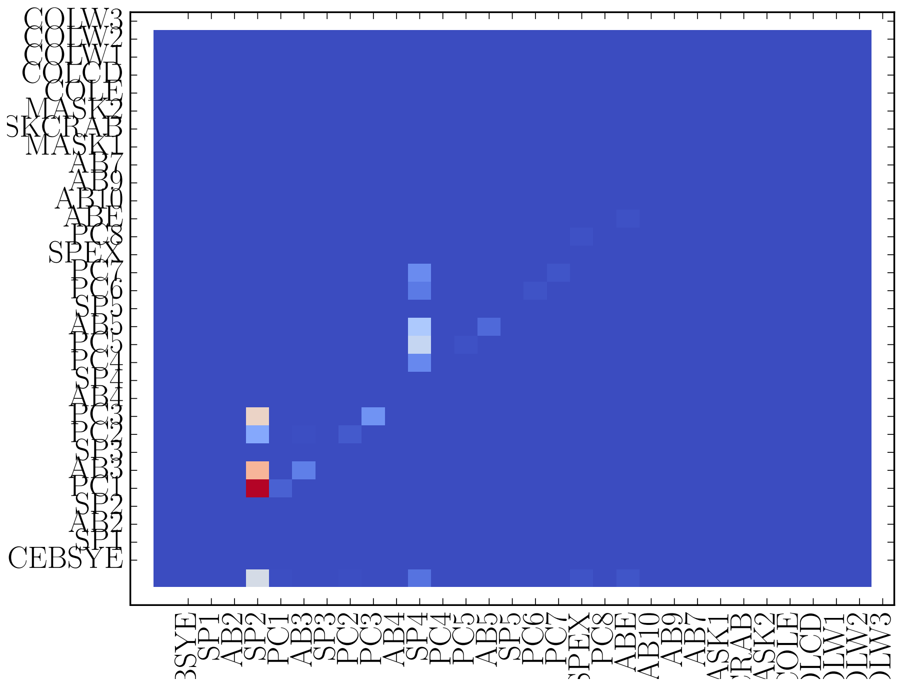
- ILC muon production interesting as large distance between production point and IP
  - Interaction in collimation system produces large number of muons
- Halo
  - 2×10^{10} electrons per bunch
  - Halo is 1×10^{-3} of total beam
  - $1/\varepsilon_{SP}$ distribution
  - x : 5 – 13 σ
  - y : 36 – 92 σ

S. Boogert

ILC Muons at interaction point

- Compare
  - First hit : first interaction with material
  - Last hit : last interaction with material (particle absorbed / changes to different type)
  - Number of muons produced at IP





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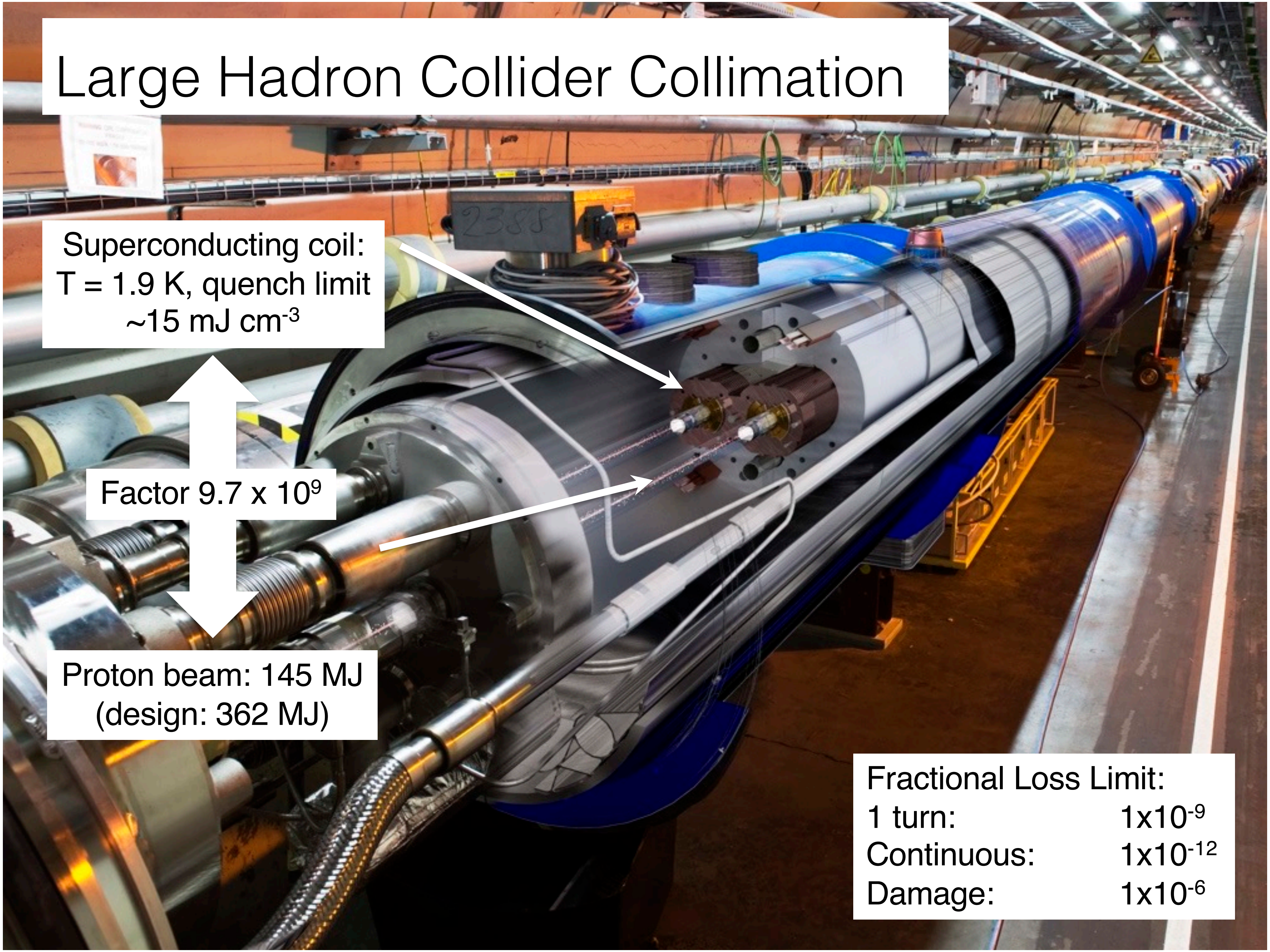
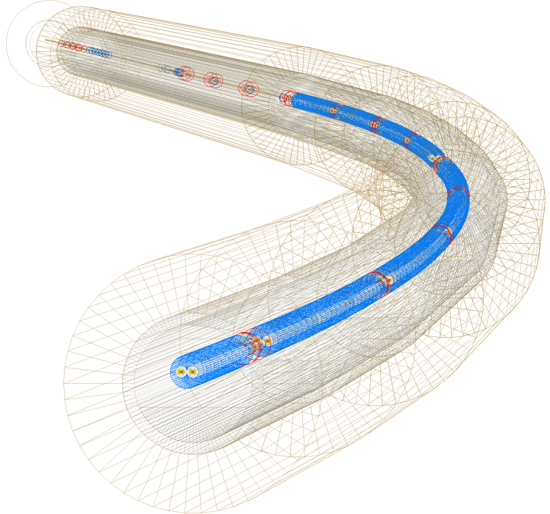
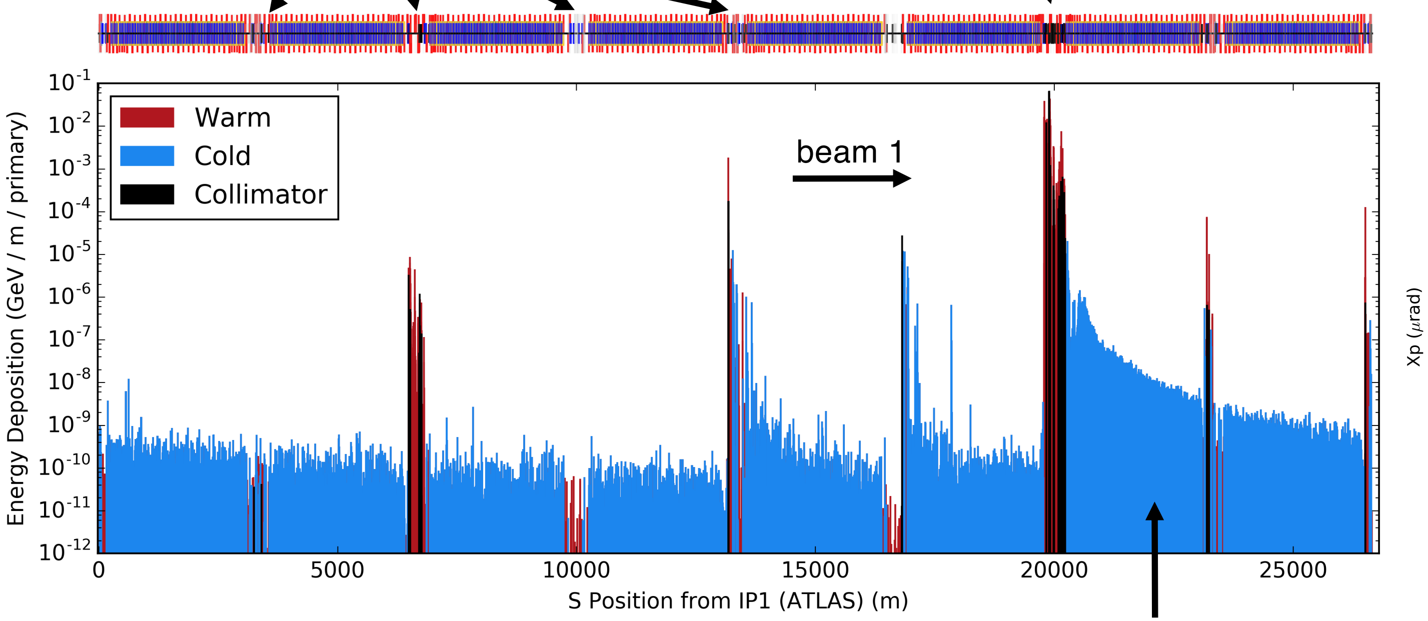
Large Hadron Collider Collimation



LHC Collimation

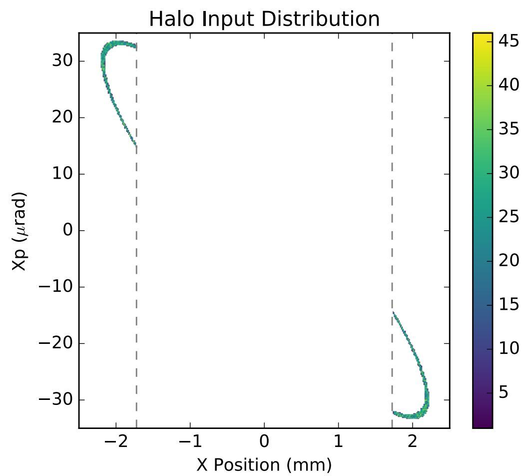
- Halo populated during beam storage
- Continually removed
- Simulate halo as it touches collimators
- LHC-style dipoles & quadrupoles
- Require 1:10^6 precision





B1 4TeV energy deposition map

Example halo distribution



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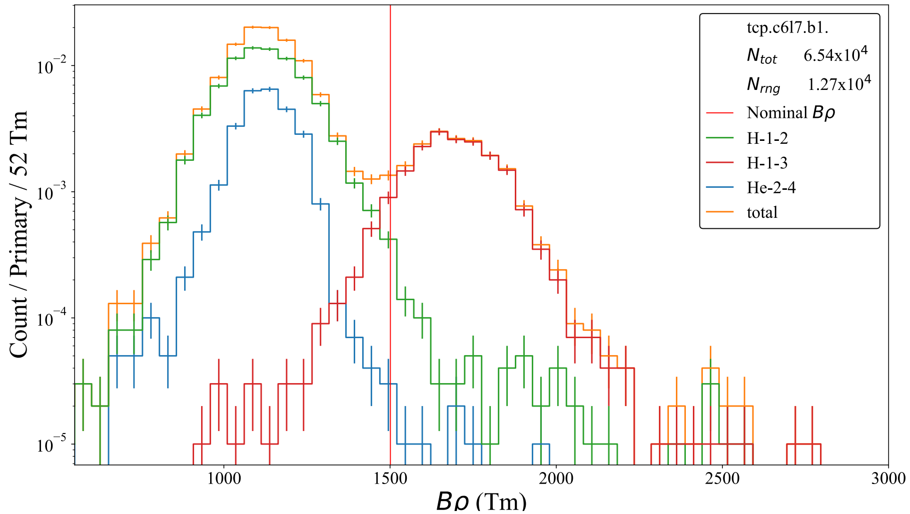
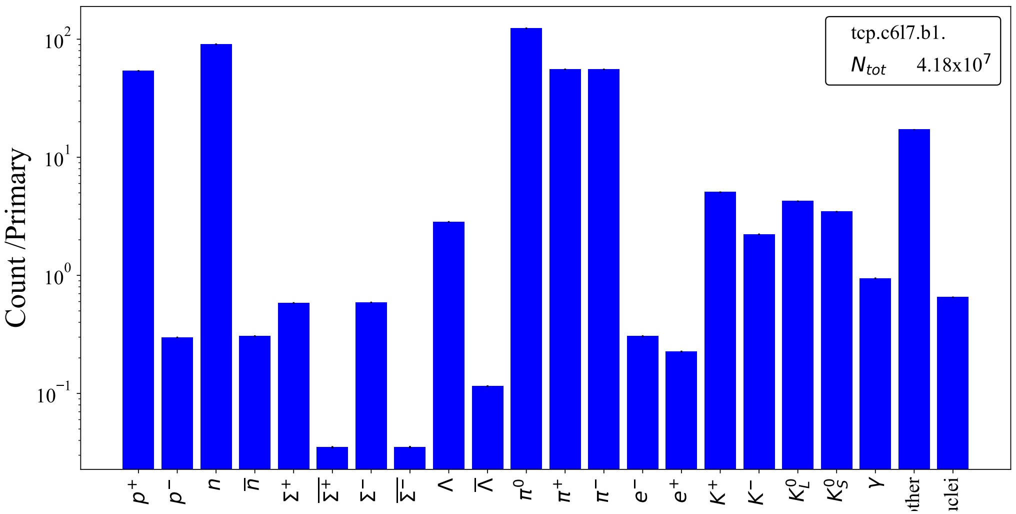
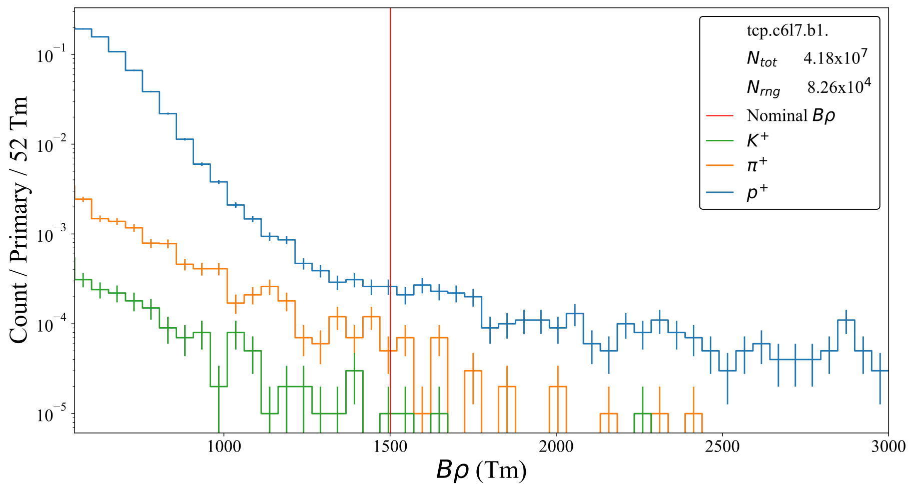
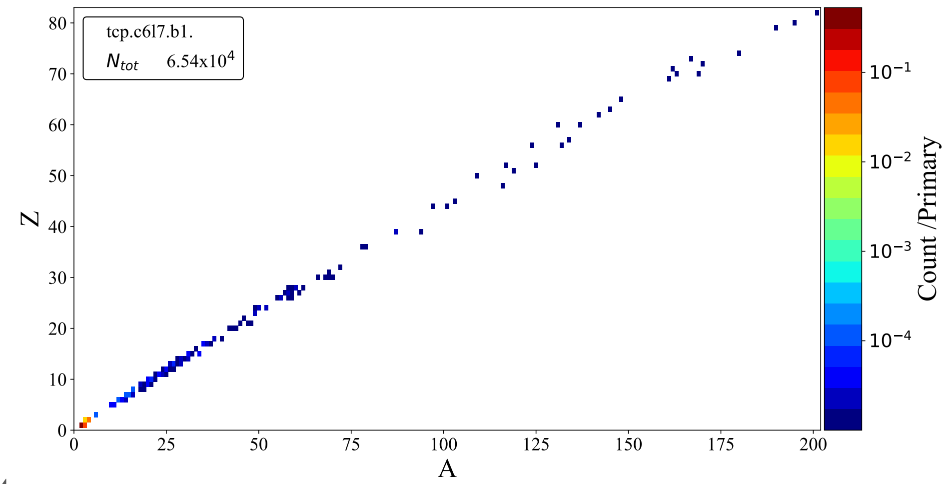
LHC Ion Collimation

- Similarly, same model can be used with ions
- Fragmentation - many fragments around nominal Bρ





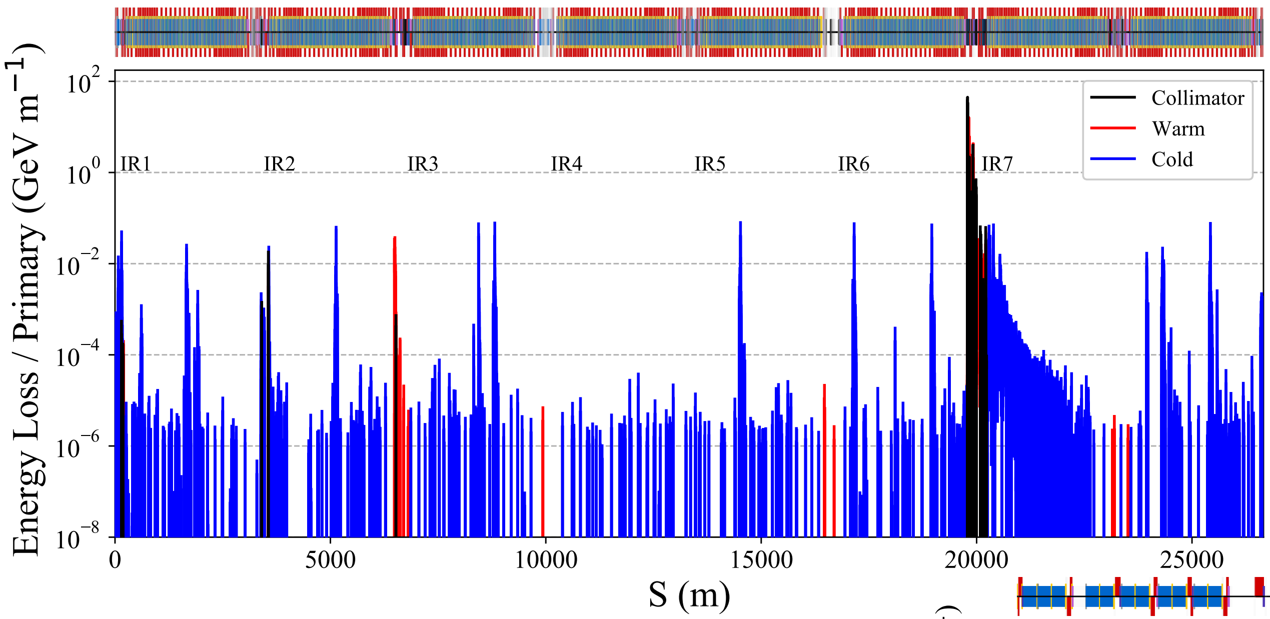




A. Abramov

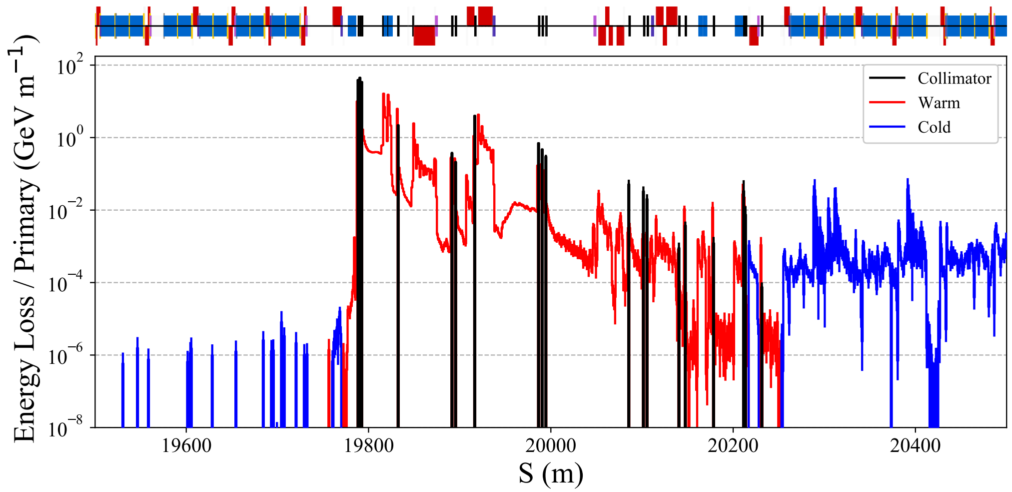
LHC Ion Collimation II

- Energy deposition around ring



- Significantly more loss spikes around ring
- Beam intensity limit much lower
- Collimator impacts only at S = 20000m here

- Zoom of collimation section ('IR7')
- Coded losses on collimators, warm and cold sections

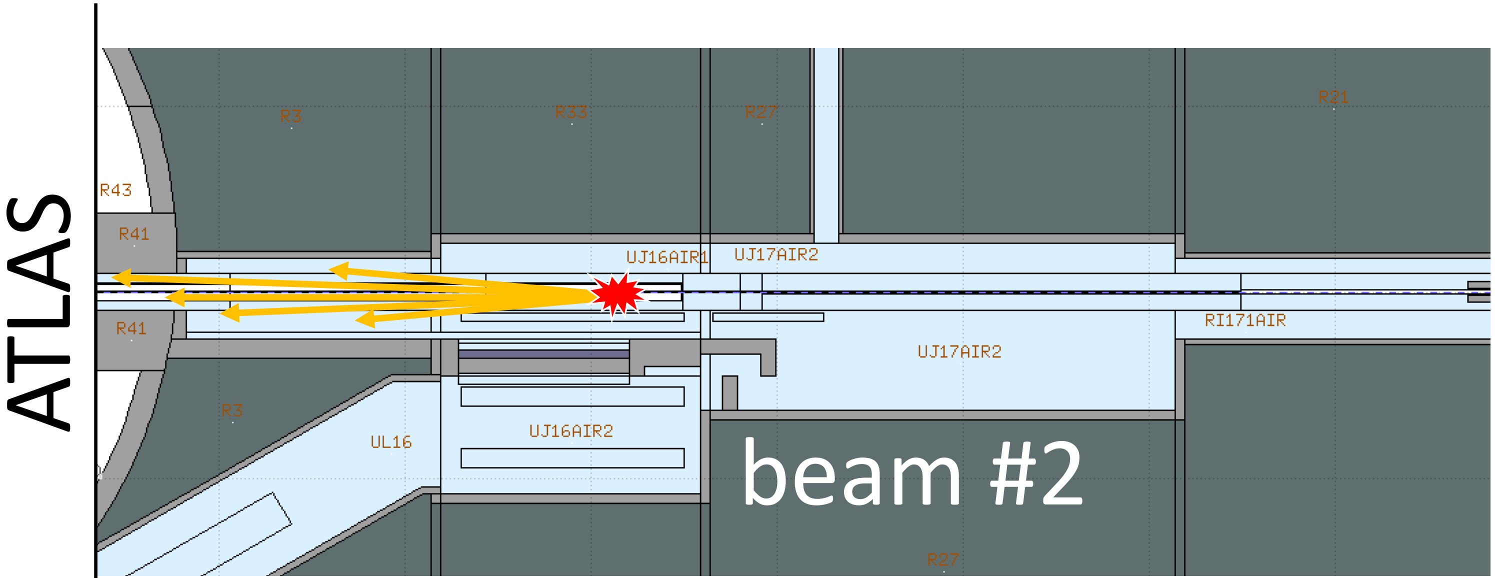


A. Abramov

LHC Non-Collision Backgrounds

ROYAL HOLLOWAY UNIVERSITY OF LONDON

- Interaction with residual vacuum creates measurable background in ATLAS and CMS detectors
- Modelling ATLAS background using BDSIM
  - last 500m of machine before ATLAS
  - single pass simulation
  - Predict observed rates in pixel detector
- Bias proton inelastic scattering with residual vacuum
  - subsequent interactions with normal weighting



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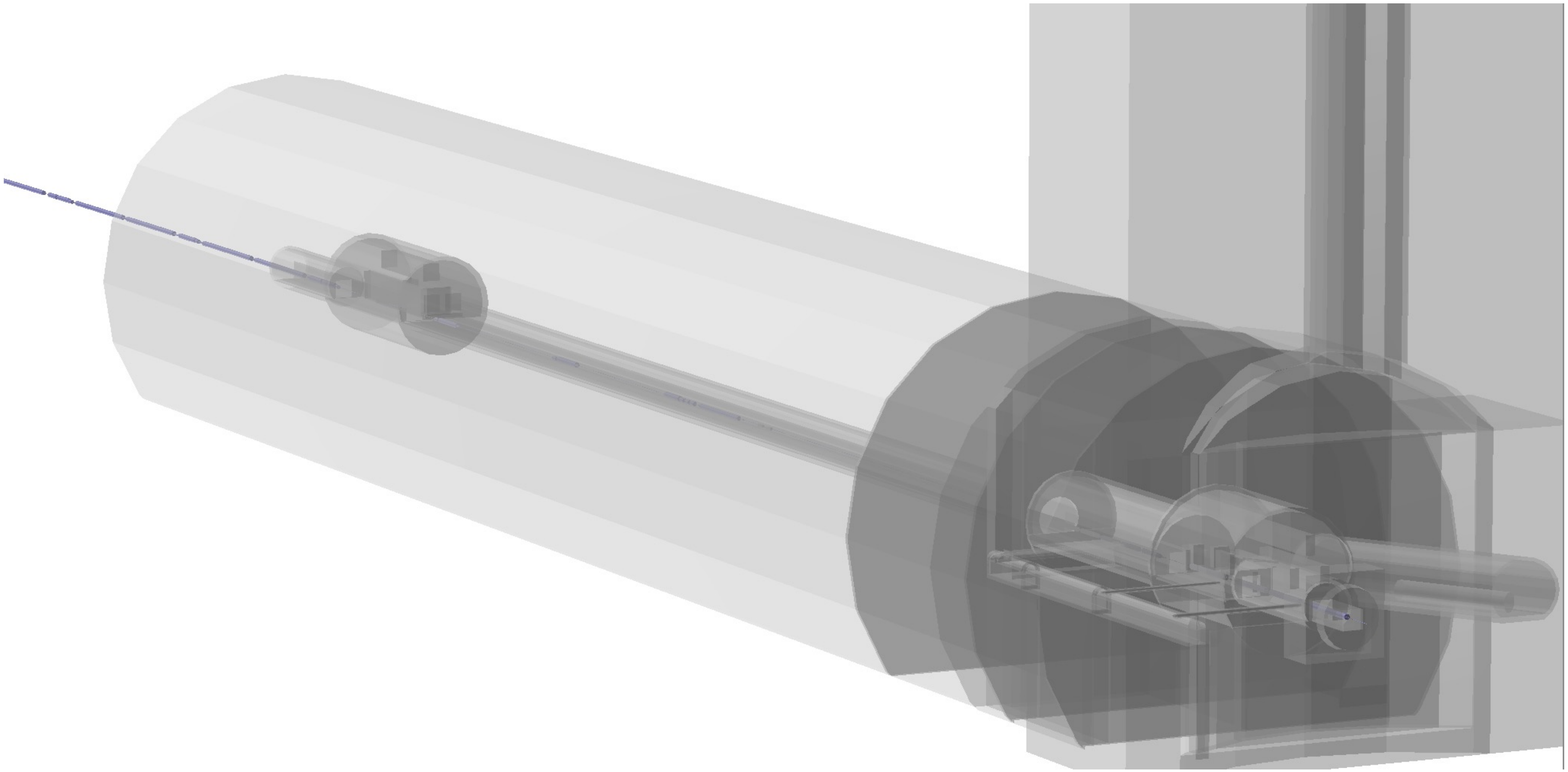
LHC Non-Collision Backgrounds II

- Tunnel model converted from FLUKA format
  - 'pyfluka' package by S. Walker at JAI@RHUL
- Tunnel and shielding placed around BDSIM beam line



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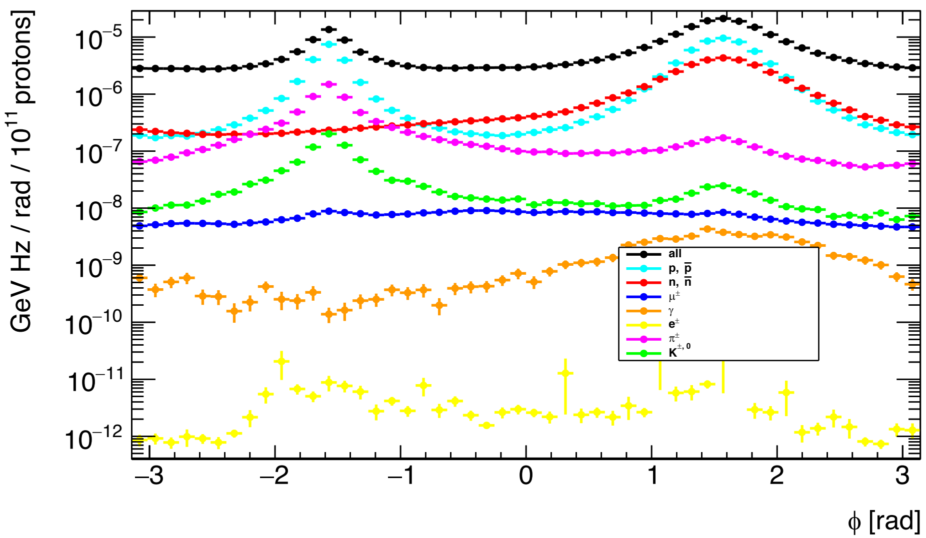
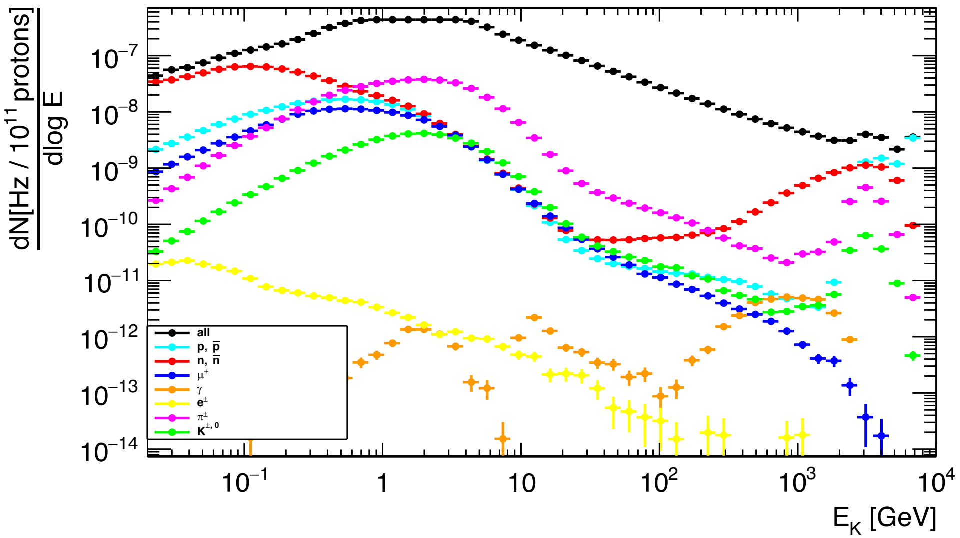
LHC Non-Collision Backgrounds III

Azimuthal rate for different species

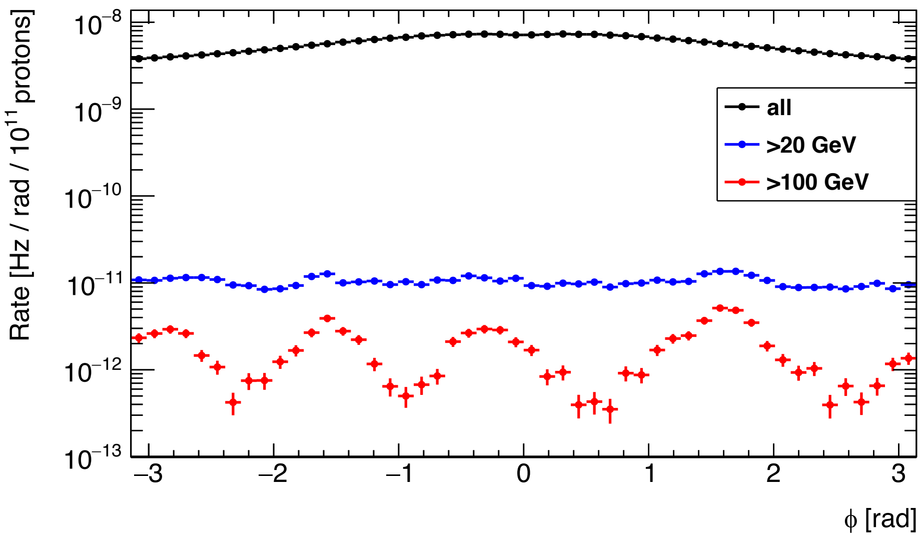




Overall particle spectra at interface plane

- Particles recorded at 'interface plane'
  - start of detector cavern
- Transferred to dedicated ATLAS simulation

Azimuthal rate for different muon energies



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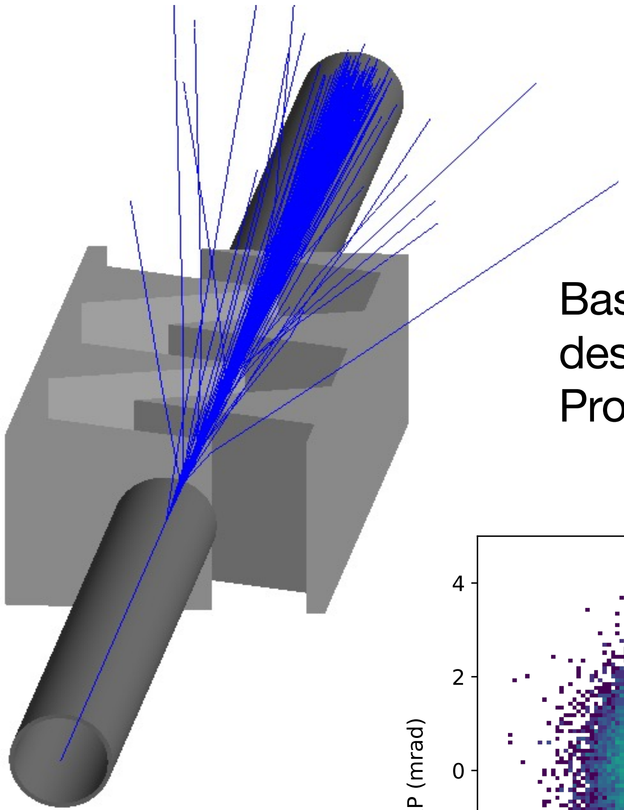
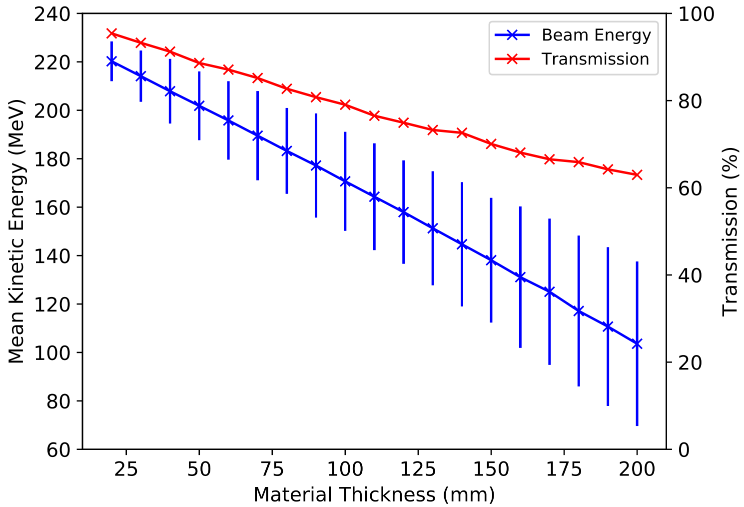
Hadron Therapy Degrader

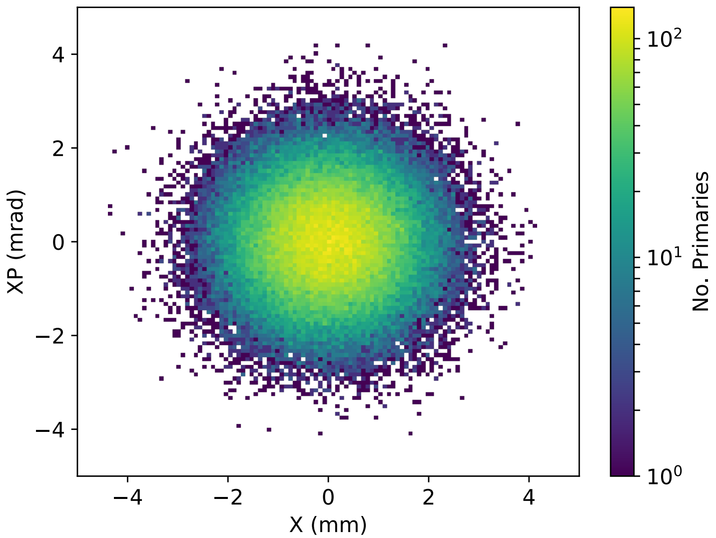
- Use variable material depth to degrade beam energy

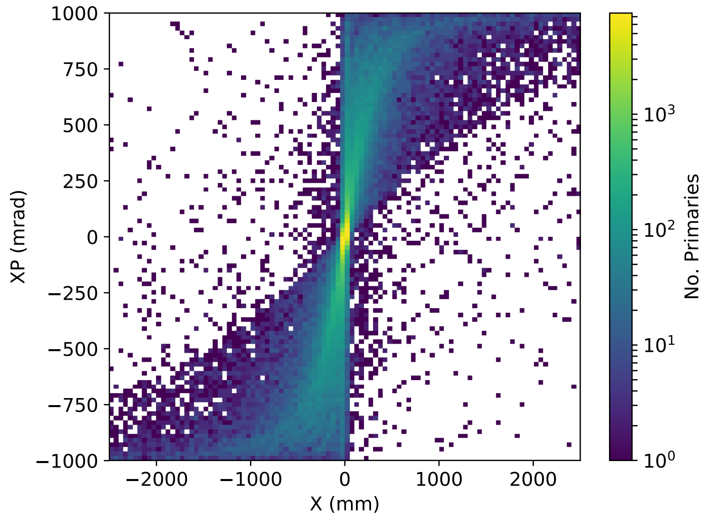


Based on the degrader design at the Center for Proton Therapy at PSI.



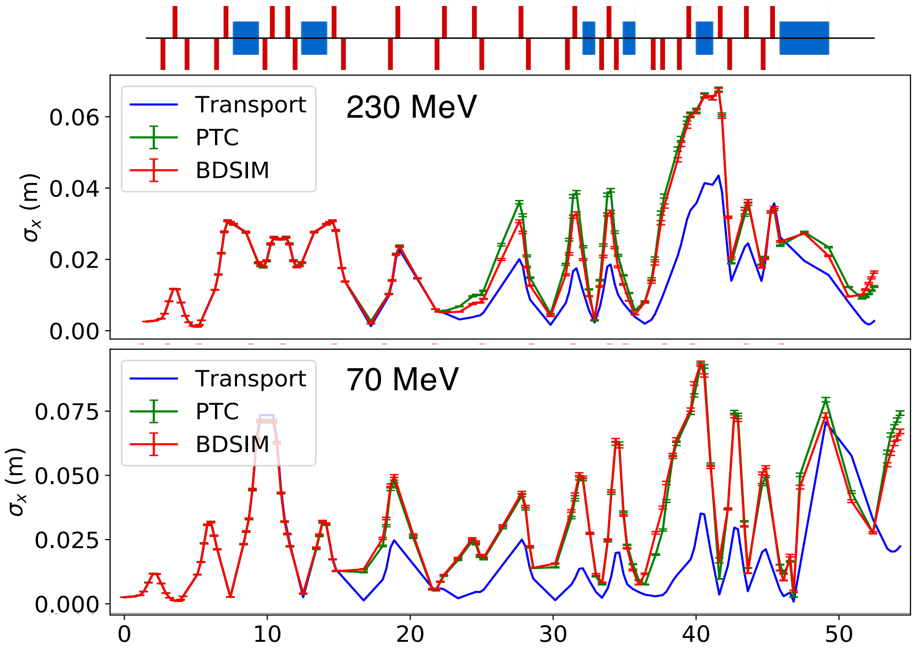
Horizontal phase space before (left) and after (right) a degrader.

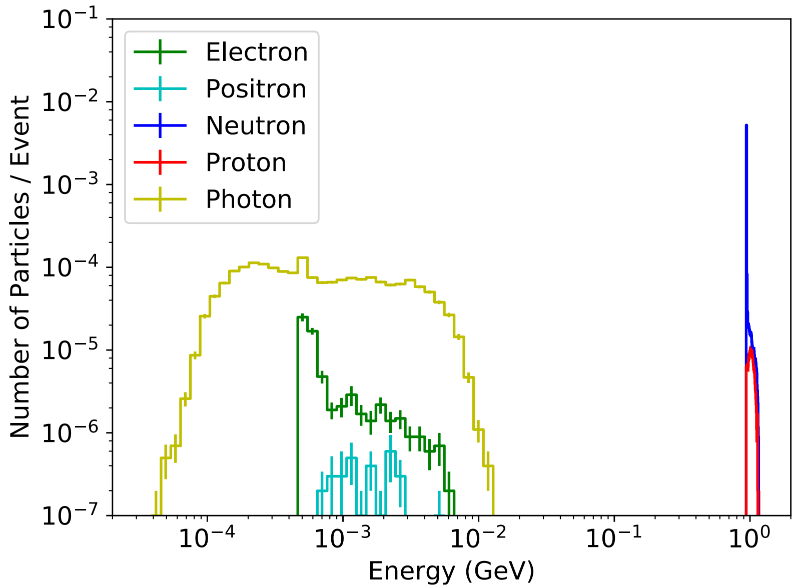




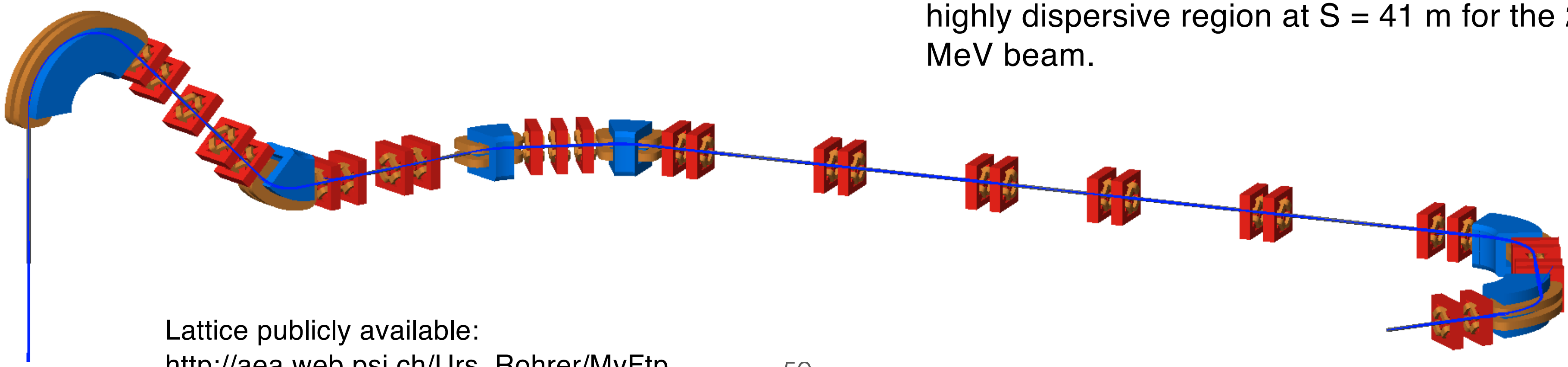
PSI Gantry II

- Optical comparison and validation





Secondaries generated from primary losses in a highly dispersive region at S = 41 m for the 230 MeV beam.

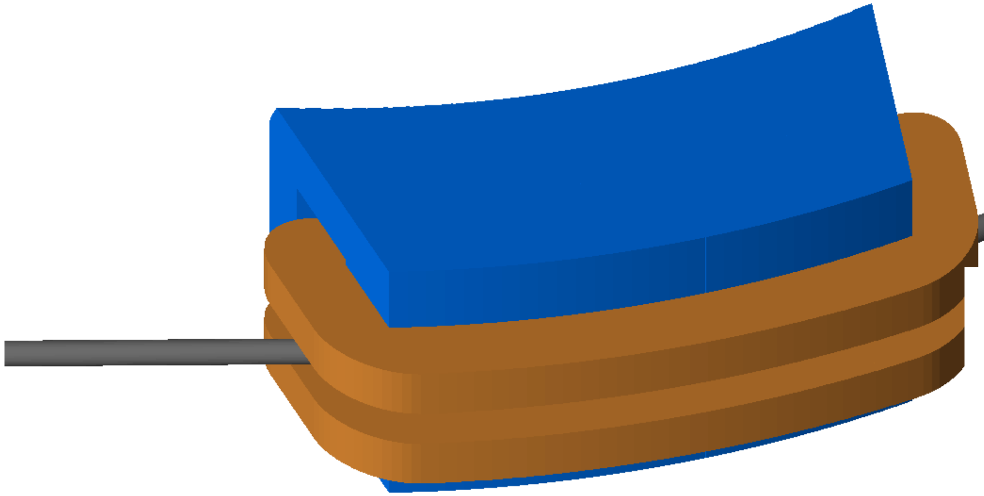


Lattice publicly available:
http://aea.web.psi.ch/Urs_Rohrer/MyFtp

Published at IPAC 2018 - MOPML061

Pole Face Rotations

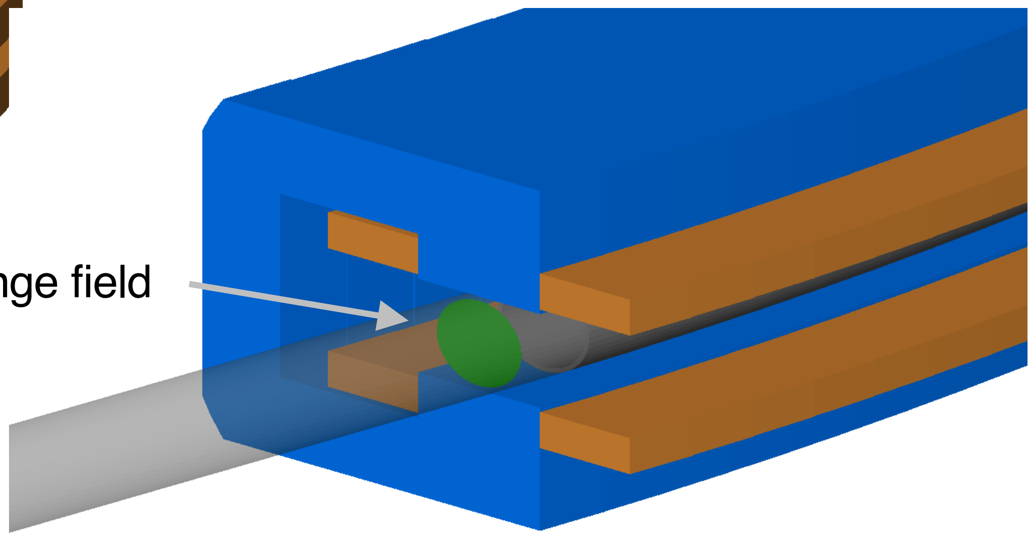
- Crucial for low energy applications
- Pole face rotations contribute significantly to optics
- Implementation using 1st order matrix formalism



Revert to Geant4 based integrator in non–paraxial limit.

Angled beam pipe and yoke geometry as well as coils

Thin element for fringe field

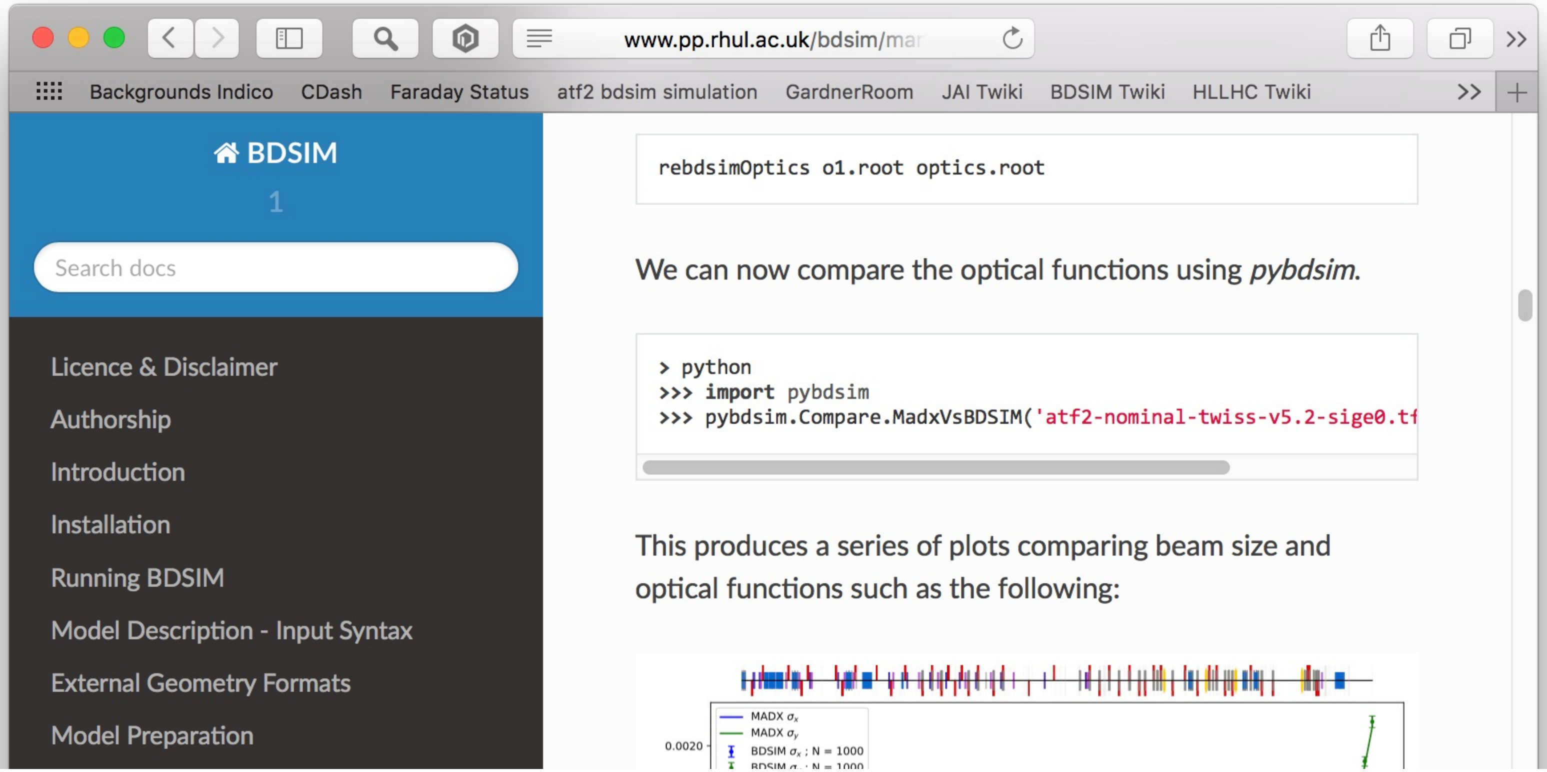


Future Development & Collaboration

- BDSIM highly suited for many studies now
- However, open source and constantly being developed
- Collaboration welcome
- Please discuss with us!

Links

- main website: http://www.pp.rhul.ac.uk/bdsim
- manual: http://www.pp.rhul.ac.uk/bdsim/manual
- git repo: https://bitbucket.org/jairhul/bdsim/
- Issue tracking & feature request
  - https://bitbucket.org/jairhul/bdsim/issues

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Thank you