Nuclear modifications of fragmentation functions and rescaling models

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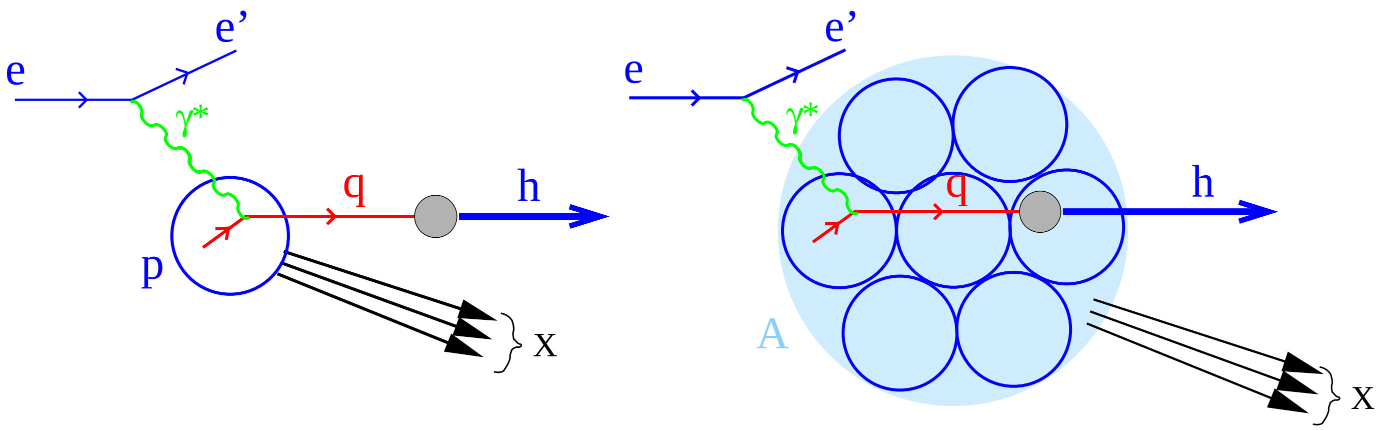
SUMMARY

- Rescaling models
  - Partial deconfinement in nuclei
- Results at EMC energy
  - Nuclear absorption
  - Charged hadron production
- Results at HERMES energy
  - Hermes'01: charged hadrons
  - Hermes'02: charge separation
- Conclusions

Nuclear modifications of FF's

Is the nucleus just a "sum" of protons and neutrons?



a) $e\ p \longrightarrow h\ X$ b) $e\ A \longrightarrow h\ X$

If so, in DIS the photon would only see a bigger target, but the same number of hadrons *per scattered electron* would be produced:

$$\frac{1}{N_A^\ell}\frac{dN_A^h}{dz} = \frac{1}{N_D^\ell}\frac{dN_D^h}{dz} \times \boxed{R_M^h(z)}$$

with $\boxed{R_M^h(z) = 1}$.

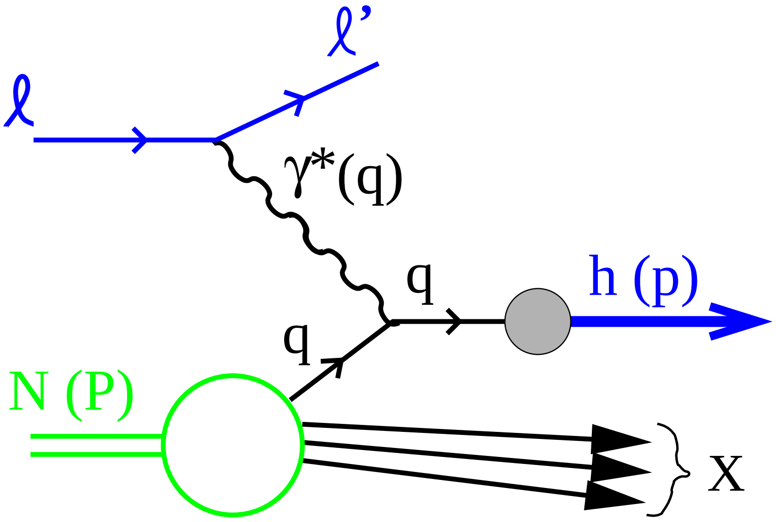
BUT experimentally: $R_M^h(z) \neq 1 \Longrightarrow$ NUCLEAR EFFECTS

What is changing inside the nucleus?

- $\rightsquigarrow$ virtual photon penetration in the nucleus?
- $\rightsquigarrow$ quark composition of the nucleons? $\surd$
- $\rightsquigarrow$ struck quark propagation?
- $\rightsquigarrow$ hadron creation process? $\surd$
- $\rightsquigarrow$ hadron propagation (nuclear absorption)? $\surd$

Formalism

DIS and hadron production



KINEMATIC VARIABLES

$$x = \frac{-q^2}{2q \cdot P} = \frac{Q^2}{2M\nu}$$
$$\nu = \frac{q \cdot P}{\sqrt{P^2}} = E_\ell - E'_\ell$$
$$z = \frac{q \cdot p}{q \cdot P} = \frac{E_h}{\nu}$$

$$Q^2 = -q^2 = 2Mx\nu$$

Experimentally

Hadron production presented in terms of the *multiplicity ratio*

$$R_M^h(z) = \frac{1}{N_A^\ell}\frac{dN_A^h}{dz} \Bigg/ \frac{1}{N_D^\ell}\frac{dN_D^h}{dz}$$

Experiments: $R_M^h(z) \neq 1 \Longrightarrow$ NUCLEAR EFFECTS

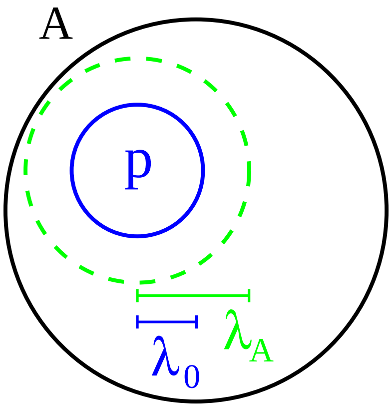
Theoretical models

- nuclear absorption Bialas & Chmaj '83, Bialas & Gyulassy '87
- gluon-bremsstrahlung model Kopeliovich et al. '95
- higher-twist effects Guo & Wang '00, Qiu & Sterman '01, Wang^2 '02
- rescaling models

Rescaling models

Let's assume a change of confinement scale in nuclei:

$$\lambda_A > \lambda_0$$



Parton Distributions

Nachtmann & Pirner '84,Close et al. '84

For valence quarks $\lambda_0 Q_0 = \lambda_A Q_A$:

$$q_f\big(x, Q_0\big) = q_f^A\big(x, Q_A = \frac{\lambda_0}{\lambda_A} Q_0\big)$$

where Q_0 = starting scale for DGLAP evolution.

Fragmentation functions

Dias de Deus '87

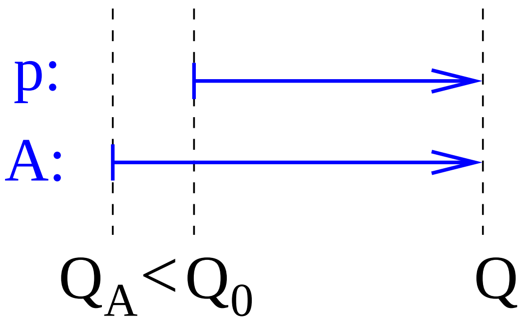
Quark and hadron effective masses sensitive to λ_A:

$$D_f^h\big(z, Q_0\big) = D_f^{h|A}\big(z, Q_A = \frac{\lambda_0}{\lambda_A} Q_0\big)$$

where Q_0 = physical threshold for hadron formation.

pQCD evolution:

longer in nuclei than in isolated nucleons



$$\boxed{q_f^A(x, Q) = q_f(x, \xi_A(Q) Q)} \quad \boxed{D_f^{h|A}(z, Q) = D_f^h(x, \xi_A(Q) Q)}$$

Two models for deconfinement:

- Partial (CJRR): $\lambda_A - \lambda_0 \propto$ nucl. overlap

$$\xi_A = \xi_A(Q) = \left(\lambda_A/\lambda_0\right)^{\frac{1}{2}\frac{\alpha_s(Q_0)}{\alpha_s(Q)}}$$

- Maximal (NP): $\lambda_A = R_A$ (nuclear radius)

$$\xi_A = R_A/R_p$$

	^{2}D$_1$	^{14}N	^{63}Cu	^{84}Kr
λ_A/λ_0	1.015	1.108	1.154	1.169
$\xi_{\mathrm{CJJR}}(Q = 4.5\ \mathrm{GeV})$	1.07	1.62	2.02	2.17
ξ_{NP}	1.93	2.0	3.79	4.20

PDF's and FF's parameterizations:

- **PDF's:** GRV98
- **FF's:**
  - Kretzer: LO & NLO - no protons - charge sep.
  - KKP: LO & NLO - protons - no charge sep.
  - BFGW: only NLO - only had's - no charge sep.

Multiplicity ratio in detail:

$$R_M^h(z) = \frac{1}{N_A^\ell}\frac{dN_A^h}{dz} \Bigg/ \frac{1}{N_D^\ell}\frac{dN_D^h}{dz}$$

- At leading order (also FF's and PDF's):

$$\frac{1}{N_A^\ell}\frac{dN_A^h}{dz} = \frac{1}{\sigma^{\gamma^* A}}\int_{\text{exp. cuts}} dx\, d\nu \sum_f e_f^2\, q_f(x, \xi_A Q)\, \underbrace{\frac{d\sigma^{\gamma^* q}}{dx\, d\nu}}_{\text{pQCD at LO}} D_f^h(z, \xi_A Q)$$

$$\sigma^{\gamma^* A} = \int_{\text{exp. cuts}} dx\, d\nu \sum_f e_f^2\, q_f(x, \xi_A Q)\, \overbrace{\frac{d\sigma^{\gamma^* q}}{dx\, d\nu}}$$

- LO $\gamma^* q$ cross-section:

$$\frac{d\sigma^{\gamma^* q}}{dx\, d\nu} = \frac{18\alpha_s^2(Q^2)M_p}{\pi}\frac{1}{Q^4}\left[1 + (1-w)^2\right]$$

where $w = \dfrac{Q^2}{x^2 M_p^2 + 2x M_p E_{\text{lab}}}$

$$Q^2 = 2Mx\nu$$

REMARK:

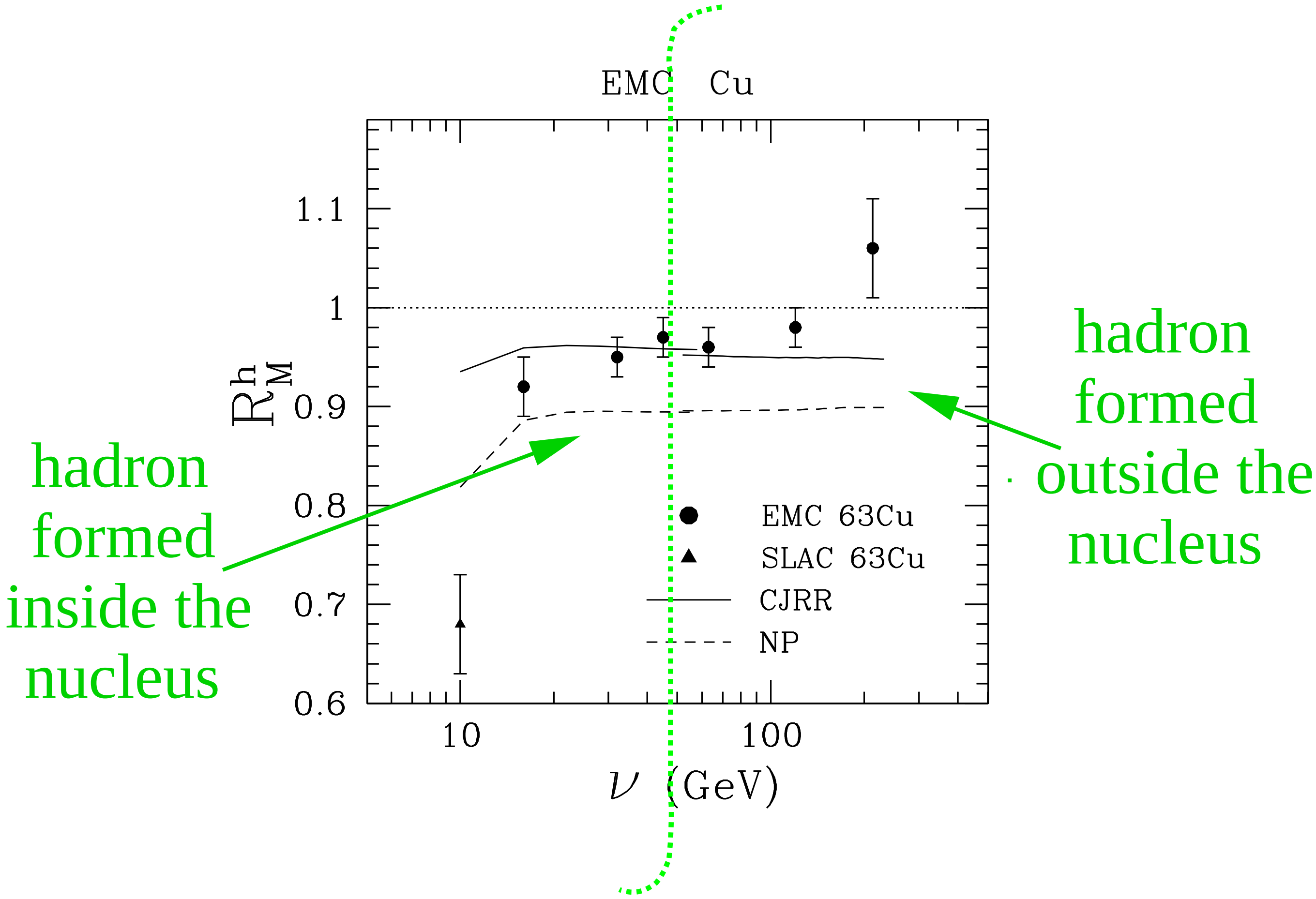
- No (z, ν) correlation in the LO $\gamma^* q$ cross-section
- Weak (z, ν) correlations in $D_f^h(z, Q)$.

Results at EMC

E_{lab} =100-280 GeV $\Longrightarrow \begin{cases} \text{high } \nu\text{'s} \\ \text{large formation time } \tau_F \end{cases}$

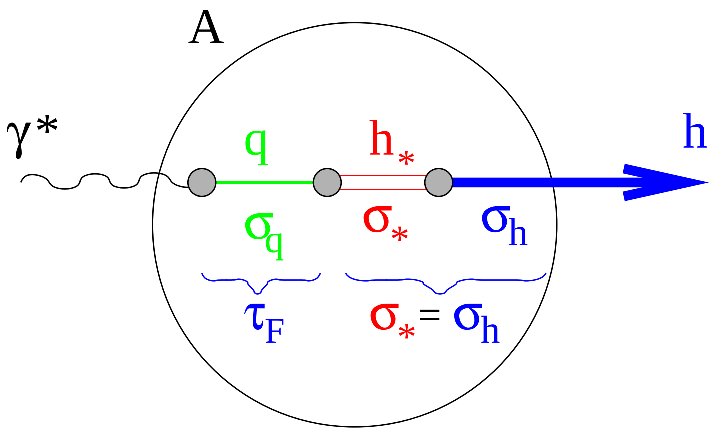
$\tau_F \propto \nu$ due to Lorentz dilatation

ν-distribution $(0.2 \leq z \leq 1)$



- rescaling models good at high ν (hadron formed outside the nucleus)
- nuclear absorption needed at low ν

Nuclear absorption



$\sigma_q = 0$ mbarn
$\sigma_* = \sigma_h = 20$ mbarn
$\kappa = 0.25$ GeV/fm

${}^2D_1 \to$ Reid's Soft Core ρ
$R_D = 2.17$ fm
${}^AN_Z \to$ Woods-Saxon ρ
$R_A = 1.12A^{1/3} - 0.86A^{-1/3}$

Nuclear absorption factor

Bialas & Chmaj, PLB133(83)241

Average over production points with prob. dens. ρ...

$$\mathcal{N}_A(z,\nu) = \int d^2b \int_{-\infty}^{\infty} dy\, \rho_A(b,y)\, [S_A(b,y)]^{A-1}$$

...of the hadron survival probability

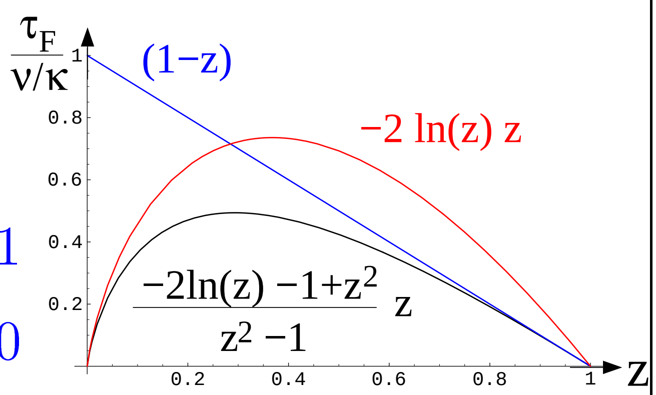
$$S_A(b,y) = 1 - \sigma_h \int_y^{\infty} dy' \rho_A(b,y') \left(1 - e^{-(y'-y)/\tau_F}\right)$$

Formation time

Bialas & Gyulassy, NPB291(87)813

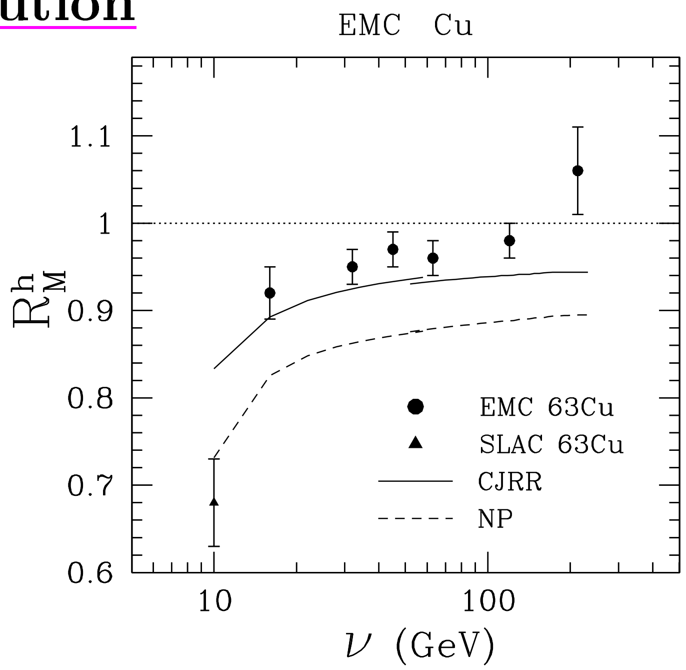
$$\tau_F = \left(\frac{-\ln(z^2) - 1 + z^2}{1 - z^2} \right) \frac{z\nu}{\kappa}$$

$$\tau_F \longrightarrow \begin{cases} (1-z)\nu/\kappa & z \to 1 \\ -2\ln(z) z\nu/\kappa & z \to 0 \end{cases}$$

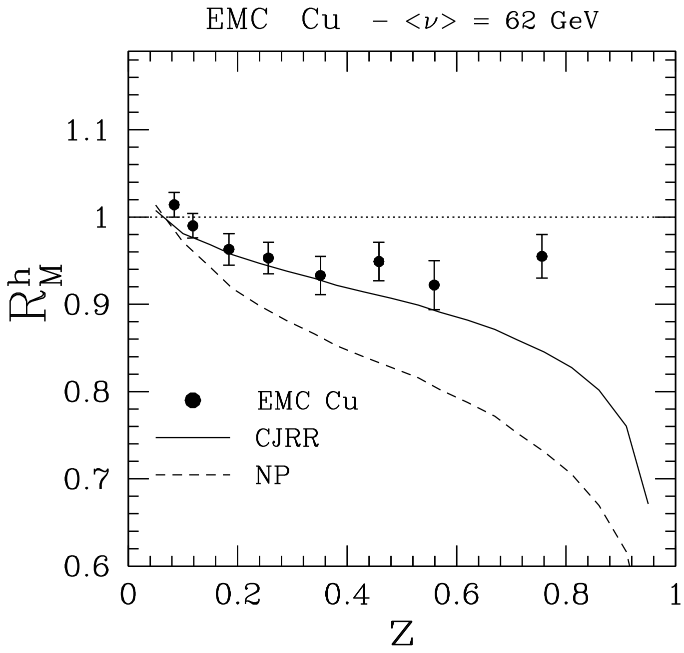


Results at EMC with absorption

ν-distribution

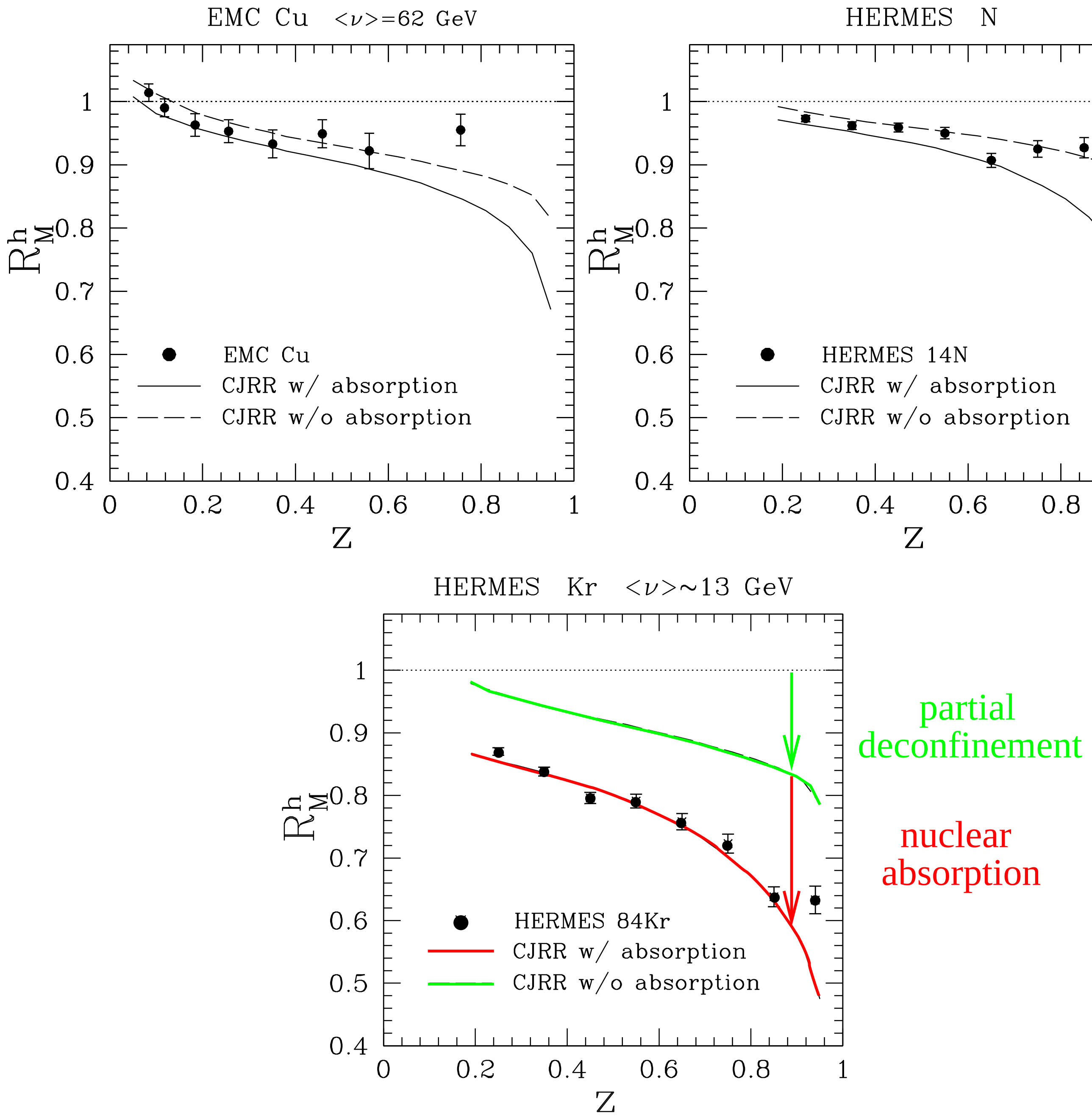


z-distribution



- Maximal deconfinement (NP) RULED OUT
- Partial deconfinement (CJRR) OK

Rescaling vs. absorption

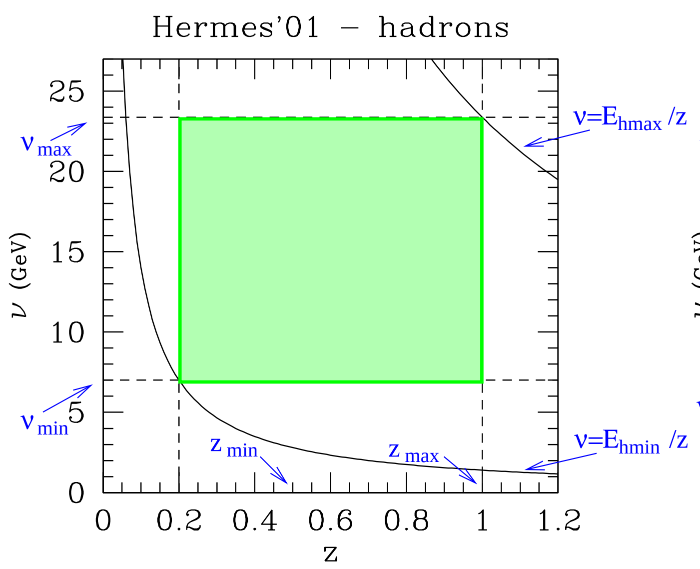


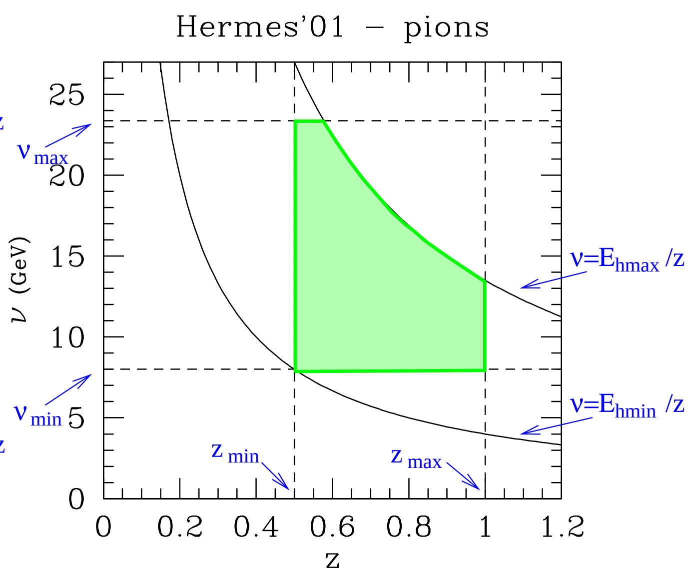
- At large $\langle \nu \rangle$ (EMC) rescaling is the dominant effect
- At small $\langle \nu \rangle$ (HERMES) absorption is dominant
- Rescaling larger at HERMES than at EMC

HERMES '01

Experimental cuts

		h	π
Q^2_{min}	GeV^2	1	...
W^2_{min}	GeV^2	4	...
y_{max}		0.85	...
x_{min}		0.06	...
x_{max}		1	...
z_{min}		0.2	0.5
z_{max}		1	...
ν_{min}	GeV	7	8
ν_{max}	GeV	23.375	...
$E_{h\text{min}}$	GeV	1.4	4
$E_{h\text{max}}$	GeV	23.375	13.5

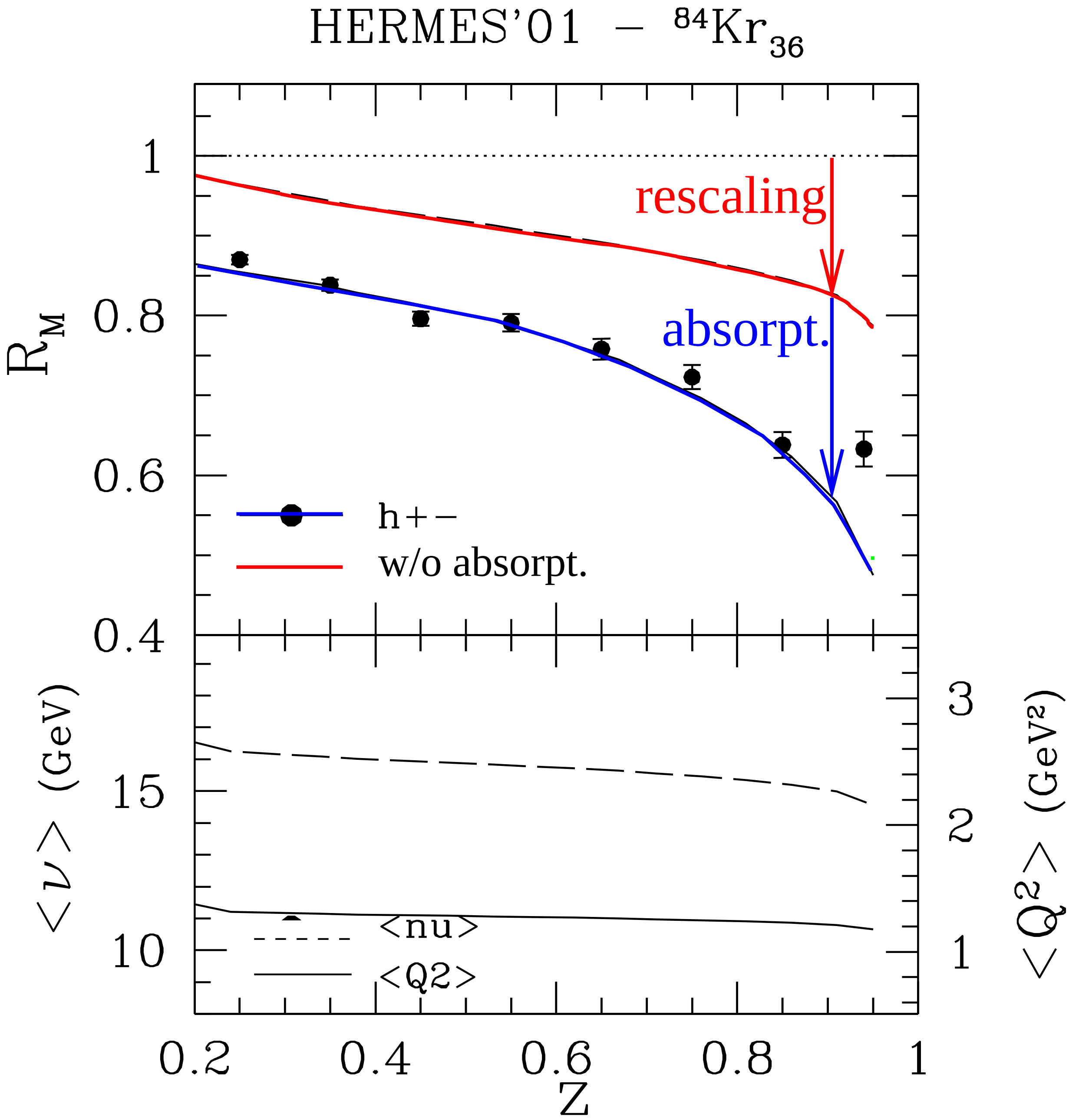




Note:
- $E_h = z\nu$: hadron energy
- $y = \nu / E_{lab}$
- $W^2 = M_p^2 + 2M_p\nu - Q^2$

Charged hadrons - Krypton

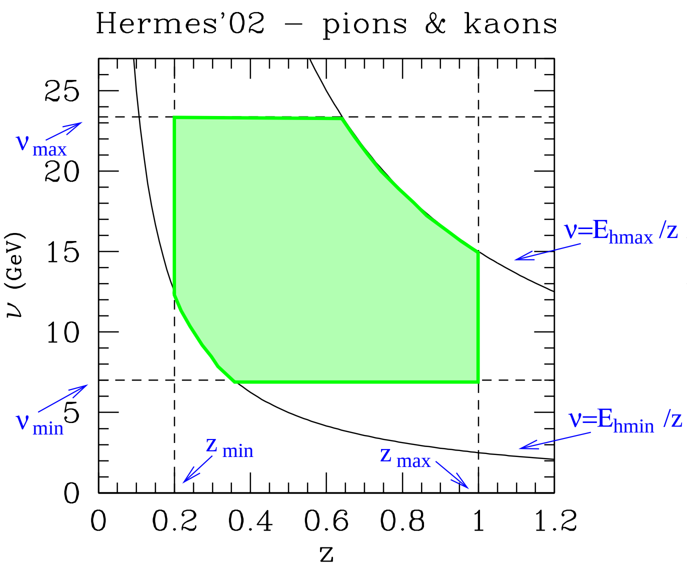
$$\sigma_h^{\text{in}} = 20 \text{ mbarn}$$

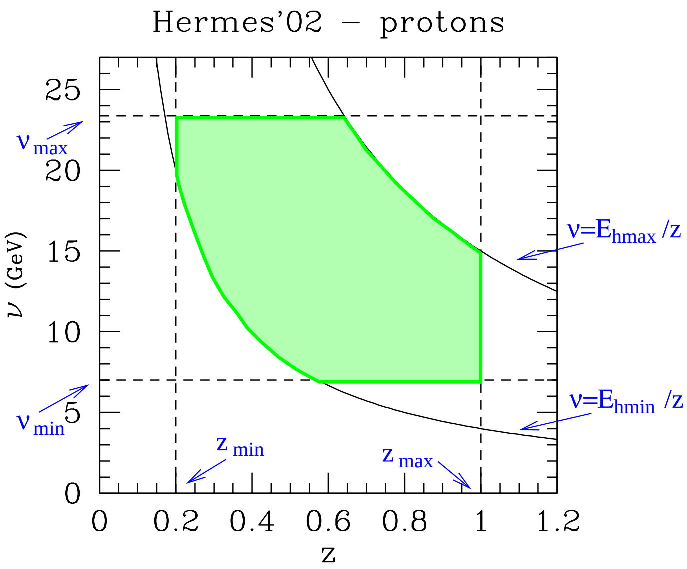


HERMES '02

Experimental cuts

		$\pi,\ K$	p
$Q^2_{\rm min}$	GeV^2	1	...
$W^2_{\rm min}$	GeV^2	4	...
$y_{\rm max}$		0.836	...
$x_{\rm min}$		0.02	...
$x_{\rm max}$		1	...
$z_{\rm min}$		0.2	...
$z_{\rm max}$		1	...
$\nu_{\rm min}$	GeV	7	...
$\nu_{\rm max}$	GeV	23.0	...
$E_{h\rm min}$	GeV	2.5	4
$E_{h\rm max}$	GeV	15	...



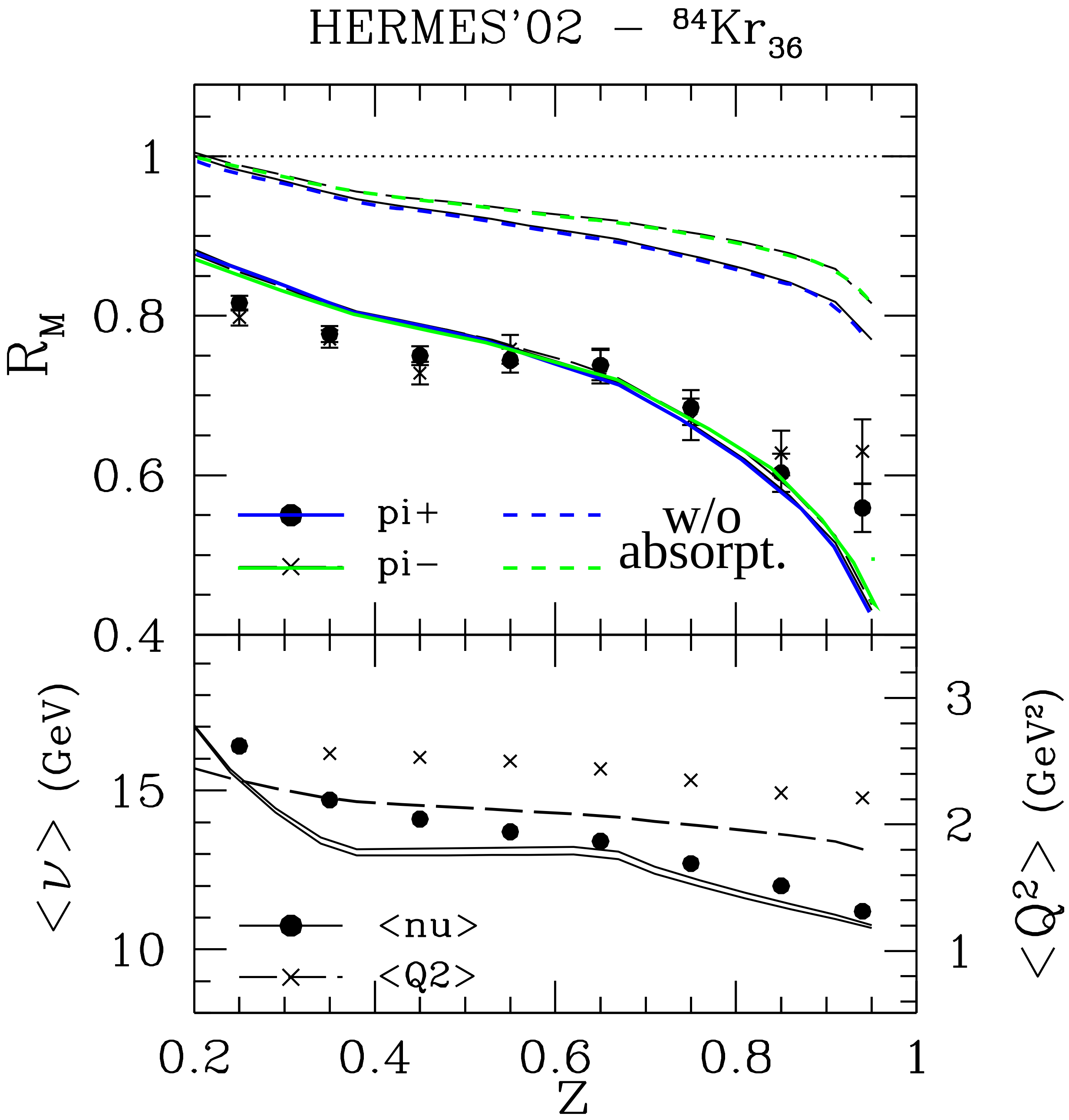


Note:

- $E_h = z\nu$: hadron energy
- $y = \nu / E_{lab}$
- $W^2 = M_p^2 + 2M_p\nu - Q^2$

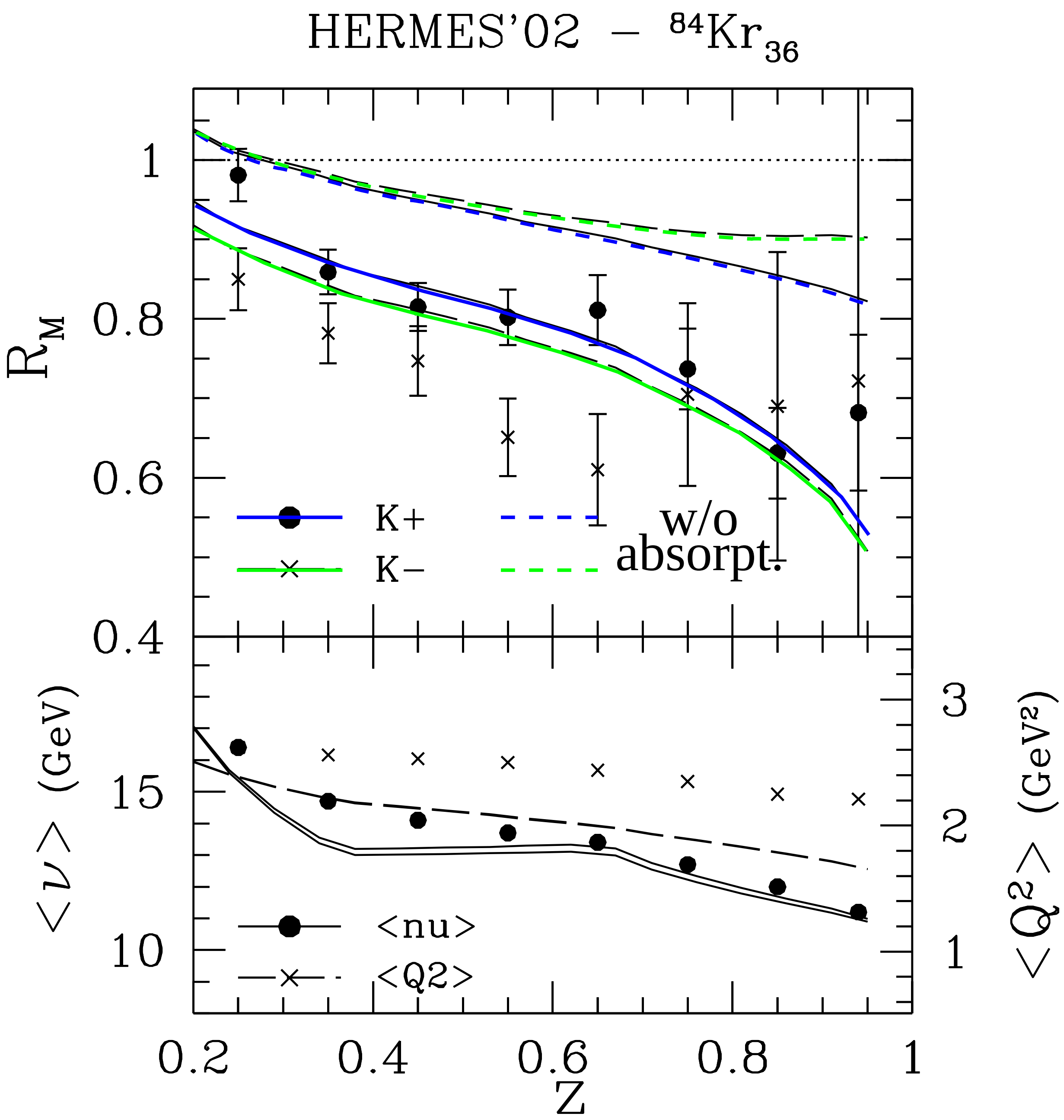
Pions - charge separated

$\sigma^{in}_{\pi+} = 20$ mbarn $\qquad \sigma^{in}_{\pi-} = 22$ mbarn

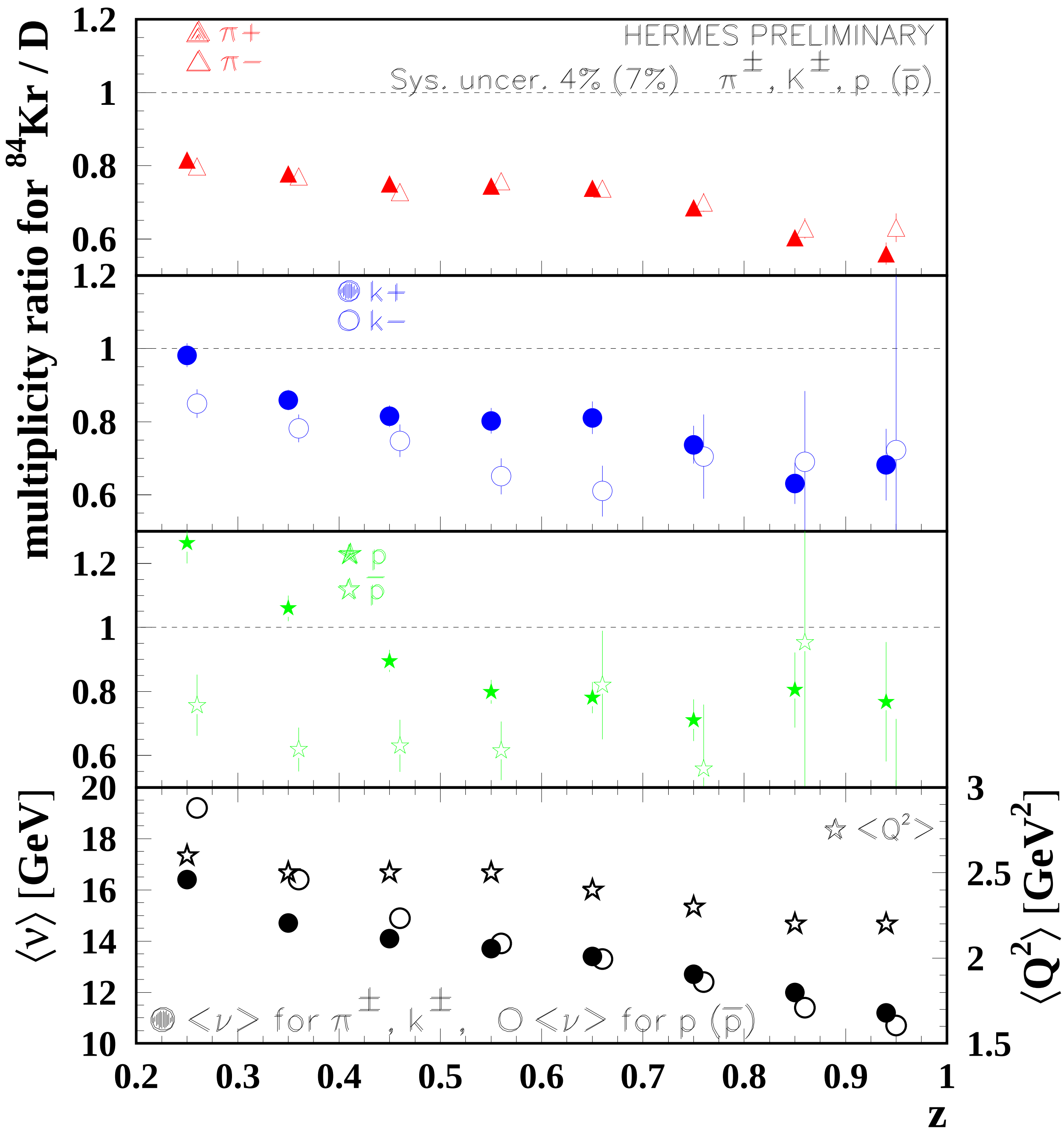


Kaons - charge separated

$\sigma^{\text{in}}_{K+} = 14$ mbarn $\qquad \sigma^{\text{in}}_{K-} = 20$ mbarn



Protons and anti-protons



⇝ proton knock-out at low-z ?

What else?

Energy- and hadron- dependent cross-sections

Inelastic cross-sections (mbarn)

process	2.5 GeV	4.5 GeV	10 GeV	100 GeV
$(\pi+\ p)$	22	21	20	20
$(\pi\text{-}\ p)$	26	24	22	21
$(K+\ p)$	12	13	14	16
$(K\text{-}\ p)$	22	21	20	18
$(p\ p)$	27	27	30	31
$(p\ n)$	18	22	40	
$(\bar{p}\ p)$	53	46	40	35

- Regge theory Gasiorowicz "El. part. phys." '67:

$$\sigma_{\text{had}}^{\text{tot}}(s) = X s^{\epsilon} + Y s^{-\eta}$$

$$\sigma_{\text{had}}^{\text{el}}(s) = \int dt\, \frac{\left[\sigma_{\text{had}}^{\text{tot}}(s)\right]^2}{16\pi}\, e^{-at - bt^2}$$

$$\simeq \text{const} \times \left[\sigma_{\text{had}}^{\text{tot}}(s)\right]^2$$

$$\boxed{\sigma_{\text{had}}^{\text{inel}}(s) = \sigma_{\text{had}}^{\text{tot}}(s) - \sigma_{\text{had}}^{\text{el}}(s)}$$

$\rightsquigarrow$ also hadron-neutron cross-sections computable

Conclusions

- The CJJR rescaling model is supported by data (but smallish "string-tension" k).
- Theoretical uncertainties due to
  - FF's parametrizations ($\simeq 2\%$; worse at high-z)
  - unadequate treatment of $\langle \nu \rangle$ and $\langle Q^2 \rangle$
- Actually: $\Delta R_M^h|_{theor.} \simeq 3 - 4\%$
  $k \simeq 0.25 - 0.6$ GeV/fm
- Extra effects need to be included in the comp's;
  - Energy and hadron dependent $\sigma_{\rm had}^{\rm in}(E_h, h)$
  - NLO $\gamma^* q$ cross-section
    (for the moment use exp. $\langle Q^2 \rangle$ and $\langle \nu \rangle$)
- Model is very promising for Hermes'02 data interpretation.