

# $\gamma$ FACTORY

Bruno AUTIN

CERN

Introduction

Layout

Proton beam

Pion beam

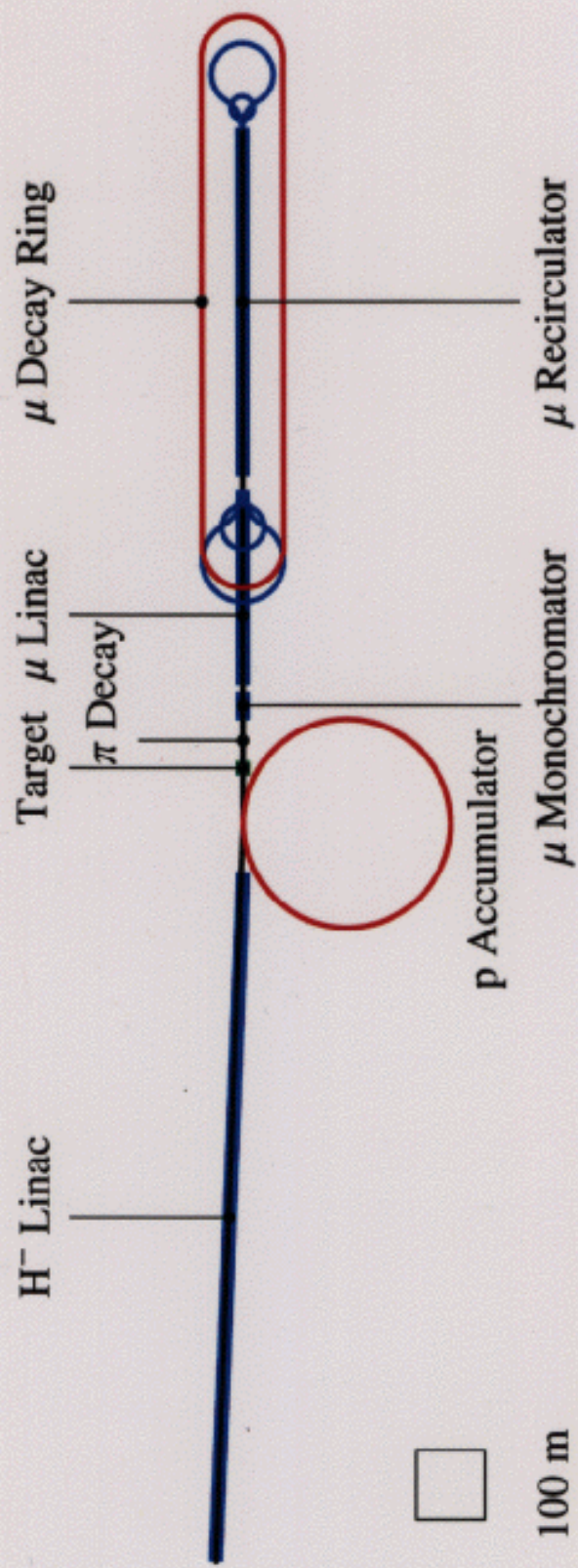
Muon beam

Final remarks

## Introduction

1. Explore the parameter space of low energy proton beams.
2. Exploit the simplifications proper to  $\nu$  beams:
  - High flux (not high luminosity!)
  - Independent manipulation of  $\mu^+$  and  $\mu^-$ .
3. Early physics at affordable (?) cost.
4. Compatibility with  $\mu$  colliders front ends.

# $\nu$ Factory



## **$H^-$ Linac**

T : 2 GeV

$\Delta T$  :  $\pm 2$  MeV

$\Delta t_b$  : 24 ps

r.m.s. normalized transverse emittance :  $0.6 \mu\text{m}$

$I_{\text{MaxCW}}$  : 10 mA ( $6 \cdot 10^{16} p/s$ )

length : 1 km

RF frequency : 352 MHz

RF power : 34 MW

Number of klystrons : 43

# FEASIBILITY STUDY OF A 2 GEV SUPERCONDUCTING H<sup>+</sup> LINAC AS INJECTOR FOR THE CERN PS

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## Abstract

This preliminary feasibility study is based on the availability of the CERN LEP2 superconducting RF system after LEP de-commissioning. The option that is explored is to use this system as part of a high energy H<sup>+</sup> linac injecting at 2 GeV into the CERN PS, with the aim of reliably providing at its output twice the presently foreseen transverse beam brightness at the ultimate intensity envisaged for LHC. This requires the linac to be pulsed at the PS repetition rate of 0.8 Hz with a mean beam current of 10 mA which is sufficient for filling the PS in 240  $\mu$ s (i.e. about 100 turns) with the ultimate intensity foreseen for injection for the LHC.

The linac is composed of two RFQs with a chopping section, a room temperature DTL, a superconducting section with reduced beta cavities up to 1 GeV, and a section of LEP2 cavities up to 2 GeV. This study deals, in particular, with the problems inherent in H<sup>+</sup> acceleration up to high energy and in the pulsed operation of SC cavities. Means for compensating microphonic vibrations in the SC cavities are considered, with the aim of reducing the final overall energy spread to the tight requirements for injection into a synchrotron. Other possible applications of such a machine are also briefly reviewed, that make use of its potential for working at a higher duty cycle than required for LHC alone.

## 1 INTRODUCTION

Most of the RF equipment of the CERN LEP-2 will be available after the year 2000. Among the possible re-uses of this valuable hardware [1-4] the realisation of a 2 GeV Linac injector for the PS is an attractive option with many benefits with respect to the present scheme for LHC injection [5].

As a result of the smaller emittance of the Linac beam and of the higher injection energy into the PS (at present 1.4 GeV), the LHC would profit from an increased brightness of the proton beam delivered by the PS injector complex. The peak beam intensity in the PS could be improved as well by filling the entire aperture. Beam losses would be reduced by the efficient charge exchange injection in the transverse planes, and by the chopped beam in the longitudinal phase plane. The injectors of the PS could be modernised and re-built with standardised equipment, with advantages in terms of reliability and maintenance.

Other potential applications of this facility at a higher duty cycle justify the use of SC cavities. They include: 1) neutron production with a spallation target, using the PS as an accumulator ring; 2) feeding a second generation ISOL facility for the production of radioactive ion beams; and 3) any physics application requiring intense secondary beams.

A small study group has concentrated on the main accelerator technology topics and on the most promising scenario. A first report indicating the feasibility of such a facility is being prepared [6].

## 2 PARAMETERS AND LAYOUT

The Superconducting Proton Linac, SPL, (Figure 1) is made of an H<sup>+</sup> source, two RFQs with a chopper in between, a Drift Tube Linac up to 100 MeV and a superconducting section up to 2 GeV. The main design parameters are given in Tables 1 and 2.

Table 1: Linac Beam Parameters

Number of Particles / PS Pulse	1.5	10 <sup>11</sup>
Mean Linac Current during Pulse	10	mA
Pulse Length	250	$\mu$ s
Repetition Rate	0.83	Hz
Filling Factor of Linac Buckets	1/2	
N. of Linac Bunches per PS Bucket	11	
SPL Micropulse (11 bunches)	59.6	ns
Chopping Factor	46	%
Mean Bunch Current (in an RF period, for a full bucket)	37	mA
Source Current	20	mA
Beam Duty Cycle (for PS filling)	0.021	%
Maximum Design Duty Cycle	5	%
Maximum Average Current	500	$\mu$ A
Transverse Emittance, source exit, rms	0.2	$\mu$ m
Transverse Emittance, PS input, rms	0.6	$\mu$ m
Longitudinal Emittance (5 rms)	3	°MeV

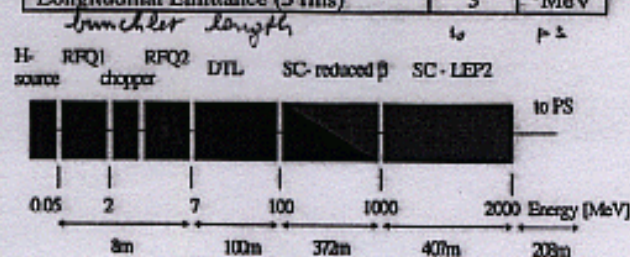
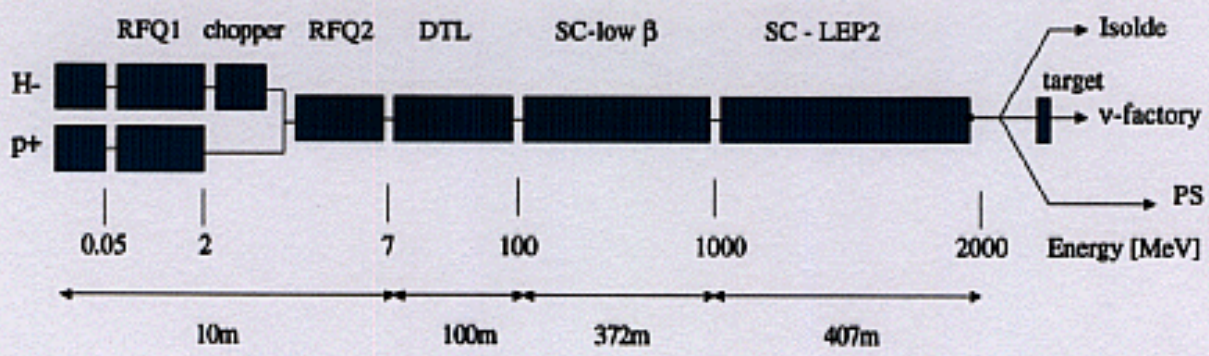


Figure 1: Schematic layout of the Linac.



## p Accumulator

Accumulation in transverse phase space

Length smaller than  $\mu$  ring length :  $\sim 950\text{ m}$  (ISR)

Path length adjusted to maintain short bunches on target

Number of turns  $N$  and revolution period  $t_r$  such that :

$$N t_r \sim \gamma_{\mu} \tau_{\mu} \text{ (200 turns)}$$

$$2 \cdot 10^8 < \text{Number of particles per bunch} < 4 \cdot 10^{10}$$

Problems : stripping efficiency, space charge, ultra low loss

## Possible lattice for a proton accumulator

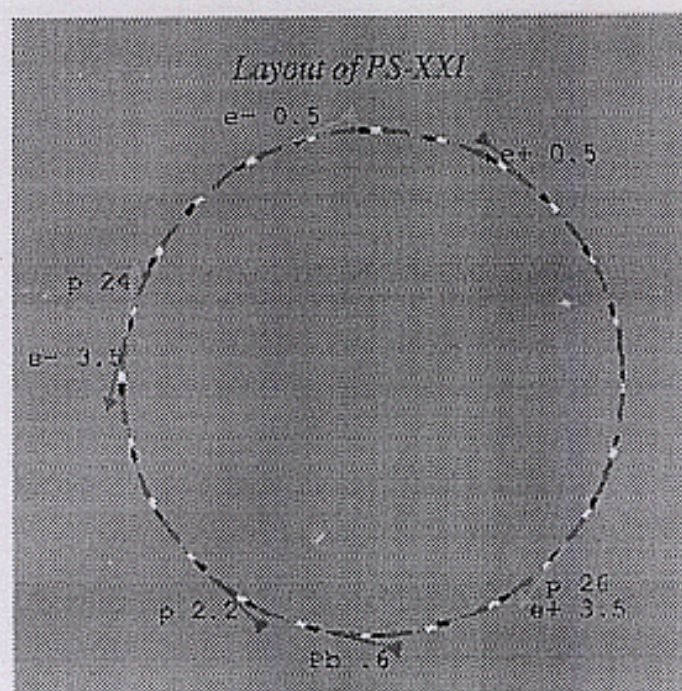
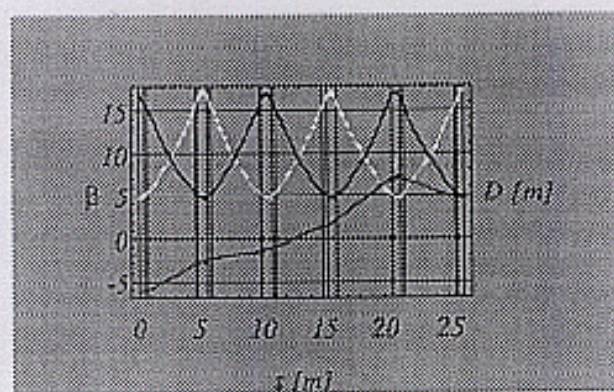
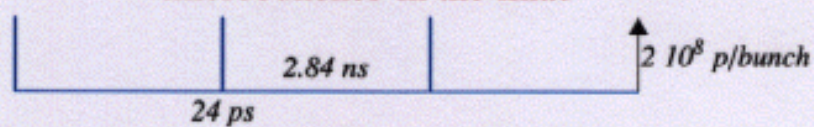


Figure 7

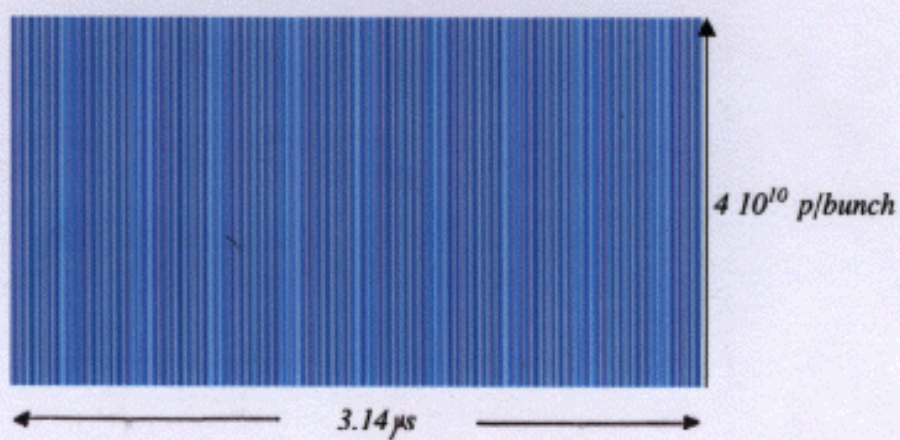
Figure 6.  $\beta_h$  (black),  $\beta$  (white) and  $D$  (gray) functions over half a superperiod

# Time structure of the proton beam

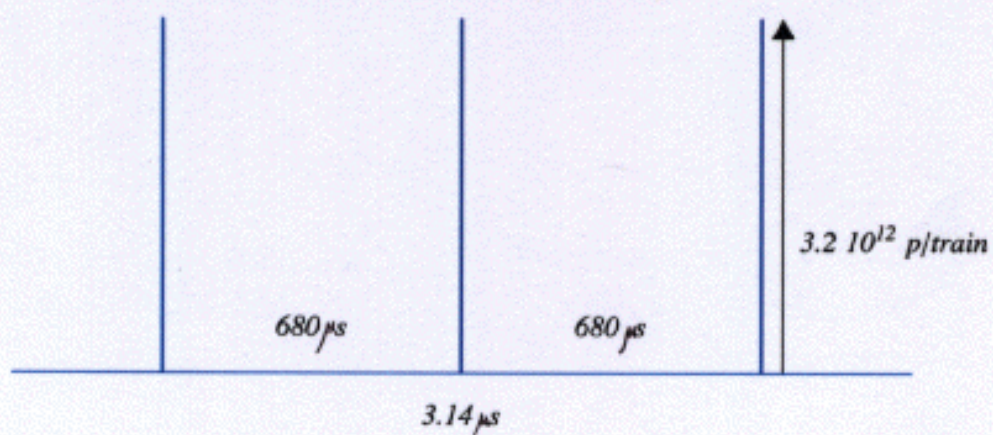
microbunches in the linac



train of 808 bunches in the accumulator (ISR)



trains of bunches on the target



## Beam on target

	<u><math>\gamma</math> factory</u>	<u><math>\mu</math> collider</u>
Repetition frequency [Hz]	$1.6 \times 10^3$	15
Pulse length [ns]	$3.14 \times 10^3$	1
Protons per pulse	$3 \times 10^{13}$	$10^{14}$
Density [ $s^{-1}$ ]	$10^{10}$	$10^{14}$
Power [MW]	20	4
Kinetic energy [GeV]	2	16

## Target

Heavy metal (Hg)

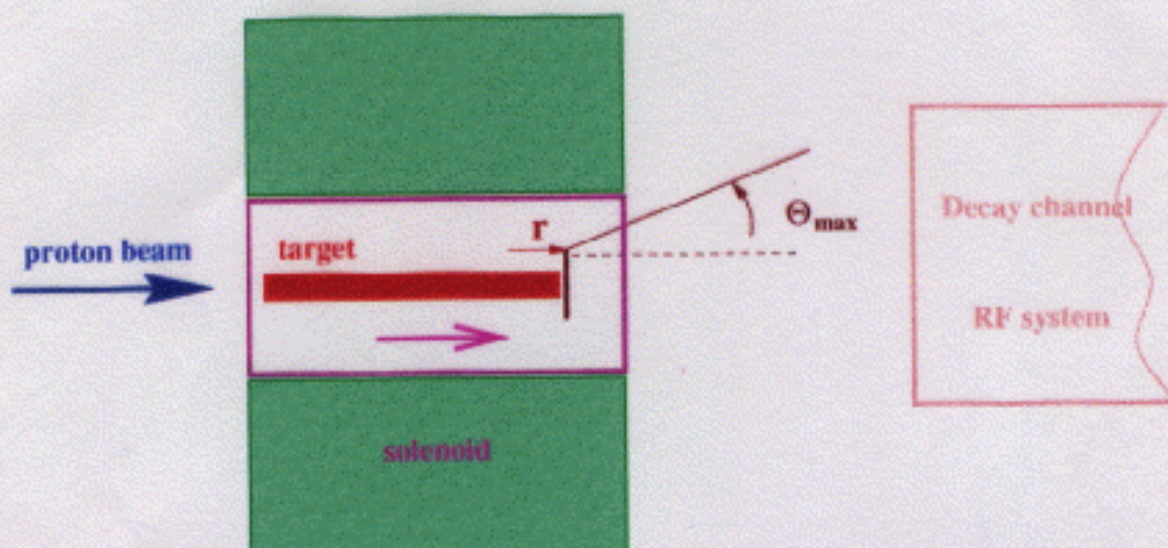
length  $< 20\text{ cm}$

radius  $\sim 10\text{ mm}$

$2\text{ GeV} < T < 16\text{ GeV}$

Solenoidal field  $\sim 20\text{ T}$

## Pion production issues



**$\pi$  collection :**  $P_t^{\max}(\text{GeV}) = 0.15 \, r(\text{m}) \, B(\text{T})$

**$\pi$  beam emittance = decay channel acceptance**

$$\epsilon_n(\text{m.rad}) = \beta \gamma \, r \, \theta_{\max} = r \, P_t^{\max} / m_\pi$$

$$P_t^{\max}(\text{GeV}) = (0.0209 \, \epsilon_n(\text{m.rad}) \, B(\text{T}))^{1/2}$$

**B= 20T**

$$\epsilon_n = 6 \, 10^{-3} \rightarrow P_t^{\max} = 50\text{MeV}, \, r = 17\text{mm}$$

$$\epsilon_n = 24 \, 10^{-3} \rightarrow P_t^{\max} = 100\text{MeV}, \, r = 34\text{mm}$$

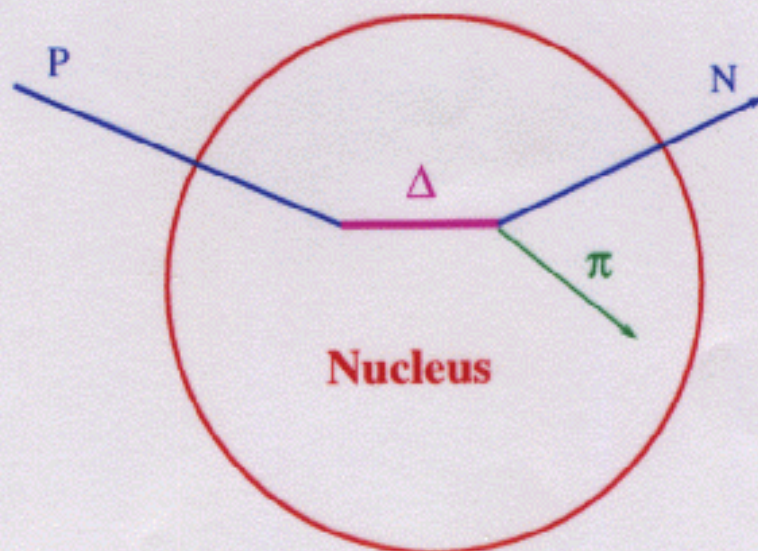
**B= 30T**

$$\epsilon_n = 24 \, 10^{-3} \rightarrow P_t^{\max} = 123\text{MeV}, \, r = 27\text{mm}$$

**RF system :**  $\beta_z$  or  $y = \tanh^{-1}(\beta_z)$

$$\Delta\beta_z \rightarrow \Delta y$$

## Pion Production Model



Experimental data : Cochran et al , Phys.Rev. D6 (1972) 3085 ,  $E_p = 740$  MeV

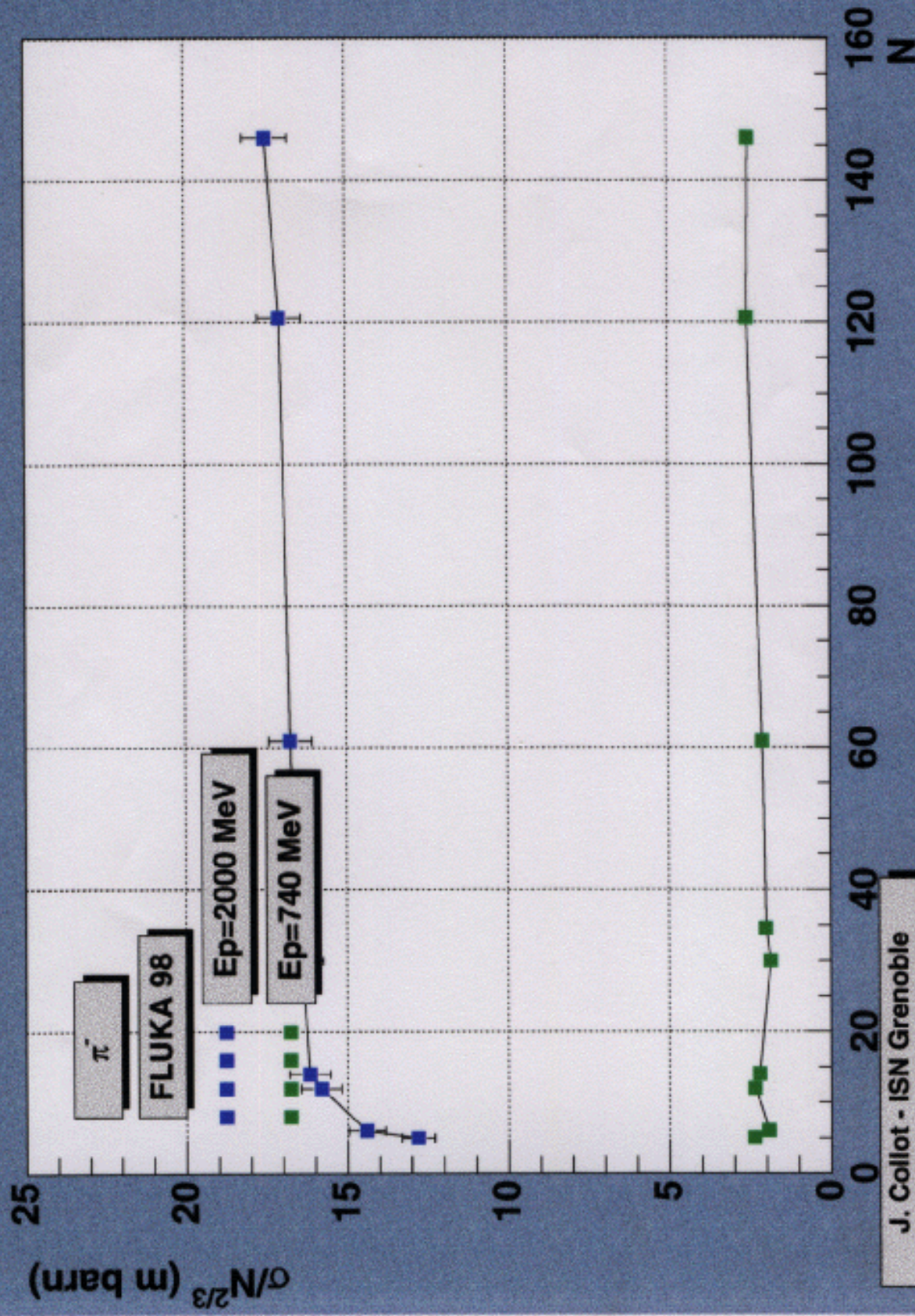
Theoretical work : M. Sternheim and R. Silbar , Phys. Rev. D6 (1972) 3117

Pion abs.  $\rightarrow \sigma(\pi^+) \propto A^{1/3} \propto Z^{1/3}$

Pion abs. + charge exch.  $\rightarrow \sigma(\pi^-) \propto N^{2/3}$

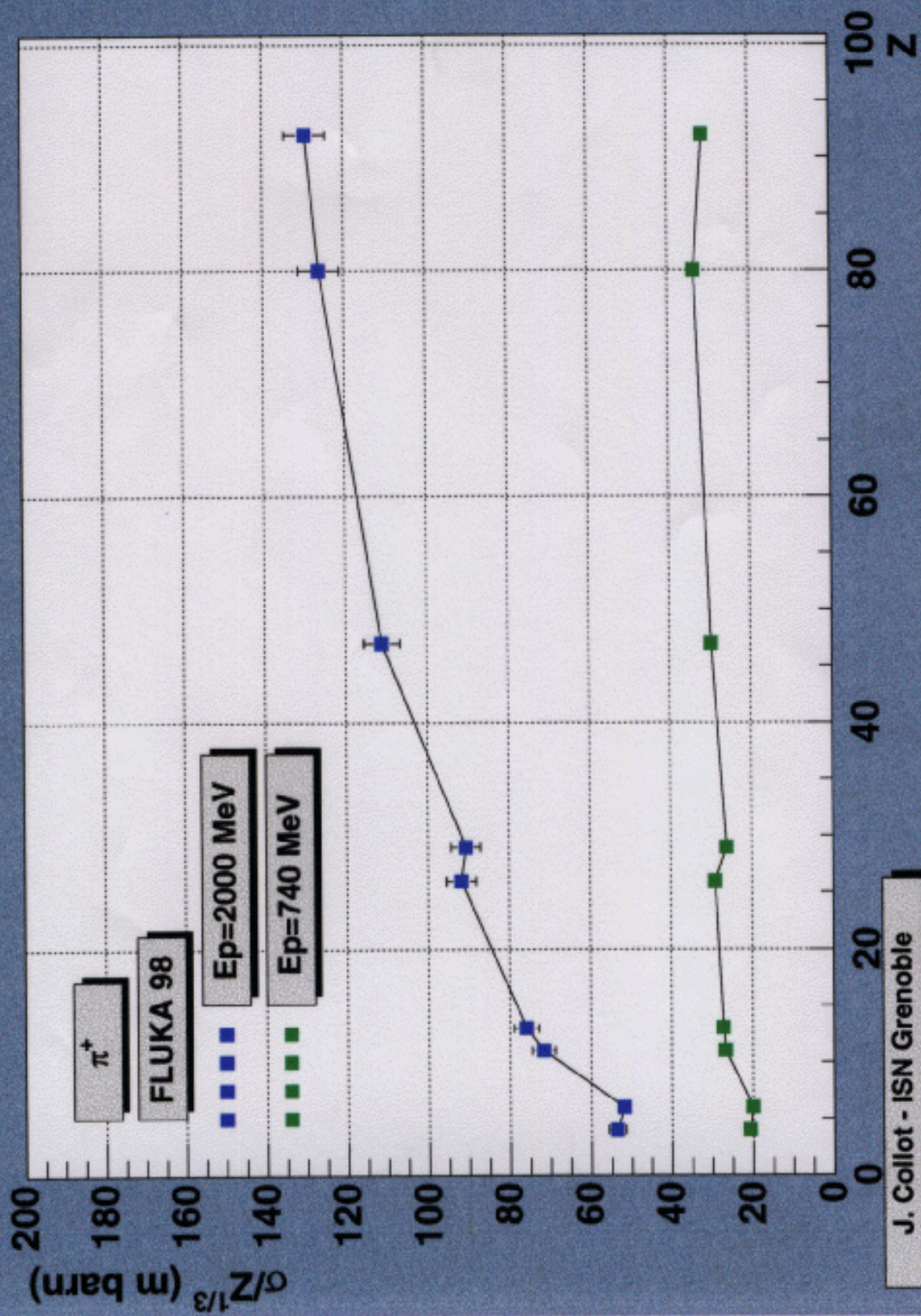
$\sigma(\pi^+)/\sigma(\pi^-) \searrow$  when  $A \nearrow$

# pion production cross-sections

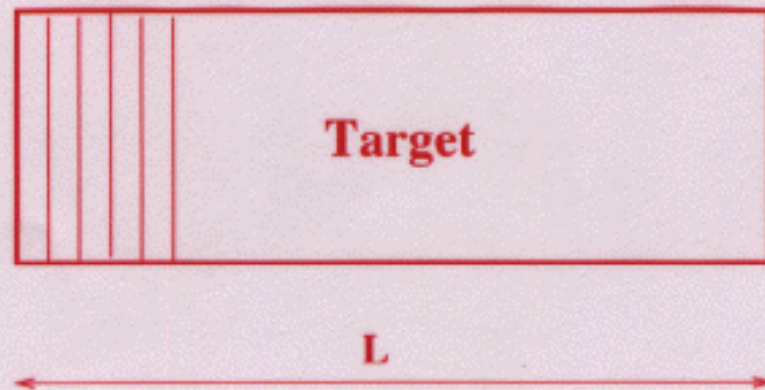


J. Collot - ISN Grenoble

# pion production cross-sections



## Pion Total Production

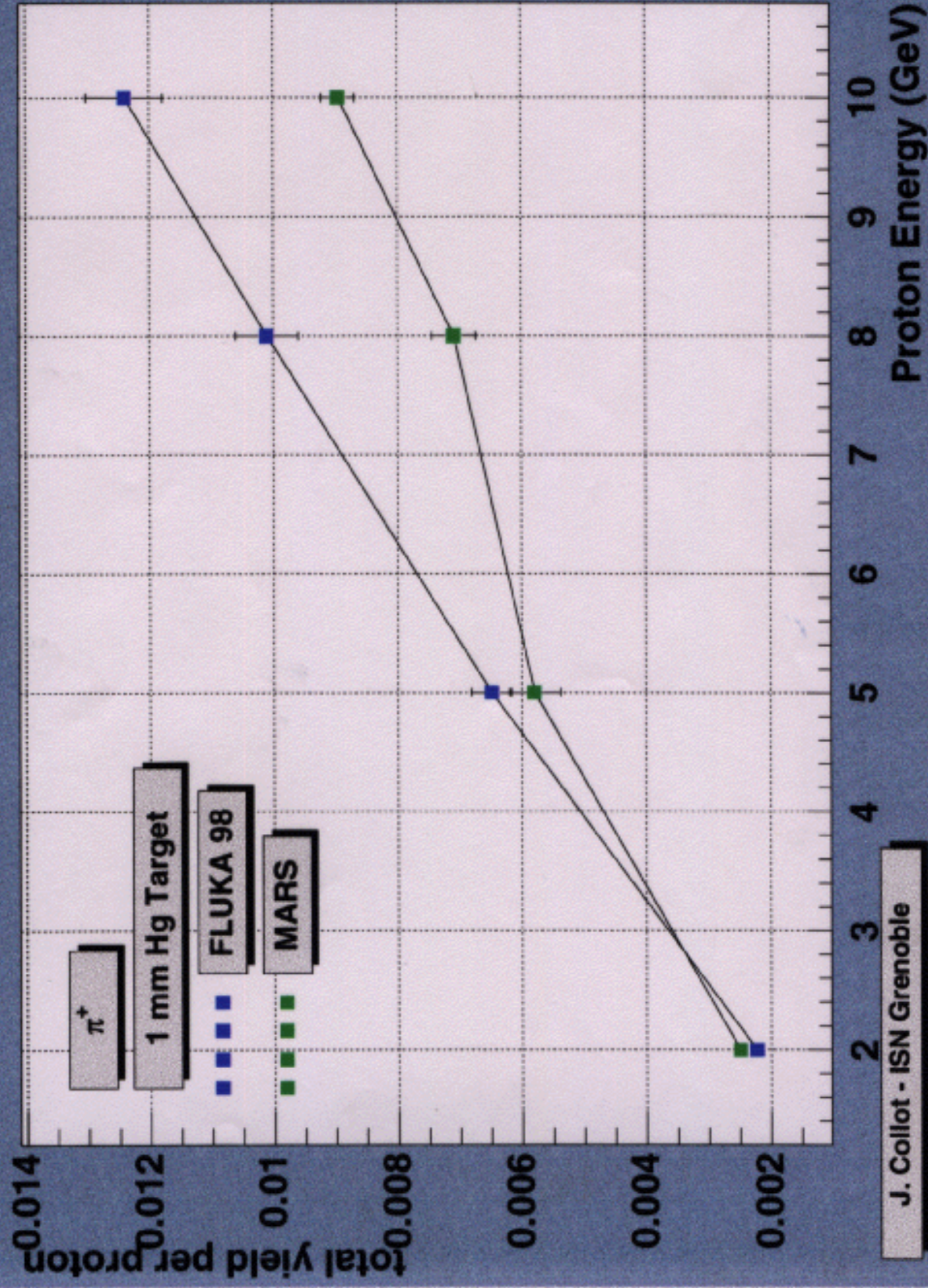


$$T(\pi/pr) = P_{\pi} \Lambda_{\text{int}} (1 - \exp(-L/\Lambda_{\text{int}}))$$

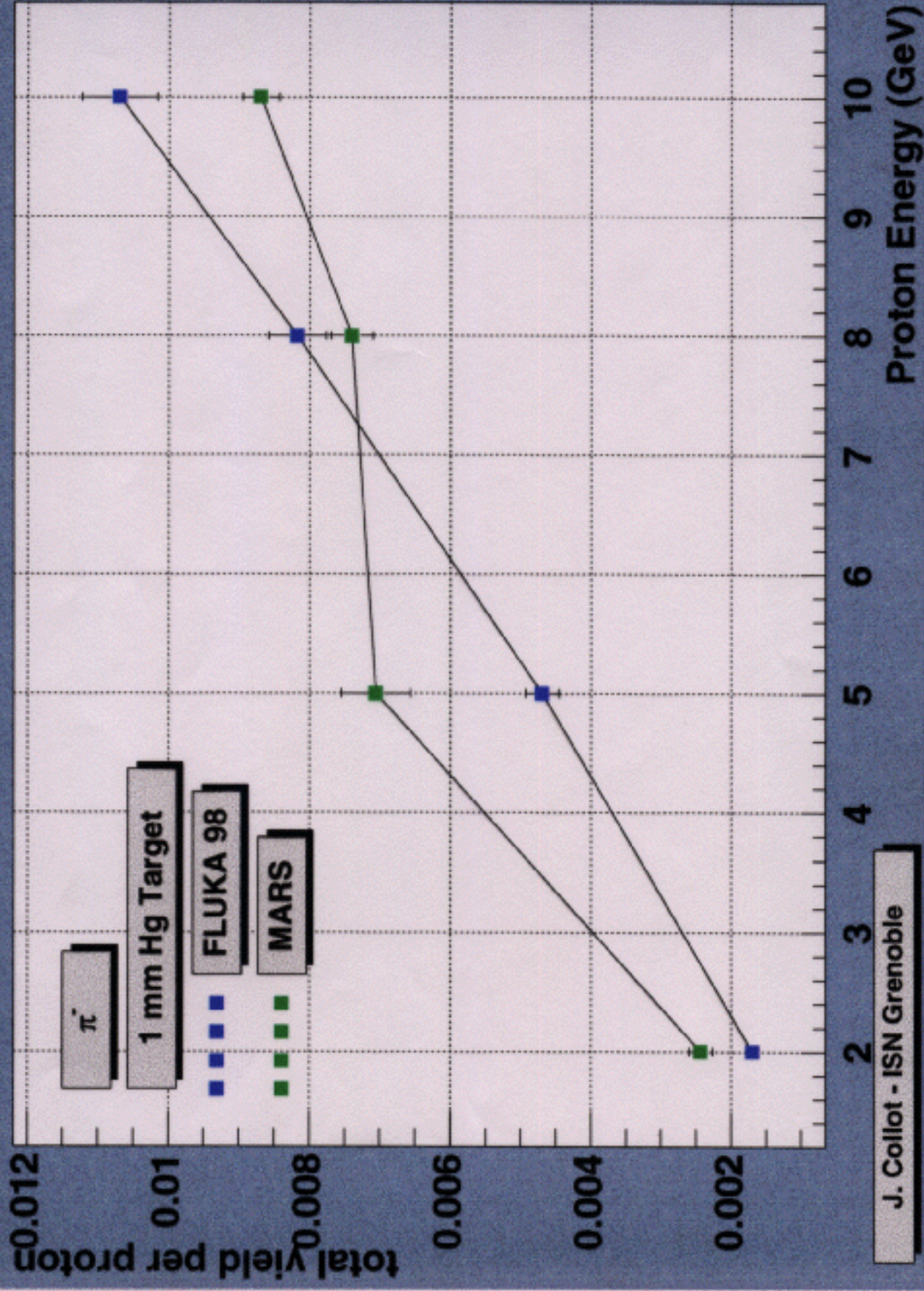
$P_{\pi}$ : Pion total yield per target unit length

$\Lambda_{\text{int}}$ : inelastic interaction length of target material

# pion production yield



# pion production yield



## PION YIELD FROM MERCURY

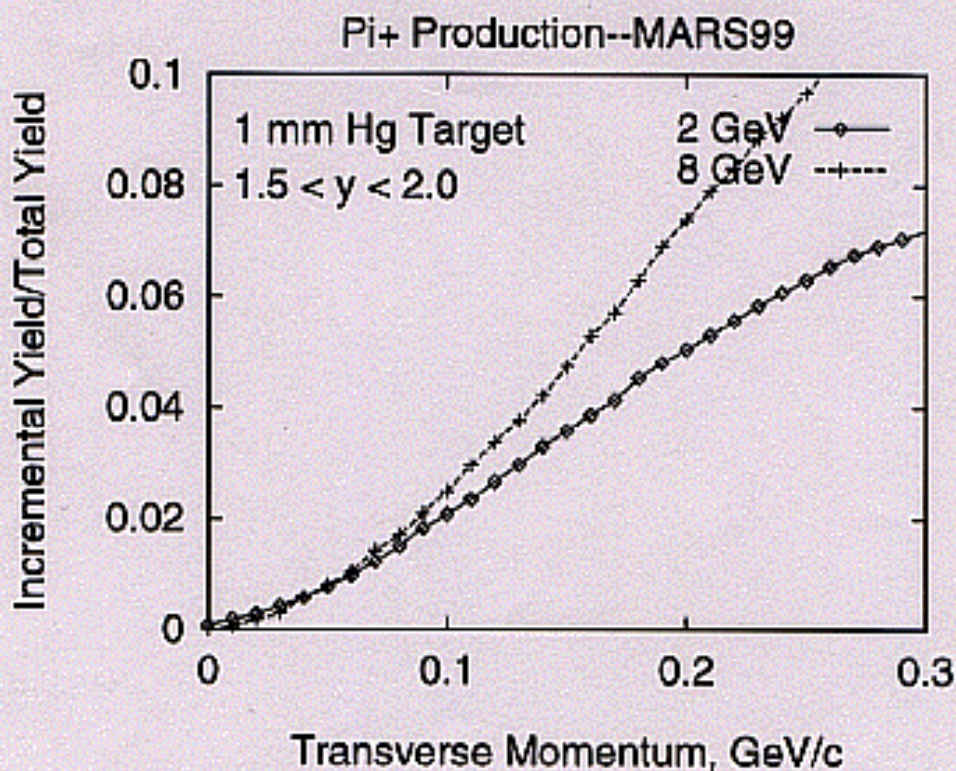
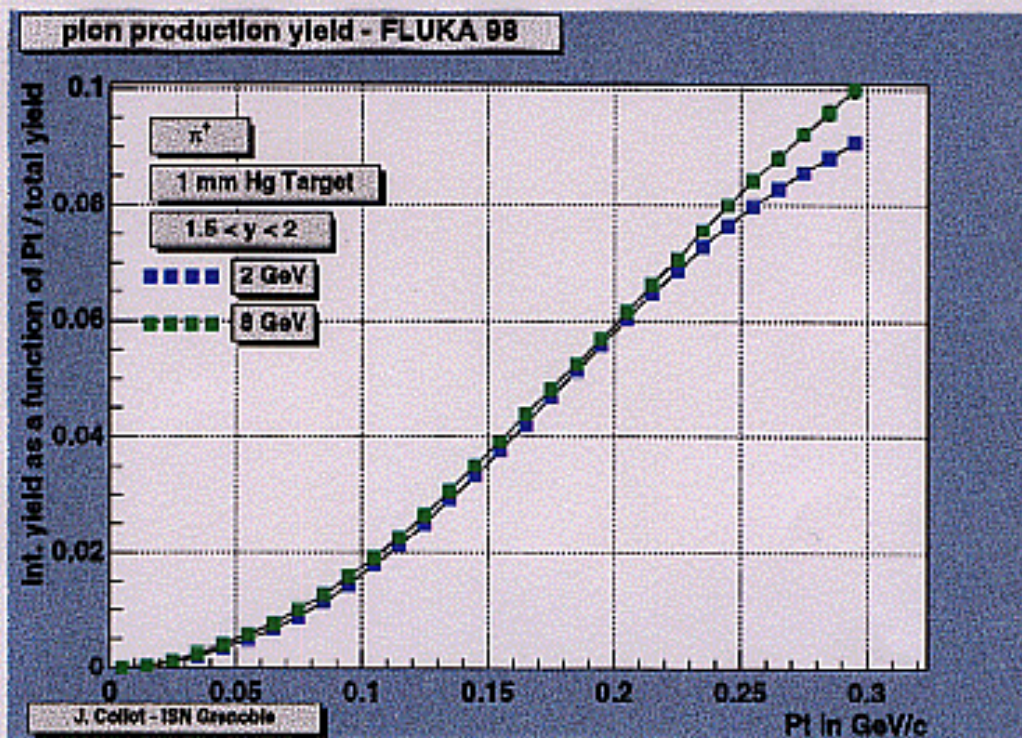
*\*10<sup>-3</sup>*

Table 1: Total pion yields per a proton incident on a 1 mm Hg target as calculated with MARS13(99) YM and FLUKA98 YF.

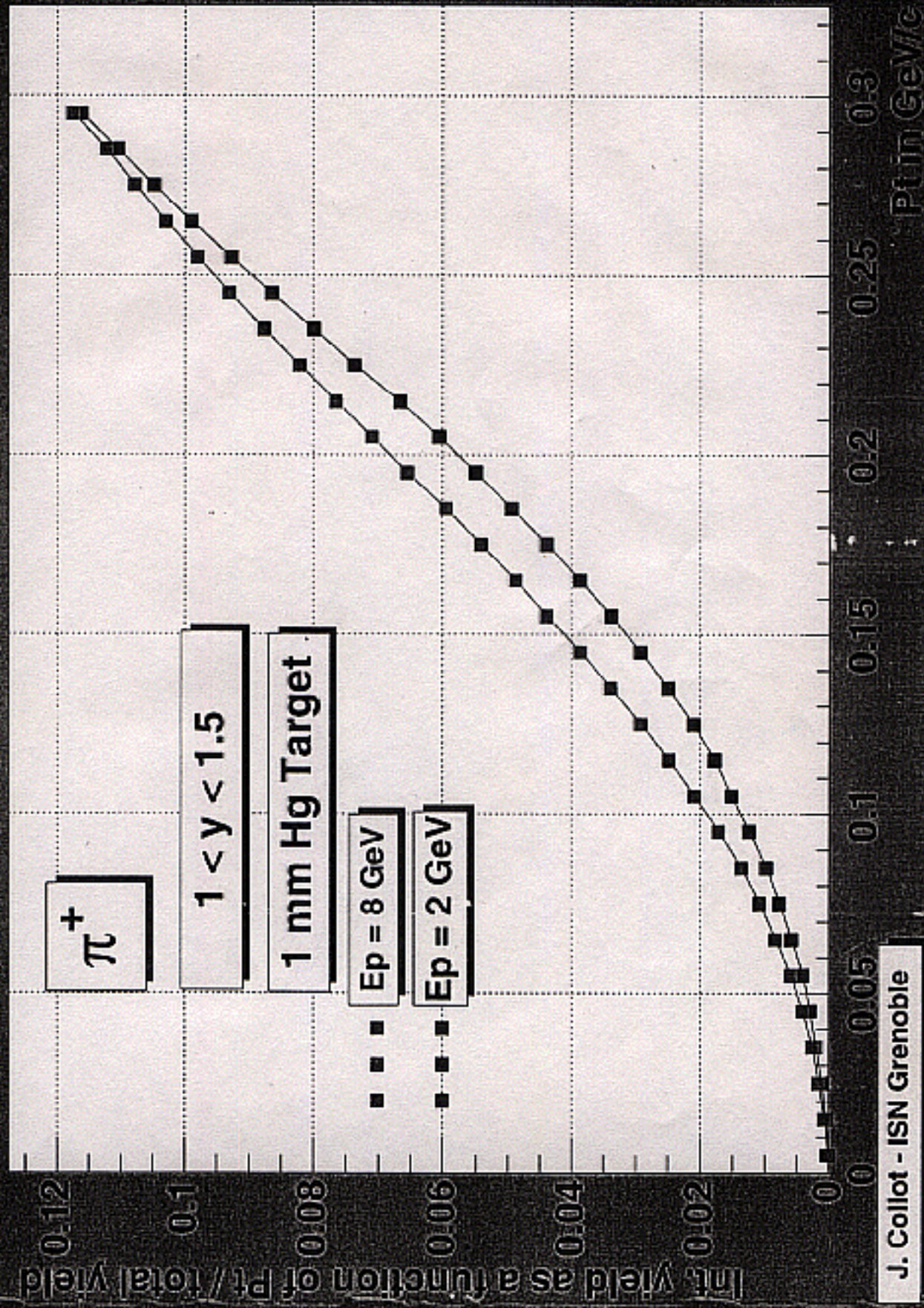
KE(GeV)	YM <sub>π<sup>+</sup></sub>	YM <sub>π<sup>-</sup></sub>	YF <sub>π<sup>+</sup></sub>	YF <sub>π<sup>-</sup></sub>
2	2.547	2.654	2.23	1.70
5	6.025	7.552		
8	7.326	7.626	10.1	8.18
8(*)	7.014	7.280		
10(*)	8.832	8.706		

(\*) Using the production x-section for the Y-to-YT conversion rather than the inelastic one, which might be more appropriate at KE > 5 GeV.

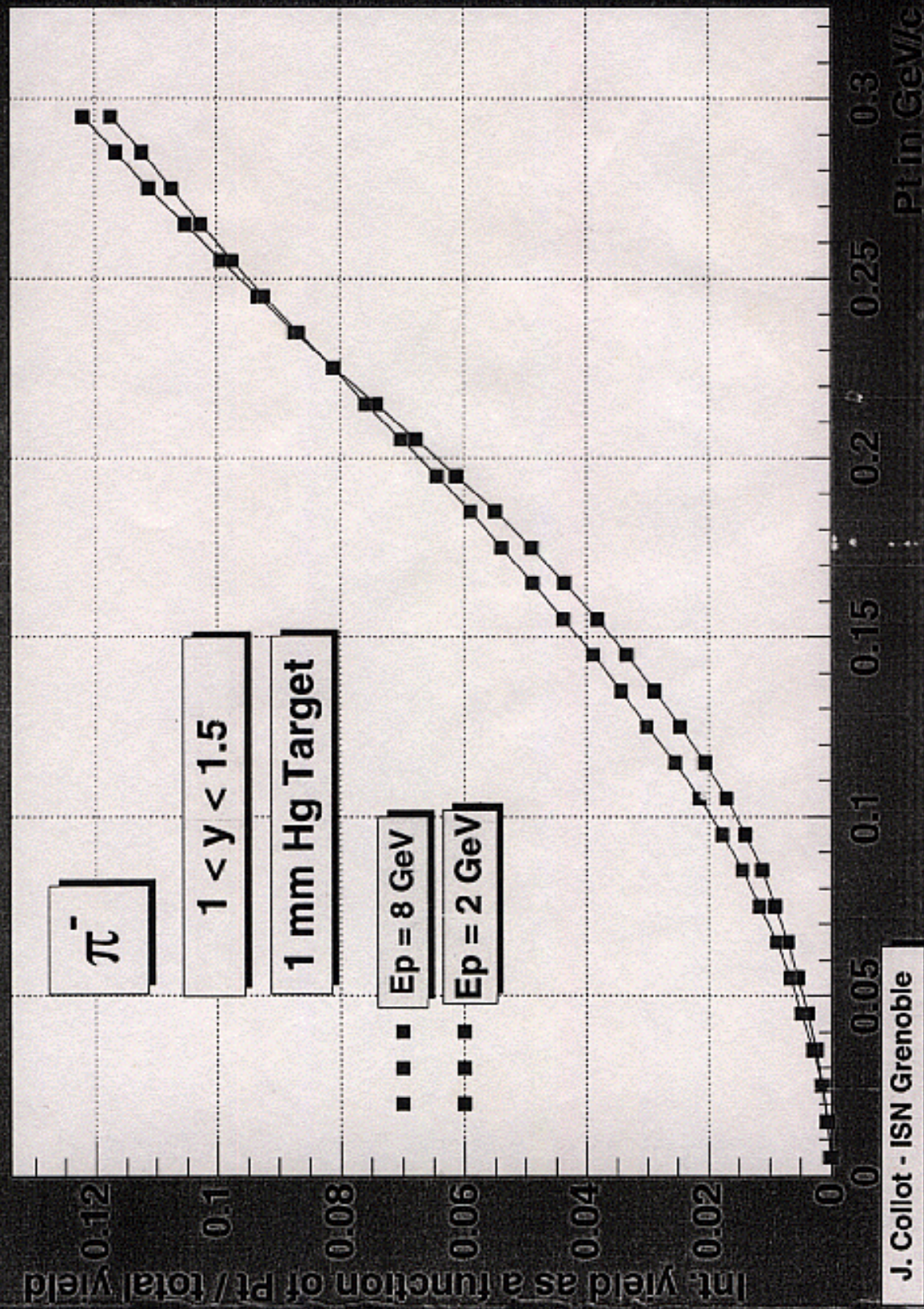
## Comparison of event generators



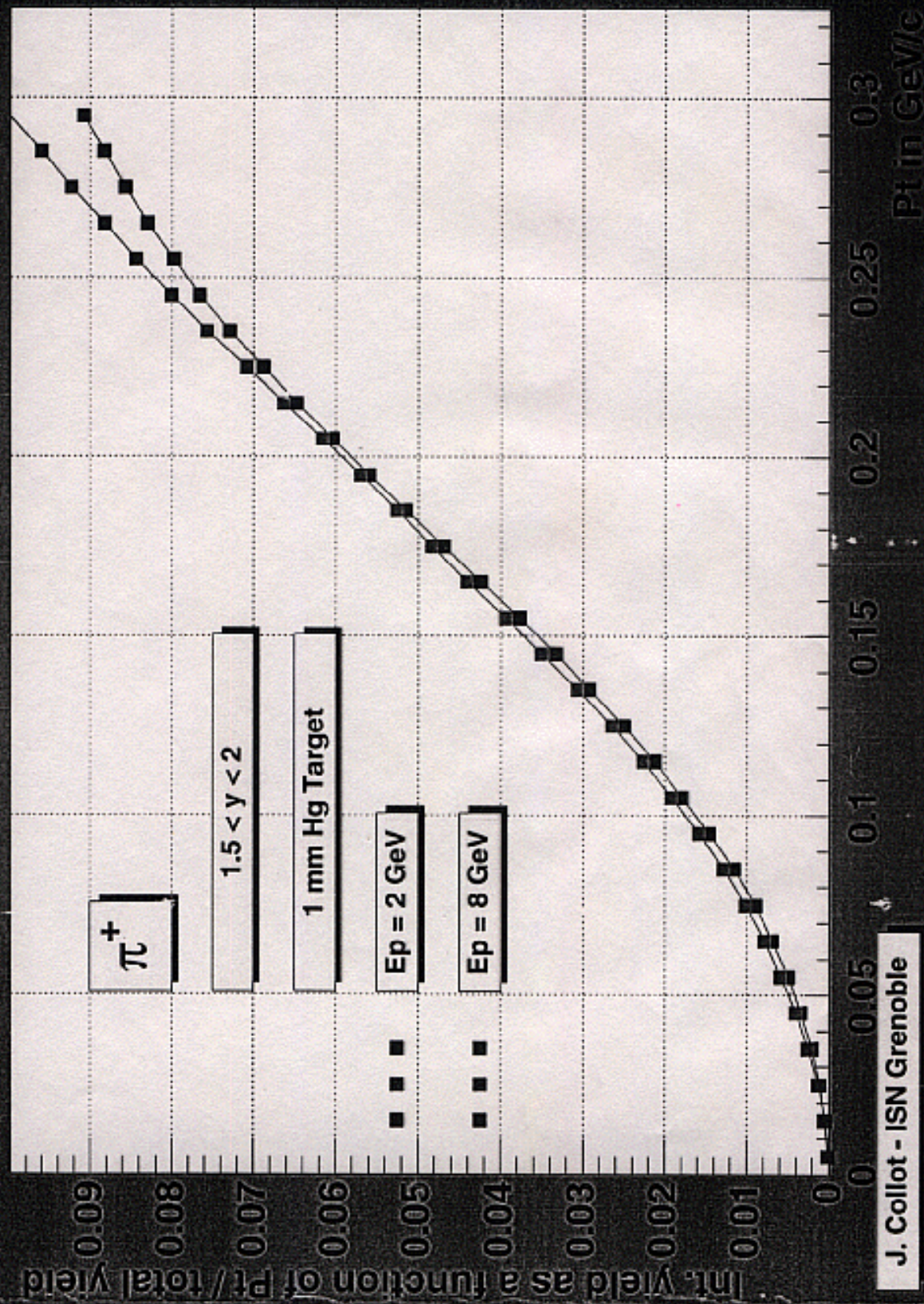
## pion production yield - FLUKA 98



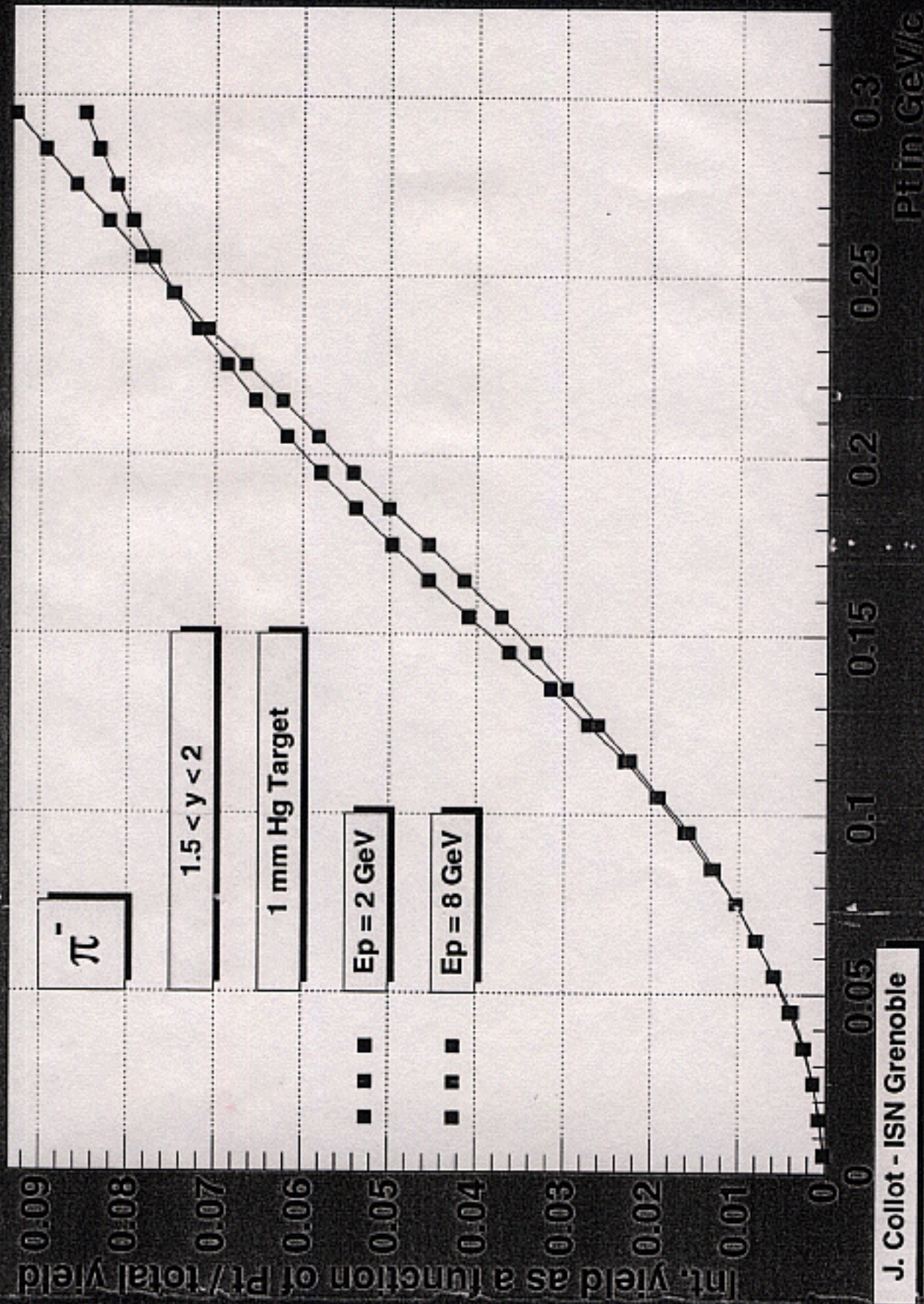
## pion production yield - FLUKA 98



## pion production yield - FLUKA 98



## pion production yield - FLUKA 98



## Angular collection

Canonical variables:  $p_T, r$

Invariant normalized emittance:  $\epsilon_N = \frac{p_T r}{m}$

Real emittance:  $\epsilon = \frac{p_T r}{p}$

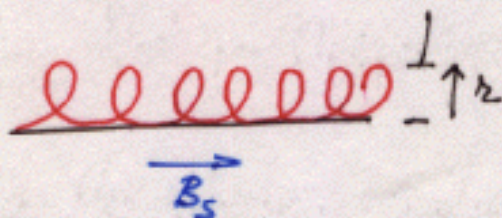
Reference emittance for  $\bar{p}$  collectors  
at 3.5 GeV/c:  $200 \pi \cdot 10^{-6}$

Normalized emittance for  $\mu$ 's:

$$\epsilon_{n\mu} = \frac{m_p}{m_\mu} \epsilon_{np} = 6.6 \pi \cdot 10^{-3}$$

Normalized emittance for  $\pi$ 's:  $\epsilon_{n\pi} = 6 \pi \cdot 10^{-3}$

Magnetized target:



$$p_T = 0.15 B_s r$$

$$r = \sqrt{\frac{m_\pi \epsilon_N}{0.15 B_s}}$$

$\beta$ -function at the end of the target:

$$\beta^* = \frac{r^2}{\epsilon}$$

# Optics

Target field :  $B_s = 20 \text{ T}$

$\Delta y$	1.5 - 2	1 - 2
$\epsilon_N \text{ (m)}$	$6 \cdot 10^{-3}$	$24 \cdot 10^{-3}$
$\bar{p}_z \text{ (MeV/c)}$	401.5	335.
$\frac{\Delta p_z}{p_z}$	$\pm 0.25$	$\pm 0.5$
$\hat{p}_t \text{ (MeV/c)}$	50	100
$r \text{ (mm)}$	16.75	33.5
$\beta^* \text{ (cm)}$	13.7	12.2

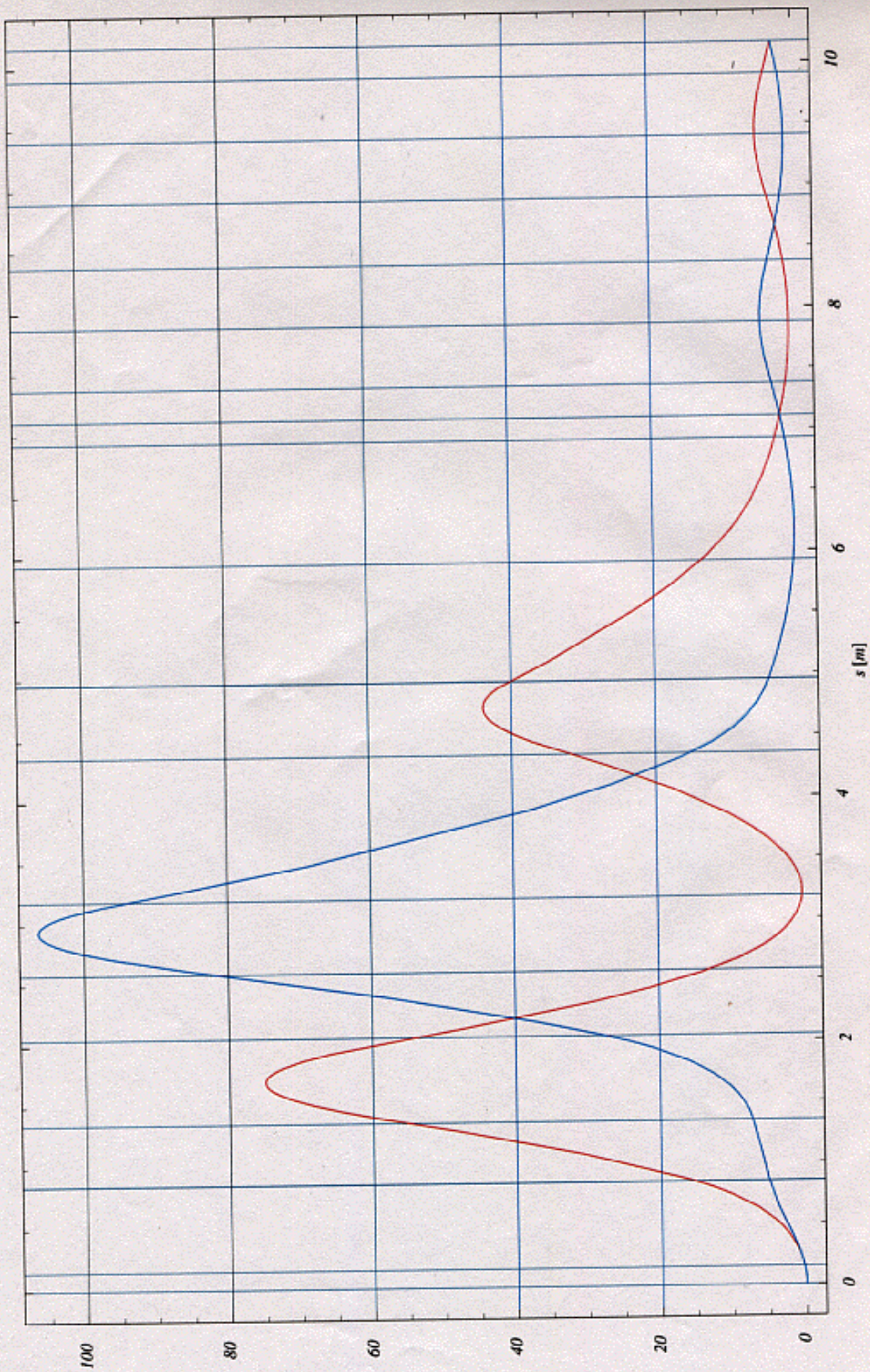
Doublet + Triplet

To be done : Chromatic + Geometric properties

Beam separation ( $p, \pi^+, \pi^-$ )

Ph. Royer

$\beta$  [m]





# Pion Collection

Input:  $\epsilon = 2.1 \cdot 10^{-3} \text{ m} \cdot \text{rad}$

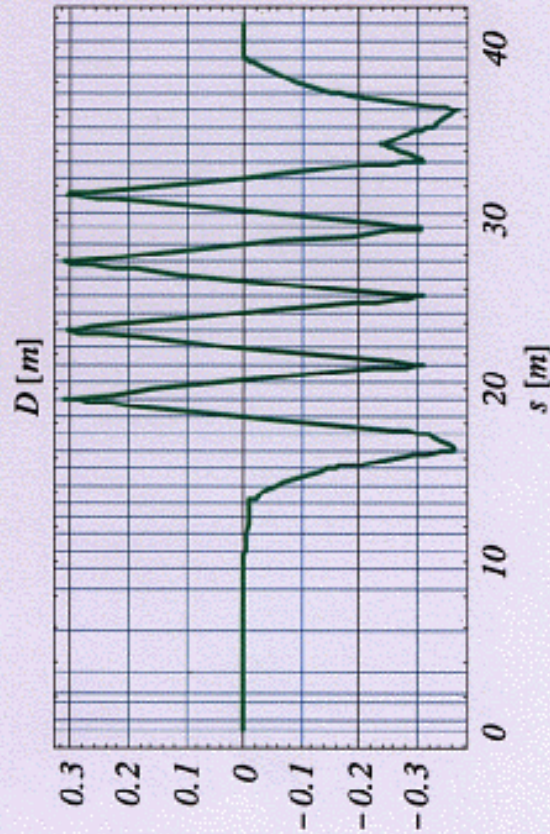
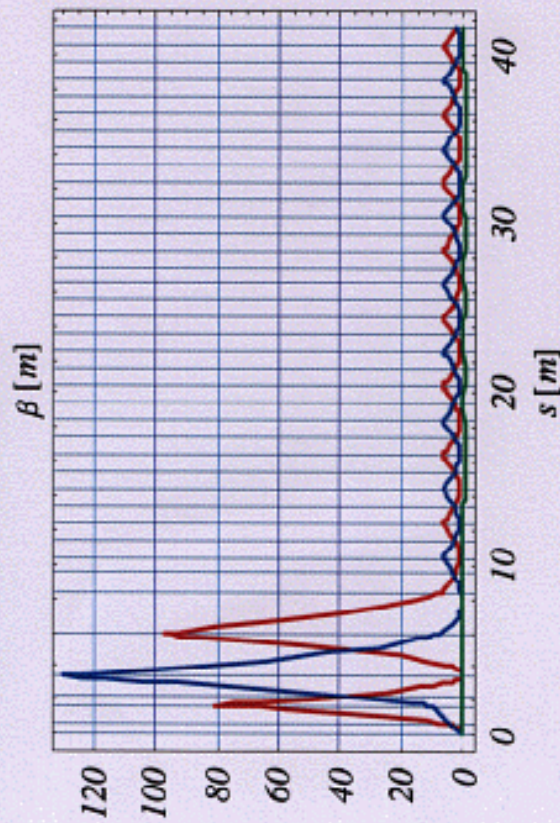
$\beta = 0.08 \text{ m}$

$\alpha = 0 \text{ m}$

$D = D' = 0 \text{ m}$

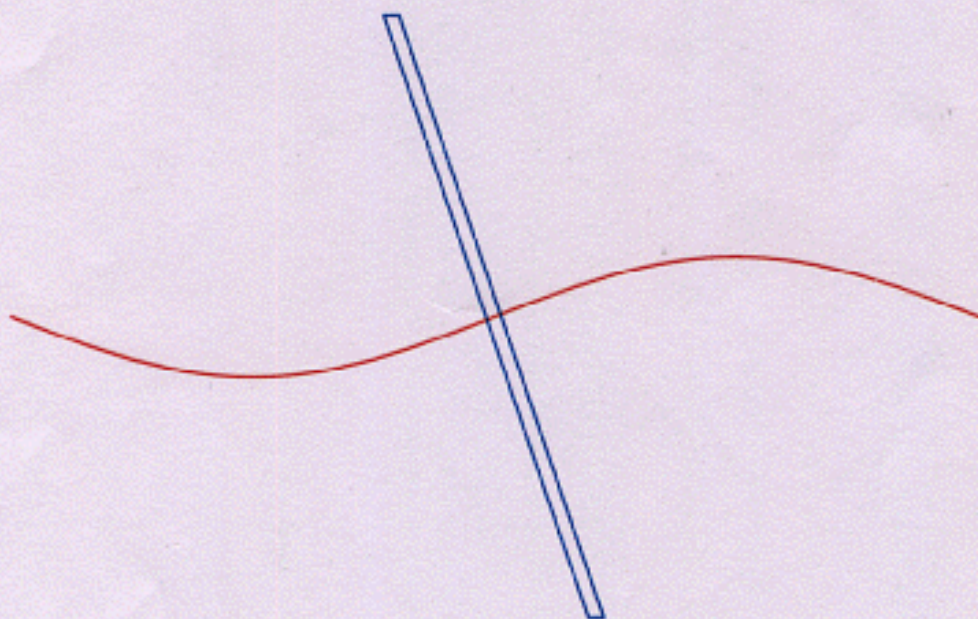


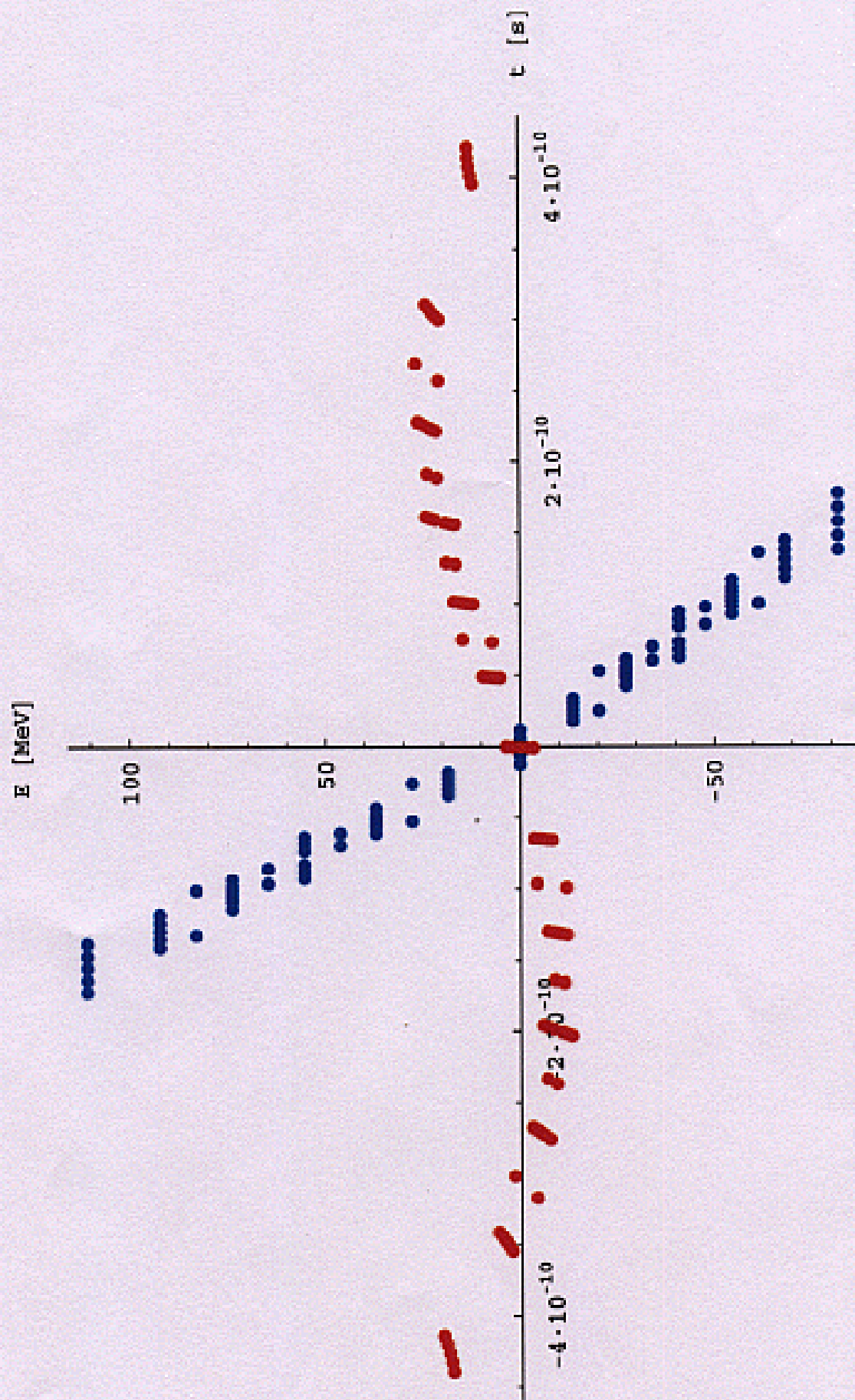
After detailed tracking studies, this type of wiggler does not allow the correct transport of a short bunch. The concept is nevertheless valid and other undulating structures have to be designed.



## Bunch Rotation

Peak voltage [MV]	5
$f$ [MHz]	704
RF structure length [m]	8.5
$\Delta t_1$ [ps]	50
$\Delta E_1$ [MeV]	200
$\Delta t_2$ [ps]	800
$\Delta E_2$ [MeV]	40





$\pi$  production

Proton current: 10 mA ( $6 \cdot 10^{16}$  p/s)

Proton kinetic energy: 2 GeV

$\Delta y$ $p_t$ [MeV/c]	1.5 - 2	1 - 2
50	$0.54 \cdot 10^{21}$	$1 \cdot 10^{21}$
100	$2.1 \cdot 10^{21}$	$4 \cdot 10^{21}$

Number of pions per year ( $10^7$  s)

## Muon acceleration

1. Present studies on combined rotation and acceleration.

<http://nicwww.cern.ch/~serirens/bunchrot/bunchrot1.html>

2. Optimum distance between cavities.

3. Focusing: Solenoids vs quadrupole doublets.

## Re-circulator

shape : dog – bone for optimum use of RF

number of arcs :  $2 * 5$

energy gain per passage : 5 GeV

frequency : 700 MHz

linac length : 500 m

*Check beam-beam.*

*Feasibility of FFAG arcs ?*

*Isosynchronicity.*

*Acceptable momentum spread.*

## $\mu$ accumulator

shape : race – track for optimum use of straight sections

energy :  $\sim 20$  GeV

$e$  – folding time :  $< 0.44$  ms or  $\sim 100$  turns

accumulation system

polarization measurement

Maximum energy ?

Superconducting quadrupoles

Radiation.

*General remarks*

No clear need for proton kinetic energies higher than 2 GeV.

The minimal scheme may meet the threshold of interest for a  $\nu$  factory:

$\sim 5 \cdot 10^{20} \mu / \text{year}$ .

Cost effective high frequency systems ( $\geq 350$  MHz) can be used provided the bunches of  $\pi$ 's (or  $\mu$ 's) with a large velocity spread can be maintained small on long distances using wigglers.

Problems common to high intensity machines (Neutron Spallation Sources or Accelerator Driven Systems):

Exceedingly low loss rates ( $\sim 10^{-7}$ )

Target technology.

Specific problems not yet fully explored: very large acceptance collection systems.