Beam Target Optimization for

DAEδALUS

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APS April Meeting
April 2, 2012

Decay
At-rest
Experiment for
δ_{cp} studies
At the
Laboratory for
Underground
Science

$$U =$$

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$P_{osc}\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right) =$$

$$\left(\sin^2\theta_{23}\sin^2 2\theta_{13}\right)\left(\sin^2\Delta_{31}\right)$$

$$+\sin\delta\left(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\right)\left(\sin^2\Delta_{31}\sin\Delta_{21}\right)$$

$$+\cos\delta\left(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\right)\left(\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}\right)$$

$$+\left(\cos^2\theta_{23}\sin^2 2\theta_{12}\right)\left(\sin^2\Delta_{21}\right)$$

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

[in vacuum!]

$$P_{osc}\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right) =$$

δ_{CP}

$$
\begin{aligned}
& \left(\sin^2\theta_{23}\sin^2 2\theta_{13}\right)\left(\sin^2\Delta_{31}\right) \\
\mp \sin\delta & \left(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\right)\left(\sin^2\Delta_{31}\sin\Delta_{21}\right) \\
+\cos\delta & \left(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\right)\left(\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}\right) \\
& + \left(\cos^2\theta_{23}\sin^2 2\theta_{12}\right)\left(\sin^2\Delta_{21}\right)
\end{aligned}
$$

Sign change
ν vs. $\bar{\nu}$

$$\Delta_{ij} = \Delta m^2_{ij} L / 4E_\nu$$

[in vacuum]

$$P_{osc}\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right) =$$

δ_{CP} | **Mixing Angles**

$$\left(\sin^2\theta_{23}\sin^2 2\theta_{13}\right)\left(\sin^2\Delta_{31}\right)$$

$$\mp\sin\delta\left(\sin2\theta_{13}\sin2\theta_{23}\sin2\theta_{12}\right)\left(\sin^2\Delta_{31}\sin\Delta_{21}\right)$$

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Sign change ν vs. $\bar{\nu}$

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[in vacuum]

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δ$_{CP}$ Mixing Angles

	$\left(\sin^2\theta_{23}\sin^2 2\theta_{13}\right)$	$\left(\sin^2\Delta_{31}\right)$
$\mp\sin\delta$	$\left(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\right)$	$\left(\sin^2\Delta_{31}\sin\Delta_{21}\right)$
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	$+\left(\cos^2\theta_{23}\sin^2 2\theta_{12}\right)$	$\left(\sin^2\Delta_{21}\right)$

Sign change
ν vs. $\bar{\nu}$

Dependence on distance from source

$$\Delta_{ij} = \Delta m^2_{ij} L / 4E_\nu$$

[in vacuum]

Measuring Effect of δ_{CP} On Oscillations

Traditional Method

Compare neutrino and anti-neutrino measurement

Use high energy neutrinos

$\hookrightarrow$ Long oscillation wavelength

$\hookrightarrow$ Matter effects

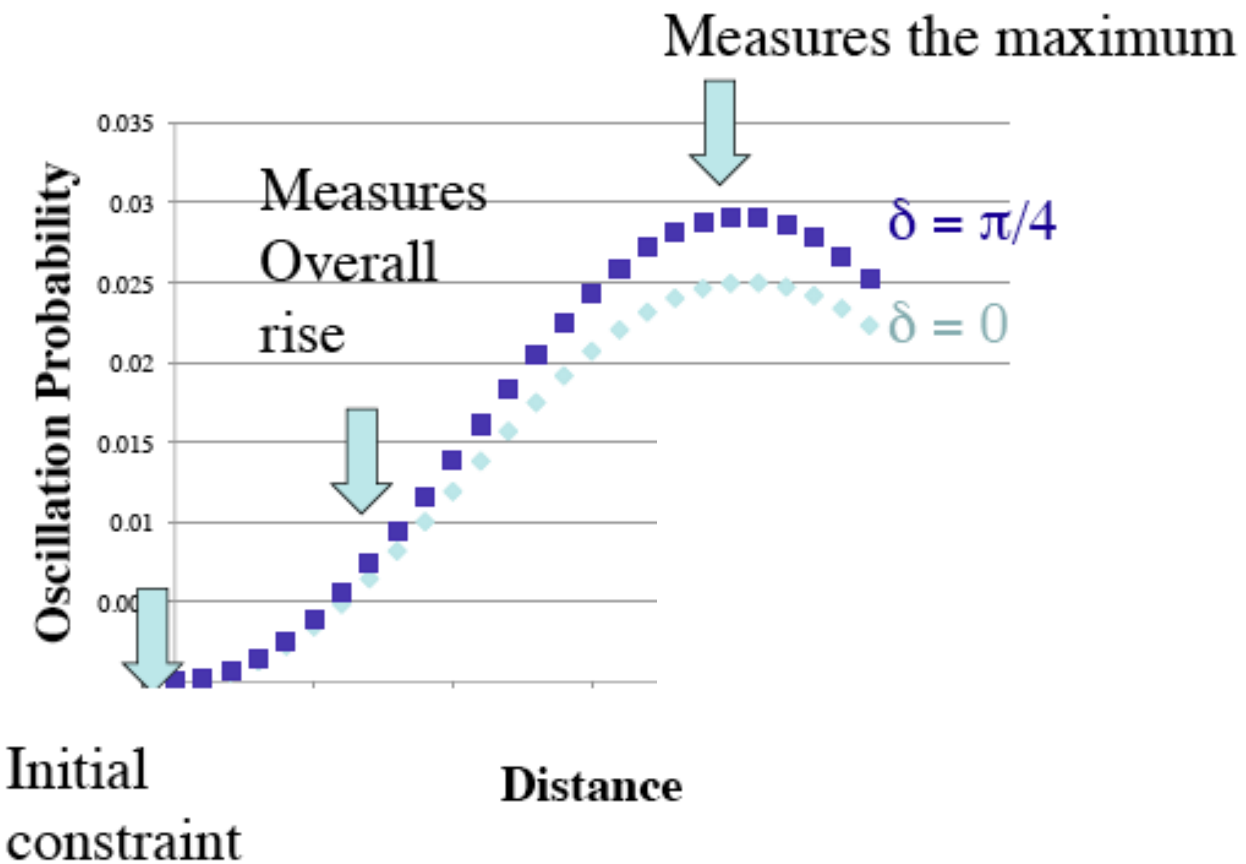
Measuring Effect of δ_{CP} On Oscillations

<u>DAEδALUS's Approach</u>

Utilize distance dependence of probability.

Measure flux at 3 distances:

Initial constraint, rise, and maximum.

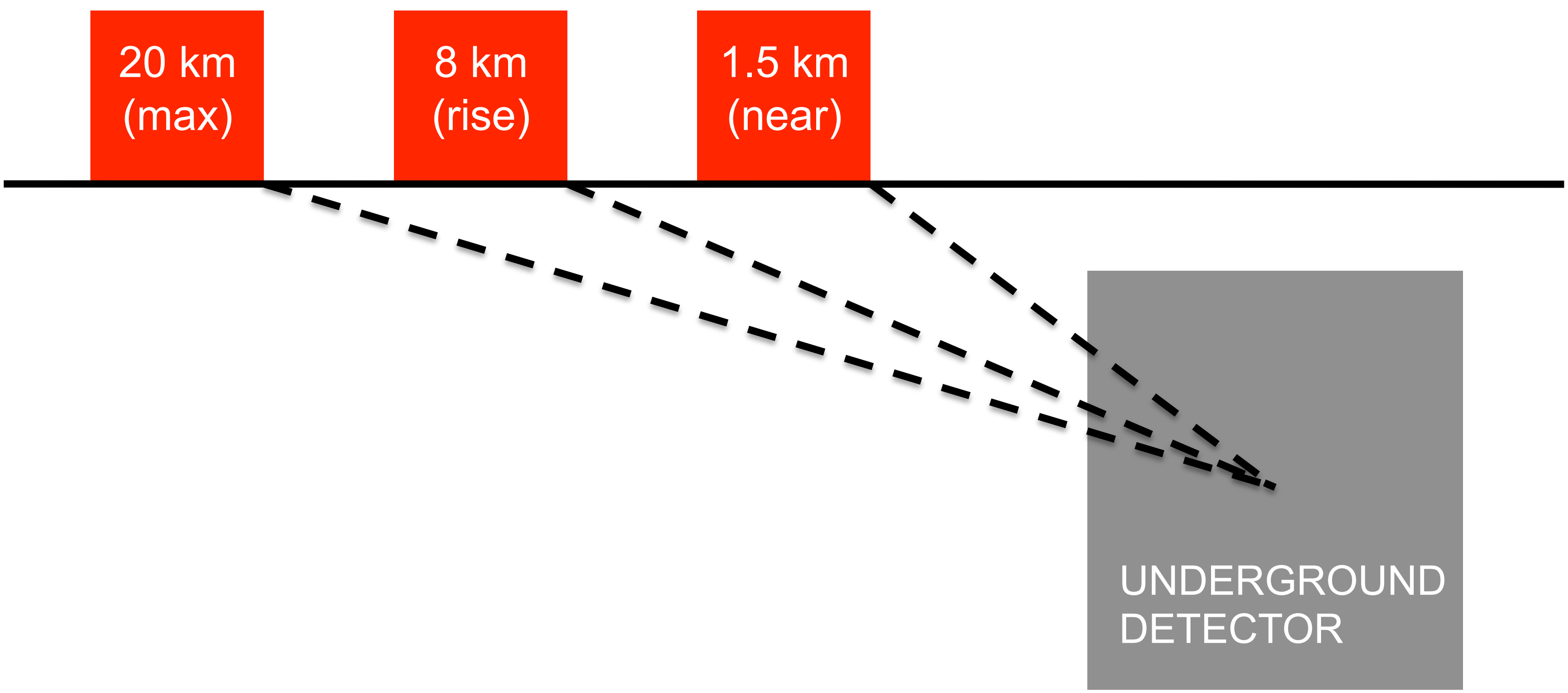


DAEδALUS - Design

3 sources, 1 detector

Each source:

- 1 H_2^+ compact cyclotron - ~800MeV Protons out
- 1 Beam Target



Target Design Considerations

Delta Resonances:

$$\Delta^+ \rightarrow \pi^+ n \qquad \Delta^- \rightarrow \pi^- n$$

Pion Decays:

$$\pi^+ \rightarrow \mu^+ \nu_\mu \qquad \pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

$$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e \qquad \hookrightarrow e^- \nu_\mu \bar{\nu}_e$$

Target Design Considerations

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$$\Delta^{+} \rightarrow \pi^{+} n \qquad \Delta^{-} \rightarrow \pi^{-} n$$

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$$\hookrightarrow e^{+} \boxed{\bar{\nu}_{\mu}} \nu_{e}$$

$$\pi^{-} \rightarrow \mu^{-} \bar{\nu}_{\mu}$$
$$\hookrightarrow e^{-} \nu_{\mu} \boxed{\bar{\nu}_{e}}$$

Maximize muon antineutrino flux
Minimize electron antineutrino background
NOT melt the target
Keep radiation to acceptable levels

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$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$
$$\hookrightarrow e^- \nu_\mu \boxed{\bar{\nu}_e}$$

- ✔ Maximize muon antineutrino flux
- ✔ Minimize electron antineutrino background
- NOT melt the target
- Keep radiation to acceptable levels

I will focus on the first two.

Target Design Considerations

✔ Maximize muon antineutrino flux
- Maximize π^+ production (Low Z)

✔ Minimize electron antineutrino background
- Use material that will capture π^- (High Z)

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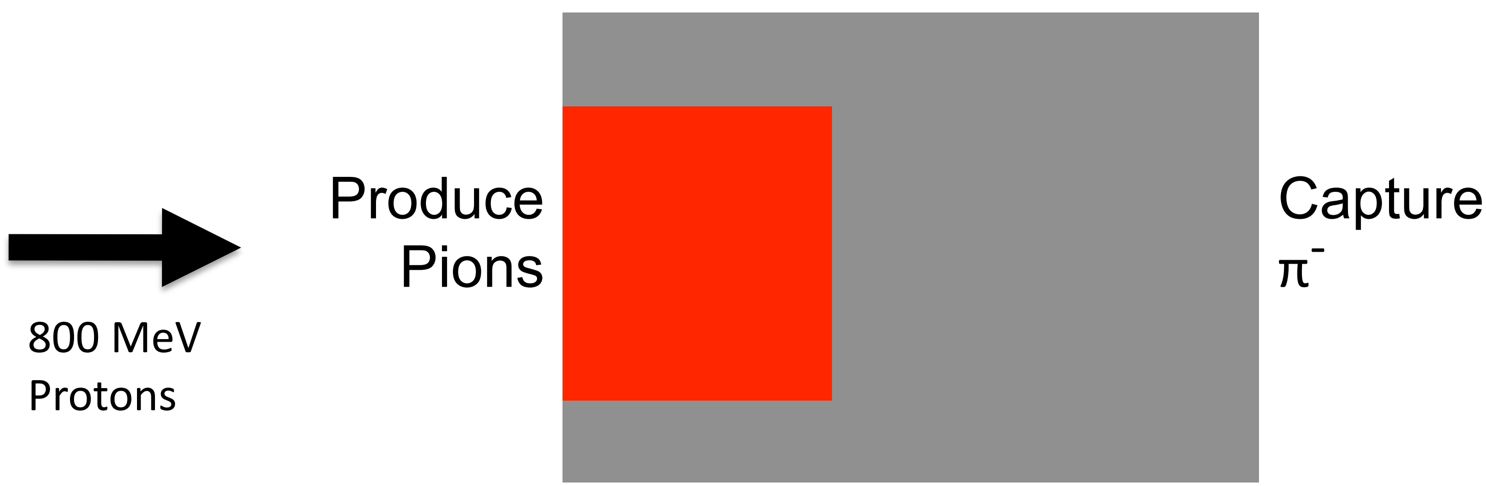
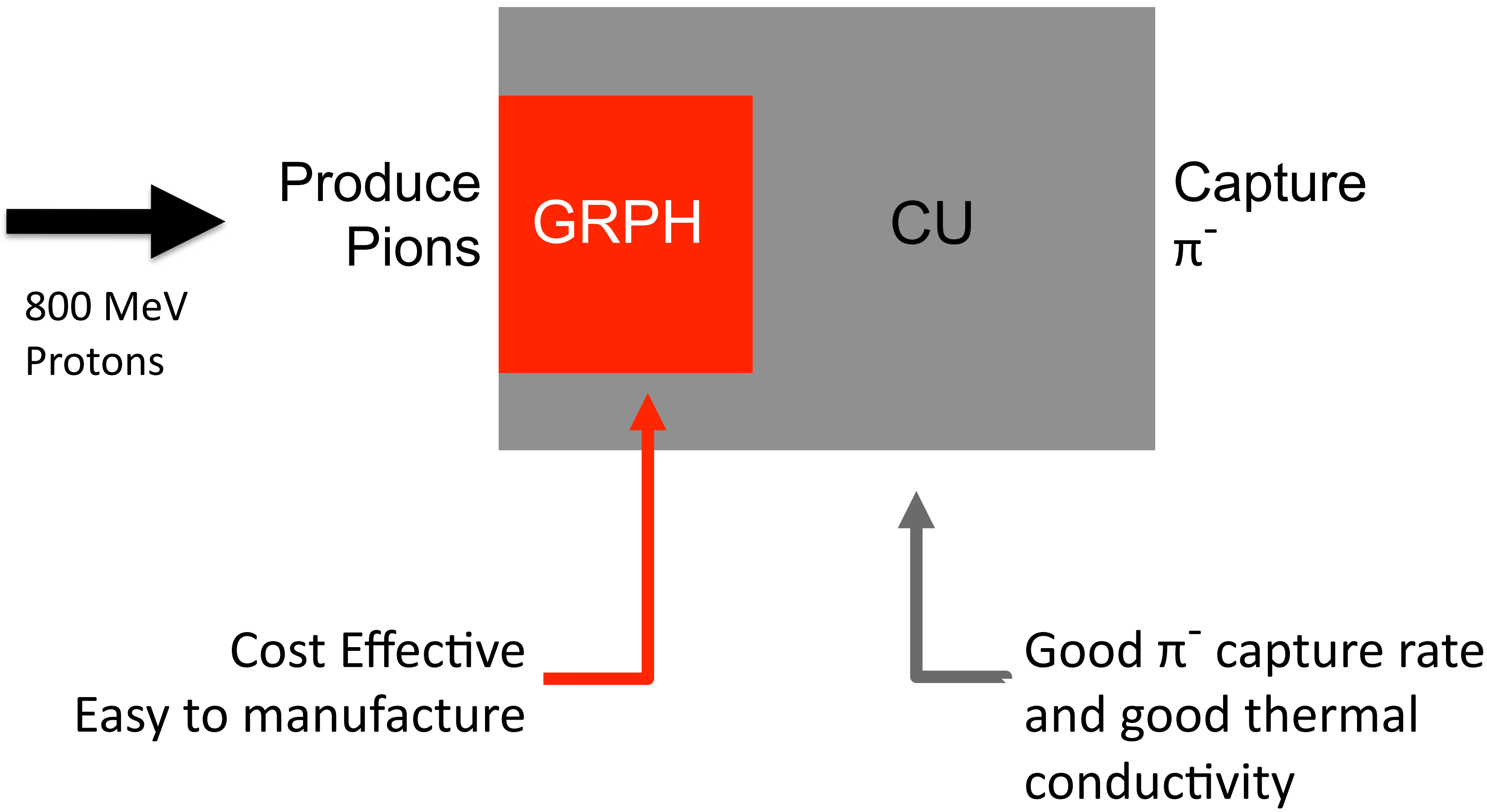
Two material target

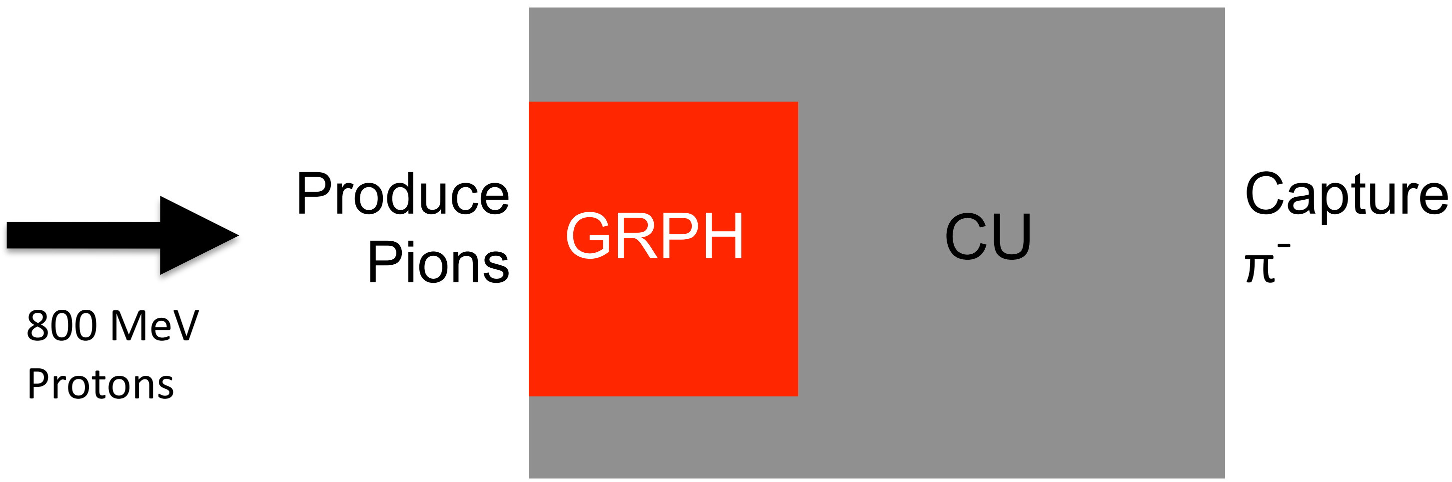


High Z



800 MeV
Protons
Produce
Pions
GRPH
CU
Capture
π^-
Cost Effective
Easy to manufacture
Good π^- capture rate
and good thermal
conductivity

Target Geometry



Graphite needs to be thin enough for pions to enter copper before decaying. *Competing effects*.

- Thickness of GRPH determined by simulation.
  - + Optimal thickness ~80 cm (interaction length)
- Further shaping deduced from heat transfer analysis.

Pion Production – MARS and GEANT4

+ Pion production is our figure of merit. Gives us our neutrinos.
+ Want to compare simulation output to experimental values.

Compare:

Pions per **interacting** proton.

[simulation]

$$\sigma_{pion} / \sigma_{inelast}$$

[experimental]

+ Tricky to compare.
+ We do not have σ_{pion} and $\sigma_{inelast}$ cross-sections at **SAME** energies!

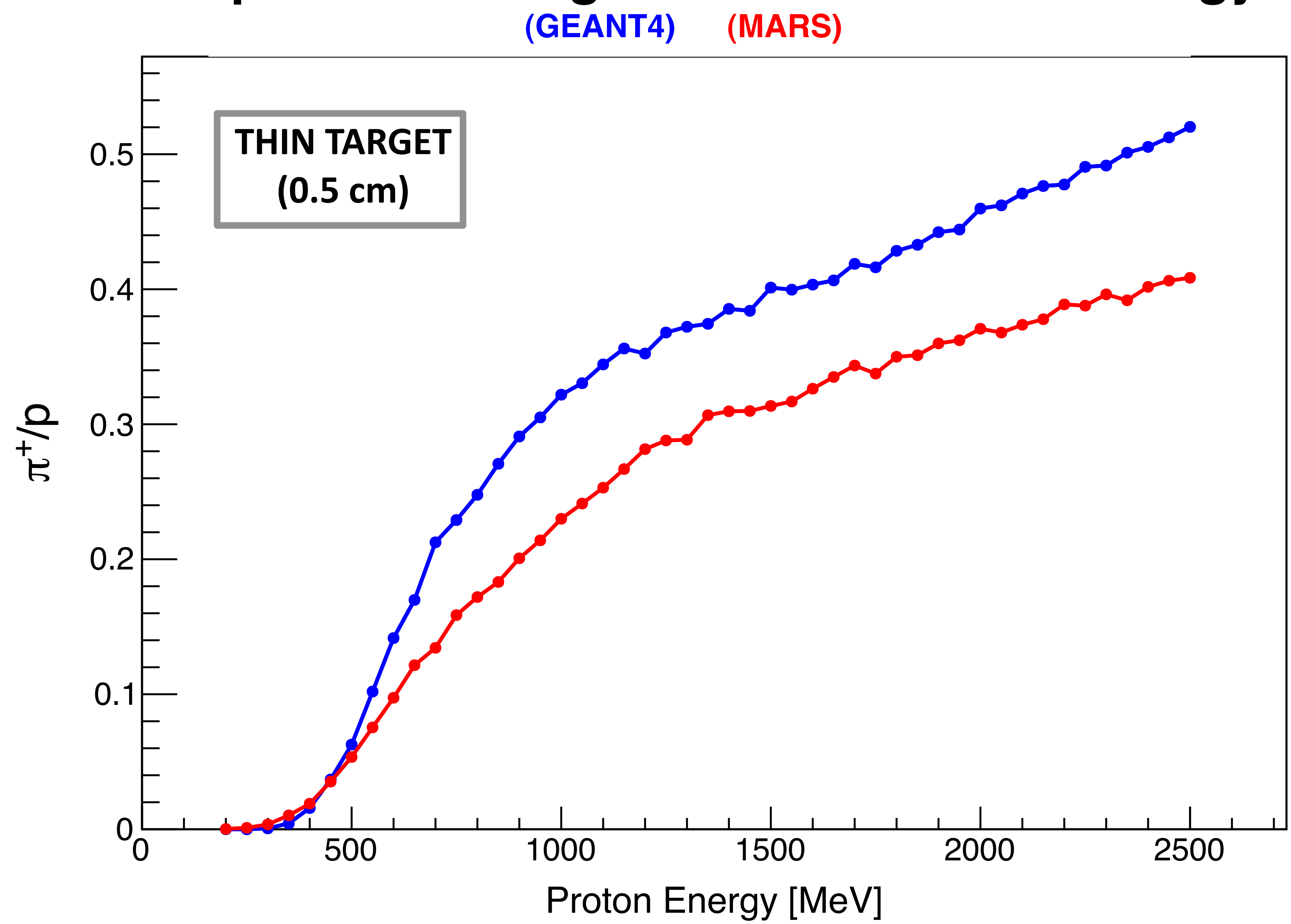
Pion Production – MARS and GEANT4

To get $\sigma_{pion}/\sigma_{inelast}$ *for Experimental Data:*

$\rightarrow$ Interpolate σ_{pion} and errors
$\rightarrow$ Interpolate $\sigma_{inelast}$ and errors
$\rightarrow$ Divide interpolations and propagate interpolated errors to get ratio.

Pion Production – MARS and GEANT4

π^+ per Interacting Proton vs. Proton Energy



Pion Production – MARS and GEANT4

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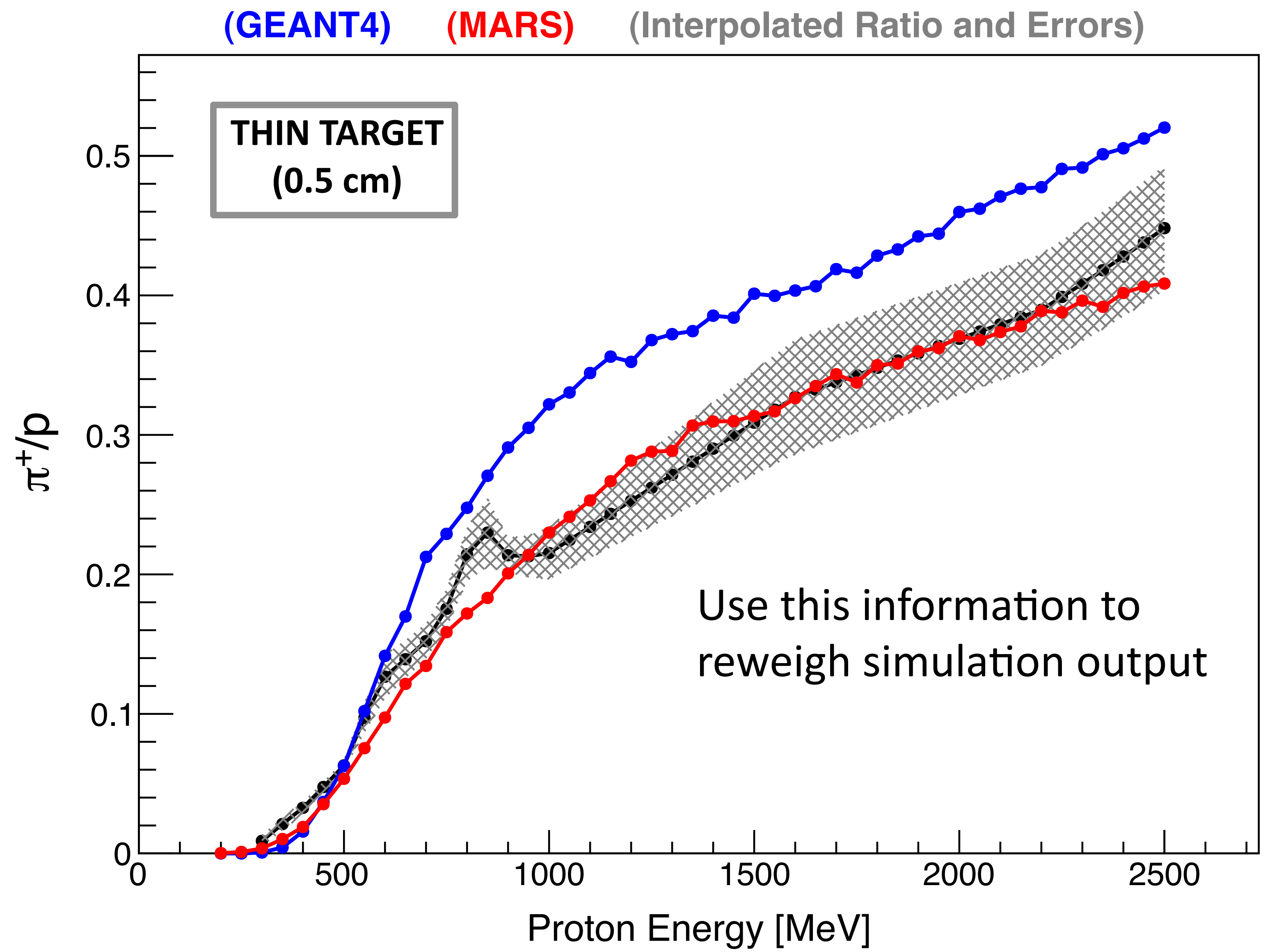
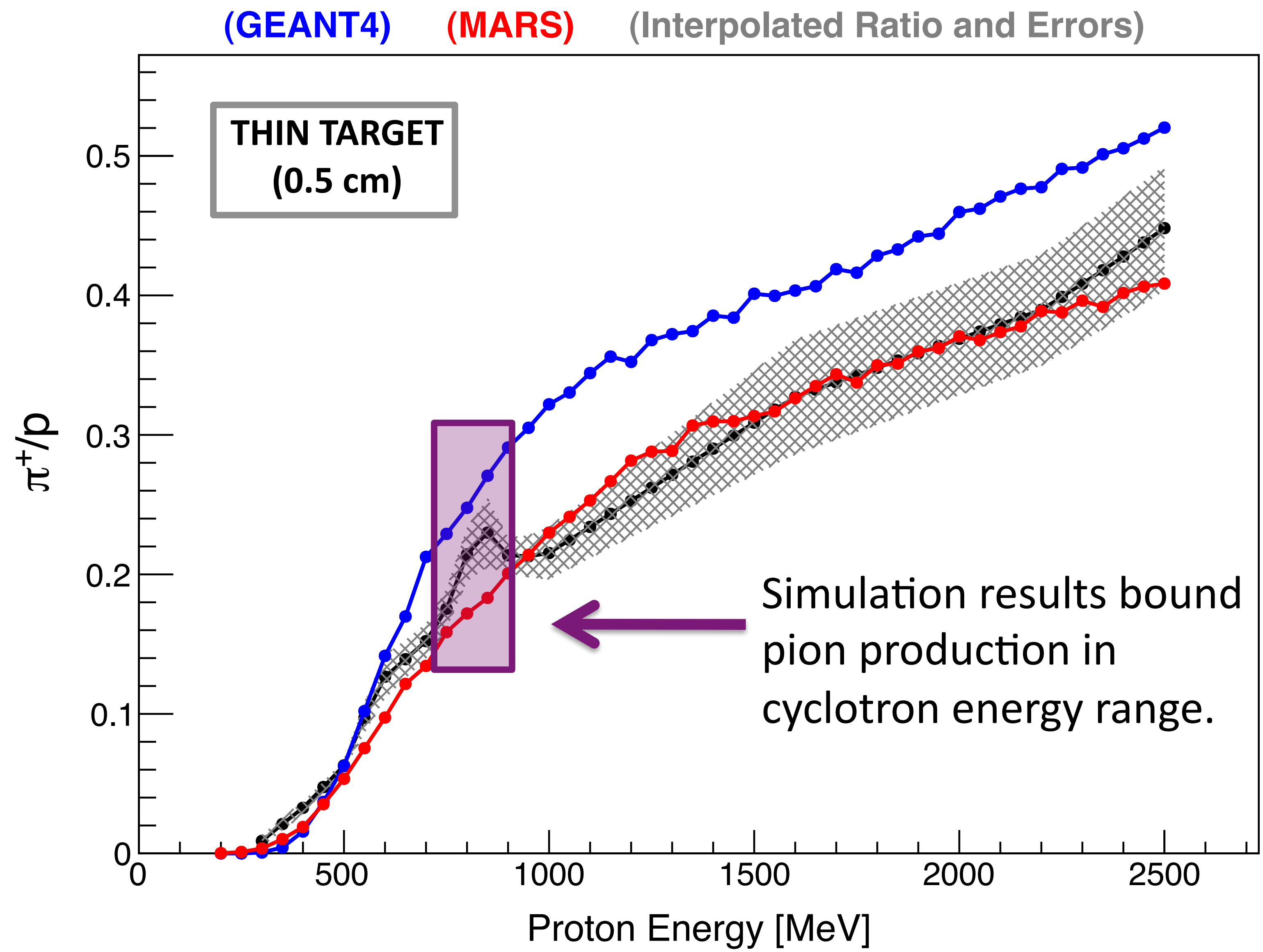


Use this information to reweigh simulation output

Pion Production – MARS and GEANT4

π^+ per Interacting Proton vs. Proton Energy



Conclusion

DAEdALUS will make measurements of electron antineutrino appearance by measuring signal from sources at three distances.

The materials and geometry of the beam targets impact the neutrino flux and background.

For pion production, we can use comparison with experimental data to reweigh simulation output. Without such reweigh, GEANT4 and MARS bound the potential flux of our sources.

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Thank you!

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Special thanks to Adriana Bungau for GEANT4 data, Janet Conrad, and the DAEdALUS Collaboration.

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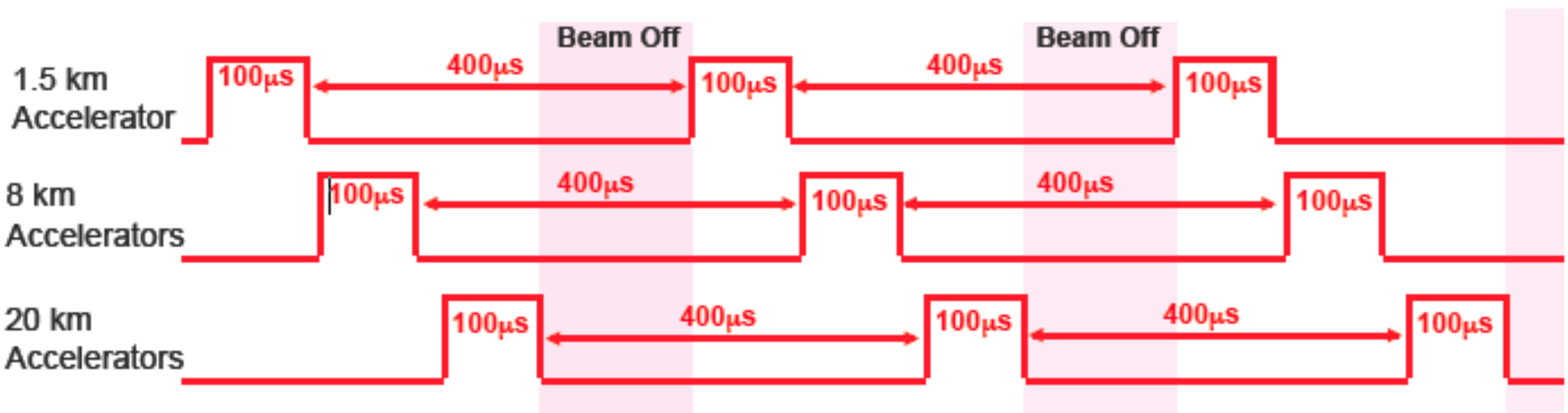
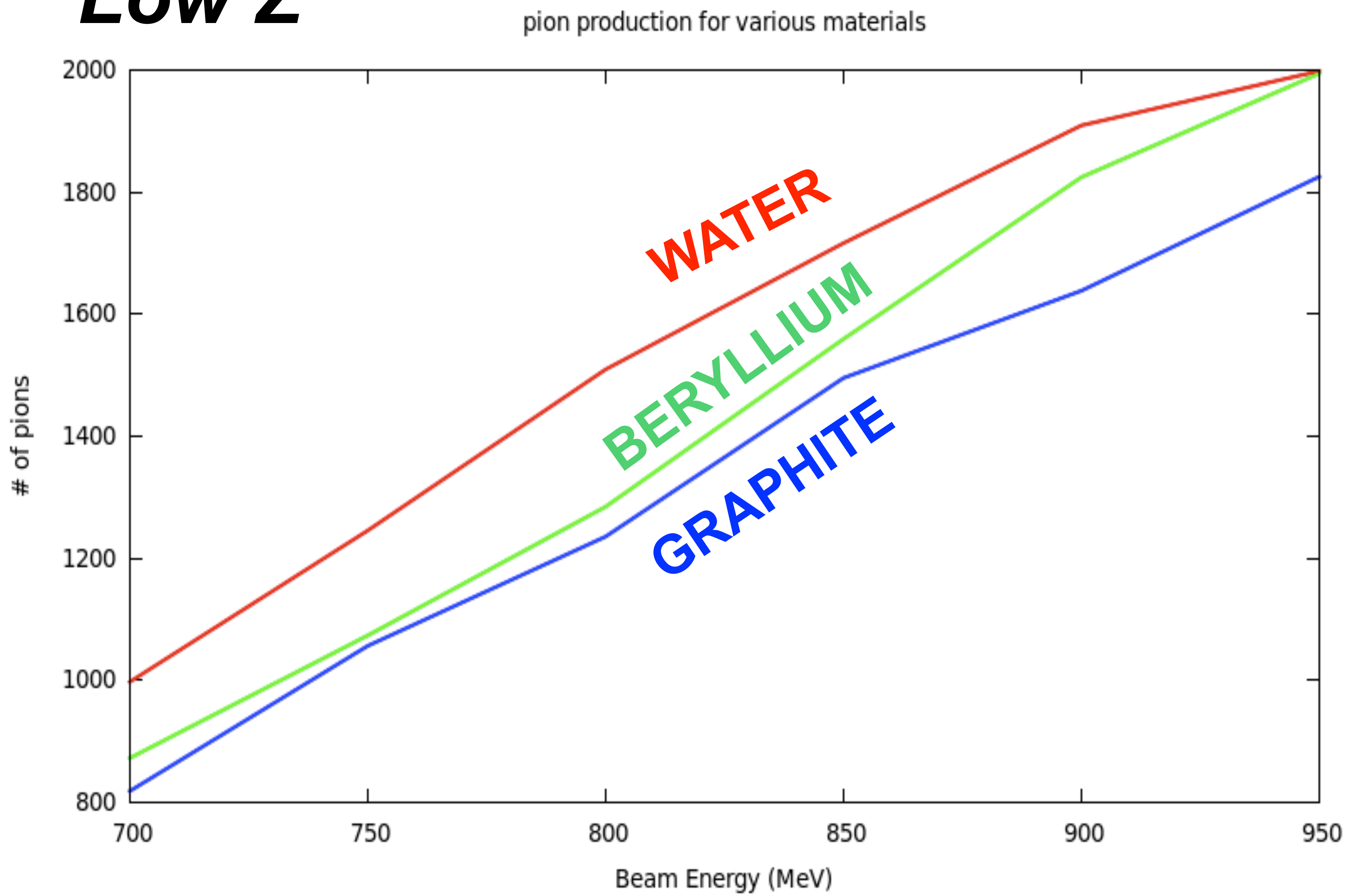
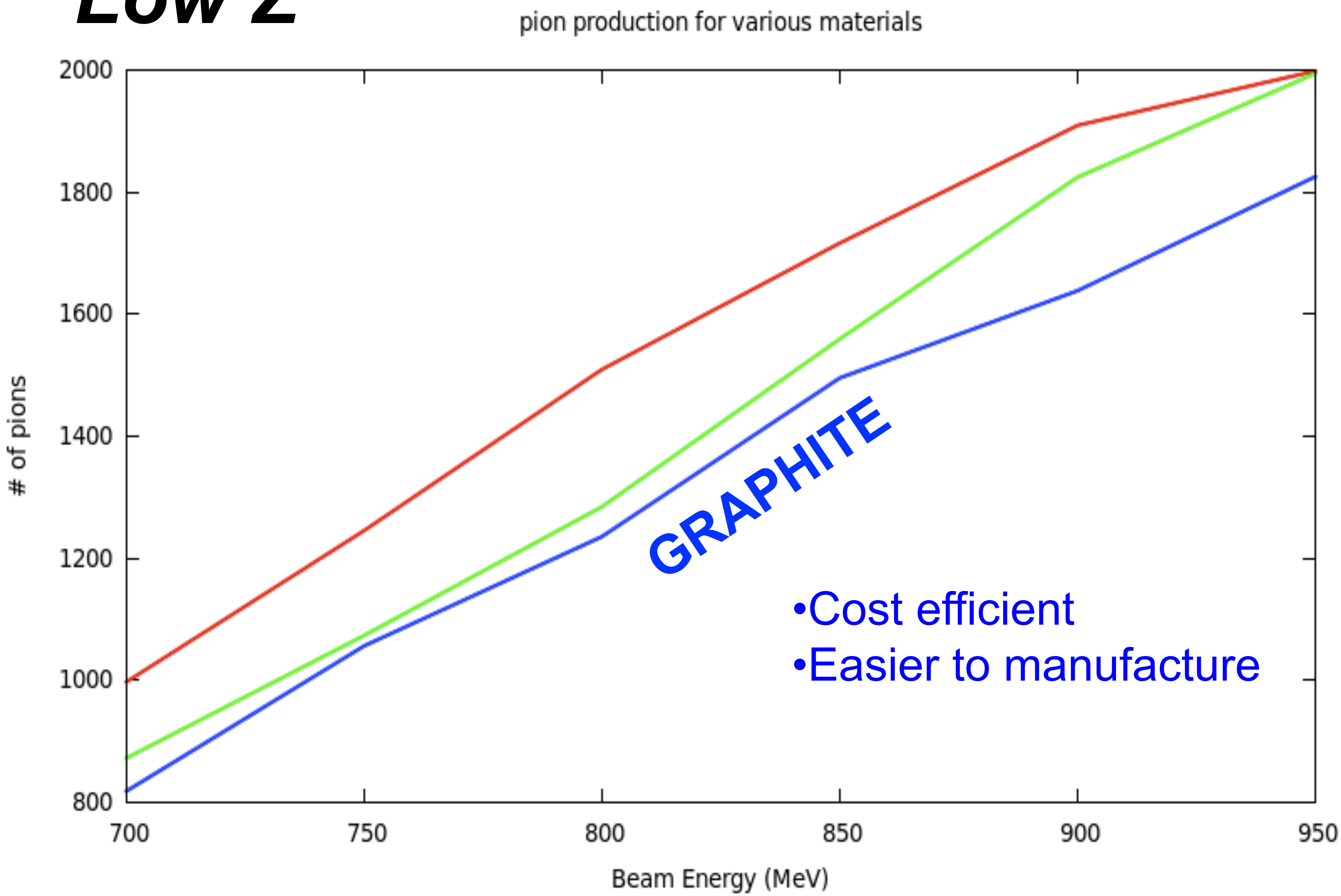


Low Z



Plot by Adrien Houlier

Low Z



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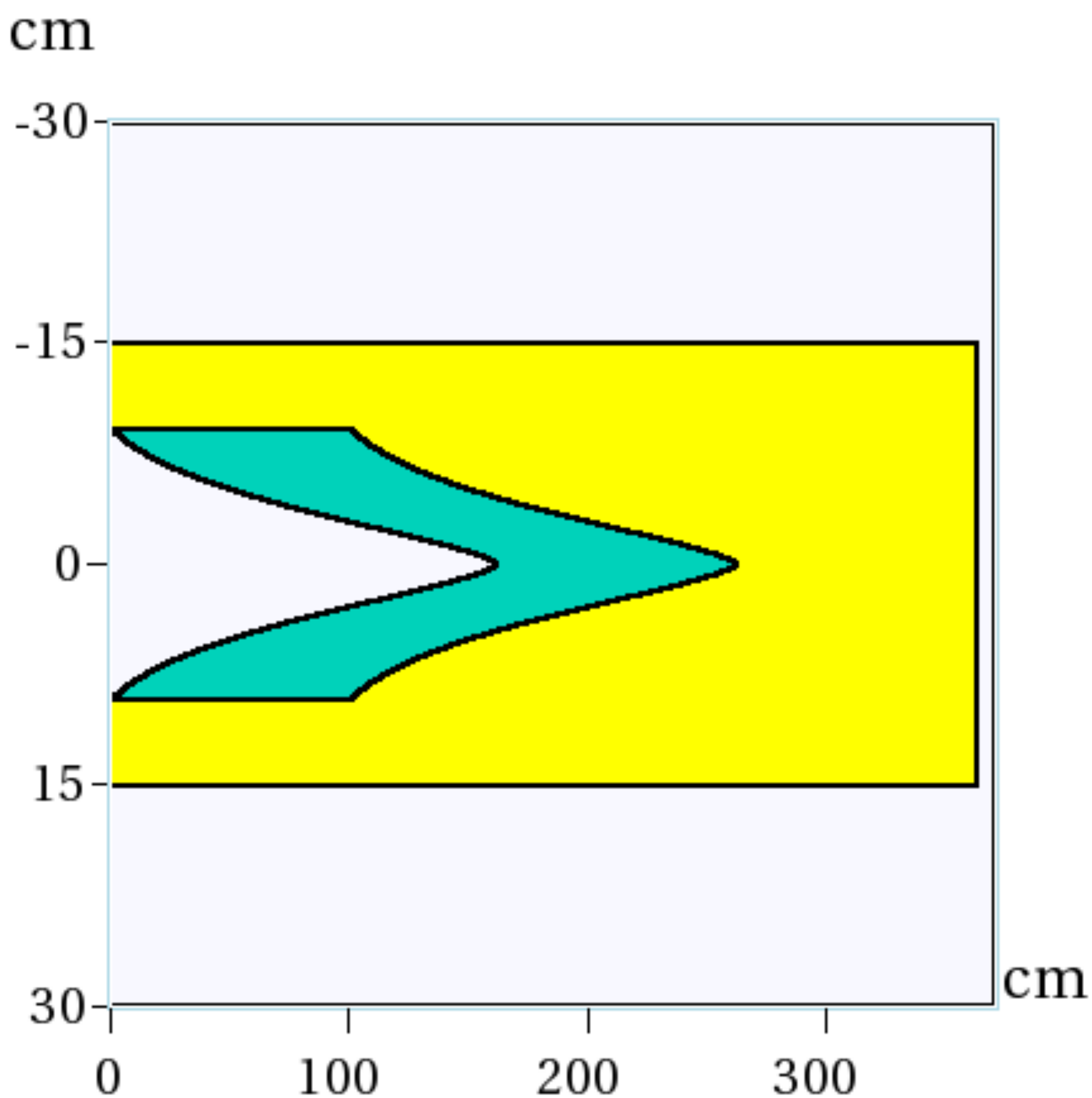
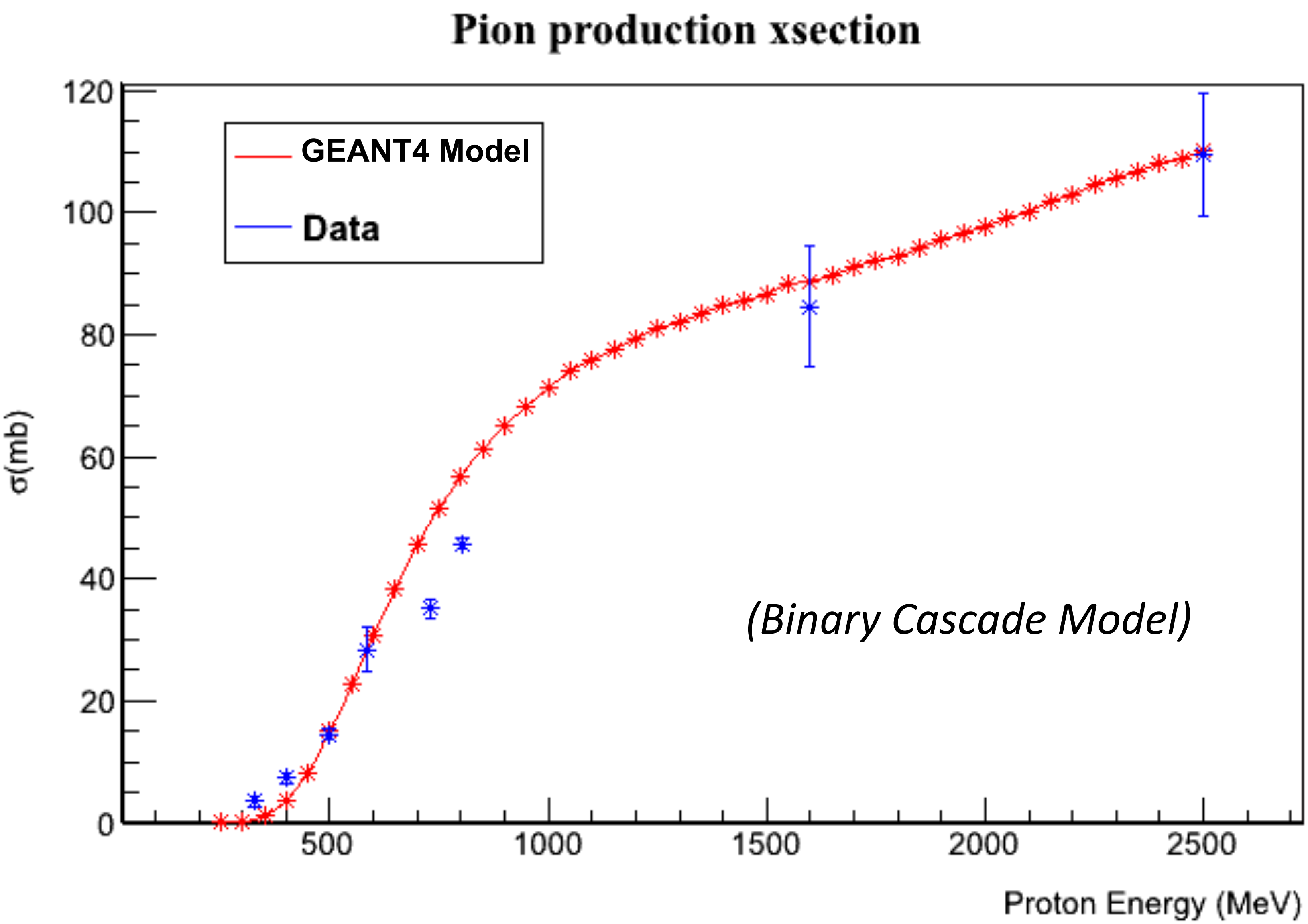
Example of Shaping wrt to heat transfer analysis





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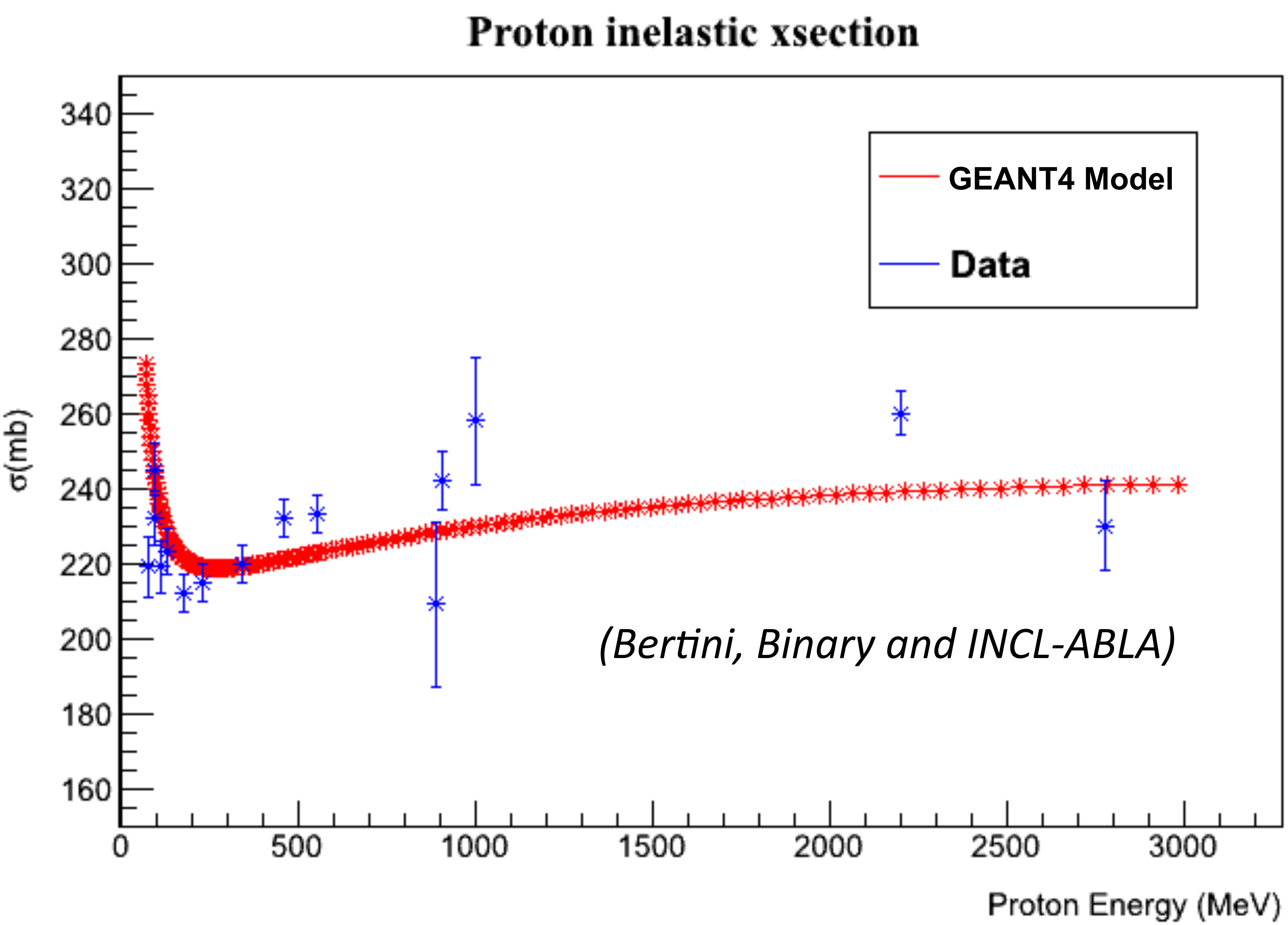

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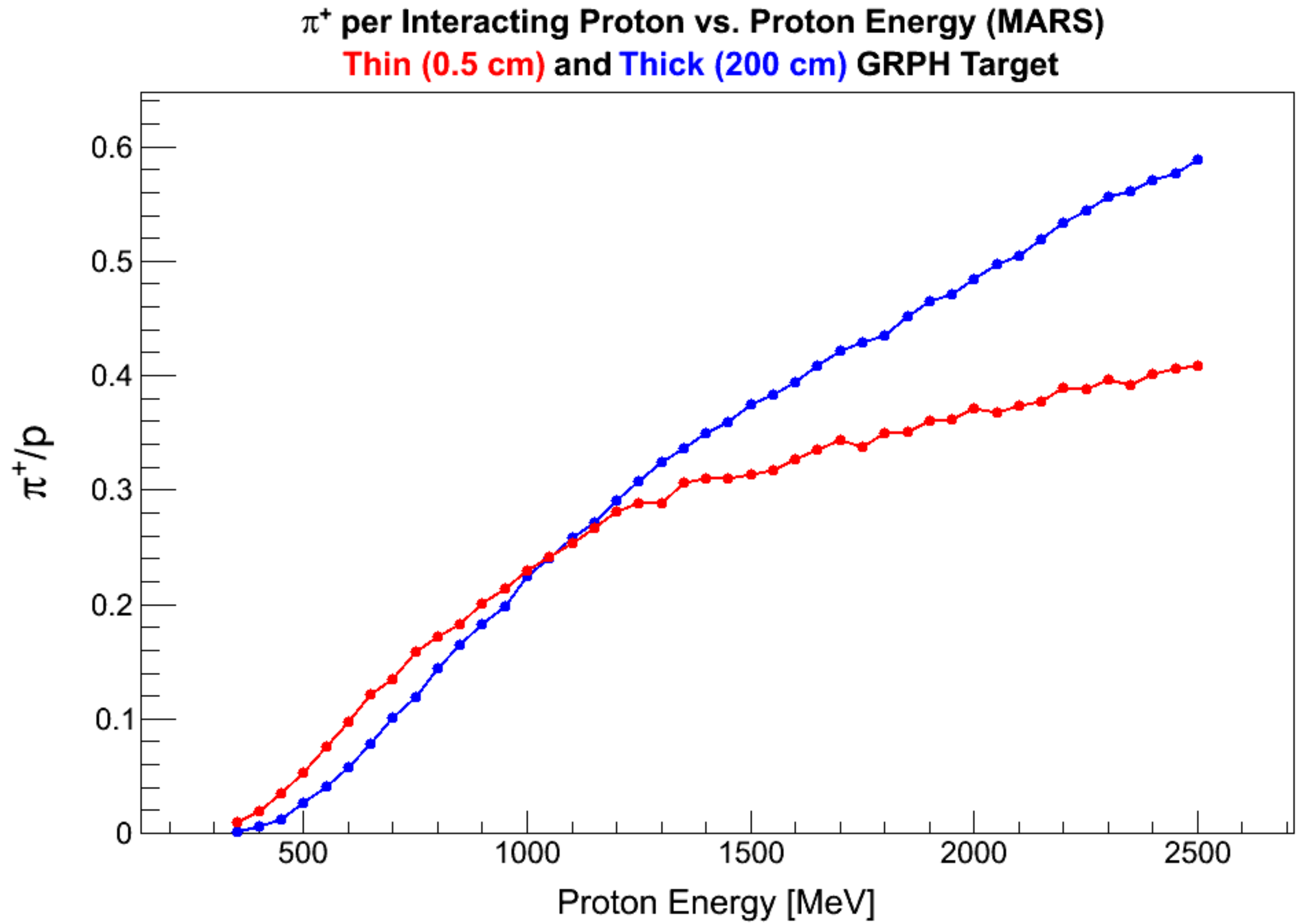
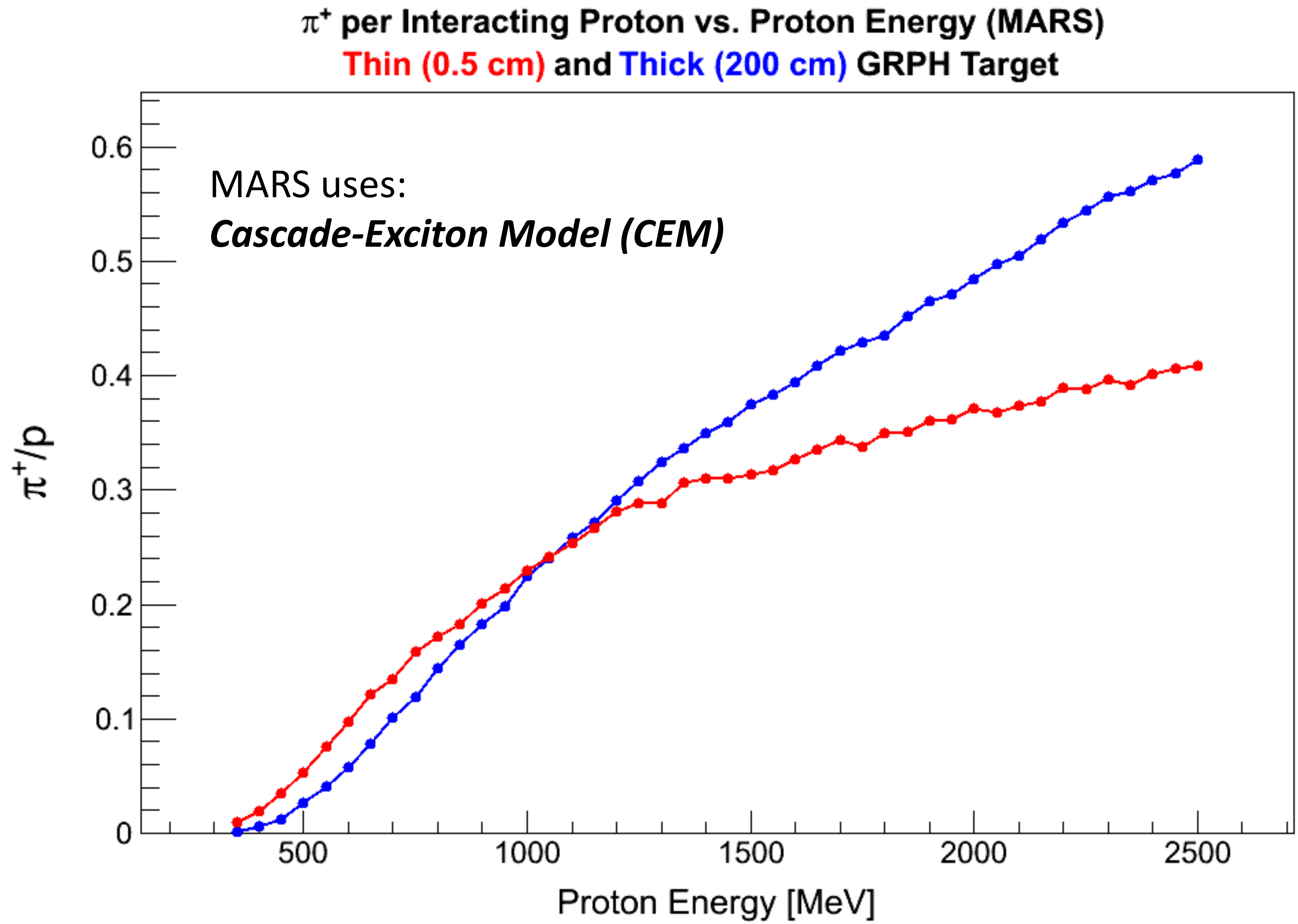
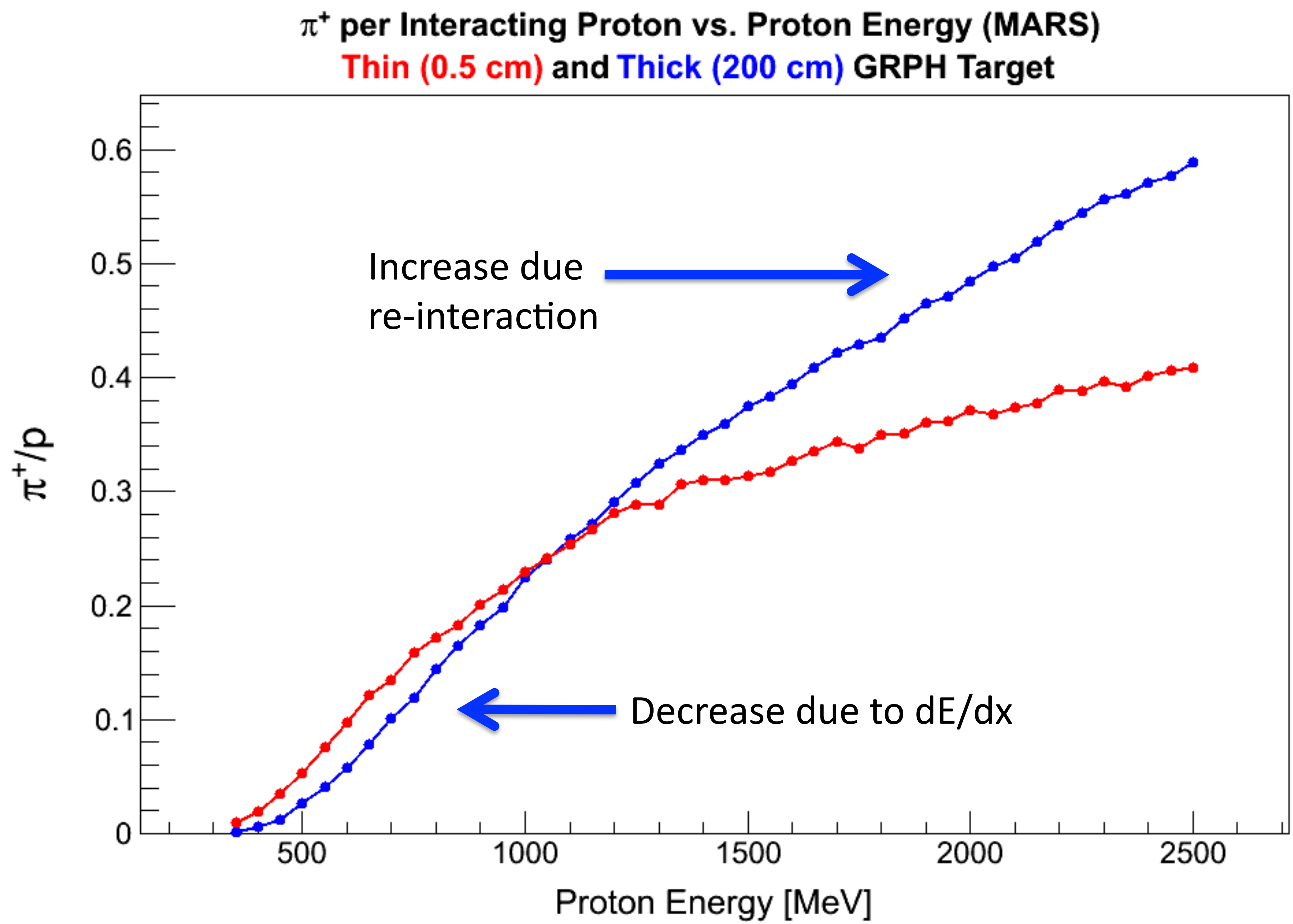


π+ per Interacting Proton vs. Proton Energy (MARS)
Thin (0.5 cm) and Thick (200 cm) GRPH Target
π+/p
0.6
0.5
0.4
0.3
0.2
0.1
0
500
1000
1500
2000
2500
Proton Energy [MeV]


π+ per Interacting Proton vs. Proton Energy (MARS)
Thin (0.5 cm) and Thick (200 cm) GRPH Target
MARS uses:
Cascade-Exciton Model (CEM)
π+/p
0
0.1
0.2
0.3
0.4
0.5
0.6
500
1000
1500
2000
2500
Proton Energy [MeV]



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π+/p
0.6
0.5
0.4
0.3
0.2
0.1
0
500
1000
1500
2000
2500
Proton Energy [MeV]
Increase due re-interaction
Decrease due to dE/dx