Karlsruhe Institute of Technology

Investigation of Nuclear Fragmentation and Neutral Pion Production with NA61/SHINE

High-Energy Universe Group Seminar

Johannes Bennemann | 26 October 2023

Outline

1. Nuclear Fragmentation

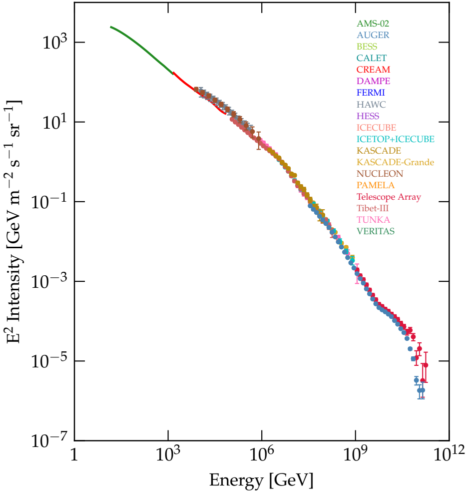
- Motivation
- NA61/SHINE
- Cosmic ray propagation
- Concept of measurement
- Target calculations
- Summary

2. Neutral Pion Production

- Air showers
- Idea of measurement
- Particle identification
- Invariant mass cut
- Pair production cross section
- Corrections
- Results
- Summary

Part I: Nuclear Fragmentation

Cosmic rays

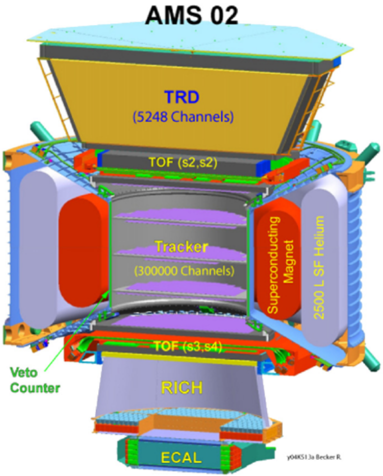


Carmelo Evoli. The Cosmic-Ray Energy Spectrum. Dec. 2020.

- charged particles
- wide energy range
- mostly protons (90%)
- nuclei up to iron

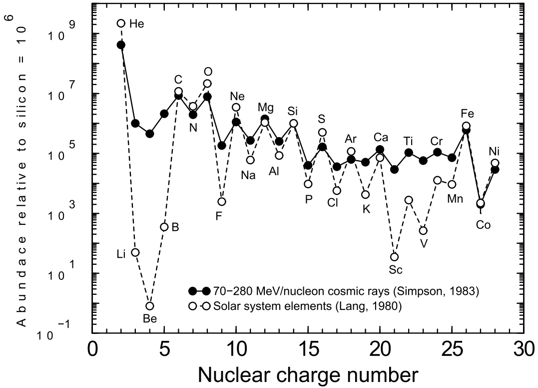
AMS

- Alpha Magnetic Spectrometer
- located at the ISS
- tracking system
- Cherenkov detector
- transition radiation detector



V. Bindi "The alpha magnetic spectrometer AMS-02: Soon in space" Nucl. Instrum. Meth. A

Abundance of light elements



S. G. Mashnik. "On solar system and cosmic rays nucleosynthesis and spallation processes"

- composition of cosmic rays
- not compatible with stellar nucleosynthesis
- excess of lithium, beryllium and boron

Cosmic ray propagation

Diffusion-loss equation

$$\frac{\partial N_i}{\partial t} = D\,\nabla^2 N_i + \frac{\partial}{\partial E}(b(E)\,N_i) + Q_i - \frac{N_i}{\tau_i} + \sum_{j>i} \frac{P_{ji}}{\tau_j} N_j$$

- describes the propagation of cosmic rays
- includes spallation processes
- fragmentation cross sections known with poor precision $\mathcal{O}(20\%)$
  $\Longrightarrow$ measurements required

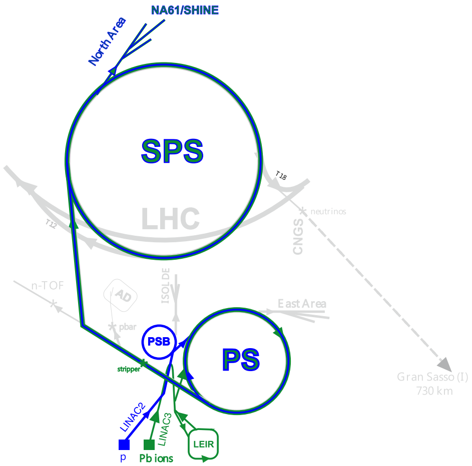
NA61/SHINE

Photo taken by Neeraj Amin

- SPS Heavy Ion and Neutrino Experiment
- located at CERN North Area
- hadron spectrometer
- multiple targets present
- various hadronic beams available

SPS

- Super Proton Synchrotron
- 6.8 km circumference
- provides protons up to 400 GeV
- provides lead ions up to 160 GeV per nucleon
- beryllium target at H2 beamline
- rigidity selection



N. Abgrall et al. “NA61/SHINE facility at the CERN SPS: beams and detector system”. JINST 9.06 (), P06005–P06005.

Detector layout

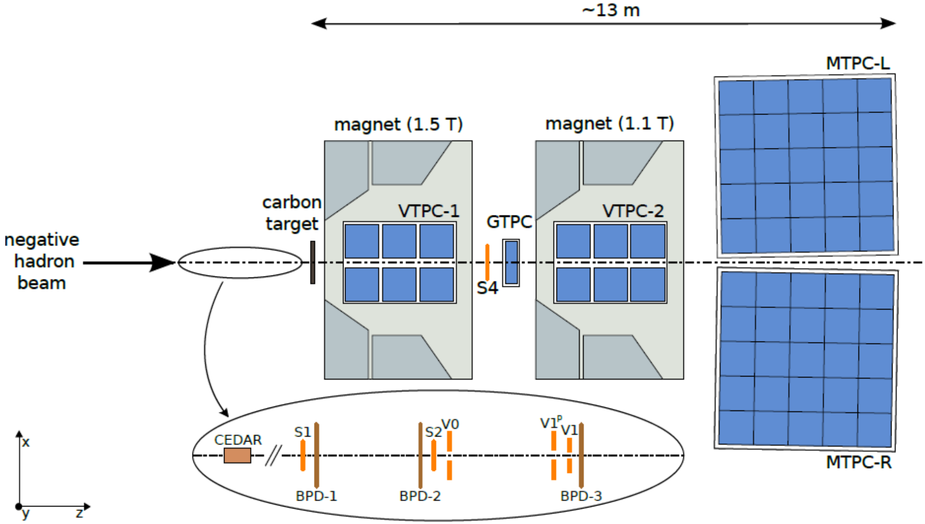
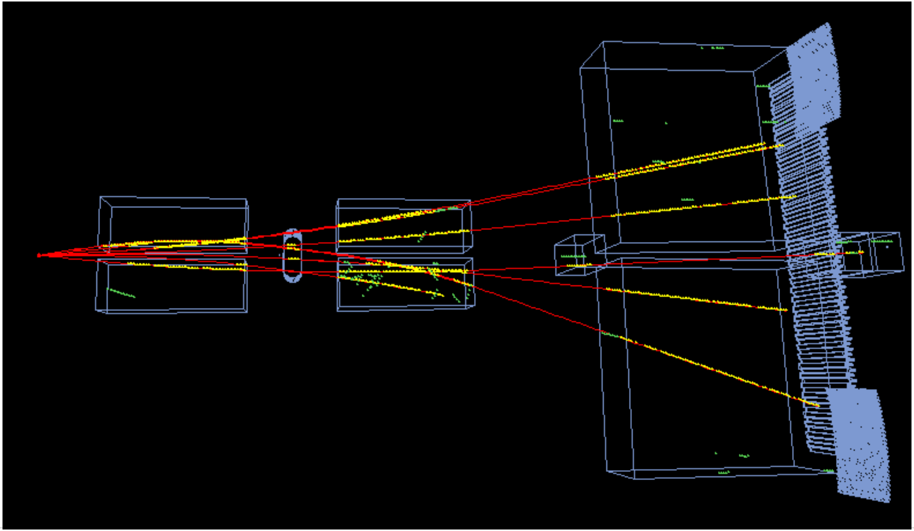


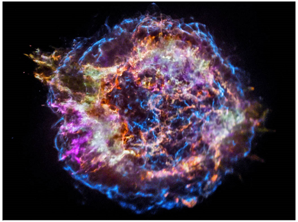
Image from arXiv:2209.10561

Reconstruction



Screenshot from SHINE event browser

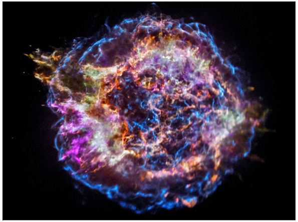
Cosmic ray propagation



Cassiopeia A; NASA/CXC/SAO

^{16}O
^{12}C
$\longrightarrow$

Cosmic ray propagation



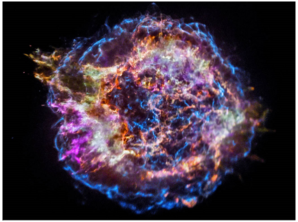
Cassiopeia A; NASA/CXC/SAO

$\xrightarrow{^{16}O \; ^{12}C}$

NGC 6357; Very Large Telescope/ESO

$\xrightarrow{^{10}B \; ^{6}Li}$

Cosmic ray propagation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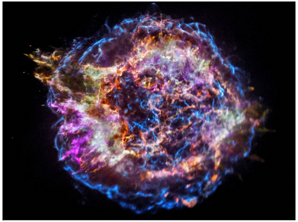
AMS; AMS-02

Cosmic ray propagation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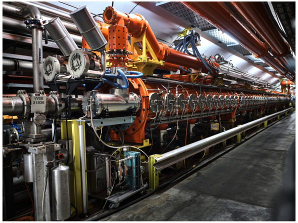
SPS; Julien Ordan/CERN

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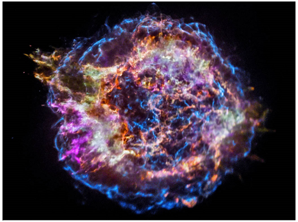
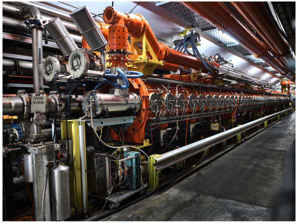
Cosmic ray propagation



Cassiopeia A; NASA/CXC/SAO



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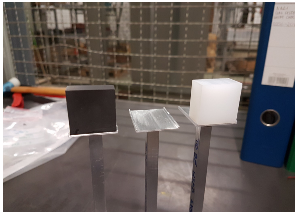
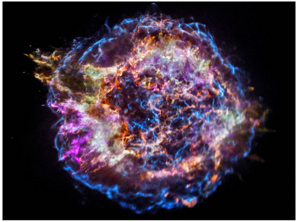


Target holder; Magdalena Kuich

^{10}B
^{6}Li
$\longrightarrow$

AMS; AMS-02

Cosmic ray propagation



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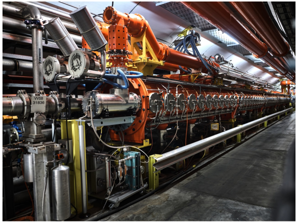

SPS; Julien Ordan/CERN

^{16}O
^{12}C
→

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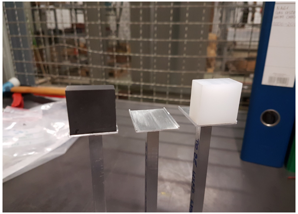

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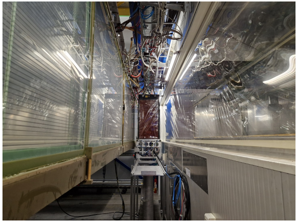


NA61; Johannes Bennemann

Concept of measurement

Before target:

- known rigidity
- measure charge (scintillator)
  $\Longrightarrow$ momentum of nucleus
- measure time of flight $\rightarrow$ velocity
  $\Longrightarrow$ mass of nucleus $m = \frac{p}{\gamma\beta}$

Concept of measurement

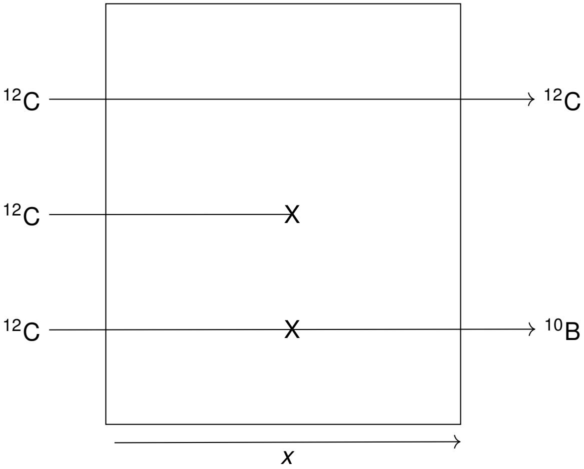
Before target:

- known rigidity
- measure charge (scintillator)
  $\Longrightarrow$ momentum of nucleus
- measure time of flight $\rightarrow$ velocity
  $\Longrightarrow$ mass of nucleus $m = \frac{p}{\gamma\beta}$

After target:

- known momentum per nucleon
- measure momentum (deflection)
  $\Longrightarrow$ number of nucleons
- measure charge ($\frac{dE}{dx}$)

Target

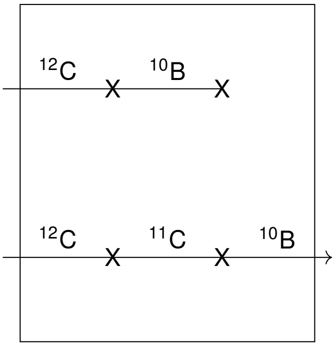


- interaction length $\lambda_{^{12}\text{C}}$
- $N_{^{12}\text{C}}(x) = N_{^{12}\text{C}}(0)\exp\left(-\frac{x}{\lambda_{^{12}\text{C}}}\right)$
- partial int. length $\lambda_{^{12}\text{C}\rightarrow{}^{10}\text{B}}$
- How to calculate $N_{^{10}\text{B}}(x)$?

Destruction and feed down

Additional difficulties:

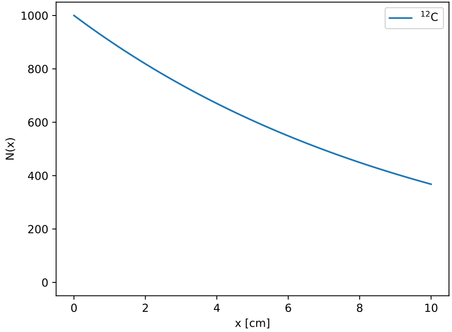
- ^{10}B destroyed within the target (destruction)
- ^{10}B from fragmentation of other nuclei (feed down)
- old solution: use thin target
  $\Longrightarrow$ minimal destruction and feed down
  $\Longrightarrow$ low statistics!
- new solution: calculate destruction and feed down
  $\Longrightarrow$ thick target possible $\rightarrow$ high statistics
  $\Longrightarrow$ requires auxiliary measurements



Differential equation

	^{12}C	^{11}C	^{11}B	^{10}B
$\frac{d}{dx}N_{^{12}\mathrm{C}}$	$^{12}\mathrm{C} \rightarrow \mathrm{X}$			
$\frac{d}{dx}N_{^{11}\mathrm{C}}$				
$\frac{d}{dx}N_{^{11}\mathrm{B}}$				
$\frac{d}{dx}N_{^{10}\mathrm{B}}$				

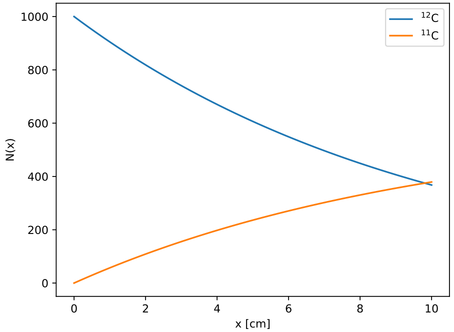
$$\frac{d}{dx}N_{^{12}\mathrm{C}} = -\frac{1}{\lambda_{^{12}\mathrm{C}}}N_{^{12}\mathrm{C}}$$



Differential equation

	^{12}C	^{11}C	^{11}B	^{10}B
$\frac{d}{dx}N_{^{12}C}$	$^{12}C \rightarrow X$			
$\frac{d}{dx}N_{^{11}C}$	$^{12}C \rightarrow {}^{11}C$			
$\frac{d}{dx}N_{^{11}B}$				
$\frac{d}{dx}N_{^{10}B}$				

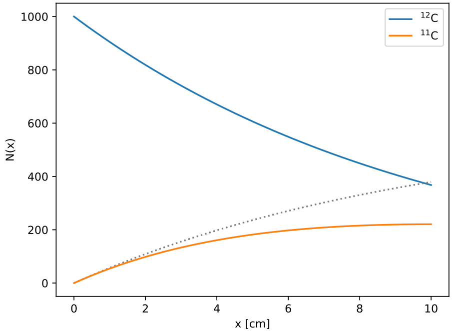
$$\frac{d}{dx}N_{^{11}C} = \frac{1}{\lambda_{^{12}C \rightarrow {}^{11}C}} N_{^{12}C}$$



Differential equation

	^{12}C	^{11}C	^{11}B	^{10}B
$\frac{d}{dx}N_{^{12}C}$	$^{12}C \to X$			
$\frac{d}{dx}N_{^{11}C}$	$^{12}C \to {}^{11}C$	$^{11}C \to X$		
$\frac{d}{dx}N_{^{11}B}$				
$\frac{d}{dx}N_{^{10}B}$				

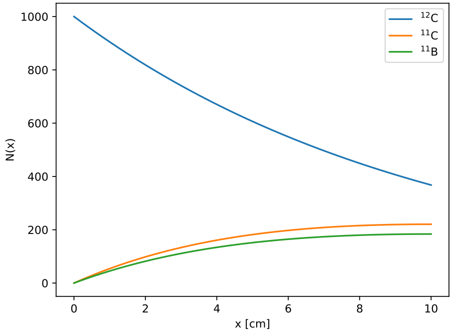
$$\frac{d}{dx}N_{^{11}C} = \frac{1}{\lambda_{^{12}C \to {}^{11}C}} N_{^{12}C} - \frac{1}{\lambda_{^{11}C}} N_{^{11}C}$$



Differential equation

	^{12}C	^{11}C	^{11}B	^{10}B
$\frac{d}{dx}N_{^{12}C}$	$^{12}C \rightarrow X$			
$\frac{d}{dx}N_{^{11}C}$	$^{12}C \rightarrow {}^{11}C$	$^{11}C \rightarrow X$		
$\frac{d}{dx}N_{^{11}B}$	$^{12}C \rightarrow {}^{11}B$	-	$^{11}B \rightarrow X$	
$\frac{d}{dx}N_{^{10}B}$				

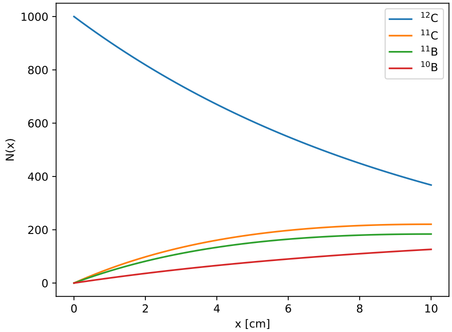
$$\frac{d}{dx}N_{^{11}B} = \frac{1}{\lambda_{^{12}C \rightarrow {}^{11}B}} N_{^{12}C} - \frac{1}{\lambda_{^{11}B}} N_{^{11}B}$$



Differential equation

	^{12}C	^{11}C	^{11}B	^{10}B
$\frac{d}{dx}N_{^{12}C}$	$^{12}C \rightarrow X$			
$\frac{d}{dx}N_{^{11}C}$	$^{12}C \rightarrow {}^{11}C$	$^{11}C \rightarrow X$		
$\frac{d}{dx}N_{^{11}B}$	$^{12}C \rightarrow {}^{11}B$	-	$^{11}B \rightarrow X$	
$\frac{d}{dx}N_{^{10}B}$	$^{12}C \rightarrow {}^{10}B$			

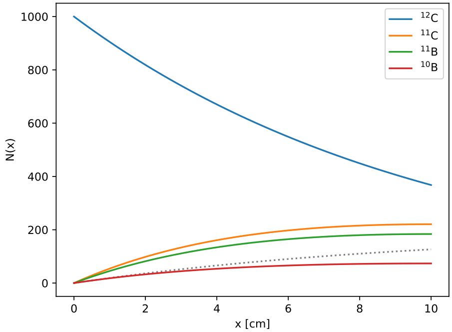
$$\frac{d}{dx}N_{^{10}B} = \frac{1}{\lambda_{^{12}C \rightarrow {}^{10}B}} N_{^{12}C}$$



Differential equation

	^{12}C	^{11}C	^{11}B	^{10}B
$\frac{d}{dx} N_{^{12}C}$	$^{12}C \rightarrow X$			
$\frac{d}{dx} N_{^{11}C}$	$^{12}C \rightarrow {}^{11}C$	$^{11}C \rightarrow X$		
$\frac{d}{dx} N_{^{11}B}$	$^{12}C \rightarrow {}^{11}B$	-	$^{11}B \rightarrow X$	
$\frac{d}{dx} N_{^{10}B}$	$^{12}C \rightarrow {}^{10}B$			$^{10}B \rightarrow X$

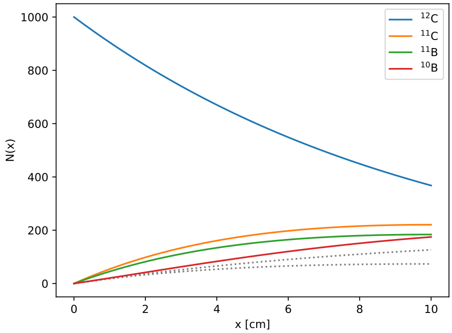
$$\frac{d}{dx} N_{^{10}B} = \frac{1}{\lambda_{^{12}C \rightarrow {}^{10}B}} N_{^{12}C} - \frac{1}{\lambda_{^{11}C}} N_{^{10}B}$$



Differential equation

	$^{12}\mathrm{C}$	$^{11}\mathrm{C}$	$^{11}\mathrm{B}$	$^{10}\mathrm{B}$
$\frac{d}{dx}N_{^{12}\mathrm{C}}$	$^{12}\mathrm{C} \rightarrow \mathrm{X}$			
$\frac{d}{dx}N_{^{11}\mathrm{C}}$	$^{12}\mathrm{C} \rightarrow {}^{11}\mathrm{C}$	$^{11}\mathrm{C} \rightarrow \mathrm{X}$		
$\frac{d}{dx}N_{^{11}\mathrm{B}}$	$^{12}\mathrm{C} \rightarrow {}^{11}\mathrm{B}$	-	$^{11}\mathrm{B} \rightarrow \mathrm{X}$	
$\frac{d}{dx}N_{^{10}\mathrm{B}}$	$^{12}\mathrm{C} \rightarrow {}^{10}\mathrm{B}$	$^{11}\mathrm{C} \rightarrow {}^{10}\mathrm{B}$	$^{11}\mathrm{B} \rightarrow {}^{10}\mathrm{B}$	$^{10}\mathrm{B} \rightarrow \mathrm{X}$

$$\frac{d}{dx}N_{^{10}\mathrm{B}} = \frac{1}{\lambda_{^{12}\mathrm{C}\rightarrow{}^{10}\mathrm{B}}}N_{^{12}\mathrm{C}} + \frac{1}{\lambda_{^{11}\mathrm{C}\rightarrow{}^{10}\mathrm{B}}}N_{^{11}\mathrm{C}} + \frac{1}{\lambda_{^{11}\mathrm{B}\rightarrow{}^{10}\mathrm{B}}}N_{^{11}\mathrm{B}} - \frac{1}{\lambda_{^{11}\mathrm{C}}}N_{^{10}\mathrm{B}}$$



Matrix notation

Write interactions as a matrix:

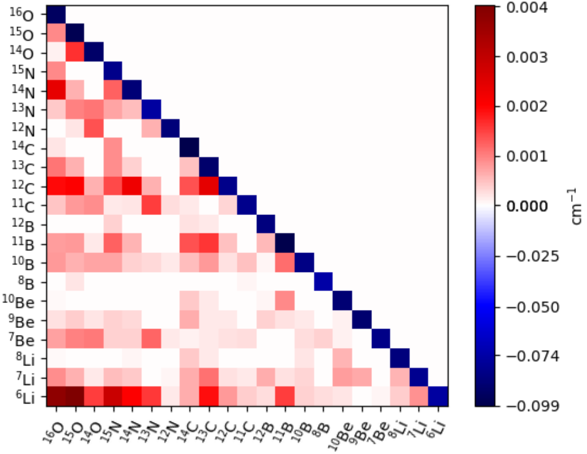
$$M_{ij} = \begin{cases} \frac{1}{\lambda_{j \to i}} & \text{if } j \text{ fragments to } i \\ -\frac{1}{\lambda_i} & \text{if } i = j \\ 0 & \text{otherwise} \end{cases}$$

Write particle numbers as a vector:

$$\vec{N}(x) = (\ldots, N_{^{12}\mathrm{C}}(x), \ldots, N_{^{10}\mathrm{B}}(x), \ldots)^T$$

Write differential equation as:

$$\frac{d}{dx}\vec{N}(x) = M\vec{N}(x)$$



Solution

Solution

Solution of the differential equation describing interactions inside the target:

$$\vec{N}(x) = \exp\left(Mx\right) \vec{N}(0)$$

- simple formula
- no approximation
- complete description of the target
- can be evaluated by computer algebra systems

Summary

Karlsruhe Institute of Technology

- secondary cosmic rays produced by fragmentation
- lab experiment to study fragmentation with NA61

- developed an analytical description of the target
- proposed thick target measurement

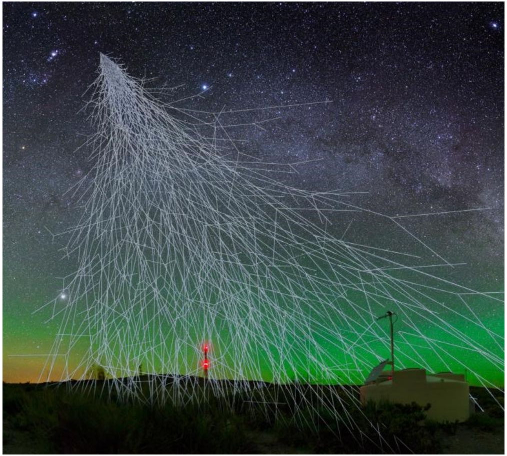
- optimization of target thickness
- elimination of target uncertainties (systematics)

Cassiopeia A; NASA/CXC/SAO, modified

Part II: Neutral Pion Production

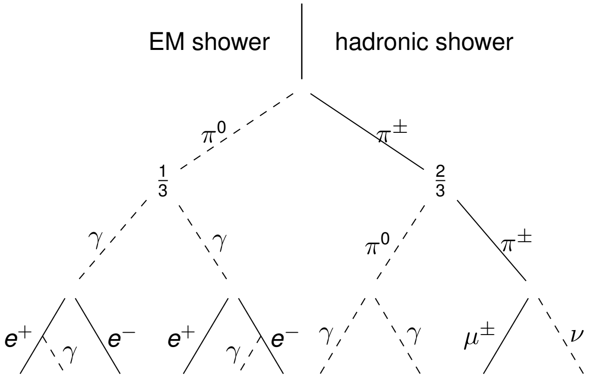
Extensive air showers

- highly energetic particles $E \gtrsim 10^{18}$ eV
- interactions in the atmosphere trigger extensive air showers
- detected by ground-based detectors (e.g. the Pierre Auger Observatory)
- simulated with hadronic interaction models
- observation: more muons than expected
  e.g. Astrophys. Space Sci. 367 (2022) 3, 27 arXiv:2105.06148



Artist's impression of an air shower over a particle detector at the Pierre Auger Observatory, seen against a starry sky. By A. Chantelauze, S. Staffi, L. Bret

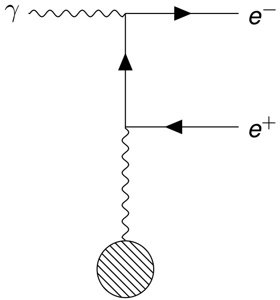
Air shower development



- nuclear reactions produce pions
- π^+, π^- and π^0 in 1:1:1 ratio
- $\frac{2}{3}$ of energy stays in hadronic shower
- $\frac{1}{3}$ of energy goes to electromagnetic shower
- hadronic shower energy available for μ production: $E_{\text{had}} = \left(\frac{2}{3}\right)^n E_0$

Idea of measurement

- problem: detector has no electromagnetic calorimeter
- solution: reconstruct electron-positron pairs
- momentum of γ is almost conserved in pair production
- use pair momentum as photon momentum
- calculate invariant mass of pair

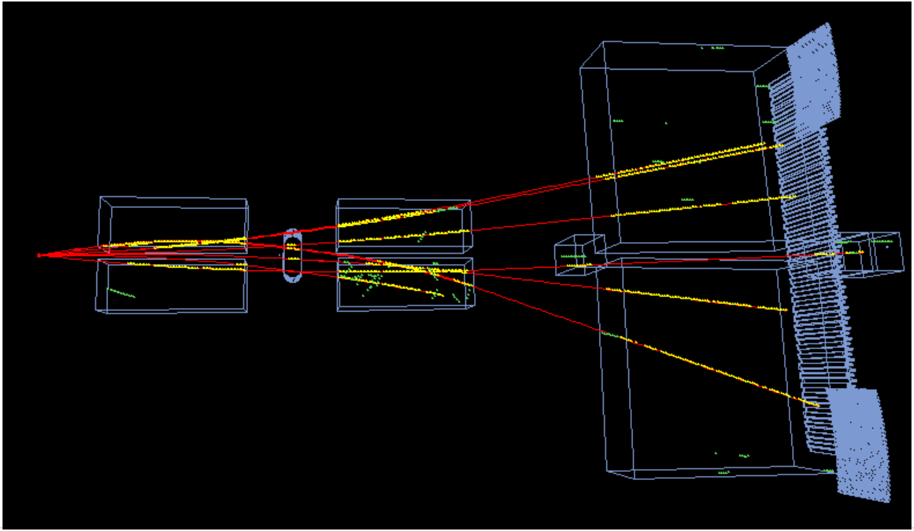


Available data

Photo taken by Johannes Bennemann

- 2009 pion run
- π^- beam
- 158 GeV/c beam momentum
- 2 cm graphite target
- $5.5 \cdot 10^6$ events
- analyzed for charged hadrons in Phys. Rev. D 107, 062004 (2023)

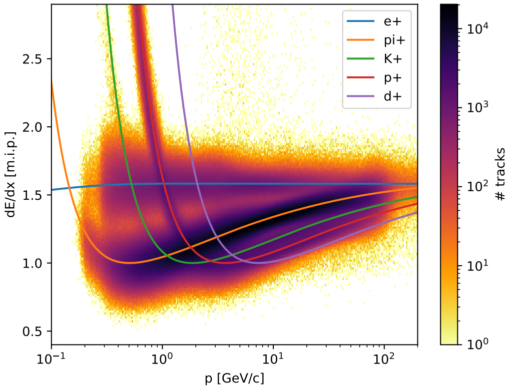
Particle tracks



Screenshot from SHINE event browser

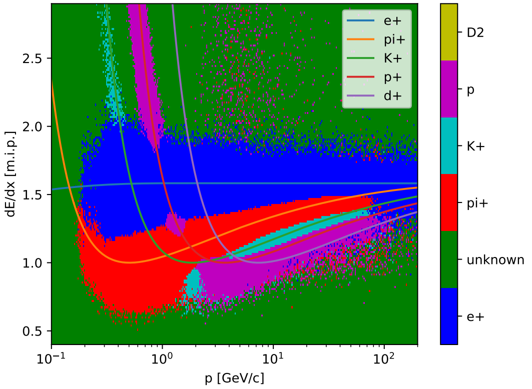
Particle tagging

- tracks yield energy loss and momentum
- $\frac{dE}{dx}$ follows Bethe formula
- particles can be identified

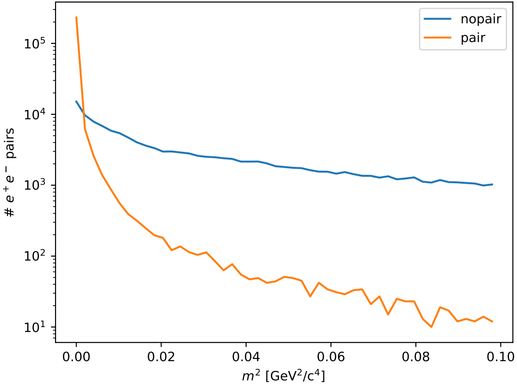


Particle tagging

- tracks yield energy loss and momentum
- $\frac{dE}{dx}$ follows Bethe formula
- particles can be identified
- select regions with e^{+}/e^{-}



Invariant mass



- match all e^+ and e^- candidates
- calculate invariant mass of an e^+e^- pair:

$$m^2 = \left(E^+ + E^-\right)^2 - \left(\vec{p}^+ + \vec{p}^-\right)^2$$

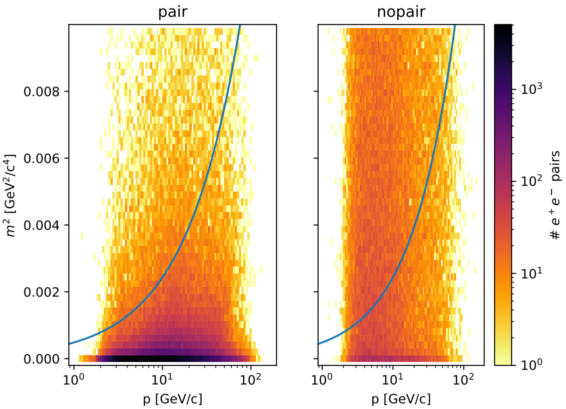
- simulation shows a clear difference

Invariant mass cut

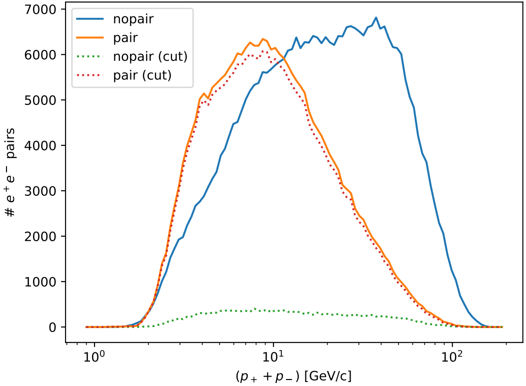
- momentum resolution decreases with $\vec{p}$
- momentum dependent cut needed:

$$m^2 < m_0^2\, p^\alpha$$

- high efficiency up to 100 GeV
- reasonable background

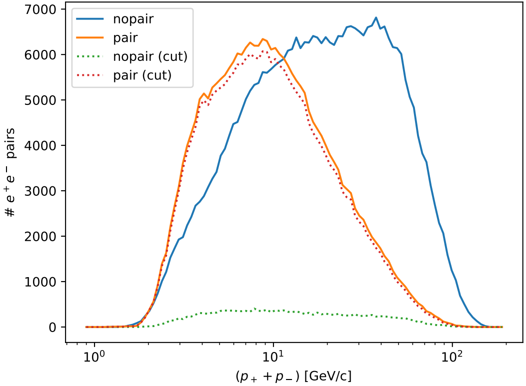


Photon spectrum?



- check with simulation
- pairs pass the cut
- background gets rejected

Photon spectrum?



- check with simulation
- pairs pass the cut
- background gets rejected
- unexpected shape
- dropoff below 10 GeV

Pair production cross section

Formula 3D–1003

[The Bethe–Heitler Formula: Screened Point Nucleus for Extreme-Relativistic Energies]

$$\frac{d\sigma}{dE_+} = \frac{\alpha Z^2 r_0^2}{k^3}\{(E_+^2+E_-^2)[\Phi_1(\gamma)-\tfrac{4}{3}\ln Z]+\tfrac{2}{3}E_+E_-[\Phi_2(\gamma)-\tfrac{4}{3}\ln Z]\},$$

where the screening functions $\Phi_1(\gamma)$ and $\Phi_2(\gamma)$ are defined as

$$\Phi_1(\gamma)=4\left\{\int_\delta^1 (q-\delta)^2[1-F(q)]^2\frac{dq}{q^3}\right\}+4+\tfrac{4}{3}\ln Z,$$

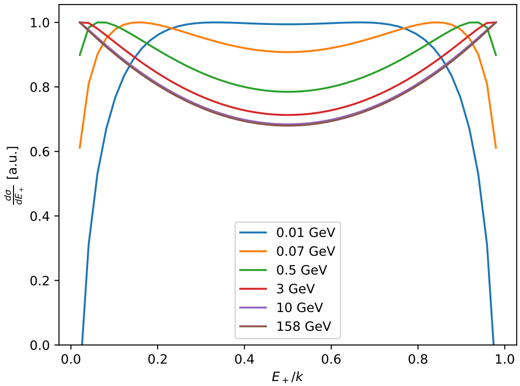
$$\Phi_2(\gamma)=4\int_\delta^1\left[q^3-6\delta^2 q\ln\left(\frac{q}{\delta}\right)+3\delta^2 q-4\delta^3\right][1-F(q)]^2\frac{dq}{q^4}+\tfrac{10}{3}+\tfrac{4}{3}\ln Z,$$

with $\gamma=100k/(E_+E_-Z^{1/3})$ and $\delta=k/(2E_+E_-)$. $F(q)$ = atomic form factor which is defined in Sec. II and which is evaluated for different screening approximations by Motz, Olsen, and Koch (1964, Formula 1A–102).

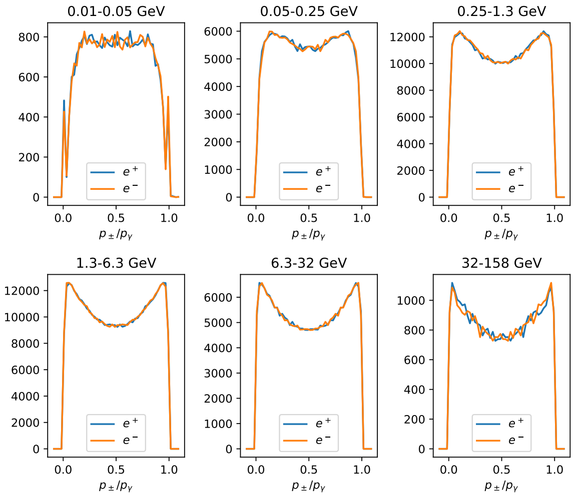
Motz et al, Rev. Mod. Phys. 41 (1969), pp. 581-639.

Pair production cross section

- distribution of energy between e^+ and e^-
- uneven distribution preferred for high energies
- one high and one low energy pair particle



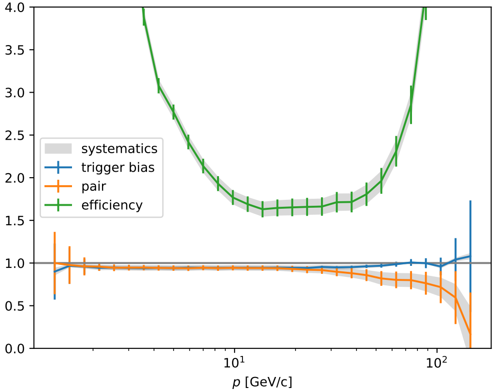
Simulated cross section



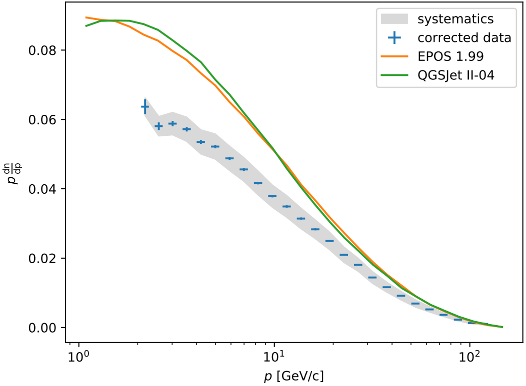
- predicted effect visible in simulation
- NA61's sensitivity drops off below 200 MeV
- photon dropoff expected at about 10 GeV
- explains shape of pair spectrum
- needs to be corrected

Corrections

- efficiency and acceptance
- trigger bias
- invariant mass cut
- introduces model-dependent systematics



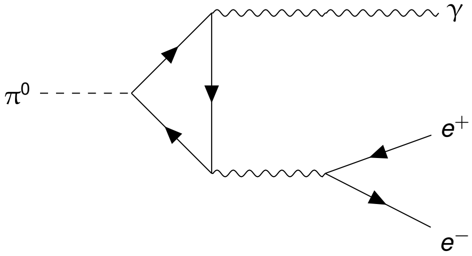
Results



- multiplicity of e^+e^- pairs
- compared with hadronic interaction models
- 30% overprediction!
- photon spectrum?

Comparability

- pair production probability $P_{\gamma \rightarrow e^+e^-} = 3.3\%$
- additional decay channels
- $N^{\pi}_{\pm} = 0.078$ pairs per pion
- additional pairs from etas
- π^0 and η numbers from model $\rightarrow e^+e^-$ pairs
- all factors are known



source particle	channel	branching ratio
π^0	$\gamma\gamma$	98.8%
π^0	$e^+e^-\gamma$	1.2%
η	$\gamma\gamma$	39.4%
η	$\pi^+\pi^-\gamma$	4.3%
η	$e^+e^-\gamma$	0.7%

Summary

- new method for neutral pion measurement
- successful e^+e^- spectrum measurement with NA61/SHINE
- corrections for detector effects and efficiency
- less e^+e^- pairs than expected

- results useful for model tuning
- step toward the solution of the muon puzzle