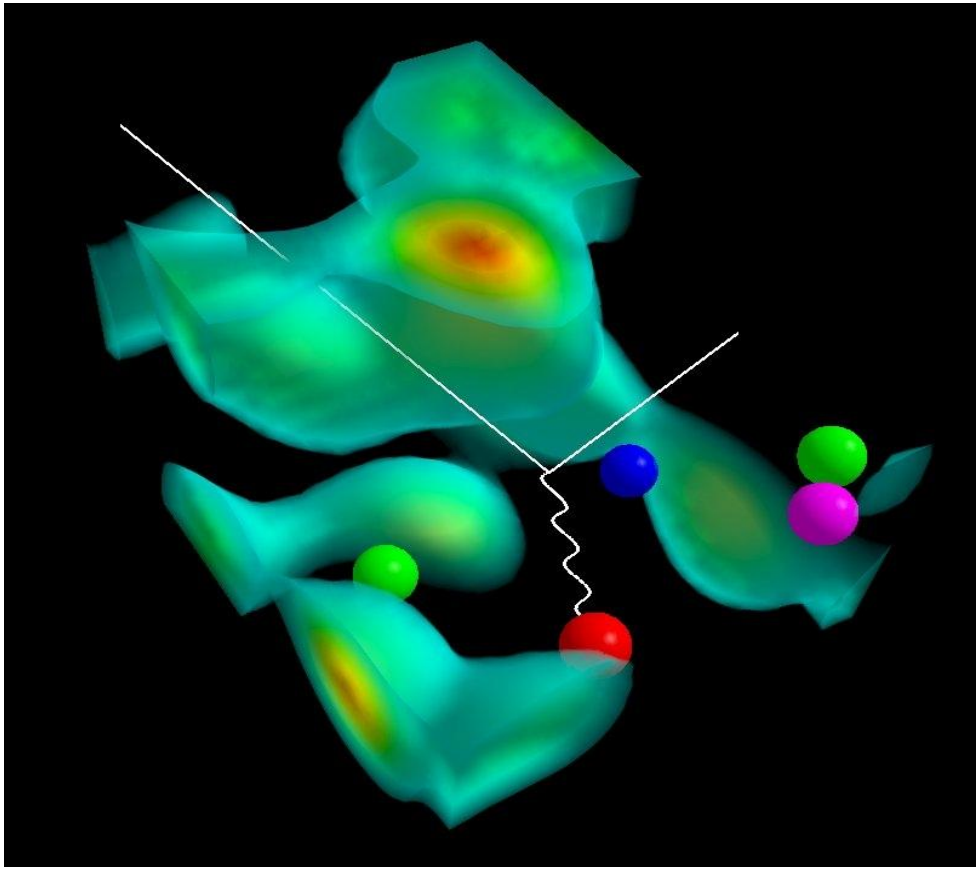
QCD and Hadronic Nuclear Physics (hadrons and nucleons)



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Anthony W. Thomas

ADELAIDE UNIVERSITY AUSTRALIA

IUPAP WG.9 Nuclear Science Symposium
Frascati – May 31st 2013

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Outline

- **QCD and Hadronic Physics**
  - **chiral symmetry breaking**
  - **confinement**
- **Hadron properties as emergent phenomena**
- **Recent progress in understanding nucleon structure**
- **Open challenges**
- **Facilities**

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QCD within the Standard Model

- **Standard Model is complete with Higgs discovery**

- **Built upon local gauge symmetries**

- **Strong sector is *unique* – fundamental degrees of freedom (*dof*) do not exist outside hadrons!**
  − despite searching everywhere, including moon rocks, deep ocean sediments, cosmic rays....

Confinement

- **In our world the fundamental *dof* are almost massless**
  BUT we are not!

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Building Blocks of our Universe

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	−1	d down	0.006	−1/3

Force Carriers of the Universe

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	**Mass GeV/c^2**	**Electric charge**
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	**Mass GeV/c^2**	**Electric charge**
g gluon	0	0

QCD and the Origin of Mass

$$\begin{array}{lccccccc} & u & + & u & + & d & = & \text{proton} \\ \text{mass:} & 0.003 & + & 0.003 & + & 0.006 & \neq & 0.938 \end{array}$$

No other sector of the Standard Model is like this

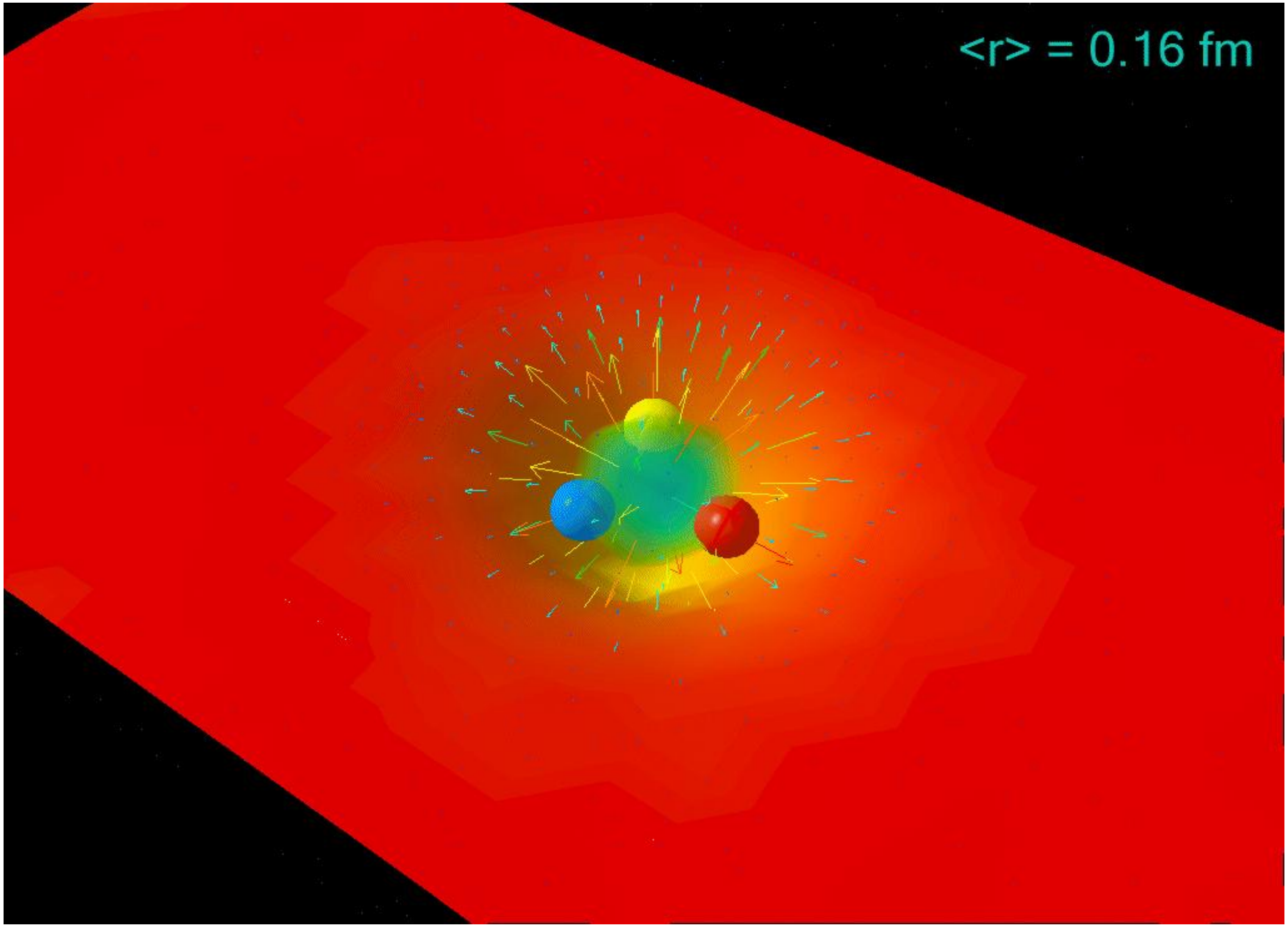
- **tear a table into its constituent atoms and the masses (of table and its components)are identical to one part in a billion**

HOW is this possible?

Dynamically Broken Chiral Symmetry

- **Near massless quarks ➡ near degeneracy of opposite parity states**
- **BUT N(940) and nearest negative parity is N(1535) !**
- **Goldstone's theorem implies near massless pion (and less so the K)**
- **Chiral limit crucial but bizarre**
  - **p *and* n charge radii infinite**
- ***Such a light pion completely undermines the conventional picture of confinement***

Confinement for infinitely heavy quarks?



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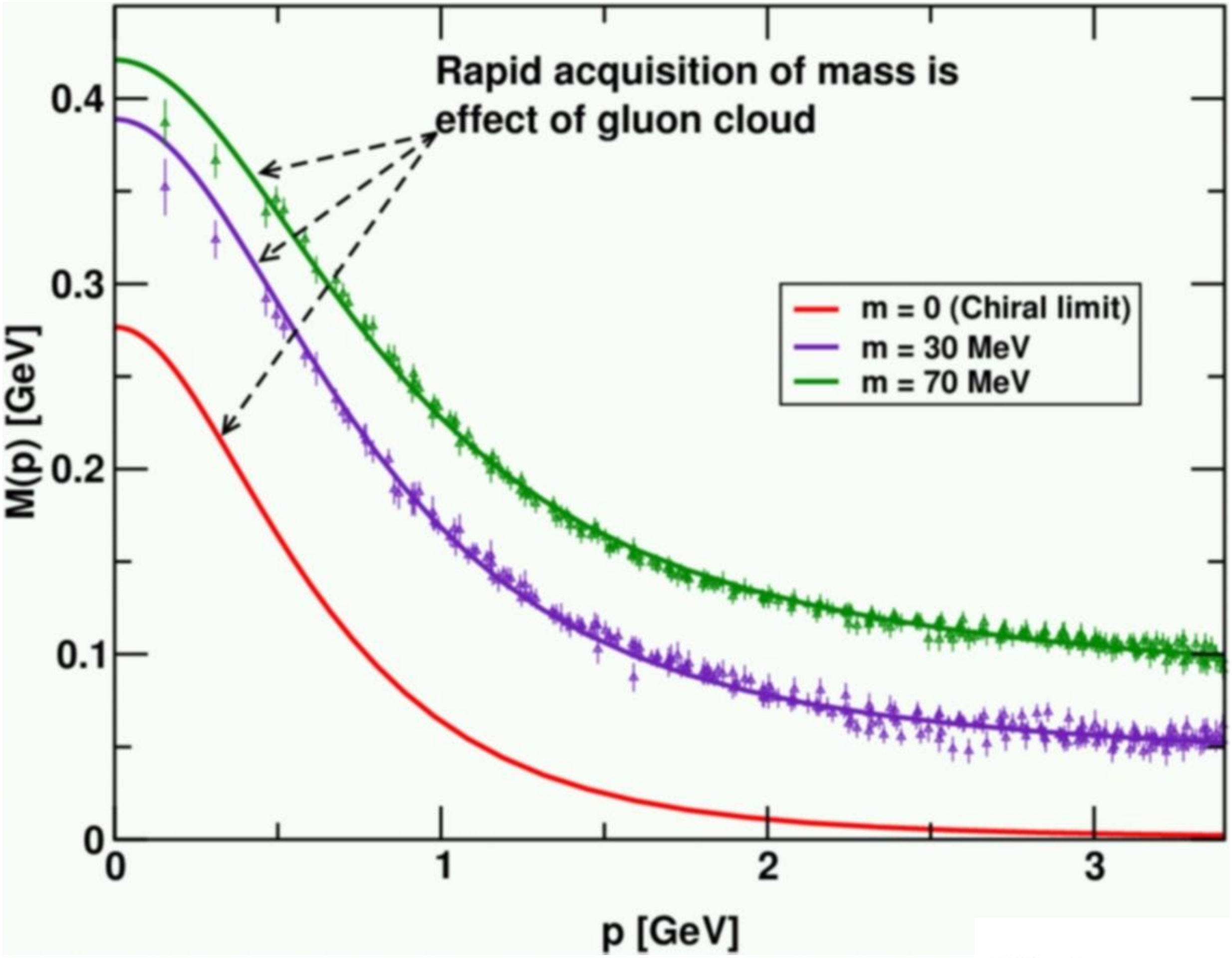
Quark mass function through χSB



$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$

Lattice studies & Dyson-Schwinger modelling in excellent agreement

− χSB is origin of constituent quark mass

Three generations of quarks & leptons

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	−1	d down	0.006	−1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	−1	s strange	0.1	−1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	−1	b bottom	4.3	−1/3

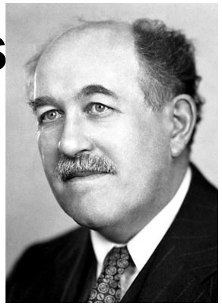
While important the physics of c, b and t is very different − χSB not of major importance − fascinating new states around 3.8-4.2GeV being found at BES (and Belle)

Our challenges

- Discover how the properties of hadrons emerge as non-perturbative properties of this beautiful, non-linear theory
- Test that it is indeed fully correct
- Investigate the role of hadron structure for atomic nuclei, dense matter, etc.

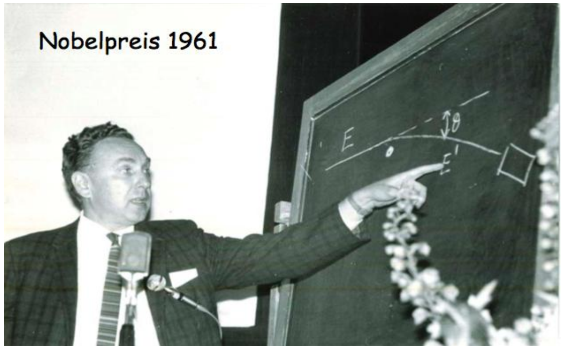
Investigation of Hadron Structure

- **Historically use electromagnetic and weak probes to excite and study**
- **Anomalous magnetic moments showed nucleons were not elementary Dirac particles in 1930s**



Stern

- **Elastic electron scattering (since 1950s) directly measures the Fourier transforms of charge and current distributions**
  - **$G_{E,M}$ (Q^2)**
- **Neutrino scattering adds G_A (Q^2) and G_P (Q^2)**

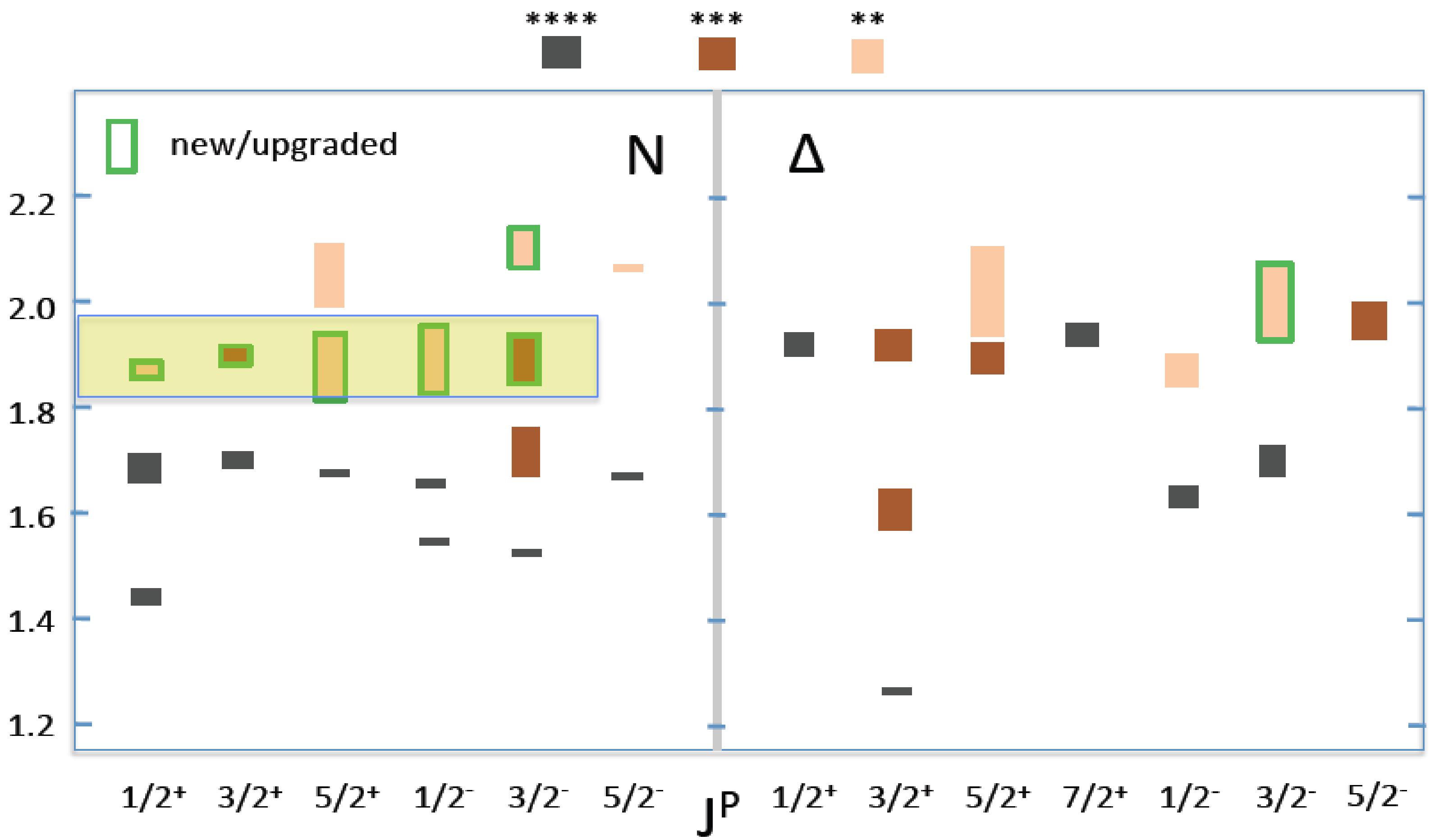


Hofstadter

Highlights of what we have learnt

N/Δ spectrum in PDG RPP 2012

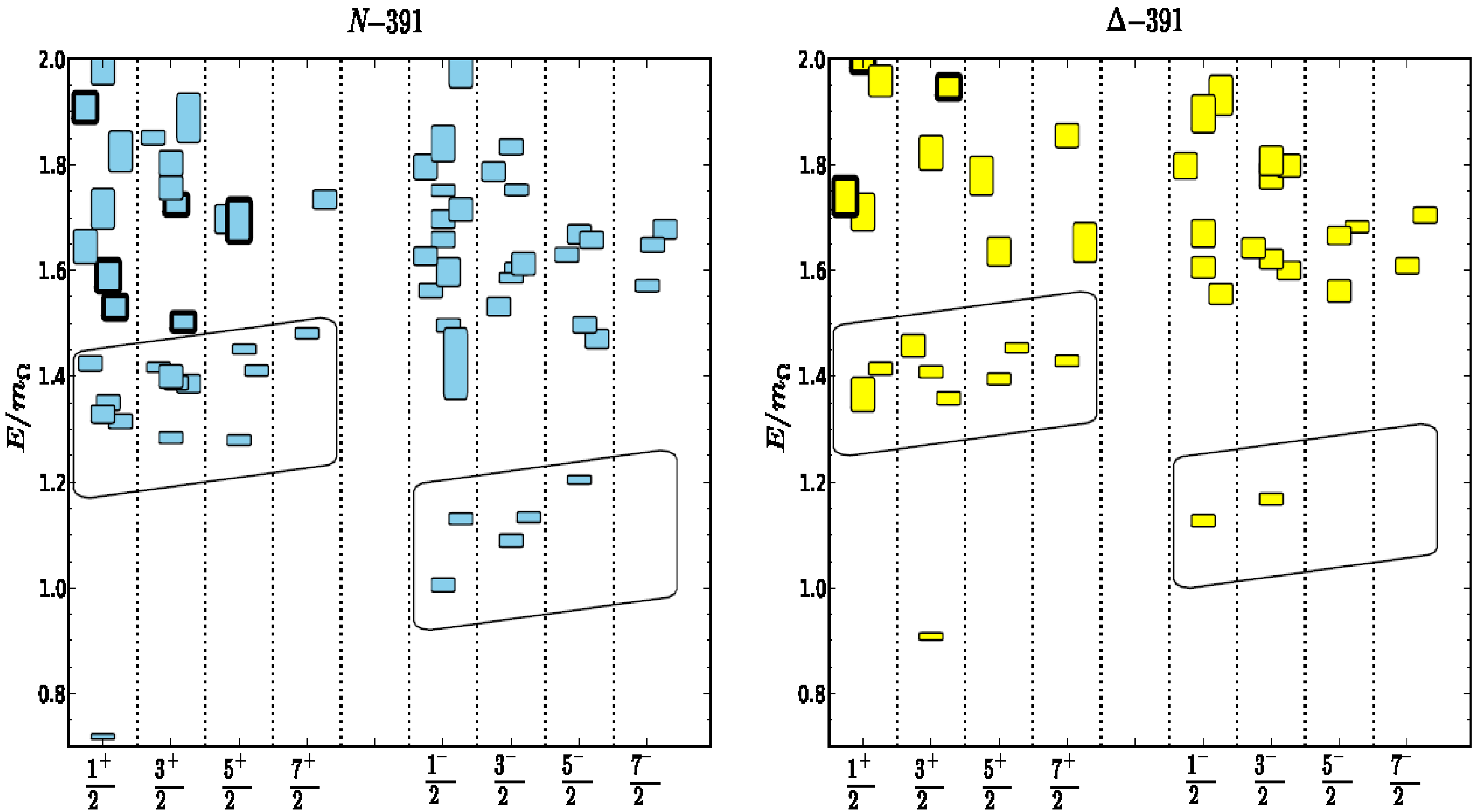
Experiments at JLab and Mainz : new baryonic states



All new candidate states need confirmation in independent analyses

Impressive results on excited states : lattice QCD

- **Recent results from JLab (m_π = 391 MeV)**



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Edwards et al., arXiv:1212.5236 (JLab)

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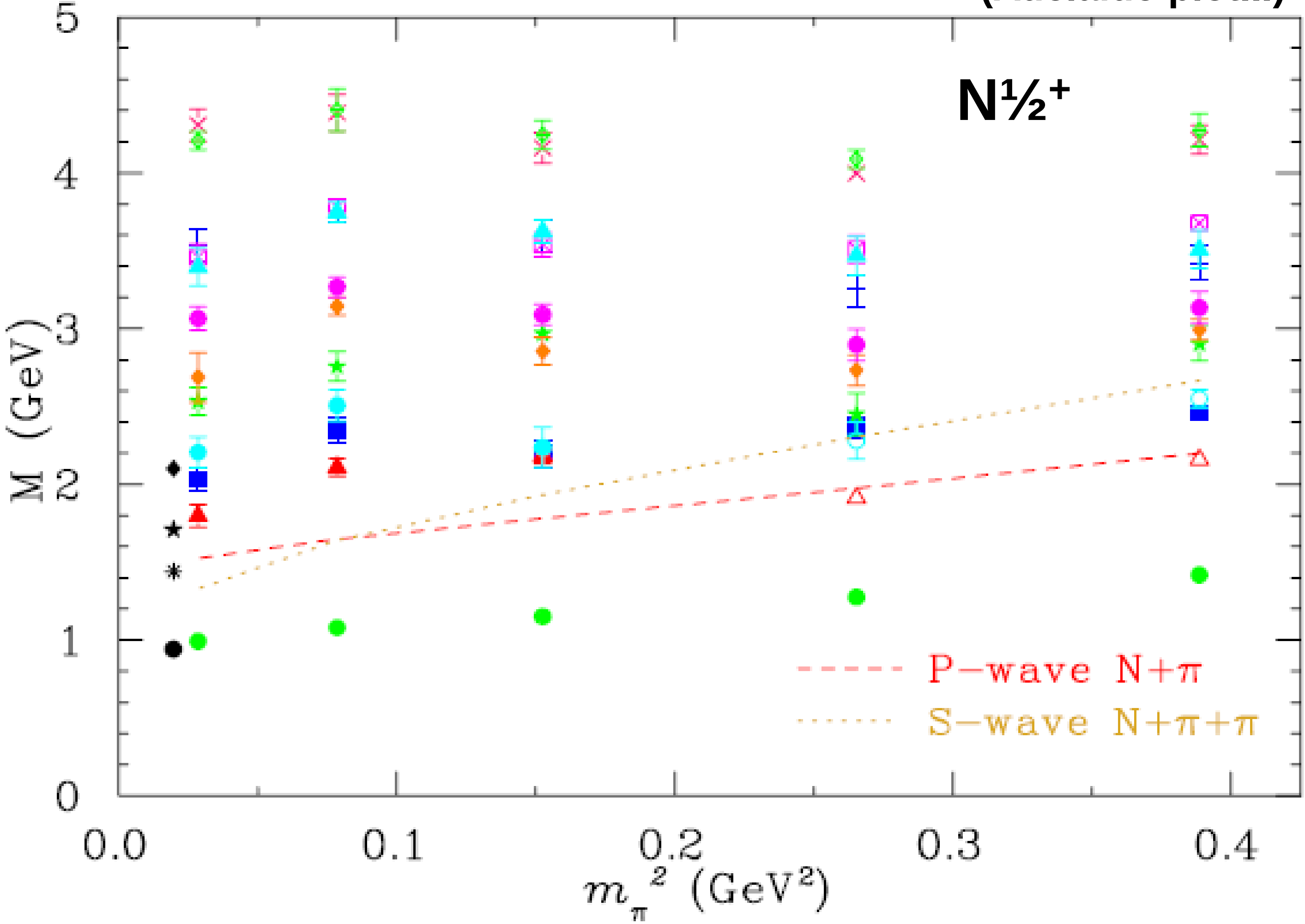
....and from CSSM

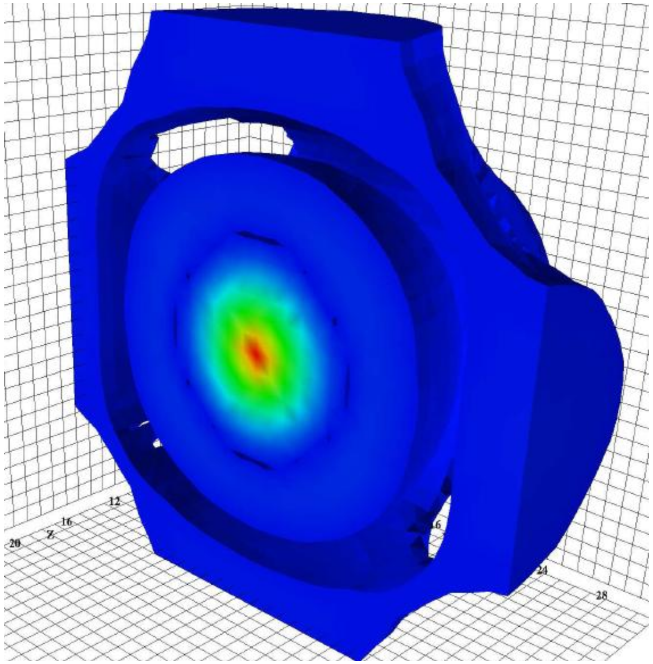
(Adelaide plot...)



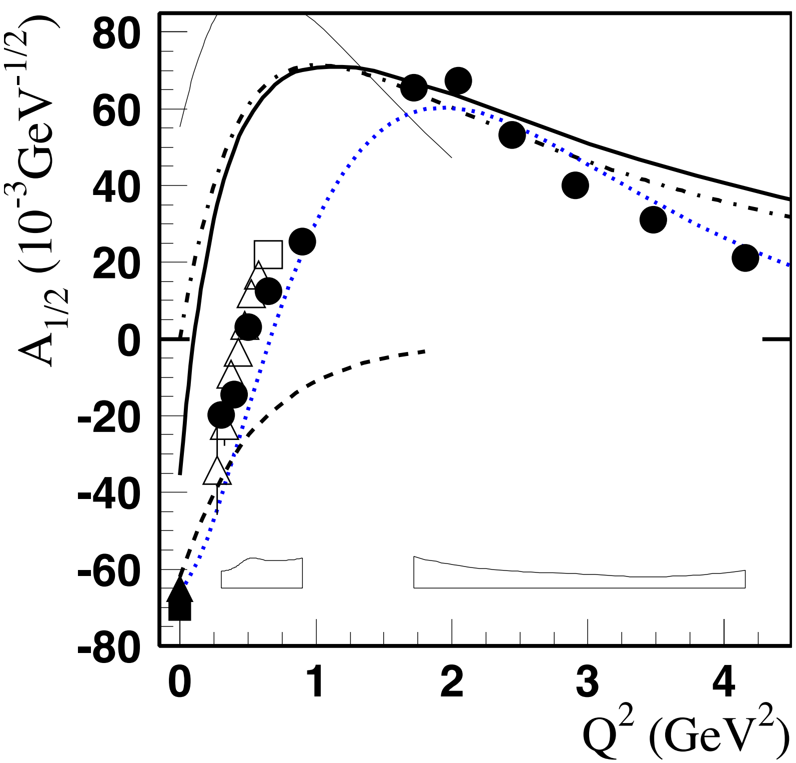
Mahbub et al., arXiv:1302.2987

More detailed information coming – experiment & lattice!

e.g. Nature of the Roper – 1450 MeV

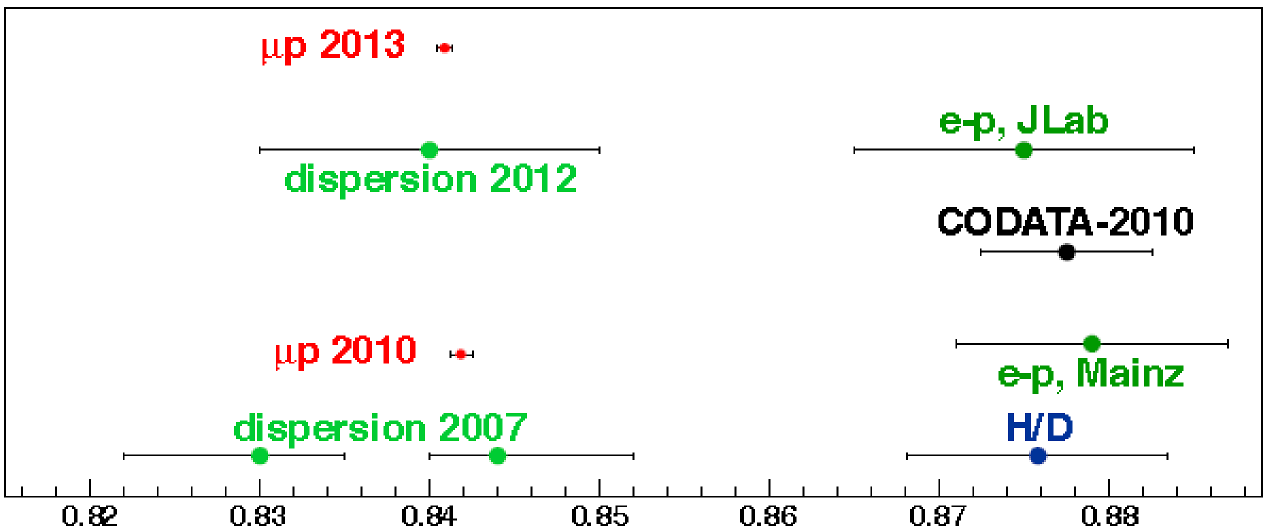


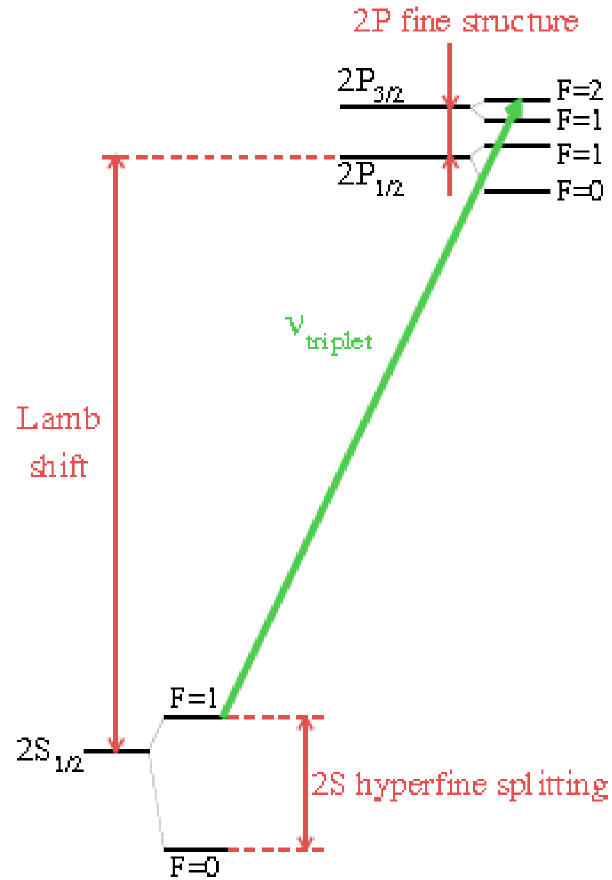
arXiv:1304.0325



Burkert et al., CLAS

Proton Radius Puzzle?





r_p = 0.84087 (26)$_{exp}$ (29)$_{th}$ = 0.84087 (39) fm

R. Pohl *et al.*, Nature 466, 213 (2010).

A. Antognini, RP *et al.*, Science 339, 417 (2013).

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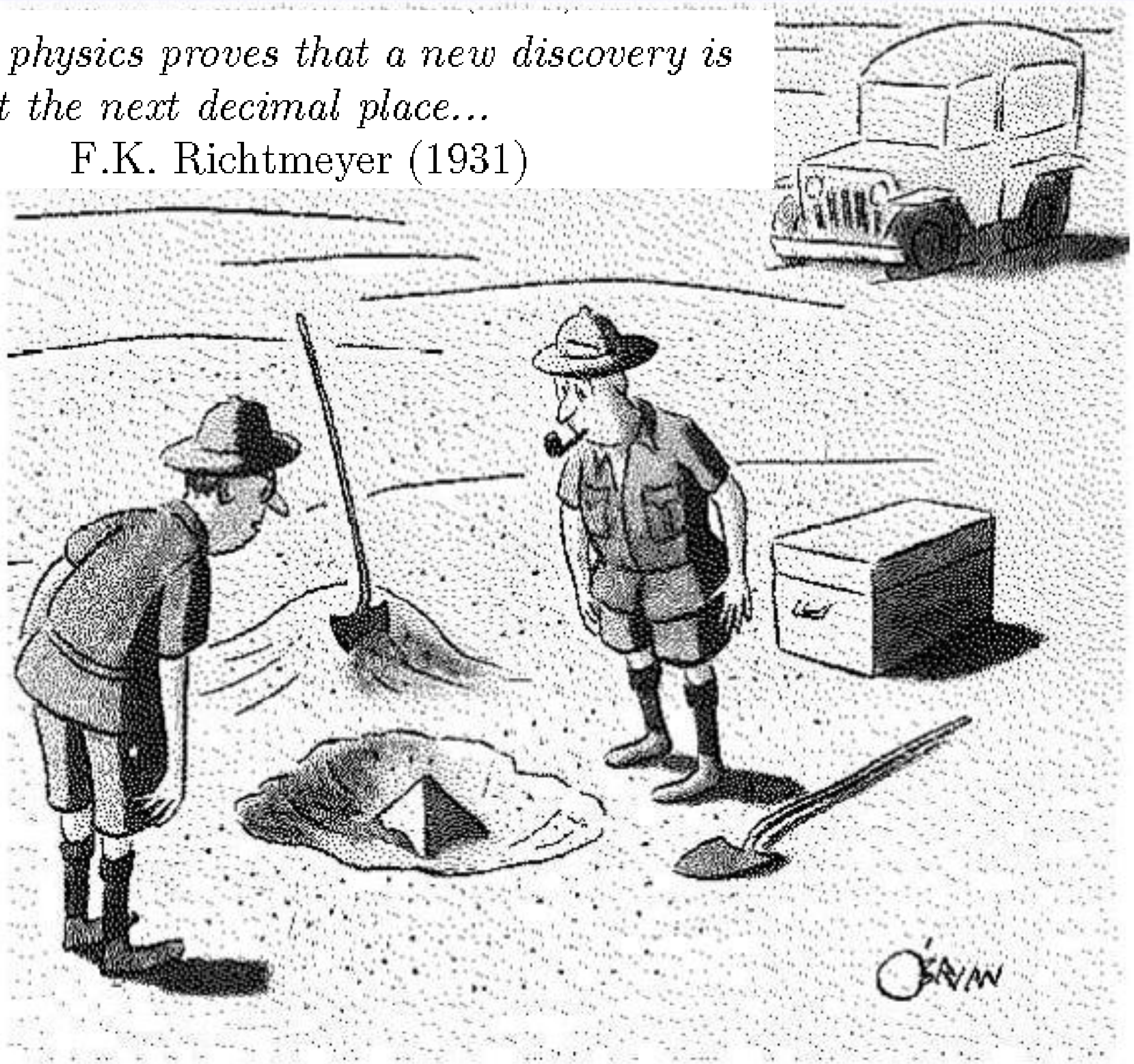
The proton radius puzzle

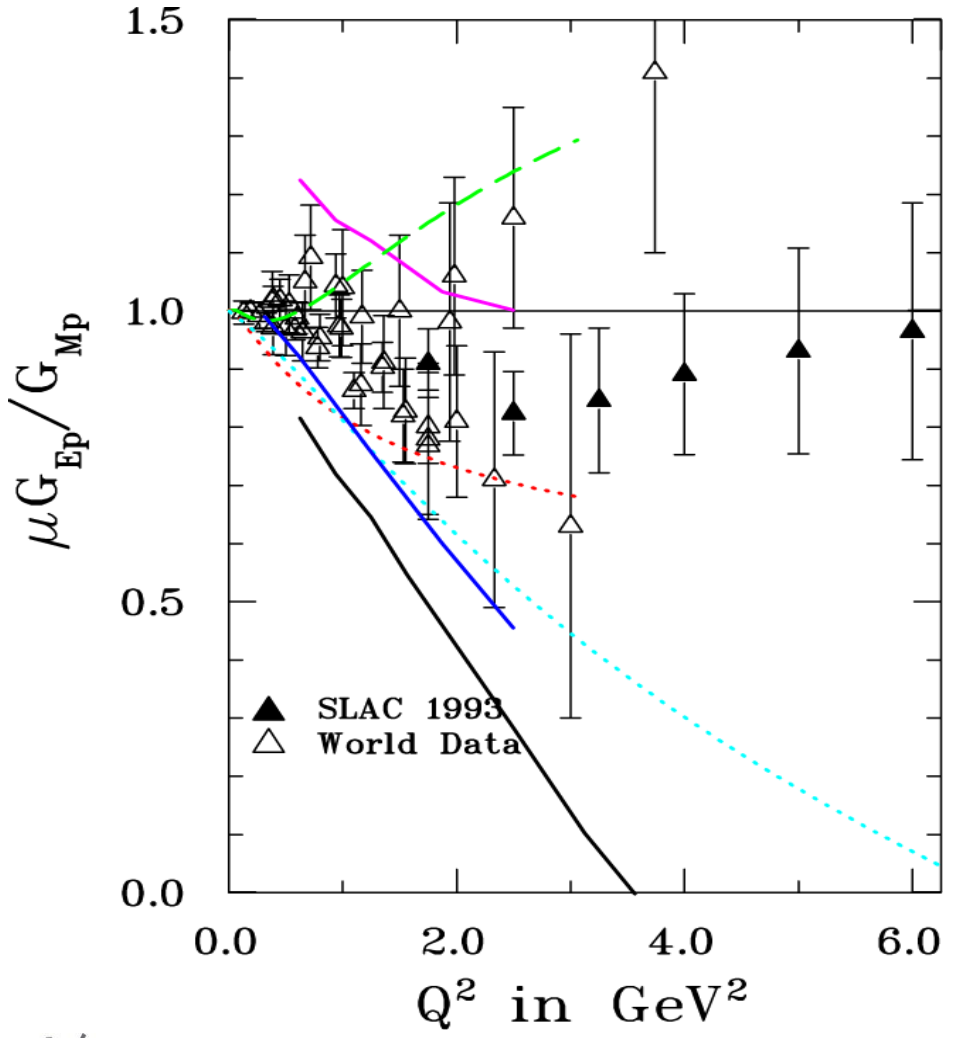
The whole history of physics proves that a new discovery is quite likely lurking at the next decimal place...

F.K. Richtmeyer (1931)



"This could be the discovery of the century. Depending, of course, on how far down it goes."

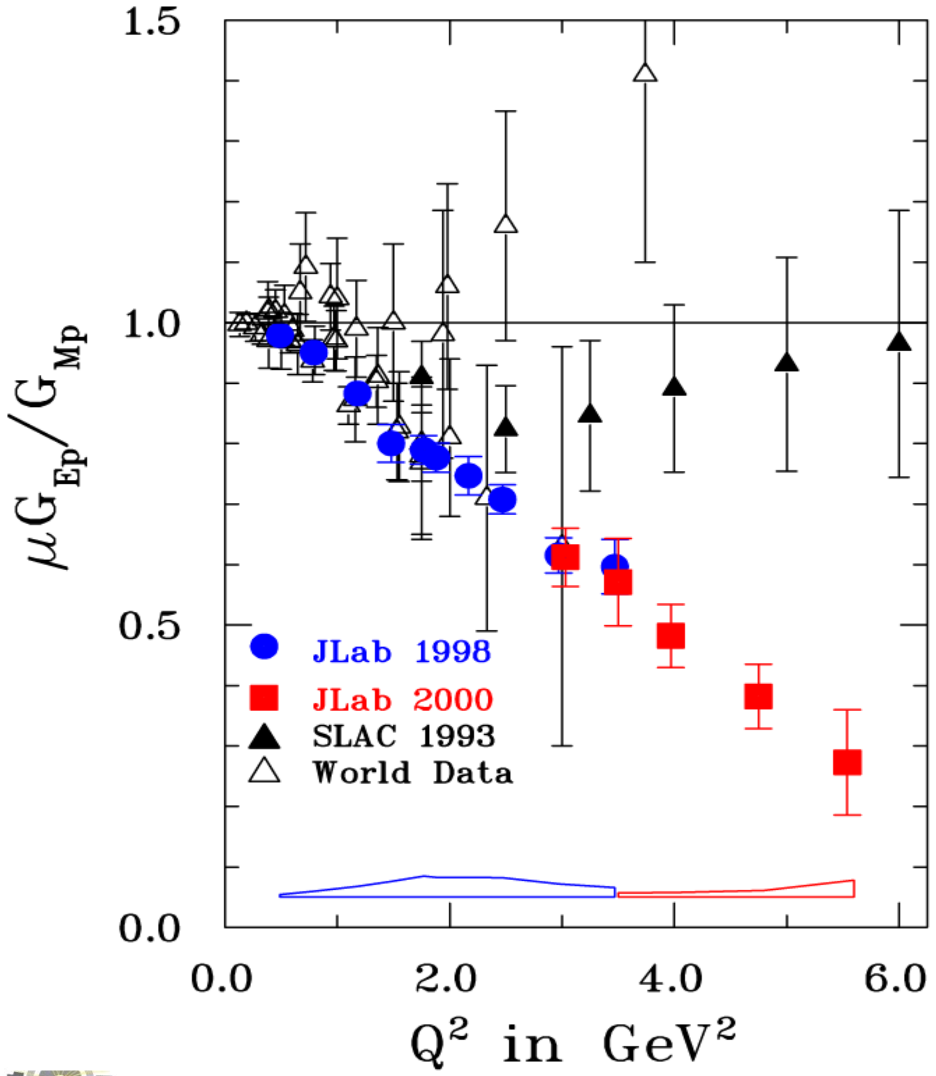
Initial Investigation of Charge vs Current in the Proton at SLAC



- Distribution of charge and magnetization in the proton seemed identical

- The experiments were limited by the precision of absolute cross section measurements

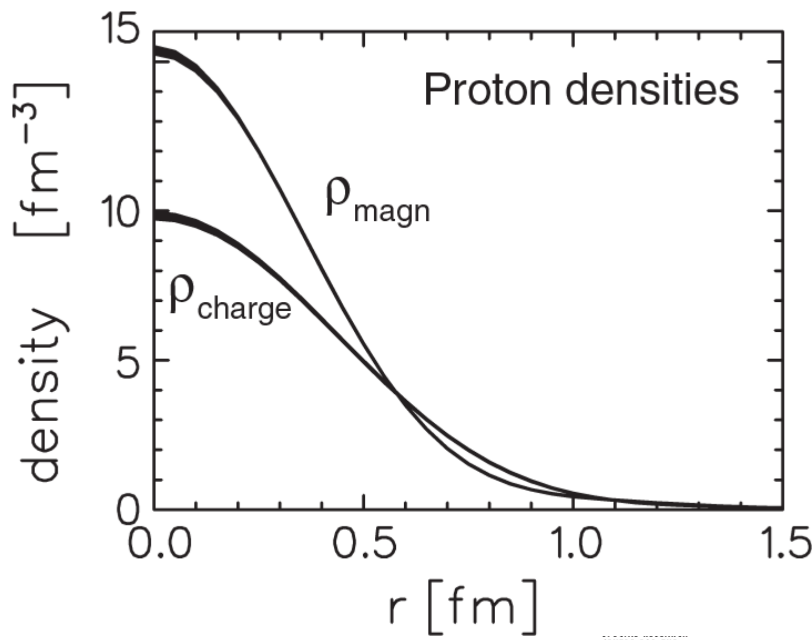
Text Book Re-written



- High Intensity
- High Duty Factor
- High Polarization

Revolutionized our knowledge

$\Rightarrow$



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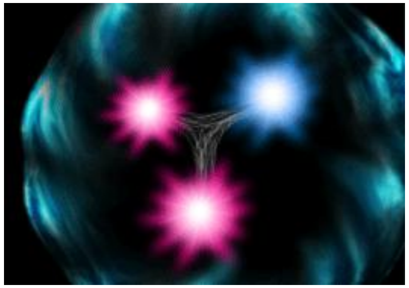
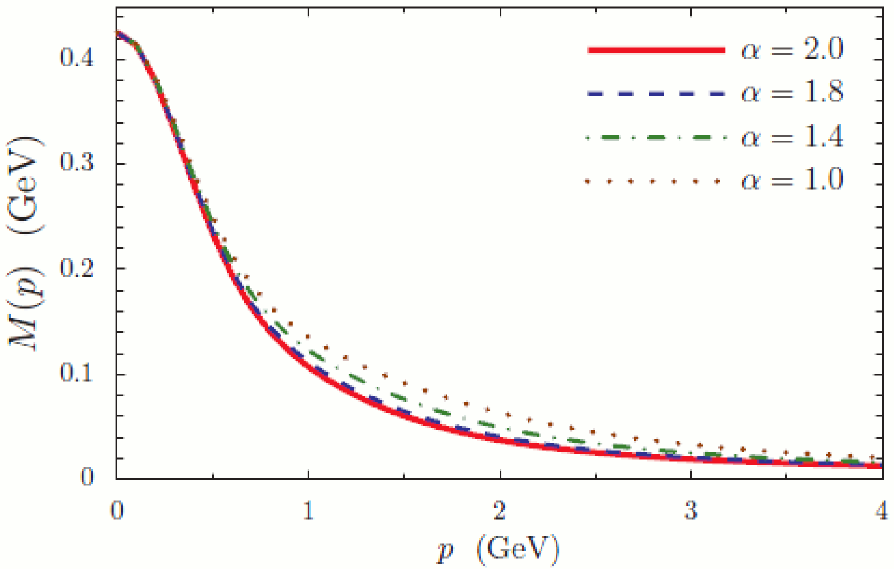
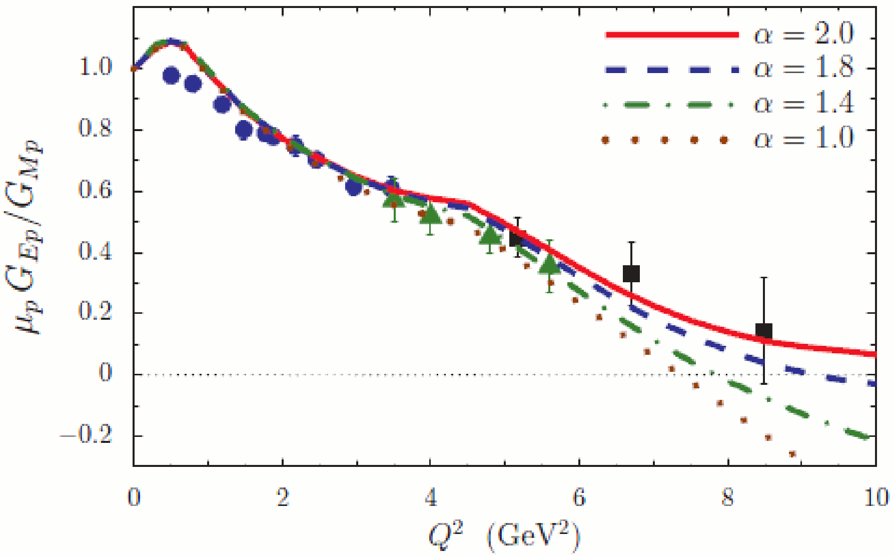
Potential link to xSB





- Small changes in M(p) within the domain 1<p(GeV)<3
  have striking effect on the electric form factor



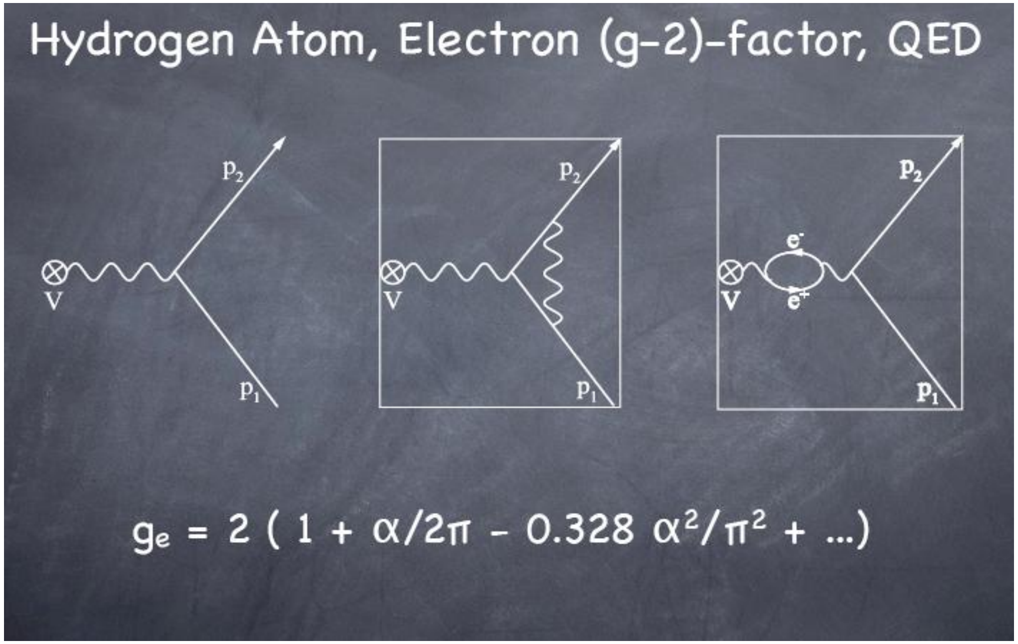
- Ratio $[\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)]$ provide information on the nature of the quark-quark interaction in the transition region from pQCD to non-perturbative QCD

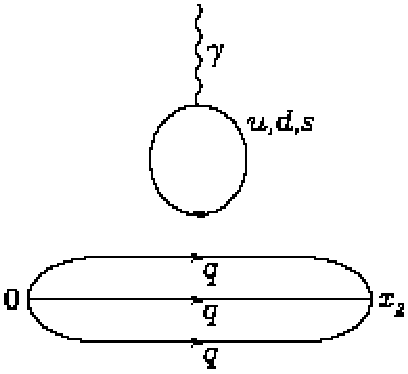
$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$

I.C. Cloët et al.: "Revealing dressed-quarks via the proton's charge distribution", arXiv: 1304.0855 [nucl-th]

Fundamental Test of Non-Perturbative QCD

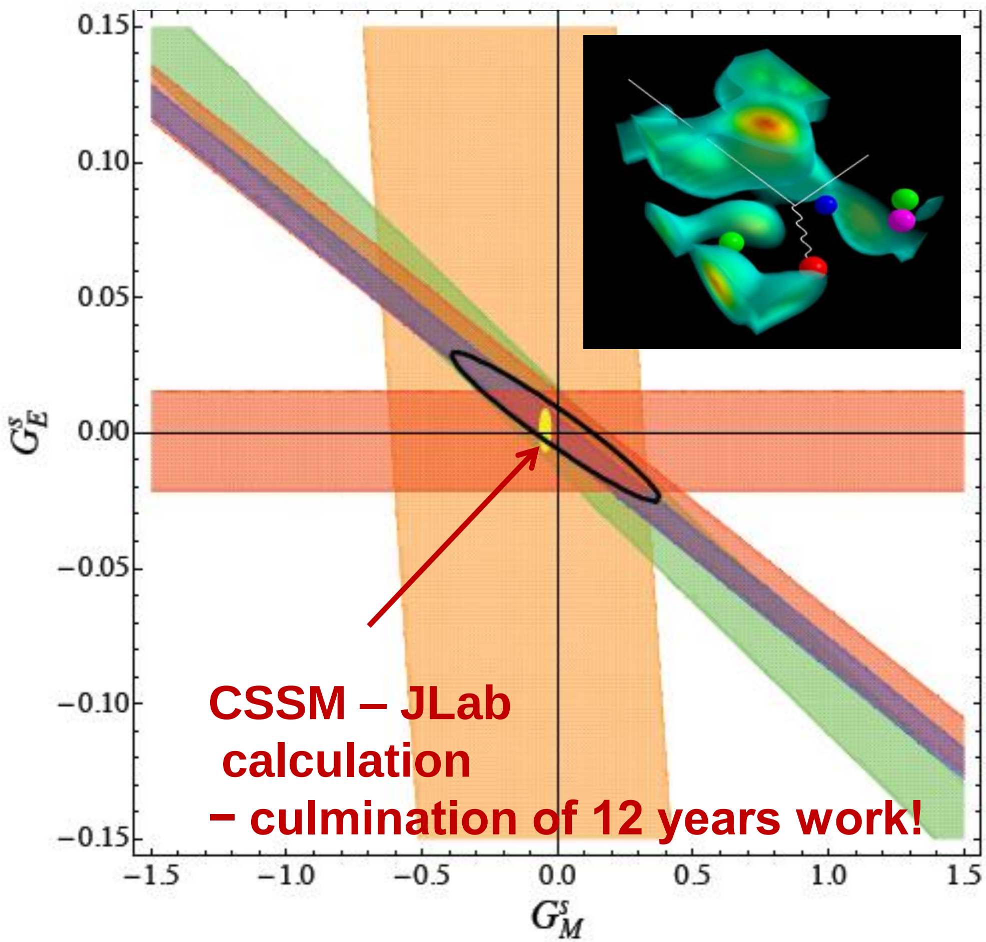
- **Strangeness contribution is a vacuum polarization effect, *analogous to Lamb shift in QED***





It is a fundamental test of QCD

A unique case : theory 10 times more accurate than data



CSSM – JLab calculation
− culmination of 12 years work!

Experimental program took three major laboratories 20 years!

Thomas Jefferson National Accelerator Facility (JLab) (plus Mainz & Bates)

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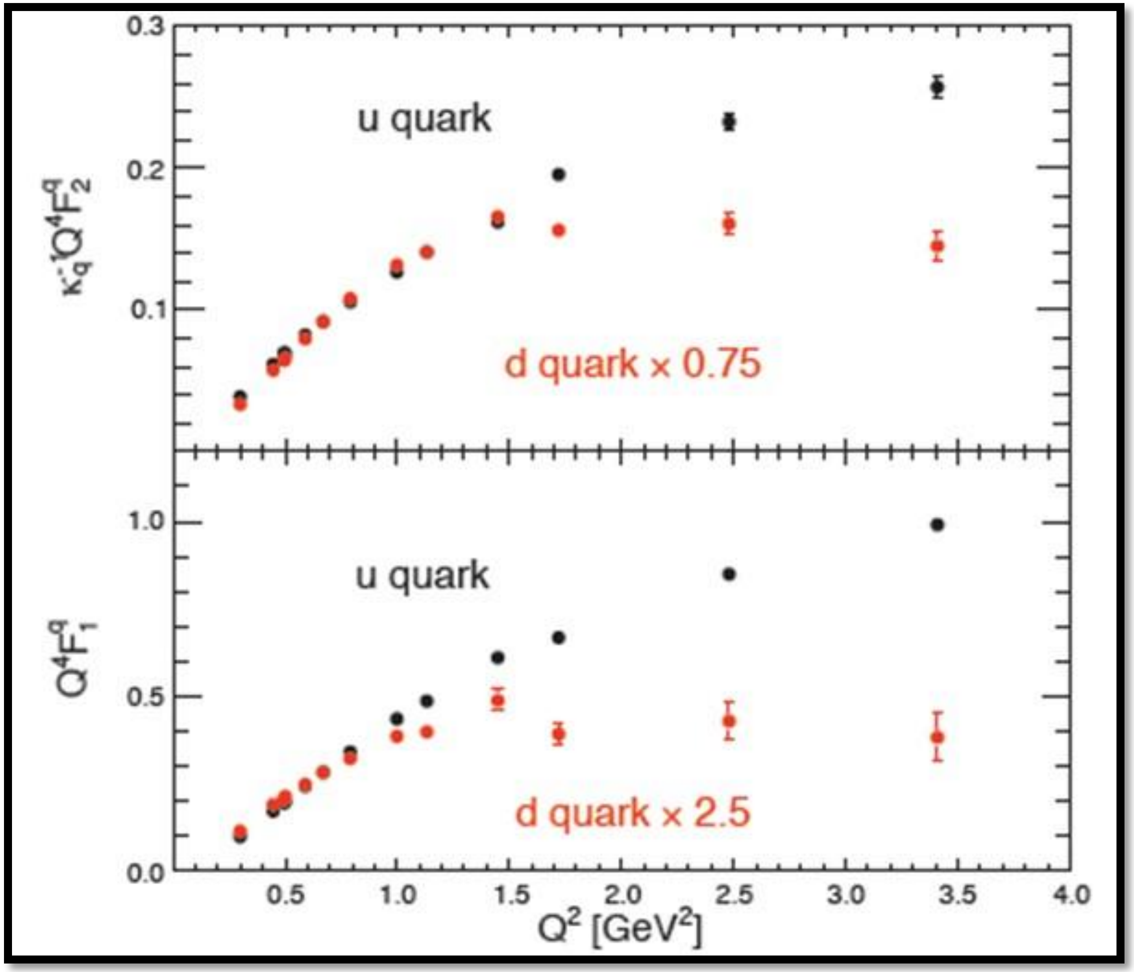
Flavor separation of proton form factors now possible….

$Q^4F_2^q/\kappa$

$Q^4 F_1^q$

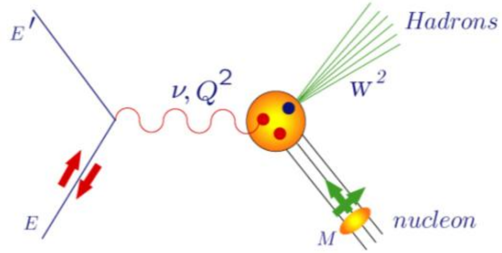
Cates, de Jager, Riordan, Wojtsekhowski, PRL 106 (2011) 252003



Very different behavior for *u* & *d* quarks suggests apparent scaling in proton F_2/F_1 may be *accidental*

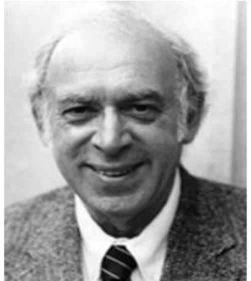
Direct confirmation of Quarks through Deep Inelastic Scattering

- At high energy and momentum transfer in inelastic electron (muon and neutrino) scattering one directly measures the momentum distribution of the quarks



- Polarised electrons also enable the spin of the quarks to be determined

- Later Drell-Yan (quark-anti-quark) annihilation added crucial new information

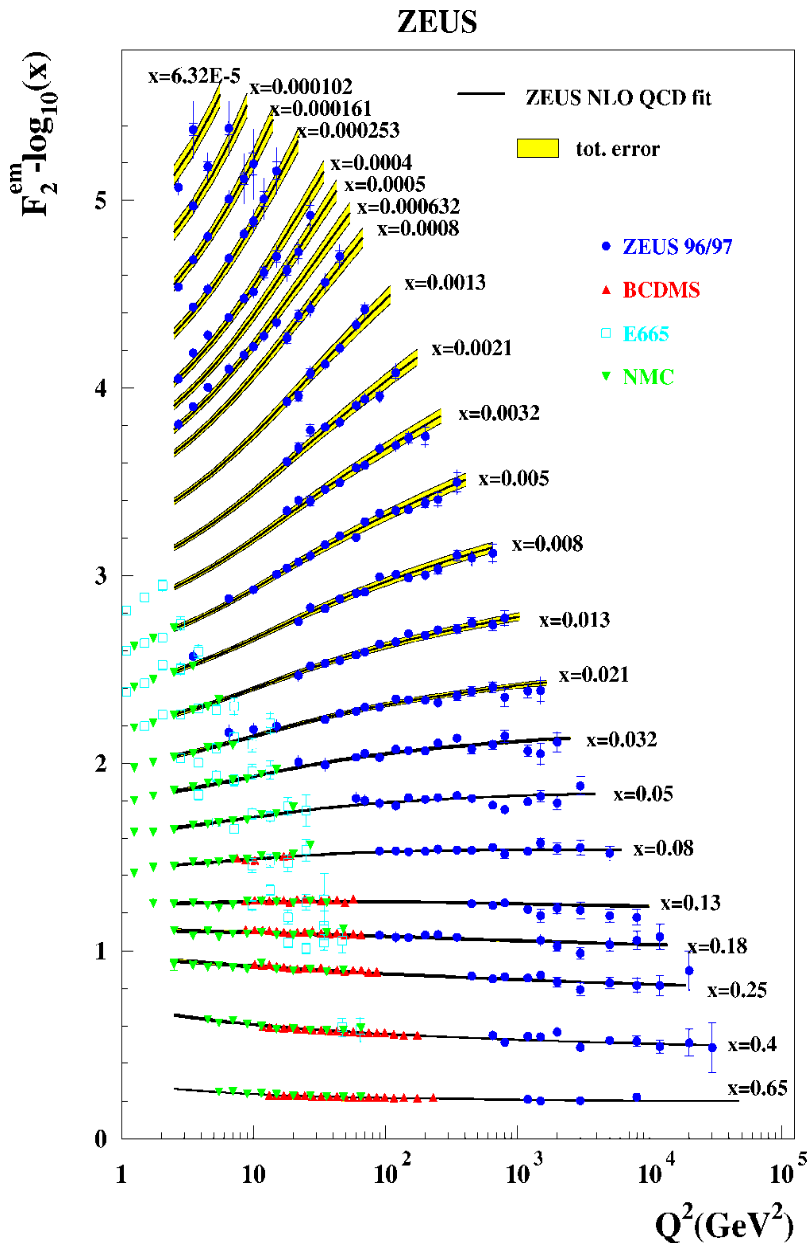


Unpolarized Structure Function F_2

- **Bjorken Scaling**
- **Scaling Violation**
- **Gluon radiation –**
- QCD evolution

  NLO: Next-to-Leading-Order

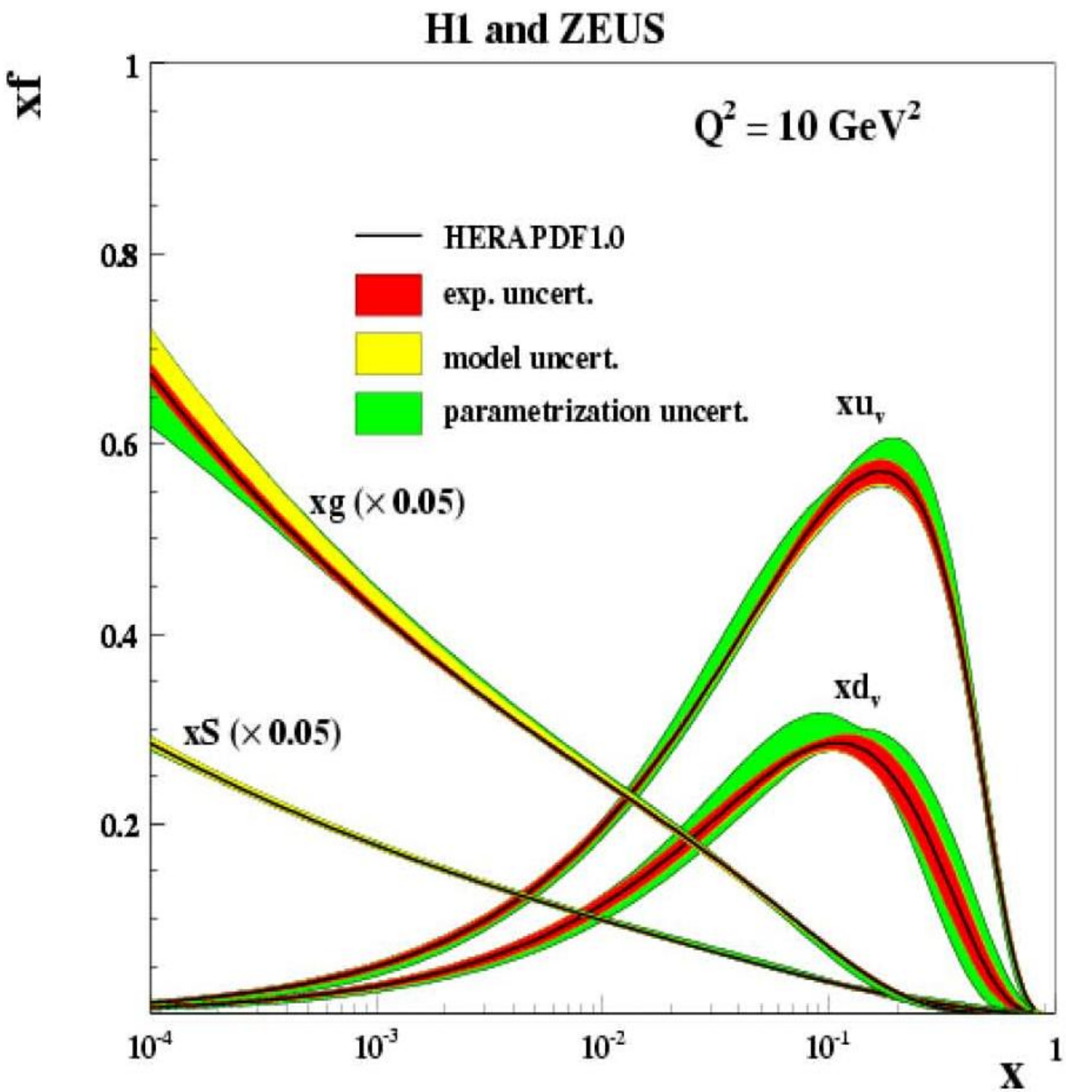
  …….

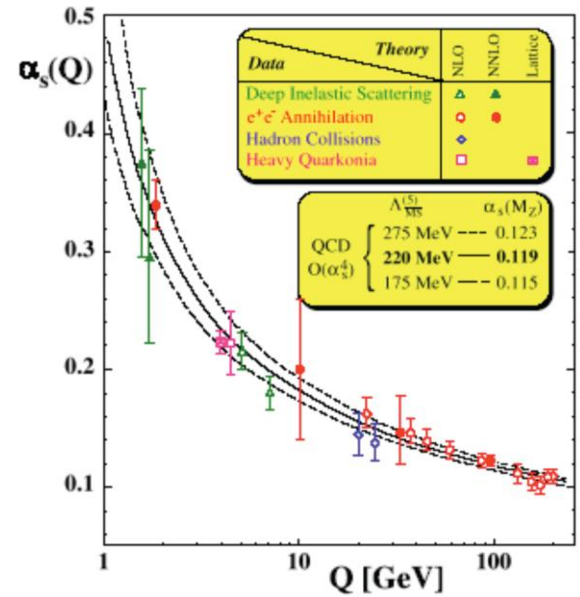


SLAC
CERN
FNAL
DESY

- One of the best experimental tests of QCD

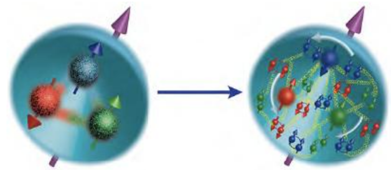
Parton Distribution Functions (CTEQ6)

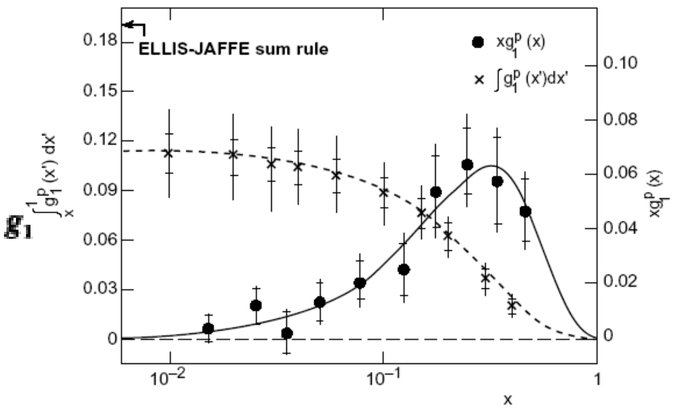




JHEP 1001: 109 (2010)

Volume 206, number 2 PHYSICS LETTERS B 19 May 1988





A MEASUREMENT OF THE SPIN ASYMMETRY AND DETERMINATION OF THE STRUCTURE FUNCTION g_1 IN DEEP INELASTIC MUON–PROTON SCATTERING

European Muon Collaboration

Aachen, CERN, Freiburg, Heidelberg, Lancaster, LAPP (Annecy), Liverpool, Marseille, Mons, Oxford, Rutherford, Sheffield, Turin, Uppsala, Warsaw, Wuppertal, Yale

J. ASHMAN [a], B. BADELEK [b,1], G. BAUM [c,2], J. BEAUFAYS [d], C.P. BEE [e], C BENCHOUK [f],

(93 authors)

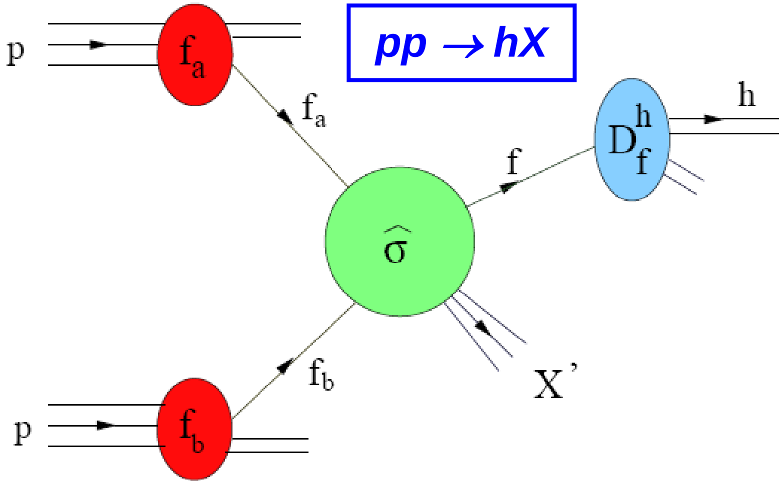
The spin asymmetry in deep inelastic scattering of longitudinally polarised muons by longitudinally polarised protons has been measured over a large x range $(0.01 < x < 0.7)$. The spin-dependent structure function $g_1(x)$ for the proton has been determined and its integral over x found to be $0.114 \pm 0.012 \pm 0.026$, in disagreement with the Ellis–Jaffe sum rule. Assuming the validity of the Bjorken sum rule, this result implies a significant negative value for the integral of g_1 for the neutron. These values for the integrals of g_1 lead to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nucleon.

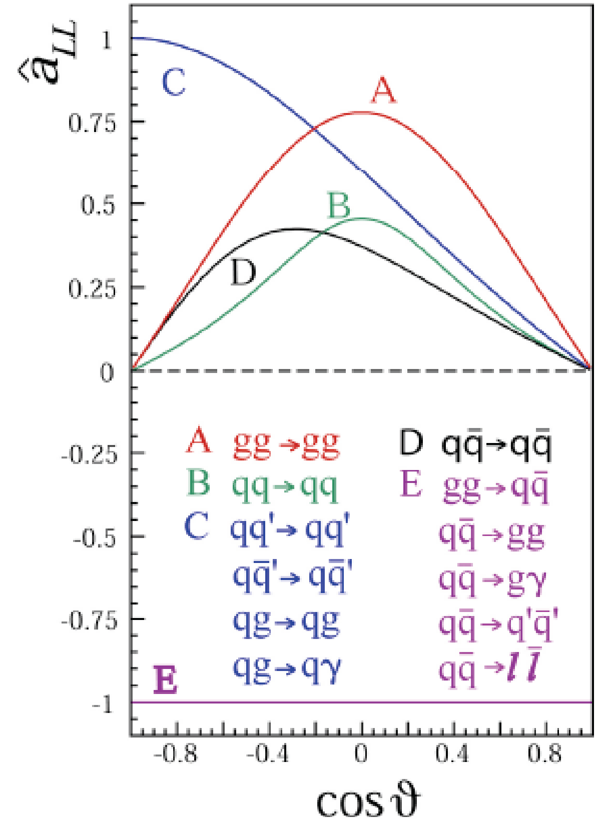
$\Sigma = 14 \pm 3 \pm 10$ % :

i.e. 86% of spin of p NOT carried by its quarks

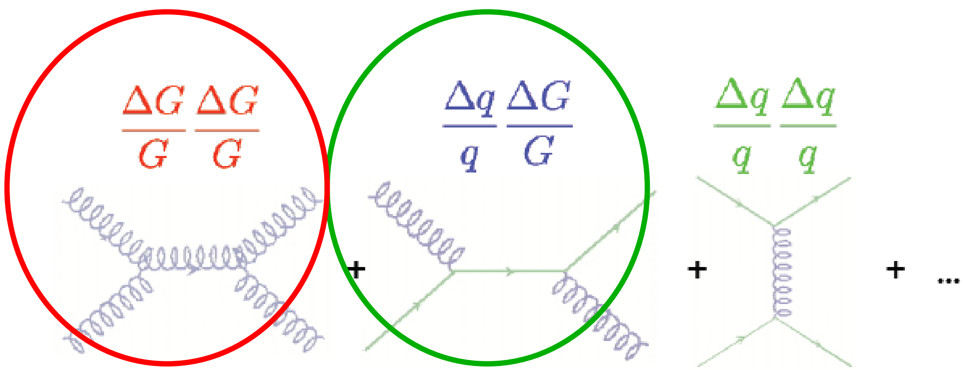
Probing ΔG in pol. pp collisions

$pp \to hX$





$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{\sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes d\hat\sigma^{f_a f_b \to fX} \cdot \hat a_{LL}^{f_a f_b \to fX} \otimes D_f^h}{\sum_{a,b} f_a \otimes f_b \otimes d\hat\sigma^{f_a f_b \to fX} \otimes D_f^h}$$



Double longitudinal spin asymmetry A_{LL} is sensitive to ΔG

Polarized pp collider at RHIC

Where is the Spin of the proton?

- **Modern data (Hermes, COMPASS) yields:**
  $\Sigma = 0.33 \pm 0.03 \pm 0.05$

  (c.f. $0.14 \pm 0.03 \pm 0.10$ originally)

- **In addition, there is little or no polarized glue**
  - COMPASS: $g^D_1 = 0$ to $x = 10^{-4}$
  - A_{LL} (π^0 and jets) at PHENIX & STAR: $\Delta G \sim 0$ -
  Hermes, COMPASS and JLab: $\Delta G / G$ small

- **Hence: axial anomaly plays at most a small role in explaining the spin crisis**

- **Suggests alternate explanation lost in the rush to explore the anomaly :**
  chiral symmetry and gluon exchange

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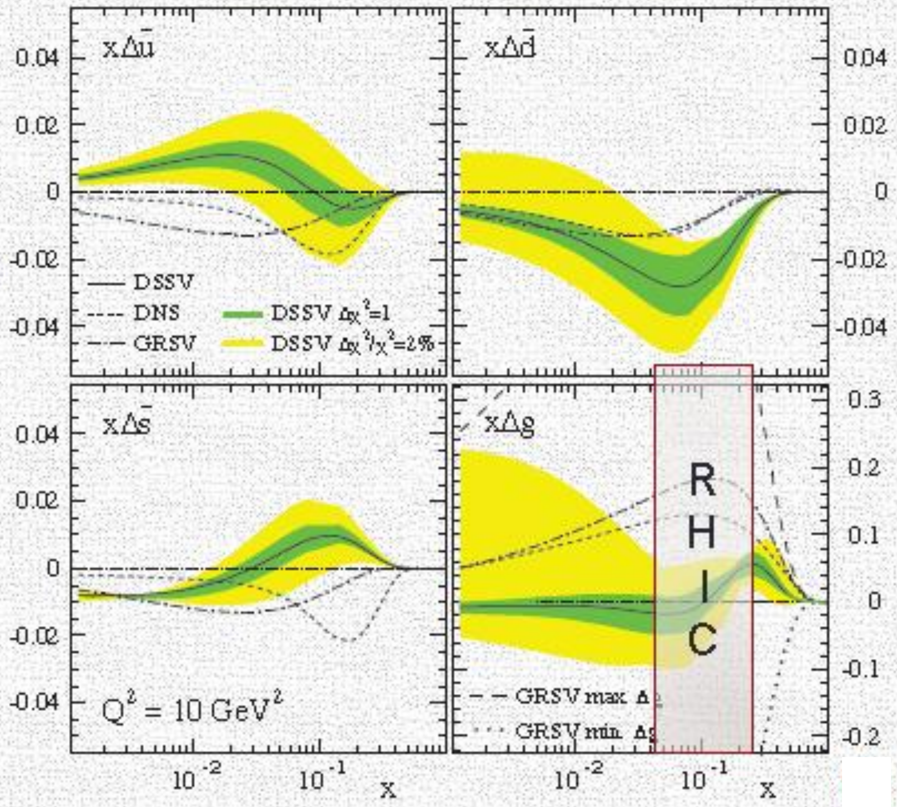
Nucleon Spin Puzzle

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta g + L_g$$

- ½ ($\Delta\Sigma$) ~ 0.15 : From fixed target pol. DIS experiments performed in 1990s
- Recent RHIC-Spin: (2000s)
  - *Δg ~0.1 +/- 0.1*
  - *Not as large as anticipated in the 1990s but seems to be non-zero (currently with large uncertainty)*
- ***Precision needed***
- ***Low-x coverage needed***

DSSV, arXiv:0804.0422



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Recent Result on Quark Spins for the Octet

- **Rather than experimental measurements on the octet, we now have lattice QCD - in this case QCDSF (Phys. Rev. D 84, 054509 (2011) and Phys. Lett. B 714, 97 (2012)) − see final column**

	MIT Bag	MIT Bag + OGE	MIT Bag + M. Cloud	MIT Bag + OGE + M. Cloud	Model	Lattice
N	65.4	53.8	51.9	43.8	1.0	1.0
Λ	77.1	67.3	66.4	58.9	1.35 (1.33)	-
Σ	61.5	50.8	50.5	42.6	0.97 (0.98)	0.92 (13)
Ξ	80.9	72.3	72.0	65.2	1.49 (1.44)	1.61 (33)

- **The other columns show the results for the cloudy bag model that worked so well for the nucleon applied to whole octet**

- **Agreement remarkably good... suppression is not universal!**

Shanahan et al., Phys Rev Lett 110 (2013) 202001

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G_A - a fundamental test

AXIAL NUCLEON FORM FACTORS FROM LATTICE QCD PHYSICAL REVIEW D **83,** 045010 (2011)

TABLE IV. In the second, third and fourth column we give the interpolated values of g_A at the value of $m_\pi r_0$ given in the first column. We used $r_0/a = 5.22(2)$, 6.61(3) and 8.31(5) for $\beta = 3.9, 4.05$ and 4.2, respectively. In the fifth column we give the value of g_A after extrapolating to $a = 0$ using a constant fit. In the parenthesis we give the corresponding values when using a linear fit. In the last column we give the continuum value of g_A for the volume-corrected data.

$r_0 m_\pi$	$g_A(\beta = 3.9)$	$g_A(\beta = 4.05)$	$g_A(\beta = 4.2)$	$g_A(a \to 0)$	$g_A(L \to \infty, a \to 0)$
1.1019	1.165(18)	1.173(25)	1.130(26)	1.159(13) [1.127(40)]	1.165(13) [1.144(40)]
1.0	1.132(25)	1.172(33)		1.147(20)	1.153(20)
0.95	1.125(29)	1.175(31)		1.148(21)	1.155(21)
0.85	1.138(28)	1.179(37)		1.153(22)	1.165(22)
0.686	1.110(39)	1.194(66)		1.127(34)	1.129(34)
0.615	1.153(47)	1.199(69)	1.138(43)	1.154(29) [1.142(76)]	1.165(29) [1.156(76)]

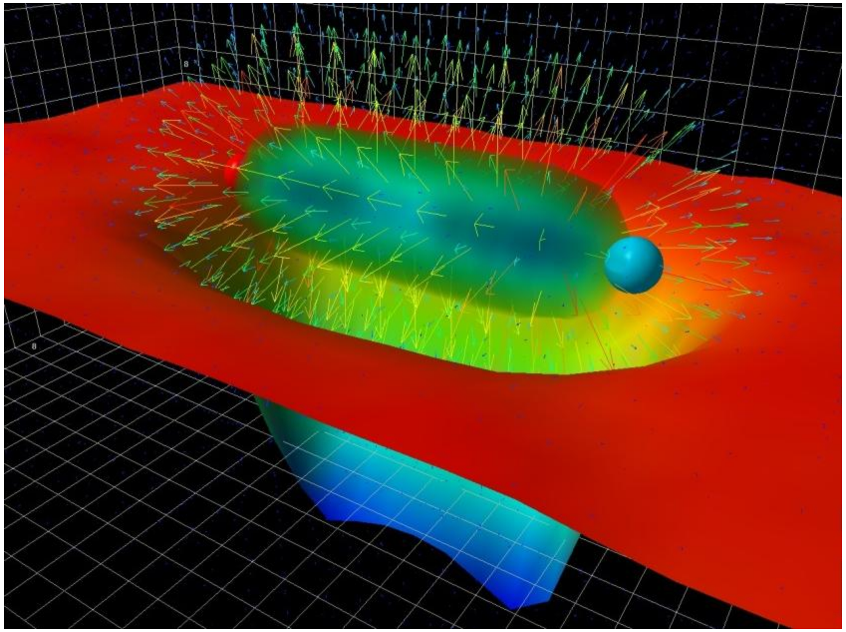
Therefore still a caution on lattice QCD !

Future challenges

Spectroscopy

- how do excited states emerge from QCD
- what are the fundamental degrees of freedom

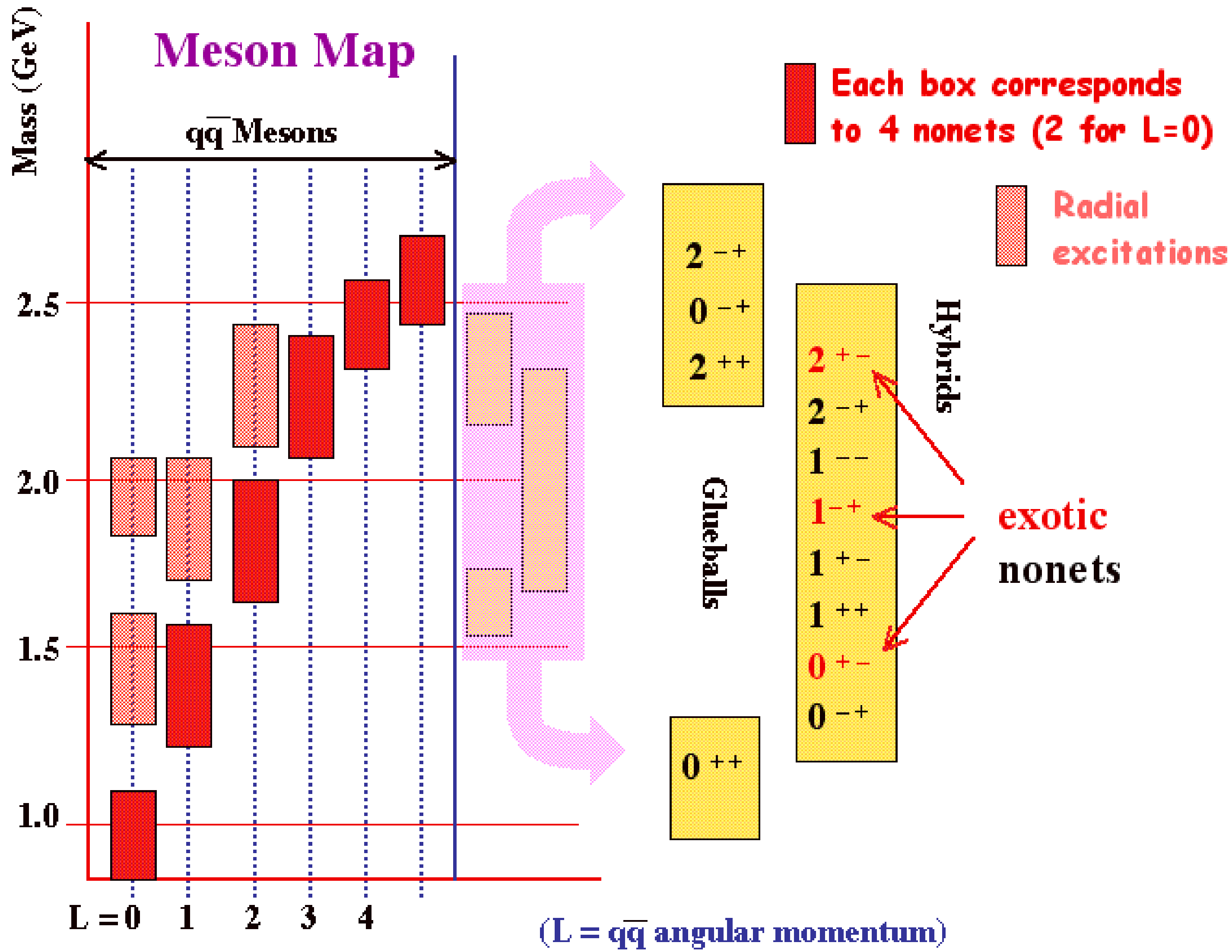
Gluonic Excitations and the Origin of Confinement



QCD predicts a rich spectrum of as yet to be discovered gluonic excitations

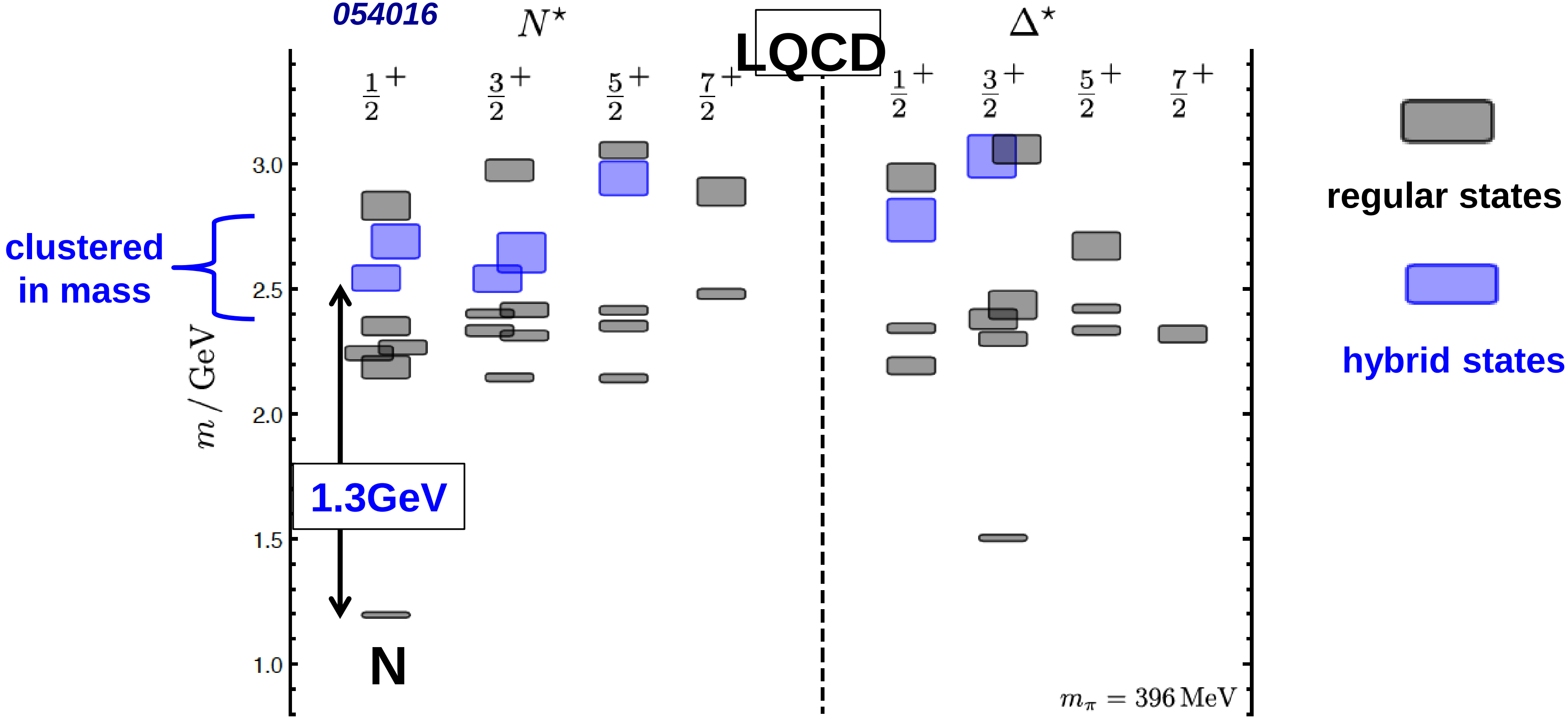
− their experimental verification is crucial for our understanding of QCD in the non-perturbative regime.

Glueballs and hybrid mesons : Hall D at Jlab?



Hybrid Baryons in LQCD

J.J. Dudek and R.G. Edwards, PRD85 (2012) 054016   *T. Barnes and F.E. Close, PLB128, 277 (1983)*



Hybrid states have same J^P values as Q^3 baryons. How to identify them?

- Overpopulation of $N1/2^+$ and $N3/2^+$ states compared to QM projections?

- Transition form factors in electro-production (different Q^2 dependence)

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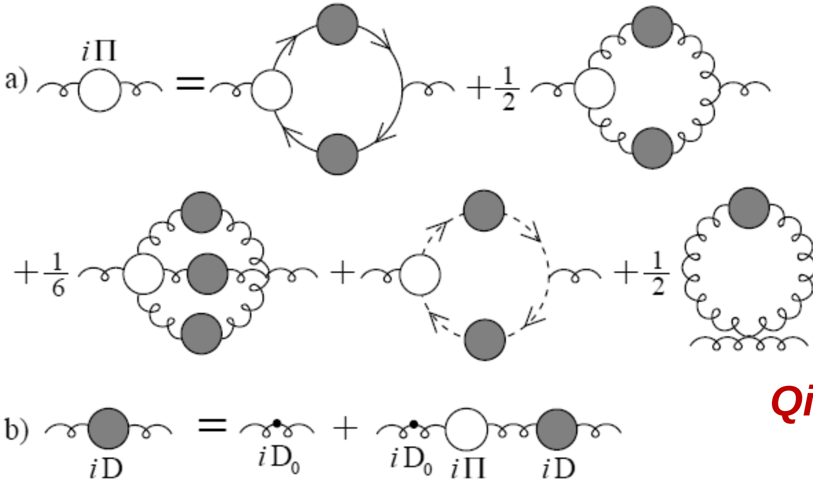
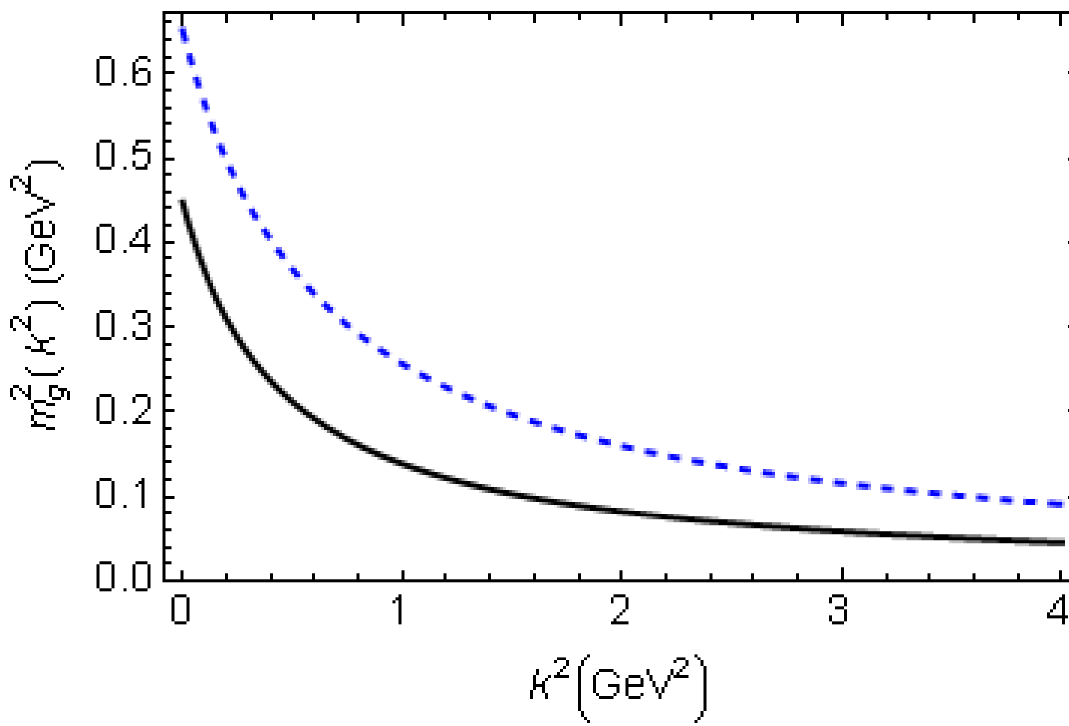
Gluon, too, has non-perturbative mass!



Qin et al., [*Phys. Rev. C 84 042202(Rapid Comm.) (2011)*]

$m_G^2(k^2) \approx m_G^4/(k^2+m_G^2)$

- **Running gluon mass**
  - **Gluon is massless in UV, in agreement with pQCD**
  - **Massive in infrared**
    - **$m_G(0)$ = 0.67-0.81 GeV**



- **DSE prediction confirmed by numerical simulations of lattice-regularised QCD**

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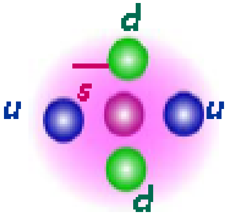
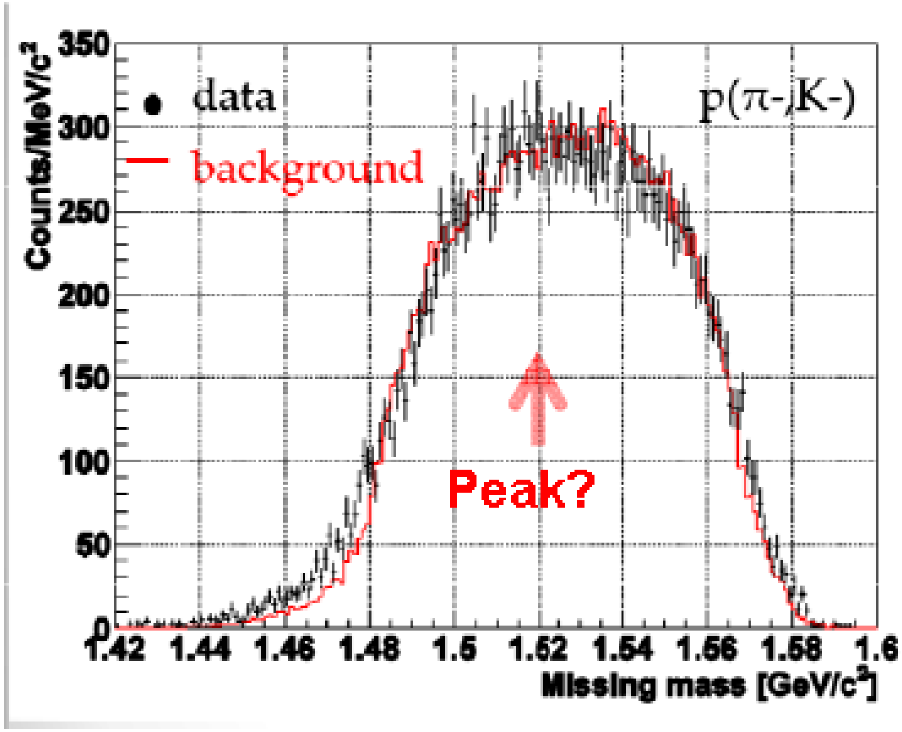
First results from J-PARC

E19: Pentaquark Θ^+ not observed in $\pi^- p \rightarrow K^- X$ reaction

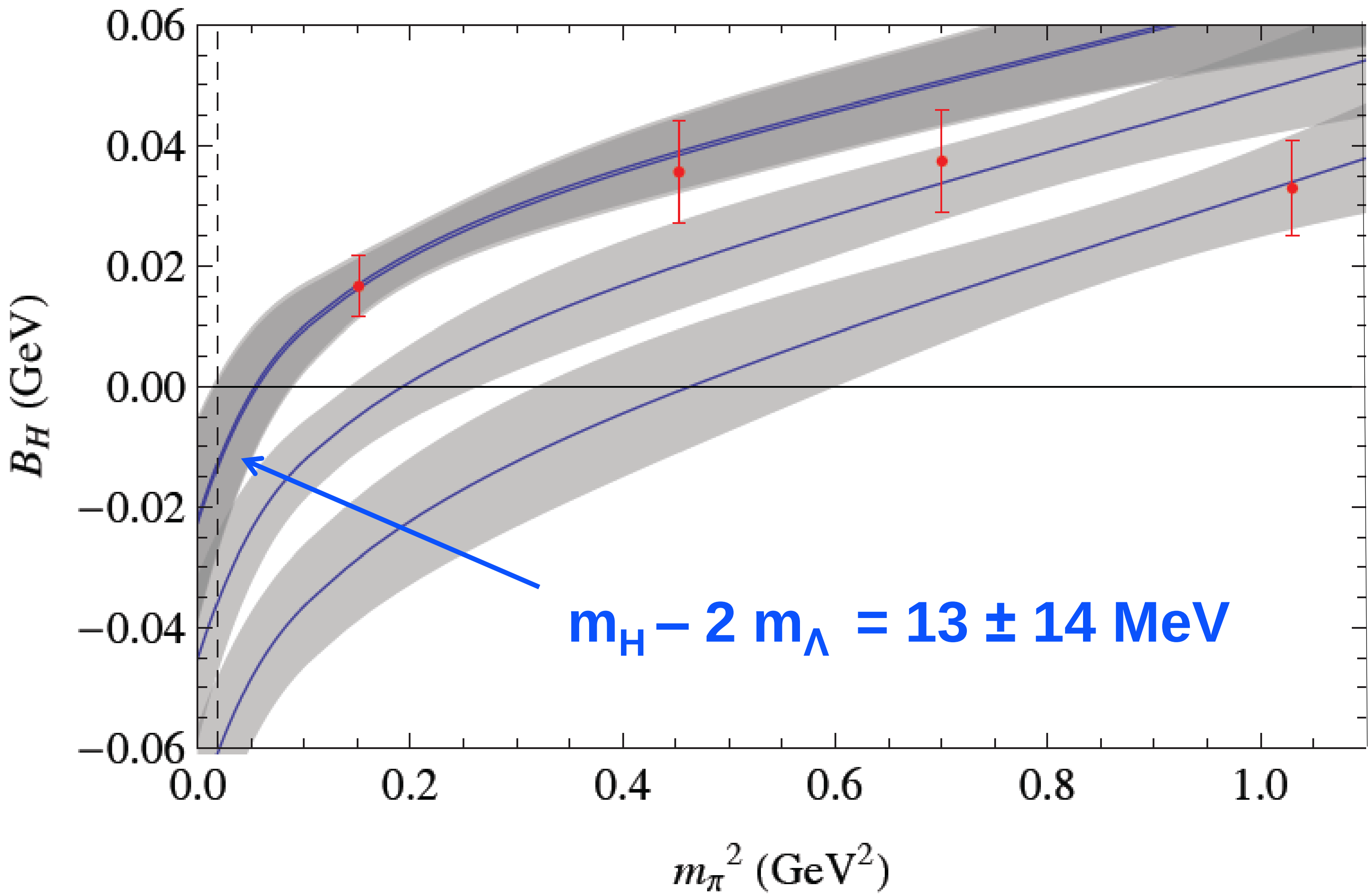




Upper limit 0.26 μb/sr (90%CL)
To be published in PRL

The H di-baryon again?

Using data from NPLQCD & HAL: H bound at larger m_l
$\rightarrow$ H-di-baryon almost bound at physical masses



Shanahan at al., Phys Rev Lett (arXiv:1106.2851)

Dibaryons re-visited

Pionic corrections and multi-quark bags

J. Phys. G: Nucl. Phys. **9** (1983) 1159–1167.

Table 4. Mass of lowest $Y=0$ dibaryon (H) in cases A and B (see caption to table 2).

				A		B	
I	S	Δ	Σ	$R(\mathrm{GeV}^{-1})$	$M(\mathrm{GeV})$	$R(\mathrm{GeV}^{-1})$	$M(\mathrm{GeV})$
0	0	−6	−56/−48	6.09	2.15	6.11	2.22/2.23

H prediction seems pretty good – what about S=-1?

Table 3. Masses of lowest two $Y=1$ dibaryons in cases A and B (see caption to table 2).

				A		B	
I	S	Δ	Σ	$R(\mathrm{GeV}^{-1})$	$M(\mathrm{GeV})$	$R(\mathrm{GeV}^{-1})$	$M(\mathrm{GeV})$
$\frac{1}{2}$	1	$-\frac{7}{3}$	−67/−57	6.38	2.16	6.28	2.20/2.22
$\frac{1}{2}$	2	−1	−57/−39	6.47	2.23	6.33	2.27/2.31

Remarkably close to apparent state seen at FINUDA in (K^-,Λp) at 2.26 GeV on a variety of nuclei : Agnello et al., Phys Rev Lett 94, 212303 (2005)

Deep-Inelastic scattering

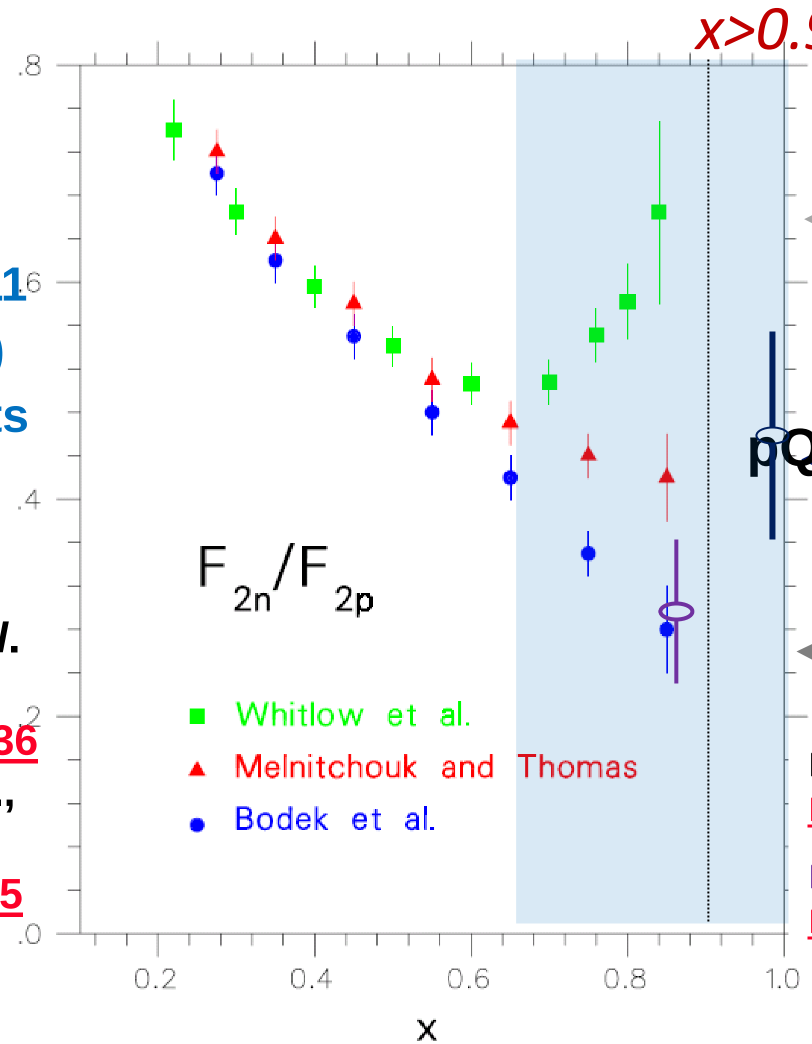
– spin and flavor structure

– symmetry breaking

Neutron Structure Function at high-x

Reviews:

- **S. Brodsky *et al.***
  NP B441 (1995)
- **W. Melnitchouk et al.,**
  PL B377 (1996) 11
- **N. Isgur, PRD 59 (1999)**
- **R.J. Holt & C.D. Roberts**
  RMP (2010)



SU(6) symmetry

DSE: "realistic"

pQCD, uncorrelated *Ψ*

0^+ qq only

Melnitchouk, Accardi *et al.*
Phys.Rev. D84 (2011) 117501

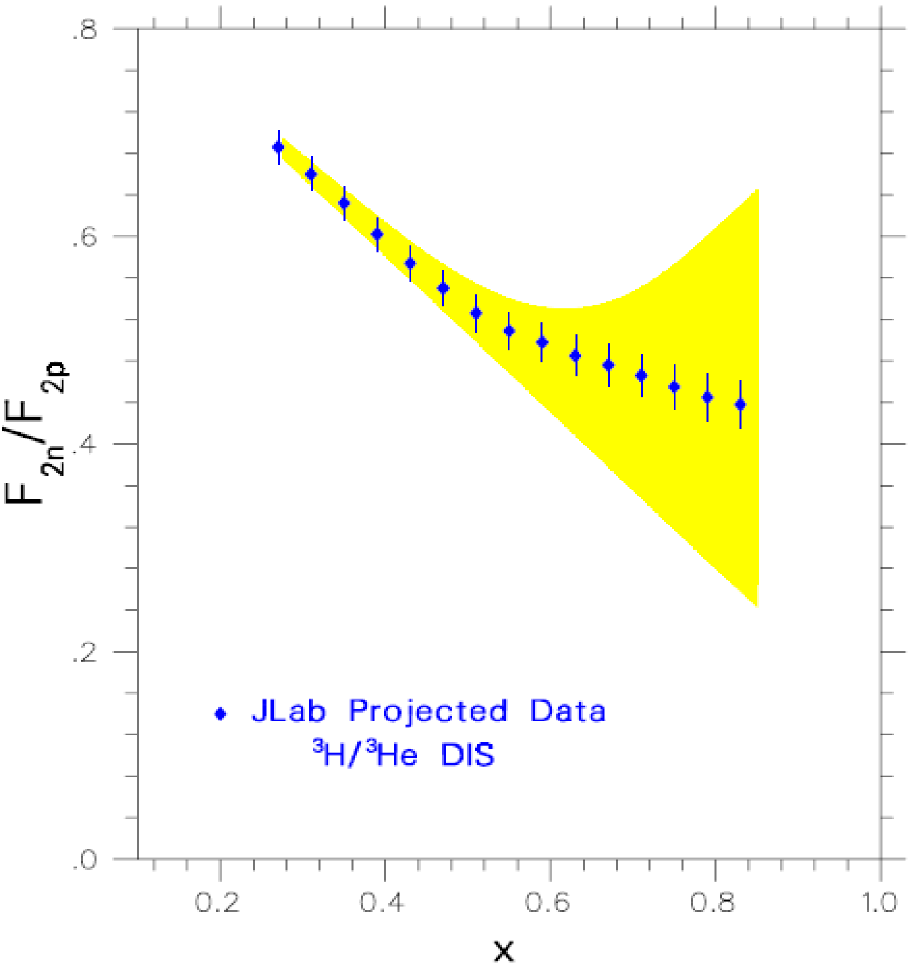
Melnitchouk, Arrington *et al.*
Phys.Rev.Lett. 108 (2012) 252001

I.C. Cloët, C.D. Roberts, *et al.*
arXiv:0812.0416 [nucl-th],
Few Body Syst. 46 (2009) 1-36
D. J. Wilson, I. C. Cloët et al.,
arXiv:1112.2212 [nucl-th],
Phys. Rev. C85 (2012) 025205

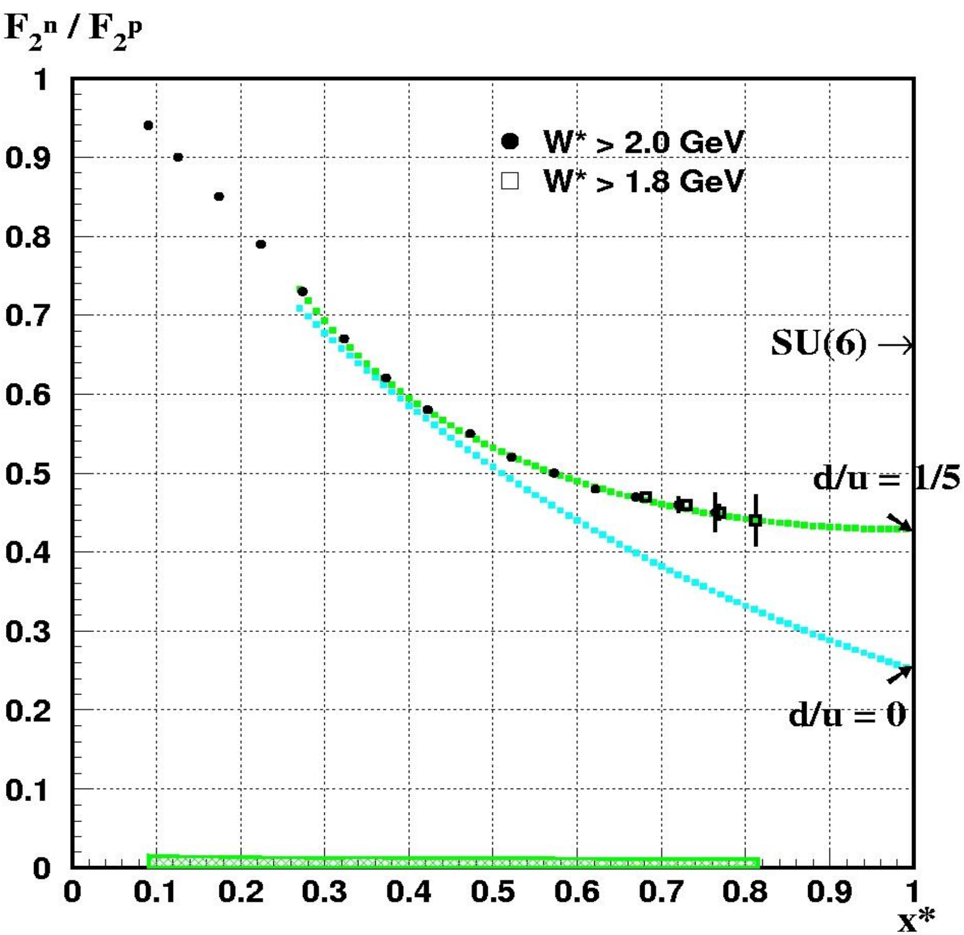
Distribution of neutron's momentum amongst quarks on the valence-quark domain – UNKNOWN!

Jlab 12 GeV : Unambiguous Flavor Structure x ~ 1

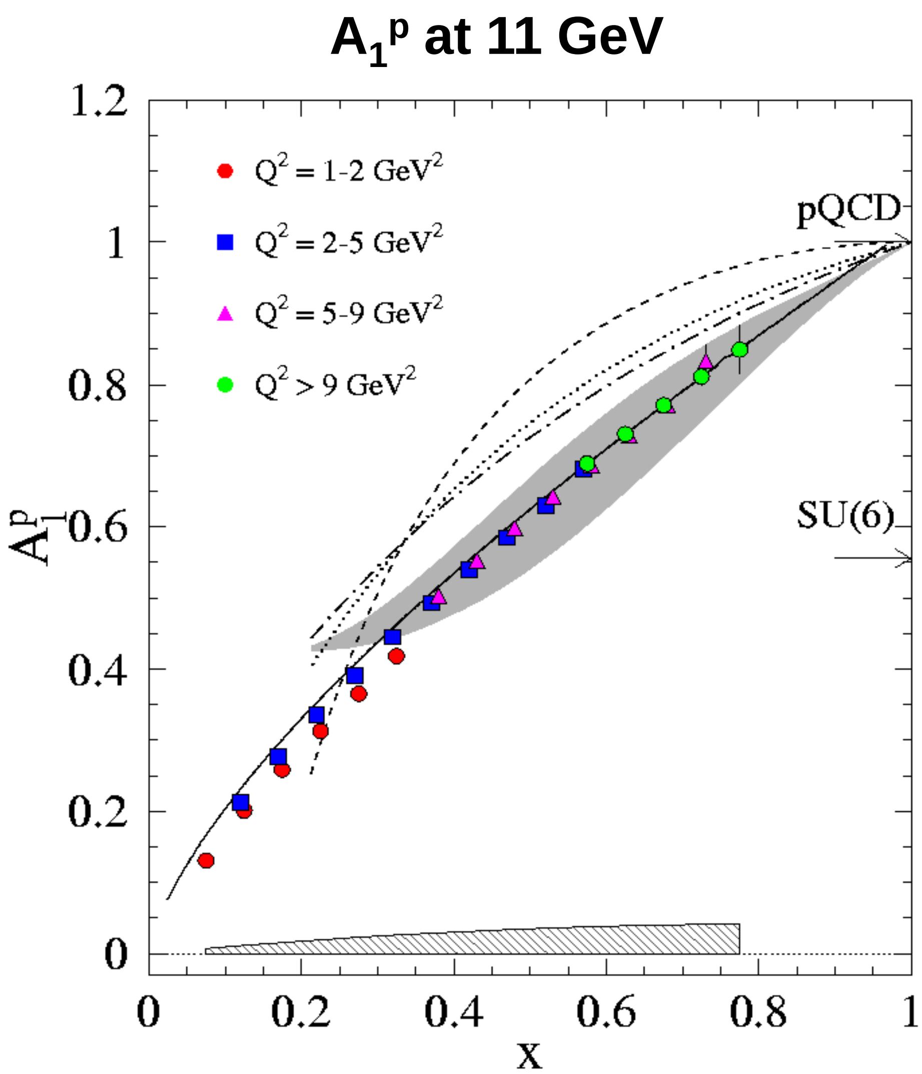
Hall A 11 GeV with HMS

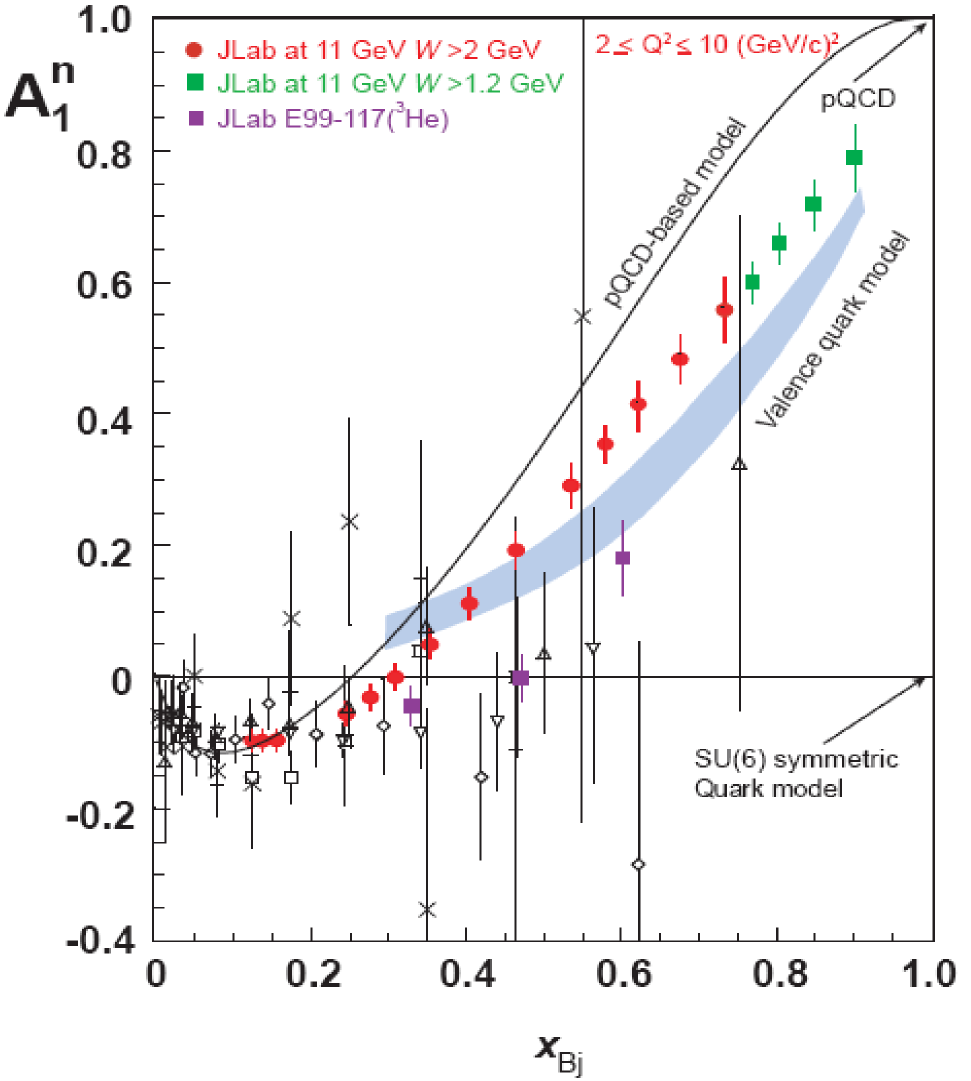


Hall B 11 GeV with CLAS12



and Unambiguous Resolution of Valence Spin





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Chiral symmetry and the sea of the nucleon

- asymmetry in $\bar{d} - \bar{u}$ and $s - \bar{s}$
- polarization of the sea and vacuum structure

Dependence of s- $\bar{s}$ on assumed cross-over

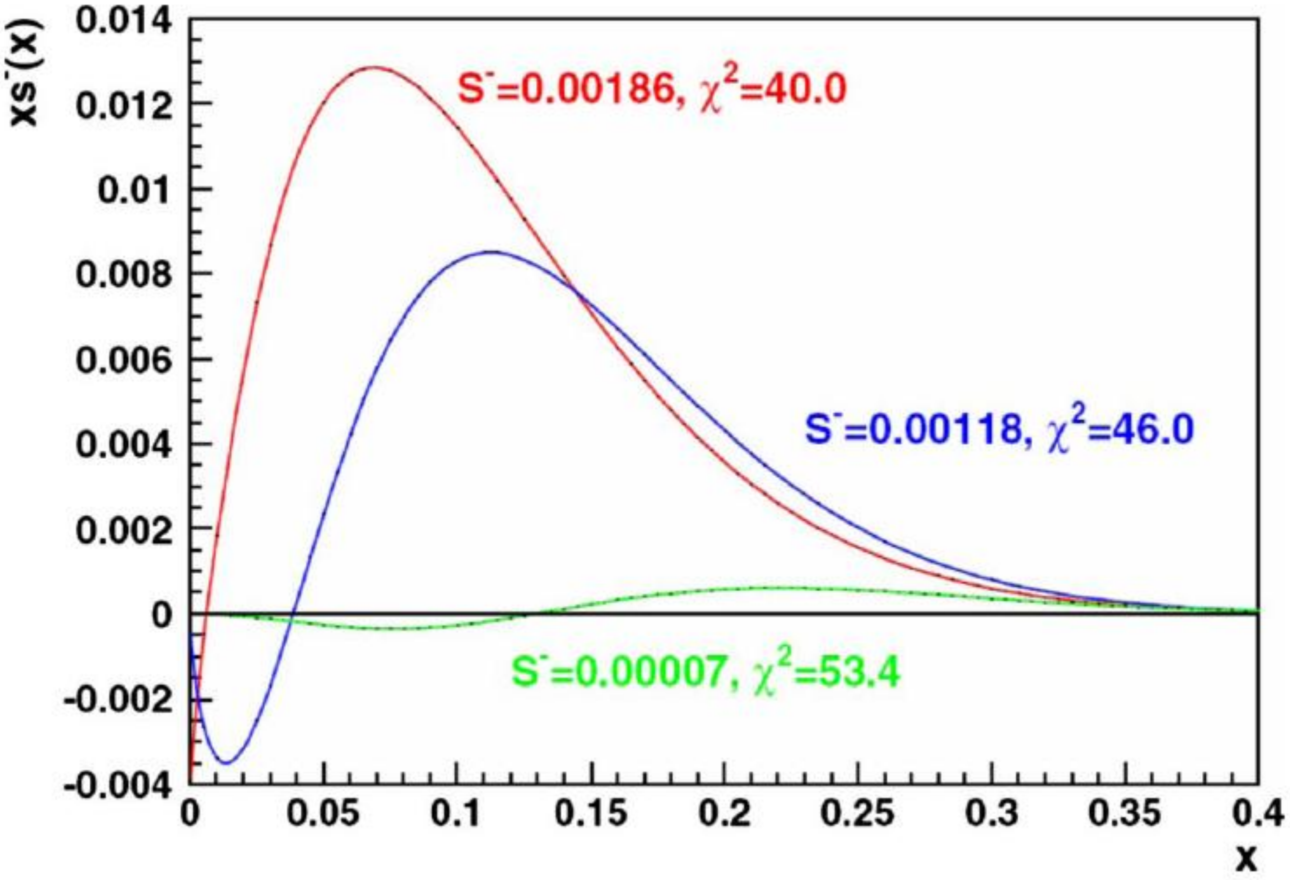
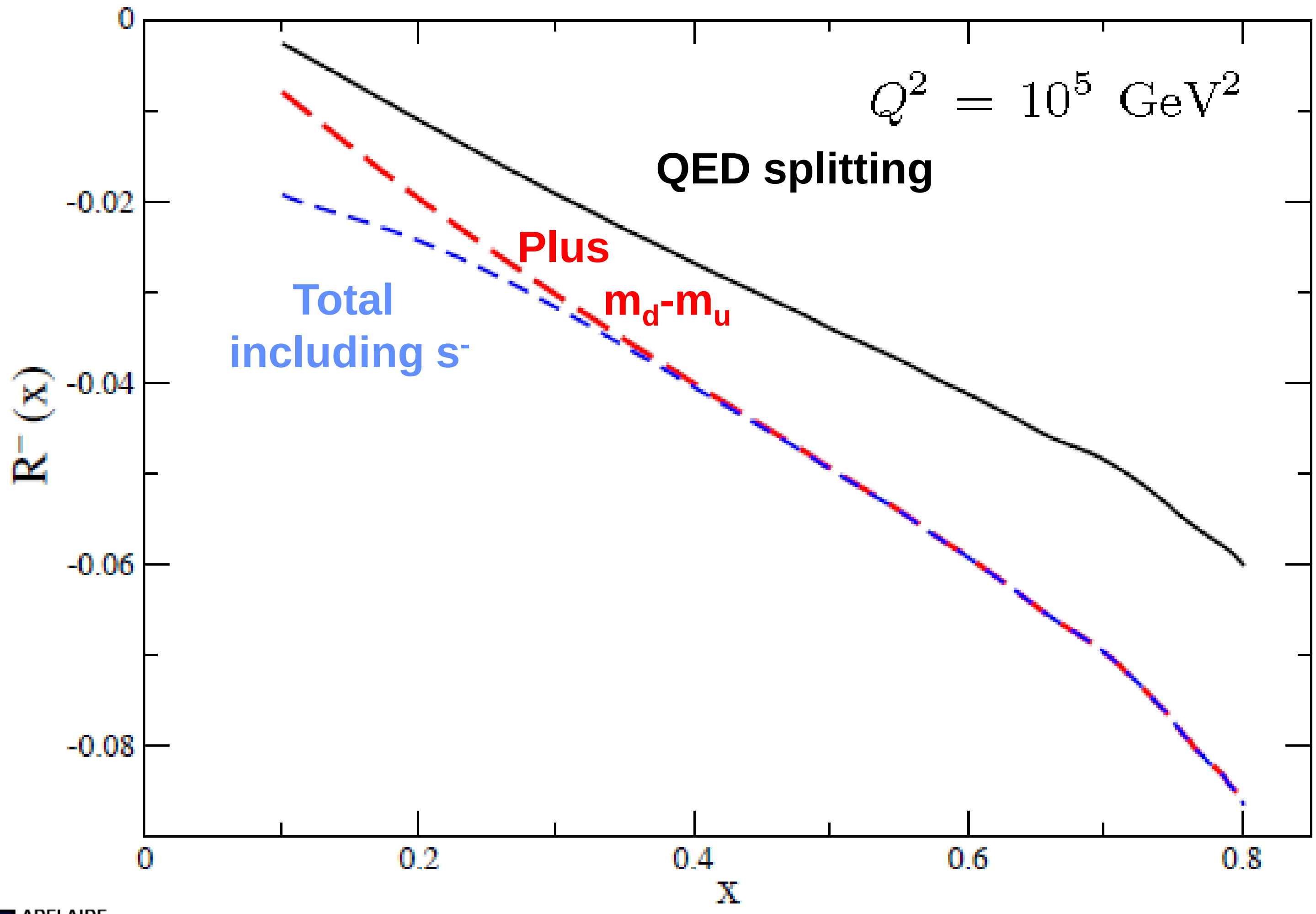


FIG. 16. (Color online) The quantity $xs^-(x) = x[s(x) - \bar{s}(x)]$ vs x, as extracted by the NuTeV Collaboration. Three different results are shown, corresponding to different values of the zero-crossing point. The χ^2 value is listed for each curve. From Mason *et al.*, 2007.

Charge Symmetry : Future EIC or LHeC

$$R^-(x) \equiv \frac{2(F_2^{W^-D}(x) - F_2^{W^+D}(x))}{F_2^{W^-p}(x) + F_2^{W^+p}(x)}$$



Hobbs et al., Phys Lett (arXiv:1101.3923 [hep-ph])

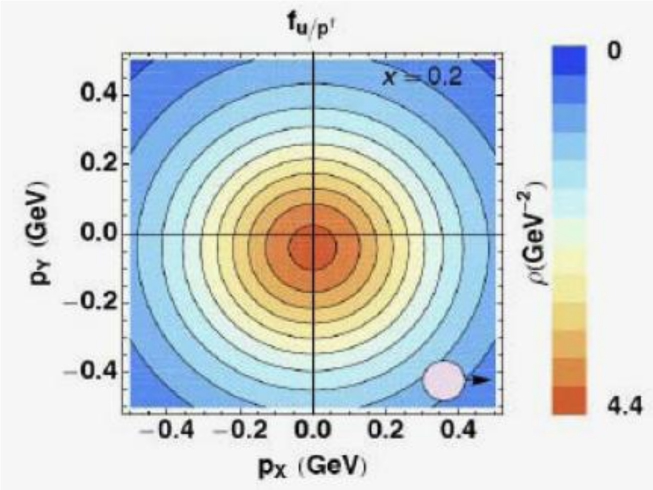
New observables

– 3D imaging of the nucleon

3-D Imaging - Two Approaches

TMDs

2+1 D picture in **momentum space**

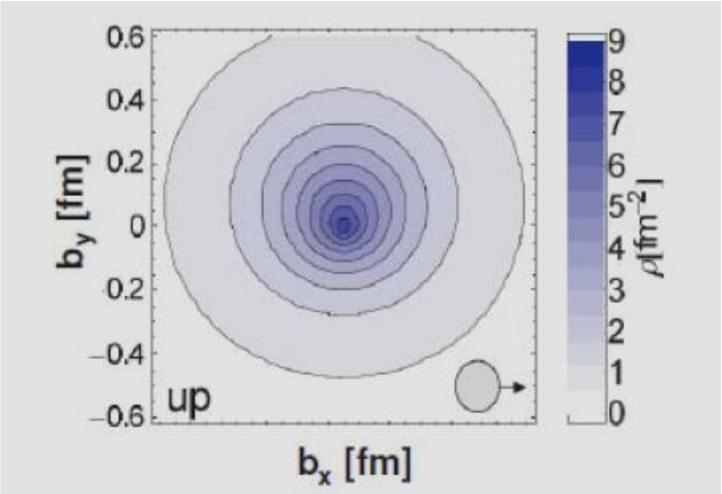


Bacchetta, Conti, Radici

- intrinsic transverse motion
- spin-orbit correlations- relate to OAM
- non-trivial factorization
- accessible in SIDIS (and Drell-Yan)

GPDs

2+1 D picture in **impact-parameter space**



QCDSF collaboration

- collinear but long. momentum transfer
- indicator of OAM; access to Ji's total $J_{q,g}$
- existing factorization proofs
- DVCS, exclusive vector-meson production

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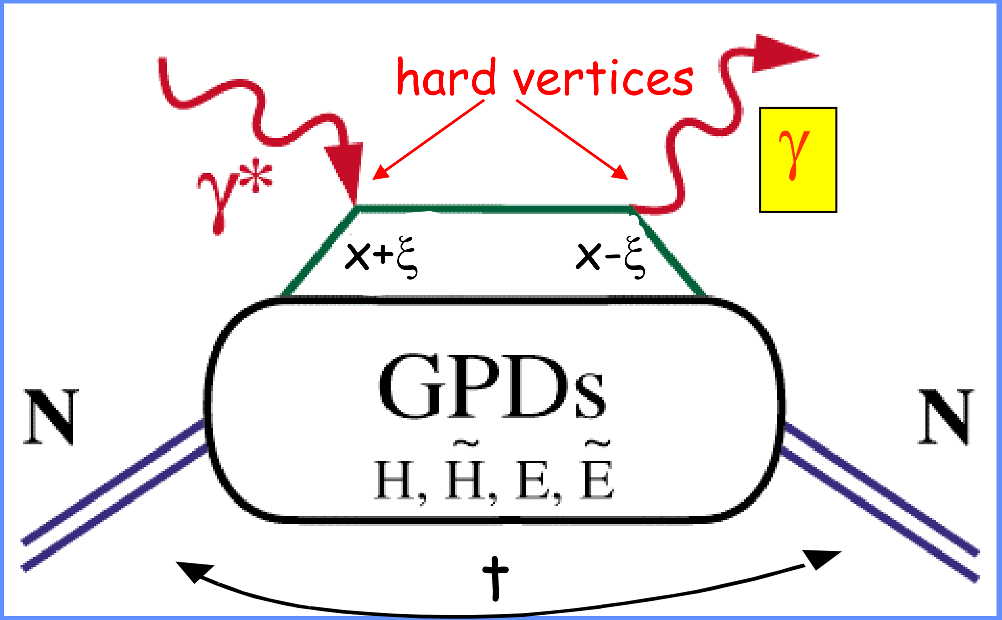
GPDs & Deeply Virtual Exclusive Processes
- New Insight into Nucleon Structure

Deeply Virtual Compton Scattering (DVCS)



x – quark momentum fraction

ξ– longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

At large Q^2 : QCD factorization theorem → hard exclusive process can be described by 4 transitions (Generalized Parton Distributions) :

Vector : $H(x, \xi, t)$ **Axial-Vector** : $\tilde{H}(x, \xi, t)$

Tensor : $E(x, \xi, t)$ **Pseudoscalar** : $\tilde{E}(x, \xi, t)$

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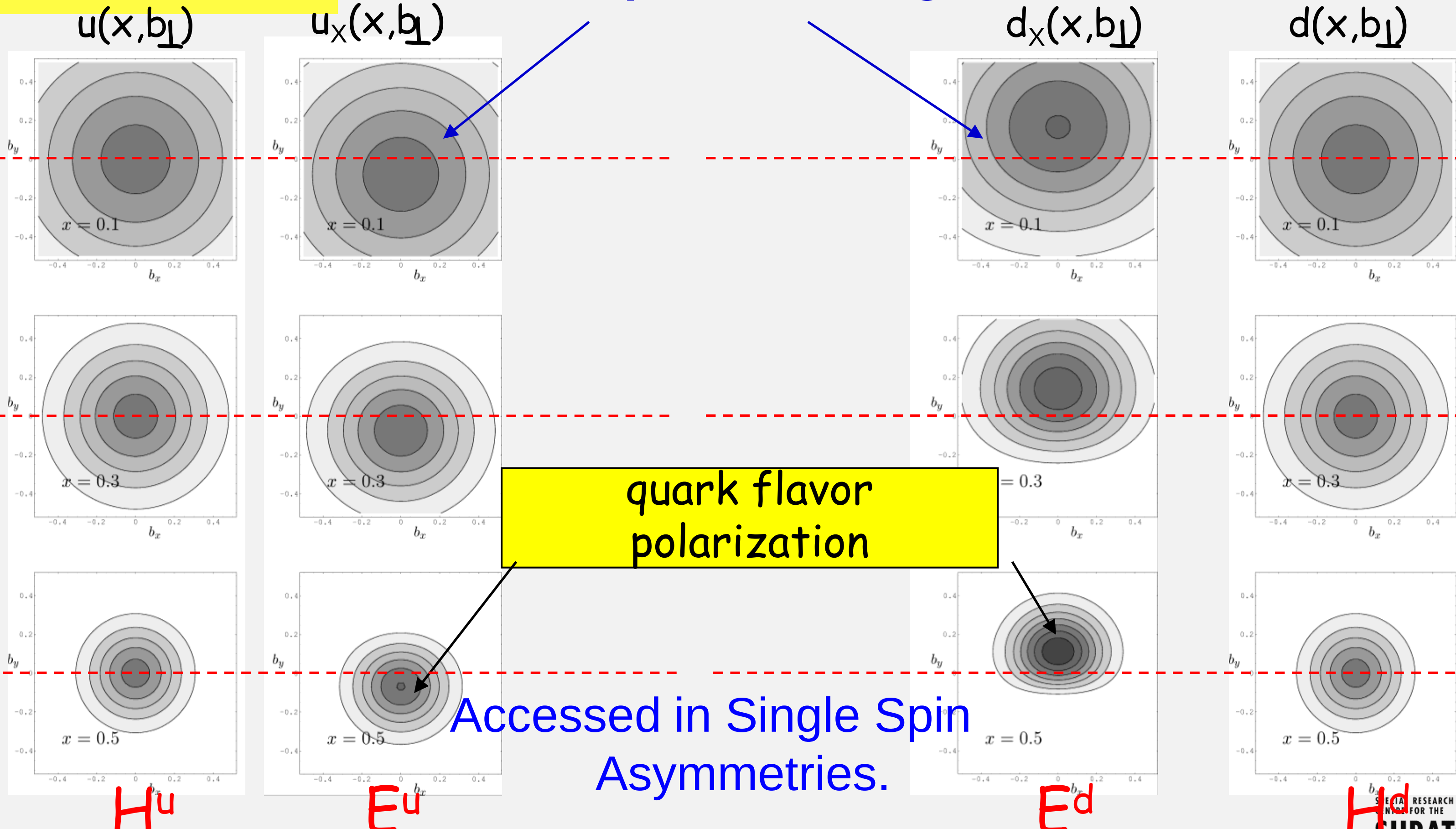
3D Images of the Proton's Quark Content

$$q(x,\mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{\Delta}_\perp \cdot \mathbf{b}_\perp} H(x,0,-\mathbf{\Delta}_\perp^2).$$

$b_\perp$ - Impact parameter

transverse polarized target



quark flavor polarization

Accessed in Single Spin Asymmetries.

M. Burkardt PRD 66, 114005 (2002)

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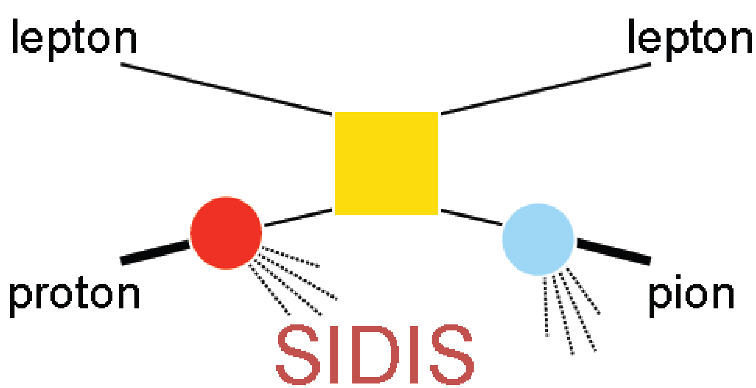
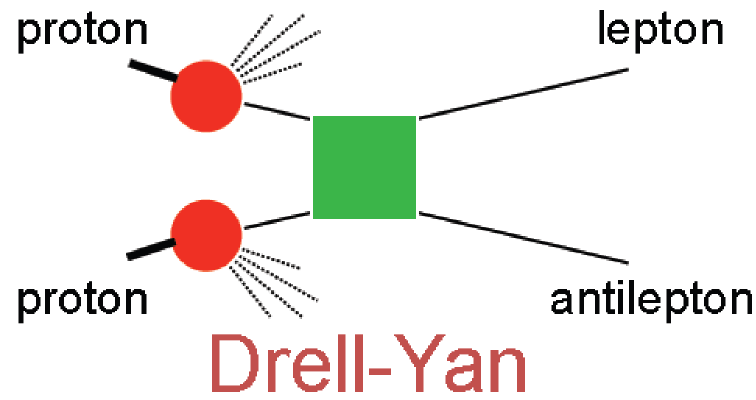
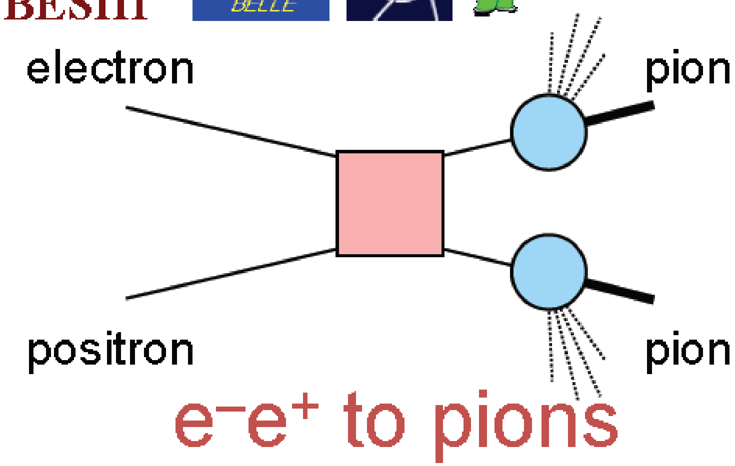
Access TMDs through Hard Processes







- Yellow square: Partonic scattering amplitude
- Light blue circle: Fragmentation amplitude
- Red circle: Distribution amplitude

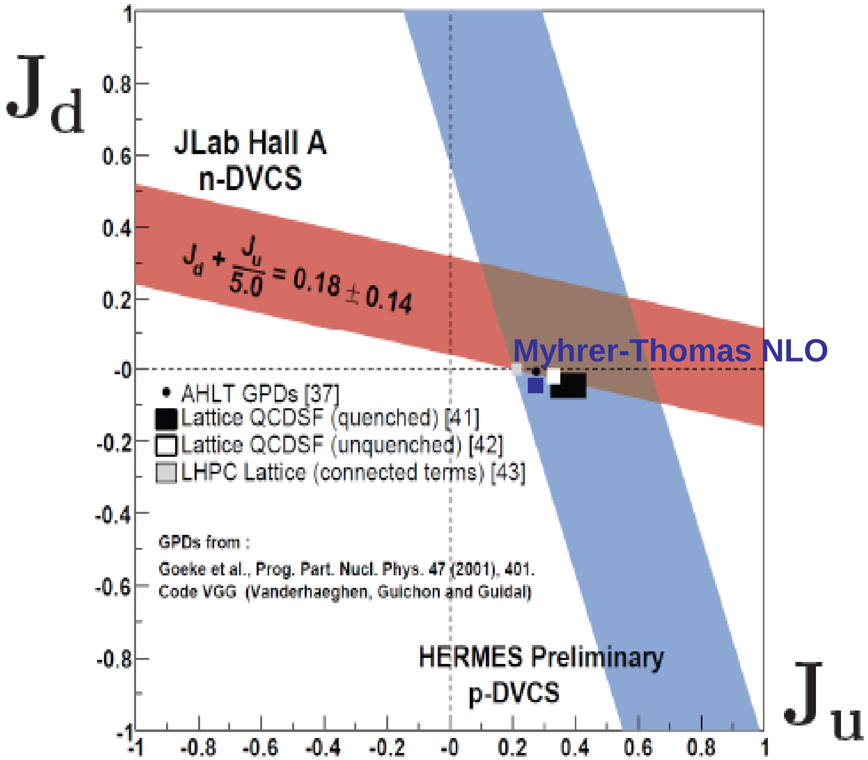
$$f_{1T}^{\perp q}(\mathrm{SIDIS}) = -f_{1T}^{\perp q}(\mathrm{DY})$$

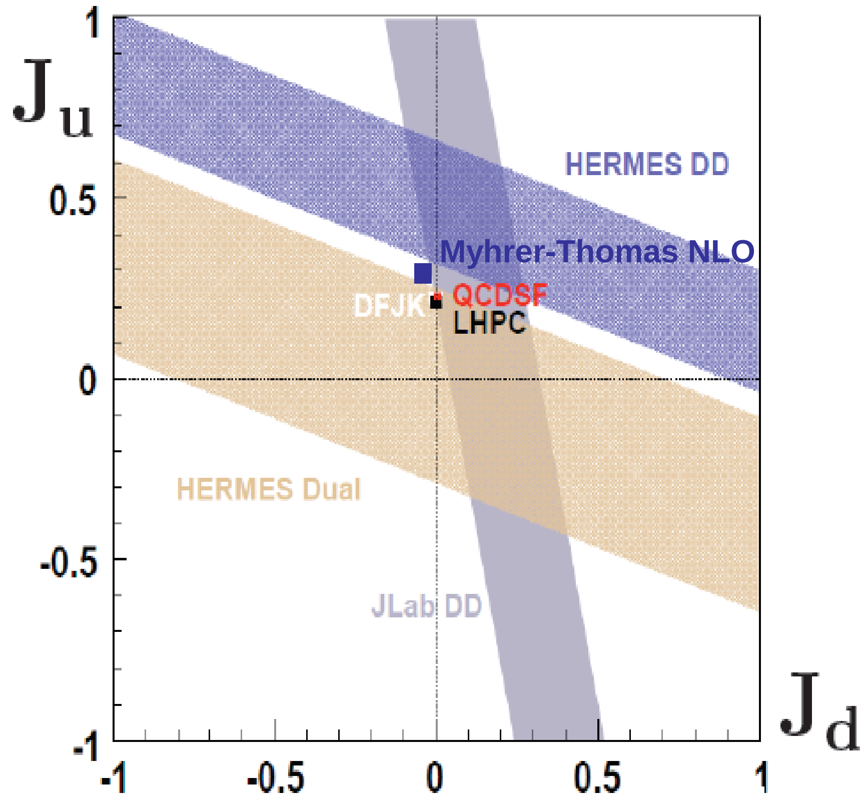
$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY})$$

Experimental effort just beginning!

For the moment the analysis is highly model dependent ....

- … from DVCS: (**JLAB** PRL 99 (2007) 242501 and **HERMES** JHEP 0806:066 (2008)

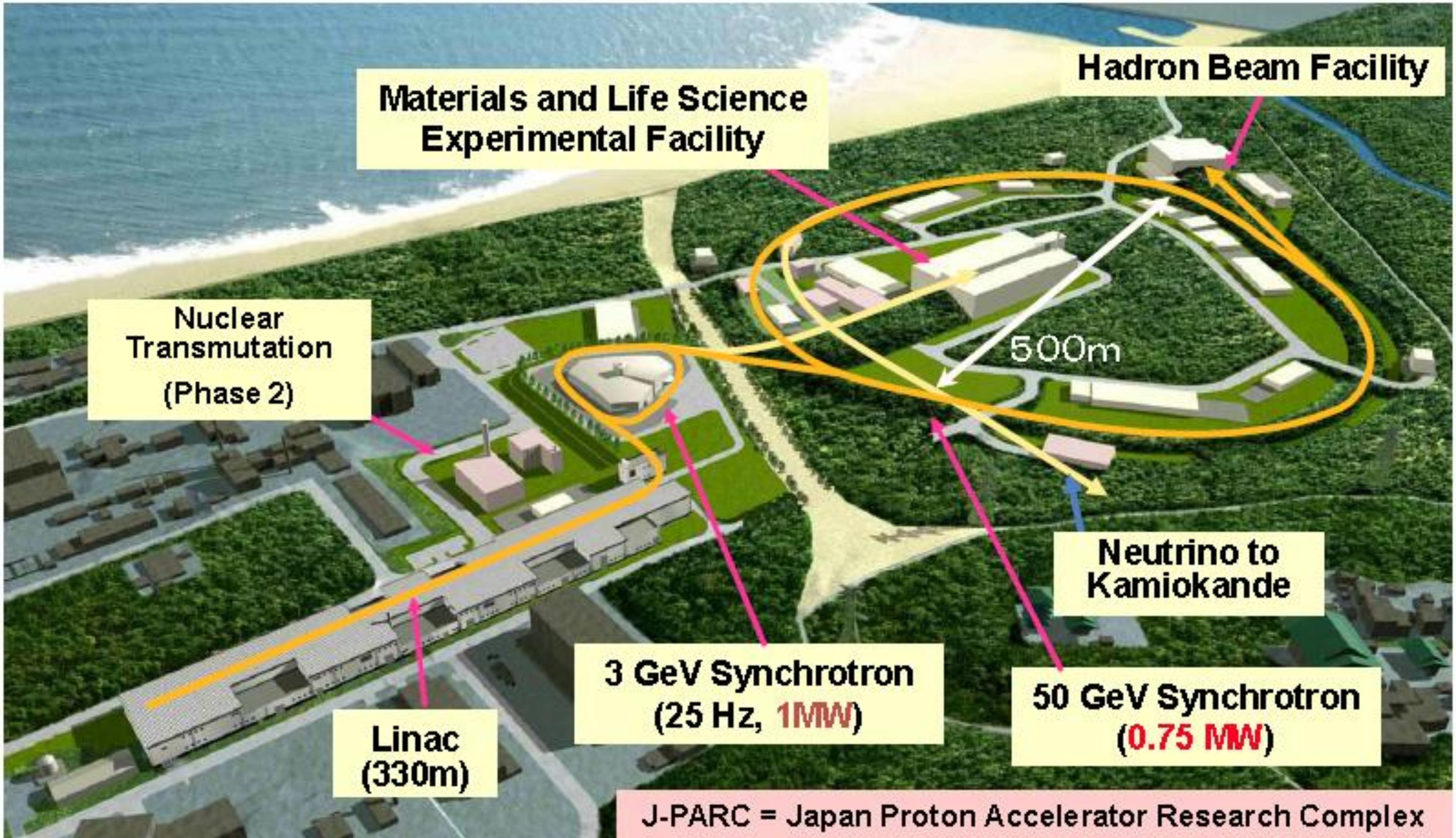




The Facilities to address these questions

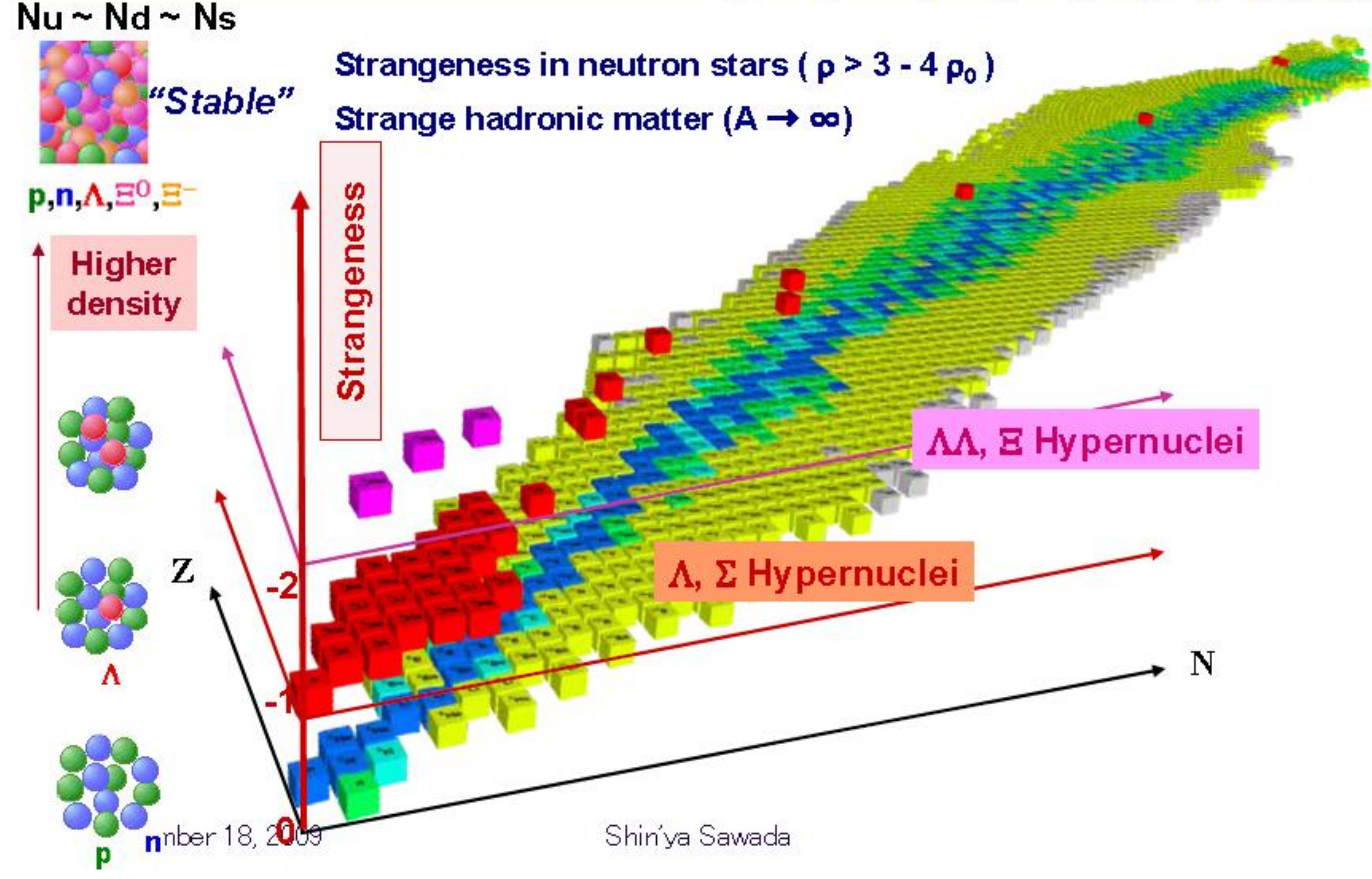
– **hadrons**

J-PARC Facility

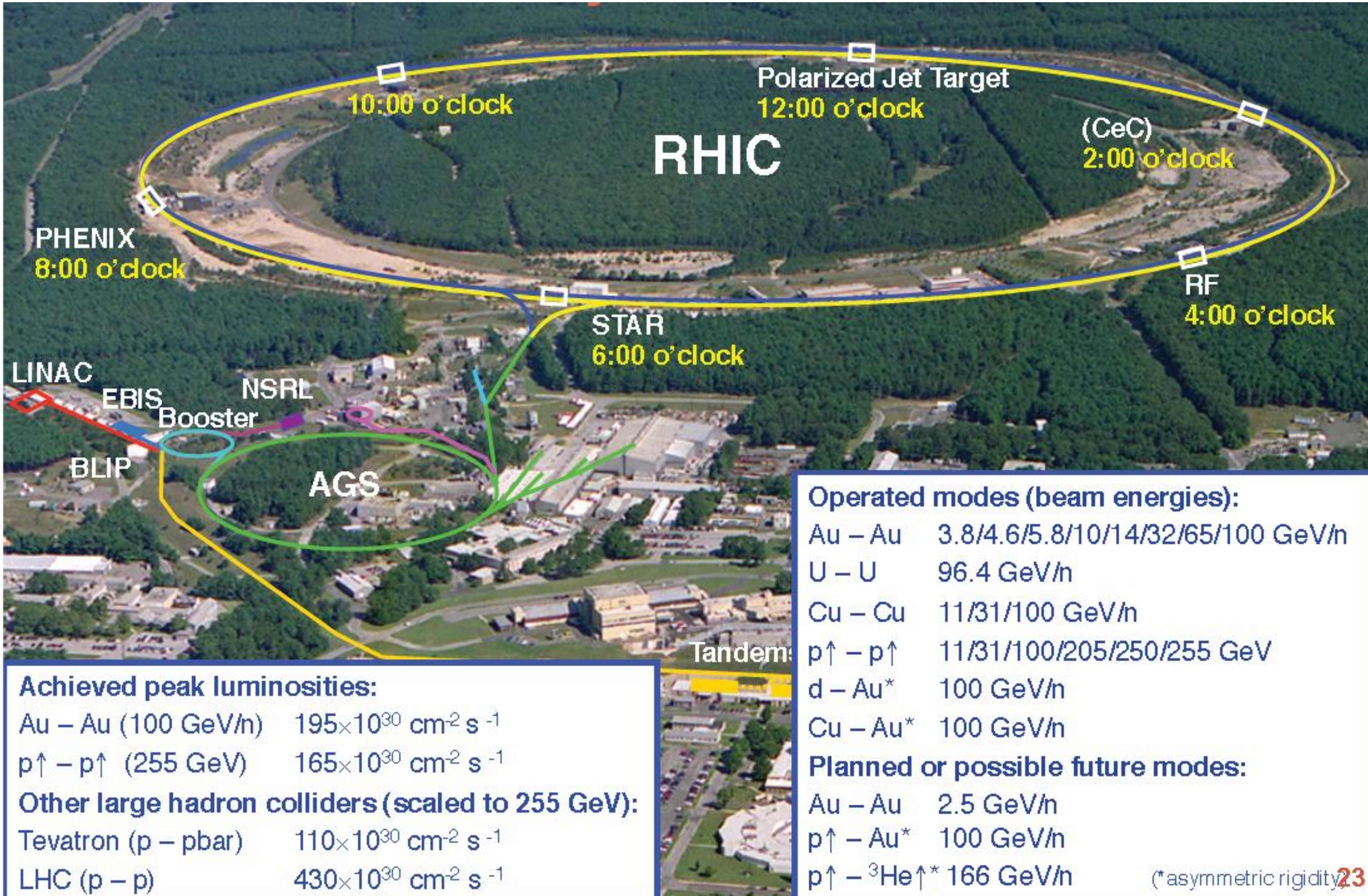


Joint Project between KEK and JAEA

Three Dimensional Nuclear Chart



RHIC : Polarised p-p collisions



Achieved peak luminosities:

Au – Au (100 GeV/n)	195×10^{30} cm^{-2} s^{-1}
p↑ – p↑ (255 GeV)	165×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 255 GeV):

Tevatron (p – pbar)	110×10^{30} cm^{-2} s^{-1}
LHC (p – p)	430×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
U – U	96.4 GeV/n
Cu – Cu	11/31/100 GeV/n
p↑ – p↑	11/31/100/205/250/255 GeV
d – Au*	100 GeV/n
Cu – Au*	100 GeV/n

Planned or possible future modes:

Au – Au	2.5 GeV/n
p↑ – Au*	100 GeV/n
p↑ – ^{3}He↑*	166 GeV/n

(*asymmetric rigidity)

* Facility for Antiproton & Ion Research

Nuclear Structure & Astrophysics
(Rare-isotope beams)

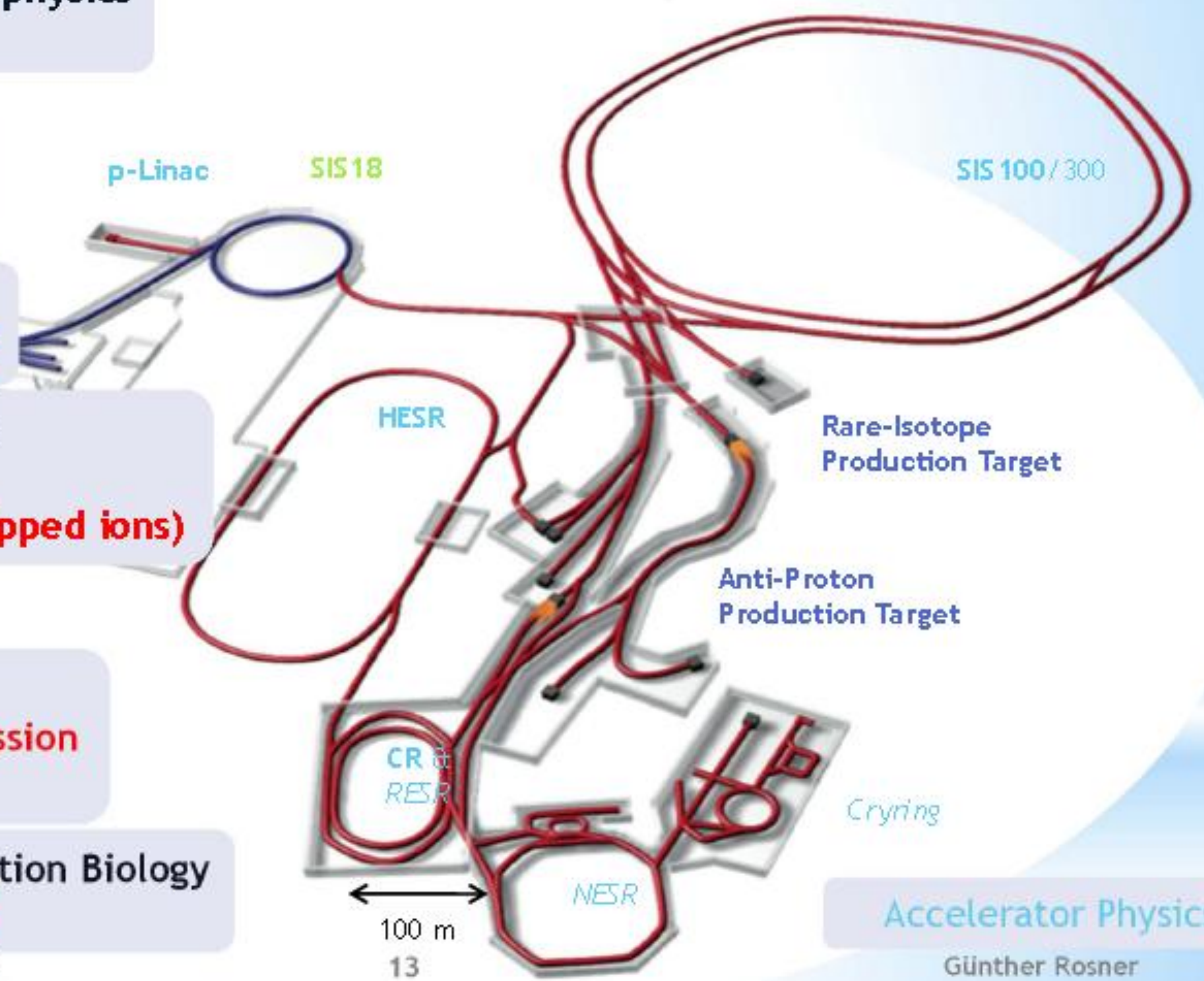
Hadron Physics
(Stored and cooled
14 GeV/c anti-protons)

QCD-Phase Diagram
(HI beams 2 to 45 GeV/u)

Fundamental Symmetries
& Ultra-High EM Fields
(Antiprotons & highly stripped ions)

Dense Bulk Plasmas
(Ion-beam bunch compression
& petawatt-laser)

Materials Science & Radiation Biology
(Ion & antiproton beams)

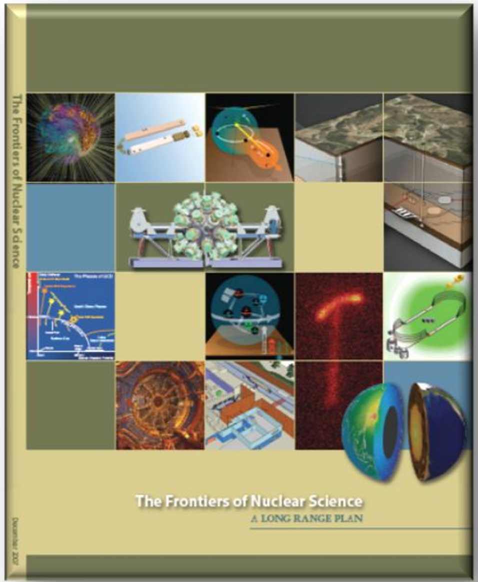


Accelerator Physics

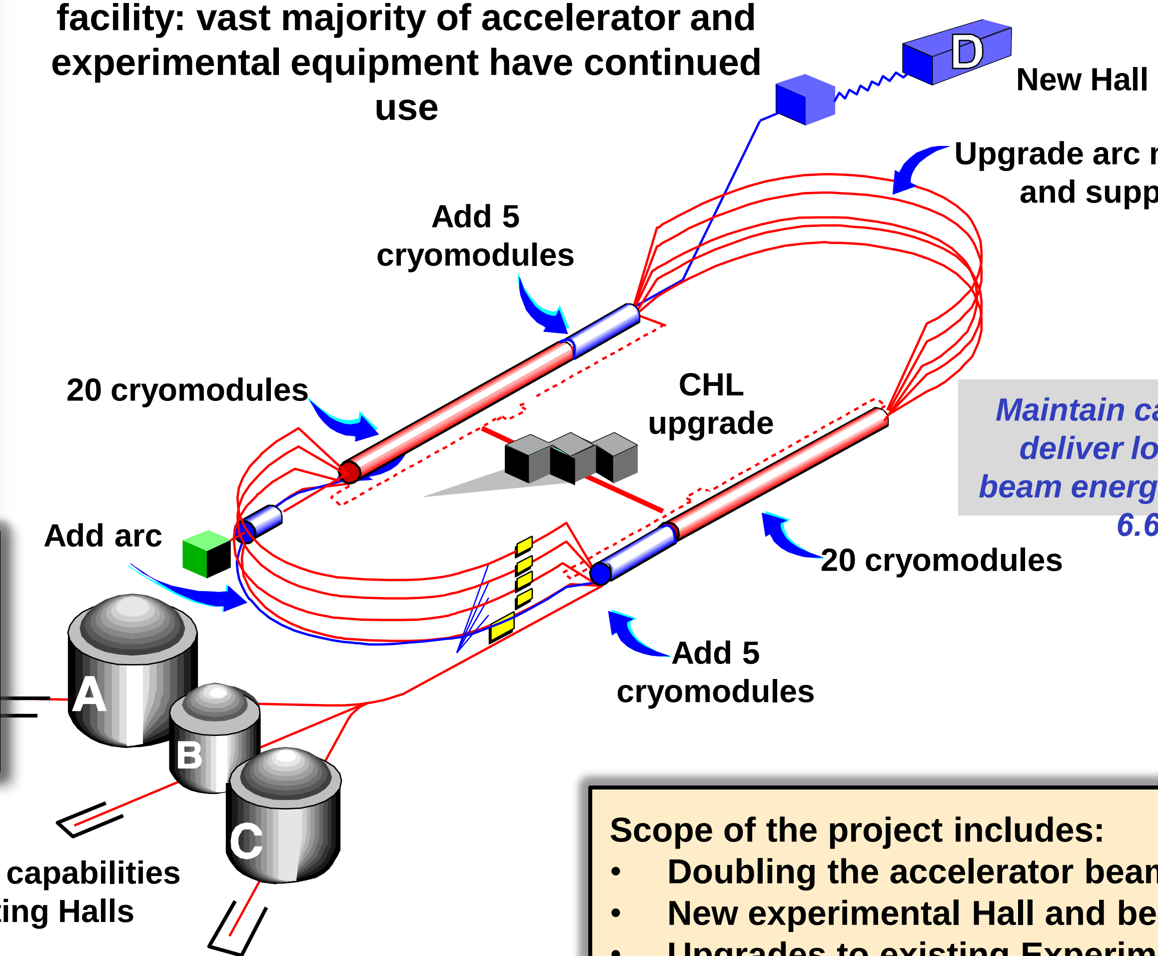
The Facilities to address these questions

– electrons

12 GeV Upgrade Project at JLab



Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use



Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6….

The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

Scope of the project includes:

- **Doubling the accelerator beam energy**
- **New experimental Hall and beamline**
- **Upgrades to existing Experimental Halls**

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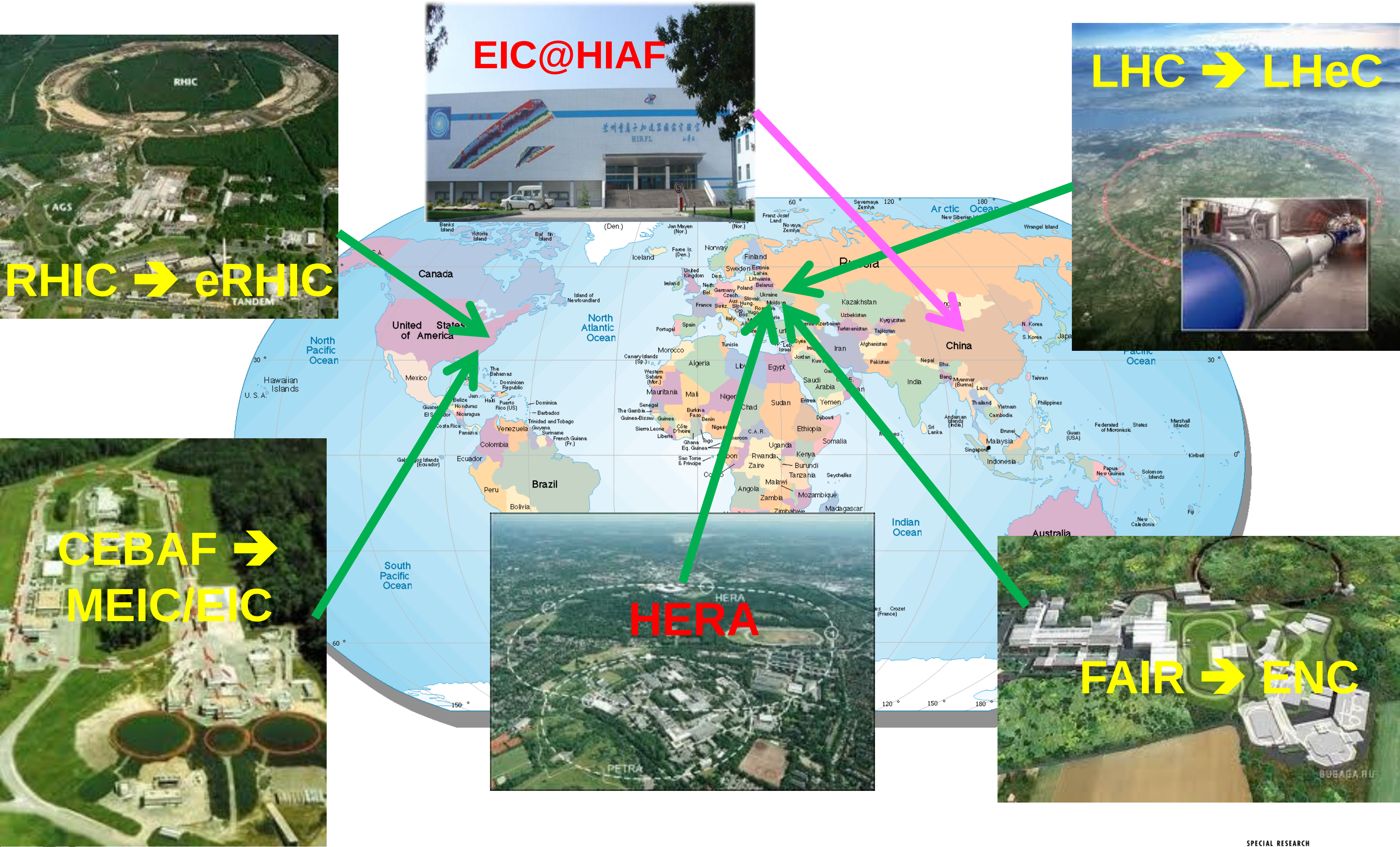
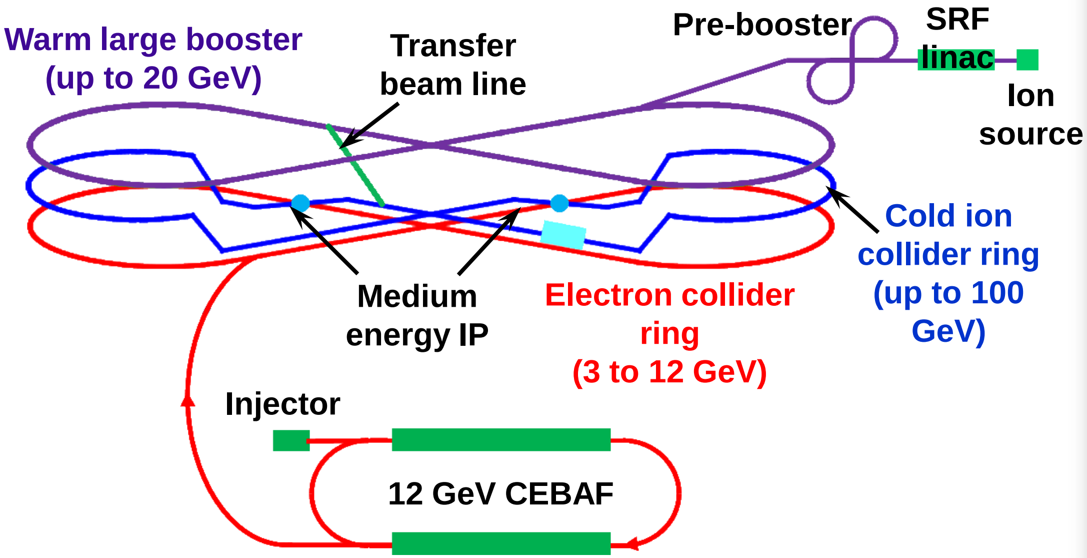
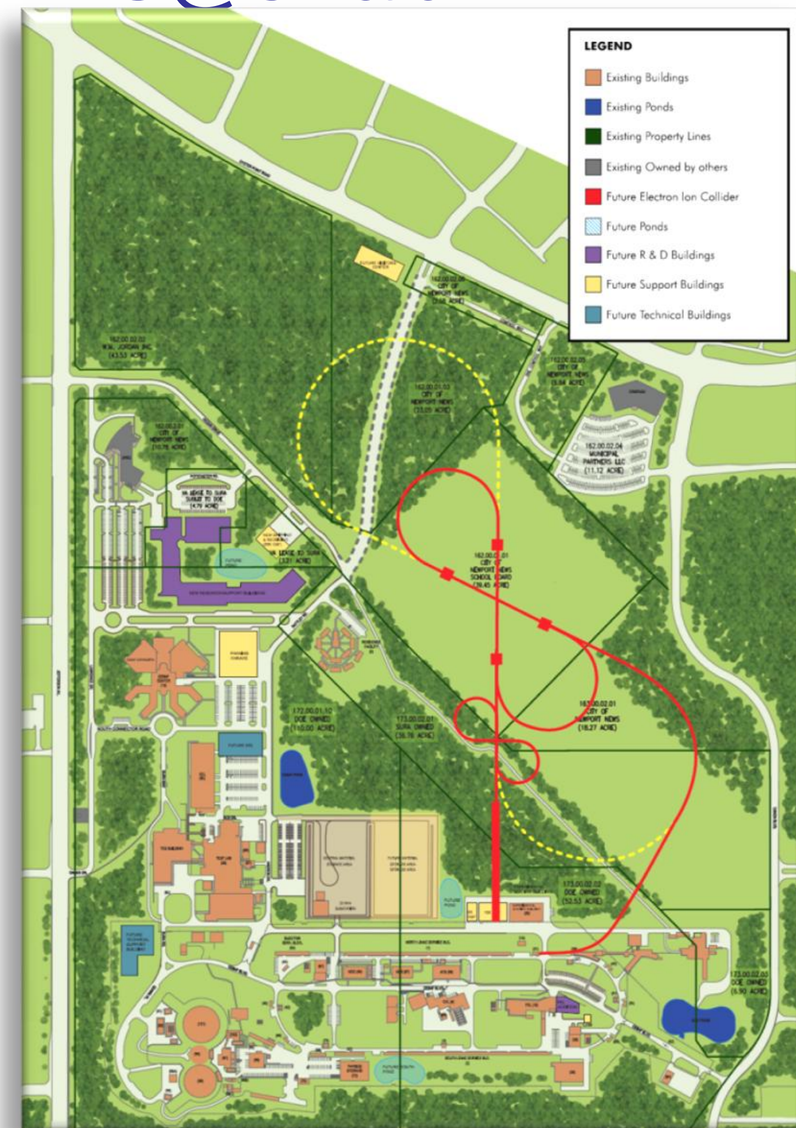
EIC Plans



Medium Energy EIC@JLab



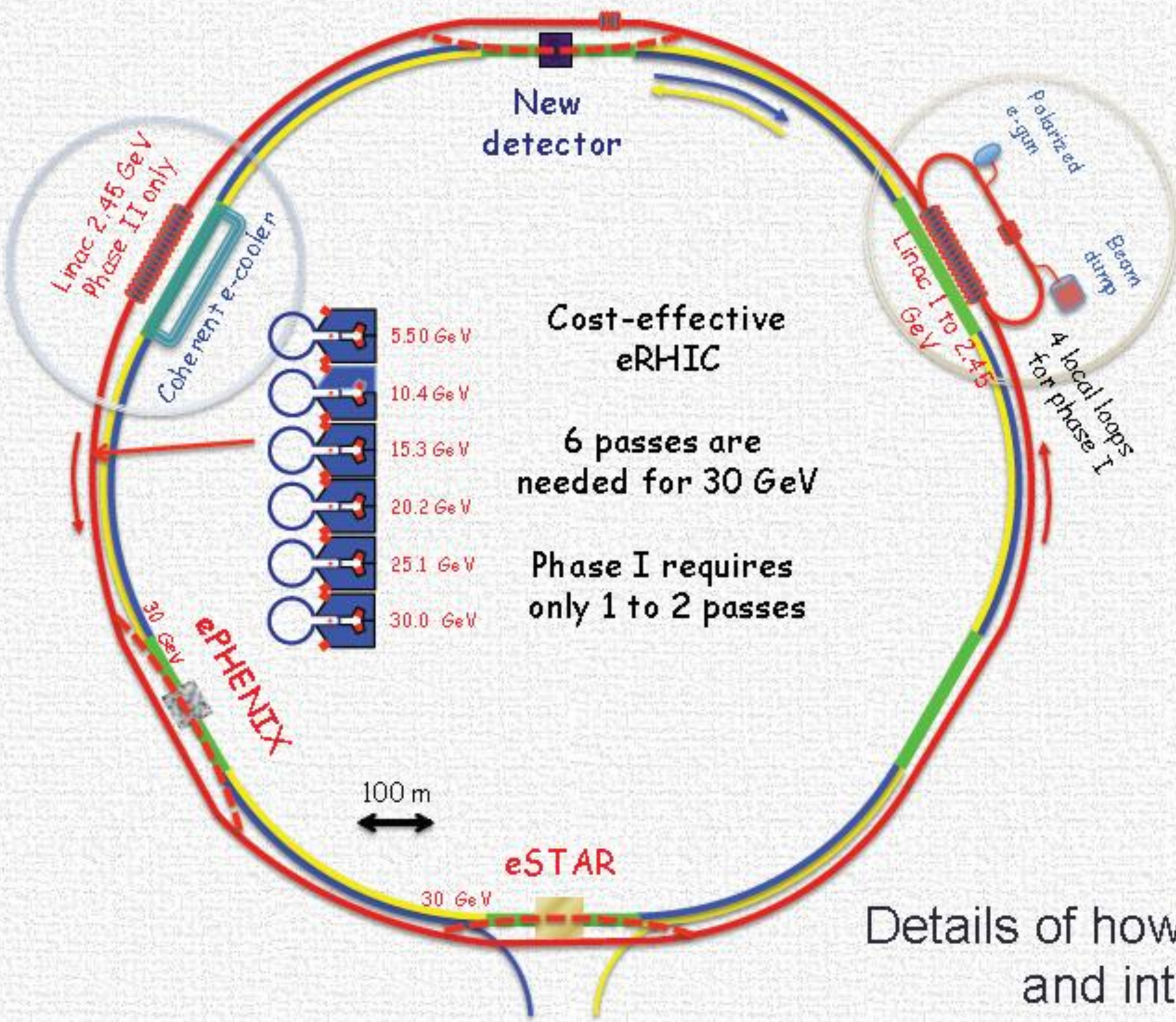
JLab Concept



- **MEIC:**
  - **3-12 GeV on 20-100 GeV ep/eA collider**
  - **fully-polarized, longitudinal and transverse**
  - **luminosity: up to few x 10^{34} e-nucleons cm^{-2} s^{-1}**

Upgradable to higher energies (250 GeV protons)

eRHIC at Brookhaven National Laborato



Stage I:
√s ~ 60-100 G

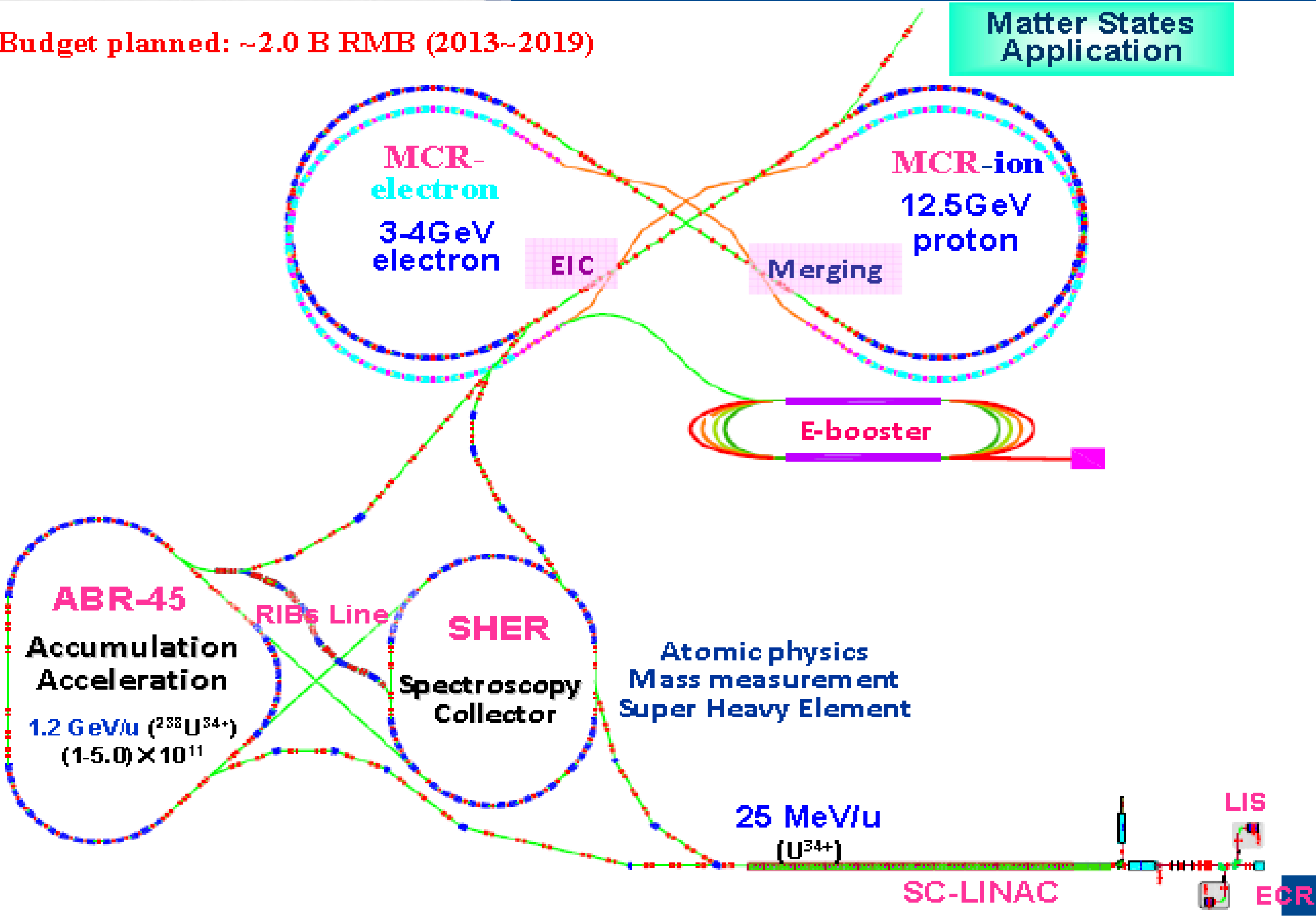
Stage II:
√s > 100 Ge

$L = 10^{33\text{-}34}$ cm^{-2}se
100-1000 times H
→ 50-500 fb^{-1} integrated luminosity in 10 yrs

Details of how the eRHIC design, detect
and integration with the accelera
See talk by Elke As

Future Facility: HIAF

Budget planned: ~2.0 B RMB (2013~2019)



EIC@HIAF

◆ HIAF was approved, EIC on HIAF is being proposed

◆ Schedule

1. HIAF Phase-1: ~2019: 3 x12 GeV

2. HIAF Phase-2: ~2030: 15 x 100 GeV

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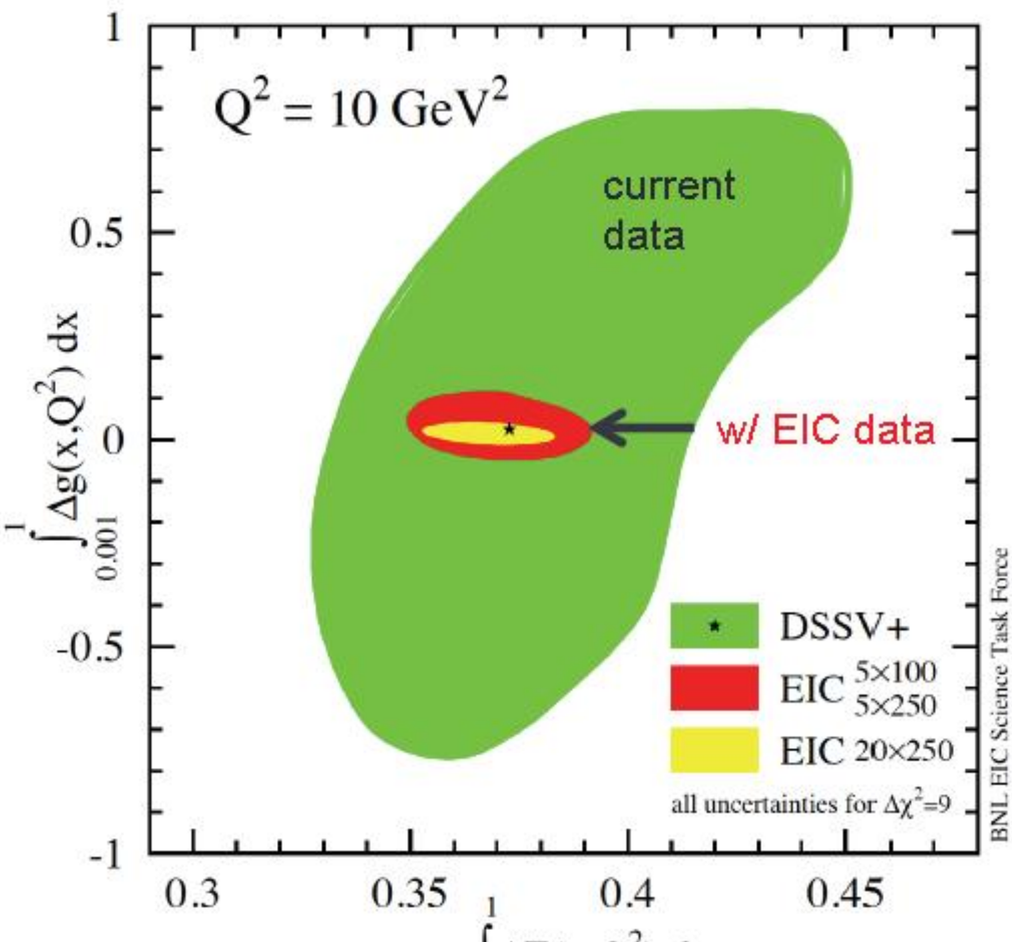
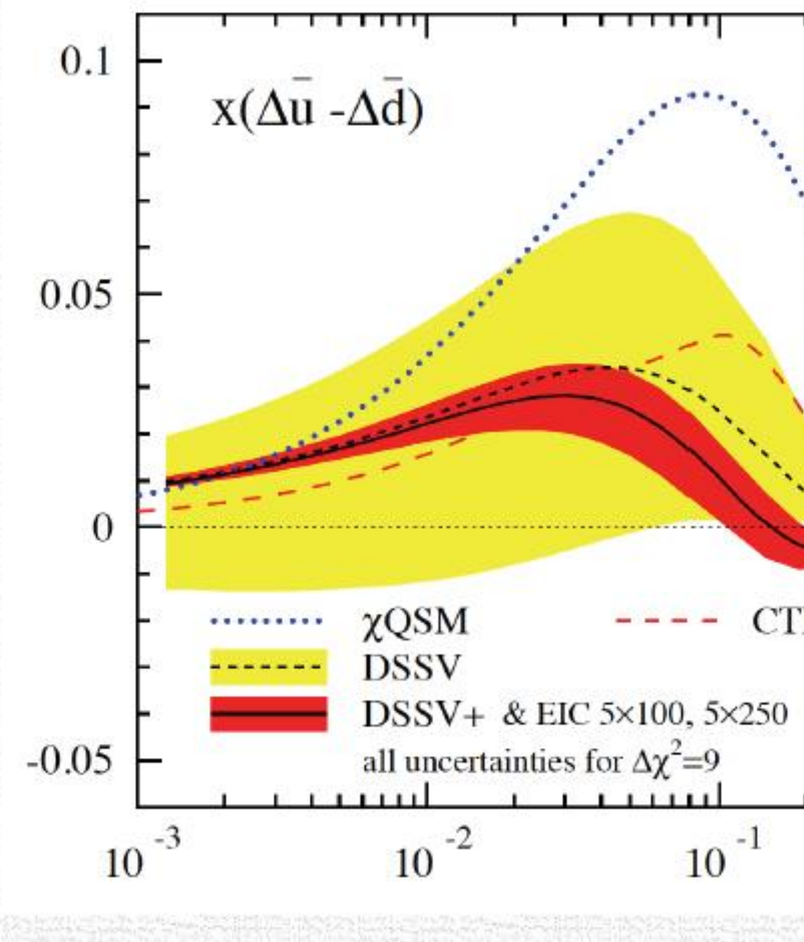
Precision: Gluon & Sea Quark *polarizati*

--Beyond the current experimental capabilities!

ΔG and ΔΣ in helicity sum

Are the sea quark polarization





Summary

- **We have a wealth of exciting, fundamental questions to address**

- **Lattice QCD, phenomenology and experiment working beautifully together**

- **Appropriate investment is needed to:**

  - **exploit the facilities now operating/nearing completion**

  - **provide HPC facilities for further lattice QCD (and share the fruits of those investments)**

  - **build future EIC(s) at high luminosity**

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