Simulation of Anti-Matter Matter Interaction in Geant4

A. Galoyan, V. Uzhinsky, A. Ribon 7.07.2017

One of the most exciting puzzles in cosmology is connected with the question of the existence of anti-matter in the Universe. A number of dedicated cosmic ray experiments aim to search for anti-nuclei : **PAMELA, AMS, BESS, CAPRICE**

Anti-Proton (in cosmic rays) 1955, Emilio Segre and Owen Chamberlain (Nobel Prize in Physics)

Anti-Neutron, 1956, Bruce Cork and colleagues (BNL)

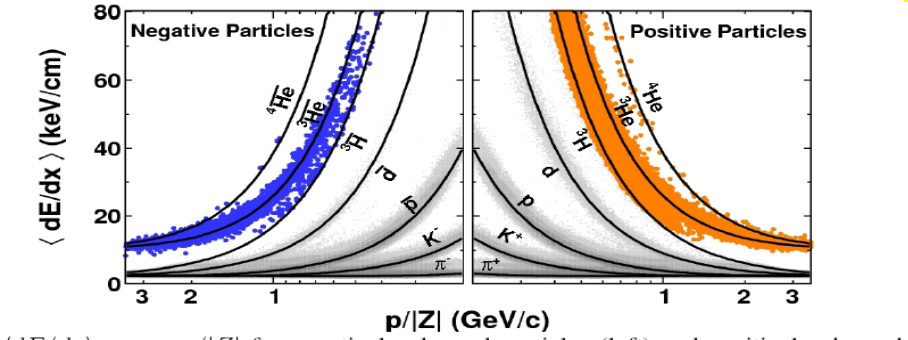
Anti-Deuterium, 1965, Antonino Zichichi et al. (CERN), D.E. Dorfan et al. (BNL)

Anti-Helium-3, 1974, Y.M. Antipov et al. (IHEP)

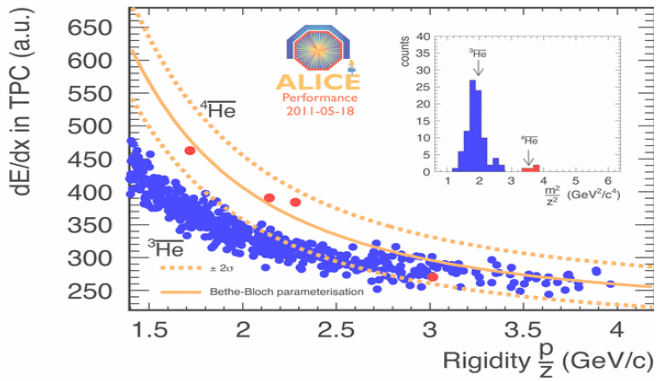
Anti-Helium-4, March 2011, Star Collab, H. Agakishiev et al. (RHIC)
Observation of the antimatter helium-4 nucleus, arXiv:1103.3312, Au+Au, 200

ALICE Collab. LHC 5 Anti-He-4, QM 2011

18 Anti-He-4



$\langle dE/dx \rangle$ versus $p/|Z|$ for negatively charged particles (left) and positively charged



Tunguska meteor , 30 June 1908

P.J. Wyatt, **Possible Existence of Anti-Matter in Bulk** Nature, v. 181, 1958, p. 1194

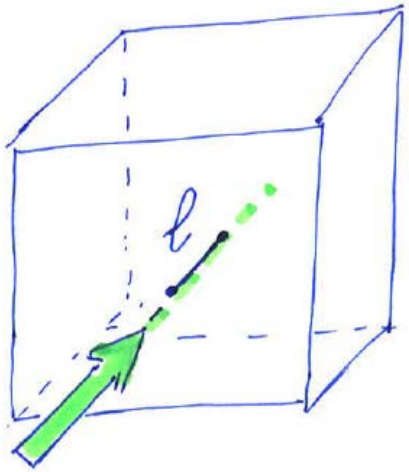
C. Cowan, C.R. Atluri, W.F. Libby **Possible Anti-Matter Content of the Tunguska Meteor of 1908** Nature, v. 206, 1965, p. 861

Simulation of Anti-Matter Matter Interaction in Geant4

Central question – How to simulate Anti-Matter Matter interactions?
A short answer – Use GEANT4 package!

Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science. geant4.cern.ch.

We use Monte Carlo technique to simulate particle interactions with a matter.



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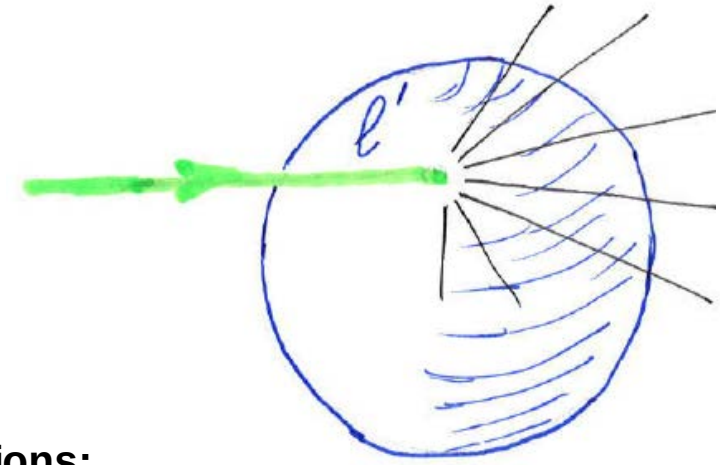


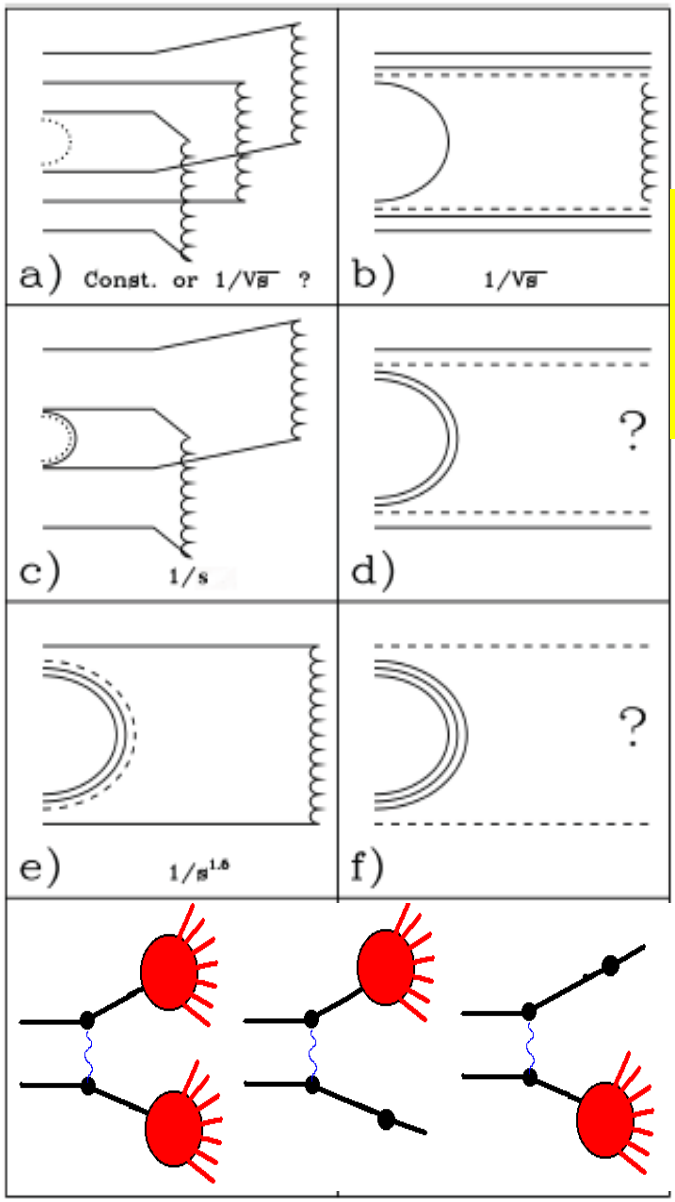
- Multiplicity
- Types of part.
- Momenta
- Direction
- And so on

1. **Antibaryon-baryon interactions:**
   - **Processes**
   - **Cross sections**
   - **Channel cross sections**
   - **Inclusive distributions**
2. **Nuclear cross sections;**
3. **Validation of the model;**

Geant4 is installed at cluster **HybriLIT** by group of LIT JINR. Calculations in Geant4 have been performed using HybriLIT .

Simulation of Anti-Matter Matter Interaction in Geant4

Antibaryon-Baryon Interactions



The question marks mean that the corresponding estimations are absent.

We use as a base the Dual-Parton Model (DPM)!

A. Capella, U. Sakhatme et al., Phys. Rep. 236, 225 (1994)
A.B. Kaidalov, Zeit. Fur Phys. C12, 63 (1982)
It combines:
Regge Phenomenology + Quark ideas + 1/Nf QCD

XS 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,

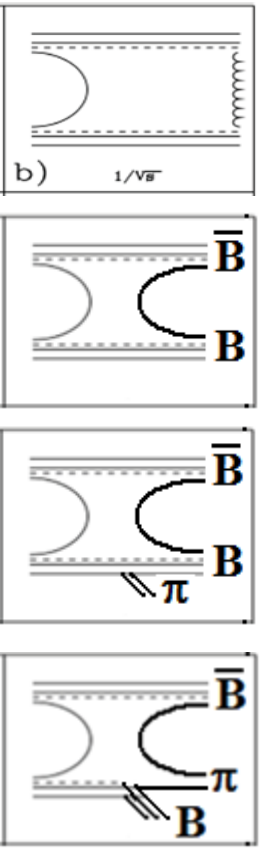
Physics Performance Report for: PANDA (AntiProton Annihilations at Darmstadt) Strong Interaction Studies with Antiprotons

Implementation:

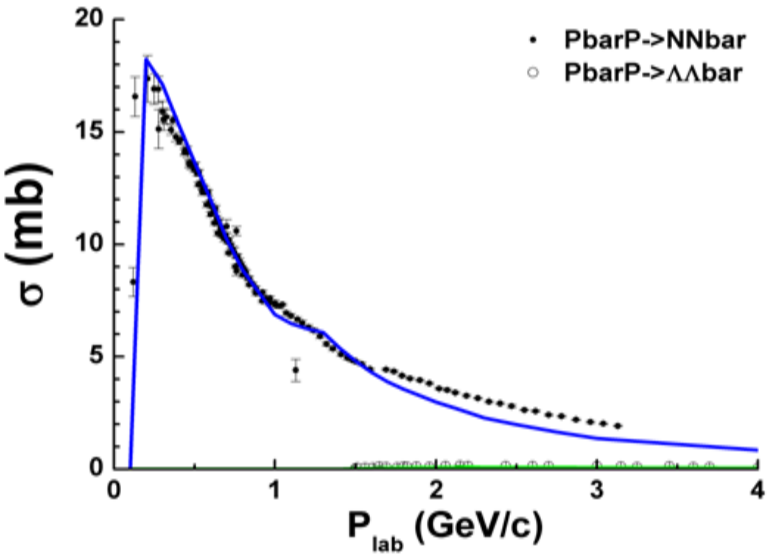
A.Galoian and V.Uzhinsky, AIP Conf. Proc. 796: 79, 2005

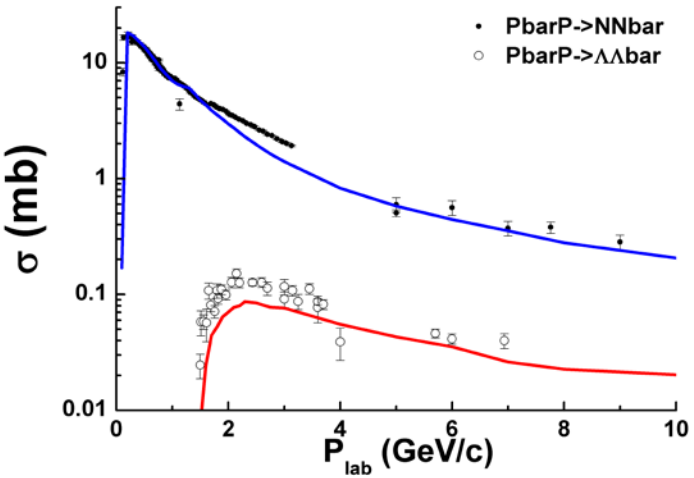
New Monte Carlo implementation of quark-gluon string model of anti-p p interactions.

Cross sections, process “b”, anti-diquark – diquark string creation



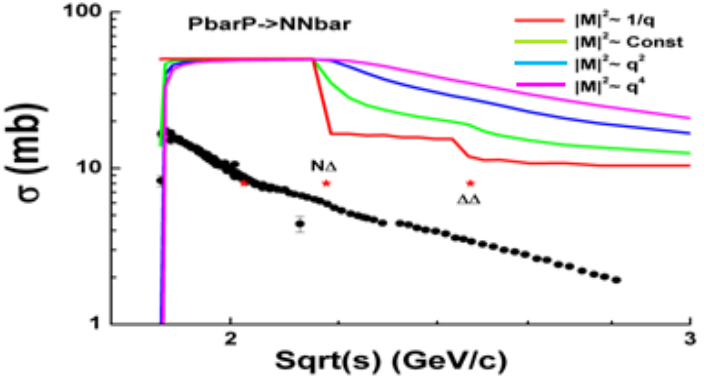
2-particle decay $\sigma_{N\bar{N}} \propto \sigma_b \, P_2(M=\sqrt{s}) \quad \sigma_{\Lambda\bar{\Lambda}} \propto \sigma_b \, P_2(M=\sqrt{s}) P_{s\bar{s}}$

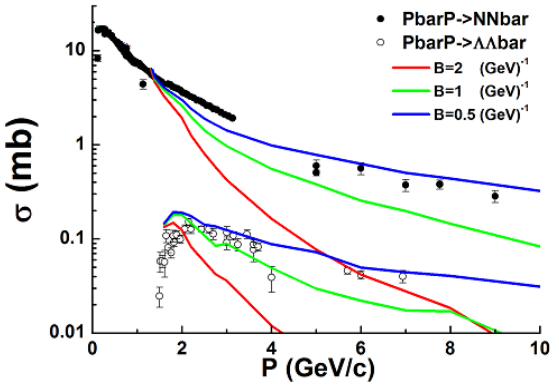


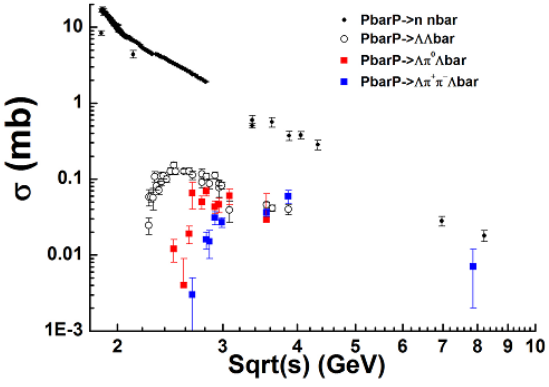


$$\sigma_b = 15.65 + 700 * (2.172 - \sqrt{s})^{2.5} \quad (mb), \quad \sqrt{s} \le 2.172 \quad (GeV)$$

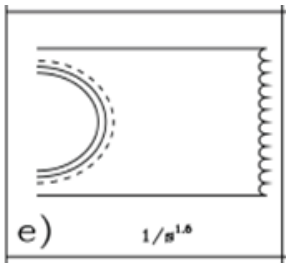
$$\sigma_b = 34/\sqrt{s} \quad (mb), \quad \sqrt{s} > 2.172 \quad (GeV)$$







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

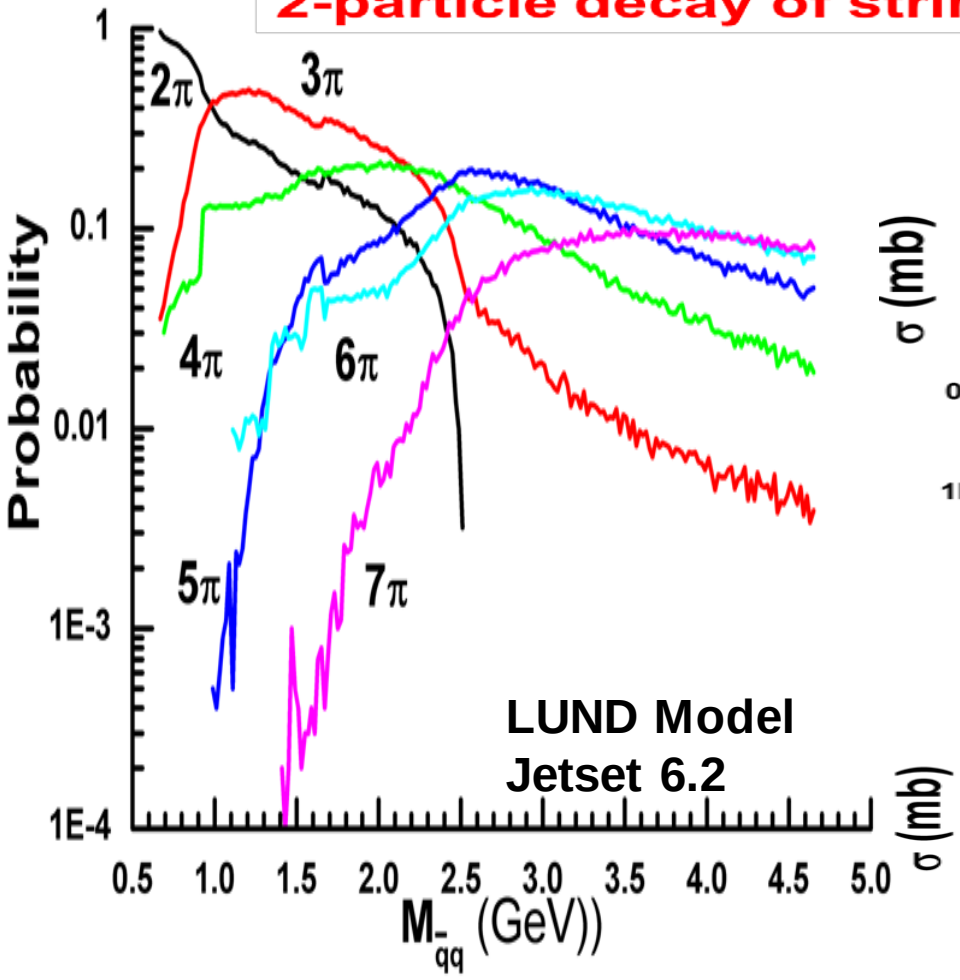


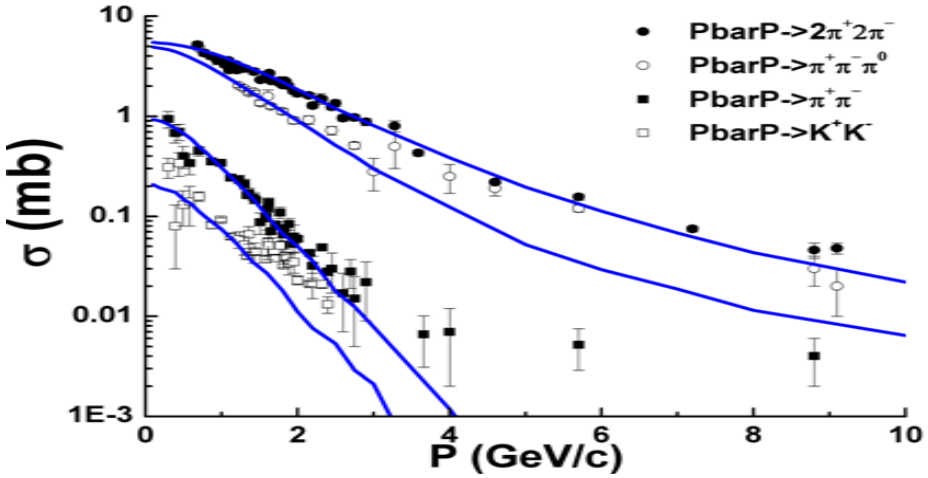
Antibaryon-Baryon Interactions. Diagram e)

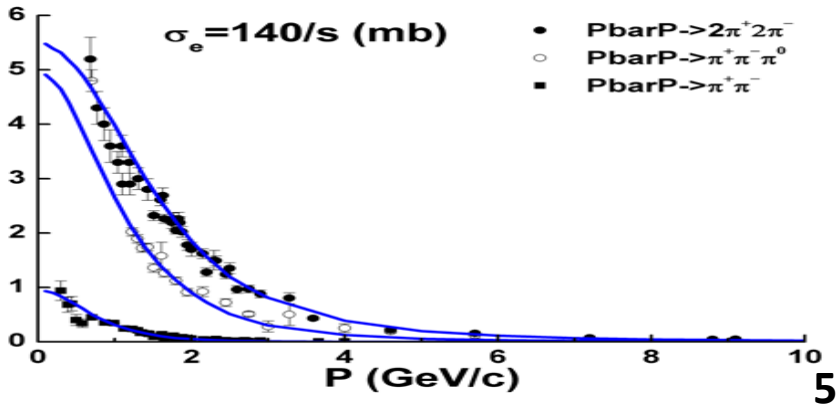
$$\sigma_{\pi^+\pi^-} \propto \sigma_e \; P_2(M = \sqrt{s}) \qquad \sigma_{\pi^+\pi^-\pi^0} \propto \sigma_e \; (1 - P_2(\sqrt{s})) \int P_F(\sqrt{s}, M) \; P_2(M) \; dM$$

$P_2 = \exp(-B\,(M_{string}^2 - M_{th}^2))$

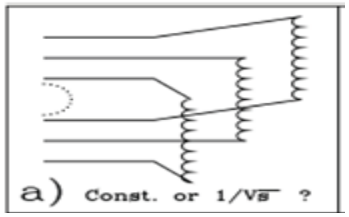
2-particle decay of strings is the problem in all MC





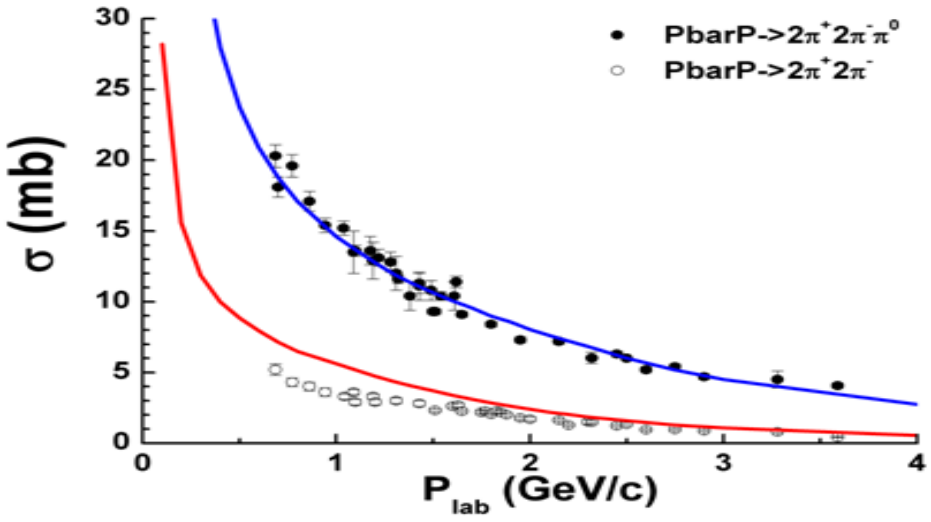


Well known Pythia!



Antibaryon-Baryon Interactions. Diagram a)

$$\sigma_a = \frac{16}{\sqrt{s-4m^2}}\left[(s-4m^2)^{-0.175} + 3.125 * (1 - 1.88/\sqrt{s})\right] \quad (mb)$$



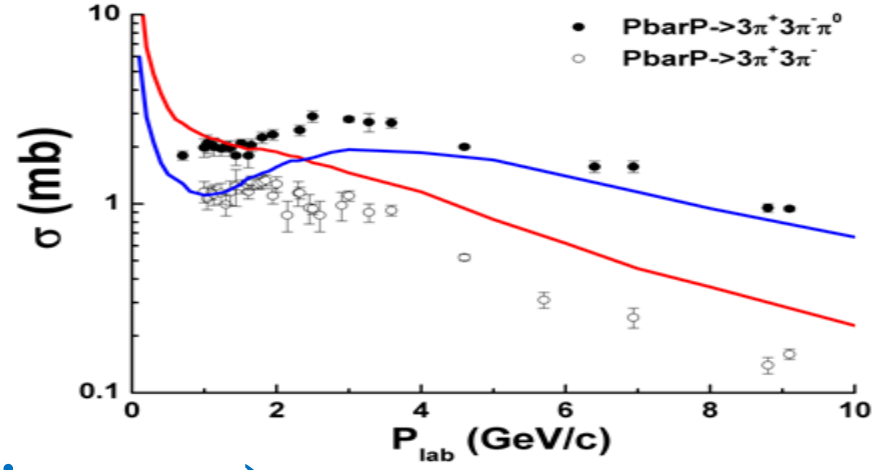
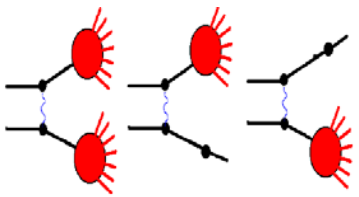
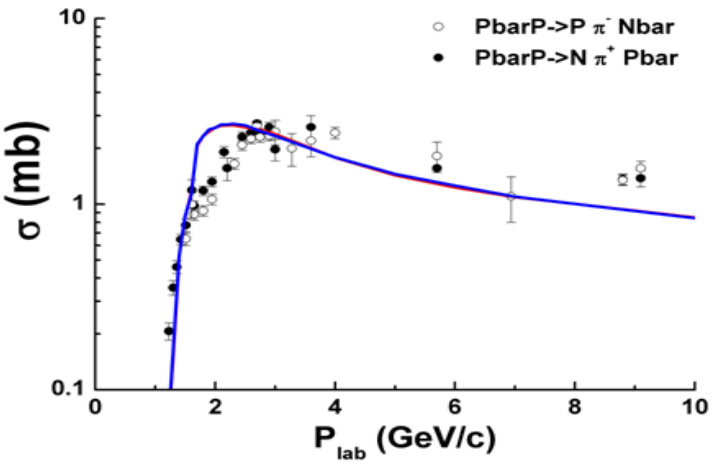
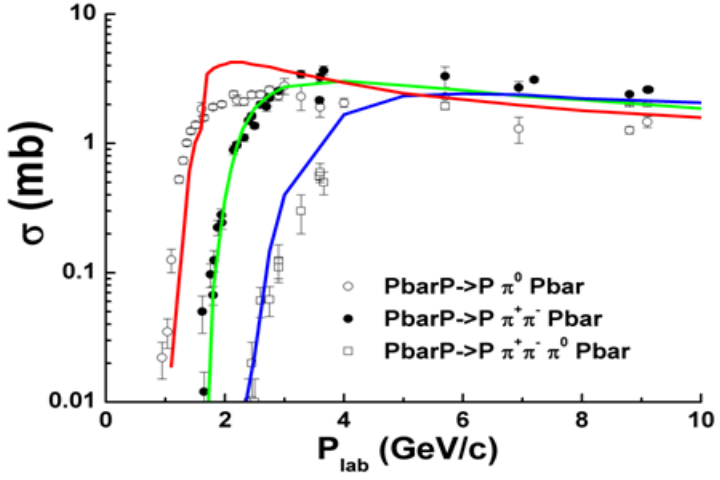


Diagram g)



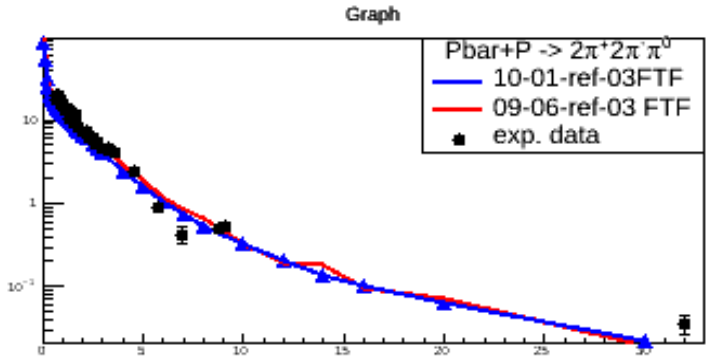
$$\sigma_{FTF} = 35 * (1. - 2.1/\sqrt{s}) \quad (mb)$$

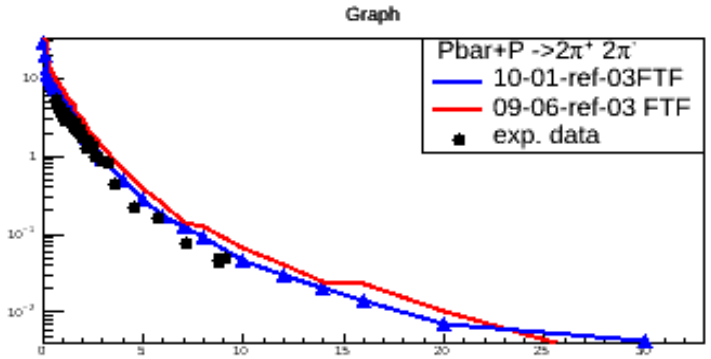


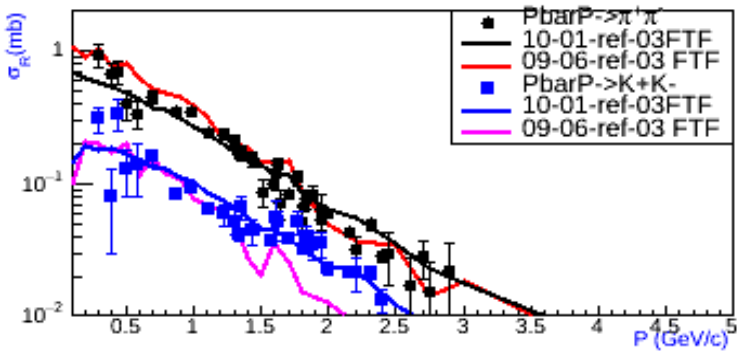


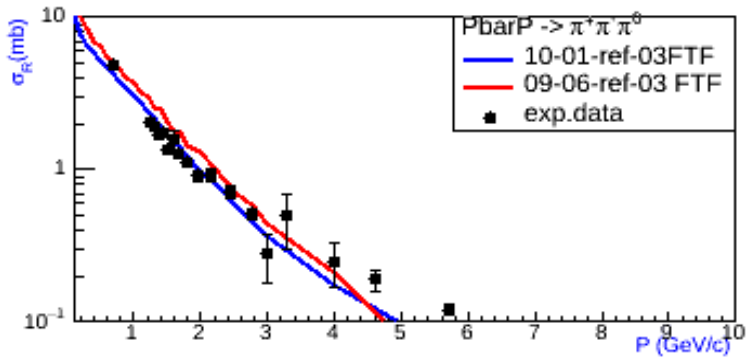
All channels of Pbar-P interactions are reasonable reproduced!

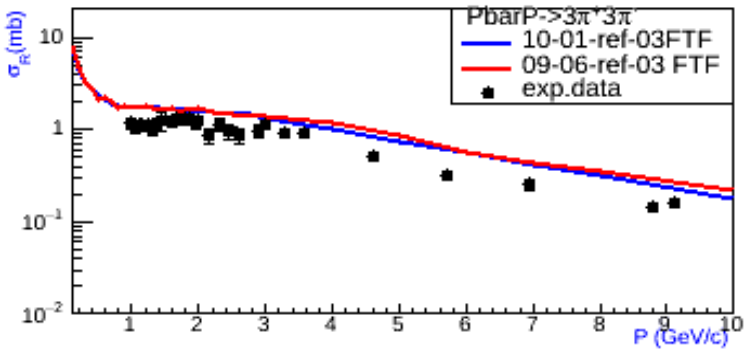
Pbar-P annihilation channel cross sections

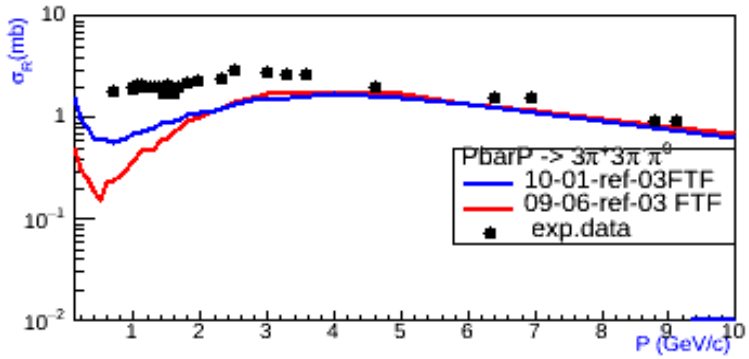






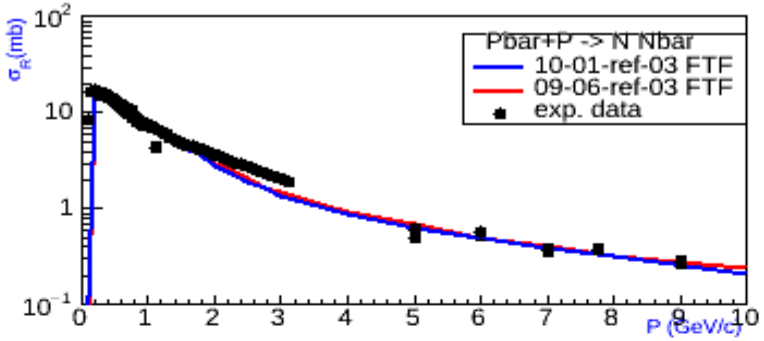


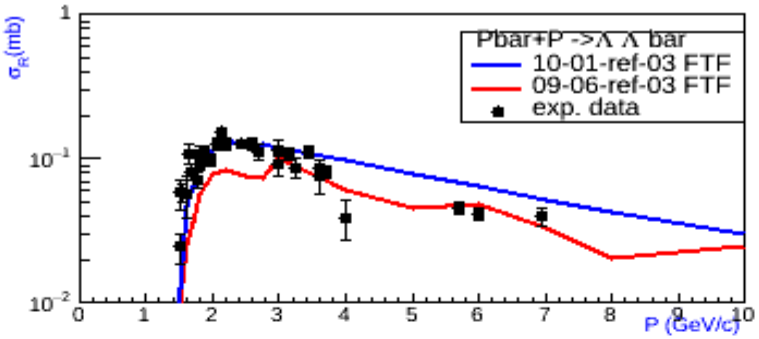


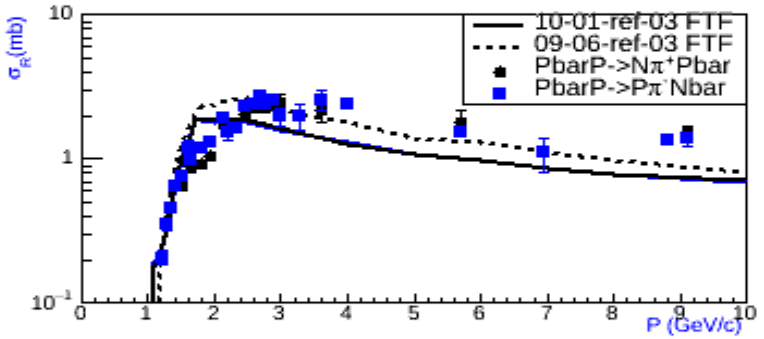


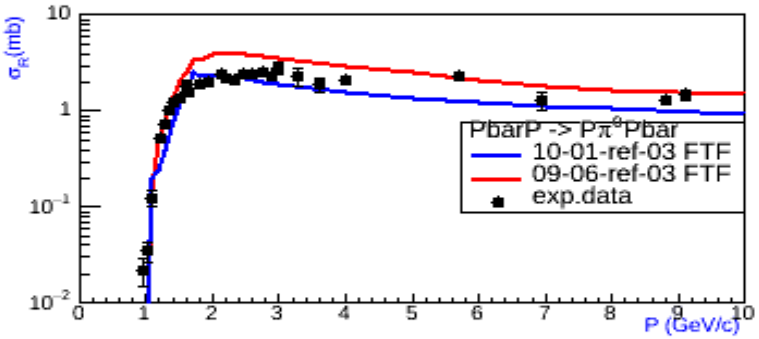
Exp. data: E.Bracci et al.,CERN/HERA 73-1(1973)

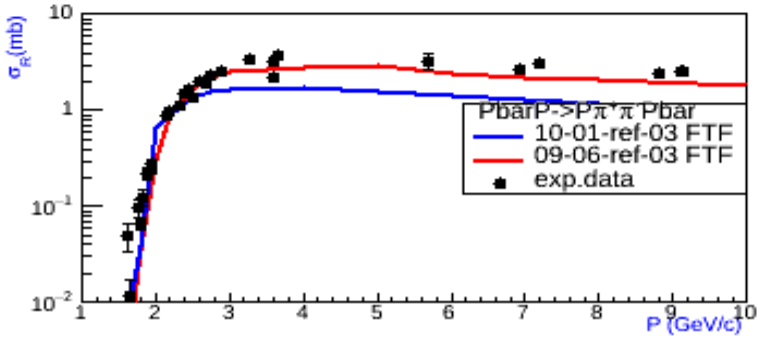
Pbar-P channel cross sections with baryons in final states

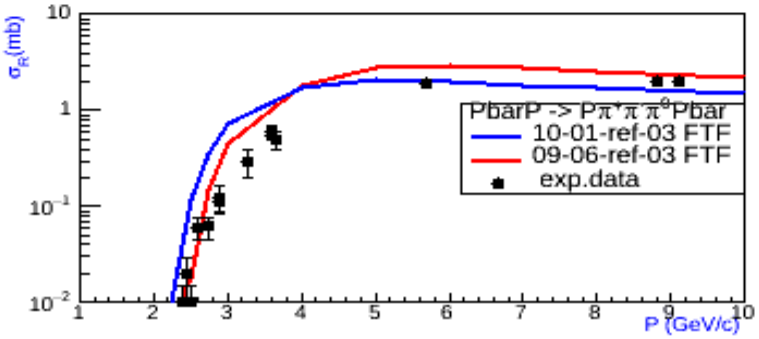






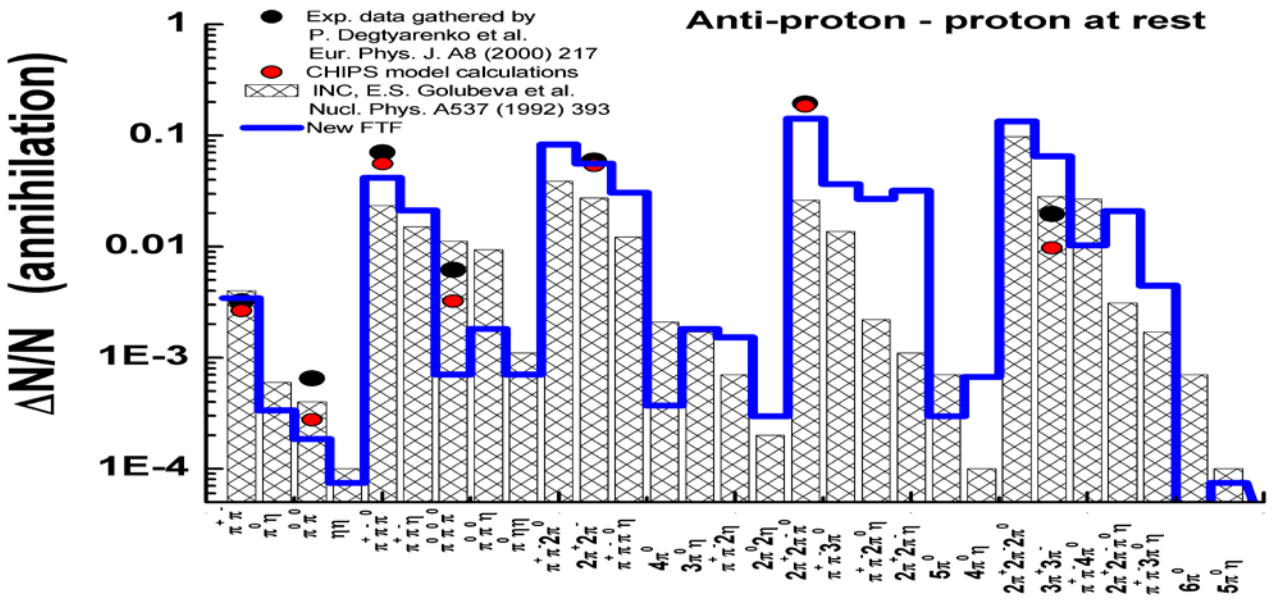






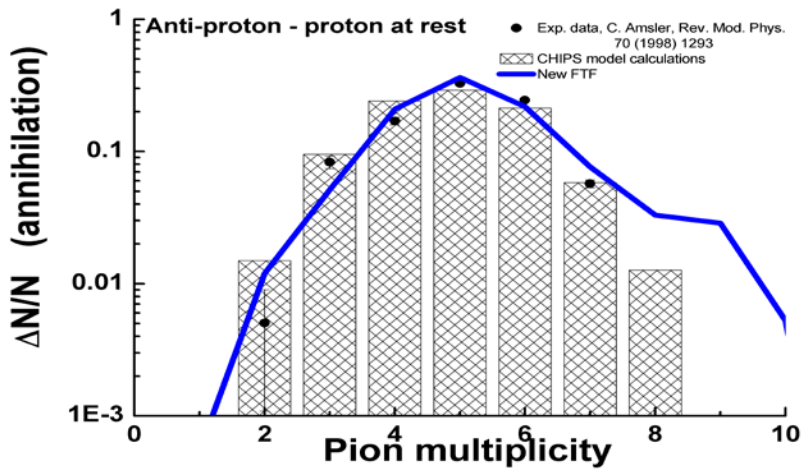
Exp. data: E.Bracci et al.,CERN/HERA 73-1(1973)

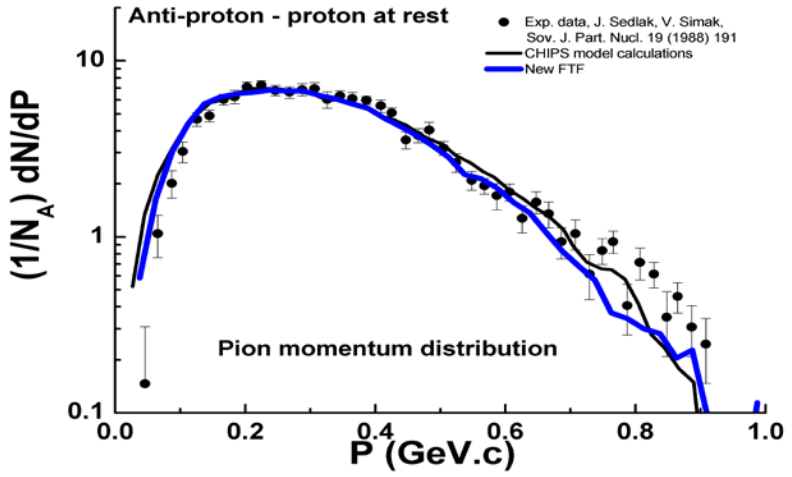
Pbar-P Annihilation at rest



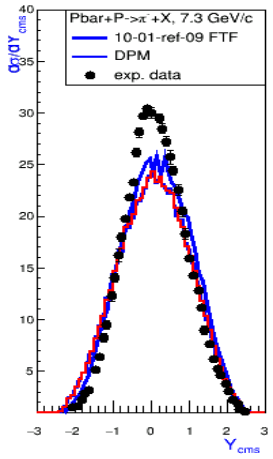
See more data in:
C. Amsler F. Myhrer
Ann. Rev. Nucl. Part. Sci.
v. 41 (1991) 219.

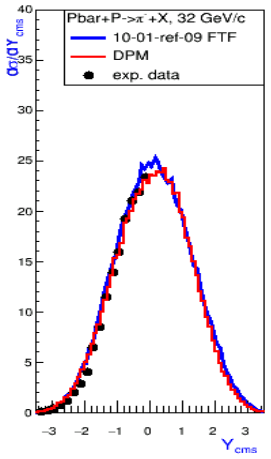
C. Amsler **Rev. Mod. Phys. 70 (1998) 1293**

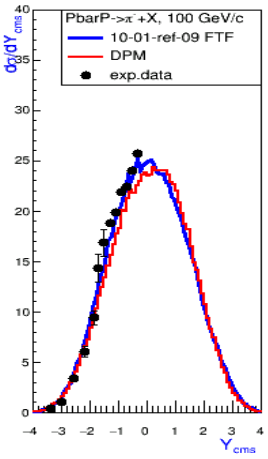


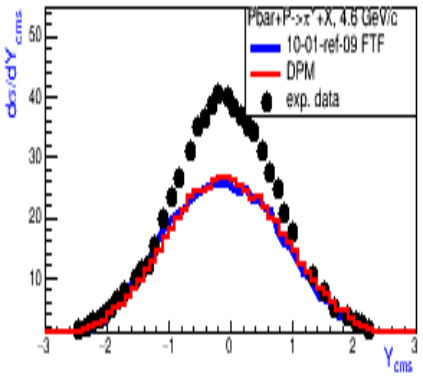


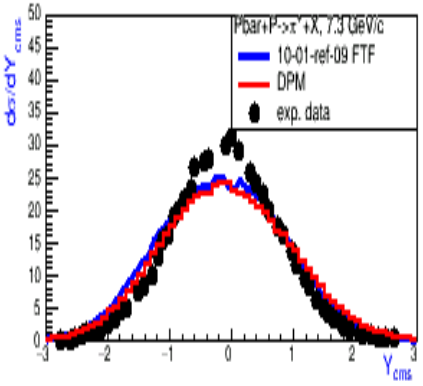
Kinematic spectra of π- π+ and Protons in Pbar-P reactions

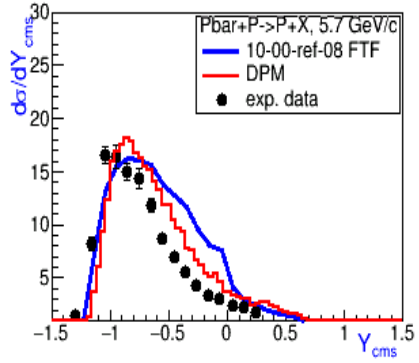


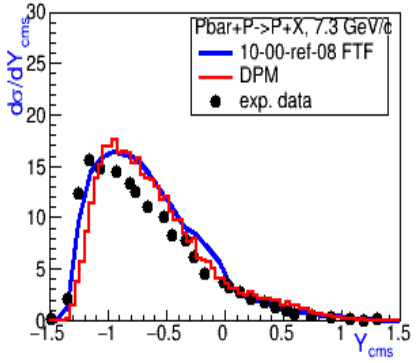


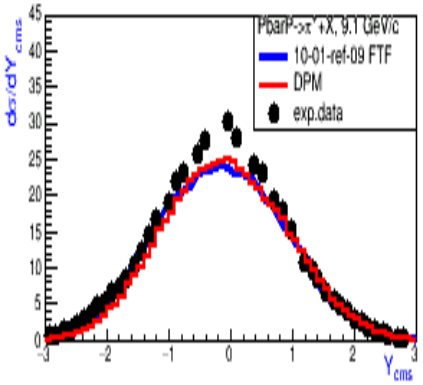


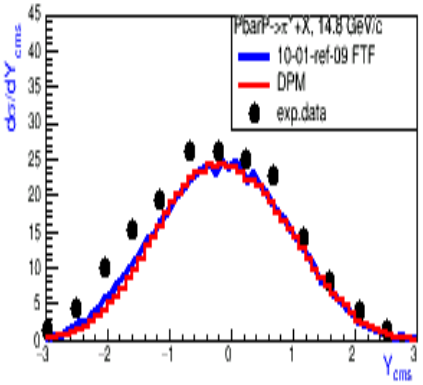


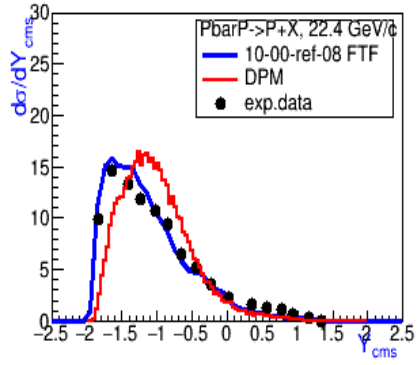


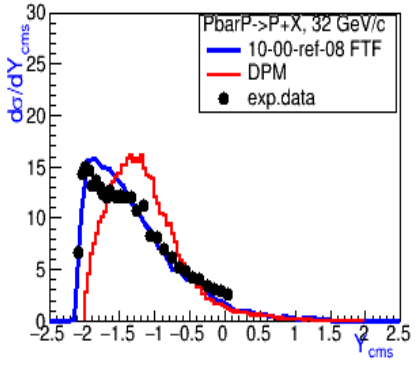


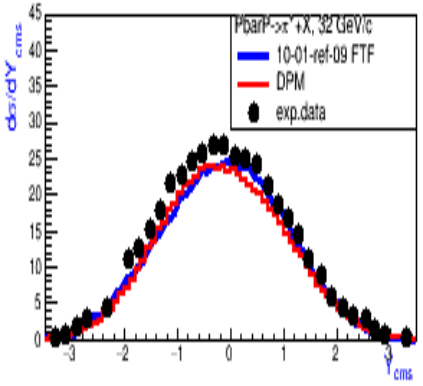


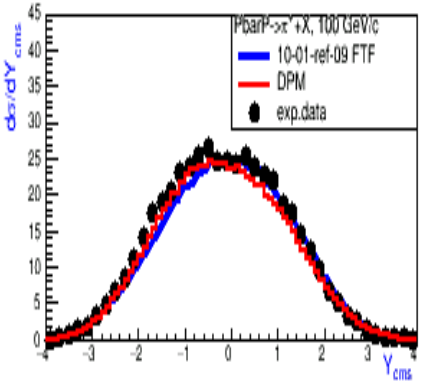












Glauber theory for antiproton-nucleus interactions

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

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

$$d^2\sigma/d^2q = |F_{hA}(\vec{q})|.$$

Differential elastic scattering cross section

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

Nuclear cross sections. How to calculate?

We have proposed a parameterization of PbarP cross sections

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

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

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

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

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

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

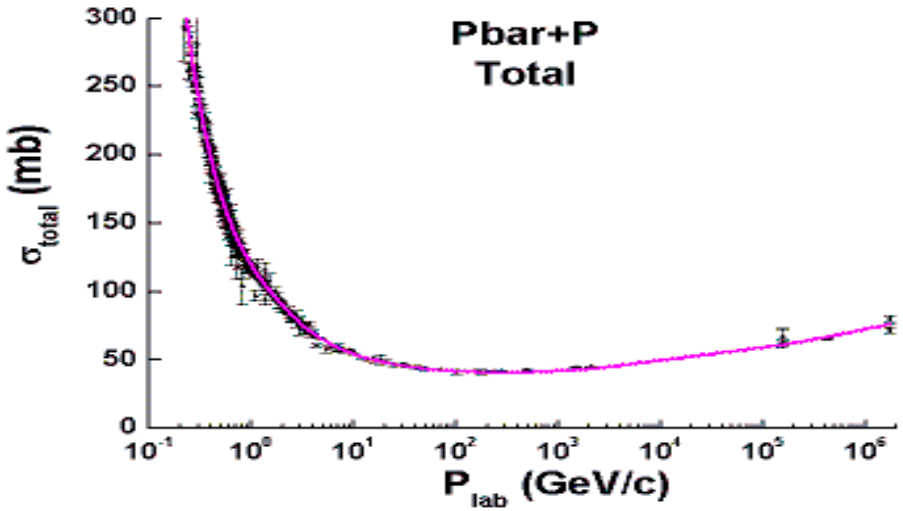
$$\sigma^{el}_{asmpt} = 4.5 + 0.101\ \ (log(s/33.0625))^2$$

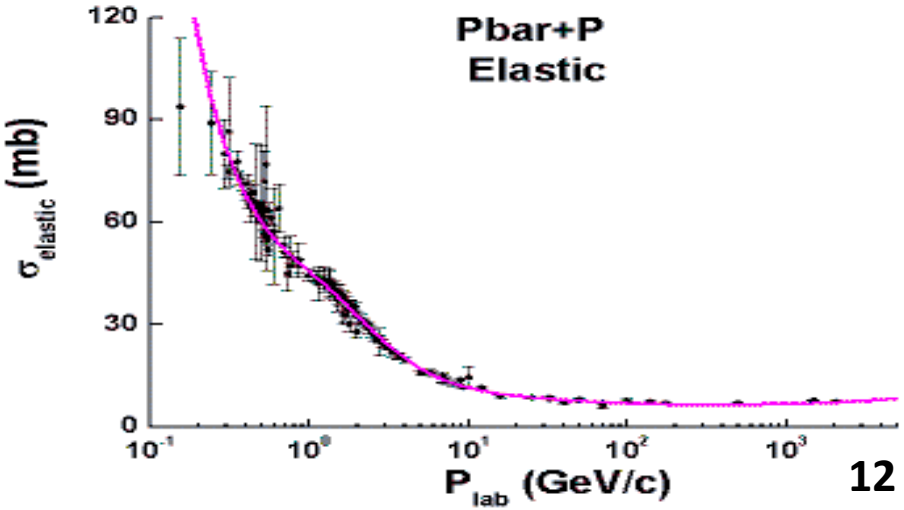
$$R_0 = \sqrt{0.40874044\,\sigma^{tot}_{asmpt} - B}$$

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

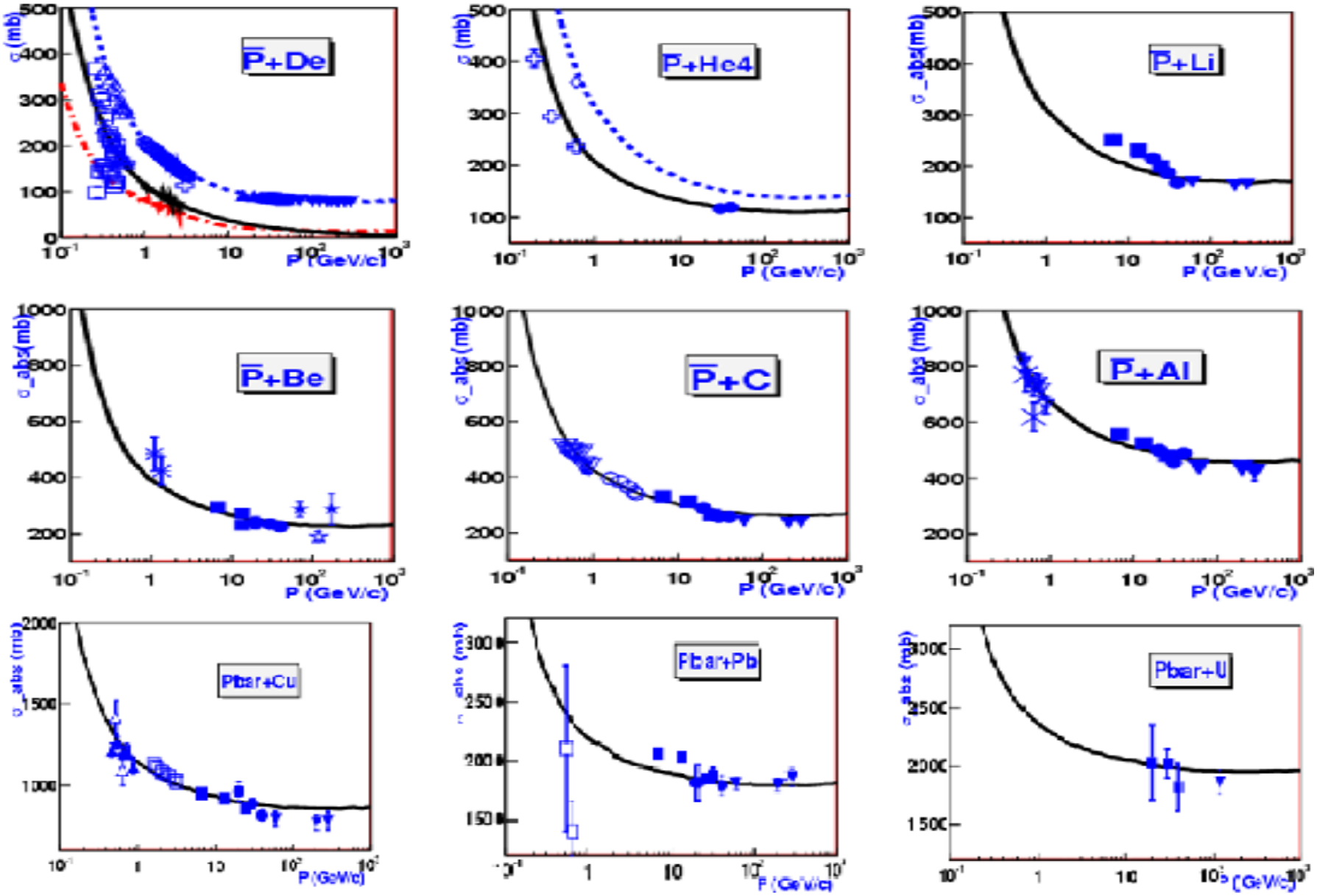
$$C = 59.27,\ d_1 = -6.95,\ d_2 = 23.54,\ d_3 = -25.34$$

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





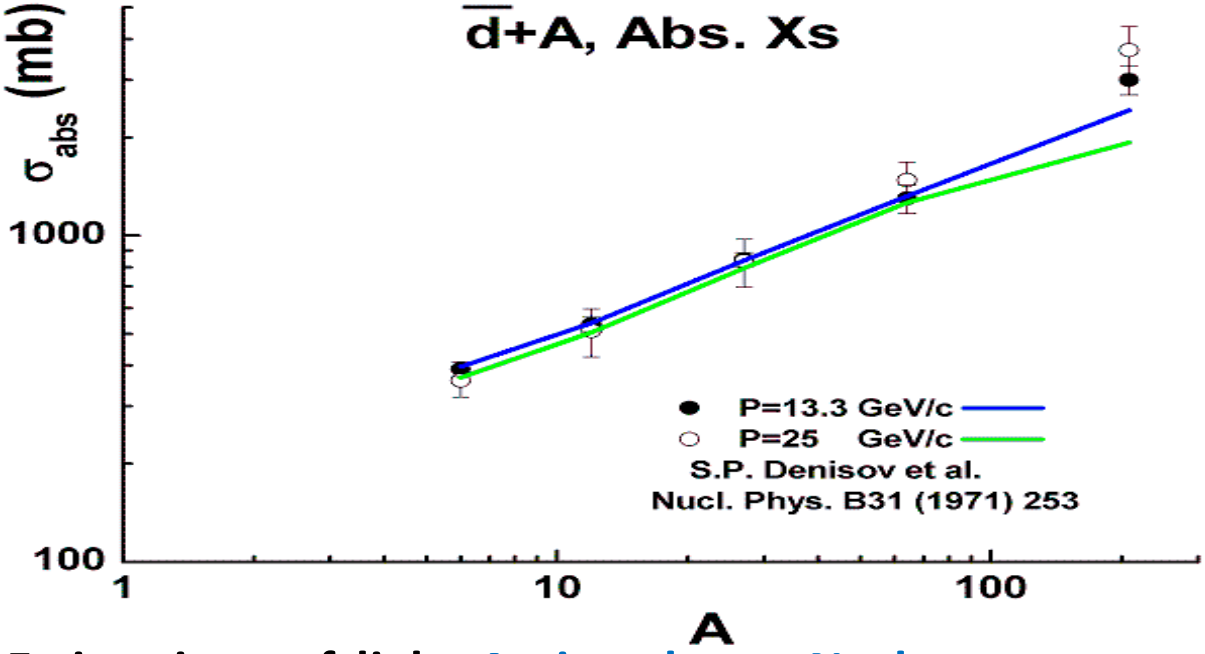
Cross sections of Antiproton–Nucleus interactions



V. Uzhinsky, J. Apostolakis , A. Galoyan et al. // Phys. Lett. B705 (2011) 235

The Glauber approach works well!

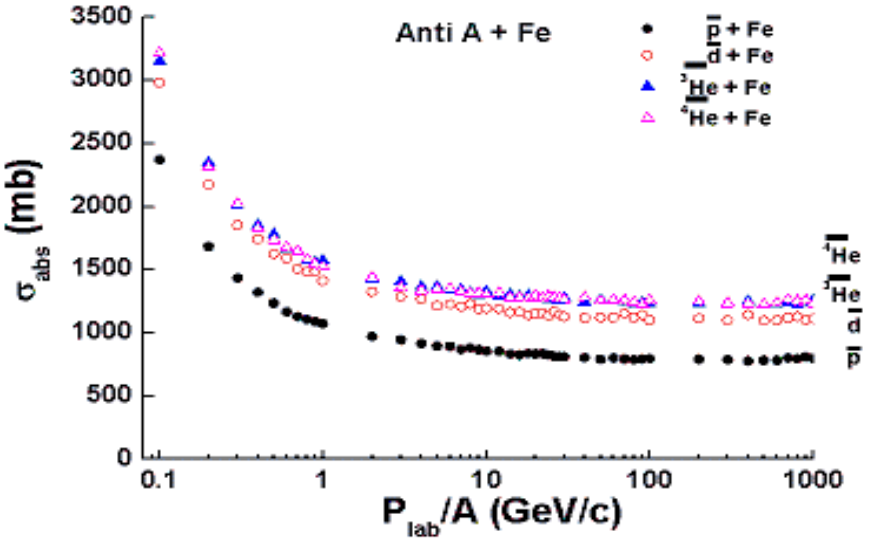
Nuclear cross sections – absorption X's

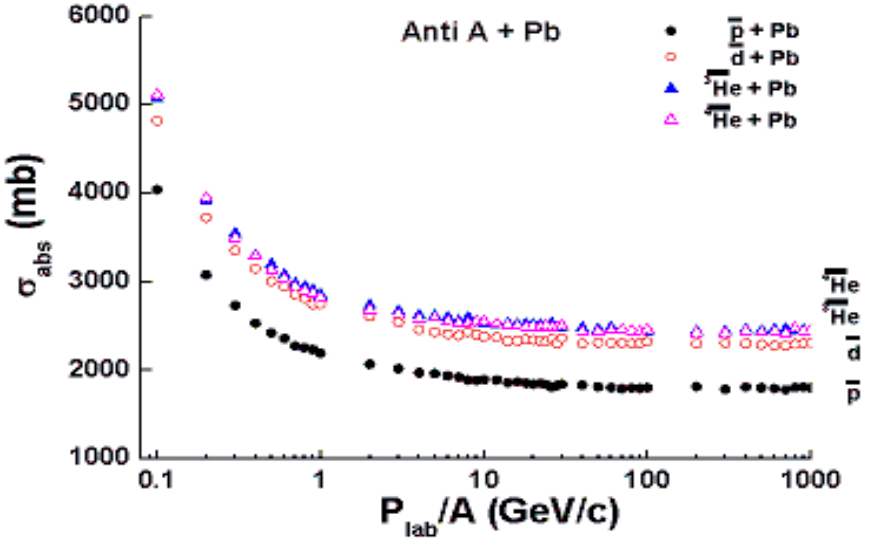


The solid and open points are the experimental data at anti-deuteron momenta of 13.3 and 25 GeV/c

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

Estimations of light Anti-nucleus – Nucleus cross sections



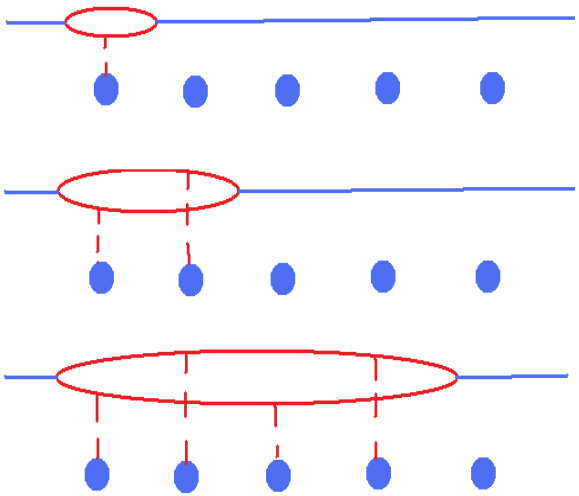


Simulation of Antibaryon–Nucleus interactions in FTF model

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

"Simulations of light antinucleus-nucleus interactions"

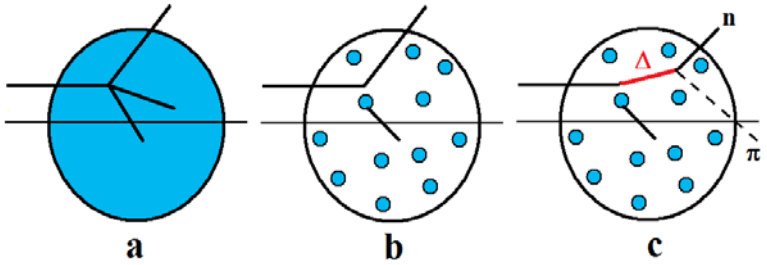
$$\sigma_{\bar{p}A}^{in} = \int d^2b[1 - e^{-\sigma_{\bar{p}n}^{in} T(\vec{b})}] = \sum_{\nu=1}^{\infty} \int d^2b \frac{[-\sigma_{\bar{p}n}^{in} T(\vec{b})]^{\nu}}{\nu!} e^{-\sigma_{\bar{p}n} T(\vec{b})}$$

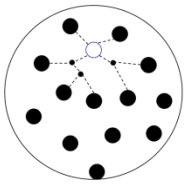


Low energy, Std. cascade.

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

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

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

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

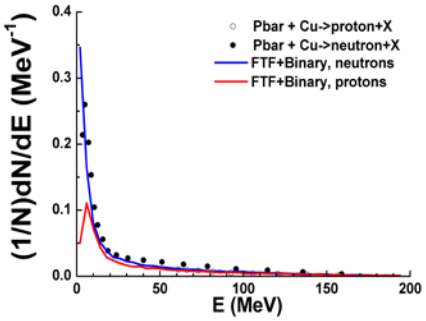
S.Yu. Shmakov, V.V. Uzhinsky, Zeit. fur Phys. C36:77,1987.

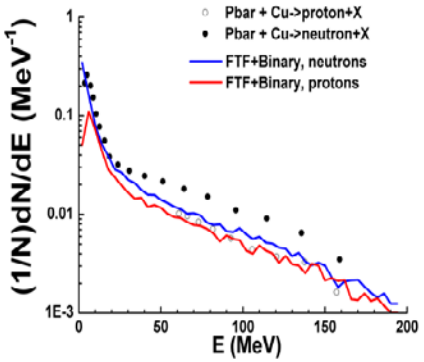
Max. cross section method:

W.A. Coleman: Nucl. Sci. Eng. 32 (1968) 76

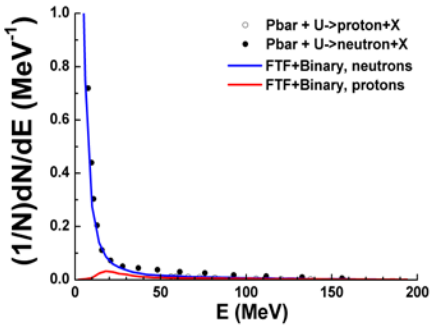
Annihilation Pbar-A at rest.

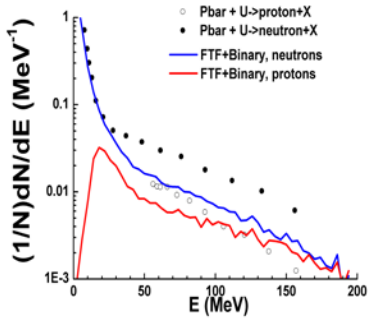
Cu



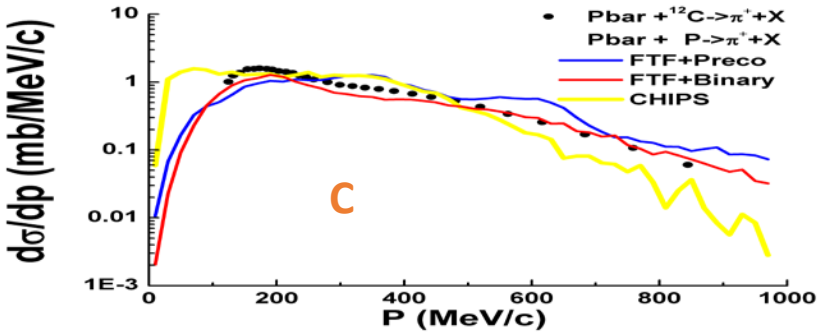


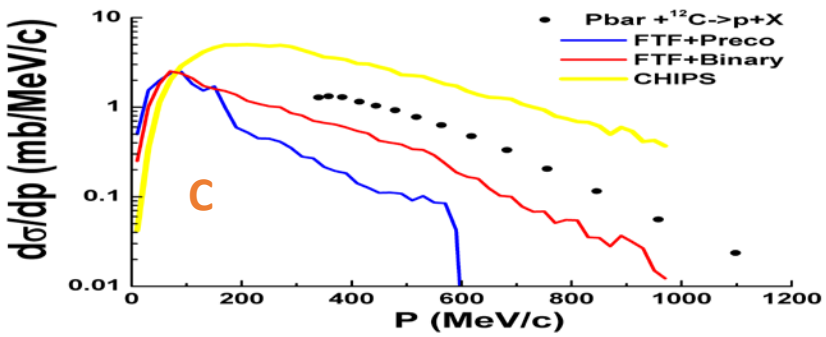
U

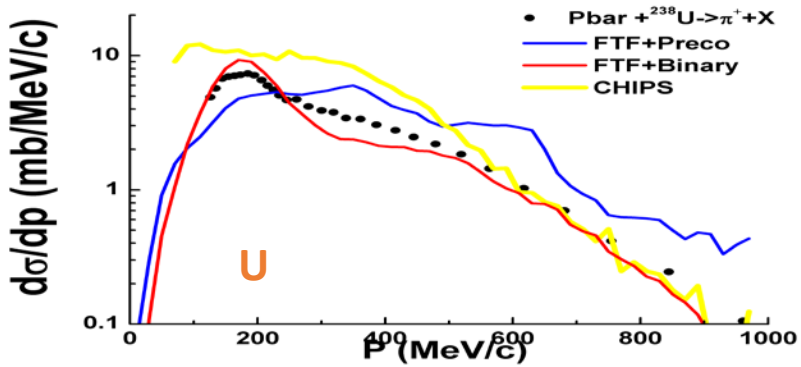


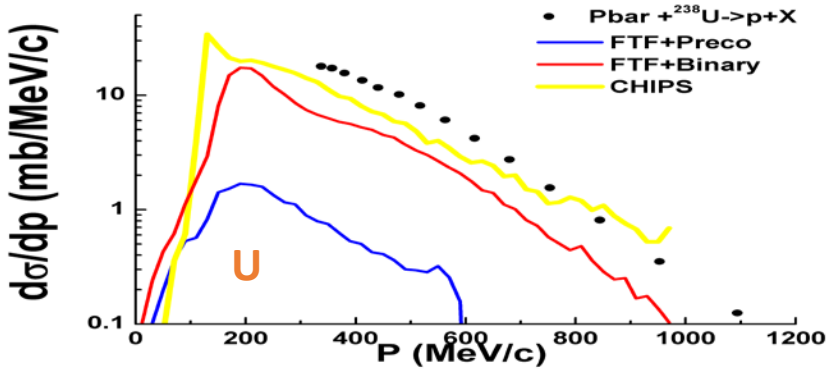


Simulation of pbar-A at Plab= 608 MeV/c





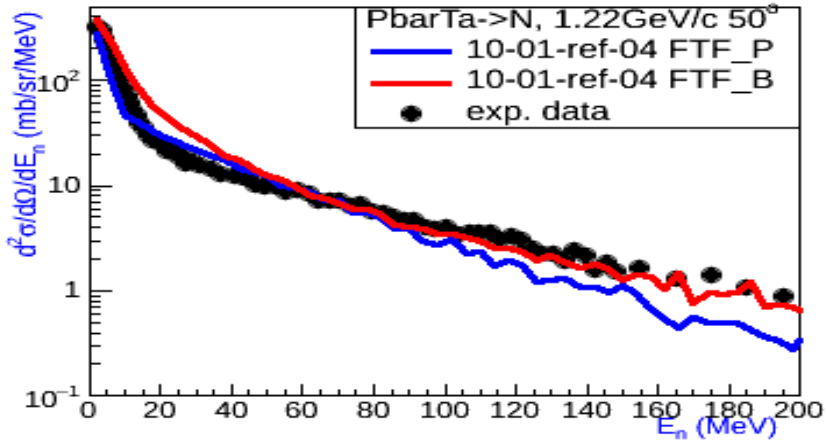


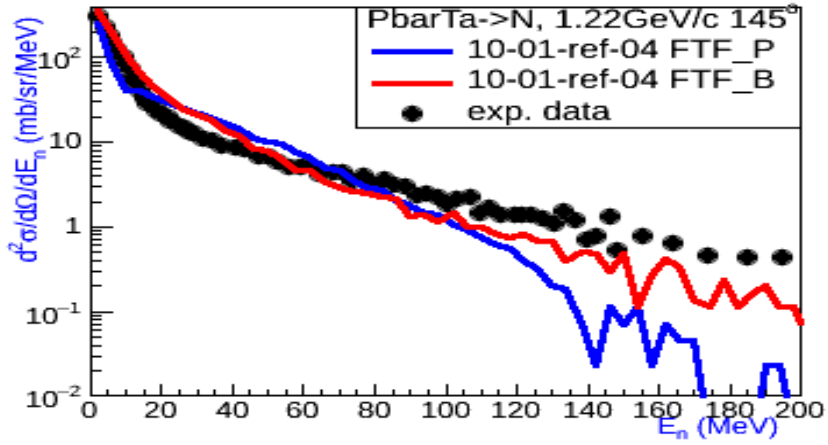


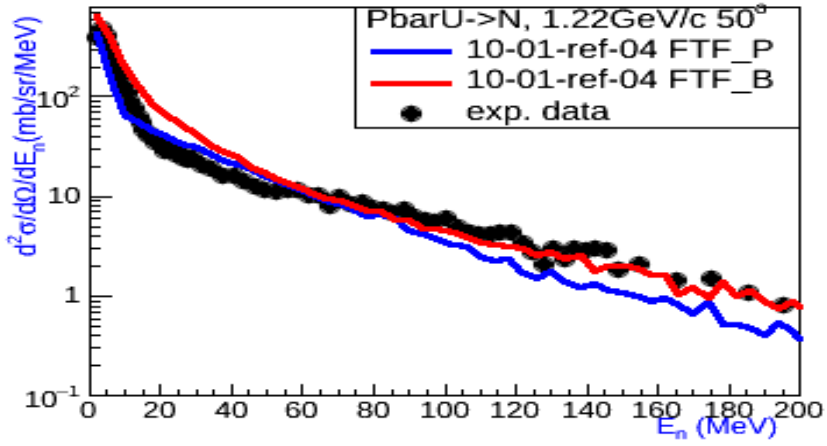
Results of FTF validation for Antiproton–Nucleus

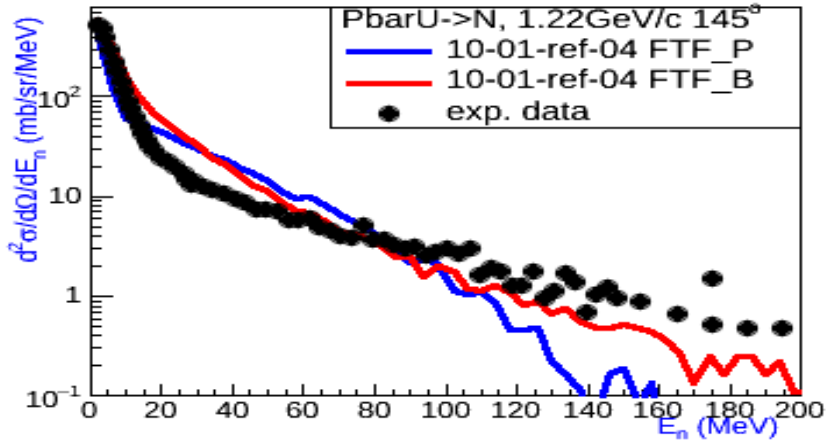
Kinetic energy spectra of neutrons produced in Pbar-Ta, Pbar-U

A. Galoyan, V. Uzhinsky // PoS (Baldin-ISHEPP-XXII) (2015) 049





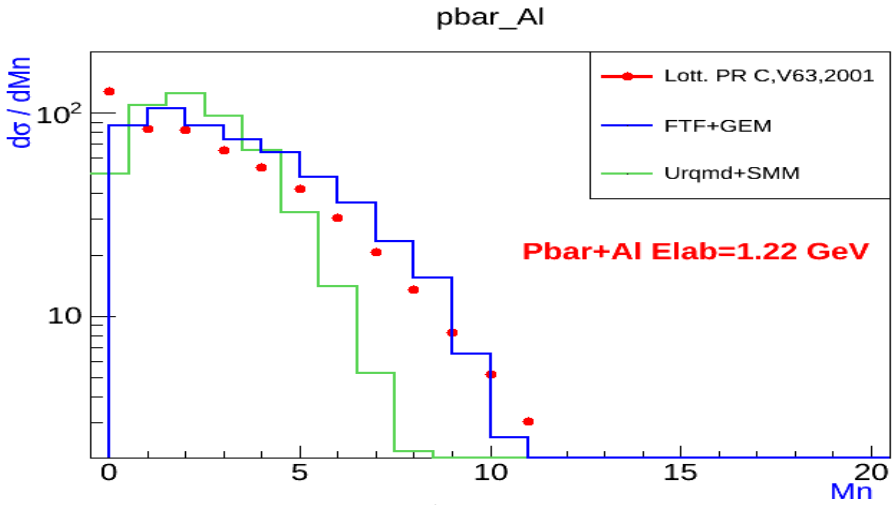


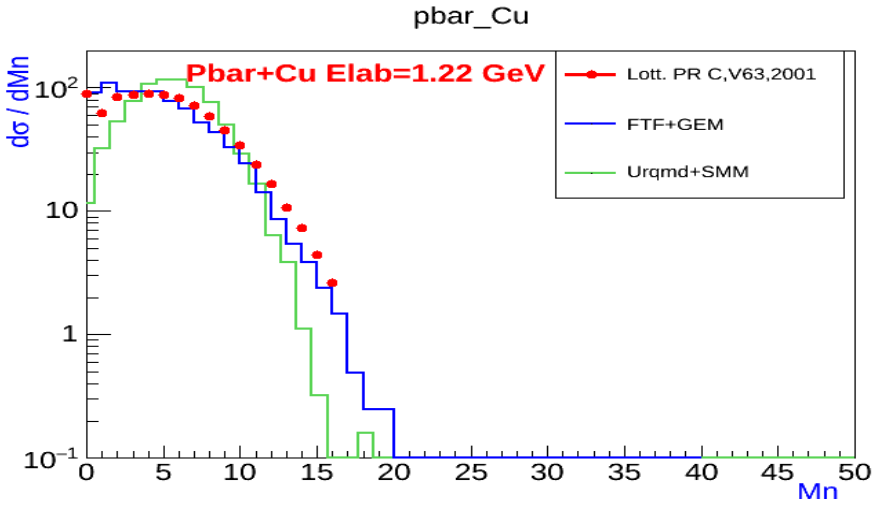


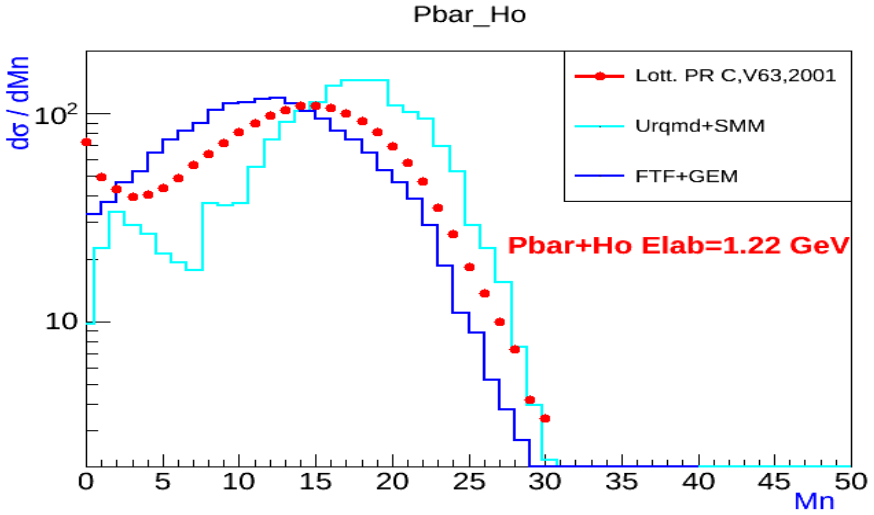
Exp: T. von Egidy et al., Eur. Phys. J. A 8, 197 (2000) LEAR collab. data

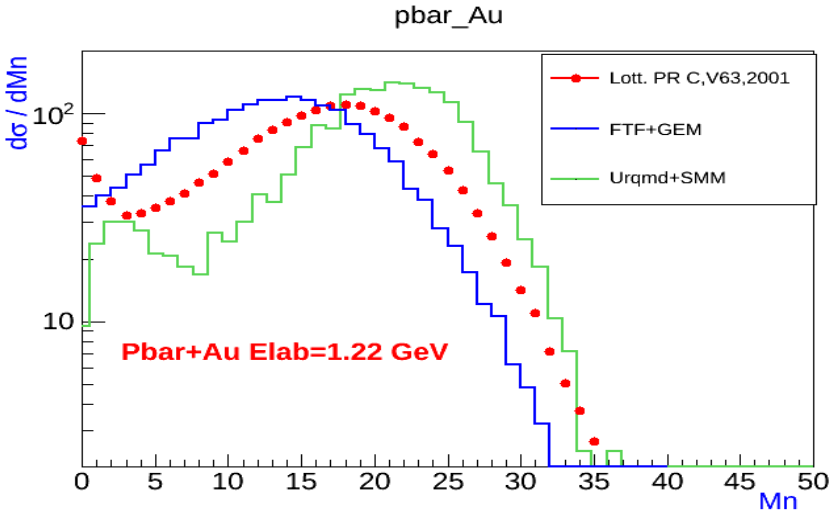
Results of FTF validation for Antiproton–Nucleus reactions

Multiplicity distributions of neutrons produced in Pbar-Nucleus at energy 1.22 GeV in FTF and UrQMD models





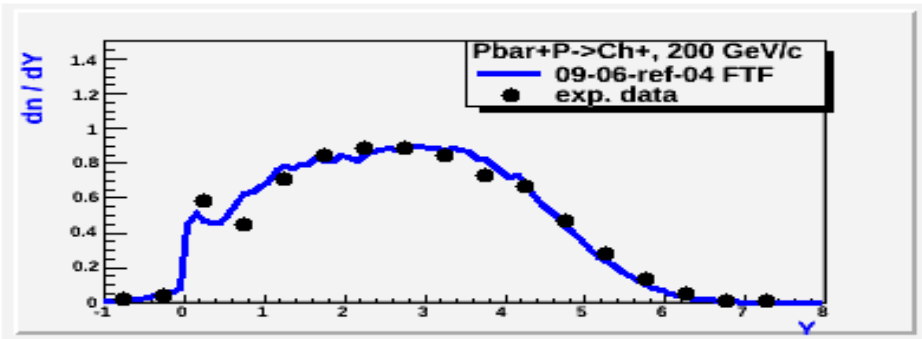


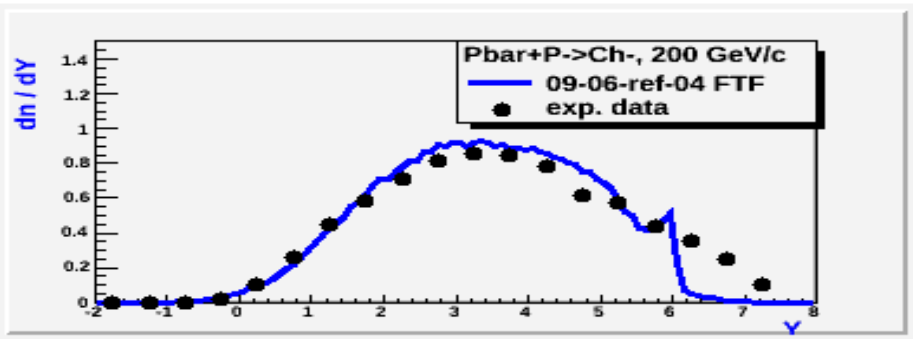


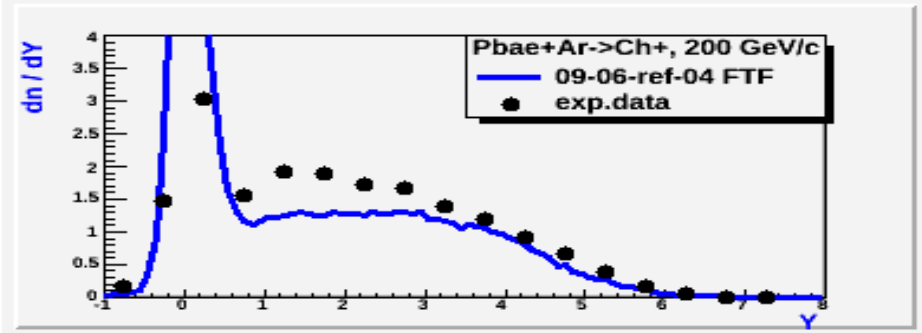
A.S.Galoyan et al., «Scaling and Asymptotical Properties of Slow Neutron Inclusive Cross Sections ...» JETP Letters, 2015, Vol. 102, No. 6, pp. 324-328 Exp.data : B. Lott et al., Phys.Rev.C 63 034616

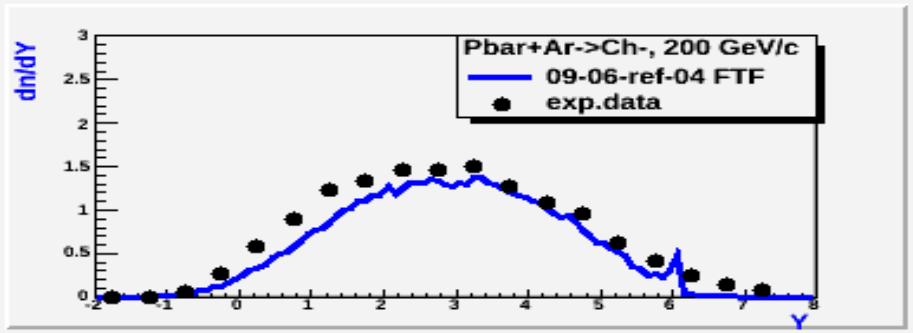
Results for FTF validation for Pbar-Nucleus interactions at p= 200 GeV/c

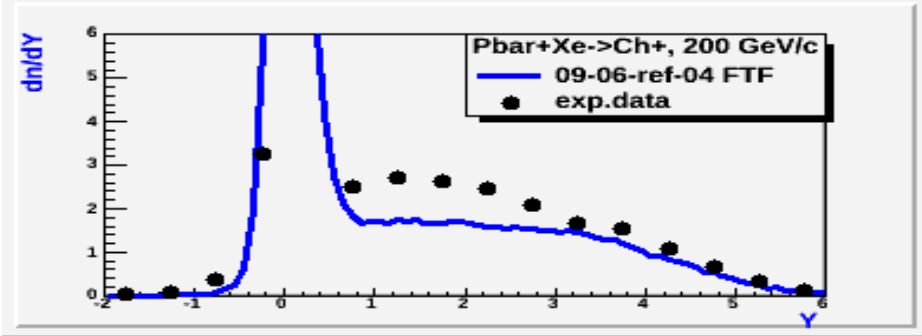
Rapidity Ch+, Rapidity Ch- mesons

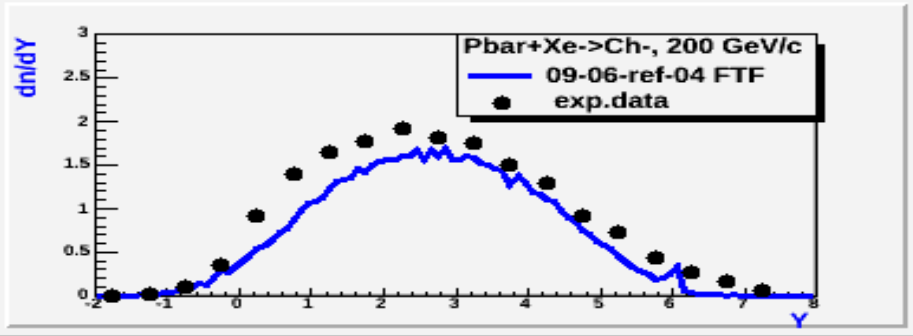












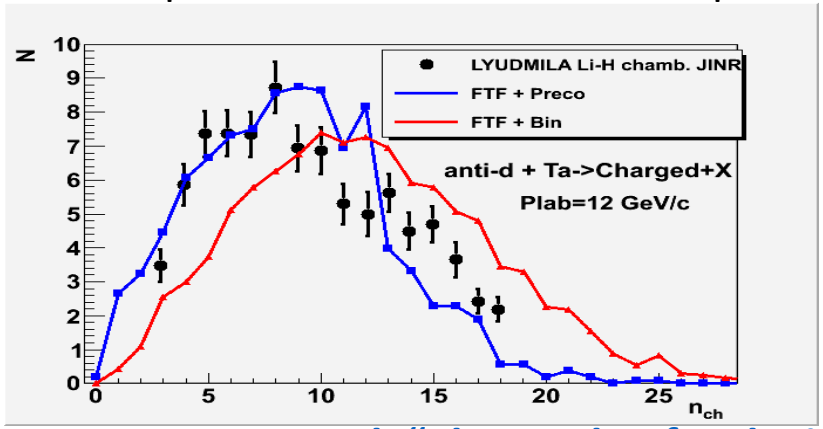
Multi-particle production on hydrogen, argon and xenon targets in a streamer chamber by 200 GeV/c proton and antiproton beams. De Marzo et al. Phys. Rev. D26 (1982) 1019

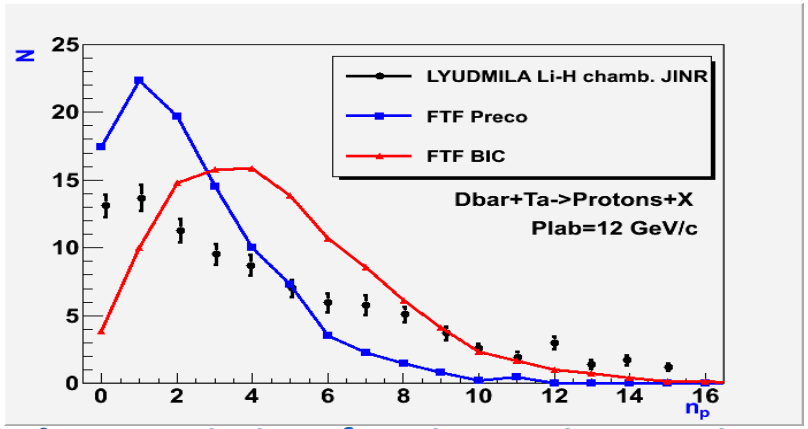
Anti-deuteron - Nucleus interaction at 12.2 GeV/c

V.F. Andreev et. al, "Multiplicities and Correlations of Secondary Charged Particles in the Interactions of Antineutrons and Antideytrons…" IL Nuovo Cimento, Vol. 103 A, N8, 1989.

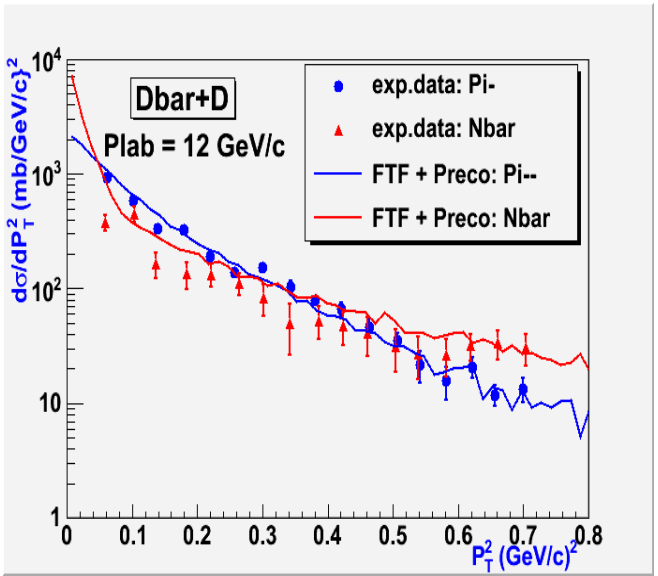
The exp. data were obtained using 2 meter liquid hydrogen chamber of LHE, JINR.

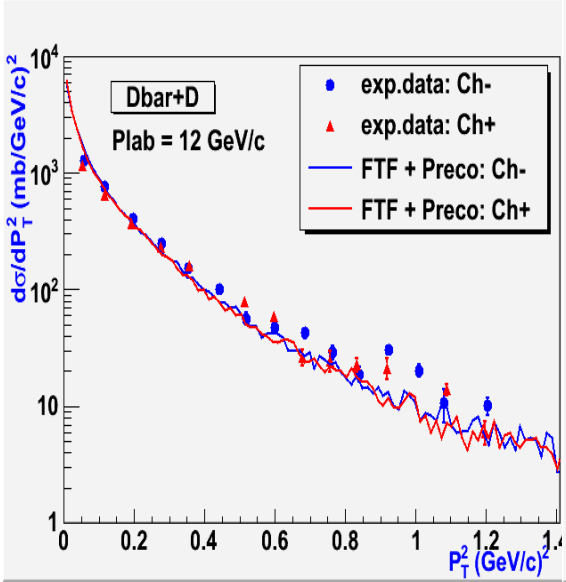
A tantalum plate in the chamber was exposed a beam of antideutrons at 12.2 GeV/c

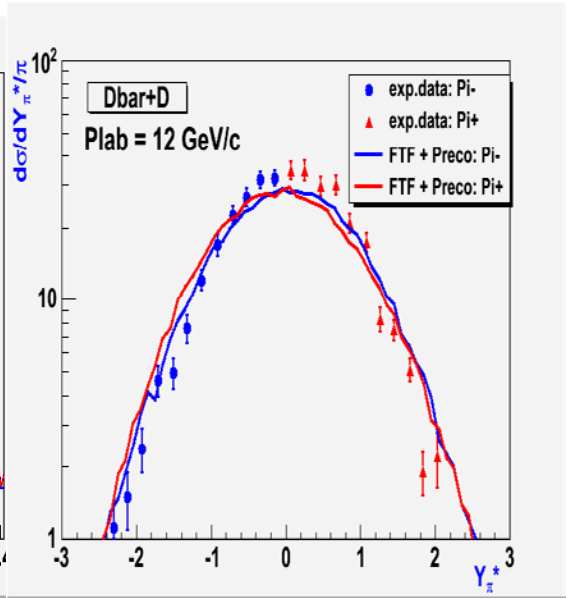




B.V. Batyunya et. al, "The Study of Inclusive Characteristics of antiD-D – interactions at 12 GeV/c", JINR Preprint P1-87-849







Conclusion

1. Antiproton-Nucleus and Anti-nucleus-nucleus cross sections are estimated in the Glauber approach and implemented in GEANT4.

2. Differential elastic cross sections of Antiproton-Nucleus and Anti-Nucleus-Nucleus scattering are also calculated in Glauber approach.

3. New implementation of the quark-gluon-string model for baryon annihilation is created. Validation region: 0– 1000 GeV/c.

4. First code for simulation of anti-nucleus – nucleus interactions is created. Validation region: 0 – 1000 GeV/c/nucleon.

5. Quark-gluon-string model works astonishingly well for antiproton-proton, antiproton-Nucleus and Anti-Nucleus-Nucleus interactions !

Geant4 allows now a simulation of anti-matter – matter interaction!

Returning to Tunguska meteor, we can suppose that it was vacuum explosion!

C. Cowan, C.R. Atluri, W.F. Libby

Possible Anti-Matter Content of the Tunguska Meteor of 1908

Nature, v. 206, 1965, p. 861

Assume that every neutron produced is absorbed in the reaction $^{14}N(n,p)^{14}C$, and that the radiocarbon so produced is rapidly oxidized to carbon dioxide in the atmosphere. Thus $(2{\cdot}7 \pm 1{\cdot}4) \times 10^{27}$ molecules of radio-CO_2 mix with the atmospheric gases. Taking the total mass of the

NATURE May 29, 1965 Vol. 206

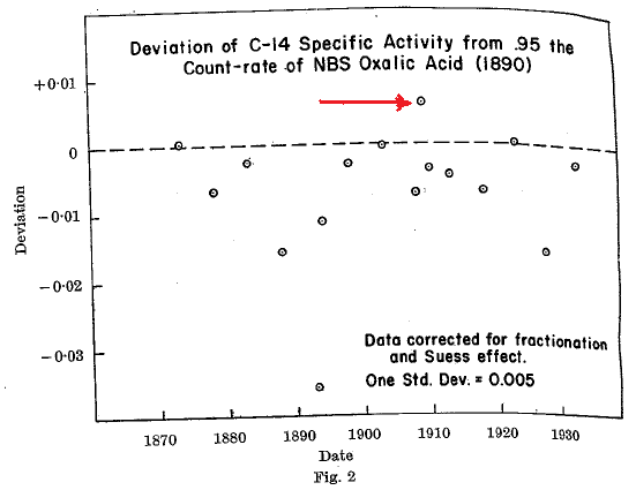


Fig. 2

P.J. Wyatt

Possible Existence of Anti-Matter in Bulk

Nature, v. 181, 1958, p. 1194

$\bar{p} + {}^{14}N$

$< \pi^- >$	1.71
$< \pi^+ >$	1.22
$< \pi^0 >$	1.13
$< n_p >$	0.52
$< n_n >$	0.37
$< n_{\bar{p}} >$	0.
$< n_{\bar{n}} >$	0.

$\bar{\alpha} + {}^{14}N$

$< \pi^- >$	3.23
$< \pi^+ >$	3.23
$< \pi^0 >$	2.46
$< n_p >$	0.81
$< n_n >$	0.74
$< n_{\bar{p}} >$	0.88
$< n_{\bar{n}} >$	0.88

$\bar{p} + {}^{14}N$

		$\sum E$ (Mev)	$< E_\gamma >$ (Mev)
$< \gamma >$	3.65	621	170
$< e^- >$	1.93	304	91
$< e^+ >$	1.42		

$\bar{\alpha} + {}^{14}N$

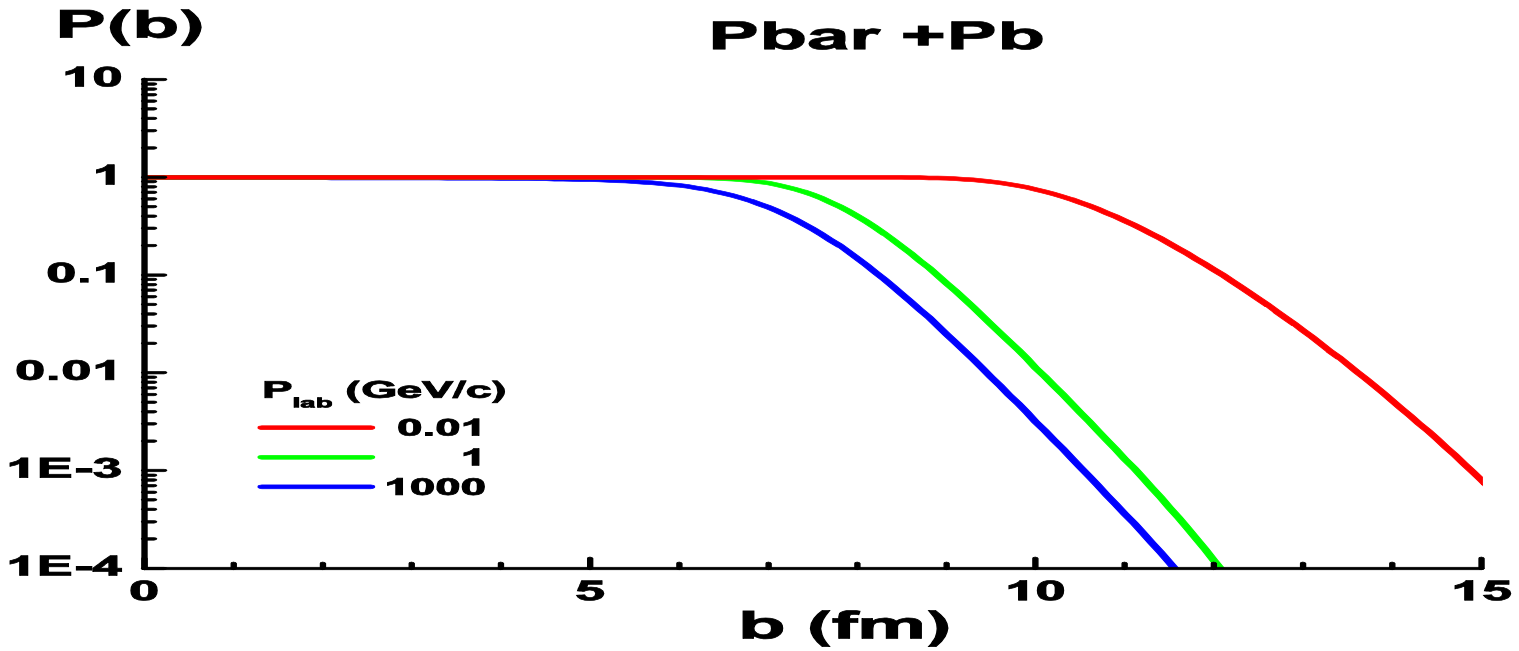
		$\sum E$ (Mev)	$< E_\gamma >$ (Mev)
$< \gamma >$	7.68	1322	172
$< e^- >$	3.72	717	86
$< e^+ >$	4.59		

There will be a huge electro-magnetic cascade!

Simulation of Anti-Nucleus-Nucleus Elastic Scattering

Calculation results for Profile functions in Glauber model

Generator of inelastic nucleus-nucleus interaction diagrams, Computer Physics Communications, 54 (1989)125, S. Yu. Shmakov, V. V. Uzhinskii, A. M. Zadorozhny



Profile functions P(b) for pbar+Pb at Plab=0.1, 1, 1000 GeV/c

According **to black disk model** approximation 2-dimensional **Fourie transform of P(b):**

$$F(q) = \pi R^2 \left[\frac{J_1(Rq)}{Rq}\right] \left[\frac{\pi cq}{sinh(\pi cq)}\right] \qquad (1)$$

W.E. Frahn, R.H. Venter// Ann. Phys. 24 (1963) 234;
D.C. Choudhury// Phys. Rev. C22 (1980) 1848;
Yu.A. Berezhnoy, V.Yu. Korda// Inter. J. Mod. Phys. 7 (1998) 723

Simulation of Anti-Nucleus-Nucleus Elastic Scattering

$$P(b) = \left[1 + e^{\frac{b-R}{c}}\right]^{-1}$$

D.W.L. Sprung, J. Martorell// J. Phys. **A30** (1997) 6525.

D.W.L. Sprung, J. Martorell// J. Phys. **A31** (1998) 8973.

$$F(q)/i = R^2 \frac{J_1(Rq)}{Rq} - \frac{(\pi c)^2}{6}\left[Rq\ J_1(Rq) - J_0(Rq)\right] + \ldots$$

$$F(q)/i = R^2 \frac{\pi c q}{sinh(\pi c q)}\left[\frac{J_1(Rq)}{Rq} + \frac{1}{2}\left(\frac{\pi c q}{tanh(\pi c q)} - 1\right)\frac{J_0(Rq)}{(Rq)^2} + \ldots\right]$$

Strong Absorption Model, or Black Disk Model

$$F(q) = i\ R^2 \left[\frac{J_1(Rq)}{Rq}\right] \left[\frac{\pi c q}{sinh(\pi c q)}\right]$$

Simulation of antiproton-proton and antiproton-nucleus Elastic Scattering

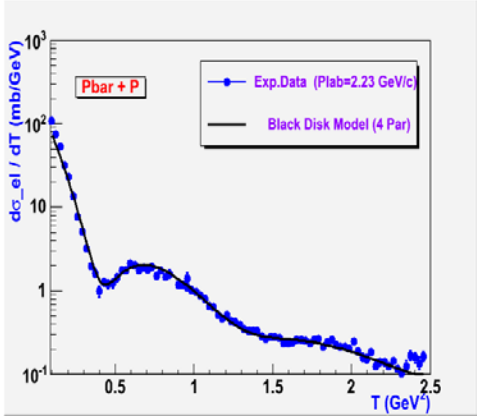
Black disk model approximation with diffuse boundary with Imaginary and Real parts of elastic scattering amplitude

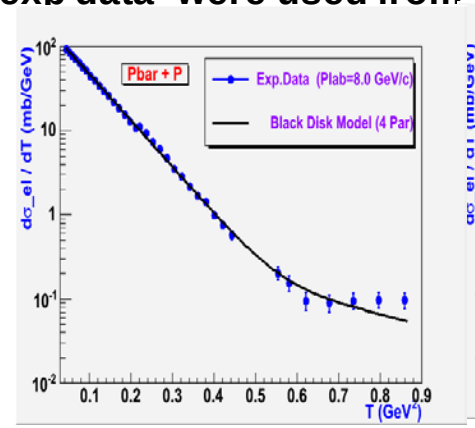
$$F(s,q) = i\ A_1 \frac{\pi c q}{\mathrm{sh}(\pi c q)} \frac{J_1(Rq)}{Rq} + A_2 \frac{\pi c q}{\mathrm{sh}(\pi c q)} J_0(Rq)$$

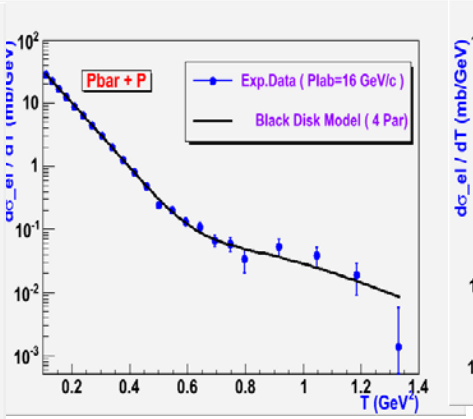
"Structure of antiproton-proton elastic scattering amplitude"

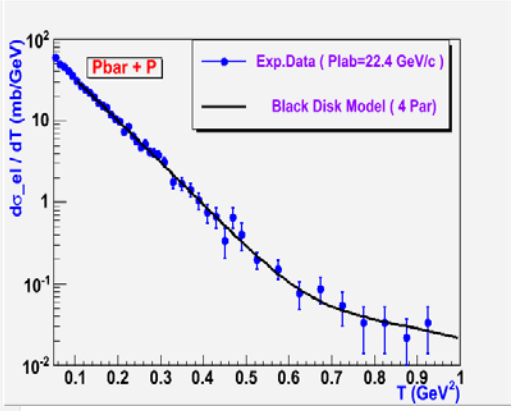
A. Galoyan, V.Uzhinsky, JETP Letters, v. 94, No 7 (2011)

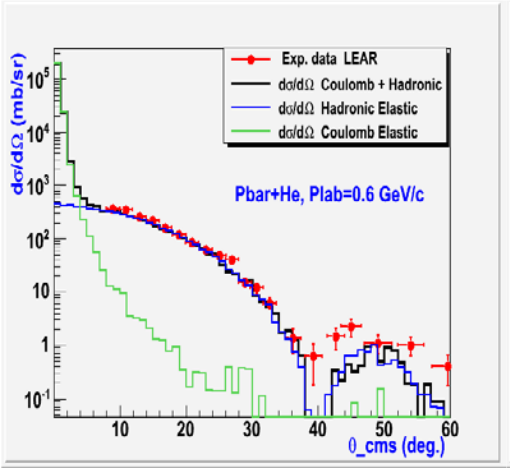
94 sets of pbar-p exp data were used from Plab=181 MeV/c up to sqrt(S)=1800 GeV

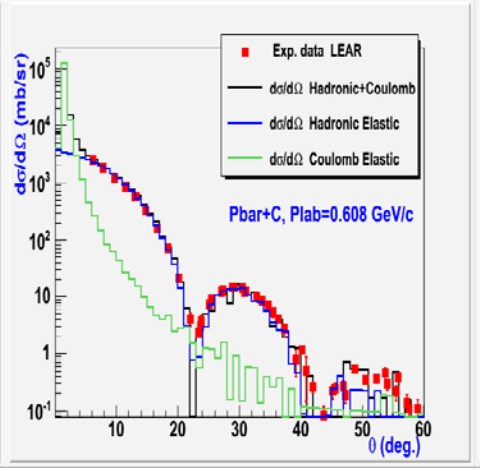


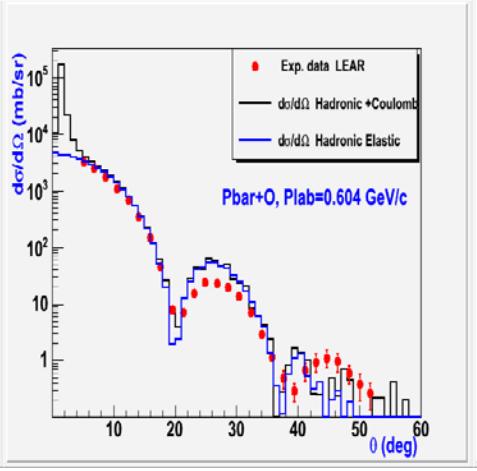


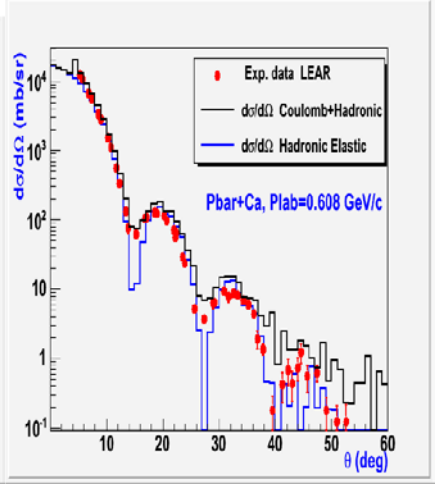




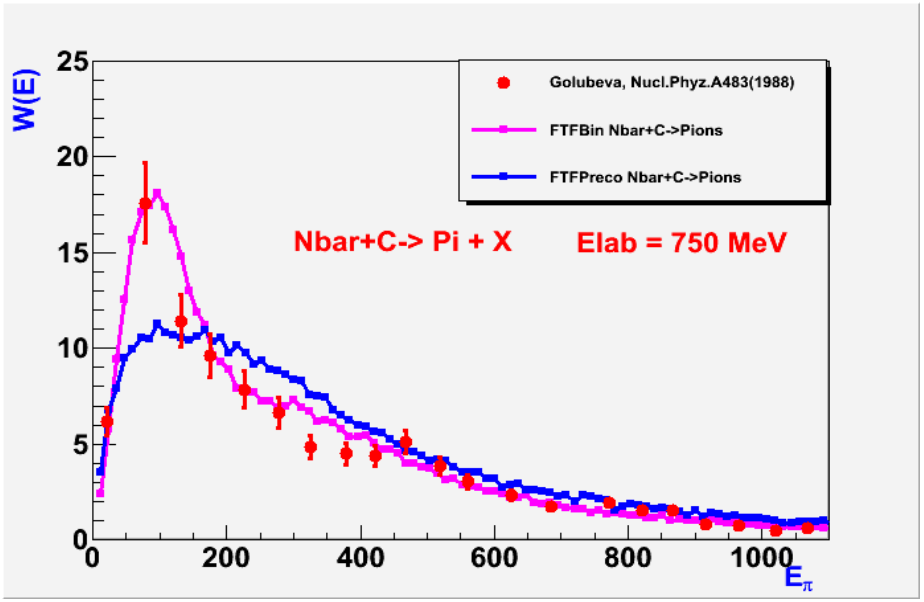


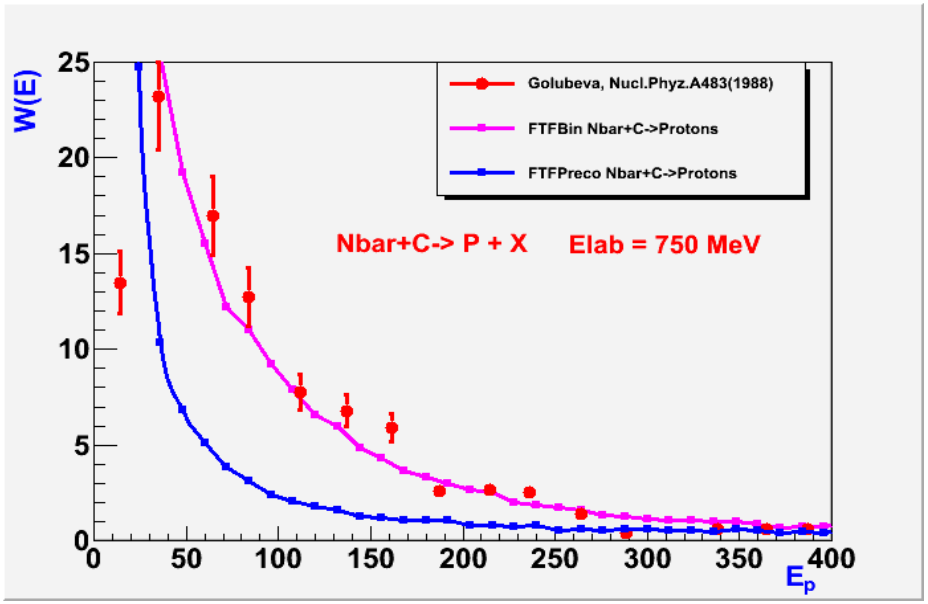


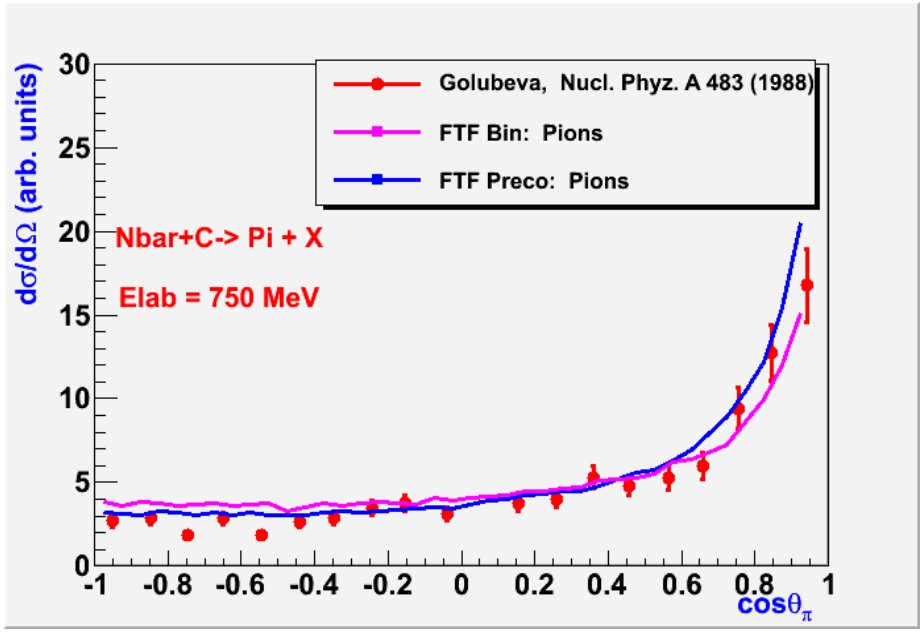


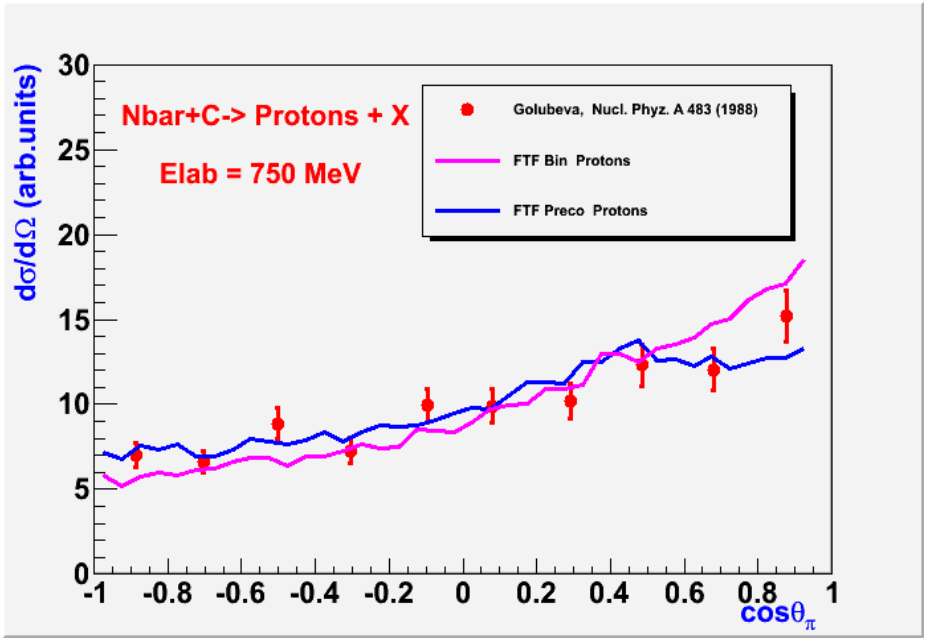


Antineutrons at Plab=1.4 GeV/c



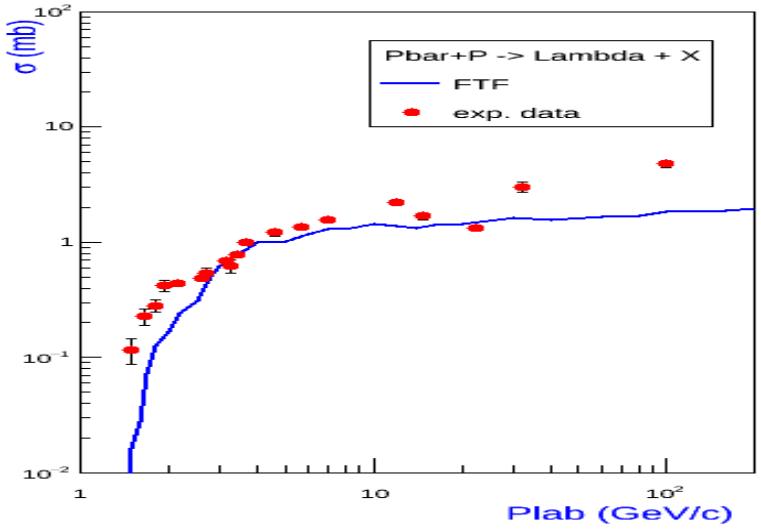


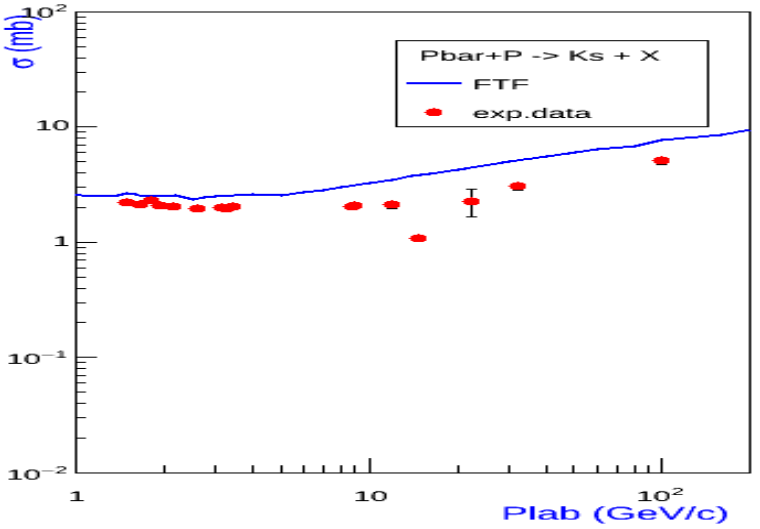




Inclusive Cross Sections of PbarP->Λ+X and PbarP->Ks^0+X processes

Exp.data: S. Banerjee et al., TIFR-BC-78-8





Xf and Pt^2 distributions of Ks^0 in PbarP->Ks^0 +X at Plab=0.76 GeV/c

Exp.data: A.M. Cooper et al., Nucl.Phys.B 136, 1978, P.365