N* Physics with CLAS

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University of Connecticut

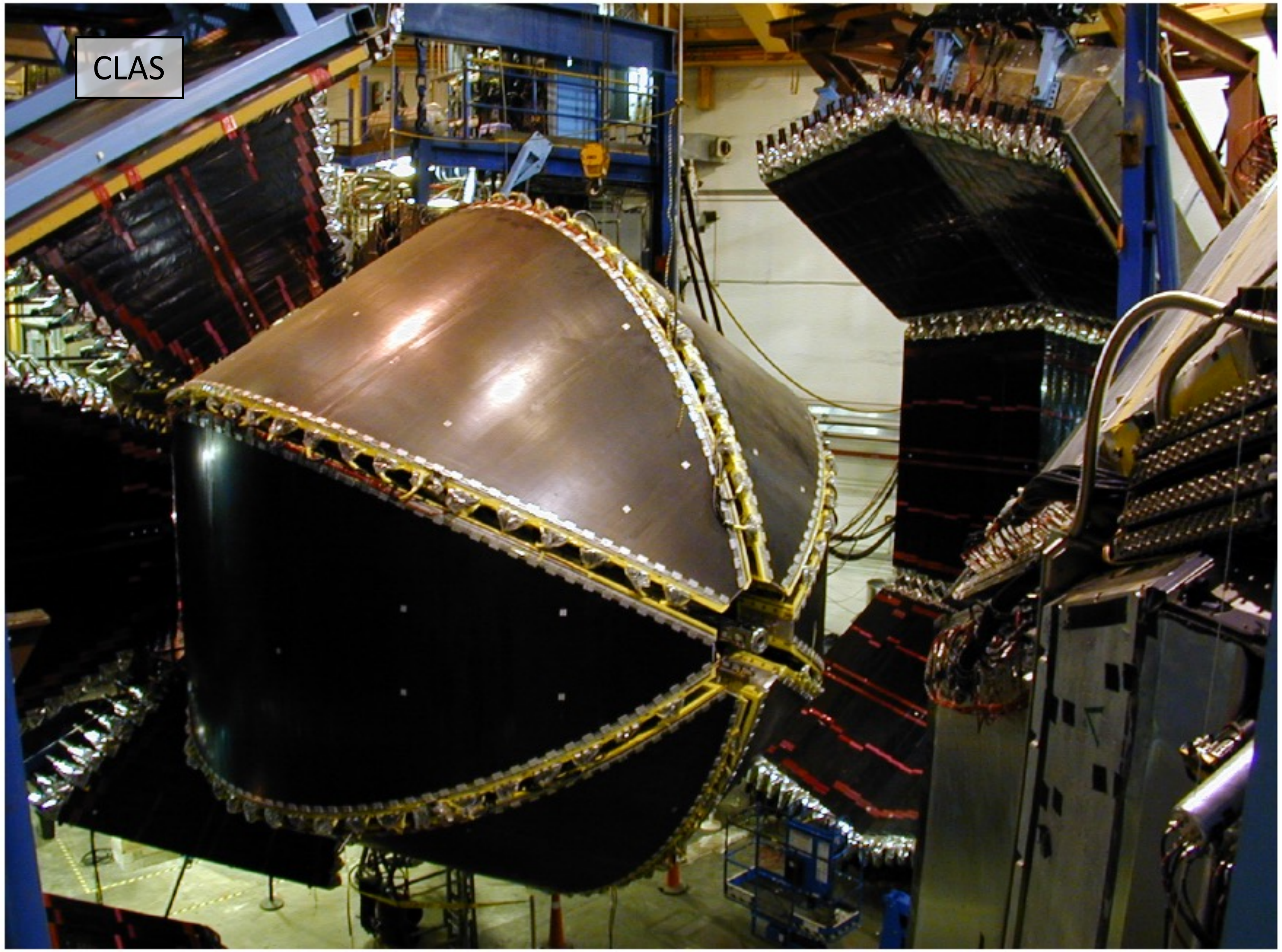
For the CLAS Collaboration

ECT*-APCTP Joint Workshop: Exploring Exploring Resonance Structure with Transition GPDs

August 21-25, 2023

Trento, Italy

CLAS EXPERIMENT 1997- 2012



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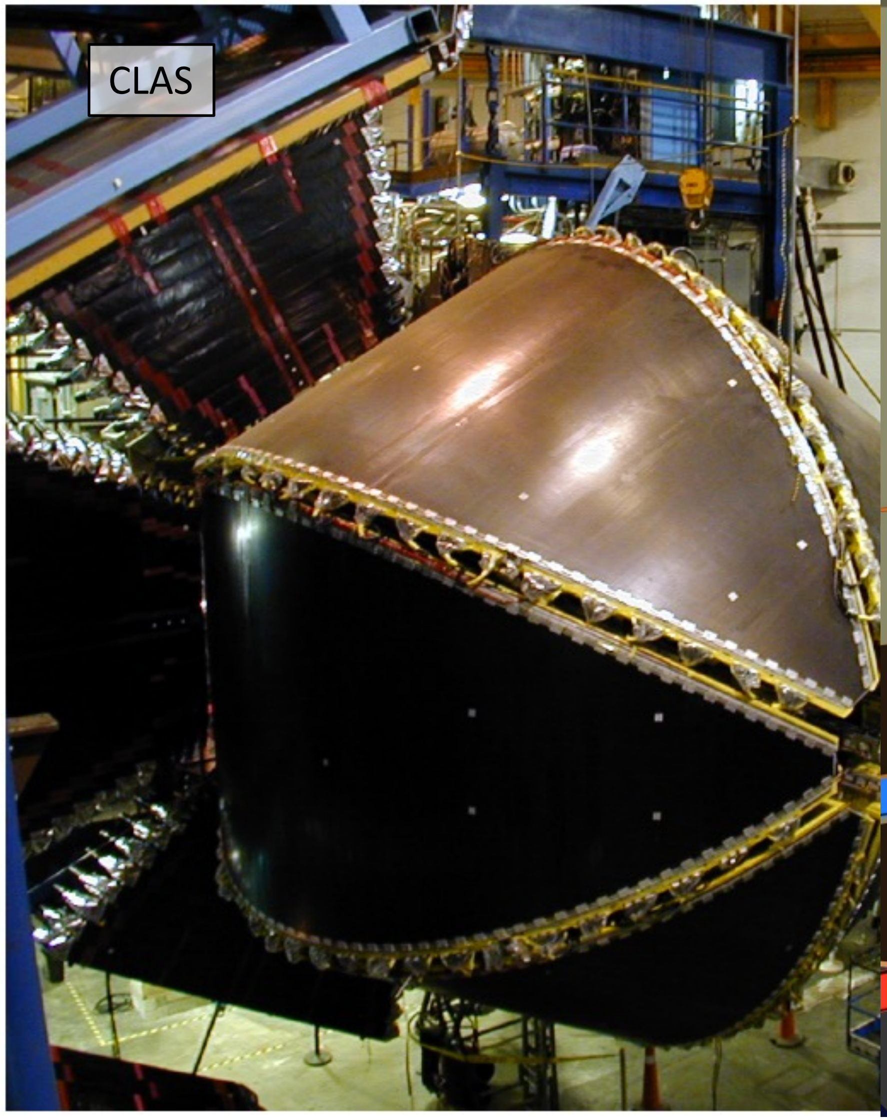
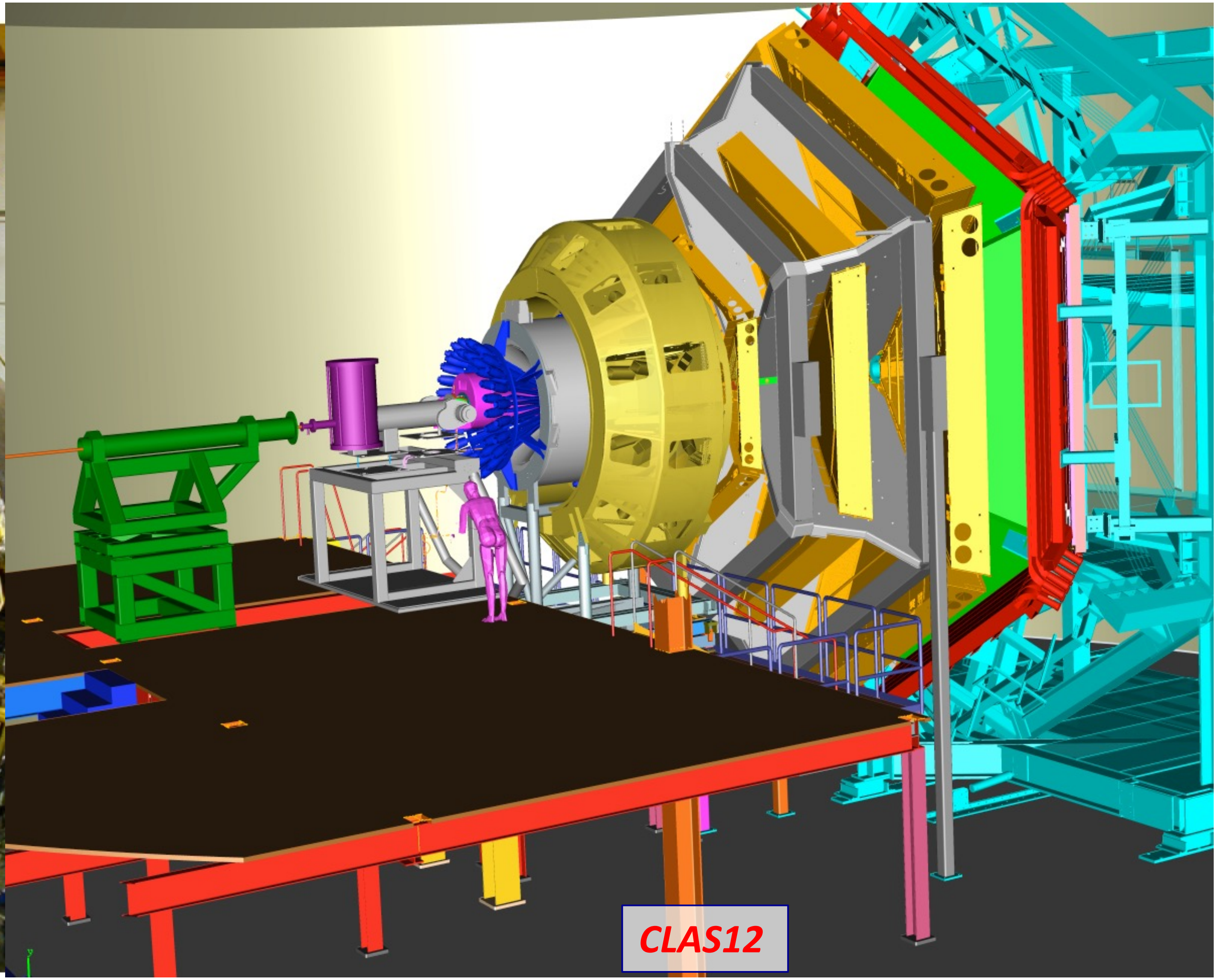
CLAS12 EXPERIMENT 2018 ~



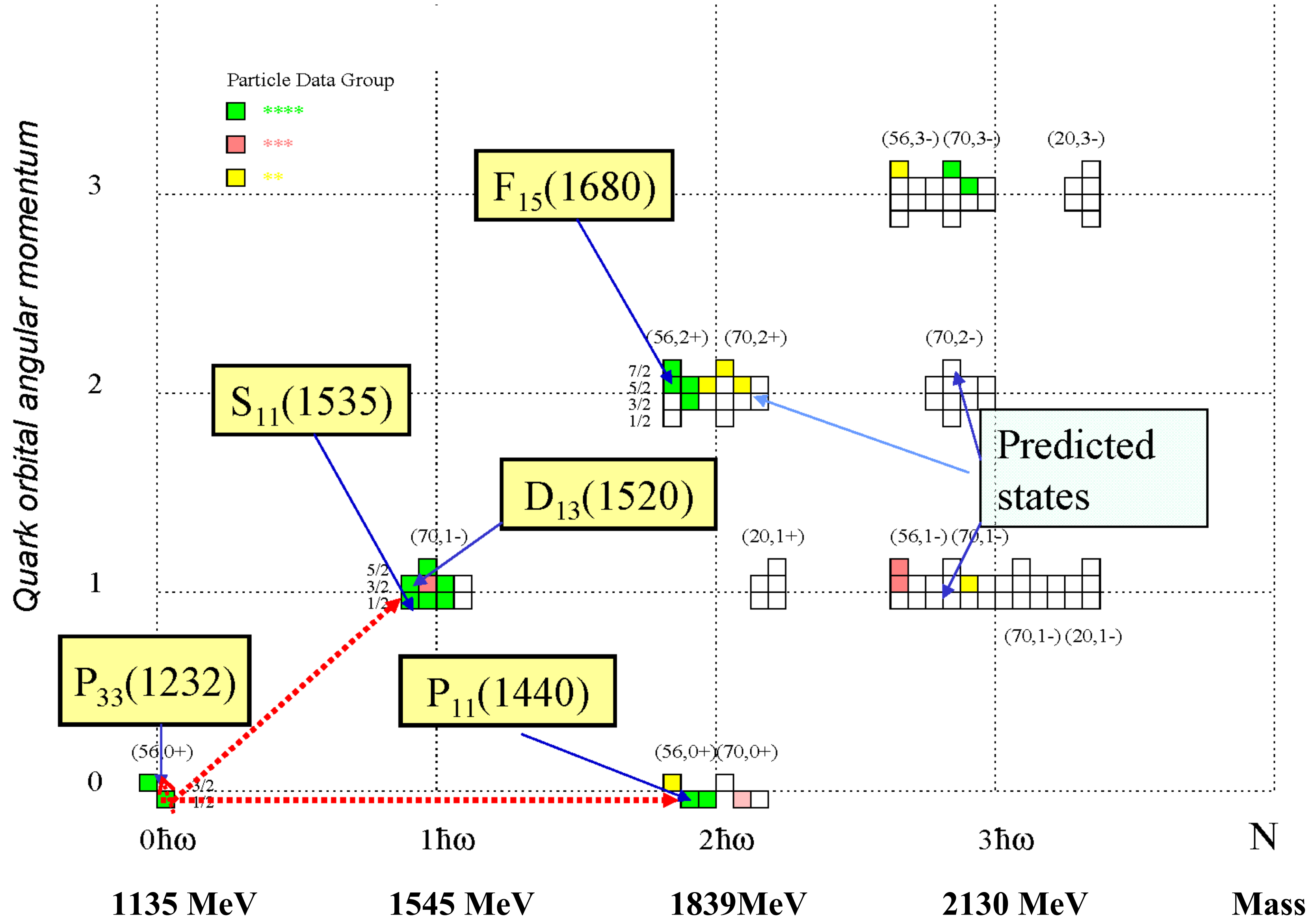


N* Program

1. Spectroscopy (mainly driven by real photon scattering)
    - Measure the N* spectrum more precisely and more completely.
    - The impact of nucleon spectroscopy for QCD compared with that of atomic spectroscopy for QED.

2. Structure of excited baryons (mainly driven by electron scattering)
    - Studying underlying symmetries of hadron system
    - Understanding the effective degrees of freedom

Quark Model Classification of N*



Search for excited baryons in 2-body channels

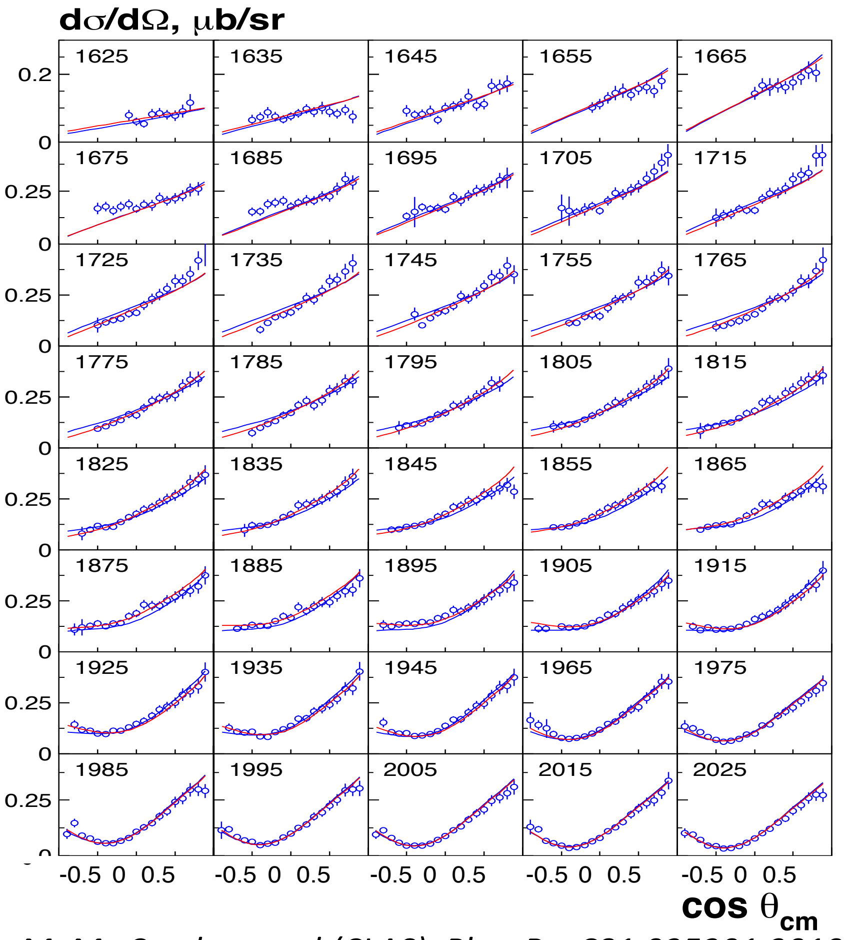
data acquired ✔ *- analyzed/published*

Observable	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$\gamma p \to X$																
$p\pi^0$	✔	✔	✓		✓	✓	✓	✓								
$n\pi^+$	✔	✔	✓		✔	✓	✓	✓								
$p\eta$	✔	✔	✓		✔	✓	✓	✓								
$p\eta'$	✔	✔	✓		✓	✓	✓	✓								
$K^+\Lambda$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	✔	✔
$K^+\Sigma^0$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	✔	✔
$p\omega/\phi$	✔	✔	✔		✔	✓	✓	✓	✔ SDME							
$K^{+*}\Lambda$	✔			✔					✔ SDME							
$K^{0*}\Sigma^+$	✔	✓									✓	✓	SDME			
$\gamma n \to X$																
$p\pi^-$	✔	✔			✔	✓	✓									
$p\rho^-$	✓	✓			✓	✓	✓									
$K^-\Sigma^+$	✔	✓			✓	✓	✓									
$K^0\Lambda$	✔	✓	✓	✓	✔	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✔	✓	✓	✓	✔	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓									✓	✓				

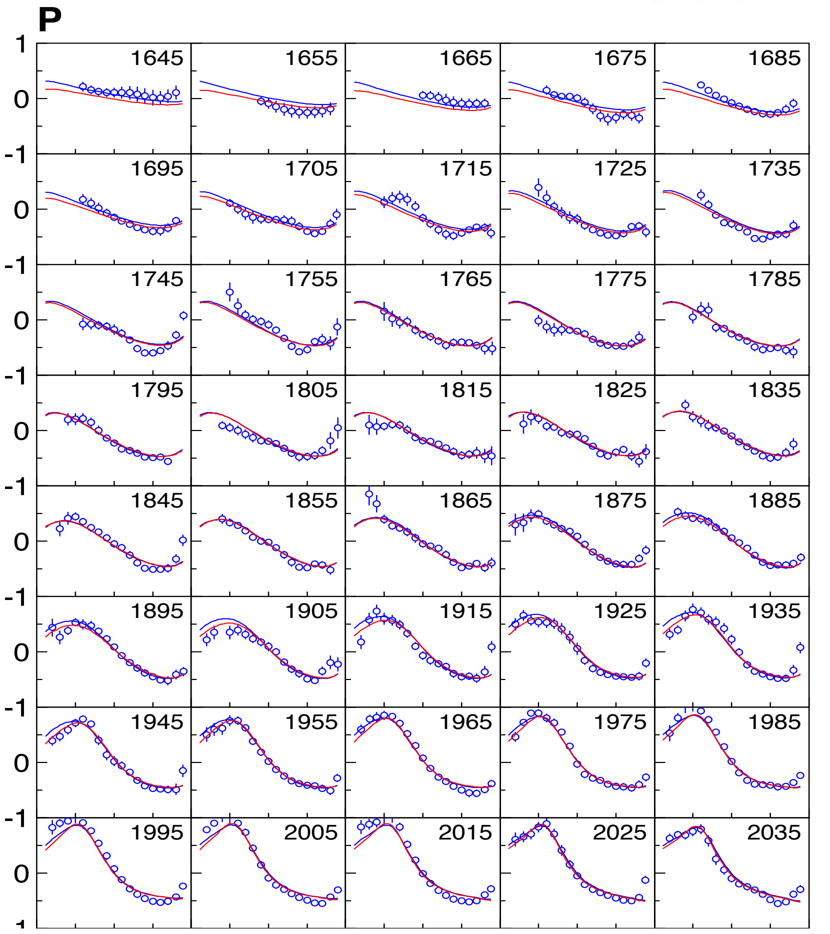
Establishing the N* spectrum

Hyperon photoproduction $\gamma p \rightarrow K^+\Lambda \rightarrow K^+ p \pi^-$

CLAS
CEBAF Large Acceptance Spectrometer



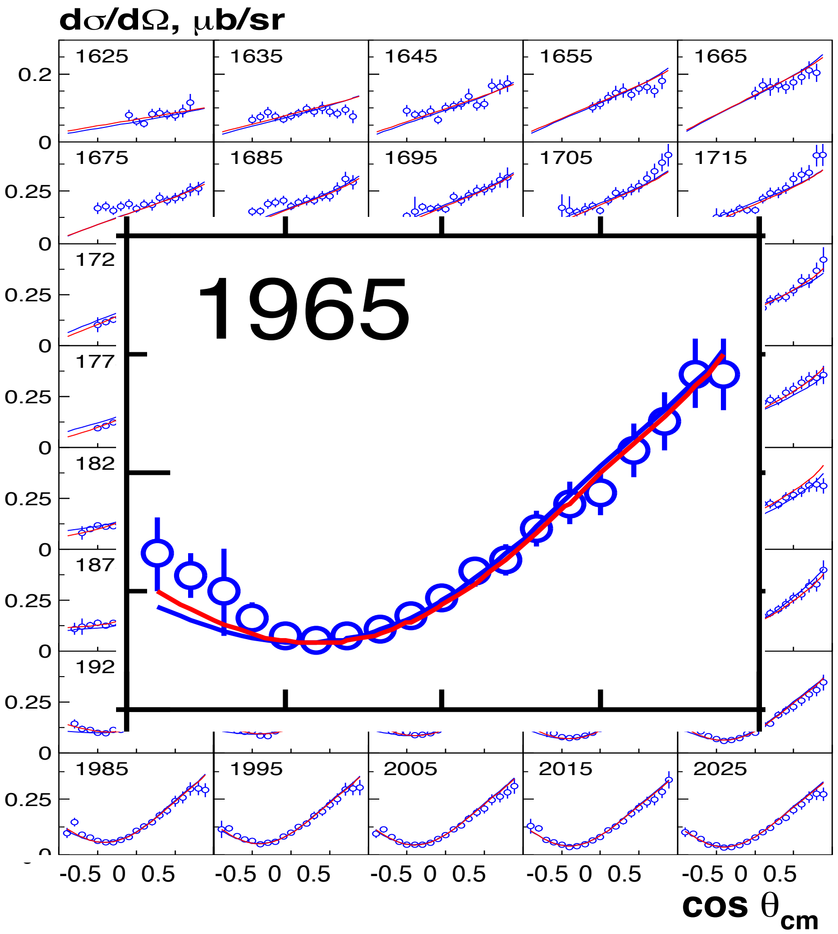
M. Mc Cracken et al.(CLAS), Phys.RevC81,025201,2010



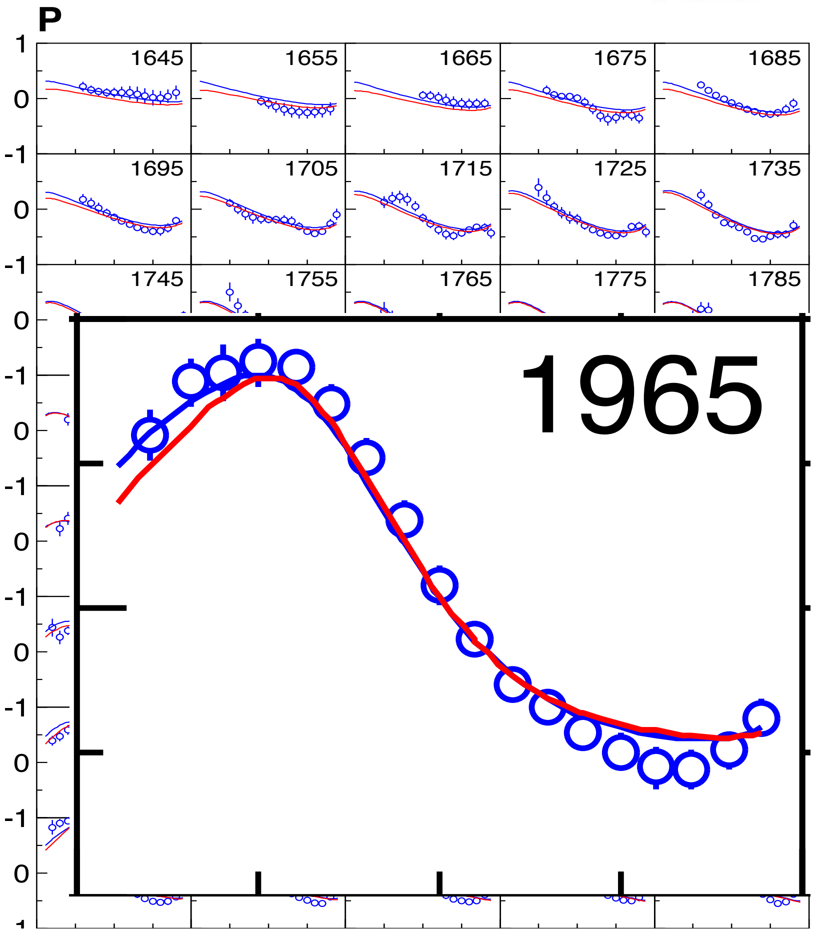
Fit: A.V. Anisovich et al, EPJ A48, 15 (2012)

Establishing the N* spectrum

Hyperon photoproduction $\gamma p \rightarrow K^+\Lambda \rightarrow K^+ p \pi^-$



M. Mc Cracken et al.(CLAS), Phys.RevC81,025201,2010

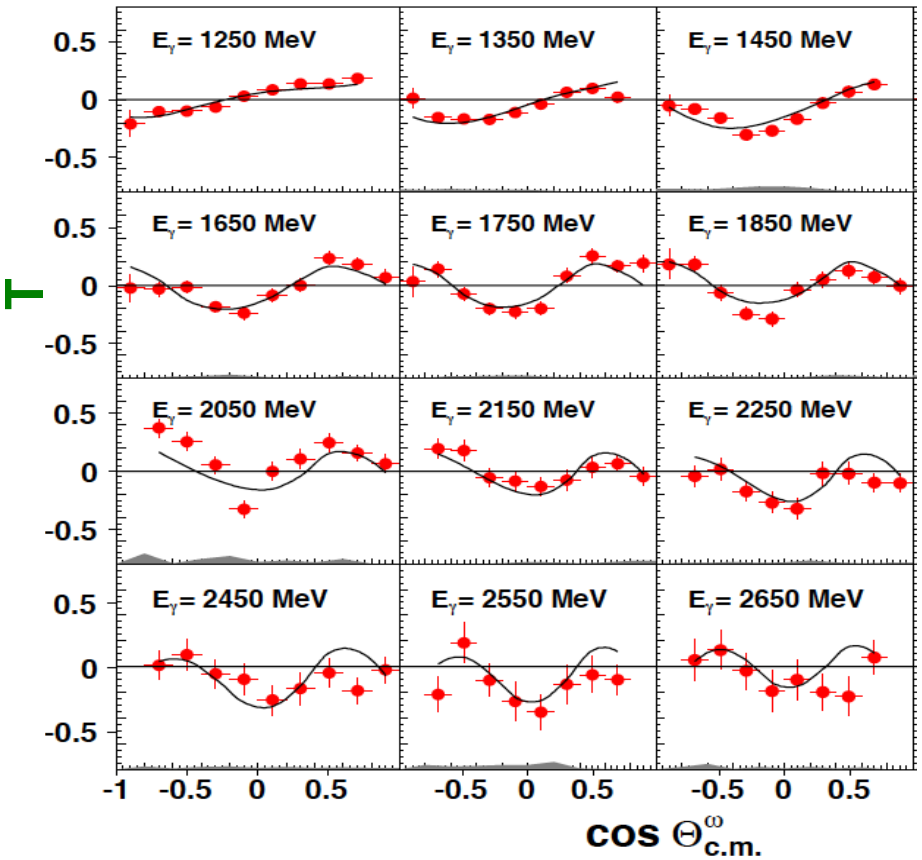


Fit: A.V. Anisovich et al, EPJ A48, 15 (2012)

Target T and beam-target E spin asymmetries

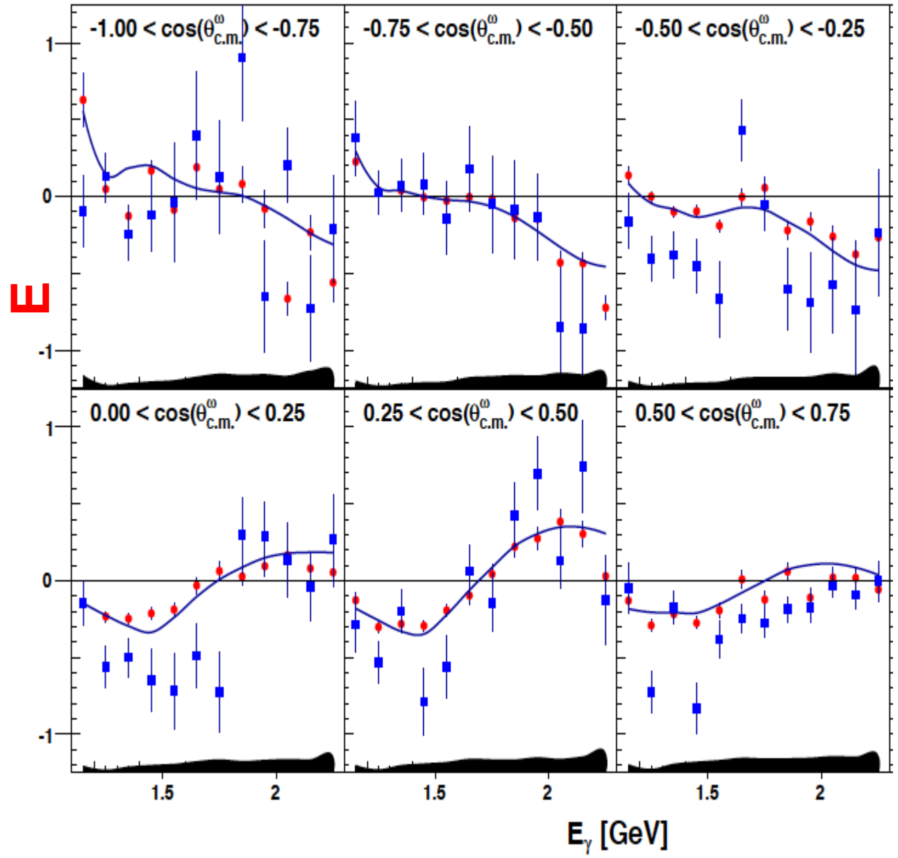
$p(\gamma,p\omega)$

Transverse target



Longitudinal target

● CLAS
■ CBELSA



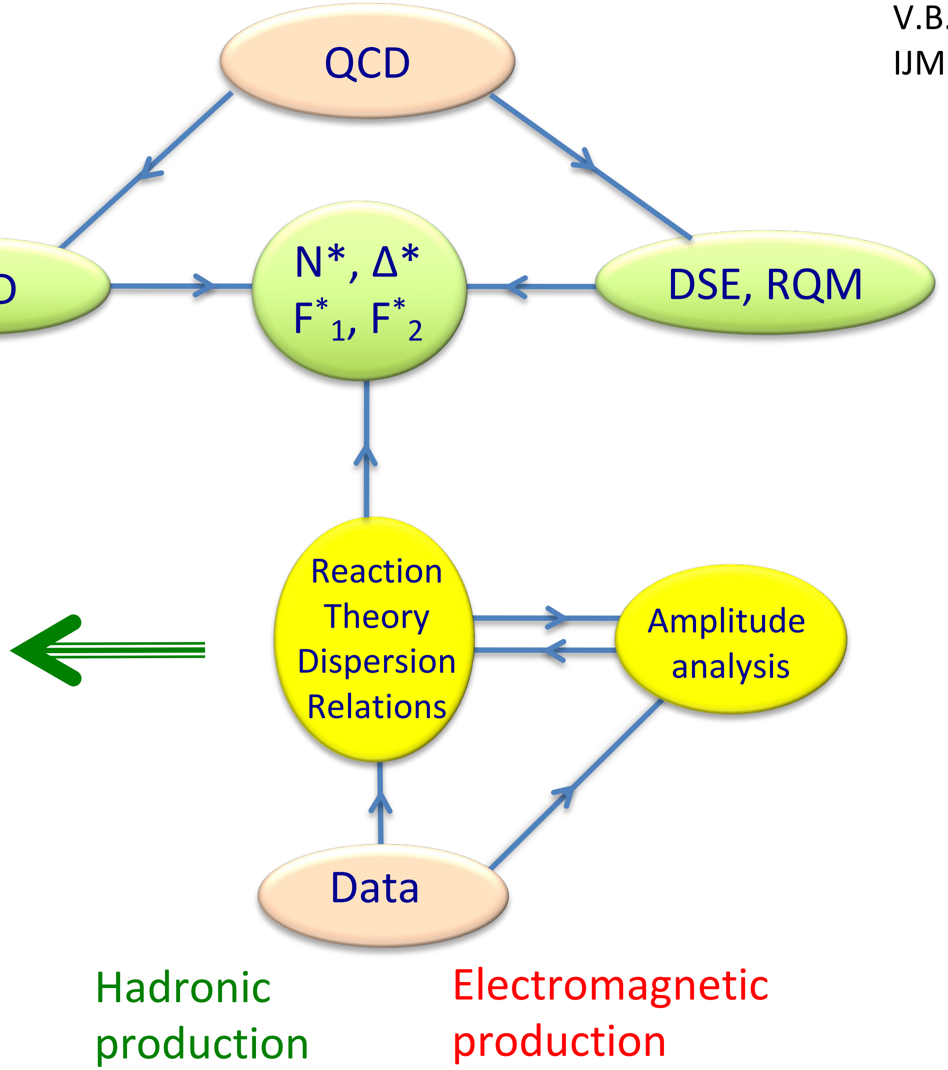
P. Roy et al. PRC97 (2018) no.5, 055202

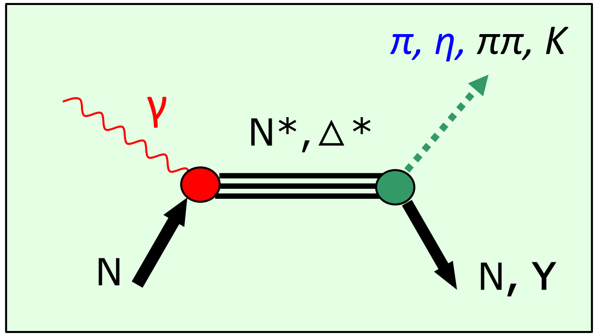
Fit: Bonn-Gatchina

Establishing the N* and Δ* Spectrum

Precision data require accurate analysis procedures to establish the baryon spectrum

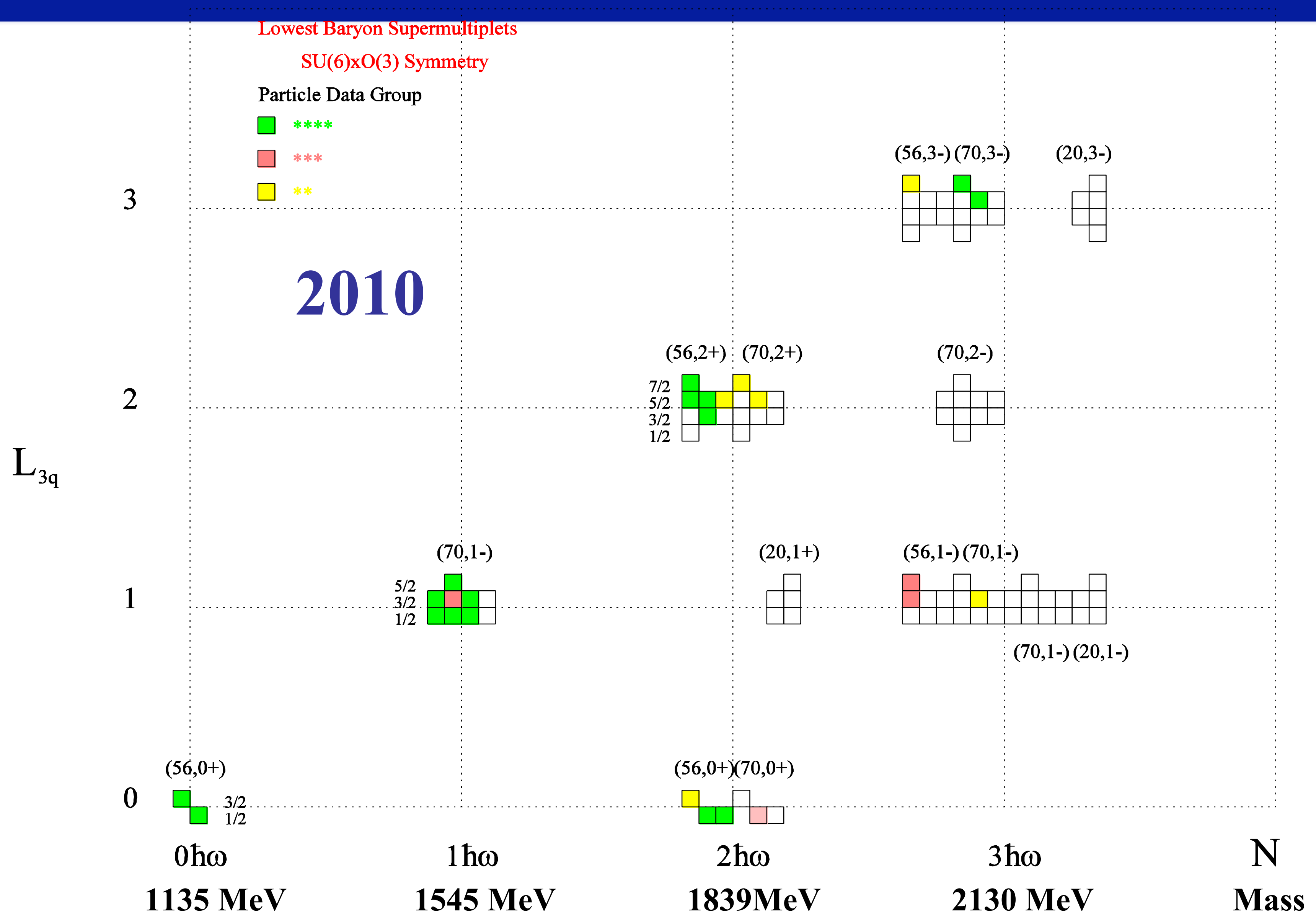
V.B., T.S.-H. Lee
IJMP E13 (2004)





Quark Model Classification of N*

Dietmar Menze



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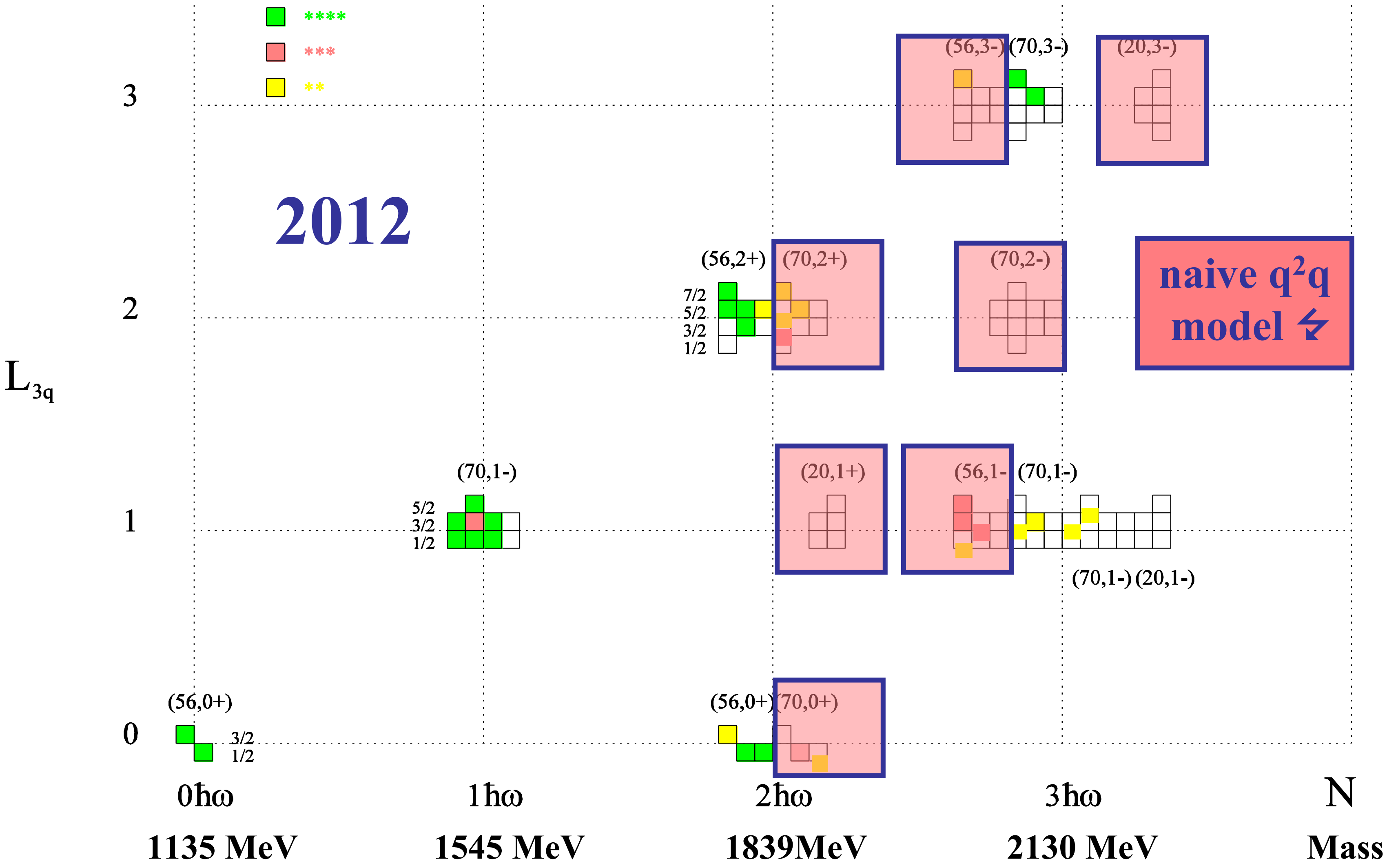
Quark Model Classification of N*

BnGa energy-dependent coupled-channel PWA of CLAS $K^+\Lambda$ and other data



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New evidence for excited nucleons

State N((mass)J^P	PDG pre 2012	PDG 2018 evidence	Mass (Pole)
N(1710)$1/2^+$	***	****	1700
N(1880)$1/2^+$		***	1860
N(2100)$1/2^+$	*	***	2100
N(1895)$1/2^-$		****	1910
N(1900)$3/2^+$	**	****	1920
N(1875)$3/2^-$		***	1900
N(2120)$3/2^-$		***	2100
N(2060)$5/2^-$		***	2070
Δ(2200)$7/2^-$	*	***	2150

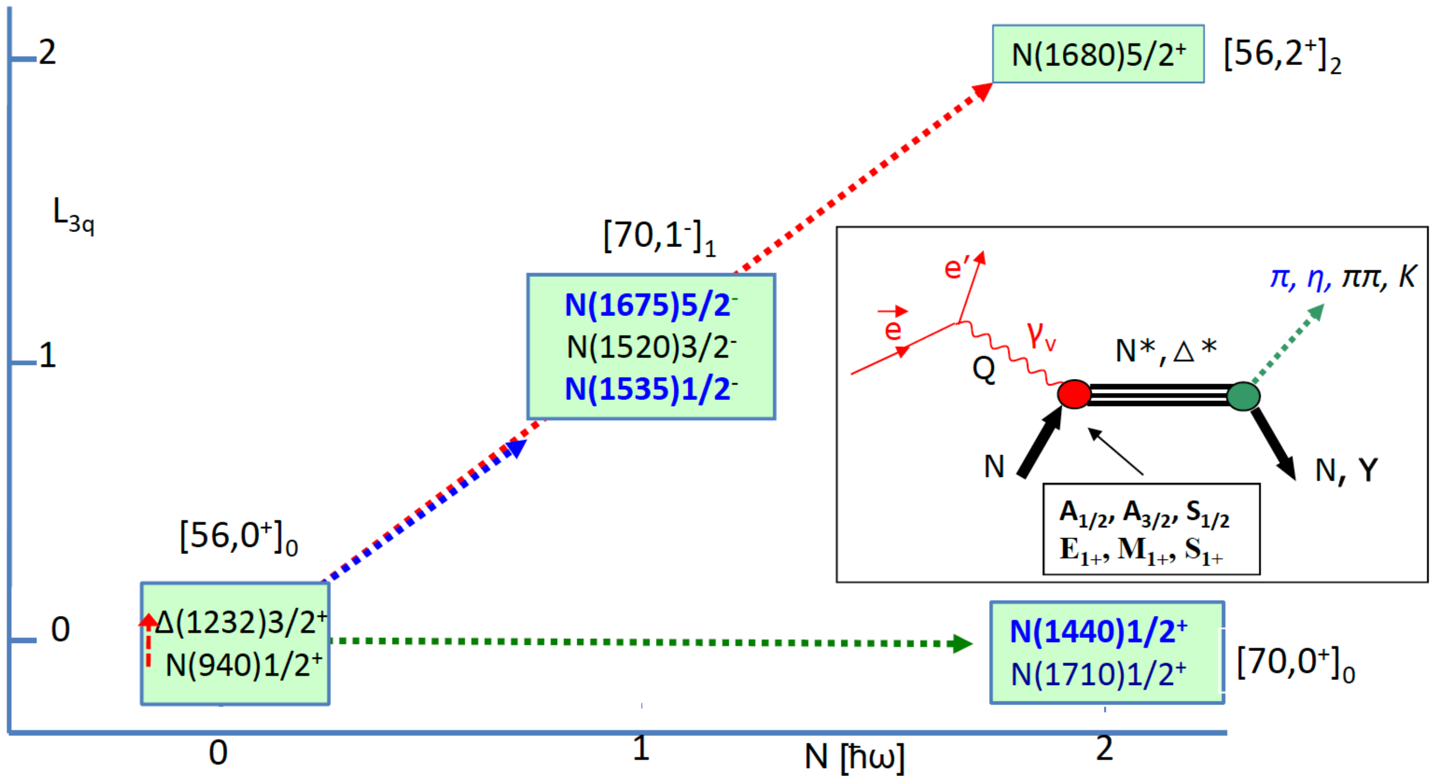
**** - existence is certain
*** - existence is likely
** - evidence of existence is fair
* - evidence of existence is poor

Photoproduction data led to the discovery of new states and fully established poorly known states.

Structure of Excited Baryons with Electromagnetic Probes

Central question in hadron physics

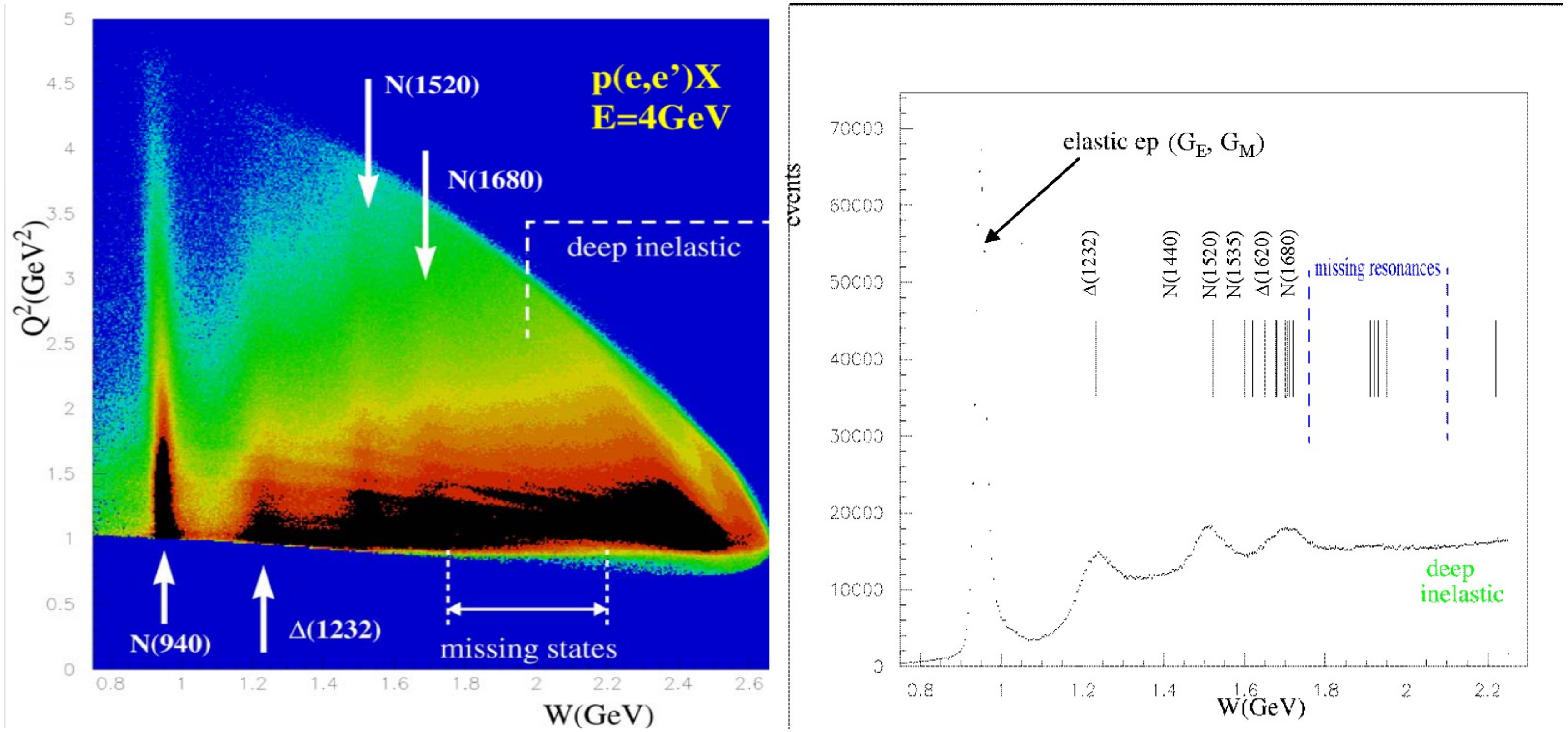
What are the effective degrees of freedom at varying distance scale?



Measure the strength of resonance excitations versus distance scale in meson electroproduction

Inclusive electron scattering

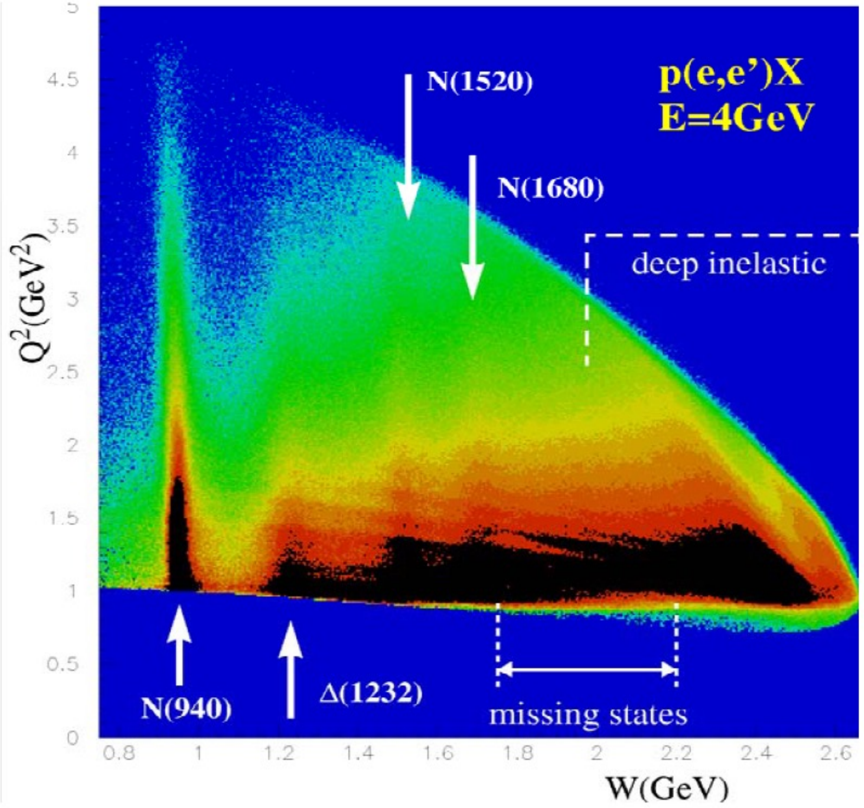
p(e,e')X



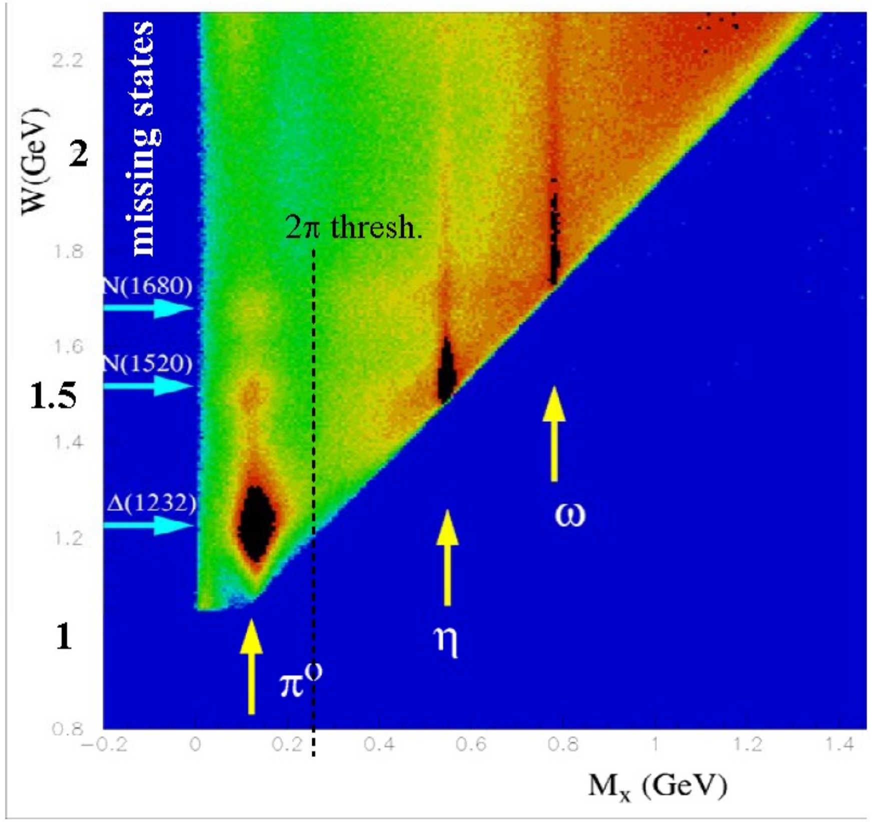
- In contrast to elastic scattering, resonances cannot be uniquely separated in inclusive scattering → need to measure exclusive processes.

Inclusive vs. Exclusive electron scattering

p(e,e')X



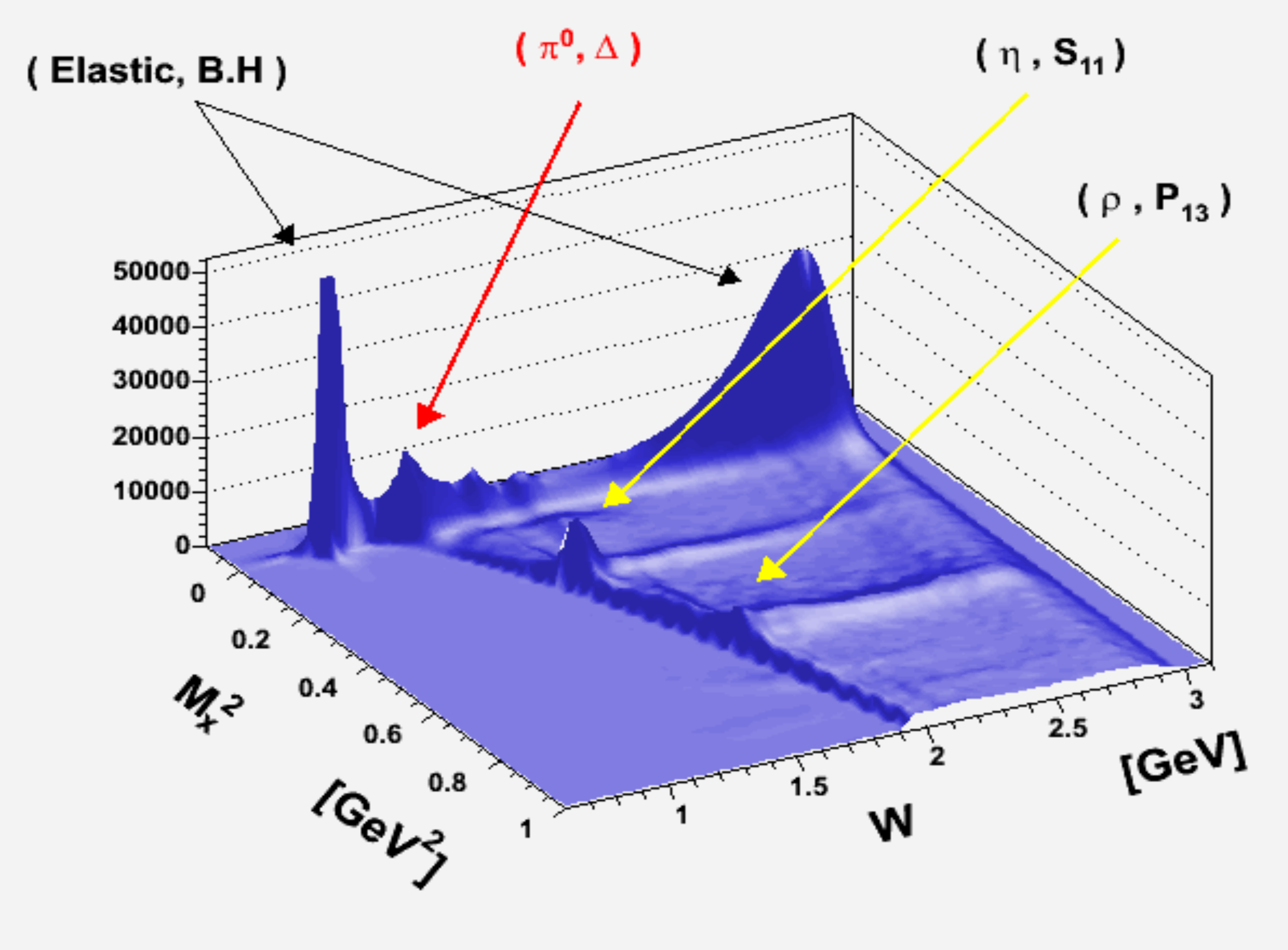
p(e,e'p)X



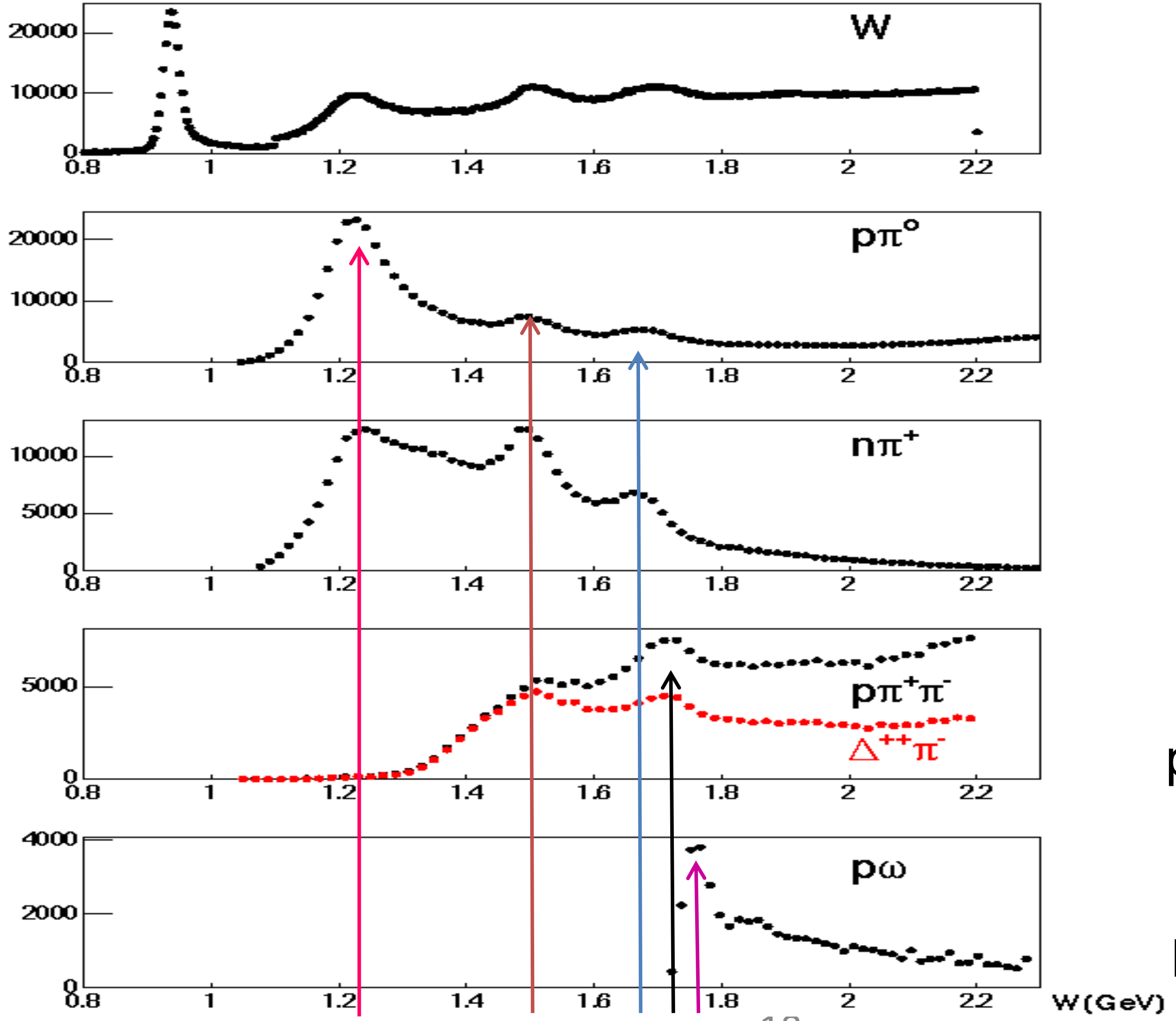
- Resonance states can be better isolated by exclusive processes.

Missing Mass^2 vs W for $ep \rightarrow e'pX$

Final data sample from 6 GeV run (e16)



W-Dependence of Selected Exclusive Channels



$p(e,e')X$
(trigger)

$p(e,e'p)\pi^0$

$p(e,e'\pi^+)n$

$p(e,e'p\pi^+)\pi^-$

$p(e,e'p\pi^+)X$

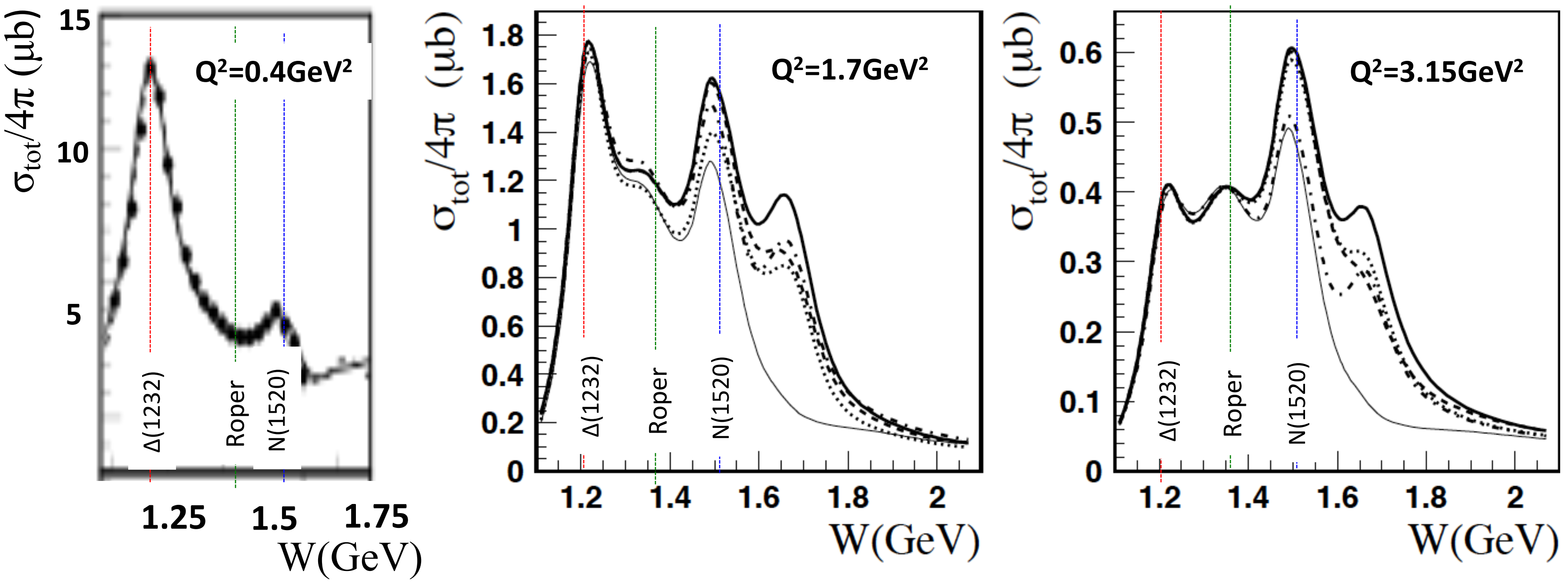
Integrated cross section in the resonance region

$\gamma^* p \longrightarrow \pi^+ n$

K. Park et al., PR C77 (2008) 015208; PR C91 (2015) 045203

CEBAF Large Acceptance Spectrometer

Why study more than one resonance, aren't they all the same?

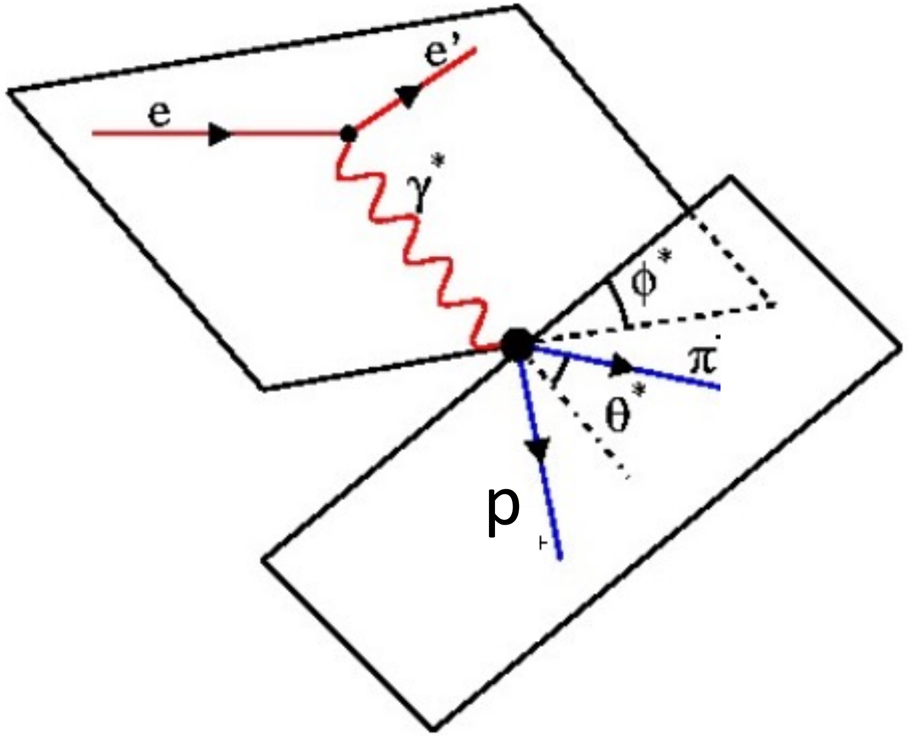


→ States with different quantum numbers respond differently to increase in Q^2.

Exclusive Electroproduction x-section and BSA

Cross section (longitudinally pol. beam and unpol. target

$$2\pi \frac{d^2\sigma}{dt d\phi} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \cdot cos(2\phi) \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cdot cos(\phi) \frac{d\sigma_{LT}}{dt} + h \cdot \sqrt{2\epsilon(1-\epsilon)} \cdot sin(\phi) \frac{d\sigma_{LT'}}{dt}$$



Beam Spin Asymmetry:

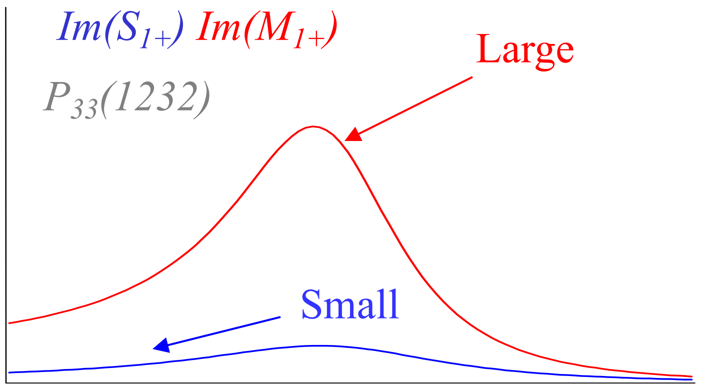
$$BSA(t, \phi, x_B, Q^2) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{\sqrt{2\epsilon(1-\epsilon)} \frac{\sigma_{LT'}}{\sigma_0} \sin\phi}{1 + \sqrt{2\epsilon(1+\epsilon)} \frac{\sigma_{LT}}{\sigma_0} \cos\phi + \epsilon \frac{\sigma_{TT}}{\sigma_0} \cos 2\phi}$$

Power of Interference

- Unpolarized structure function

  $\sigma_{LT} \sim Re(L^*T)$
  $= Re(L)Re(T) + Im(L)Im(T)$

  – Amplify small resonance multipole by an interfering larger resonance multipole

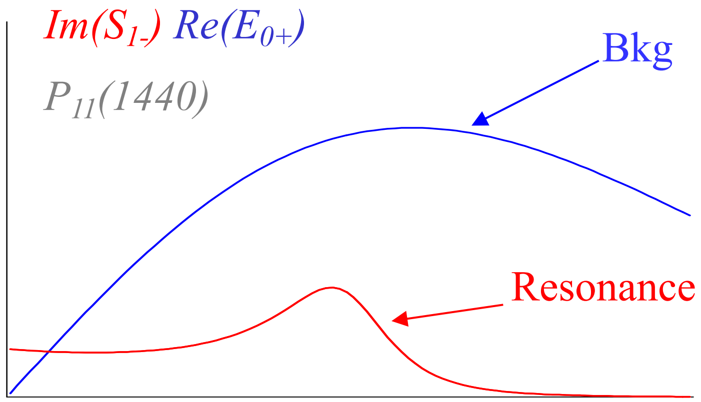


K. Joo et al. (CLAS Collaboration), Phys. Rev. Lett. 88, 122001 (2002).

- Polarized structure function

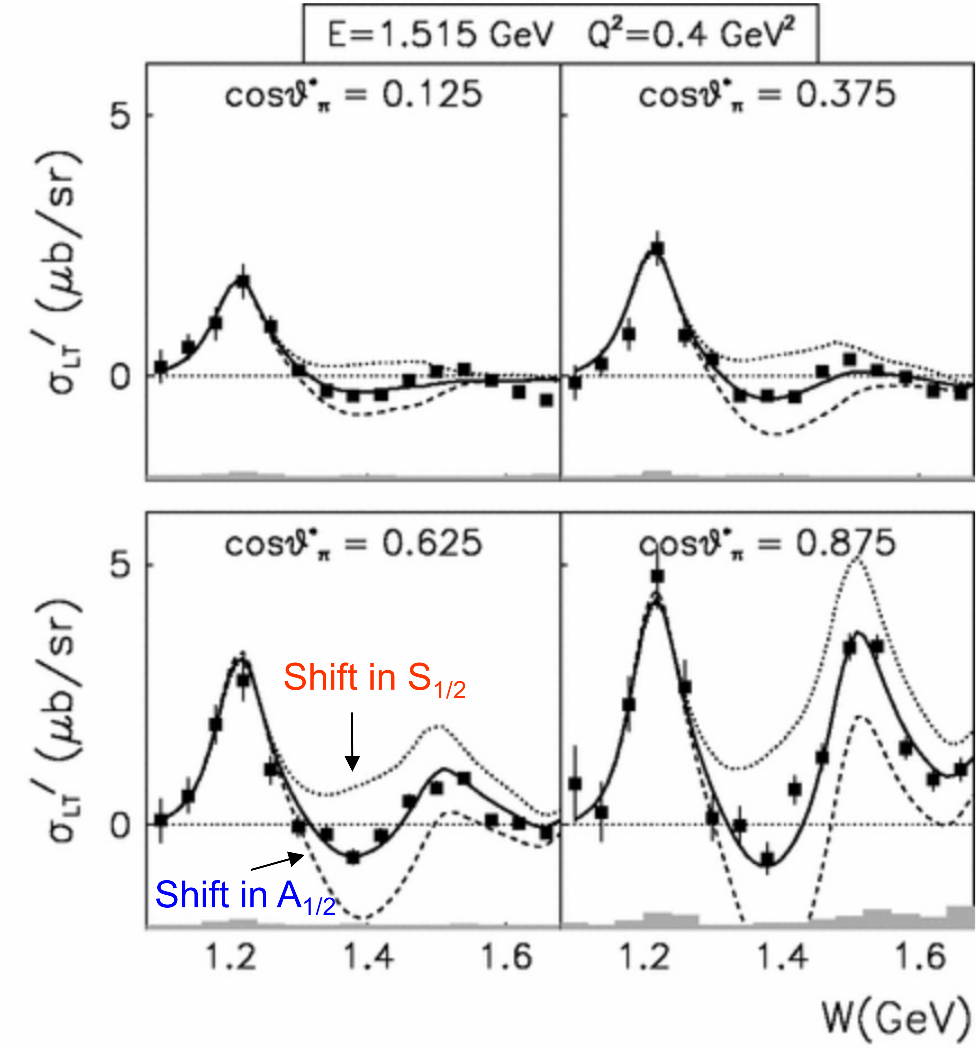
  $\sigma_{LT'} \sim Im(L^*T)$
  $= Re(L)Im(T) + Im(L)Re(T)$

  – Amplify resonance multipole by a large background amplitude



K. Joo et al. (CLAS Collaboration), Phys. Rev. C 72, 058202 (2005)
K. Joo et al. (CLAS Collaboration), Phys. Rev. C 70, 042201 (2004)
K. Joo et al. (CLAS Collaboration), Phys. Rev. C 68, 032201 (2003)

Power of Interference (sensitivity to $P_{11}(1440)$)



$\vec{e}p \rightarrow e\pi^+ n$

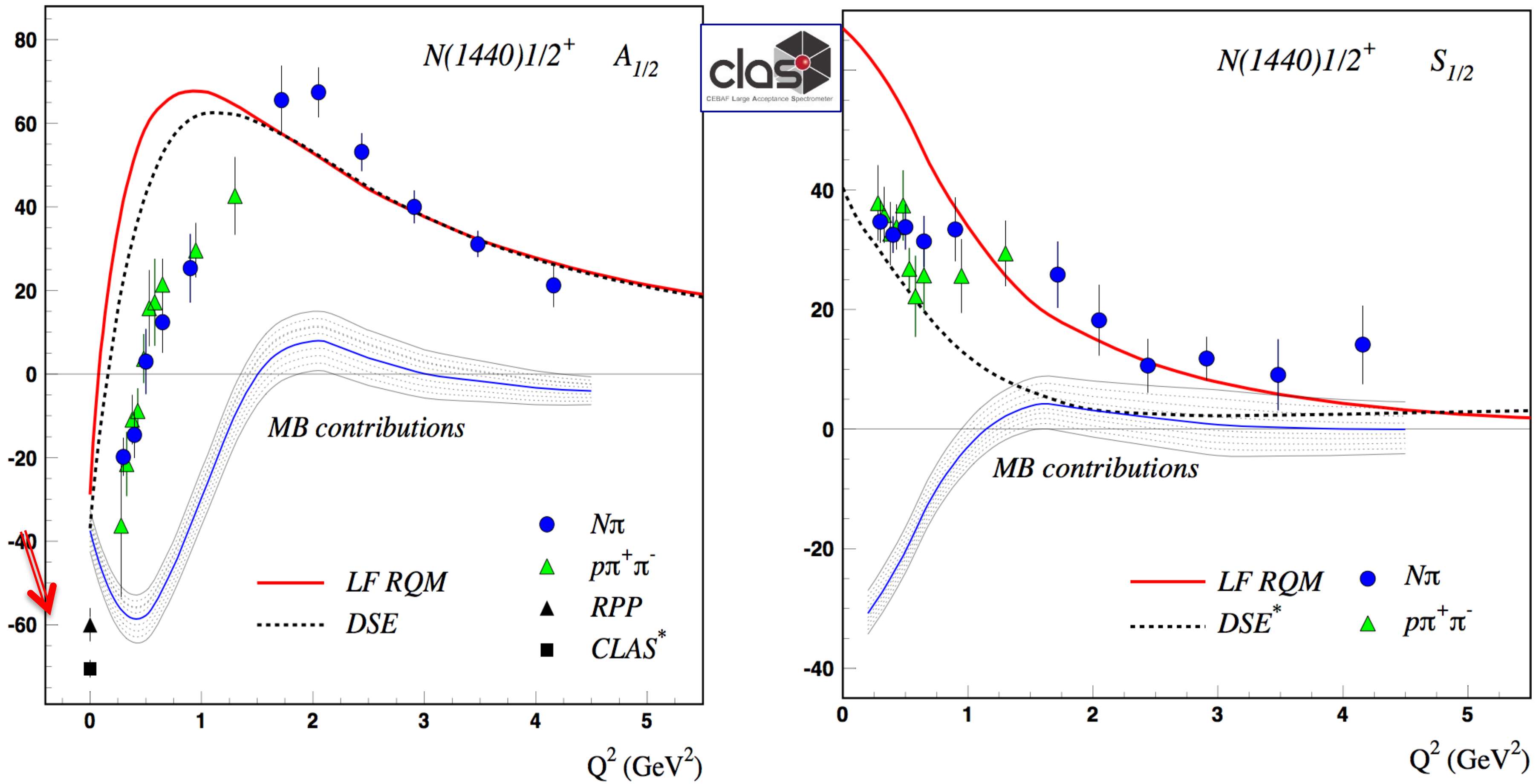
$\sigma_{LT'}$ structure function is sensitive to imaginary part of $P_{11}(1440)$ through interference with real non resonant background.

K. Joo et al. (CLAS Collaboration), Phys. Rev. C 72, 058202 (2005)
K. Joo et al. (CLAS Collaboration), Phys. Rev. C 70, 042201 (2004)
K. Joo et al. (CLAS Collaboration), Phys. Rev. C 68, 032201 (2003)

Solving the Roper N(1440)1/2$^+$ Puzzle

DSE: J. Segovia et al., PRL 115 (2015); 1504.04386

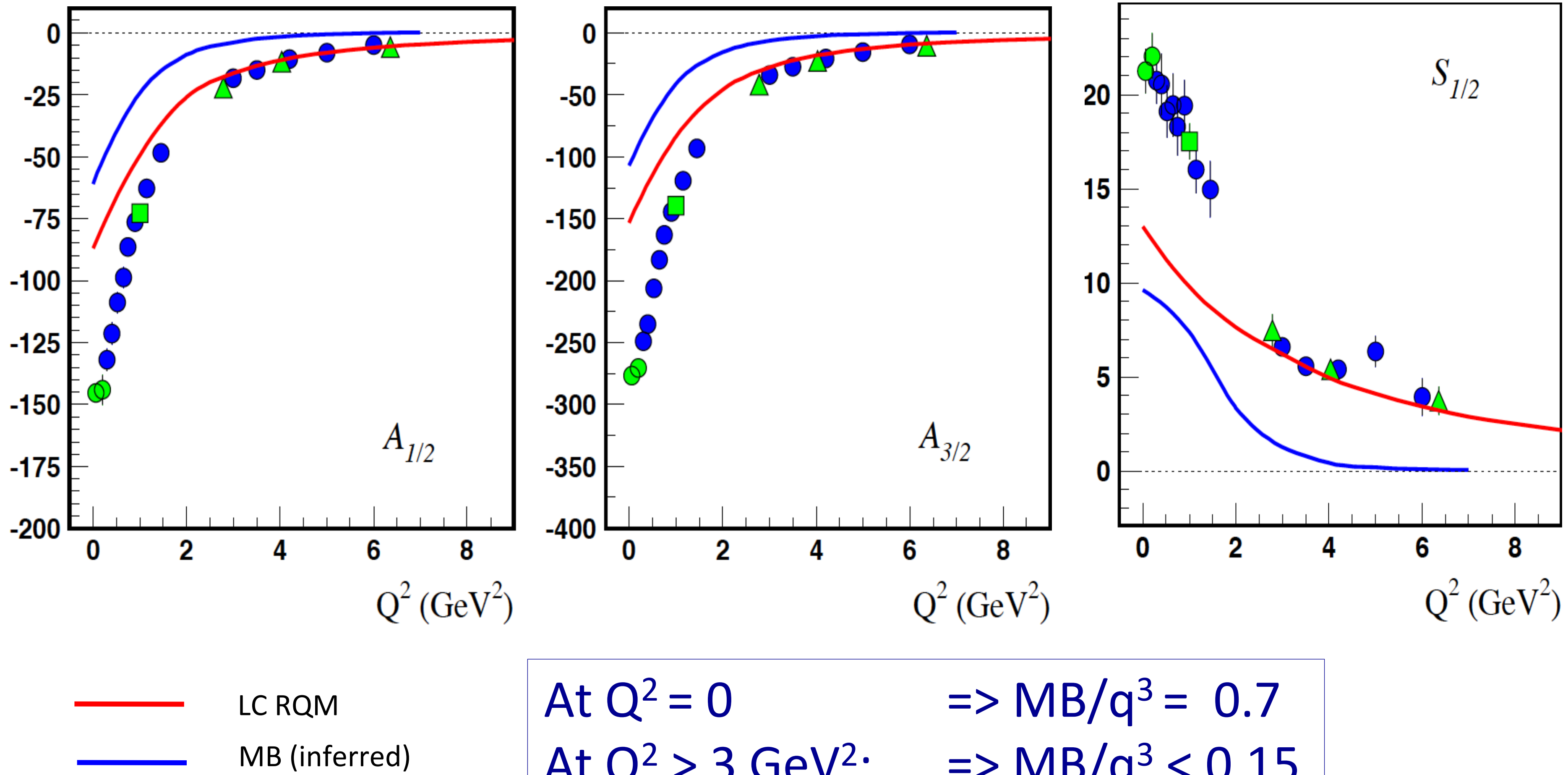
LF RQM: I. Aznauryan, V.B., 1603.06692



- Importance of MB at $Q^2 < 1.5 GeV^2$. Quark core contributions dominate at $Q^2 > 2 GeV^2$

The 1st radial excitation of the 3-quark core seen when the probe penetrates the MB cloud.

q^3 and MB contributions in NΔ(1232)



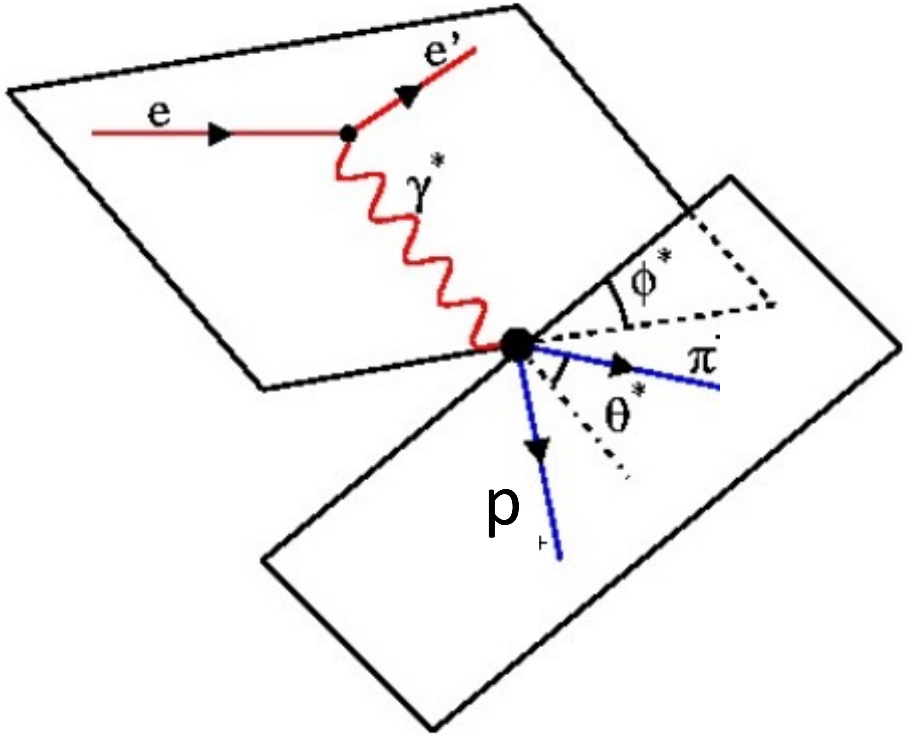
At $Q^2 = 0$ => $MB/q^3 = 0.7$

At $Q^2 > 3$ GeV^2: => $MB/q^3 < 0.15$

Exclusive Electroproduction x-section and BSA

Cross section (longitudinally pol. beam and unpol. target

$$2\pi \frac{d^2\sigma}{dt d\phi} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \cdot cos(2\phi) \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cdot cos(\phi) \frac{d\sigma_{LT}}{dt} + h \cdot \sqrt{2\epsilon(1-\epsilon)} \cdot sin(\phi) \frac{d\sigma_{LT'}}{dt}$$



Beam Spin Asymmetry:

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Multipoles, CGLN Amplitudes and Structure Functions

G. Knöchlein, D. Drechsel, L. Tiator, Z.Phys.A352:327-343,1995; arXiv:nucl-th/9506029v1

$$
\begin{aligned}
{}^{c}R^{00}_{TL} &= \sin\Theta \mathrm{Re}\{-F_2^*F_5 - F_3^*F_5 - F_1^*F_6 - F_4^*F_6 \\
&\quad - \cos\Theta\,(F_4^*F_5 + F_3^*F_6)\}\,, \\
{}^{s}R^{00}_{TL'} &= -\sin\Theta \mathrm{Im}\{F_2^*F_5 + F_3^*F_5 + F_1^*F_6 + F_4^*F_6 \\
&\quad + \cos\Theta\,(F_4^*F_5 + F_3^*F_6)\}\,,
\end{aligned}
$$

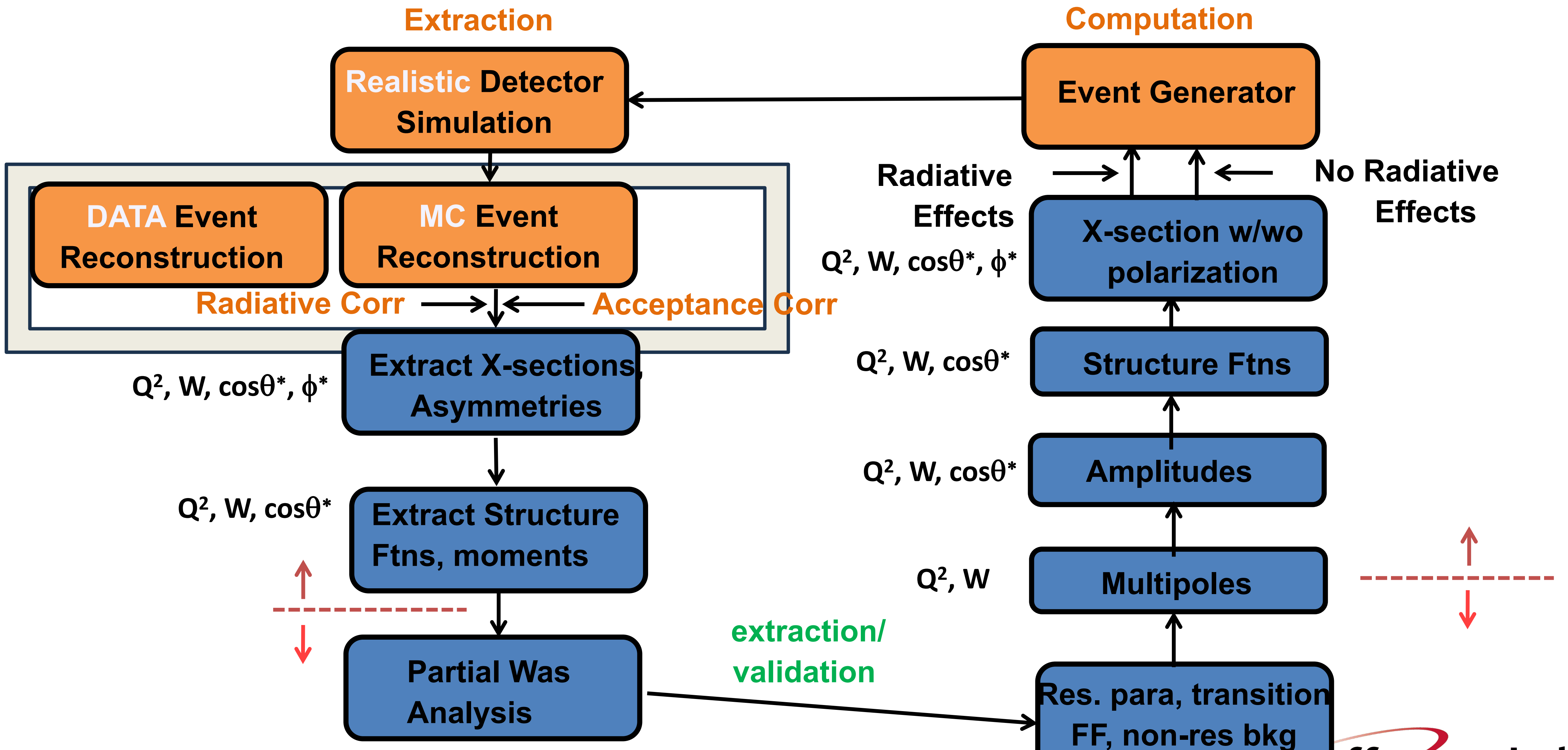
$$
\begin{aligned}
F_1 &= \sum_{l\geq 0}\{(M_{l+} + E_{l+})\,P'_{l+1} \\
&\quad + [(l+1)\,M_{l-} + E_{l-}]\,P'_{l-1}\}\,, \\
F_2 &= \sum_{l\geq 1}[(l+1)\,M_{l+} + lM_{l-}]\,P'_l\,, \\
F_3 &= \sum_{l\geq 1}[(E_{l+} - M_{l+})\,P''_{l+1} \\
&\quad + (E_{l-} + M_{l-})\,P''_{l-1}]\,, \\
F_4 &= \sum_{l\geq 2}(M_{l+} - E_{l+} - M_{l-} - E_{l-})\,P''_l\,, \\
F_5 &= \sum_{l\geq 0}[(l+1)\,L_{l+}P'_{l+1} - lL_{l-}P'_{l-1}]\,, \\
F_6 &= \sum_{l\geq 1}[lL_{l-} - (l+1)L_{l+}]\,P'_l\,.
\end{aligned}
$$

$$
\begin{aligned}
E_{l+} &= \frac{1}{l+1}A_{l+} + \frac{l}{2(l+1)}B_{l+}\,, \\
E_{l-} &= -\frac{1}{l}A_{l-} + \frac{l+1}{2l}B_{l-}\,, \\
M_{l+} &= \frac{1}{l+1}A_{l+} - \frac{l+2}{2(l+1)}B_{l+}\,, \\
M_{l-} &= \frac{1}{l}A_{l-} + \frac{l-1}{2l}B_{l-}\,, \\
S_{l+} &= \frac{1}{l+1}C_{l+}\,, \\
S_{l-} &= -\frac{1}{l}C_{l-}\,.
\end{aligned}
$$

$$
\begin{aligned}
A_{l\pm} &= \pm K A^N_{1/2}, \\
B_{l\pm} &= \mp K\sqrt{\frac{4}{l(l+2)}}A^N_{3/2}, \\
C_{l\pm} &= \pm K C^N_{1/2}.
\end{aligned}
$$

$$
K = \sqrt{\frac{k_\gamma^{cm}}{|\vec{k}|}\frac{m}{W}\frac{\Gamma_\eta}{\pi\,(2J+1)}}\frac{M^*}{M^{*2} - W^2 - iW\Gamma}.
$$

Data Analysis Frame Work



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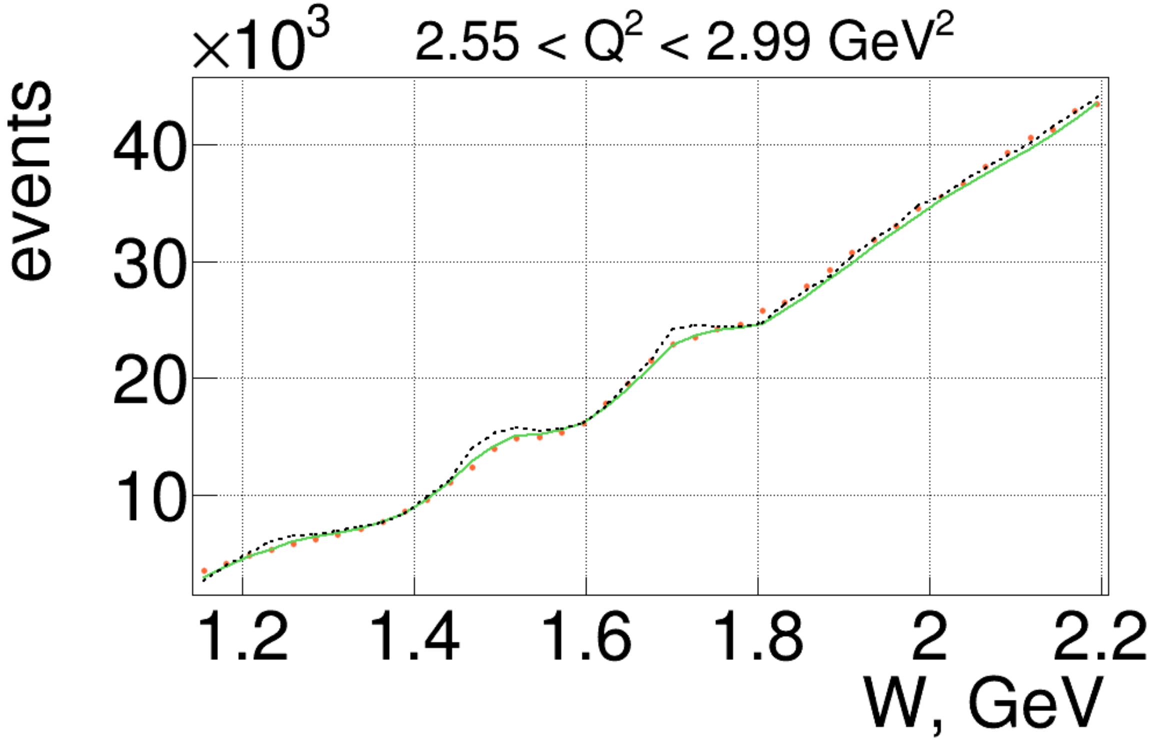
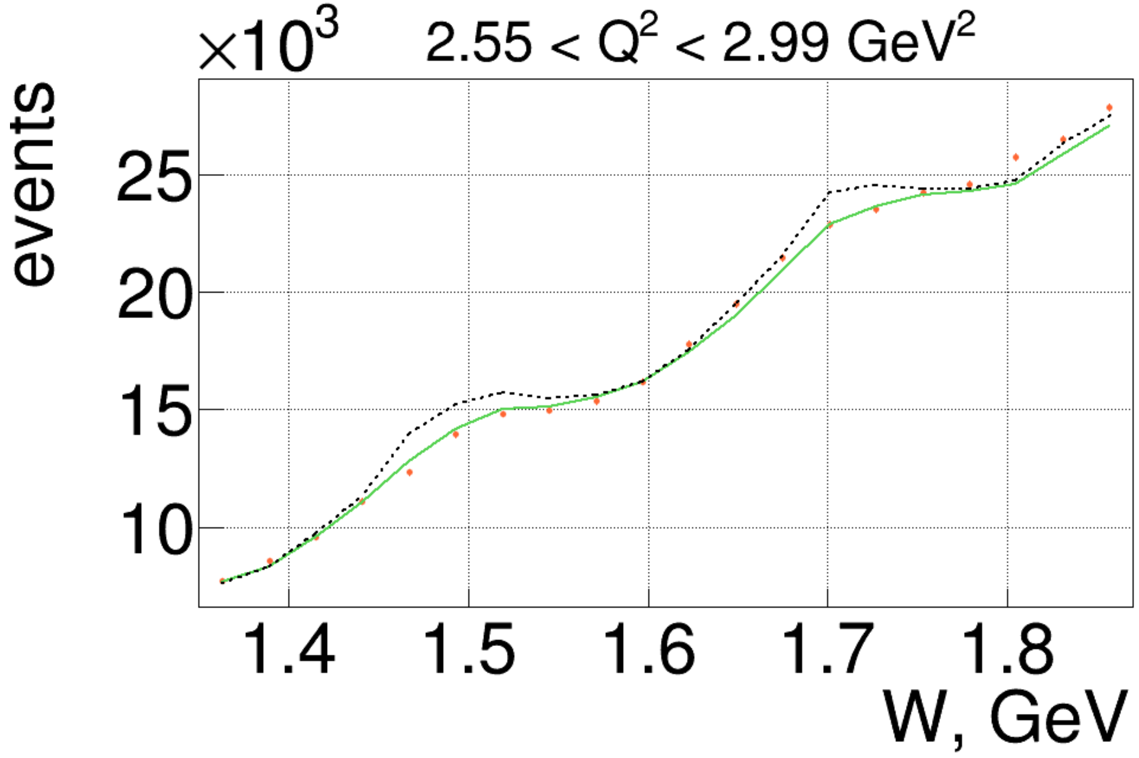
Inclusive Data Analysis from 10.6 GeV with CLAS12

W yield in Q^2 bins, Normalization to integral

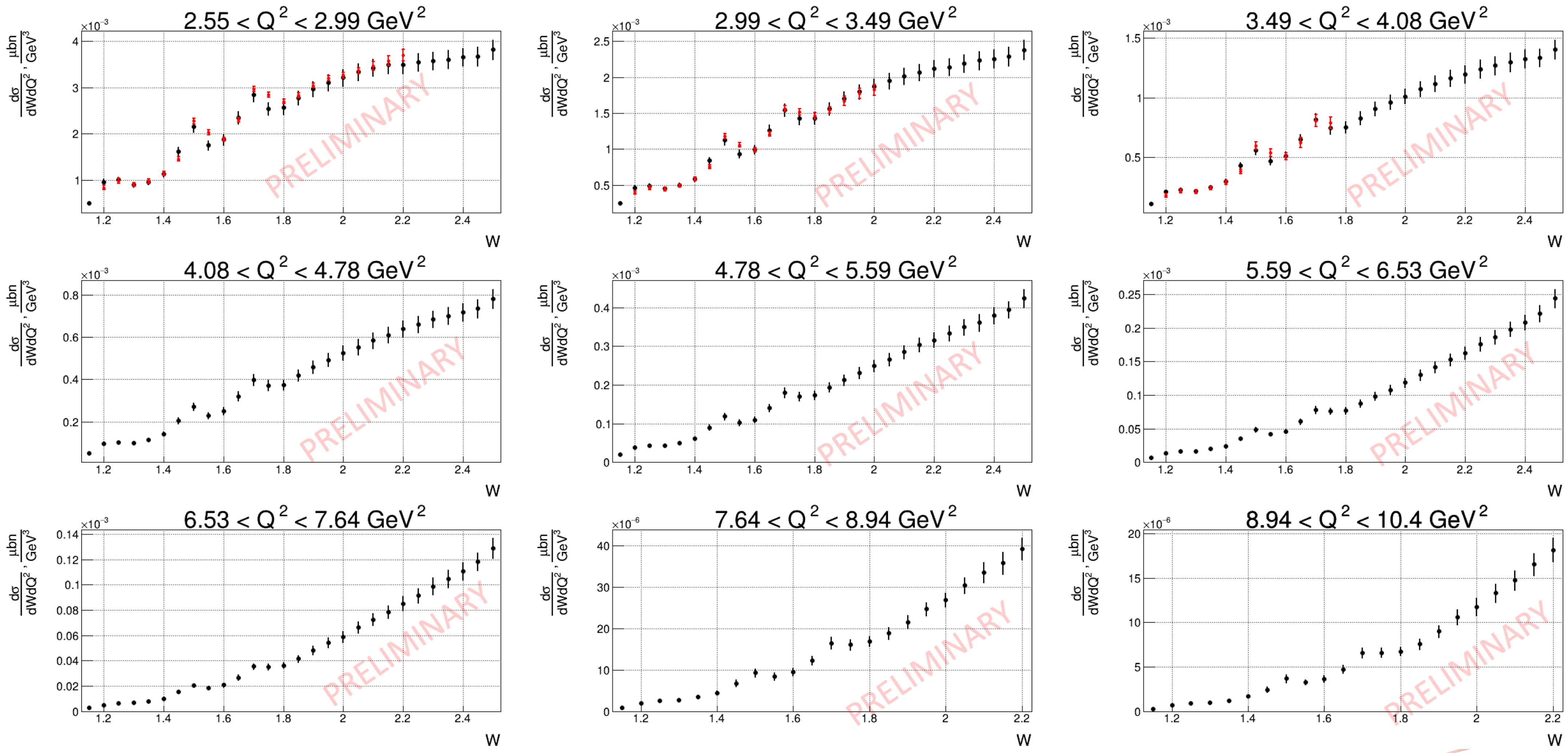
- **Orange** – Data
- **Black Dashed Line** – MC no smearing
- **Green** – F = 0.8 smearing



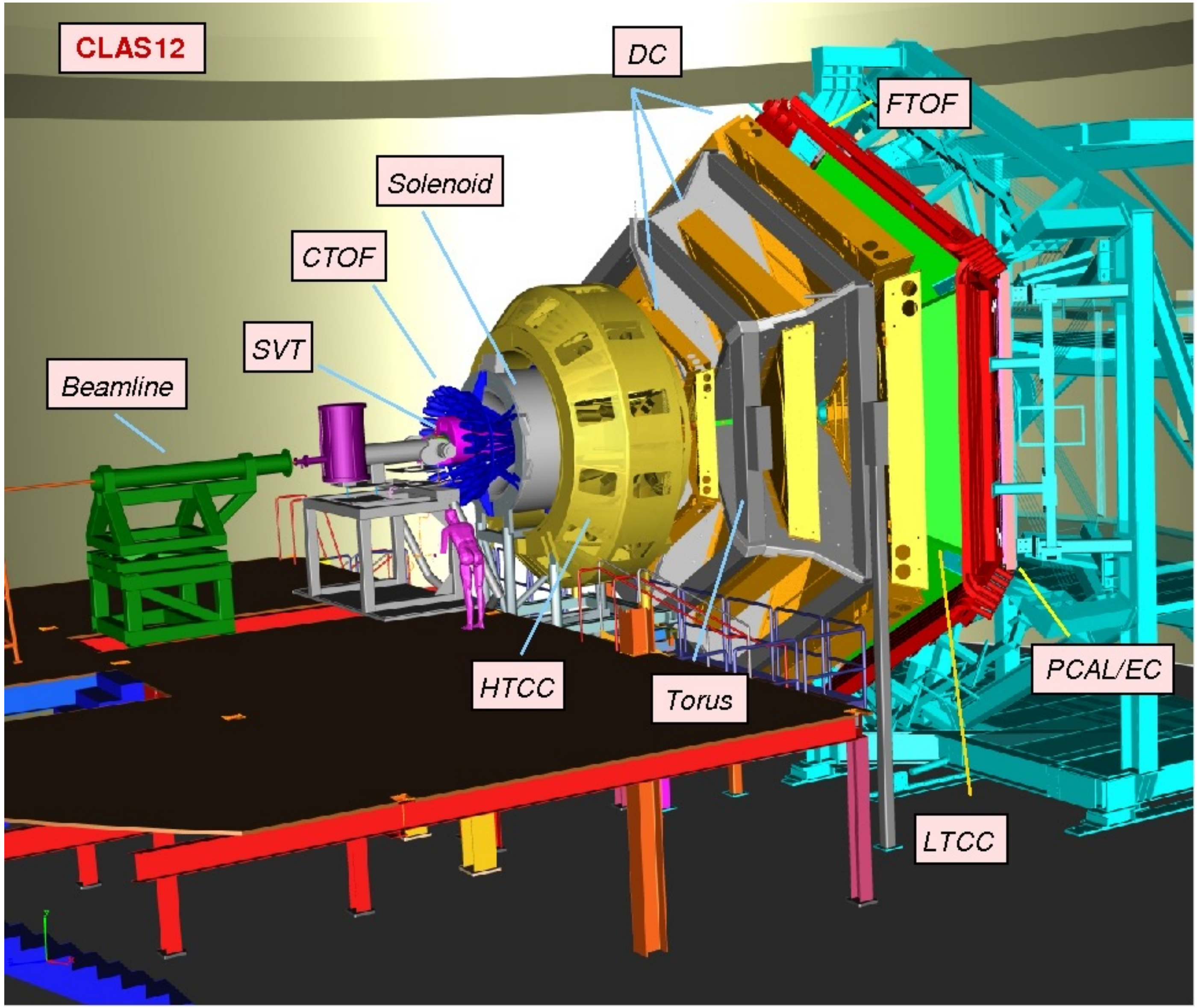


Inclusive Cross Sectioins from 10.6 GeV with CLAS12

- Preliminary CLAS12 measurements.
- CLAS data (after interpolation into the grid of our experiment), Phys. Rev. D67, 092001 (2003).



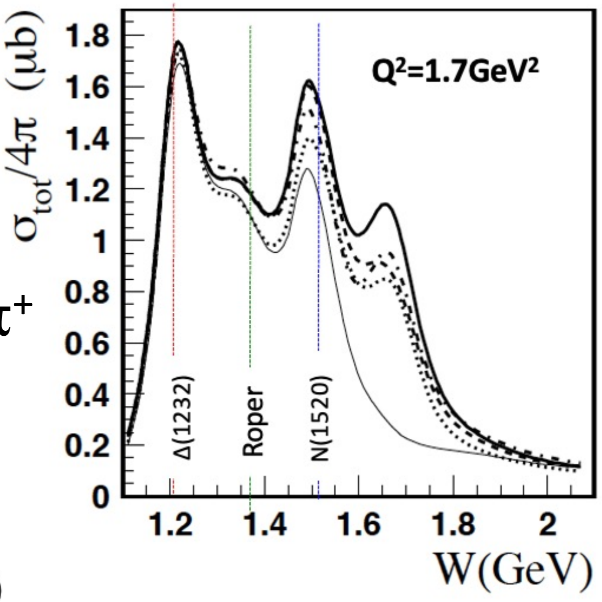
CLAS12 N* Program

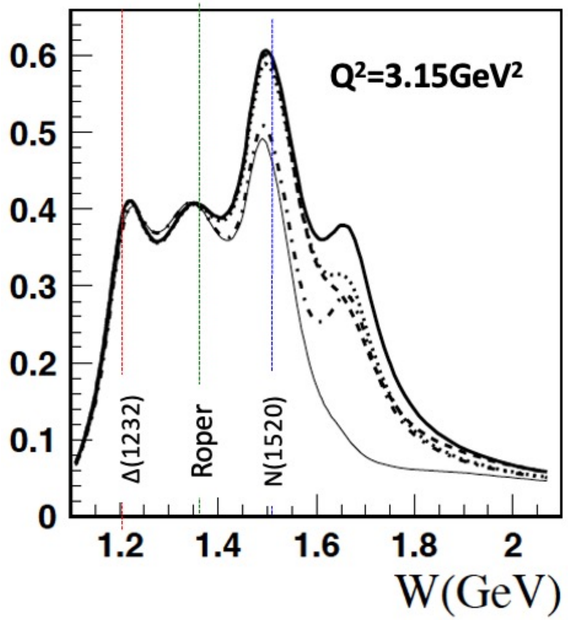


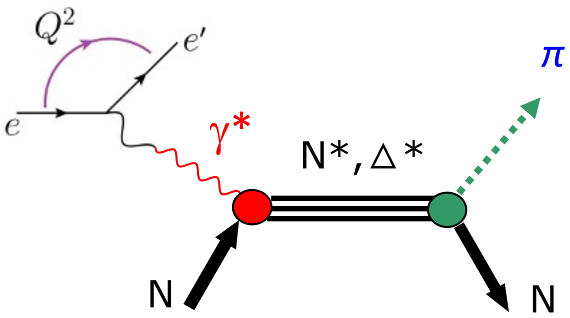
- Extend the Q2 to a higher range.
- Study the hyper-baryon program.
- Map out the transition of strong QCD to pertubative QCD
- Extend to Transition GPDs

ep->enπ$^+$ vs. ep->eγnπ$^+$

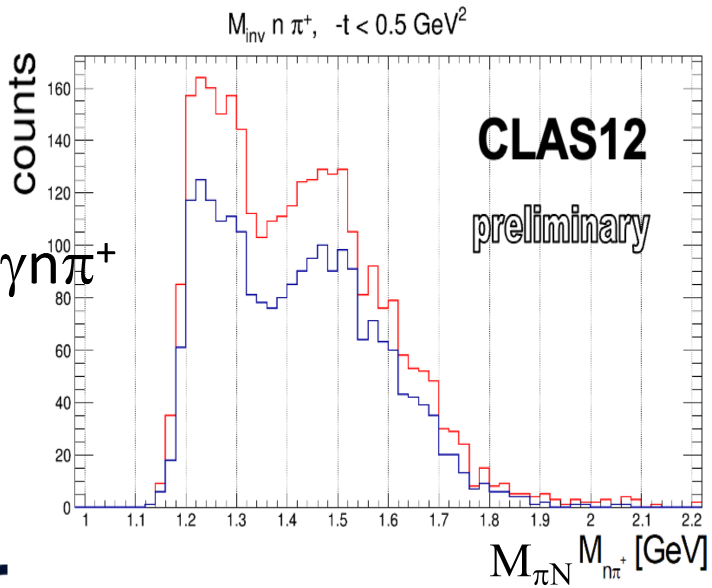
ep->enπ$^+$

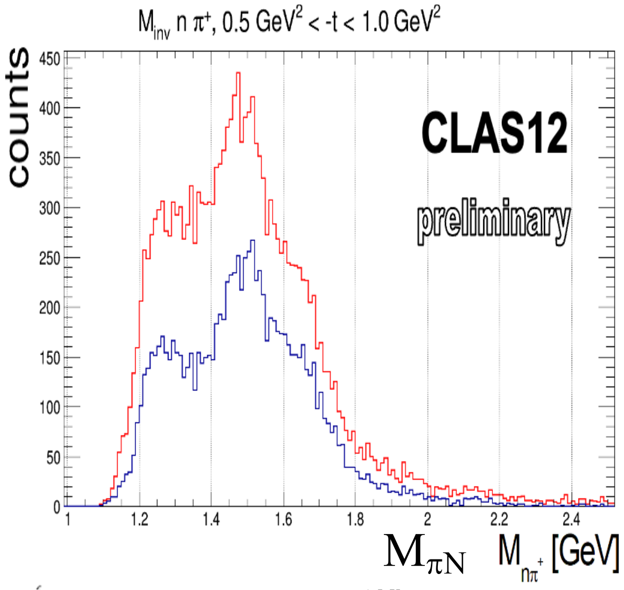




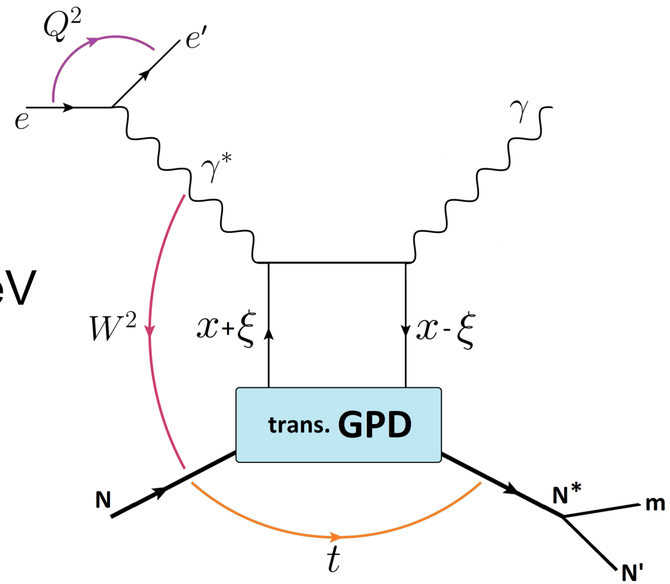


ep->eγnπ$^+$





W > 2 GeV



Electron scattering binning scheme

	Resonance Region	DIS Region
Inclusive Scattering	Q^2, W	Q^2, x_B
Exclusive Process (γ, π, ρ, ϕ, …)	Q^2, W, $\cos\theta^*$, ϕ^*	Q^2, x_B, -t, ϕ^*
Off-diagonal DVCS or DVMP	Q^2, x_B, -t, ϕ^*, $M_{\pi N}$, $\cos\theta_{cm}$, ϕ_{cm}	

Summary

- First high precision photo- and electroproduction data have become available and led to a new wave of significant developments in N* program.
- Large amounts of high precision data and multi-channel PWA have been essential in the discovery of new N* resonances.
- Electroexcitation of nucleon resonances are sensitive to the effective degrees of freedom versus distance scale.

Transition Form Factors (N* Physics) at 6 GeV JLab Era → Transition GPDs (3D N* Physics) at 12-22 GeV JLab Era

Establishing the N* spectrum

Photon	Target				Recoil			Target + Recoil			
	–	–	–	–	x'	y'	z'	x'	x'	z'	z'
	–	x	y	z	–	–	–	x	z	x	z
transverse unpolarized (T)	σ_0	0	T	0	0	P	0	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
transverse (linear pol.) (TT)	$-\Sigma$	H	$(-P)$	$-G$	$O_{x'}$	$(-T)$	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(-L_{x'})$	$(-T_{x'})$
transverse (circular pol.) (TT')	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0