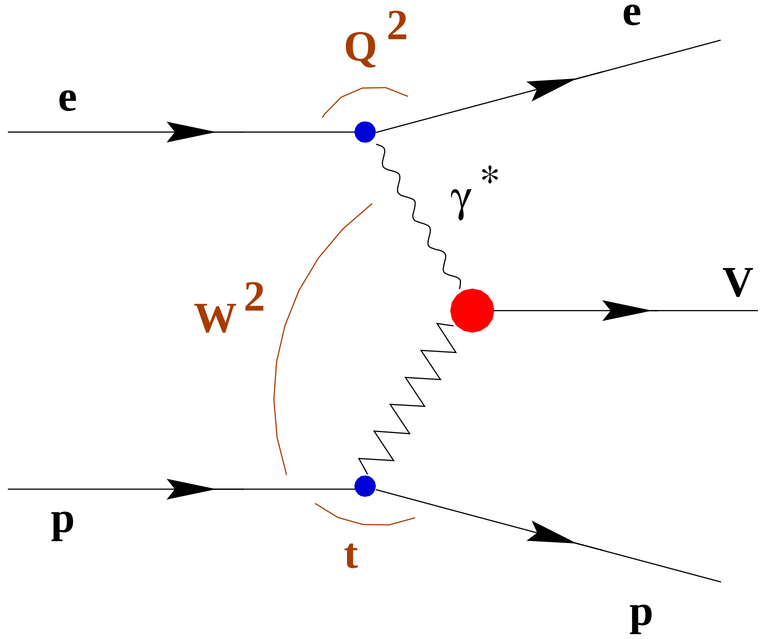
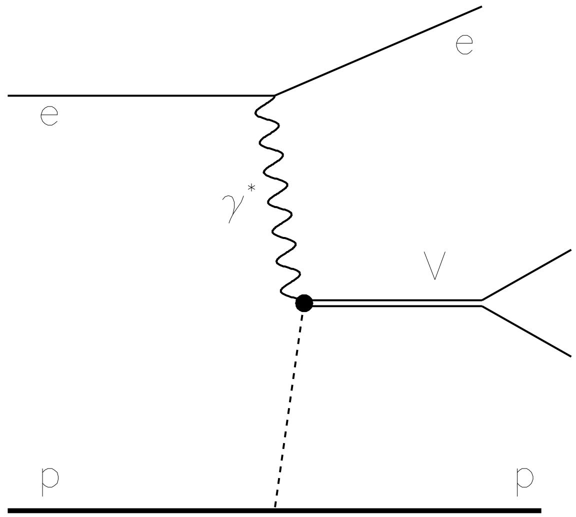
HERMES Results on Vector Meson Production at Intermediate Energies



Michael Tytgat

University of Gent

Exclusive Vector Meson Production



$e + p \rightarrow e + p + V$

incoming,outgoing lepton : k, k'
initial nucleon : $p \overset{lab}{=} (0, M)$
recoiling nucleon : p'
vector meson : v

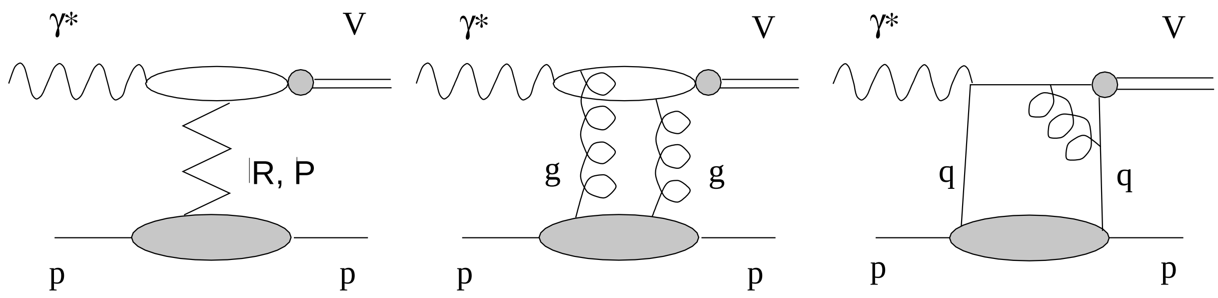
photon virtuality : $Q^2 \equiv -q^2 = -(k - k')^2 \overset{lab}{\approx} 4\,E\,E' \sin^2(\frac{\theta}{2})$
$(0.7 < Q^2 < 5.0$ GeV$^2)$

Bjorken-x : $x \equiv \dfrac{Q^2}{2\,p \cdot q} = \dfrac{Q^2}{2\,M\,\nu}$ with $\nu \equiv \dfrac{p \cdot q}{M} \overset{lab}{=} E - E'$ $(0.02 < x < 0.22)$

center-of-mass energy squared :
$s = W^2 = (q + p)^2 = M^2 + 2\,M\,\nu - Q^2 = M^2 + Q^2 \frac{1-x}{x}$ $(4.0 < W < 6.0$ GeV$)$

squared momentum transfer to hadronic vertex : $t = (q - v)^2 = (p - p')^2 < 0$

Exclusive Vector Meson Production



- Vector Meson Dominance Model :

$$|\gamma > \simeq |\gamma_B > + \sqrt{\alpha} |\gamma_h >$$

photon fluctuates into light vector meson (ρ^0, ω or ϕ) before interaction

$\rightarrow$ Hadronic content of photon, unification of photon-hadron and hadron-hadron interactions

- Regge theory :

exchanged object in t-channel = particle resonance (Reggeon) at low W and Pomeron at high W

- Perturbative QCD regime (high Q^2, high $|t|$ or heavy quark production) :

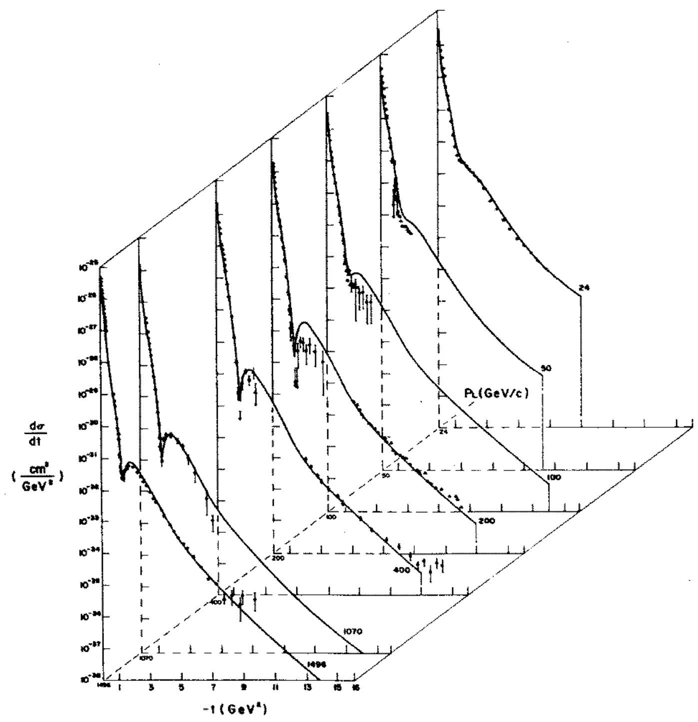
factorization $\rightarrow$ $A = \Psi^*_{\gamma^* \rightarrow q\bar{q}} \otimes A_{q\bar{q}+p \rightarrow q\bar{q}+p} \otimes \Psi_{q\bar{q} \rightarrow V}$

- Pomeron has partonic structure : gg, $q\bar{q}$

Diffraction in Particle Physics

- Diffraction in optics : characteristic pattern of minima and maxima behind an obstruction of a wavefront

- Similar observations in angular distributions of particle scattering



- Steep momentum transfer (angular) distributions; at small t : $e^{-b|t|}$

- Slope of angular distributions increases slowly with energy

- Total cross sections at high energy increase slowly with energy

The HERMES Experiment

HERMES = HERa MEasurement of Spin

Study nucleon spin content, mainly by inclusive and semi-inclusive double spin asymmetries in polarized deep inelastic scattering

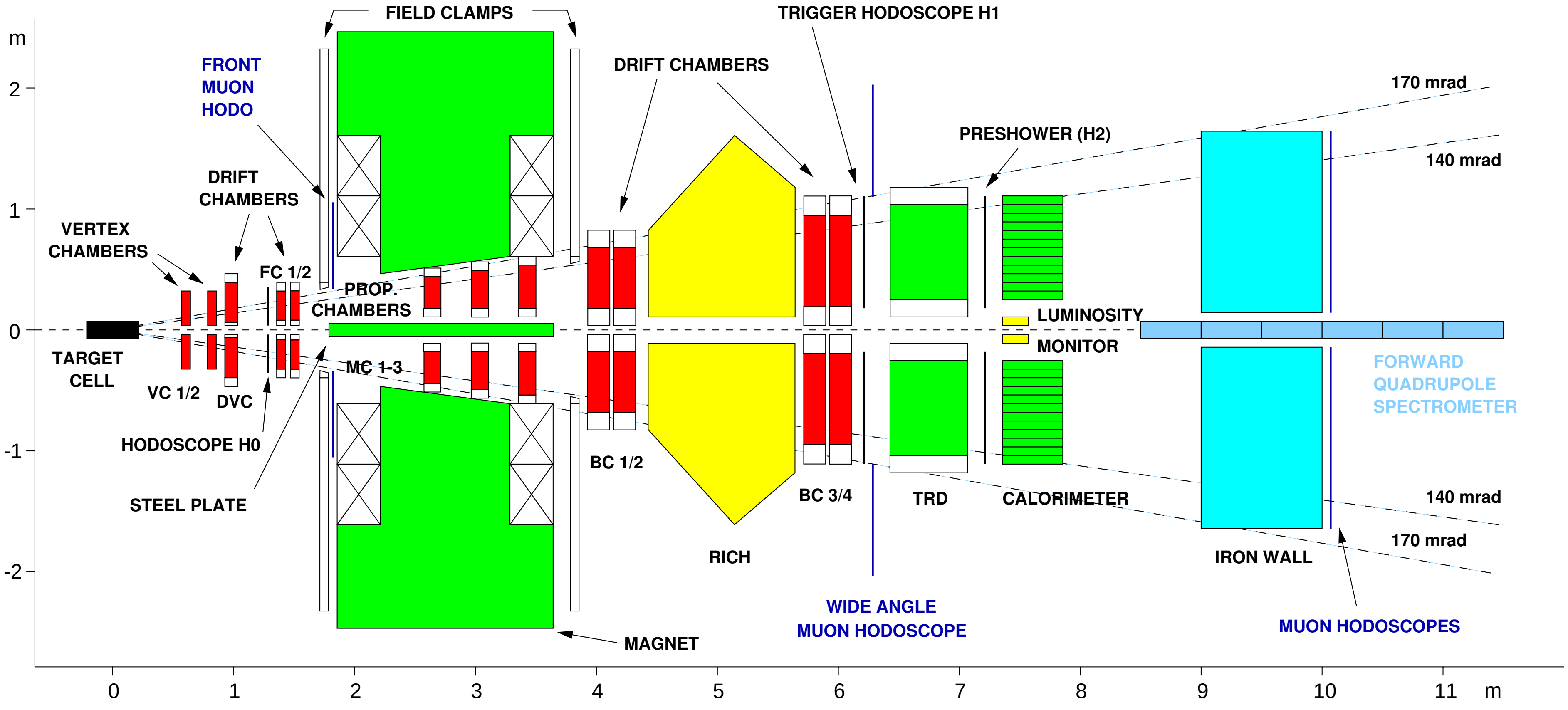
$$\Rightarrow \begin{cases} \text{polarized HERA e-beam} \\ \text{internal gas target} \begin{cases} \text{polarized } ^3\vec{\text{He}},\ ^1\vec{\text{H}} \text{ and } ^2\vec{\text{H}} \\ \text{unpolarized } ^1\text{H},\ ^2\text{H},\ ^3\text{He},\ ^{14}\text{N},\ ^{84}\text{Kr} \ldots \end{cases} \end{cases}$$

Forward spectrometer : $40 < |\theta_y| < 140$ mrad, $|\theta_x| < 170$ mrad

Particle identification : mainly lepton/hadron separation; since 1998 RICH for hadron identification

$$\Rightarrow \text{Vector meson production :} \begin{cases} \rho^0 \to \pi^+\pi^- \\ \omega \to \pi^+\pi^-\pi^0(\to 2\gamma), \gamma\pi^0(\to 2\gamma) \\ \phi \to K^+K^- \\ J/\Psi \to e^+e^-, \mu^+\mu^- \end{cases}$$

HERMES Spectrometer



Exclusive, Diffractive Production @ HERMES

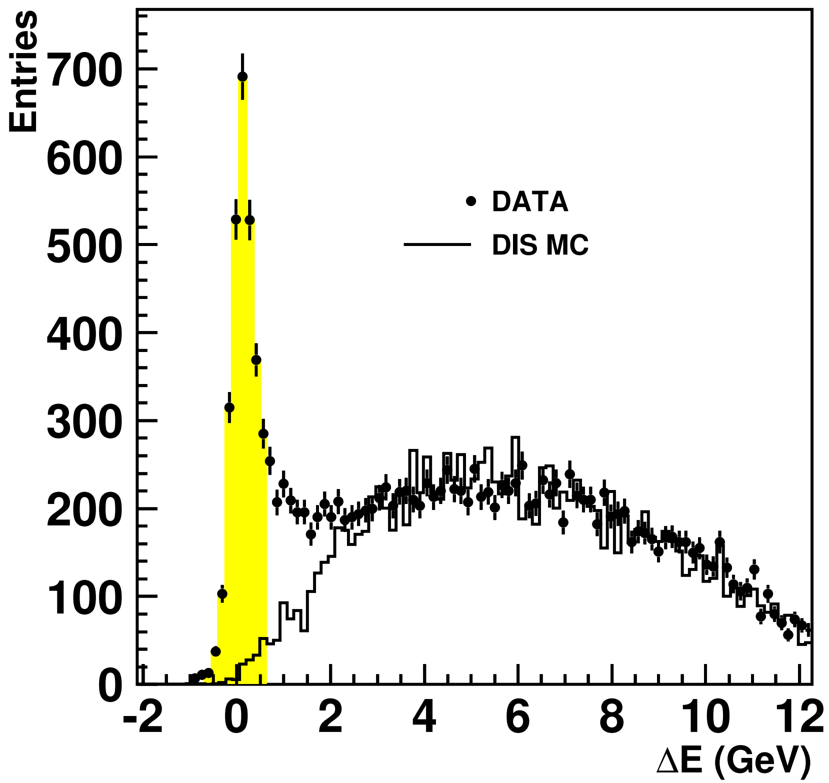
No recoil detection (so far . . .)

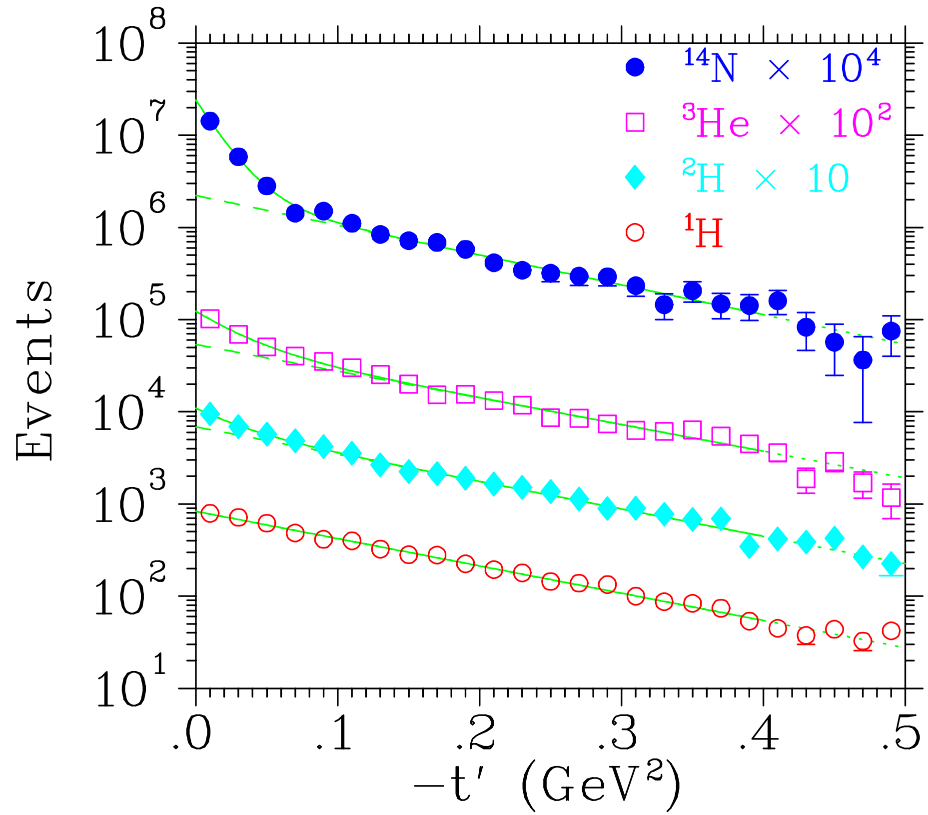
$\rightarrow$ Exclusivity : $\Delta E = \dfrac{M_X^2 - M_p^2}{2\, M_p}$

with $M_X^2 = (p + q - v)^2$

Diffractive production @ low $|t'| = |t - t_0|$

Incoherent / coherent production

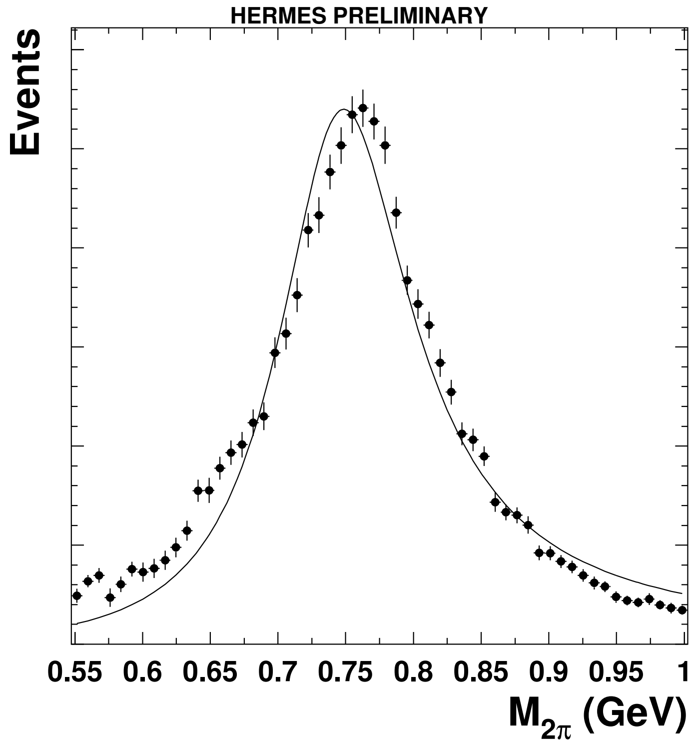




ρ^0 Invariant Mass Distribution

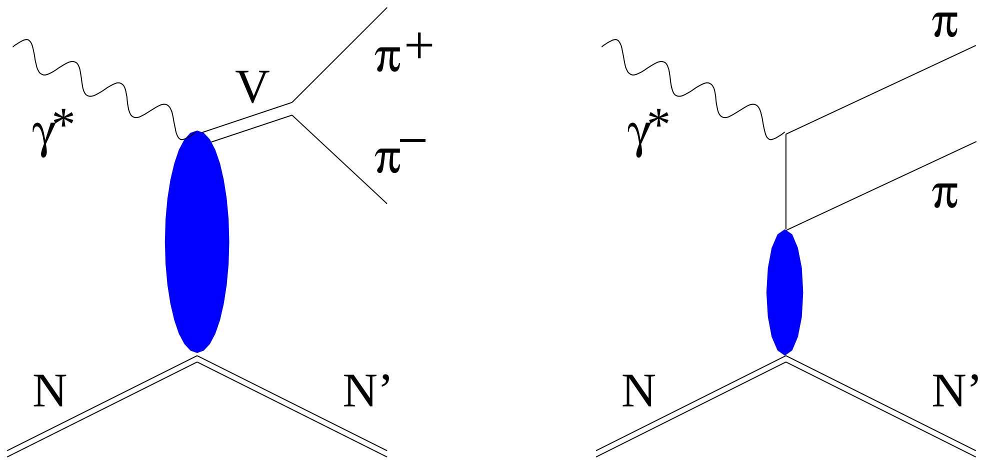
p-wave Breit-Wigner :

$$\frac{\mathrm{d}N}{\mathrm{d}M_{2\pi}} \equiv BW(M_{2\pi}) = \frac{2}{\pi} \frac{M_{2\pi}\, M_\rho\, \Gamma(M_{2\pi})}{(M_\rho^2 - M_{2\pi}^2)^2 + M_\rho^2\, \Gamma^2(M_{2\pi})}$$



$\Rightarrow$ ρ^0 resonance is skewed

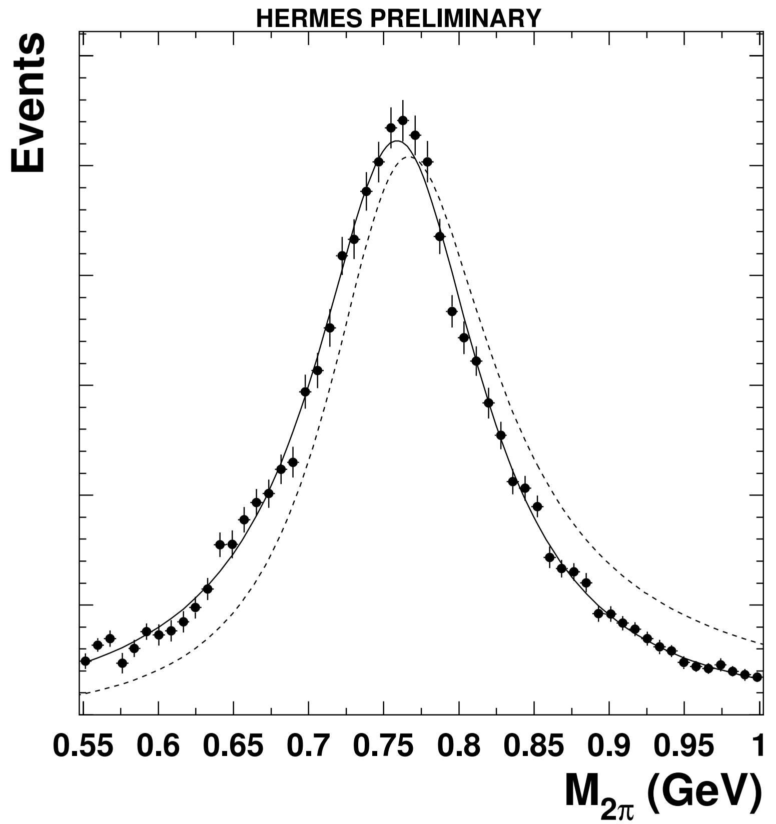
- Interference of resonant diagram with non-resonant 2-pion production



ρ^0 Resonance Skewing

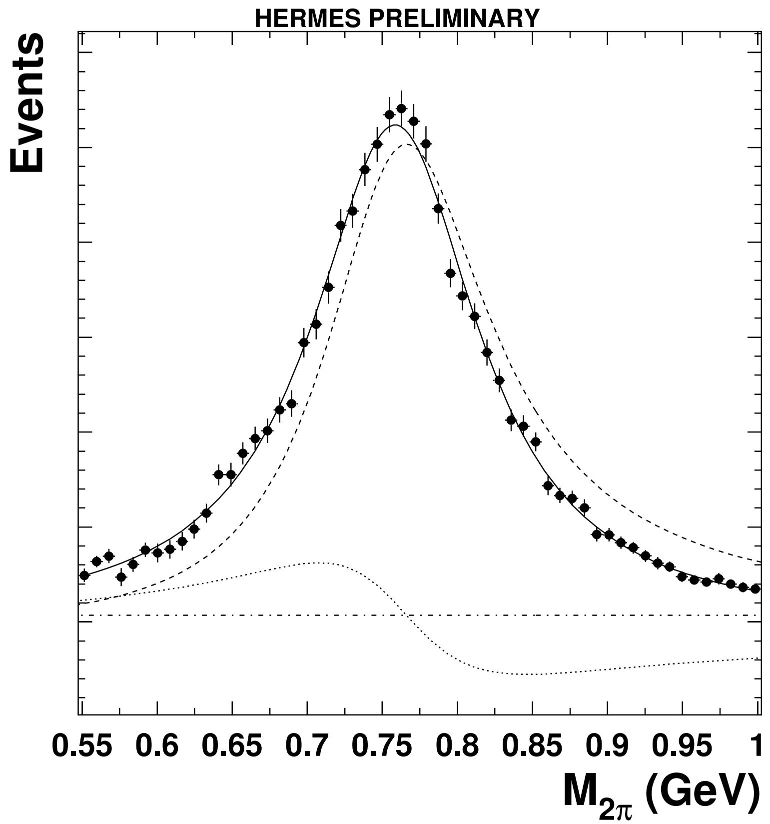
Ross-Stodolsky :

$$\frac{dN}{dM_{2\pi}} = BW(M_{2\pi}) \left(\frac{M_\rho}{M_{2\pi}}\right)^{n_{skew}}$$

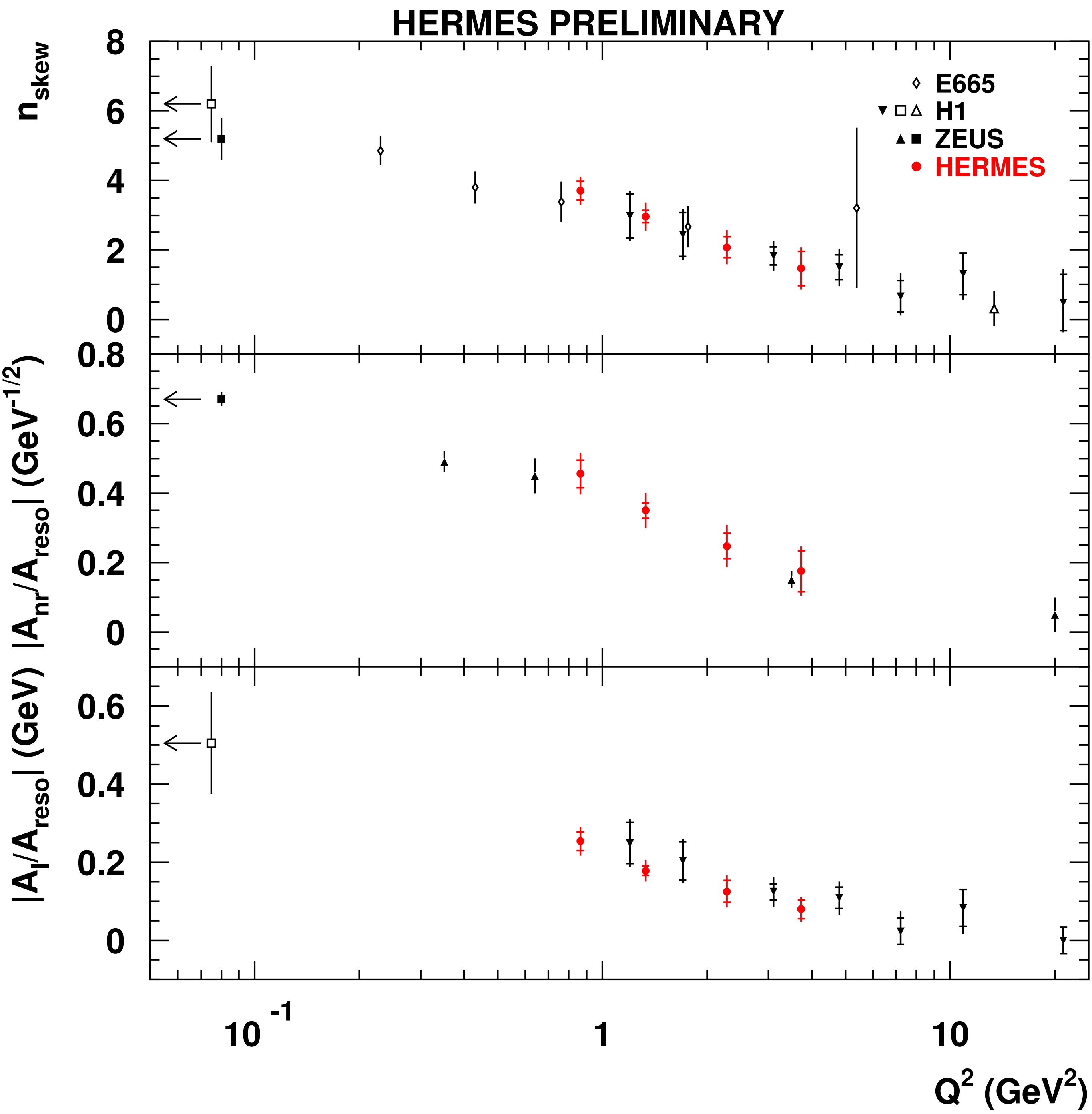


Söding :

$$\frac{dN}{dM_{2\pi}} = \left| A_{reso} \frac{\sqrt{M_{2\pi}\, M_\rho\, \Gamma(M_{2\pi})}}{M_{2\pi}^2 - M_\rho^2 + i\, M_\rho\, \Gamma(M_{2\pi})} + A_{nr} \right|^2$$



ρ^0 Resonance Skewing



$\Rightarrow$ Skewing Q^2 dependent, disappears @ high Q^2

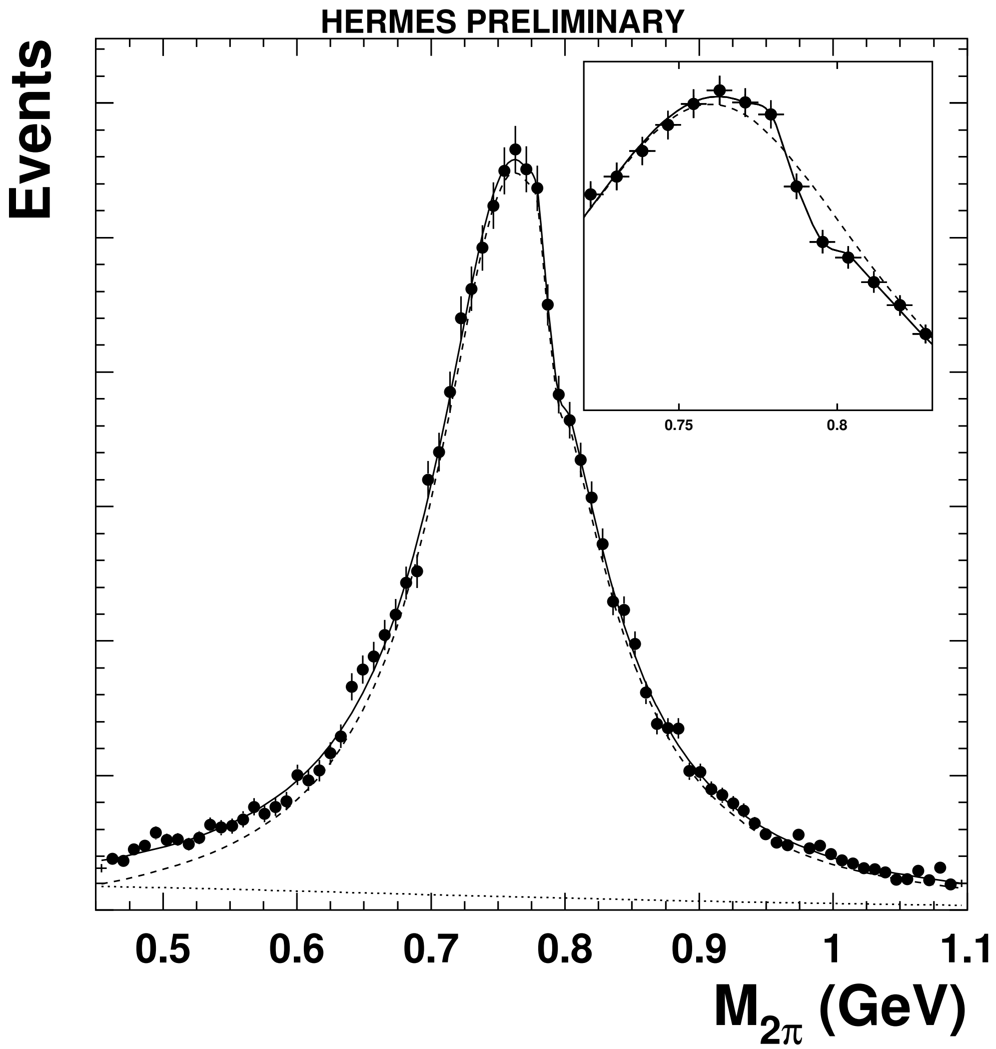
$\Rightarrow$ Skewing exhibits no W dependence

$\Rightarrow$ No significant t-dependence found

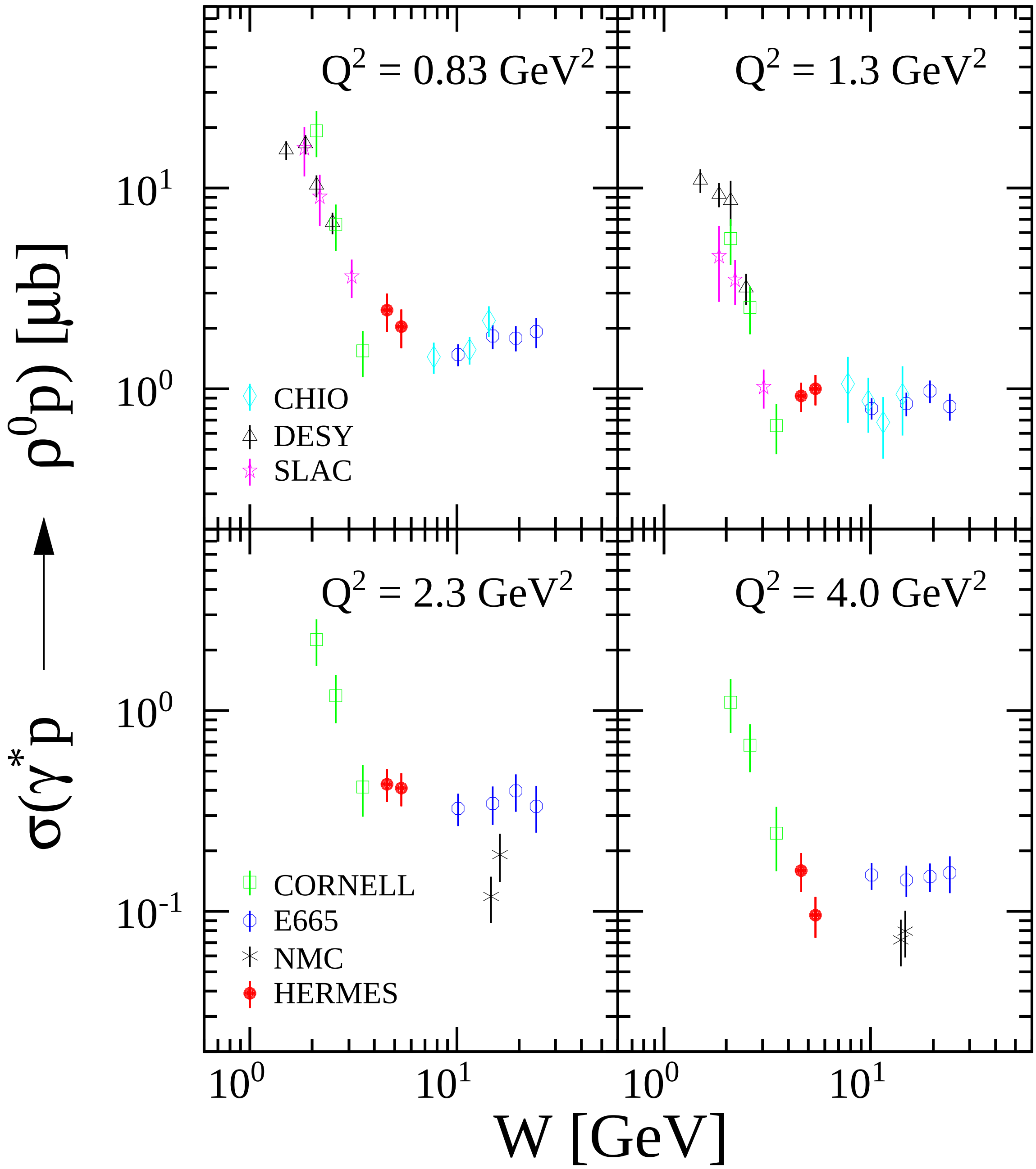
$\rho^0 - \omega$ Interference

ω meson has small $\pi^+\pi^-$ decay mode and $M_\omega \approx M_{\rho^0}$
$\rightarrow$ $\rho^0 - \omega$ mixing

$$\frac{\mathrm{d}N}{\mathrm{d}M_{2\pi}} = \frac{2}{\pi} M_{2\pi} M_\rho \Gamma(M_{2\pi}) \left(\frac{M_\rho}{M_{2\pi}}\right)^{n_{skew}} \cdot$$
$$\left| \frac{1}{M_{2\pi}^2 - M_\rho^2 + i\, M_\rho \Gamma(M_{2\pi})} + \frac{\xi\, e^{i\alpha}}{M_{2\pi}^2 - M_\omega^2 + i\, M_\omega \Gamma_\omega} \right|^2$$



ρ^0 Production Cross Section

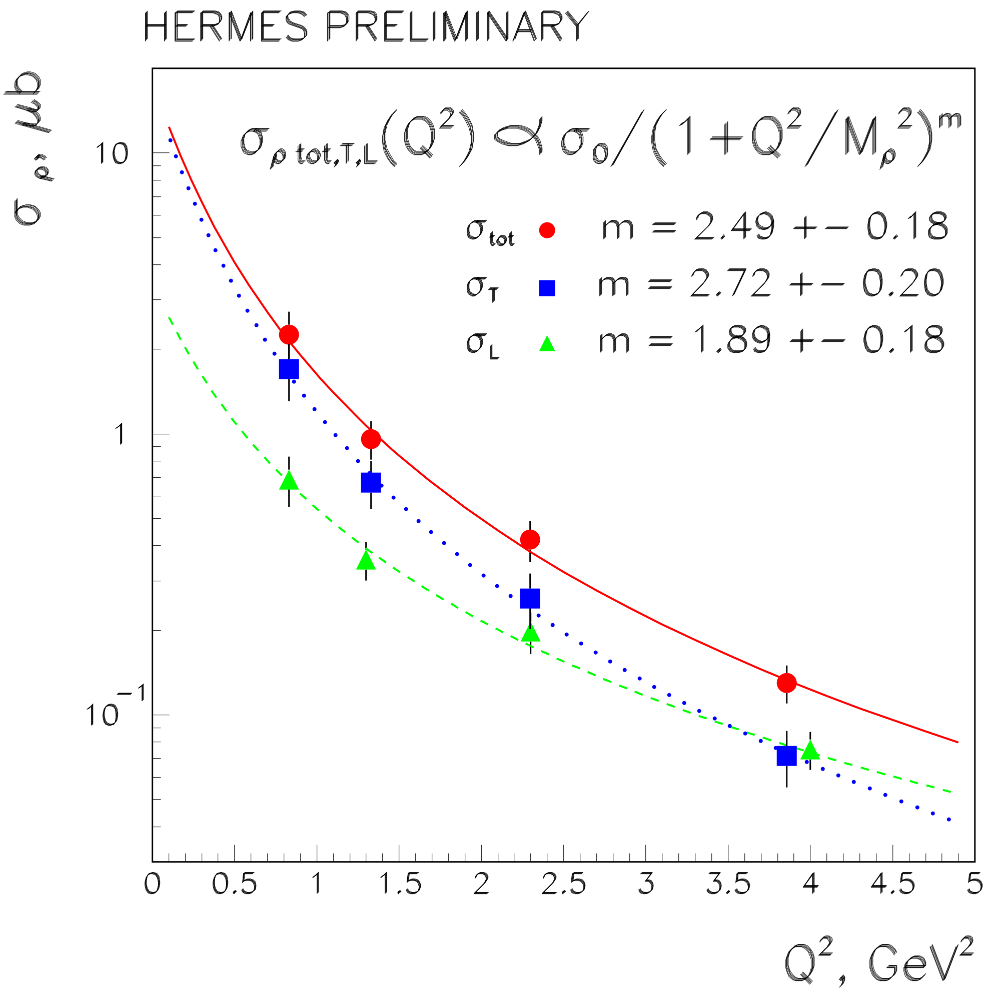


⇒ HERMES data in transition region
between low and high energy regime

⇒ Mixture of different production mechanisms ?

ρ^0 Production Cross Section

$$\sigma(Q^2) = \sigma_0 \left(\frac{M_V^2}{Q^2 + M_V^2}\right)^m (1 + \epsilon\, R(Q^2))$$



Vector Meson Dominance model : $m = 2$

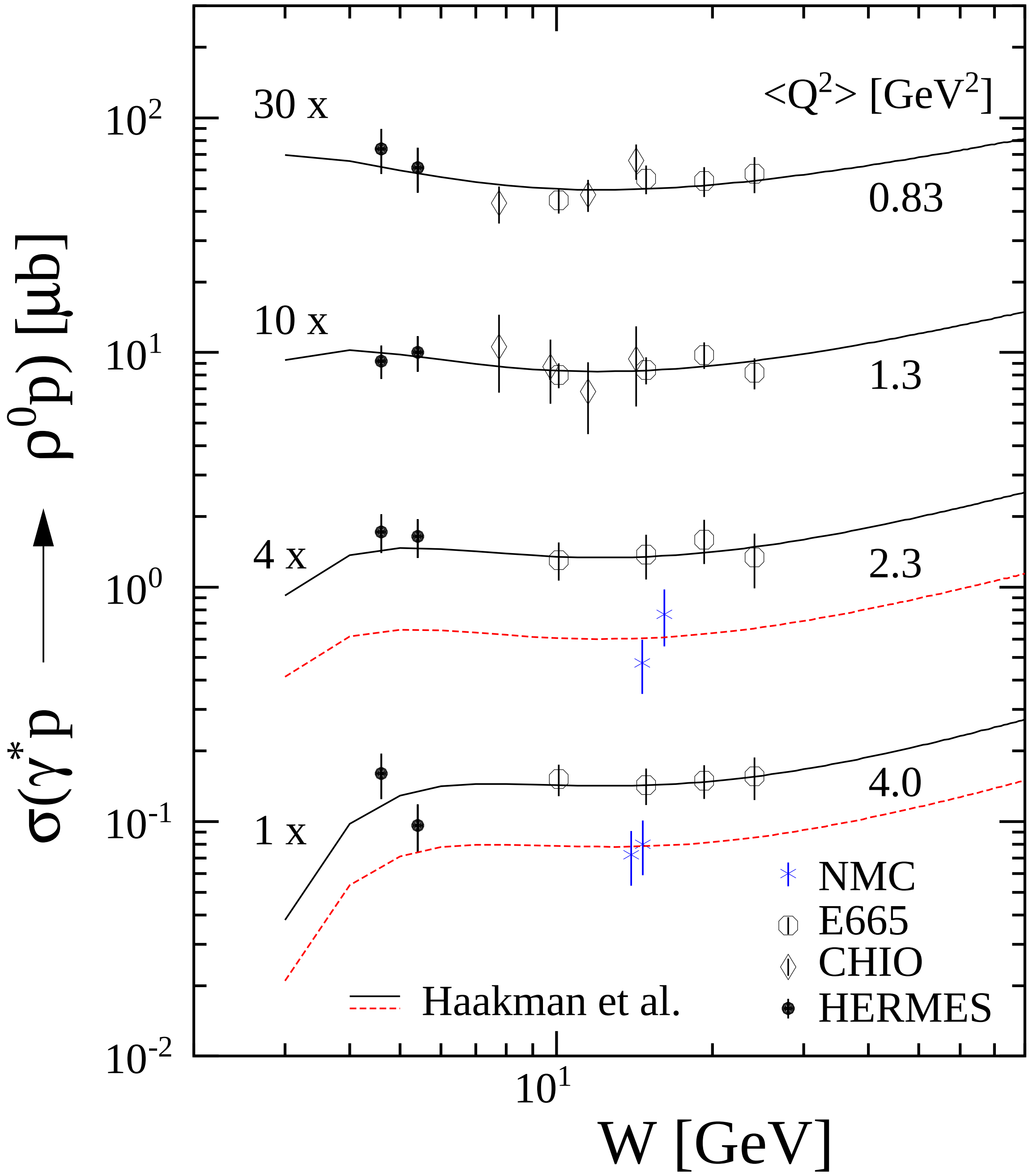
pQCD models : $m_{\sigma_L} \approx 3$

$\Rightarrow$ Onset of pQCD region @ HERMES ?

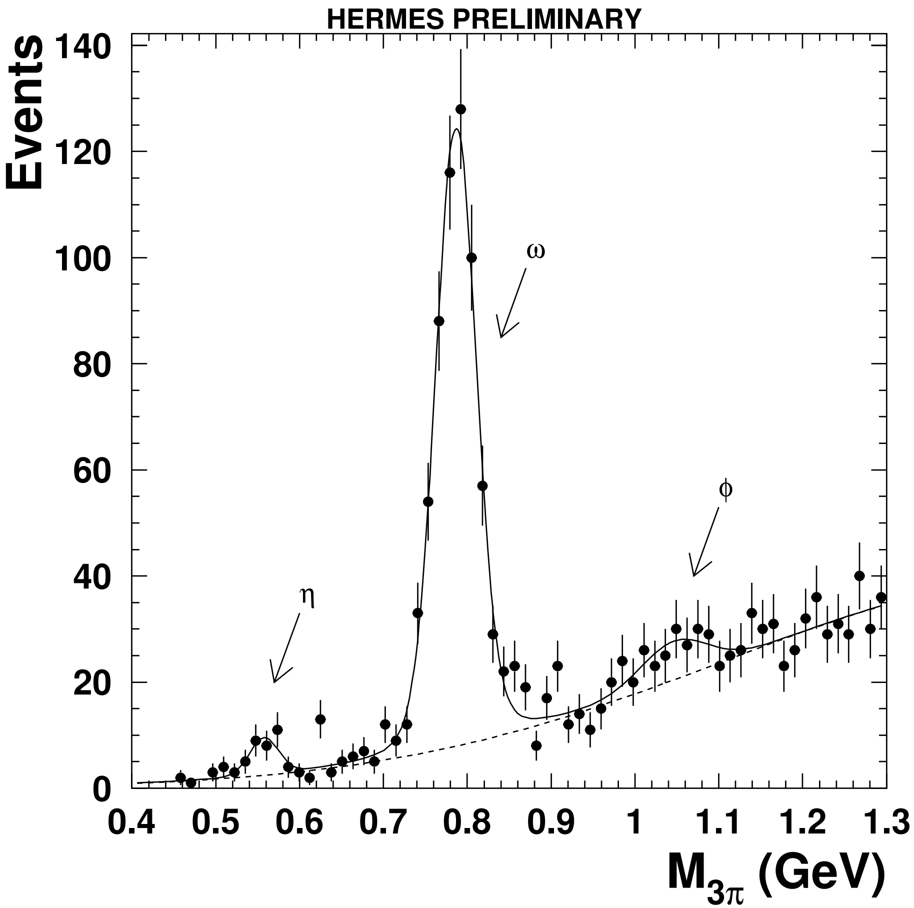
ρ^0 Production Cross Section

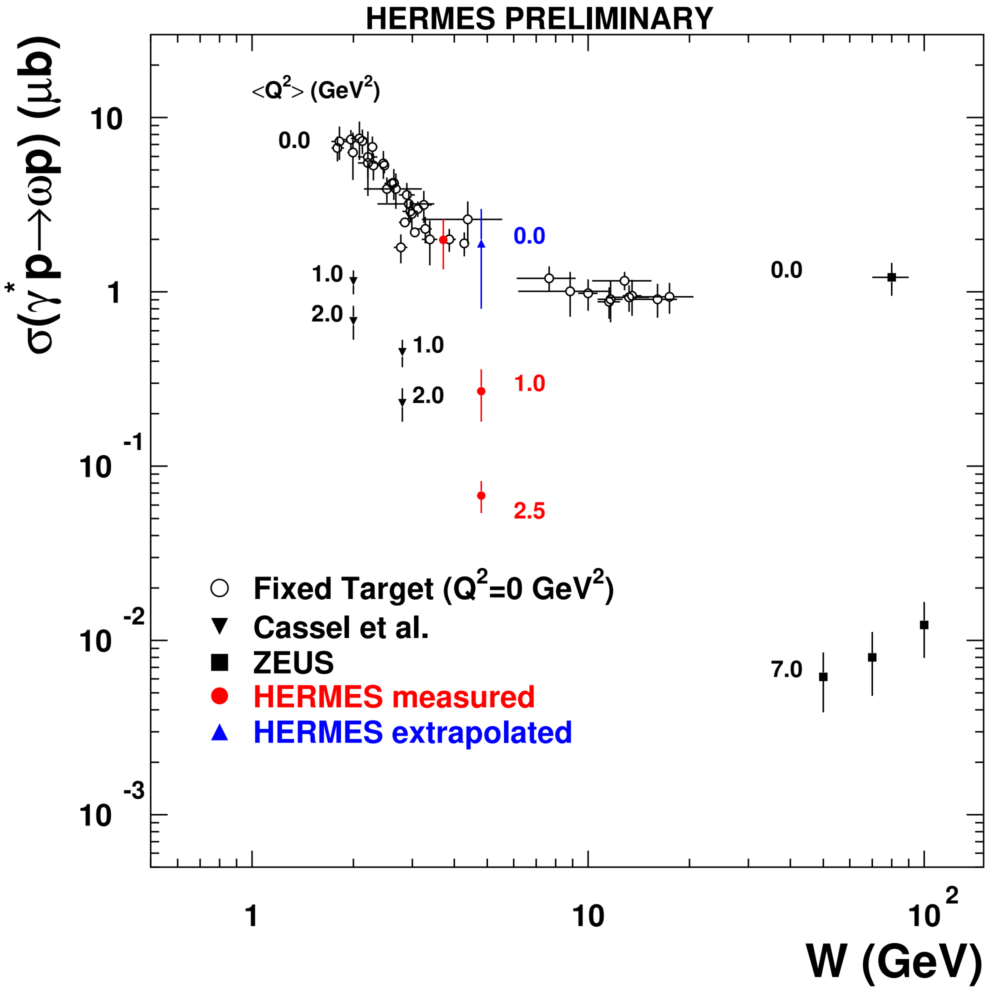
Haakman *et al.*, **PLB 365** (1996) 411

$\rightarrow$ Regge based parametrization of F_2^p



ω Production Cross Section





Off Forward Parton Distribution Formalism

Off Forward Parton Distributions :

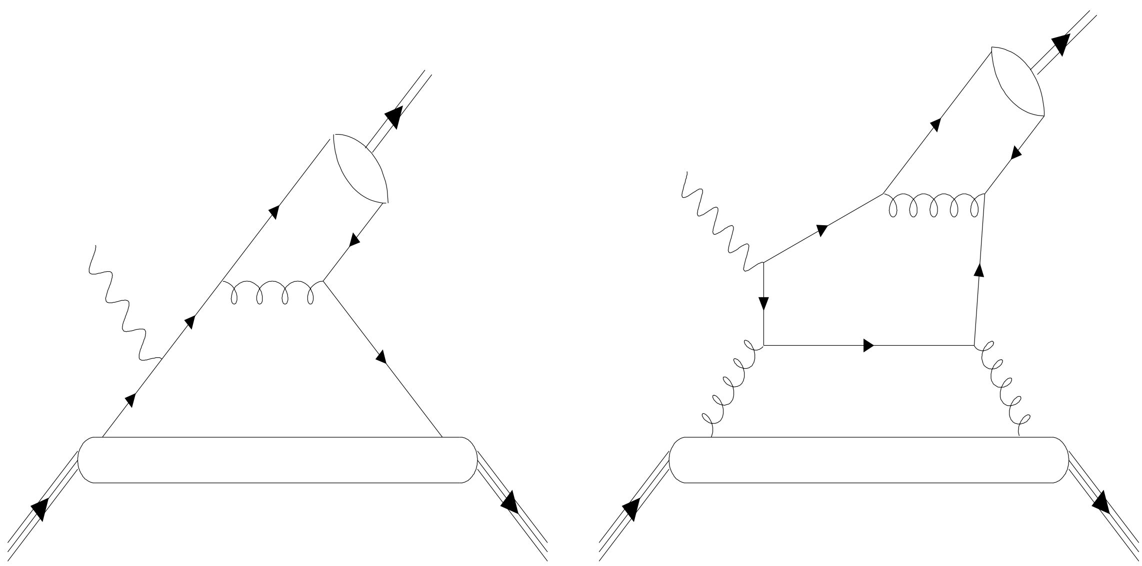
$\rightarrow$ generalization of standard parton distributions from DIS; relation with nucleon form factors

$\rightarrow$ Uniform description of exclusive processes, i.e. vector mesons, pseudo-scalar and real photons (Compton scattering)

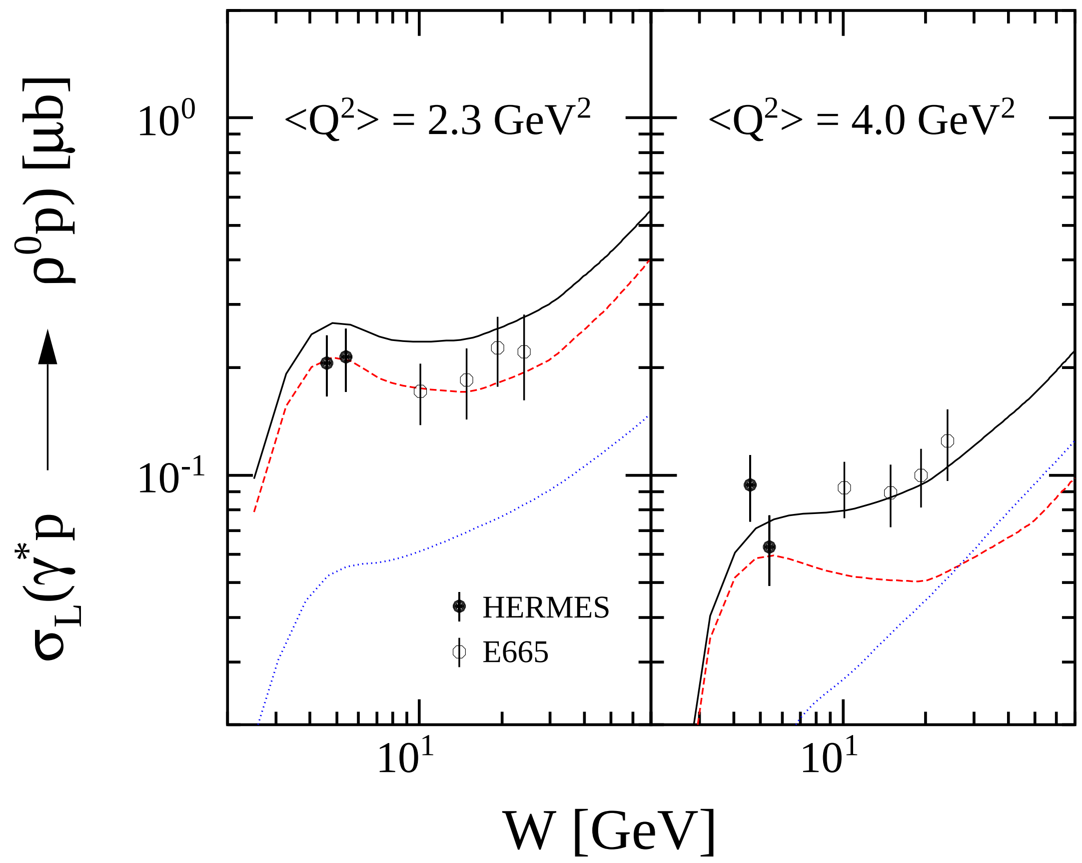
$\rightarrow$ Determine quark and gluon total spin contributions to nucleon spin

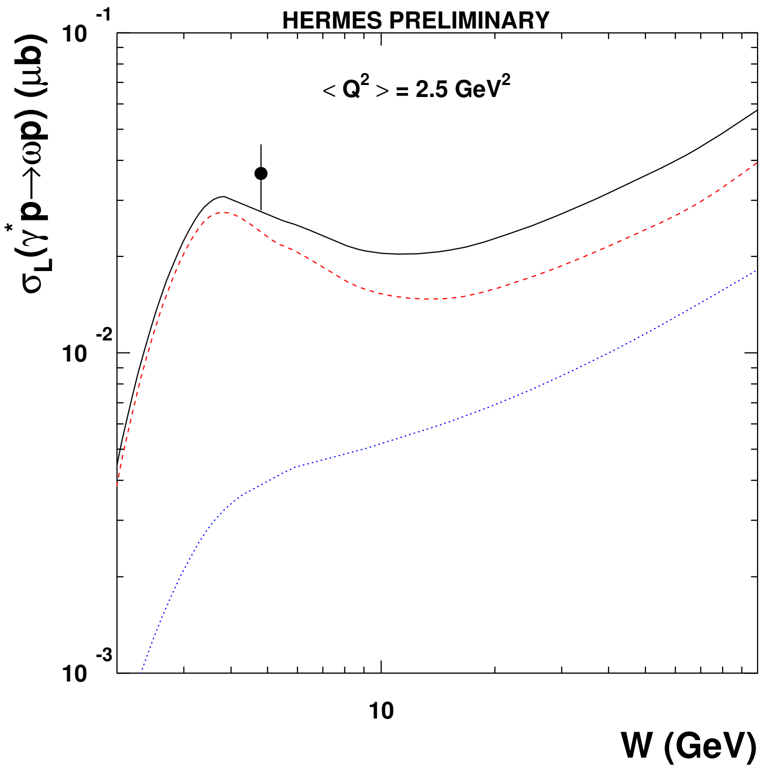
Vanderhaeghen *et al.*, **PRD 60** (1999) 094017

$\rightarrow$ OFPD based calculation



ρ^0 and ω Production Cross Section



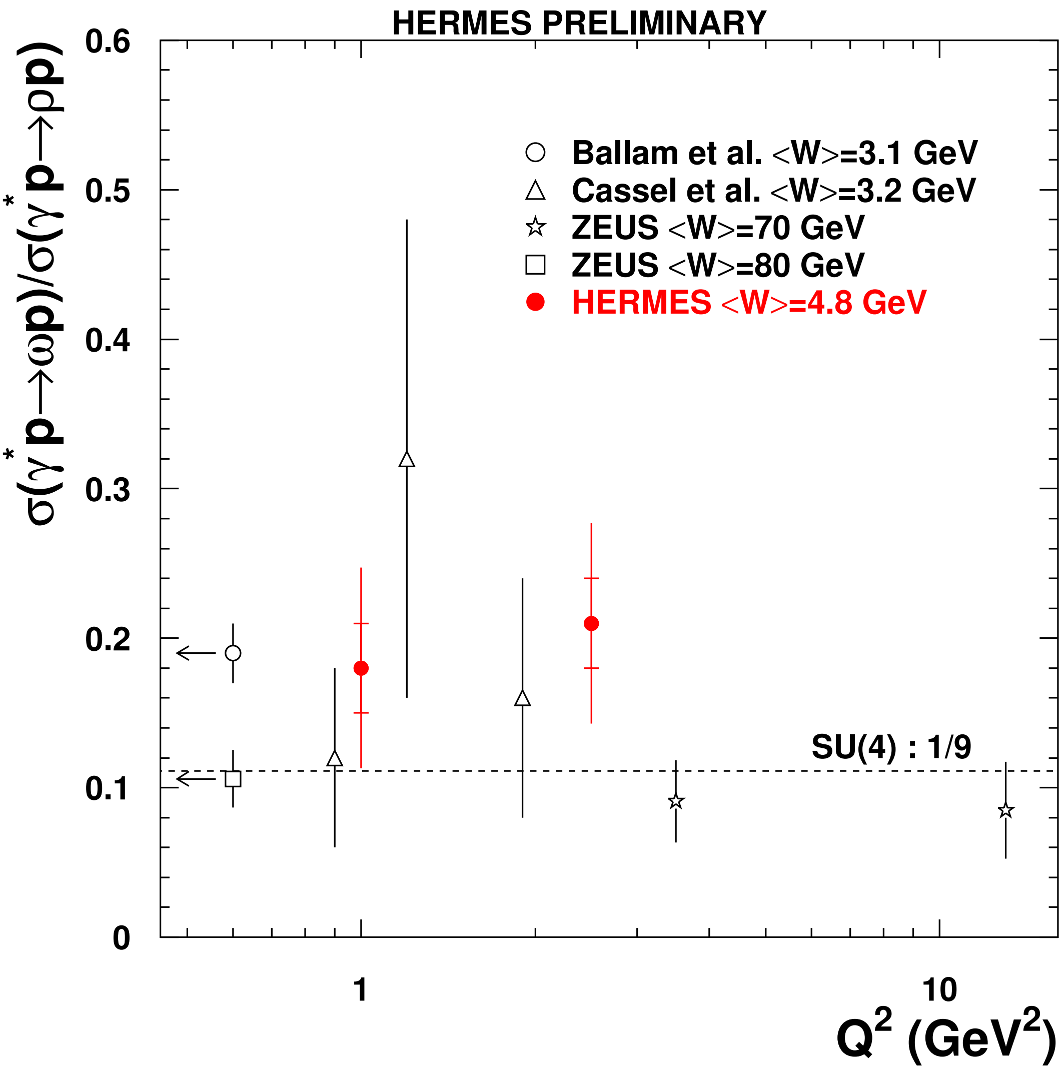


Quark exchange / 2-gluon exchange

$\Rightarrow$ Quark exchange dominates for ρ^0 and ω @ HERMES

Production Ratios

SU(4) prediction : $\omega : \rho^0 = 1 : 9$

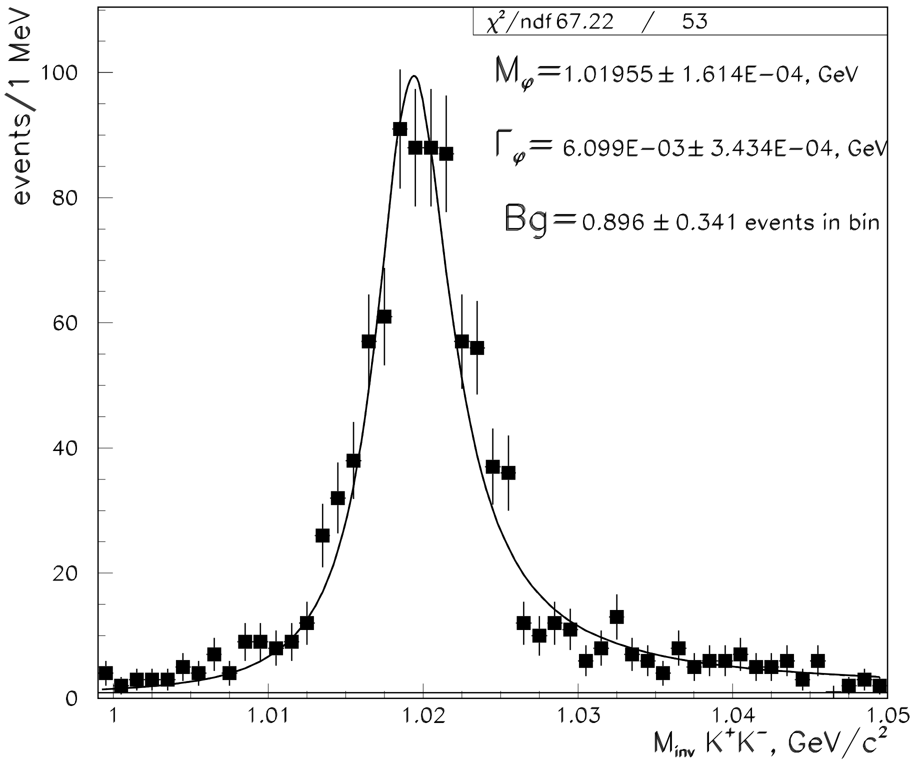


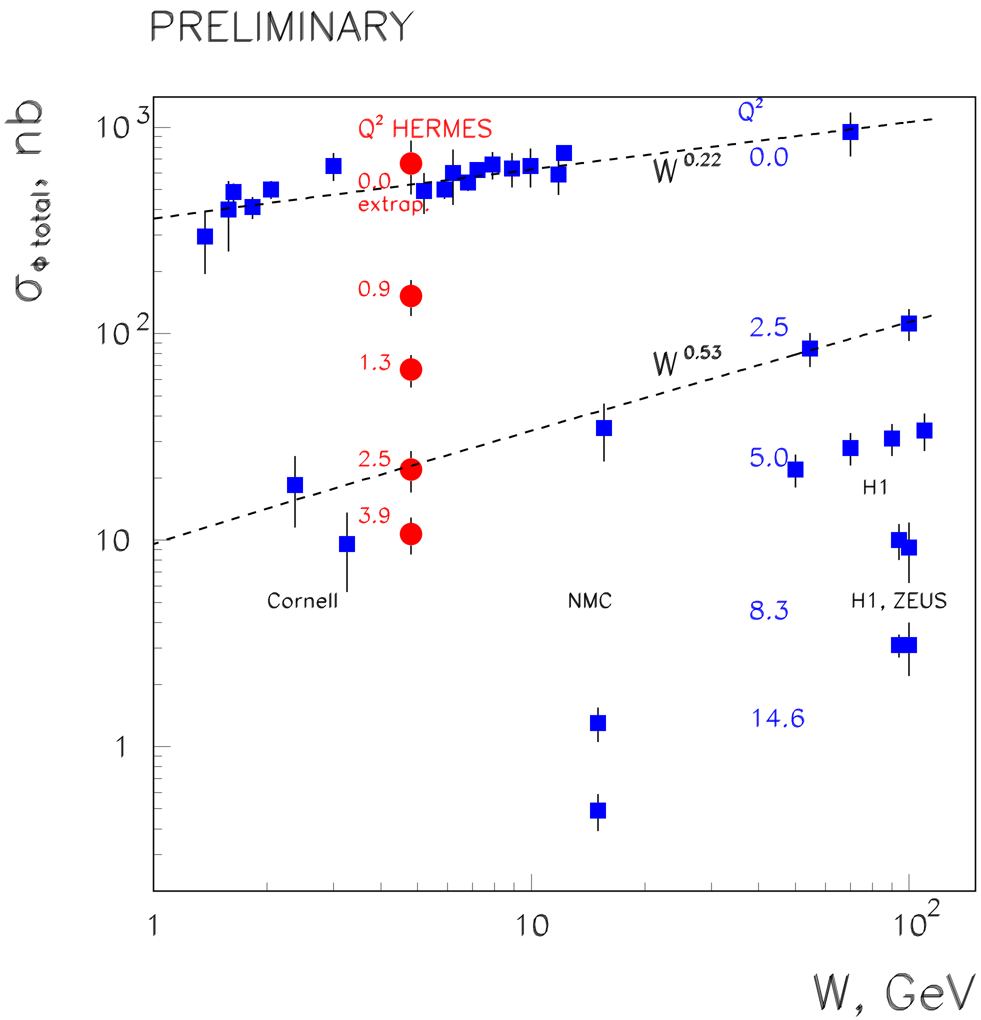
$\Rightarrow$ $\sigma_\omega/\sigma_\rho$ independent of Q^2

$\Rightarrow$ Clear W-dependence observed

Vanderhaeghen *et al.* : $\sigma_\omega/\sigma_\rho \approx 0.2$ @ HERMES

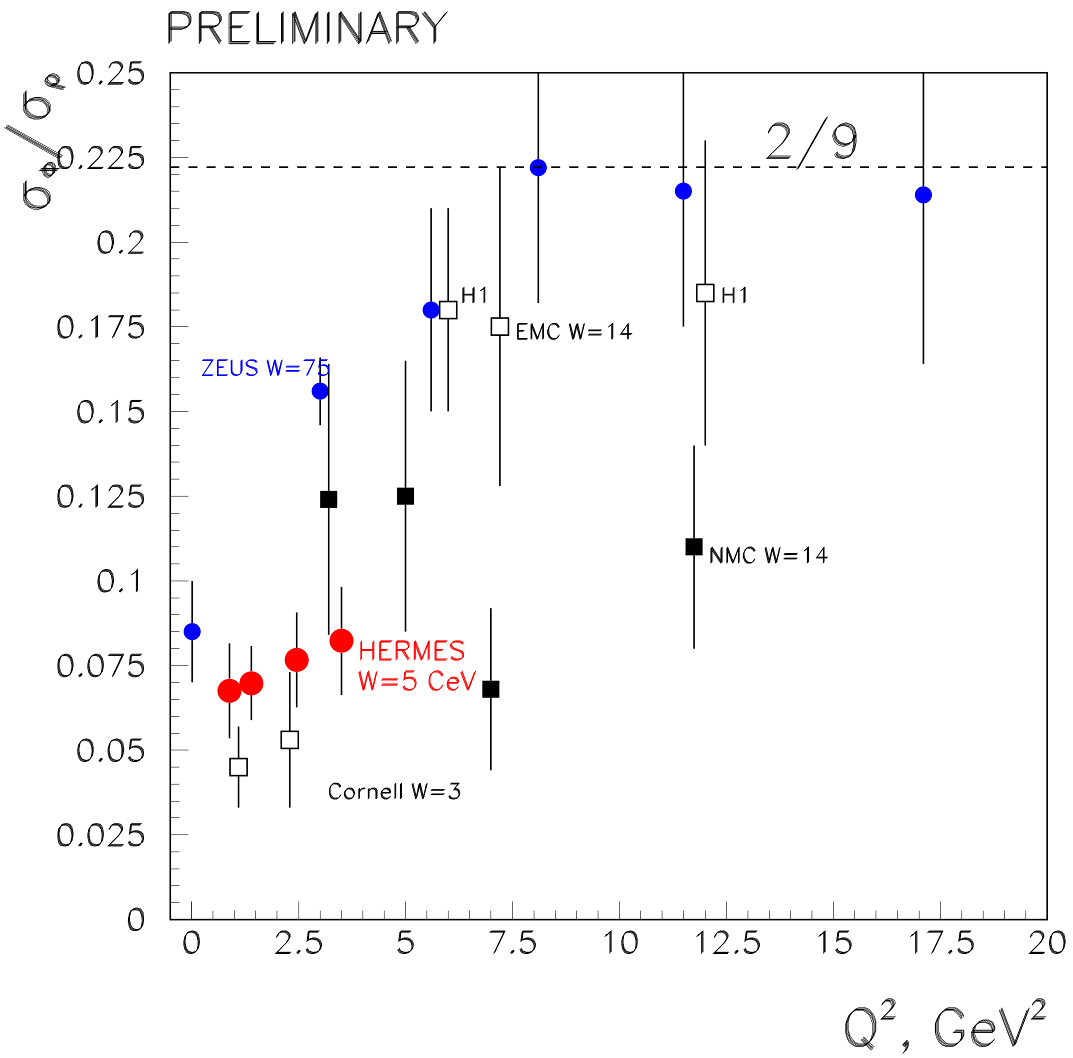
ϕ Production Cross Section





Production Ratios

SU(4) prediction : $\phi : \rho^0 = 2 : 9$

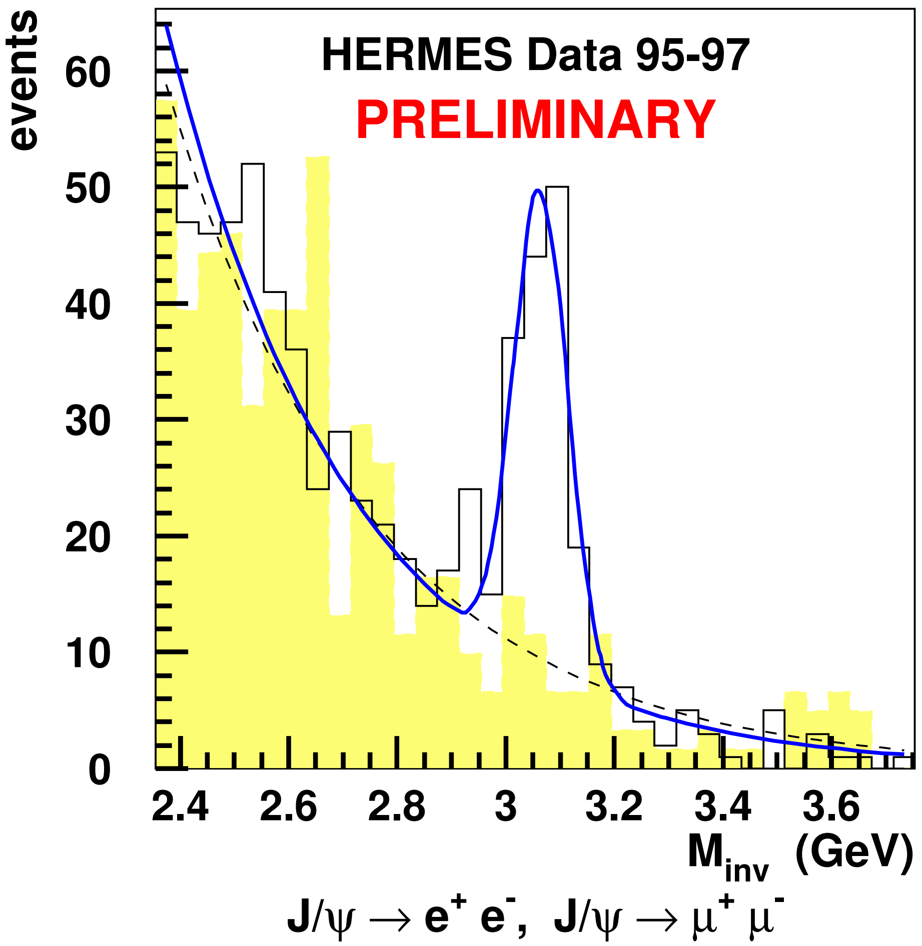


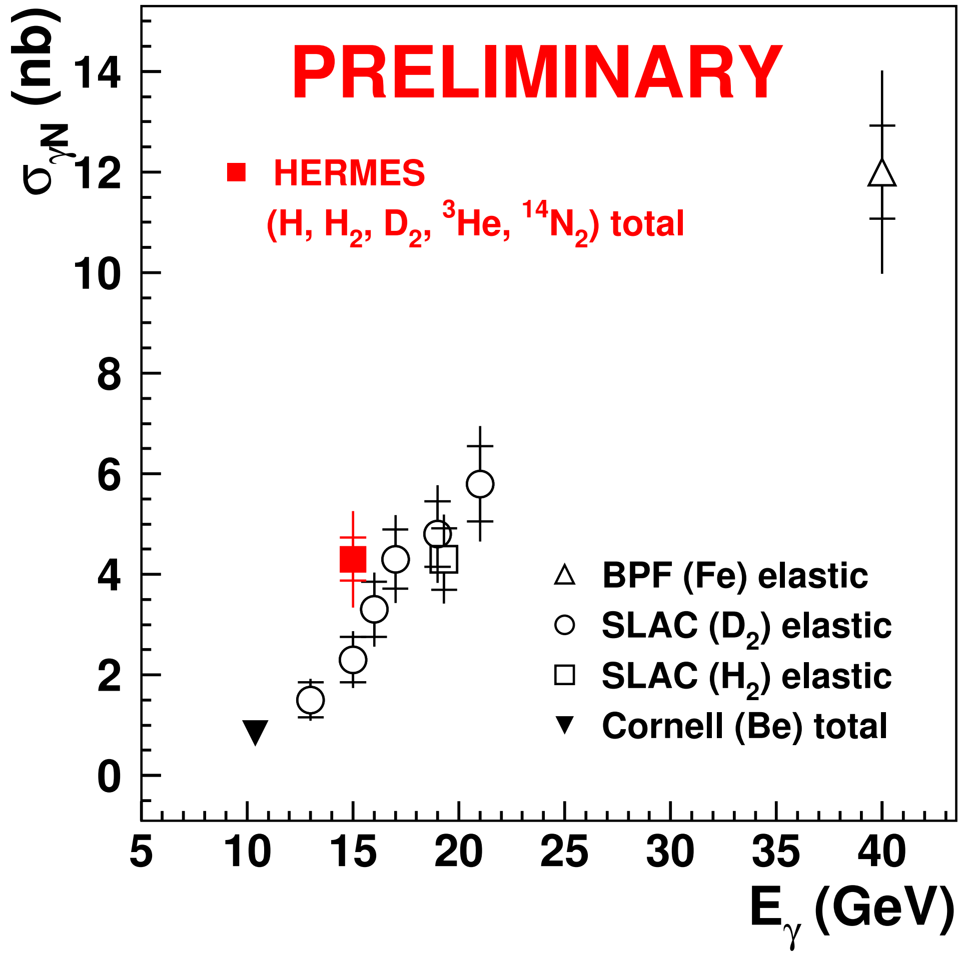
$\Rightarrow$ Clear W-dependence of σ_ϕ/σ_ρ observed

$\Rightarrow$ Q^2-dependence observed

Total J/Ψ Production Cross Section

Scattered positron not detected; quasi-real photoproduction





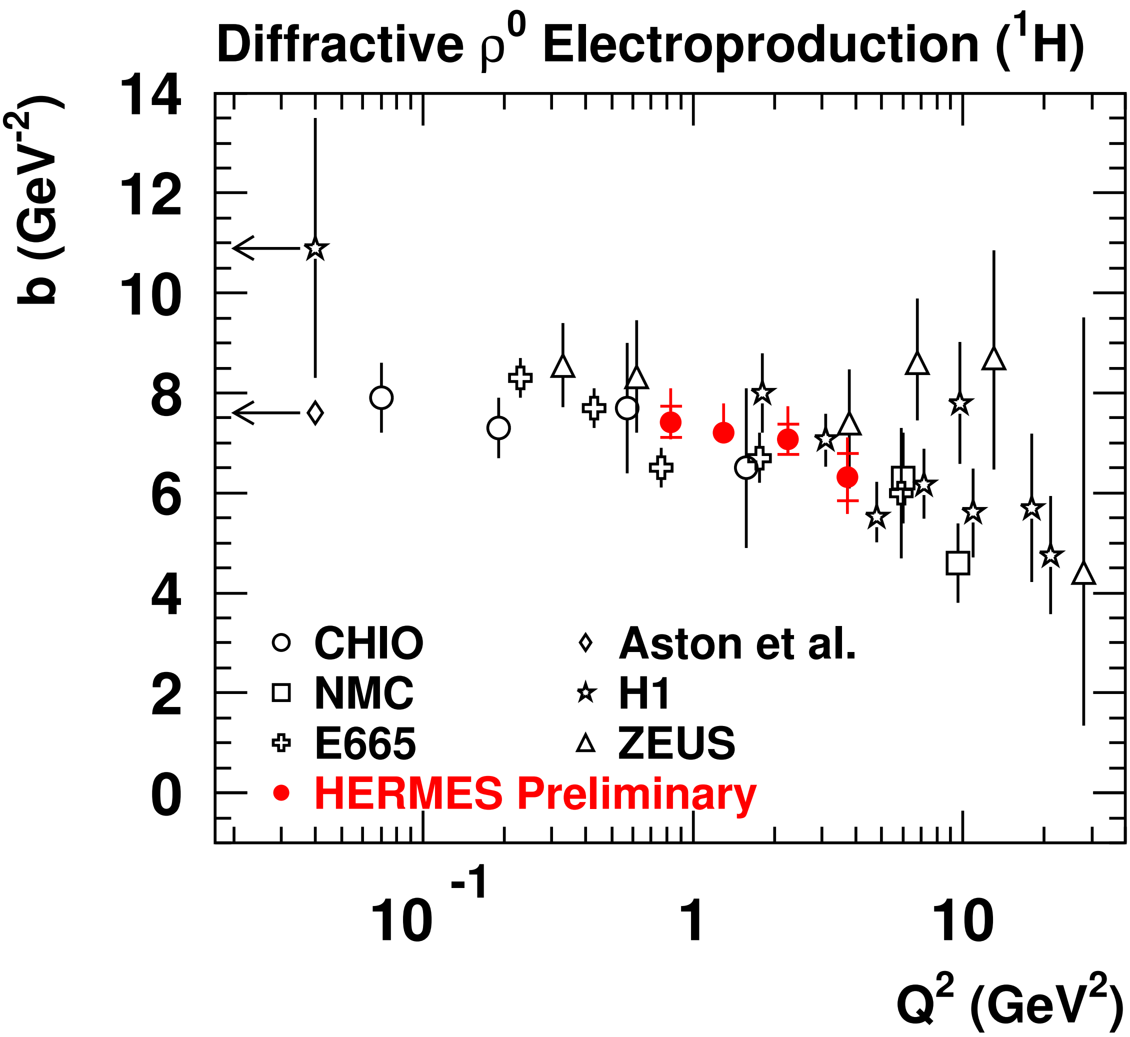
Diffractive Slope Parameter

Diffractive production mainly at low $-t'$: $e^{-b|t'|}$

$$b \sim \frac{1}{3}\left(< r_V^2 > + < r_p^2 >\right)$$

$$b_{\rho^0} = 7.08 \pm 0.14\ \text{(stat.)}^{+0.58}_{-0.08}\ \text{(syst.) GeV}^{-2}$$

$$b_\omega = 7.34 \pm 0.67\ \text{(stat.)}^{+1.59}_{-0.64}\ \text{(syst.) GeV}^{-2}$$

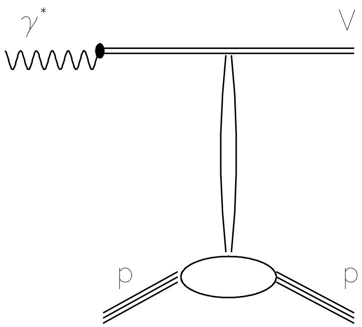


⇒ Clear Q^2-dependence

⇒ No strong W-dependence

Vector Meson Polarization Study

$\mathbf{T} \longrightarrow \mathbf{T} : \mathbf{T}_{11}, \mathbf{T}_{1\text{-}1}, \mathbf{T}_{\text{-}11}, \mathbf{T}_{\text{-}1\text{-}1}$
$\mathbf{L} \longrightarrow \mathbf{L} : \mathbf{T}_{00}$
$\mathbf{T} \longrightarrow \mathbf{L} : \mathbf{T}_{01}, \mathbf{T}_{0\text{-}1}$
$\mathbf{L} \longrightarrow \mathbf{T} : \mathbf{T}_{10}, \mathbf{T}_{\text{-}10}$



- Spin-1 vector meson decays into spin-0 pions $\rightarrow$ spin state of vector meson reflected in orbital angular momentum of decay particles
- $T_{\lambda_V \lambda_\gamma}$ describe helicity transfer from virtual photon to vector meson
- s-channel helicity conservation (SCHC) ? $\rightarrow$ helicity of photon retained by vector meson and nucleon helicity unaltered

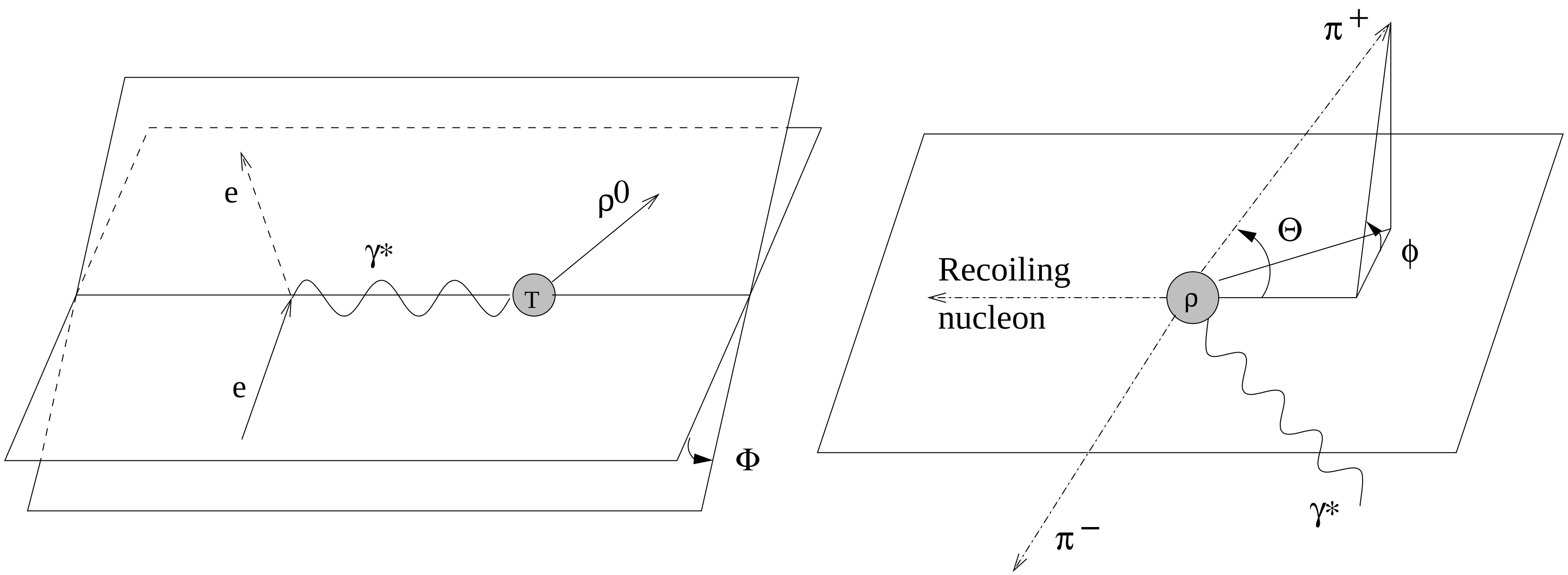
- $\dfrac{\mathrm{d}\sigma_{\gamma^* N \rightarrow VN}}{\mathrm{d}t\,\mathrm{d}\Phi} \propto \mathrm{Tr}\left(T\rho(\gamma)T^\dagger\right) \propto \mathrm{Tr}\left(\rho(V)\right)$ with $\rho(V)$ VM spin density matrix

$$\rho(V) = \sum_{\alpha=0}^{8} \Pi_\alpha \rho^\alpha \text{ with } \rho^\alpha_{\lambda_V \lambda'_V} = \frac{1}{2N_\alpha} \sum_{\lambda_\gamma, \lambda'_\gamma} T_{\lambda_V \lambda_\gamma} \Sigma^\alpha_{\lambda_\gamma \lambda'_\gamma} T^*_{\lambda'_V \lambda'_\gamma}$$

$\alpha = 0$ unpolarized transverse photons; $\alpha = 1, 2$ linear polarization; $\alpha = 3$ circular polarization; $\alpha = 4$ longitudinal polarization; $\alpha = 5 \ldots 8$ L/T interference

Angles in the Helicity Analysis

s-channel helicity frame $\rightarrow$ VM rest frame with quantization (z) axis along opposite direction of recoiling nucleon



Φ = angle between hadron and lepton production plane

θ, ϕ = decay angles in meson rest frame

$\Psi = \phi - \Phi$ = angle between meson decay and lepton scattering plane

Vector Meson Polarization Study

- 3-dimensional decay angle distribution

  $$W(\cos\theta, \phi, \Phi) = f(\rho^{\alpha}_{\lambda_V \lambda'_V})$$

  $\rightarrow$ 26 independent $\rho^{\alpha}_{\lambda_V \lambda'_V}$

- Without L/T separation : (known $R = \dfrac{\sigma_L}{\sigma_T}$)

  (23 $r^{\alpha}_{\lambda_V \lambda'_V}$ and $r^{04}_{\lambda_V \lambda'_V}$) = combinations of $\rho^{\alpha}_{\lambda_V \lambda'_V}$

- $W(\cos\theta, \phi, \Phi) = W^{unpol.}(\cos\theta, \phi, \Phi) + W^{pol.}(\cos\theta, \phi, \Phi)$

  HERMES : longitudinal beam polarization

  $\rightarrow$ 15 unpolarized + 8 polarized SDME's

- SCHC : $T_{\lambda_V \lambda_{N'}, \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda_{N'}, \lambda_\gamma \lambda_N} \delta_{\lambda_V \lambda_\gamma} \delta_{\lambda_{N'} \lambda_N}$

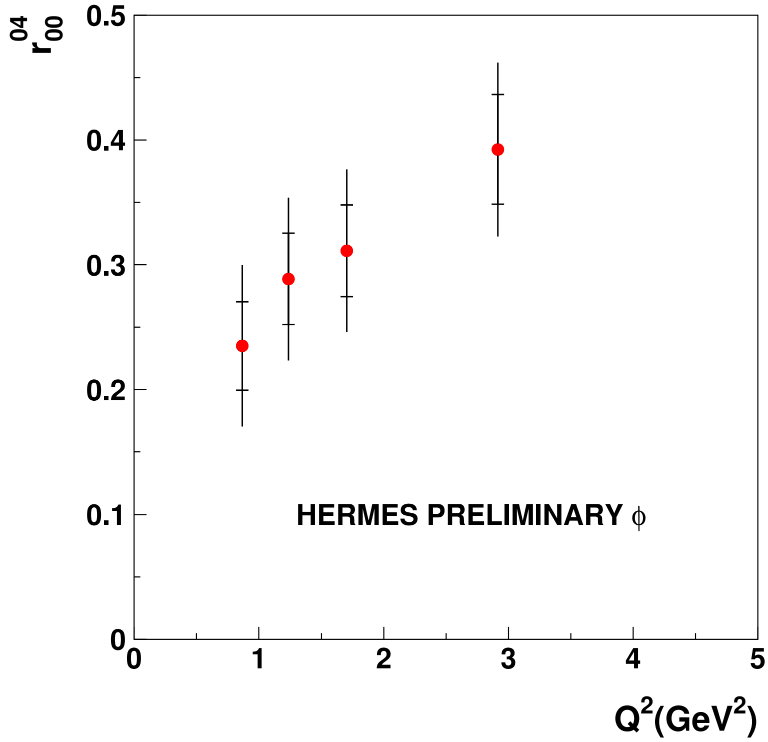
  All SDME vanish, except r^{04}_{00}, r^{1}_{1-1}, Im r^{2}_{1-1}, Re r^{5}_{10}, Im r^{6}_{10}, Im r^{7}_{10} and Re r^{8}_{10}.

- Natural parity exchange in t-channel :

  $$T_{-\lambda_V \lambda_{N'}, -\lambda_\gamma \lambda_N} = (-1)^{(\lambda_V - \lambda_\gamma)} T_{\lambda_V \lambda_{N'}, \lambda_\gamma \lambda_N}$$

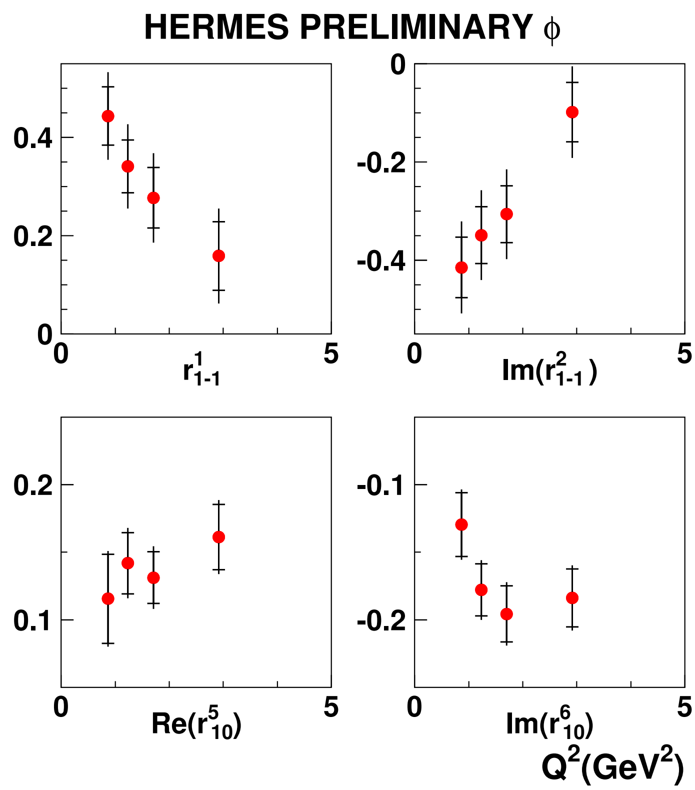
ϕ Spin Density Matrix Elements

r_{00}^{04} : Long. ϕ polar.

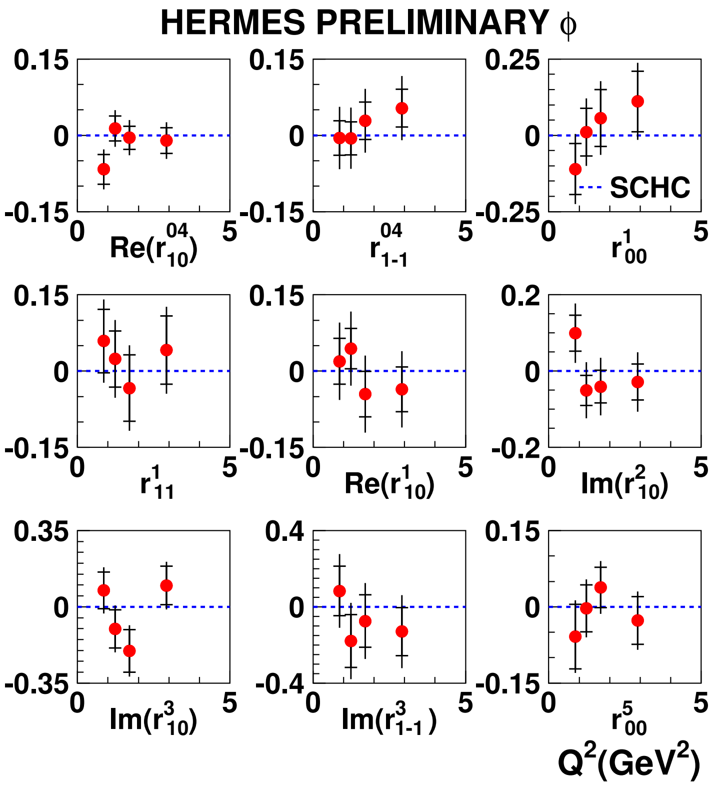


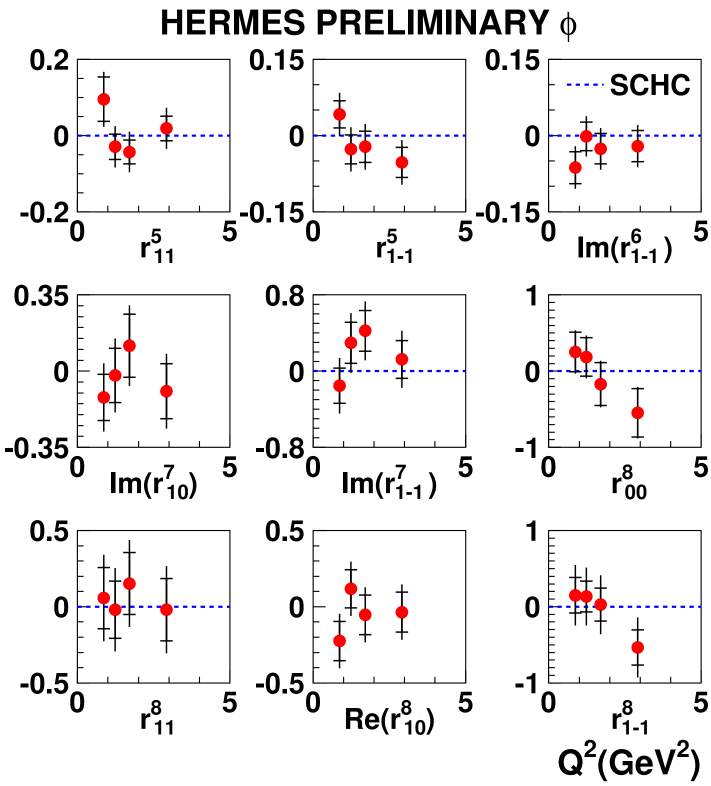
SCHC :

$$\begin{cases} r_{1-1}^{1} = -\text{Im}\ r_{1-1}^{2} \\ \text{Re}\ r_{10}^{5} = -\text{Im}\ r_{10}^{6} \end{cases}$$



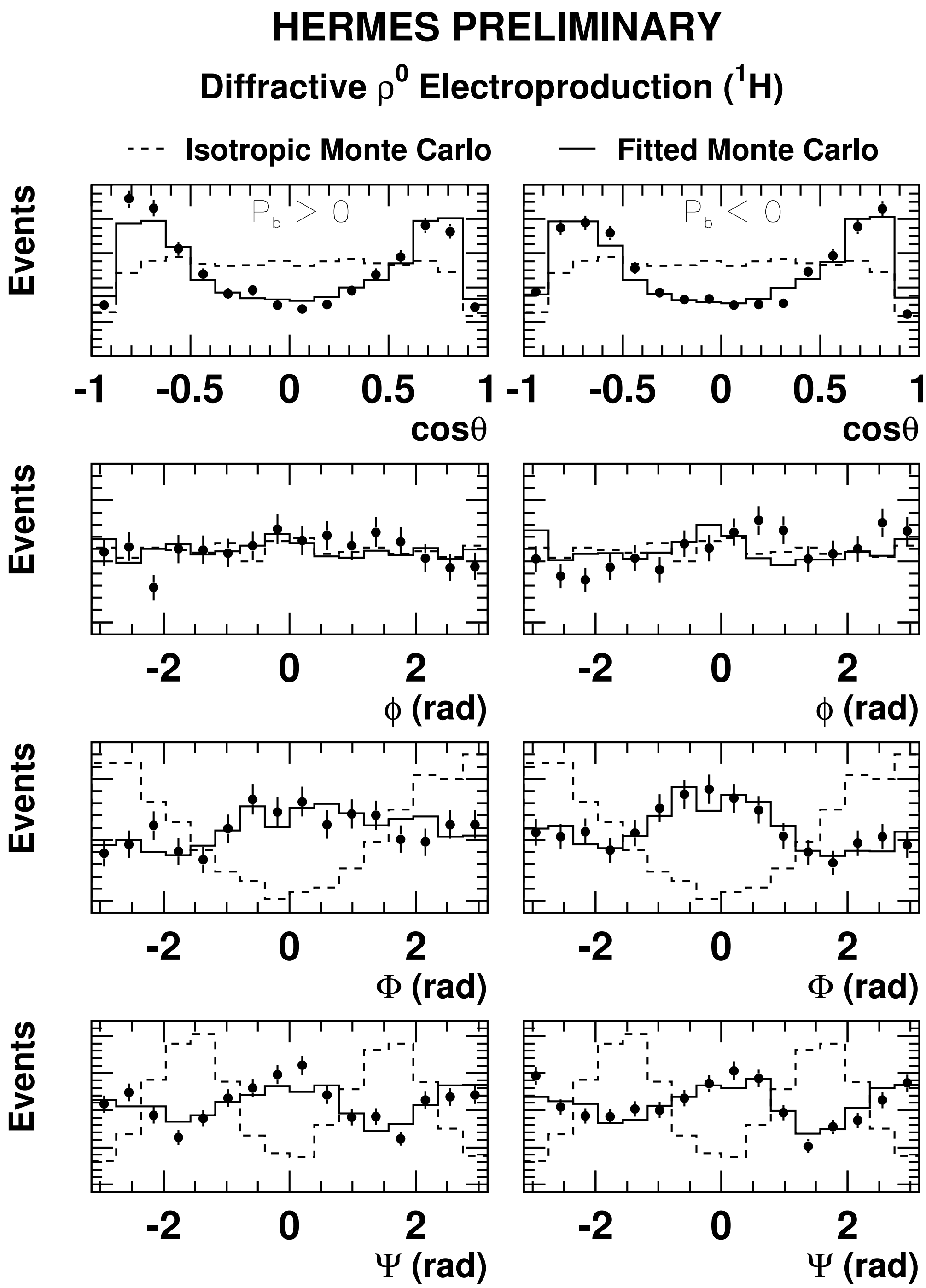
ϕ Spin Density Matrix Elements





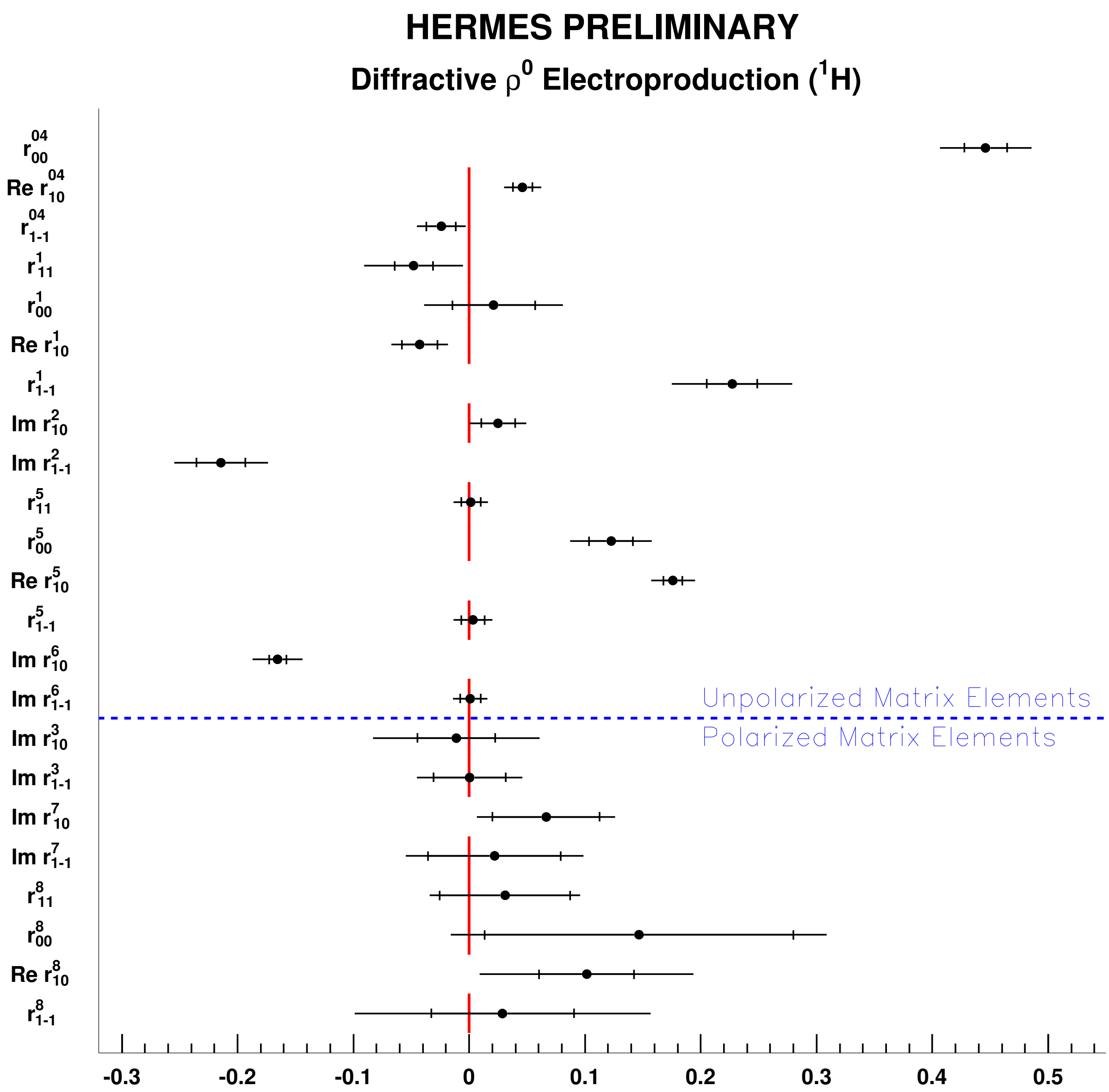
$\Rightarrow$ ϕ results compatible with SCHC

ρ^0 Decay Angle Distributions



$\Rightarrow$ SDME are free parameters in a maximum likelihood fit of an isotropically generated Monte Carlo 3-dim. decay angle matrix $(\cos\theta, \phi, \Phi)$ to the measured data

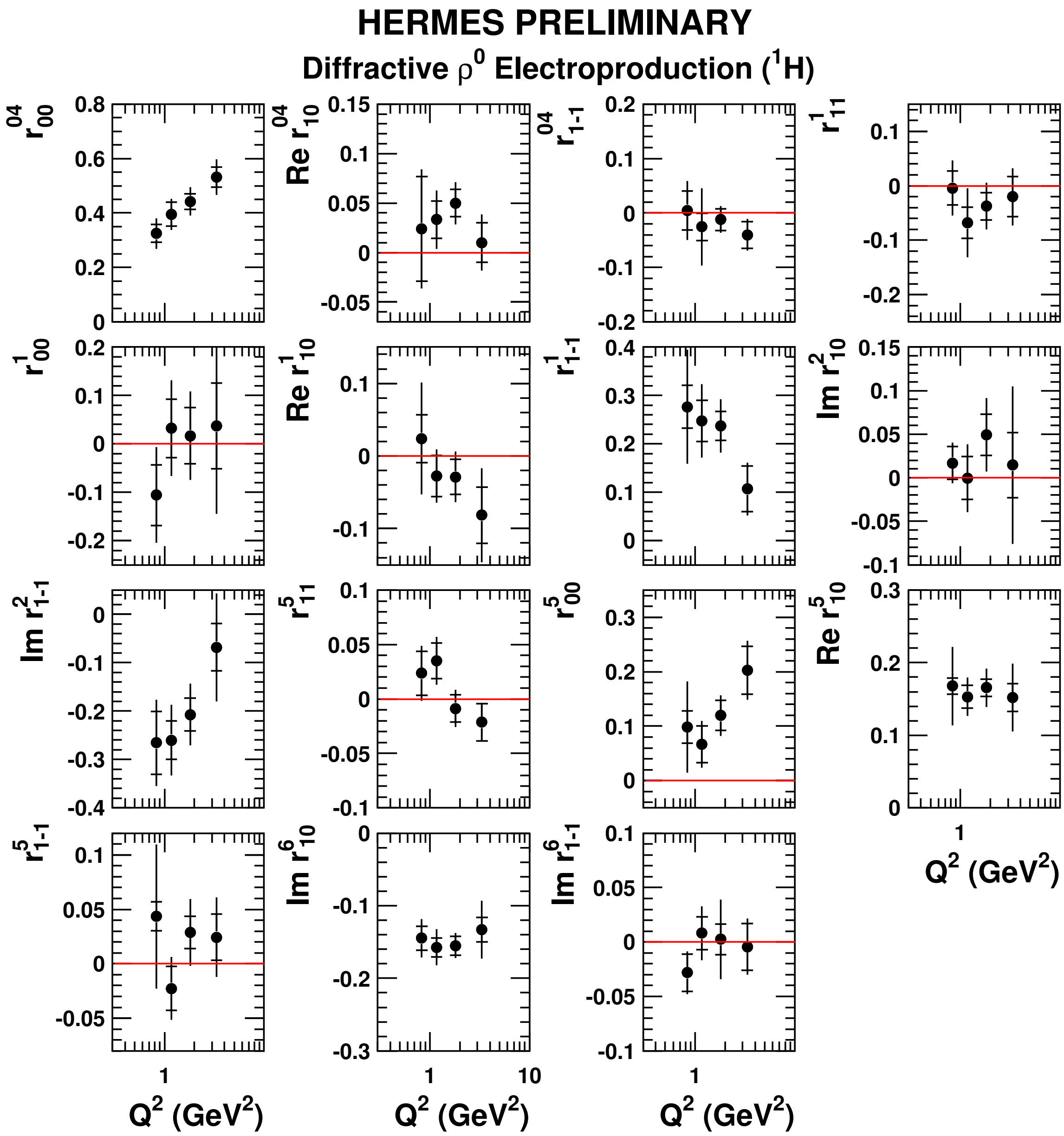
ρ^0 Spin Density Matrix Elements



- SCHC symmetry relations fullfilled
- r^5_{00} significantly different from zero

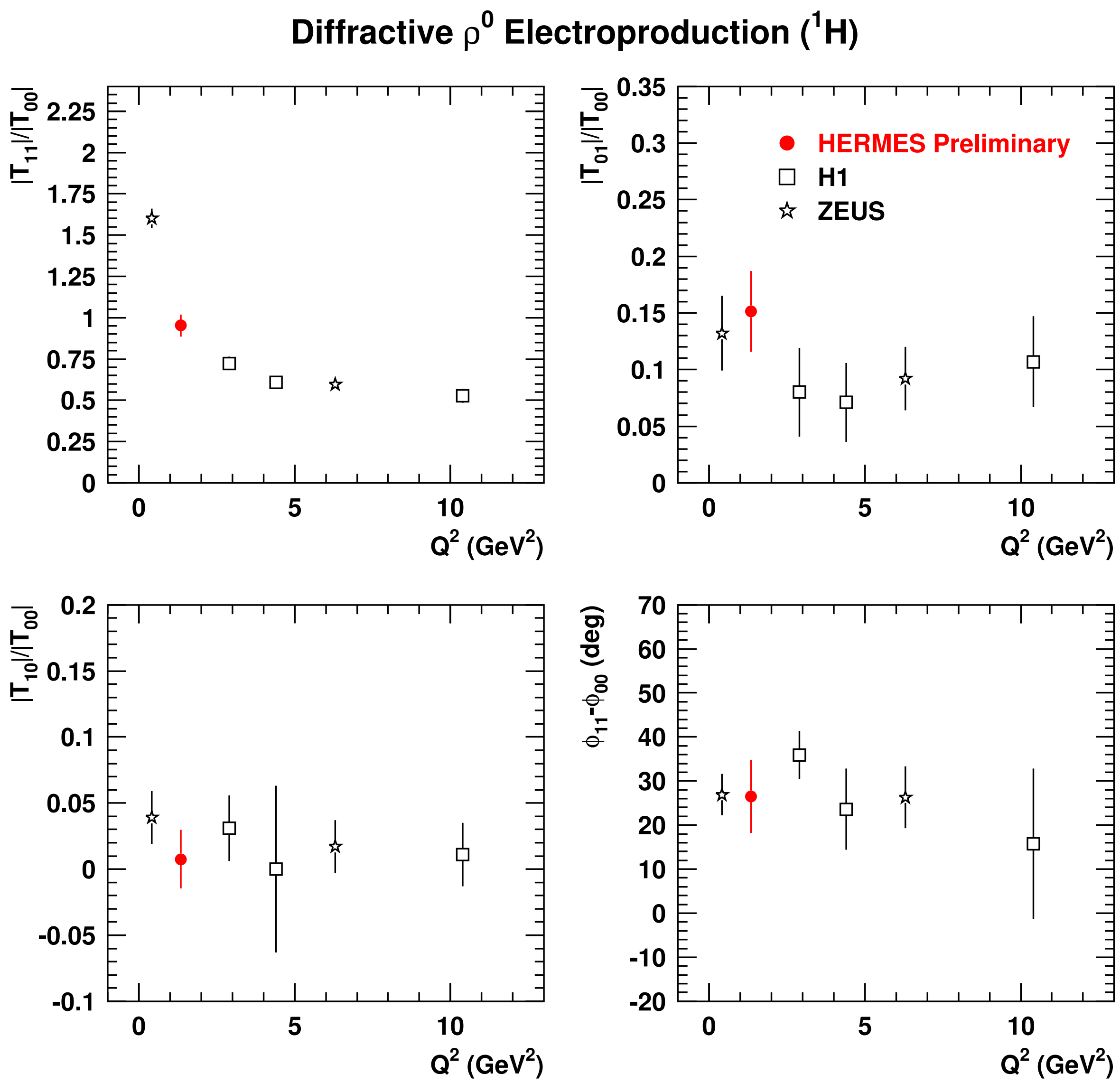
$\Rightarrow$ small SCHC violation in ρ^0 data

ρ^0 Spin Density Matrix Elements



ρ^0 Helicity Amplitudes

Assume natural parity exchange in t-channel
$\rightarrow$ 5 independent complex amplitudes
T_{00}, T_{11}, T_{01}, T_{10} and T_{1-1}

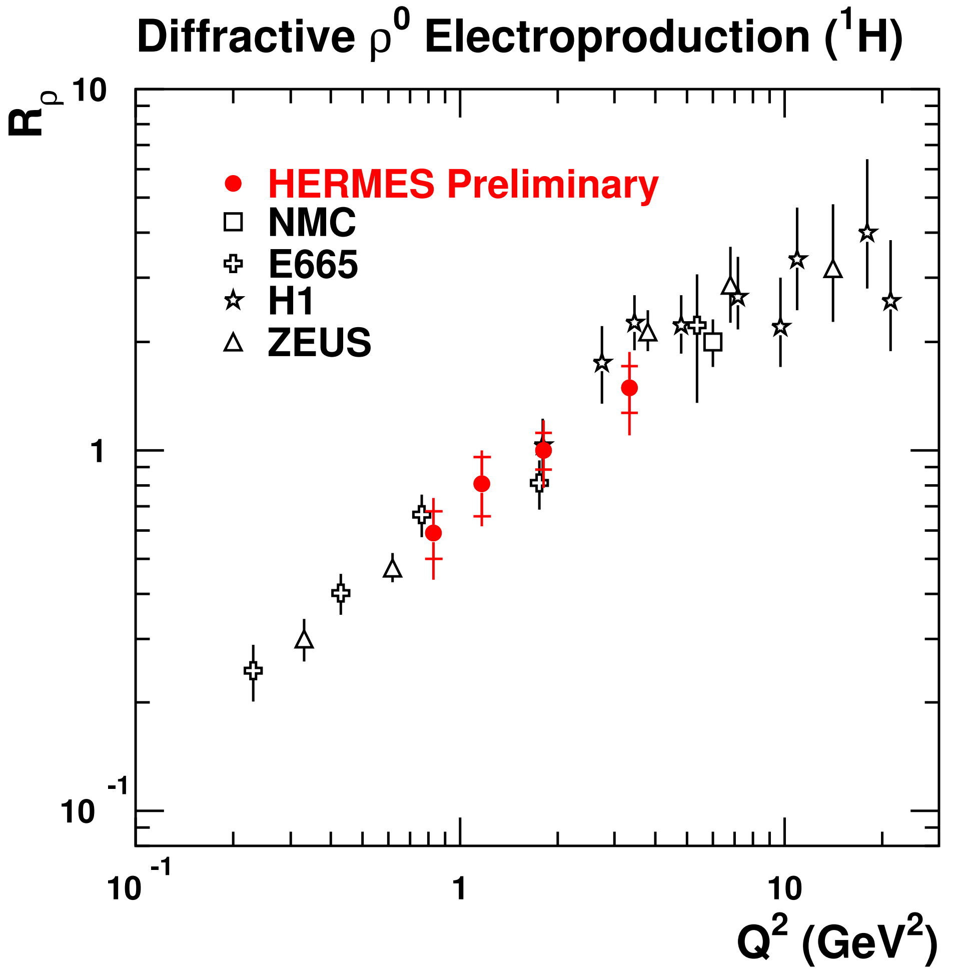


$\Rightarrow$ non-zero helicity single-flip amplitude T_{01}
(transverse $\rightarrow$ longitudinal)

$\Rightarrow$ No strong W-dependence

ρ^0 R-ratio

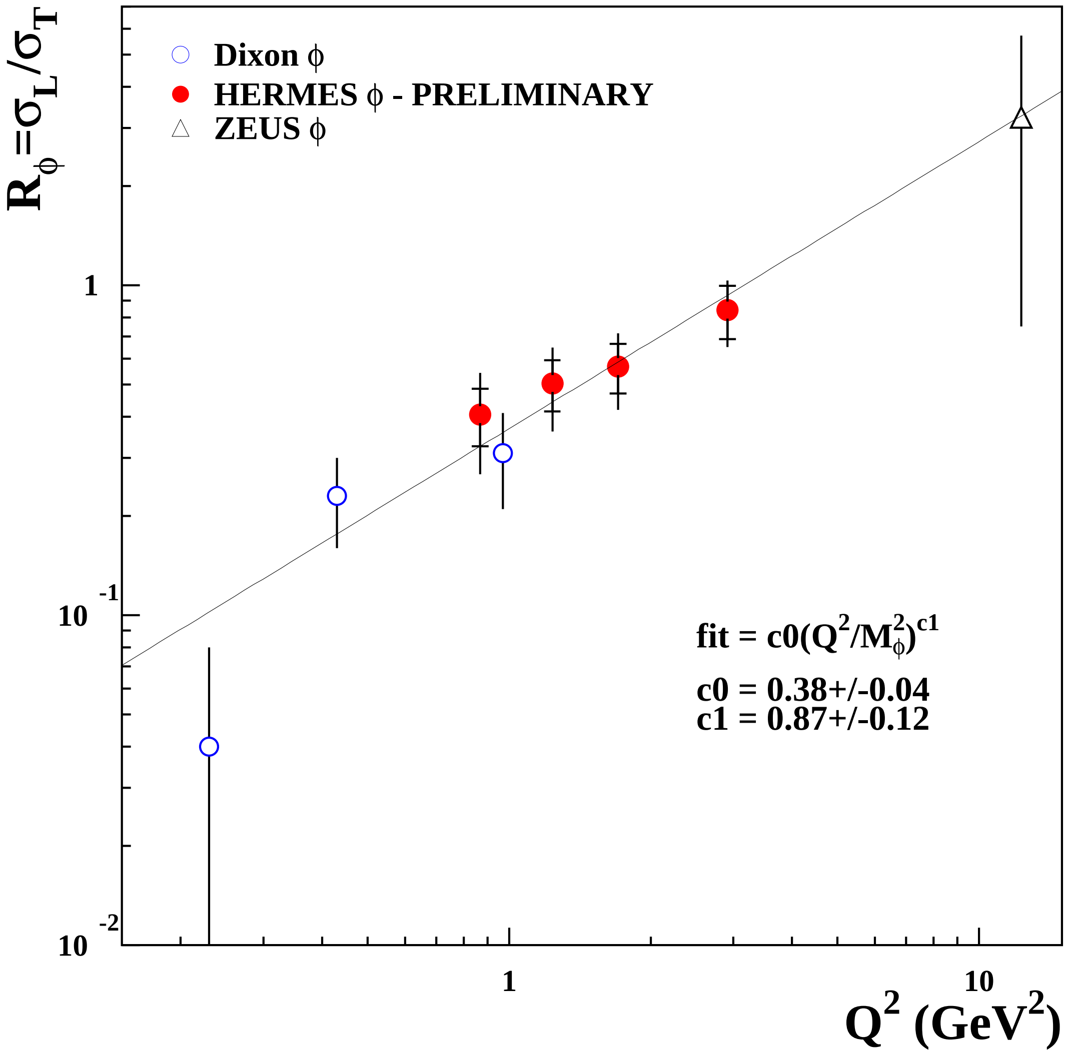
SCHC : $R_\rho = \frac{\sigma_L}{\sigma_T} = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1 - r^{04}_{00}}$ SCHNC : $R_\rho = \frac{1}{\epsilon}\frac{r^{04}_{00} - \Delta^2}{1 - (r^{04}_{00} - \Delta^2)}$ with $\Delta \approx r^5_{00}\sqrt{\frac{\epsilon}{2r^{04}_{00}}}$



$\rightarrow$ SCHNC effect less than 10 %

$\Rightarrow$ No strong W-dependence

ϕ R-ratio



$\Rightarrow$ ϕ results compatible with world data

ρ^0 Double Spin Asymmetry

$$A_1 = \frac{\sigma^{1/2} - \sigma^{3/2}}{\sigma^{1/2} + \sigma^{3/2}} = \frac{A_{\|}}{D} - \eta A_2$$

A_2: in deep inelastic scattering ≈ 0

in VM production $A_2^\rho < \sqrt{R_\rho}$

D: photon depolarization factor ≈ 0.40 at HERMES;

η : kinematical factor ≈ 0.06 at HERMES

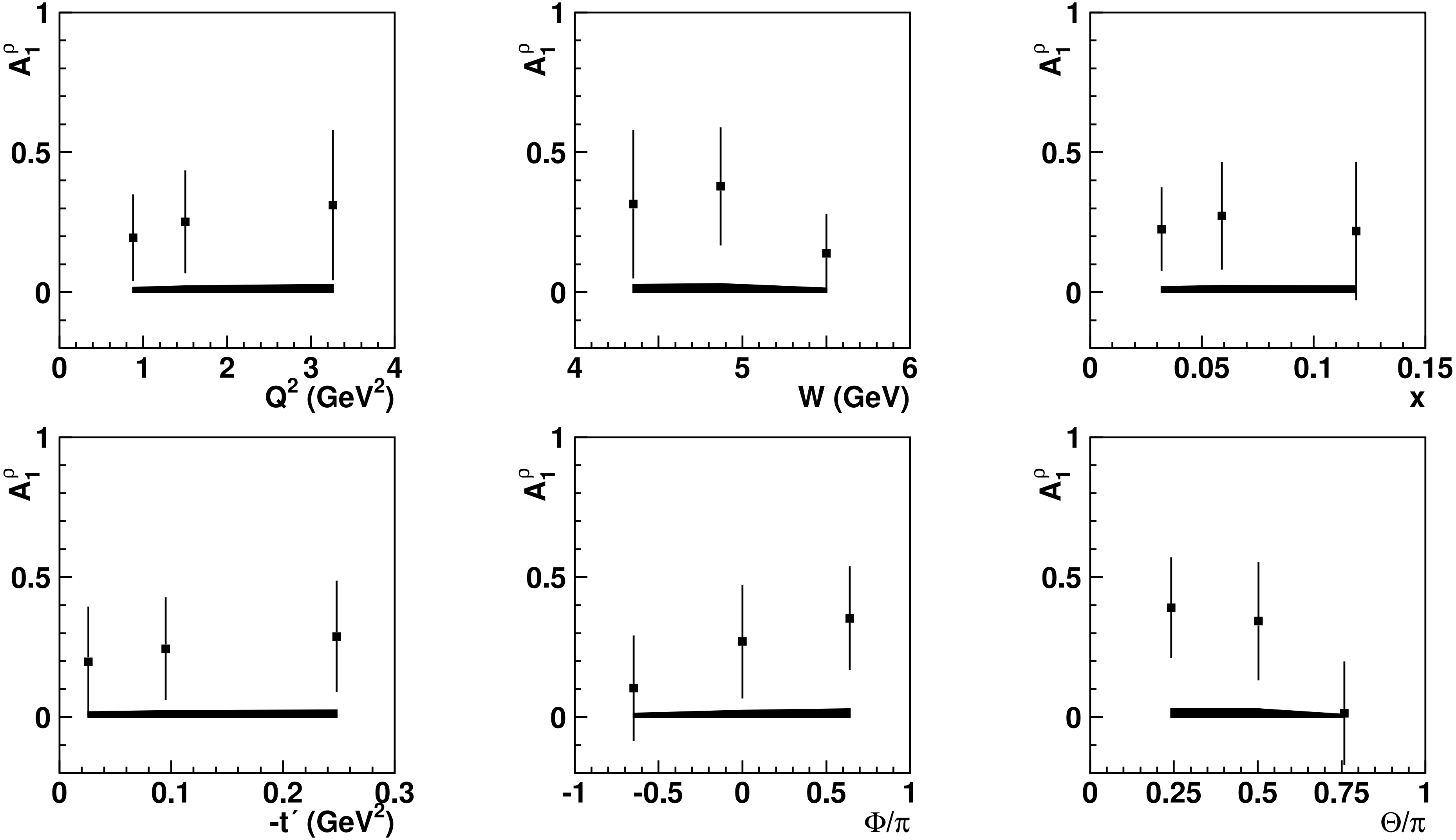
$$A_{\|} \equiv \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = \frac{N^{\uparrow\downarrow}L^{\uparrow\uparrow} - N^{\uparrow\uparrow}L^{\uparrow\downarrow}}{N^{\uparrow\downarrow}L_p^{\uparrow\uparrow} + N^{\uparrow\uparrow}L_p^{\uparrow\downarrow}} \qquad \text{with} \qquad L_p =< L|P_{beam}P_{target}| >$$

$$\boxed{< A_1^\rho >= 0.24 \pm 0.11 \text{ (stat.)} \pm 0.02 \text{ (syst.)}}$$

A_1: in deep inelastic scattering $A_1 \approx \dfrac{g_1}{F_1}$

in VM production $A_1 =$?$\rightarrow \left\{ \begin{array}{l} \text{H. Fraas, } \textbf{NPB 113} \text{ (1976) 532 : } A_1^\rho \approx 2A_1^{\gamma^* p} \\ \text{SMC : } A_1^\rho \approx 0 \rightarrow \text{diff. production mechanism ?} \end{array} \right.$

ρ^0 Double Spin Asymmetry



$\Rightarrow$ No significant kinematical dependence observed

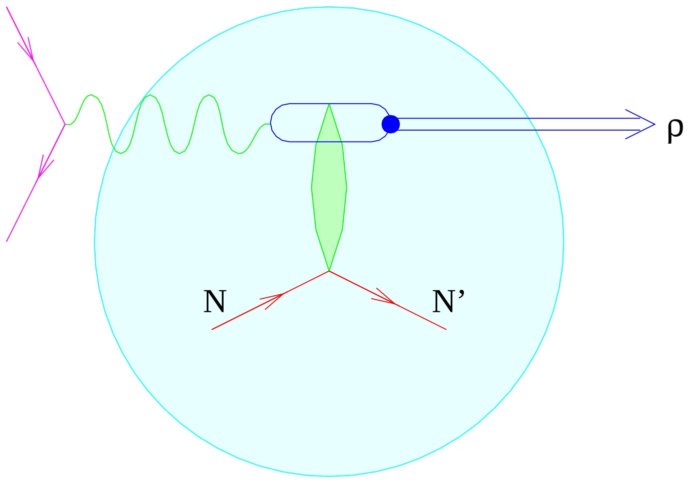
Incoherent Nuclear Transparency

VM production on composite targets $\rightarrow$ study nuclear medium effects on production rate

coherence length : $l_c \equiv \dfrac{2\nu}{M_{q\bar{q}}^2 + Q^2}$ (~ lifetime of $q\bar{q}$ pair)

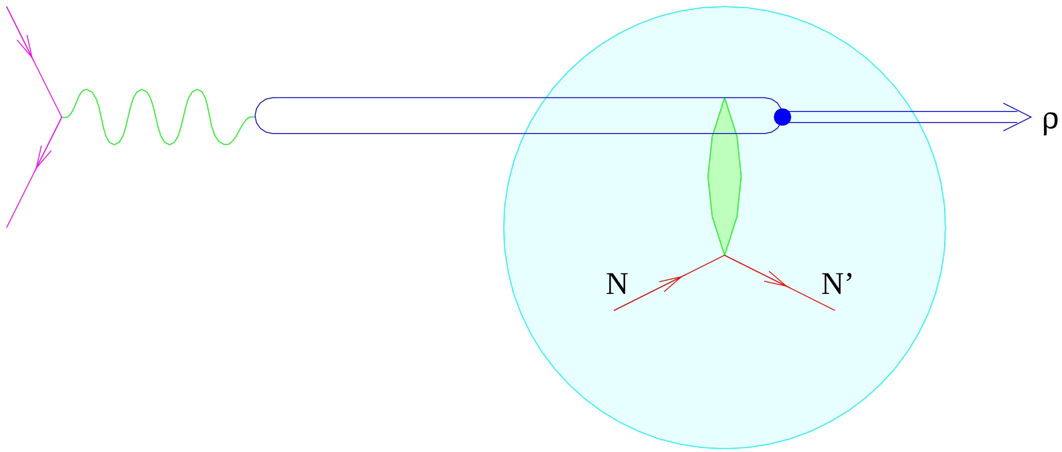
$\rightarrow$ Strength of inital state interactions (ISI) depends on l_c :

$l_c \ll r_A$:



$\rightarrow$ Weak electromagnetic ISI

$l_c \gg r_A$:

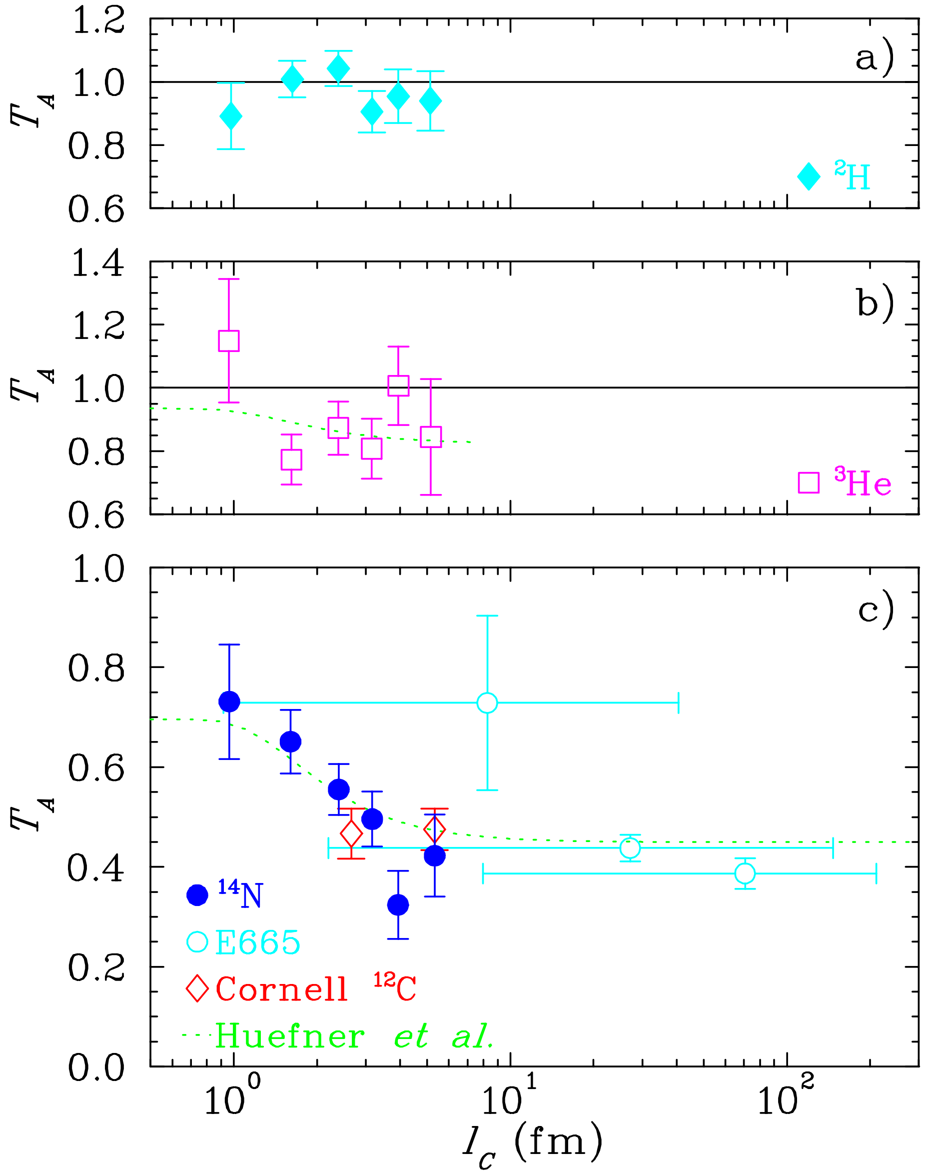


$\rightarrow$ Hadronic ISI

Incoherent Nuclear Transparency

⇒ Incoherent nuclear transparency : $T_A \equiv \dfrac{\sigma_A}{A\,\sigma_N}$

→ Without ISI and FSI : $T_A = 1$



⇒ ISI of $\gamma^*/q\bar{q}$ and FSI of ρ^0 meson

⇒ $T_A(l_c \to \infty) \approx [T_A(l_c \to 0)]^2$

⇒ Results compatible with Glauber calculations

Summary & Conclusions

- HERMES has made measurements of diffractive ρ^0, ω, ϕ and J/Ψ vector mesons on several different nuclear targets.

- The HERMES data are in the transition region at intermediate energy and may receive contributions from different production mechanisms. The dominant contributions come from quark exchange diagrams for ρ^0 and ω and gluon exchange diagrams for ϕ ($\rightarrow$ cross sections, production ratios).

- ρ^0 resonance skewing and slope parameter compatible with high energy data

- The ρ^0 data exhibit a clear indication of a small s-channel helicity non-conserving amplitude.

- A non-zero double spin asymmetry is observed in diffractive ρ^0 production.

- A clear coherence length effect is observed in incoherent diffractive ρ^0 production on nuclear targets. More data on heavier targets underway . . .