# *Bose-Einstein Correlations at the Electron-Ion Collider (EIC)*

*G.P. Gilfoyle*

Outline

1. Introduction
2. Scientific Motivation
3. Existing Measurements
4. Simulations with Pythia
5. Conclusions and Questions

# Scientific Motivation of the EIC

- Precision Study of the Gluon Distribution of the Nucleon.
- The Nucleon Spin Structure.
- What are the properties of high-density partonic matter?

*A High-Luminosity, High-Energy, Electron-Ion-Collider*, The Electron Ion Collider Working Group,

White Paper prepared for the NSAC Longe-Range Plan, April, 2007.

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Bose-Einstein Correlations (BEC) probe

- the space-time extent of the correlated particle source.
- regions of high-density within nucleons and nuclei.

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# Interferometry with Identical Particles

- Bose-Einstein Correlations (Hanbury Brown and Twiss or HBT effect) between two or more identical particles can be used to explore space-time features of production mechanisms.
- Intensity interferometry developed for astronomy in 1950's to measure angular size of stars.
- Adopted by particle and nuclear physics since the 1960's.
- Many measurements in heavy ion community through last 3 decades.
- Can also use non-identical particles!

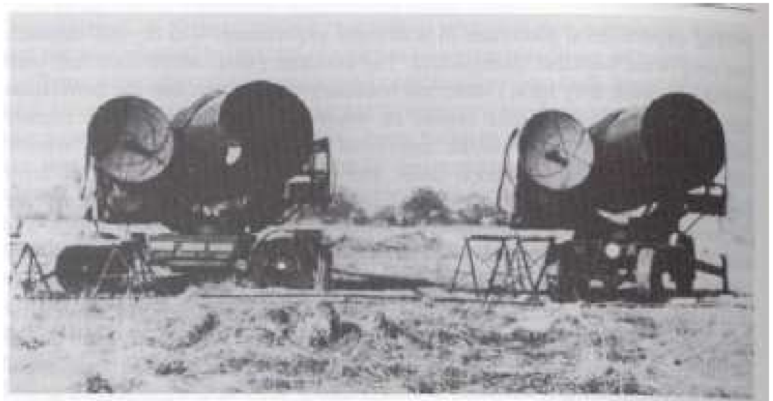


**Figure 10.1** The first stellar intensity interferometer; the pilot model of the stellar intensity interferometer at Jodrell Bank in 1955. Two Army searchlights were used to make the first measurement of the angular diameter of a main sequence star (Sirius).

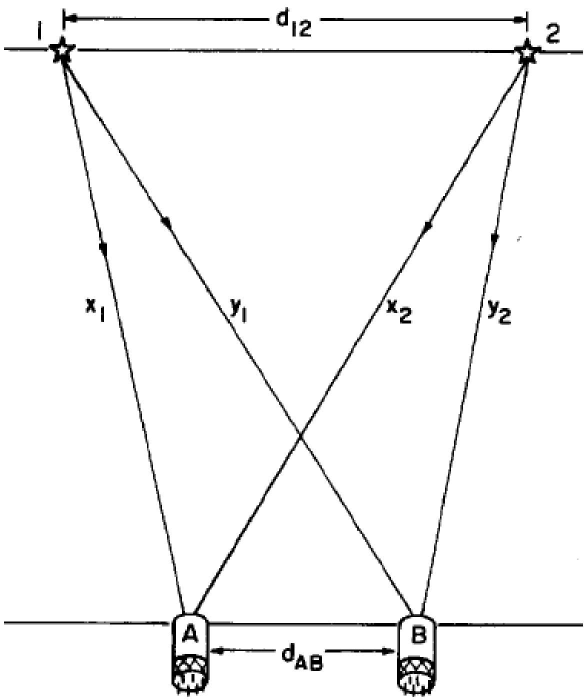
# Interferometry with Identical Particles

- The interference between two waves/particles establishes a correlation between them
- The correlation in momentum-energy space gives information about position-time distributions
- The correlation function can be defined as

$$R(Q_{12}) = \frac{P(Q_{12})}{P_0(Q_{12})}$$

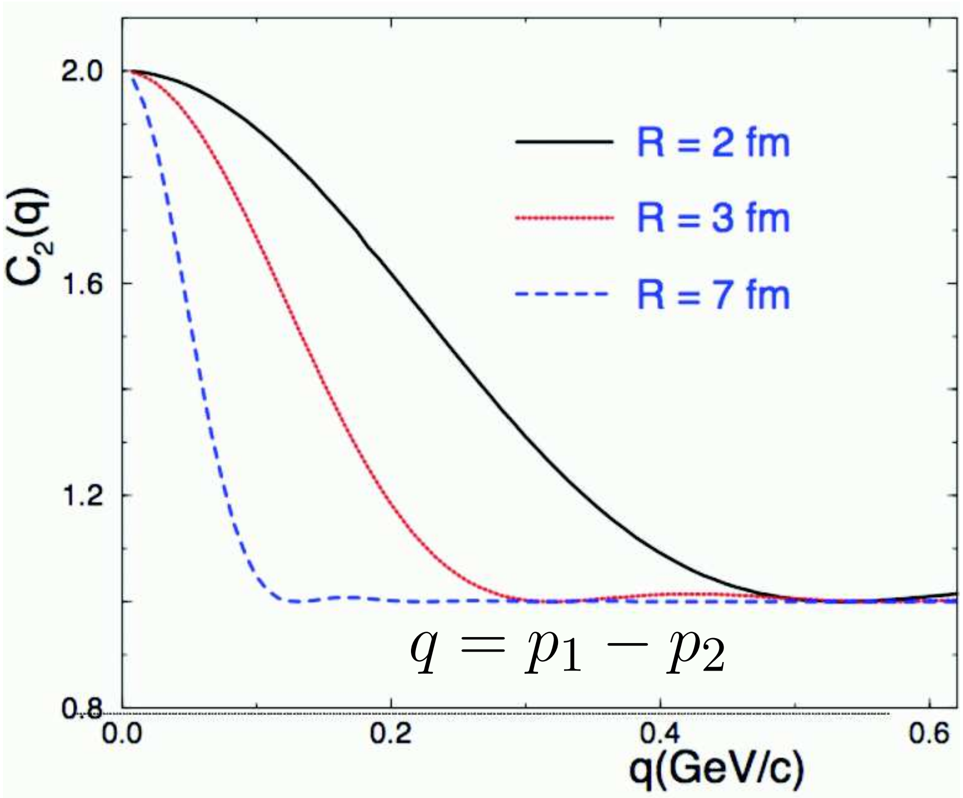
where $Q_{12} = \sqrt{-(p_1 - p_2)^2}$, $P(Q_{12})$ is the two-particle density, and $P_0(Q_{12})$ is the two-particle density in the absence of BEC.

- The reference spectrum $P_0(Q_{12})$ is generated by mixing particles from different events, Monte Carlo calculations, *etc.*



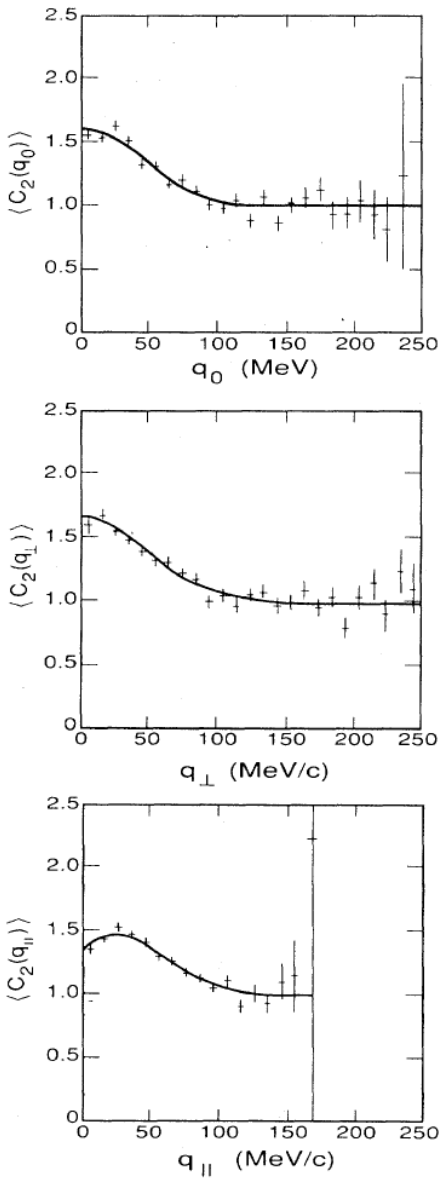
# Interferometry with Identical Particles

Theoretical calculation: Pions in sphere of radius $R$.




$$C_2(\mathbf{p_1},\mathbf{p_2}) = \frac{P_2(\mathbf{p_1},\mathbf{p_2})}{P_1(\mathbf{p_1})P_1(\mathbf{p_2})} = 1 + \frac{|\sum_\lambda N_\lambda \psi^*_\lambda(\mathbf{p_1})\psi_\lambda(\mathbf{p_2})|^{\mathbf{2}}}{\sum_\lambda N_\lambda |\psi^*_\lambda(\mathbf{p_1})|^{\mathbf{2}}|\psi^*_\lambda(\mathbf{p_2})|^{\mathbf{2}}}$$

# Interferometry with Identical Particles




Two-pion correlations in 1.54 GeV/nucleon Ni+Ni Chacon et al., Phys. Rev. C 43, 2670 (1991)

$$C_2(\vec{p}_1, \vec{p}_2) = 1 + |\rho(\vec{q}, q_0)|^2$$

where

$$q = p_2 - p_1 \qquad q_0 = |E_2 - E_1|$$

and

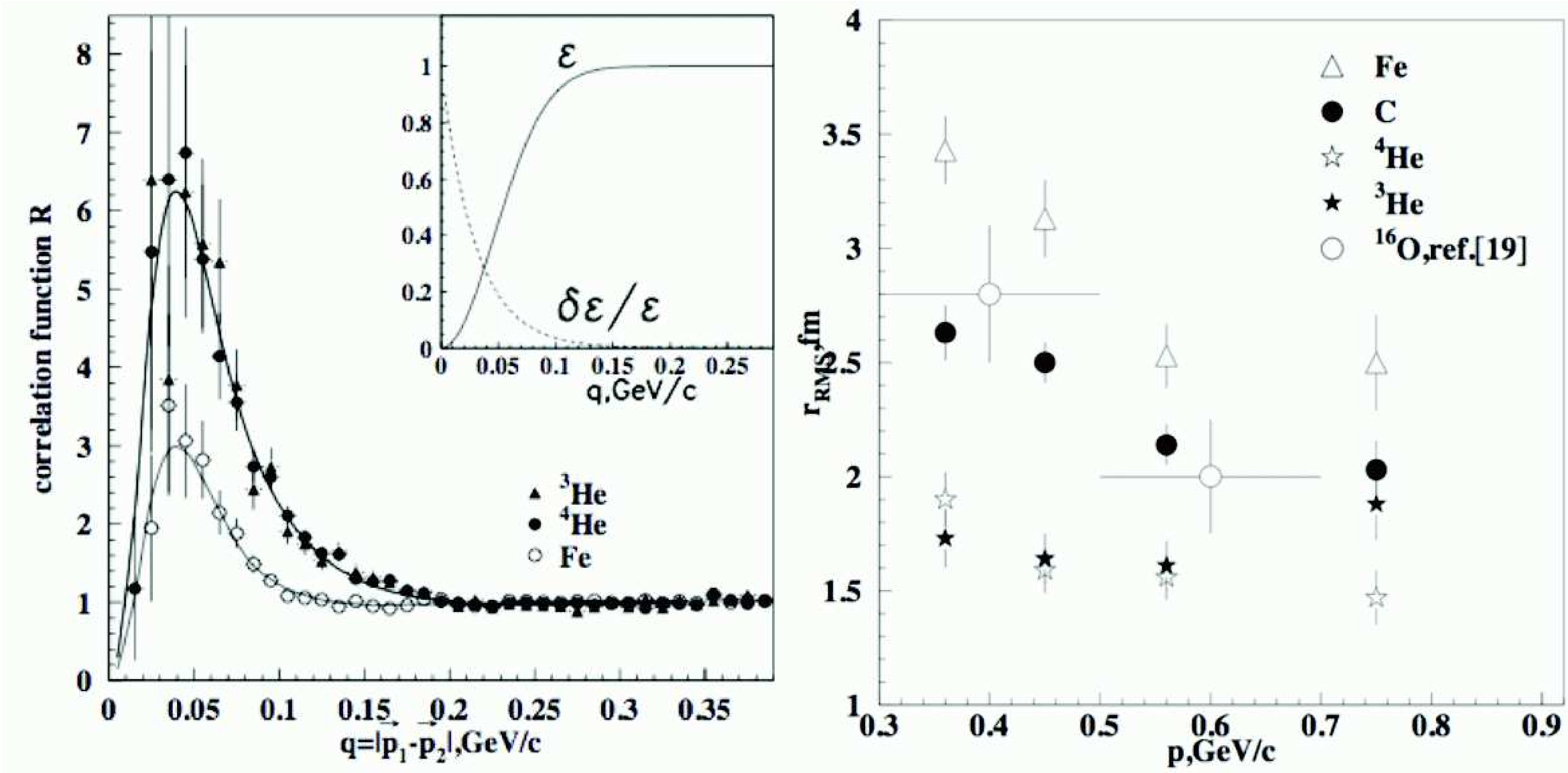
$$\rho(\vec{q}, q_0) = \int\int e^{i(\vec{q}\cdot\vec{x} - q_0 t)} \rho(\vec{x}, t) d^3x dt$$

(the Fourier transform of $\rho(\vec{x}, t)$).

$$C_2(\vec{p}_1, \vec{p}_2) = 1 + \lambda \exp\left[-\left(\frac{q_\perp^2 R_\perp^2}{2}\right) - \left(\frac{q_\parallel^2 R_\parallel^2}{2}\right) - \left(\frac{q_0^2 \tau^2}{2}\right)\right]$$

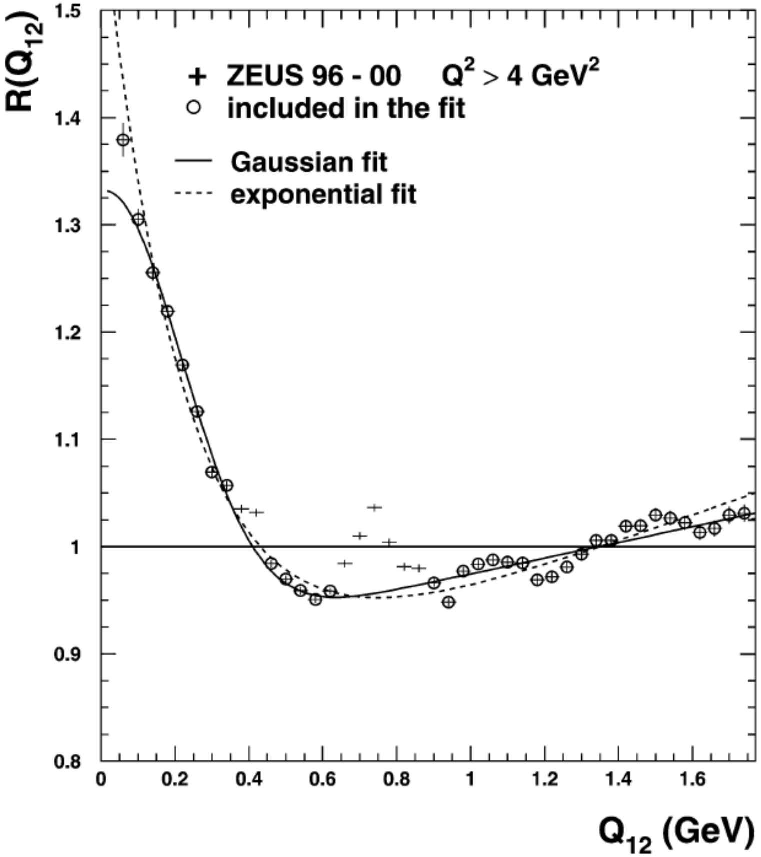
Lisa, Pratt, Soltz, Wiedemann, Ann. Rev. Nucl. Part. Sci.55:357-402,2005; M. Luzum, J. G. Cramer, G. A. Miller, Phys. Rev. C78:054905,2008

# $A(e,e'pp)$ for $^3$He, $^4$He, $^{12}$C, and $^{56}$Fe




A. Stavinsky et al. (CLAS Collaboration) Phys. Rev. Lett.93:192301,2004

# SIDIS, charged particles, pions, DESY/Zeus




$$Q_{12} = \sqrt{-(p_1 - p_2)^2}$$

$$R(Q_{12}) = \frac{P(Q_{12})}{P_0(Q_{12})}$$

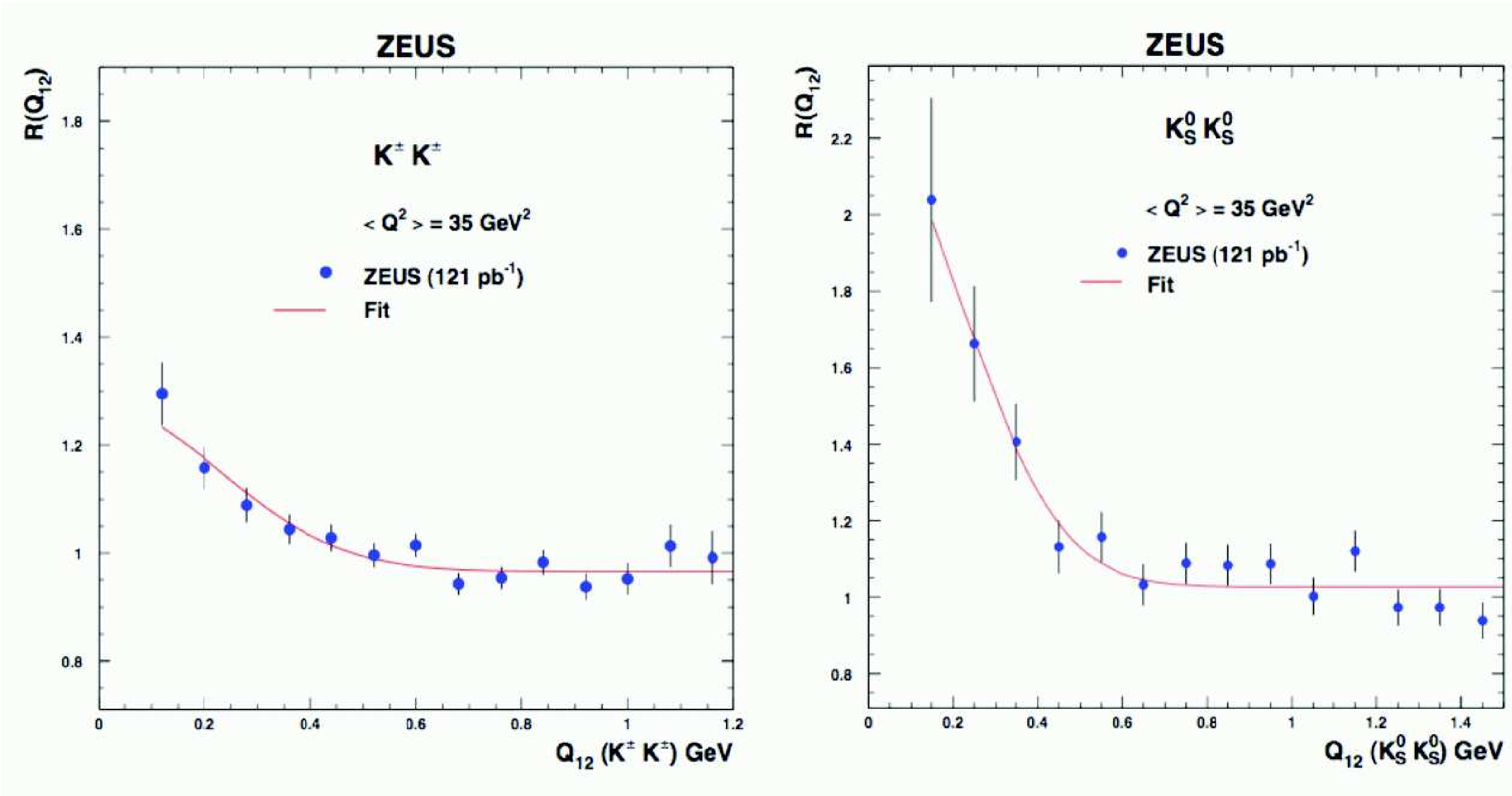
$$R(Q_{12}) = \alpha\,(1+\beta Q_{12})\left(1+\lambda e^{-r^2 Q_{12}^2}\right)$$

$$R(Q_{12}) = \alpha\,(1+\beta Q_{12})\left(1+\lambda e^{-r Q_{12}}\right)$$

The measured Bose-Einstein correlation function, $R(Q_{12})$, together with the Gaussian and the exponential fits. The error bars show the statistical uncertainties.

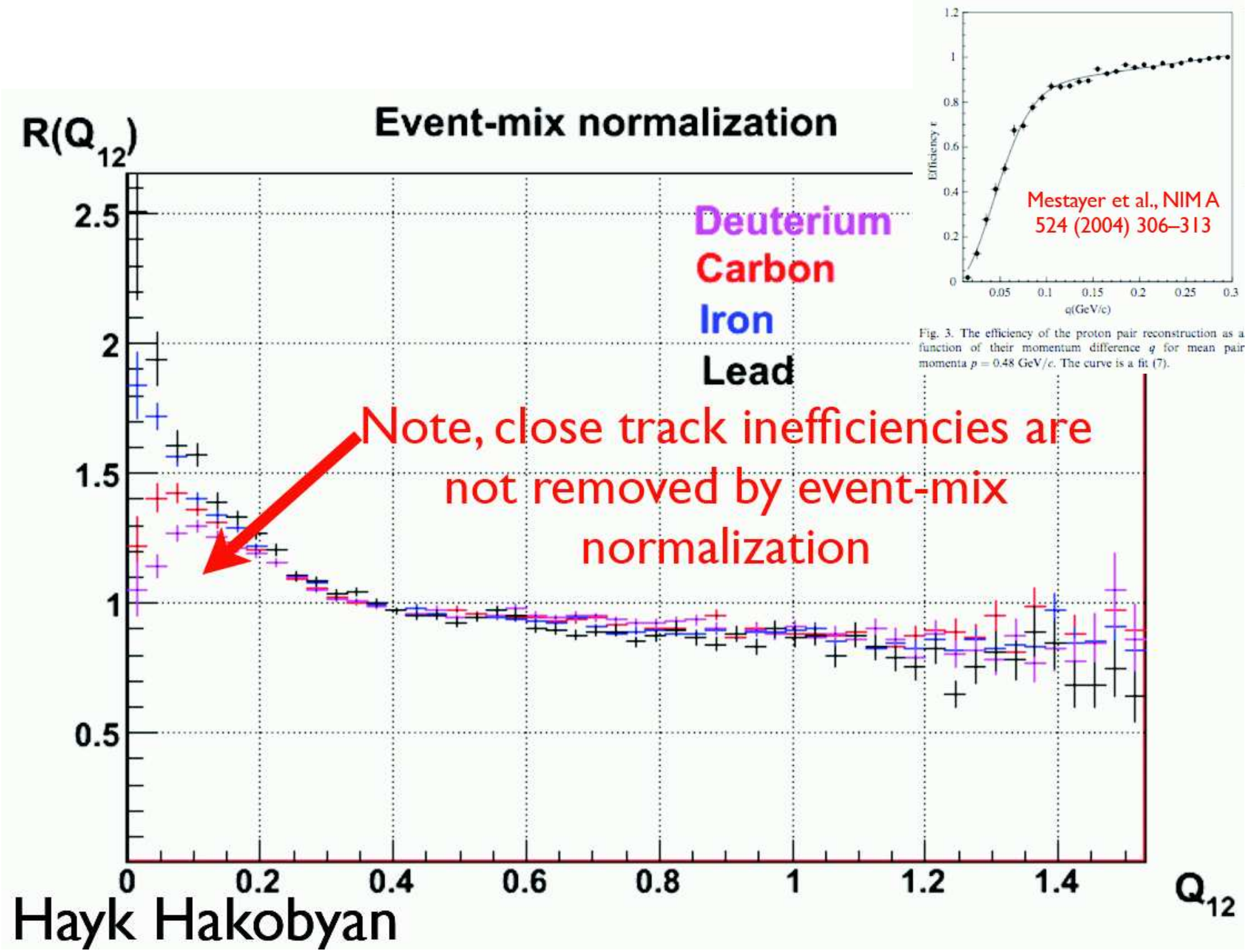
Physics Letters B 583 (2004) 231-246

# Data from ZEUS/DESY on kaons




http://arxiv.org/abs/0706.2538v1, Phys. Lett. B652:1-12, 2007

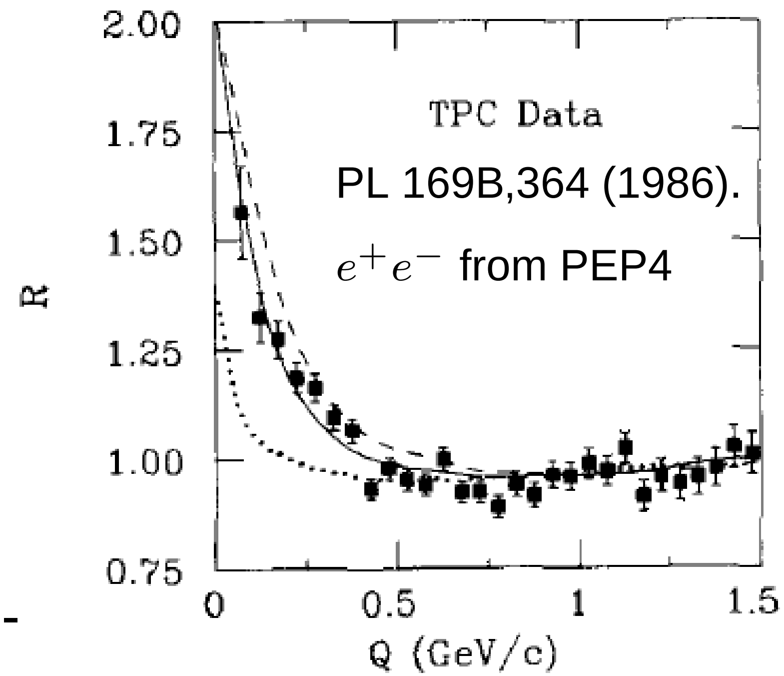
# CLAS preliminary data SIDIS, two positive pions



# Simulations of BECs at the EIC

Goals:

1. Will there be observable correlations?
2. What can we learn?
   - String tension effects?
   - Fragmentation?



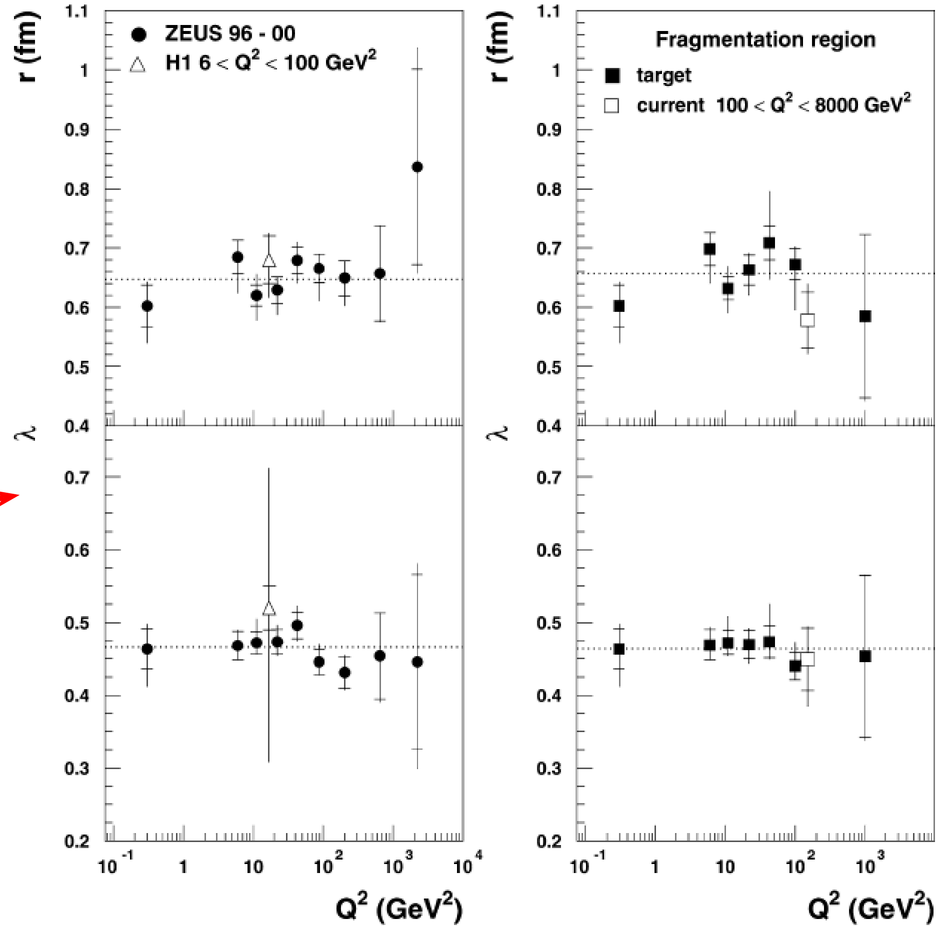

Tools:

1. Pythia - event generator (T. Sjostrand *et al.* [hep-ph/0603175]).
2. Fragmentation models in Pythia - Lund model (B. Andersson, Cambridge, 2005) and independent fragmentation.
3. Parameterization of BEC effect in Pythia:

$$R = 1 + \lambda \exp(-(rQ_{12})^n) \qquad n = 1, 2$$

# Inputs to the Simulations

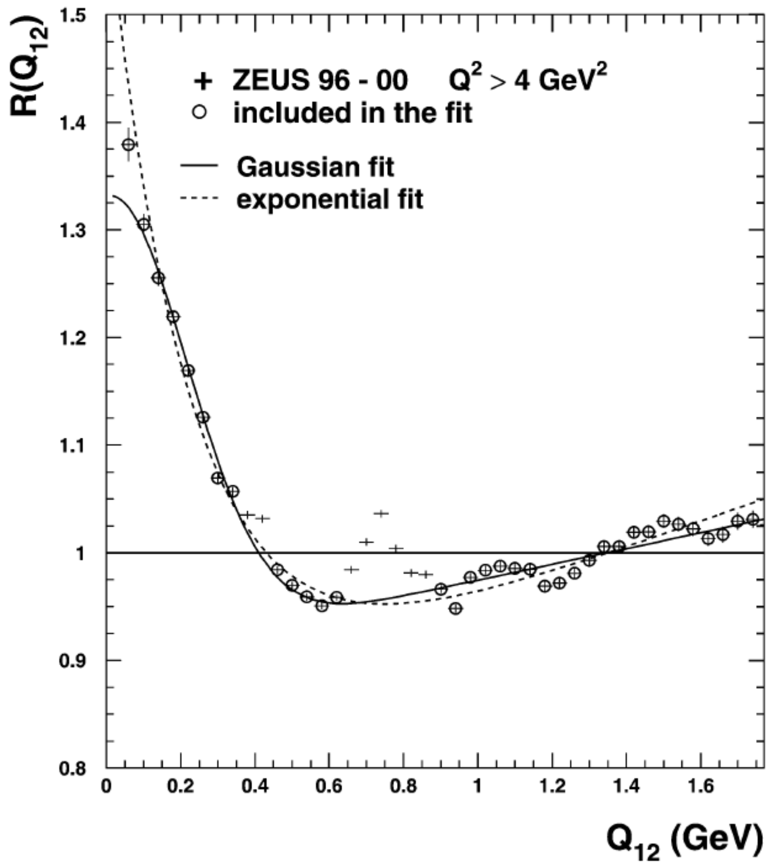
1. Study $\pi^+\pi^+$ correlations.
   - Large cross sections.
   - Compare with other experiments.
2. Use ZEUS results for guidance (Physics Letters B 583 (2004) 231-246).
3. $r$ and $\lambda$ constant with $\mathrm{Q}^2$.
4. $R \approx 0.93\ fm$,$\lambda \approx 0.87$, exponential form.
5. Lund model is starting point.
6. Explore effects of asymmetric momentum distributions in independent fragmentation.

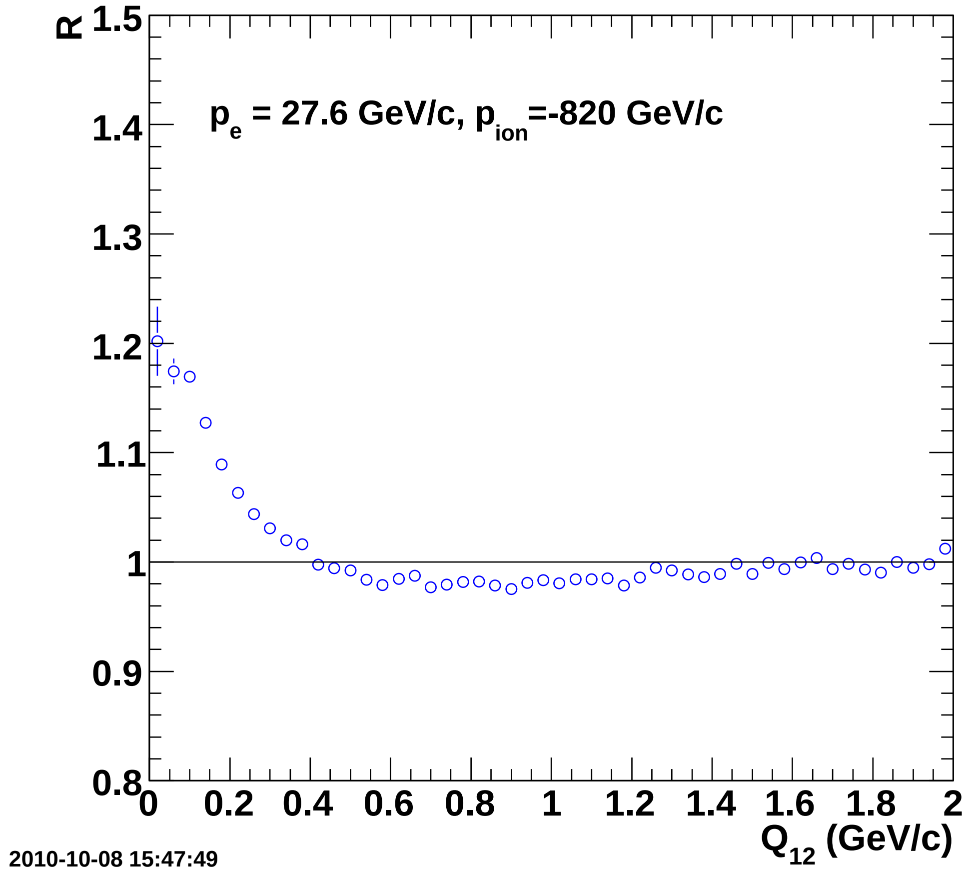



7. Count rates - $Rate = L \times \sigma \approx 10^{34}\ s^{-1}cm^{-2} \times 10^{-29}cm^2 = 10^5 Hz$.

# Results (1)

Consistency check of the simulation - ZEUS simulations.



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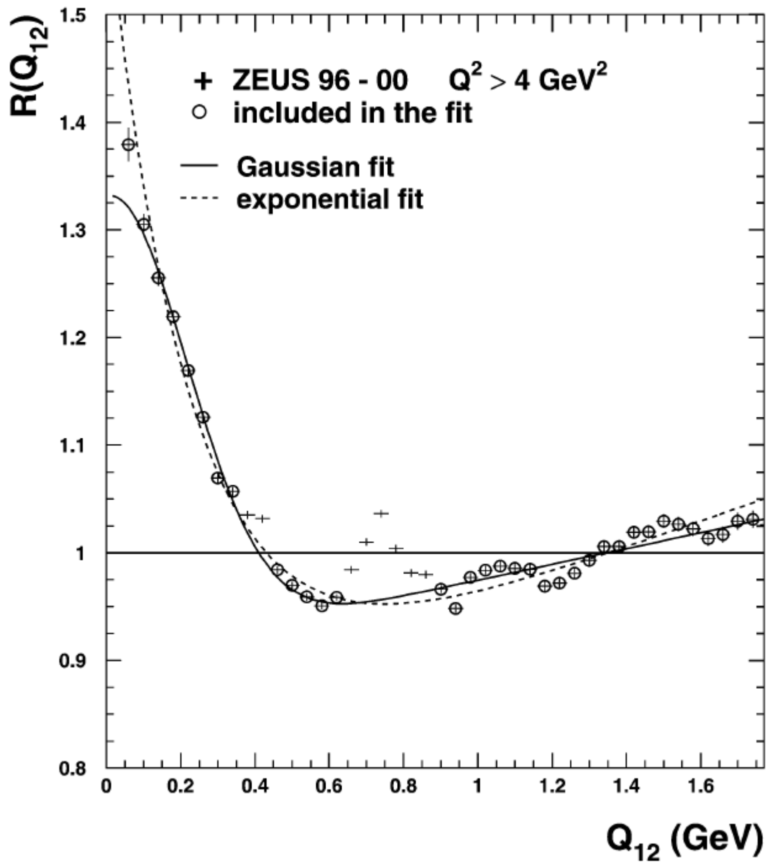


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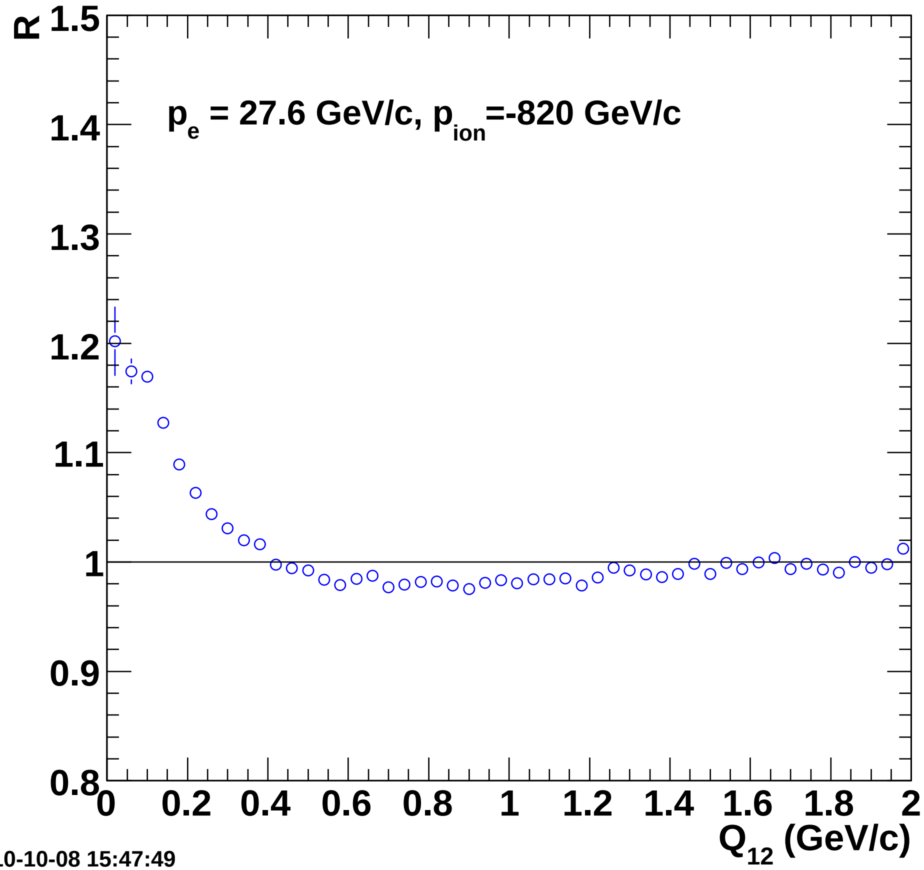
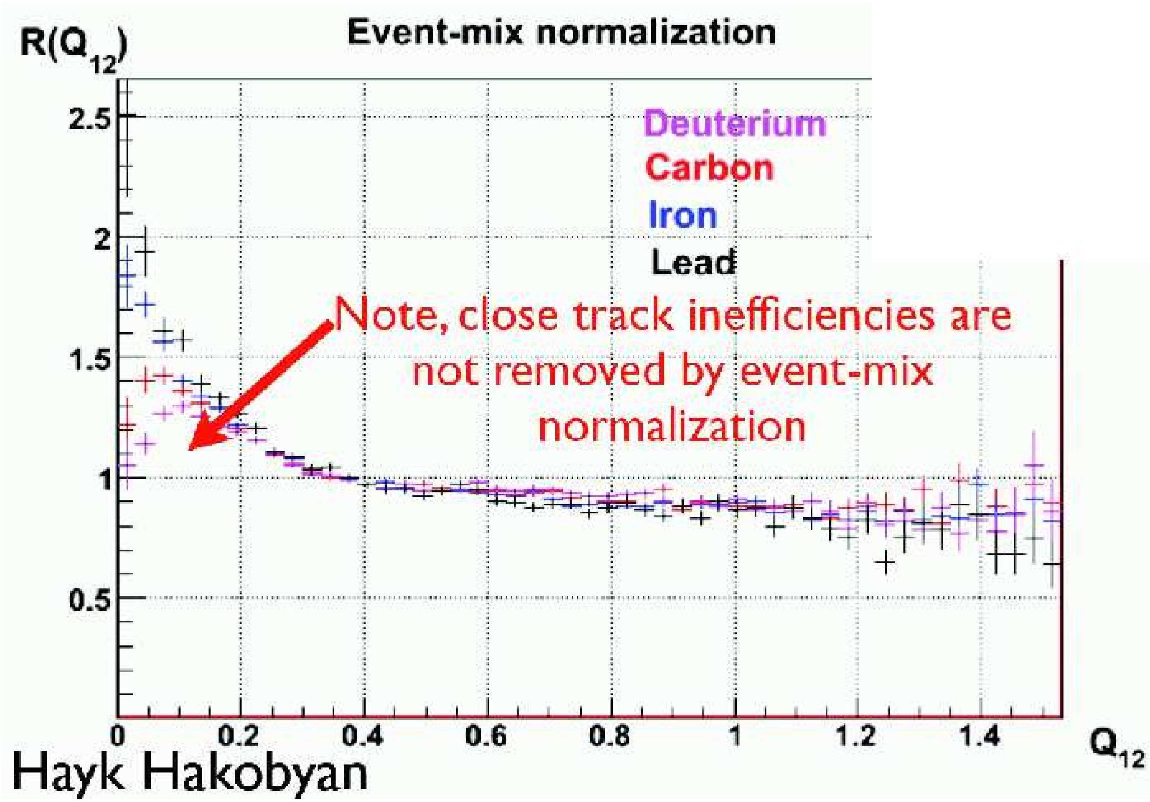
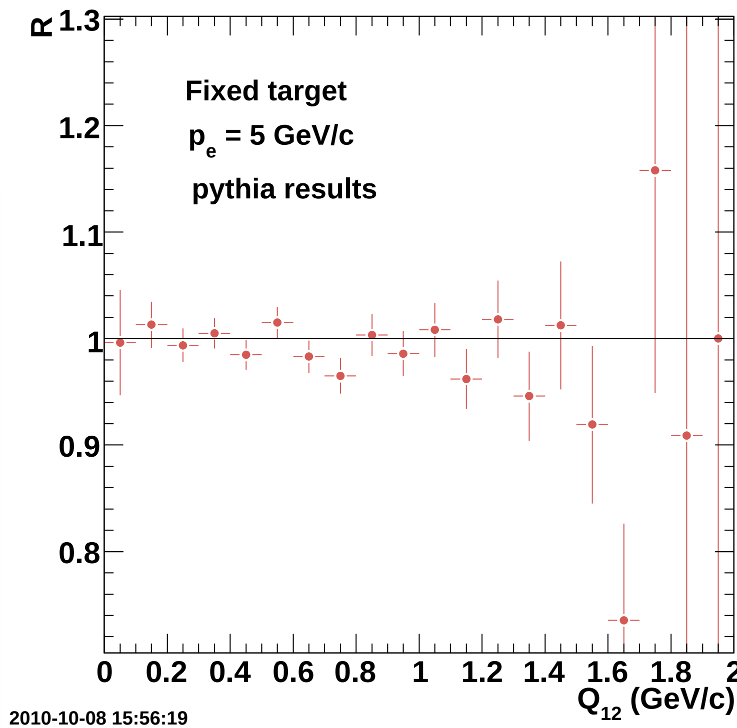



Our Pythia simulation underestimates the BECs.

# Results (2)

## Consistency check of the simulation - EG2



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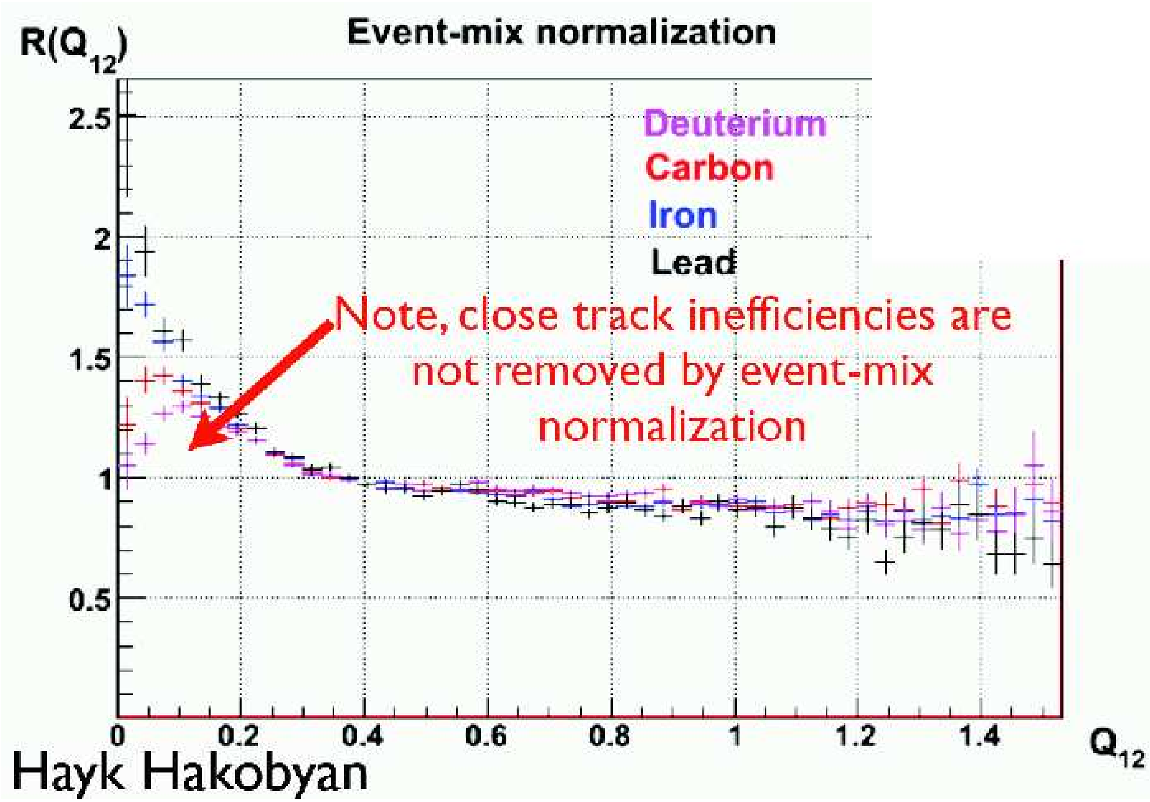
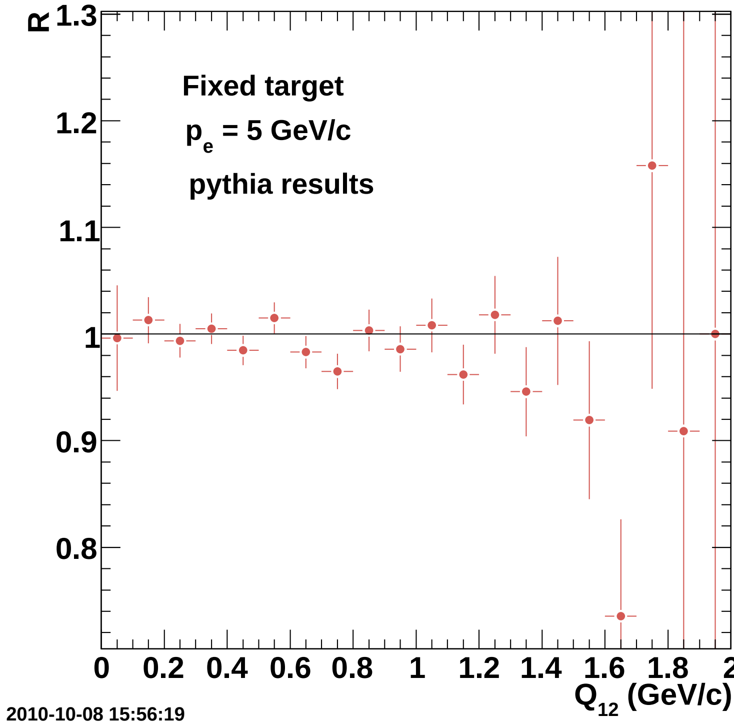


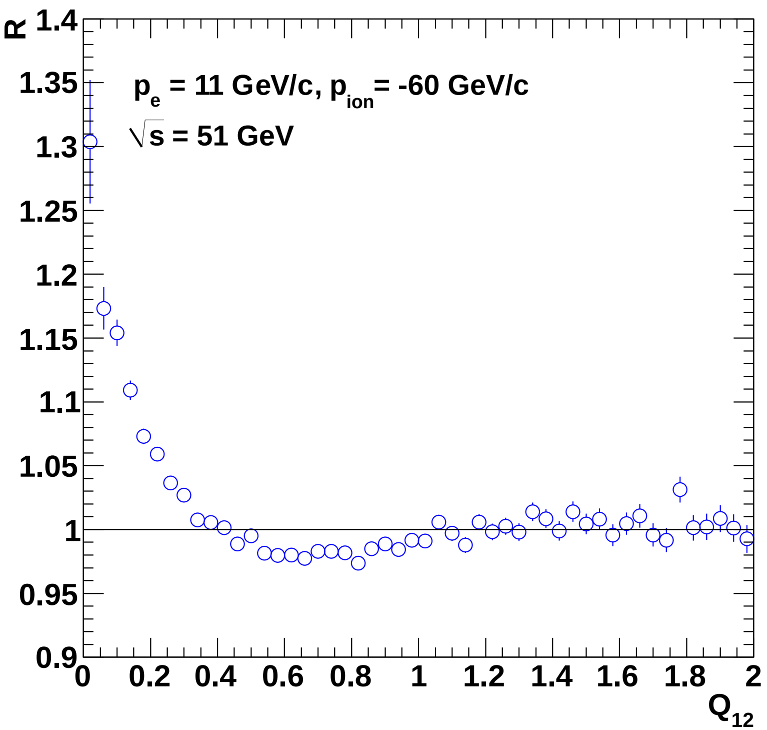




Much lower particle multiplicity at lower energies.

# Results (3)

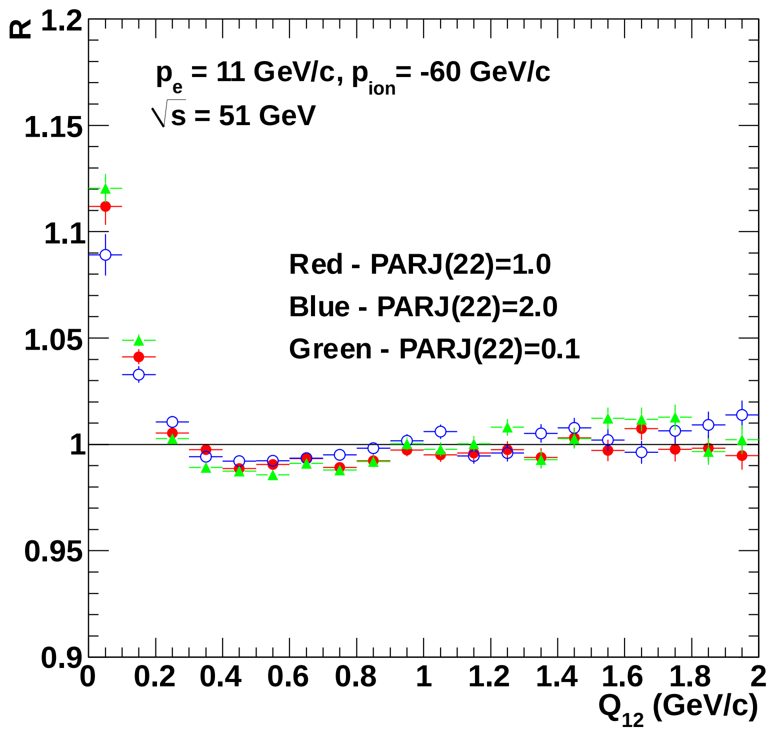
Use ZEUS parameters at EIC kinematics.

Lund model




Big (20%) Effect!

Independent fragmentation




Modest change.

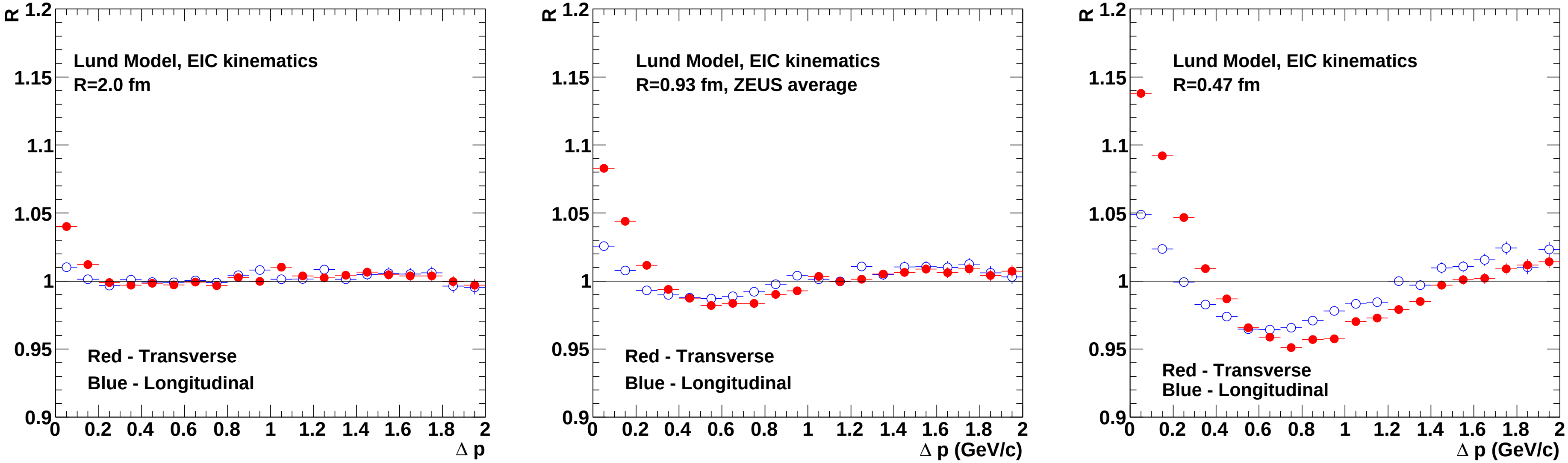
# Explore LT Source Size Differences (1)

1. It is anticipated that the source will become elongated in the direction of the initial parton (Physics Letters B 583 (2004) 231-246).
2. Different boson source sizes in the longitudinal (L) and transverse (T) directions relative to the initial parton direction.
3. Work in the Longitudinal Center-of-Mass System (LCMS).

   The LCMS is defined as the frame of reference in which the sum of the longitudinal components of the two particles momenta along the jet axis add to zero (PL B421 (1998) 283-288).

# Explore LT Source Size Differences (2)

Effect of source size.



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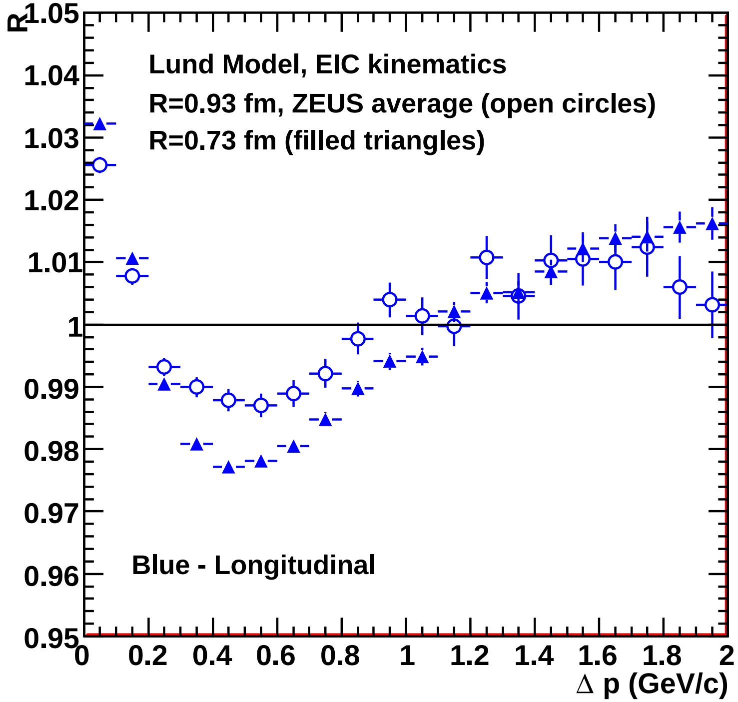
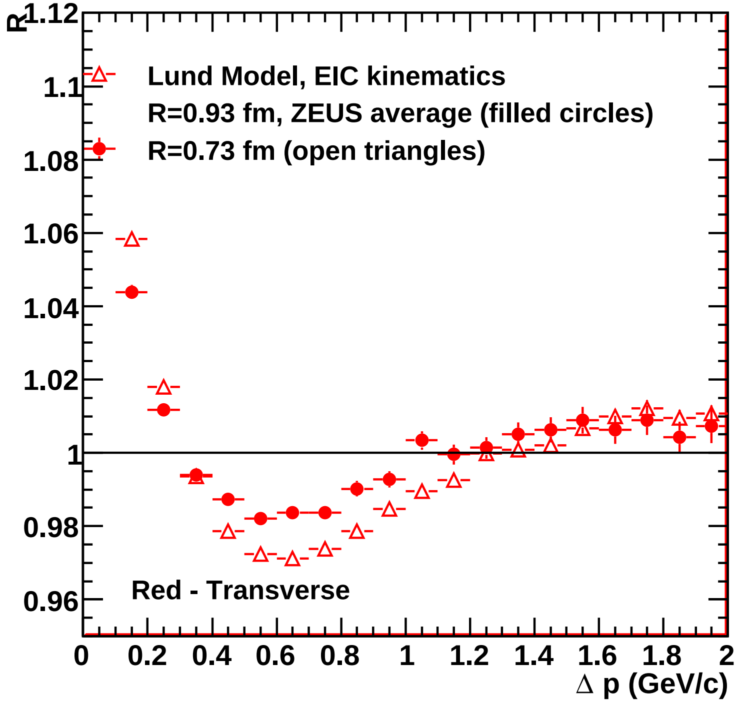
Effect of source size.



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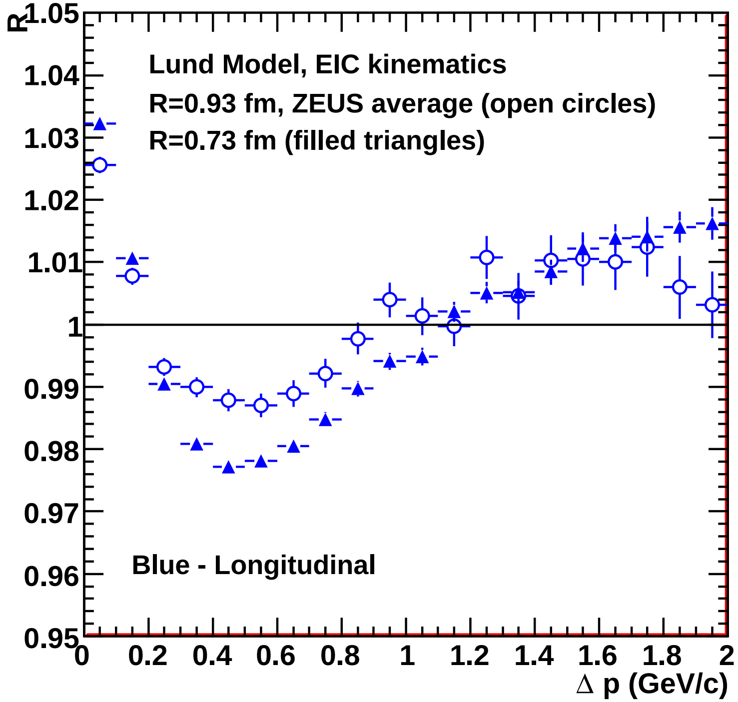
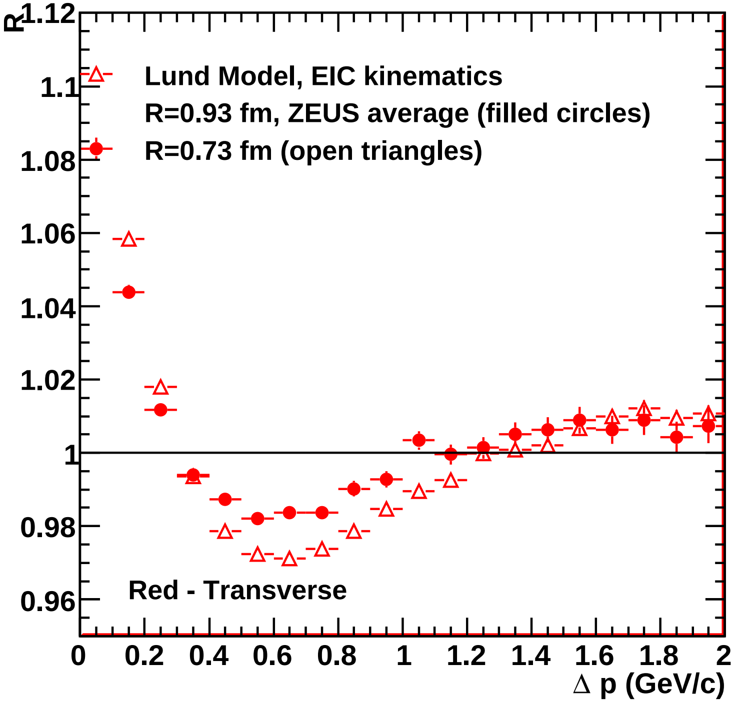
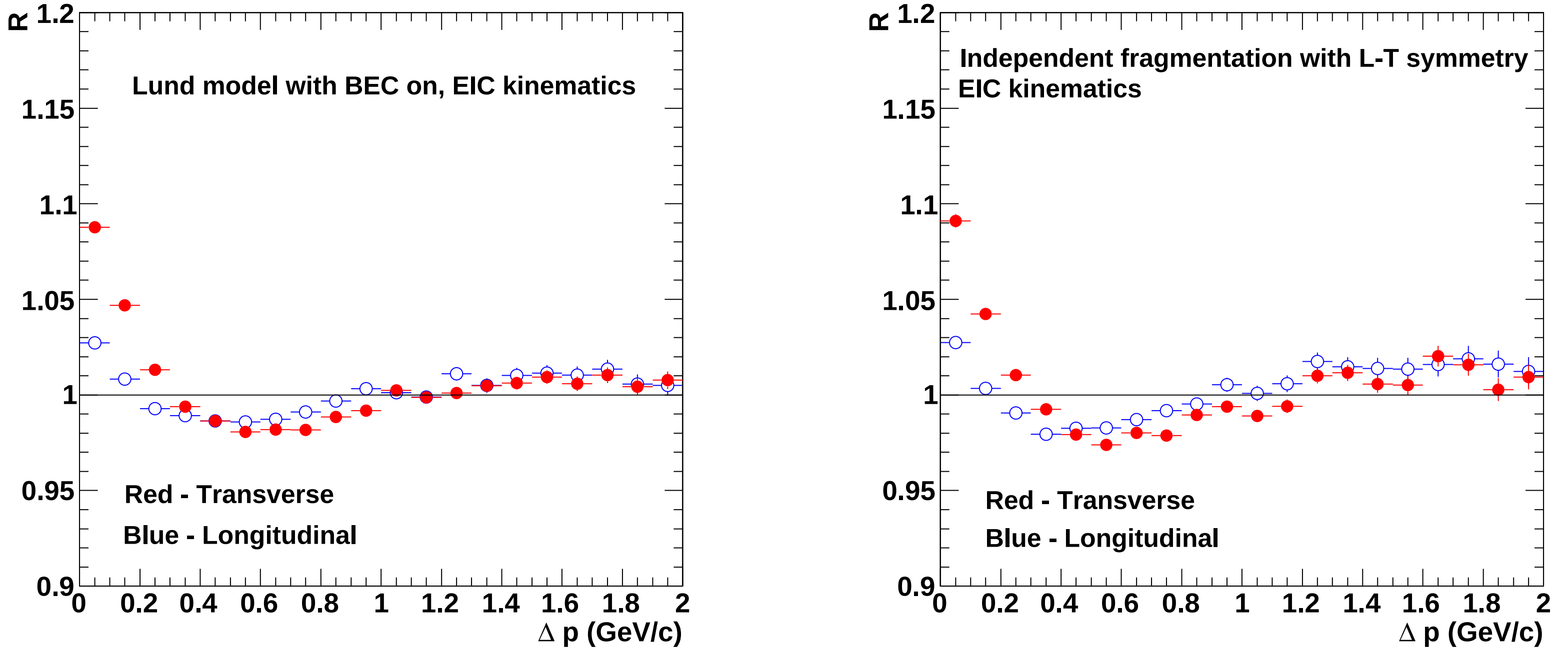



BEC sensitive to source radius.

# Explore LT Source Size Differences (4)

Use results from ZEUS for BEC parameters in LCMS.



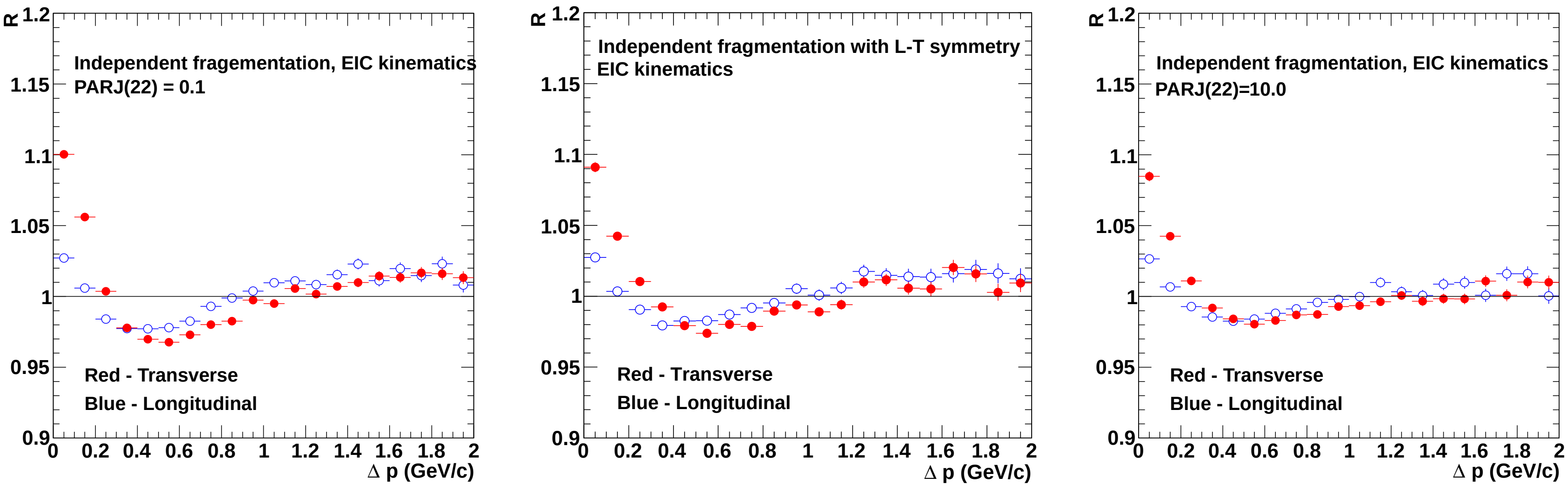

Lund Model

Independent Fragmentation

Lund and default parameters for independent fragmentation give similar results.

# Explore LT Source Size Differences (5)

Effect of Asymmetric Momentum Distribution using Independent Fragmentation.



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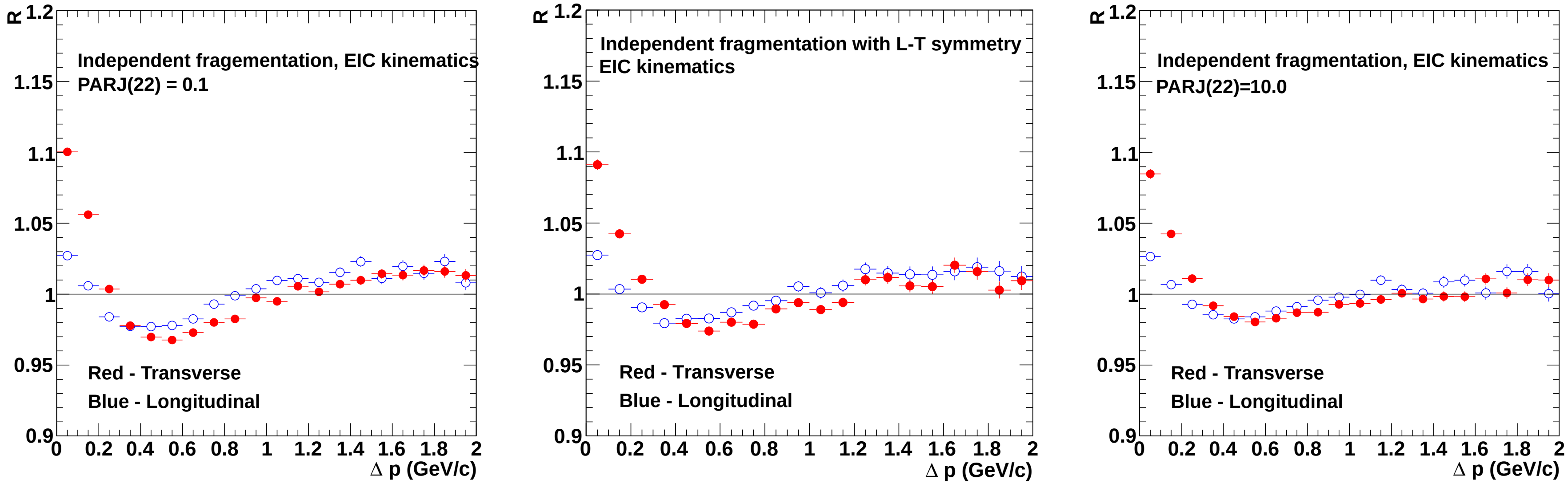
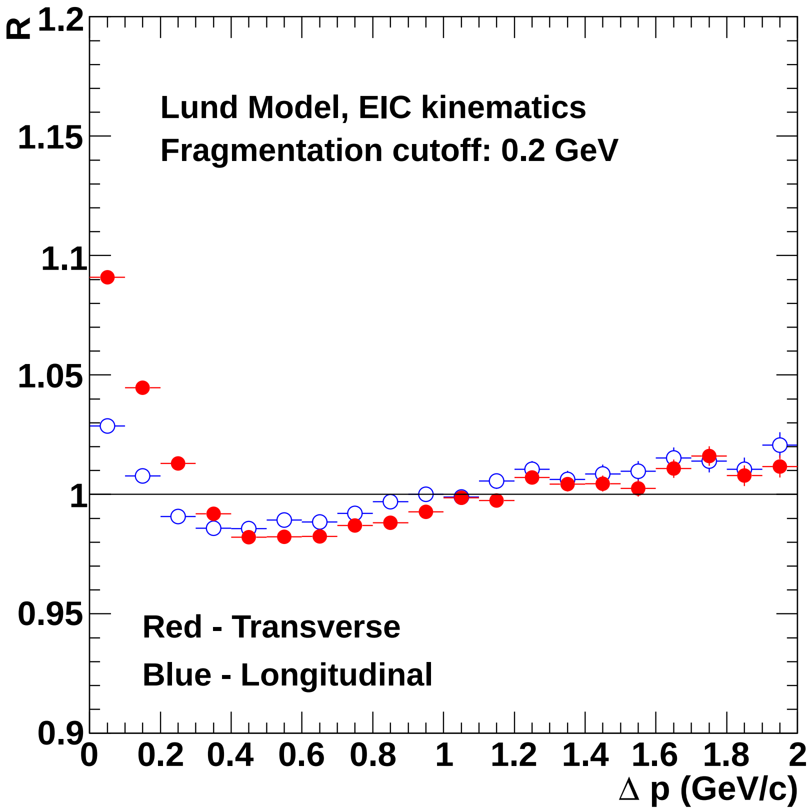
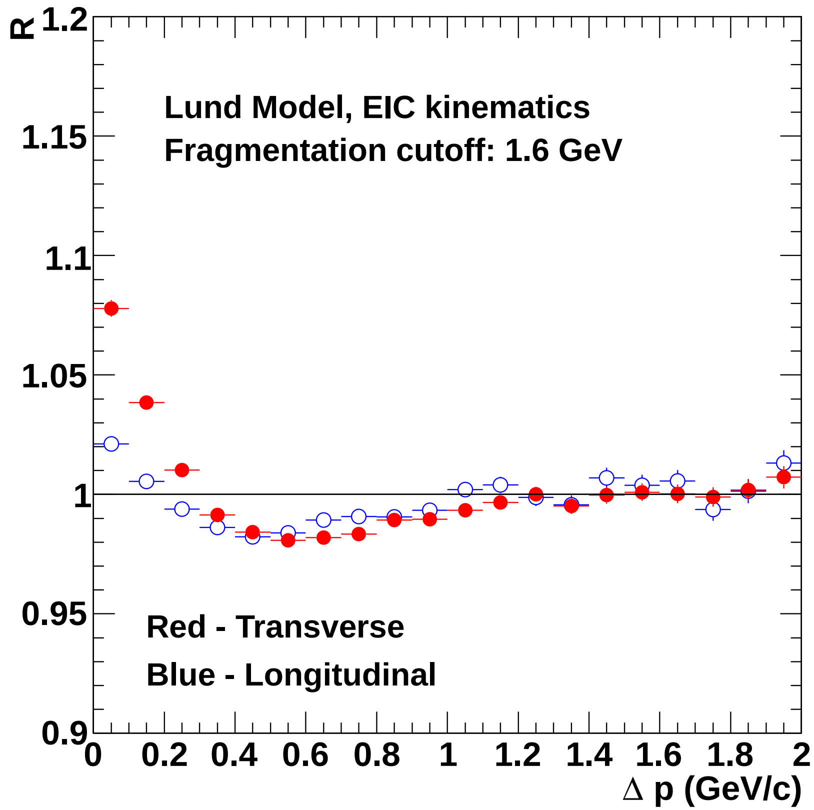



BEC insensitive to asymmetries in L-T momentum distributions.

# Explore LT Source Size Differences (6)

Effect of changing fragmentation cutoff parameter in Pythia.



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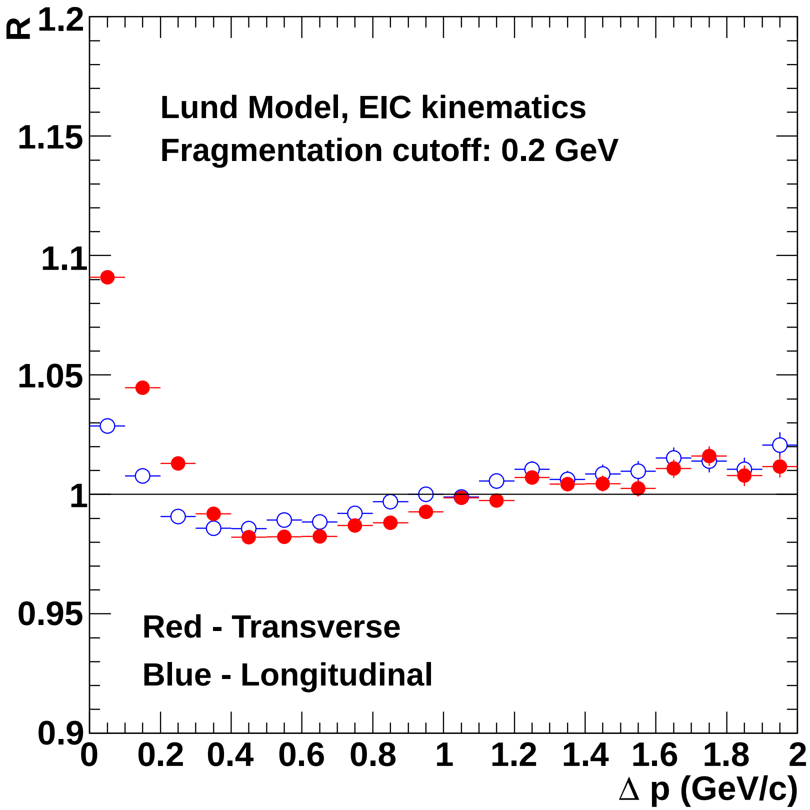


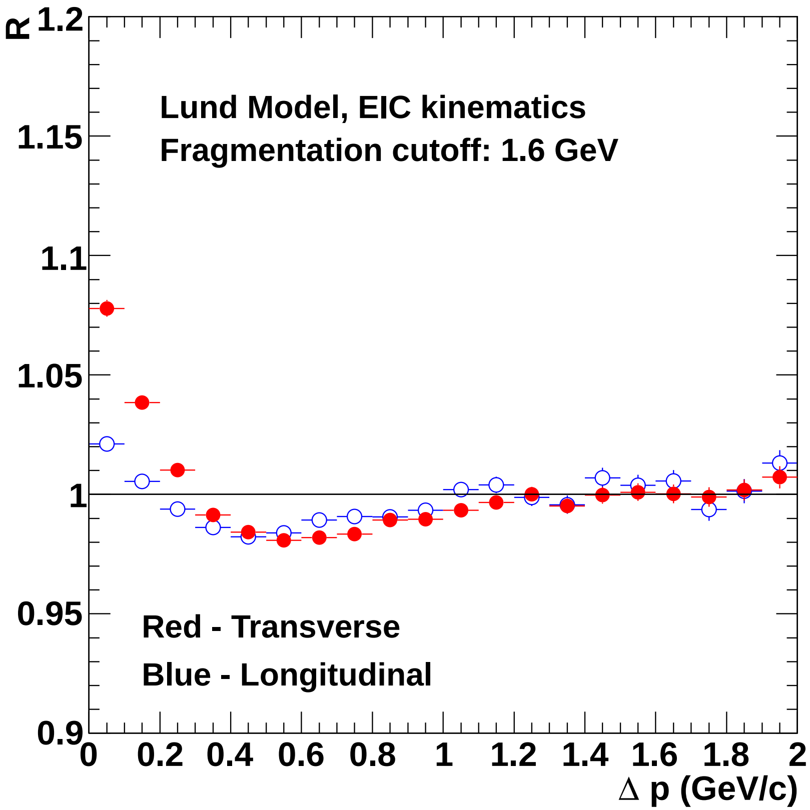


BEC insensitive to fragmentation cutoff.

# Conclusions and Questions

Conclusions

1. Two-pion correlation function independent of $Q^2$ in EIC range (ZEUS and others).
2. We see a large (20%) correlation in our Pythia simulation at EIC kinematics.
3. Dramatic difference between longitudinal and transverse correlations in LCMS.
4. L-T correlation functions sensitive to source size and insensitive to to asymmetric momentum distributions or fragmentation cutoffs.
5. The strong two-pion correlations observed in CLAS for deuterium, carbon, iron, and lead targets are unaccounted for in our Pythia calculations (feature or bug?).

Questions:

1. Can we learn about the string tension, fragmentation, cold, nuclear densities??
2. Defend a program in measuring BECs?
3. What happens when you measure the same observable in a nucleus?
4. Theory input?
5. Where's the nail?

# Additional slides

# ZEUS Results

| $Q^2$ (GeV$^2$) | $\lambda$ | r (fm) | $\lambda'$ | r$'$ (fm) |
|---|---|---|---|---|
| 4 - 8000 | $0.475 \pm 0.007^{+0.011}_{-0.003}$ | $0.666 \pm 0.009^{+0.022}_{-0.036}$ | $0.913 \pm 0.015^{+0.099}_{-0.005}$ | $0.928 \pm 0.023^{+0.005}_{-0.094}$ |
| 100 - 8000 | $0.431 \pm 0.015^{+0.014}_{-0.013}$ | $0.646 \pm 0.021^{+0.004}_{-0.029}$ | $0.815 \pm 0.037^{+0.110}_{-0.014}$ | $0.859 \pm 0.059^{+0.012}_{-0.113}$ |
| 0.1 - 1 | $0.464 \pm 0.027^{+0.020}_{-0.044}$ | $0.602 \pm 0.036^{+0.020}_{-0.051}$ | $0.929 \pm 0.069^{+0.076}_{-0.132}$ | $0.785 \pm 0.071^{+0.119}_{-0.075}$ |
| 4 - 8 | $0.468 \pm 0.020^{+0.009}_{-0.006}$ | $0.685 \pm 0.028^{+0.004}_{-0.054}$ | $0.892 \pm 0.043^{+0.117}_{-0.008}$ | $0.954 \pm 0.069^{+0.015}_{-0.168}$ |
| 8 - 16 | $0.472 \pm 0.016^{+0.029}_{-0.001}$ | $0.620 \pm 0.018^{+0.031}_{-0.038}$ | $0.911 \pm 0.041^{+0.163}_{-0.004}$ | $0.857 \pm 0.054^{+0.040}_{-0.089}$ |
| 16 - 32 | $0.473 \pm 0.017^{+0.017}_{-0.009}$ | $0.629 \pm 0.022^{+0.007}_{-0.035}$ | $0.926 \pm 0.052^{+0.174}_{-0.019}$ | $0.829 \pm 0.066^{+0.014}_{-0.113}$ |
| 32 - 64 | $0.496 \pm 0.018^{+0.020}_{-0.013}$ | $0.679 \pm 0.022^{+0.022}_{-0.032}$ | $0.941 \pm 0.042^{+0.100}_{-0.018}$ | $0.910 \pm 0.060^{+0.042}_{-0.076}$ |
| 64 - 128 | $0.445 \pm 0.017^{+0.019}_{-0.003}$ | $0.665 \pm 0.024^{+0.006}_{-0.049}$ | $0.843 \pm 0.038^{+0.132}_{-0.007}$ | $0.901 \pm 0.063^{+0.006}_{-0.114}$ |
| 128 - 400 | $0.431 \pm 0.021^{+0.010}_{-0.011}$ | $0.649 \pm 0.030^{+0.005}_{-0.036}$ | $0.821 \pm 0.050^{+0.087}_{-0.013}$ | $0.879 \pm 0.081^{+0.004}_{-0.129}$ |
| 400 - 1200 | $0.454 \pm 0.059^{+0.005}_{-0.024}$ | $0.657 \pm 0.080^{+0.016}_{-0.018}$ | $0.852 \pm 0.139^{+0.081}_{-0.019}$ | $0.889 \pm 0.216^{+0.027}_{-0.066}$ |
| 1200 - 8000 | $0.446 \pm 0.120^{+0.063}_{-0.086}$ | $0.837 \pm 0.164^{+0.117}_{-0.073}$ | $0.841 \pm 0.234^{+0.132}_{-0.173}$ | $1.227 \pm 0.389^{+0.237}_{-0.169}$ |

# Interferometry with Identical Particles

- High luminosity of CLAS12 will permit good statistics in SIDIS HBT measurements
- 10X more rate, plus larger event multiplicities
- Focusing spectrometers experiments?
- Experience suggests that ultimate limit will be systematic uncertainties - many subtle effects