Spanning the Time-Like and Space-Like Divide

• PHY-1615146

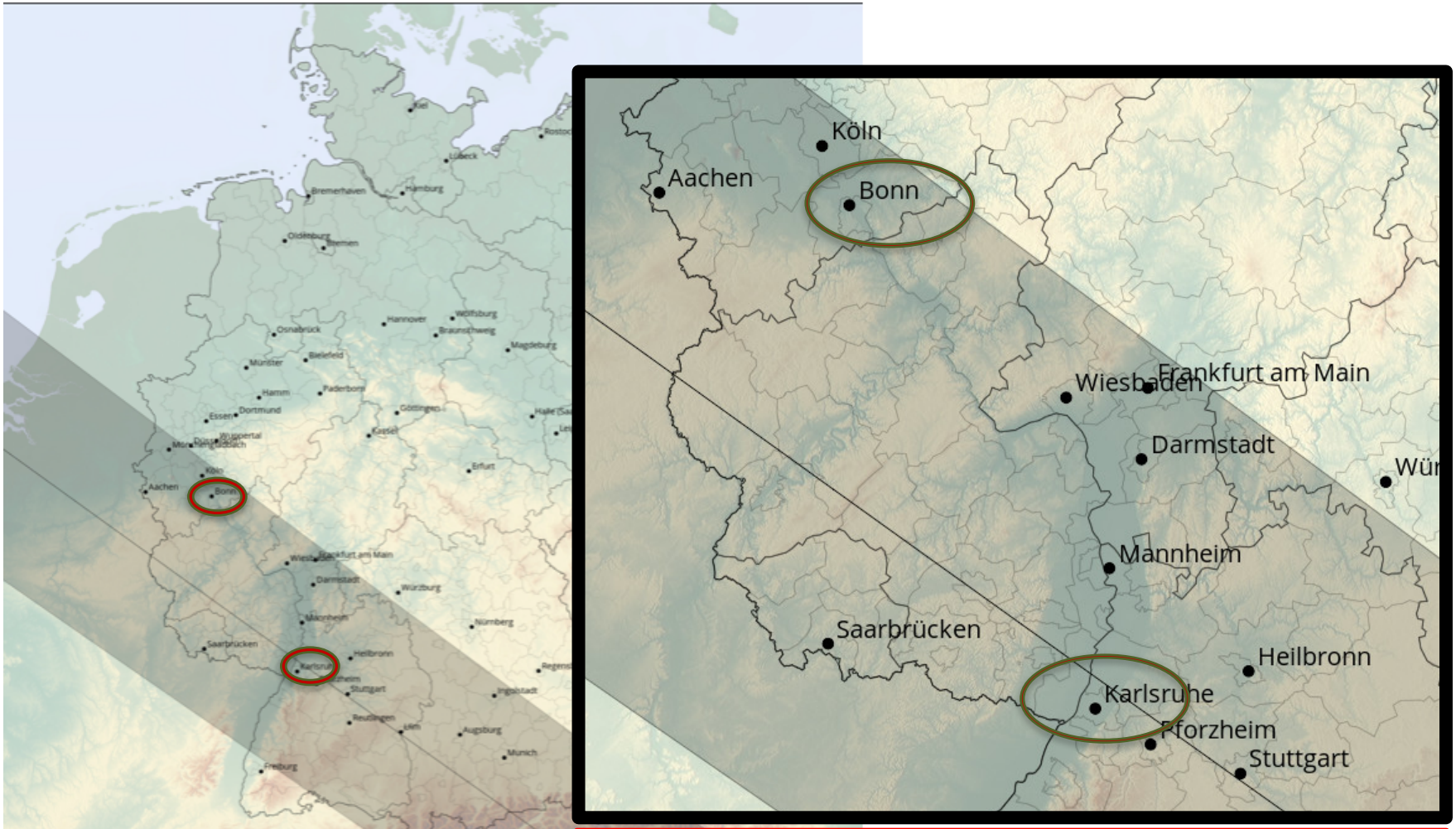
Philip Cole
Lamar University

June 12, 2019

NSTAR 2017

Thanks to Lothar Tiator

NSTAR 2151?



Next Total Solar Eclipse in Bonn, Germany (June 14, 2151)

NSTAR 2019

- Baryon spectrum through meson photoproduction
- Baryon resonances in experiments with hadron beams and in the e^+e^- collisions
- Baryon resonances in heavy ion collisions and their role in cosmology
- **Baryon structure through meson electroproduction, transition form factors, and time-like form factors**
- Partial wave analyses and baryon resonance parameter extraction
- Baryon spectrum and structure from first principles of QCD
- Advances in the modeling of baryon spectrum and structure
- Facilities and future projects
- Other topics related to N* physics

There are dedicated sessions on space-like and time-like transition form factors.

First time this session was at NSTAR 2017

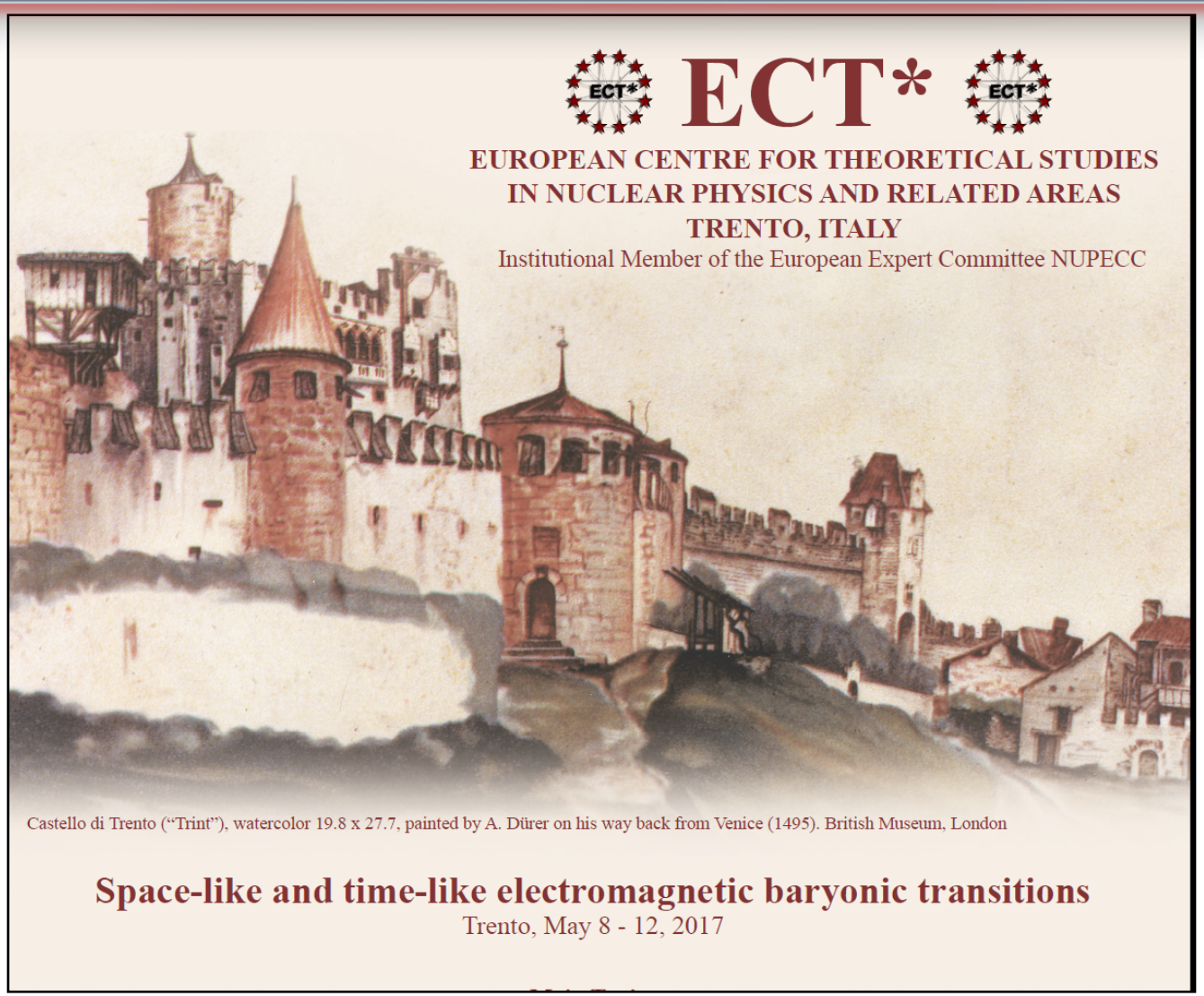
Certainly way before NSTAR 2151

We will have solved the Conundrum of the Proton

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

Report on the ECT* Workshop:
Space-like and time-like electromagnetic baryonic transitions

https://indico.in2p3.fr/event/14330/overview



Diquark Correlations in Hadron Physics: Origin, Impact and Evidence

https://ectstar.fbk.eu/node/4449

Monday, 23 September, 2019 - 08:00 to Friday, 27 September, 2019 - 14:00

Abstract:

The last decade has seen a dramatic shift in the way we understand the internal structure of hadronic systems. Modern experimental facilities, new theoretical techniques for the continuum bound-state problem and progress with lattice-regularized QCD have provided strong indications that **soft quark-quark (diquark) correlations play a crucial role in hadron physics. For example, theory indicates that the appearance of such correlations is a necessary consequence of dynamical chiral symmetry breaking, viz. the mechanism responsible for emergence of almost all visible mass in the universe;** experiment has uncovered signals for such correlations in the flavour-separation of the proton's electromagnetic form factors; and phenomenology suggests that diquark correlations might be critical to the formation of exotic tetra- and penta-quark hadrons. This workshop will gather experimentalists and theorists to undertake a critical review of existing information, consolidate the facts, and therefrom develop a coherent, unified picture of hadron structure.

Organizers:

Jacopo Ferreti Yale University jacopo.ferretti@yale.edu

Craig Roberts Argonne National Laboratory cdroberts@anl.gov

Elena Santopinto INFN-GE santopinto@ge.infn.it

Jorge Segovia Institut de Física d'Altes Energies (IFAE) and Barcelona Institute of Science and Technology (BIST) Universitat Autònoma de Barcelona jsegovia@ifae.es

Bogdan Wojtsekhowski Jefferson Lab bogdanw@jlab.org

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.

Workshop at GSI in Oct 22-25, 2018

Electromagnetic Structure of Strange Baryons

22-25 October 2018
GSI Helmholtzzentrum für Schwerionenforschung GmbH
Europe/Berlin timezone

- Overview
- Timetable
- Venue and Travel information
- Accommodation
- Registration
  - Registration Form
- Participant List
- Open Symposium
- Data protection

Support

k.stix@gsi.de

Based on their self-analyzing decays, hyperons give a complementary point of view on the structure of baryons. This Rapid Reaction Task Force will provide an igniting spark for a concerted effort to explore the structure of hyperons.

The meeting is by invitation only.
The symposium on Monday, October 22nd, is open for public (no registration needed).

Starts Oct 22, 2018 08:00
Ends Oct 25, 2018 18:00
Europe/Berlin

GSI Helmholtzzentrum für Schwerionenforschung GmbH
KBW lecture hall
Planckstr. 1
64291 Darmstadt

Galatyuk, Tetyana
Leupold, Stefan
Meißner, Ulf-G. Meißner
Schönning, Karin

What have we been doing for the past 4 years?

- White Paper – Physics Opportunities with Meson Beams (Briscoe *et al.*, 2015)
- NSF PIRE grant (Cole *et al., 2016*)
- H2020 European Integrating Initiative in Hadron Physics (Pena *et al*., 2017)
- White paper J-PARC/JLab (Briscoe *et al., 2018*)

- Progress is slow.
- What do we need to do?
- How do we ramp up progress?

Think on this as we go through this talk

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.

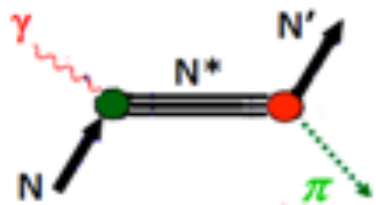
135 endorsers from 77 labs worldwide

Status of Data for Specific Reactions

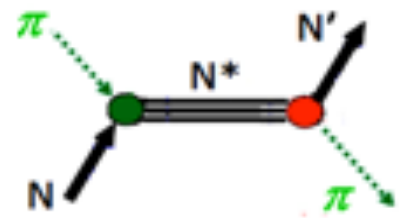
- Measurements of final states involving single **pseudoscalar meson** & **spin-1/2 baryon** are particularly interesting due to simple interpretation.

- The reactions involving **πN** channels include:

$\gamma p \rightarrow \pi^0 p$
$\gamma p \rightarrow \pi^+ n$
$\gamma n \rightarrow \pi^- p$
$\gamma n \rightarrow \pi^0 n$



$\pi^+ n \rightarrow \pi^0 p$
$\pi^+ n \rightarrow \pi^+ n$
$\pi^- p \rightarrow \pi^- p$
$\pi^- p \rightarrow \pi^0 n$
$\pi^+ p \rightarrow \pi^+ p$



- Only $\pi^+ p \rightarrow \pi^+ p$ corresponds to **isospin 3/2** while rest of reactions is mixture of **isospins 1/2 & 3/2**.

PDG Available data for **πN** elastic scattering are still **incomplete**.

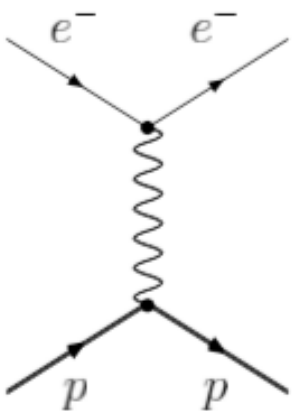
- Measurements of **P**, **A**, & **R** observables (limited number of data available) are needed to construct truly unbiased **PW amplitudes**.

GW **πN** elastic scattering data have allowed establishment of **4*** resonances.

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 $q^2 < 0$

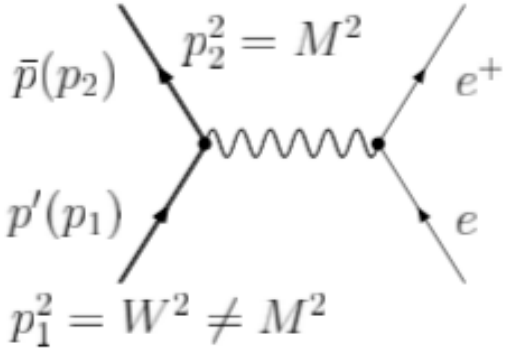


$q^2 \leq 0$

Most world data is CLAS data

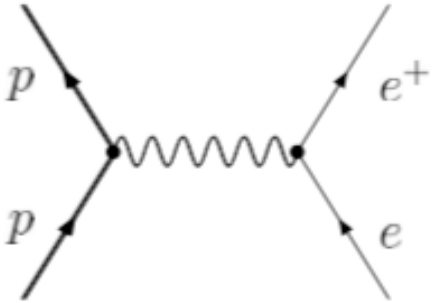
Time-like $q^2 > 0$

Unphysical



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

Physical

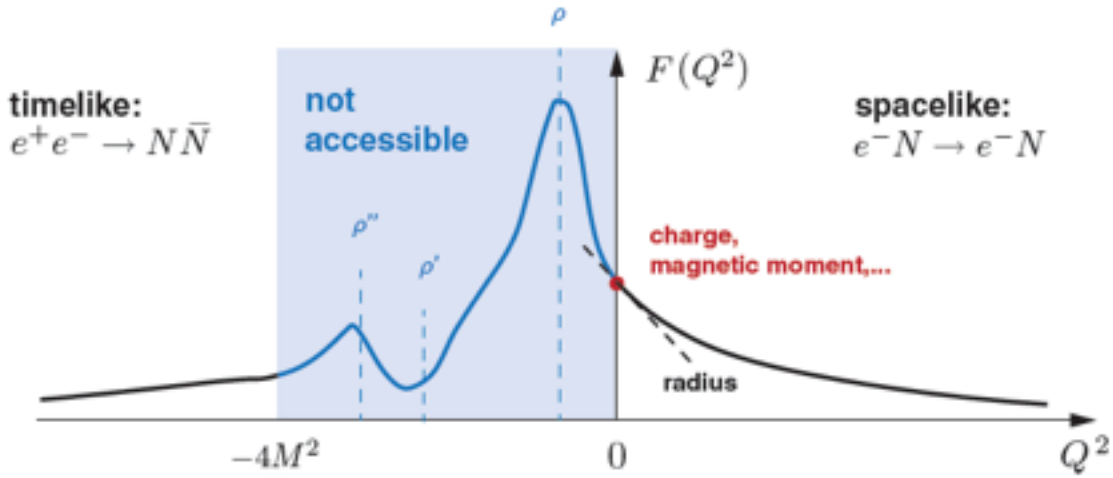


$q^2 \geq 4M^2$

HADES, BES III, FAIR

Radiative Hyperon Decays

- Timelike ($G_M(q^2)$, $G_E(q^2)$) complementary to Spacelike
- Low energy TL complementary to high energy TL (e.g. BES-III, CLEO)



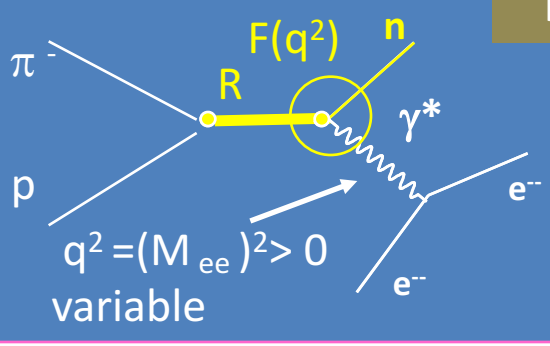
$\bar{B}B \to M\, e^+e^-$ $B_1 \to B_2 e^+e^-$

Jim Ritman

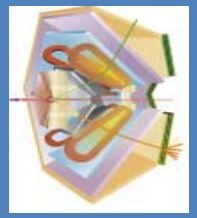
Electromagnetic baryonic transitions in time-like and space-like regions: towards a global picture?

Time-Like electromagnetic form factors

preliminary studies with HADES/GSI

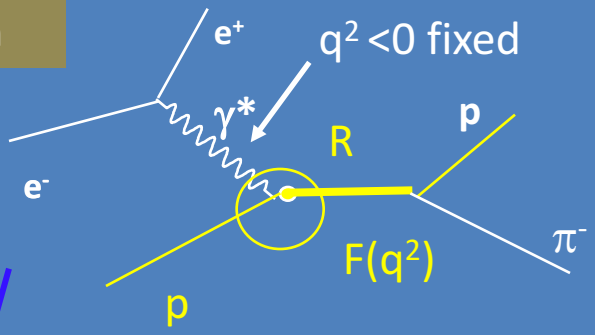


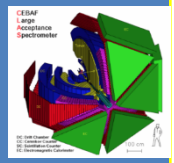
Inverse pion electroproduction

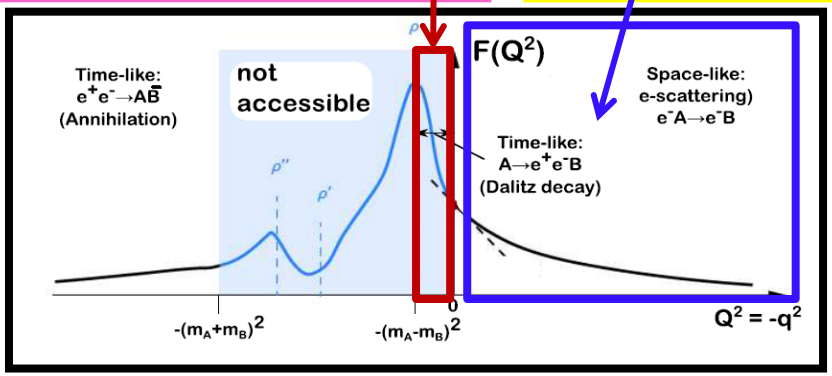


Space-Like electromagnetic form factors

Precise data from JLab/CLAS up to $-q^2$=4 GeV^2







- ***Theoretical tools: Dispersion Relations, Dyson-Schwinger, Vector Dominance, Constituent Quarks ?***

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

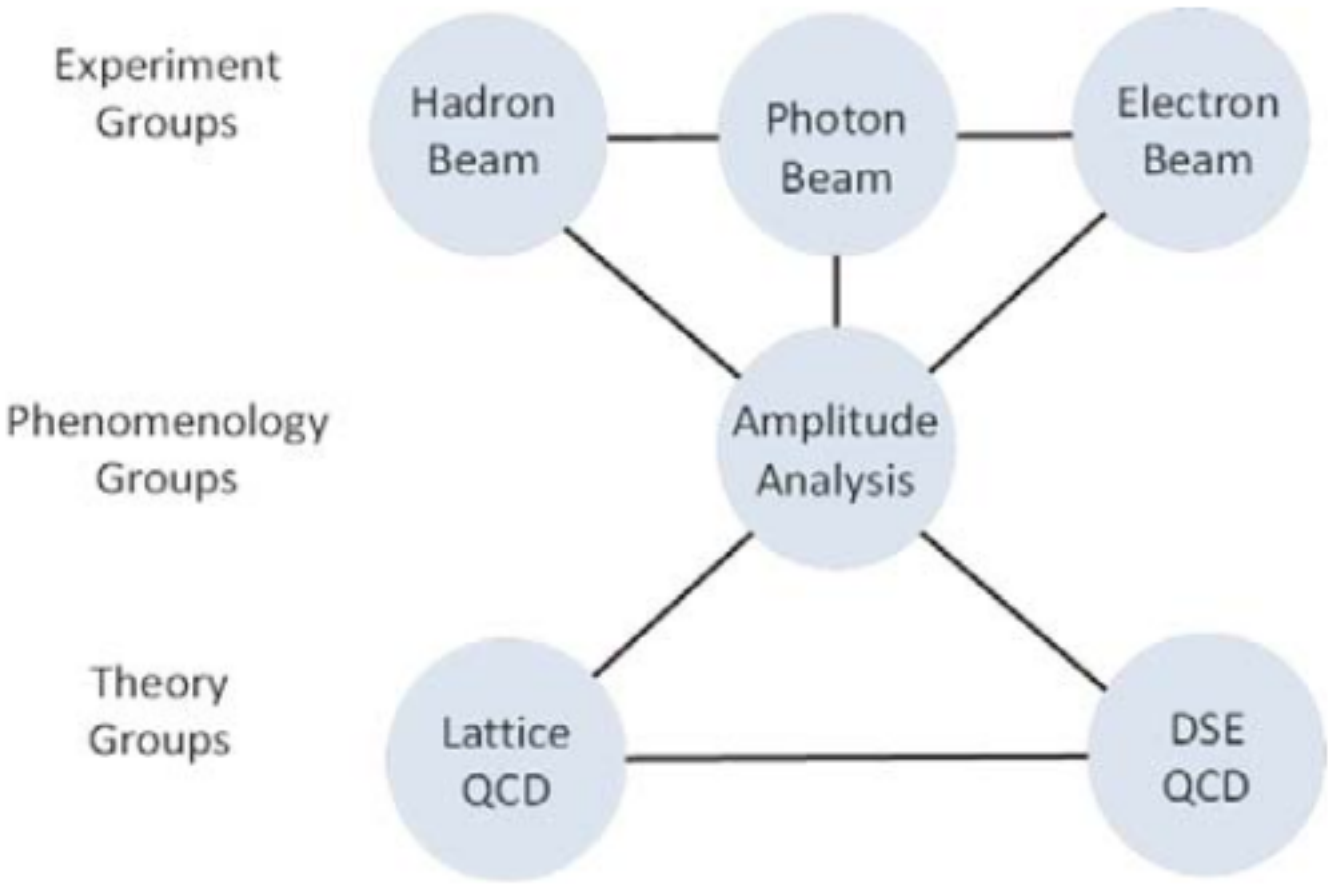
William Briscoe (*Professor and Chair of Physics*), **Helmut Haberzettl** (*Professor of Physics*)
Igor Strakovsky (*Research Professor*), **Ronald Workman** (*Research Professor*)
Department of Physics, George Washington University, Washington, DC 20052

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

LOI: NSF PIRE Submitted: Sept 8, 2016

Project Summary: Emergent Structures from Quarks and Gluons

Concept: We seek to understand how quarks and gluons self-assemble and thereby emerge in forming protons and neutrons. We therefore seek a better understanding of the nature of the proton, a particle central to physics, chemistry, and the biochemical properties of life. Recent results from interrogating protons with polarized photon and electron beams at Jefferson Lab in Newport News, Virginia, have given us remarkably precise information on the substructure of protons and their excitations leading us to a deeper understanding of the proton. Laboratories in Germany and Japan, however, are using pion beams to probe other aspects of the internal structure of protons. Such beams will not be available to the U.S. anytime in the foreseeable future, however. That is a serious lack, for to reveal the internal structure of the proton requires both electron/photon and pion beams. It follows, therefore, that there must be a coordinated effort among the laboratories in Japan (J-PARC and LEPS), Germany (ELSA, GSI, and MAMI), and the U.S. (JLab) employing photon, electron, and pion beams to make the necessary advances in both theory and phenomenology. We appear to be on the verge of solving the fundamental problem of what makes a proton a proton, but only through coordinating our efforts globally and across disciplines will we be adequately poised to crack the conundrum of the proton.



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*;

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

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We need 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 baryon 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.

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:

White Paper

US-JAPAN COLLABORATION ON HADRONIC PHYSICS AT J-PARC AND JEFFERSON LAB

Edited by: W. Briscoe (George Washington U.), W-C Chang (Academia Sinica), P.L. Cole (Lamar U.), Lei Guo (Florida International U.), K. Hicks (Ohio U.), K. Joo (U. of Connecticut), Jen-Chieh Peng (U. of Illinois Urbana-Champaign)

Executive Summary

We are at the dawn of a new era in the study of nuclear physics of how nuclear structure emerges from quark and gluons. The nonperturbative strong interaction is enormously challenging. The degrees of freedom are not the asymptotically free current quarks and gauge gluons assumed by some theoretical models. The nonperturbative interaction of quarks and gluons is entirely different from what exists within the perturbative QCD realm and it gets quite complicated with all current quarks and gauge gluons becoming "dressed" by a cloud of virtual gluons and quark-antiquark pairs. In the regime of large quark-gluon coupling, the dressing of current bare quarks by dressed gluons gives rise to a momentum-dependent dynamical mass and structure of dressed quarks, which are the effective degrees of freedom employed in constituent quark models. In addition, meson-baryon effects need to be included for a full description of nucleon structure at large distances. Understanding the strong force at intermediate distances is enormously important, for it is in this transitional regime where the nonperturbative nature of the strong force generates about 99% of the total mass of the nucleon through Dynamical Chiral Symmetry Breaking. This non-Abelian nature of Quantum Chromodynamics (QCD) and the resulting strong coupling at low energies represent a significant challenge to nuclear physicists.

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regimes will yield prospects in extending studies of the Generalized Parton Distributions and will afford promising connections with a future EIC project.

We propose a new U.S.-Japan collaboration to provide the unique opportunity for physicists from Japan and the U.S. to foster cooperation and collaborations, exchange ideas on hadronic physics. We ultimately seek to strengthen existing links and forge entirely new ones within the U.S-Japan hadronic physics community. The research at J-PARC and JLab will allow for the structure of

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The construction of J-PARC in Japan was completed in 2009, and its operation started in 2010. J-PARC provides the world highest-power hadron beams for particle and nuclear experiments. It has a whole program of strange particle and hyper-nuclear reactions, which will explore strange hadronic systems with high intensity kaon and pion beams. The current maximum momentum of secondary beamlines of 2 GeV/c is available. There is also an ambitious upgrade plan to create high energy beamlines in the momentum range 5 – 15 GeV/c, which will shed light on the effective degrees of freedom inside the hadrons and will elucidate the mechanism of how the hadrons are excited in reactions by the hadronic probes.

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

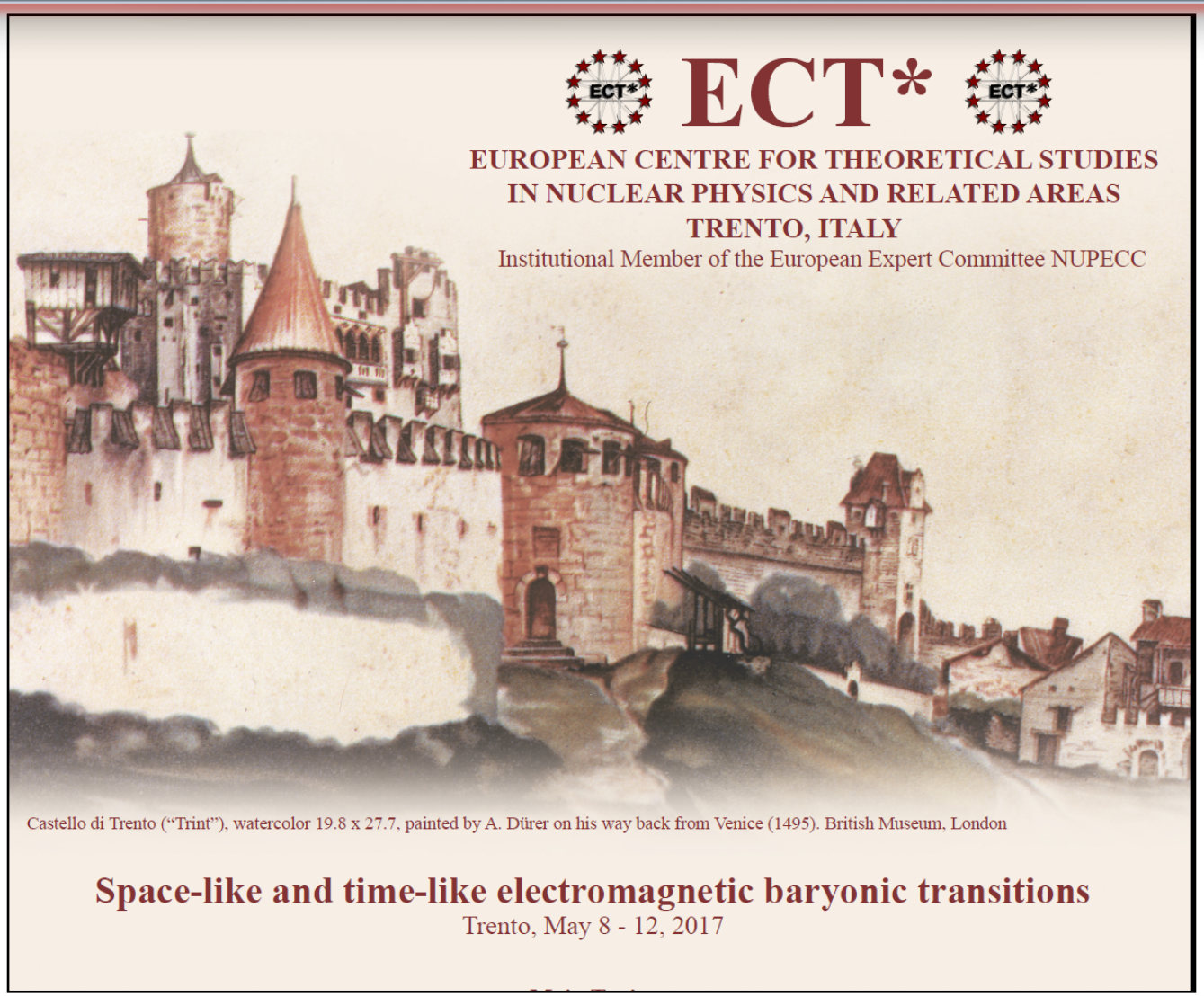
- Daniele Binosi (ECT* Trento)
- Vladimir Braun (University of Regensburg)
- William Briscoe (George Washington University)
- Susanna Costanza (University of Pavia)
- Annalisa D'Angelo (University of Rome)
- Michael Döring (George Washington University)
- Christian Fischer (University of Giessen)
- Bengt 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

Report on the ECT* Workshop:
Space-like and time-like electromagnetic baryonic transitions

https://indico.in2p3.fr/event/14330/overview



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)

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**

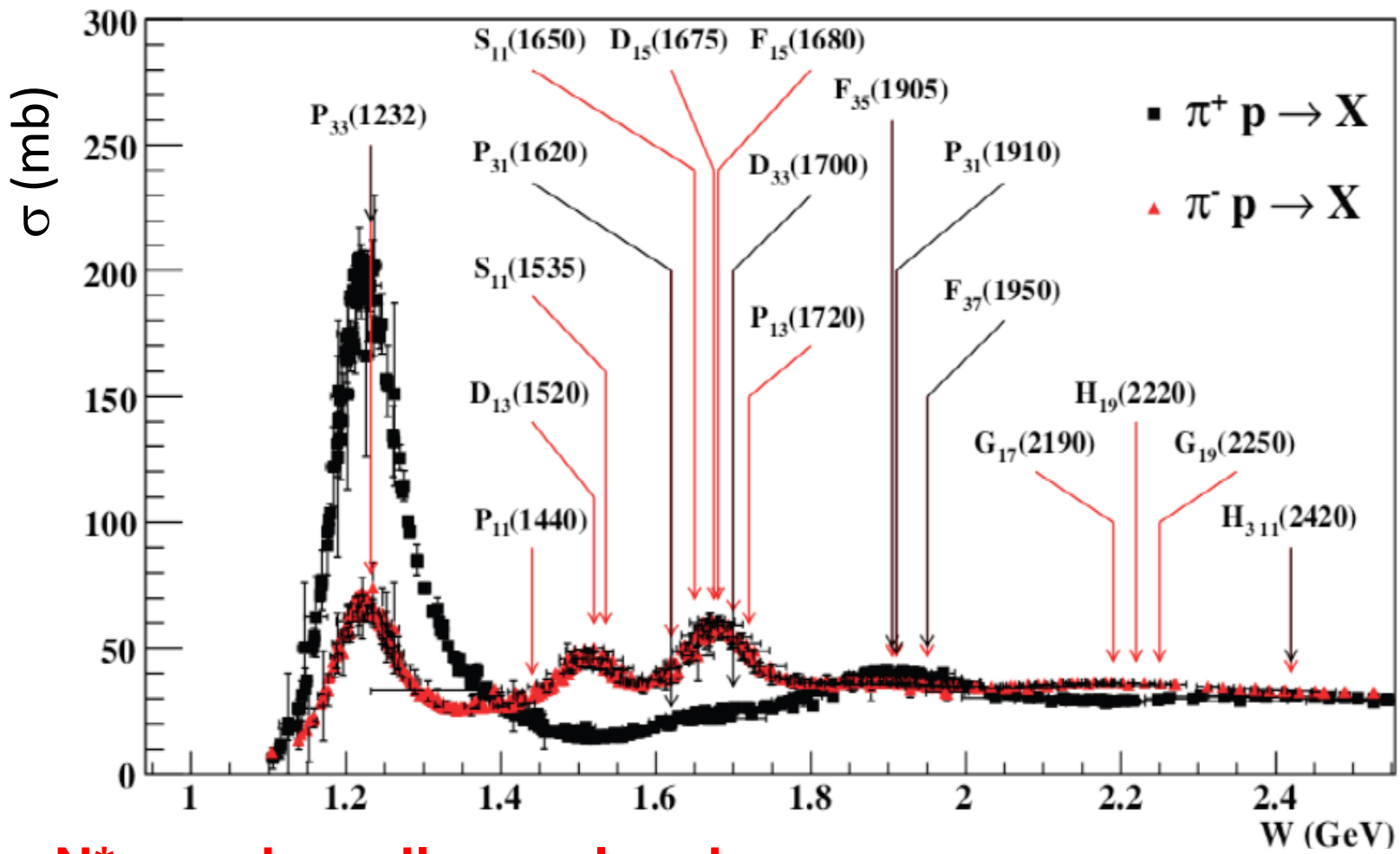
Coupled-channels picture of resonance excitation [Motivation]

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

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

$$T = \begin{pmatrix} T_{\pi N\to\pi N} & T_{\eta N\to\pi N} & T_{\gamma N\to\pi N} & T_{\rho N\to\pi N} & T_{\sigma N\to\pi N} & T_{K\Lambda\to\pi N} & T_{K\Sigma\to\pi N} \\ T_{\pi N\to\eta N} & T_{\eta N\to\eta N} & T_{\gamma N\to\eta N} & T_{\rho N\to\eta N} & T_{\sigma N\to\eta N} & T_{K\Lambda\to\eta N} & T_{K\Sigma\to\eta N} \\ T_{\pi N\to\gamma N} & T_{\eta N\to\gamma N} & T_{\gamma N\to\gamma N} & T_{\rho N\to\gamma N} & T_{\sigma N\to\gamma N} & T_{K\Lambda\to\gamma N} & T_{K\Sigma\to\gamma N} \\ T_{\pi N\to\rho N} & T_{\eta N\to\rho N} & T_{\gamma N\to\rho N} & T_{\rho N\to\rho N} & T_{\sigma N\to\rho N} & T_{K\Lambda\to\rho N} & T_{K\Sigma\to\rho N} \\ T_{\pi N\to\sigma N} & T_{\eta N\to\sigma N} & T_{\gamma N\to\sigma N} & T_{\rho N\to\sigma N} & T_{\sigma N\to\sigma N} & T_{K\Lambda\to\sigma N} & T_{K\Sigma\to\sigma N} \\ T_{\pi N\to K\Lambda} & T_{\eta N\to K\Lambda} & T_{\gamma N\to K\Lambda} & T_{\rho N\to K\Lambda} & T_{\sigma N\to K\Lambda} & T_{K\Lambda\to K\Lambda} & T_{K\Sigma\to K\Lambda} \\ T_{\pi N\to K\Sigma} & T_{\eta N\to K\Sigma} & T_{\gamma N\to K\Sigma} & T_{\rho N\to K\Sigma} & T_{\sigma N\to K\Sigma} & T_{K\Lambda\to K\Sigma} & T_{K\Sigma\to K\Sigma} \end{pmatrix}$$

Baryon resonances (N*s and Δ*s)

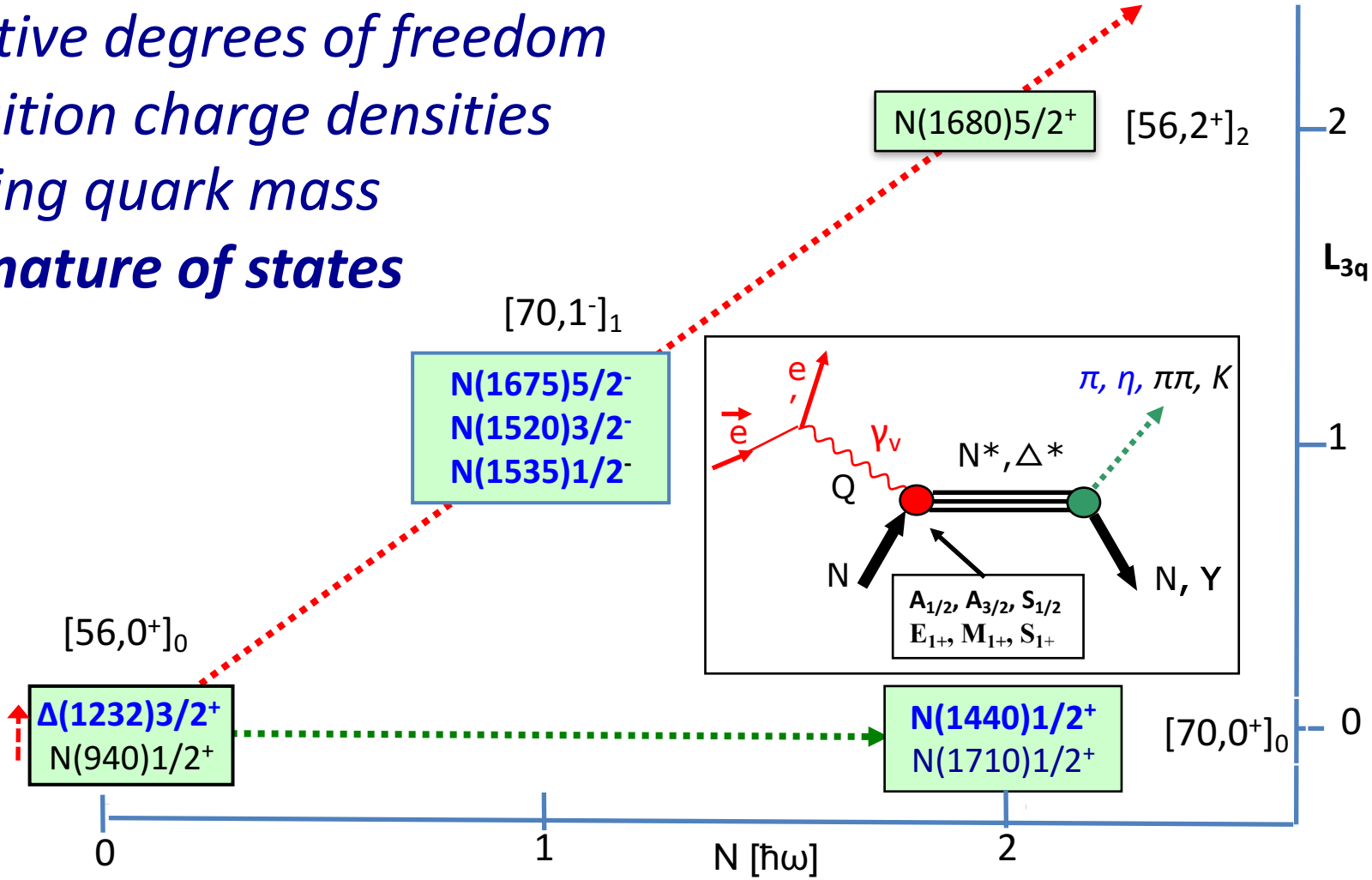


- **N*s are broadly overlapping**
- **Hard to disentangle without polarization observables**

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'pπ+π-)

Evidence for New N* in KY Final State

State N(mass)J^P	PDG pre 2010	PDG 2016	KΛ	KΣ	Nγ
N(1710)$1/2^+$	***	****	****	**	****
N(1880)$1/2^+$		**	**		**
N(1895)$1/2^-$		**	**	*	**
N(1900)$3/2^+$	**	***	***	**	***
N(1875)$3/2^-$		***	***	**	***
N(2150)$3/2^-$		**	**		**
N(2000)$5/2^+$	*	**	**	*	**
N(2060)$5/2^-$		**		**	**

Study these states in electroproduction and extend to higher masses

Annalisa D'Angelo ECT* 2017

The Quest for Excited Nucleons

Precision meson photo-production data led to the discovery of several new states and the full establishment of poorly known states, in the mass range up to 2200 MeV.

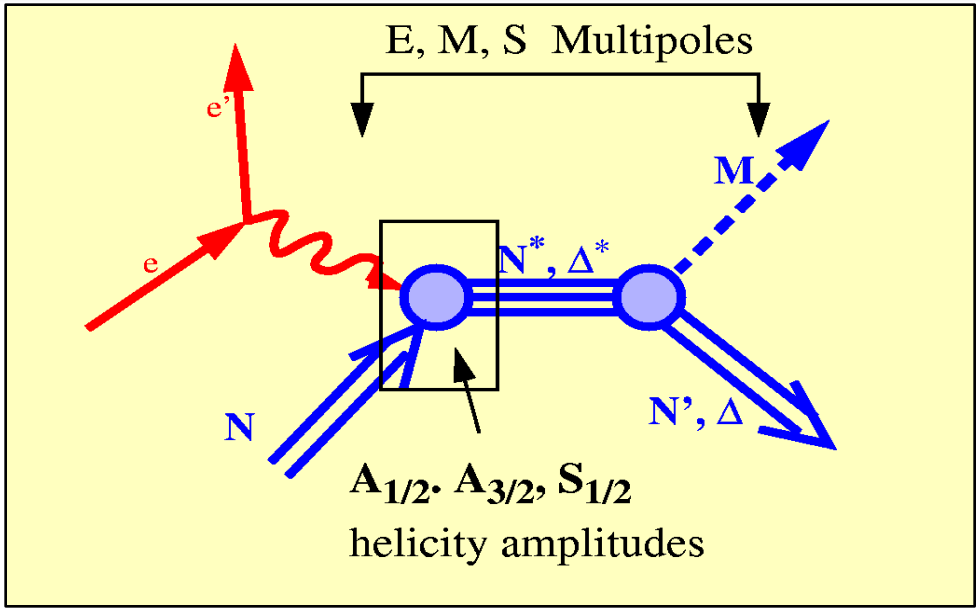
State N((mass)J^P	PDG 2010	PDG 2018
N(1710)$1/2^+$	***	****
N(1880)$1/2^+$		***
N(2100)$1/2^+$	*	***
N(1895)$1/2^-$		****
N(1900)$3/2^+$	**	****
N(1875)$3/2^-$		***
N(2120)$3/2^-$		***
N(2060)$5/2^-$		***
Δ(1600)$3/2^+$	***	****
Δ(1900)$1/2^-$	**	***
Δ(2200)$7/2^-$	*	***

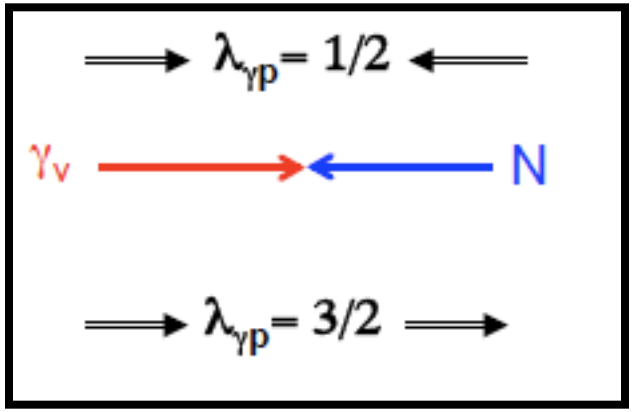
**** - existence is certain
*** - existence is likely
** - evidence of existence is fair
* - evidence of existence is poor

http://pdg.lbl.gov/2019/reviews/rpp2018-rev-n-delta-resonances.pdf

Volker Burkert NSTAR 2019

Electroproduction





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

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

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

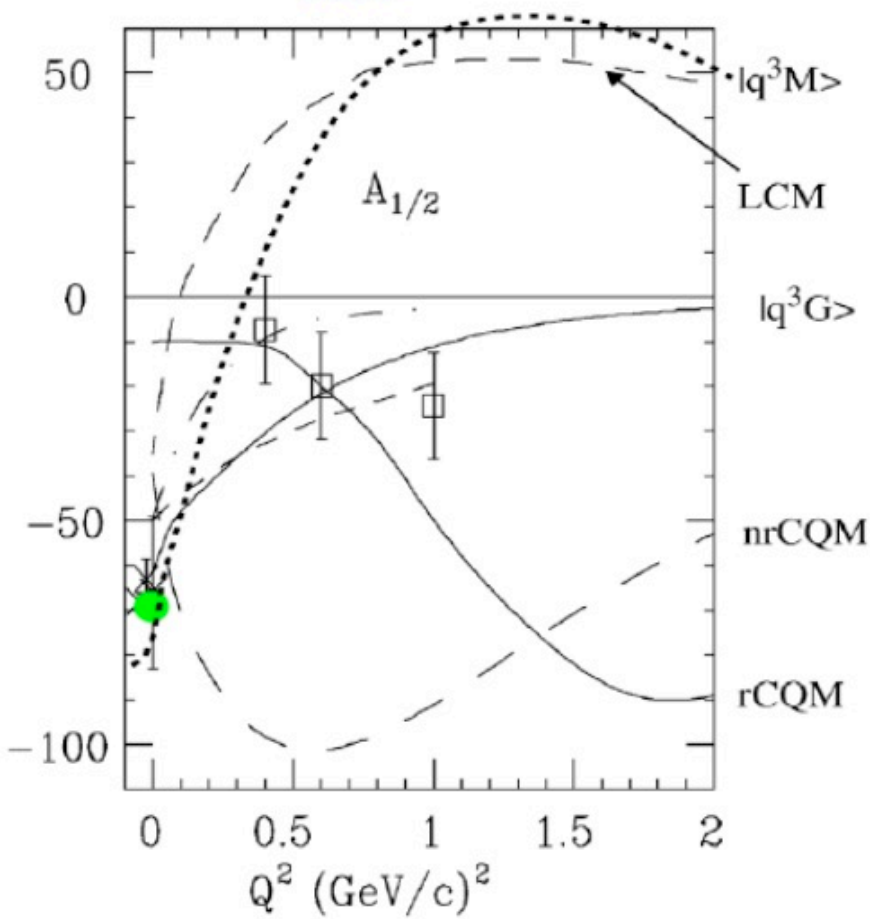
$S_{1/2}$: $\langle N^*, S_z^* = +\tfrac{1}{2} | \varepsilon_\mu^{(0)} J^\mu_{em} | N, S_z = +\tfrac{1}{2} \rangle$

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

Longitudinal
- $S_{1/2}$

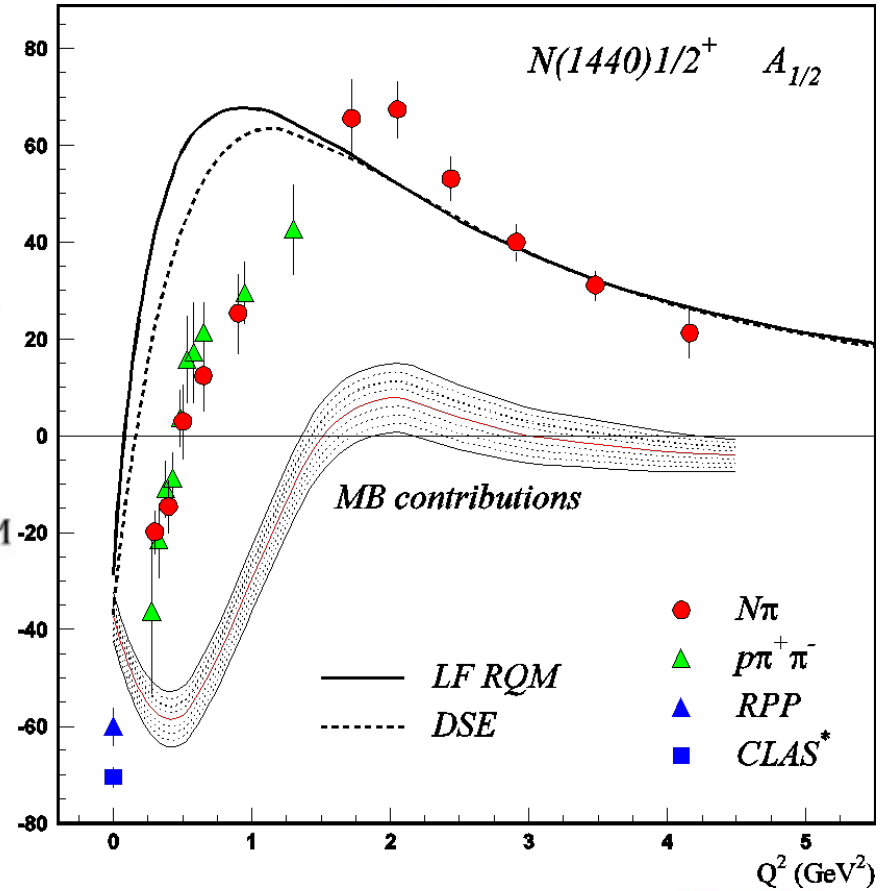
Roper resonance in 2002 & 2016

2002



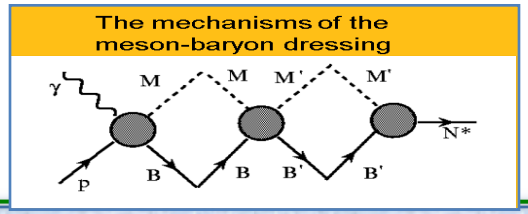
V. Burkert, Baryons 2002

2016

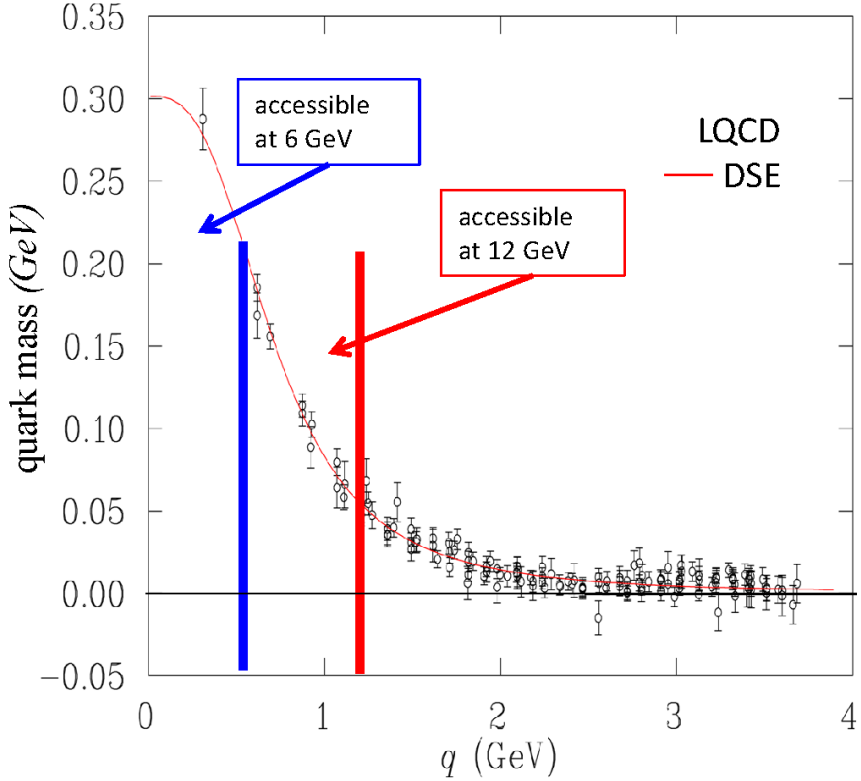


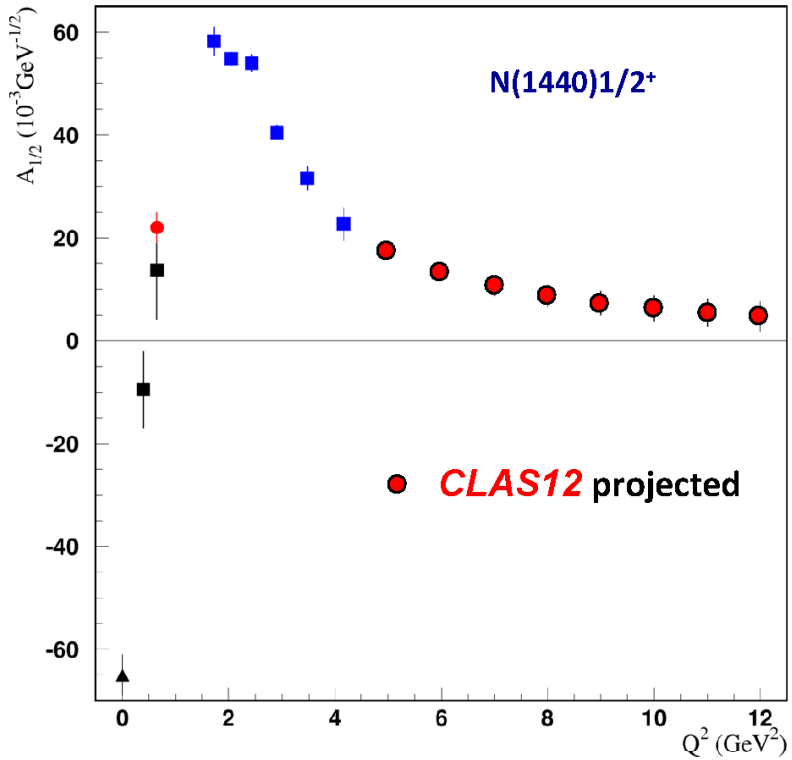
V. D. Burkert, Baryons 2016

DSE describe successfully the nucleon elastic and the transition $N\to\Delta(1232)3/2^+$, $N\to N(1535)1/2^-$ form factors <u>with the same dressed quark mass function (J.Segovia, et al., PRL 115, 171801 (2015)).</u>



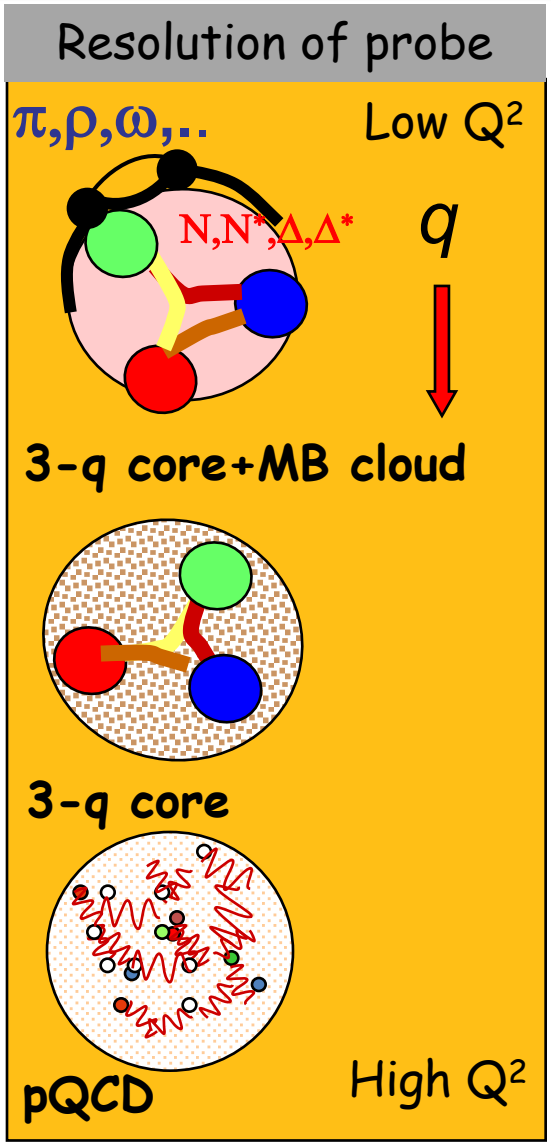
Probing the running quark mass with CLAS12





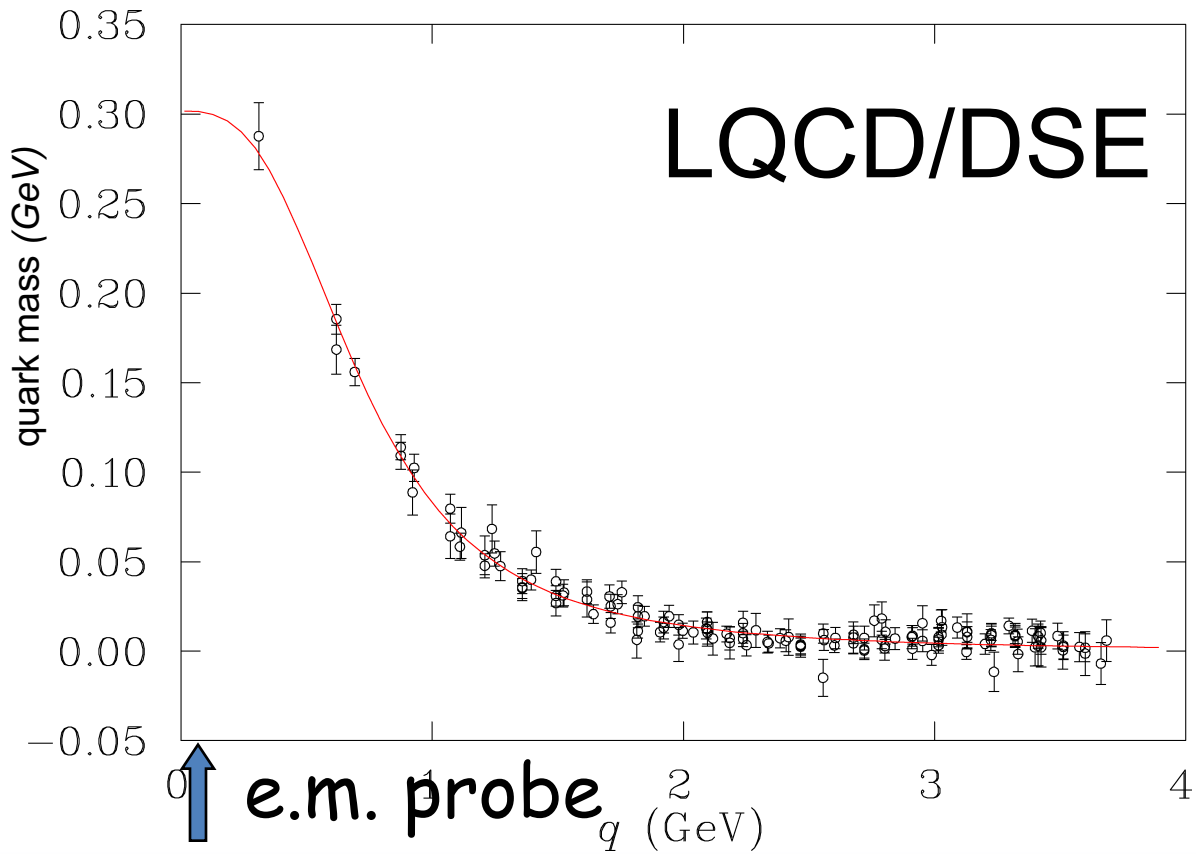
Nucleon resonance transitions amplitudes probe the quark mass function from constituent quarks to dressed quarks and elementary quarks.

One clear goal



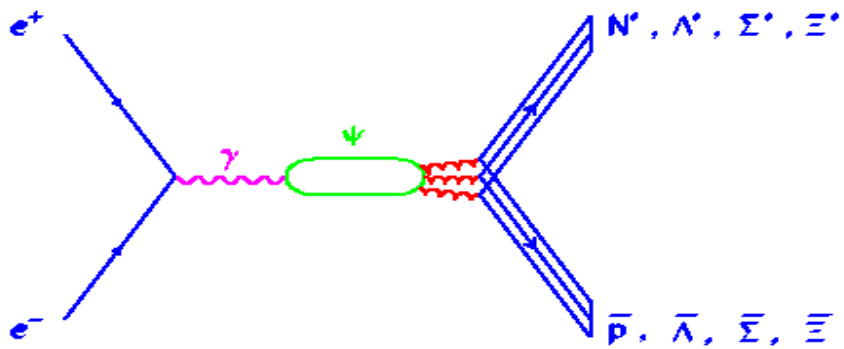
Allows us to address central the question:

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



Baryon spectroscopy from J/ψ decays at BES/BEPC

$$J/\Psi \rightarrow \overline{B}BM \Rightarrow N^*, \Lambda^*, \Sigma^*, \Xi^*$$

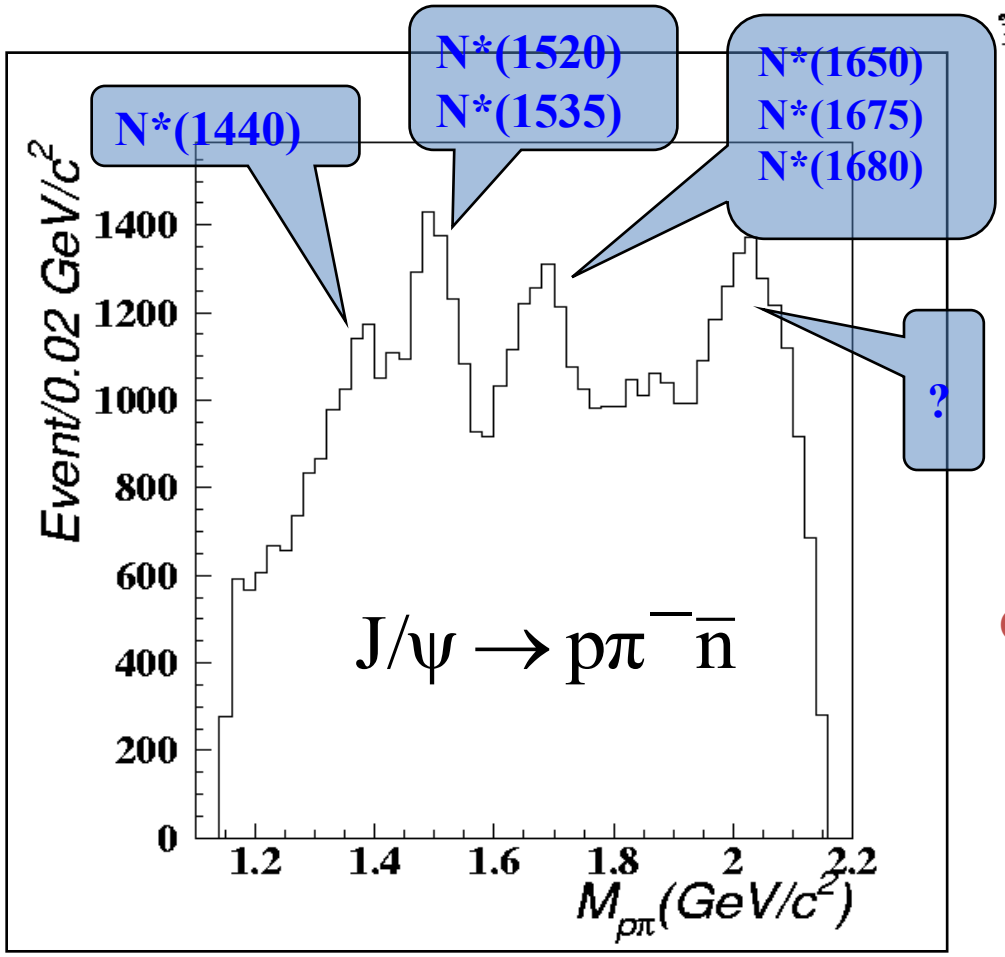


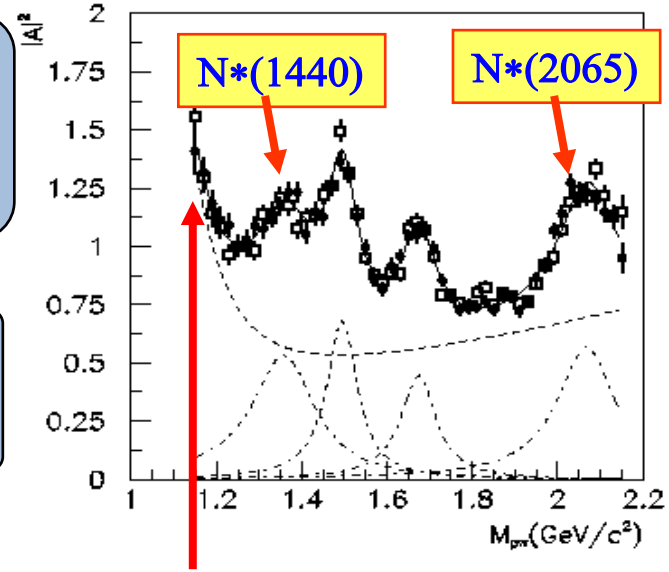
New mechanism for baryon production & an ideal isospin filter

BingSong Zou MENU 07

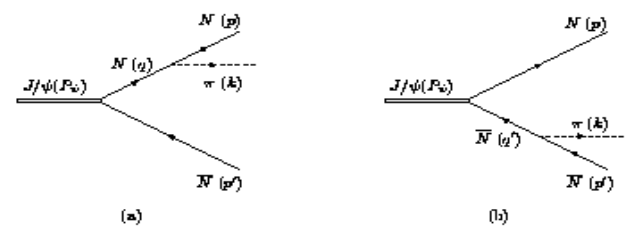
PRL 97, 062001 (2006) PHYSICAL REVIEW LETTERS week ending 11 AUGUST 2006

Observation of Two New N^* Peaks in $J/\psi \to p\pi^-\bar{n}$ and $\bar{p}\pi^+ n$ Decays





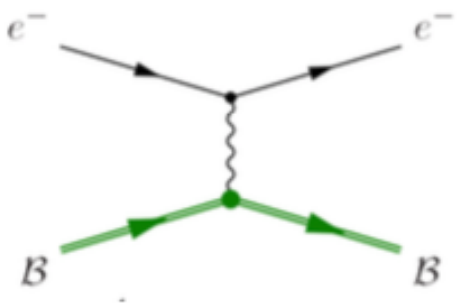
Off-shell nucleon contribution



Nucleon-pole diagrams for $J/\psi \to \pi N \bar{N}$ decay.

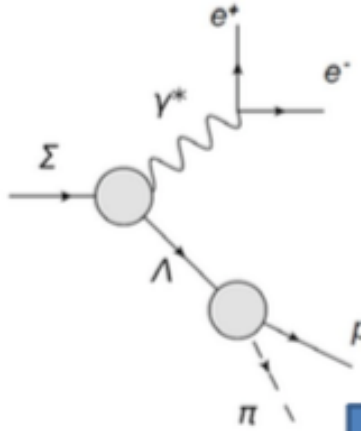
BingSong Zou MENU 07

Space-like *vs.* time-like FF's



$e^- B \to e^- B$

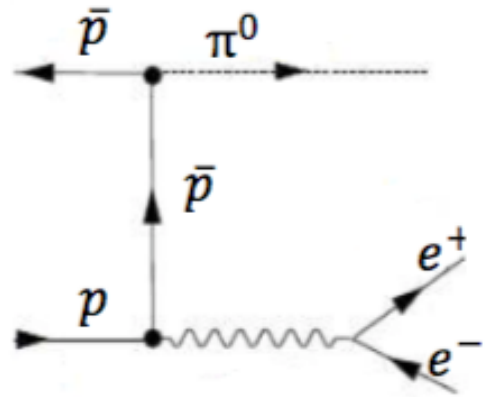
e.g. JLAB



$B_1 \to B_2 e^+ e^-$

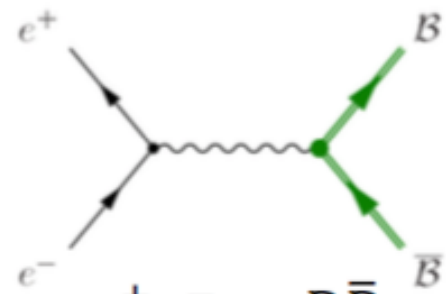
HADES

PANDA



unphysical region

PANDA



$e^+e^- \to B\bar{B}$

$\bar{B}B \to e^+e^-$

BES III

BELLE II

PANDA

$-Q^2 = q^2 < 0$ $\quad$ $q^2 = 0$ $\quad$ $q^2 = (m_{B1} - m_{B2})^2$ $\quad$ $q^2 = (m_{B1} + m_{B2})^2$ $\quad$ q^2

$B_1 \to B_2 \gamma$

UPPSALA UNIVERSITET

Time-like form factors

- Time-like FF's are complex:
  - $G_E(q^2) = |G_E(q^2)| \cdot e^{i\Phi_E}$
  - $G_M(q^2) = |G_M(q^2)| \cdot e^{i\Phi_M}$
  - $\Delta\Phi = \Phi_M - \Phi_E$ = relative phase between G_E and G_M
- The phase between G_E and G_M – polarization effects on the final state even when the initial state is unpolarized.

BESIII

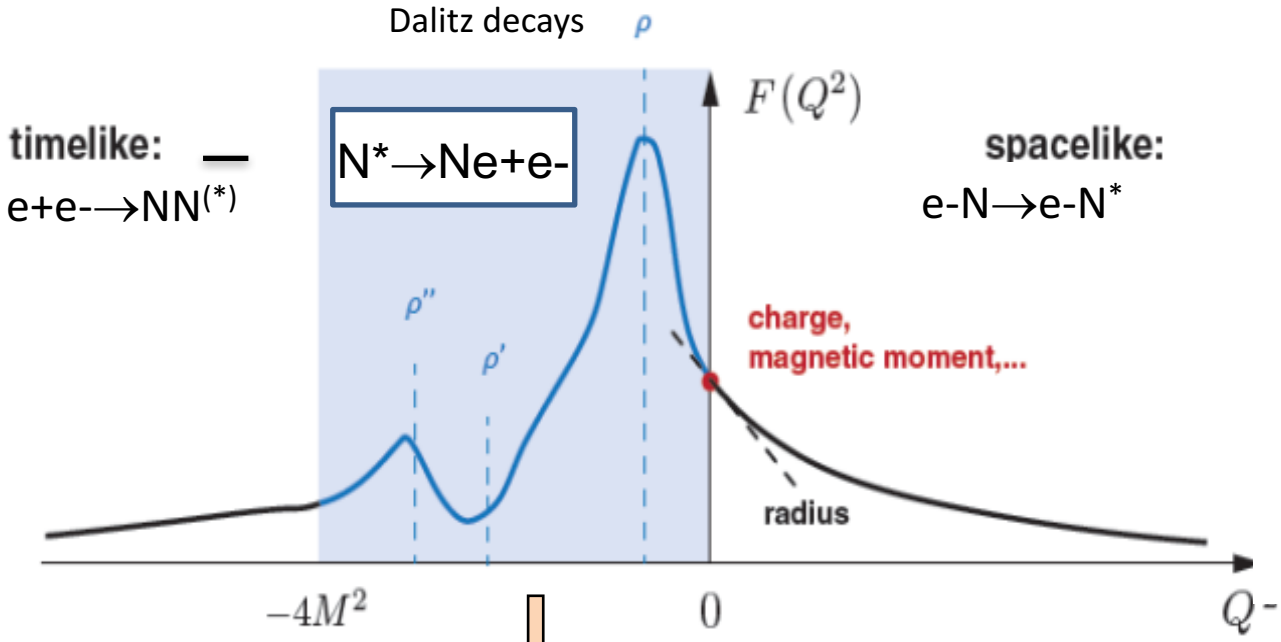
p̄anda

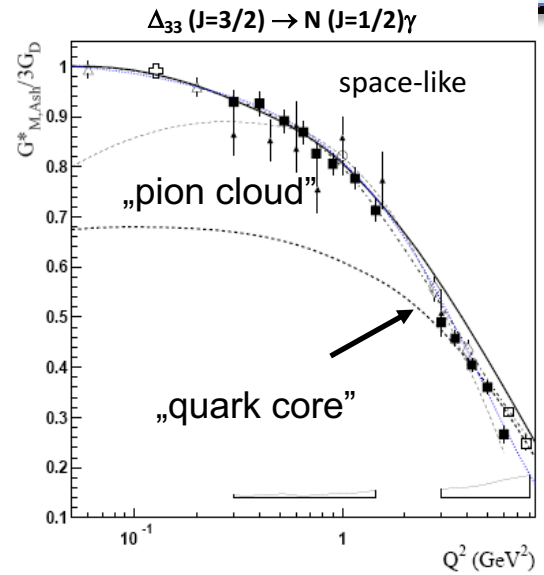
Discussion Focus and Ultimate Goals

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.

White Paper

Electromagnetic structure of baryons





I. G. Aznauryan and V. D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)

$$d\Gamma(R \to Nl^+l^-) = \frac{\alpha}{3\pi} d\Gamma(R \to N\gamma^*)[1 - \frac{4m_l^2}{q^2}]^{1/2}[1 + \frac{2m_l^2}{q^2}]\frac{dq^2}{q^2}$$

for example for J=1/2

$$\Gamma(R \to N\gamma*) = H(m, M)(2|G^{\pm}_{M/E(M)}|^2 + \frac{M}{m}|G_C(M)|^2)$$

„QED"

R→ Nγ* : em. Transition Form Factors

R (J≥3/2) : (3) G_M (q^2), G_E (q^2) , G_C (q^2)

R (J=1/2) : (2) $G_{M/E}$ (q^2), G_C (q^2)

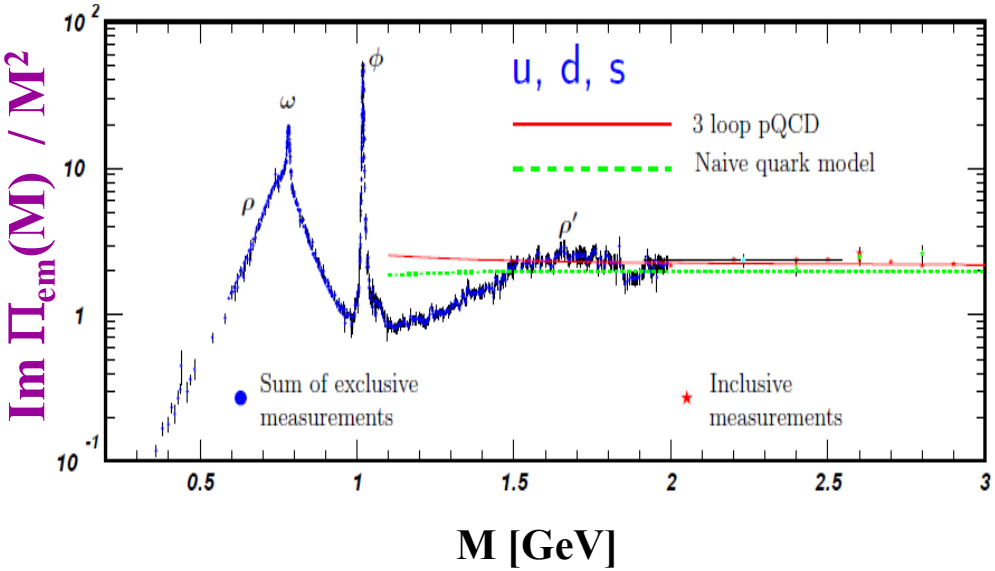
.. or covariant eTFF

M. I. Krivoruchenko, et. al
Annals Phys. 296, 299 (2002)

Change in Degrees of Freedom

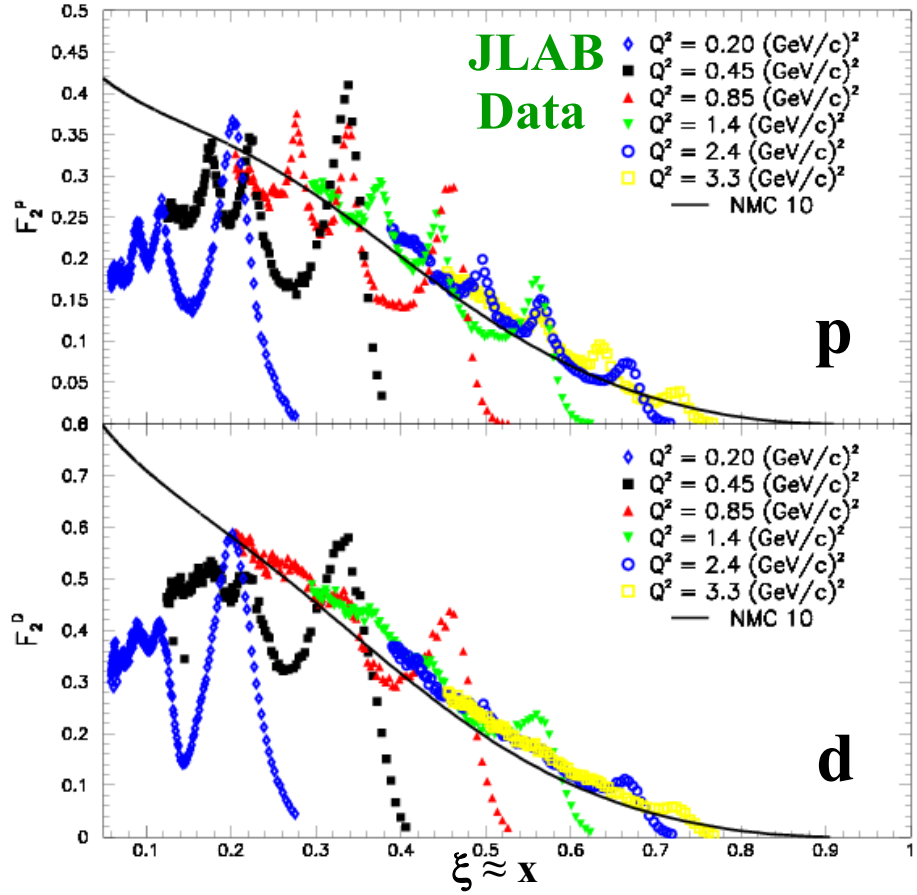
- As function of q^2

Timelike: $e^+e^- \rightarrow$ hadrons



- $Q^2_{\text{dual}} \sim 2.5\text{-}3\ \text{GeV}^2$
- depends on channel?

Spacelike: F_2-Structure Funct.



- average → Quark-Hadron Duality
- lower onset-Q^2 in nuclei?

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).
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?

What have we been doing for the past 4 years?

- Progress is slow.
- What do we need to do?
- How do we ramp up progress?

Would do you think?


Thank
You
Merci
Gracias
Danke
Spacibo
Hvala
Arigatô
KamSahHamnida
Mèsi
Xièxie
Grazie
Chokrane
Kiitos
Dziakuju
Mauruuru
GratiasAgimus
Ačiū
Dankie
Tak
TänanVäga
Motashakkeram
GratiasAgo
KopKhunKha
Gracie
CámOn
Multumesc
Saha
Salamat
Obrigado
Bayarlalaa
Nirringrazzjak
Efharisto
Faleminderit
Gràcies
NajisTuke
TerimaKasih
Mercé
Taiku
Rahmat
Blagodaram
ThintKo
Buznyg
WaadMahadsantahay
TapadhLeat
Köszönöm
Murakoze
aDank
Takk
BarakAllahuFiik
Grazzi
Tanemirt
Tenki
Grandmercé
Chnorakaloutioun
Gratzias
Barkal
Sagolun
Tanmirt
Akiba
Gràcie
Asante
Mahalo
Graciñas
Marahaba
Diky
TakkFyri
Miigwetch
Aabhar
Trugarez
Dhanyavaad
Bedankt
Zikomo
Enkosi
M-Sapo
Ngiyabonga
Shukriya
AsanteSana
Waita
Matondo
Welalin
TangioTumas
Dhanyavad
Sukriya
Mamnun
Taiman
KeYaLeboha
Vinaka
Dankon
Barka
Toda
Meisi
Dhanyavadagalu
Nizzik ajr
Aguyjé
Dakujem
aNiKié
Nandri
Merkzi
Akun
Meharbani
ÇoxSağOlun
Blagodaria
Dhanyavadalu
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Eskerrik Asko
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Paldies
Üpereßieut
ANiKie
Teşekkür Ederim
Sobodi
AabhariAahe
Yekeniele
KurreSumanga
KhobChaiDeu
Milester
Trugéré
Misaotra
Akpé
Graçie
MaloTeOfa
KoxSagOlun
KyayTzuTinPaTe
GoRaibhMaithAgat
Mochchakkeram
Dhanyabaad
KopKhunKrap
Tau
Nanni