Test frame for capture at rest reactions in Geant4: pions and antiprotons.

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1. Creation of tests/test29 for capture at rest reactions 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.

Test29 is the first tool of "19/29" club in Geant4.

- geant4/tests/test29 & geant4/test/test19 contain CHIPStest executable;
- separate files: testX9_c.cc for CHIPS processes and testX9_g.cc for GHAD processes (testX9_f.cc for FLUKA C++ wrappers?);
- $\bar{p}p$, $\bar{p}A$, and $\pi^- A$ tests are done, $\mu^- A$ and $K^- A$ are desirable, $\Sigma^- A$, $\Xi^- A$, and $\Omega^- A$ are possible, nA and $\bar{n}A$ are questionable;
- Projectile PDG Code = 0 in chipstest.in means "all projectiles".
- PAW kumac files of subdirectories start CHIPStest with chipstest.in input file and convert the output ASCI files to ntuples for analysis;
- if GHAD has two or more processes for the same projectile, one can edit the test29_g.cc file and select the particular process.
- one can collect new data sets and create a new subdirectory in test29.

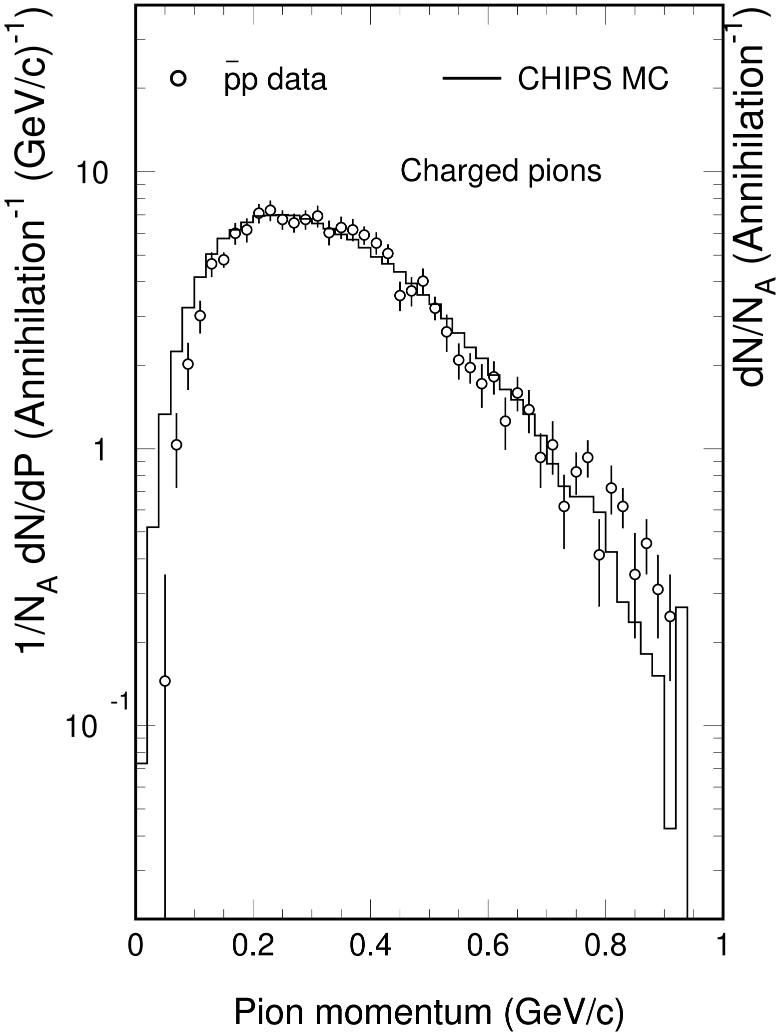
Universal G4QCaptureAtRest CHIPS process for all hadrons.

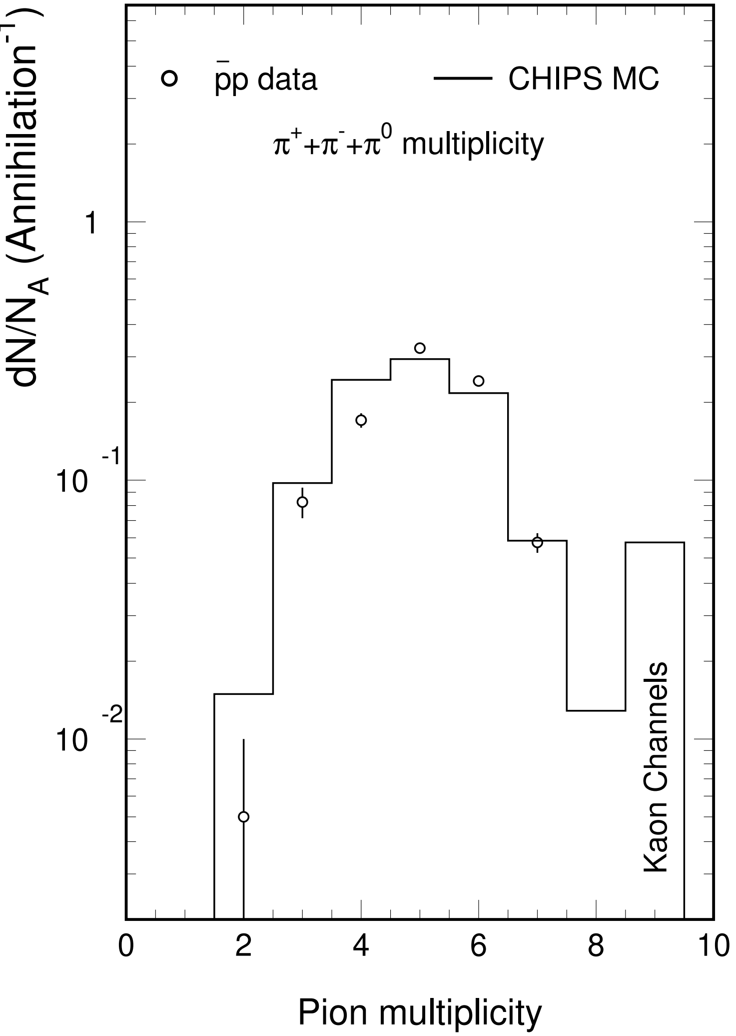
- CHIPS has G4QCaptureAtRest process for all negative hadrons (test29) and G4QCollision process for all hadrons on flight (test19);
- CHIPS conserves energy, momentum, charge, and baryon number;
- CHIPS provides simulated number of neutrons in target nuclei and the residual energy-momentum conservation 4-momentum;
- test29 $\&$ test19 define special (Z, N) monoisotopical 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 (for mesons), so there is no Quark Exchange hadronization (for 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 spectrum for the quark content;
- for this hadronic reaction there are only three parameters of CHIPS Chaos: a critical temperature, 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
π⁺+π⁻+π⁰ 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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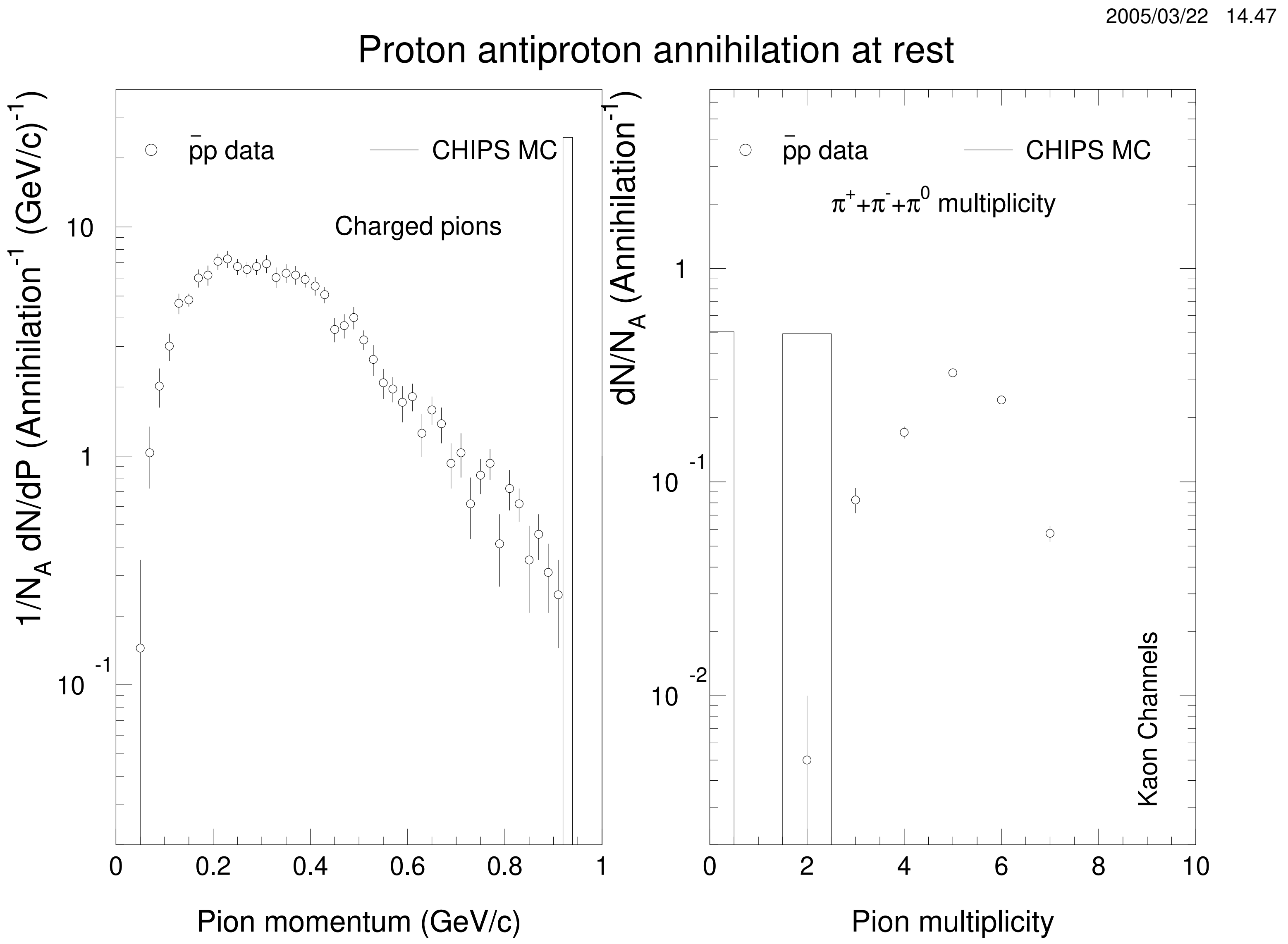


Non-relativistic evaporation package in CHIPS

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):

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

$$\frac{dN}{\sqrt{T} dE} \propto \left(1 - \frac{T}{W_n}\right)^{\frac{3}{2}n-4}.$$

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

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

Inclusive CHIPS, invariant phase space, K-variable.

Baryons (one dimensional consideration of quark exchange):

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

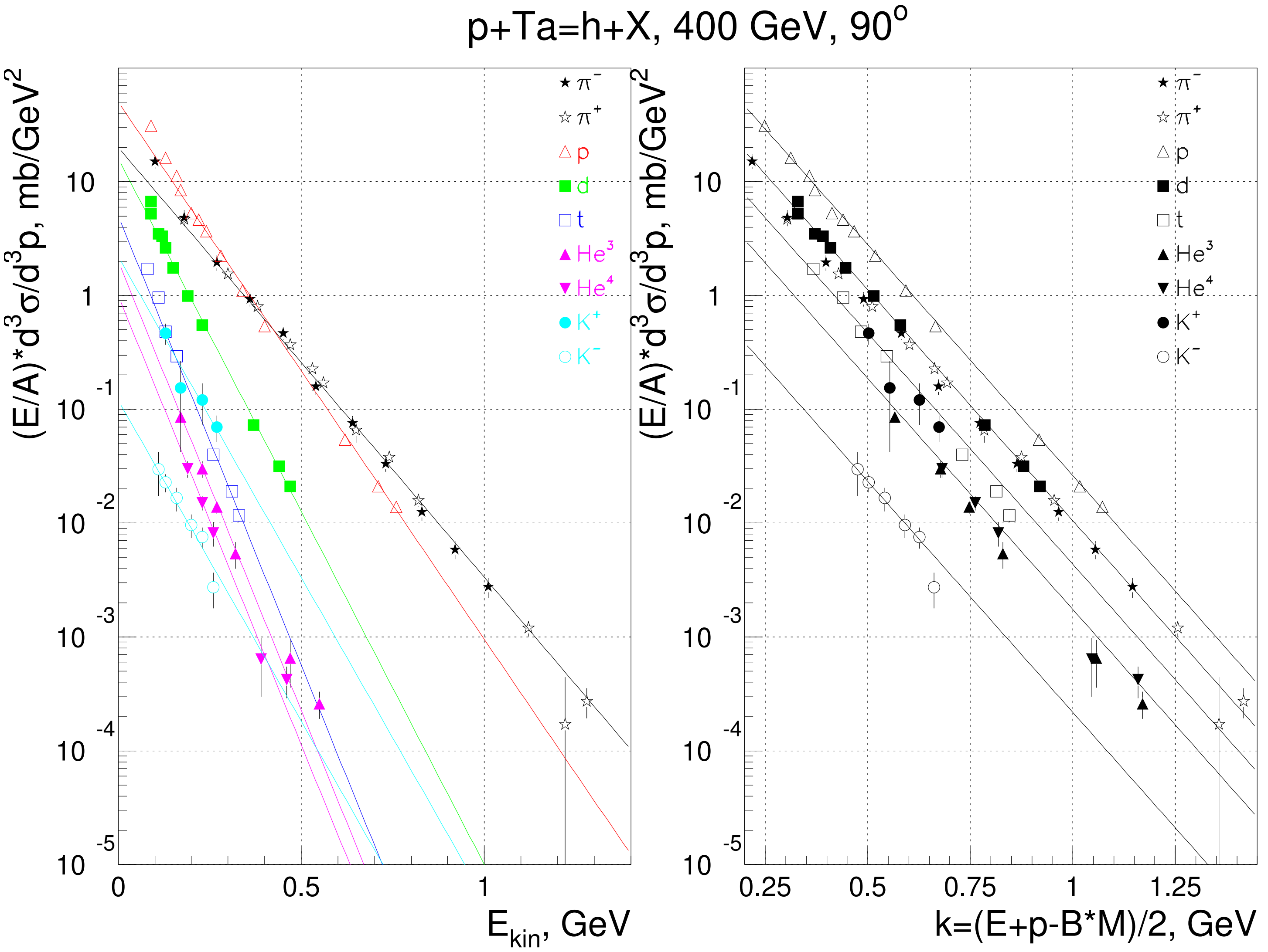
Mesons (one dimensional consideration of quark fusion):

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

Antibaryons (antiquark-antidiquark fusion):

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

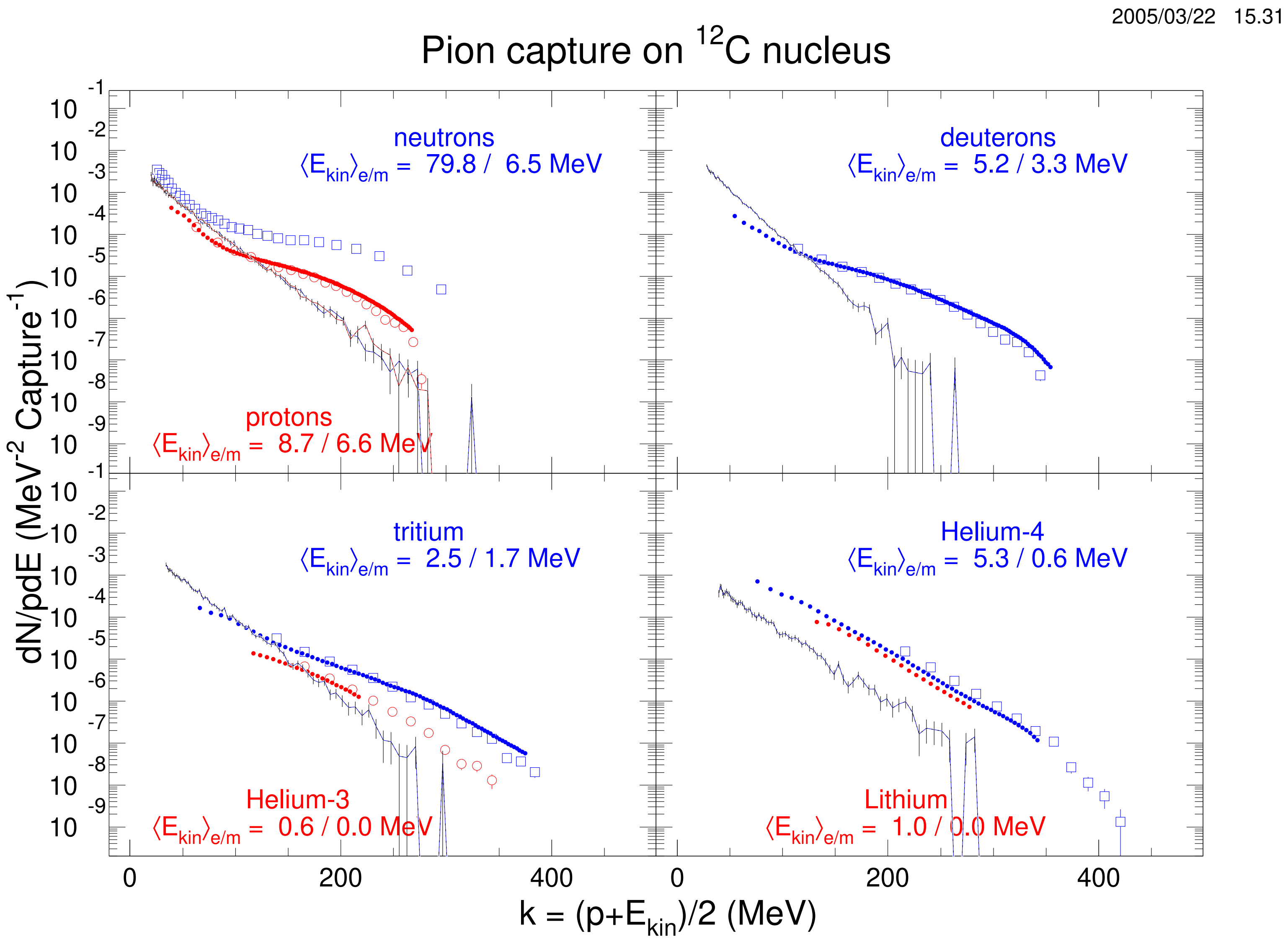
$$\frac{Ed\sigma}{d^3p} \propto \frac{d\sigma}{pdE} \propto EXP\left\{-\frac{(k-\Delta)[1 - v \cdot cos(\theta)]}{T\sqrt{1-v^2}}\right\}$$


p+Ta=h+X, 400 GeV, 90^o
(E/A)*d^{3}σ/d^{3}p, mb/GeV^2
π^-
π^+
p
d
t
He^3
He^4
K$^+$
K$^-$
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
0.5
1
E$_{kin}$, GeV
0.25
0.75
1.25
k=(E+p-B*M)/2, GeV

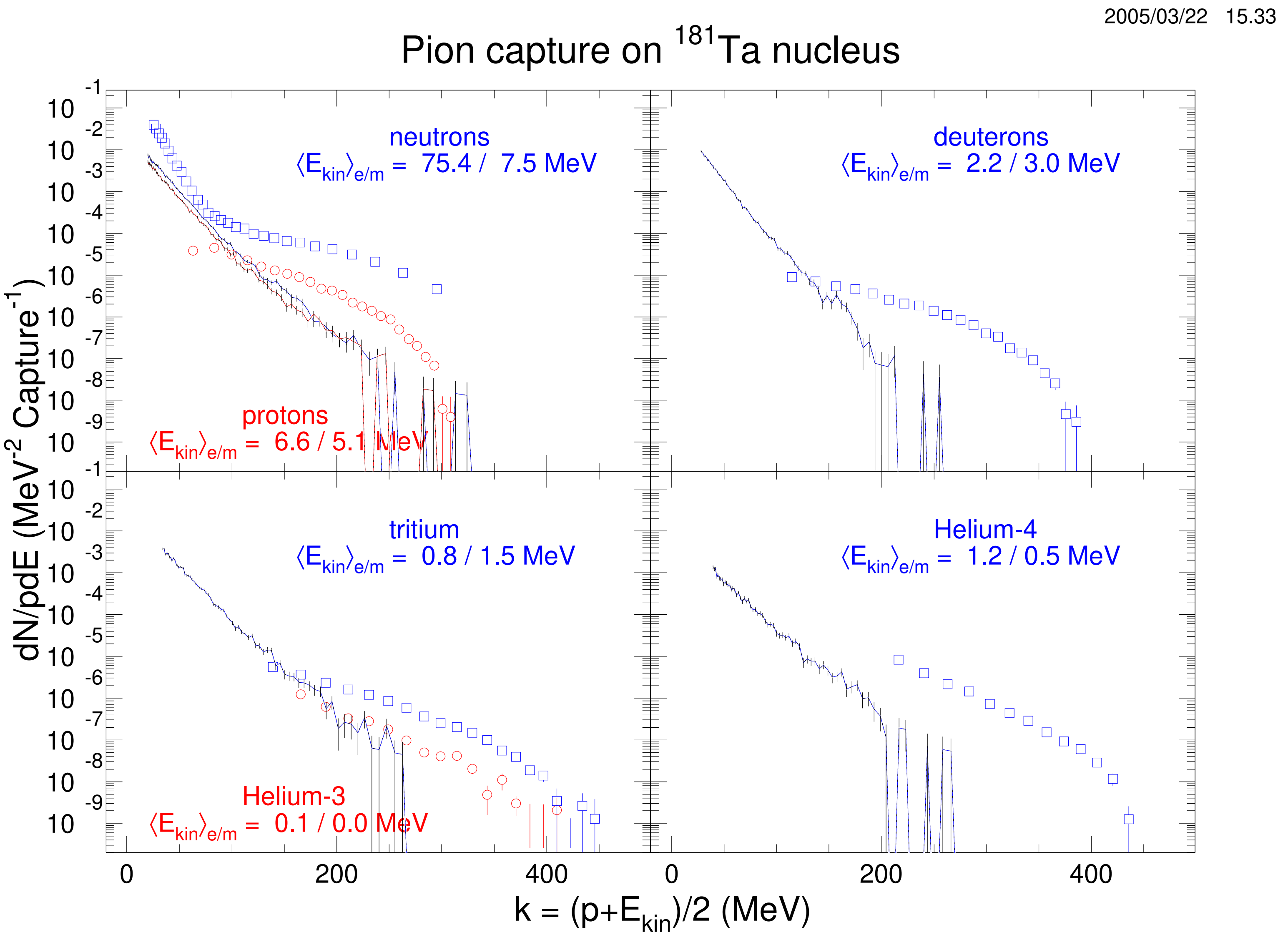
Simulation of $\pi^- A$ by CHIPS ("picap" subdirectory).

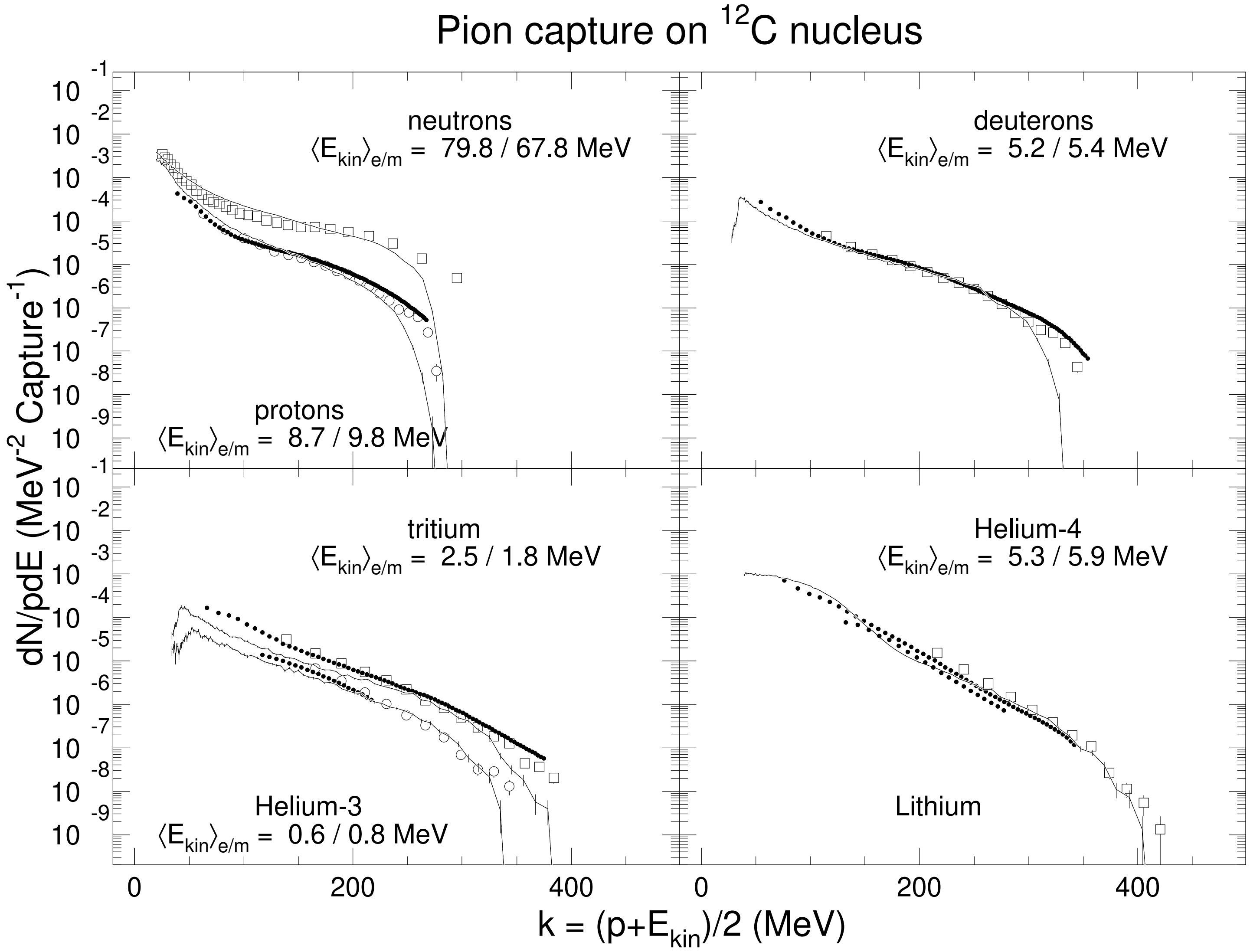
Published in Eur.Phys.J.A9(2000)411(vs.G4PionMinusAbsorptionAtRest)

- Quark Exchange hadronization for nuclear fragments and vacuum hadronization for mesons are defined by a Vacuum/Matter parameter;
- condition of switching from quark level to baryon level simulation;
- Coulomb Barriers for hadrons and nuclear fragments are tunable;
- virtuallity of intermediate Quasmons is tuned by effective nucleons;
- uncertainty of kinematic factors of secondaries (competition);
- uncertainty of the first (initial) interaction of the projectile;
- uncertainty in the Final State Interaction of secondaries.

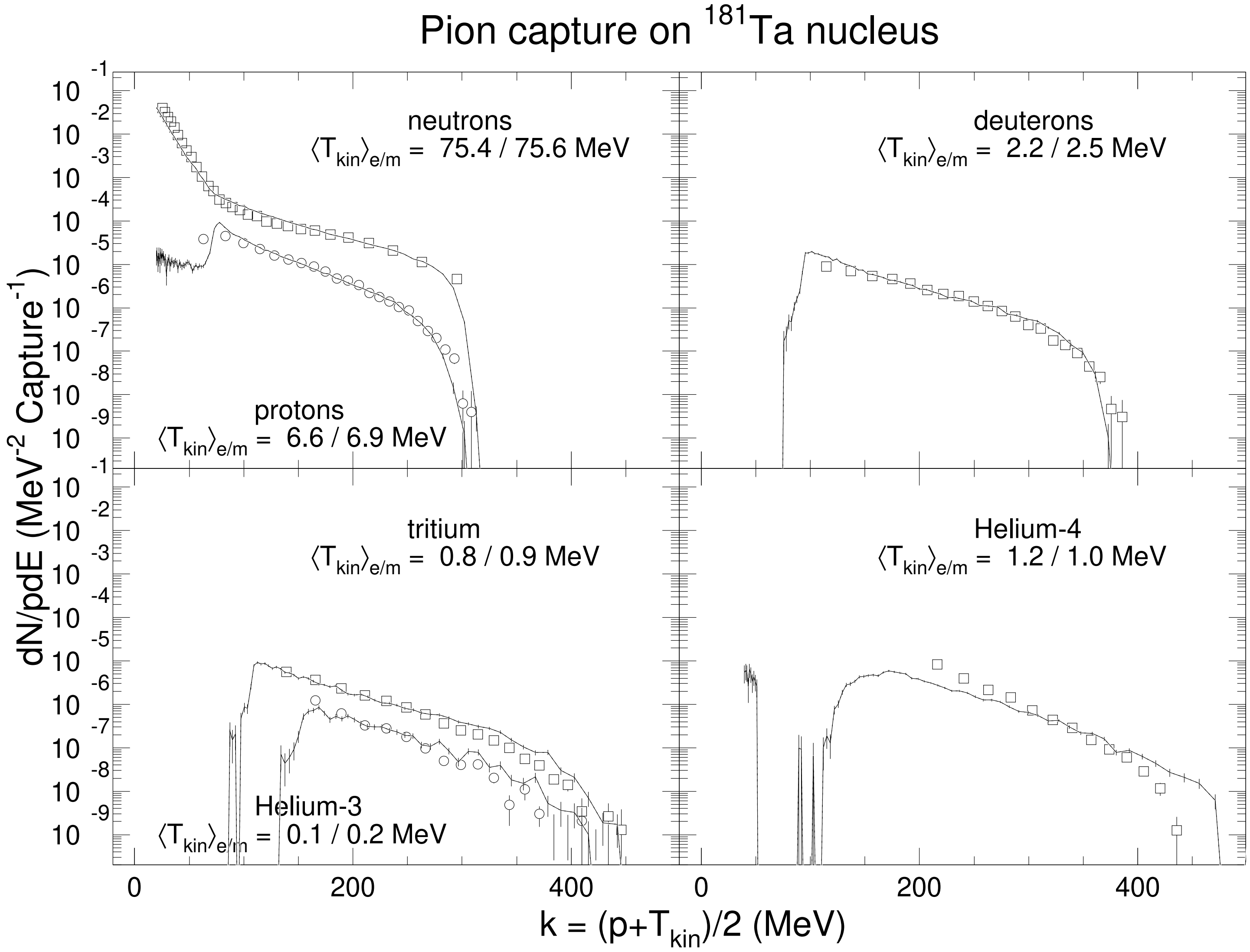


2005/03/22 15.31
Pion capture on ^{12}C nucleus
neutrons
$\langle E_{kin}\rangle_{e/m}$ = 79.8 / 6.5 MeV
protons
$\langle E_{kin}\rangle_{e/m}$ = 8.7 / 6.6 MeV
deuterons
$\langle E_{kin}\rangle_{e/m}$ = 5.2 / 3.3 MeV
tritium
$\langle E_{kin}\rangle_{e/m}$ = 2.5 / 1.7 MeV
Helium-3
$\langle E_{kin}\rangle_{e/m}$ = 0.6 / 0.0 MeV
Helium-4
$\langle E_{kin}\rangle_{e/m}$ = 5.3 / 0.6 MeV
Lithium
$\langle E_{kin}\rangle_{e/m}$ = 1.0 / 0.0 MeV
dN/pdE (MeV^{-2} Capture^{-1})
k = (p+E$_{kin}$)/2 (MeV)


2005/03/22 15.33
Pion capture on ^{181}Ta nucleus
neutrons
$\langle E_{kin}\rangle_{e/m}$ = 75.4 / 7.5 MeV
protons
$\langle E_{kin}\rangle_{e/m}$ = 6.6 / 5.1 MeV
deuterons
$\langle E_{kin}\rangle_{e/m}$ = 2.2 / 3.0 MeV
tritium
$\langle E_{kin}\rangle_{e/m}$ = 0.8 / 1.5 MeV
Helium-3
$\langle E_{kin}\rangle_{e/m}$ = 0.1 / 0.0 MeV
Helium-4
$\langle E_{kin}\rangle_{e/m}$ = 1.2 / 0.5 MeV
dN/pdE (MeV^{-2} Capture^{-1})
k = (p+E$_{kin}$)/2 (MeV)


Pion capture on ^{12}C nucleus
neutrons
$\langle E_{kin} \rangle_{e/m}$ = 79.8 / 67.8 MeV
protons
$\langle E_{kin} \rangle_{e/m}$ = 8.7 / 9.8 MeV
deuterons
$\langle E_{kin} \rangle_{e/m}$ = 5.2 / 5.4 MeV
tritium
$\langle E_{kin} \rangle_{e/m}$ = 2.5 / 1.8 MeV
Helium-3
$\langle E_{kin} \rangle_{e/m}$ = 0.6 / 0.8 MeV
Helium-4
$\langle E_{kin} \rangle_{e/m}$ = 5.3 / 5.9 MeV
Lithium
dN/pdE (MeV^{-2} Capture^{-1})
k = (p+E$_{kin}$)/2 (MeV)
0
200
400

CERN


Pion capture on ^{181}Ta nucleus
neutrons
$\langle T_{kin}\rangle_{e/m}$ = 75.4 / 75.6 MeV
protons
$\langle T_{kin}\rangle_{e/m}$ = 6.6 / 6.9 MeV
deuterons
$\langle T_{kin}\rangle_{e/m}$ = 2.2 / 2.5 MeV
tritium
$\langle T_{kin}\rangle_{e/m}$ = 0.8 / 0.9 MeV
Helium-3
$\langle T_{kin}\rangle_{e/m}$ = 0.1 / 0.2 MeV
Helium-4
$\langle T_{kin}\rangle_{e/m}$ = 1.2 / 1.0 MeV
dN/pdE (MeV^{-2} Capture^{-1})
k = (p+T$_{kin}$)/2 (MeV)
0
200
400

CERN

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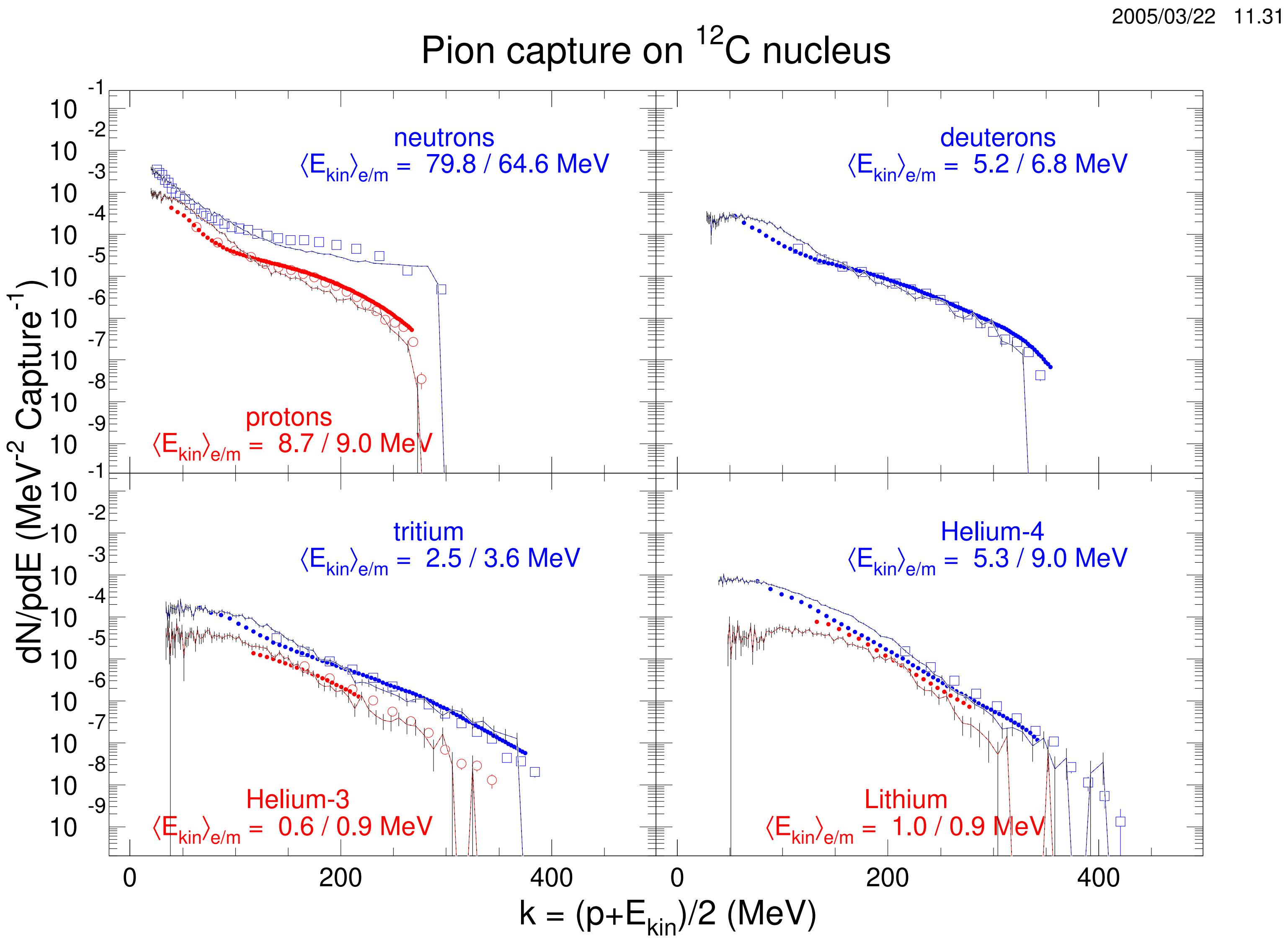
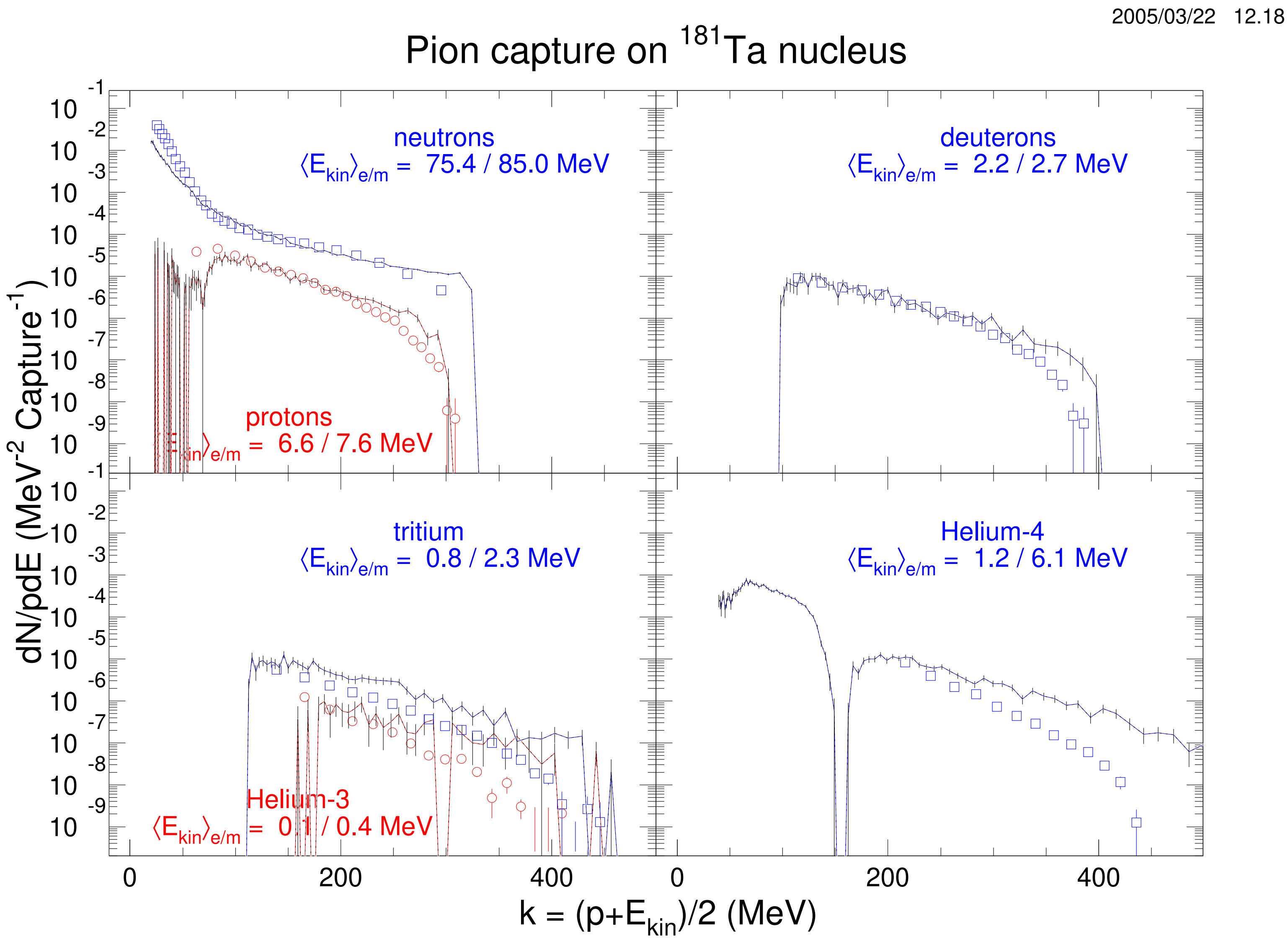


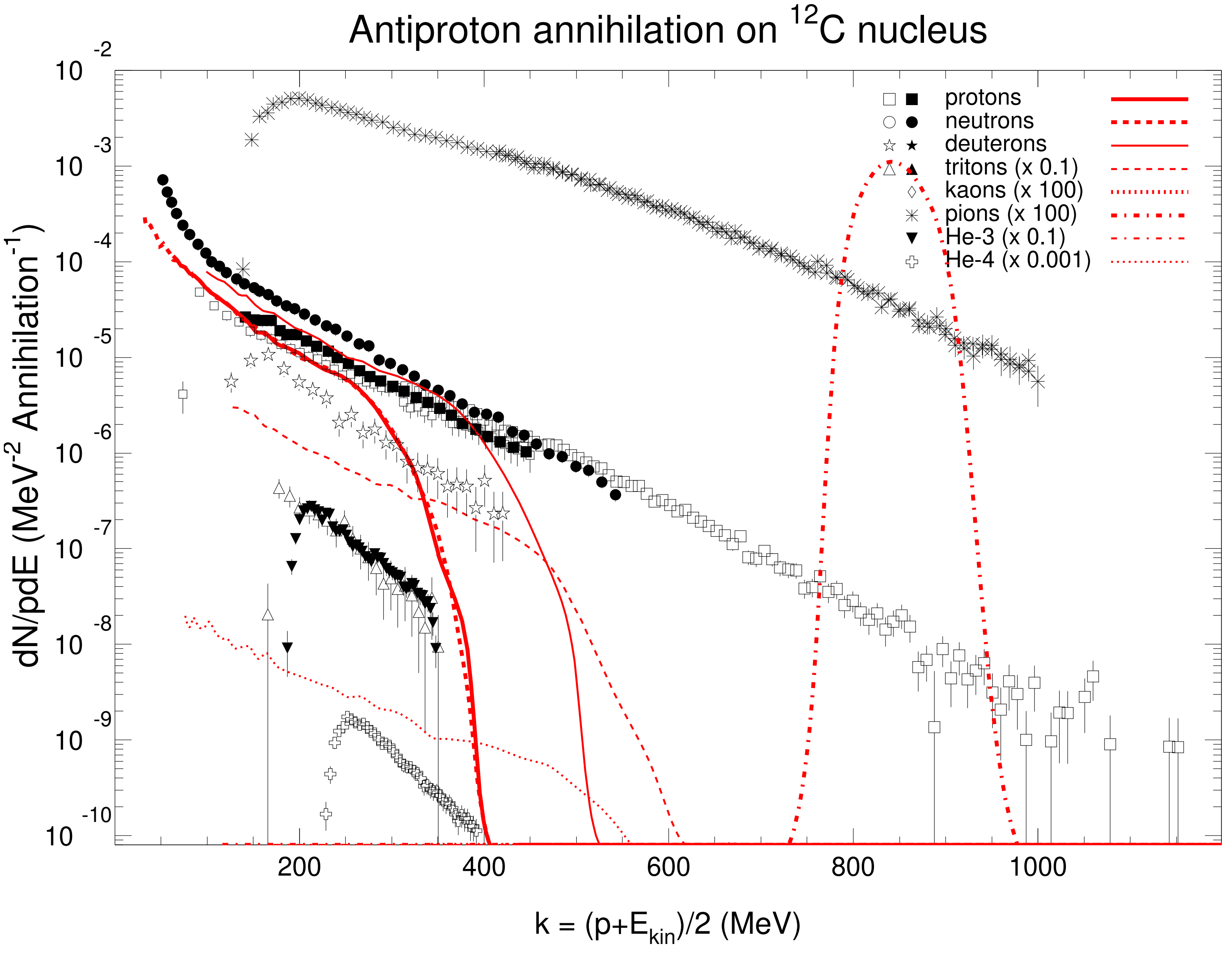
Test frame for capture at rest reactions in Geant4: pions and antiprotons.



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

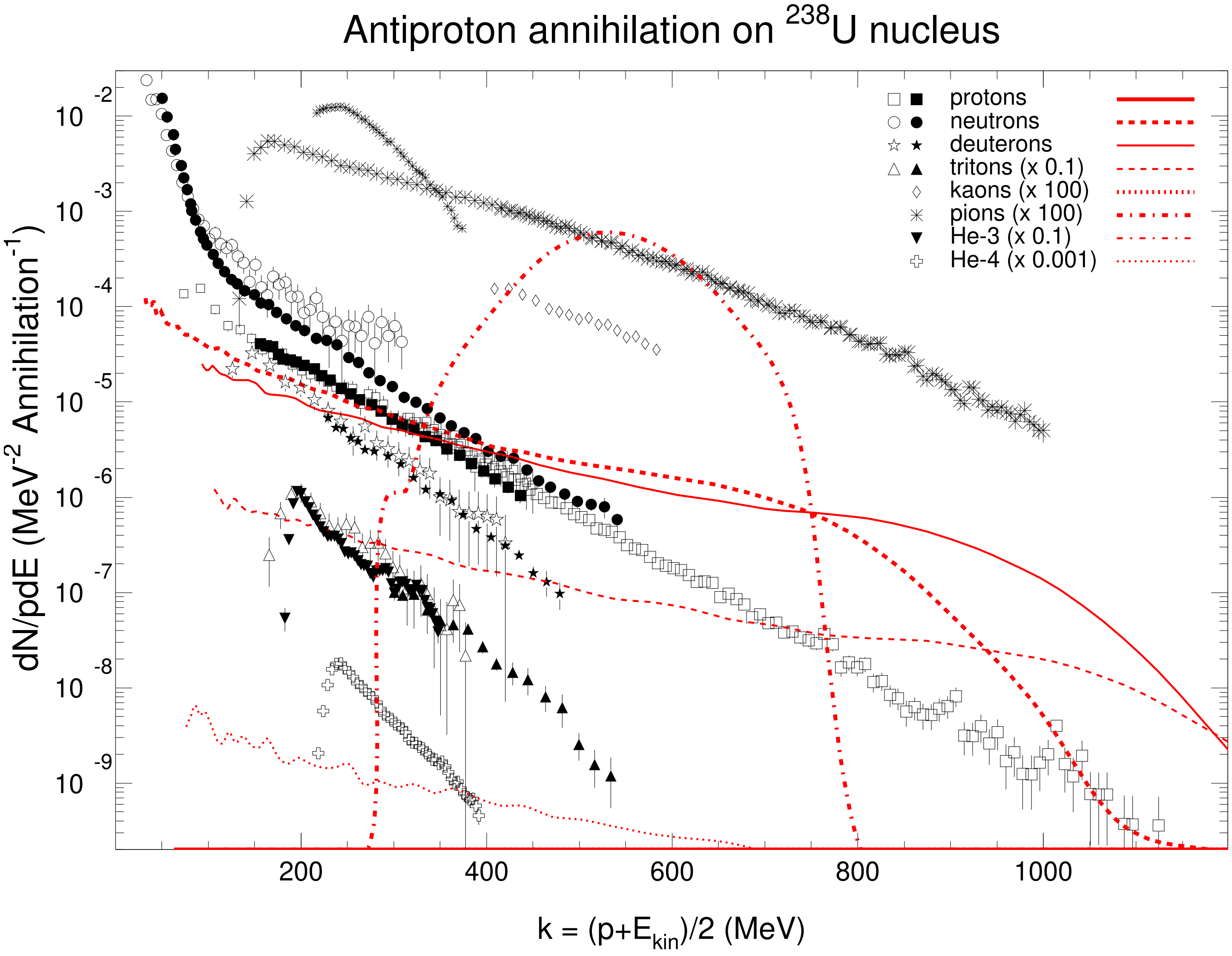
Compared with the G4AntiProtonAnnihilationAtRest process of GHAD.

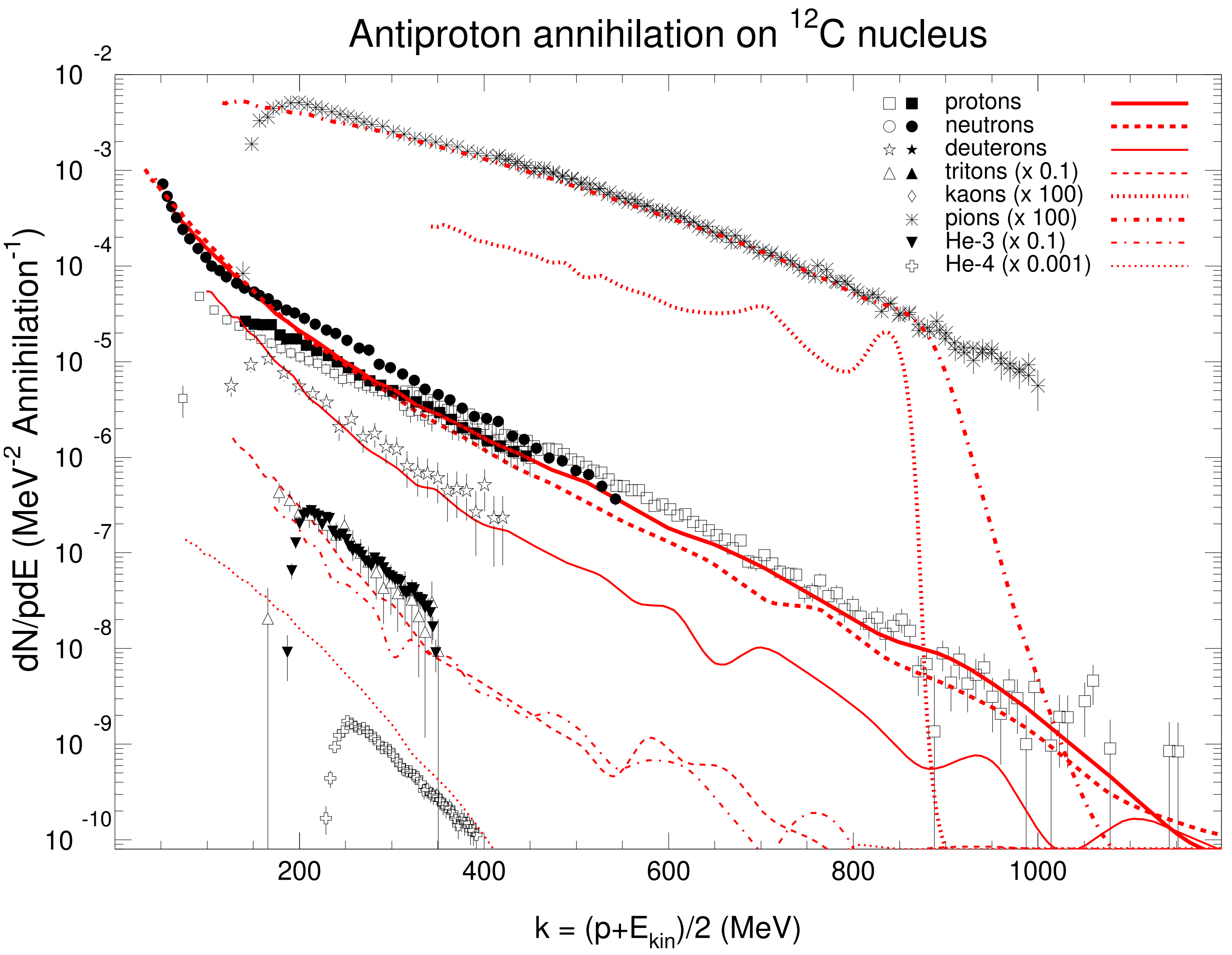
- $\bar{p}N$ annihilation on periphery of the target nucleus;
- absorb secondary mesons inside a Solid Angle (a parameter);
- put to output secondary mesons outside the Solid Angle;
- make a multi-Quasmon excitation in the residual nucleus;
- hadronize excited nuclei in hadrons and fragments (DINR);
- if the DINR hadronization is exhausted, then evaporate the residual;
- if the residual nucleus is far from the lane of stability, make a cascade of n, p, or α decays (can produce fragments below Coulomb Barriers).


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)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
200
400
600
800
1000

CERN

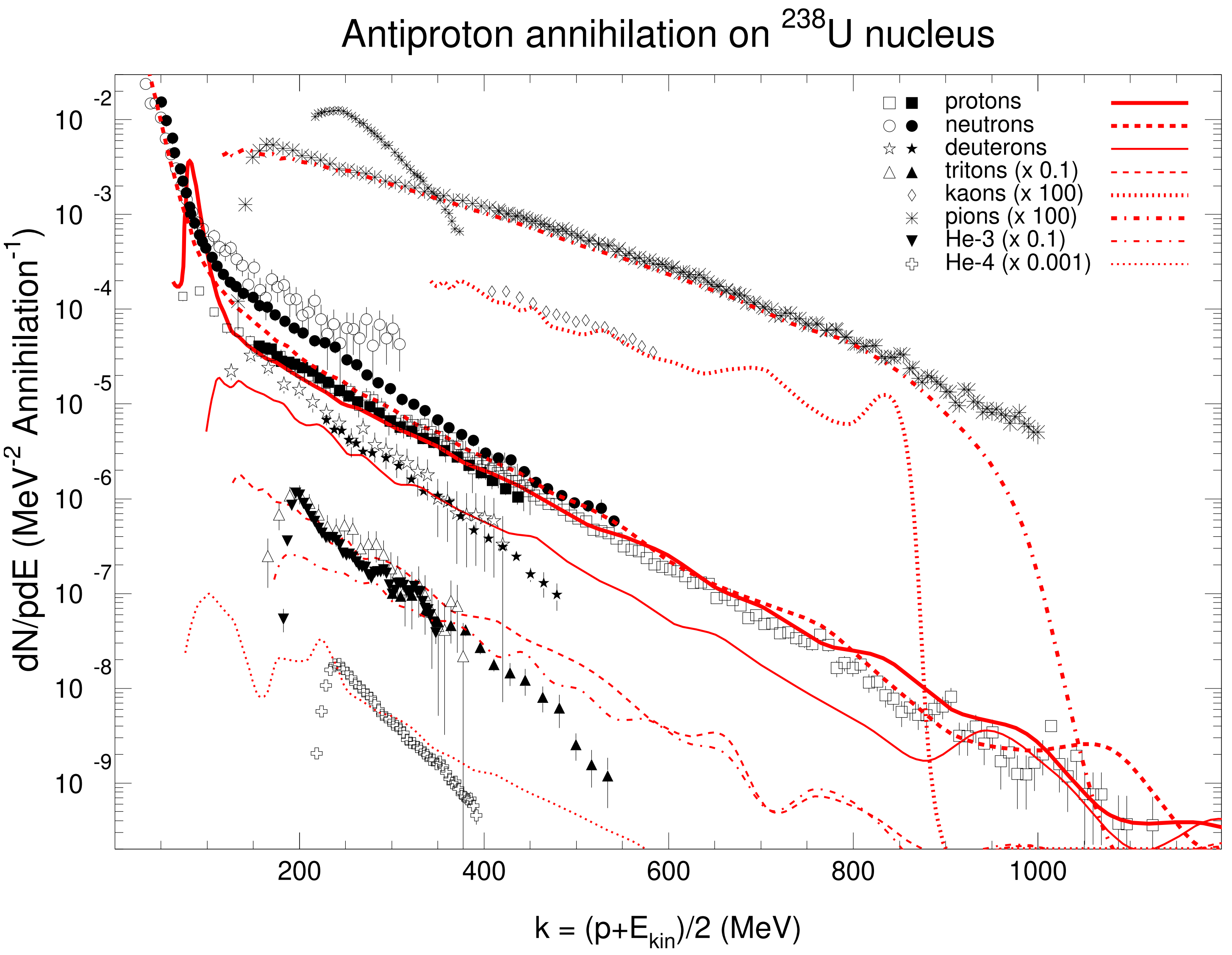
Test frame for capture at rest reactions in Geant4: pions and antiprotons.

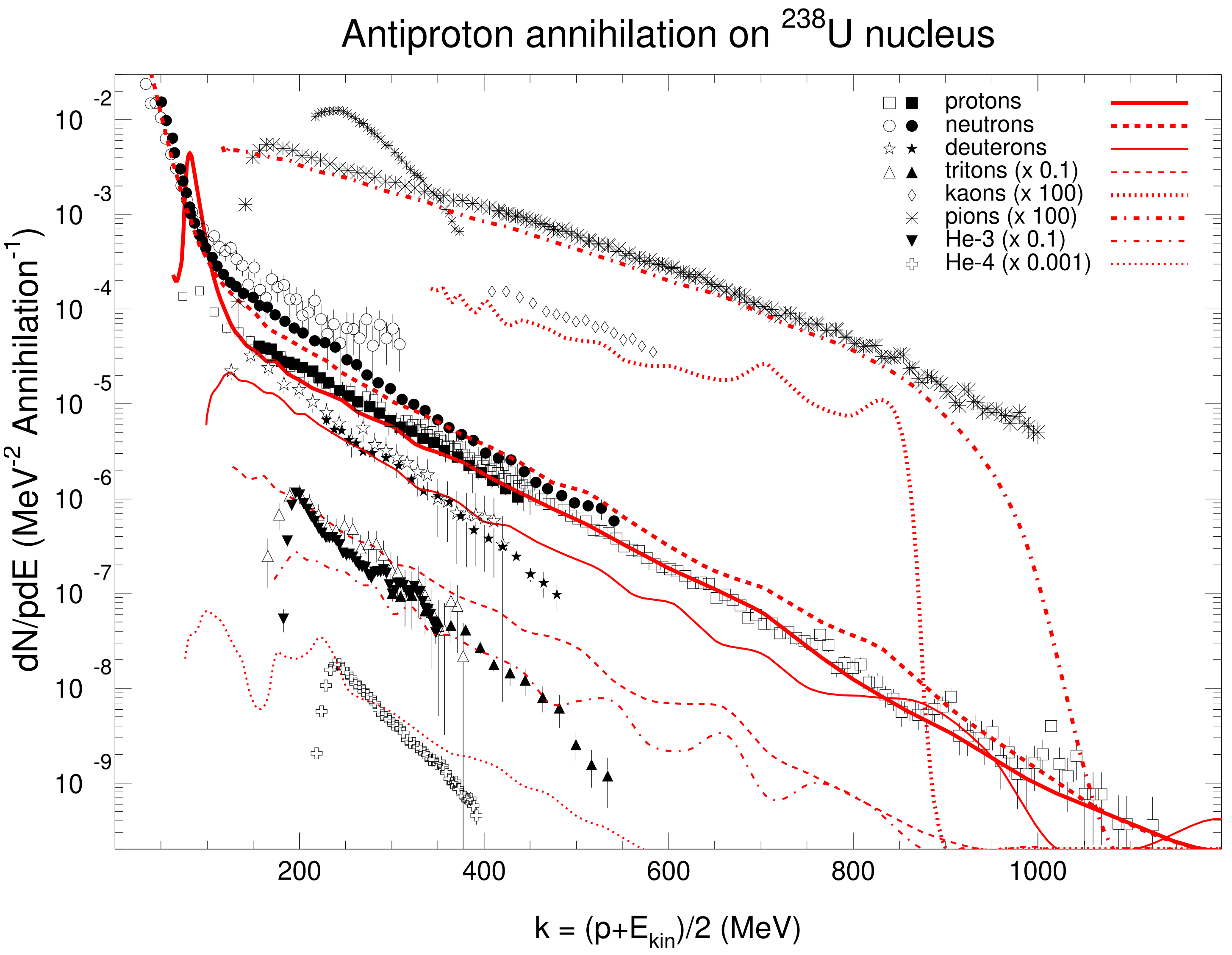



Antiproton annihilation on ^{12}C nucleus
dN/pdE (MeV^{-2} Annihilation^{-1})
k = (p+E$_{kin}$)/2 (MeV)
protons
neutrons
deuterons
tritons (x 0.1)
kaons (x 100)
pions (x 100)
He-3 (x 0.1)
He-4 (x 0.001)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
200
400
600
800
1000

CERN

Test frame for capture at rest reactions in Geant4: pions and antiprotons.




Antiproton annihilation on ^{238}U 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}

Conclusion

- "19/29" club is open for contribution of users, which are interested in particular energy range of particular hadron-nuclear interactions;
- $p\bar{p}$, $\bar{p}A$, $\pi^- A$ subdirectories can be used as examples for new tests;
- test19 is like test29 with spectra normalized by total cross-sections;
- the first On Flight tests are going to be: photo-nuclear and antiproton-nuclear reactions (they already exist in another form);
- the default versions of "19/29" tests try all hadrons in a loop, and can be used for performance tests of hadronic processes in Geant4;
- "19/29" tests can be used as physics tests for new Geant4 releases;
- studying results of the existing "19/29" tests users can select the best processes for their Physics Lists for the Geant4 simulation;