Some recent developments in the nucleon structure study

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- Introduction
- Electromagnetic form factors
- N ! Δ transition form factors
  - ² deformation of the Δ (1232)
- Outlook and conclusion

Colloquium at National Tsing-Hua University, May 11, 2005

History of Nuclear Physics

- 1932 Chadwick discovered neutron
  marked the birth of nuclear physics

- Nuclei $^{A}_{Z}Name$ with A=1-292, Z=1-116 have been discovered
  A= 1: nuclear matter, e.g., neutron stars
  nuclear astrophysics (Bethe)

Spectroscopy, electron scatterings (Hofstadter), nuclear reactions (fission, fusion, β–decay, fragmentation.....), high-spin states, super-deformed nuclei, super-heavy nuclei etc.

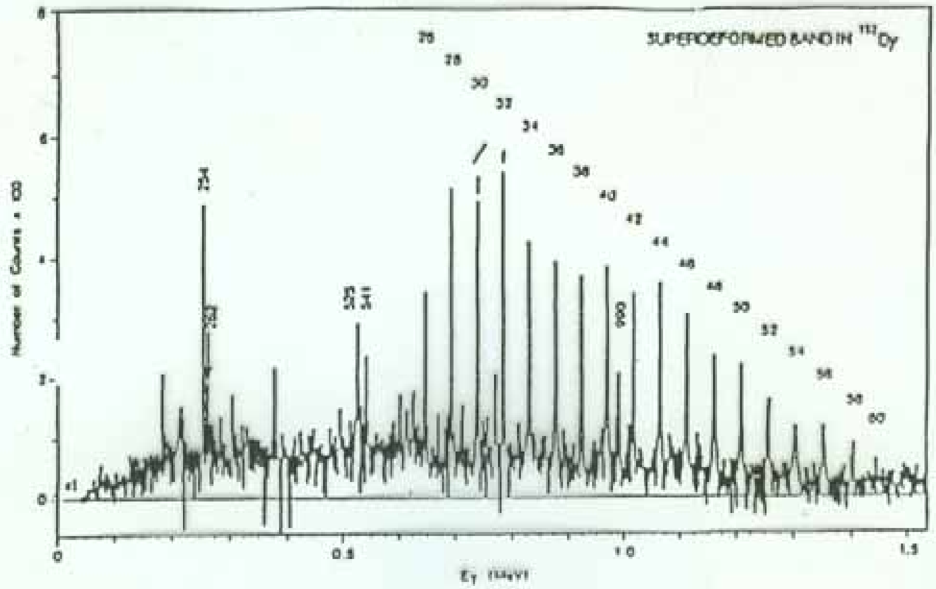


Figure 3

Gamma-ray spectrum in ^{152}Dy after a heavy ion fusion reaction with which the superdeformed states have been detected. The spectrum shows transitions from angular momentum 60 to 58 and from 58 to 56 and so on till down to angular momentum 26. The regular spacing of this gamma-ray transition energies indicates an extremely constant moment of inertia within the superdeformed band. The axis ratio 2:1 is established by measuring the E2 transition probabilities.

Standard model of nuclear physics

Non-relativistic quantum mechanics with

Three-body force

$$H = \sum_i \frac{\vec{p}_i^{\,2}}{2m_i} + \sum_{<ij>} V_{ij}(NN) + \sum_{<ijk>} W_{ijk}(NNN)$$

- Bethe-Salpeter equation
- Faddeev equation, Faddeev-Yacubovsky equation
- Green's function Monte Carlo method etc.
- Quantum many-body theory

Models

- shell model -- Mayer and Jensen
- collective model – Bohr and Mottelson
- interacting boson model – Iachello and Arima

Developments of QCD

- 1964 Gell-Mann and Zweig proposed
  quark model
- 1969 Friedman, Kendall, and Taylor
  discovered partons in deep
  inelastic scattering of electrons
  from nucleon
- 1973 formulation of QCD by
  Gross, Politzer, and Wilczek
  t'Hooft

$\Rightarrow$ Hadron physics

Hadron physics

- Structure of hadrons (baryons and mesons)
  experiments mostly performed with electron accelerators like MAMI (Mainz), Bates (MIT), Jlab etc.

- Quark-gluon plasma (QGP)
  experiments mostly performed with heavy-ion accelerators like SPS, GSI, RHIC, and LHC

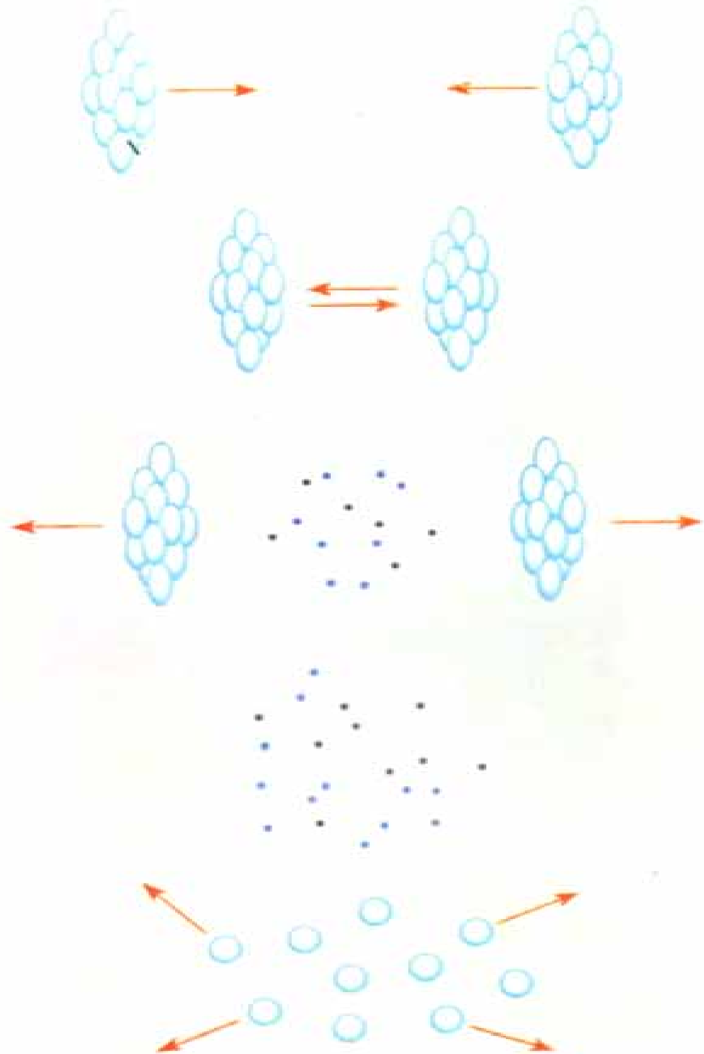
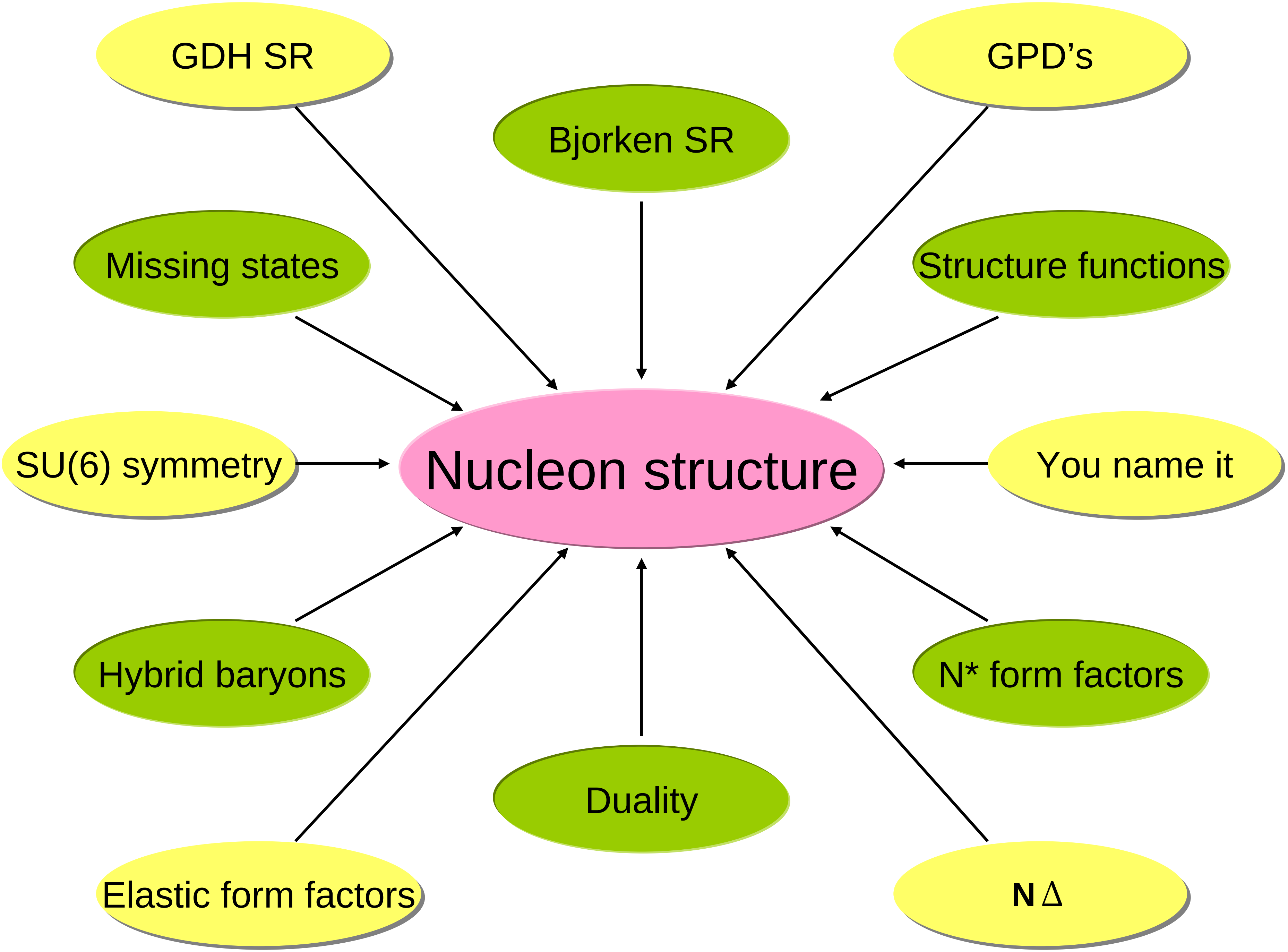


Figure 4. Quark-gluon plasma is a state of matter that must have existed in the first moments of the universe and that could be re-created if laboratory experiments attain a high enough temperature (perhaps 10^{12} degrees Celsius). The experiments bring about head-on collisions between heavy nuclei accelerated to relativistic velocity. (It is an effect of relativity that makes the on-rushing nuclei appear flattened.) The nuclei pass through each other, but they leave behind in the collision zone a region of intense excitation, where hundreds or thousands of quarks and gluons materialize. At this high temperature the quarks and gluons can briefly remain in a plasma phase, before they condense to form hadrons.

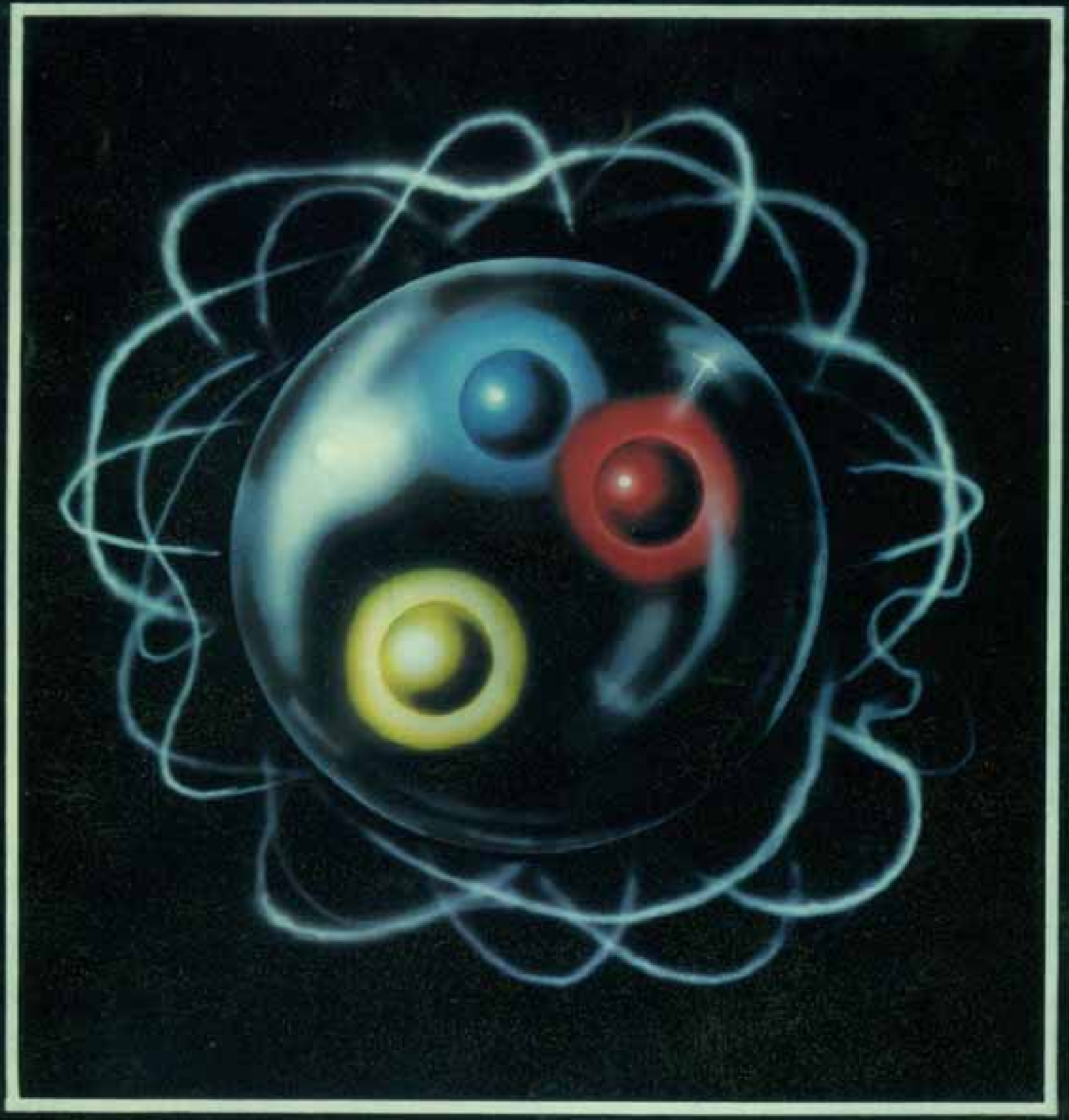

GDH SR
Bjorken SR
GPD's
Missing states
Structure functions
SU(6) symmetry
Nucleon structure
You name it
Hybrid baryons
N* form factors
Duality
Elastic form factors
N Δ

Constituent
Quark Model

Chiral
Bag Model

Deformed
Bag Model

Soliton
Skyrme-Model



STRUCTURE OF THE NUCLEON

Little bag of Brown and Rho

Electromagnetic form factors

➢ Rutherford scattering

(1) Electron (spin-1/2) scattered by a spin-0 charged particle with mass M (Mott scattering)

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = 4(Ze^2)^2 \frac{E^2}{(qc)^4} \frac{(1-\beta^2 \sin^2 \frac{\theta}{2})}{1+\frac{2E}{M}\sin^2\frac{\theta}{2}}, \quad \beta = \frac{\mathrm{v}}{\mathrm{c}}$$

(2) Mott scattering from a spin-0 particle with extended structure

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left|F(\vec{q}^{\,2})\right|^2, \quad F(\vec{q}^{\,2}) = \int d^3r\, \rho(\vec{r}) \exp(i\vec{q}\cdot\vec{r})$$

form factor

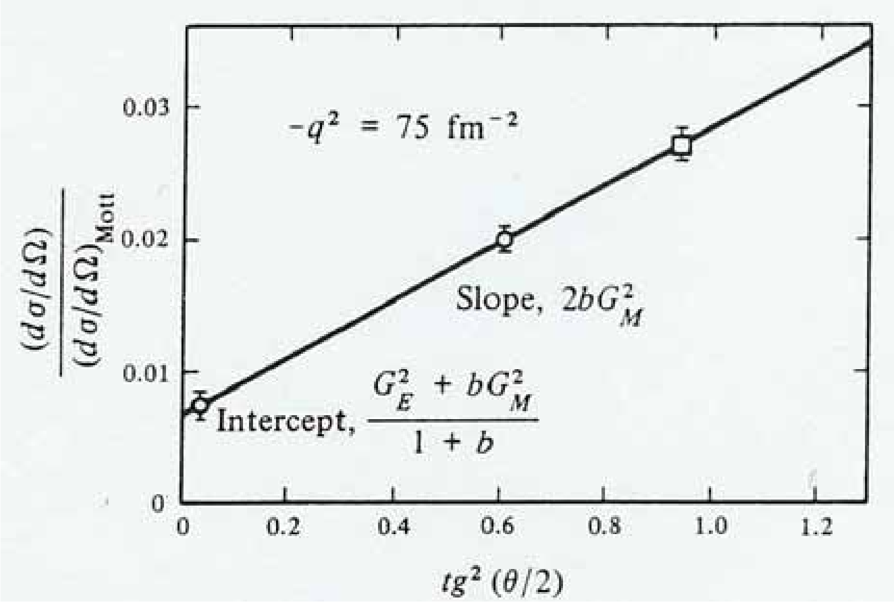
charge density

(3) Electron scattering from proton (Dirac particle) with finite extension
and anomalous magnetic moment,
in one-photon-exchange approximation,

Rosenbluth formular

$$\frac{d\sigma}{d\Omega}=\left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\frac{G_E^2\left(Q^2\right)+bG_M^2\left(Q^2\right)}{1+b}+2bG_M^2\left(Q^2\right)\tan^2\left(\frac{\theta}{2}\right)\right],$$

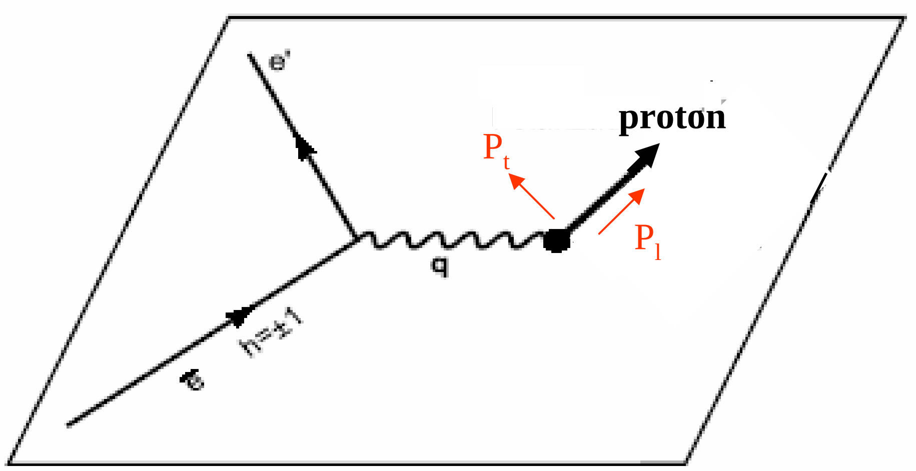
$$G_E^p\left(0\right)=1,\quad G_M^p\left(0\right)=1+\kappa_p=2.79=\mu_p,\quad b=\frac{Q^2}{4m_N}$$



(4) In elastic scattering of longitudinally polarized electrons from unpolarized protons, in one-photon-exchange approximation,

$$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l}\frac{E+E'}{2m_N}\tan\left(\frac{\theta}{2}\right),$$

P_t, P_l : polarization components of the recoiling proton perpendicular and parallel to its momentum in the scattering plane



The one-photon-exchange polarized electron-photon elastic scattering

Polarization transfer experiments from Jlab

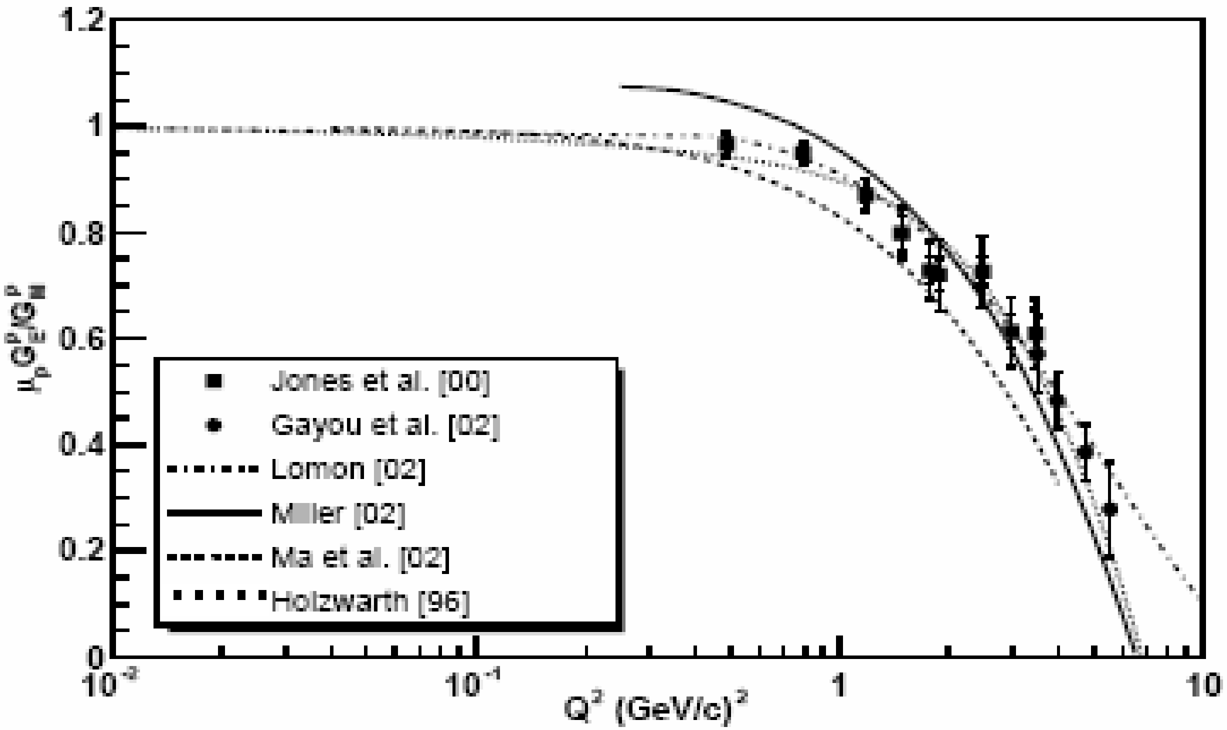


Fig. 16. *Jefferson Lab data* [56,58] *on the proton form factor ratio,* $\frac{\mu G_E^p}{G_M^p}$ *as a function of* Q^2 *together with calculations by Lomon* [116] *(dash-dotted), Miller* [107] *(solid curve), Holzwarth* [100] *(dotted curve), and Ma, Qing, and Schmidt* [129] *(dashed curve).*

Proton form factors

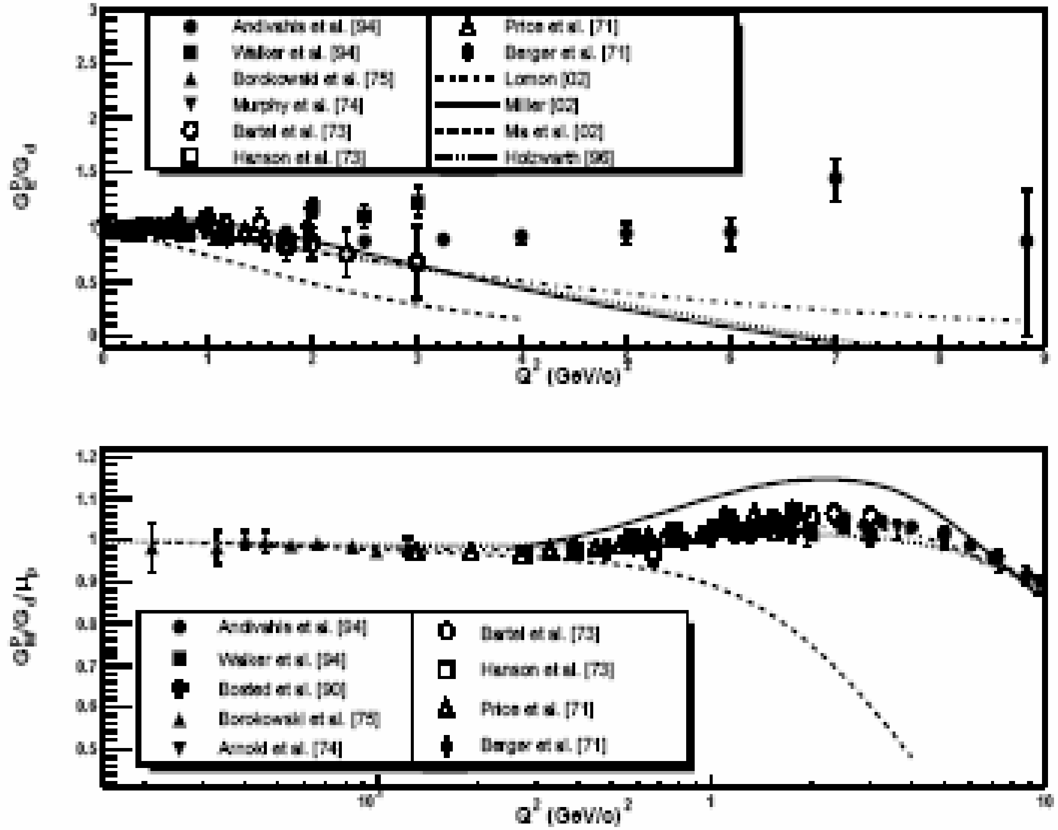


Fig. 17. *World data on proton electromagnetic form factor, G_E^p and $\frac{G_M^p}{\mu_p}$ since 1970 in the unit of the standard dipole parameterization as a function of Q^2 together with calculations by Lomon* [116] *(dash-dotted), Miller* [107] *(solid curve), Holzwarth* [100] *(dotted curve), and Ma, Qing, and Schmidt* [129] *(dashed curve).*

$$G_d(Q^2) = \left[1 + \left(\frac{Q^2}{Q_0^2}\right)\right]^{-2}, \quad Q_0^2 = 0.71\ (GeV/c)^2$$

Neutron form factors

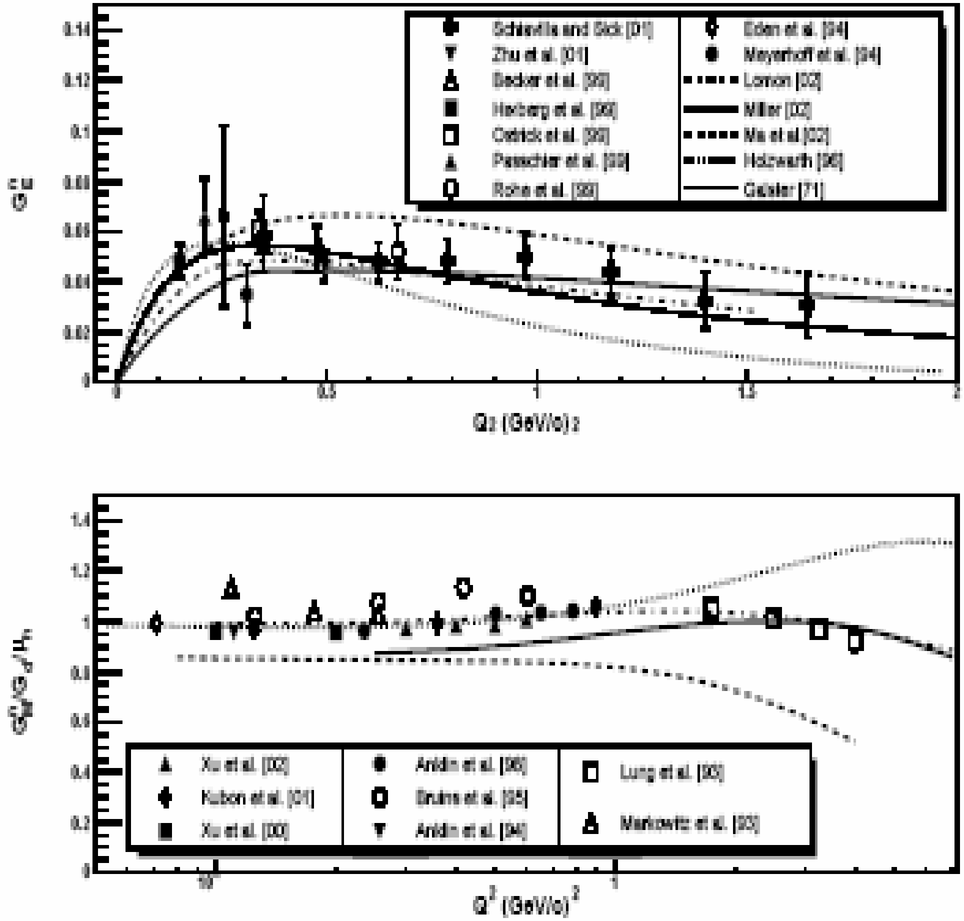
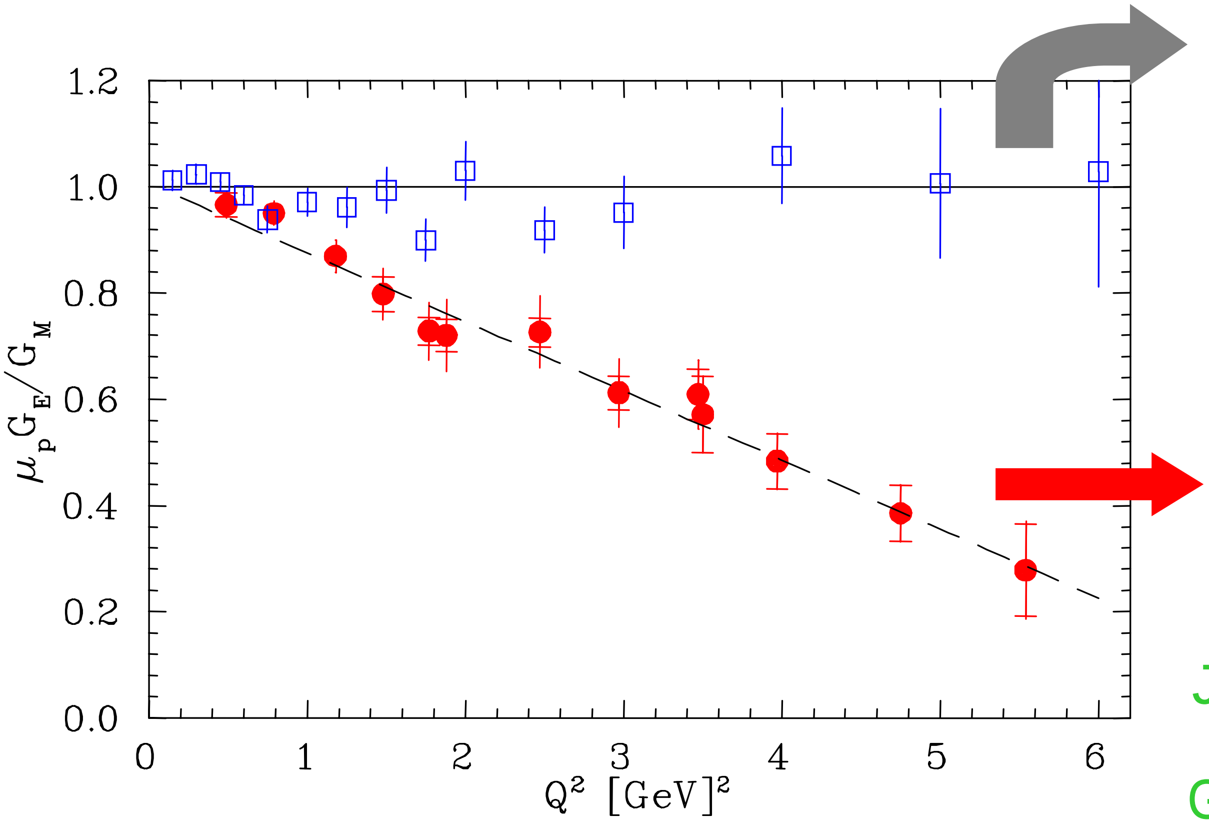


Fig. 18. *World data on neutron electromagnetic form factor,* G_E^n *and* $\frac{G_M^n}{\mu_n}$ *since 1990 as a function of* Q^2 *together with calculations by Lomon* [116] *(dash-dotted), Miller* [107] *(solid curve), Holzwarth* [100] *(dotted curve), and Ma, Qing, and Schmidt* [129] *(dashed curve).*

Rosenbluth vs polarization transfer measurements of G_E/G_M of proton



SLAC

Rosenbluth data

Jlab/Hall A

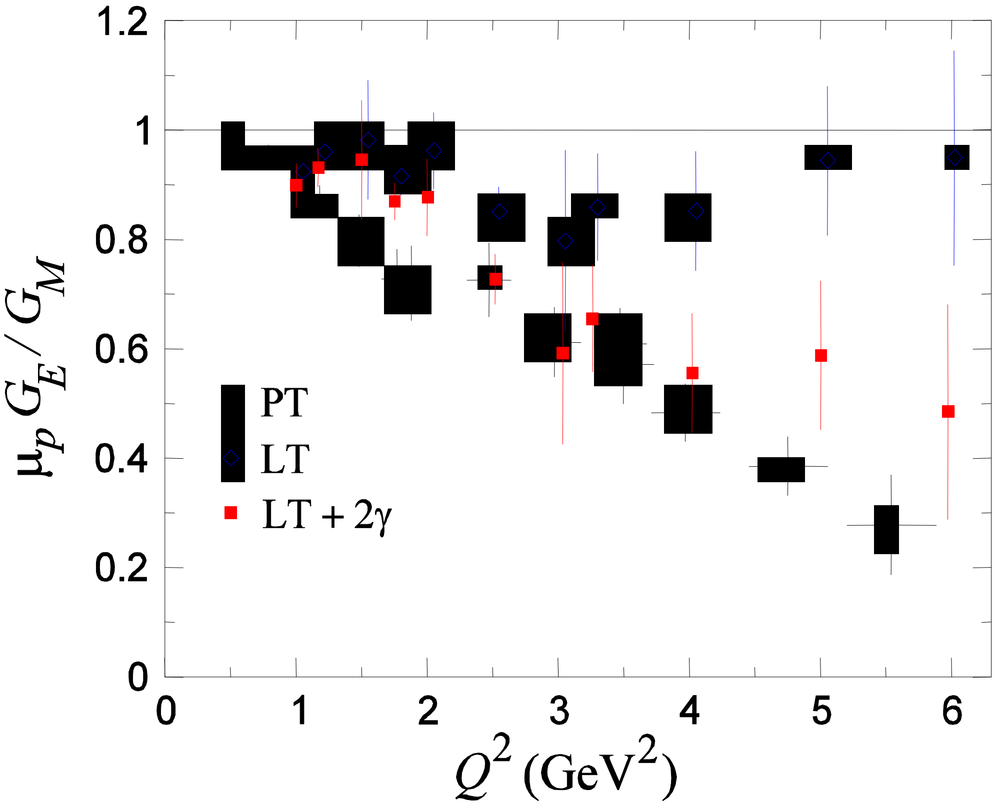
Polarization data

Jones et al. (2000)

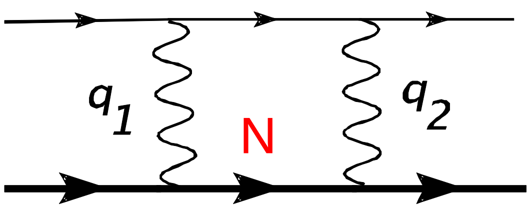
Gayou et al. (2002)

Two methods, two different results !

Two-photon exchange calculation : elastic contribution



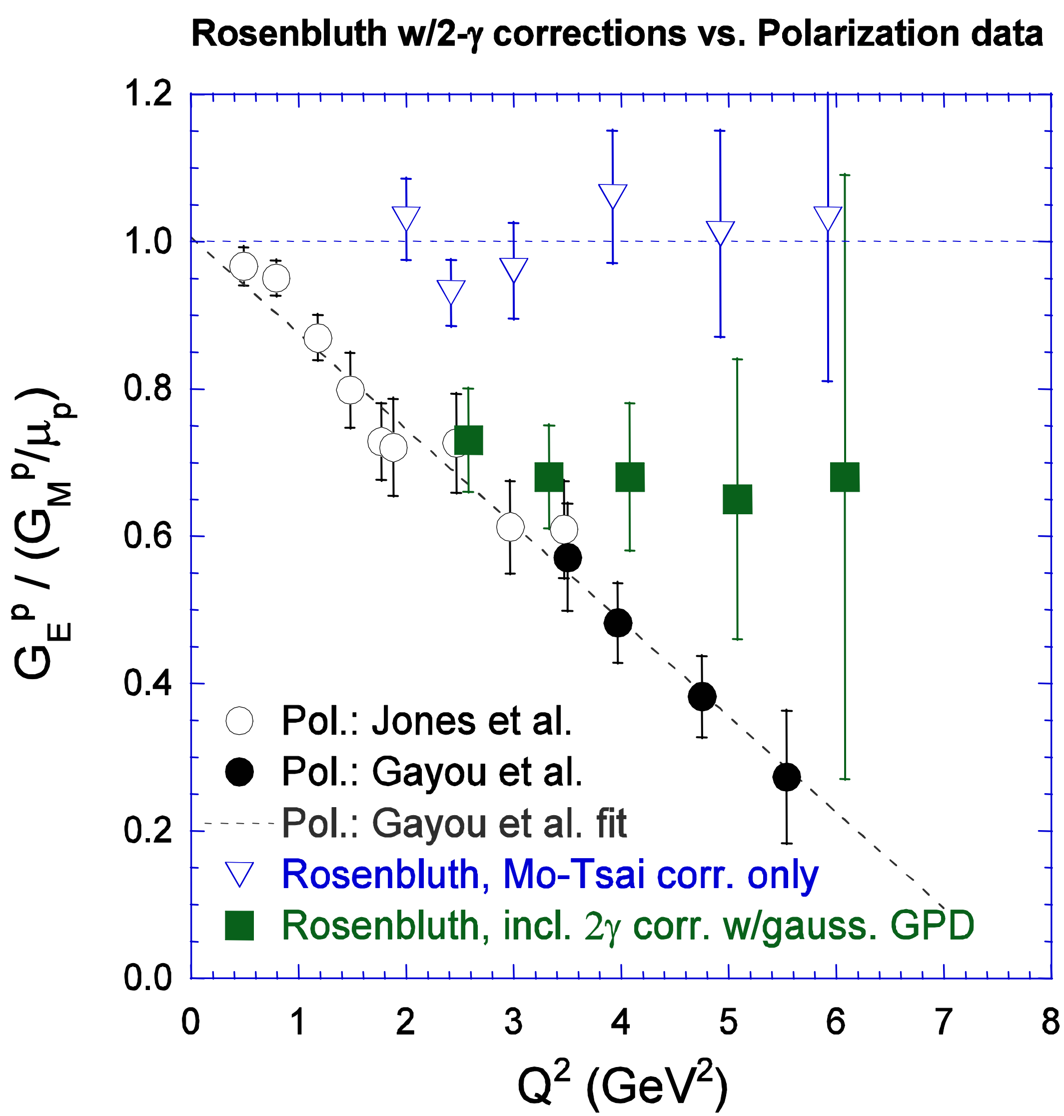
world Rosenbluth data

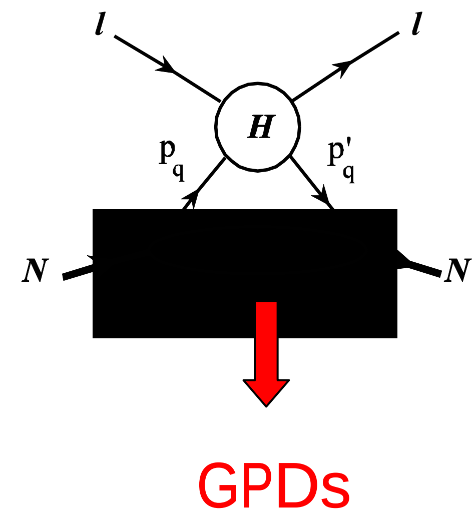


Polarization Transfer

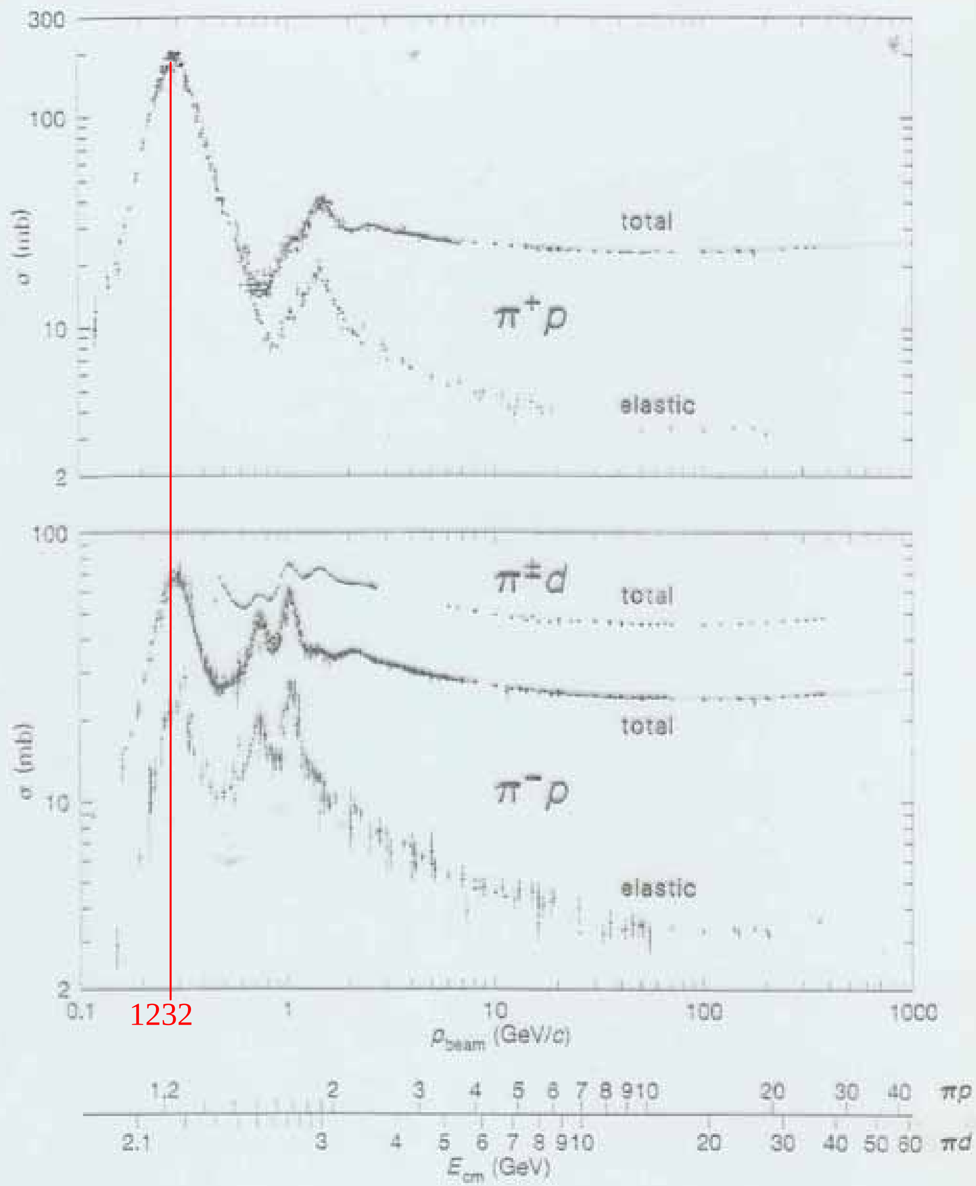
Blunden, Tjon, Melnitchouk (2003, 2005)

Two-photon exchange : partonic calculation





Chen, Afanasev, Brodsky, Carlson, Vdh (2004)

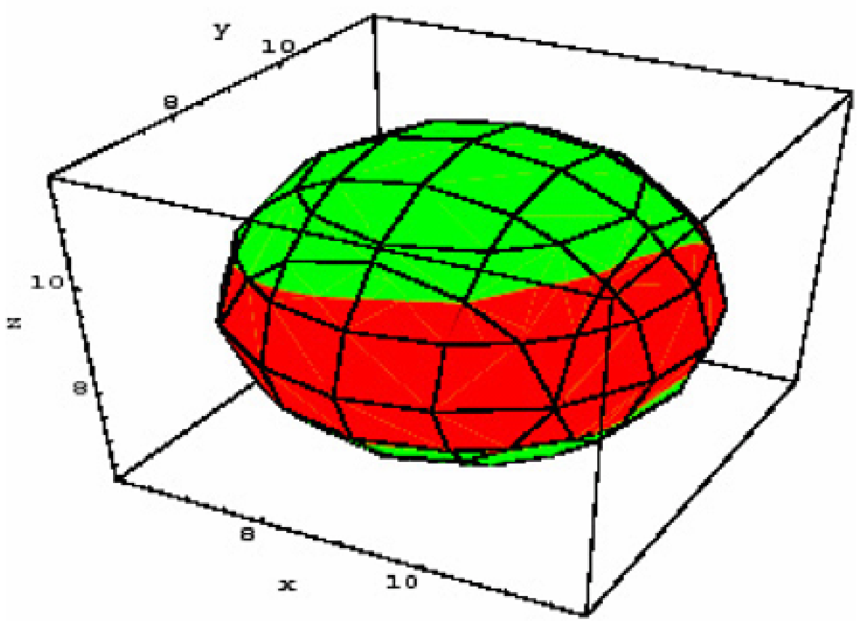


Hadronic total and elastic cross sections vs. laboratory beam momentum and total center-of-mass energy. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, Russia. See *Total Cross Sections for Reactions of High Energy Particles*, Landolt-Börnstein, New Series Vol. I/12 a and I/12 b, ed. H. Schopper (1988). Gray curve shows Regge fit from Table 33.2.

Properties of Δ

- M_Δ = 1232 MeV, Γ_Δ = 120 MeV
- $I(J^P) = \frac{3}{2}\left(\frac{3}{2}^+\right)$, *i.e*, spin $= \frac{3}{2}$, isospin $= \frac{3}{2}$ $\left(\Delta^{++}, \Delta^{+}, \Delta^{0}, \Delta^{-}\right)$

  $\Delta \rightarrow \pi N$ (branching ratio > 99%)
- Is Δ spherical? Namely, does it have a D-state?



Alexandrou et al
Lattice QCD calculation
Nucl-th/0311007

In constituent quark model,

$$H = T + V_{conf} + V_{OGEP},$$

$$V_{OGEP}(ij) = \frac{2\alpha_s}{2m_i m_j}\left\{\underbrace{\frac{8\pi}{3}\delta^{(3)}(\vec{r}_{ij})\vec{S}_i\cdot\vec{S}_j}_{\text{Fermi contact term}} + \overbrace{\frac{1}{r_{ij}^3}\left(3\vec{S}_i\cdot\hat{r}_{ij}\vec{S}_j\cdot\hat{r}_{ij} - \vec{S}_i\cdot\vec{S}_j\right)}^{\text{Tensor force } [R_{ij}^{(2)}\times S_{ij}^{(2)}]^{(0)}}\right\},$$

$$V_{conf} = V_{H.O.}$$

D-state component

	P_D(%)	Q(fm^2)
N(938)	0.4	0
Δ(1232)	1.9	-0.089

Small effect !!

How to measure it?

$\gamma^* N \leftrightarrow \Delta$ transition

Parity and angular momentum of multipole radiation

- electric multipole of order (l,m), parity = $(-1)^l$
- magnetic multipole of order (l,m), parity = $(-1)^{l+1}$

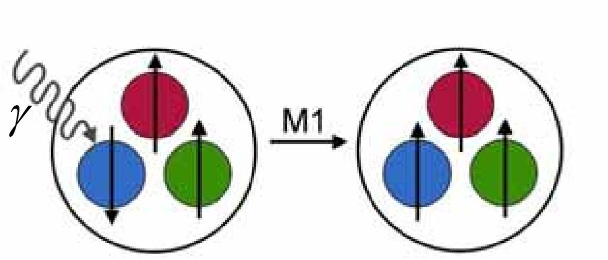
$$\gamma + N(J_i = \frac{1}{2},\ P_{\mathrm{i}} = +) \to \Delta(J_f, P_f = +)$$

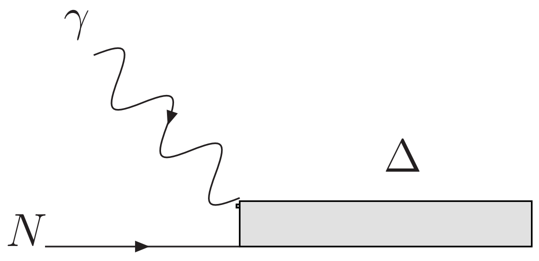
Allowed multipole orders are l=1 and 2, with parity = +

$$l = 1:\ \cancel{P(E1) = (-1)^l = -},\ P(M1) = (-1)^{l+1} = + \qquad \mathrm{S} \to \mathrm{S}$$

$$l = 2:\ P(E2) = +,\qquad \cancel{P(M2) = -} \qquad \mathrm{S} \to \mathrm{D}$$

N(J=1/2)   Δ=(J=3/2)





G_{M1}, G_{E2}

$|G_{E2}| << |G_{M1}|$

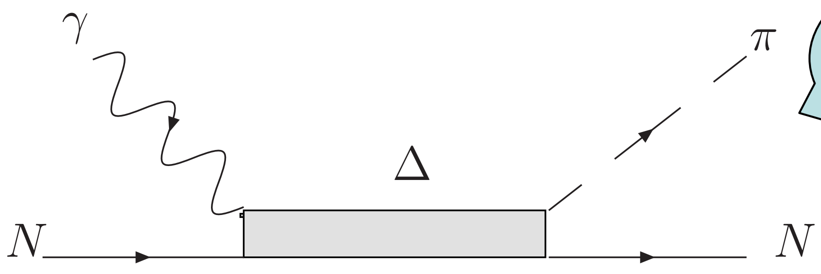
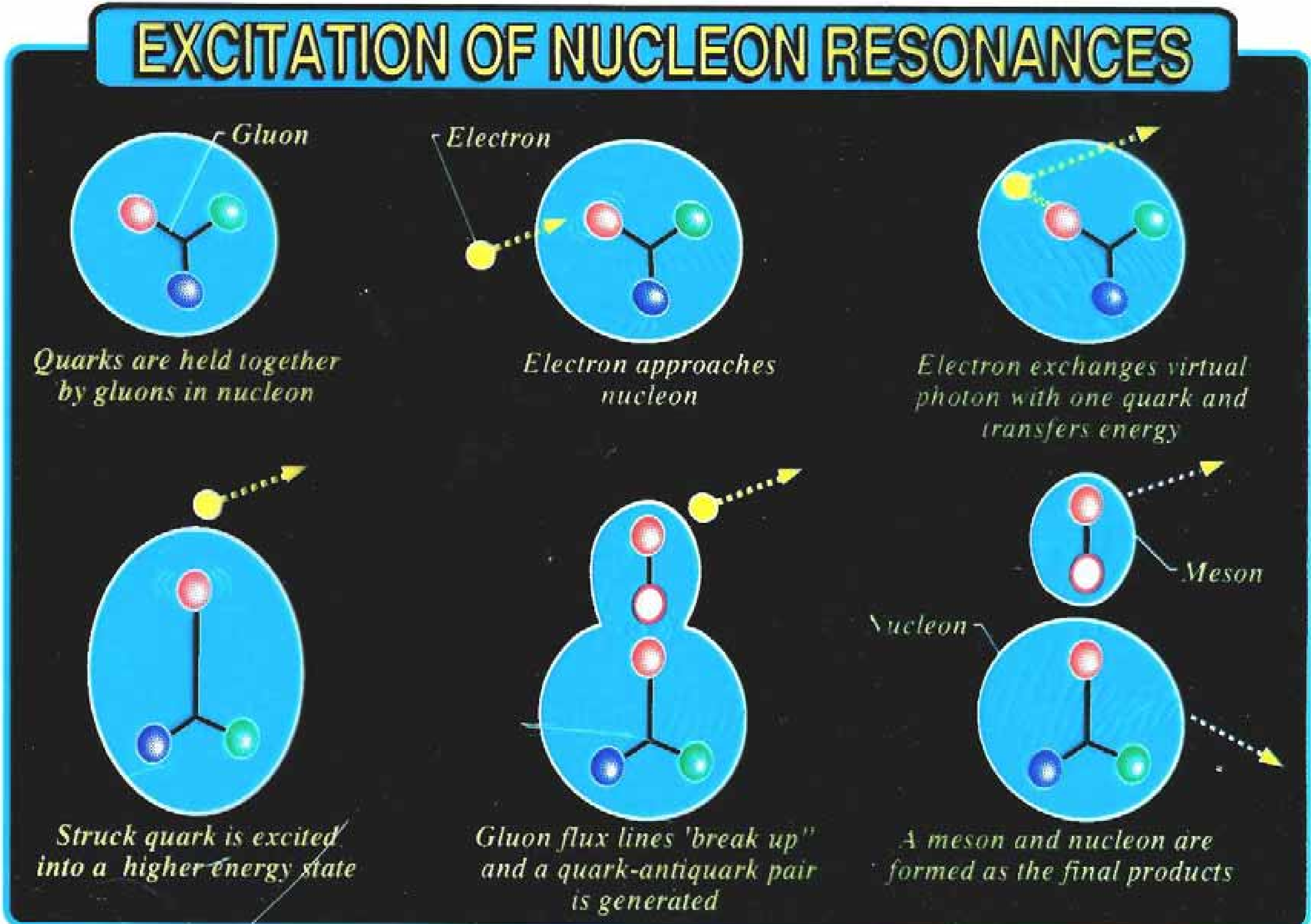


photo- and
electro-production
of pion

$$\gamma + N \rightarrow \pi + N$$

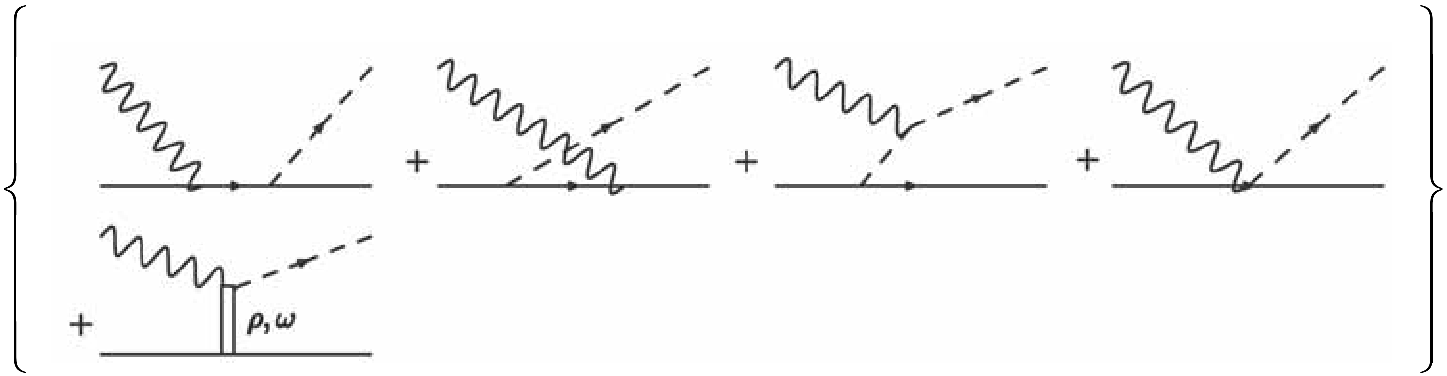
$$e + N \rightarrow e' + \pi + N \quad (\gamma^* + N \rightarrow \pi + N)$$



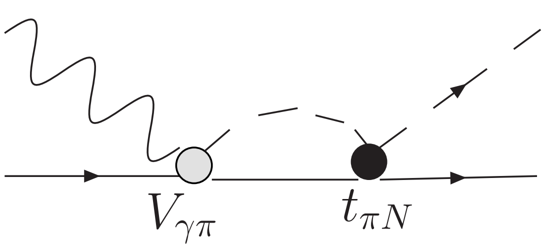
v.burkert/excnucrsnCvg jm 5/20/93

Tree diagrams

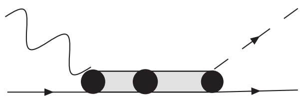
$$v^{B}_{\gamma\pi} =$$

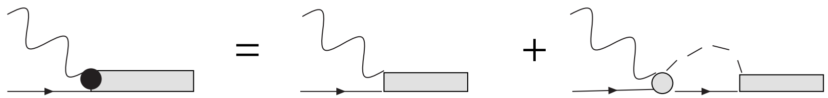


and rescatterings

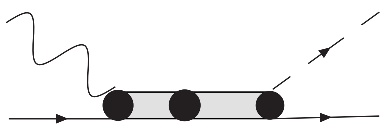


Experimentally, it is only possible to extract the contribution of the following process,



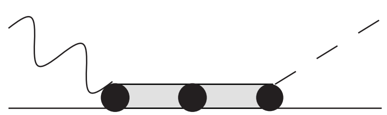


In particular, interests have been focused on the extraction of EMR and CMR from experiments

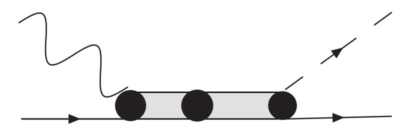


E2

EMR = ―――――――――――― $= \dfrac{E_{1+}}{M_{1+}}$

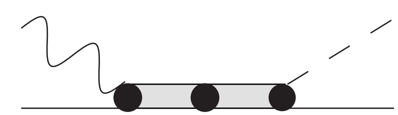


M1



C2

CMR= ―――――――――――― $= \dfrac{S_{1+}}{M_{1+}}$

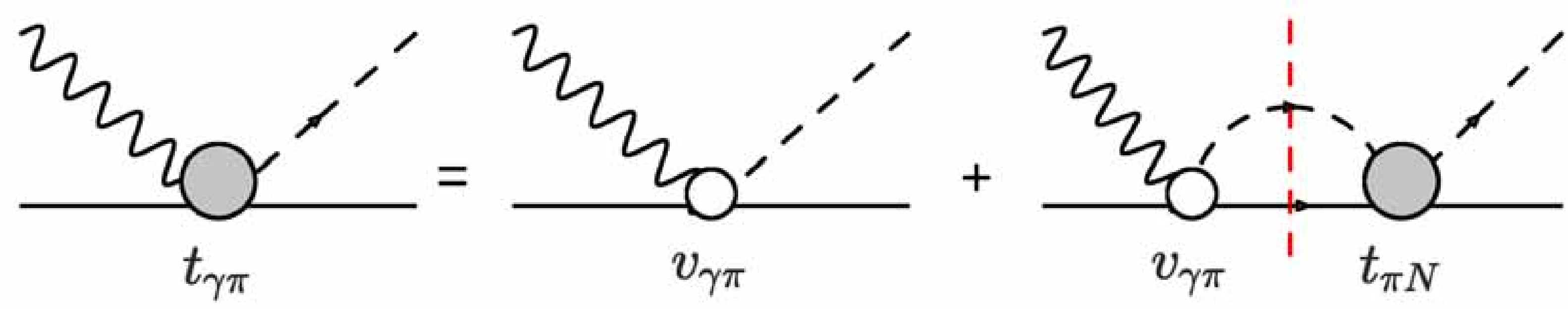


M1

NEED A GOOD THEORY OF

ELECTROMAGNETIC PRODUCTION OF PION

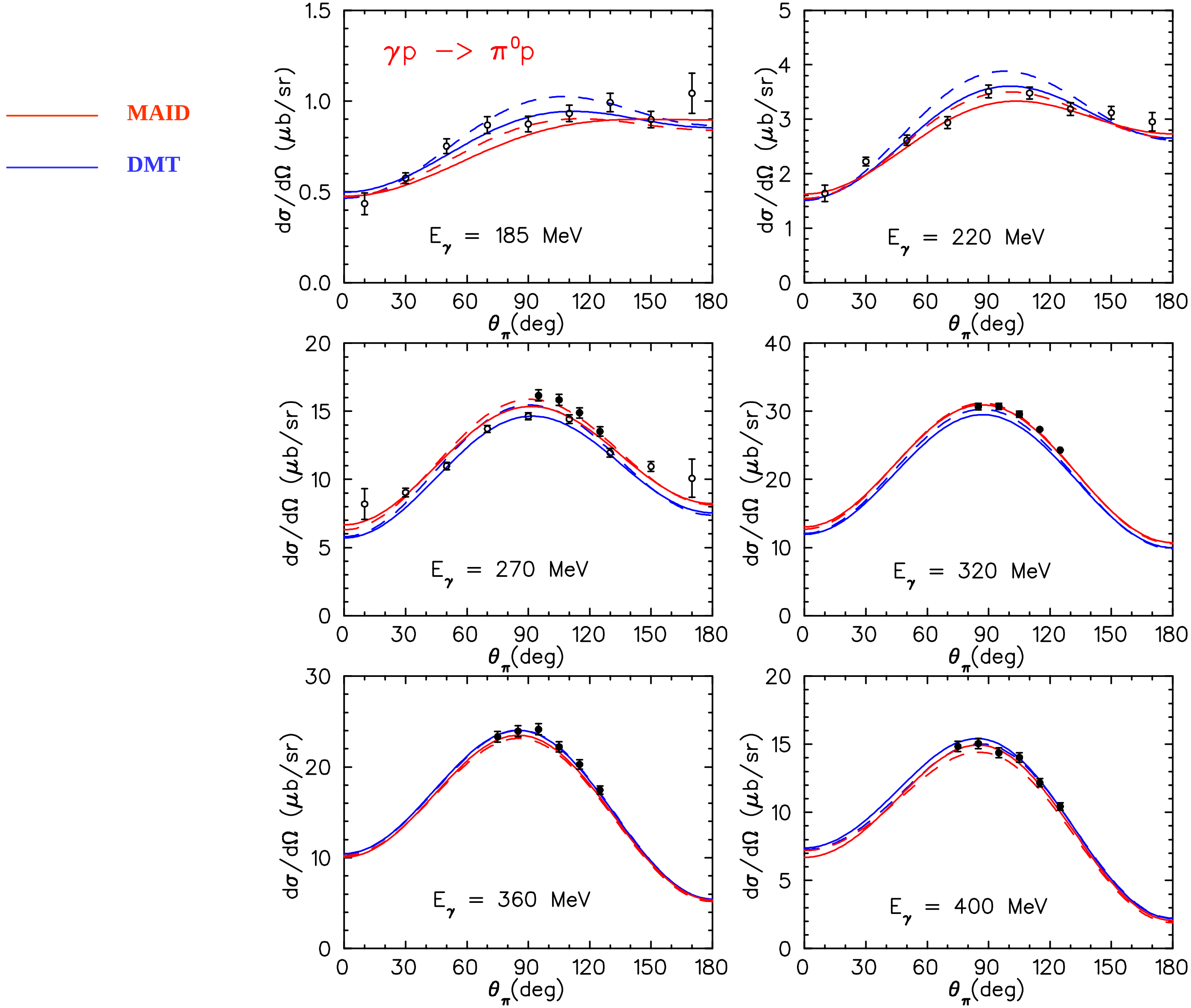
Dynamical approach



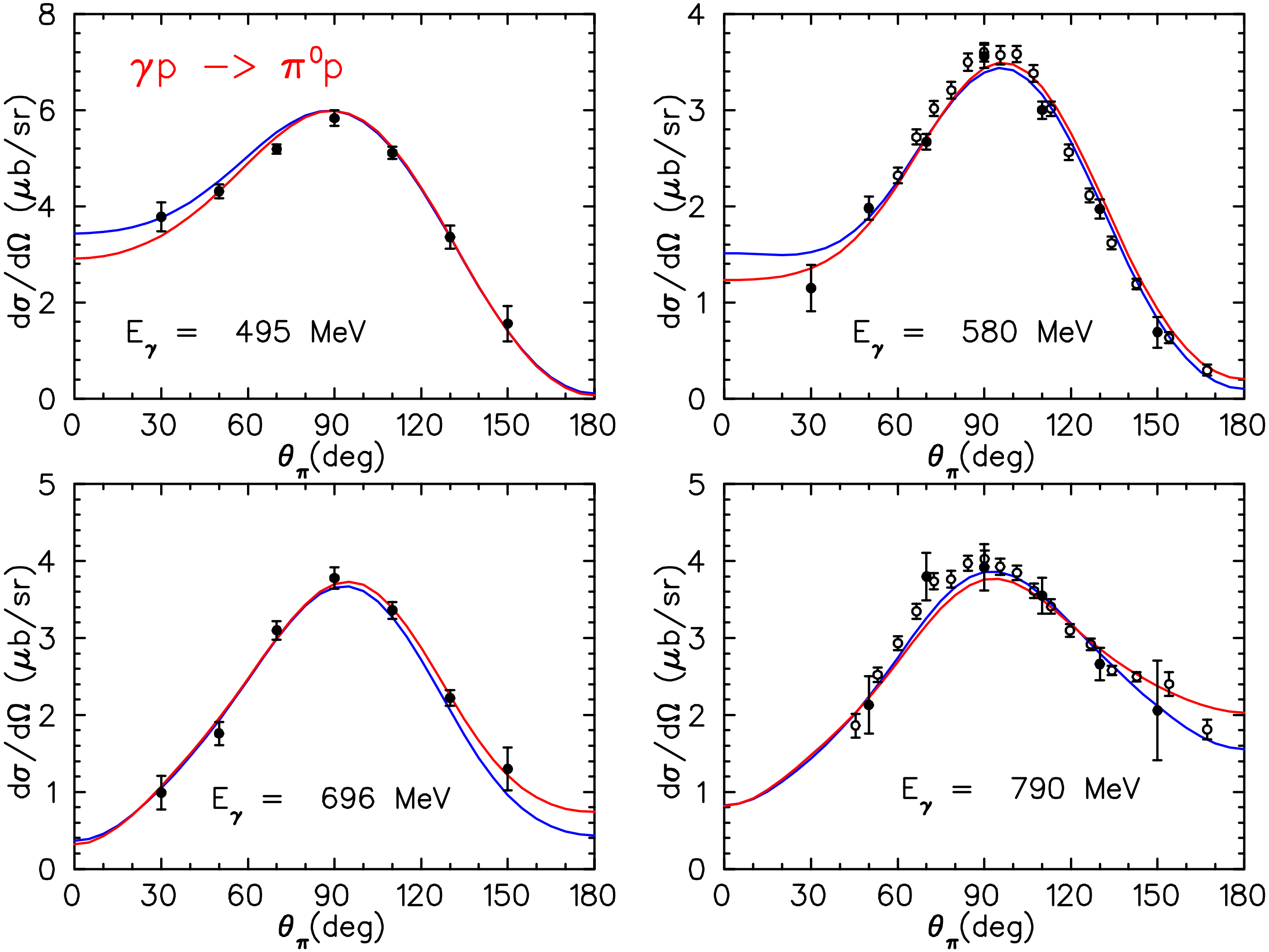
Both on- & off-shell

- Dubna-Mainz-Taipei (DMT)
- Sato-Lee

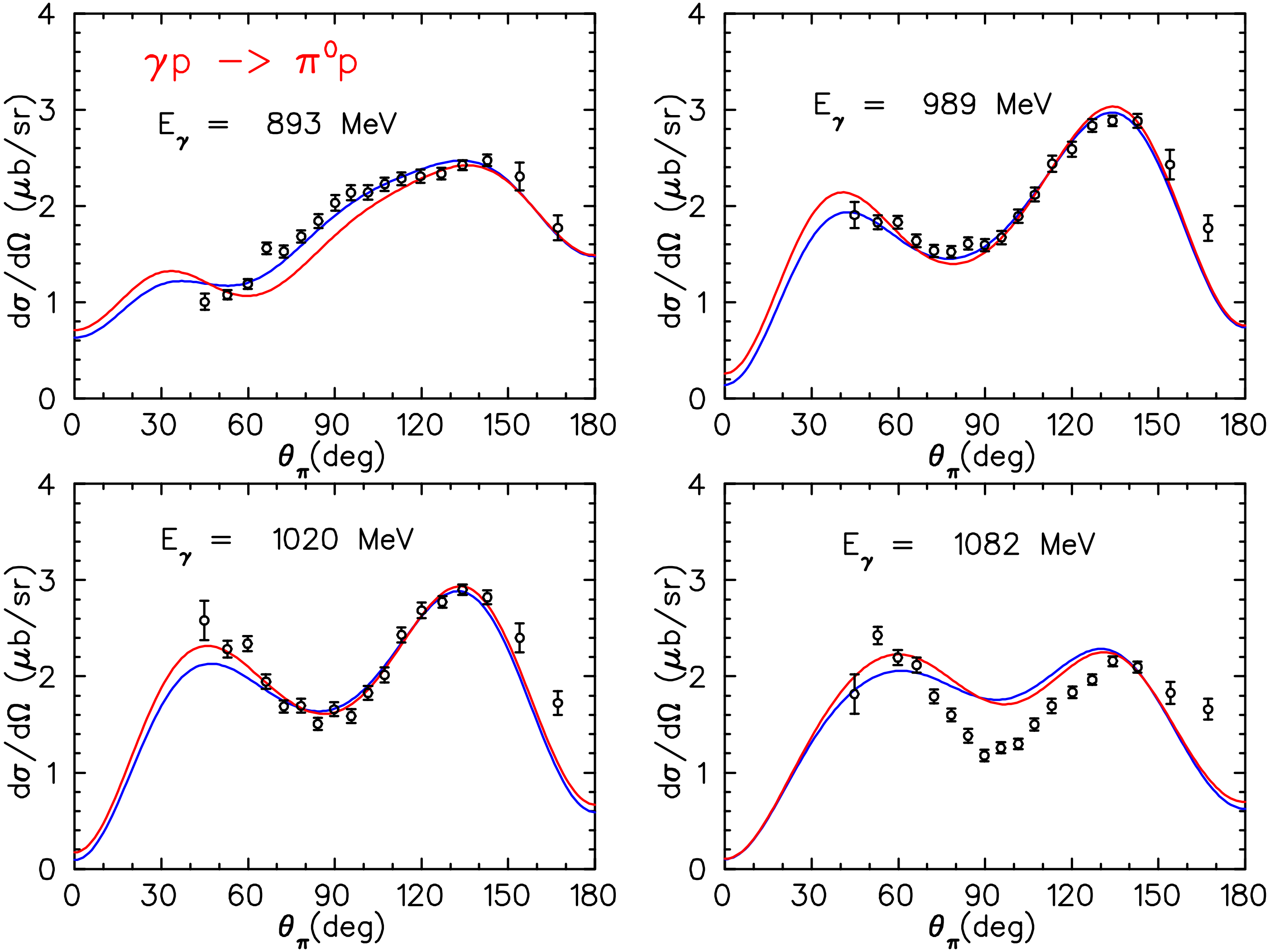
◆ MAID – K-matrix approximation

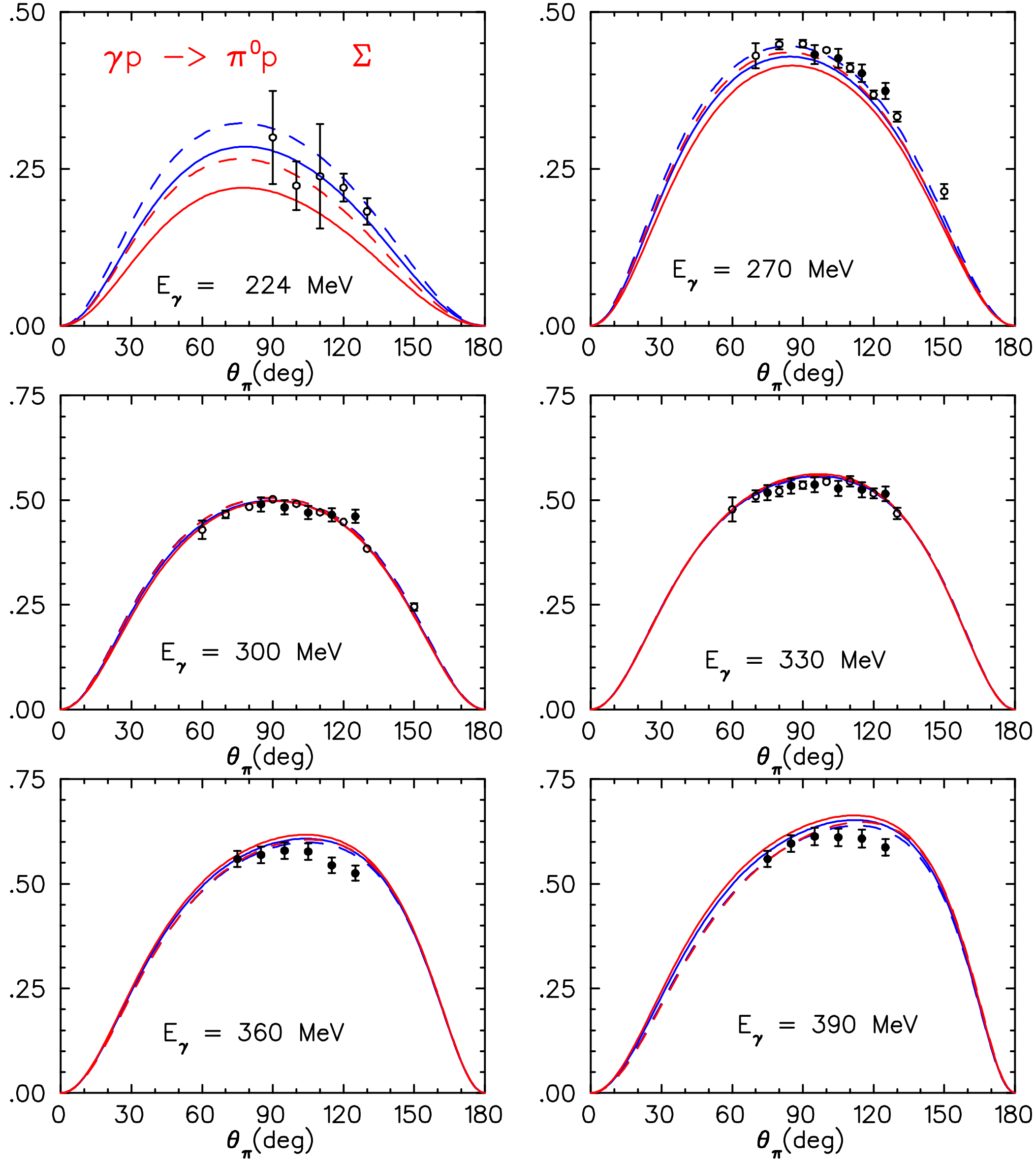


MAID
DMT
γp -> π⁰p
E_γ = 185 MeV
E_γ = 220 MeV
E_γ = 270 MeV
E_γ = 320 MeV
E_γ = 360 MeV
E_γ = 400 MeV
dσ/dΩ (μb/sr)
θ_π(deg)

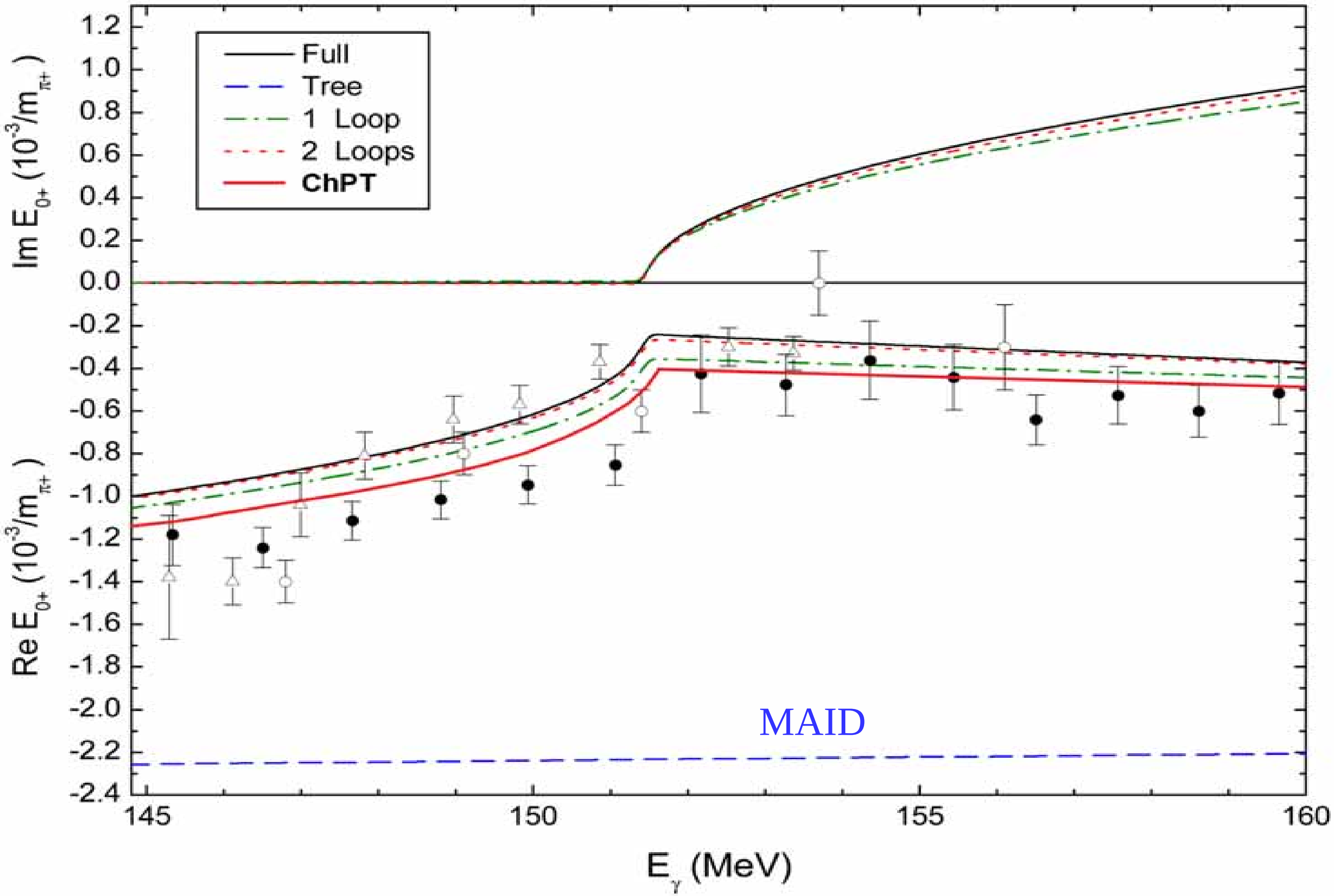


γp -> π⁰p
dσ/dΩ (μb/sr)
θπ(deg)
Eγ = 495 MeV
Eγ = 580 MeV
Eγ = 696 MeV
Eγ = 790 MeV
0
30
60
90
120
150
180


γp -> π⁰p
E_γ = 893 MeV
E_γ = 989 MeV
E_γ = 1020 MeV
E_γ = 1082 MeV
dσ/dΩ (μb/sr)
θ_π(deg)
0
1
2
3
4
0
30
60
90
120
150
180


γp −> π⁰p Σ
E_γ = 224 MeV
E_γ = 270 MeV
E_γ = 300 MeV
E_γ = 330 MeV
E_γ = 360 MeV
E_γ = 390 MeV
θ_π(deg)
.00
.25
.50
.75
0
30
60
90
120
150
180

$\gamma p \rightarrow \pi^0 p$

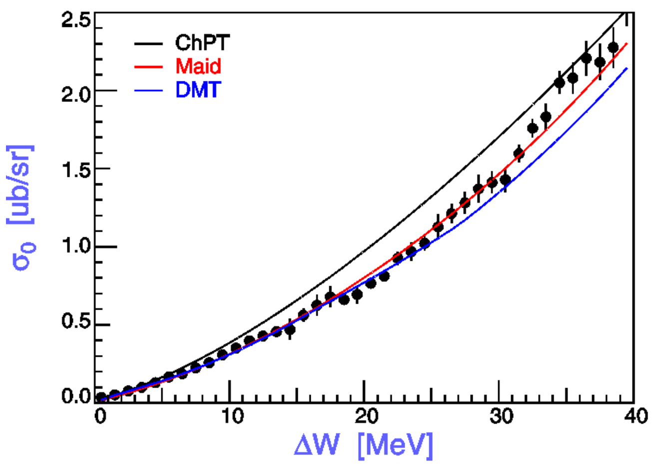


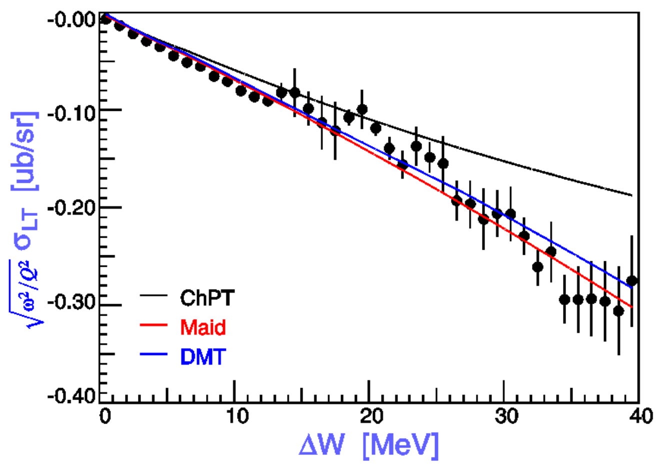
$p(\vec{e},e'p)\pi^0$ Electroproduction near Threshold

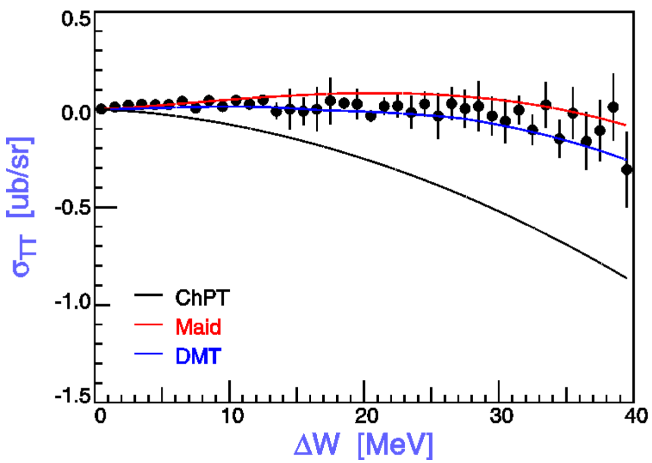
E_0=854.5 MeV, Q^2=0.05 GeV²/c², ε=0.03, θ=90°, ϕ=90°

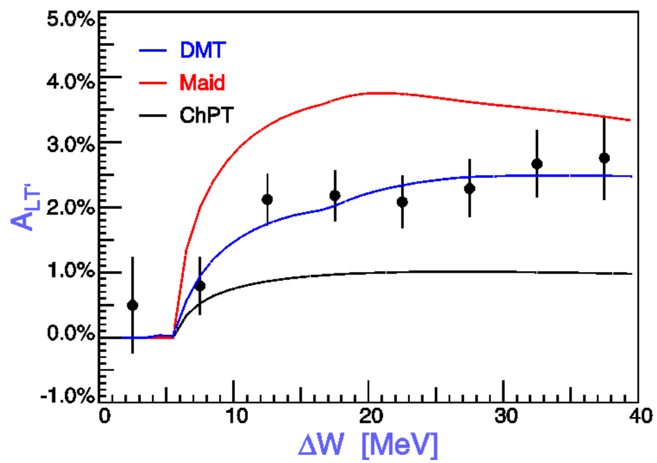
exp. data: M. Weis, Mainz 2003

$$\frac{d\sigma_v}{d\Omega} = \frac{d\sigma_T}{d\Omega} + \varepsilon\frac{d\sigma_L}{d\Omega} + \sqrt{2\varepsilon(1+\varepsilon)}\frac{d\sigma_{LT}}{d\Omega}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{d\Omega}\cos 2\phi + h\sqrt{2\varepsilon(1-\varepsilon)}\frac{d\sigma_{LT'}}{d\Omega}\sin\phi$$

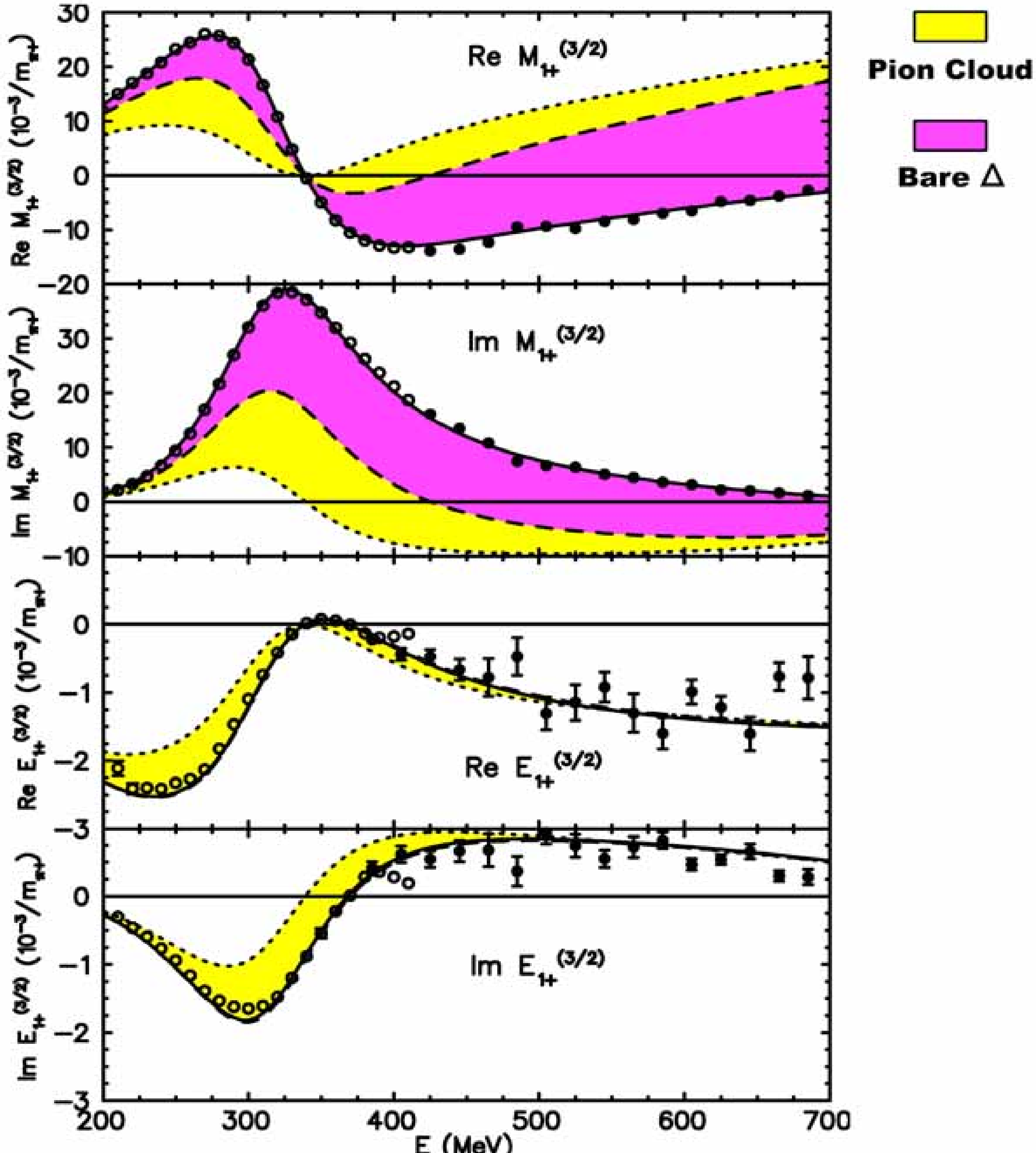








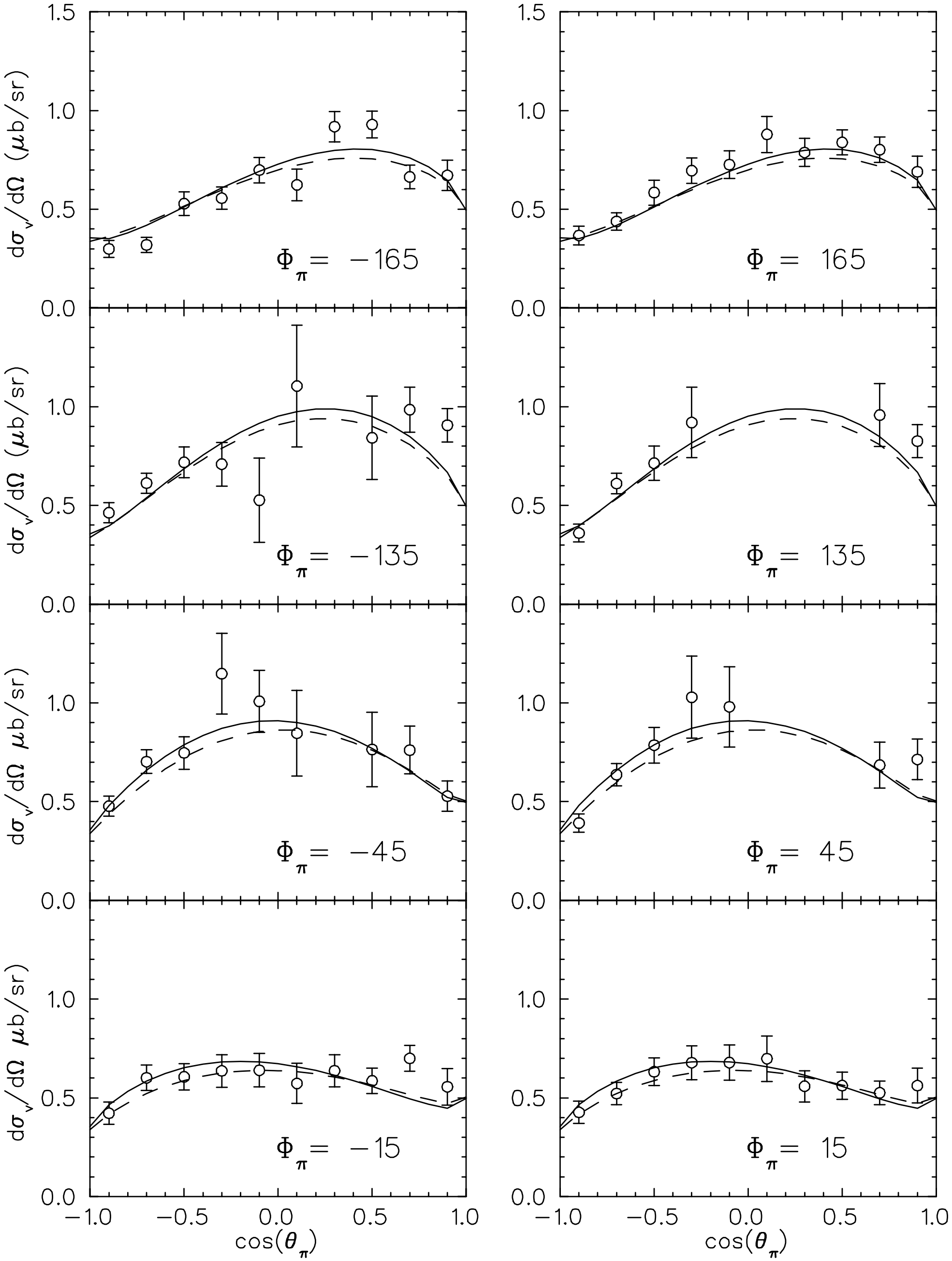
$$A_{LT'} = \frac{\sqrt{2\varepsilon(1-\varepsilon)}\,\sigma_{LT'}}{\sigma_T + \varepsilon\,\sigma_L - \varepsilon\,\sigma_{TT}}$$



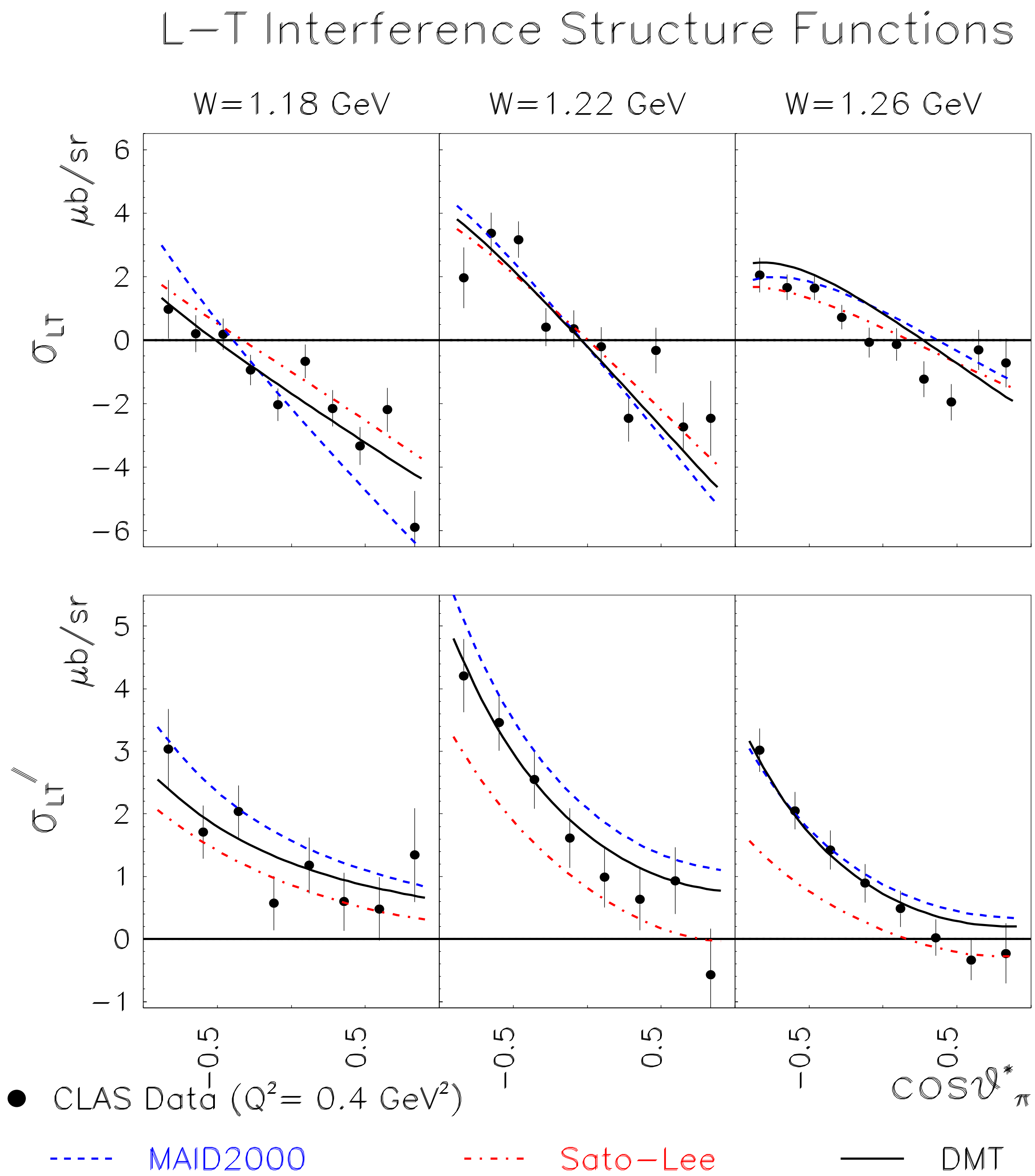
Pion Cloud
Bare Δ
Re M1+(3/2)
Im M1+(3/2)
Re E1+(3/2)
Im E1+(3/2)
Re M1+(3/2) (10⁻³/mπ+)
Im M1+(3/2) (10⁻³/mπ+)
Re E1+(3/2) (10⁻³/mπ+)
Im E1+(3/2) (10⁻³/mπ+)
Eγ(MeV)

	$A_{1/2}$ $(10^{-3}GeV^{-1/2})$	$A_{3/2}$	$Q_{N\,!\,\Delta}$ (fm^2)	$\mu_{N}\,!\,\Delta$
PDG	**-135**	**-255**	**-0.072**	**3.512**
LEGS	**-135**	**-267**	**-0.108**	**3.642**
MAINZ	**-131**	**-251**	**-0.0846**	**3.46**
DMT	**-134** **(-80)**	**-256** **(-136)**	**-0.081** **(0.009)**	**3.516** **(1.922)**
SL	**-121** **(-90)**	**-226** **(-155)**	**-0.051** **(0.001)**	**3.132** **(2.188)**

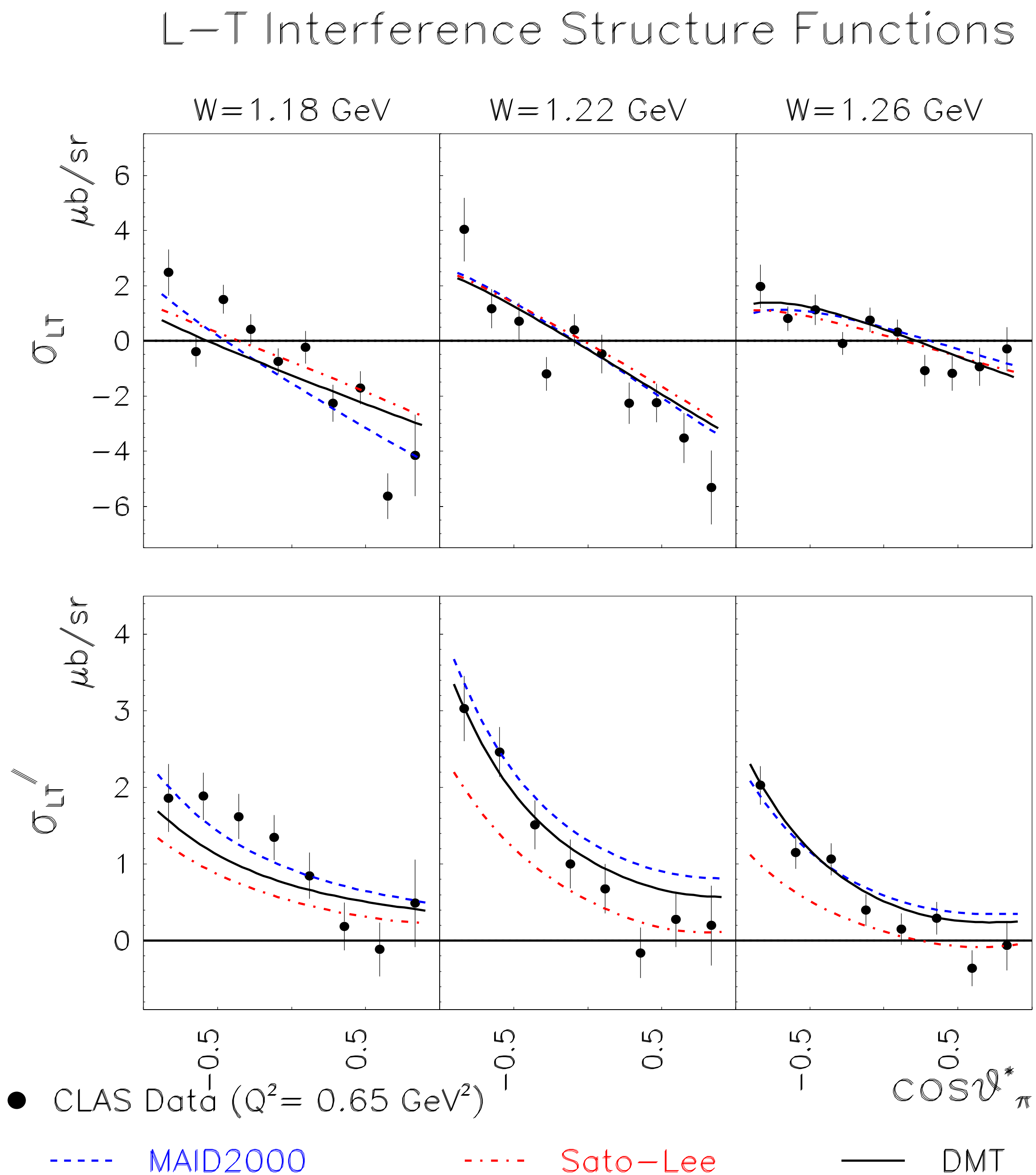
Comparison of our predictions for the helicity amplitudes, $Q_{N\,!\,\Delta}$, and $\mu_{N\,!\,\Delta}$ with experiments and Sato-Lee's prediction. The numbers within the parenthesis in red correspond to the bare values.



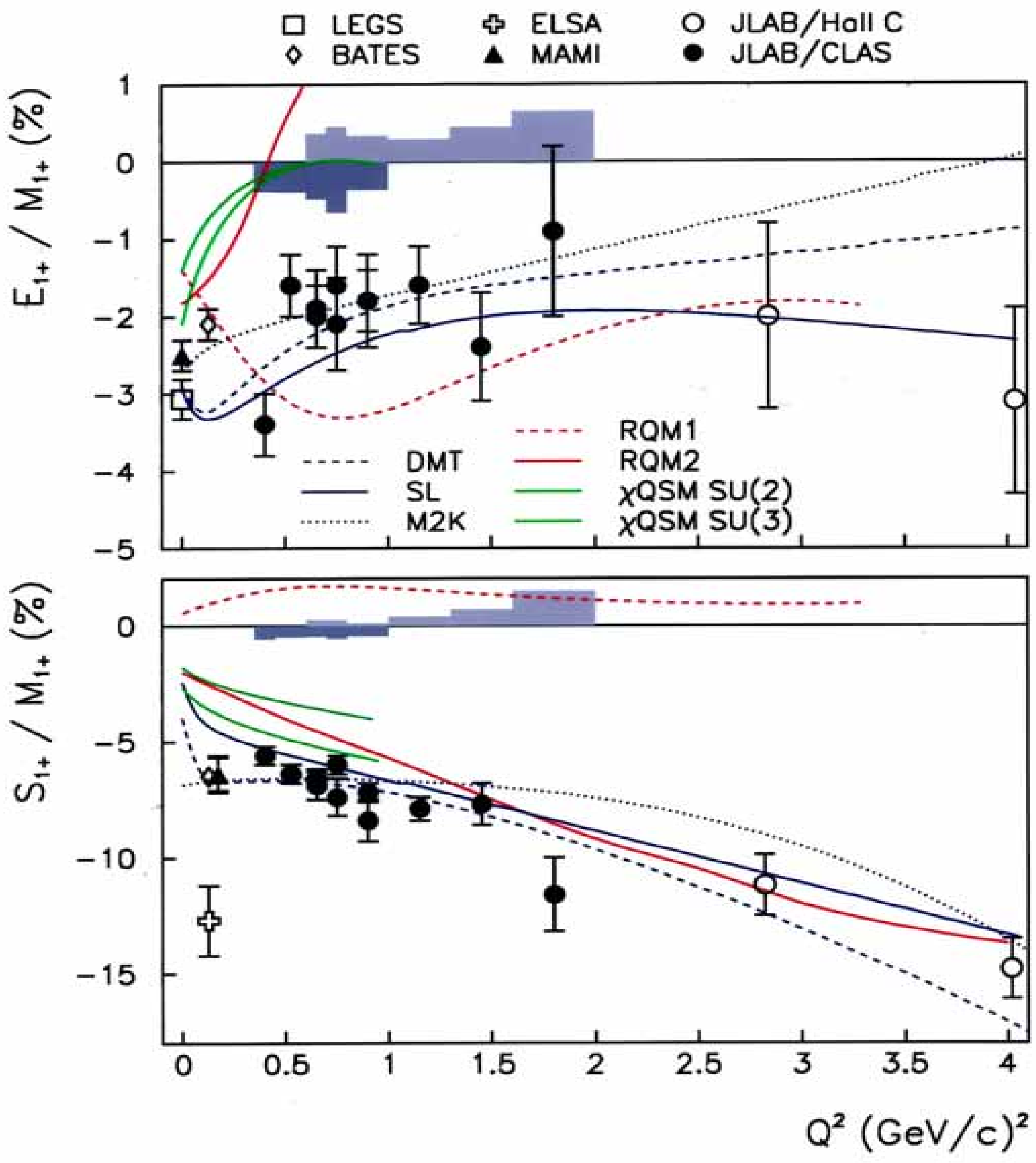
$d\sigma_v/d\Omega$ (μb/sr)
$\cos(\theta_\pi)$
$\Phi_\pi = -165$
$\Phi_\pi = 165$
$\Phi_\pi = -135$
$\Phi_\pi = 135$
$\Phi_\pi = -45$
$\Phi_\pi = 45$
$\Phi_\pi = -15$
$\Phi_\pi = 15$



L−T Interference Structure Functions
W=1.18 GeV
W=1.22 GeV
W=1.26 GeV
σ_{LT} μb/sr
σ_{LT}' μb/sr
$\cos\vartheta^*_\pi$
● CLAS Data (Q^2= 0.4 GeV^2)
MAID2000
Sato−Lee
DMT

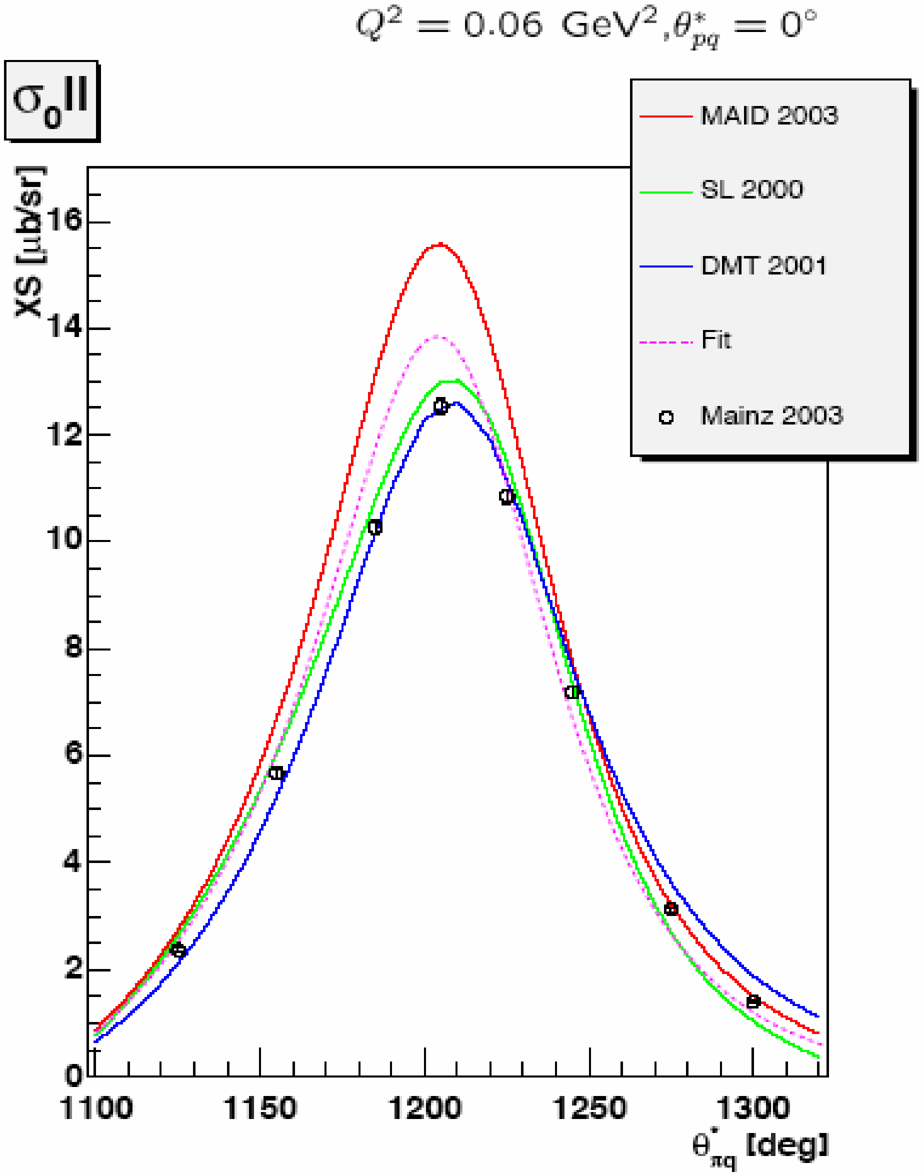


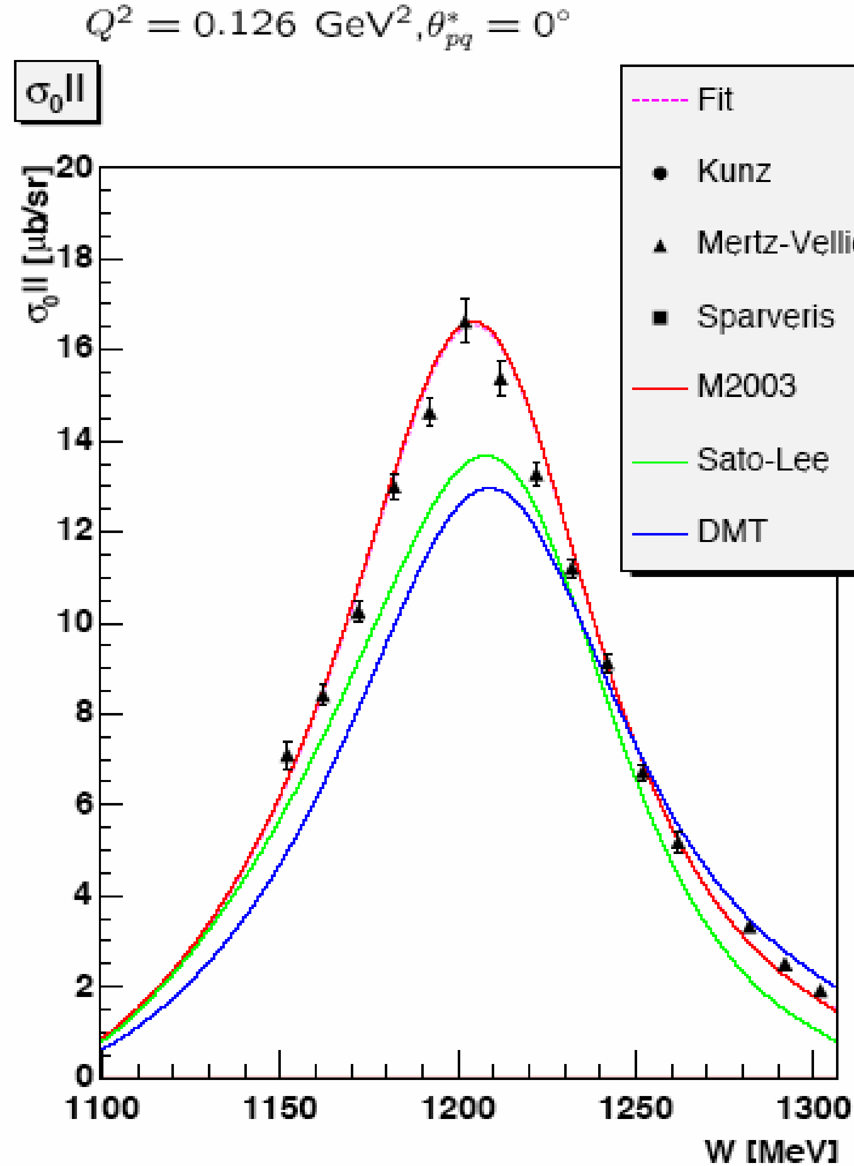
L−T Interference Structure Functions
W=1.18 GeV
W=1.22 GeV
W=1.26 GeV
μb/sr
σLT
σLT′
cosϑ*π
CLAS Data (Q²= 0.65 GeV²)
MAID2000
Sato−Lee
DMT



LEGS
BATES
ELSA
MAMI
JLAB/Hall C
JLAB/CLAS
E1+ / M1+ (%)
DMT
SL
M2K
RQM1
RQM2
χQSM SU(2)
χQSM SU(3)
S1+ / M1+ (%)
Q² (GeV/c)²

σ_0 W Dependence





PRELIMINARY

OUTLOOK and Conclusion

➢ Nucleon form factors

- Jlab 12 GeV upgrade will extend the proton G_E/G_M measurement to Q^2=14 $(GeV/c)^2$
- G_E^n will be extended to Q^2=4 $(GeV/c)^2$ via $^3\overrightarrow{He}\,(\vec{e},e'n)$ and G_M^n to Q^2=10 $(GeV/c)^2$ via ratio technique of $D(e,e'n)/D(e,e'p)$
- new analyses for the form factors, including the two-photon-exchange corrections needed to be carried out

➢ N-Δ transition form factors

- Jlab 12 GeV upgrade will extend the EMR and CMR measurements to Q^2=14 $(GeV/c)^2$
- several precision measurements at low Q^2 are still being analyzed
- Δ is deformed and oblate

➢Theory

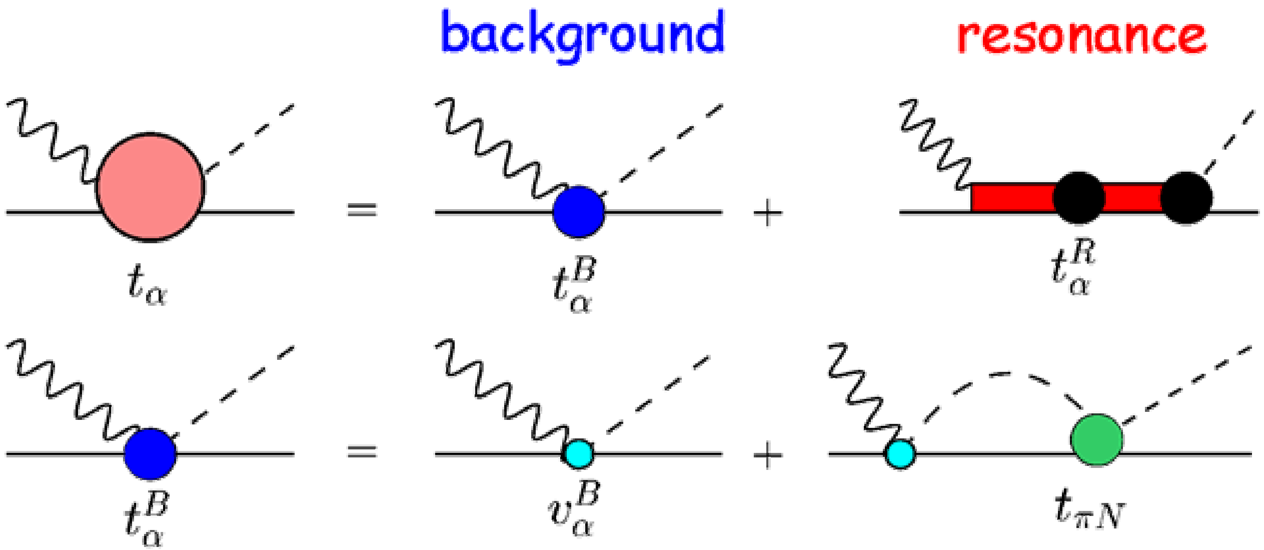
- **significantly improved nucleon model is urgently needed**
- **better reaction description of** $e + p \rightarrow e' + \pi + N$ **is needed**
- **lattice QCD calculations**

The End

Thanks you for your attention!

Dynamical Model

Dubna-Mainz-Taipei (DMT)



$$t_\alpha^B(DM) = v_\alpha^B e^{i\delta_\alpha} \cos\delta_\alpha + \underbrace{P\int_0^\infty dq' \frac{q'^2 t_{\pi N}^{(\alpha)}(q_E, q')\, v_\alpha^B(q')}{E - E_{\pi N}(q')}}_{\sim \sin\delta\, e^{i\delta}}$$

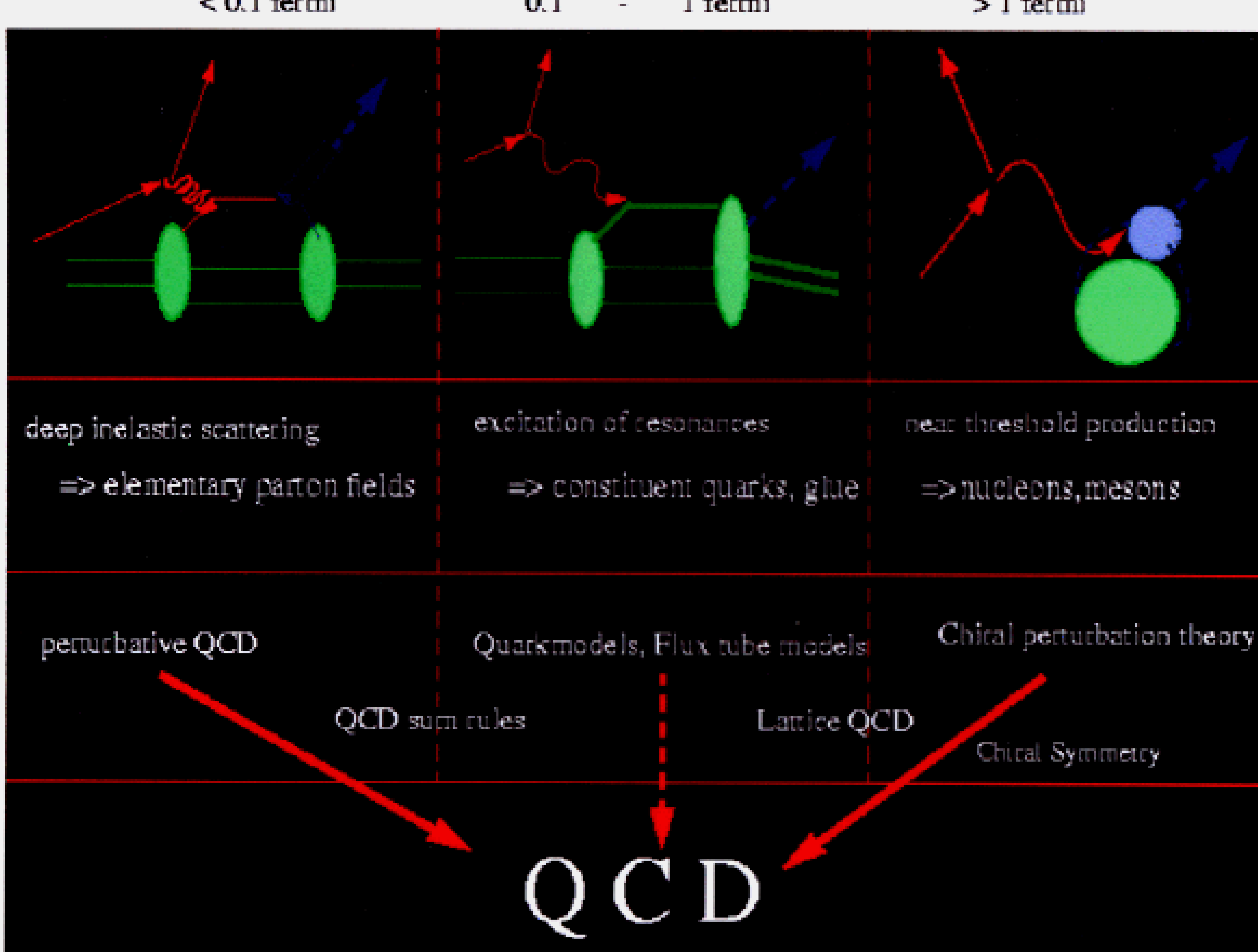
The $\gamma N\Delta(1232)$ Transition

=> Model descriptions of the $\gamma N\Delta$ transition multipoles require quarks and pions as the effective degrees of freedom
- M_{1+} , R_{EM} , R_{SM} (Q^2)

=> Description of $\gamma N\Delta$ from Lattice QCD?
- early LQCD results gave $R_{EM} = 0.03(11)$
  compared to experiment $R_{EM} = -0.0275(50)$
- expect a factor 10 improvement from LQCD?
- absolute multipoles?

=> Measure multipoles with higher precision and to higher Q^2
- zero crossing of R_{EM} (Q^2)?
- will R_{SM} (Q^2) continue to get more negative?
- Measurements at 6 GeV planned at JLab in 2001
- develop analysis tools beyond truncated MP analysis
- polarization observables to reduce model-dependence

=> Crystal Ball @ MAMI - μ_Δ , ...



< 0.1 fermi
0.1 - 1 fermi
> 1 fermi
deep inelastic scattering
=> elementary parton fields
excitation of resonances
=> constituent quarks, glue
near threshold production
=> nucleons, mesons
perturbative QCD
Quarkmodels, Flux tube models
Chiral perturbation theory
QCD sum rules
Lattice QCD
Chiral Symmetry
QCD

EMR: E2/M1 Ratio (Theory)

SU(6):
0.0

MIT bag model:
0.0

Non. rel. quark model:
0 to -2.0%

Konuik, Isgur	Phys. Rev. D21（1980）1868
Gershteyn	Sov. J. Phys. 34（1981）870
Drechsel, Giannini	Phys. Lett. 143 B（1992）2864

Relativized quark model:
-0.1%

Capstick, Karl	Phys. Rev. D41（1990）2767
Capstick	Phys. Rev. D46（1992）2864

Cloudy bag model:
-2.0 to -3.0%

Kalbermann	Phys. Rev. D28（1983）71
Bermuth	Phys. Rev. D37（1988）89

Chiral constituent quark model: -1.0 to
-4.0%

Glozman, Riska	Phys. Report 268（1996）263
Sato, Lee	Phys. Rev. C56（1997）1246

Skyrme model: -2.5 to -6.0%

Adkins, Witten Nucl. Phys. B228（1983）552

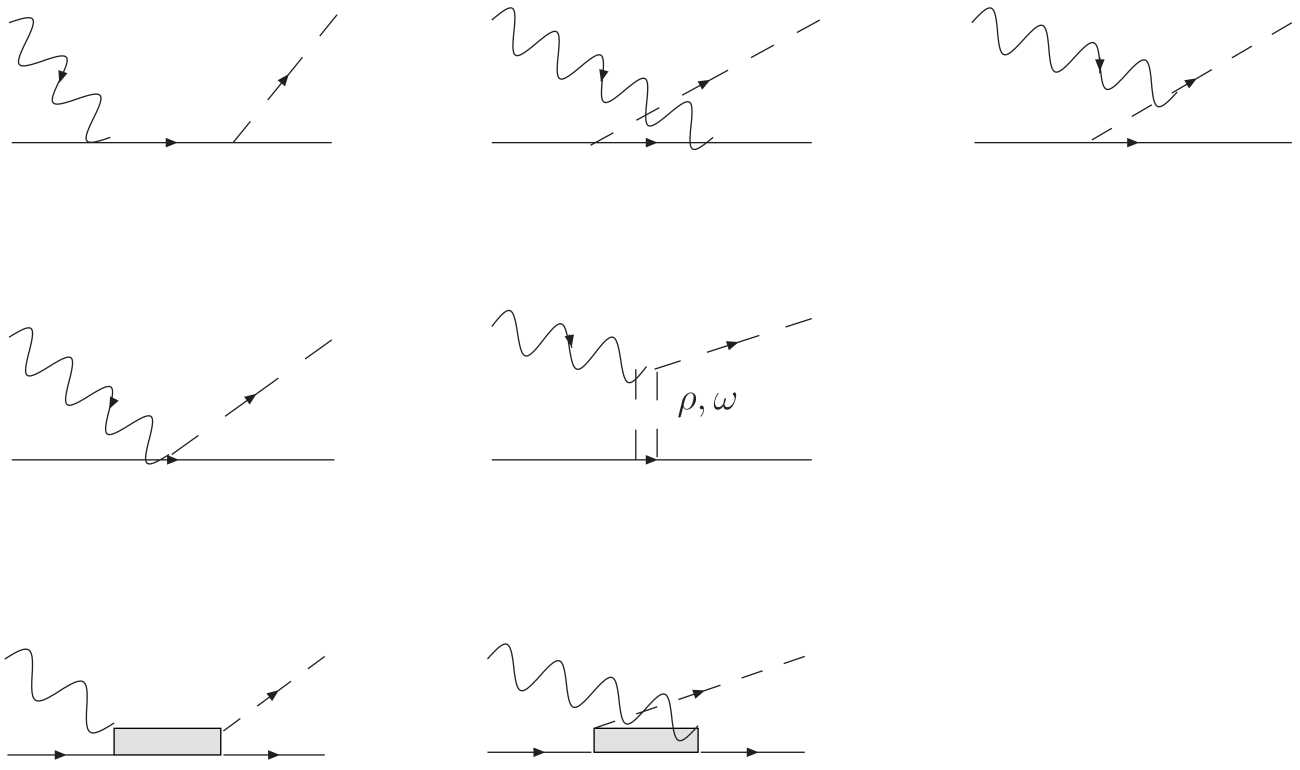
Weise Phys. Lett. B188（1987）6

Lattice QCD: - 6.0 to -12.0%

Leinweber Baryon 1992

PQCD: -100%

Tree diagrams



and rescatterings