New Geant4.9.0 Models for Muon-Nuclear Interactions

Mikhail Kosov, 12th Geant4 Workshop (GB, Sept. 2007)

Muon-nuclear interactions on flight

- Important use-cases of μ-nuclear interactions
  - Background for Underground experiments
  - Muon Chambers in high energy physics (LHC)
- Energetic muon-nuclear interactions provide
  - Correlated background of muons and neutrons
  - Catastrophic energy loss of muons in μ-chambers
- **G4QCollision** and **G4MuNuclearInteraction**
  - CHIPS against γ=50%π^++50%π^- +QGS+Cascade
  - Nan's in G4MuNuclearInteraction at low energies

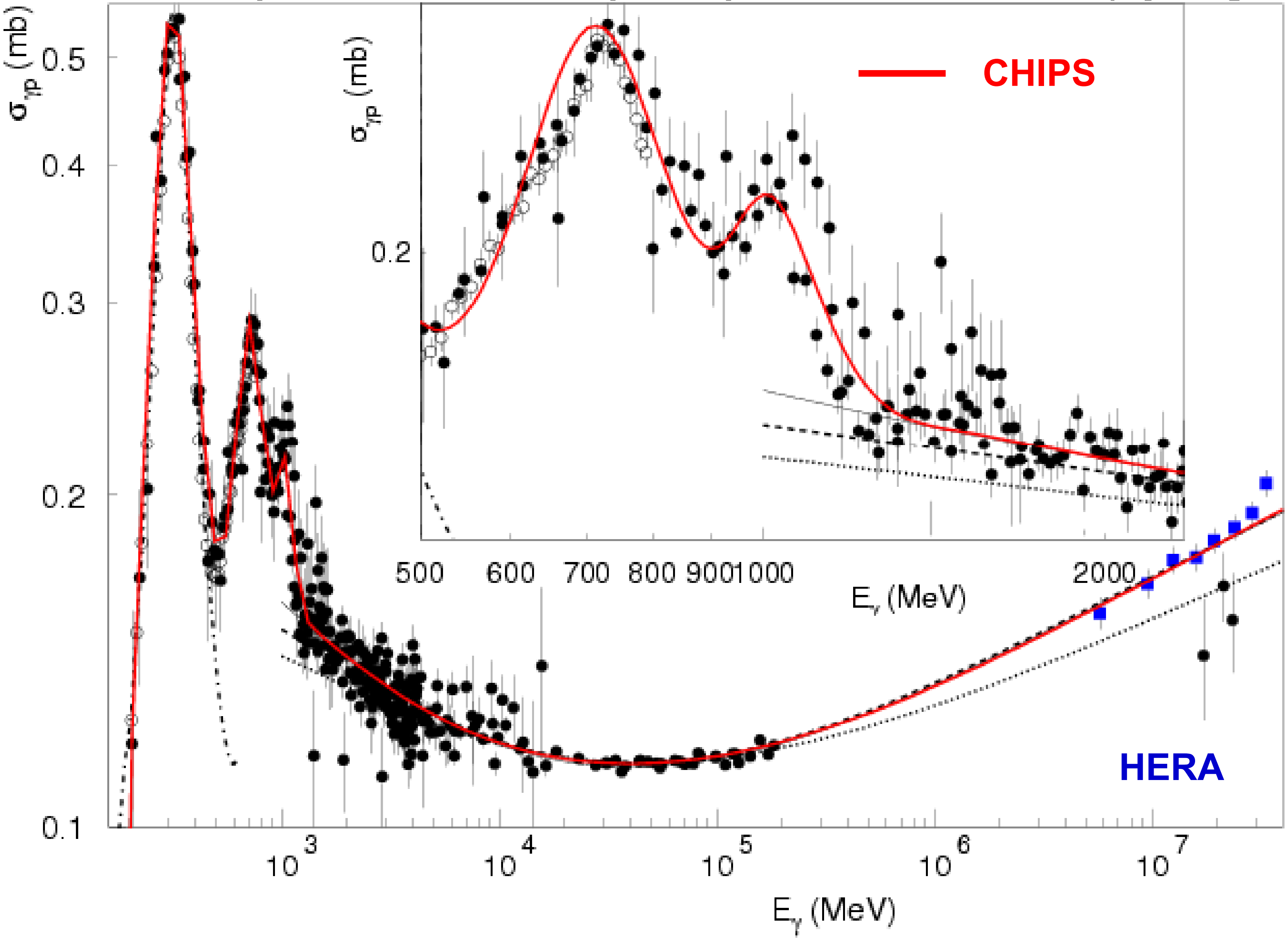
Development of CHIPS μ-nuclear

- CHIPS algorithm is published: **Eur.Phys.J. A14 (2002) 377**

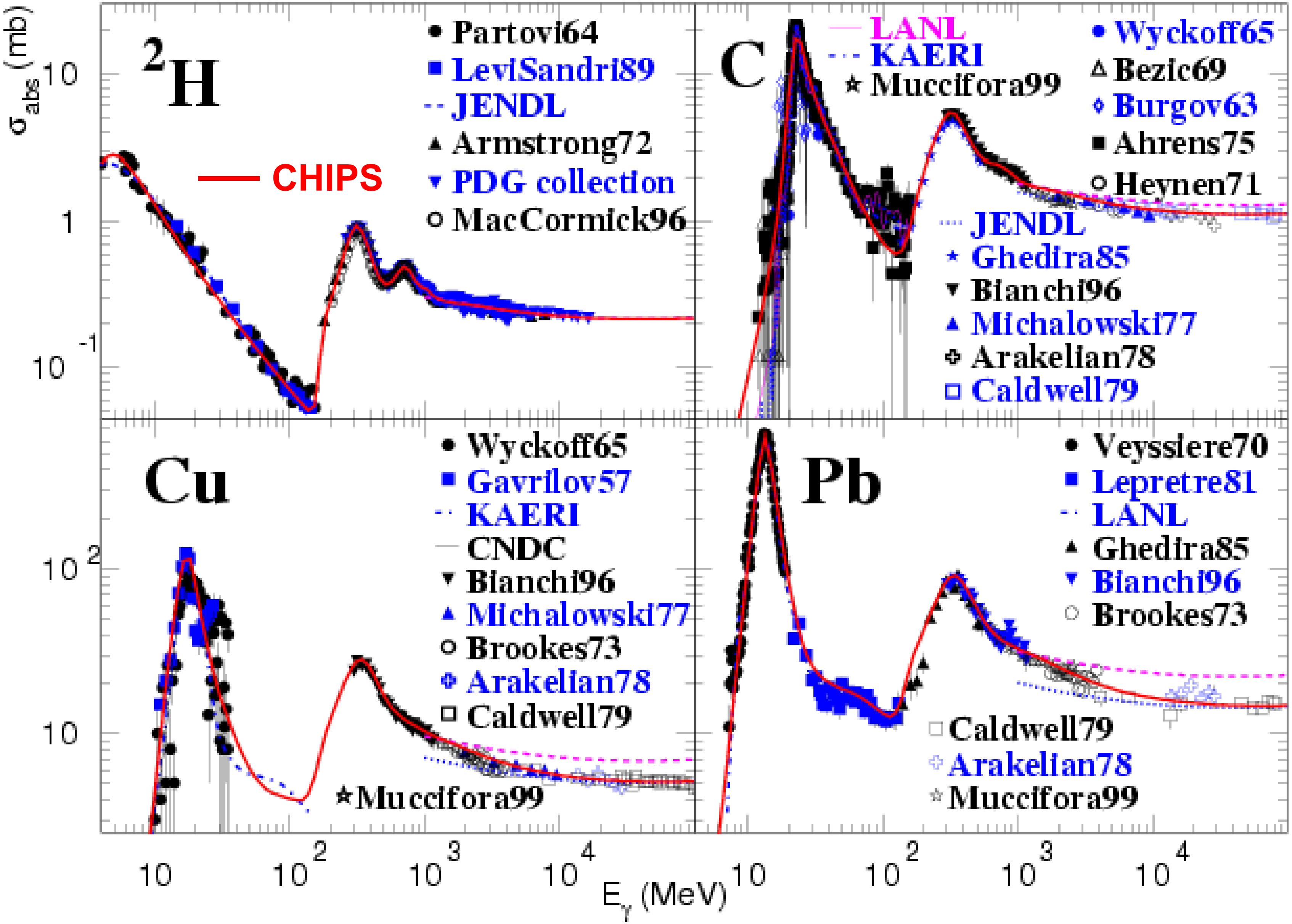
for electron-nuclear reactions and now for μ- and τ-nuclear too

- Universal **G4QCollision** process is made for **e**, μ, τ, and γ:
  - **e**-nuclear with G4QElectroNuclearCrossSection cross-sections
  - μ-nuclear with G4QMuonNuclearCrossSection cross-sections
  - τ-nuclear with G4QTauNuclearCrossSection cross-sections
  - γ-nuclear with G4QPhotoNuclearCrossSection cross-sections
- **G4QCollision** CHIPS process can be used instead of
  - **e**: G4ElectronNuclearProcess/G4PositronNuclearProcess (wrappers)
  - μ: G4MuNuclearInteraction (the only old electro-nuclear process)
  - τ: *** **G4QCollision** is unique ***
  - γ: G4PhotoNuclearProcess (a wrapper for the original CHIPS model)
  - (ν,μ) reactions on nuclei: *** **G4QCollision** is unique ***
- **Till now photo- and lepto-nuclear CHIPS processes are not used in any Recommended Physics List**

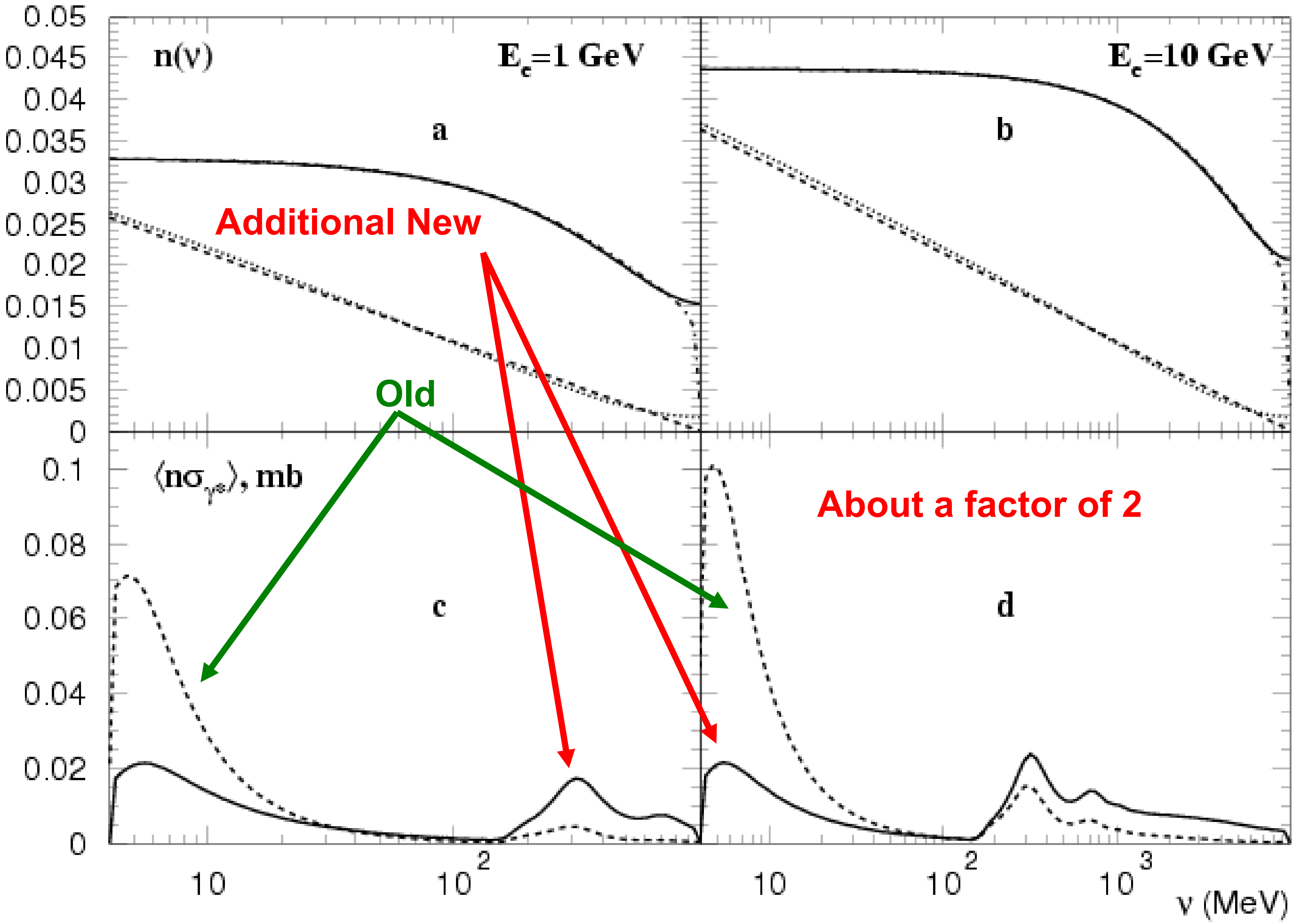
A detailed parameterization of photo-proton cross-section (Hydrogen)



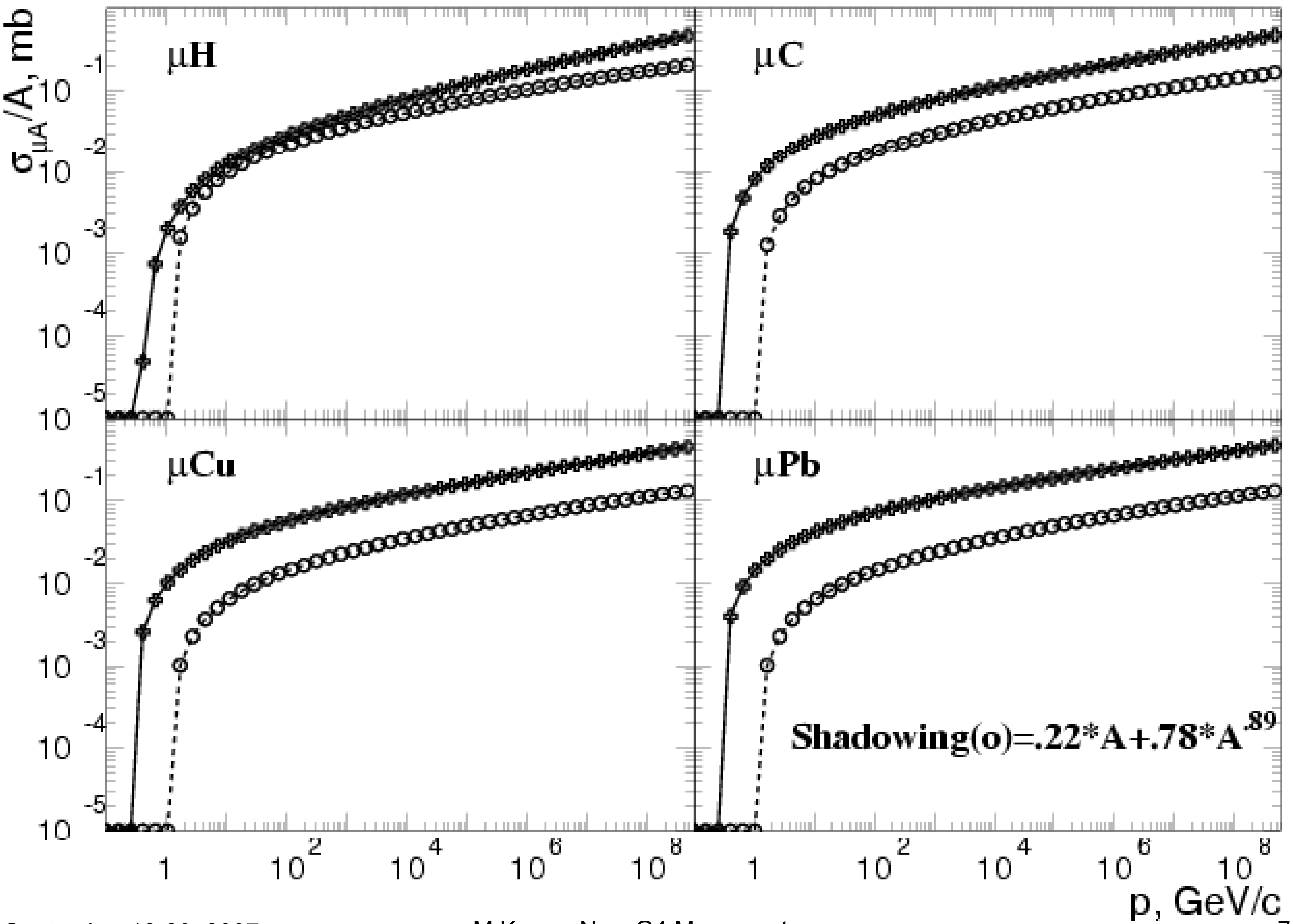
A unique parameterization of photo-nuclear cross-sections (78 nuclei)



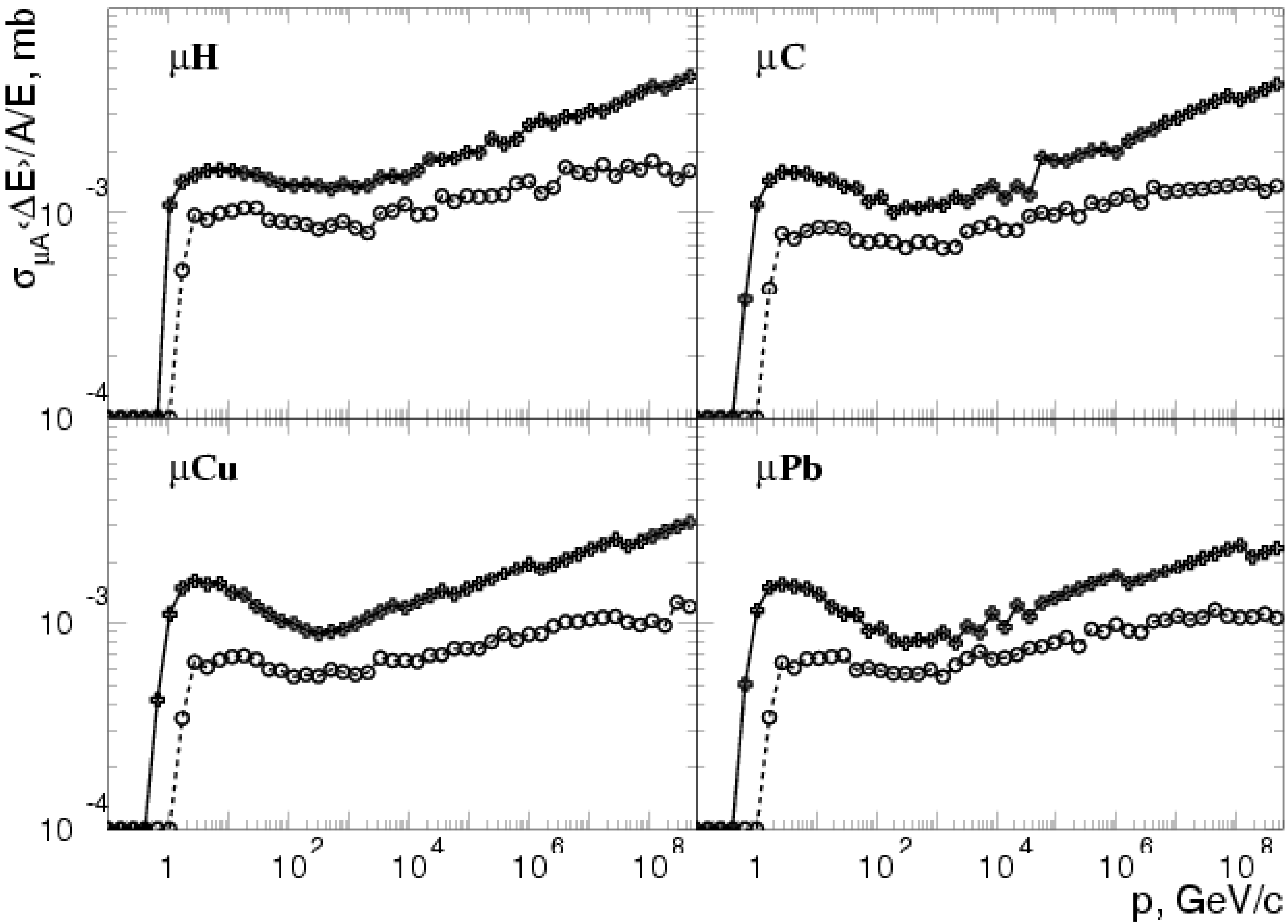
Quasi-real effective photons (dashed lines), high Q^2 (solid lines), (a,b) a sum



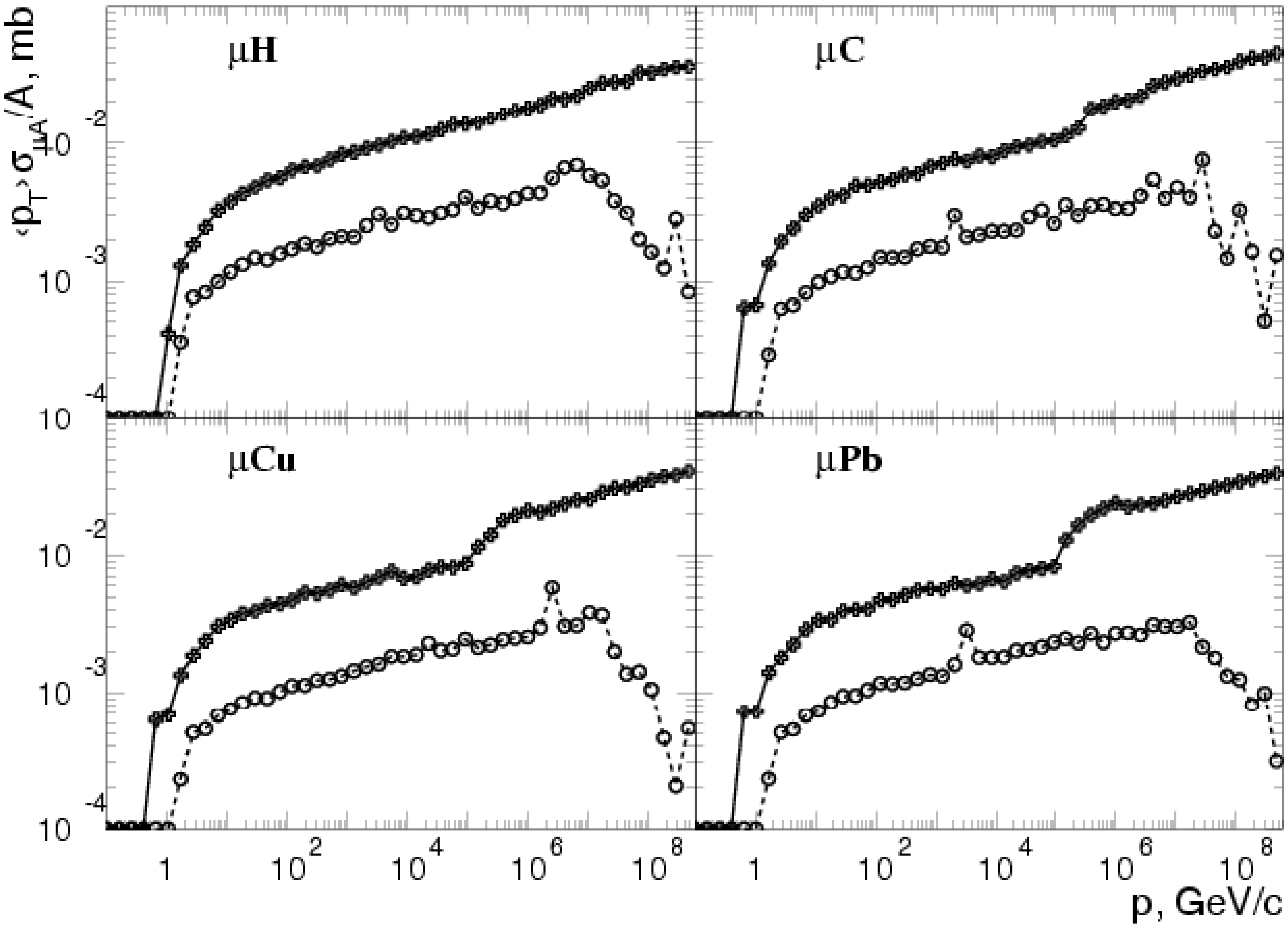
p-dependence of μ-Nuclear: G4MuNuclearInteraction(o), G4QCollision(+)



p-dep of σ‹ΔE›/A/E of μA: G4MuNuclearInteraction(o), G4QCollision(+)



p-dep of ‹p_T›σ/A of μA: G4MuNuclearInteraction(o), G4QCollision(+)



Intermediate conlusion for μ-nuclear

- G4MuNuclearInteraction process gave nan's for cross-sections below T = 1 GeV. Now just skips it.
- The same muon-nuclear reactions can be simulated by the CHIPS G4QCollision process, which uses all power of CHIPS photo-nuclear reactions:
  - It does not produce nan's & works from the threshold.
  - It doubles the deposited energy & the scattering angle.
  - It produces more neutrons and nuclear fragments.
  - It is SU(3) symmetric and produces strange particles.

Neutrons from nuclear μ^- capture at rest

- 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 $T_n=m^2_\mu/2(m_N+m_\mu)=5.3$ MeV<E_{split}
- Absolute normalization of nuclear μ^--capture depends on a nuclear capture rate $\Lambda_c=1/\tau_c$ [$0.45(H_2)\div12610(U)\mu s^{-1}$] & on a decay rate Λ_d
- As muons are bounded, the decay rate Λ_d is reduced by Huff factor (H): $\Lambda_d=H/\tau_\mu=H\cdot455\ \mu s^{-1}$
- For light nuclei: $\Lambda_c<<\Lambda_d$, heavy nuclei: $\Lambda_c>>\Lambda_d$

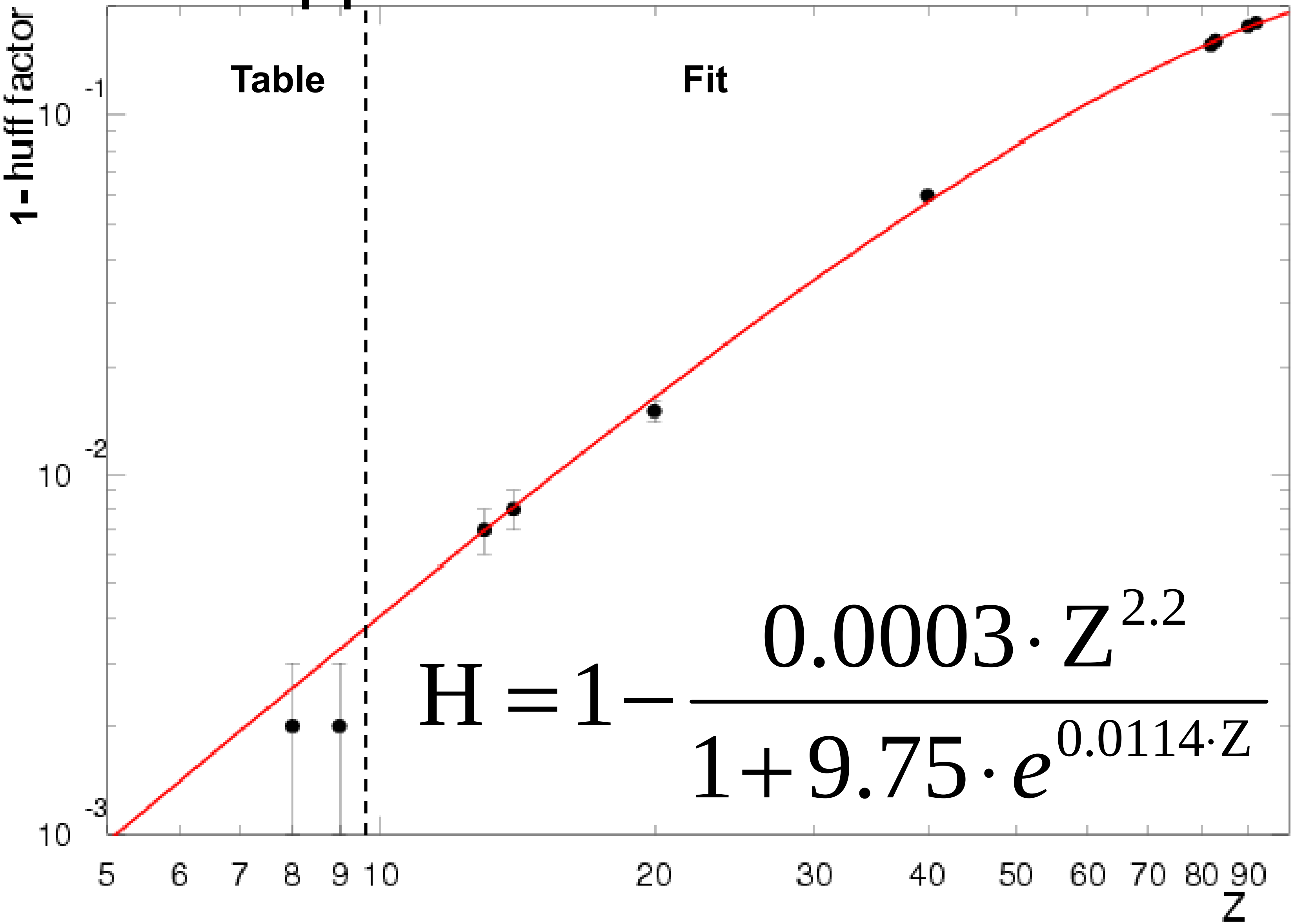
Parameterization of atomic coefficients

- 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 **H** is tabulated till ^{19}F and for Z>9 it is parameterized as a function of Z (only)
- Isotope variation of the nuclear capture rate can be estimated by a **Primakoff** formula:

$$\Lambda_c(A,Z) = C(Z)\cdot\left(1.-3.125\cdot(A-Z)/2A\right)$$

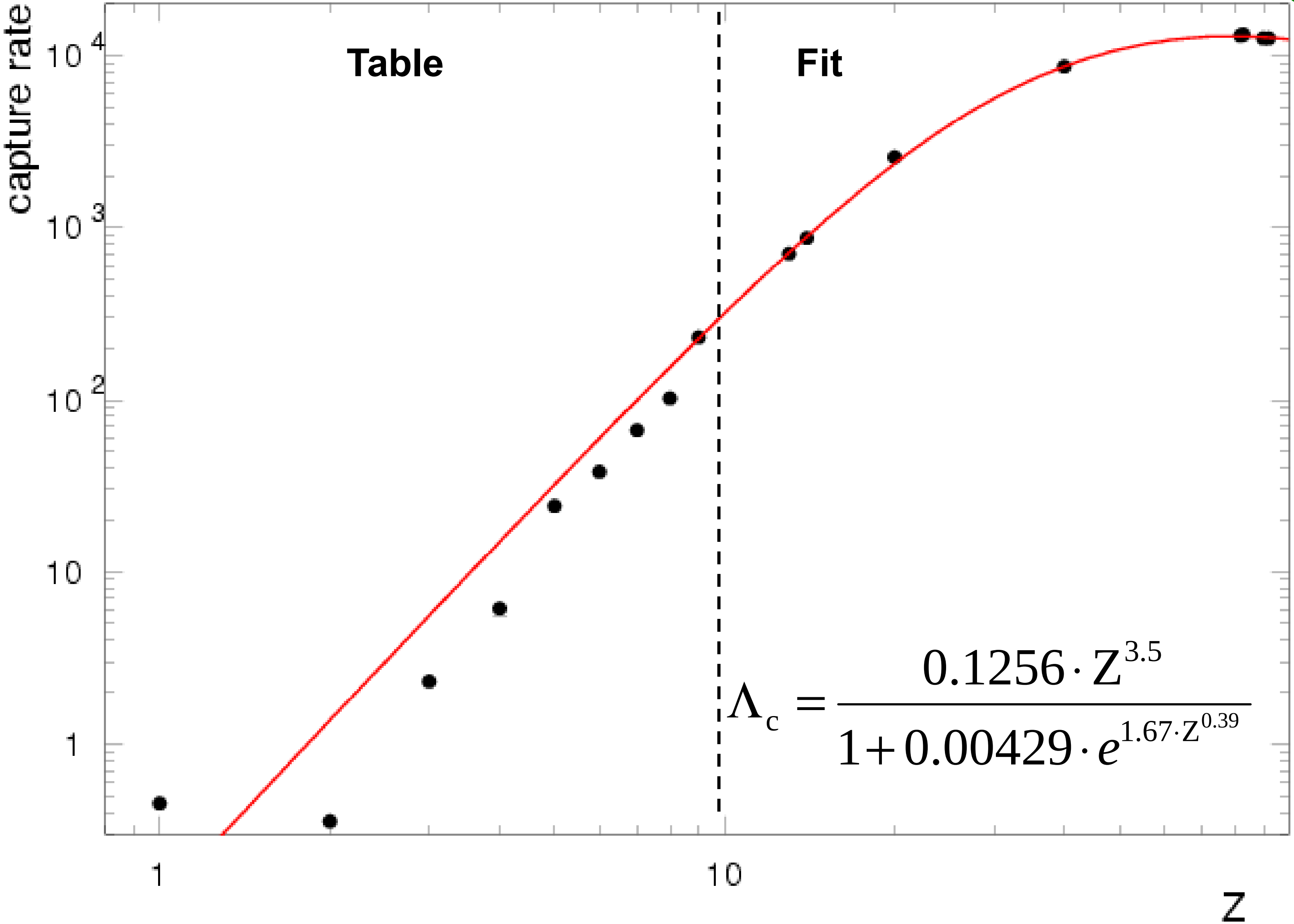
- In CHIPS Λ_c is tabulated till ^{19}F and for Z>9 it is parameterized as a function of Z (only)

CHIPS approximation of the Huff factor



$$H = 1 - \frac{0.0003 \cdot Z^{2.2}}{1 + 9.75 \cdot e^{0.0114 \cdot Z}}$$

CHIPS fit of μ^--nuclear capture rate (Λ_c)

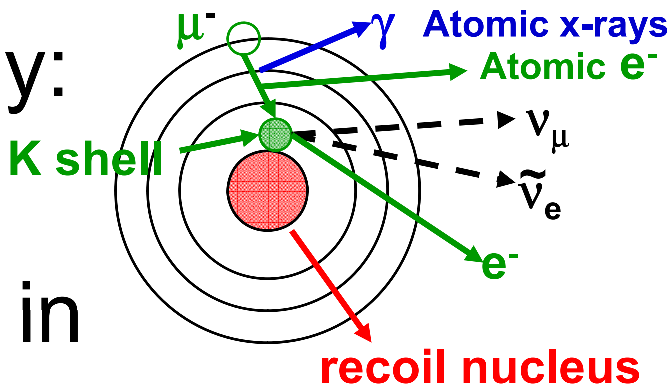


$$\Lambda_c = \frac{0.1256 \cdot Z^{3.5}}{1 + 0.00429 \cdot e^{1.67 \cdot Z^{0.39}}}$$

Simulation of decay of bounded muon

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

  Recently electron spectra were accurately calculated in

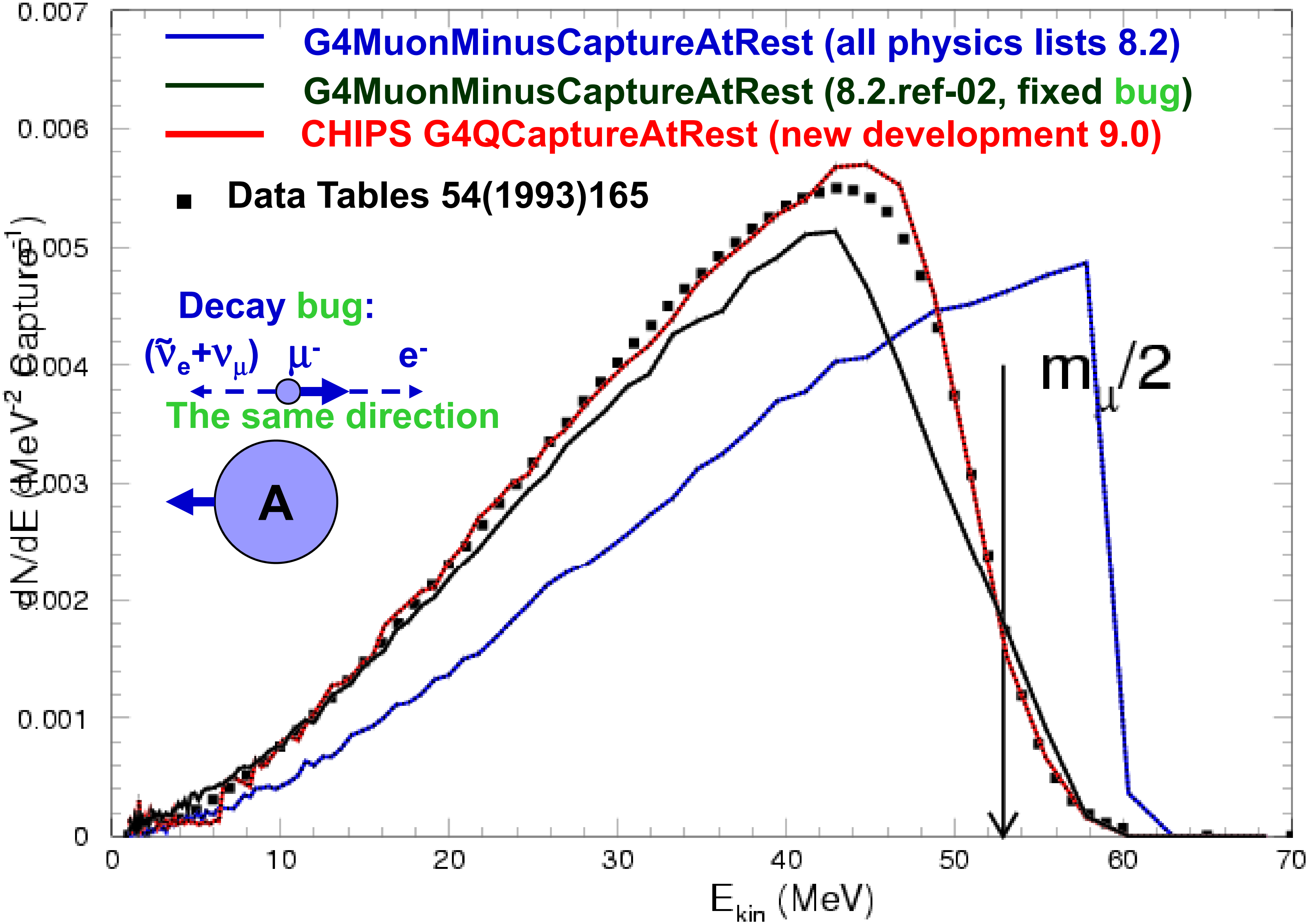
  Atomic Data and Nuclear Data Tables, v.54 (1993) 165

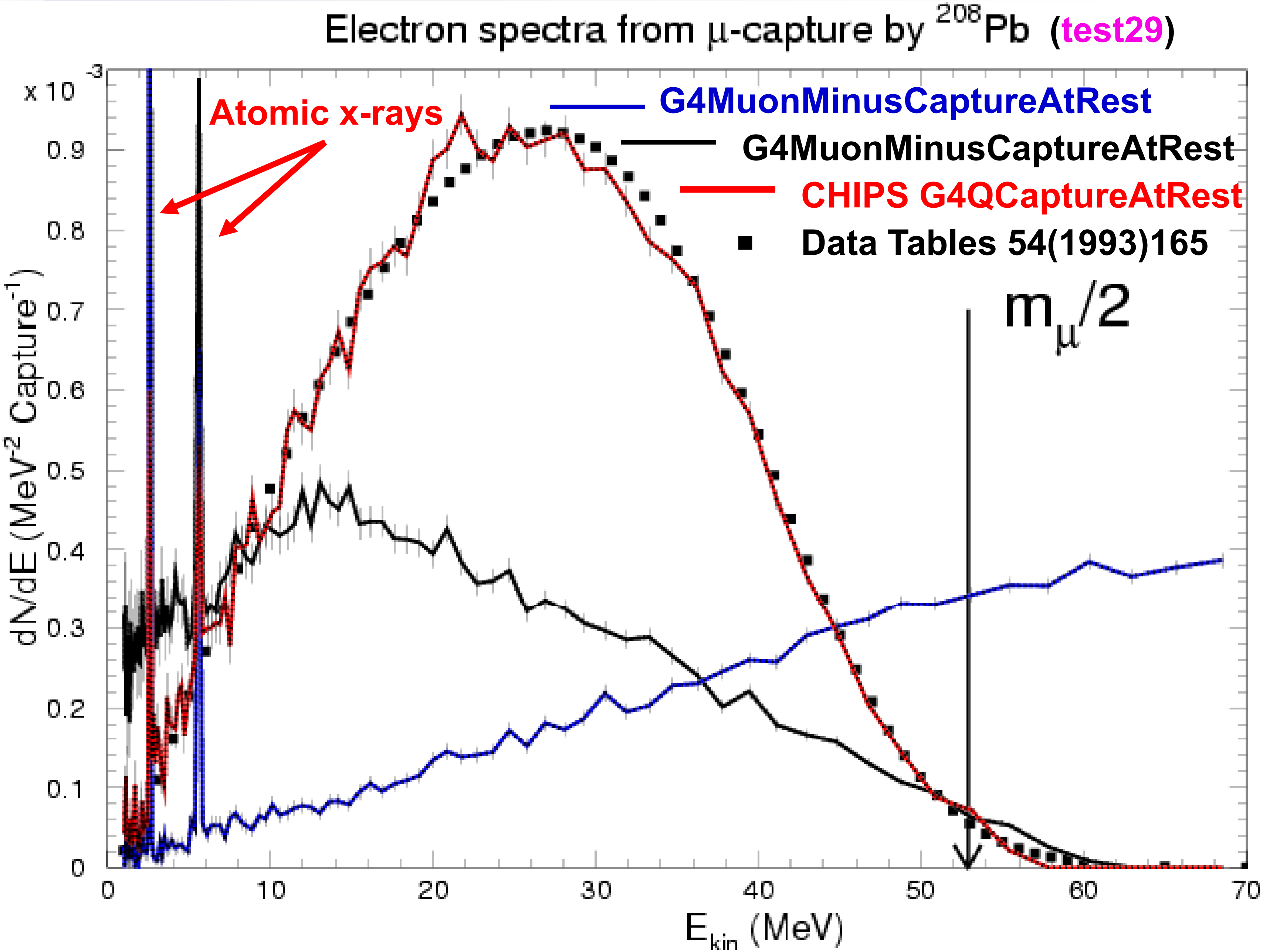
- The electron spectrum can exceed a free $\mathbf{m_\mu/2}$ threshold, because the momentum can be transferred to the **recoil nucleus**.
- For simulation geant4/tests/test29 was used

Geant4 processes for muon capture

- The inherited from GEANT3 (FLUKA) process G4MuonMinusCaptureAtRest was substituted (in G4.8.0.) by a process with the same name
- The algorithm of this process is a pre-compound de-excitation after the $\mu^-(p_{bound},n_{free})\nu_\mu$ reaction
- An alternative process is a G4QCaptureAtRest process G4.9.0: M.Kosov, Eur.Phys.J. A33 (2007) 7
- It is based on the CHIPS de-excitation after ~96% of $\mu^-(d,u)\nu_\mu$ and ~4% of $\mu^-\rightarrow\bar{d}+u+\nu_\mu$ reactions
- Pictures: blue curves are old, red curves are new, dots are from the **Nuclear Data Tables** publication

Electron spectra from μ-capture by ^{40}Ca (test29)

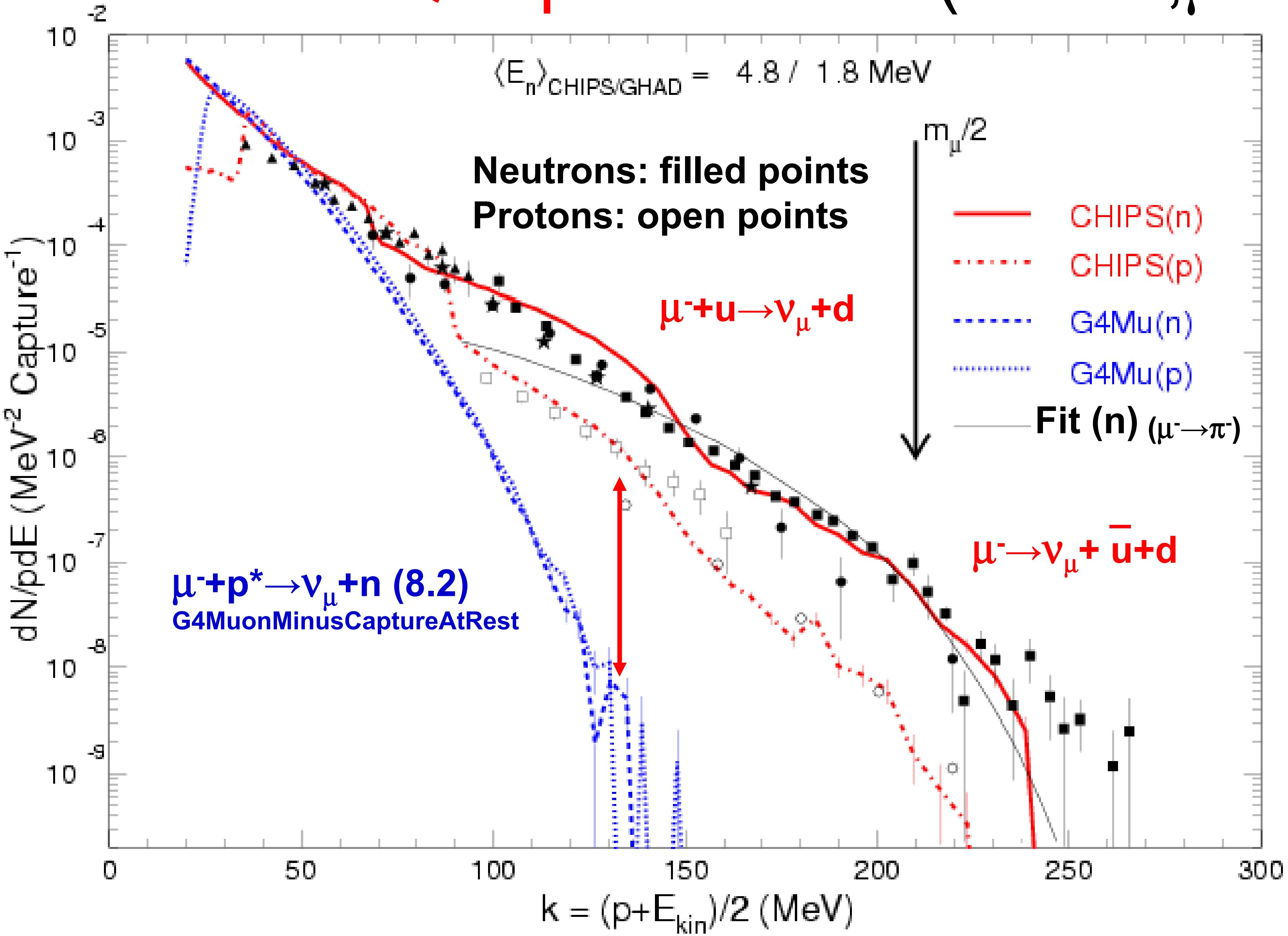



Electron spectra from μ-capture by 208Pb (test29)
x 10-3
Atomic x-rays
G4MuonMinusCaptureAtRest
G4MuonMinusCaptureAtRest
CHIPS G4QCaptureAtRest
Data Tables 54(1993)165
mμ/2
dN/dE (MeV-2 Capture-1)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
Ekin (MeV)

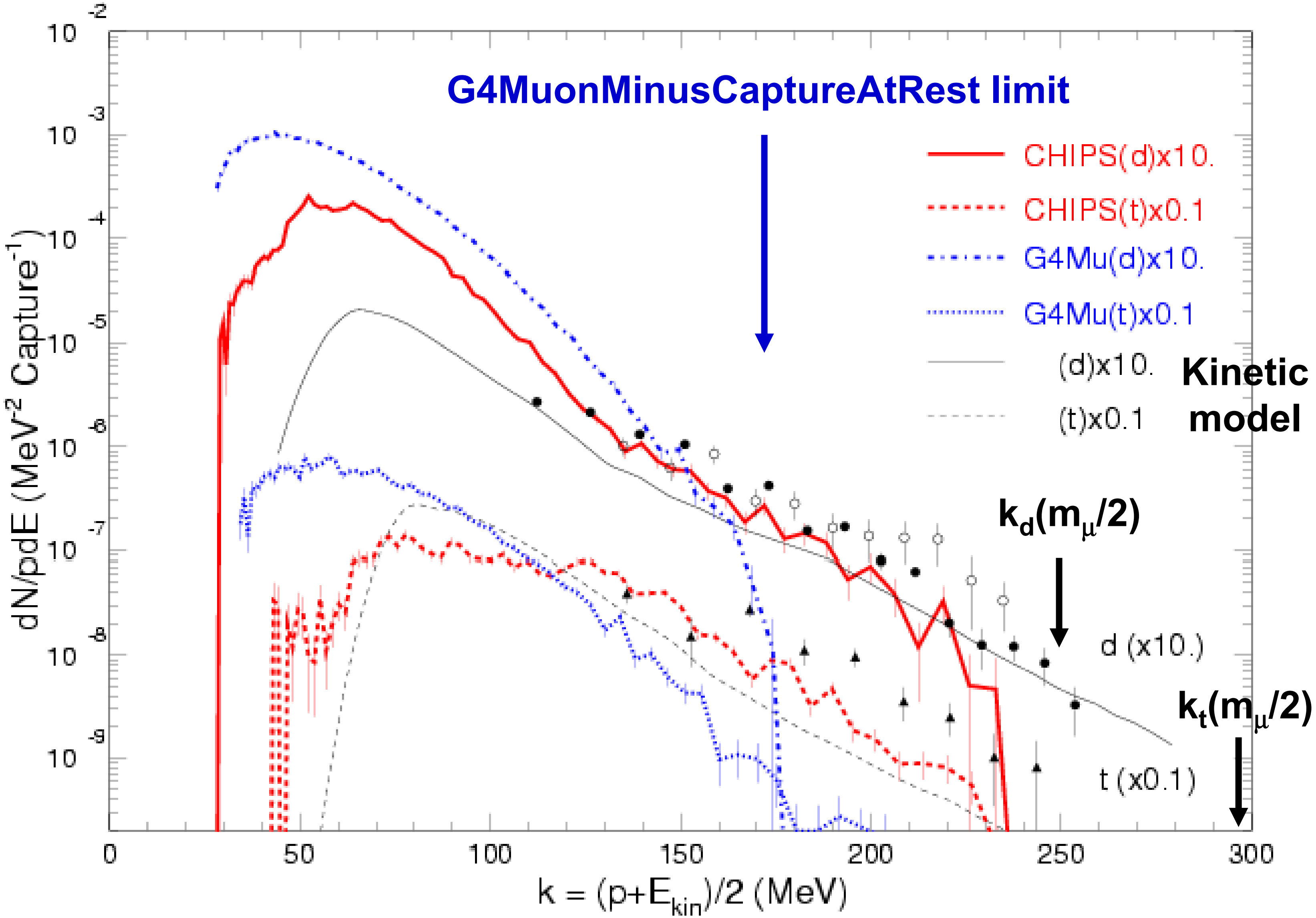
Spectra of nucleons in nuclear μ^--capture

- 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** (*) There are recent data for neutron spectra:
  - **for ^{16}O (Nucl.Phys. A408 (1983) 573) $^{16}O(\mu^-,\nu_\mu x n)$**
  - **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)**
- Spectra of **d** and **t** (**Si**): **Sov.Phys.JETP,33(1971)11, Sov.J.Nucl.Phys,28(1978)297 (Si(d): o, ●, Si(t): ▲)**

CHIPS:G4QCaptureAtRest(test29,μ^-Ca)



CHIPS:G4QCaptureAtRest(test29, μ^-S)



Conclusion for muon capture at rest

- A **bug** was found in electron spectra simulated by the **G4MuonMinusCaptureAtRest** class: **electron is radiated in muon momentum direction**
- The $\mu^{-}(p_{bound},n_{free})\nu_{\mu}$ capture is unrealistic. On hadron level the **PCAC** idea can be used: **J.Bernabeu, T.E.O. Ericson, C.Jarlskog, Phys. Lett., 69B (1977) 161**
- **Pre-compound** model cannot reproduce the difference between proton and neutron spectra
- **CHIPS** with **4%** parameter for $\mu^{-}\rightarrow d+\bar{u}+\nu_{\mu}$ decay fits both μ* decay and μ nuclear capture