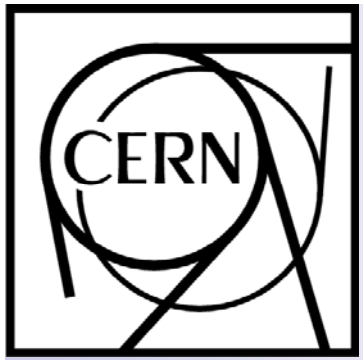
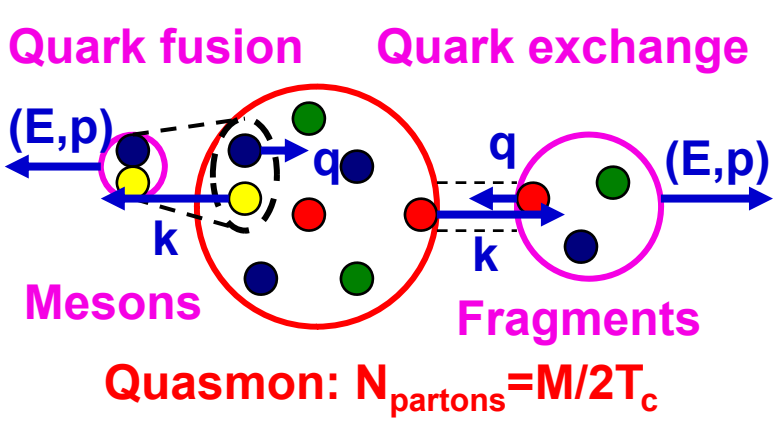


CHIPS Review/Summary

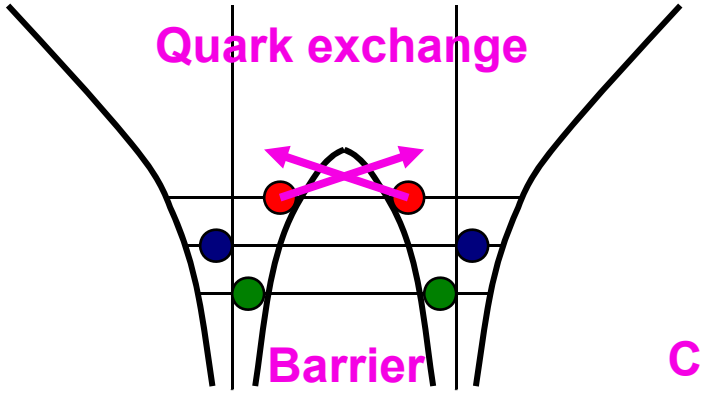
Mikhail Kosov, 12th Geant4 Workshop (GB, Sept. 2007)

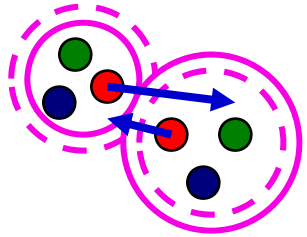
Welcome to CHIPS World

CHiral Invariant Phase Spase (CHIPS) is the first 3D low energy parton model



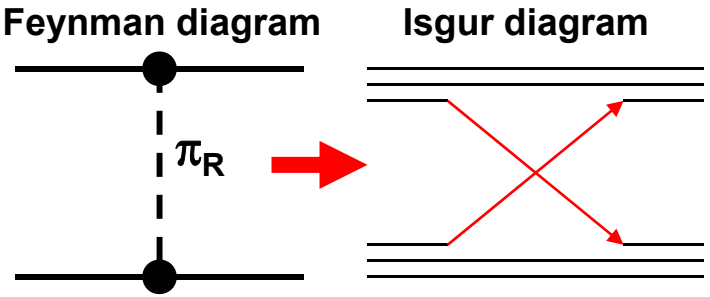
Quasmon: $N_{partons}=M/2T_c$



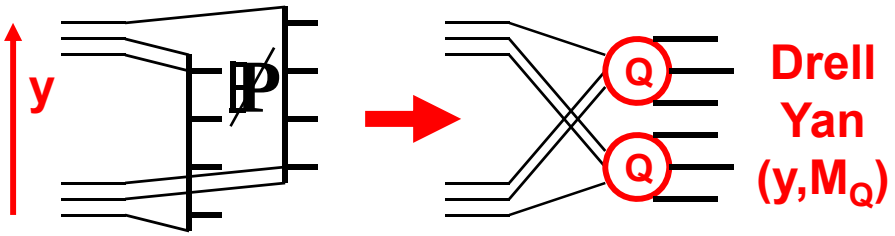


1. Asymptotic freedom of quark-partons
2. Critical temperature of virtual gluons T_c
3. Quark fusion (secondary mesons)
4. Quark exchange (nuclear fragments)
5. Nuclear clusterization (N-clusters)
6. Energy-momentum conservation
7. Transition from low to high energies:

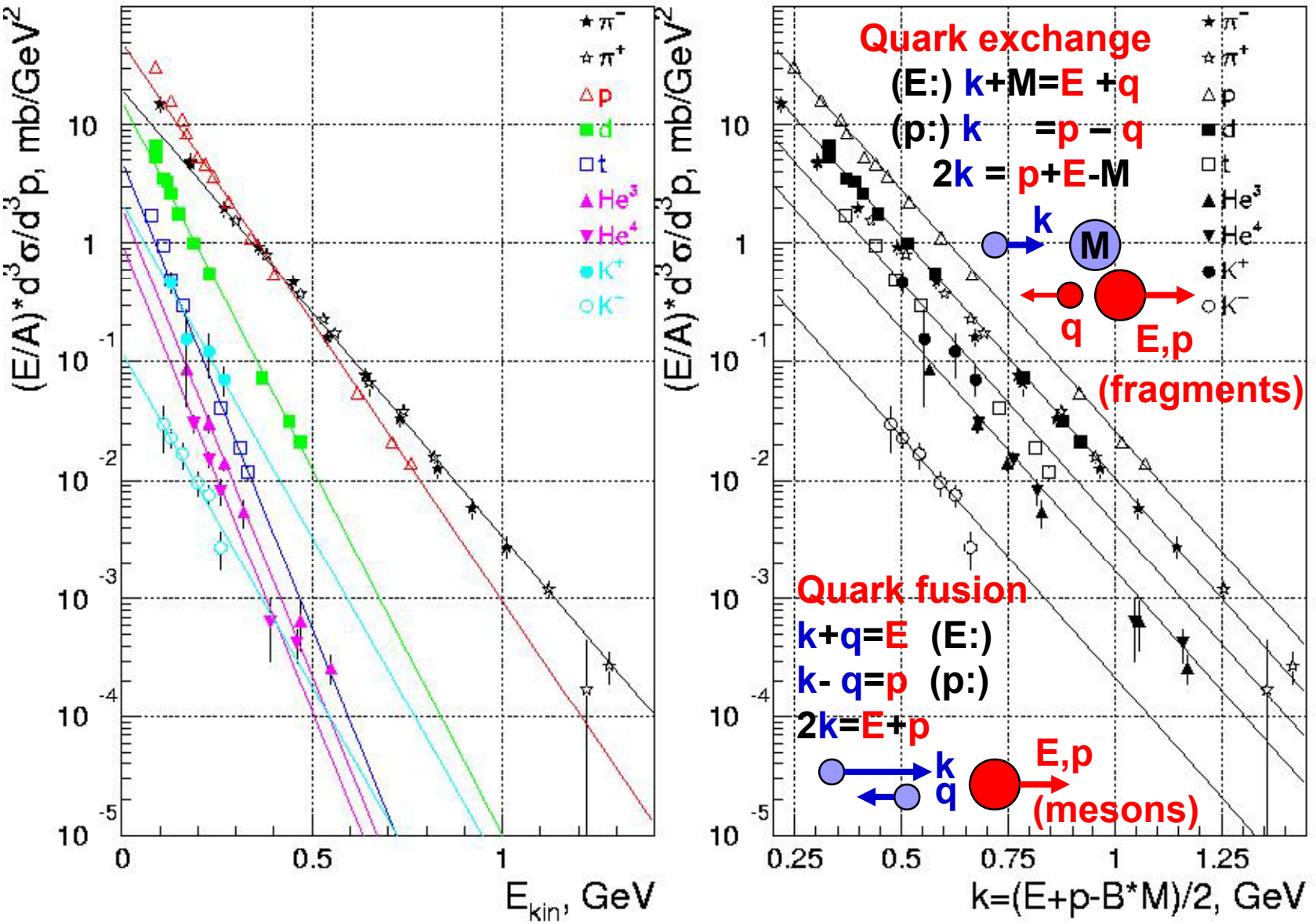
$dW/kdk \sim (1-2k/M)^{n-3} \rightarrow dW/xdx \sim (1-x)^{n-2}$



N. Isgur, Nucl.Phys., A497 (1989) 91



(Frees-out Boltzmann) p+Ta=h+X, 400 GeV, 90° (inclusive CHIPS)



CHIPS processes already in Geant4

- **CH**iral **I**nvariant **P**hase **S**pace physics model:
  - Since v7.1 photo- & lepto-nuclear reactions: G4QCollision
    - **γA and Equivalent Photon method for eA, μA, τA**
    - **Weak (ν_e,e), (ν_μ,μ), (ν_τ,τ) reactions from thresholds**
  - Since v7.1 simulation of nuclear fragmentation in QGSC
  - Since v8.1 all stopping is made by G4QCaptureAtRest
    - **Stopping of negative hadrons: π^-, K^-, $\bar{p}$, Σ^-, $\bar{\Sigma}^+$, Ξ^-, Ω^-**
    - **n/$\bar{n}$ (thermal) and μ^- capture (including bounded μ^- decay)**
- Supplementary CHIPS classes
  - Since 8.3 nucleon-nuclear elastic scattering: G4QElastic
    - **Low energy neutron elastic can be upgraded using HP**
  - Since 9.0 quasi-elastic scattering (QGS): G4QuasiFreeRatios
    - **8 groups**: pp/nn,pn/np,π^-p/π^+n,π^+p/π^-n,KN,K$\bar{N}$,HyperonN,$\bar{B}$N

CHIPS processes on R&D level

- **CH**iral **I**nvariant **P**hase **S**pace physics model
  - G4QEvaporation class evaporates the residual nucleus. It is based on the G4QNucleus.EvaporateNucleus() function, which as one step process uses the G4QNucleus.EvaporateBaryon() function.
  - G4QDiffraction process simulates single projectile and target diffractions, uses G4QDiffractionRatio class
  - G4QLowEnergy process: fast simulation of inelastic low energy ion-ion interactions, uses G4QEvaporation
  - G4QCollision for inelastic pA interactions, uses G4QuasiFreeRatios for quasi-elastic (on nucleons and clusters)
- Supplementary CHIPS classes
  - Ion-Ion elastic and inelastic G4QIonIonCrossSections
  - Consistent pA inelastic cross-sections for CHIPS inelastic
  - Coherent charge exchange process

Encapsulation of all model definitions

- Working with the Model Level users should know
  - how to construct the models out of the different parts (e.g. for G4TheoFSGenerator model there are SetTransport, SetFragmentationModel, SetHighEnergyGenerator, etc.)
  - how to define appropriate smearing energy ranges
  - how to select appropriate cross-sections (DataSet)
  - how to read other necessary tables (e.g. in HP package)
- According to the CHIPS strategy all that knowledge is encapsulated in the process and does not demand additional efforts from users. If one process is better than another in some particular energy range (e.g. the HP process) it can be mixed on the Process Level using the G4QDiscProcessMixer class.

G4QDiscProcessMixer

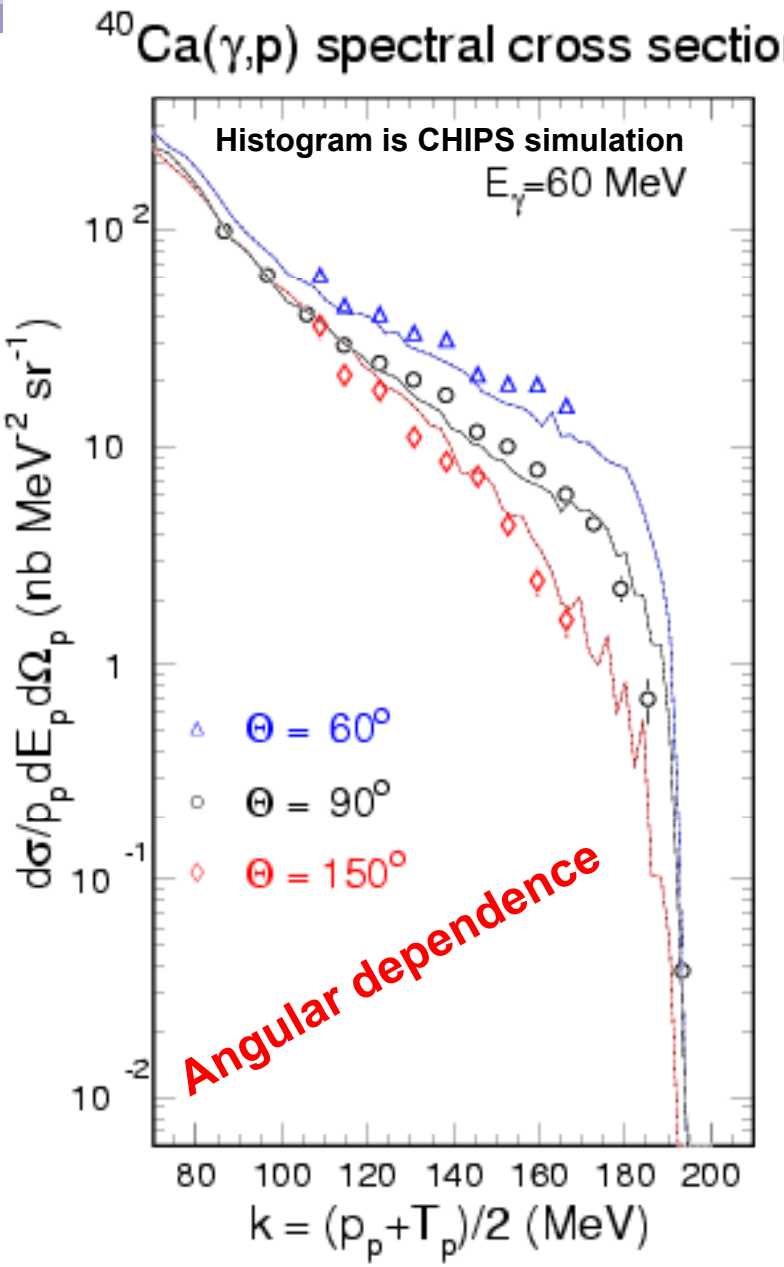
- The G4QDiscProcessMixer(G4ParticleDefinition) constructor defines a particle for which it is created.
- The Mixer uses a G4QDiscreteProcessVector of std::pair<G4VDiscreteProcess*, maxEnergy> .
- The only new function arranging Processes for mixing is AddDiscreteProcess(Process*, maxEnergy) .
- The Processes should be added in increasing order of the maxEnergy parameters (otherwise error appears).
- The minEnergy of the first process is zero, and minEnergy(N)=maxEnergy(N-1) – no smearing.
- The G4QDiscProcessMixer can be called as an ordinary process for the particle mentioned in the constructor.

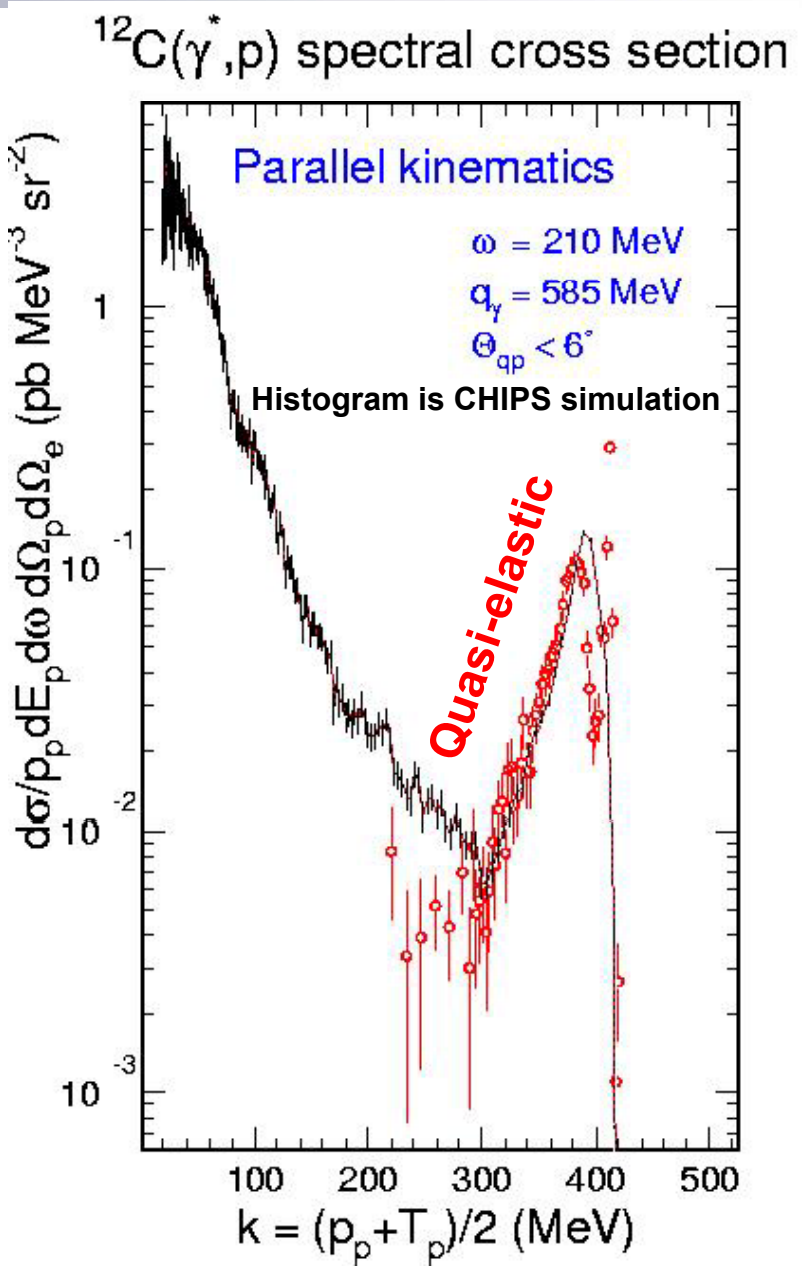
CHIPS databases and tests (process level)

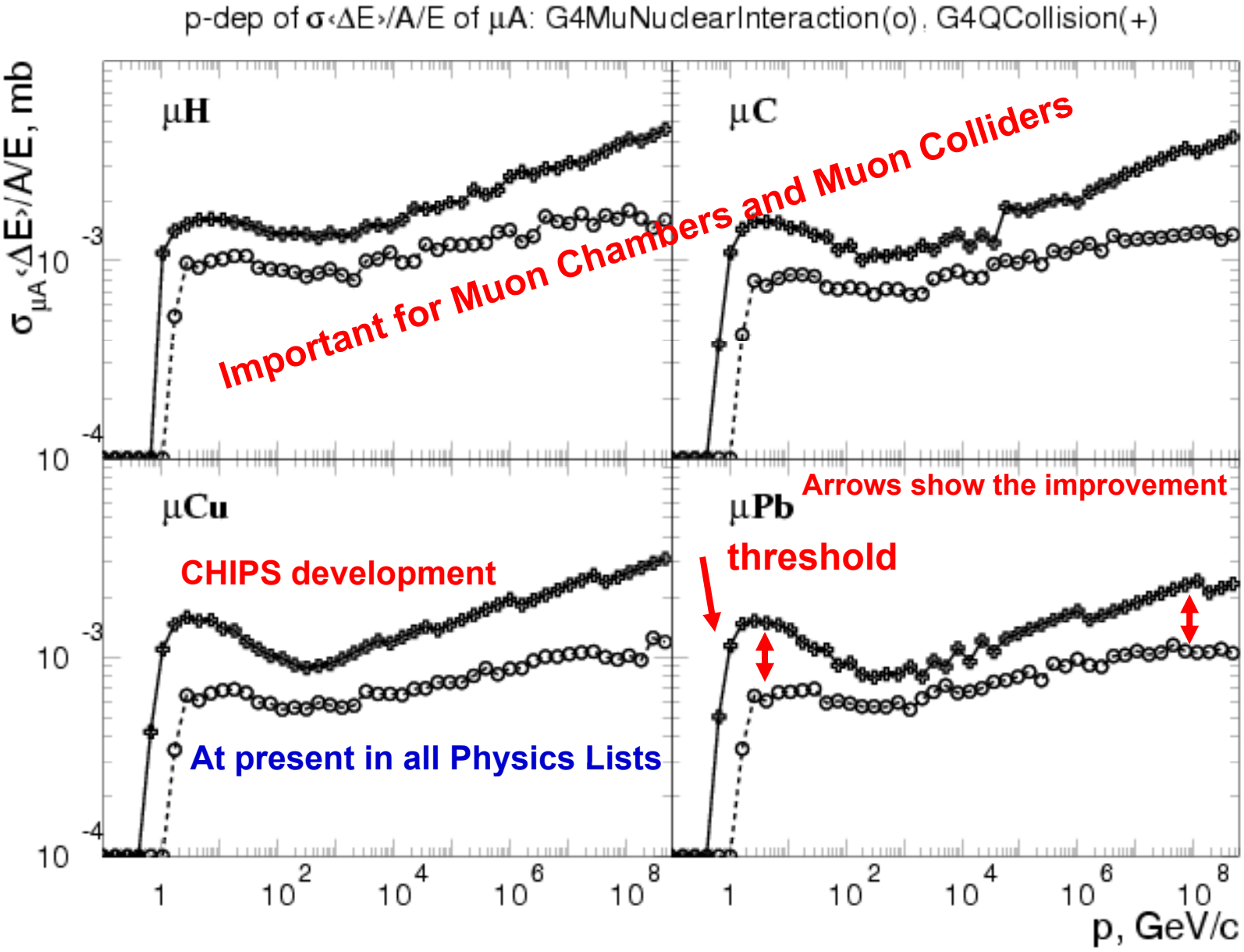
- CHIPS **test29**: for at rest processes of Geant4
  - "/aph": antiproton-proton annihilation DB
  - "/apcap": antiproton-nucleus annihilation DB
  - "/picap": π^--nuclear capture DB
  - "/mucap": μ^- atomic and nuclear captur DB
- CHIPS **test19** : for on flight processes of Geant4
  - ("/gamma": photo-nuclear DB
  - "/preco": pre-compound reactions (pA 90 MeV, etc.)
  - "/diffra": diffraction reactions
- CHIPS **test39**: elastic and quasi-elastic reactions
- External Data Bases for G4 CHIPS development:
  - Total and elastic hadron-nuclear cross-sections
  - Elastic differential cross sections (about 300 papers)
  - Gamma-nuclear cross-sections (78 nuclei are covered)

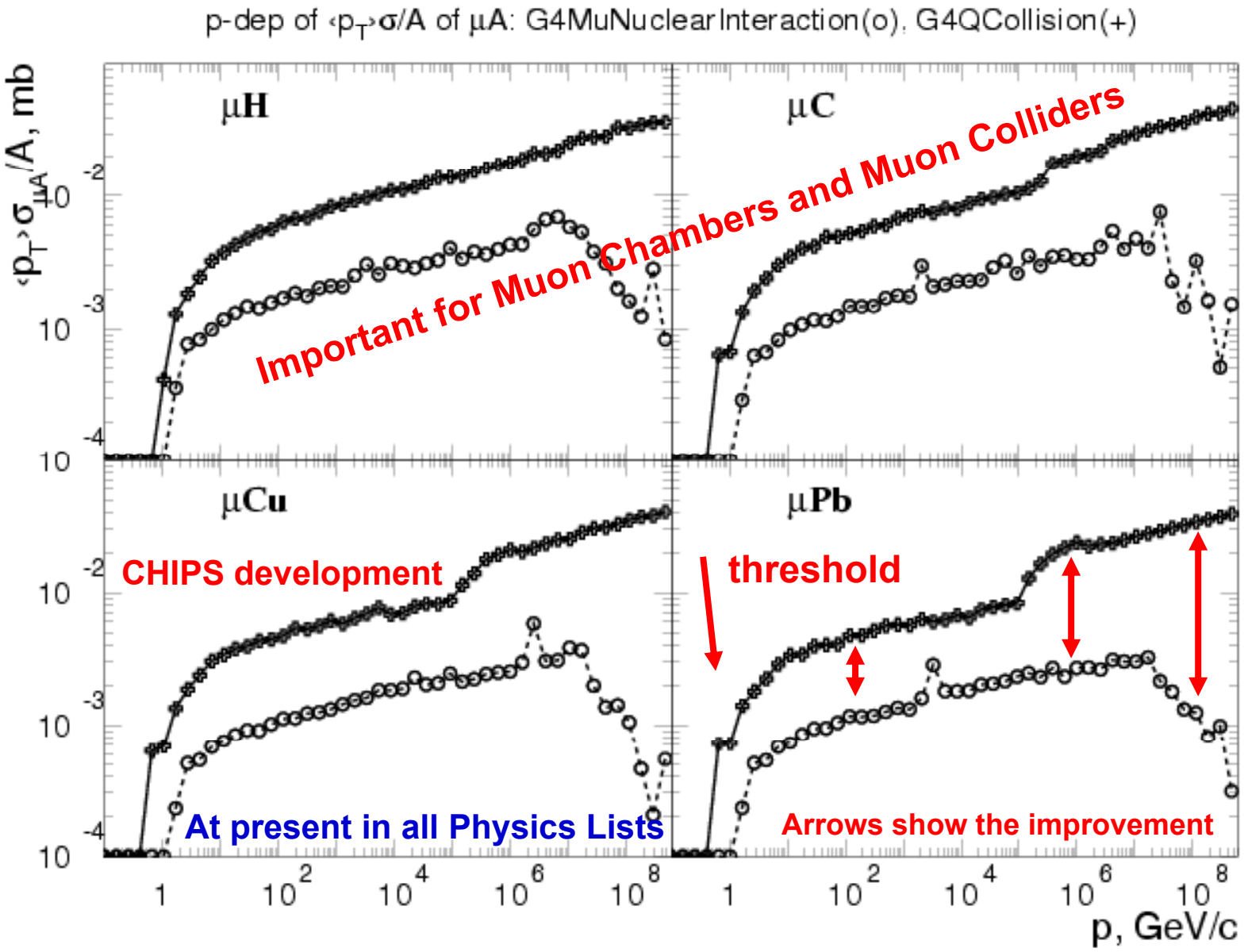
CHIPS photo- & lepto-nuclear reactions

- **CHIPS** photo-nuclear reactions: **Eur.Phys.J.A14(2002)377**
  - γ : **G4QPhotoNuclearCrossSection**
  - e : **G4QElectroNuclearCrossSection**
  - μ : **G4QMuonNuclearCrossSection**
  - τ : **G4QTauNuclearCrossSection**
  - (ν_ℓ,ℓ): **G4QNuMuNuclearCrossSection**
- **CHIPS** γ**A** fragmentation: **Eur.Phys.J.A 9(2000) 421, …441**
- **G4QCollision** can be used instead of:
  - γ: G4PhotoNuclearProcess (interface to CHIPS+QGS@E>3GeV)
  - e: G4ElectronNuclearProcess,G4PositronNuclearProcess
  - μ: **G4MuNuclearInteraction** (original: $\gamma^* \rightarrow$ 50% π^-, 50% π^+)
  - τ: *** **G4QCollision** is unique ***
  - (ν_ℓ,ℓ): *** **G4QCollision** is unique ***

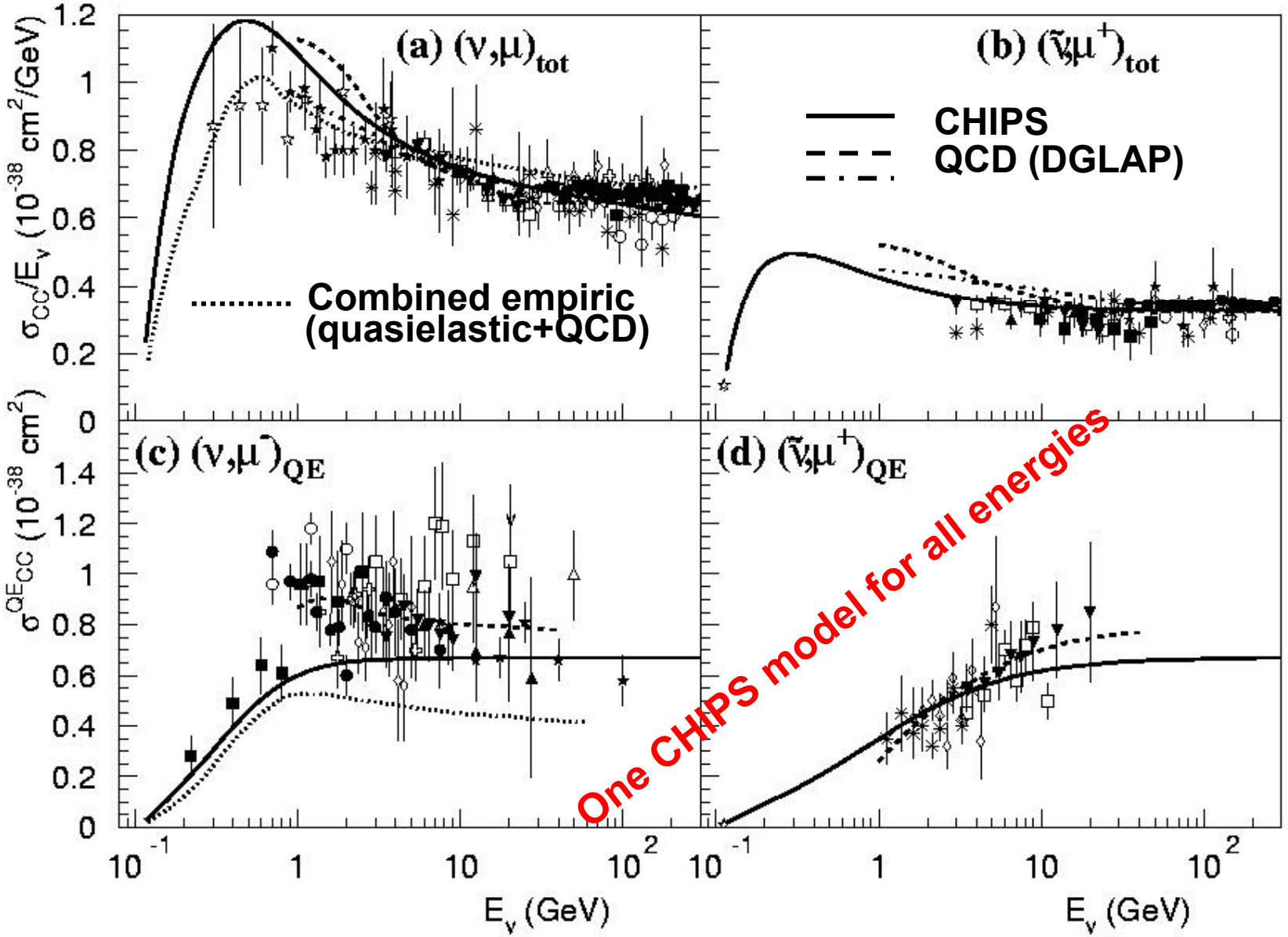

^{40}Ca(γ,p) spectral cross section
Histogram is CHIPS simulation
E_γ=60 MeV
Θ = 60°
Θ = 90°
Θ = 150°
Angular dependence
$d\sigma/p_p dE_p d\Omega_p$ (nb MeV^{-2} sr^{-1})
k = (p_p+T_p)/2 (MeV)


^{12}C(γ*,p) spectral cross section
Parallel kinematics
ω = 210 MeV
q_γ = 585 MeV
Θ_{qp} < 6°
Histogram is CHIPS simulation
Quasi-elastic
$d\sigma/p_p dE_p d\omega\, d\Omega_p d\Omega_e$ (pb MeV^{-3} sr^{-2})
k = (p_p+T_p)/2 (MeV)


p-dep of σ‹ΔE›/A/E of μA: G4MuNuclearInteraction(o), G4QCollision(+)
σμA‹ΔE›/A/E, mb
μH
μC
μCu
μPb
Important for Muon Chambers and Muon Colliders
Arrows show the improvement
threshold
CHIPS development
At present in all Physics Lists
p, GeV/c


p-dep of ‹p_T›σ/A of μA: G4MuNuclearInteraction(o), G4QCollision(+)
μH
μC
μCu
μPb
‹p_T›σ_μA/A, mb
p, GeV/c
Important for Muon Chambers and Muon Colliders
CHIPS development
threshold
At present in all Physics Lists
Arrows show the improvement

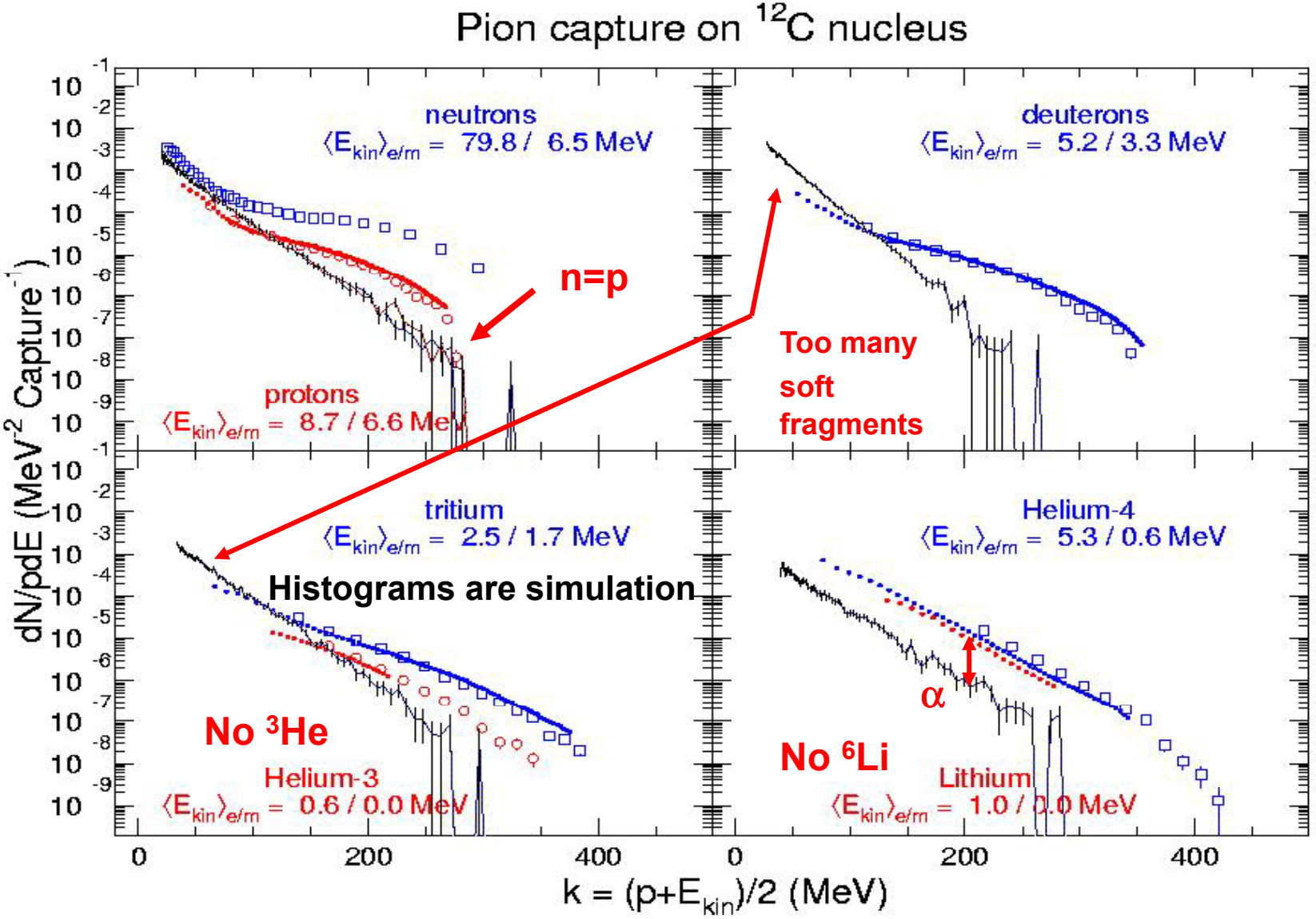
CHIPS improvement of weak charged current (ν,μ) reactions



CHIPS improvement of stopping in Geant4

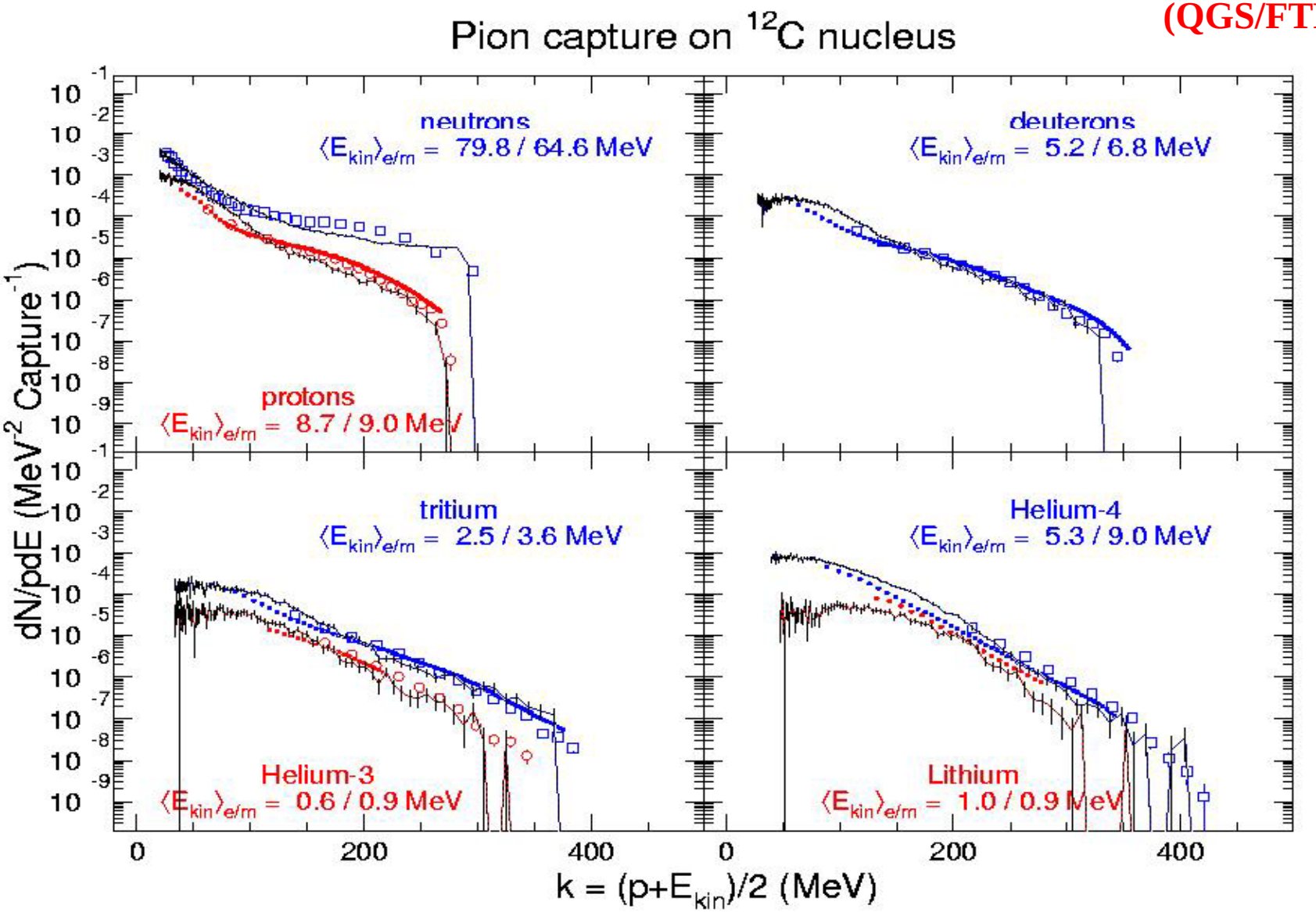
- **G4QCaptureAtRest** simulates isotropic spectra of hadrons and nuclear fragments.
- Pion capture (**Eur.Phys.J.A9(2000)411**) is compared with G4PionMinusCapture (8.0)
- Anti-proton capture (**EPJA 14(2000)217, IEEE Trans.N.S. 52(2005)2832**) is compared with G4AntiProtonAnnihilationAtRest (8.0)
- CHIPS muon capture is compared with G4MuonMinusCaptureAtRest (8.2, present)
  - Decay of bound μ^- is improved in CHIPS

G4PionMinusAbsorptionAtRest (test29) **LHEP**

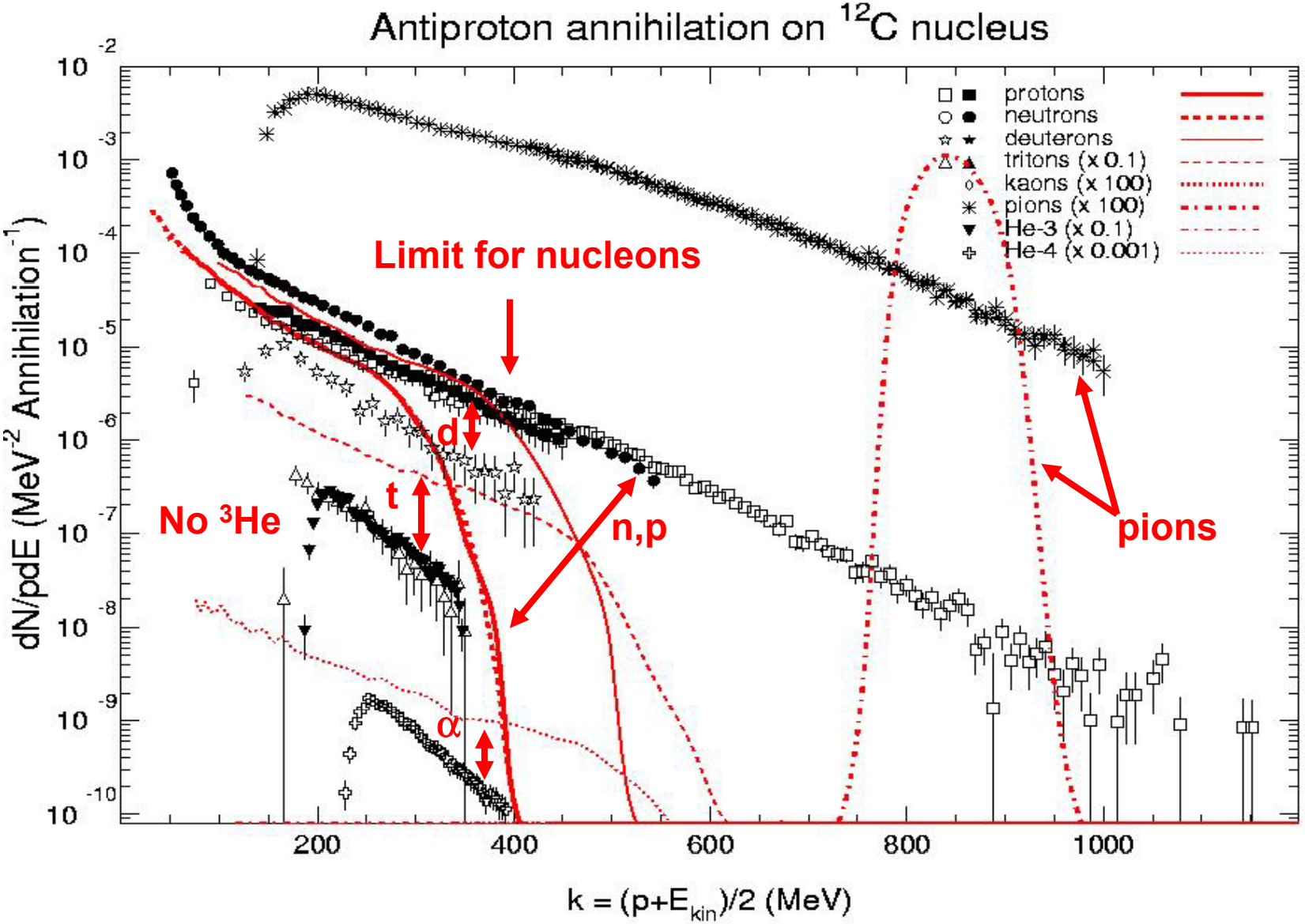


CHIPS: G4QCaptureAtRest (test29) **G4.8.1**

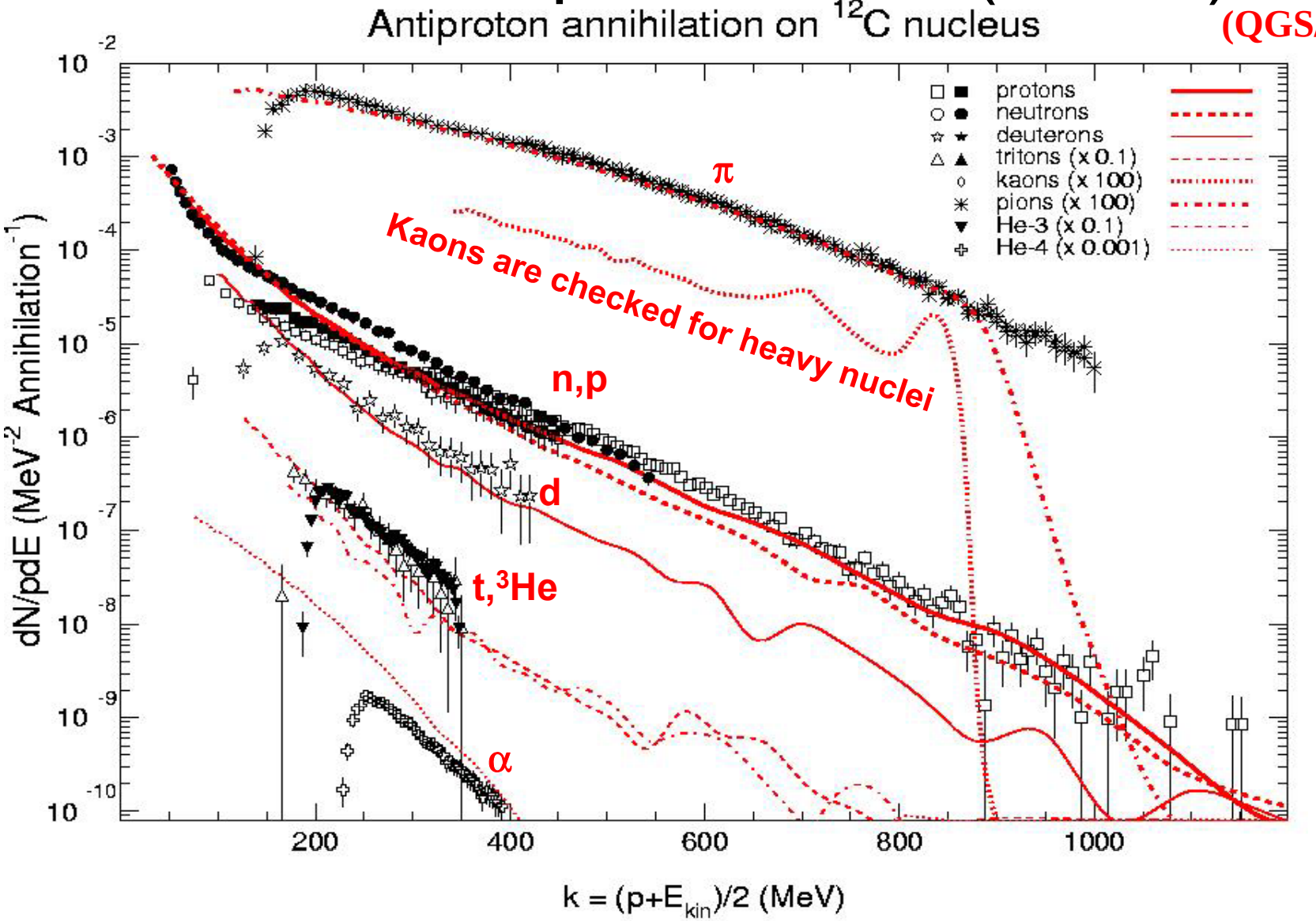
(QGS/FTF)



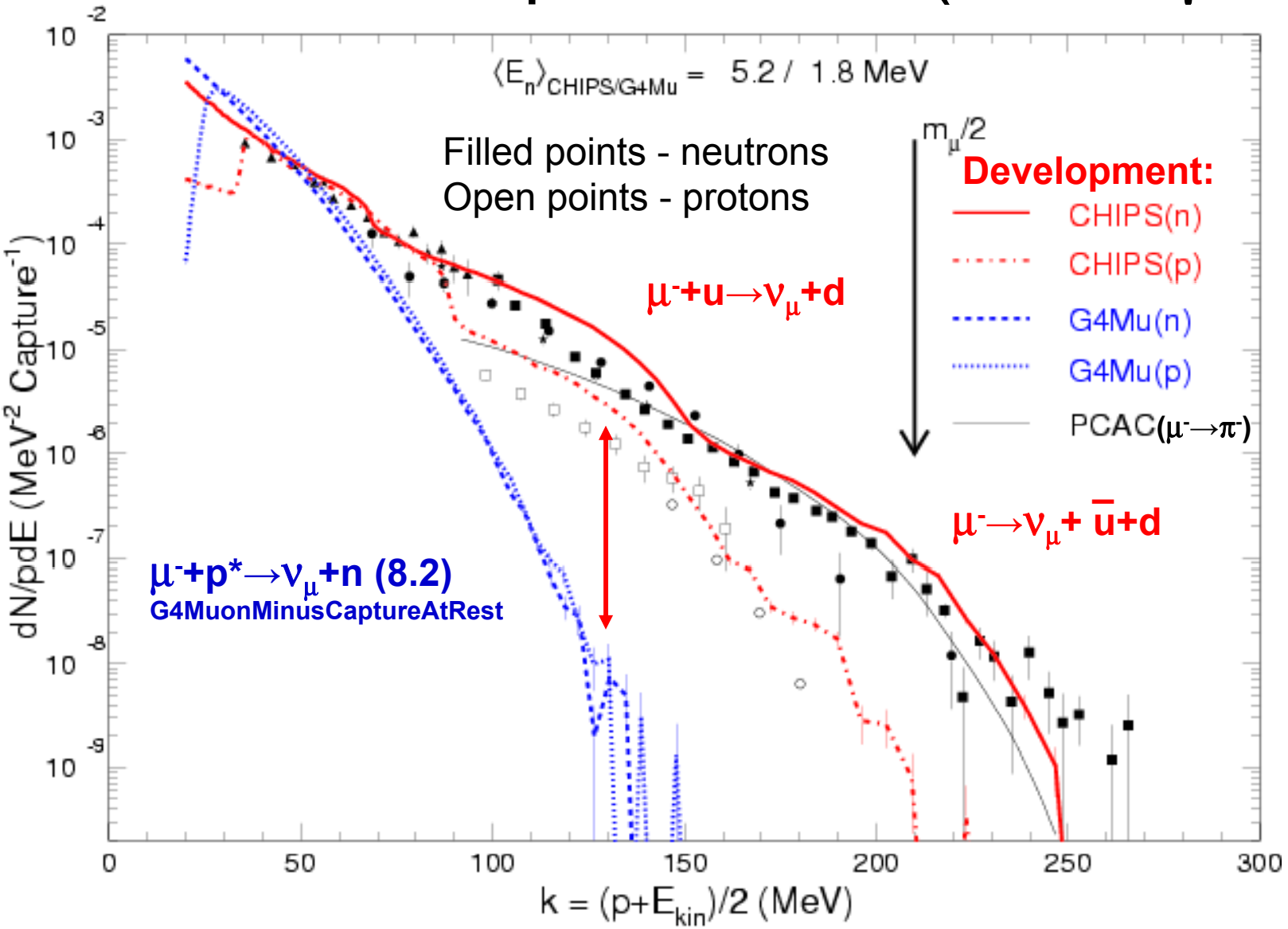
G4AntiProtonAnnihilationAtRest (test29) **LHEP**

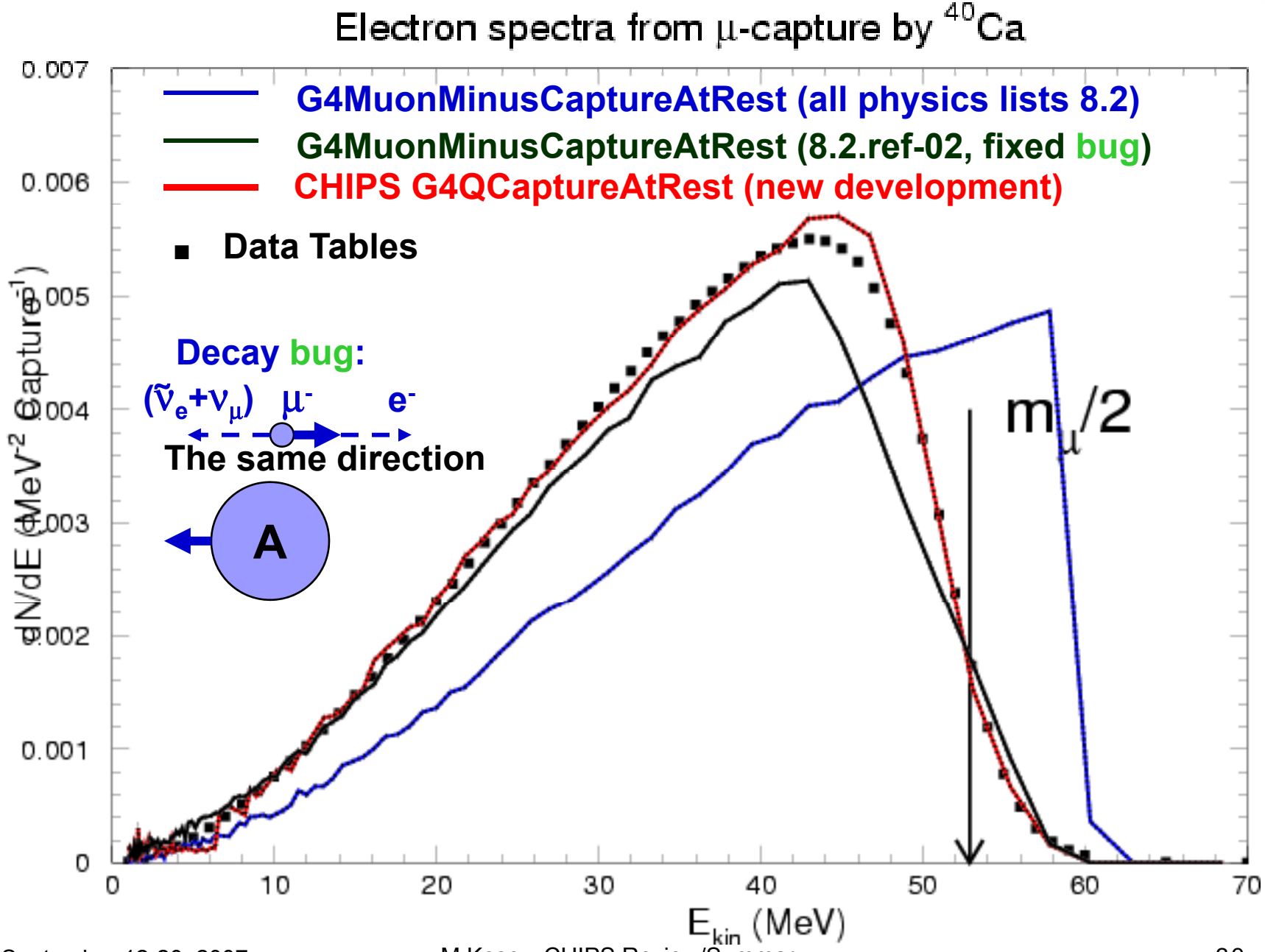


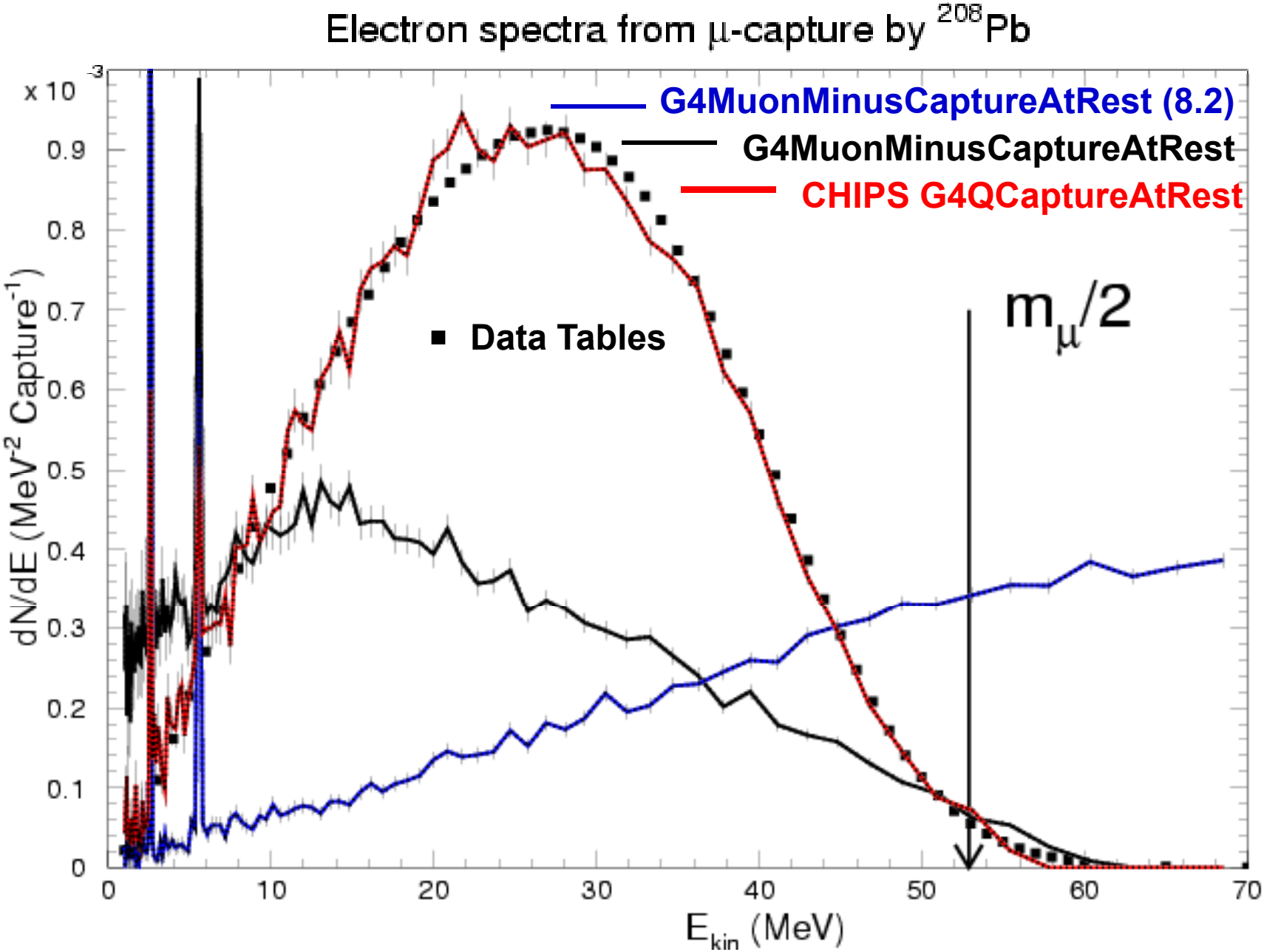
CHIPS: G4QCaptureAtRest (test29) G4.8.1 (QGS/FTF)



CHIPS:G4QCaptureAtRest(test29,μ^-Ca)



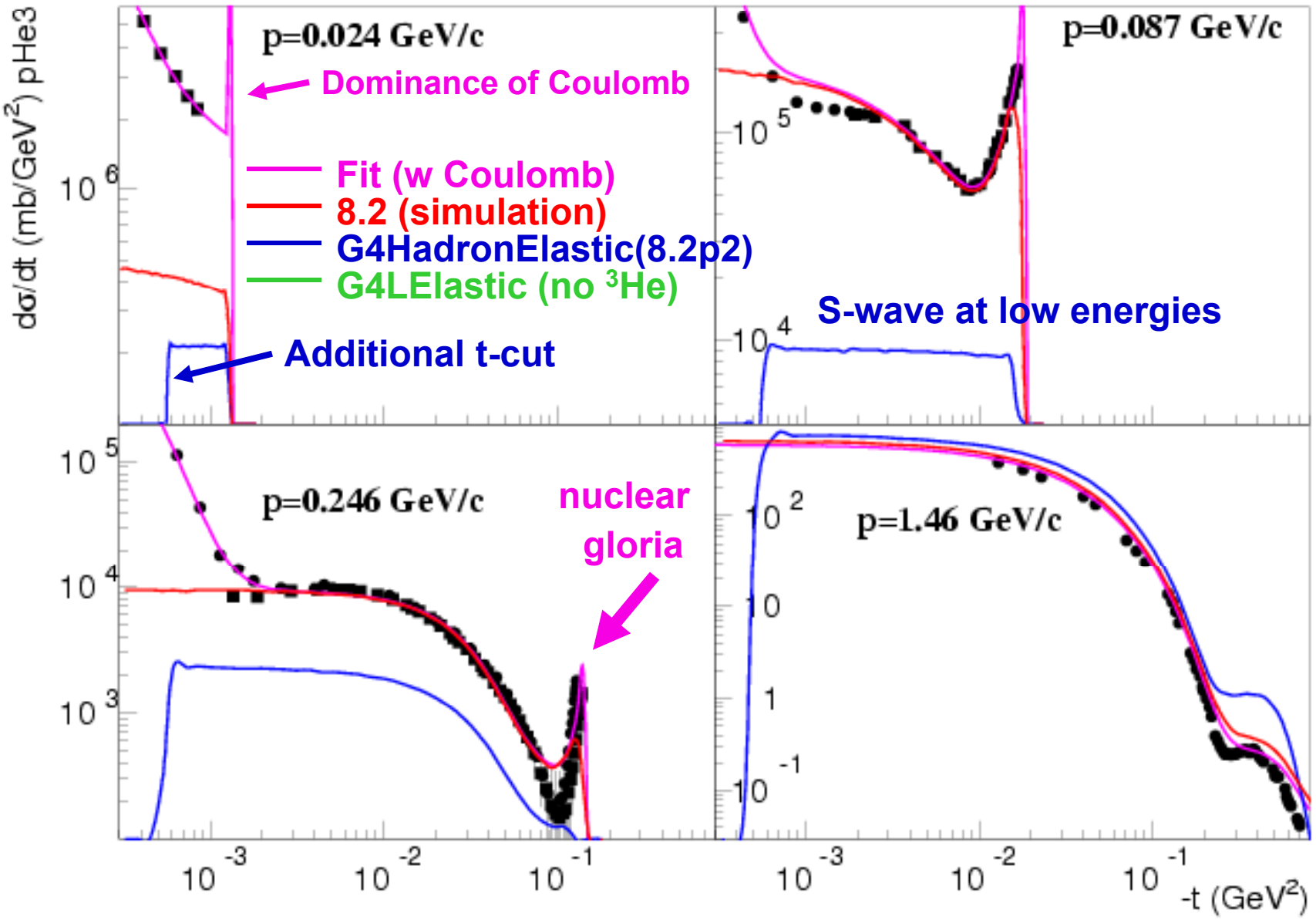

Electron spectra from μ-capture by ^{40}Ca
G4MuonMinusCaptureAtRest (all physics lists 8.2)
G4MuonMinusCaptureAtRest (8.2.ref-02, fixed bug)
CHIPS G4QCaptureAtRest (new development)
Data Tables
Decay bug:
$(\tilde{\nu}_e+\nu_\mu)$ μ^- e^-
The same direction
A
$m_\mu/2$
dN/dE (MeV^{-2} Capture^{-1})
E_{kin} (MeV)
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
10
20
30
40
50
60
70

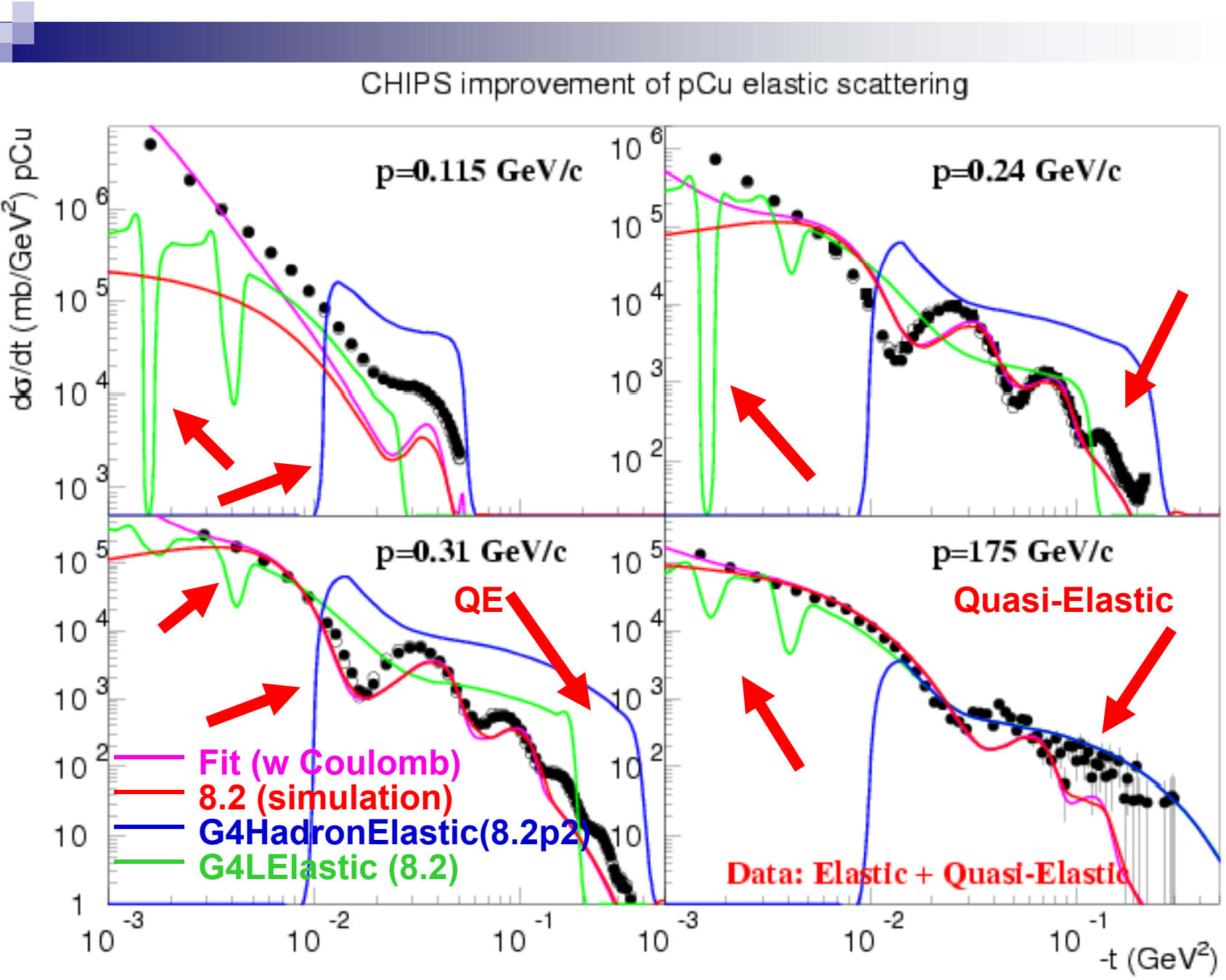

Electron spectra from μ-capture by ^{208}Pb
G4MuonMinusCaptureAtRest (8.2)
G4MuonMinusCaptureAtRest
CHIPS G4QCaptureAtRest
Data Tables
$m_\mu/2$
x 10^{-3}
dN/dE (MeV^{-2} Capture^{-1})
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
10
20
30
40
50
60
70
E_{kin} (MeV)

CHIPS improvement of elastic scattering

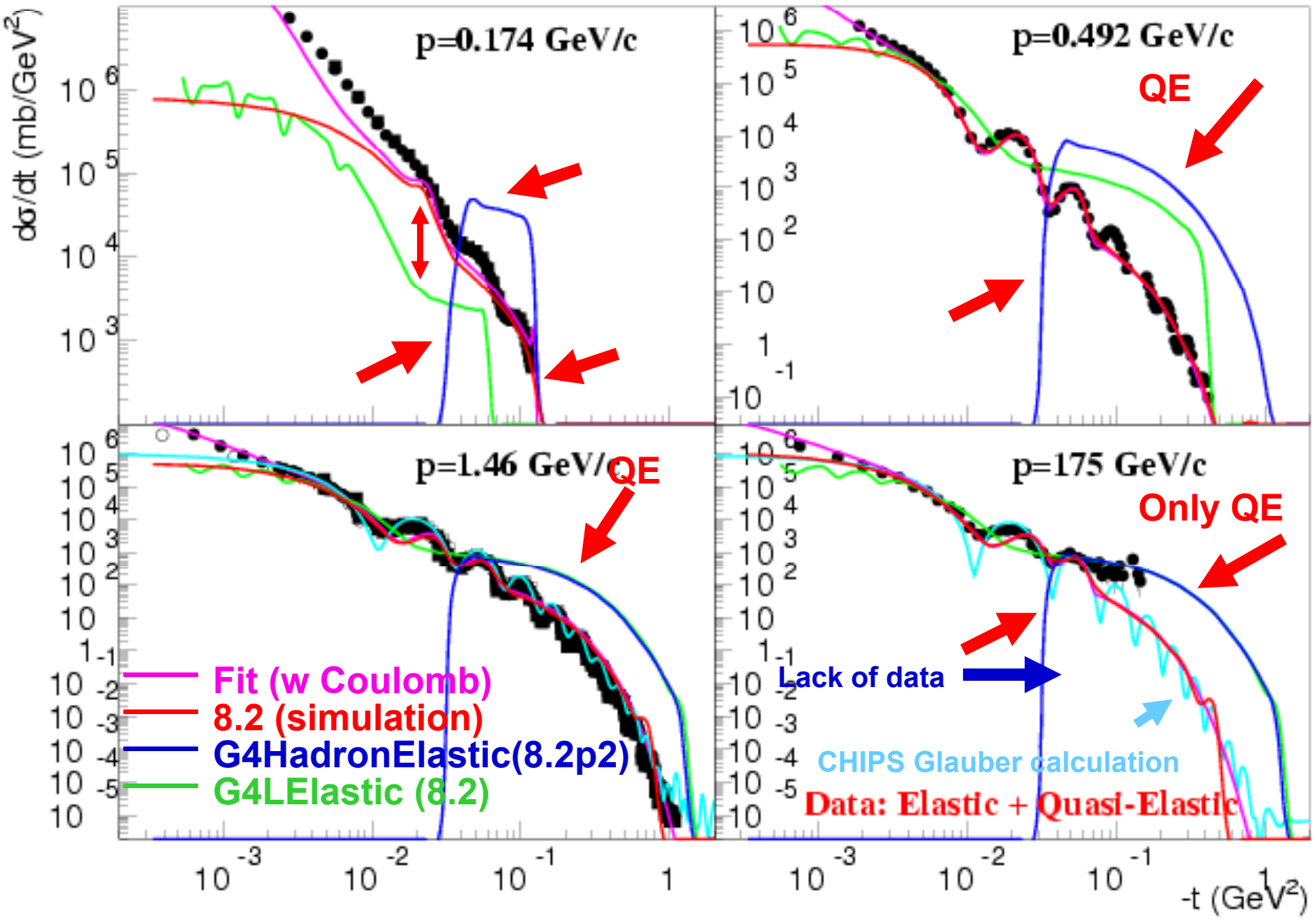
- G4QElastic simulates both forward (t-chenel) diffraction and backward (u-chenel) nuclear gloria
- At high **energies** and high **t** there is no data so the Glauber model calculations were approximated
- The CHIPS (G4QElastic,**QGSC**) is compared with SAID PWA (G4Lnp/G4pp, **Not in Physics Lists**), G4LElastic (**LHEP**) and G4HadronElastic (**QGSP**)
- G4HadronElastic: G4QElastic for A<5, G4LElastic (+ energy-momentum conservation) for A>4, **+…**
- Double counting of quasi-elastic: excluded in G4Q
- Coulomb scattering can be a new discrete process

CHIPS improvement of pHe3 elastic scattering




CHIPS improvement of pCu elastic scattering
dσ/dt (mb/GeV²) pCu
p=0.115 GeV/c
p=0.24 GeV/c
p=0.31 GeV/c
p=175 GeV/c
QE
Quasi-Elastic
Fit (w Coulomb)
8.2 (simulation)
G4HadronElastic(8.2p2)
G4LElastic (8.2)
Data: Elastic + Quasi-Elastic
-t (GeV²)

CHIPS improvement of pPb elastic scattering



CHIPS developments for Shower Shape

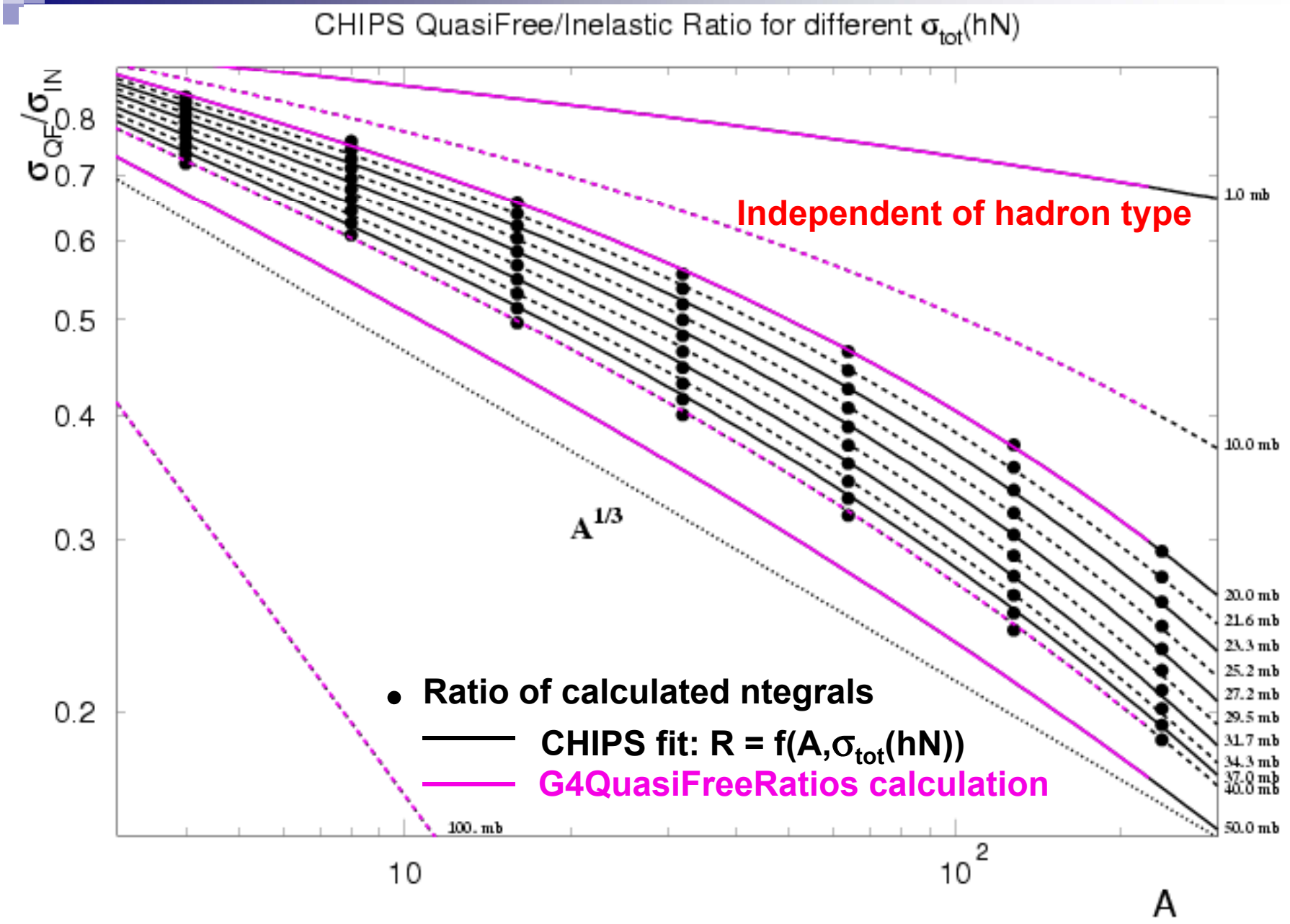
- There are four steps to reduce the part of production cross-section σ_{prod} (string fragmentation of QGS) in σ_{in} cross-section
  - Quasi-elastic part of σ_{in} (G4QuasiFreeRatios)
  - Single diffraction excitation of the target
  - Single diffraction excitation of the projectile
  - Coherent Charge Exchange part of σ_{in}
- Better description is needed for charge and momentum transfer (rapidity gap) in QGS

CHIPS method for quasi-elastic scattering

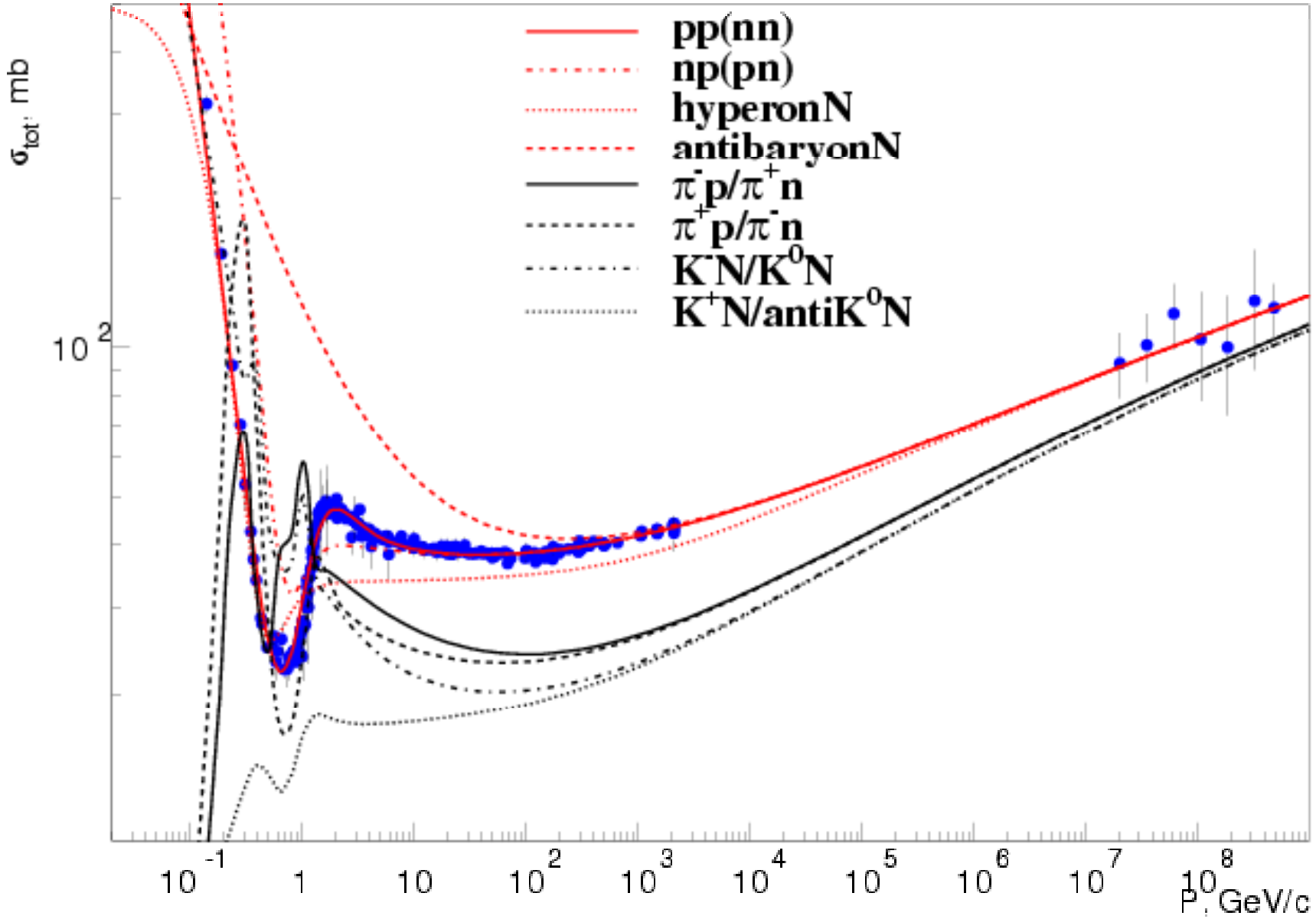
- Calculate and approximate R=QE/Inelastic
  - Probability of interaction: $\sigma_{in}=\int 1-e^{-\sigma\cdot T(b)}d^2\mathbf{b}$, $\sigma=\sigma^{tot}(hN)$
  - Probability to interact once: $\sigma_{QF}=\int \sigma\cdot T(b)\cdot e^{-\sigma\cdot T(b)}d^2\mathbf{b}$
- Precize approximation of $\sigma^{el}(hN)$ & $\sigma^{tot}(hN)$
  - $n\bar{n}/pp$ and np/pn interactions
  - N-N and Hyperon-N interactions
  - π^-p/π^+n and π^+p/π^-n interactions
  - K^-N/K^0N and $K^+N/\bar{K}^0N$ interactions

  } **8 isotopic groups**

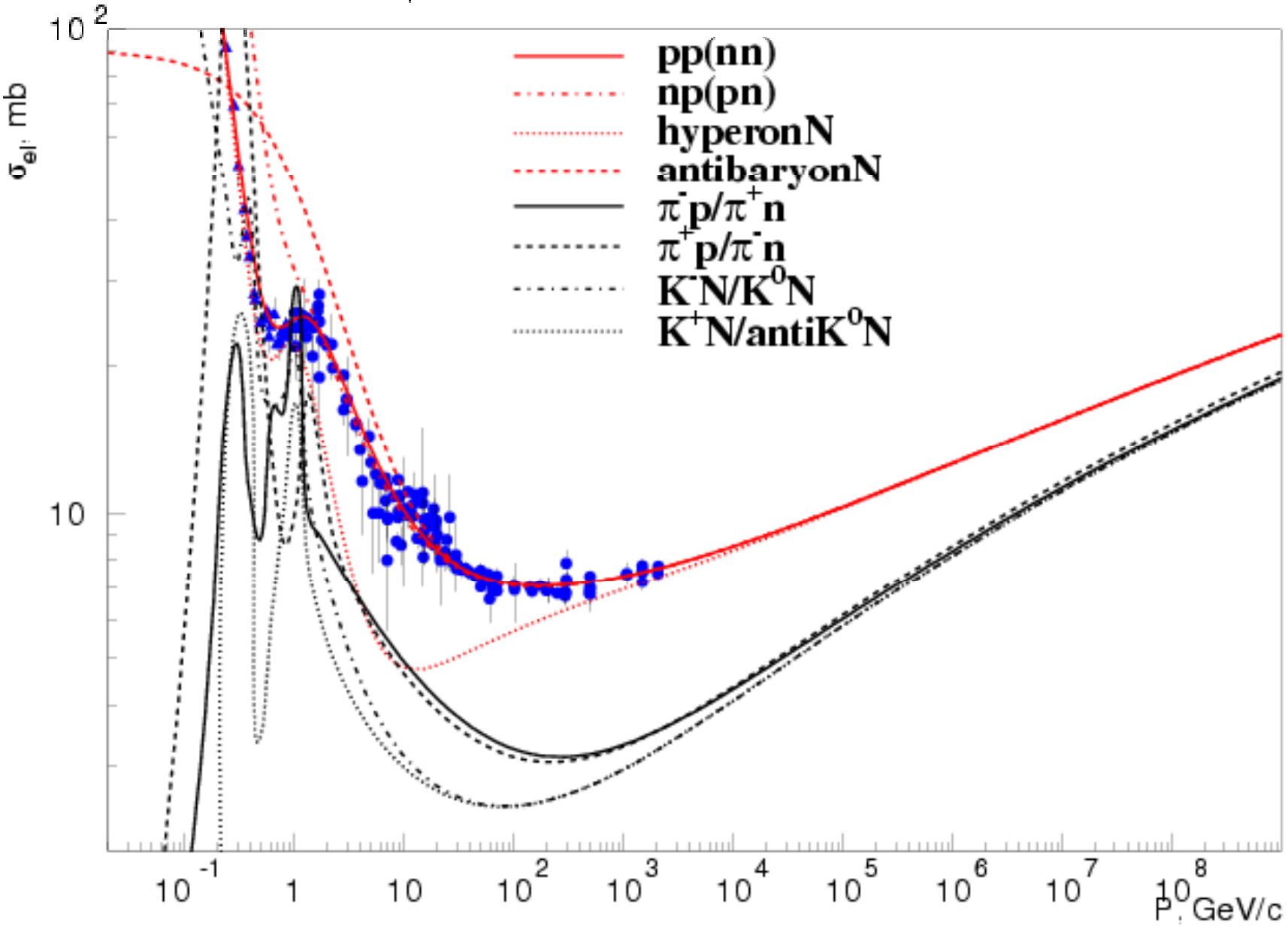
- Calculation of QElastic/In & QFree/In ratios

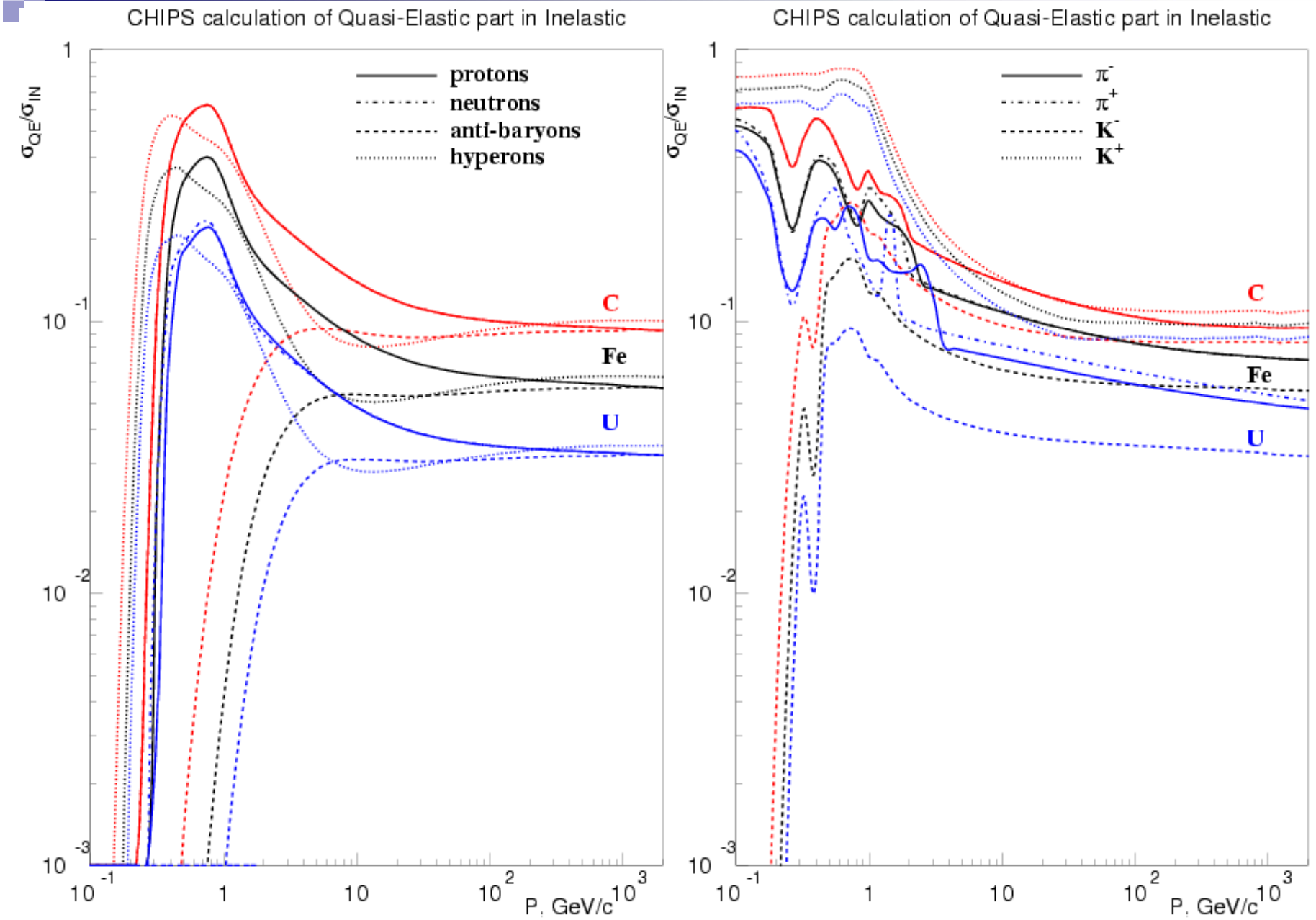

CHIPS QuasiFree/Inelastic Ratio for different σtot(hN)
σQF/σIN
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Independent of hadron type
A1/3
1.0 mb
10.0 mb
20.0 mb
21.6 mb
23.3 mb
25.2 mb
27.2 mb
29.5 mb
31.7 mb
34.3 mb
37.0 mb
40.0 mb
50.0 mb
100. mb
• Ratio of calculated ntegrals
CHIPS fit: R = f(A,σtot(hN))
G4QuasiFreeRatios calculation
10
10 2
A

CHIPS improvement of hadron-nucleon total cross-section

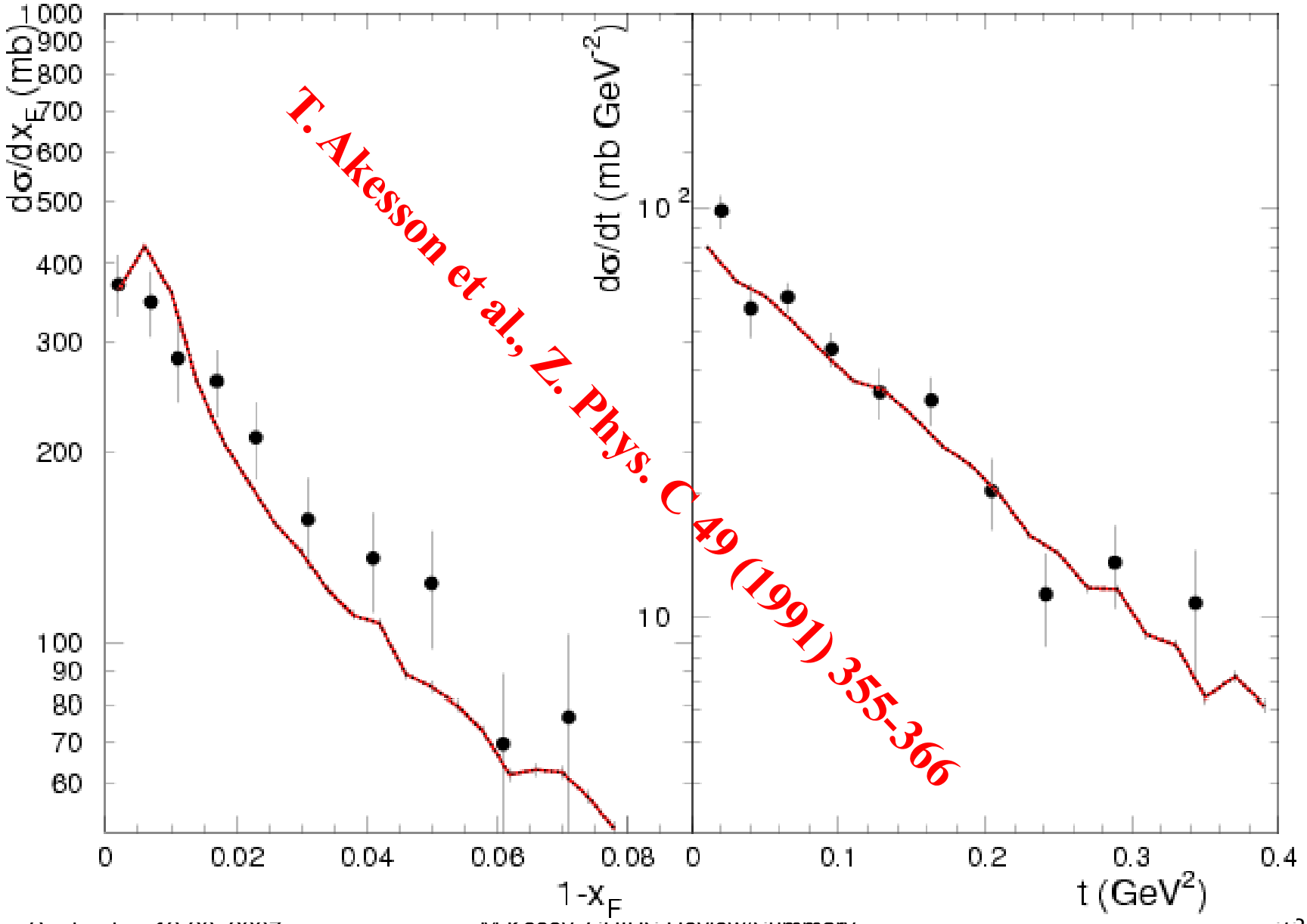


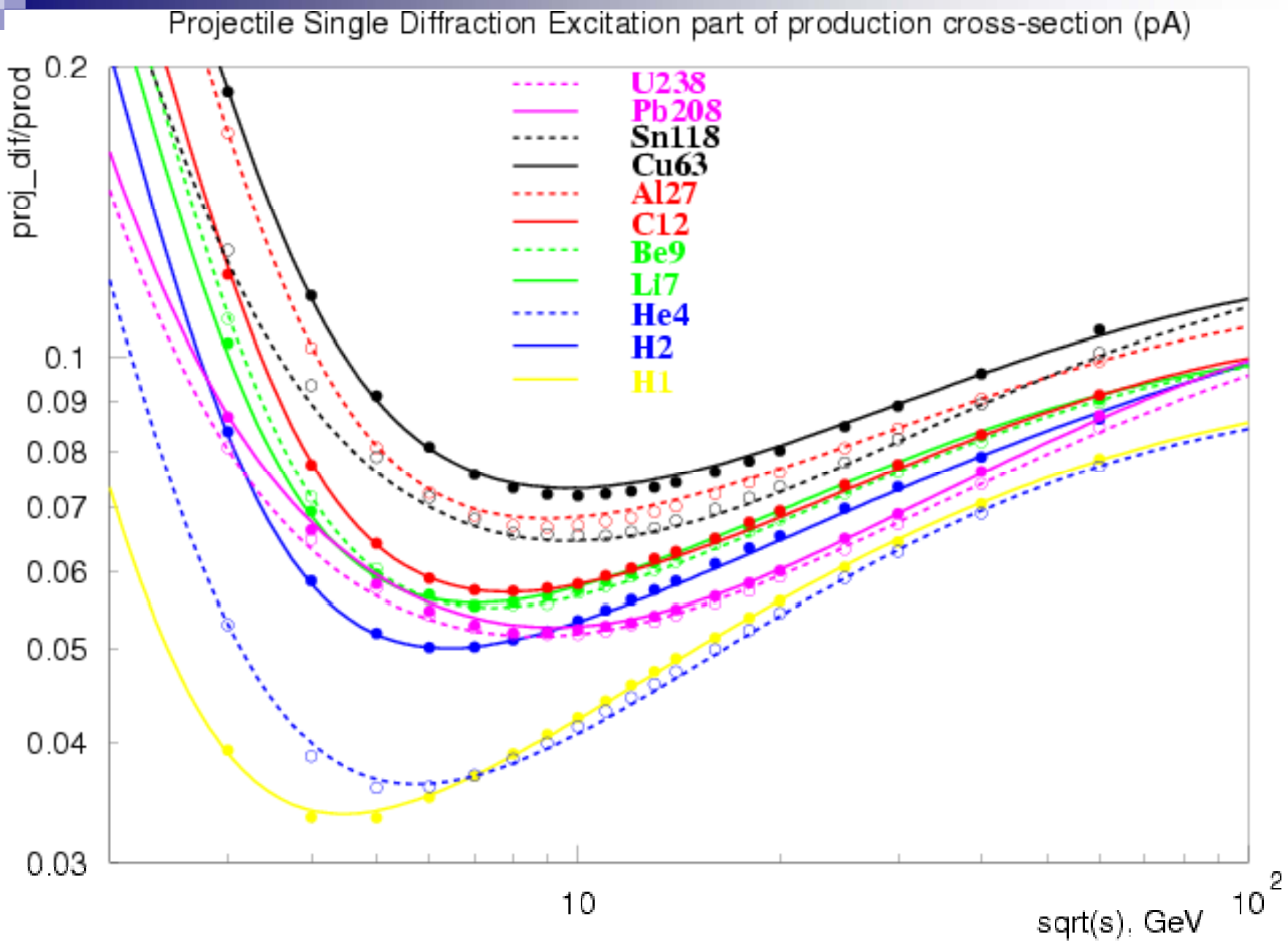
CHIPS improvement of hadron-nucleon elastic cross-section




CHIPS calculation of Quasi-Elastic part in Inelastic
σ_{QE}/σ_{IN}
protons
neutrons
anti-baryons
hyperons
C
Fe
U
P, GeV/c
CHIPS calculation of Quasi-Elastic part in Inelastic
σ_{QE}/σ_{IN}
π^-
π^+
K^-
K^+
C
Fe
U
P, GeV/c

Single Target Diffraction in $Al^{27}(p,p)X$ reaction (G4QDiffraction process)



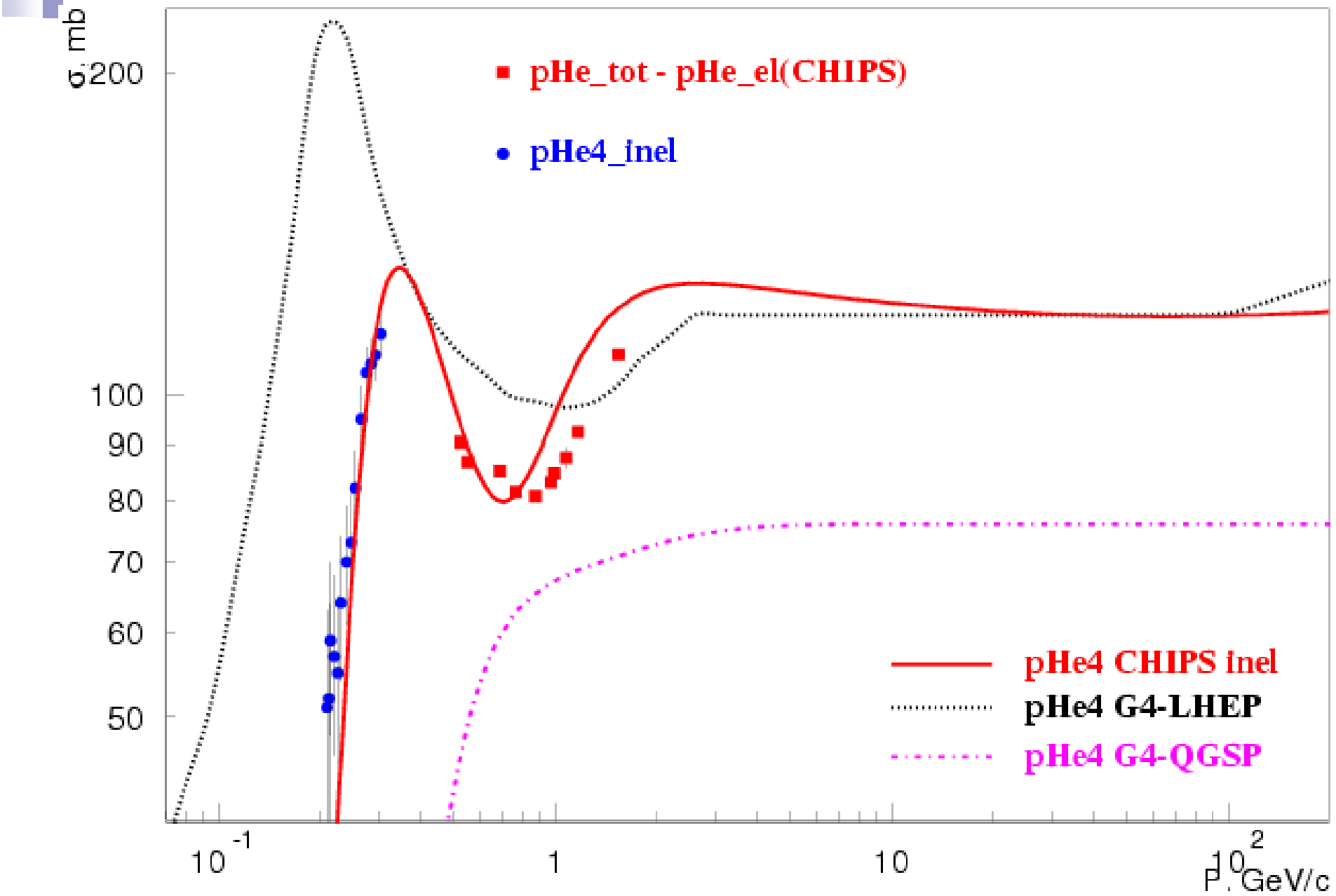

Projectile Single Diffraction Excitation part of production cross-section (pA)
proj_dif/prod
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
U238
Pb208
Sn118
Cu63
Al27
C12
Be9
Li7
He4
H2
H1
10
10^2
sqrt(s), GeV

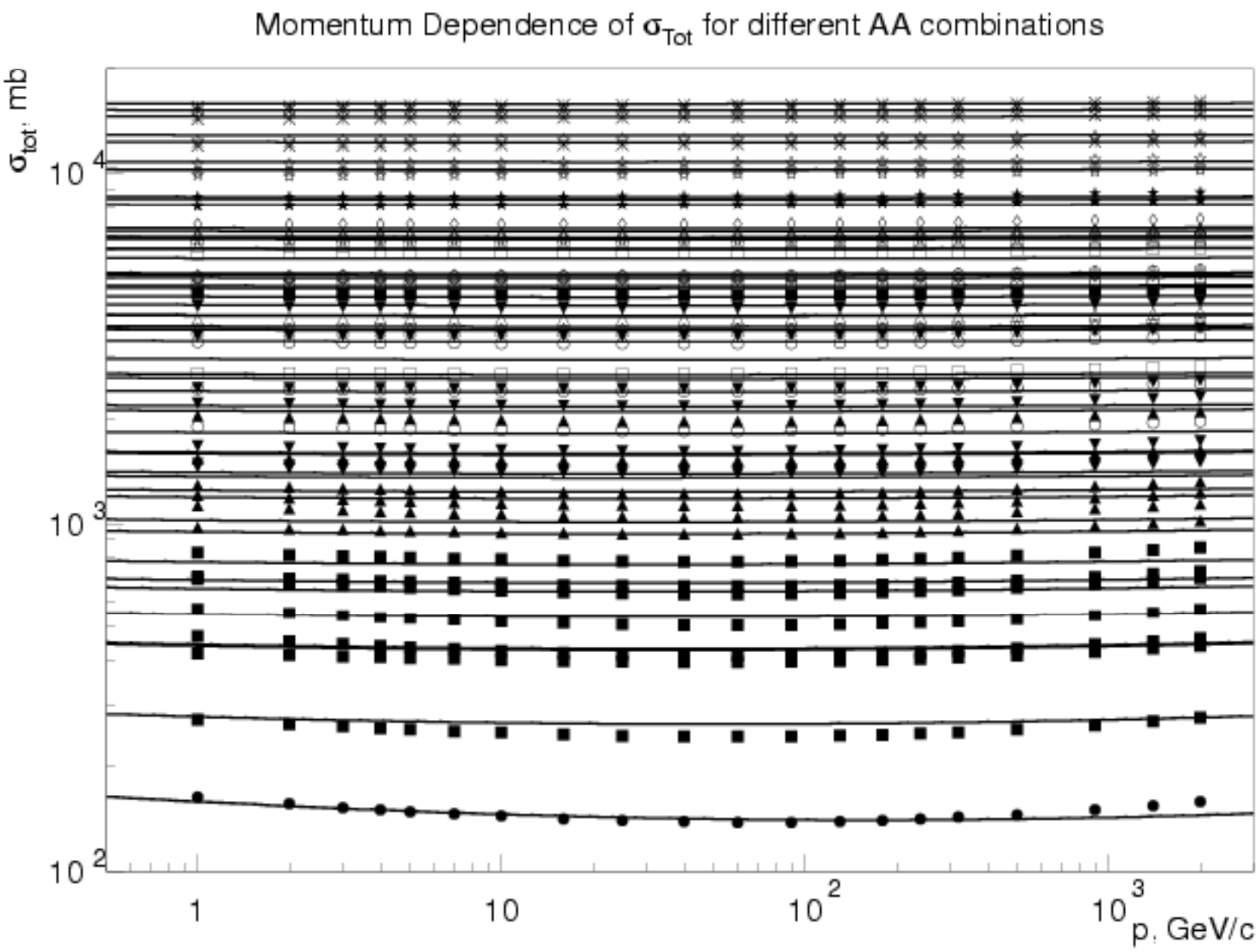
R&D of hadronic CHIPS package

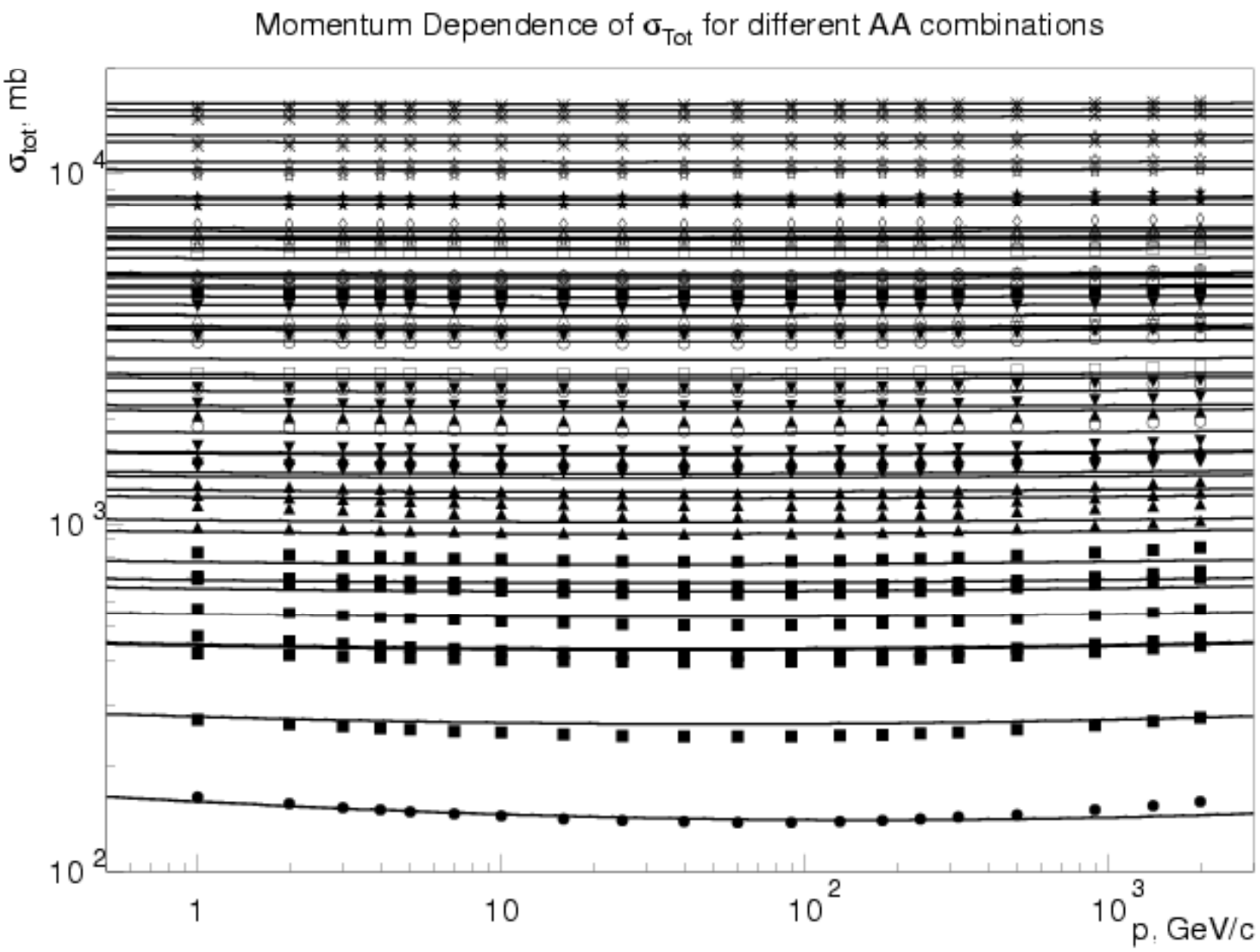
- First of all: transport of the SU(3) secondary's
  - Geant4 transport for Hyper-fragments (demand for EM)
  - Geant4 transport for Anti-fragments (demand for EM)
  - Short Lived Iso-fragments (no transport, no EM)
  - Improved multiple scattering for charged hadrons
  - Improved elastic scattering for all hadrons/fragments
  - Improved decay rates and decay channels for isotopes
  - Improved fit and extrapolation of the isotope masses
- Elastic & inelastic interactions of hadrons/fragments
  - Cross-sections for hadrons, fragments (+ Hyper- + Anti-)
  - Fast models for inelastic interactions (**G4QLowEnergy**)

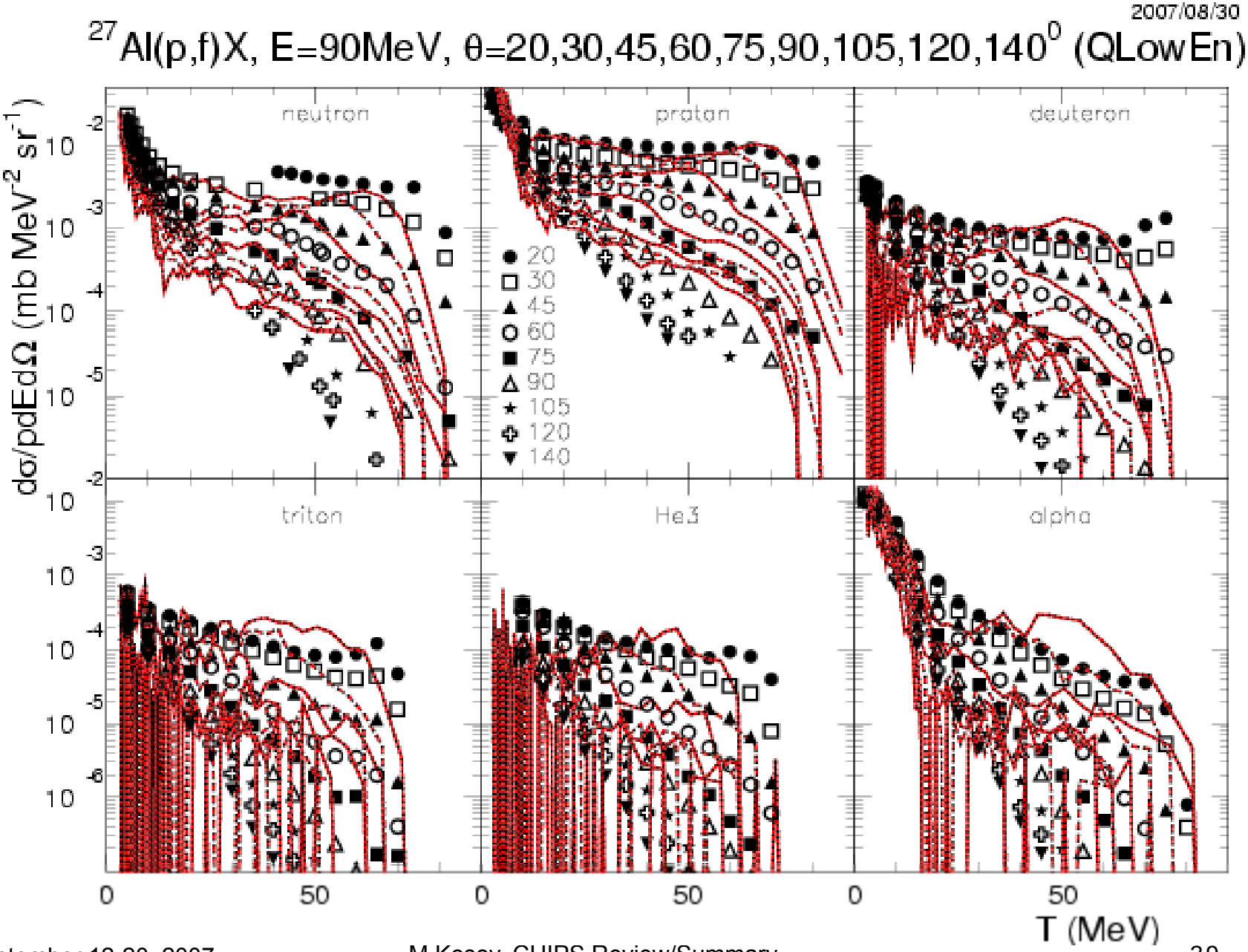
CHIPS fit of inelastic NA and AA reactions

- Consistent fit of $\sigma_{in}=\sigma_{tot}-\sigma_{el}$ NA cross-sections
  - It is based on the unique CHIPS fit of σ_{el}
  - Analytic parameterization of $\sigma_{in}(A,P)$
- Glauber calculation and analytic fit of $\sigma_{tot}(AA)$ and $\sigma_{el}(AA)$ cross-sections
  - Glauber calculations take into account individual nuclear densities of nuclei
  - Two separate analytic formulas for $\sigma_{tot}(AA)$ and for $R(AA)=\sigma_{el}/\sigma_{tot}$,which is >40% for heavy nuclei


σ, mb
200
100
90
80
70
60
50
pHe_tot - pHe_el(CHIPS)
pHe4_inel
pHe4 CHIPS inel
pHe4 G4-LHEP
pHe4 G4-QGSP
10^-1
1
10
10^2
P, GeV/c


Momentum Dependence of σTot for different AA combinations
σtot, mb
10 4
10 3
10 2
1
10
10 2
10 3
p, GeV/c


Momentum Dependence of σTot for different AA combinations
σtot, mb
10 4
10 3
10 2
1
10
10 2
10 3
p, GeV/c


2007/08/30
27Al(p,f)X, E=90MeV, θ=20,30,45,60,75,90,105,120,140^0 (QLowEn)
neutron
proton
deuteron
triton
He3
alpha
dσ/pdEdΩ (mb MeV^-2 sr^-1)
20
30
45
60
75
90
105
120
140
T (MeV)

Conclusion

- At present CHIPS model covers all **hadronic stopping** and all **electro-weak** nuclear reactions (including A(ν,μ))
- For hadronic reactions it has
  - **inelastic NA and AA cross-sections (not meson-nuclear!)**
    - coherent elastic interactions (including coherent charge exchange)
    - quasi-elastic interactions (including scattering on quasi-free clusters)
    - inelastic interactions (with emphasis on low energies and light nuclei)
  - **inelastic models for low energy (including fragments)**
    - G4QCollision for pA interactions (two times slower than G4Binary)
    - Fast G4QLowEnergy (fragments, hyper-fragments)
  - **high energy applications**
    - nuclear fragmentation in QGSC and FTFC
    - high energy diffraction (competitor of FTF)
- CHIPS fit of EM elastic scattering can improve multiple scattering for hadrons (π/μ difference). Not used now!