A new data set for antiproton-nuclear interactions at rest.

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February 23, 2005

1. Advantages of reactions at rest (interaction and angular dependence).
2. Invariant phase space distributions and the $K = (E + P)/2$ variable.
3. A new data set with spectra of secondary nuclear fragments.

Why the antiproton annihilation at rest?

- Research on the Antiproton Decelerator at CERN will be continued;
- Capture at rest processes do not demand energy dependent interaction cross-sections;
- CHIPS simulation in Geant4 is realized in the G4CaptureAtRest class for $\mu-$, π^-, K^-, $\bar{p}$, and other negative hadrons;
- There is no angular dependence for secondary hadrons, so the Complete Experiment is possible.
- The energy deposition is huge (about 2 GeV), so the simulation comes beyond the Precompound model (hadronization in pions).
- A lot of nuclear fragments are radiated and locally stopped.

Inclusive CHIPS, invariant phase space, K-variable.

Baryons (one dimensional consideration of quark exchange):

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

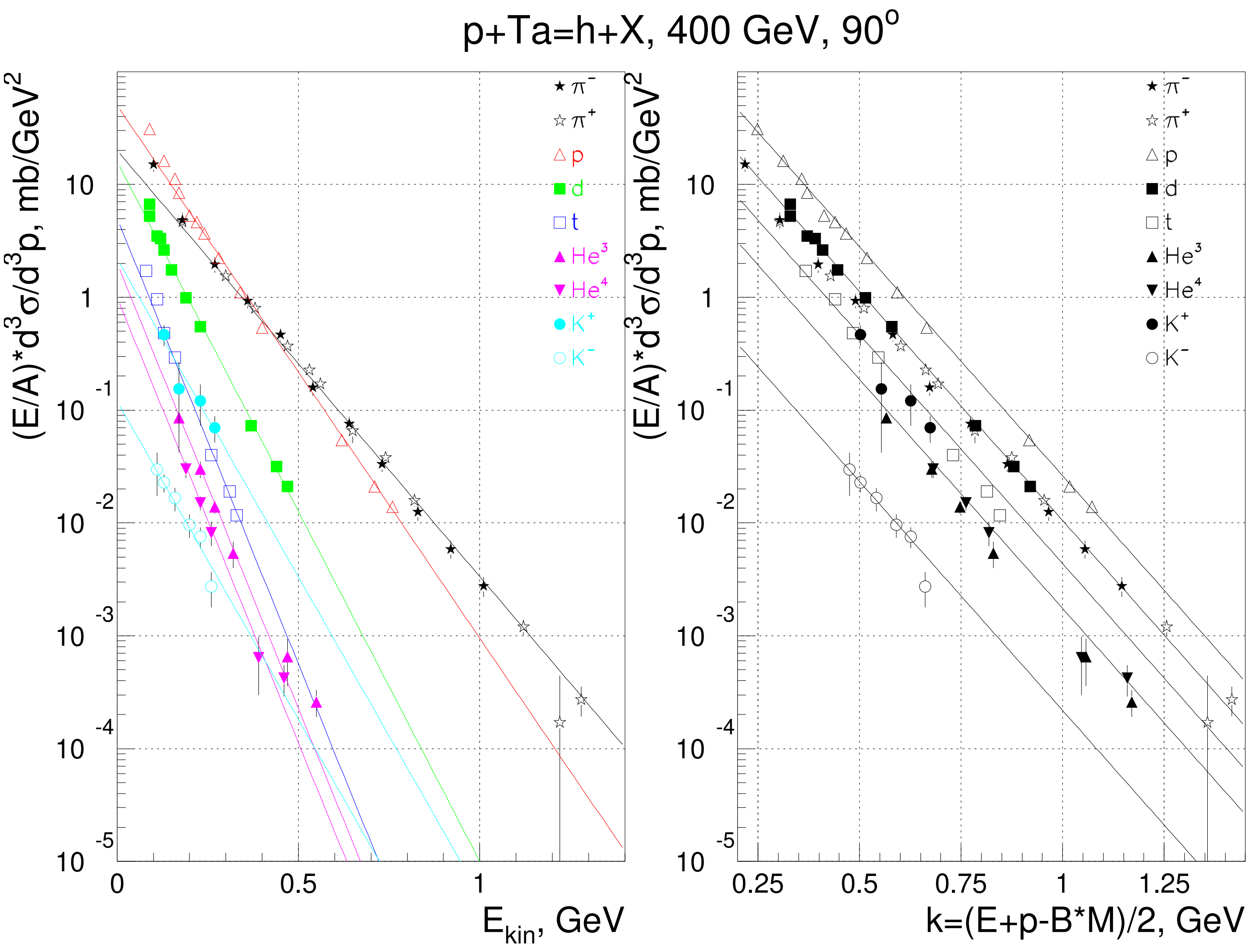
Mesons (one dimensional consideration of quark fusion):

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

Antibaryons (antiquark-antidiquark fusion):

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

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

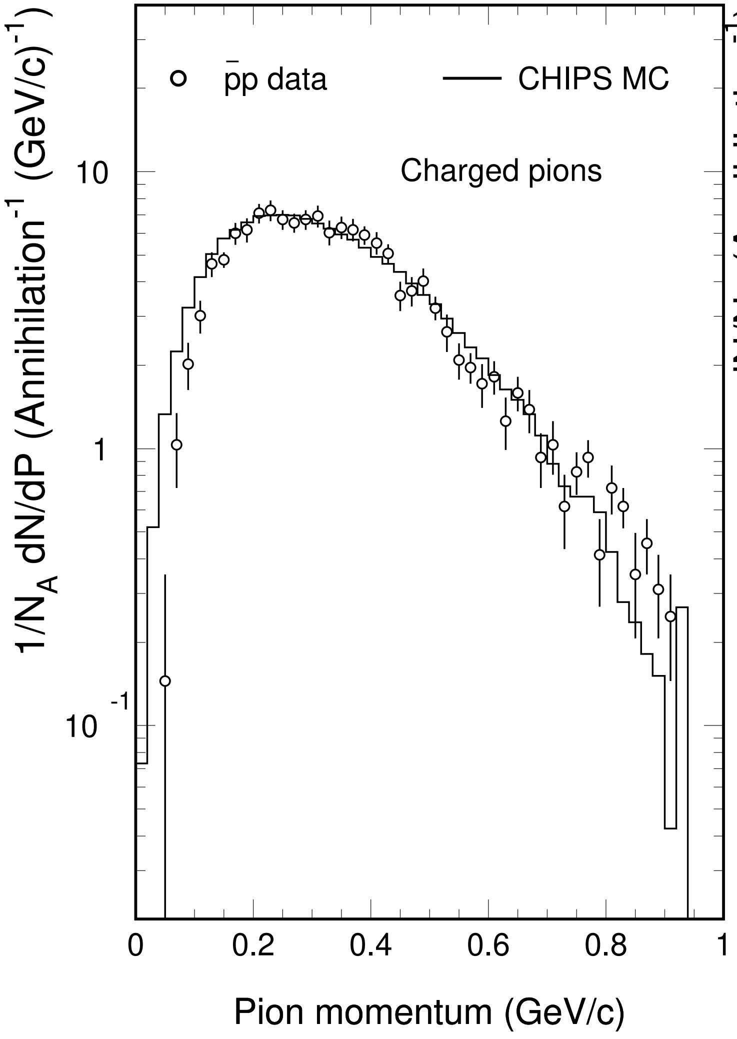


p+Ta=h+X, 400 GeV, 90°
(E/A)*d³σ/d³p, mb/GeV²
E_kin, GeV
k=(E+p-B*M)/2, GeV
π⁻
π⁺
p
d
t
He³
He⁴
K⁺
K⁻

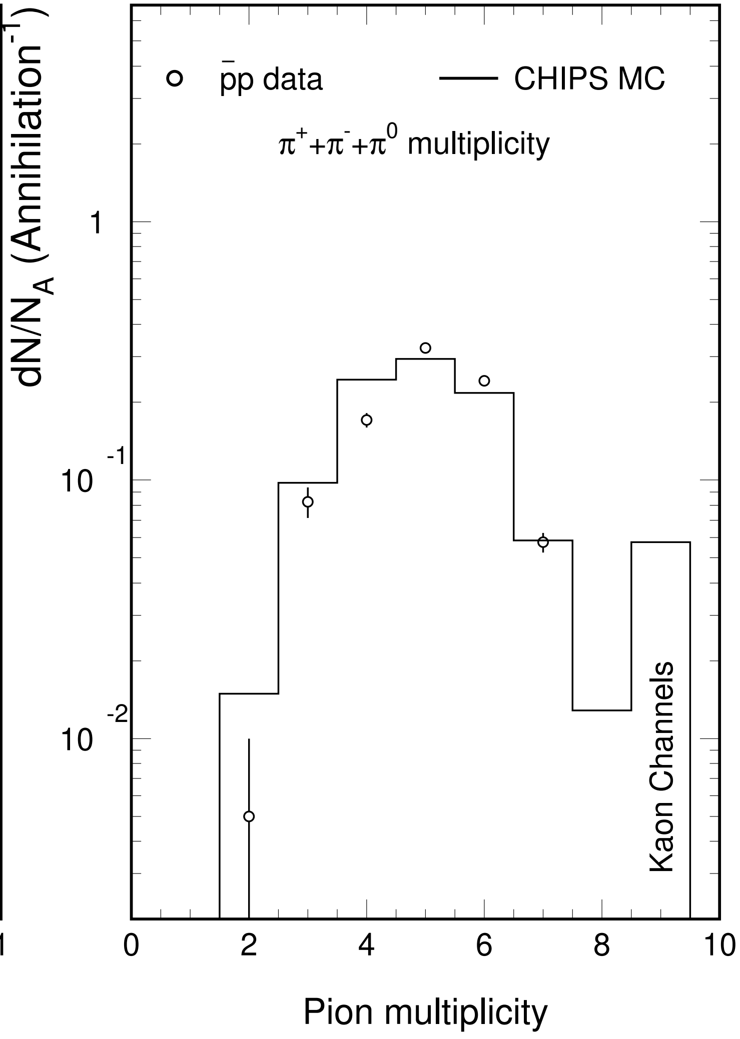
Just to remind how CHIPS describes $p\bar{p}$.

It is published in Eur. Phys. J 8 (2000) 217.

- This is a reaction with vacuum hadronization (for mesons), so there is no quark-exchange hadronization (for nuclear fragments);
- Quark fusion is not one-dimensional but 3D with phase space integrals;
- Resonances are created as a discrete spectrum for the quark content;
- There are only three parameters for the CHIPS Chaos: temperature, s-suppression, and η-suppression;
- The overall multiplicity is regulated by the temperature parameter;
- 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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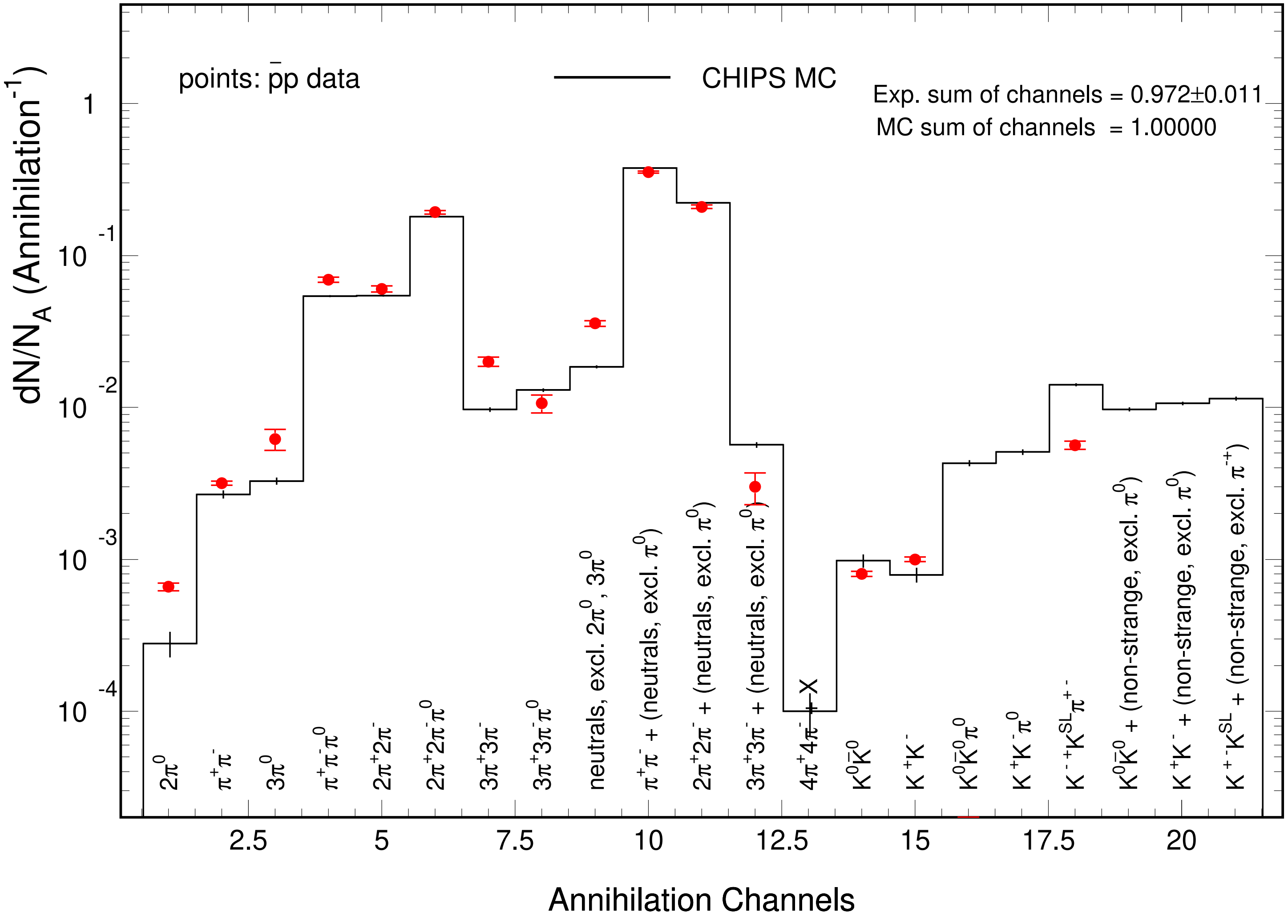

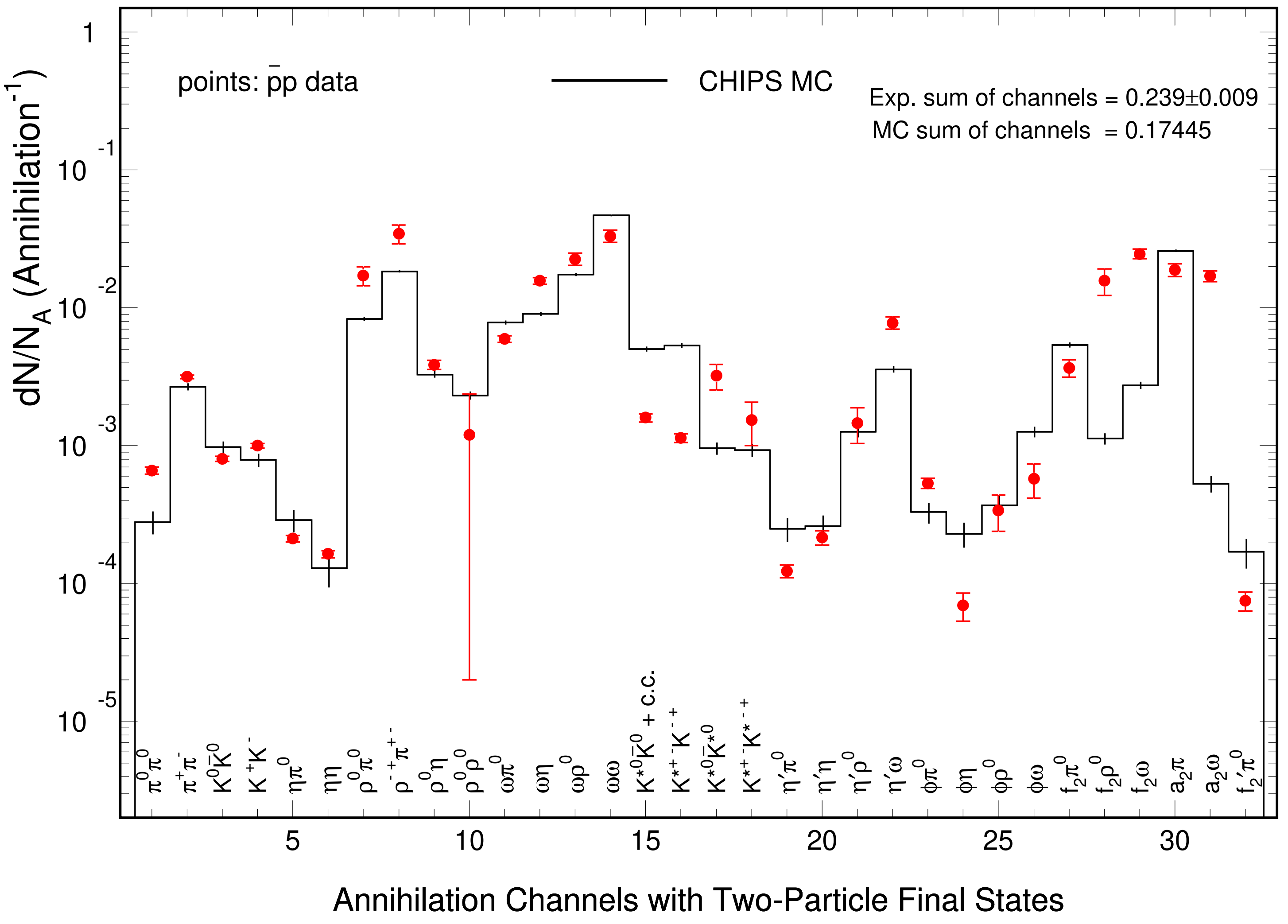
points: p̄p data
CHIPS MC
Exp. sum of channels = 0.239±0.009
MC sum of channels = 0.17445
dN/N_A (Annihilation^-1)
Annihilation Channels with Two-Particle Final States
1
10^-1
10^-2
10^-3
10^-4
10^-5
5
10
15
20
25
30
π0π0
π+π-
K0K̄0
K+K-
ηπ0
ηη
ρ0π0
ρ-+π+-
ρ0η
ρ0ρ0
ωπ0
ωη
ωρ0
ωω
K*0K̄0 + c.c.
K*+-K-+
K*0K̄*0
K*+-K*-+
η'π0
η'η
η'ρ0
η'ω
φπ0
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φρ0
φω
f2π0
f2ρ0
f2ω
a2π
a2ω
f'2π0

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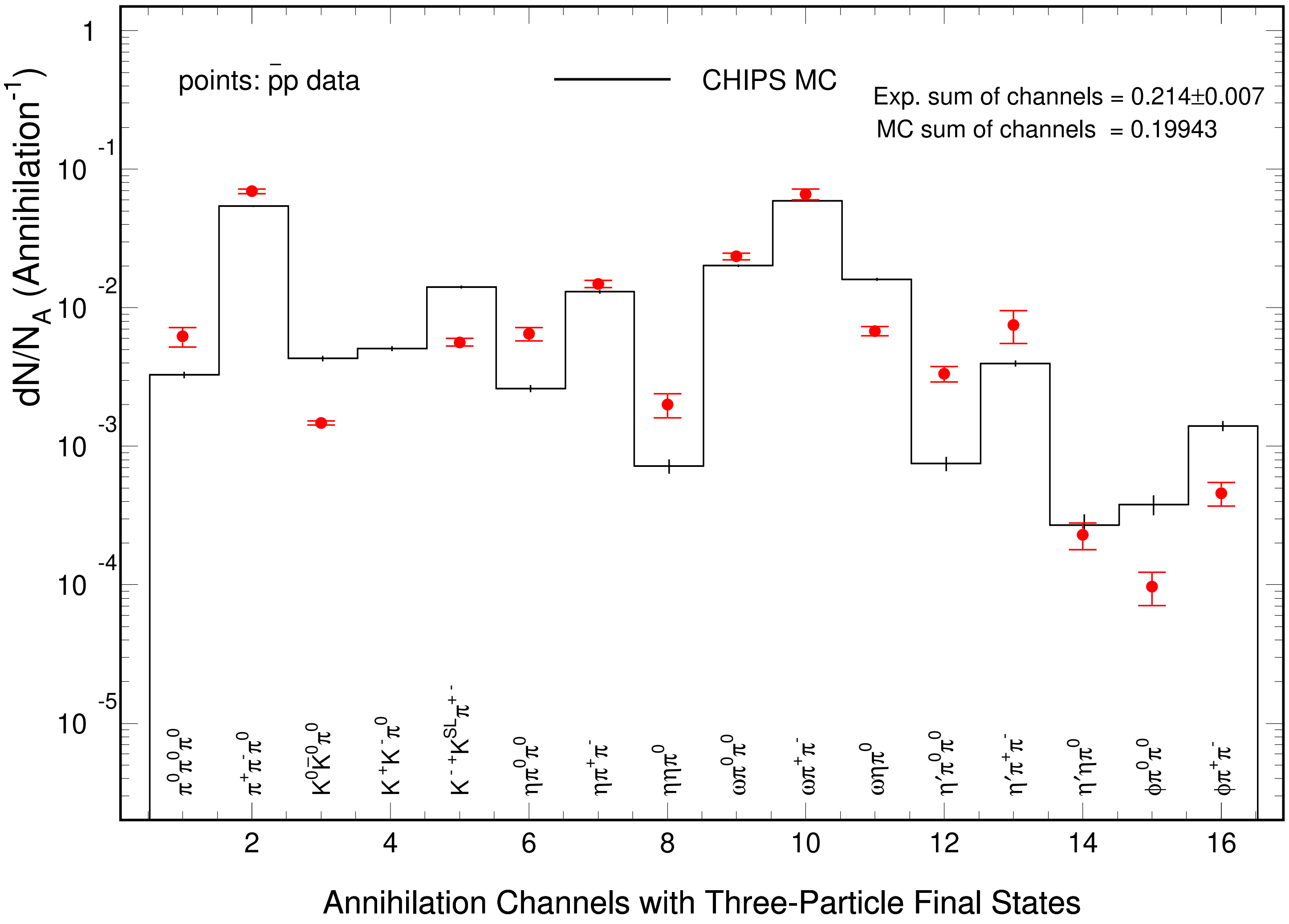
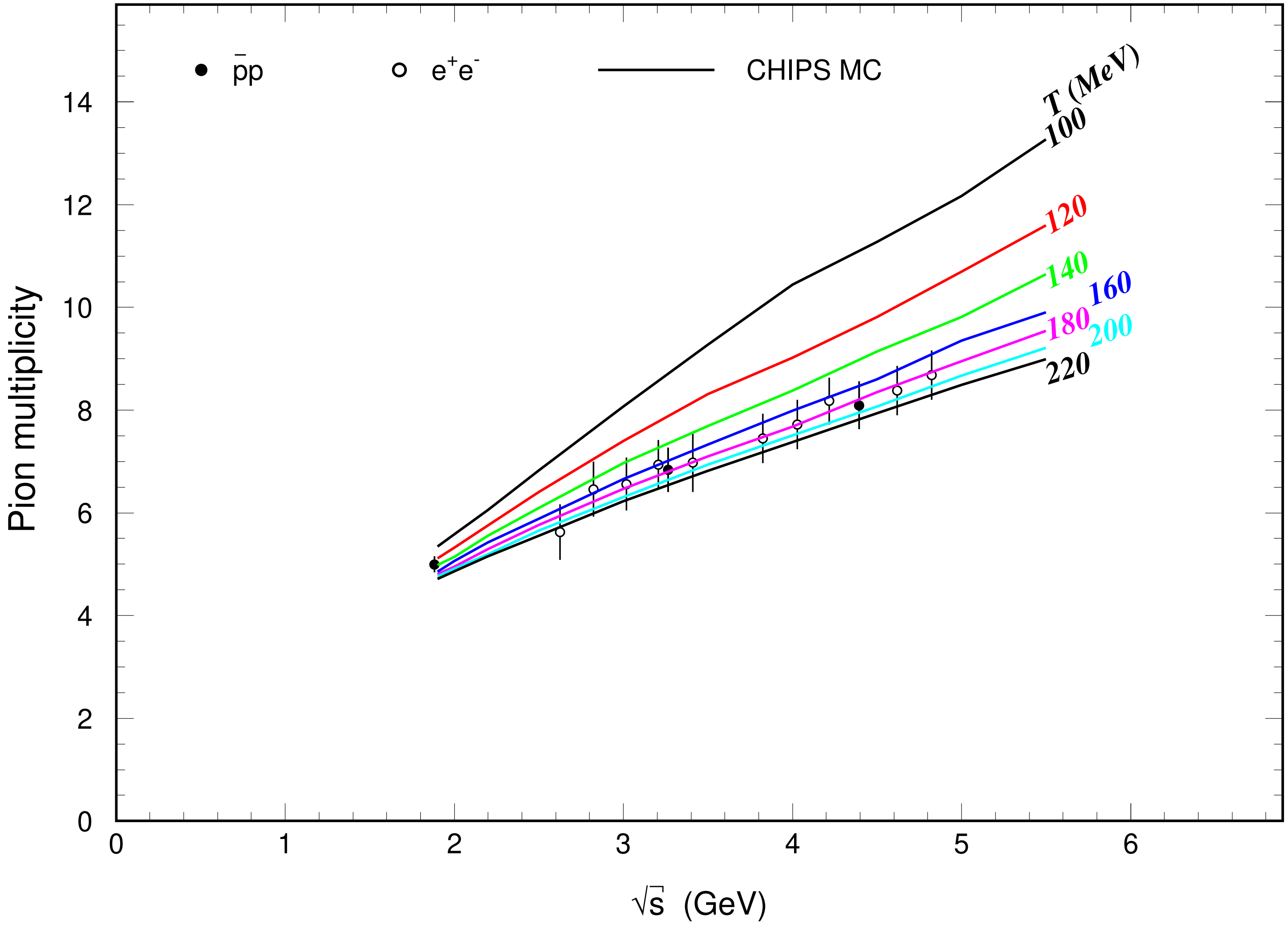


points: p̄p data
CHIPS MC
Exp. sum of channels = 0.214±0.007
MC sum of channels = 0.19943
dN/N_A (Annihilation^-1)
Annihilation Channels with Three-Particle Final States



p̄p
e+e-
CHIPS MC
T (MeV)
100
120
140
160
180
200
220
Pion multiplicity
√s (GeV)
0
2
4
6
8
10
12
14
0
1
2
3
4
5
6

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

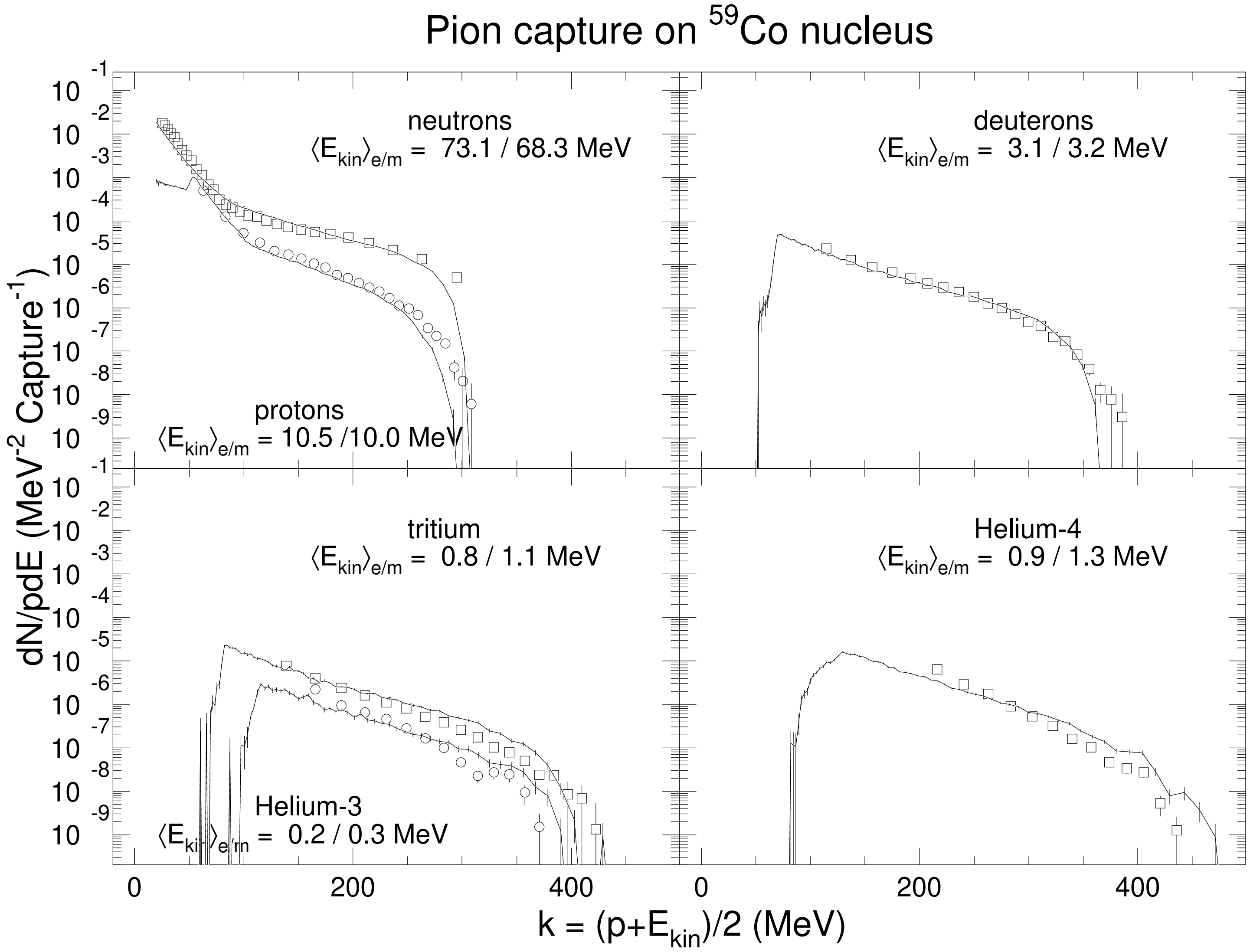
Quark exchange forces clustering nuclei.

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

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


Pion capture on 59Co nucleus
neutrons
⟨Ekin⟩e/m = 73.1 / 68.3 MeV
protons
⟨Ekin⟩e/m = 10.5 /10.0 MeV
deuterons
⟨Ekin⟩e/m = 3.1 / 3.2 MeV
tritium
⟨Ekin⟩e/m = 0.8 / 1.1 MeV
Helium-3
⟨Ekin⟩e/m = 0.2 / 0.3 MeV
Helium-4
⟨Ekin⟩e/m = 0.9 / 1.3 MeV
dN/pdE (MeV-2 Capture-1)
k = (p+Ekin)/2 (MeV)
0
200
400
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9

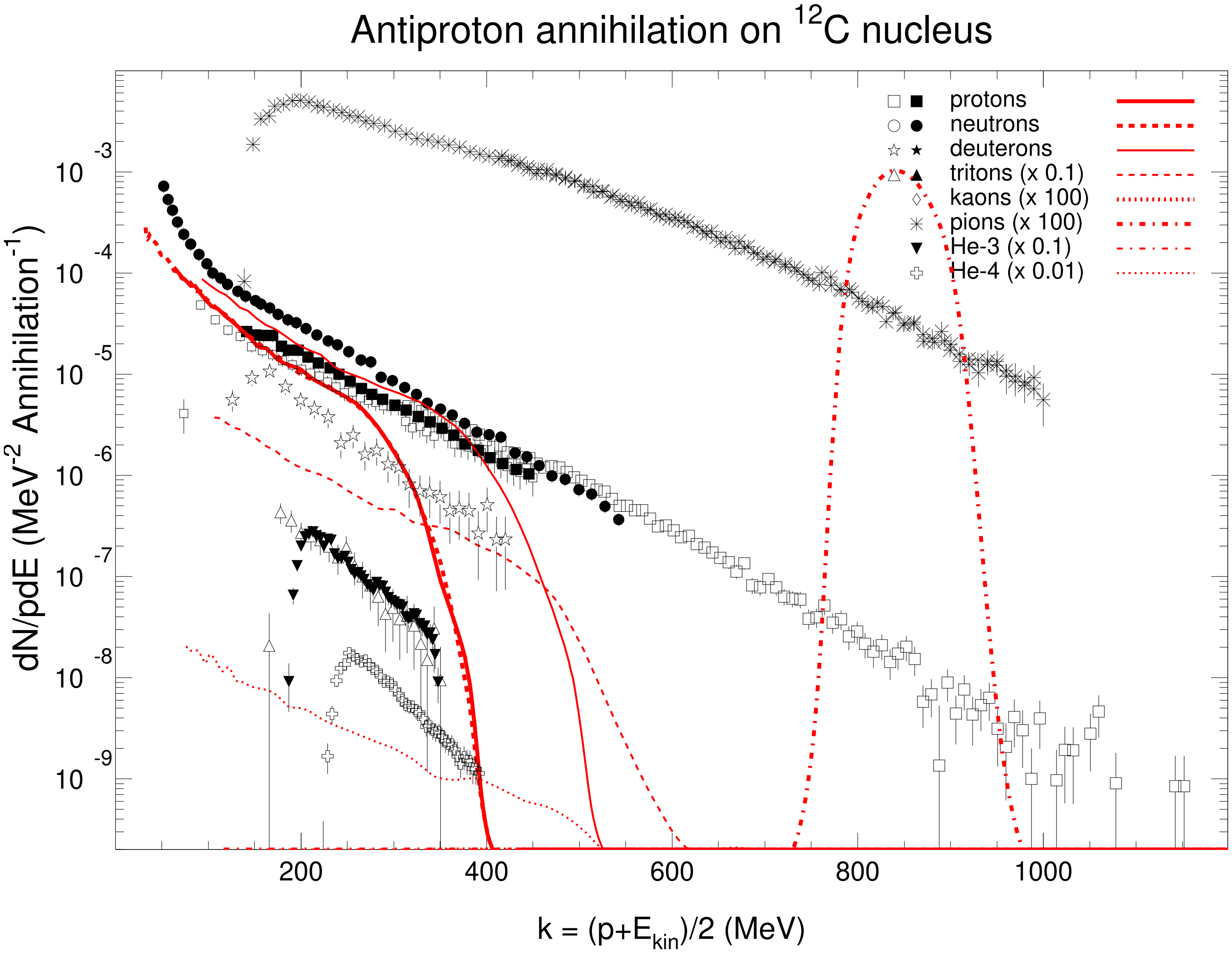
Present status of $\bar{p}A$ at rest simulation

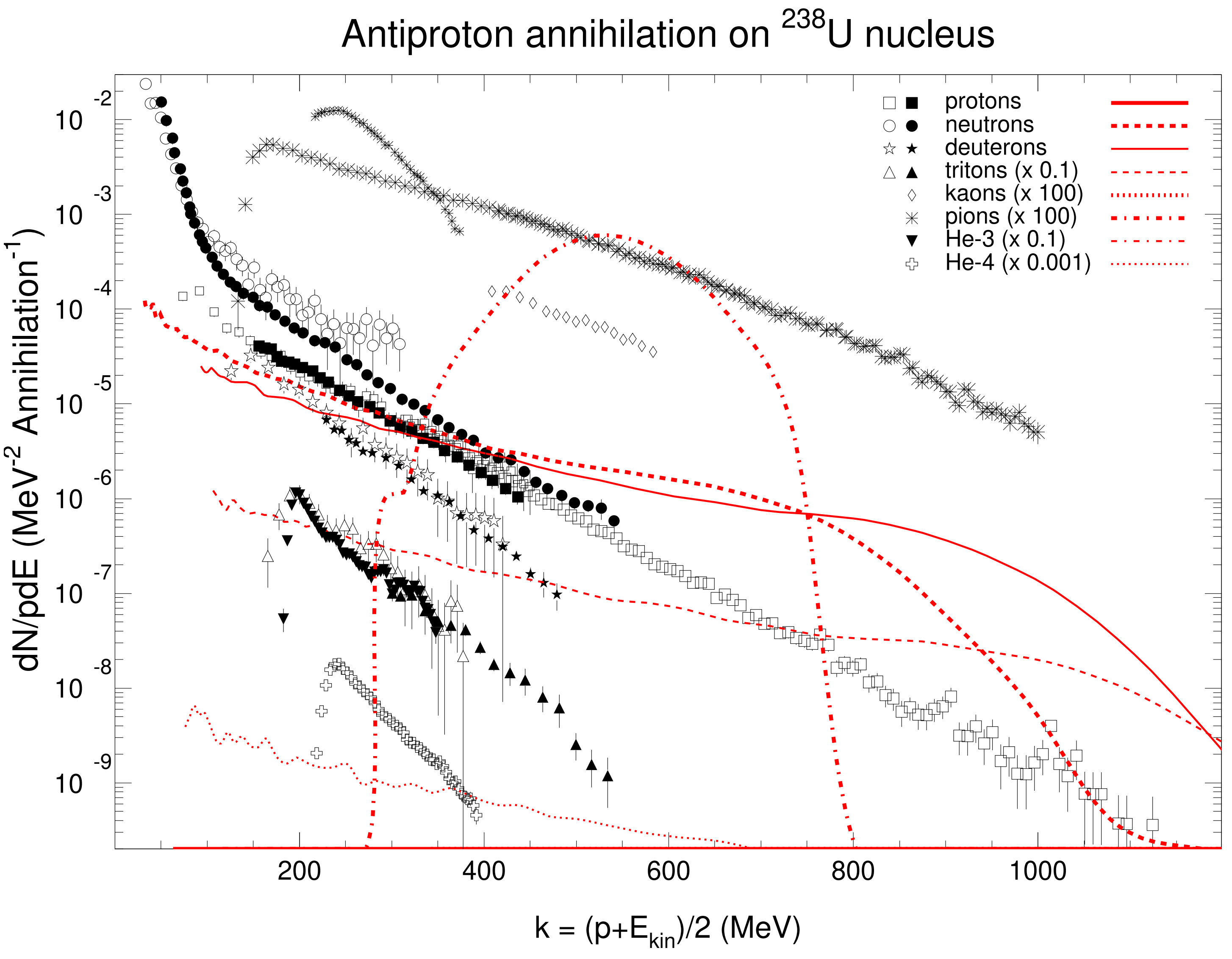
In hadronic Physics Lists (GHAD) for antiprotons the G4AntiProtonAnnihilationAtRest class is used (Larry Felawka, 1998).

It was tried in the test/test29 Test Facility made for CHIPS Physics Validation of different Capture At Rest reactions.

It looks like it is using the idea of " primary $\bar{p}p$ to two pions annihilation" like in INC (IntraNuclear Cascade) model.

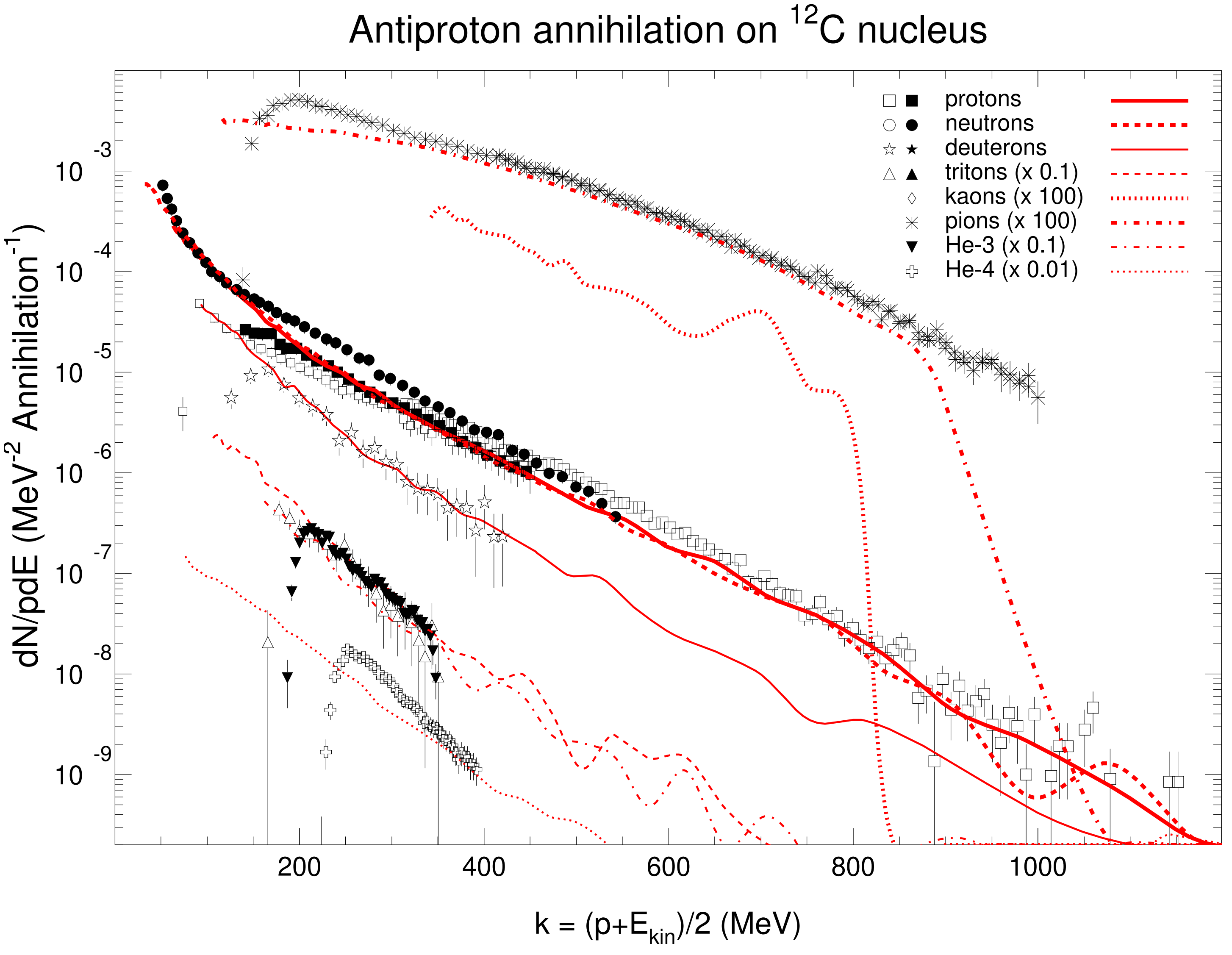
It is 50 times faster than the corresponding CHIPS simulation but does not conserve energy and momentum.


Antiproton annihilation on ^{12}C nucleus
protons
neutrons
deuterons
tritons (x 0.1)
kaons (x 100)
pions (x 100)
He-3 (x 0.1)
He-4 (x 0.01)
dN/pdE (MeV^{-2} Annihilation^{-1})
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
200
400
600
800
1000
k = (p+E$_{kin}$)/2 (MeV)


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}

CHIPS algorithm of Antiproton Capture At Rest

- annihilate antiproton-N on the periphery of the target nucleus;
- absorb secondary mesons inside a Solid Angle (a parameter);
- accept the secondary mesons outside the Solid Angle;
- make a multi-Quasmon excitation in the residual nucleus;
- hadronize the excited nucleus in hadrons and fragments;
- if the DINR hadronization is exhausted, evaporate the residual;
- if the residual nucleus is far from the lane of stability, make a cascade of n, p, or α decays (can be below a Coulomb Barrier).



Antiproton annihilation on ^{12}C nucleus
protons
neutrons
deuterons
tritons (x 0.1)
kaons (x 100)
pions (x 100)
He-3 (x 0.1)
He-4 (x 0.01)
dN/pdE (MeV^{-2} Annihilation^{-1})
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
200
400
600
800
1000
k = (p+E$_{kin}$)/2 (MeV)

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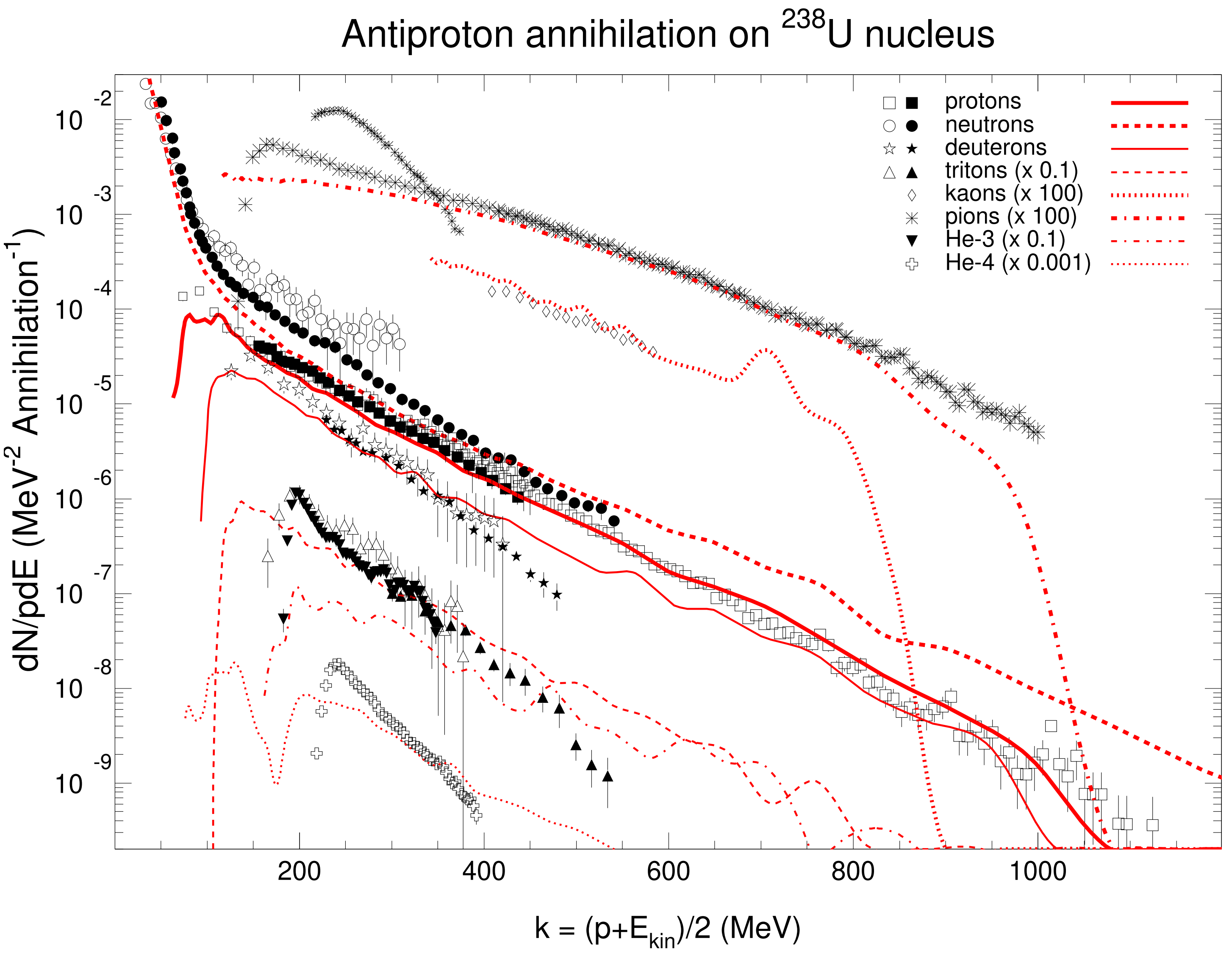
Antiproton annihilation on ^{238}U nucleus
dN/pdE (MeV^{-2} Annihilation^{-1})
k = (p+E$_{kin}$)/2 (MeV)
protons
neutrons
deuterons
tritons (x 0.1)
kaons (x 100)
pions (x 100)
He-3 (x 0.1)
He-4 (x 0.001)

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Conclusion

- CHIPS 3D/SU(3) event generator can be applied to $\bar{p}A$ at rest;
- it is working longer than G4AntiProtonAnnihilationAtRest but better;
- probably the primary annihilation on di-nucleons must be added;
- the Quasmon virtuality in heavy nuclei must be tuned in CHIPS;
- clusterization parameters must be tuned (the reaction is peripheral);
- competition of vacuum and medium hadronization must be tuned;
- capture cross-sections for mesons must be used for absorbed mesons;
- a better Complete Experiment data set is needed for the final tuning.