Dynamics of Interactions of Anti-Protons and Anti-Nuclei with Nuclei in Geant4

A.Galoyan and V. Uzhinsky
(on behalf of the Geant4 Collaboration)

Anti-He-4, March 2011, STAR Collab. , Au+Au (RHIC).
ALICE Collab., Pb+Pb LHC - CERN

Anti-Matter at Accelerators

Discovery of Anti-Nuclei in cosmic rays? - > PAMELA, BESS, AMS, CAPRICE

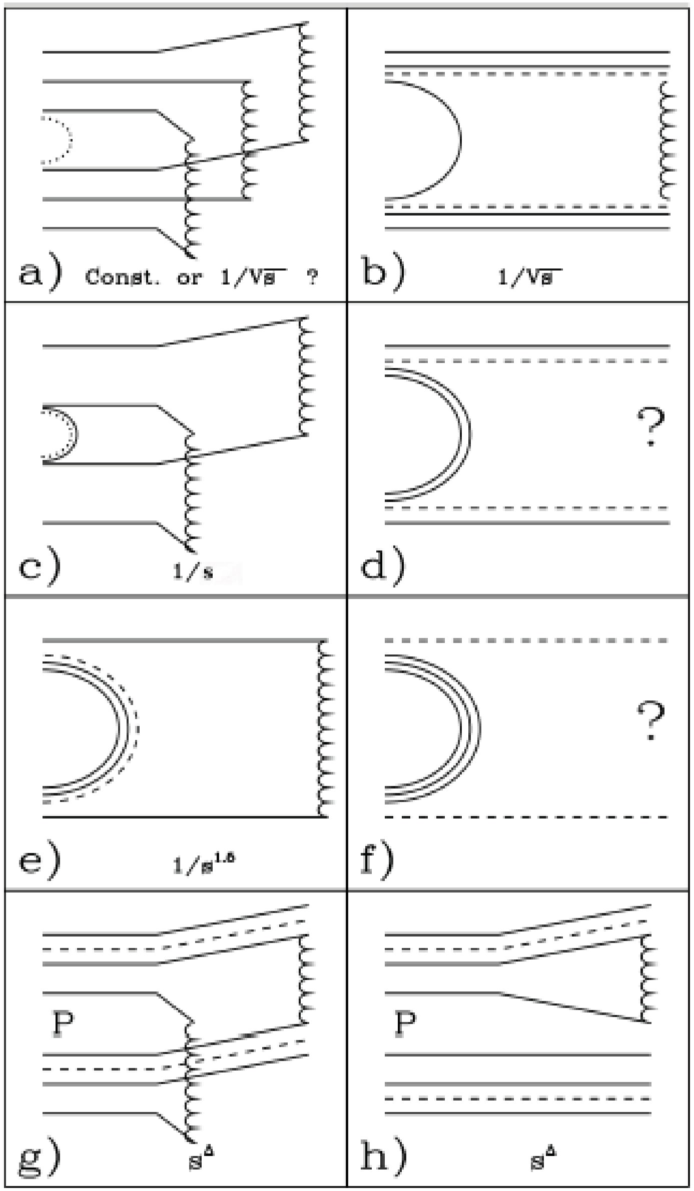
Geant4 9.5 realese (http://geant4.cern.ch/support/source_archive.shtml)

Interactions of anti-baryons (including anti-hyperons) and light anti-nuclei with matter have been implemented in the Fritiof (FTF) model. This model is valid for incident anti-baryon energies from 0 to 1 TeV, and for incident anti-nucleus momenta from 150 MeV/c/nucleon up to 1 TeV/c/nucleon. Corresponding anti-baryon and anti-nuclear cross section classes have also been added. New processes were added to handle inelastic reactions of anti-deuterons, anti-tritons, anti-3He and anti-alphas. (from the release Note)

Content

1. Dynamics of Pbar– P interactions in DPM
2. Determination of cross sections of Pbar-P processes
3. Comparison of calculations of Pbar-P interactions by our model with exp. data
4. Cross sections of antiprotons and light anti-nuclei interactions with nuclei
5. Dynamics of antiproton-nucleus and anti-nucleus – nucleus interactions
6. Description of known antiproton – nucleus exp. data by the FTF model
7. Validation of the FTF model for light anti-nucleus – nucleus interactions

Dynamics of Pbar-P interactions



The question marks mean that the corresponding estimations are absent.

Calculation procedure:

V.V. Uzhinsky and A.S. Galoyan, hep-ph/0212369

Cross-sections of various processes in anti-P P interactions.

Physics Book of PANDA Collaboration,

Physics Performance Report for PANDA
(AntiProton Annihilations at Darmstadt)
Strong Interaction Studies with Antiprotons

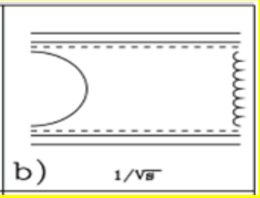
$$\begin{aligned}
\sigma_a &= 51.6/s^{0.5} - 58.8/s + 16.4/s^{1.5}, \\
\sigma_b &= 77.4/s^{0.5} - 88.2/s + 24.6/s^{1.5}, \\
\sigma_c &= 93/s - 106/s^{1.5} + 30/s^2, \\
\sigma_d &= \sigma_e = \sigma_f = 0, \\
\sigma_g &= 18.6/s^{0.08} - 33.5/s^{0.5} + 30.8/s, \\
\sigma_h &= 0,
\end{aligned}$$

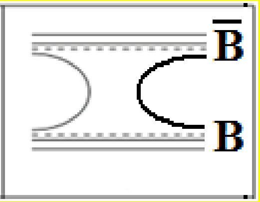
Implementation:

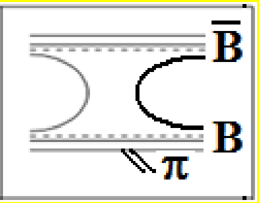
A.Galoian and V.Uzhinsky,AIP Conf.Proc.796:79,2005

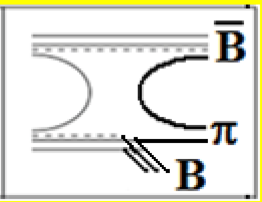
New Monte Carlo implementation of quark-gluon string model of anti-p p interactions.

Cross sections, process "b", anti-diquark – diquark string creation



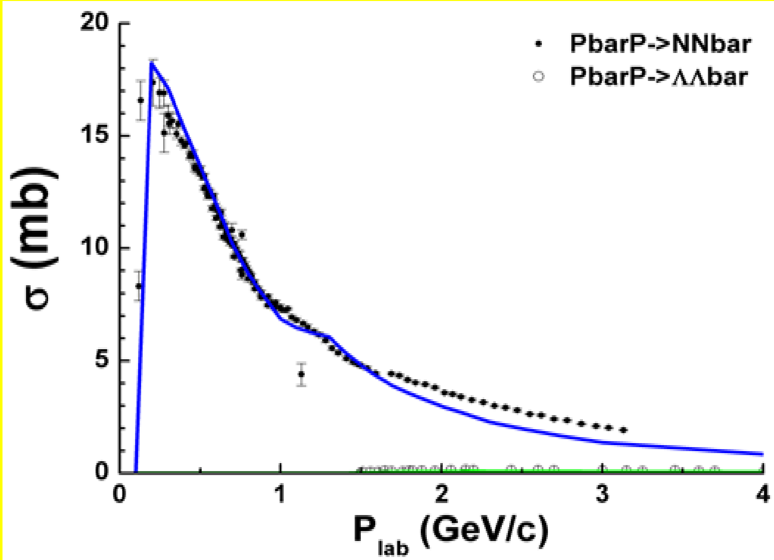


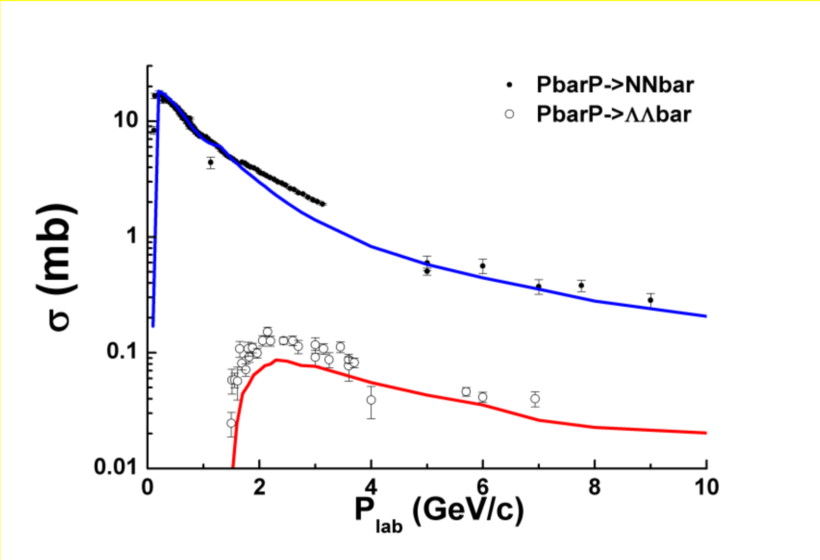




2-particle decay

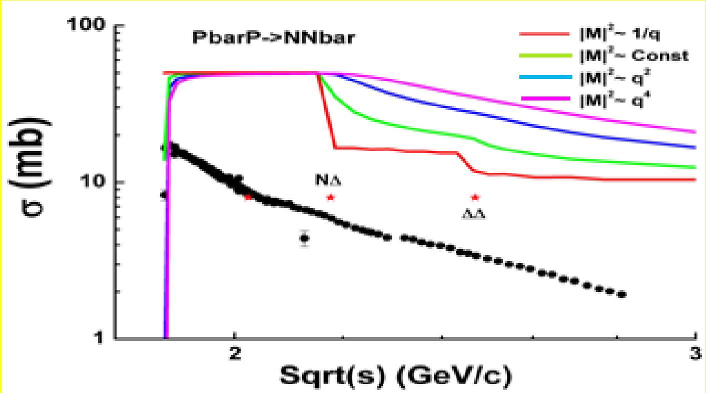
$$\sigma_{N\bar{N}} \propto \sigma_b \; P_2(M=\sqrt{s}) \qquad \sigma_{\Lambda\bar{\Lambda}} \propto \sigma_b \; P_2(M=\sqrt{s}) P_{s\bar{s}}$$

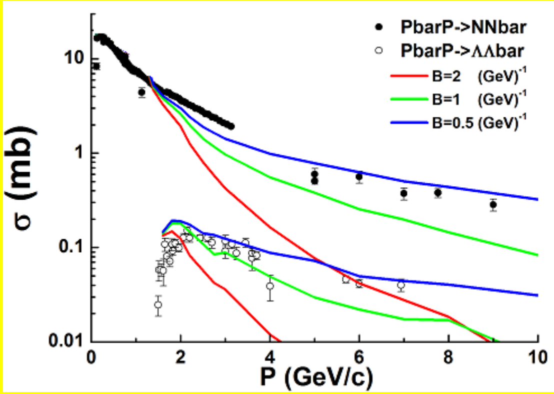


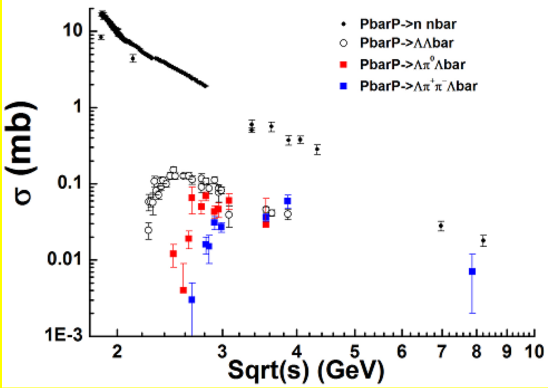


$$\sigma_b = 15.65 + 700 * (2.172 - \sqrt{s})^{2.5} \quad (mb), \qquad \sqrt{s} \leq 2.172 \quad (GeV)$$

$$\sigma_b = 34/\sqrt{s} \quad (mb), \qquad \sqrt{s} > 2.172 \quad (GeV)$$

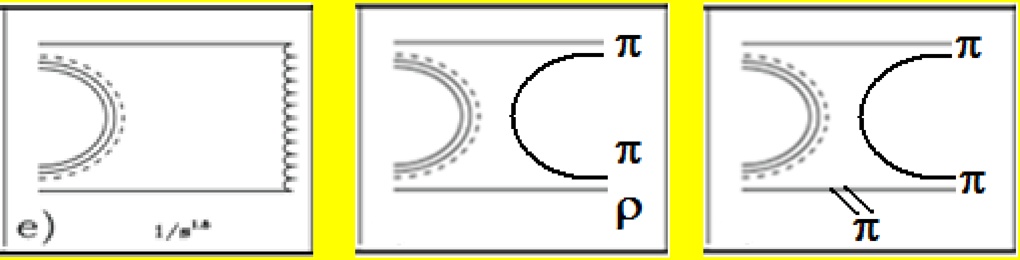






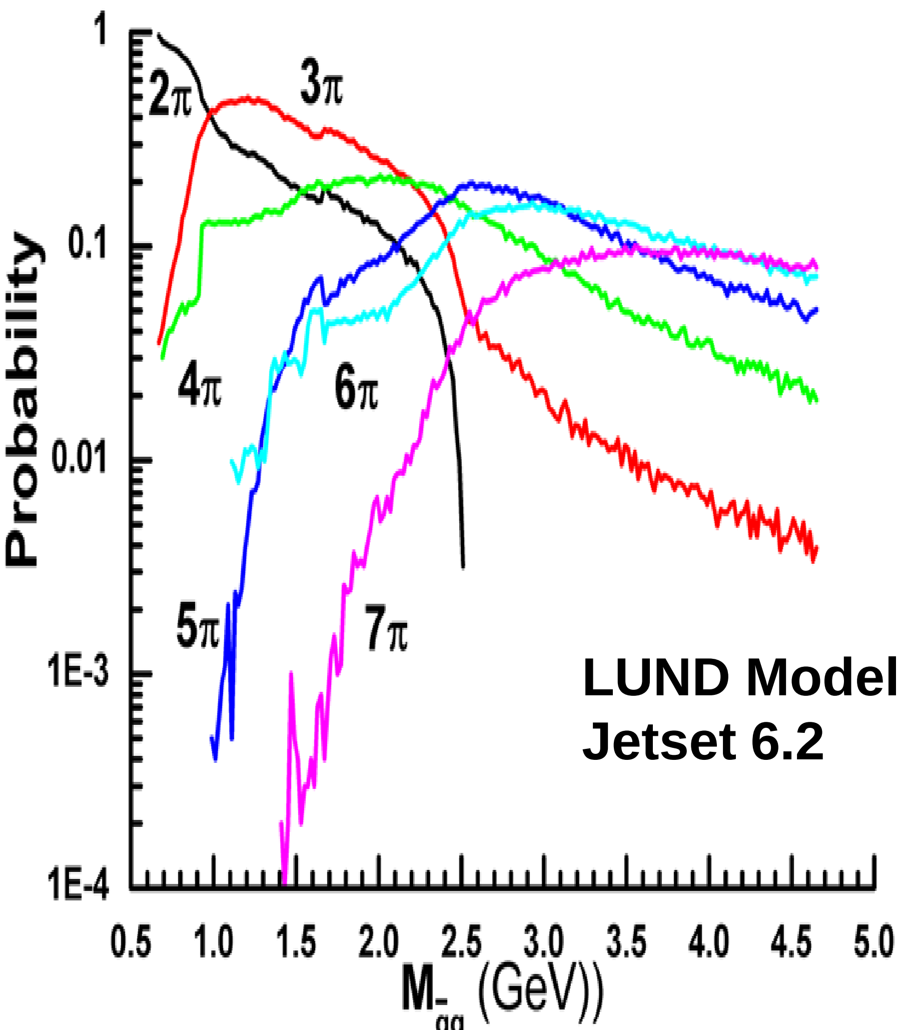
$P_2 = 1$ (no fragmentation) $\qquad P_2(M) = exp[-B*(M - M_{min})]$

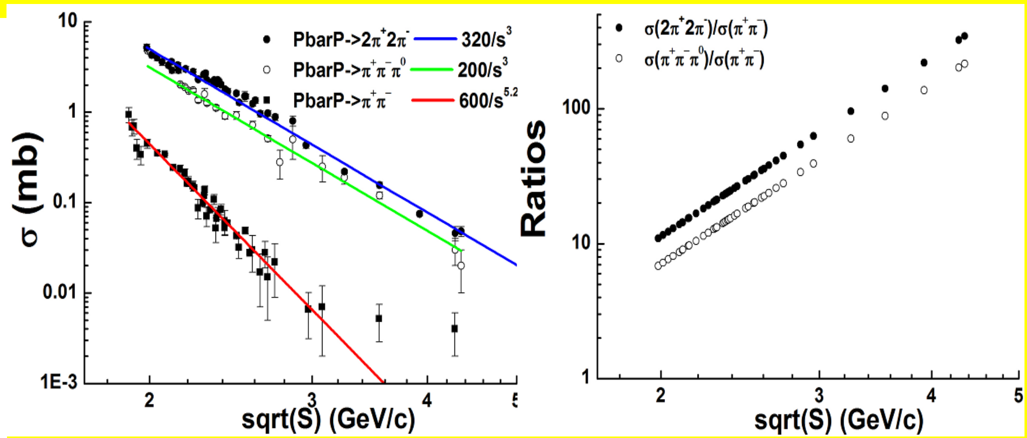
Cross sections, process “e”, anti-quark – quark string creation

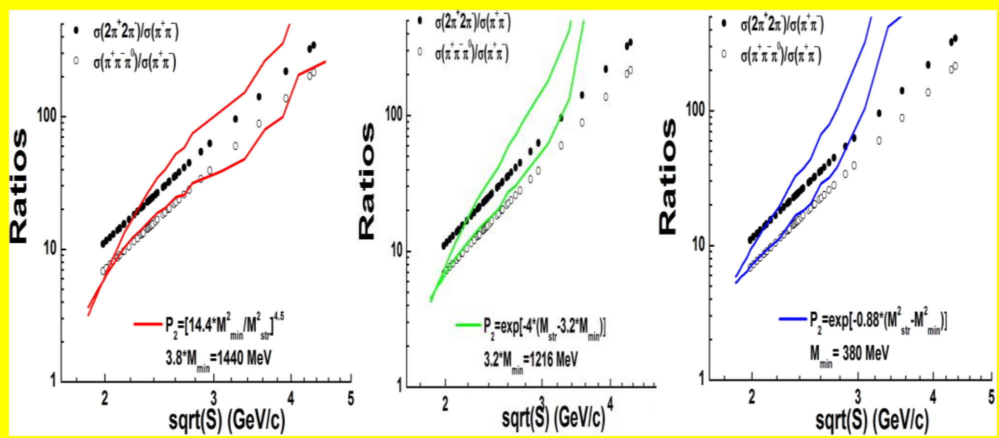


$$\sigma_{\pi^+\pi^-} \propto \sigma_e \; P_2(M = \sqrt{s})$$

$$\sigma_{\pi^+\pi^-\pi^0} \propto \sigma_e \; (1 - P_2(\sqrt{s})) \int P_F(\sqrt{s}, M) \; P_2(M) \; dM$$

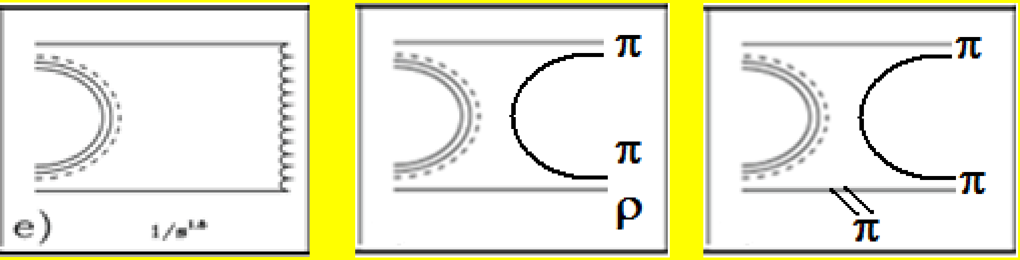






$$P_2(M) = exp[-B * (M^2 - M_{min}^2)]$$

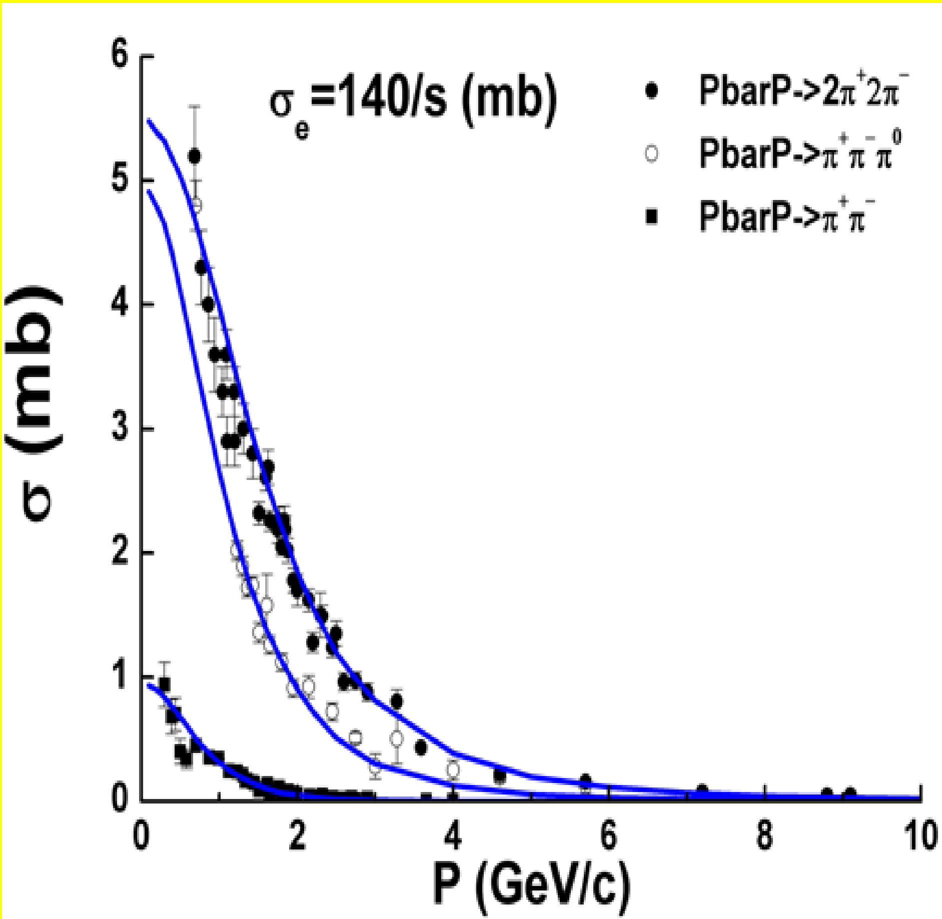
Cross sections, process “e”, anti-quark – quark string creation

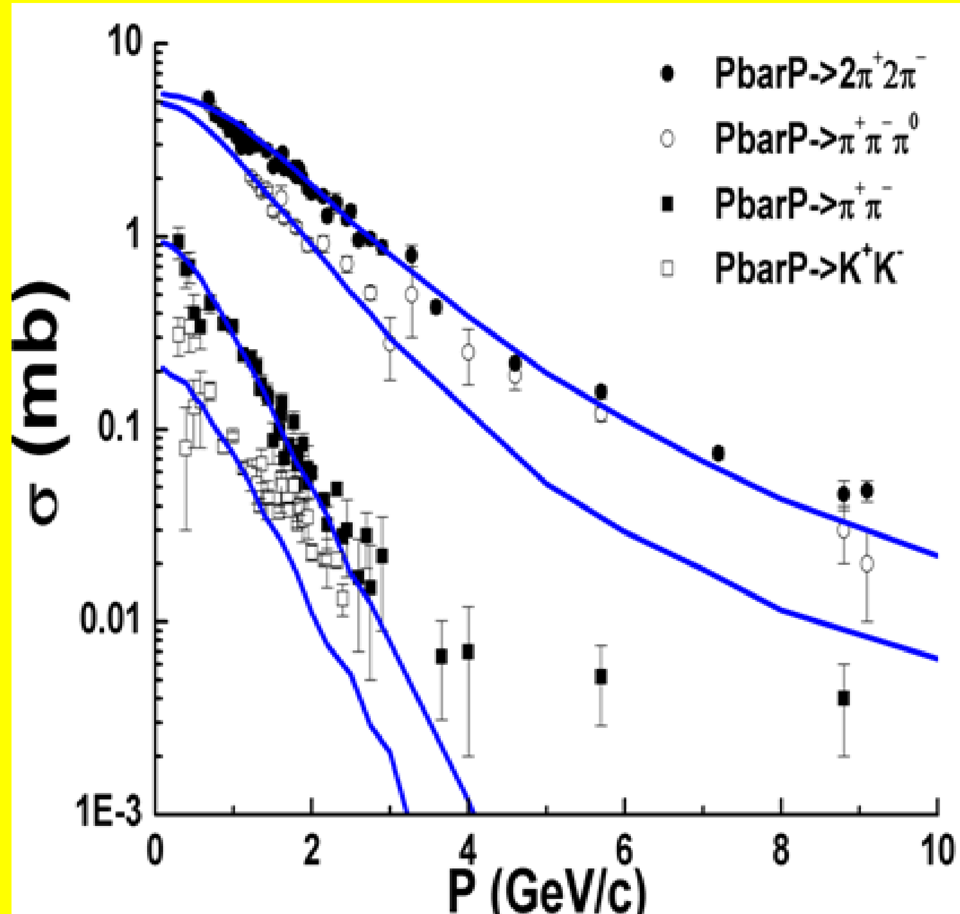


$$\sigma_{\pi^+\pi^-} \propto \sigma_e \; P_2(M=\sqrt{s})$$

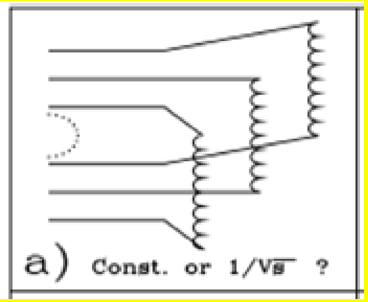
$$\sigma_{\pi^+\pi^-\pi^0} \propto \sigma_e \; (1-P_2(\sqrt{s})) \int P_F(\sqrt{s},M) \; P_2(M) \; dM$$

$$P_2(M) = exp[-B*(M^2-M^2_{min})]$$



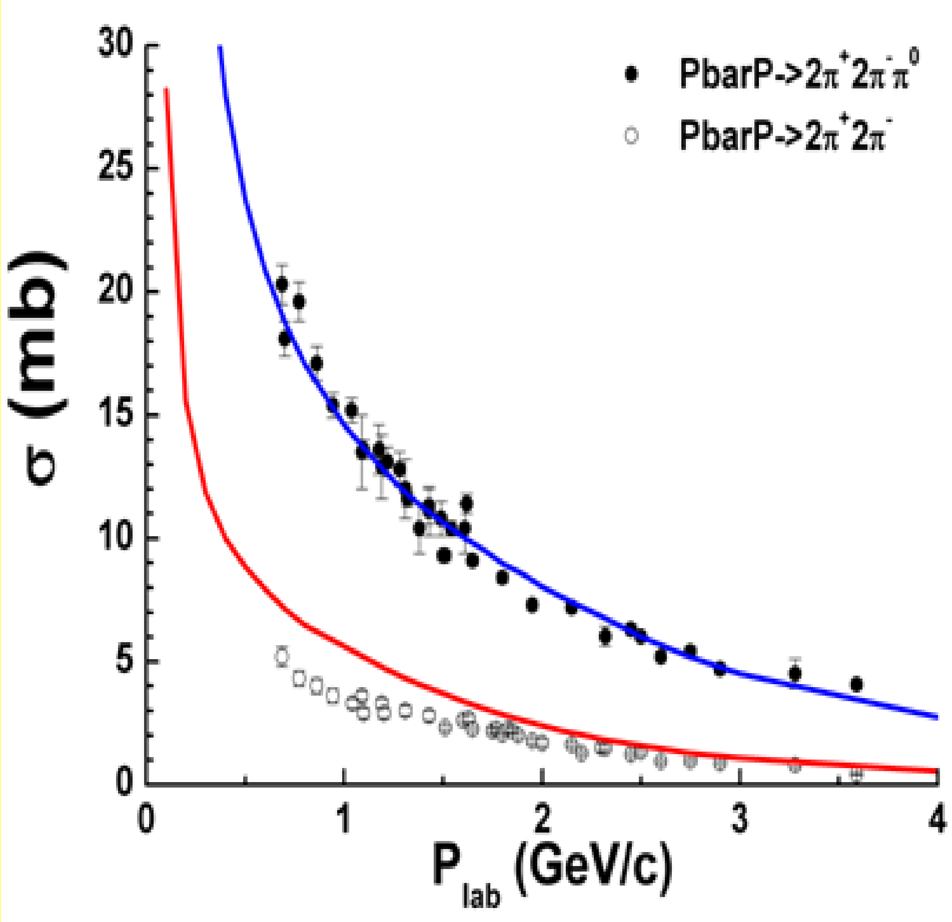


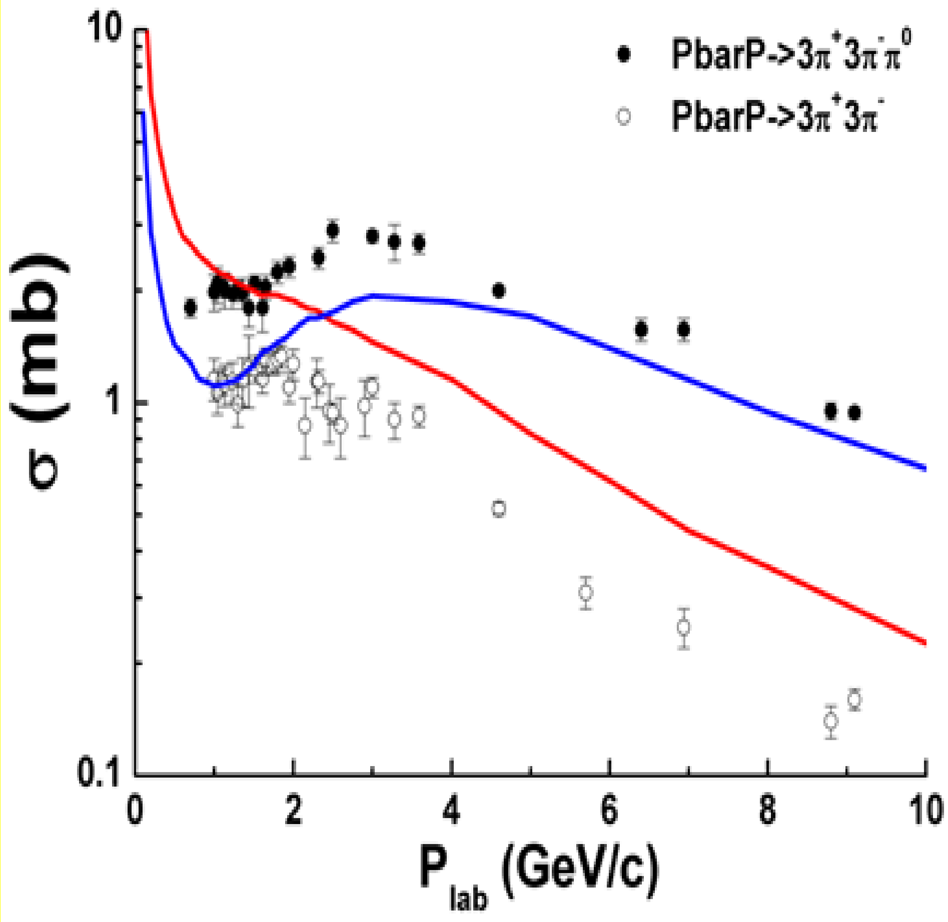
$$\sigma_e = 140/s \quad (mb)$$



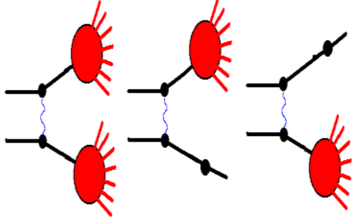
Cross sections, process "a",
3 anti-quark – quark string creation

$$\sigma_a = \frac{25}{\sqrt{s - 4m^2}} \quad (mb)$$



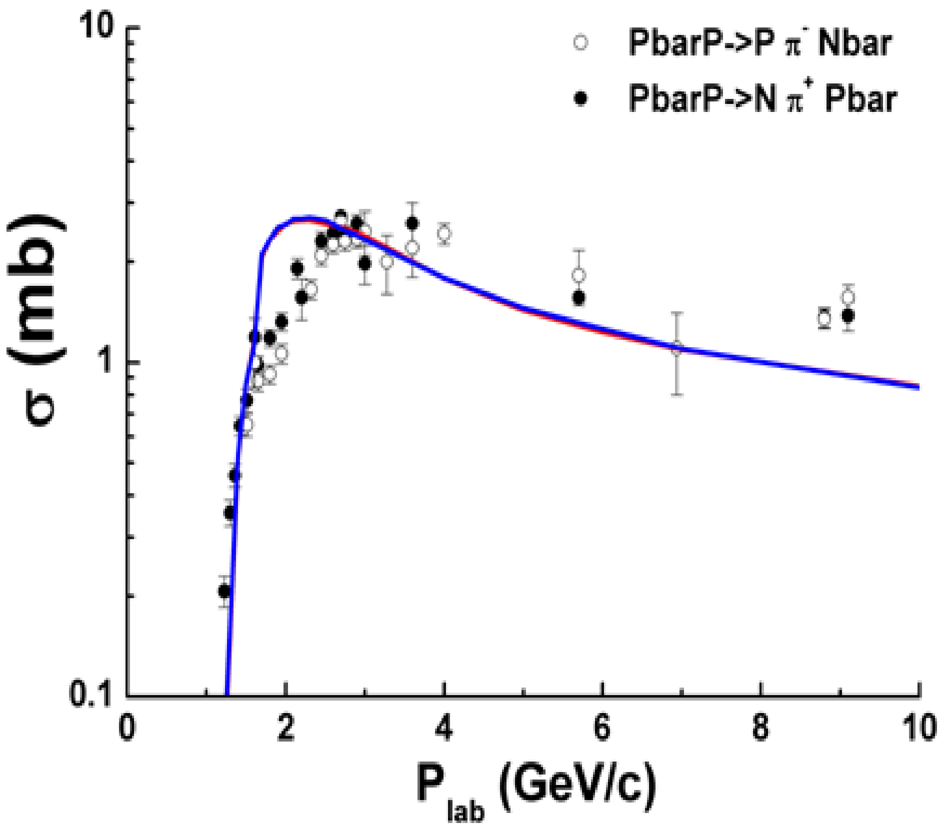


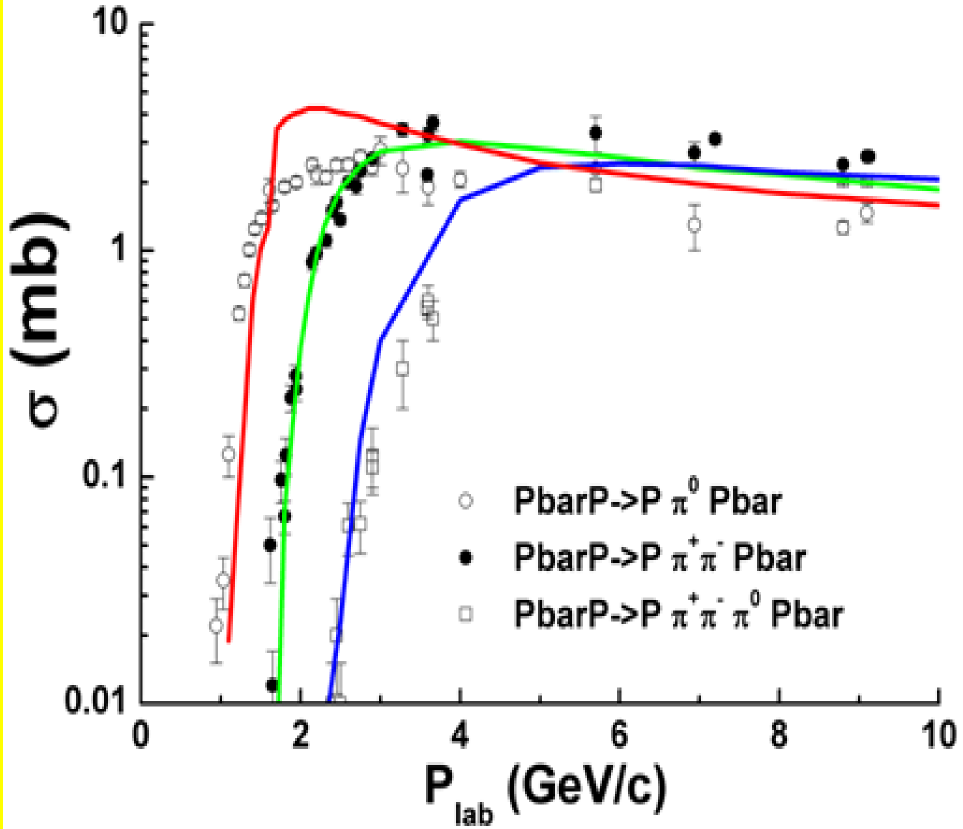
Main channels of antiproton – proton interactions are reproduced!



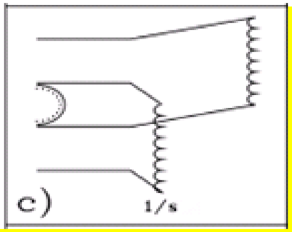
Cross sections, process “g/h”, high energy interactions

$$\sigma_{FTF} = \sigma_{in} - \sigma_a - \sigma_b - \sigma_c - \sigma_e \simeq 35 * (1. - 2.1/\sqrt{s}) \quad (mb)$$



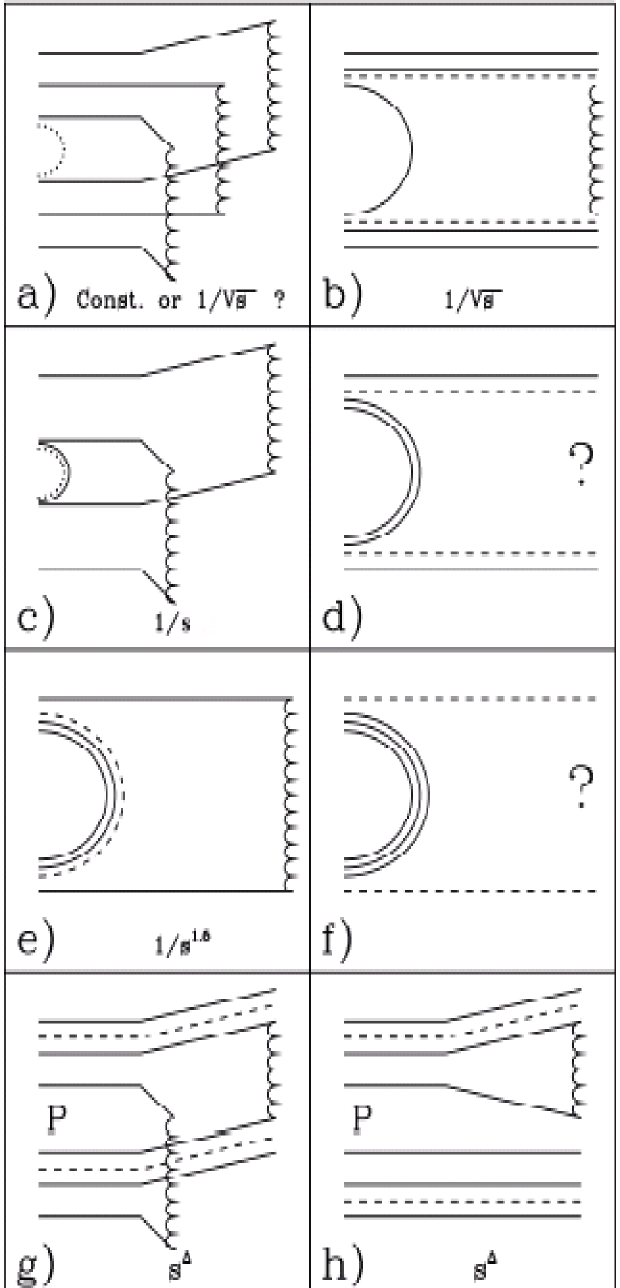


Cross sections, process “c”, creations of 2 anti-quark – quark strings



$$\sigma_c = \frac{2}{\sqrt{s - 4m^2}} \left(\frac{m_p + m_t}{s} \right)^2 \quad (mb)$$

Cross sections of Pbar-P processes in FTF model of Geant4



$$\sigma_a = \frac{25}{\sqrt{s-4m^2}} \quad (mb)$$

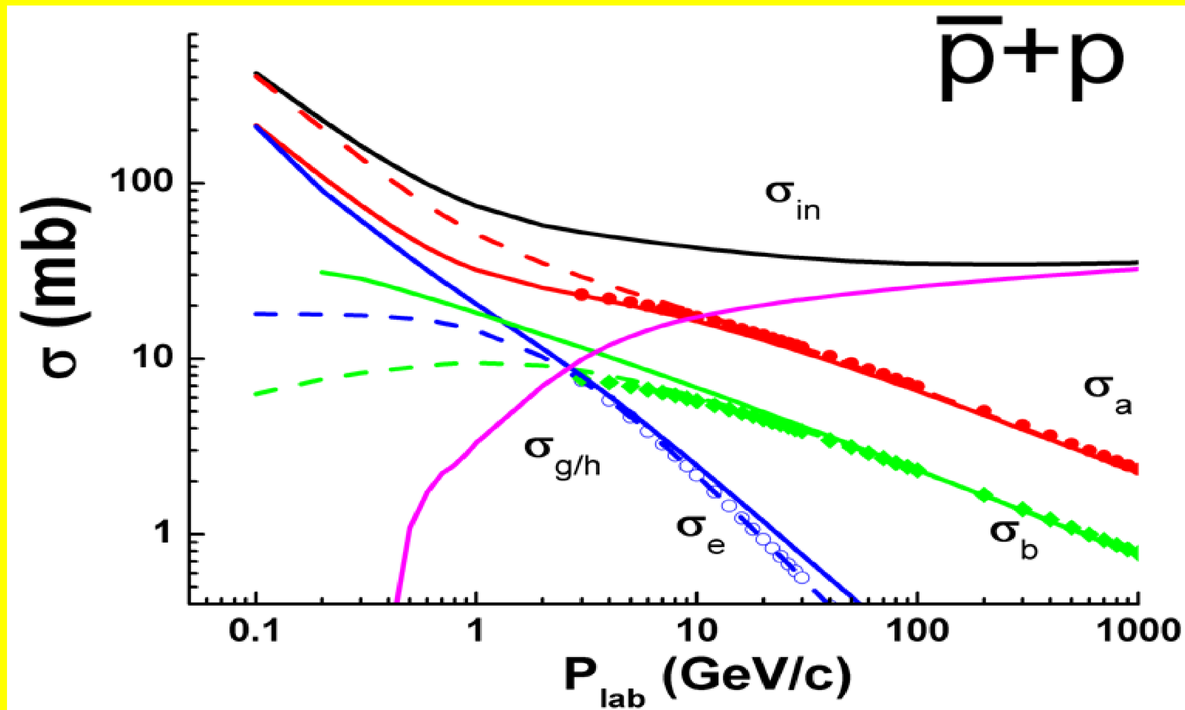
$$\sigma_b = 15.65 + 700 * (2.172 - \sqrt{s})^{2.5} \quad (mb), \quad \sqrt{s} \leq 2.172 \quad (GeV)$$

$$\sigma_b = 34/\sqrt{s} \quad (mb), \quad \sqrt{s} > 2.172 \quad (GeV)$$

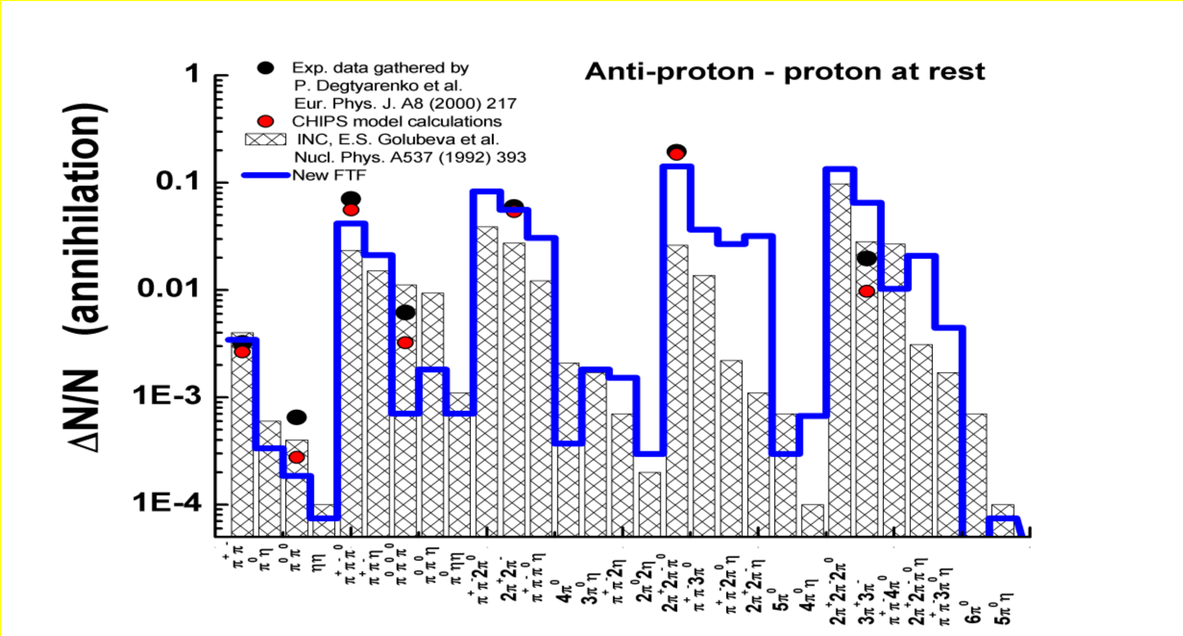
$$\sigma_c = \frac{2}{\sqrt{s-4m^2}} \left(\frac{m_p + m_t}{s} \right)^2 \quad (mb)$$

$$\sigma_e = 140/s \quad (mb)$$

$$\sigma_{FTF} = 35 * (1. - 2.1/\sqrt{s}) \quad (mb)$$

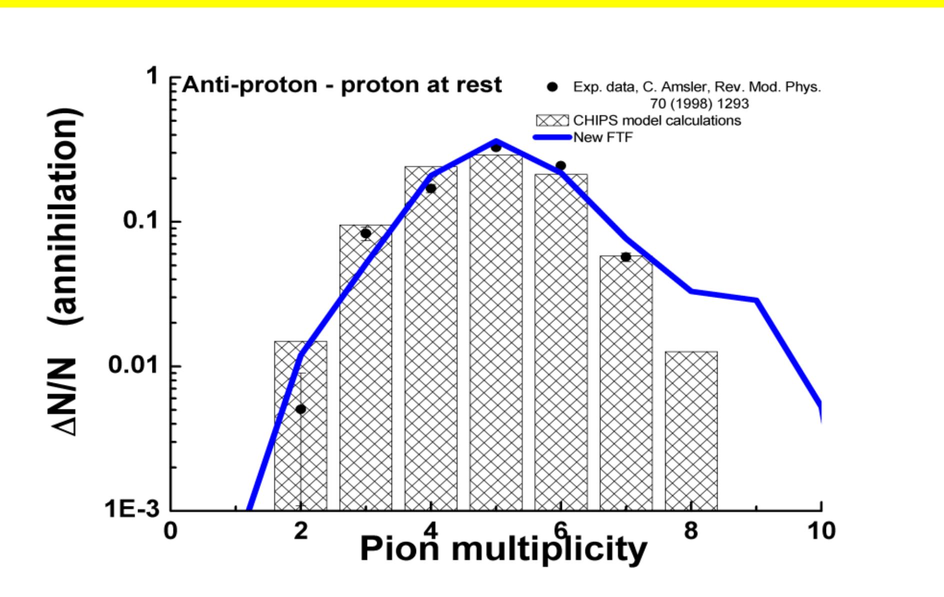


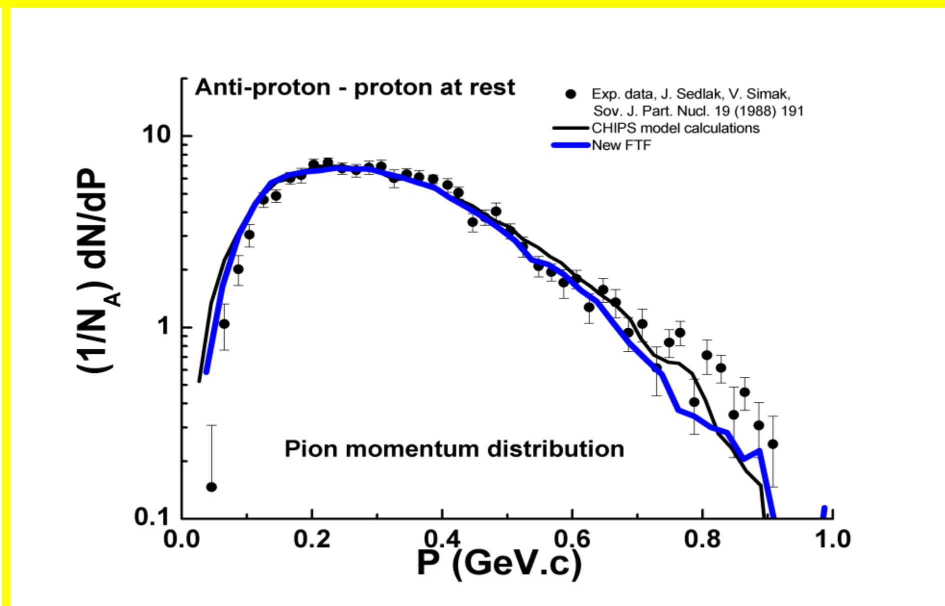
Validation of FTF model, Pbar-P annihilation at rest



See more data in:
C. Amsler F. Myhrer
Ann. Rev. Nucl. Part. Sci.
v. 41 (1991) 219.

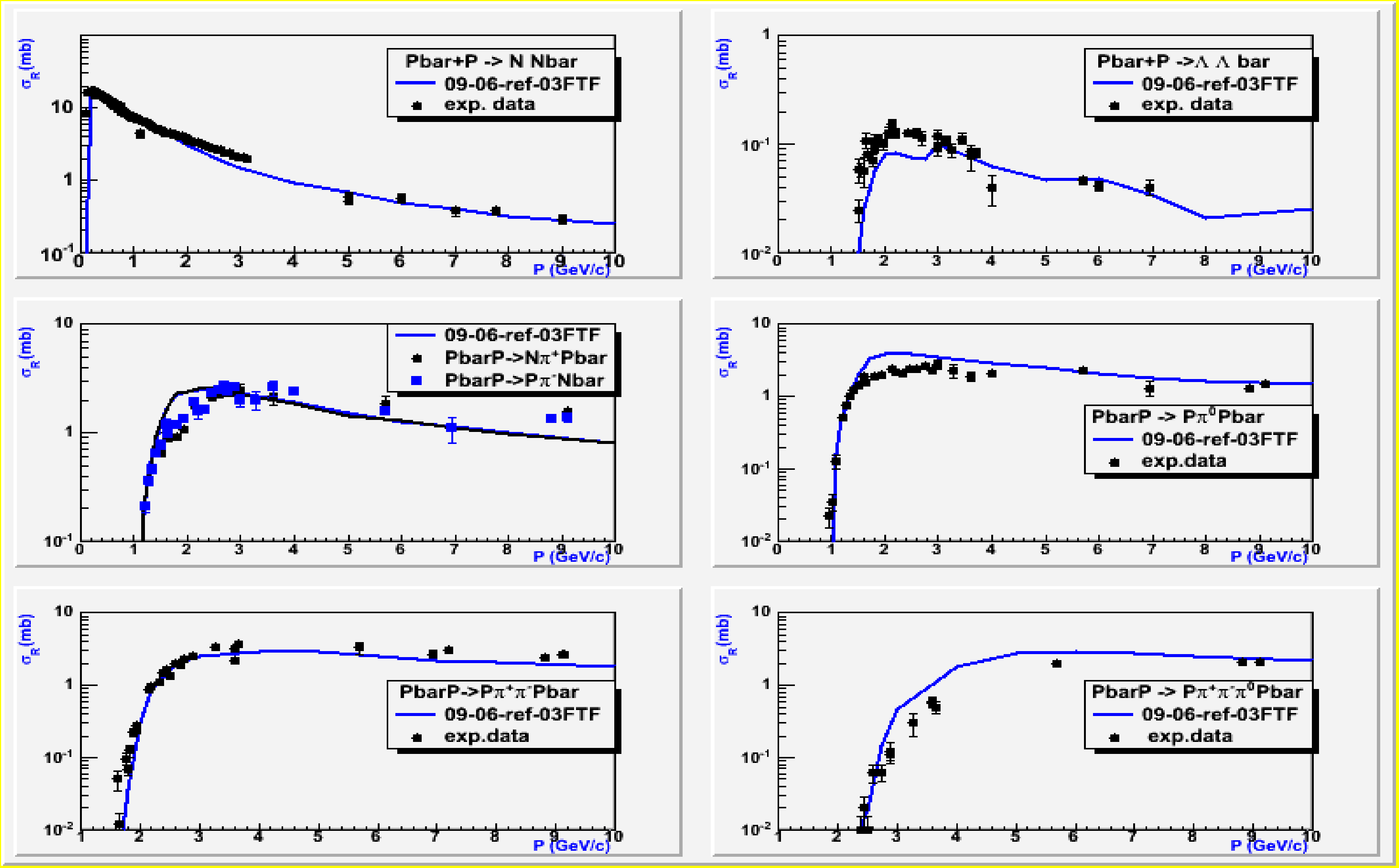
C. Amsler **Rev. Mod. Phys. 70 (1998) 1293**





Pbar-P channel cross sections with baryons in final states

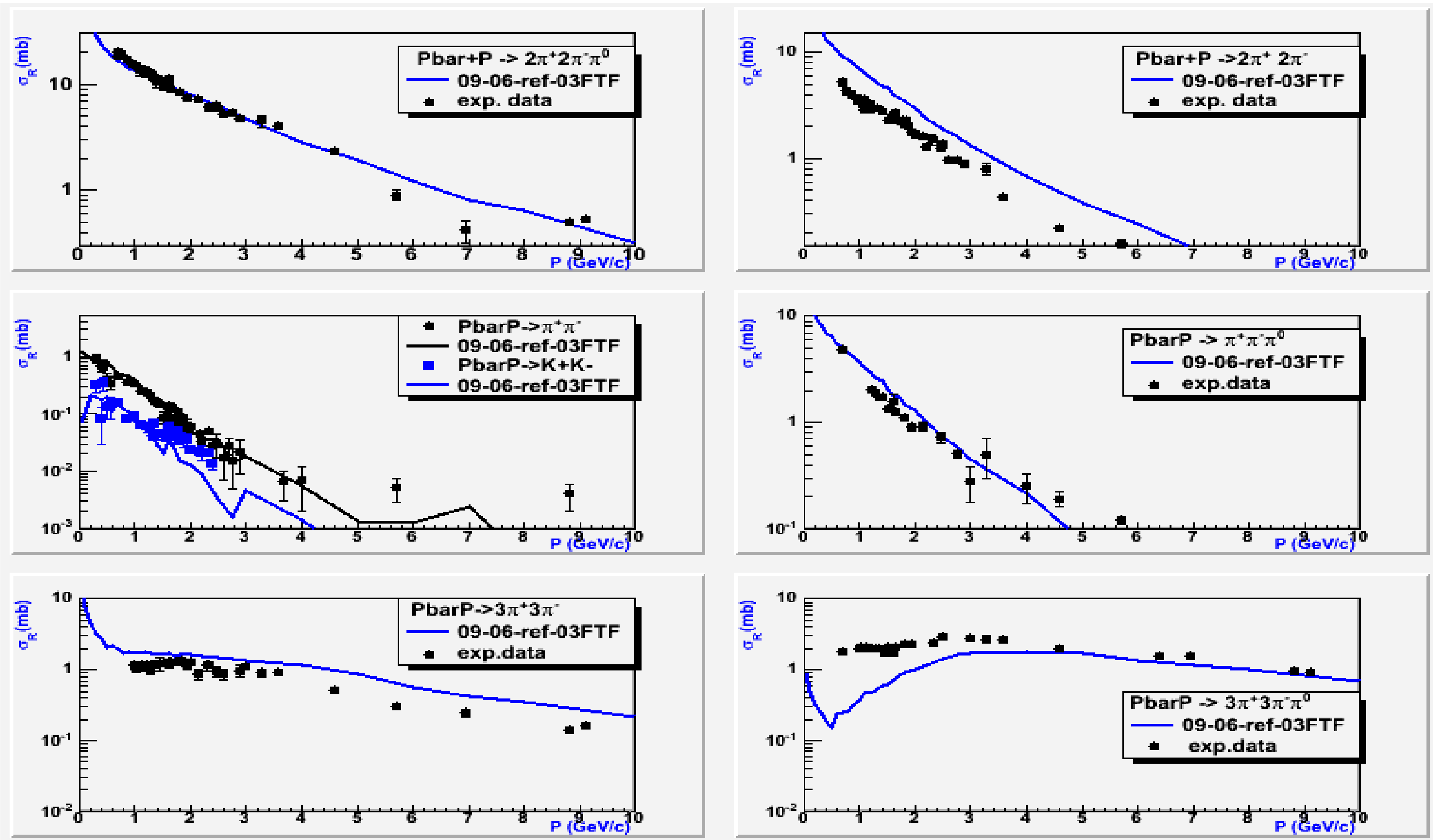
http://g4validation.fnal.gov:8080/G4ValidationWebApp/G4ValHAD.jsp



E.Bracci et al.,CERN/HERA 73-1(1973)

Pbar-P annihilation channel cross sections

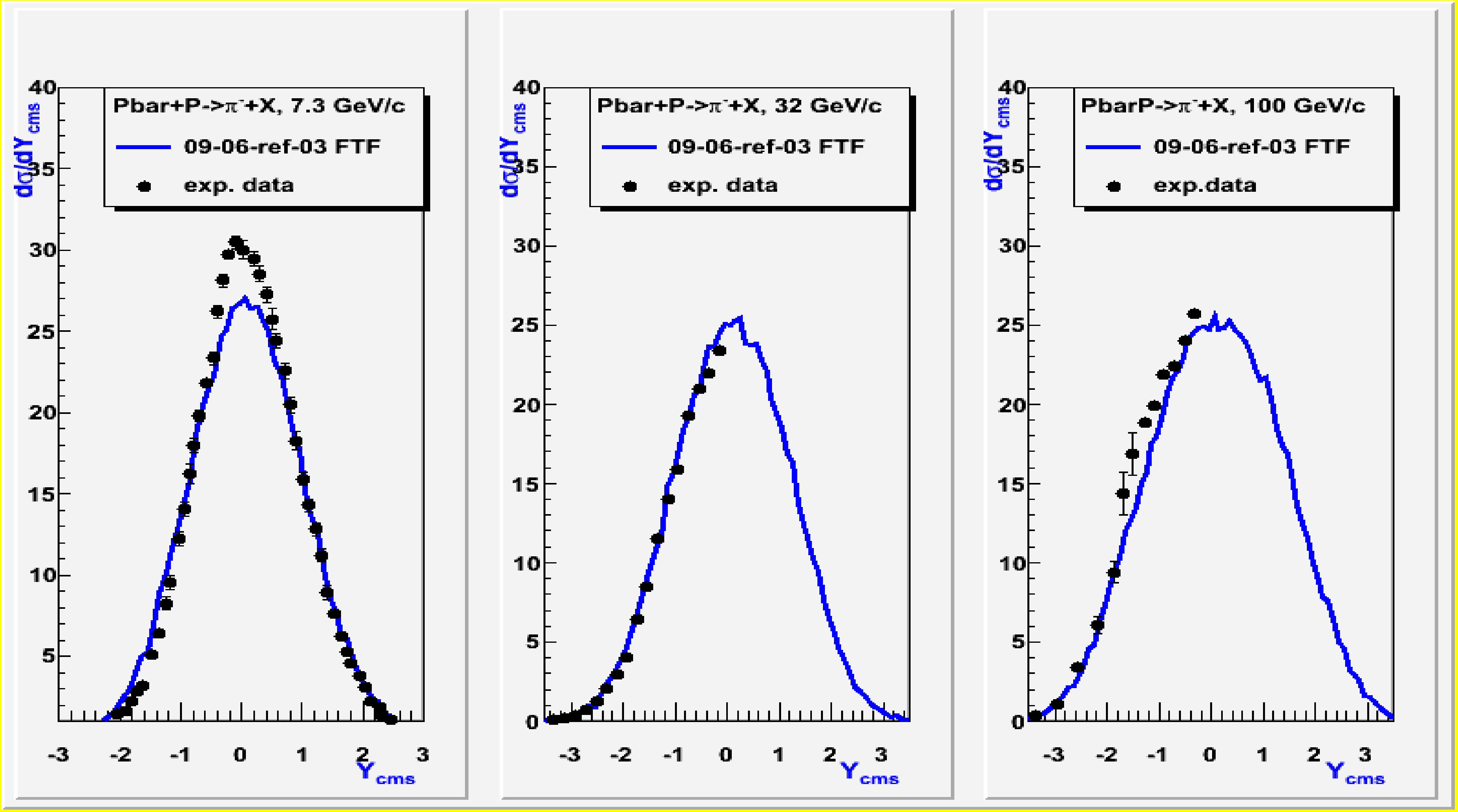
http://g4validation.fnal.gov:8080/G4ValidationWebApp/G4ValHAD.jsp



Exp. Data: E.Bracci et al.,CERN/HERA 73-1(1973)

Results for inclusive cross sections of Antiproton – Proton reactions

Rapidity distributions of pi- mesons in Pbar-P interactions.



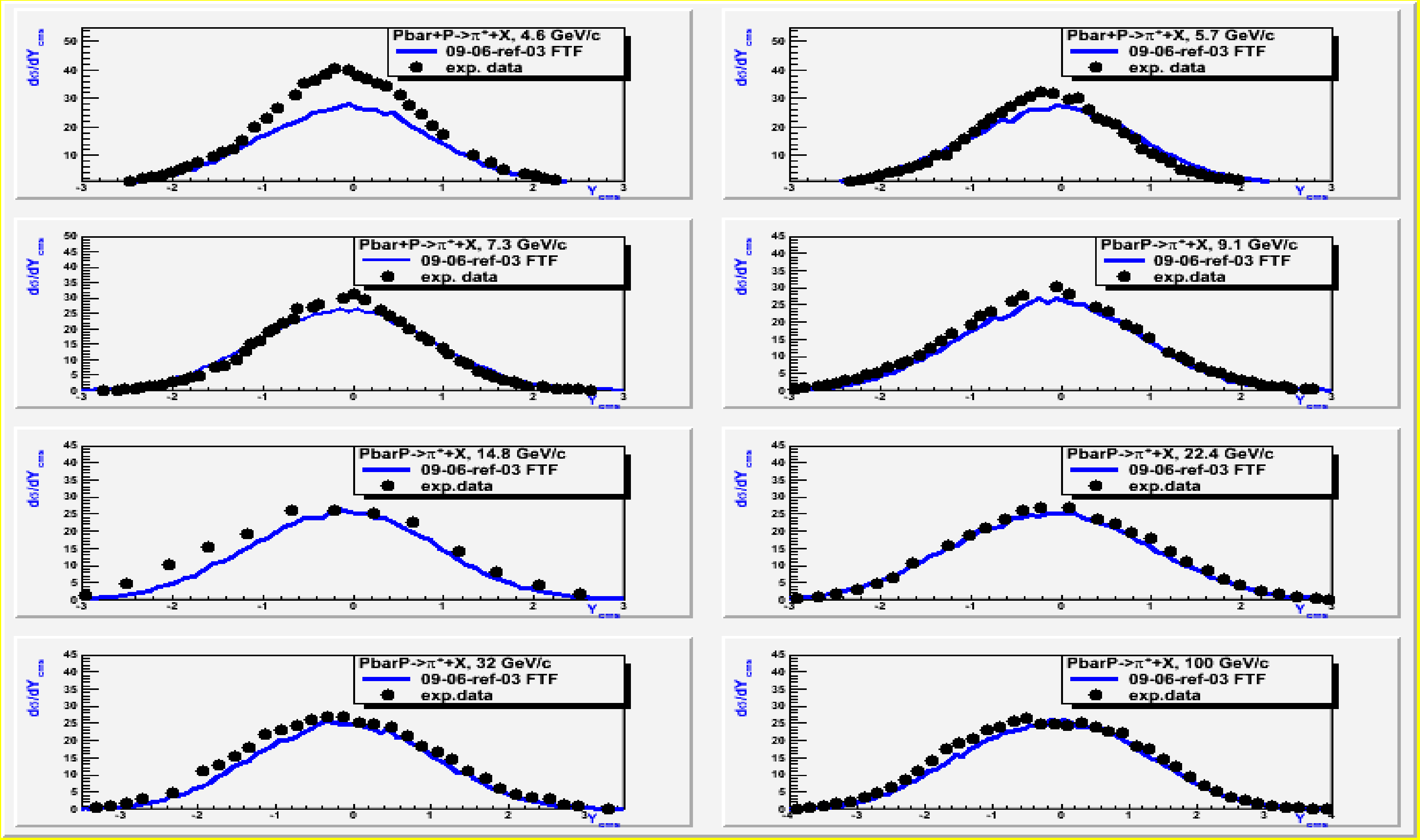
G.D. Patel et al., Z. Phys. C - Particles and Fields 12,189, 1982

C.P. Ward et al., Nucl. Phys. B153 299 1979

E.E. Zabrodin et al., Phys. Rev.D, V52, N3, 1995

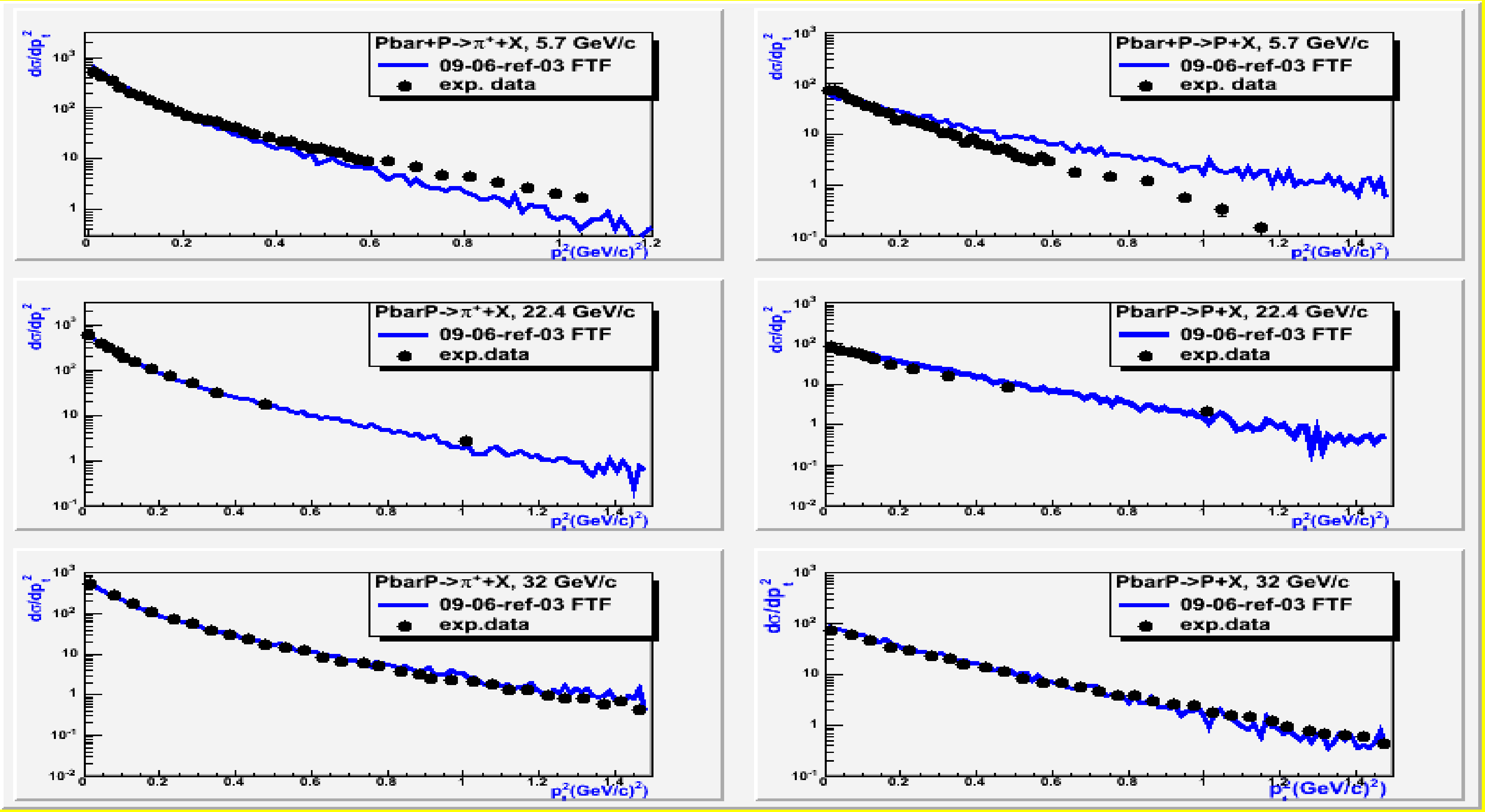
Results for inclusive cross sections of Antiproton – Proton reactions

Rapidity distributions of pi+ mesons in Pbar-P interactions in a wide energy range



Results for inclusive cross sections of Antiproton–Proton reactions

P_T^2 of Pi+ mesons **P_T^2 of Protons**



J. Chyla, Czech. J. Phys. B 30 1980

E .G. Boos et al., Nucl. Phys. B174 45, 1980

E.V. Vlasov, Z. Phys. C - Particles and Fields 13, 95, 1982

Glauber theory for antiproton-nucleus interactions

For the first time a good description of Pbar D interactions was reached in the paper by
V. Franco, R.J. Glauber Phys. Rev. 142 (1966) 119 High-energy deuteron cross-sections.

O.D. Dalkarov, V.A. Karmanov Nucl.Phys.A445:579-604,1985.

Amplitude of hadron-nucleus elastic scattering

$$F_{hA}(\vec{q}) = \frac{1}{2\pi} \int d^2b \, e^{i\vec{q}\vec{b}} \left\{1 - \prod_{i=1}^{A}\left[1 - \gamma(\vec{b} - \vec{s}_i)\right]\right\} |\Psi_A|^2 \left(\prod_{i=1}^{A} d^3 r_i\right) = \int bP_{hA}(b) \, J_0(qb)db,$$

Differential elastic scattering cross section $d^2\sigma/d^2q = |F_{hA}(\vec{q})|.$

Amplitude of elastic hN scattering in impact parameter representation

$$\gamma(\vec{b}) = \frac{\sigma_{hN}^{tot} \, (1 - i\rho)}{2\pi \, \beta} \, e^{-\vec{b}^2/2B},$$

ß is the slope parameter of hN differential elastic cross section

$$\beta = (\sigma_{hN}^{tot})^2(1 + |\rho|^2)/(16 \, \pi \, \sigma_{hN}^{el} \, 0.3897).$$

Square module of the wave function is written as:

$$|\Psi_A|^2 = \delta(\sum_{i=1}^{A} \vec{r}_i/A) \prod_{i=1}^{A} \rho_A(\vec{r}_i).$$

Diagen: Generator Of Inelastic Nucleus-nucleus Interaction Diagrams.
S. Shmakov, V.Uzhinsky, A.Zadorozhny, Comp. Phys. Comm., 54 (1989) 125

Our parameterization of Pbar–P cross sections

$$\sigma^{tot}_{\bar{p}p} = \sigma^{tot}_{asmpt}\left[1 + \frac{C}{\sqrt{s-4m_N^2}}\frac{1}{R_0^3}\left(1+\frac{d_1}{s^{0.5}}+\frac{d_2}{s^1}+\frac{d_3}{s^{1.5}}\right)\right]$$

$$\sigma^{tot}_{asmpt} = 36.04 + 0.304\ \left(log(s/33.0625)\right)^2$$

$$R_0 = \sqrt{0.40874044\ \sigma^{tot}_{asmpt} - B}$$

$$B = 11.92 + 0.3036\ \left(log(\sqrt{s}/20.74\right)^2$$

$$C = 13.55,\ d_1 = -4.47,\ d_2 = 12.38,\ d_3 = -12.43$$

$$\sigma^{el}_{\bar{p}p} = \sigma^{el}_{asmpt}\left[1 + \frac{C}{\sqrt{s-4m_N^2}}\frac{1}{R_0^3}\left(1+\frac{d_1}{s^{0.5}}+\frac{d_2}{s^1}+\frac{d_3}{s^{1.5}}\right)\right]$$

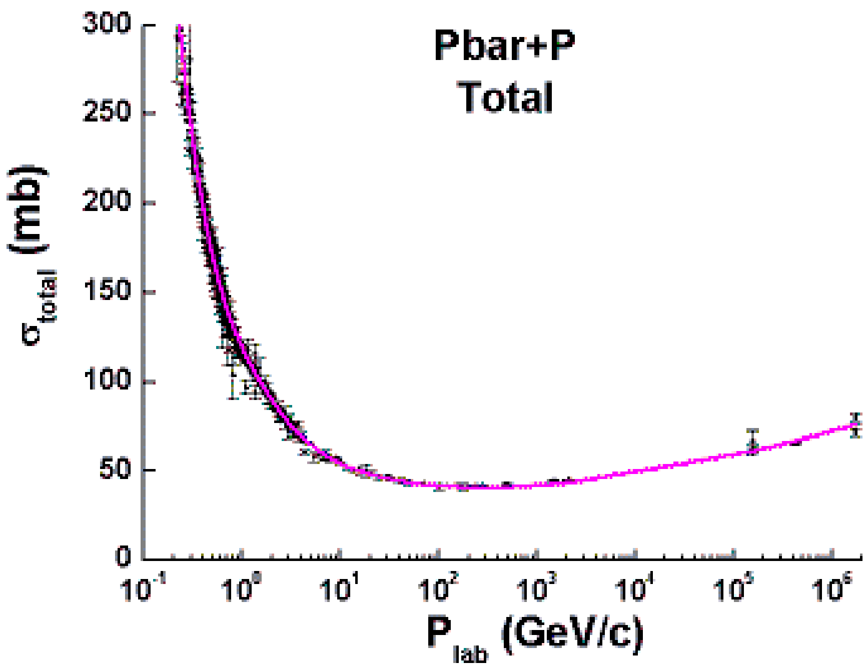
$$\sigma^{el}_{asmpt} = 4.5 + 0.101\ \left(log(s/33.0625)\right)^2$$

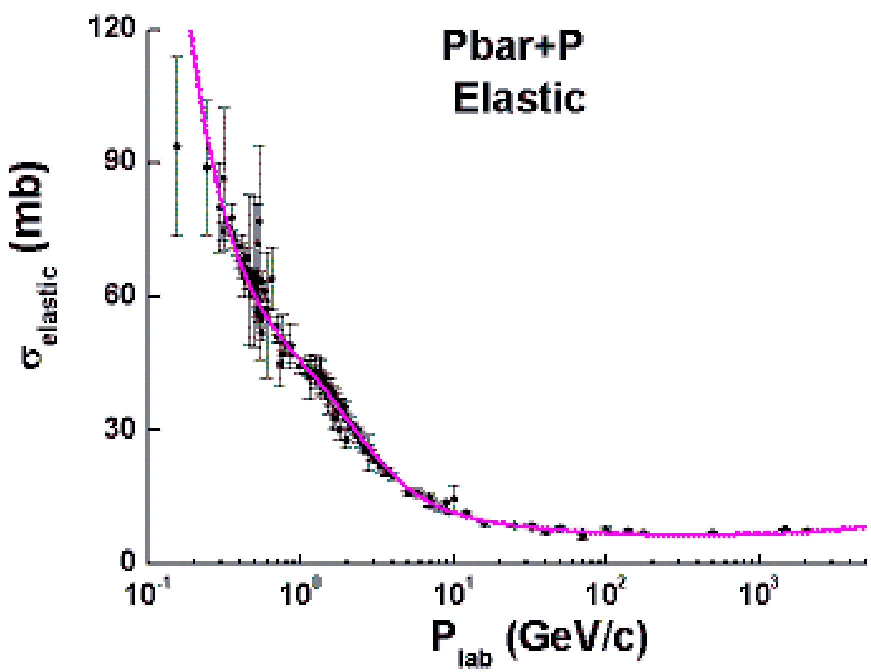
$$R_0 = \sqrt{0.40874044\ \sigma^{tot}_{asmpt} - B}$$

$$B = 11.92 + 0.3036\ \left(log(\sqrt{s}/20.74\right)^2$$

$$C = 59.27,\ d_1 = -6.95,\ d_2 = 23.54,\ d_3 = -25.34$$

$\sigma_{el}/\sigma_{tot}=1/(2\ C_{sh})\approx 1/3$, according to the quasi-eikonal approach of the reggeon field theory (K.A. Ter-Martirosyan, A.B. Kaidalov)



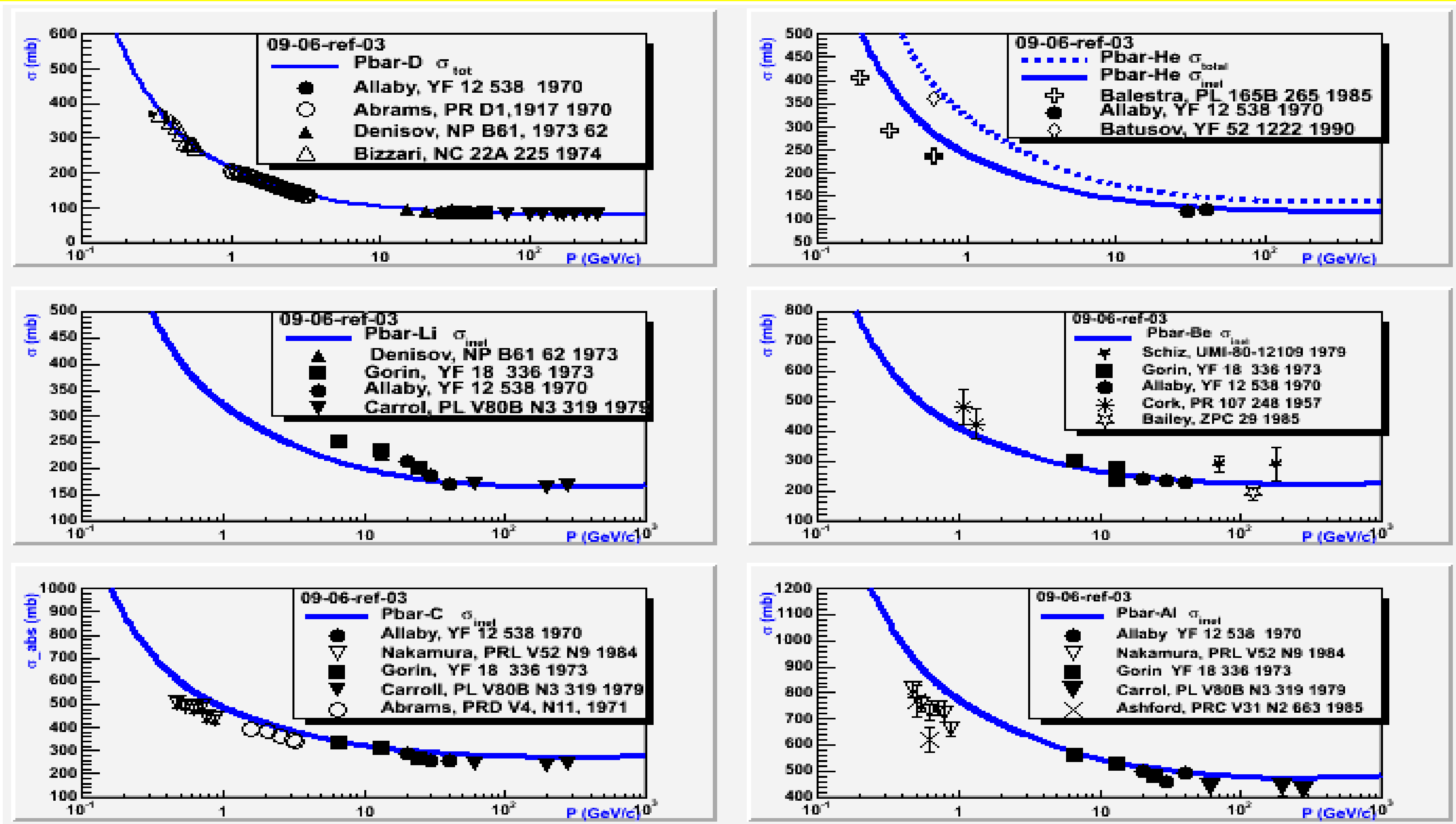


Antiproton–Nucleus interactions, cross sections for light nuclei

V. Uzhinsky, J. Apostolakis , A. Galoyan et al.

Phys. Lett. B705 (2011) 235

Antiproton-nucleus cross sections implemented in Geant4 PhysicsList – FTF_BERT



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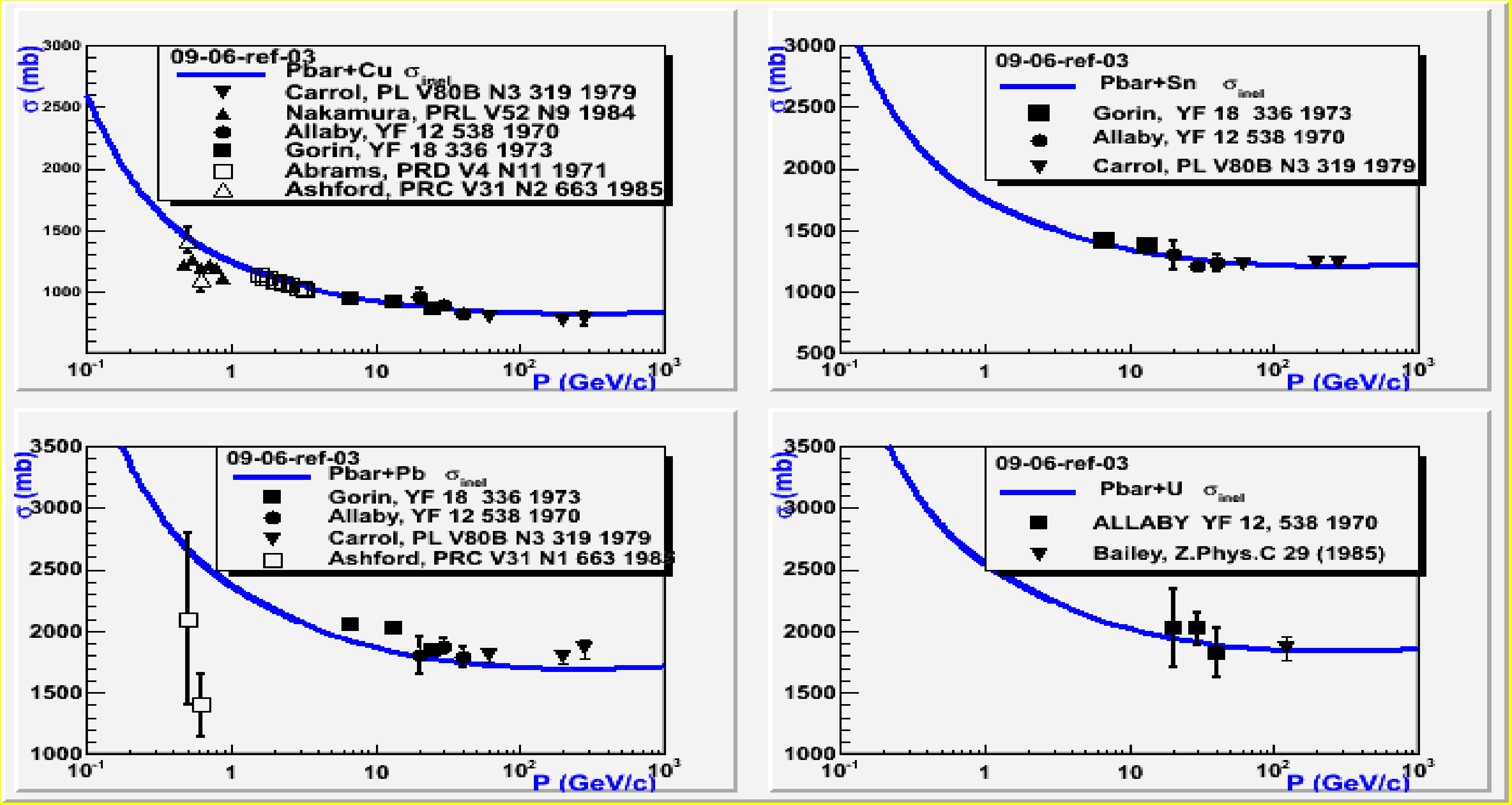
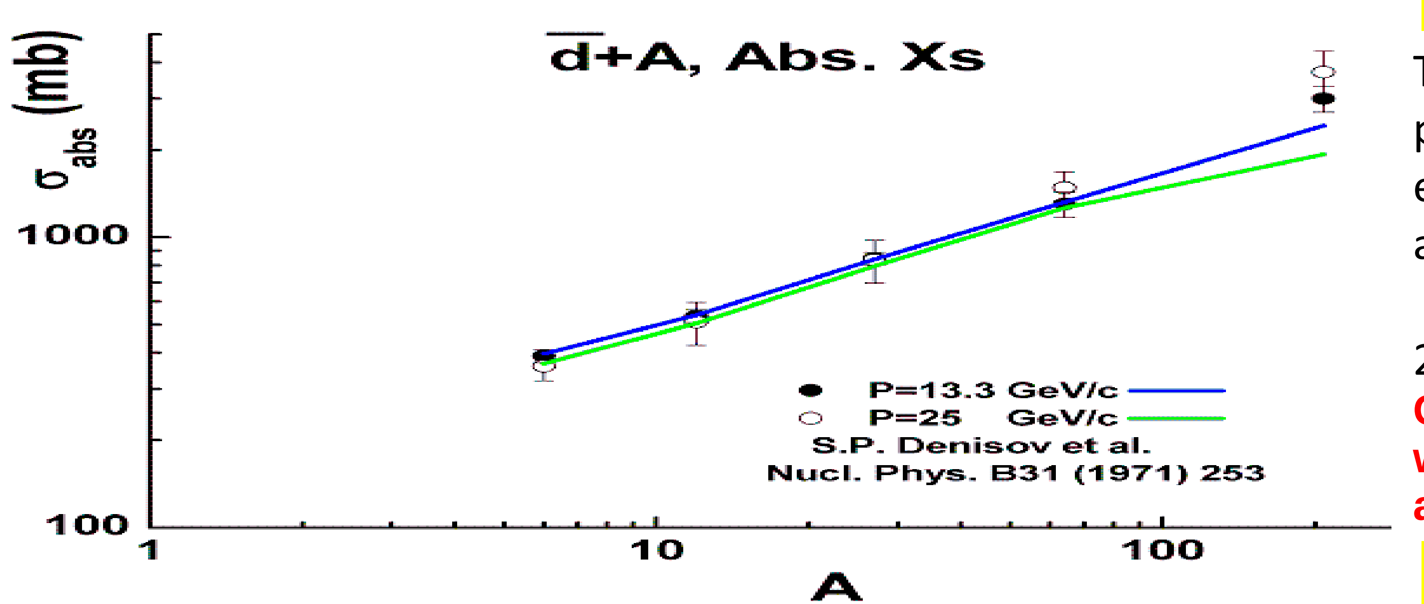


We gathered and described all exp.data on antiproton-nucleus cross-sections

Anti-nucleus—Nucleus cross sections, absorption XS

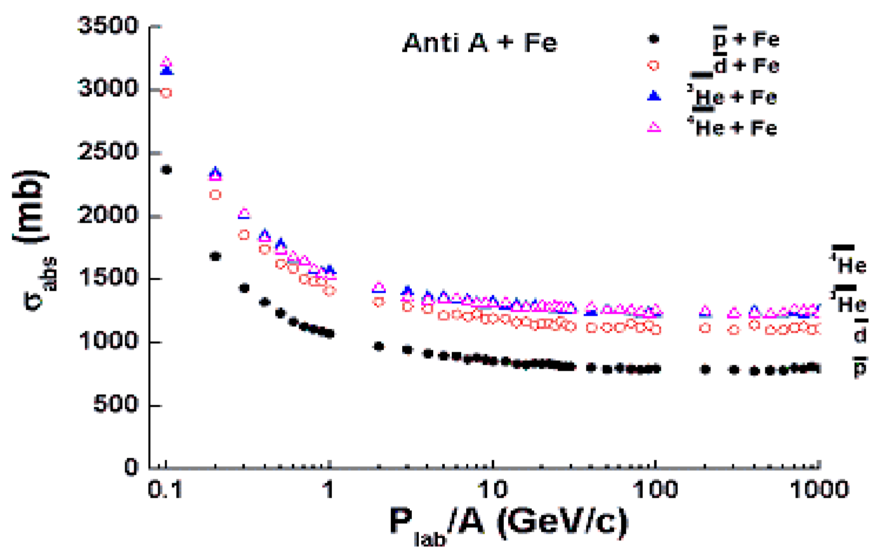
Geant4 class **G4ComponentAntiNuclNuclearXS** **for Pbar–Nucleus** and light **Anti-Nucleus – Nucleus cross sections. PhysicsList – FTF_BERT**

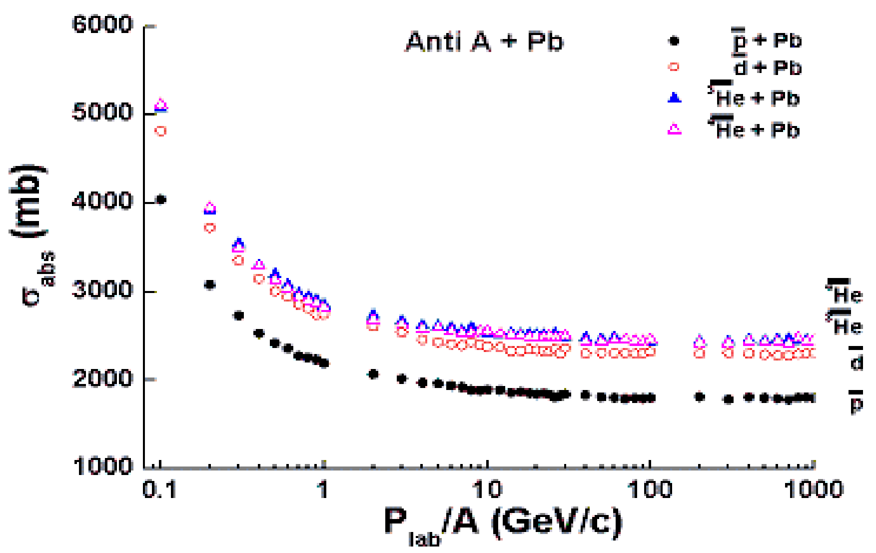


The solid and open points are the experimental data at anti-deuteron momenta of 13.3 and 25 GeV/c

Glauber approach well describes exp. anti-D – Nucleus XS!

Estimations of light Anti-nucleus – Nucleus cross sections



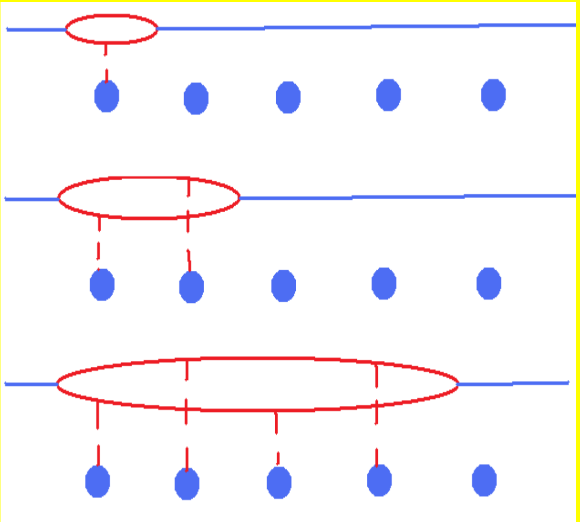


Dynamics of Antibaryon–Nucleus interactions

A. Galoyan, Hyperfine Interactions: v. 215 (2013) 69

"Simulations of light antinucleus-nucleus interactions"

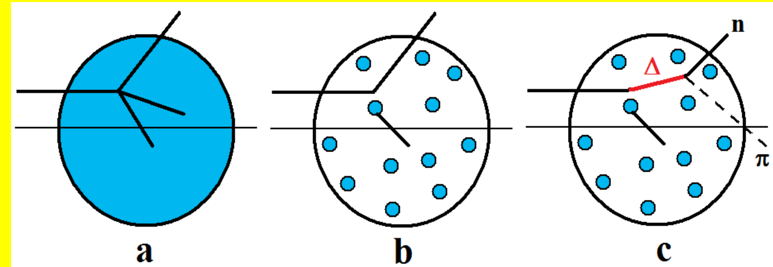
$$\sigma^{in}_{\bar{p}A} = \int d^2b[1 - e^{-\sigma^{in}_{\bar{p}n}T(\vec{b})}] = \sum_{\nu=1}^{\infty} \int d^2b \frac{[-\sigma^{in}_{\bar{p}n}T(\vec{b})]^{\nu}}{\nu!} e^{-\sigma_{\bar{p}n}T(\vec{b})}$$

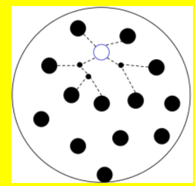


Low energy, Std. cascade.

Cascade+ Resonances

High energy, Std. QGS.





Model of nuclear disintegration
In high-energy nucleus nucleus interactions.
K. Abdel-Waged, V.V. Uzhinsky
Phys.Atom.Nucl.60:828-840,1997.

Correction of multiplicity of intra-nuclear collisions

$$N_{max} = \sigma\rho < \tau > v\gamma = \sigma\rho < \tau > P^{proj}_{lab}/m_{proj} = P_{lab}/P_0$$

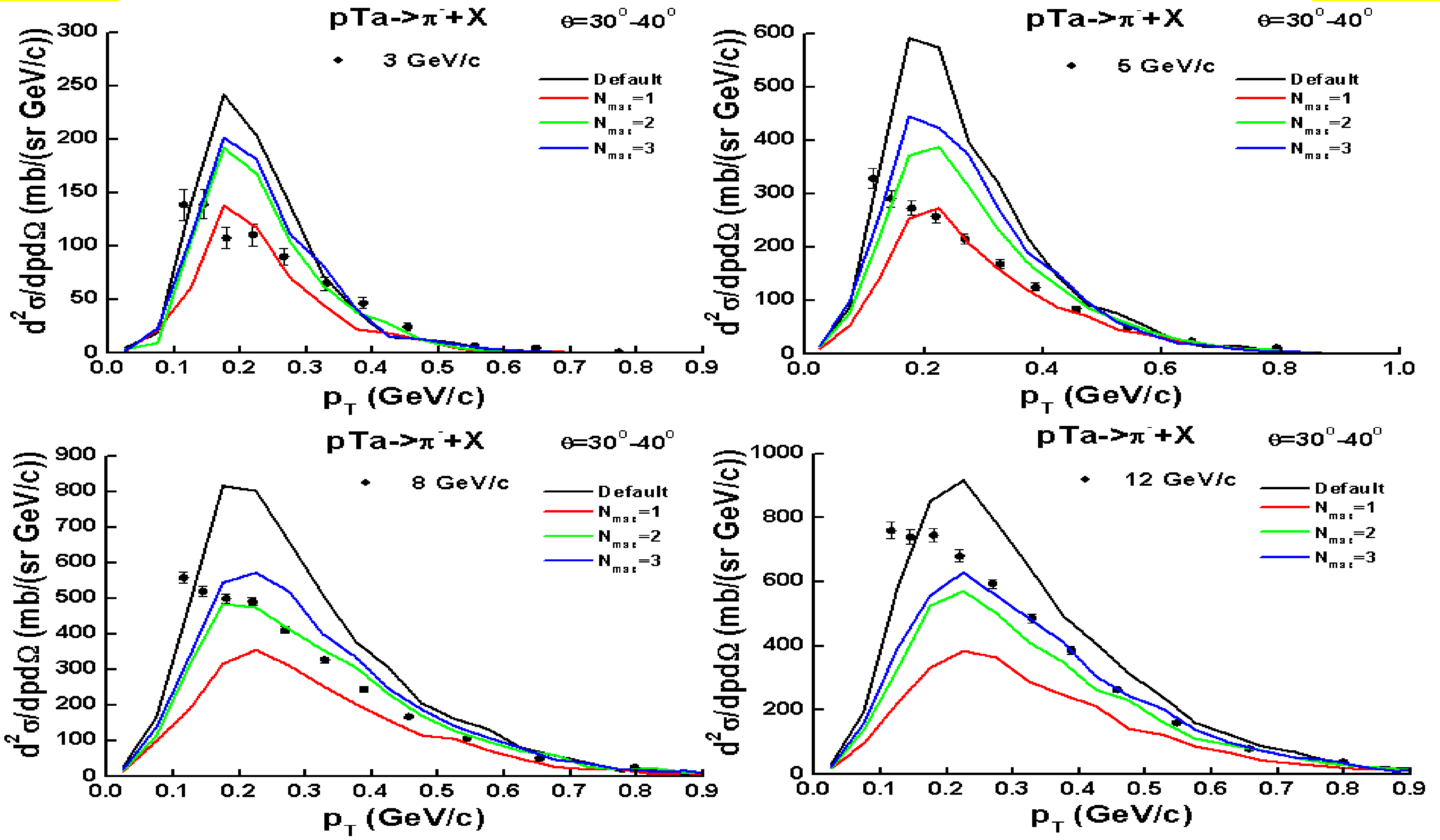
$$\sigma^{in}_{\bar{p}A} = \int d^2b[1 - e^{-\sigma^{in}_{\bar{p}n}T(\vec{b})}] = \int d^2b[1 - e^{-N_{max}\frac{\sigma^{in}_{\bar{p}n}}{N_{max}}T(\vec{b})}] =$$

$$\sum_{\nu=1}^{N_{max}} C^{\nu}_{N_{max}} \int d^2b[1 - e^{-\frac{\sigma^{in}_{\bar{p}n}}{N_{max}}T(\vec{b})}]^{\nu} e^{-(N_{max}-\nu)\frac{\sigma^{in}_{\bar{p}n}}{N_{max}}T(\vec{b})}$$

S.Yu. Shmakov, V.V. Uzhinsky,
Zeit. fur Phys. C36:77,1987.
Max. cross section method:
W.A. Coleman: Nucl. Sci. Eng. 32 (1968) 76

Antibaryon–Nucleus interactions, inelastic interactions

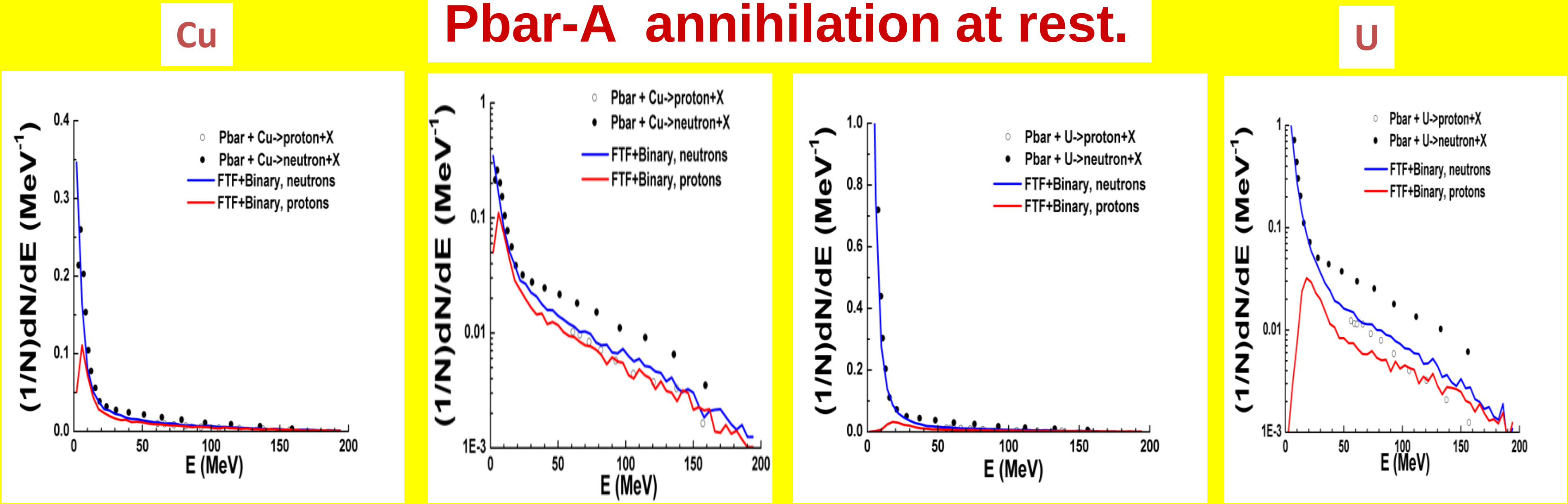
Correction of multiplicity of intra-nuclear collisions, HARP-CDP exp. data



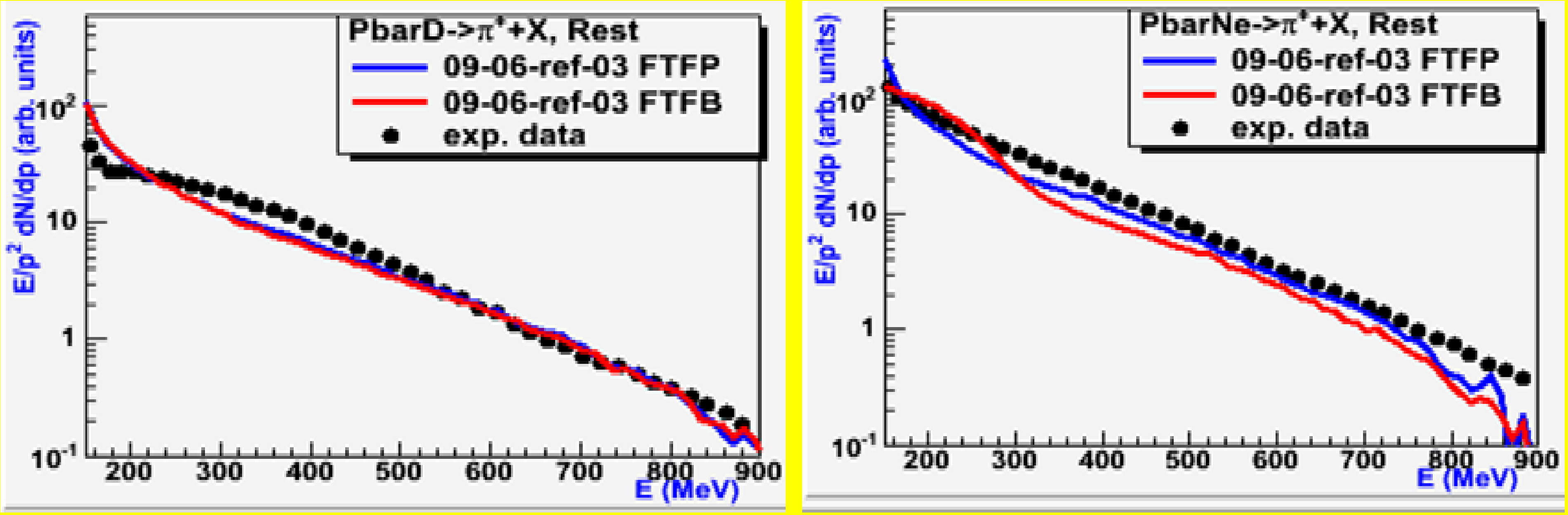
Nmax=1, Plab=3, 5 GeV/c: Nmax=2, Plab=8 GeV/c: Nmax=3, Plab=12

The same is true for anti-nucleus – nucleus interactions

Pbar-A annihilation at rest.



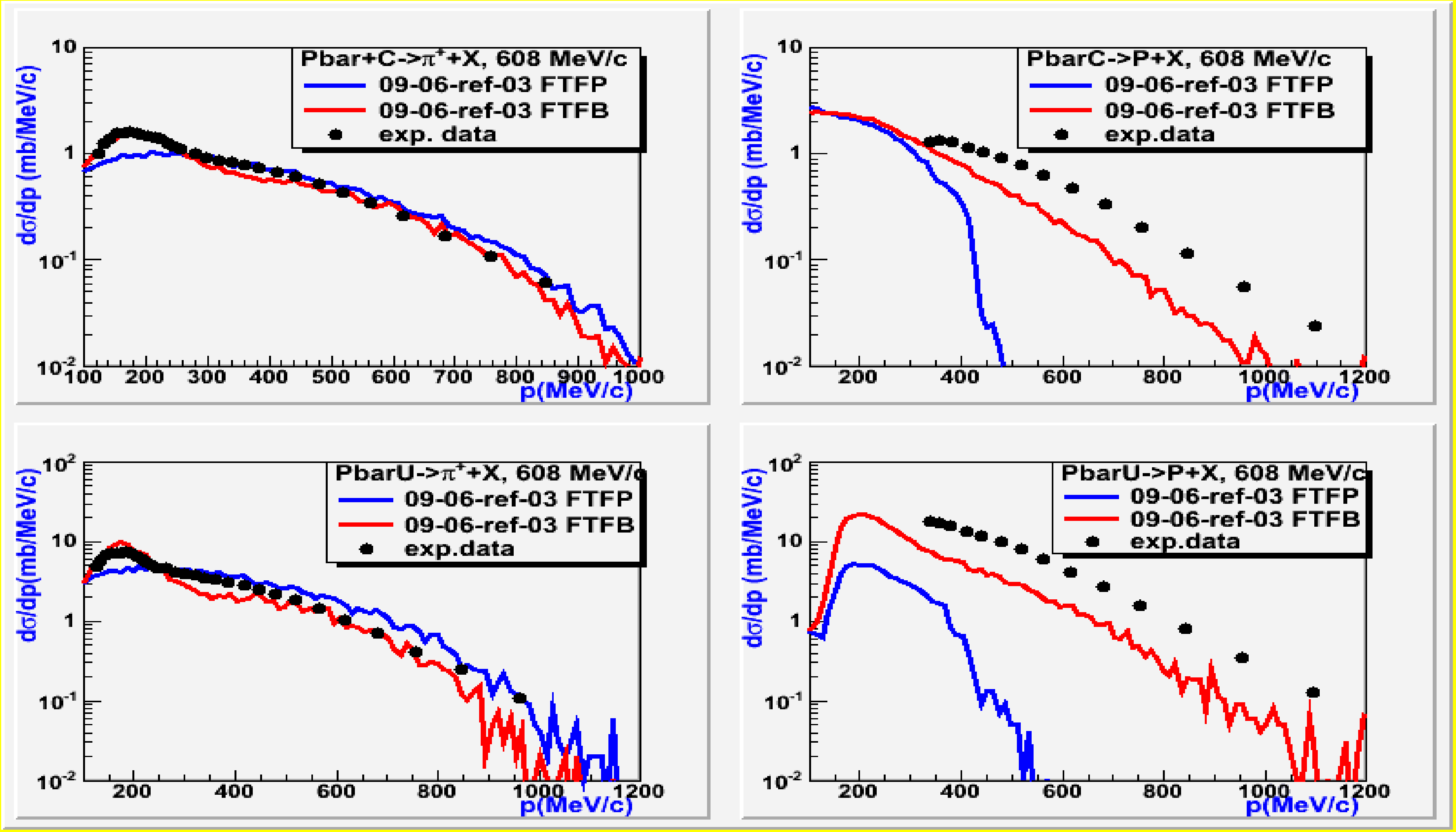
Energy spectra of pi+ mesons produced in Pbar–D/Ne at rest



J. Rielberger, Nuclear Physics B (Proc Suppl) 8 (1989) 288-293

Results of FTF validation for Antiproton–Nucleus reactions inflight

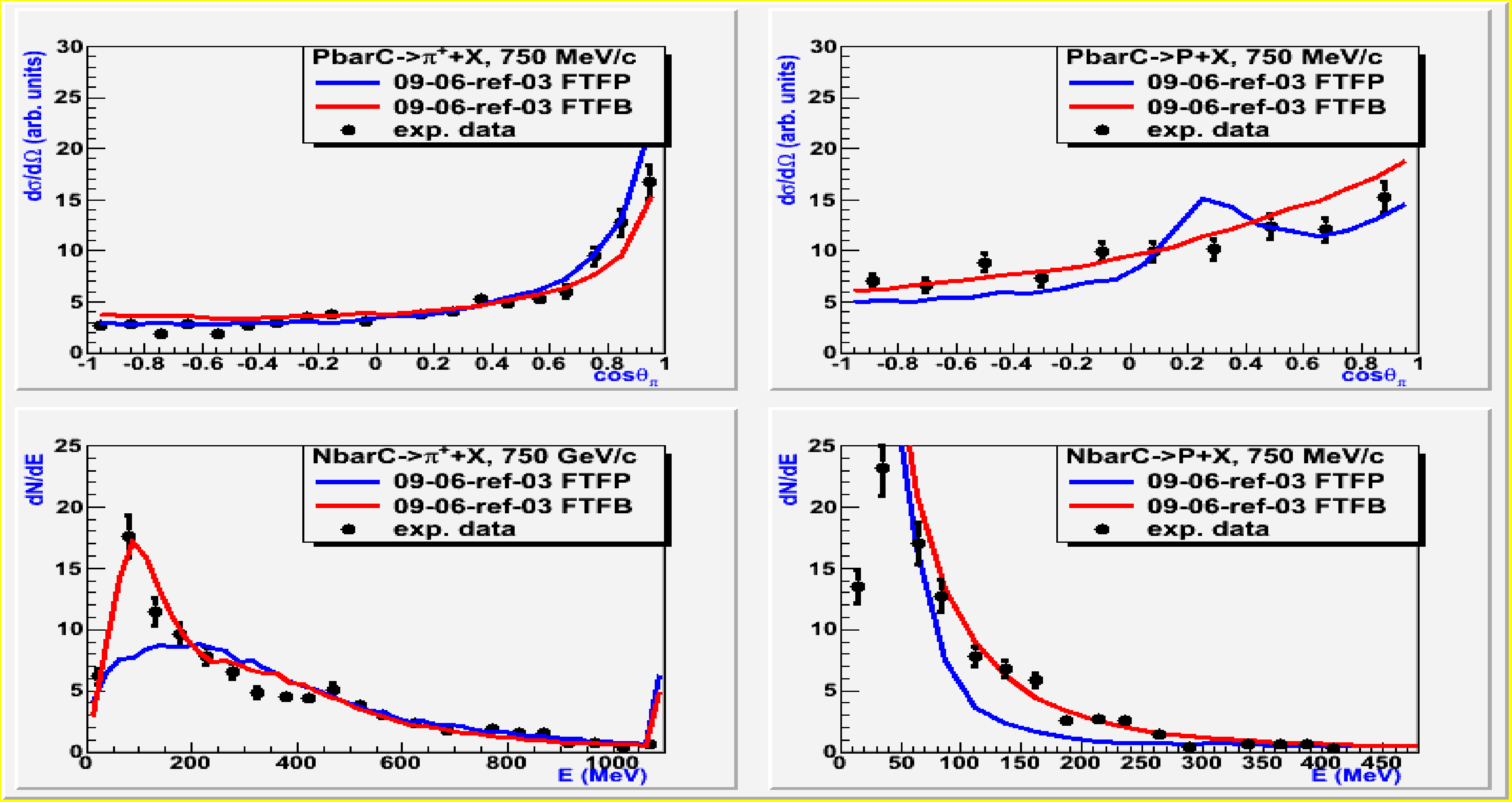
Momentum distributions of π+ Momentum distributions of Protons



P.L.McGaughey et al., Phys. Rev. Lett. V56, N20, 1986

Results of FTF validation for AntiProton–Nucleus reactions inflight

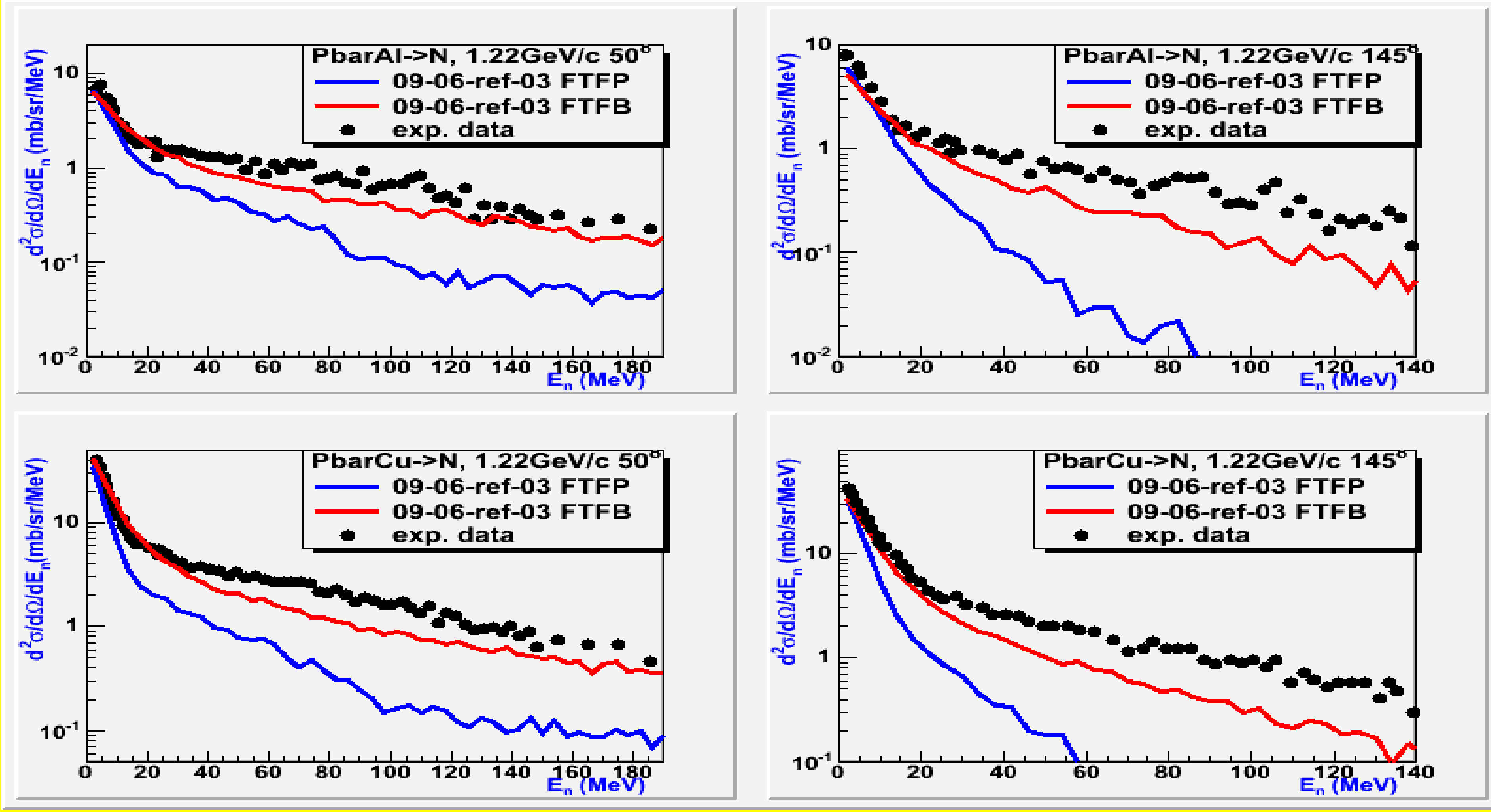
Angle and energy distributions of pions and protons in Pbar-C /Nbar-C interactions at projectile momentum 750 MeV.c



P.L.McGaughey et al., Phys. Rev. Lett. V56, N20, 1986

Results of FTF validation for AntiProton–Nucleus reactions inflight

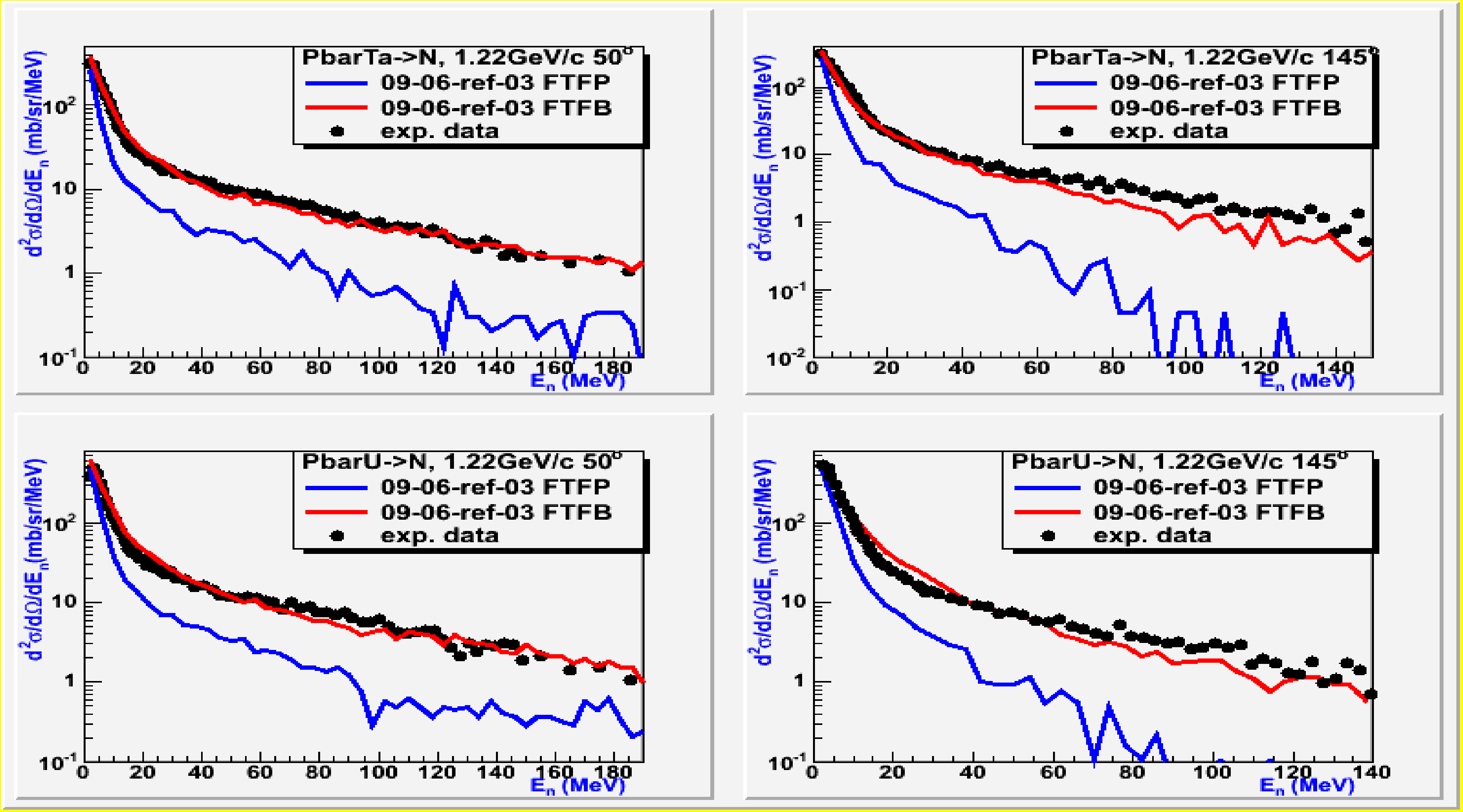
Kinetic energy spectra of neutrons produced in Pbar-Al, Pbar-Cu at projectile momenta 1.22 GeV/c



T. von Egidy et al., Eur. Phys. J. A 8, 197 (2000) LEAR collab. data

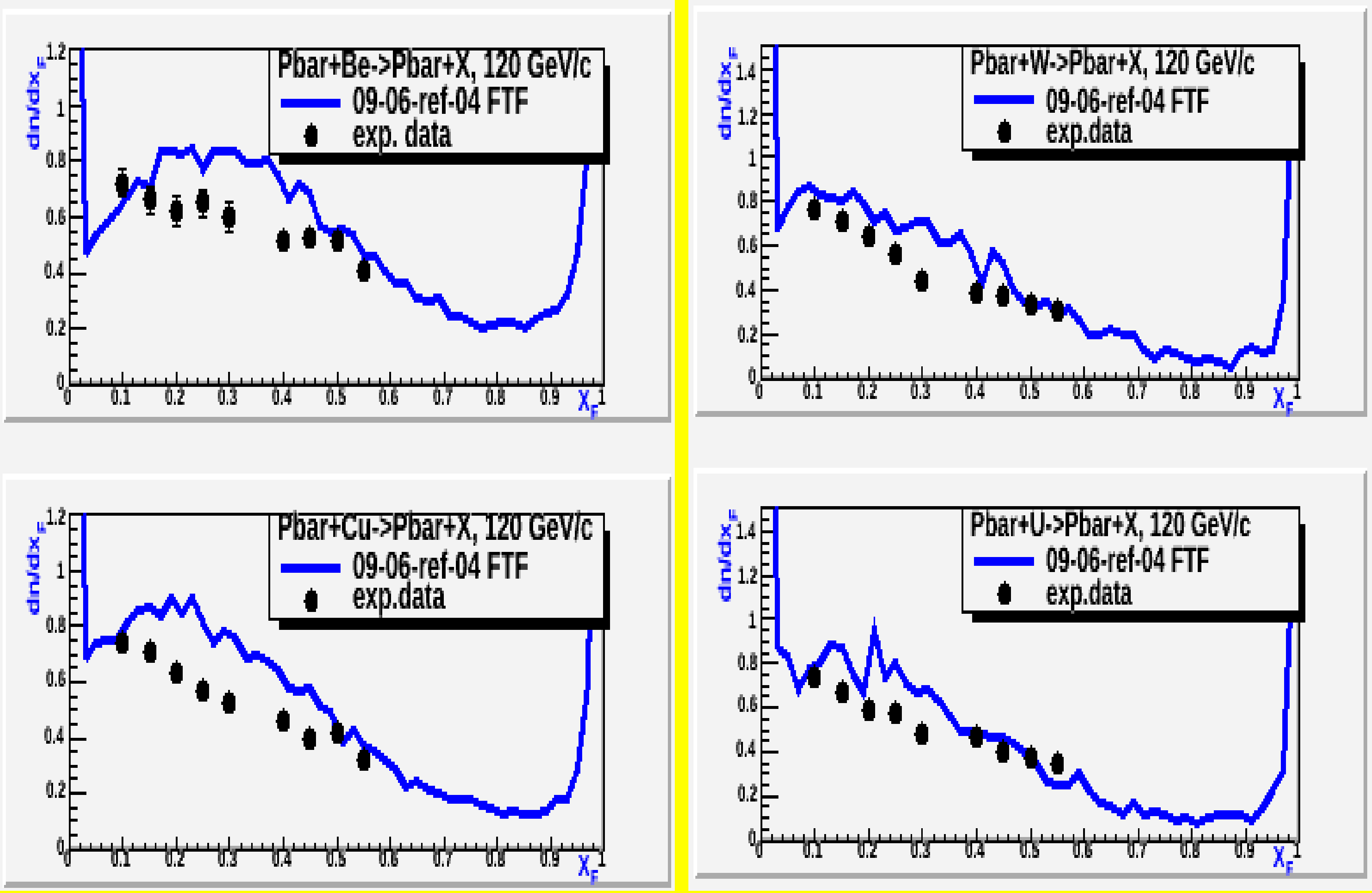
Results of FTF validation for Antiproton–Nucleus reactions inflight

Kinetic energy spectra of neutrons produced in Pbar-Ta, Pbar-U at projectile momenta 1.22 GeV/c



T. von Egidy et al., Eur. Phys. J. A 8, 197 (2000) LEAR collab. data

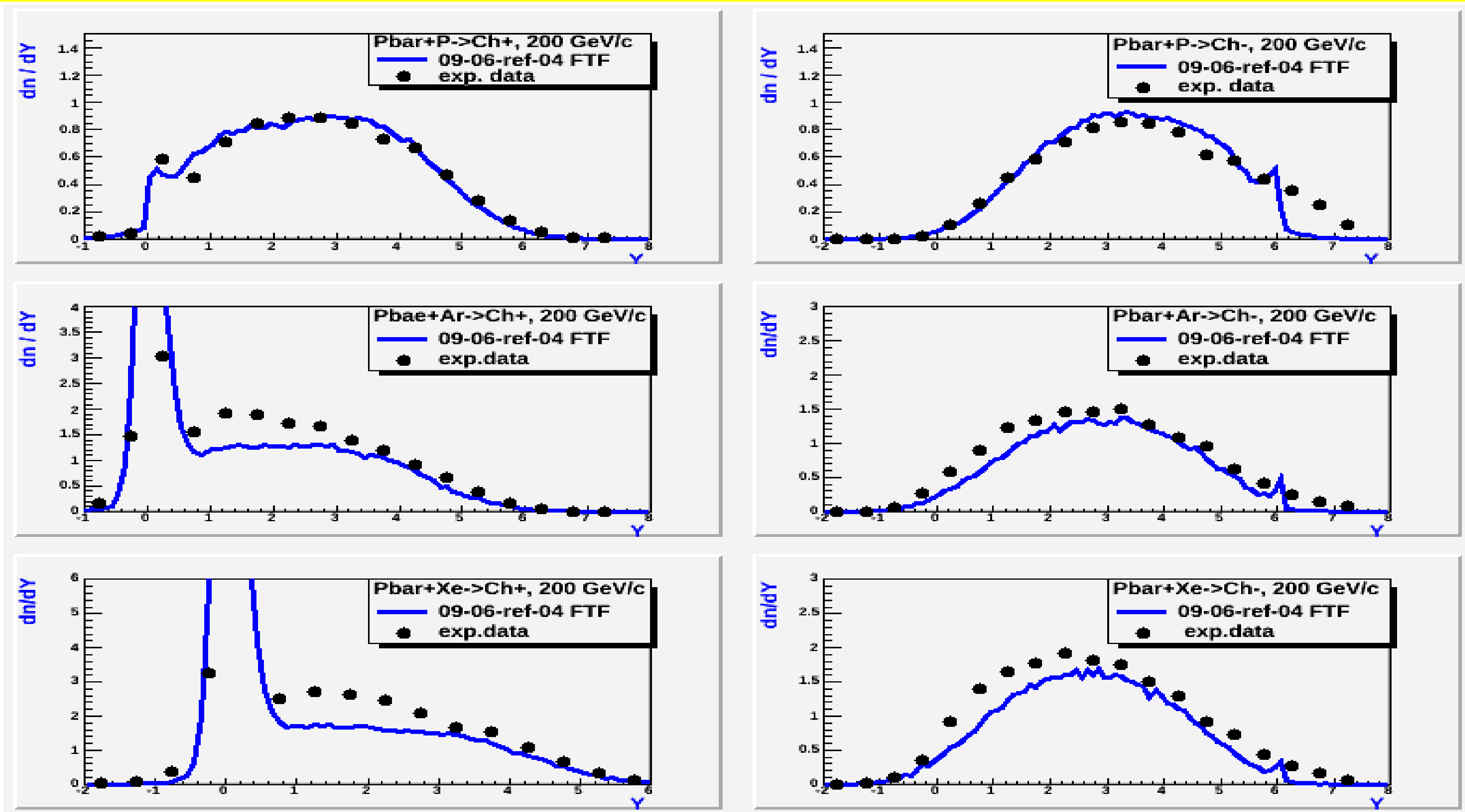
Leading antiproton spectra in Pbar-A interactions at high energies



pA-interactions at 120 GeV/c,R. Bailey et al., Z. Phys. C29 (1985) 1.

Results of FTF validation for Pbar-Nucleus interactions at p= 200 GeV/c

Rapidity Ch+, Rapidity Ch- mesons



Multi-particle production on hydrogen, argon and xenon targets in a streamer chamber by 200 GeV/c proton and antiproton beams. De Marzo et al. Phys. Rev. D26 (1982) 1019

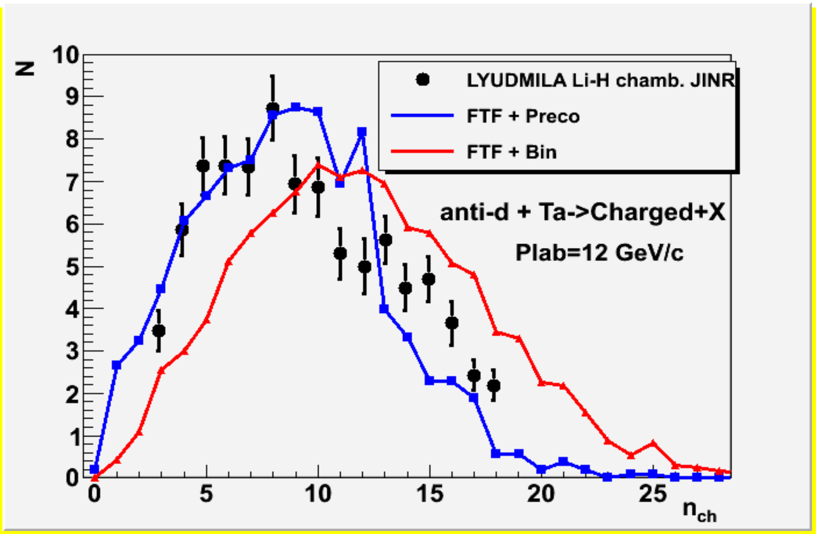
Validation of FTF model for antinucleus-nucleus interactions

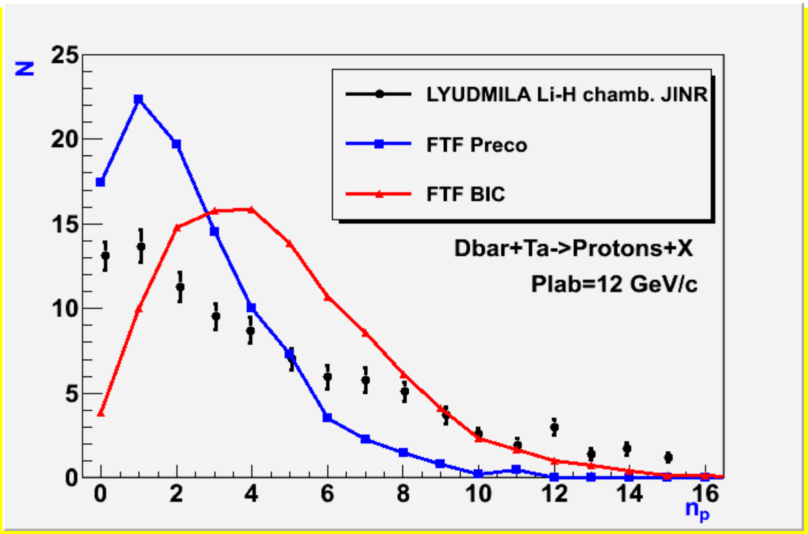
We have found only 2 papers with exp. data on Dbar-nucleus interactions:

1. **V.F. Andreev et. al, "Multiplicities and Correlations of Secondary Charged Particles in the Interactions of Antineutrons and Antideutrons with a Momentum of 6.1 GeV/c per Nucleon with Tantalum Nuclei"**
   IL Nuovo Cimento, Vol. 103 A, N8, 1989.

2. **B.V. Batyunya et. al, "The Study of Inclusive Characteristics of antiD-D – interactions at 12 GeV/c", JINR Preprint P1-87-849**

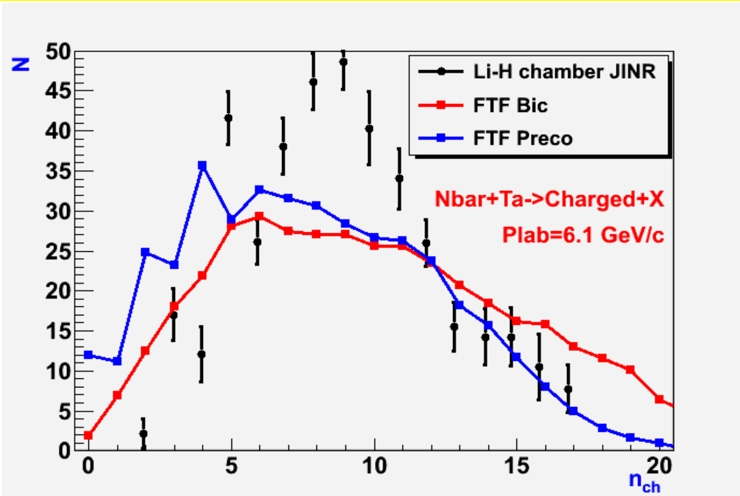
The exp. data were obtained using 2 meter liquid hydrogen chamber of LHE, JINR.
A tantalum plate in the chamber was exposed a beam of antideutrons at 12.2 GeV/c

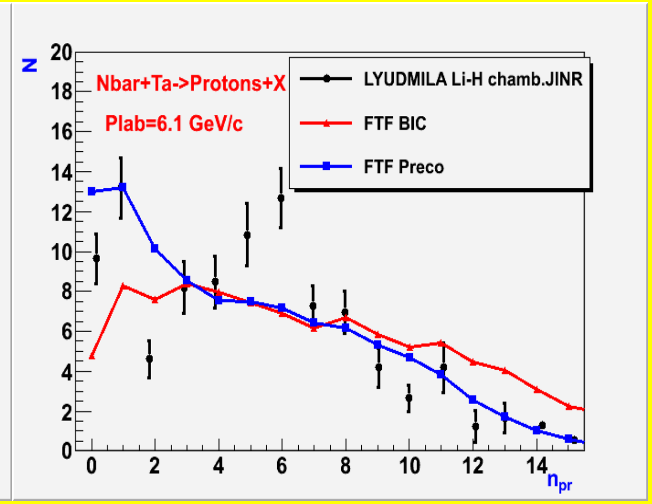




The difference between exp. data and calculations can be connected with beam background ~ 40% from π- mesons and other exp. conditions.

Multiplicities of secondary particles produced in Nbar – Ta

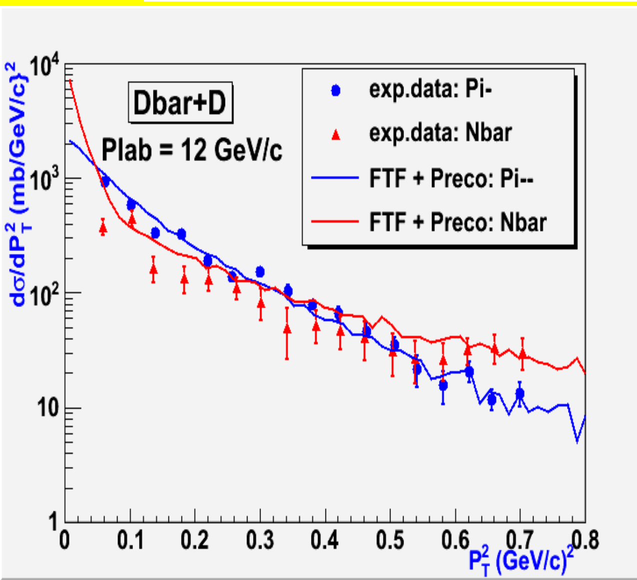


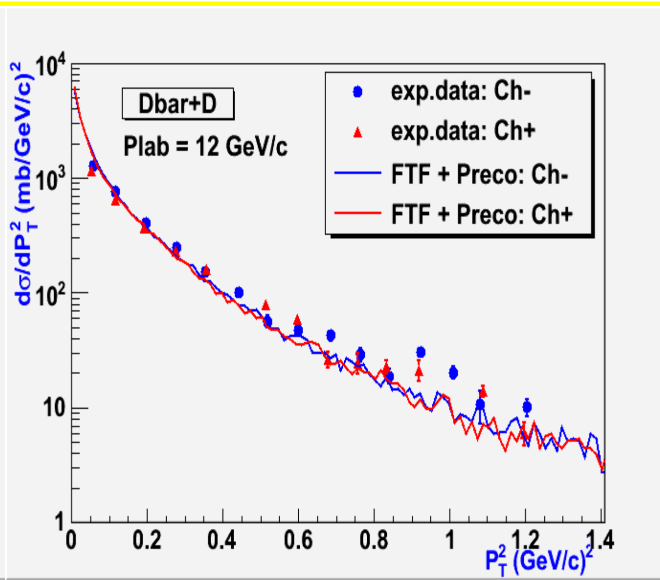


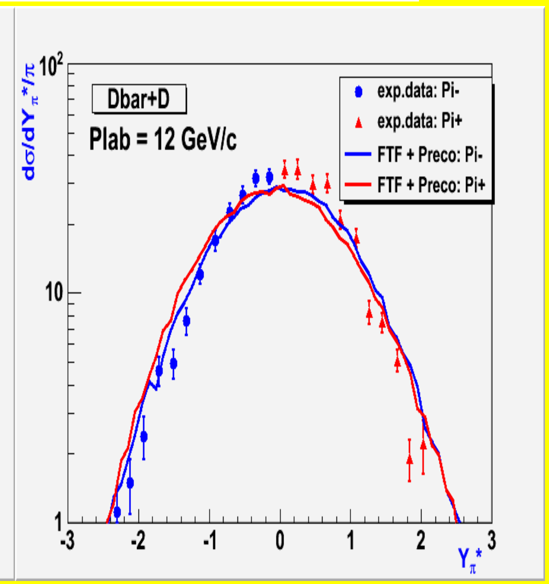
Antineutrons with momentum 6.1 GeV/c were produced in the stripping of antideutrons on hydrogen in the "Lyudmila" liquid hydrogen chamber.

Kinematical spectra of secondary particles produced in Dbar-D interactions at 12 GeV/c

Exp. data from paper: JINR Preprint P1-87-849







Conclusion

Dynamics of processes induced by Antiprotons and light Anti-Nuclei has been considered in the extended Dual Parton Model.

1. Cross sections of Pbar-P processes are determined at energies from 100 MeV to 1000 GeV and implemented in the FTF model of Geant4. Good description of Pbar-P interactions has been reached with the FTF model.
2. Method for calculations of Pbar–Nucleus and Light Anti-Nucleus– Nucleus cross sections has been developed and implemented in Geant4. Good description of known exp. data on cross sections is obtained.
3. Extension of the FTF model on Antiproton-Nucleus and Anti-Nucleus – Nucleus reactions has been proposed. Promising results have been obtained.
4. The extended FTF model has been implemented in Geant4 toolkit.

Antiproton-Nucleus interactions, elastic scattering on nuclei

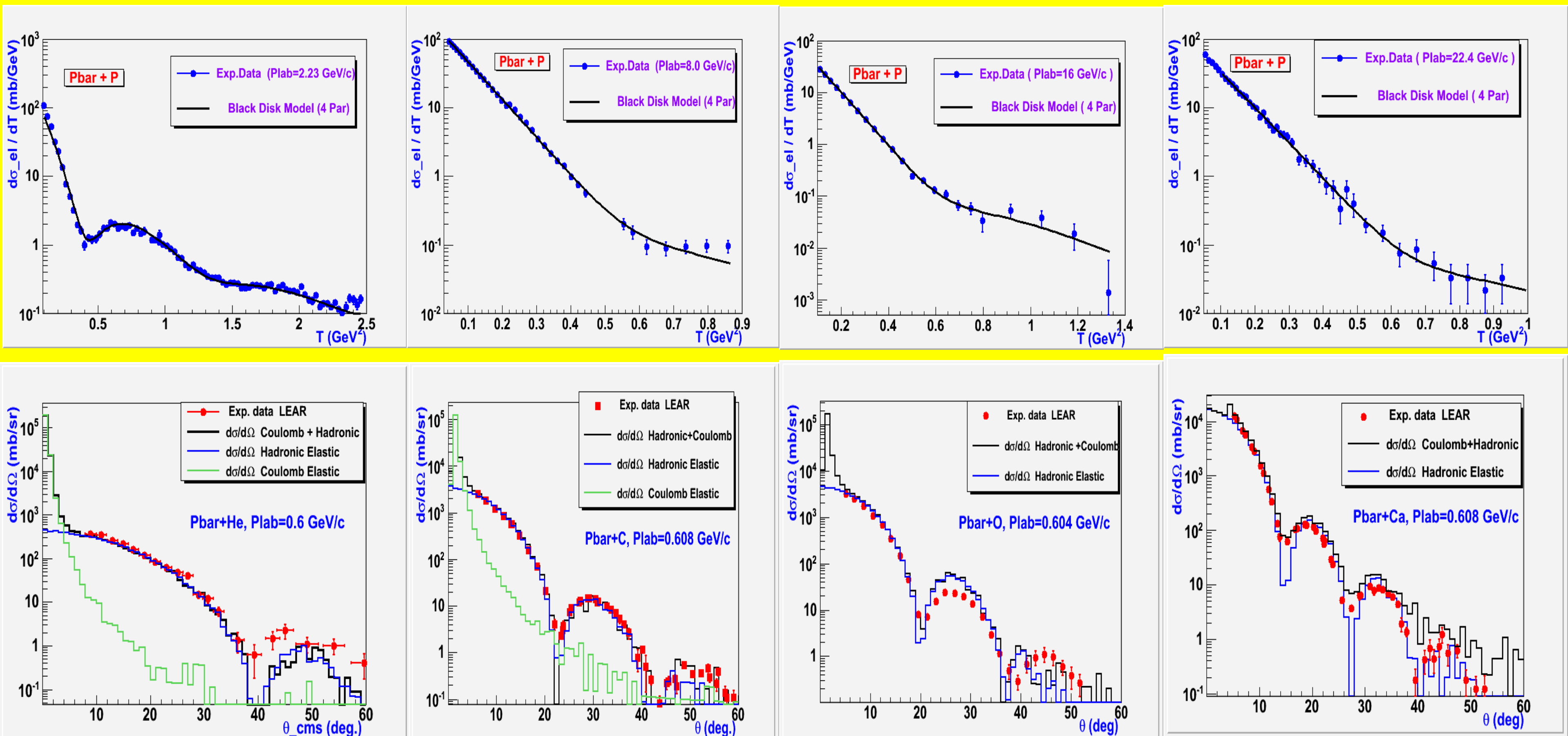
Black disk model approximation with diffuse boundary and Imaginary and Real parts of elastic scattering amplitude

$$F(s,q) = i\ A_1 \frac{\pi c q}{\mathrm{sh}(\pi c q)} \frac{J_1(Rq)}{Rq} + A_2 \frac{\pi c q}{\mathrm{sh}(\pi c q)} J_0(Rq)$$

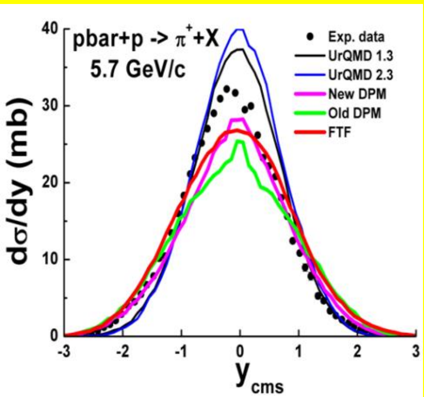
"Structure of antiproton-proton elastic scattering amplitude"

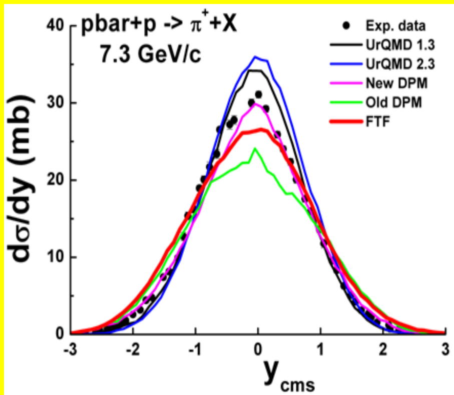
A. Galoyan, V.Uzhinsky, JETP Letters, v. 94, No 7 (2011)

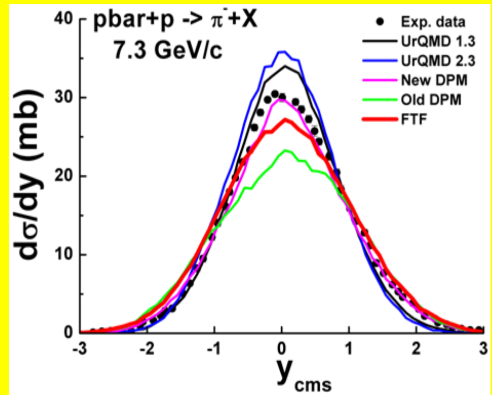
94 sets of pbar-p exp data were used from Plab=181 MeV/c up to sqrt(S)=1800 GeV



Description of Antiproton-Proton Interactions by FTF, DPM and UrQMD models







Some experimental data agree well with **our FTF model.** Some data which do not agree are probably **suspect!**