Nuclear Interactions of ***b***-hadrons, ***c***-hadrons and ***τ***-lepton

Alberto Ribon
CERN PH/SFT

FCC software meeting, CERN, 25 April 2018

The Problem

To take into account the **nuclear interactions** of highly boosted ***b***-hadrons, ***c***-hadrons and ***τ***-lepton in the beam pipe and tracker of FCC

- Useful values to keep in mind:

B± (longest-lived b-hadron) : $c \cdot \tau$ = **0.492 mm** (m = 5279 MeV)
D± (longest-lived c-hadron) : $c \cdot \tau$ = **0.312 mm** (m = 1870 MeV)
τ± : $c \cdot \tau$ = **0.087 mm** (m = 1777 MeV)

therefore these particles must have kinetic energies of several tens / hundreds of GeV to reach the tracker

Note: the **elastic hadron interactions** of these energetic b-hadrons and c-hadrons can be safely neglected (because they would cause only rare and tiny deviations...)

The "*Right*" Solution

- Use a Monte Carlo event generator (e.g. Pythia8, Herwig7) to get the multiplicities and kinetic spectra of the ***b***-hadrons, ***c***-hadrons and ***τ***-lepton, produced by the *p*-*p* beam collisions, capable to reach the beam pipe and the tracker
- Feed these particles to the Geant4-based detector simulation
  - Cannot be done now because Geant4 does **not** include the simulation of nuclear interactions of ***b***-hadrons, ***c***-hadrons and ***τ***-lepton !
    - Note that electromagnetic physics interactions of these particles (i.e. multiple scattering and ionization) are already included in Geant4 !
  - If these interactions are needed for the next phase of FCC (Technical Design), then a formal request should be made by the FCC Collaboration at the Geant4 Technical Forum
    - This extension of Geant4 requires a few years of work !

The “*Work-Around*” Solution

The same as the “*Right*” Solution, except that

- Instead of feeding in input to Geant4 ***b***-hadrons and ***c***-hadrons, we replaced them with **kaon mesons** (or hyperons, in the case of baryons, but this should be a small correction because of the higher mass and shorter lifetimes with respect to mesons) of the same kinetic energy
  - Geant4 includes the nuclear interactions of ***s***-hadrons
  - For multi-GeV energies, the cross sections depend very weakly on the energy, whereas differences with respect *b*-hadrons and *c*-hadrons are expected mostly at low energies (resonances)
- Instead of feeding in input to Geant4 $\boldsymbol{\tau}$-lepton, we replaced it with a **muon** of the same kinetic energy
  - Geant4 includes $\boldsymbol{\mu}$-nuclear interactions
  - The dependency of the cross sections with the energy of the lepton is mild (at least at high energies, which is the case of interest)

Note: both the rate of interactions and the secondaries that are produced by these interactions are, of course, approximated !

The "*Quick-and-Dirty*" Solution (1/3)

Estimate only the probability of hadronic interactions (not the f.s.) in a layer of a given material and thickness assuming a "resonable" value of the mean-free-path in that material

- Due to the weak dependency of the cross sections on the kinetic energy of the projectile, we can use a single **mean-free-path *λ*** for each material, regardless of energy of the projectile

$$\lambda \equiv A / (N_A * \rho * \sigma)$$

- Then the probability that a particle with mean-free-path ***λ*** has an interaction traversing a thickness ***x*** is :

$$\boldsymbol{p = 1 - e(- x/\lambda)} \approx x/\lambda \quad \text{for} \quad x << \lambda$$

- One can use this probability in two ways:

1. During the Geant4 simulation, throwing a flat random number and deciding (e.g. at the level of Geant4 UserSteppingAction) whether the particle (*b*-hadron, *c*-hadron, or *τ*-lepton) has a nuclear interaction or not

2. Or, more simply, by directly estimating the probability of interaction when crossing a layer of a given thickness, e.g. **~1 mm Be** (beam-pipe), **~0.5 mm Si + ~0.5 mm C** (silicon pixel/layer tracker)

The "*Quick-and-Dirty*" Solution (2/3)

- Here are two "reasonable" approximations for ***λ***

a. From the cross sections of *K*- and *μ* at 1 TeV, respectively:

		for ***b***-hadrons & ***c***-hadrons		for ***τ***-lepton	
Be	:	σ ~ 150 mb	**λ ~ 0.55 m**	σ ~ 0.27 mb	**λ ~ 300 m**
C	:	σ ~ 190 mb	**λ ~ 0.53 m**	σ ~ 0.35 mb	**λ ~ 285 m**
Al	:	σ ~ 380 mb	**λ ~ 0.44 m**	σ ~ 0.74 mb	**λ ~ 225 m**
Si	:	σ ~ 400 mb	**λ ~ 0.50 m**	σ ~ 0.77 mb	**λ ~ 260 m**

b. Assuming a conservative (i.e. likely underestimated) "round" λ value for all light elements (relevant for the beam pipe and tracker):

for ***b***-hadrons & ***c***-hadrons in Be, C, Al, Si : **λ ~ 0.40 m**

for ***τ***-lepton in Be, C, Al, Si : **λ ~ 200 m**

The "*Quick-and-Dirty*" Solution (3/3)

- Here are the probabilities using method "***2 b***"
  - For **~1 mm** beam pipe (Be) or
    tracker layer (~0.5 mm Si + ~0.5 mm C)
    the probability of having a nuclear interaction is:
    - for ***b***-hadrons & ***c***-hadrons

      Prob(1 mm) ≈ 1 mm / 0.4 m = **0.25%**

      - So ~2 % probability for traversing the beam pipe and the whole tracker (note: very few heavy hadrons will survive enough to do so!)

    - for ***τ***-lepton

      Prob(1 mm) ≈ 1 mm / 200 m = **0.0005%**

      - So << 0.1 % probability for traversing the beam pipe and the whole tracker (note: nearly none of τ-lepton will survive enough to do so!)

Conclusions

- Hadronic interactions of ***τ***-lepton in the FCC beam pipe and tracker are expected to be negligible
  - Due to very low cross sections and its short lifetime

- Hadronic interactions of ***b***-hadrons and ***c***-hadrons in the FCC beam pipe and tracker are expected to be at the **%** level
  - Likely within a factor of ~ 2

Note: these conclusions should hold also for other HEP collider experiments, like ATLAS, CMS, LHCb, ILC/CLIC, etc.