Verification of nuclear capture at rest in G4.

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July 18, 2006

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.

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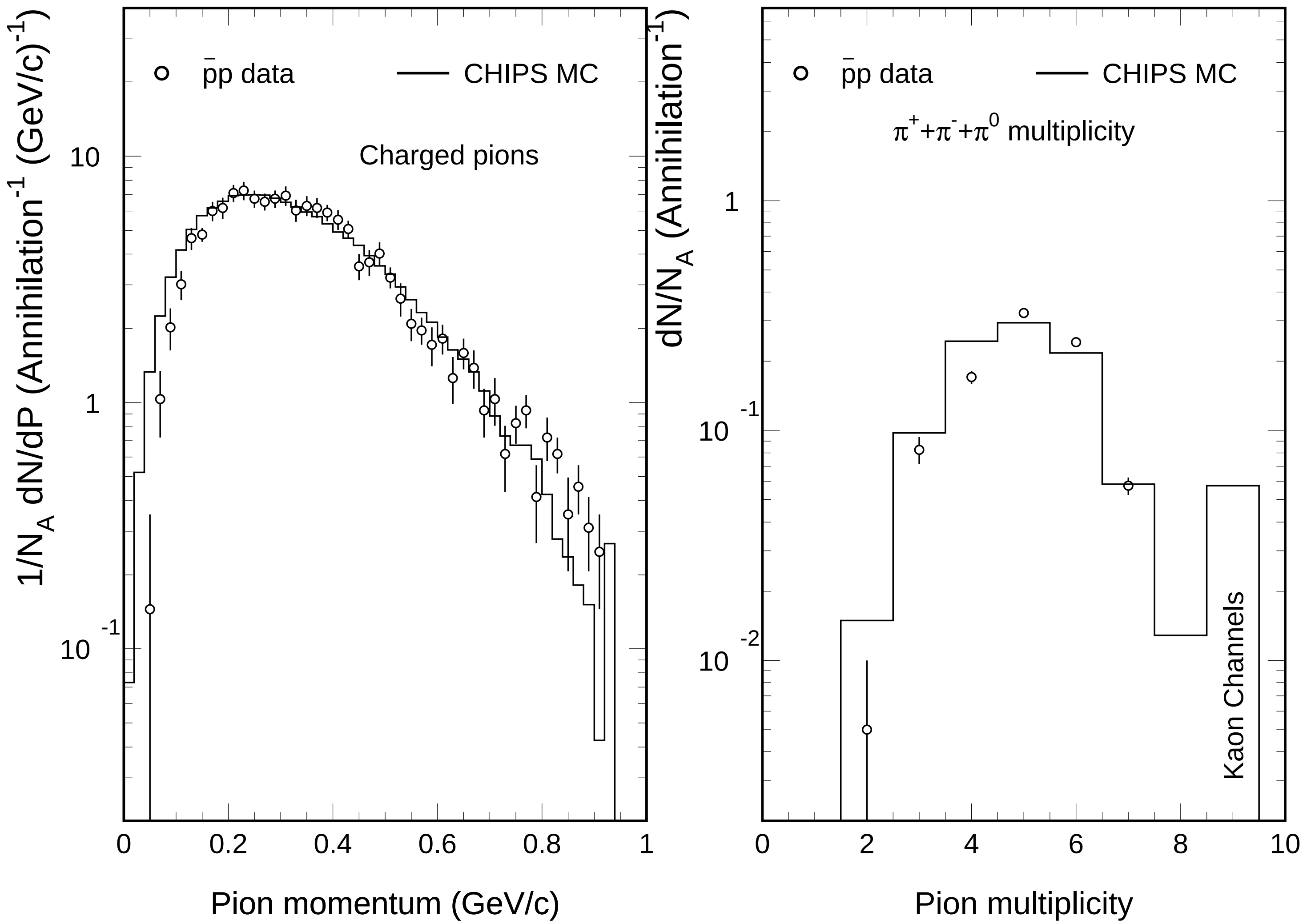

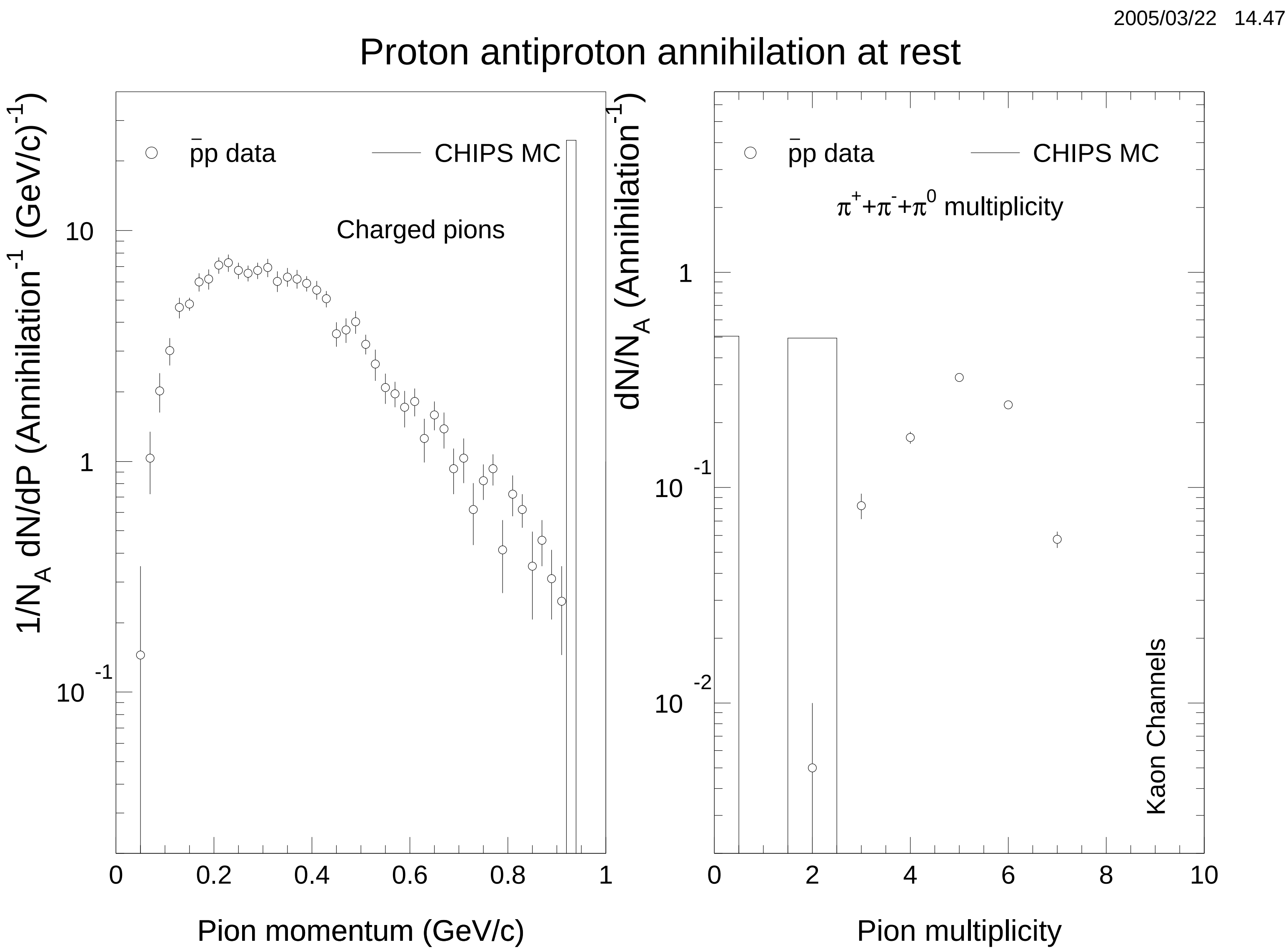
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Proton antiproton annihilation at rest
p̄p data
CHIPS MC
Charged pions
1/N_A dN/dP (Annihilation^-1 (GeV/c)^-1)
Pion momentum (GeV/c)
π+ + π- + π0 multiplicity
Kaon Channels
dN/N_A (Annihilation^-1)
Pion multiplicity

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):

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

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

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

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

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Inclusive CHIPS, invariant phase space, K-variable.

Baryons (one dimensional consideration of quark exchange):

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

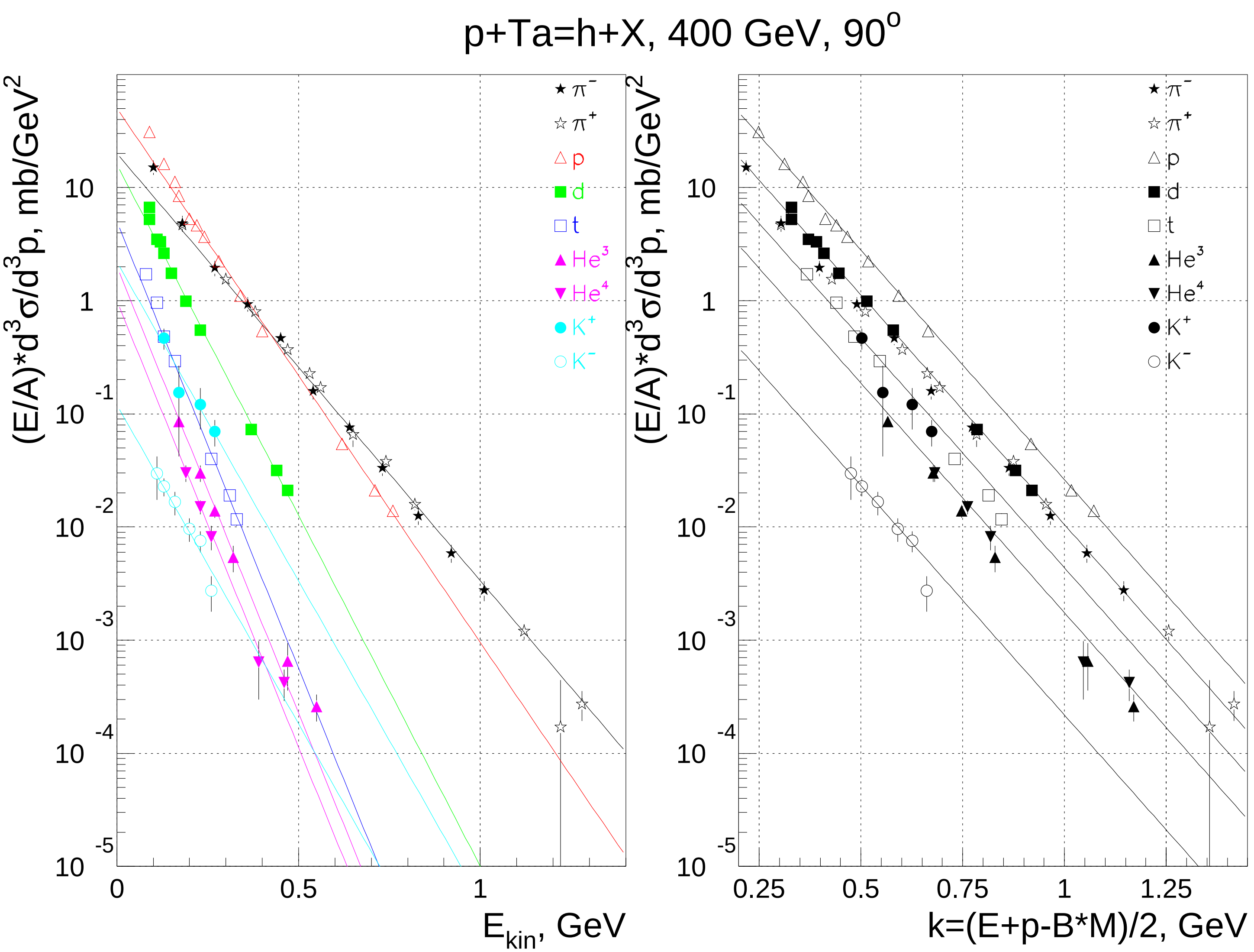
Mesons (one dimensional consideration of quark fusion):

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

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
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0
0.5
1
E_kin, GeV
π⁻
π⁺
p
d
t
He³
He⁴
K⁺
K⁻
0.25
0.5
0.75
1
1.25
k=(E+p-B*M)/2, GeV

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.

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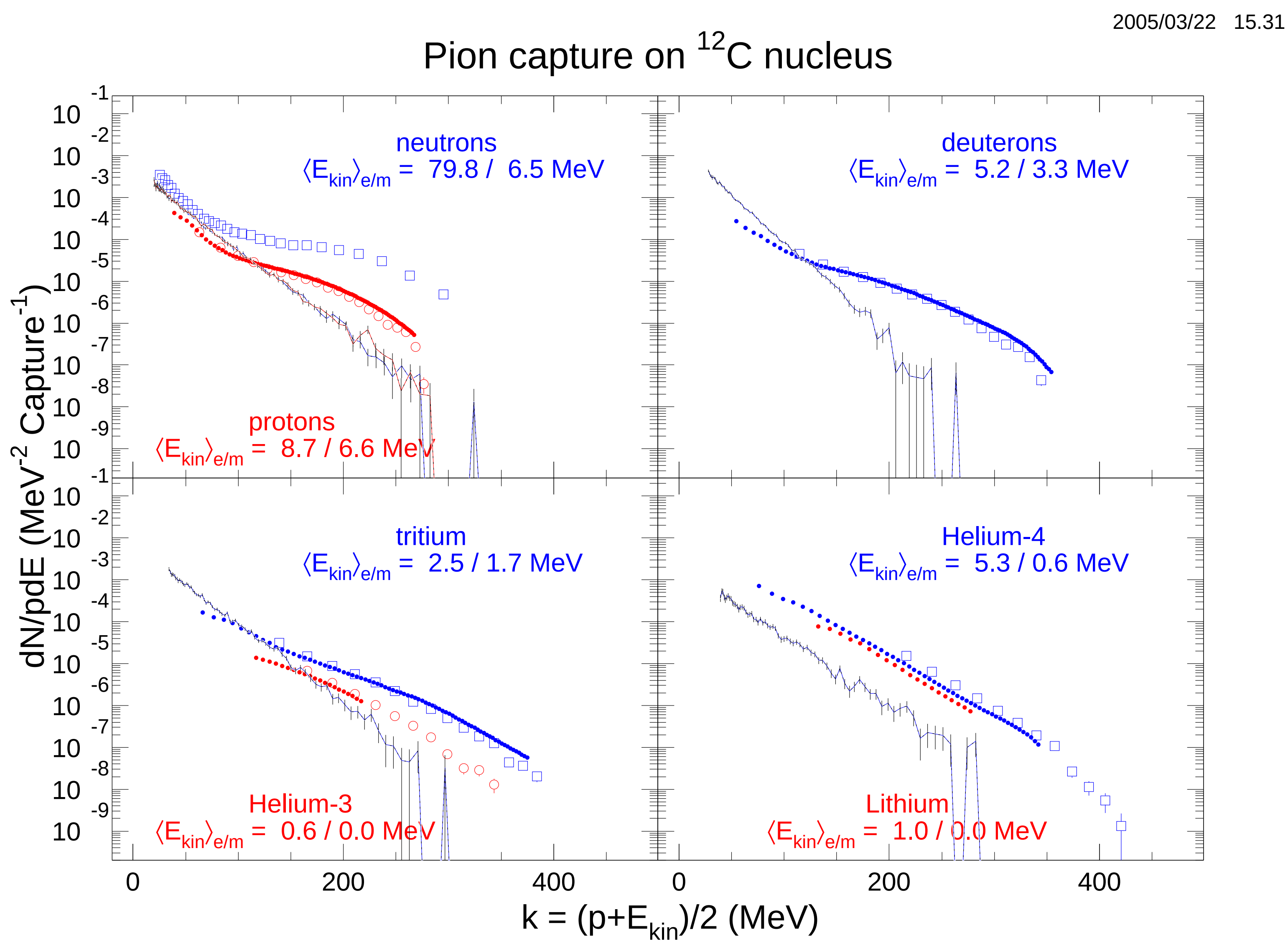
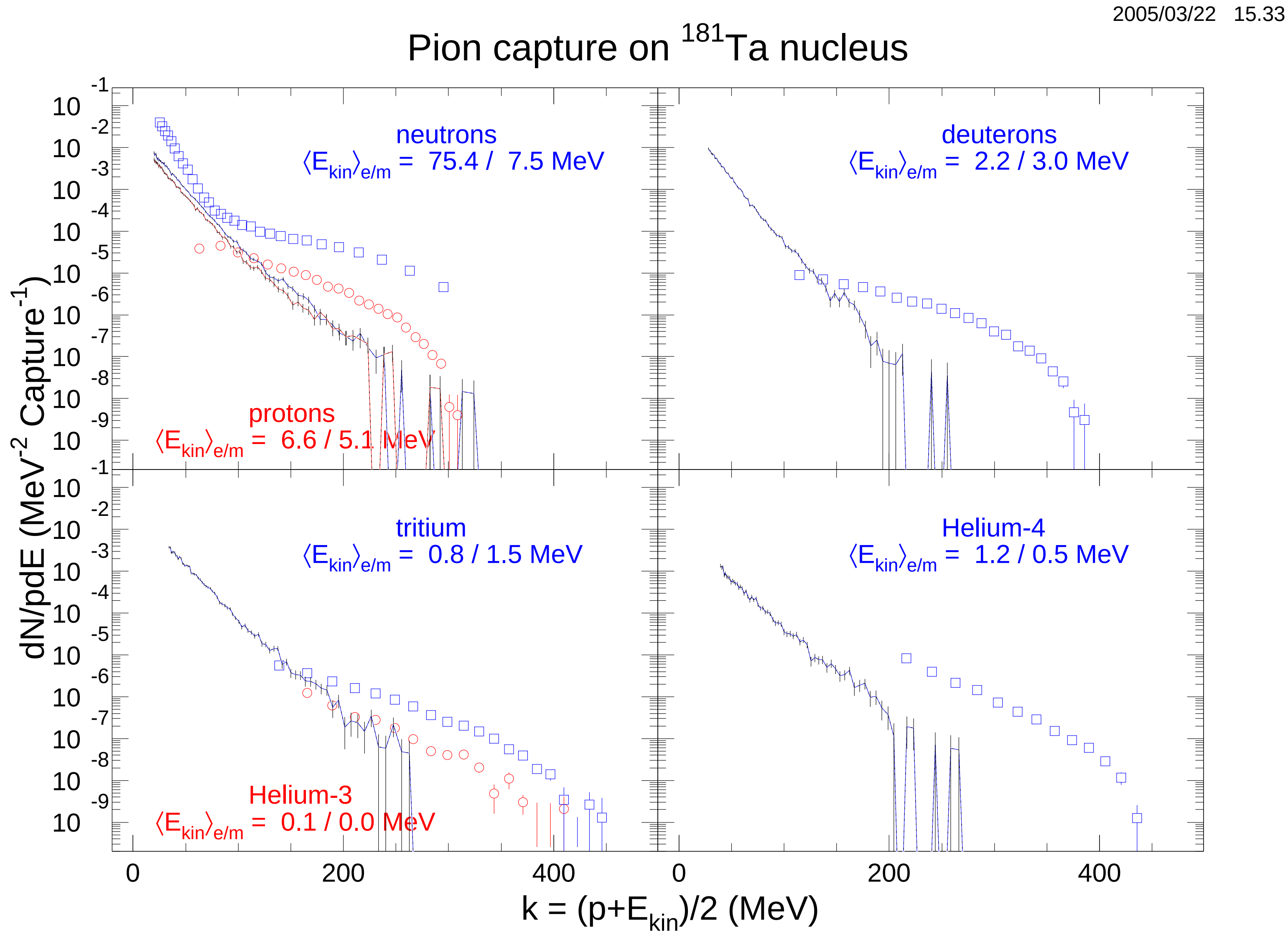
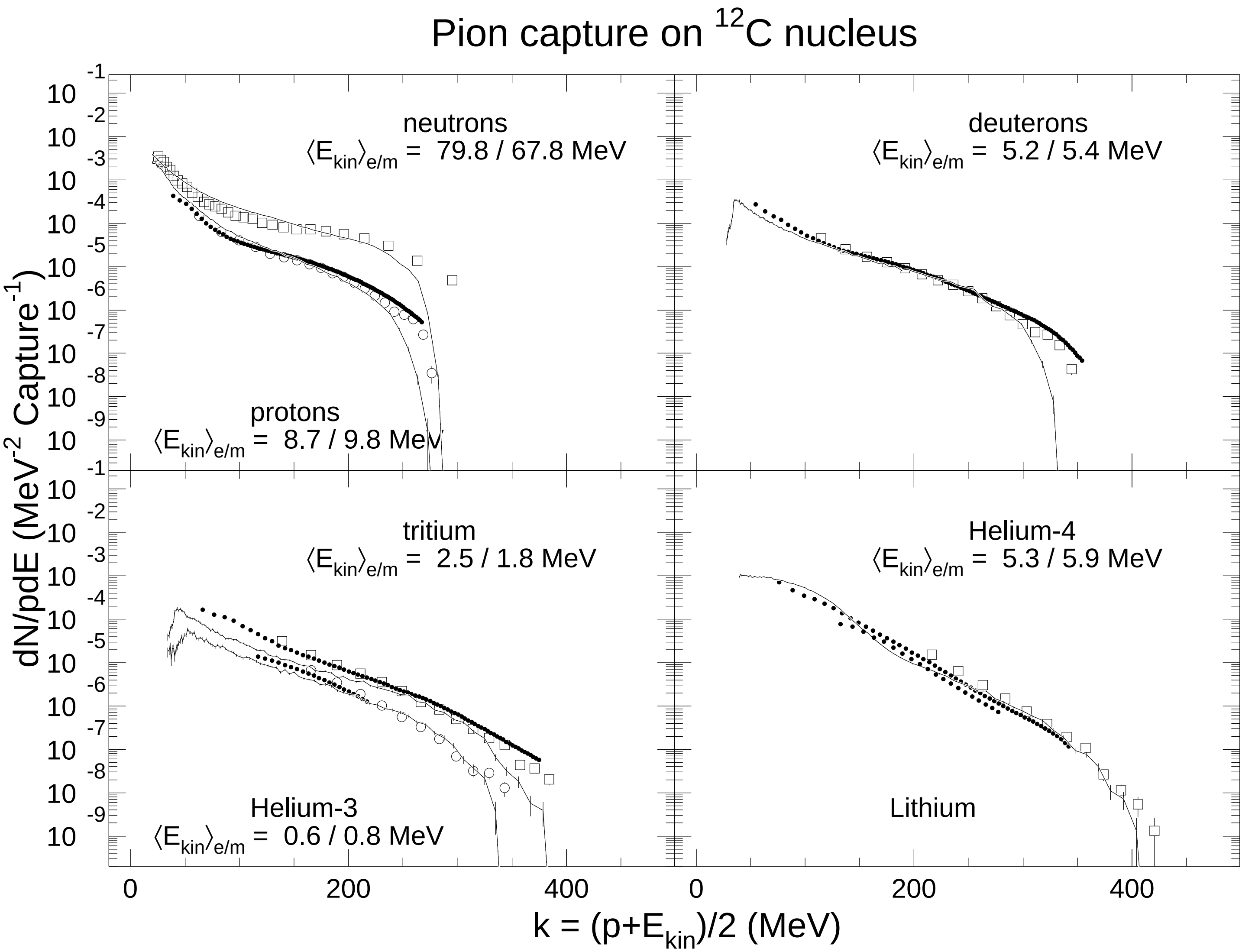
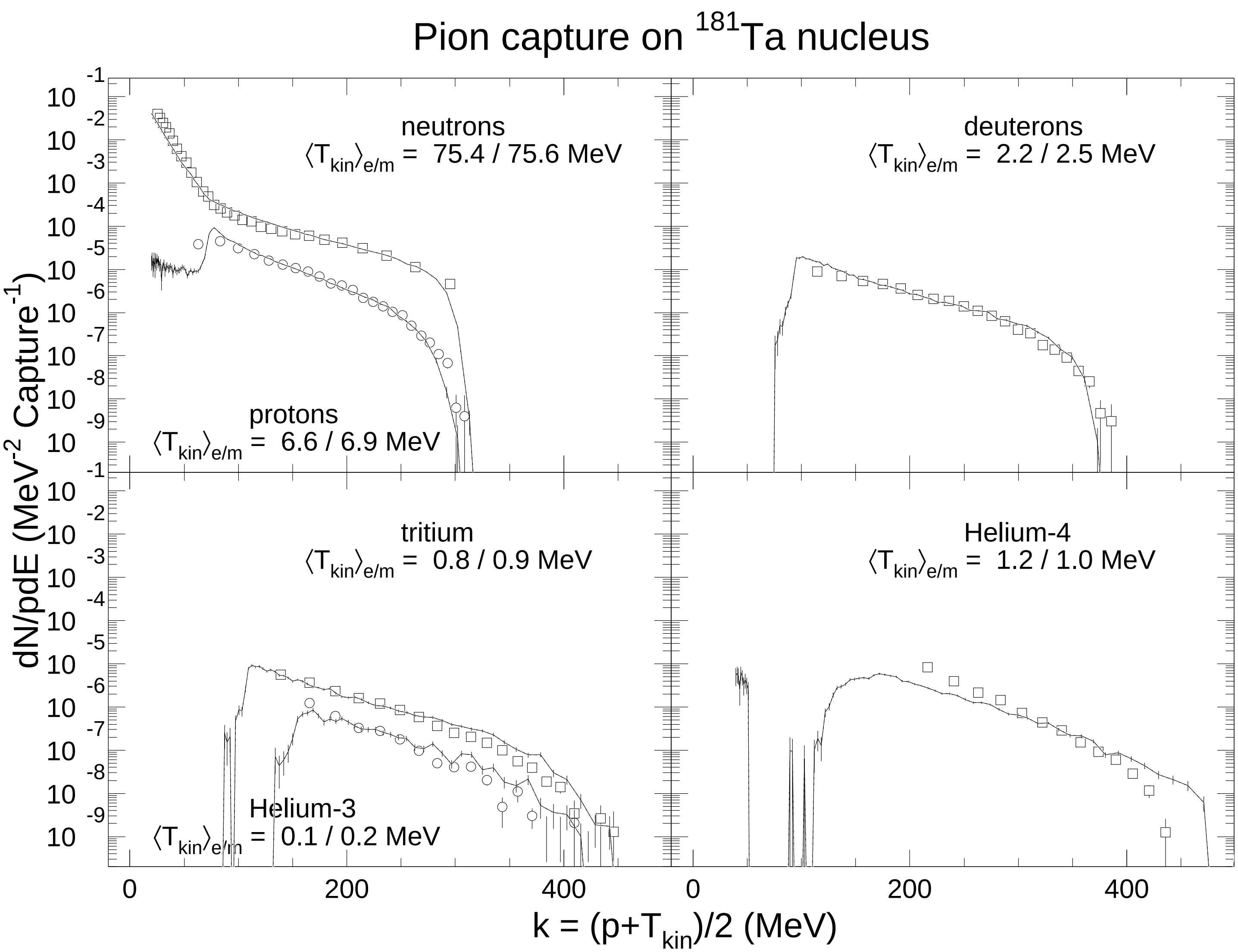


Verification of nuclear capture at rest in G4.

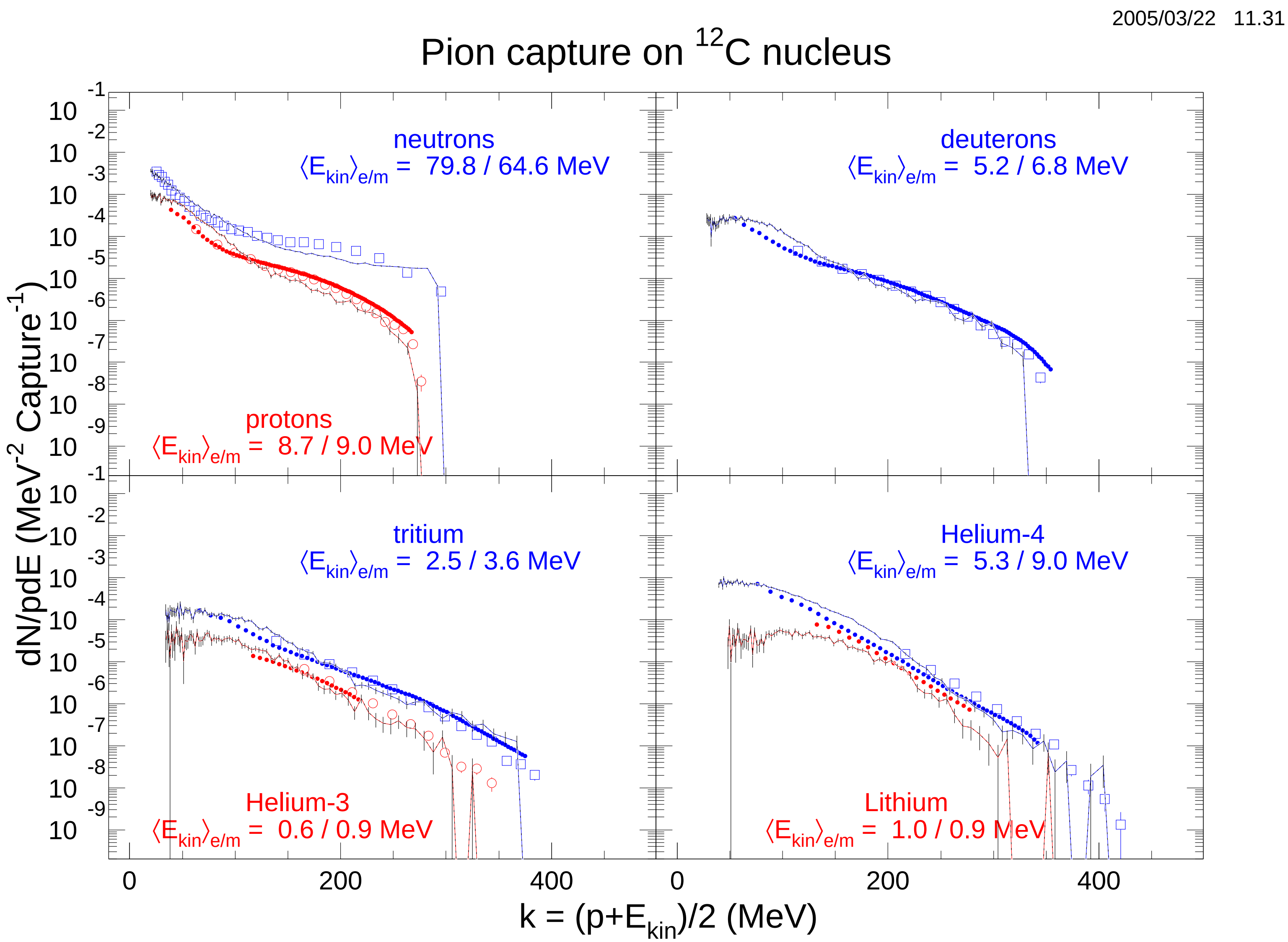


Verification of nuclear capture at rest in G4.




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
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9

Verification of nuclear capture at rest in G4.



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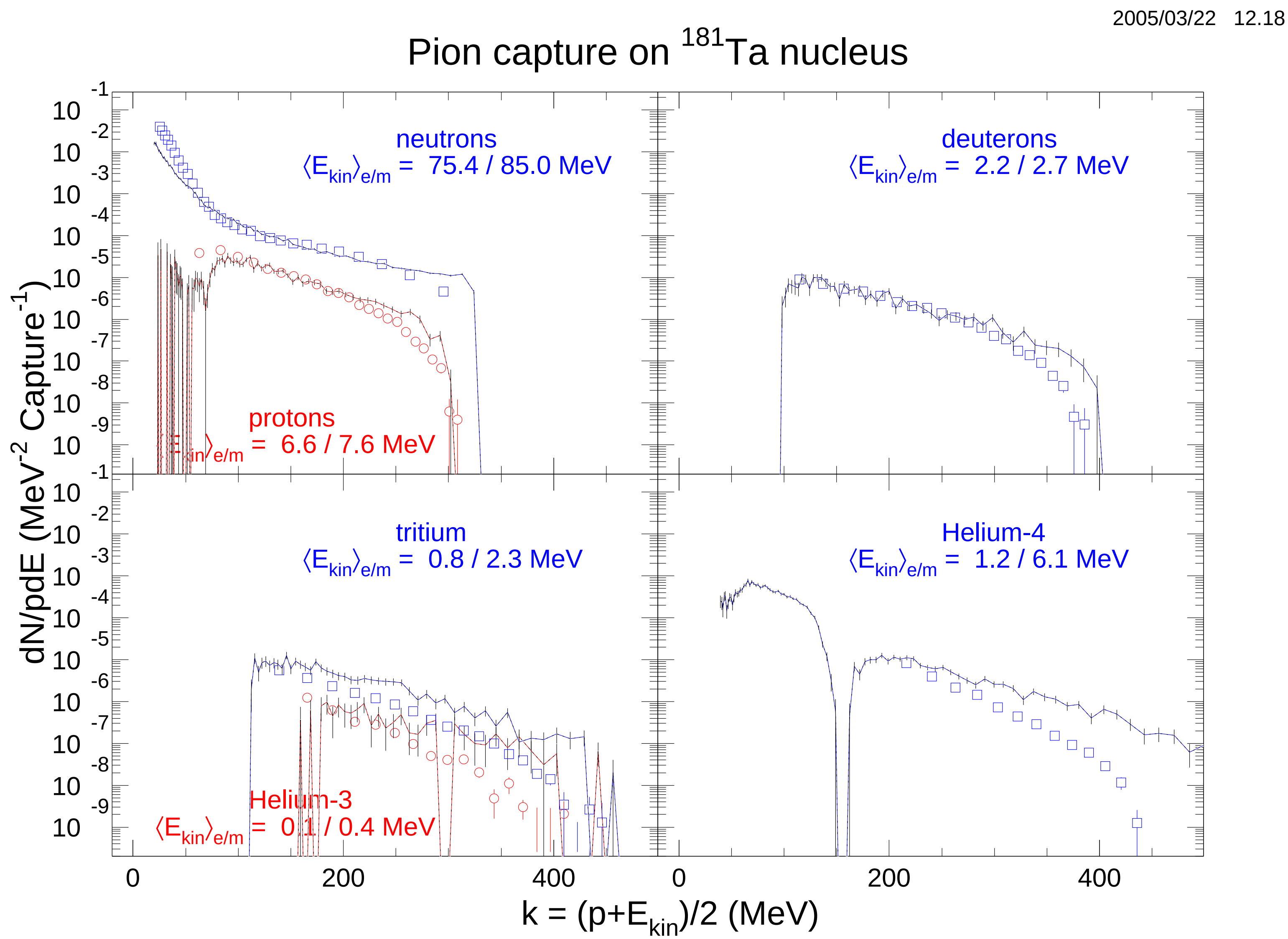

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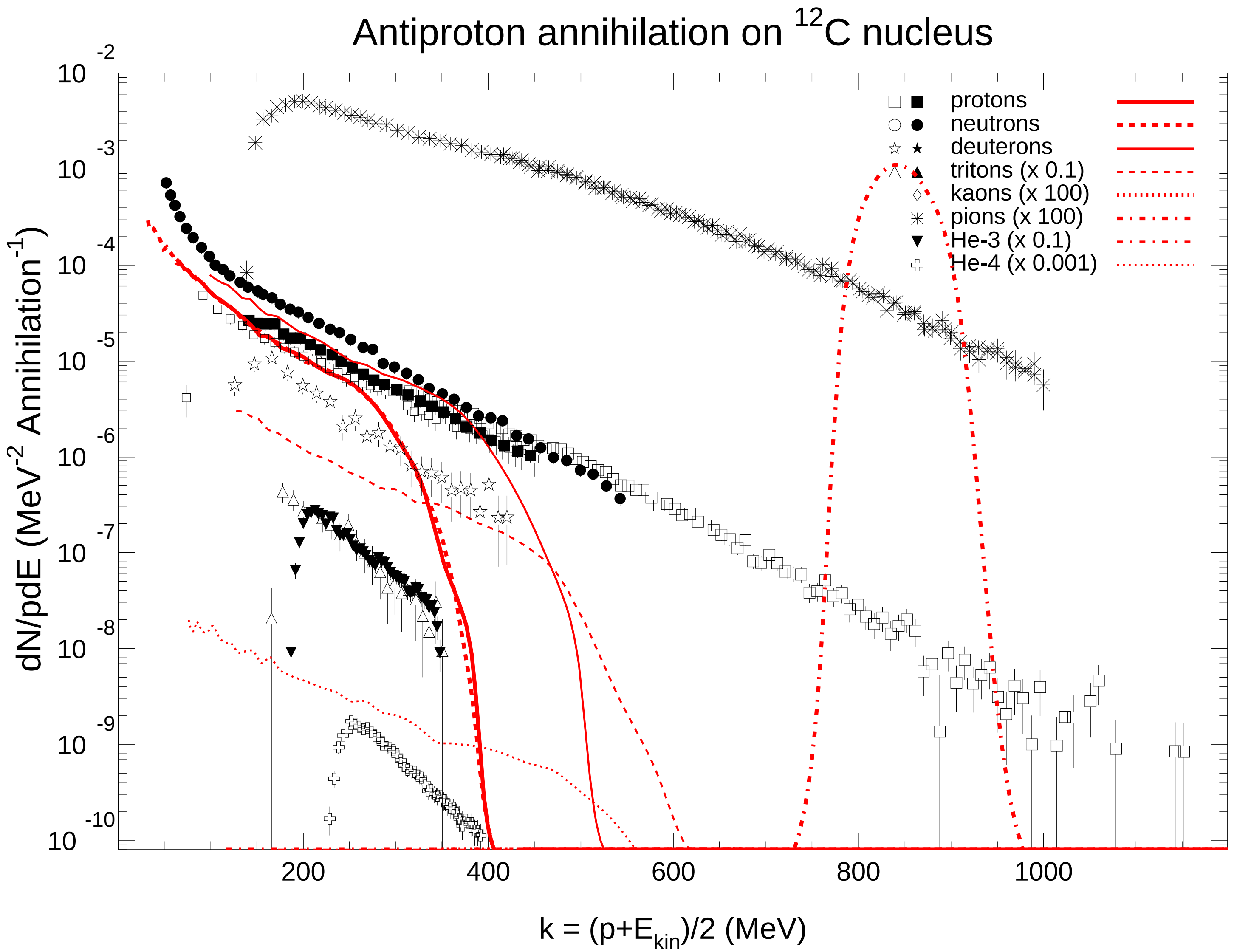
CHIPS algorithm for $\bar{p}A$ ("apcap" subdirectory).

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

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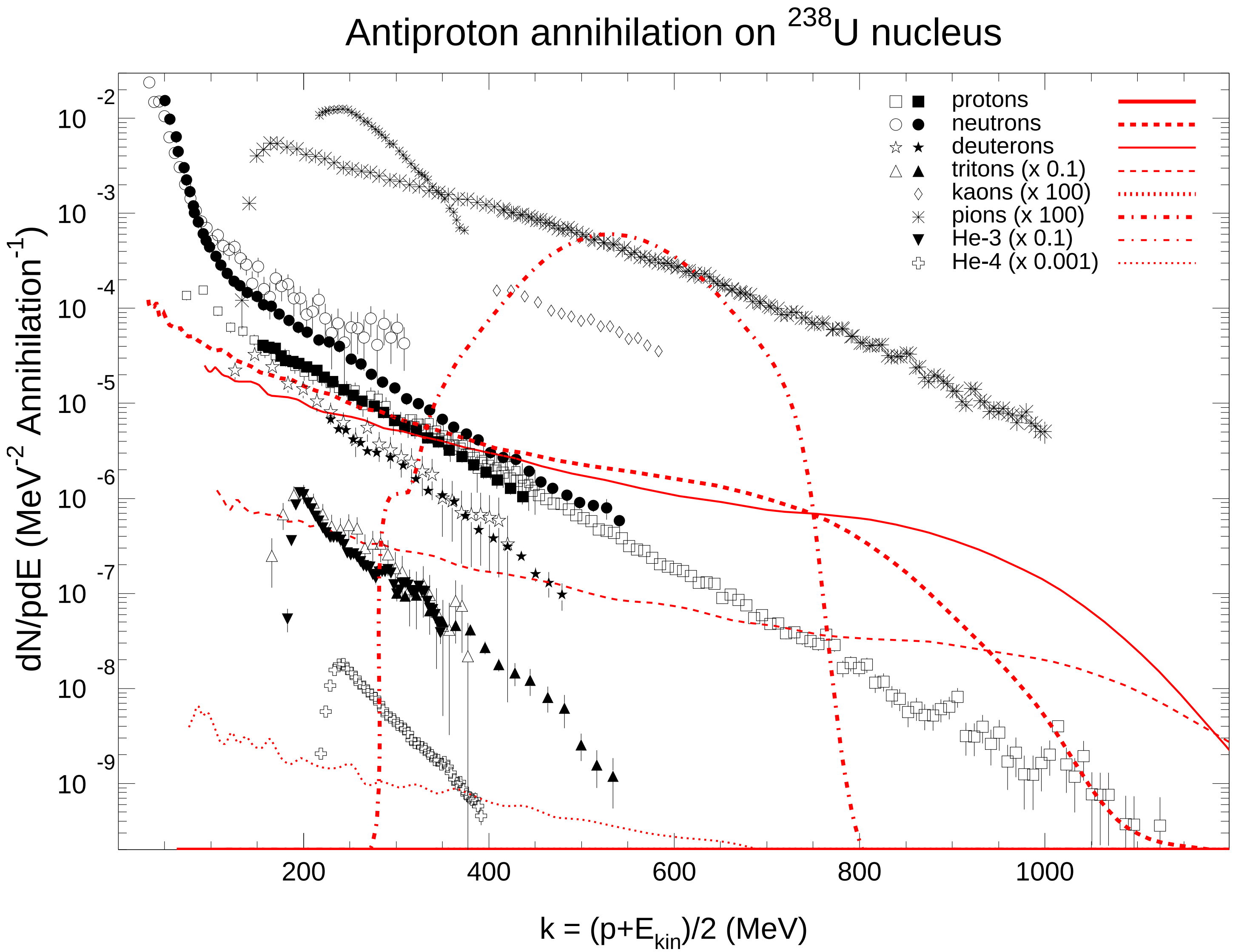
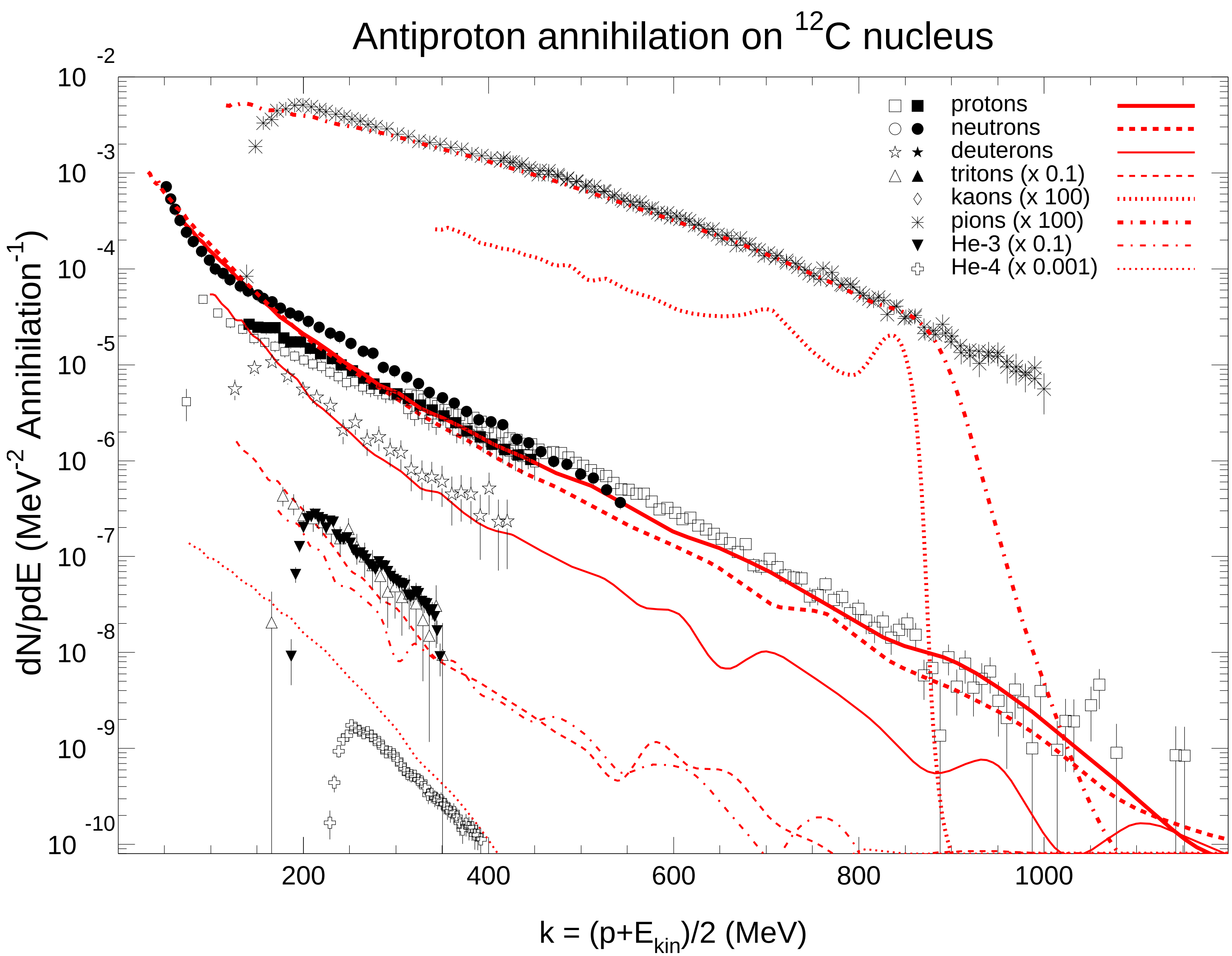
Verification of nuclear capture at rest in G4.




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
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10

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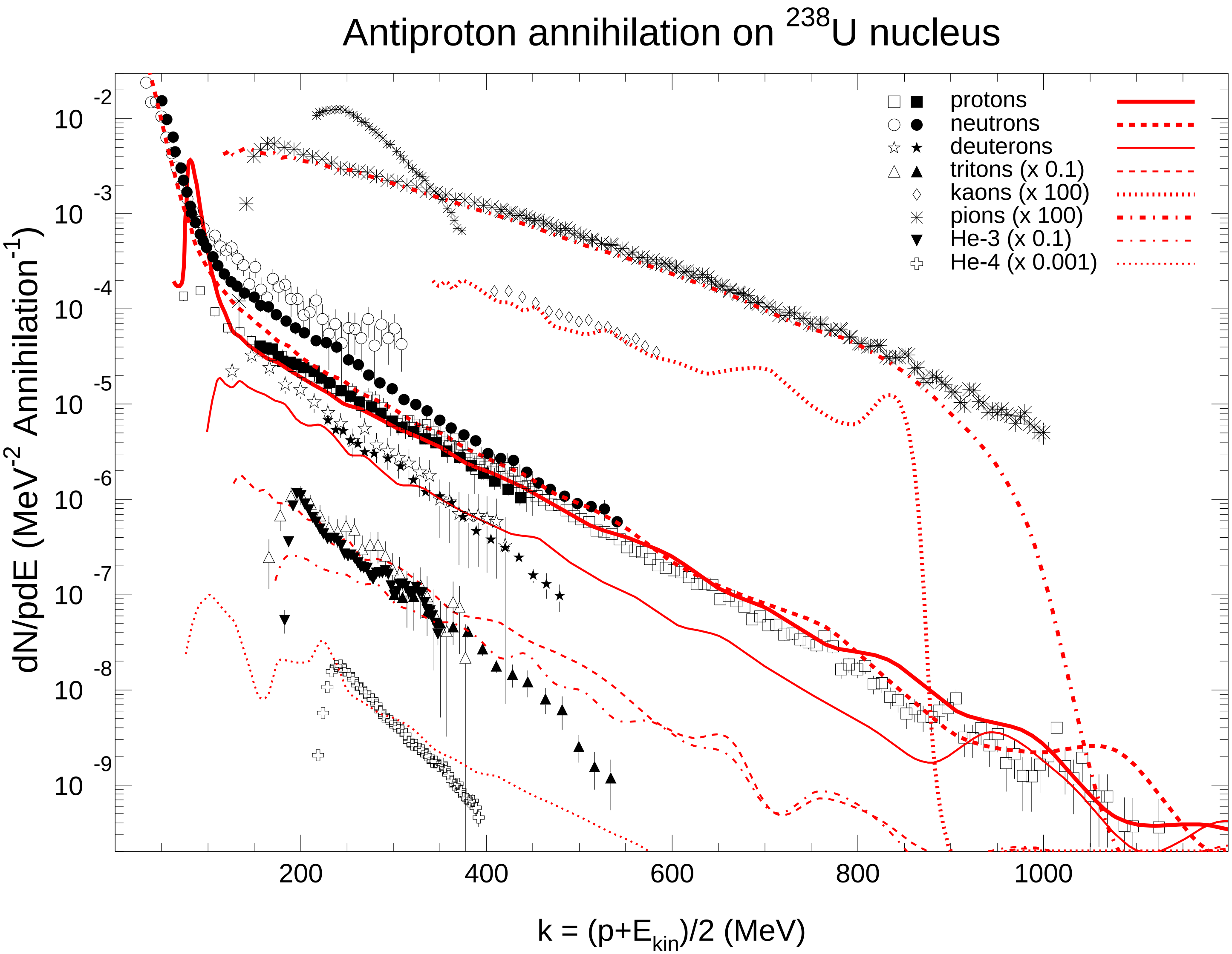
Antiproton annihilation on 238U nucleus
dN/pdE (MeV-2 Annihilation-1)
k = (p+Ekin)/2 (MeV)
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
200
400
600
800
1000
protons
neutrons
deuterons
tritons (x 0.1)
kaons (x 100)
pions (x 100)
He-3 (x 0.1)
He-4 (x 0.001)

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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.