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

*) See several NM’s journal papers of 1999 to 2001.
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 $\Delta$ and $N^*$ resonance production and interaction at $E < 4.5$ GeV with pions produced in $\Delta$ decays.
Inclusive Pion Production (Default)

12.3 GeV/c p+Be -> \( \pi^- \) vs BNL E910
MARS15 vs HARP for p+Al $\rightarrow \pi^+X$ at 12.9 GeV/c

$\pi^+$ production in proton aluminum interaction at 12.9 GeV/c

MARS15 (default)
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.
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.
TABLE VIII: Computed $\chi^2$ between data and MonteCarlo simulations, assuming a 20% systematics on simulation

<table>
<thead>
<tr>
<th>model</th>
<th>Beryllium</th>
<th>Tantalum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 GeV</td>
<td>5 GeV</td>
</tr>
<tr>
<td></td>
<td>$\pi^+$</td>
<td>$\pi^-$</td>
</tr>
<tr>
<td>ndof</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Bertini</td>
<td>181.1</td>
<td>156.8</td>
</tr>
<tr>
<td>Binary</td>
<td>180.8</td>
<td>196.9</td>
</tr>
<tr>
<td>LHEP</td>
<td>149.8</td>
<td>43.2</td>
</tr>
<tr>
<td>QGSP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FTFP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MARS</td>
<td>9.4</td>
<td>46.2</td>
</tr>
</tbody>
</table>
**MARS15 & Geant4 Pion Production vs HARP for pBe and pTa**

July 22, 2009

<table>
<thead>
<tr>
<th>model</th>
<th>Be 3 GeV</th>
<th>Ta 3 GeV</th>
<th>Be 5 GeV</th>
<th>Ta 5 GeV</th>
<th>Be 8 GeV</th>
<th>Ta 8 GeV</th>
<th>Be 12 GeV</th>
<th>Ta 12 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\pi^+$</td>
<td>$\pi^-$</td>
<td>$\pi^+$</td>
<td>$\pi^-$</td>
<td>$\pi^+$</td>
<td>$\pi^-$</td>
<td>$\pi^+$</td>
<td>$\pi^-$</td>
</tr>
<tr>
<td>Bertini</td>
<td>0.35</td>
<td>1.02</td>
<td>0.45</td>
<td>0.53</td>
<td>0.70</td>
<td>1.12</td>
<td>0.29</td>
<td>0.35</td>
</tr>
<tr>
<td>Binary</td>
<td>0.36</td>
<td>0.75</td>
<td>0.28</td>
<td>0.34</td>
<td>0.73</td>
<td>0.88</td>
<td>0.16</td>
<td>0.23</td>
</tr>
<tr>
<td>LHEP</td>
<td>0.40</td>
<td>0.86</td>
<td>0.81</td>
<td>0.91</td>
<td>0.76</td>
<td>0.98</td>
<td>0.36</td>
<td>0.45</td>
</tr>
<tr>
<td>QGSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.78</td>
<td>0.91</td>
<td>0.58</td>
<td>0.66</td>
</tr>
<tr>
<td>FTFP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.40</td>
<td>1.43</td>
<td>0.80</td>
<td>0.75</td>
</tr>
<tr>
<td>MARS</td>
<td>0.83</td>
<td>1.29</td>
<td>1.10</td>
<td>1.16</td>
<td>1.21</td>
<td>1.38</td>
<td>1.17</td>
<td>1.35</td>
</tr>
</tbody>
</table>

*) 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

\[ \text{p}(3 \text{ GeV/c}) + ^{27}\text{Al} 5 \pi^- + X \]

\[ \text{p}(8 \text{ GeV/c}) + ^{181}\text{Ta} 5 \pi^- + X \]
Some work is still needed in LAQGSM for pions with $E_{\text{kin}} < 150$ MeV.

FLUKA results: Courtesy A. Ferrari
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.
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.
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.
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.
Pion production for nufact/mu-collider - N.V. Mokhov

HARP Acceptance-Weighted Yields/E_p

HARP

HARP-CDP

AHIP A Workshop, Fermilab, October 19-21, 2009
HARP Acceptance-Weighted Yields/E_p

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

Relative acceptance-weighted total pion yield by two HARP groups.
Total pion yield from $2\lambda$ 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 \( 2 < E_p < 12 \) 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.