One-model CHIPS Physics List

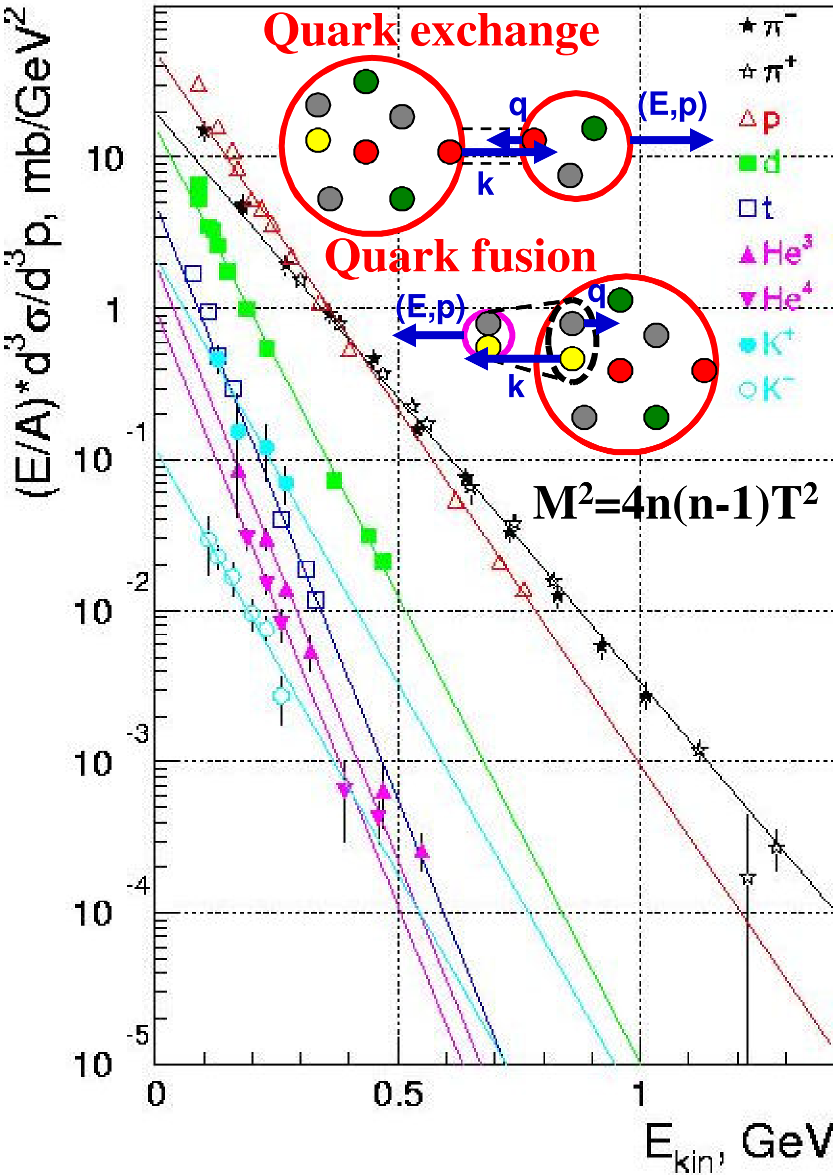
Mikhail Kosov, Geant4 tutorial 2010

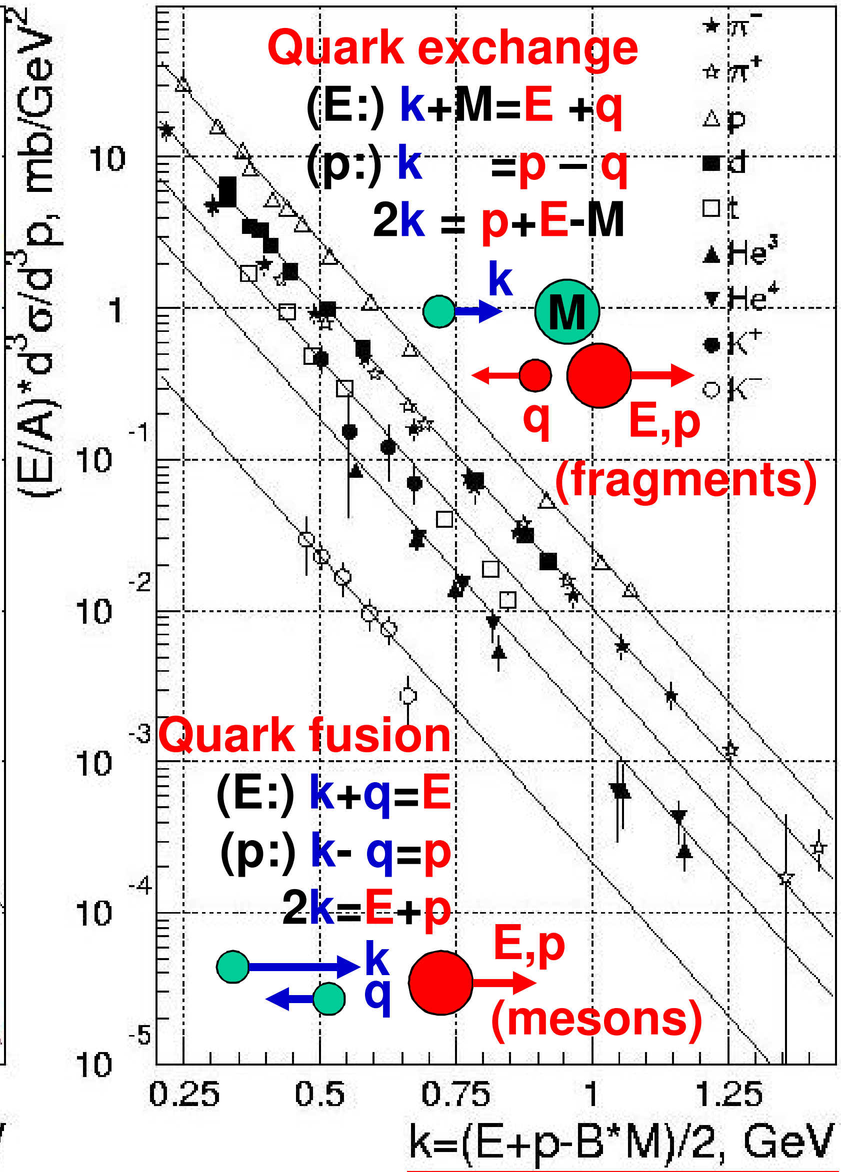
ITEP

Introduction to CHIPS physics in G4

- A goal of implementation of CHIPS to G4 is to create a physics list, which do not use any other hadronic models than CHIPS.
  - The CHIPS physics package is already unique or the best in Geant4 for:
    - All at rest nuclear capture processes for negative (and neutral) hadrons
    - Neutrino-nuclear, electron-, muon-, tau-nuclear and photo-nuclear reactions
    - Elastic scattering of hardrons (NEW! G4QElastic: now for all hadrons)
    - Quasi-elastic scattering for the Geant4 QGS model (G4QuasiFreeRatio)
- Recent 2009 developments:
  - On flight hadron-nuclear interactions
    - Low energy 3-D hadronic CHIPS model (excitation and decay of Quasmons)
    - High energy CHIPS-string interaction interface extended to low energies
  - Nuclear-nuclear interactions
    - Fast (G4QLowEnergy) simulation is reasonable only for low energies
    - All-energies CHIPS ion-ion process (G4QIonIonCollision, under development)
  - CHIPS interaction cross-sections for hadron-nuclear and ion-ion interactions
    - New hadron-nuclear σ_{el} and σ_{in} for al categories of projectile hadrons

(Termolization) p+Ta=h+X, 400 GeV, 90^o (CHIPS)





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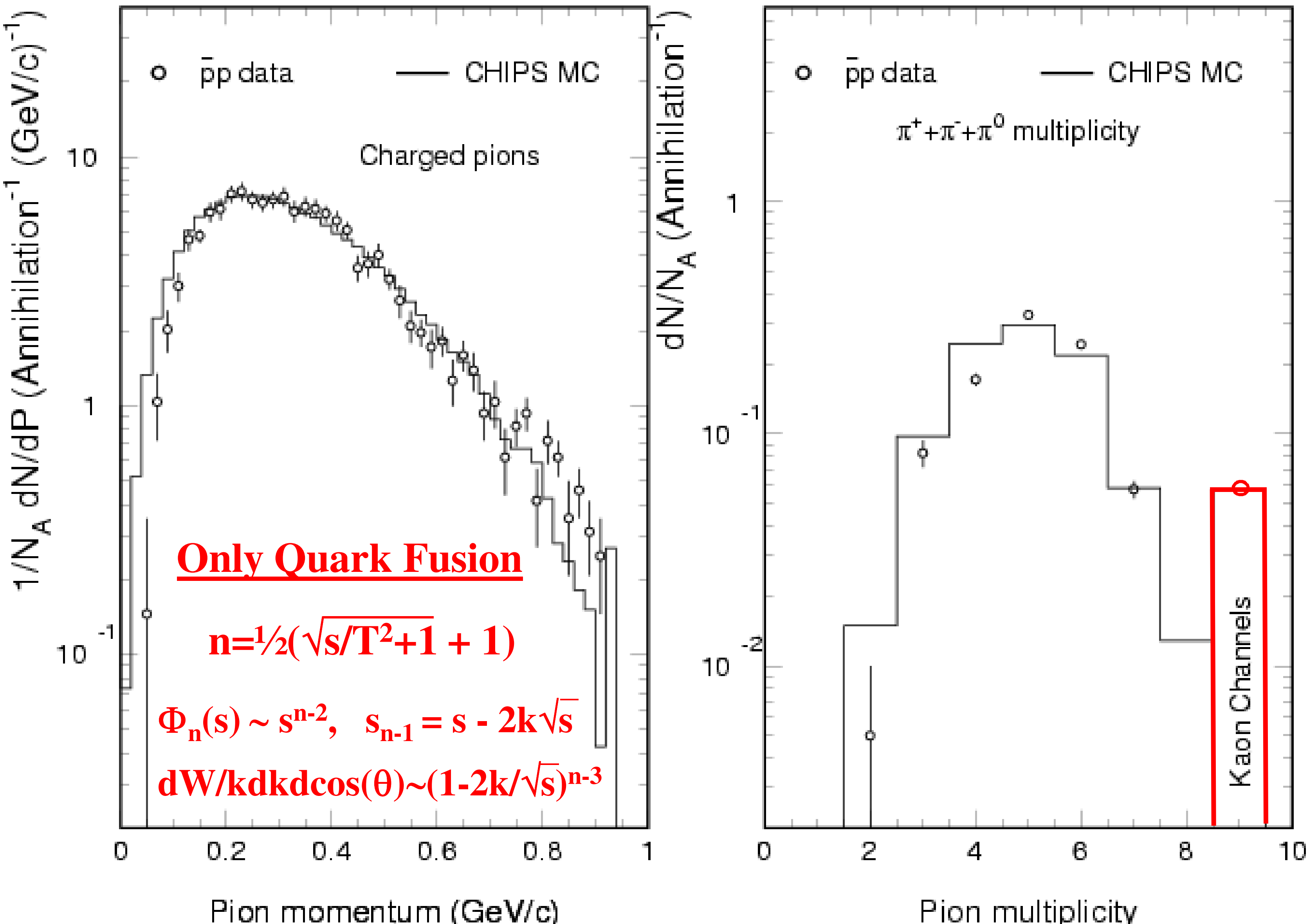
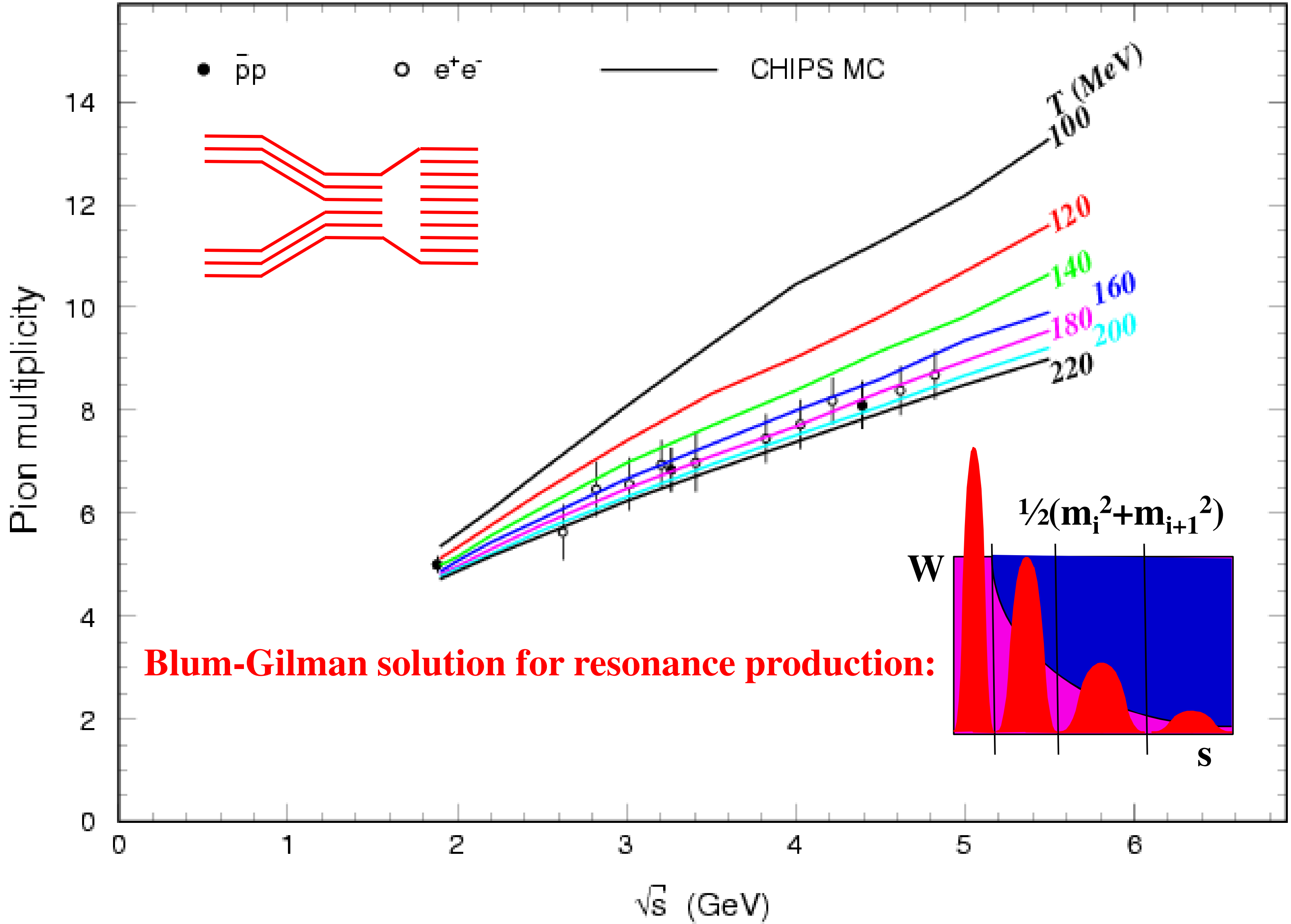
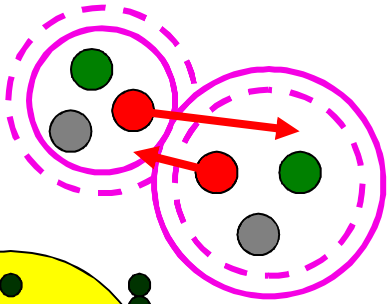
Pon spectra and multiplicity distribution for $p\bar{p}$ at rest



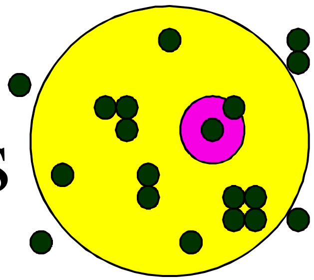
E-dependence of pion multiplicity: "thermometer" ($p\bar{p}/e^+e^-$)



Nuclear clusterization

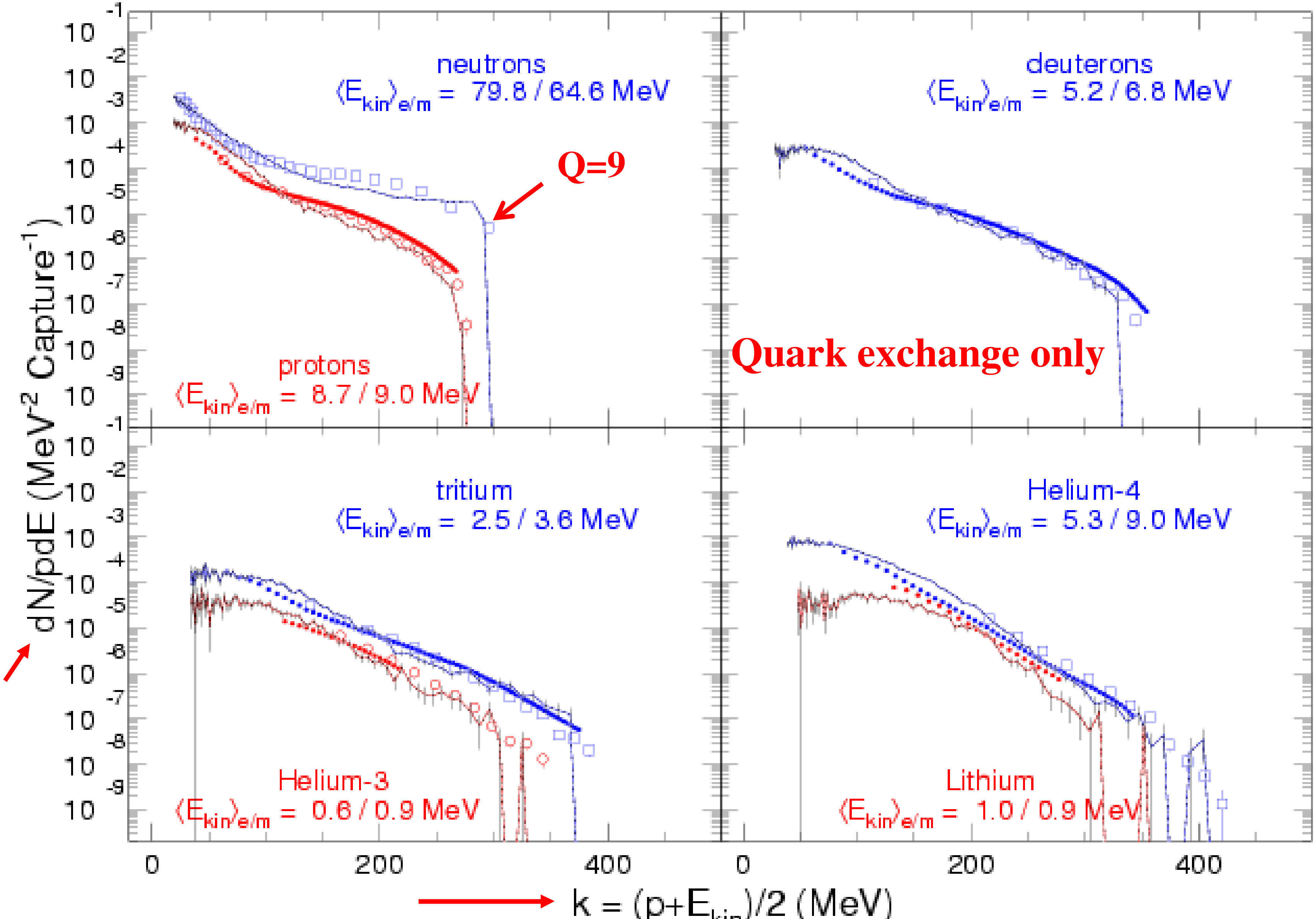


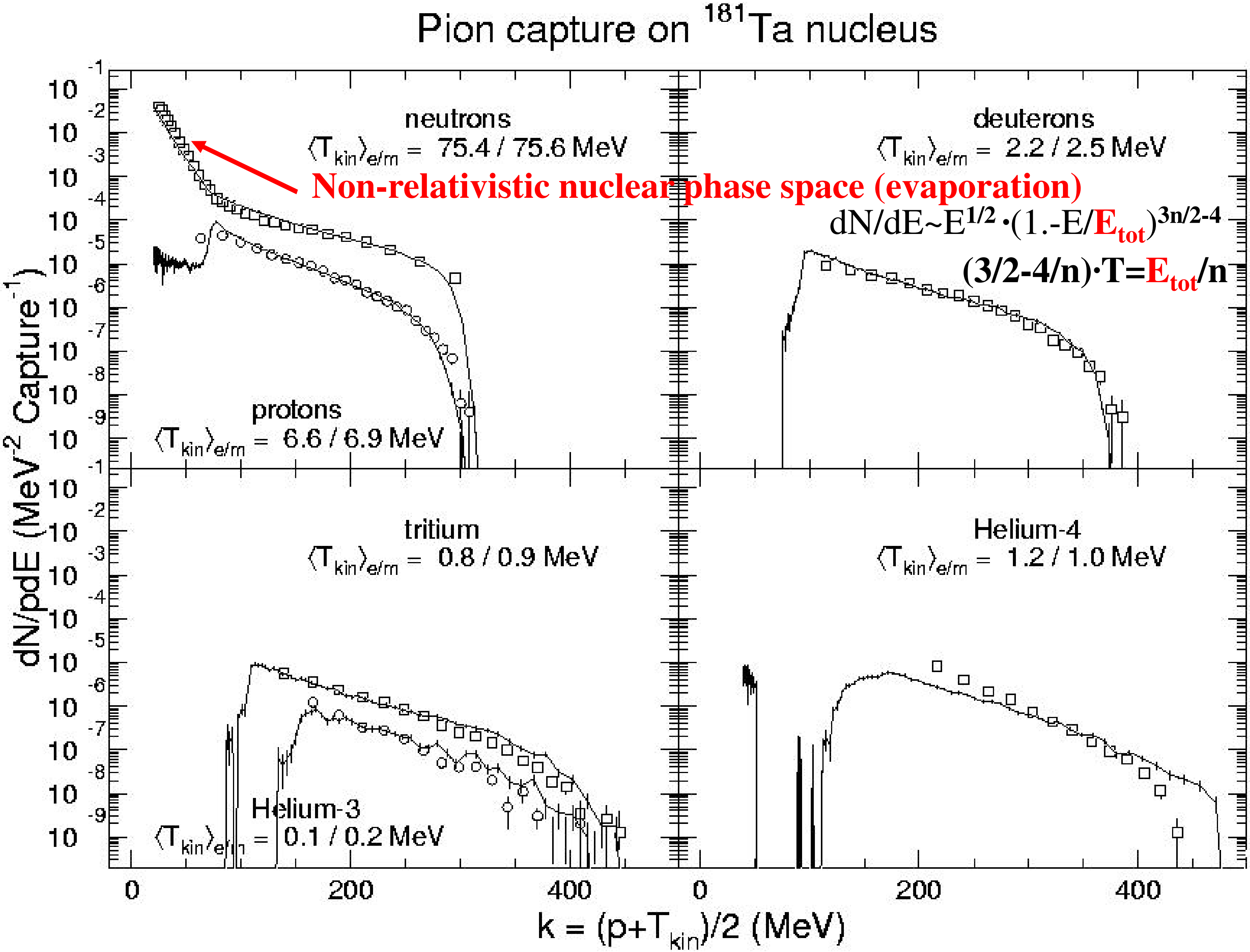
- Quark exchange between nuclear nucleons shifts them from the mass shell and prevents separation
- Clusterization probability is defined by the exchange radius (the clusterization volume).



- On nuclear surface only additional quasi-free baryons and quasi-free di-baryons can exist
- Quasi-free additional part is A-dependent
- For heavy nuclei the intermediate di-baryon phase disappears & gas-liquid is separated

Pion capture on ^{12}C nucleus (points are data)

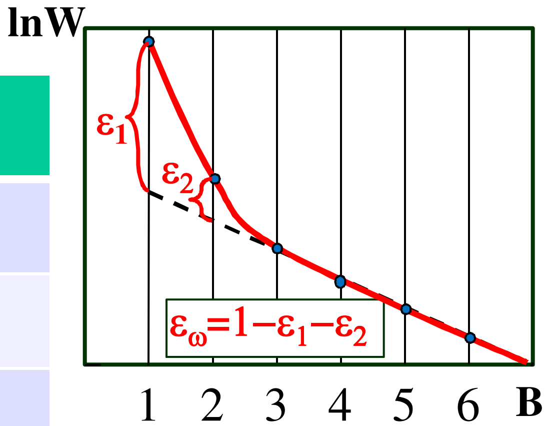




Pion capture on 181Ta nucleus
neutrons
⟨Tkin⟩e/m = 75.4 / 75.6 MeV
protons
⟨Tkin⟩e/m = 6.6 / 6.9 MeV
deuterons
⟨Tkin⟩e/m = 2.2 / 2.5 MeV
Non-relativistic nuclear phase space (evaporation)
dN/dE~E1/2 ·(1.-E/Etot)3n/2-4
(3/2-4/n)·T=Etot/n
tritium
⟨Tkin⟩e/m = 0.8 / 0.9 MeV
Helium-3
⟨Tkin⟩e/m = 0.1 / 0.2 MeV
Helium-4
⟨Tkin⟩e/m = 1.2 / 1.0 MeV
dN/pdE (MeV-2 Capture-1)
k = (p+Tkin)/2 (MeV)

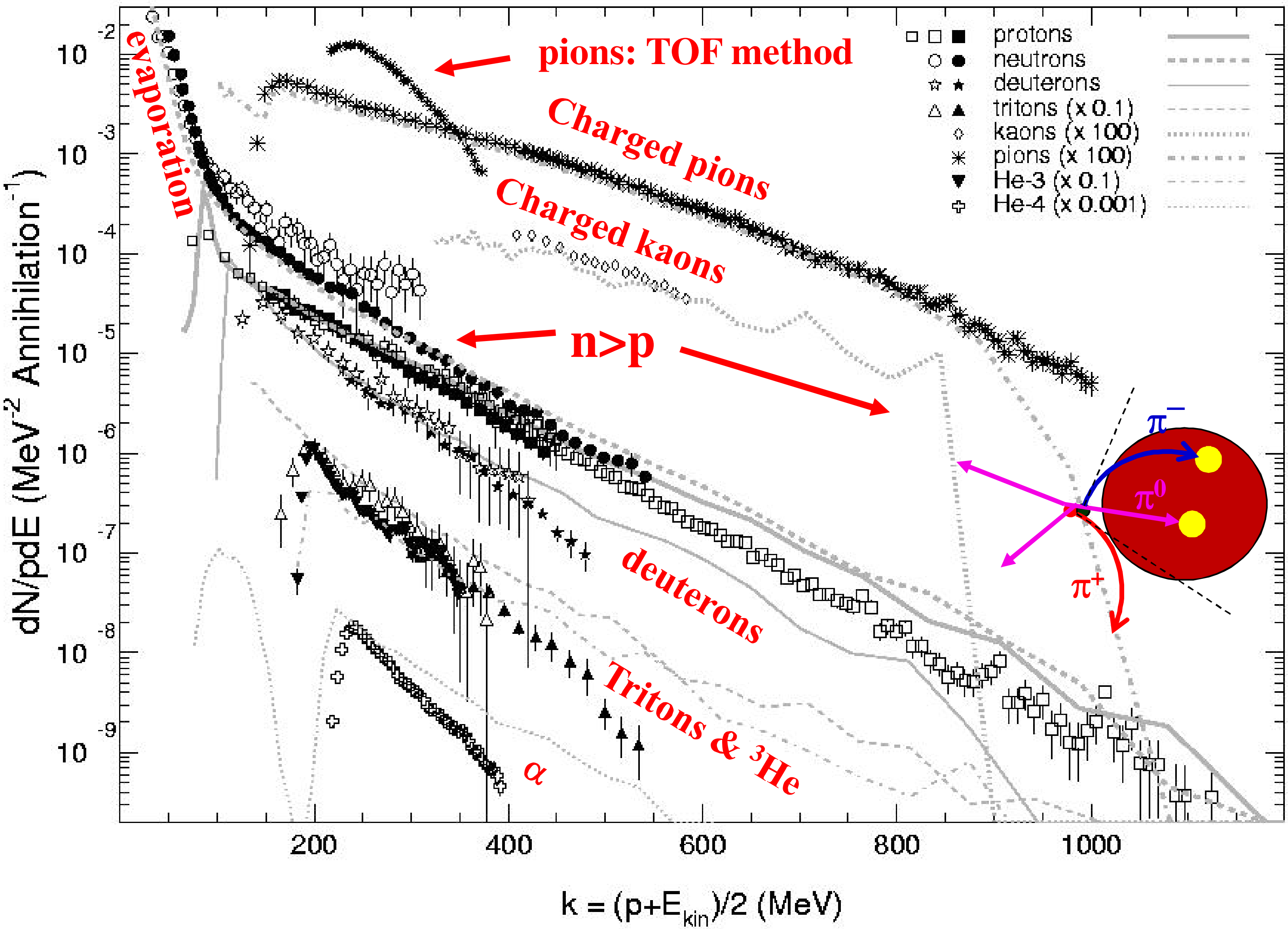
Nuclear clusterization parameters

	^{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



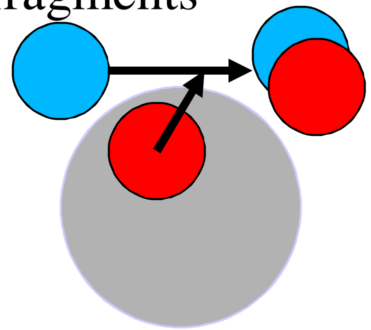
1. **Peripheral gas phase (ε_1) drops with A increasing**
2. **Intermediate dibaryon phase (ε_2) disappears for big A**
3. **Nuclear clusterization ω inside nuclei is A-independent**
4. **Clusterization helps to produce high energy nuclear fragments (quasmon-cluster quark exchange)**

Annihilation at rest of anti-protons on Uranium nuclei

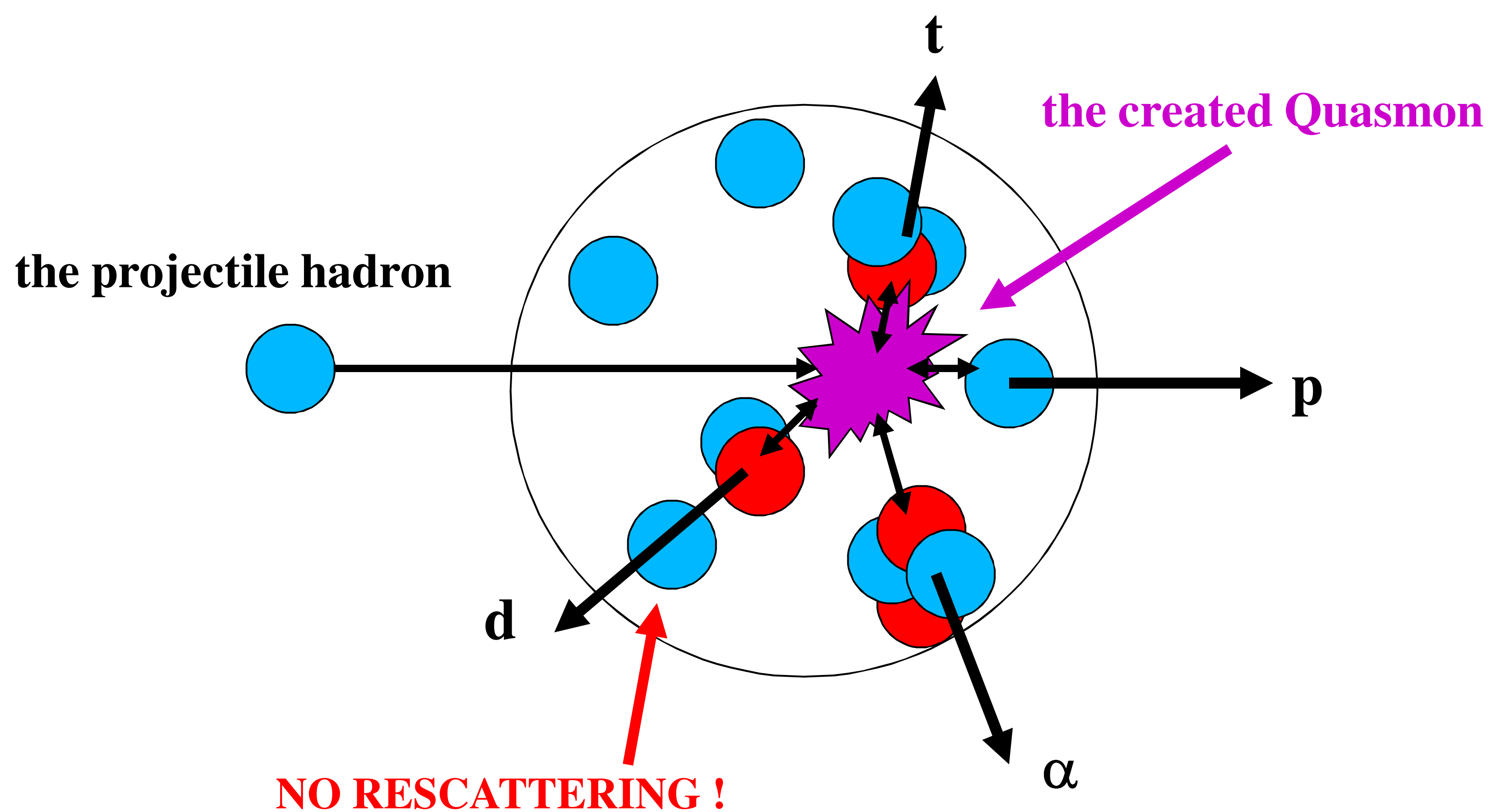


Algorithm of the low energy CHIPS

- Low energy inelastic is identical to the stopping algorithm
  - Nuclei are clusterized (Pion capture: Eur. Phys. J. A8 (2000) 217)
  - 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 algorithm is exhausted, nuclear evaporation is started
- A few decoupled processes are added !
  - Quasi-elastic scattering of the projectile on nucleons and nuclear clusters
    - G4QElastic class is used for this scattering on nucleons or on clusters
    - G4QuasiElasticRatios includes the best energy dependent fit of $\sigma_{el}(hN)$, $\sigma_{tot}(hN)$
  - Pick up process, which provides high energy forward nuclear fragments
- Final State Interaction of produced secondaries
  - A kind of nuclear fusion FSI of produced hadrons
  - Energy and momentum correction in case of problems !



CHIPS algorithm of the deep inelastic hadron-nuclear interaction

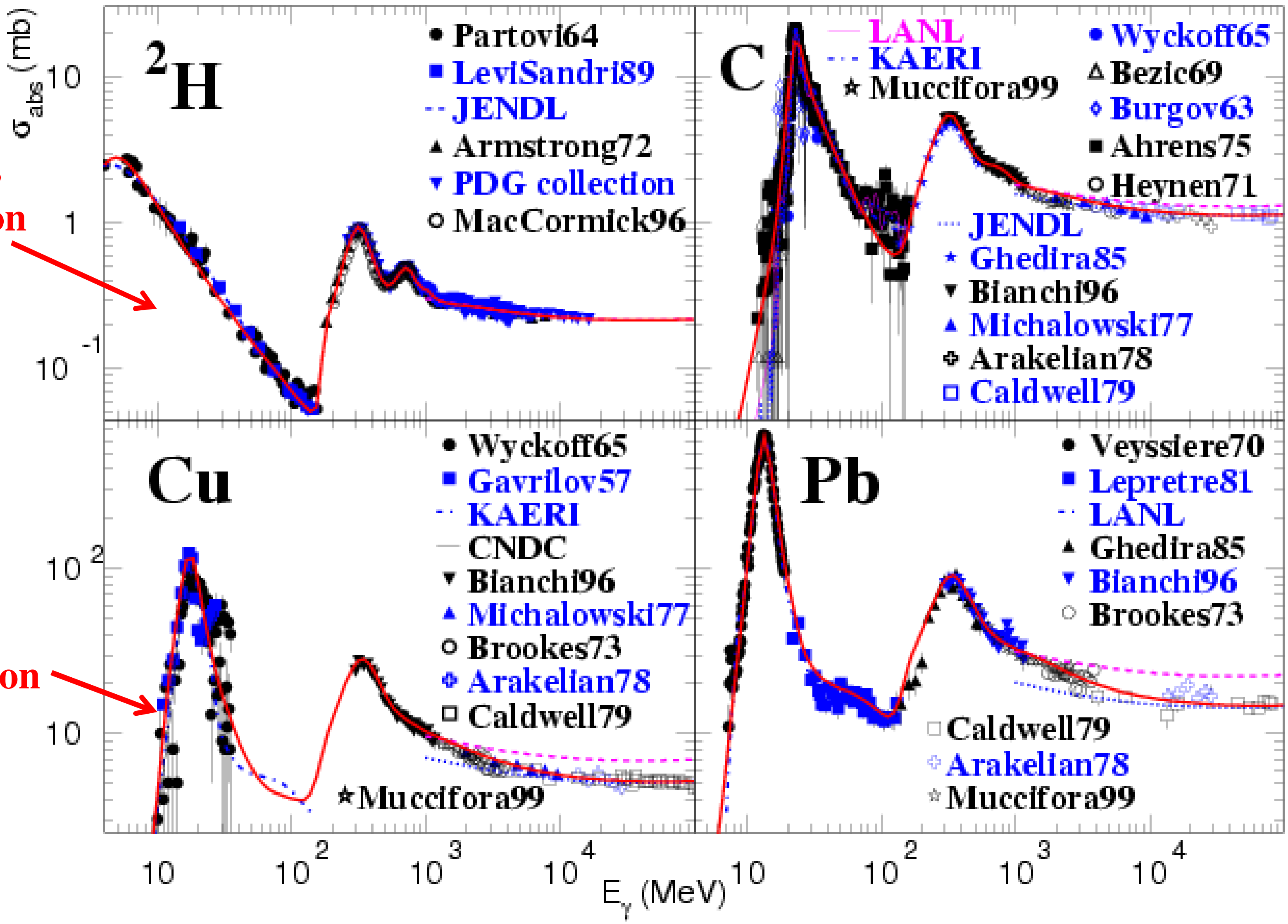


NO CASCADE, JUST a Quasmon DECAY !

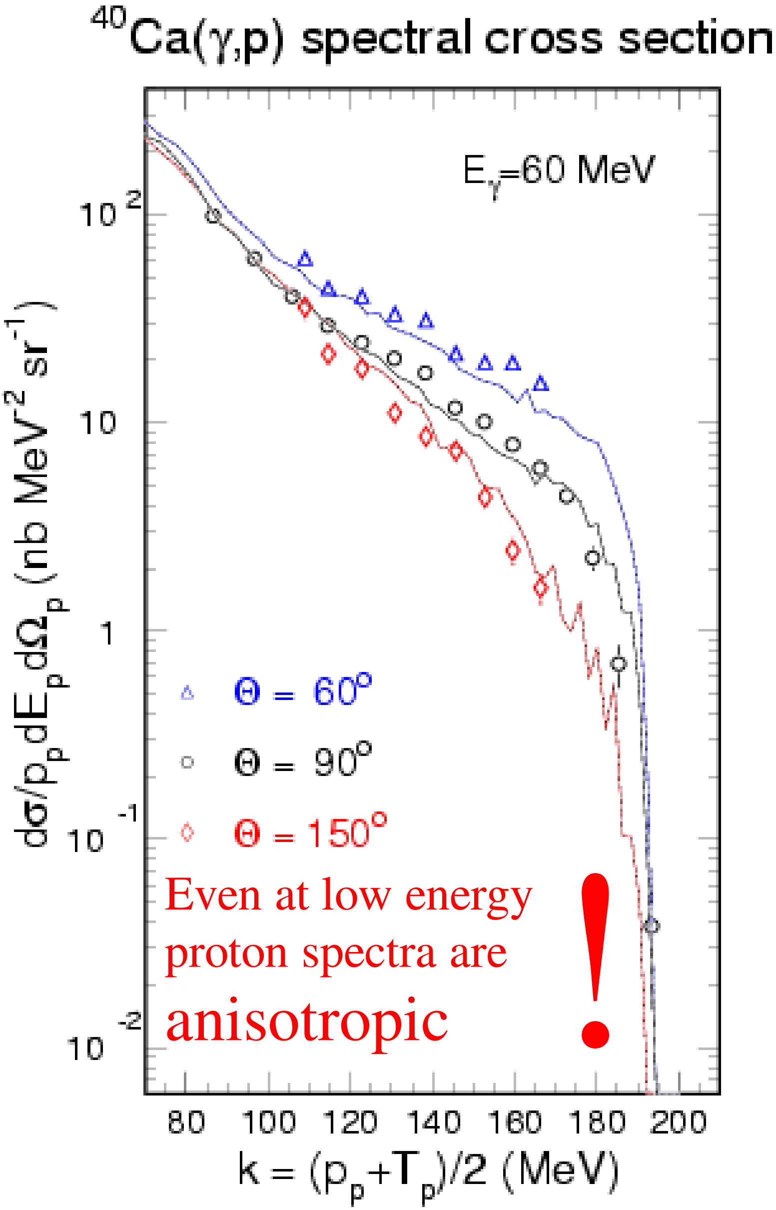
Unique CHIPS approximation of γA cross-sections for 87 nuclei (EPJA14,377)

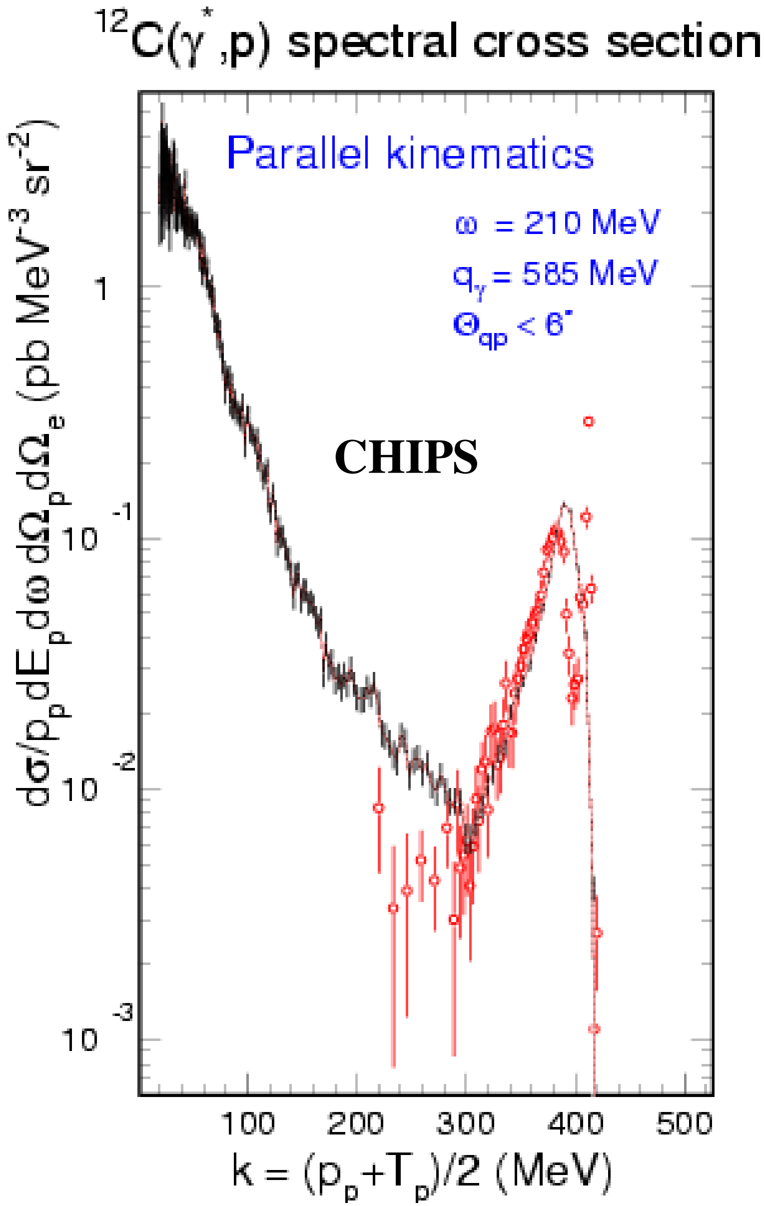
Deuterons dissociation

Clusters dissociation

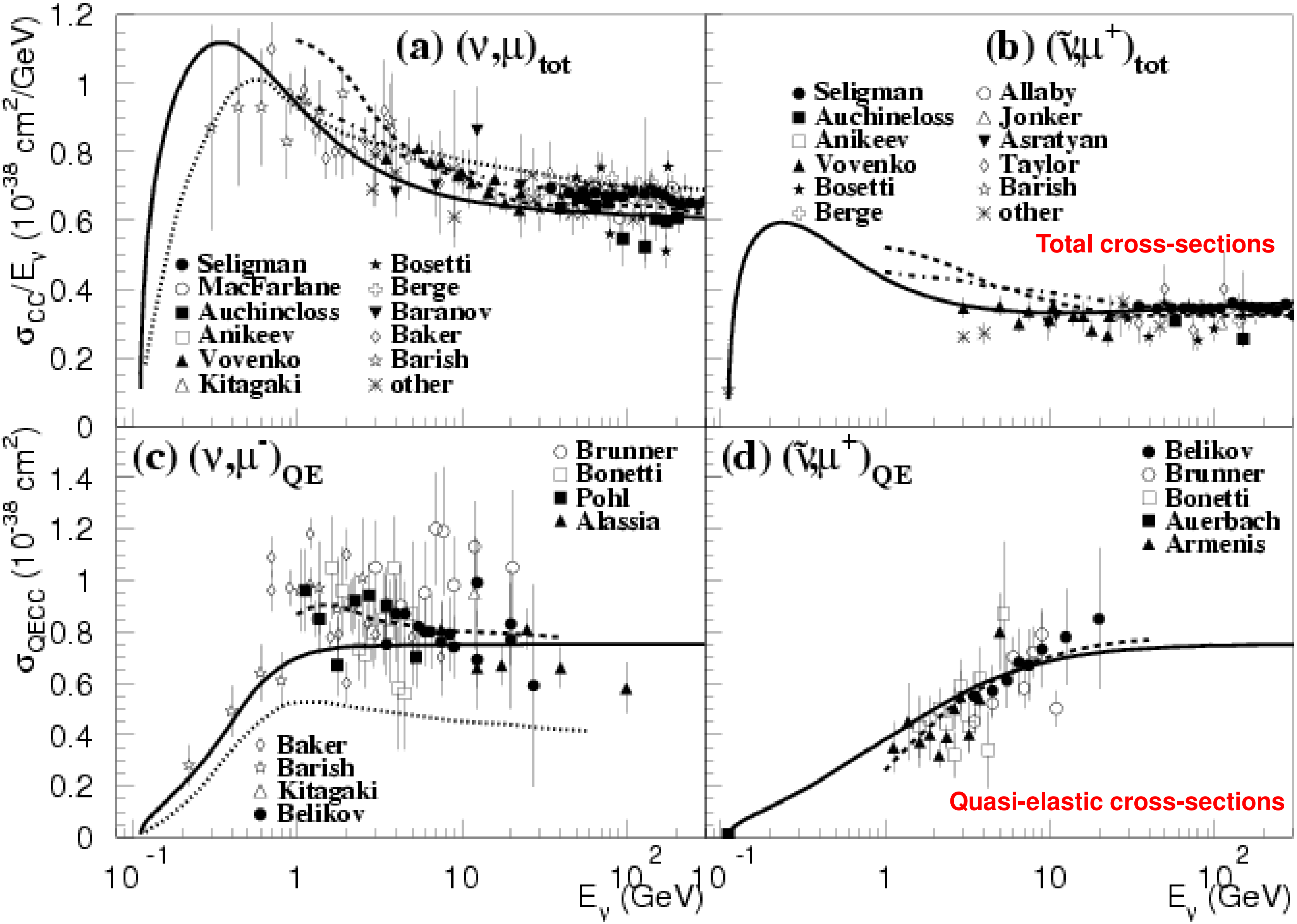


Nucleon spectra in photo- and electro-nuclear reactions

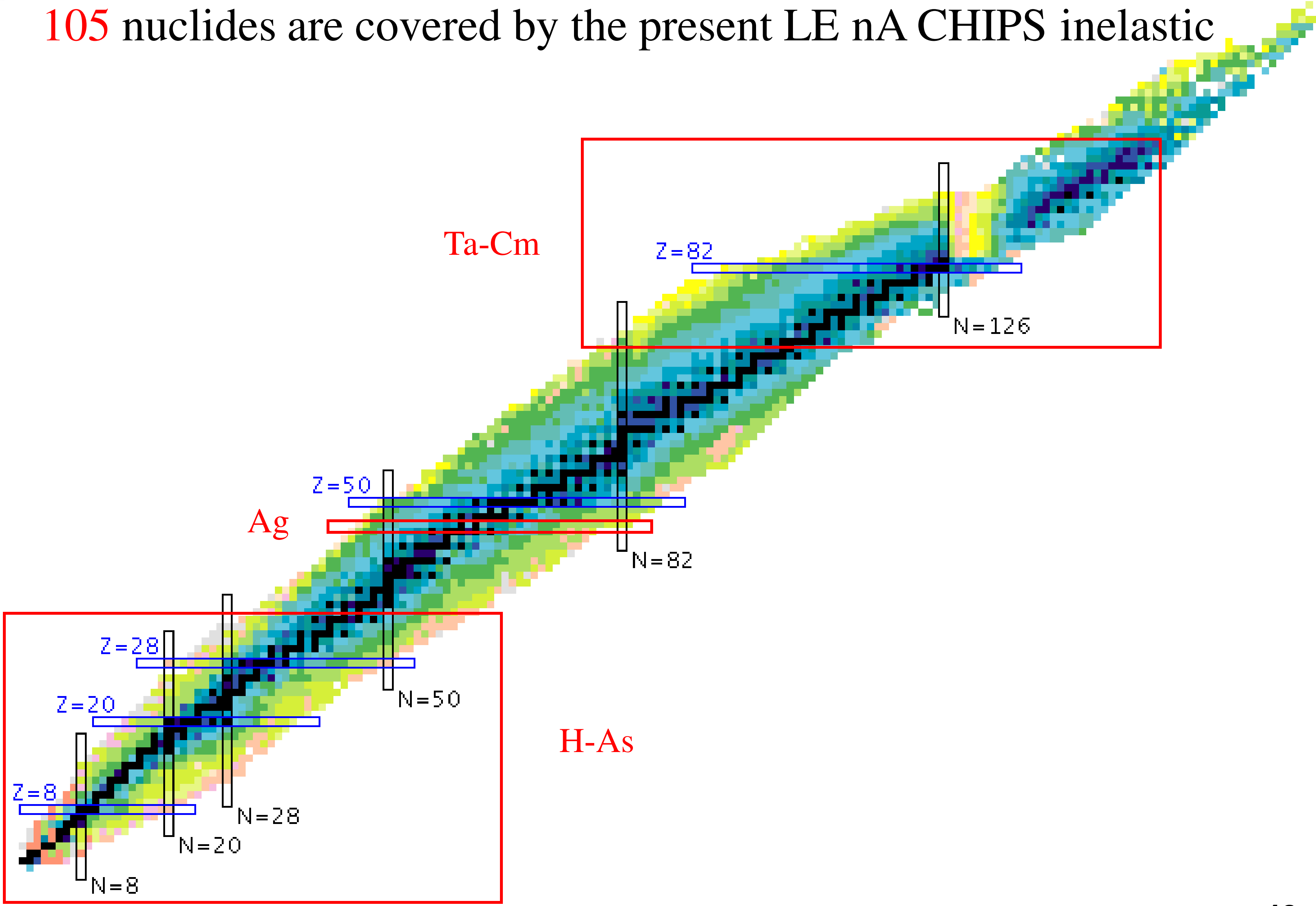


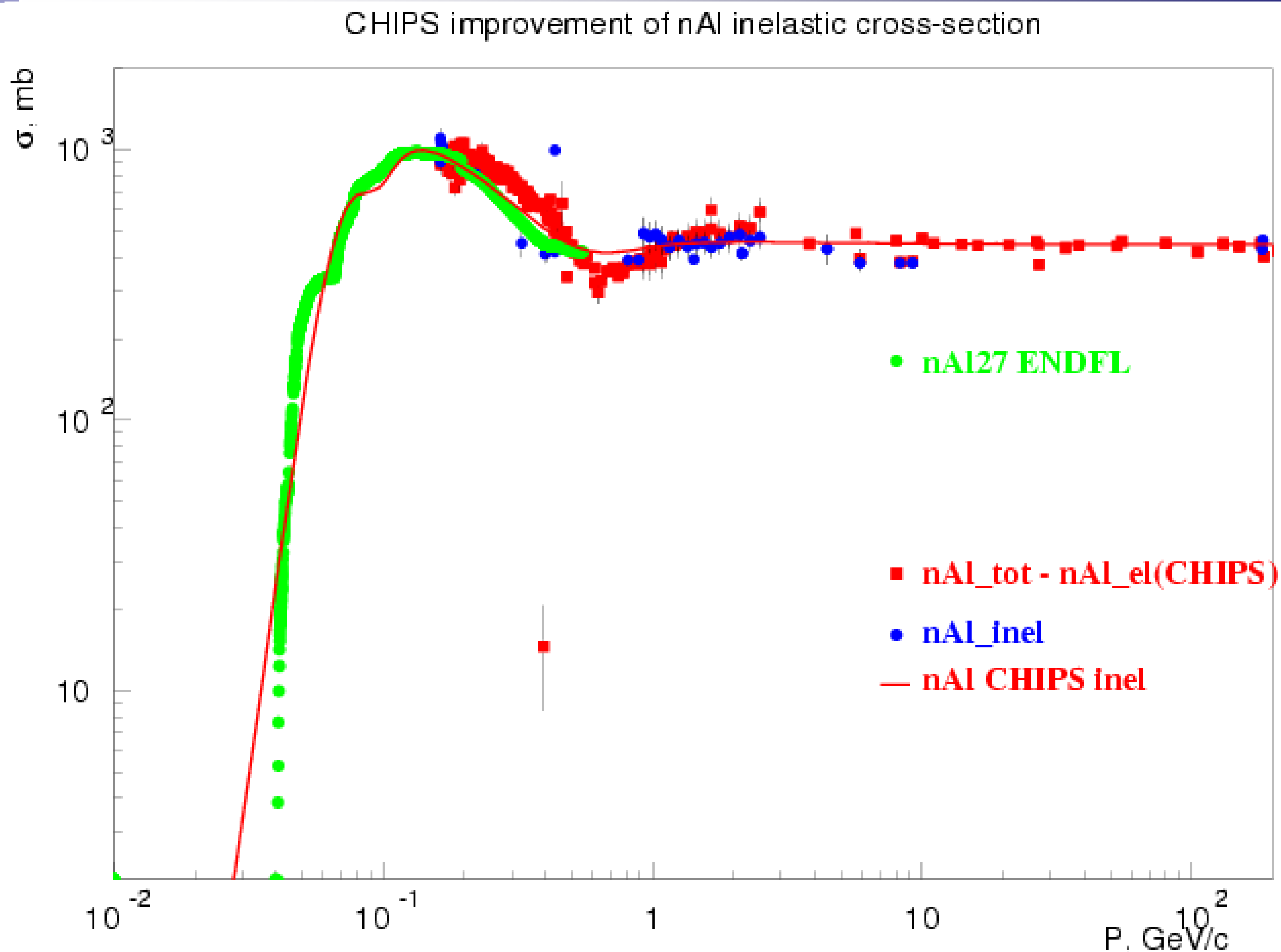


Non-perturbative approximation of neutrino-nuclear interaction cross-sections

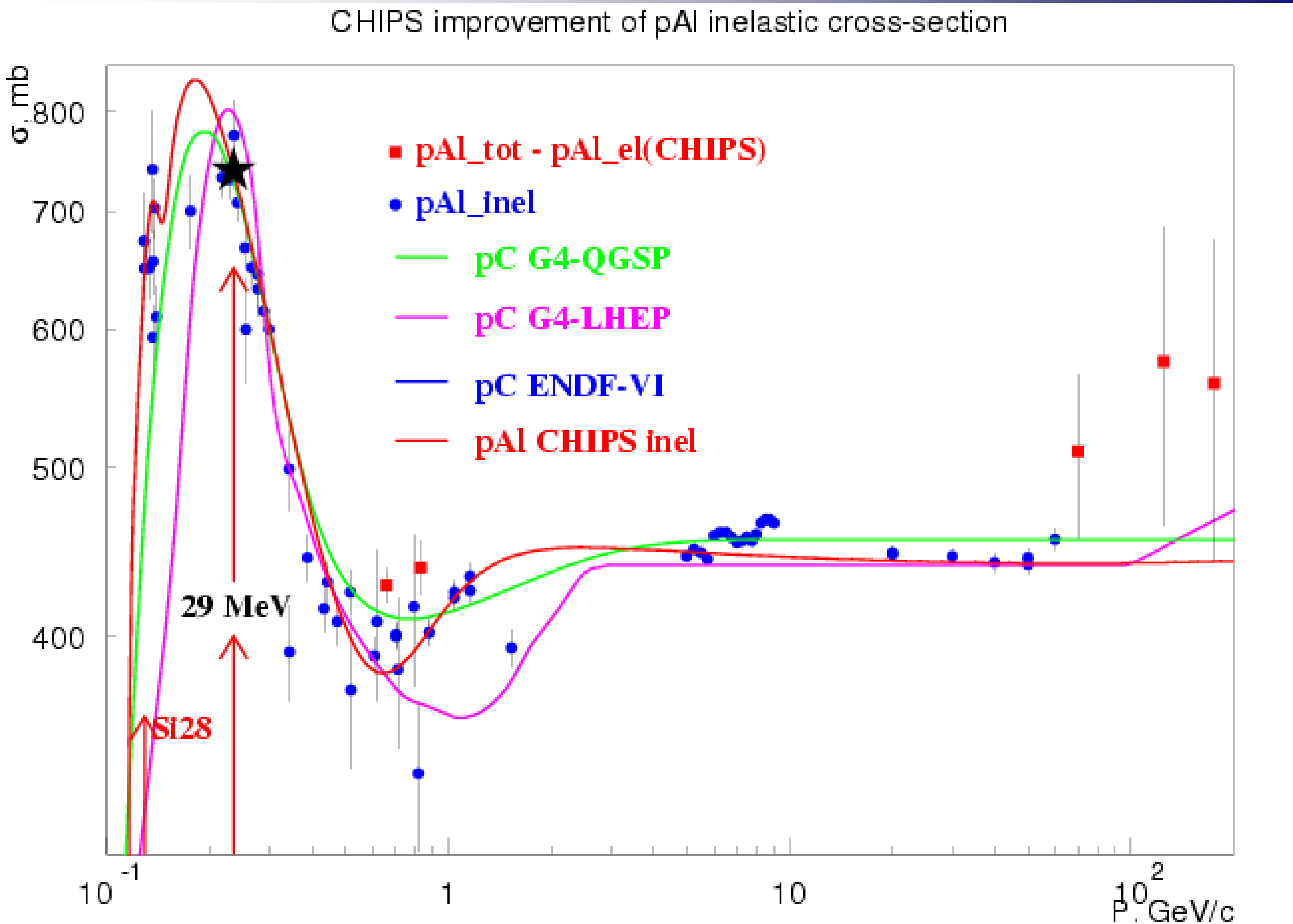


105 nuclides are covered by the present LE nA CHIPS inelastic

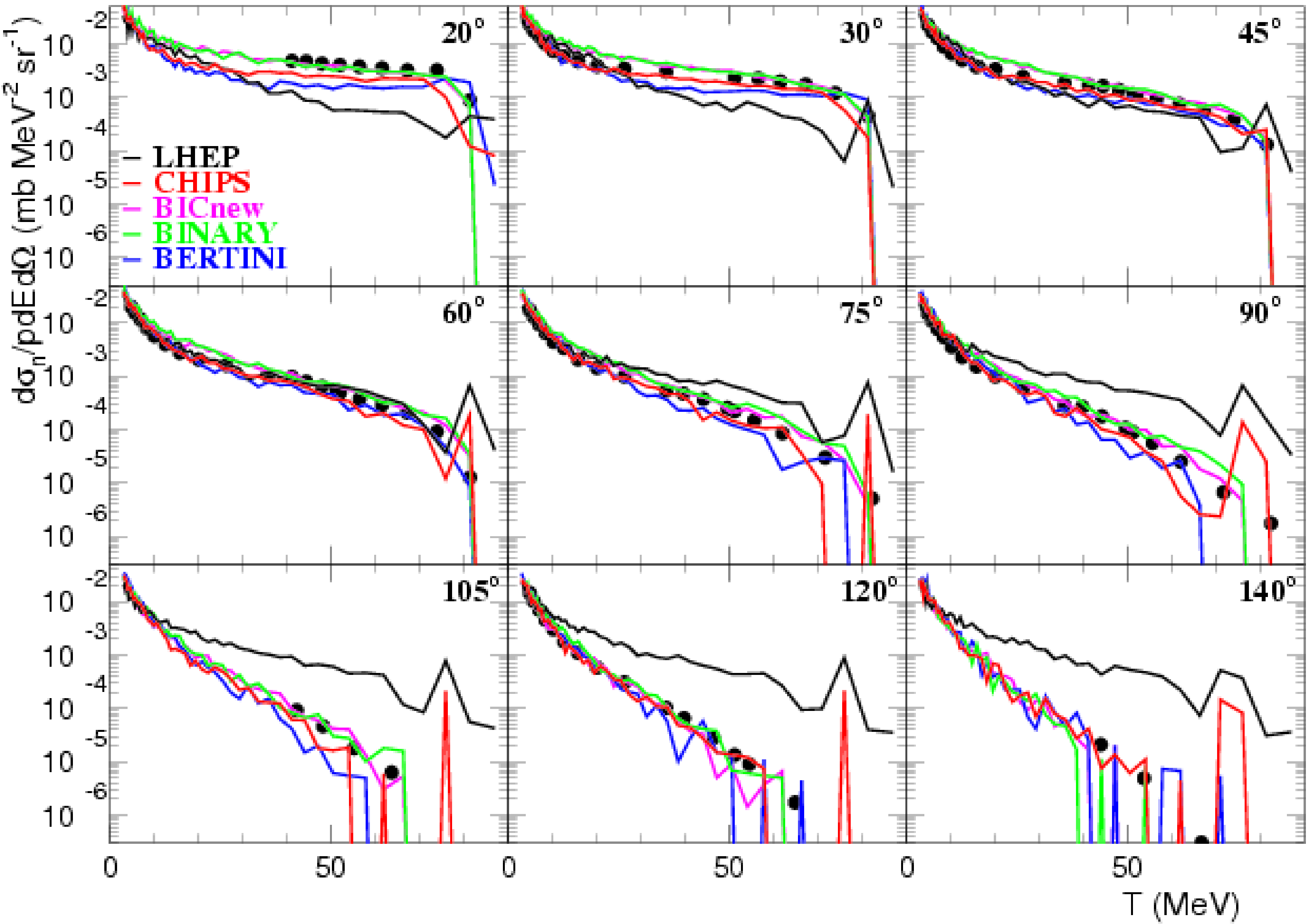



CHIPS improvement of nAl inelastic cross-section
σ, mb
10^3
10^2
10
10^{-2}
10^{-1}
1
10
10^2
P, GeV/c
nAl27 ENDFL
nAl_tot - nAl_el(CHIPS)
nAl_inel
nAl CHIPS inel

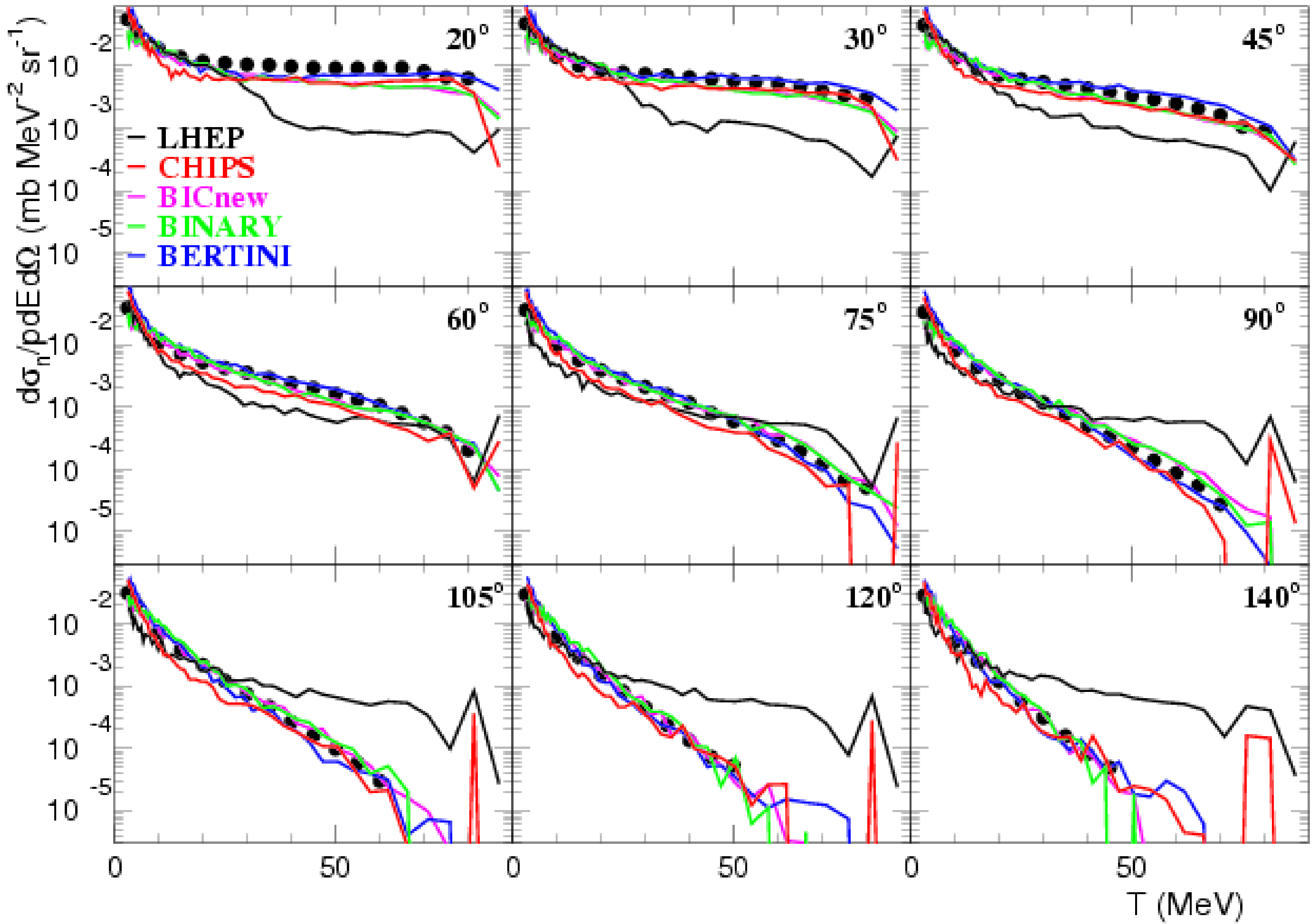
New CHIPS approximation for hadron-nuclear inelastic cross-sections (πA example)

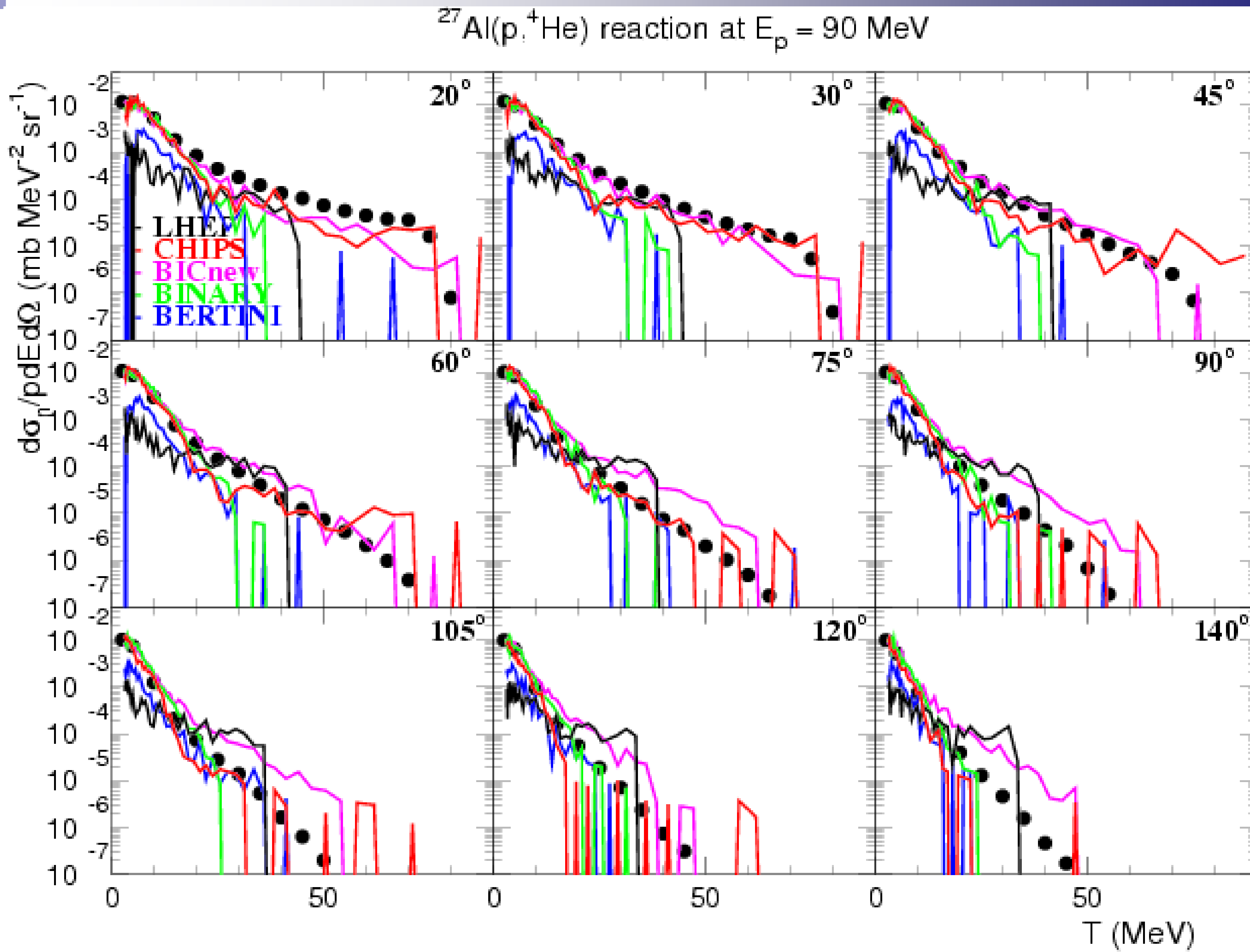


$^{27}Al(p,n)$ reaction at E_p = 90 MeV

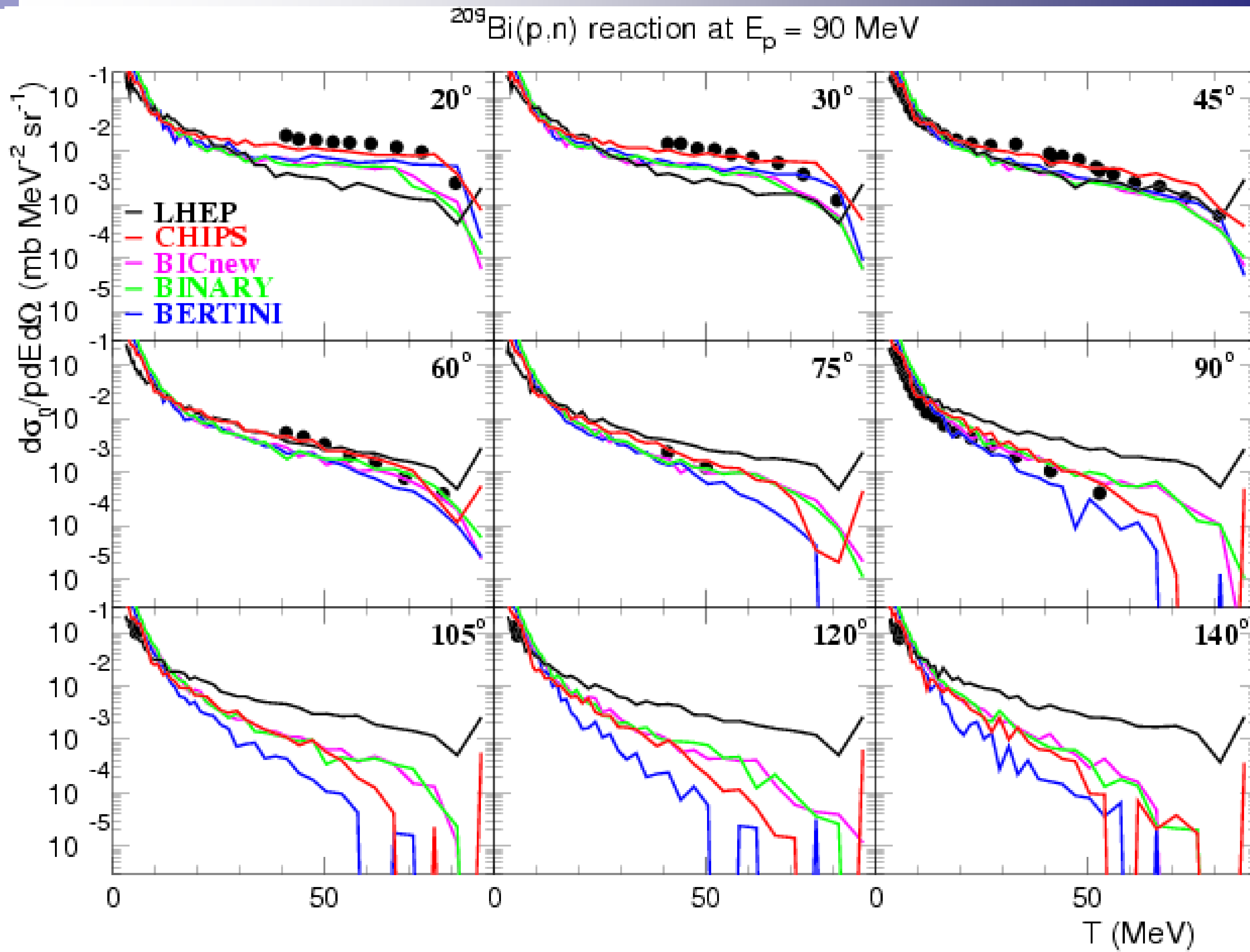


$^{27}Al(p,p)$ reaction at E_p = 90 MeV



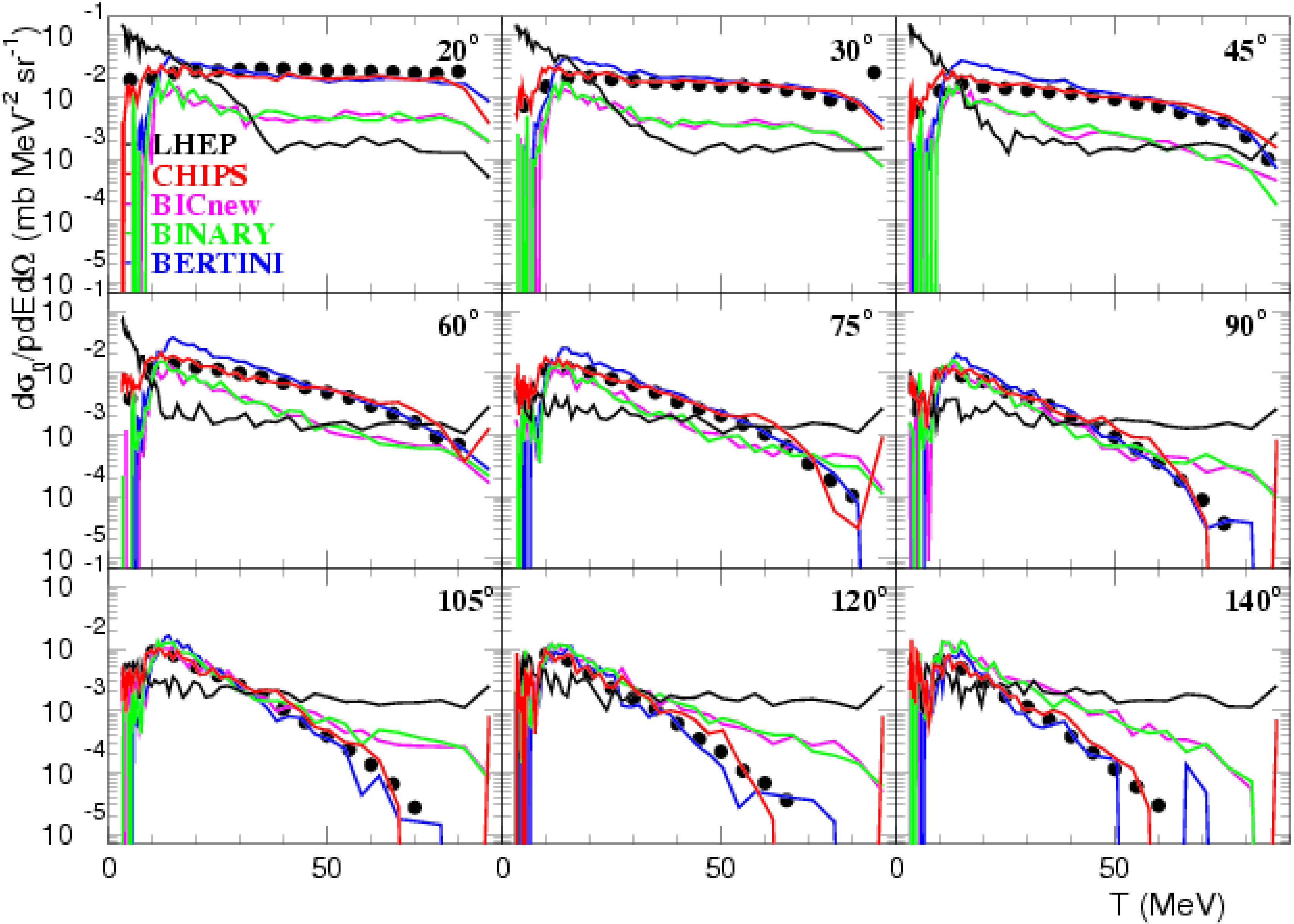


$^{27}Al(p,^{4}He)$ reaction at E_p = 90 MeV
20°
30°
45°
60°
75°
90°
105°
120°
140°
LHEP
CHIPS
BICnew
BINARY
BERTINI
$d\sigma_{in}/pdEd\Omega$ (mb MeV^{-2} sr^{-1})
T (MeV)

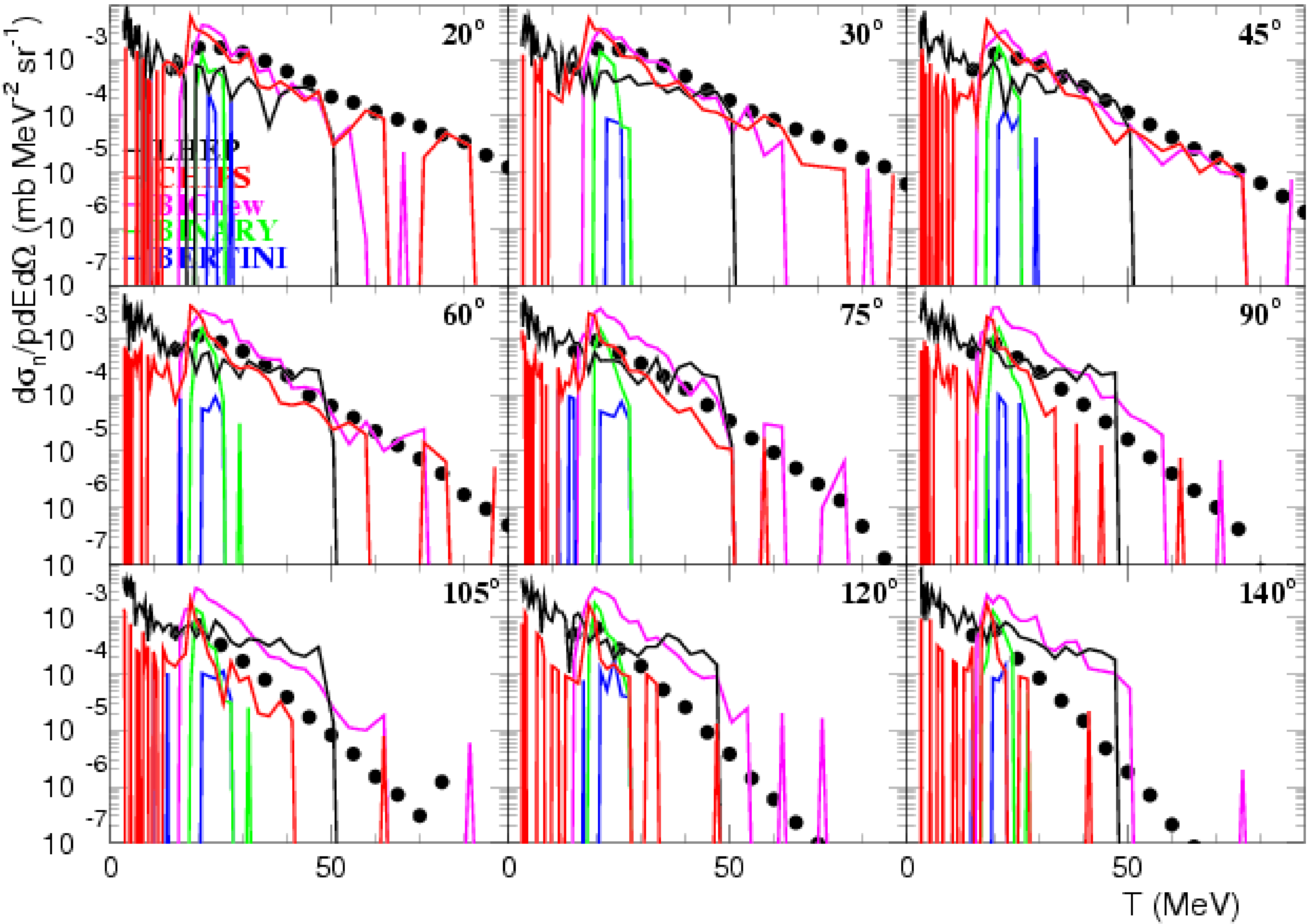


^{209}Bi(p,n) reaction at E_p = 90 MeV
$d\sigma_n/pdEd\Omega$ (mb MeV^{-2} sr^{-1})
20°
30°
45°
60°
75°
90°
105°
120°
140°
LHEP
CHIPS
BICnew
BINARY
BERTINI
T (MeV)

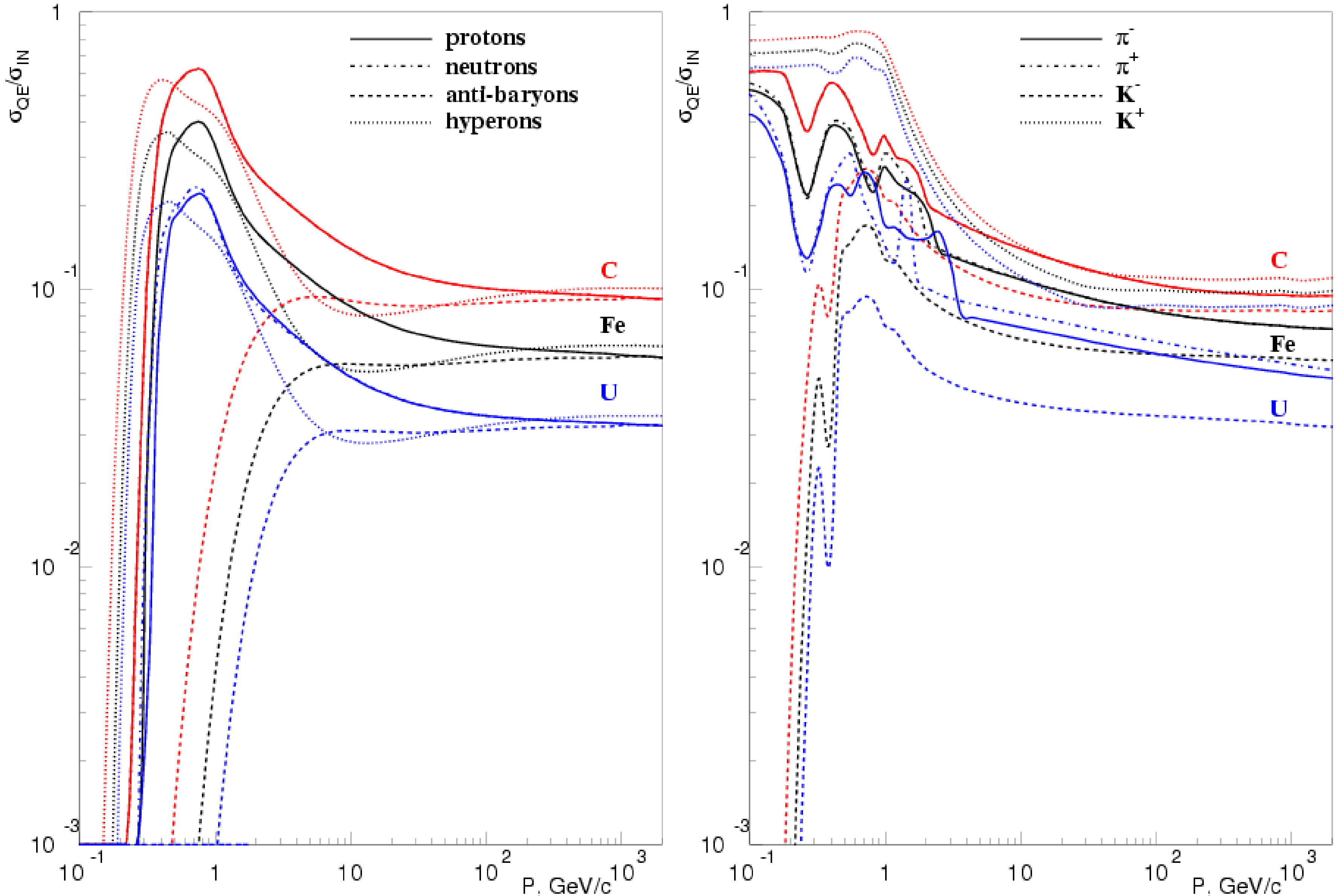
^{209}Bi(p,p) reaction at E_p = 90 MeV



$^{209}Bi(p,{}^4He)$ reaction at E_p = 90 MeV

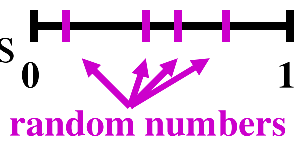


CHIPS quasi-elastic scattering part: G4QuasiFreeRatios (for all hadrons)



New CHIPS string algorithm

- The 1-D CHIPS String is similar to the Quark-Gluon String, but…
  - All partons are massless (current) instead of heavy (constituent, QGS) ones
  - Thus the CHIPS string algorithm can work from E=0 (formally $E \gg m_q$)
  - 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



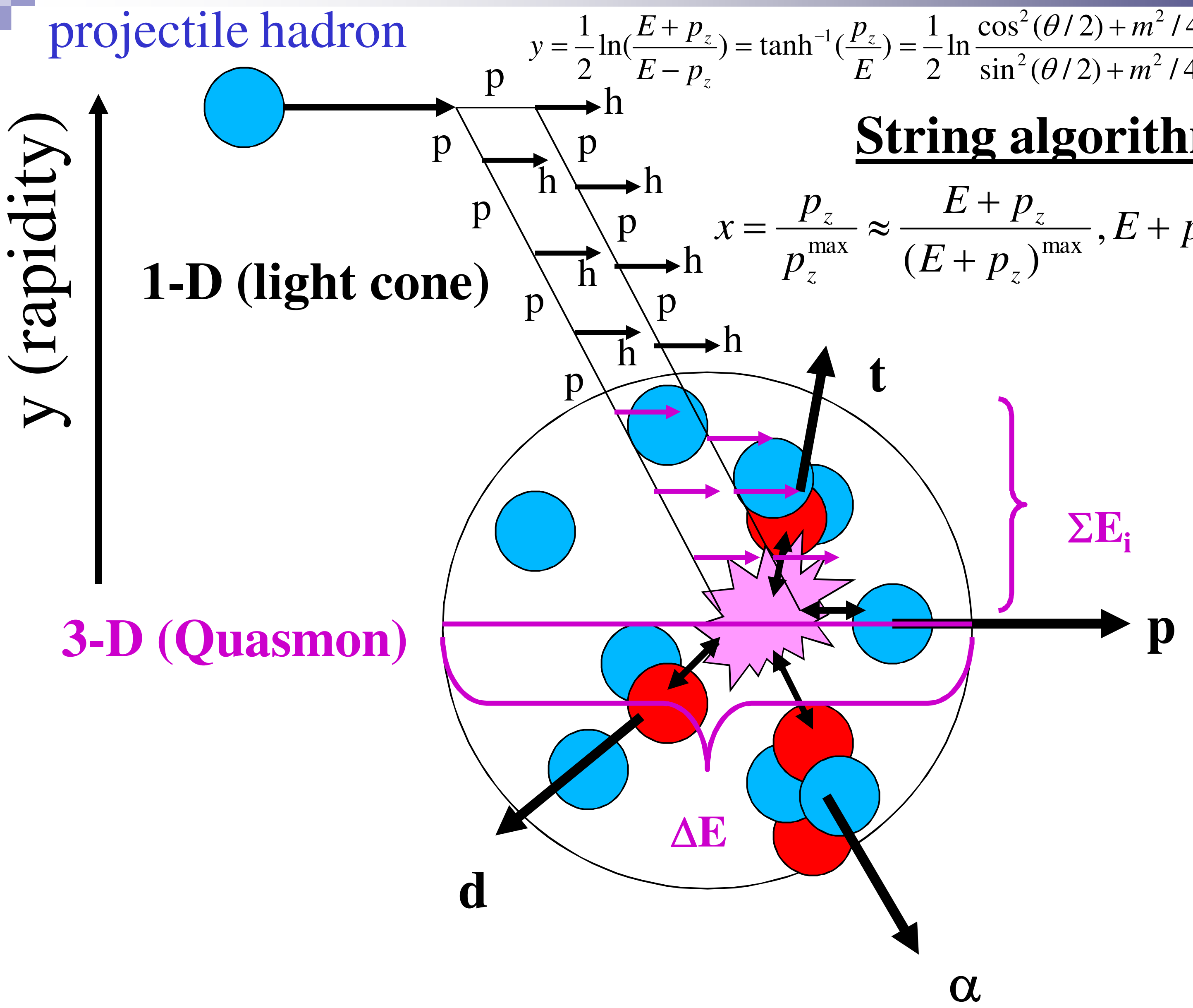
- Connection to the 3D CHIPS algorithm
  - In nuclear matter string looses (ΣE_i) about $k \approx 1$ GeV/fm ($\Delta E = k*T(b)/r(0)$)
    - This energy is converted to the Quasmon excitation
    - The rest (high rapidity part of the string) is hadronized outside of the nucleus
  - If at low energies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

$$y=\frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)=\tanh^{-1}\left(\frac{p_z}{E}\right)=\frac{1}{2}\ln\frac{\cos^2(\theta/2)+m^2/4p^2+\ldots}{\sin^2(\theta/2)+m^2/4p^2+\ldots}\approx-\ln\tan(\theta/2)=\eta$$

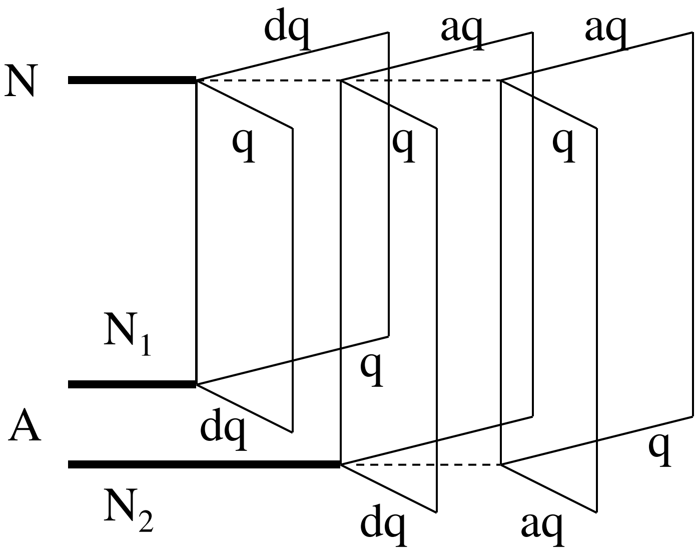
String algorithm

$$x=\frac{p_z}{p_z^{\max}}\approx\frac{E+p_z}{(E+p_z)^{\max}},\ E+p_z=m_T e^y,\ x\approx e^{y-y_{\max}}$$

!



String fusion algorithm to avoid too low or imaginary string mass



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

String fusion examples

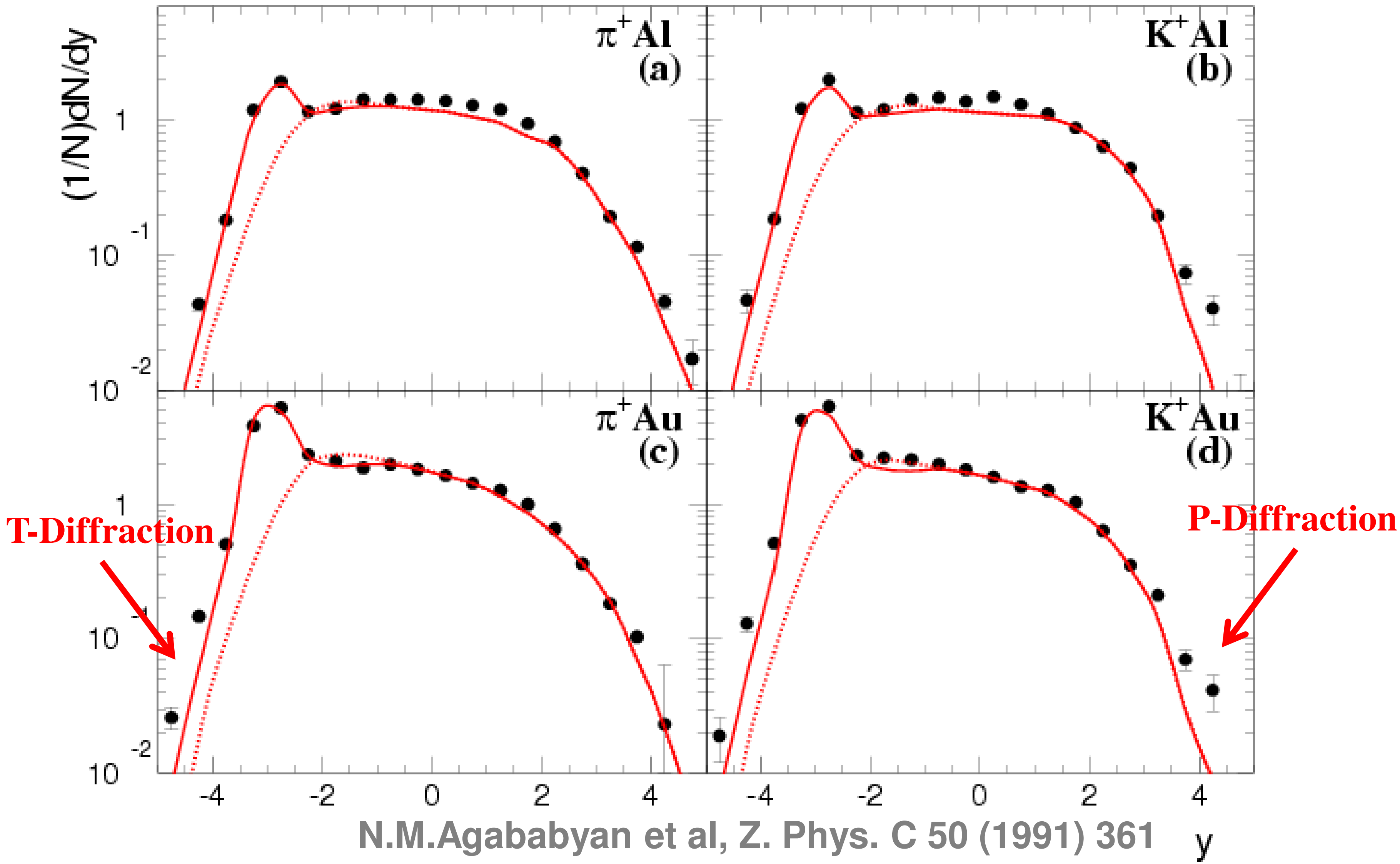
aq-q	aq-q	aq-q	q-dq	q-dq
aq-adq	aq-q	dq-adq	q-aq	adq-aq
adq-aq	adq-dq	q-aq	dq-q	aq-q

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

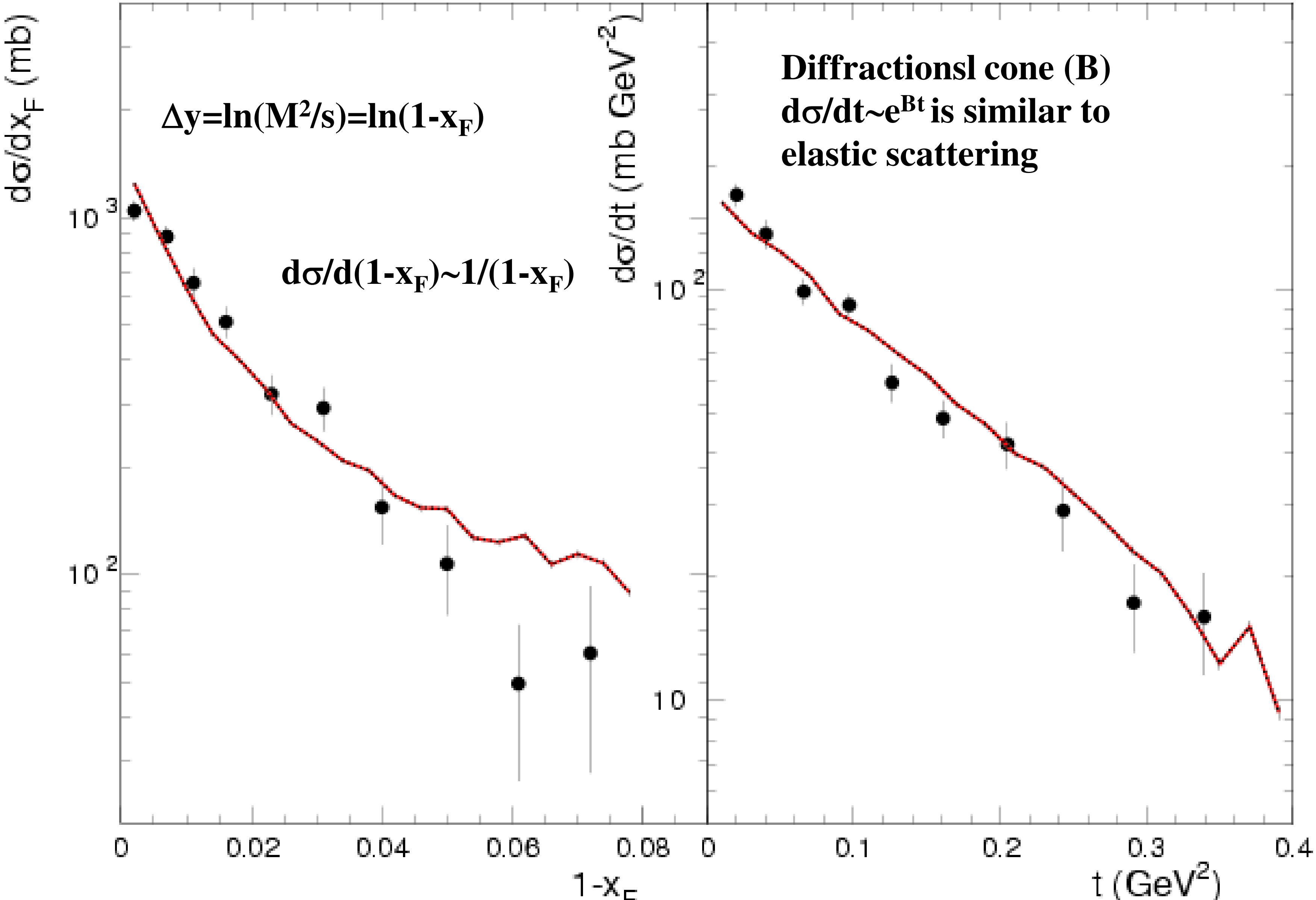
Emergency diquark reduction: (us – anti-d anti-s) → (u – anti-d)

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

Comparison of QGSP (QGS+Precompound, dotted line) with QGSC (QGS+CHIPS)

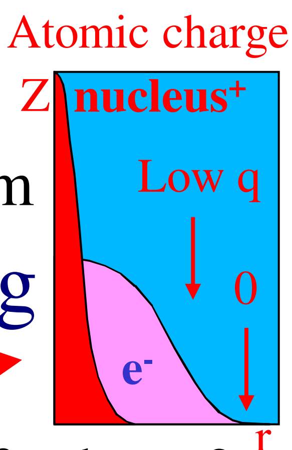


CHIPS simulation of the diffraction excitation in pW interactions (HELIOS data)

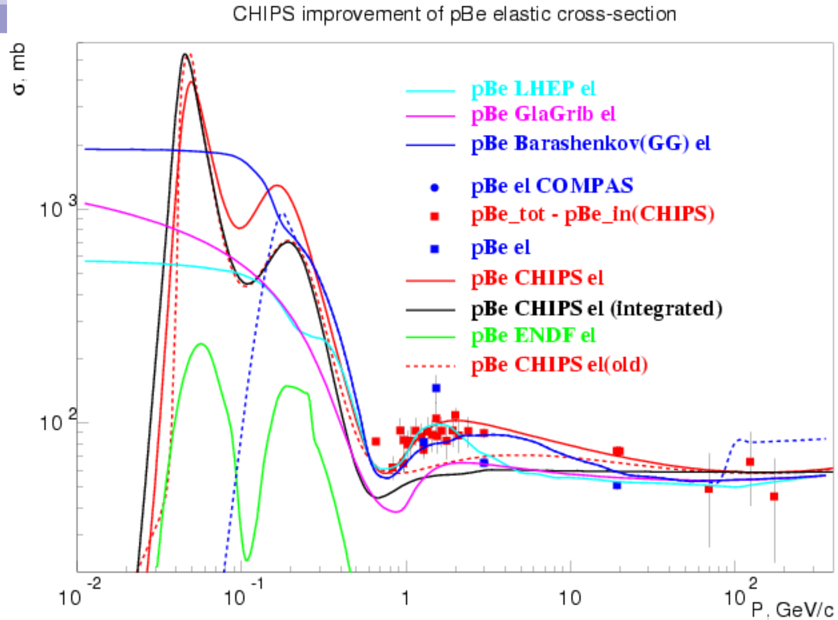


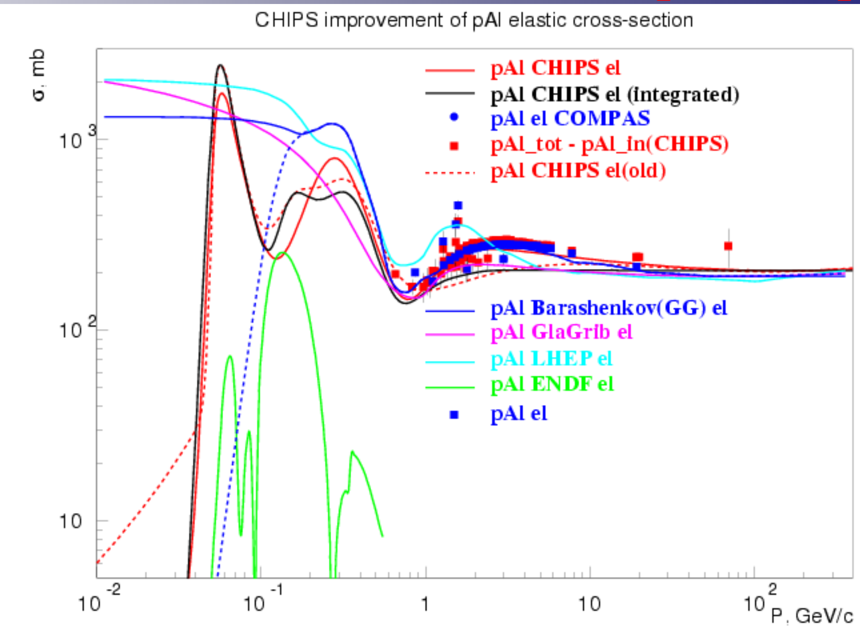
EM Multiple & hadronic coherent elastic scattering

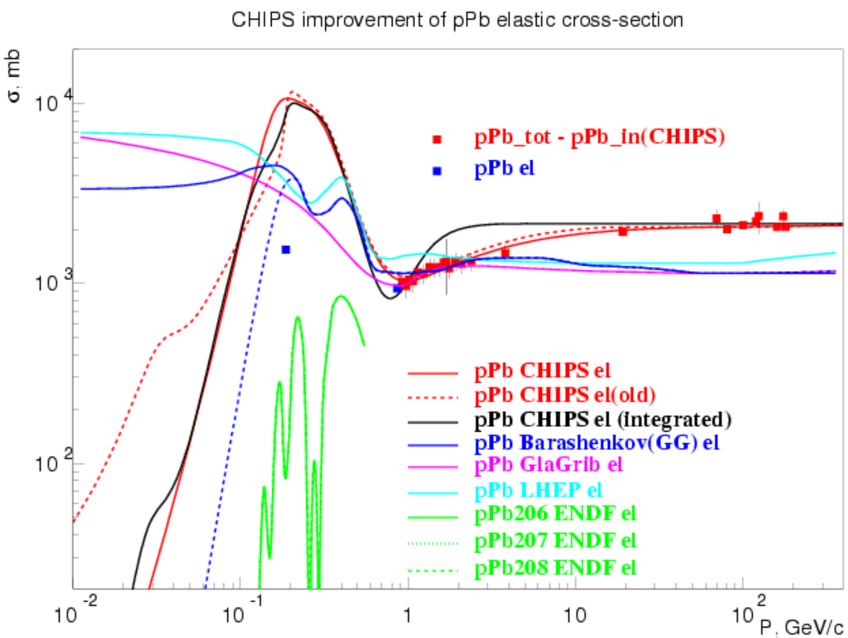
- In CHIPS physics package the processes are not subdivided in "electromagnetic" and "hadronic", because in general this is impossible !
  - Photo-, lepto-nuclear reactions including quasi-elastic
  - e^+e^- pair production on atonic electrons and on nuclei
  - Multiple scattering is an example of the 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 $(ds/dt \sim 1/(t+A))$ right?
  - Fortunately now we have measurements and can fit them

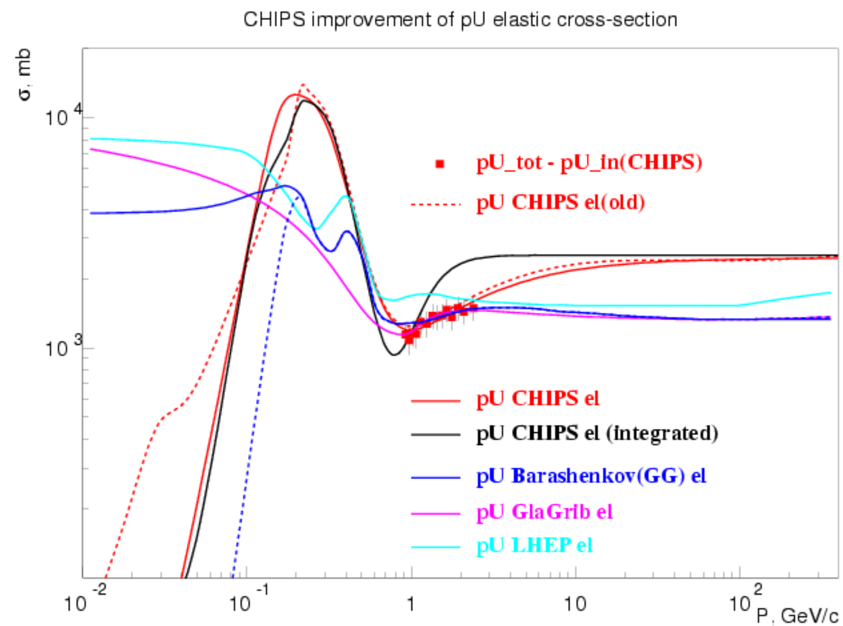


New CHIPS approximation for hadron-nuclear elastic cross-sections (pA example)

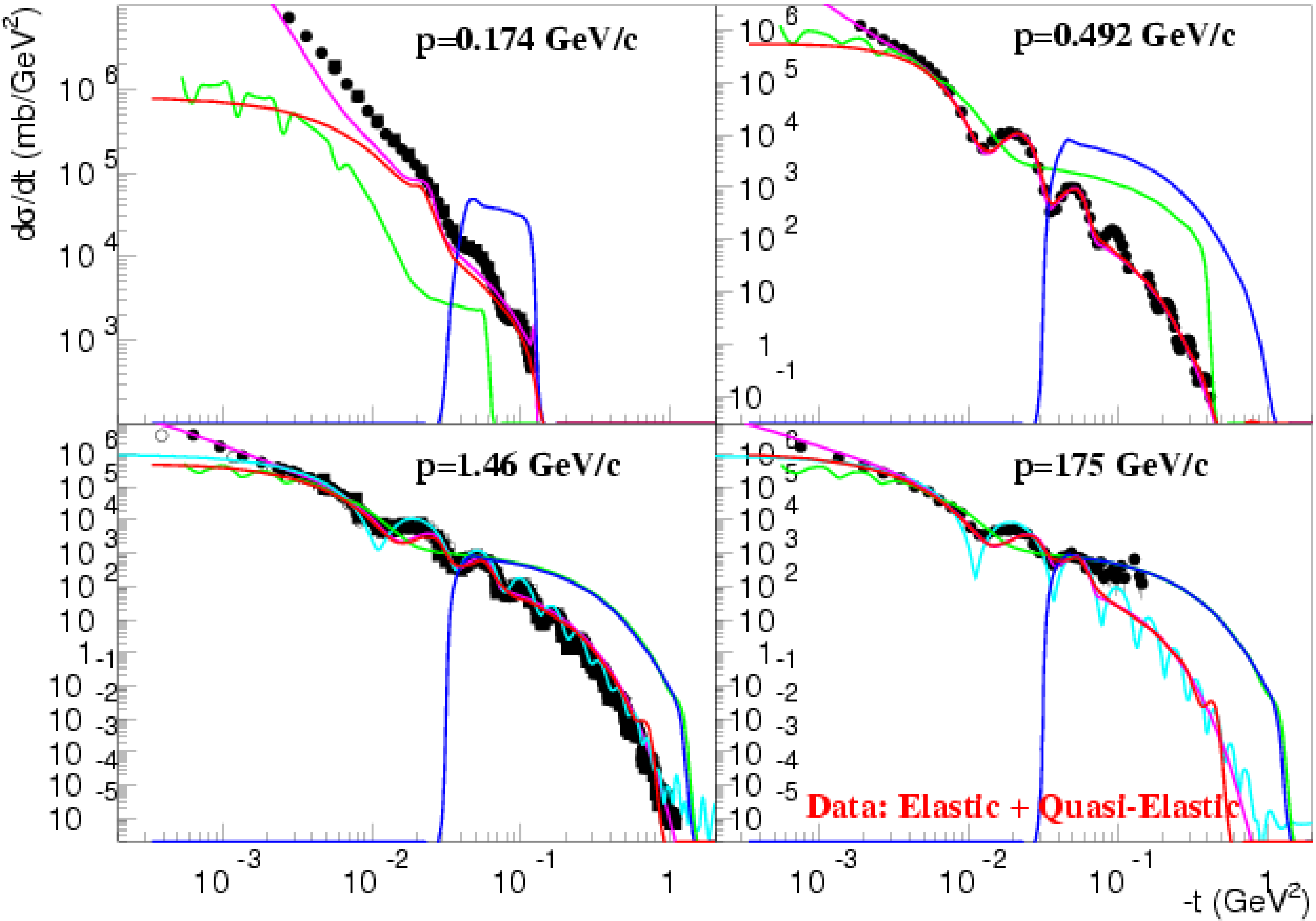


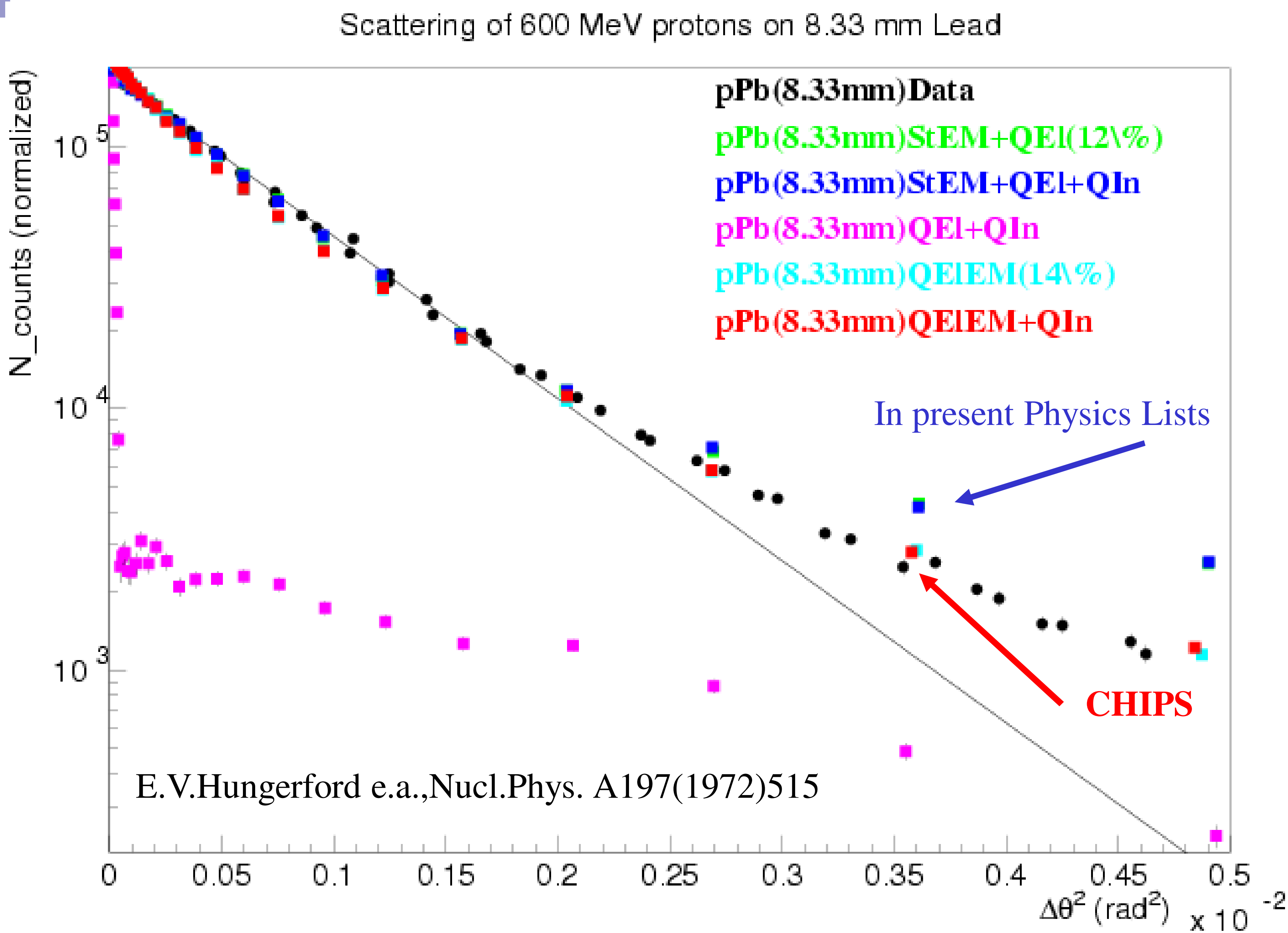






CHIPS improvement of pPb elastic scattering

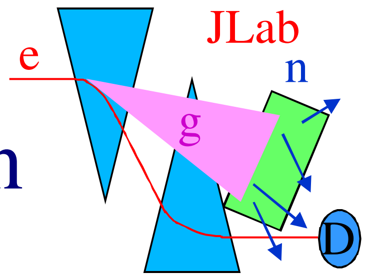




Scattering of 600 MeV protons on 8.33 mm Lead
pPb(8.33mm)Data
pPb(8.33mm)StEM+QEl(12\%)
pPb(8.33mm)StEM+QEl+QIn
pPb(8.33mm)QEl+QIn
pPb(8.33mm)QElEM(14\%)
pPb(8.33mm)QElEM+QIn
In present Physics Lists
CHIPS
E.V.Hungerford e.a.,Nucl.Phys. A197(1972)515
N_counts (normalized)
10^5
10^4
10^3
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Δθ² (rad²) x 10^-2

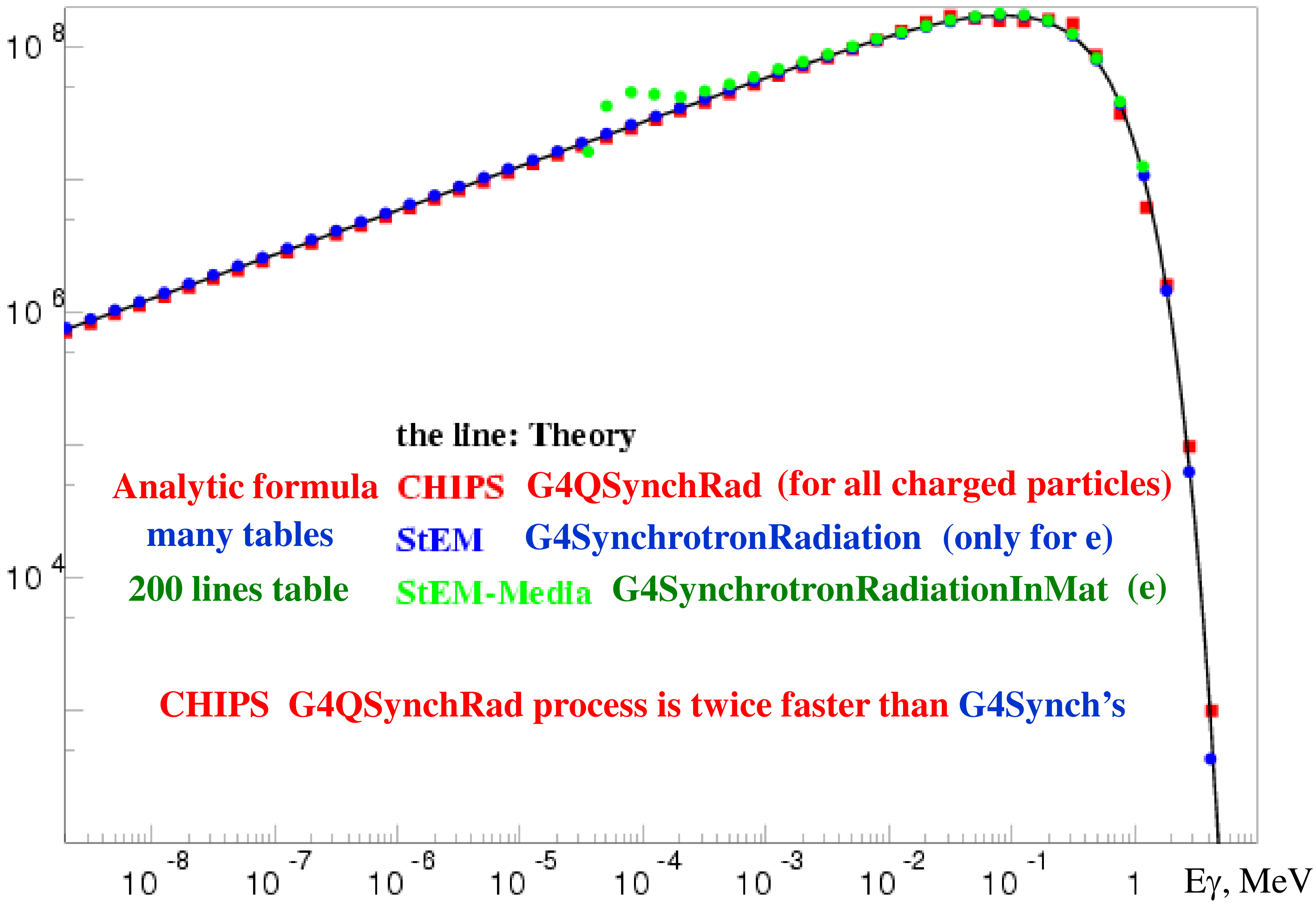
CHIPS Synchrotron Radiation

- 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)



Conclusion: CHIPS Physics List

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

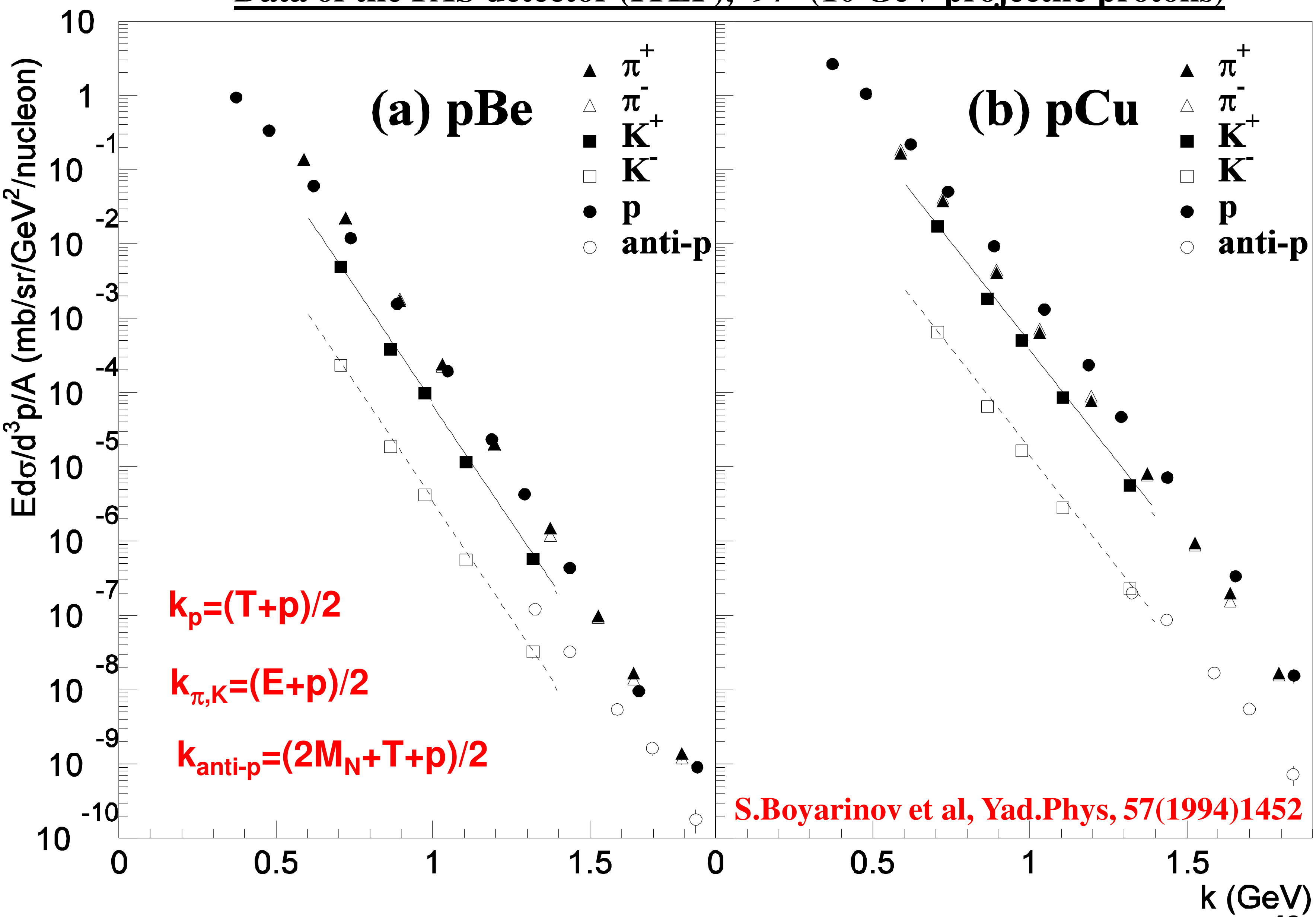
Backup slides following

CHIPS (CHiral Invariant Phase Space) publications

0. Thermodinamic quark-parton model: Preprint ITEP-165-84
1. Light SU(3) hadron masses: Eur.Phys.J. A14 (2002) 265
2. Proton-antiproton annihilation at rest: Eeur.Phys.J.A8(2000)217
3. Nuclear p^- capture at rest: Eur.Phys.J. A9 (2000) 414
4. Nuclear m^- capture at rest: Eur.Phys.J. A33 (2007) 7
5. Anti-proton capture at rest: IEEE Trans.Nucl.Sci. 52 (2005)2832
6. Low energy γA reactions: Eur.Phys.J. A9 (2000) 421
7. Cross-sections of γA/eA reactions: Eur.Phys.J. A14 (2002) 377
8. Nucleon structure functions: Eur.Phys.J A34 (2007) 283
9. Drell-Yan $\mu^+\mu^-$ pair production: Eur.Phys.J A36 (2008) 289

Official Page with more information about CHIPS:
http://mkossov.home.cern.ch/mkossov/Welcome.html

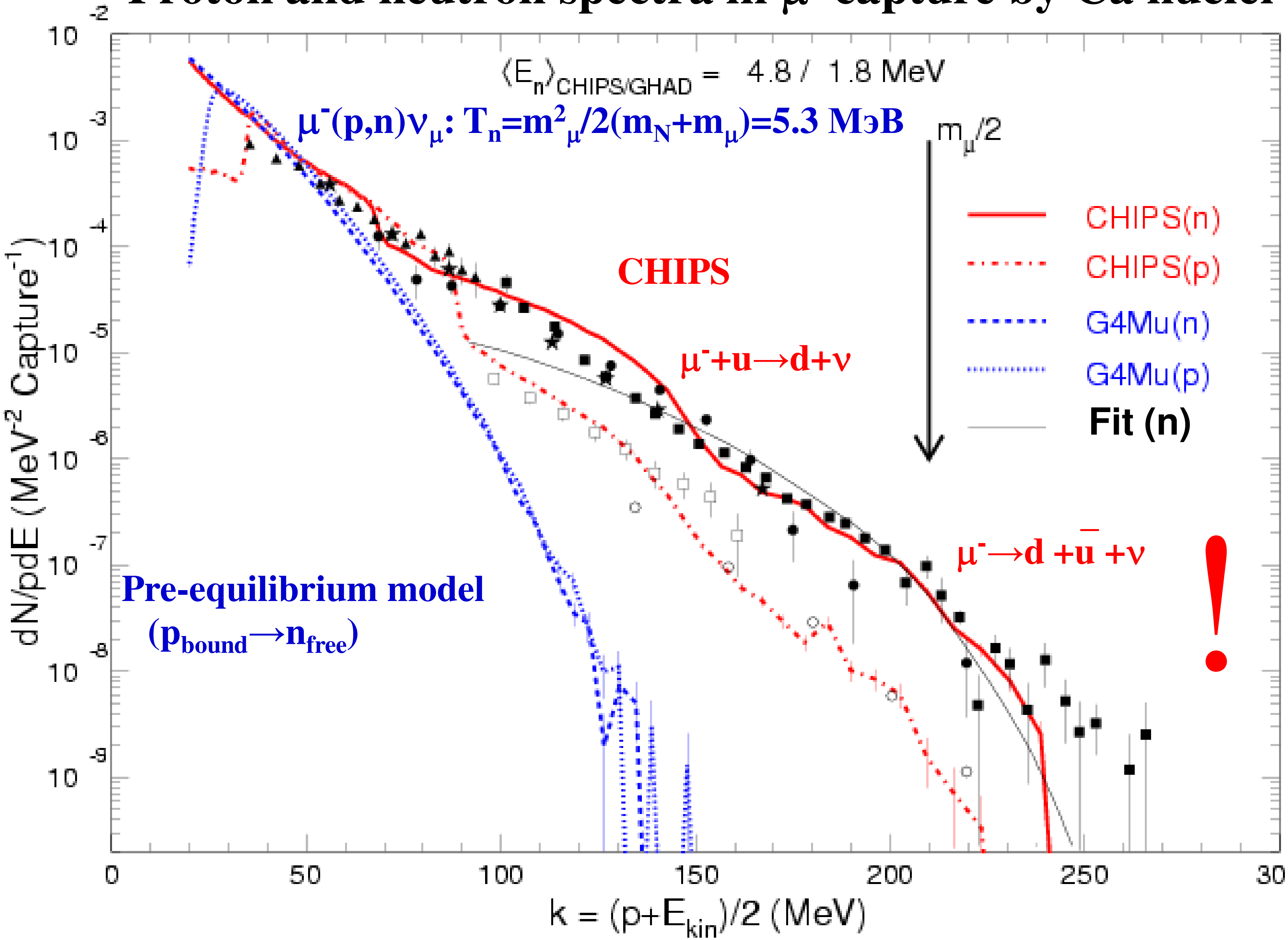
Data of the FAS detector (ITEP), 97⁰ (10 GeV projectile protons)

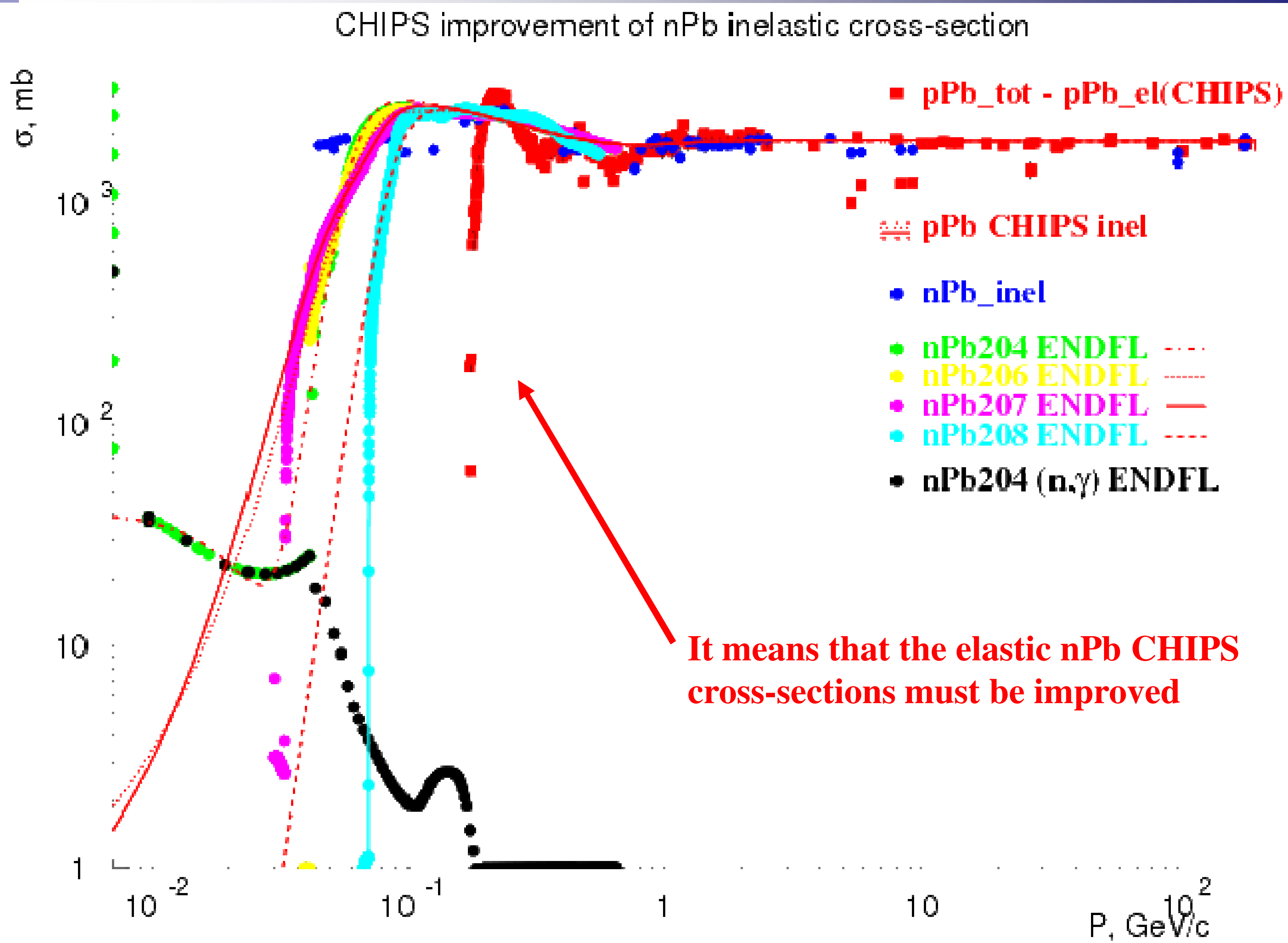


CHIPS ($T_c \approx$ 200 MeV) and Bag model calculation oh hadronic masses

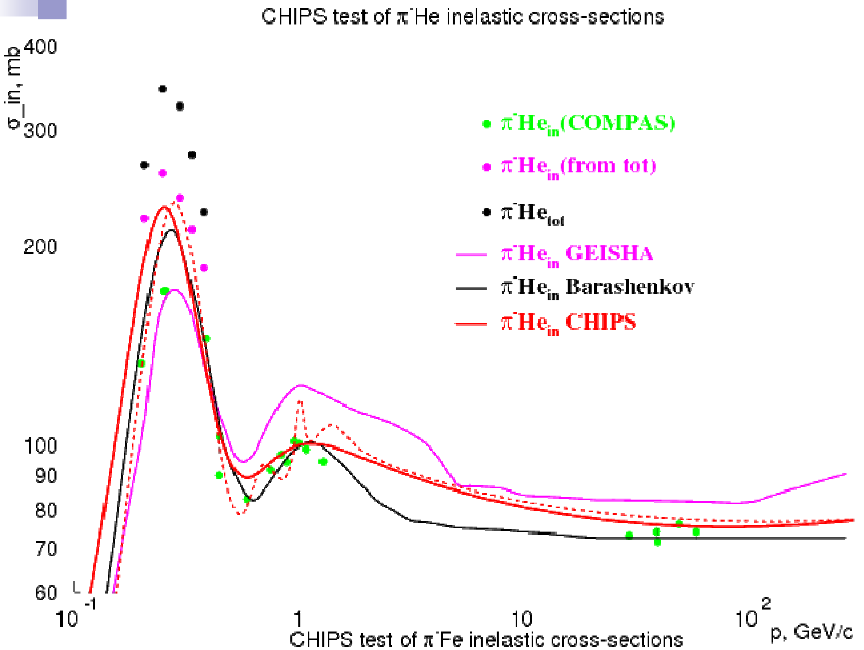
	Exp.	M_{bag}	ΔM_{bag}	$M(T_c)$	$\Delta M(T_c)$		Exp.	M_{bag}	ΔM_{bag}	$M(T_c)$	$\Delta M(T_c)$
π^0	140	280	140	152	12	Σ^0	(4) 1193	1144	49	(3) 1185	8
ω	783	783	0	785	2	Σ^-	(4) 1197	1144	53	(2) 1187	10
p	938	938	0	939	1	Σ^{*+}	1383	1382	1	1382	1
n	(1) 939	938	1	(2) 941	2	Σ^{*0}	1384	1382	2	1384	0
Δ	1232	1233	1	1231	1	Σ^{*-}	1387	1382	5	1385	2
K^+	494	497	3	485	9	ϕ	1019	1068	49	1018	1
K^0	(4) 498	497	1	(4) 489	9	Ξ^0	1315	1289	26	1320	5
K^{*+}	[illegible] (1)	928	36	[illegible] (1)	6	Ξ^-	(6) 1321	1289	32	(3) 1323	2
K^{*0}	896	928	32	899	3	Ξ^{*0}	[illegible] (3)	1529	3	[illegible] (2)	1
Λ	73	39		69	7	Ξ^{*-}	1535	1529	6	1533	2
Σ^+	1189	1144	45	1182	7	Ω^-	1673	1672	1	1674	1

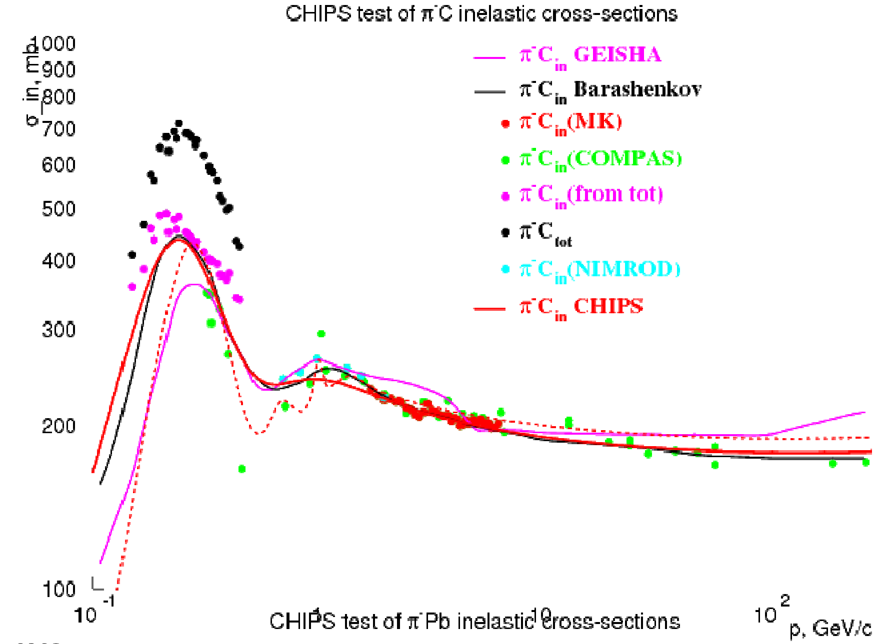
Proton and neutron spectra in μ^- capture by Ca nuclei

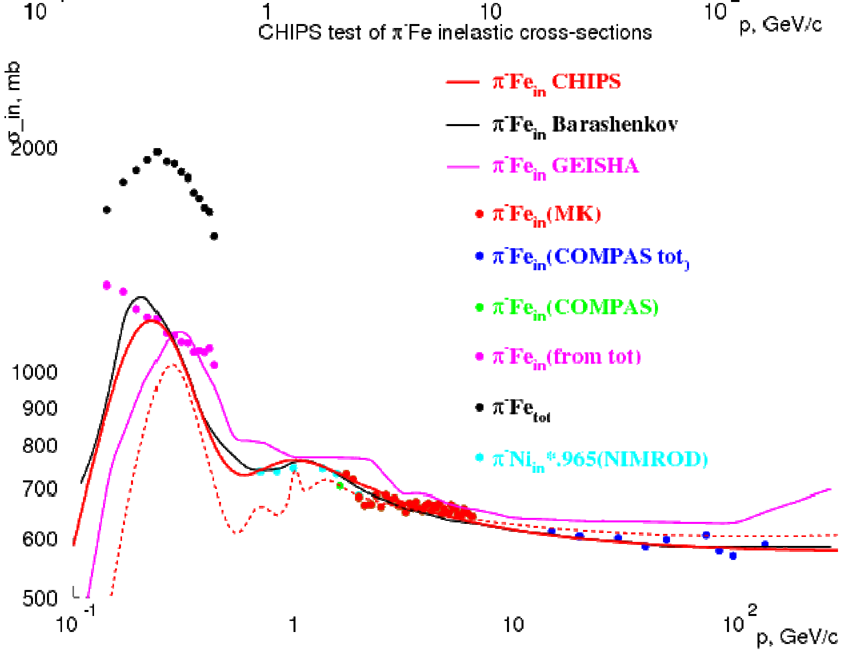


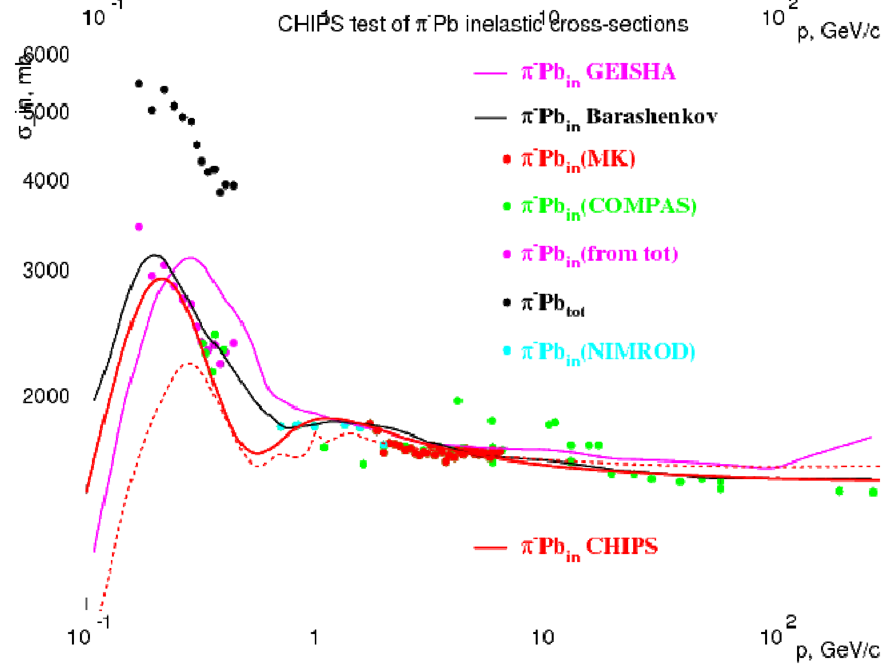

CHIPS improvement of nPb inelastic cross-section
σ, mb
10 3
10 2
10
1
10 -2
10 -1
1
10
10 2
P, GeV/c
pPb_tot - pPb_el(CHIPS)
pPb CHIPS inel
nPb_inel
nPb204 ENDFL
nPb206 ENDFL
nPb207 ENDFL
nPb208 ENDFL
nPb204 (n,γ) ENDFL
It means that the elastic nPb CHIPS cross-sections must be improved

New CHIPS approximation for hadron-nuclear inelastic cross-sections (πA example)

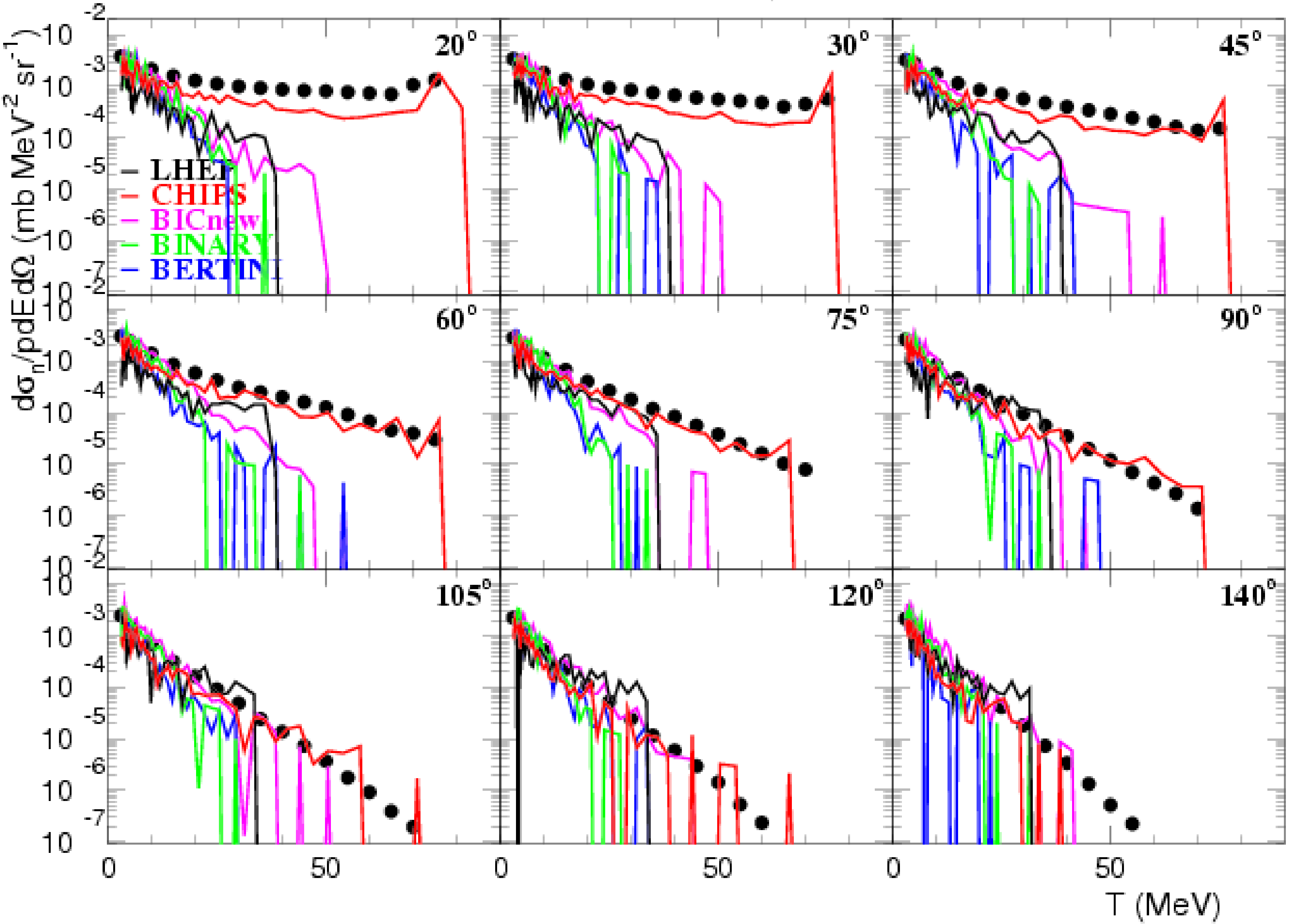


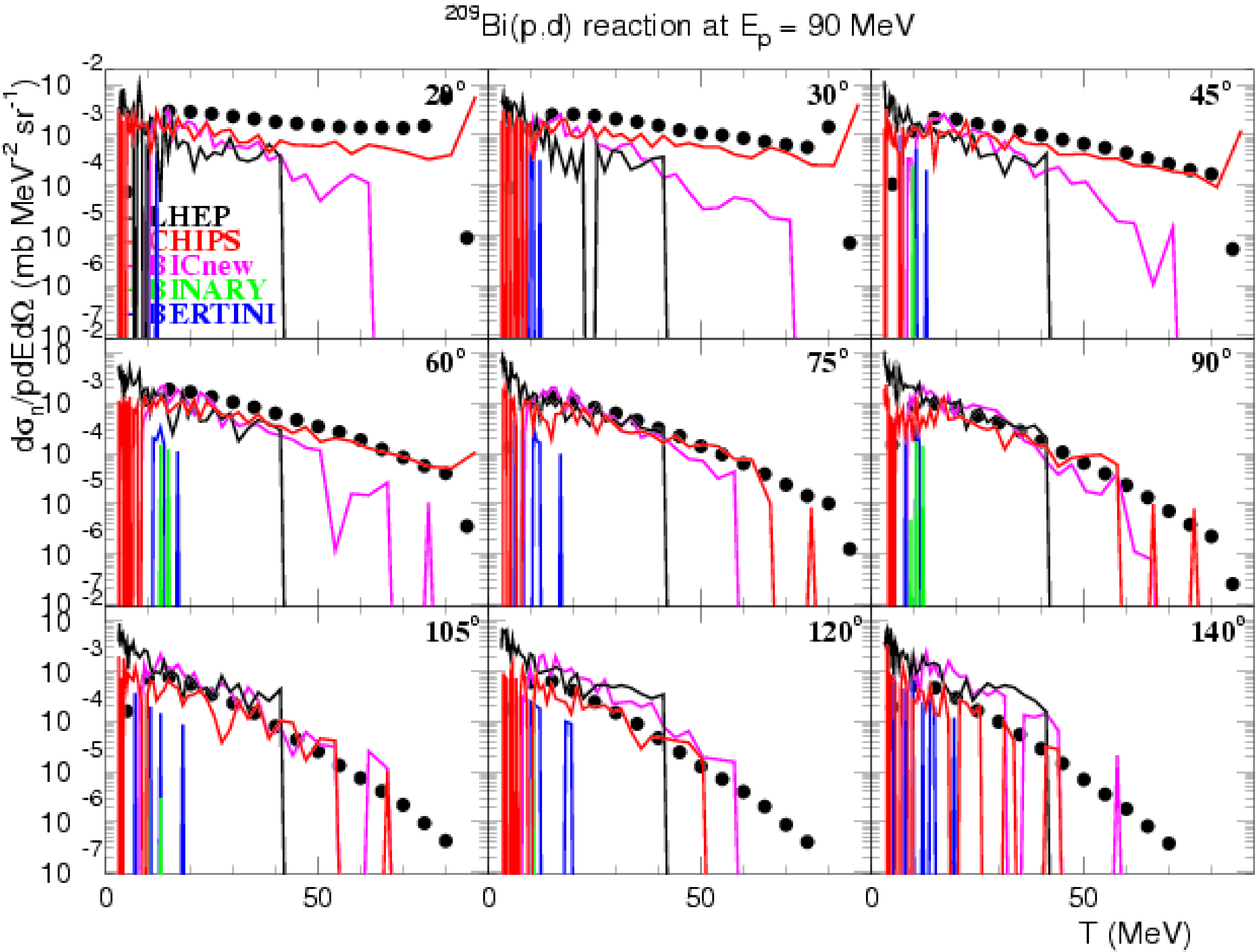






^{27}Al(p,d) reaction at E_p = 90 MeV

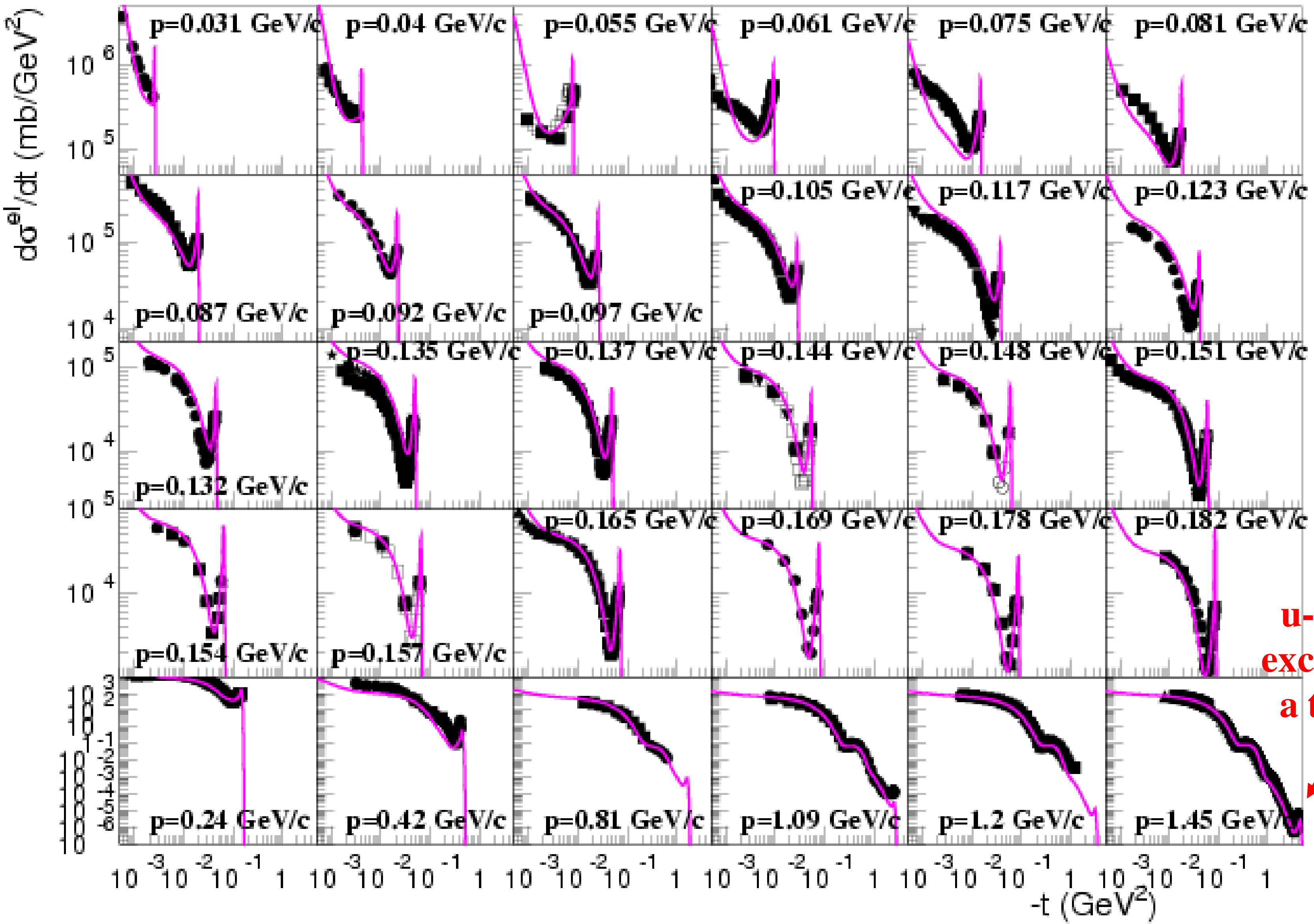




^{209}Bi(p,d) reaction at E_p = 90 MeV
20°
30°
45°
60°
75°
90°
105°
120°
140°
LHEP
CHIPS
BICnew
BINARY
BERTINI
$d\sigma_n/pdEd\Omega$ (mb MeV^{-2} sr^{-1})
T (MeV)

CHIPS differential proton elastic on ^4He

Nuclear gloria is backward diffraction



u-channel exchange by a t-cluster