Geant4 Hadron Kinetic Model
for intra-nuclear transport

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Hadronic physics in Geant4

The most complete hadronic simulation kit on the market

- *data-driven,*
- *parameterisation-driven*
- *theory-driven models*

complementary and alternative models

Common basic approach of Geant4 physics

expose the physics through OO design

to provide the **transparency** required for the **validation** of physics results

Energy range of hadronic models

Evaporation phase

Pre-equilibrium phase: *~20 -100 MeV*

Intra-nuclear transport: *~100 MeV - 5 GeV* (the "resonance" region)

String phase

Geant4 Hadron Kinetic Model addresses the intra-nuclear transport phase

A look at the past...

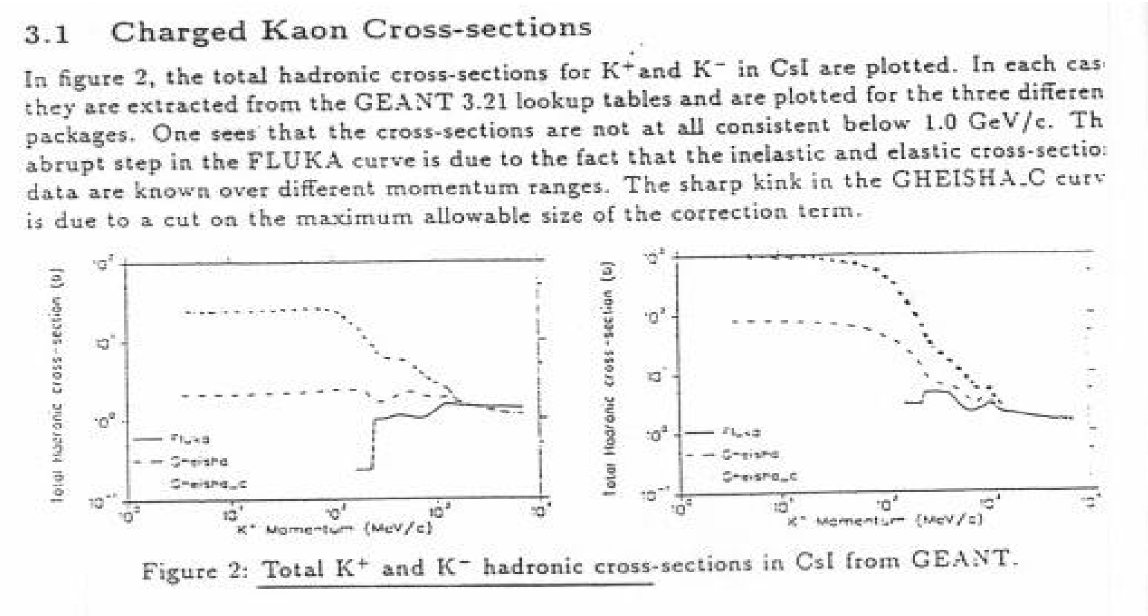
Hadronic simulation was handled through "packages"

- *monolithic: either take all of a package or nothing*
- *difficult to understand the physics approach*
- *hard to disentangle the data, their use and the physics modeling*

...keeping in mind that this is difficult physics, often with poor support of experimental data

Charged K in Geant3

p^- in Geant3


3.1 Charged Kaon Cross-sections

In figure 2, the total hadronic cross-sections for K^+ and K^- in CsI are plotted. In each cas[e] they are extracted from the GEANT 3.21 lookup tables and are plotted for the three differen[t] packages. One sees that the cross-sections are not at all consistent below 1.0 GeV/c. Th[e] abrupt step in the FLUKA curve is due to the fact that the inelastic and elastic cross-sectio[n] data are known over different momentum ranges. The sharp kink in the GHEISHA_C curv[e] is due to a cut on the maximum allowable size of the correction term.

Figure 2: Total K^+ and K^- hadronic cross-sections in CsI from GEANT.

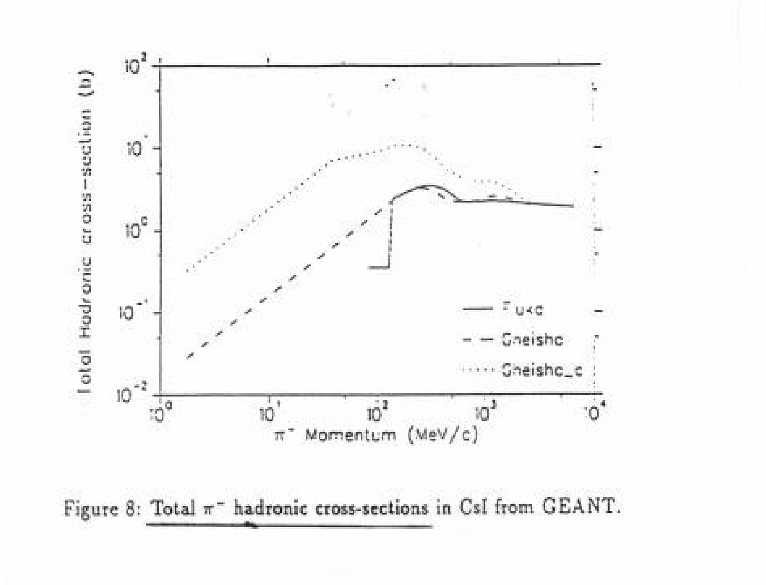


Figure 8: Total π^- hadronic cross-sections in CsI from GEANT.

Largely different behaviour in two packages

Cross sections differ by an order of magnitude in the “official” and “ad hoc” code

Crystal Barrel *(A. J. Noble)*

BaBar IFR μ and K^0_L detector

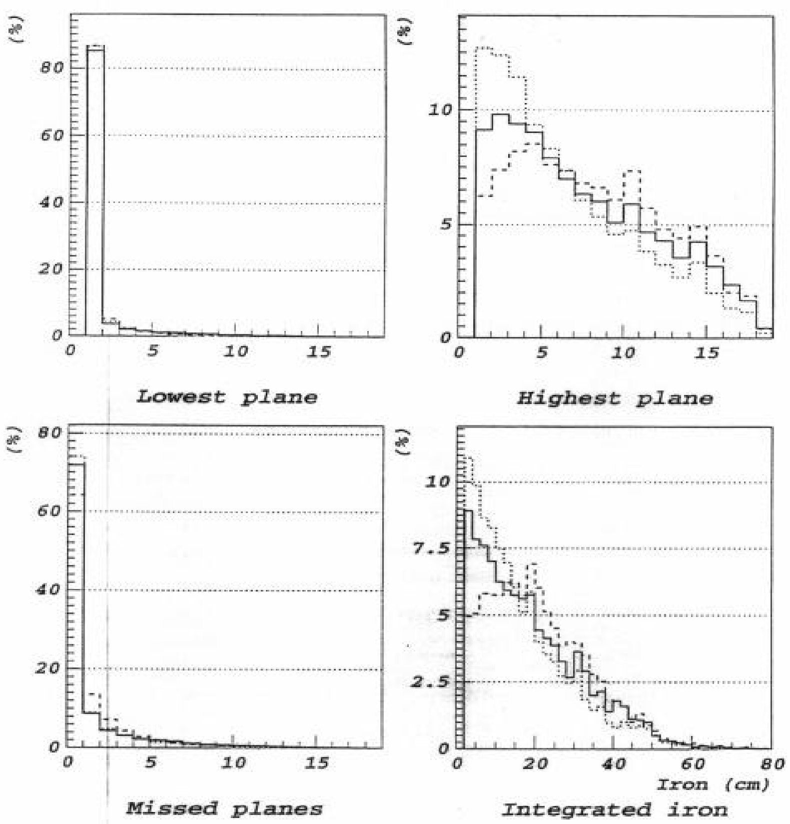


Figure 16 First and last hit layers, total number of intermediate IFR layers with no hits, iron thickness traversed (barrel), π^-, 1-1.25 GeV/c; solid line is Gcalor, dashed line is Fluka, dotted line is Gheisha.

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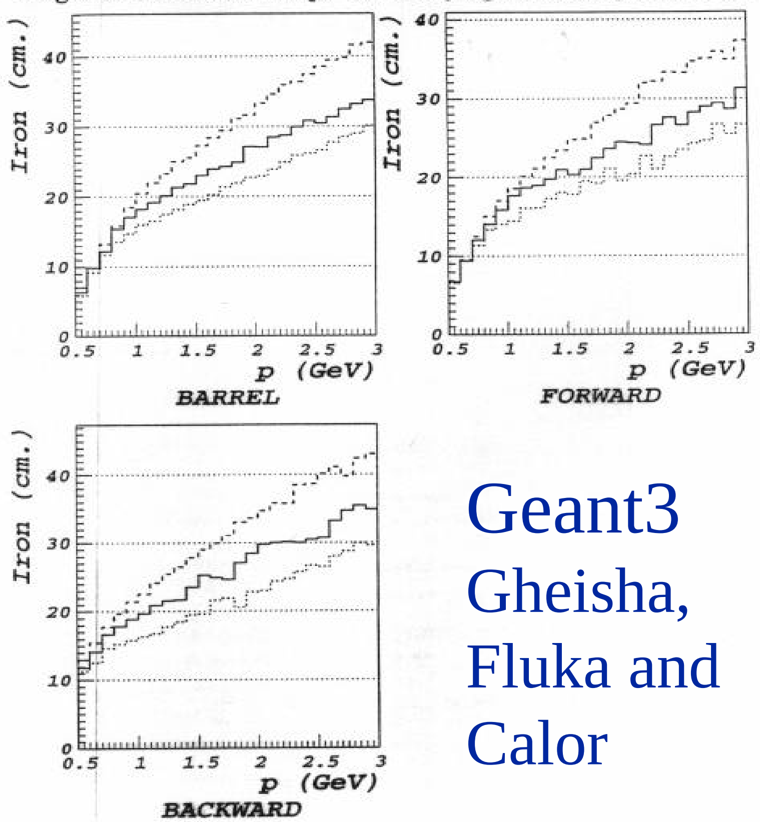
Integrated traversed iron, pi- not decaying/interacting before IFR



Geant3 Gheisha, Fluka and Calor

Figure 13 Iron traversed in the IFR barrel and end-caps by π^- as a function of momentum; solid line is Gcalor, dashed line is Fluka, dotted line is Gheisha.

Large inconsistencies
Why?

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The context

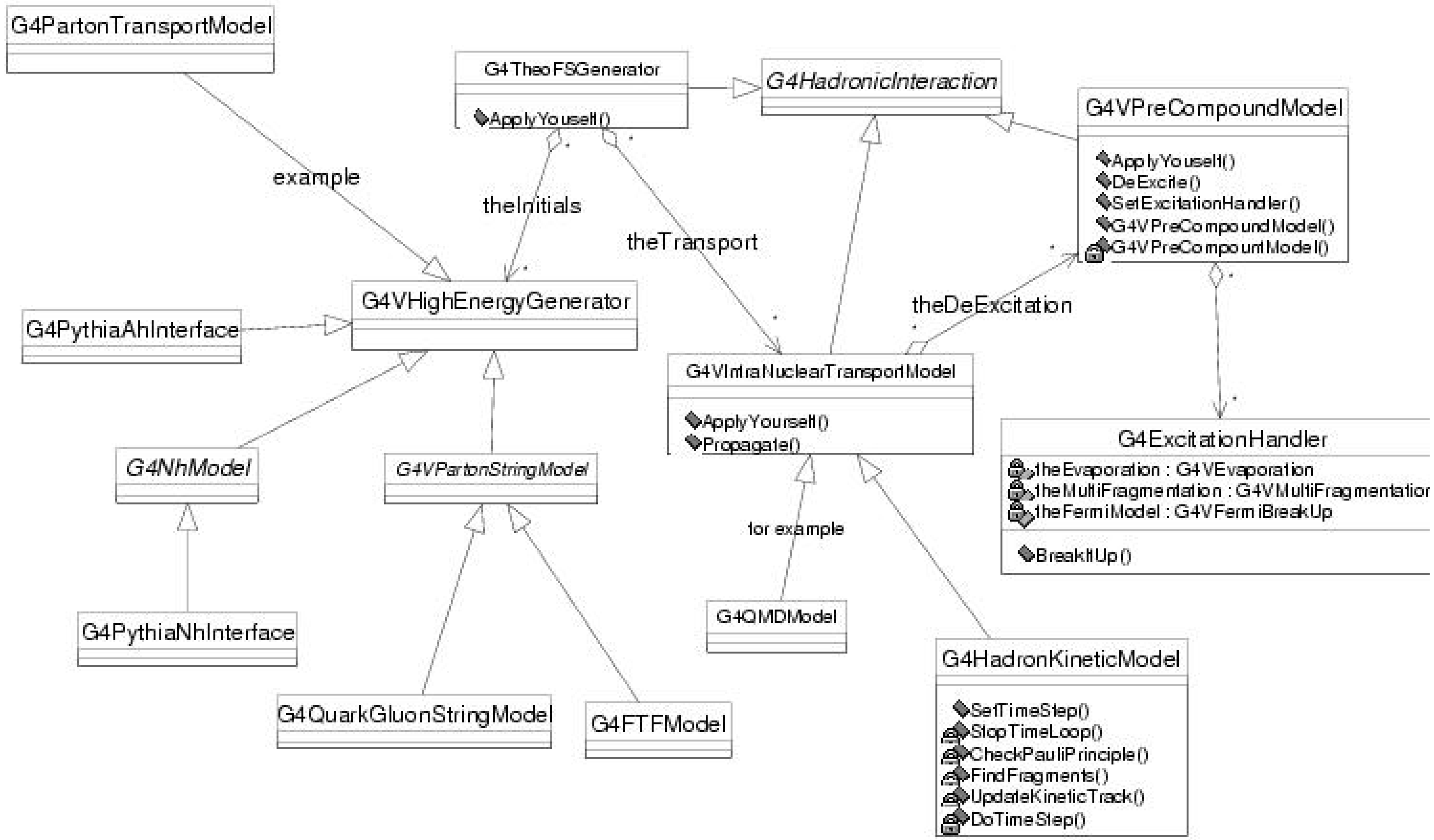
The Hadron Kinetic Model is situated in the context of Geant4 IntraNuclearTransport models

It must satisfy the requirements

as a model to be used directly by the processes

as a back-end to higher energy models

Geant4 hadronic theory-driven models



The physics idea

Introduce the concept of

$\boxed{\textit{“time development”}}$

into the traditional approach of intra-nuclear cascade

Provides means to address interactions and transport with more sophisticated modeling, i.e. with greater precision

The Kinetic Algorithm

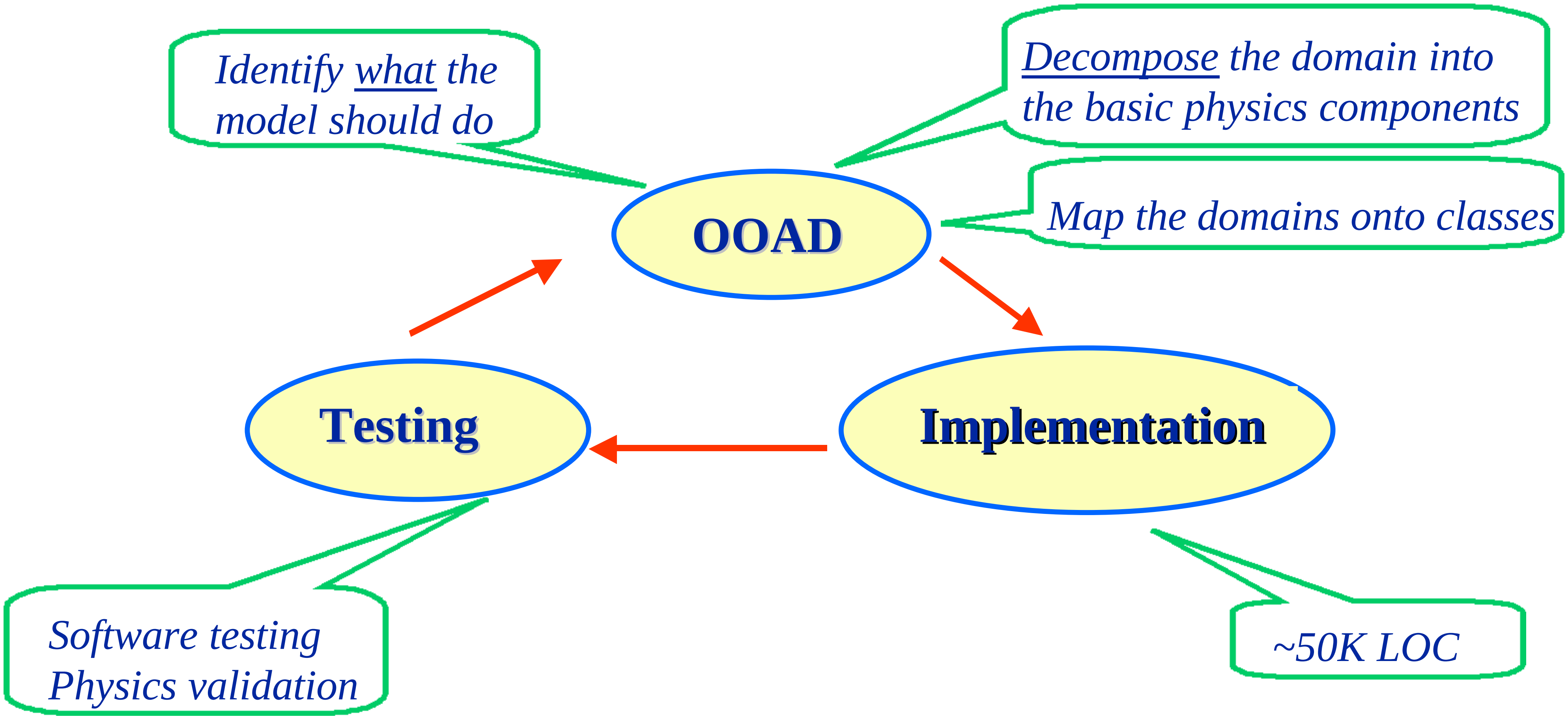
A step by step updating of a particle vector:

Create a vector of particles, assign initial particle types, coordinates and momenta etc., assign initial value for the time evolution parameter

- For a given ***step*** of the time evolution parameter find pairs of particles, according to a collision criterion, which are assumed to **collide** and particles which, according to their lifetimes, are assumed to **decay**
- Perform particle **collisions** and particle **decays**, determining the generation of outgoing particles; during this step particle coordinates and momenta are updated (particle **propagation**)
- Starting from ✗, perform the next step

(all this taking into account the Pauli blocking)

The software process



The OO technology

- Openness to extension and evolution
  - *new physics models, data sources, algorithms can be added to the model without needing to modify the existing code*
- Extensive use of patterns
  - *to abstract the physics complexity into archetypes*
  - *to help handling alternative algorithms or physics options*
- Close collaboration of OO “experts” with theoreticians

Model domains

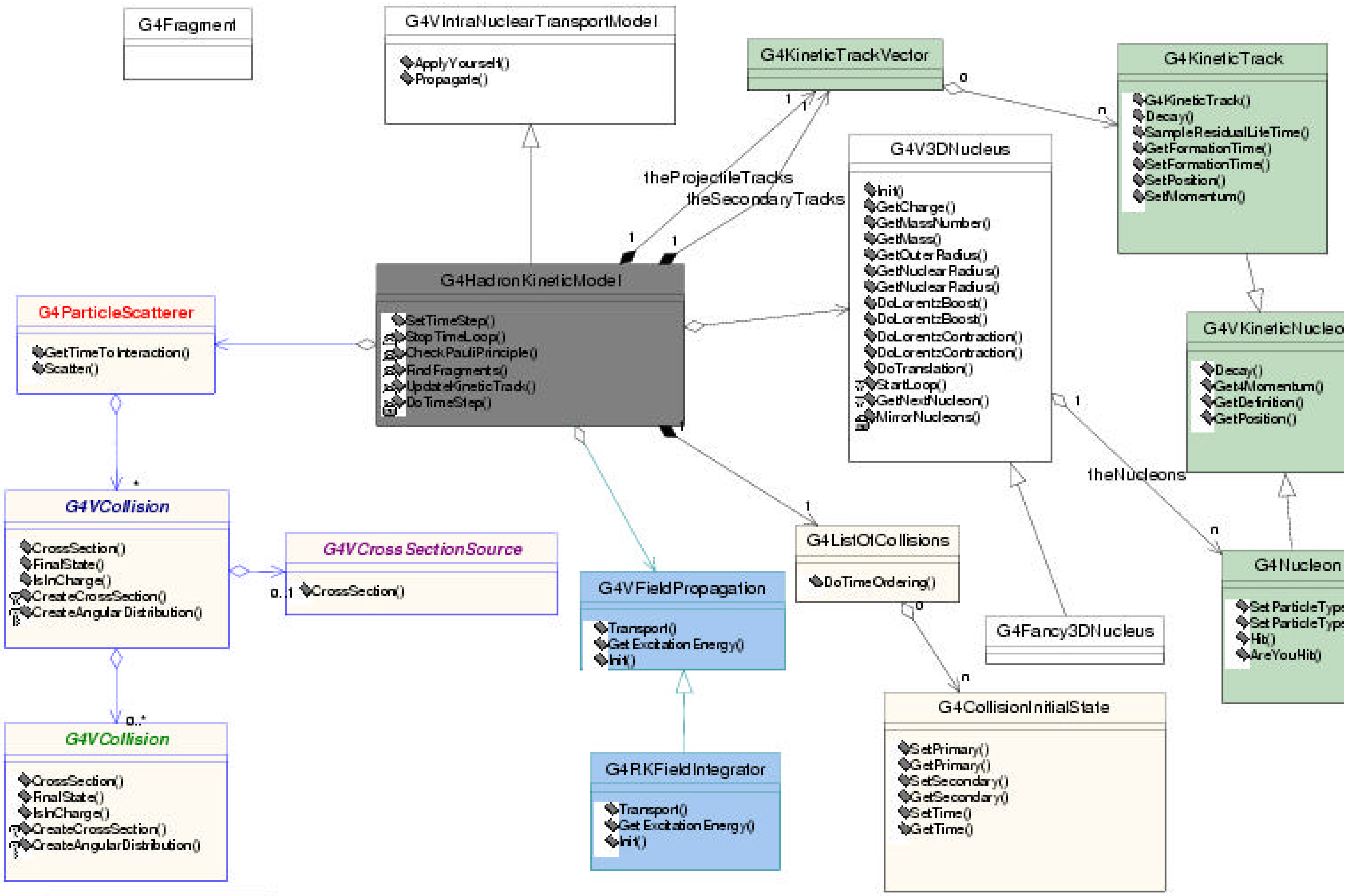
Model-specific →

- The time-development control
- The scattering of particles
- The intra-nuclear transport

Common to other Geant4 theoretical models →

- The 3D modeling of the nucleus
- The description of the interacting particles

The Hadron Kinetic Model



The Scatterer

- ***Two-body hadron elastic and inelastic scattering***
  - including resonance excitation and deexcitation, particle absorption etc.
- ***Physics processes implemented:***
  - baryon-baryon interactions *(including scattering of baryon resonances)*
  - baryon-antibaryon annihilation
  - meson-baryon interactions
  - meson-meson interactions
- ***Cross sections are calculated from:***
  - tabulations of experimental data
  - from parameterisations according to an algebraic function
  - from other cross sections via general principles *(detailed balance, AQM...)*

proton proton

- NN-elastic
- N Δ
- p N*
- N Δ *
- Δ Δ
- Δ N*
- Δ Δ *
- Δ* Δ *, N*N*, N* Δ *
- AQM-string

proton neutron

- np-elastic
- N Δ
- π N*
- N Δ*
- Δ Δ
- Δ N*
- Δ Δ*
- Δ*Δ*, N*N*, N* Δ *
- AQM-string

D N

- elastic
- N Δ → NN
- N Δ → Δ Δ
- AQM-string

N* N

- elastic
- pp → NN*
- AQM-inelastic
- AQM-string

D N*

- elastic
- pp → N* Δ
- AQM-inelastic
- AQM-string

D* N

- elastic
- pp N Δ*
- AQM-inelastic
- AQM-string

D D*

- elastic
- pp → Δ* Δ
- AQM-inelastic
- AQM-string

D D

- elastic
- ΔΔ → NN
- ΔΔ → Δ N
- AQM-inelastic
- AQM-string

D* D*, D* N*, N* N*

- elastic
- pp →Δ*Δ*, N*N*, N*Δ*
- AQM-inelastic
- AQM-string

meson baryon

- elastic
- MB $\rightarrow$ B'
- MB $\rightarrow$ 1 string *(s-channel)*
- MB $\rightarrow$ 2 string *(t-channel)*

meson meson

- elastic
- MM $\rightarrow$ M'
- MB $\rightarrow$ 1 string *(s-channel)*
- MB $\rightarrow$ 2 string *(t-channel)*

baryon antibaryon

- BBbar annihilation
- BBbar elastic
- BBbar annihilation

baryon baryon (generic)

- elastic
- AQM-string

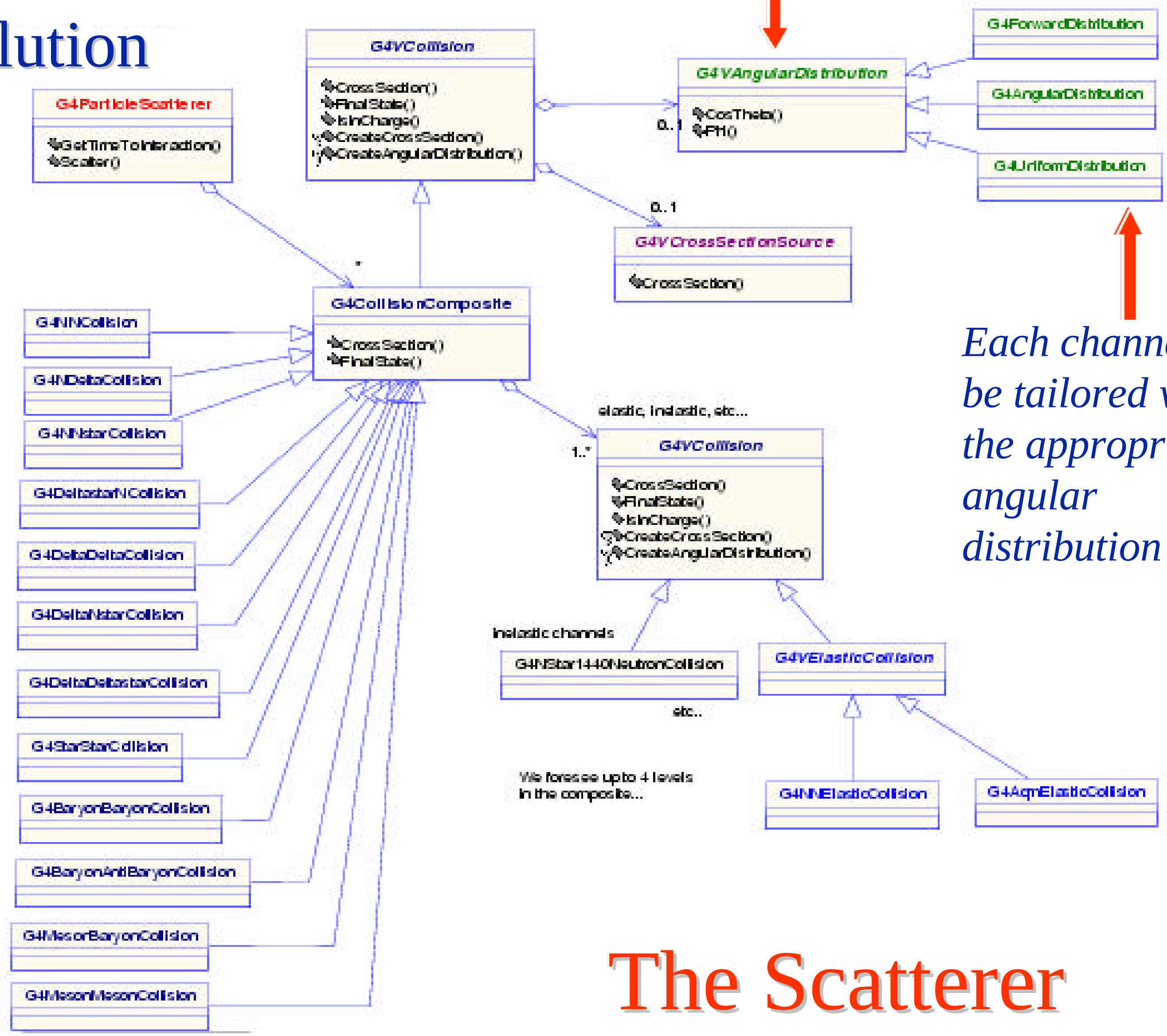
It is a good approximation to assume that 2-body channels saturate the total cross section

Angular distributions handled through an abstract interface

Openness to evolution

All physics channels are handled through the same abstract interface

the model can be easily extended by adding new channels in a transparent way

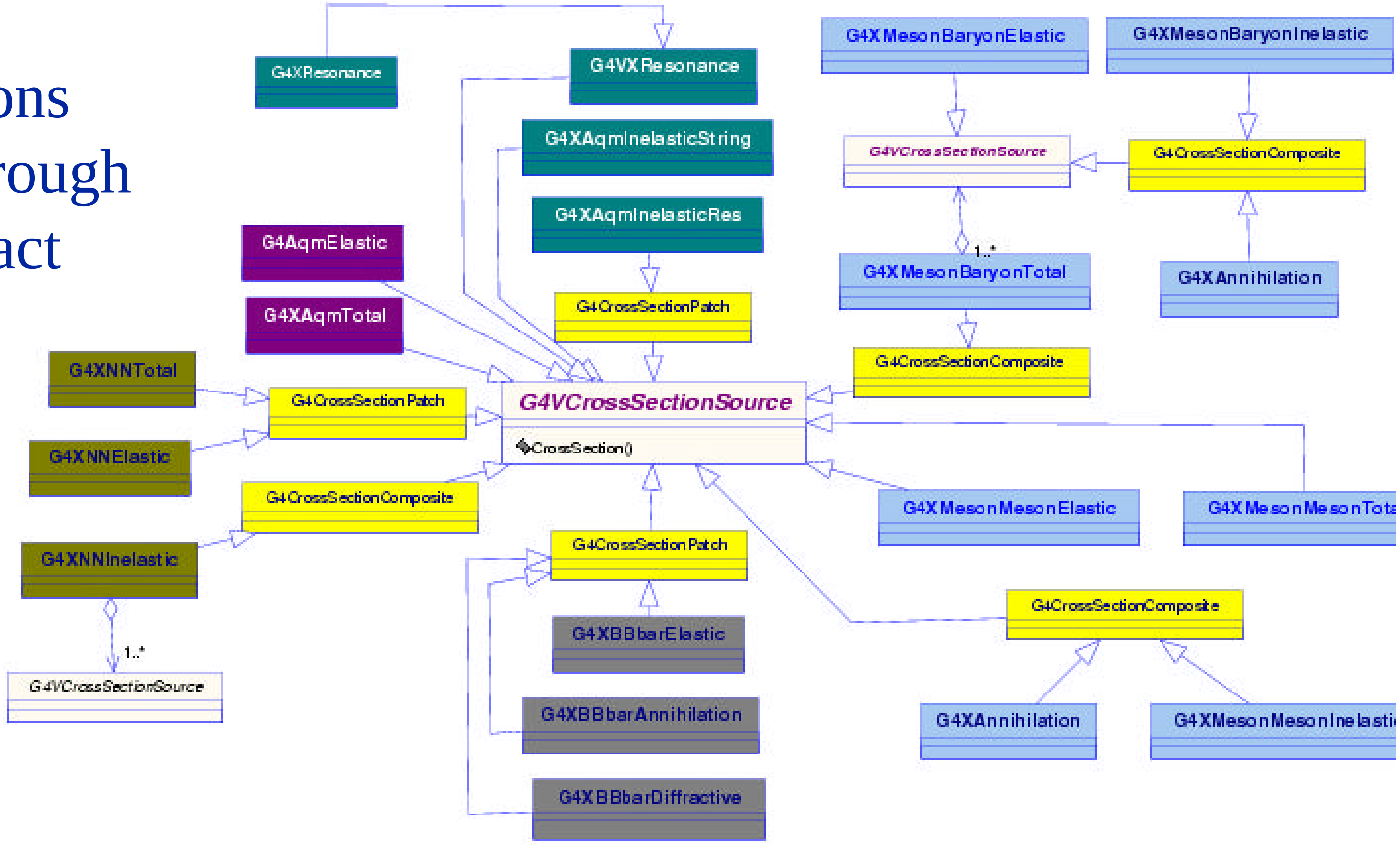


Each channel can be tailored with the appropriate angular distribution

The Scatterer

Overview of the cross sections

All cross sections are handled through the same abstract interface



Composite pattern

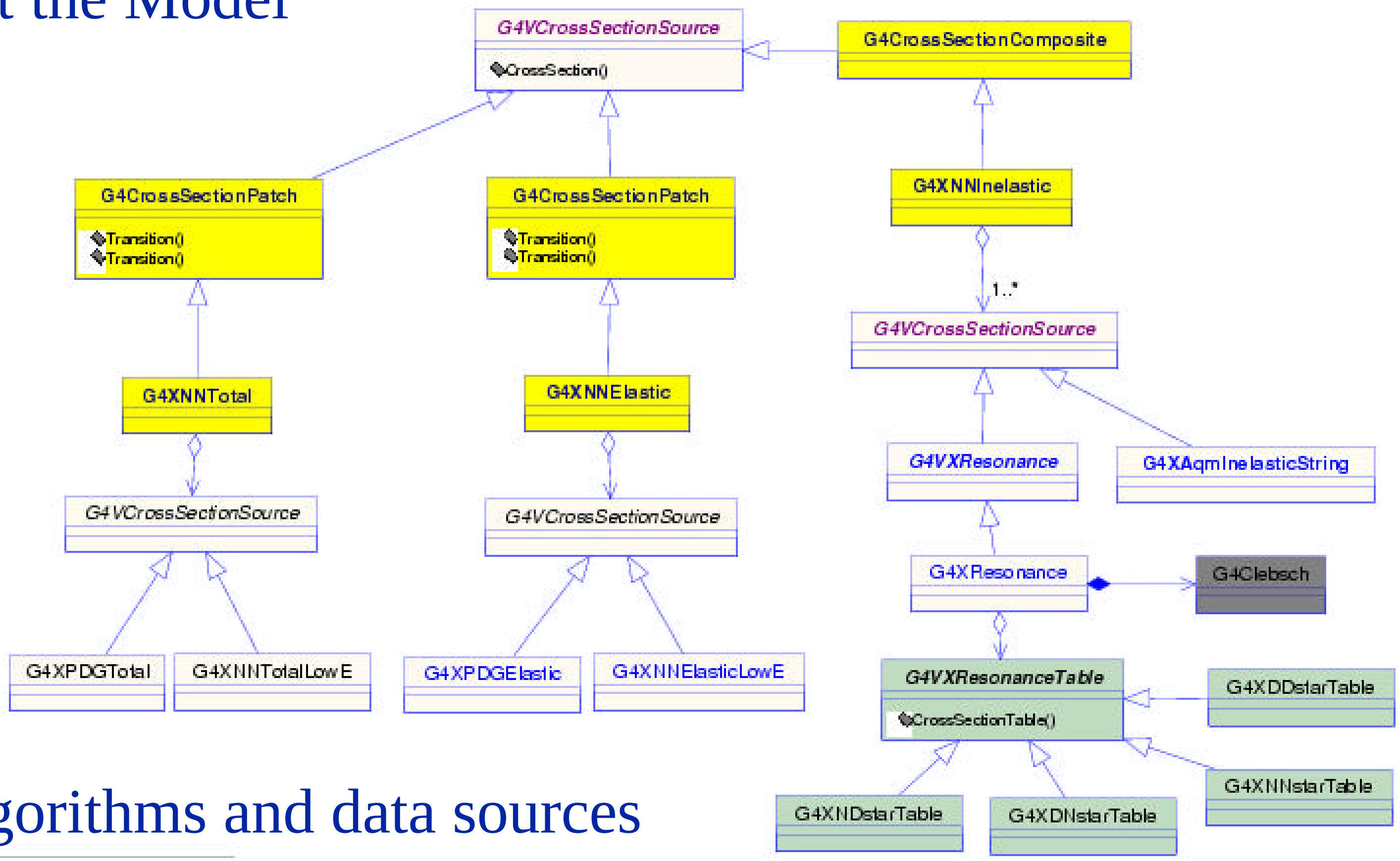
Transparent way of handling total cross sections

directly calculated when known

otherwise summed over the channels

NN cross sections

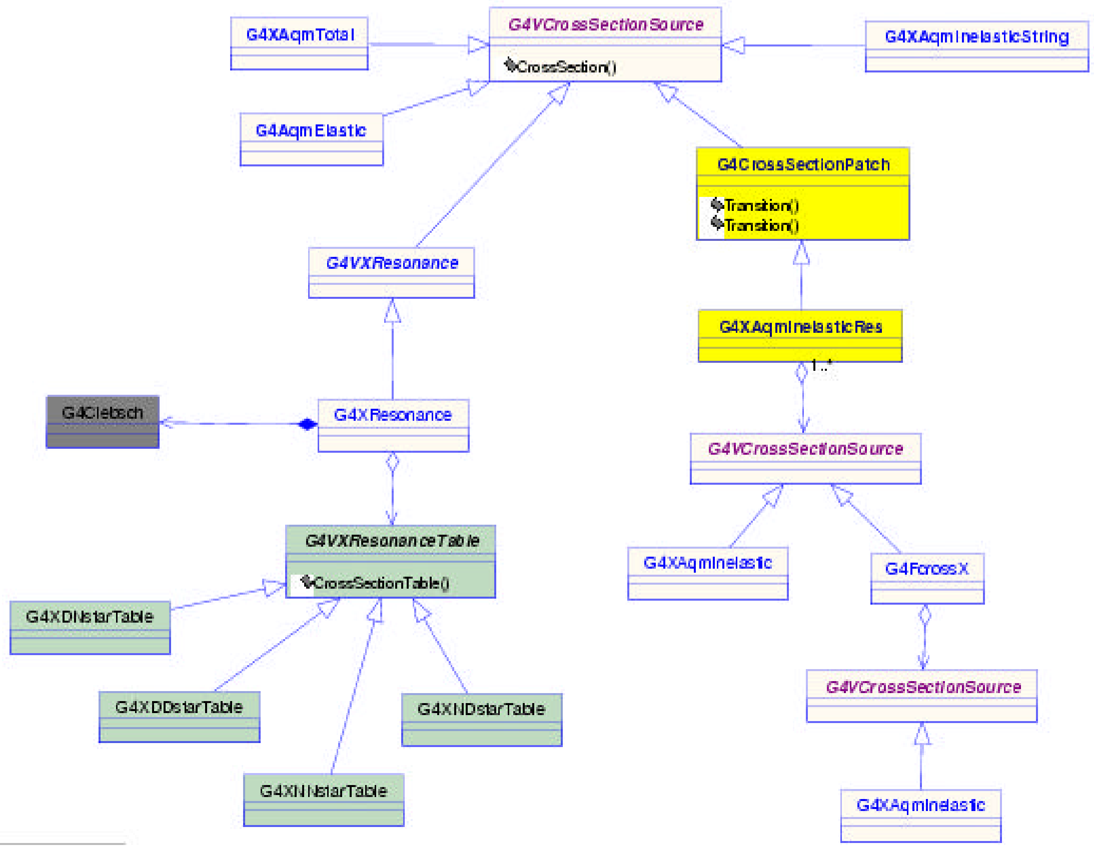
The user is exposed to the physics models and data sources throughout the Model



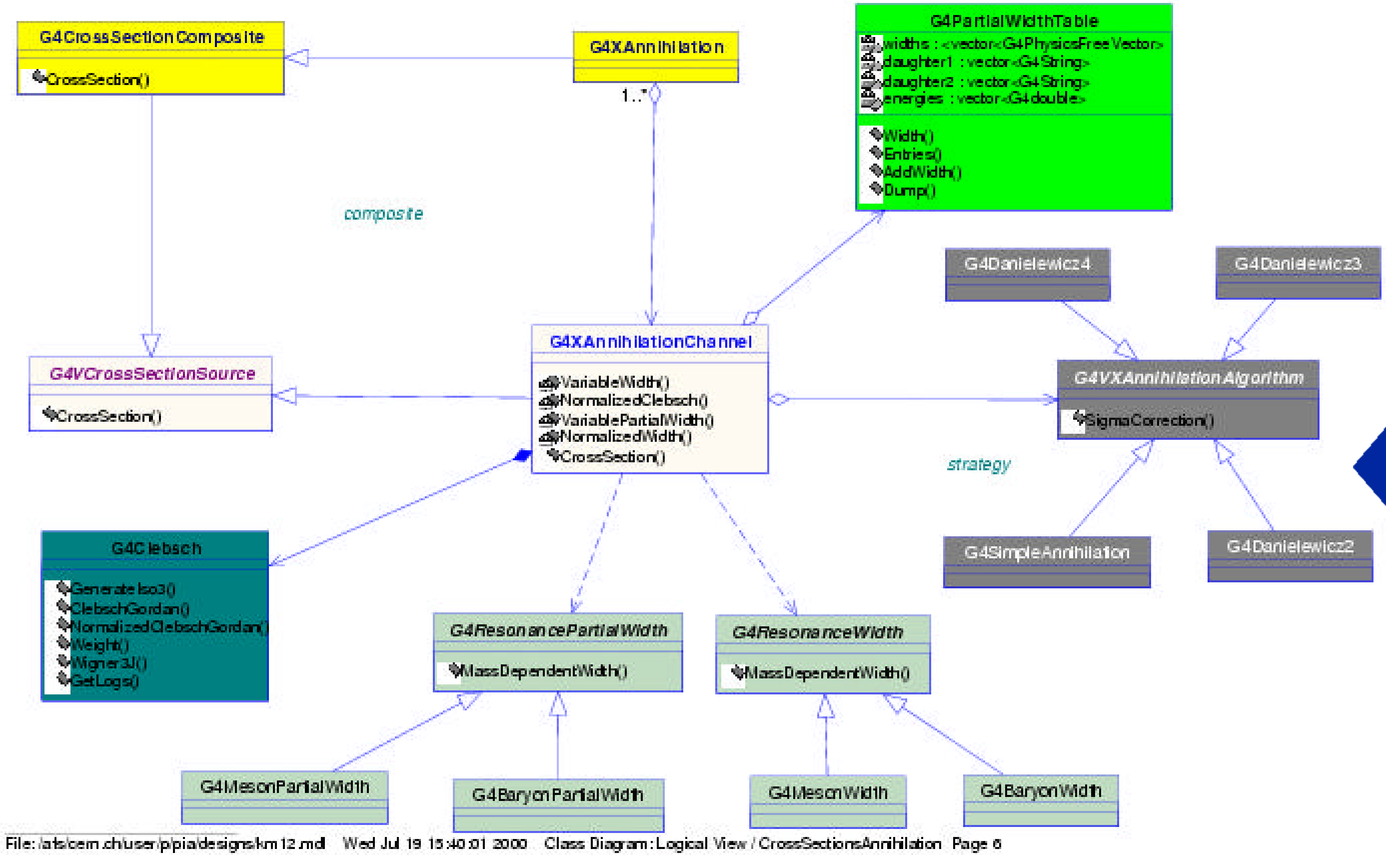
Different algorithms and data sources are used over the validity range of the Model

D*D*, D*N*, N*N*, N N*, D N*, D*N, D D* cross sections

Theoretical models
and
parameterisations
(from experimental data or from analytical calculations)
can be mixed and matched in a transparent way



Each annihilation channel corresponds to a meson or baryon resonance



Extension through alternative algorithms

The field transport

At every step coordinates and momenta of all particles travelling through the nucleus are updated from the values at the time of previous interaction to the current time

- For the transportation purpose the particle-nucleus interaction is described through phenomenological potentials *(optical potentials)*
- The particle propagation can be operated
  - with the **cascade approach**, i.e. along a straight line trajectory
    - *using potentials only to evaluate the final particle energy at the end of the step*
  - with a numerical **integration of the equations of motion**
    - *using the classical Runge-Kutta method*
    - *(code reuse from Geant4 Geometry-Transportation)*

What is new in this model?

- The kinetic algorithm
- The detailed and extensive scattering module
- The precise field transport
- The wealth of advanced theoretical modeling in each of its details
- **The transparency of the physics**

Conclusions

- Geant4 Hadron Kinetic Model represents a new approach to intra-nuclear transport
- **OOAD** has been the key to handle the underlying complex physics domain
- The sound **OOD** makes the model open to evolution and extension
- **OOAD** has allowed to clearly ***expose the physics*** to the users, thus contributing to the validation of physics results

Physics results from the validation phase coming soon...