The Separation of ISI and FSI

Ulrich Mosel

Institut für Theoretische Physik

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Institut für Theoretische Physik, JLU Giessen

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU** : **Quantum-Kinetic Theory and Event Generator** based on a BM solution of Kadanoff-Baym equations
- GiBUU propagates phase-space distributions, not particles
- Physics content and details of implementation in:
  Buss et al, Phys. Rept. 512 (2012) 1- 124
- Code from gibuu.hepforge.org, present version GiBUU 2017
  Details in Gallmeister et al, Phys.Rev. C94 (2016) no.3, 035502
- Generator Review: U. Mosel, J. Phys. **G46 (2019) no.11, 113001**

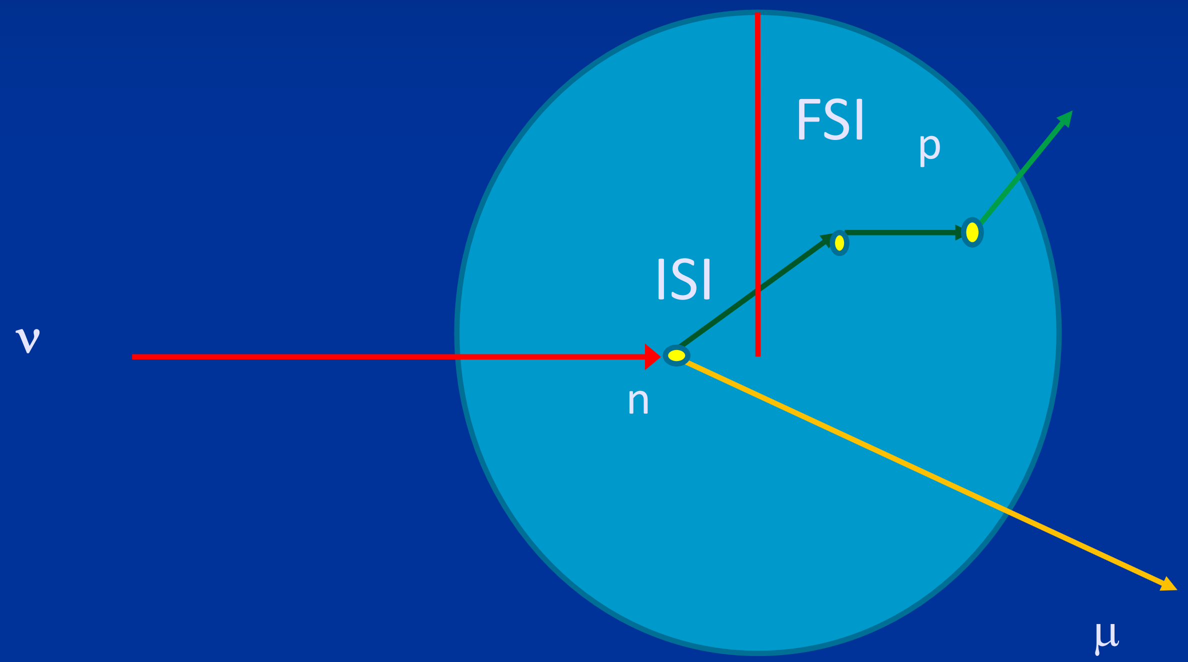
Historical Remark: FSI in GiBUU

- The FSI part of GiBUU can be run separately from the specific initial interaction, be it neutrino, electron, hadron, … in.
  - This capability exists since 2008 and was then used in connection with the MiniBooNE experiment. See Sect. 3.3 in:

Neutrino scattering with nuclei: Theory of low energy nuclear effects and its applications
Tina Leitner, Oliver Buss, Ulrich Mosel (Giessen U.), Luis Alvarez-Ruso (Murcia U.). Sep 2008. 13 pp.
Published in PoS NUFACT08 (2008) 009
DOI: 10.22323/1.074.0009
e-Print: arXiv:0809.3986 [nucl-th] | PDF

Why reinvent the wheel??

ISI and FIS do not factorize



Nuclear Density ρ(r) and Potential U(ρ(r),p)

ISI and FSI factorize only if there is no potential (and thus no density) at point of first interaction

This does not correspond to the correct physics!

ISI and FSI

- Initial State Interaction (ISI):
  $\nu + n \rightarrow p$ for a bound, Ferm-moving neutron (for CCQE)

The ‚knock-out' proton is not really ‚out', but is moving in the nuclear *potential which depends both on position and momentum!*

- This knock-out proton then undergoes Final State Interactions (FSI):
  elastic scattering + inelastic excitations. The proton moves in the same potential as at the end of the ISI! There can be no potential step between ISI and FSI!

→ ISI and FSI do not factorize

- The nucleon's energy changes during FSI and thus the potential it sees changes!

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ISI and FSI Connection

- Take home message:

The nucleon potential links ISI and FSI

Nucleon Potentials

- Coulomb potential: relatively small for ^{40}Ar ~ 7 MeV at nuclear radius, but affects behavior close to threshold, e.g. in $\pi^{+/-} + A$
- Nuclear Potential: mean-field potential binds nucleons in the groundstate, about 60 - 70 MeV deep, with radius $R \sim 1.2\, A^{1/3}$ fm
- Nuclear Potential is *p*-dependent: experimentally determined from p+A elastic scattering at kinetic energies up to about 1 GeV:
  - E. D. Cooper, S. Hama, B. C. Clark, and R. L. Mercer, Phys. Rev. C 47, 297 (1993)
  - E. D. Cooper, S. Hama, and B. C. Clark, Phys. Rev. C 80, 034605 (2009)
- And then there are potentials (selfenergies) for other hadrons

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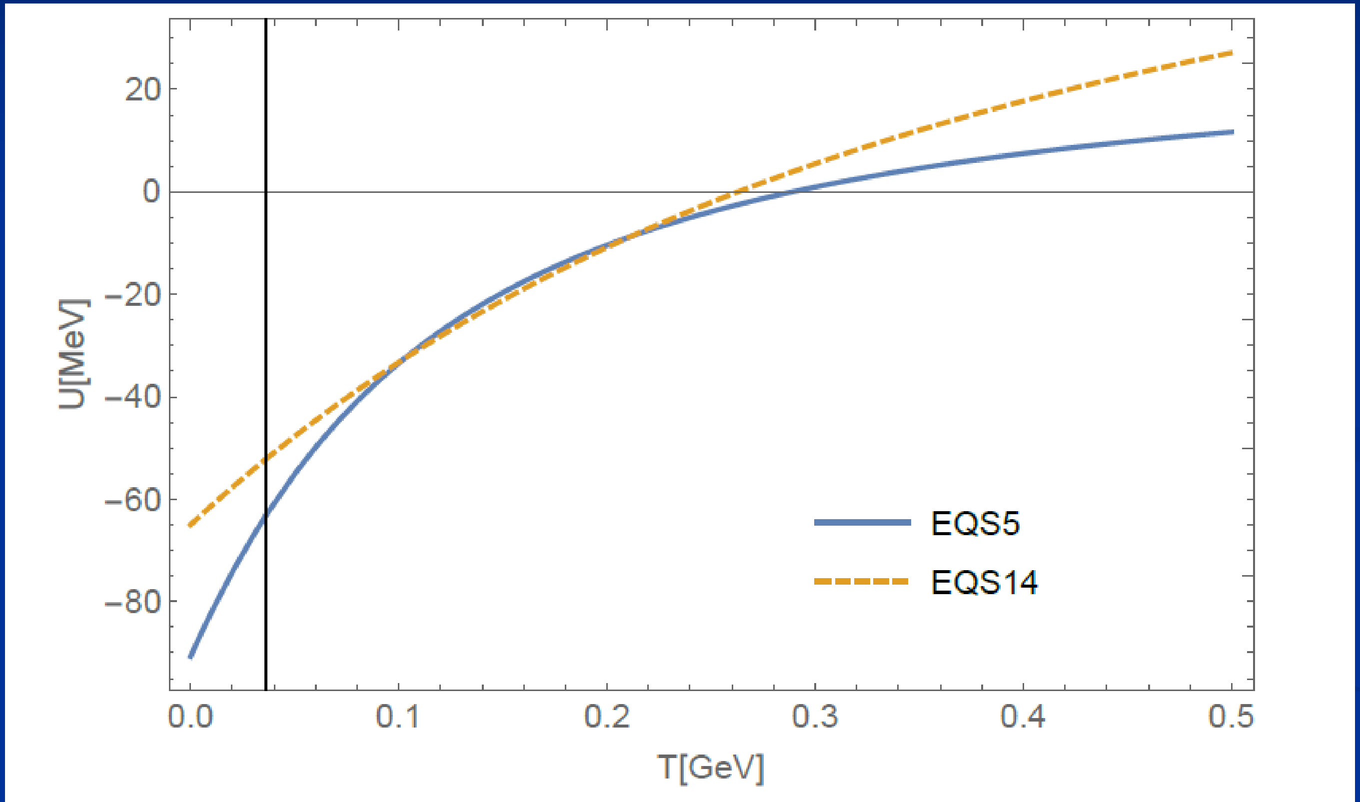
Kinetic Energy Dependence of Nucleon Potentials



The two curves approximate the experimental energy-dependence of the real potential

This potential enters into the qm calculation of the initial ν + N transition rate and into the transition rate of the following FSI

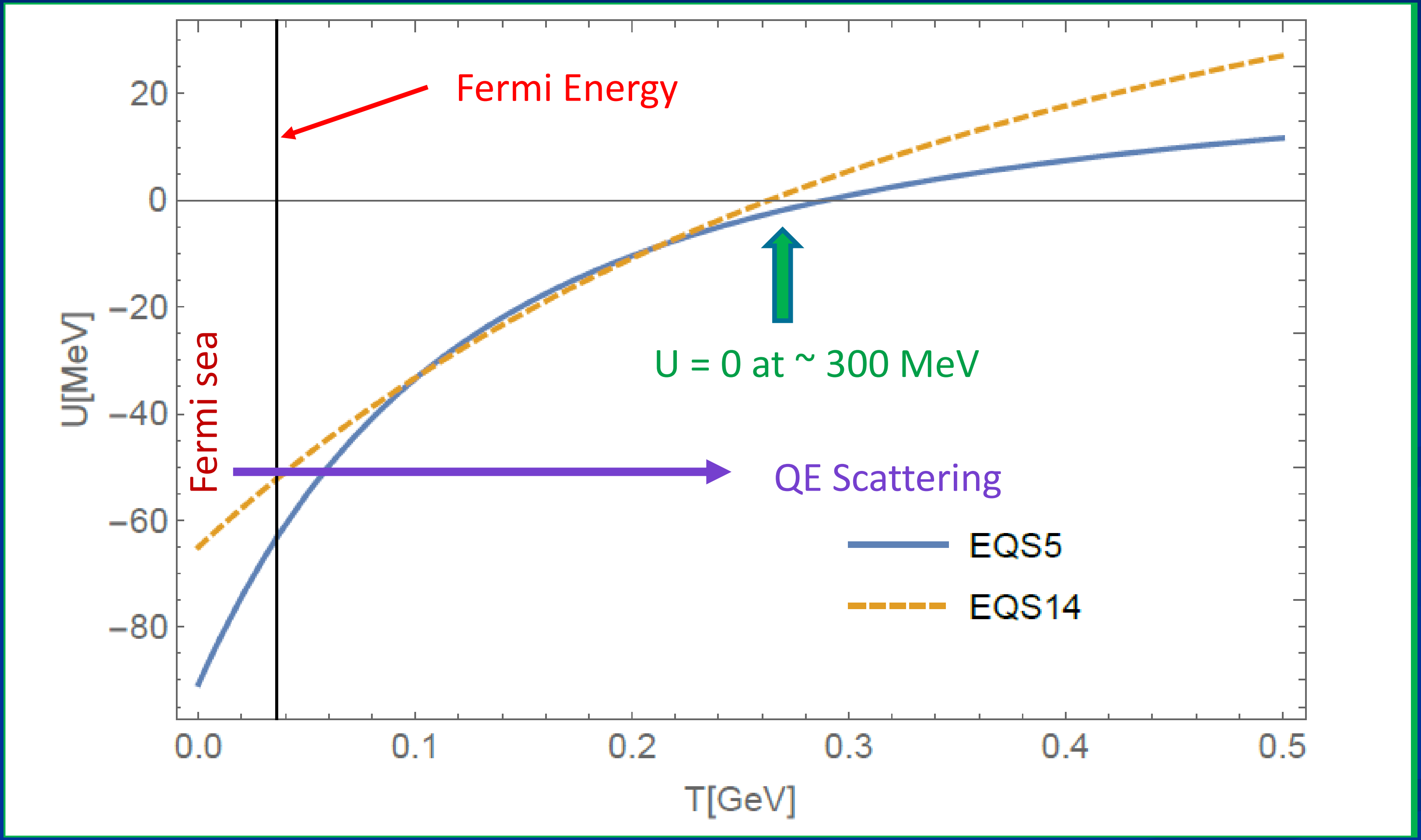
Side Remark: Optical Potential

- Optical Potential: $U + iW$
  The imaginary part W of the OM describes the loss of flux from the elastic channel, does not tell where the flux goes.
- W is related to the collisional width and the total FSI cross section σ :

$$2W(E,\rho) = -\Gamma_{\text{coll}} = -\frac{p}{E}\sigma(E)\rho$$

It is thus simulated by the MC cascade, there is no room for an additional imaginary potential

Kinetic Energy Dependence of Nucleon Potentials in QE



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Nuclear Potential in QE Scattering

- Two simplified models (for energy transfer ~ 300 MeV)
  1. *No potential* whatsoever in the initial state(GENIE, NEUT, …) :
     the outgoing particle should then see a *repulsive* potential of about +60 MeV
  2. Nuclear Many Body Theory *Spectral Function* in the initial state;
     SF contains implicitly the ground state potential:
     no potential for the final state is ok, if energy transfer ~ 300 MeV,
     incorrect otherwise
- The correct way: use one and the same (momentum-dependent) potential for the initial and the final state when calculating the transition matrix element for QE scattering. This is not done in any other generator!

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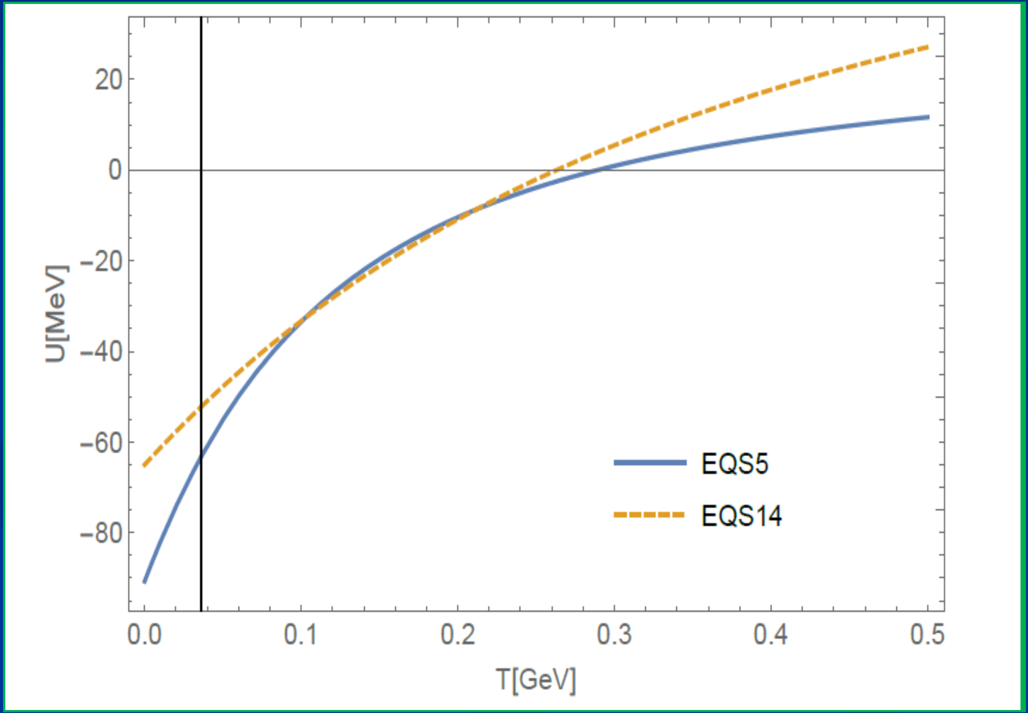

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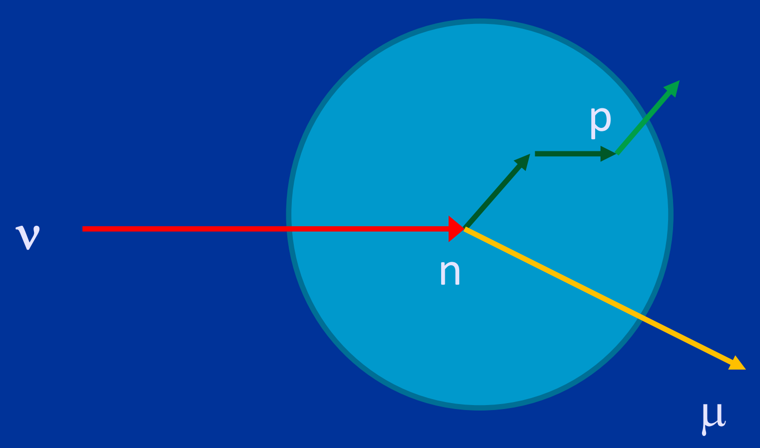
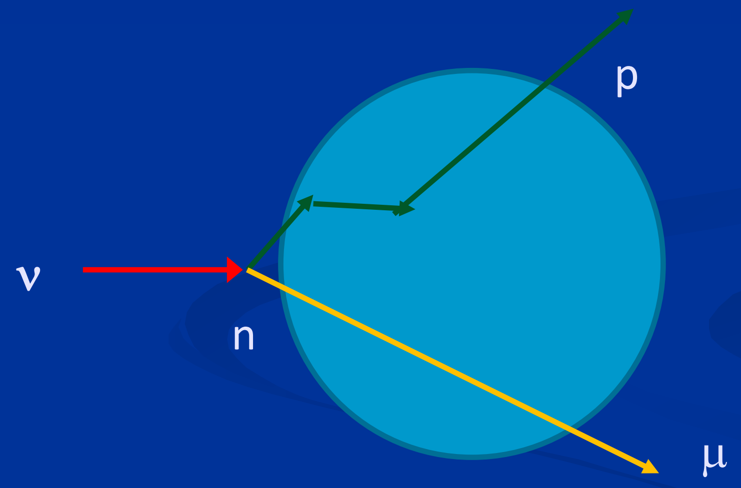
Nuclear ISI and FSI

Correct



GiBUU

Incorrect



Your favorite generator (hA, …)

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ISI and FSI do not factorize!!!

- Practical Implications:
  1. You cannot use standard MC cascade codes (Bertini, Cugnon, …) for neutrino-induced FSI without major modifications since these codes start with a particle hitting a target nucleus from the outside, not inside (as in neutrino-, electron-, photon-induced reactions). In cascade codes the first interactions always take place at low nuclear densities, in the tail.
  2. If you work without any potential for the ISI then the outgoing particle‘s energy must be corrected by a repulsive potential. This potential must then also be present during the further FSI.
  3. During following FSI the potential changes with time, because the energy of the propagated hadron is lowered due to collisions.

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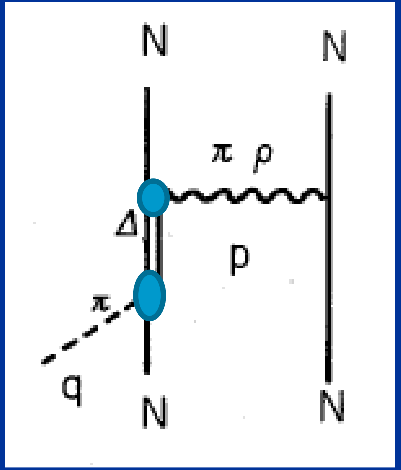
Pion FSI: Example of Consistency

- Pions also see momentum-dependent nuclear potential, option in GiBUU, but effects less pronounced (thus not often used)
- Pions (in the resonance region W < 2 GeV) are produced and absorbed through the same vertex
  ➔ Pion production and absorption must be consistent!

π production



π absorption

Time Reversal Invariance of NNπ

Violated if pions are produced through RS and absorbed through Valencia

FSI in GiBUU

- For tests of FSI you can run GiBUU for p + A or π + A . The program package contains job cards for that purpose. The nuclear part is the same as for all the neutrino-induced reactions: density, potential, FSI cross sections, …… This is a good test for FSI.

- Just remember: this is not correct for a proper treatment of FSI in electron, photon, neutrino induced reactions where the ISI take place in the nuclear interior, at some density, with possible medium modifications.

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ISI and FSI in GiBUU

- Steve Dytman in his talk mentioned a few checks of generators. Here I add to that:

1. πA reactions were calculated with an early version of GiBUU: Engel et al, Nucl. Phys. A 594 (1994)
2. Transparencies were calculated with GiBUU: Lehr et al, 2004
3. Photon induced 2H processes on various nuclei (measured by HERMES) at DESY were calculated with GiBUU: Falter et al, Phys. Rev. C70 (2004
   In all cases good agreement with data

ISI and FSI in GiBUU

- The outgoing particle of the ISI sees the same potential as the ingoing particle of the FSI. This potential is obtained from an energy-density functional that gives correct nuclear binding (energy and density).
- Calculation of particle trajectories becomes more involved; potential changes with time.
- Solving the equations of motion of all particles with a potential brings them automatically on-shell when they leave the nucleus.
- For pions (and kaons, ..) time reversal invariance is maintained

ISI and FSI in GiBUU

- ISI and FSI do not factorize, but sometimes it is useful to separate them for a better understanding of the underlying process. GiBUU allows to do that (since 2008).
- FSI depend on the momentum and density (i.e. position) at the point of the ISI. GiBUU allows to run only the FSI machinery by having a mode in which you enter:
  - kind of particle (p,n,π, ..), momentum, position
  - Potential type (depth and momentum dependence)

as starting conditions for the further quantum-kinetic transport

ISI and FSI in GiBUU jobcard

```
!-------------------------------------------------------- -*- fortran -*- ----
! sample jobcard for a given particle on Nucleus
!-----------------------------------------------------------------------------
! please visit the GiBUU homepage for further information:
! https://gibuu.hepforge.org
!-----------------------------------------------------------------------------

! file: ./inputOutput/input.f90
&input
      eventtype       =        200
      numEnsembles    =         10
      numTimeSteps    =        100
      delta_T         =  0.1    ! time step size [fm]
      freezeRealParticles    = T
      localEnsemble   = T
      length_perturbative = 200
      printParticleVectors = T
!      DoPrLevel(1) = .FALSE. ! set this for production runs
!      DoPrLevel(2) = .FALSE. ! set this for production runs
      path_To_Input   = '~/GiBUU/buuinput'
/
```

```
! file: ./density/nucleus.f90
&target
      TARGET_A        =  64 ! mass
      TARGET_Z        =  29 ! charge
!      densitySwitch_static    =   3 ! 0: density=0.0, 1: Woods-Saxon by Lenske, 2: NPA 554, 3: Woods-Saxon by Lenske, different neutron and proton radii
/
```

```
! file: ./init/initTransportGivenParticle.f90
&TransportGivenParticle
      particle_ID     =   1 ! ID of particle
      charge          =   1 ! charge of particle
      position        = 0.0, 0.0, 2.0 ! coordinates
      threemomentum   = 0.0, 0.0, 0.1 ! 3-momentum
!      mass            = 0.938 ! mass of the particle
!      maxmass         = 1.5 ! maximal mass if according spectral function
!      perweight       = 1.0 ! weight of this particle
/
```


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Summary

- ISI and FSI do not factorize because
  - *For nucleons*: final state particle of the very first interaction (ISI) moves in the same potential as initial state particle of the following final state interactions.
  - *For pions*: production and absorption are linked through time-reversal invariance

- GiBUU allows to check ISI and FSI separately by using special options on the job card: allows to insert any particle with given energy, momentum and location into the FSI machinery.

Remarks on APIs

- *Discussion: Should electron scattering be supported in theory API? What is required to go beyond table-based solution? What other interfaces with theoretical calculations are needed?*

  It should be the other way around:

1. A good generator should have, foremost, a good theory basis. This theory basis then can easily also describe electrons (just set $g_A = 0$); no special theory or generator development should be needed for electrons.

2. Table based solutions are impractical; the tables have to depend on too many variable (momentum, position, potential, …)

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Remarks on APIs

- APIs (program interfaces) are needed for linking program parts that deal with separate, independent physics (outer parts of Costas's Onion).
    1. Example: use of a given flux in a generator
    2. Example: analysis routines using events from a generator
- APIs are dangerous when linking program snippets that are connected by common physics.
    1. Example: use of different mechanisms for pion production and absorption
    2. Example: use of different groundstates (RFG, local RFG, SF, …)
- Specifying APIs for the latter helps to hide incorrect physics.

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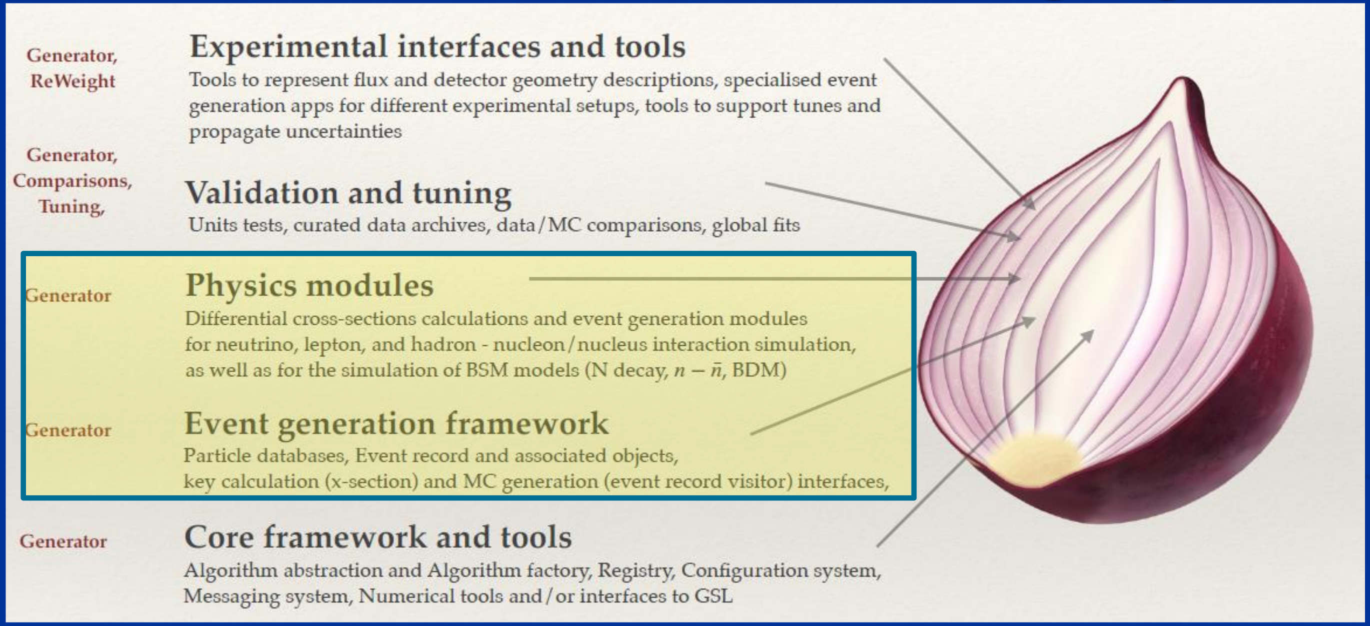
The way to go

1. Take Costas's onion model and core its mid-interior, but keep the very useful outer shells with flux drivers, target geometries and the such



Costas's yesterday talk

2. Replace the mid-core with a sound physics model

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