Verification of nuclear capture at rest in G4.

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1. Test29 as a test facility for stopping physics in Geant4.
2. CHIPS universal process G4QCaptureAtRest for negative hadrons.
3. The “aph” ($\bar{p}p$), “apcap” ($\bar{p}A$), and “picap” ($\pi^{-}A$) subdirectories.

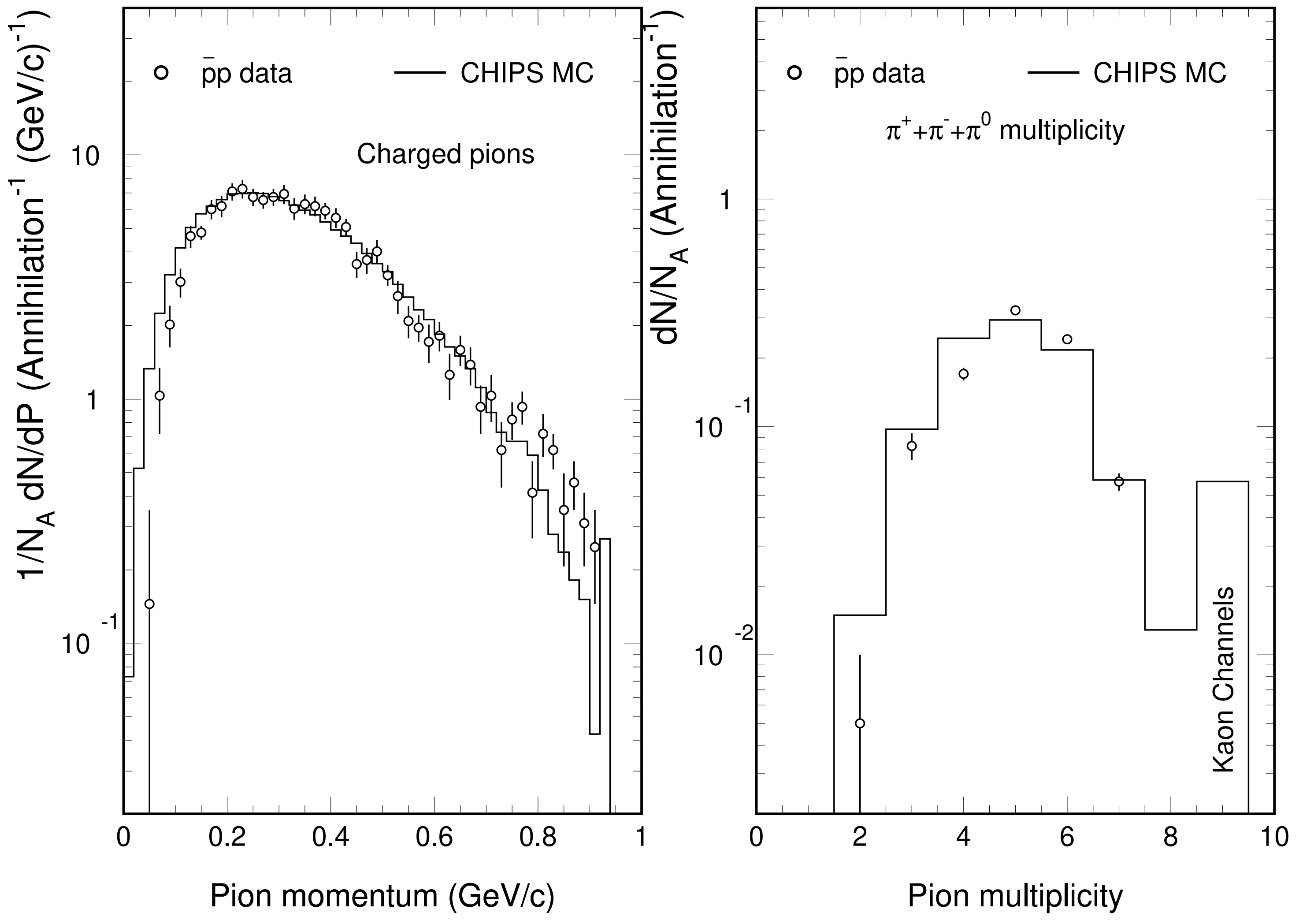
Universal G4QCaptureAtRest CHIPS process for all hadrons.

- CHIPS has universal G4QCaptureAtRest process for all negative hadrons and for μ^- capture, which includes atomic deexcitation;
- CHIPS conserves energy, momentum, charge, and baryon number;
- For checking purposes CHIPS provides a number of neutrons in the target and an internal energy-momentum conservation 4-momentum;
- For testing test29 defines a special (Z, N) monoisotopic G4Element;
- Target nuclei are defined by the 9SPPPNNN code (C12=90006006);
- Projectiles are defined by PDG codes, energy and momentum in MeV;
- virtual projectiles (e.g. γ^*, π^*, or K^*) can have nonzero kinetic energy (if the kinetic energy is 0, it is calculated from the momentum);

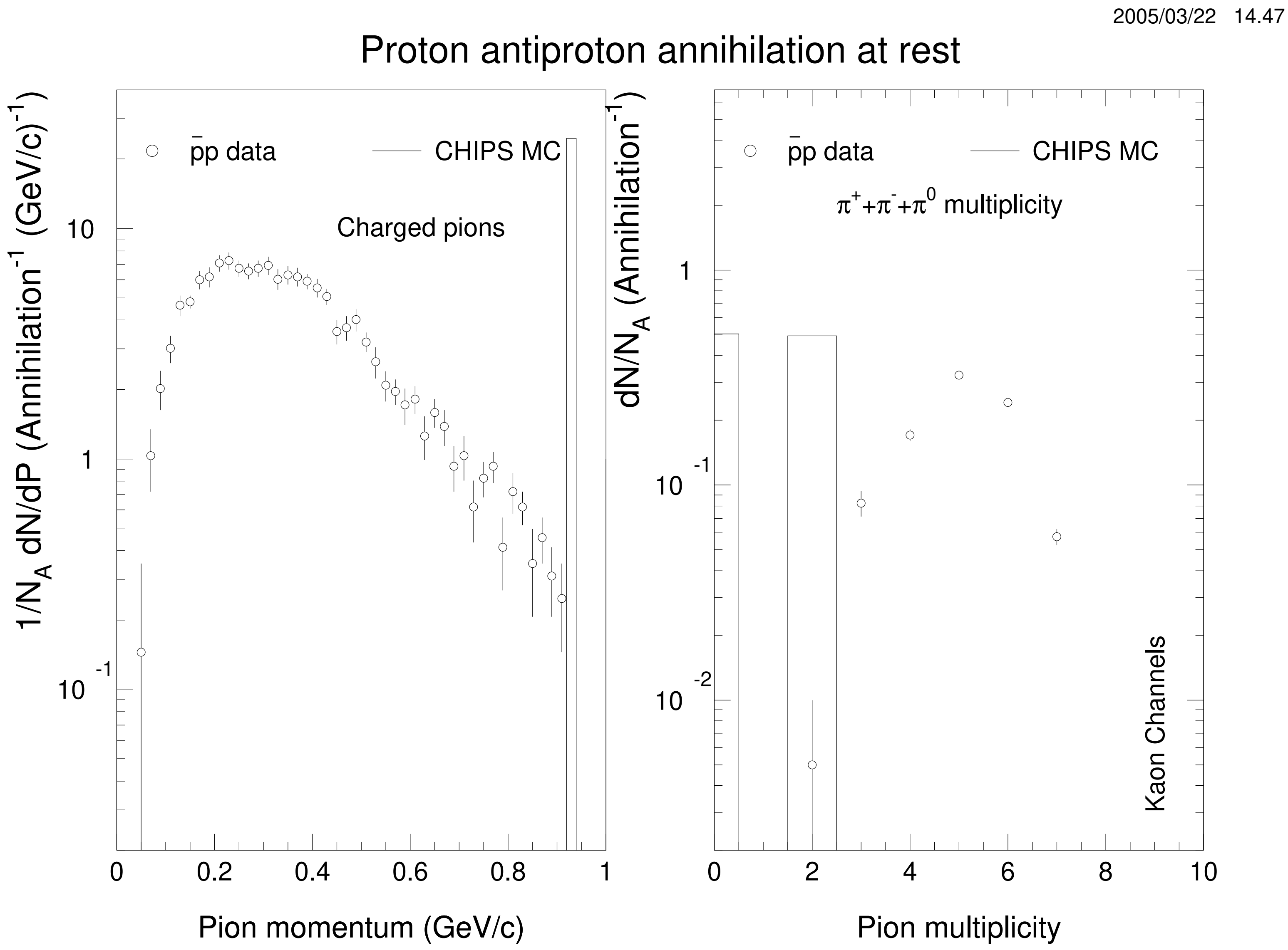
Simulation of $\bar{p}p$ by CHIPS ("aph" subdirectory).

Published in Eur.Phys.J.A8(2000)217,vs.G4AntiProtonAnnihilationAtRest

- This is a reaction with vacuum hadronization (mesons), so there is no Quark Exchange hadronization (nuclear fragments);
- Quark Fusion (vacuum hadronization) is not one-dimensional but 3-dimensional with phase space integrals for kinematic factors;
- Resonances are created as a discrete states for the quark content;
- For hadronic reactions at rest there are only three parameters of CHIPS: a critical temperature T_c, s-suppression, and η-suppression;
- The overall multiplicity is regulated by the temperature parameter T_c;
- The kaon multiplicity is regulated by the s-suppression parameter;
- The η ($\eta^/$) production is regulated by the η-suppression parameter.



p̄p data
CHIPS MC
Charged pions
$1/N_A$ dN/dP (Annihilation^{-1} (GeV/c)$^{-1}$)
10
1
10^{-1}
0
0.2
0.4
0.6
0.8
1
Pion momentum (GeV/c)
p̄p data
CHIPS MC
$\pi^+ + \pi^- + \pi^0$ multiplicity
dN/N_A (Annihilation^{-1})
1
10^{-1}
10^{-2}
Kaon Channels
0
2
4
6
8
10
Pion multiplicity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Proton antiproton annihilation at rest
$\bar{p}p$ data
CHIPS MC
Charged pions
$1/N_A\ dN/dP$ (Annihilation^{-1} (GeV/c)$^{-1}$)
Pion momentum (GeV/c)
$\pi^+ + \pi^- + \pi^0$ multiplicity
dN/N_A (Annihilation^{-1})
Kaon Channels
Pion multiplicity

Non-relativistic evaporation package in CHIPS

Ultra-relativistic phase space of 3D partons:

$$\Phi_n(E) = \int \delta(\sum_{i=1}^{n} E_i - E)\, \delta^3(\sum_{i=1}^{n} \vec{p}_i) \prod_{i=1}^{n} \frac{d^3\vec{p}_i}{2E_i} \propto s^{n-2},$$

$$\frac{dN}{pdE} \propto \left(1 - \frac{2k}{\sqrt{s}}\right)^{n-2}.$$

Non-relativistic phase space of protons and neutrons (no fragments):

$$\tilde{\Phi}_n(W_n) = \int \tilde{\Phi}_{n-1}(W_{n-1})\cdot\delta(W_n - W_{n-1} - T)\sqrt{T}dT\,dW_{n-1} \propto W_n^{\frac{3}{2}n-\frac{5}{2}}$$

$$\frac{dN}{\sqrt{T}dE} \propto \left(1 - \frac{T}{W_n}\right)^{\frac{3}{2}n-4},\ \ W_n\ is\ total\ energy\ of\ n\ nucleons.$$

$$W_A = U \cdot A + E_{\text{excitation}},\ \ U = 1.7\ MeV\ (a\ parameter).$$

Nuclear clusterization parameters

Quark exchange forces clustering nuclei.

$$P_\nu = \frac{C_\nu^a \cdot \omega^{\nu-1}}{(1+\omega)^{a-1}} + \varepsilon_\nu, \quad \omega\ is\ a\ clusterization\ parameter,$$

ε_ν - clusterization on nuclear surface, $\varepsilon_{\nu>2} = 0.$ $\quad a = 1 - \sum_{i=1}^{n} \varepsilon_i$

Parameters found for pion capture in Eur. Phys. J. 9 (2000) 411:

	^{9}Be	^{12}C	^{28}Si	^{59}Co	^{181}Ta
ε_1	0.45	0.40	0.35	0.33	0.33
ε_2	0.15	0.15	0.05	0.03	0.02
ω	5.00	5.00	5.00	5.00	5.00

Inclusive CHIPS, invariant phase space, K-variable.

Baryons (one dimensional consideration of quark exchange):

$$k + M = E + q, \quad k = p - q \quad \rightarrow \quad k = \frac{E - M + p}{2}$$

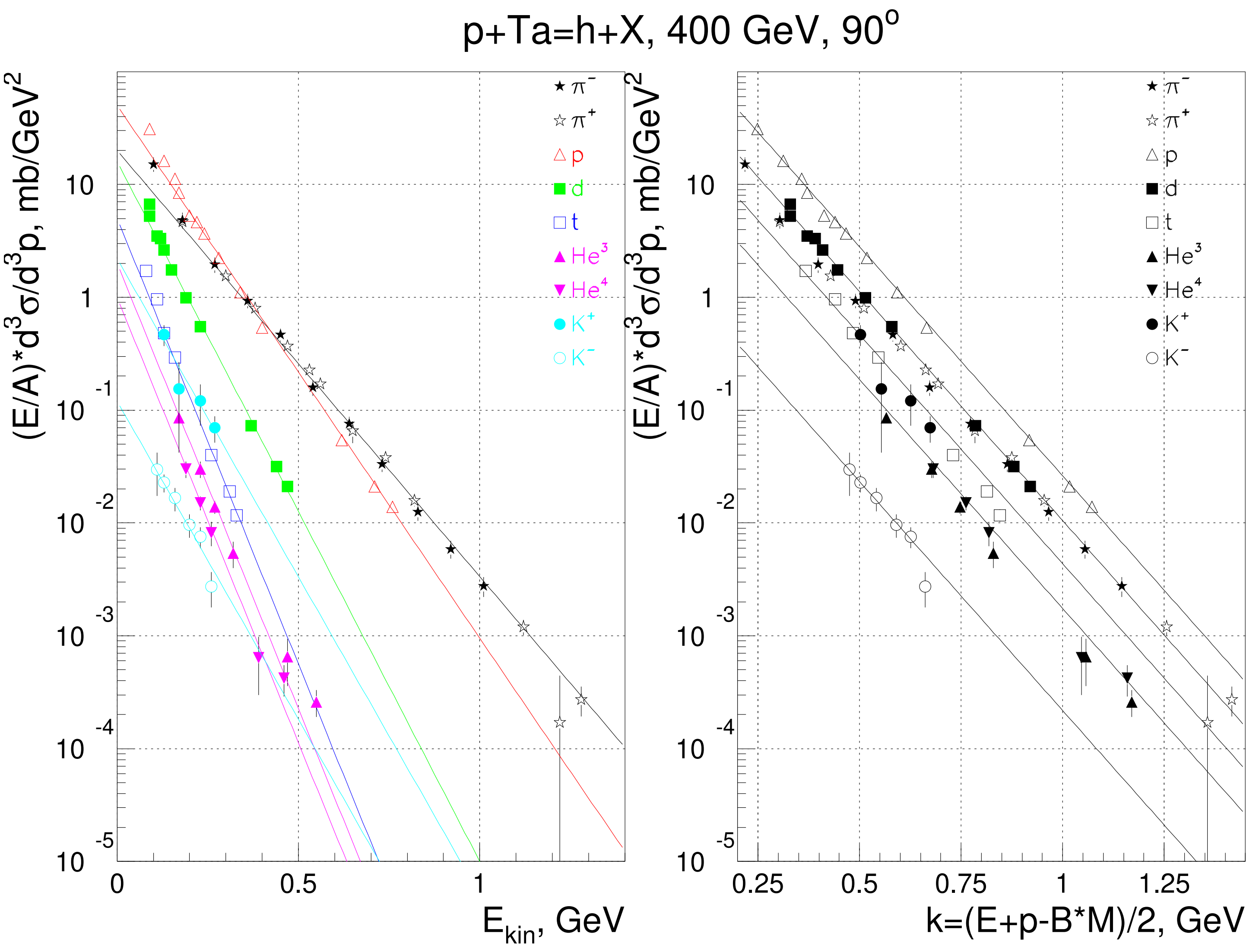
Mesons (one dimensional consideration of quark fusion):

$$k + q = E, \quad k - q = p \quad \rightarrow \quad k = \frac{E + p}{2}$$

Antibaryons (antiquark-antidiquark fusion):

$$k + q = M + E, \quad k - q = p \quad \rightarrow \quad k = \frac{E + M + p}{2}$$

$$\frac{Ed\sigma}{d^3p} \propto \frac{d\sigma}{pdE} \propto EXP\left\{-\frac{(k-\Delta)[1 - v \cdot cos(\theta)]}{T\sqrt{1-v^2}}\right\}$$

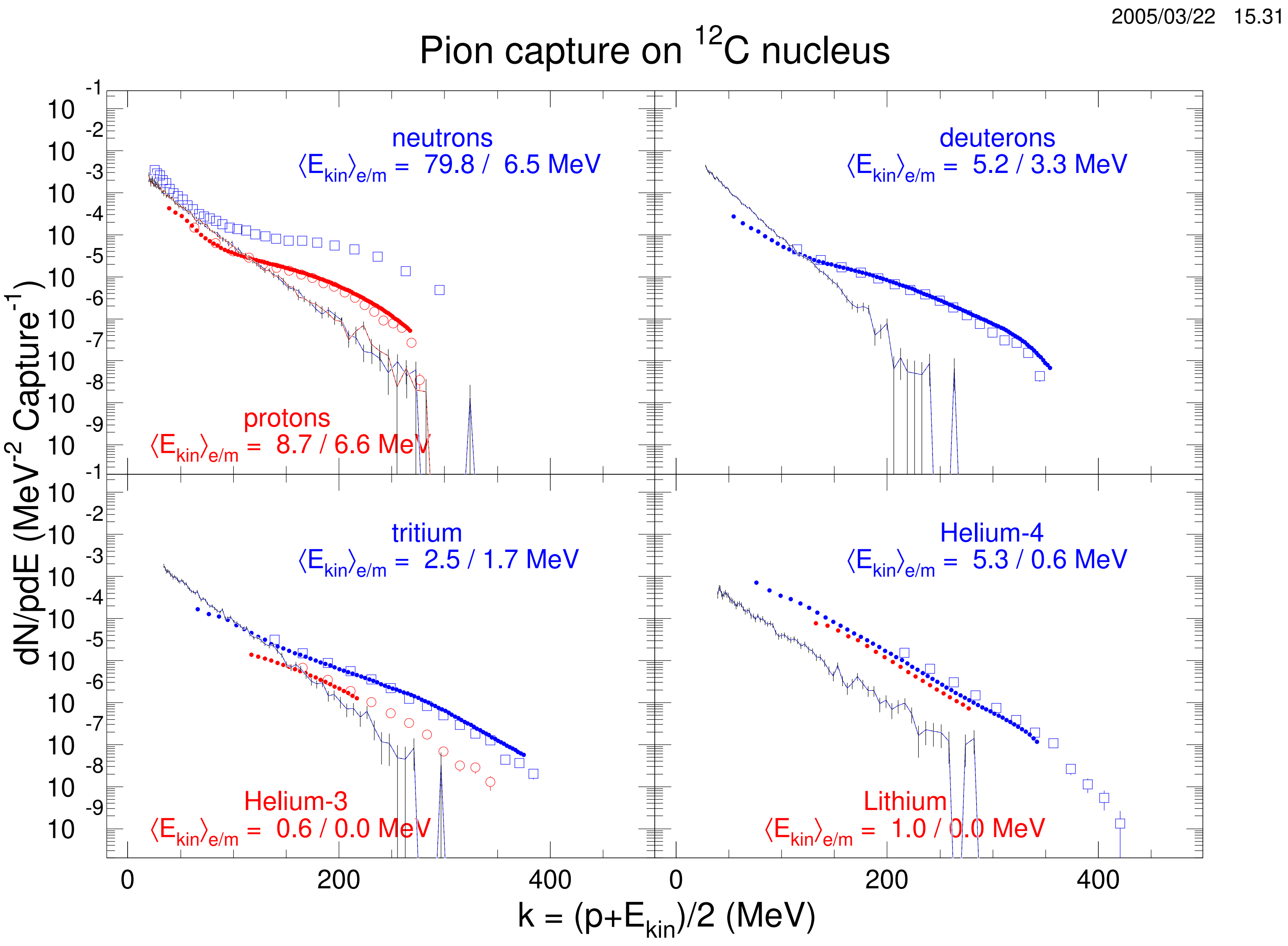

p+Ta=h+X, 400 GeV, 90°
(E/A)*d³σ/d³p, mb/GeV²
E_kin, GeV
k=(E+p-B*M)/2, GeV
π⁻
π⁺
p
d
t
He³
He⁴
K⁺
K⁻
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0
0.5
1
0.25
0.75
1.25

Simulation of $\pi^- A$ by CHIPS ("picap" subdirectory).

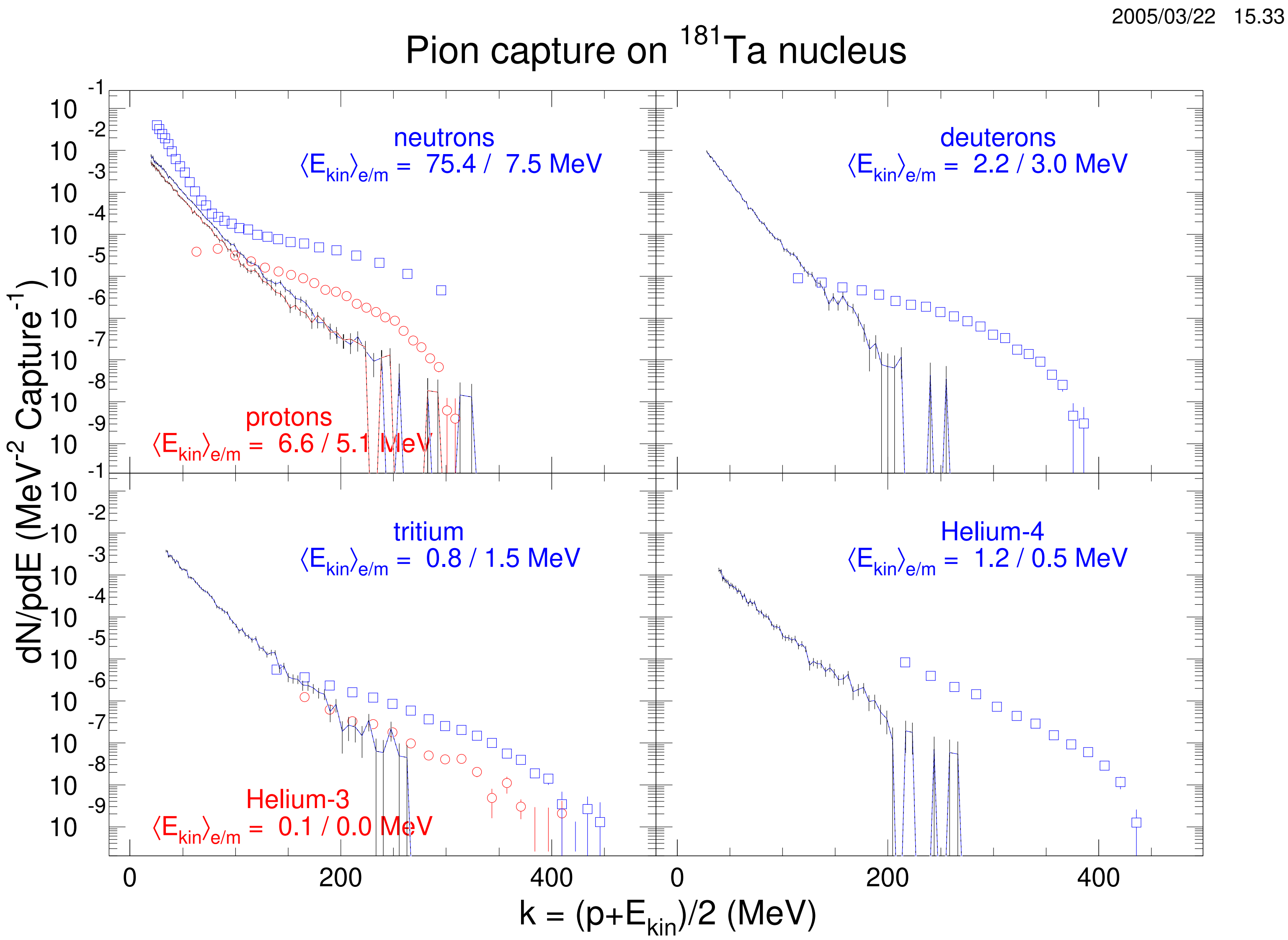
Published in Eur.Phys.J.A9(2000)411(vs.G4PionMinusAbsorptionAtRest)

- Quark Exchange hadronization for nuclear fragments and vacuum hadronization for mesons are defined by a Vacuum/Matter parameter;
- Switching from quark level to baryon level simulation is internal;
- Coulomb Barriers for hadrons and nuclear fragments are internal;
- Virtuallity of intermediate Quasmons is limited by residual nucleons;
- Competition of fragments is defined by phase space kinematic factors;
- The first (initial) interaction of the captured particle can be improved taking into account Fermi momentum of nucleons;
- The Final State Interaction of secondaries can be improved.

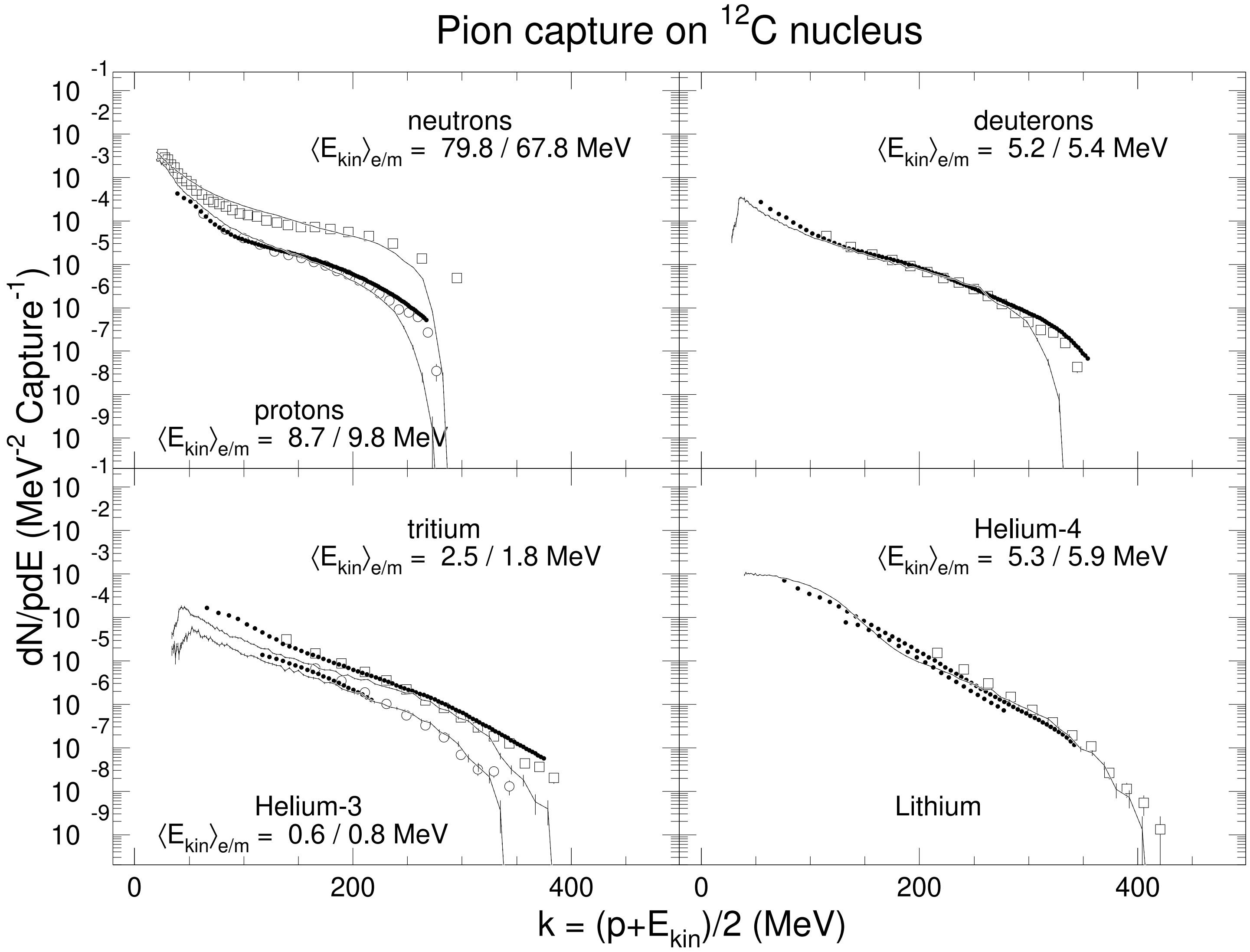
Verification of nuclear capture at rest in G4.

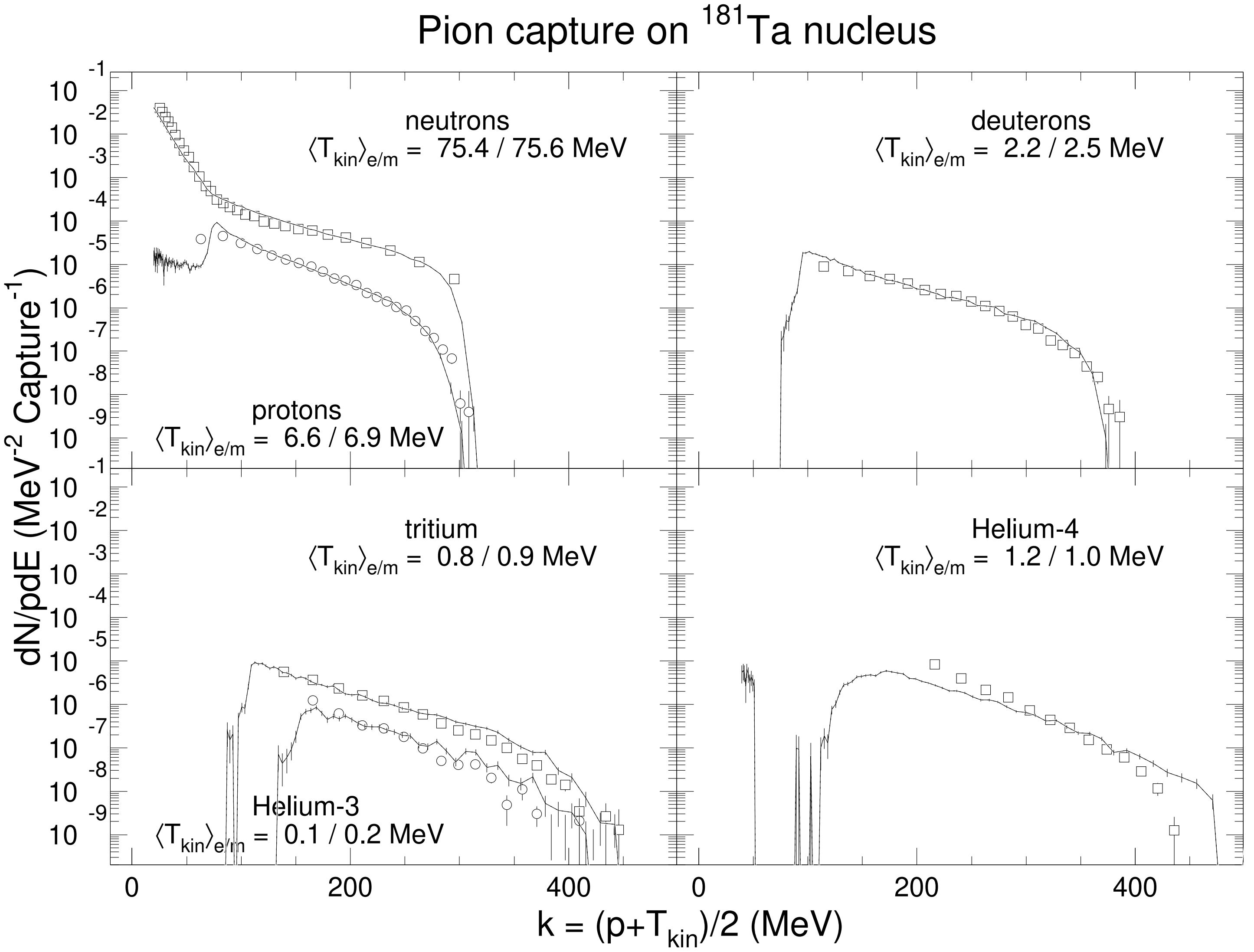


Verification of nuclear capture at rest in G4.



Verification of nuclear capture at rest in G4.




Pion capture on 181Ta nucleus
neutrons
⟨Tkin⟩e/m = 75.4 / 75.6 MeV
protons
⟨Tkin⟩e/m = 6.6 / 6.9 MeV
deuterons
⟨Tkin⟩e/m = 2.2 / 2.5 MeV
tritium
⟨Tkin⟩e/m = 0.8 / 0.9 MeV
Helium-3
⟨Tkin⟩e/m = 0.1 / 0.2 MeV
Helium-4
⟨Tkin⟩e/m = 1.2 / 1.0 MeV
dN/pdE (MeV-2 Capture-1)
k = (p+Tkin)/2 (MeV)
0
200
400

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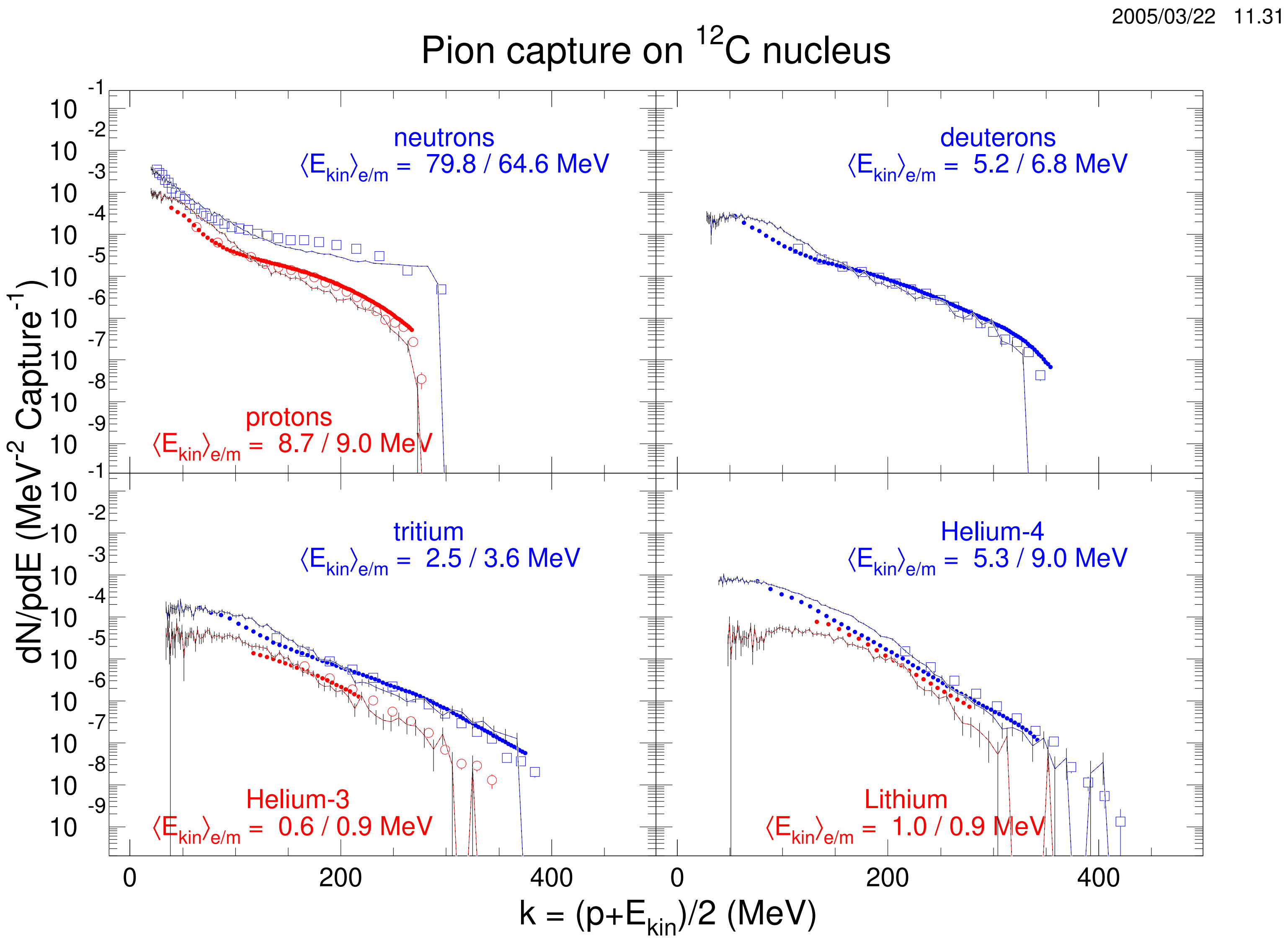
Verification of nuclear capture at rest in G4.



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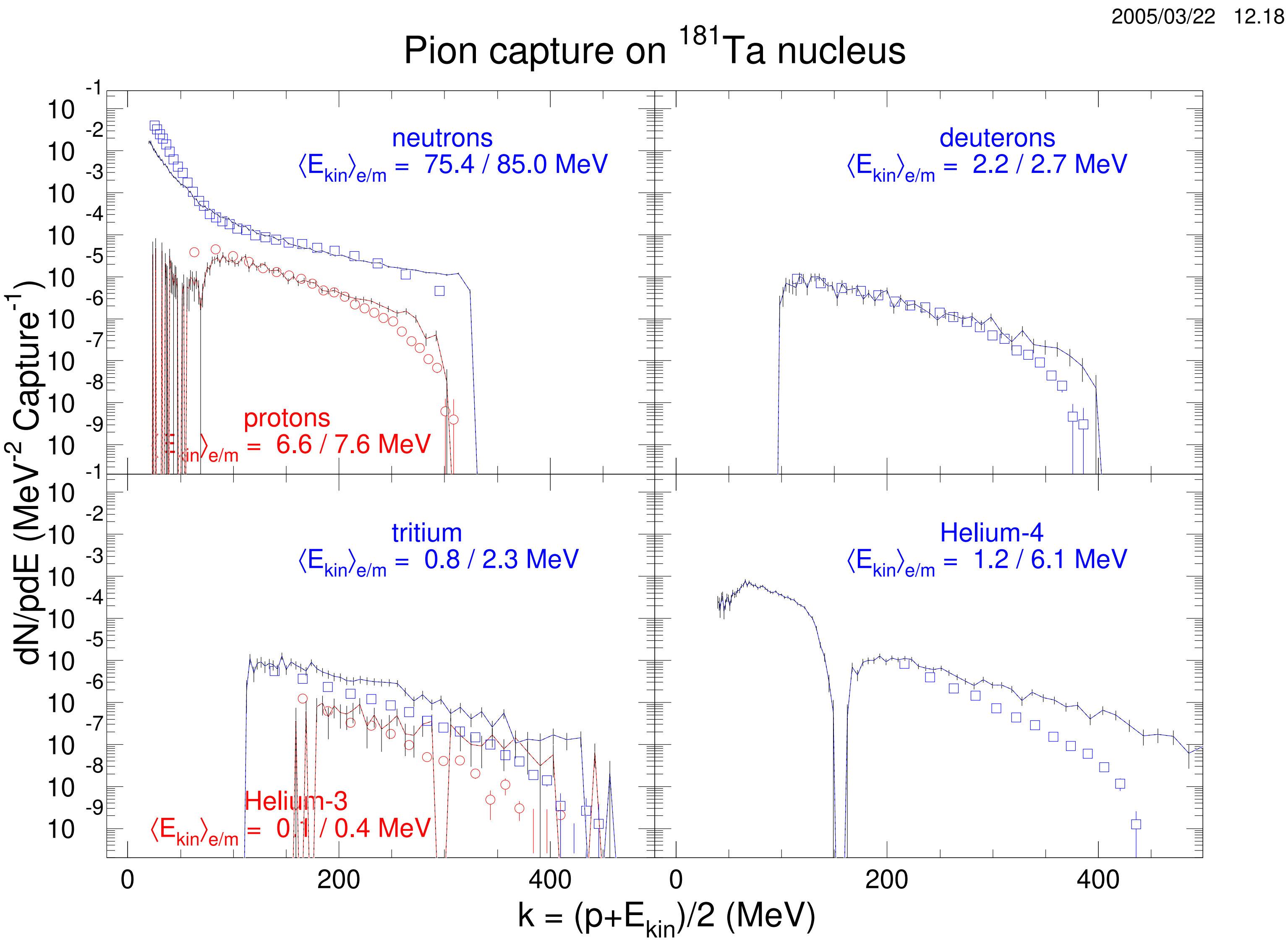
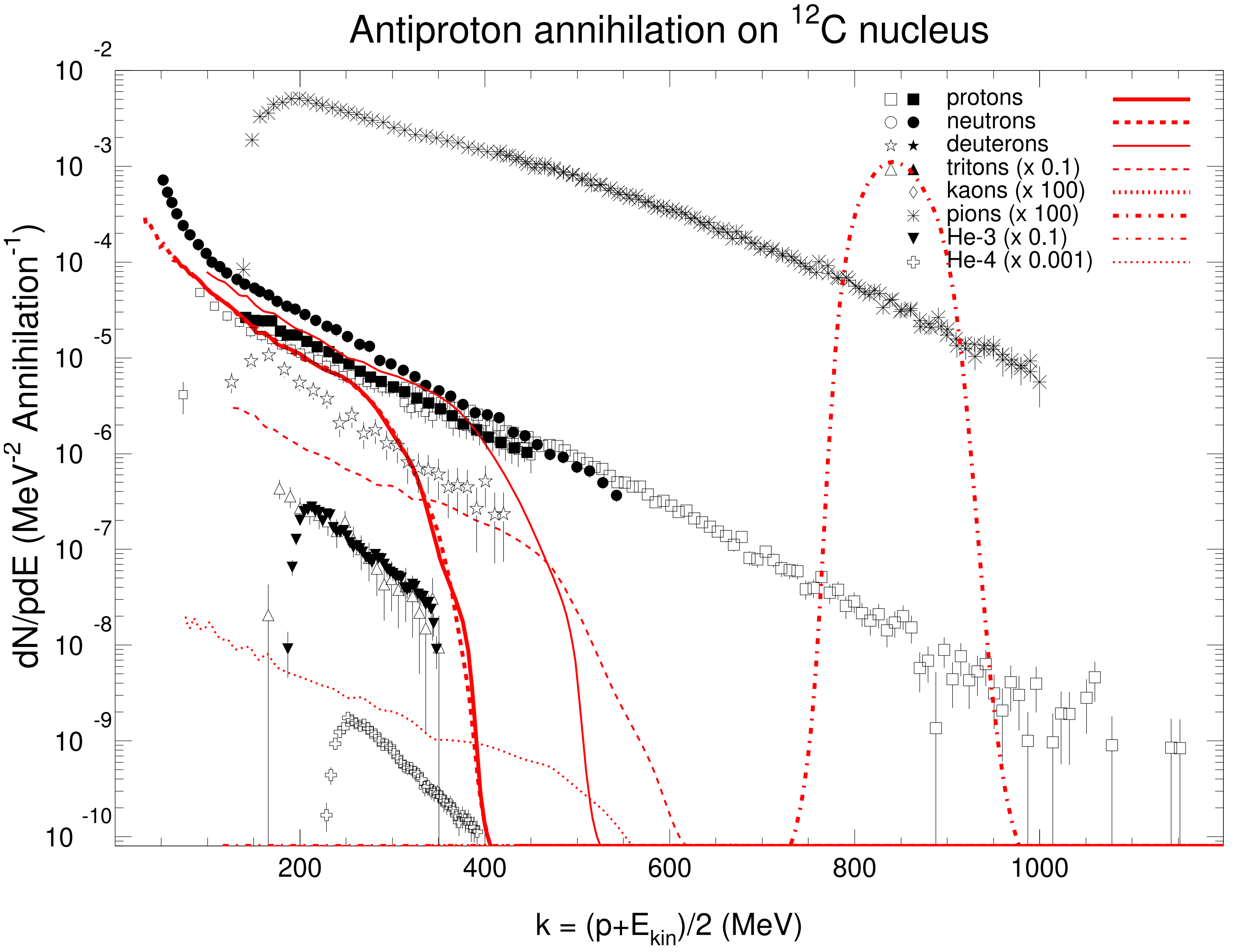
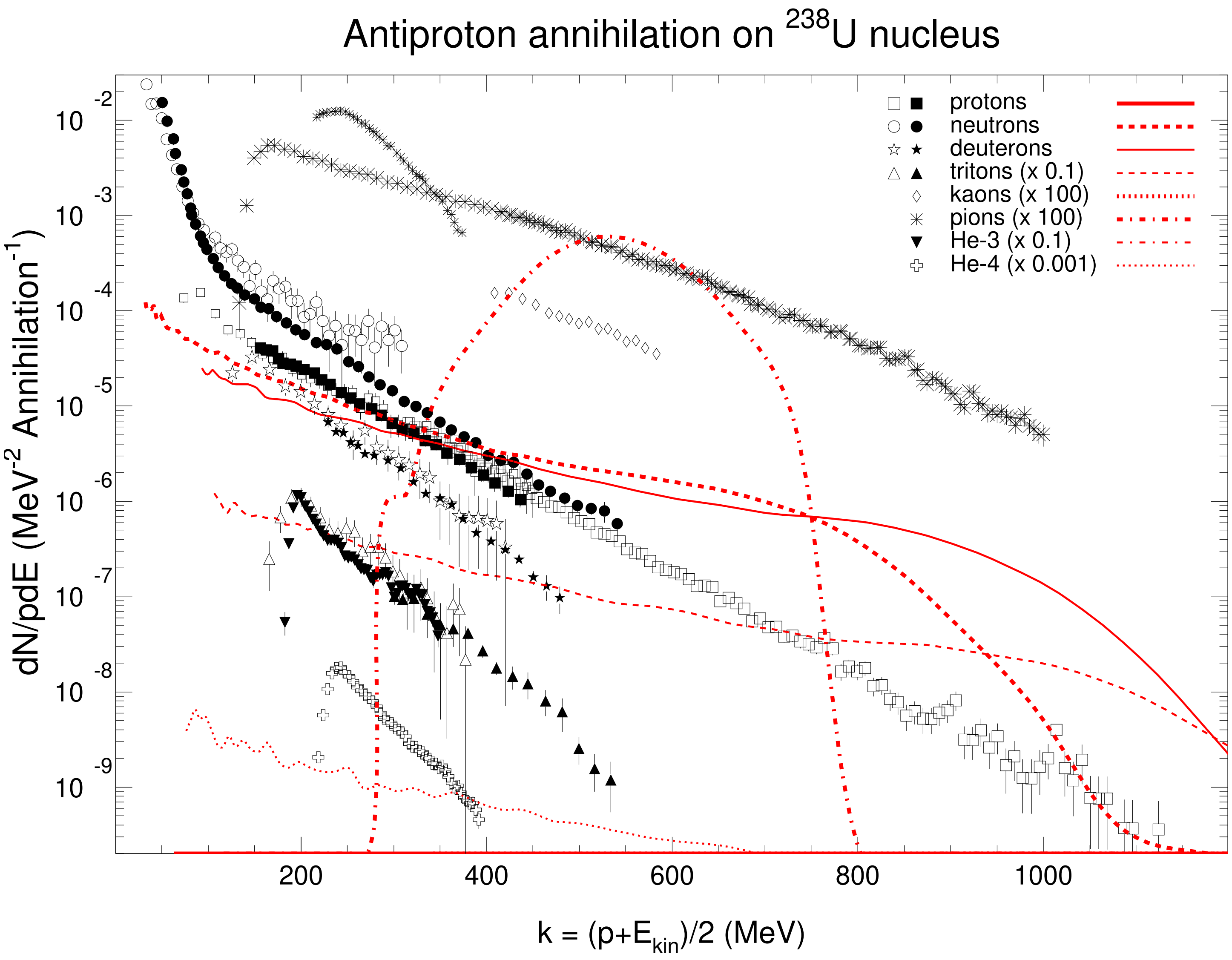

2005/03/22 12.18
Pion capture on 181Ta nucleus
neutrons
⟨Ekin⟩e/m = 75.4 / 85.0 MeV
protons
⟨Ekin⟩e/m = 6.6 / 7.6 MeV
deuterons
⟨Ekin⟩e/m = 2.2 / 2.7 MeV
tritium
⟨Ekin⟩e/m = 0.8 / 2.3 MeV
Helium-3
⟨Ekin⟩e/m = 0.1 / 0.4 MeV
Helium-4
⟨Ekin⟩e/m = 1.2 / 6.1 MeV
dN/pdE (MeV-2 Capture-1)
k = (p+Ekin)/2 (MeV)
0
200
400

CHIPS algorithm for $\bar{p}A$ (“apcap” subdirectory).

Compared with the G4AntiProtonAnnihilationAtRest process of GHAD.

- $\bar{p}N$ annihilation happens on periphery of the target nucleus;
- Beyond a Solid Angle secondary mesons are going to output;
- Secondary mesons are captured inside the Solid Angle;
- They make multi-quasmon excitation in the residual nucleus;
- Quark Exchange between each quasmon in a loop with clusters of the residual nucleus provides secondary quark-level fragments;
- If the quark-level hadronization is exhausted, evaporation starts;
- If the residual nucleus is far from the lane of stability, CHIPS makes a fast cascade of n, p, or α decays to avoid short living isotopes.


Antiproton annihilation on 12C nucleus
dN/pdE (MeV-2 Annihilation-1)
k = (p+Ekin)/2 (MeV)
protons
neutrons
deuterons
tritons (x 0.1)
kaons (x 100)
pions (x 100)
He-3 (x 0.1)
He-4 (x 0.001)
200
400
600
800
1000


Antiproton annihilation on 238U nucleus
protons
neutrons
deuterons
tritons (x 0.1)
kaons (x 100)
pions (x 100)
He-3 (x 0.1)
He-4 (x 0.001)
dN/pdE (MeV-2 Annihilation-1)
k = (p+Ekin)/2 (MeV)
200
400
600
800
1000
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9

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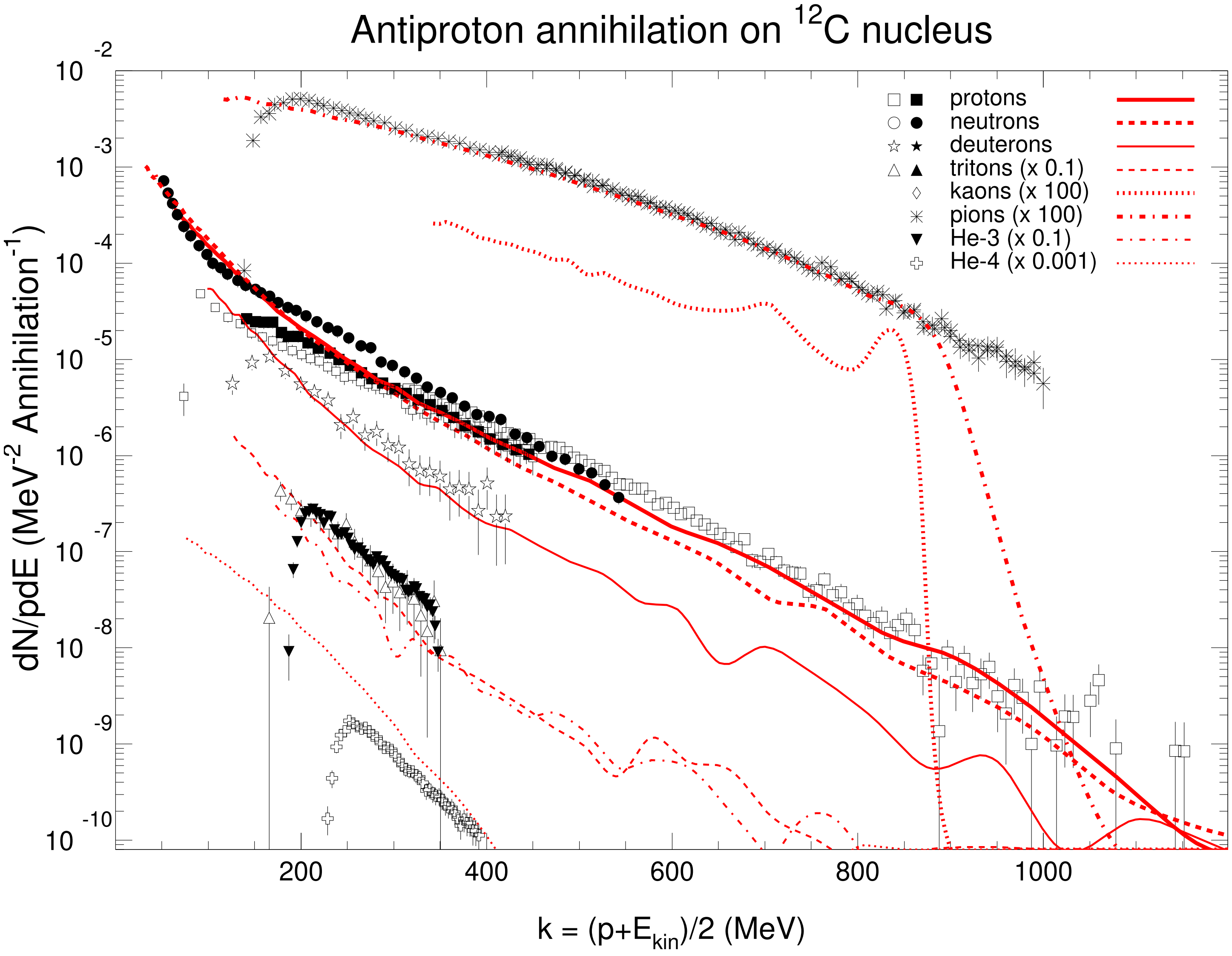
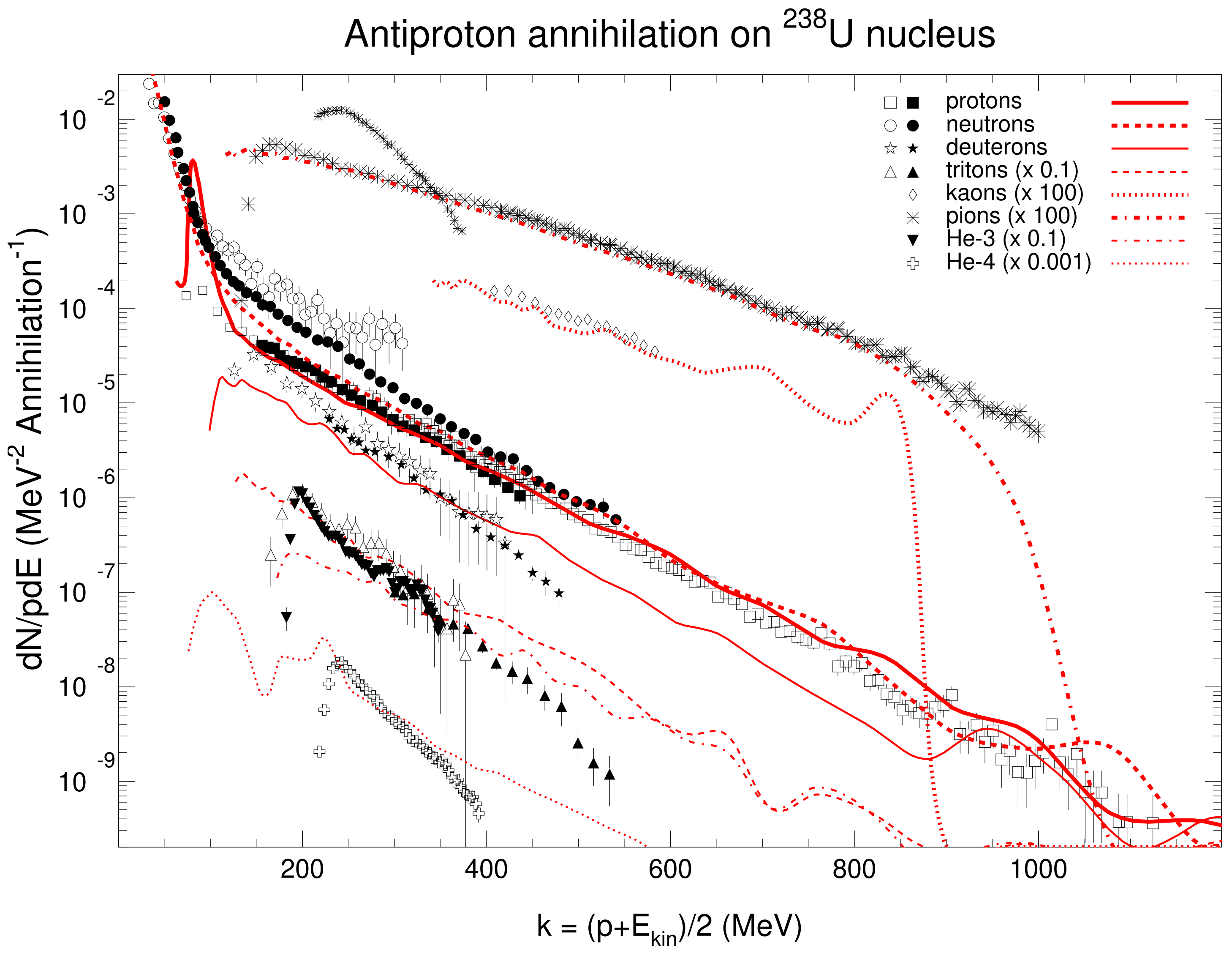

Antiproton annihilation on ^{12}C nucleus
dN/pdE (MeV^{-2} Annihilation^{-1})
k = (p+E$_{kin}$)/2 (MeV)
protons
neutrons
deuterons
tritons (x 0.1)
kaons (x 100)
pions (x 100)
He-3 (x 0.1)
He-4 (x 0.001)
200
400
600
800
1000
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}



Antiproton annihilation on ^{238}U nucleus
protons
neutrons
deuterons
tritons (x 0.1)
kaons (x 100)
pions (x 100)
He-3 (x 0.1)
He-4 (x 0.001)
dN/pdE (MeV^{-2} Annihilation^{-1})
k = (p+E$_{kin}$)/2 (MeV)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
200
400
600
800
1000

Conclusion

- CHIPS provides reasonable simulation of spectra of nuclear fragments;
- Agreement with data is good both in the evaporation and in the quark-level energy ranges of secondary nucleons and fragments;
- Improvement of production of secondary soft mesons is necessary;
- Existing GHAD stopping processes are faster than G4QCaptureAtRest process but do not conserve quantum numbers and 4-momentum providing wrong hadronic spectra especially for nuclear fragments;
- $p\bar{p}$, $\bar{p}A$, $\pi^- A$ subdirectories can be used as examples for new tests;
- The default versions of test29 simulates all hadrons and nuclei in a loop, and is used for the performance test of G4QCaptureAtRest;
- New tests at least for μ^- and K^- capture must be done.

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