Simulation of nuclear muon capture by CHIPS in Geant4

Mikhail Kosov, Physics Validation, **28.02.2007**

Neutron spectra in μ^--capture reactions

- Since 60's there exists a problem of high energy neutrons in muon capture reactions
- Maximum neutron energy in the $\mu^-(p,n)\nu_\mu$ reaction is $T=m^2_\mu/2m_N$=5.3 MeV (E_n>80 MeV)
- Absolute normalization of nuclear μ-capture reaction depends on a nuclear capture rate $\Lambda_c=1/\tau_c$ (.45÷12610.) and on a decay rate Λ_d.
- As muons are bounded, the decay rate Λ_d is reduced by a Huff factor (H): $\Lambda_d=H/\tau_\mu=H\cdot 455.16$
- For light nuclei: $\Lambda_c<<\Lambda_d$, heavy nuclei: $\Lambda_c>>\Lambda_d$

Parameterization of atomic coefficients

- The **Huff** factor (**I.W. Huff, Ann.Phys. (N.Y.) 16 (1961) 288**) was investigated in **I.M. Blair et al., Proc.Phys.Soc. London 80 (1962) 938**: **H=1÷0.82(U)**
- In CHIPS it is tabulated till ^{19}F and for Z>9 it is parameterized as a function of Z (only)
- The nuclear capture rate Λ_c can be roughly approximated by a **Primakoff** formula

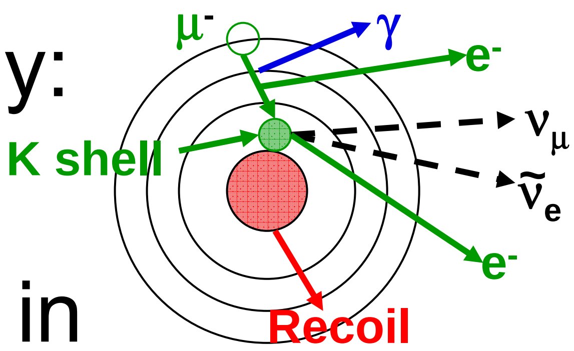
$$\Lambda_c(A,Z)=Z^4_{eff}\cdot(170s^{-1})\cdot[1-3.125\cdot(A-Z)/2A]$$

- In CHIPS it is tabulated till ^{19}F and for Z>9 it is parameterized as a function of Z (only)

Simulation of decay of bounded muon

- The effective nuclear charge Z_{eff} and the nuclear mass A can be used for simulation of the bounded muon decay:

  Recently electron spectra were accurately calculated in

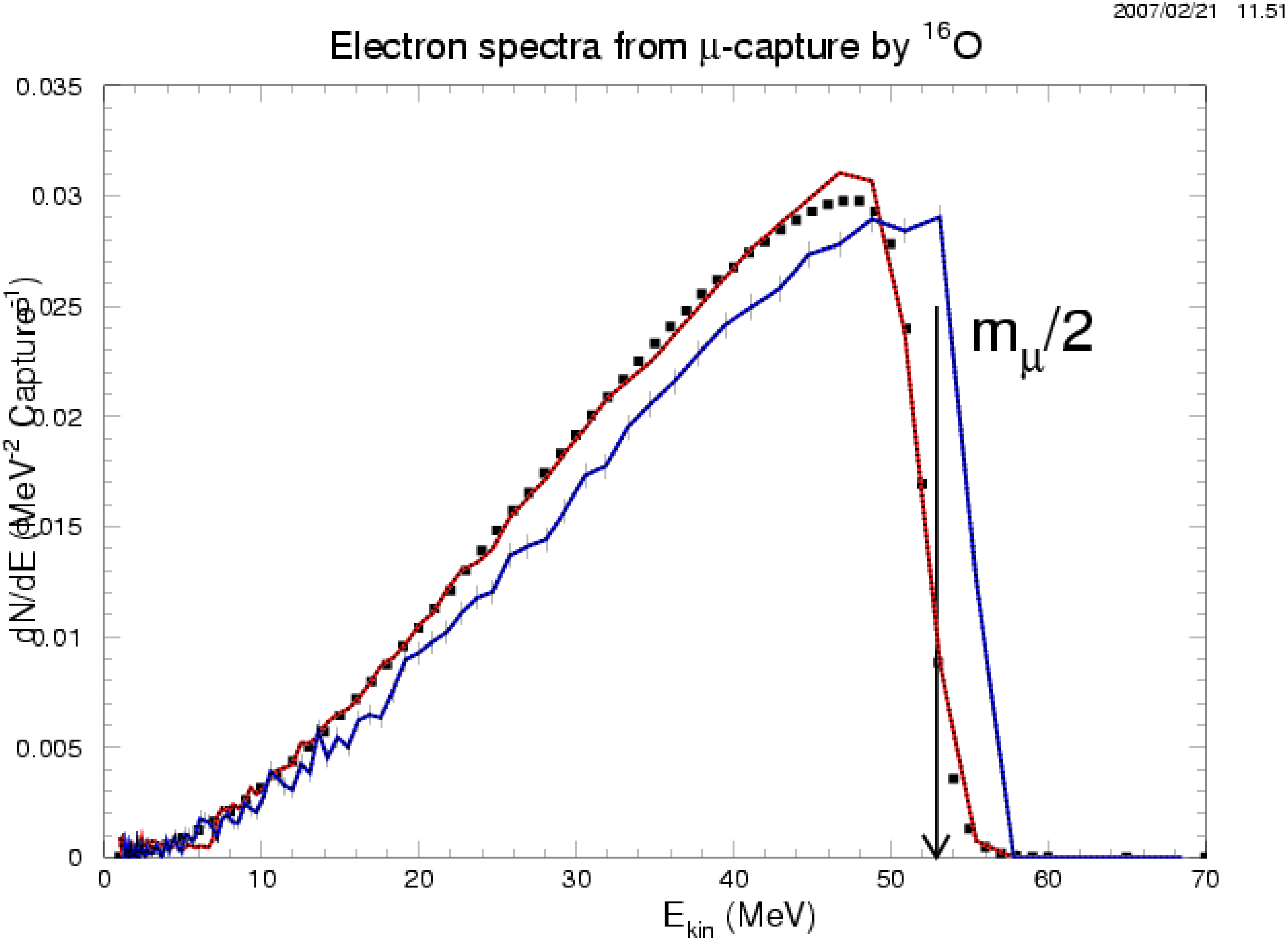


Atomic Data and Nuclear Data Tables,v.54(1993)165

- The electron spectrum can exceed the free $m_\mu/2$ threshold, because momentum can be transferred to the recoil nucleus.

Geant4 processes for muon capture

- Historically there was an inherited from GEANT3 G4MuonMinusCaptureAtRest process. It was rewritten by FLUKA demand.
- Now the algorithm of this process is a pre-compound deexcitation after $\mu^-(p_{bound},n_{free})\nu_\mu$.
- An alternative process is G4QCaptureAtRest
- It is based on the CHIPS deexcitation after 97.5% $\mu^-(q,q)\nu_\mu$ and 2.5% $\mu^-\rightarrow q+\bar{q}+\nu_\mu$.
- On pictures: old – blue curves, new (CHIPS) – red curves, dots are from published **Tables**.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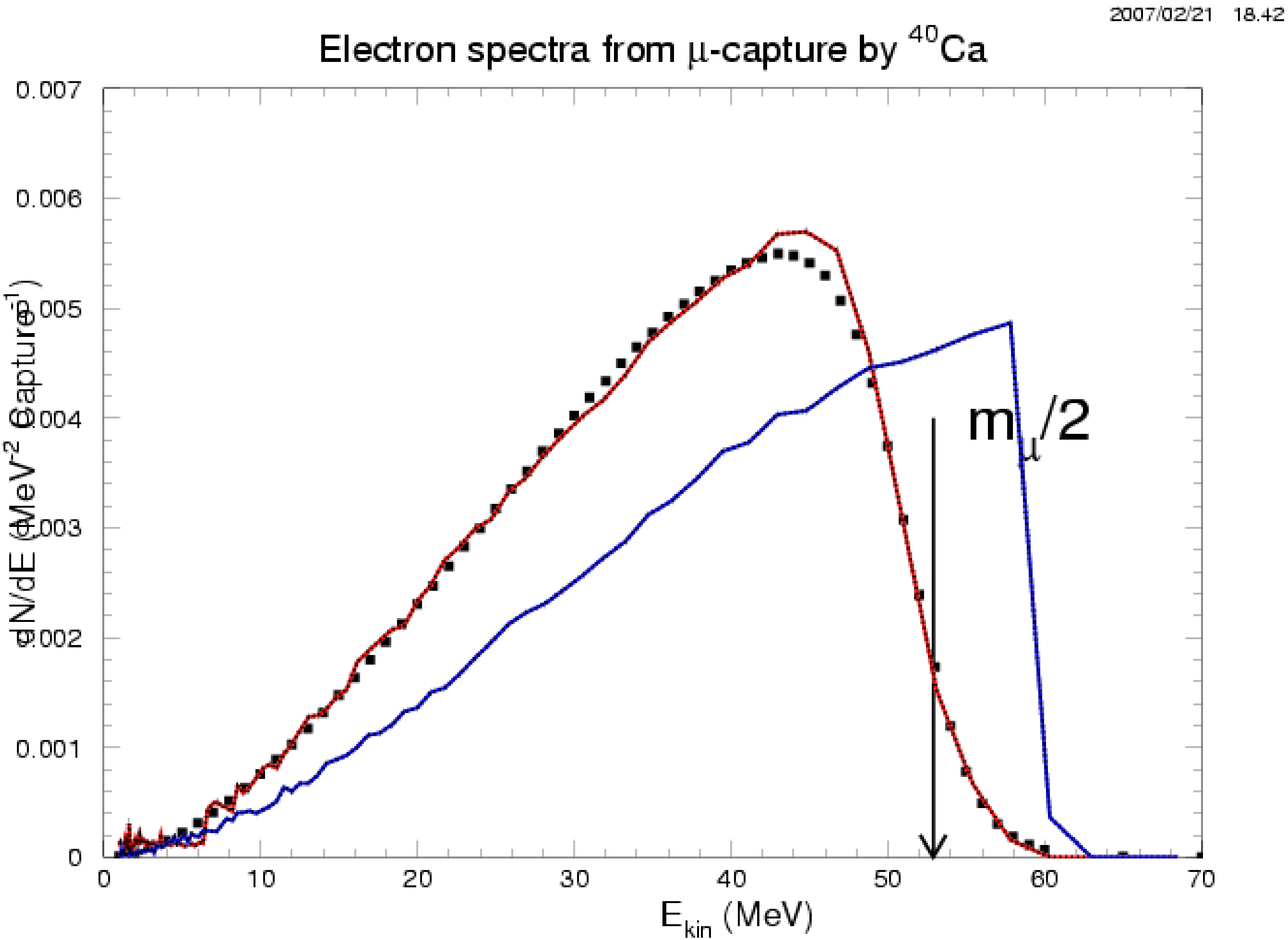
Electron spectra from μ-capture by ¹⁶O
dN/dE (MeV⁻² Capture⁻¹)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
10
20
30
40
50
60
70
E_kin (MeV)
m_μ/2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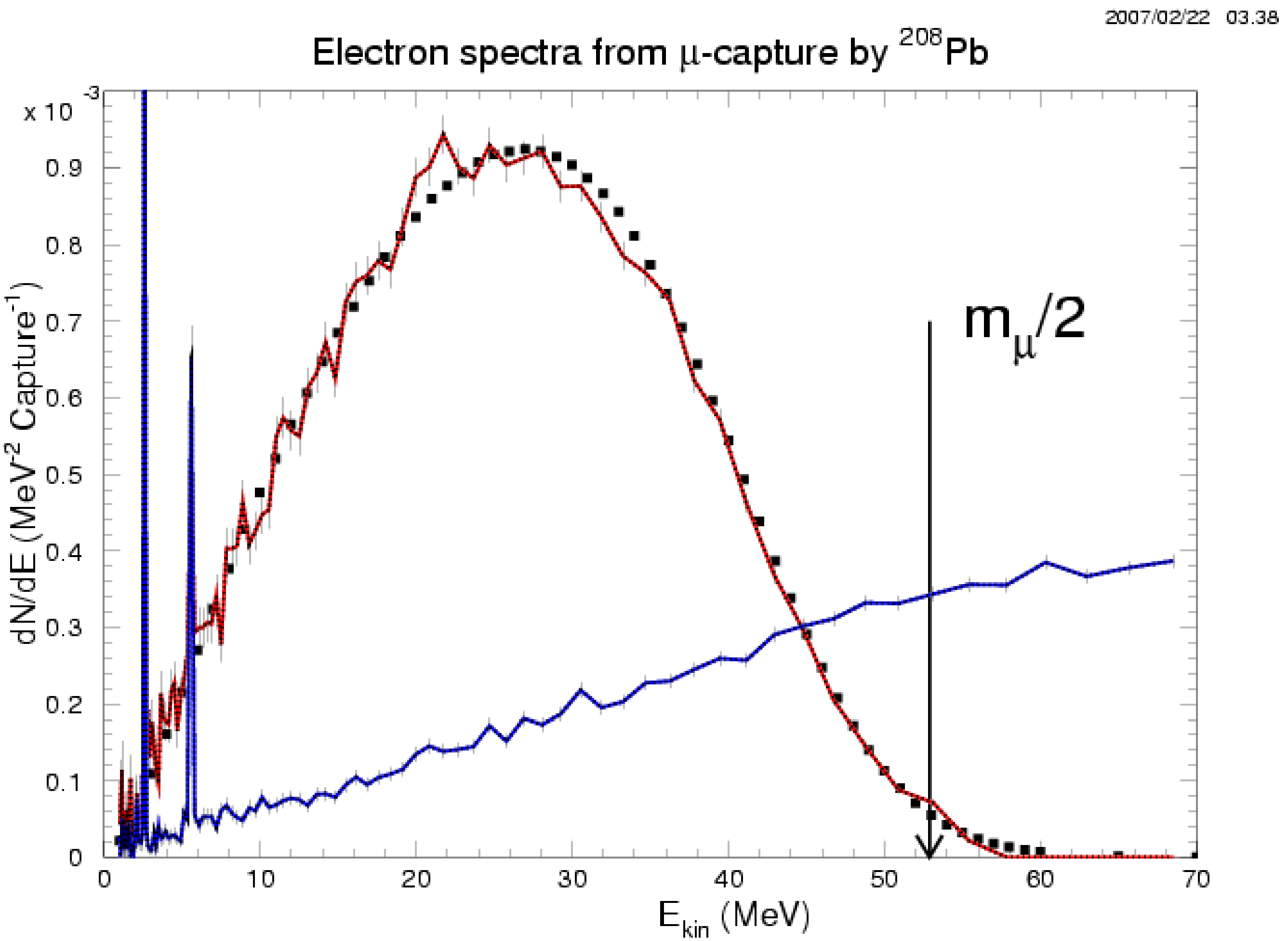
Electron spectra from μ-capture by 40Ca
dN/dE (MeV-2 Capture-1)
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
10
20
30
40
50
60
70
Ekin (MeV)
mμ/2



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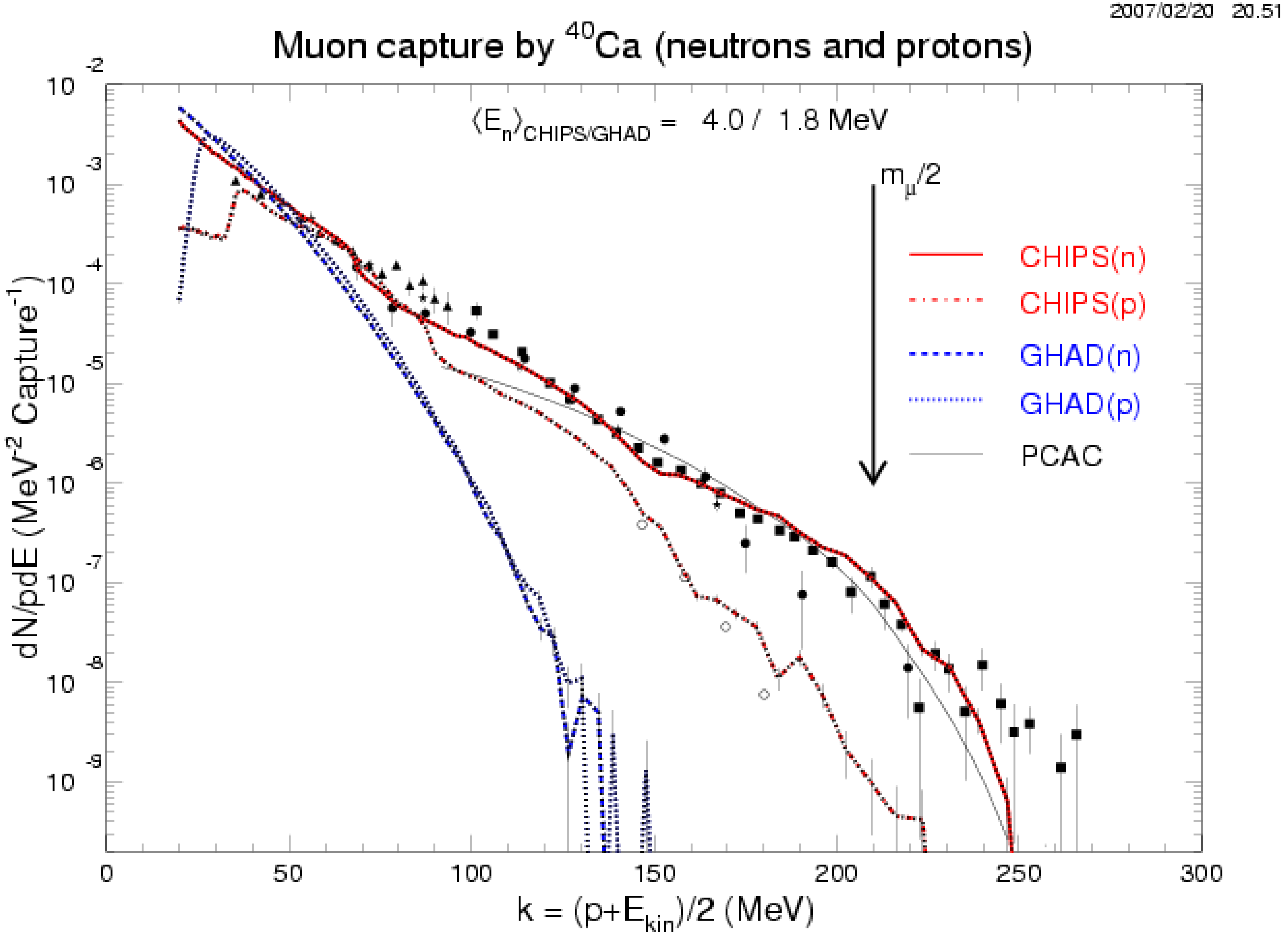
Electron spectra from μ-capture by 208Pb
x 10-3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
dN/dE (MeV-2 Capture-1)
0
10
20
30
40
50
60
70
Ekin (MeV)
mμ/2

Spectra of nucleons in nuclear μ-capture

- In addition to classic E. Segre data for **Ca** (▲) (**Experimental Nuclear Physics, N.-Y., Wiley,1953**) and R.M. Sudelin, R.M. Edelstein measurements (**Phys.Rev. C7 (1973) 1037**) on Si, S, and **Ca** nuclei (*) there are recent data for neutron spectra:
  - for ^{16}O (**Nucl.Phys. A408 (1983) 573**) $^{16}O(\mu^-,\nu_\mu xn)$
  - for ^{165}Ho (**Phys. Lett., B137 (1984) 339**) (■)
  - for O, Si, **Ca**, Pb (**Nucl. Phys. A436 (1985) 717**) (●)
  - for ^{40}**Ca** (**Phys. Lett., B177 (1986) 21**) (■)
- The only μ-nuclear (**Ca**, Y) spectra of protons are **W.J.Cumming, Nuclear Muon Capture in Extreme Kinematics, Stanford University, Thesis (Ph.D), 1992** **(o)**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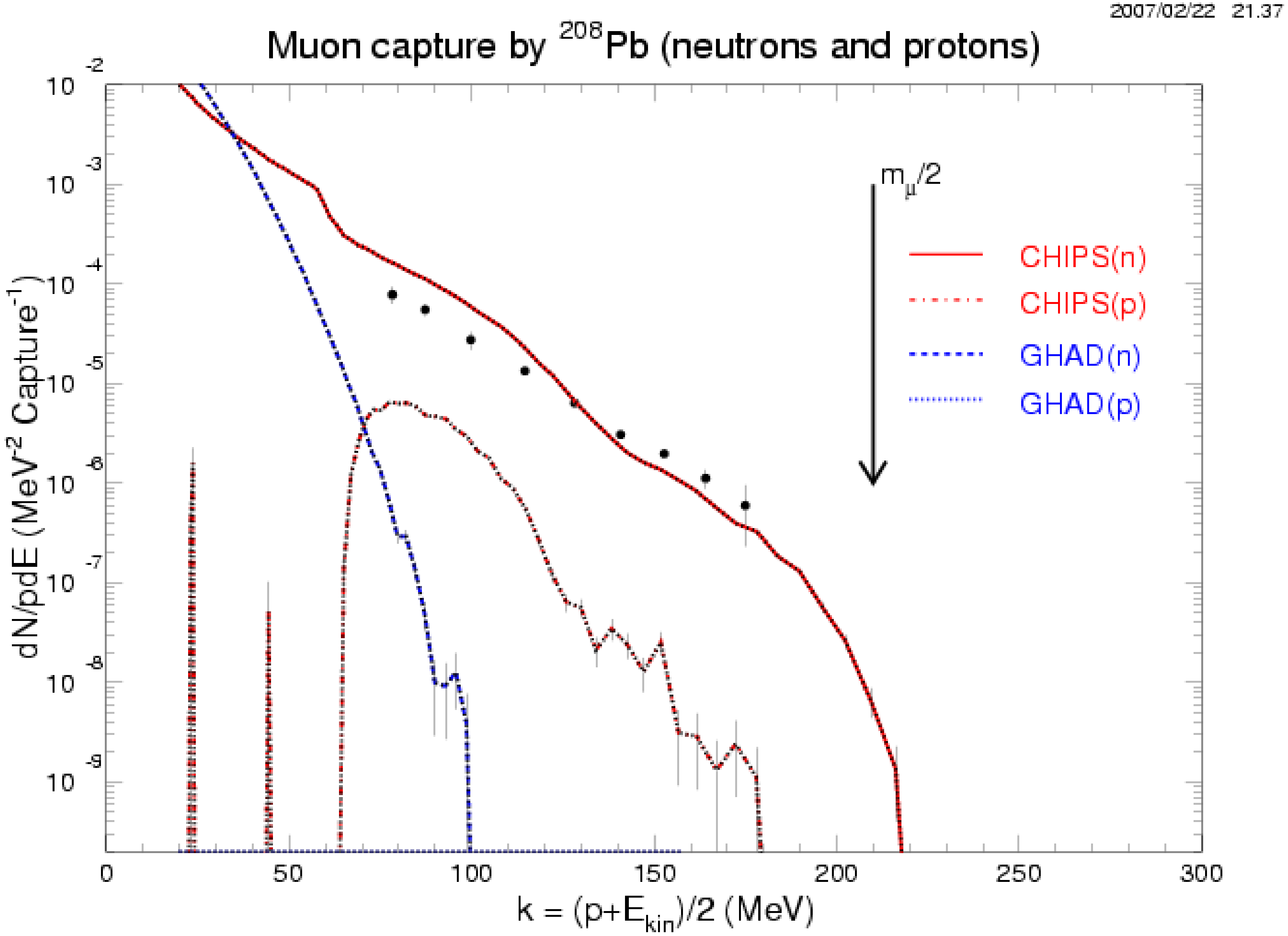
Muon capture by ^{40}Ca (neutrons and protons)
$\langle E_n \rangle_{CHIPS/GHAD}$ = 4.0 / 1.8 MeV
$m_\mu/2$
CHIPS(n)
CHIPS(p)
GHAD(n)
GHAD(p)
PCAC
dN/pdE (MeV^{-2} Capture^{-1})
k = (p+E$_{kin}$)/2 (MeV)
0
50
100
150
200
250
300
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}



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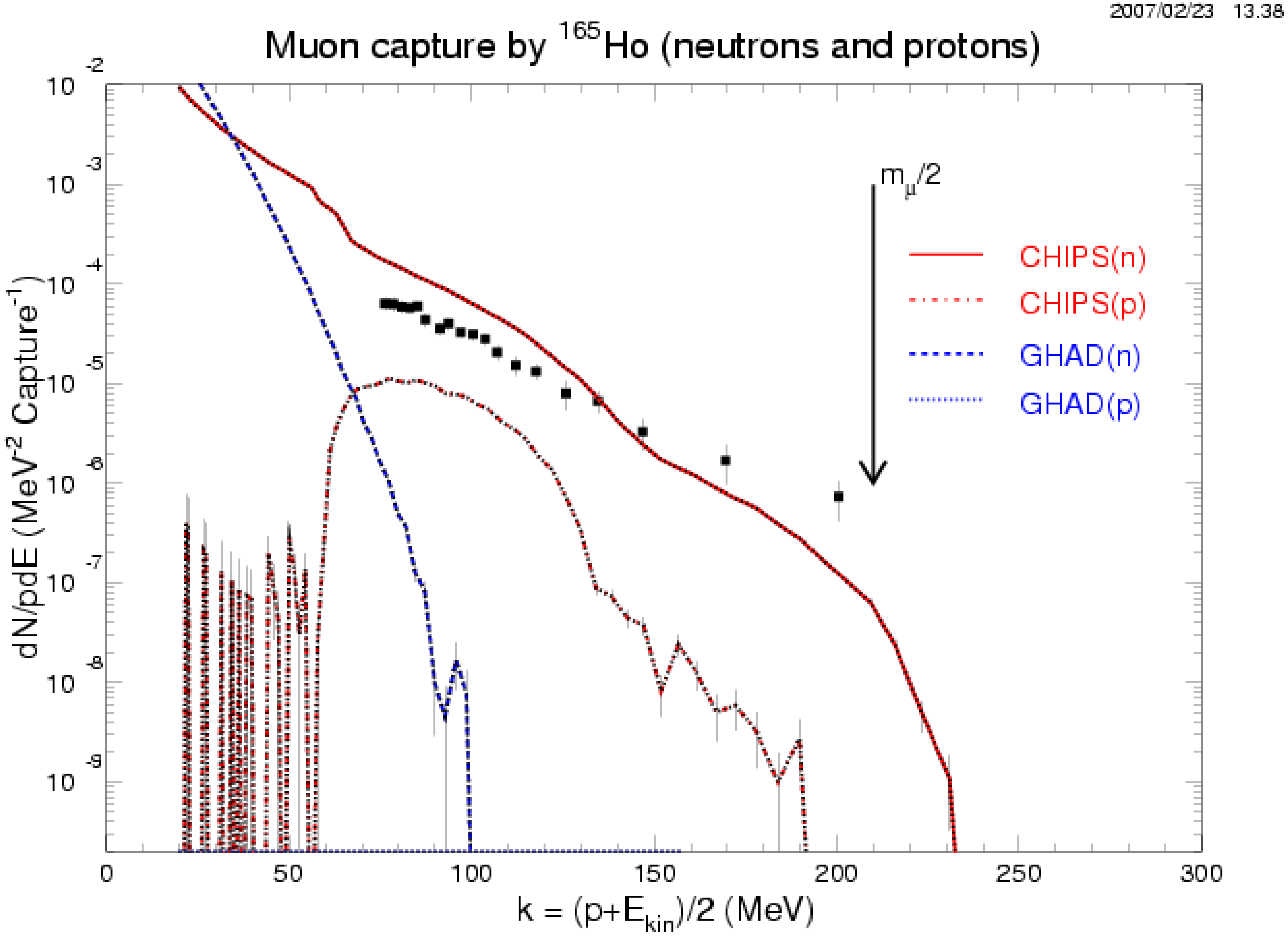
Muon capture by 208Pb (neutrons and protons)
dN/pdE (MeV-2 Capture-1)
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
0
50
100
150
200
250
300
k = (p+Ekin)/2 (MeV)
mμ/2
CHIPS(n)
CHIPS(p)
GHAD(n)
GHAD(p)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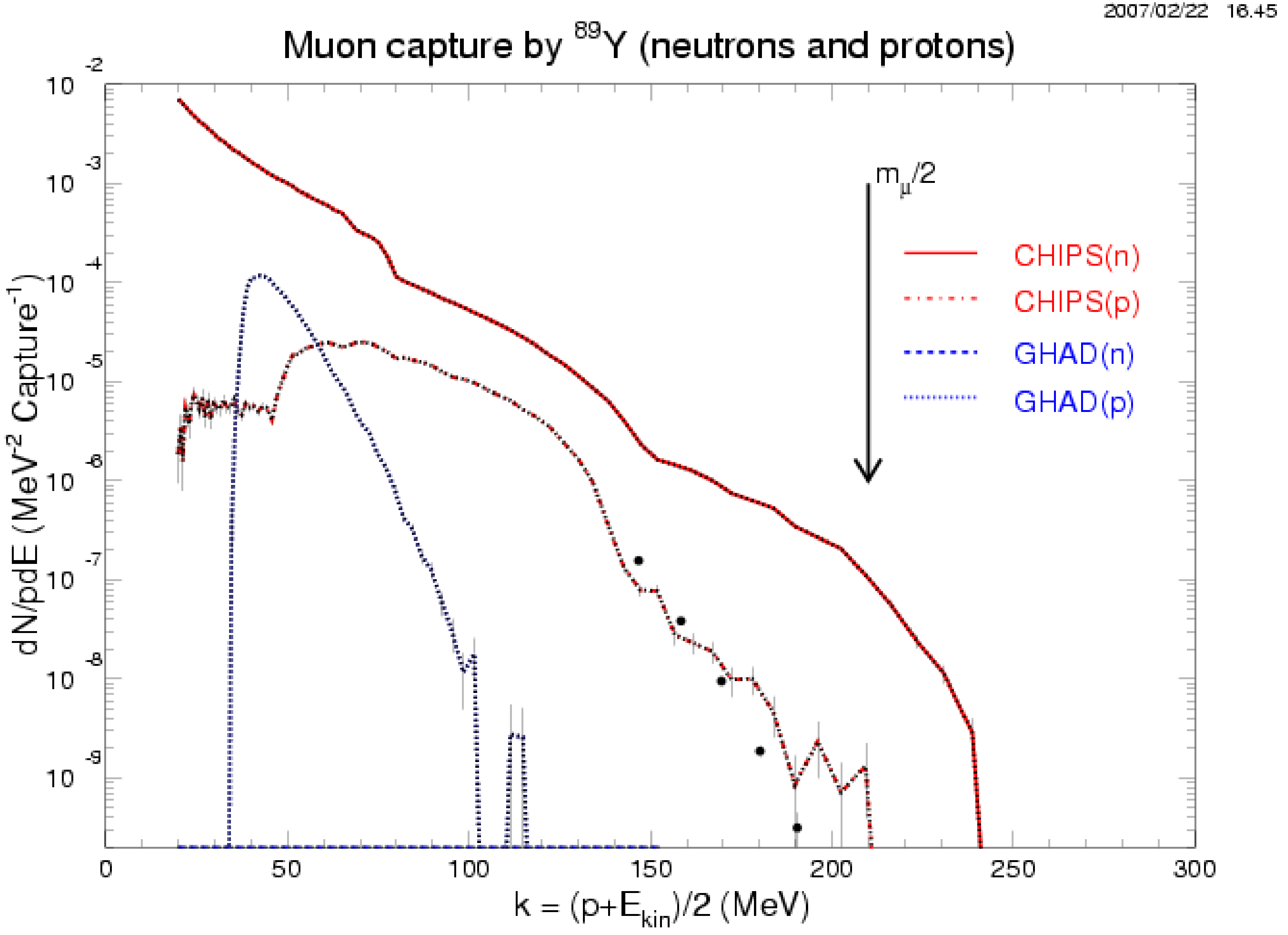
Muon capture by 165Ho (neutrons and protons)
dN/pdE (MeV-2 Capture-1)
k = (p+Ekin)/2 (MeV)
mμ/2
CHIPS(n)
CHIPS(p)
GHAD(n)
GHAD(p)
0
50
100
150
200
250
300
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9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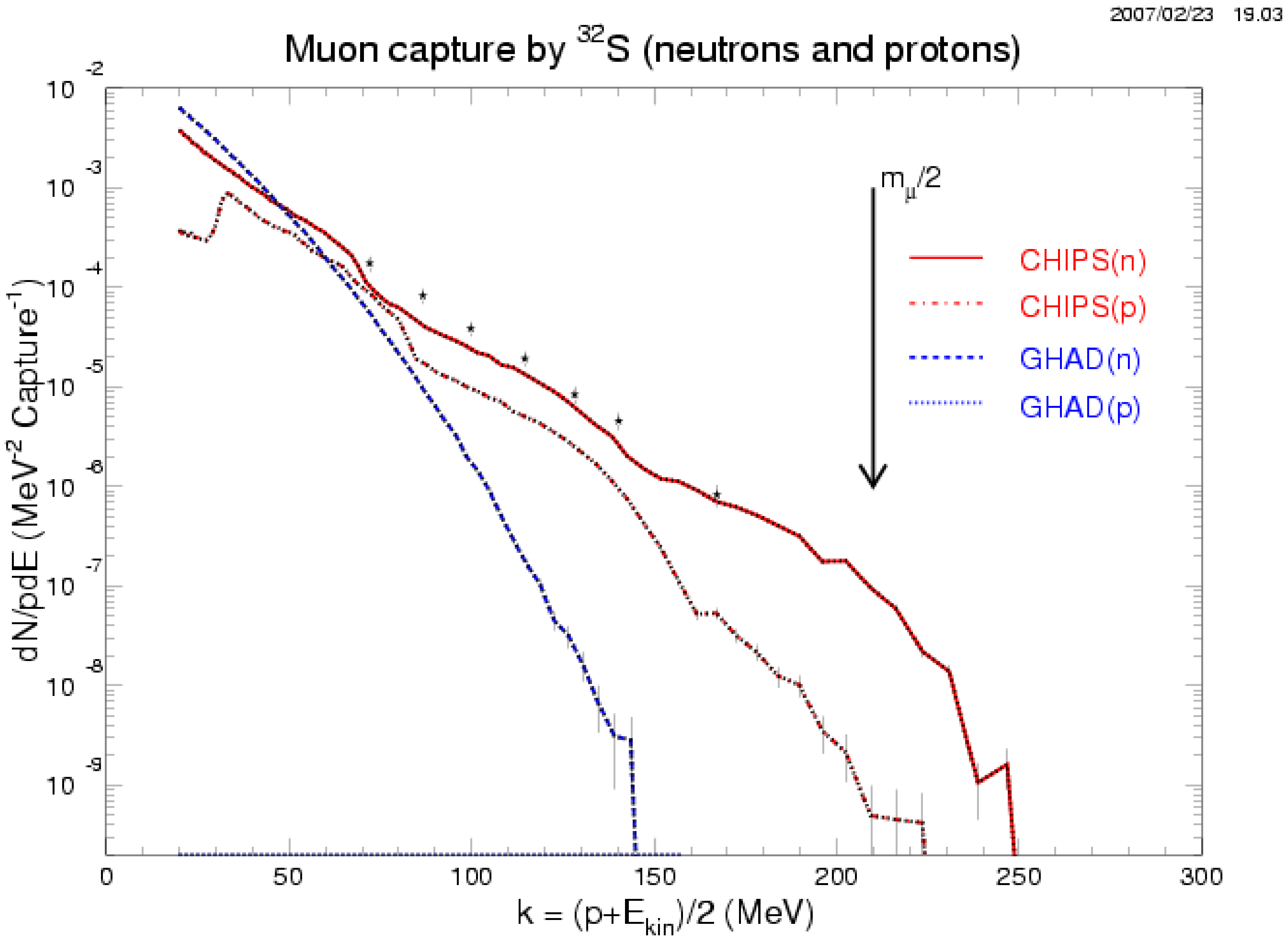
Muon capture by 89Y (neutrons and protons)
dN/pdE (MeV-2 Capture-1)
k = (p+Ekin)/2 (MeV)
mμ/2
CHIPS(n)
CHIPS(p)
GHAD(n)
GHAD(p)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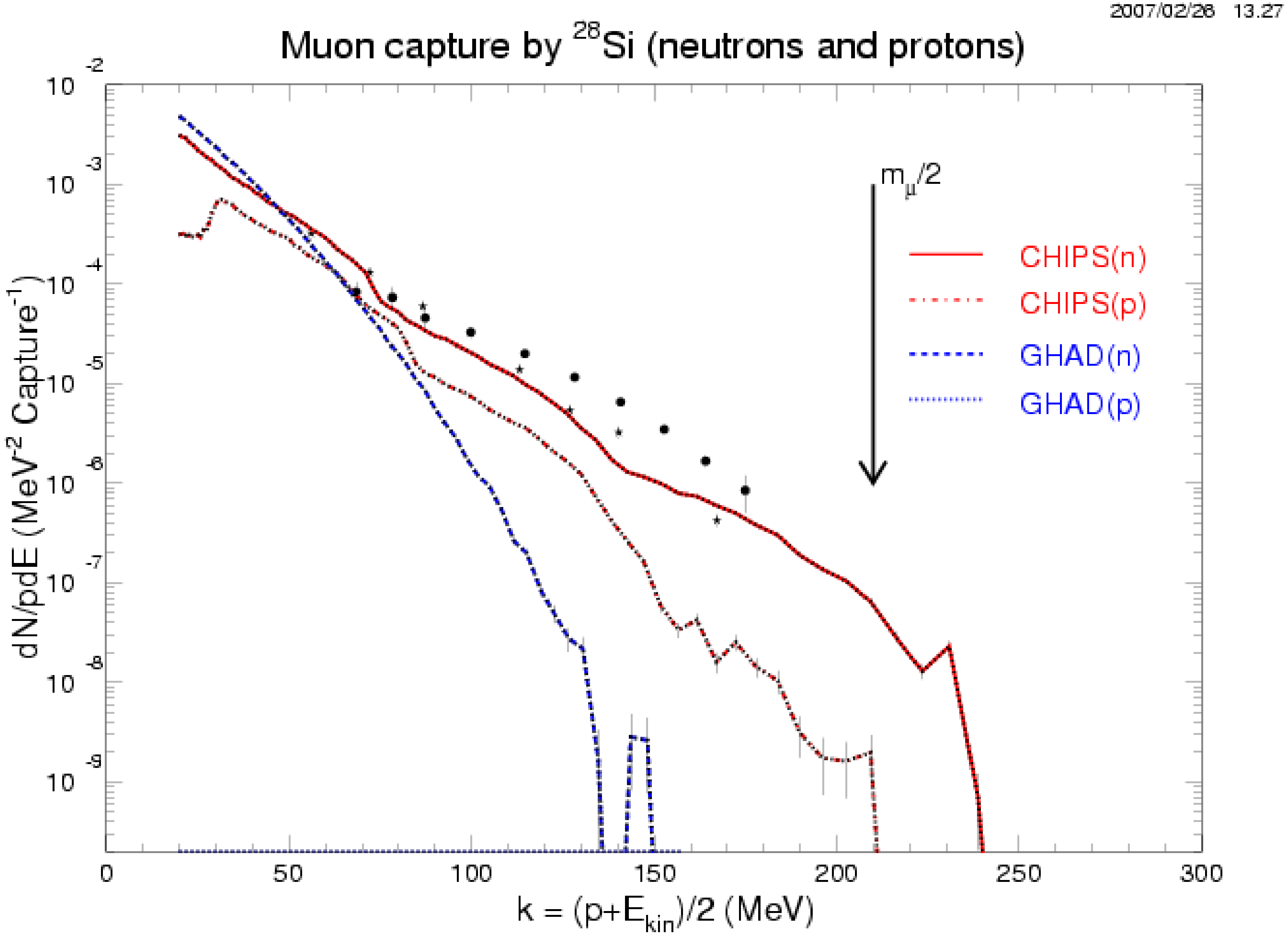
Muon capture by ^{32}S (neutrons and protons)
dN/pdE (MeV^{-2} Capture^{-1})
k = (p+E$_{kin}$)/2 (MeV)
m$_\mu$/2
CHIPS(n)
CHIPS(p)
GHAD(n)
GHAD(p)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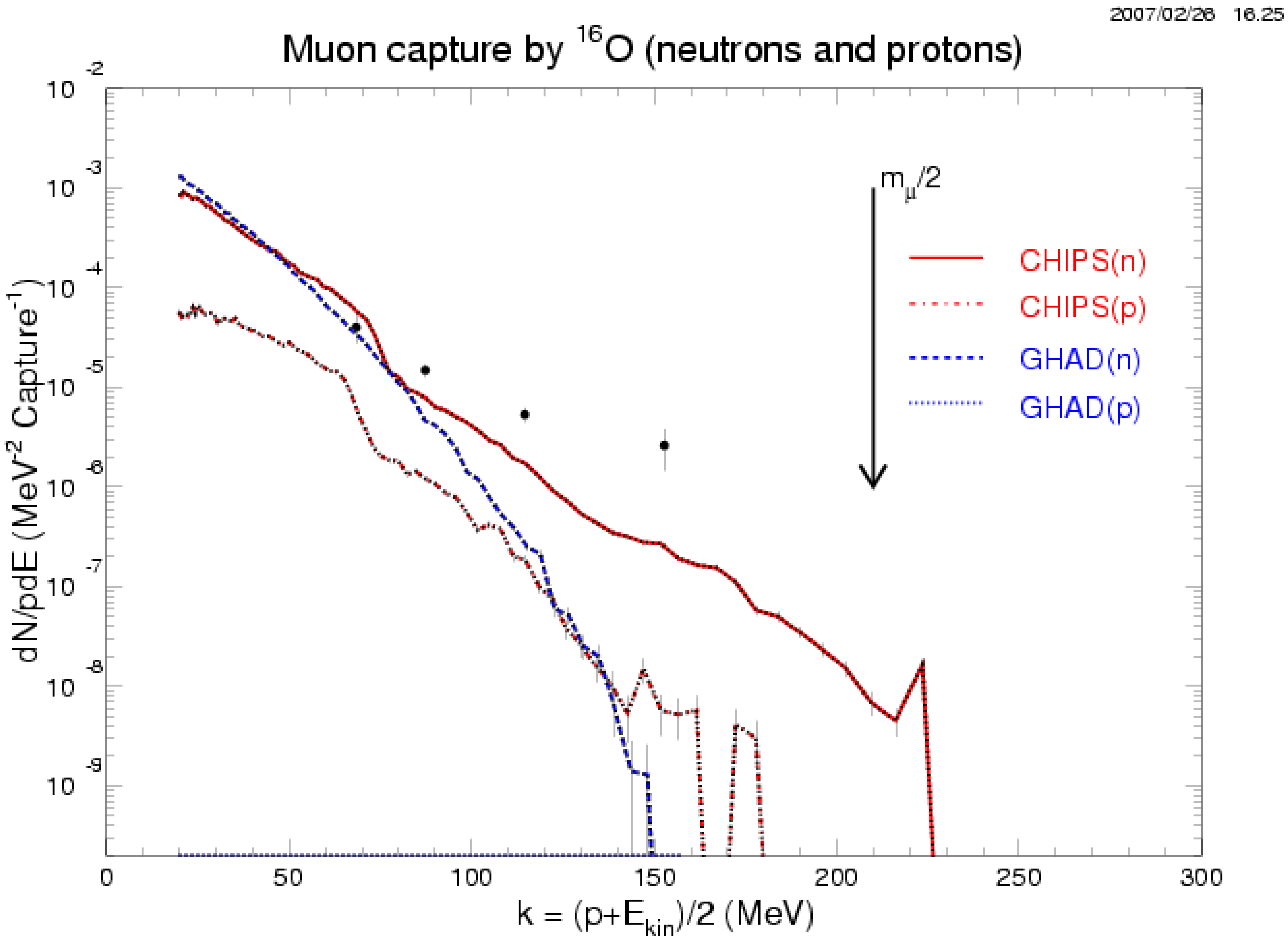
Muon capture by 28Si (neutrons and protons)
dN/pdE (MeV-2 Capture-1)
k = (p+Ekin)/2 (MeV)
mμ/2
CHIPS(n)
CHIPS(p)
GHAD(n)
GHAD(p)
0
50
100
150
200
250
300
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9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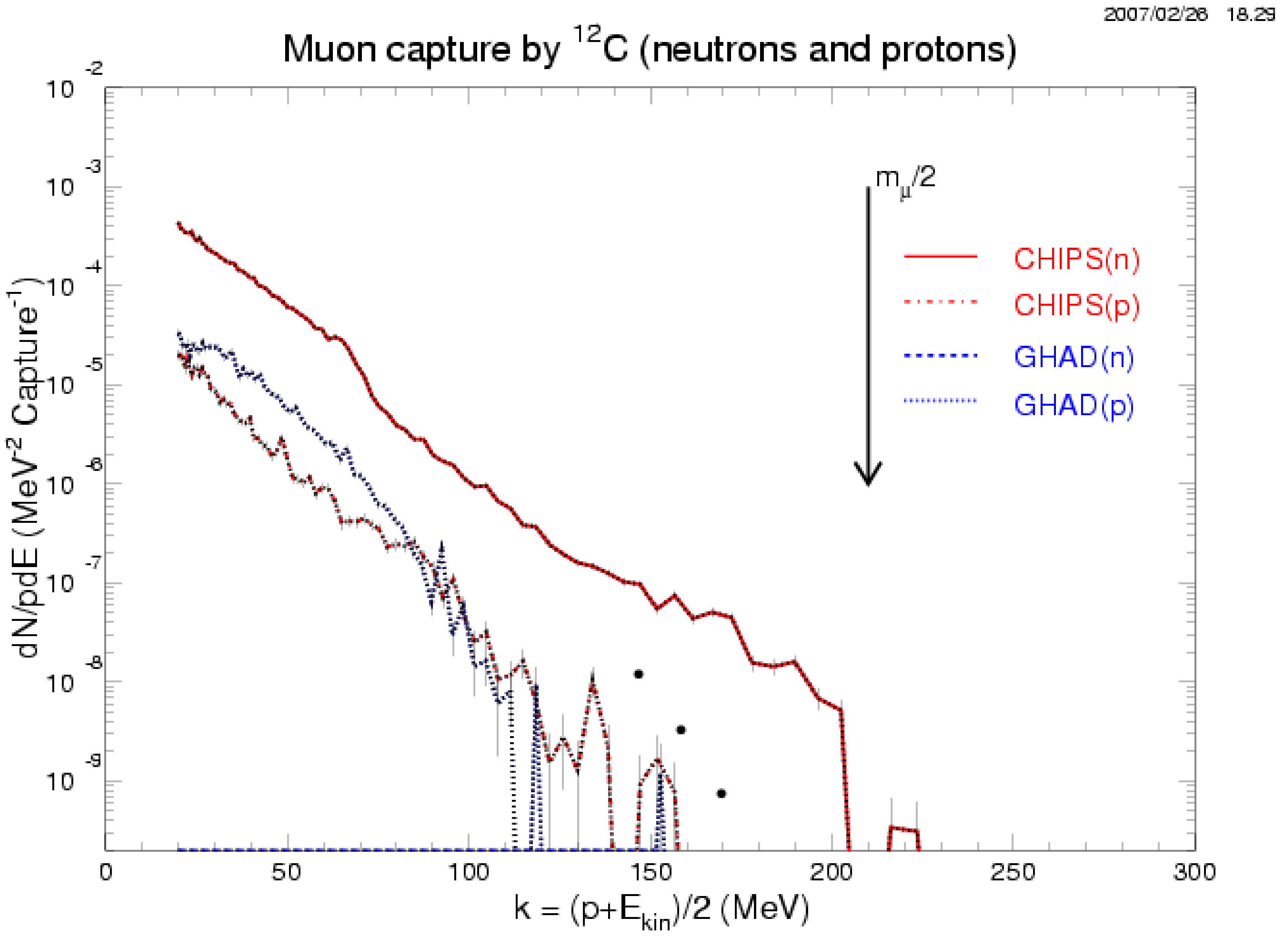
Muon capture by 16O (neutrons and protons)
dN/pdE (MeV-2 Capture-1)
k = (p+Ekin)/2 (MeV)
mμ/2
CHIPS(n)
CHIPS(p)
GHAD(n)
GHAD(p)
0
50
100
150
200
250
300



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Muon capture by 12C (neutrons and protons)
dN/pdE (MeV-2 Capture-1)
k = (p+Ekin)/2 (MeV)
mμ/2
CHIPS(n)
CHIPS(p)
GHAD(n)
GHAD(p)

Conclusion

- A bug was found in electron spectra simulation by the **G4MuonMinusCaptureAtRest** class: **electron is radiated in muon momentum direction**
- The $\mu^-(p_{bound},n_{free})\nu_\mu$ capture is unrealistic and can be substituted by the **PCAC** mechanism: **J.Bernabeu, T.E.O. Ericson, C.Jarlskog, Phys. Lett., 69B (1977) 161**
- **Precompound** model can not reproduce the difference between proton and neutron spectra
- The CHIPS **2.5%** parameter (for $\mu^-\rightarrow q+\bar{q}+\nu_\mu$) chosen for **Ca** can be A-dependent and nuclear parameters can be different from those for pion capture (in this calculations they are the same)