# Comparisons between MARS and HARP data*

NuFact 09
24 July 2009

Jim Strait, Nikolai Mokhov, Sergei Striganov
Fermilab

* Title as given by organizers

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# HARP Data and $E_{min}$ for Proton Driver**

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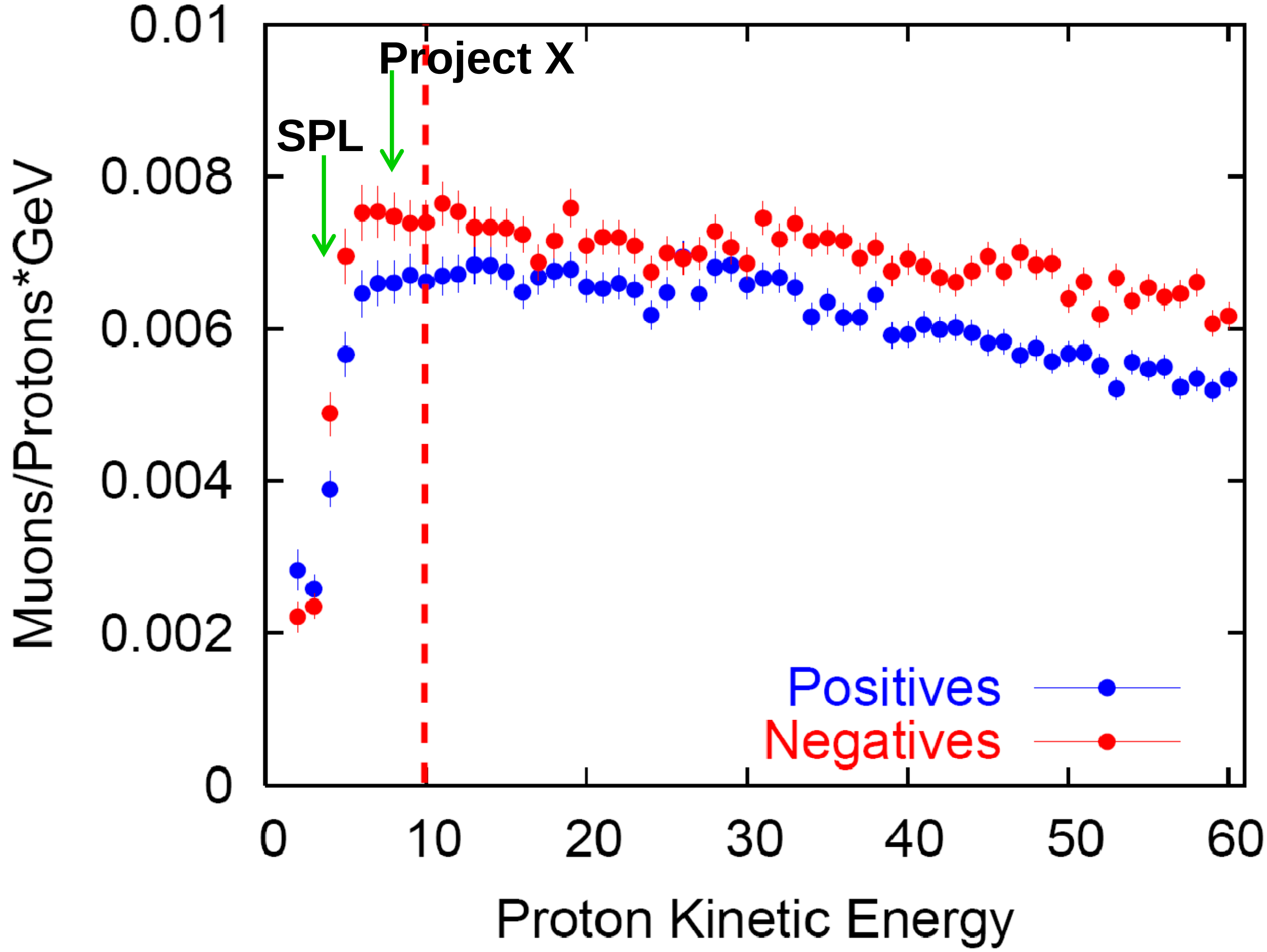
** Actual subject

# What is the Minimum Feasible Energy for the Front-End Proton Driver?




International Scoping Study, RAL-TR-2007-23

Fig. 9. Calculated production efficiency of positive and negative muons at the end of the Study 2a cooling channel, per proton and per GeV of proton beam energy, for a mercury-jet target. Although the curves are rather flat, an optimum energy, roughly 10 GeV, is discernible. Below about 5 GeV, the calculations show an abrupt fall-off in production. Above 10 GeV the fall-off is small but, from the muon production perspective, there is no benefit to increasing the beam energy beyond 10 GeV.

# "Below about 5 GeV, the calculations show an abrupt fall-off…" Why????

5 GeV is far above pion production threshold. . . .

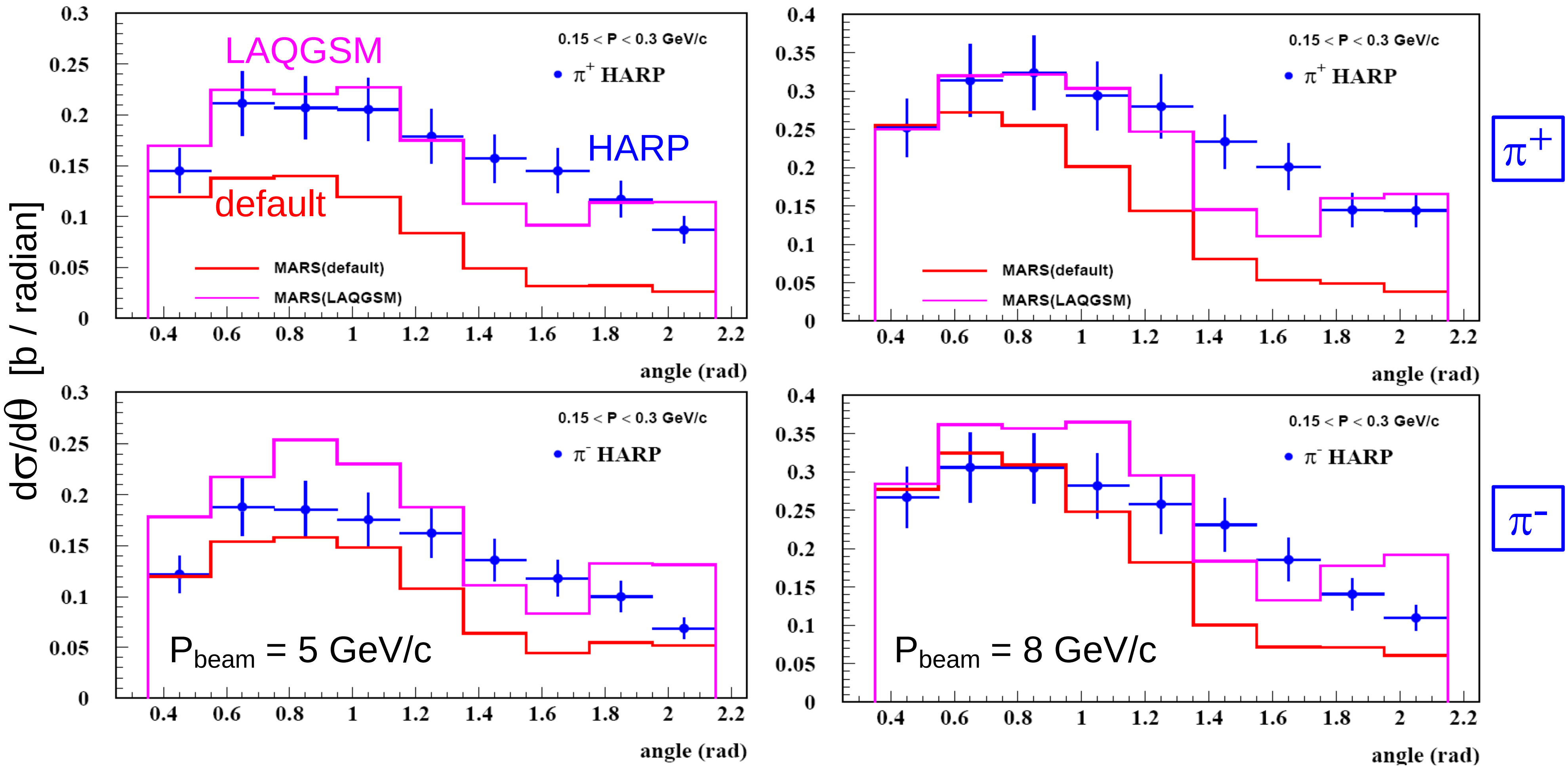
What is the physics behind the apparent drop in yield at low energy?

This result comes from a MARS simulation. Possible causes of the drop-off include:

- The default MARS pion production model may not be suitable for these low energies.
- There may be a greater "amplification" at higher energy due to hadron showers in a thick target.
- There may be a real drop-off in pion production ($\sigma_{tot}(\pi^{+-})$ / $E_{beam}$)
- There may be a poorer match between the acceptance of front-end channel and the phase space of pion production at low beam energy.

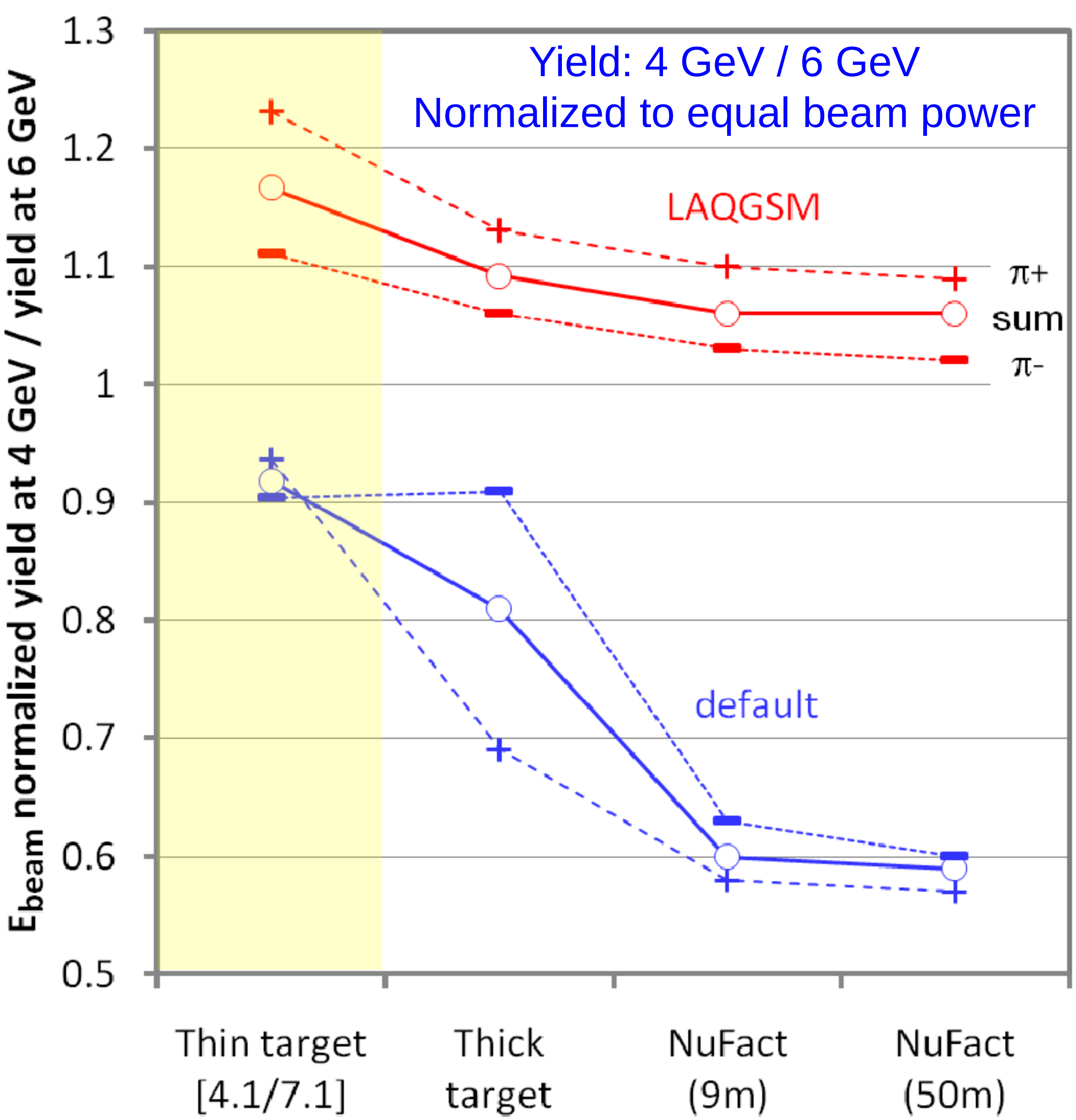
HARP data allow us to address most of these possibilities.

# MARS Pion Generators and HARP Data




- MARS default generator underestimates $\sigma(\pi)$ . . . and more strongly at lower energy.
- LAQGSM model matches $\pi^+$ data better, but overestimates $\pi^-$.

# Model Dependence




As a quick survey, compare pion yields in range:

- $0.1 < p < 0.34$ GeV/c
- $p_T < 0.225$ GeV
- $\theta < \pi/2$

among the following cases:

- thin target ($0.08\lambda$)
- thick target ($1.65\lambda$)
- full NuFact simulations.

Conclusions:

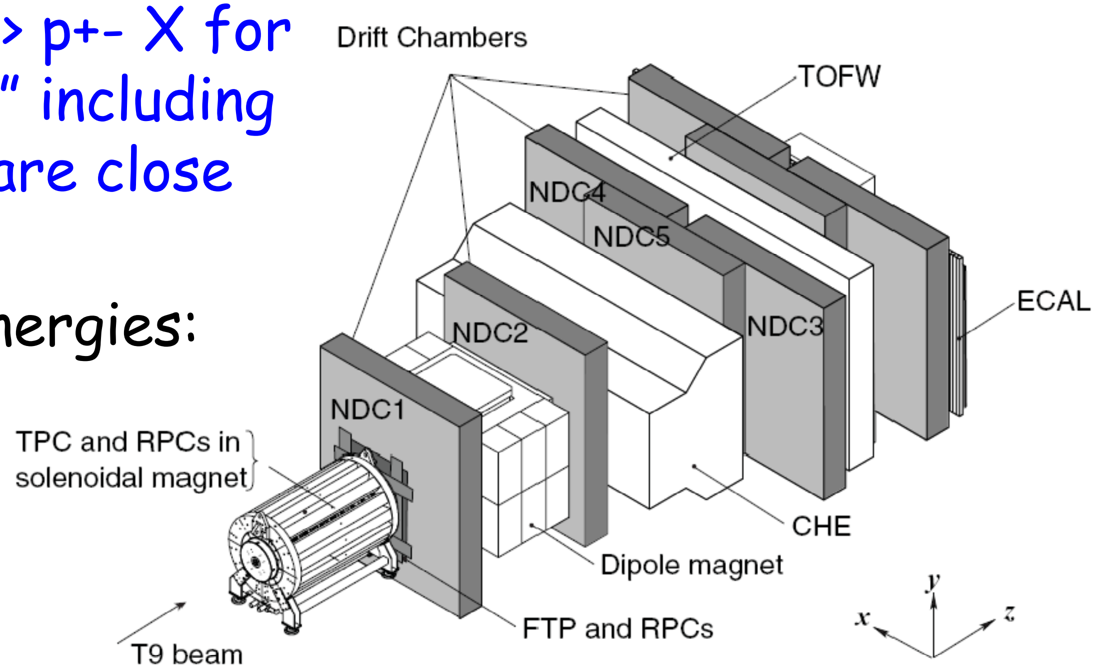
- A thick target enhances the yield by about 10% at 6 GeV relative to 4 GeV.
- Results depend strongly on the event generator used => need real data to settle the issue.

# HARP Data

HARP collected data on p+A -> p+- X for a wide variety of targets "A," including Ta (181) and Pb (207), which are close in A to Hg (201).

Data at the following beam energies:

| | |
|---|---|
| 3 GeV/c | (2.2 GeV) |
| 5 GeV/c | (4.1 GeV) |
| 8 GeV/c | (7.1 GeV) |
| 12 GeV/c | (11.1 GeV) |
| 15 GeV/c | (14.1 GeV) |




For this study, we have used results published by the main HARP group in: M. Catanesi et al., Phys Rev C 77, 055207 (2008).

Cross-check with results published by the HARP-CDP group in: A. Bolshakova et al., arXiv:0906.0471v2 (2009).

# HARP Data

HARP data cover the range

$p > 0.1$ GeV/c; $0.35 < \theta < 2.2$ rad

The main HARP group presents

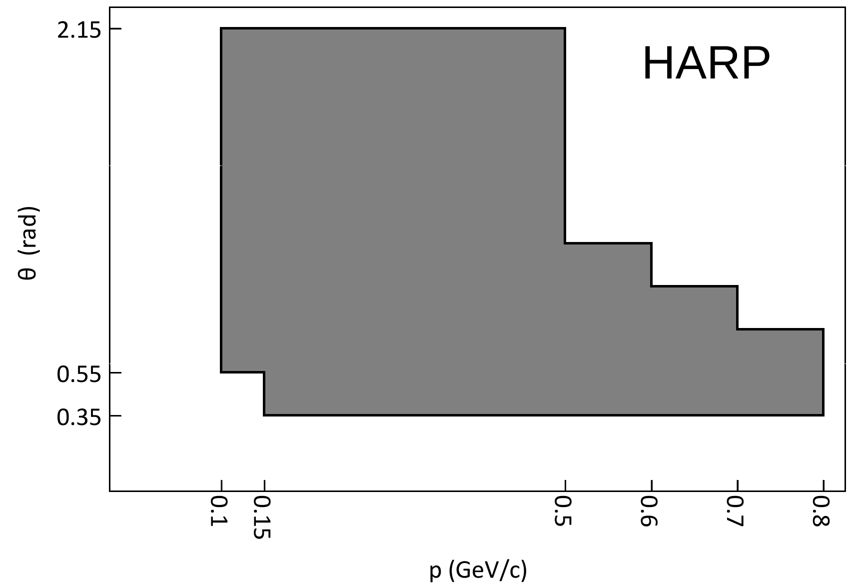
$d^2\sigma/(dp\, d\theta)$ [b / (rad GeV/c)]

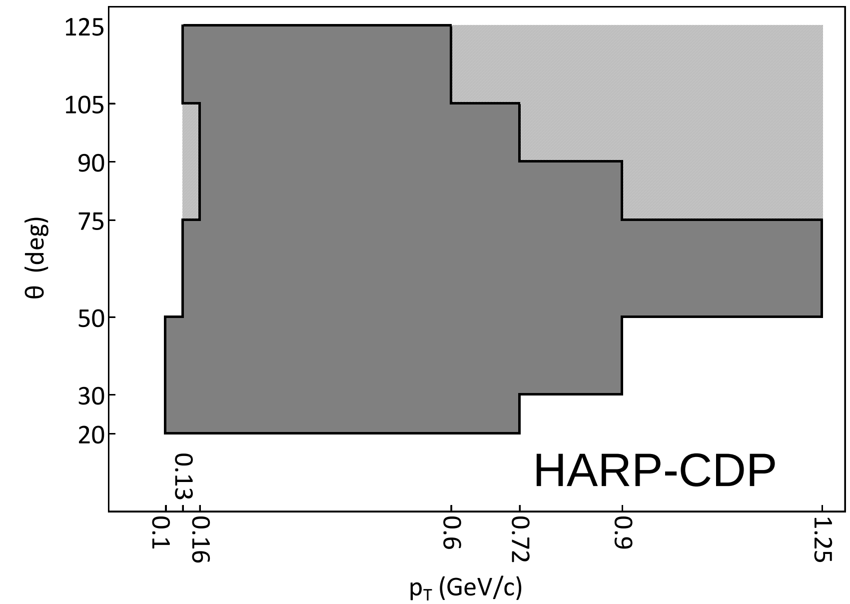
The HARP-CDP group presents

$d^2\sigma/(dp\, d\Omega)$ [mb / (sr GeV/c)]

The two groups differ (at least) in:

- Momentum calibration
- Particle ID
- Phase space analyzed

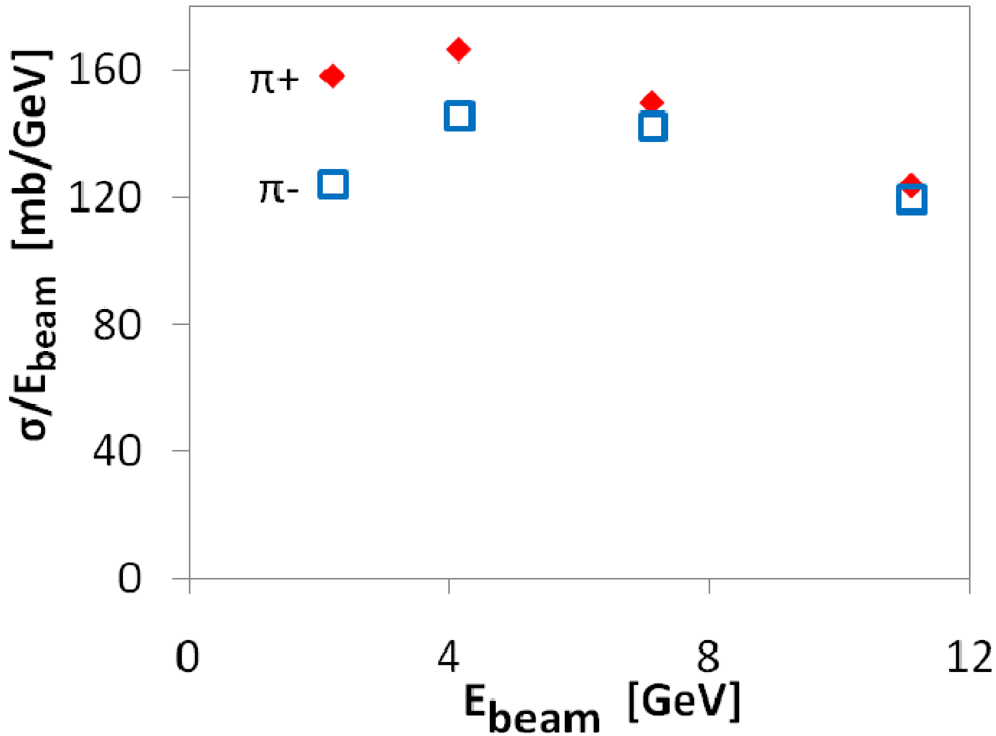


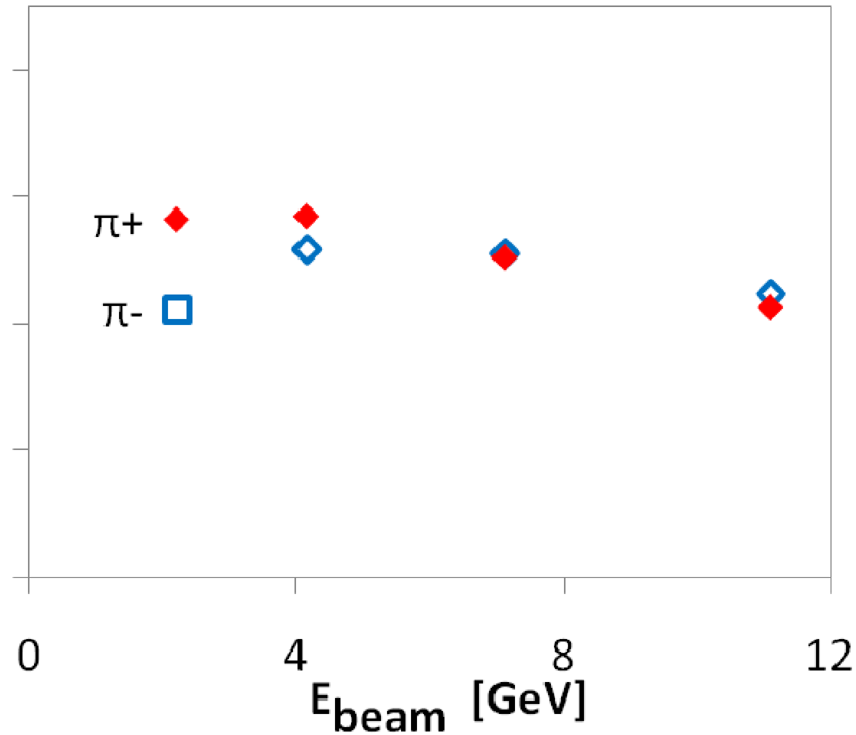
# Real drop-off in pion production ($\sigma_{tot}(\pi^{+-})$ / $E_{beam}$) ?

$\sigma(\pi^{+-})$ /$E_{beam}$, integrated over the measured phase space
(*different for the two groups*).

HARP (p + Pb -> $\pi^{+-}$ X)




HARP-CDP (p + Ta -> $\pi^{+-}$ X)



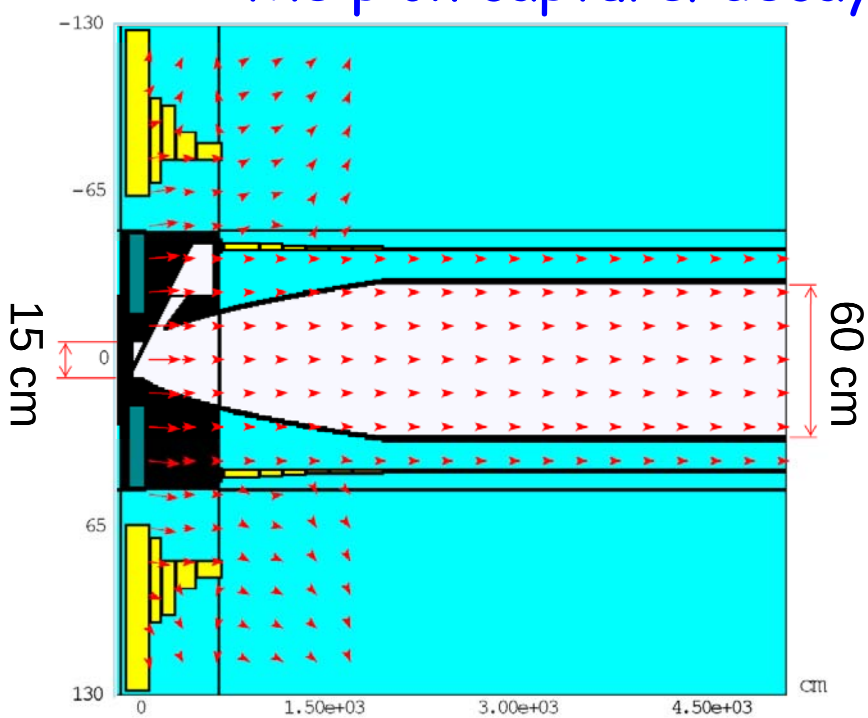

σ peaks in range 4~7 GeV => no dramatic low E drop-off

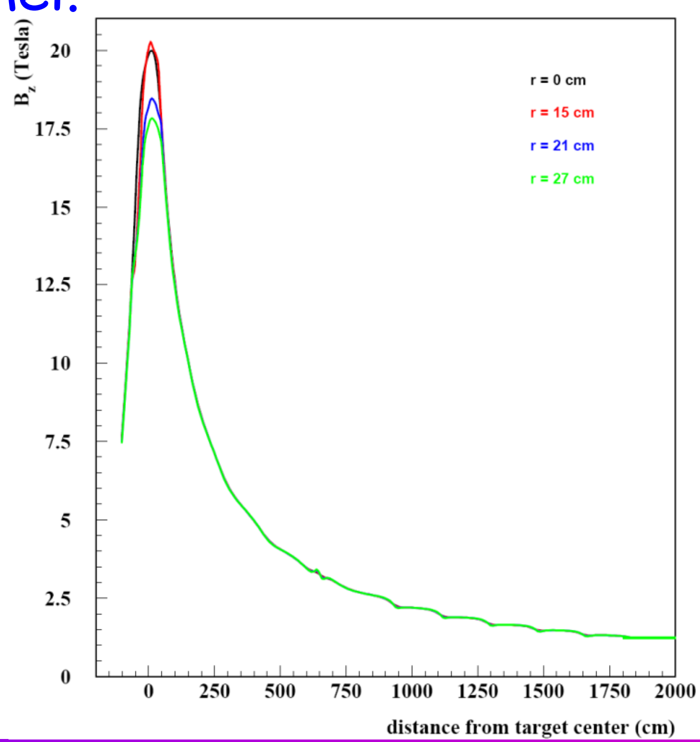
# Poor match between front-end channel acceptance and the phase space of pion production at low $E_{beam}$?

Although the integrated $\sigma/E_{beam}$ is ~flat with beam energy, perhaps at lower $E_{beam}$, the pion phase space match less well the acceptance of the front-end channel.

=> Use MARS to compute the front-end acceptance:

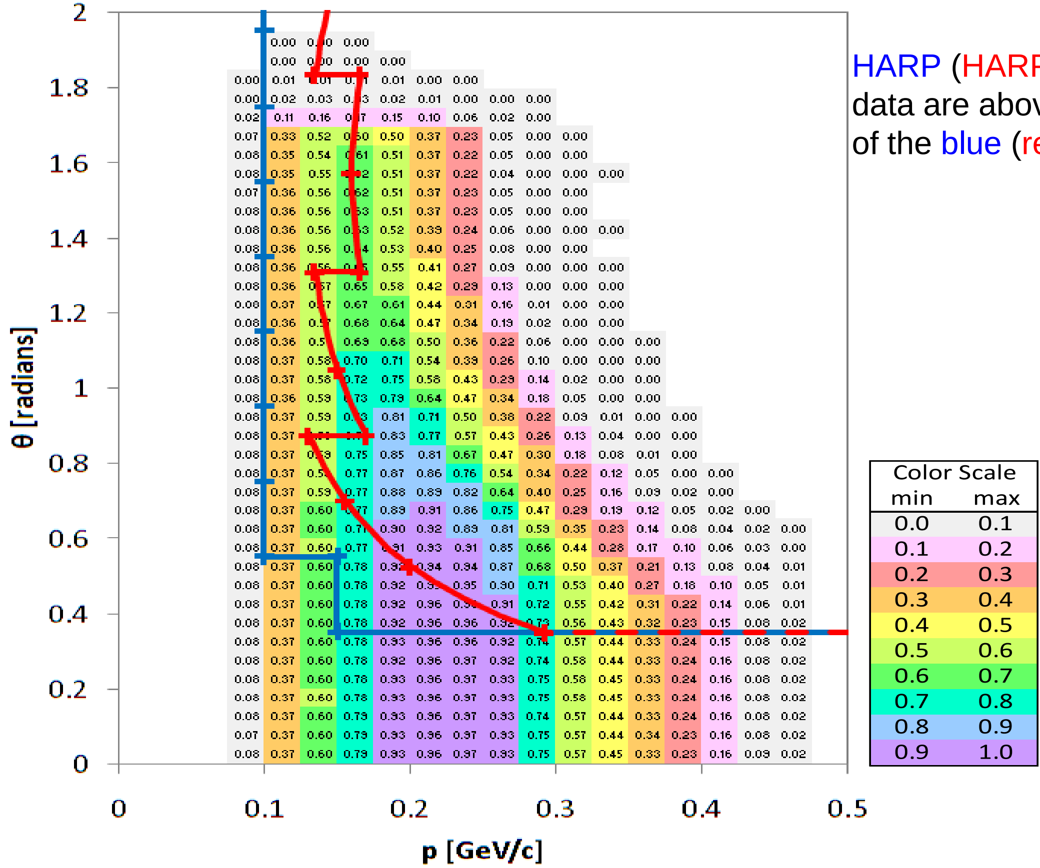
A = Probability that $\pi^{+-}$ produced at [p,θ] (or [$p_T$,θ]) at the target produces $\mu^{+-}$ with 40 < $T_\mu$ < 180 MeV at the end of the pion capture/decay channel.



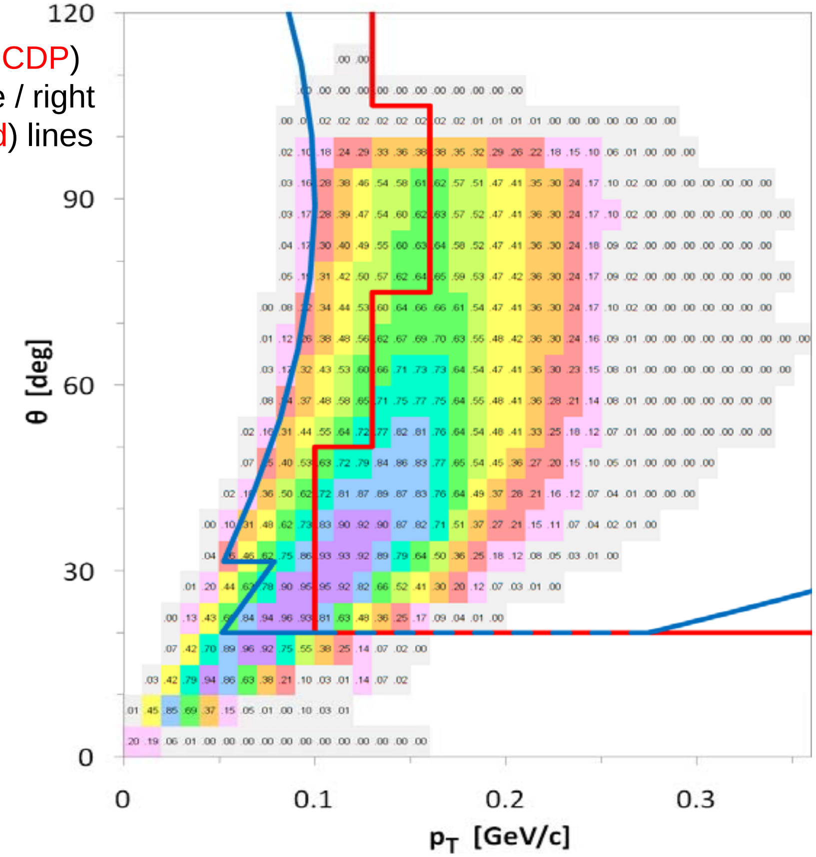
# Acceptance of Front-End Channel

"HARP Units"



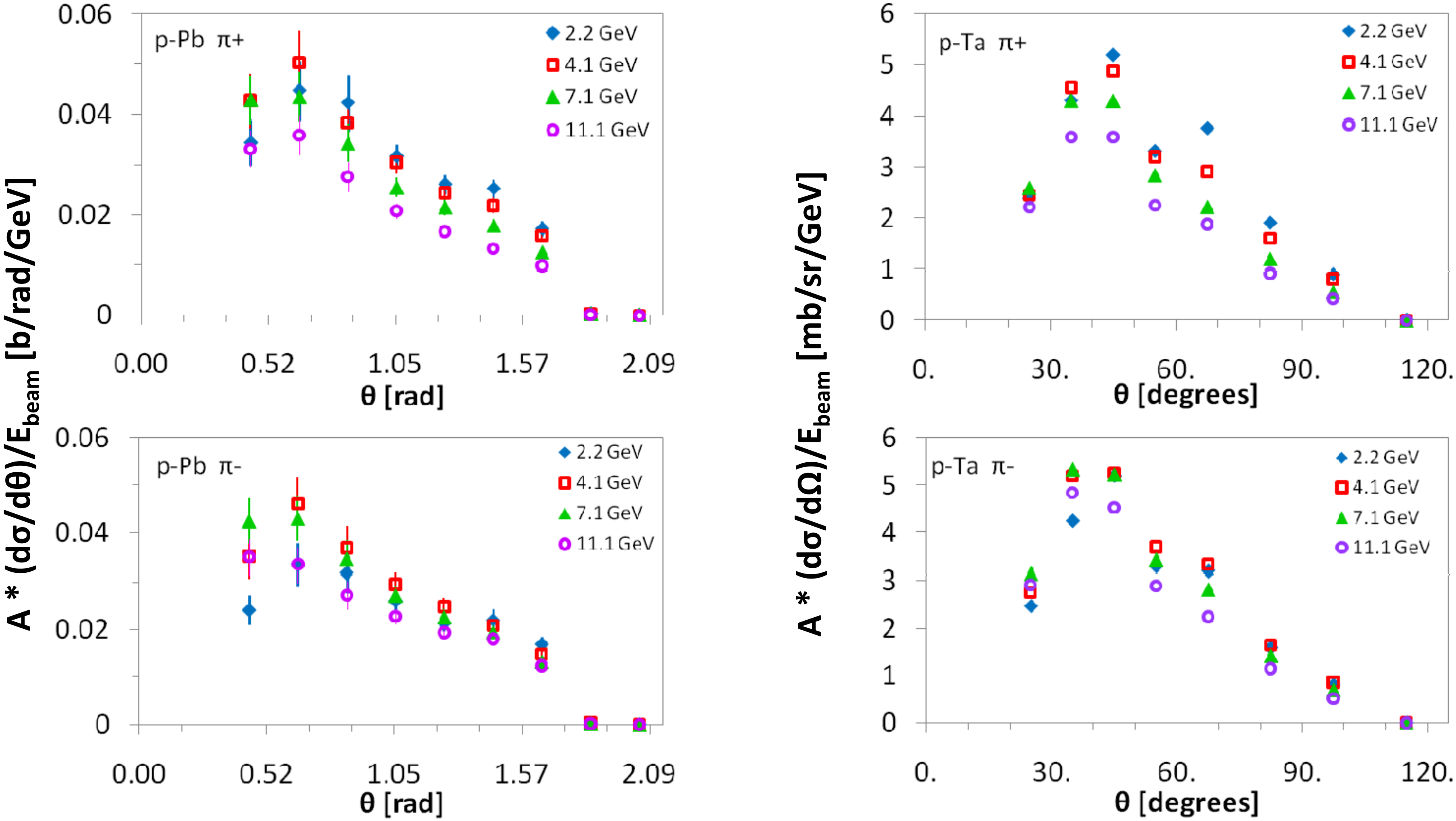

HARP (HARP-CDP) data are above / right of the blue (red) lines

"HARP-CDP Units"



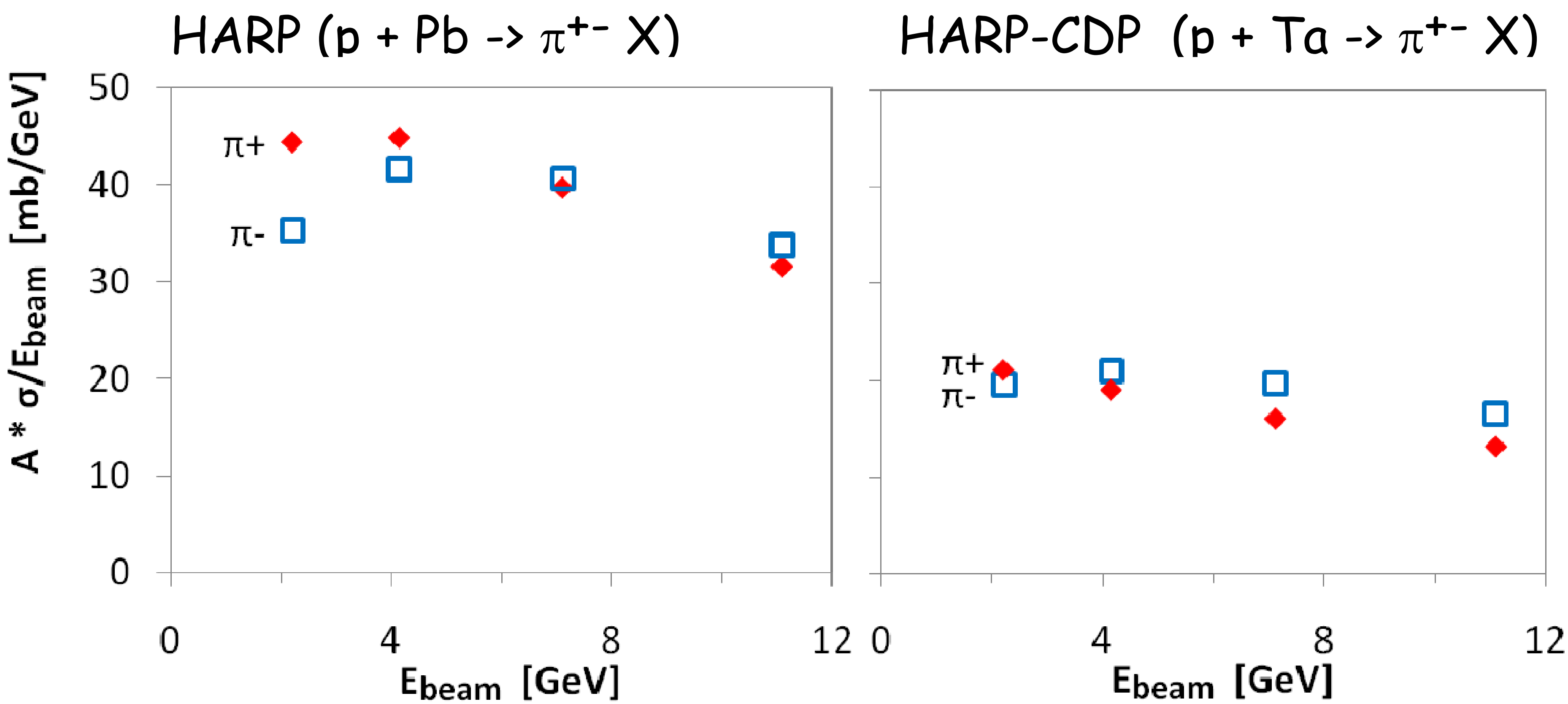

- HARP (HARP-CDP) phase space covers about 65% (60%) of the acceptance of the front-end channel.
- All relevant momenta are covered, but the acceptance remains high data for θ < 350 mrad (20°), where data are missing.

# Cross-Sections x Acceptance integrated over p ($p_T$)



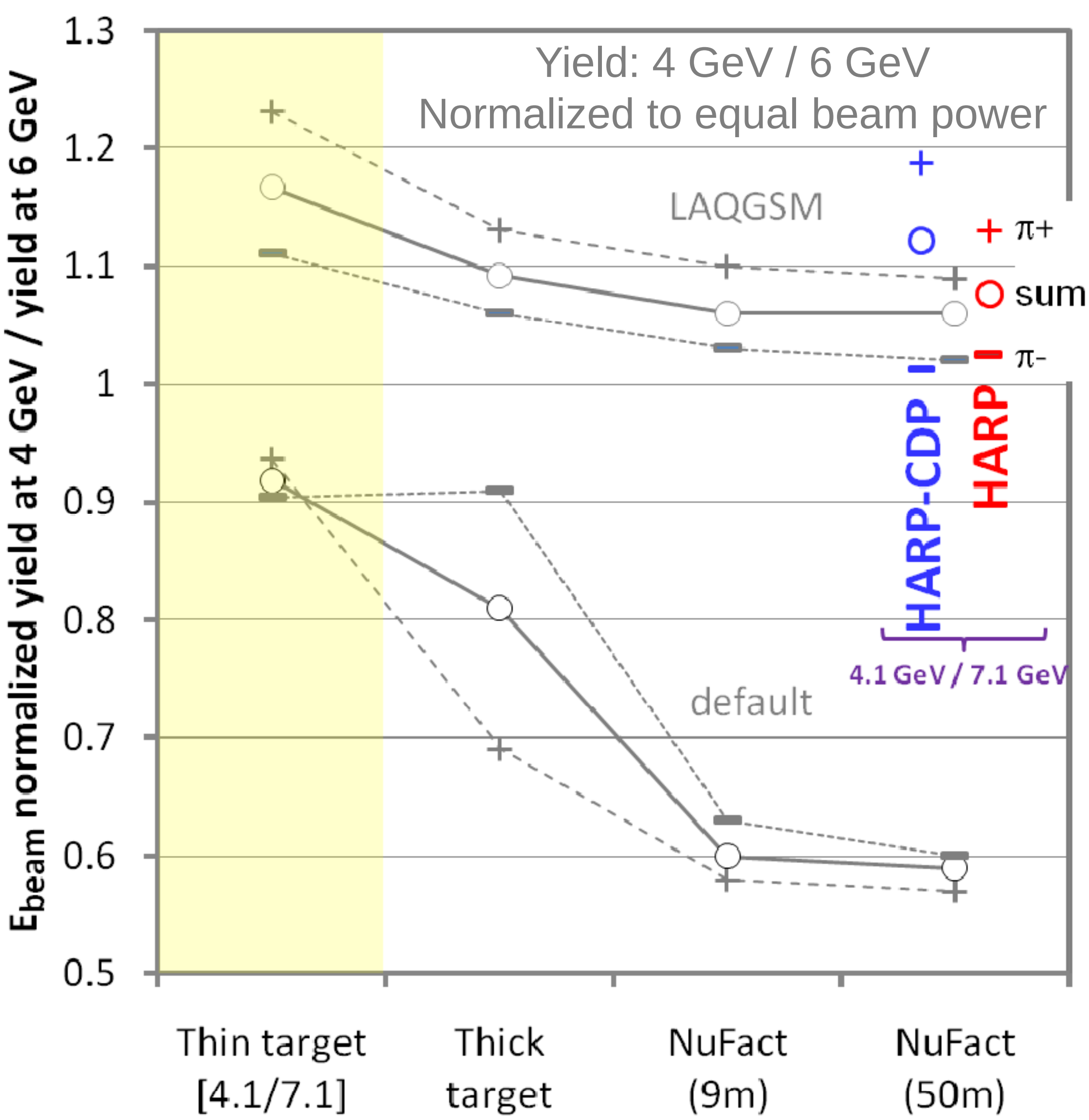

$A \times d\sigma/d\theta$ is flat or falling for $\theta$ < 0.65 rad (40°) and has similar slope for all $E_{beam}$ => "missing" low $\theta$ data unlikely to bias results.

# HARP Cross-Sections x Acceptance integrated over p ($p_T$) and θ




HARP pion production cross-sections, weighted by the acceptance of the front-end channel, and normalized to equal incident beam power, are relatively independent of beam energy.

# Compare Results with Earlier Simulations




Approximate effect of thin -> thick target

# Conclusions

- The "abrupt fall-off in (pion) production" below about 5 GeV, shown in the ISS, appears to be an artifact of the default MARS pion generator, which is not well tuned for low-energy pion production at low proton energy.
  - o Work is nearly complete on a stable LAQGSM option in MARS, thoroughly benchmarked in this region.
- HARP cross-section data show that, normalized to equal beam power, an incident proton beam energy of 4 GeV is comfortably sufficient for the proton driver for a neutrino factory.
- This conclusion stands including the roughly 10% decreas in relative yield at 4 GeV vs 6 GeV, when going from the raw cross-section (thin-target) case to a full length target.
- This conclusion does not depend on whether one uses the data published by the main HARP collaboration, or the HARP-CDP collaboration.