Biasing in HEP & with Geant4

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Marc Verderi
LLR, Ecole polytechnique
For the Geant4 Collaboration

Few words

- **Analog simulation:**
  - This is the regular or standard simulation
- **Biased simulation:**
  - Modified simulation
  - Biased does not mean “wrong” here !
- **Biasing, “event biasing”, “variance reduction”:**
  - I’ll be using these almost as synonymous

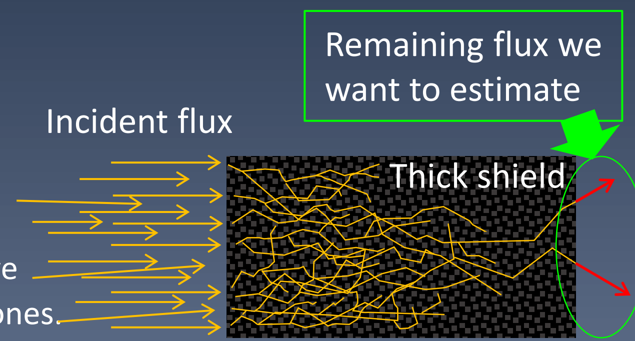
Introduction

Introduction

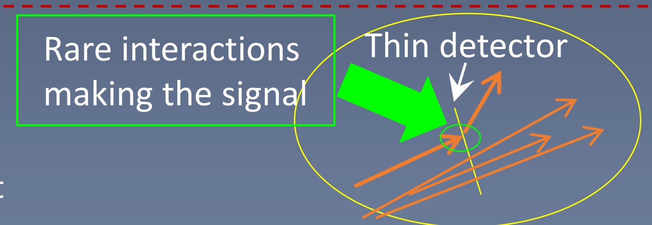
- Biasing is a set of techniques to simulate "rare events" efficiently:
  - By focusing the computing power where it is most profitable to the problem
  - They have been used since the beginning of Monte Carlo software
    - To overcome the limited CPU resources
- They are used in low energy domains
  - E.g.: neutron transport, or medical imaging, etc.
- They have some usage in HEP and Intensity Frontier:
  - With the cavern background simulation
- But they are not much used in detector simulation:
  - HEP detectors are built to see the most they can in an event
  - And hence don't have areas where it is most profitable to focus the CPU on…
- So, no hope for further biasing ?
- Let's step back first, and then see…
- This presentation is for a large part general to biasing.

Rare event problems ?

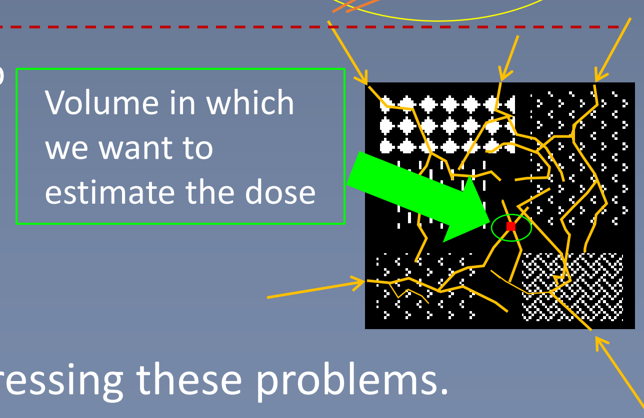
- There are simulation problems in which what we are interesting in is “*rare*”
  - rare because of the physics,
    - Higgs production, B decays, neutrino interactions, etc.
  - or because of the setup, or both, etc.
- Examples of such problems:
  - Estimating the efficiency of a shield
    - A large flux enters a shield…
    - … with a lot of interactions inside, which is CPU intensive
    - … and only a tiny fraction of particles exiting : the rare ones.



  - Obtaining the response of a very thin detector
    - For example to obtain the response to neutrons
    - Most of them do not interact in
    - But the signal is made by the rare ones which interact



  - Estimating the dose in a very small part of a big setup
    - For example an electronic chip inside a large accelerator structure
    - Most of the time is spent simulating showers that do not contribute the dose
    - While we want to tally this dose



- An “analog” simulation is very inefficient in addressing these problems.

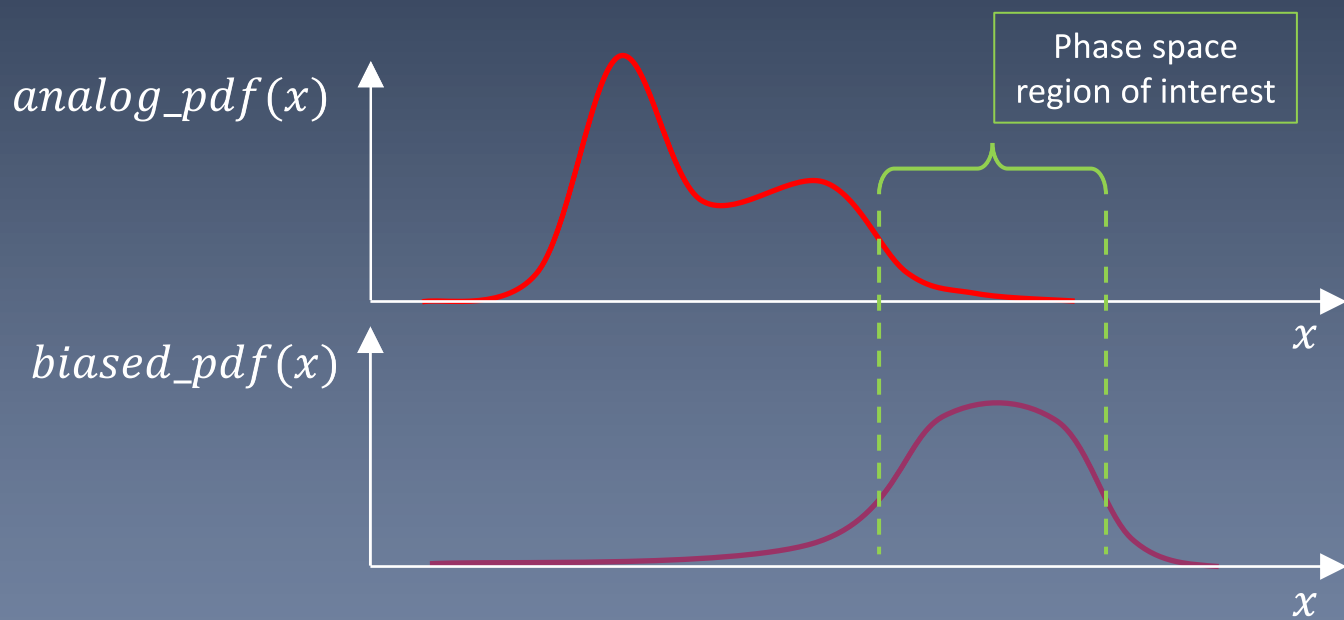
What is “event biasing” ?

- Event biasing is for simulating rare events efficiently
  - It is an accelerated simulation with respect to these events
    - And to these events only : ie *not everywhere*
  - It “focuses” on what we want to tally
- It can provide LARGE CPU improvements
  - Several orders of magnitude ! Depending on the problem.
- “Biasing” stands for using a “biased simulation”:
  - Simulation is “biased” because the region of the phase space that contributes to the tally is enhanced compared to the analog simulation.
  - This enhancement comes together with the computation of statistical ”weights” that are used to go back to analog quantities , ie to “de-bias”.
    - Eg : $E_{deposit} = \sum_{i=track} weight_i \times E^i_{deposit}$

- Many biasing techniques exist
- But two methods make the actual “backbone” of most of them:
  - Importance Sampling
  - Splitting

Importance Sampling

- In "importance sampling" techniques, the analog probability density functions (pdf) are replaced by biased ones
- In other words, we explicitly modify the physics laws:

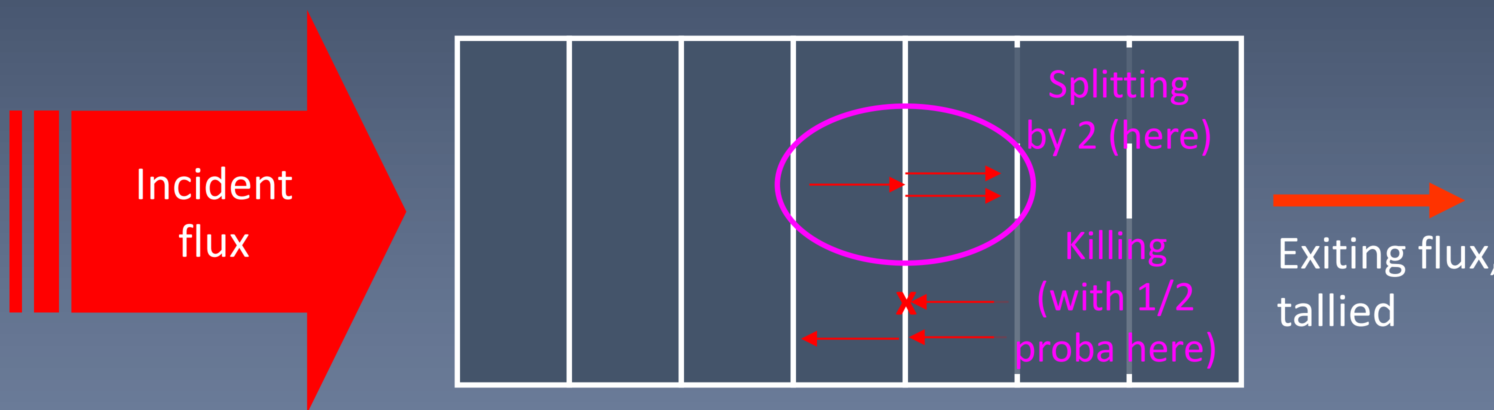


- So, we sample $biased\_pdf(x)$
- and to each x sampled value we associate the weight:

$$w(x) = \frac{analog\_pdf(x)}{biased\_pdf(x)}$$

Splitting

- In splitting techniques
  - the physics distributions are unchanged
  - but a “splitting” occurs at some places when particles move towards the tally
- Example of a shielding problem:
  - Idea: splitting compensates for the physical absorption in the shield

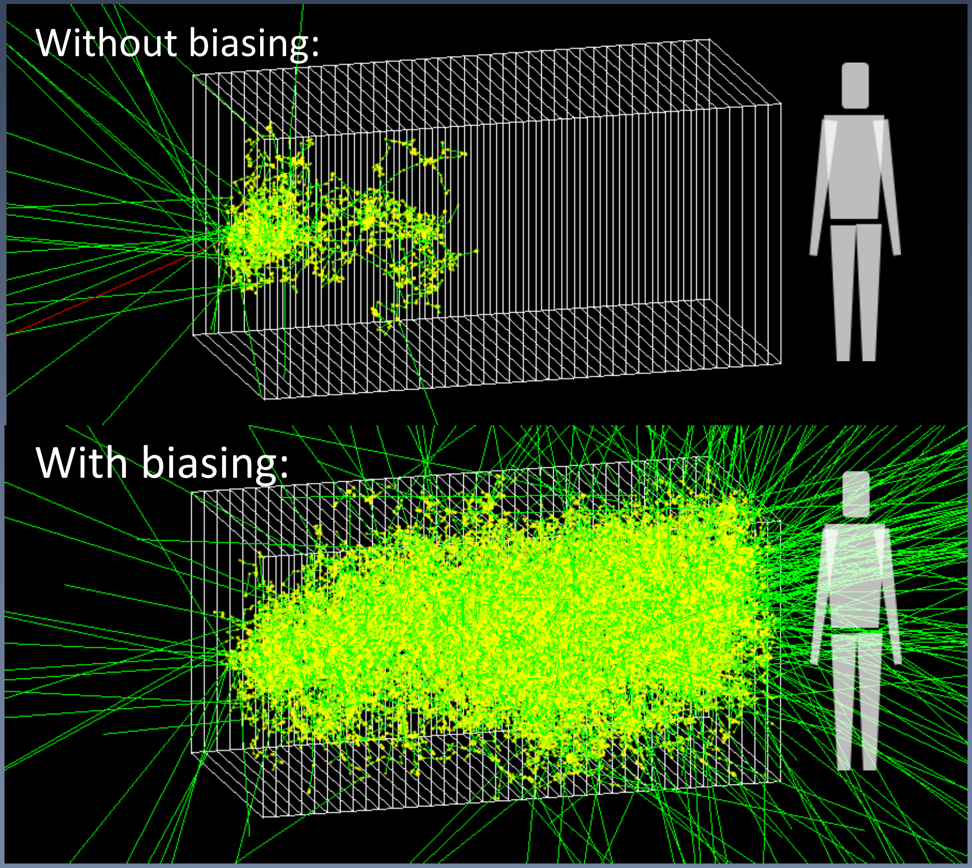


  - In above example, particles moving:

- **Forward are cloned**
  - Clones receive a weight ½ of initial weight
- **Backward are randomly killed**
  - with probability ½
  - particle weight is multiplied by 2 if it survives

This is the “Russian Roulette” technique.
Allows “population” control.

Example of a shielding problem



Biasing versus other acceleration techniques ?

- Other acceleration techniques exist:
  - "fast simulation" : replacement of detailed simulation by approximate but faster model
  - Deterministic computation (in some cases)

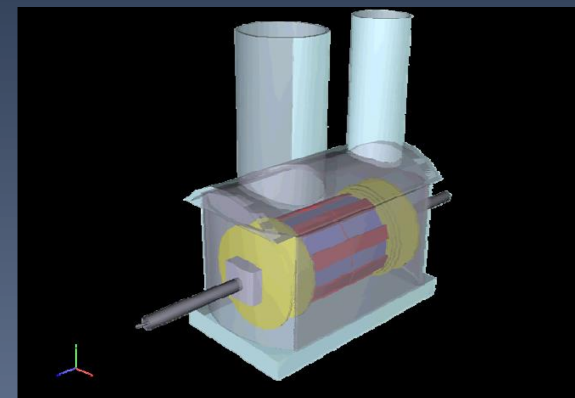
- Interest of biasing:
  - ***Biasing physics is the same as the detailed simulation***
  - Rare events are hence simulated with the same physics accuracy
    - Biasing is hence a tool of choice to explore tails of distributions

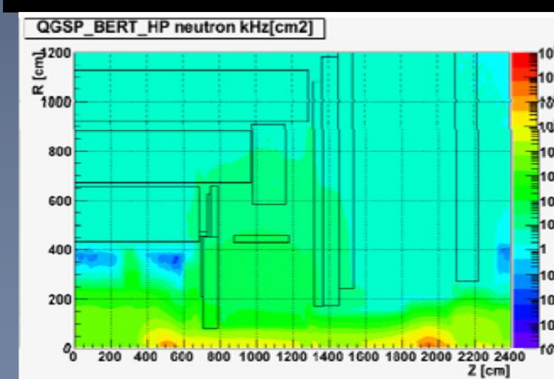
- Difficulties with biasing:
  - Not all problems can be treated this way
    - Only "rare event" problems
  - Ensuring a proper convergence can be difficult
    - Problem of large weights that may appear from time to time
  - Beware when correlations between tracks are needed
    - Correlations are lost with some techniques

Existing biasing in HEP

Biasing in HEP

- Biasing at generator level:
  - Signal of interest are often rare:
    - Higgs
    - Specific B decay channels
    - Neutrino interactions
  - Productions of these types of events are separated from production of "background events"
  - With weighting of these components in analysis
- Machine-induced/cavern background:
  - Made to estimate the background level from
    - Beam halo particles interacting in upstream collimators
    - Beam particle – residual gas collisions
    - Background near IP from beam losses
    - …
  - Biasing applied in some parts:
    - Eg : Rare muon production for far production
  - FLUKA, MARS, alone, or in combination with Geant4 (FLUGG) are often used
    - Using in particular MARS biasing capabilities
- Population control:
  - In CMS : Russian roulette applied to slow neutrons to avoid tracking all of them
    - Introduced by Vladimir Ivanchenko
    - Gain of about 30% in detector simulation stage





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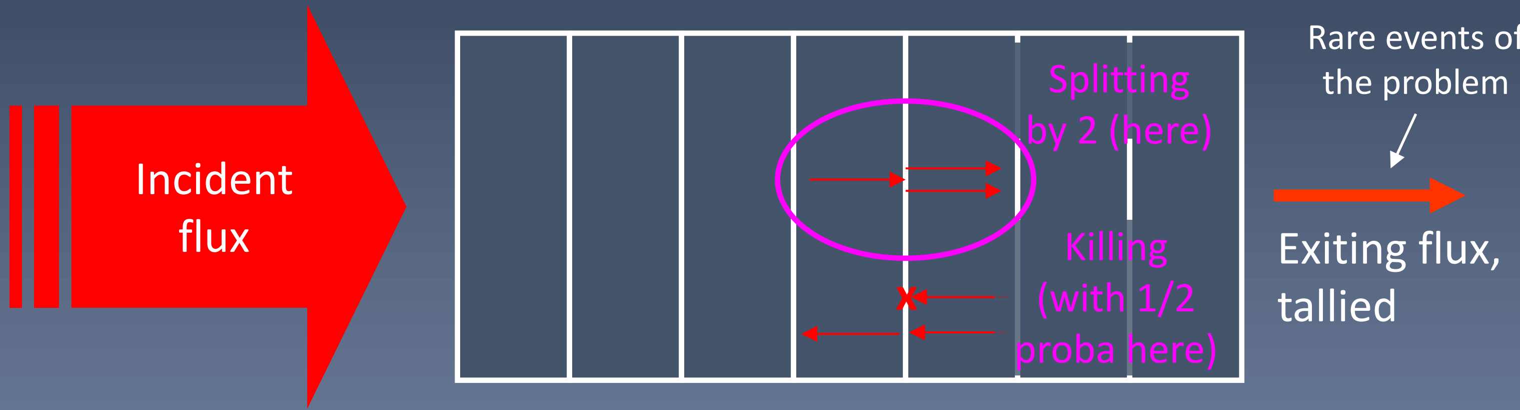
Further biasing in HEP ?

Where to apply ?

- Can we find other case(s) where to apply biasing ?
  - Guideline : identify if rareness is at play in the problem, and where
- Remember the shield problem:



Where to apply ?

- Can we find other case(s) where to apply biasing ?
  - Guideline : identify if rareness is at play in the problem, and where
- Now let's think it as a "filter" problem:

Rare events at generation : but we know how to handle

Signal events

Detector response, Trigger(s), Physics analysis

Try to keep as much of them : they are not rare here (if efficiency is high…)

Selected signal events

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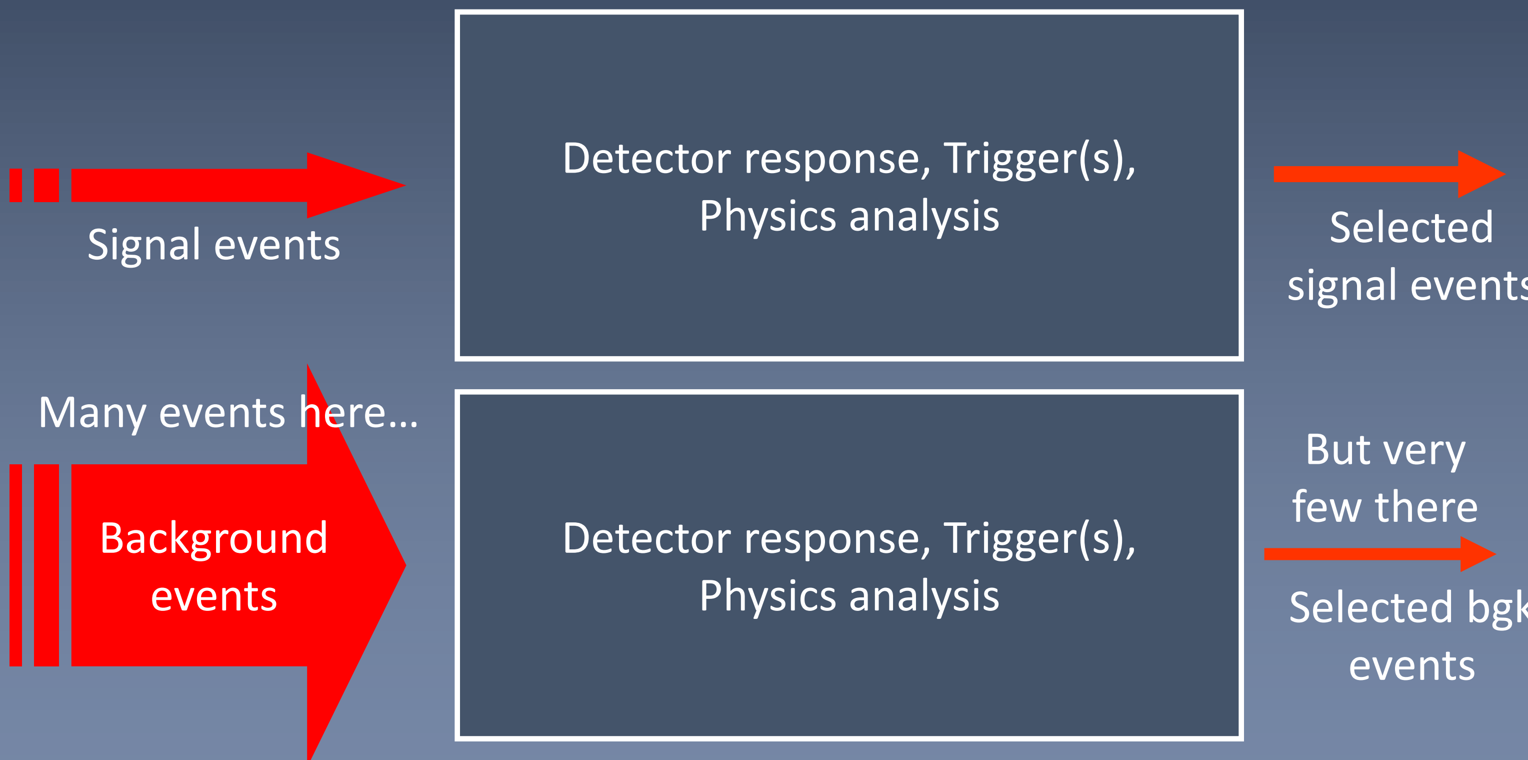


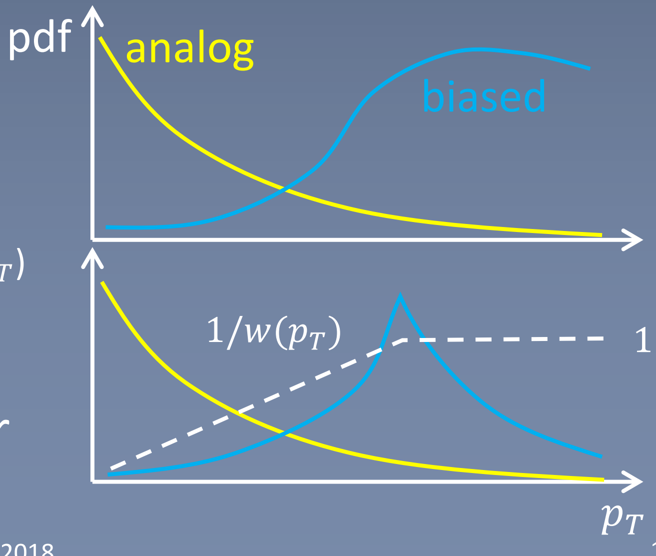
  - Even though it looks shocking : selected background events are rare events in the problem…

Modifying background productions ?

- Tailor productions based on some analysis or set of analyses needs ?

- E.g. Higgs analysis in ATLAS:
  - Threshold on p_T for leptons O(10 – 20 GeV) or highest gammas O(40 – 50 GeV)
  - Dynamic of background events has to be roughly similar to signal one
    - Ie : favors high momenta
  - Can we have a dedicated production with biased spectra ?
  - Can we have enhancement of lepton production in background events ?

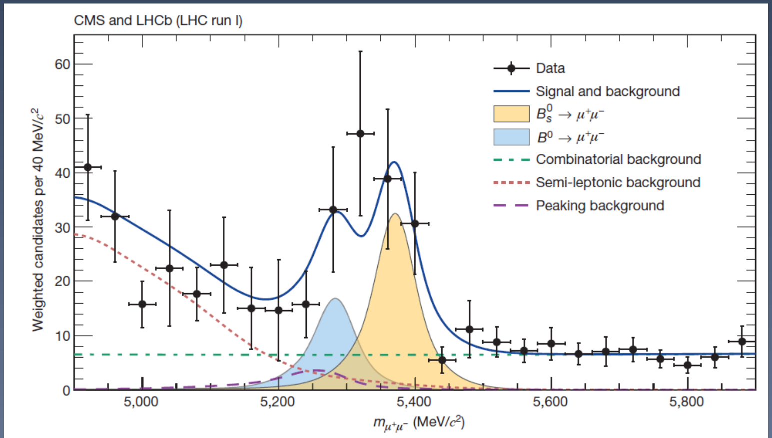
- E.g. : can we consider biasing the dynamics at generator level ?
  - With importance sampling:
    - Need to know analytical PDF of events
      - For the biased PDF, we chose what we want
    - Invasive to the generator, but efficient
  - Or with Russian roulette:
    - Choosing some weight function $w(x)$ (eg $x \equiv p_T$)
      - Using $w(x)$ as rejection function
    - Less efficient, but not invasive to the generator



- Would similar approach be of interest for the case of low efficiency signal(s) ?

Modifying background detector simulation ?

- Backgrounds are estimated on data directly as much as possible
- In some case, this is not possible:
  - Eg : peaking background in the signal region in B physics
- Biasing of detector simulation has not be done in HEP
  - To my knowledge



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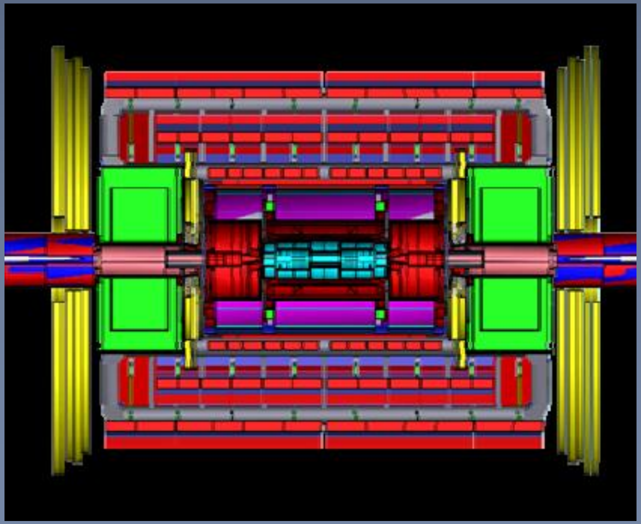
- Would this be of interest ?
  - Could be, again if rareness is at play…
- For example:
  - Rare processes inducing wrong PID:
    - Charge exchange : making a charged pion looking-like an electron
    - Charged pion punch-through : making a pion looking-like a muon
  - Other ?
- **Input from people doing physics analysis would be precious.**

Biasing in Geant4

Biasing in Geant4

- Geant4 offers a large set of biasing functionalities
  - And continues to extend it
- Since release 10.0 a toolkit-like scheme is available:
  - A generic scheme in which a few base classes are defined
    - They are used to implement ready-to-use functionalities
    - But are open to users to implement their own scheme
- Today are provided:
  - Forced interaction, cross-section biasing for neutral particles (for charged particles under way), splitting, Russian roulette, hooks for biasing final state generation, etc.
  - Decisions on biasing to apply are made per step
  - Ability to use parallel geometries
- Doing background studies (from cavern or from interaction point) all within Geant4 should hence be possible
  - For example:
    - using parallel geometry for background studies from interaction point, with splitting on boundaries



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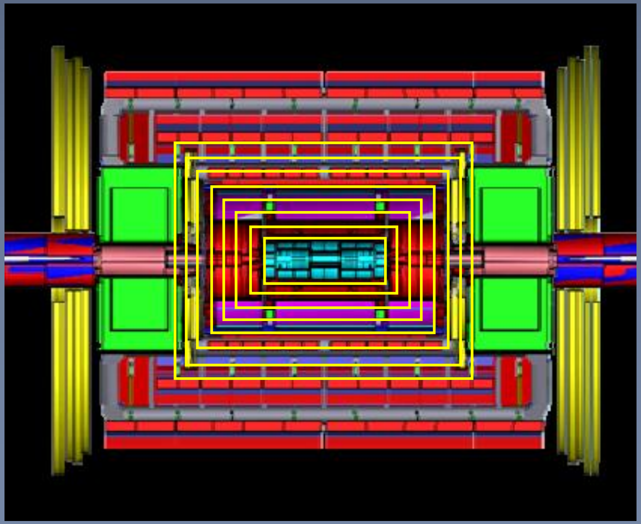
- Biasing part of the detector response also:
  - By enhancing cross-section or forcing interaction or non-interaction to fake mis-PID



- **User requests and needs are the most welcome to improve Geant4 !**

Conclusion

- Rare event problems can be efficiently simulated with biasing techniques
- These techniques have to be tailored to a specific problem or set of problems
- Event biasing techniques have been used in HEP for cavern background studies since many years
- Could they be used in physics simulation production ?
  - With set of productions dedicated to family of analyses
  - For example
    - biasing generators to improve the statistics of background events retained for some analyses ?
    - biasing the detector simulation stage to favor topologies that pass the analyses criteria ?
  - **Input from physics analyses would be must appreciated !**
- Geant4 offers a wide set of biasing functionalities
  - **Users requests are very welcome to keep improving Geant4 !**