Geant4 Physics (EM / Hadron)

歳藤利行
KEK/JST

- Standard EM processes
- LowE EM processes
- Hadron processes (model structure)
- Neutron physics
- Ion Physics
- Radioactive decay
- Optical photons
- Decays
- Physics Validation

Standard EM process

Standard EM packages

- γ , e up to 100 TeV
- hadrons up to 100 TeV
- ions up to 100 TeV
- muons up to 1 PeV
- X-ray and optical photon production processes
  - G4Cerenkov, G4Scintillation and G4TransitionRadiation

Gamma and Electron Transport

- Photon processes:

  - e^+e^- 対生成

  - コンプトン散乱

  - 光電効果

- Electron and positron processes:

  - Ionization

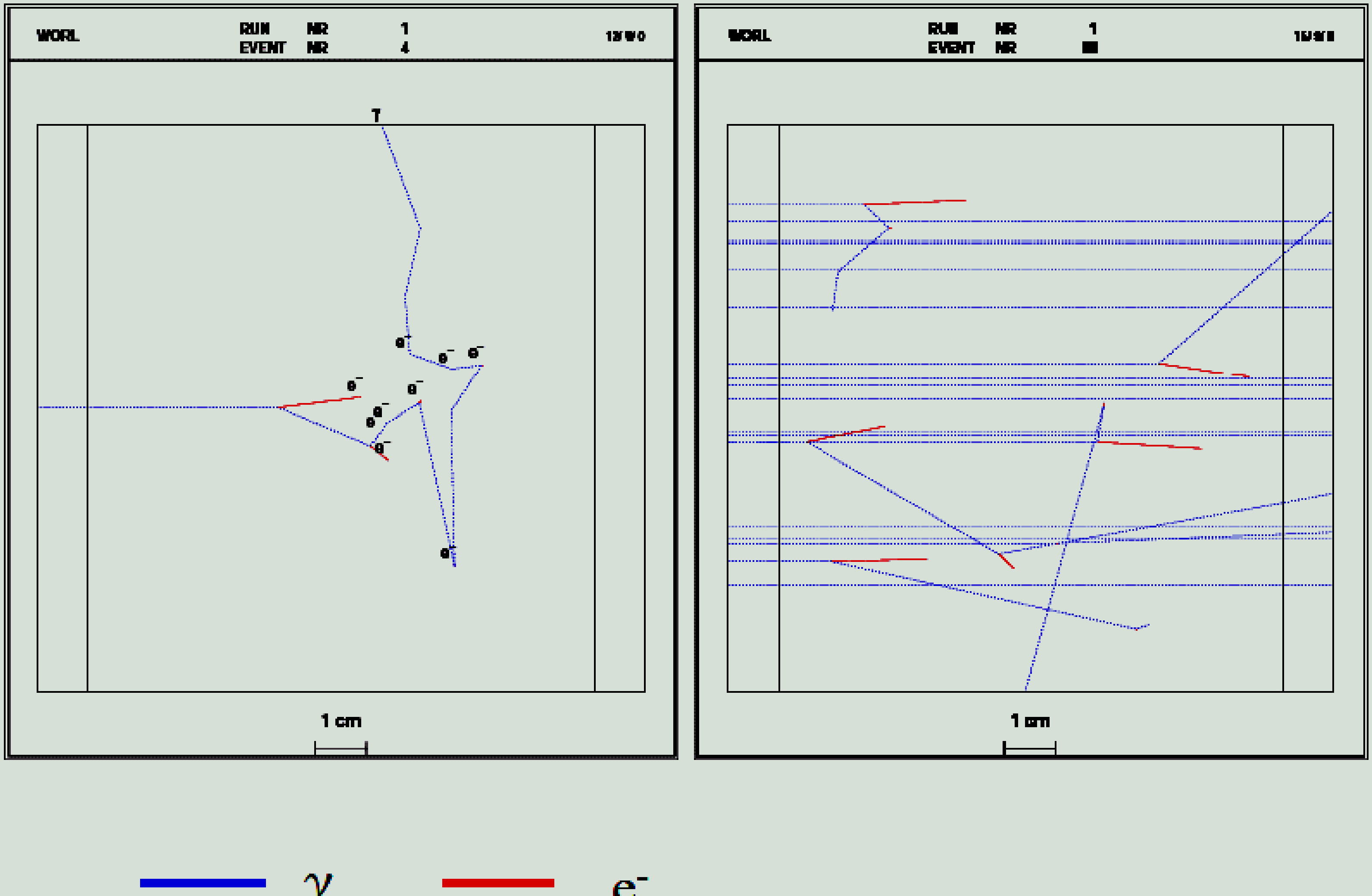
  - クーロン散乱、多重散乱

  - 制動放射

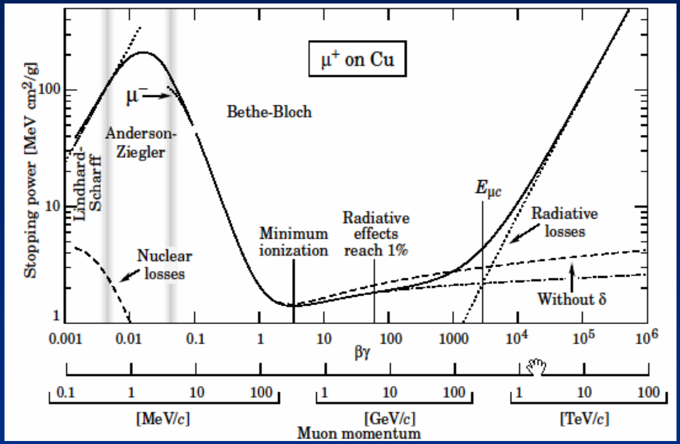
- Positron annihilation

コンプトン散乱

γ 10 MeV in 10 cm Aluminium: Compton scattering



Muon EM Physics Simulation



- 主要なprocess:

  -Ionization

  -制動放射

  -e^+e^- 対生成

  -Muon-nuclear interactions in

  hadronic packages

Hadron and ion EM physics

- クーロン散乱
- Ionization
  - Bethe-Bloch formula with corrections used for E>2 MeV

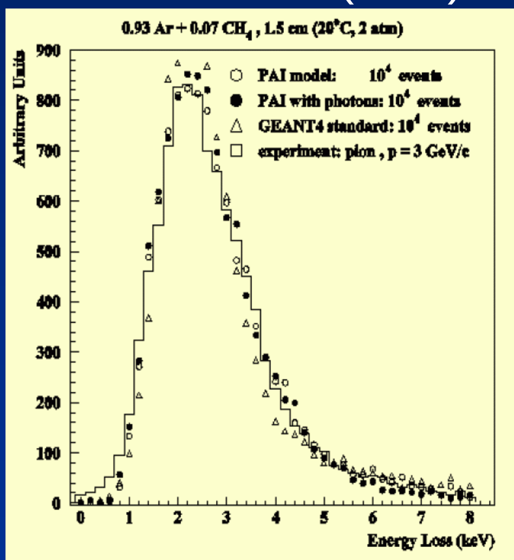
$$-\frac{dE}{dx} = 4\pi N_e r_0^2 \frac{z^2}{\beta^2}\left(\ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \frac{\beta^2}{2}\left(1-\frac{T_c}{T_{max}}\right) - \frac{C}{Z} + \frac{G-\delta-F}{2} + zL_1 + z^2 L_2\right)$$

  - – C – shell correction
  - – G – Mott correction
  - – δ – density correction
  - – F – finite size correction
  - – L1- Barkas correction
  - – L2- Bloch correction
  - – Nuclear stopping
  - – Ion effective charge
  - Bragg peak parameterizations for E< 2 MeV
    - ICRU’49 and NIST databases

エネルギー損失のゆらぎ

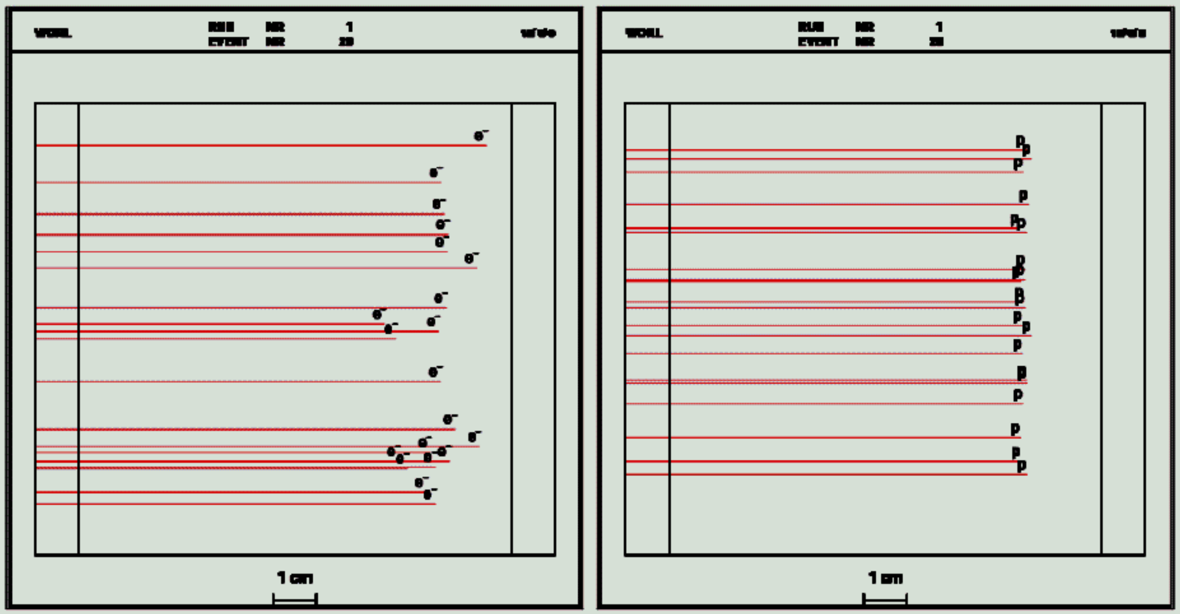
物質量が多い(厚い)場合
ガウス分布

物質量が少ない(薄い)場合

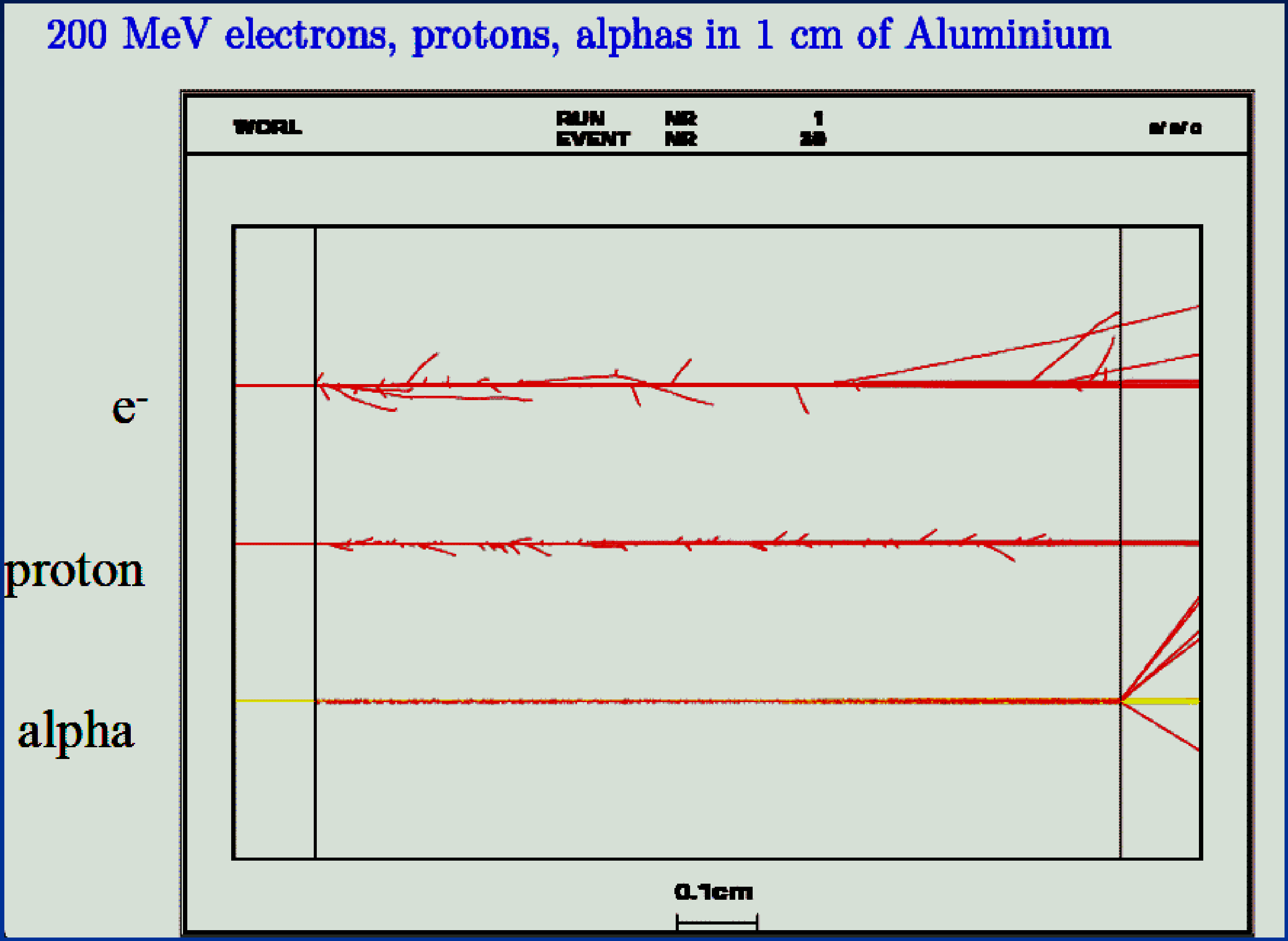


Fluctuations on ΔE lead to fluctuations on the actual range (straggling).

penetration of e^- (16 MeV) and proton (105 MeV) in 10 cm of water.



デルタ線



200 MeV electrons, protons, alphas in 1 cm of Aluminium
e-
proton
alpha
WORL
RUN NR 1
EVENT NR
0.1cm

LowE EM process

- Low energy 領域への拡張
  - ~250 eV / 100 eV 電子、photonに対して
  - ハドロン、イオンに対しては、ほぼ物質中のイオン化ポテンシャルと同じ程度まで
  - 上限は 100 GeV くらい

- モデルが詳細
  - ガンマ線、電子断面積は理論式・実験式とデータ ベースを併用
    - **EADL** (Evaluated Atomic Data Library)
    - **EEDL** (Evaluated Electrons Data Library)
    - **EPDL97** (Evaluated Photons Data Library)
  - dE/dxの計算モデルが豊富
    - Ziegler1977p,Ziegler1985,ICRU_R49,SRIM2000
  - 原子の殻構造を考慮
  - 角度分布が精密
  - 蛍光X線、Auger効果、Rayleigh散乱なども取り扱い可能

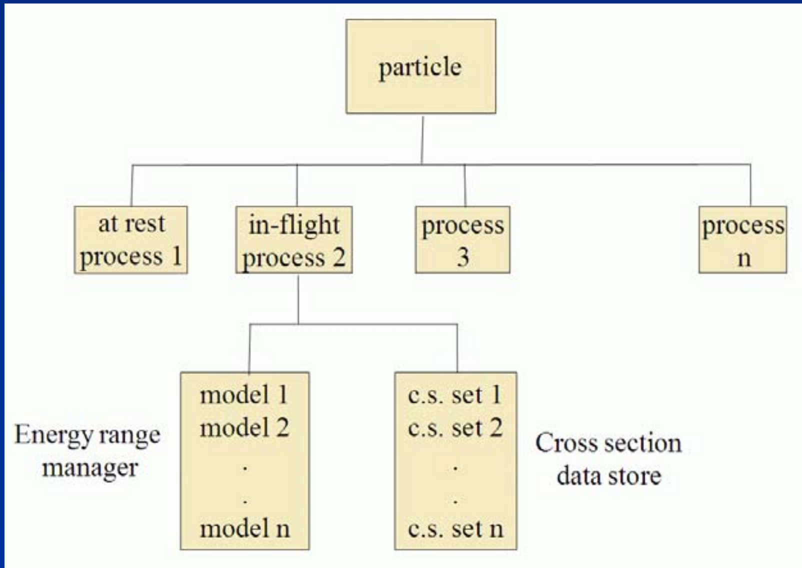
- “standard” electromagnetic packageに対して 相補的な役割

- 医療、宇宙分野への応用

Hadronic Physics

ハドロニック プロセス
モデル 断面積

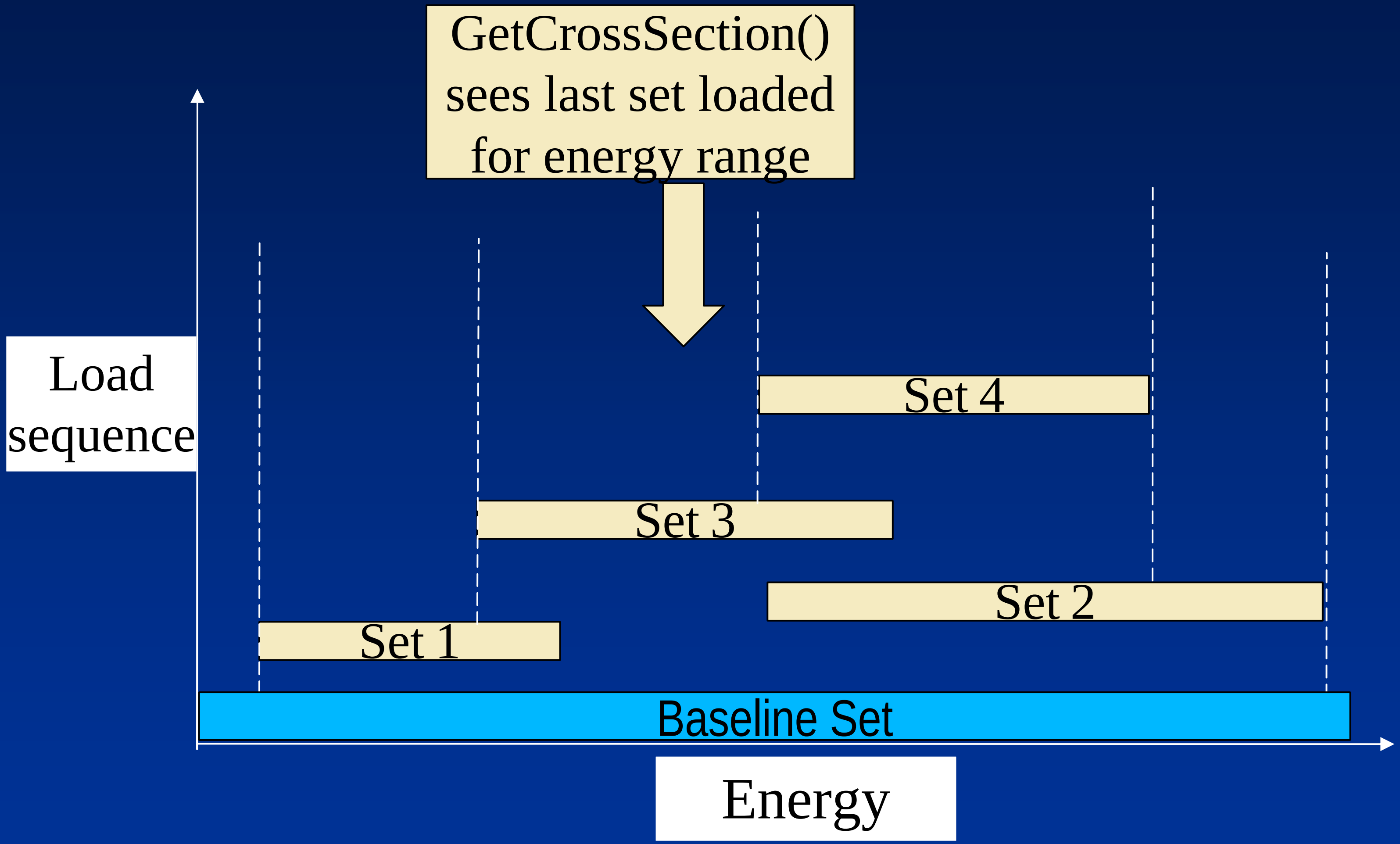
- Geant4ではprocessを通して粒子に物理過程を割り当てる
- 電磁相互作用 原則として1process →1model, 1cross section
- ハドロン物理には1processに対して多数のmodelが存在する
  - 断面積も複数存在する
- ユーザーはどのmodel, 断面積が適切か、決めなければならない。



断面積

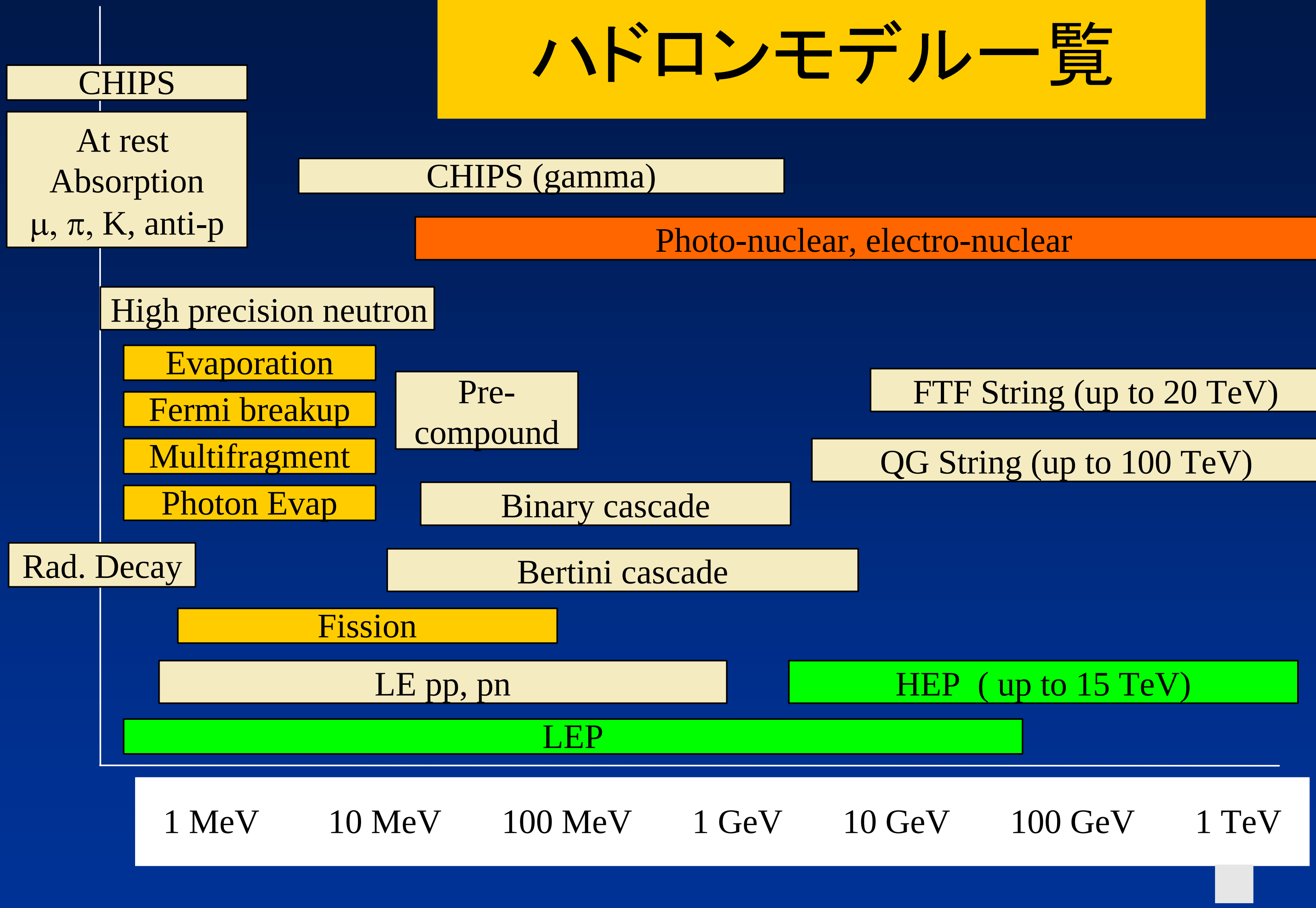
- デフォルトの断面積が、各ハドロニックプロセスに与えられている
  - 上書きや置き換えが可能
- 断面積のタイプ
  - 大規模なデータベースになっているもの
  - 純粋に理論的なもの
  - パラメータ化されたもの

断面積のManagement



より後で登録した断面積が優先される

ハドロンモデル一覧


CHIPS
At rest Absorption μ, π, K, anti-p
CHIPS (gamma)
Photo-nuclear, electro-nuclear
High precision neutron
Evaporation
Fermi breakup
Multifragment
Photon Evap
Pre-compound
FTF String (up to 20 TeV)
QG String (up to 100 TeV)
Binary cascade
Rad. Decay
Bertini cascade
Fission
LE pp, pn
HEP (up to 15 TeV)
LEP
1 MeV
10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
1 TeV

Hadronic Models – Data Driven

- データによって特徴づけられている
  - 断面積
  - 角度分布
  - 多重度
  - etc.
- データを内挿して反応長や終状態を得る
  - 断面積、多項式の係数など
- 例
  - 中性子 (E < 20 MeV)
  - コヒーレント弾性散乱 (pp, np, nn)
  - 不安定同位体の崩壊

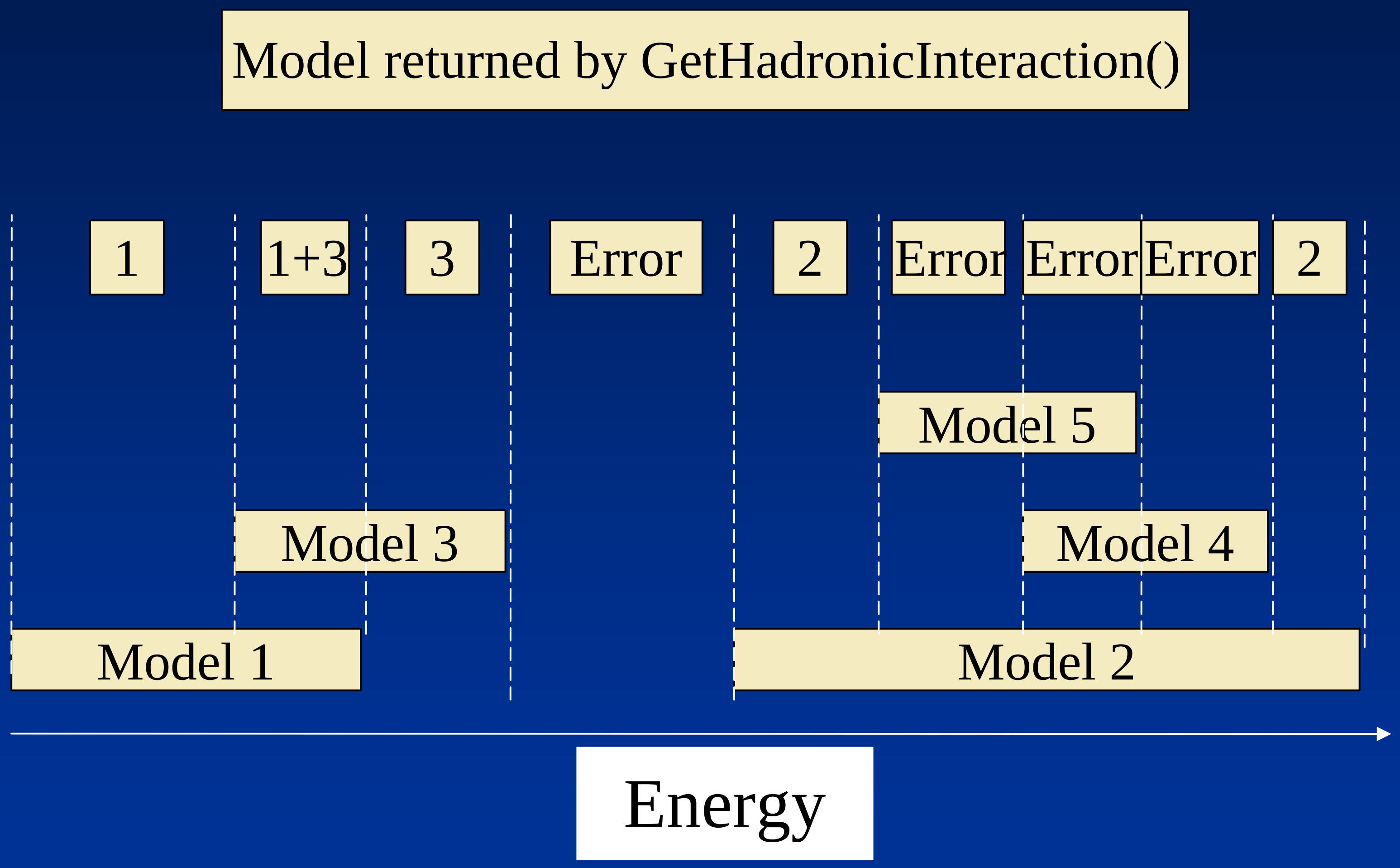
Hadronic Models – Theory Driven

- 理論に基づく
  - データはほとんど使われない
- 終状態は理論分布をサンプリングして決められる
- 例:
  - quark-gluon string (projectiles with E > 20 GeV)
  - intra-nuclear cascade (intermediate energies)
  - nuclear de-excitation and breakup

Hadronic Models - Parameterized

- データを適当なモデルでフィットしパラメータ化
- ２つのモデルが利用可能:
  - Low Energy Parameterized (LEP) for < 20 GeV
  - High Energy Parameterized (HEP) for > 20 GeV
  - 各モデルは多数のモデルの寄せ集め
- Geant3で使われたGHEISHAがベース
- Core code:
  - hadron fragmentation
  - cluster formation and fragmentation
  - nuclear de-excitation

モデルのManagement



Neutron Physics

Low energy (< 20MeV) neutrons physics

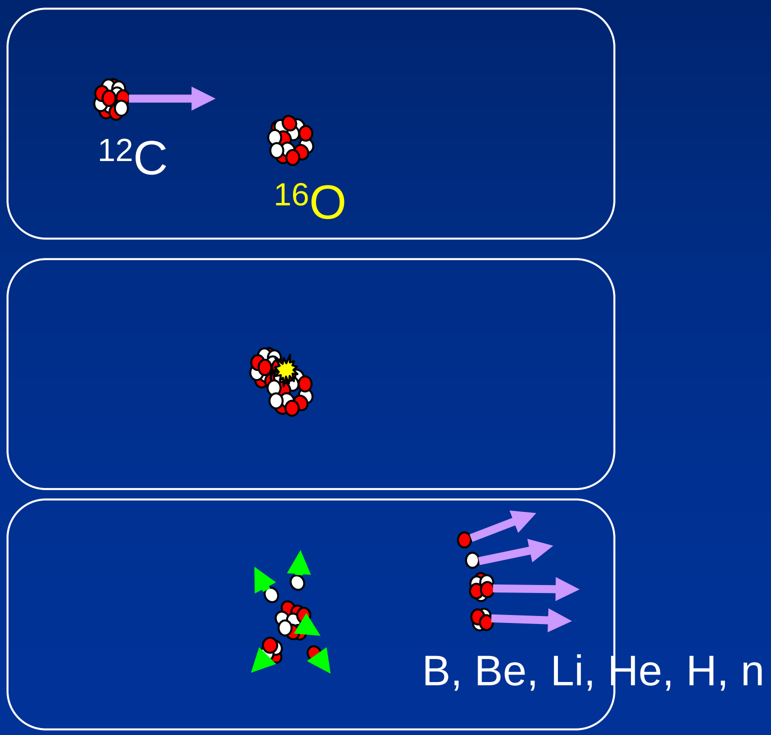
- High Precision Neutron Models (and Cross Section Data Sets)
  - G4NDL (Geant4 Neutron Data Library)
    - ENDF (Evaluated Nuclear Data File)
  - Elastic
  - Inelastic
  - Capture
  - Fission
- NeutronHPorLEModel(s)
- ThermalScatteringModels (and Cross Section data Sets)
- JENDL (Japanese Evaluated Nuclear Data Library) High Energy Files (66の核種に対する中性子、陽子反応データ cross sections < 3GeV)

Ion Physics

- イオンはGenericIonという形で実装されている (G4GenericIon)　d,t,^{3}He, α は例外

Ion Physics
非弾性反応

- 断面積
- モデル
  - G4BinaryLightIon
  - G4WilsonAbrasion



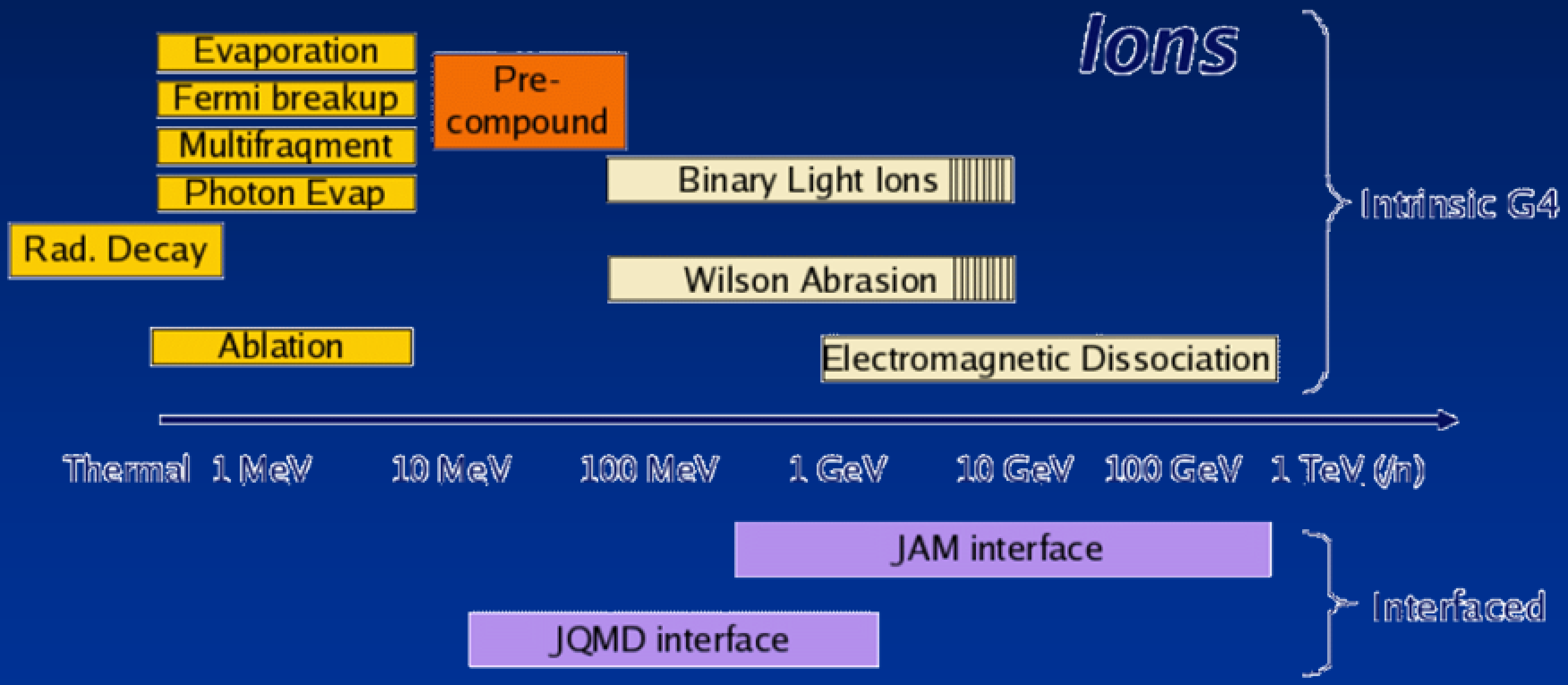
原子核-原子核反応の全断面積

- Geant4には多数のtotal断面積の公式が組み込まれている
  - Tripathi, Shen, Kox and Sihver
- 理論的な洞察に基づいた経験的なパラメータ化された公式

原子核-原子核反応断面積のリファレンス

- Tripathi Formula
  - NASA Technical Paper TP-3621 (1997)
- Tripathi Light System
  - NASA Technical Paper TP-209726 (1999)
- Kox Formula
  - Phys. Rev. C 35 1678 (1987)
- Shen Formula
  - Nuclear Physics. A 49 1130 (1989)
- Sihver Formula
  - Phys. Rev. C 47 1225 (1993)

Existing Geant4 Nuclear-Nuclear Final State Models



イオンの崩壊

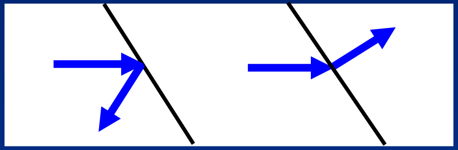
- 不安定核の崩壊がシミュレーションされる
- α, β^+, β^-,電子捕獲(EC)が組み込まれている
- Evaluated Nuclear Structure Data File (ENSDF) のデータが使われる
  - 半減期
  - 親粒子、娘粒子のレベル構造
  - 崩壊分岐比
  - 崩壊過程でのエネルギー
- 崩壊の娘核が励起状態ならば、そのde-excitationはG4PhotonEvaporation を使って扱われる

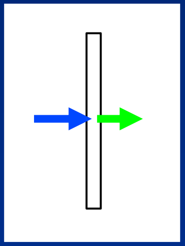
Optical processes

Optical photon のレイ･トレース

Optical Photons

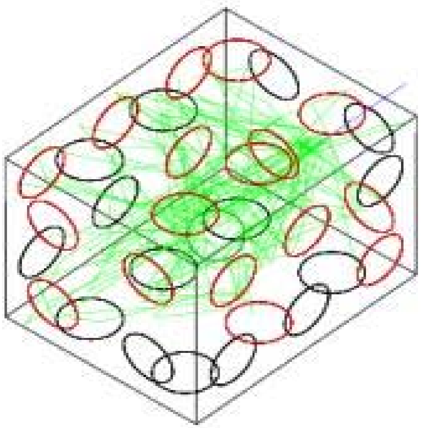
- 波長 >> 原子スケール
  - 波動として扱う（しかし干渉はしない)
- Optical photons undergo:
  - Rayleigh scattering
  - 吸収
  - 境界面での屈折、反射
  - wavelength shifting



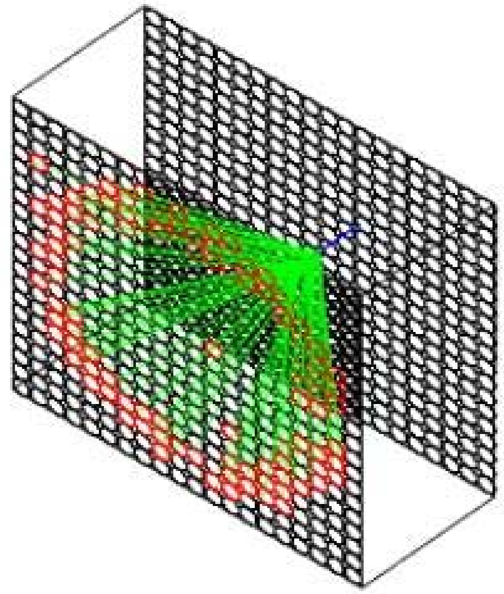


- Optical properties can be specified in G4Material
  - 反射率, 透過率, 誘電率, surface properties (polished, rough, …)

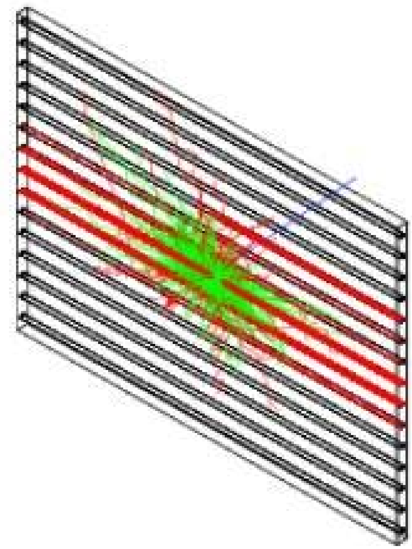
/examples/extended/optical/LXe



Scintillation



Cerenkov



WaveLengthShifting

Decays

- プロセスの一部として実装されている

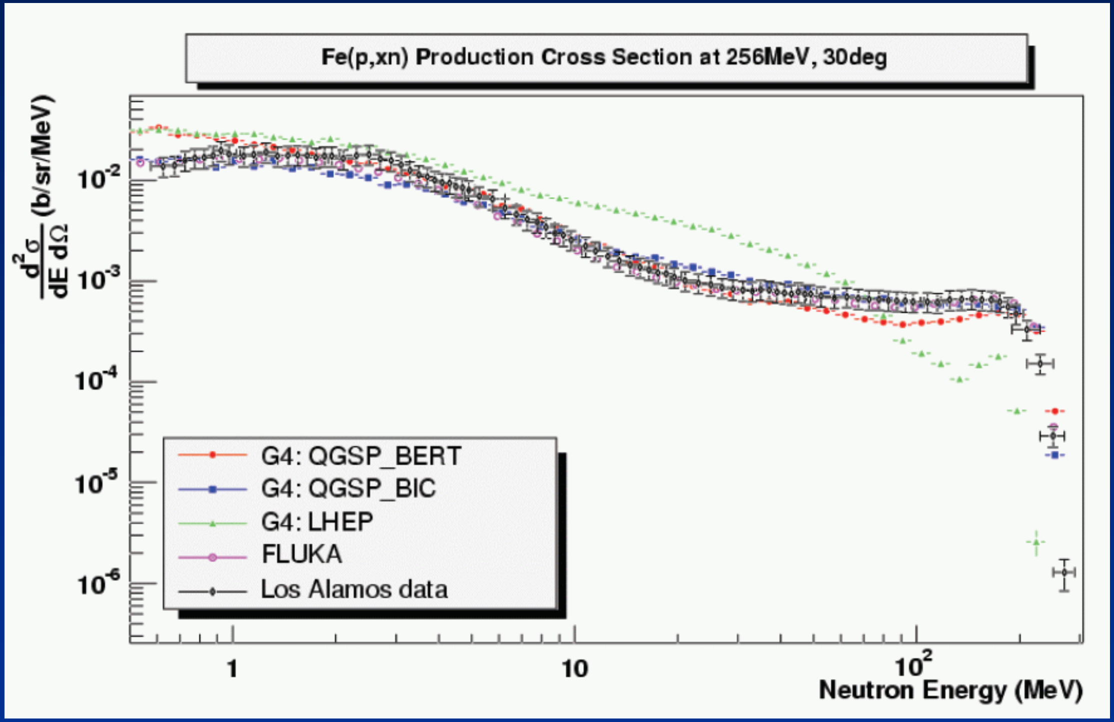
The Decay Process

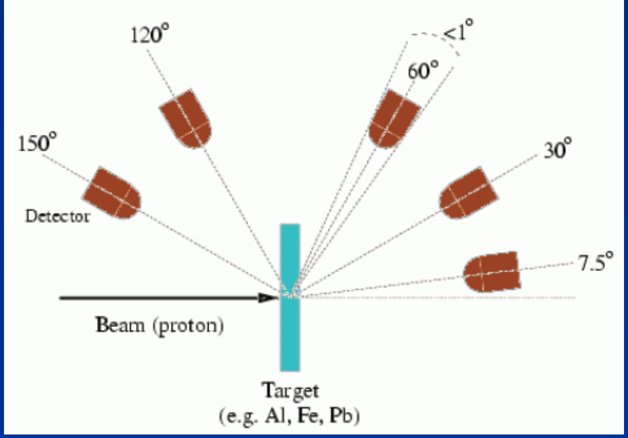
- in-flight あるいは at rest のプロセスとして扱われる
- 崩壊の取り扱いのできるすべての粒子に対して同じprocessが使われる
  - 粒子ごとにDecay Table(G4DecayTable)があり、分岐比やモードの情報が入っている
- 利用可能なdecay modes
  - Phase space:
    - 2-body e.g. $\pi^0 \to \gamma\gamma$, $\Lambda \to p\,\pi^-$
    - 3-body e.g. $K^0_L \to \pi^0\,\pi^+\,\pi^-$
    - many body
  - Dalitz: $P^0 \to \gamma\, l^+\, l^-$
  - Muon decay
    - V – A, no radiative corrections, mono-energetic neutrinos
  - Leptonic tau decay
    - like muon decay
  - Semi-leptonic K decay: $K \to \pi\, l\, \nu$
- Heavy flavour particleに対しては特別な取り扱いが必要
  - Pre-assigned decay modeあるいはexternal decay handler (G4VExtDecayer)を使う

Physics validation

- 様々なModel、断面積が存在している
- Validationが重要

Fe(p,xn)反応の2重微分断面積





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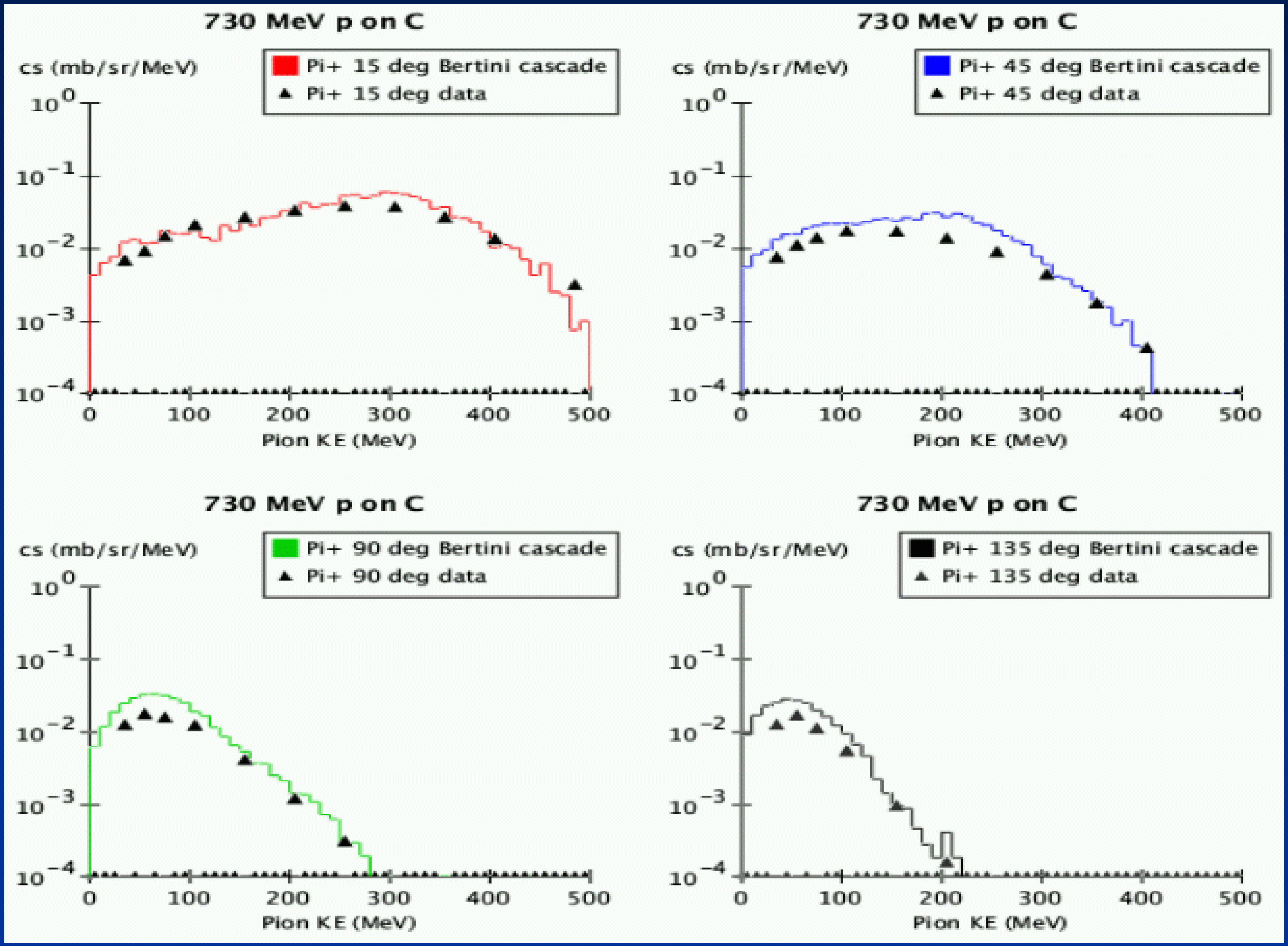
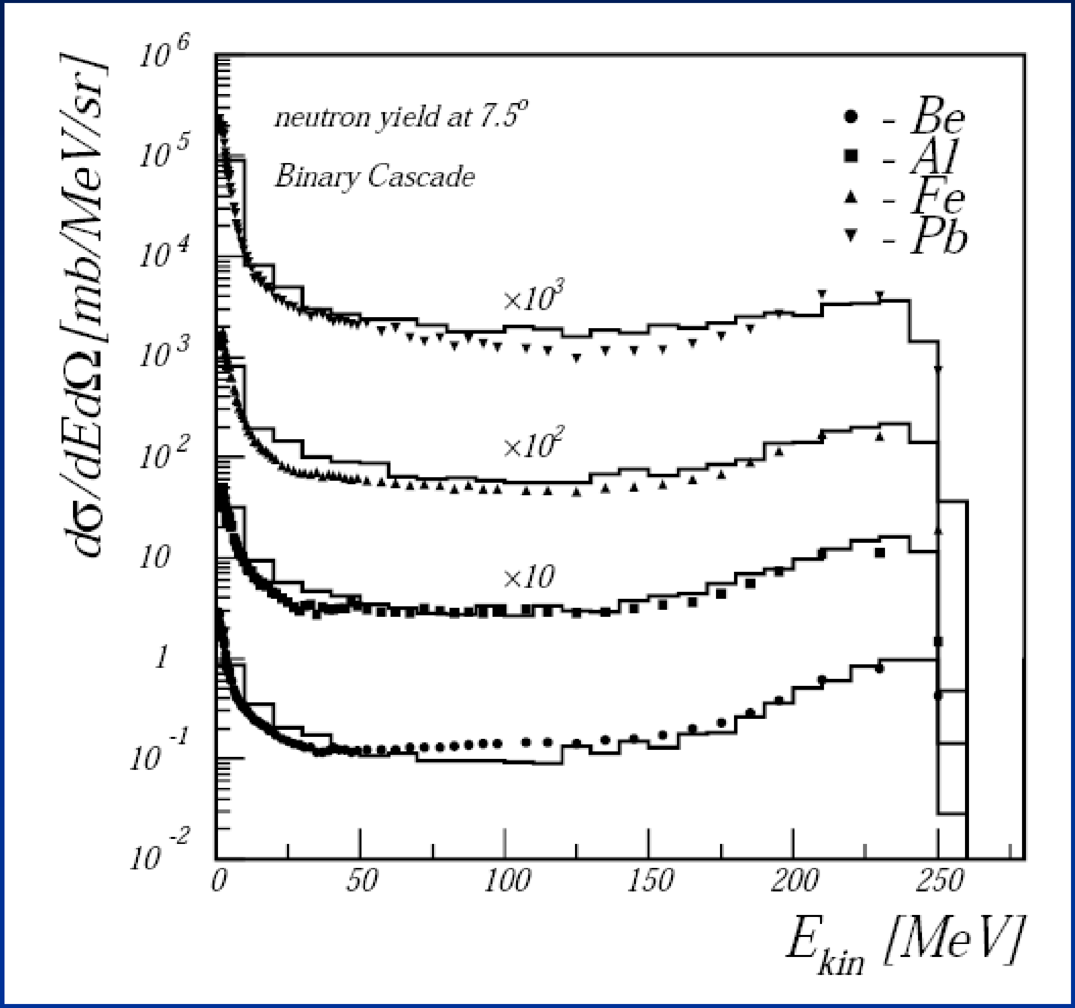
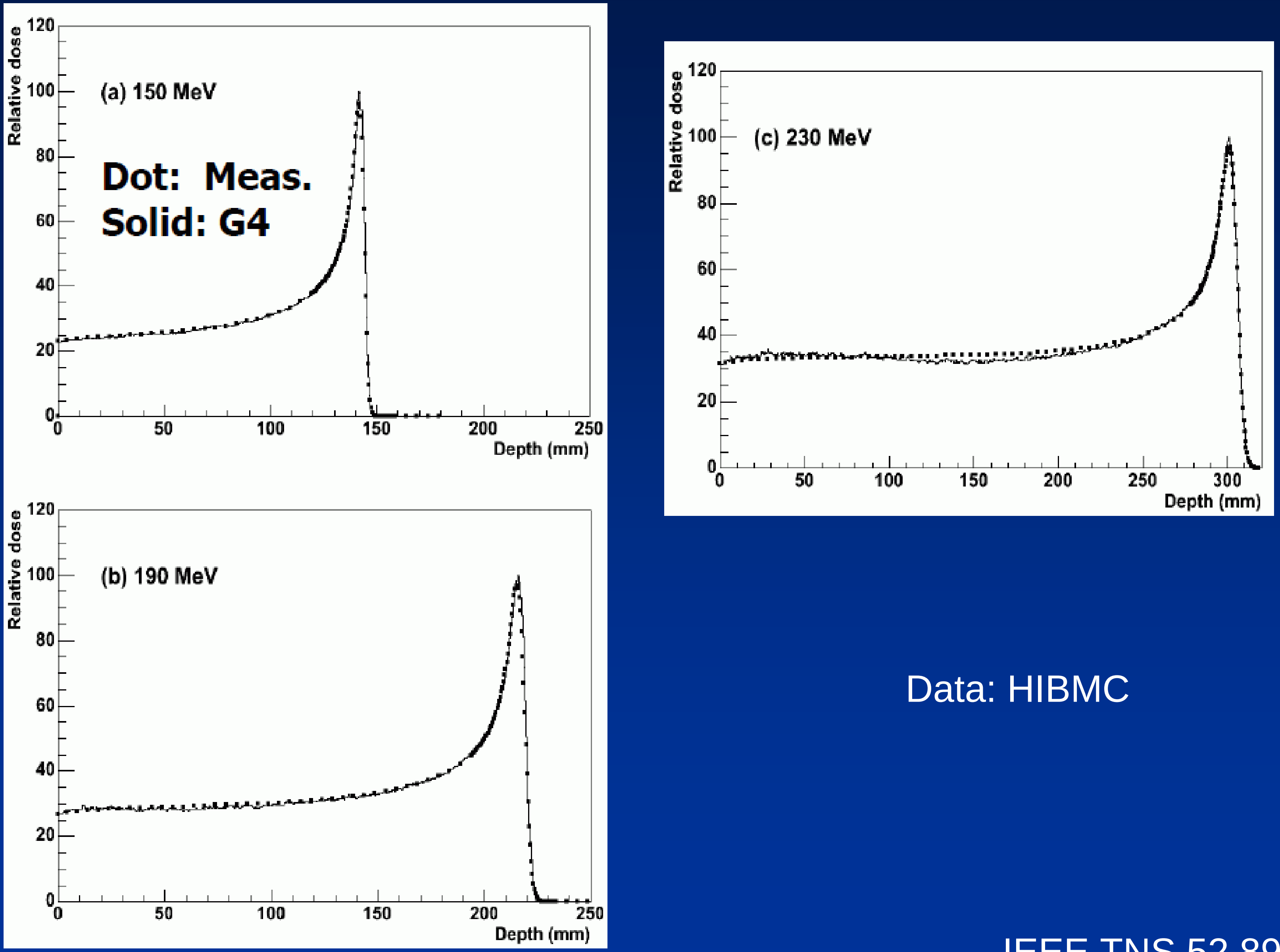
Validation of the Bertini Cascade



Validation of the Binary Cascade 256 MeV protons



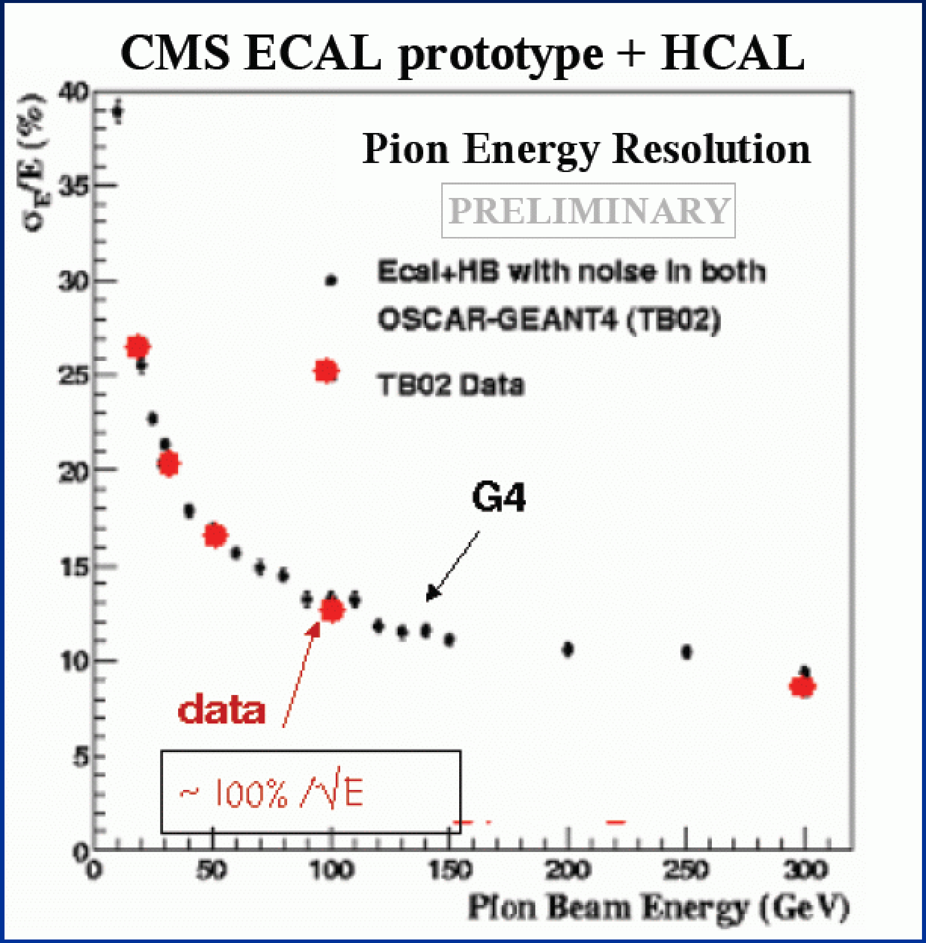
陽子線の水中のブラッグピーク

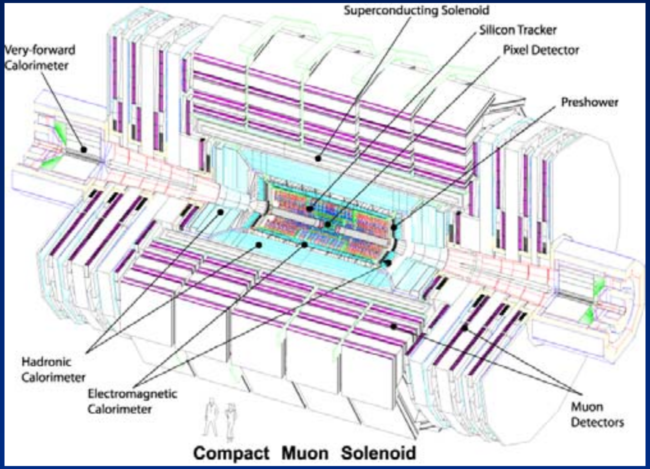


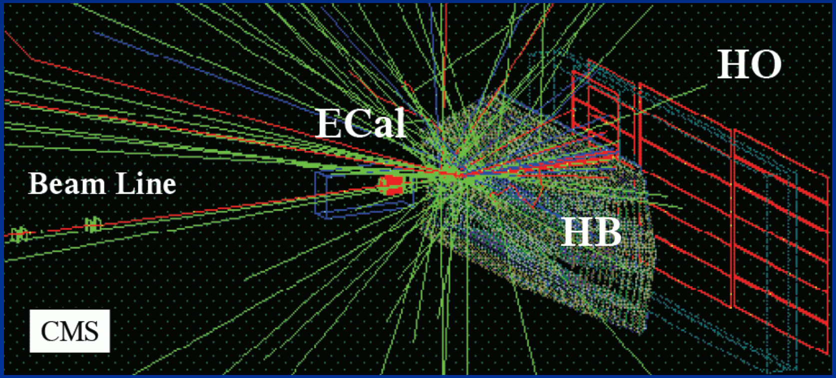
Data: HIBMC

IEEE TNS 52 896 (2005)

Pion energy resolution in CMS







まとめ

- Geant4には検出器のシミュレーションに必要な、放射線が起こす様々な相互作用がモデル化して組み込まれている(Physics Reference Manualを参照)
- Optical Photonのシミュレーションも可能
- 物理モデルの検証作業が精力的になされている

Hadron Elastic Scattering

- GHEISHA-style (G4LElastic)
  - classical scattering (not all relativistic)
  - simple parameterization of cross section, angular distribution
  - can be used for all long-lived hadron projectiles, all energies
- Coherent elastic
  - G4LEpp for (p,p), (n,n) : taken from detailed phase-shift analysis, good up to 1.2 GeV
  - G4LEnp for (n,p) : same as above
  - G4HadronElastic for (h,A) : nuclear model details included as well as interference effects, good for 1 GeV and above, all long-lived hadrons
  - G4QElastic for (p,A), (n,A) : parameterization of experimental data (M.Kossov), part of CHIPS modeling

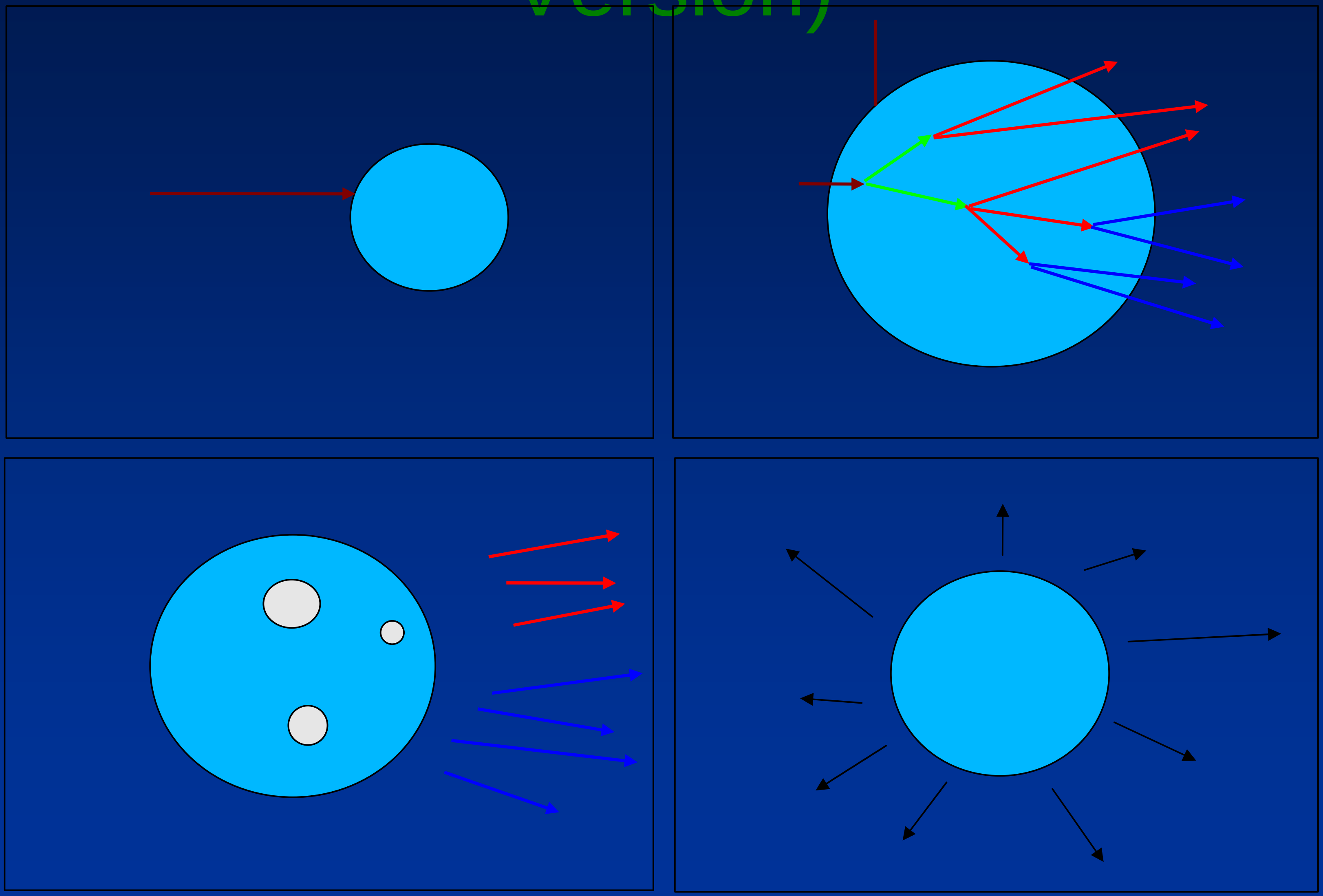
Precompound Models (1)

- G4PreCompoundModel is used for nucleon-nucleus interactions at low energy and as a nuclear de-excitation model within higher-energy codes
  - valid for incident p, n from 0 to 170 MeV
  - takes a nucleus from a highly-excited set of particle-hole states down to equilibrium energy by emitting p, n, d, t, 3He, alpha
  - once equilibrium state is reached, four other models are called to take care of nuclear evaporation and breakup
    - these models not currently callable by users
- The parameterized and cascade models all have nuclear de-excitation models embedded in them

Bertini Cascade Model

- The Bertini model is a classical cascade:
  - it is a solution to the Boltzman equation on average
  - no scattering matrix calculated
  - can be traced back to some of the earliest codes (1960s)
- Core code:
  - elementary particle collider: uses free-space cross sections to generate secondaries
  - cascade in nuclear medium
  - pre-equilibrium and equilibrium decay of residual nucleus
  - detailed 3-D model of nucleus

Bertini Cascade (Comic Book Version)



Bertini Cascade (text version)

- Modeling sequence:
  - incident particle penetrates nucleus, is propagated in a density-dependent nuclear potential
  - all hadron-nucleon interactions based on free-space cross sections, angular distributions, but no interaction if Pauli exclusion not obeyed
  - each secondary from initial interaction is propagated in nuclear potential until it interacts or leaves nucleus
  - during the cascade, particle-hole exciton states are collected
  - pre-equilibrium decay occurs using exciton

Using the Bertini Cascade

- In Geant4 the Bertini model is currently used for p, n, π, K^+, K^-, $K^0{}_L$, $K^0{}_S$, Λ, Σ^+, Σ^-, Ξ^-, Ξ^0, Ω^-
  - valid for incident energies of 0 – 10 GeV
  - may be extended to 15 GeV when new validation data are available
  - currently being extended to kaons and hyperons
- Invocation sequence
  - G4CascadeInterface* bertini = new G4CascadeInterface(); G4ProtonInelasticProcess* pproc = new G4ProtonInelasticProcess(); pproc -> RegisterMe(bertini); proton_manager -> AddDiscreteProcess(pproc);

Binary Cascade

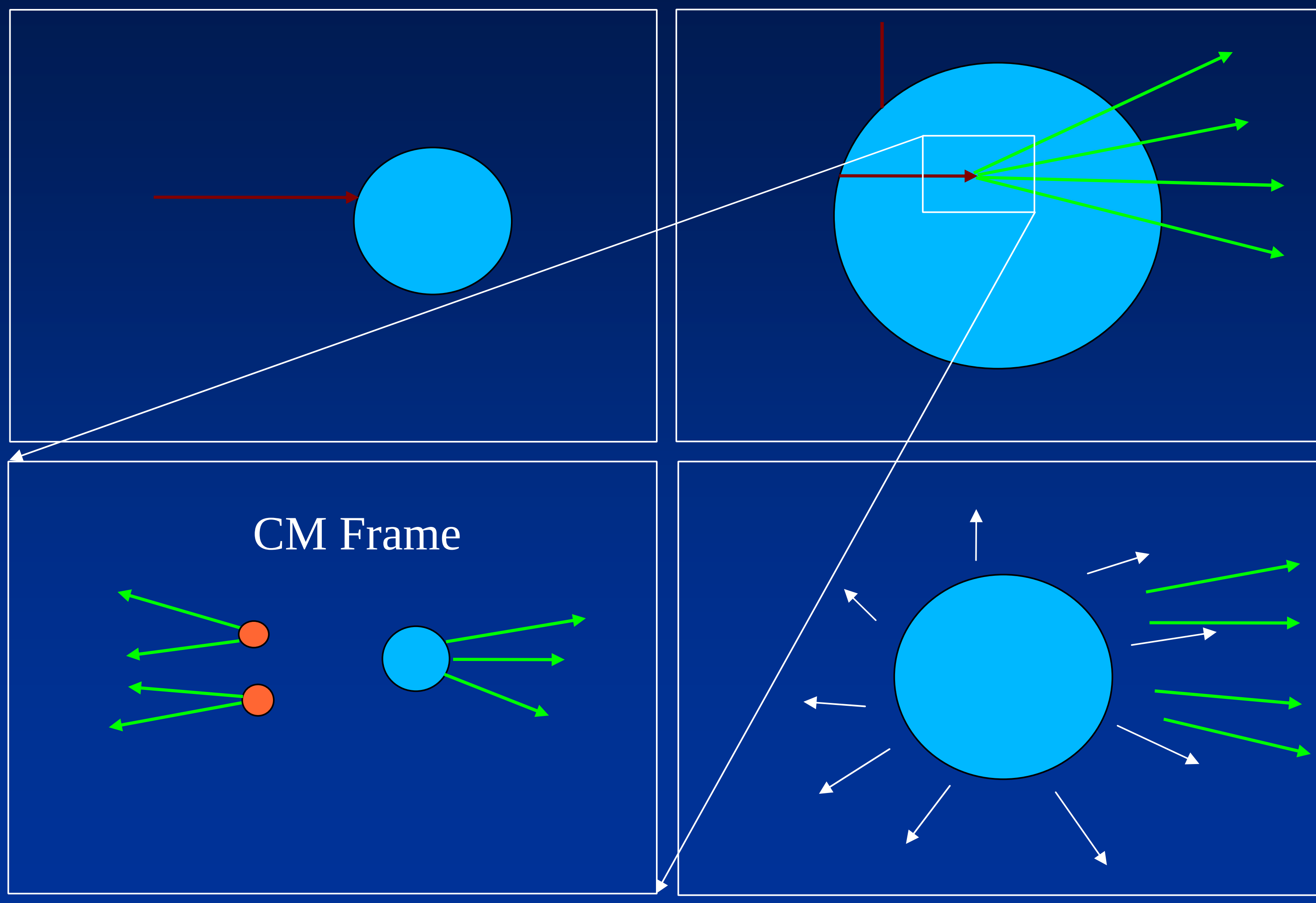
- Modeling sequence similar to Bertini, except that
  - hadron-nucleon collisions handled by forming resonances which then decay according to their quantum numbers
  - particles follow curved trajectories in nuclear potential
- In Geant4 the Binary cascade model is currently used for incident p, n and π
  - valid for incident p, n from 0 to 10 GeV
  - valid for incident π^+, π^- from 0 to 1.3 GeV
- A variant of the model,

Binary Cascade

- ハドロンに対してはp,n,πについて適用できる
  - p, n　0 から 10 GeV まで
  - π^+, π^-　0 から 1.3 GeV まで

- 原子核の反応にも適用できる

LEP, HEP (Comic Book Version)



LEP, HEP models (text version)

- Modeling sequence:
  - initial interaction of hadron with nucleon in nucleus
  - highly excited hadron is fragmented into more hadrons
  - particles from initial interaction divided into forward and backward clusters in CM
  - another cluster of backward going nucleons added to account for intra-nuclear cascade
  - clusters are decayed into pions and nucleons
  - remnant nucleus is de-excited by emission of p, n, d, t, alpha

Using the LEP and HEP models

- The LEP and HEP models are valid for p, n, π, K, Λ, Σ, Ξ, Ω, α, t, d
  - LEP valid for incident energies of 0 – ~30 GeV
  - HEP valid for incident energies of ~10 GeV – 15 TeV

Summary (1)

- Geant4 hadronic physics allows user to choose how a physics process should be implemented:
  - cross sections
  - models
- Many processes, models and cross sections to choose from
  - hadronic framework makes it easier for users to add more
- Two main types of elastic scattering are available:
  - GHEISHA-style
  - coherent

Summary (2)

- Cascade models (Bertini, Binary) are valid for fewer particles over a smaller energy range
  - more theory-based
  - more detailed
  - slower
- Parameterized models (LEP, HEP) handle the most particle types over the largest energy range
  - based on fits to data and some theory
  - not very detailed
  - fast

Overview of physics

- **Photons**
  - Compton Scattering
  - Compton Scattering by Linearly Polarized Gamma Rays
  - Rayleigh Scattering
  - Gamma Conversion
  - Photoelectric effect

- **Electrons**
  - Bremsstrahlung
  - Ionisation

- **Hadrons and ion ionisation**
  - Energy loss of slow & fast hadrons
  - Energy loss in compounds
  - Delta-ray production
  - Effective charge of ions
  - Barkas and Bloch effects (hadron sign + relativistic)
  - Nuclear stopping power
  - PIXE

Atomic relaxation

- Fluorescence
- Auger process

Photons and electrons

- Based on **evaluated data libraries from LLNL** :
  - EADL (Evaluated **Atomic** Data Library)
  - EEDL (Evaluated **Electrons** Data Library)
  - EPDL97 (Evaluated **Photons** Data Library)

  ...especially formatted for Geant4 distribution (courtesy of D. Cullen, LLNL)

- Validity range **250 eV - 100 GeV**
  - The processes can be used down to 100 eV, with degraded accuracy
  - In principle the validity range of the data libraries extends down to ~10 eV

- Elements **Z=1 to Z=100**
  - Atomic relaxation : Z > 5 (transition data available in EADL)

G4NeutronHPElastic

- The final state of elastic scattering is described by sampling the differential scattering cross-sections
  - tabulation of the differential cross-section
  - a series of legendre polynomials and the legendre coefficients

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}\left(\cos\theta, E\right)$$

$$\frac{2\pi}{\sigma(E)}\frac{d\sigma}{d\Omega}\left(\cos\theta, E\right) = \sum_{l=0}^{n_l}\frac{2l+1}{2}a_l(E)P_l(\cos\theta)$$

G4NeutronHPInelastic

- Currently supported final states are (nA) nγs (discrete and continuum), np, nd, nt, n ^{3}He, nα, nd2α, nt2α, n2p, n2α, np , n3α, 2nα, 2np, 2nd, 2nα, 2n2α, nX, 3n, 3np, 3nα, 4n, p, pd, pα, 2p d, dα, d2α, dt, t, t2α, ^{3}He, α, 2α, and 3α.
- Secondary distribution probabilities are supported
  - isotropic emission
  - discrete two-body kinematics
  - N-body phase-space distribution
  - continuum energy-angle distributions
    - legendre polynomials and tabulation distribution
    - Kalbach-Mann systematic $A + a \rightarrow C \rightarrow B + b$, C:compound nucleus
  - continuum angle-energy distributions in the laboratory system

G4NeutronHPCapture

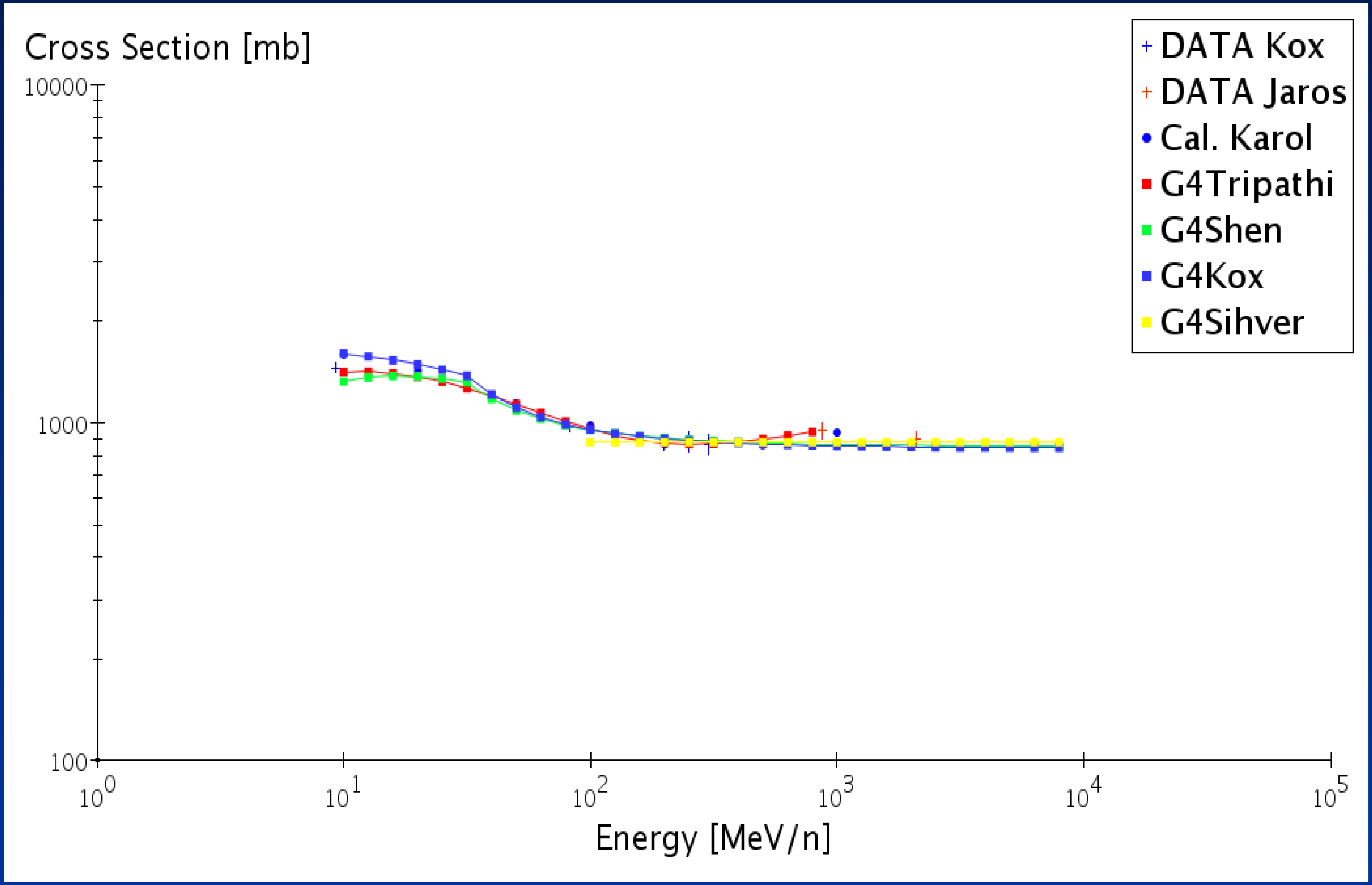
- The final state of radiative capture is described by either photon multiplicities, or photon production cross-sections, and the discrete and continuous contributions to the photon energy spectra, along with the angular distributions of the emitted photons.
- For discrete photon emissions
  - the multiplicities or the cross-sections are given from data libraries
- For continuum contribution
  - E neutron kinetic energy, E_γ photon energies
  - p_i and g_i are given from data libraries

$$f\left(E \rightarrow E_\gamma\right) = \sum_i p_i\left(E\right) g_i\left(E \rightarrow E_\gamma\right)$$

G4NeutronHPFission

- Currently only Uranium data are available in G4NDL
- first chance, second chance, third chance and forth chance fission are into accounted.
- The neutron energy distributions are implemented in six different possibilities.
  - tabulated as a normalized function of the incoming and outgoing neutron energy - $f(E \rightarrow E')$
  - Maxwell spectrum - $f(E \rightarrow E') \propto \sqrt{E'} e^{E'/\Theta(E)}$
  - a general evaporation spectrum - $f(E \rightarrow E') \propto E' e^{E'/\Theta(E)}$
  - evaporation spectrum -
  - the energy dependent Watt spectrum - $f(E \rightarrow E') \propto e^{E'/a(E)} \sinh \sqrt{b(E)E'}$ $f(E \rightarrow E') = f\left(E'/\Theta(E)\right)$
  - the Madland Nix spectrum - $f(E \rightarrow E') = \frac{1}{2}\left[g\left(E', \langle K_l \rangle\right) + g\left(E', \langle K_h \rangle\right)\right]$

Inelastic Cross Section C12 on C12



G4NDL
(Geant4 Neutron Data Library)

- The neutron data files for High Precision Neutron models
- The data are including both cross sections and final states.
- The data are derived evaluations based on the following evaluated data libraries (in alphabetic order)
  - Brond-2.1
  - CENDL2.2
  - EFF-3
  - ENDF/B-VI.0, 1, 4
  - FENDL/E2.0
  - JEF2.2
  - JENDL-FF
  - JENDL-3.1,2
  - MENDL-2
- The data format is similar ENDF, however it is not equal to.

Evaluated Nuclear Data File-6

- “ENDF” is used in two meanings
- One is Data Formats and Procedures
  - How to write Nuclear Data files
  - How to use the Nuclear Data files
- The other is name of recommended libraries of USA nuclear data projects.
  - ENDF/B-VI.8
    - 313 isotopes including 5 isomers
    - 15 elements
  - ENDF/B-VII.0
    - Released on 2006 Dec
    - almost 400 isotopes
    - not yet migrated

- After G4NDL3.8 (3.10 is latest) we concentrated translation from ENDF library.
  - No more evaluation by ourselves.

G4NeutornHPorLEModels

- Many elements remained without data for High Precision models.
- Those models make up for such data deficit.
- If the High Precision data are not available for a reaction, then Low Energy Parameterization Models will handle the reaction.
- Those can be used for not only for models (final state generator) but also for cross sections.
- Elastic, Inelastic, Capture and Fission models are prepared.

Thermal neutron scattering from chemically bound atoms

- At thermal neutron energies, atomic translational motion as well as vibration and rotation of the chemically bound atoms affect the neutron scattering cross section and the energy and angular distribution of secondary neutrons.
- The energy loss or gain of incident neutrons can be different from interactions with nuclei in unbound atoms.
- Only individual Maxwellian motion of the target nucleus (Free Gas Model) was taken into account the default NeutronHP models.

Thermal neutron scattering files from the evaluated nuclear data files ENDF/B-VI, Release2

- These files constitute a thermal sub-library
- Use the File 7 format of ENDF/B-VI
- Divides the thermal scattering into different parts:
  - Coherent and incoherent elastic; no energy change
  - Inelastic; loss or gain in the outgoing neutron energy
- The files and NJOY are required to prepare the scattering law S(α , β) and related quantities.

$$\text{Scattering cross section}: \sigma(E \rightarrow E', \mu) = \frac{\sigma_b}{2kT}\sqrt{\frac{E'}{E}}S(\alpha, \beta);$$

$$\text{momentum transfer}: \alpha = \frac{E' + E - 2\sqrt{E'E}\mu}{AkT}, \text{energy transfer}: \beta = \frac{E' - E}{kT}$$

Japanese Evaluated Nuclear Data Library (JENDL) High Energy Files 2004

- JENDL Are been making by the Nuclear Data Evaluation Center of Japan Atomic Energy Agency with the aid of Japanese Nuclear Data Committee
- High Energy Files 2004
  - Neutron- and proton-induced reaction data up to 3 GeV for 66 nuclides.

環境変数　G4RADIOACTIVEDATA　でdata fileのあるディレクトリを指定する
最新版はRadioactiveDecay3.2

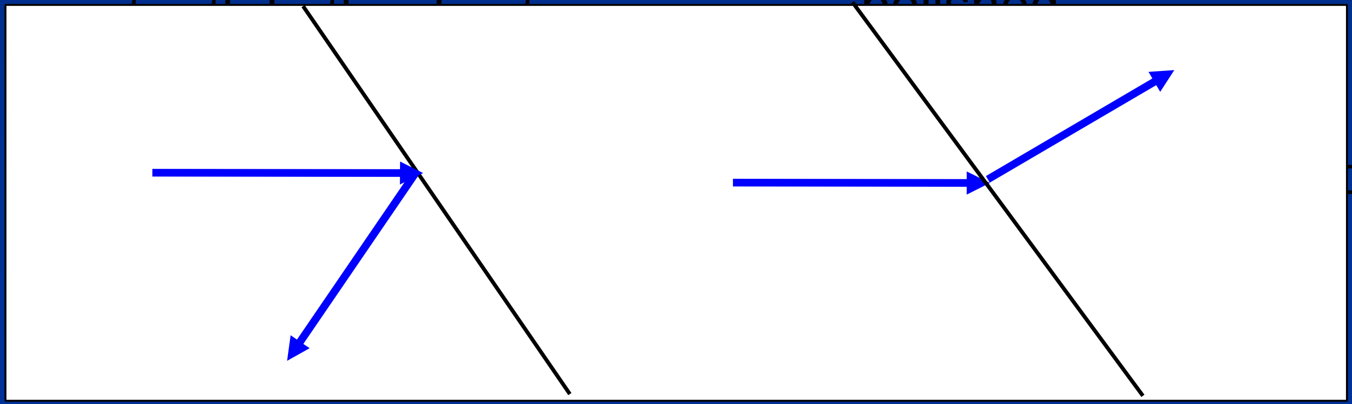
z6.a14 など不安定核について一個ずつファイルがある

Absorption and Rayleigh Scattering

- G4OpAbsorption
  - uses photon attenuation length from material properties to get mean free path
  - photon is simply killed after a selected path length
- G4OpRayleigh
  - elastic scattering including polarization of initial and final photons
  - builds it own private physics table (for mean free path) using G4MaterialTable
  - may only be used for optical photons

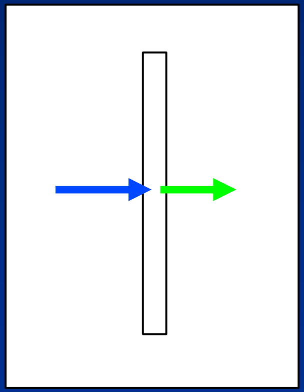
Boundary Interactions

- Handled by G4OpBoundaryProcess
  - refraction
  - reflection
- Geant4 demands particle-like behaviour for tracking:
  - thus, no “splitting”
- User must supply surface properties using G4OpticalSurfaceModel
- Boundary properties
  - dielectric-dielectric
  - dielectric-metal
  - dielectric-black material
- Surface properties:
  - polished
  - d, ...



Wavelength Shifting

- Handled by G4OpWLS
  - initial photon is killed, one with new wavelength is created
  - builds it own physics table for mean free path
- User must supply:
  - absorption length as function of photon energy
  - emission spectra parameters as function of energy
  - time delay between absorption and re-emission



Decay process

The Decay Process

- Derived from G4VRestDiscreteProcess, i.e. decay can happen in-flight or at rest
- Same decay process for all eligible unstable, long-lived particles
  - decay process retrieves BR and decay modes from decay table stored in each particle type
- Different from other physical processes:
  - mean free path for most processes: $\lambda = N\rho\sigma / A$
  - for decay in-flight: $\lambda = \gamma\beta c\tau$
- Available decay modes
  - Phase space:
    - 2-body e.g. $\pi^0 \to \gamma\gamma$, $\Lambda \to p\, \pi^-$
    - 3-body e.g. $K^0_L \to \pi^0\, \pi^+\, \pi^-$
    - many body
  - Dalitz: $P^0 \to \gamma\, l^+\, l^-$
  - Muon decay
    - V – A, no radiative corrections, mono-energetic neutrinos

Specialized Decay Processes

- G4DecayWithSpin
  - produces Michel positron spectrum with 1^{st} order radiative corrections
  - initial muon spin is required
  - propagates spin in magnetic field (precession) over remainder of muon lifetime
- G4UnknownDecay
  - only for “unknown” particles (Higgs, SUSY, etc.)
  - discrete process – only in-flight decays allowed
  - pre-assigned decay channels must be supplied by user or generator

Importing “exotic” particles

- “Exotic” particle means a type of particle that Geant4 physics processes do not know how to deal with and would never generate as a secondary.
  - It is thus not provided as a class in particle category of Geant4 distribution.
  - E.g. Higgs, W/Z boson, SUSY particle, r-hadron, monopole, black hole, etc.
- “Exotic” particle also includes a type of particle that should not be seen outside of a hadron.
  - It is used inside Geant4 processes, but it should not be treated as a track.
  - E.g. quark, gluon.
- Such exotic particle can be imported as a G4PrimaryParticle object.
  - It should have pre-assigned decay products (if it decays), since

Exotic particle that decays immediately

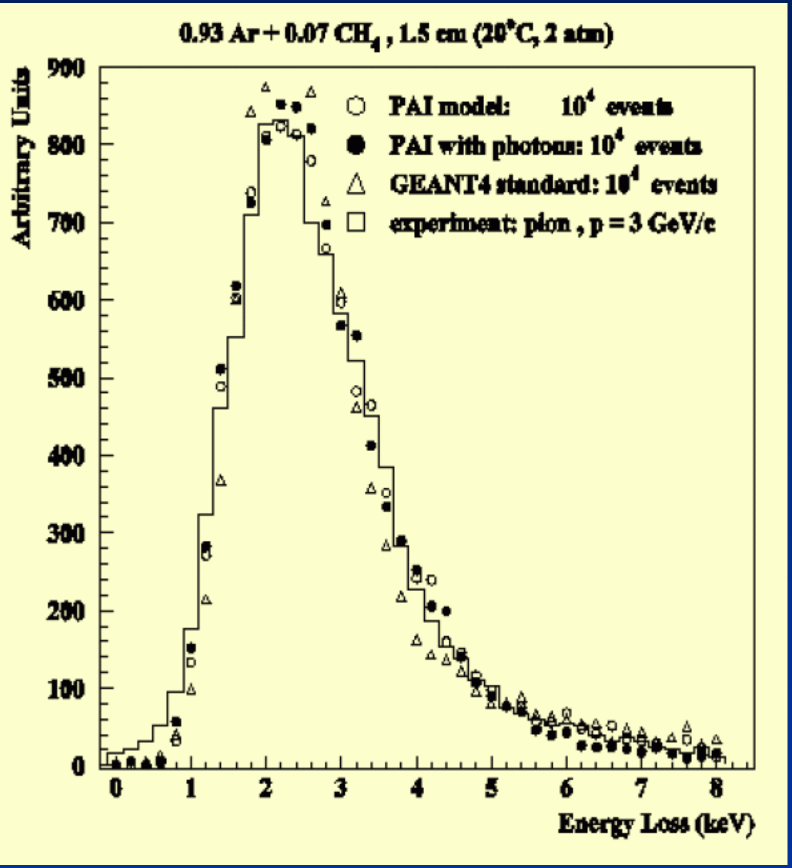
- As a default, Geant4 ignores such exotic particle and takes its pre-assigned decay products as primaries.
  - Anyway, such a particle should not travel through your geometry.
- In case you want to see it as a primary track (so that it has a unique track ID and it is recorded as a trajectory), use G4UnknownParticle.
  - G4UnknownParticle must be defined in your physics list with G4UnknownDecay process attached.
  - G4UnknownDecay process immediately enforces such particle to decay in its first step naively using pre-assigned decay products.
- Once G4UnknownParticle is defined in your physics list, G4PrimaryTransformer converts whatever the exotic particle to a G4Track object of Unknown.
  - If you want to limit this conversion to be applied only to some kinds of exotic particle types, create your own PrimaryTransformer to override a method.

Exotic particle that travels

- As a default, Geant4 cannot deal with such a particle. Geant4 does not know what to do. You have to do the followings to import such exotic particle.
- Implement ParticleDefinition concrete class to represent (a family of) exotic particle(s).
  - Typically one concrete class for each category and each charge state.
    - MyRHadronZero, MyRHadronPlus, etc.
    - BMesonStarPlus, BMesonStarMinus, etc.
  - PDG code in ParticleDefinition object for such exotic particle must be 0, and the mass could be arbitrary value. G4DynamicParticle::GetPDGcode() and G4DynamicParticle::GetMass() will return correct values for each individual track.
- Assign reasonable processes to it.
  - G4Transportation, G4Decay (don't use G4UnknownDecay), EM

Energy loss fluctuations

- Urban model based on a simple model of particle-atom interaction
  - Atoms are assumed to have only two energy levels E1 and E2
  - Particle-atom interaction can be:
    - an excitation of the atom with energy loss E = E1 - E2
    - an ionization with energy loss distribution g(E)~1/E2
- PAI model uses photo absorption data
  - All energy transfers are sampled with production of secondary e- or γ
  - Very slow model, should be applied for sensitive region of detector



X-ray and optical photon simulation

- Standard packages:
  - Cherenkov radiation　　発生はすべてEM、optical photonのレイトレース
  - Synchrotron radiation
  - Transition radiation
  - Scintillation
- Low-energy EM package:
  - Atomic relaxations – fluorescence and Auger transitions
- Optical
  - Reflection
  - Refraction
  - Absorption
  - Rayleigh scattering　　photonに対して

Specialized Decay Processes

- G4DecayWithSpin
  - produces Michel positron spectrum with 1st order radiative corrections
  - initial muon spin is required
  - propagates spin in magnetic field (precession) over remainder of muon lifetime
- G4UnknownDecay
  - only for "unknown" particles (Higgs, SUSY, etc.)
  - discrete process – only in-flight decays allowed
  - pre-assigned decay channels must be supplied by user or generator

Standard と LowE EM

- standard EM
  - cross sectionは、モデル計算
  - 電子の内部状態を考慮しない
  - Ekin > a few keV
- lowE EM
  - cross sectionは、データも使用 (EPDL97/EEDL/EADL)
    - 環境変数　G4LEDATAで指定
  - 電子の内部状態を考慮
  - 特性X線、Auger効果、Rayleigh散乱なども取扱い可
  - Ekin > 250 ev

EM Physics of photon

- *standard*
  - 入射粒子のエネルギーE_{kin} > 1keV
  - 原子・分子の軌道電子は quasi-freeとして扱う
  - 原子核にはエネルギーが与えられない
  - 物質は“均一”、“等方”、“無構造”
  - 断面積は理論式・実験式を使用

EM Physics of photon

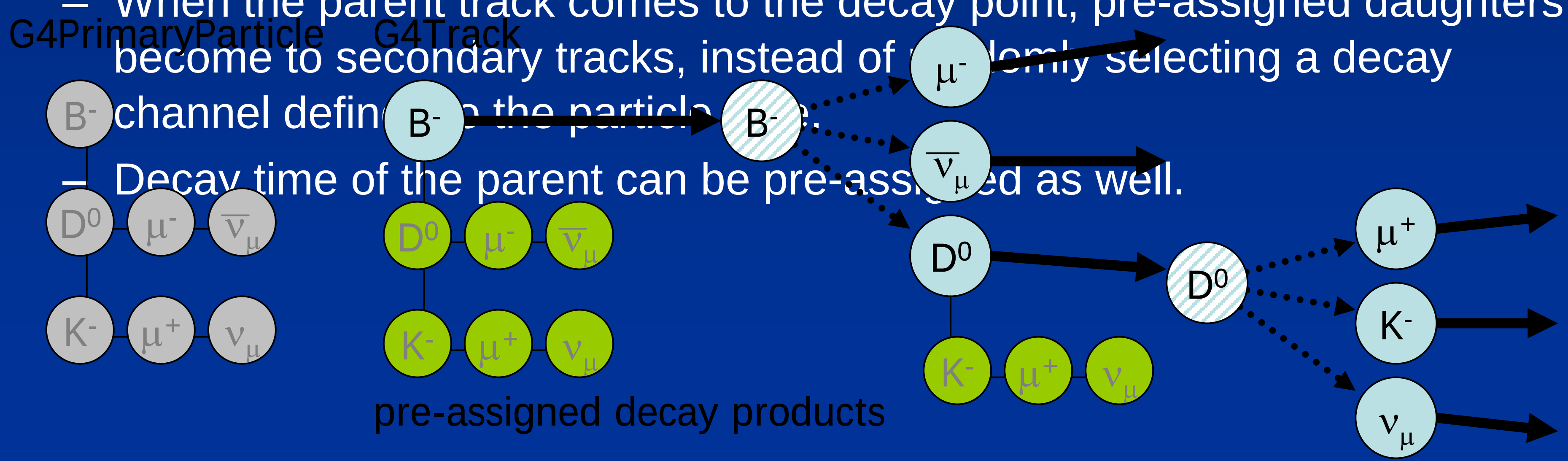
- *lowenergy*
  - 入射粒子のエネルギーE_{kin} > 200eV
  - 束縛エネルギーが無視できない
  - 物質には “構造”がある
  - ガンマ線は偏極も考慮
  - 断面積は理論式･実験式とデータ　ベースを併用
    - **EADL** (Evaluated Atomic Data Library)
    - **EEDL** (Evaluated Electrons Data Library)
    - **EPDL97** (Evaluated Photons Data Library)

hadronics

- Model
  - 一つのプロセス（例えばπ-inelestic）に対して様々な**“model”**を適用できる
  - low_energy: Ｅ＜２０ＧｅＶ
    - *GEANT3.21 GHEISHA compatible*
  - high_energy: Ｅ＞２０ＧｅＶ
    - *GHEISHA High Energy Collision model*
  - theo_high_enregy: Monte Carlo theoretical models
    - parton string model
    - Quantum Molecular Dynamics model
  - cascade: medium energy

Pre-assigned decay products

- Geant4 provides decay modes for long-lived particles, but decay modes for short-lived (e.g. heavy flavour) particles are not provided by Geant4
  - decay process can invoke an external decay handler (G4VExtDecayer)
  - Or, user must "pre-assign" proper lifetime and decay products to the parent G4PrimaryParticle.
- A parent particle in the form of G4Track object travels in the detector, bringing "pre-assigned" decay daughters as objects of G4DynamicParticle.
  - When the parent track comes to the decay point, pre-assigned daughters become to secondary tracks, instead of randomly selecting a decay channel defined to the particle type.
  - Decay time of the parent can be pre-assigned as well.



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