Two-Pion Bose-Einstein Correlation measurements with CLAS detector

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Introduction

- Bose-Einstein correlations (BEC) arise from **quantum mechanical interference** between the symmetrized wave functions of **identical bosons**.
- This effect was first studied in astronomy by Hanbury Brown and Twiss to measure stellar radii.
- The same methodology can be applied to particle physics experiments.
- The bosons studied in this work were π^+ in the **DIS regime** (Deep inelastic scattering).
- The main objective of the study was to measure the **size** (r), **shape** (r_t/r_l) and **coherence degree** (λ) of the **pions source**.

Definition

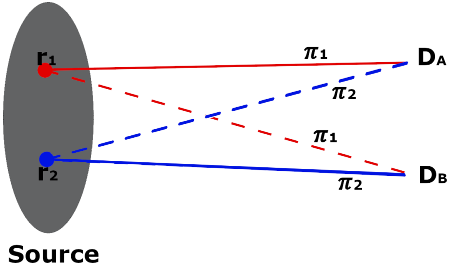
In order to study Bose-Einstein correlations we define a two-particle function in the following way:

$$R_{(p1,p2)} = \frac{D(p_1, p_2)}{D(p_1)D(p_2)} \tag{1}$$

where p_1 and p_2 are the bosons' 4-momentum, and $D(p_1, p_2)$, $D(p_1)$, $D(p_2)$ are the two-particle and one-particle probability densities.

Derivation of BEC

Two identical pions are emitted in the same event in the points r_1 and r_2 and detected in the detectors D_A and D_B with momenta k_A and k_B respectively.



Because of their indistinguishability and the boson nature of the pions, the pions wave functions must be symmetric under exchange. Two scenarios are possible.

Derivation of BEC

These scenarios are represented with continuous lines and segmented lines:

$$\Psi_{A,B}(1,2) = \frac{\Psi_{1A}\Psi_{2B} + \Psi_{1B}\Psi_{2A}}{\sqrt{2}} \tag{2}$$

where Ψ_{1A} is the wave function of a pion produced in r_1 with momentum k_A and detected in the detector A.
Assuming that both pions can be described by plane waves in the form $\Psi_{1A} \propto e^{ik_A r_1}$, the wave function of the process is given by:

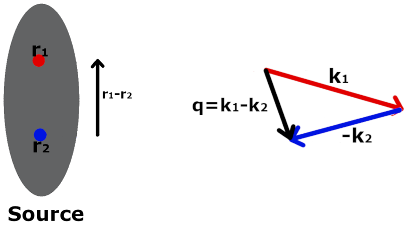
$$\Psi_{k_A,k_B}(1,2) = \frac{1}{\sqrt{2}}[e^{i(k_A r_1 + k_B r_2)} + e^{i(k_A r_2 + k_B r_1)}] \tag{3}$$

Derivation of BEC

If we work the last expression a little bit, we get:

$$|\Psi_{k_A,k_B}(1,2)|^2 = 1 + cos[q(r_1 - r_2)] \quad (4)$$

This shows that the probability of the process depends on the spatial distance $(r_1 - r_2)$ between both pion sources and the momentum difference $q = k_A - k_B$ between the observed pions.



Derivation of BEC - Coherence parameter

In a more general case, we can consider a source with density $\rho(r)$ and a "phase" in each point of the source. We can now calculate the correlation function in a more general way, getting:

$$R(Q) = 1 + \lambda|\widetilde{\rho}(Q)|^2 \tag{5}$$

Where $Q = \sqrt{-(p_1 - p_2)^2}$ and λ is called coherence parameter.

- $\lambda = 0$: completely coherent source $\Rightarrow$ No BEC.
- $\lambda = 1$: completely incoherent source $\Longrightarrow$ Max BEC.

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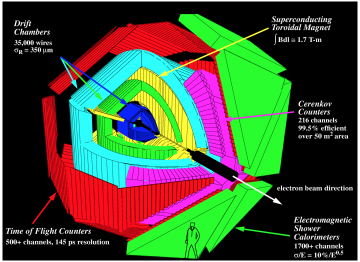
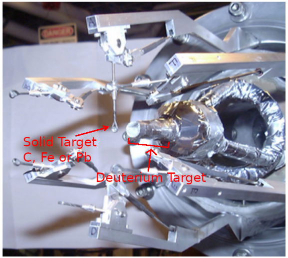
Experimental setup

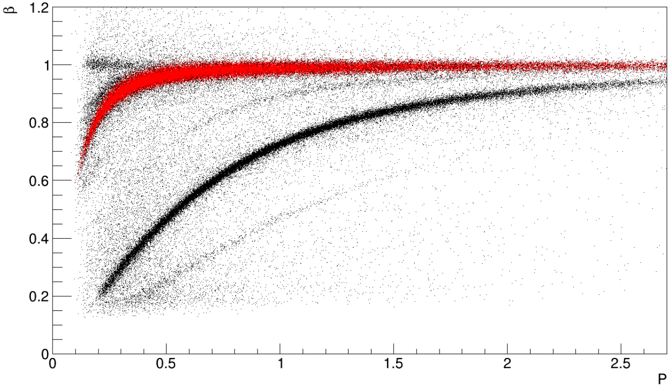
- Data analyzed from experiments conducted in experimental hall B in Thomas Jefferson National Accelerator Facility, VA.
- 5 GeV electron beam against multiple nuclear targets using CLAS (CEBAF Large Acceptance Spectrometer) detector.
- Studied targets: C, Fe and Pb.





Pion identification

- First particle of the event must be an well identified electron.
- DIS regime cuts.
- Main information to identify pions come form to a TOF (Time of Flight) and DC (Drift Chambers).



Pion pair construction

- BEC require one- and two-particle distributions.
- One-particle distributions are replaced by a two-particle distribution called background distribution $D_b(p_1, p_2)$.
- The background was constructed using pions from different events (mixed events)
- The background distribution must not present BEC.

The experimental Bose-Einstein correlation function has the form:

$$R_{(p_1,p_2)} = \frac{D(p_1, p_2)}{D_b(p_1, p_2)} \tag{6}$$

Double Ratio correction

- Correction based on simulations.
- Double ratio correction helps to correct experimental systematic biases.
- Simulations have same behavior as data, but they don't present BEC.
- We divide the experimental correlation function by the simulated correlation function.

Double ratio correction for correlation function is defined:

$$R(Q_{12}) = R(Q_{12})^{data} / R(Q_{12})^{simul} \tag{7}$$

$$R(Q_{12}) = \left(\frac{D(Q_{12})_{same}}{D(Q_{12})_{mix}}\right)^{data} / \left(\frac{D(Q_{12})_{same}}{D(Q_{12})_{mix}}\right)^{simul} \tag{8}$$

Dynamical correlations should cancel out. This procedure also correct biases from efficiency/acceptance, violation of energy-momentum conservation in the background, particle misidentification and selection cuts.

Correlation Function Fit

Goldhaber parametrization is an approximation that considers the pion source as a spherical Gaussian distribution.
The experimental Goldhaber parametrization has the form:

$$R(Q_{12}) = \gamma(1 + \lambda exp(-r^2 Q_{12}^2))(1 + \delta Q_{12} + \epsilon Q_{12}^2) \quad (9)$$

Where r and λ parameters are extracted by fitting the final correlation function obtained.

- r represents the source size.
- λ represents the source coherence.

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One dimensional study

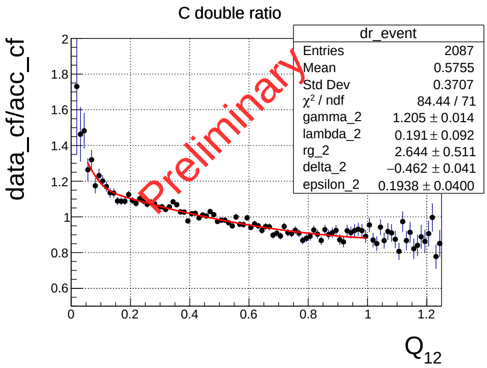

Figure: BEC - C target, double ratio correction applied

Target	r [fm]	λ
C	2.64 ± 0.51	0.19 ± 0.09
Fe	2.79 ± 0.32	0.40 ± 0.11
Pb	2.43 ± 0.49	0.35 ± 0.14

Table: One-dimensional BEC fit parameters

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Two-dimensional study

The two-dimensional study was made in the same way as the one-dimensional one. The correlation in two-dimensions is calculated by:

$$R(q_l, q_t) = R(q_l, q_t)^{data} / R(q_l, q_t)^{simul} \quad (10)$$

A two-dimensional Goldhaber fit is applied to fit the correlation this time. This parametrization has the form:

$$R(q_l, q_t) = \gamma(1 + \lambda exp[-(r_l^2 q_l^2 + r_t^2 q_t^2)])(1 + \delta_l q_l + \delta_t q_t) \quad (11)$$

- r_l and r_t can be interpreted as the longitudinal and transverse size of the pion source with respect to the virtual photon.
- λ is the coherence parameter.

Two-dimensional study

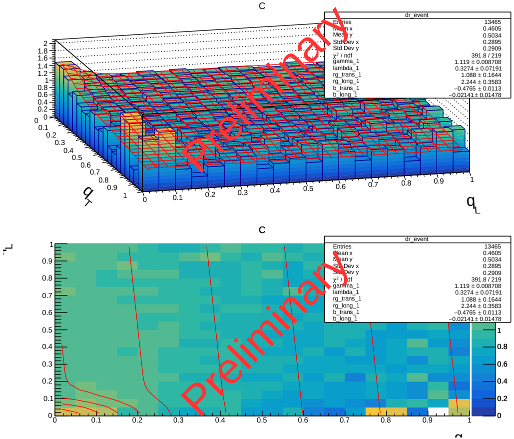

Figure: BEC - C target, double ratio correction applied

Target	r_t	r_l	r_t/r_l	λ
C	1.09 ± 0.16	2.24 ± 0.36	0.48 ± 0.11	0.33 ± 0.07
Fe	1.35 ± 0.12	2.22 ± 0.15	0.61 ± 0.07	0.45 ± 0.05
Pb	1.25 ± 0.18	1.79 ± 0.19	0.70 ± 0.13	0.38 ± 0.07

Table: Two-dimensional BEC fit parameters

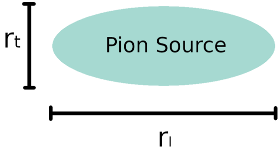

Figure: Schematic shape of the pion source

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Conclusions

- Bose-Einstein correlations are clearly present in all nuclear targets.
- Pion source size was found to be similar for all targets around 2.6 fm
- We can observe an elongation in the pion source along the longitudinal direction.

Acknowledgments

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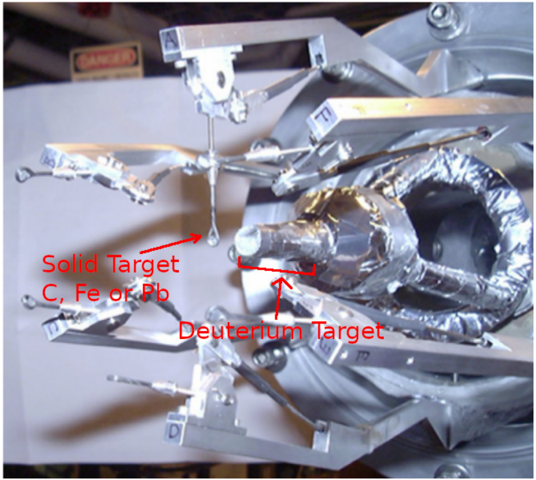
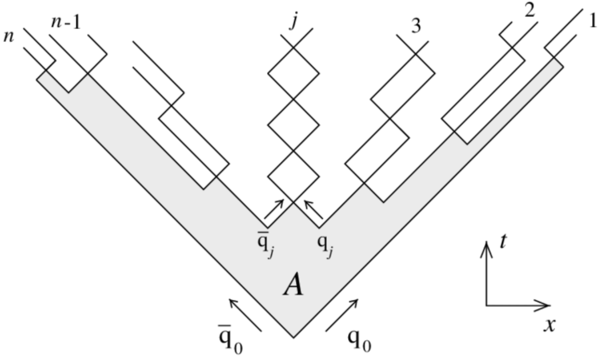
Backup Slides

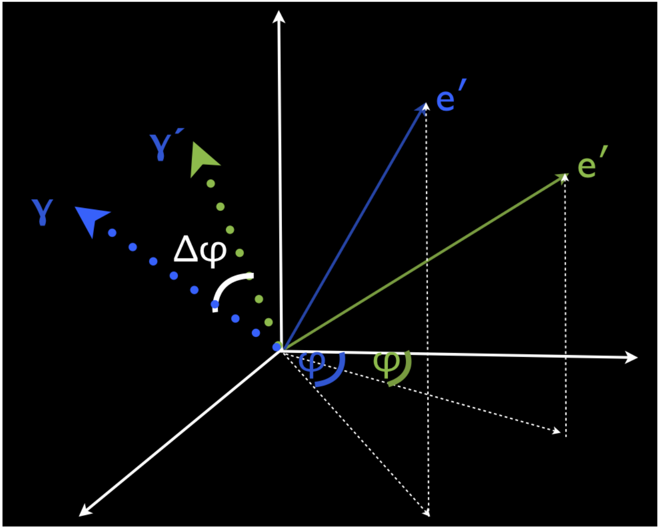
Target photo



Lund String Model



Event Rotation

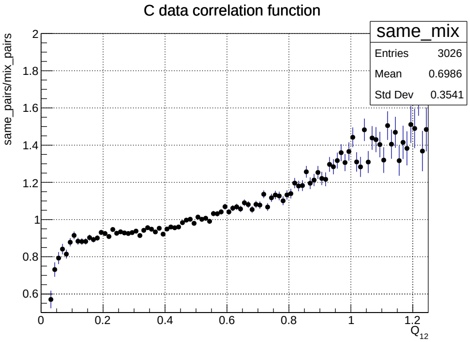


Background construction - Mixing Event Method

- The background was constructed using $\pi^+\pi^+$ from different events.
- These pairs are not correlated.
- The main problem with this method is the energy-momentum violation because os combining pions from different events.
- The second event is rotated to align both virtual photons from the two events.

Correlation function

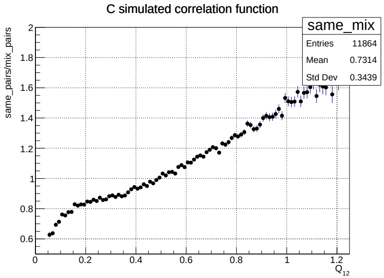
With both, signal and background distributions, we can calculate the correlation function.



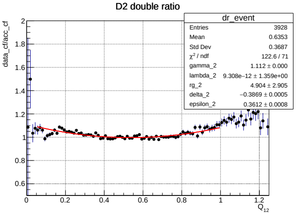
- Low detector acceptance at low Q_{12}.
- Mixing problems at high Q_{12}.
- Correlation function must be corrected.

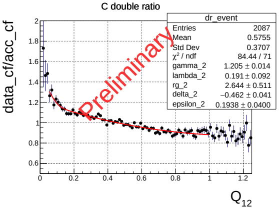
Simulations

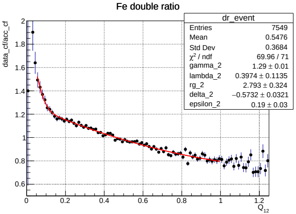
- Needed to fix problems found in the correlation, such a as detector acceptance and mixing problems.
- This can be achieved by performing a double ratio correction.
- The simulated events were processed in the same way as the data to construct an simulated correlation function.
- The simulations do not contain BEC.

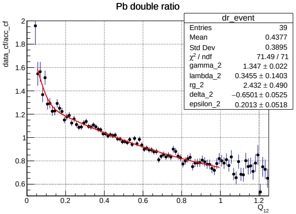


Correlation Function - Double Ratio









Two-dimensional study

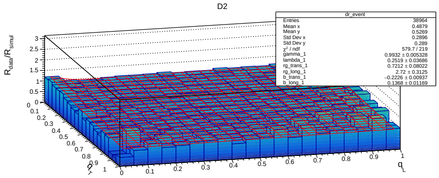
- We can obtain more source's detailed information using a spheroid-like shape.
- This give us information about the elongation of the source.
- The Longitudinally Co-Moving System (LCMS) is used as system of reference. The LCMS represents the local rest frame of a string in the Lund-String model.

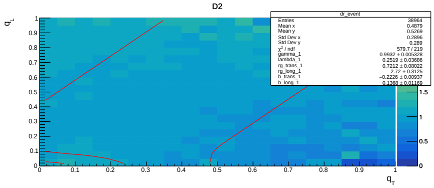
The LCMS is defined such as sum of the two pion momenta $\overrightarrow{p}_{12} = (\overrightarrow{p}_1 + \overrightarrow{p}_2)$ is perpendicular to the virtual photon axis.

- We measure the longitudinal and transverse components of the momentum difference of the pair with respect to the virtual photon: $(q_l$ and $q_t)$.

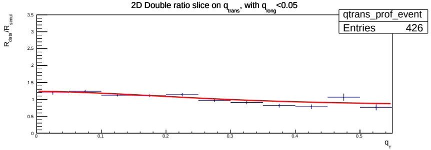
Double Ratio Correction

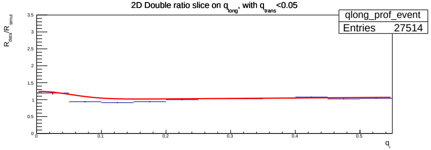
2D Correlation function for Deuterium





Slices in the first bin on q_l(top) and q_j(bottom)

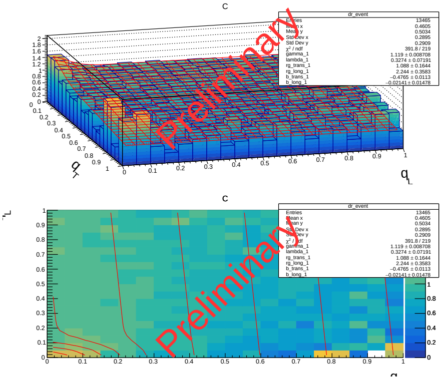




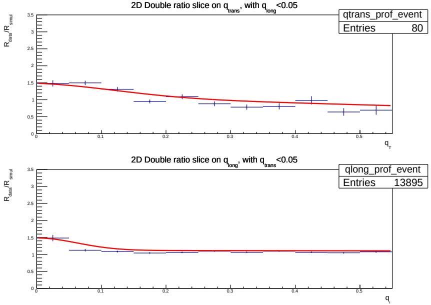
Red line shows the 2D Goldahber fit.

Double Ratio Correction

2D Correlation function for Carbon



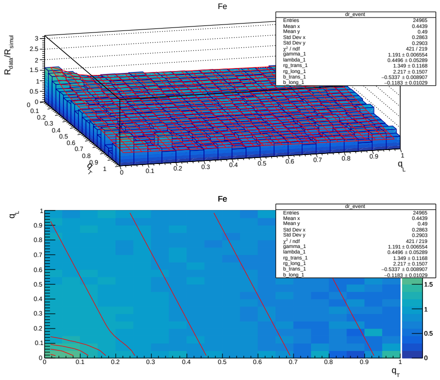
Slices in the first bin on q_l(top) and q_j(bottom)



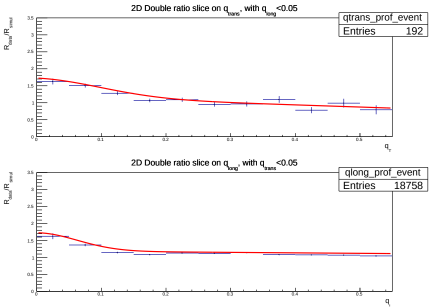
Red line shows the 2D Goldahber fit.

Double Ratio Correction

2D Correlation function for Iron



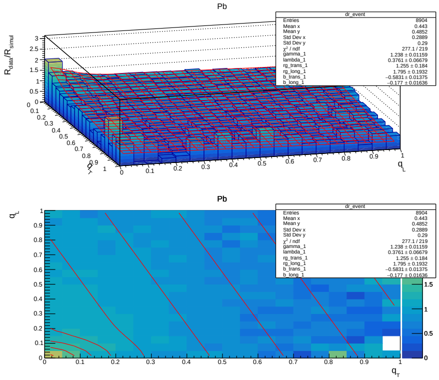
Slices in the first bin on q_l(top) and q_j(bottom)



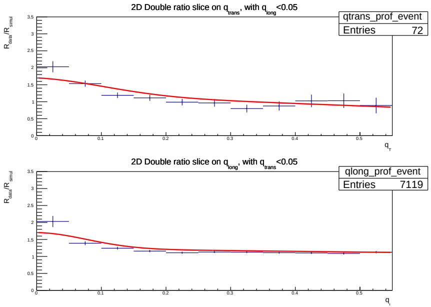
Red line shows the 2D Goldahber fit.

Double Ratio Correction

2D Correlation function for Lead

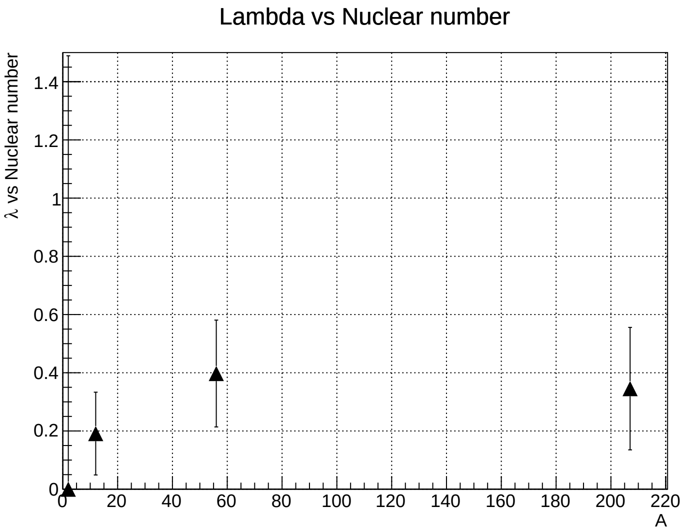


Slices in the first bin on q_l(top) and q_j(bottom)

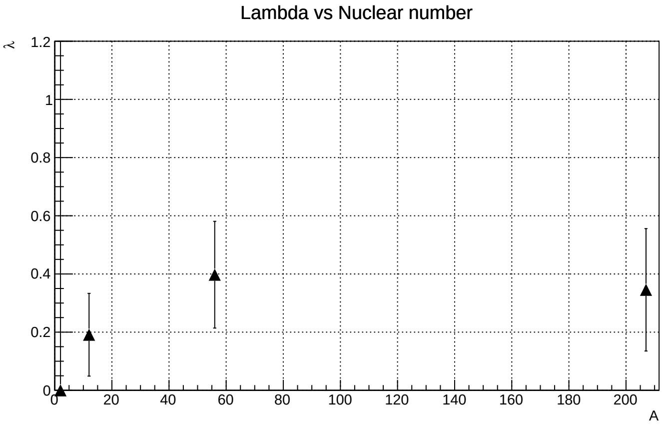


Red line shows the 2D Goldahber fit.

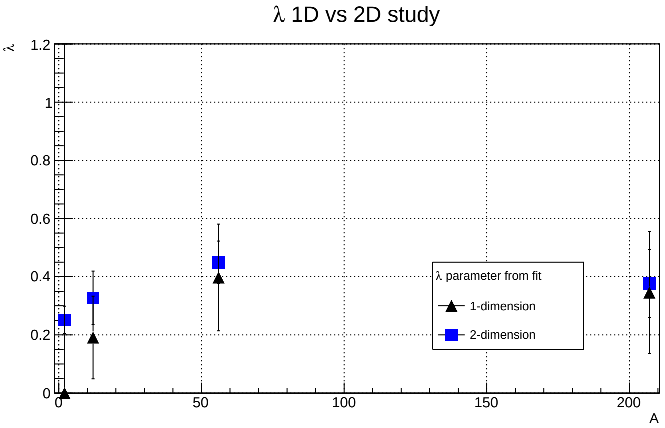
Lambda vs A


Lambda vs Nuclear number
λ vs Nuclear number
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
160
180
200
220
A

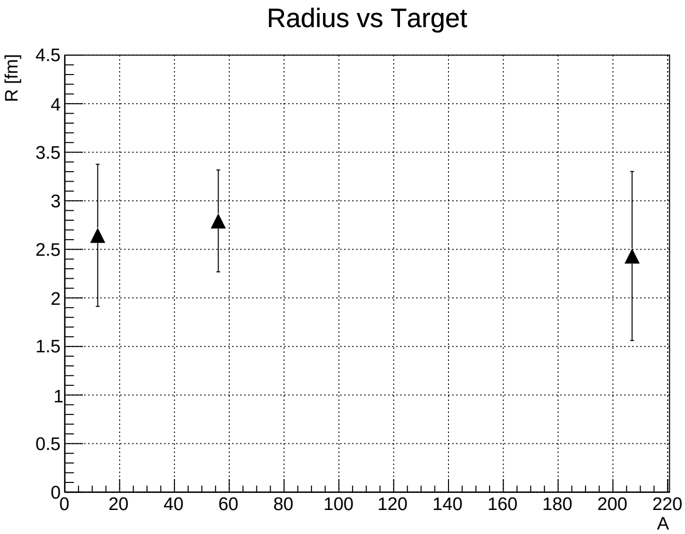
Lambda vs A - 2D



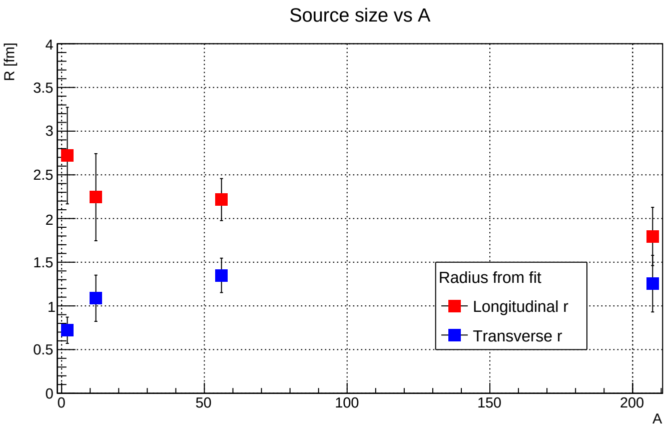
Lambda 1D vs 2D



Source size


Radius vs Target
R [fm]
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
220
A

Source Size - 2D



Source elongation