

PION THERMAL MODEL FOR SPACE RADIATION CODES

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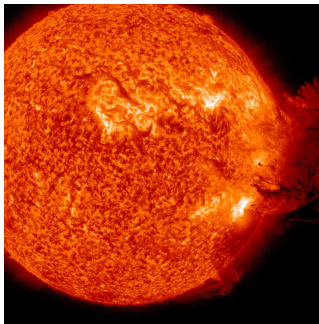
November 1, 2011

- Space Radiation Environment
- Radiation Transport
- Motivation
- Thermal Model
- Results
- Conclusions

SPACE RADIATION ENVIRONMENT

- Solar Particle Events

- Protons with energies reaching hundreds of MeV
- Electrons with energies ranging from keV to MeV

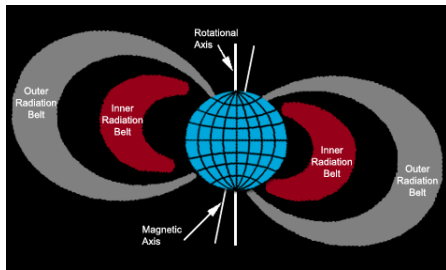


NASA/Solar Dynamics Observatory: June 10, 2011

SPACE RADIATION ENVIRONMENT

- Geomagnetically Trapped Particles

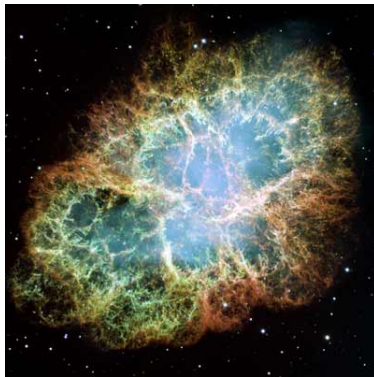
- Consists mostly of protons and electrons trapped in magnetic field
- Energies range from keV to MeV



NASA (Public Domain)

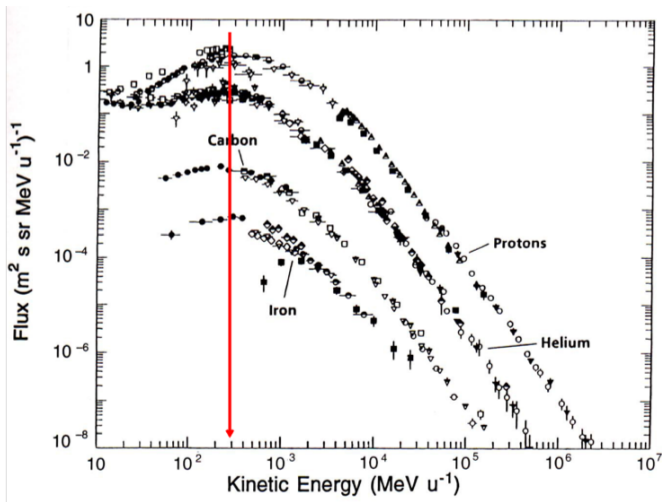
SPACE RADIATION ENVIRONMENT

- Galactic Cosmic Rays
 - Consists mostly of protons and heavier nuclei
 - Energies reach up to TeV per nucleon
 - Spectrum peaks in MeV range



Hubble Telescope Image

GCR SPECTRUM



Galactic Cosmic Ray Spectrum¹

¹J.A. Simpson, *Ann. Rev. Nucl. Part. Sci.*, 33 (1983) 323.

RADIATION EXPOSURE



Astronaut Michael Gernhardt

① Radiation Transport

- Monte Carlo: simulate particle trajectories
- Deterministic: solve the Boltzmann transport equation

② NASA: HZETRN (High Z and Energy TRaNsport)

- 1-D deterministic code
- Uses straight ahead and continuous slowing down approximations

③ 1-D Transport

- Spectral flux at boundary
- Total absorption cross section
- Spectral distribution $\frac{d\sigma}{dE}$

- What is transported in HZETRN?
 - Light particle ($A \leq 4$): n, p, and isotopes of hydrogen and helium
 - Heavier ions
- What would be needed for 3-D deterministic code?
 - Double Differential Cross sections $\frac{d^2\sigma}{dEd\Omega}$
- Mesons are currently being incorporated into transport

MOTIVATION: PION TRANSPORT

- Nucleon-nucleon, nucleon-nucleus, and nucleus-nucleus scattering produces hadrons
- Some hadrons are transported, but mesons are still being incorporated.
- Are mesons important?
- Recent study²
 - 1 GCR spectrum
 - 2 Behind 5 gm/cm² Al and 30 gm/cm² of tissue:
Total dose increase of 9% with inclusion of pion channel
 - 3 Behind 20 gm/cm² Al and 30 gm/cm² of tissue:
Total dose increase of 16% with inclusion of pion channel

²S.K. Aghara et al. *Nuclear Instruments and Methods in Physics B* 267 (2009) 1115-1124.

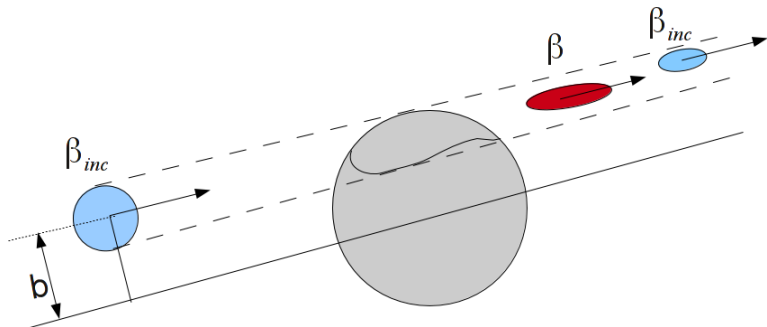
MOTIVATION: PION CROSS SECTIONS

- Study³ of charged pion production for p-p collisions for > 20 GeV energies: Badhwar was found to give best representation of data
- Study⁴ of 158 AGeV p-p and p-C reactions
 - Badhwar and Mokhov models were found to provide best fits to p-p data
 - Badhwar and Mokhov models provide moderately good fit to p-C data
- Thermal model⁵ at low energy represents nucleus-nucleus cross sections well

³Blattnig et al. *Phys. Rev. D* 62, 094030 (2000).

⁴Norbury et al. *Phys. Rev. D* 75, 034001 (2007).

⁵J. W. Norbury *Phys. Rev. C* 79, 037901 (2009).



Thermal Model of Collision⁶

⁶G.D. Westfall et al. *Physical Review Letters*, 37 (1976).

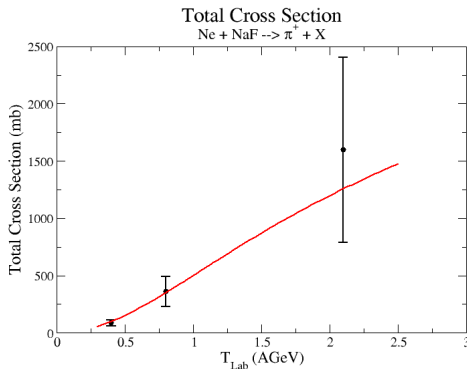
LORENTZ INVARIANT DIFFERENTIAL CROSS SECTION

$$E \frac{d^3\sigma}{dp^3} = N \exp \left(\frac{-T_{\text{cm}}}{E_0} \right)$$

- T_{cm} is the kinetic energy of pion in nucleon-nucleon COM frame
- E_0 is the fireball temperature

TOTAL CROSS SECTIONS

- Parameterizations⁷ of σ_{tot} for pions as function of A_{proj} , A_{targ} , and Lab Energy



⁷Norbury et al. *Nucl. Inst. and Meth. in Phys. Res. B.* 25 (2007) 187.

THERMAL MODEL TEMPERATURE

THERMAL MODEL

$$E \frac{d^3\sigma}{dp^3} = N \exp \left(\frac{-T_{\text{cm}}}{E_0} \right)$$

- Can this be expressed as function of A_{proj} , A_{targ} , and lab energy?
- Parameterization of temperature E_0

Temperatures⁸ for different lab energies: $\text{Ne} + \text{NaF} \rightarrow \pi^- + X$

$$E_0[T_L] = \frac{1}{1000} [72 + 38 \log(T_L/T_0)]$$

where T_L and T_0 are in GeV.

⁸S. Nagamiya et al. *Phys. Rev. C.* 24 (1981) 971.

THERMAL MODEL NORMALIZATION

THERMAL MODEL

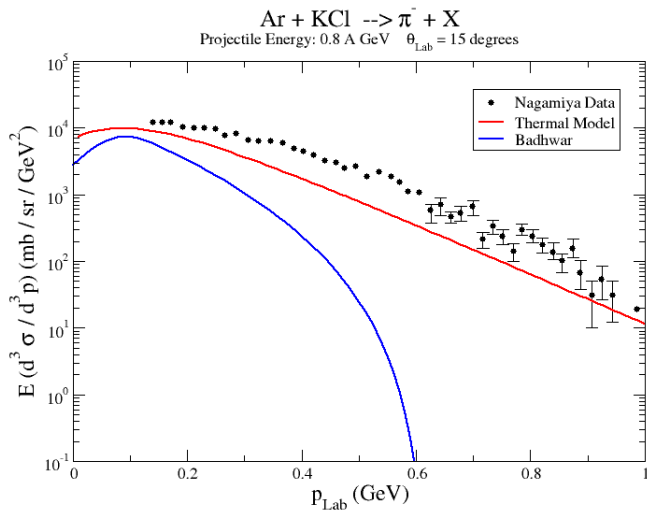
$$E \frac{d^3\sigma}{dp^3} = N \exp \left(\frac{-T_{\text{cm}}}{E_0} \right)$$

- Now integrate over angles and pion energy
- Set equal to total parameterized cross sections

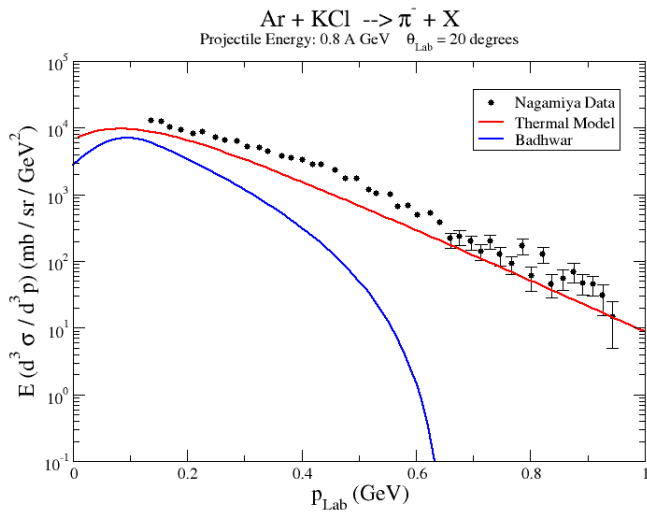
PARAMETERIZED DOUBLE DIFFERENTIAL CROSS SECTION

$$E \frac{d^3\sigma}{dp^3} = f(T_{\text{Lab}}, A_{\text{proj}}, A_{\text{targ}})$$

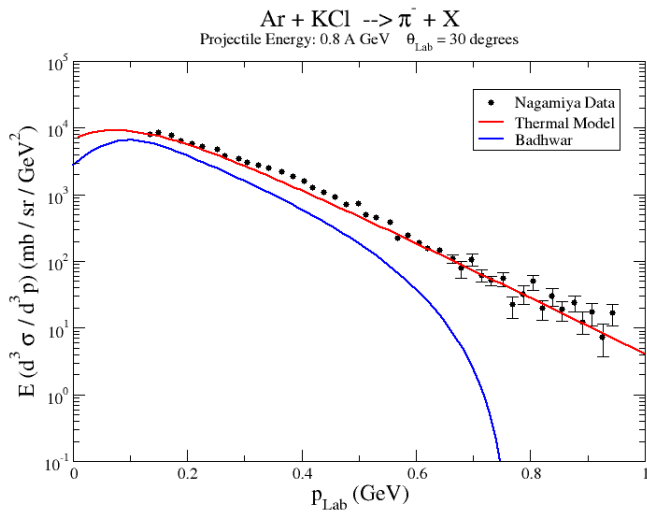
RESULTS



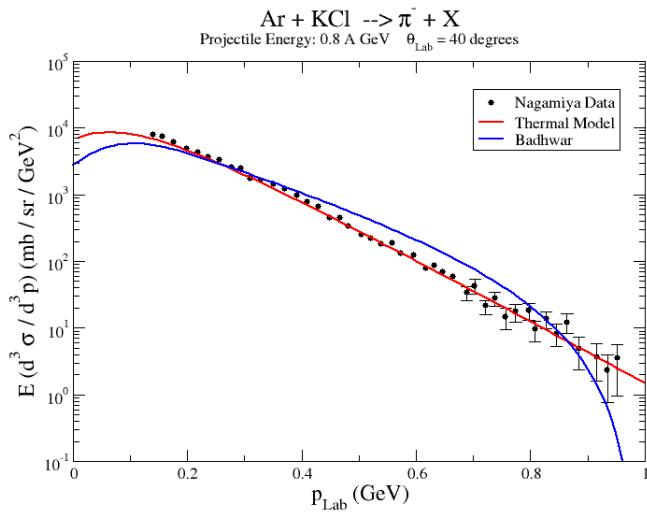
RESULTS



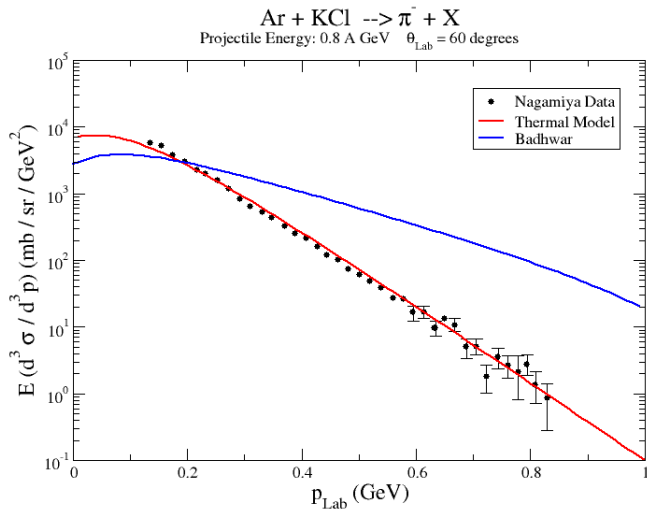
RESULTS



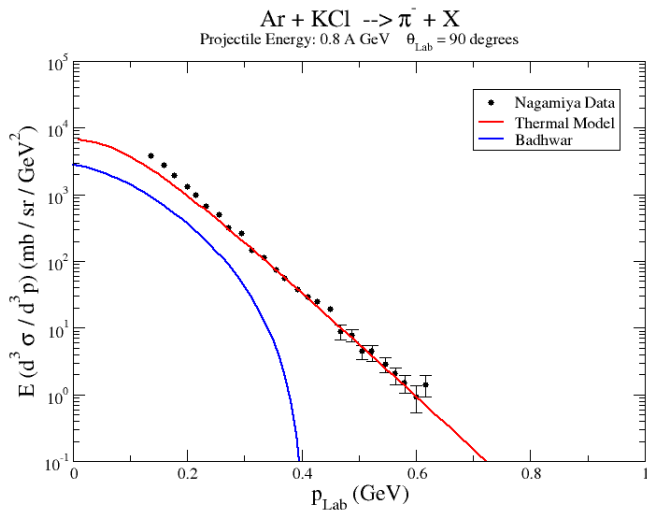
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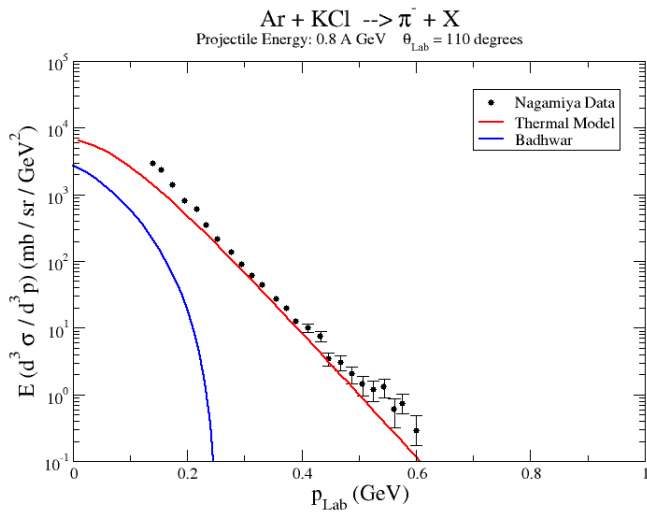
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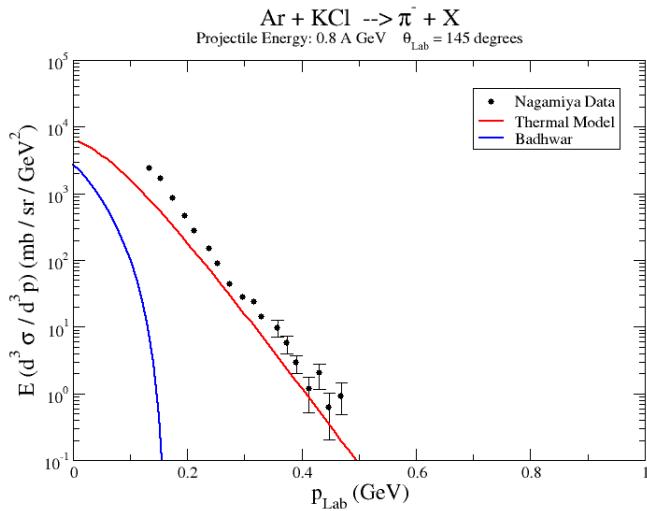
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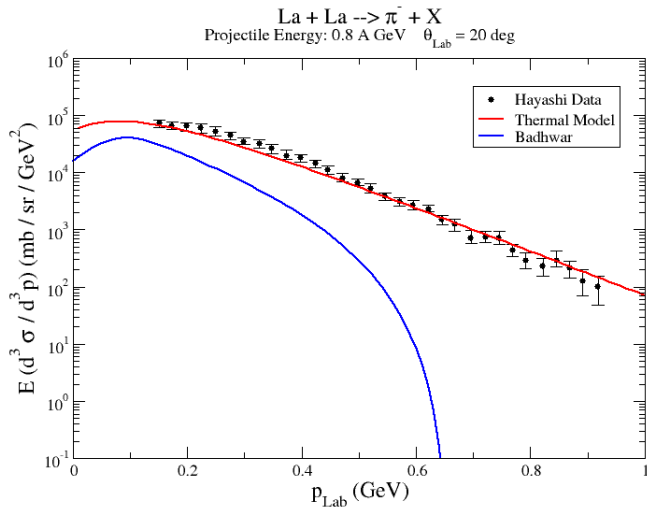
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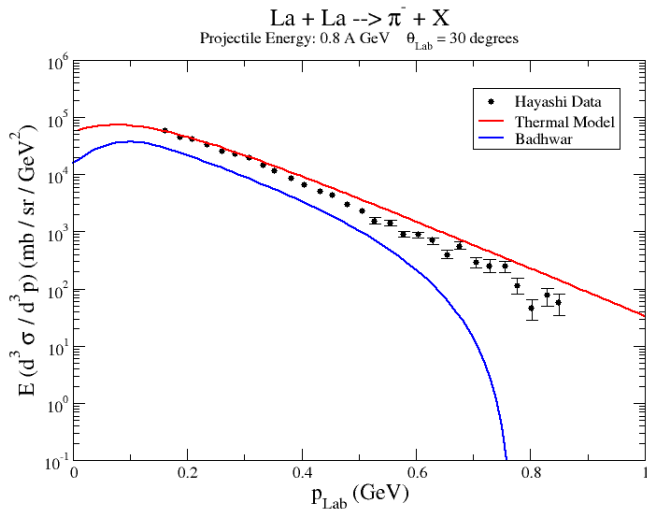
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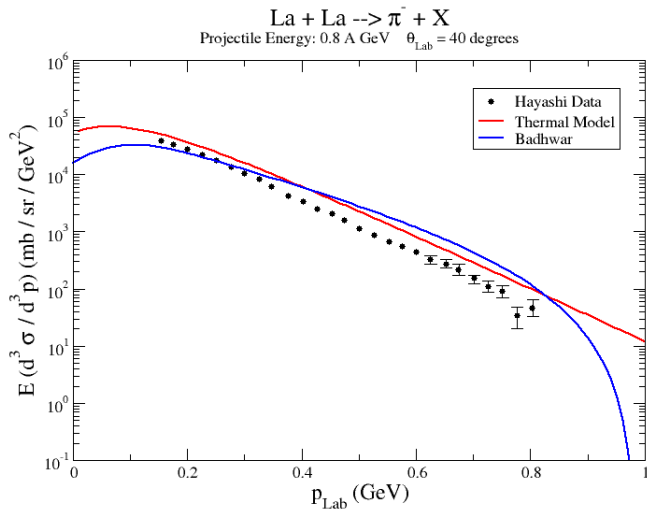
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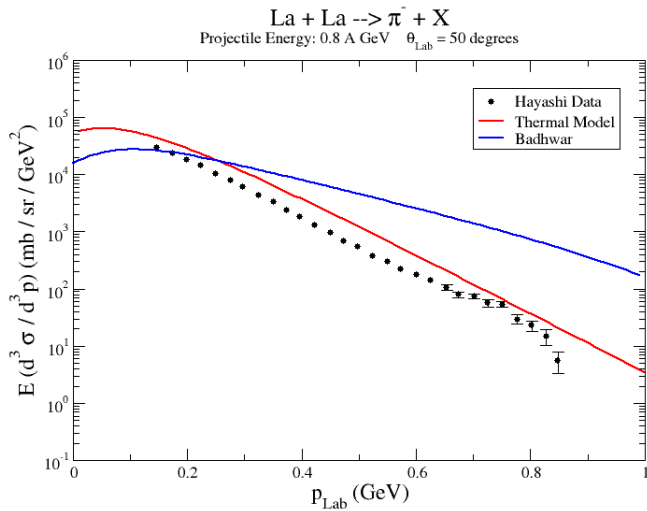
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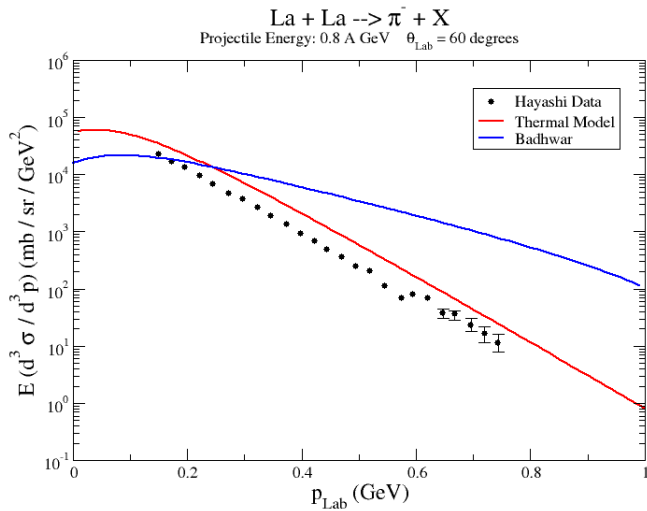
RESULTS



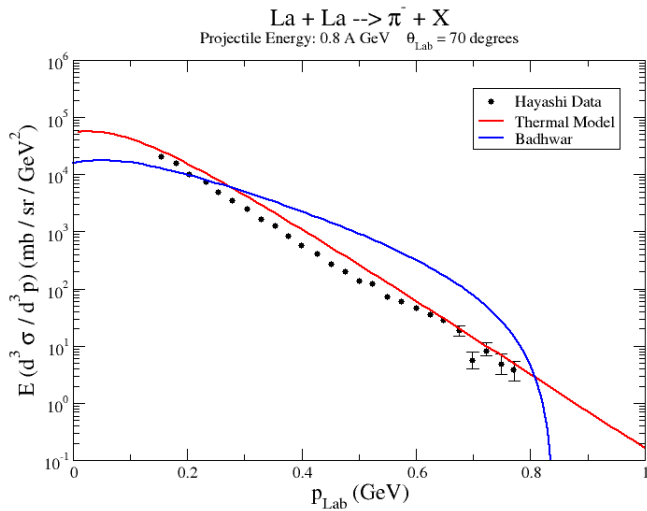
RESULTS



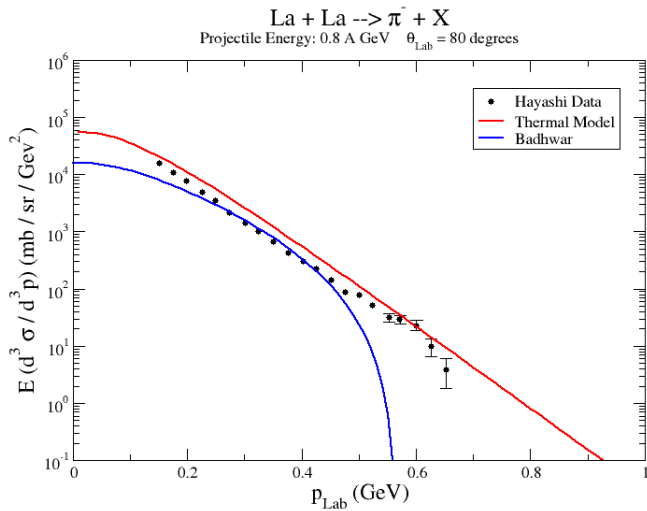
RESULTS



RESULTS



RESULTS



CONCLUSIONS

- Thermal model has been parameterized as a function of projectile and target size and Lab energy
- Thermal and Badhwar model predictions of cross sections were compared at low energy
- Thermal model works better than Badhwar for low energy nucleus-nucleus reactions
- Thermal model should be compared to higher energy nucleus-nucleus data
- Thermal Model should be compared to low and higher energy nucleon-nucleus data