Bose-Einstein correlations in hadron pairs, determined from nuclei ranging from hydrogen to xenon at HERMES kinematics.

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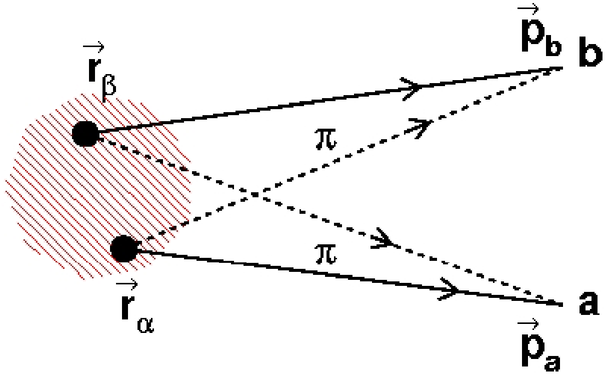
XVI International Workshop on Deep Inelastic Scattering and Related Subjects
7-11 April, 2008, University College London

Bose-Einstein effect



Bose-Einstein correlations (BEC) is expected from basic quantum-mechanical principles. They originate from the symmetrization of the two-particle wave functions of identical bosons.

The wave function describing the two bosons must be symmetric under the exchange of both particles.

The interference term in the cross-section describes correlation in the following form: $I(\vec{p}_\alpha, \vec{p}_\beta) = 1 + \cos(\vec{q} \times \vec{r})$

where $\vec{q} = \vec{p}_a - \vec{p}_b$ and $\vec{r} = \vec{r}_\alpha - \vec{r}_\beta$

The effect is maximal at $\vec{q} = 0$

Bose-Einstein statistics leads to an enhanced production of identical bosons with similar momenta.

Experimentally the BEC can be measured from two particle correlation function $R(T) = D(T)/D_{ref}(T)$,
where T is negative four-momenta difference squared

$$T^2 = -(p_1 - p_2) = M^2 - 4m_h^2$$

$D(T)$ is normalized two-particle density measured in experiment,
$D_{ref}(T)$ is a reference distribution – hypothetical two-particle, density in the absence of the BEC,
M is invariant mass of two particles.

Correlation function was analyzed with the **Goldhaber form** as the most widely used parameterization:

$$R(T) = N \cdot (1 + \lambda \cdot e^{-T^2 r_G^2})(1 + \delta \cdot T^2)$$

r_G - radius of the source from which particles originate

λ - chaoticity parameter

$1 + \delta \cdot T^2$ - term describing long-range correlations at large T

First observation of the BEC was performed more than 40 years ago.
Since that time the effect has been observed in many experiments.
In spite of many efforts an understanding of the effect is still rather poor.

1990 G.Goldhaber: “What is clear is that we have been working on this effect for thirty years. What is not clear is that we have come much closer to a precise understanding of the effect.”

2000 K.Zalewski: “It is unlikely that the progress made during the last ten years would make G.Goldhaber give a much more optimistic view.”

Advantage of the present study is that it based on data obtained in electron scattering off various nuclear targets. The effect provides an information on particle emitting region therefore one may investigate does the region size depend on target mass or not.

HERMES sample

Data sample

1996-2006 $e^{\pm} N \rightarrow e^{\pm} h^{\pm} h^{\pm} X$

Track selection

$$2\, GeV/c < P_{hadron} < 15\, GeV/c$$

$$P_{lepton} > 3.5\, GeV/c$$

DIS

$$Q^2 > 1\, GeV^2$$

$$W^2 > 10\, GeV^2$$

in present analysis all charged hadrons were treated as pions (for calculating correlation function)

Number of events and hadron pairs

target	H	D	He3	He4	N	Ne	Kr	Xe
N ev	1145046	1297356	34391	70776	92968	175594	211456	106274
h±h±	512946	680143	15295	30539	41112	75898	91391	46130
h+h-	958185	1178797	29165	59244	78402	146145	172946	87125

Reference sample (RS)

Reference sample can be a main source of systematic uncertainties.

The level of systematic uncertainties associated with the RS can be estimated by using different methods f or the RS construction.

In this analysis we applied two approaches to build the RS:

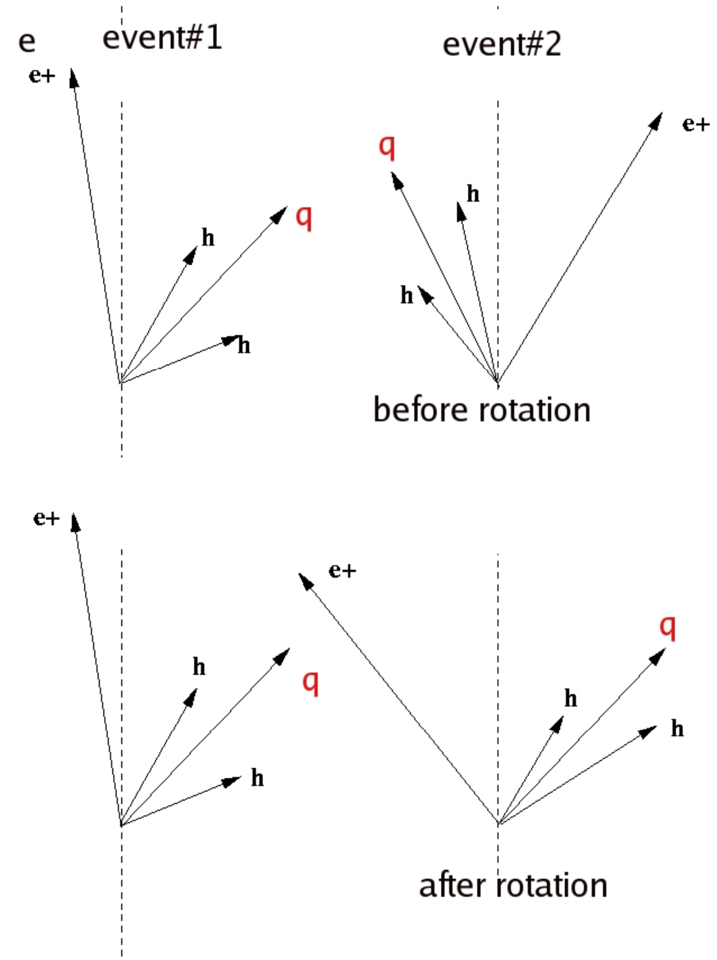
- unlike-sign two-particle density,
- two-particle density obtained with Method of Event Mixing (MEM)

Neither the MEM nor the unlike-sign RS is perfect.
Monte-Carlo simulation was used to correct the measured correlation function R(T) for the imperfection of the reference samples by forming double-ratios:

$$R^{unlike} = (like / unlike)^{data} / (like / unlike)^{MC}$$

$$R^{MEM} = (like / mixed)^{data} / (like / mixed)^{MC}$$

Because of low hadron multiplicity at HERMES we have to take very careful approach to the RS construction.



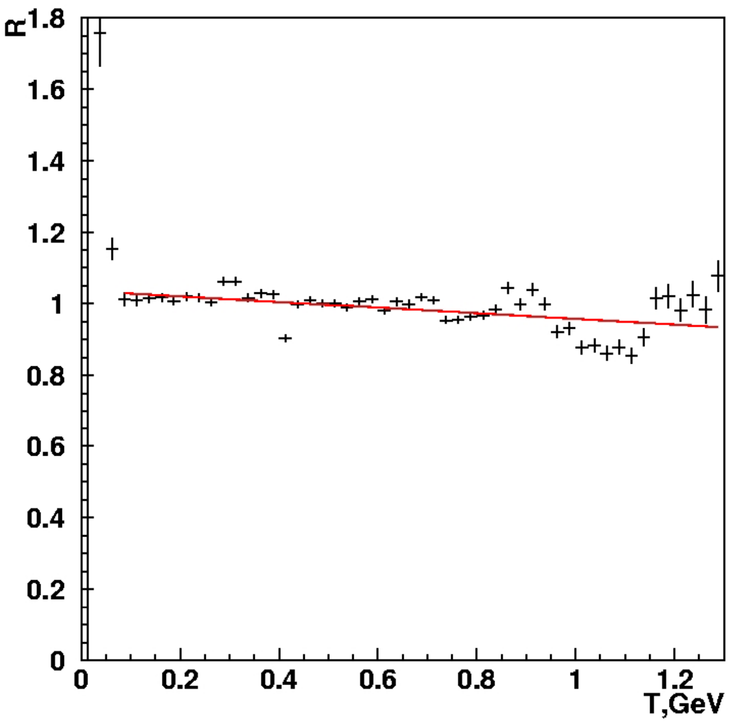
MEM uses a combination of charge hadrons from different events. To avoid unreasonable angles between two particles the second event must be rotated (all particles of the event) in a way to get the collinearity of vectors $\vec{q} = \vec{p}_e - \vec{p}_e'$ for those two events, where $\vec{p}_e$ and $\vec{p}_e'$ are momenta of incident and scattered lepton.

Only events with similar W and similar multiplicity of negative and positive hadrons were mixed.

Test of the MEM with unlike-sign sample.

Hydrogen data

$$R = (unlike / mixed)^{data} / (unlike / mixed)^{MC}$$



Data in the figure were fit with the Goldhaber form (red curve) giving the value $\lambda = 0.000 \pm 0.002$

Figure shows:

- **the MEM works above ~0.05GeV: with the fit restricted to this range no BEC signal is observed.**

- **the HERMES MC describes reliably the average two-particle density of unlike-sign hadrons.**

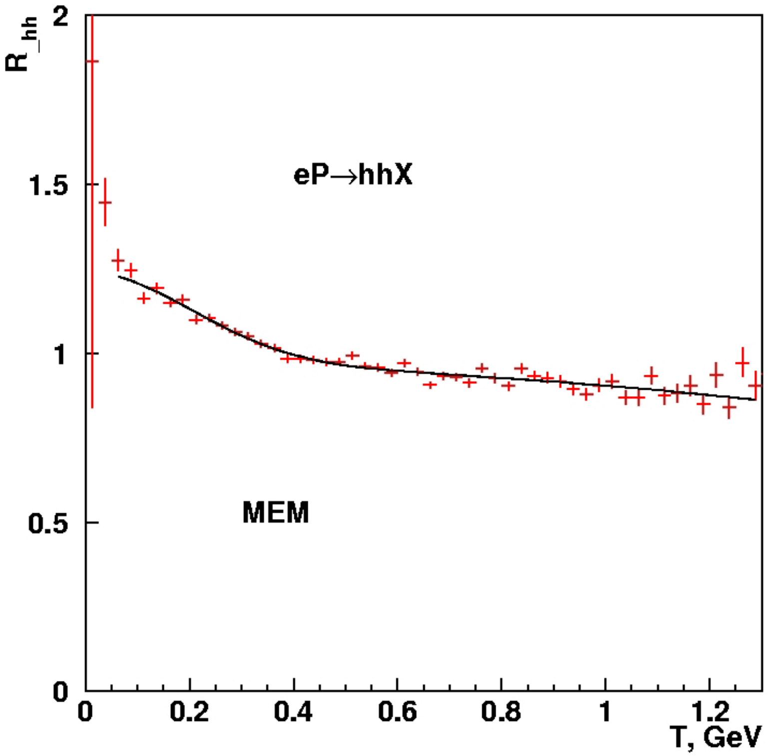
Systematic uncertainty from variation of the fit function and range.

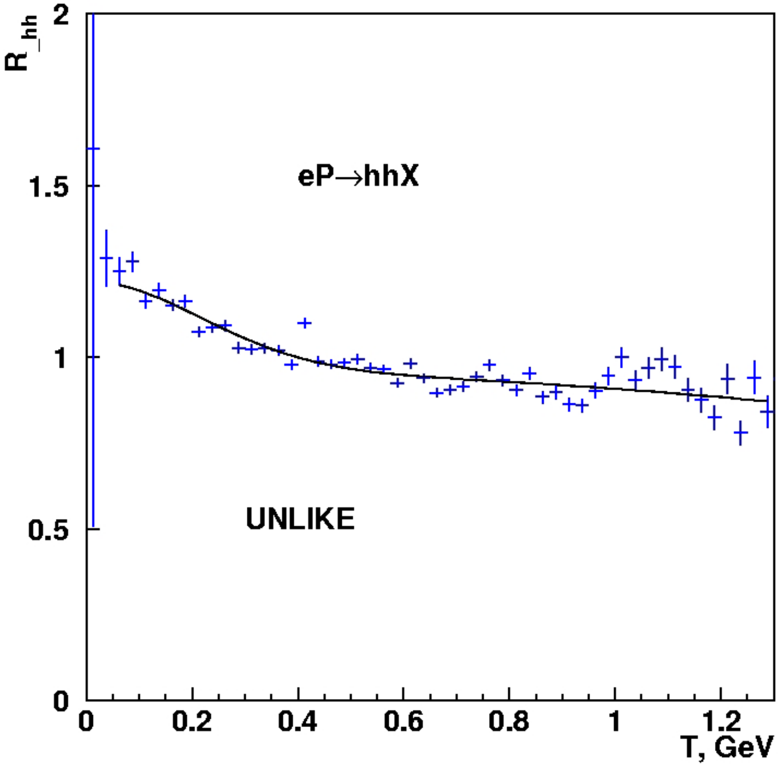
Hydrogen sample (maximum statistics) and Method of Event-Mixing used.
Table shows deviation in parameters with respect to the main fit.
Uncertainties on r_G and λ are statistical only.

Main fit: $0.05<T<1.3$ GeV, bin width=25 MeV and $(1+\delta T^2)$ included.

Variant of the fit	λ	r_G	χ^2 / ND
main fit	0.28 ± 0.01	0.64 ± 0.03	60/46
0.05<T<1 GeV	0.27 ± 0.02	0.68 ± 0.04	42/34
0<T<1.3 GeV	0.28 ± 0.01	0.66 ± 0.03	67/48
(1+δT) instead of (1+δT²)	0.23 ± 0.02	0.65 ± 0.06	56/46
0.05<T<1.3 GeV, bin width=50 MeV	0.28 ± 0.01	0.65 ± 0.03	38/21
0.05<T<1.5GeV	0.25 ± 0.01	0.60 ± 0.03	84/54
maximal deviation from main fit	+0.00 -0.05	+0.04 -0.04	

The correlation function, obtained for hydrogen data sample with the MEM and the unlike-sign method.





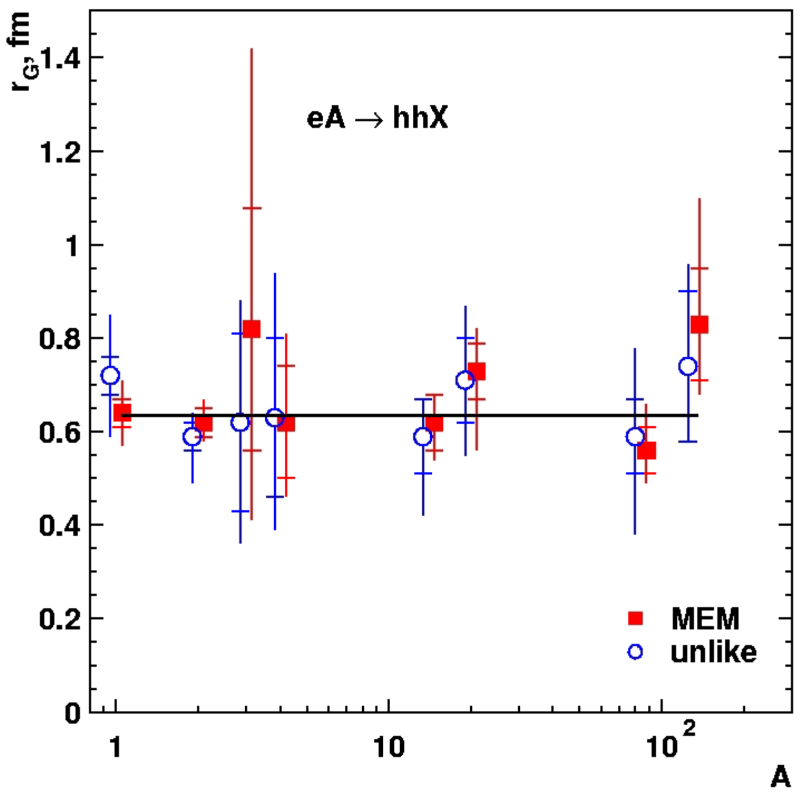
Hydrogen:

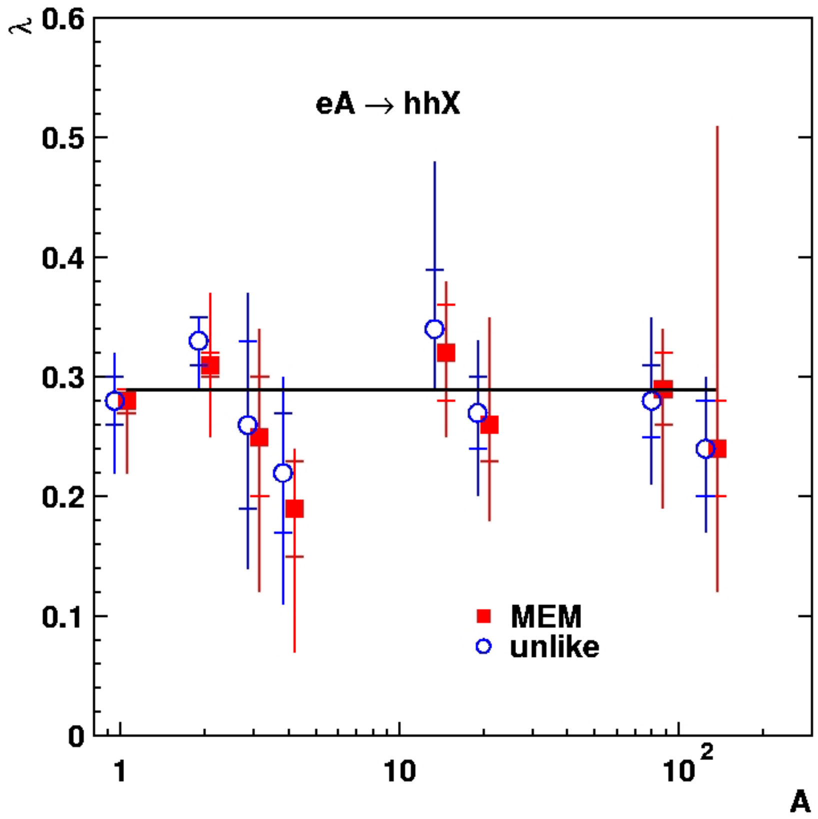
$r_G = \boldsymbol{0.64} \pm \boldsymbol{0.03}^{+0.04}_{-0.04}(sys)$ $\lambda = \boldsymbol{0.28} \pm \boldsymbol{0.01}^{+0.00}_{-0.05}(sys)$ MEM

$r_G = \boldsymbol{0.72} \pm \boldsymbol{0.04}^{+0.09}_{-0.09}(sys)$ $\lambda = \boldsymbol{0.28} \pm \boldsymbol{0.02}^{+0.02}_{-0.04}(sys)$ unlike-sign

Parameters r_G and λ as a function of atomic mass.

Both statistical and systematic uncertainties are shown



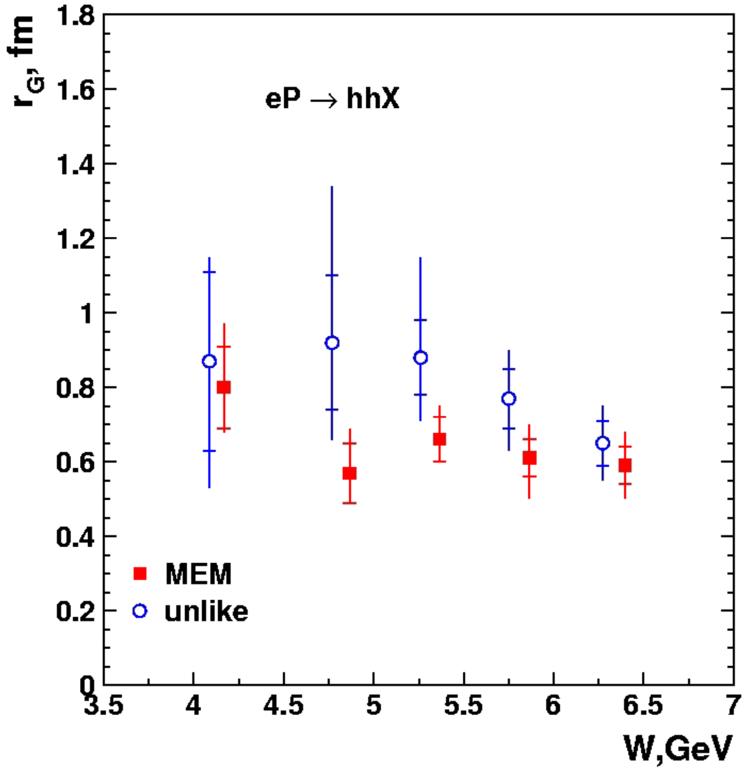


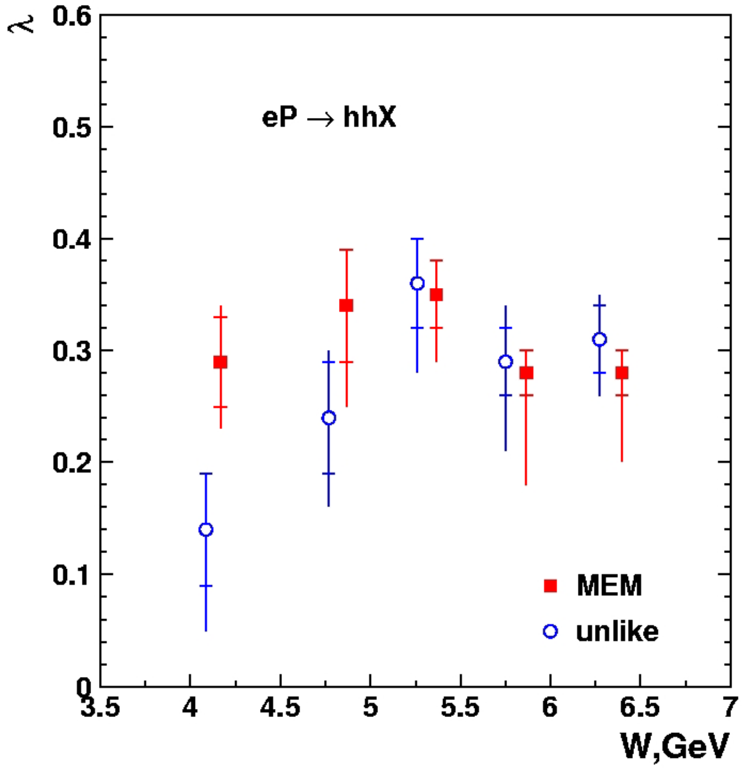
➢ No dependence of correlation parameters on target mass is observed.

Parameters r_G and λ for $h^{\pm}h^{\pm}$ pairs as a function of W

Hydrogen sample

Both statistical and systematic uncertainties are shown

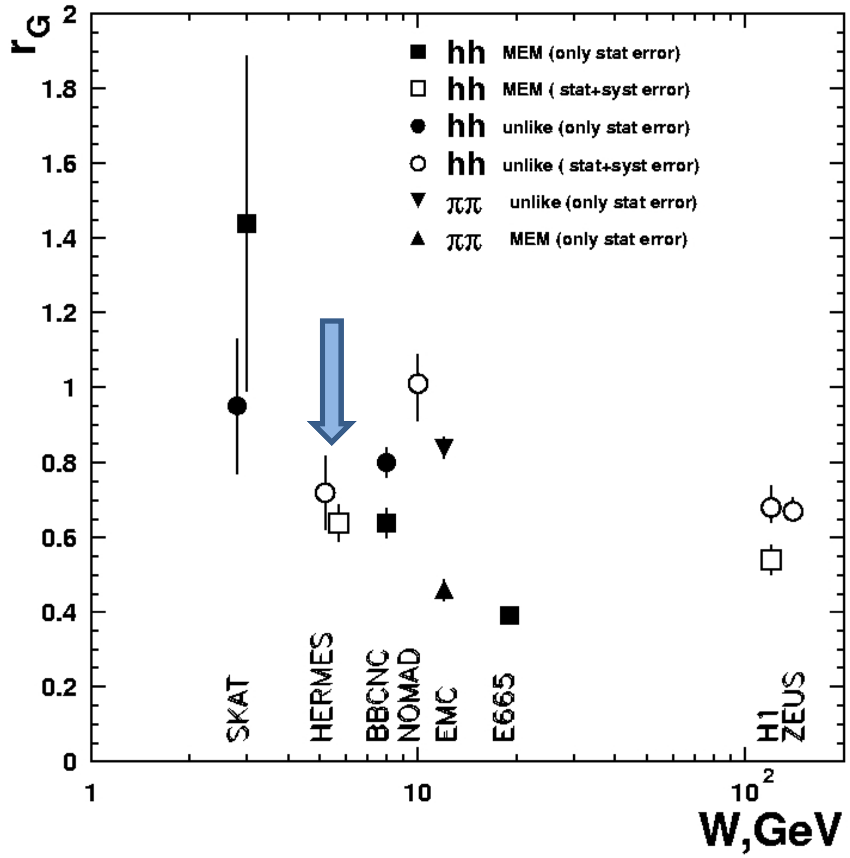


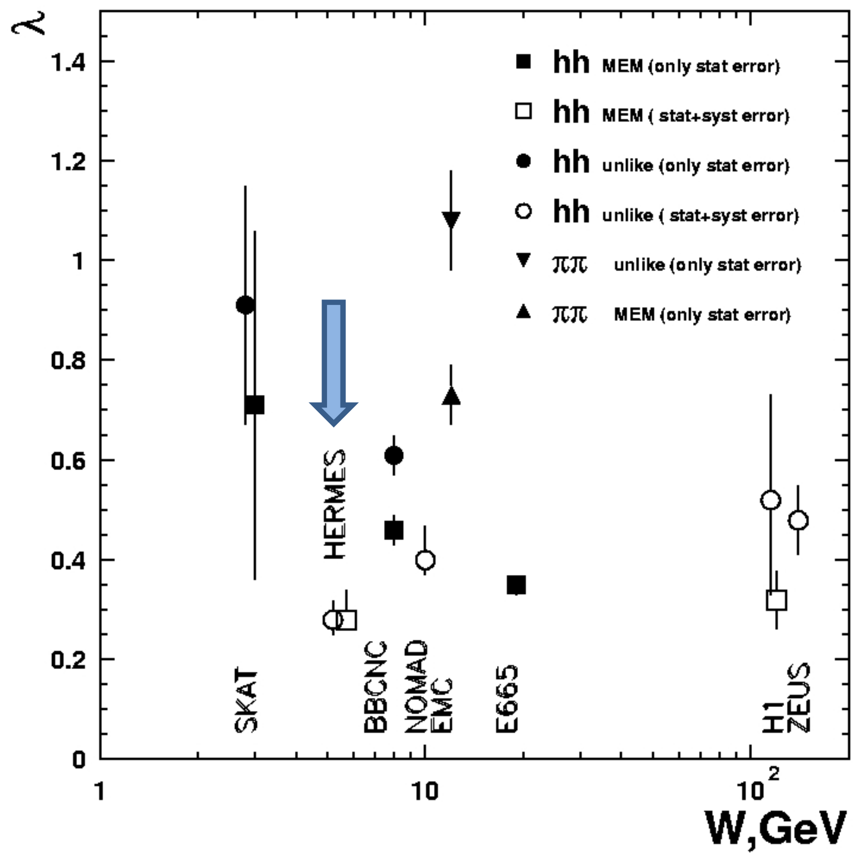


➢No clear dependence of the correlation parameters on ***W*** is observed within the systematic and statistical uncertainties of this analysis.

Goldhaber radius r_G and chaoticity λ as measured in lepton-nucleon interactions.

The HERMES error bars are the quadrature sum of statistical and systematic uncertainties.





- Considerable spread in existing measurements of r_G and λ;
- HERMES results from unlike-sign and MEM agree (in contrast to several other measurements).

Conclusions

- Results obtained with two different reference samples are consistent within estimated uncertainties.
- Within experimental uncertainties no dependence of the radius r_G and the chaoticity λ on the ***target mass*** was observed. The values of parameters averaged over eight targets (***H,D,He3,He4,N,Ne,Kr,Xe***) are:

$$\boldsymbol{r_G} = 0.65^{+0.07}_{-0.06} \qquad \boldsymbol{\lambda} = 0.26^{+0.03}_{-0.08} \qquad \textbf{MEM}$$

$$\boldsymbol{r_G} = 0.62^{+0.07}_{-0.10} \qquad \boldsymbol{\lambda} = 0.29^{+0.05}_{-0.05} \qquad \text{unlike-sign}$$

- No clear dependence of parameters r_G and λ on the hadronic invariant mass ***W*** was found.