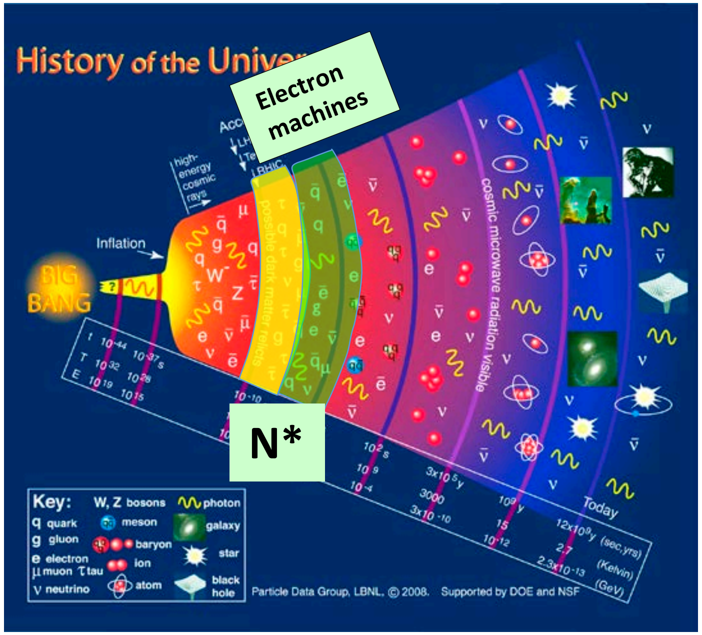
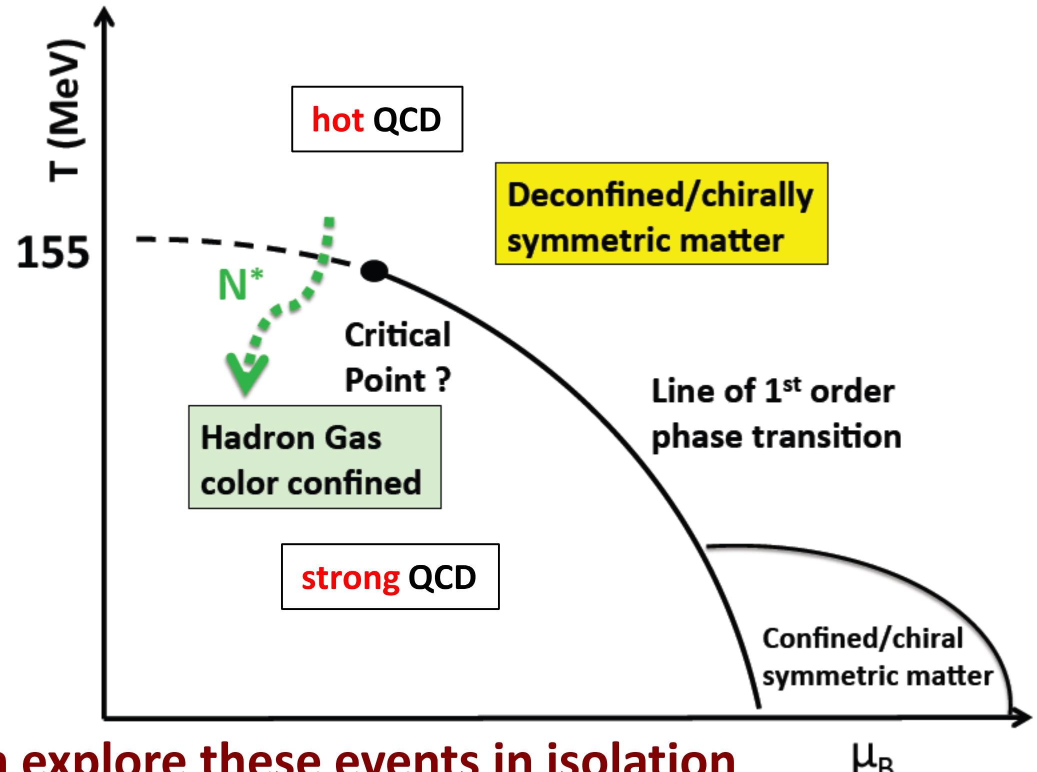
Role of N*'s in the history of the Universe



Dramatic events occur in the micro-second old universe during the transition from the QGP phase to hadron phase.

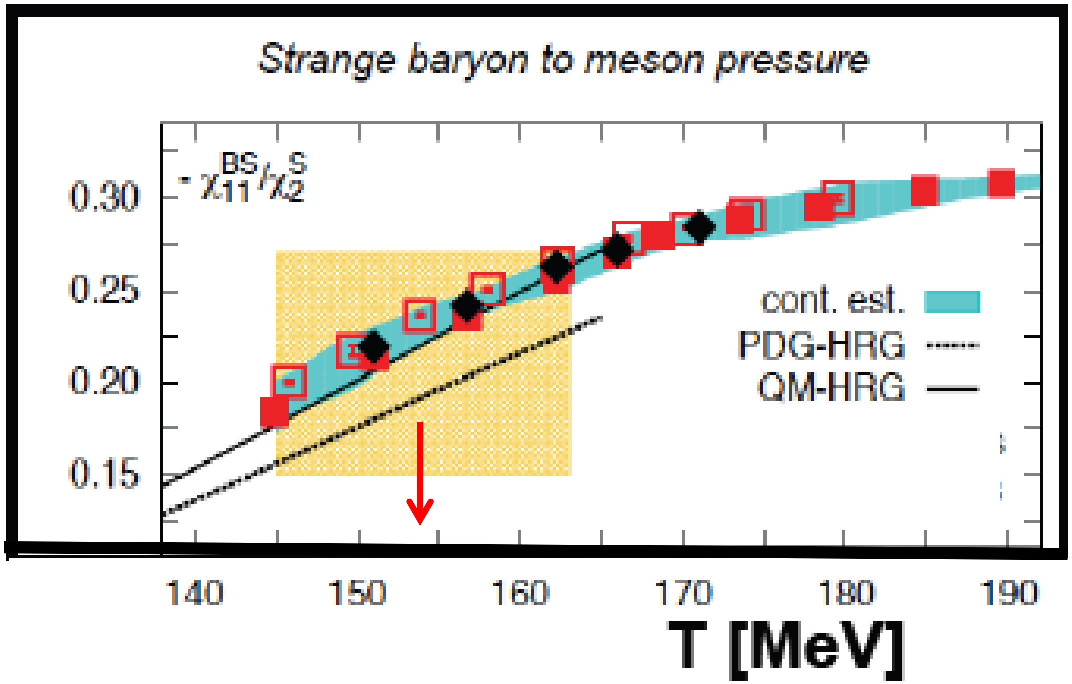
- Chiral symmetry is broken
- Quarks acquire dynamical mass
- Quark resonances occur
- Color confinement established

=> strong QCD is born



With JLab electron machine we can explore these events in isolation

The quest for missing excited baryons

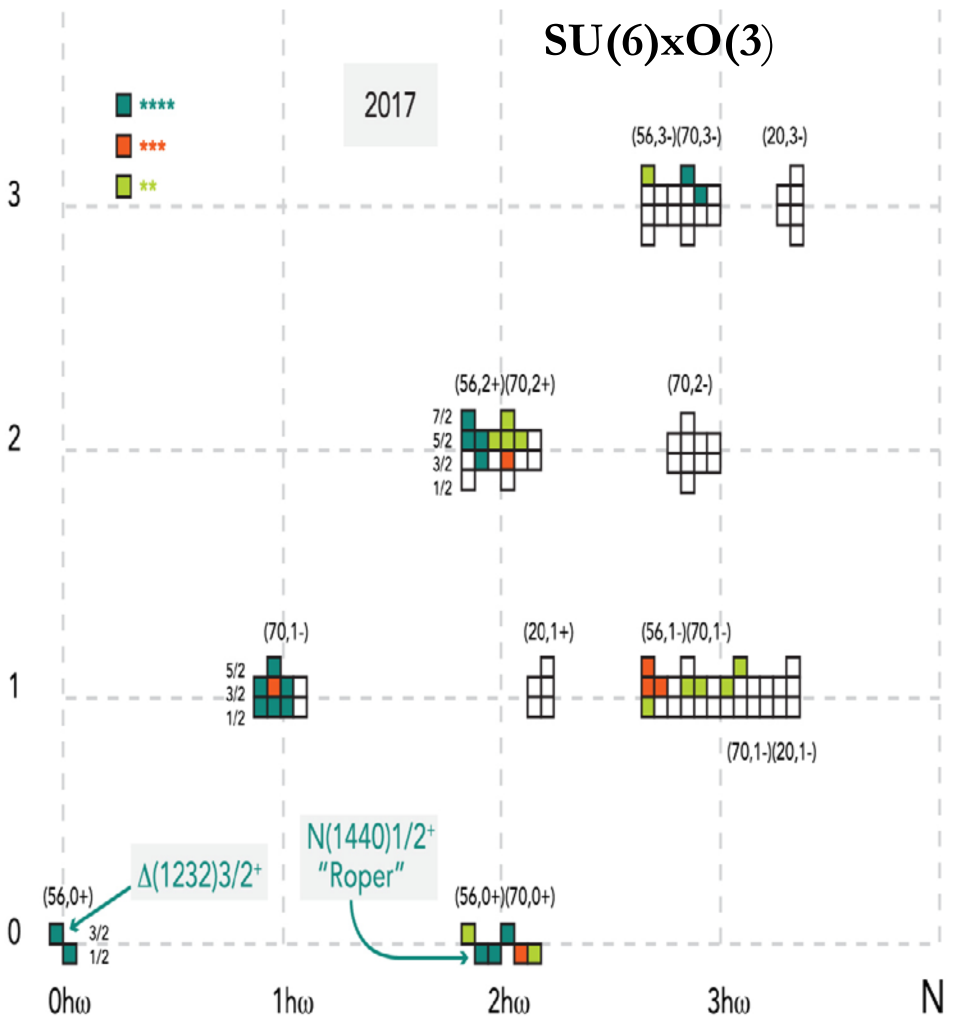


A. Bazavov et al., Phys.Rev.Lett. 113 (2014) 7, 072001

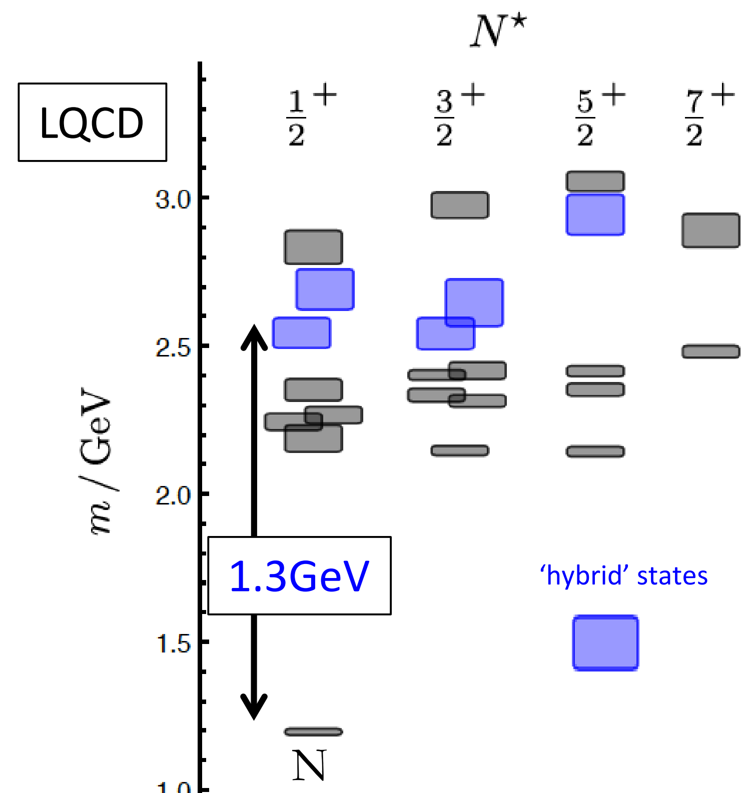
Baryons in the PDG **of all flavors (u, d, s, c)** fall short of explaining the freeze out behavior

➔ ***We do not describe the transition near the cross over temperature without accounting for the full complement of quark model baryon resonances.***

Projected Baryons N*, Δ*, N_G,

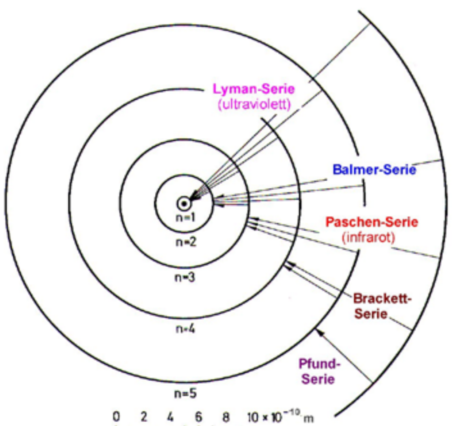


J.J. Dudek and R.G. Edwards, PRD 85 (2012) 054016

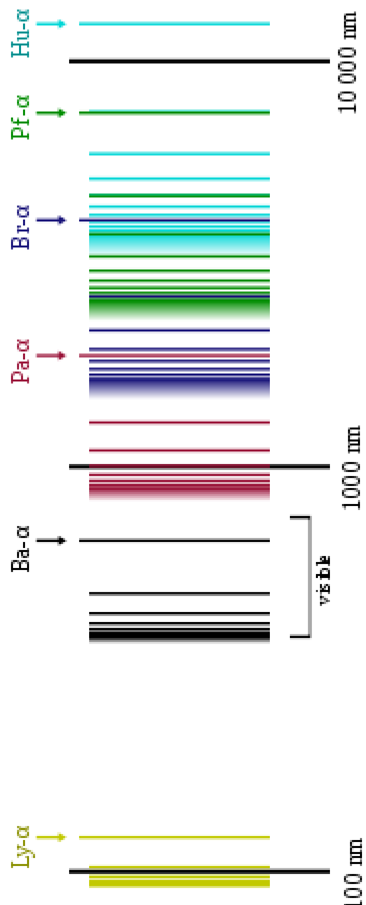


From the H spectrum to the N* spectrum

Niels Bohr, model of the hydrogen atom, 1913.

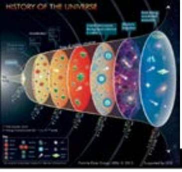


Spectral series of hydrogen

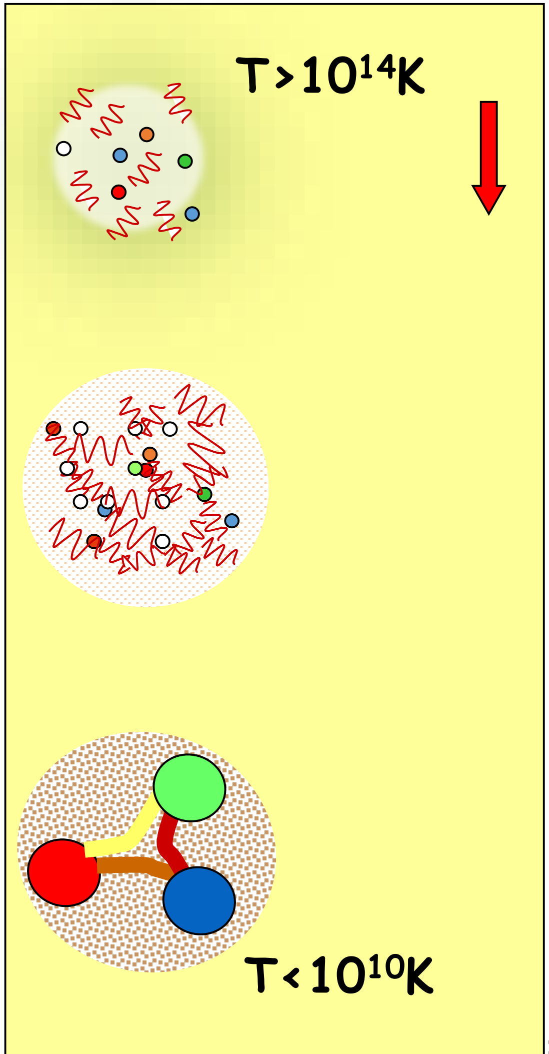


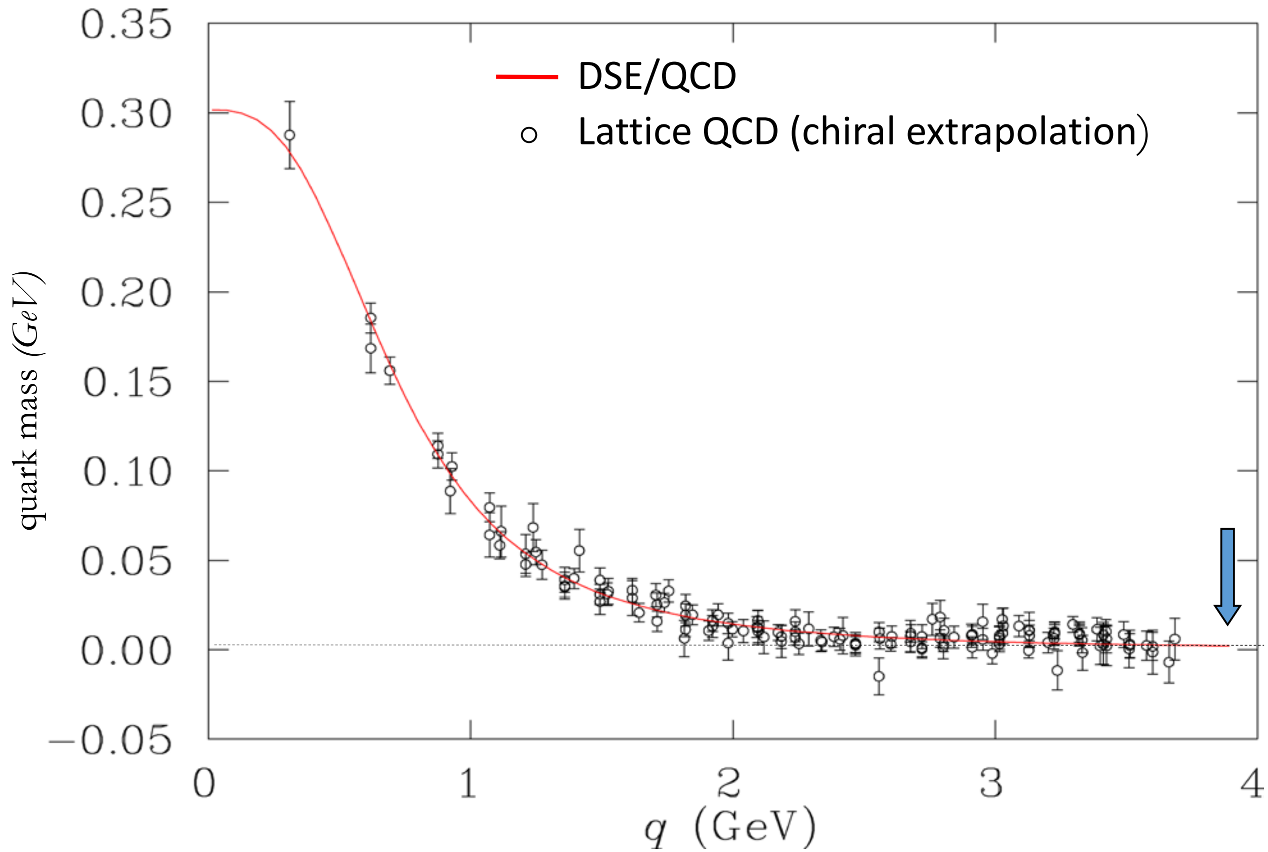
- Understanding the hydrogen atom requires understanding its spectrum of *sharp energy levels*
  -> From the *Bohr model* to ***QED***

- Understanding the proton requires understanding its energy spectrum of *broad energy levels*
  -> From the *quark model* to **strong *QCD***



How do light quarks acquire mass?





As the Universe cools down, quarks couple to gluons and become massive. They form resonances with other quarks.

=> **Measure N* observables that are sensitive to the quark mass.**

The Burning Questions

- What are the key roles of N* resonances in *inclusive DIS* in the context of *quark-hadron duality*? => next session?

- What are the key elements to demonstrate the theoretical consistency of the interplay of *confining* and *chiral* forces for the nucleon and its excited states? (Organizers)

- How should we search *for (un)predicted excited baryon* states*?* What are the relevant channels at high mass*?* Are analysis frameworks sufficiently flexible to find new states?

- Can we probe the *running quark m*ass? What are the observables? Is the interpretation sound?

- Can we probe baryon *resonance transitions GPDs* using N^*VCS data?

- What theory support is needed for the 12 GeV N* program (Mokeev)

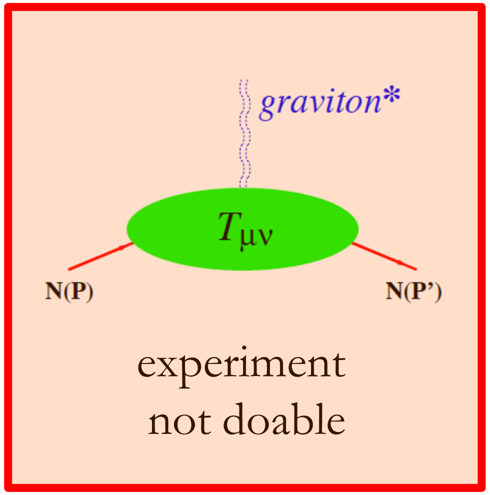
Chiral and confining forces in nucleon and N*

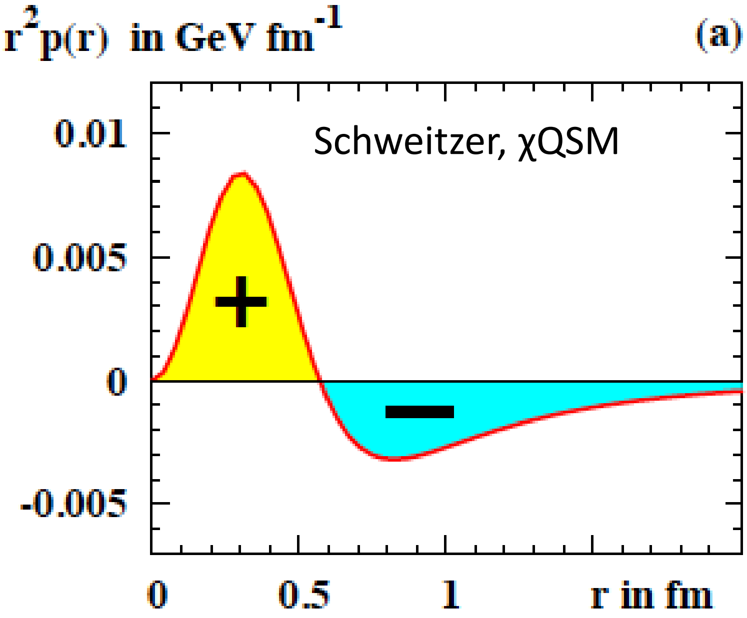
Chiral forces & confining forces.

What are the key elements to demonstrate the theoretical consistency of the interplay of *confining* and *chiral* forces for the nucleon and its excited states?

EMT

H. Pagels, PR 144, 1966





2nd Mellin moment of GPD H^q

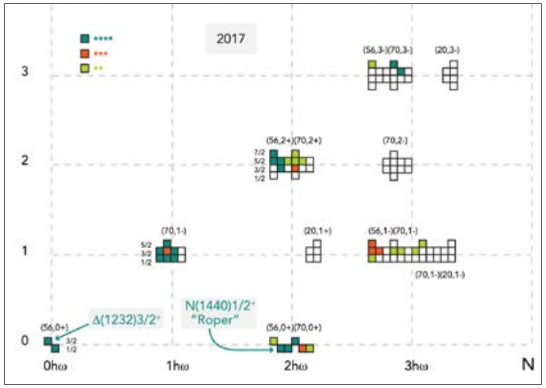
$$\int dx\, x\, H^q(x,\xi,t) = A^q(t) + \tfrac{4}{5}\xi^2 d_1^q(t)$$

The Burning Questions

Search for predicted excited baryon states.

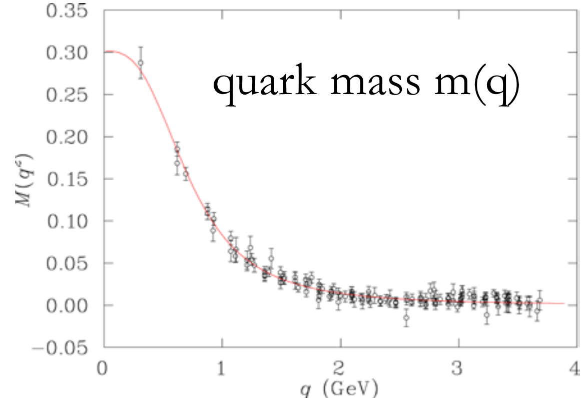
=> We (will) have the data in range of M = 1.8 – 3 GeV

⇒ Do we have the tools for complex analysis of 2- and 3-body final states, e.g. Nπ, KY, Nππ...at M = 1.8 – 2.5 GeV and search for new states in a systematic way?



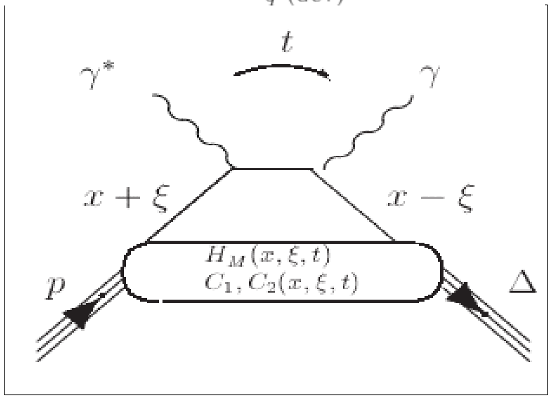
Probing the running dynamical quark mass.

=> Do we have the tools to extract transition form factors of prominent baryon resonances for Q^2 = 5 – 12 GeV^2, and interpret them within QCD linked approaches.



Probing baryon resonance transitions within GPD framework using N*VCS data.

⇒ Can we develop the GPD framework for a few lower-spin states Δ(1232), N(1440)1/2+, N(1535)1/2-, [N(1520)3/2-, N(1685)5/2+]



Discussion on Theory Support of the N* Program with CLAS/CLAS12

1. **What can we learn on strong QCD dynamics from the CLAS/CLAS12 results on $\gamma_v NN^*$ electrocouplings in the mass range W<2.0 GeV and 0.<Q^2<12 GeV^2 within the framework of :**

- approaches based on the first principles of QCD (Lattice and Continuous QCD,…,) ;
- the models with a traceable connection to the QCD (DSE hadron kernels, chiral soliton, large Nc,…);
- quark models that employ effective potentials (quark running mass and dynamical structure, emergence of MB-cloud from confined quark core, studies over full N* spectrum, ``missing" and hybrid-baryon masses and electrocouplings,…) ?

2. **Extension of the global coupled channel approaches for extraction of $\gamma_v pN^*$ electrocouplings from the CLAS/CLAS12 electroproduction data (Argonne/Osaka, Julich/GWU, Bonn/Gatchina,…):**

- capabilities to cover the range of W<2.5 GeV and photon virtualities Q^2<12 GeV^2 , implementation of quark degrees of freedom;
- the π^+n, π^0p, $\pi^+\pi^-p$, and KY electroproduction amplitudes fit to the CLAS/CLAS12 data will be obtained including resonant, non-resonant, and any particular term contributions. How we can use fit to the data individual channel amplitudes in the global multi-channel analyses?

3. **Preparing for the next step in the N* structure studies:**

- Modeling of the transition GPDs: $p\rightarrow\Delta(1232)3/2^+$, $p\rightarrow N(1440)1/2^+$, $p\rightarrow N(1520)3/2^-$, $p\rightarrow N(1535)1/2^-$, and $p\rightarrow N(1680)5/2^+$ accounting for the constraints imposed by the CLAS/CLAS12 results on these resonance electrocouplings at Q^2<12 GeV^2;
- Development of the reaction models for the transition GPD extraction from the $\gamma_r N\pi$ -electroproduction off protons.

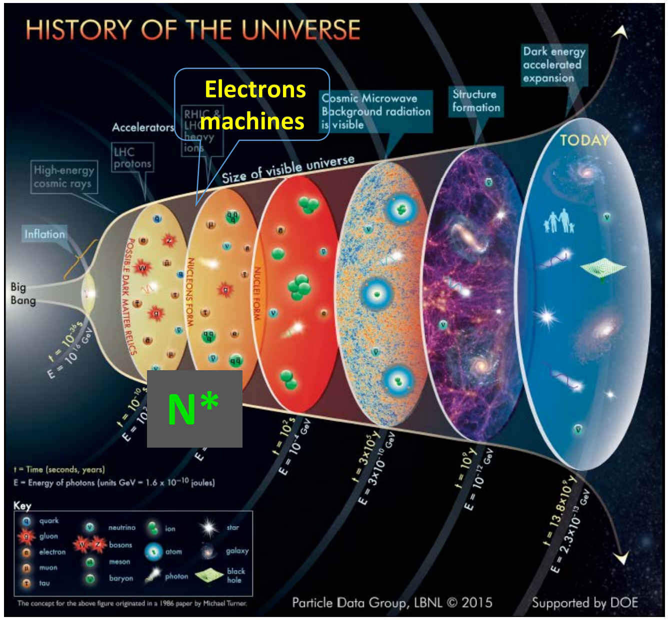
Summary of the Results on $\gamma_v pN^*$ Electrocouplings from CLAS

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 0.5-1.5

The values of resonance electrocouplings can be found in: https://userweb.jlab.org/~mokeev/resonance_electrocouplings/ (see back-up slides for more details on the available results).

In 1-2 years, $\gamma_v pN^*$ electrocouplings of most nucleon resonances in the mass range up to 2.0 GeV will become available at $0<Q^2<5.0$ GeV^2.

Role of N*'s in the history of the Universe



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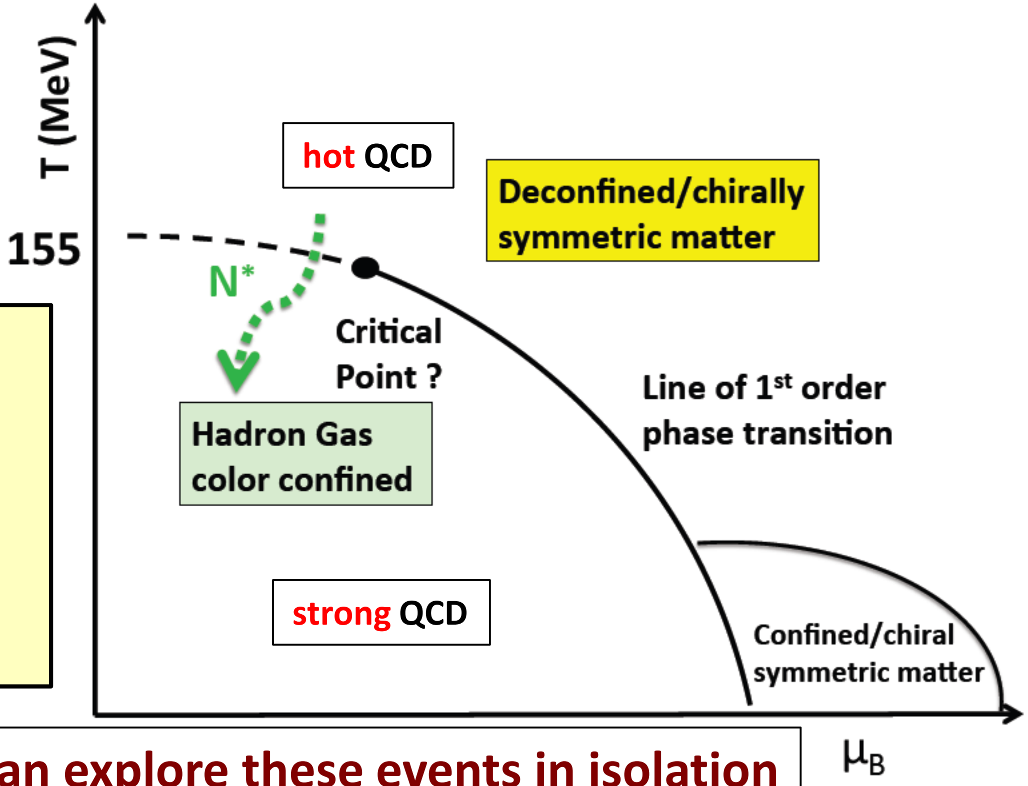

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