Bridging the Machine Detector Interface

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JAI John Adams Institute for Accelerator Science

BDSIM Beam Delivery Simulation

GEANT4 A SIMULATION TOOLKIT

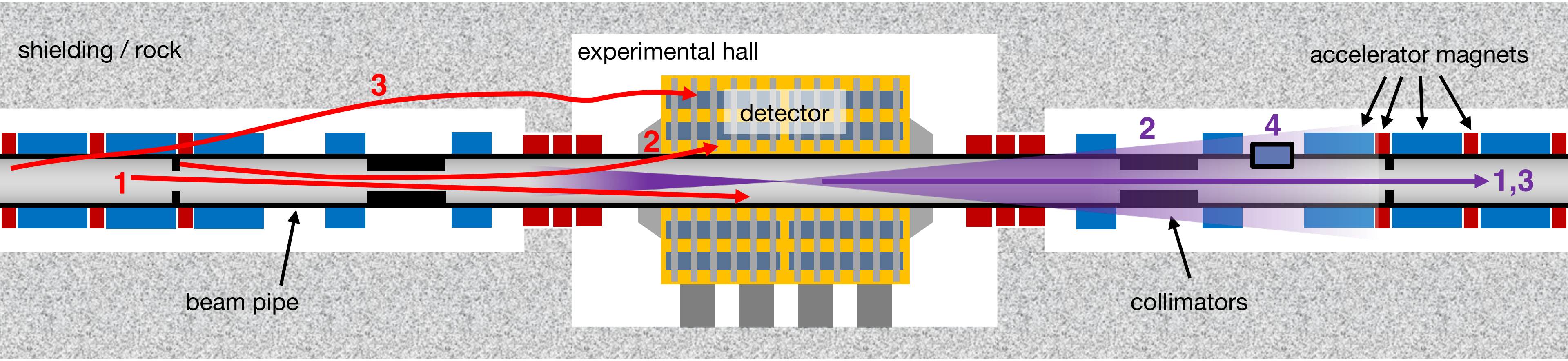
[1]

The Machine Detector Interface

- Radiation / particles in both directions - both are interesting

Incoming:
1. products from residual gas interaction
2. leakage from collimation system
3. secondaries from beam loss

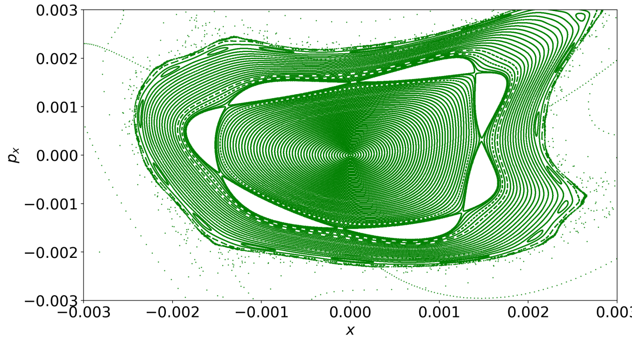
Outgoing:
1. lightly scattered primaries
2. physics debris
3. forward physics
4. forward experiments



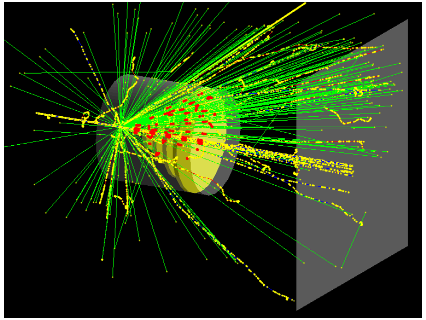
Goal: Simulate far reaching particles ***in*** and ***out*** of experiment and understand them
Need: accurate magnetic particle tracking + interaction with matter

Simulating the Machine Detector Interface

- Accurate tracking required for many (>100s) magnets
  - numerical integration (like 4th order Runge Kutta) is not accurate enough
- Specialised codes exist for accelerator tracking
  - MADX, SAD, PTC, Elegant, COSY Infinity, SixTrack, OPAL, Zgoubi, Merlin
  - these often exploit specific maps for pure fields
  - ***no*** interaction with material or only limited in select places (e.g. collimators)
  - typically ***no*** secondaries tracked or their production considered
- Typically 'losses' are when coordinates exceed aperture
  - high energy particles don't just stop! (although correlation works in some cases)

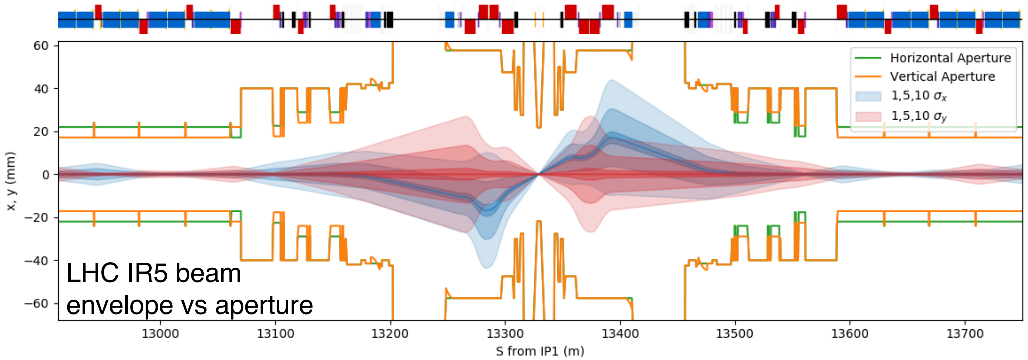


Example Poincaré map through nonlinear fields



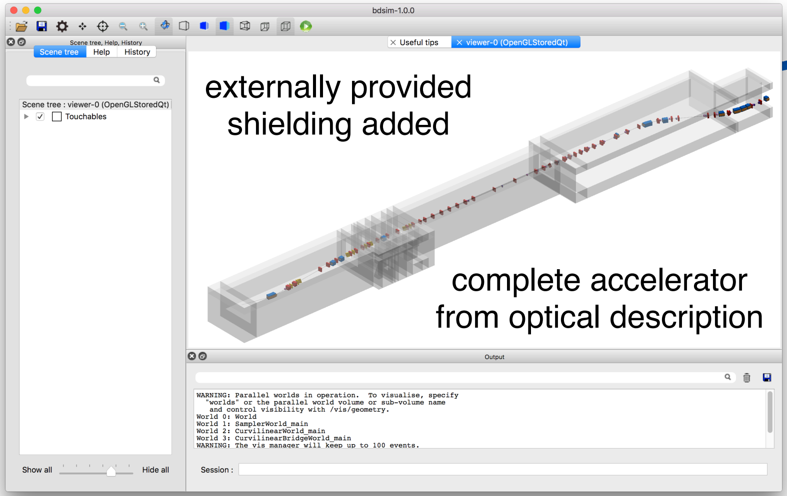
simple example Geant4 detector model

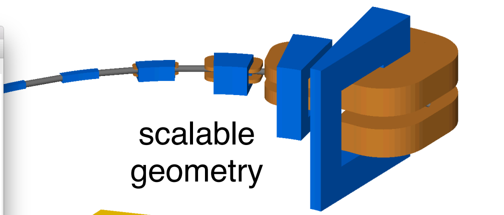
3D detector radiation transport models are often ***complex*** and highly specialised

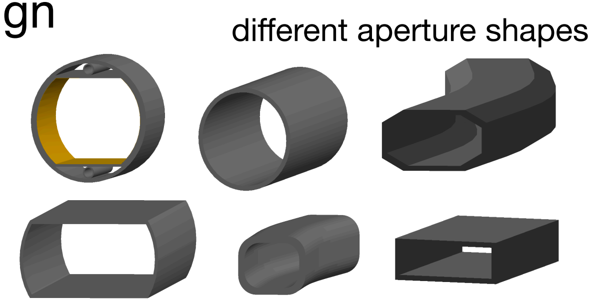


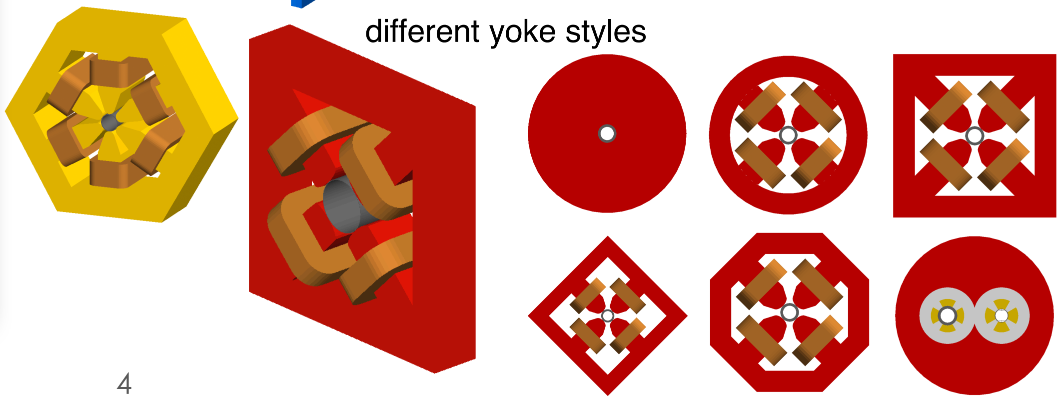
A Solution: Accelerator Tracking + Geant4

- Geant4 is a widely used open source C++ library for modelling detectors
  - regularly updated and developed based on latest results by community
- Use this and add accelerator tracking
- Accelerators are typically repetitive and similar in design
  - add library of typical accelerator components with adjustable proportions



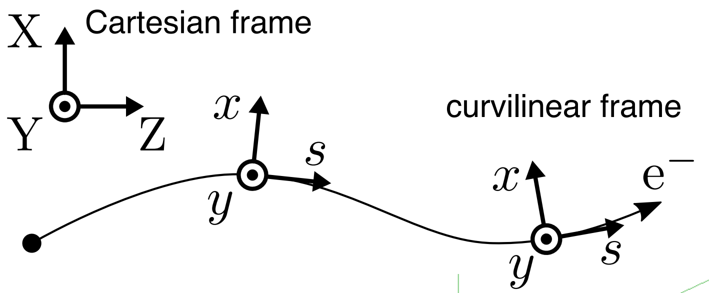


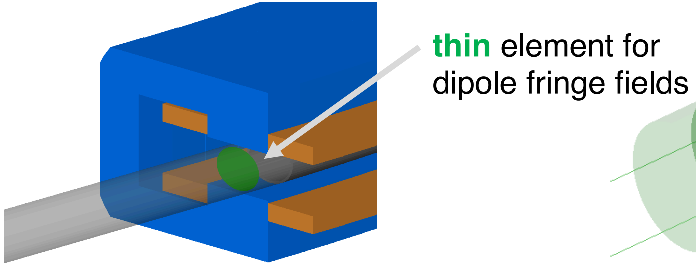


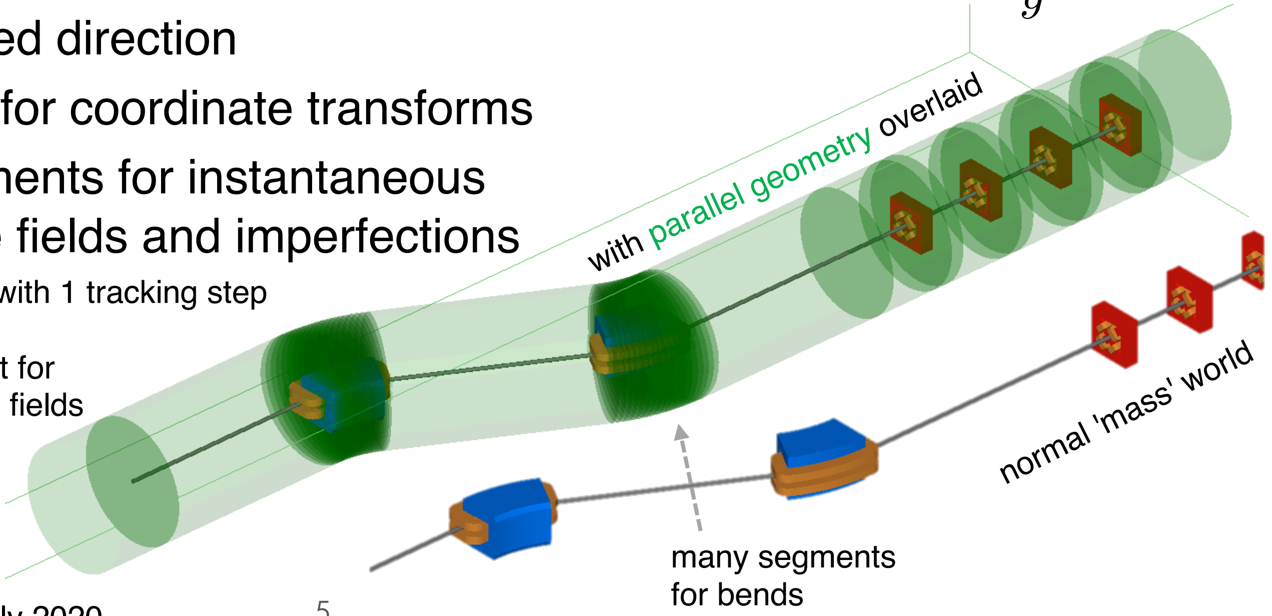


Coordinate Systems & "Thin" Elements

- Accelerator tracking is done in a ***curvilinear*** coordinate system following the beam line
  - increased precision and only relative motion
  - beam of particles typically moves together in one direction
- Radiation transport models use ***Cartesian*** coordinates - no preferred direction
- Use ***parallel geometry*** for coordinate transforms
- Tracking uses 'thin' elements for instantaneous kicks - for magnet fringe fields and imperfections
  - include as very short elements with 1 tracking step

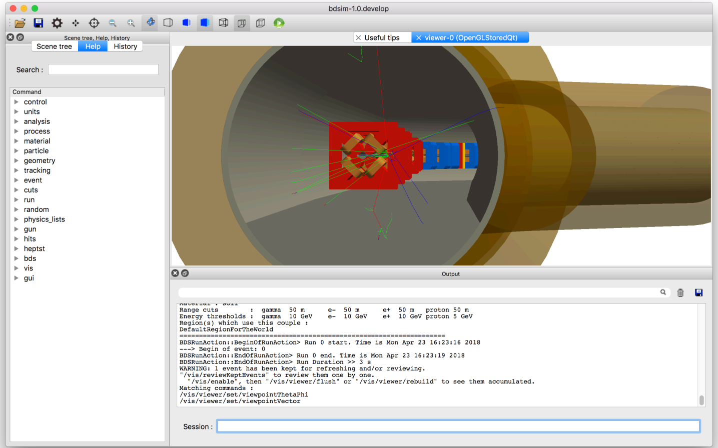


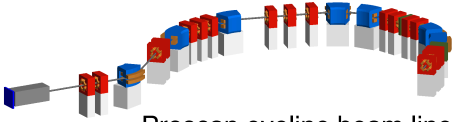




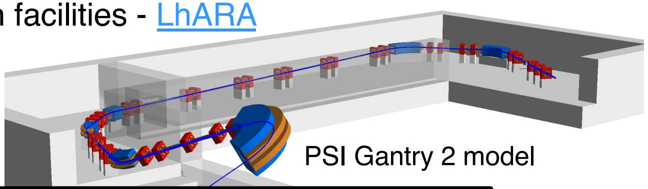
Beam Delivery Simulation (BDSIM) History

- Beam Delivery Simulation (BDSIM) application started in 2004 by G. Blair at Royal Holloway for Linear Collider backgrounds
  - open source C++ - see references at end for links
- Automatic Geant4 models of accelerators
  - start from scratch with text input or convert from optical format
  - actively developed and modernised since 2013
- Applied to many experiments and machines
  - ***ILC / CLIC***, ***AWAKE***, ***XFEL*** *undulators*, ***LHC*** *collimation*, ***Laserwires***,
  - ***FASER***, ***ATLAS*** *non-collision backgrounds*, ***MAGIX*** *at* ***MESA***
- Also for **medical** applications
  - proton therapy gantries with ULB & IBA
  - radiobiological research facilities - LhARA



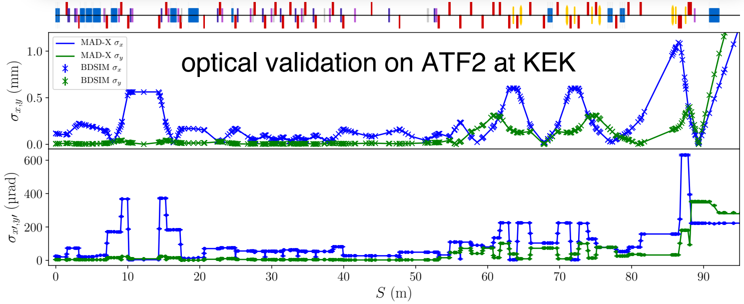


Proscan eyeline beam line



PSI Gantry 2 model

Computer Physics Communications (252), July 2020, 107200

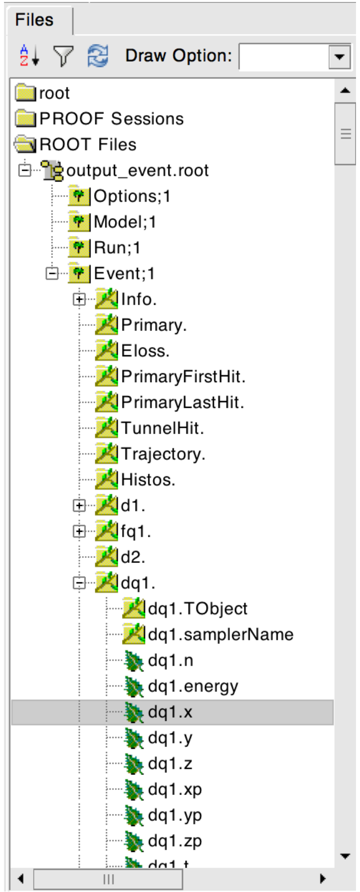


*don't forget the 'i' when googling it

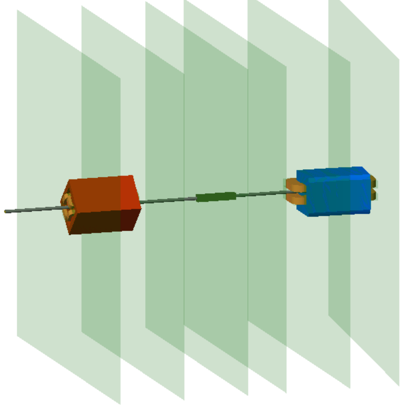
BDSIM Integration & Data

- Modern CMake build system
  - uses Geant4, ROOT & CLHEP
- Can be used as a class inside another application
- Data is stored in ROOT format with per-event structure
  - accelerator tracking simulations are typically 1 particle in, 1 particle with much simpler data format
  - radiation transport model requires more advanced format and analysis tools
  - ***trajectory filtering*** and linking back to primary
- Data format and included analysis tools key to understanding the origin of energy deposition
  - easy filtering / selection in analysis and skimming
- Strong reproducibility from output data
  - recreate single or multiple events afterwards
- Invisible "sampler" planes to record distributions after an object

example data tree structure

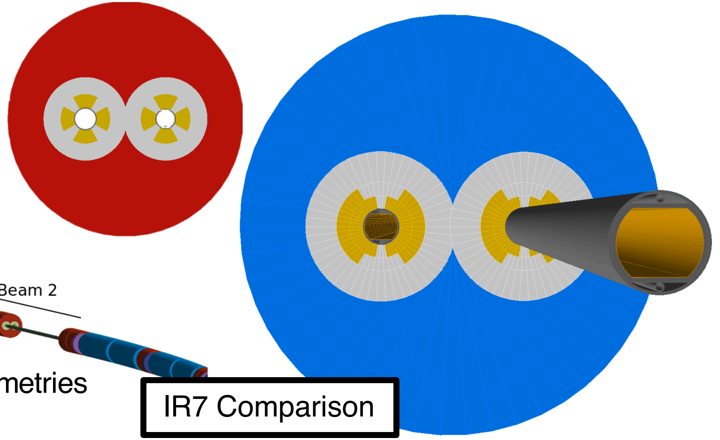


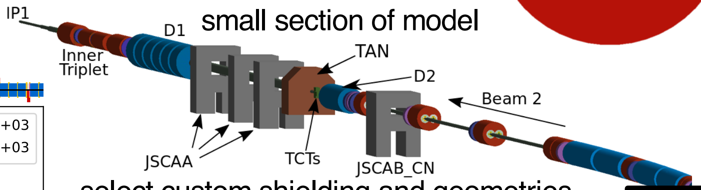
sampling planes after each element (normally invisible)

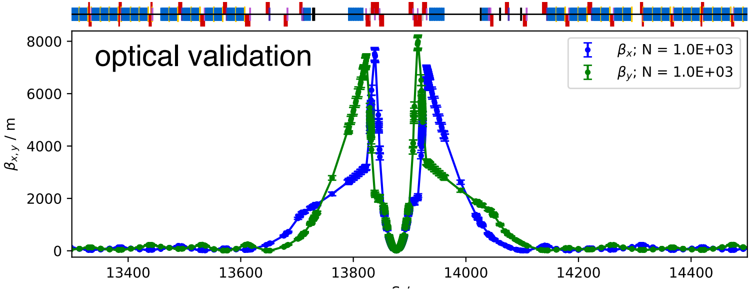


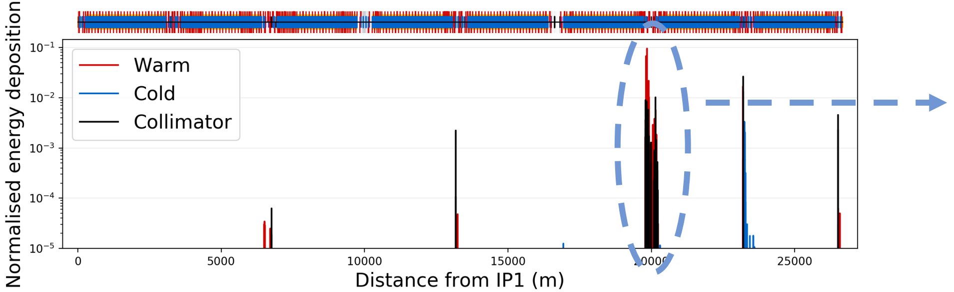
Model of the Full LHC Accelerator

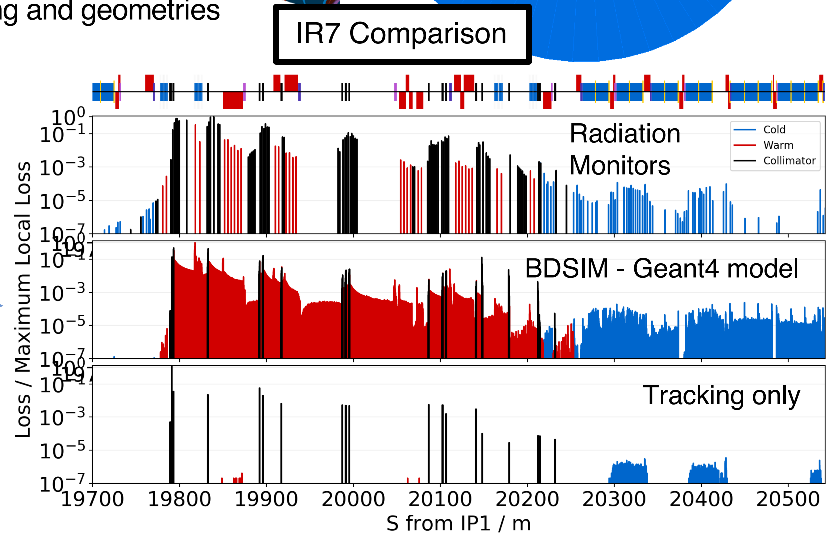
- Full LHC ring model created in BDSIM / Geant4
  - for studying collimation and detector backgrounds
  - ~15k beam line elements with ~300k volumes
  - supports multi-turn tracking
  - mostly based on simplified geometry





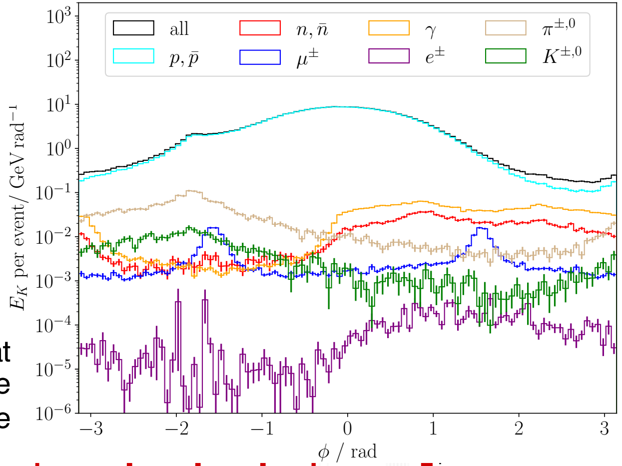






ATLAS Non-Collision Backgrounds

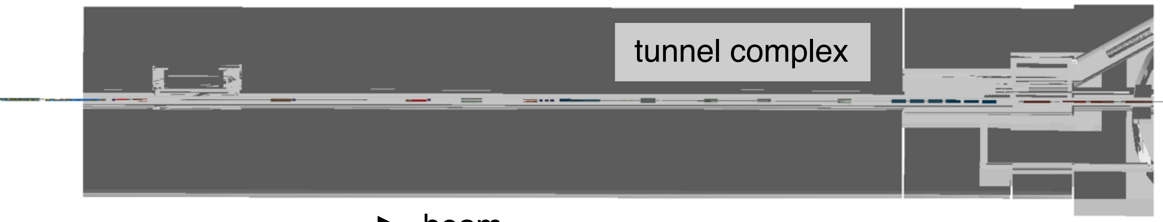
- Detailed model of IR1 leading up to ATLAS created
- Beam simulated up to "interface plane" 22.6m before
  – hand off to dedicated ATLAS simulation
- Simulate experimental pressure bumps using cross-section biasing in select regions
- Simulations allow understanding of origin and transport of penetrating background
- Good agreement with experimental data found



spectra at interface plane

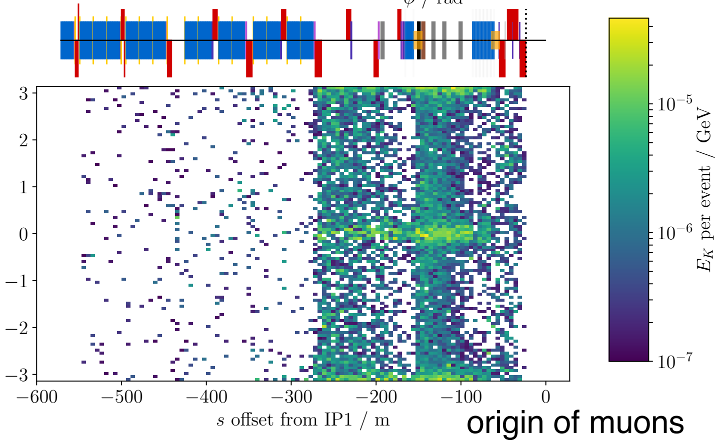
S.D. Walker thesis 2020

~300m before ATLAS



beam

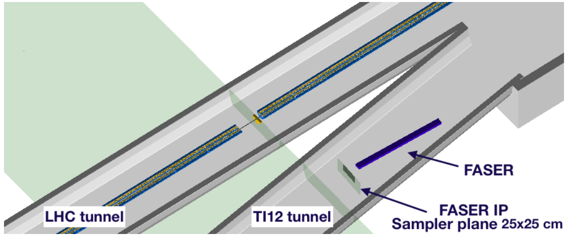
ATLAS IP

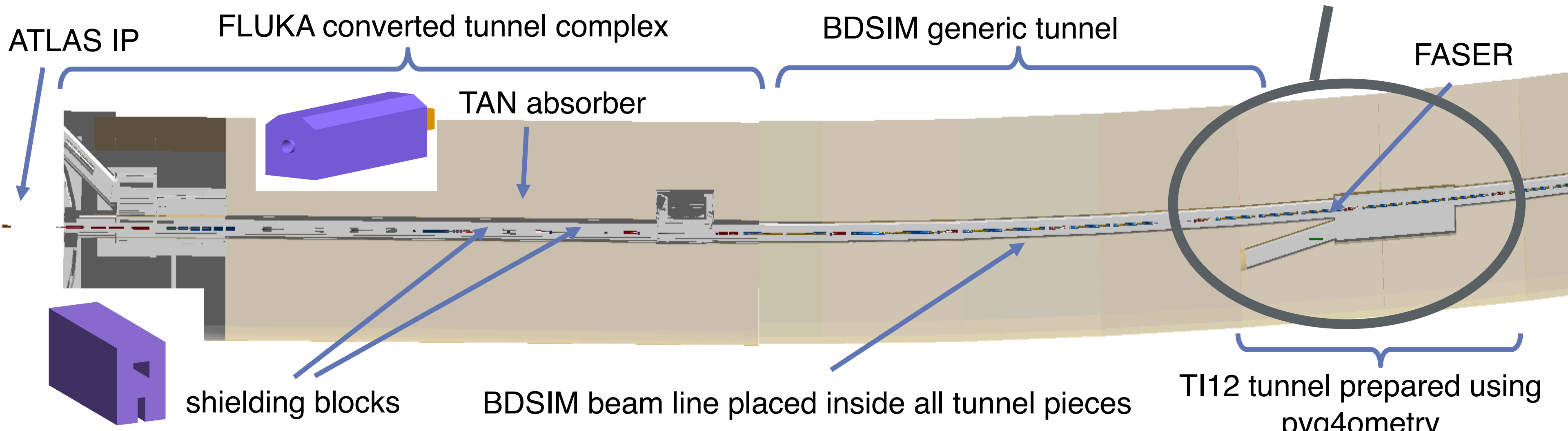


origin of muons

Forward Experiment Simulations

- Exploiting the same model but outgoing for forward experiment FASER
  - further detail added in tunnel geometry, side tunnel and absorbers
- See ***H. Lefebvre's*** poster today
  - https://indico.cern.ch/event/868940/contributions/3815740/
- Used to predict muon and neutrino flux

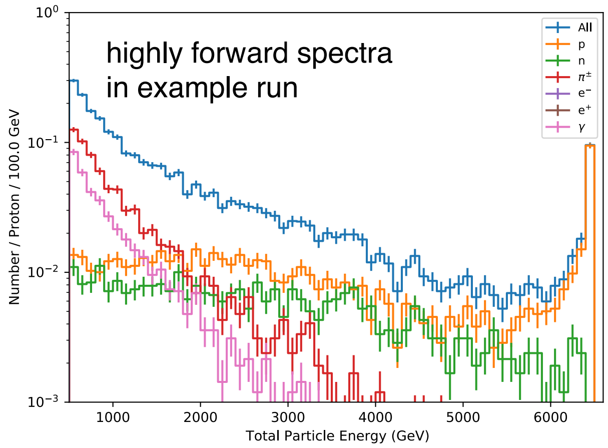


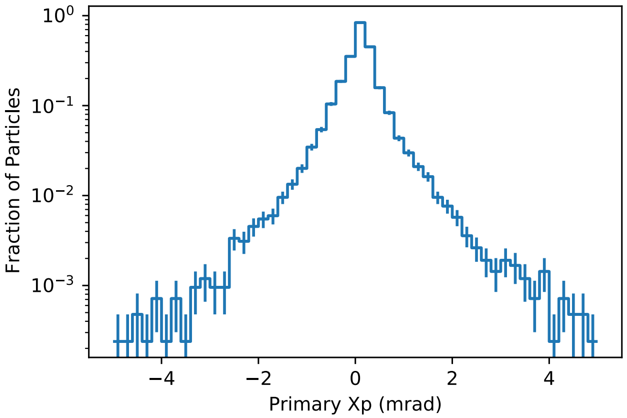


H. Lefebvre

LHC Physics Debris

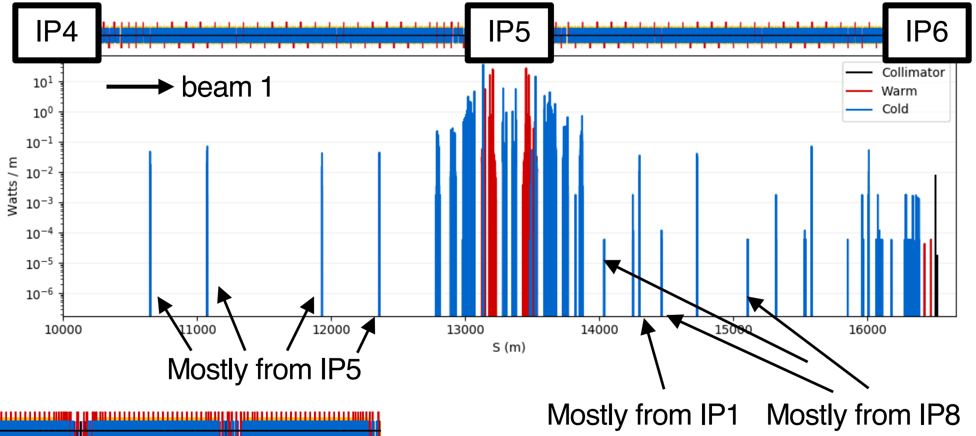
- A very interesting application is physics debris
- Elastically and inelastically scattered protons and *secondaries* can reach far from the experiments into the accelerator
- Certain beam loss monitors are highly correlated with luminosity and not with the stored beam intensity
- This isn't a problem for the machine but it is measurable
- We can use this to measure the luminosity or, assuming the luminosity: the total cross-section
  - with down-selection to beam loss monitors that only represent luminous beam losses
- *Potential for forward physics simulations!*

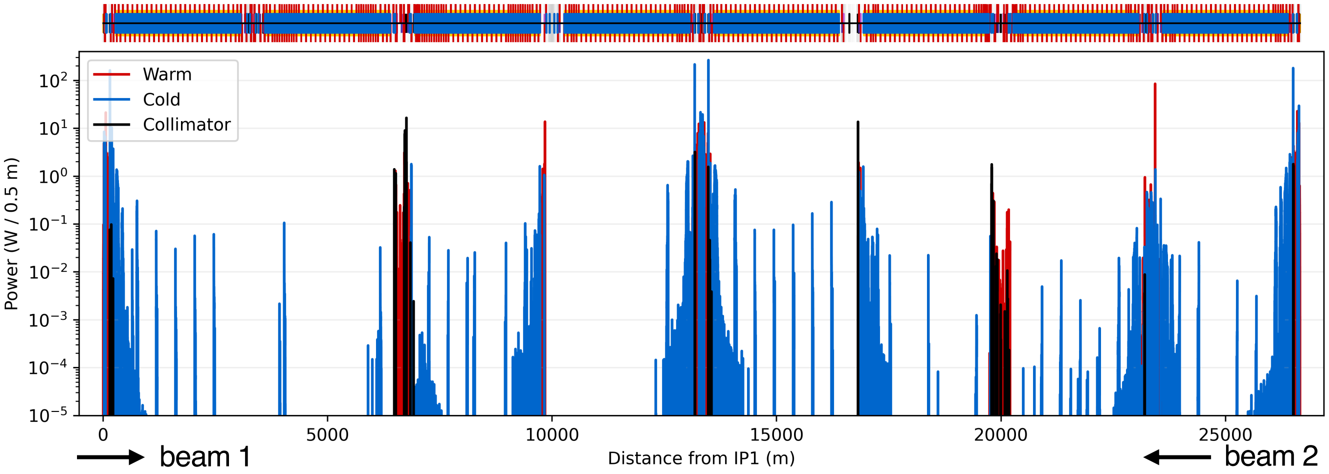




LHC Physics Debris Simulations

- Simulate head-on p-p collision with event generator at IPs 1,5 and 8
  - CRMC using SIBYLL 2.3 model
  - add on beam collision angle to primaries and propagate from each IP
- Record energy deposition throughout
  - individual peaks in arcs agree well with known BLMs to be correlated with luminosity



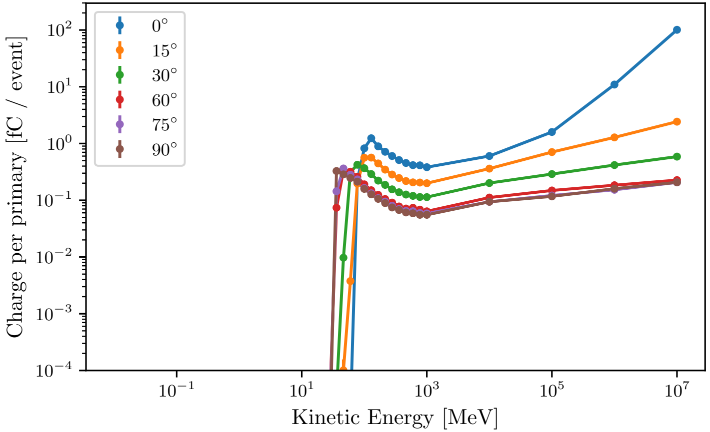


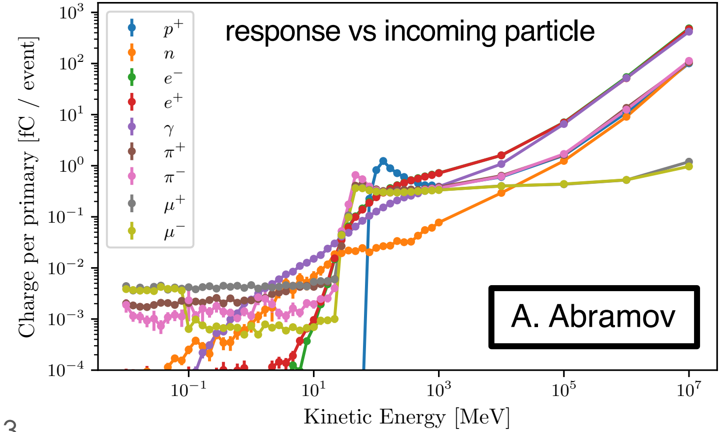
Weighted combination of each study according to luminosity

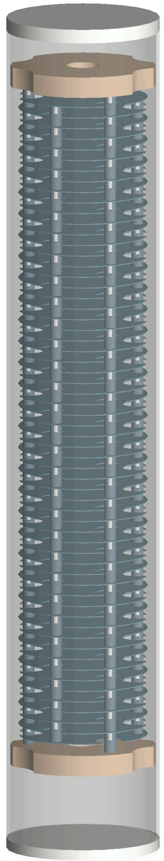
IP	Luminosity
1	1.5×10^{34}
5	1.5×10^{34}
8	0.05×10^{34}

Beam Loss Monitor Modelling

- LHC is instrumented with ~ 3600 beam loss monitors for machine protection
  - mostly gas ionisation chambers
  - too high losses and beam dumped to protect machine
- Geometry modelled in GDML using ***pyg4ometry*** package
  - see backup slides for rapid geometry package
- Calibration simulations as separate model recording charge deposited
  - agrees very well with published literature
- Use as parameterised model for simple geometry in complete LHC model
  - parameterise signal also on the collimator hits as high kinetic energy cuts can lead to lack of particles intercepting BLMs
  - place all ~ 3600 in BDSIM / Geant4 model of the LHC



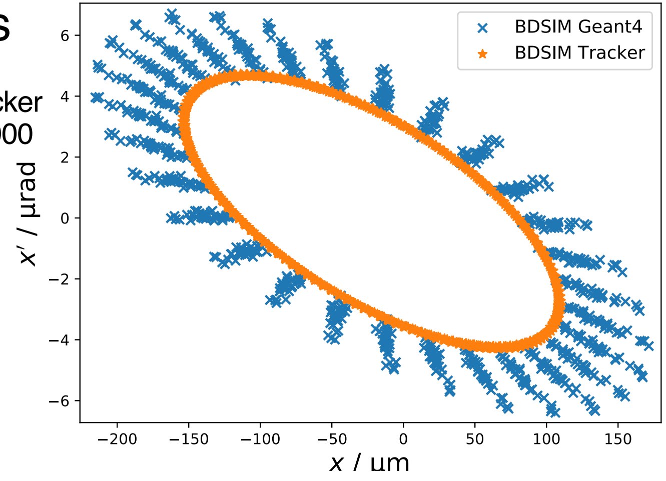


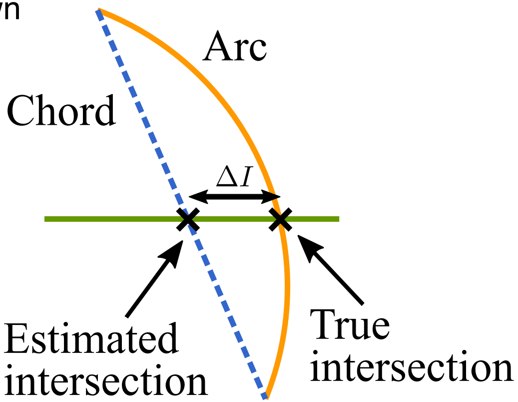


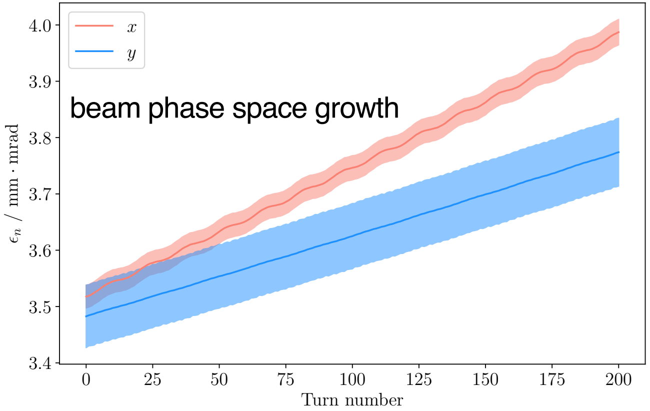
Limitations & Symplecticity

- For longer term ring tracking we start to see limitations
  - "longer term" here is 100s to 1000s of turns of the LHC
  - for single pass models the tracking is very accurate
- Small numerical errors can build up
- '***Symplectic***' tracking conserves phase space
- Here, errors build up due to the convergence of the intersection with each boundary
  - each step of an algorithm is fine on its own
  - there is always a geometrical tolerance
  - leads to inaccurate result eventually
  - loss of precision with large models
  - a particle tracker has no such problem
- Tracker applies one map at a time
  - no ambiguity along direction of travel
- Need to retain accuracy

comparison of tracker with Geant4 for 1000 turns of LHC



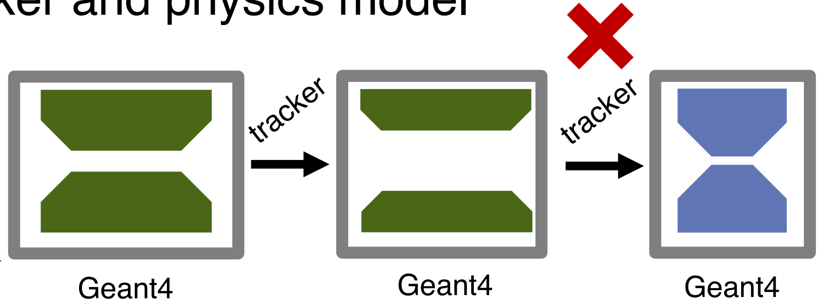




Combined Simulation Strategy

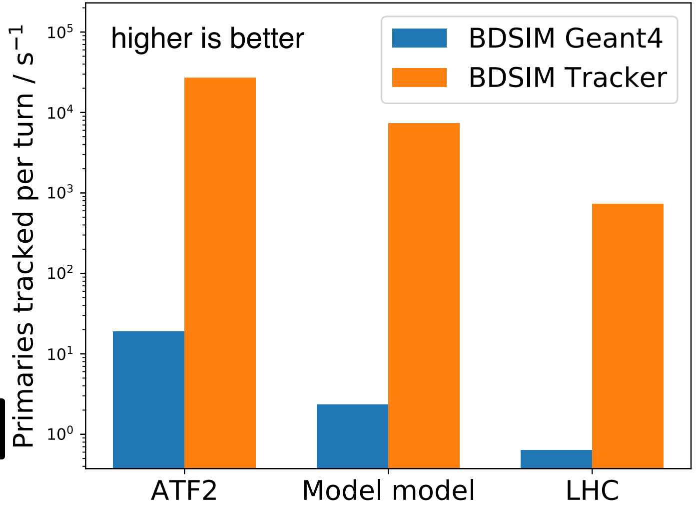
- Several possible strategies for combined tracker and physics model
  - apart from already described BDSIM full Geant4 model

1. Pass over once from tracker to 3D model
   - if particle is expected to go with beam first then be 'lost'
   - after initial scatter assume won't complete multiple turns
2. Discrete regions for physics processes
   - particle tracked in tracker
   - for select elements propagate in 3D model
   - works well for collimation - but no physics in tracker



3. Truly integrated tracking ✓ **choose this option**
   - override transportation process in Geant4
   - maintain concurrent curvilinear and Cartesian coordinates
   - transform from curvilinear to Cartesian to push particle in 3D world
   - no stringent intersection to maintain tracking accuracy (faster)
   - tracking library written ✓
   - ***integration underway***

tracker alone is ~10^3 times faster

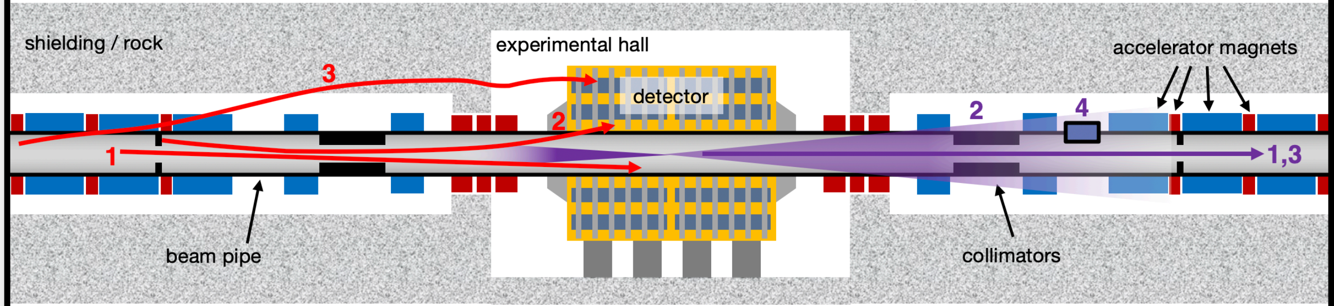


Conclusions - Bridging The Machine Detector Interface

- Ability to create Geant4 detector-like models of accelerators exists
  - permits understanding and analysis of origins of many background sources as well as signal propagation
  - include matter interaction and secondary particles
- Shown how to track *all* particles including ions and partially stripped ions

Incoming:
1. products from residual gas interaction
2. leakage from collimation system
3. secondaries from beam loss

Outgoing:
1. lightly scattered primaries
2. physics debris
3. forward physics
4. forward experiments



Goal: Simulate far reaching particles ***in*** and ***out*** of experiment and understand it
Need: accurate magnetic particle tracking + interaction with matter

Conclusions & Outlook

- Complete multi-turn ***Geant4 model of the LHC*** accelerator
- Future work to use model with all ~ 3600 beam loss monitors to disentangle *luminous* and *non-luminous* losses
  - potentially make independent luminosity measurement
- Upcoming ***fully symplectic*** particle tracker with in-flight Geant4 physics
- Many exciting extensions being added
  - laser-Compton scattering for laserwires
  - photo-detachment; excitation; spontaneous emission for in-flight partially stripped ions (see Gamma Factory)
  - Geant4 crystal channelling model for crystal collimation and beam extraction
  - halo generation throughout from residual gas interaction

- Please contact if interested in collaboration!
  - potential for joint PhD projects also

Thank you

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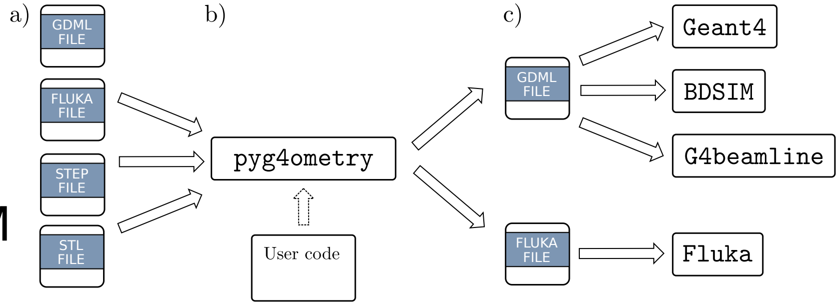
BDSIM - website - manual - paper

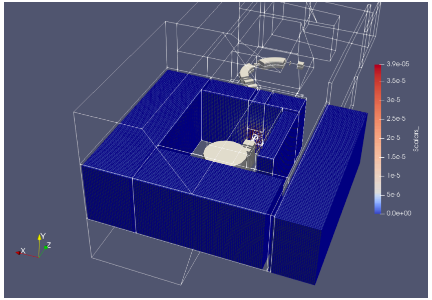
[1] Title slide image credit; CERN + BDSIM model

pyg4ometry

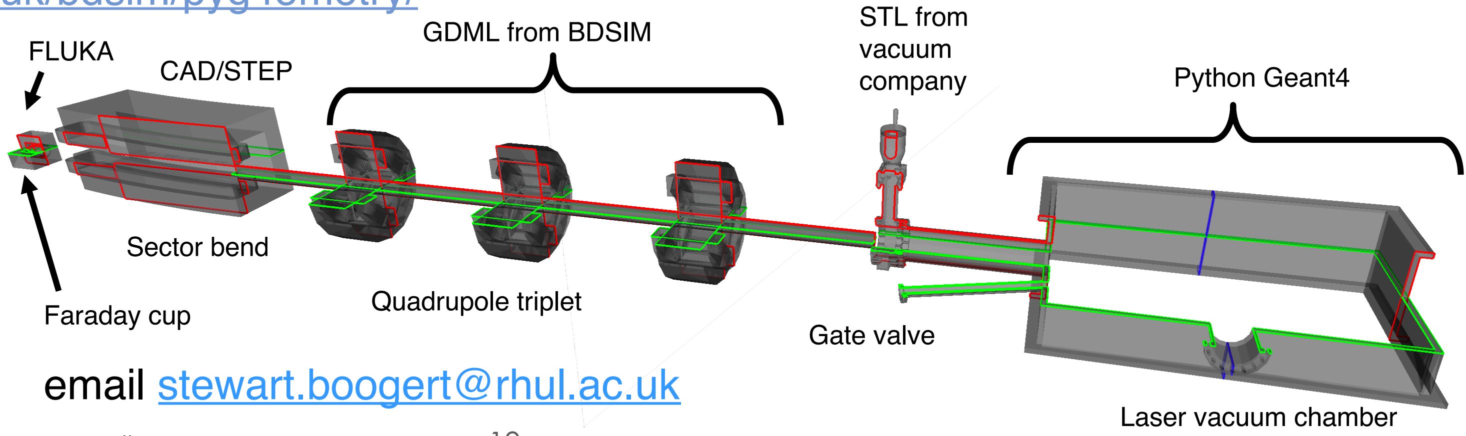
- python package to rapidly prepare and convert geometry for Geant4 & FLUKA
  - create / convert / composite geometry
  - validate and ensure safe for tracking (no overlaps etc)
- Place custom components in Geant4 / BDSIM
- Have parity with models in Geant4 & FLUKA



https://bitbucket.org/jairhul/pyg4ometry/src/develop/
http://www.pp.rhul.ac.uk/bdsim/pyg4ometry/



Shielding and beam line



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