Particle production and correlations at HERA

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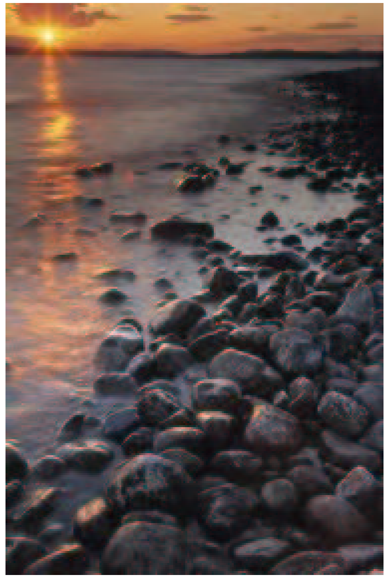
On behalf of the H1 and ZEUS collaborations

- Introduction;
- Event shapes as a test of pQCD and hadronisation;
- Inclusive cross sections of identified mesons; Universal law?
- Bose-Einstein effect - universal final-state interaction?
- Summary.



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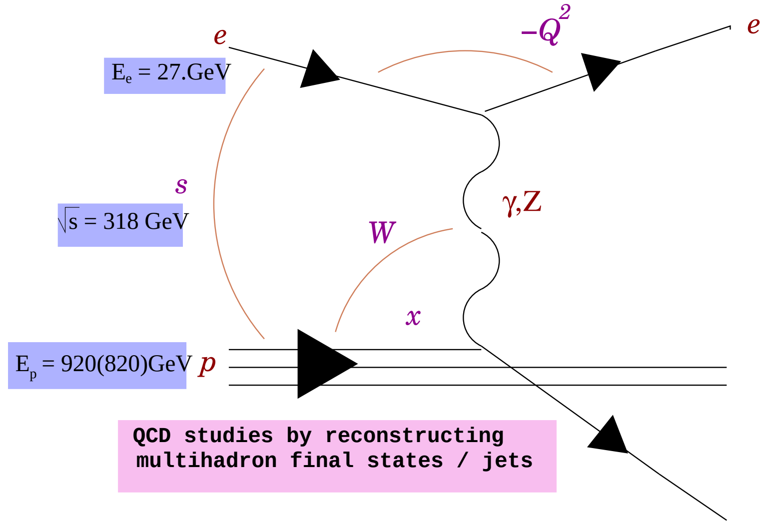
Introduction

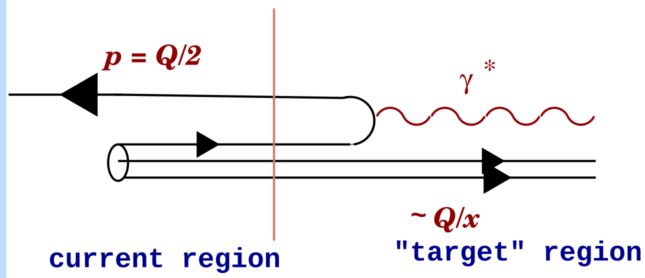
The HERA collider provides a unique laboratory for the study of the hadronic final states:

- QCD tests over a large range of Q^2;
- observation of the hadronisation processes due to the precise reconstruction of charged particles by central tracking detector.



Breit frame:

- virtual boson collides head–on with quark from proton;
- the separation between the current jet and the proton remnant is maximal;
- similar to 1/2 e^+e^- event.



Event shapes

Topology of the event described by event shape variables (Breit frame):

- thrust,

$$T = \frac{\sum_i |\boldsymbol{p}_i \cdot \boldsymbol{n}|}{\sum_i \boldsymbol{p}_i}$$

- jet broadening,

$$B = \frac{\sum_i |\boldsymbol{p}_i \times \boldsymbol{n}|}{\sum_i \boldsymbol{p}_i}$$

$\boldsymbol{n}$ along: ▶ γ^*,▶ thrust axis.

- the invariant jet mass,

$$M^2 = \frac{(\sum_i |p_i^{\mu}|)^2}{(2\sum_i E_i)^2}$$

- the C–parameter.

$$C = \frac{3\sum_{ij} |\boldsymbol{p}_i||\boldsymbol{p}_j| sin^2\theta_{ij}}{\sum_i \boldsymbol{p}_i}$$

Variables defined at the parton level and calculated using pQCD:

- NLO (DISASTER++),
- resummed NLL calculations matched to NLO (DISRESUM).

The non–perturbative effects due to hadronisation taken into account with power corrections proportional to $1/Q$ (Dokshitzer et al.).

Event shapes

- the average of event shape variable :
  $< F > = < F >_{pQCD} + < F >_{pow}$
- the differential distribution:

$$\frac{1}{\sigma_{tot}} \frac{d\sigma(F)}{dF} = \frac{1}{\sigma_{tot}} \frac{d\sigma^{pQCD}(F - < F >_{pow})}{dF}$$

$< F >_{pQCD}$ – contribution from pQCD calculations,
$< F >_{pow}$ – power correction term.

- parameter $\bar{\alpha}_0$ to describe non–perturbative effects:

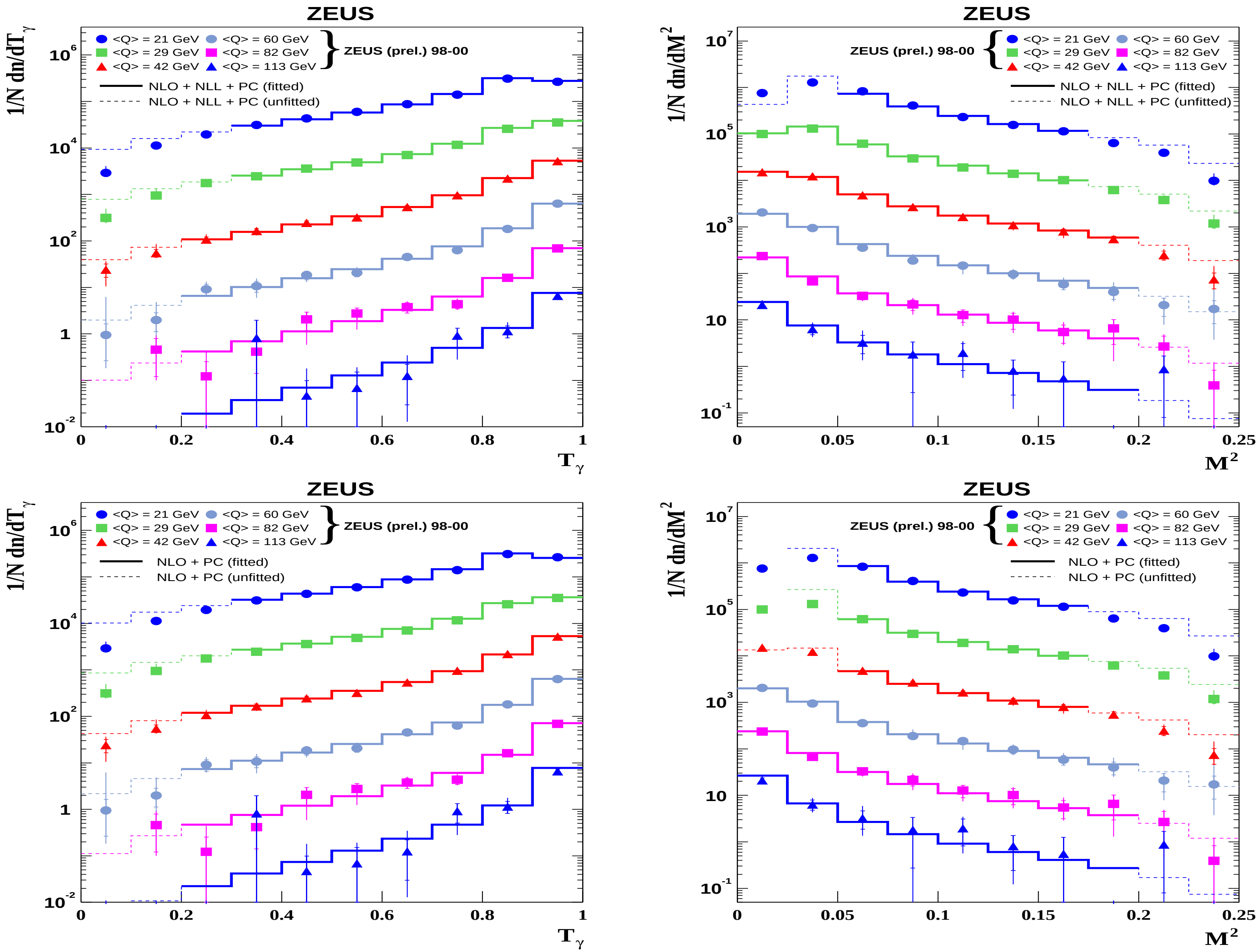
$$\bar{\alpha}_0 = \frac{1}{\mu_I} \int_0^{\mu_I} \alpha_{eff}(\mu_R) d\mu_R$$

$$< F >_{pow} \propto \frac{1}{Q} \left[\bar{\alpha}_0 - \alpha_S(\mu_R) - \frac{\beta_0}{2\pi} \left(ln \left(\frac{\mu_R}{\mu_I} \right) + \frac{K}{\beta_0} + 1 \right) \alpha_S(\mu_R) \right]$$

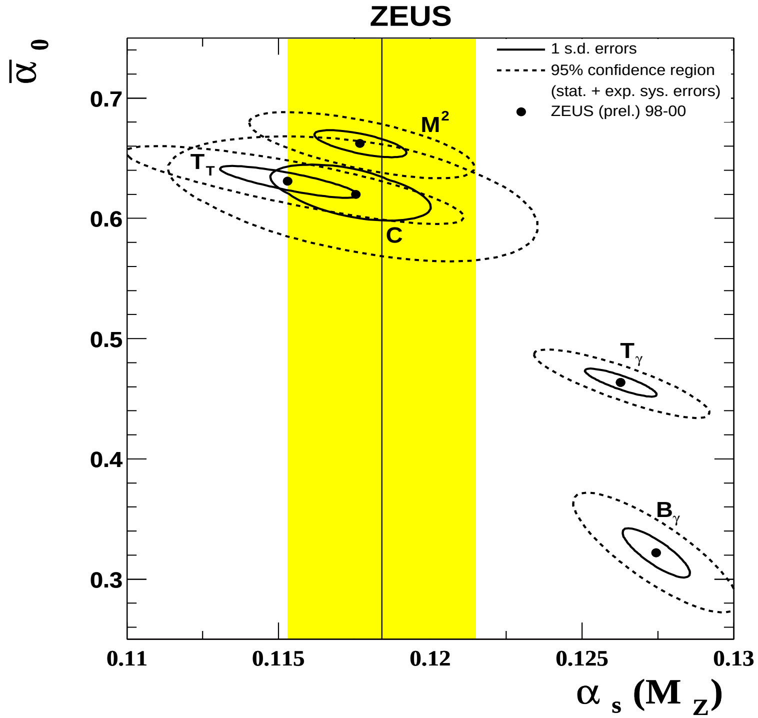
- two free parameters: $\alpha_S(M_Z)$ and $\bar{\alpha}_0$
- **QCD doesn't fit well all the range of the differential distributions. Only certain regions are well fitted, the regions used to extract $\alpha_S(M_Z)$ and $\bar{\alpha}_0$ are shown as solid lines in the figures (next page).**

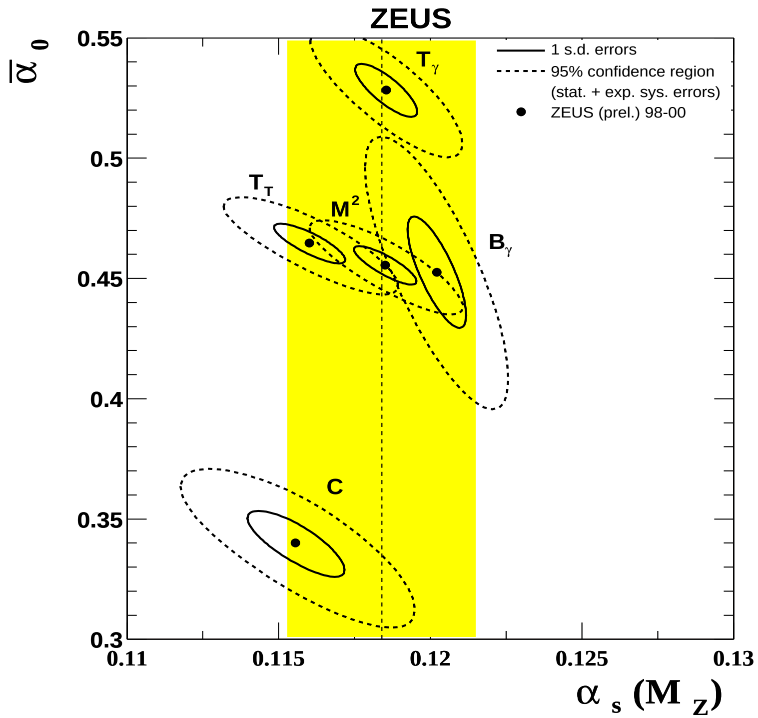
Event shapes – results

$10 < Q^2 < 20480 GeV^2$, $6 \times 10^{-4} < x < 0.6$,
$0.04 < y < 0.95$



Event shapes – results





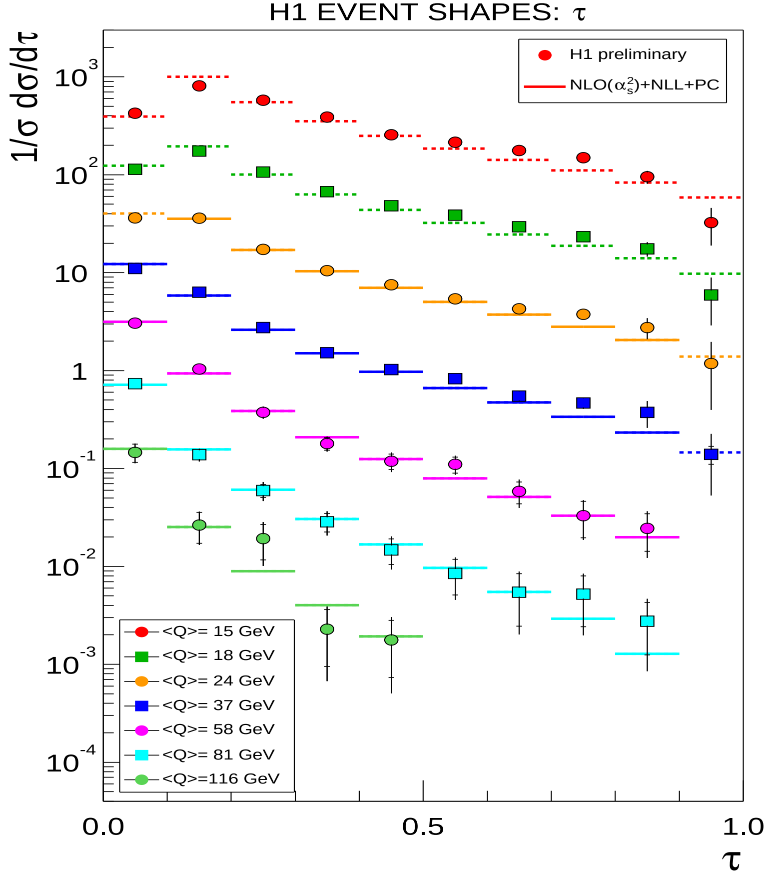
NLO:

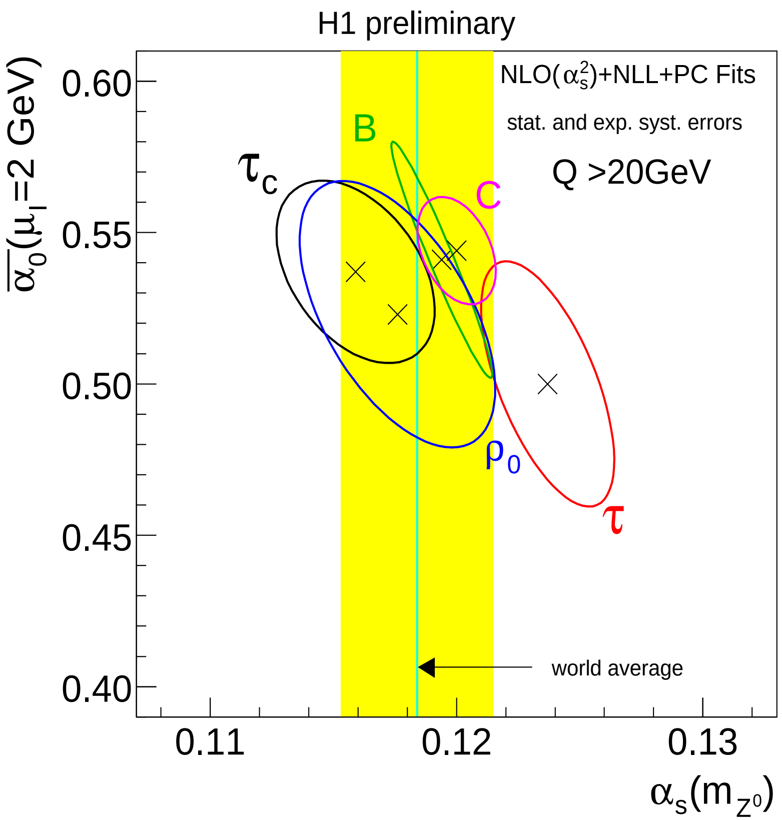
- Range usable for fit increases with Q^2;
- all variables fitted with reasonable χ^2.
- Photon axis variables fit with high α_S
- but other variables consistent in α_S and $\bar{\alpha}_0$

NLO+NLL:

- Increase of usable range;
- χ^2 reasonable except for C.
- Results consistent with $\alpha_S = 0.118$ and suggest $\bar{\alpha}_0 \approx 0.5$.
- Dominant theory errors are renormalisation scale and factor in log terms.

Event shapes – results



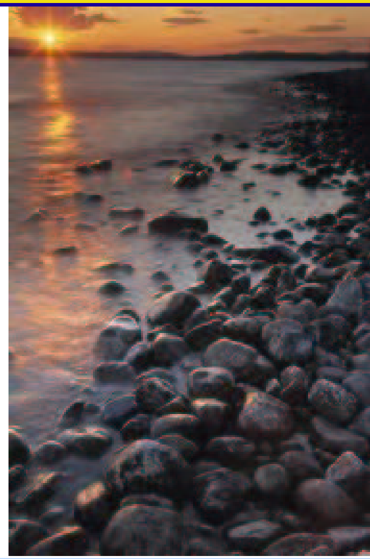


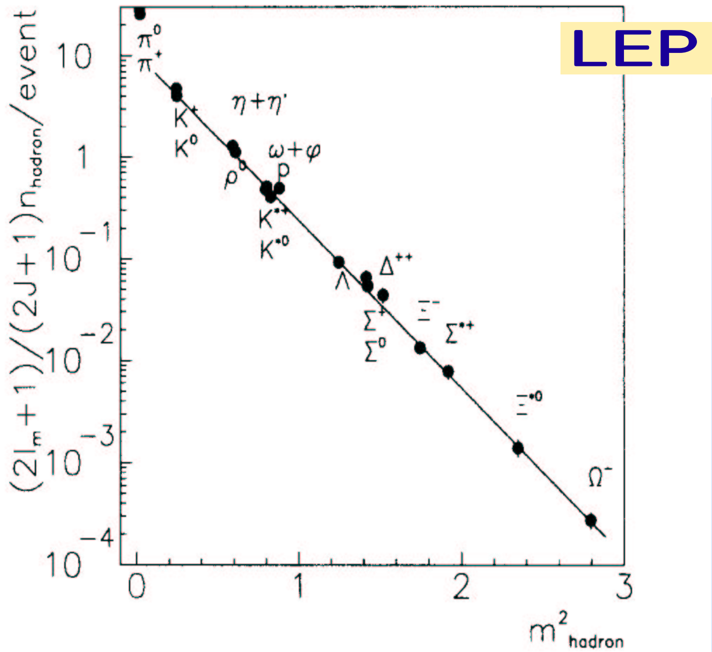
H1 and ZEUS results are compatible.

$$\tau = 1 - T_\gamma$$

Inclusive cross sections of identified mesons

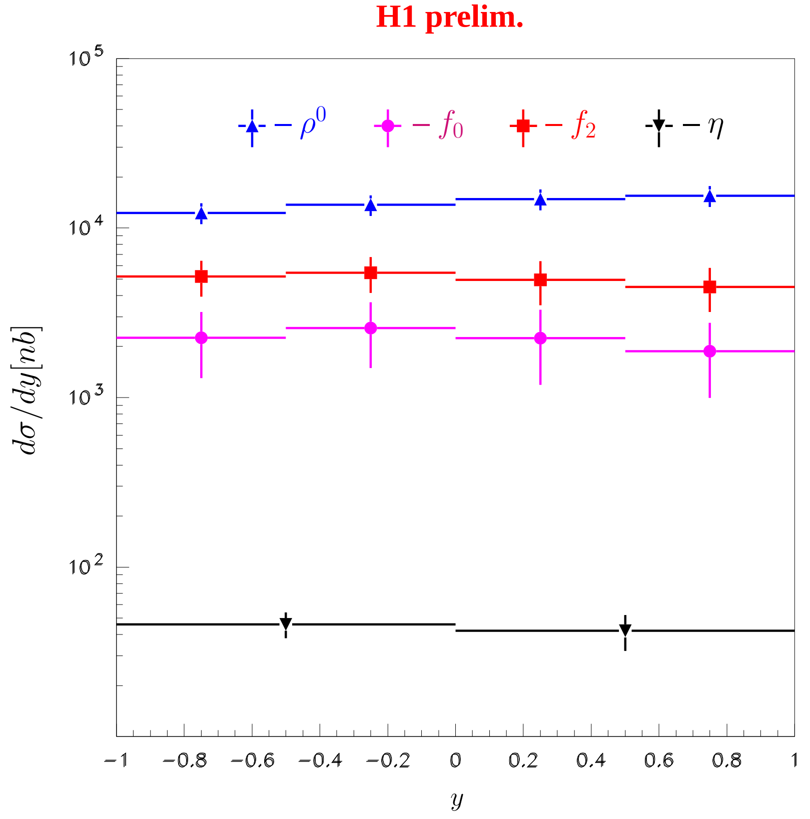
- One of the least understood areas of non–perturbative QCD – the physics of the hadronisation phase;
- search for the universal features in the properties of the final hadronic systems in ep, e^+e^- and hadron scattering.

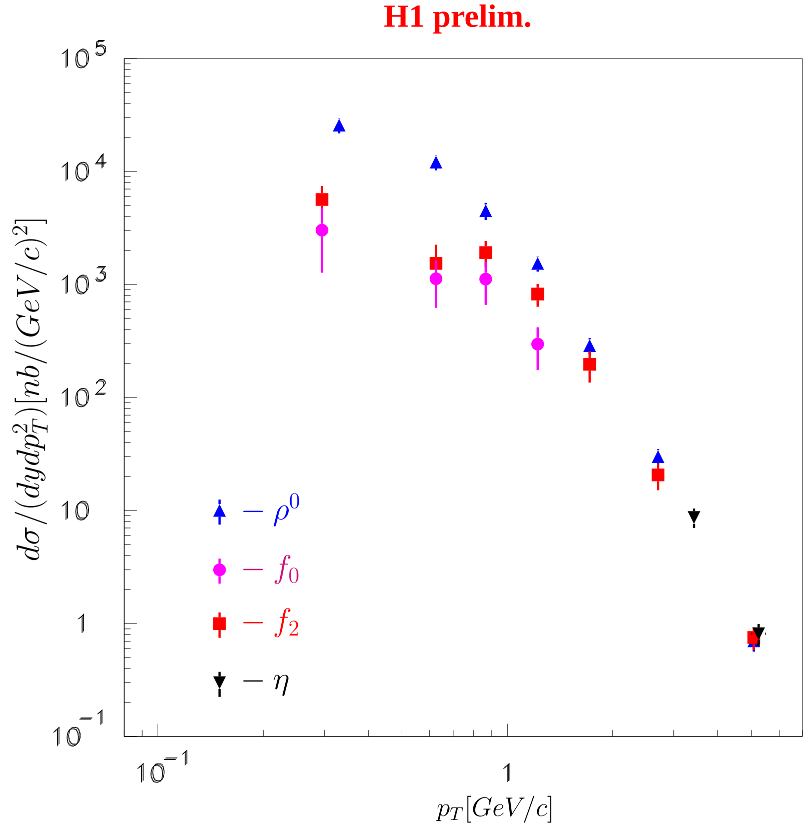




- Measurements of the inclusive photoproduction of charged particles, long lived hadrons like K_s^0 mesons, Λ^0 baryons and charmed mesons at HERA display interesting regularities.
- Latest H1 study – the inclusive photoproduction of neutral hadronic resonances at W = 210 GeV.

Inclusive cross sections of identified mesons

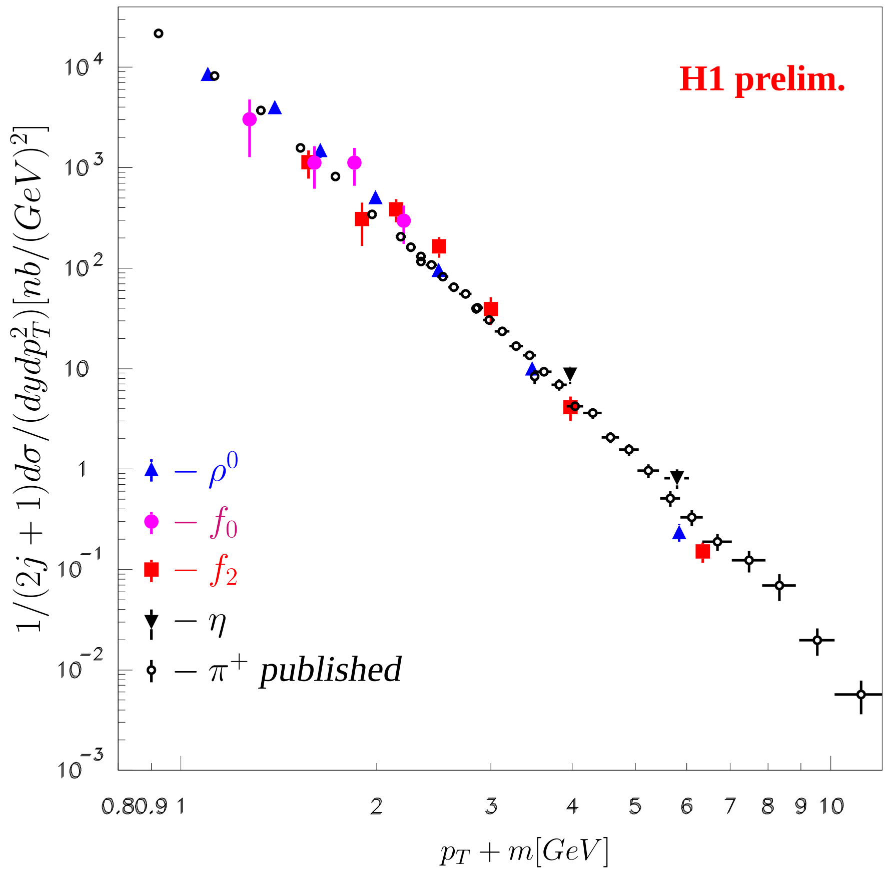




Within the measured rapidity interval the resonance production rates are flat ($|y_{lab}| < 1$).

The transverse momentum spectra follow the power law.

Inclusive cross sections of identified mesons



- All cross sections follow the same power law as a function of $p_\perp + m$
- $(2j+1)$ spin counting factor is needed,
- but the production rates seem to be independent on the internal structure of hadrons.

- This observation supports a thermodynamical picture of particle production
- and a similar production mechanism for light long-lived hadrons, low mass vector mesons and orbitally excited tensor mesons.

Bose–Einstein correlations

Correlation function:

$$R(p_1, p_2) = \frac{\rho(p_1, p_2)}{\rho(p_1)\rho(p_2)} = 1 + \mid f(p_1 - p_2) \mid^2$$

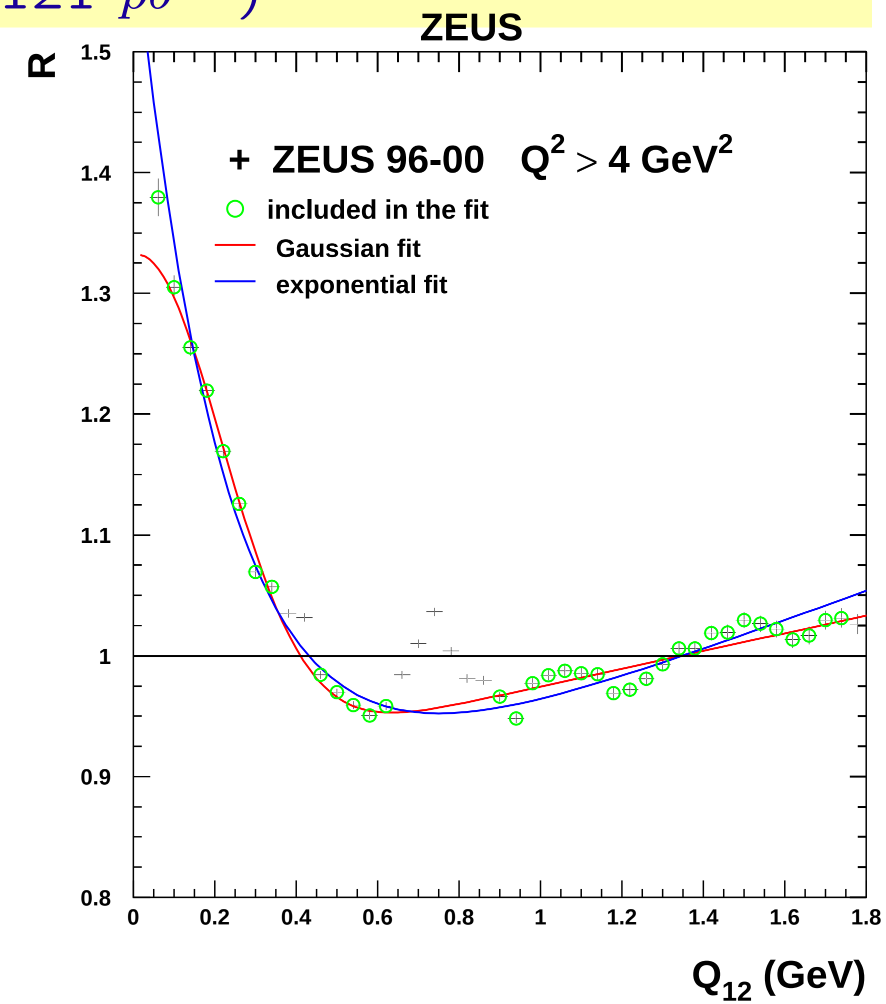
where $f(q)$ is the Fourier transform of the space-time density distribution of the source if emitters are motionless in the rest frame of the source .

p_1, p_2 – four momenta of the two particles
$\rho(p_1, p_2)$ – two particle density distribution function
$\rho(p_1)$, $\rho(p_2)$ – single particle density distribution functions

A tool for the investigation of the space-time structure of particle production processes.
DIS studies of BEC may reveal changes of the size of the source with energy scale – photon virtuality Q^2, and sensitivity of the effect to hard subprocesses.

Bose–Einstein correlations – results

DATA: $0.1 < Q^2 < 8000 GeV^2$, $(121\ pb^{-1})$



Calculate the normalised inclusive two-particle density: $\rho = \frac{1}{N_{ev}} \frac{dn_{pairs}}{Q_{12}}$ for:

- like sign pairs $(\pm, \pm)$
  - BEC present.
- unlike sign pairs (+,-)
  - no BEC,
  - short range correlations mainly due to resonance decays.

$$R = \frac{(\rho(\pm,\pm)/\rho(+,-))_{DATA}}{(\rho(\pm,\pm))/\rho(+,-))_{MC}}$$

$$= \alpha(1 + \beta Q_{12})(1 + \lambda \exp(-r^2 Q_{12}^2))$$

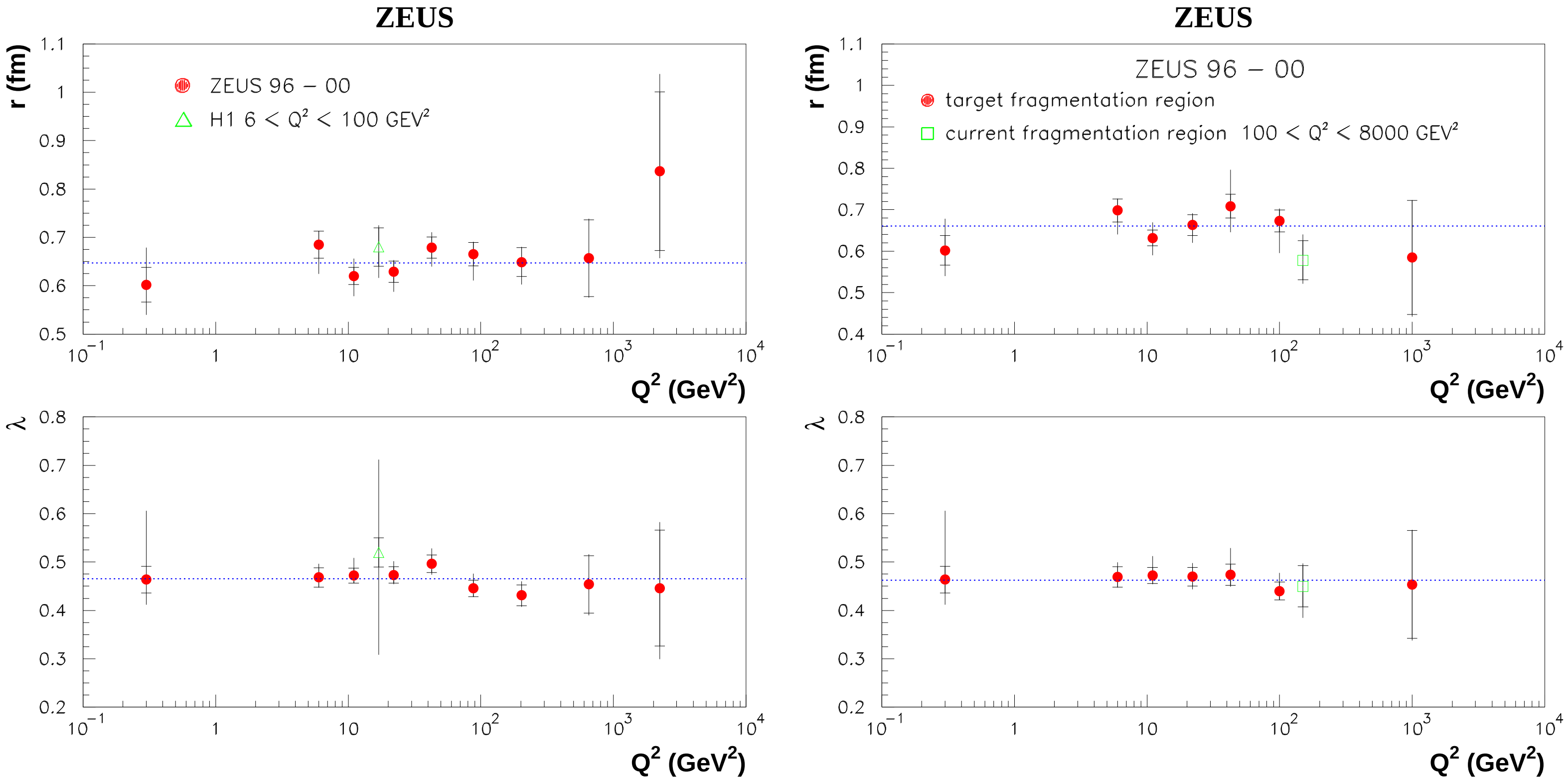
r – the source radius,

λ – the degree of incoherence,

$(1 + \beta Q_{12})$ – background,

α – the normalisation factor.

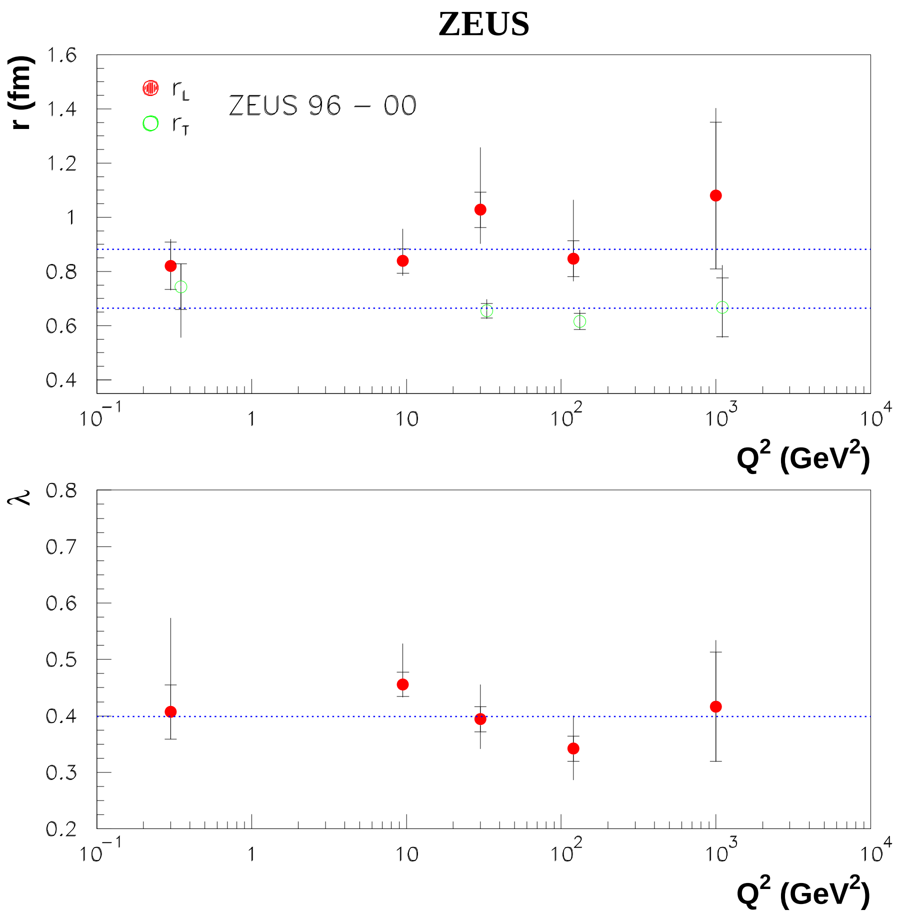
Bose–Einstein correlations – results



No dependence of r and λ on Q^2 in the range $0.1 < Q^2 < 8000 GeV^2$.

No difference between current– and target fragmentation regions.

Bose–Einstein correlations – results



The source is of elongated shape which does not depend on Q^2 .

In 2 dimensions: Longitudinally Co-Moving System (LCMS): each pair of particles is boosted along $\gamma^* p$ axis so that its longitudinal momentum component along the axis is zero.

$\boldsymbol{Q = p_1 - p_2}$

is decomposed into:

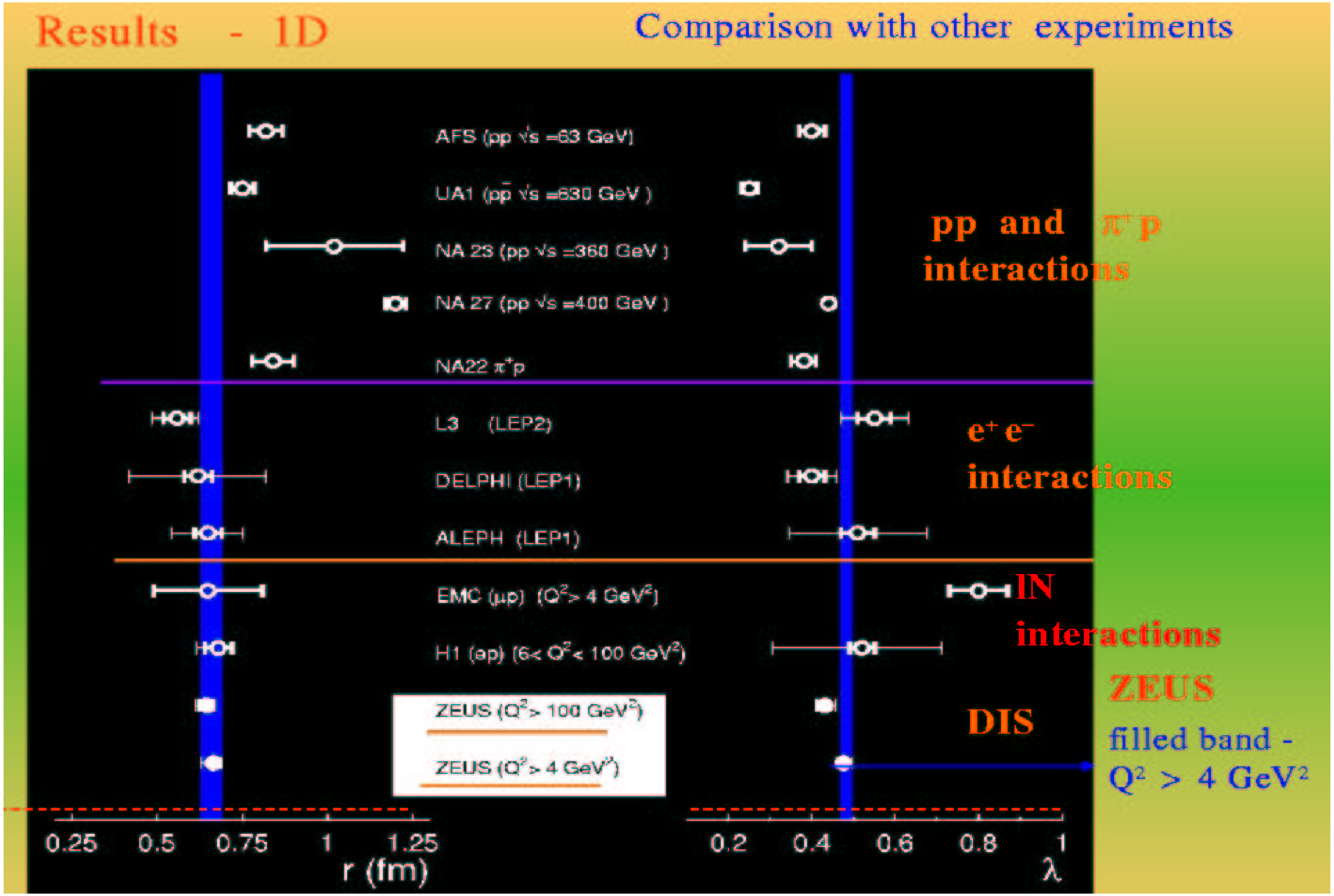
Q_t – transverse and

Q_l – longitudinal component.

$R = \alpha(1 + \beta_t Q_t + \beta_l Q_l)(1 + \lambda \exp(-r_t^2 Q_t^2 - r_l^2 Q_l^2))$

Now r_t – the transverse and r_l – the longitudinal extent of the pion source.

Bose–Einstein correlations – comparison



Summary

- pQCD calculations closer and closer to the data,
- however particle production description in terms of thermodynamical models seems still to be adequate.
- BE effect – universal feature of hadronisation.