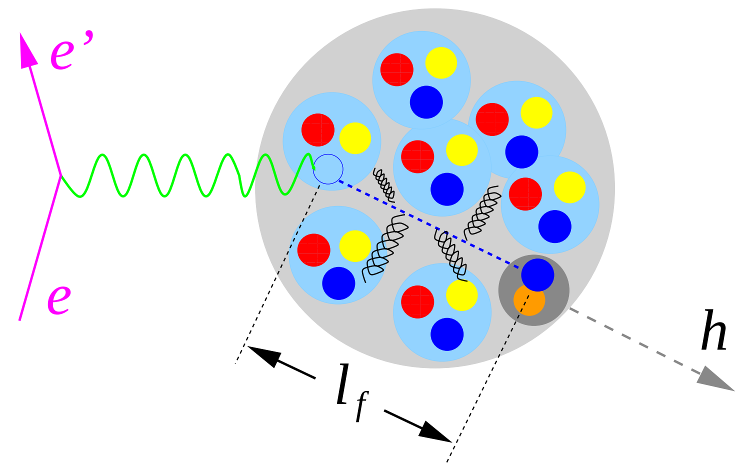
**7th international workshop on High-$p_T$ Physics at LHC, Frankfurt 2012**

# Color Transparency Effect in Deep Inelastic Scattering and at LHC era




- HERMES experiment and its kinematic
- Coherence length effect in exclusive $\rho^0$ electroproduction
- Color transparency effect
- Data on hadron formation and $p_T$-broadening at HERMES
- $R_{AA}$ from ALICE and CMS data
- Summary and Outlook

**Alexander Borissov, Hanay, 27.03.2012**

# Preamble

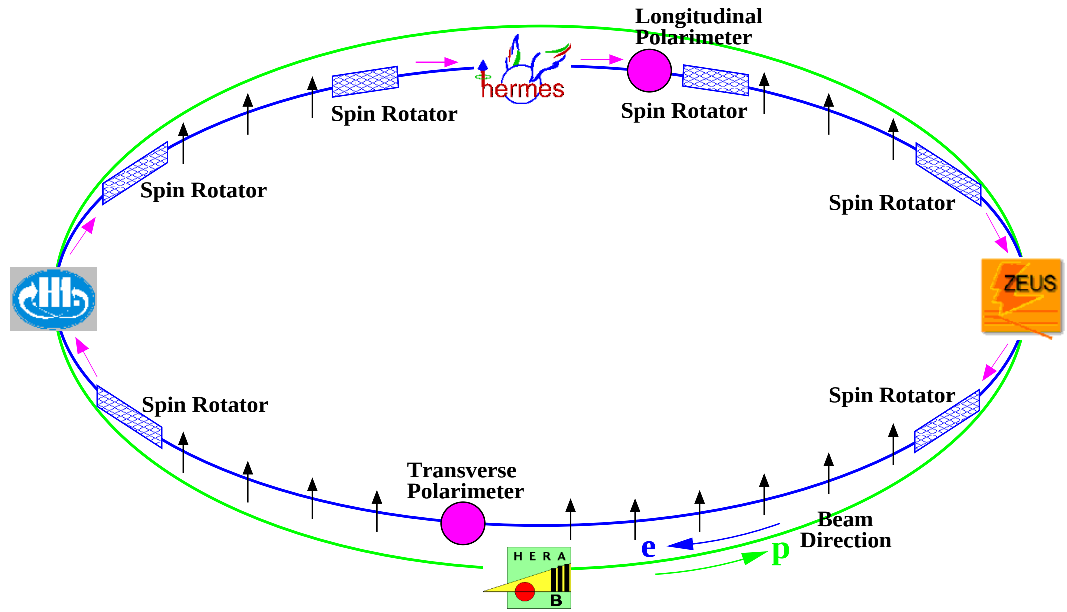
- Recent ALICE and CMS data on $R_{AA}$ of charge hadrons are compared with the calculations from several models.

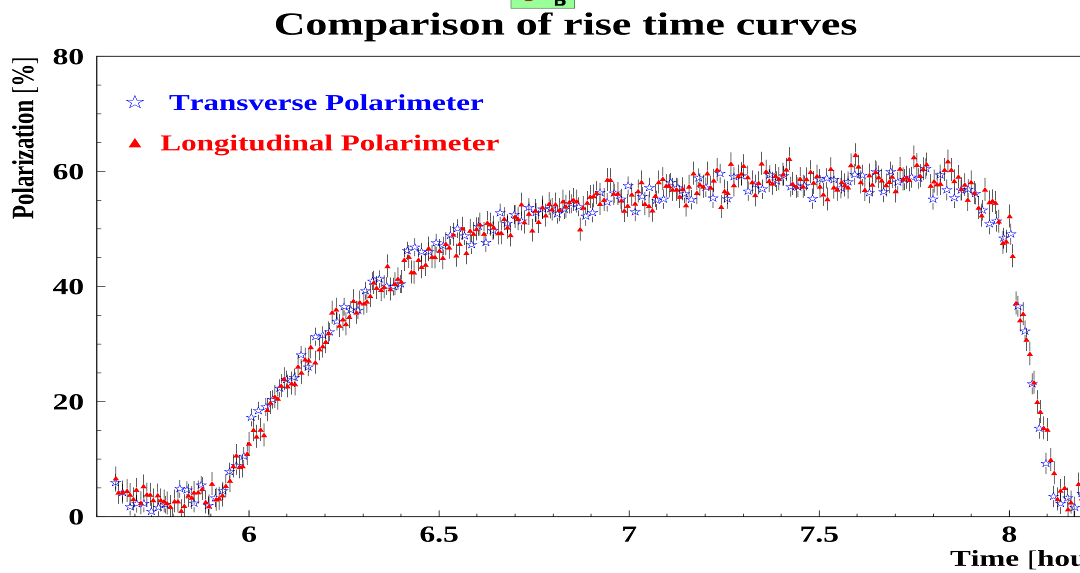
- Paper "Color transparency and suppression of high-$p_T$ hadrons in nuclear collisions" (B.Z.Kopeliovich, I.K.Potashnikova and I.Schmidt, Phys.Rev. C. 83, 021901 (R), 2011) provides one of the model-dependent explanations.

- Described below HERMES data on exclusive $\rho^0$ (coherent length and color transparency effects) and semi-inclusive hadron electroproduction (hadron formation and $p_T$ broadening) have been compared with the calculations and, in a such way, support its applicability.

# Longitudinally Polarized $e^{+(-)}$ Beam at HERA

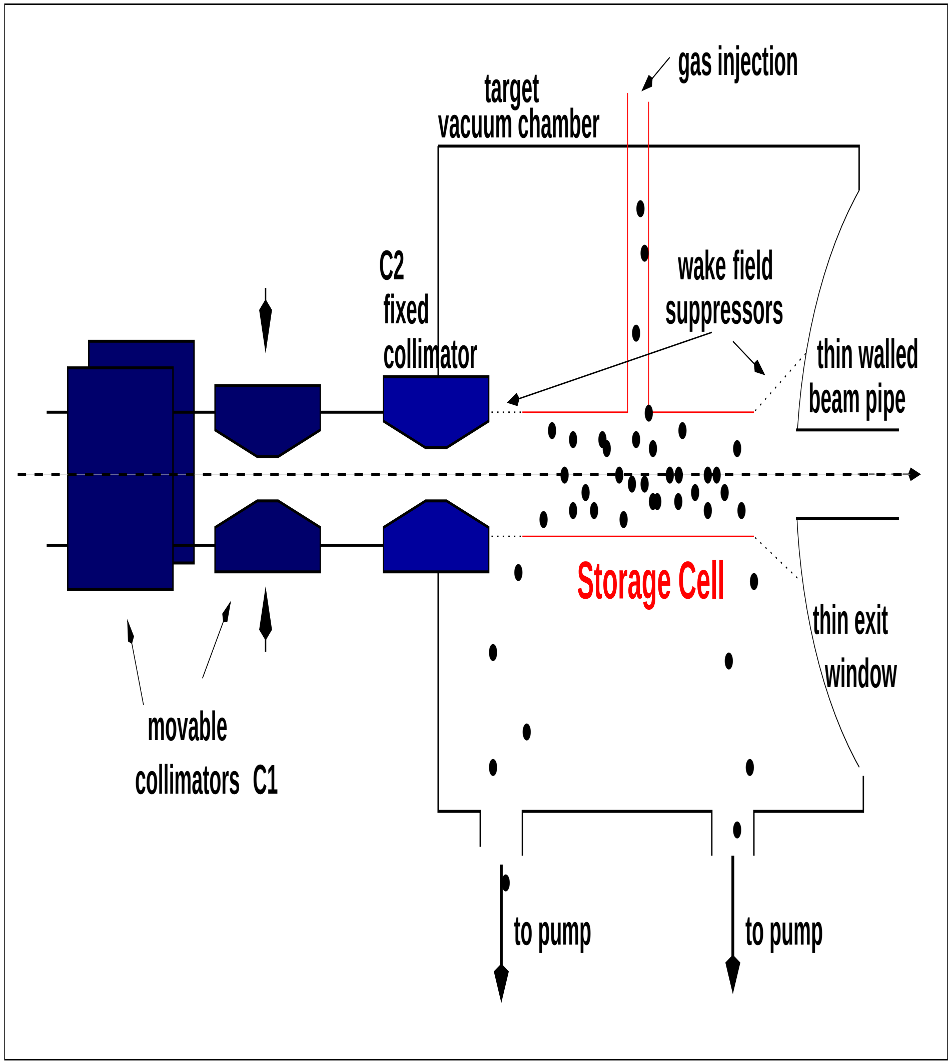
$P = 27.56$ GeV/c, current $50 \ldots 100$ mA, polarization of about $55 \pm 2\%$

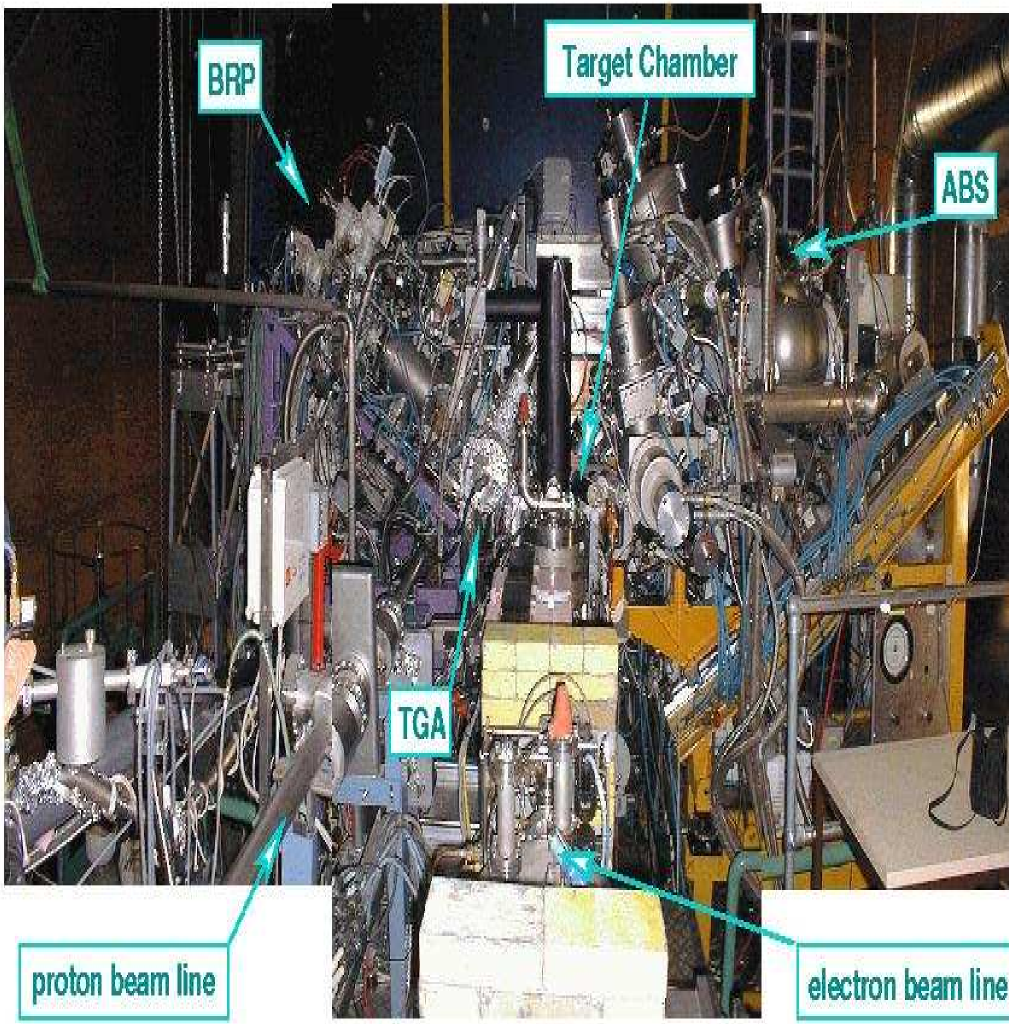



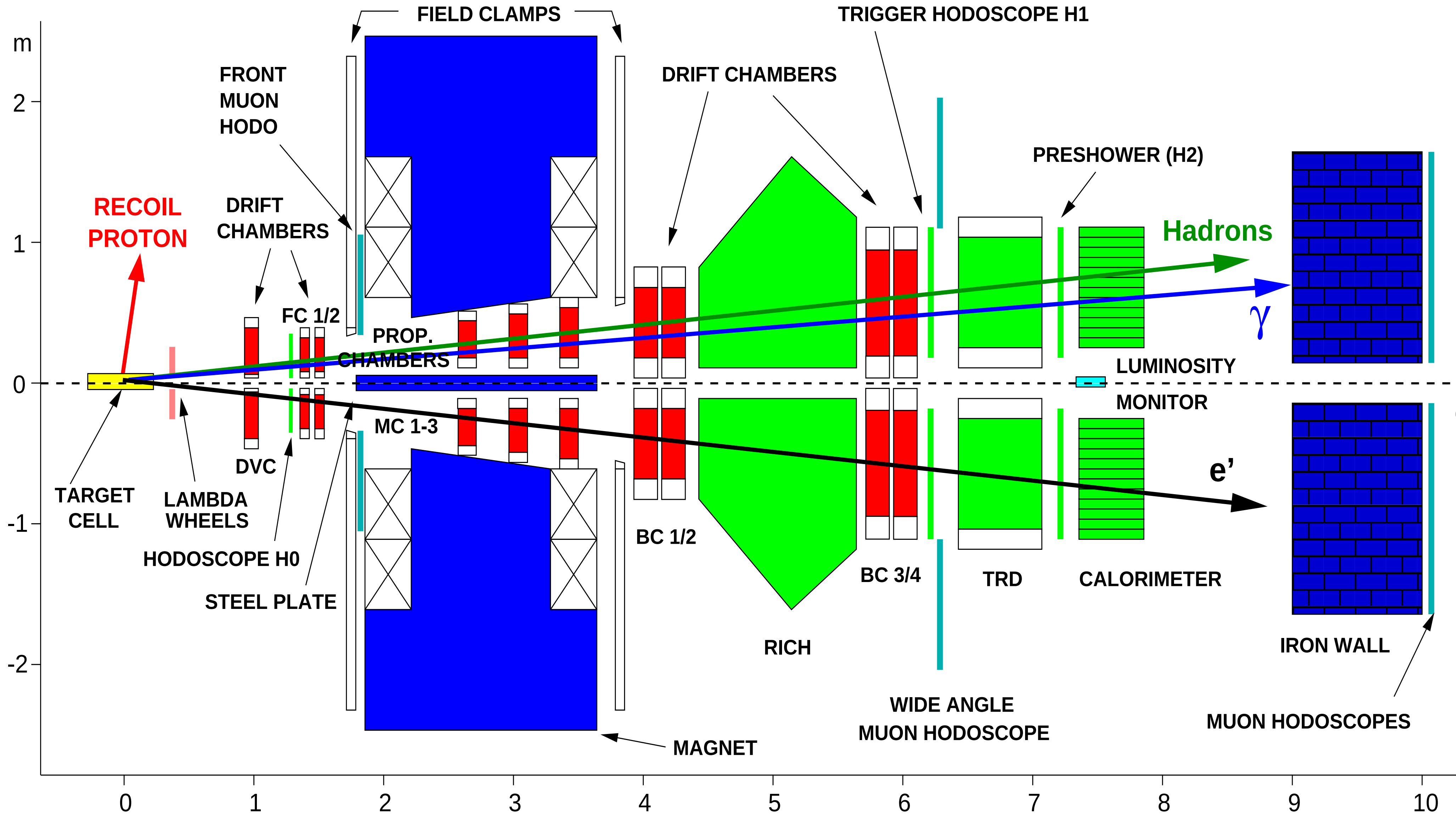
# Internal Storage Cell Gas Target

polarized: $\sim 10^{14}$ nucl/cm$^2$, longitudinal polarization $\sim 88\%$: $^1$H, $^2$H; transverse $\sim 78\%$: $^1$H
unpolarized: $\sim 5 \cdot 10^{15}$ nucl/cm$^2$: $^1$H, $^2$H, $^4$He, $^{14}$N, $^{20}$Ne, $^{84}$Kr, $^{131}$Xe



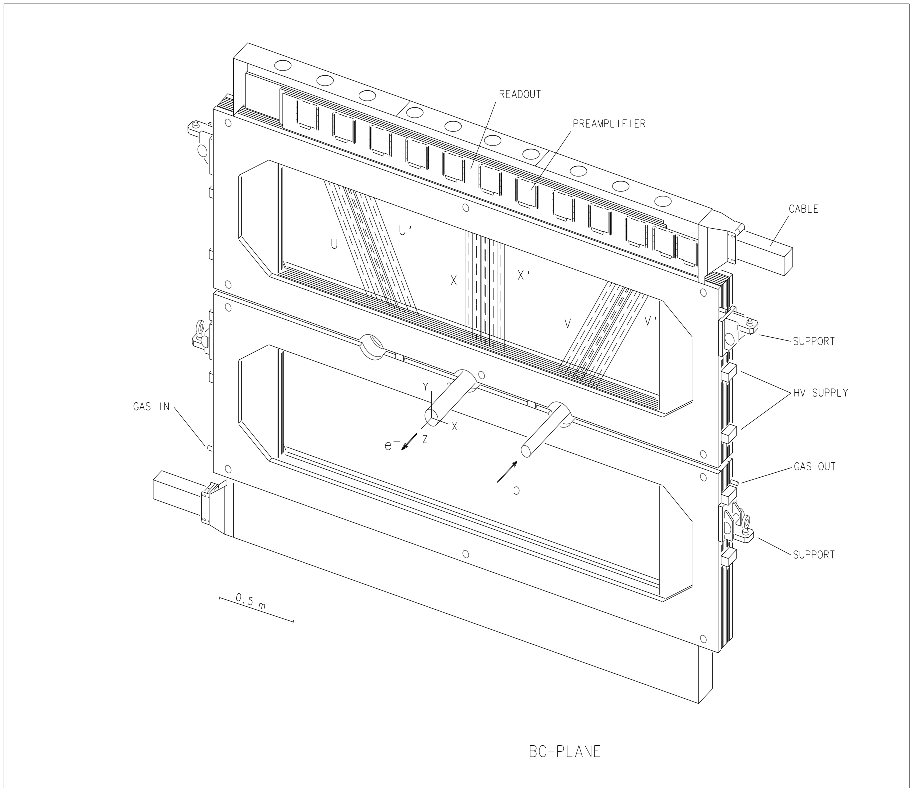
# HERMES Detector *was* (1995-2007) Two Identical Halves of Forward Spectrometer




- Acceptance: $40 < \Theta < 220$ mrad, $|\Theta_x| < 170$ mrad, $40 < |\Theta_y| < 140$ mrad
- Resolution: $\delta p/p \leq 1\%$, $\delta\Theta \leq 0.6$ mrad

# Tracking and Particle Identification

Forward and Backward Drift Chambers:
- $Ar$(90 %), $CO_2$(5 %), $CF_4$(5 %) gases,
- drift time $\leq$ 300 ns,
- 1877 FASTBUS TDCs readout,
- order of 250 $\mu$m resolution

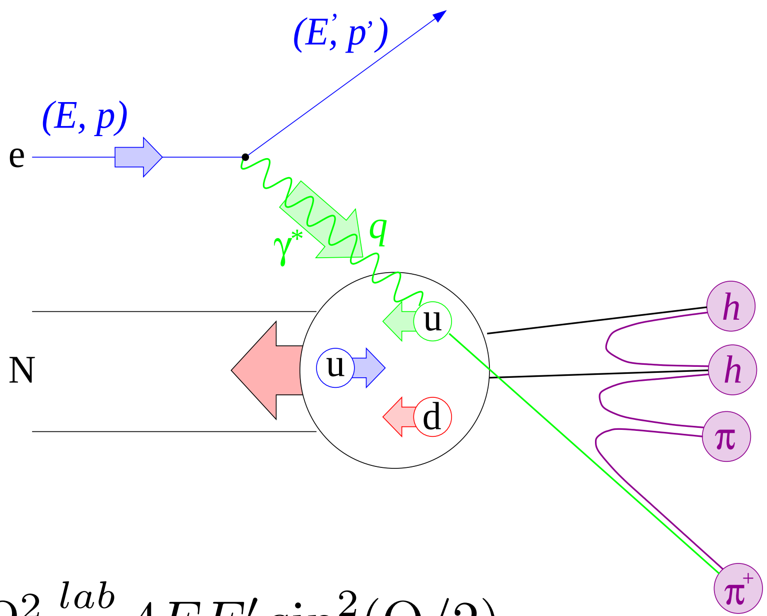


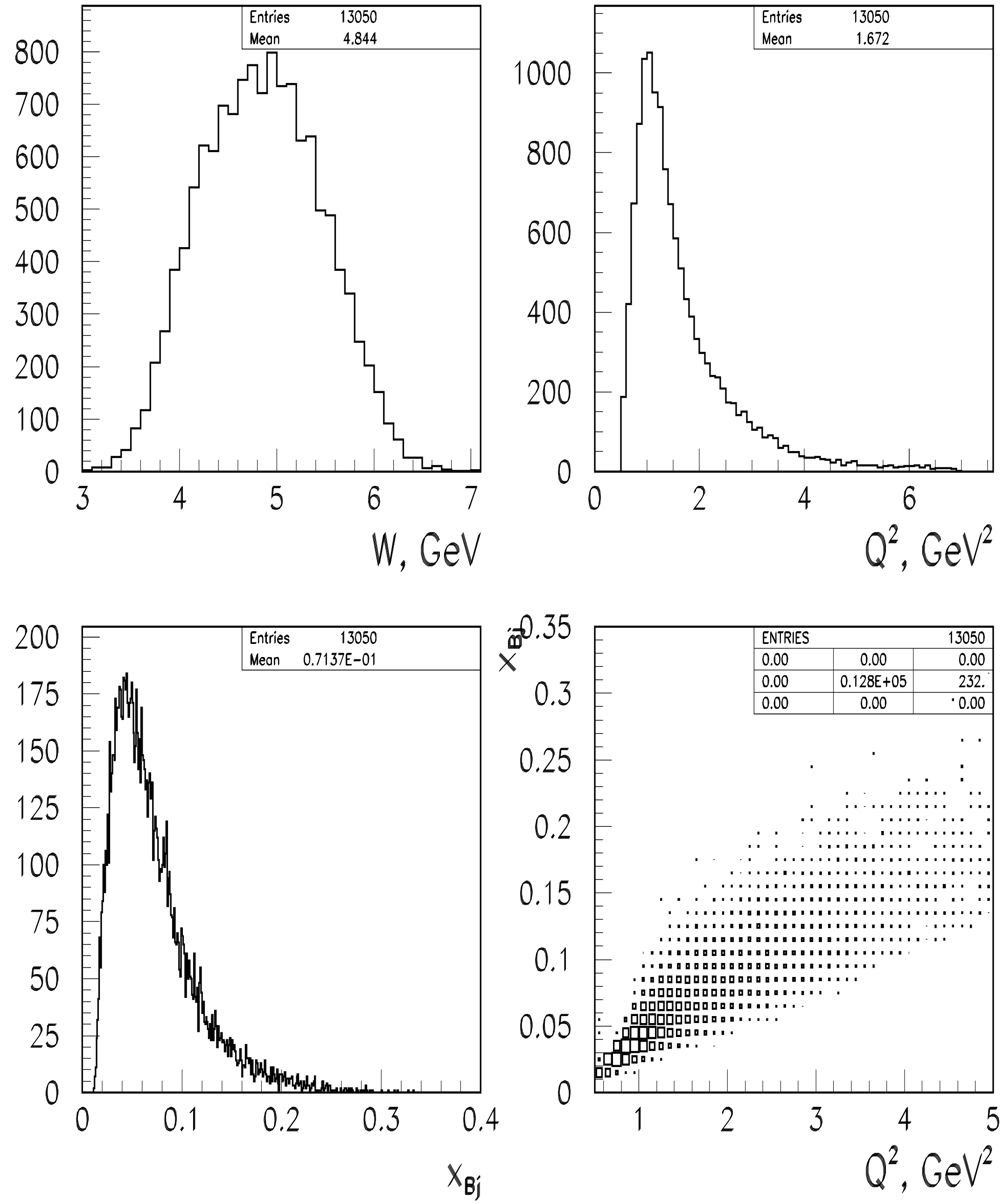

- Electron identification done by RICH, TRD, Preshower, Calorimeter: efficiency $\geq 98\%$, hadron contamination $\leq 1\%$

- Calorimeter
  - lead glass (F101) blocks $9 \times 9 \times 50$ cm in array of 420 for top and bottom parts
  - resolution: $\Delta E/E[\%] = 1.5_{\pm 0.5} + 5.1_{\pm 1.1}/\sqrt{E[GeV]}$
  - $M_{\pi^0} = 134.9 \pm 0.2$ MeV, $\sigma = 12.5 \pm 0.2$ MeV

- RICH from 1998 for $\pi^{\pm}$ vs $K^{\pm}$ and $p(\bar{p})$ separation: $\sim$4000 PMTs, aerogel and $C_4F_{10}$
  - Dual rings of Cherenkov photons, $n$=1.03 for aerogel and $n$=1.0014 for $C_4F_{10}$
  - Probability-Matrix for one track, no impact on $p_t^2$ of tracks
  - RICH efficiencies over all kinematic region: $\pi$: 98 %, $K$: 88%

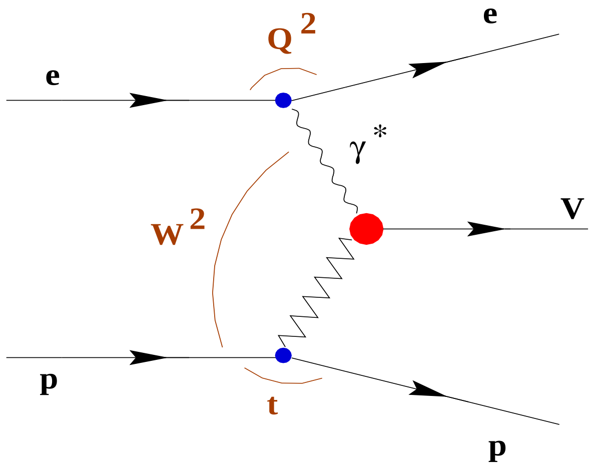
# Deep Inelastic Scattering: Variables and Kinematic Distributions



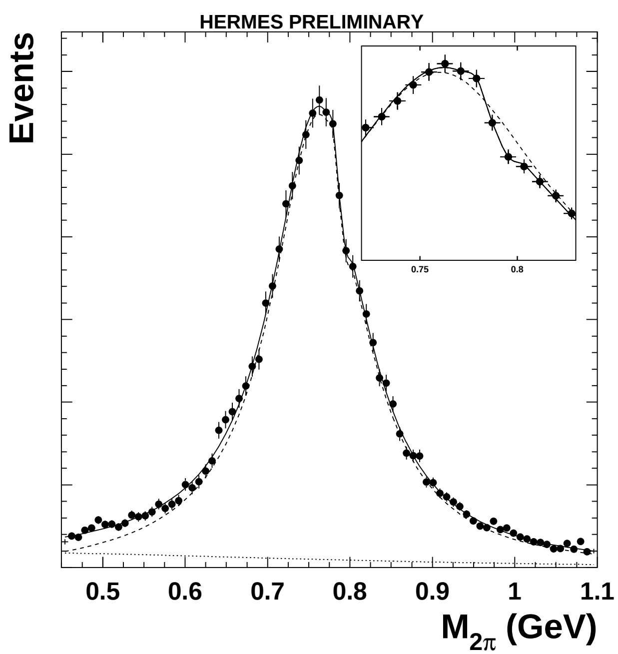

- $Q^2 \stackrel{lab}{=} 4EE' \sin^2(\Theta/2)$
- $\nu \stackrel{lab}{=} E - E'$
- $x_{Bj} \stackrel{lab}{=} Q^2/2M\nu$
- $W^2 \stackrel{lab}{=} M^2 + 2M\nu - Q^2$
- $z \stackrel{lab}{=} E_h/\nu$

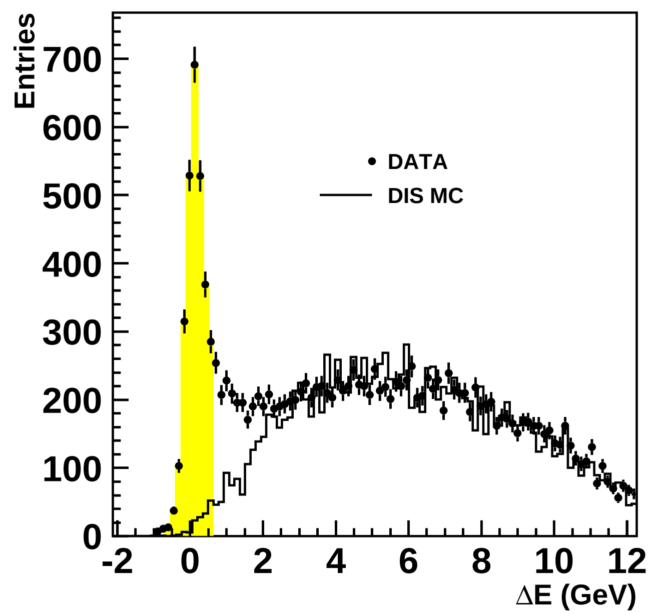
# Kinematics of Exclusive $\rho^0$ Electroproduction




- $\nu = 5 \div 24$ GeV, $<\nu>= 13.3$ GeV,
- $Q^2 = 1.0 \div 5.0$ GeV$^2$, $< Q^2 >= 2.3$ GeV$^2$
- $W = 3.0 \div 6.5$ GeV, $< W >= 4.9$ GeV
- $x_{Bj} = 0.01 \div 0.35$, $< x_{Bj} >= 0.07$

Clean mass and exclusive peaks for $\rho^0$:

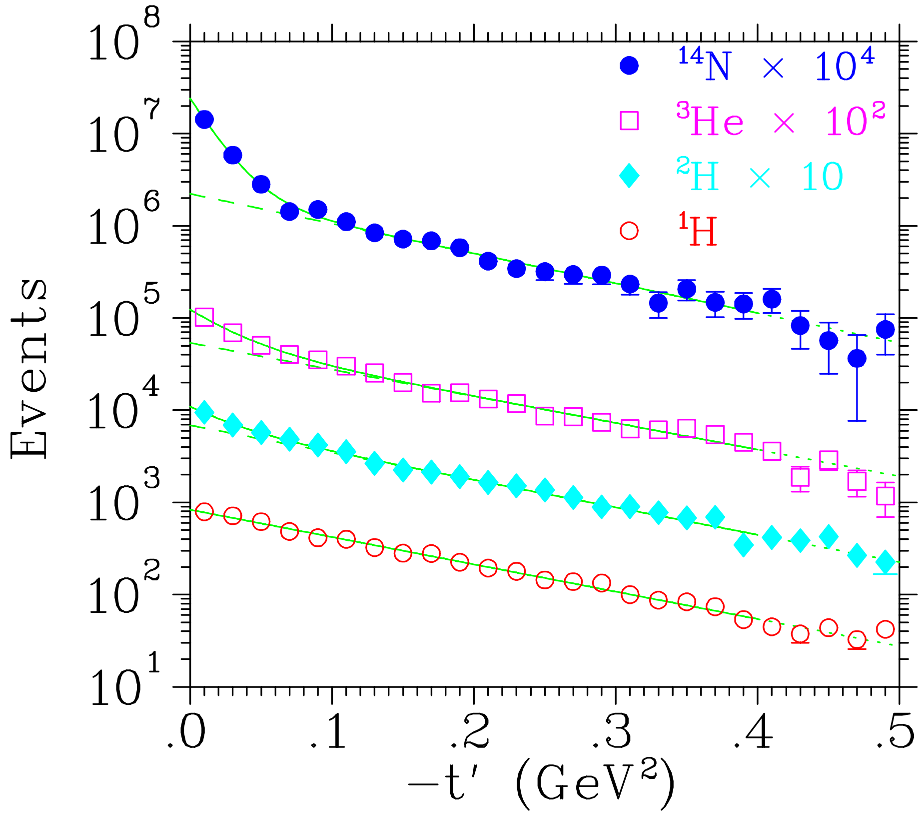


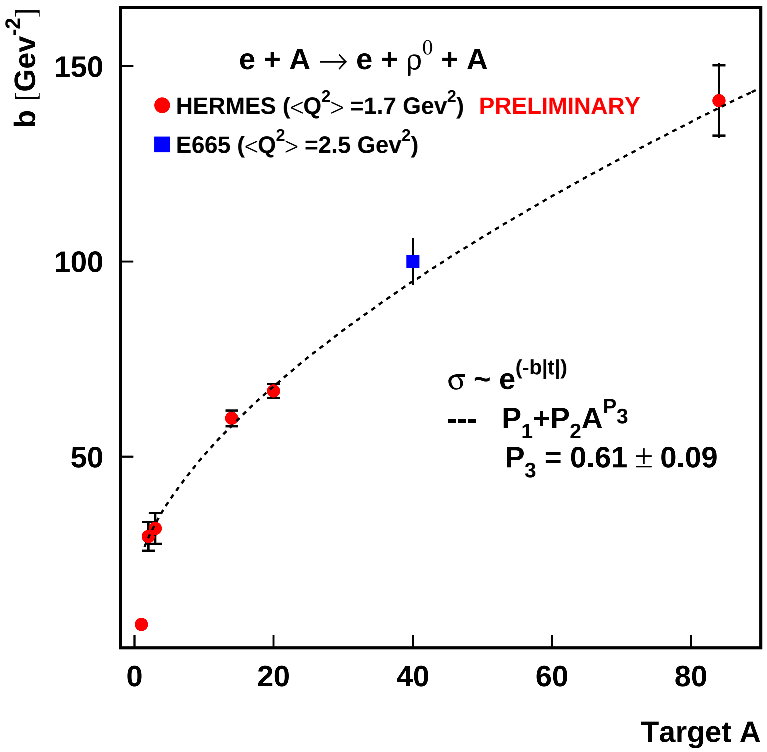




$\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$, $M_X^2 = (p + q - V)^2$, background is subtracted using PYTHIA MC.

# Nuclear Effects of Exclusive $\rho^0$ Production: Coherent and Incoherent $\rho^0$

HERMES collab., Phys.Lett.B 513 (2001) 301-310; Eur.Phys.J. C 29, 171 - 179 (2003)




$d\sigma_{tot}/dt \propto a_1 exp(b_{coh}t) + a_2 exp(b_{inc}t)$

at $-t \lesssim 0.045$ GeV$^2$ coherent $\rho^0$ dominates,
at $-t \gtrsim 0.1$ GeV$^2$ incoherent.

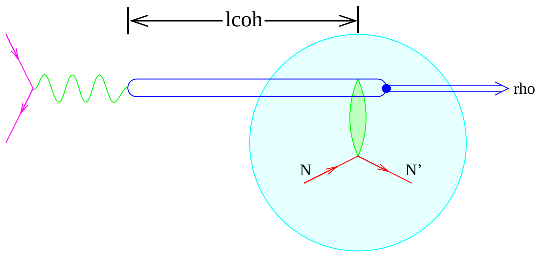
$b_{coh} \approx r_A^2/3$ is in agreement with world data of nuclear size measurements

(H.Alvensleben et al,Phys.Rev.Let. **24**,792 (1970)).

# Kinematics of exclusive $\rho^o$ matches dimension of Nuclei

- radius of the nucleus: $r_{14_N} \simeq 2.5$ fm

- coherence length: distance traversed by $q\bar{q}$ fluctuation of the virtual photon:

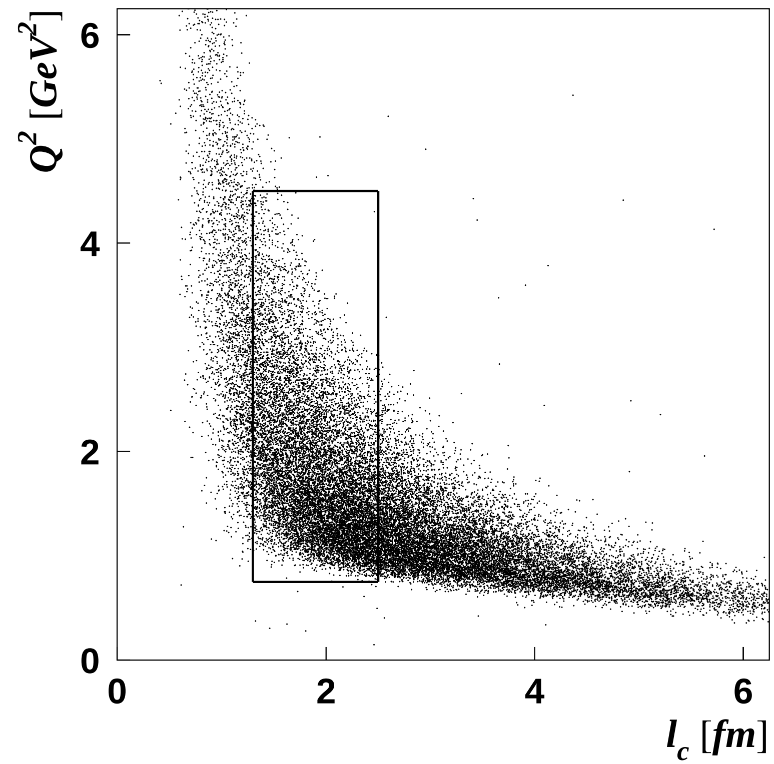



$l_c = \frac{2\cdot\nu}{Q^2+m_V^2} = 0.6 \div 8$ fm,
$< l_c >= 2.7$ fm

- $\rho^0$ formation length: after $q\bar{q}$ is put on-shell it will evolve into $\rho^0$ over distance:
$l_{form} = \frac{2\cdot\nu}{m_{V'}^2 - m_V^2} = 1.3 \div 6.3$ fm
$\langle l_{form} \rangle = 3.47$ fm

- color transparency: transverse size of the $q\bar{q}$ of the wave packet
$r_{q\bar{q}} \sim 1/\langle Q \rangle \simeq 0.4$ fm, $r_p = 1$ fm

$Q^2$ vs $l_c$ of exclusive $\rho^0$ at HERMES:



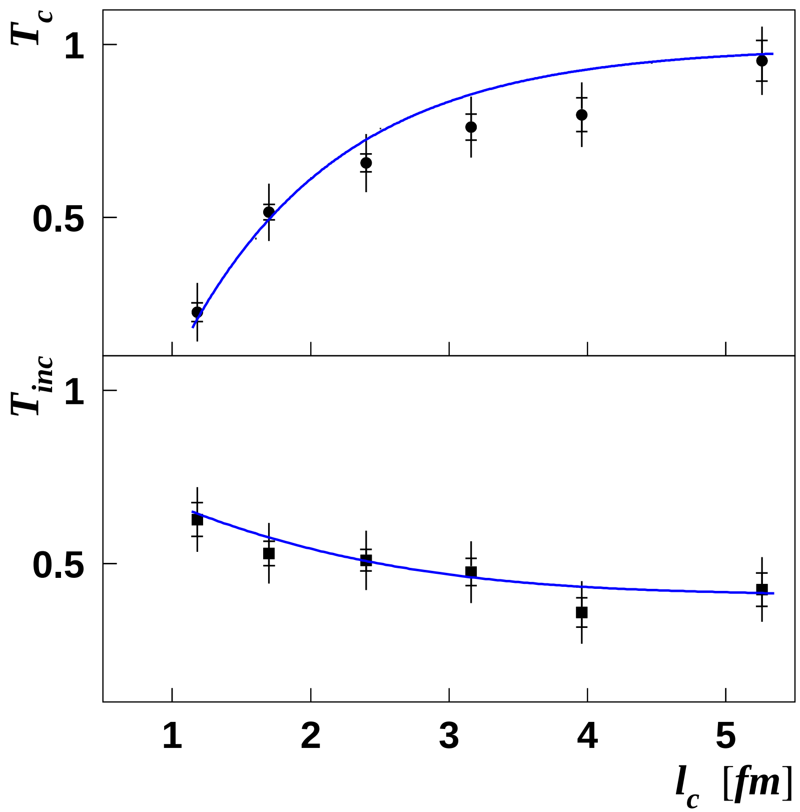

$\rightarrow \rho^0$ absorption at $l_c \leq r_{14_N}$

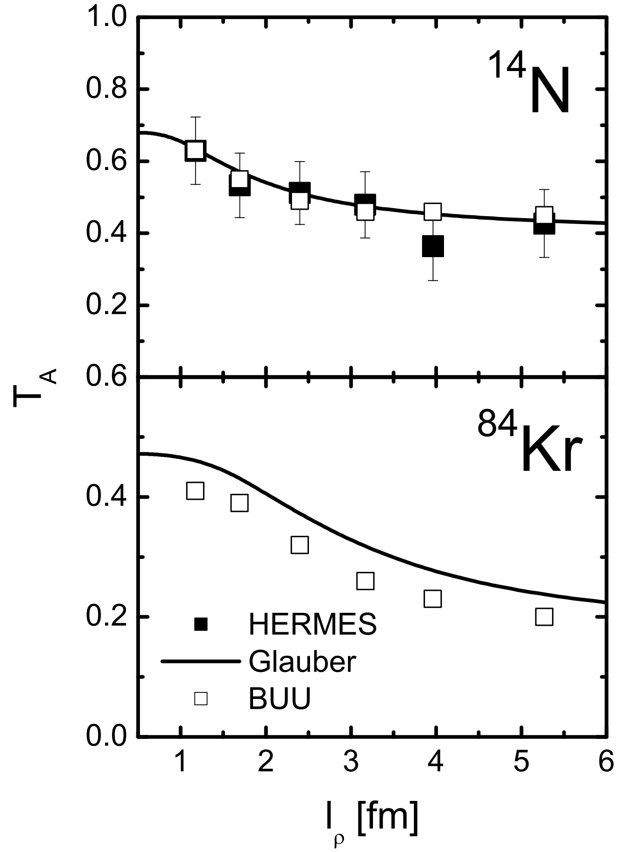
$\Longrightarrow$ 2-dimensional analysis of $Q^2$, $l_c$ dependencies

# Coherent Length Effect

(HERMES collab., Phys. Rev. Let. **82**, 1999; Phys.Rev.Let., **90**, 5, 2003)

$$T_{c/inc}(l_c) = \frac{\sigma_{Ac/inc}}{A\sigma_H} = \frac{N_{Ac/inc} \cdot L_H}{A \cdot N_H \cdot L_A}, \; A = {}^{14}\mathrm{N}$$

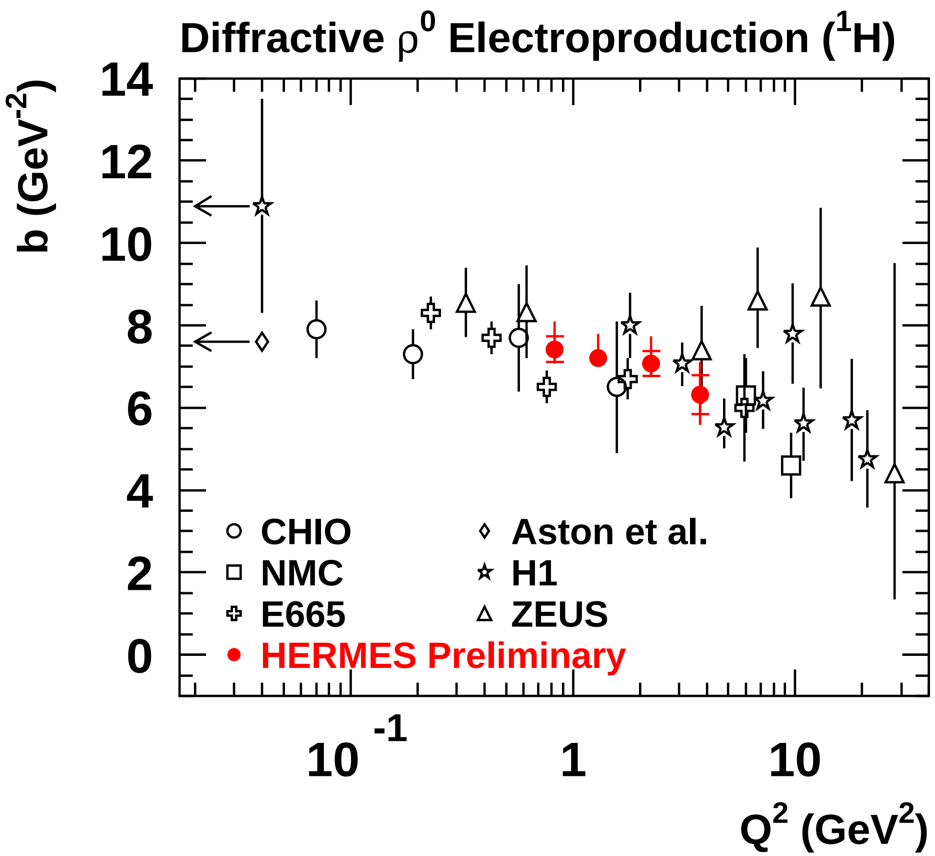



- Left panel. Combined effect of initial and final state interactions for incoherent $\rho^0$ and additional effect of nuclear formfactor for coherent $\rho^0$. Agreement with calculations (blue curves) based on CT approach (B.Z. Kopeliovich et al, Phys.Rev. C, **65**, 035201, 2002).

- Right panel. Calculations for incoherent production of semi-classical transport model without CT presented on right panel. (T.Falter, W.Cassing, K.Gallmeister and U.Mosel, nucl-th/0309057).

# 'Photon Shrinkage' ($b_{inc}(Q^2)$) a Prerequisite for Color Transparency




→ Size of virtual photon controlled via $Q^2$

→ No strong $W-$dependence

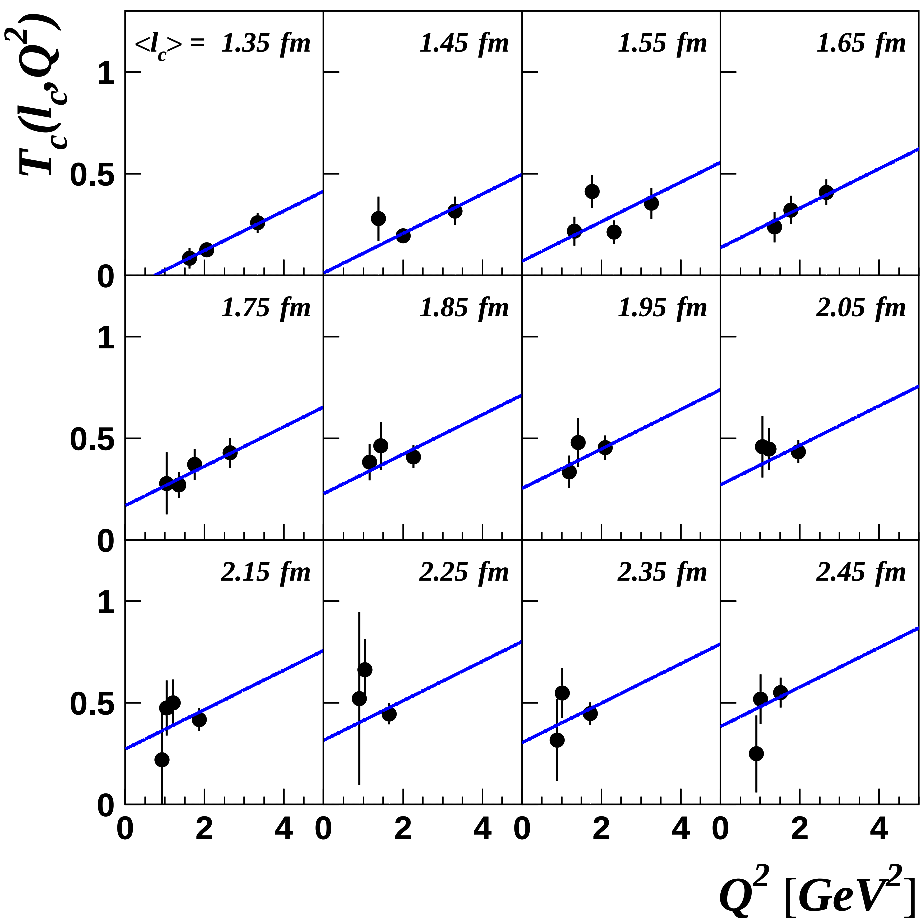
# Color Transparency Effect (HERMES collab., Phys.Rev.Let.,90,5,052501,2003)

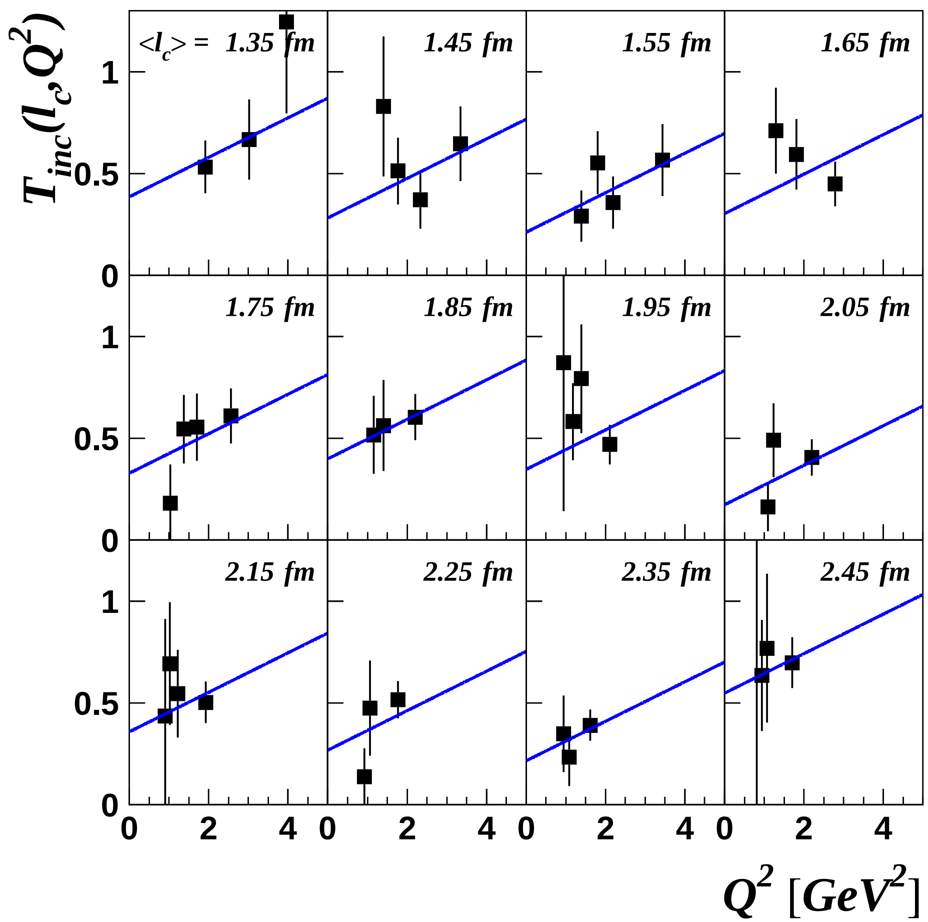
The QCD factorization theorem rigorously not possible without the onset of the color transparency: (J.Collins,L.L.Frankfurt,M.Strikman Phys.Rev.D**56**,2982 (1997); M.Strikman, Nucl.Phys.A663&664,**64**,2000)

$\rightarrow r(qq)$ decreases with the increase of $Q^2$

$\rightarrow Tr^A(Q^2, l_{coh}) = \sigma^A_{(in)coh}/\sigma^H$ grows with $Q^2$

At fixed $l_{coh}$:



# Color Transparency Effect (HERMES collab., Phys.Rev.Let.,90,5,052501,2003)

| data | Slope of $Q^2$-dependence, GeV$^{-2}$ | Prediction, GeV$^{-2}$ |
|---|---|---|
| N incoh. | $0.089 \pm 0.046_{st} \pm 0.020_{syst}$ | 0.060 |
| N coh. | $0.070 \pm 0.027_{st} \pm 0.017_{syst}$ | 0.048 |
| N combined | $0.074 \pm 0.023$ | 0.058 |

Agreement with theoretical calculations where positive slope of $Q^2$-dependence was derived from the onset of the color transparency effect (B.Z. Kopeliovich et al, Phys.Rev. C, **65**, 035201, 2002)

$\Longrightarrow$ **Different CT effects are predicted for $ep$, $\pi p$, $pp$ and $pA$ collisions**

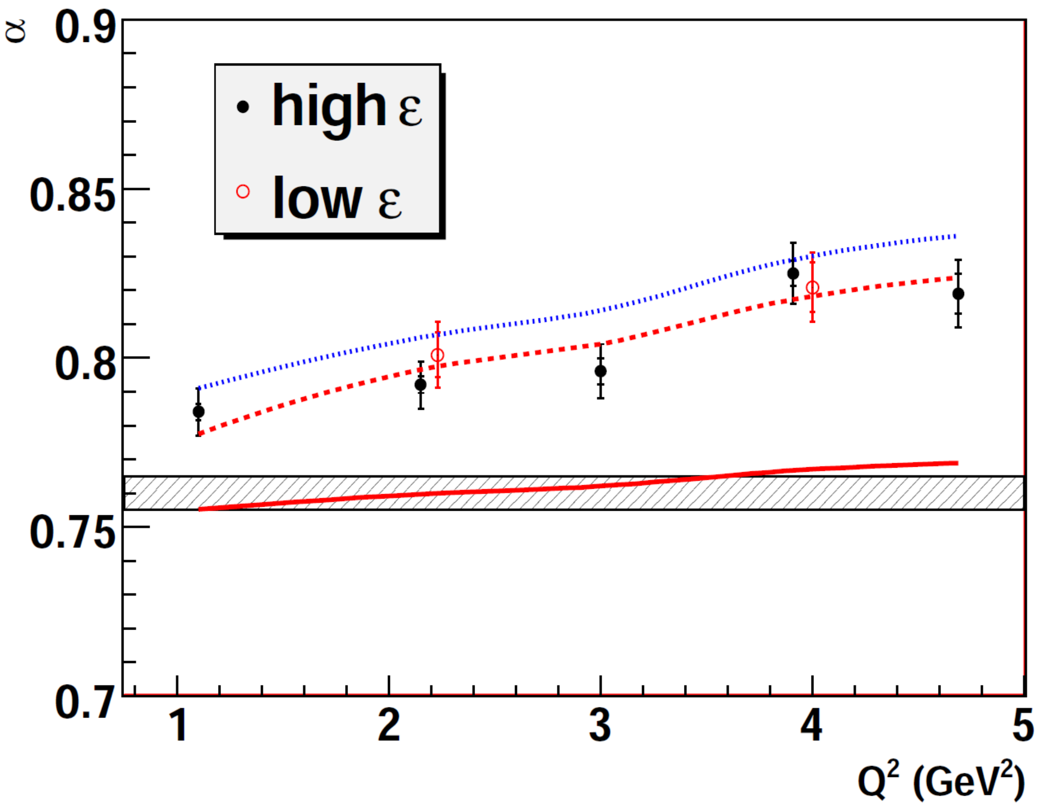
see, e.q.: G.Miller and M.Strikman talks on the workshop "Hard Exclusive Processes", Munich, 9-11 November 2009.

# Color Transparency Effect from Jefferson Lab data: $e + p \to e' + \pi^+ + (n)$

(X.Qian et al, Phys.Rev.C, **81**, 055209, 2010) Kinematics:

$4 \leq E^{beam} \leq 5.8$ GeV $\quad 0.9 \leq E^{e'} \leq 1.7$ GeV $\quad W \approx 2$ GeV

Transparency $T = \frac{\sigma^A}{A\sigma^N} \frac{= A^\alpha \sigma^N}{A\sigma^N} = A^{\alpha-1}$




Parameter $\alpha$ was measured from $^1$H, $^2$H, $^{12}C$, $^{27}$Al, $^{63}$Cu and $^{197}$Au data and compared with $\alpha$ extracted from pion-nucleus scattering data (hatched band).

$\Longrightarrow$ Noticeable dependence of $\alpha$ on $Q^2$ measured and compared with calculations: Glauber (solid), Glauber+CT (dashed), Glauber+CT with short-range correlations (dotted).

$\epsilon$ is the longitudinal polarization of the virtual photon measured from $e'$ kinematics

# HERMES SIDIS Data on Heavy Targets

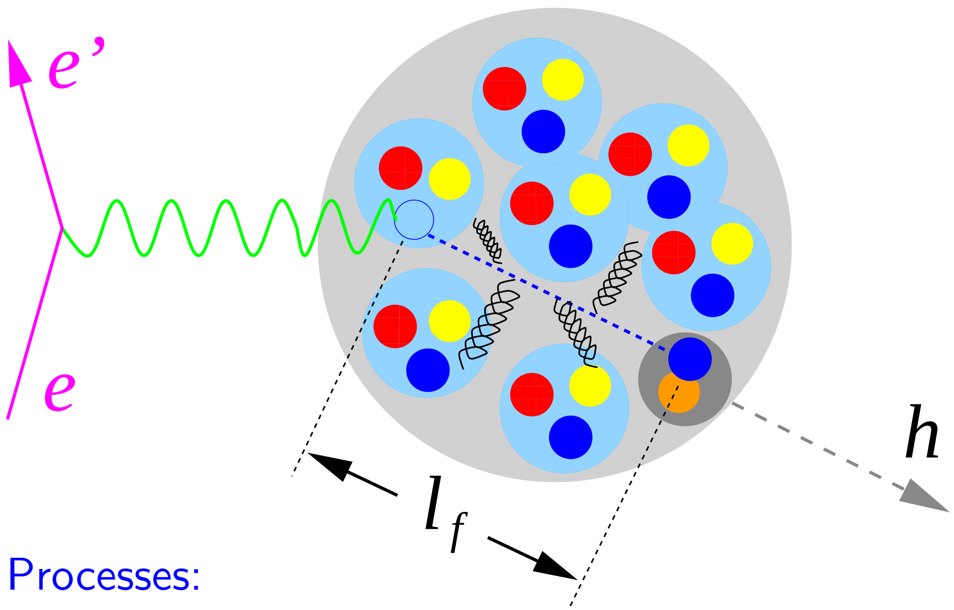
- Kinematic cuts:
  - $1 < Q^2 < 10$ GeV$^2$
  - $W^2 > 10$ GeV$^2$, no resonances
  - $\nu < 23.5$ GeV, radiative effects
  - $0.2 < z < 1.0$

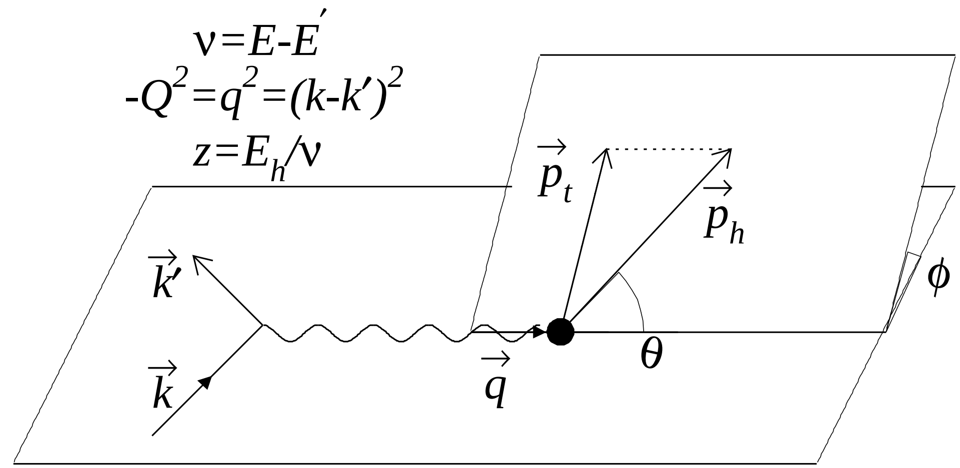
| Target | $N^{\pi^+} \times 10^3$ | $N^{\pi^-} \times 10^3$ | $N^{K^+} \times 10^3$ |
|---|---|---|---|
| $^2$D | 1781 | 1445 | 356 |
| $^4$He | 134 | 107 | 27 |
| $^{20}$Ne | 380 | 303 | 82 |
| $^{84}$Kr | 321 | 260 | 72 |
| $^{131}$Xe | 193 | 157 | 44 |

- Corrections:
  - Acceptance and smearing
  - Radiative effects
  - Nuclear transparency for exclusive $\rho^0$ production at one $\pi^\pm$ accepted

- To study contributions to the transverse momentum distributions from:
  - primordial transverse momentum
  - gluon radiation of the struck quark
  - multiple interactions of the “pre-hadron”
  - interactions of the formed hadrons

# Hadron Electroproduction in Cold Nuclear Matter




Processes:

- Scattering on a quark
- Quark energy loss in nuclear medium
- Fragmentation of quark to hadron (pre-hadron formation)
- Absorption of (pre-)hadron

Formation length from DIS to final hadron in various models for (pre-)hadron formation and absorption: $l_f \propto \nu(1-z)/k$

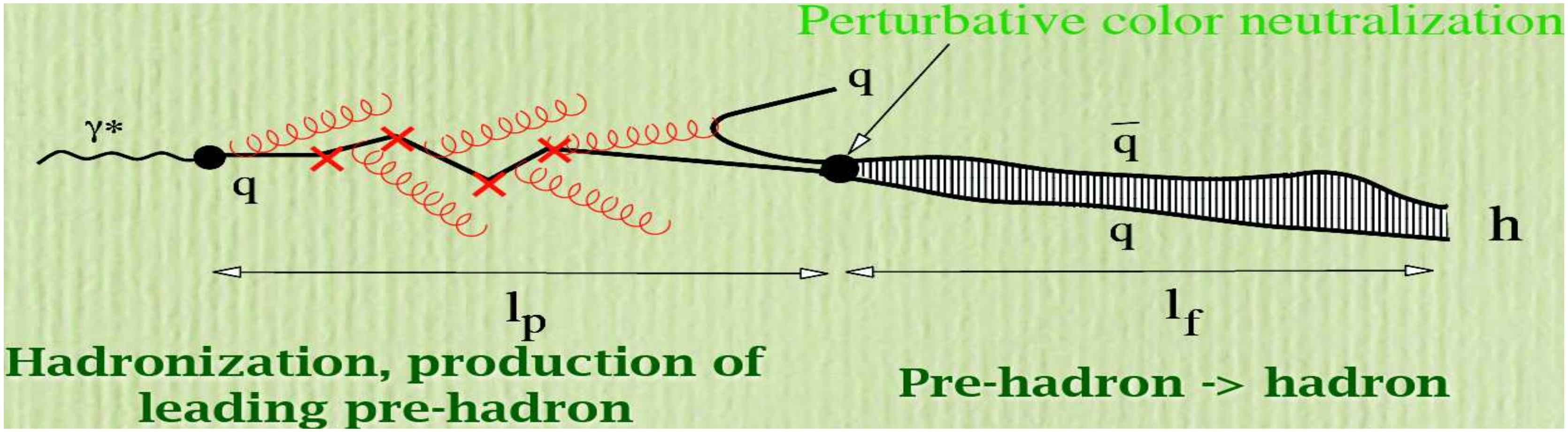
Experimental access to the hadronization through the measured multiplicity ratio:

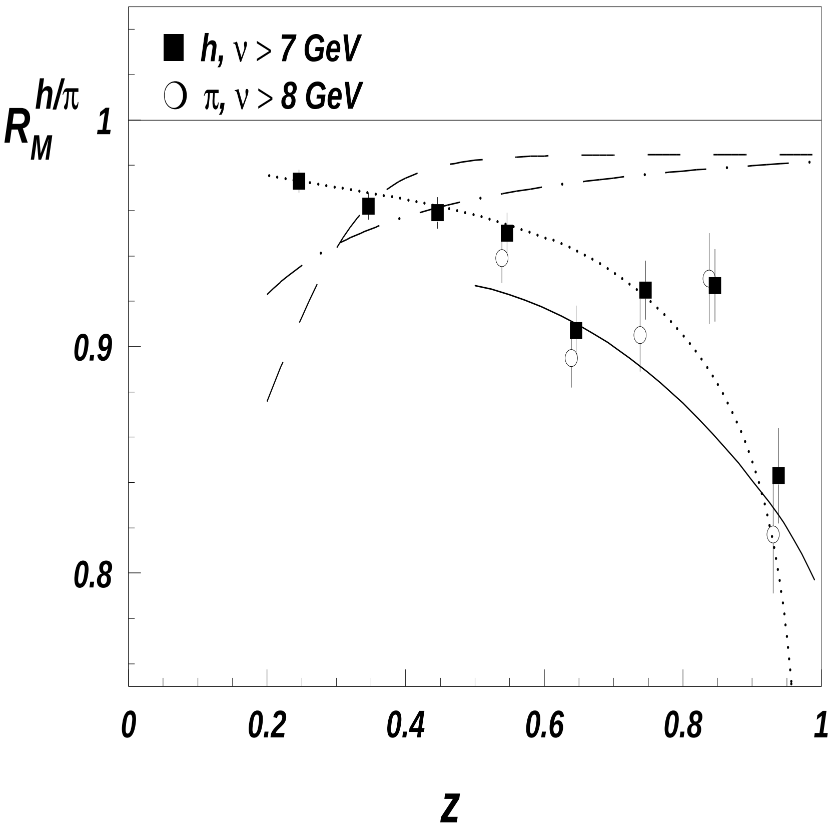
$$R_A^h(\nu, Q^2, z, p_t^2) = \frac{\left(\frac{N^h(\nu,Q^2,z,,p_t^2)}{N^{e'}(\nu,Q^2)}\right)_A}{\left(\frac{N^h(\nu,Q^2,z,p_t^2)}{N^{e'}(\nu,Q^2)}\right)_D}$$

data integrated over $\phi$ and $\Theta$, see e.g.:

HERMES collab., Nucl. Phys. B 780 (2007) 1-27; arXiv:0704.3270

# Hadron Formation in DIS in a Nuclear Enviroment




$\Longrightarrow$ Absorption is large at $z \to 1$, where $l_f \propto \nu(1-z)/k$ is short.

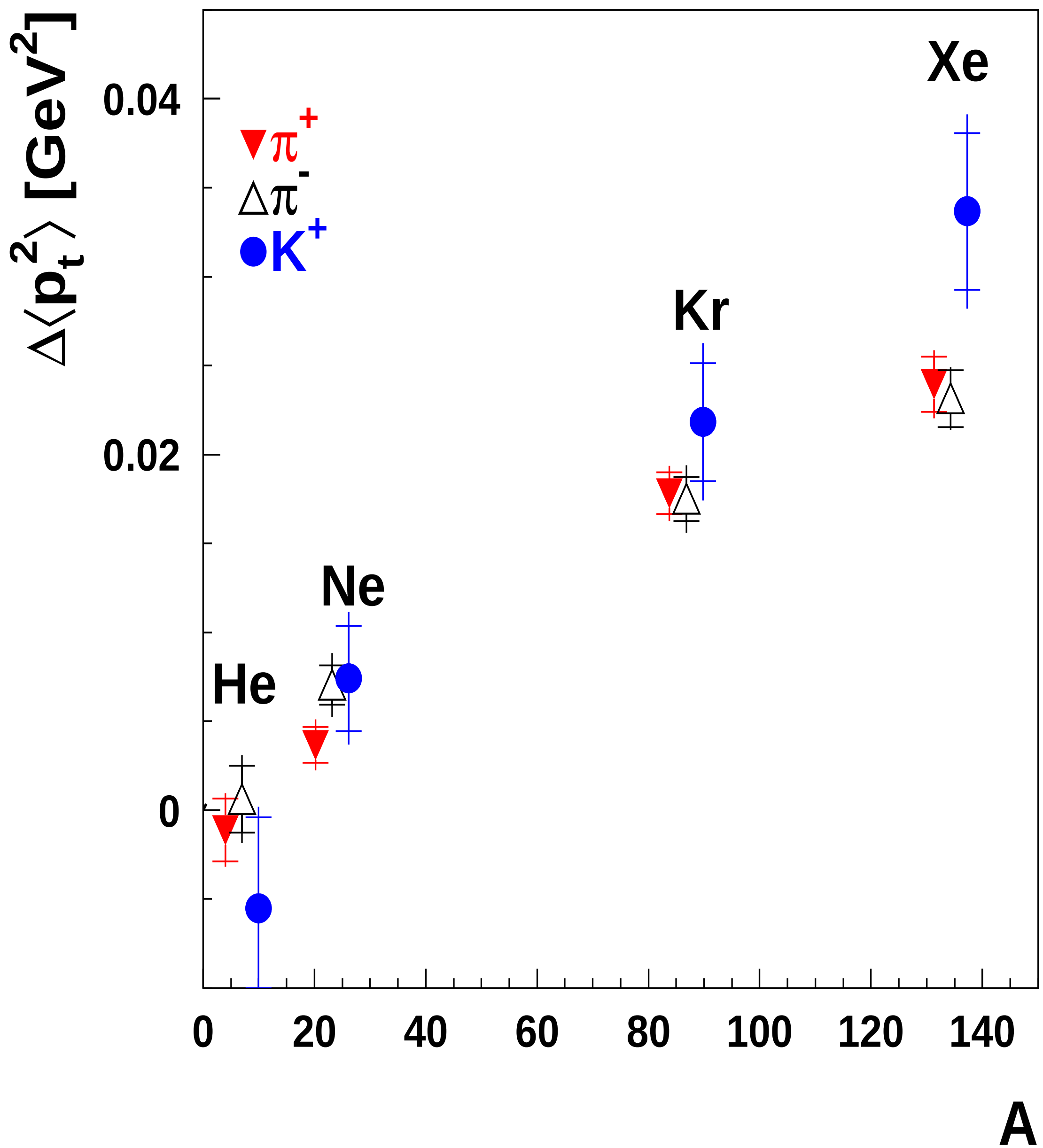
The fractional energy $z_h$ is directly measured and compared with the prediction of B.Z.Kopeliovich, J.Nemchik, E.Predazzi in 1995, see S.Domdey,D.Gruenewald,B.Z.Kopeliovich ans H.J.Pirner, Nucl.Phys. A 825, 200, 2009.

$\Longrightarrow$ Fast hadrons have a relatively short formation time, leading to the reduction of the ratio.

(HERMES Collab., Eur. Phys. J. C 20, 479 (2001))

## A-dependence of Nuclear $p_t$-broadening: $\Delta\langle p_t^2\rangle^h = \langle p_t^2\rangle_A^h - \langle p_t^2\rangle_D^h$

(HERMES collab., Phys. Lett. B 684 (2010) 114-118;; arXiv:0906.2478, hep-ex)

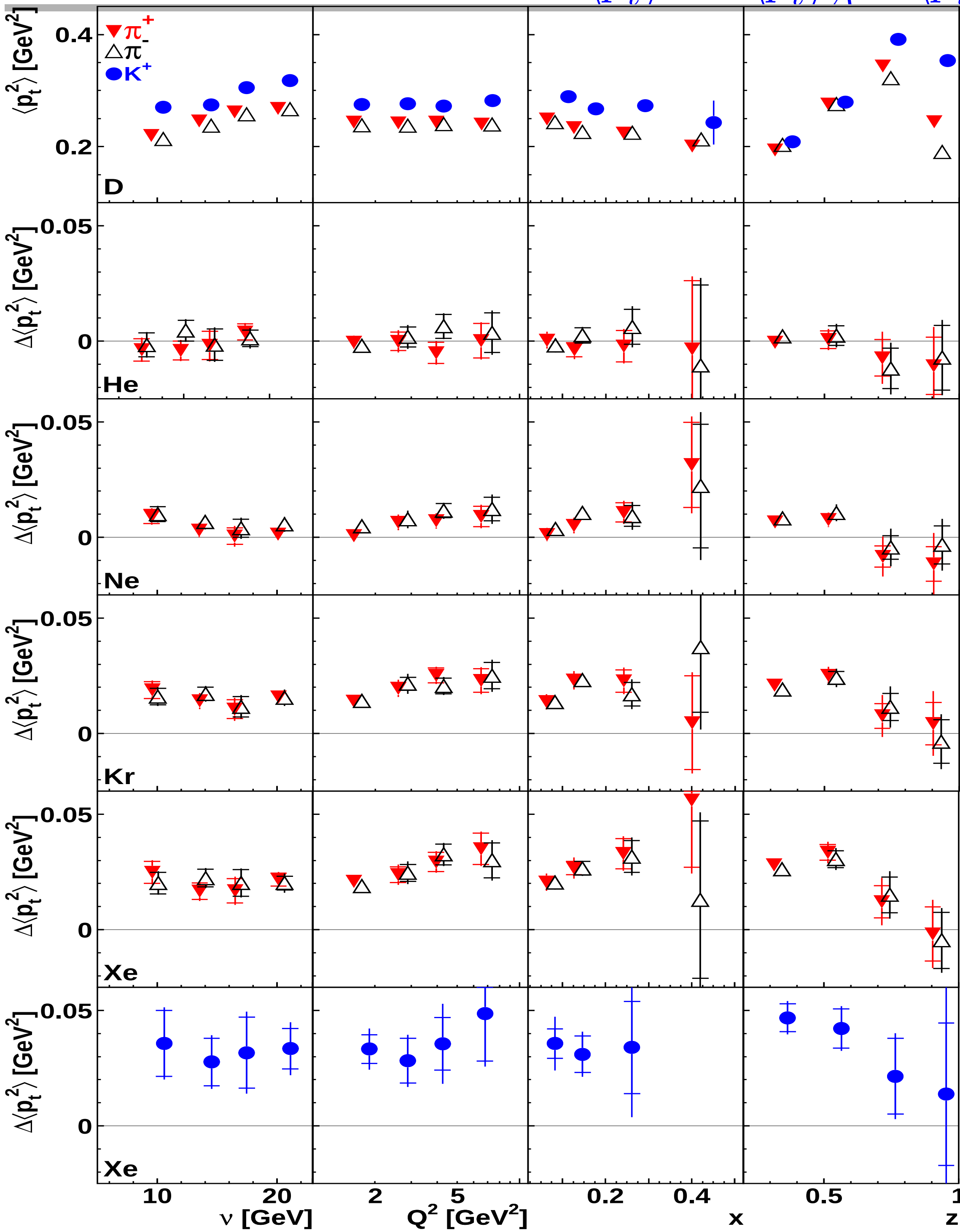



- Effect of 1-10 % relative $\langle p_t^2\rangle_D^h \approx 0.25$ GeV$^2$:

$\Longrightarrow$ Direct evidence of $p_t$-broadening in leptoproduction

# Kinematic Dependencies of Nuclear $p_t$-broadening:

$\Delta\langle p_t^2\rangle^h = \langle p_t^2\rangle^h_A - \langle p_t^2\rangle^h_D$

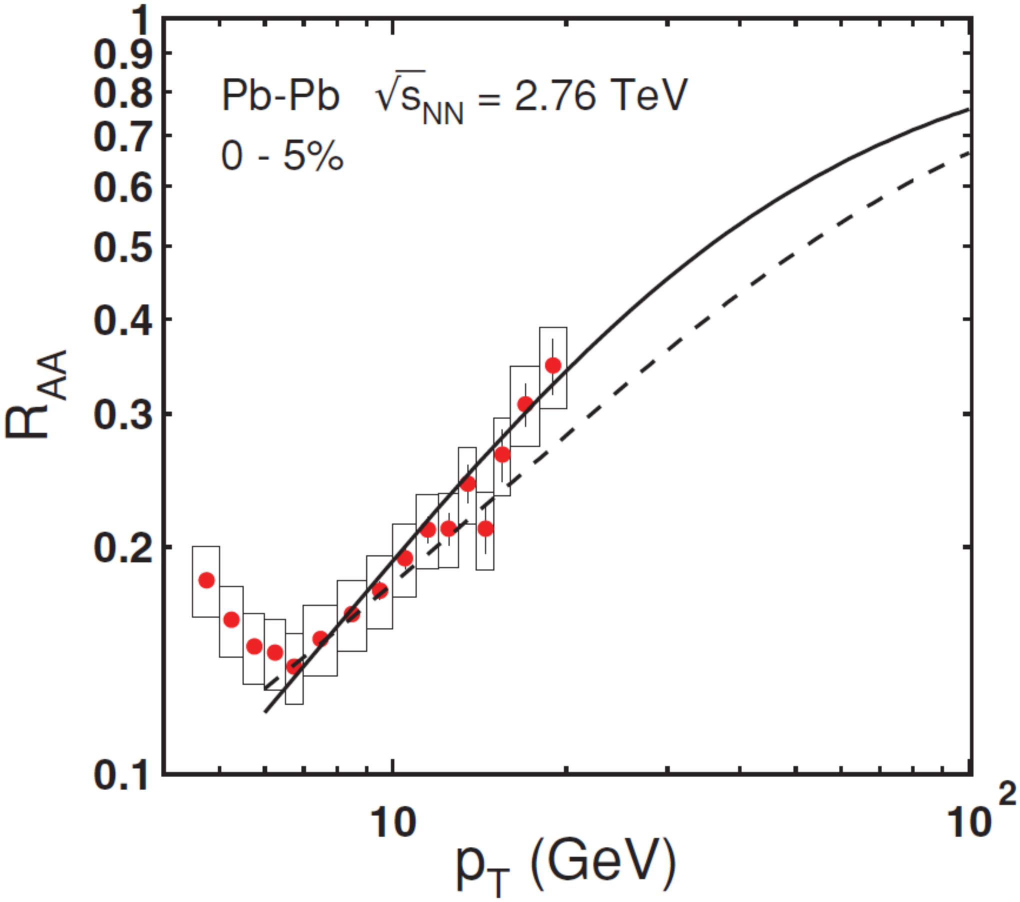



- Broadening goes slightly down with increasing $\nu$
- Broadening goes up with $Q^2$
- Clear $z = E_h/\nu$ dependence. At $z \to 1$
  - $p_t$-broadening consistent with zero due to energy conservation: the struck quark cannot have lost energy
  - it is not due to elastic scattering of (pre-)hadrons (B.Z.Kopeliovich et al, Nucl.Phys. A740 (2004) 211; S.Domdey,D.Gruenewald, B.Z.Kopeliovich ans H.J.Pirner, Nucl.Phys. A 825, 200, 2009.)

$\Longrightarrow$ Constraint on pre-hadron production mechanism

# The $R_{AA}$ data from ALICE as "Color transparency and suppression of high-$p_T$ hadrons in nuclear collisions"

see B.Z.Kopeliovich, I.K.Potashnikova and I.Schmidt, Phys.Rev. C. 83, 021901 (R), 2011.




Calculations include:

- propagation of colorless dipole (pre-hadron) through a dense medium,
- its short production length,
- intensive energy loss at the early stage.

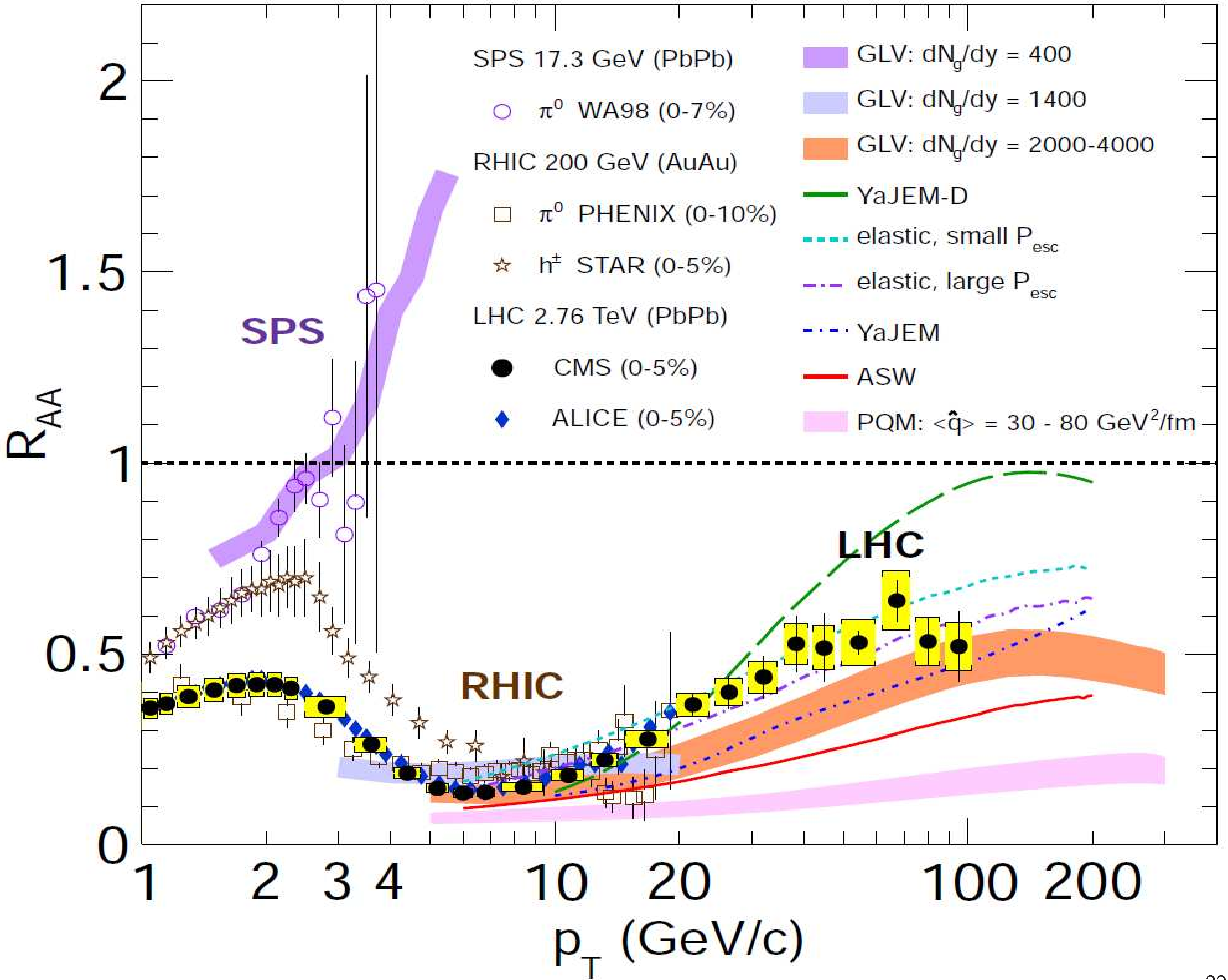
Data on high-$p_T$ hadron production in heavy ion collisions include:

- the uncertainties from the variation in space and time of the medium properties,
- unmeasured fractional energy $z_h$ convoluted with initial parton distribution, hard cross section and the fragmentation function,
- the contribution of the initial state effects in cold nuclear models.

data from ALICE collab., Phys. Lett. B 696 (2011) 30-39

$\Longrightarrow$ Global analysis of experimental data to test the models is desirable...

# ALICE data are confirmed and extended by CMS ( arXiv:1202.2554v1 [nucl-ex])



# Summary

- Data on nuclear transparency of exclusive $\rho^0$ production on $^{14}$N are in agreement with Color Transparency based calculations.
  $\Longrightarrow$ Phenomenon of color transparency, based on factorization theorem and small size configuration, could be used to study GPDs and their possible modifications in the cold or hot nuclear matter.

- HERMES data provide a strong support for shortness of the production length

- The first direct determination of $p_T$-broadening in SIDIS was performed on He, Ne, Kr and Xe targets. $\Longrightarrow$ It increases with $A$ and remains constant with $\nu$ suggesting that effect is due to the "partonic" stage and that color neutralization happens near the surface or outside the nucleus.

- A colorless dipole created on a short production length evolves its size during propagation in medium.

- The energy dependence of this evolution and color transparency explain well the recent data from ALICE and CMS on nuclear suppression of light hadrons with large enough $p_T$.

# Outlook: much more data on heavy targets are published by HERMES:

- *Multidimensional Study of Hadronization in Nuclei*, Eur. Phys. J. A 47 (2011) 113; arXiv:1107.3496.
- *Transverse momentum broadening of hadrons produced in semi-inclusive deep-inelastic scattering on nuclei* , Phys. Lett. B 684 (2010) 114-118; arXiv:0906.2478 (hep-ex).
- *Nuclear-mass dependence of beam-helicity and beam-charge azimuthal asymmetries in DVCS*, Phys. Rev. C 81 (2010) 035202; arXiv:0911.0091 (hep-ex) and DESY-09-190
- *Hadronization in Semi-inclusive deep inelastic scattering on nuclei*, Nucl. Phys. B 780 (2007) 1-27; Eprint numbers: arXiv:0704.3270 and DESY-07-050
- *Double hadron leptoproduction in the nuclear medium*, Phys. Rev. Lett, 96 (2006) 162301; Eprint numbers: hep-ex/0510030 and DESY-05-205
- *Quark Fragmentation to* $\pi^{+/-}, \pi^0$, $K^{+/-}$, *p and* $\bar{p}$ *in the Nuclear Environment*, Phys. Lett. B 577 (2003) 37-46; Eprint numbers: hep-ex/0307023 and DESY-03-088
- $Q^2$*-dependence of Nuclear Transparency for coherent and incoherent* $rho^0$ *production*, Phys. Rev. Lett. 90 (2003) 052501; Eprint numbers: hep-ex/0209072 and DESY-02-152
- *Observation of a Coherence Length Effect in Exclusive* $\rho^0$ *Electroproduction*, Phys. Rev. Lett. 82 (1999) 3025-3029; Eprint numbers: hep-ex/9811011 and DESY-98-178