Pion yield studies for proton drive beams of 2-8 GeV kinetic energy for stopped muon and low-energy muon decay experiments

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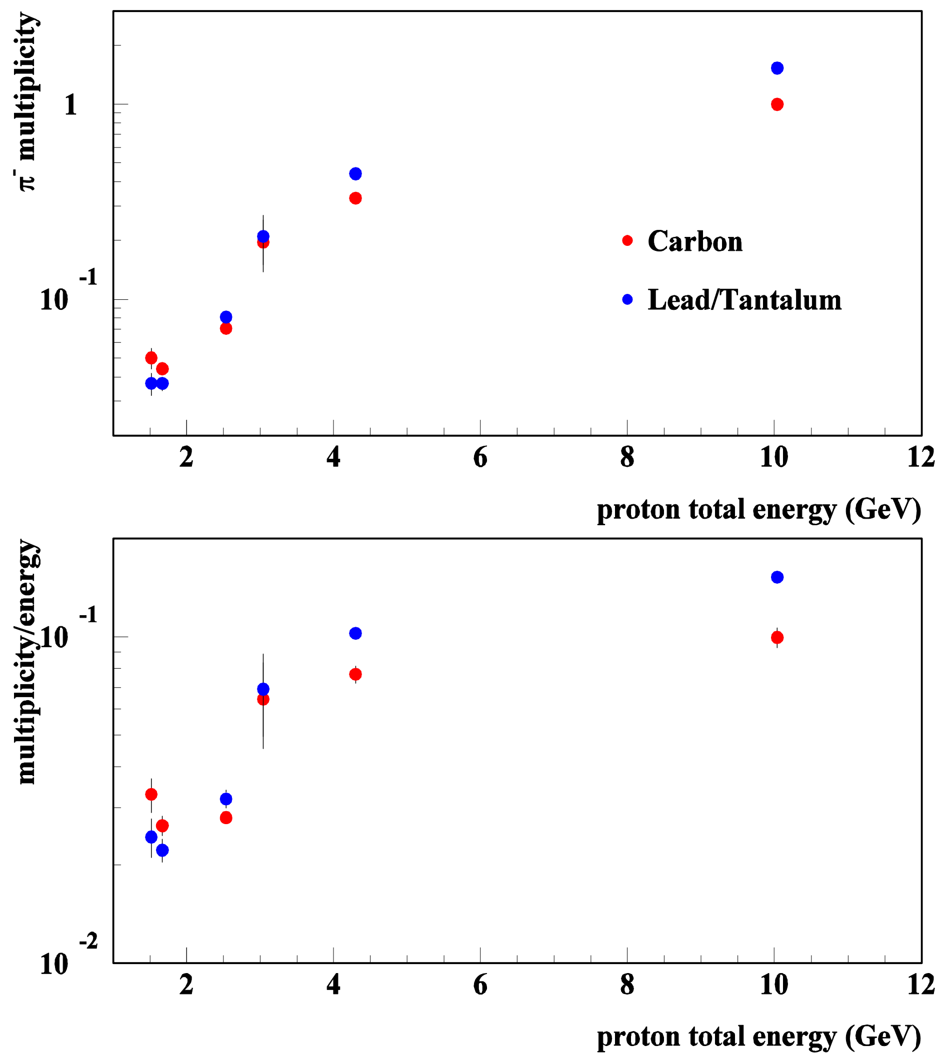
Workshop on Applications of High Intensity Proton Accelerators

Fermilab

October 19-21, 2009

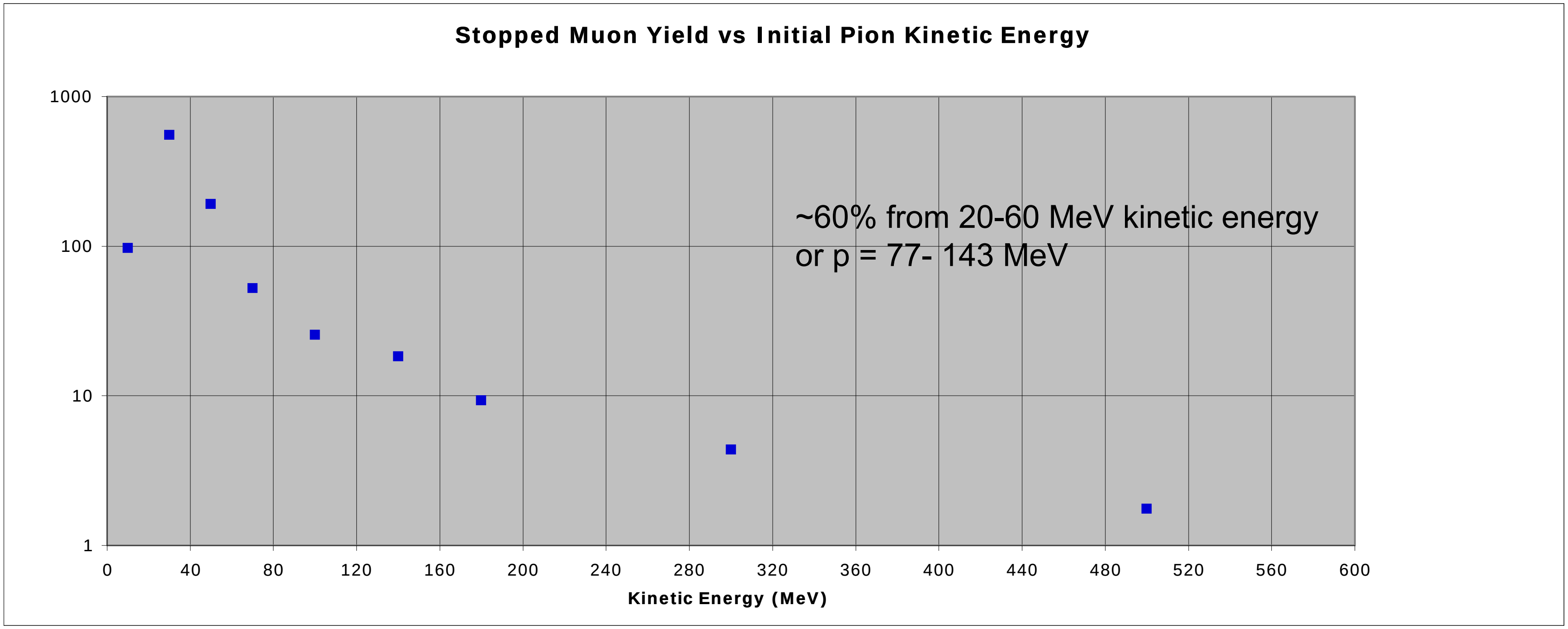
Task

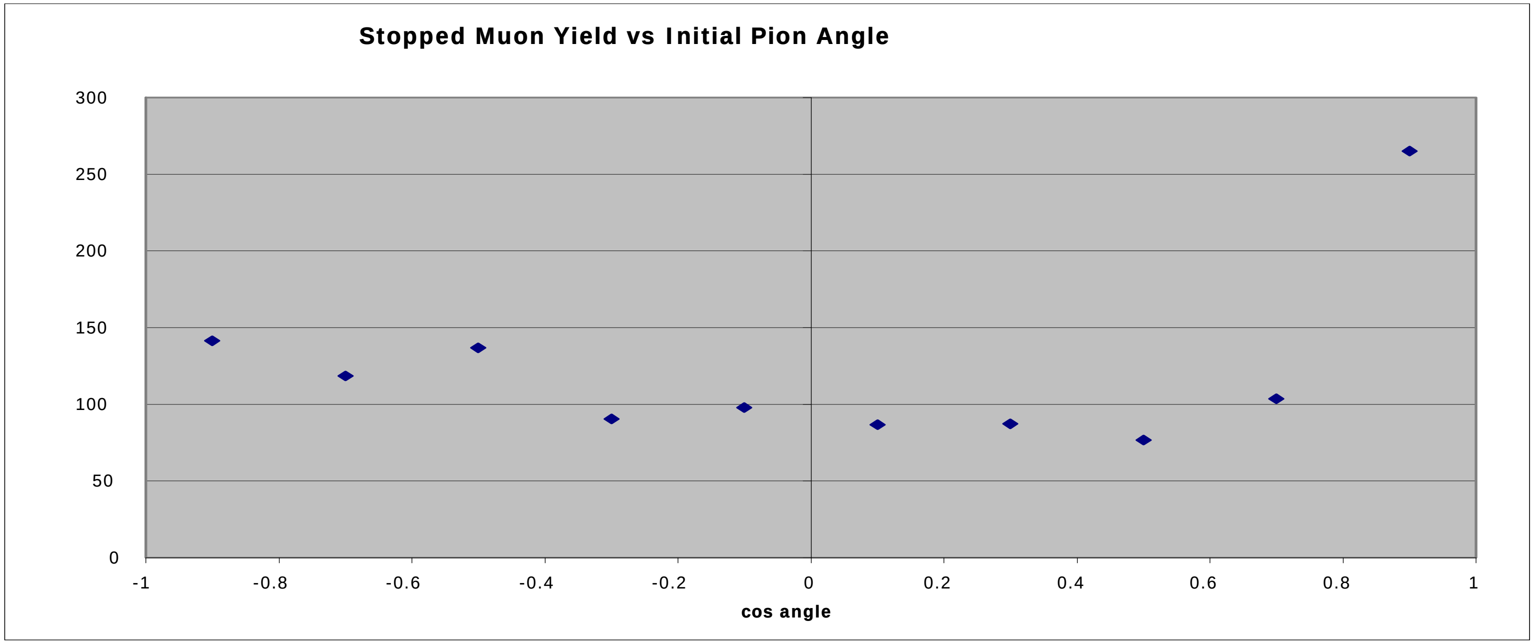
- Long targets with small radius made from heavy material are usually used for low energy pion/muon production
- Mu2e - target size and material were optimized at 8 GeV/c – 16 cm long, 0.3 cm radius gold target
- Secondary/tertiary interactions, ionization energy losses could be important for thick target. Thick target effect is energy dependent.
- Full simulation of thick target is needed to estimate low energy pion yield at different energies
- Simulation code should be tested in wide energy range



Experimental data on π^- multiplicity in proton-nucleus interactions

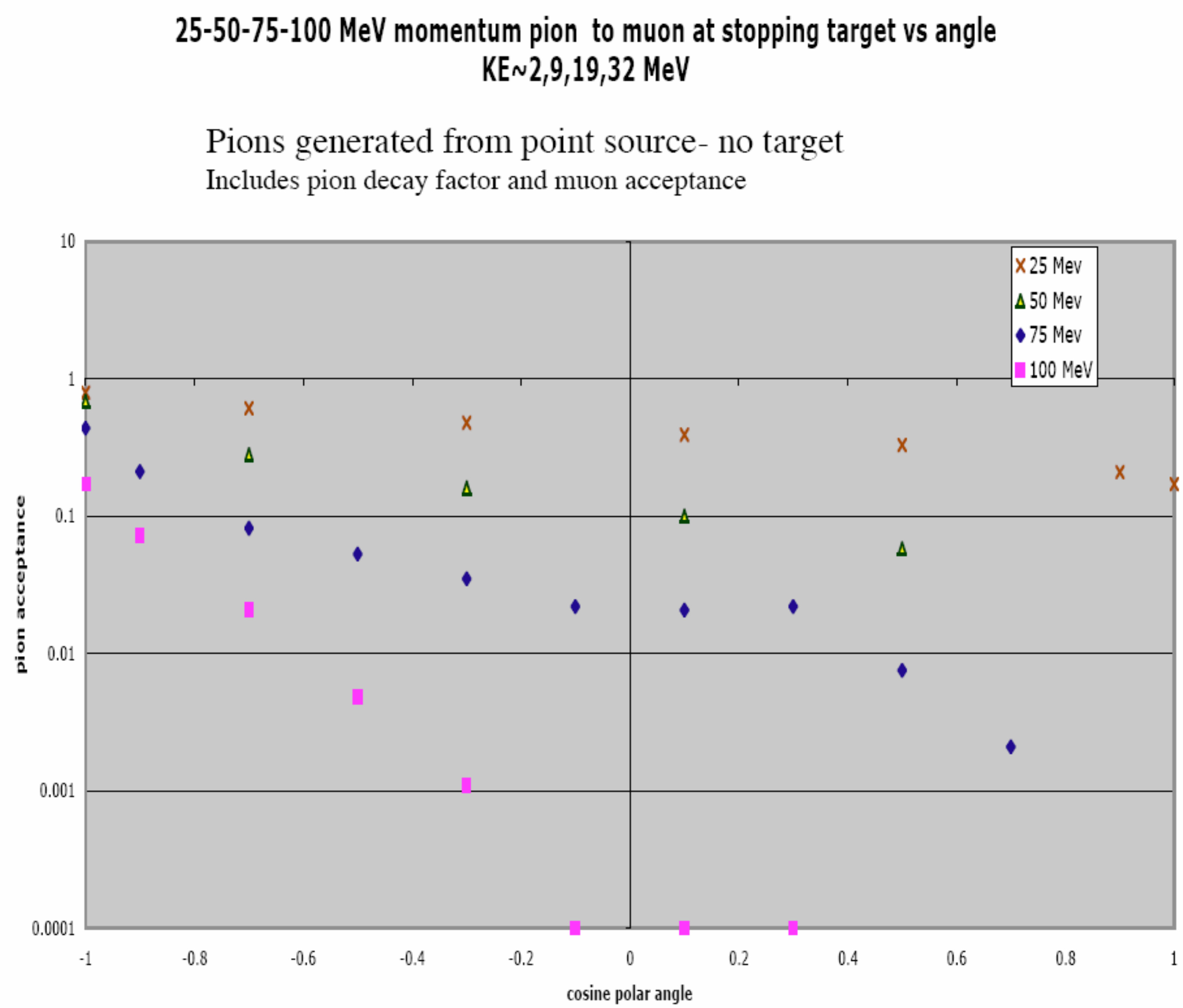
Pion Production- what energies and angles are important?





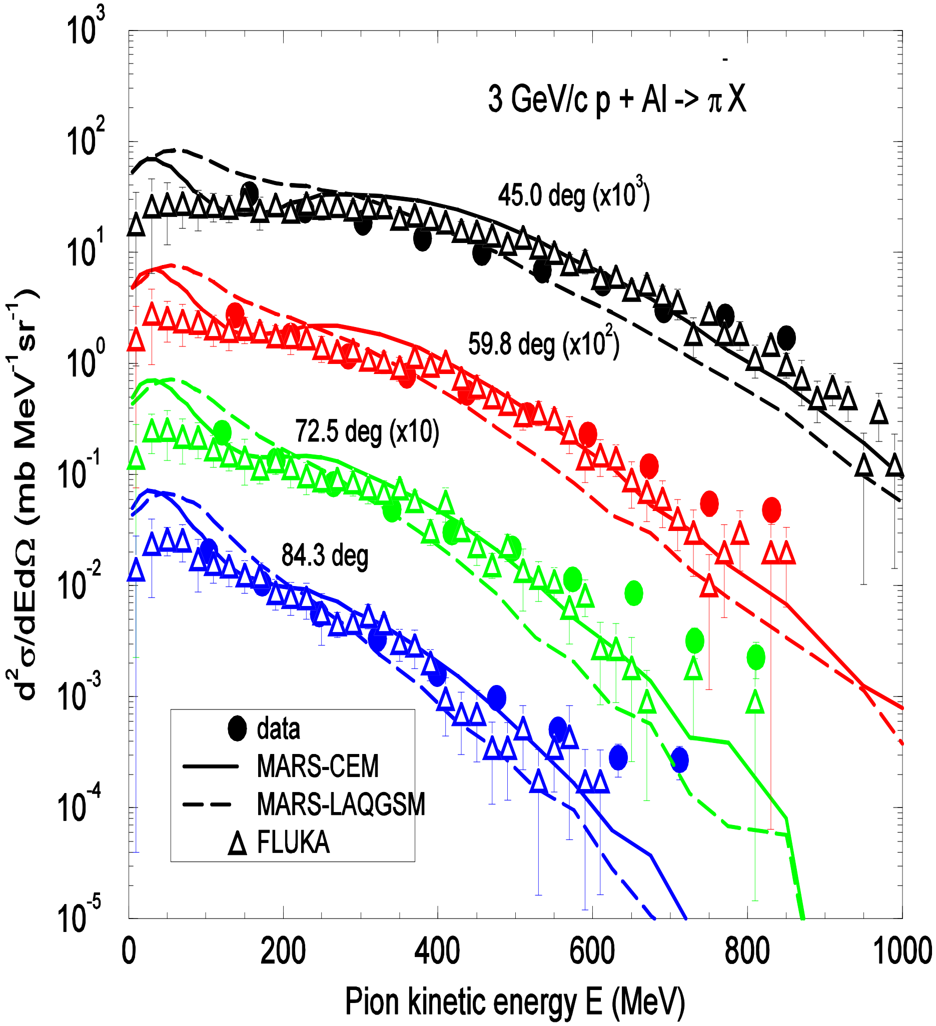
Courtesy to Rick Coleman, Mu2e collaboration

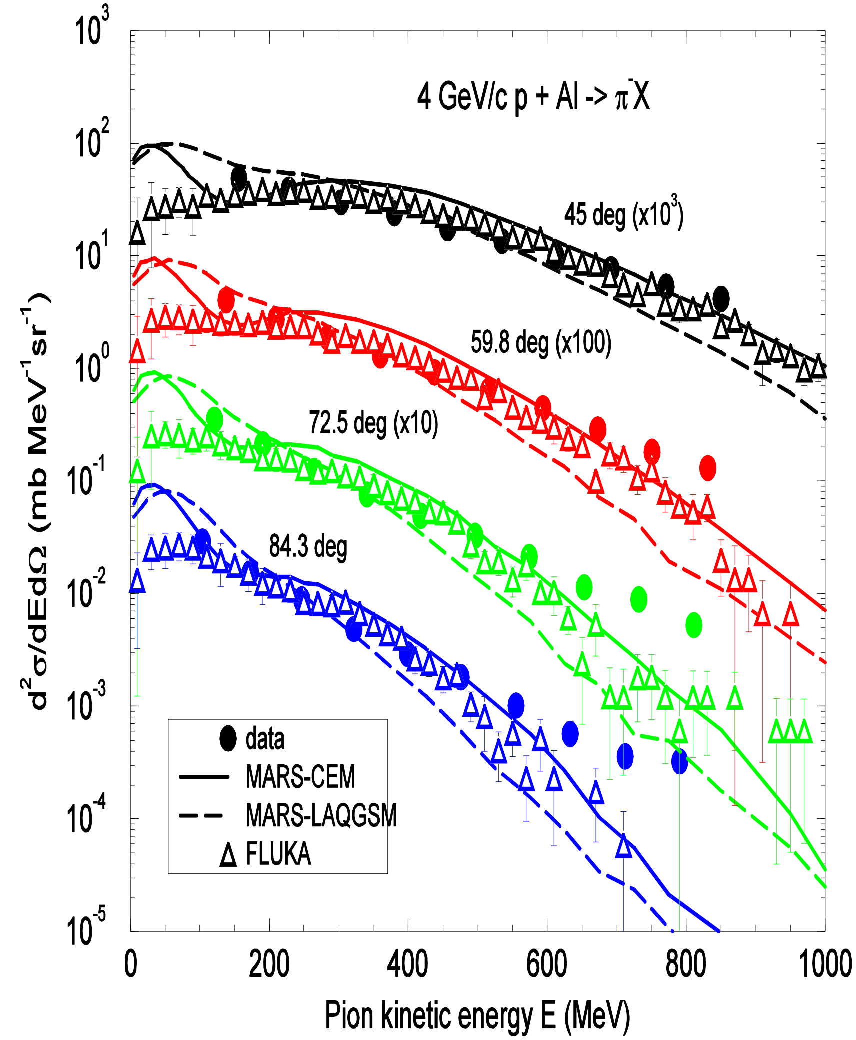
Mu2e sensitivity to pion energy&angle distribution



Courtesy to Rick Coleman, Mu2e collaboration

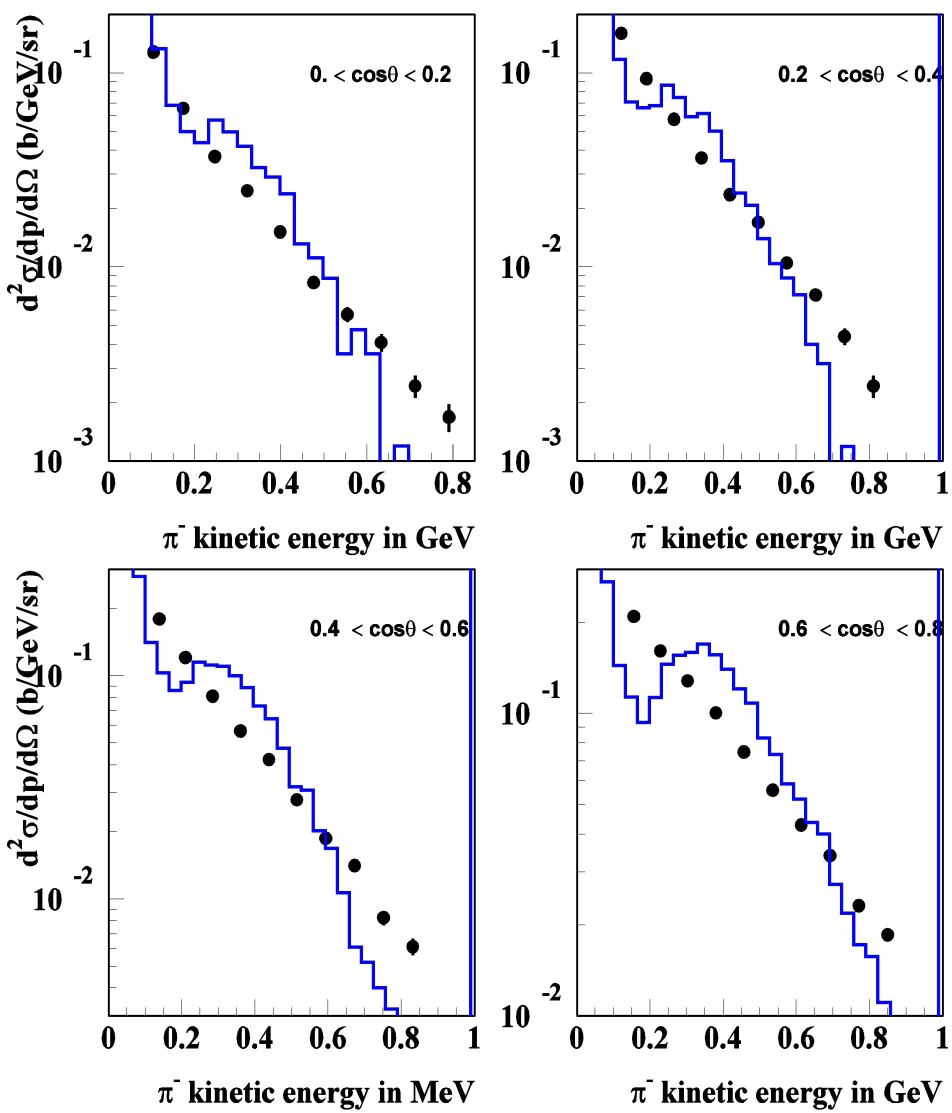
Fancy spectrometer data vs model predictions



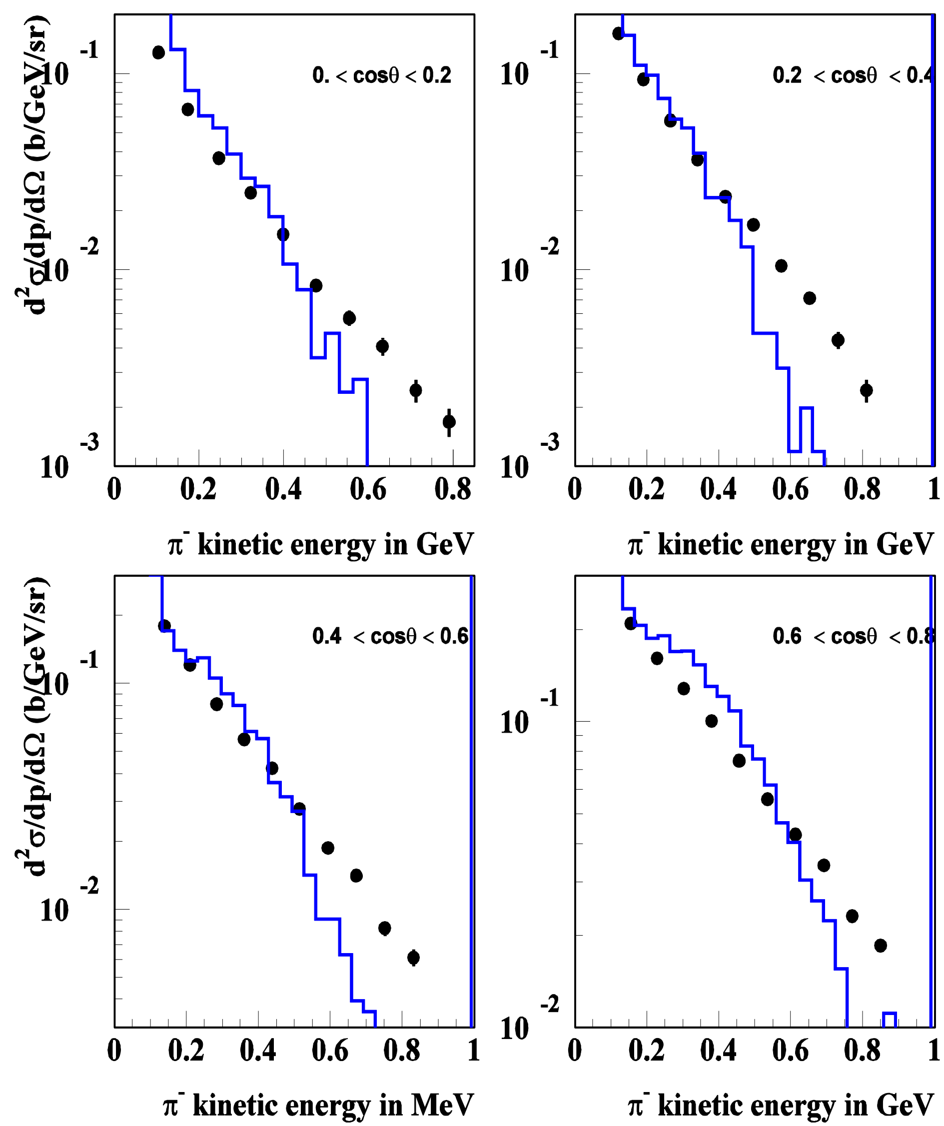


Fancy spectrometer data vs MARS models.

Pion kinetic energy of 40 MeV corresponds to momentum of 113 MeV/c



Proton lead interactions at 4 GeV/c. FANCY data and MARS(default)



Proton lead interactions at 4 GeV/c. FANCY data and MARS(LAQGSM)

HARP data.

Pion kinetic energy of 40 MeV corresponds to momentum of 113 MeV/c

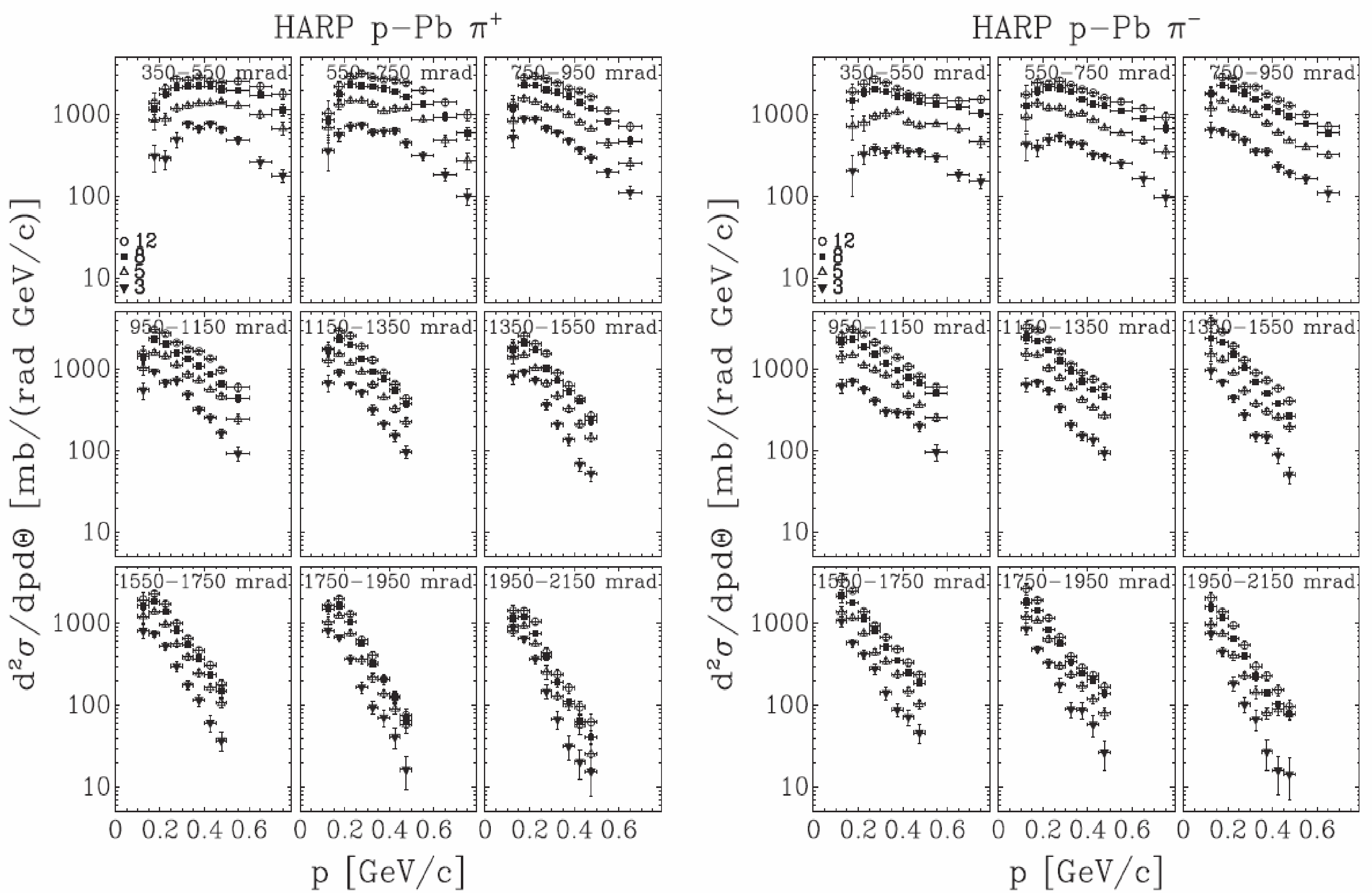
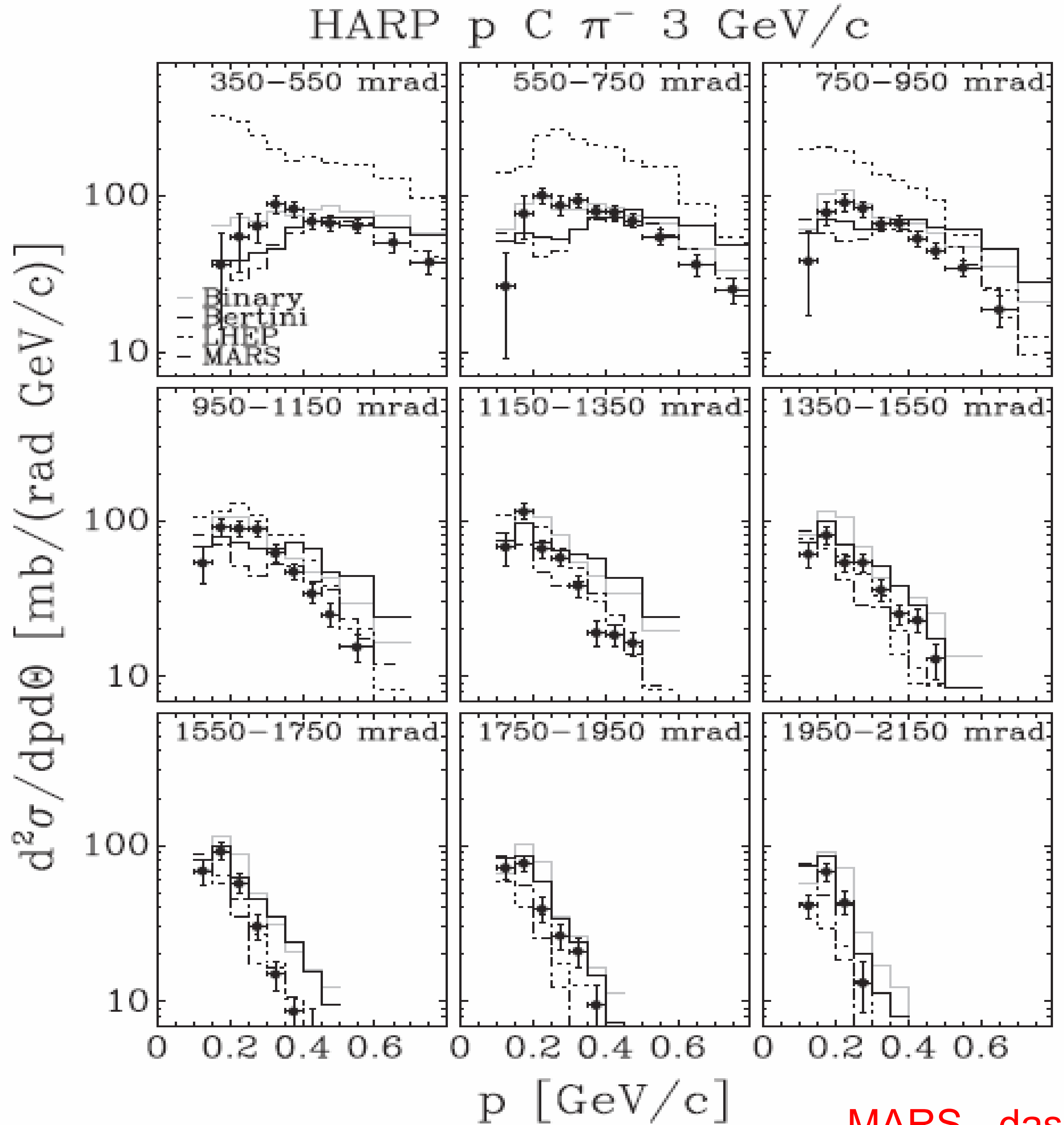
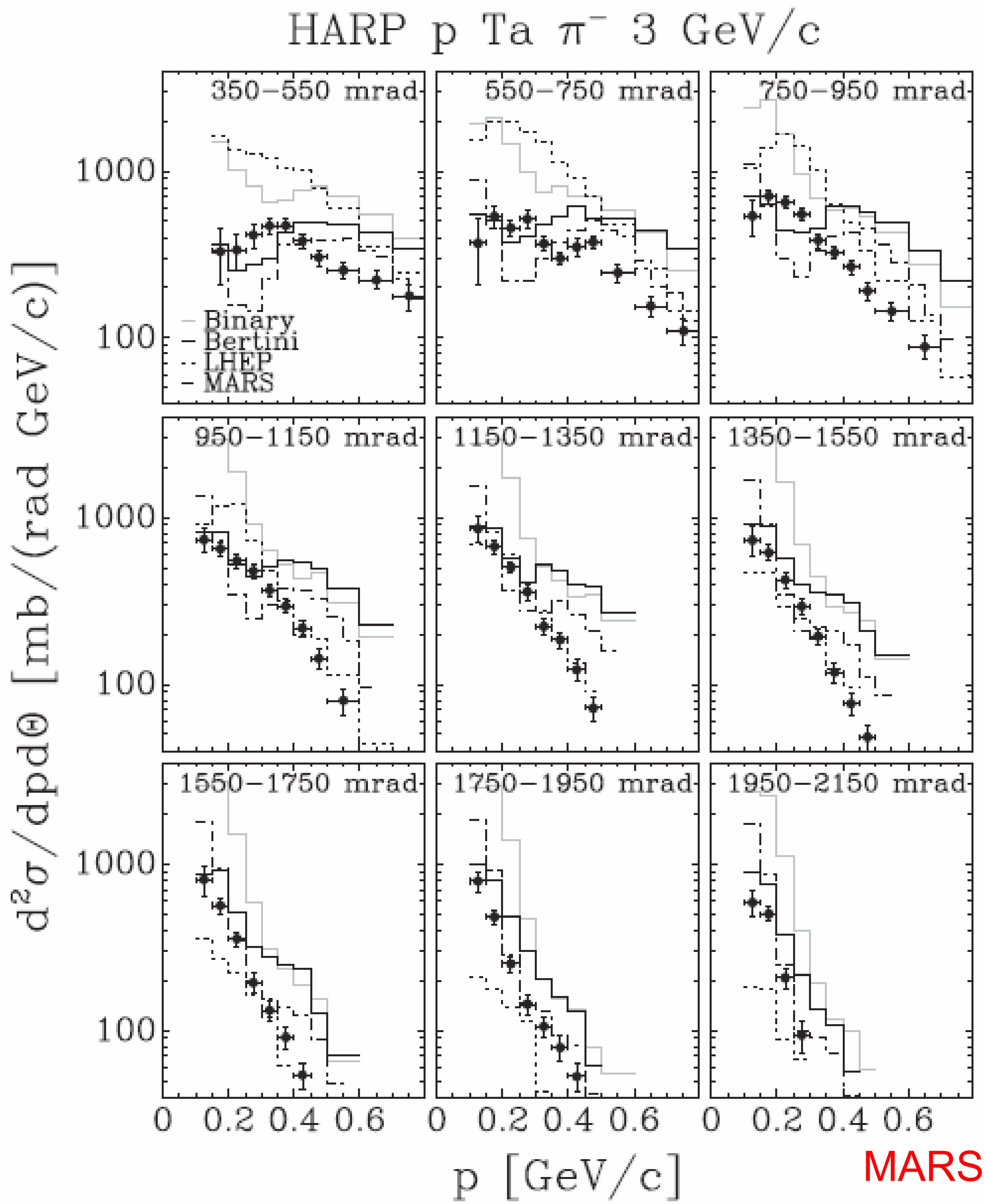


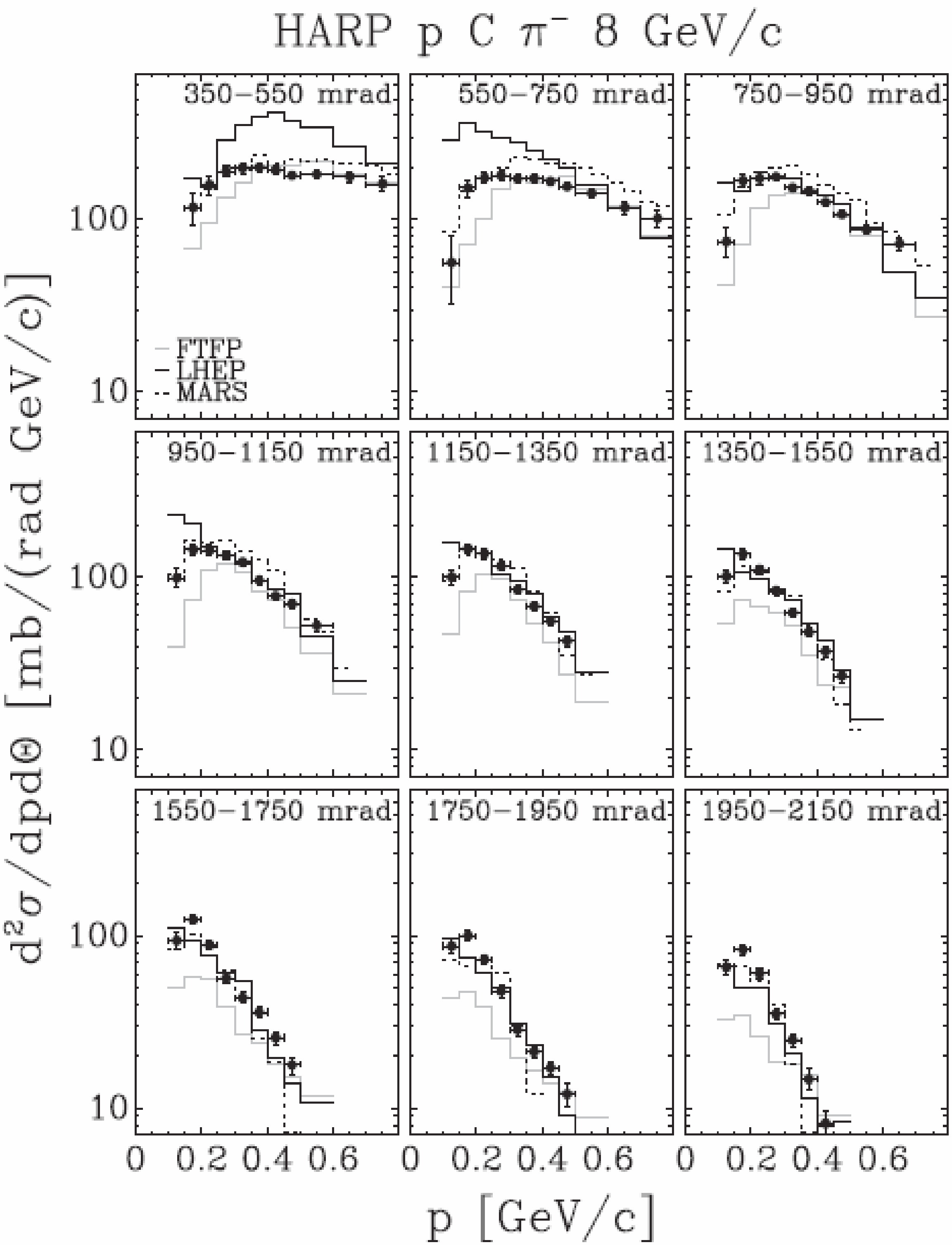
FIG. 12. Double-differential cross sections for π^+ production (left) and π^- production (right) in p-Pb interactions as a function of momentum displayed in different angular bins (shown in mrad in the panels). The error bars represent the combination of statistical and systematic uncertainties.



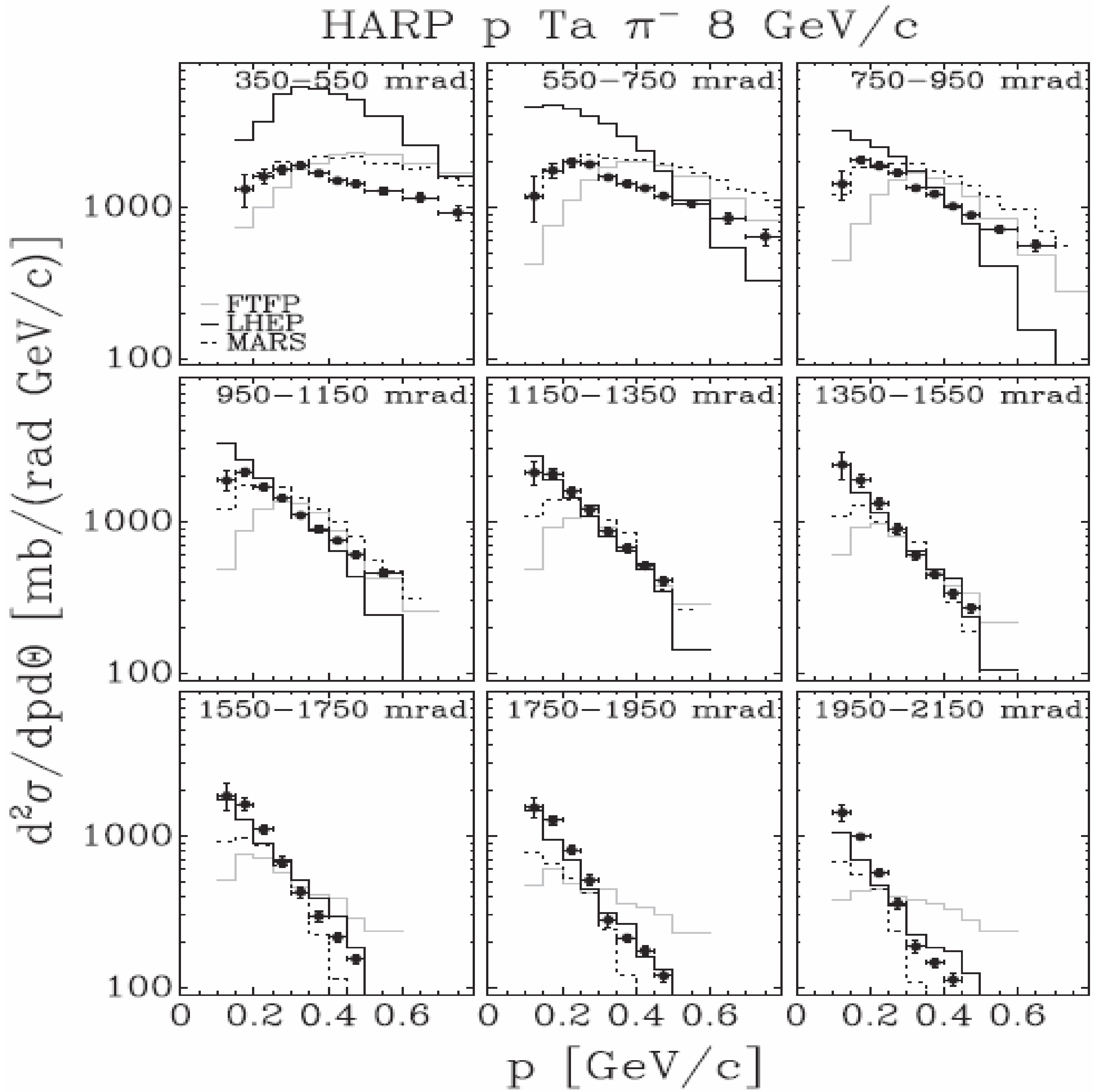
MARS - dash-dotted lines



MARS - dash-dotted lines



HARP p C π⁻ 8 GeV/c
350−550 mrad
550−750 mrad
750−950 mrad
950−1150 mrad
1150−1350 mrad
1350−1550 mrad
1550−1750 mrad
1750−1950 mrad
1950−2150 mrad
FTFP
LHEP
MARS
d²σ/dpdΘ [mb/(rad GeV/c)]
p [GeV/c]
10
100
0
0.2
0.4
0.6

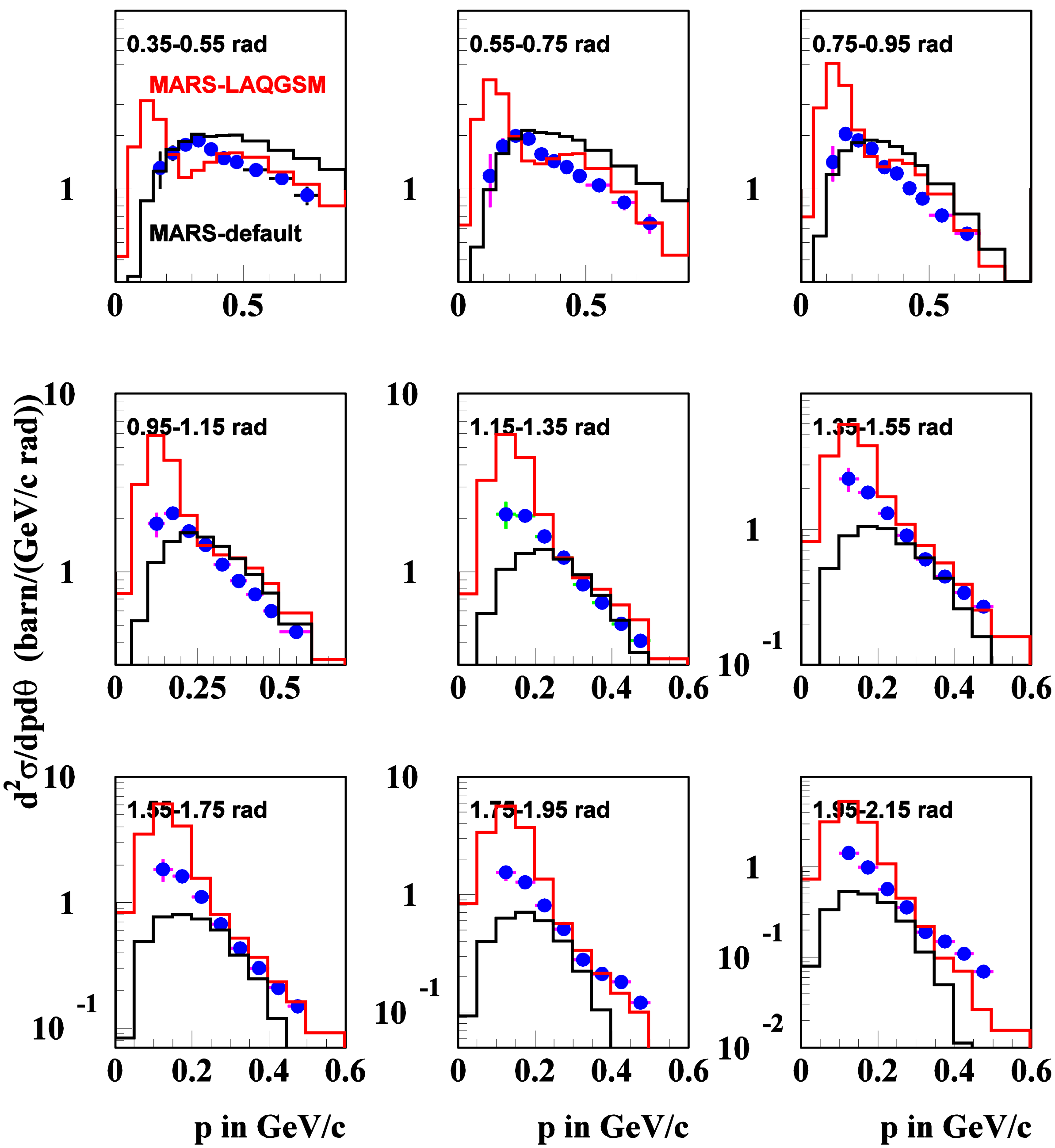


HARP p Ta π⁻ 8 GeV/c
350−550 mrad
550−750 mrad
750−950 mrad
950−1150 mrad
1150−1350 mrad
1350−1550 mrad
1550−1750 mrad
1750−1950 mrad
1950−2150 mrad
FTFP
LHEP
MARS
d²σ/dpdΘ [mb/(rad GeV/c)]
p [GeV/c]
100
1000
0
0.2
0.4
0.6

HARP collaboration conclusion

None of the considered models describe fully our data. However, backward or central region production seems to be described better than relatively more forward production, especially at higher incident momenta. In our data, the lowest angular bin corresponds to a transition region from forward to central production, that is more difficult to describe by MC models.

In general, π^+ production is better described than π^- production. At higher energies the FTP model (from GEANT4) and the MARS model describe better the data, while at the lowest energies the Bertini and binary cascade models (from GEANT4) seem more appropriate. Parametrized models, as LHEP from GEANT4, show relevant discrepancies: up to a factor three in the forward region at low energies.



π^- production in proton tantalum interaction at 8 GeV/c

HARP vs HARP-CDP

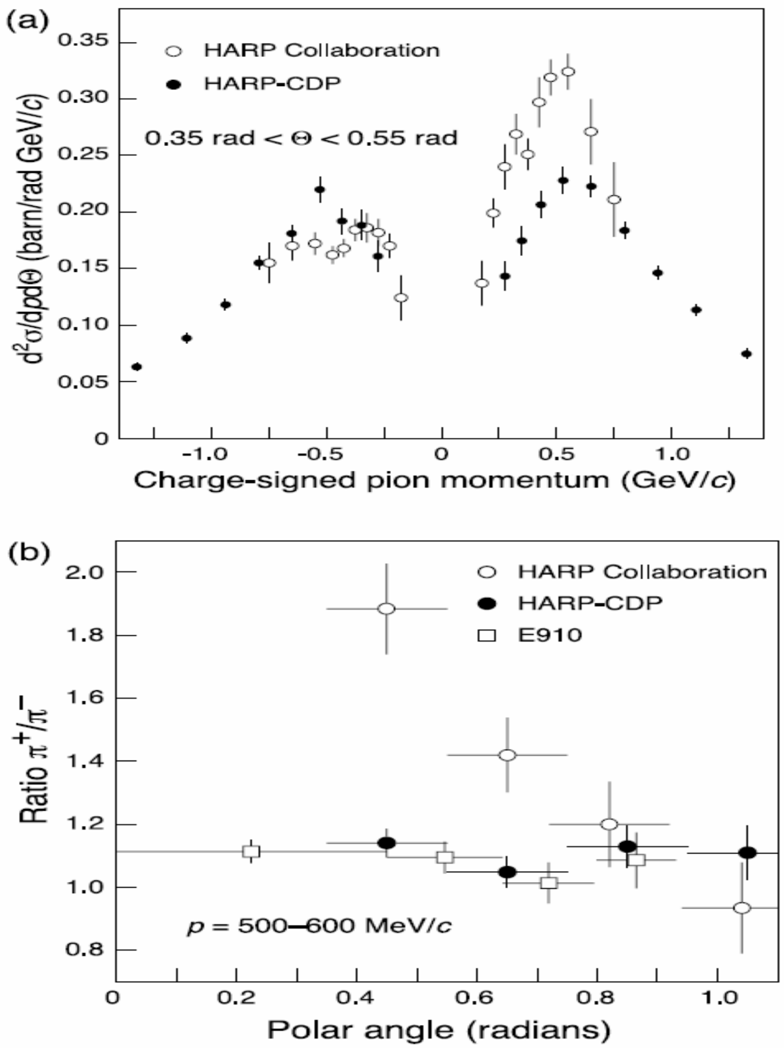
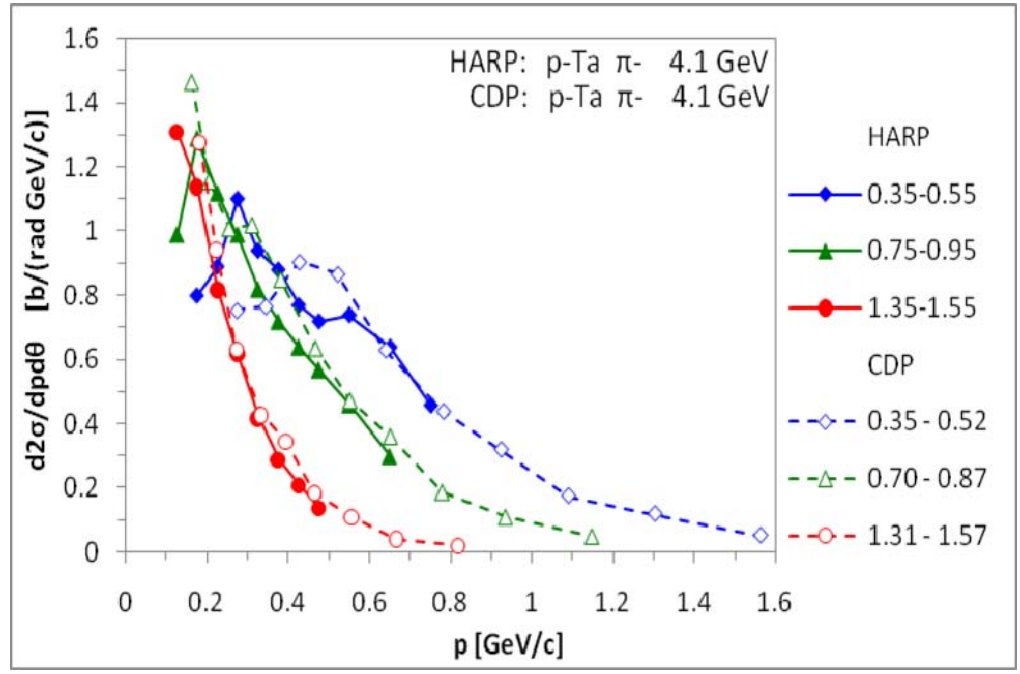
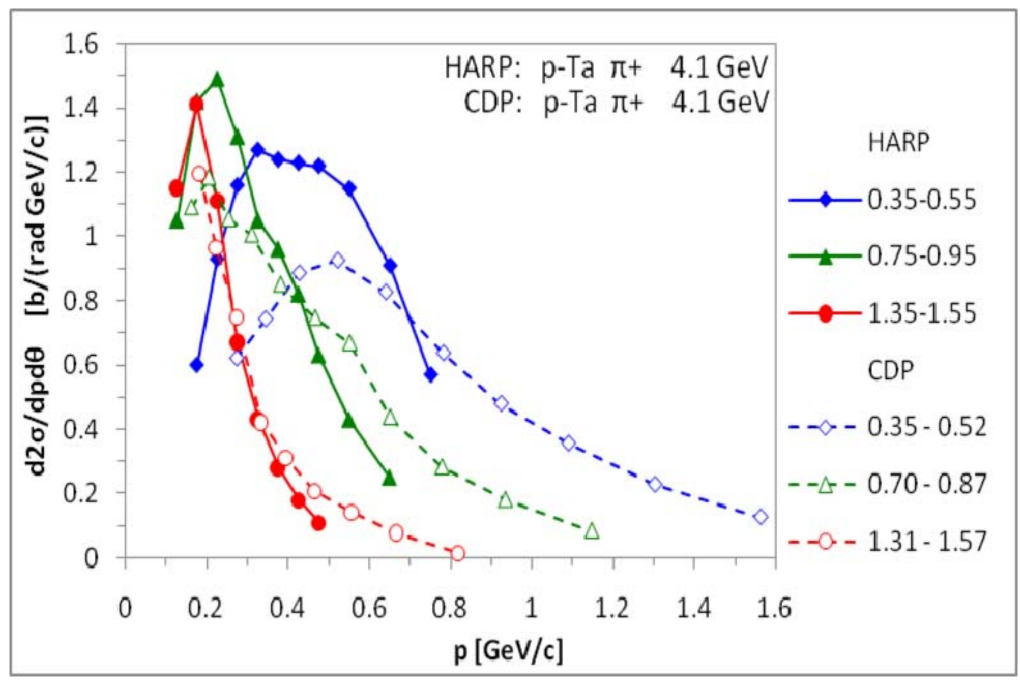


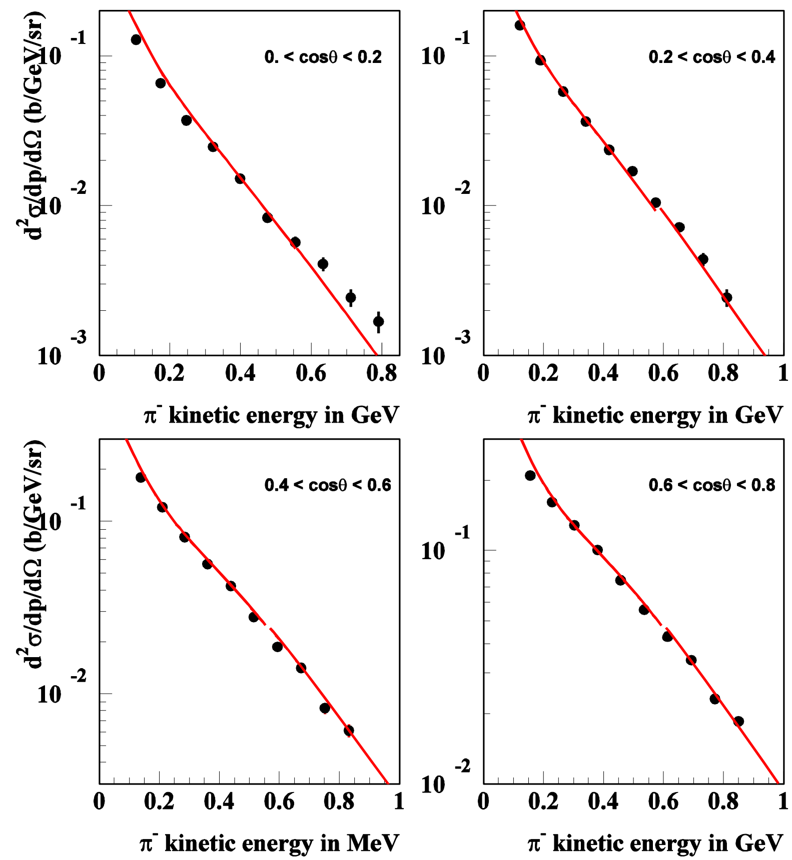
Fig. 10 (a) Comparison of our cross-sections (*black circles*) of $\pi^{\pm}$ production by +12.0 GeV/c protons off beryllium nuclei with the cross-sections published by the HARP Collaboration (*open circles*); (**b**) Comparison of our ratio π^+/π^- at +12.0 GeV/c beam momentum as a function of the polar angle θ with the ratios published by the HARP Collaboration; also shown are the ratios π^+/π^- published by the E910 Collaboration for a +12.3 GeV/c beam momentum; in (**a**) total errors are shown; in (**b**) for the HARP Collaboration total errors are shown (only those are published), for E910 and our group, the errors are statistical only





FANCY measurements and fit

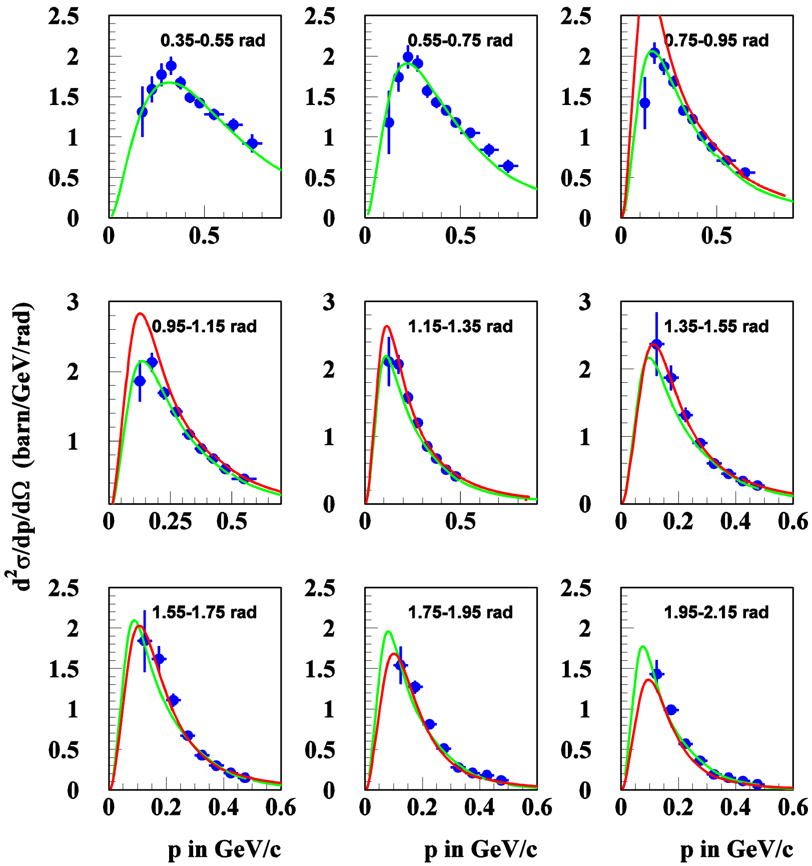
- Pion yield was measured by FANCY spectrometer at KEK for p Al at 3 GeV/c and p Al, p Pb at 4 GeV/c.
- Pion kinetic energies were from 100 to 850 MeV, angles - from 36 to 90 degrees.
- Collaboration has fitted each data set by two-fireball model (6 parameters, with clear A-dependence of each fireball)



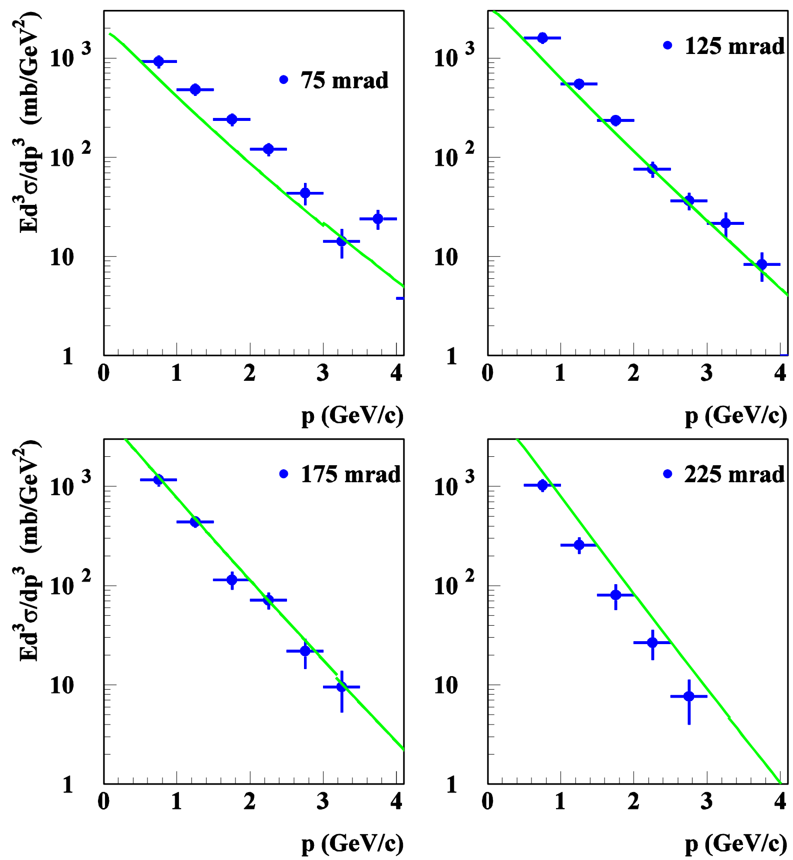
Proton lead interactions at 4 GeV/c

Two-fireball model vs HARP data

Green line – fit of 8 GeV/c HARP data,
red line – renormalized fit of 4 GeV/c FANCY data



π^- production in proton tantalum interaction at 8 GeV/c. HARP data.

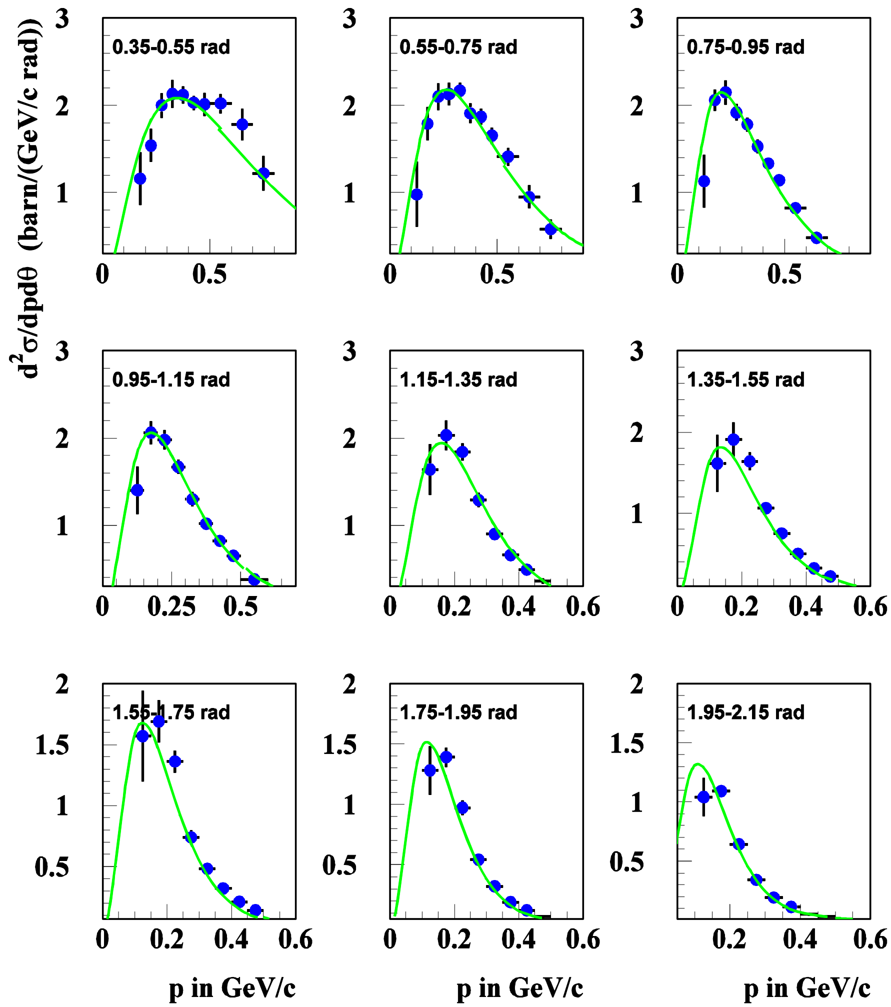


π^- production in proton tantalum interaction at 8 GeV/c. HARP data.

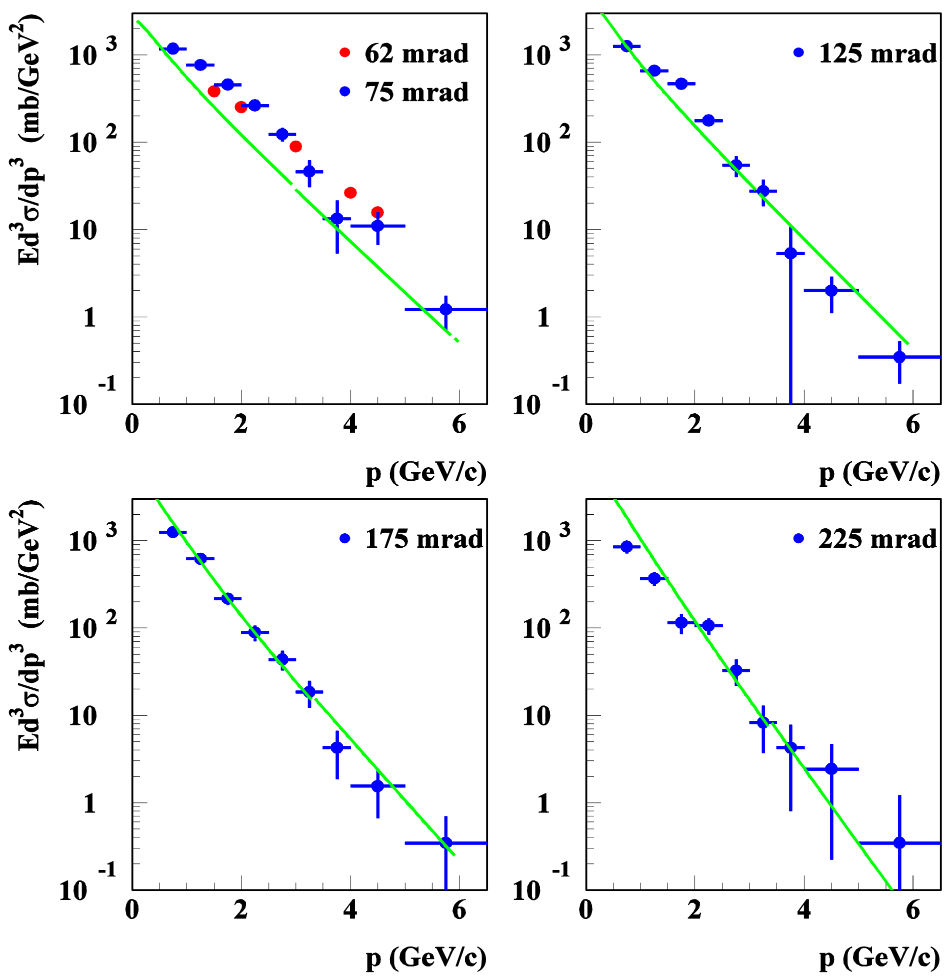
Large angles only - X^2/ndf =0.94

All angles - X^2/ndf =2.6

Two-fireball model vs HARP data



π^+ production in proton tantalum interaction at 8 GeV/c.HARP data.



π^+ production in proton tantalum interaction at 8 GeV/c.HARP data.

Large angles only - X^2/ndf =0.93

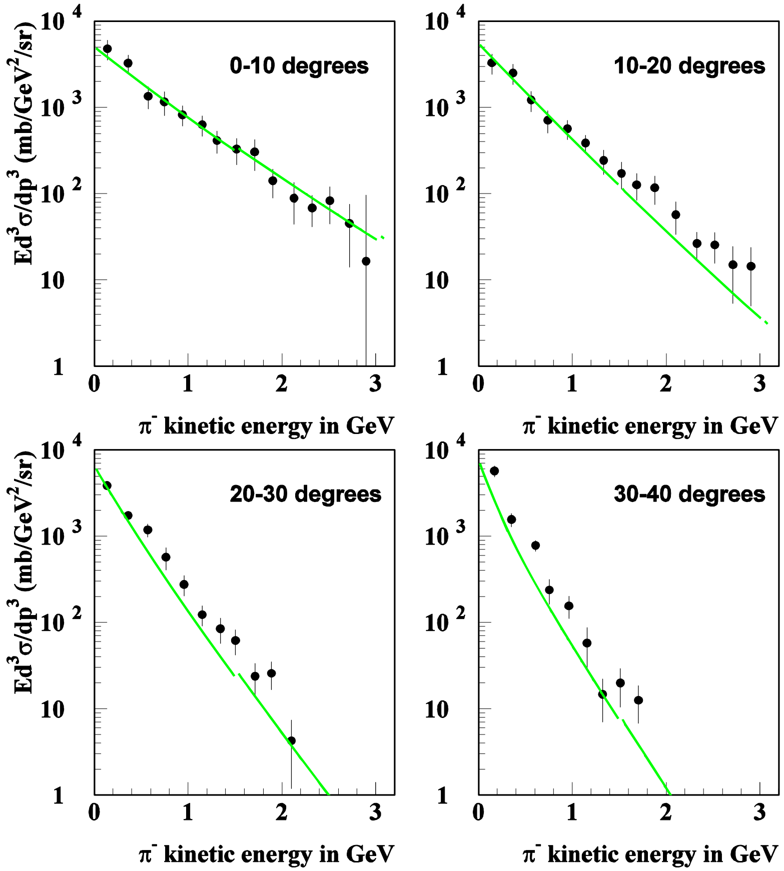
All angles - X^2/ndf =3.4

Low angle pion production

- Negative pion yield was studied at 10 GeV/c using JINR 2-m propane bubble chamber. Two tantalum plate (1mm thick) were placed in working volume.

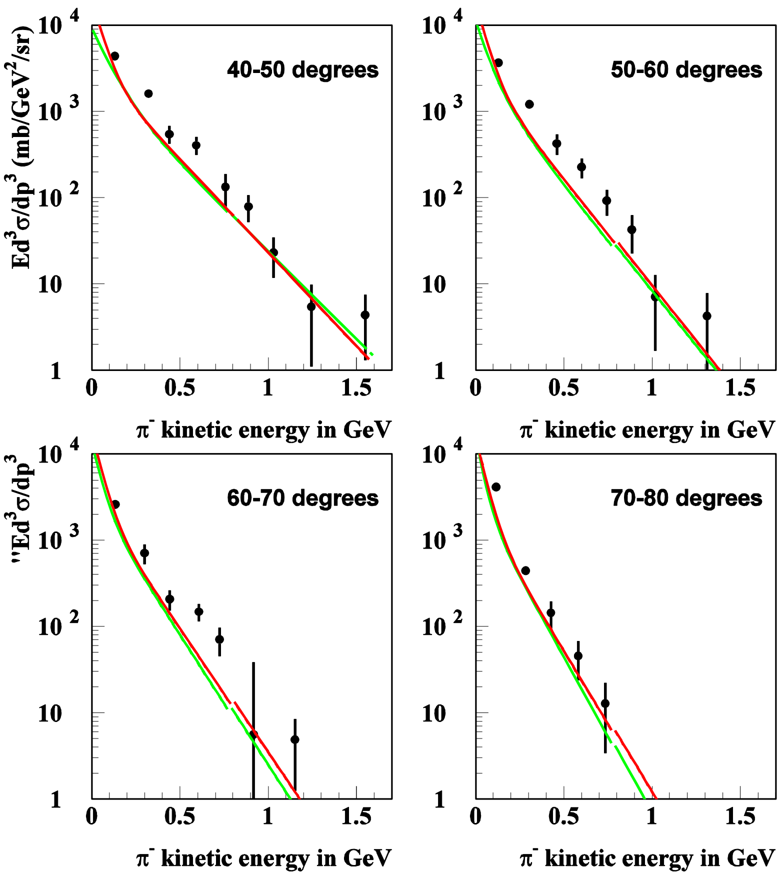
- Differential cross sections of negative pion and proton production were measured in proton-carbon and proton-tantalum interaction. Pion kinetic energies - 0.080 to 3 GeV, angles - 0 to 180 degrees.

- Two-fireball fit of HARP 8 GeV/c tantalum data (renormalized by ratio of proton kinetic energies) agrees well with this measurement at least for low energy pions.

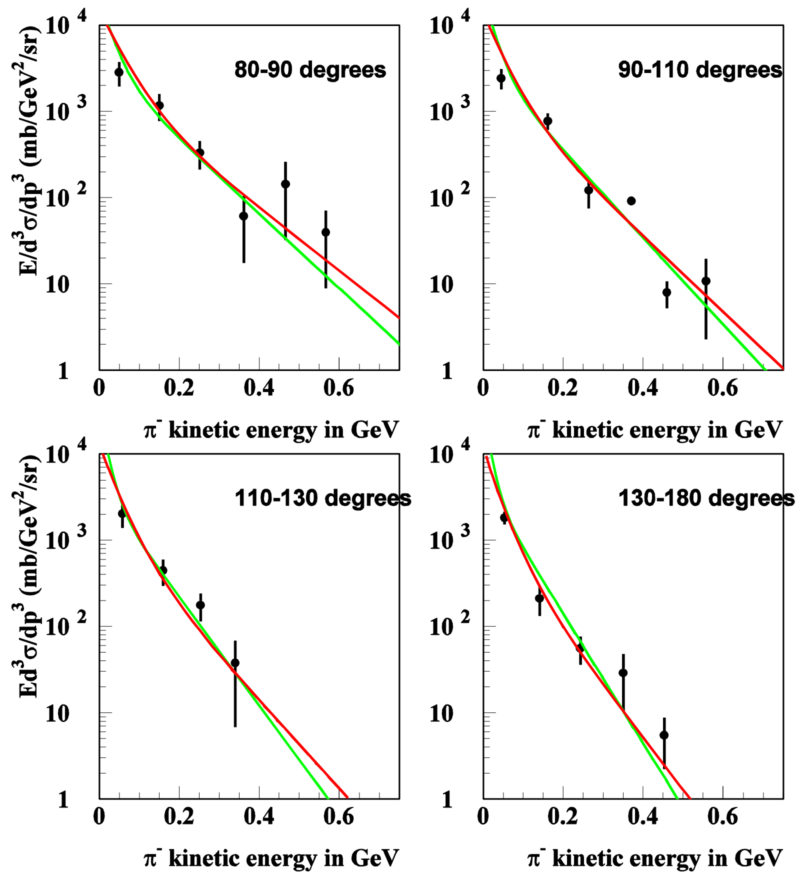


JINR data and two-fireball fits

Green line – renormalized fit of 8 GeV/c HARP data,
red line – renormalized fit of 4 GeV/c FANCY data

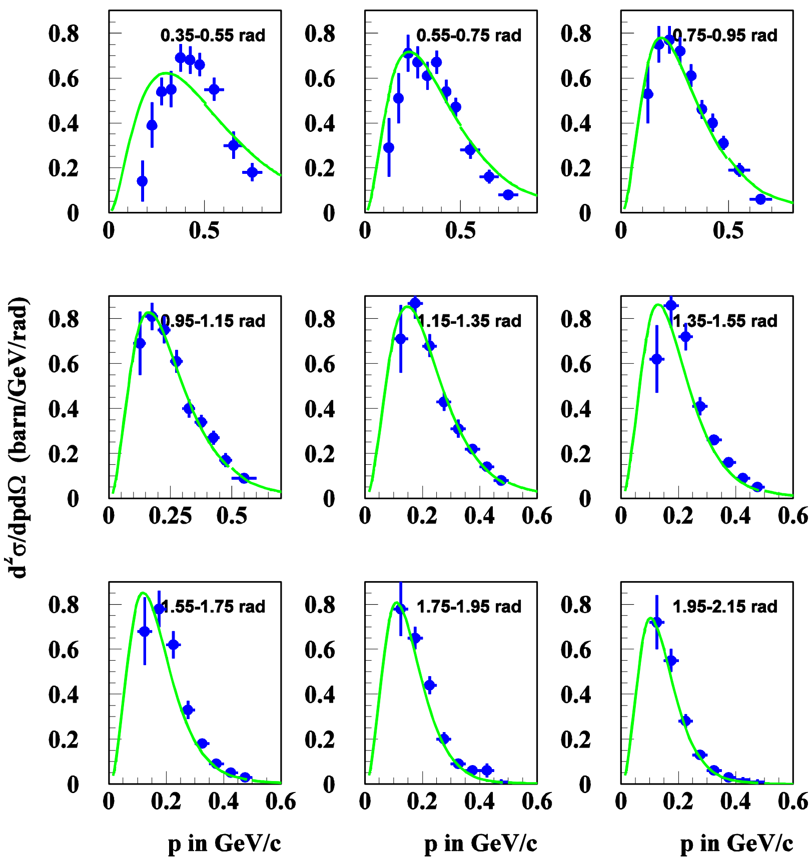


Proton tantalum interactions at 10 GeV/c

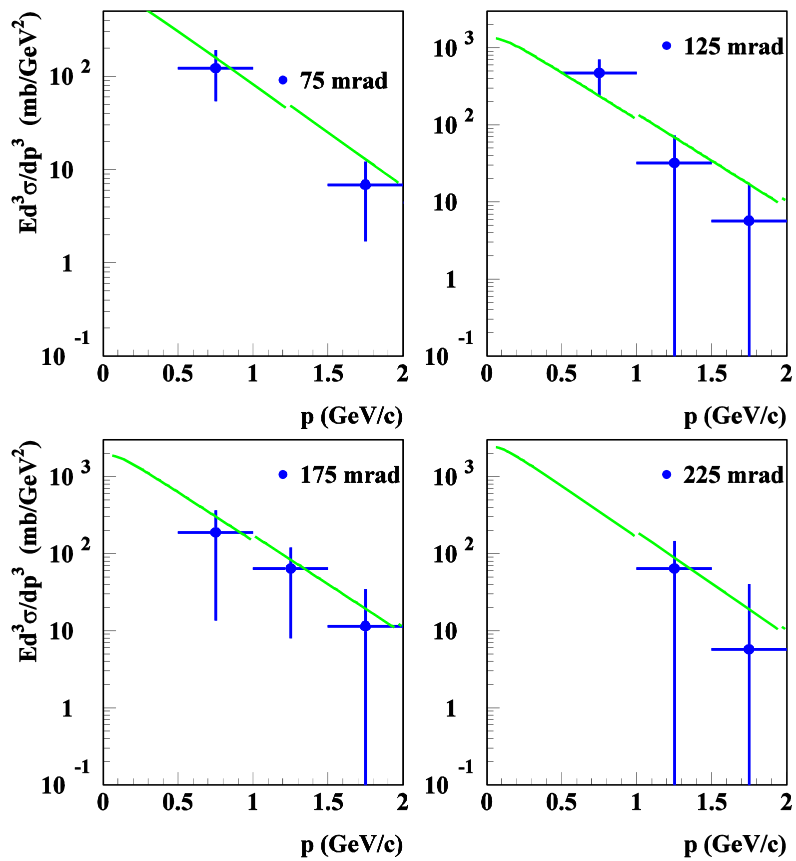


Proton tantalum interactions at 10 GeV/c

Two-fireball fit vs HARP data



π^+ production in proton tantalum interaction at 3 GeV/c. HARP data.



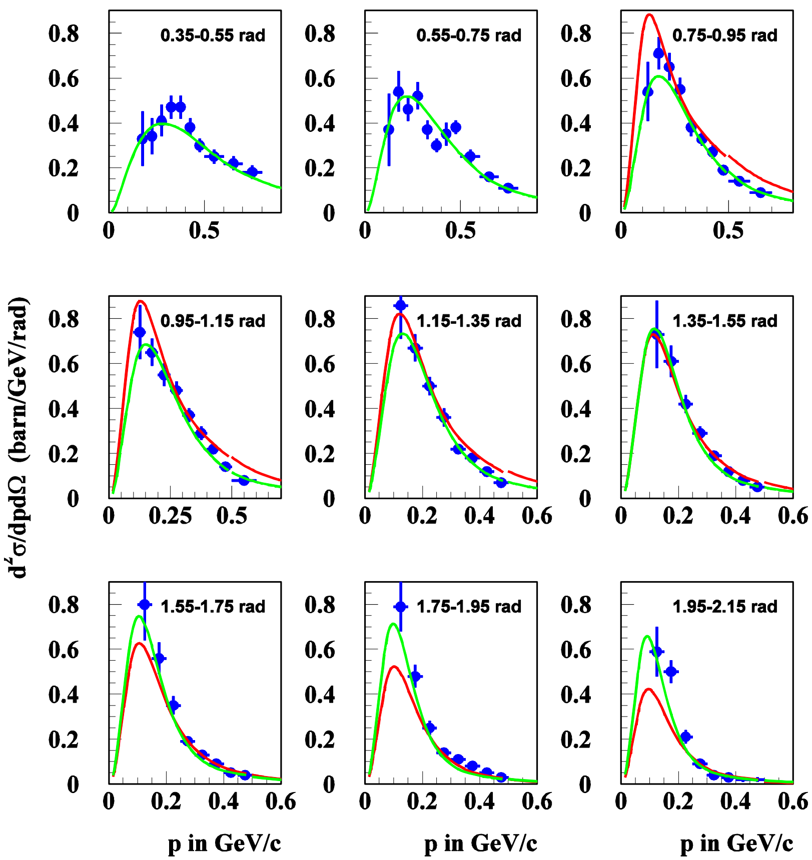
π^+ production in proton tantalum interaction at 3 GeV/c

Large angles only - X^2/ndf =1.6

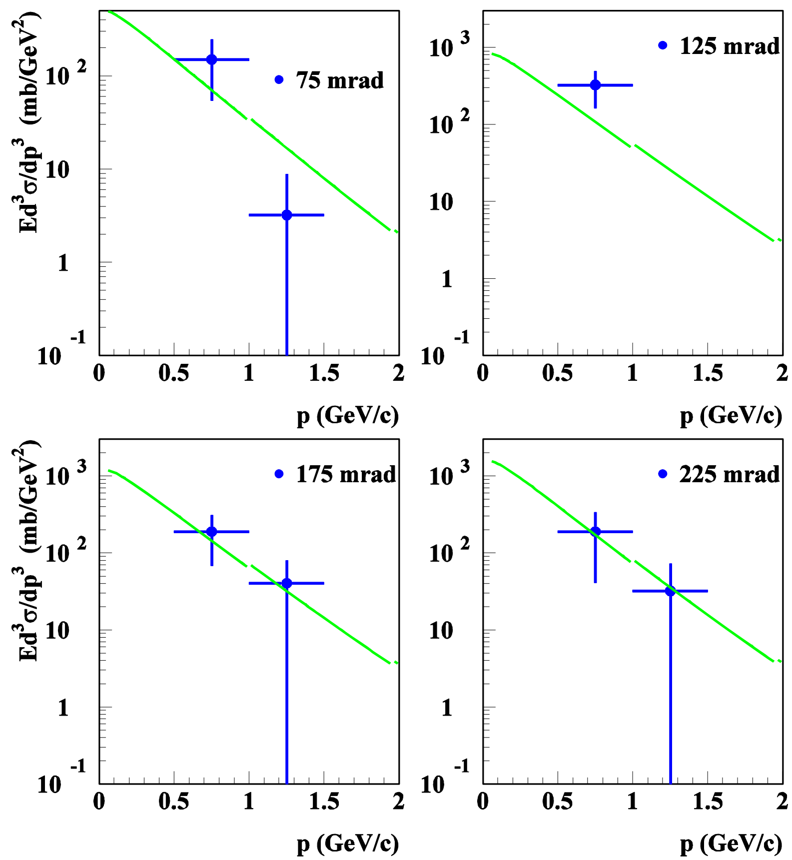
All angles - X^2/ndf =1.6

Two-fireball model vs HARP data

Green line – fit of 3 GeV/c HARP data,
red line – renormalized fit of 4 GeV/c FANCY data



π^- production in proton tantalum interaction at 3 GeV/c. HARP data.



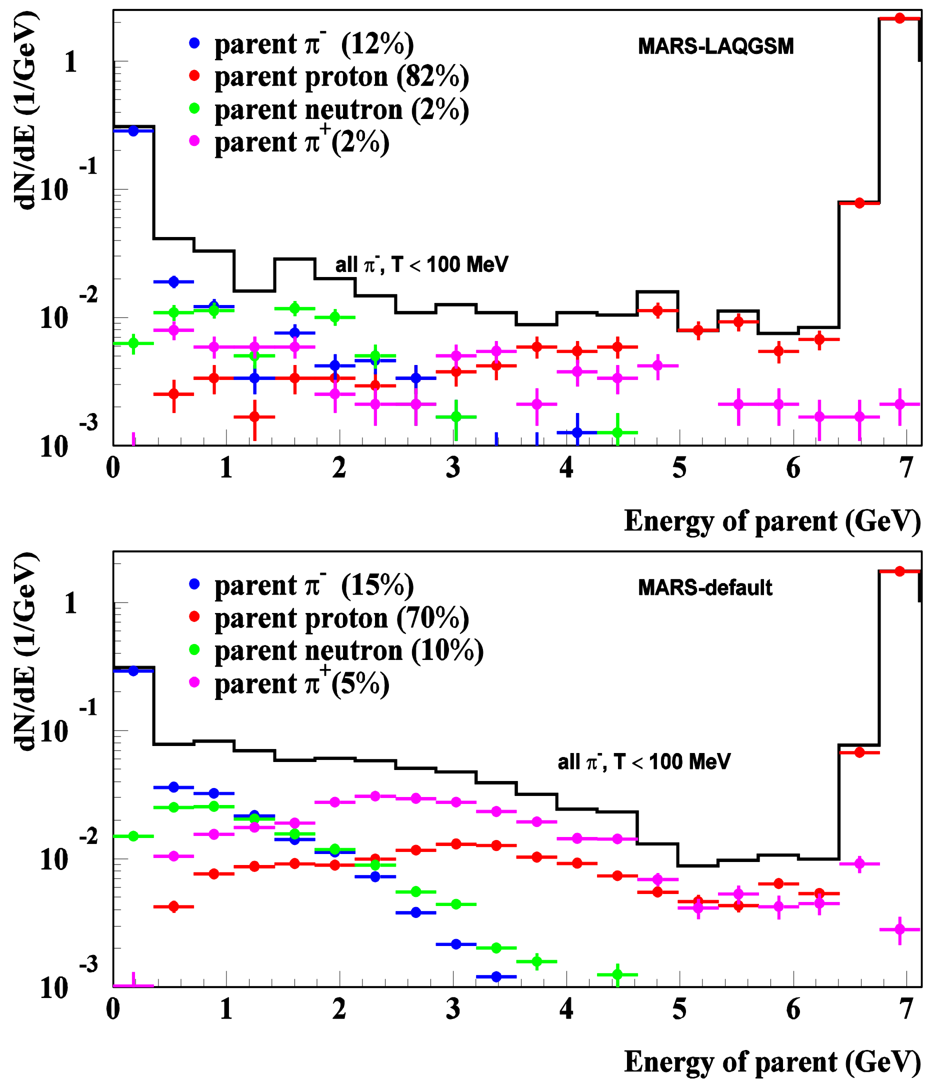
π^- production in proton tantalum interaction at 3 GeV/c.HARP data.

Large angles only - X^2/ndf = 1.1

All angles - X^2/ndf =1.2

Thick target effects - I

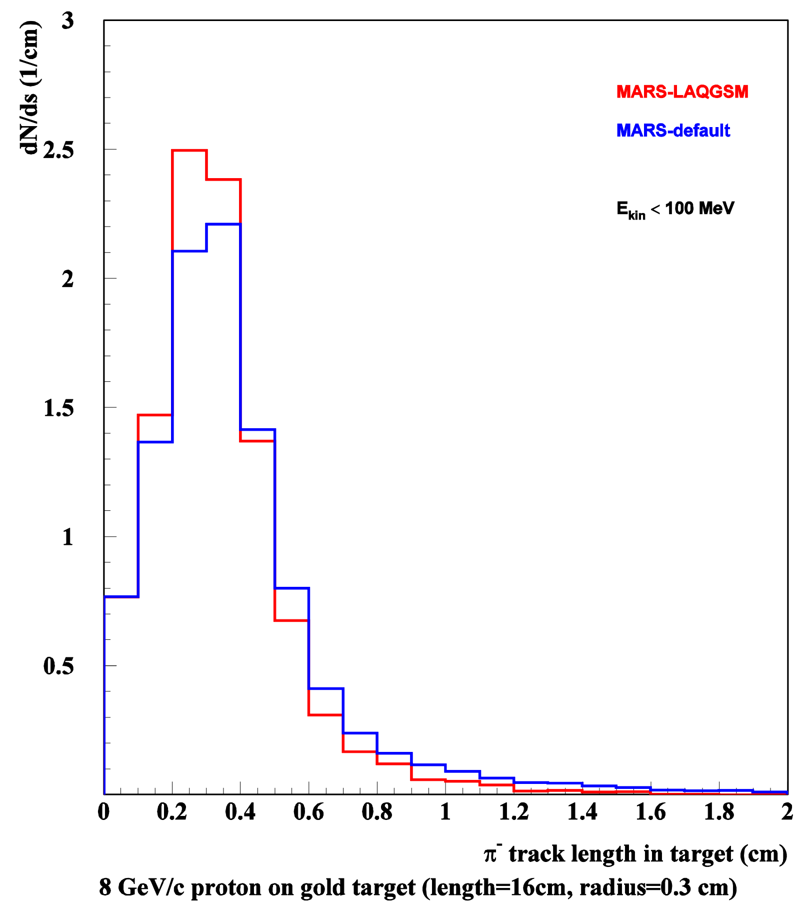
- Mu2e target is long (16 cm of gold) . It is about 1.6 nuclear interaction length
- Low energy pions could be produced in secondary, tertiary … interactions
- Pion with kinetic energies < 100 MeV are mostly produced in primary proton interactions and near elastic scattering of low energy negative pion
- Results obtained using MARS- default and MARS-LAQGSM are similar
- Low energy negative pion yield from thick target with about 10% precision is proportional to low energy pion yield in proton-nucleus interactions



8 GeV/c proton on gold target (length=16cm, radius=0.3 cm)

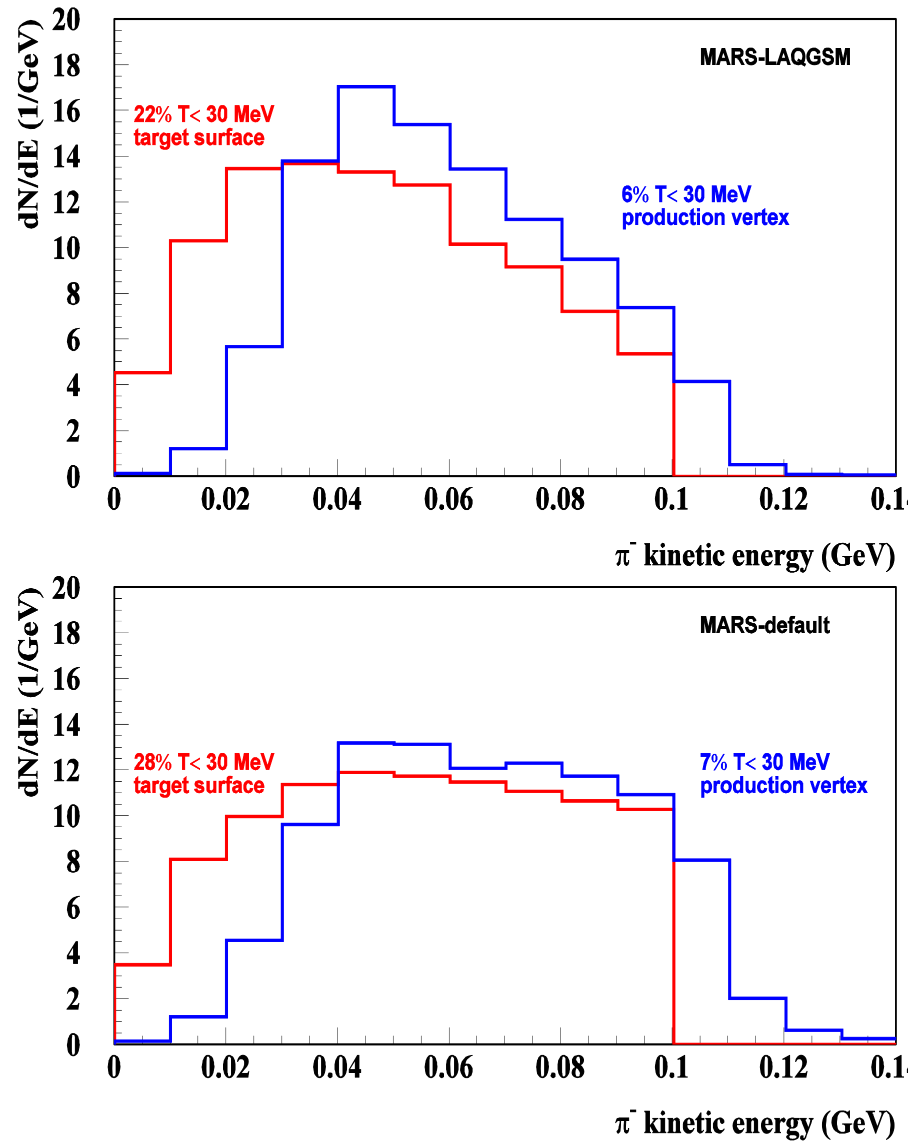
Thick target effects - II

- Mu2e target - gold, length is 16 cm, radius 0.3 cm. Gaussian beam with $\sigma_x = \sigma_y = 0.1$ cm.
- Mu2e mostly collects pion with kinetic energies < 100 MeV
- Distribution of track length of negative pion inside target has maximum near target radius
- Distributions obtained using MARS-LAQGSM and default version are similar
- Due to ionization energy losses energy of pion at target surface is lower than at production vertex



Thick target effects - III

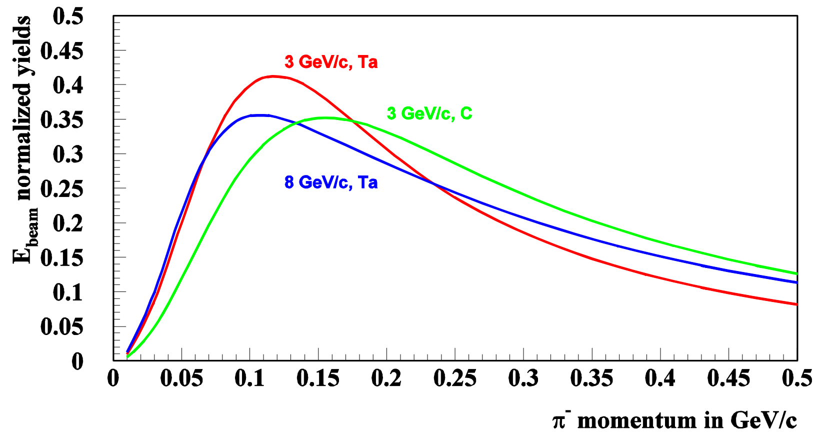
- There are no experimental data on low energy pion production (< 30 MeV) at proton mometum 3-10 GeV/c
- Most of pions with kinetic energies < 30 MeV at production vertex are stopped inside target
- Only 6-7% of pion with energy < 100 MeV at target surface are produced by pions which has energy < 30 MeV in production point
- HARP collaboration measured yield of pions with energy > 30 MeV in proton- nucleus collision (production vertex) at proton momentum of 3 and 8 GeV/c. This data could be used to estimate ratio of low energy negative pion yield at low and high proton energy

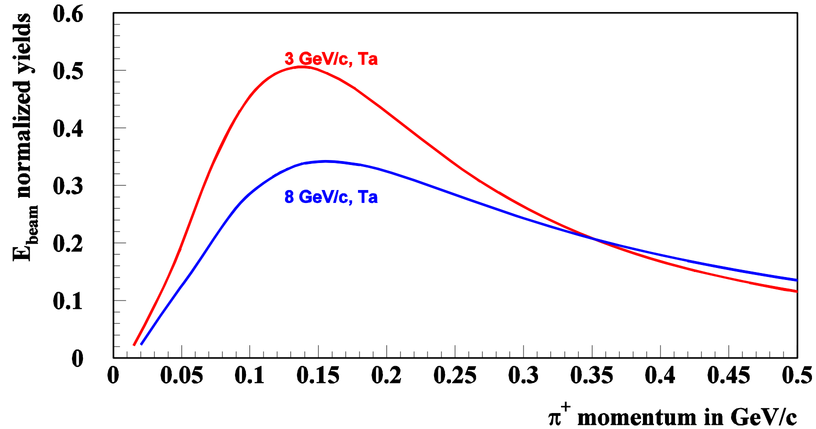


8 GeV/c proton on gold target (length=16cm, radius=0.3 cm)

Low energy pion yield

- For comparison of yields from thick target pion with kinetic energies > 30 MeV should be compared. Pion with lower energies are mostly stopped in target
- Low energy negative pion production from heavy target nearly linearly depend on kinetic energy of primary proton
- Low energy negative pion yield from tantalum is larger then yield from carbon at 3 GeV/c
- Normalized low energy positive pion yield is larger at 3 GeV/c than at 8 GeV/c





Conclusion

- Current versions of GEANT4 and MARS do not agree with data on low energy pion production in energy range from 3 to 10 GeV/c. FLUKA, PHITS ?
- Data on negative pion production looks like compatible, positive pion production measurement HARP and HARP-CDP does not agree each other.
- Experimental data on low energy pion production in energy range from 3 to 10 GeV/c can be fitted by two-fireball model
- Calculation based on this model predicts nearly linear rise of negative pion yield (< 100 MeV) with primary proton kinetic energy and more weak energy dependence for low energy positive pions

Normalized per kinetic energy pion yield is larger at 2 GeV than at 8 GeV