Measurement of Generalized Form Factors near the Pion Threshold In high momentum transfer square

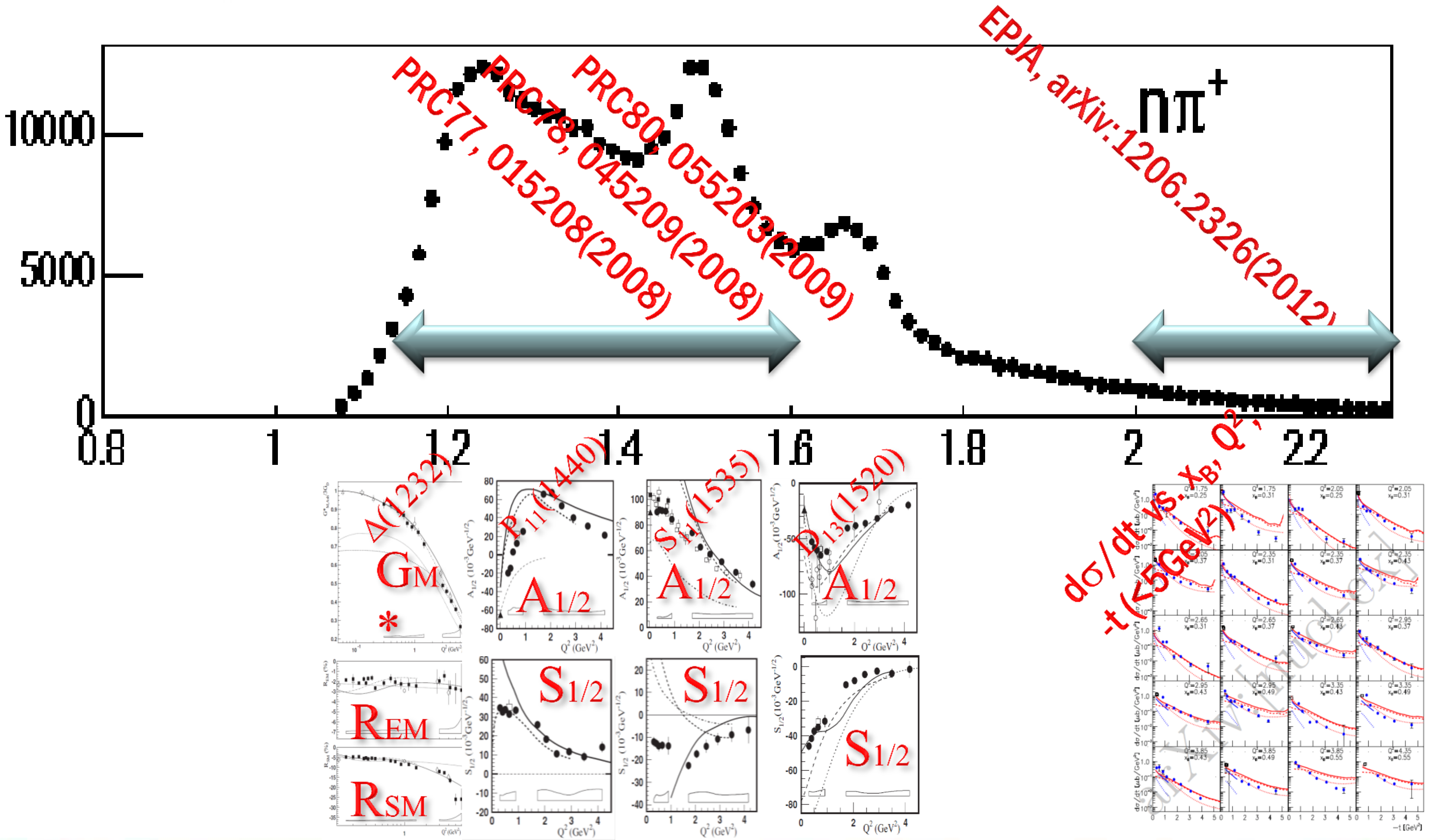
Aug. 13 - 15, 2012
γ*NN* Workshop at USC

K. Park
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Exclusive single positively charged pion electroproduction off the proton

$Q^2 < 5.0 GeV^2$

from CLAS



Exclusive single positively charged pion electroproduction off the proton

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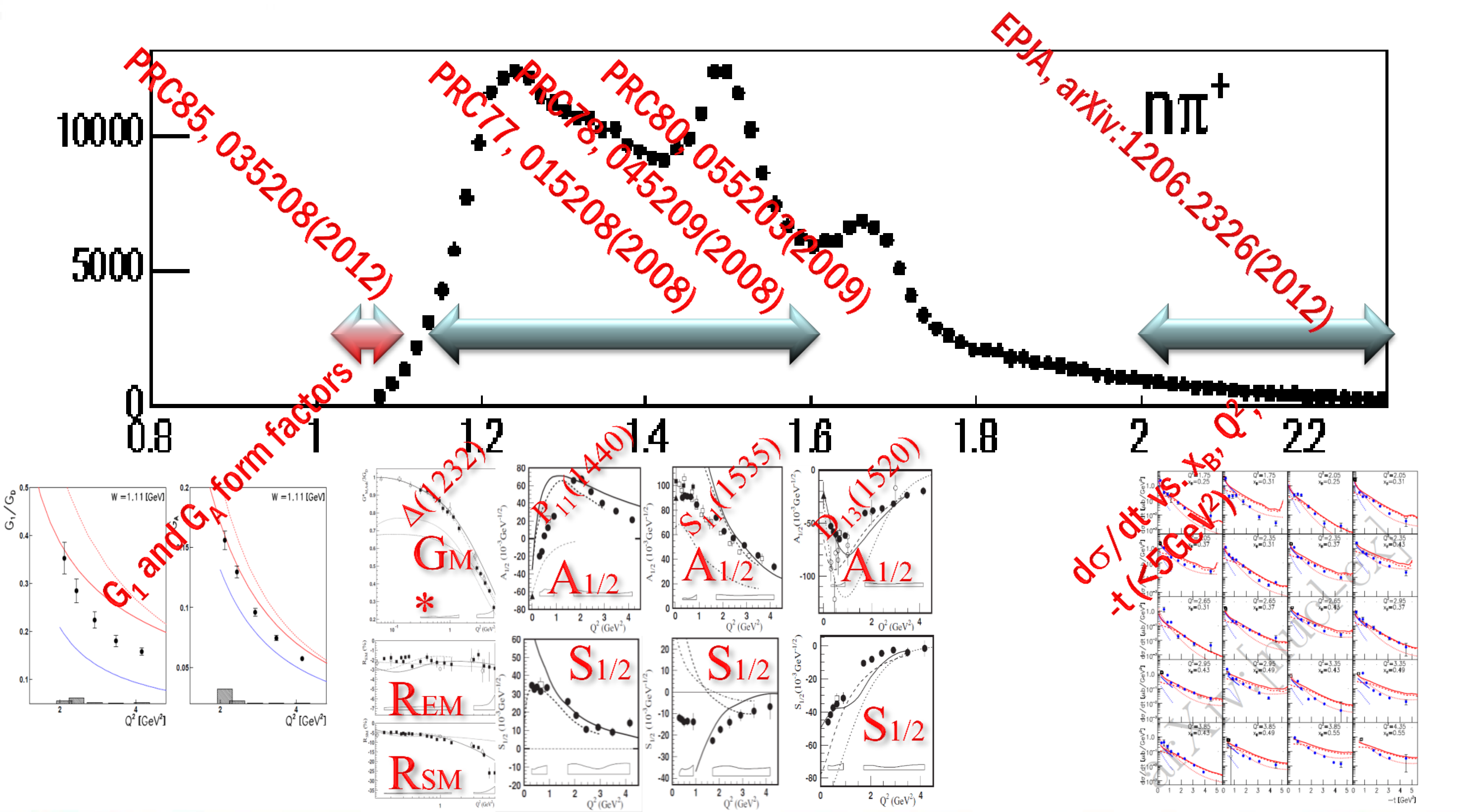

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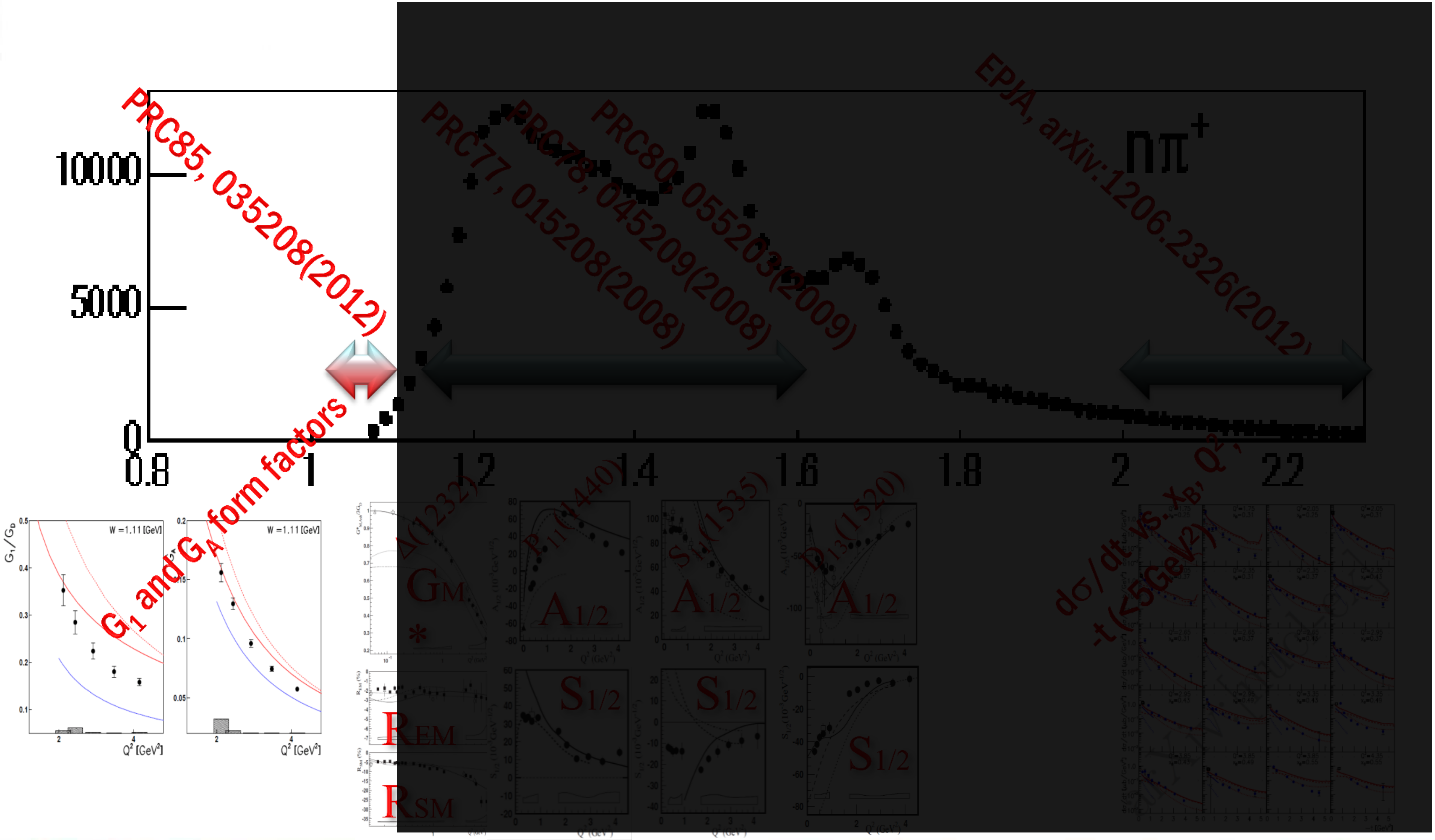


- Historically, threshold pion in the photo- and electroproduction is the very old subject that has been receiving continuous attention from both experiment and theory sides for many years.

- Pion mass vanishing approximation in Chiral Symmetry allows us to make an exact prediction for threshold cross section known as LET

- The LET established the connection between charged pion electroproduction and axial form factor in nucleon.

- Therefore, It is very interesting to extracting Axial Form Factor which is dominated by S- wave transverse multipole E_{0+} in LCSR

Perspective of soft pion in terms of Q^2 at threshold

$Q^2=0$ GeV^2

Low-Energy Theorem (LET) for $Q^2=0$
Restriction to the charged pion
Chiral symmetry + current algebra for electroproduction

1954
Kroll-Ruderman

1960s
Nambu, Laurie, Schrauner

$Q^2 << \Lambda/m_\pi \sim 1$GeV^2

Re-derived LETs
Current algebra + PCAC
Chiral perturbation theory

1970s
Vainshtein, Zakharov

1990s
Scherer, Koch

$Q^2 \sim 1 - 10$ GeV^2

???

$Q^2 >> \Lambda/m_\pi$

pQCD factorization methods
Brodsky, Lepage, Efremov, Radyunshkin, Pobylitsa, Polyakov, Strikman, et al

LCSR (Light Cone Sum Rule)

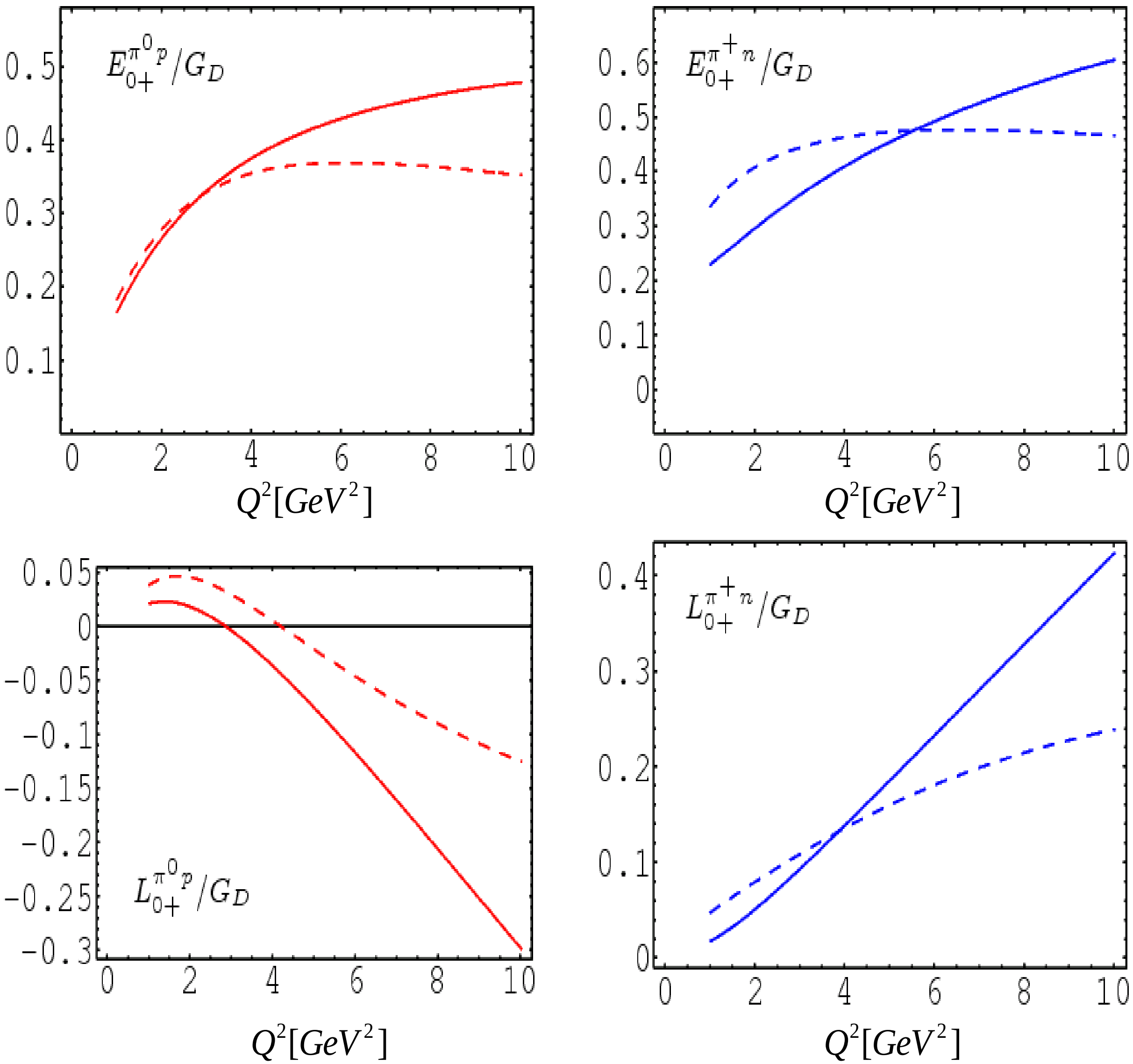
$$\langle N(P')\pi(k)|j_\mu^{em}(0)|p(P)\rangle = -\frac{i}{f_\pi}\bar{N}(P')\gamma_5\left\{(\gamma_\mu q^2 - q_\mu \not{q})\frac{1}{m_N^2}G_1^{\pi N}(Q^2) - \frac{i\sigma_{\mu\nu}q^\nu}{2m_N}G_2^{\pi N}(Q^2)\right\}p(P)$$

$$+\frac{ic_\pi g_A}{2f_\pi[(P'+k)^2 - m_N^2]}\bar{N}(P')\not{k}\gamma_5(\not{P}' + m_N)\left\{F_1^p(Q^2)\left(\gamma_\mu - \frac{q_\mu \not{q}}{q^2}\right) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_N}F_2^p(Q^2)\right\}p(P)$$

- S-wave: generalized form factors from LCSR ($G_1^{\pi N}$ and $G_2^{\pi N}$)
- P-wave: pion emission from final state nucleon

- **Constructed relating the amplitude for the radiative decay of $\Sigma^+(p\gamma)$ to properties of the QCD vacuum in alternating magnetic field.**
- **An advantage of study because soft contribution to hadron form factor can be calculated in terms of DA's that enter pQCD calculation without other non-perturbative parameters.**
- **New technique : the expansion of the standard QCD sum rule approach to hadron properties in alternating external fields.**

Prediction - LCSR



$$G_D(Q^2) = 1/(1 + \frac{Q^2}{\mu_0^2})^2$$

$$\mu_0^2 = 0.71 GeV^2$$

symbol index

Dashed Lines :
pure LCSR

Solid Lines :
LCSR using experimental EM form factor as input

V. M. Braun et al., Phys. Rev. D 77:034016, 2008.

Differential Cross-section

$$\frac{d^4\sigma}{dQ^2 dW d\Omega_\pi^*} = |J|\Gamma_v \frac{d^2\sigma_u}{d\Omega_\pi^*}$$

$$|J|\Gamma_v = \frac{\alpha}{2\pi^2 Q^2} \frac{(W^2 - M_p^2)E_f}{2M_p E_i(1-\epsilon)}$$

$$\epsilon = \left[1 + 2\left(1 + \frac{\nu^2}{Q^2}\right)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

$$\frac{d^2\sigma_u}{d\Omega_\pi^*} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos 2\phi_\pi^* + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi_\pi^*$$

Differential Cross-section

$\sigma_T \rightarrow G_1^{\pi N}, G_M^2$

$\sigma_{TT} \rightarrow 0$

No D-wave contribution

$\sigma_L \rightarrow G_2^{\pi N}, G_E^2$

$\sigma_{LT} \rightarrow \text{Re } G_1^{\pi N}, \text{Re } G_2^{\pi N}, G_E, G_M$

$\sigma'_{LT} \rightarrow \text{Im } G_1^{\pi N}, \text{Im } G_2^{\pi N}, G_E, G_M$

Legendre moments vs. Form Factors

V. Braun PRD 77(2008)

$$D_0^{T+L} = \frac{1}{f_\pi^2}\left[\frac{4\vec{k}_i^{\,2}Q^2}{m_N^2}|G_1^{n\pi^+}|^2 + \frac{c_\pi^{\,2}g_A^{\,2}\vec{k}_f^{\,2}}{W^2-m_N^2}Q^2m_N^2{G_M^n}^2 + \epsilon\left(\vec{k}_i^{\,2}|G_2^{n\pi^+}|^2 + \frac{4c_\pi^{\,2}g_A^{\,2}\vec{k}_f^{\,2}}{W^2-m_N^2}m_N^4{G_E^n}^2\right)\right]$$

$$D_1^{T+L} = \frac{1}{f_\pi^2}\frac{4c_\pi g_A|k_i||k_f|}{W^2-m_N^2} \times \left[Q^2G_M^n\mathrm{Re}(G_1^{n\pi^+}) - \epsilon m_N^2G_E^n\mathrm{Re}(G_2^{n\pi^+})\right]$$

$$D_0^{LT} = -\frac{1}{f_\pi^2}\frac{c_\pi g_A|k_i||k_f|}{W^2-m_N^2} \times Qm_N\left[G_M^n\mathrm{Re}(G_2^{n\pi^+}) + 4G_E^n\mathrm{Re}(G_1^{n\pi^+})\right]$$

G_M^n and G_E^n Sachs form factors

$c_\pi = \sqrt{2}$ isospin factor.

$f_\pi = 93$ MeV pion decay constant

$g_A = 1.267$ axial coupling

Legendre moments vs. Form Factors

V. Braun PRD 77(2008)

assumption $m_\pi \sim 0$ $G_E^n \sim 0$

$$D_0^{T+L} = \frac{1}{f_\pi^2}\left[\frac{4\vec{k}_i^{\,2} Q^2}{m_N^2}|G_1^{n\pi^+}|^2 + \frac{c_\pi^{\,2} g_A^{\,2} \vec{k}_f^{\,2}}{W^2 - m_N^2} Q^2 m_N^2 G_M^{n\,2} + \epsilon\left(\vec{k}_i^{\,2}|G_2^{n\pi^+}|^2\right)\right]$$

$$D_1^{T+L} = \frac{1}{f_\pi^2}\frac{4c_\pi g_A |k_i||k_f|}{W^2 - m_N^2}\left[Q^2 G_M^n \mathrm{Re}\left(G_1^{n\pi^+}\right)\right]$$

$$D_0^{LT} = -\frac{1}{f_\pi^2}\frac{c_\pi g_A |k_i||k_f|}{W^2 - m_N^2} Q m_N \left[G_M^n \mathrm{Re}\left(G_2^{n\pi^+}\right)\right]$$

G_M^n and G_E^n
Sachs form factors

$c_\pi = \sqrt{2}$
isospin factor.

$f_\pi = 93$ MeV
pion decay constant

$g_A = 1.267$
axial coupling

Multipoles vs. F. F. for $n\pi^+$ channel

$G_1^{n\pi^+}$ $E_{0+}^{n\pi^+}$

$$\frac{E_{0+}^{n\pi^+}}{G_D} = \frac{\sqrt{4\pi\alpha_{em}}}{8\pi} \frac{Q^2\sqrt{Q^2+4m_p^2}}{m_p^3 f_\pi} \frac{G_1^{n\pi^+}}{G_D}$$

$$G_D = 1/(1+Q^2/\mu_0)^2,\ \mu_0 = 0.71$$

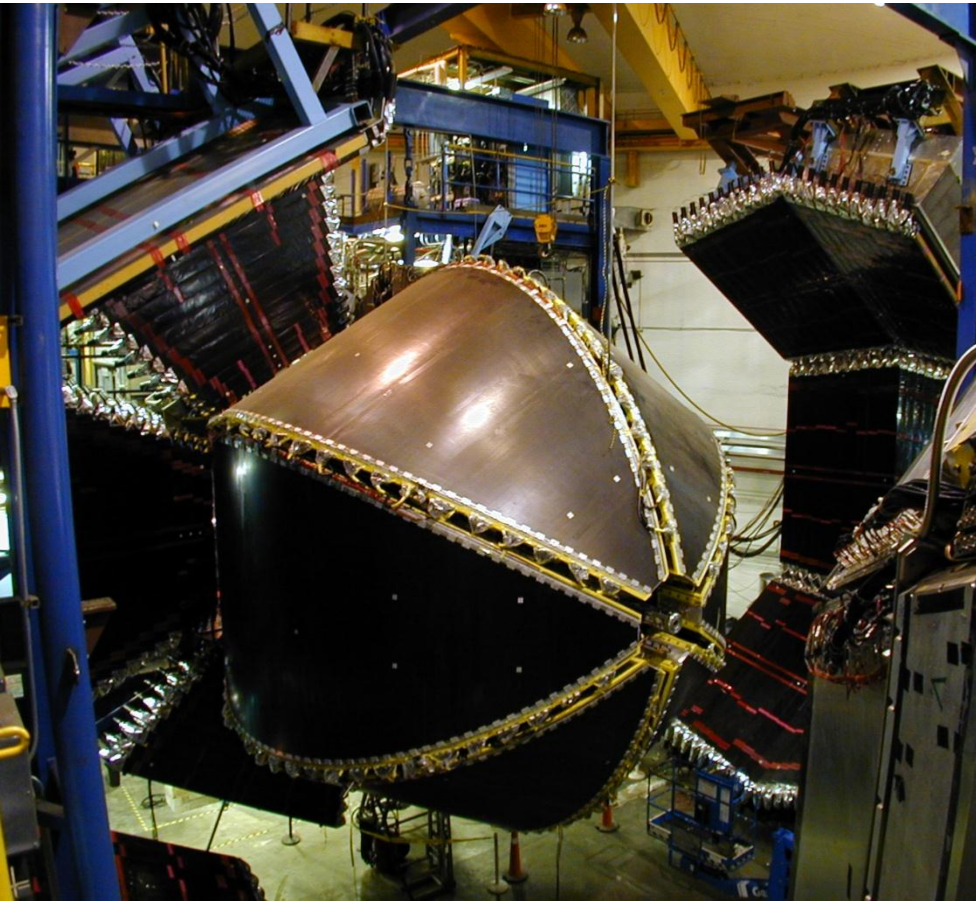
$$\frac{Q^2}{m_N^2} G_1^{n\pi^+} = \frac{g_A}{\sqrt{2}} \frac{Q^2}{Q^2+2m_N^2} G_M^n + \frac{1}{\sqrt{2}} G_A$$

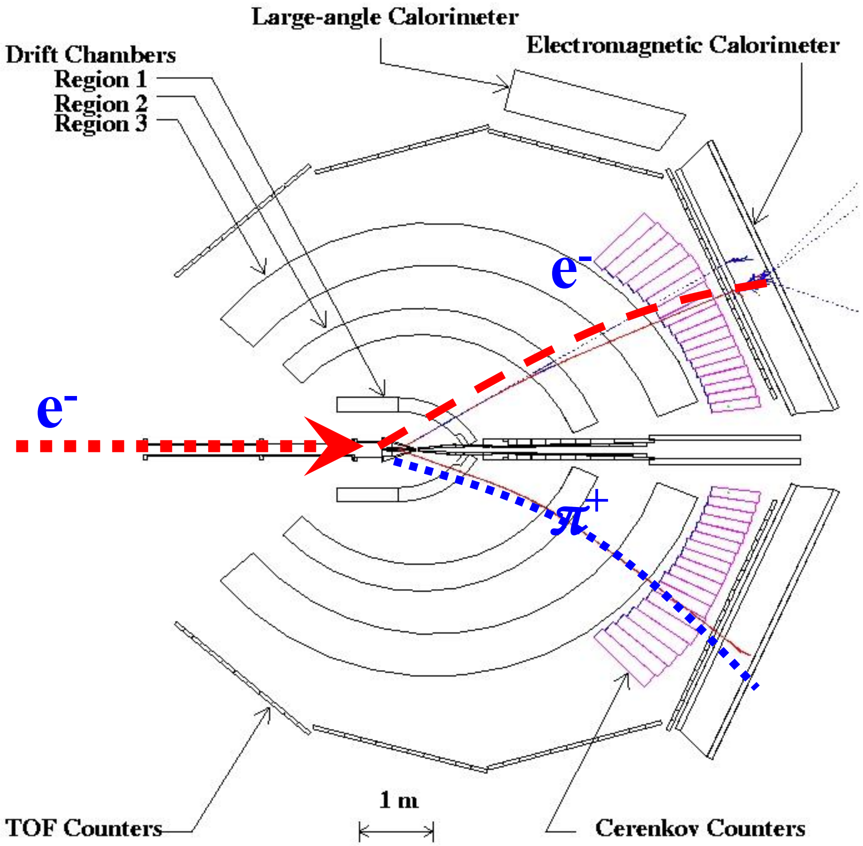
$$G_2^{n\pi^+} = \frac{2\sqrt{2} g_A m_N^2}{Q^2+2m_N^2} G_E^n$$

$G_E^n \sim 0$

$G_2^{n\pi^+}$ is negligible.

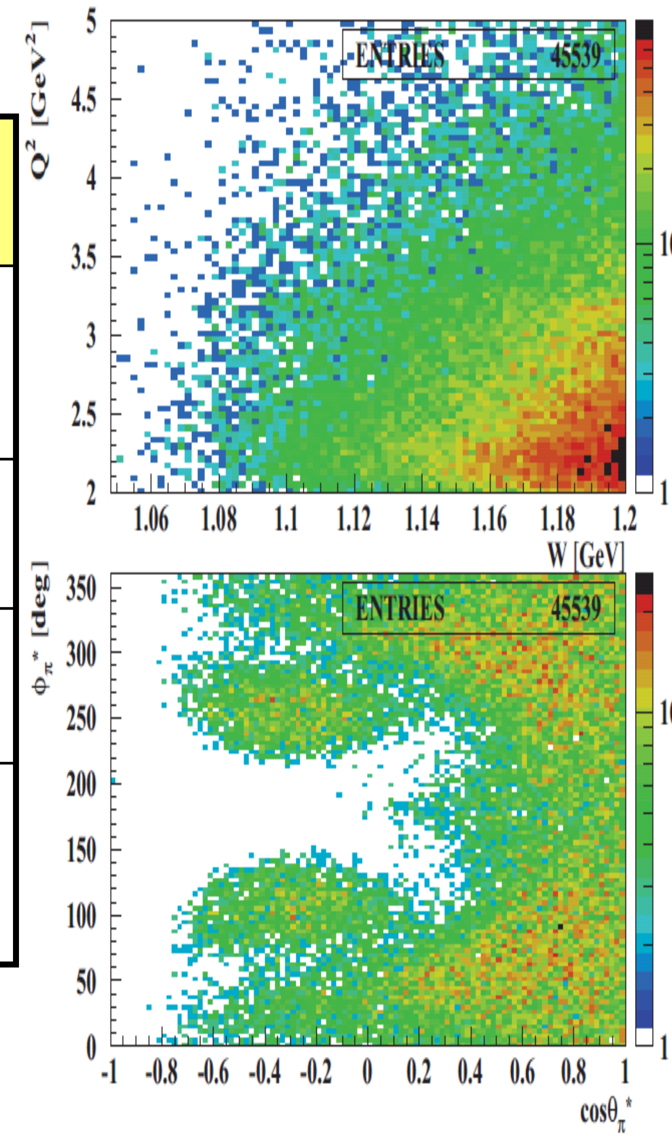
CLAS & Event display



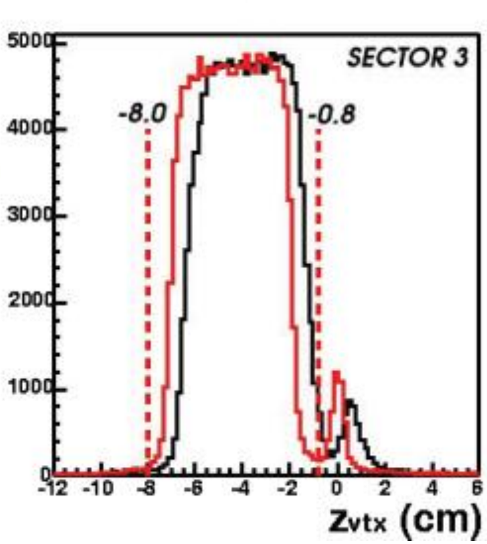


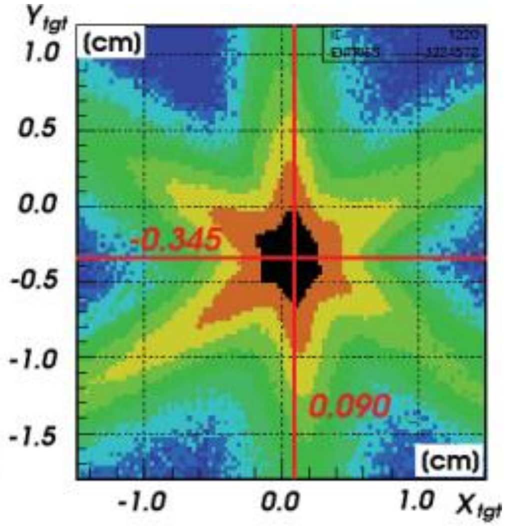
Kinematic regions

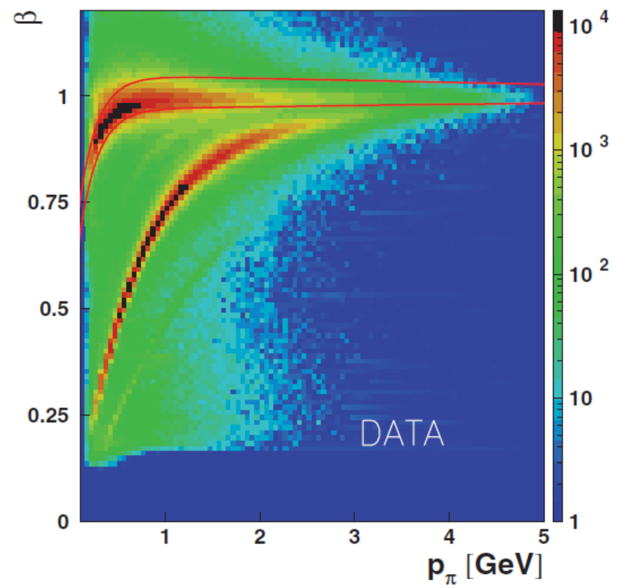
Variable	Unit	Range	# Bin	Width
Q^2	GeV^2	2.12 ~ 4.16	5	various
W	GeV	1.11 ~ 1.15	3	0.02
$\cos\theta^*_\pi$		-1.0 ~ 1.0	10	0.2
Φ^*_π	deg	0 ~ 360 0 ~ 360	12 6	$\cos\theta^*_\pi \geq -0.1$ $\cos\theta^*_\pi < -0.1$

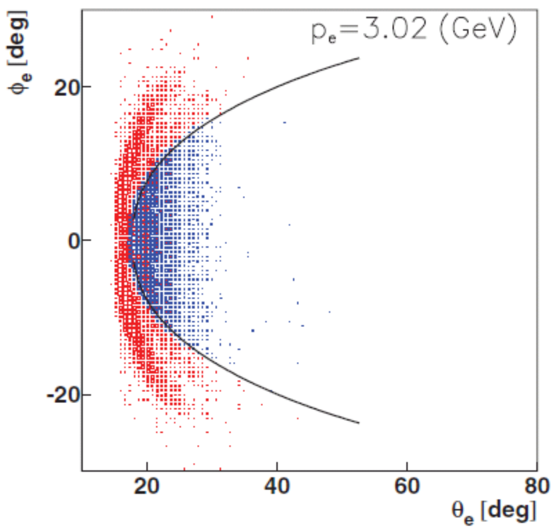


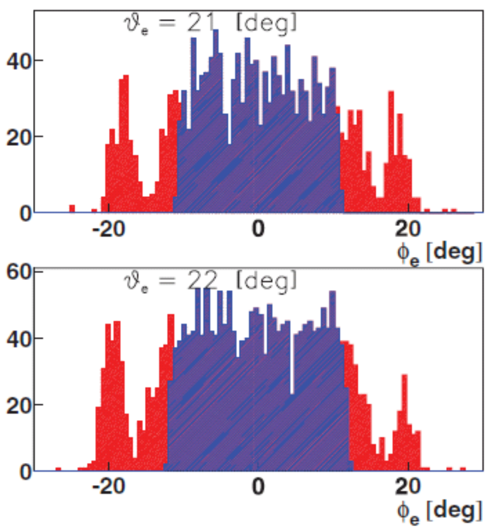
Snap shot of PID

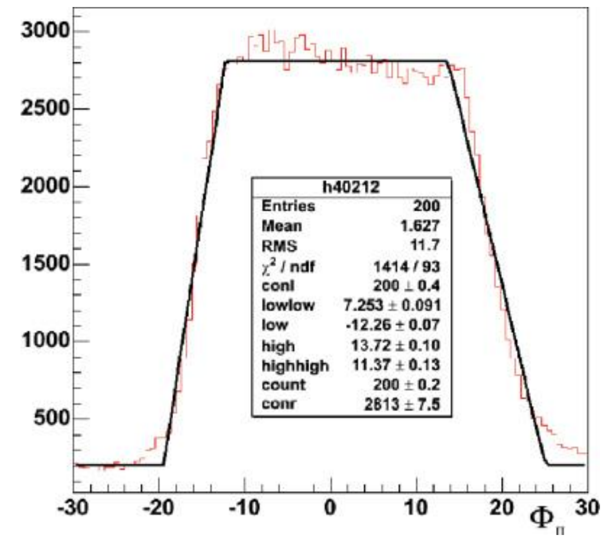




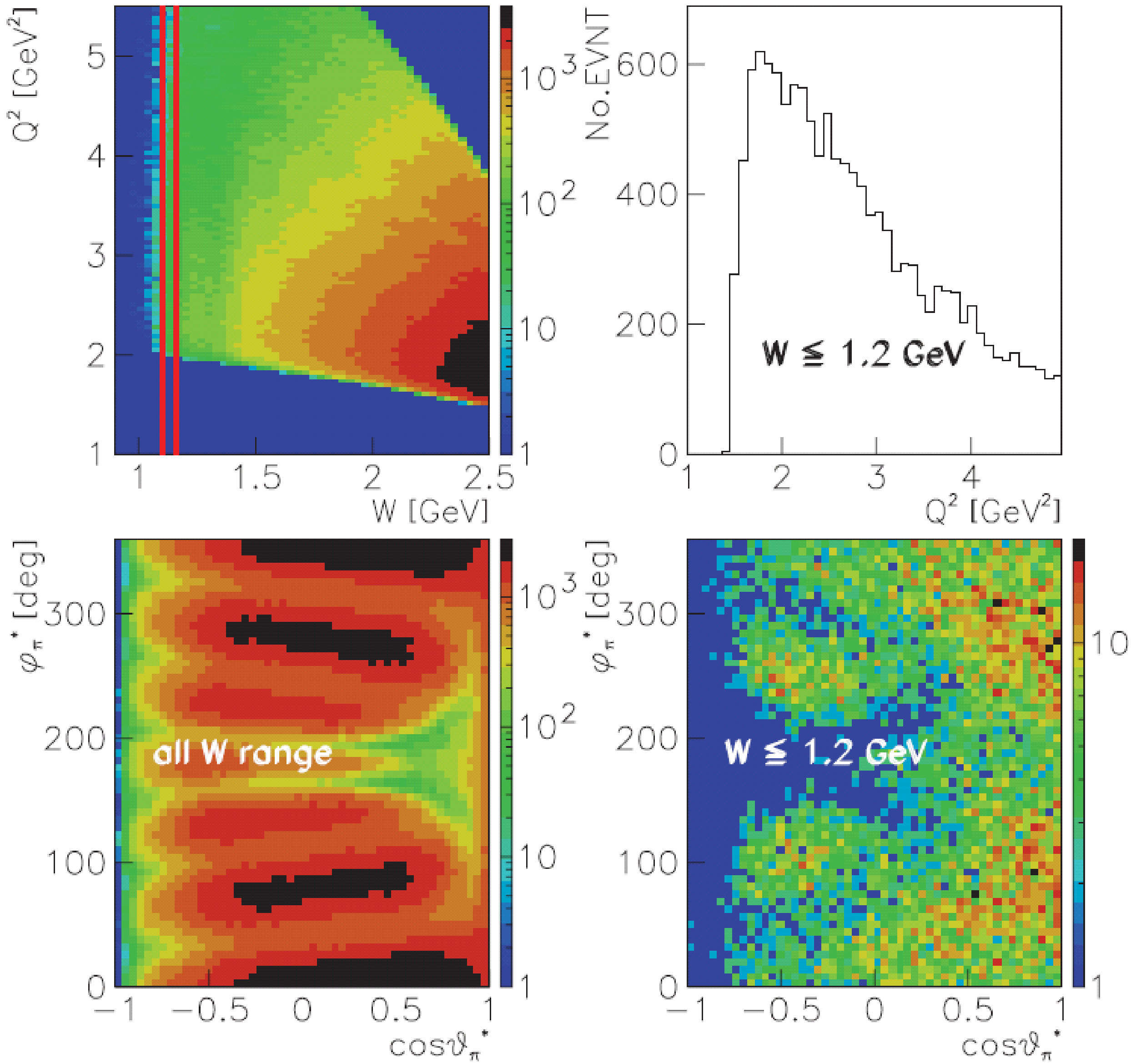




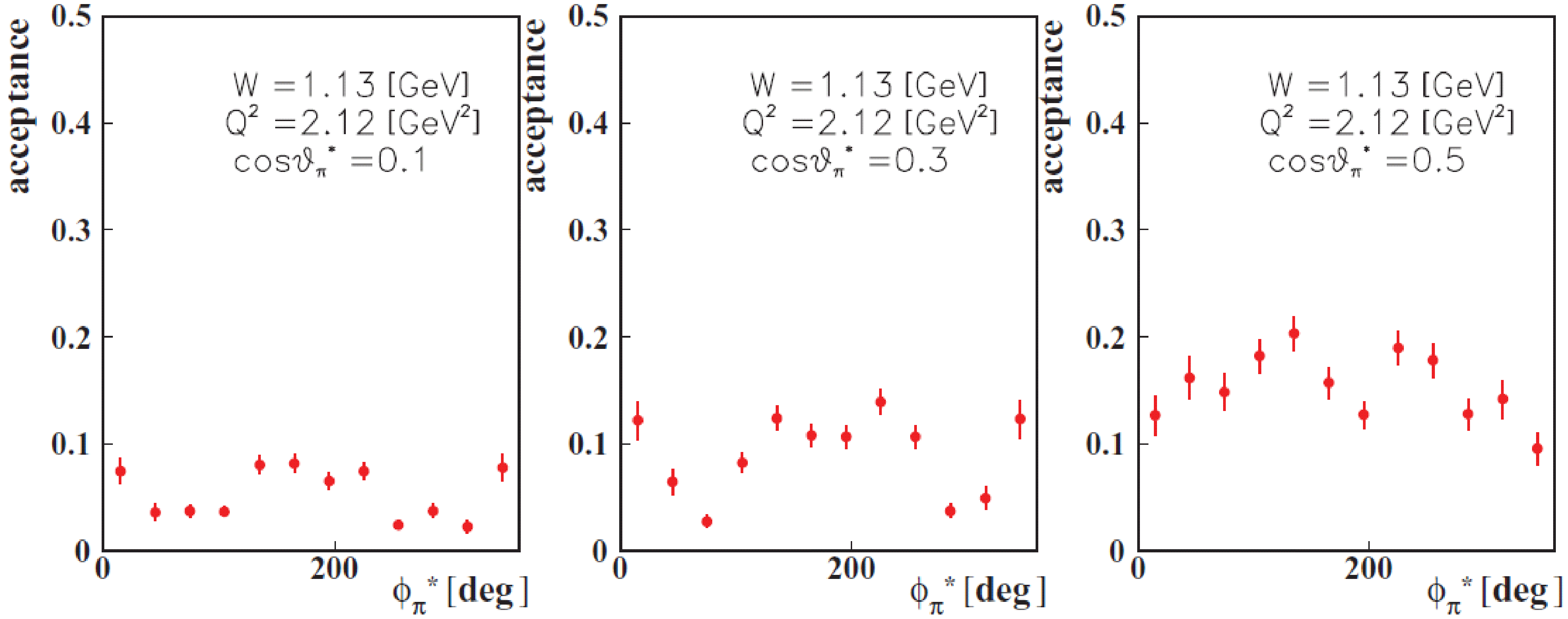




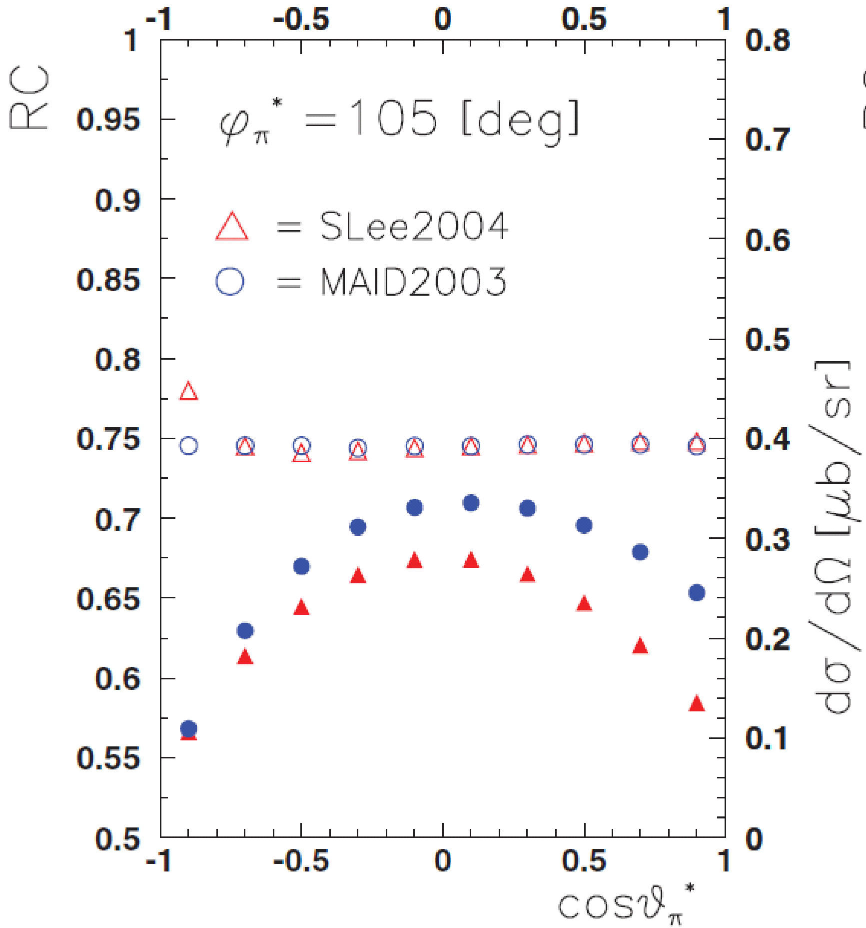
MC – GEANT3 Simulation

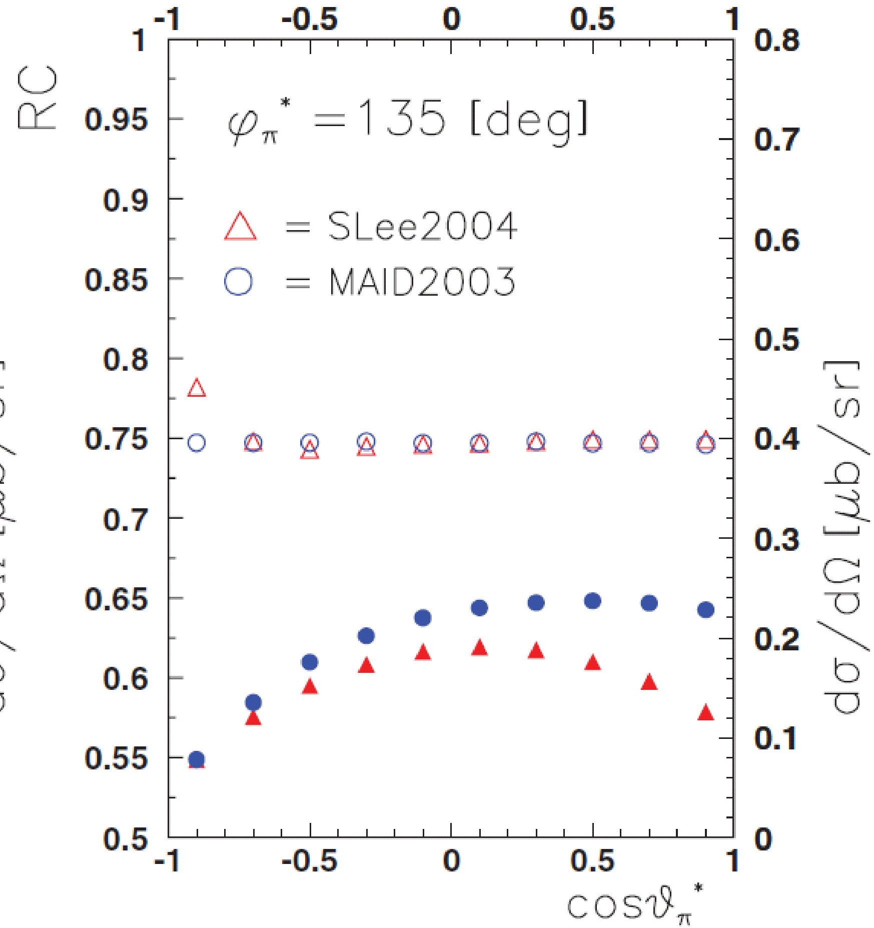


Acceptances – AAO_RAD



Radiative correction [EXCLURAD]

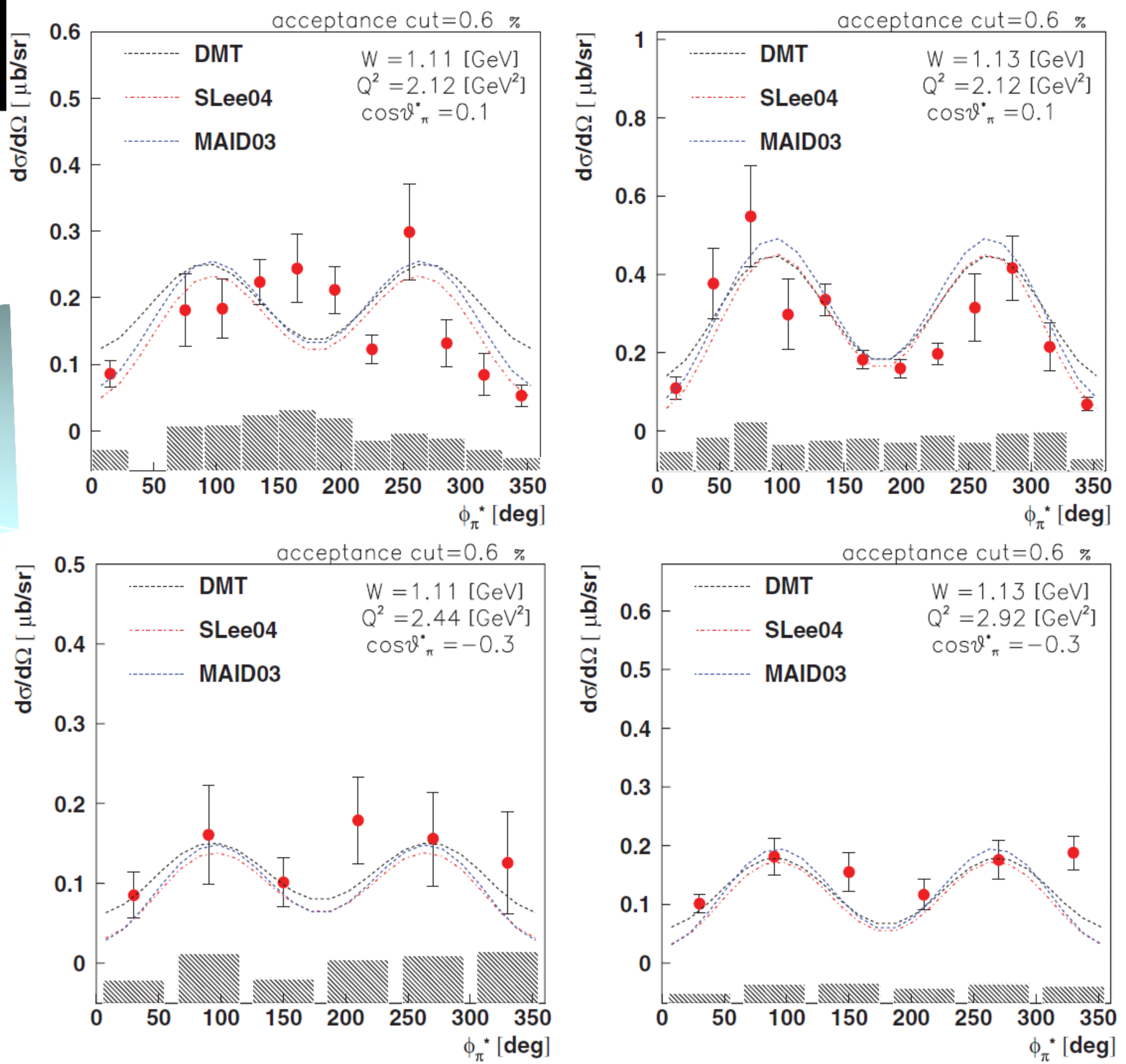




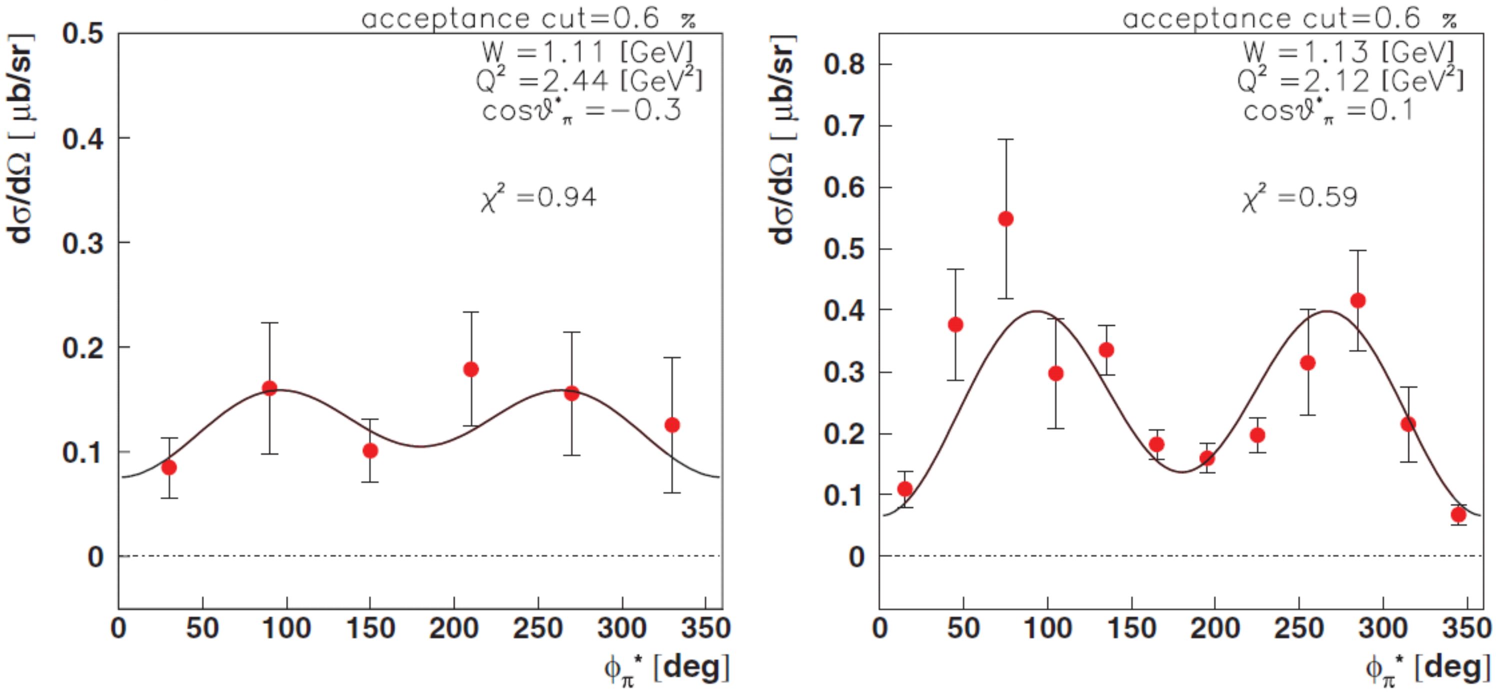
Differential Cross Section (φ^*)

φ^* – dependent cross section in term of W, Q^2, $\cos\theta^*$

Various physics models



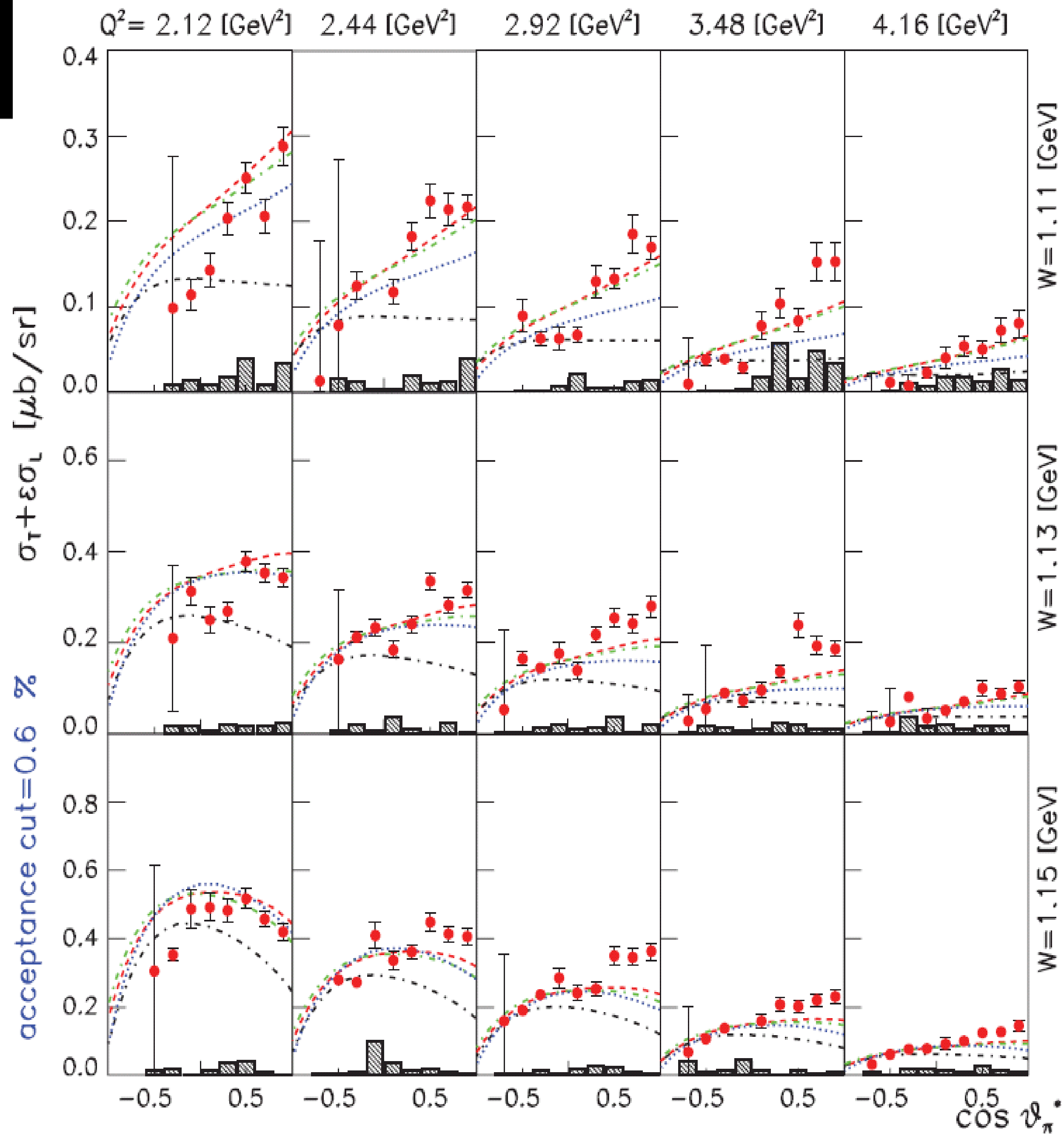
A sample of fit



Structure Function

$\sigma_T + \varepsilon\sigma_L$

E_{0+} **sensitive !**



MAID2003

(red bold dash) full multipoles

(green bold dash) without S_{0+}

(black dash-dot) without E_{0+}

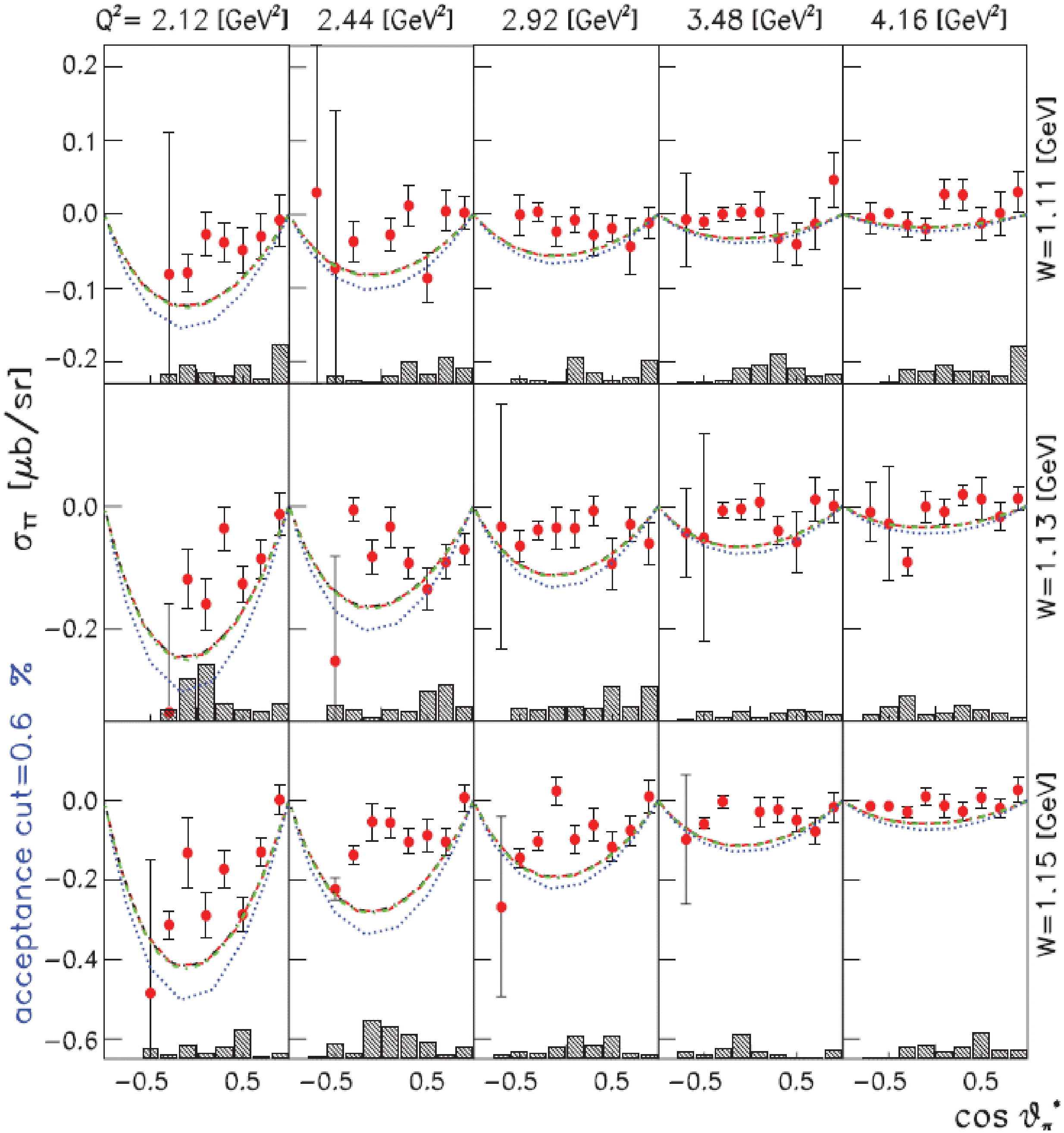
MAID2007

(blue bold dot)

Structure Function

σ_{TT}

E_{0+} **insensitive !**



MAID2003

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MAID2007

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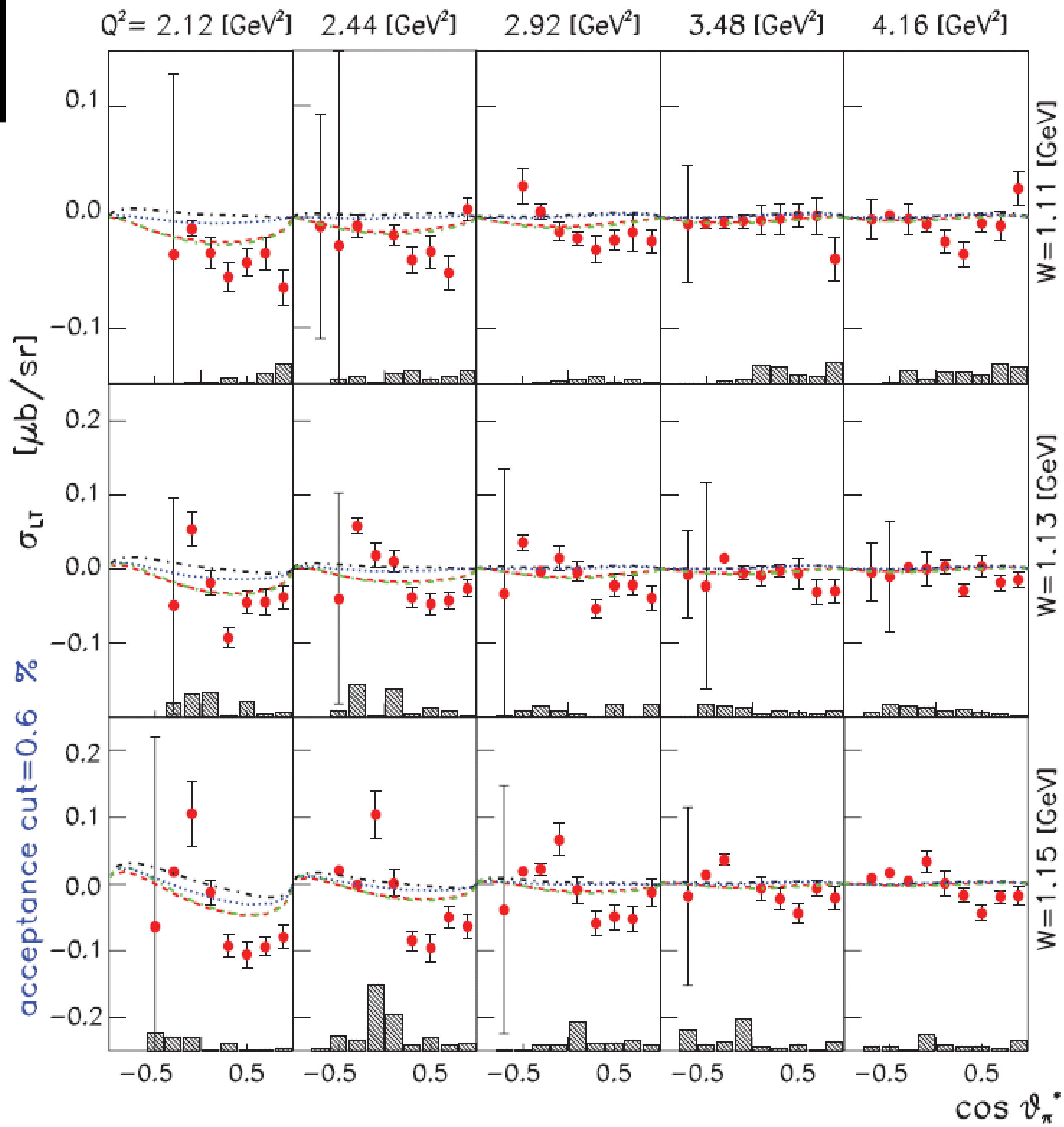
Structure Function

σ_{LT}

E_{0+} **sensitive !**



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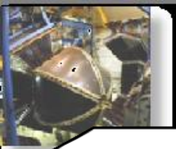
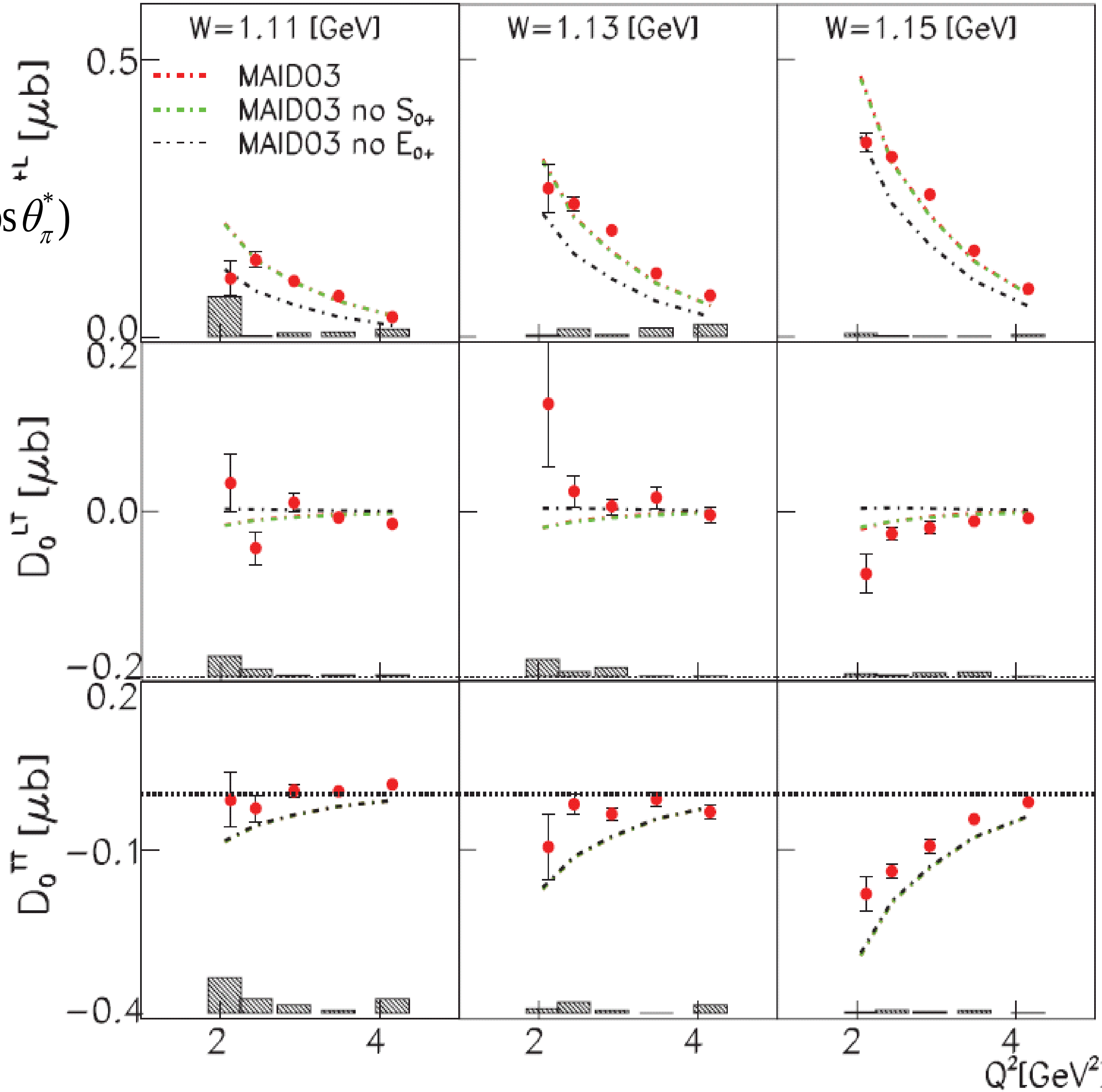


$$D_0^{T+L} + D_1^{T+L} P_1(\cos\theta_\pi^*)$$

$$\sigma_T + \varepsilon_L \sigma_L = D_0^{T+L} + D_1^{T+L} P_1(\cos\theta_\pi^*)$$

$$\sigma_{LT} =$$
$$D_0^{LT} + D_1^{LT} P_1(\cos\theta_\pi^*)$$

$$\sigma_{TT} = D_0^{TT}$$



Multipole extraction

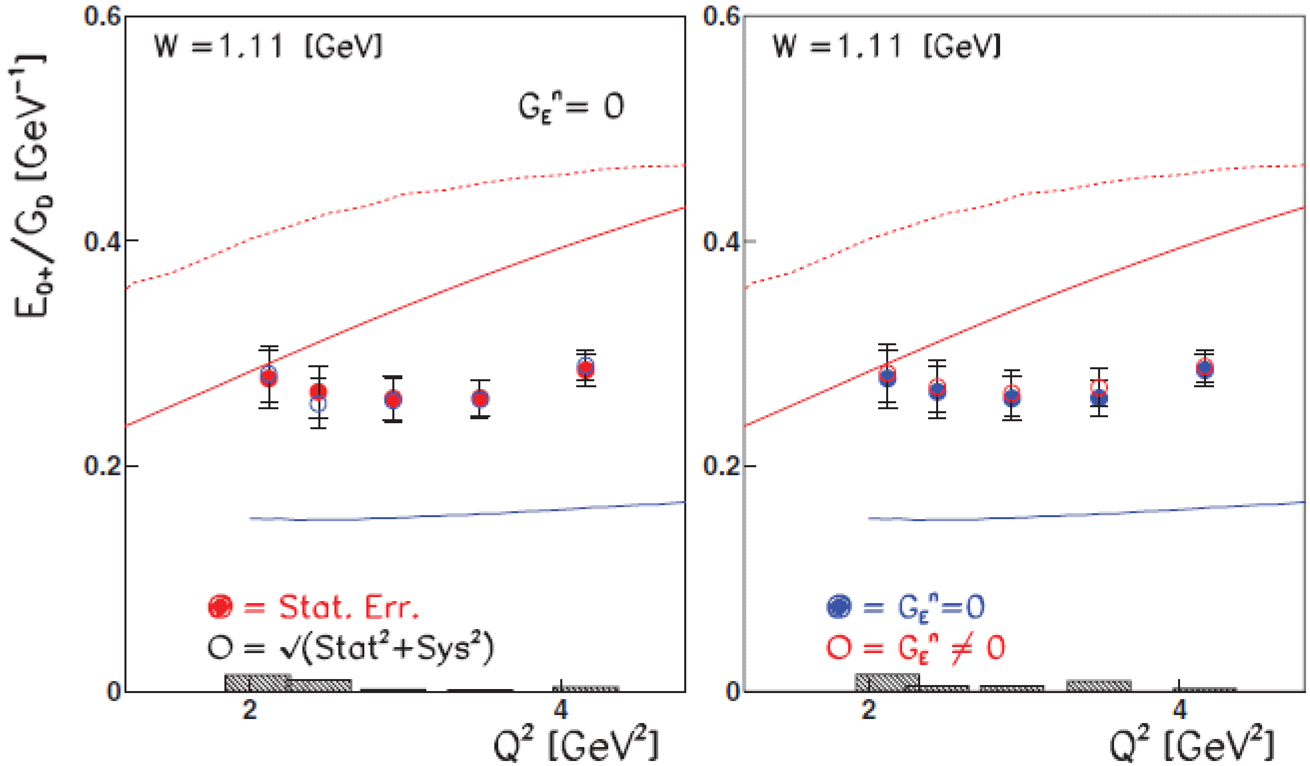
Q^2 dependence of the Normalized E_{0+} Multipole by dipole F. F.

Assumption of $Im(G_2)=y_2=0$

Assumption of $G_E^n=0$

Red lines : LCSR
solid line : pure calc.
dash line :exp. F. F. input

Blue line : MAID07, E0+
Black MAId07 L0+



Form factors and Multipole for $n\pi^+$ channel

$$G_1^{\pi N} = G_1^{\pi^+ n} \quad G_M = G_M^n \approx \mu_n G_D(Q^2)$$

$$G_2^{\pi N} = G_2^{\pi^+ n} \quad G_E = G_E^n \approx 0 \quad G_E = G_E^n \neq 0$$

P.E. Bosted
Phys. Rev. C 51 (1995)

S. Platchekov
Nucl.Phys. A 70 (1990)

J.J. Kelly
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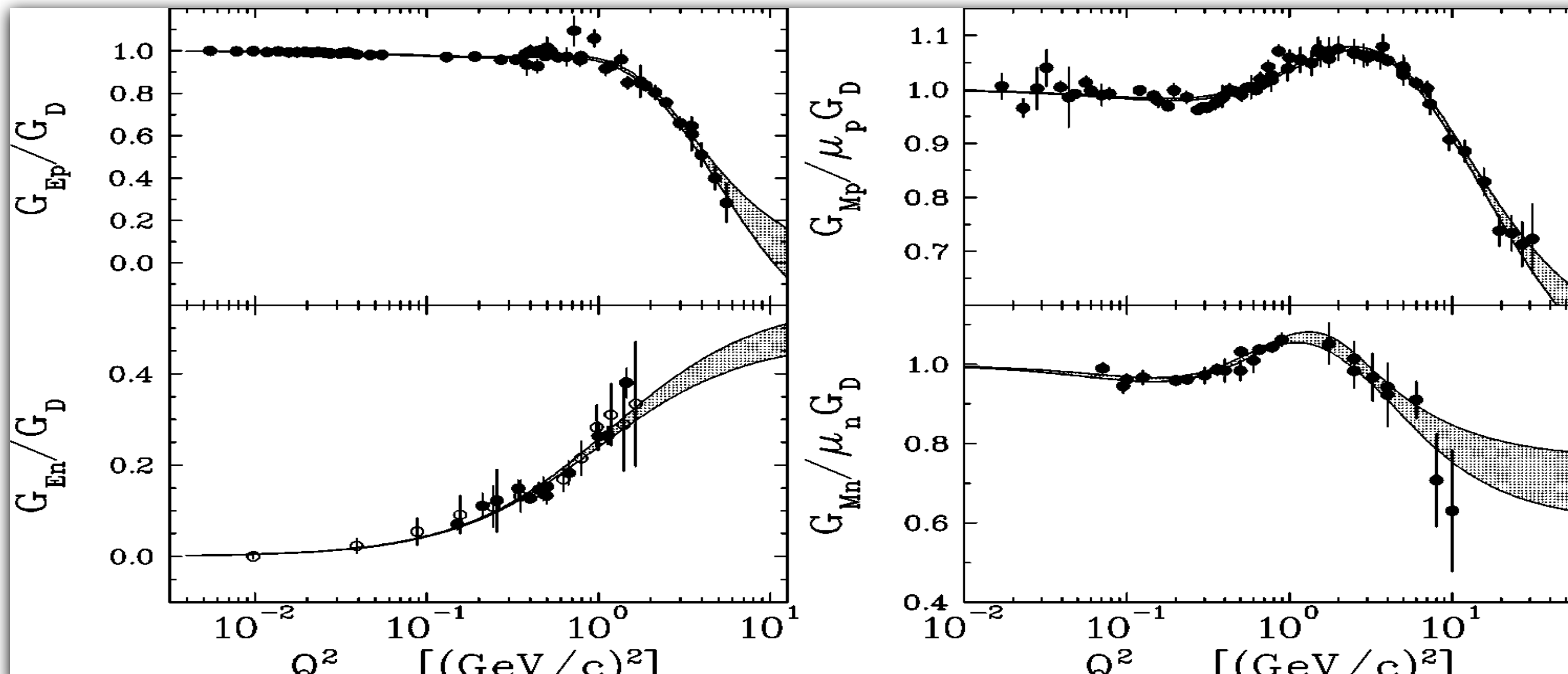
J. J. Kelly *et al.*, **PRC 70:068202 (2004)**



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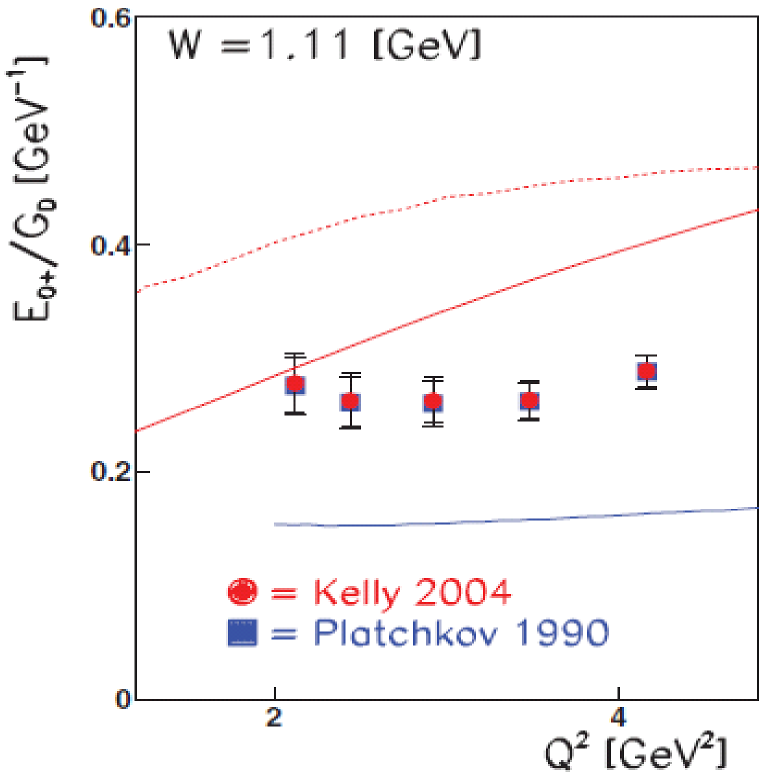

Blue : E_{0+} using J.J.Kelly form

Red : E_{0+} using S. Platchekov form

Form factors and Multipole for $n\pi^+$ channel

$$G_1^{\pi N} = G_1^{\pi^+ n}$$ $$G_M = \text{CLAS DATA}$$

J. Lachniet (2009)
Phys. Rev. Lett. 102

$$G_2^{\pi N} = G_2^{\pi^+ n}$$ $$G_E = G_E^n \neq 0$$

J.J. Kelly
Phys. Rev. C 70 (2004)

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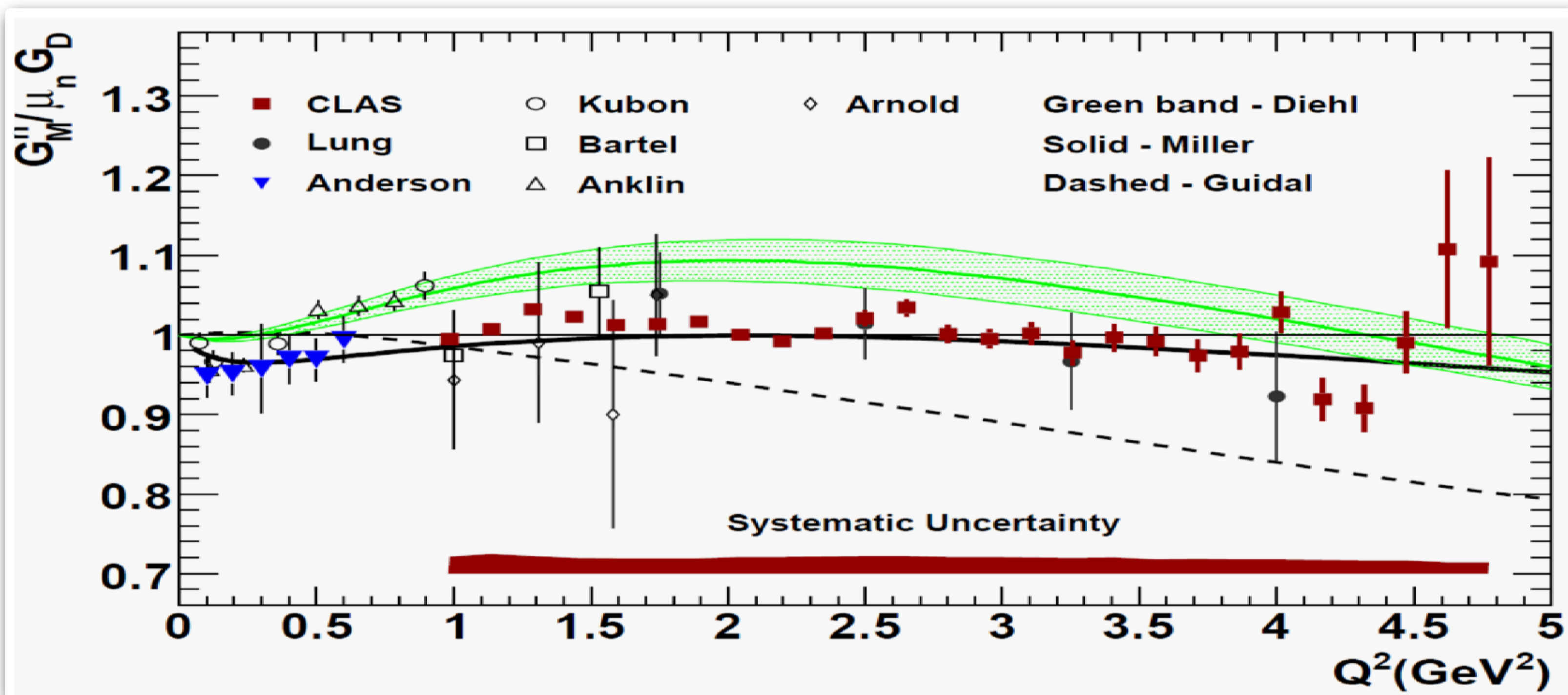

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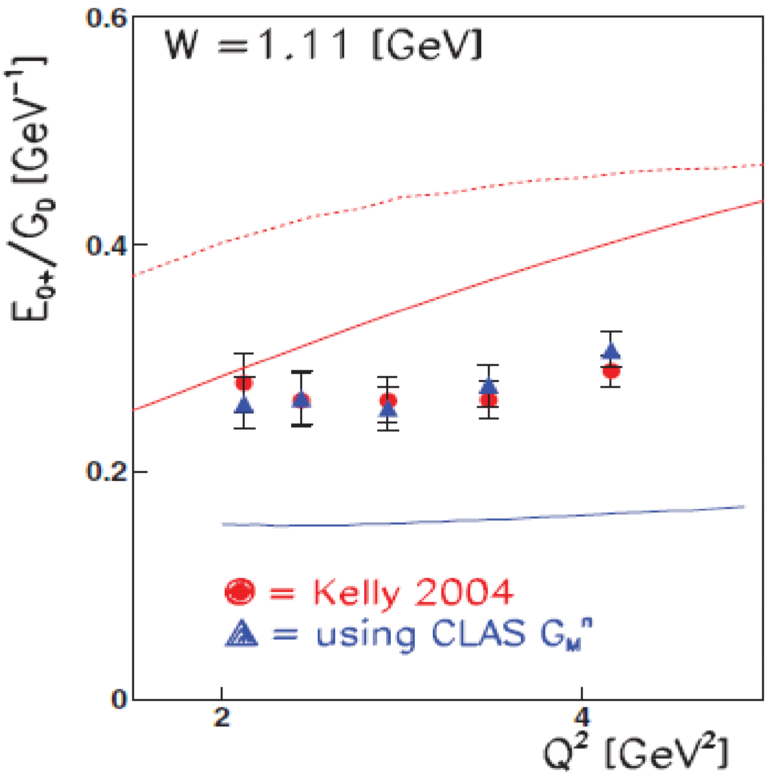


- Blue: E_{0+} using CLAS G_M^n measurement
- Red: E_{0+} using G_M^n parameterization

Multipole extraction

Q^2 dependence of the Normalized E_{0+} Multipole by dipole F. F.

Blue line : MAID07, E_{0+}

Black MAId07 L_{0+}

Using….

(1) Measurement of differential cross sections

(2) Extract structure functions (σ_{T+L}, σ_{TT}, σ_{LT})

(3) Extract Legendre moments

(4) Plug into LCSR…

Multipole analysis

Using six amplitudes (f_i)
** if $l_\pi = 1$

$$f_1 = E_{0+} + 3\cos\theta^*_\pi (E_{1+} + M_{1+})$$

$$f_2 = 2M_{1+} + M_{1-}$$

$$f_3 = 3(E_{1+} - M_{1+})$$

$$f_4 = 0$$

$$f_5 = S_{0+} + 6\cos\theta^*_\pi S_{1+}$$

$$f_6 = S_{1-} - 2S_{1+}$$

I. G. Aznauryan, PRD 57, 2727 (1998)

Multipoles Analysis

Helicity amplitudes (H_i)

$$H_1 = \frac{-1}{\sqrt{2}} \cos\frac{\theta_\pi^*}{2} \sin\theta_\pi^* (f_3 + f_4)$$

$$H_2 = -\sqrt{2}\cos\frac{\theta_\pi^*}{2}\left[f_1 - f_2 - \sin^2\frac{\theta_\pi^*}{2}(f_3 - f_4)\right]$$

$$H_3 = \frac{1}{\sqrt{2}} \sin\frac{\theta_\pi^*}{2} \sin\theta_\pi^* (f_3 - f_4)$$

$$H_4 = \sqrt{2}\sin\frac{\theta_\pi^*}{2}\left[f_1 + f_2 + \cos^2\frac{\theta_\pi^*}{2}(f_3 + f_4)\right]$$

$$H_5 = \frac{-\sqrt{Q^2}}{|k_{\mathrm{c.m.}}|} \cos\frac{\theta_\pi^*}{2}(f_5 + f_6)$$

$$H_6 = \frac{\sqrt{Q^2}}{|k_{\mathrm{c.m.}}|} \sin\frac{\theta_\pi^*}{2}(f_5 - f_6)$$

I. G. Aznauryan, PRD 57, 2727 (1998)

Structure functions vs. Helicity amplitudes ($\boldsymbol{H_i}$) :

$$\sigma_T + \epsilon\sigma_L = \frac{1}{2}\sum_{i=1}^{4}|H_i|^2 + \epsilon(|H_5|^2 + |H_6|^2),$$

$$\sigma_{TT} = \mathrm{Re}(H_2^* H_3 - H_1^* H_4),$$

$$\sigma_{LT} = \frac{-1}{\sqrt{2}}\mathrm{Re}[H_5^*(H_1 - H_4) + H_6^*(H_2 + H_3)].$$

Multipoles Analysis

Constraints :

* E_{0+}, S_{0+} are dominated in this regime.
** M_{1-}, S_{1-} were used from MAID2007 model prediction.

*** for ***I=3/2*** case, following correlation functions are acceptable.

→ $G_{D'} = (1+Q^2/\mu_{02})^2$
→ $G_M = 3.*\exp(-0.21*Q^2)/(1. +0.0273*Q^2 -0.0086*Q^4)/G_{D'}$

→ $M_{1+} = (Y_0/52.437)* G_M * \mathrm{sqrt}(((2.3933+Q^2)/2.46)^2 -0.88)* 6.786$

→ $E_{1+} = -0.02 * M_{1+}$

→ $R_{SM} = -6.066 -8.5639*Q^2 +2.3706*Q^4 +5.807* \mathrm{sqrt}(Q^2) -0.75445* Q^4* \mathrm{sqrt}(Q^2)$

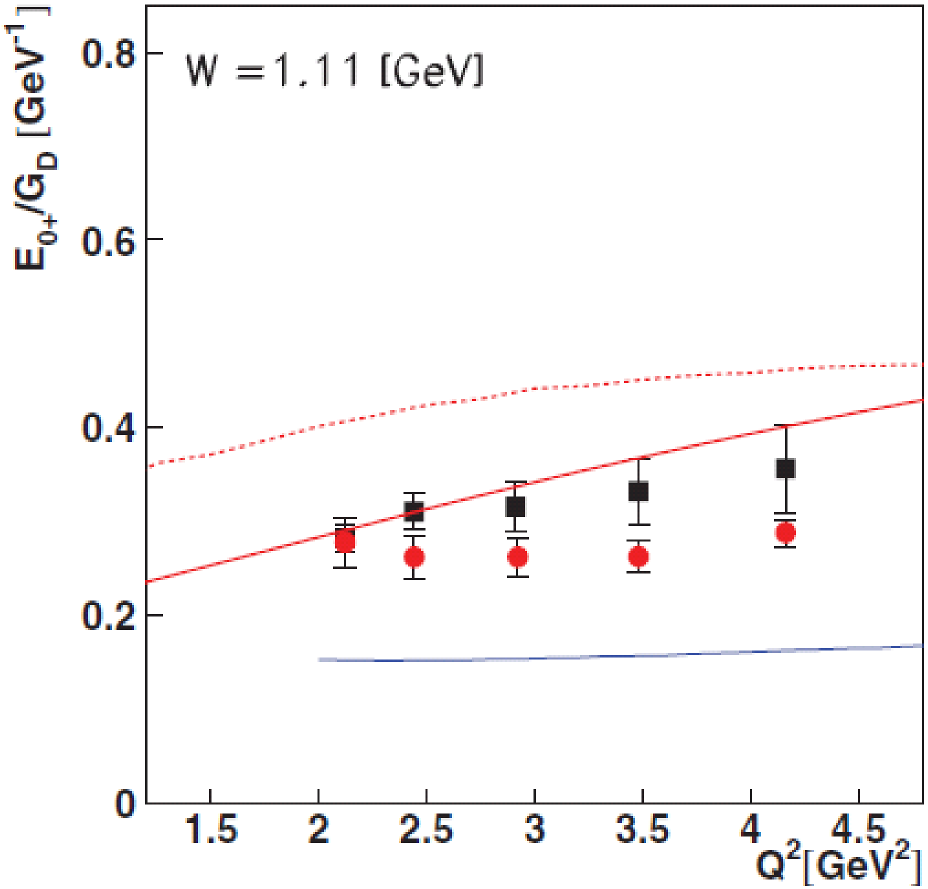
→ $S_{1+} = R_{SM}*M_{1+}/100.$

where, $\mu_{02} = 0.71$, Y_0 is the interpolation value from SAID model.

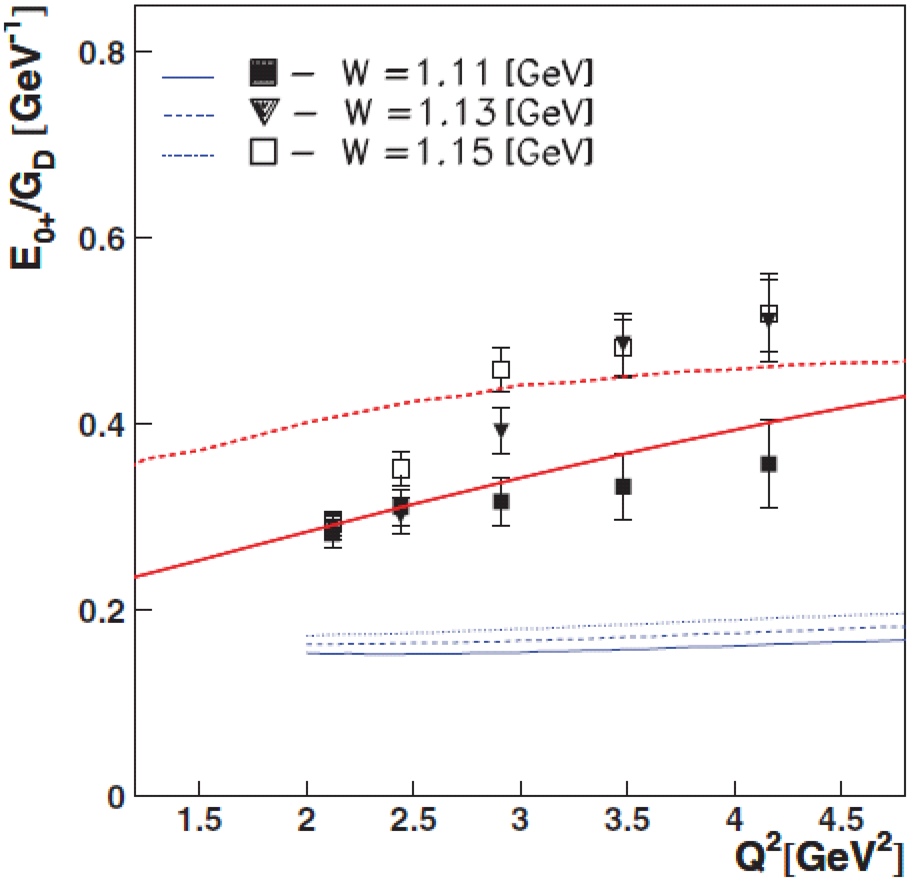
I. G. Aznauryan, PRD 57, 2727 (1998)

Multipoles extraction

Q^2 dependence of the Normalized E_{0+} Multipole by dipole F. F.



Results of multipole
LCSR w/o pion-mass



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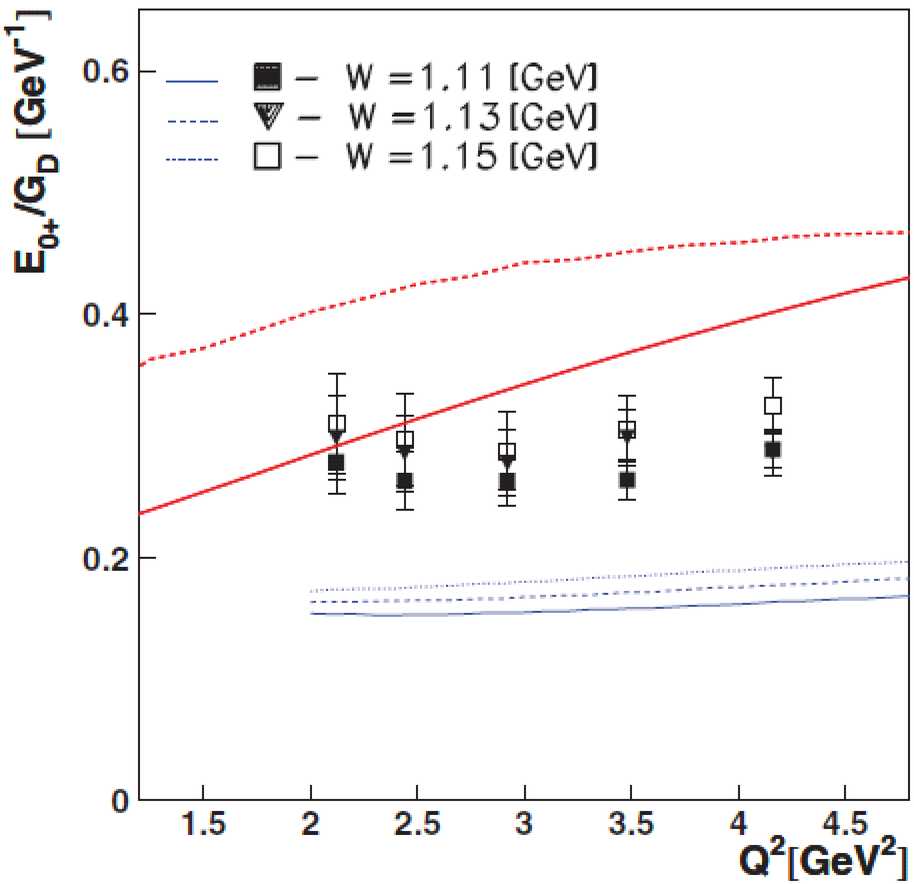
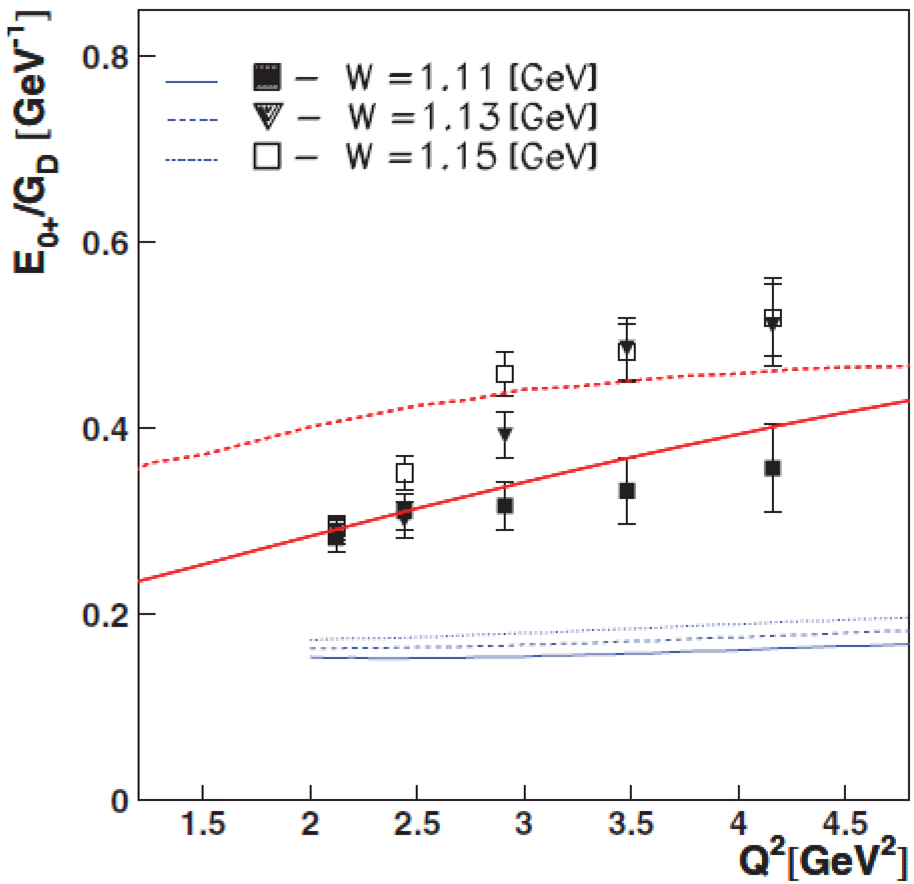


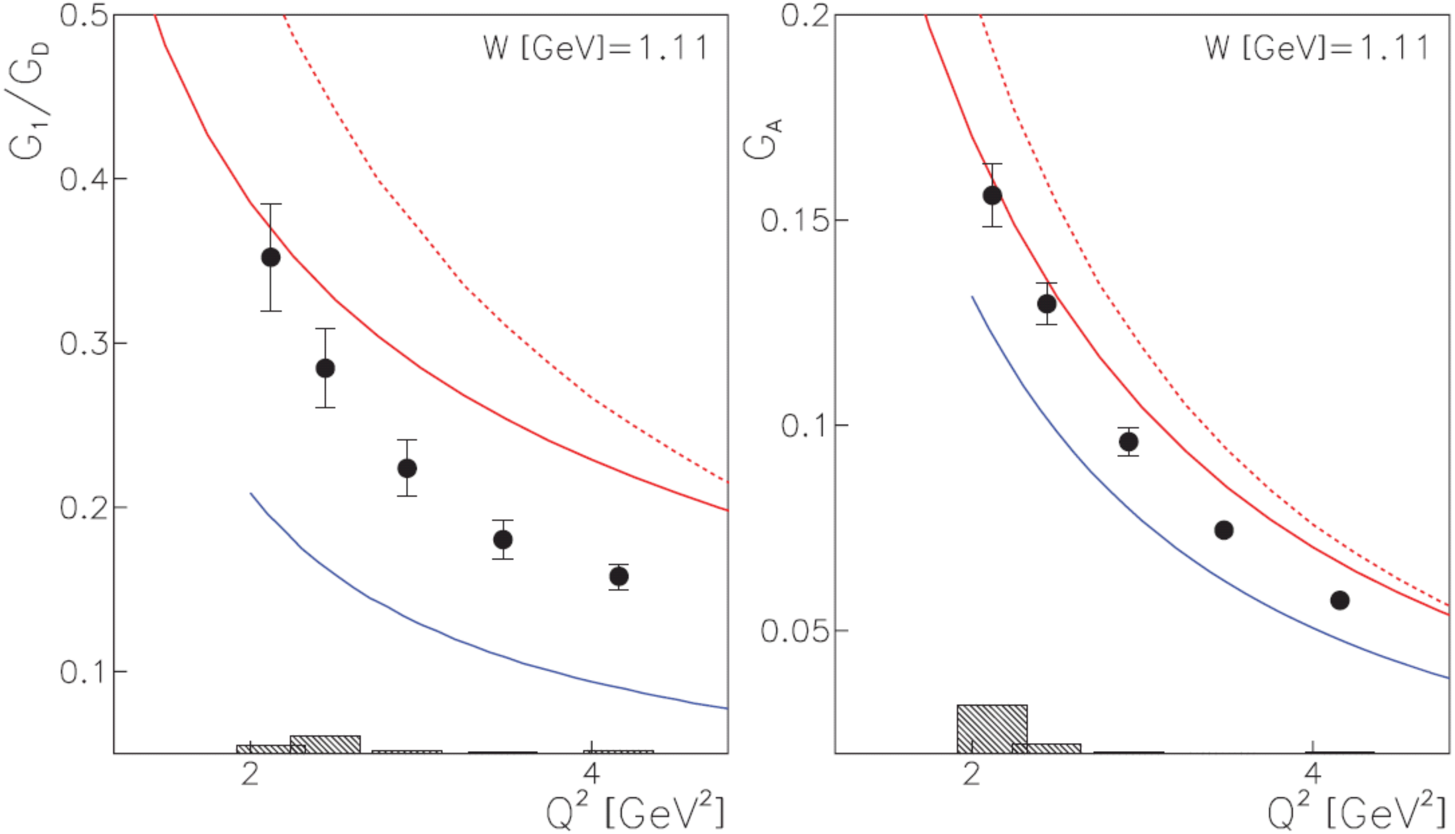
LCSR w/o pion-mass



Results of multipole

W- dependence

G_1 and Axial form factor



Summary

- As first time, E_{0+} multipole extraction and comparison near pion threshold W = 1.11–1.15 GeV at high Q^2 = 2.12–4.16 GeV^2 with two methods (LCSR, multipole fit) was performed.

- Multipole analysis gives us similar answer for extracting , E_{0+} multipole with LCSR method and showing 0.3 GeV^{-1} and almost Q^2 independent at threshold.

- Independent of pion mass and G^E_n parameterization considerations, the $n\pi^+$ channel is dominated by the transverse s-wave multipole E_{0+}.

- These data give strong constraints on theoretical developments, especially on the extrapolation away from threshold and away from the chiral limit.

Thank you for your attention ~!

Legendre –moment vs. F. F. for $n\pi^+$ channel

$$G_1^{\pi N} = G_1^{\pi^+ n} \qquad G_M = G_M^n \approx \mu_n G_D(Q^2)$$

$$G_2^{\pi N} = G_2^{\pi^+ n} \qquad G_E = G_E^n \approx 0$$

P.E. Bosted
Phys. Rev. C 51 (1995)

Assumption in LCSR
V.Braun PRD77(2008)

Due to low-energy theorem(LET) relates the S-wave multipoles or equivalently, the form factor G_1, G_2 @ threshold $m_\pi = 0$

$$\frac{Q^2}{m_N^2} G_1^{\pi^+ n} = \frac{g_A}{\sqrt{2}} \frac{Q^2}{Q^2 + 2m_N^2} G_M^n + \frac{1}{2} G_A$$

$$G_2^{\pi^+ n} = \frac{2\sqrt{2} g_A m_N^2}{Q^2 + 2m_N^2} G_E^n = 0$$

Scherer, Koch,
NPA534(1991)
Vainshtein, Zakharov
NPB36(1972)

Legendre moments vs. Form Factors

$$G_1^{\pi^+ n} \quad G_2^{\pi^+ n}$$

$$G_1^{\pi^+ n} = x_1 + iy_1$$
$$G_2^{\pi^+ n} = x_2 + iy_2$$

$$A_0 = D_0^{T+L} = \frac{1}{f_\pi^2}\left[\frac{4\vec{k}_i^{\,2} Q^2}{m_p^2}\left|G_1^{\pi^+ n}\right|^2 + \frac{c_\pi^2 g_A^2 \vec{k}_f^{\,2}}{W^2 - m_p^2} Q^2 m_p^2 G_M^{n2}\right]$$

$$A_1 = D_1^{T+L} = \frac{1}{f_\pi^2}\frac{4c_\pi g_A |k_i||k_f|}{W^2 - m_p^2}\left(Q^2 G_M^n \operatorname{Re}\left(G_1^{\pi^+ n}\right)\right)$$

$$C_0 = C_0^{TT} = 0$$

$$D_0 = D_0^{LT} = 0$$

$$g_A = 1.267$$

$$c_{\pi^+} = \sqrt{2}$$

$$f_\pi = 93 MeV$$

l-moments vs. F. F. for $n\pi^+$channel

$$G_1^{\pi N} = G_1^{\pi^+ n}$$
$$G_2^{\pi N} = G_2^{\pi^+ n}$$

$$G_M = G_M^n \approx \mu_n G_D(Q^2)$$
$$G_E = G_E^n \neq 0$$

P.E. Bosted
Phys. Rev. C 51
(1995)

Due to low-energy theorem(LET) relates the S-wave multipoles or equivalently, the form factor G_1, G_2 @ threshold $m_\pi = 0$

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$$A_1 = D_1^{T+L} = \frac{1}{f_\pi^2}\frac{4c_\pi g_A |k_i||k_f|}{W^2 - m_N^2}\left(Q^2 G_M \,\mathrm{Re}\left(G_1^{\pi N}\right) - \varepsilon_L m_N^2 G_E \,\mathrm{Re}\left(G_2^{\pi N}\right)\right)$$

$$C_0 = C_0^{TT} = 0$$

$$D_0 = D_0^{LT} = -\frac{1}{f_\pi^2}\frac{c_\pi g_A |k_i||k_f|}{W^2 - m_N^2} Q m_N\left(G_M \,\mathrm{Re}\left(G_2^{\pi N}\right) + 4G_E \,\mathrm{Re}\left(G_1^{\pi N}\right)\right)$$

$g_A = 1.267$

$c_{\pi^+} = \sqrt{2}$

$f_\pi = 93 MeV$

Legendre moments vs. Form Factors

$$G_1^{\pi^+ n} = x_1 + i y_1$$
$$G_2^{\pi^+ n} = x_2 + i y_2$$

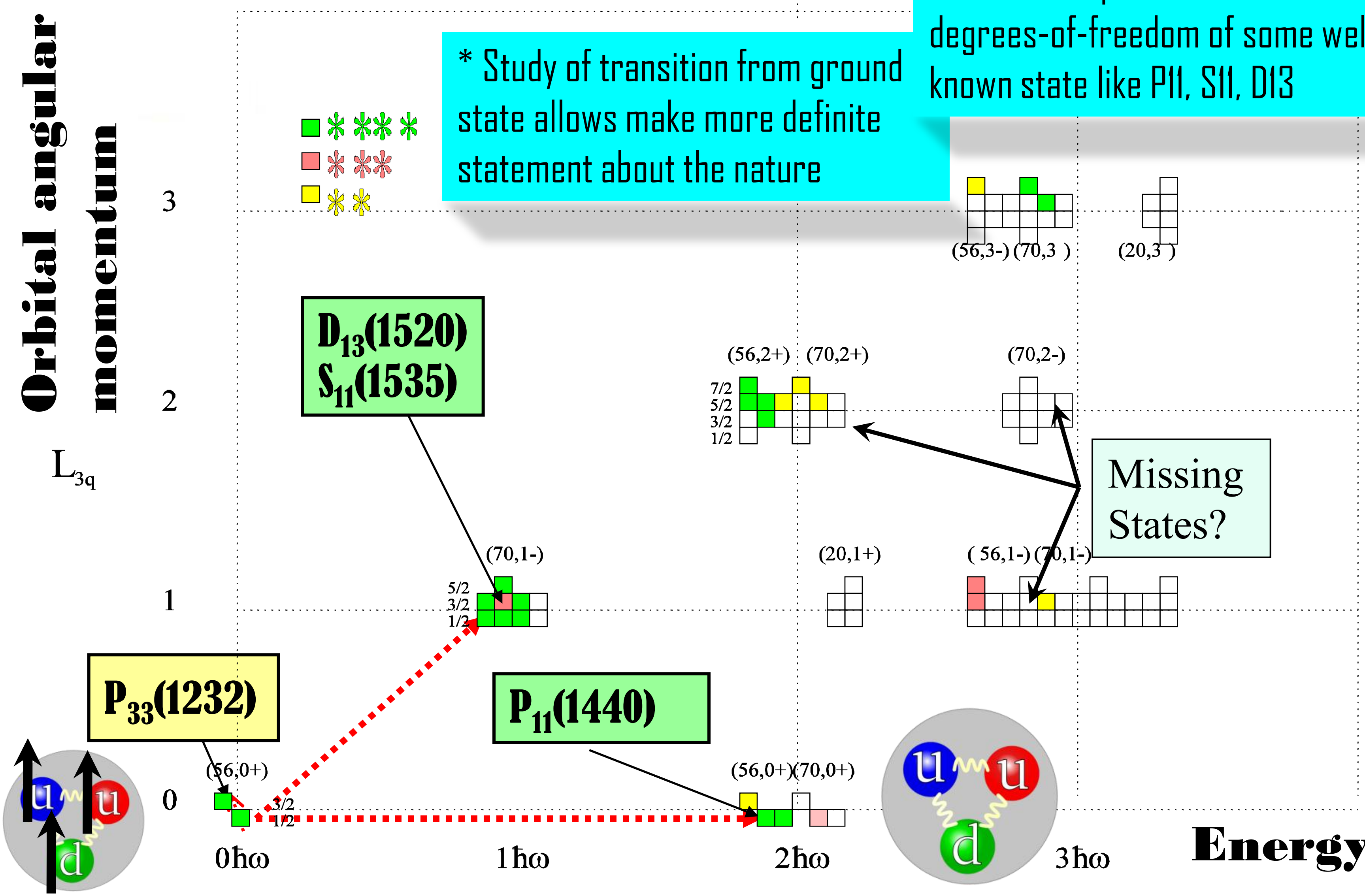
* 3 Eqs. 4 parameter should be determined
* Real parts x1, x2 can be determined by A1, D0 legendre coeff.
* Imaginary parts y1, y2 can be determined in 2cases
* Asymmetry helps to determine complete form factor

$$D_0^{/} = D_0^{LT/} = -\frac{1}{f_\pi^2} \frac{c_\pi g_A |k_i||k_f|}{W^2 - m_N^2} Q m_N \left(G_M \operatorname{Im}\left(G_2^{\pi N}\right) - 4 G_E \operatorname{Im}\left(G_1^{\pi N}\right)\right)$$

SU(6)xO(3) Classification of Baryons

* There are questions about underlying degrees-of-freedom of some well known state like P11, S11, D13

* Study of transition from ground state allows make more definite statement about the nature



Alternative check !

Using six amplitudes (f_i)

** if $l_\pi = 1$

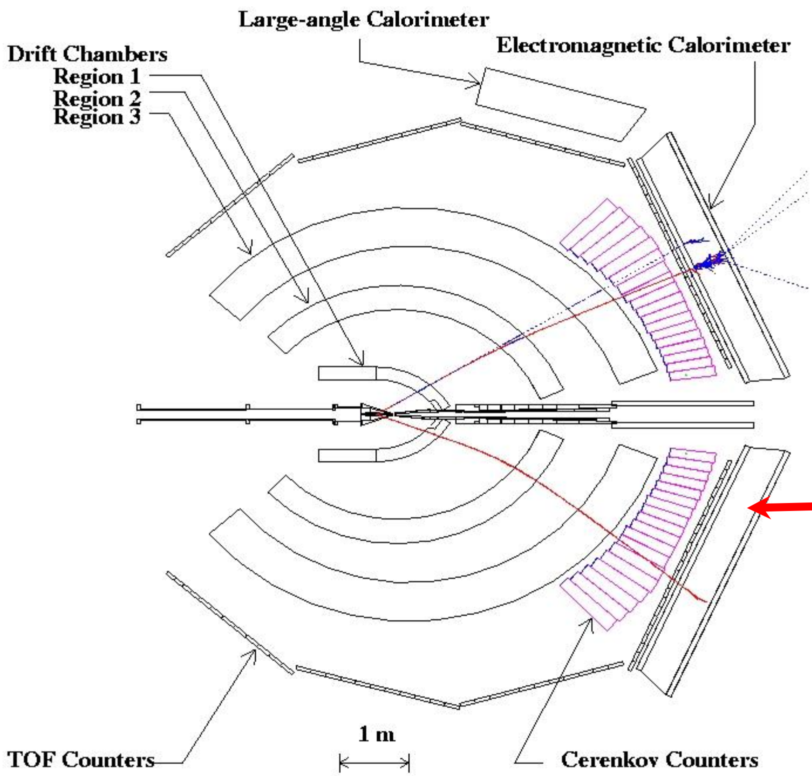
$$f_1 = E_{0+} + 3*\cos(\theta)*(E_{1+} + M_{1+})$$
$$f_2 = 2*M_{1+} + M_{1-}$$
$$f_3 = 3*(E_{1+} - M_{1+})$$
$$f_4 = 0$$
$$f_5 = S_{0+} + 6*\cos(\theta)*S_{1+}$$
$$f_6 = S_{1-} - 2*S_{1+}$$

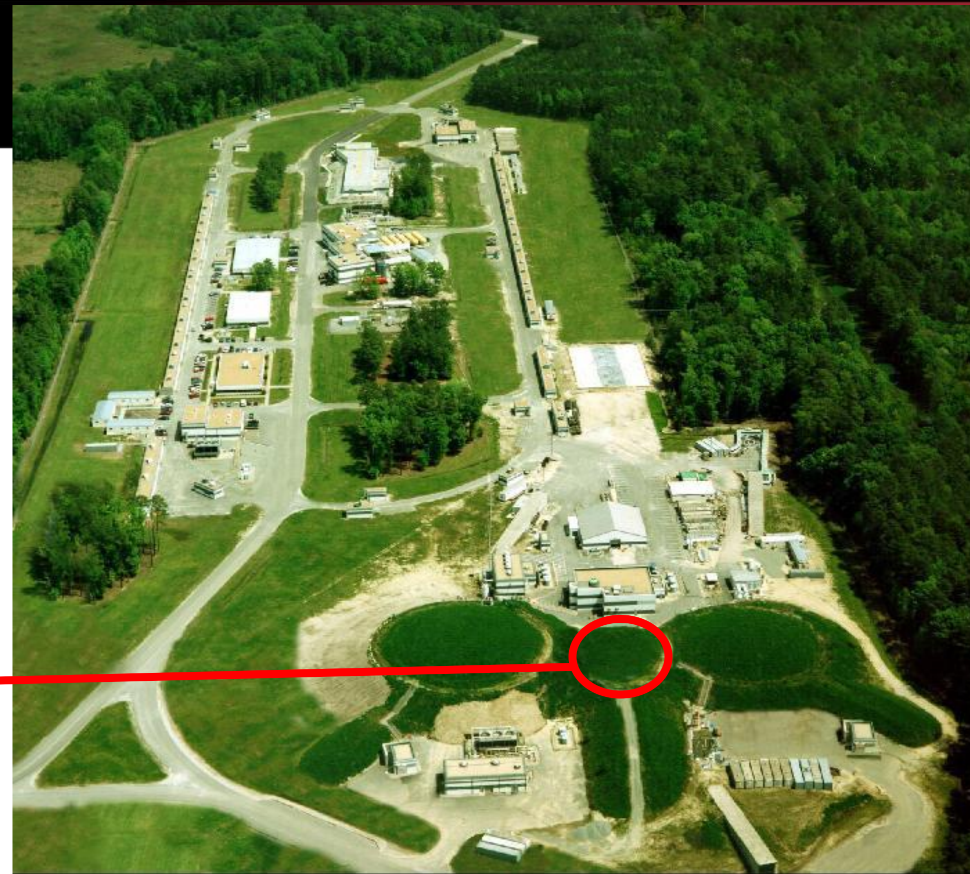
Helicity amplitudes (H_i)

$$H_1 = (-1/\mathrm{sqrt}(2))*\cos(\theta/2)*\sin(\theta)*(f_3 + f_4)$$
$$H_2 = -1*\mathrm{sqrt}(2)*\cos(\theta/2)*(f_1 - f_2 - \sin(\theta)*(f_3 - f_4))$$
$$H_3 = (1/\mathrm{sqrt}(2))*\sin(\theta/2)*\sin(\theta)*(f_3 - f_4)$$
$$H_4 = \mathrm{sqrt}(2)*\sin(\theta/2)*(f_1 + f_2 +(\cos(\theta/2))**2*(f_3 + f_4))$$
$$H_5 = -1*(\mathrm{sqrt}(Q^2)/\mathrm{abs}(k\_cm))*\cos(\theta/2)*(f_5 + f_6)$$
$$H_6 = (\mathrm{sqrt}(Q^2)/\mathrm{abs}(k\_cm))*\sin(\theta/2)*(f_5 - f_6)$$

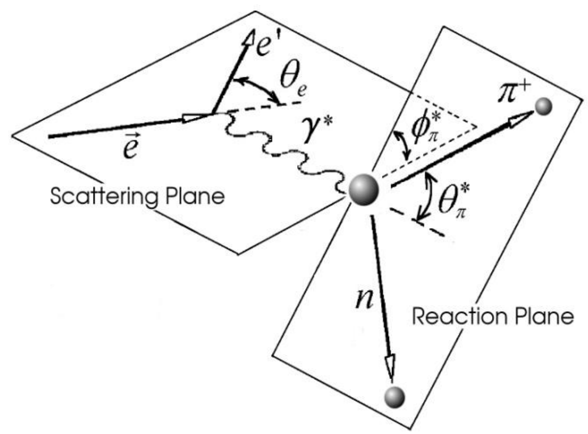
I. G. Aznauryan, PRD 57, 2727 (1998)

JLab & CLAS

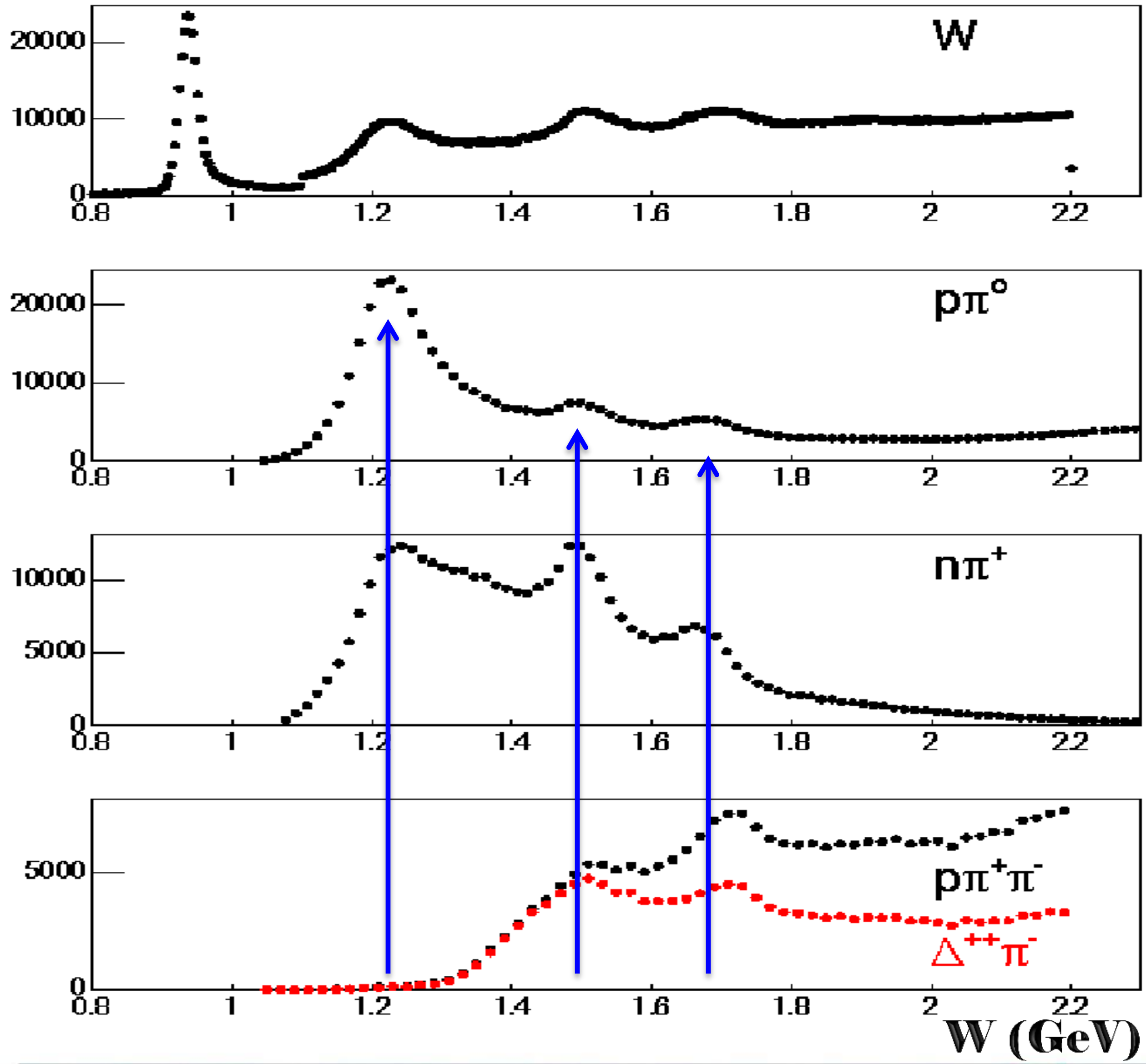




- **Experiment (Oct.2001 - Jan.2002)**
  E_0 =5.754GeV
  B_I = 3375A
  LH2 target
  Almost 4π angular coverage



Single and double pion electroproduction



- Provides information that is complementary to the Nπ channel

Single and double pion electroproduction

▪Provides information that is complementary to the Nπ channel