UNCERTAINTIES IN ENERGY DEPOSITION PREDICTIONS

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OUTLINE

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INTRODUCTION

Beam intensities can exceed 10^{14} protons per pulse, with a beam size as small as a fraction of a millimeter. Therefore, interaction of even a tiny fraction of such beams with targets, accelerator and detector components results in macroscopic effects: quenching of superconducting magnets, unacceptable temperature rise, melting, shock wave creation destructing the components, density reduction at an absorber and target axis up to a continuous hole drilling, fast buildup of radiation defects deteriorating mechanical and electrical properties and damaging multi-million dollar electronics components etc.

Mitigating these effects via beam abort and collimation systems, beam sweeping, light materials (sparse graphite) for targets and absorbers, liquid jets and rotating bands for targets, graphite shadow masks and sacrificial objects in front of the crucial components etc.

With conventional radiation protection on top of that.

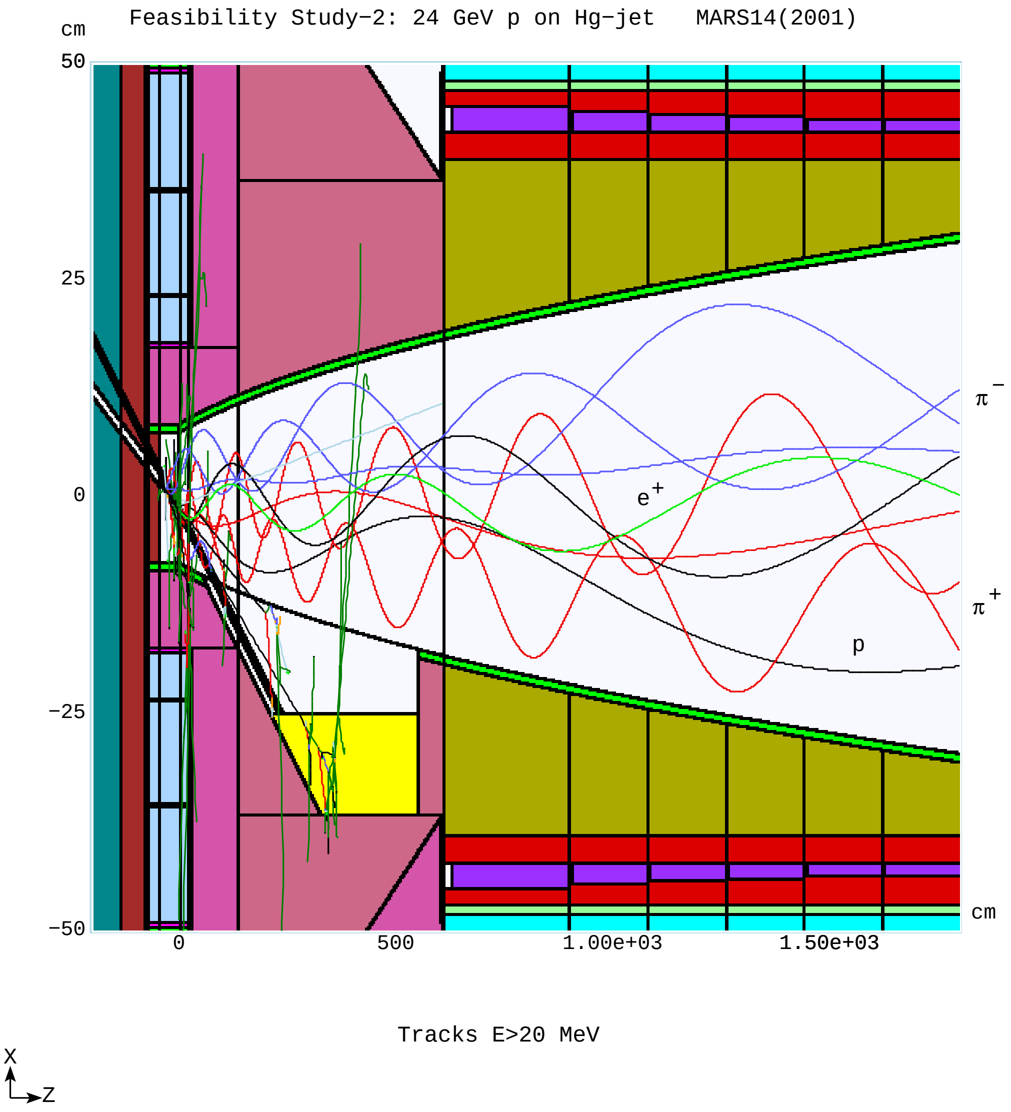
TARGETRY ISSUES

To achieve adequate parameters of secondary beams at any accelerator facility, it is necessary to produce and collect large numbers of particles of interest: neutrons at SNS, positrons at linear colliders, $\overline{p}$ at Tevatron, and pions in ν-experiments.

List of targetry issues includes – but not limited to – particle yield maximization, suppression of background particles transported down the beamline, protection of a focusing system including provision of superconducting coil quench stability, heat loads, radiation damage and activation of materials near the beam, spent beam handling, and numerous shielding issues from prompt radiation to ground-water activation.

All these issues must be addressed in detailed Monte Carlo simulations, done for all of the above applications (except SNS) with the MARS code. These issues are especially challenging for those setups involving bunched energetic proton, electron or heavy-ion beams, and requires in addition research in many areas including material radiation damage, compatibility, fatigue, stress limits, erosion and remote handling.

1-MW NEUTRINO FACTORY TARGET



ENERGY DEPOSITION: PHYSICS TO SIMULATE

On top of accurate treatment of usual things such as geometry, tracking, scoring, hadro-production, “neutronics” etc down to a micron size, the code must describe as precise as possible the following items vital for energy deposition density:

- Leading particles (elastic, diffractive and inelastic).
- Multiple Coulomb scattering (not a simple Gaussian or Molier!).
- Low-p_t π^0 production.
- Hadron, muon and heavy-ion electromagnetic processes with knock-on electron treatment and – at high energies – bremsstrahlung and direct pair production (not a simple dE/dx!).
- Full accurate modeling of electromagnetic showers generated in two processes above.
- Accurate tracking in magnetic field.
- Stopped hadrons and muons.
- Effective interfaces to ANSYS and hydrodynamics codes.

GENERAL-PURPOSE EVENT GENERATORS AND TRANSPORT CODES (2003)

Consistent soft and hard multiparticle production in hA, (AA), γA and νA at MeV to many TeV (**EG**) and corresponding full transport codes (**TC**) at a fraction of eV to many TeV in target/accelerator/detector/shielding systems of any complexity.

- **DPMJET-III (EG)** by J. Ranft et al, (AA)
- **MARS14 (EG+TC)** by N. Mokhov et al
- **FLUKA (EG+TC)** by A. Ferrari et al, (not GFLUKA or FLUKA86)
- **CEM2kph (EG)** by S. Mashnik et al ($E_0 \leq 3$ GeV)

Promising:

- LAQGSM (EG) – LANL (AA) (currently $E_0 \leq 100$ GeV)
- MCNPX (TC) – LANL (currently $E_0 \leq$ a few GeV)
- GEANT4 (TC) – CERN

2003 HEAVY ION TRANSPORT CODE STATUS

In maturity order:

- HZETRN (NASA): 1D, very approximate, $E_0 \leq 1$ GeV
- HETC-CYRIC (Tohoku Univ., Japan): $E_0 \leq 1$ GeV, good start!
- SHIELD (INR, Russia): currently $E_0 \leq 1$ GeV, good start!
- FLUKA (INFN, Italy): developments with DPMJET (→NASA, LHC)
- MARS14 (FNAL): developments with DPMJET and LAQGSM (→NASA, LHC, RHIC etc.)
- MCNPX (LANL): first steps
- GEANT4 (CERN): first steps

UNCERTAINTIES IN RADIATION ESTIMATES AT LHC (1)

The uncertainties of the radiation environment predictions arise from various sources and most of them are not easy to quantify. A very basic uncertainty is found already in the inelastic *pp* cross section at 7 TeV. To this adds the uncertainty in the structure of the events, i.e. the multiplicity and energy flow as a function of rapidity. These have been studied by using different event generators and a variation by about a factor of 1.3 was observed. This uncertainty gives the minimum error bar that should be always added to all LHC radiation predictions. For instance for an inner pixel detector, where effects due to geometry and scattering are negligible, this can be expected to be the dominant uncertainty.

Uncertainties from a "well-defined" source term: 30%.

UNCERTAINTIES IN RADIATION ESTIMATES AT LHC (2)

Elsewhere other effects are likely to be far more significant. Very important is the accuracy of the description of the geometry and the material composition. It is difficult to quantify this uncertainty, but experience has shown that already rather small changes, which easily go unnoticed, can change the result by a factor of 2 or even 3 when a shielding is designed to give an overall reduction by 3 orders of magnitude – like the CMS forward shielding. In the case of the CMS shielding the geometry description slowly becomes more realistic when detailed designs emerge and get implemented into the simulations. In general these tend to increase estimates because detailed design usually introduce more cracks. It seems justified to argue that while the estimates tend to increase the uncertainty due to geometry inaccuracies should correspondingly decrease. While this is most probably the case, it is just as difficult to quantify as the original uncertainty.

Uncertainties from simplifications in the description of the geometry and the material composition: range from negligible in simple cases to up to a factor of 2 to 3 (easily) in complex, extended systems with "cracks" etc.

UNCERTAINTIES IN RADIATION ESTIMATES AT LHC (3)

The third source of uncertainty arises from the accuracy of the simulation code itself, i.e. given certain well defined conditions, how accurately can the code predict the radiation environment. This is exactly what benchmarking experiments try to test, but as discussed above they are confronted with uncertainties in the real geometry (like composition of concrete) and purely experimental uncertainties. The importance of this third source of uncertainty is estimated by comparing the results of codes (e.g., FLUKA and MARS) in a simple well-defined geometry. The advantage of this, compared to an experiment, is that the other uncertainties discussed above can be completely removed. The obvious disadvantage is that the codes could be wrong the same way. The latter worry is diminished if two completely independent codes are used and this again suggest that a comparison of FLUKA with MARS is very reasonable since these two codes are based on different physical models, tracking algorithms and geometry description.

Uncertainties from simulation codes: a few % to 30% with the appropriate codes to a factor of 2 to 3 (easily) with "immature" codes.

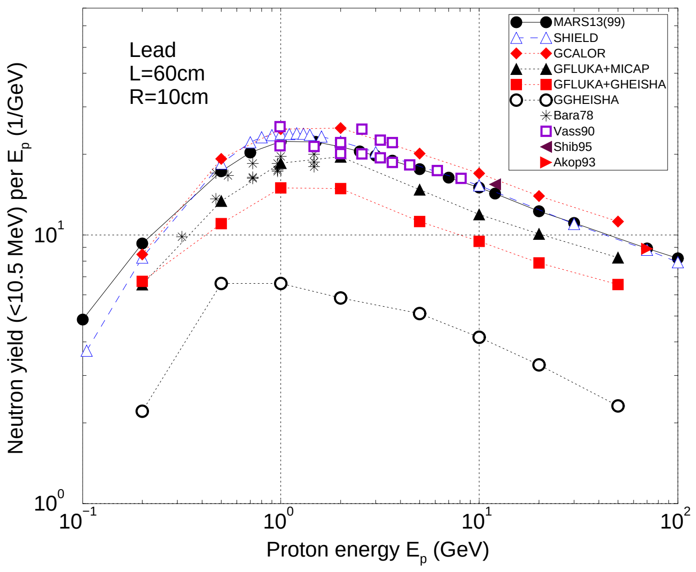
BENCHMARKING

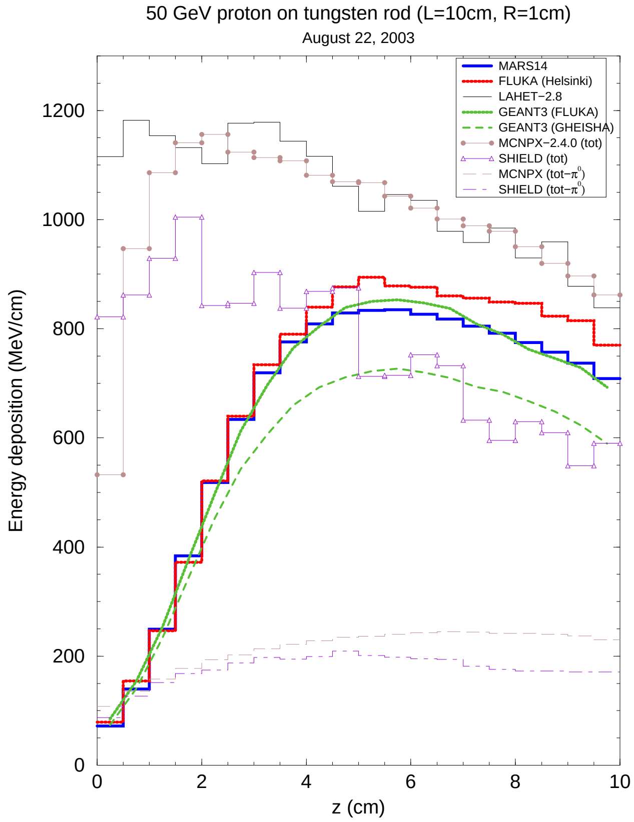
X-sections, double-differential x-sections, electromagnetic physics, targets, absorbers, SATIF-3, QUADOS-2003, CERN-2003, tungsten rod.

2003 SUMMARY ON UNCERTAINTIES IN ENERGY DEPOSITION PREDICTIONS AT LHC

Based on numerous international benchmarking on micro and macro levels, status of the current event generators, thorough sensitivity analysis in the inner triplet over last seven years (event generators, physics other than event generators, geometry, materials, fields, crossing etc), numerous discussions and analyses of the results by the community over the same seven years, understanding of the Monte Carlo aspects, **we would claim that we predict the maximum power density in the coils with an accuracy better than 30%**. This should be true for the innermost layers of the SC coils (just a beginning of showers with almost no attenuation) for the *given* configuration, not for the one with possible changes. The uncertainty is higher at larger radii and larger distances from the IP, often because of statistics. **Integral energy deposition and integral flux values** in the components such as azimuthal average, power dissipation (dynamic heat load) **are predicted with about 10-15% accuracy**. **Residual dose rates are estimated within a factor of two to three.**

NEUTRON YIELD AND ENERGY DEPOSITION





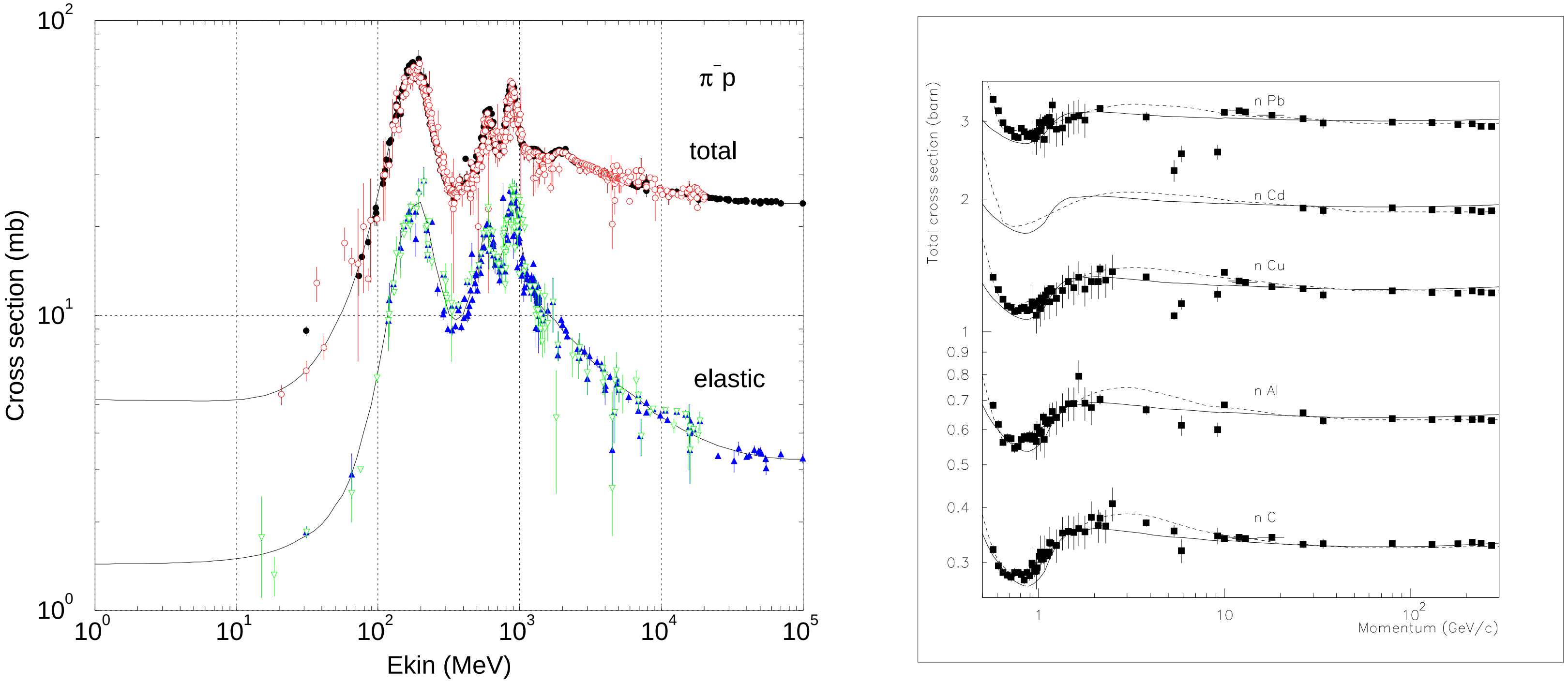
CONCLUSIONS

Several codes can predict maximum energy deposition density for hadron, electron, photon and muon MeV to TeV beams with better than 30% accuracy, for well-defined geometry and source term.

More work needs to be done: better, faster electromagnetic shower algorithms coupled to hadron transport codes, heavy-ion beams.

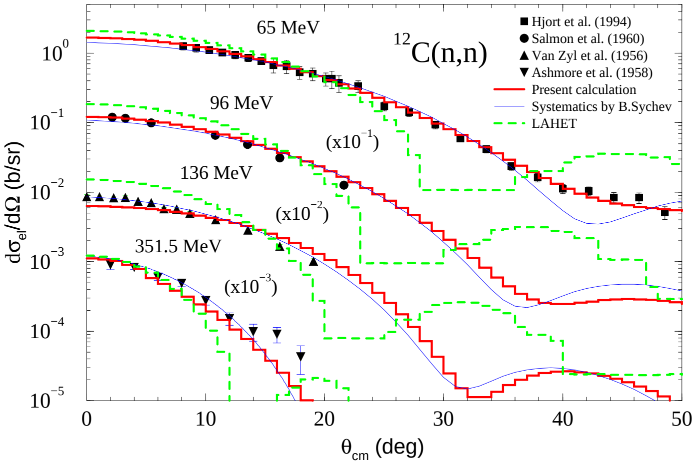
International benchmarking on energy deposition in targets is quite desirable, at the level of “neutronic” activity.

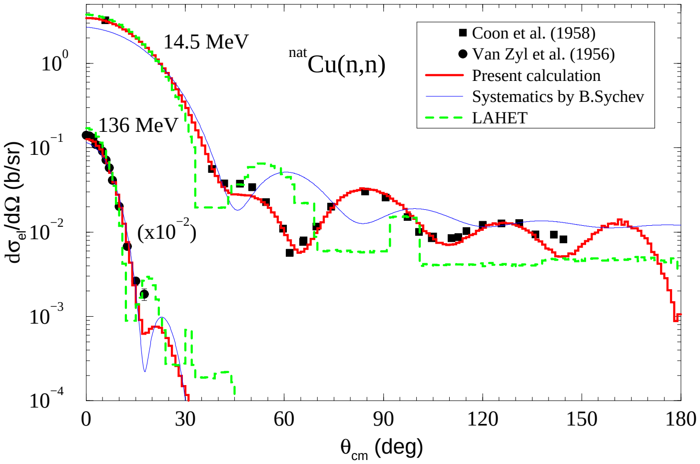
MARS X-SECTIONS *vs* DATA



MARS cross sections in comparison with experimental data: (a) σ_{tot} and σ_{el} for $\pi^- p$ collisions as a function of pion kinetic energy; (b) σ_{tot} for neutrons *vs* beam momentum.

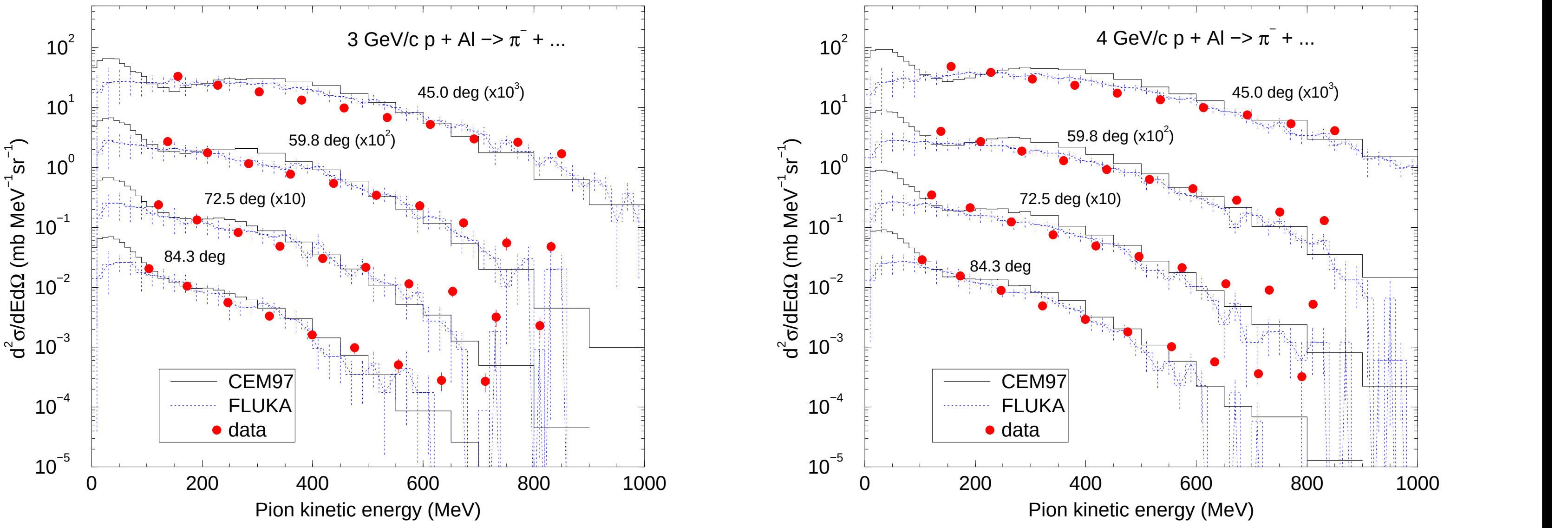
MARS14 ELASTIC SCATTERING (1)





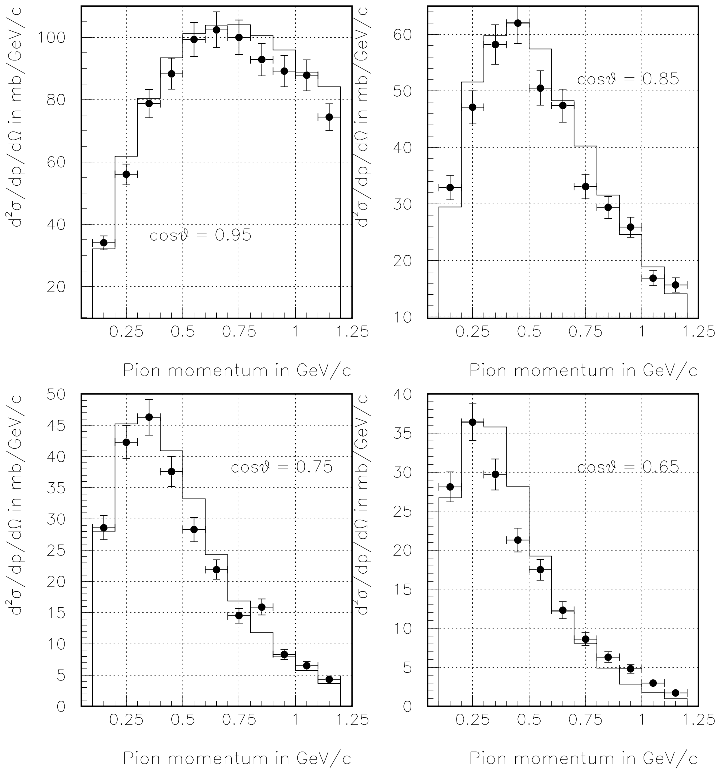
MARS elastic model at E<5 GeV is based on evaluated nuclear data from LA-150, ENDF/HE-VI and Sukhovitski, Chiba et al supplied with phenomenology where needed. At E>5 GeV it is a set of phenomenological models.

MARS/CEM AND FLUKA *vs* DATA

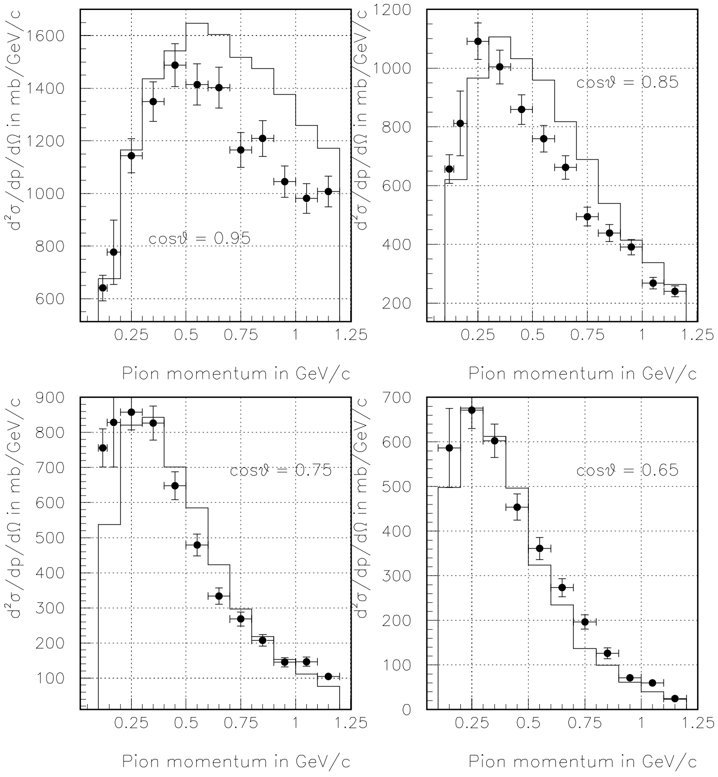


Comparison of MARS/CEM and FLUKA calculated pion spectra to data by Chiba et al. at incident proton momenta of 3 and 4 GeV/c on aluminum nucleus

MARS14 *vs* E-910 DATA



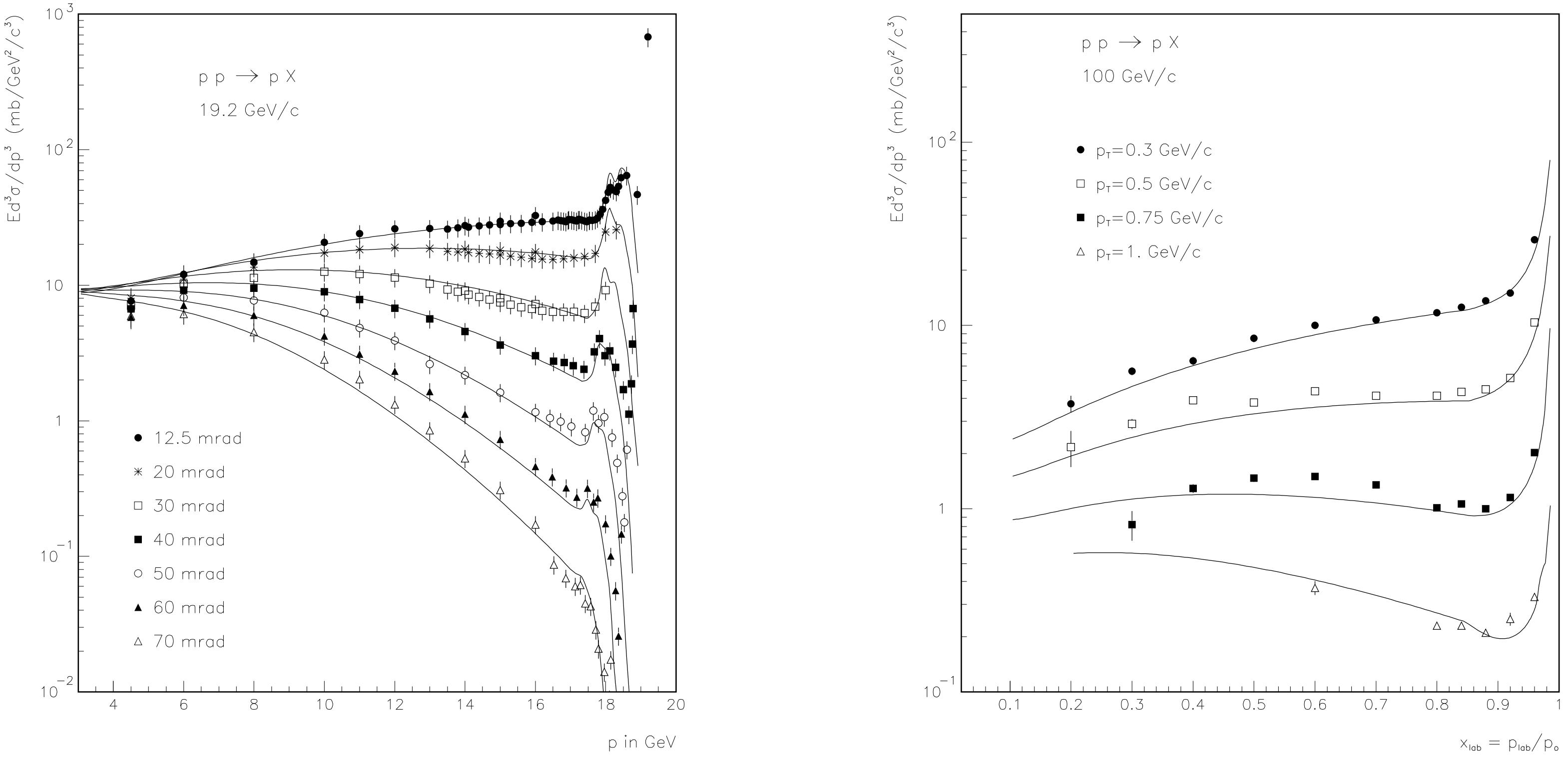
Negative pion production in proton berillium interaction at 12.3 GeV/c



Negative pion production in proton gold interaction at 17.5 GeV/c

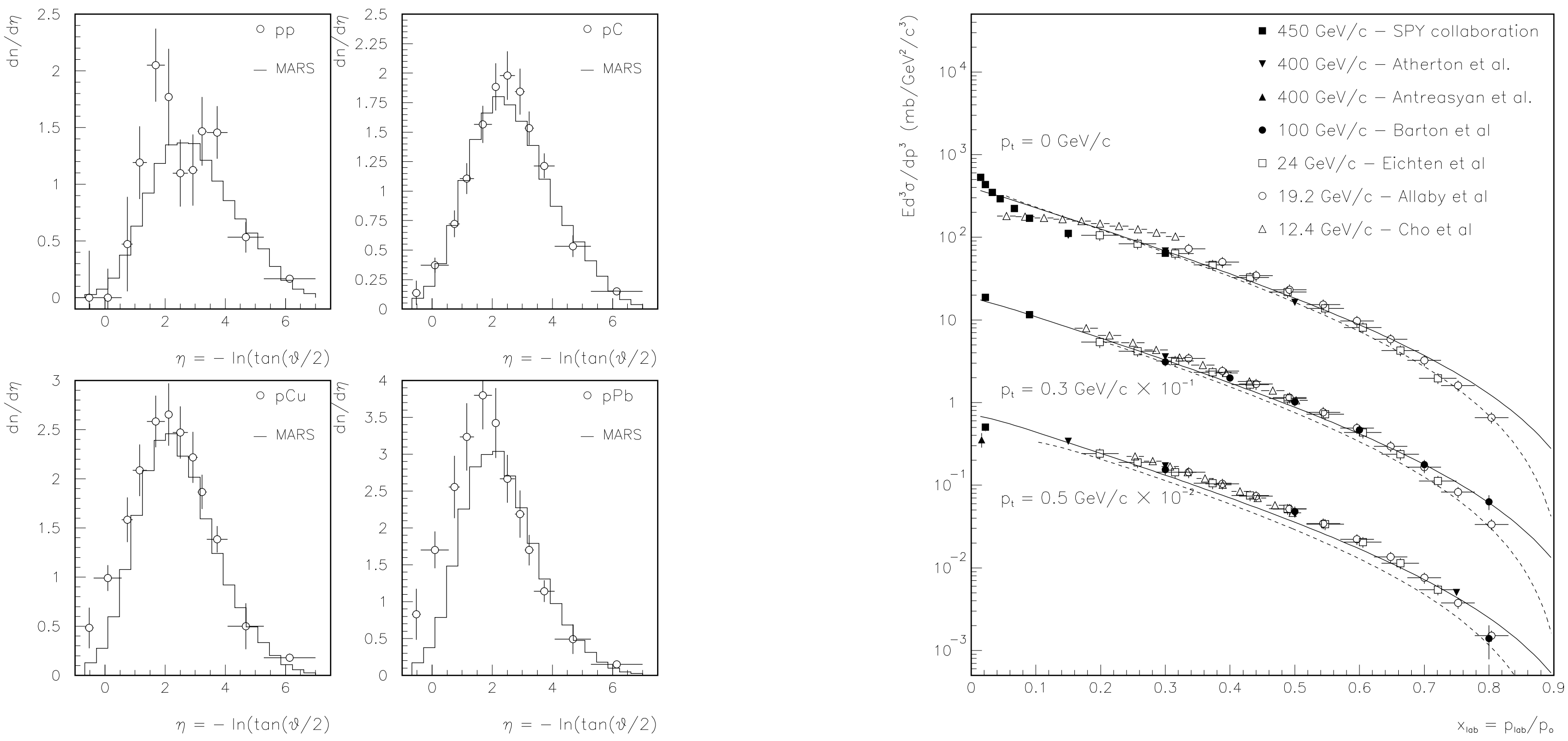
π^- spectra in *pBe* at 12.3 GeV/c (left) and in *pAu* at 17.5 GeV/c (right) as calculated with MARS (histogram) and measured in the BNL E-910 (symbols).

PROTON PRODUCTION



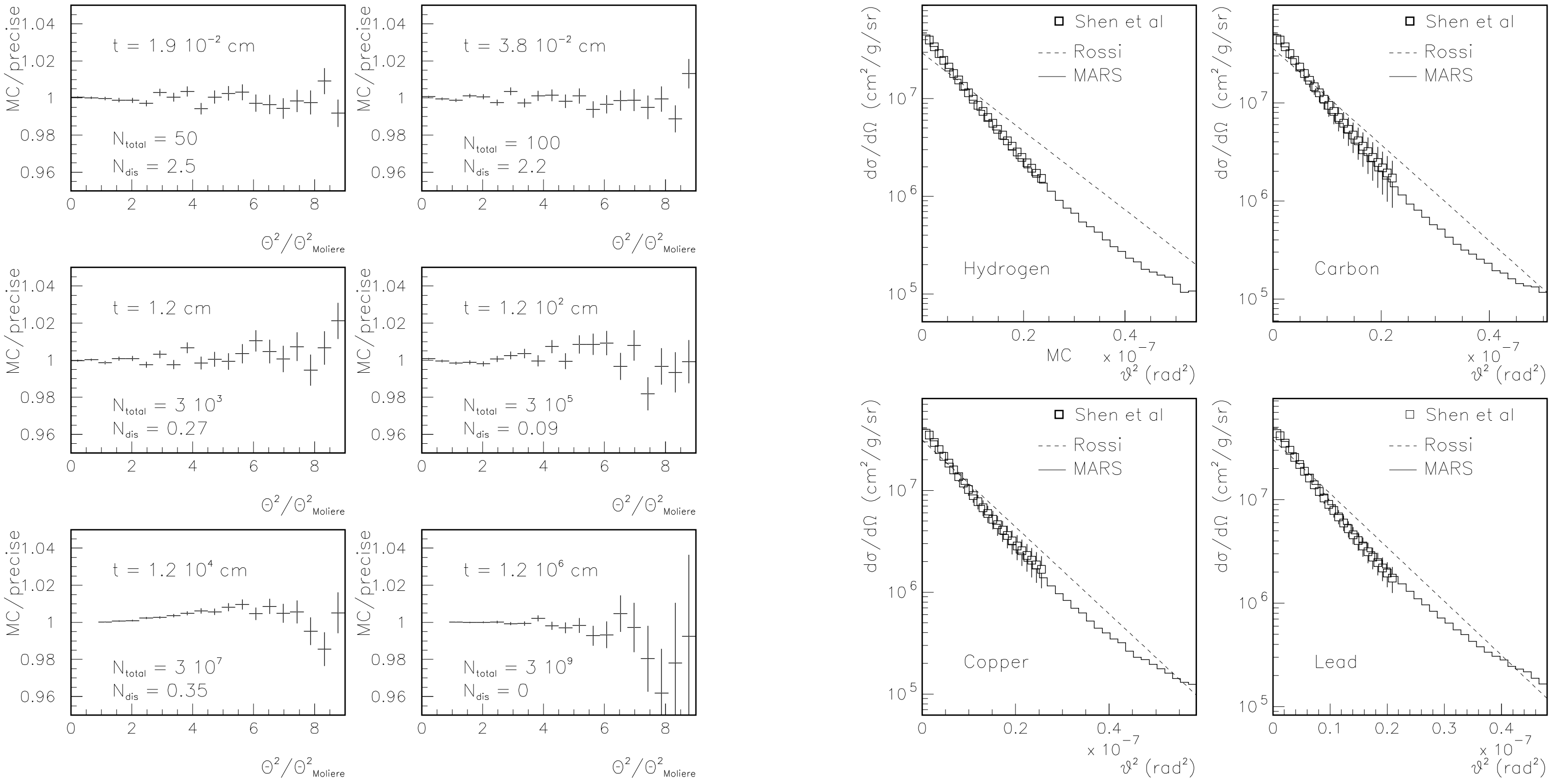
Proton spectra in *pp*-collisions at 19.2 GeV/c (left) and 100 GeV/c (right) as calculated with MARS (lines) and measured (symbols).

MARS14 *vs* DATA



Charged particle ($\beta > 0.85$) production in *pA* interactions at 50 GeV (left) and π^+ production in *pBe* interactions at 12.4 to 450 GeV/c (right) as calculated with MARS (lines) and measured (symbols).

MULTIPLE COULOMB SCATTERING (2)



Angular distribution after a lithium absorber (left) and after 0.05 X_0 of different absorbers irradiated by 70 GeV protons (right).