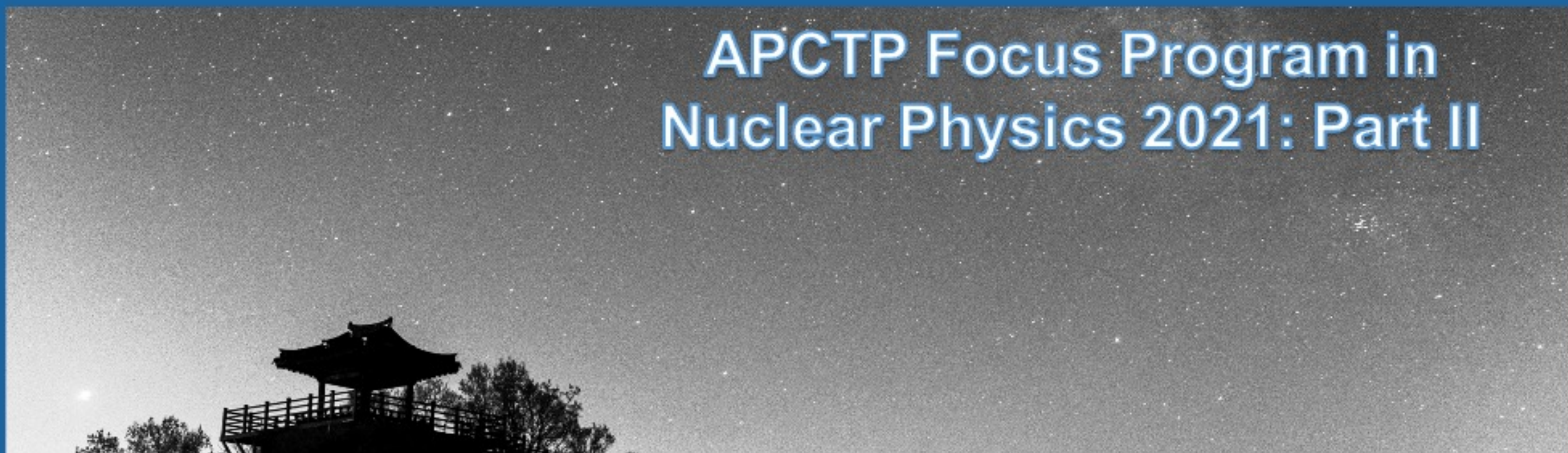
Space-like and Time-like Form Factors in Nucleon Resonance Production II



APCTP Focus Program in Nuclear Physics 2021 Part II: Science Opportunities with EIC

Asia Pacific Center for Theoretical Physics

apctp asia pacific center for theoretical physics

NSF

- PHY-1615146
- PHY-2012826

FULBRIGHT Association

Philip Cole
Lamar University

LAMAR UNIVERSITY

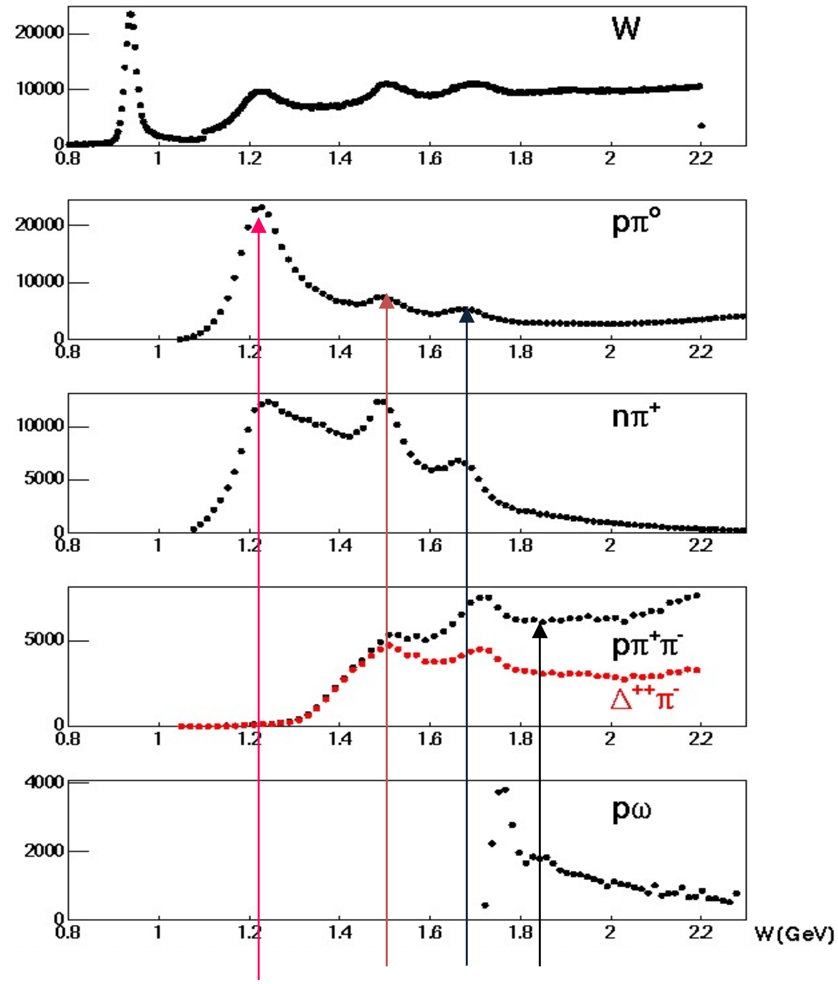
July 21, 2021

Why Nπ/Nππ electroproduction channels are important

- **Nπ/Nππ channels are the two major contributors in N* excitation region;**
- **these two channels combined are sensitive to almost all excited proton states;**
- **they are strongly coupled by πN→ππN final state interaction;**
- **may substantially affect exclusive channels having smaller cross sections, such as ηp, KΛ, and KΣ.**

Therefore, knowledge on Nπ/Nππ electroproduction mechanisms is key for the entire N* Program

CLAS data on meson electroproduction at $Q^2 < 4.0$ GeV²



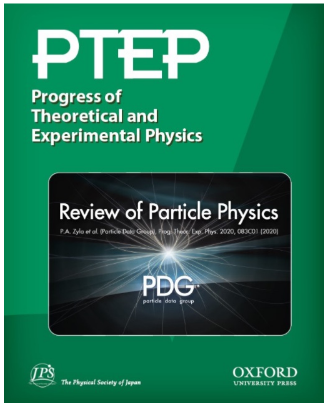
Where have all the πs gone?

Particle J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N $1/2^+$	****										
$N(1440)1/2^+$	****	****	****	****	***						
$N(1520)3/2^-$	****	****	****	****	**	****					
$N(1535)1/2^-$	****	****	****	***	*	****					
$N(1650)1/2^-$	****	****	****	***	*	****	*				
$N(1675)5/2^-$	****	****	****	****	***	*	*	*			
$N(1680)5/2^+$	****	****	****	****	***	*	*	*			
$N(1700)3/2^-$	***	**	***	***	*	*			*		
$N(1710)1/2^+$	****	****	****	*		***	**	*	*	*	
$N(1720)3/2^+$	****	****	****	***	*	*	****	*	*	*	
$N(1860)5/2^+$	**	*	**		*	*					

No Data?

$N(1440)\ 1/2^+$

Decay Modes



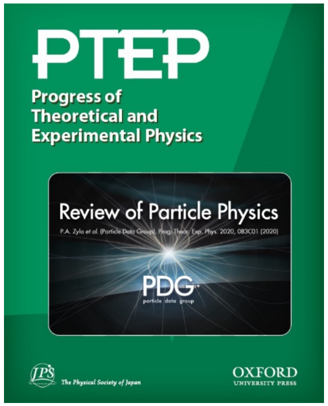
$N(1440)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	55–75 %
Γ_2	$N\eta$	<1 %
Γ_3	$N\pi\pi$	17–50 %
Γ_4	$\Delta(1232)\pi$, P-wave	6–27 %
Γ_5	$N\sigma$	11–23 %
Γ_6	$p\gamma$, helicity=1/2	0.035–0.048 %
Γ_7	$n\gamma$, helicity=1/2	0.02–0.04 %

$N(1520)\ 3/2^-$

Decay Modes



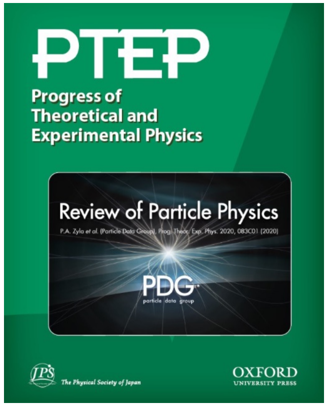
$N(1520)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	55–65 %
Γ_2	$N\eta$	0.07–0.09 %
Γ_3	$N\pi\pi$	25–35 %
Γ_4	$\Delta(1232)\pi$	22–34 %
Γ_5	$\Delta(1232)\pi$, S-wave	15–23 %
Γ_6	$\Delta(1232)\pi$, D-wave	7–11 %

$N(1535)\ 1/2^-$

Decay Modes



N(1535) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	32–52 %
Γ_2	$N\eta$	30–55 %
Γ_3	$N\pi\pi$	3–14 %
Γ_4	$\Delta(1232)\pi$	
Γ_5	$\Delta(1232)\pi$, D-wave	1–4 %
Γ_6	$N\rho$	
Γ_7	$N\rho$, S=1/2	
Γ_8	$N\rho$, S=3/2 , D-wave	
Γ_9	$N\sigma$	2–10 %
Γ_{10}	$N(1440)\pi$	5–12 %
Γ_{11}	$p\gamma$, helicity=1/2	0.15–0.30 %
Γ_{12}	$n\gamma$, helicity=1/2	0.01–0.25 %

Space-Like is not the whole story….

Where are we in understanding the time-like and space-like divide?

- Photon/electron beams
- Pion beams
- Electron/positron collisions

PHYSICAL REVIEW C **102**, 024001 (2020)

Two-pion production in the second resonance region in $\pi^- p$ collisions with the High-Acceptance Di-Electron Spectrometer (HADES)

The new data on the $\pi^- p \to \pi^+\pi^- n$ and $\pi^- p \to \pi^+\pi^- n$ reactions provide important information about decay properties of the resonances in the region of center-of-mass energies around 1.5 GeV. In particular, this is a unique source to study the decay properties of the resonances into the ρN channel.

ρ decay mode for the
N(1520) and N(1535)

Two-pion production in the second resonance region in $\pi^- p$ collisions with the High-Acceptance Di-Electron Spectrometer (HADES)

This new analysis should be particularly useful for the decay into the ρN channel BR $= 12.2\% \pm 1.9\%$ and BR $= 3.2\% \pm 0.7\%$ for the $N(1520)\frac{3}{2}^-$ and $N(1535)\frac{1}{2}^-$ resonances, respectively, as no information is available in the Review of Particle Physics [7].

Two-pion production for the N(1520) and N(1535)

Victor Mokeev's Talk

Nucleon Resonance Electrocouplings from Data On Exclusive Meson Electroproduction with CLAS

Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v pN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$	0.16-6.0 0.30-4.16
$\pi^+ n$	$N(1675)5/2^-$, $N(1680)5/2^+$ $N(1710)1/2^+$	1.6-4.5
ηp	$N(1535)1/2^-$	0.2-2.9
$\pi^+\pi^- p$	$N(1440)1/2^+$, $N(1520)3/2^-$ $\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$	0.25-1.50 2.0-5.0 (preliminary) 0.5-1.5

- The N* electroexcitation amplitudes ($\gamma_v pN^*$ electrocouplings) in a broad range of Q^2 offer a unique opportunity to explore universality on environmental sensitivity of dressed quark mass function
- Consistent results on dressed quark mass function from $\gamma_v pN^*$ electrocouplings of different resonances validate insight into EHM in a nearly model-independent way

Jefferson Lab

V.I. Mokeev, Science Opportunities with EIC, APCTP Workshop, July 19-24, 2021 9

The Puzzle of the Proton

- ECT* Workshops are a start (May 2017 + Sept. 2019)
- Special topic session (for NSTAR 2017 and NSTAR 2019) is a start
- GSI Workshop on Electromagnetic Structure of Strange Baryons (Oct. 2018) is a start
- The US-Japan Collaboration (JPARC/JLab) White Paper is a start.
- The workshop on Baryon Production at BESIII (Sept 2019, Hefei, PRC) is a start.
- This workshop is a start.

At some point, we must go beyond the starting point for unraveling the SL/TL conundrum of excited baryons

LOI: NSF PIRE Submitted: Sept 8, 2016

PIRE: Emergent Structures from Quarks and Gluons

Request: $5,000,000
Length of Study: 5 Years
Lead Institution: Idaho State University

PI/CoPIs:

Philip L. Cole (*PI and Program Manager, Professor of Physics*)
Department of Physics, Idaho State University, Pocatello, ID 83209

Chaden Djalali (*CoPI, Dean of the College of Liberal Arts & Sciences, Professor of Physics*)
Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242

Michael Doring (*CoPI, Asst. Professor of Physics*)
Department of Physics, George Washington University, Washington, DC 20052

Ralf W. Gothe (*CoPI, Professor of Physics*)
Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208

Kenneth Hicks (*CoPI, Professor of Physics*)
Department of Physics & Astronomy, Ohio University, Athens, OH 45701

Kyungseon Joo (*CoPI, Professor of Physics*)
Department of Physics, University of Connecticut, Storrs, CT 06269

Huey-Wen Lin (*CoPI, Asst. Professor of Physics*)
Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48823

Foreign Collaborators:

Anthony Thomas (*Australian Liaison, Professor, Director*), **Derek Leinweber** (*Professor*), **Waseem Kamleh** (*Asst. Professor*) Centre for the Subatomic Structure of Matter, University of Adelaide, SA 5005, Australia

Béatrice Ramstein (*French Liaison, Research Physicist*), Institut Physique Nucléaire, Orsay, France

Hartmut Schmieden (*German Liaison, Prof. Dr.*), Universität Bonn, Physikalisches Institut
Reinhard Beck (*Prof. Dr.*), **Bernhard Ketzer** (*Prof. Dr.*), **Ulrike Thoma** (*Prof. Dr.*) Universität Bonn, Helmholtz-Institut für Strahlen- und Kernphysik Bonn, Germany
Michael Ostrick (*Prof. Dr.*) Universität Mainz, Institut für Kernphysik, Mainz, Germany
Vladimir Braun (*Prof. Dr.*) Universität Regensburg, Fakultät Physik, Regensburg, Germany
Joachim Stroth (*Prof. Dr.*) Goethe-Universität, Institut für Kernphysik, Frankfurt am Main, Germany

Hiroyuki Sako (*Japanese Liaison, Dr. Principle Researcher*), **Makoto Oka** (*Group Leader, Professor*), Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Japan.
Takashi Nakano (*Professor, RCNP Director*), **Toru Sato** (*Professor*) Dept. of Physics, Osaka University, Osaka, Japan
Hiroyuki Kamano ((*Research Associate*) Theory Center, Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

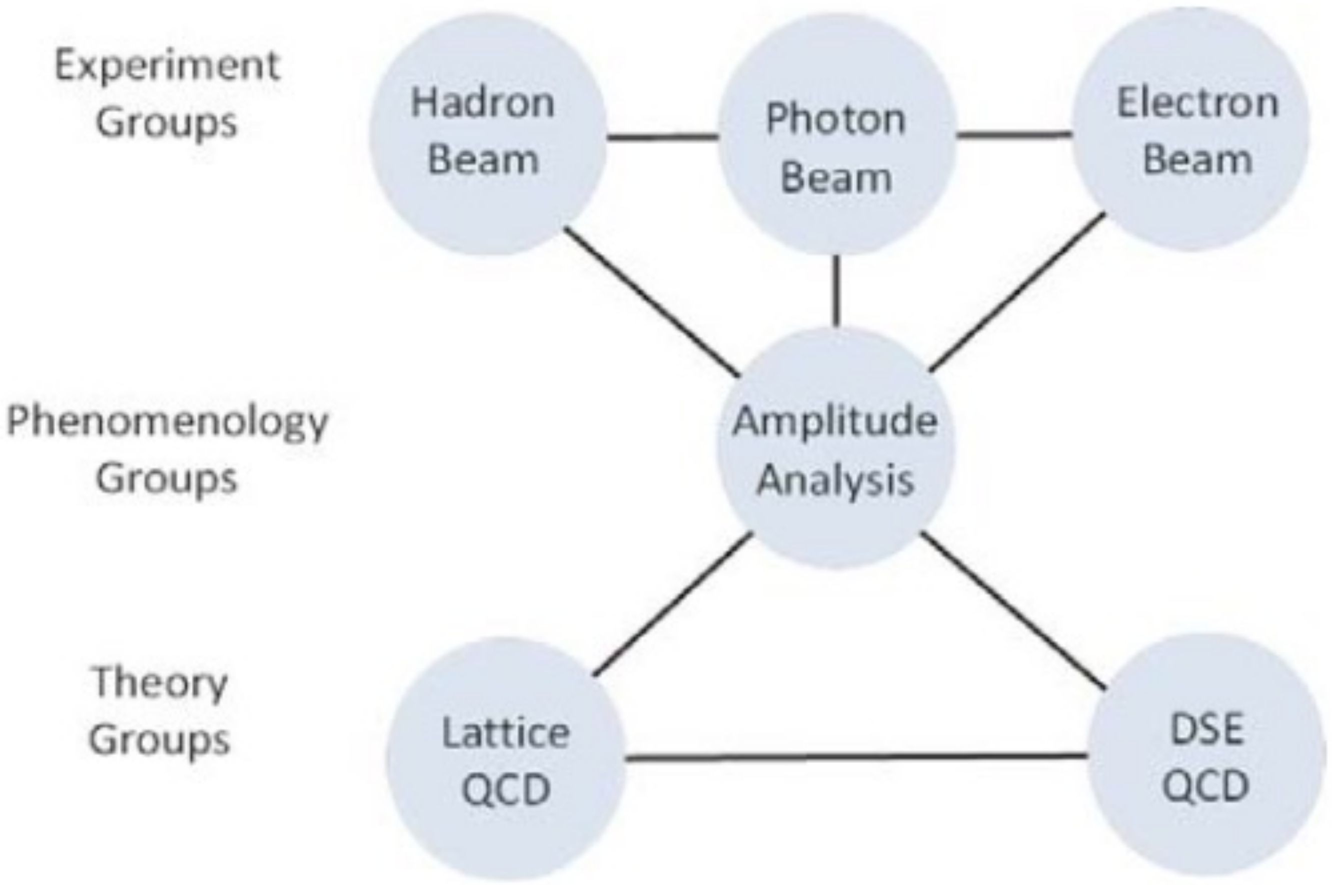
Jung Keun Ahn (*South Korean Liaison, Professor*), Korea University, Seoul, South Korea
Yongseok Oh (*Professor*) Kyungpook National University, Daegu, South Korea

Senior Personnel:

Volker D. Burkert (*Hall B Leader*), **Latifa Elouadrhiri** (*Assistant Project Manager, 12 GeV Upgrade – Hall B*), **Victor I. Mokeev** (*Hall B Staff Scientist II*) TJNAF (JLab), Newport News, VA 23606

William Briscoe (*Professor and Chair of Physics*), **Helmut Haberzettl** (*Professor of Physics*)
Igor Strakovsky (*Research Professor*), **Ronald Workman** (*Research Professor*)
Department of Physics, George Washington University, Washington, DC 20052

Craig Roberts (*Senior Physicist, Group Leader*), **Tsung-Shung Harry Lee** (*Senior Physicist*)
Physics Division, Argonne National Laboratory, Argonne, IL 60439



Research Organizational Chart.

Experimental/Theory/Phenomenology for $q^2 < 0$, $q^2 = 0$, $q^2 > 0$ (space-like/photon/time-like)

1. Perform $\gamma N \rightarrow \pi N$, $\gamma N \rightarrow \pi\pi N$, $\gamma N \rightarrow KY$ measurements at photon beam facilities such as Bonn [3] and Mainz [4] in Germany and SPRING-8/LEPS [5] in Japan, which would be essential in establishing the nucleon excitation spectrum. These efforts will be led by the *Photon Beam Group*;

Lab in U.S., which would be essential in establishing the structure of the excited nucleons through space-like transition form factors. These efforts [6] will be led by the *Electron Beam Group*;

2. Perform $\gamma^* N \rightarrow \pi N$, $\gamma^* N \rightarrow \pi\pi N$, $\gamma^* N \rightarrow KY$ measurements in an electron beam facility, i.e. Jefferson Lab in U.S., which would be essential in establishing the structure of the excited nucleons through space-like transition form factors. These efforts [6] will be led by the *Electron Beam Group*;

3. Perform $\pi N \rightarrow \pi N$, $\pi N \rightarrow \pi\pi N$, $\pi N \rightarrow KY$ measurements in a hadron beam facility such as J-PARC in Japan [7], which would be essential in establishing the nucleon excitation spectrum, and are complementary to measurements in photon beam and electron beam facilities [8]. Also perform the leptonic pair (e^+e^-) in Dalitz decay measurements in a hadron beam facility such as HADES in Germany, which would be essential in determining time-like transition form factors [9]. These efforts will be led by the *Hadron Beam Group*;

4. Perform amplitude analyses to establish the nucleon excitation spectrum as well as reaction models simultaneously using all experimental data from photon beam, electron beam, and hadron beam facilities. Also determine space-like and time-like transition form factors. These efforts will be led by the *Partial Wave Analysis (PWA)/Amplitude Analysis Group*;
5. Perform Lattice QCD calculations on the nucleon excitation spectrum, transition form factors (including multi-hadron states) as well as dressed quark mass function [6,10]. These efforts will be led by the *Lattice QCD Group*; and
6. Refine the dressed-quark mass function by calculating elastic and space-like/time-like transition form factors via Dyson-Schwinger Equation (DSE) approach and comparing them with experimental results. These efforts will be led by the *DSE QCD Group* [6,10,11,12].

Experimental/**Theory**/**Phenomenology** for $q^2 < 0$, $q^2 = 0$, $q^2 > 0$ (space-like/photon/time-like)

To achieve our research goals, the N* PIRE group will perform the following six research activities:

1. Perform $\gamma N \to \pi N$, $\gamma N \to \pi\pi N$, $\gamma N \to KY$ measurements at photon beam facilities such as Bonn [3] and Mainz [4] in Germany and SPRING-8/LEPS [5] in Japan, which would be essential in establishing the nucleon excitation spectrum. These efforts will be led by the *Photon Beam Group*;
2. Perform $\gamma^* N \to \pi N$, $\gamma^* N \to \pi\pi N$, $\gamma^* N \to KY$ measurements in an electron beam facility, i.e. Jefferson Lab in U.S., which would be essential in establishing the structure of the excited nucleons through space-like transition form factors. These efforts [6] will be led by the *Electron Beam Group*;
3. Perform $\pi N \to \pi N$, $\pi N \to \pi\pi N$, $\pi N \to KY$ measurements in a hadron beam facility such as J-PARC in Japan [7], which would be essential in establishing the nucleon excitation spectrum, and are

3

4. Perform amplitude analyses to establish the nucleon excitation spectrum as well as reaction models simultaneously using all experimental data from photon beam, electron beam, and hadron beam facilities. Also determine space-like and time-like transition form factors. These efforts will be led by the *Partial Wave Analysis (PWA)/Amplitude Analysis Group*;

5. Perform Lattice QCD calculations on the nucleon excitation spectrum, transition form factors (including multi-hadron states) as well as dressed quark mass function [6,10]. These efforts will be led by the *Lattice QCD Group*; and

models simultaneously using all experimental data from photon beam, electron beam, and hadron

6. Refine the dressed-quark mass function by calculating elastic and space-like/time-like transition form factors via Dyson-Schwinger Equation (DSE) approach and comparing them with experimental results. These efforts will be led by the *DSE QCD Group* [6,10,11,12].

form factors via Dyson-Schwinger Equation (DSE) approach and comparing them with experimental results. These efforts will be led by the *DSE QCD Group* [6,10,11,12].

LOI "Crossing the boundaries to explore baryon resonances" was submitted Oct. 5, 2017 to the steering committee of the H2020 European Integrating Initiative in Hadron Physics.

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We live in exciting times where near-future prospects in extracting high-quality data will improve the knowledge of the spectrum of baryon resonances together with their space-like and time-like structure properties. In turn, this will help us clarify the role of in-medium properties of hadrons such as the origin of the perplexing excess of dilepton production. Bringing together experimental and theoretical groups into a joint enterprise in the form of a JRA is crucial to study and understand this interplay.

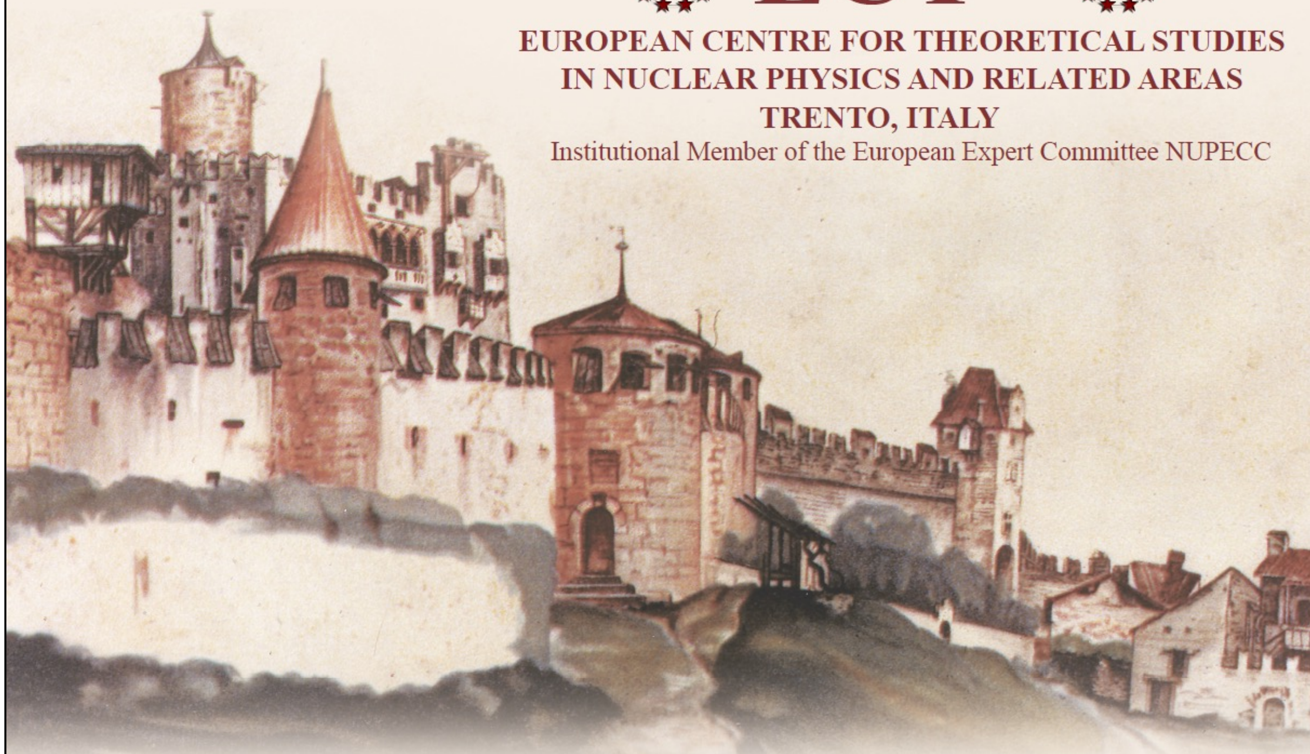
European Institutions	Non-European Institutions
IST ULisboa & LIP (Teresa Pena, Gernot Eichmann)	UNICSUL/Sao Paulo (Gilberto Ramalho)
University of Franfurt & GSI (Joachim Stroth)	Jefferson Lab (Viktor Mokeev)
TU Darmstadt & GSI (Tetyana Galatyuk)	University of South Carolina (Ralf Gothe)
IPN Orsay (Beatrice Ramstein)	Lamar University (Philip Cole)
JU Kraków (Piotr Salabura)	J-PARC (Hiroyuki Sako)
Uppsala University (Stefan Leupold, Karin Schönning)	Texas A&M University (Ralf Rapp)
JLU Gießen (Christian Fischer, Kai Brinkmann)	
University of Graz (Reinhard Alkofer, Hèlios Sanchis-Alepuz, Wolfgang Schweiger)	
Wigner RCP Budapest (Miklós Zétényi, Gyorgy Wolf)	
Forschungszentrum Jülich (James Ritman)	
Bonn-Gatchina (Andrey Sarantsev)	
ELSA (Hartmut Schmieden)	
FIAS (Hannah Petersen)	
INFN Genova (Elena Santopinto)	

We apply for a **total of 640K €** over 4 years:

Report on the ECT* Workshop:
Space-like and time-like electromagnetic baryonic transitions
https://indico.in2p3.fr/event/14330/overview

ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY
Institutional Member of the European Expert Committee NUPECC



Castello di Trento (“Trint”), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum, London

Space-like and time-like electromagnetic baryonic transitions
Trento, May 8 - 12, 2017

Reason for the Workshop

This ECT* workshop brought together several different experimental and theoretical communities, whose research

spans the kinematical regimes in q^2 between the *space-like* and *time-like* regions

- **$q^2 = 0$ [anchor point]** photon-beam (unpolarized & linearly- and circularly polarized experiments (ELSA, JLab, LEPS, & MAMI)
- **$q^2 > 0$ [time-like]** meson-beam experiments (GSI and J-PARC)
  proton-antiproton beam experiments (FAIR)
- **$q^2 < 0$ [space-like]** electron-beam experiments (JLab)

Our Research Vision

We sought to **bring together a representative sample of experimental, phenomenology, and theory groups**, who are working on the nucleon resonance problem.

- Discuss the direction on the study of understanding the underlying structure of nucleons in terms of the **time-like** and **space-like** electromagnetic **baryonic form factors** and **transitions**;
- Delineate the spectrum of excited baryon states;
- Describe and detail how quarks are confined and acquire mass through the mechanism of dynamical chiral symmetry breaking.

Confirmed Speakers at ECT* (SL/TL) and at NSTAR 2019

- Daniele Binosi (ECT* Trento)
- Vladimir Braun (University of Regensburg)
- William Briscoe (George Washington University)
- Susanna Costanza (University of Pavia)
- Annalisa D'Angelo (University of Rome)
- Michael Döring (George Washington University)
- Christian Fischer (University of Giessen)
- Bengt Friman (TU Darmstadt)
- Tetyana Galatyuk (TU Darmstadt)
- Leonid Glozman (University of Graz)
- Ralf Gothe (University of South Carolina)
- Kyungseon Joo (University of Connecticut)
- Helmut Haberzettl (George Washington University)
- Hiroyuki Kamano (Osaka University)
- Eberhard Klempt (University of Bonn)
- Stefan Leupold (Uppsula University)

- Victor Nikonov (University of Bonn and PNPI, Gatchina)
- Teresa Peña (IST Lisbon)
- Ralph Rapp (Texas A&M University)
- Hiroyuki Sako (JAEA)
- Piotr Salabura (Jagiellonian University in Krakow)
- Hartmut Schmieden (University of Bonn)
- Karin Schönning (Uppsula University)
- Federico Scozzi (IPN Orsay and TU Darmstadt)
- Kirill Semenov-Tyan-Shanskiy *(PNPI, Gatchina)*
- Igor Strakovsky (George Washington University)
- Joachim Stroth (Goethe University Frankfurt)
- Annika Thiel (University of Bonn)
- Lothar Tiator (University of Mainz)
- Ralf-Arno Tripolt (ECT* Trento)
- Jochen Wambach (TU Darmstadt and ECT* Trento)

+ The SL/TL ECT* Organizers: Philip Cole, Béatrice Ramstein, and Andrey Sarantsev

Following topics were covered

- **Electromagnetic baryon excitations through meson electroproduction**
- **Theoretical approaches for baryon transition form factors in the *space-like* region**
- **Baryon spectroscopy from photoproduction and meson beam experiments**
- **Amplitude analysis and extraction of baryonic resonances properties**
- **Electromagnetic transitions through dilepton production**
- **Unified description of *space-like* and *time-like* baryon electromagnetic transitions**
- **Vector mesons in medium**
- **Prospects for future experimental studies**

Physics Opportunities with Meson Beams

William J. Briscoe (GW), Michael Döring (GW), Helmut Haberzettl (GW), D. Mark Manley (KSU), Megumi Naruki (Kyoto Univ.), Igor I. Strakovsky (GW), Eric S. Swanson (Univ. of Pittsburgh)

(Submitted on 26 Mar 2015)

Over the past two decades, meson photo- and electro-production data of unprecedented quality and quantity have been measured at electromagnetic facilities worldwide. By contrast, the meson-beam data for the same hadronic final states are mostly outdated and largely of poor quality, or even nonexistent, and thus provide inadequate input to help interpret, analyze, and exploit the full potential of the new electromagnetic data. To reap the full benefit of the high-precision electromagnetic data, new high-statistics data from measurements with meson beams, with good angle and energy coverage for a wide range of reactions, are critically needed to advance our knowledge in baryon and meson spectroscopy and other related areas of hadron physics. To address this situation, a state of-the-art meson-beam facility needs to be constructed. The present paper summarizes unresolved issues in hadron physics and outlines the vast opportunities and advances that only become possible with such a facility.

135 endorsers from 77 labs worldwide

Bill Briscoe ECT* 2017

Coupled-channels picture of resonance excitation [Motivation]

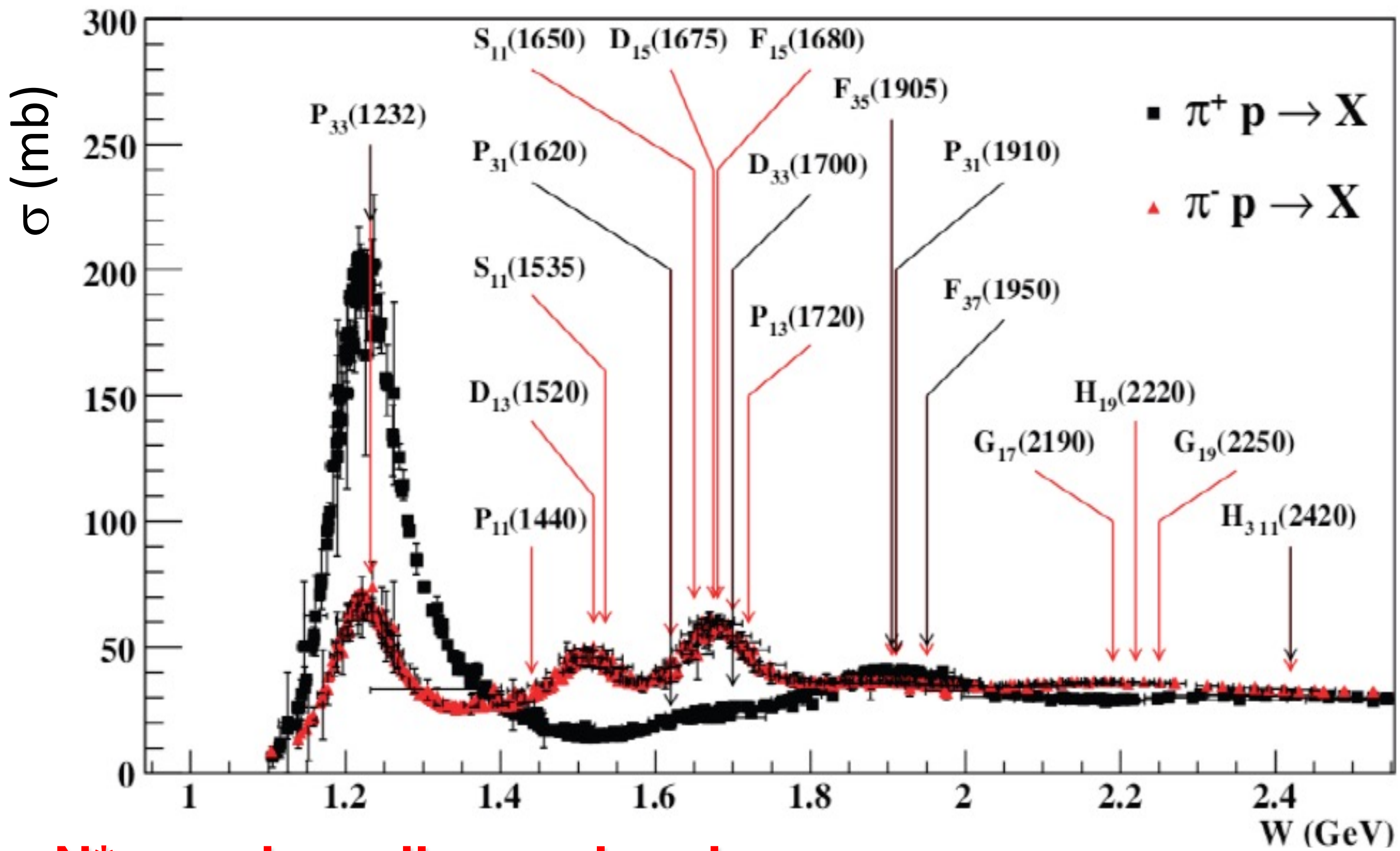
$$\gamma N \rightarrow N^* \rightarrow \begin{cases} \pi N \\ \pi\pi N \\ \eta N \\ K\Lambda \\ K\Sigma \end{cases}$$

The same N* resonance must be found in different reaction channels in a consistent way!

T=

$T_{\pi N\rightarrow\pi N}$	$T_{\eta N\rightarrow\pi N}$	$T_{\gamma N\rightarrow\pi N}$	$T_{\rho N\rightarrow\pi N}$	$T_{\sigma N\rightarrow\pi N}$	$T_{K\Lambda\rightarrow\pi N}$	$T_{K\Sigma\rightarrow\pi N}$
$T_{\pi N\rightarrow\eta N}$	$T_{\eta N\rightarrow\eta N}$	$T_{\gamma N->\eta N}$	$T_{\rho N\rightarrow\eta N}$	$T_{\sigma N\rightarrow\eta N}$	$T_{K\Lambda\rightarrow\eta N}$	$T_{K\Sigma\rightarrow\eta N}$
$T_{\pi N\rightarrow\gamma N}$	$T_{\eta N\rightarrow\gamma N}$	$T_{\gamma N\rightarrow\gamma N}$	$T_{\rho N\rightarrow\gamma N}$	$T_{\sigma N\rightarrow\gamma N}$	$T_{K\Lambda\rightarrow\gamma N}$	$T_{K\Sigma->\gamma N}$
$T_{\pi N\rightarrow\rho N}$	$T_{\eta N\rightarrow\rho N}$	$T_{\gamma N\rightarrow\rho N}$	$T_{\rho N\rightarrow\rho N}$	$T_{\sigma N\rightarrow\rho N}$	$T_{K\Lambda\rightarrow\rho N}$	$T_{K\Sigma\rightarrow\rho N}$
$T_{\pi N\rightarrow\sigma N}$	$T_{\eta N\rightarrow\sigma N}$	$T_{\gamma N\rightarrow\sigma N}$	$T_{\rho N\rightarrow\sigma N}$	$T_{\sigma N\rightarrow\sigma N}$	$T_{K\Lambda\rightarrow\sigma N}$	$T_{K\Sigma\rightarrow\sigma N}$
$T_{\pi N\rightarrow K\Lambda}$	$T_{\eta N\rightarrow K\Lambda}$	$T_{\gamma N\rightarrow K\Lambda}$	$T_{\rho N\rightarrow K\Lambda}$	$T_{\sigma N\rightarrow K\Lambda}$	$T_{K\Lambda\rightarrow K\Lambda}$	$T_{K\Sigma\rightarrow K\Lambda}$
$T_{\pi N\rightarrow K\Sigma}$	$T_{\eta N\rightarrow K\Sigma}$	$T_{\gamma N\rightarrow K\Sigma}$	$T_{\rho N\rightarrow K\Sigma}$	$T_{\sigma N\rightarrow K\Sigma}$	$T_{K\Lambda\rightarrow K\Sigma}$	$T_{K\Sigma\rightarrow K\Sigma}$

Baryon resonances (N*s and Δ*s)

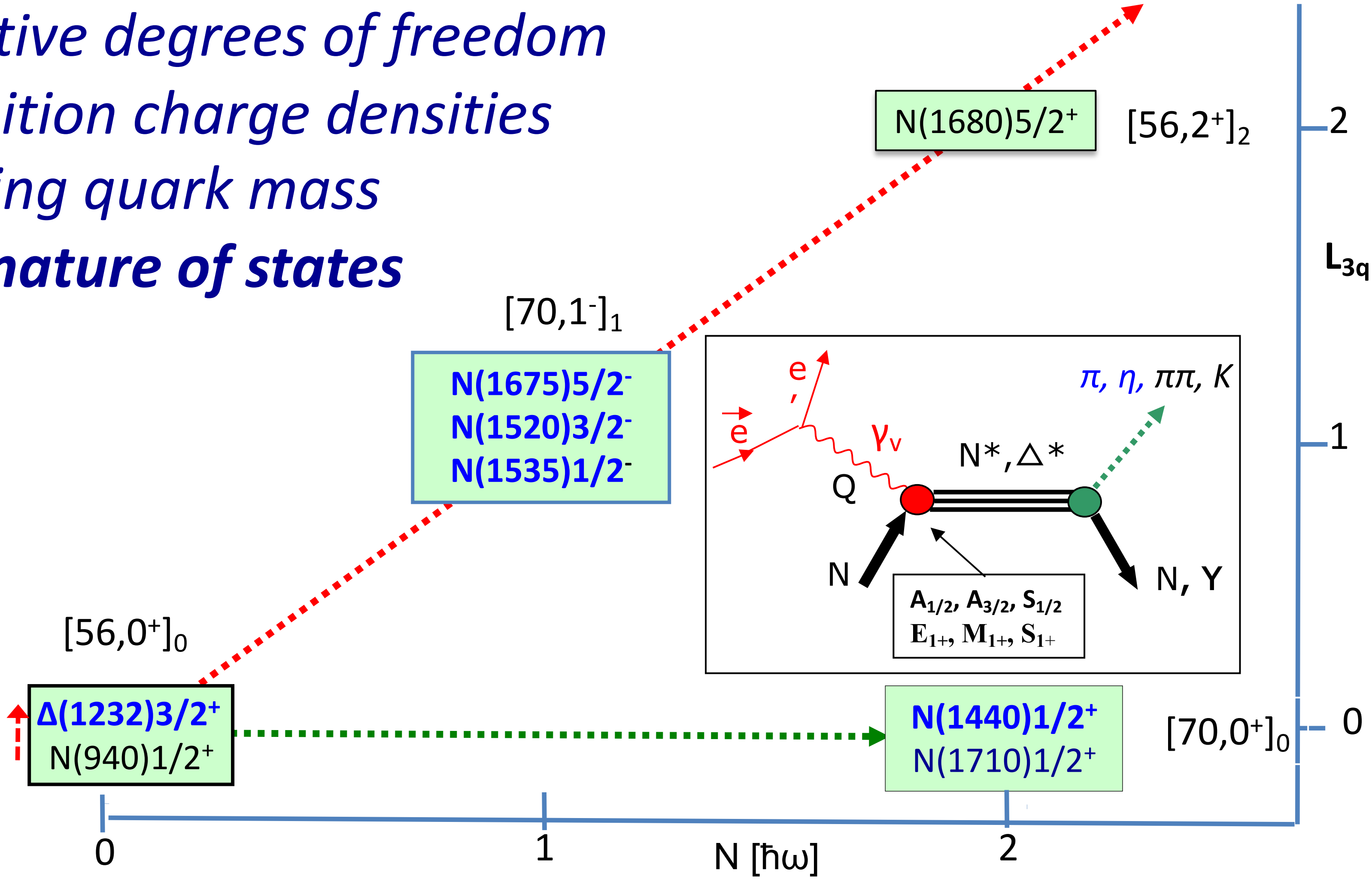


- N*s are broadly overlapping
- Hard to disentangle without polarization observables

Structure of excited baryons

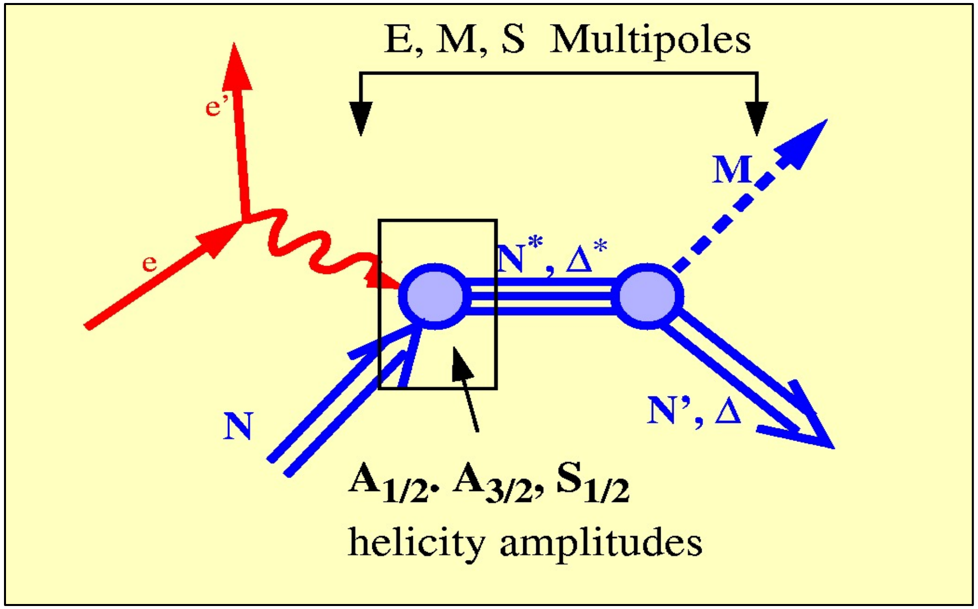
- *effective degrees of freedom*
- *transition charge densities*
- *running quark mass*

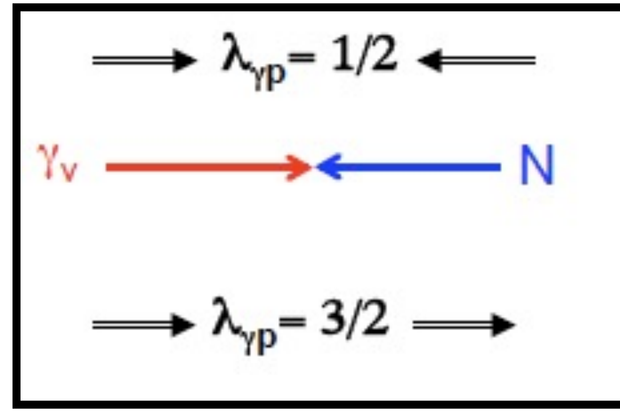
  => nature of states



I.G. Aznauryan et al., Analysis of p(e,e'Nπ); V.I. Mokeev et al., Analysis of $p(e,e'p\pi^+\pi^-)$

Electroproduction





The helicity amplitudes are related to the matrix elements of the electromagnetic current via:

$A_{1/2}$: $\langle N^*, S_z^* = +\frac{1}{2} | \varepsilon_\mu^{(+)} J^\mu_{em} | N, S_z = -\frac{1}{2} \rangle$

$A_{3/2}$: $\langle N^*, S_z^* = +3/2 | \varepsilon_\mu^{(+)} J^\mu_{em} | N, S_z = +\frac{1}{2} \rangle$

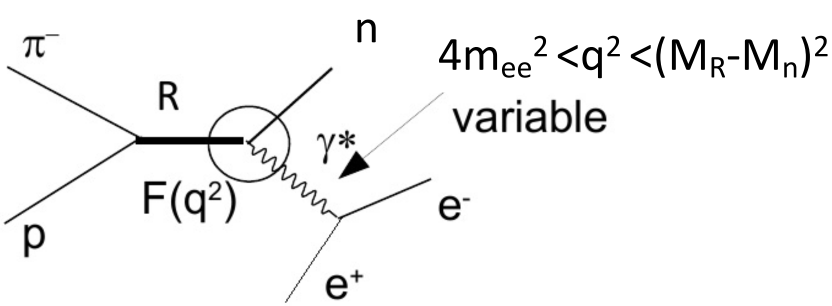
$S_{1/2}$: $\langle N^*, S_z^* = +\frac{1}{2} | \varepsilon_\mu^{(0)} J^\mu_{em} | N, S_z = +\frac{1}{2} \rangle$

Transverse
- $A_{1/2}$
- $A_{3/2}$

Longitudinal
- $S_{1/2}$

Electromagnetic form factors

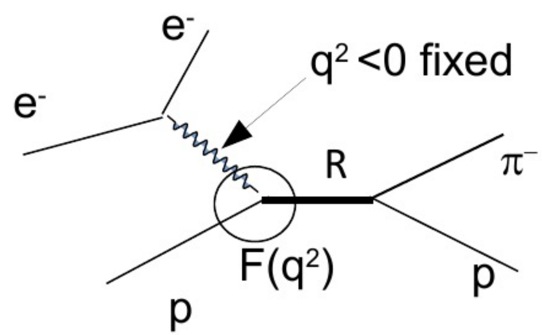
Time-like electromagnetic form factors



No data are available

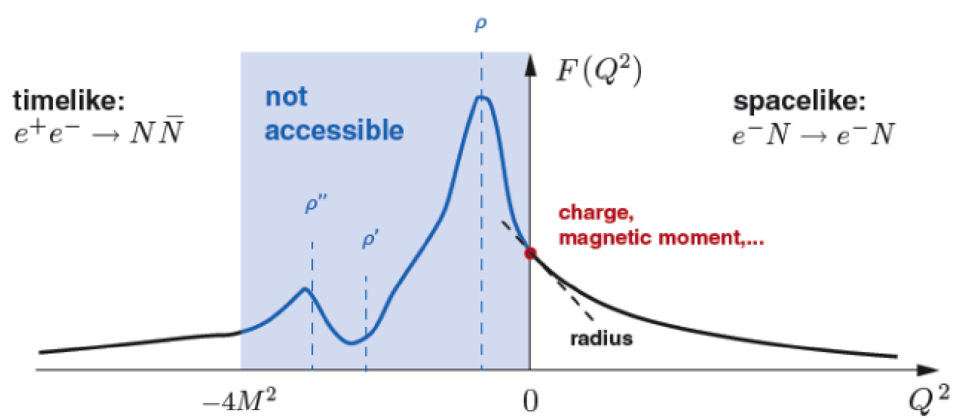
Limit at q^2=0 given by real photon decay

Space-like electromagnetic form factors



Data from Jlab (CLAS) up to $-q^2 = 4$ GeV^2

Exploration of higher q^2 with CLAS12

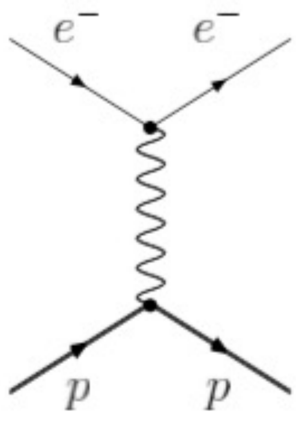


Role of quark core and meson cloud in the TL region ?

N* Electron-production(CLAS/JLab) and dilepton production (HADES/GSI) data complement each other.

The knowledge gained from the CLAS/JLAB data can be used to constrain the interpretation of HADES/GSI data.

Space-like $q^2 < 0$

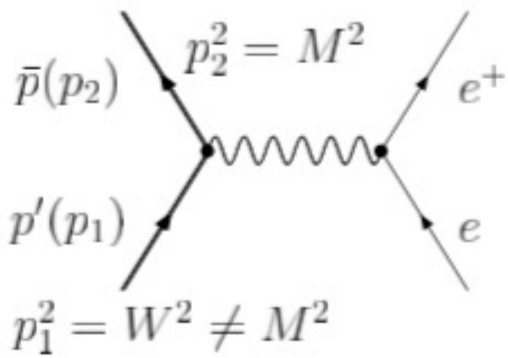


$q^2 \leq 0$

Most world data is CLAS data

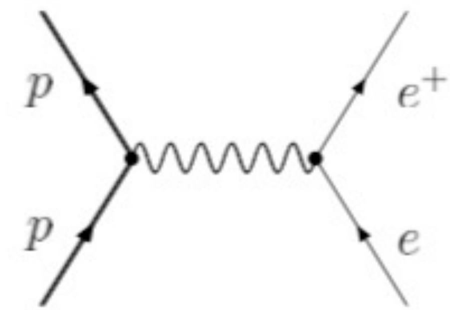
Time-like $q^2 > 0$

Unphysical



$4m_e^2 \leq q^2 \leq 4M^2$

Physical



$q^2 \geq 4M^2$

HADES, BES III, FAIR

Teresa Peña ECT* 2017

N(1535)1/2$^-$ CLAS (SL)

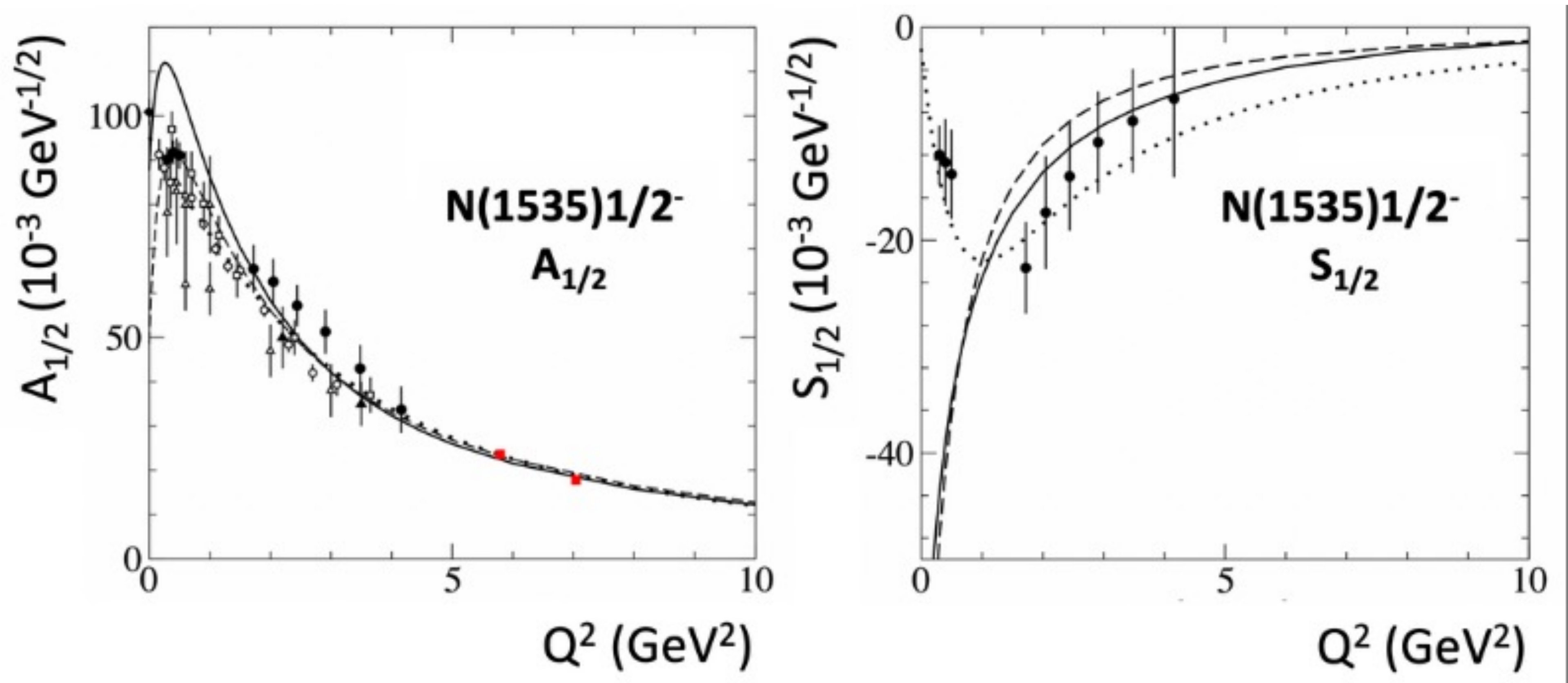


Fig. 11 Improvements in the description of the results on the $\gamma_v pN^*$ electrocouplings [37, 71] achieved after accounting for the contributions of the meson-baryon cloud and the quark core. A description of the $N(1535)1/2^-$ is shown for the relativistic quark model [16] accounting for the contributions from $K\Lambda$ loops and the quark core (solid lines) and the quark core only (dashed line). The AdS/CFT results [79] are shown by the dotted lines.

Daniel S. Carman, Kyungseon Joo, and Victor I. Mokeev, Few-Body Systems (2020) 61:20

N(1535)1/2$^-$

- Let's compare TL and SL for the N(1535)1/2$^-$

Covariant model for the Dalitz decay of the $N(1535)$ resonance

G. Ramalho[1] and M. T. Peña[2,3]

- We observe that

$$G_E = \frac{1}{\mathcal{B}} A_{1/2}, \qquad G_C = \frac{1}{\sqrt{2}\mathcal{B}} \frac{M_R}{|\mathbf{q}|} S_{1/2}, \qquad (2.9)$$

$$\mathcal{B} = \frac{e}{2}\sqrt{\frac{Q_+^2}{M_N M_R K}}, \; K = \frac{M_R^2 - M_N^2}{2M_R}$$

PHYSICAL REVIEW D **101,** 114008 (2020)

N(1535)1/2$^-$

The empirical data associated with the electromagnetic structure of the $\gamma^* N \to N(1535)$ transition are usually represented in terms of the helicity amplitudes in the resonance rest frame. In this frame the momentum transfer is

$$q = \left(\frac{M_R^2 - M_N^2 - Q^2}{2M_R}, \mathbf{q} \right). \tag{2.2}$$

Here $\mathbf{q}$ is the photon three-momentum, with magnitude

$$|\mathbf{q}| = \frac{\sqrt{Q_+^2 Q_-^2}}{2M_R}, \tag{2.3}$$

with

$$\begin{aligned} Q_\pm^2 &= (M_R \pm M_N)^2 + Q^2 \\ &= (M_R \pm M_N)^2 - q^2. \end{aligned} \tag{2.4}$$

N(1535)1/2⁻ CLAS (SL)

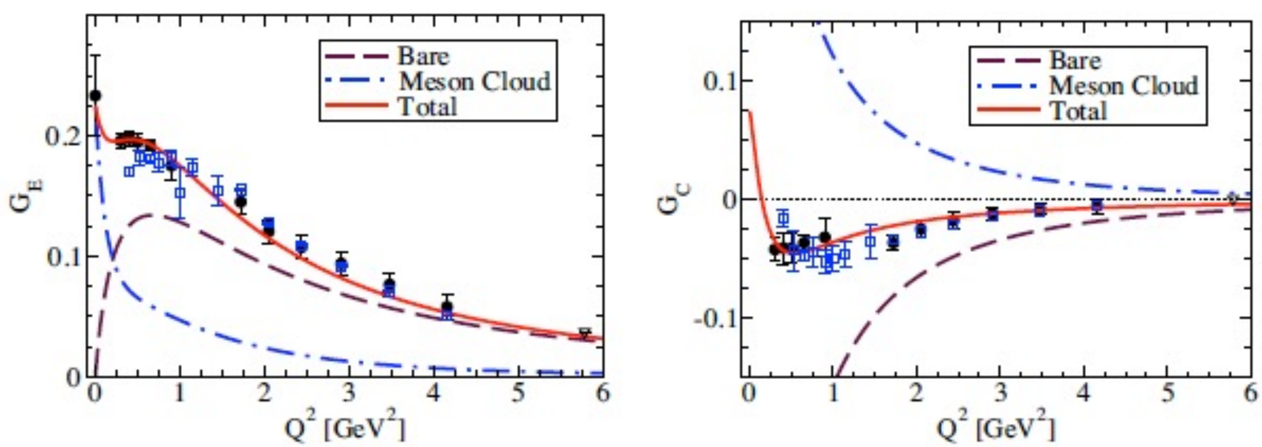


FIG. 2. $\gamma^* N \to N(1535)$ transition form factors G_E and G_C for proton target. Data from CLAS [48] (circles), MAID [50] (squares), and JLab/Hall C [49] (triangles). The data at $Q^2 = 0$ is from PDG [52].

N(1535)1/2⁻ CLAS (SL) + TL

COVARIANT MODEL FOR THE DALITZ DECAY OF THE … PHYS. REV. D **101**, 114008 (2020)

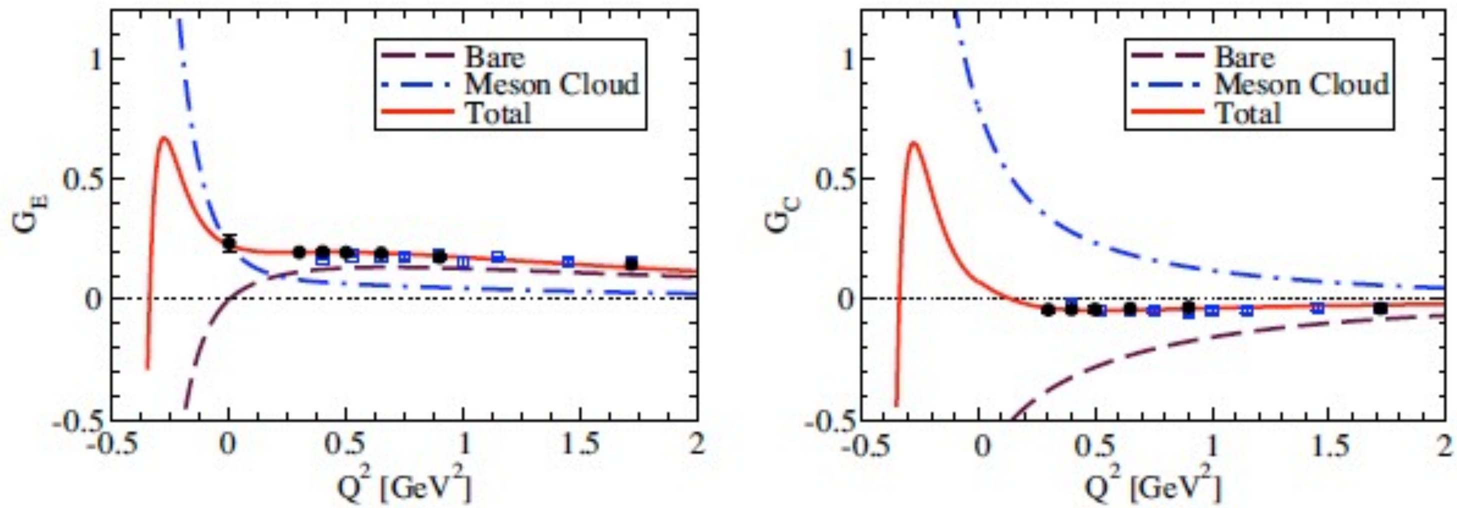


FIG. 7. Real part of $\gamma^* N \to N(1535)$ transition form factors in the spacelike and timelike region, for proton target for $W = 1.535$ GeV. Same data as in Fig. 1.

Continuation from the Space-like to the Time-like regime

Discussion Focus and Ultimate Goals

1. Establish the nucleon excitation spectrum and reaction models with emphasis on the high-mass region and gluonic excitations;

2. Measure space-like and time-like baryonic transition form factors, and thereby quantify the role of the active degrees of freedom in the nucleon excitation spectrum;

3. Pin down the dressed-quark mass as a function of quark momentum, which will critically deepen our understanding of mass generation dynamics and emergence of quark-gluon confinement.

4. Provide the analysis tools to enable comparisons of future lattice QCD simulations with experimental results.

Should we write a White Paper?

Message to take home.

Why N*s are important. (quoted from Nathan Isgur[1,2])

- *The first is that nucleons are the stuff of which our world is made.*

- *My second reason is that they are the simplest system in which the quintessentially nonabelian character of QCD is manifest.*

- *The third reason is that history has taught us that, while relatively simple, baryons are sufficiently complex to reveal physics hidden from us in the mesons*"

[1]Workshop on Excited Nucleons and Hadronic Structure (2000).

[2]Baryon Spectroscopy, E. Klempt and J.-M. Richard, arXiv:0901.2055v1[hep-ph]1 4 Jan 2009

We need to spread the word to lay and expert audiences alike that excited baryon research is indeed exciting and crucial to science.

Some Questions to Ponder

1. How to compare Helicity Amplitudes between SL and TL?
2. Can the data in the SL region afford constraints for those in the TL regime? (e.g. Covariant Spectator Theory, Teresa Peña and Gilberto Ramalho).
3. What is the relationship between the **density matrix elements** for SL → TL? Again, do they offer any constraints on the Helicity Amplitudes between the SL and TL regimes?
4. Will there be scaling in $q^2 > 0$ and $q^2 < 0$ (i.e. $Q^2 > 0$)?
5. Can we find a consistent *ab initio* approach for the QCD d.o.f. in determining the SL and TL transition FFs?
6. What role does the MB Cloud play? (again, for SL and TL)? And how to separate? [Through comparing to other models?]
7. What are the relevant d.o.f. as a function of q^2 for the SL and TL regimes?

J-PARC Opportunity [!]

We have the opportunity to run 45 shifts at the

K1.8 beamline at J-PARC

- $\pi N \rightarrow \pi N$
- $\pi N \rightarrow \pi\pi N$
- $\pi N \rightarrow KY$

W: 1.54 to 2.15 GeV

KEK/J-PARC-PAC 2012-3

Proposal for J-PARC 50 GeV Proton Synchrotron

3-Body Hadronic Reactions for New Aspects of Baryon Spectroscopy

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Thank
You
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Takk
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BarakAllahuFiik
Mèsi
Xièxie
Grazie
Chokrane
Kiitos
Dziakuju
GratiasAgimus
GratiasAgo
Motashakkeram
KopKhunKha
Gracie
CámOn
Multumesc
Saha
Salamat
Obrigado
Bayarlalaa
Nirringrazzjak
NajisTuke
Efharisto
Faleminderit
Gràcies
Dakujem
Taiku
Mercé
Matondo
Blagodaram
ThintKo
Buznyg
TapadhLeat
Köszönöm
Murakoze
WaadMahadsantahay
Tanemirt
Tenki
Aabhar
Dhanyavaad
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