VII. μ–p COLLIDERS

Z. Parsa, Chair

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SOME PHYSICAL PROBLEMS FOR FUTURE μp COLLIDERS

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I assume that $\mu^+\mu^-$ collider can be converted relatively easiely into the μ^-p collider if use initial protons instead of μ^+ for acceleration.

The final proton energy will be the same as for μ^+ and the luminosity should be the same or even higher than that of the basic $\mu^+\mu^-$ collider

The muon polarization is necessary for this collider

This collider has interest for $E > 200$ GeV

This collider has much higher physical potential than the LINAC-RING ep colliders discussed now due to much higher luminosity.

Basic points

In this report I discuss the problem:

What really new can be studied at μp collider AFTER studies at basic $\mu\mu$ collider and LHC. collider

Let us enumerate characteristic new features of this collider.

1. New type of collisions — μp instead of modern ep.
2. Lepton—proton collision in new energy domain (the same as in the basic $\mu^+\mu^-$ collider).
3. High luminosity (the same as for the basic $\mu^+\mu^-$ collider or larger by a factor $3 \div 10$).
4. Large enough degree of muon polarization (I expect about 60%).
5. High monochromaticity.
6. Small energy loss due to bremsstrahlung.

Some of these features give real basis for obtaining new results here and some of them seem inessential in the discussed studies.

Modern (HERA) studies continuation

Structure functions, etc. There is large list of modern studies here, which will be continued at this machine. Large extension of the studied region in the x, Q^2 space is provided by much higher energy and luminosity (points 2, 3), much more accuracy in the results is expected due to practical absence of Initial State Radiation (point 6).

Breaking of factorization. The cross sections for the production of heavy particles or events with high $p_\perp$ are written usually in the simple factorizable form like

$$\sigma \propto \int f(x_1, Q^2) f(x_2, Q^2) \hat{\sigma}(x_1 x_2 s)$$

with factorization of parton densities. At small enough values of x_i this factorization should be broken

(see e.g. *I.F. Ginzburg, D.Yu. Ivanov, V.G. Serbo, Proc. Workshop on Physics and Experiments with Linear e^+e^- Colliders. Hawaii (1993) v.II, 600–604, World Sc. Singapore.*)

This phenomenon is close to the effect of unitariztion of BFKL Pomeron.

The expected high accuracy of data at μp collider together with data from LHC provides opportunity to see in detail this breaking.

The study of *hard diffractive processes* provides opportunity to test pQCD and to investigate perturbative Pomeron and Odderon in reactions

$$\gamma p \to \rho^0 + ..., \ \gamma p \to (q\bar{q}) + ..., \ \gamma p \to \gamma + ..., \gamma p \to \pi^0 + ...$$

with rapidity gap.

It is stated now

(*I.F. Ginzburg, D.Yu. Ivanov, Phys. Rev.* **D54** *(1996) 5523–5535.*)

that pQCD become be valid for the description of these phenomena at very high $p_\perp \geq 7 \div 10$ GeV — the cross section here is very small. This region become achievable due to higher luminosity and energy (points 2, 3). Besides, the pQCD become be valid at lower $p_\perp \geq 3 \div 4$ GeV in the hard Compton effect with rapidity gap; the cross section here is not so small. However, in ep collisions the extraction of this hard Compton from the data is very difficult task due to strong bremstrahlung from electron. This background reduces strong at μp collision. So, this process can be studied good here (point 6). One can expect to see here the regime of BFKL Pomeron (if it exist) and its unitarization (good theory of this effect based on pQCD is absent till now).

Structure function from Z — axial structure function

The studied process is

$$\mu_{\uparrow\downarrow} p \to \mu + ... \quad (Q^2 = -(p_\mu - p_\mu^{'})^2).$$

The discussed structure function differs from that usually used (vector structure function) more strong than it is assumed usually due to axial current anomaly (at $Q^2 < m_q^2$ — $q = c, b, t$). The opportunity of these studies provides by high energy and luminosity together with variable longitudinal polarization of muons (points 2, 3 and 4 together with 6).

The standard DIS experiment with polarized muons at high Q^2 is described by diagrams with both photon and Z exchange (other diagrams contribute negligibely).

Let σ^L and σ^R are the cross sections for light–hand polarized and right–hand polarized electron. One can connect these cross sections with contributions of vector current M_V and axial current M_A. The last obliged by interaction with photon (J^γ) and Z (J^Z):

$$M_V = \frac{1}{Q^2}J^\gamma + \frac{1/4 - \sin^2\Theta_W}{Q^2 + M_Z^2}J_V^Z; \quad M_A + \frac{1}{Q^2 + M_Z^2}J_A^Z.$$

(We see that in the good approximation $M_V \propto J^\gamma$.)

With these notations

$$\sigma_{L,R} \propto |M_V \pm M_A|^2;$$
$$\Delta\sigma = \sigma^L - \sigma^R \propto Re(M_V^* M_A),$$
$$\sigma^{np} = \frac{\sigma^L + \sigma^R}{2} \propto |M_V|^2 + |M_A|^2.$$

The difference $\Delta\sigma$ should be not small in comparison with separate cross sections σ^L and σ^R at $Q^2/M_Z^2 \gg 0$, for example at $Q^2 > (1 \div 3) \cdot 1000$ GeV^2. Therefore, the reliable accuracy in the extraction of axial contribution is possible here.

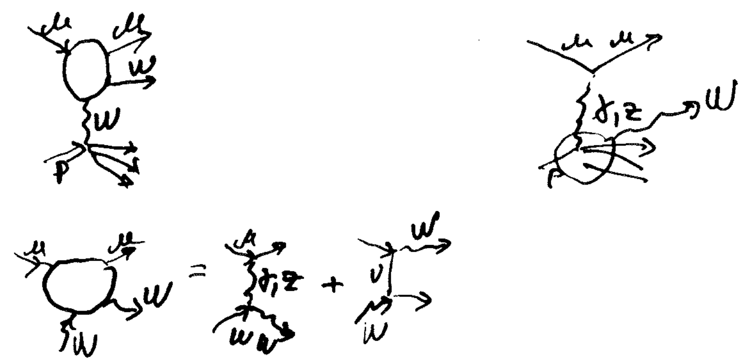
Structure functions for charged current

Let us consider the process

$$\mu p \to \mu W + ...$$

It describes by two diagrams in Figure. At $p_{\perp\mu}$, $p_{\perp\mu} \lesssim M_W$ the first of them dominates — with W exchange between virtual photon (or Z) and hadrons. One can study here the charged current interaction with hadrons with the KNOWN ENERGY of exchanged W. This opportunity is very new in comparison with the modern studies of process like $\mu p \to \nu + X$, where the energy of W is unknown. Until now we have here only calculations in the parton model with very rough testing. The detail calculations here are in progress.

This opportunity is obliged by large energy and luminosity of μp collider (points 2, 3).



Leptoquarks, etc.

This collider gives really new opportunity to see leptoquark in the fusion of muon with quark from proton (mainly, s or c).

It is natural (only NATURAL) to expect that the coupling of this "light" leptoquark with quarks and leptons is similar to that in Yukawa interaction of quark with Higgs (produced Higgs mass):

$$g_{\ell q} \sim \left(\frac{m_\ell + m_q}{v}\right) |S_{\ell q}| \text{ with } v = 1\sqrt{/G_F\sqrt{2}} = 246 \text{ GeV}.$$

Besides, it seems to be natural that the mixing between generations is small, and the masses of muon and s or c quarks are summed here. Therefore, the expected rate of "electroquarks" is very low, and their discovery in such experiments seems to be hardly probable. Oppositely, for the "muoquark" this coupling constant become not so small,

$$g_{\mu c} \sim 0.005, \quad g_{\mu s} \sim 0.002,$$

and one can expect here large effect (if such muoquark exists).

There is limited list of new opportunities here related to the discovery of some other new particles (SUSY, etc.). The simple example provide us *the gluino search* in the reaction

$$\gamma g \to \tilde{\gamma}\tilde{g}$$

The expected high luminosity here provides high potential for the gluino discovery in this process.

ABOUT LUMINOSITY MONITORING

AT μp AND $\mu\mu$ COLLIDER

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To know luminosity of collider precisely, one should present some way for luminosity monitoring. The problems related to this way are very different for the both colliders discussed.

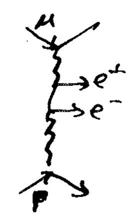
The μp collider

The rough estimate of cross section of main process here $\mu p \to \mu + hadrons$ is given by equation

$$\sigma_{tot} \sim \frac{\alpha\sigma_0}{\pi} \ln\frac{2E^2}{2m_p m_\pi} \ln\frac{2E^2 m_\rho}{m_\mu^2 m_\pi}.$$

Here we considered the cross section σ_0 of subprocess $\gamma p \to hadrons$ to be energy independent, $\sigma_0 \sim 100$ μb. It gives 40 μb for $E = 50$ GeV and 100 μb for $E = 2$ TeV.

The way which I propose here is similar to that proposed for the large proton colliders, Tevatron and LHC *I.F. Ginzburg, NIMR, in print* and earlier for ISR *V.M. Budnev, I.F. Ginzburg, G.V. Meledin, V.G. Serbo. Phys. Lett.* **39B** *(1972) 526; Nucl.Phys.* **B63** *(1973) 519.*.



For this goal, we propose **to record the electrons and positrons from the process $\mu p \to \mu p e^+ e^-$ in anticoincidences with other particles**. Besides, some **two–stage procedure for realization of this idea is presented below**. The total cross section of the process is

$$\sigma = \frac{28}{27\pi}\frac{\alpha^4}{m_e^2}\left[(\ell - 2.12)^3 + 2.2(\ell - 2.12) + 0.4\right], \quad \ell = \ln\frac{4E^2}{m_\mu m_p}.$$

It is ~ 1.2 mb for $\sqrt{s} = 50$ GeV and ~ 6.6 mb for $\sqrt{s} = 4$ TeV. These values are higher than those of process studied.

Let $\vec{k}_{i\perp}$ $(i = 1, 2)$ are the transverse components of the momenta of electron or positron. The distribution over the total transverse momentum of the pair $\vec{k}_\perp = \vec{k}_{1\perp} + \vec{k}_{2\perp}$ is peaked near zero:

$$d\sigma \sim \frac{\alpha^4}{m_e^2}\frac{dk_\perp^2}{k_\perp^2}\cdot\begin{cases} \frac{28}{9\pi}\left[\ln\left(\gamma^2 k_\perp^2/m_e^2\right)\right]^2 & \text{at} \quad m_e/\gamma < |k_\perp| < m_e; \\ \frac{m_e^2}{k_\perp^2} & \text{at} \quad |k_\perp| > m_e. \end{cases}$$

The other important distribution is that over acoplanarity angle 2ψ, which is the angle between $\vec{k}_{1\perp}$ and $-\vec{k}_{2\perp}$:

$$d\sigma \propto \frac{\ln(\gamma^2\sin^2\psi)}{\sqrt{\sin^2\psi + 1/\gamma^2}}d\psi.$$

The scale of effective sizes for the process m_e^{-1} is much higher than that for the hadron processes, form factors etc. $(< m_\pi^{-1})$. It is the reason why the main contribution to this process is calculable within QED with accuracy better $< (m_e/m_\pi)^2 \sim 0.1\%$ without any phenomenological parameters. The real accuracy of monitoring is limited by the accuracy of signature. In this respect the using of small part of the final phase space can be useful. *The precise equations for the process in tree approximation (i.e. with accuracy better 0.5%) are written in the cited paper of 1973).*

The qualitative description of this process is well known (see e.g. above refs.). It is obtained easily with the aid of Equivalent Photon Approximation.

The produced pairs distribute almost uniformly in the rapidity scale. The distribution over the total energy of pair ϵ is

$$d\sigma = \begin{cases} \frac{14\alpha^4}{9\pi m_e^2}\frac{dk_z}{\epsilon}\left[\ell^2 - \ln^2\frac{\epsilon}{m}\right] & \text{at} \quad m_e\frac{E}{m_\mu} \ge k_{z\,e} \ge -m_e\frac{E}{m_p}; \\ \sim \frac{\alpha^4}{m_e^2}\frac{d\epsilon}{\epsilon}\left(\frac{4E^2m_e^2}{m_\mu m_p\epsilon^2}\right)^2 & \text{at} \quad k_z \ge m_e\frac{E}{m_\mu}, \quad k_z \le -m_e\frac{E}{m_p}. \end{cases}$$

Here k_z is the longitudinal momentum of the pair and ϵ is its energy, $|k_z| \approx \epsilon$.

Typically, the electron and positron energies in each pair differ strong from each other. Therefore, the total energy of pair is near the energy of electron or positron. It is the reason why *the distribution over the energy of one electron* ϵ_1, emitted along the motion of initial μ^+, has the the same form as that for distribution over the total energy of pair with the replacement of total energy and longitudinal momentum of pair to the energy and longitudinal momentum of electron $\epsilon \to \epsilon_1$, $k_z \to k_{1z}$.

Two difficulties seem to forbid the using of this process for luminosity monitoring.

- The energies of produced electrons and positrons are small in comparison with that of collided muons and protons, their escape angles are small too. There are necessary the special devices to record these soft particles under very small angles.
- The expected number of events $\mu p \to \mu + hadrons$ per one bunch crossing will be ~ 1 or larger. Therefore it is almost impossible to see e^+ and e^- under interest among large number of pions produced in the main process.

The possible program to overcome these difficulties can be of two stages:

1. At the first stage collider should work with small enough luminosity $\sim 10^{26}$ cm^{-2} per bunch crossing (total $> 10^{31}$ cm^{-2}s^{-1}). In this case the second difficulty disappears. To record e^+e^- pairs from our process one can use the vertex detector *Telnov private communication* (protons will be remained within the beam, they will be invisible). Events with our process differ from hadron background for which the larger number of pions (tens) will cross vertex detector simultaneously. Therefore, only the cases with pair particles production should be considered (in anticoincidences with production of some additional particles). The sharp distributions over total transverse momentum and acoplanarity angle can be used for additional testing of origin of events.

   In this auxiliary stage one can consider the detector as that divided for two parts, left and right. The left part has no variations as compare with the main stage. The special device can be added to the right part for this run for recording of our pairs.

   These measurements should give us the absolute value of total luminosity during this auxiliary run.

Simultaneously in this regime it is necessary to measure the number of events with simple and definite signature (reference observations) in the left side of detector, for example,

- The number of muons scattered within some angular interval for instance $5-15°$ and with energy which is larger than E/2.
- The jet production within the angle $5-15°$ relative to the proton beam and with $E_{jet} > 0.1E$.
- The π^0 flux with $p > 0.01E$ in the same angular interval.
- $W \to e\nu$ production with some lower boundary for E_W
- ....

This comparative measurement should give us the absolute normalization of the reference cross section[1].

2. At the second stage, during the normal run the reference observations with known cross section can be used for the luminosity monitoring.

The problems related with other backgrounds, possible random coincidence at the first stage etc. should be studied separately. The old analysis of 1973 should be reconsidered for new set–up.

[1]It is evident that for new energy the procedure should be repeated. Therefore the additional requirement to the reference observation is smooth dependence on energy to calibrate it at smaller set of energies.

1 The $\mu^+\mu^-$ collider

The problem here is more difficult. The methods which used at the modern e^+e^- colliders are unsuitable here. Indeed,

1) The cross section of *double bremstrahlung* ($\sim \alpha^4/m_\mu^2$) is much lower than that of the two–photon production of hadrons which is about 10 nb for $E = 50$ GeV and about 75 nb for $E = 2$ TeV.

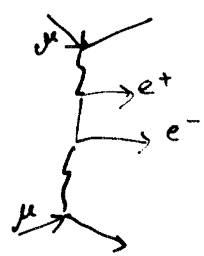
2) To will be useful in the complete discovery of Higgs boson, muons should have high enough degree of longitudinal polarization. The cross sections of majority of processes (including Bahba scattering) depend strong on this polarization (the annihilation diagram is switched on or off with variation of muon longitudinal polarization). Therefore their using gives not the absolute normalization of luminosity but some combination of real luminosity and polarization.

It seems useful to calibrate the luminosity with the process which cross section does not depend on the polarization and to measure polarization independently.

For this goal one use the process $\mu^+\mu^- \to \mu^+\mu^-e^+e^-$ with cross section about 2.2 mb for $E = 50$ GeV and about 9.5 mb for $E = 2$ TeV.

The same as for μp collider two–stage procedure is necessary here. However, the choice of reference observation is more delicate here. It is necessary to use for this aim the process with cross section which is independent on muon polarizations. That are processes of two–photon production of hadrons, for example, small angle jet production.

The more detailed studies are necessary in both cases.



μ p Colliders

- Contact Interactions
- Leptoquarks
- Leptogluons

Kingman Cheung
12/97 $\mu^+\mu^-$

Outline

- Kinematics
- Sensitivity to New Physics
  - Effective μq contact interactions
  - Leptoquarks ($L_{\mu q}$)
    ($\not R_p$ squarks)
  - Leptogluons

Muon - Proton Colliders

μ beam	$\otimes$	p beam	$\sqrt{S}$	$\mathcal{L}$
30 GeV		820 GeV	314	0.1
50 GeV		1 TeV	447 GeV	2
* 200 GeV		1 TeV	894 GeV	13
1 TeV		1 TeV	2 TeV	110
2 TeV		3 TeV	4.9 TeV	280

$\mathcal{L} \sim (E_{\mu\,beam})^{4/3}$ using *

Physics Opportunities

- Structure Functions
  - higher Q^2, lower x
- e - μ universality
- New Physics specific to μ
  - μq Leptoquarks
  - μg Leptogluon
  - μq contact interactions
- Other similar to e-p colliders
  - SUSY, QCD

Success & Excitement of ep

- Proton structure functions

  $q(x, Q^2)$

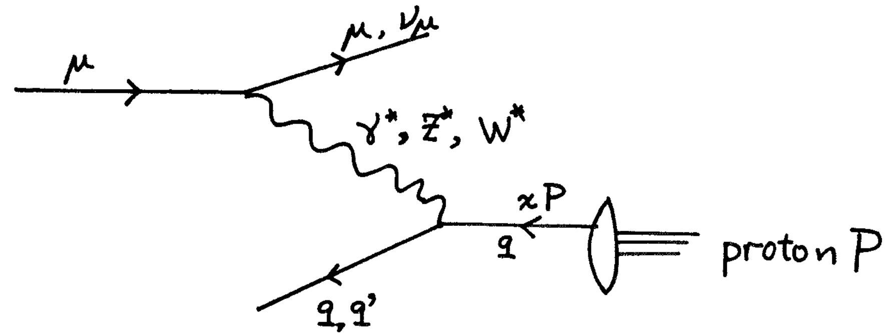
  Q^2 up to $\sim$ ~~5~~ 1 $\times 10^4$ GeV^2

  x as small as 3.10^{-4}

  becomes experimental inputs to other predictions.

- QCD Tests
- NC & CC phenomena
- SUSY Searches
- Other exotics Search

Deep Inelastic Scattering



Momentum Transfer $\quad Q^2 = -\hat{t} = -(\mu_{out} - \mu_{in})^2$

$$x = \frac{Q^2}{2P\cdot(\mu_{out} - \mu_{in})}$$

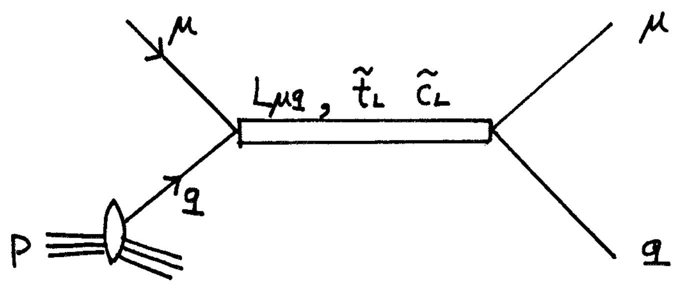
$$y = \frac{-\hat{t}}{\hat{s}} = \frac{Q^2}{s\,x}$$

Measure : $E_{\mu_{out}}$, $\cos\theta_{\mu_{out}}$

$\Rightarrow Q^2, x, y$

Sensitivity

Leptoquarks ($\not R$ squarks)



Such a s-channel Resonance.

will enhance production at

$$\hat{s} = M^2$$

$$x = \frac{M^2}{s}$$

$\Rightarrow$ Excess in a single x bin

2nd Generation Leptoquarks

$L^{0,1}_{\mu c}$ $\quad L^{0,1}_{\mu s}$

0: Scalar

1: Vector

$$\begin{aligned}\mathcal{L} = \; & \lambda^0_{\mu c} \left(\bar{c} \mu L^0_{\mu c} + h.c. \right) \\ & + \lambda^0_{\mu s} \left(\bar{s} \mu L^0_{\mu s} + h.c. \right) \\ & + \lambda^1_{\mu c} \left(\bar{c} \gamma^\mu \mu L^1_{\mu c\,\mu} + h.c. \right) \\ & + \lambda^1_{\mu s} \left(\bar{s} \gamma^\mu \mu L^1_{\mu s\,\mu} + h.c. \right)\end{aligned}$$

$$\sigma = \frac{4\pi^2}{s} \cdot \frac{\Gamma}{M} (2J+1) \cdot f_{q/p}(x, Q^2)$$

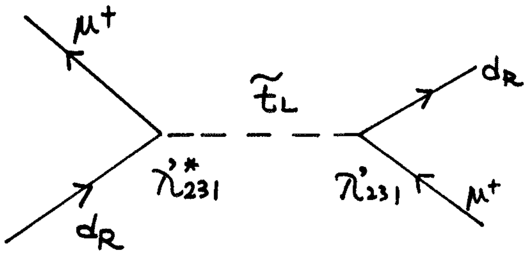
$\not{R}_P$ Squarks

$$W_{\not{R}} = \lambda'_{ijk} L_i Q_j \overline{D_k}$$

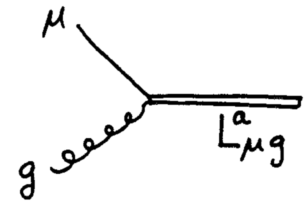
$$\mathcal{L} = \lambda'_{2j1} \left(\overline{d_{kR}} \mu_L \tilde{u}_{jL} + h.c. \right)$$

choose $j=3$: $\tilde{t}_L$

$$\sigma_{\tilde{t}_L} = \frac{\pi |\lambda'_{231}|^2}{4S} \, d\left(x = \frac{M_{\tilde{t}_L}^2}{S}, Q^2\right)$$



Leptogluon



$$\mathcal{L} = g_s \frac{M(L_{\mu g})}{2\Lambda^2} \overline{L^a_{\mu g}} \sigma^{\mu\nu} G^b_{\mu\nu} \mu \cdot \delta_{ab}$$

$$\Gamma = \frac{\alpha_s}{2} \frac{M^5(L_{\mu g})}{\Lambda^4}$$

$$\sigma = 4\pi^2 \left(\frac{M^2_{L_{\mu g}}}{\Lambda^2} \right)^2 \frac{\alpha_s}{S} f_{g/p}(x, Q^2)$$

To estimate the sensitivity

- Assume $\tilde{t}_L$ falls into a mass bin

$$0.9\, m_{\tilde{t}_L} < m < 1.1\, m_{\tilde{t}_L}$$

In this mass bin, calculate the SM DIS cross section and obtain the expected no. of events (use an $\epsilon \simeq 0.8$) n^{sm}

- Use Poisson statistics to calculate n^{th}

$$\sum_{n=0}^{n^{th}} \frac{(n^{sm})^n e^{-n^{sm}}}{n!} > 0.95$$

$\Rightarrow$ Probability that n^{sm} can fluctuate to n^{th} $= 5\%$.

- From n^{th} calculate λ'_{231}, this is the smallest λ' that the expt. sensitive to.

Table 2: 95% sensitivity on λ'_{231} for a few choices of $m_{\tilde{t}_L}$ at various $\mu^+ p$ colliders. The luminosity of the machine roughly scales as $(E_\mu)^{\frac{4}{3}}$ from 13 fb^{-1} at 200 GeV $\otimes$ 1 TeV collider.

	30GeV $\otimes$ 820GeV	50GeV $\otimes$ 1TeV	200GeV $\otimes$ 1TeV	1TeV $\otimes$ 1TeV	2TeV $\otimes$ 3TeV
$\sqrt{s}$(GeV)	314	447	894	2000	4899
$\mathcal{L}$(fb^{-1})	0.1	2	13	110	280
$m_{\tilde{t}_L}$ (GeV)					
200	0.014	0.0045	0.0025	0.0015	0.0010
300	–	0.0094	0.0032	0.0018	0.0014
400	–	0.055	0.0041	0.0021	0.0017
500	–	–	0.0056	0.0024	0.0019
600	–	–	0.0086	0.0027	0.0021
700	–	–	0.016	0.0030	0.0023
800	–	–	0.045	0.0033	0.0025
900	–	–	–	0.0037	0.0026
1000	–	–	–	0.0043	0.0027
1500	–	–	–	0.012	0.0034
2000	–	–	–	–	0.0043
2500	–	–	–	–	0.0056
3000	–	–	–	–	0.0078
3500	–	–	–	–	0.013
4000	–	–	–	–	0.024
4500	–	–	–	–	0.081

Table 3: 99% sensitivity reach on the coupling λ for leptoquarks and the new physics scale Λ for leptogluon via the resonance production $\mu p \to L$. The energy and the luminosity choices are the same as the last table.

	30GeV ⊗ 820GeV	50GeV ⊗ 1TeV	200GeV ⊗ 1TeV	2TeV ⊗ 4TeV
$\sqrt{s}$(GeV)	314	447	894	5657
$\mathcal{L}$(fb^{-1})	0.1	2	13	280
$M^0_{\mu c}$	200GeV	300GeV	500GeV	1500GeV
$\lambda^0_{\mu c}$	0.089	0.043	0.010	0.0014
$M^0_{\mu s}$	200GeV	300GeV	500GeV	1500GeV
$\lambda^0_{\mu s}$	0.068	0.034	0.0080	0.0011
$M^1_{\mu c}$	200GeV	300GeV	500GeV	1500GeV
$\lambda^1_{\mu c}$	0.063	0.031	0.0072	0.0010
$M^1_{\mu s}$	200GeV	300GeV	500GeV	1500GeV
$\lambda^1_{\mu s}$	0.048	0.024	0.0055	0.0008
$M_{\mu g}$	200GeV	300GeV	500GeV	1500GeV
$\Lambda_{\mu g}$(TeV)	20	49	190	1700

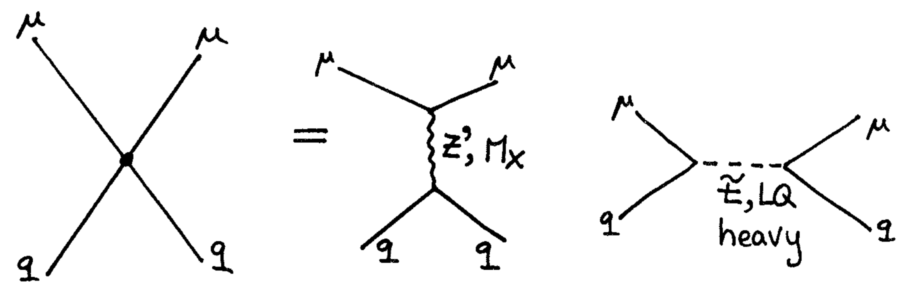
μq Contact Interactions

$$\mathcal{L} = \sum_q \left[\eta^{\mu q}_{\alpha\beta} \left(\overline{\mu_\alpha} \gamma^\mu \mu_\alpha\right)\left(\overline{q_\beta} \gamma_\mu q_\beta\right)\right]$$

$\alpha, \beta = L, R$

$$\eta^{\mu q}_{LL} \quad \eta^{\mu q}_{LR} \quad \eta^{\mu q}_{RL} \quad \eta^{\mu q}_{RR}, \quad q = u, d$$

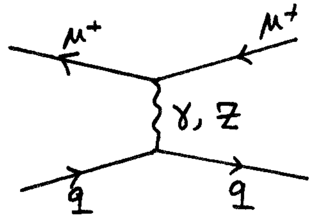
$$\eta^{\mu q}_{\alpha\beta} \equiv \frac{\epsilon\, 4\pi}{\left(\Lambda^{\mu q}_{\alpha\beta}\right)^2}, \quad \epsilon = \pm 1$$

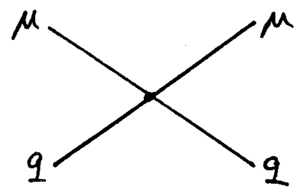


Fermion Compositeness

At present there are constraints from $p\bar{p} \to \mu^+\mu^-$, μN scattering.

$\mu^+ q \longrightarrow \mu^+ q$





$$\frac{d^2\sigma}{dx\,dy} = \frac{s\,x}{16\pi}\Big\{ u(x,Q^2)\Big[|M^{\mu u}_{LR}|^2 + |M^{\mu u}_{RL}|^2 + (1-y)^2\big(|M^{\mu u}_{LL}|^2 + |M^{\mu u}_{RR}|^2\big)\Big] + d(x,Q^2)\Big[|M^{\mu d}_{LR}|^2 + |M^{\mu d}_{RL}|^2 + (1-y)^2\big(|M^{\mu d}_{LL}|^2 + |M^{\mu d}_{RR}|^2\big)\Big]$$

$$M^{\mu q}_{\alpha\beta} = \frac{-e^2 Q_q}{\hat{t}} + \frac{e^2}{\sin^2\theta_W \cos^2\theta_W}\,\frac{g^\mu_\alpha\, g^q_\beta}{\hat{t} - M_Z^2} + \eta^{\mu q}_{\alpha\beta}$$

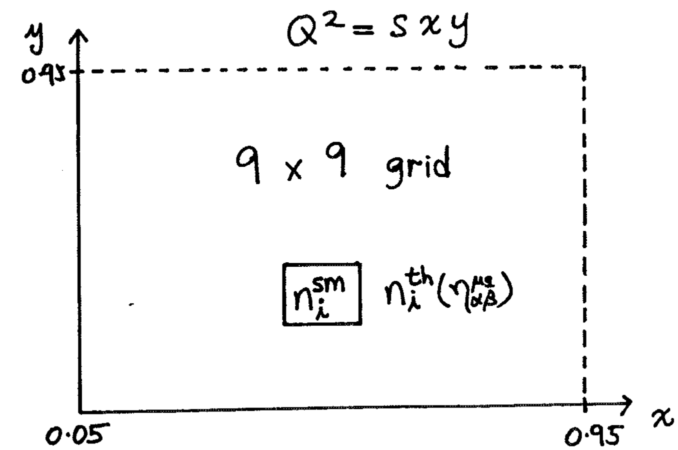
8 parameters $\eta^{\mu q}_{\alpha\beta}$, $q = u, d$

✱ $\eta^{\mu c}$, $\eta^{\mu s}$ also possible but considerably weaker than $\eta^{\mu d}$ & $\eta^{\mu u}$.

Sensitivity to $\mu\mu q q$ contact Interaction

$$\mathcal{L} = \sum_{\substack{q \\ \alpha,\beta = L,R}} \eta^{\mu q}_{\alpha\beta}\,(\overline{\mu_\alpha}\gamma^\mu \mu_\alpha)(\overline{q_\beta}\gamma_\mu q_\beta)$$

$$\eta^{\mu q}_{\alpha\beta} = \frac{\epsilon\, 4\pi}{(\Lambda^{\mu q}_{\alpha\beta})^2}$$



$$\chi^2(\eta^{\mu q}_{\alpha\beta}) = \sum_i \left[2(n^{th}_i - n^{sm}_i) + 2\, n^{sm}_i \log \frac{n^{sm}_i}{n^{th}_i} \right]$$

One nonzero $\eta^{\mu q}_{\alpha\beta}$ at a time

$\Rightarrow$ 80 d.o.f.

95 % CL needs a $\chi^2(\eta^{\mu q}_{\alpha\beta}) \simeq 102$

Calculate $\eta^{\mu q}_{\alpha\beta}$ that can produce such a $\chi^2 = 102$.

Convert $\eta^{\mu q}_{\alpha\beta} = \frac{\epsilon\, 4\pi}{(\Lambda^{\mu q}_{\alpha\beta})^2}$

Table 1: The 95% sensitivity of the $\Lambda^{\mu q}_{\alpha\beta}$, $(\alpha, \beta = L, R;\ q = u, d)$ that can be reached at the various $\mu^+ p$ colliders, by assuming that what will be observed is given by the SM prediction.

	30GeV ⊗ 820GeV		50GeV ⊗ 1TeV		200GeV ⊗ 1TeV		1TeV ⊗ 1TeV		2TeV ⊗ 3TeV	
$\sqrt{s}$(GeV)	314		447		894		2000		4899	
$\mathcal{L}$ (fb^{-1})	0.1		2		13		110		280	
	+	−	+	−	+	−	+	−	+	−
$\Lambda^{\mu u}_{LL}$	1.4	0.8	3.9	3.7	9.4	9.2	24	23	46	46
$\Lambda^{\mu u}_{LR}$	2.0	1.3	4.9	4.3	11	9.2	26	23	50	40
$\Lambda^{\mu u}_{RL}$	1.9	1.3	4.3	3.2	8.9	6.4	21	14	40	29
$\Lambda^{\mu u}_{RR}$	1.4	0.8	3.5	3.2	8.4	7.9	21	20	40	37
$\Lambda^{\mu d}_{LL}$	0.7	1.1	2.2	2.7	6.2	6.6	17	17	32	34
$\Lambda^{\mu d}_{LR}$	1.1	1.3	2.1	2.8	4.5	6.0	10	14	31	29
$\Lambda^{\mu d}_{RL}$	1.2	1.2	2.5	2.2	5.6	4.4	14	10	29	22
$\Lambda^{\mu d}_{RR}$	0.8	1.0	1.5	2.4	3.7	5.1	9.9	13	18	25

Conclusions

- Muon-proton colliders are rather unique in searching for
  - A massive object with muon & baryon number, or $\not{R}_P$ violation:

    $$L_{\mu c} \quad L_{\mu s} \quad L_{\mu g} \quad (\tilde{t}_L, \tilde{c}_L, \tilde{u}_L)$$

  - μp colliders can search such objects up to $\sqrt{s}$:
    with typical sensitivity of

    $$\lambda' \sim 10^{-2} - 10^{-3}$$

- Contact Interaction Limits for

μ ⊗ p	
50 GeV ⊗ 1 TeV	$\Lambda \sim 2-5$ TeV
200 GeV ⊗ 1 TeV	$\Lambda \sim 4-9$ TeV
1 TeV ⊗ 1 TeV	$\Lambda \sim 10-26$ TeV
2 TeV ⊗ 3 TeV	$\Lambda \sim 18-50$ TeV

Neutrino Physics at a Muon Collider

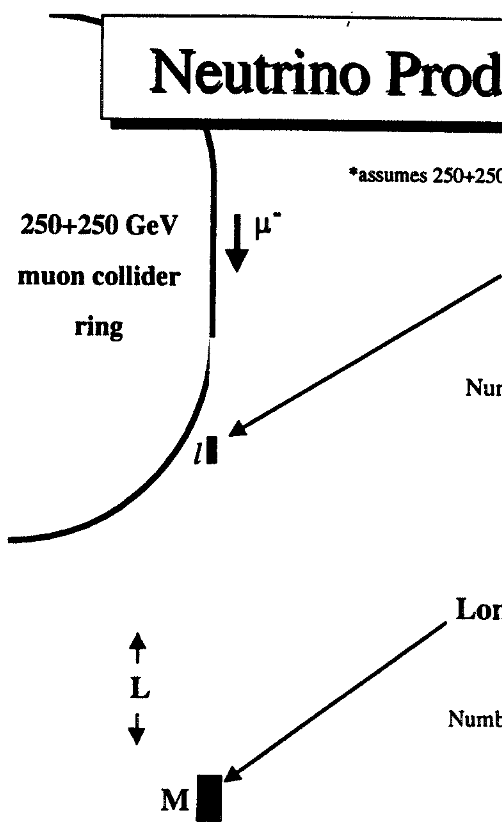
Bruce King
Brookhaven National Laboratory
bking@sun2.bnl.gov

Outline:

- Neutrino Beam
- Example Neutrino Detector
- Physics Outline & Opportunities

Neutrino Production and Event Rates*

*assumes 250+250 GeV collider, 200 m straight section & 6 x 10^{20} μ^-/year



General purpose detector

$$\text{Number of} \begin{bmatrix} \nu_\mu - CC \\ \nu_\mu - NC \\ \overline{\nu}_e - CC \\ \overline{\nu}_e - NC \end{bmatrix} \text{events/yr} \approx \begin{bmatrix} 2.6 \\ 0.8 \\ 1.4 \\ 0.5 \end{bmatrix} \times 10^7 \times l\,[g.cm^{-2}]$$

$$\overline{5.3}$$

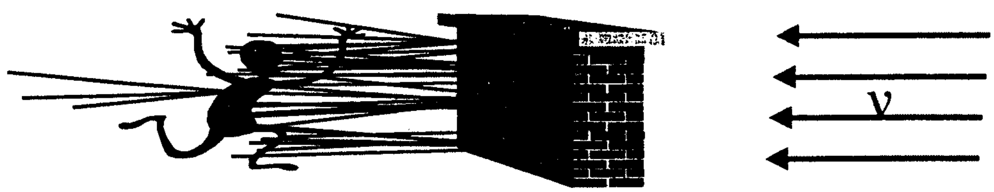
Long baseline detector for ν oscillations

$$\text{Number of} \begin{bmatrix} \nu_\mu - CC \\ \nu_\mu - NC \\ \overline{\nu}_e - CC \\ \overline{\nu}_e - NC \end{bmatrix} \text{events/yr} \approx \begin{bmatrix} 1.4 \\ 0.4 \\ 0.7 \\ 0.2 \end{bmatrix} \times 10^7 \times \frac{M[kg]}{(L[km])^2}$$

$$\overline{2.7}$$

Aside on Neutrino Radiation Hazard

Hazard is charged particles from ν interactions in surroundings...



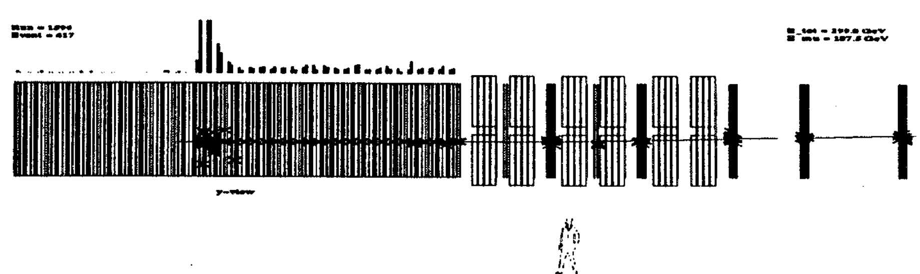
Predicted dose downstream from straight section:

$$\frac{\text{Radiation Dose}}{\text{U.S. Fed. Limit}} \cong 0.3 \times \left(\frac{\text{length of str. section}}{\text{collider depth}}\right) \times \left(\frac{\text{muon current}}{6\times10^{20}\ \mu^- /\text{year}}\right) \times \left(\frac{E_\mu}{250\ \text{GeV}}\right)^3$$

(spherical Earth & non-tilted ring)

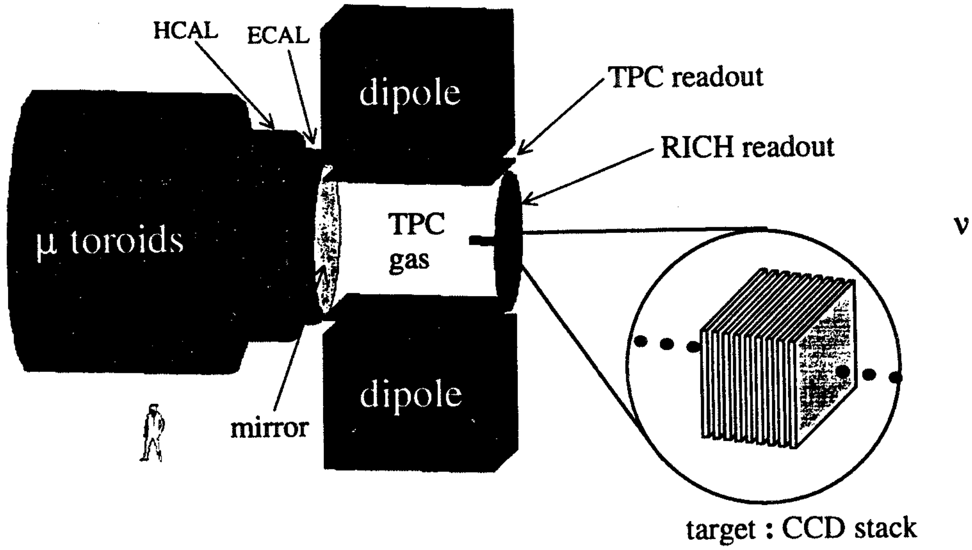
Today's Neutrino Detector (FNAL Lab E)

ν



- ν target is 690 tonne coarse-sampling calorimeter
- several million ν interactions over ~15 year lifetime

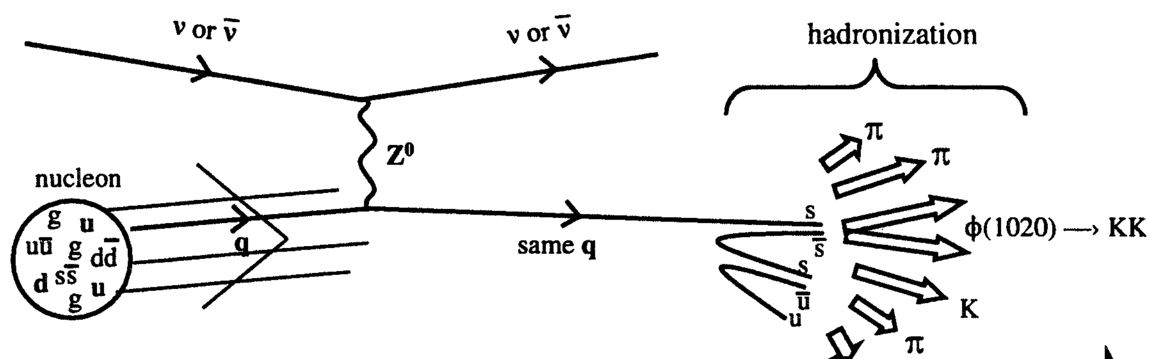
Neutrino Detector at a Muon Collider



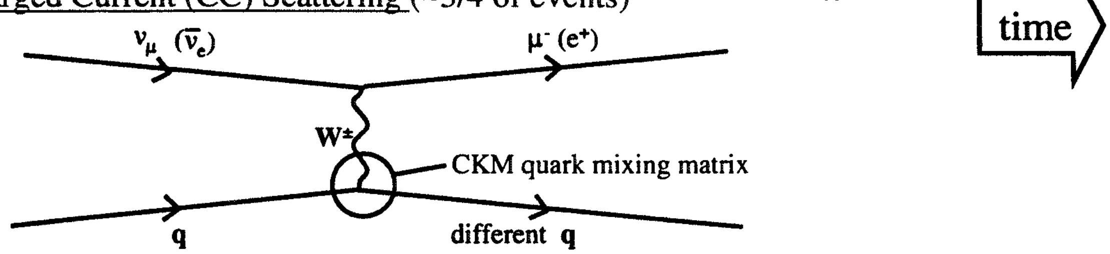
- HUGE statistics: 50 g/cm^2 target => 3x10^9 events/year
- outstanding reconstruction of CC & NC event kinematics
- full particle ID => ID of struck quark

Neutrino-Nucleon Deep Inelastic Scattering (DIS)

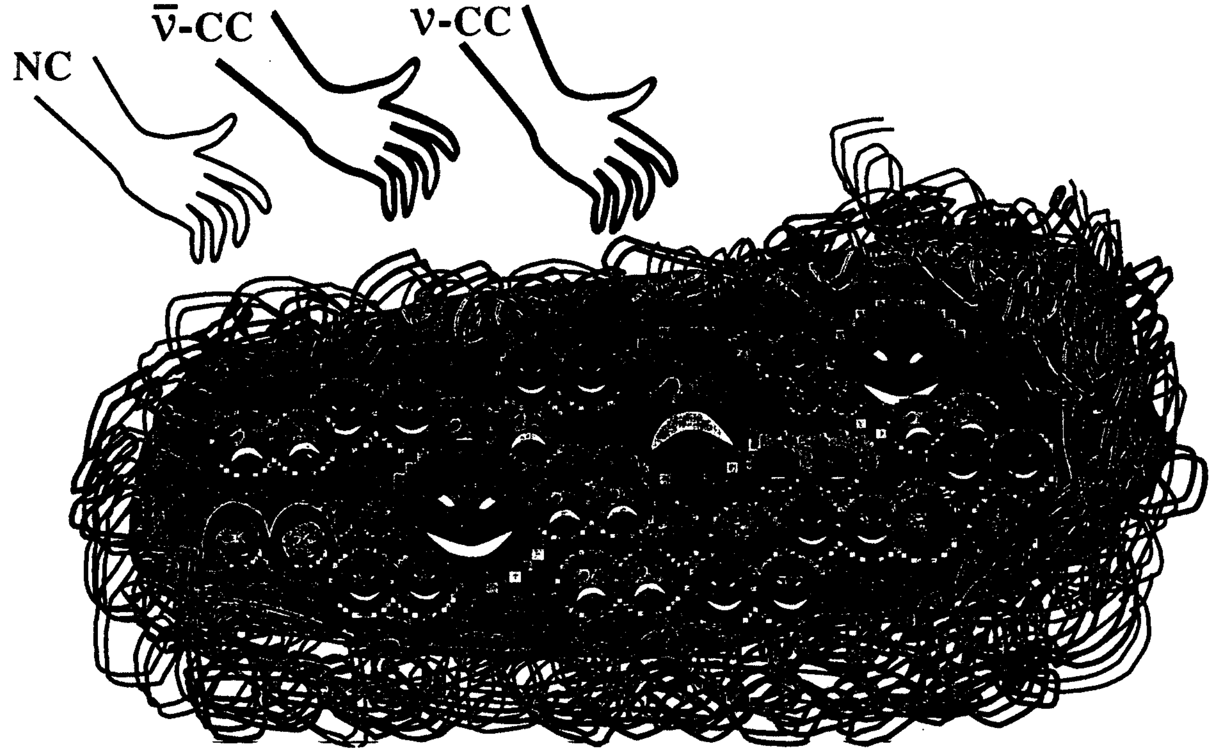
Neutral Current (NC) Scattering (~1/4 of events)



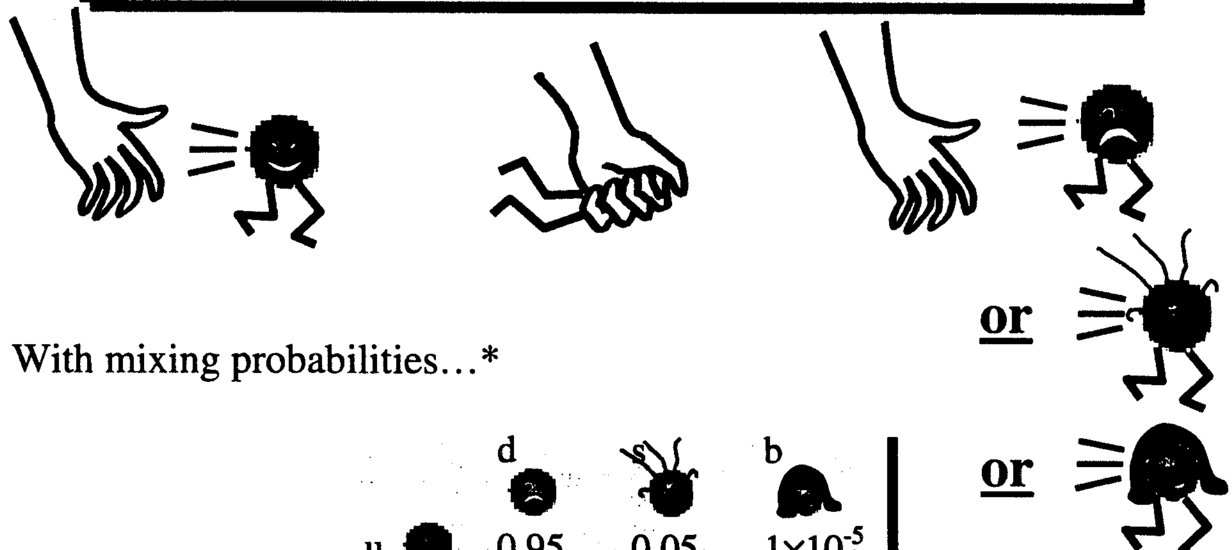
Charged Current (CC) Scattering (~3/4 of events)



Nucleon "Critters"



Quark Mixing in Action!



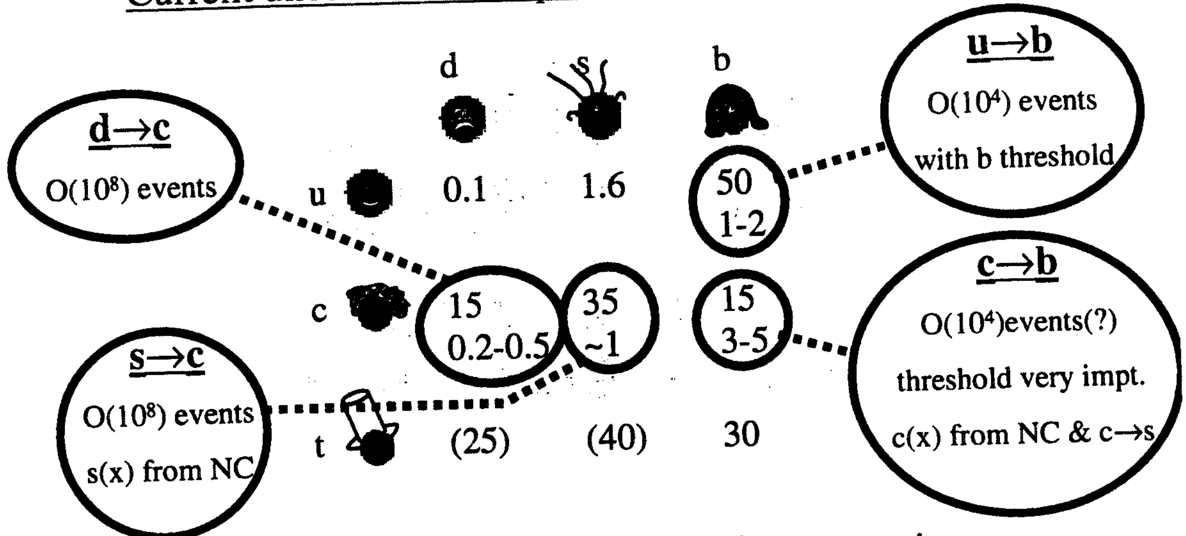
With mixing probabilities…*

	d	s	b
u	0.95	0.05	1×10^{-5}
c	0.05	0.95	0.002
t	1×10^{-4}	0.001	1

*neglecting quark masses

A Windfall for Quark Mixing Studies...

Current uncertainties in quark mixing probabilities (%)



& a guess at uncertainties with 10^{10} ν interactions

- Cause of CP violation?
- Mystery of 3 quark generations etc.

Physics Opportunities

- Quark Mixing
- Tests of Nucleon Structure and QCD
  - **structure functions (SF):** precise NC & CC, each quark, polarized, H_2 & D_2
  - **QCD:** precise α_s, QCD evolution of SF, quark sum rules...
- Electroweak Measurements

  e.g. $\sin^2\theta_W$ from νq & νe scattering ⇒ ΔM_W ~ **O(10 MeV) !?!**
- Neutrino Properties e.g. search for neutrino oscillations
- Searches for Exotic Particles (neutral heavy leptons etc.)
- Charm Factory!

  O(10^8) charm events, ~optimal reconstruction, lifetime information, tagged c production sign (⇒ first observation of D mixing?)

Summary & Outlook

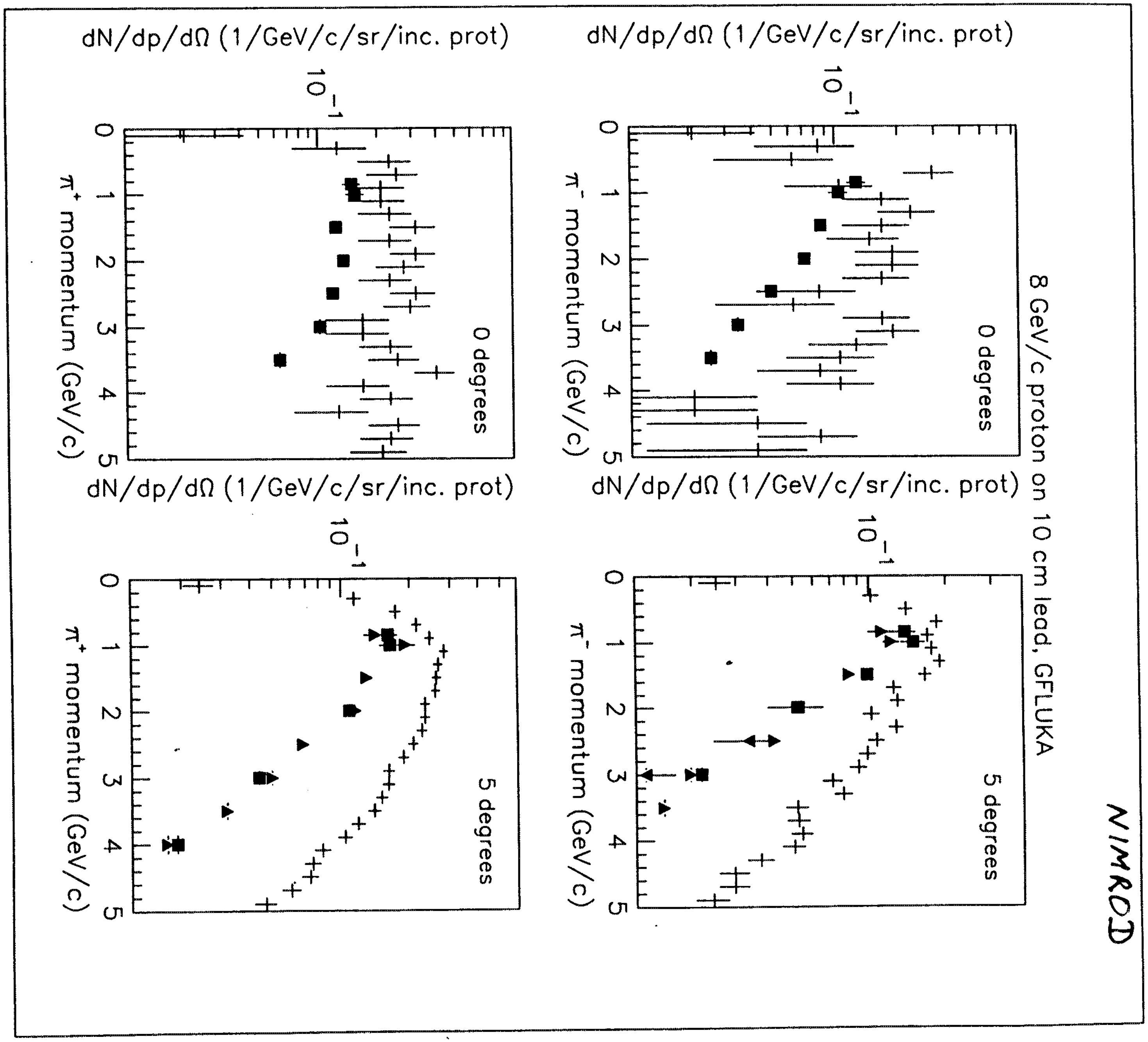
This is a whole new realm for neutrino experiments and elementary particle physics!

An informal working group is now forming to look further into the physics possibilities. Join us!

PION PRODUCTION AND TARGETRY AT $\mu^+\mu^-$ COLLIDERS

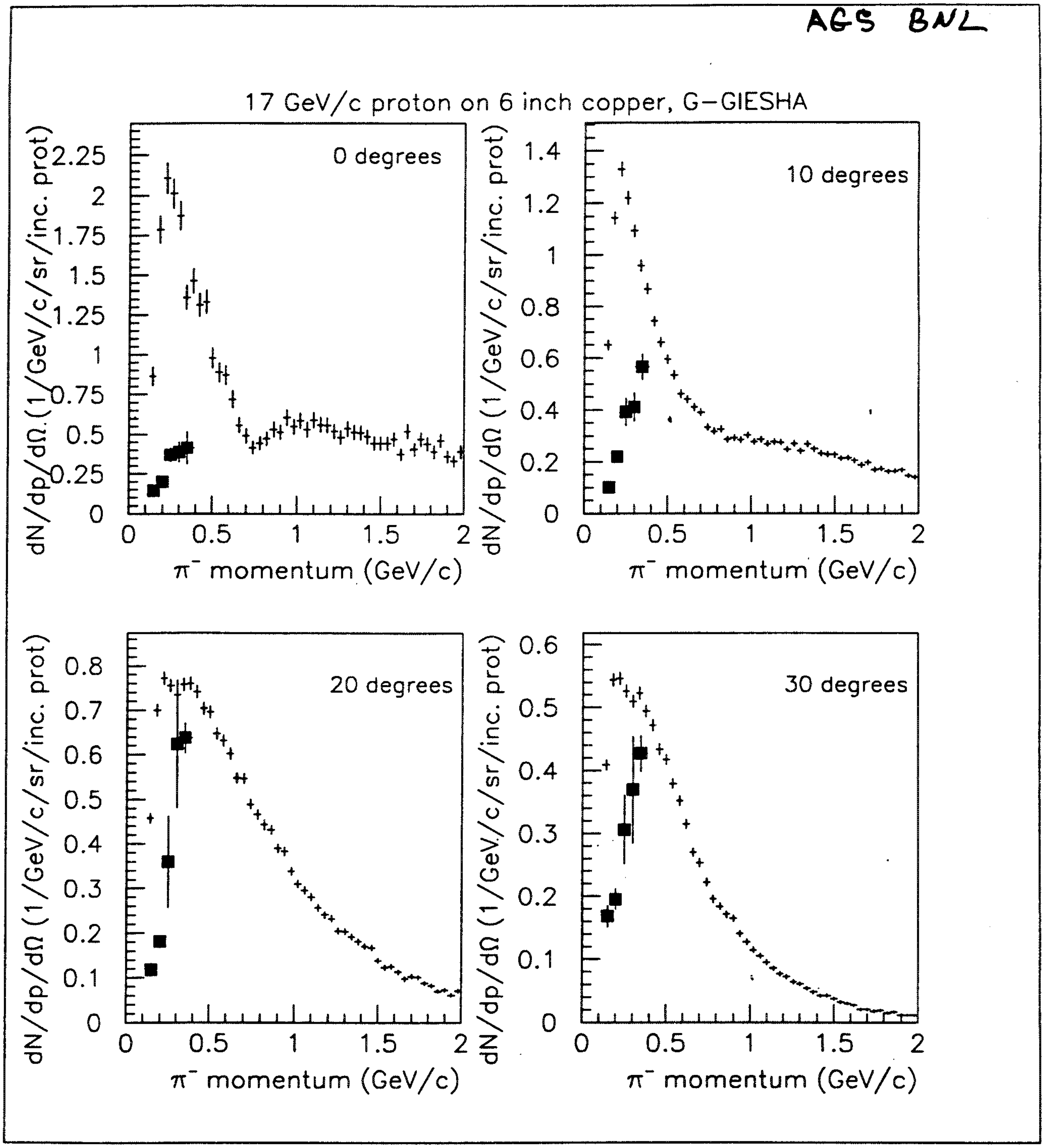
N. Mokhov
Fermilab

- MARS13(97) pion production model development and verification
- Pion yield and power dissipation *vs* target material, length, radius, beam energy and spot size and solenoid aperture
- Tilted solid and jet targets
- Conclusion



NIMROD
8 GeV/c proton on 10 cm lead, GFLUKA
dN/dp/dΩ (1/GeV/c/sr/inc. prot)
10⁻¹
0 degrees
5 degrees
π⁻ momentum (GeV/c)
π⁺ momentum (GeV/c)
0
1
2
3
4
5

GHEISHA


AGS BNL
17 GeV/c proton on 6 inch copper, G-GIESHA
0 degrees
10 degrees
20 degrees
30 degrees
dN/dp/dΩ (1/GeV/c/sr/inc. prot)
π⁻ momentum (GeV/c)

Phenomenological model for low energy pion production

$$\frac{d^2\sigma^{pA\to\pi^\pm X}}{dpd\Omega} = R^{pA\to\pi^\pm X}(A, E_0, p, p_\perp)\frac{d^2\sigma^{pp\to\pi^\pm X}}{dpd\Omega},$$

where E_0 – proton energy, p and $p_\perp$ – total and transverse momentum of $\pi^\pm$.

It is known from experiment that $R^{pA\to\pi^\pm X}$

- almost independent on $p_\perp$
- it's dependence on E_0 and p is much weaker than for differential cross-section

Atomic mass dependence of differential cross section is convenient to describe as A^α. The power α almost independent on secondary particle type. Most measurements are consistent with a common dependence on x_F.

For proton with energy ≥ 70 GeV

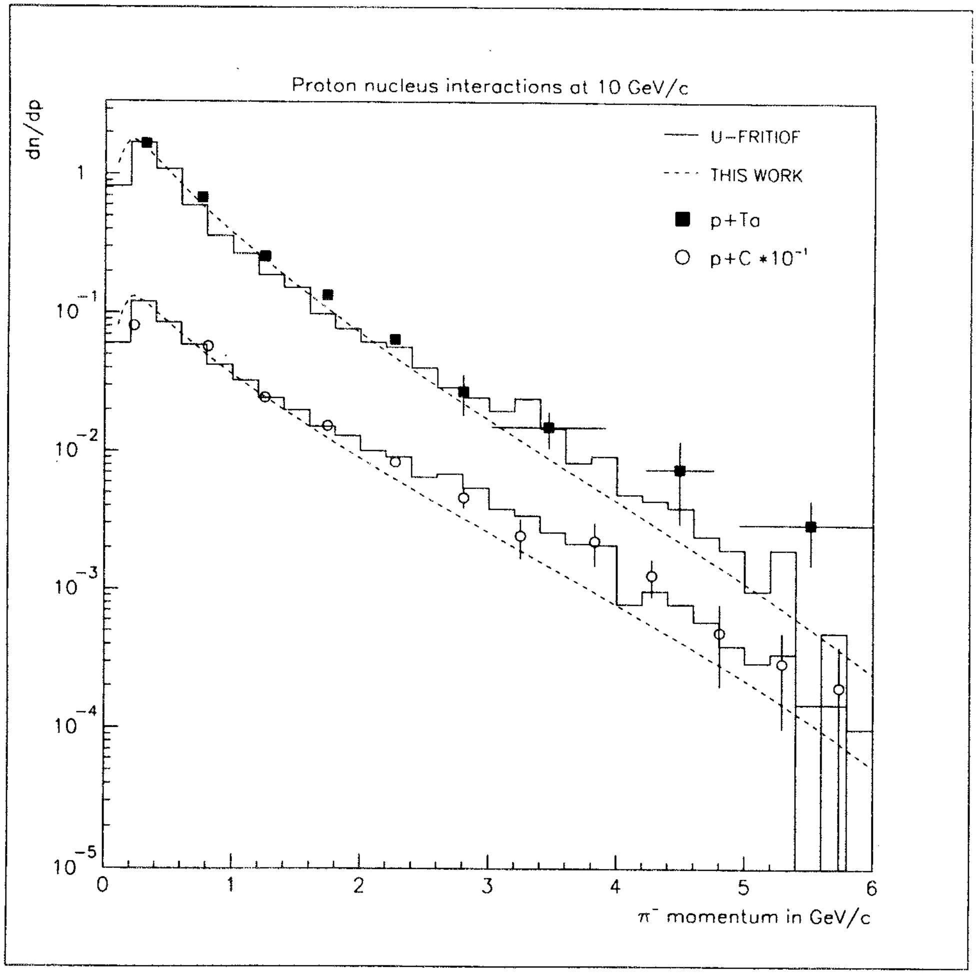
$$\alpha = 0.8 - 0.75 * x_F + .45 * x_F^3/|x_F| + 0.1 * p_\perp^2$$

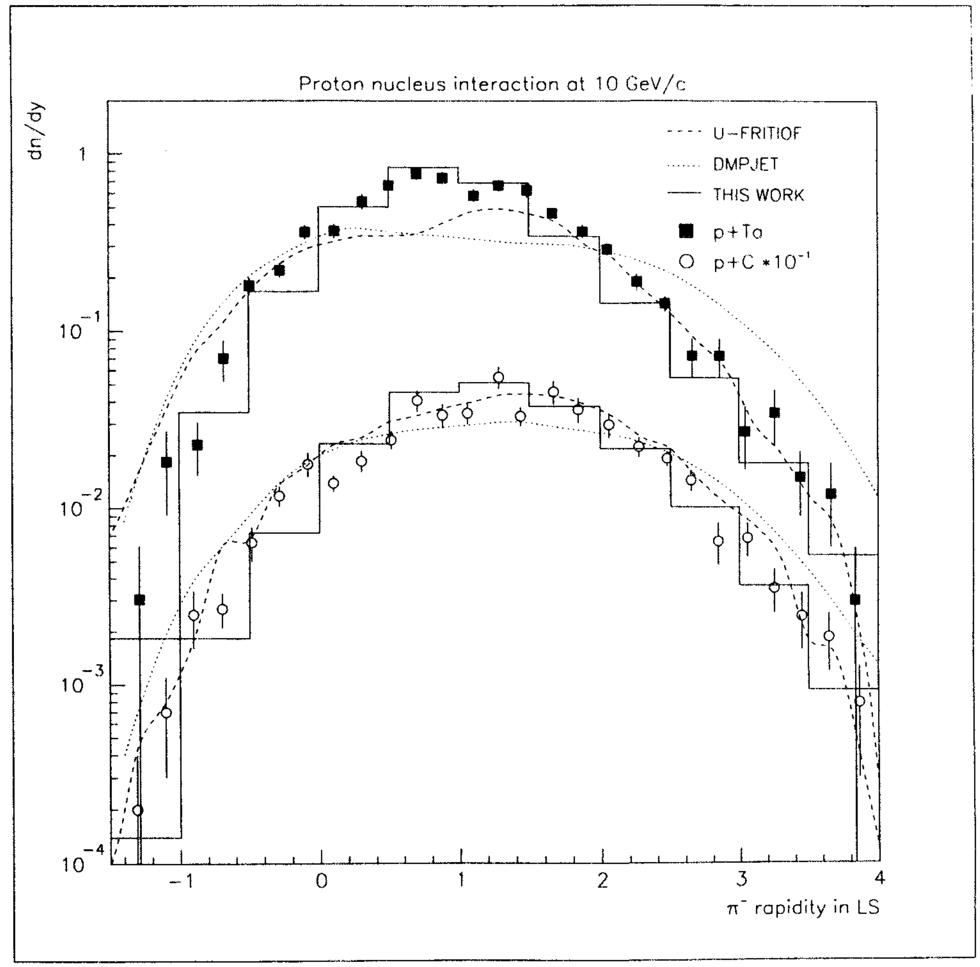
Does α depend on proton energy?

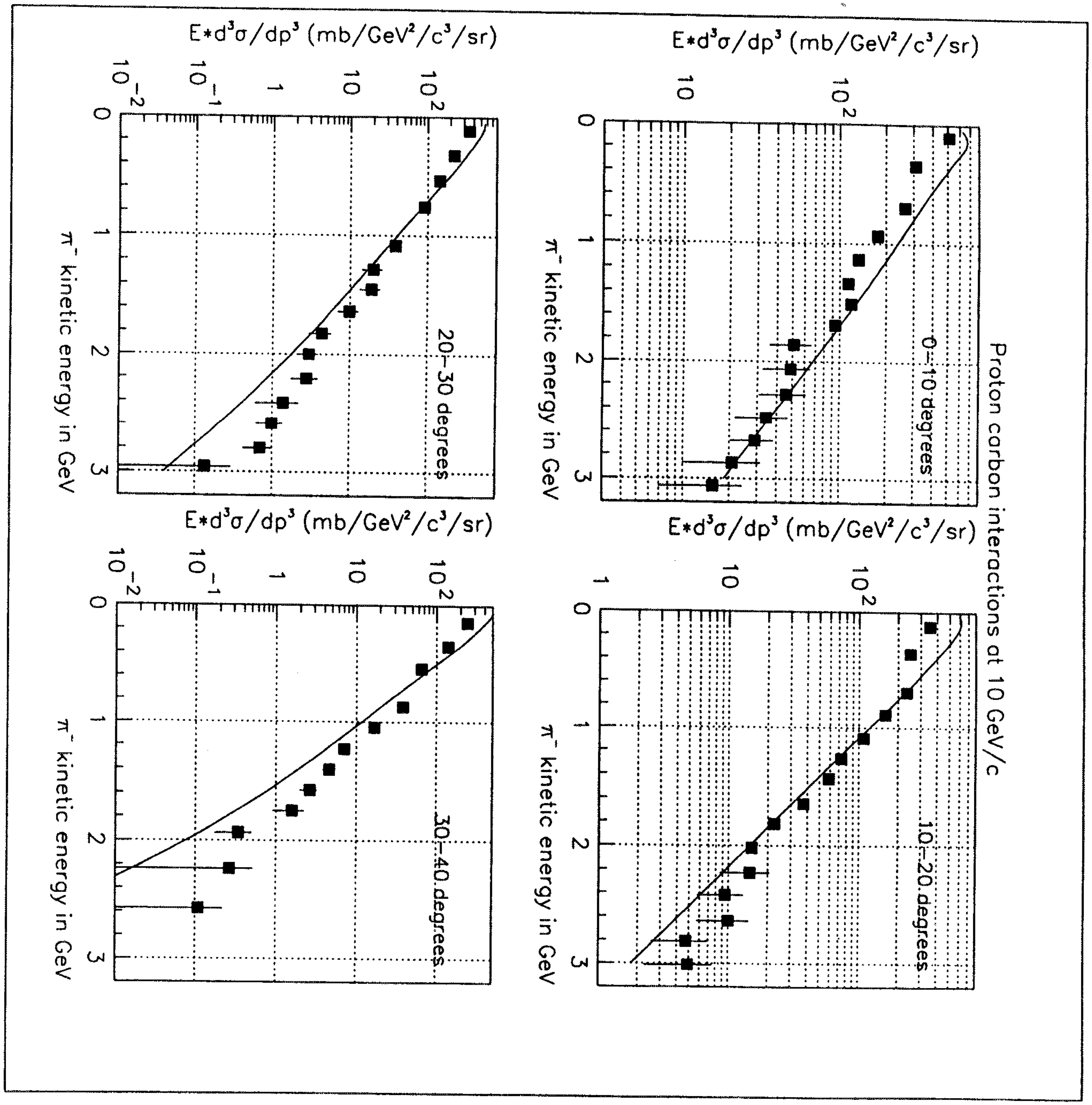
Extrapolation of differential cross sections using the power law A^α usually does not match measurements done with hydrogen targets, mainly due to difference in yields in proton proton and proton neutron interactions. To take this difference into account we can write

$$R^{pA\to\pi^\pm X} = (\frac{A}{2})^\alpha \frac{d\sigma}{dp}(pd \to \pi^\pm)/\frac{d\sigma}{dp}(pp \to \pi^\pm)$$

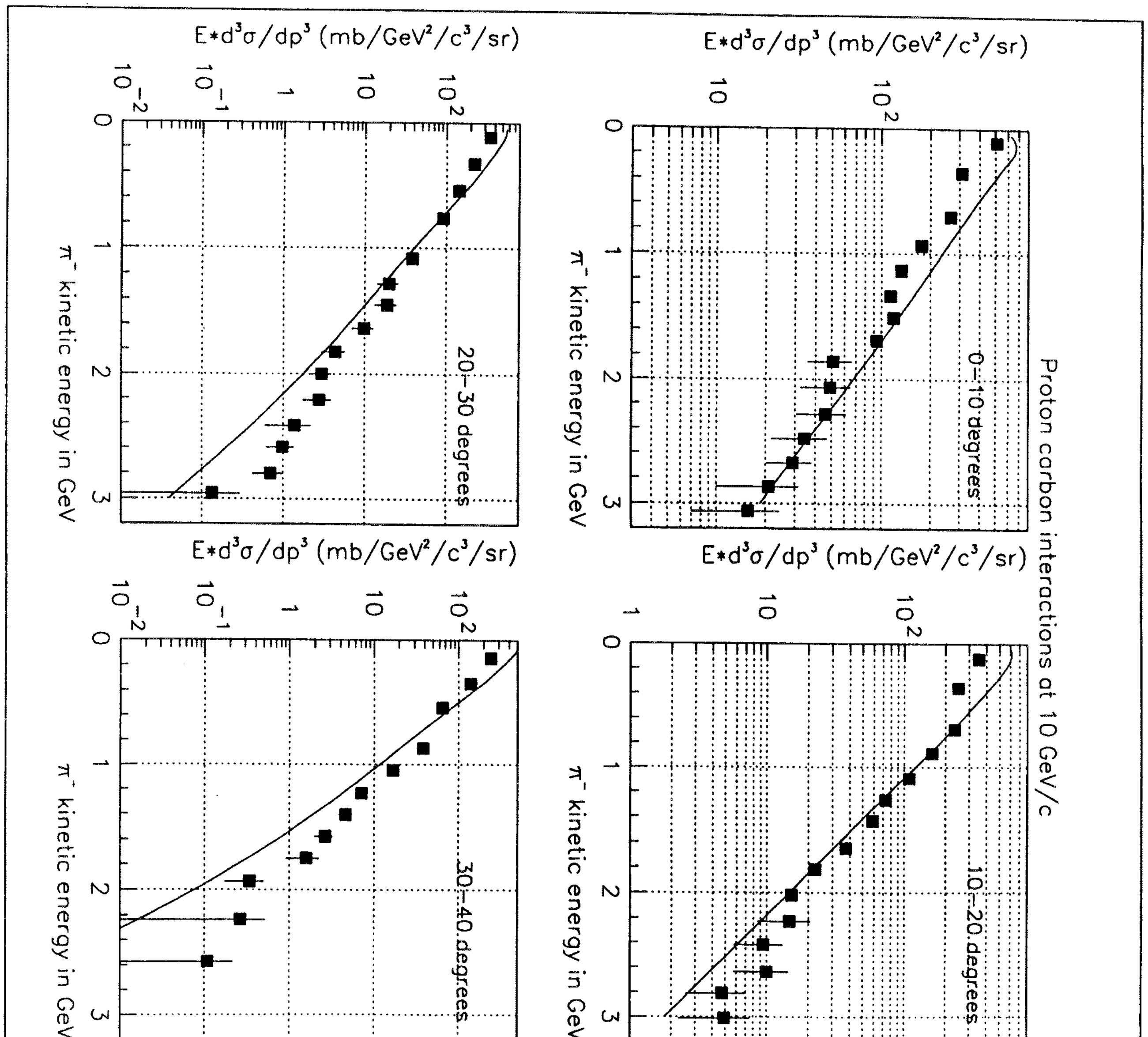
Ratio of yields from deuteron and proton is ~ 1. For its estimation we use approximation of FRITIOF results.


Proton nucleus interactions at 10 GeV/c
dn/dp
U-FRITIOF
THIS WORK
p+Ta
p+C *10⁻¹
π⁻ momentum in GeV/c

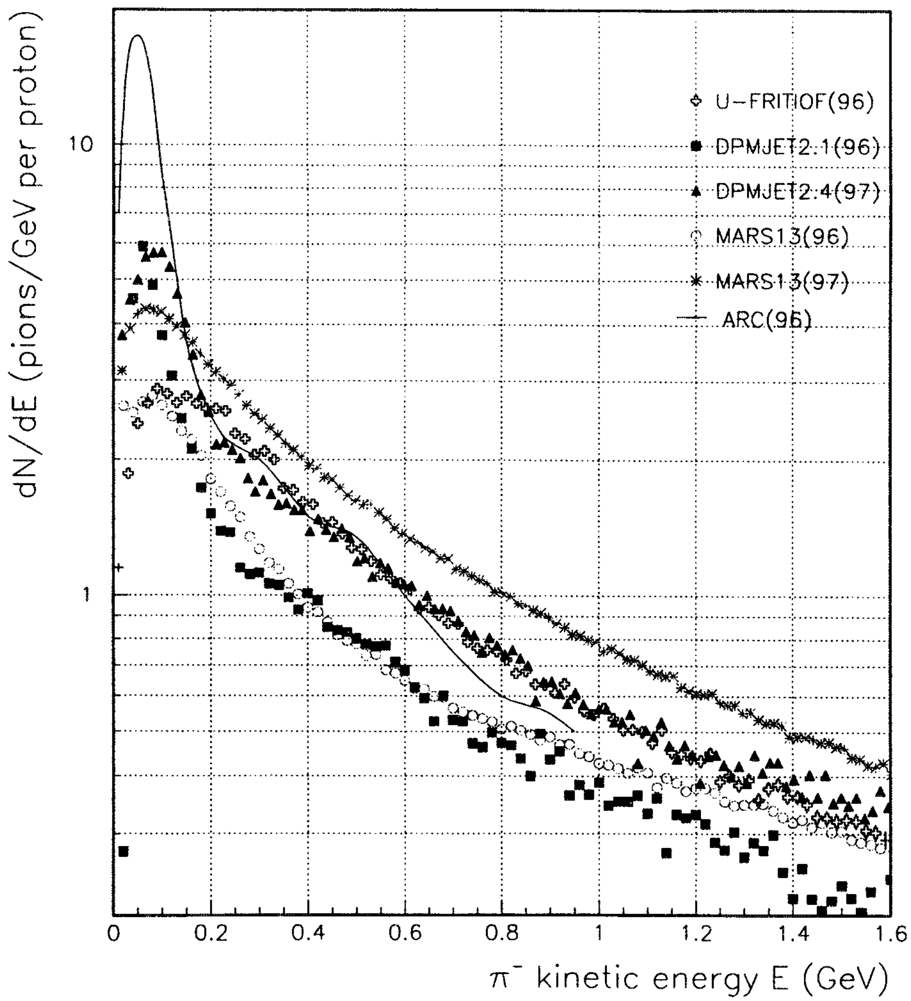

Proton nucleus interaction at 10 GeV/c
dn/dy
U-FRITIOF
DMPJET
THIS WORK
p+Ta
p+C *10⁻¹
π⁻ rapidity in LS



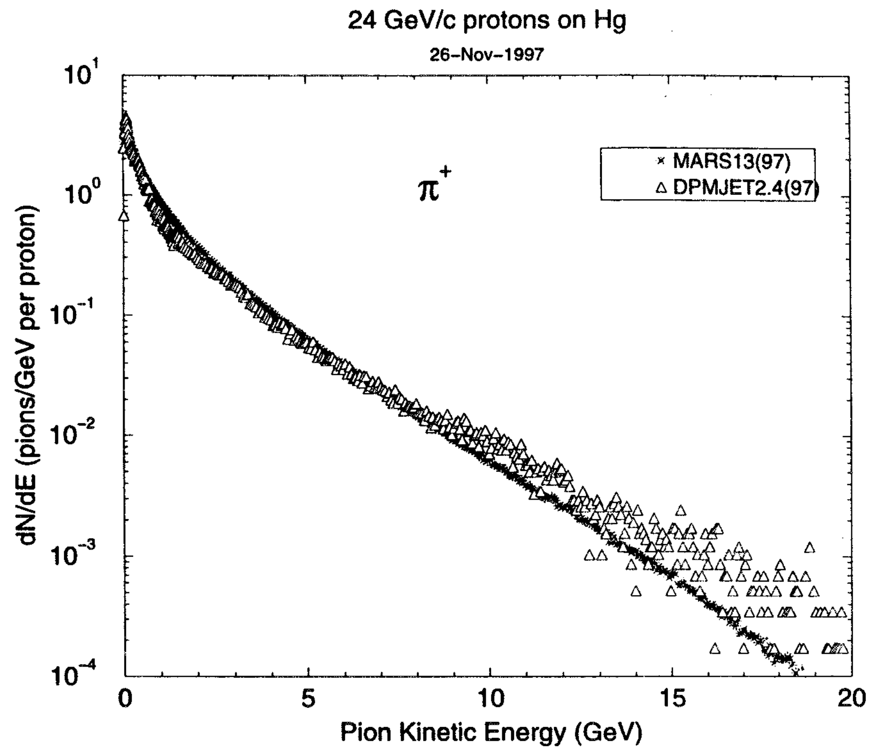
Proton carbon interactions at 10 GeV/c
0–10 degrees
10–20 degrees
20–30 degrees
30–40 degrees
E*d³σ/dp³ (mb/GeV²/c³/sr)
π⁻ kinetic energy in GeV

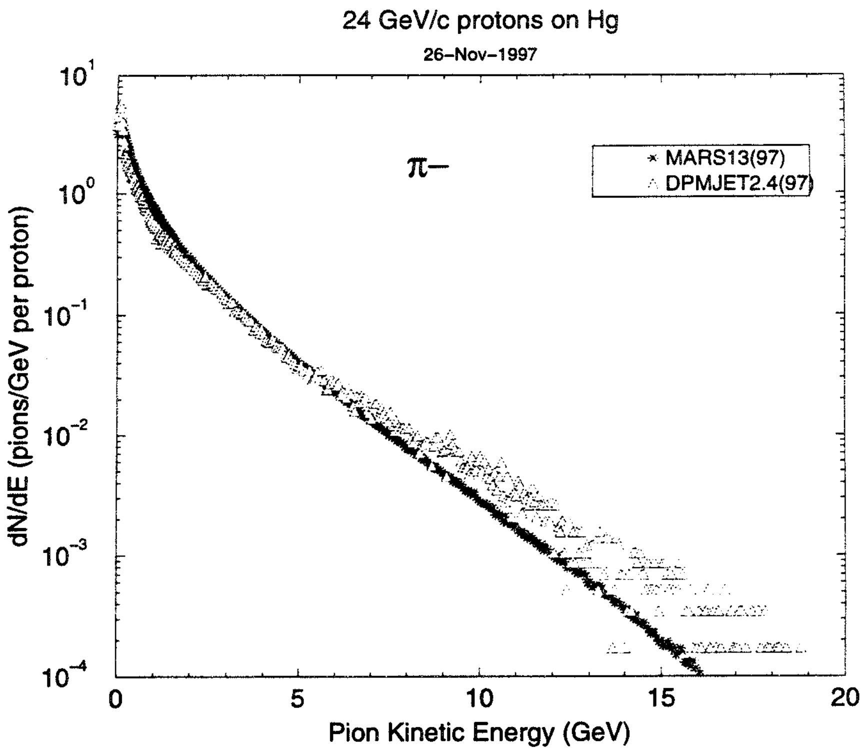


Proton carbon interactions at 10 GeV/c
0–10 degrees
10–20 degrees
20–30 degrees
30–40 degrees
$E*d^3\sigma/dp^3$ (mb/GeV^2/c^3/sr)
π^- kinetic energy in GeV



24 GeV/c protons on Hg

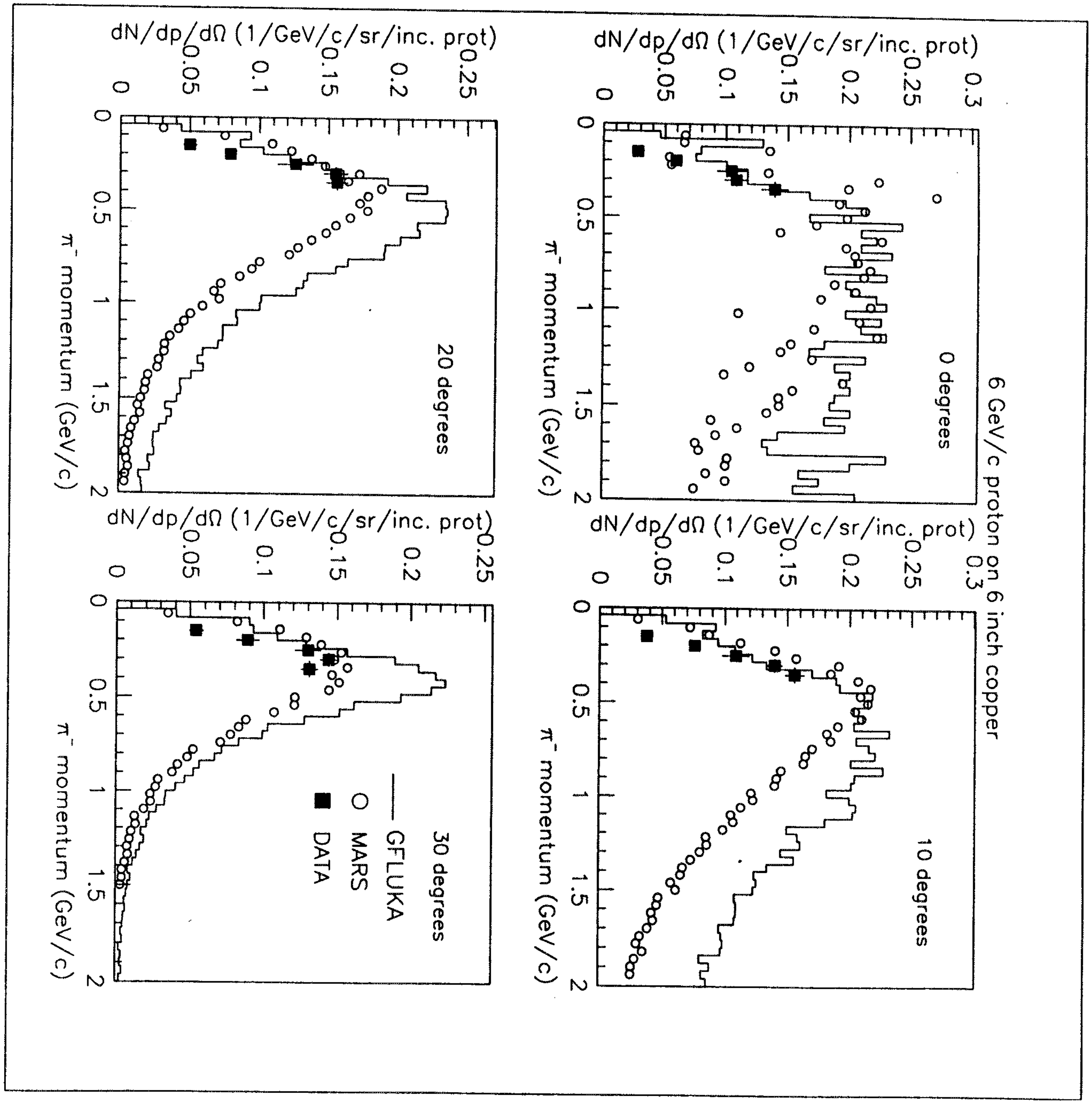


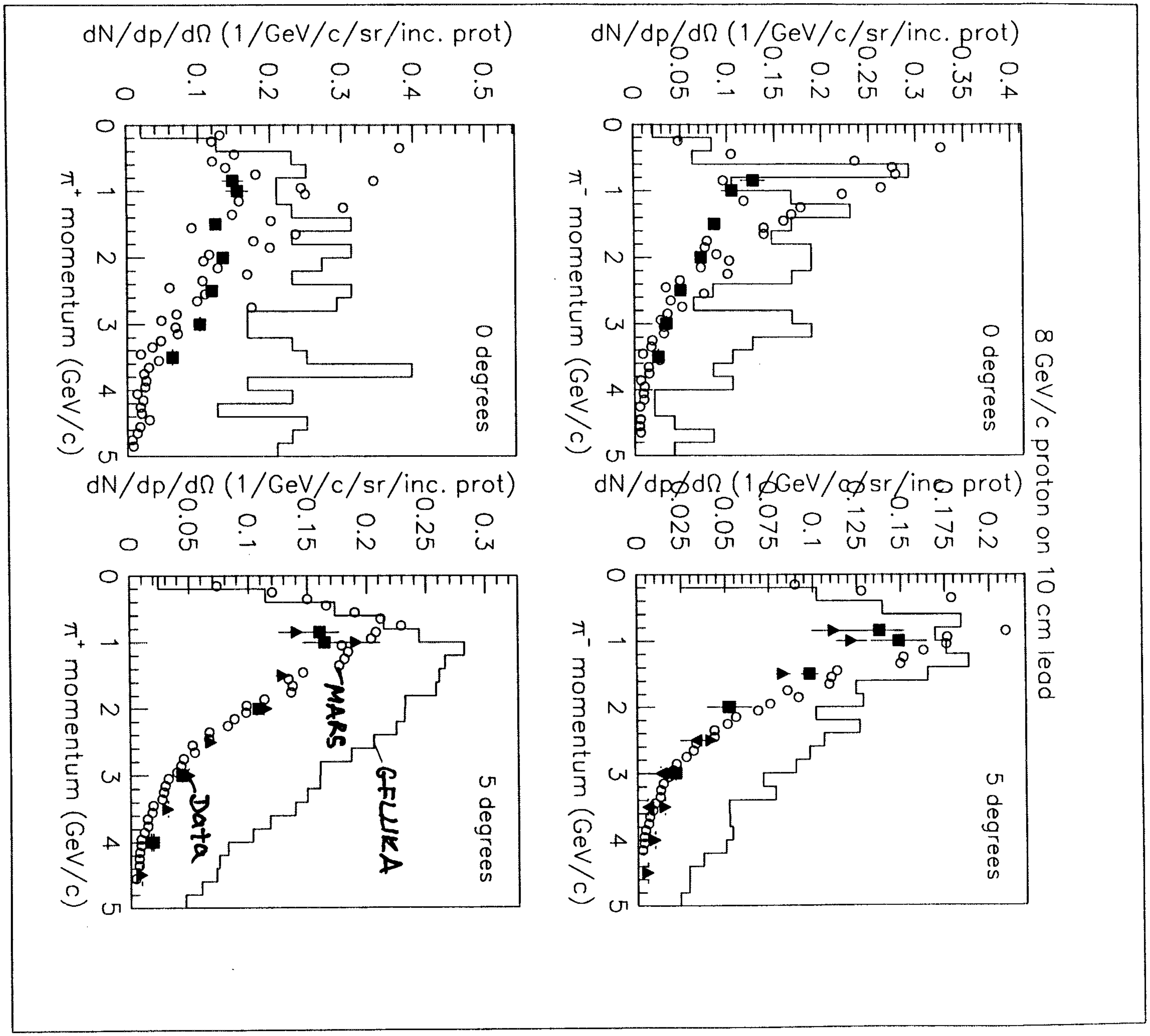


CODE EVALUATION

Low-energy hadron spectra at p_0=6-30 GeV/c:

- GHEISHA and CALOR options in GEANT are not recommended.
- G-FLUKA, DPMJET2.4(97) and FRITIOF (>10 GeV, version by Uzhinsky, Dubna, 1996) are in a reasonable agreement with data, can be used with care.
- The latest version of MARS13(97) with new phenomenological model for pions gives best overall description.
- Work is in progress on further refinement for other particles.


6 GeV/c proton on 6 inch copper
0 degrees
10 degrees
20 degrees
30 degrees
dN/dp/dΩ (1/GeV/c/sr/inc. prot)
π⁻ momentum (GeV/c)
GFLUKA
MARS
DATA


8 GeV/c proton on 10 cm lead
0 degrees
5 degrees
dN/dp/dΩ (1/GeV/c/sr/inc. prot)
π⁻ momentum (GeV/c)
π⁺ momentum (GeV/c)
MARS
GFLUKA
Data

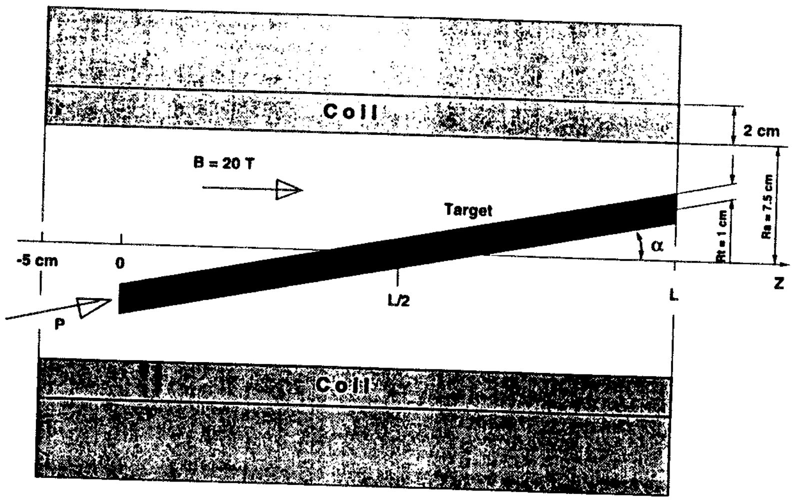


Figure 1: Tilted target in 20-T solenoid

Dec. 97
NVM

MARS13(97) Target Studies

Proton beam: 8, 16, 24 and 30 GeV
RMS beam spot size $0.4 \le \sigma_{x,y} \le 1$ cm

20 T solenoid: Aperture radius R_a = 7.5 and 15 cm
Length -5cm to L

Target:

Material:

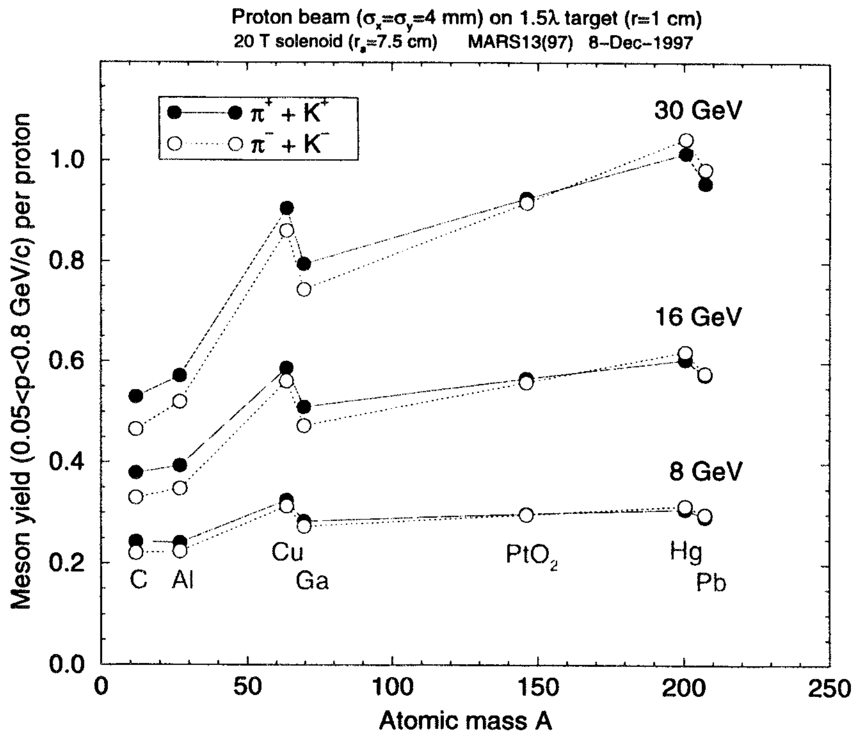
	C	Al	Cu	Ga	PtO_2	Hg	Pb
A	12.01	26.98	63.55	69.72	146.01	200.59	207.19
ρ (g/cc)	2.26	2.7	8.96	6.0	10.2	13.55	11.35
λ (cm) at 16 GeV	39.9	41.1	15.8	24.2	17.9	14.9	17.9

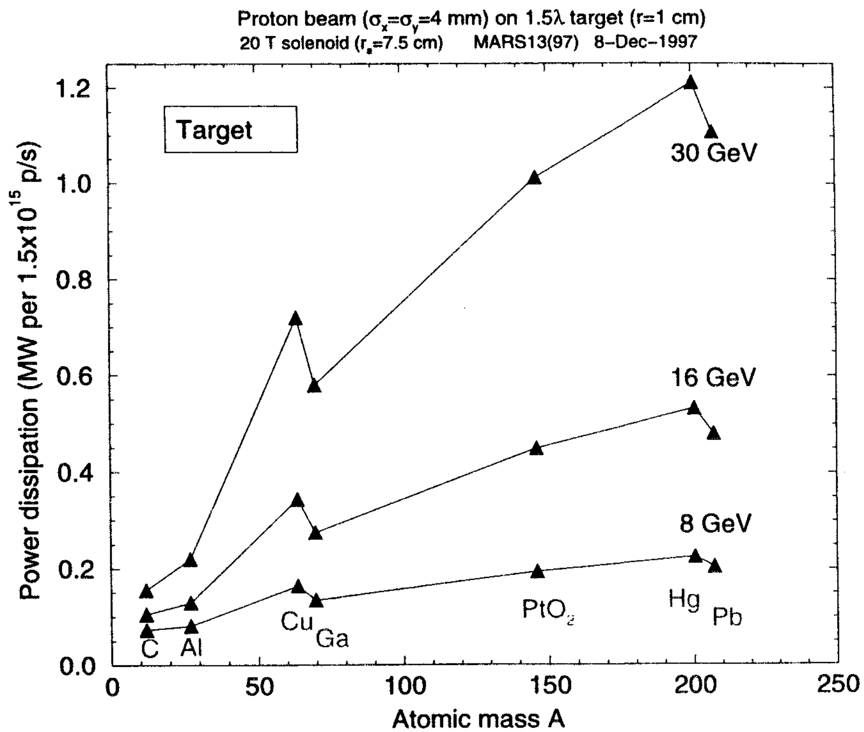
Length L: 0.5, 1, 1.5, 2, 2.5, 3 λ

-dius: $R = 2.5\sigma_{x,y}$ (1 and 3 cm)

-t tilt angle w.r.t. L/2:
-, 25, 50, 75, 100, 150, 200, 300, 400 mrad

-K yield
-r dissipation in target and Solenoid

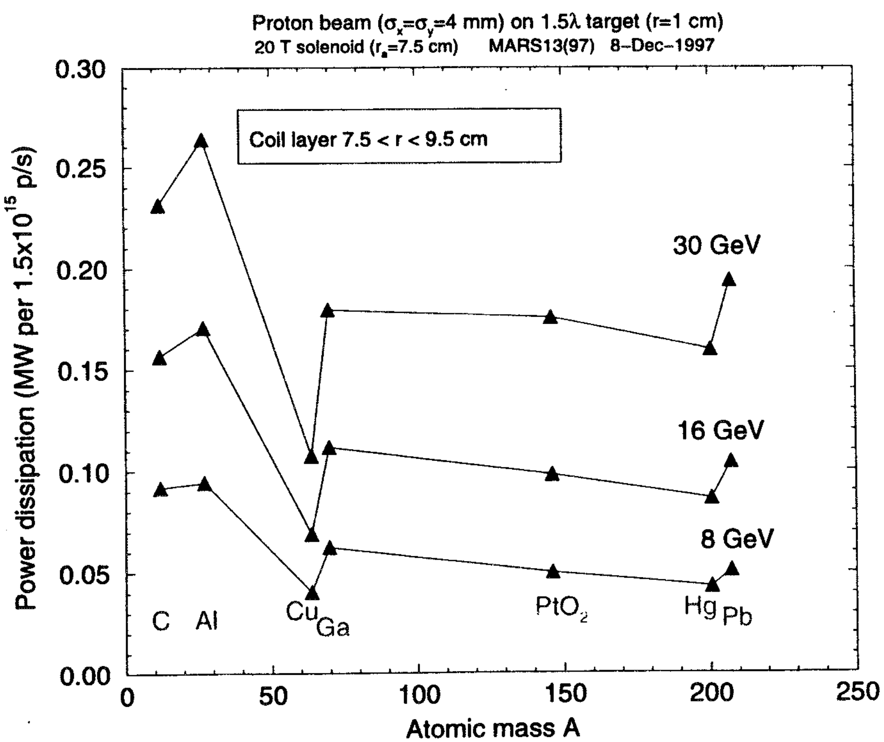

Proton beam (σ_x=σ_y=4 mm) on 1.5λ target (r=1 cm)
20 T solenoid (r_s=7.5 cm) MARS13(97) 8-Dec-1997
$\pi^+ + K^+$
$\pi^- + K^-$
30 GeV
16 GeV
8 GeV
C
Al
Cu
Ga
PtO_2
Hg
Pb
Meson yield (0.05<p<0.8 GeV/c) per proton
Atomic mass A

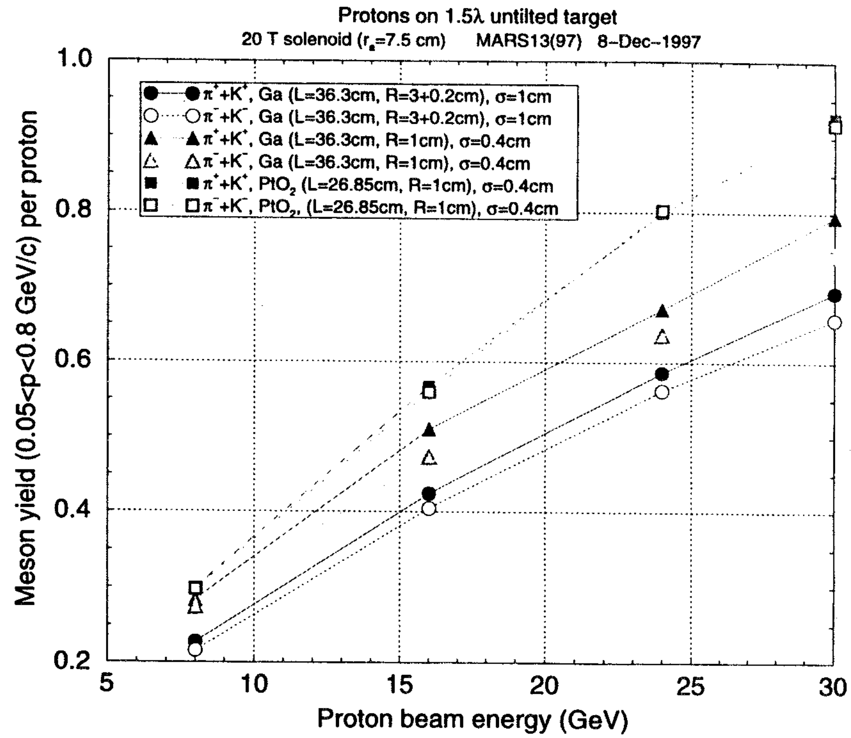

Proton beam (σ_x=σ_y=4 mm) on 1.5λ target (r=1 cm)
20 T solenoid (r_s=7.5 cm) MARS13(97) 8-Dec-1997
Target
30 GeV
16 GeV
8 GeV
C
Al
Cu
Ga
PtO_2
Hg
Pb
Power dissipation (MW per 1.5×10^{15} p/s)
Atomic mass A

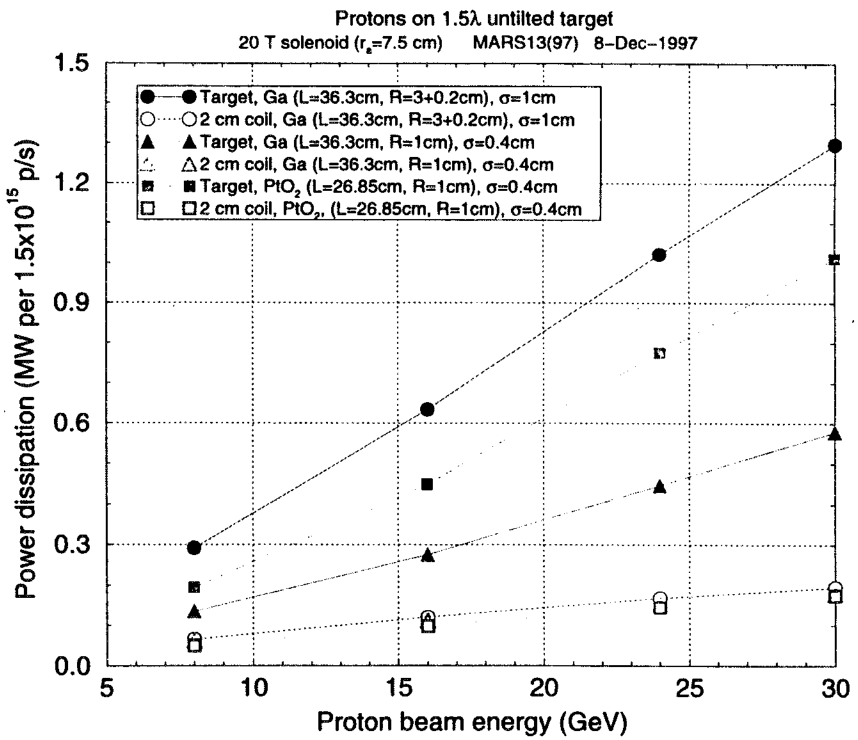
16 GeV on Ga, L = 60 cm, R = 3 cm, R_a = 7.5 cm

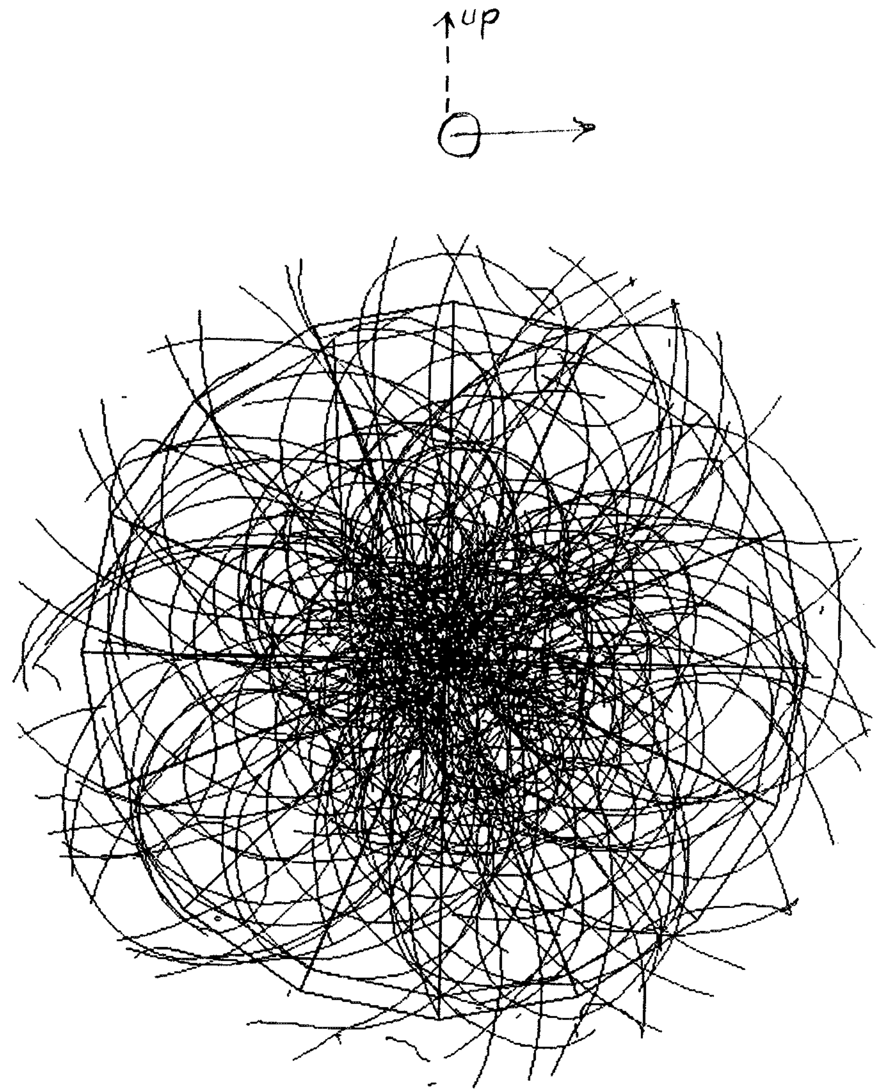
In solenoid:

$$\frac{P(7.5 < r < 35 cm)}{P(7.5 < r < 9.5 cm)} = \frac{0.70 MW}{0.28 MW} = 2.5$$

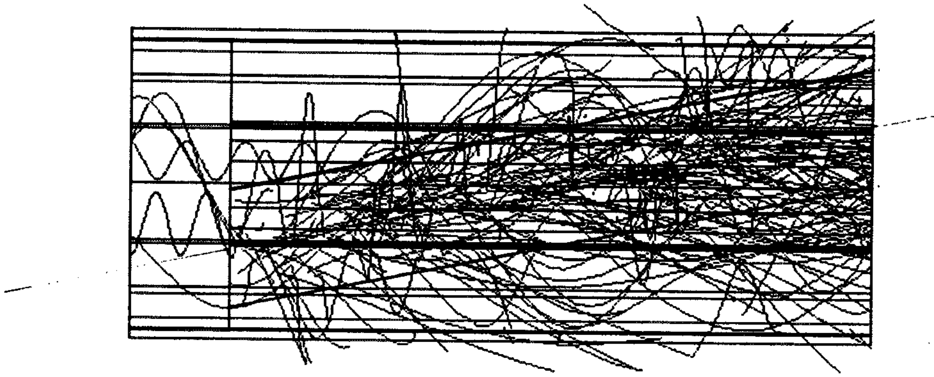








$0 < z < 33 cm, \alpha = 0$

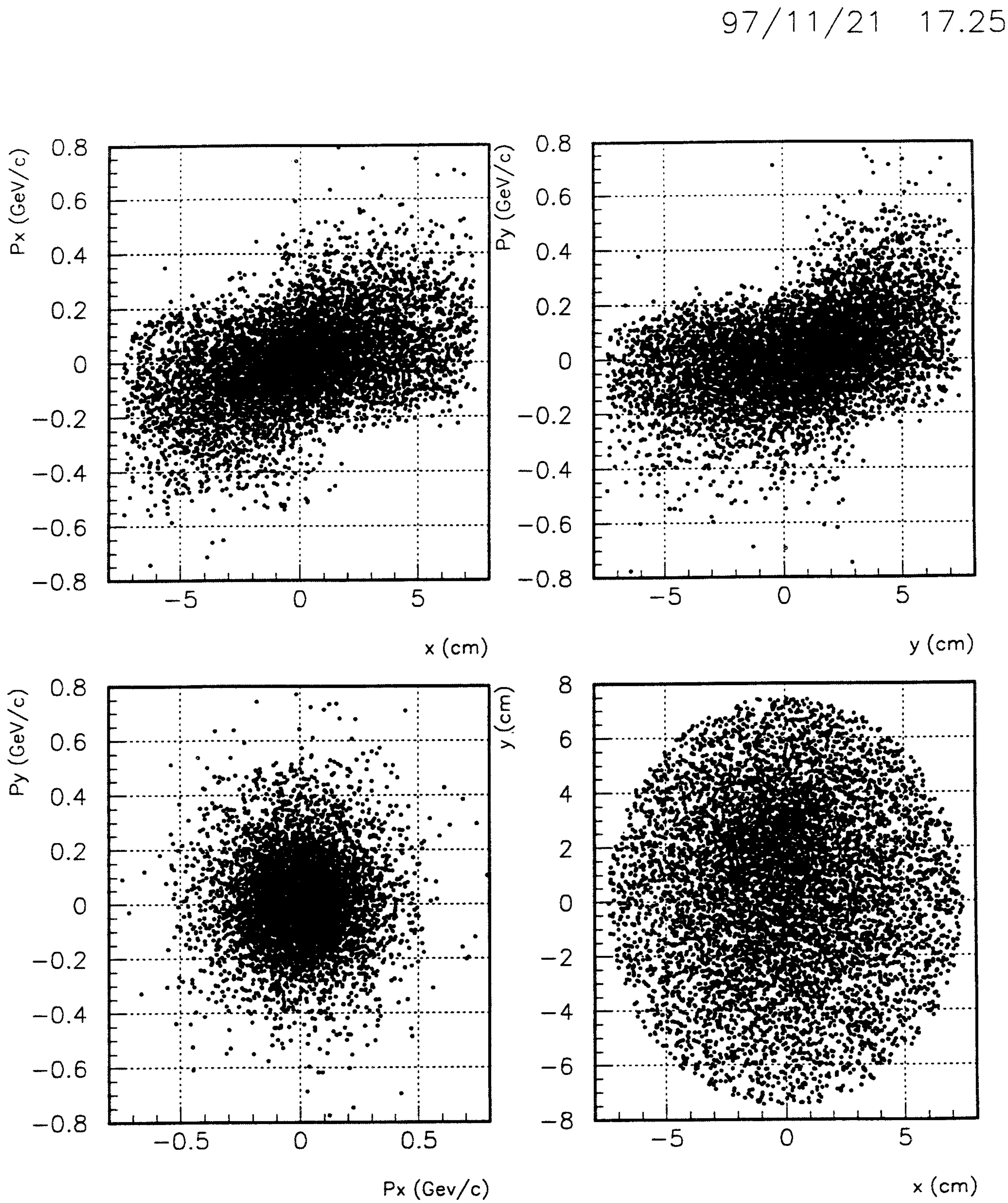


16 GeV on Ga, $L = 33$ cm, $R = 3$ cm $+ 0.2$ cm Fe
$\sigma_x = \sigma_y = 1$ cm

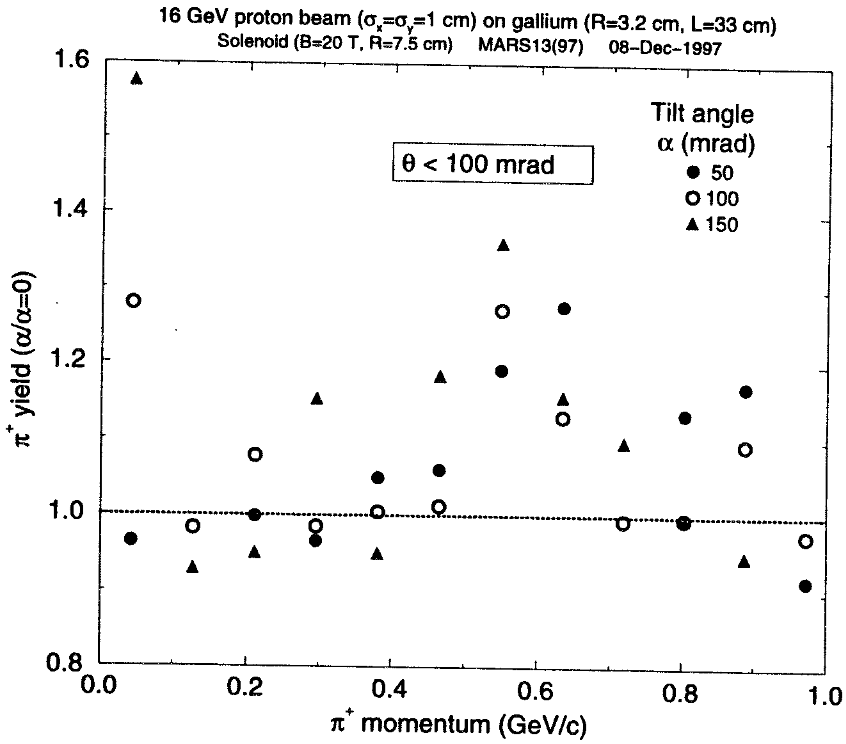
N_c – a number of secondary target intersections by pions with $0.05 < p < 0.8$ GeV/c

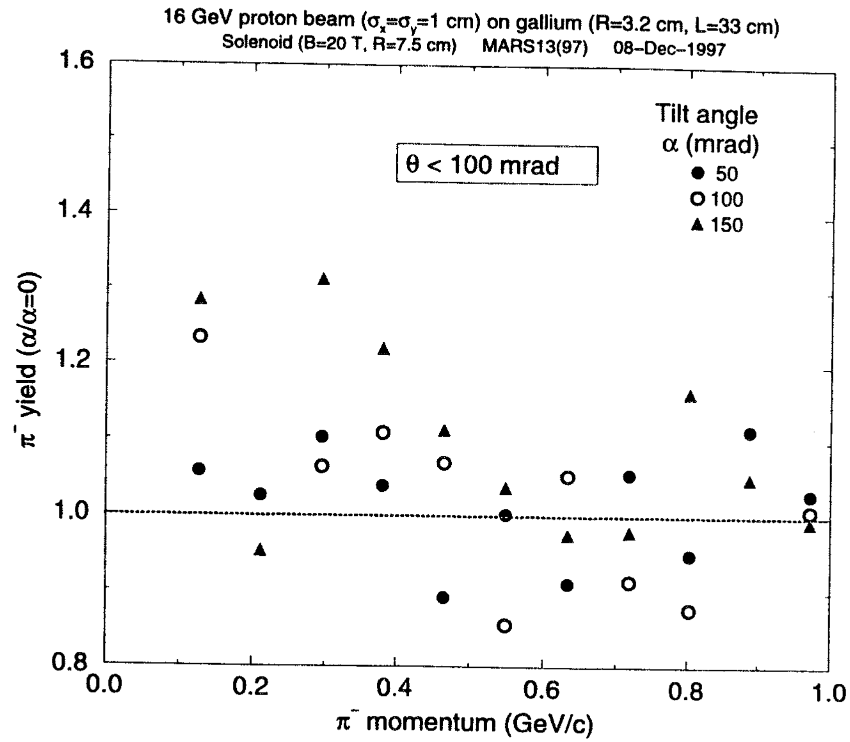
Y – total yield at $\theta < \frac{\pi}{2}$

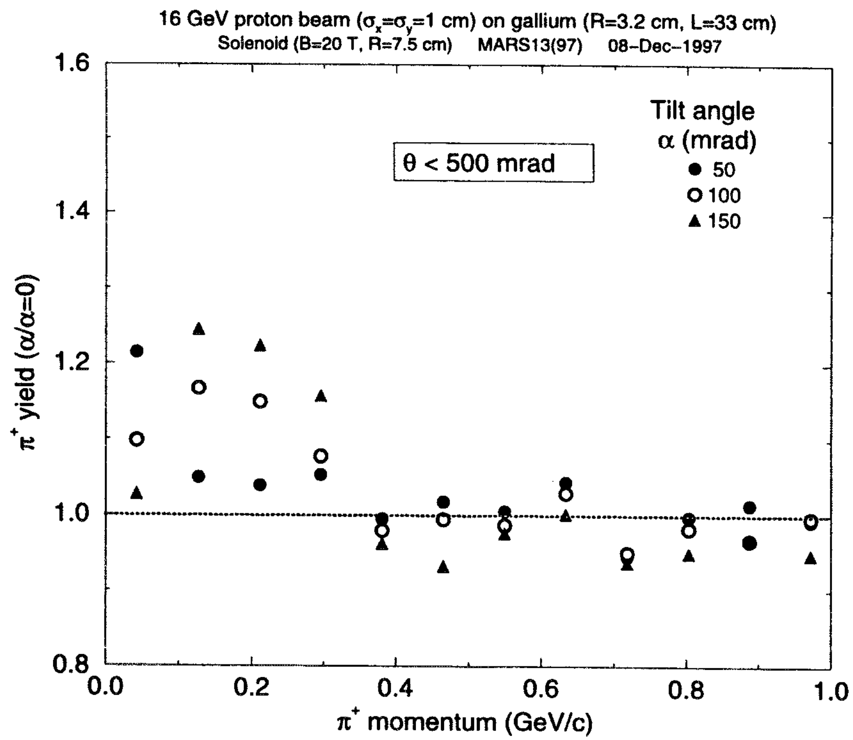
Solenoid aperture R_a		MARS	MARS a'la ARC
7.5cm	$N_c^{\pi^+}$	0.8	2.2
	$N_c^{\pi^-}$	1	2.8
	Y^{π^+}	1.40	1.7
	Y^{π^-}	1.17	1.5
15cm	$N_c^{\pi^+}$	1.2	2.6
	$N_c^{\pi^-}$	1.5	3.3
	Y^{π^+}	1.8	2.1
	Y^{π^-}	1.6	1.9

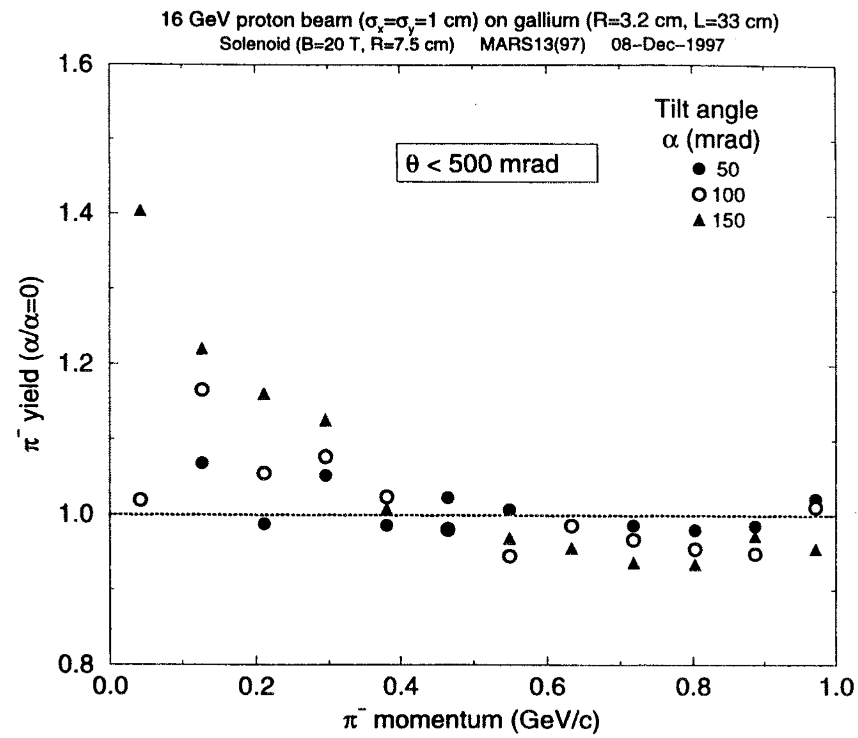


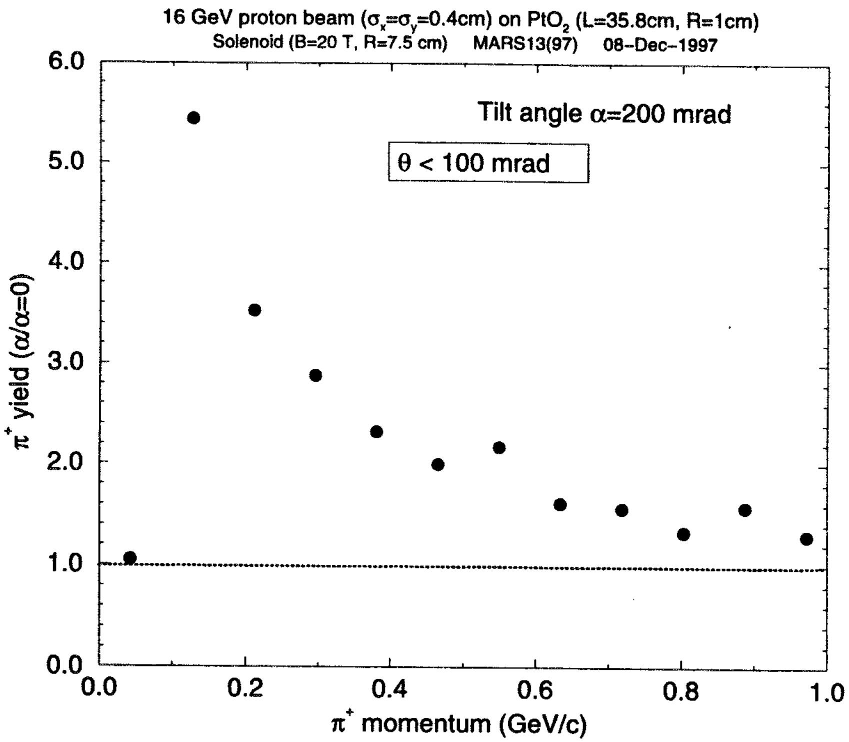
16 GeV protons on 33cm GA tilted target at the exit of a 20T solenoid

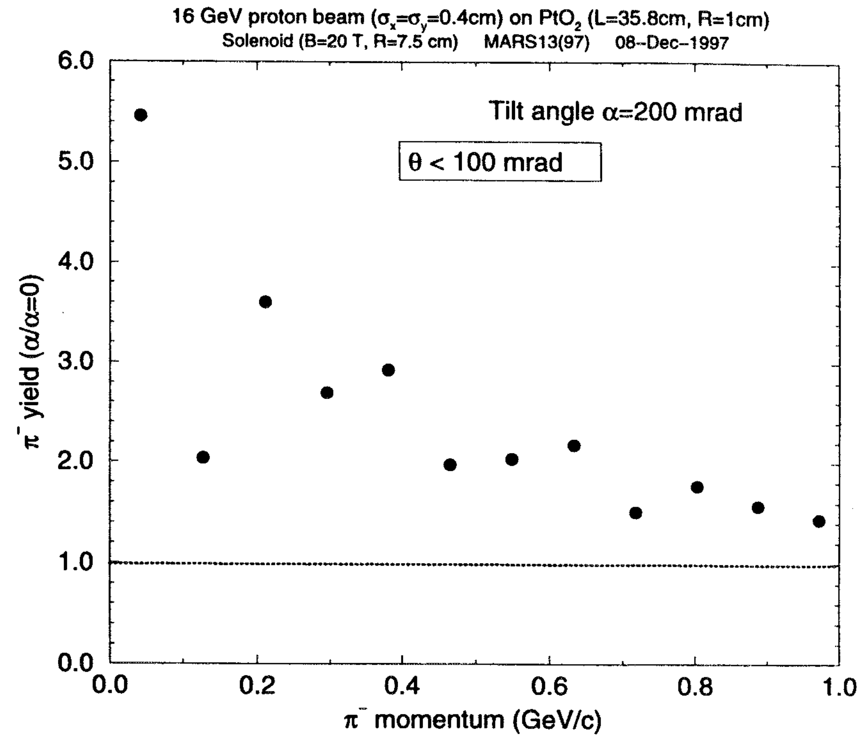

16 GeV proton beam (σ_x=σ_y=1 cm) on gallium (R=3.2 cm, L=33 cm)
Solenoid (B=20 T, R=7.5 cm) MARS13(97) 08-Dec-1997
θ < 100 mrad
Tilt angle
α (mrad)
50
100
150
π^+ yield (α/α=0)
π^+ momentum (GeV/c)
0.0
0.2
0.4
0.6
0.8
1.0
0.8
1.0
1.2
1.4
1.6

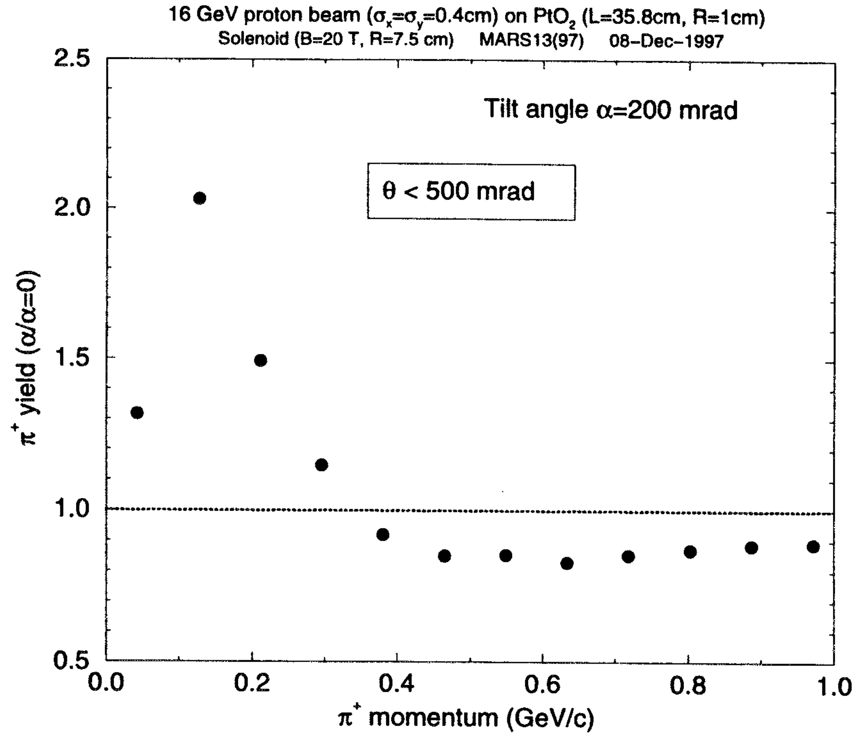

16 GeV proton beam (σ_x=σ_y=1 cm) on gallium (R=3.2 cm, L=33 cm)
Solenoid (B=20 T, R=7.5 cm) MARS13(97) 08-Dec-1997
θ < 100 mrad
Tilt angle
α (mrad)
50
100
150
π^- yield (α/α=0)
π^- momentum (GeV/c)
0.0
0.2
0.4
0.6
0.8
1.0
0.8
1.0
1.2
1.4
1.6

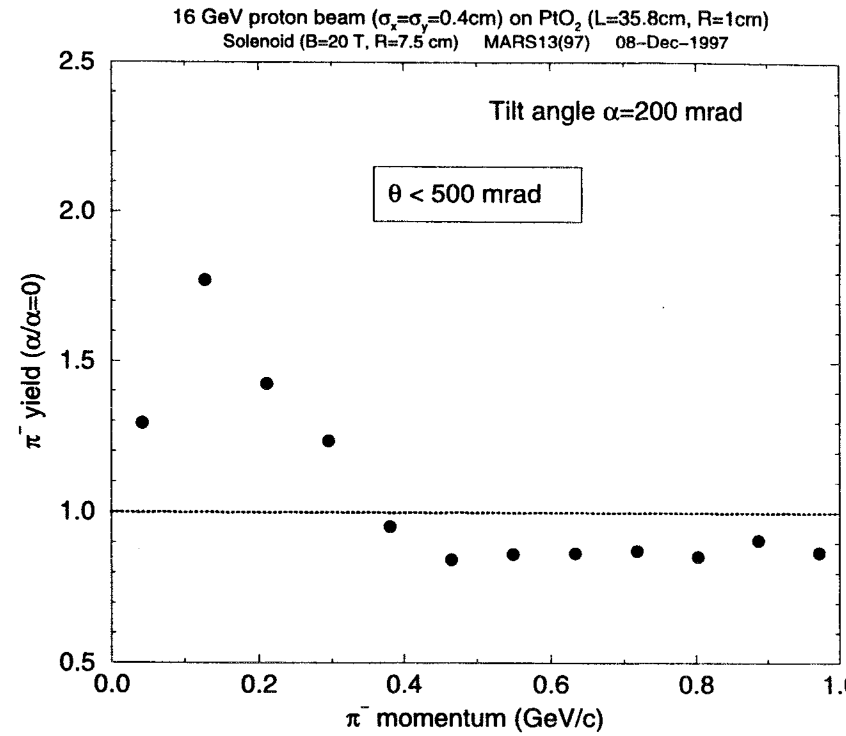

16 GeV proton beam (σ_x=σ_y=1 cm) on gallium (R=3.2 cm, L=33 cm)
Solenoid (B=20 T, R=7.5 cm) MARS13(97) 08-Dec-1997
θ < 500 mrad
Tilt angle
α (mrad)
50
100
150
π^+ yield (α/α=0)
π^+ momentum (GeV/c)
1.6
1.4
1.2
1.0
0.8
0.0
0.2
0.4
0.6
0.8
1.0

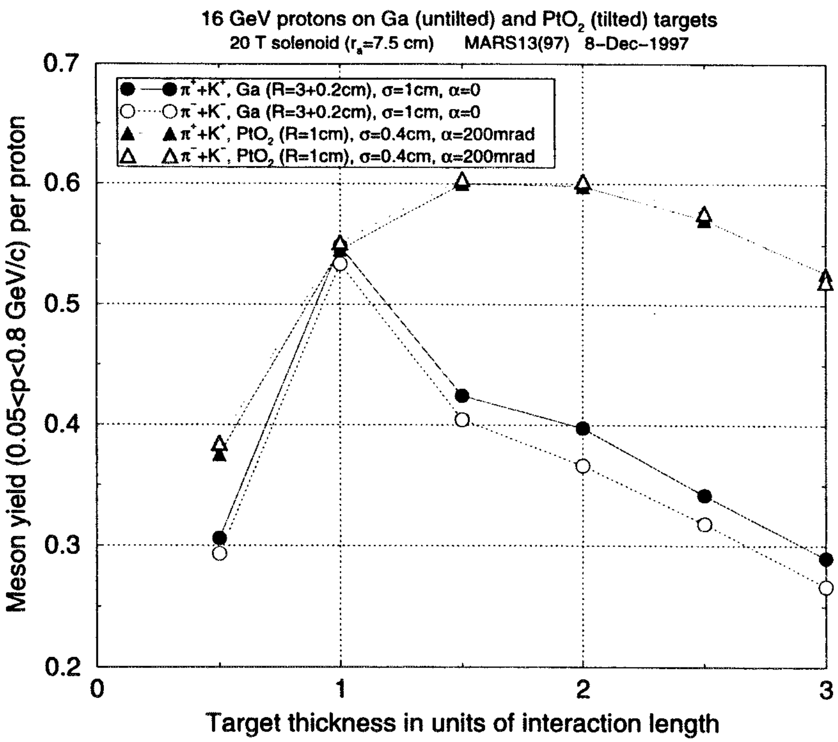

16 GeV proton beam (σ_x=σ_y=1 cm) on gallium (R=3.2 cm, L=33 cm)
Solenoid (B=20 T, R=7.5 cm) MARS13(97) 08-Dec-1997
θ < 500 mrad
Tilt angle
α (mrad)
50
100
150
π^- yield (α/α=0)
π^- momentum (GeV/c)
1.6
1.4
1.2
1.0
0.8
0.0
0.2
0.4
0.6
0.8
1.0

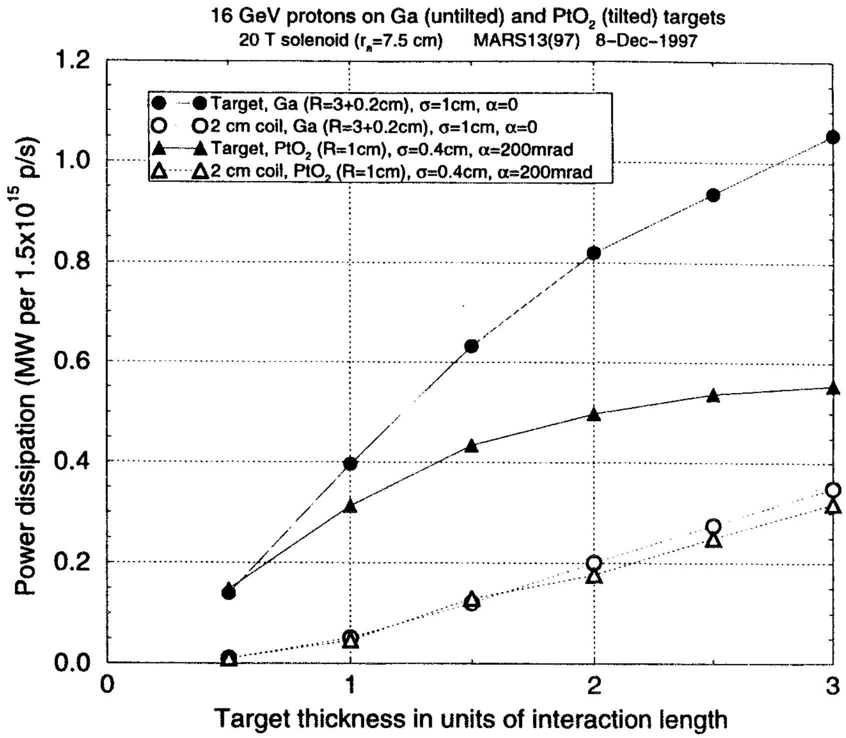

16 GeV proton beam (σx=σy=0.4cm) on PtO2 (L=35.8cm, R=1cm)
Solenoid (B=20 T, R=7.5 cm) MARS13(97) 08-Dec-1997
Tilt angle α=200 mrad
θ < 100 mrad
π+ yield (α/α=0)
π+ momentum (GeV/c)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
0.2
0.4
0.6
0.8


16 GeV proton beam (σx=σy=0.4cm) on PtO2 (L=35.8cm, R=1cm)
Solenoid (B=20 T, R=7.5 cm) MARS13(97) 08-Dec-1997
Tilt angle α=200 mrad
θ < 100 mrad
π- yield (α/α=0)
π- momentum (GeV/c)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
0.2
0.4
0.6
0.8


16 GeV proton beam (σx=σy=0.4cm) on PtO2 (L=35.8cm, R=1cm)
Solenoid (B=20 T, R=7.5 cm) MARS13(97) 08-Dec-1997
Tilt angle α=200 mrad
θ < 500 mrad
π+ yield (α/α=0)
π+ momentum (GeV/c)


16 GeV proton beam (σx=σy=0.4cm) on PtO2 (L=35.8cm, R=1cm)
Solenoid (B=20 T, R=7.5 cm) MARS13(97) 08-Dec-1997
Tilt angle α=200 mrad
θ < 500 mrad
π- yield (α/α=0)
π- momentum (GeV/c)


16 GeV protons on Ga (untilted) and PtO2 (tilted) targets
20 T solenoid (ra=7.5 cm) MARS13(97) 8-Dec-1997
π+ +K+, Ga (R=3+0.2cm), σ=1cm, α=0
π- +K-, Ga (R=3+0.2cm), σ=1cm, α=0
π+ +K+, PtO2 (R=1cm), σ=0.4cm, α=200mrad
π- +K-, PtO2 (R=1cm), σ=0.4cm, α=200mrad
Meson yield (0.05<p<0.8 GeV/c) per proton
Target thickness in units of interaction length


16 GeV protons on Ga (untilted) and PtO2 (tilted) targets
20 T solenoid (ra=7.5 cm) MARS13(97) 8-Dec-1997
Target, Ga (R=3+0.2cm), σ=1cm, α=0
2 cm coil, Ga (R=3+0.2cm), σ=1cm, α=0
Target, PtO2 (R=1cm), σ=0.4cm, α=200mrad
2 cm coil, PtO2 (R=1cm), σ=0.4cm, α=200mrad
Power dissipation (MW per 1.5x10^15 p/s)
Target thickness in units of interaction length

```
From mokhov@FNAL.GOV Mon Dec  8 12:38:59 1997
Date: Mon, 08 Dec 1997 12:38:03 -0600 (CST)
From: Nikolai Mokhov <mokhov@FNAL.GOV>
To: Bob Palmer <palmer@bnl.gov>, Juan Gallardo <jcg@fel.cap.bnl.gov>,
    Andy Van Ginneken <VANGIN@cns40.fnal.gov>,
    Robert Noble <noble@FNAL.GOV>
Cc: Nikolai Mokhov <mokhov@FNAL.GOV>
Subject: Gallium and Platinum Oxide pion files

                                                     8-Dec-1997
Colleagues,

Platinum oxide runs are completed, results look somewhat better
than for gallium targets.

Both files for liquid targets of optimal length L
(pioutl6.ga-363-1.200.75 and pioutl6.pto2-358-1.200.75) of pions out
of the current baseline target/solenoid system are
in http://www-ap.fnal.gov/mokhov/mumu/target/
This file is there too as README.LIQUID.

They are for 250000 incident protons at 16 GeV for
sigma_x=sigma_y=0.4 cm, target radius is 1 cm.
The solenoid (Bz=20 T, Ra=7.5 cm) occupies the -5 cm < z < L region,
the targets are at 0 < z < L.
The beam and the targets are tilted up by 200 mrad with respect
to the solenoid (Bz=20 T, Ra=7.5 cm) axis and its center (L/2).
Optimal (for the above parameters at 16 GeV) lenghts are

   Liquid gallium L=36.3 cm (1.5 int. length)
   Liquid PtO2    L=35.8 cm (2.0 int. length)

The pioutl6.ga-363-1.200.75 file (8.9 Mb) has 108865 pions.
The pioutl6.pto2-358-1.200.75 file (9.75 Mb) has 118884 pions.

The files for pi+ (jj=3) and pi- (jj=4) are written as

         WRITE(9,101)NI,JJ,K,W,X,Y,Z,PX,PY,PZ
 101     FORMAT(I8,2I3,E10.3,3F9.4,3F10.6)

where NI is event number, JJ is pion type, K is vertex number in
the cascade tree, W is statistical weight, X,Y,Z (cm) are pion
coordinates at the exit (Z > 36.3 cm), PX,PY,PZ are momentum components.
Note that in this studies x-axis is up and y-axis is to the right.

I'll be keeping for a while four other files: muons due to forced decays
at 0 < Z < 36.3 cm (Ga, 16.3 Mb, 198619 muons, W ~ 1.e-4 - 1.e-3,
PtO2, 20.4 Mb, 248625 muons) and other particles (p,n,K+,K-,e+,e-,gamma;
Ga, 39 Mb, 475976 particles; PtO2, 32.8 Mb, 399554 particles).

                        Cheers,
                                  Nikolai Mokhov,
                                  Fermilab, MS 220, BD/Physics
                                  P.O. Box 500, Batavia, IL 60510-0500
                                  Phone: (630) 840-4409
                                  FAX:   (630) 840-6039
                                  Email: mokhov@fnal.gov
```

12/12/97
NVM

Summary

1. Reliable π/K production model available
2. Target studies with MARS13(97) performed for a variety of beam, target and solenoid parameters at 8, 16, 24 and 30 GeV
   - π/K yield
   - power dissipation in target
   - power dissipation in solenoid
3. Yield vs beam energy:
   at 8 GeV either material heavier than Cu is OK
   at $\geq$ 16 GeV higher A gives higher yield
4. Performance is better with:
   smaller target radius ($R \sim 1$ cm)
   larger solenoid aperture
   target length $L \sim 1.5$-$2\ \lambda$
   tilt angle $\alpha \sim 200$ mrad
5. PtO_2 is excellent choice, but cost ?
6. Files of particles out of solenoid available
   http://www-ap.fnal.gov/mokhov/mumu/target

Ring Cooler for Muon Collider

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Fermi National Accelerator Laboratory
P. O. Box 500, Batavia, IL 60510

December 8, 1997

A possibility of using a racetrack–like ring accelerator for ionization cooling of a muon beam is considered.

3D cooling is achievable.

It can be used as a precooler for muon collider.

Muon Beam Parameters

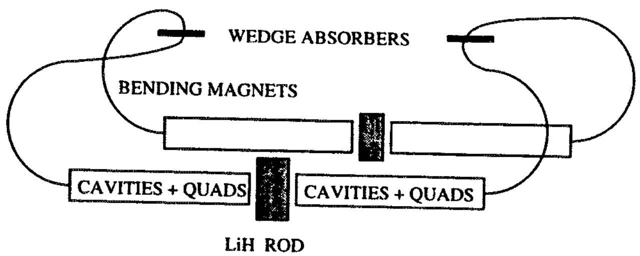
	Injected beam	Cooled beam
Momentum	225 MeV/c	170-225 MeV/c
σ_x	70 mm	9.9 mm
σ_y	70 mm	16 mm
σ_x	1500 mm	69 mm
$\sigma_{x'}$	0.15 rad	0.11 rad
$\sigma_{y'}$	0.15 rad	0.11 rad
$\sigma_{\Delta p/p}$	7.8%	3.3%
R.m.s. X-emittance	22 mm-rad	2.0 mm-rad
R.m.s. Y-emittance	22 mm-rad	3.3 mm-rad
R.m.s. Z-emittance	225 mm	3.7 mm
6D emittance	11×10^4 mm^3	24 mm^3

$$\epsilon_x = \sigma_x \sigma_{p_x}/mc$$

$$\epsilon_z = c\sigma_T \sigma_E/mc^2$$

Cooling time 20 turns
Beam loss about 25%+25%

Schematic of the Cooler



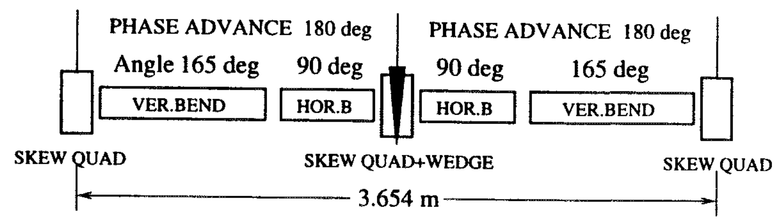
Parameters of the Cooler

Particles momentum	170 – 225 MeV/c
Circumference	28.4 m
Bending radius	0.411 m
Length of straight sections	9.607 m
Revolution frequency	9.29 MHz
Energy rate in SS (average)	5 MeV/m
Length of main absorber (LiH)	27.6 cm
Angle of the wedge absorber	15.7 deg

Bending Sections

- Provides a longitudinal cooling by LiH wedge absorber.
- Creates a dispersion at the center of the section where the wedge absorber is placed.
- Creates a large momentum compaction factor to get the revolution frequency not depending on energy.

Lattice



- Betatron phase advances 180^o+180^o.
- Turns both in vert. and hor. directions.
- Bending magnets: Field index 0.5;

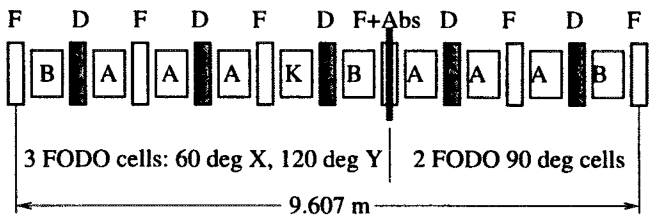
$B = 1.6\,T$; $R = 41.1$ cm; Aperture about 20 cm.
- Skew quads to control dispersion in SS

GS = 0.926 T.

Straight Sections

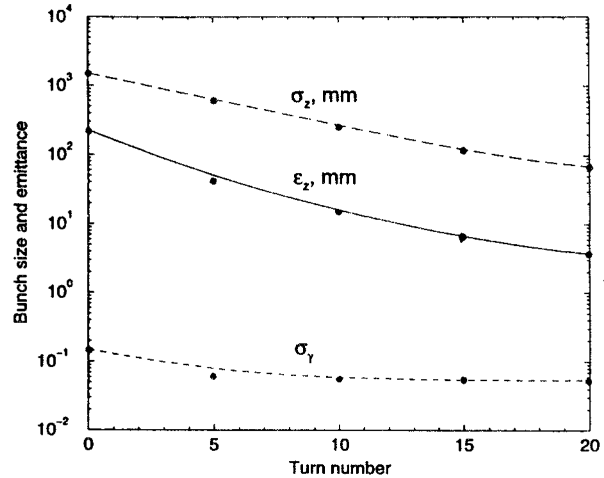
- Provides a transverse cooling by LiH absorber
- Provides a matching of phase volume in transverse and longitudinal directions.
- Section length is chosen to get the revolution frequency not depending on energy.

A possible Lattice



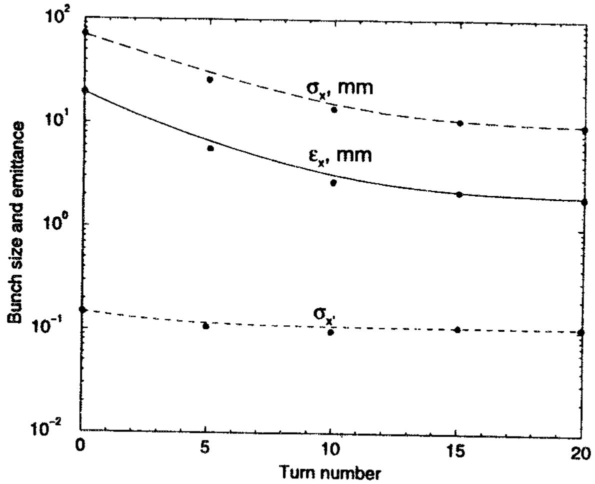
F,D - quads, A, B - accelerating cavities and bunchers , K - kicker

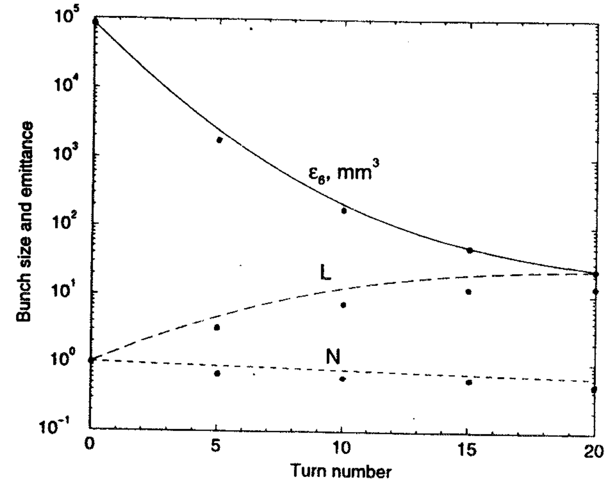
- Acceleration:
dE/ds = (5-6) MeV/m , f = 18.6 MH.
- Bunchers: dV/dz = (4-5) MV/m.



Longitidinal Cooling

$$\epsilon_z = \sigma_z \sigma_\gamma$$





Transverse Cooling

$$\epsilon_x = \sigma_x \sigma_{x'} / \beta\gamma$$

ϵ_6 – 6D emittance

N – Intensity

$$L \propto N^2/\sqrt{\epsilon_6}$$

Conclusion

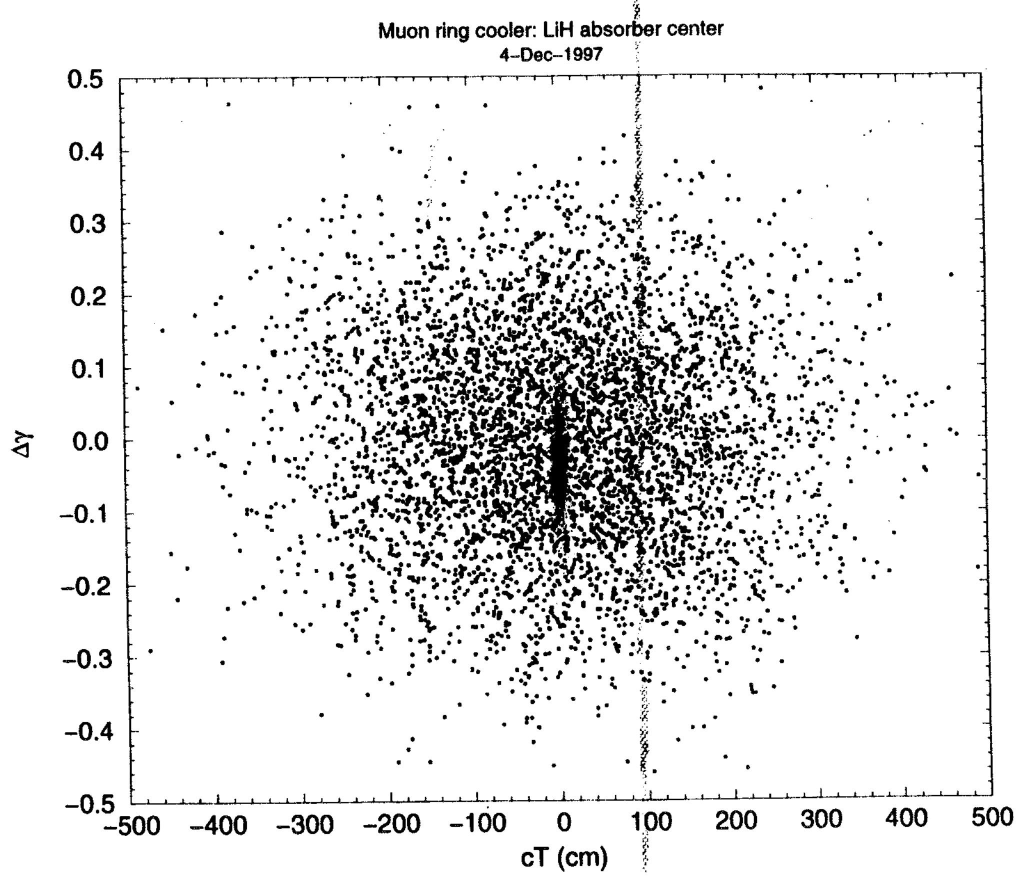
• A ring cooler appears capable of satisfactory cooling a muon beam both in transverse and longitudinal directions.

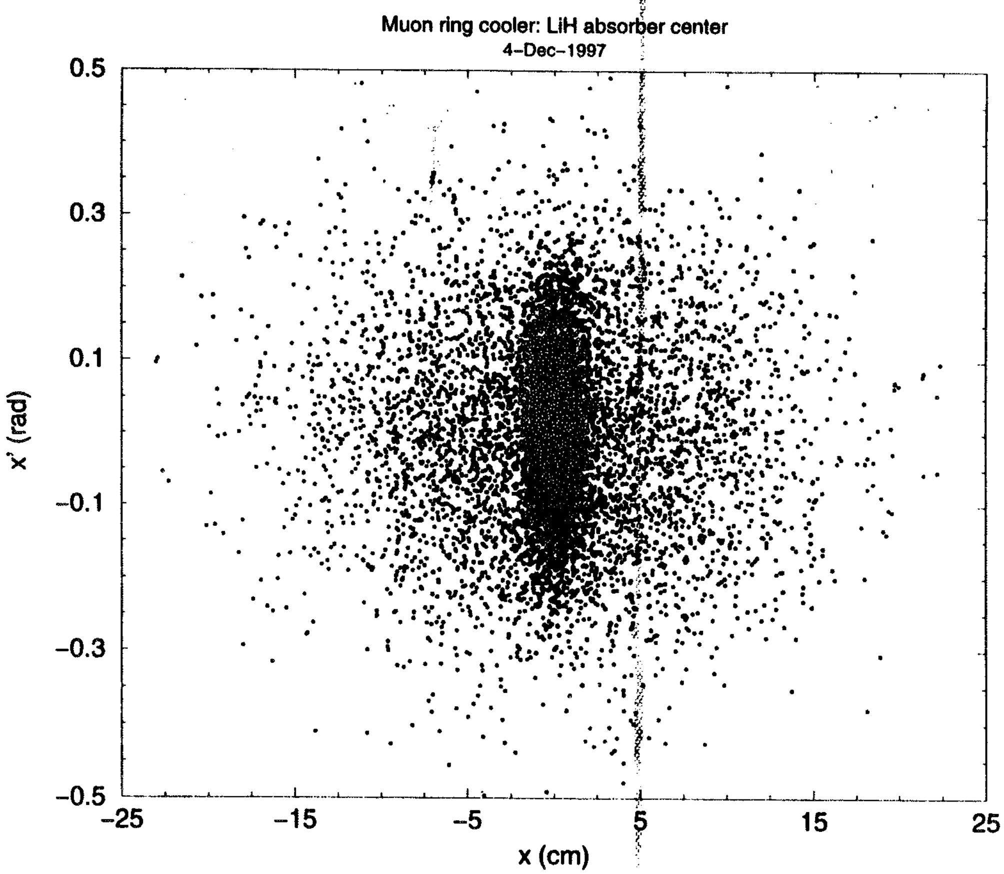
• The achievable emittance lets to use it as a precooler in muon collider scheme.

• The main problem is a big aperture of some magnets and high rate of acceleration.

• Run a full tracking through magnets and cavities is needed to investigate and suppress both chromatic and nonlinear effects

• 20 T solenoid gives decrease of 6D emittance about 4 times (effective β-function decreases from 16 cm to 8 cm).




Muon ring cooler: LiH absorber center
4-Dec-1997
0.5
0.3
0.1
-0.1
-0.3
-0.5
x' (rad)
-25
-15
-5
5
15
25
x (cm)