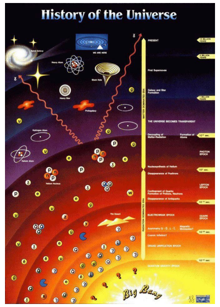
Today 7 years ago

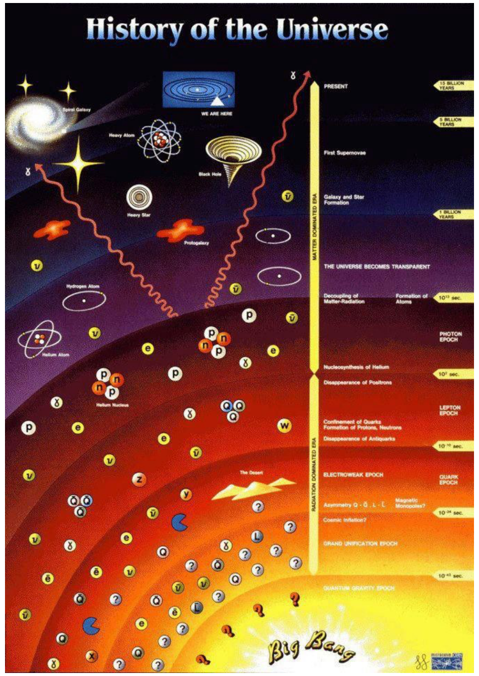
On November 6, 2012, Charles Darwin received 4,000 write-in votes from voters in Athens-Clarke County, Georgia, protesting the reelection of an anti-science fundamentalist, Paul Broun, who ran unopposed in the general election as a U.S. Representative. Broun sat on the **Science, Space and Technology Committee.** Yet, on 27 Sep 2012, he called evolution and the Big Bang Theory, **"lies straight from the pit of hell".**



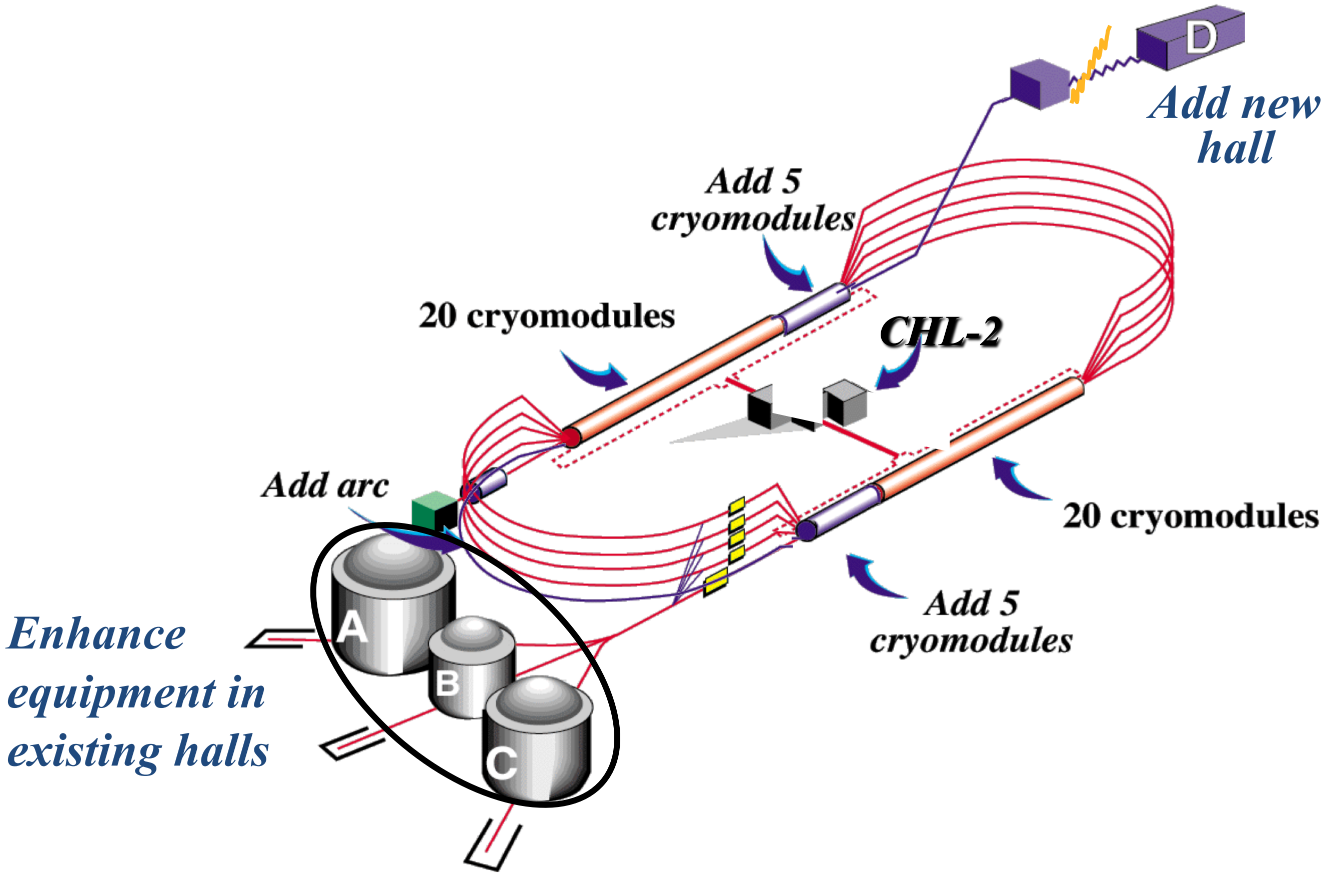
Exploring Strong QCD in the JLab Experiments of the 12 GeV Era

Volker D. Burkert

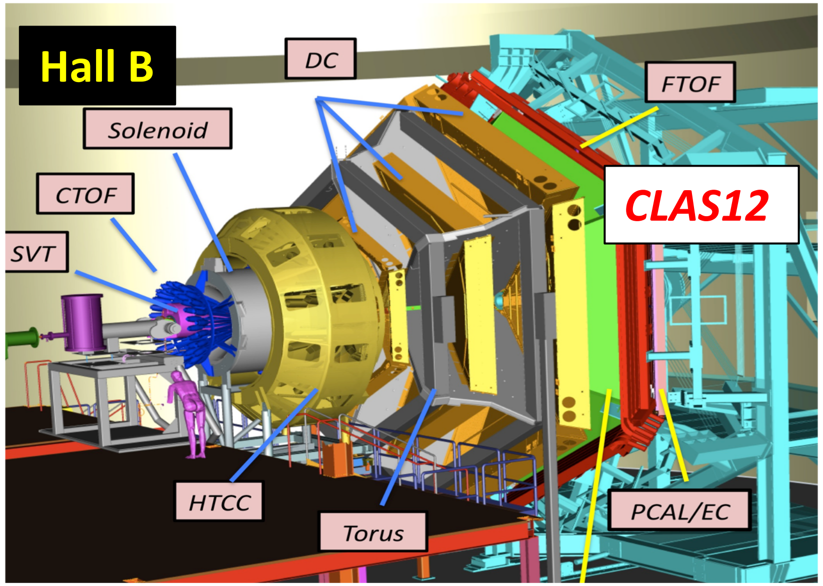
Jefferson Laboratory

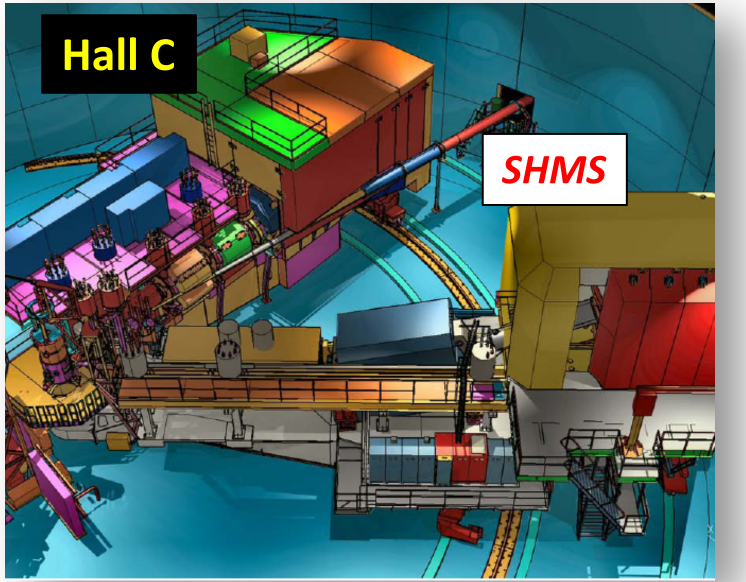


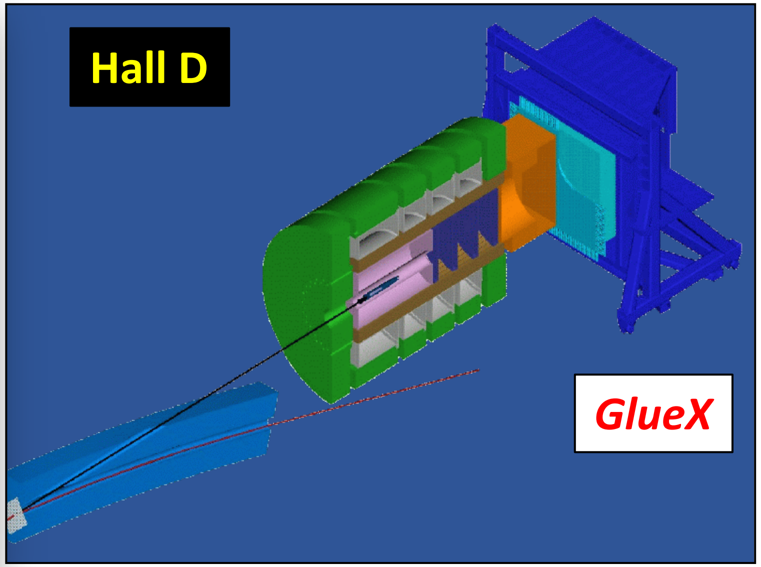
JLab @ 12 GeV Project

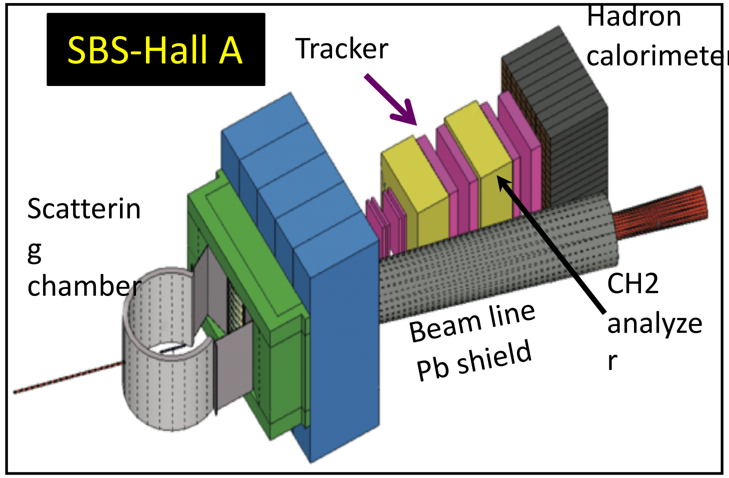


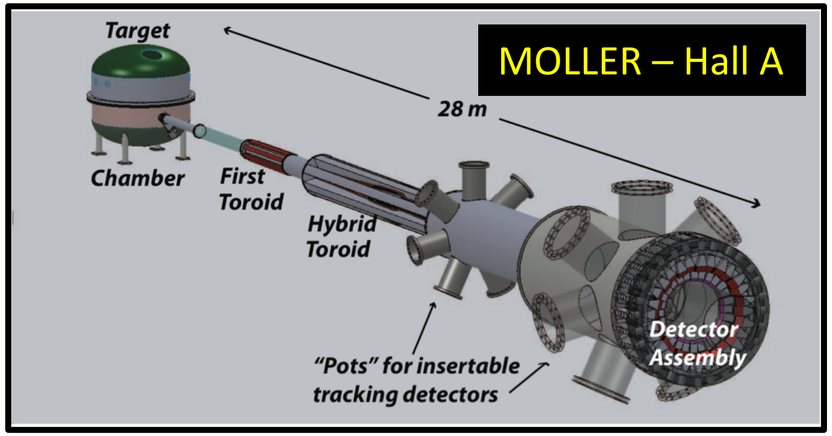
JLab @ 12 GeV Equipment

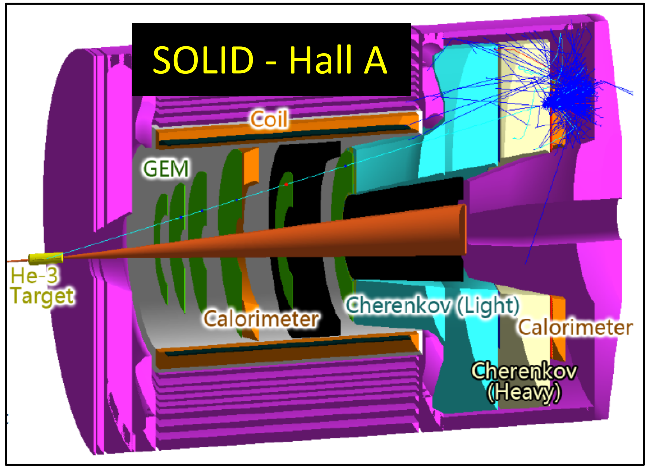




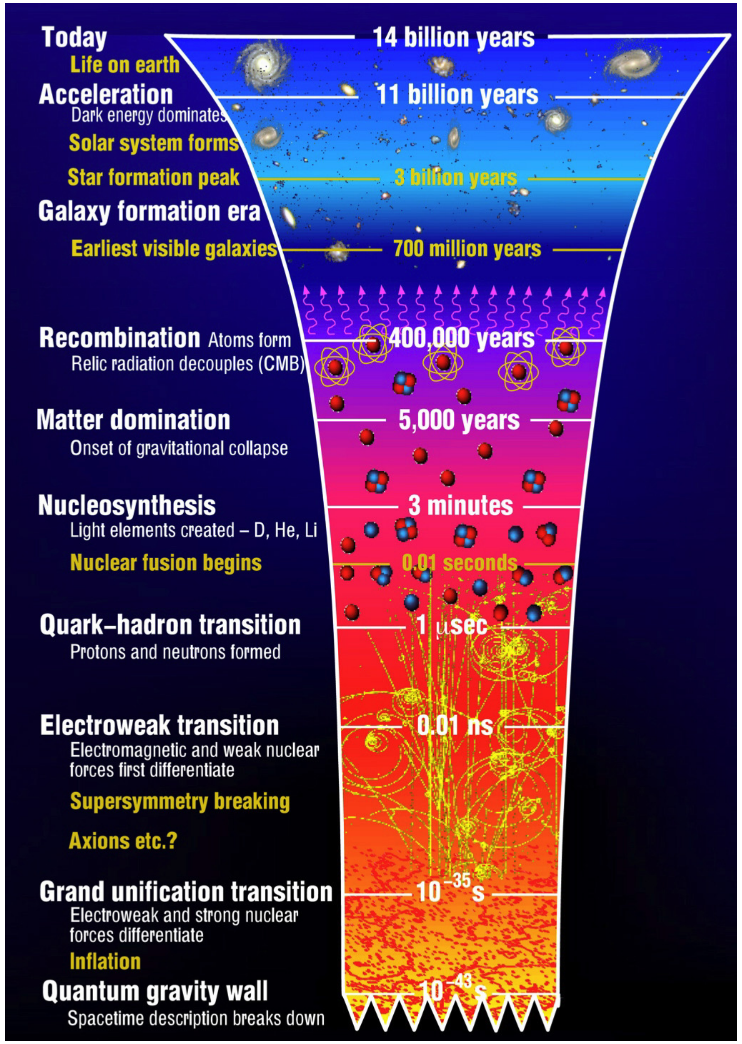








Strong QCD is born ~ 1μsec after the Big Bang

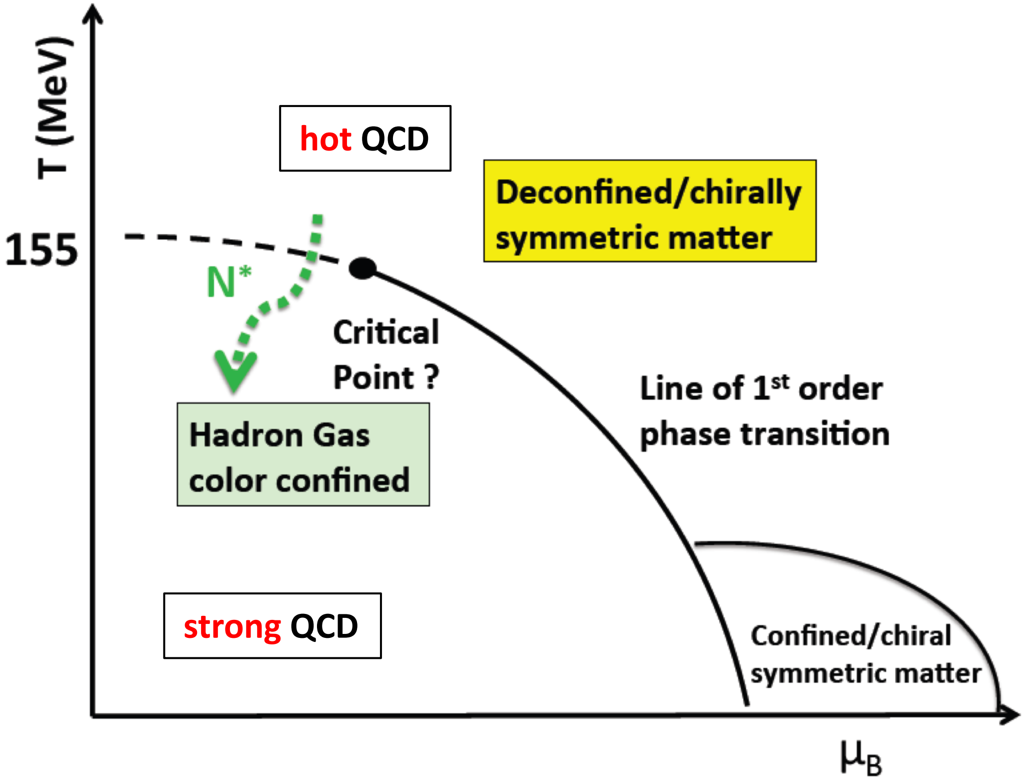


Time after the Big Bang

$T \sim 10^2$ s: nuclei

$T \sim 10^{-6}$ s: Nucleons

$T \sim 10^{-9}$ s: QGP



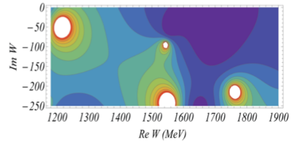
$T \sim 10^{-6}$ s: Transition from the QGP to Nucleons

- chiral symmetry is broken
- light quarks acquire mass dynamically
- color confinement becomes manifest

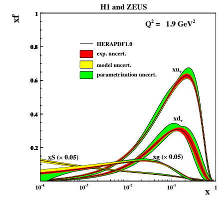
With Jlab6 and JLAB12 we explore these events in (relative) isolation

Probing baryons to learn about strong QCD

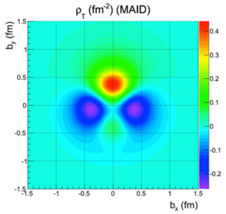
- Energy spectrum - Search for new states ➪ QGP to hadron transition, symmetries underlying hadronic matter



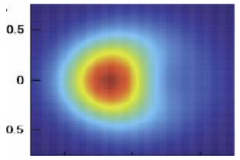
- Structure functions ➪ Parton and spin distributions (1D)



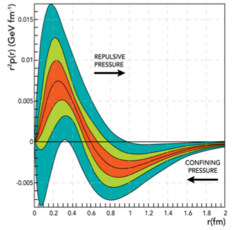
- Form factors ➪ Effective degrees of freedom versus distance (2D)



- Deeply exclusive/semi-inclusive processes & GPD/TMD ➪ 3D imaging of nucleon

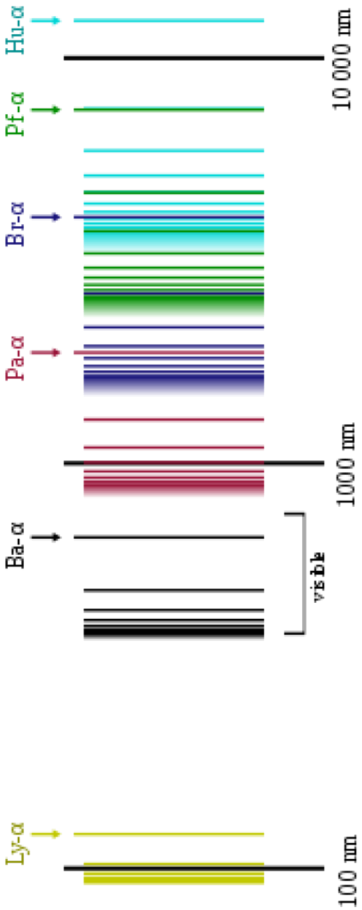


- Moments of GPDs ➪ Forces on quarks, confinement

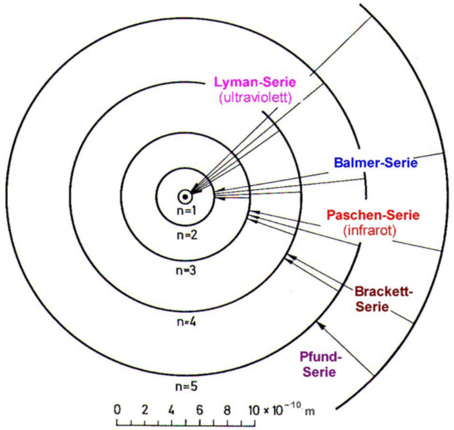


From the H spectrum to the N* spectrum

Spectral series of hydrogen



Niels Bohr, model of the hydrogen atom, 1913.



Analogy *QCD & QED => path to discoveries ?*

- Understanding the hydrogen atom required understanding its spectrum of ***sharp energy levels***

-> From the ***Bohr model*** to ***QED***

-> Lamb shift, …

- Understanding the proton requires mapping out its full energy spectrum of ***broad energy levels***

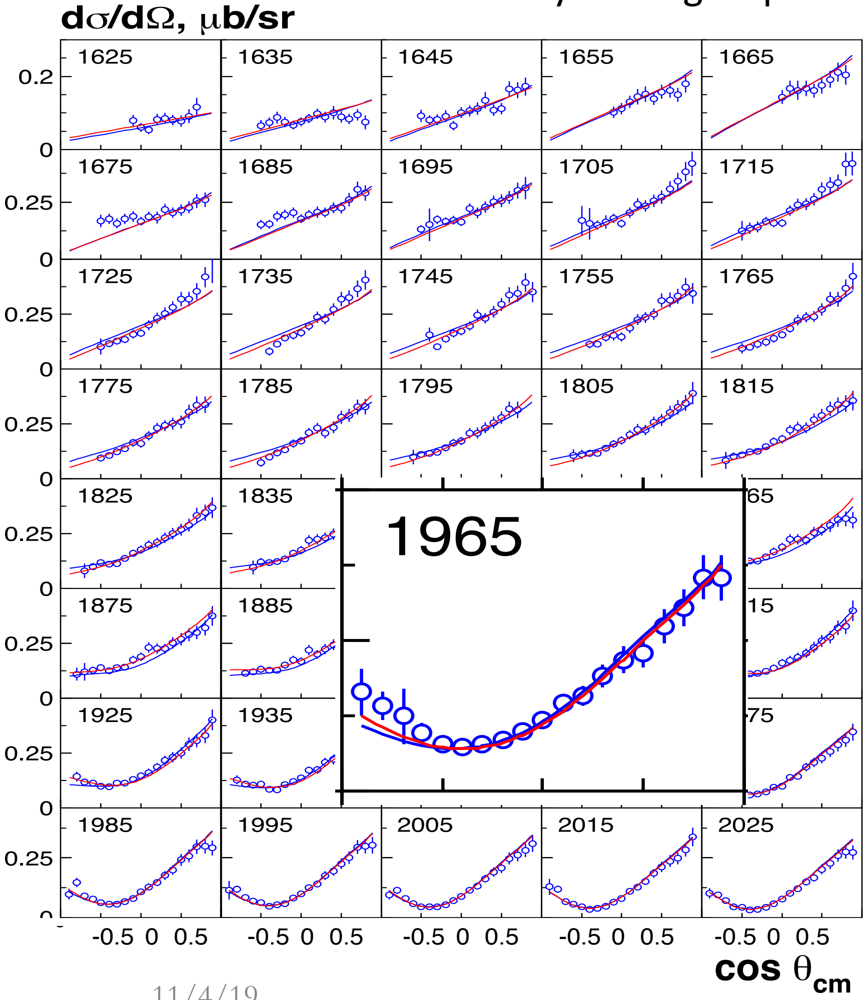
-> From the ***Quark model*** to ***QCD***

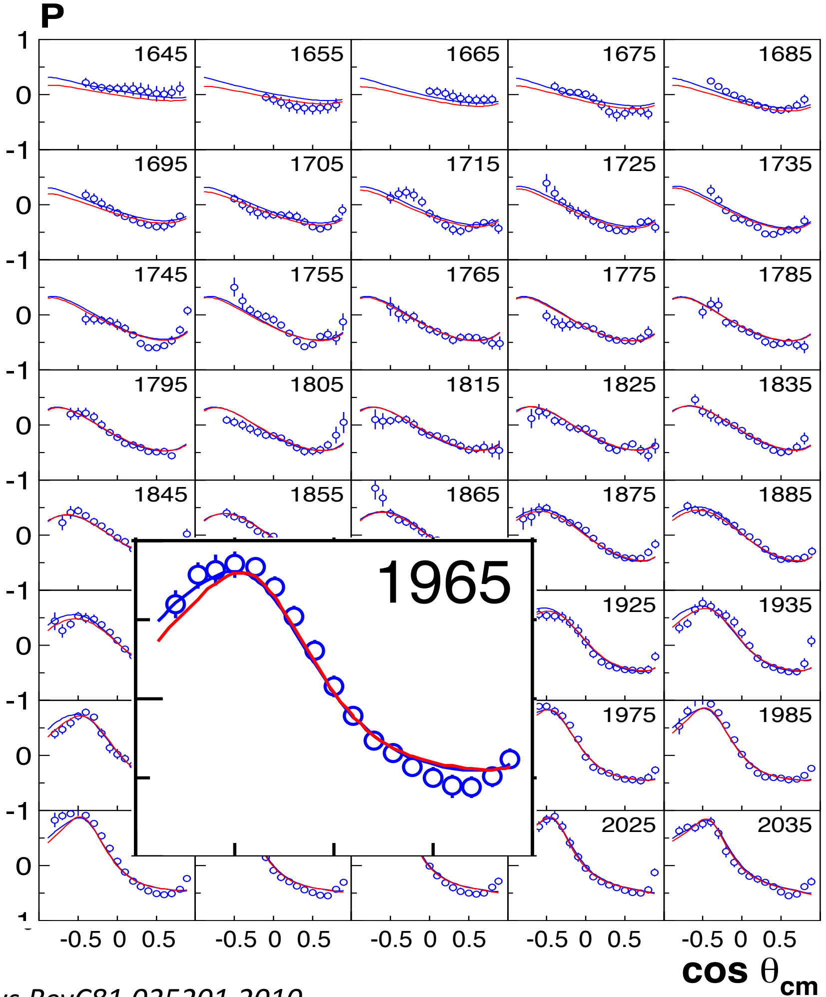
-> Accuracy of predictions should be commensurate with experiments, i.e. O(few MeV), to allow for surprises.

Establishing the N* spectrum – Precision & Polarization are essential

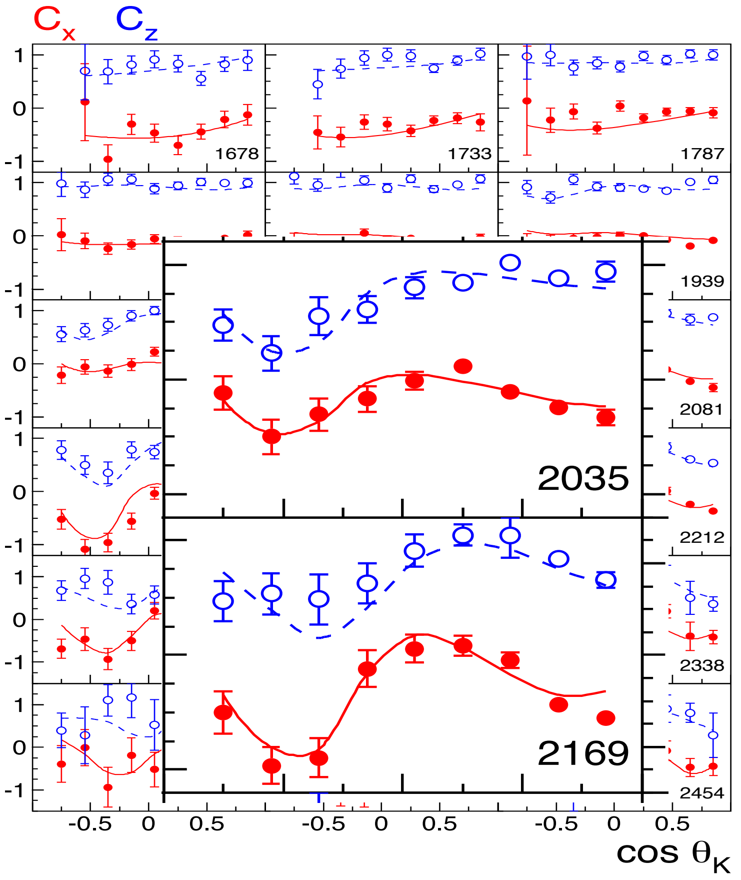
Hyperon photoproduction $\gamma p \rightarrow K^+ \Lambda \rightarrow K^+ p \pi^-$

Fit by BnGa group *A.V. Anisovich et al, EPJ A48, 15 (2012)*





γ->Λ Polarization transfer



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

D. Bradford et al. (CLAS), Phys.Rev. C75, 035205, 2007

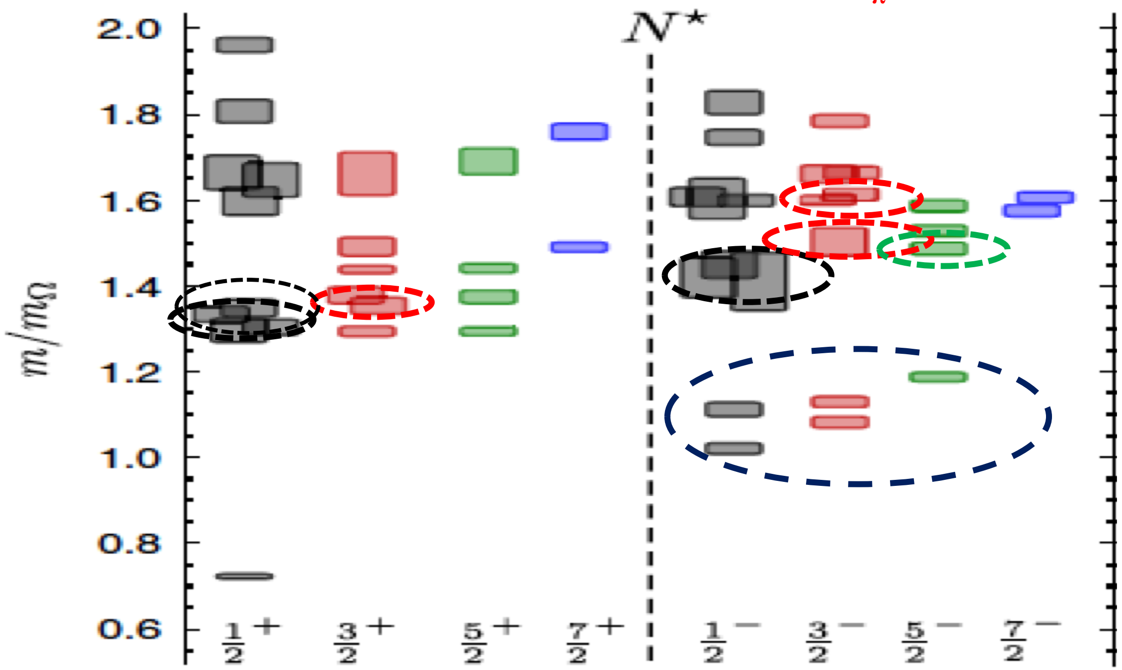
Do new states correlate with predicted LQCD states?

R. Edwards et al., Phys.Rev. D84 (2011) 074508

m_Ω = 1672 MeV

m_π=396MeV

N(1900)3/2⁺
N(2100)1/2⁺
N(1880)1/2⁺



N(2060)5/2⁻
N(2120)3/2⁻
N(1875)3/2⁻
N(1895)1/2⁻

N(1675)5/2⁻
N(1700)3/2⁻
N(1520)3/2⁻
N(1650)1/2⁻
N(1535)1/2⁻

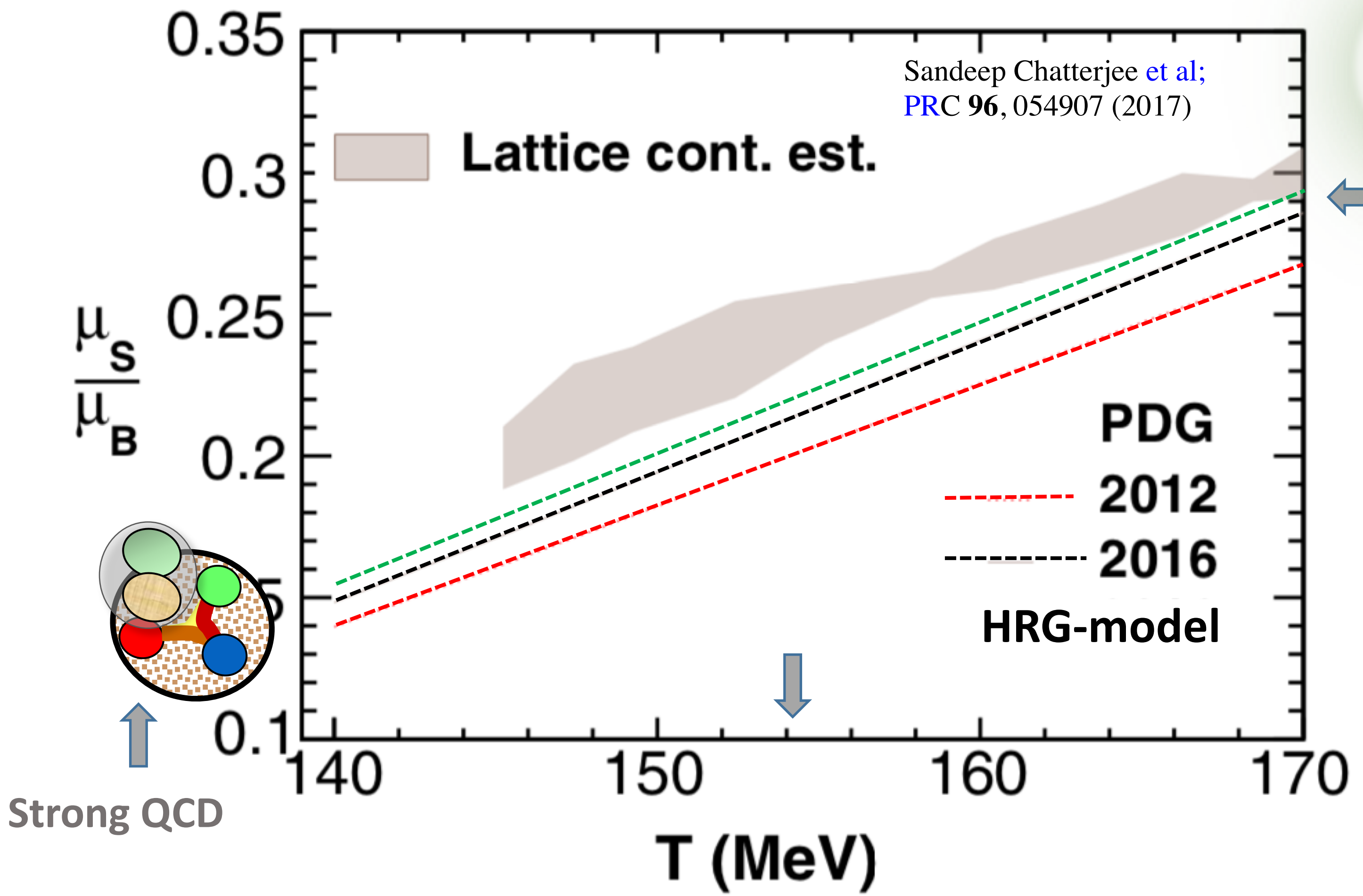
Lowest J⁺ states 500 -700 MeV high

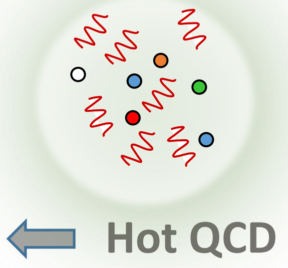
Lowest J⁻ states 200-300 MeV high

Ignoring the mass scale, the new states correlate with unoccupied J^P levels in the LQCD spectrum.

For quantitative comparisons projections at or near the physical pion mass are needed.

Impact of new excited baryons





not included

PDG 2016 with *, **

$N(1860)$	$N(1880)$
$N(1895)$	
$N(2000)$	$N(2040)$
$N(2060)$	$N(2100)$
$N(2120)$	$N(2300)$
$N(2570)$	$N(2700)$
$\Delta(1750)$	$\Delta(1900)$
$\Delta(1940)$	$\Delta(2000)$
$\Delta(2150)$	$\Delta(2200)$
$\Delta(2300)$	$\Delta(2350)$
$\Delta(2390)$	$\Delta(2400)$
$\Delta(2750)$	$\Delta(2950)$
$N(1875)$	

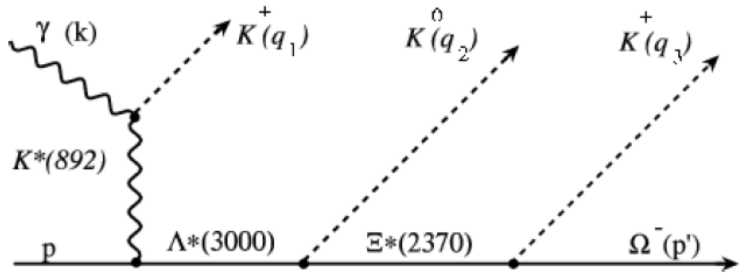
PDG 2018 with ***, ****

➔ *We do not describe the transition near the cross over temperature. Additional N* and Δ* states and hyperons will affect behavior.*

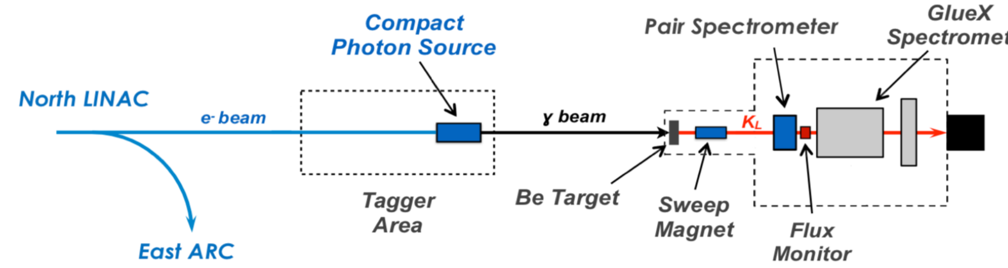
Search for strange baryons

Experiments at JLab at **GlueX** and at **CLAS12** search for excited hyperon states of $\Xi^{0,-}$ (S=-2) & Ω^{-} (S=-3)

Multi-strange baryons difficult to produce with photon beams.



Proposed $\mathbf{K_{long}}$ facility in **Hall D** to study hyperons K_Lp interactions.

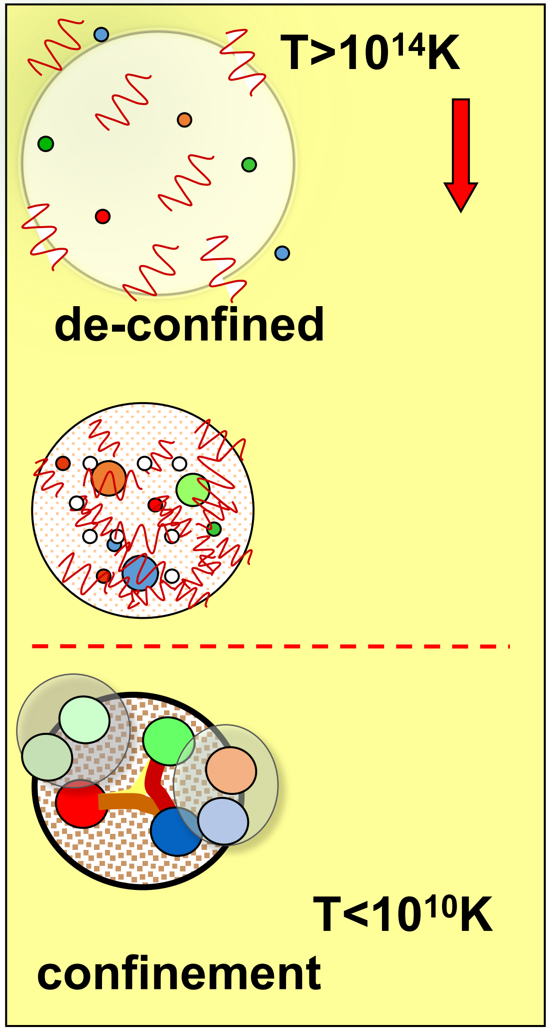


Reaction	Statistics (events)
$K_Lp \to K_Sp$	2.7M
$K_Lp \to \pi^+\Lambda$	7M
$K_Lp \to K^+\Xi^0$	2M
$K_Lp \to K^+n$	60M
$K_Lp \to K^-\pi^+p$	7M

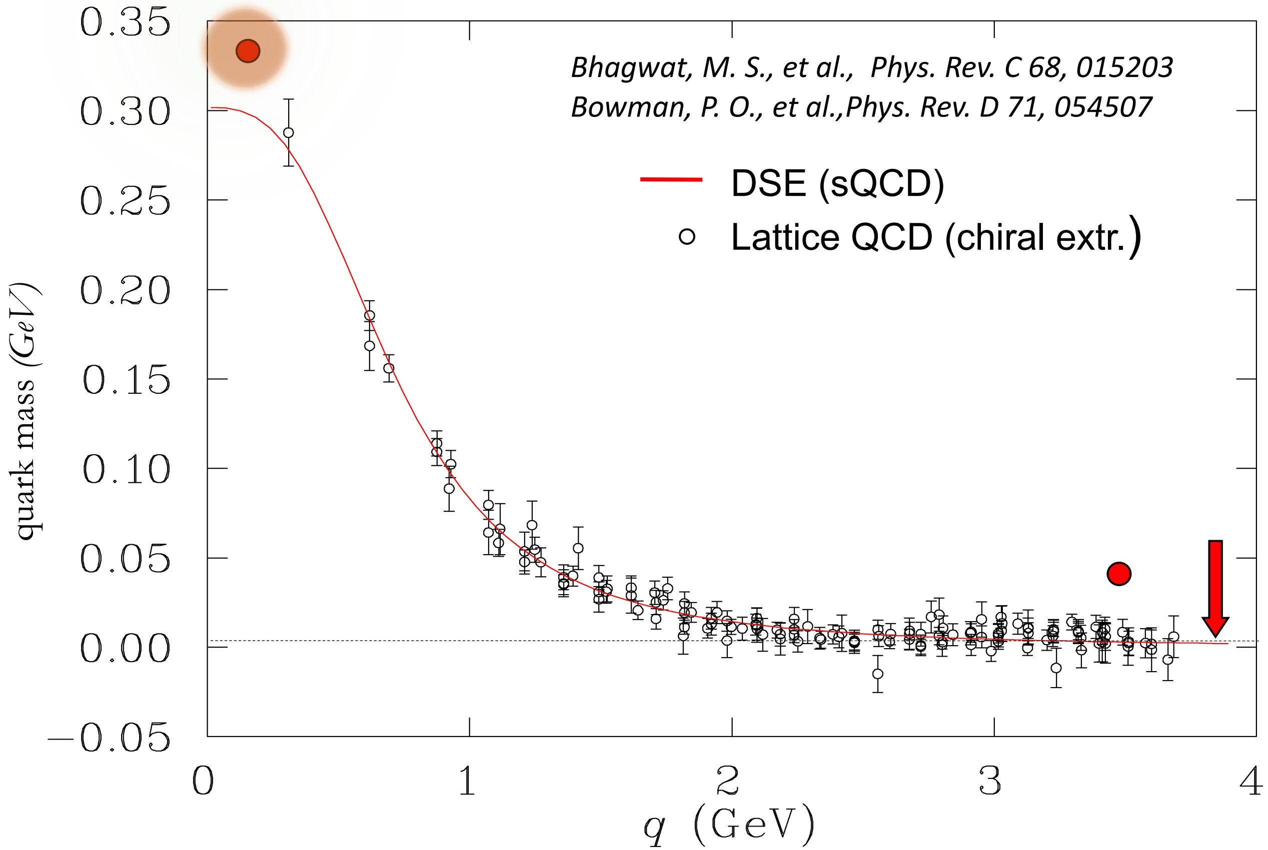
Expected statistics for some final states and 100 days data taking.

A fertile ground for LQCD calculations.

Generating mass as the universe cools



Dynamical generation of mass modeled on the Lattice and in DSE on single quarks.

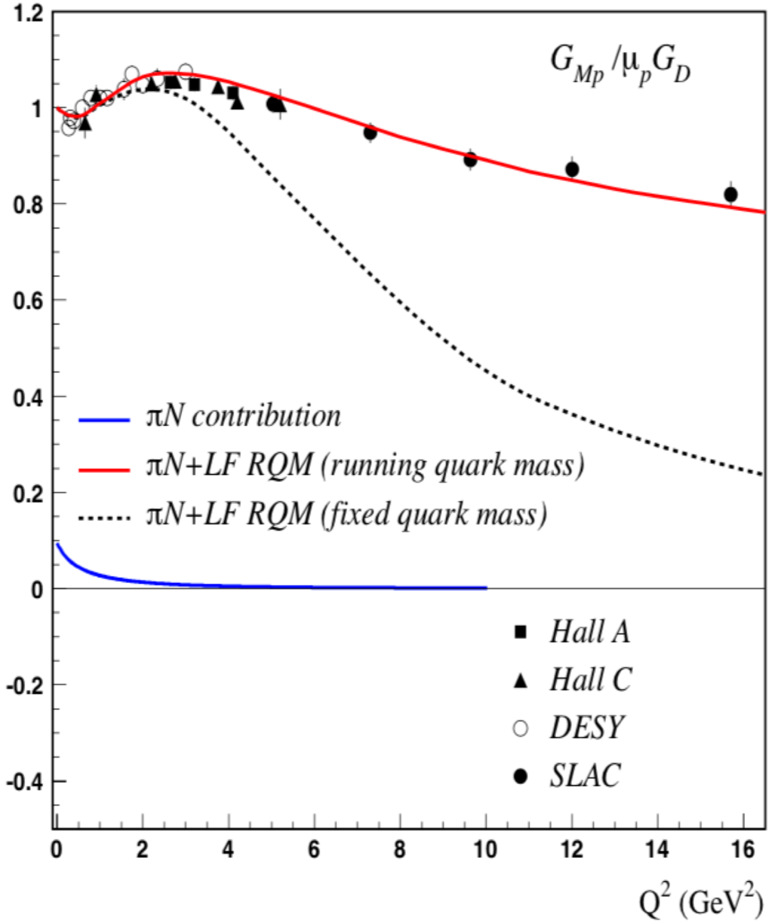


Study this in measurements that are sensitive to the running quark mass.

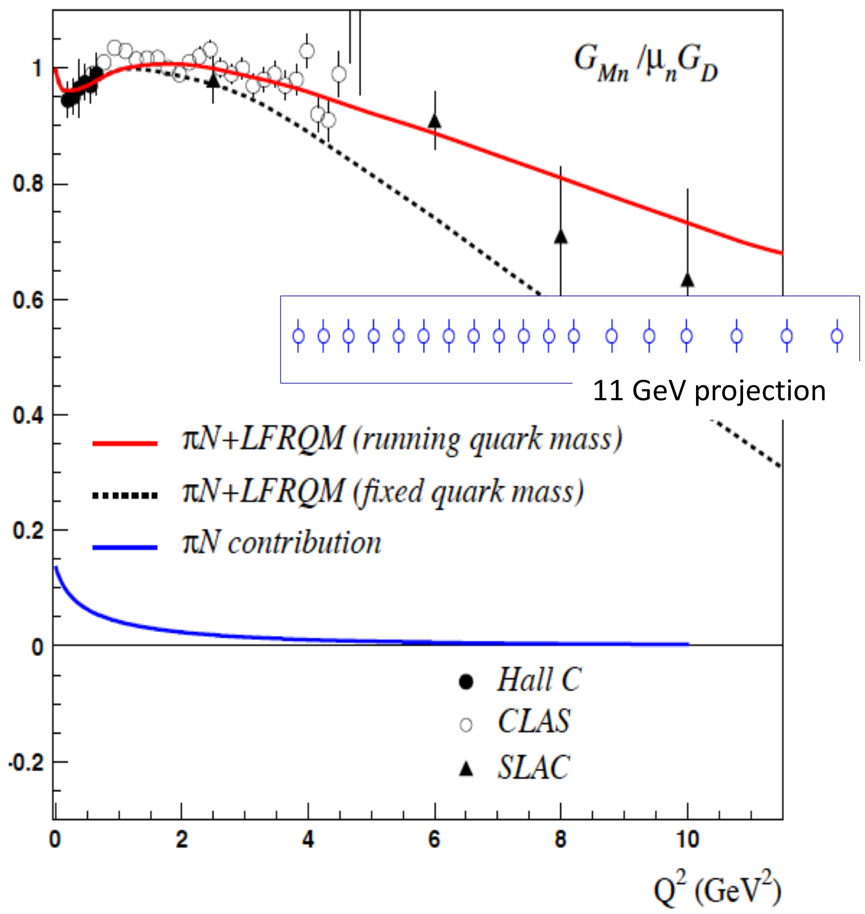
Structure of e.m. FF of proton and neutron

- Encode charge and current densities in the light cone frame.
- Small (~10%) non-quark πN contributions at small Q^2.
- Strong sensitivity to the running quark mass function.
- Measurements up to higher Q^2 planned or completed.

Magnetic proton FF



Magnetic neutron FF

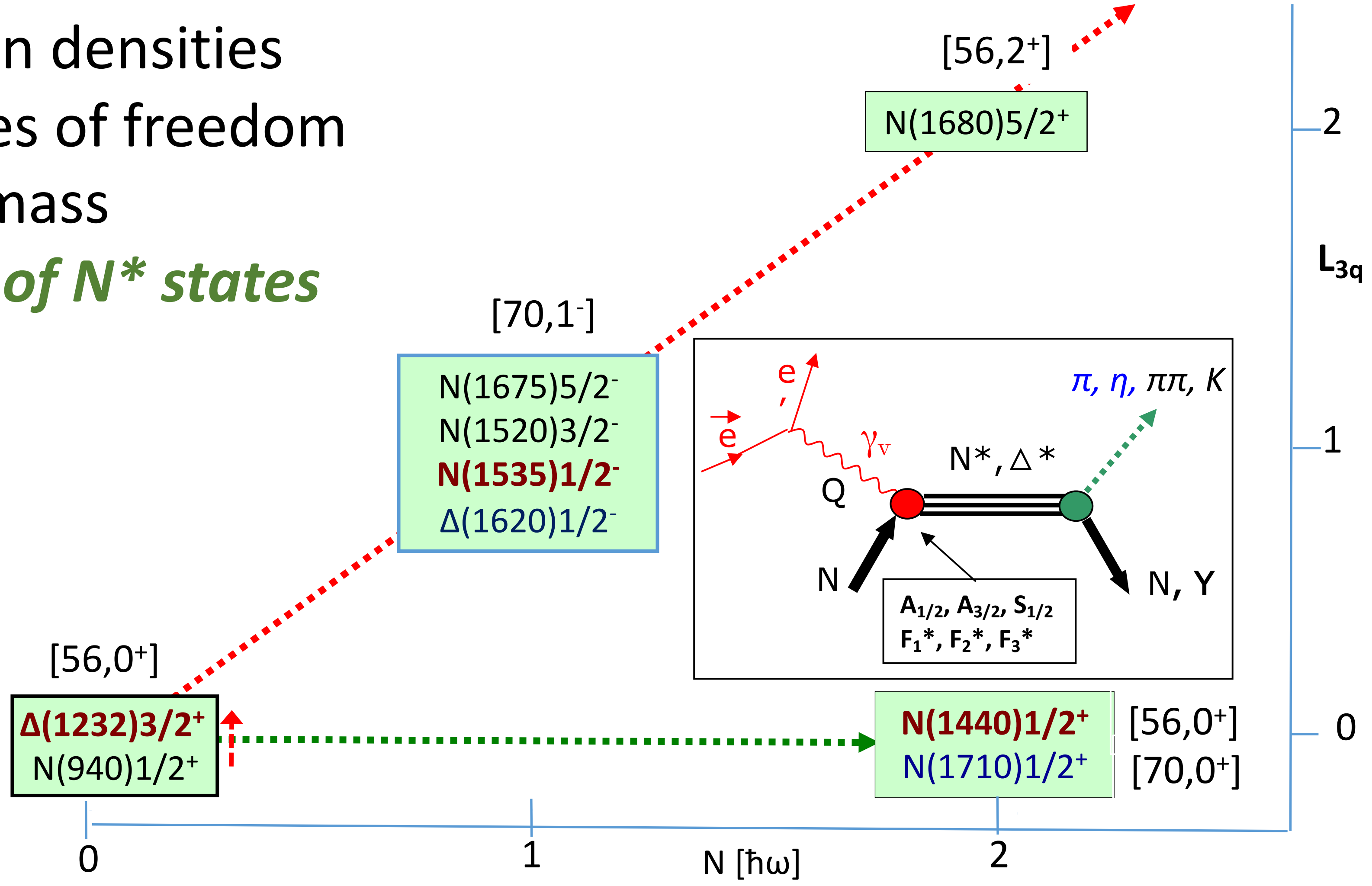


The quark mass function should be universal and apply also to N* transitions.

Structure of excited baryons

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

=> reveal nature of N* states

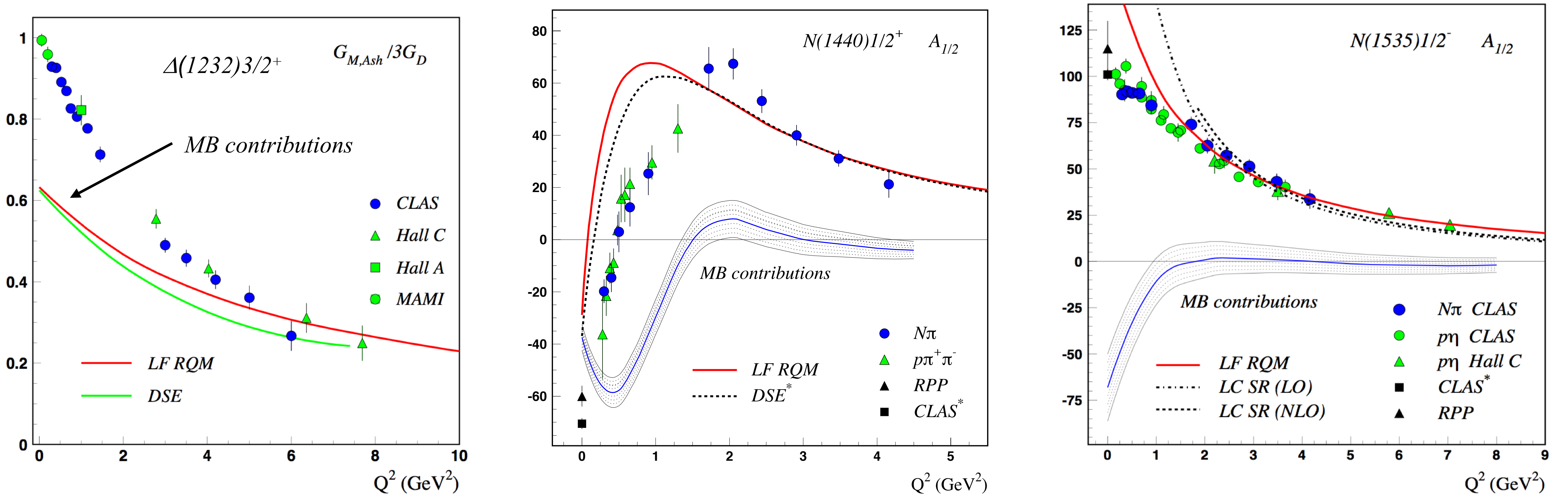


http://pdg.lbl.gov/2019/reviews/rpp2018-rev-n-delta-resonances.pdf

Transition amplitudes of prominent resonances

DSE: J. Segovia, C.D. Roberts et al., PRC94 (2016) 042201
LF RQM: I. Aznauryan, V.B. arXiv:1603.06692 (2016)

LC SR: I. Anikin, V. Braun, N. Offen, PRD92 (2015) 014018

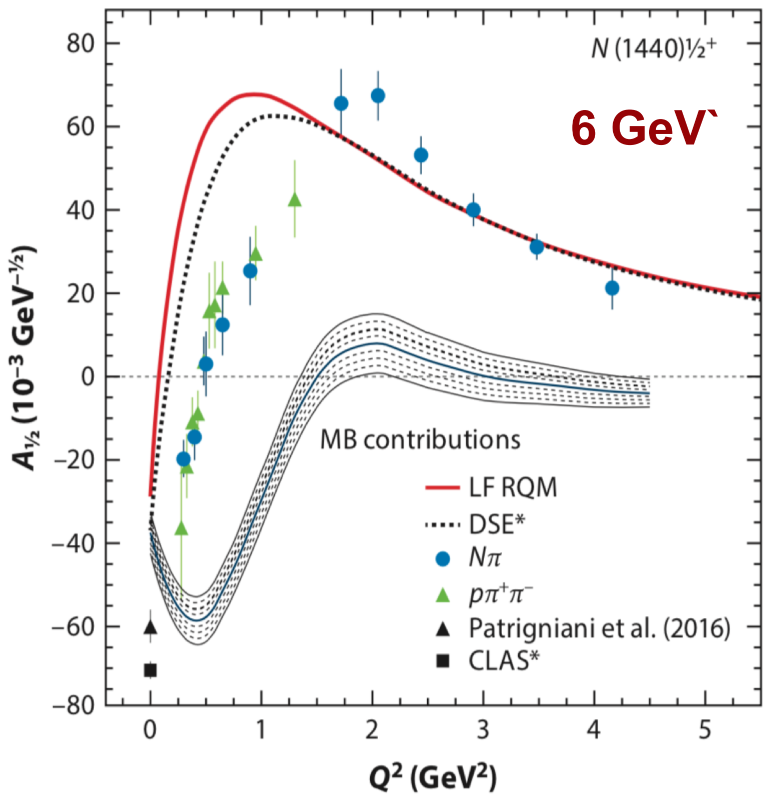


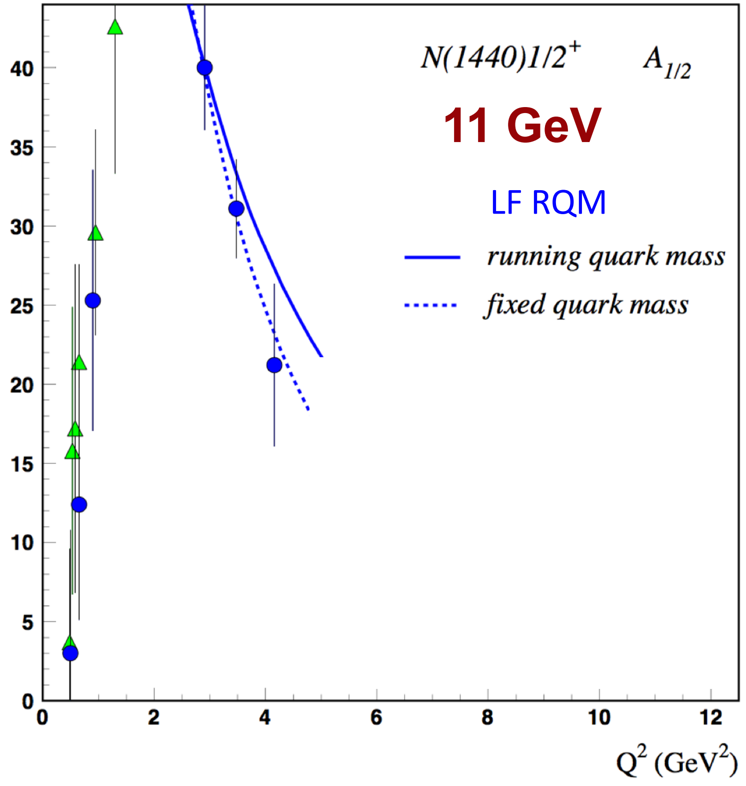
Roper N(1440)1/2+ is the **first radial** excitation of the nucleon's quark core complemented by an external meson-baryon cloud.
N(1535)1/2- is the **first orbital** excitation of the nucleon's quark core complemented by an external meson-baryon cloud.

Dressed quark-core behavior accessible at Q^2 > 2-4 GeV^2. MB terms more prominent than in elastic FF.

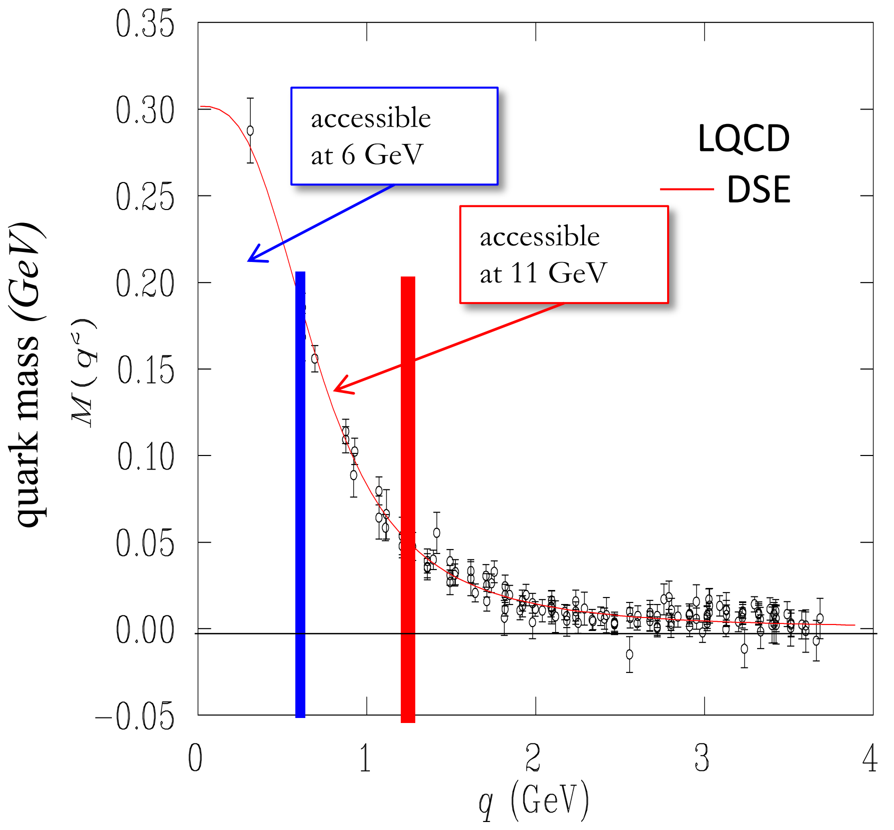
Probing the running quark mass at JLab12

Roper resonance





Running quark mass

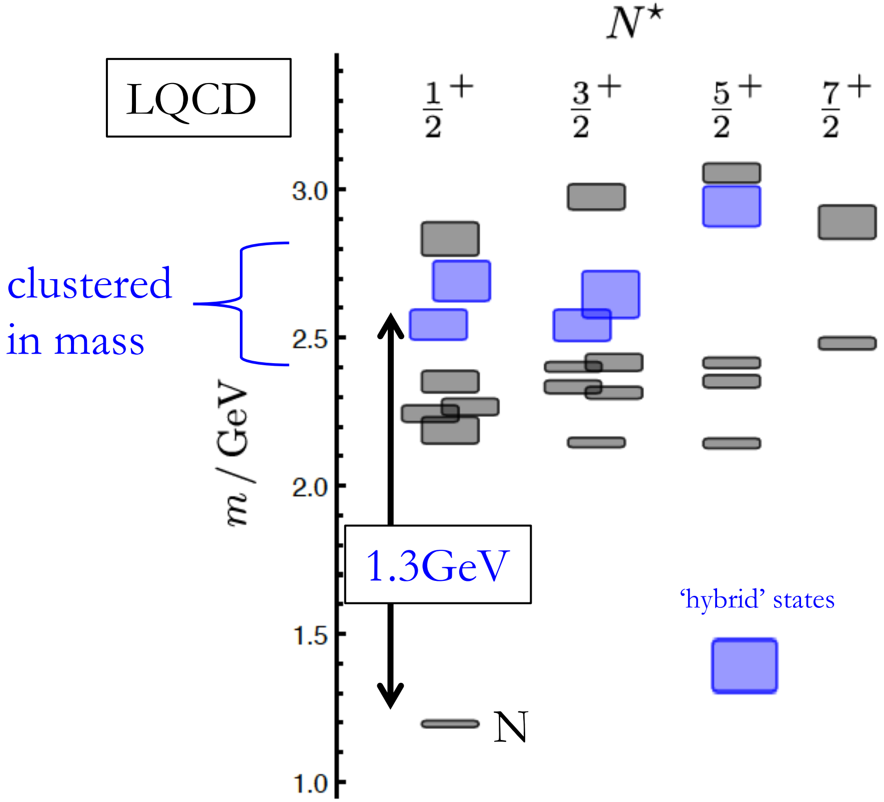


Probe the transition from the interaction on dressed quarks to elementary quarks.

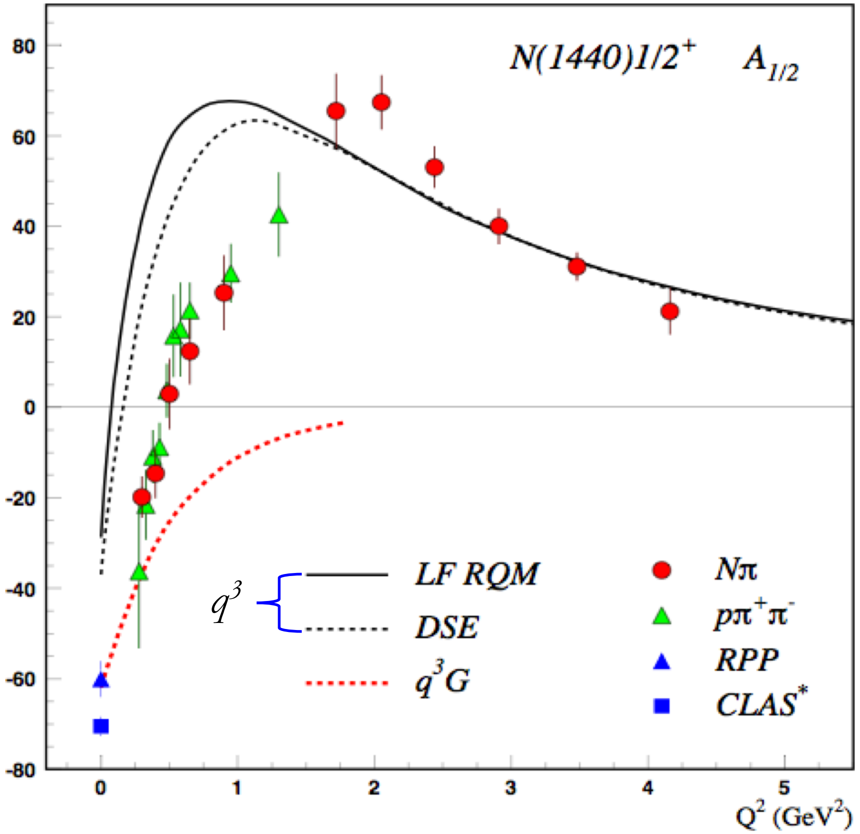
Search for Hybrid Nucleons N^G

Is glue manifest in the valence structure of excited nucleons?

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



q^3G: Z.p. Li, V.B., Z.j. Li, Phys. Rev. D46 (1992) 70



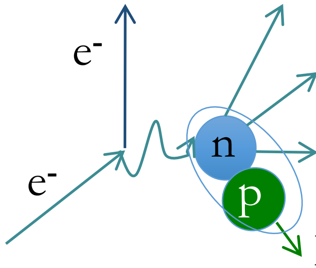
- q^3G baryons have same J^P values as q^3 baryons, but are more extended objects
- May measure Q^2 dependence to separate - Program at CLAS12
- Calculations for electrocouplings of hybrid states are needed

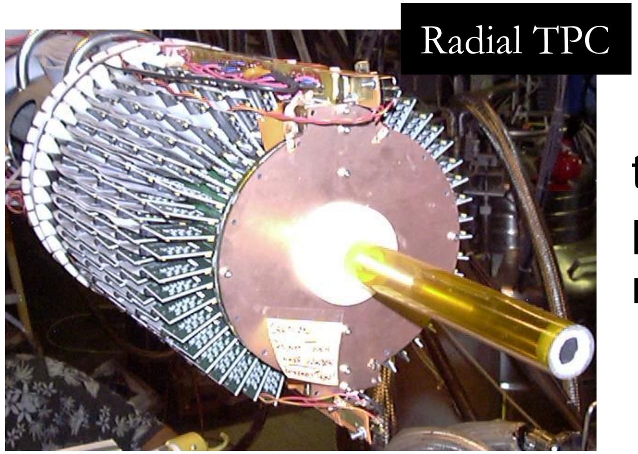
Neutron structure F_2^n/F_2^p and d/u-ratio

Measure F_2^n/F_2^p to determine d(x)/u(x)

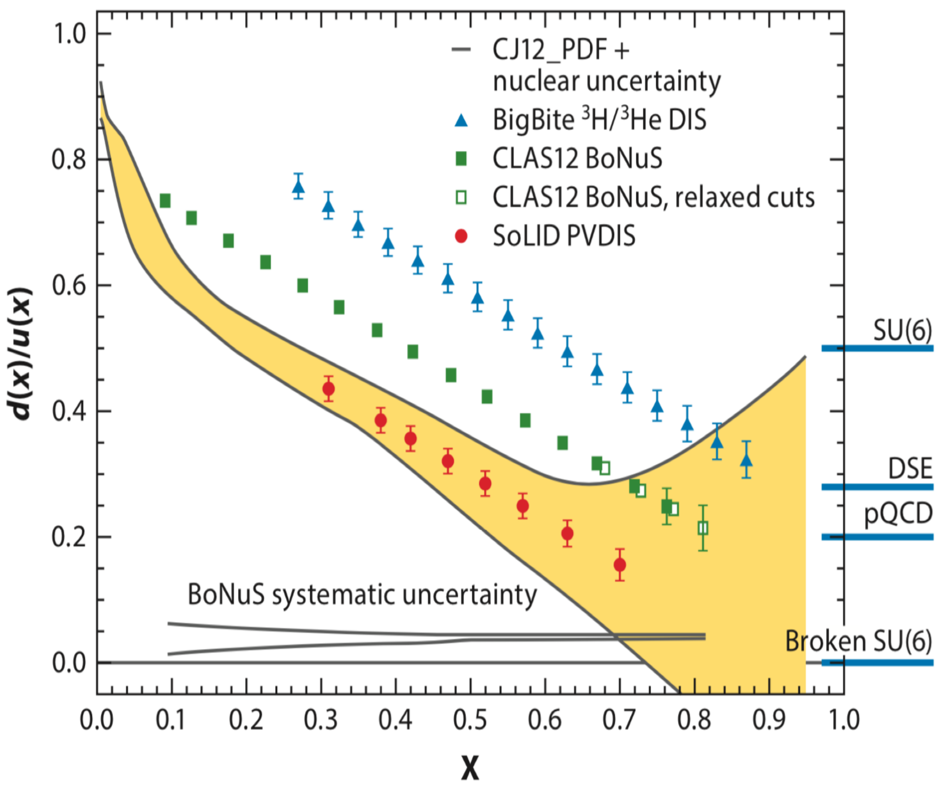
1) Measure cross section ratio $^3H/^3He$ of mirror nuclei (MARATHON, completed).
2) Detect low momentum protons to tag nearly unbound neutrons in deuterium (BoNuS12 in 2020)

$e^-D \rightarrow e^-p_sX$





track low energy protons in 5 Tesla mag. field



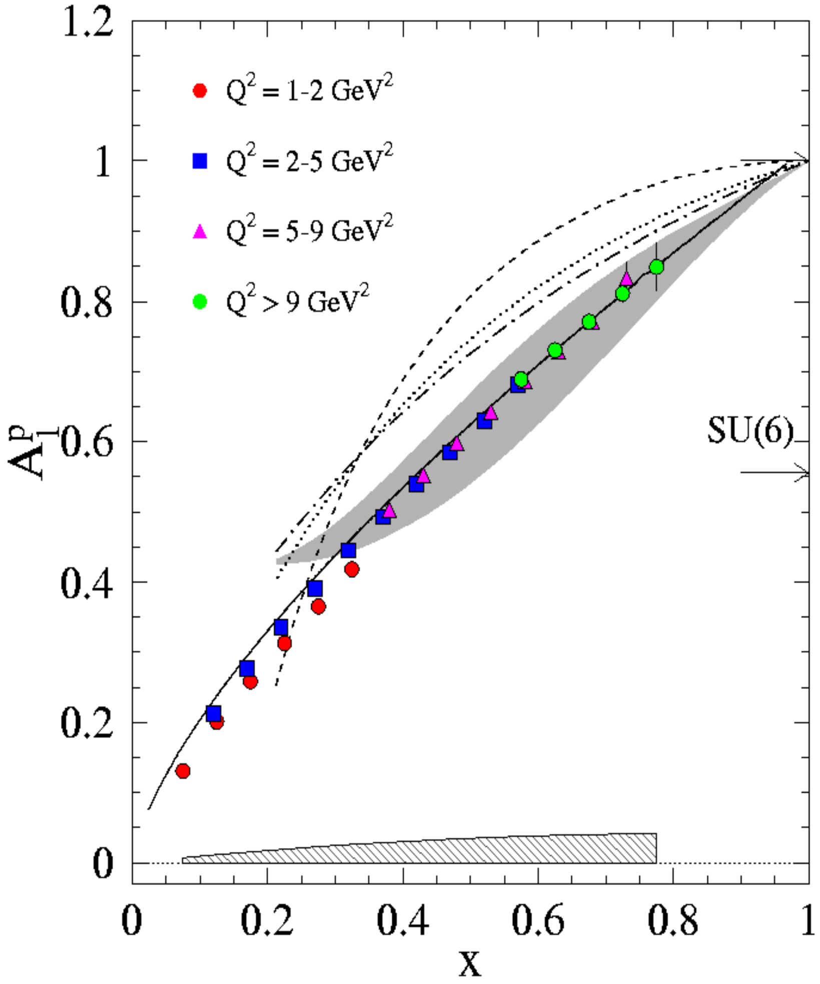
Parton distribution functions are governed by sQCD. Recent progress in theory (X. Ji) may enable computing d(x)/u(x) in LQCD.

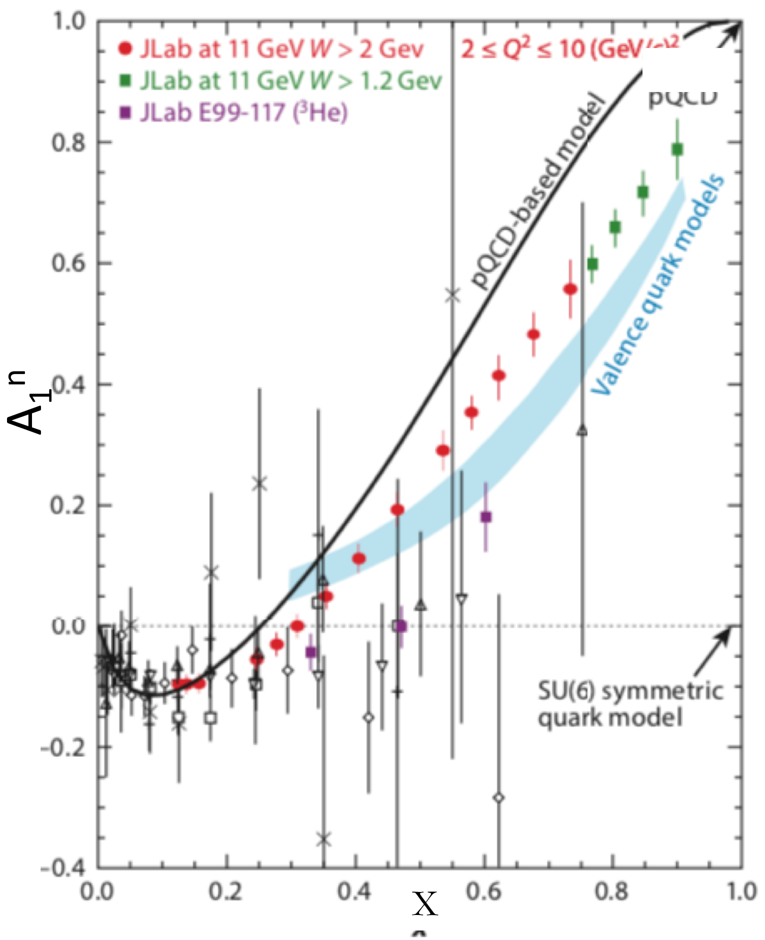
Projected results for d(x)/u(x) for 12 GeV experiments.

Polarized PDFs on $\vec{p}, \vec{d}, {}^3\vec{He}$ at 11GeV

- Two experiments to measure polarized PDFs in the range $x \leq 0.8$ on p/d and on neutrons.
- A polarized target adapted to CLAS12 can achieve high-precision results on helicity asymmetries on A_1^p and A_1^d by employing longitudinally polarized NH_3 and ND_3 targets.
- Similar coverage is projected with the use of a polarized **He-3** target in Hall A.

Beam-Target double spin asymmetry





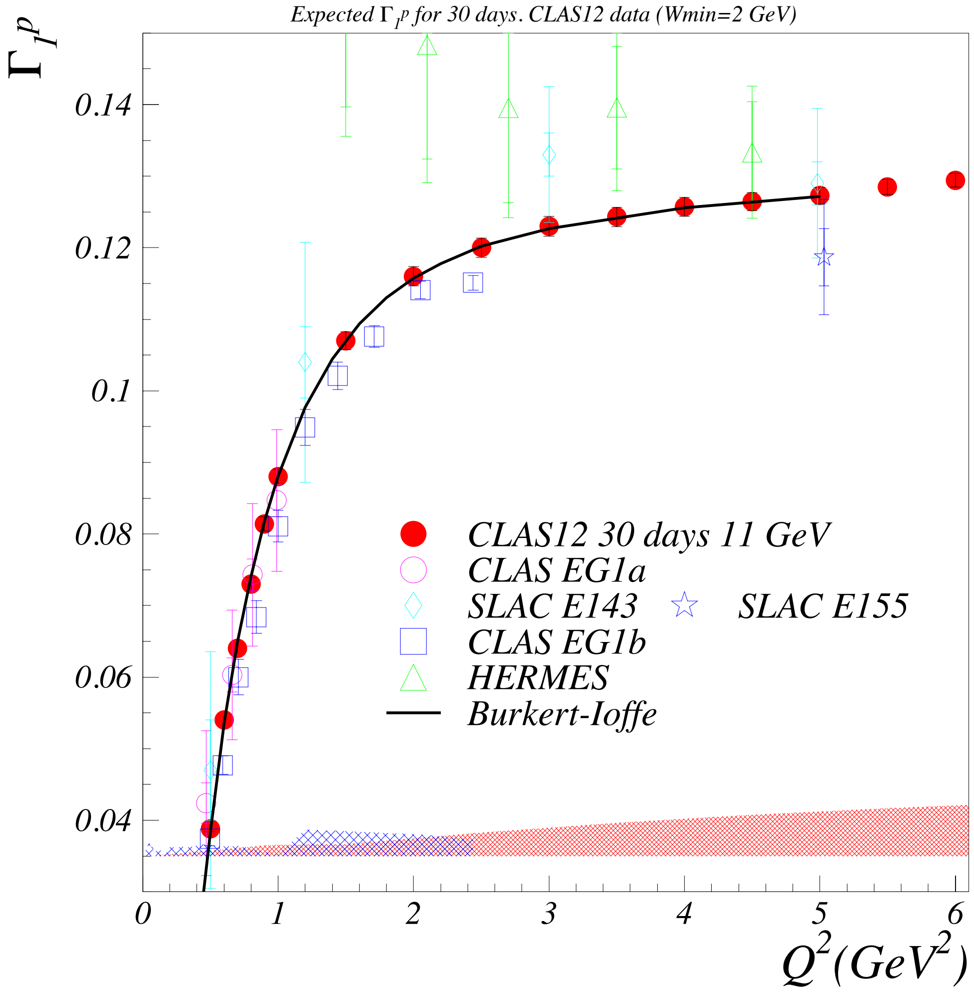
With the expected precision a serious effort should be launched to compute $A_1(x)$

Moments of Spin Structure Functions

- Inclusive polarized DIS data obtained at JLab@6GeV have permitted evaluation of the moments at low and intermediate Q^2.
- At 12 GeV the moments will be measured up to $Q^2 = 6$ GeV^2 with much improved statistical precision.
- With both proton and neutron measured, the Bjorken sum can be evaluated, which relates to the integral.

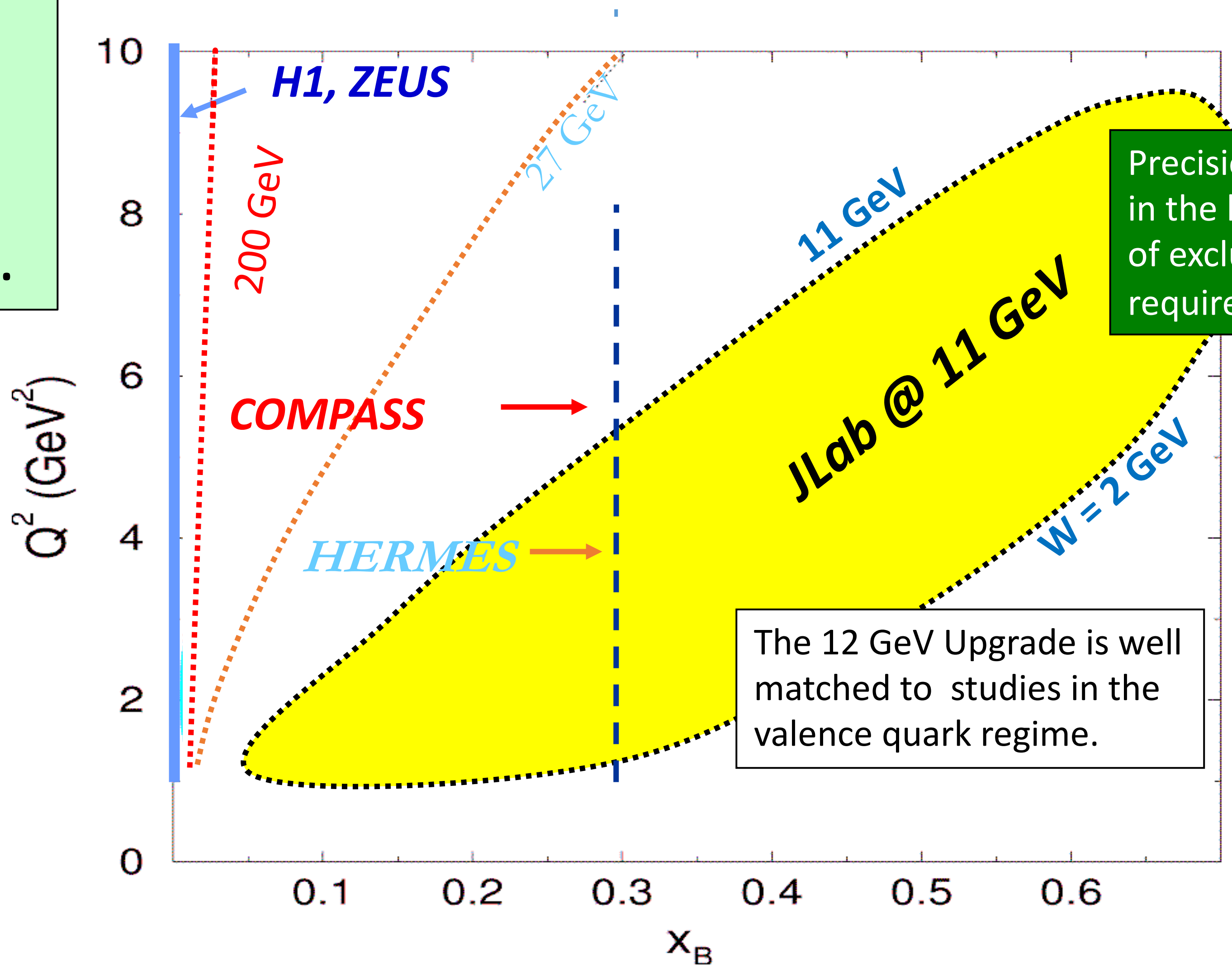
$$\Gamma_1^{p-n}(Q^2 \to \infty) = \frac{1}{6} g_A.$$

What projections from LQCD or sQCD are expected?



Kinematic coverage for Imaging @ 11GeV

A flagship program of structure studies in deeply exclusive and semi-inclusive processes.



Precision measurements in the high x_B domain of exclusive processes requires high luminosity.

The 12 GeV Upgrade is well matched to studies in the valence quark regime.

Transverse Momentum Structure of Nucleon – TMDs

(Quantum phase-space quark distribution in the nucleon)

Wigner Function $$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{\mathcal{W}}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle$$

$$W_\Gamma(\mathbf{r},\mathbf{k}) = \int \frac{dk^-}{(2\pi)^2} W_\Gamma(\mathbf{r},k)$$

Integrate over ***spatial*** dimensions

↓

Transverse Momentum-dependent Distributions (TMD)

↓

3D imaging of the nucleon in momentum space

Quark spin polarization

Nucleon polarization

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

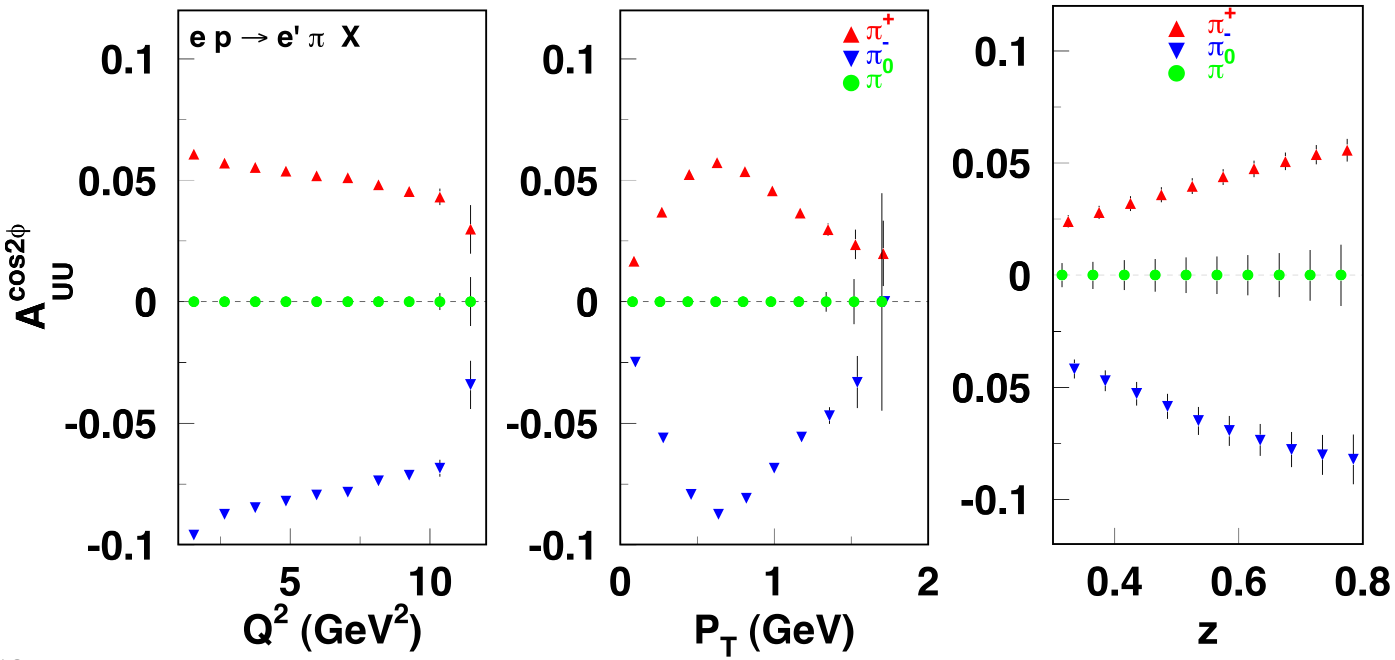
JLab has planned a complete SIDIS program with π/K to access quark TMDs

SIDIS for π on unpolarized target

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

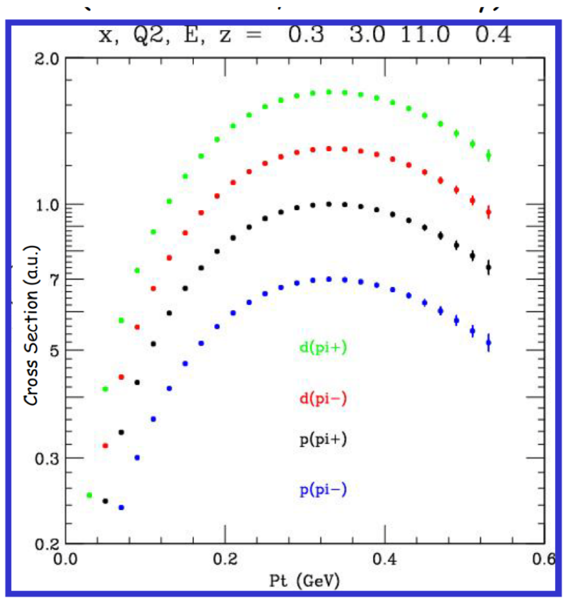
$$\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\left\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h}\right\},$$

CLAS12 projected, 4 <Q^2< 5 GeV^2



Large kinematic reach

Hall C



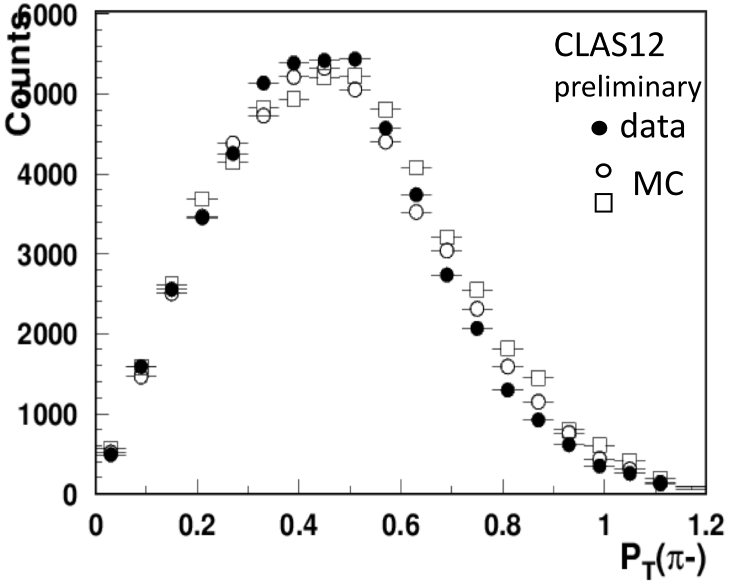
High precision

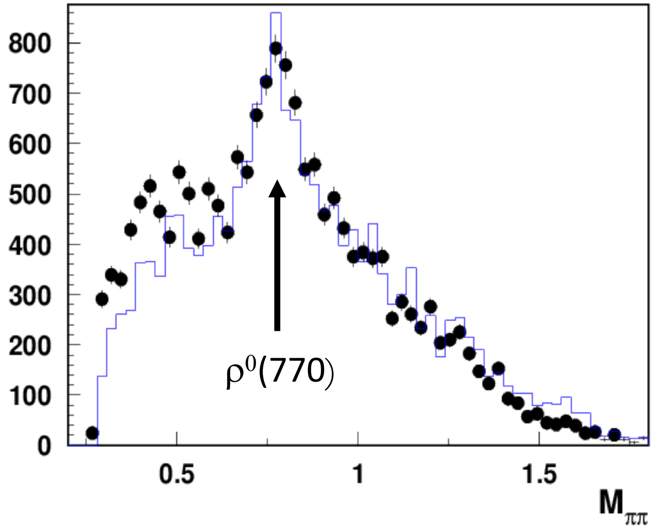
SIDIS in 2-pion production

ep→e'$\pi^+\pi^-$X

- Provides more direct insight into hadronic correlations.
- The comparison with Monte Carlo simulations indicates that there is a significant fraction of pions from VM decays.
- Precision data point to a fruitful field for **sQCD/LQCD** applications, especially for moments of observables.

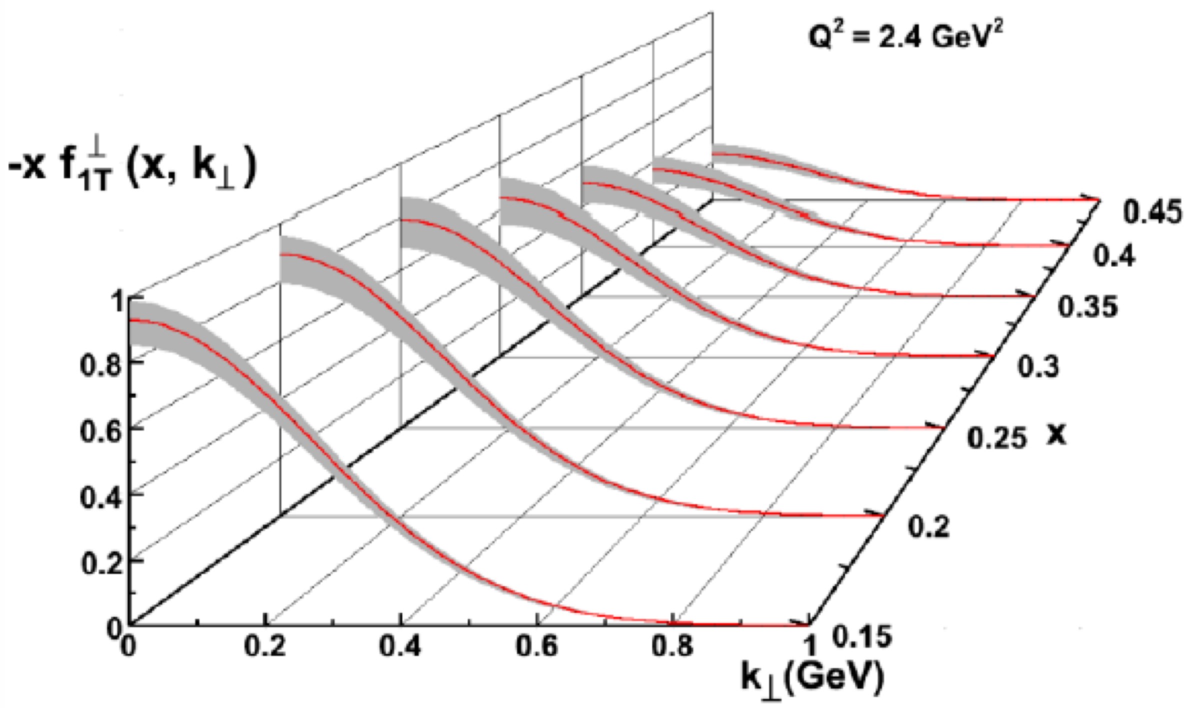
ep→e'$\pi^+\pi^-$X



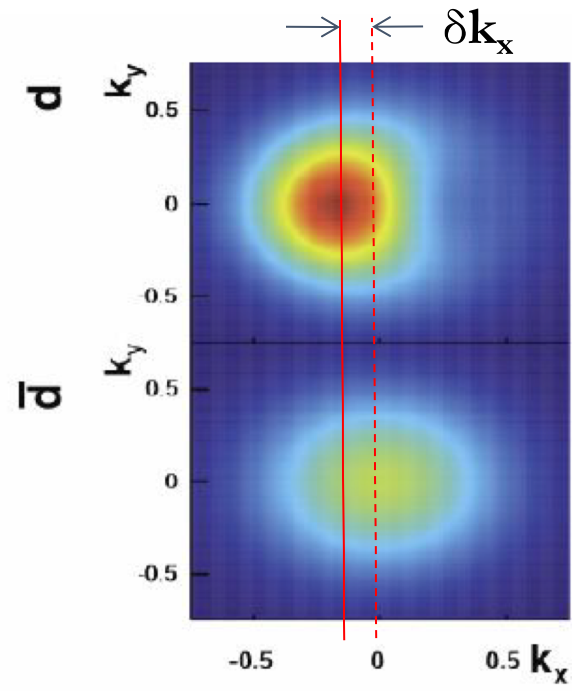


Momentum Tomography with Sivers function

Sivers function for d-quarks extracted from model simulations with a transverse polarized ^3He target.



Computable within sQCD/LQCD ?



d-quark momentum tomography for Sivers function. The d-quark momentum density shows a distortion and shift in $\mathbf{k_x}$. **A non-zero δk_x value requires a non-zero orbital angular momentum.**

Generalized Parton Distributions

(Quantum phase-space quark distribution in the nucleon)

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{W}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle ,$$

$$W_\Gamma(\mathbf{r},\mathbf{k}) = \int \frac{dk^-}{(2\pi)^2} W_\Gamma(\mathbf{r},k)$$

Integrate over **transverse momentum** space

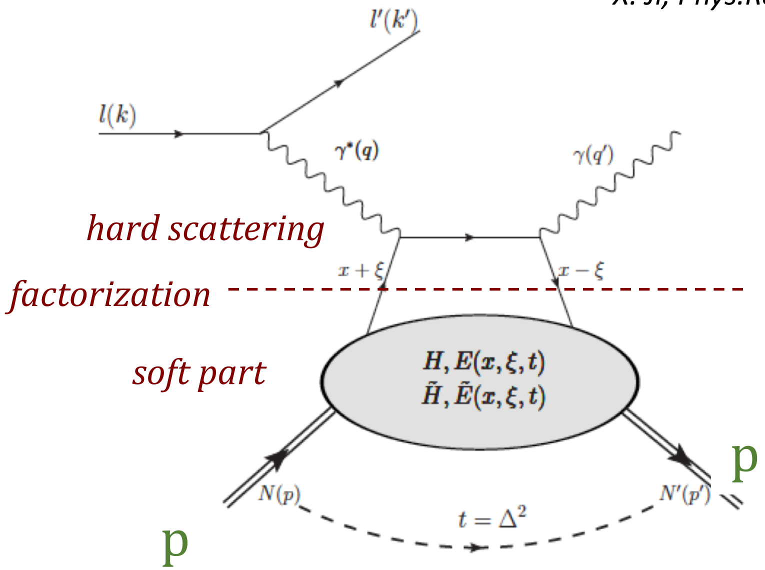
GPDs H E $\tilde{H}$, $\tilde{E}$

Probe 3D structure 2D – euclidean space and 1D - momentum space.

D. Müller et al., F. Phys. 42,1994
X. Ji, PRL 78, 610, 1997
A. Radyushkin, PLB 380, 1996

Polarized DVCS probes GPDs. JLab @ 12GeV has broad DVCS program with polarized beams and polarized targets.

X. Ji, Phys.Rev.D55, 7114 (1997)



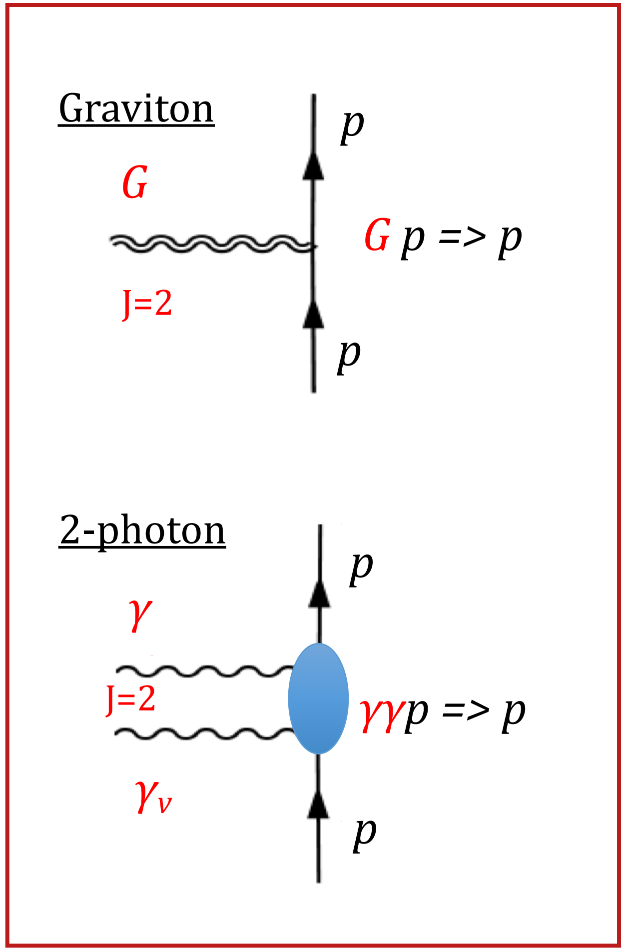
$$\xi \approx \frac{x_B}{2 - x_B}$$

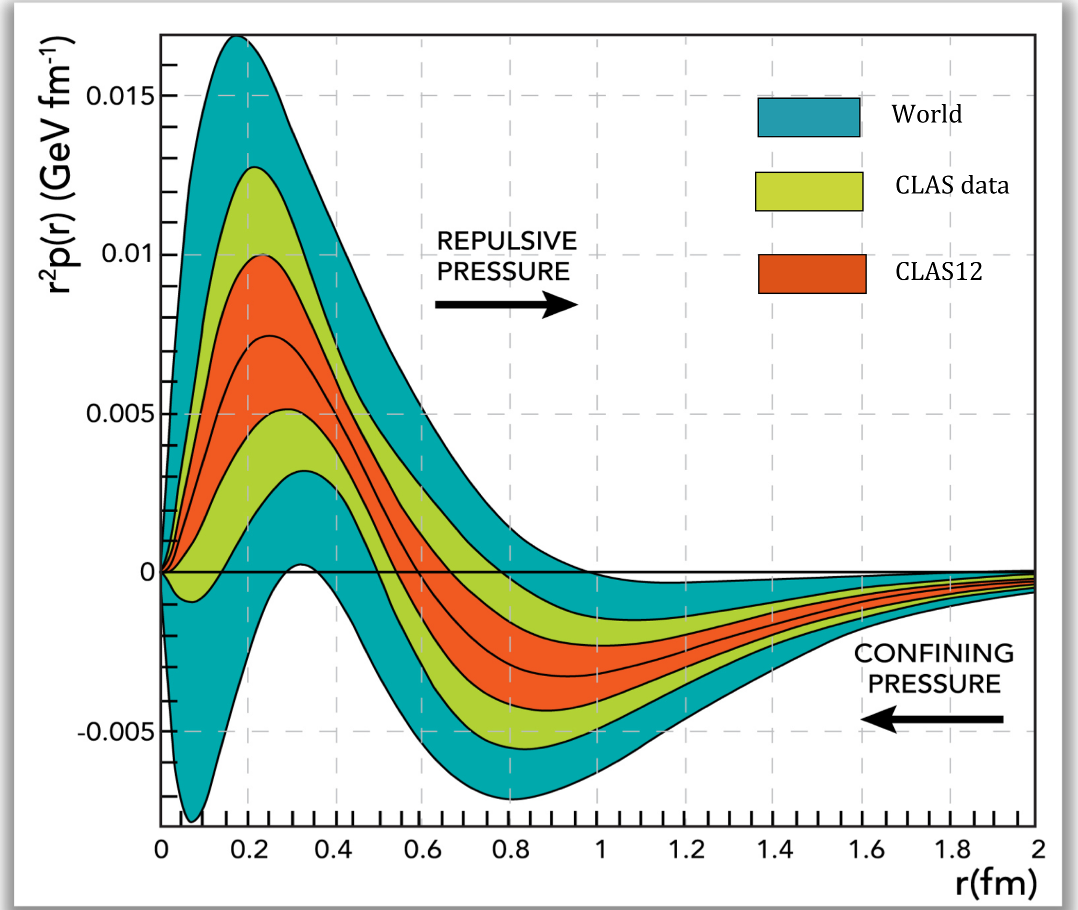
GPD ***H*** of special Importance as it gives access to the gravitational properties.

M. V. Polyakov, Physics Letters B 555 (2003) 57
I.V. Anikin and O.V. Teryaev, Phys.Rev.D76, 056007 (2007)
M. Diehl and D.Y. Ivanov, Eur. Phys. J. C52, 919, (2007)

Mapping DVCS to Gravity

The 2-γ field couples to the EMT the same way gravity does.





DVCS makes mechanical properties accessible to experiment

So how do we get insight into sQCD?

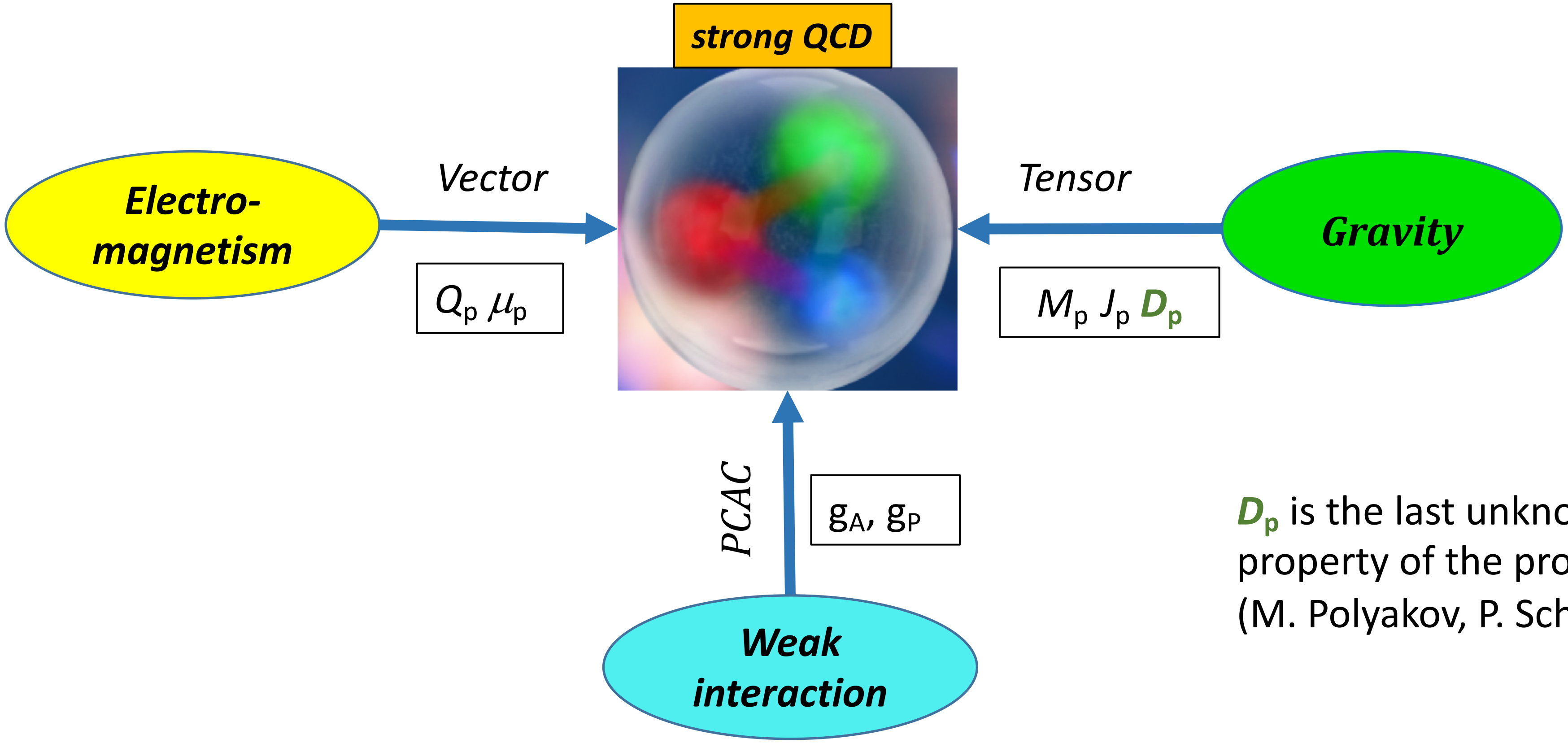
- **Strong QCD was born in the transition from free quarks and gluons to bound hadrons. The structure of all hadrons is related to sQCD. Precise measurements can give the incentive to do the calculations.**

- **The N* spectrum:** High precision data and multi-channel analyses enabled discovery of new N* states that fit by J^P values into the LQCD spectrum. Predicting the nucleon spectrum precisely is the challenge to **s**QCD.
- **Nucleon and transition form factors:** Approaches with traceable links to QCD have been successful in interpreting nucleon ground state and N* transitions FF, where dressed quarks are the active degrees of freedom. In the 12 GeV era new measurements provide insights into the running quark mass and di-quarks as active dof.
- **Spin structure functions and moments:** With the expected high precision of the 12 GeV measurements, they will be a fruitful testing ground for modeling **s**QCD.
- **Nuclear 3D imaging:** GPD-related Compton form factors and TMD related observables of protons and neutrons, should provide multi-dimensional insight into **s**QCD.
- **Mechanical properties of particles:** Mapping the normal and shear stress inside nucleons may relate to properties of confinement and is a novel testing ground of **s**QCD. Calculations within LQCD have been done- need higher precision.
- **Advanced model approaches:** LF RQM, LC SR, hQCD, EFT.. continue to provide insights when **s**QCD has not been solved.
- **Meson-baryon effects** may be crucial in addressing the confinement challenge. Calculations based on EFT may provide new insight.

Additional slides

Probing the properties of the proton

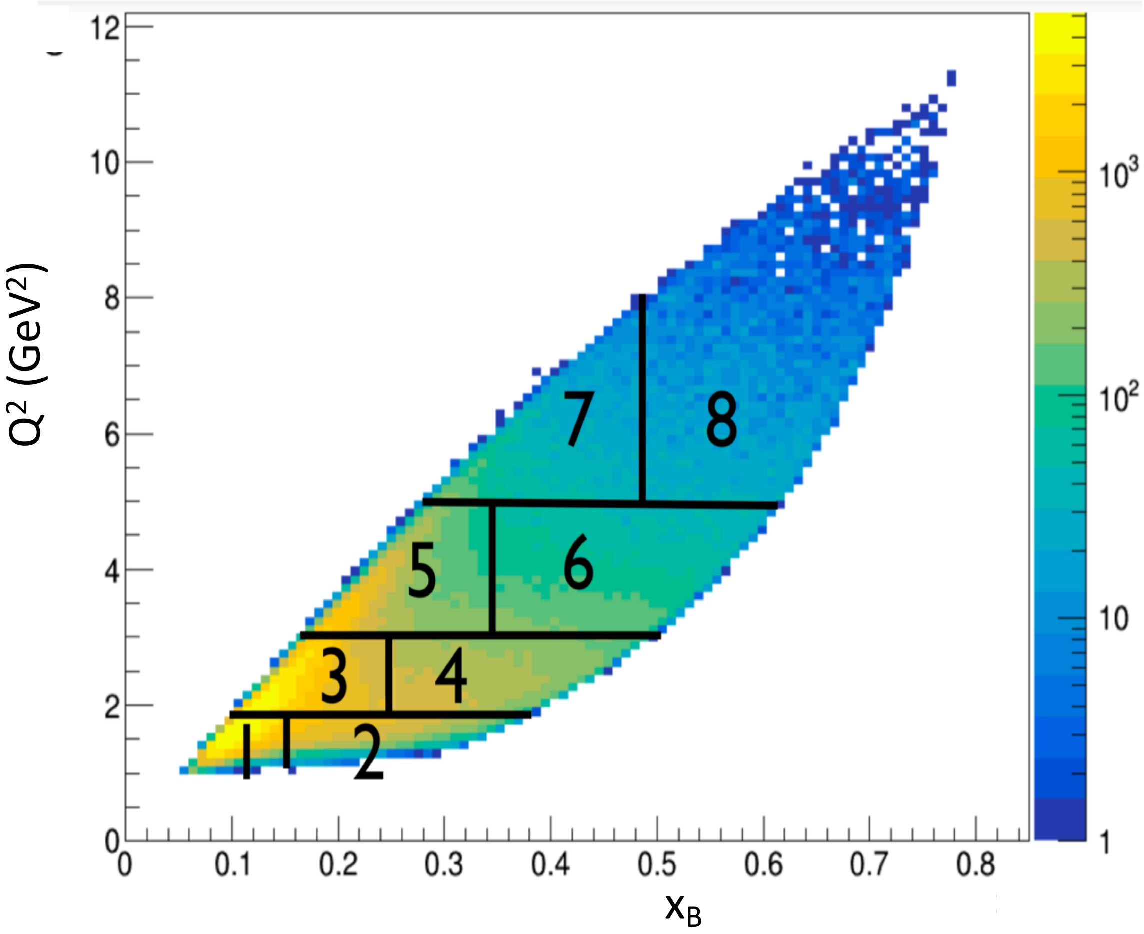
The structure of strongly interacting particles can be probed by means of the other fundamental forces: *electromagnetic, weak,* and *gravity*.



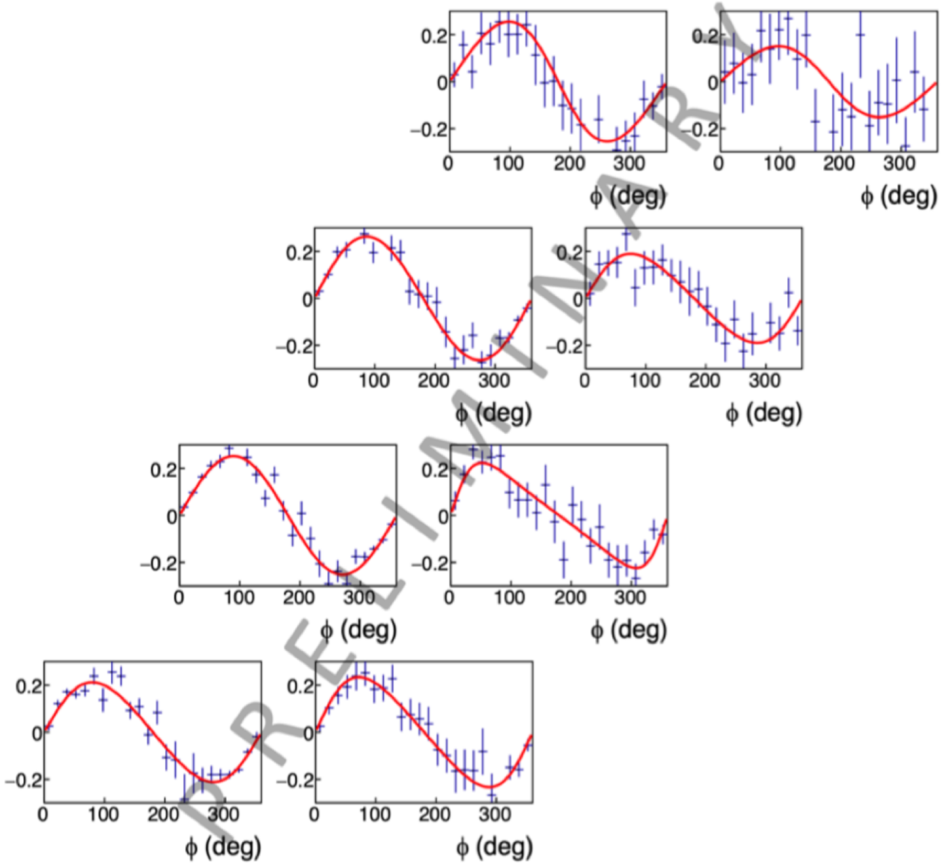
D_p is the last unknown global property of the proton.
(M. Polyakov, P. Schweitzer)

DVCS from RG-A

Kinematic reach E=10.6GeV



Beam-Spin Asymmetries



5% of expected RG-A data $t/Q^2 < 0.25$

The N/Δ Spectrum up to 2.2 GeV 2018 (PDG)