Bose-Einstein Correlations in DIS at HERA

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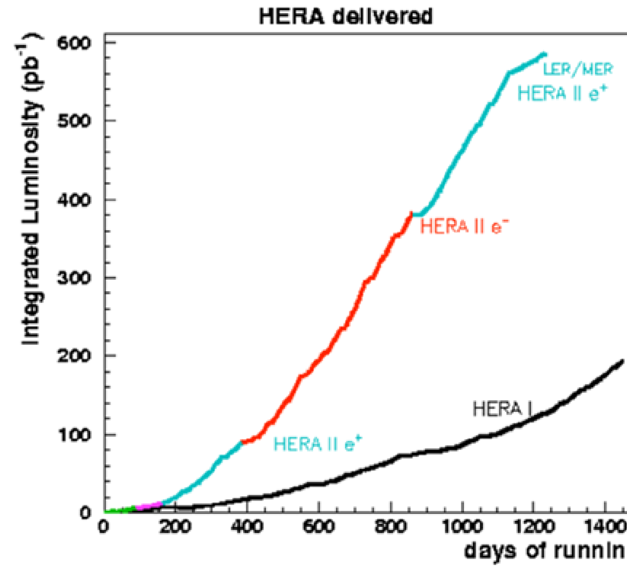
On behalf of the H1 and ZEUS collaborations

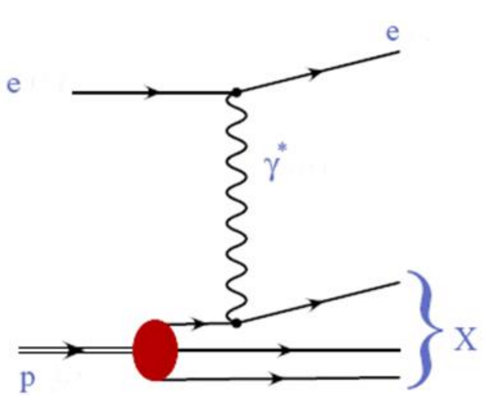


1992 -2007

Investigations:

- Fundamental forces and particles in ep collisions at the highest energy
- Quark and gluon interactions
- Properties of the hadronic final state – including the Bose-Einstein correlations
- Verification of the Standard Model
- Looking for new physics

Hadron production in ep interactions



HERA: $e^{\pm}$ (27.5 GeV) – p (820/920/575/460 GeV)

$\rightarrow$ $\gamma^* p \rightarrow$ hadrons

$Q^2 \approx 0$ (quasi-) photoproduction (PHP)

$Q^2 > 0$ deep inelastic scattering (DIS)

DIS (Quark/parton model, QPM):

γ^* proton = sum of inter. γ^* quark/parton

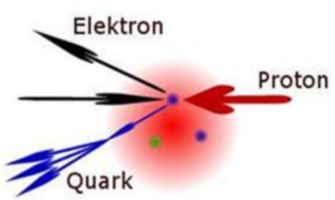
parton fragmentation $\rightarrow$ hadrons $\approx$ mesons (!)

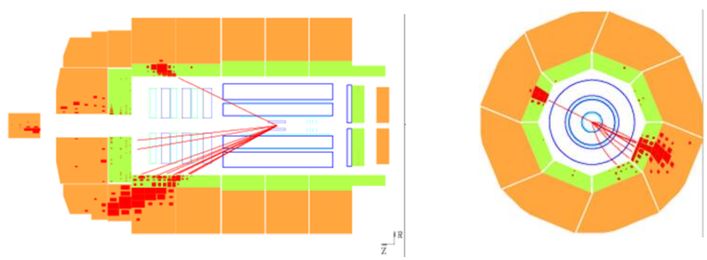
= factorisation of the „hard” and „soft” interaction

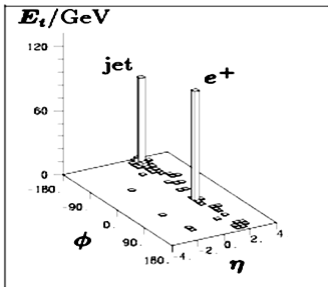
- Proton structure, quarks, gluons...
- Quantum Chromodynamics (QCD)

– theory of quarks and gluons interactions

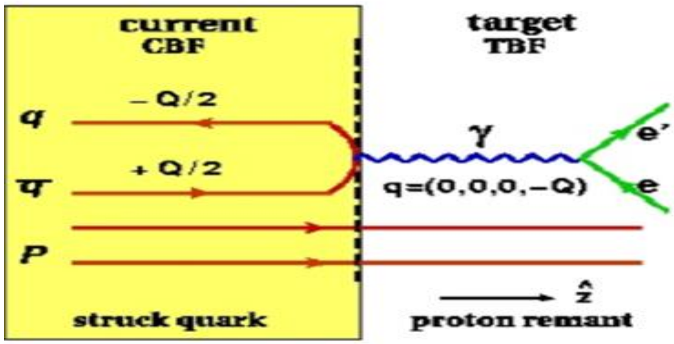
Laboratory frame







Breit frame



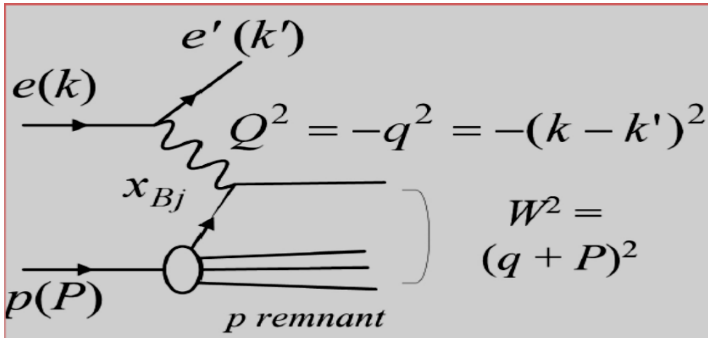
Breit frame separates struck quark (current hemisphere) and proton remnant (target hemisphere)

Current region is analogous to a single hemisphere in e^+e^- annihilation

Target region is similar to a proton fragmentation region in pp interactions

DIS interactions

Kinematic variables for $ep \rightarrow e' X$



P/k the initial-state four momenta of the proton and electron/positron

$s = (P+k)^2$ the cms energy squared of the ep system

$W = (P+q)^2$ the cms energy of the γ^* virtual-photon-proton system

DIS processes:

- $ep \rightarrow e'X$ (Neutral Current) - exchange γ^*, Z^0
- $e^+(e^-)p \rightarrow \nu(\bar{\nu})X$ (Charged Current) - exchange W^+, W^-

where X - hadronic final state

The photon virtuality Q^2 and Bjorken variables are defined as:

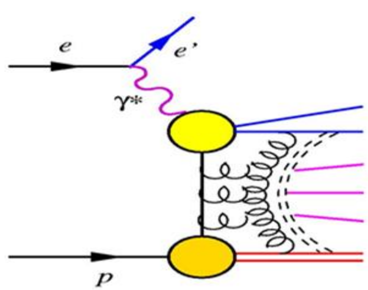
$$Q^2 = -q^2 = -(k-k')^2$$

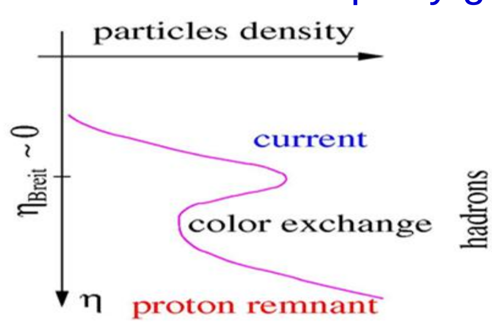
$$x_{B_J} = \frac{Q^2}{2P \cdot q} \qquad y_{B_J} = \frac{P \cdot q}{P \cdot k}$$

$$Q^2 = s \cdot x_{B_J} y_{B_J}$$

Diffractive events:

no hadrons between current and proton remnant - rapidity gap events





H1 and ZEUS contributions to the studies on BEC

All investigations have been performed in DIS

H1: DIS (e^+p scattering), one dimensional measurement (1D) , charged particles

- Different parametrisations of correlation function
  Goldhaber shape of parametrisation for a static source with Gaussian density distribution
  exponential shape in relation to the Lund string model
  power law behaviour in relation to fluctuation in particle production (intermittency case)
- Diffractive and non-diffractive events
- Different intervals of the charged multiplicity

Reference samples:

- two-particle unlike-sign inclusive distribution
- uncorrelated pairs by mixing tracks from different events - mixed events
- Monte Carlo without BEC
- double ratio using mixed events

ZEUS: DIS ($e^\pm p$ scattering) - Breit frame, charged particle , 1D and 2D

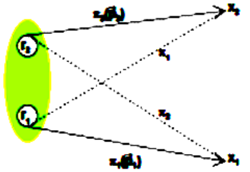
- different parametrisation (Goldhaber, exponential shape)
- charged and neutral kaons, 1D

Reference samples:

- two-particle unlike-sign inclusive distributions
- Monte Carlo without BEC
- double ratio using mixed events

Bose - Einsten Correlations (BEC)

Two bosons with momenta $\vec{p}_1, \vec{p}_1$ produced at points r_1 and r_2



π_1, π_2 - bosons

Bose - Einstein correlations originate from the symmetrization of the two-particle wave function and lead to an enhancement of boson pairs emitted with small relative momenta. BEC can be used to investigate the space –time structure of particle production in different particle interactions

BEC are usually described in terms of the two-particle normalized density **R**

$$R = P(1,2) / (P(1) * P(2)) ,$$

P(1,2) - two-particle inclusive density

P(1), P(2) - single-particle inclusive densities

In experiment, R is constructed normalizing to a reference sample P^{ref} which is two-particle density in the absence of BEC

$$R(Q_{12}) = P(Q_{12}) / P^{ref}(Q_{12}) ,$$

where Q_{12} is the Lorentz invariant four-momenta difference of the bosons with four momenta p_1 and p_2 given as:

$$Q_{12} = \sqrt{-(p_1 - p_2)^2} = \sqrt{M^2 - 4 m^2_{boson}}$$

M is invariant mass of the pair of bosons and m_{boson} is the boson rest mass

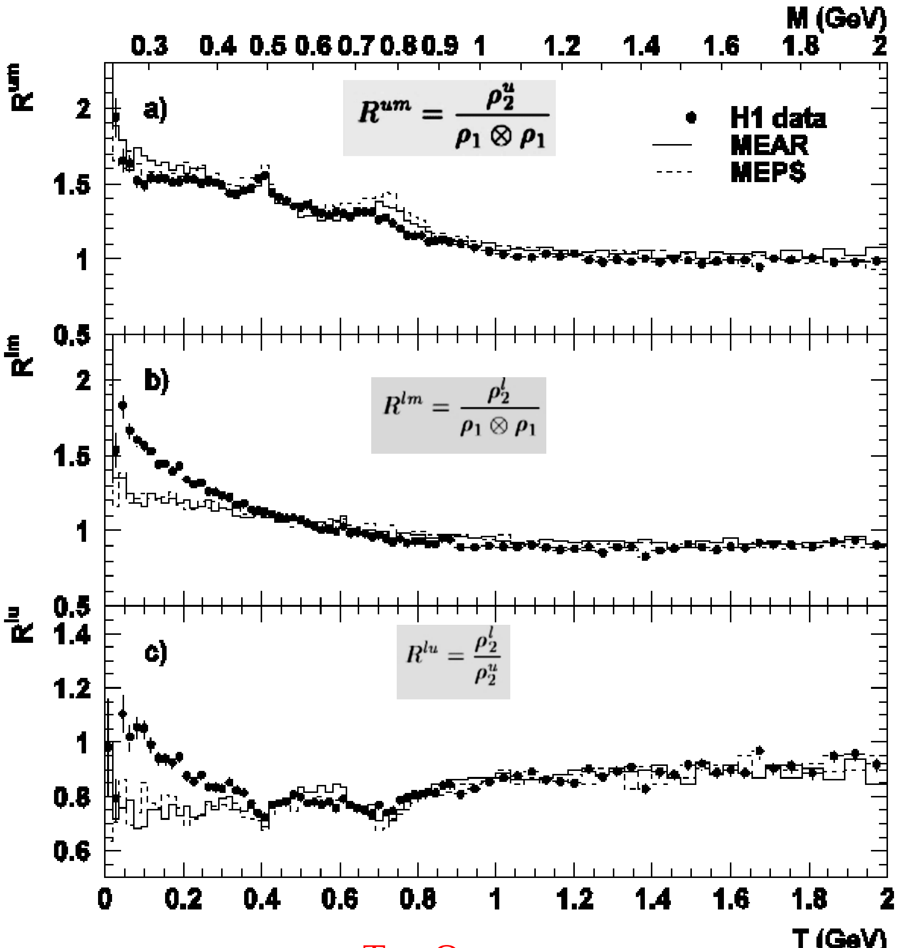
$$P(Q_{12}) = 1 / N (dn^{bb} / dQ_{12}),$$

where n^{bb} is number of boson pairs and **N** is the number of events

H1 results :

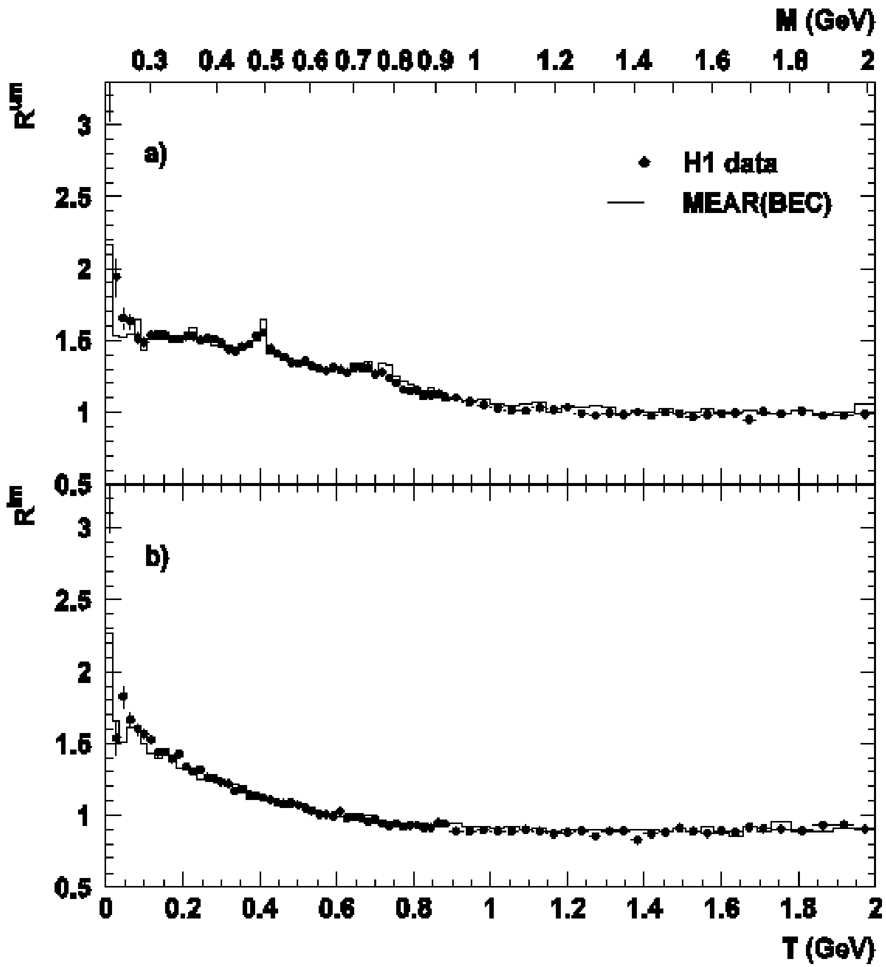
Data 1994, integrated luminosity (IL) = 1.21 pb^{-1}
non-diffractive data and Monte Carlo predictions

MC without BEC



$T \equiv Q_{12}$

MC with BEC



Bose-Einstein effect is visible in like-sign pairs

Good agreement with MC prediction
For small T <0.2 R^{lm} data systematically exceed
BE effect rises faster than expected from a Gaussian par.

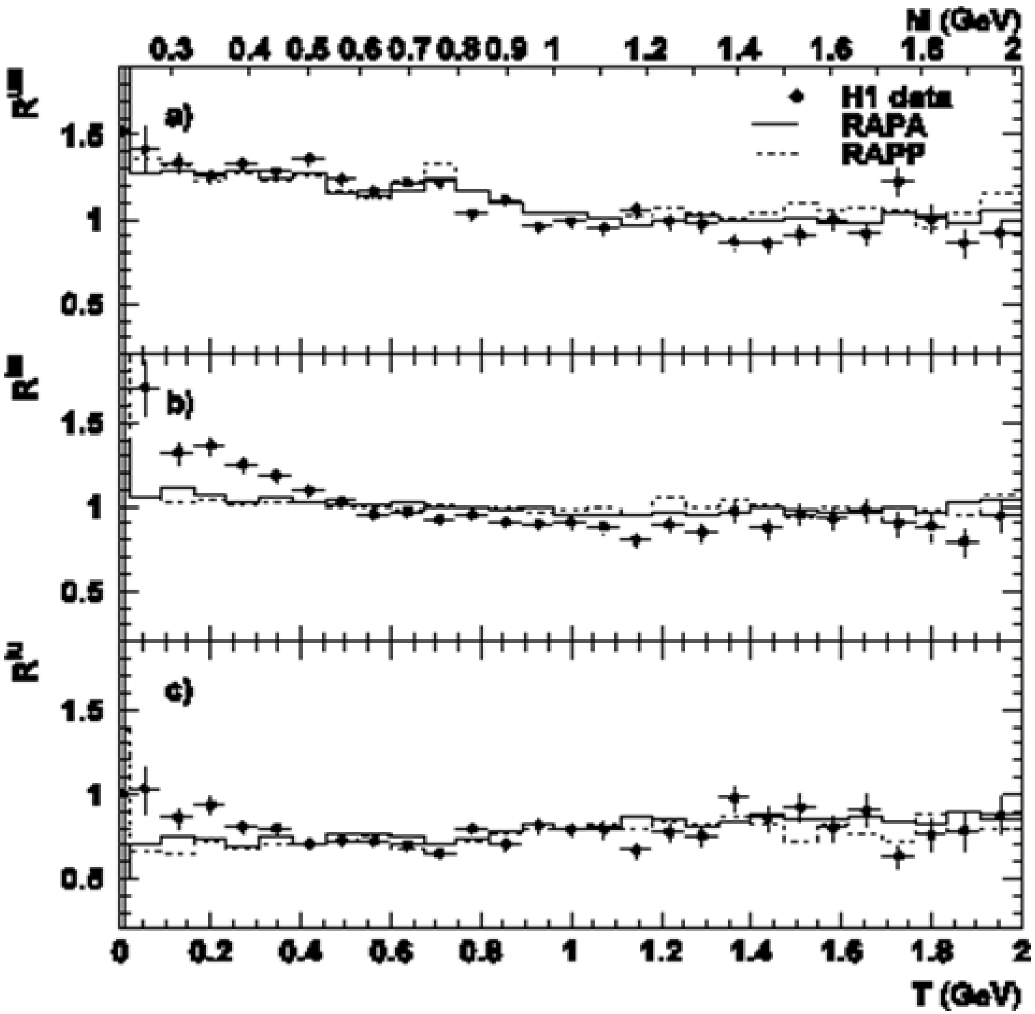
H1 results

Diffractive data nad MC

$$R^{um} = \frac{\rho_2^u}{\rho_1 \otimes \rho_1}$$

$$R^{lm} = \frac{\rho_2^l}{\rho_1 \otimes \rho_1}$$

$$R^{lu} = \frac{\rho_2^l}{\rho_2^u}$$



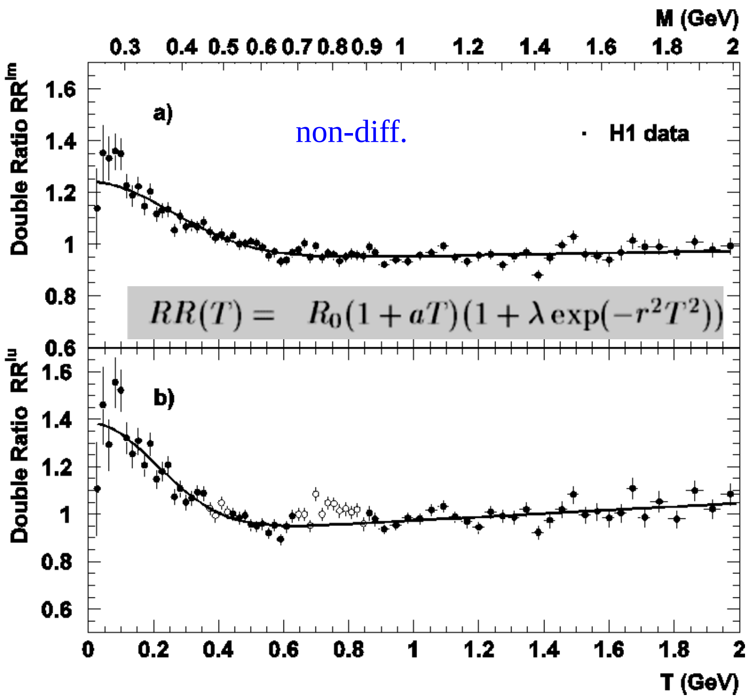
BE effect visible for like-sign pairs

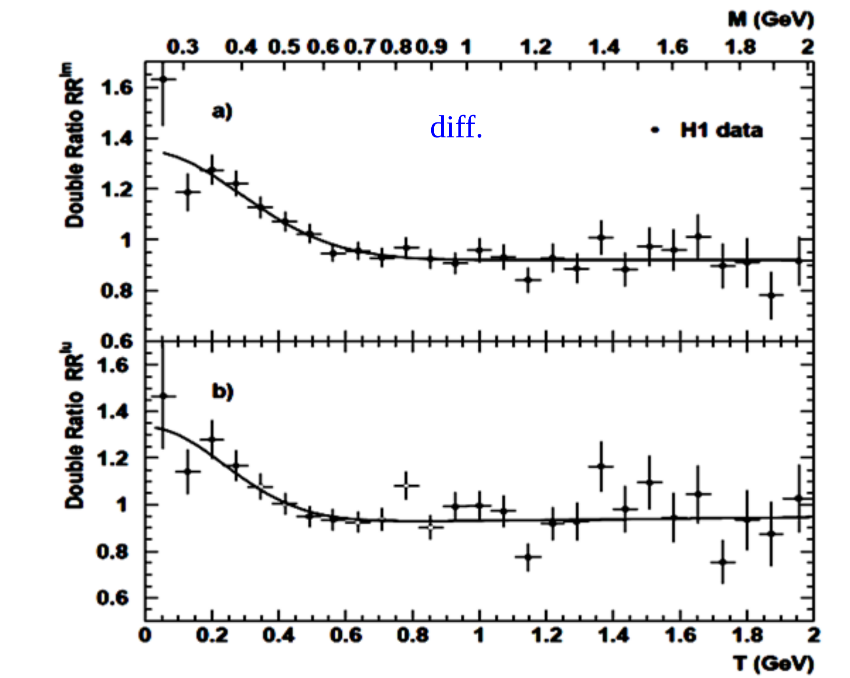
H1 results

Non-diffractive and diffractive data

Using double ratio RR: $RR(T) = \frac{R^{data}(T)}{R^{MC}(T)}$

RR discriminate BEC from other dynamical correlations, it correct for the detector acceptance, analysis cuts ...





Data set	event-mixed $\rho_1 \otimes \rho_1(T)$		
	r (fm)	λ	χ^2/ndf
non-diffractive	$0.54 \pm 0.03\,^{+0.03}_{-0.02}$	$0.32 \pm 0.02\,^{+0.06}_{-0.09}$	96/72
diffractive	$0.49 \pm 0.06\,^{+0.02}_{-0.03}$	$0.46 \pm 0.08\,^{+0.15}_{-0.08}$	18/23
Data set	**unlike-sign $\rho_2^u(T)$**		
	r (fm)	λ	χ^2/ndf
non-diffractive	$0.68 \pm 0.04\,^{+0.02}_{-0.05}$	$0.52 \pm 0.03\,^{+0.19}_{-0.21}$	77/56
diffractive	$0.59 \pm 0.13\,^{+0.05}_{-0.05}$	$0.46 \pm 0.13\,^{+0.26}_{-0.11}$	26/17

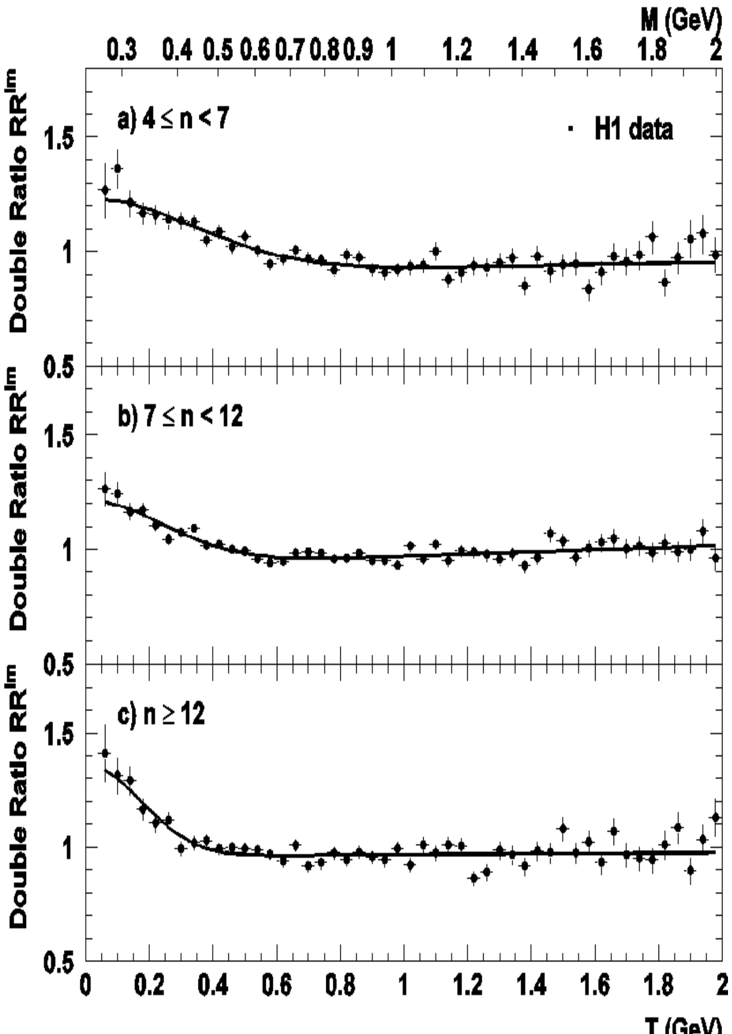
Observed differeces due to
the production of long-lived
resonances and
$\pi\pi$-interactions in the final state
r from event-mixed method
closer to input value
used in the
MC generator with BEC

H1 results

Kinematical and multiplicity dependence of BEC

Non-diffractive sample

Fit to the RR Gaussian parametrisation



	r(fm) λ	r(fm) λ	r(fm) λ
x	0.60±0.06 0.30±0.03 $(0.0001 \leq x < 0.0006)$	0.56±0.05 0.34±0.03 $(0.0006 \leq x < 0.0019)$	0.44±0.06 0.38±0.07 $(0.0019 \leq x < 0.01)$
Q^2 (GeV^2)	0.52±0.04 0.42±0.04 $(6 \leq Q^2 < 12)$	0.63±0.08 0.25±0.04 $(12 \leq Q^2 < 25)$	0.47±0.04 0.41±0.05 $(25 \leq Q^2 \leq 100)$
W (GeV)	0.52±0.07 0.26±0.05 $(65 \leq W < 120)$	0.48±0.03 0.42±0.04 $(120 \leq W < 180)$	0.68±0.08 0.34±0.04 $(180 \leq W < 240)$

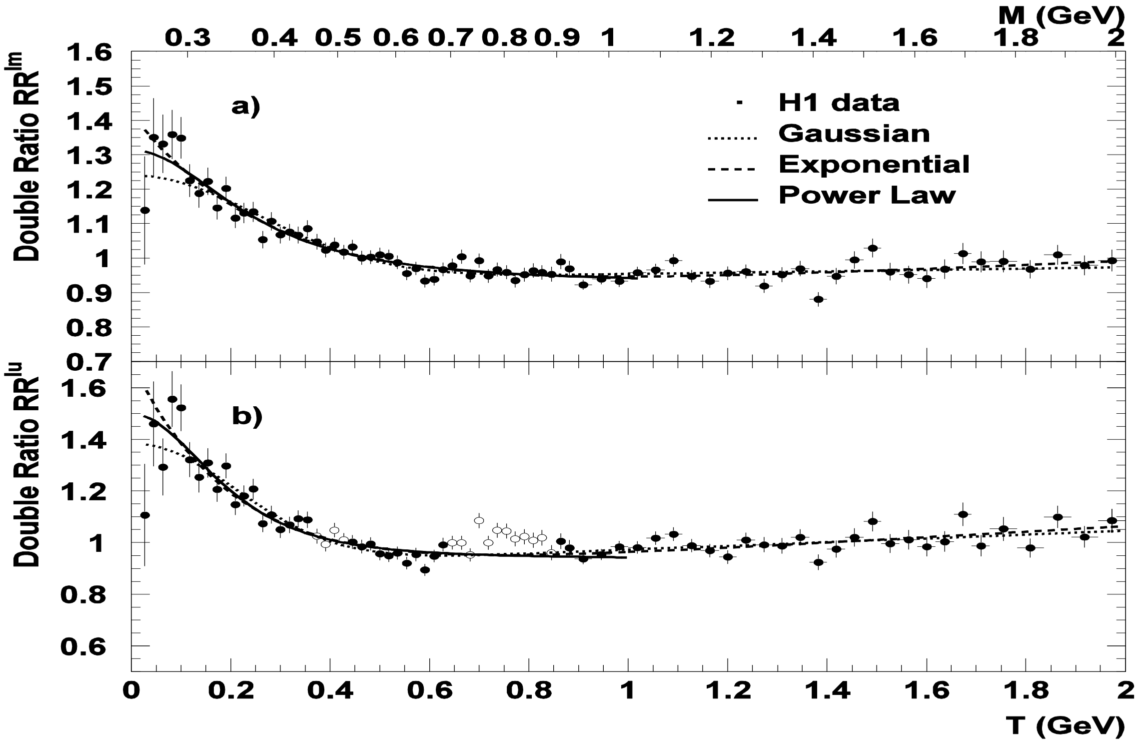
The r and λ parameters are found within statistical errors to be independent of the kinematical region considered

Observed Multiplicity	Corrected Multiplicity	event-mixed $\rho_1 \otimes \rho_1(T)$ r(fm) λ	unlike-sign $\rho_2^u(T)$ r(fm) λ
$4 \leq n < 7$	$4.9 \pm 1.1^{\dagger}$	0.42±0.05 0.37±0.05	0.53±0.06 0.54±0.08
$7 \leq n < 12$	$8.2 \pm 1.6^{\dagger}$	0.58±0.05 0.31±0.03	0.77±0.07 0.54±0.06
$n \geq 12$	$13.6 \pm 2.4^{\dagger}$	0.81±0.12 0.42±0.07	0.72±0.09 0.65±0.09

Parameter r increases with increasing multiplicity.
Small changes for λ are observed

H1 results

Alternative parametrisations of BEC



1 $RR(T) = R_0(1 + aT)(1 + \lambda \exp(-r^2 T^2))$

2 $RR(T) = R_0(1 + aT)(1 + \lambda \exp(-rT))$

3 $RR(M) = A + \epsilon \cdot M + B \left(\frac{1}{M^2}\right)^{\beta}$

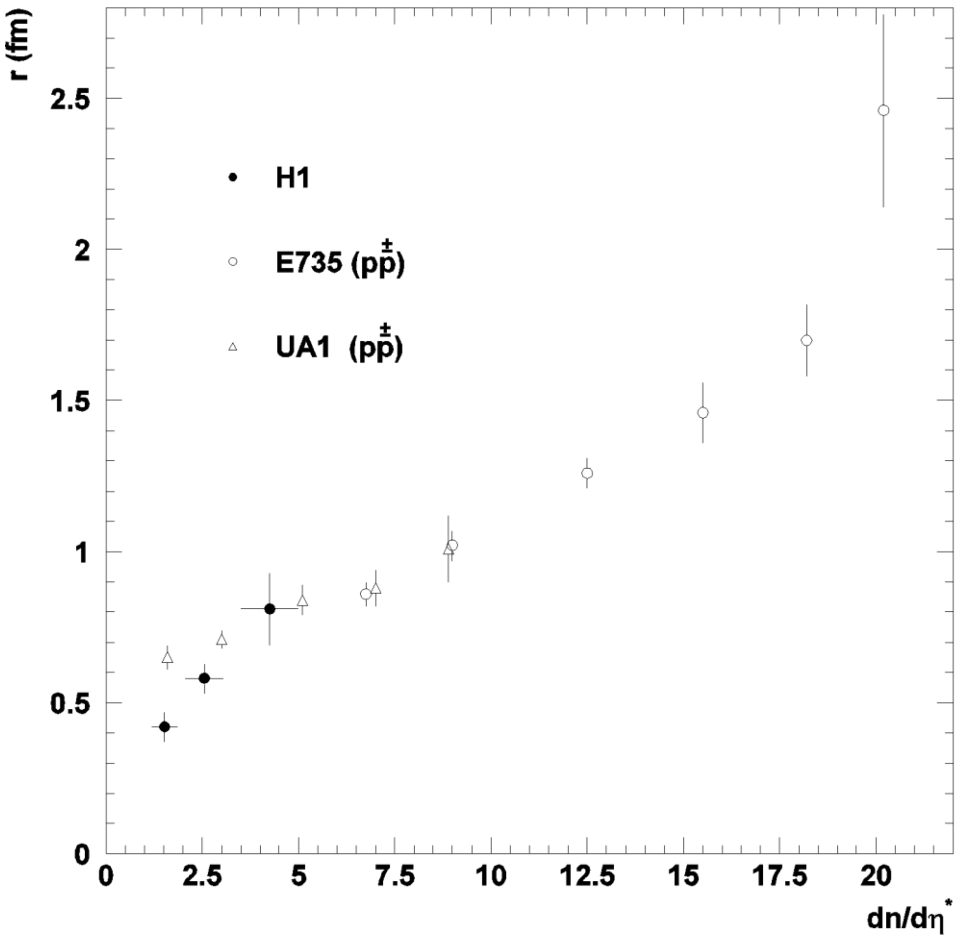
1. Gaussian
2. Exponential
3. Power Law

Power law	β	B [GeV^{-2}]	A	χ^2/ndf
RR^{lm}	$1.20 \pm 0.15\, ^{+0.15}_{-0.13}$	$0.018 \pm 0.006\, ^{+0.007}_{-0.006}$	$0.93 \pm 0.01\, ^{+0.00}_{-0.01}$	49/49
RR^{lu}	$1.82 \pm 0.20\, ^{+0.44}_{-0.34}$	$0.005 \pm 0.002\, ^{+0.004}_{-0.005}$	$0.94 \pm 0.01\, ^{+0.04}_{-0.03}$	52/33
Exponential	a [GeV^{-1}]	r [fm]	λ	χ^2/ndf
RR^{lm}	0.08 ± 0.04	$0.68 \pm 0.11\, ^{+0.09}_{-0.06}$	$0.64 \pm 0.06\, ^{+0.17}_{-0.16}$	85/72
RR^{lu}	0.13 ± 0.02	$0.99 \pm 0.09\, ^{+0.05}_{-0.27}$	$1.00 \pm 0.08\, ^{+0.68}_{-0.38}$	85/56
Gaussian	a [GeV^{-1}]	r [fm]	λ	χ^2/ndf
RR^{lm}	0.02 ± 0.01	$0.54 \pm 0.03\, ^{+0.03}_{-0.02}$	$0.32 \pm 0.02\, ^{+0.06}_{-0.06}$	96/72
RR^{lu}	0.08 ± 0.02	$0.68 \pm 0.04\, ^{+0.02}_{-0.05}$	$0.52 \pm 0.03\, ^{+0.19}_{-0.21}$	77/56

The exponential parametrisation in T and power law in invariant mass can describe the Bose-Einstein enhacement
Observation confirm the existence of a scale-invariance in multi-hadron production?

H1 and other experiments

Radius vs charged particle density



The H1 results are consistent with the trend observed in hadron-hadron collisions

ZEUS: 1D – charged particles

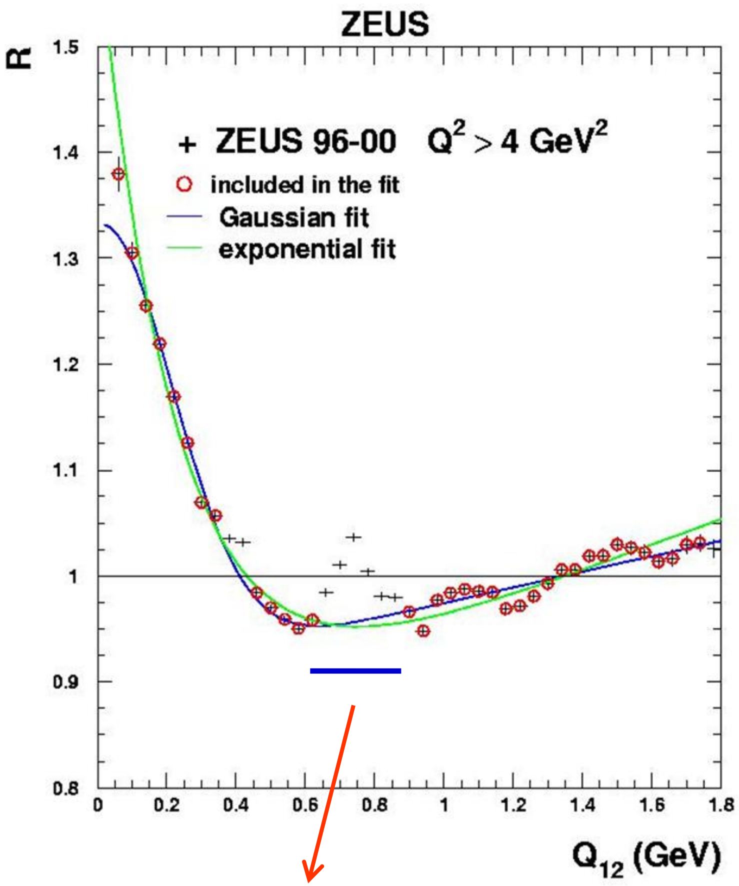
The double ratio $R(Q_{12})$ was used :

$$R(Q_{12}) = R(Q_{12})^{data} / R(Q_{12})^{MC(n0BE)}$$

Data 1996 -2000, IL = 121 pb^{-1} , $4 < Q^2 < 8000\ GeV^2$
1997 , 3.9 pb^{-1} , $0.1 < Q^2 < 1\ GeV^2$

$R^{data}(Q_{12}) = \rho^{data}(++,--) / \rho^{data}(+,-)$, where $\rho = 1/N * dn_{pairs} / dQ_{12}$
In similar way $R(Q_{12})^{MC(noBE)}$ was calculated

An example



Region with decay products of the resonances which are not well descibed by MC simulation

BE enhancement is clearly visible

Values obtained for radius of source **r** and incoherent parameter λ from

Gaussian (χ^2 / ndf = 148/35)

r = 0.666 ± 0.009 (stat.) +/- 0.023/0.036(syst.)

λ = 0.475 ± 0.007 (stat.) +/- 0.021/0.003 (syst.)

and from

exponential (χ^2 / ndf = 225/35)

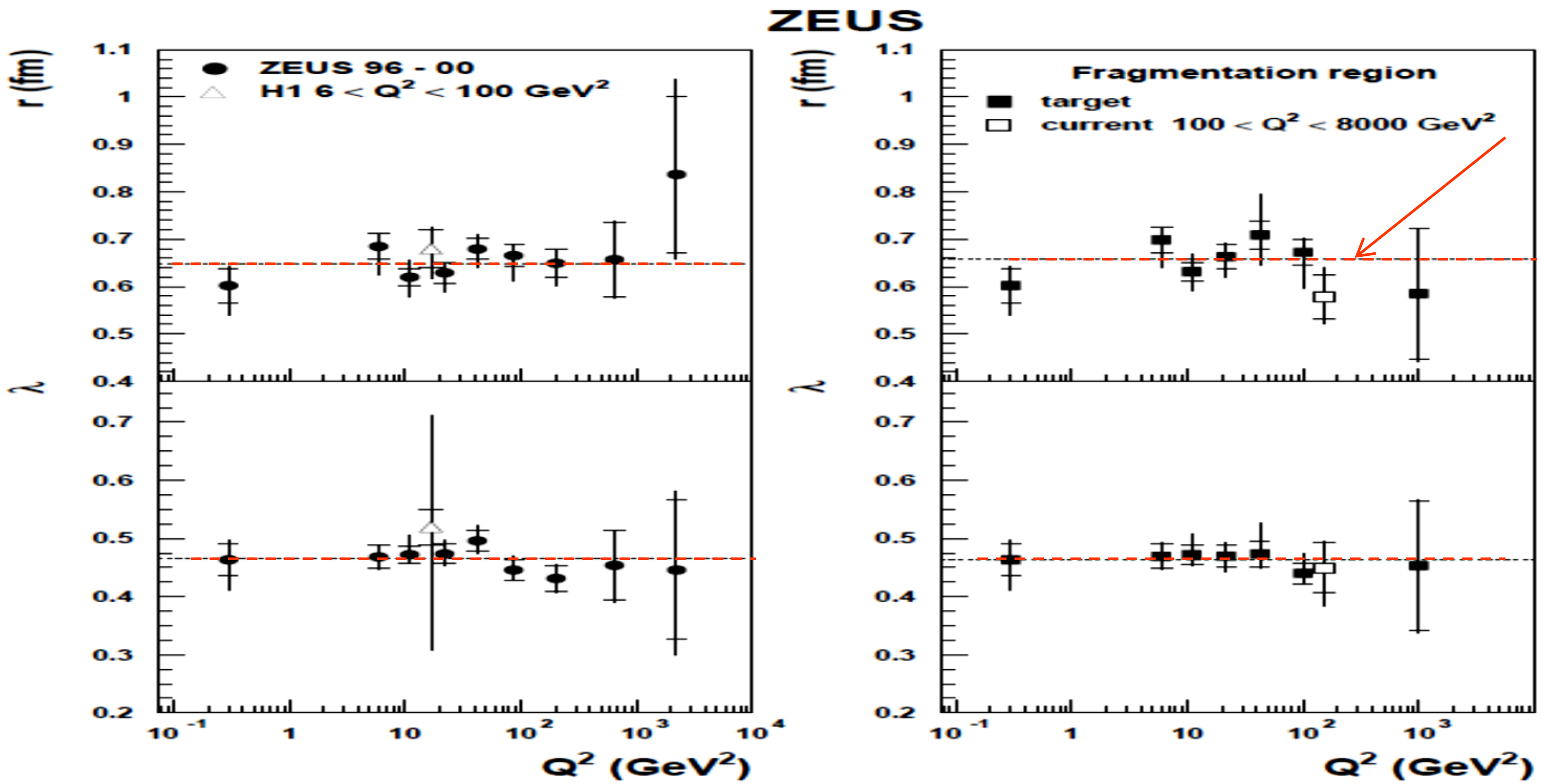
r = 0.928 ± 0.023 (stat.) +/- 0.015/0.094 (syst.)

λ = 0.913 ± 0.015 (stat.) +/- 0.104/0.005 (syst.)

Both parametrisations give fits of similar quality

ZEUS – 1D –charged particles)

Studies of Q^2 dependence of the r and λ parameters. The Gaussian parametrisation was used
This has been done for the total measured phase space
and for current and target regions of the Breit frame



Average value with χ / ndf $\approx$ 0.5

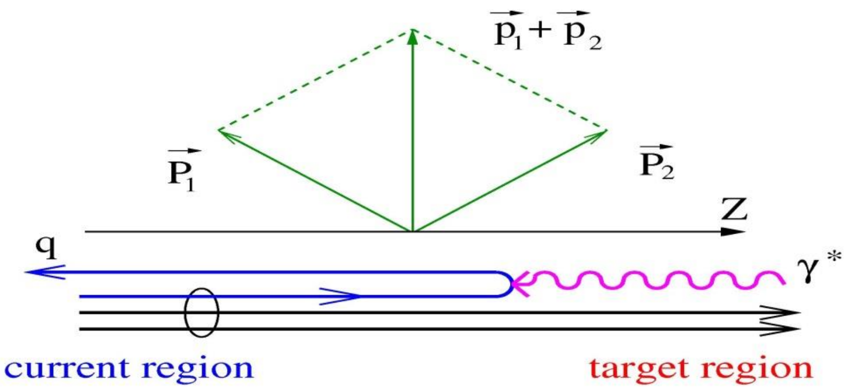
- Within the statistical and systematic uncertainties, the data indicate no variations with virtuality of the exchange photon, Q^2, in the range of $0.1 < Q^2 < 8000$ GeV^2
It is consistent with H1 measurement given for $6 < Q^2 < 100$ GeV^2

- No significant difference between the BE effects in the current and target regions of the Breit frame
- No sensitiveness to the hard subprocesses ? - possible that it is a global feature of hadronization phase

ZEUS – 2D correlation function

To probe the shape of the bosons source the Longitudinally Co-Moving System LCMS was used

In DIS (Breit frame), the LCMS is defined as :



The physical axis was chosen as the virtual photon (quark) axis

- In LCMS , for each pair of the particles, the sum of two momenta $\mathbf{p_1 + p_2}$ is perpendicular to the γ^* q axis,
- The three momentum difference $\mathbf{Q = p_1 - p_2}$ is decomposed in the LCMS into: transverse $\mathbf{Q_T}$ and longitudinal component $\mathbf{Q_L = |p_{L1} - p_{L2}|}$
- The longitudinal direction is aligned with the direction of motion of the initial quark (in the string model LCMS - local rest frame of a string)

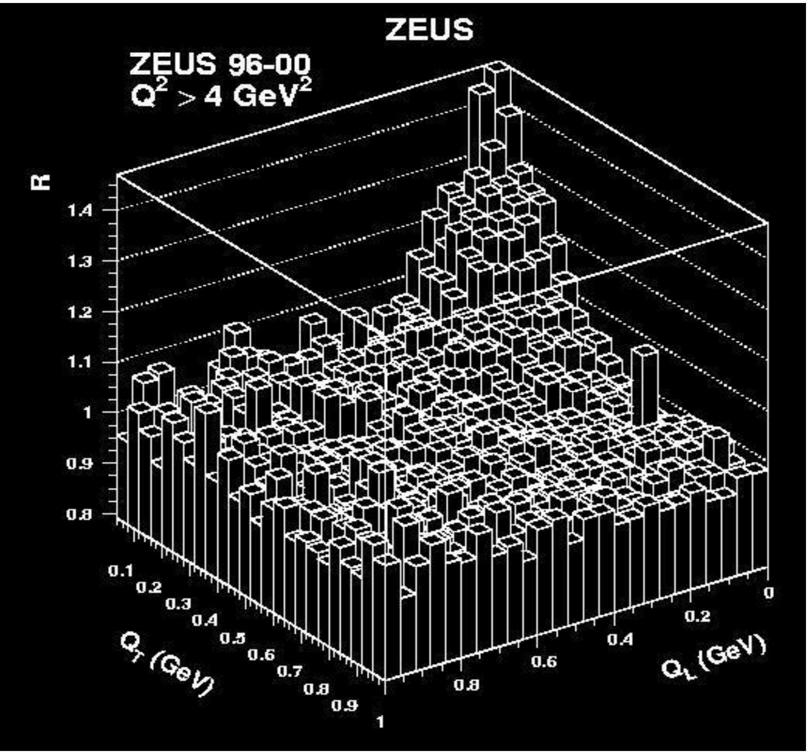
Parametrisation - in analogy to 1 D:

$$\mathbf{R = \alpha(1+ \beta_T Q_T + \beta_L Q_L)(1+\lambda\, exp(- r^2_T Q^2_T - r^2_L Q^2_L))}$$

The radii $\mathbf{r_T}$ and $\mathbf{r_L}$ reflect the transverse and longitudinal extent of the pion source

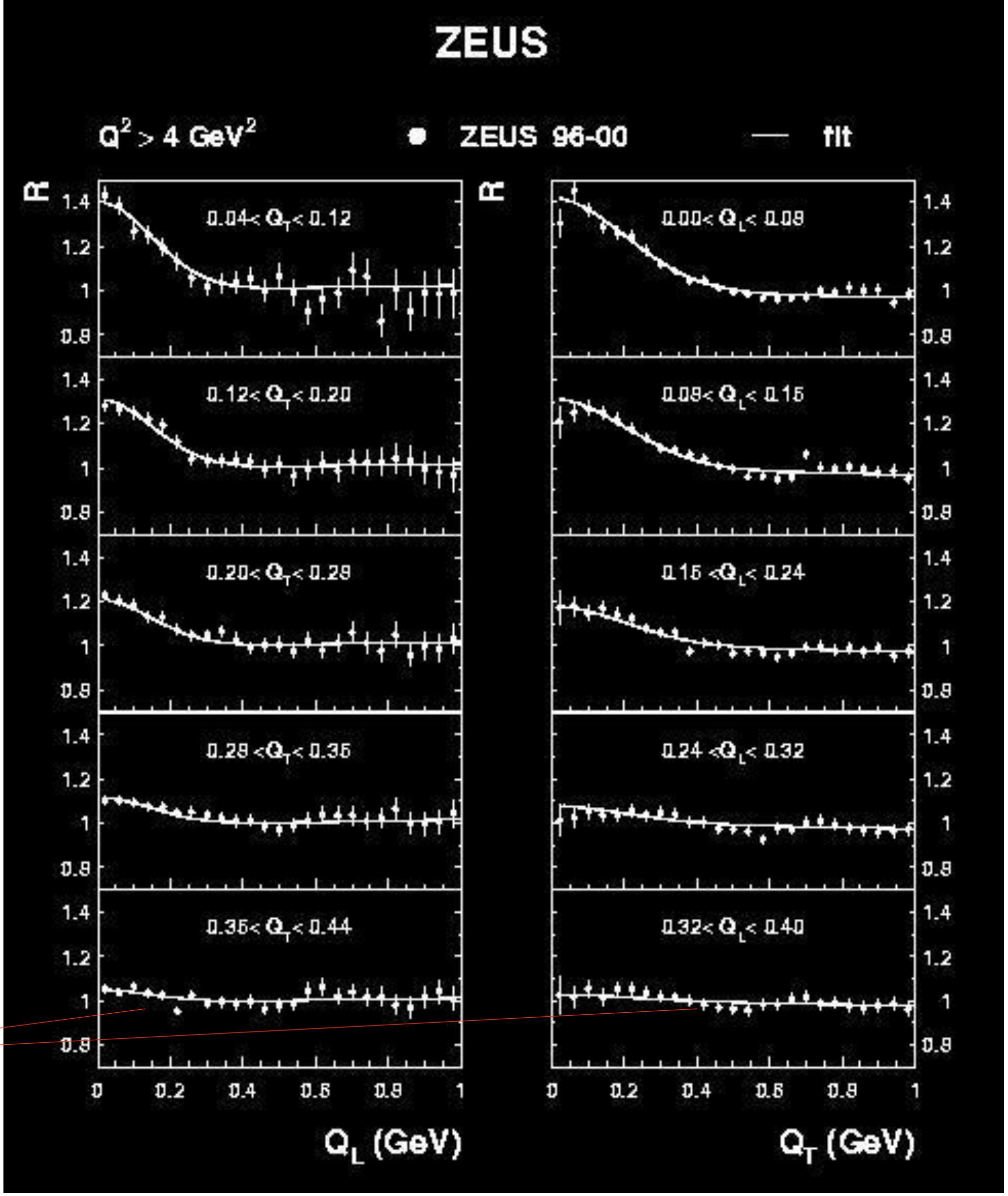
BEC - 2 D

An example :



Two - dimensional correlation function
$R(Q_L,Q_T)$ calculated in LCMS
in analogy to 1 D analysis

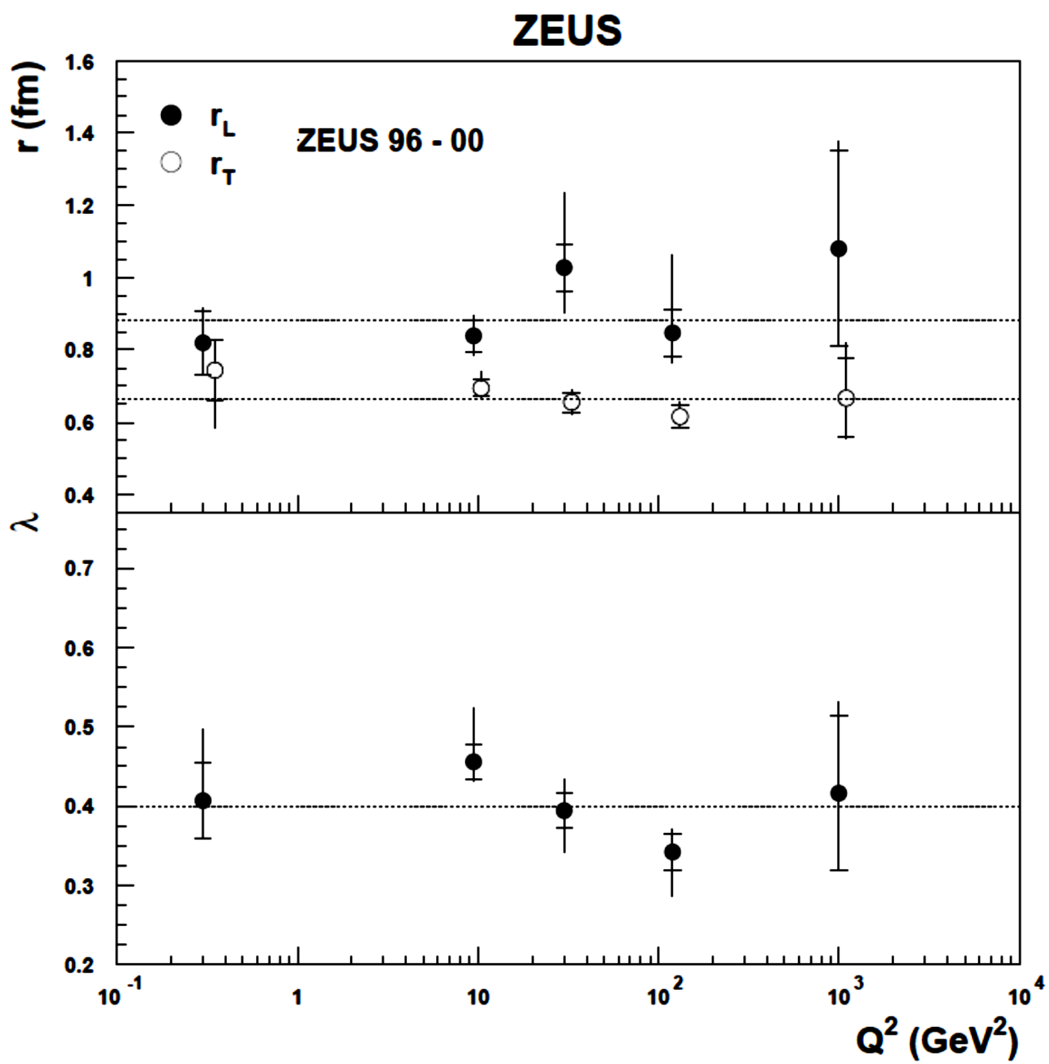
- using two-dimensional
Gaussian parametrisation



Projections :
slices in Q_L and Q_T

χ^2/ndf ≈ 1

ZEUS BEC - 2 D charged particles



The pion-emitted region, as observed in the LCMS, is elongated with r_L being larger than r_T

It was reported also by LEP (3D) experiments: DELPHI, L3, OPAL

The results confirm the string model predictions: the transverse correlations length showed be smaller than the longitudinal one

Q^2 (GeV^2)	λ	r_L (fm)	r_T (fm)	r_T/r_L
4 - 8000	$0.44 \pm 0.01^{+0.01}_{-0.03}$	$0.95 \pm 0.03^{+0.03}_{-0.08}$	$0.69 \pm 0.01^{+0.01}_{-0.06}$	$0.72 \pm 0.03^{+0.04}_{-0.03}$
100 - 8000	$0.32 \pm 0.03^{+0.02}_{-0.01}$	$0.88 \pm 0.08^{+0.03}_{-0.06}$	$0.62 \pm 0.04^{+0.05}_{-0.01}$	$0.70 \pm 0.08^{+0.06}_{-0.01}$
0.1 - 1	$0.41 \pm 0.05^{+0.08}_{-0.00}$	$0.82 \pm 0.09^{+0.03}_{-0.02}$	$0.74 \pm 0.08^{+0.01}_{-0.13}$	$0.91 \pm 0.14^{+0.03}_{-0.18}$
4 - 16	$0.46 \pm 0.02^{+0.06}_{-0.01}$	$0.84 \pm 0.04^{+0.04}_{-0.03}$	$0.69 \pm 0.02^{+0.04}_{-0.02}$	$0.83 \pm 0.05^{+0.03}_{-0.00}$
16 - 64	$0.39 \pm 0.02^{+0.03}_{-0.05}$	$1.03 \pm 0.07^{+0.20}_{-0.11}$	$0.66 \pm 0.03^{+0.02}_{-0.02}$	$0.64 \pm 0.05^{+0.07}_{-0.10}$
64 - 400	$0.34 \pm 0.02^{+0.02}_{-0.05}$	$0.85 \pm 0.07^{+0.21}_{-0.05}$	$0.62 \pm 0.03^{+0.03}_{-0.00}$	$0.73 \pm 0.07^{+0.06}_{-0.16}$
400 - 8000	$0.42 \pm 0.10^{+0.06}_{-0.01}$	$1.08 \pm 0.27^{+0.12}_{-0.00}$	$0.67 \pm 0.11^{+0.11}_{-0.03}$	$0.62 \pm 0.18^{+0.07}_{-0.05}$

No significant dependence of the elongation on Q^2

Results - 2 D : DIS and e^+e^- annihilation

Can we compare DIS results (i.e. r_T / r_L) with e^+e^- ?

In e^+e^- studies, 3D analysis and different reference samples are often used, but for OPAL and DELPHI experiments (**at LEP1**, Z^0 hadronic decay) - analysis is partially similar to ZEUS:
OPAL (Eur. Phys. J, C16, 2000, 423) - 2 D Goldhaber like fit to correlation function in (Q_T,Q_L) variables, unlike-charge reference sample,
DELPHI (Phys. Lett. B471, 2000, 460) - 2 D analysis in (Q_T,Q_L), but mixed -events as reference sample.

We try to compare them with DIS results for high Q^2 : $400 < Q^2 < 8000$ GeV^2

ZEUS: $r_T / r_L = 0.62 \pm 0.18$ (stat) +/- 0.07/0.06 (sys.)

OPAL: $r_T / r_L = 0.735 \pm 0.014$ (stat.) (estimated from reported ratio r_L/r_T)

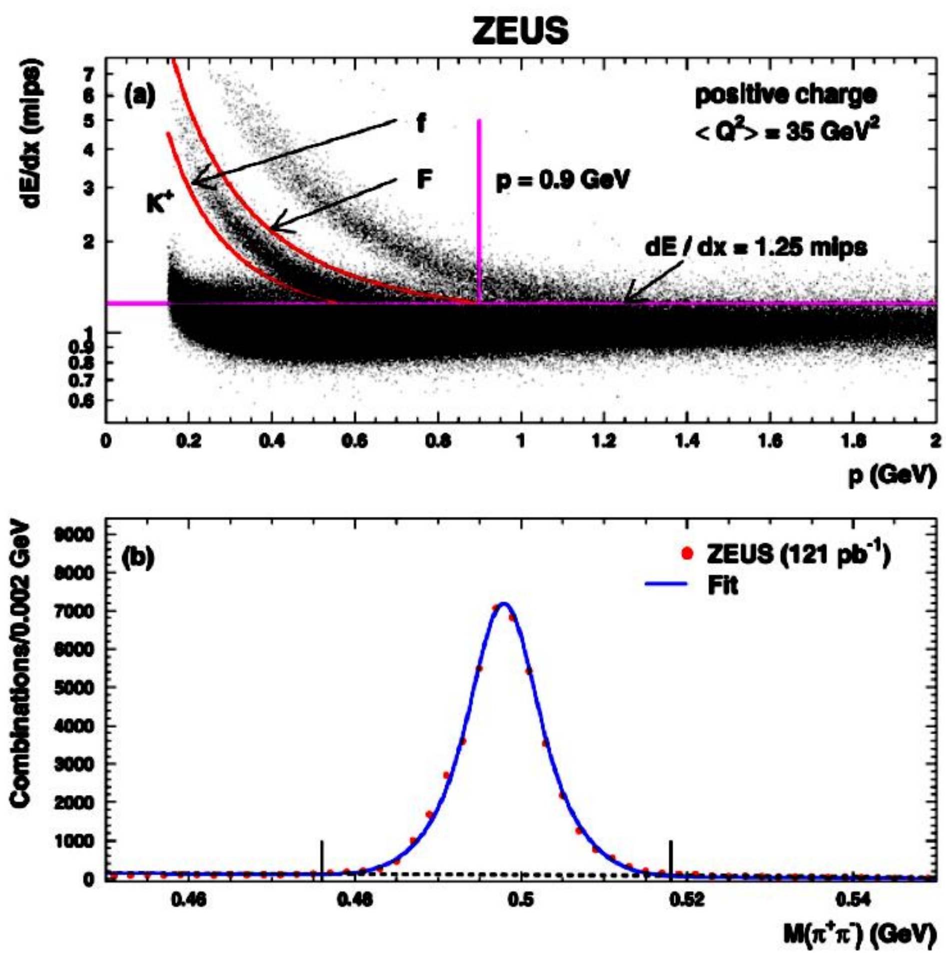
DELPHI : $r_T / r_L = 0.62 \pm 0.02$ (stat) $\pm$ 0.05 (sys.)

DIS results compatible with e^+e^-

ZEUS 1D -charged and neutral kaons

DIS events, 1996 – 2000, $\sqrt{s}$ = 300 /330 GeV, IL = 121 pb^{-1}, $2 < Q^2 < 15\,000\ GeV^2$

An example for positive charge



dE/dx vs track momentum , p

f, F - functions of p , motivated by Bethe-Bloch equation.

K^+

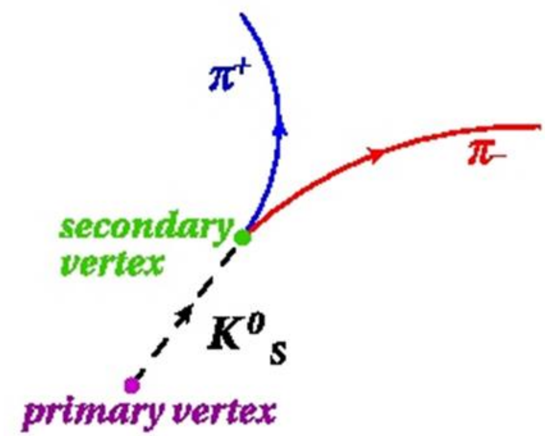
$f = 0.008/p^2 + 1.0$

$F = 0.17/p^2 + 1.03$ (mips, GeV)

K^-

$f = 0.008/p^2 + 1.0$

$F = 0.18/p^2 + 1.03$ (mips, GeV0



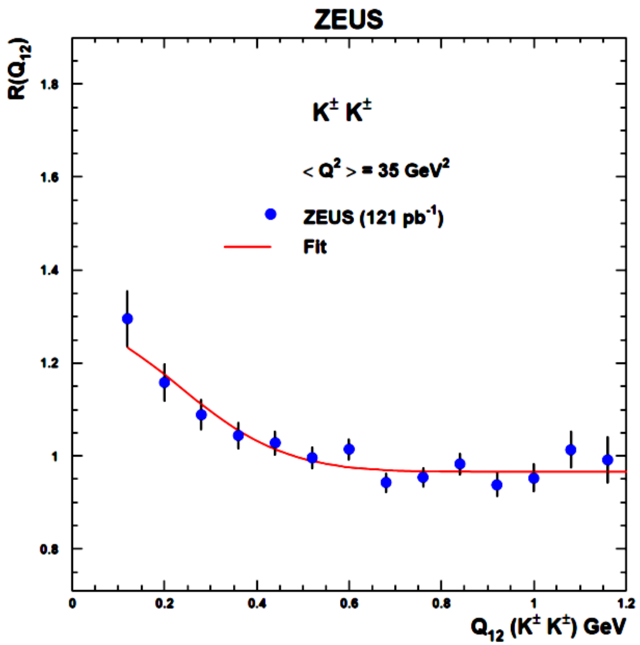
ZEUS 1D - charged and neutral kaons

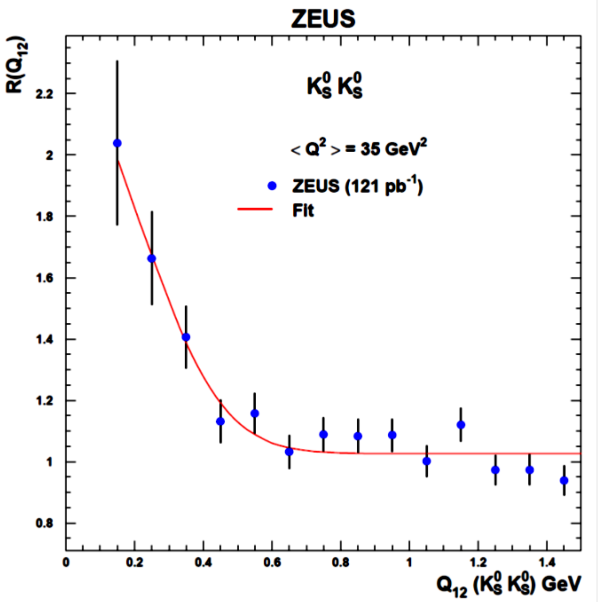
The correlation function used in analysis :

$$R(Q_{12}) = \frac{P(Q_{12})^{\text{data}}}{P_{\text{mix}}(Q_{12})^{\text{data}}} \Bigg/ \frac{P(Q_{12})^{\text{MC,noBEC}}}{P_{\text{mix}}(Q_{12})^{\text{MC,noBEC}}}$$

$$Q_{12} = \sqrt{-(\mathrm{p}_1 - \mathrm{p}_2)^2} = \sqrt{M_{KK}^2 - 4m_K^2}$$

Gaussian parametrisation: $R(Q_{12}) = \alpha(1 + \lambda e^{-Q_{12}^2 r^2})(1 + \beta Q_{12})$

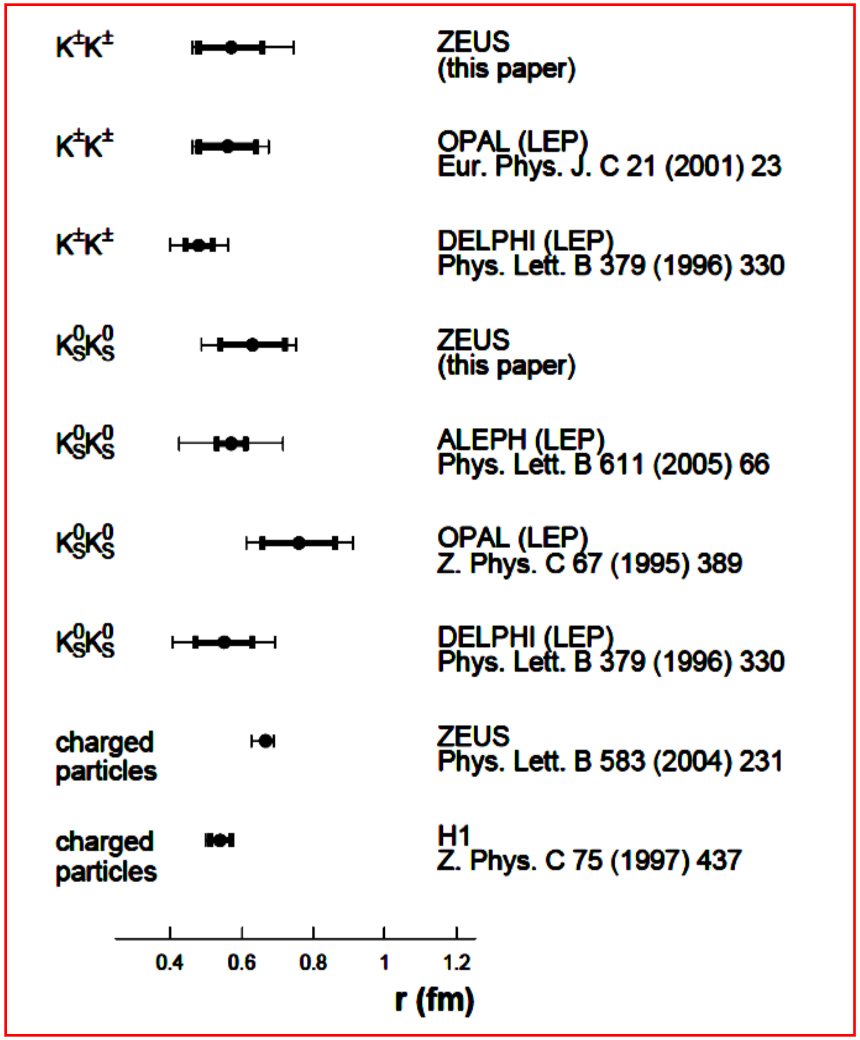


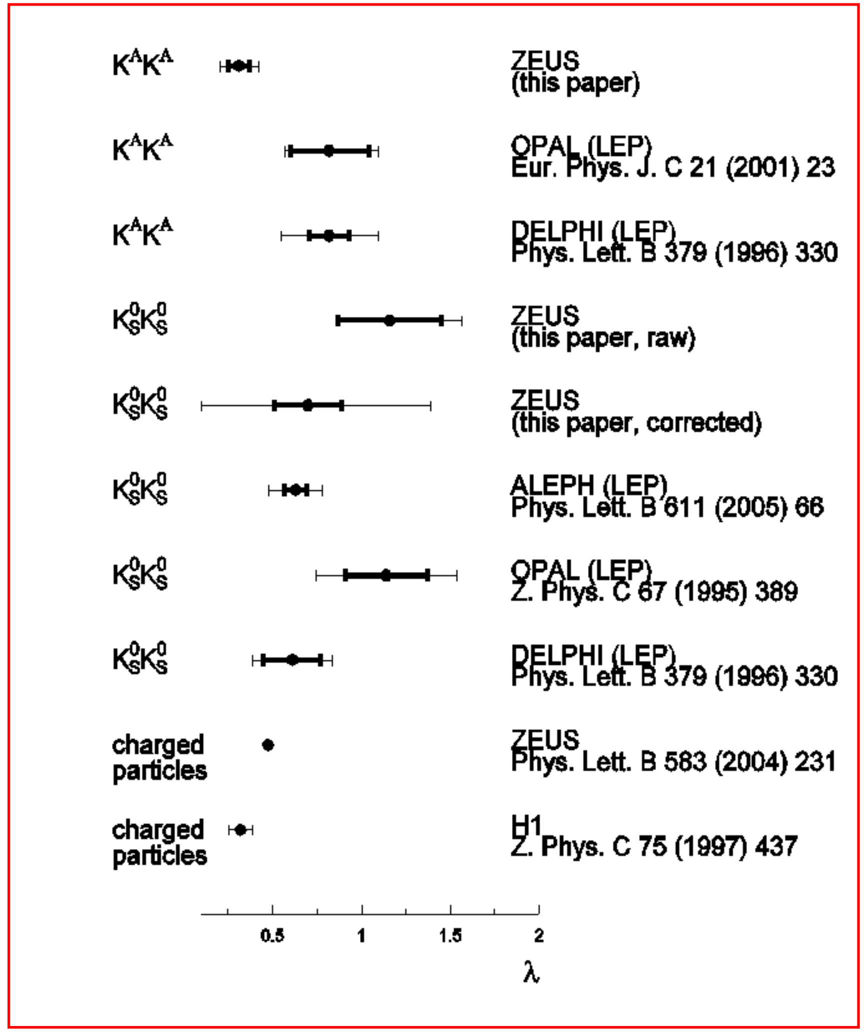


Results of analysis:

	λ	r [fm]
$K^{\pm}K^{\pm}$ (corrected)	$0.37 \pm 0.07\ ^{+0.09}_{-0.08}$	$0.57 \pm 0.09\ ^{+0.15}_{-0.08}$
$K^0_S K^0_S$ (raw)	$1.16 \pm 0.29\ ^{+0.28}_{-0.08}$	$0.61 \pm 0.08\ ^{+0.07}_{-0.08}$
$K^0_S K^0_S$ (corrected)	$0.70 \pm 0.19\ ^{+0.28+0.38}_{-0.08-0.52}$	$0.63 \pm 0.09\ ^{+0.07+0.09}_{-0.08-0.02}$

H1 + ZEUS + LEP





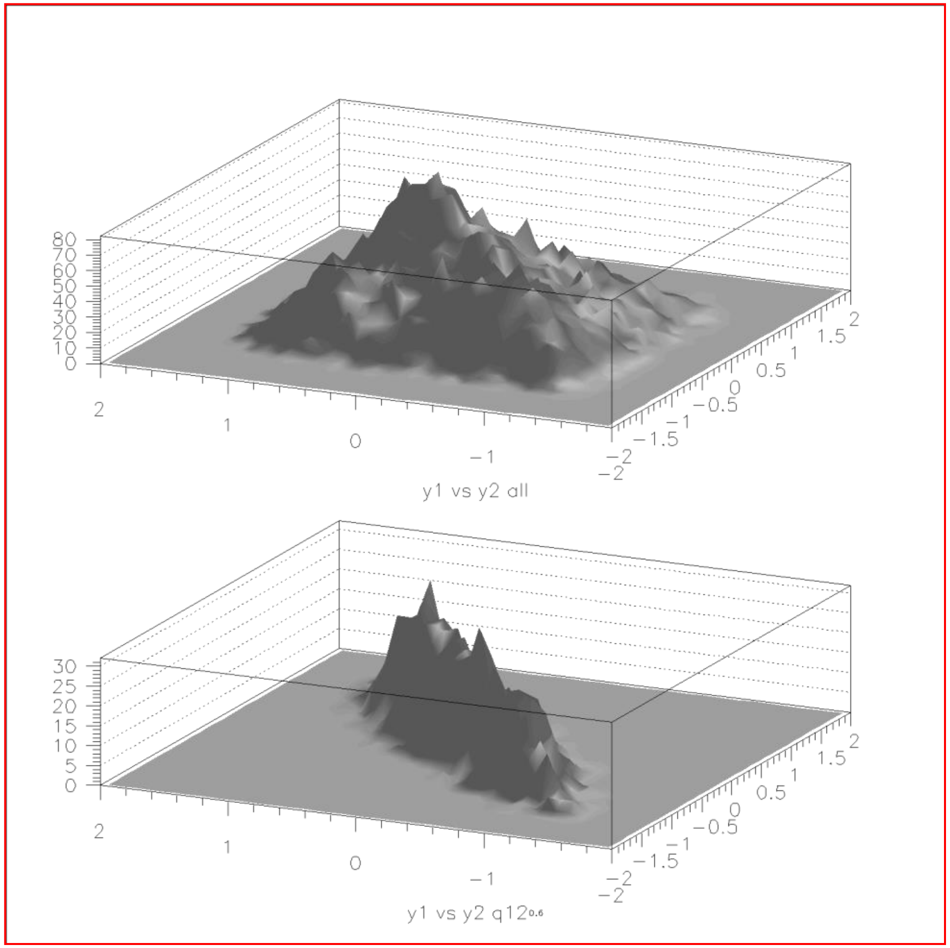
DIS results agree within the statistical and systematic uncertainties with measurements from LEP

Other studies

$K^0_S\, K^0_S$: rapidity correlations

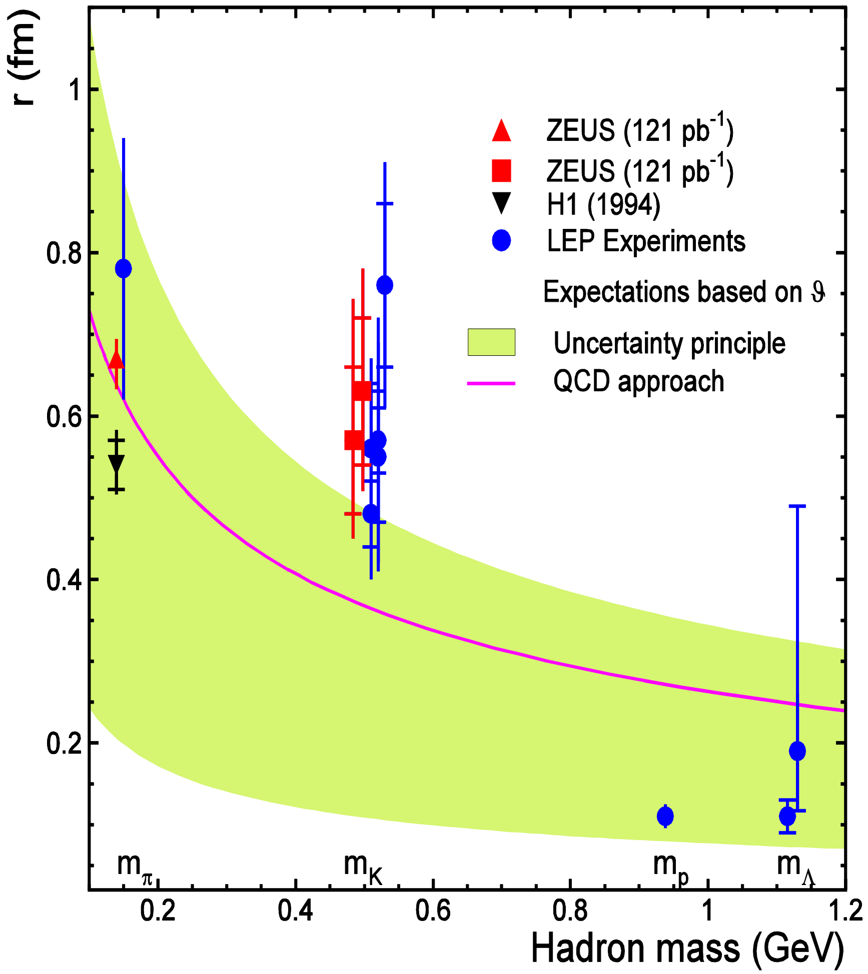
No cut for Q_{12} for kaons pairs

Cut for Q_{12} where BE effect was observed



A significant amount of short range correlations may come from BE effect

Dependence of BEC radius on hadron mass



Experimental indication:

$r(m_\pi) > r(m_K) > r(m_p) > r(m_\Lambda)$

Theory:

- LUND model does not predict such dependence of r(m)

however

- Heisenberg uncertainty relations and QCD via virial theorem can describe such mass dependence

But the situation is not so clear:
r values for pions and kaons are not so different and the large effect comes from heavier particles.

There are no HERA results for pp and $\Lambda\Lambda$ correlations due to the limited range of proton momentum available for measurements and low statistics for Λ particles.

But one can expect interesting results for FD correlations for these particles from future ILC / CLIC or FCC accelerator.

Conclusions

- The results on the Bose-Einstein correlations received by H1 and ZEUS experiments working at HERA constitute a significant contribution and deepen the knowledge of this effect

- An interesting fact is the high compatibility of the obtained values of the radius of the hadron production volume, r, between experiments where BE effect have been measured for different types of particle interactions: ep, e^+e^- , pp.

  Can it be associated with the universatility of the hadronisation phase of these interactions?

- It is expected that further theoretical and experimental efforts will allow for discovery the new aspects of BE effect