Validation of one hadronic model CHIPS physics list

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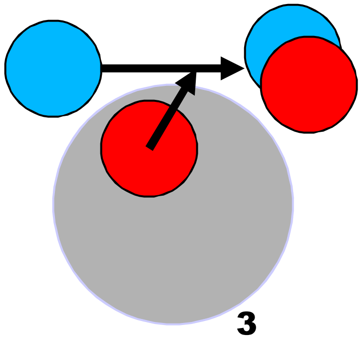
Introduction (included Physics)

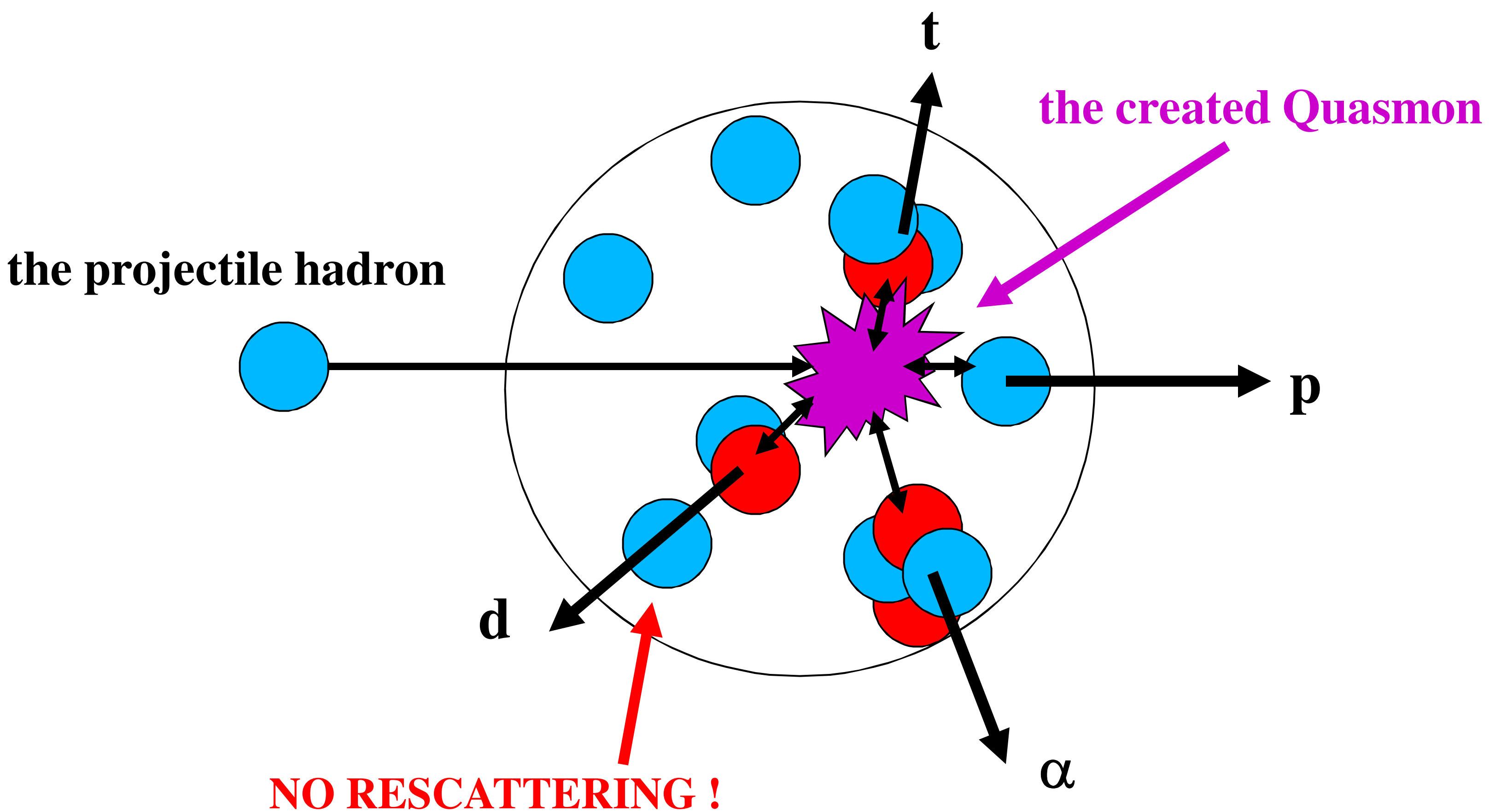
- Standard EM Physics (Used As Is):
  - Gamma: Photo-effect, Compton, e^+e^--conversion
  - All charged: **Multiple Scattering**, Ionization
  - + for e^+, e^-: Bremsstrahlung, + for e^+: Annihilation
  - + for μ, π, K, p: Bremsstrahlung, e^+e^--production (**Why only for these particles**?)
- CHIPS processes recommended for all Physics Lists.
  - Photo- and electro-nuclear Physic (now original CHIPS + **Synchrotron Radiation**)
  - Nuclear capture at rest for negative particles (not e^- = K-capture radioactivity)
  - New: μ-, τ-, and neutrino-nuclear Physics (NC and CC) – original CHIPS
- Hadronic Physics (one inelastic model for all hadrons, all energies)
  - Elastic Scattering (only p and n are simulated by the CHIPS **G4QElastic** process)
  - Inelastic reactions (simulated by the universal CHIPS **G4QInelastic** process)
- Ion Physics (As Is, CHIPS G4QLowEnergy, **G4QIonIonCollision**)
- Decay Physics (Used As Is, CHIPS has Isotope Decay DB)

Algorithm of the low energy CHIPS

- Simulation of the deep inelastic hadron-nuclear interactions is the same as in CHIPS stopping algorithm
  - Nuclei are clusterized (nucleons clusterized in di-baryons, tri-baryons etc.)
  - The projectile hadron joins with one of the clusters and creates a Quasmon
  - By quark-fusion or quark-exchange with other clusters energy is dissipated
  - When the quark level algorithms are exhausted, switch to nuclear evaporation
- A few decoupled processes are added
  - Quasi-elastic scattering of the projectile on nucleons and nuclear clusters
    - G4QElastic process is used for this scattering on nucleons or on clusters
  - Pick up process, which provides high energy forward nuclear fragments
- Final State Interaction of produced secondaries
  - A kind of the nuclear fusion FSI reactions
  - For energy and momentum correction in case of problems



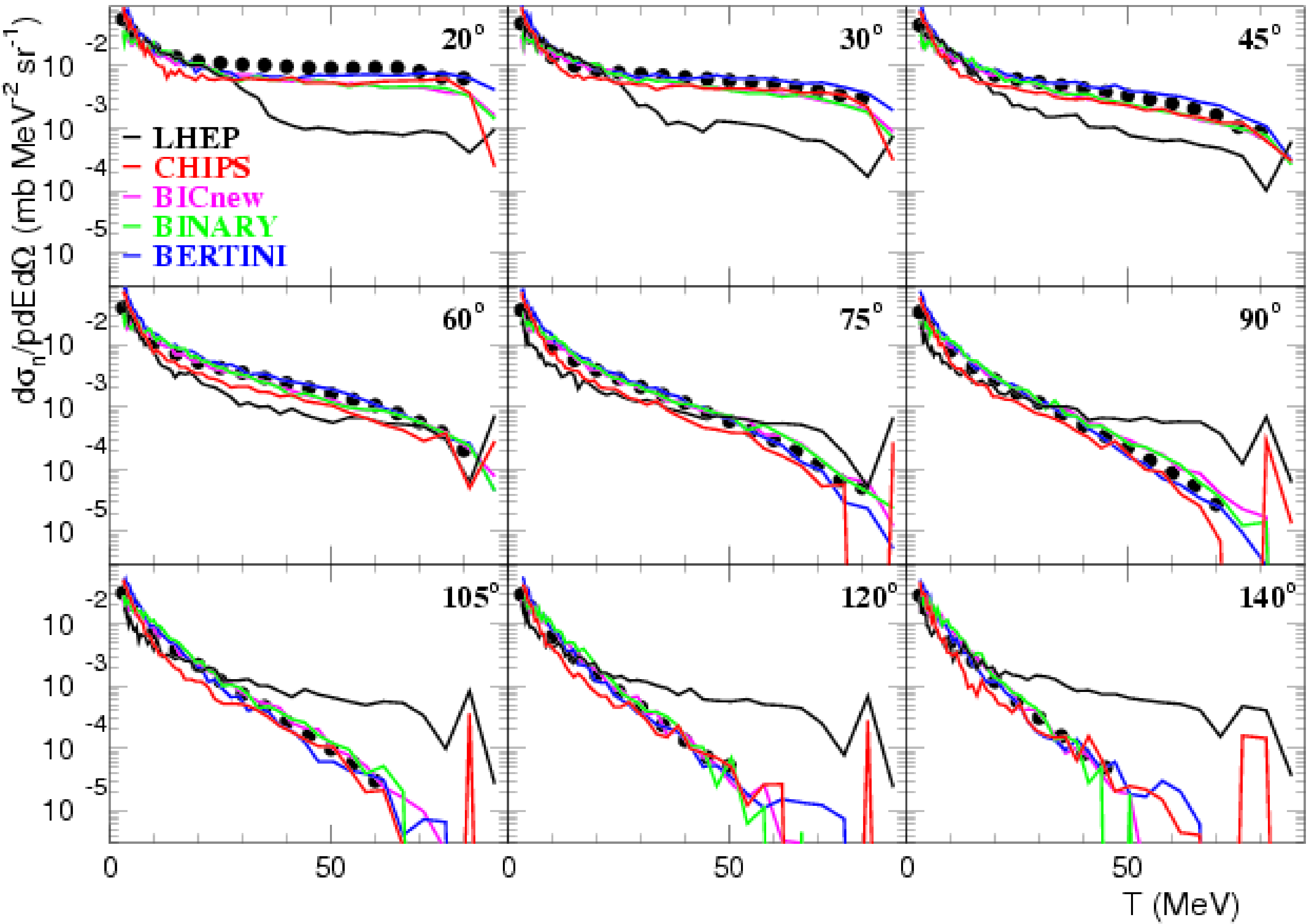
CHIPS algorithm of the deep inelastic hadron-nuclear interaction

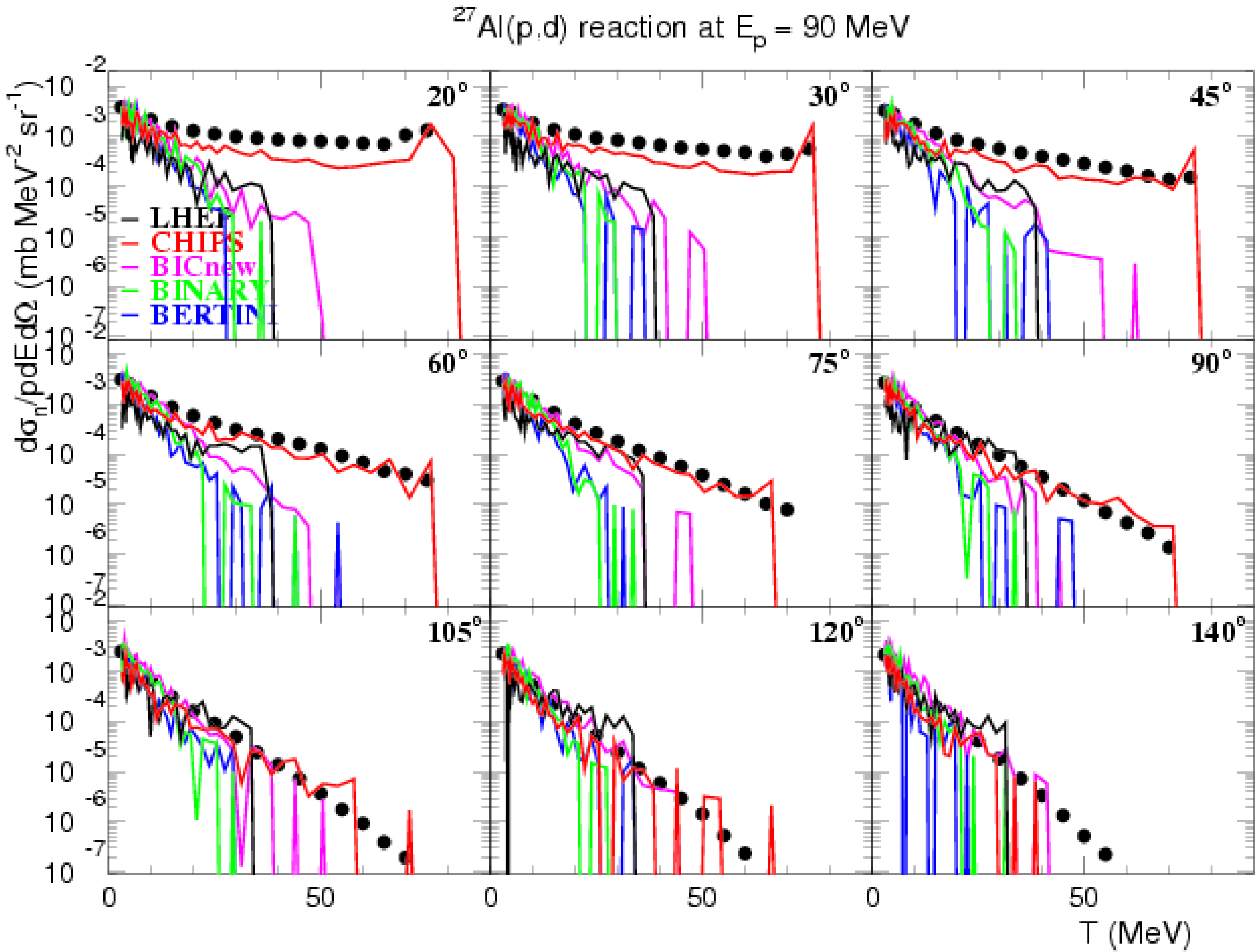


NO CASCADE, JUST A DECAY !

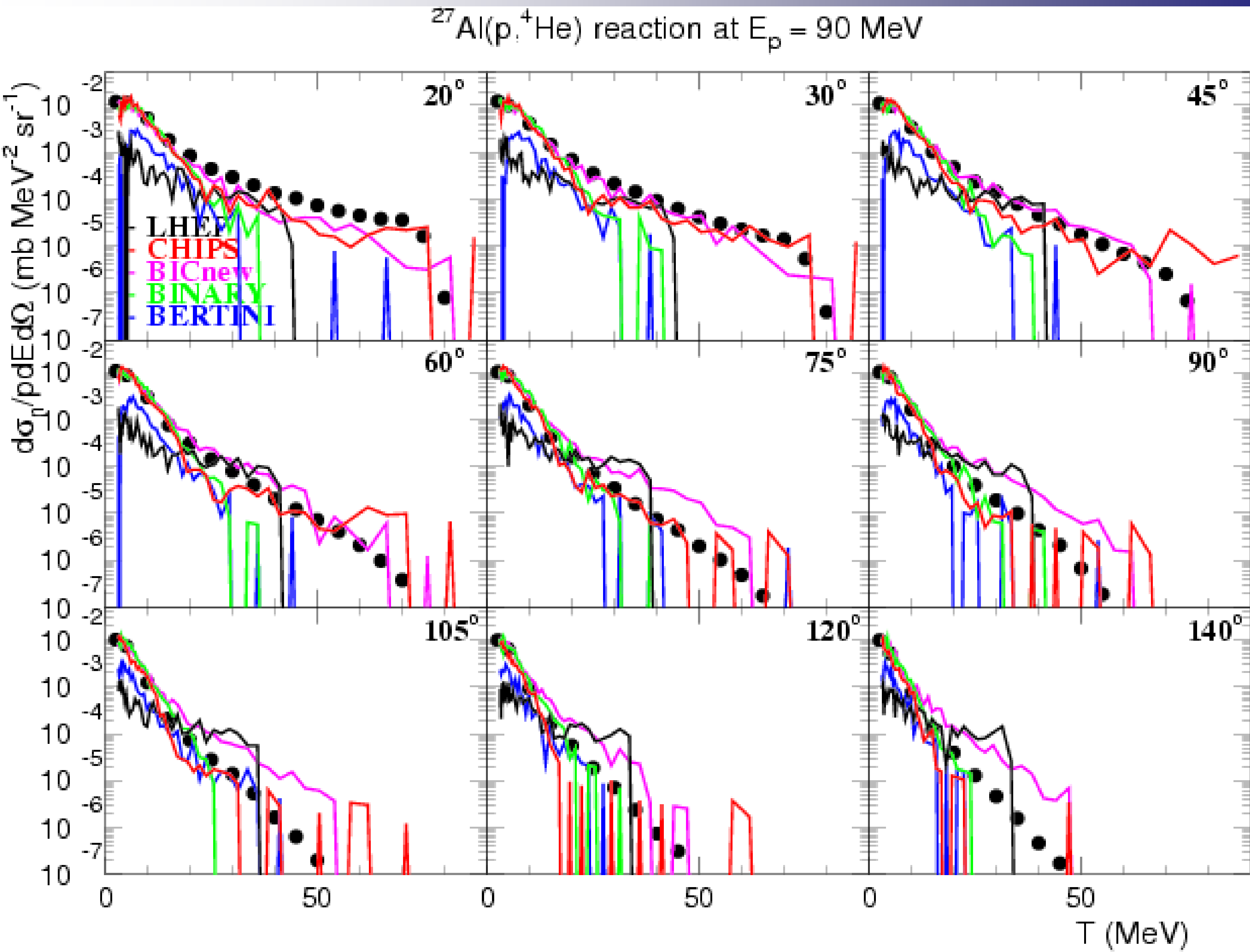
The example for 90 MeV protons on Al and Bi is following

$^{27}Al(p,p)$ reaction at E_p = 90 MeV



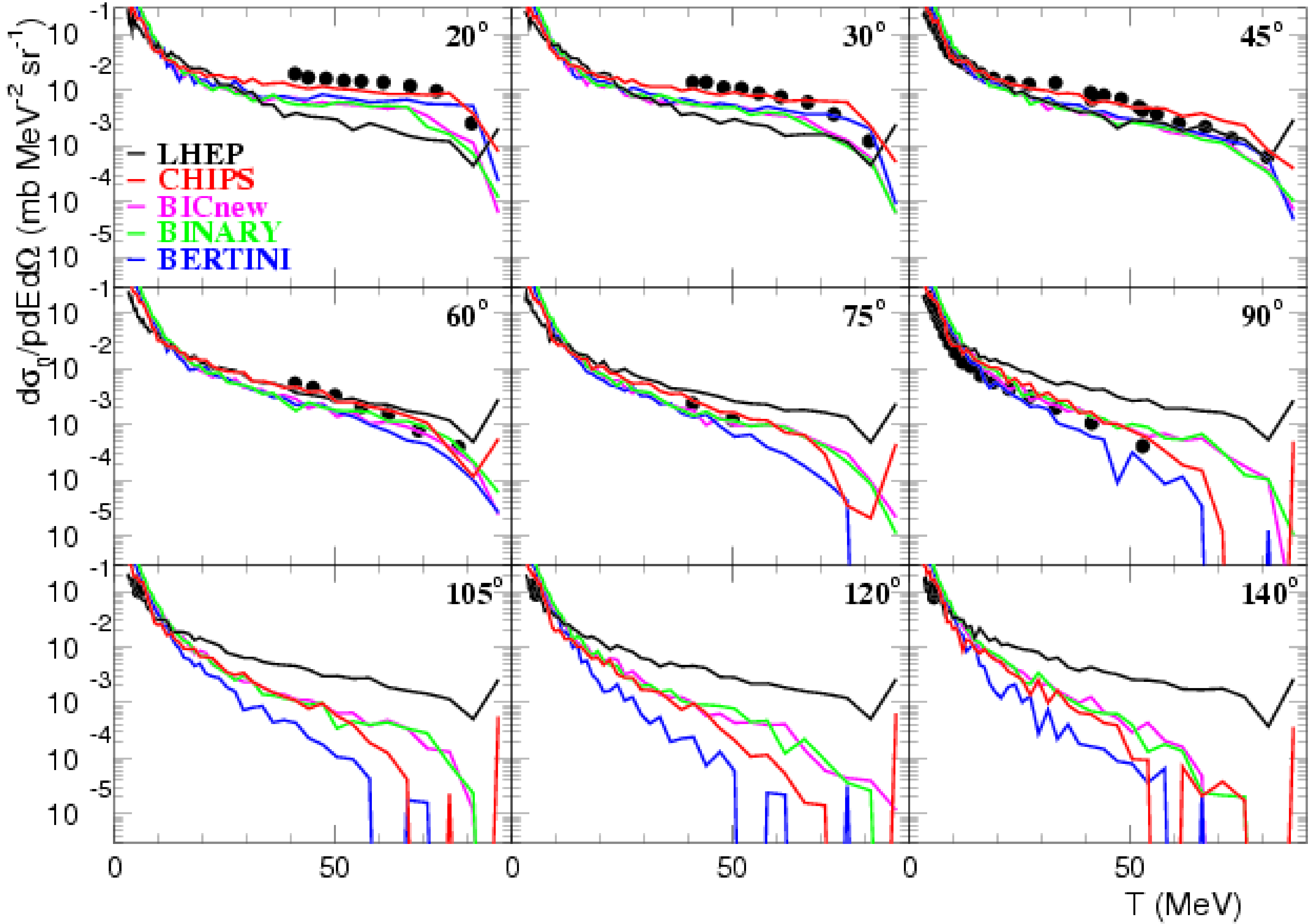


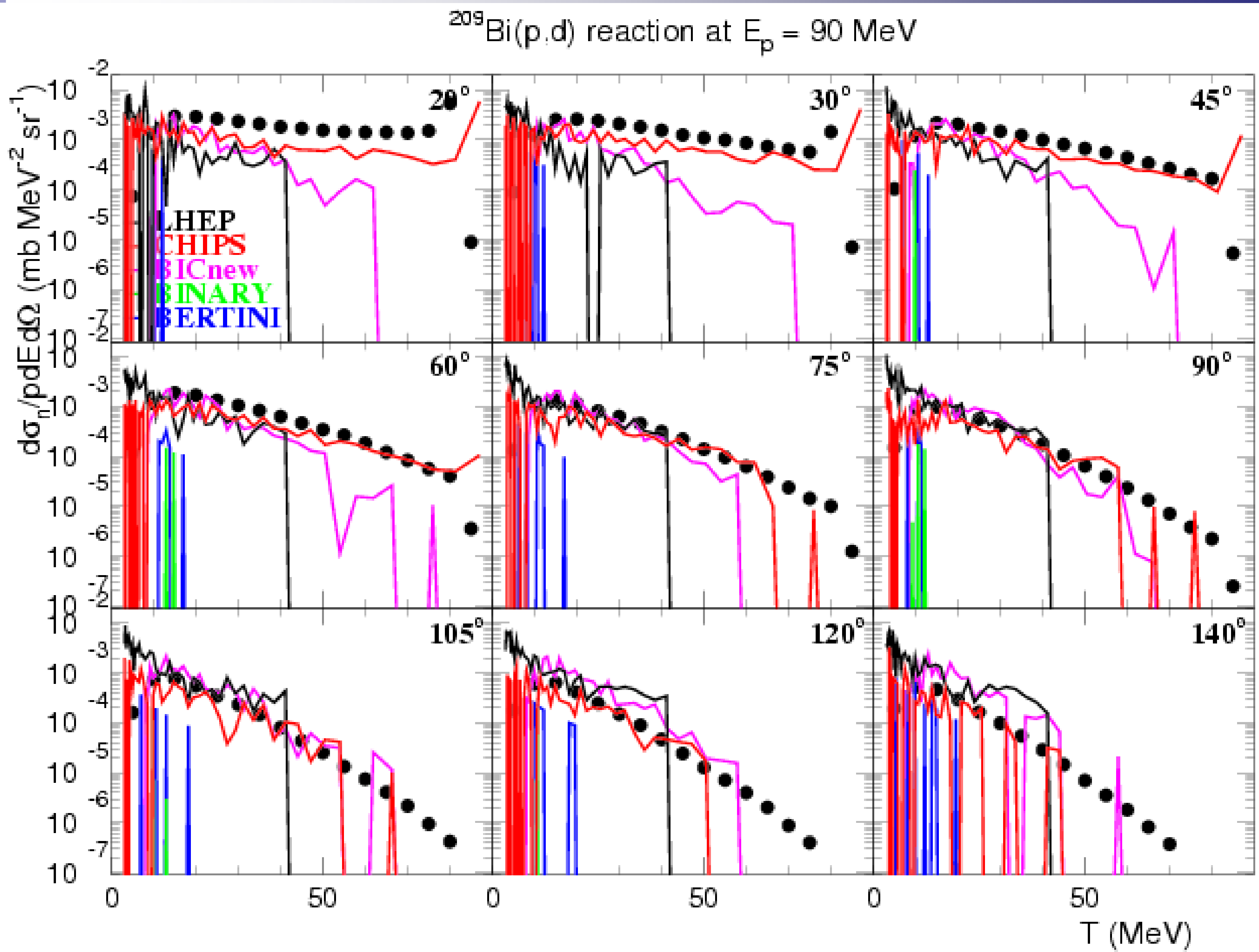
^{27}Al(p,d) reaction at E_p = 90 MeV
$d\sigma_n/pdEd\Omega$ (mb MeV^{-2} sr^{-1})
LHEP
CHIPS
BICnew
BINARY
BERTINI
20°
30°
45°
60°
75°
90°
105°
120°
140°
T (MeV)



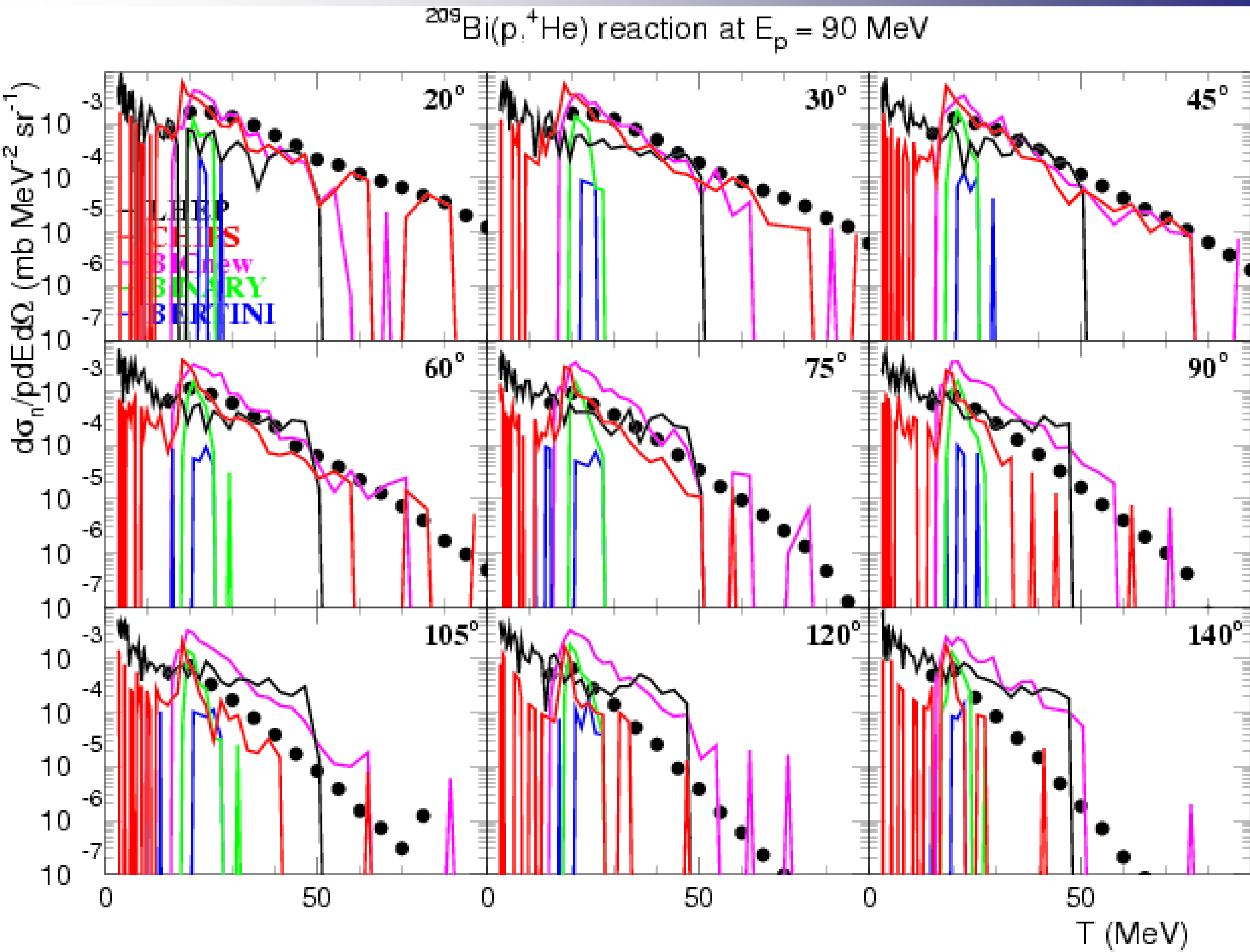
^{27}Al(p,^{4}He) reaction at E_p = 90 MeV
$d\sigma_{II}/pdEd\Omega$ (mb MeV^{-2} sr^{-1})
LHEP
CHIPS
BICnew
BINARY
BERTINI
20°
30°
45°
60°
75°
90°
105°
120°
140°
T (MeV)

$^{209}Bi(p,n)$ reaction at E_p = 90 MeV





^{209}Bi(p,d) reaction at E_p = 90 MeV
$d\sigma_n/pdEd\Omega$ (mb MeV^{-2} sr^{-1})
20°
30°
45°
60°
75°
90°
105°
120°
140°
LHEP
CHIPS
BICnew
BINARY
BERTINI
T (MeV)



^{209}Bi(p,^{4}He) reaction at E_p = 90 MeV
$d\sigma_n/pdEd\Omega$ (mb MeV^{-2} sr^{-1})
LHEP
CHIPS
BICnew
BINARY
BERTINI
20°
30°
45°
60°
75°
90°
105°
120°
140°
T (MeV)

Simulation is made using the test49 tool (Plenary Section VI) with specific CHIPS parameters

Time performance for 29 MeV and 90 MeV protons

protons 29 MeV (2009)

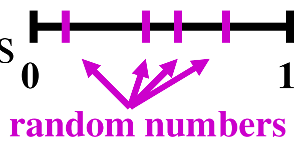
Model	Al	Au
PreCom	1.5	4.4
Binary	1.9	4.7
Bertini	0.40	0.42
CHIPS	2.7	2.8
LHEP	0.06	0.07
QLowE	0.10	0.10

protons 90 MeV (2009)

Model	Al	Bi
PreCom	2.2	5.2
Binary	3.1	8.2
Bertini	0.48	0.62
CHIPS	2.5	3.1
LHEP	0.10	0.11
QLowE	0.12	0.14

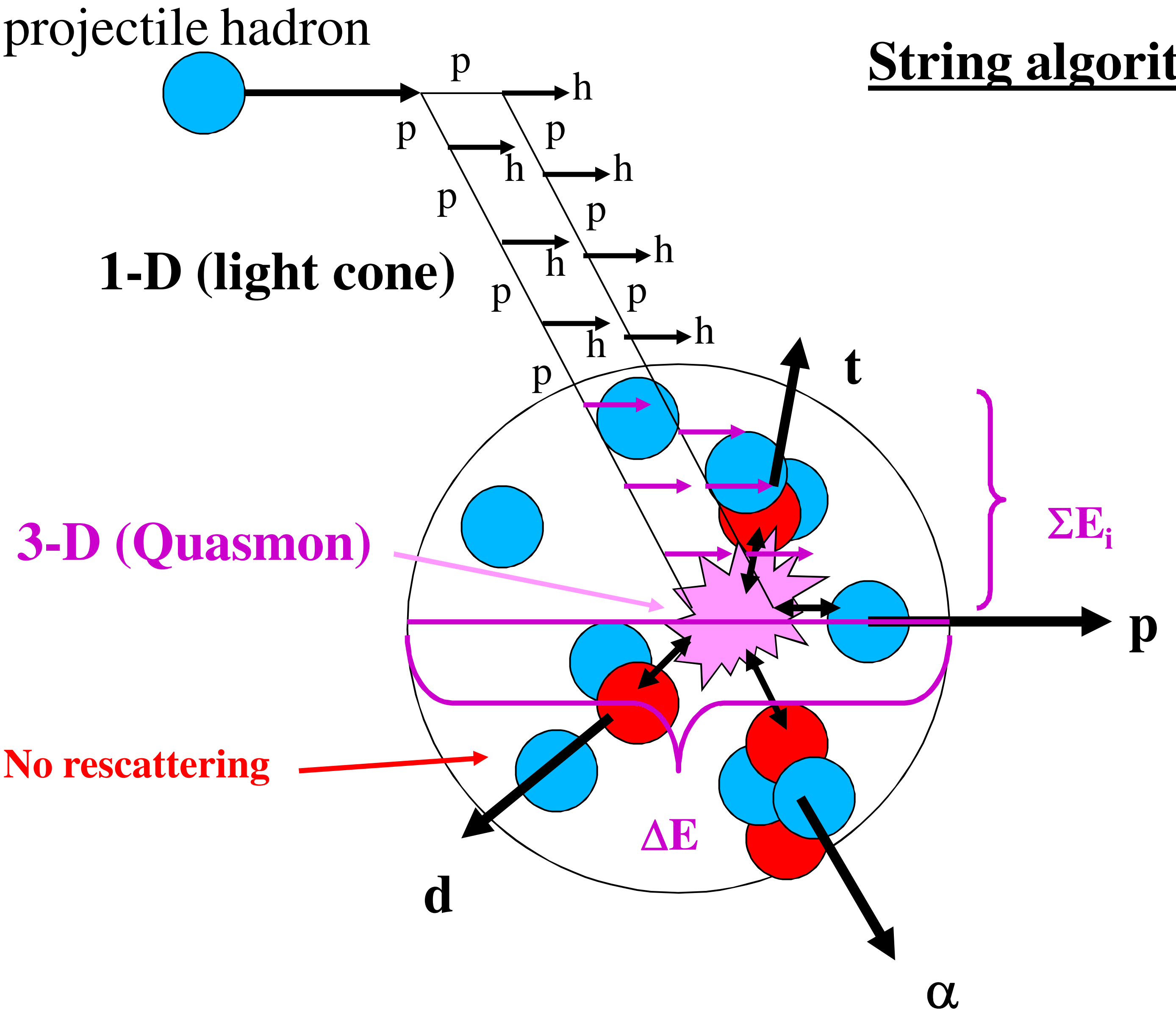
New CHIPS string algorithm

- The 1-D CHIPS String is similar to the QG String, but…
  - All partons are massless (current) instead of heavy (constituent, QGS)
  - Thus the CHIPS string algorithm can work from E=0 (formally $E>>m_q$)
  - The hadron splitting in partons is made by the CHIPS algorithm: $(1-x)^{N-2}$
  - If energy is restricted, the strings are fused or converted to hadrons

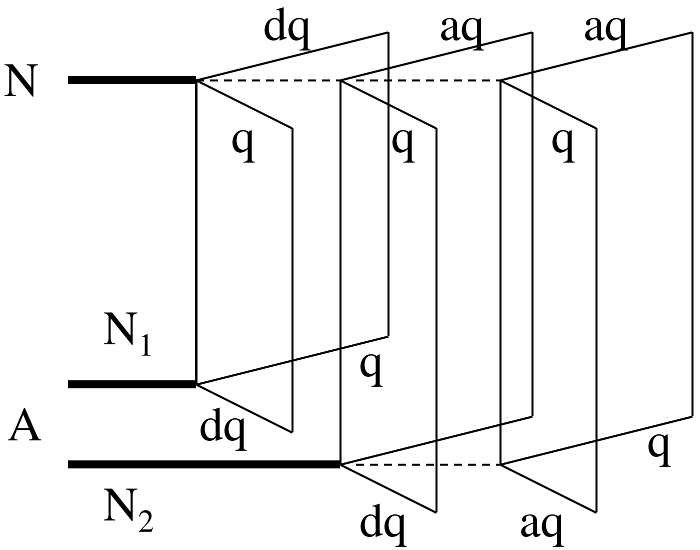


- Connection to the 3-D CHIPS algorithm
  - In nuclear matter string looses (ΣE_i) about k=1 GeV/fm ($\Delta E=k*T(b)/r(0)$)
    - This energy is converted to the Quasmon excitation
    - The rest (high rapidity part of the string) is hadronized outside of the nucleus
  - If at low energies the projectile energy is smaller than ΔE, string is skipped
- Special cases
  - At low energies the transition to 3-D CHIPS can be used as an emergency
  - Quasi-elastic on nucleons happens at all energies without the string excitation

String algorithm



New string fusion algorithm to avoid too low string mass



There are 6 strings (3 cut cylinders): 3 x q-dq , 3 x aq-q

String fusion examples

aq-q	aq-q	aq-q	q-dq	q-dq
aq-adq	aq-q	dq-adq	q-aq	adq-aq
adq-aq	adq-dq	q-aq	dq-q	aq-q

Emergency flavor reduction: (s – anti-s) → (u/d – anti-u/d) ($\eta \rightarrow \pi^0$)

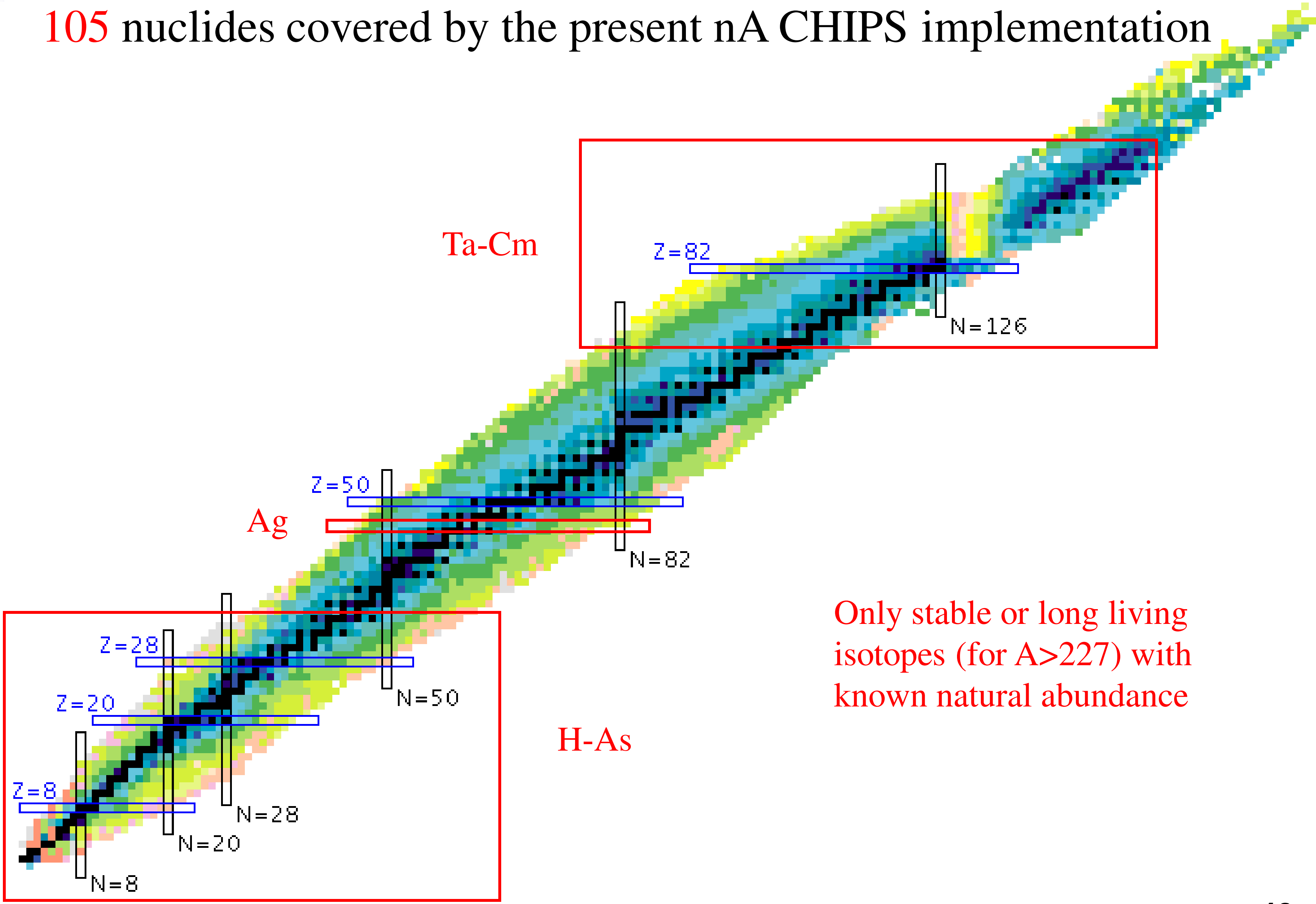
Emergency diquark reduction: (us – anti-d anti-s) → (u – anti-d)

Emergency jump to 3-D CHIPS: (u – anti-d) + N → Quasmon

New CHIPS interaction cross-sections

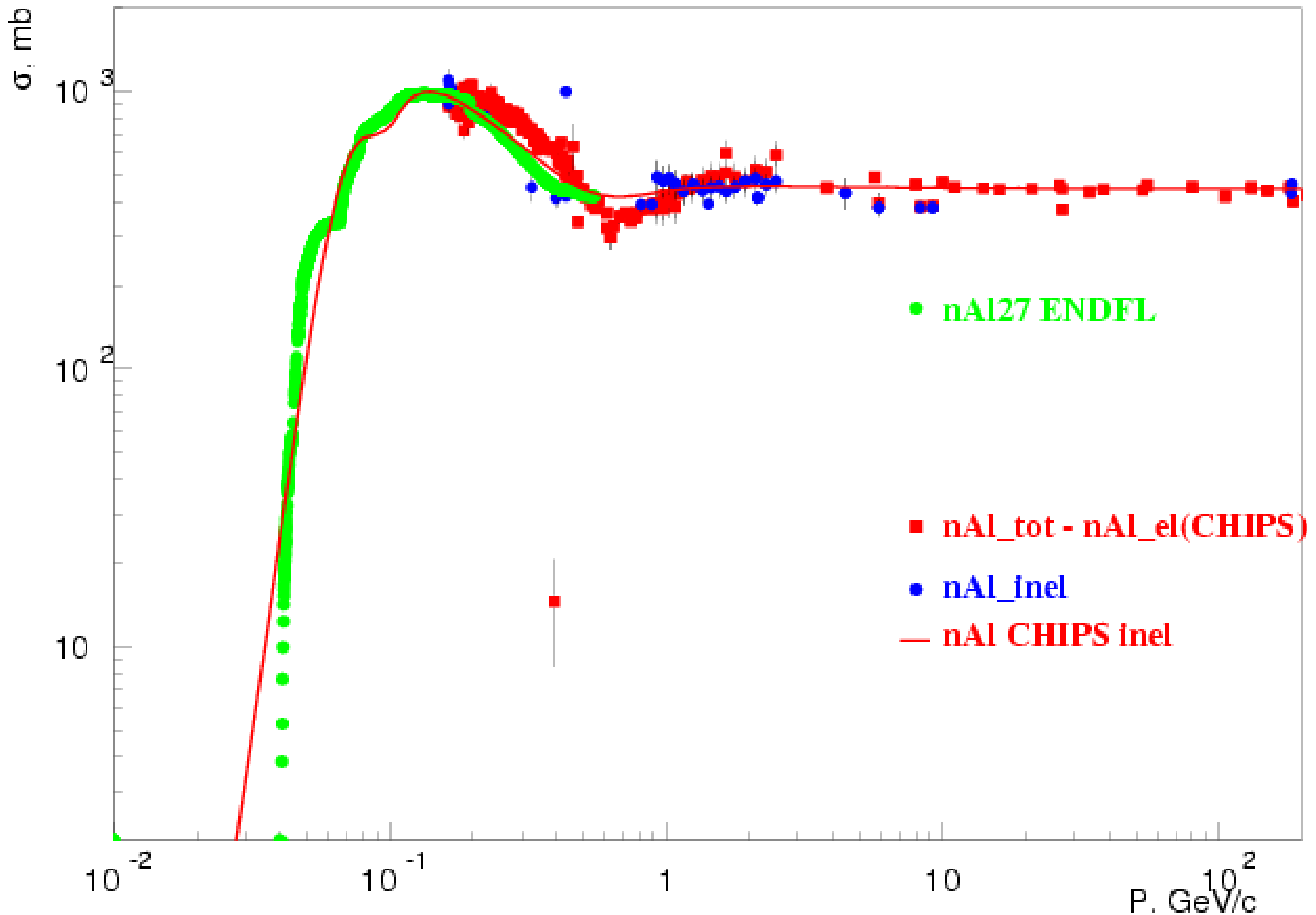
- To avoid usage of the heavy HP package the neutron-nuclear CHIPS cross-sections have been improved for low energies (including (n,γ) capture)
  - The ENDF/B-VII data base was used for the cross-sections
  - Inelastic (nonelastic) cross-section is defined as $\sigma_{in}=\sigma_{tot}-\sigma_{el}$
  - The low energy 1/v cross-section is not yet implemented
  - The (n,p), (n,d), (n,t), (n,He3), (n,α) are not yet implemented
  - The cross-sections are parameterized for more than 100 isotopes
- The CHIPS inelastic cross-sections for pion-nuclear, kaon-nuclear, hyperon-nuclear and antibaryon-nuclear interactions are calculated
  - Coulomb barrier for charged hadrons (e.g. K^+) is implemented

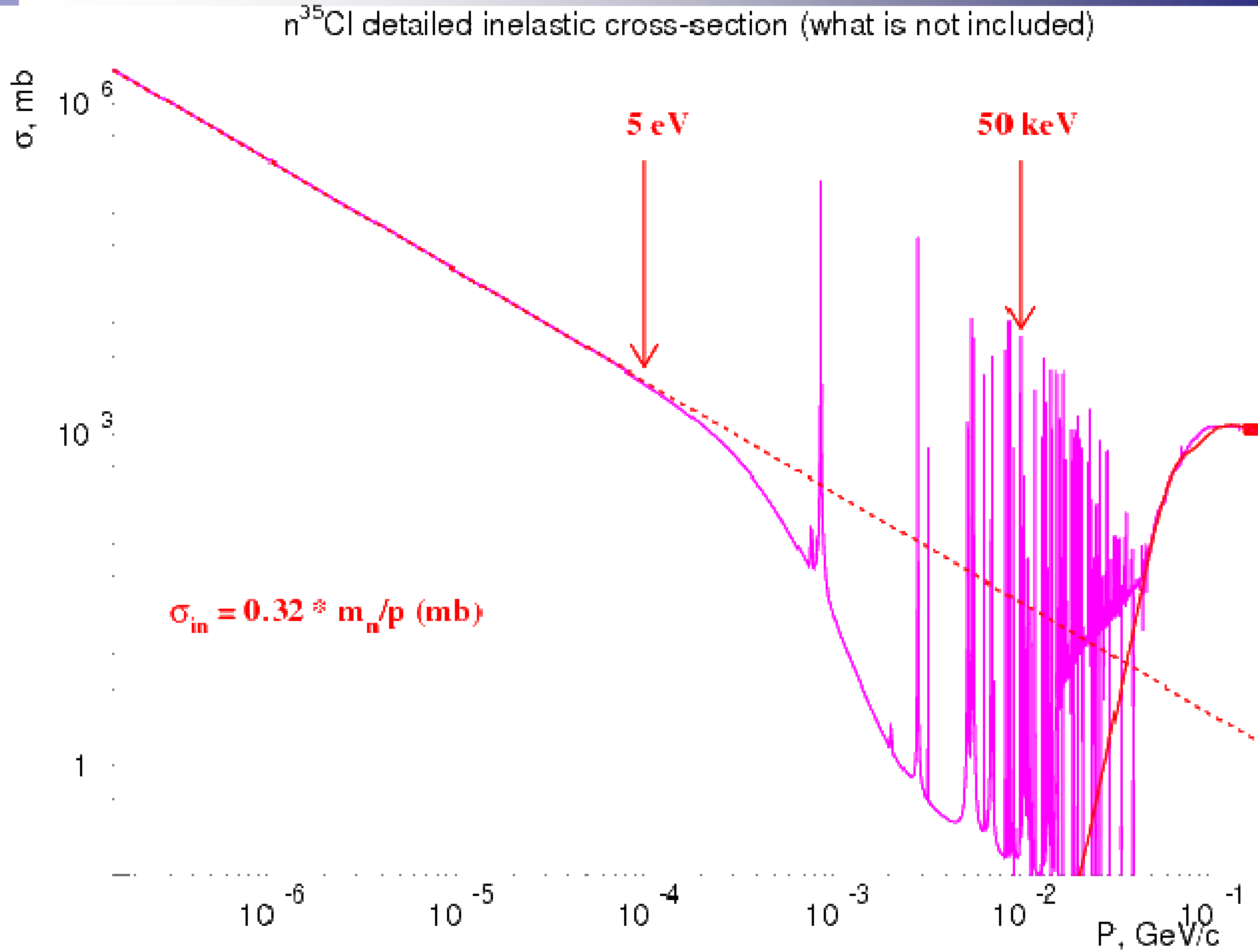
105 nuclides covered by the present nA CHIPS implementation



Only stable or long living isotopes (for A>227) with known natural abundance

CHIPS improvement of nAl inelastic cross-section

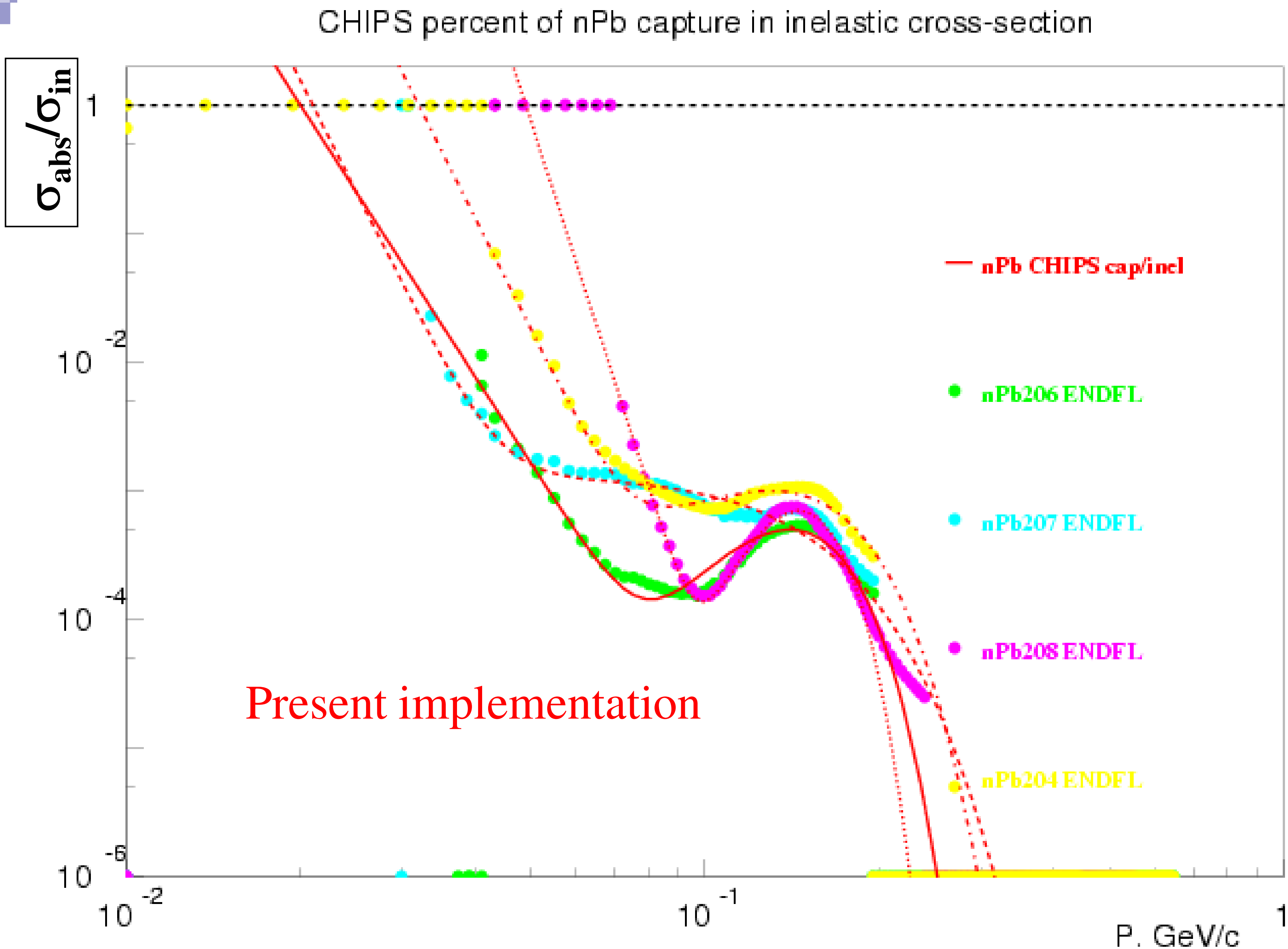


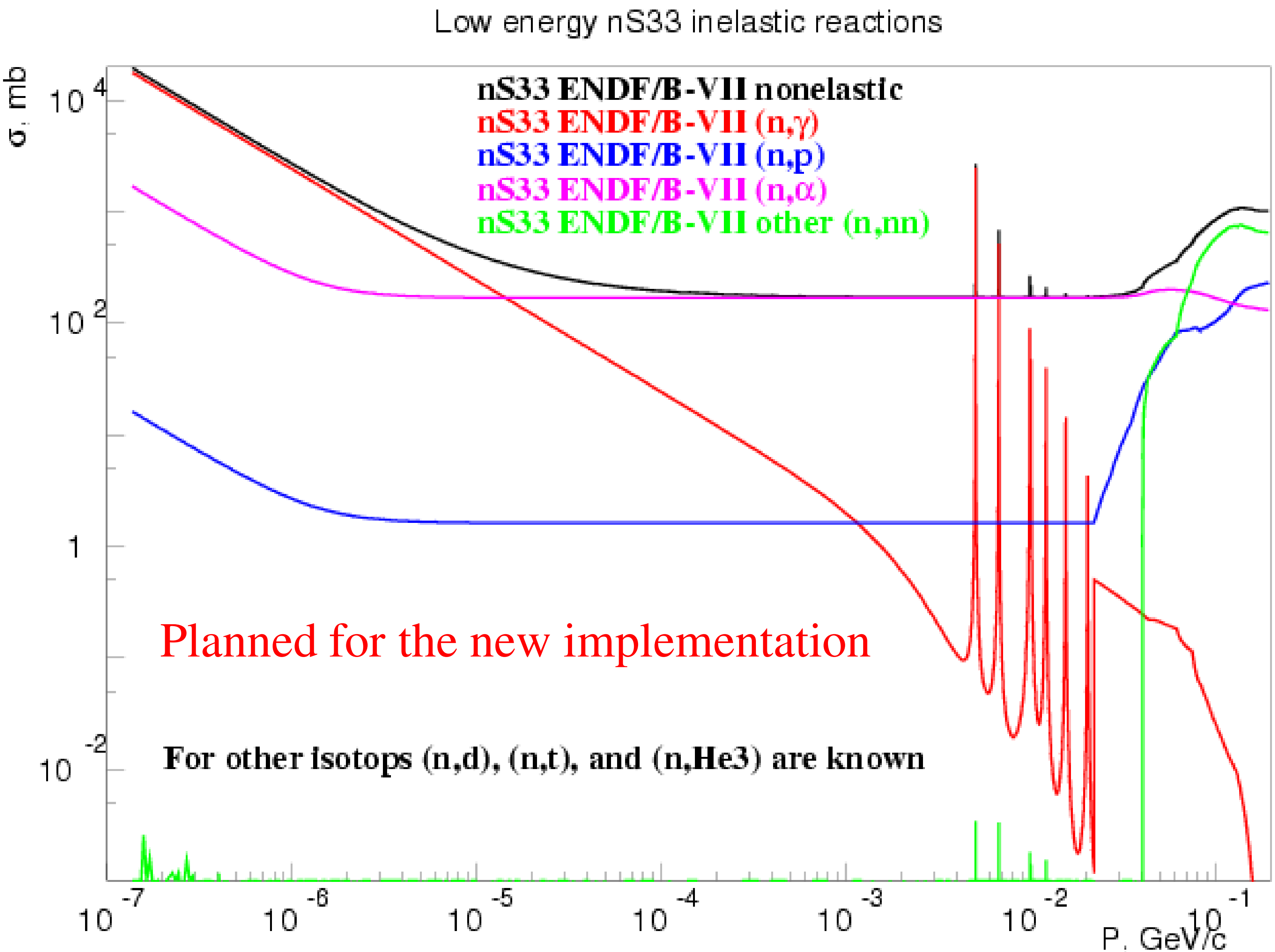


n^{35}Cl detailed inelastic cross-section (what is not included)
σ, mb
10^6
10^3
1
5 eV
50 keV
$\sigma_{in} = 0.32 * m_n/p$ (mb)
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
P, GeV/c

Fit for the absorption contribution σ_{abs}/σ_{in}

- Only ENDF/B VII evaluation data are used
  - $R(p)=\sigma_{abs}/(\sigma_{tot}-\sigma_{el})=\sigma_{abs}/\sigma_{in}$ (simple, planned to be improved)
  - Approximation: $R(p)=(p/B)^{-D}+EXP[C-(p-M)^2/W]$ (if R>1: R=1)
  - The parameter "B" is a threshold of the non-absorption reaction
- Simulation
  - The binary isotropic reaction, e.g. (n,γ), is simulated rather fast
  - Simulation of A(n,fission) reactions for A>225 is possible (?)
  - Non-binary inelastic reactions are simulated by CHIPS much slower; alternative: $(n,\gamma)+(n,p)+..+(n,\alpha)+(n,nn)$ for E<20 MeV
  - at low energies a big part of the CHIPS simulation is quasi-elastic scattering on quasi-free nucleons and nuclear clusters + "diffraction", so the low energy simulation is fast enough.

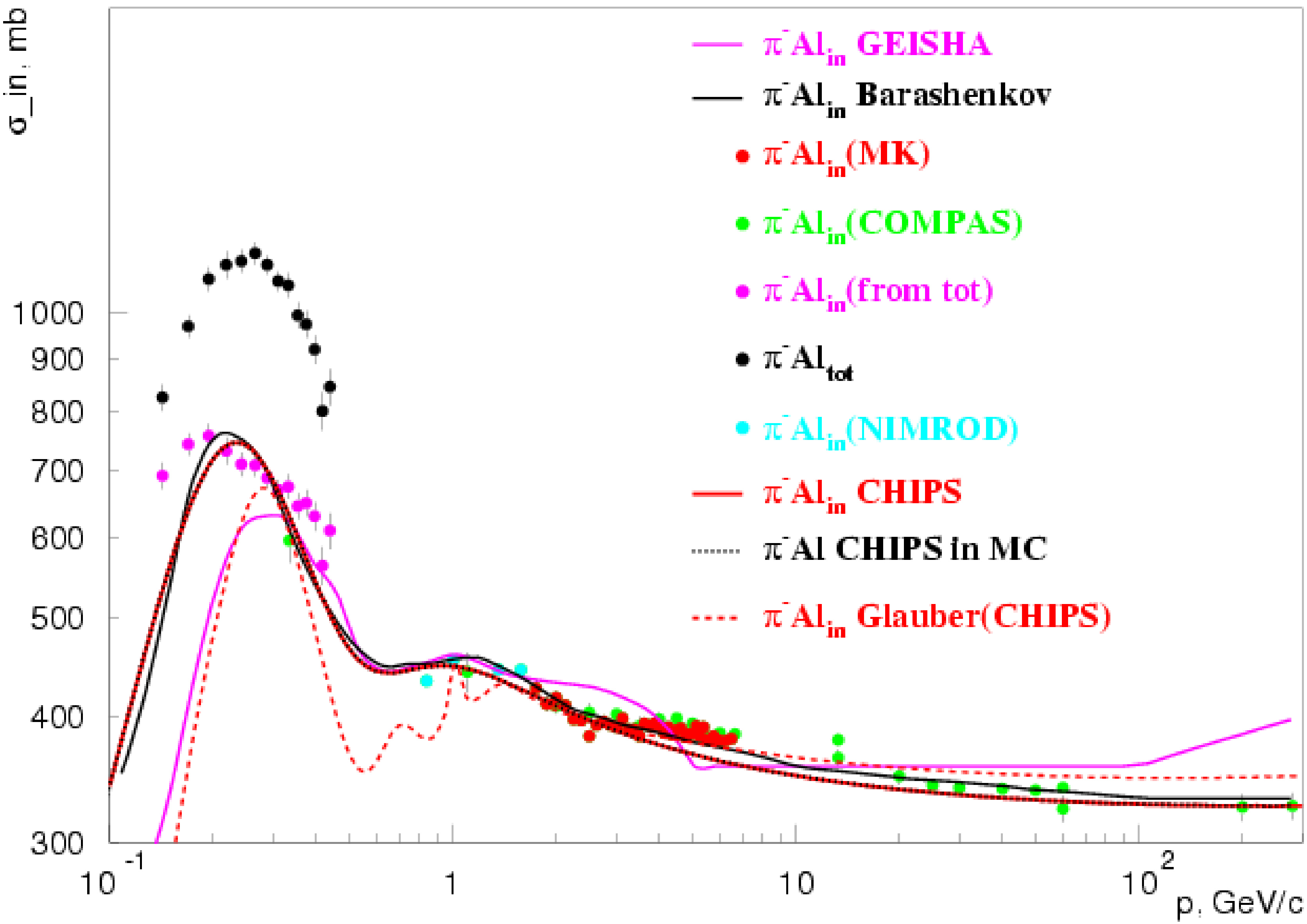

CHIPS percent of nPb capture in inelastic cross-section
σ_{abs}/σ_{in}
1
10^{-2}
10^{-4}
10^{-6}
10^{-2}
10^{-1}
1
P, GeV/c
nPb CHIPS cap/inel
nPb206 ENDFL
nPb207 ENDFL
nPb208 ENDFL
nPb204 ENDFL
Present implementation


Low energy nS33 inelastic reactions
nS33 ENDF/B-VII nonelastic
nS33 ENDF/B-VII (n,γ)
nS33 ENDF/B-VII (n,p)
nS33 ENDF/B-VII (n,α)
nS33 ENDF/B-VII other (n,nn)
Planned for the new implementation
For other isotops (n,d), (n,t), and (n,He3) are known
σ, mb
P, GeV/c

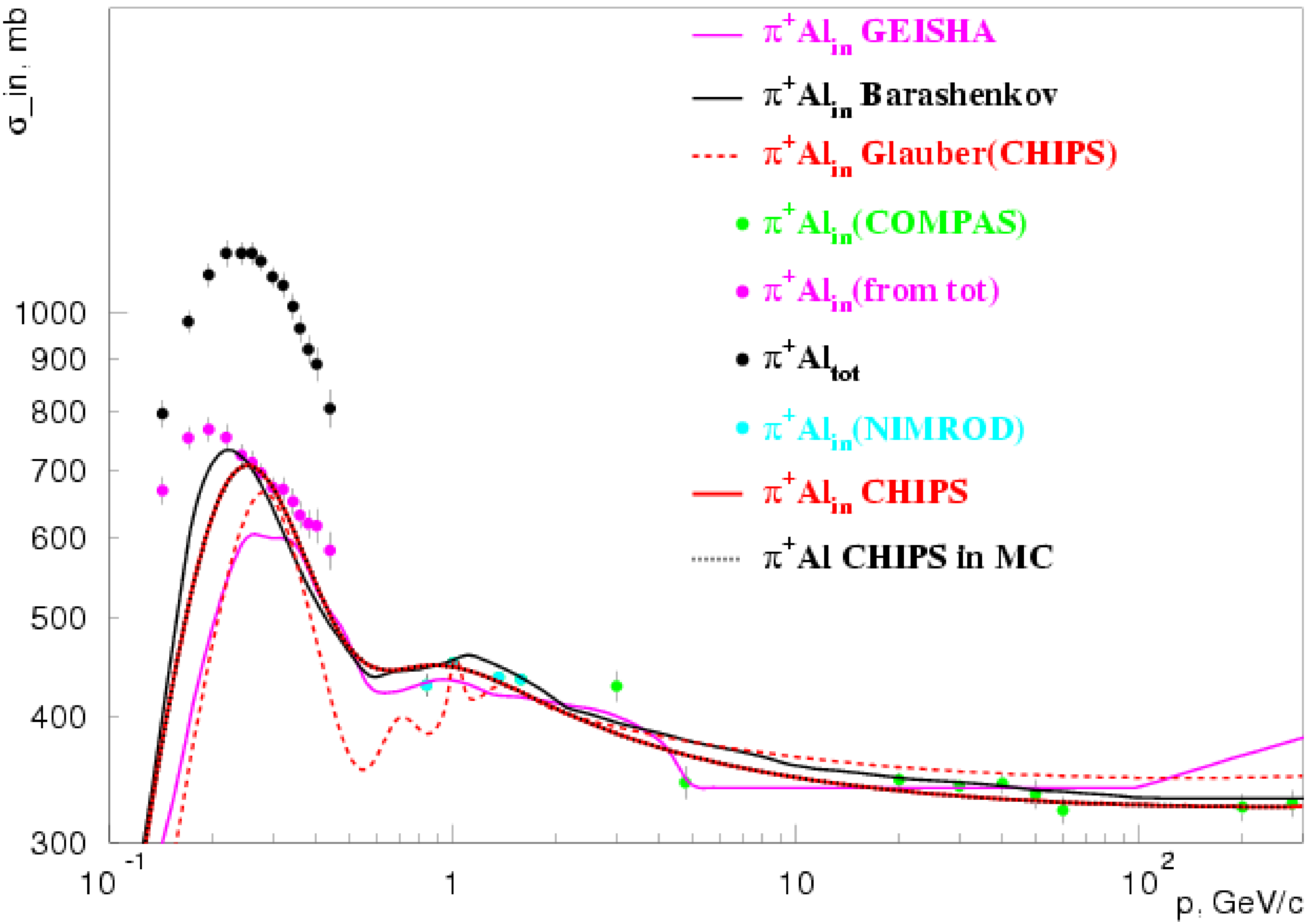
CHIPS improvement of hA inelastic XS

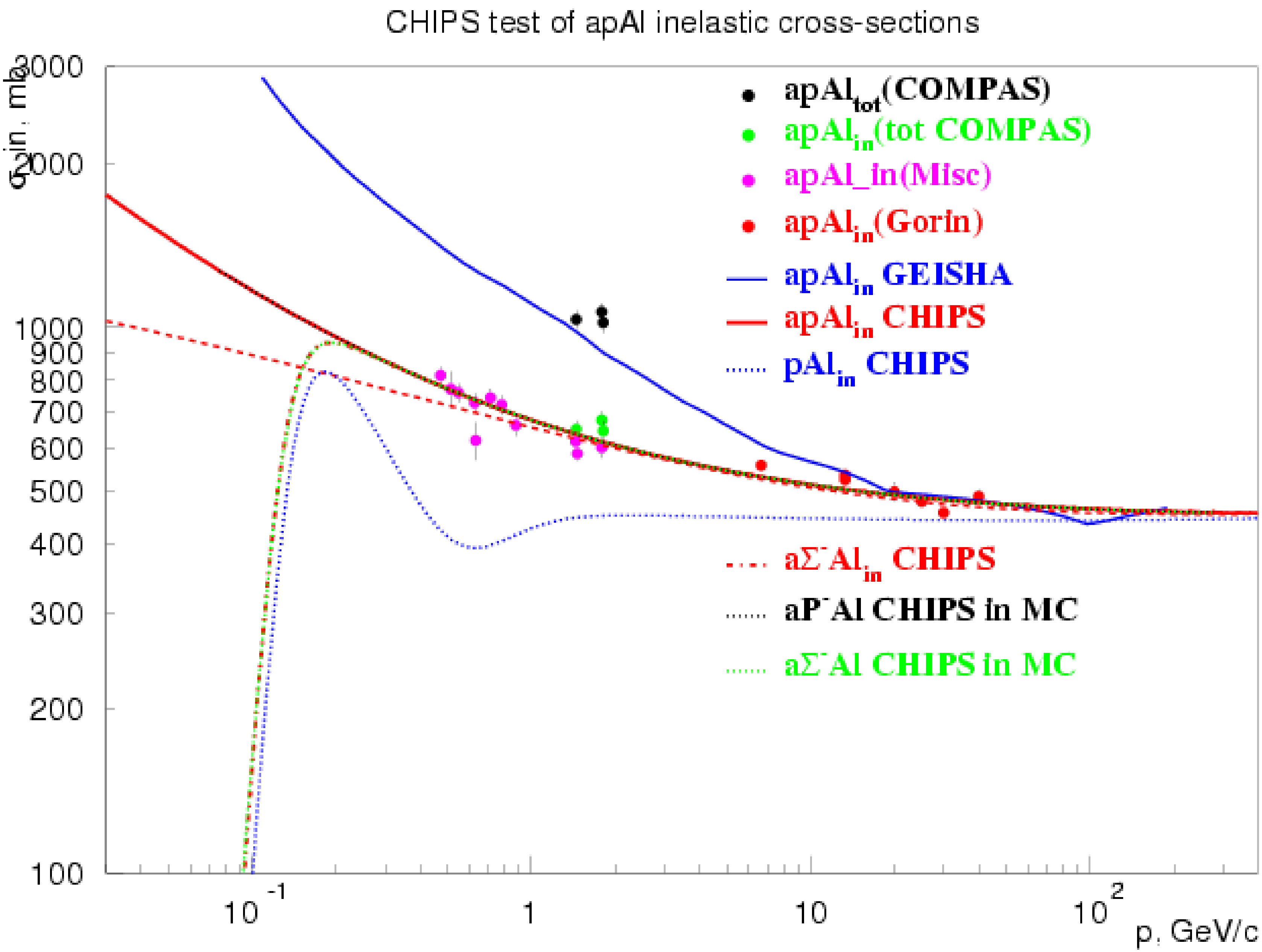
- The inelastic cross-sections are improved for the new one-model CHIPS physics list
  - The pA and nA cross-sections are already improved 2 years ago
  - CHIPS πA cross-sections are competitive with Barashenkov XS
  - Existing GEISHA K^+A cross-sections are dangerous for CHIPS
  - CHIPS cross-sections are smooth 2D σ_{in}(A,p) analytic functions
- The main points of the improvement
  - Coulomb barrier for positive hadrons (p, π^+, K^+)
  - Melting of resonances at intermediate energies
  - Evolution of the cross-section minimum because of PPP vertex
  - Glauber calculation using CHIPS hA cross-sections (dashed)
  - Total to Inelastic Glauber reduction (σ_{in}/σ_{tot} coefficient)

CHIPS test of π⁻Al inelastic cross-sections

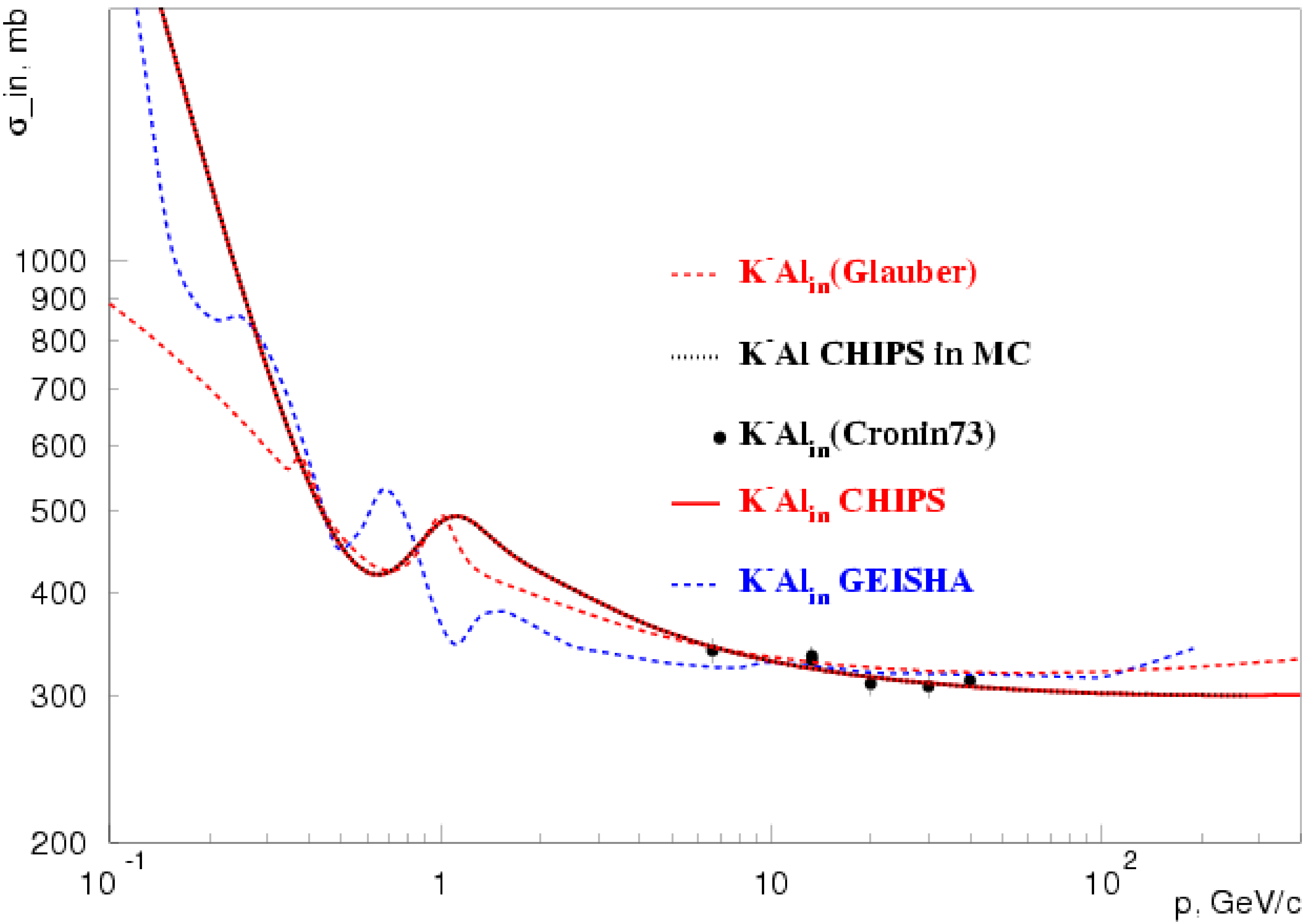


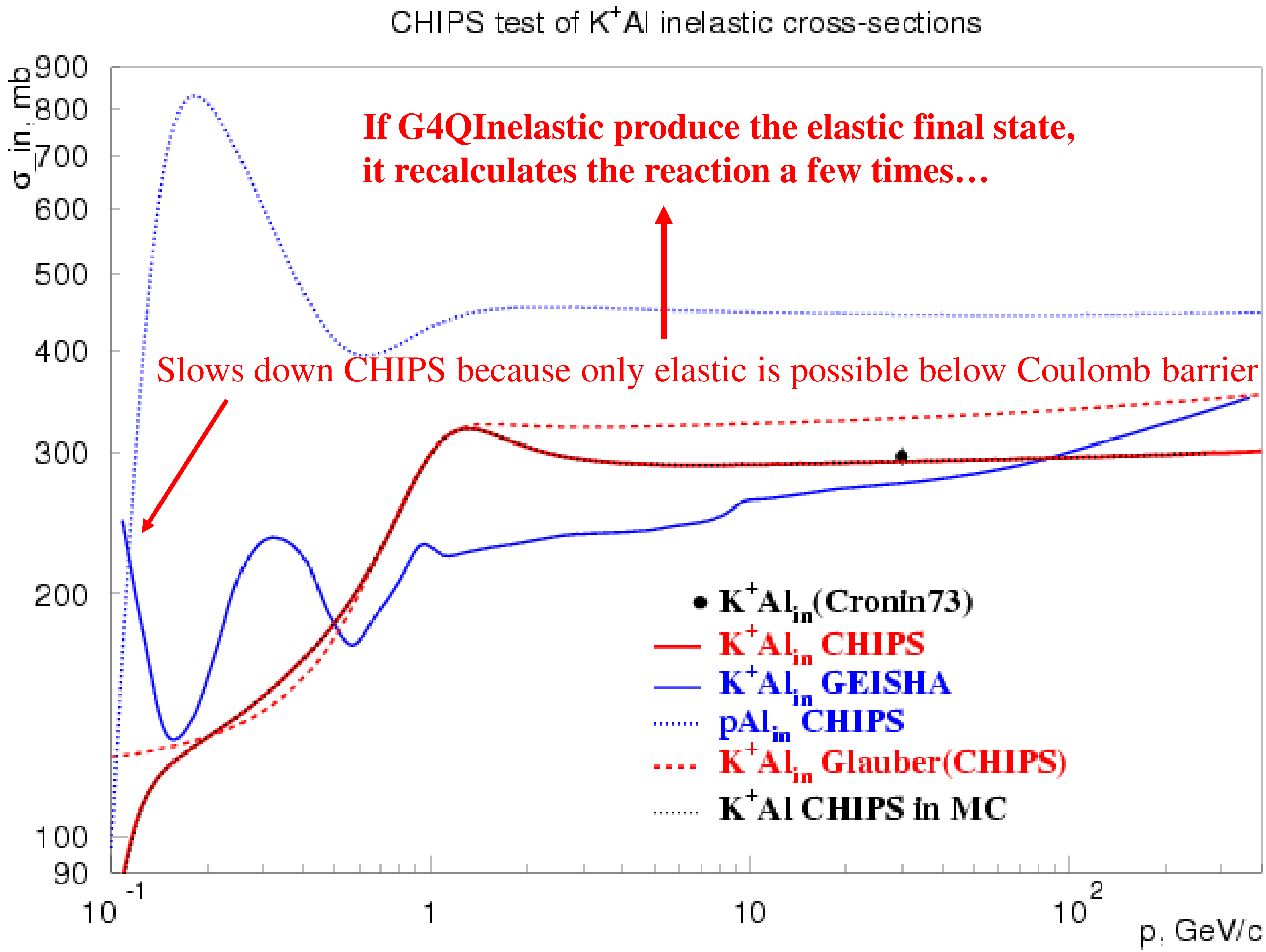
CHIPS test of π+Al inelastic cross-sections



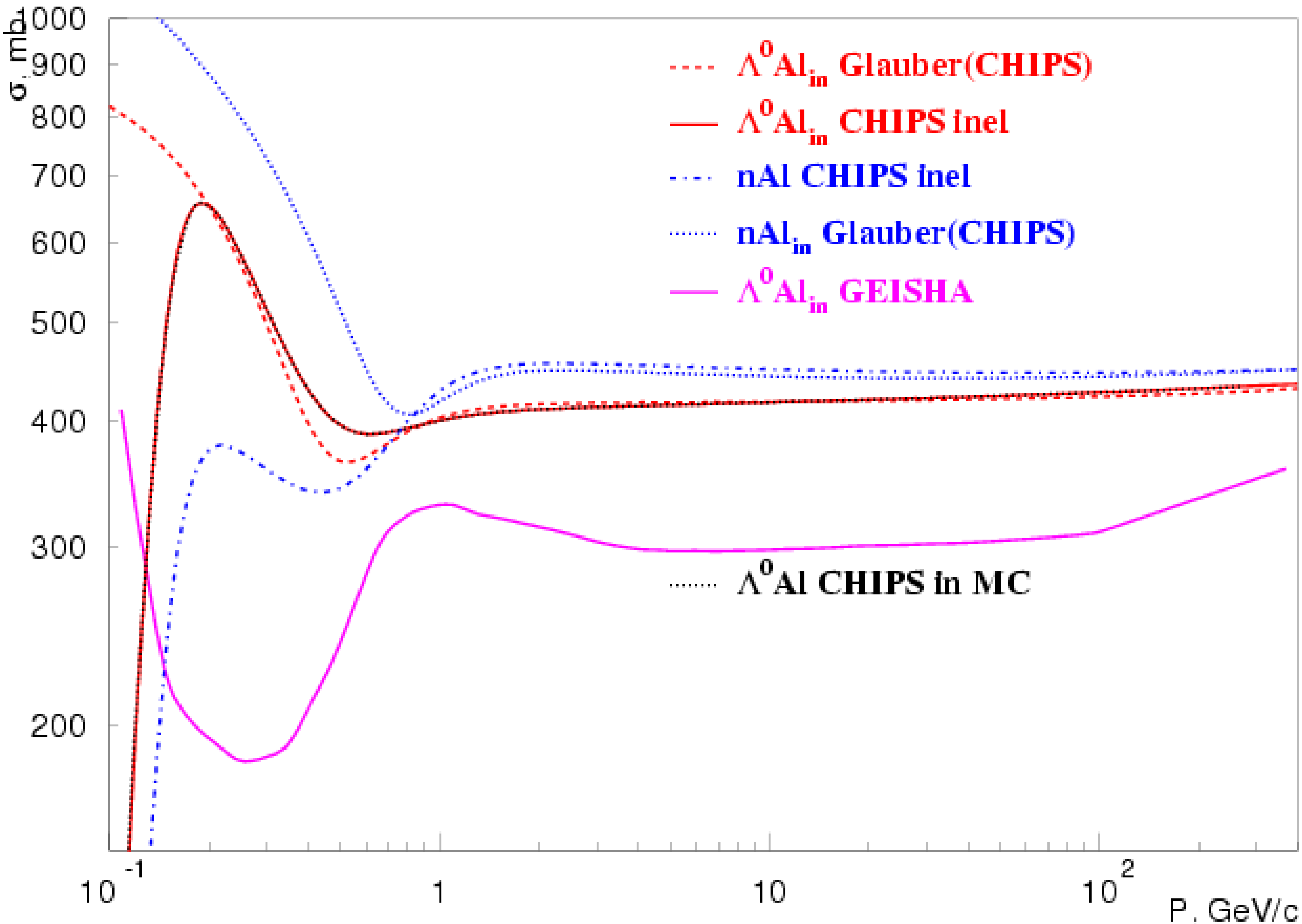

CHIPS test of apAl inelastic cross-sections
σin, mb
3000
2000
1000
900
800
700
600
500
400
300
200
100
10 -1
1
10
10 2
p, GeV/c
apAltot(COMPAS)
apAlin(tot COMPAS)
apAl_in(Misc)
apAlin(Gorin)
apAlin GEISHA
apAlin CHIPS
pAlin CHIPS
aΣ-Alin CHIPS
aP-Al CHIPS in MC
aΣ-Al CHIPS in MC

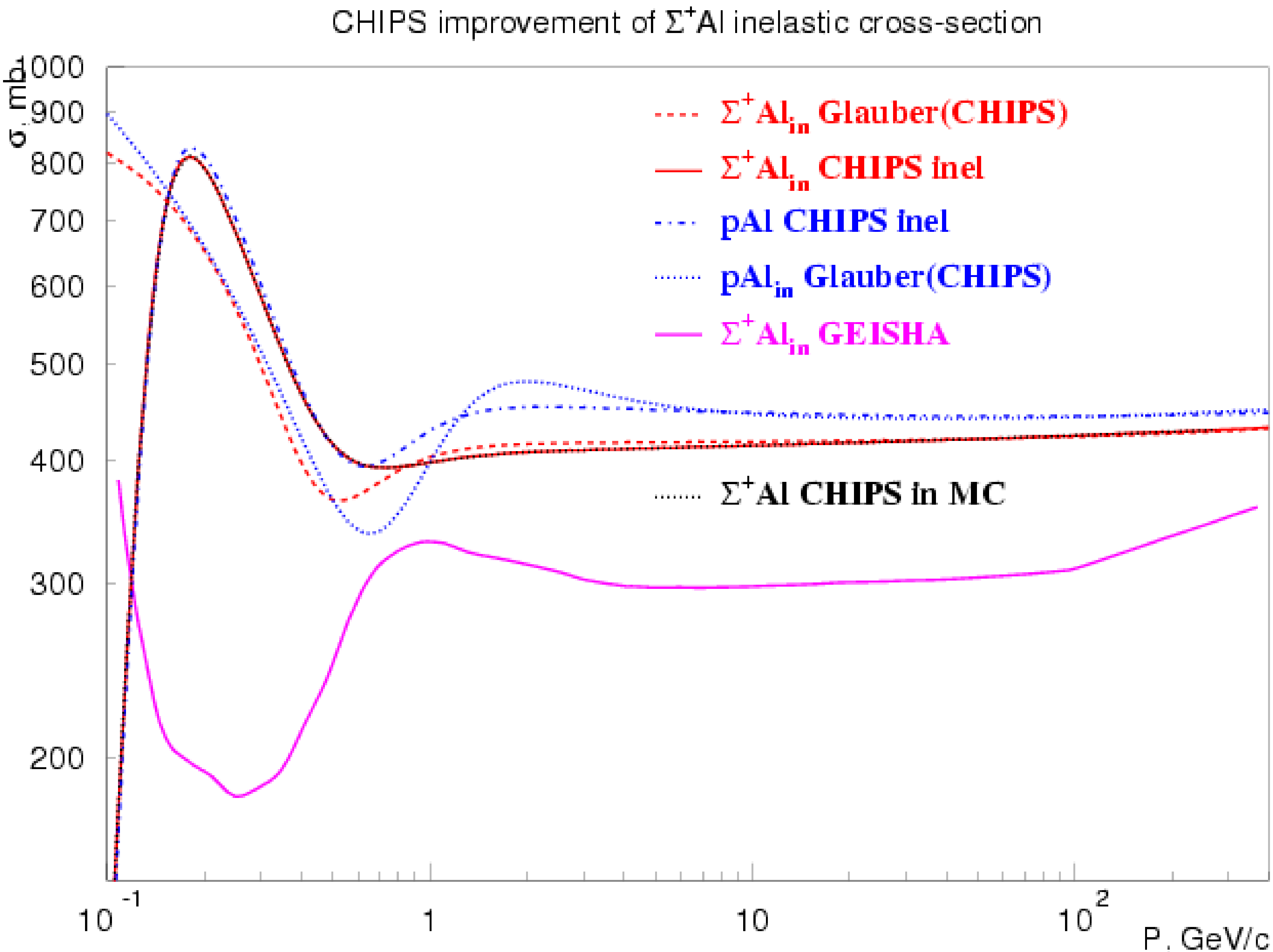
CHIPS test of K⁻Al inelastic cross-sections




CHIPS test of K+Al inelastic cross-sections
σ_in, mb
900
800
700
600
500
400
300
200
100
90
10^-1
1
10
10^2
p, GeV/c
If G4QInelastic produce the elastic final state,
it recalculates the reaction a few times…
Slows down CHIPS because only elastic is possible below Coulomb barrier
K+Al_in(Cronin73)
K+Al_in CHIPS
K+Al_in GEISHA
pAl_in CHIPS
K+Al_in Glauber(CHIPS)
K+Al CHIPS in MC

CHIPS improvement of Λ^0Al inelastic cross-section

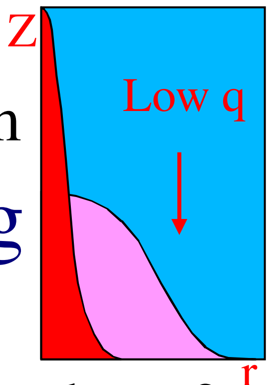




CHIPS improvement of Σ^+Al inelastic cross-section
σ, mb
1000
900
800
700
600
500
400
300
200
Σ^+Al_{in} Glauber(CHIPS)
Σ^+Al_{in} CHIPS inel
pAl CHIPS inel
pAl_{in} Glauber(CHIPS)
Σ^+Al_{in} GEISHA
Σ^+Al CHIPS in MC
10^{-1}
1
10
10^2
P, GeV/c

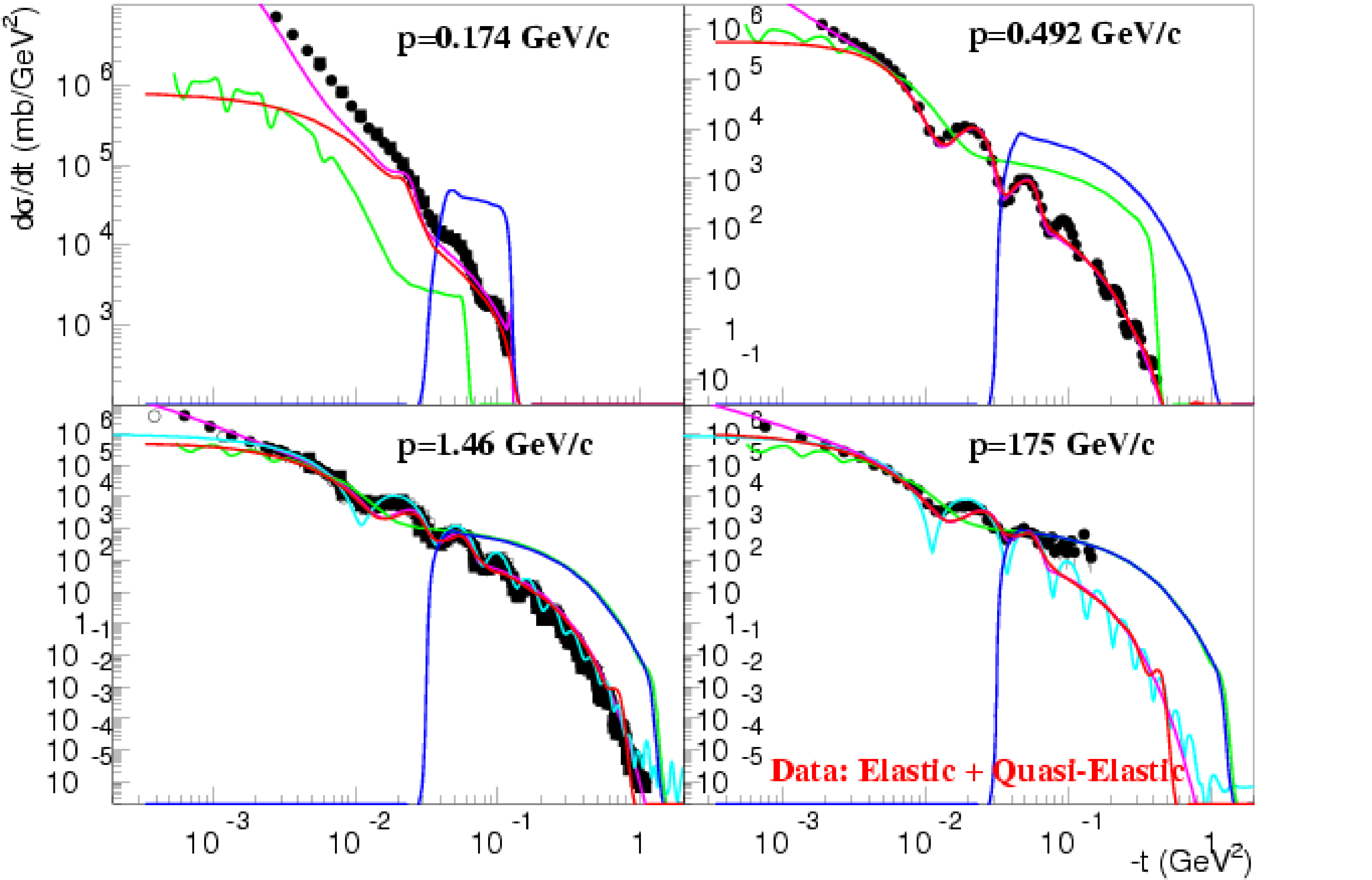
"Multiple" and elastic (coherent) scattering

- In CHIPS physics package the processes are not subdivided in "electromagnetic" and "hadronic", because this is impossible
  - Photo-, lepto-nuclear reactions: (l,l/N) quasi-elastic (e.g. (e,e/p))
  - Pair (e^+e^-) production on electrons and on the nucleus
  - Multiple scattering is an example of the similar problem

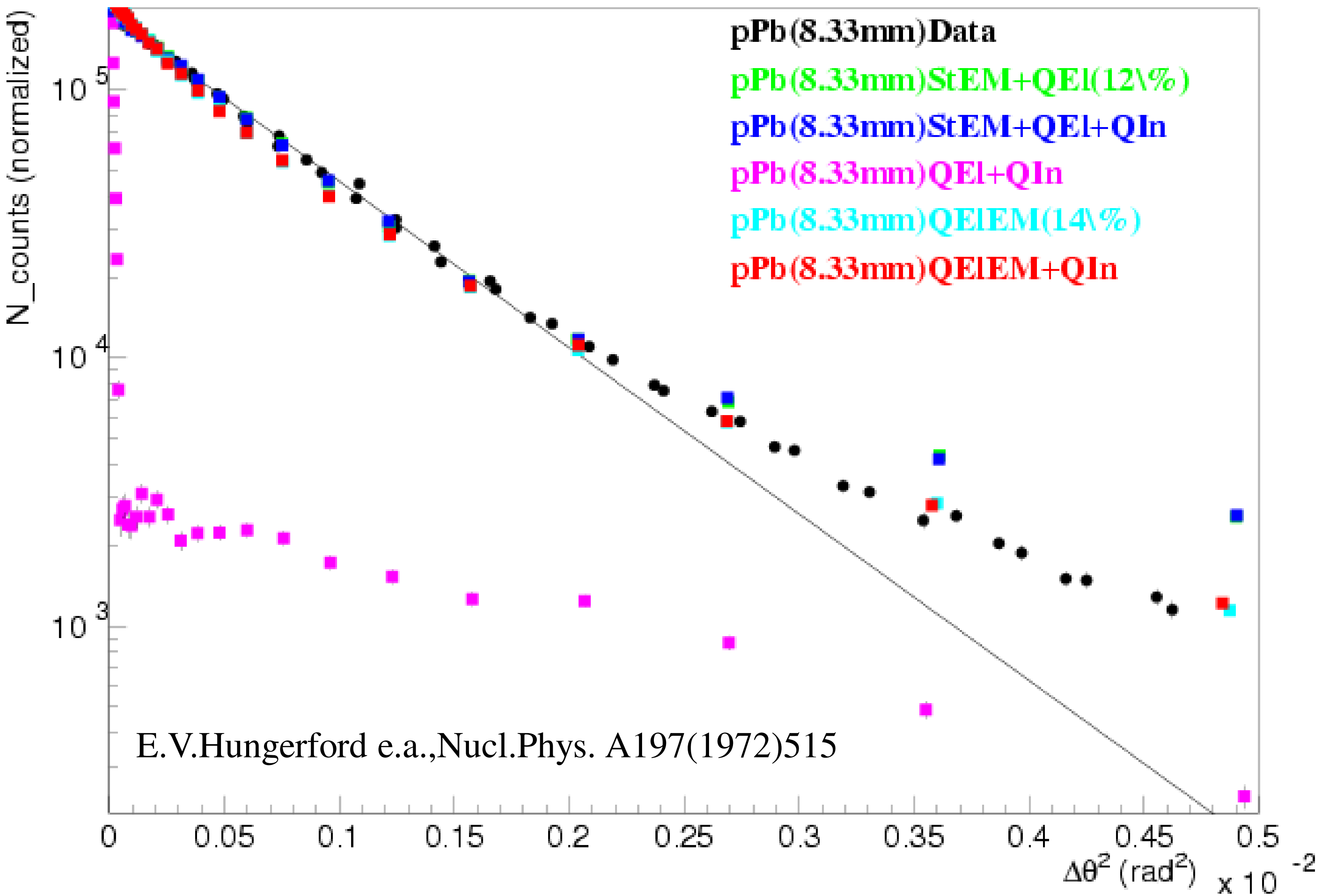


- Mythology and reality of Multiple scattering
  - Coulomb scattering cross-section is infinite?
  - One can simulate multiple for small angles and single for large?
  - $df(q)/dx= \int f(q-y)g(y)dy=f\times g \rightarrow dF(r)/dx=F(r)G(r)$, Fourier image
  - Is the old assumption of the constant term (ds/dt~1/(t+A)) right?
  - Fortunately now we have measurements and can fit them

CHIPS improvement of pPb elastic scattering

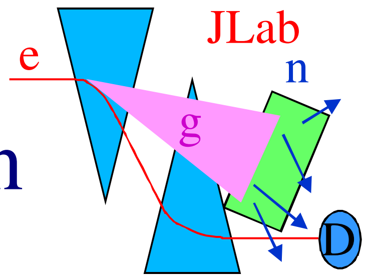


Scattering of 600 MeV protons on 8.33 mm Lead

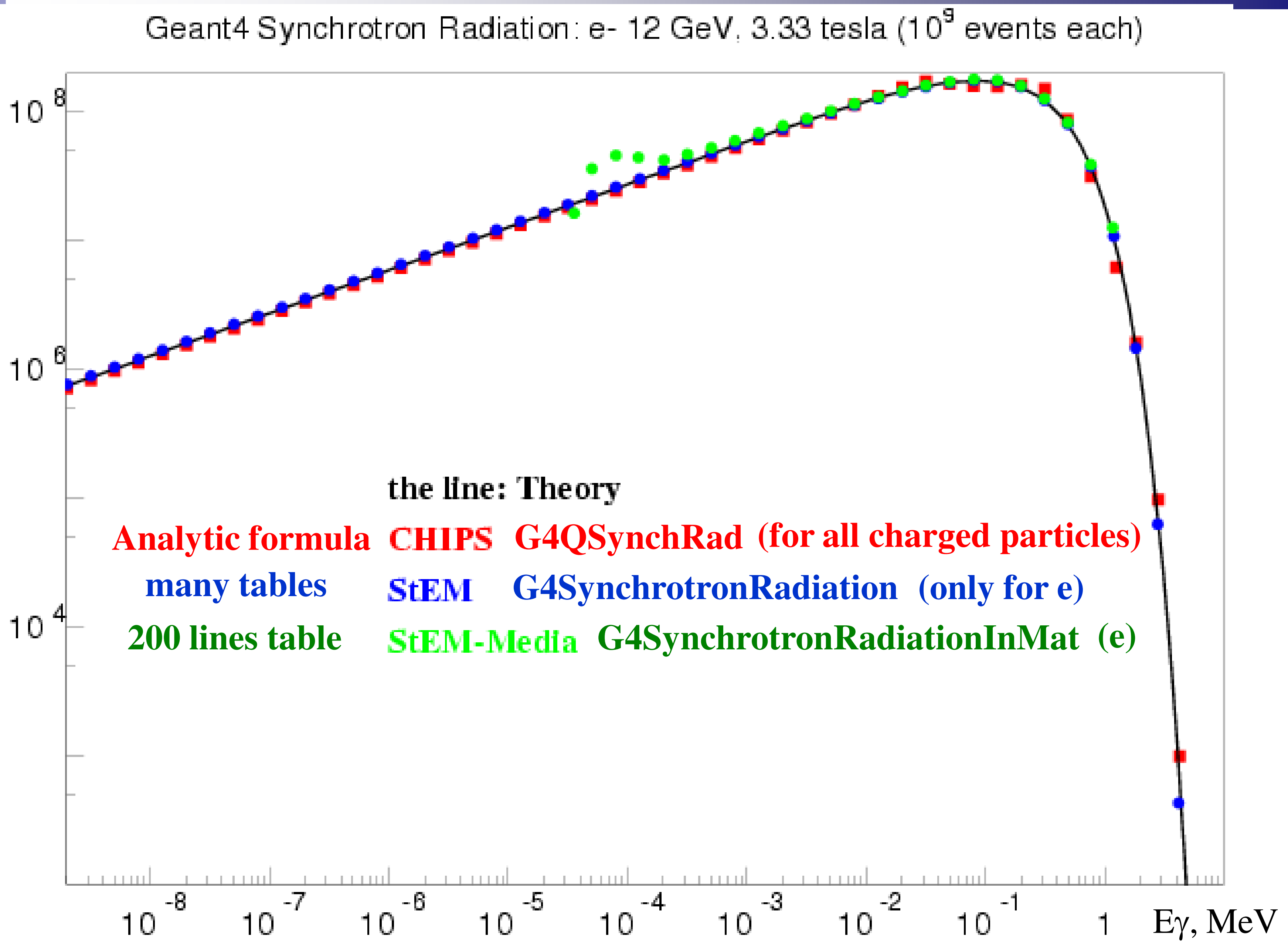


CHIPS Synchrotron Radiation

- Historically the Synchrotron Radiation process is included in the photo-nuclear physics builder
  - In the builder the original CHIPS γ- and e-A processes are used
  - In addition the original CHIPS μ- and τ-A processes are used
  - G4QSynchRad is very important for γ-A reactions



- Simple formulas of Synchrotron Radiation
  - Mean free path = $0.4 \cdot \sqrt{3} \cdot R/(\alpha\gamma) \approx$ (for e) 16 cm/tesla
  - Critical photon energy: $E_c = 1.5\gamma^3(hc)/R$, $y = E/E_c$ $(E = E_\gamma)$
  - $E \cdot dN/dE = dI/dE = (8\pi/9)\alpha\gamma F(y)$, $dN_\gamma/dx = 2.5\alpha\gamma/(\sqrt{3} \cdot R)$
  - $F(y) = (9/8\pi) \cdot \sqrt{3} \cdot y \cdot \int_y^\infty K_{5/3}(x)\, dx$
  - Mean Energy $\langle E_\gamma \rangle = 0.8\gamma^3(hc)/(\sqrt{3} \cdot R)$
  - All calculations are in the limit $\gamma \gg 1$.



Geant4 Synchrotron Radiation: e- 12 GeV, 3.33 tesla (10^9 events each)
10^8
10^6
10^4
the line: Theory
Analytic formula CHIPS G4QSynchRad (for all charged particles)
many tables StEM G4SynchrotronRadiation (only for e)
200 lines table StEM-Media G4SynchrotronRadiationInMat (e)
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
1
Eγ, MeV

Conclusion

- The basic one-model CHIPS physics list is made
  - Economic and simple: the same G4QInelastic, G4QElastic, G4qCaptureAtRest for all particles
  - Flexible: easier to fit the beam-test/calibration data as the only one model ought to be improved/tuned
- Work to be done
  - Improvement of low energy nA reactions (lateral width, $\Delta E/E$)
  - Tune CHIPS diffraction (HELIOS data, longitudinal shape)
  - Improvement of Q4QElastic (lateral width, multiple scattering)
    - Add low t ("electro⊗magnetic") part
    - Make it for particles other than already done p and n
  - Finish implementation of G4QIonIonCollision (space MC)
  - Implement Isotope decay CHIPS DB (activation)

Thank you