PION PRODUCTION FOR NEUTRINO FACTORIES AND MUON COLLIDERS

N. Mokhov, K. Gudima, J. Strait, S. Striganov

Fermilab

Workshop on Applications of
High Intensity Proton Accelerators
Fermilab
October 19-21, 2009

Outline

- Pion Production and Collection
- Event Generators in MARS15
- Recent Benchmarking
- Beam Energy Dependence*

*) For Project-X beams, in comparison with model-independent analysis of HARP data

Target System Optimization*

Thorough MARS optimization of target system in 1999-2001 for maximum yield of pions/muons at the end of decay channel for 4 to 30 GeV proton beams (with many ideas by Bob Palmer):

- Gain from high-Z target materials, especially at the high-energy end.
- Hybrid solenoid at $B \times R_a^2 = 1125$ T×cm^2 with B=20T and R_a=7.5cm followed by a matching section (to 19m) and decay channel (R=30cm, B=1.25T) to ~50 m with SC coils protected by water-cooled tungsten-carbide balls.
- Open mercury jet (R=5 mm) tilted at 100 mrad with 2λ beam-jet interaction region.
- Proton beam at 67 mrad with RMS beam spot size of 1.5 mm.
- Particle yield Y at z~50 m grows with beam energy E_p, while Y/E_p has a broad maximum at E_p ~ 6 GeV.

*) See several NM's journal papers of 1999 to 2001.

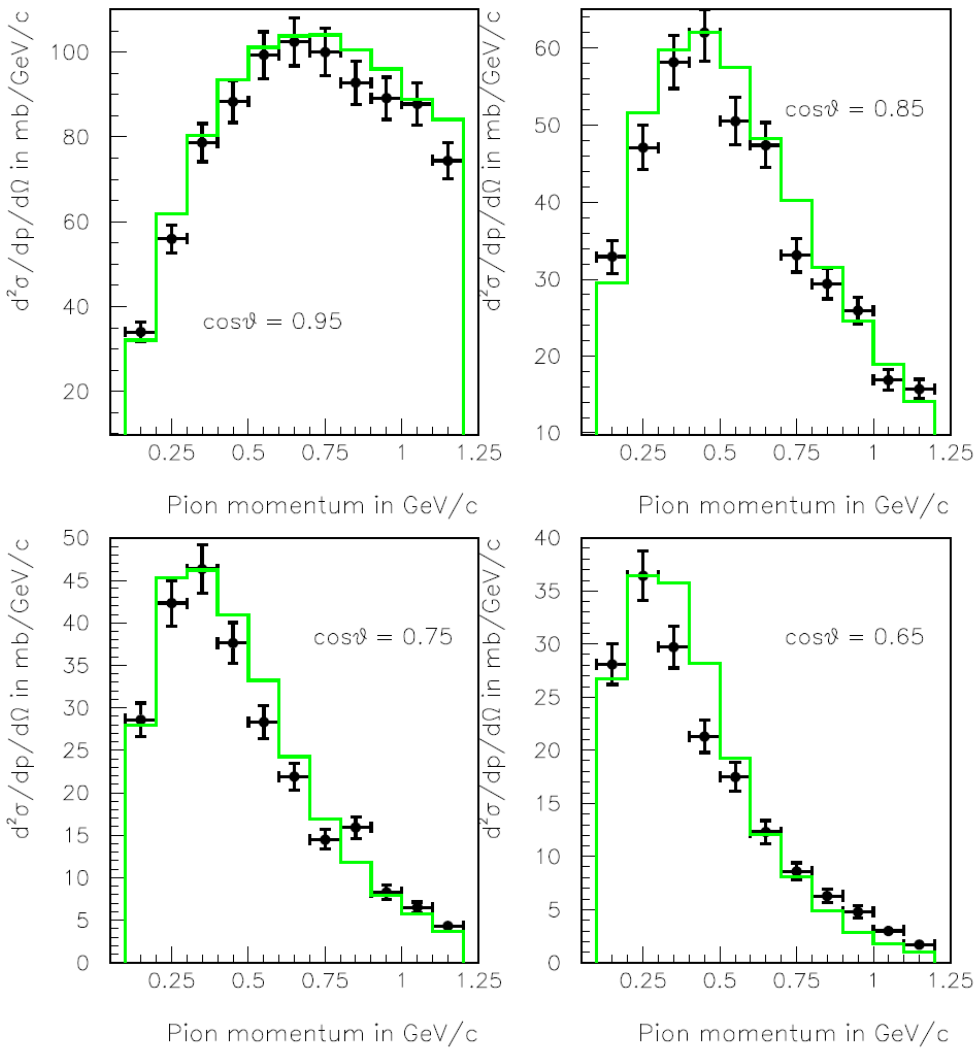
MARS15 Event Generators: Option 1 (default)

Inclusive phenomenological model from 3-5 GeV to tens of TeV and exclusive Cascade-Exciton Model code CEM03, combined with Fermi break-up model, coalescence model, and Generalized Evaporation-fission Model (GEM2). Recent multi-fragmentation extension.

MARS15 Event Generators: Option 2 (LAQGSM)

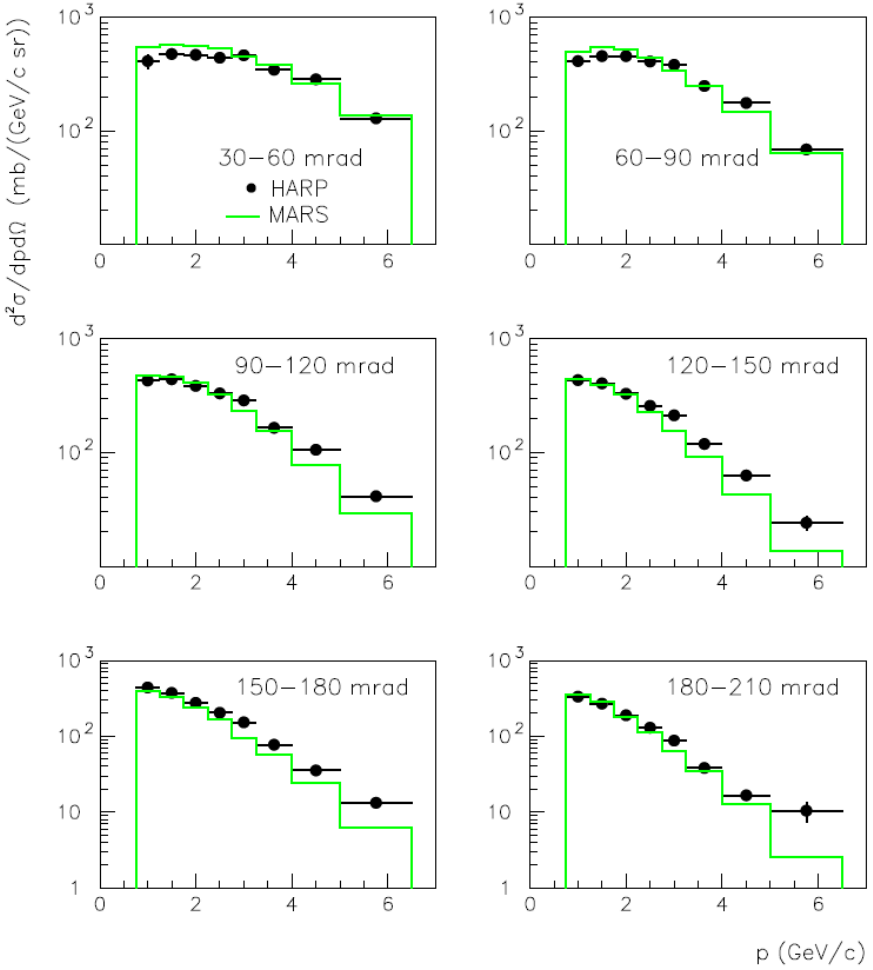
The Los Alamos Quark-Gluon String Model code, LAQGSM, for photon, hadron and heavy-ion projectiles at a few MeV/A to about a few TeV/A. Shares with CEM similar models/modules at E < 3-5 GeV. Provides a power of full theoretically consistent modeling of exclusive and inclusive distributions of secondary particles, spallation, fission, and fragmentation products. Substantially improved and extended (LAQGSM09) over last 4 months. Just recently switched to Δ and N* resonance production and interaction at E < 4.5 GeV with pions produced in Δ decays.

Inclusive Pion Production (Default)

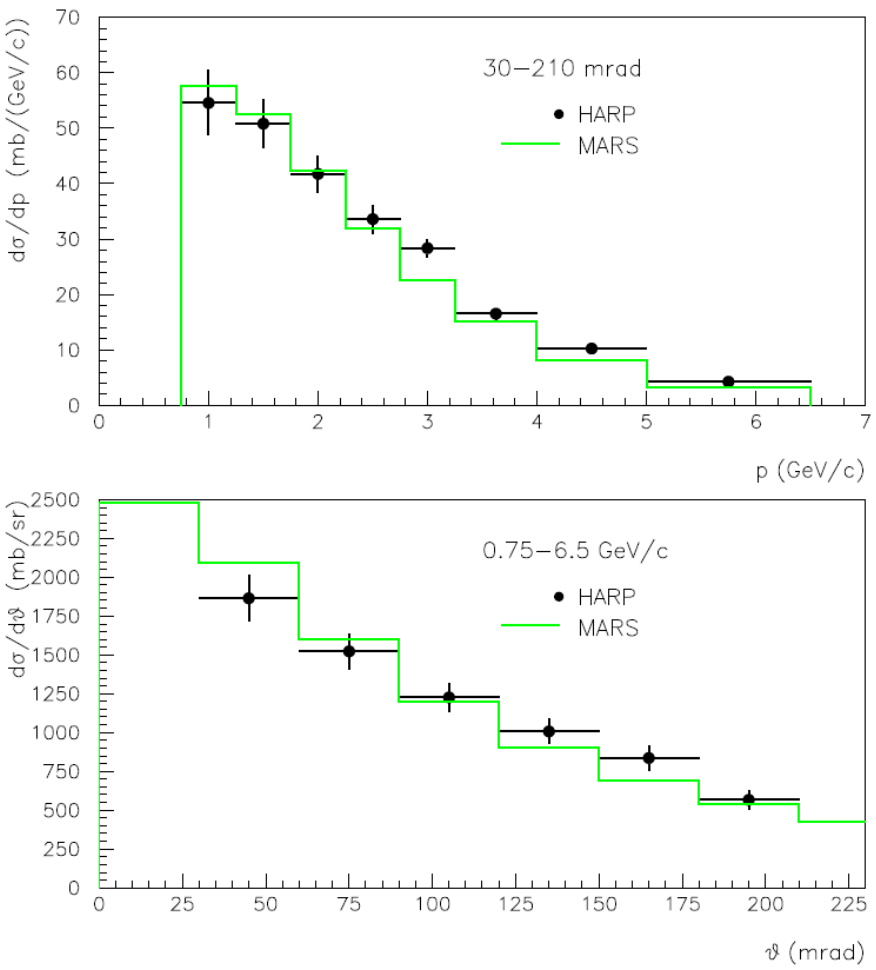


12.3 GeV/c p+Be -> π^- vs BNL E910

MARS15 vs HARP for p+Al → π^+X at 12.9 GeV/c



π^+ production in proton aluminum interaction at 12.9 GeV/c



π^+ production in proton aluminum interaction at 12.9 GeV/c

MARS15 (default)

MARS15 & Geant4 Pion Production vs HARP for pBe at 5 GeV/c

July 22, 2009

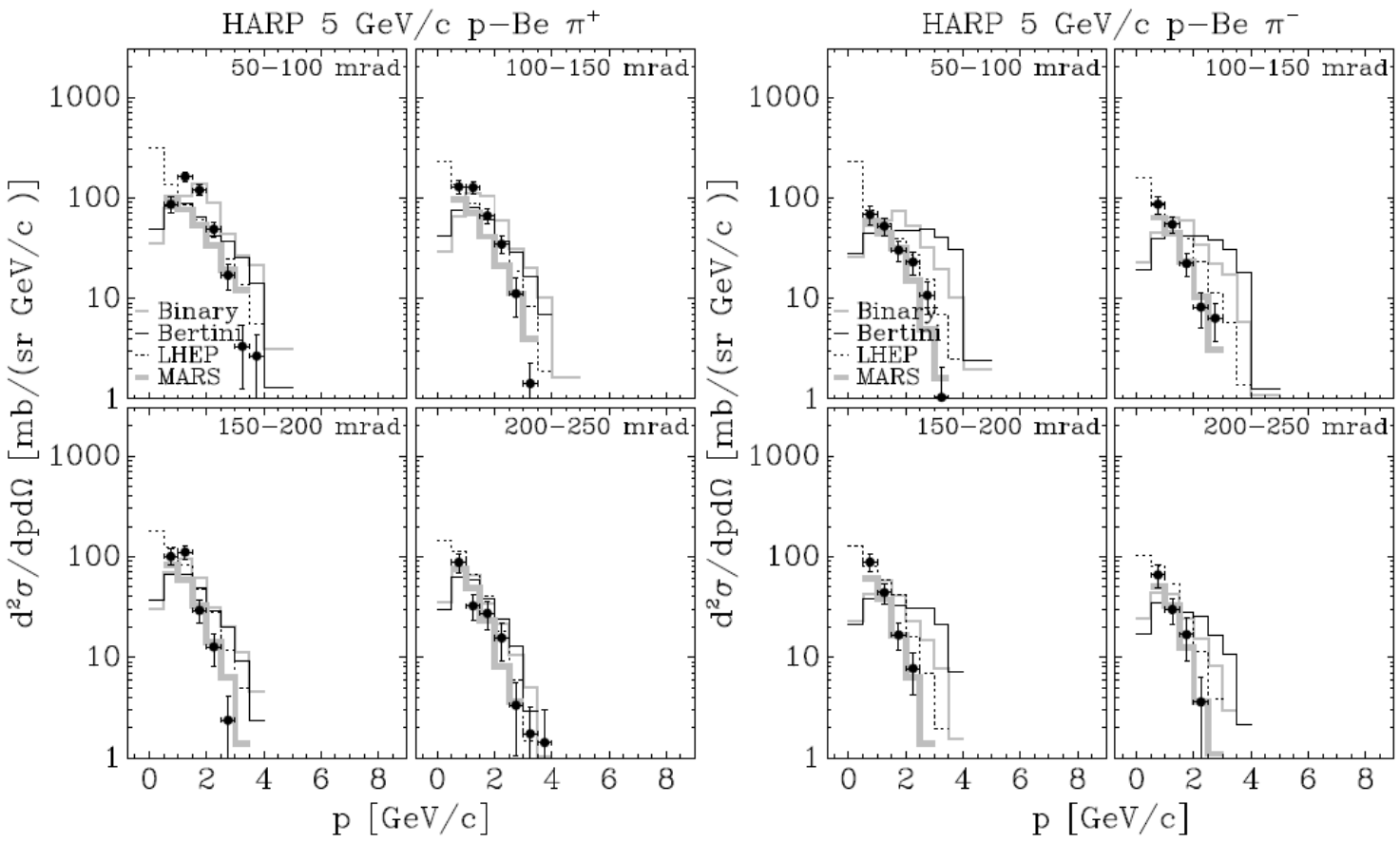


FIG. 15: Comparison of HARP double-differential $\pi^{\pm}$ cross sections for p–Be at 5 GeV/c with GEANT4 and MARS MC predictions, using several generator models (see text for details): Binary model grey line, Bertini model black solid line, LHEP model dotted line, MARS model grey solid line.

MARS15 & Geant4 Pion Production vs HARP for pTa at 8 GeV/c

July 22, 2009

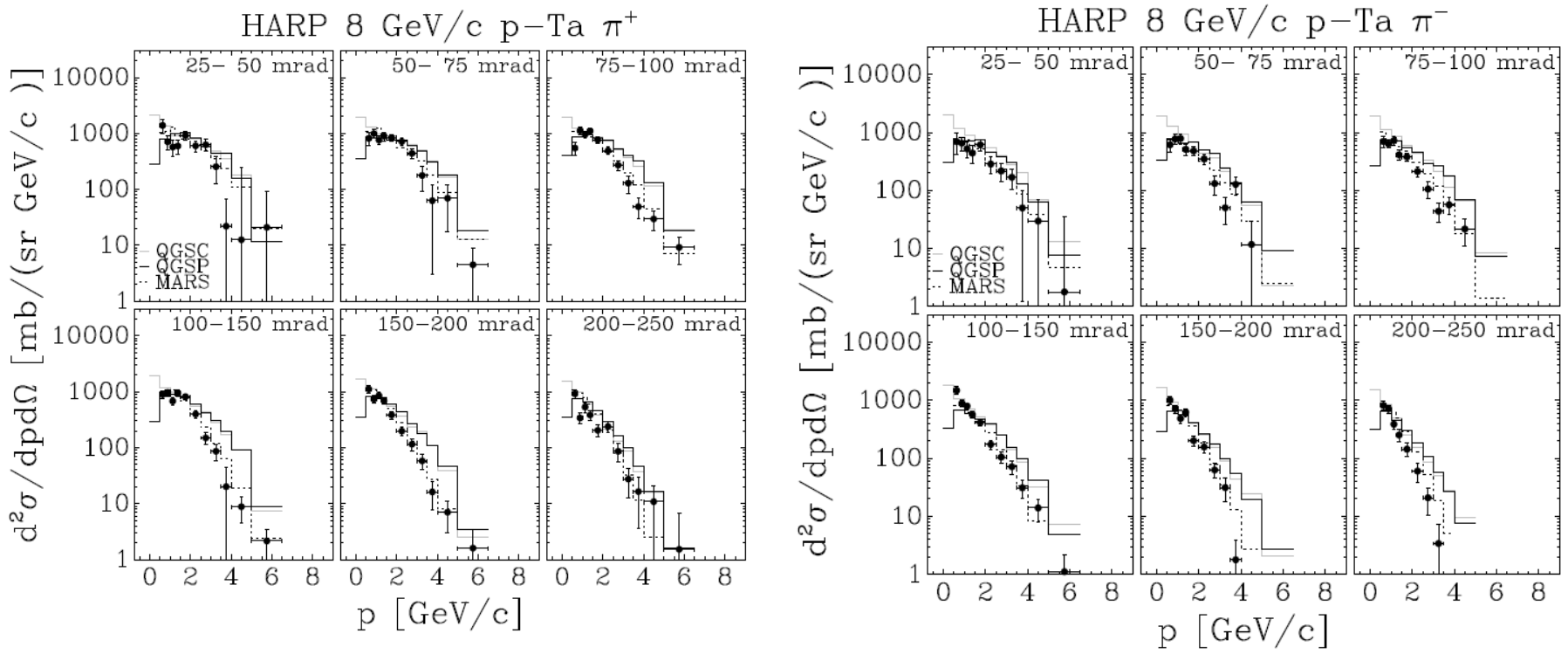


FIG. 20: Comparison of HARP double-differential $\pi^{\pm}$ cross sections for p–Ta at 8 GeV/c with GEANT4 and MARS MC predictions, using several generator models (see text for details): QGSC model dotted line, QGSP model black solid line, MARS dashed line.

MARS15 & Geant4 Pion Production vs HARP for pBe and pTa

July 22, 2009

TABLE VIII: Computed χ^2 between data and MonteCarlo simulations, assuming a 20% systematics on simulation

	3 GeV		5 GeV		8 GeV		12 GeV	
	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-
ndof	16	16	32	32	36	36	40	40
model	Beryllium							
Bertini	181.1	156.8	340.6	375.8	517.4	342.6	762.7	347.9
Binary	180.8	196.9	272.6	474.5	284.6	401.7		
LHEP	149.8	43.2	115.6	283.5	128.2	118.5	153.7	160.5
QGSP					112.2	210.6	124.9	154.3
FTFP						323.2	55.7	172.1
MARS	9.4	46.2	23.1	13.9	26.3	52.7	24.2	26.2
model	Tantalum							
Bertini	113.8	110.8	165.2	377.8	328.0	193.9	540.5	248.7
Binary	147.8	145.4	197.9	435.1	224.3	284.4		
LHEP	116.1	22.0	94.9	255.8	91.8	76.0	73.2	109.1
QGSP					163.3	169.2	38.8	82.9
FTFP						96.4	69.0	55.6
MARS	44.9	25.9	83.4	65.8	48.8	20.7	26.6	15.9

MARS15 & Geant4 Pion Production vs HARP for pBe and pTa

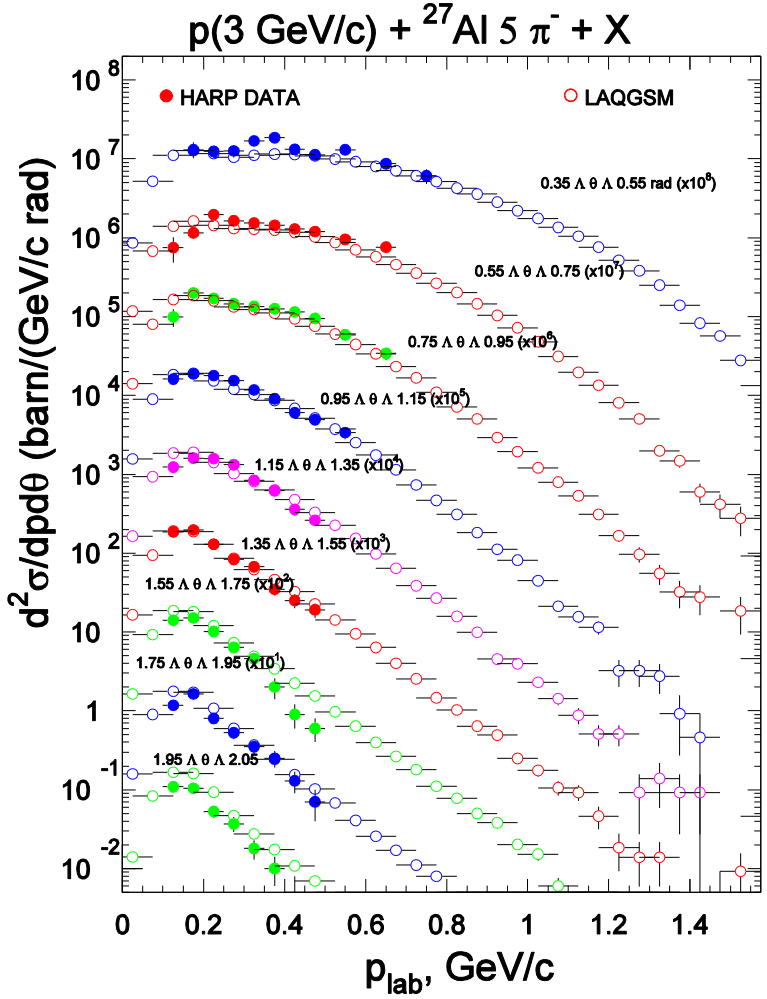
July 22, 2009

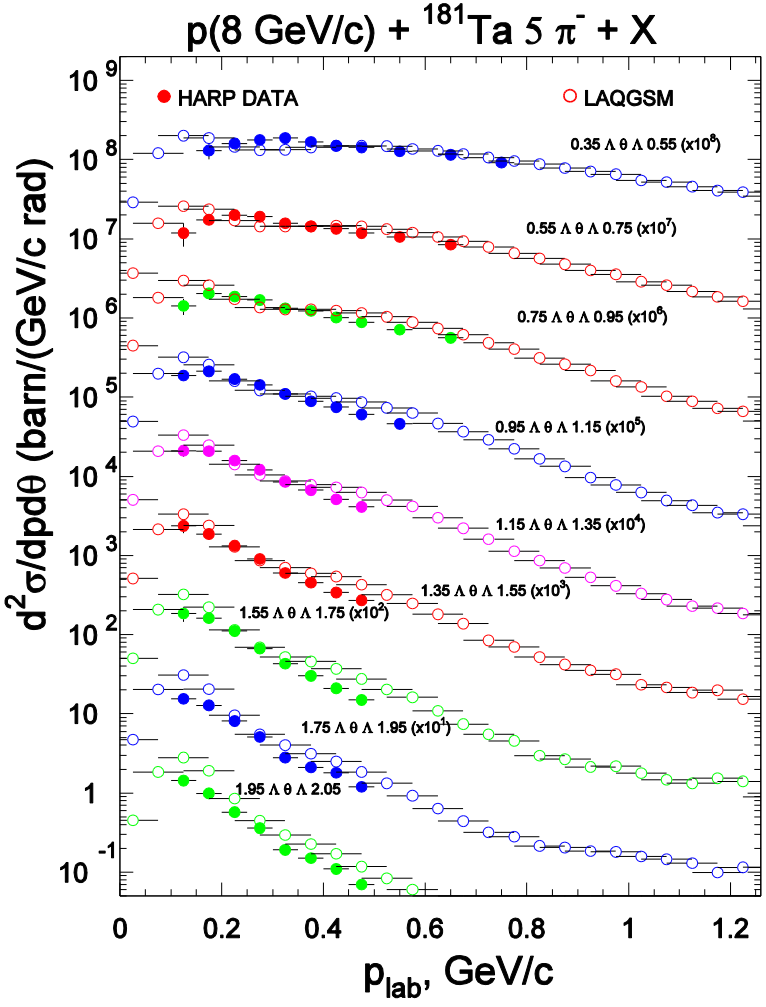
TABLE X: Normalization factors data-simulation.

model	Be 3 GeV		Ta 3 GeV		Be 5 GeV		Ta 5 GeV		Be 8 GeV		Ta 8 GeV		Be 12 GeV		Ta 12 GeV	
	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-
Bertini	0.35	1.02	0.45	0.53	0.70	1.12	0.29	0.35	1.22	1.54	0.84	1.08	1.75	1.81	1.27	1.50
Binary	0.36	0.75	0.28	0.34	0.73	0.88	0.16	0.23	0.99	1.05	0.50	0.56				
LHEP	0.40	0.86	0.81	0.91	0.76	0.98	0.36	0.45	0.78	0.91	0.58	0.66	0.75	0.82	0.54	0.59
QGSP									1.40	1.43	0.80	0.75	0.80	0.88	0.64	0.67
FTFP											0.46	0.65	1.00	1.10	0.63	0.77
MARS	0.83	1.29	1.10	1.16	1.21	1.38	1.17	1.35	1.10	1.21	0.90	0.85	1.02	1.02	0.92	0.82

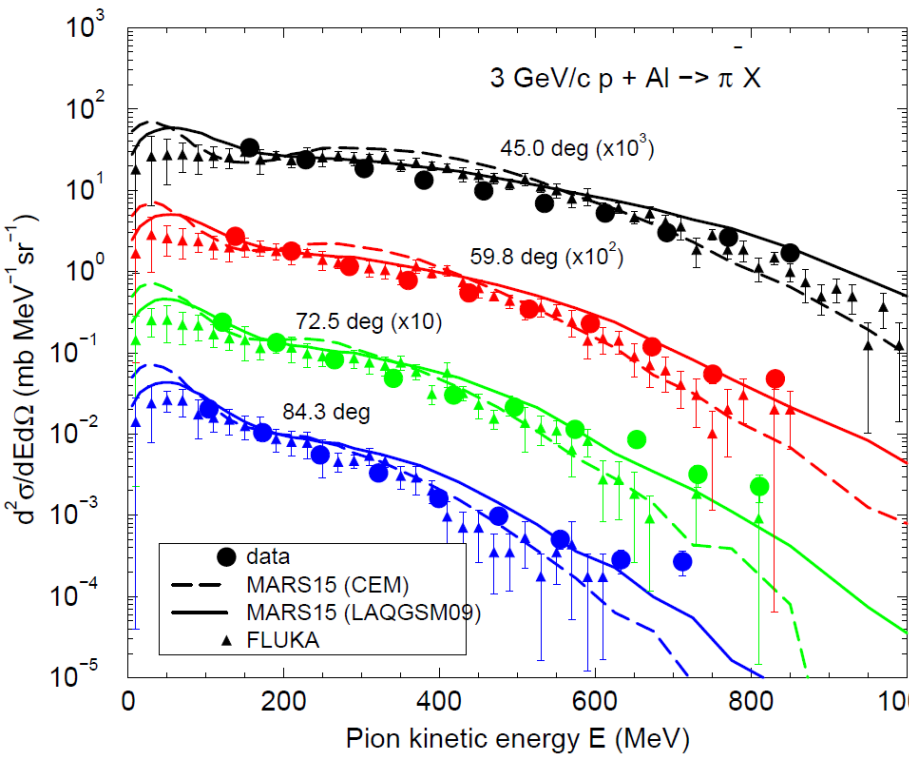
*) No inclusive (default) MARS model tuning to HARP data yet (I wish I did).
Also waiting for first MIPP published results (promised by the New Year).

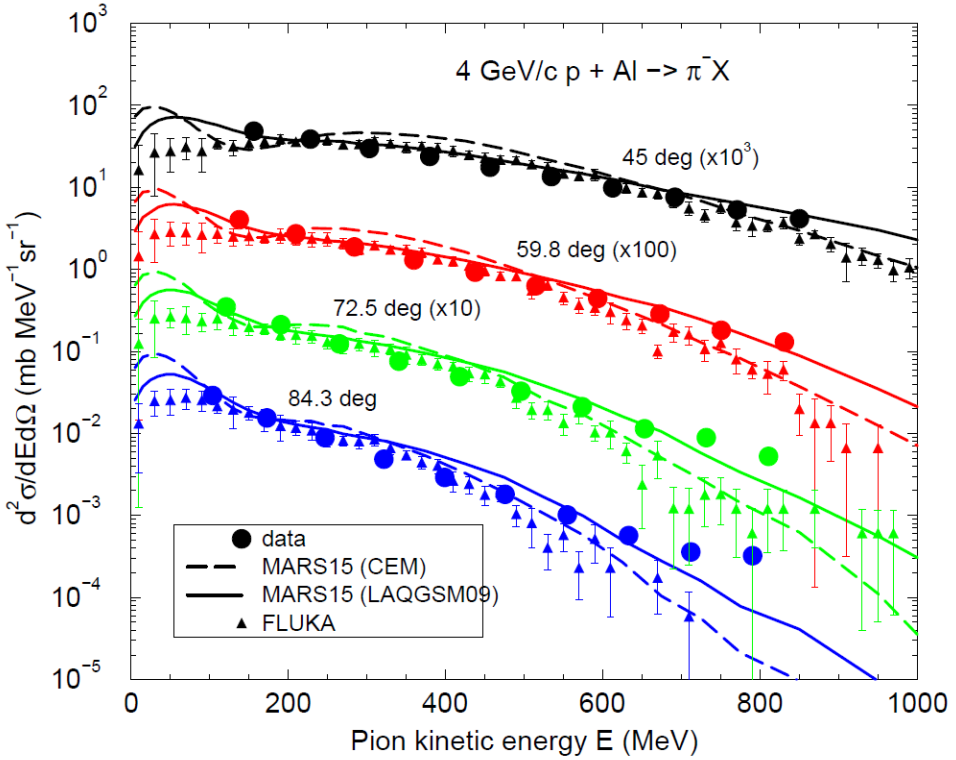
LAQGSM09 in MARS15: HARP 3 & 8 GeV/c in pAl & pTa





LAQGSM09 in MARS15: KEK 3 & 4 GeV/c p+Al

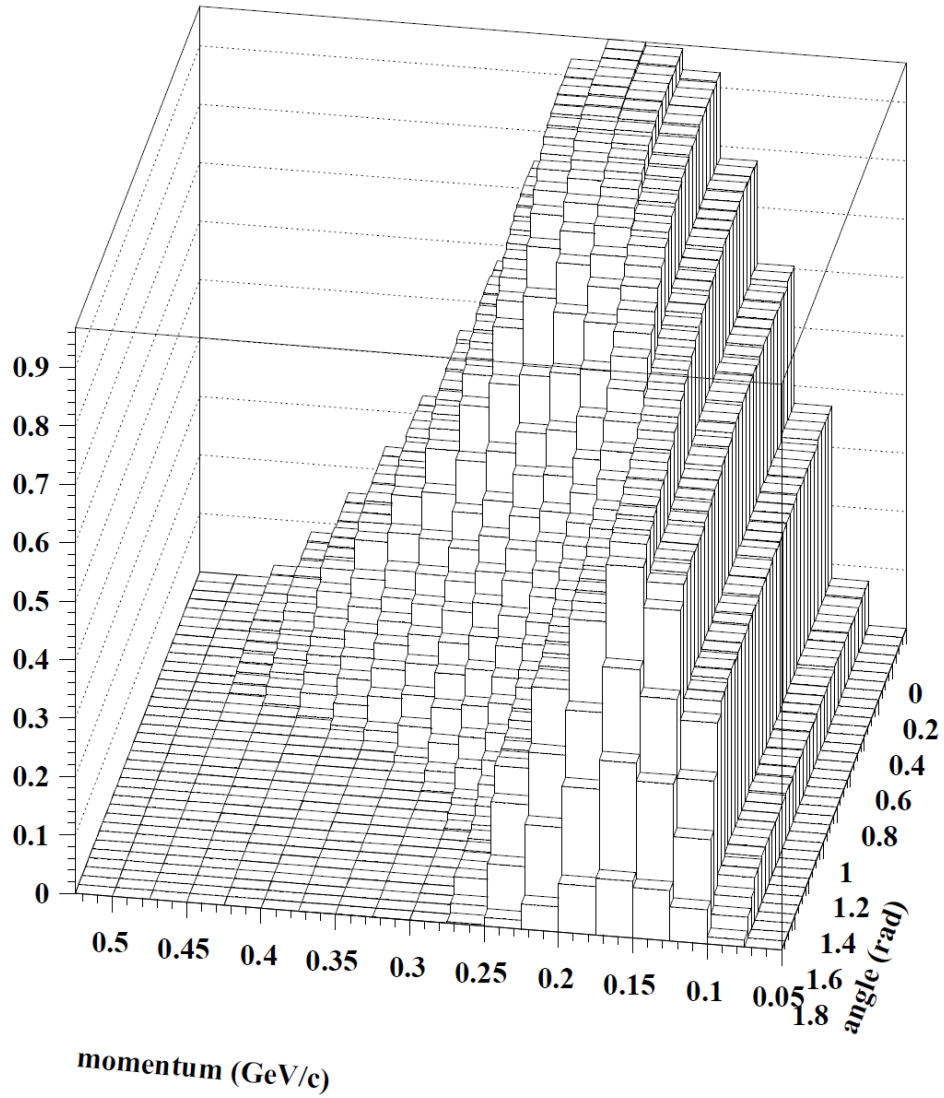




FLUKA results: Courtesy A. Ferrari

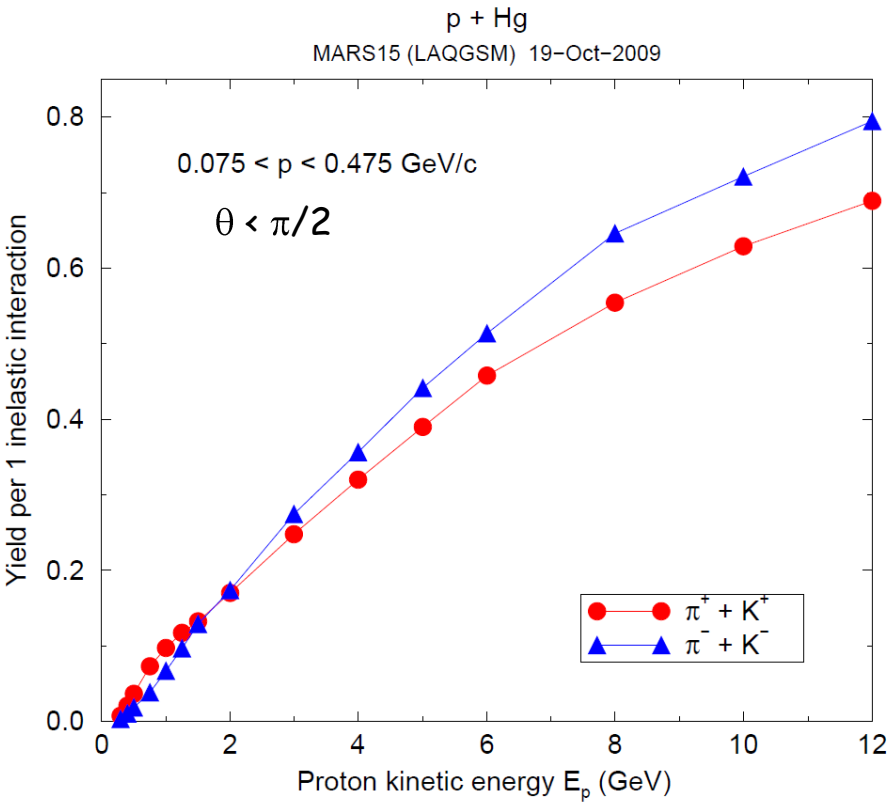
Some work is still needed in LAQGSM for pions with E_{kin}<150 MeV.

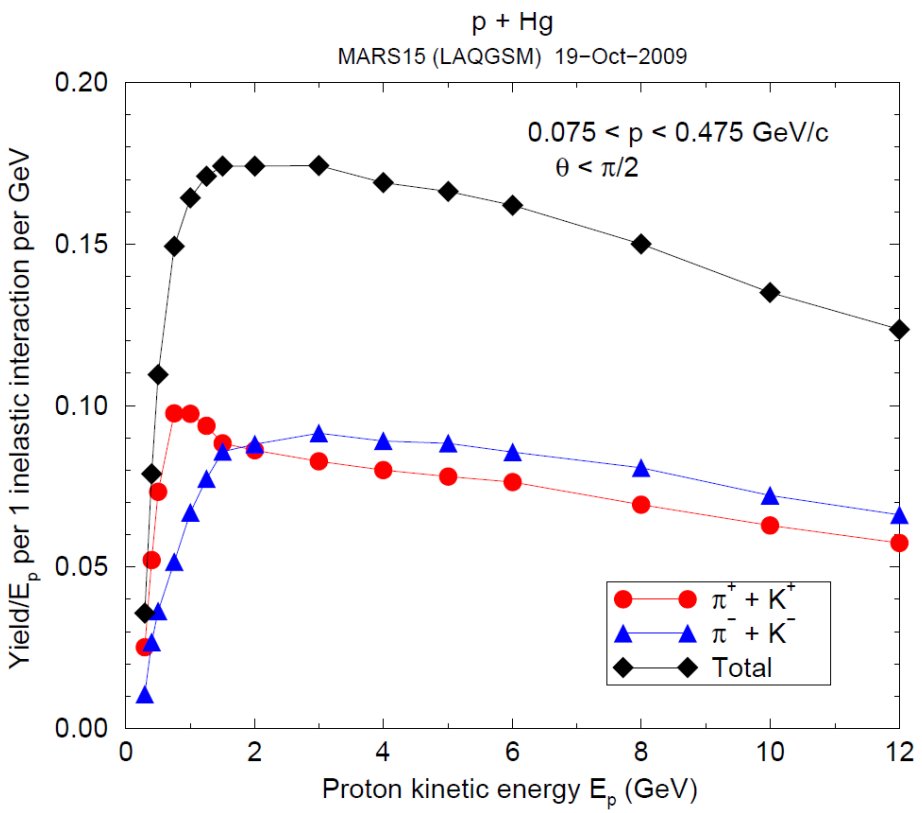
MARS-Calculated Acceptance Function of the System



The acceptance is defined to be the number of muons (or pions), as a fraction of the number of pions produced at the target, that reach the end of the 50 m long tapered solenoid channel.

Energy Dependence of Pion Yield in p+Hg





Yield in the acceptance Y/E_p for a thin target is maximum at 2-3 GeV. In thick target, absorption at low-energy end and showering at high-energy end moves the maximum to about 6 GeV.

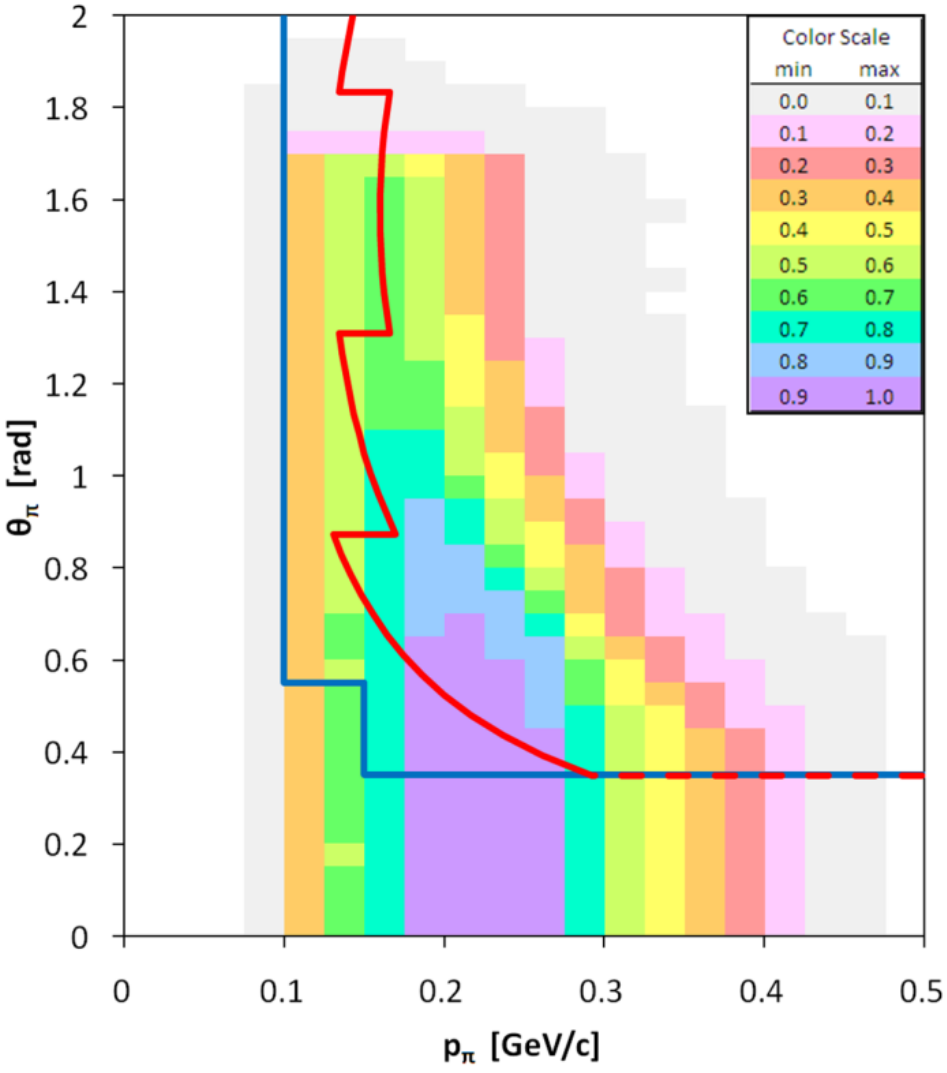
Implication of HARP Results for Energy Dependence (1)

Recent publication of data from the large angle spectrometer of the HARP experiment made it possible to address the energy dependence question with experimental data. The MARS15 calculated acceptance is convoluted with the measured double-differential cross-section of pion production from a tantalum target, which is close in atomic weight to mercury.

Implication of HARP Results for Energy Dependence (2)

The acceptance-weighted cross-section is integrated over the measured phase space, and divided by the beam kinetic energy, to give a value proportional to the muon yield normalized to constant proton beam power. Finally corrections are made for the phase space not covered by the HARP results, and for the effects of hadronic showers that develop in a thick target, and which are not accounted for in the pure cross-section data.

HARP Data Kinematic Regions

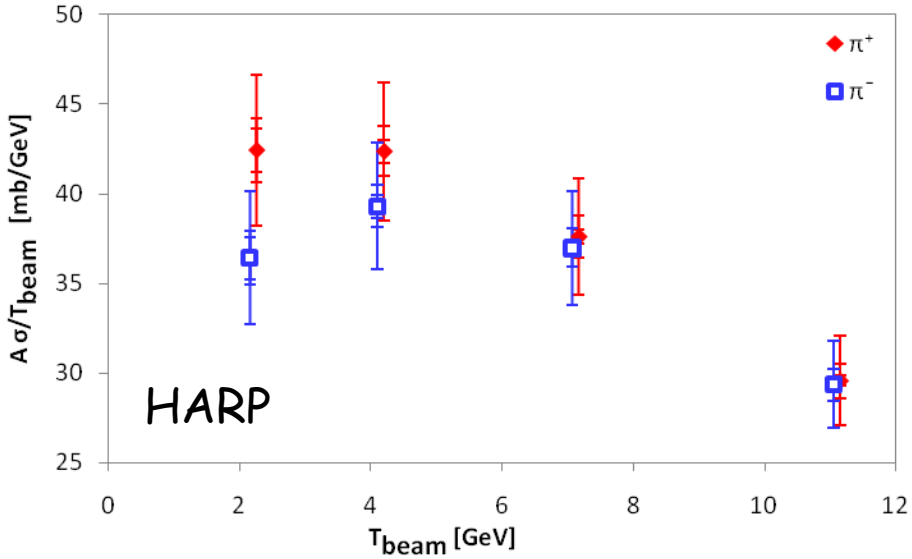


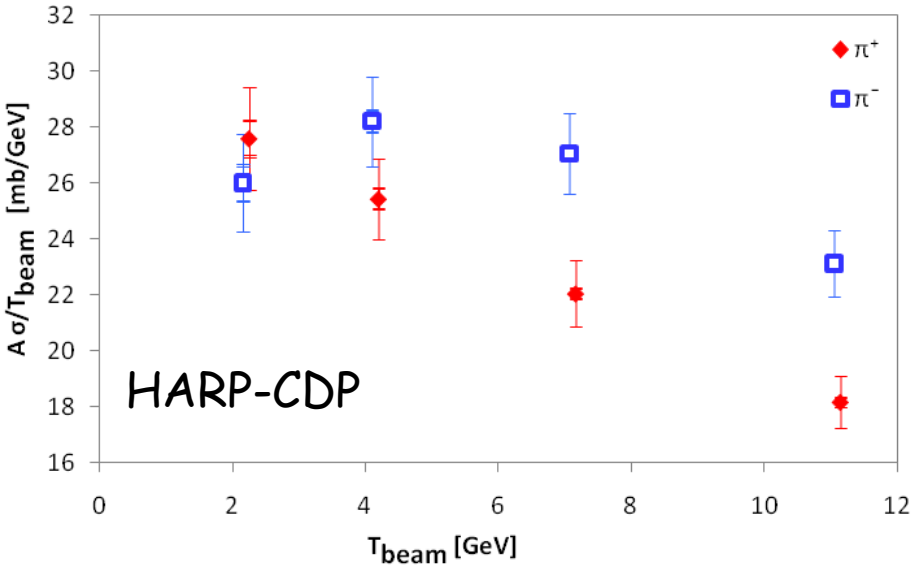
Acceptance, A, of the front-end channel, expressed in terms of the kinematic variables of the pion as it exits the production target. The kinematic region analyzed by the HARP (HARP-CDP) collaboration is the region above and to the right of the blue (red) line.

Weighted by the differential phase space $2\pi \sin\theta d\theta dp$, the region analyzed by HARP (HARP-CDP) covers 87% (65%) of the front-end channel acceptance.

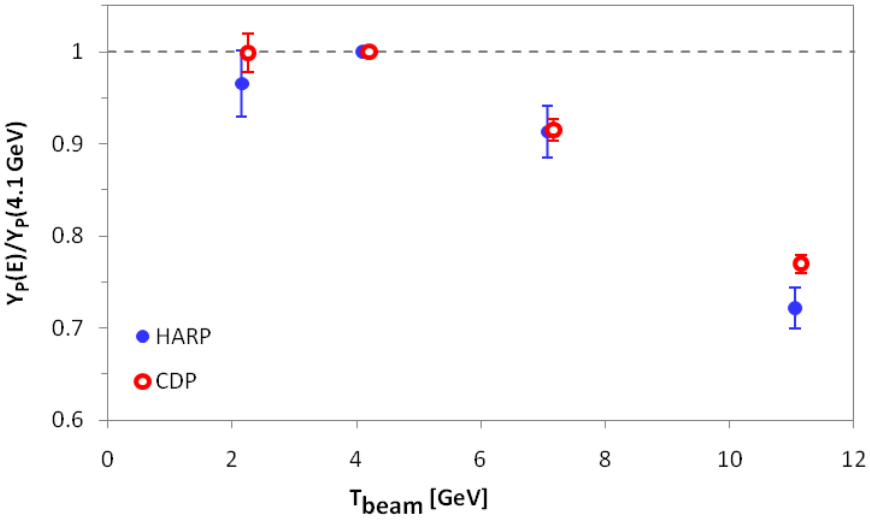
Thus the measured pion production cross-sections, weighted by the acceptance, can give a good estimation of the beam energy dependence of the muon yield even with no corrections for the fact that these data do not cover the forward region, $\theta < 350$ mrad.

HARP Acceptance-Weighted Yields/E_p



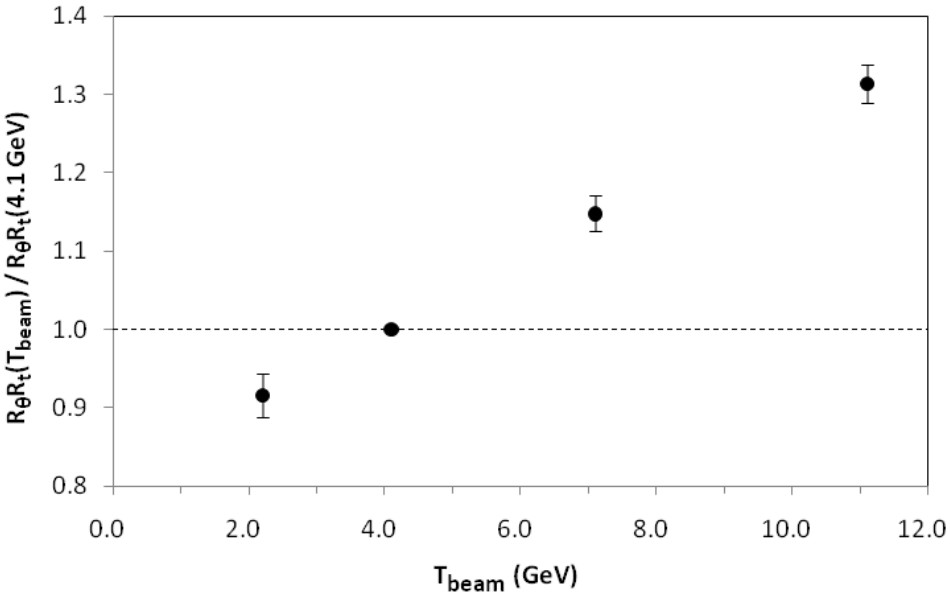


HARP Acceptance-Weighted Yields/E_p

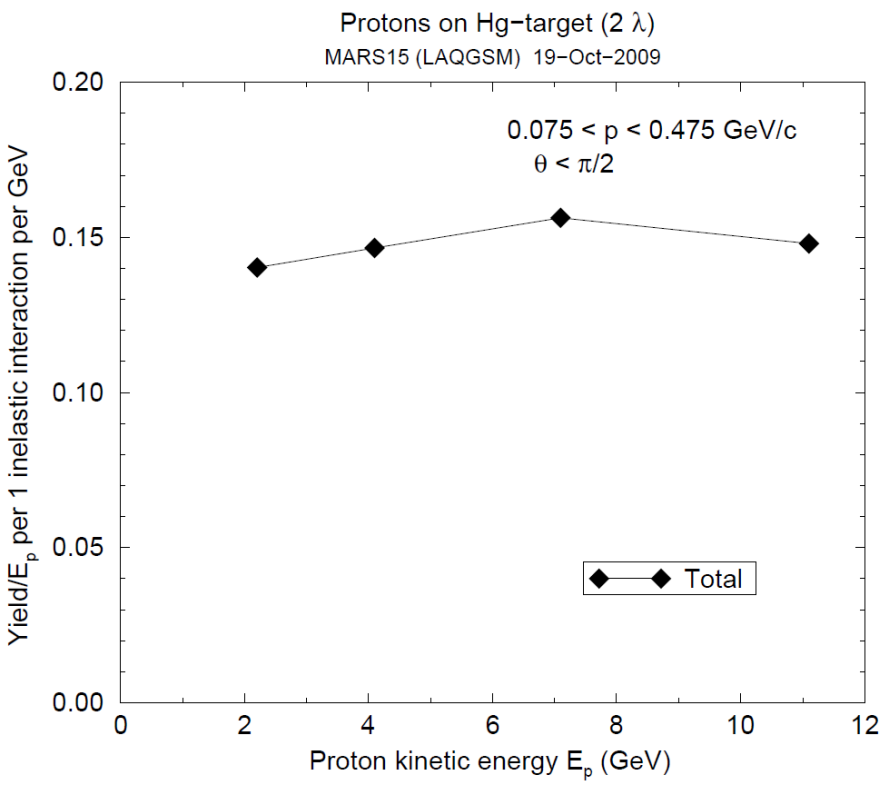


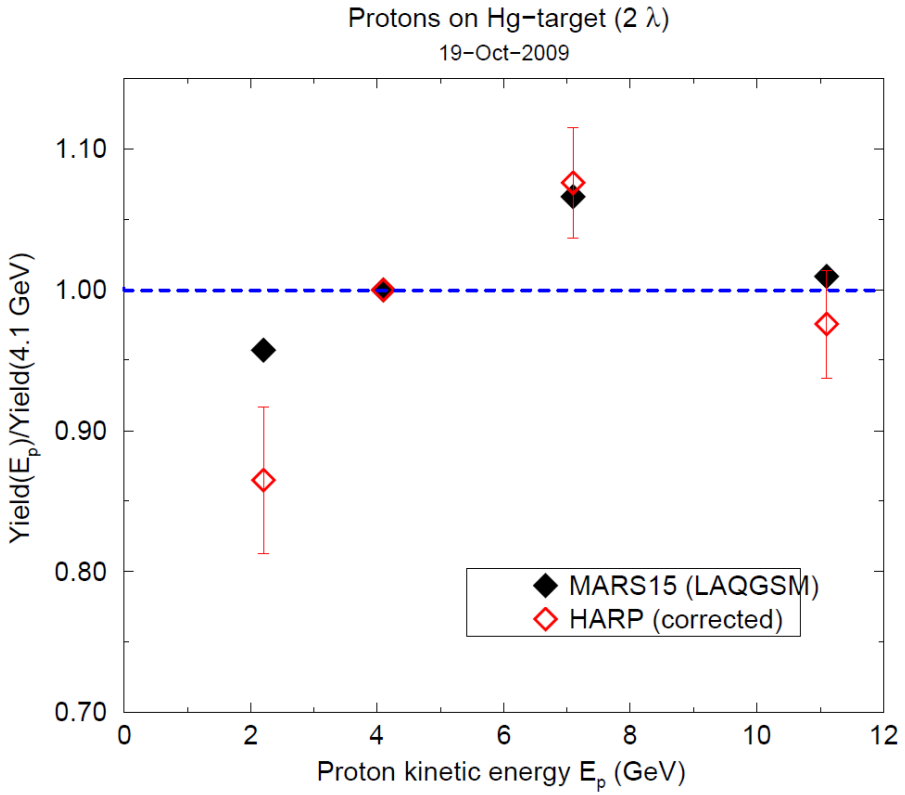
Relative acceptance-weighted total pion yield by two HARP groups.

Combined correction R_θ for the unmeasured region, $\theta < 350$ mrad (via quadratic extrapolation to q->0 of HARP group data, 12-19% effect), and R_t for the effect of hadronic shower development in a 2 λ_I target (MARS modeling), relative the correction at 4.1 GeV.



Beam-Power Normalized Yield





Total pion yield from 2λ target in the front-end channel acceptance. MARS15 results for Hg target, HARP data (corrected) for Ta target.

Summary

Particle production model in MARS15 has been further developed, with benchmarking results being quite encouraging.

Both MARS15 calculated and HARP data (corrected correspondingly) indicate that the beam-power normalized pion yield Y/E_p in the acceptance of the front-end channel is maximum for E_p of about 7 GeV, and is within 20% of this maximum for $2 < Ep < 12$ GeV. The dependence of Y/E_p on proton beam energy is relatively flat. One can, therefore, conclude that any beam energy in the 4-12 GeV range represents a good choice for the proton driver for a neutrino factory or muon collider.

This provides significant latitude in the design of high-power proton sources, which can consider many other optimization parameters than beam energy, without compromising their utility for a neutrino factory or muon collider.