HADRON PRODUCTION SIMULATION

Francesco Cerutti

NuFact'11

XIII Workshop on Neutrino Factories,

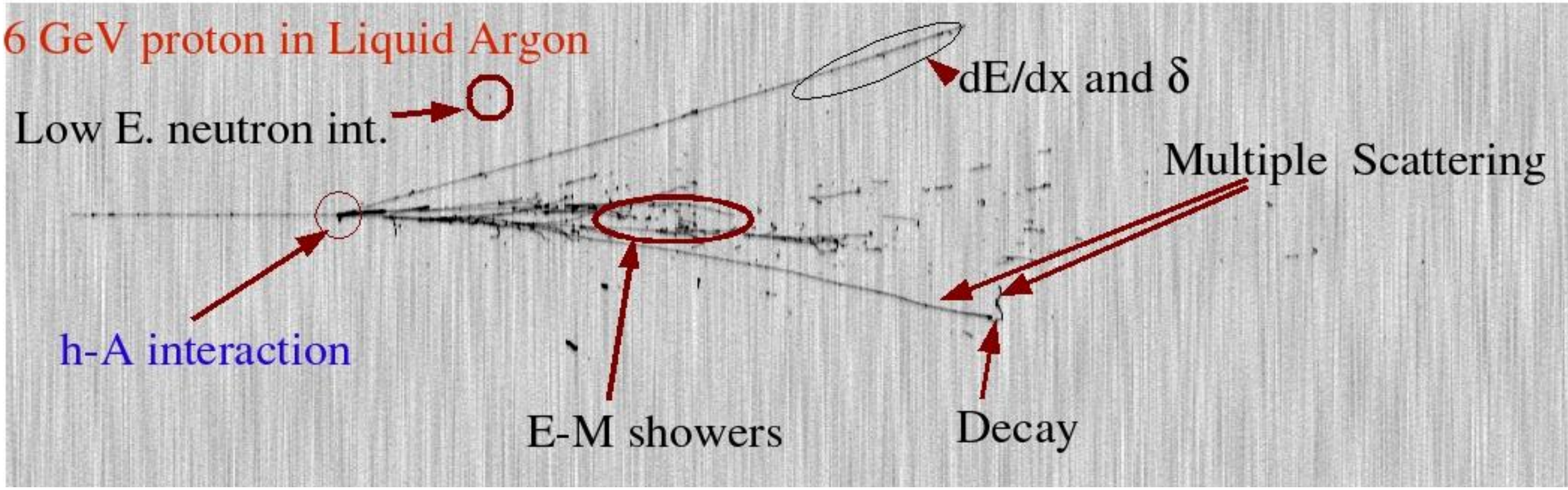
Superbeams and Beta-Beams

2011 Aug 4th

OUTLINE

- FLUKA overview
- hN, hadron-nucleon interactions
- hA, hadron-nucleus interactions
- (AA, nucleus-nucleus interactions)

THE FLUKA CODE

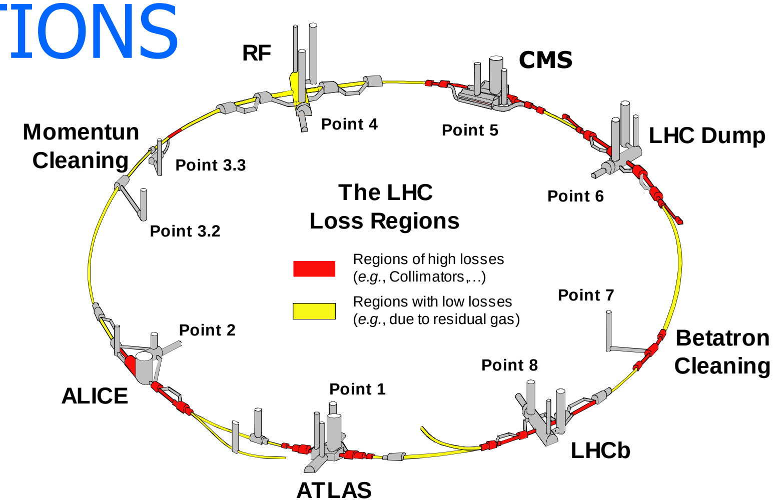


- Hadron-nucleus interactions
- Nucleus-Nucleus interactions
- Electron interactions
- Photon interactions
- Muon interactions (inc. photonuclear)
- Neutrino interactions
- Decay
- Low energy neutrons

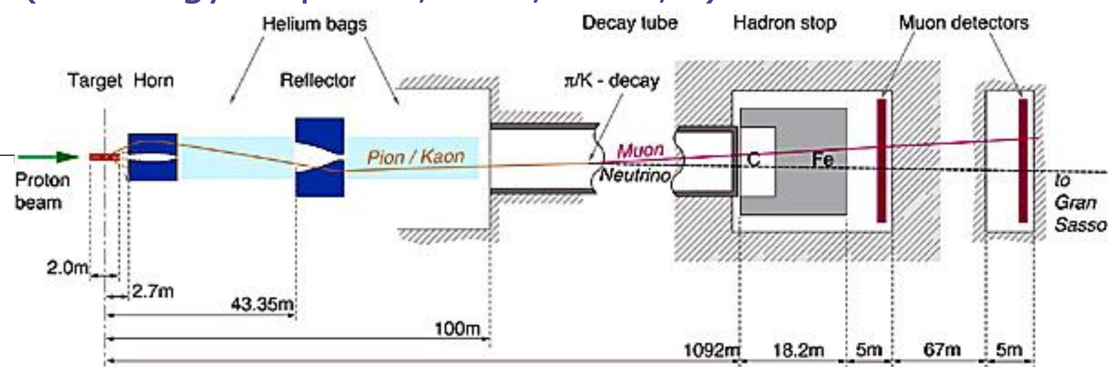
- Ionization
- Multiple scattering
- Combinatorial geometry
- Voxel geometry
- Magnetic field
- Analogue or biased
- On-line buildup and evolution of induced radioactivity and dose

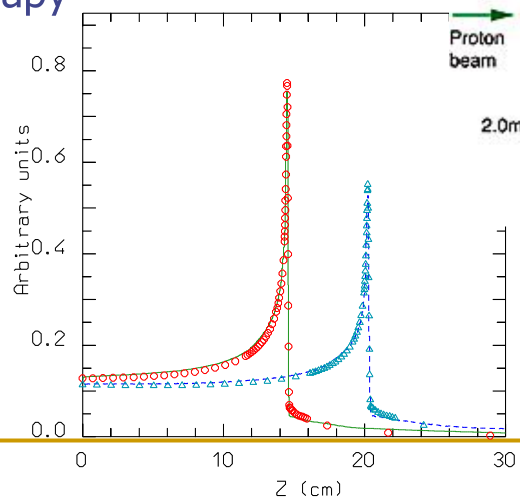
- User-friendly GUI thanks to *Flair*

THE FLUKA APPLICATIONS



- Accelerator design (→ nTOF, CNGS, LHC systems)
- Shielding design
- Dosimetry and radioprotection
- Cosmic ray physics
- Neutrino physics
- Particle physics: calorimetry, tracking and detector simulation etc. (→ ALICE, ICARUS, ...)
- ADS systems, waste transmutation (→"Energy amplifier", FEAT, TARC,...)
- Space radiation
- Hadrontherapy
- Neutronics





THE FLUKA DEVELOPMENT AND DISSEMINATION

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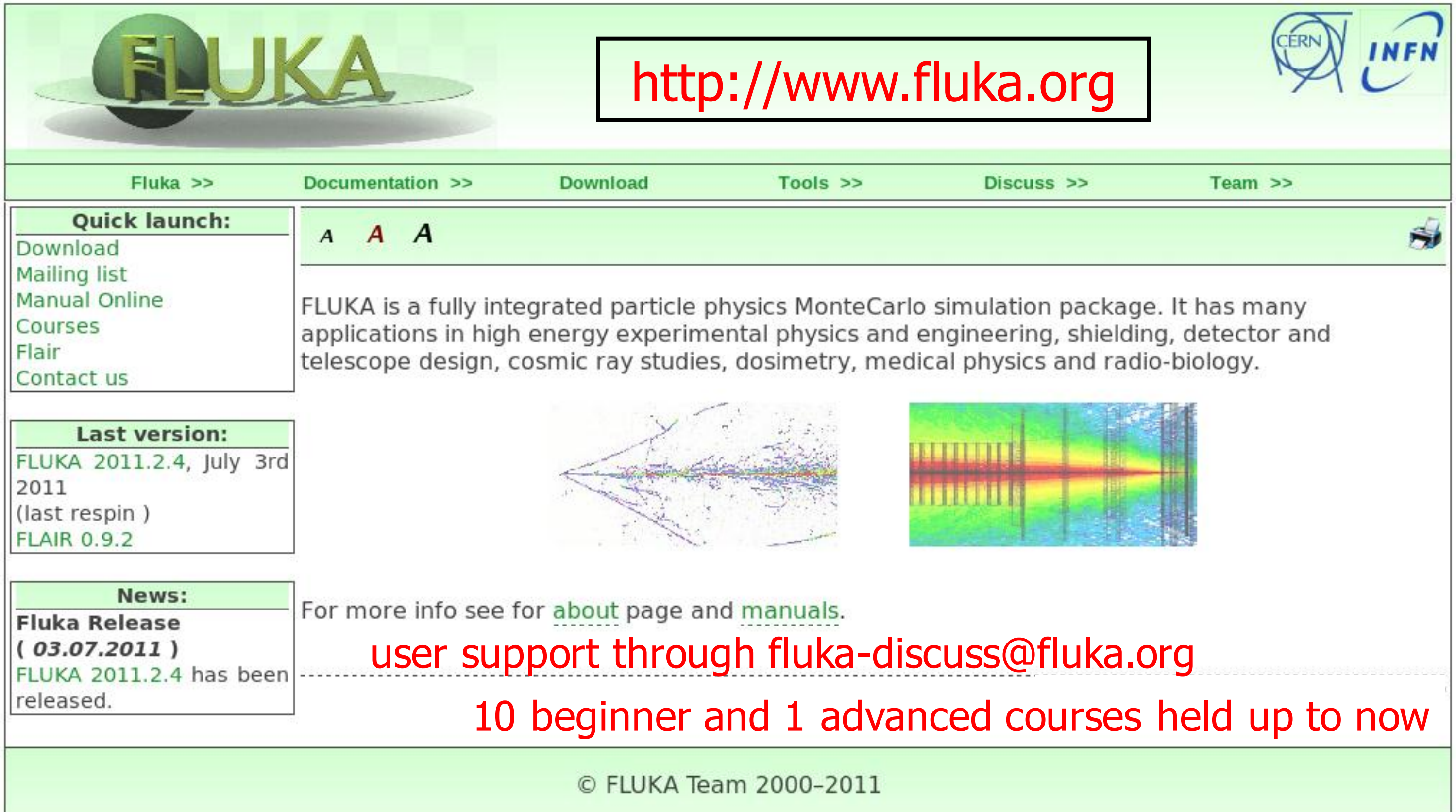

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10 beginner and 1 advanced courses held up to now

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THE FLUKA COLLABORATION

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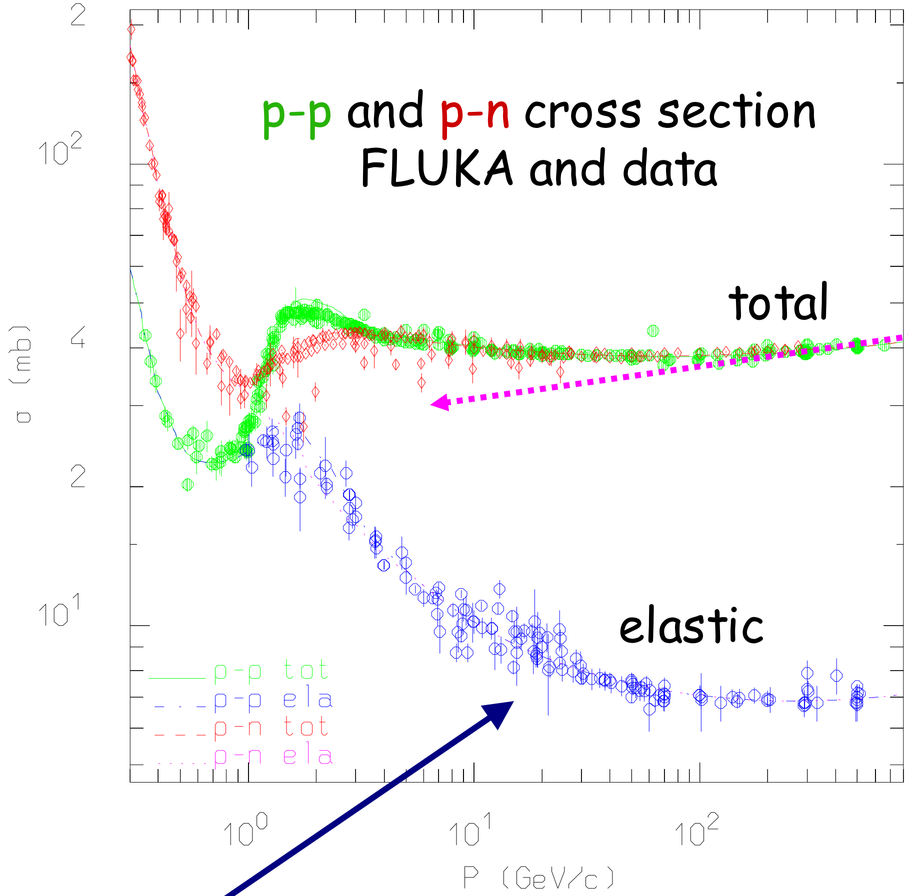
hN



Particle production interactions: two kinds of models

Those based on "resonance" production and decays, cover the energy range up to 3–5 GeV

Those based on quark/parton string models, provide reliable results up to several tens of TeV

Elastic, charge exchange and strangeness exchange reactions:

- Available phase-shift analysis and/or fits of experimental differential data
- At high energies, standard eikonal approximations are used

RESONANCE PRODUCTION

All reactions are thought to proceed through channels like:

$h + N \rightarrow X \rightarrow x_1 + \dots + x_n \rightarrow \dots$

$h + N \rightarrow X + Y \rightarrow x_1 + \dots x_n + y_1 + \dots y_m \rightarrow \dots$

where X and Y can be real resonances or stable particles (π, n, p, K) directly

Resonances can be treated as real particles: they can be transported and then transformed into secondaries according to their lifetime and decay branching ratios

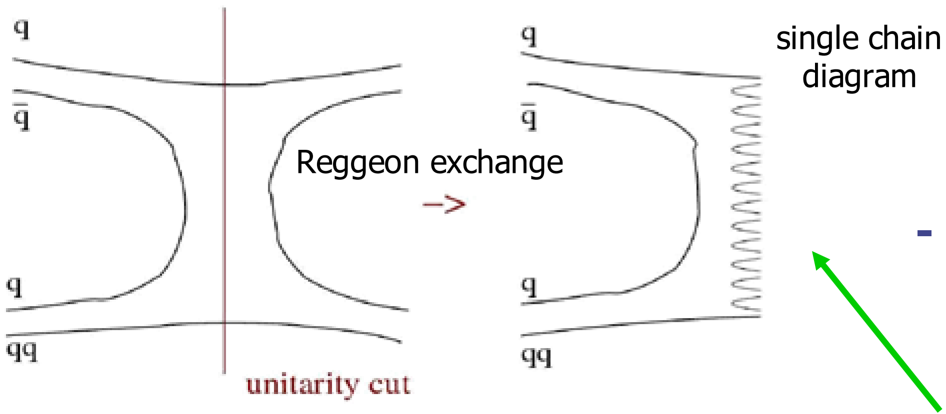
Resonance energies, widths, cross sections, branching ratios from data and conservation laws, whenever possible.
Inferred from inclusive cross sections when needed

Dominance of the Δ resonance and of the N^* resonances

FLUKA: ≈ 60 resonances, and ≈ 100 channels in describing p, n, π, pbar, nbar and K induced reactions up to 3-5 GeV/c

DPM

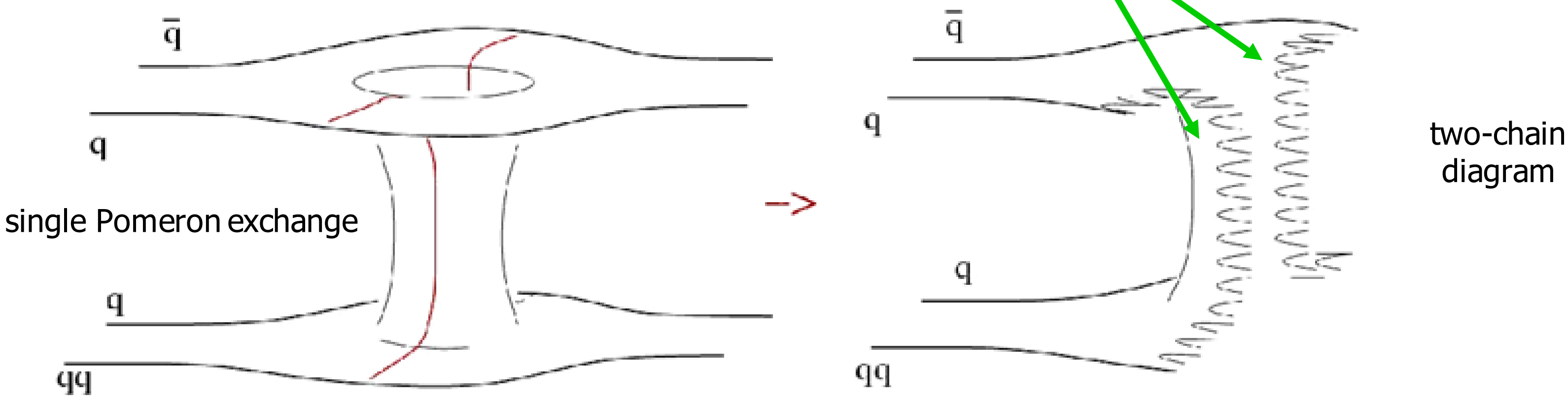
Parton and color concepts, Topological expansion of QCD, Duality



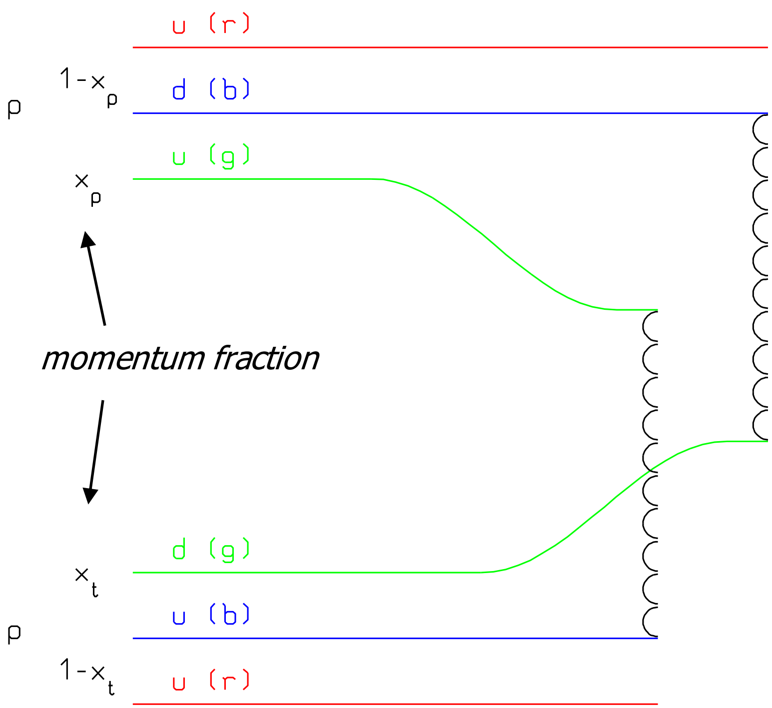
- momentum distribution functions

- fragmentation functions

color strings to be "hadronized"

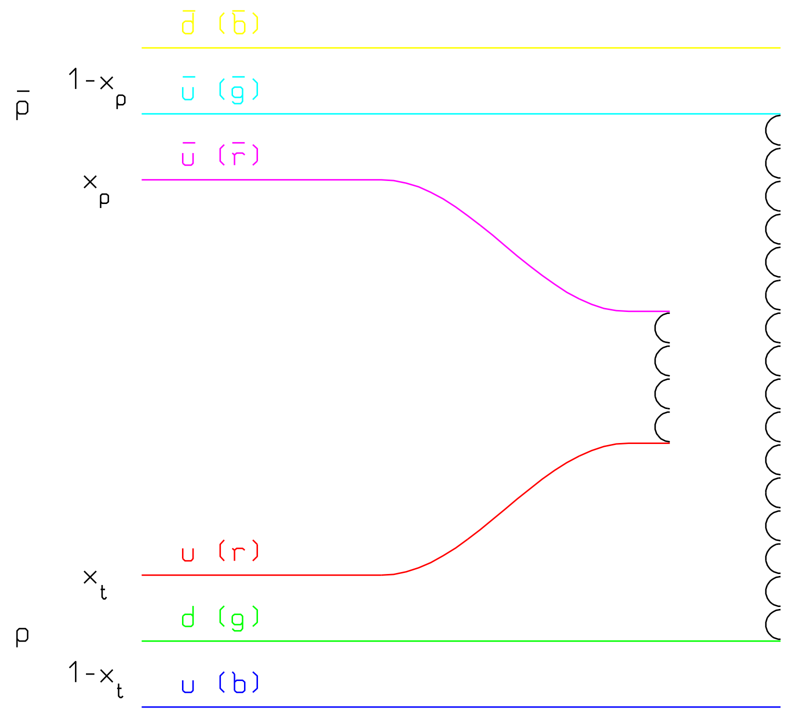


CHAIN EXAMPLES [I]



Leading two-chain diagram in DPM
for **p-p scattering**

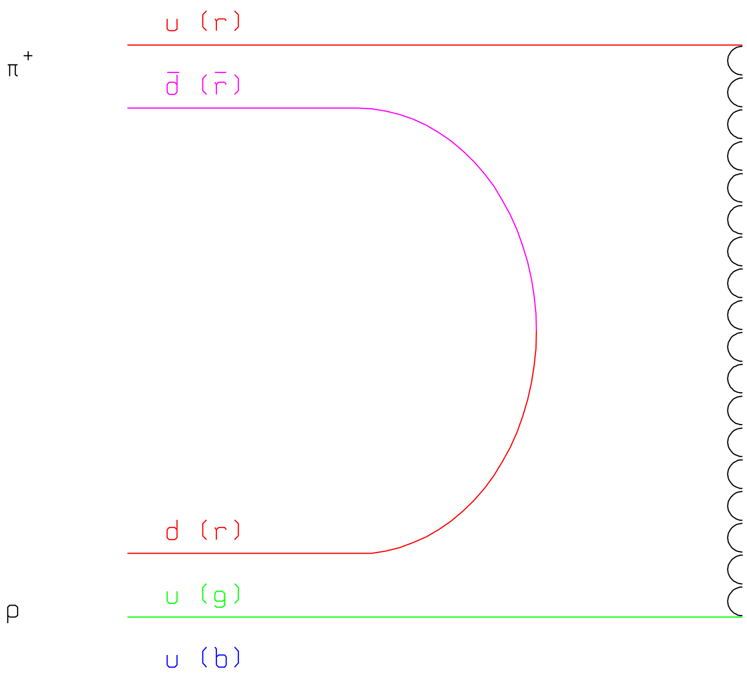
The color (red, blue, and green) and quark combination shown in the figure is just one of the allowed possibilities



Leading two-chain diagram in DPM
for **pbar-p scattering**

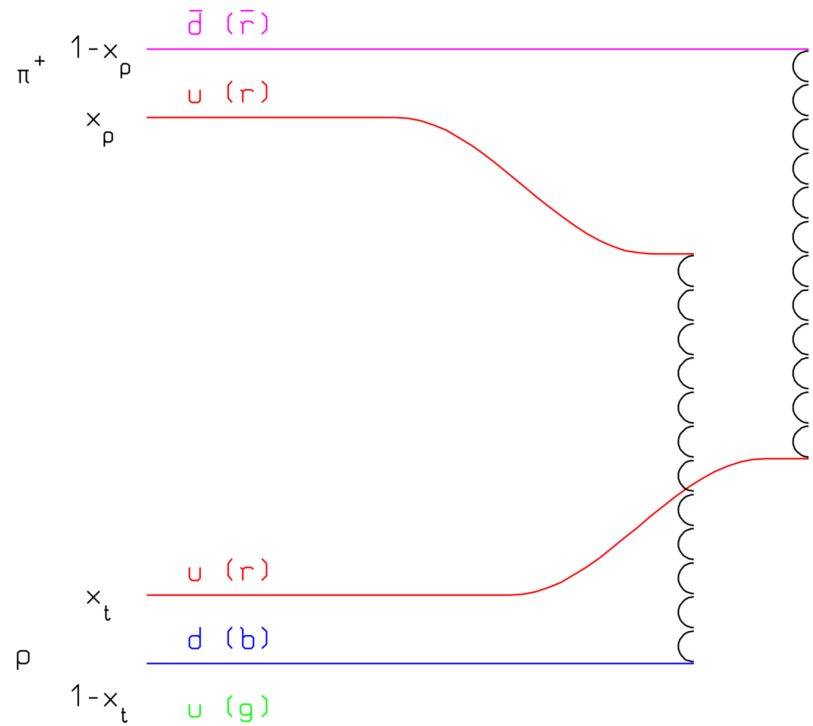
The color (red, antired, blue, antiblue, green, and antigreen) and quark combination shown in the figure is just one of the allowed possibilities

CHAIN EXAMPLES [II]



Single chain diagram in DPM $\sigma \sim 1/\sqrt{s}$
for π^+**-p scattering**

The color (red, antired, blue, and green) and quark combination shown in the figure is just one of the allowed possibilities



Leading two-chain diagram in DPM
for π^+**-p scattering**

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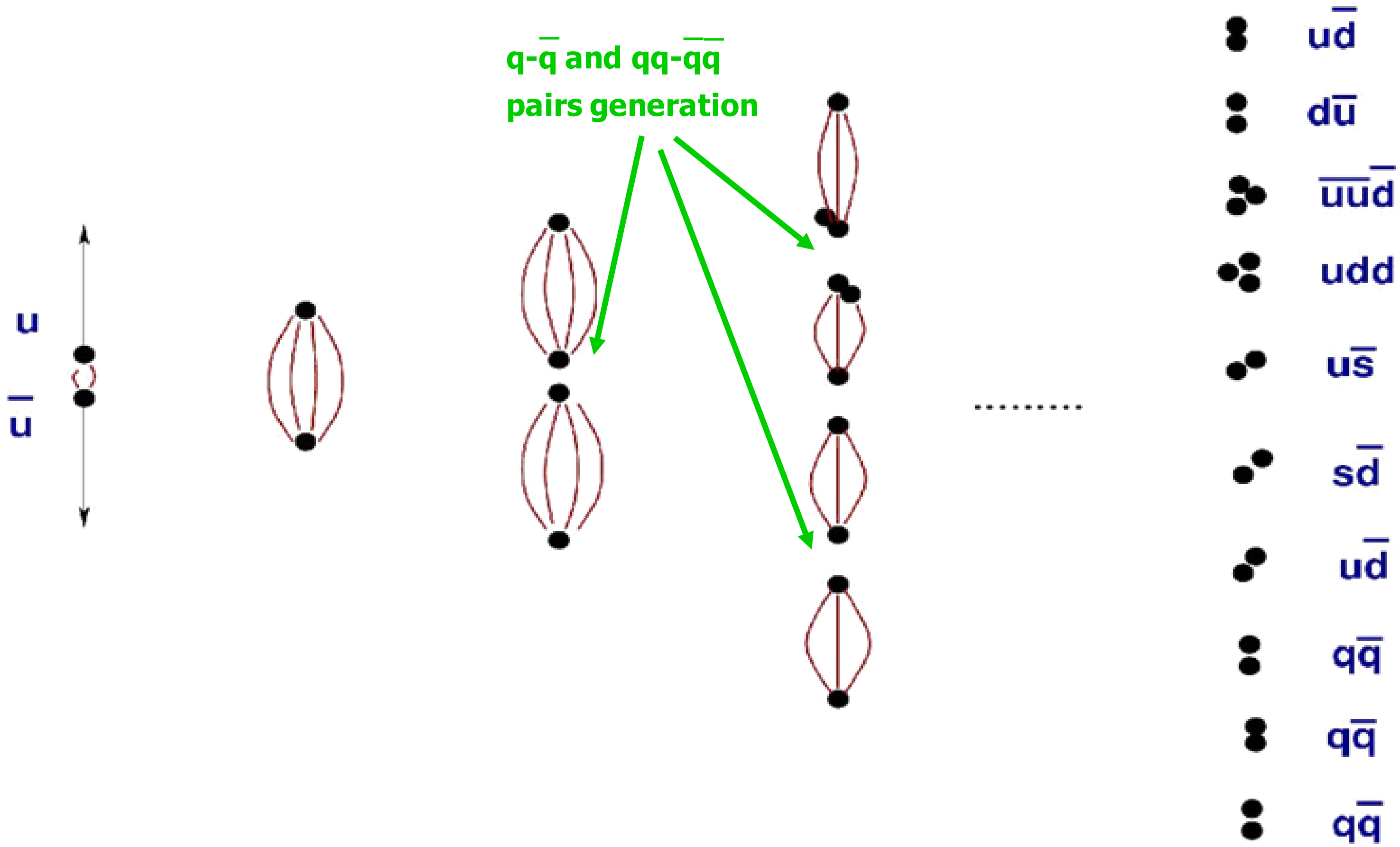
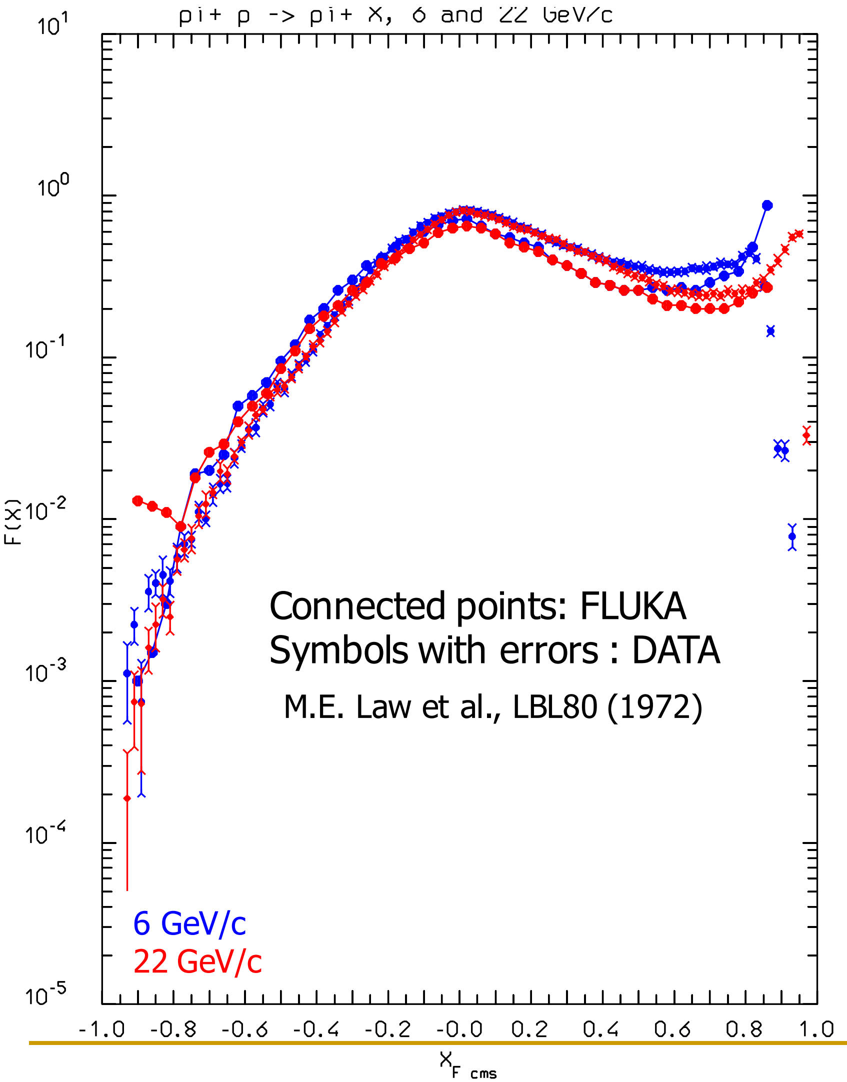
HADRONIZATION EXAMPLE

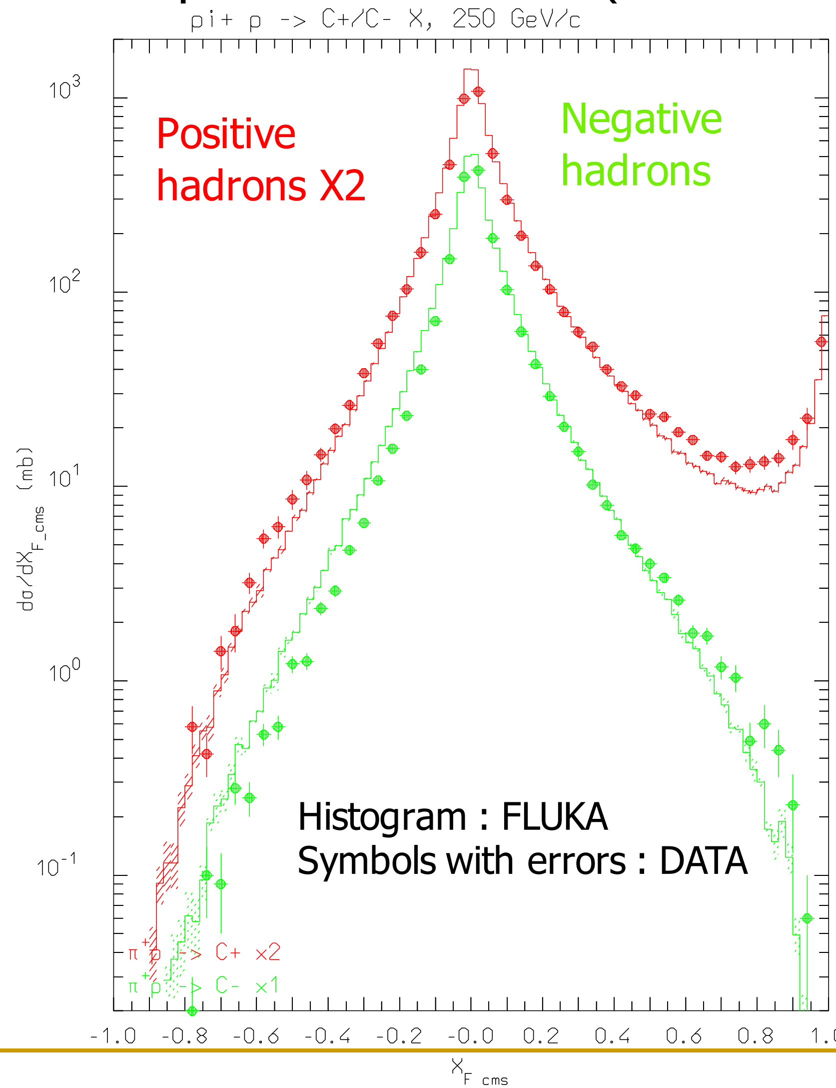


BENCHMARK

$\pi^+ + p \rightarrow \pi^+ + X$ (6 & 22 GeV/c)

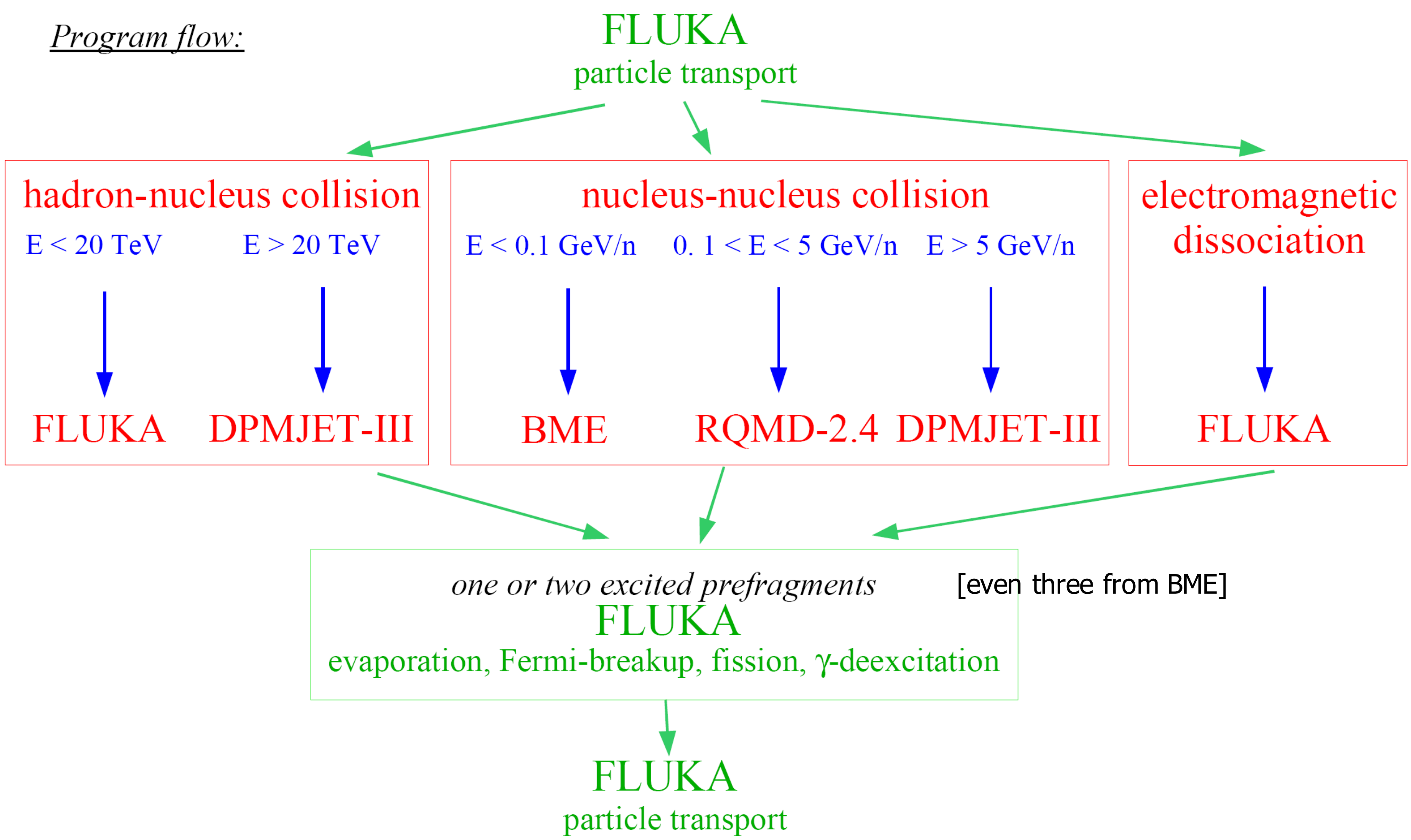


$\pi^+ + p \rightarrow Ch^+/Ch^- + X$ (250 GeV/c)



hA and AA

Program flow:



PEANUT [I]

Target nucleus description (density, Fermi motion, etc)

↓

Glauber-Gribov cascade with formation zone

↓

Generalized IntraNuclear cascade

↓

Preequilibrium stage
with current exciton configuration and excitation energy
(all non-nucleons emitted/decayed + all nucleons below 30-100 MeV)

NB: above 5 GeV PEANUT is not the default and must be explicitly selected!

↓

Evaporation/Fragmentation/Fission model

γ de-excitation

t (s)

10^{-23}

10^{-22}

10^{-20}

10^{-16}

PEANUT [II]

Some assets of the full GINC as implemented in FLUKA (PEANUT):

- Nucleus divided into 16 radial zones of different density, plus 6 outside the nucleus to account for nuclear potential, plus 10 for charged particles
- Different nuclear densities (and Fermi energies) for neutrons and protons (shell model ones for $A \leq 16$)
- Nuclear (complex) optical potential $\rightarrow$ curved trajectories in the mean nuclear+Coulomb field (reflection, refraction)
- Updating binding energy (from mass tables) after each particle emission
- Multibody absorption for $\pi^{+/0/-}$ $K^{-/0}$ μ^-
- Exact energy-momentum conservation including the recoil of the residual nucleus and experimental binding energies
- Nucleon Fermi motion including wavepacket-like uncertainty smearing, (approximate) nucleon-nucleon, and $r \leftrightarrow E_f(r)$ correlations
- Quantum effects (mostly suppressive): Pauli blocking, Formation zone, Nucleon antisymmetrization, Nucleon-nucleon hard-core correlations, Coherence length

GRIBOV INTERPRETATION OF GLAUBER MULTIPLE COLLISIONS

The absorption cross section is just the integral in the impact parameter plane of the probability of getting at least one non-elastic hadron-nucleon collision, and it is naturally written in a mutliple collision expansion

with the overall average number of collisions given by

$$\langle \nu \rangle = \frac{Z\sigma_{hp\,r} + N\sigma_{hn\,r}}{\sigma_{hA\,abs}}$$

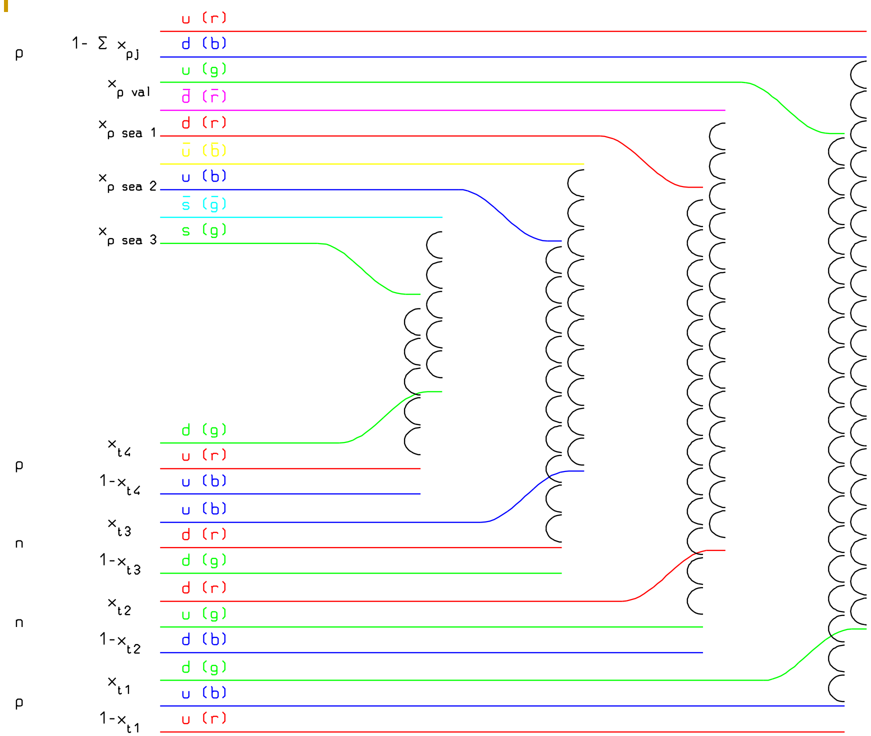
- Glauber-Gribov model = Field theory formulation of Glauber model
- Multiple collision terms $\Rightarrow$Feynman graphs
- At high energies : exchange of one or more Pomerons with one or more target nucleons

- In the Dual Parton Model language (neglecting higher order diagrams):

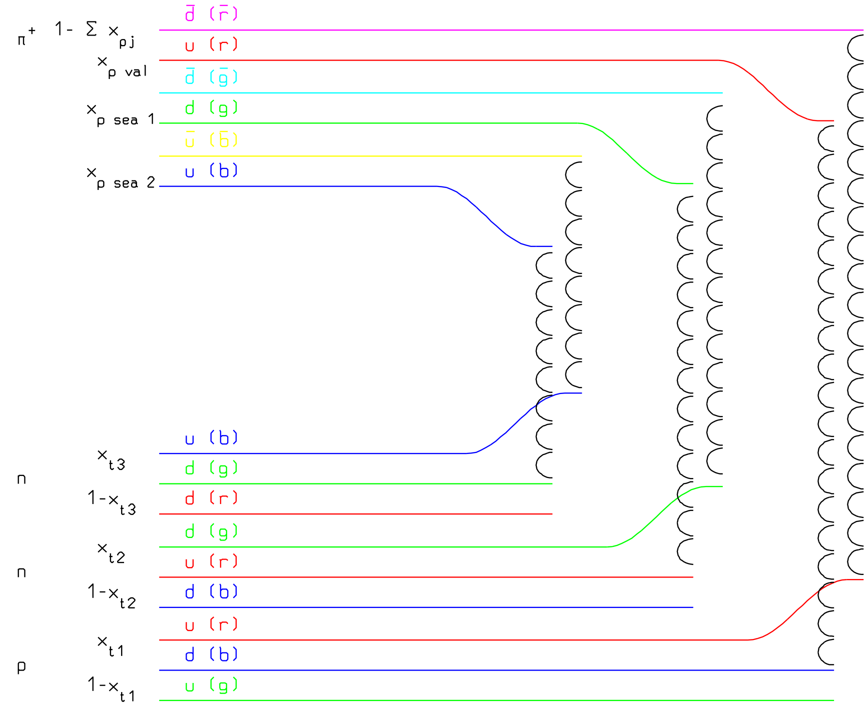
Interaction with ***n*** target nucleons $\Rightarrow$ ***2n*** chains

- Two chains from projectile valence quarks + valence quarks of one target nucleon $\Rightarrow$2 valence-valence chains
- 2(n-1) chains from sea quarks of the projectile + valence quarks of target nucleons $\Rightarrow$2(n-1) sea-valence chains

CHAIN EXAMPLES



Leading two-chain diagram in DPM for **p-A Glauber scattering** with 4 collisions



Leading two-chain diagram in DPM for **π^+-A Glauber scattering** with 3 collisions

The color (red, antired, blue, antiblue, green, and antigreen) and quark combination shown in the figure is just one of the allowed possibilities

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FORMATION ZONE

Classical INC will never work

J.Ranft applied the concept, originally proposed by Stodolski, to hA and AA nuclear int.

Naively: "materialization" time

Qualitative estimate:

In the frame where $p_{//}=0$

$$\bar{t} = \Delta t \approx \frac{\hbar}{E_T} = \frac{\hbar}{\sqrt{p_T^2 + M^2}}$$

Particle proper time

$$\tau = \frac{M}{E_T}\bar{t} = \frac{\hbar M}{p_T^2 + M^2}$$

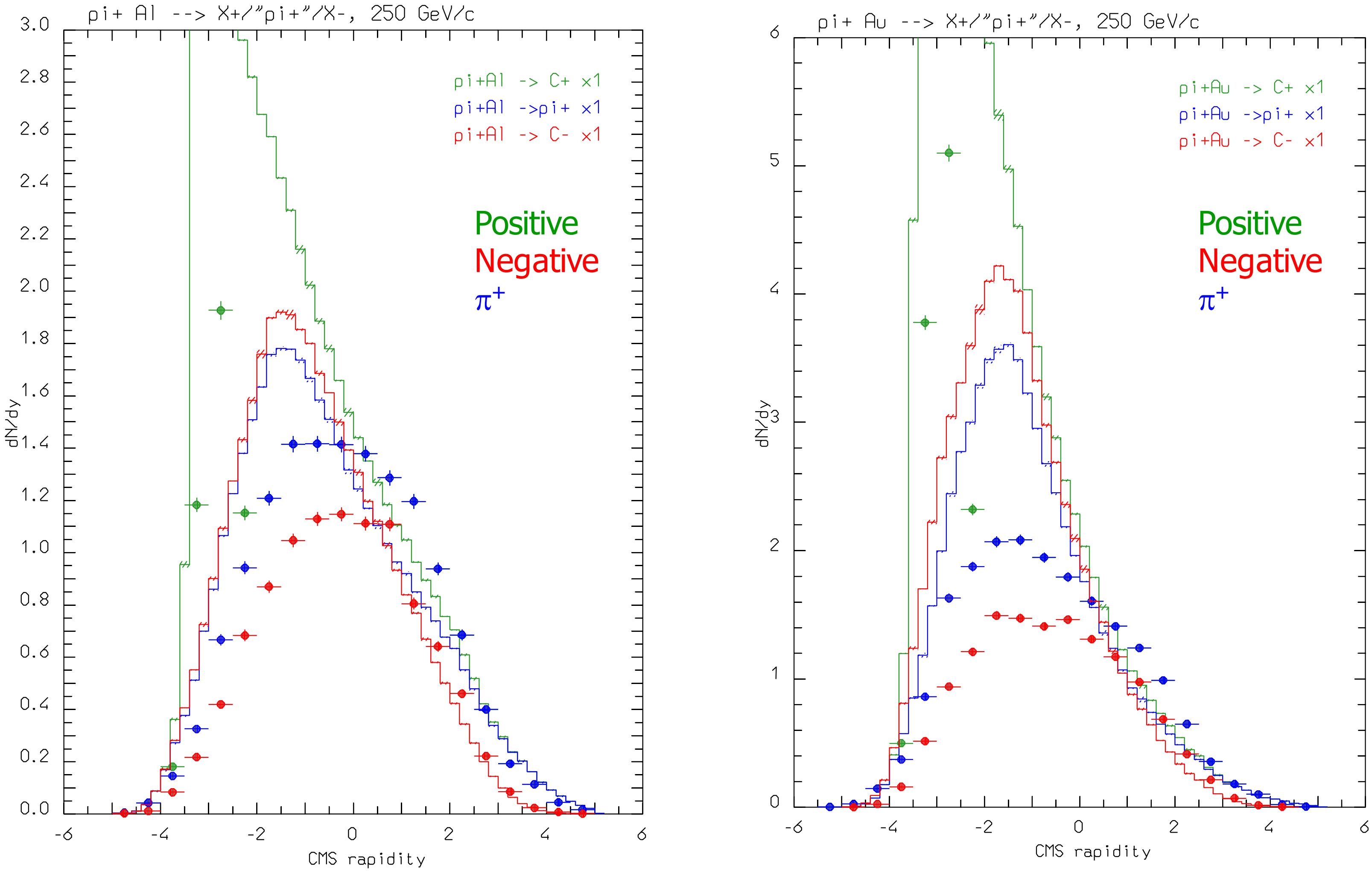
Going to the nucleus system

$$\Delta x_{for} \equiv \beta\, c \cdot t_{lab} \approx \frac{p_{lab}}{E_T}\bar{t} \approx \frac{p_{lab}}{M}\tau = k_{for}\frac{\hbar p_{lab}}{p_T^2 + M^2}$$

Condition for possible re-interaction inside a nucleus:

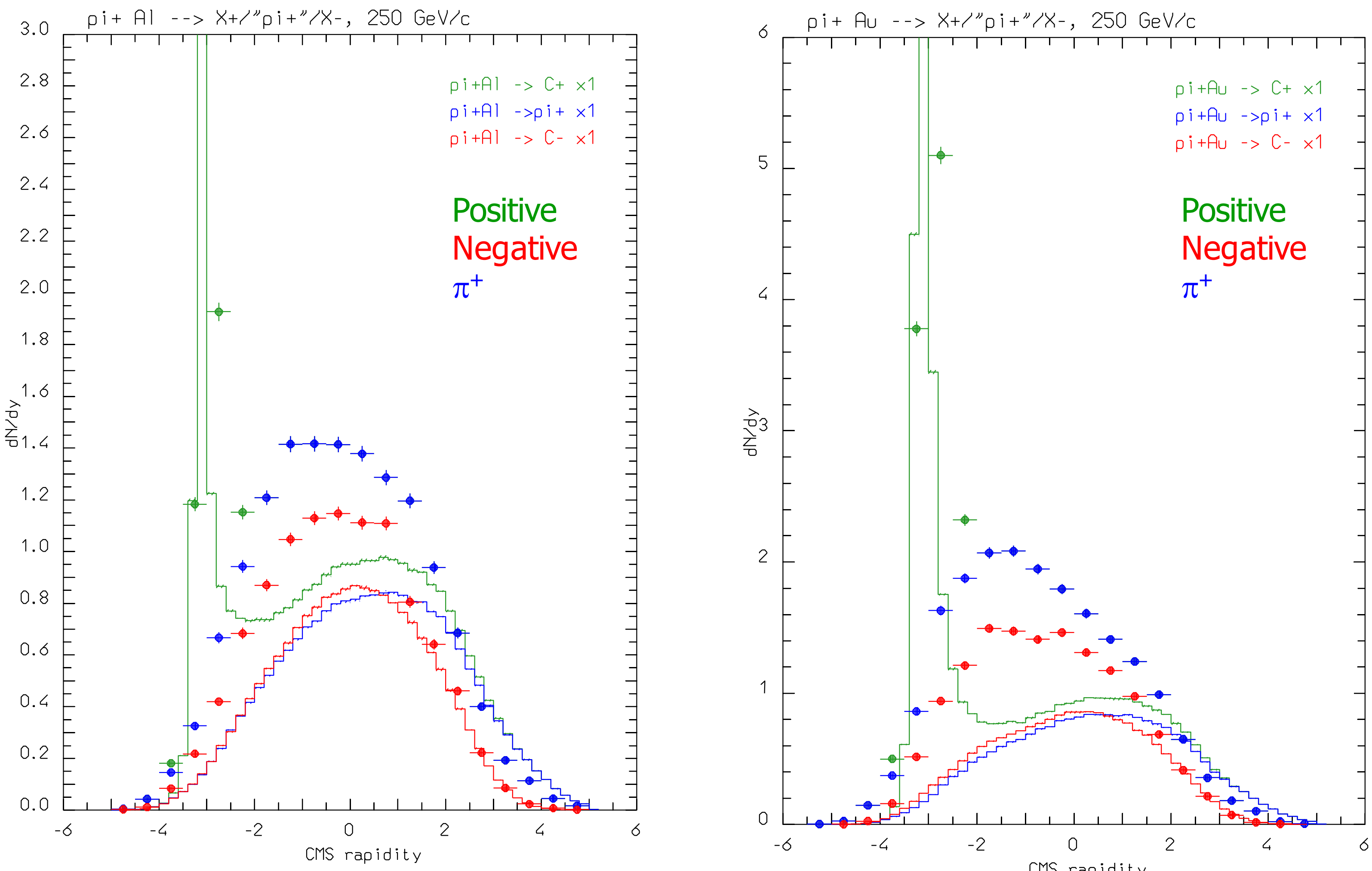
$$\Delta x_{for} \leq R_A \approx r_0 A^{\frac{1}{3}}$$

no GLAUBER, no FORMATION ZONE



Rapidity distributions of charged particles produced in 250 GeV π^+ collisions on Aluminum (left) and Gold (right)
Points: exp. data (Agababyan et al., ZPC50, 361 (1991))

no GLAUBER, yes FORMATION ZONE



Rapidity distributions of charged particles produced in 250 GeV π^+ collisions on Aluminum (left) and Gold (right)

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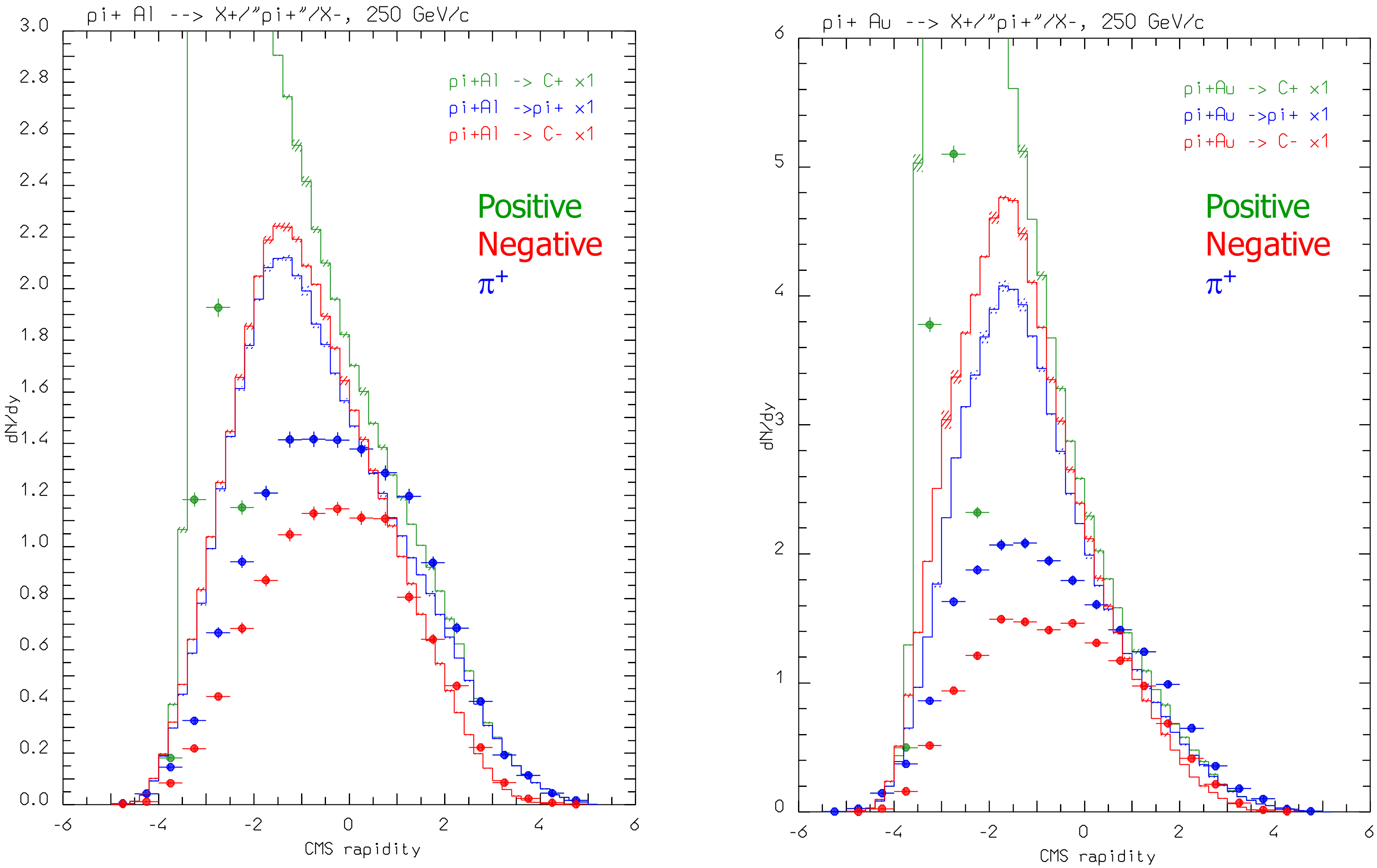

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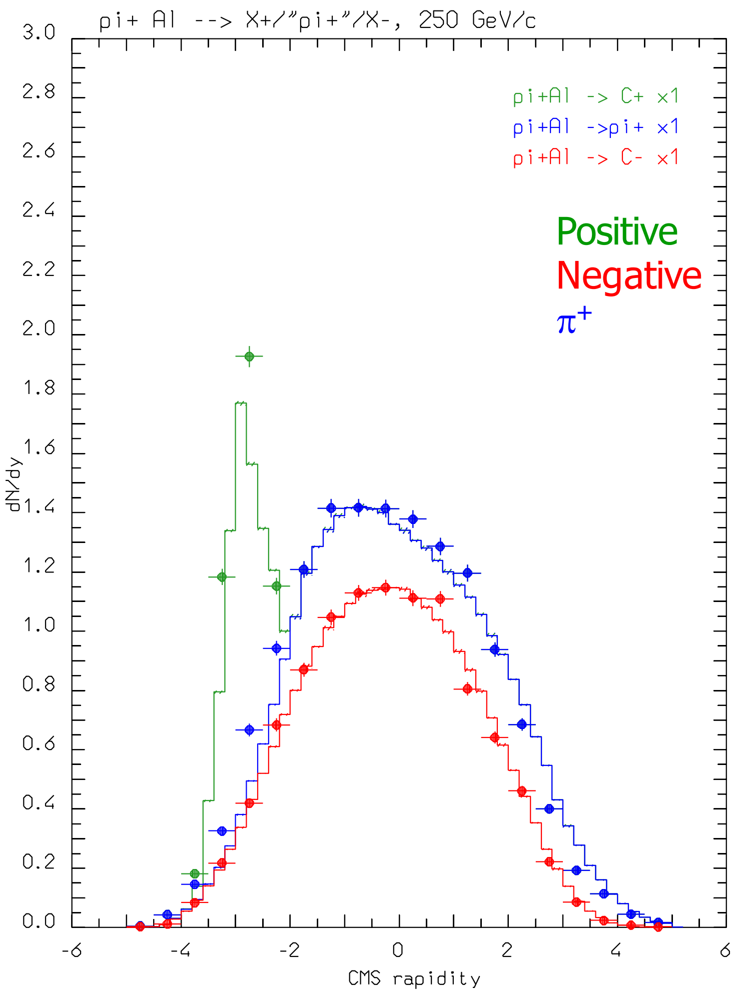
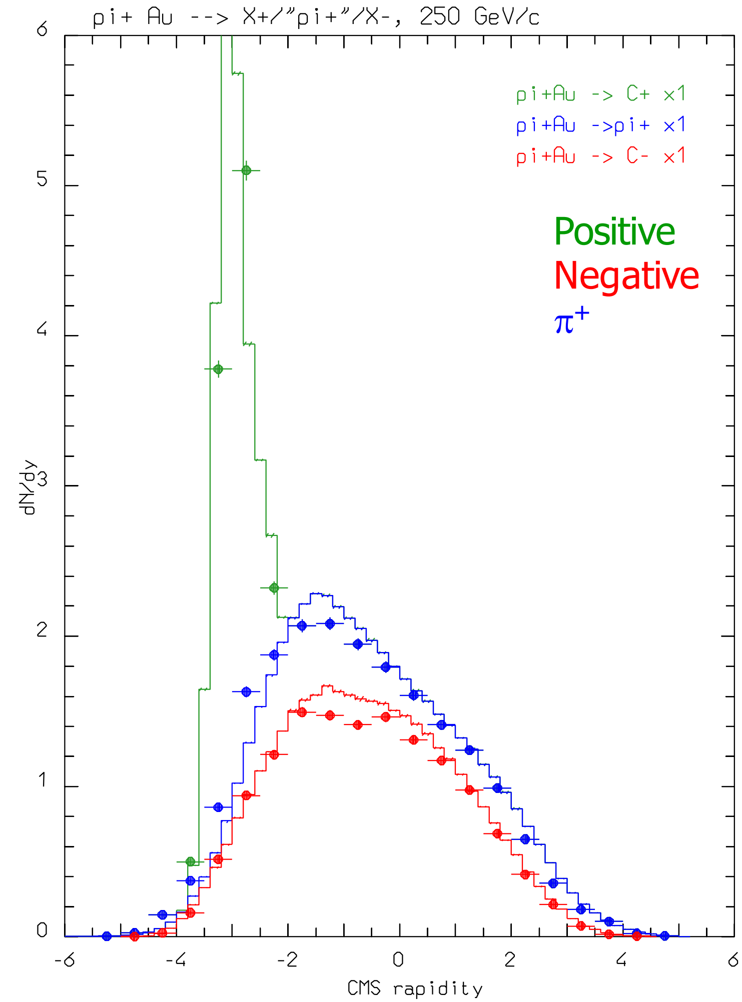
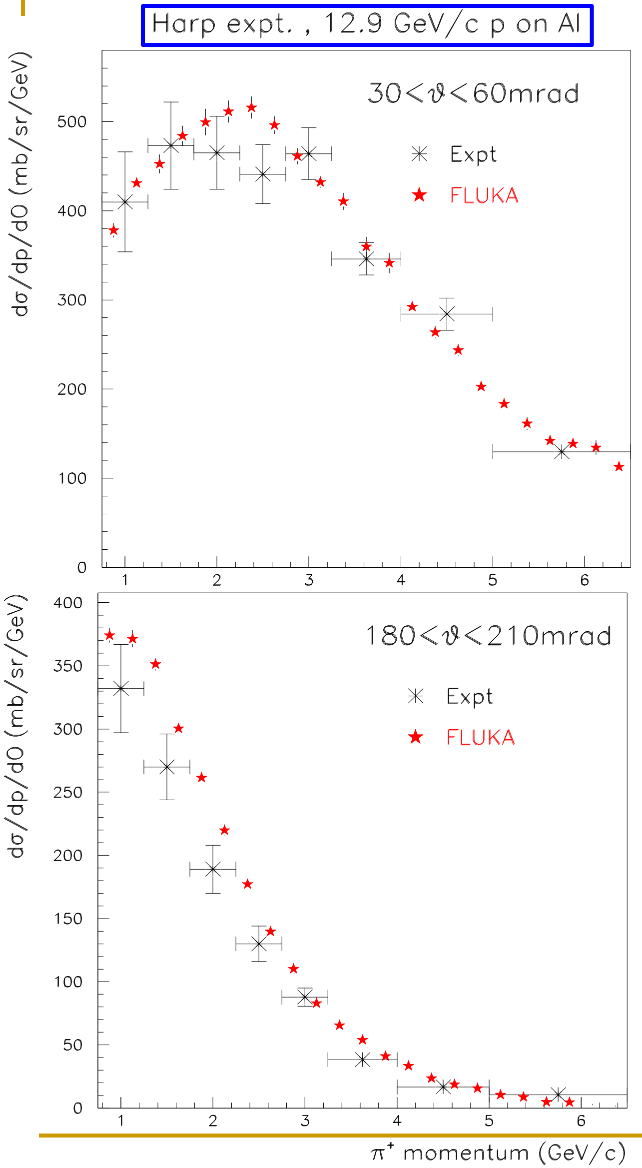


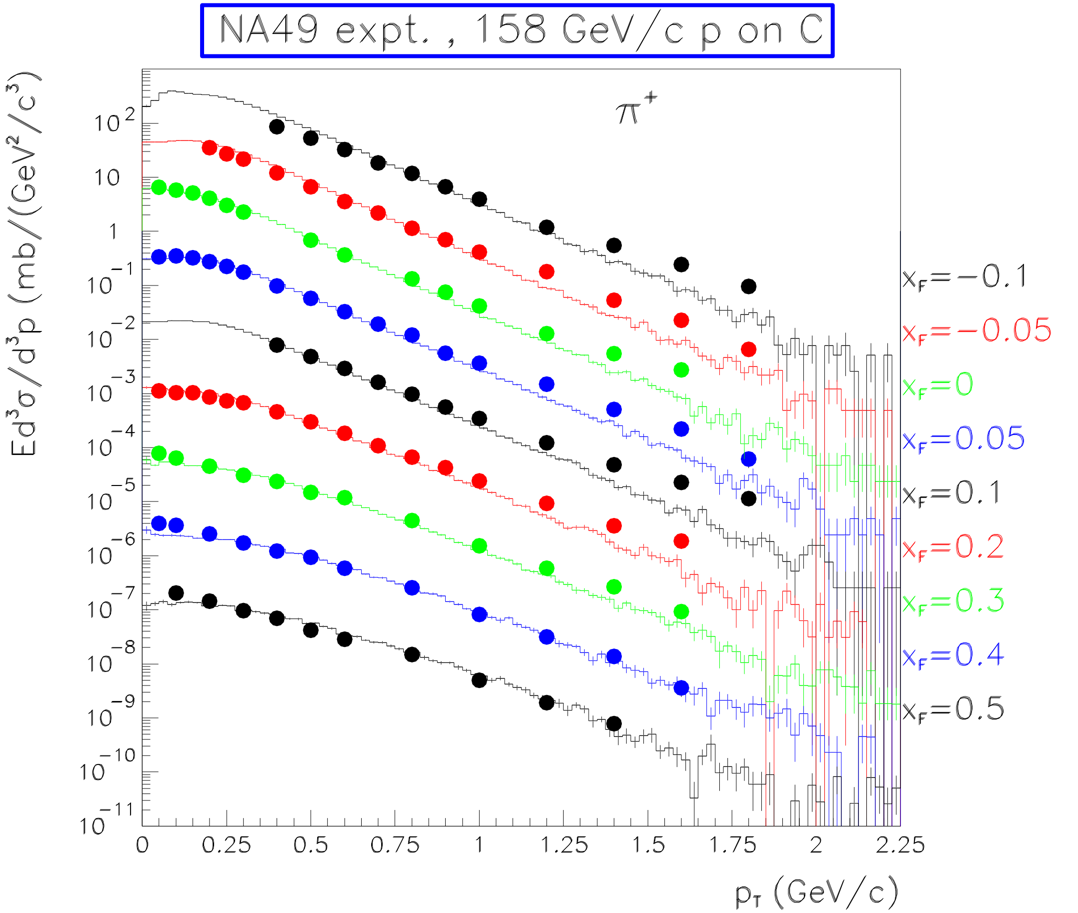


Rapidity distributions of charged particles produced in 250 GeV π^+ collisions on Aluminum (left) and Gold (right)
Points: exp. data (Agababyan et al., ZPC50, 361 (1991))

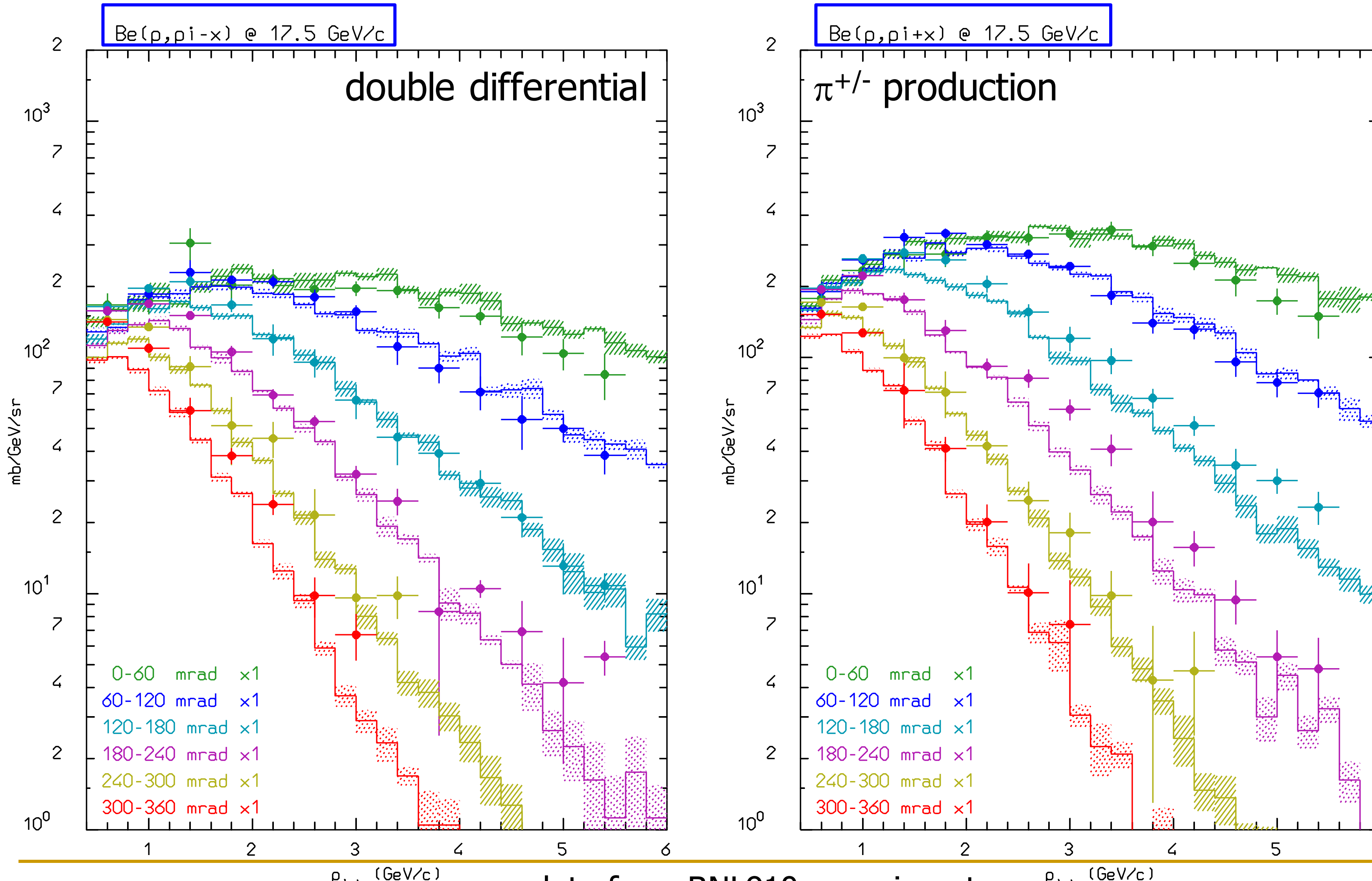
BENCHMARK

double differential π^+ production





BENCHMARK



data from BNL910 experiment

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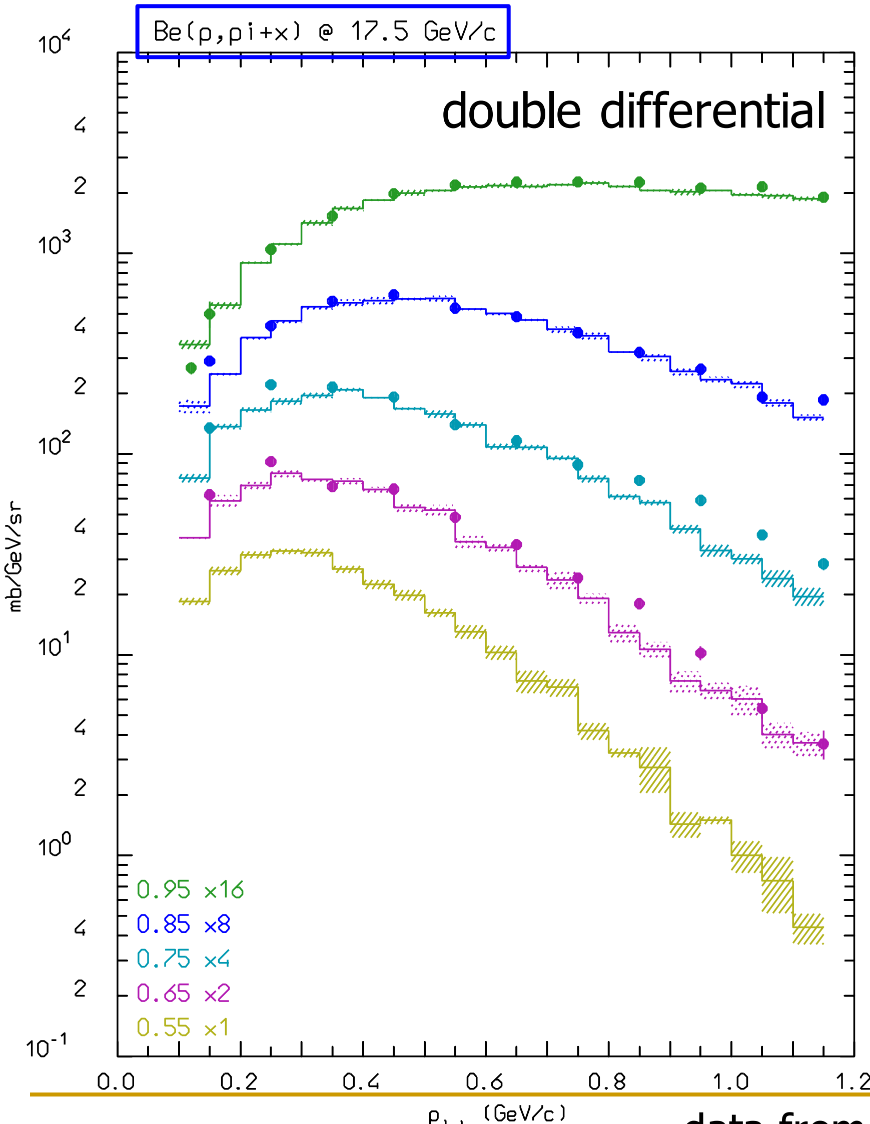

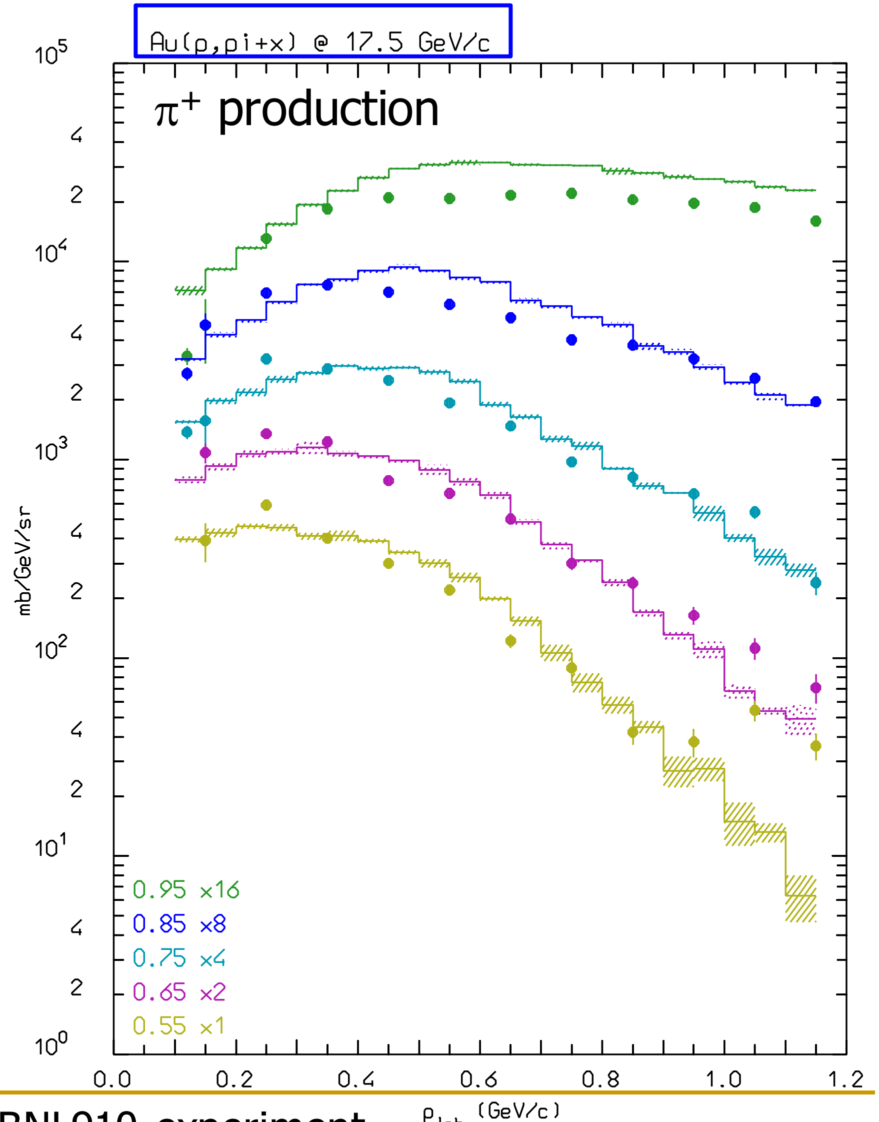

data from BNL910 experiment

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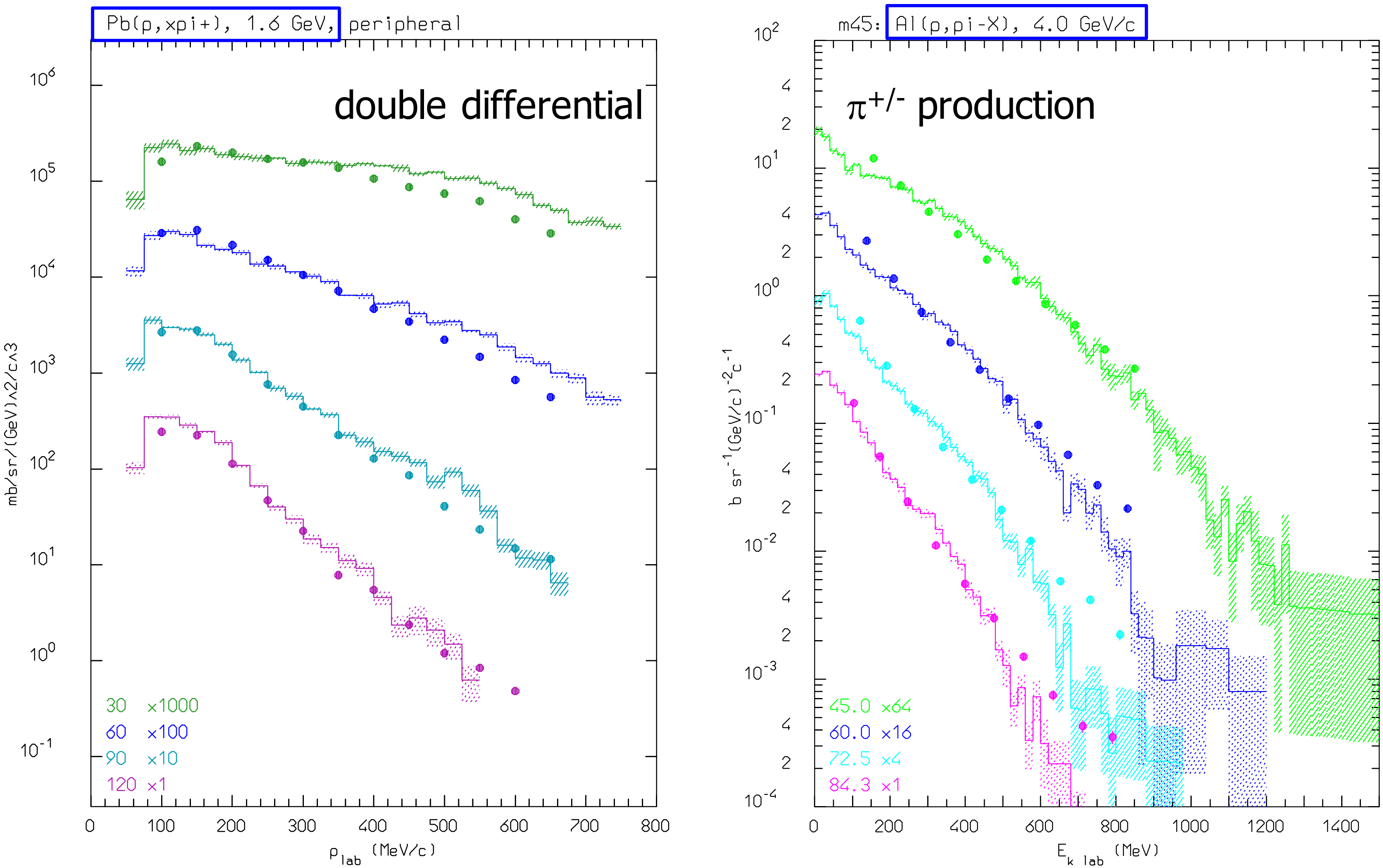
Pb(p,xpi+), 1.6 GeV, peripheral
double differential
mb/sr/(GeV)^2/c^3
p lab (MeV/c)
30 ×1000
60 ×100
90 ×10
120 ×1
m45: Al(p,pi-X), 4.0 GeV/c
π+/- production
b sr-1 (GeV/c)-2 c-1
E k lab (MeV)
45.0 ×64
60.0 ×16
72.5 ×4
84.3 ×1

AA event generators

E > 5 GeV/n

Dual Parton Model (DPM)

DPMJET-III (original code by R.Engel, J.Ranft and S.Roesler,
FLUKA-implemenation by T.Empl *et al.*)

0.1 GeV/n < E < 5 GeV/n

Relativistic Quantum Molecular Dynamics Model (RQMD)

RQMD-2.4 (original code by H.Sorge *et al.,*
FLUKA-implementation by A.Ferrari *et al.*)

E < 0.1 GeV/n

Boltzmann Master Equation (BME) theory

BME (original code by E.Gadioli *et al.,*
FLUKA-implementation by F.Cerutti *et al.*)

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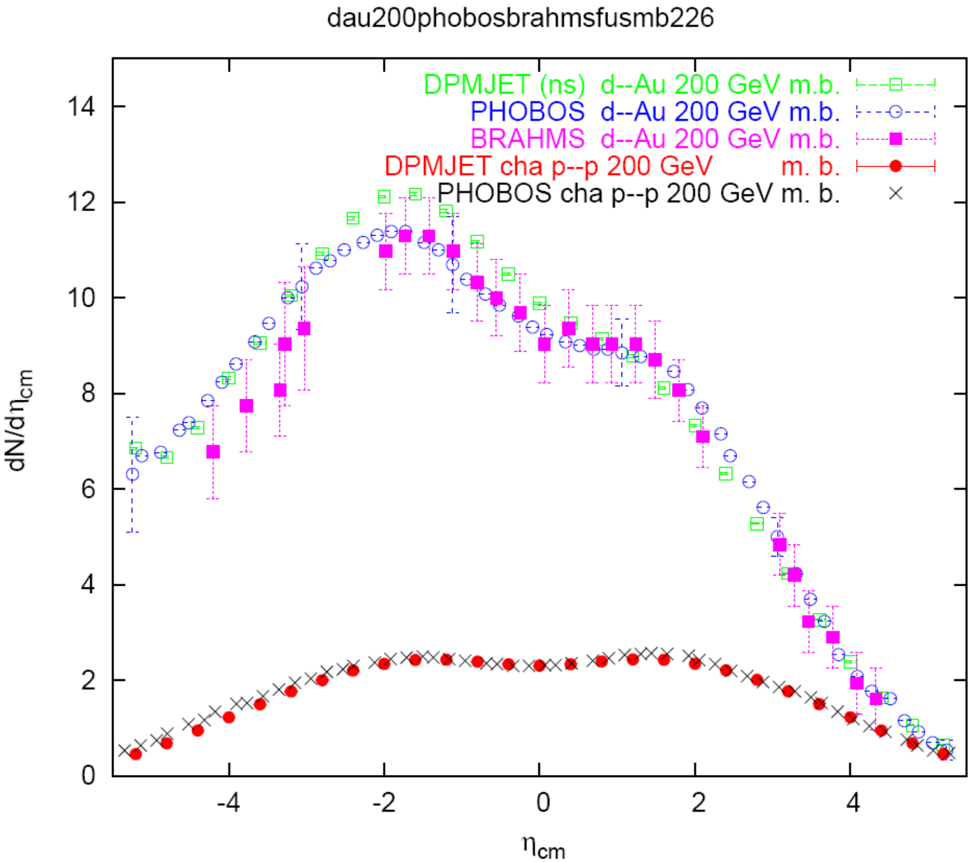

Pseudorapidity distribution of charged hadrons
produced in minimum bias d-Au and p-p collisions at a c.m. energy of 200GeV/A

Exp. data: BRAHMS- and PHOBOS-Collaborations

J.Ranft, in Proceedings of the Hadronic Shower Simulation Workshop, CP896, Batavia, Illinois (USA), 6-8 September 2006

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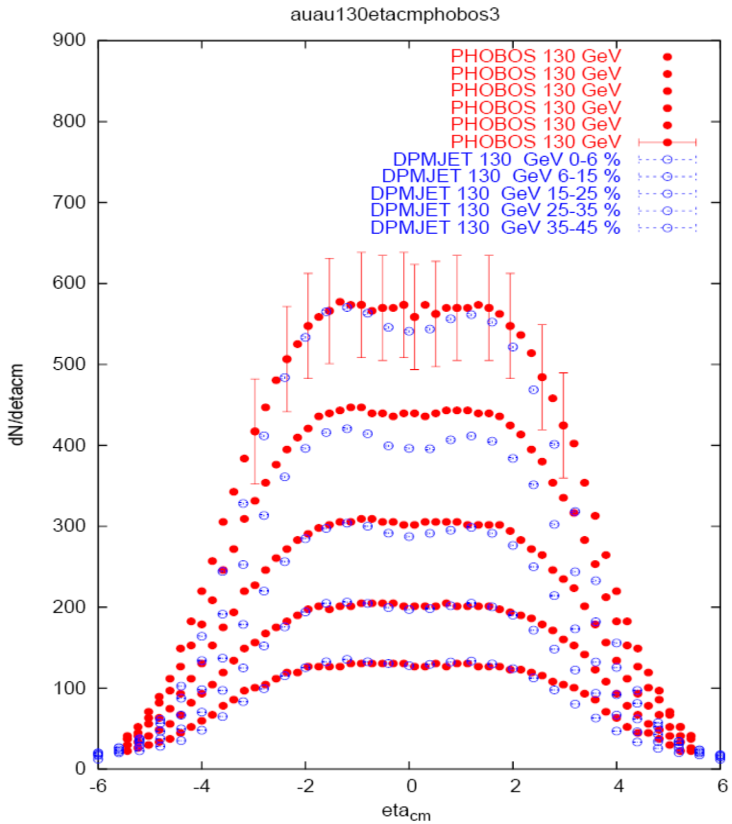

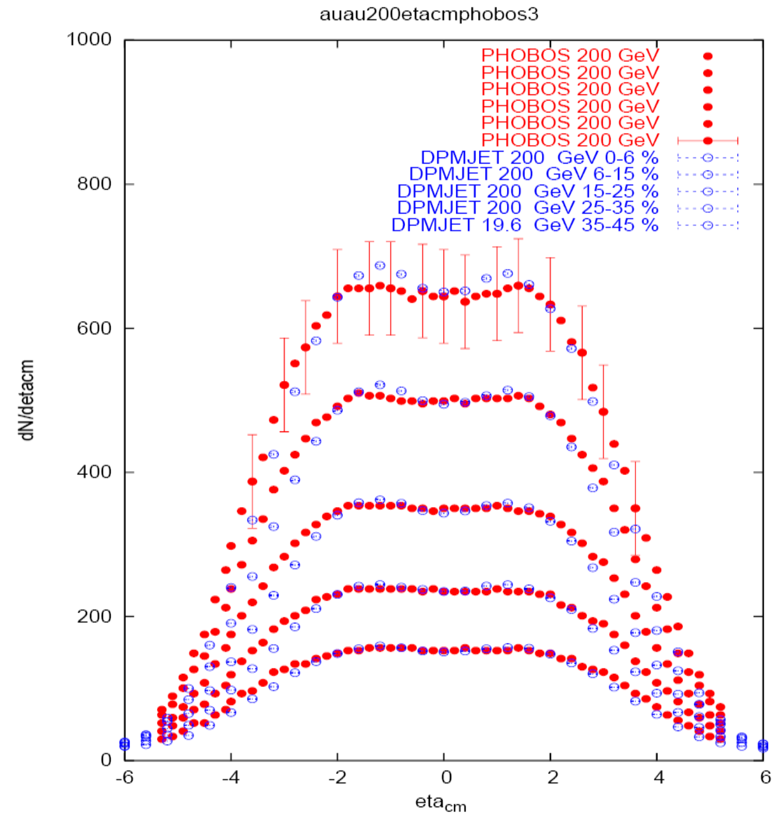

Pseudorapidity distribution of charged hadrons
produced in Au-Au collisions at a c.m. energy of 130GeV/A (left) and 200GeV/A (right)
for different ranges of centralities

Exp. data: PHOBOS-Collaboration

J.Ranft, in Proceedings of the Hadronic Shower Simulation Workshop, CP896, Batavia, Illinois (USA), 6-8 September 2006

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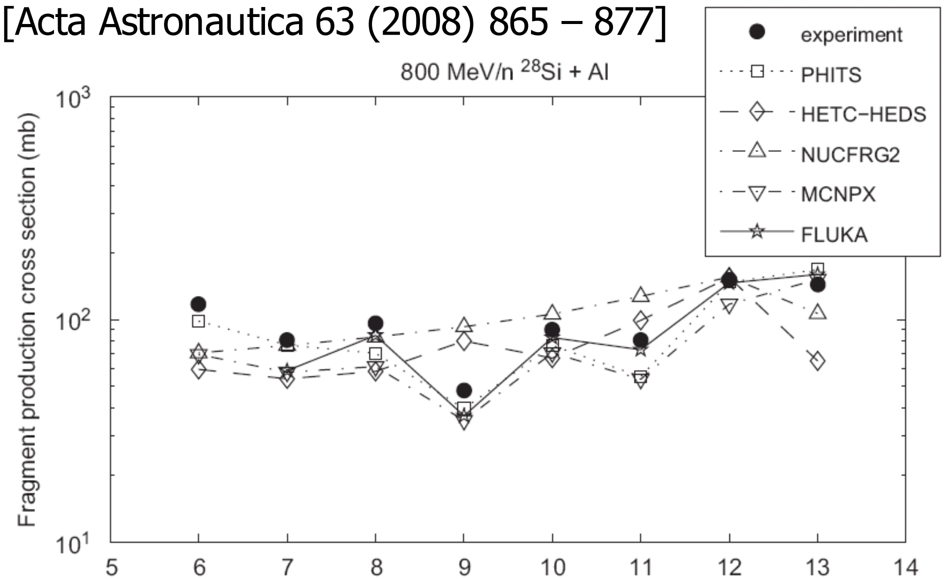
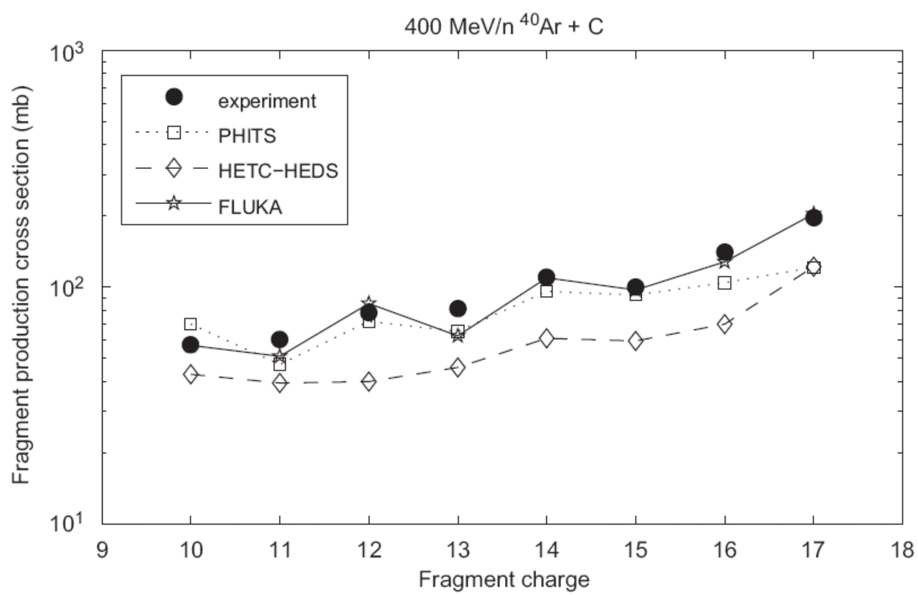
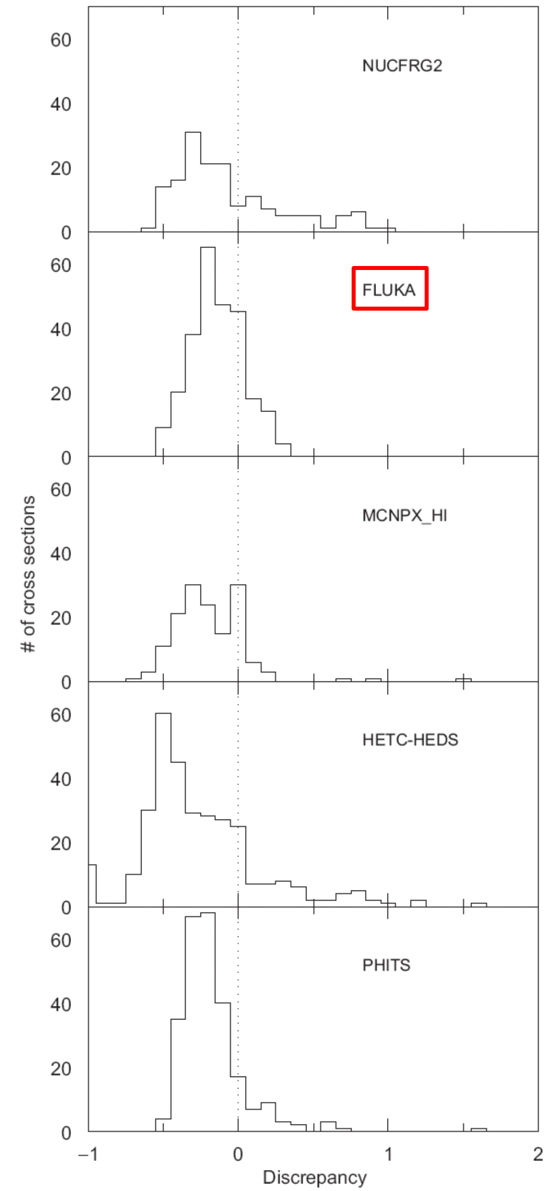
[Acta Astronautica 63 (2008) 865 – 877]







THE END

GLAUBER MODEL

$\sigma_{hA\ abs}$ can be interpreted in terms of multiple collisions of the projectile:

From the impact parameter representation of the hadron-nucleon reaction cross section

$$\sigma_{hN\,r}(s) = \int d^2\vec{b}\left[1 - \left|S_{hN}(\vec{b}, s)\right|^2\right]$$

and with $P_{rj}(b) \equiv \sigma_{hNr} T_{rj}(b)$ = probability to have an inelastic reaction on the j-th target nucleon

$$\frac{d\sigma_{hA\,abs}}{d^2\vec{b}}(b) = \sum_{\nu=1}^{A}\binom{A}{\nu} P_r^{\nu}(b)\left[1 - P_r(b)\right]^{A-\nu} \equiv \sum_{\nu=1}^{A} P_{r\,\nu}(b)$$

$$P_{r\,\nu}(b) \equiv \binom{A}{\nu} P_r^{\nu}(b)\left[1 - P_r(b)\right]^{A-\nu}$$

Since $P_r(b)$ is the probability of getting one specific nucleon hit and there are A possible trials, $P_{r\,\nu}(b)$ is exactly the binomial distribution for getting ν successes out of A trials, with probability $P_r(b)$ each

$$\sigma_{hA\,abs}(s) \equiv \int d^2\vec{b}\, P_{r\,\nu}(b)$$

ENERGY THRESHOLDS FOR CHAIN PRODUCTION

The energy/momentum fractions carried by sea (x_q^{sea}) and valence (x_q) quarks of the projectile obey in principle to the following distribution for massless partons:

$$P(\bar{x})d\bar{x} = C\, x_q^{-1/2} x_{qq}^{3/2} \prod_{j=1}^{n_{sea}} \left(X_j^{sea}\right)^{-1} \left(x_{q\,j}^{sea}\right)^{-1/2} \left(x_{\bar{q}\,j}^{sea}\right)^{-1/2} \delta\left(1 - x_q - x_{qq} - \sum_{j=1}^{n_{sea}} X_j^{sea}\right) d\bar{x}, \quad X_j^{sea} = x_{q\,j}^{sea} + x_{\bar{q}\,j}^{sea}$$

However, a minimum √s is required for the Glauber collisions to occur, and this translate to a minimum requirement on X_j^{sea} so that the following condition is satisfied:

$$s_j^{sea} \approx M_{Nj}^2 + 2X_j^{sea} p_{proj} M_{Nj} > \left(M_{8/10}^{(*)} + m_{ps/v}\right)^2 + 2E_{k?} M_{8/10}^{(*)}$$

Where $M_{8/10}^{(*)}$ and $m_{ps/v}$ are the masses of the lowest octuplet/decuplet baryons and pseudoscalar/vector mesons respectively, corresponding to the selected quark configuration

Obviously a minimum √s must be guaranteed for the valence-valence collision as well

These requirements represent another effective constraint on the onset of the Glauber cascade