Nucleon spin structure measurements at JLab

A. Deur
Thomas Jefferson National Accelerator Facility

Why do we study the nucleon spin structure?

- Spin degrees of freedom: additional handles to test theories.
- Interesting: $S_N=\frac{1}{2}=\frac{1}{2}\Delta\Sigma+\Delta G+L_G+L_q$.

- Spin permits more complete study of QCD;
  - mechanism of confinement;
  - how effective degrees of freedom (hadrons) emerge from fundamental ones (quark and gluons);
  - Test nucleon/nuclear structure effectives theories or models (χPT, AdS/QCD, Dyson-Schwinger Equations...)
- Precise PDFs needed for high energy or atomic physics.

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- Spin permits more complete study of QCD:

1970s-1980s: success of constituent quark model. Suggests $S_N = \frac{1}{2}\Delta\Sigma$

EMC (1987): $\Delta\Sigma \sim 0$

⇒Nucleon spin composition is not trivial. Thus it reveals interesting information on the nucleon structure and the mechanisms of the strong force

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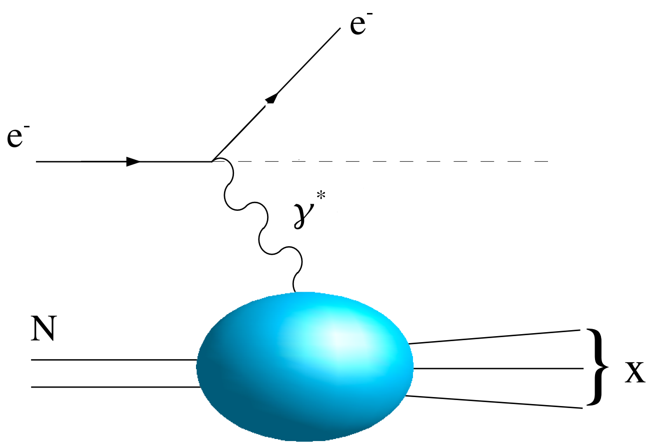
JLab is contributing to all these aspects

Lepton scattering spin structure experiments

(mostly inclusive):

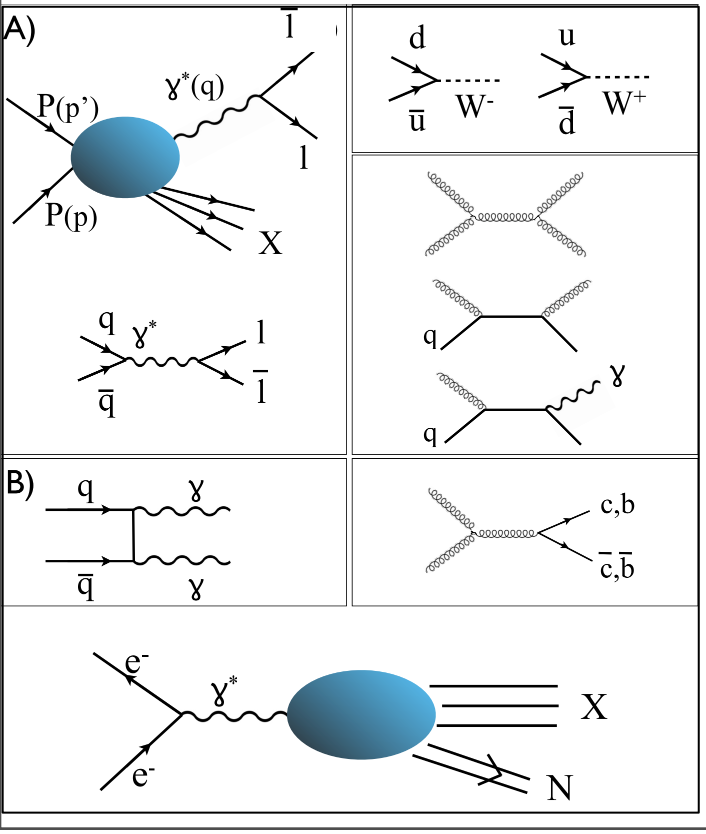


Experiment	Target	Analysis	W (GeV)	x_{Bj}	Q^2 (GeV^2)
E80 (SLAC)	p	A_1	2.1 to 2.6	0.2 to 0.33	1.4 to 2.7
E130 (SLAC)	p	A_1	2.1 to 4.0	0.1 to 0.5	1.0 to 4.1
EMC (CERN)	p	A_1	5.9 to 15.2	1.5×10^{-2} to 0.47	3.5 to 29.5
SMC (CERN)	p, d	A_1	7.7 to 16.1	10^{-4} to 0.482	0.02 to 57
E142 (SLAC)	^{3}He	A_1, A_2	2.7 to 5.5	3.6×10^{-2} to 0.47	1.1 to 5.5
E143 (SLAC)	p, d	A_1, A_2	1.1 to 6.4	3.1×10^{-2} to 0.75	0.45 to 9.5
E154 (SLAC)	^{3}He	A_1, A_2	3.5 to 8.4	1.7×10^{-2} to 0.57	1.2 to 15.0
E155/x (SLAC)	p, d	A_1, A_2	3.5 to 9.0	1.5×10^{-2} to 0.75	1.2 to 34.7
HERMES (DESY)	p, ^{3}He	A_1	2.1 to 6.2	2.1×10^{-2} to 0.85	0.8 to 20
E94010 (JLab)	^{3}He	g_1, g_2	1.0 to 2.4	1.9×10^{-2} to 1.0	0.019 to 1.2
EG1a (JLab)	p, d	A_1	1.0 to 2.1	5.9×10^{-2} to 1.0	0.15 to 1.8
RSS (JLab)	p, d	A_1, A_2	1.0 to 1.9	0.3 to 1.0	0.8 to 1.4
COMPASS (CERN) DIS	p, d	A_1	7.0 to 15.5	4.6×10^{-3} to 0.6	1.1 to 62.1
COMPASS (CERN) low-Q^2	p, d	A_1	5.2 to 19.1	4×10^{-5} to 4×10^{-2}	0.001 to 1.
EG1b (JLab)	p, d	A_1	1.0 to 3.1	2.5×10^{-2} to 1.0	0.05 to 4.2
E99-117 (JLab)	^{3}He	A_1, A_2	2.0 to 2.5	0.33 to 0.60	2.7 to 4.8
E99-107 (JLab)	^{3}He	g_1, g_2	2.0 to 2.5	0.16 to 0.20	0.57 to 1.34
E01-012 (JLab)	^{3}He	g_1, g_2	1.0 to 1.8	0.33 to 1.0	1.2 to 3.3
E97-110 (JLab)	^{3}He	g_1, g_2	1.0 to 2.6	2.8×10^{-3} to 1.0	0.006 to 0.3
EG4 (JLab)	p, n	g_1	1.0 to 2.4	7.0×10^{-3} to 1.0	0.003 to 0.84
SANE (JLab)	p	A_1, A_2	1.4 to 2.8	0.3 to 0.85	2.5 to 6.5
EG1dvcs (JLab)	p	A_1	1.0 to 3.1	6.9×10^{-2} to 0.63	0.61 to 5.8
E06-014 (JLab)	^{3}He	g_1, g_2	1.0 to 2.9	0.25 to 1.0	1.9 to 6.9
E06-010/011 (JLab)	^{3}He	single spin asy.	2.4 to 2.9	0.16 to 0.35	1.4 to 2.7
E07-013 (JLab)	^{3}He	single spin asy.	1.7 to 2.9	0.16 to 0.65	1.1 to 4.0
E08-027 (JLab)	p	g_1, g_2	1. to 2.1	3.0×10^{-3} to 1.0	0.02 to 0.4

Lepton scattering spin structure experiments

Inclusive lepton scattering is the tip of the iceberg.

Pol. SIDIS experiments.
Colliders experiments:



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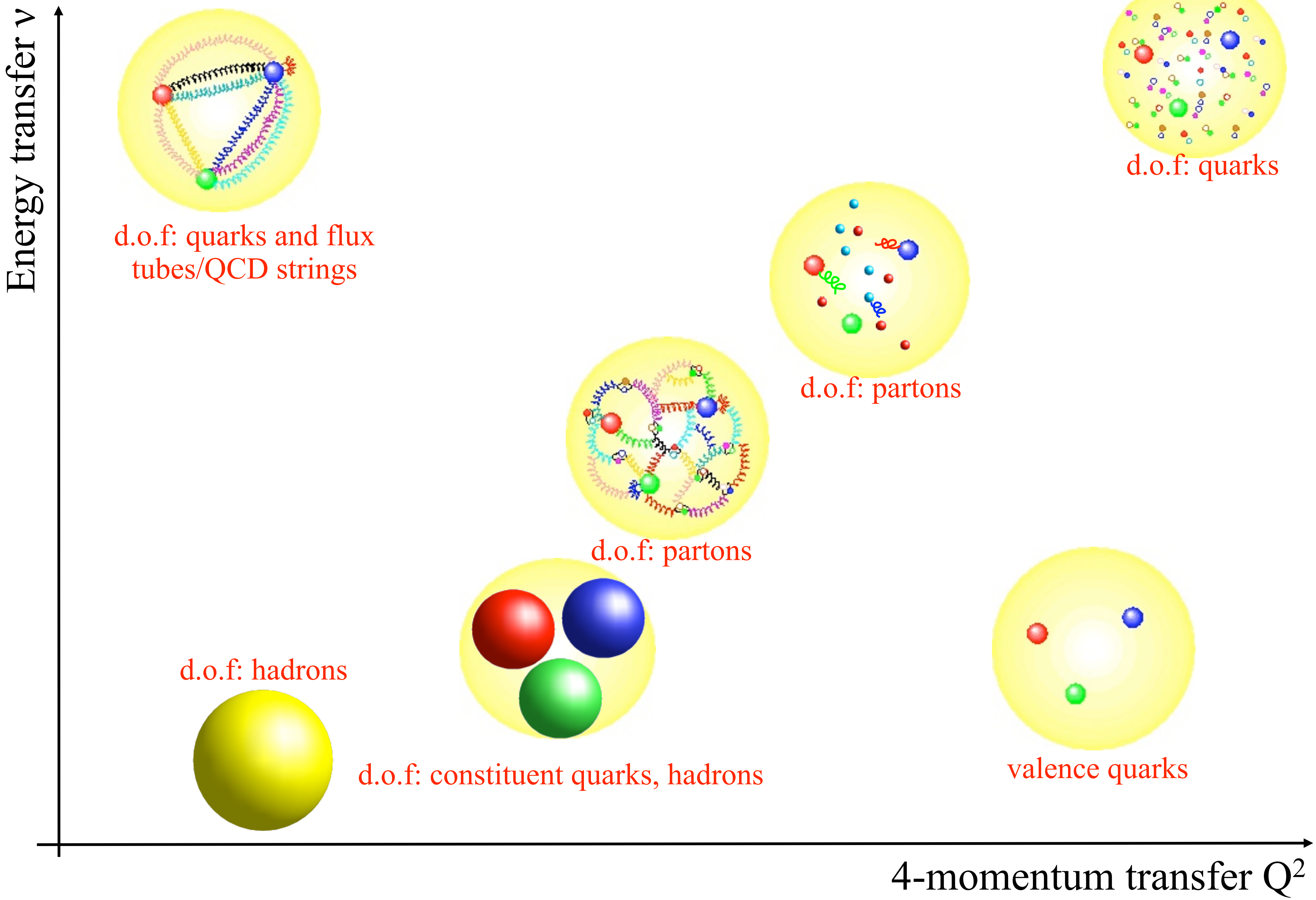
Car traffic photos

JLab’s spin program and the multiple aspects the nucleon



Energy transfer ν

d.o.f: quarks and flux tubes/QCD strings

d.o.f: quarks

d.o.f: partons

d.o.f: partons

d.o.f: hadrons

d.o.f: constituent quarks, hadrons

valence quarks

4-momentum transfer Q^2

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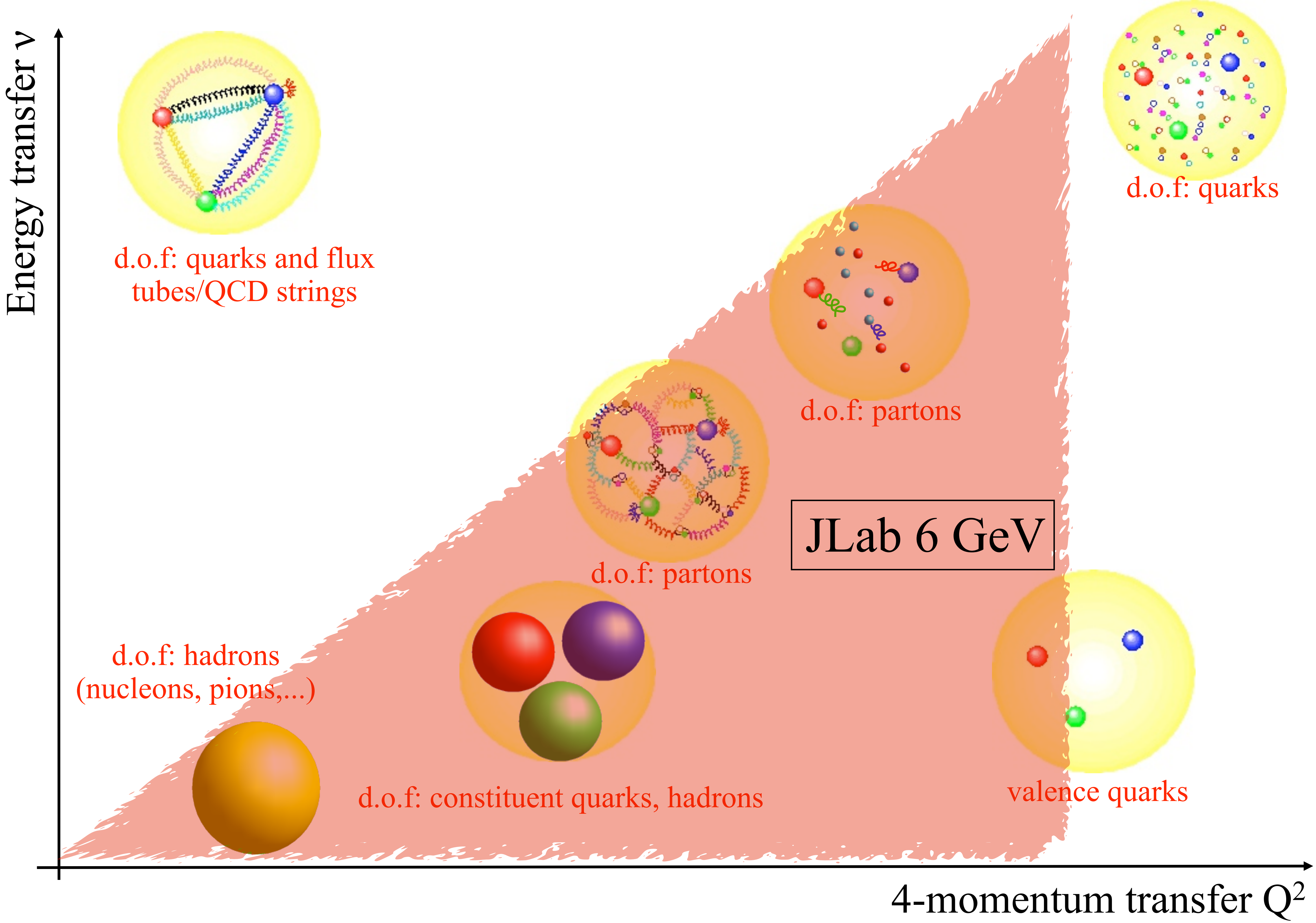

Energy transfer ν

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JLab 6 GeV

d.o.f: partons

d.o.f: hadrons (nucleons, pions,...)

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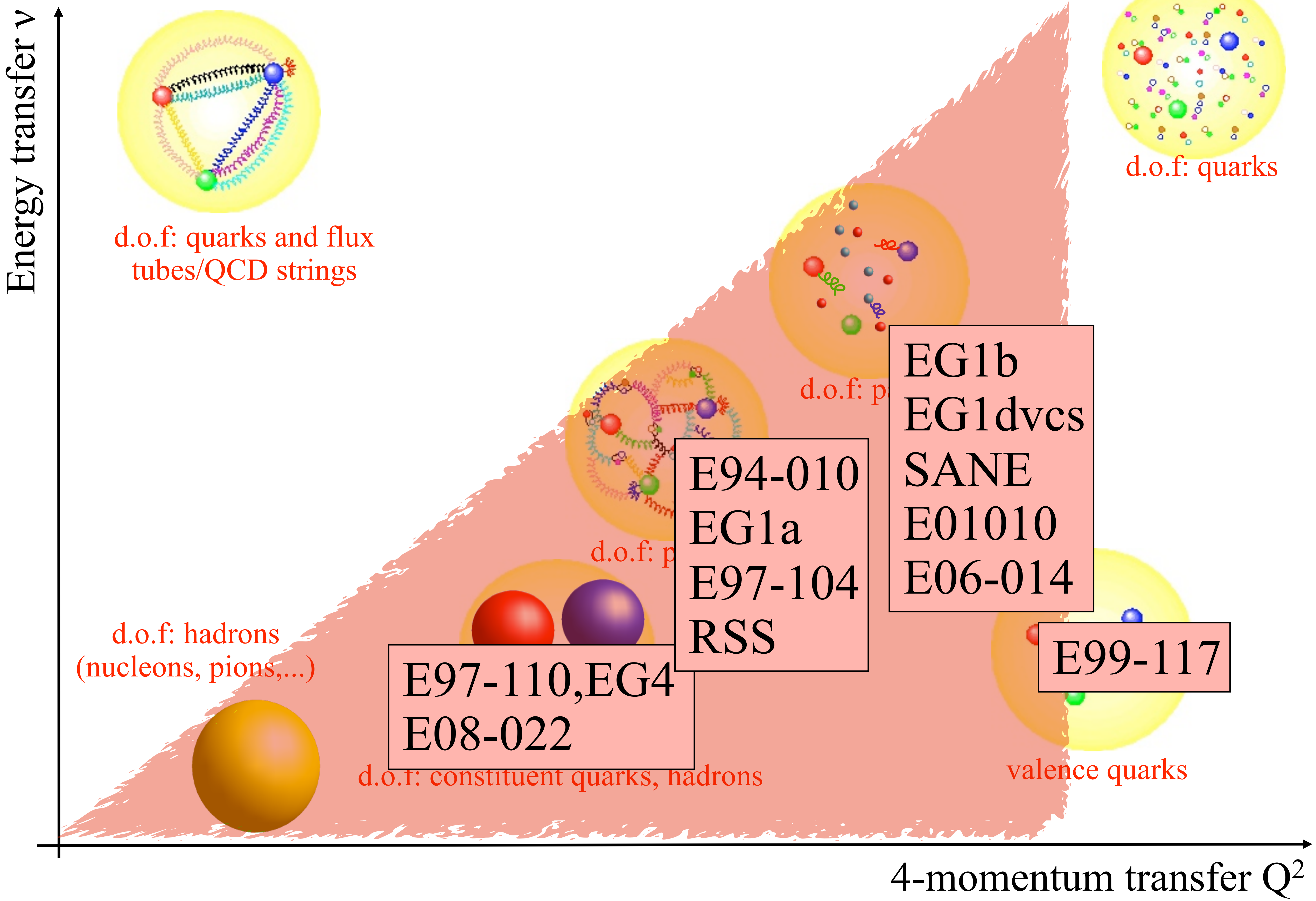

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tubes/QCD strings

d.o.f: quarks

d.o.f: p

EG1b
EG1dvcs
SANE
E01010
E06-014

d.o.f: p

E94-010
EG1a
E97-104
RSS

d.o.f: hadrons
(nucleons, pions,...)

E97-110,EG4
E08-022

E99-117

d.o.f: constituent quarks, hadrons

valence quarks

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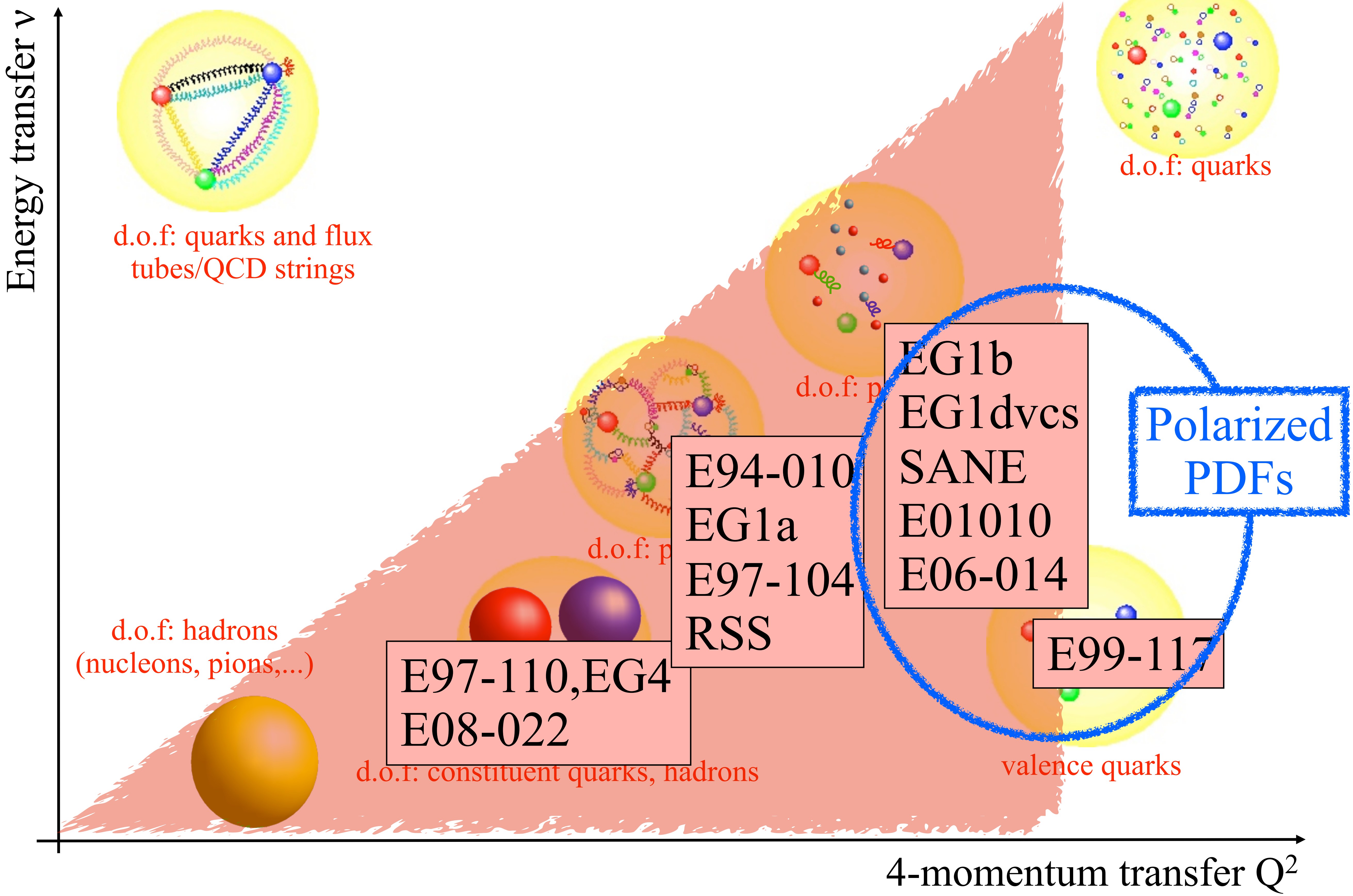

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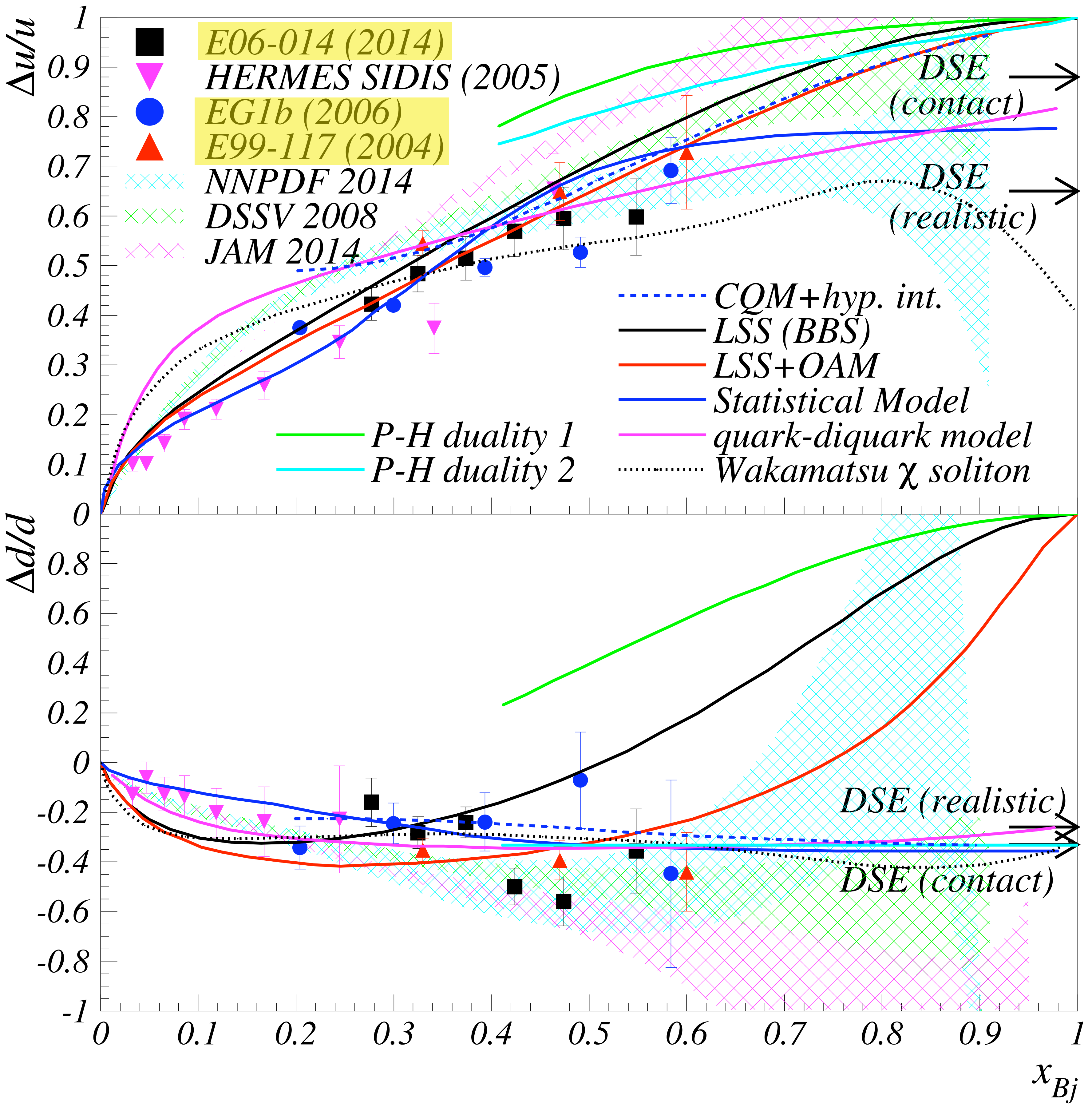
Polarized PDFs

PDFs measurements at JLab



Jefferson Lab

A. Deur CIPANP, Palm Springs. 05/31/2018

Thursday, May 31, 2018

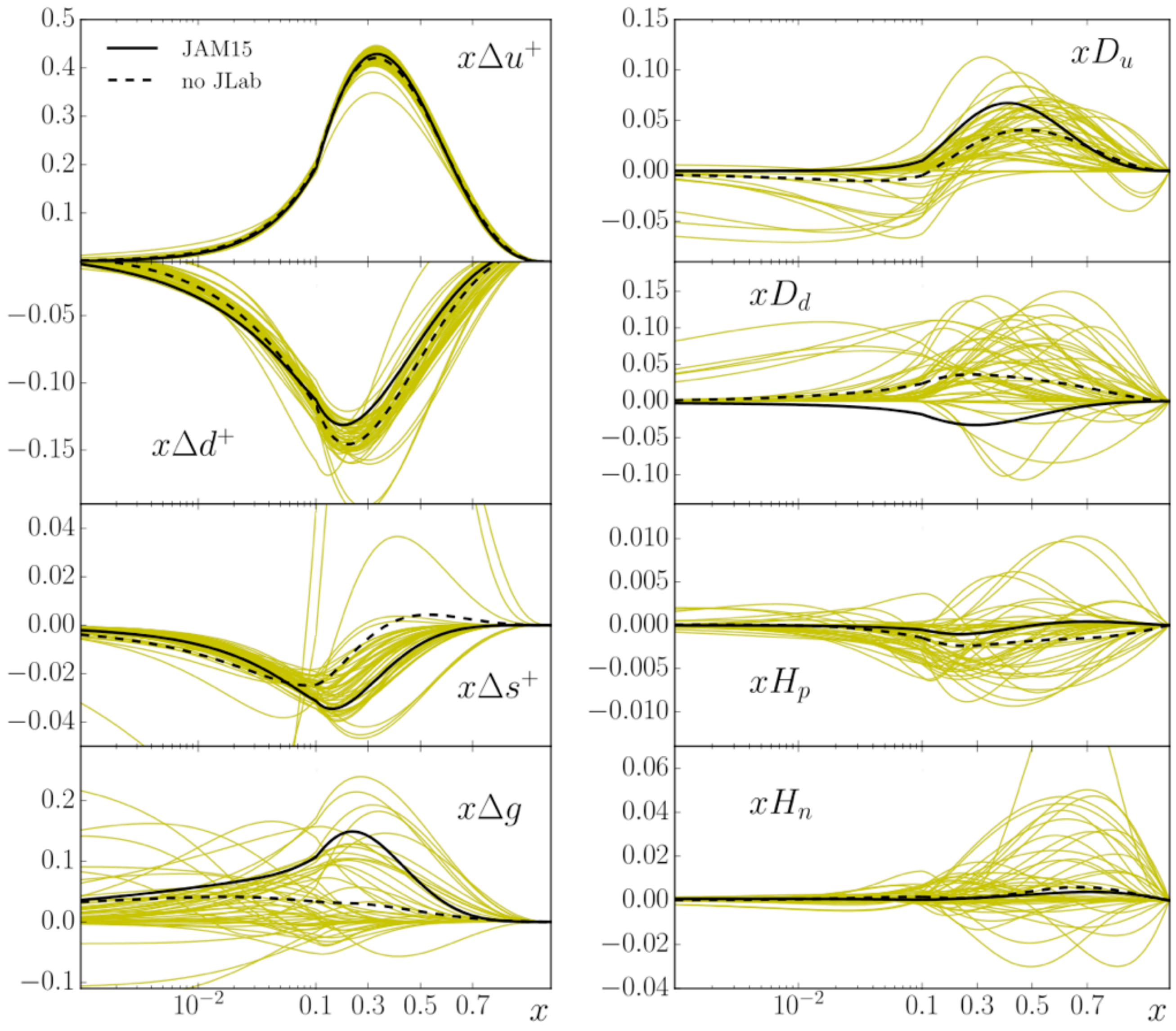
PDFs measurements at JLab

Slide from J. Ethier

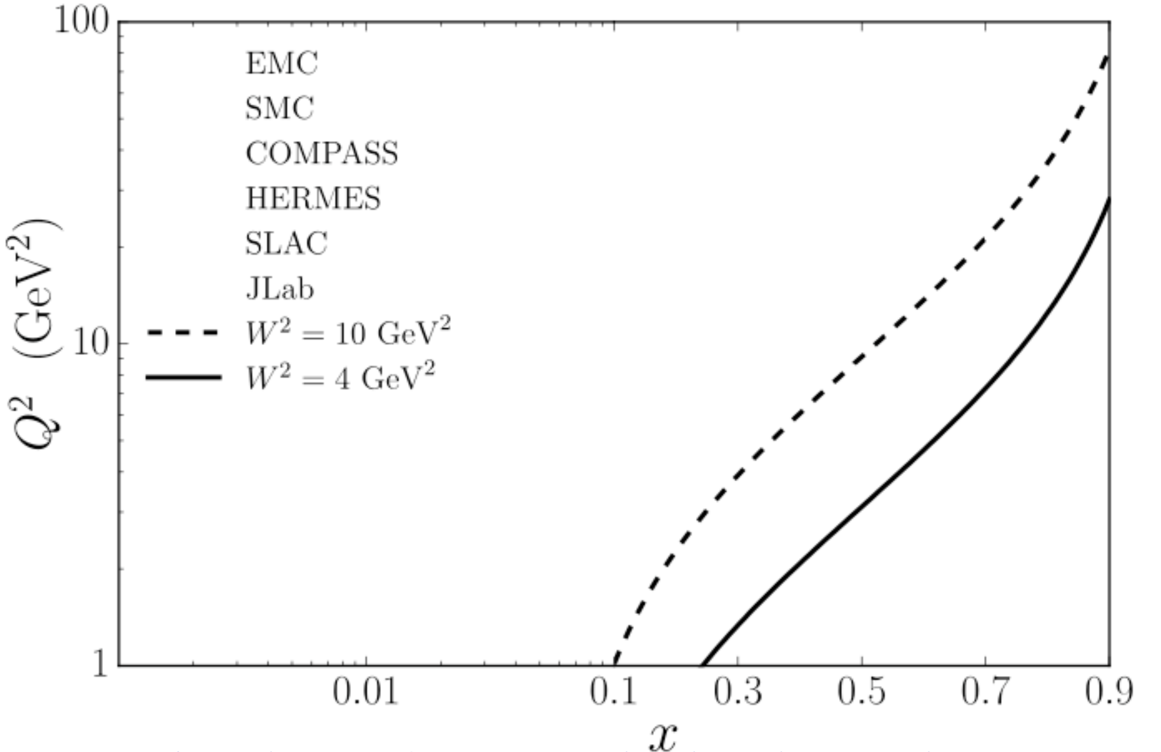
JAM15 Analysis – Impact of JLab Data

$$g_1(x,Q^2) = g_1^{\rm LT+TMC}(\Delta u^+, \Delta d^+, \Delta g, ...) + g_1^{\rm T3+TMC}(D_u, D_d) + g_1^{\rm T4}(H_{p,n})$$

$$g_2(x,Q^2) = g_2^{\rm LT+TMC}(\Delta u^+, \Delta d^+, \Delta g, ...) + g_2^{\rm T3+TMC}(D_u, D_d)$$

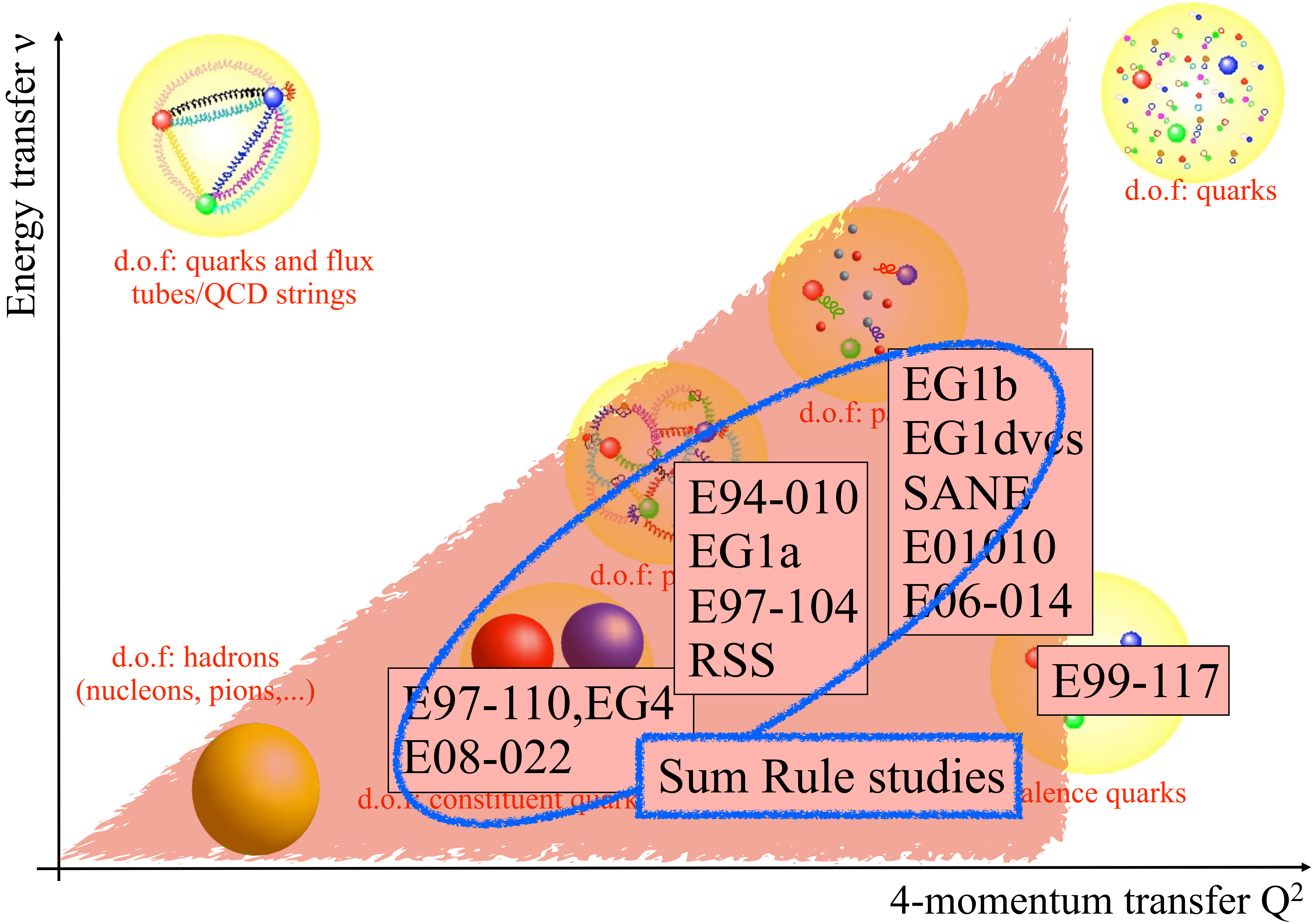


N. Sato et. al. Phys. Rev. D93 074005 (2016)



- Reduction of uncertainties in region $0.1 < x < 0.7$
- Impact on low-x uncertainties from imposing SU(3)$_f$ constraints
- JLab data prefers positive glue for $x > 0.1$
  → constrained via evolution
- Non-zero twist-3 quark distributions ; twist-4 consistent with zero

JLab's spin program and the multiple aspects the nucleon



EG1b
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E99-117

Sum Rule studies

Sum Rules

Bjorken sum rule (most famous sum rule of polarized lepton scattering):

$$\int g_1^p - g_1^n dx = \frac{1}{6} g_a \left(1 + \frac{\alpha_s(Q^2)}{\pi} + \ldots\right) + \text{non-pert. cor.}$$

↑ Axial charge

The Gerasimov-Drell-Hearn Sum Rule

GDH sum rule:

$$\int_{\nu_{thr}}^{\infty}(\sigma^{1/2} - \sigma^{3/2})\,\frac{d\nu}{\nu} = \frac{-2\alpha\pi^2\kappa^2}{M^2}$$

Photon energy

anomalous magnetic moment

α: fine structure constant

Photo-absorption cross sections

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Originally derived for photo-absorption (Q^2=0)

Later generalized to Q^2>0

spin-dep.
DDVCS

$$\frac{16\alpha\pi^2}{Q^2}\int_0^{1^-} g_1\,dx = 2\alpha\pi^2 S_1$$

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Bjorken sum rule:

$$\int g_1^p - g_1^n dx = \frac{1}{6}\, g_a\left(1+\frac{\alpha_s(Q^2)}{\pi}+\ldots\right) + \text{non-pert. cor.}$$

$$\text{GDH(proton)} - \text{GDH(neutron)} \propto Q^2 \times \text{Bjorken sum}$$

Spin polarizabilities sum rules

Sum rules with higher moments exist, e.g. spin polarizabilities sum rules:

Generalized forward spin polarizability:

$$\gamma_0 = \frac{4e^2M^2}{\pi Q^6} \int x^2(g_1 - \frac{4M^2}{Q^2} x^2 g_2)dx$$

Longitudinal-Transverse polarizability:

$$\delta_{LT} = \frac{4e^2M^2}{\pi Q^6} \int x^2(g_1+g_2)dx$$

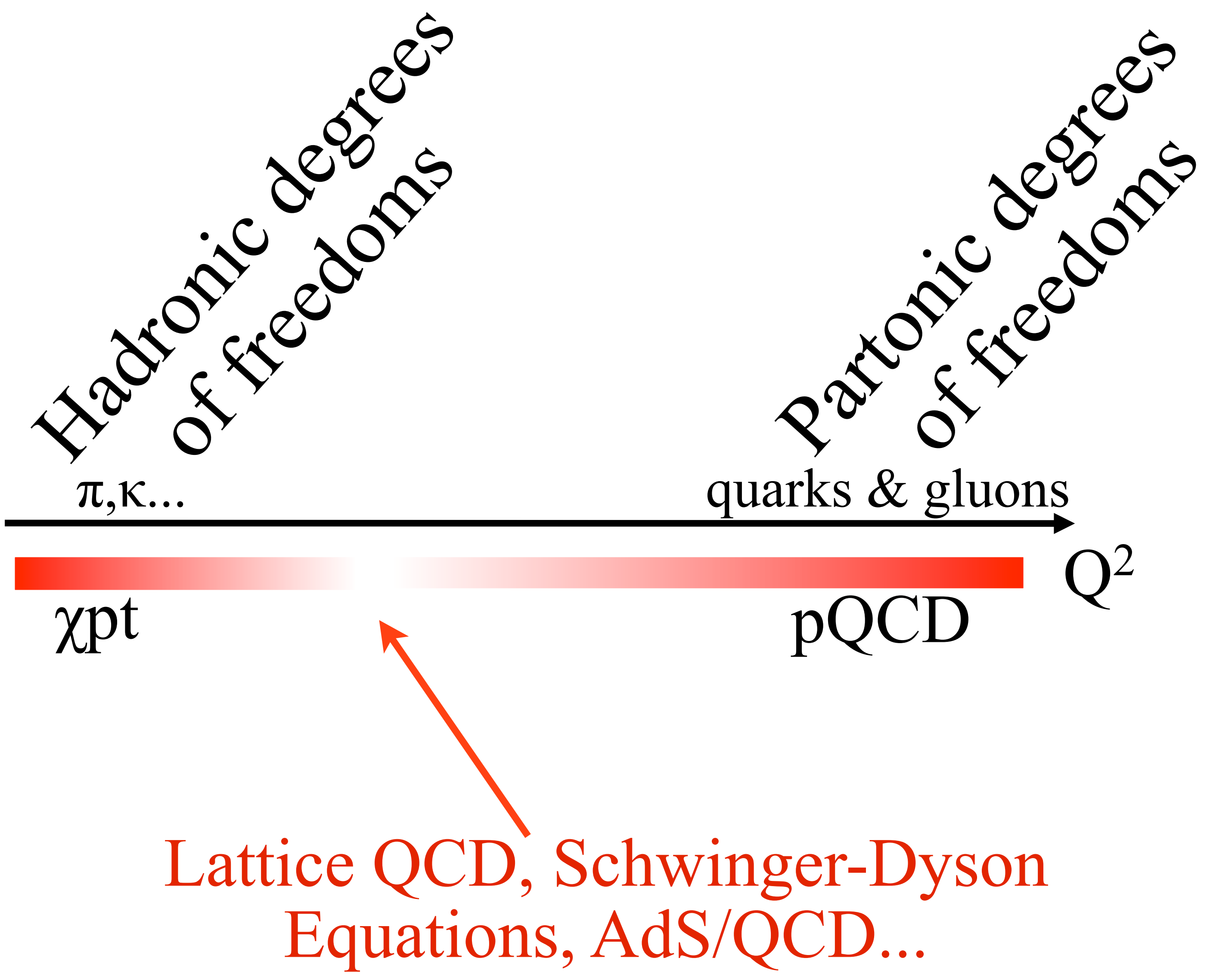
Or twist-3 term d_2:

$$d_2(Q^2) = \int_0^1 x^2 2g_1(x,Q^2) + 3g_2(x,Q^2)dx$$

Interest of the generalized GDH sum rule

Sum rule valid at all Q^2:

We can measure $\int g_1\, dx$ at different Q^2 and compute the other side of the sum rule using different techniques:



Hadronic degrees of freedoms

Partonic degrees of freedoms

π, κ...

quarks & gluons

Q^2

χpt

pQCD

Lattice QCD, Schwinger-Dyson Equations, AdS/QCD...

$\Rightarrow$ Study transition from hadronic to partonic description of strong force. Test Lattice QCD, effective approaches to QCD, and models.

Existing data on GDH sum

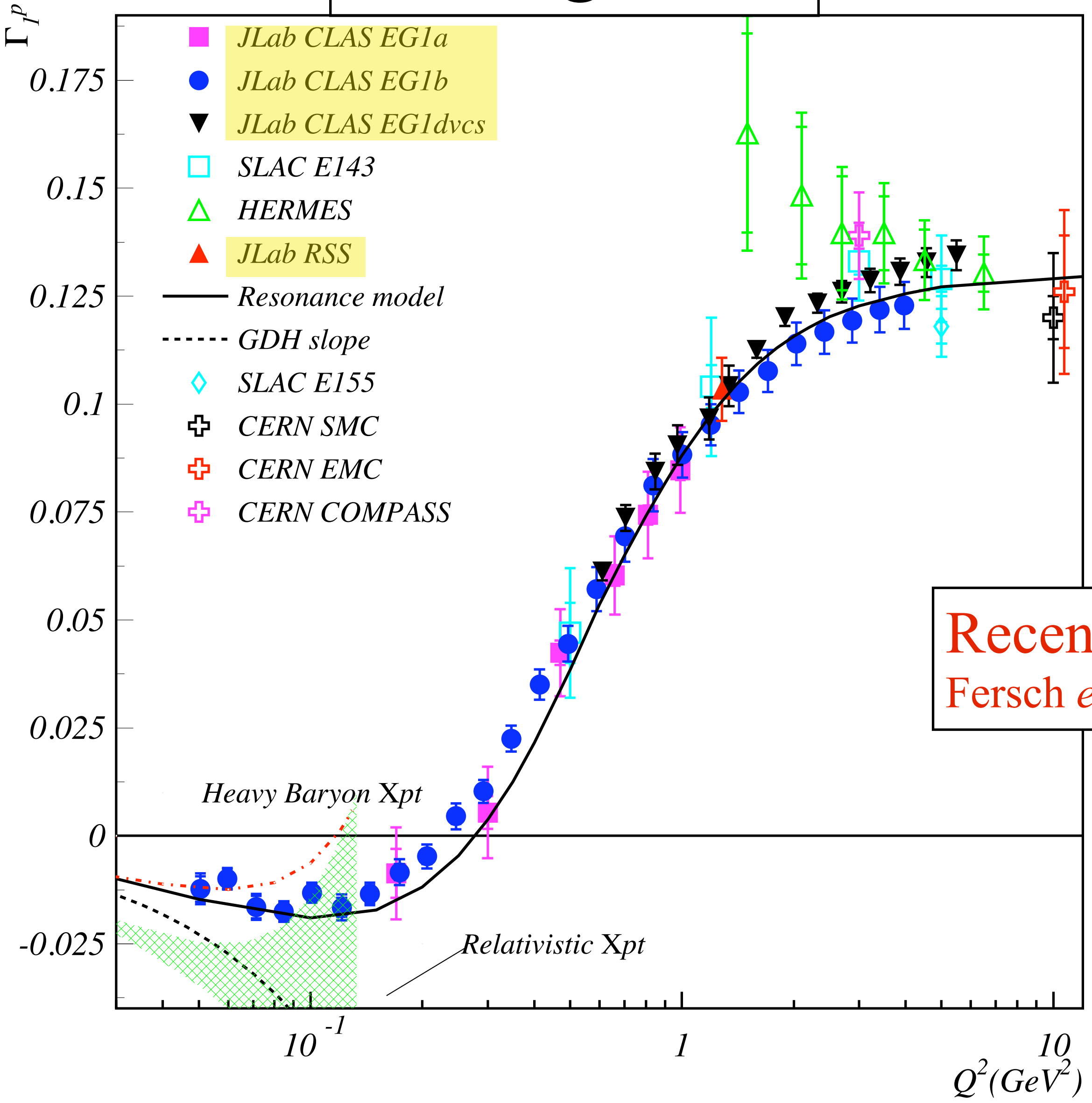
Q^2=0:
Mainz, Bonn
BNL

Intermediate Q^2:
Jlab Hall A, B & C

Large Q^2:
CERN, SLAC,
DESY (Hermes)

Existing data (proton)

$$\Gamma_1 = \int g_1\, dx$$



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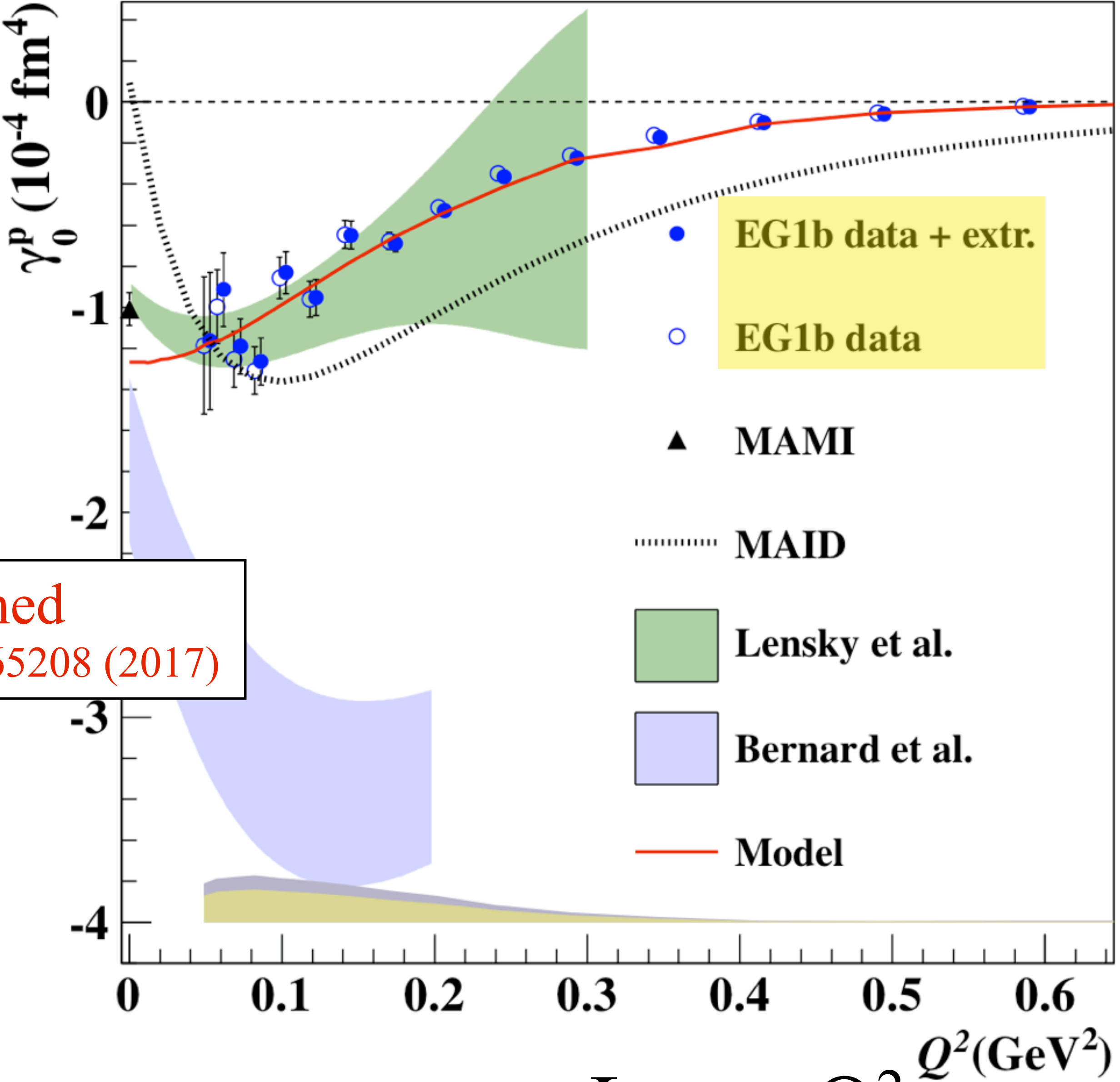

Recently published

Fersch *et al.* PC 96 065208 (2017)

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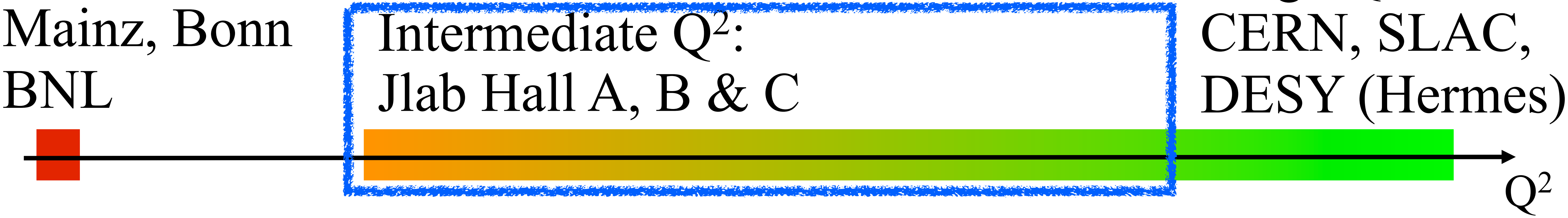
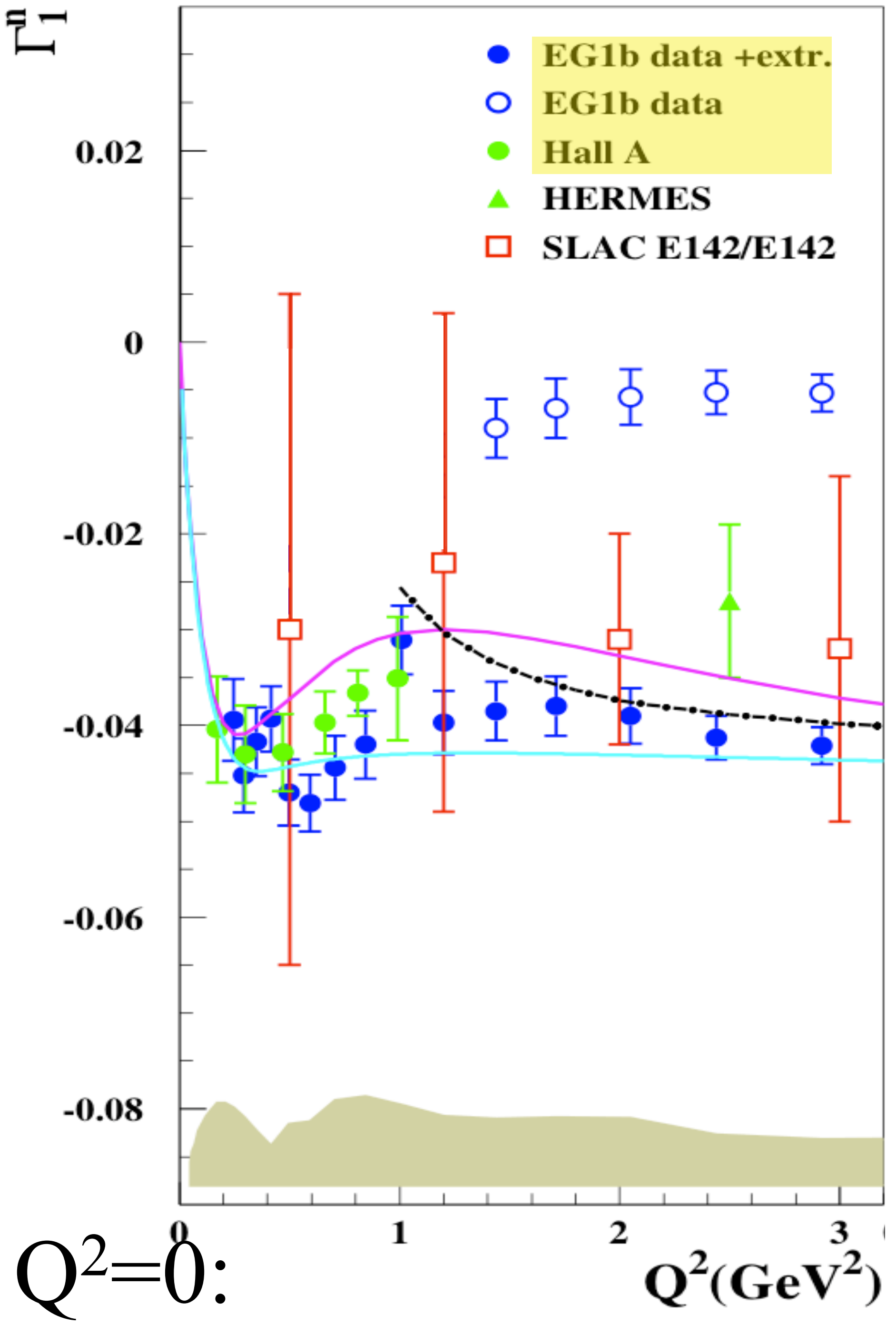
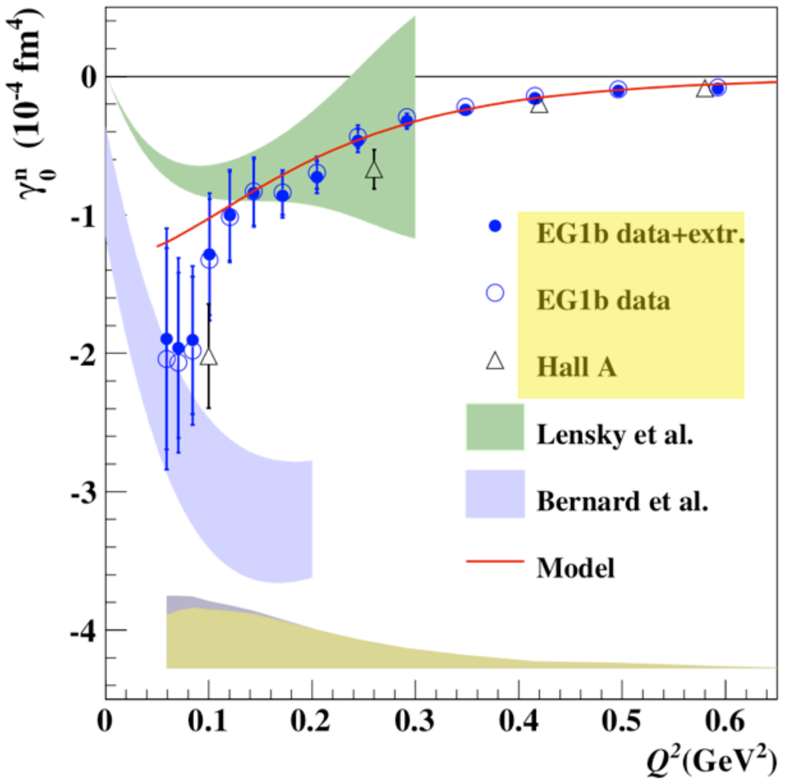
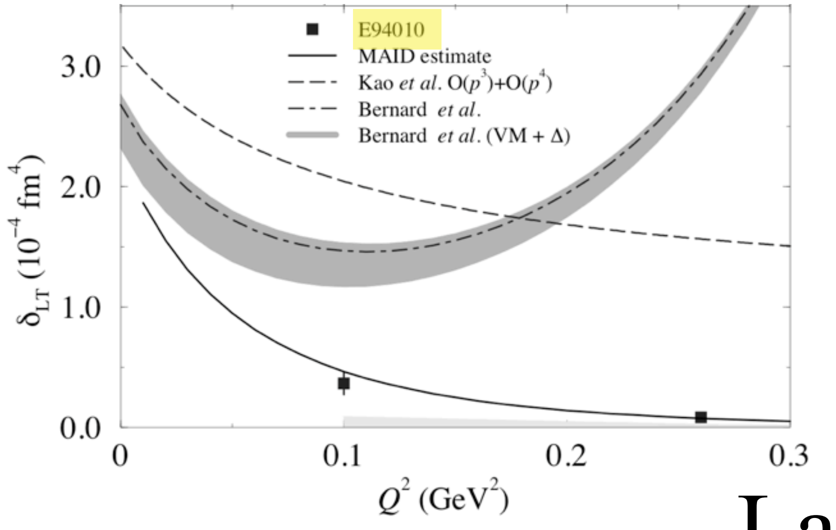
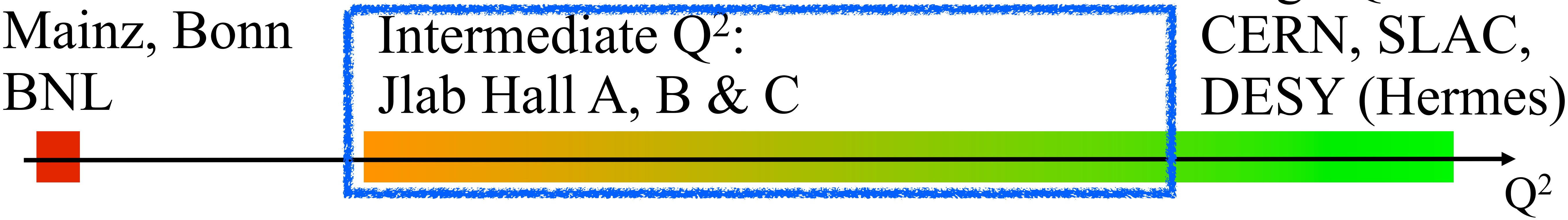


Existing data (neutron)









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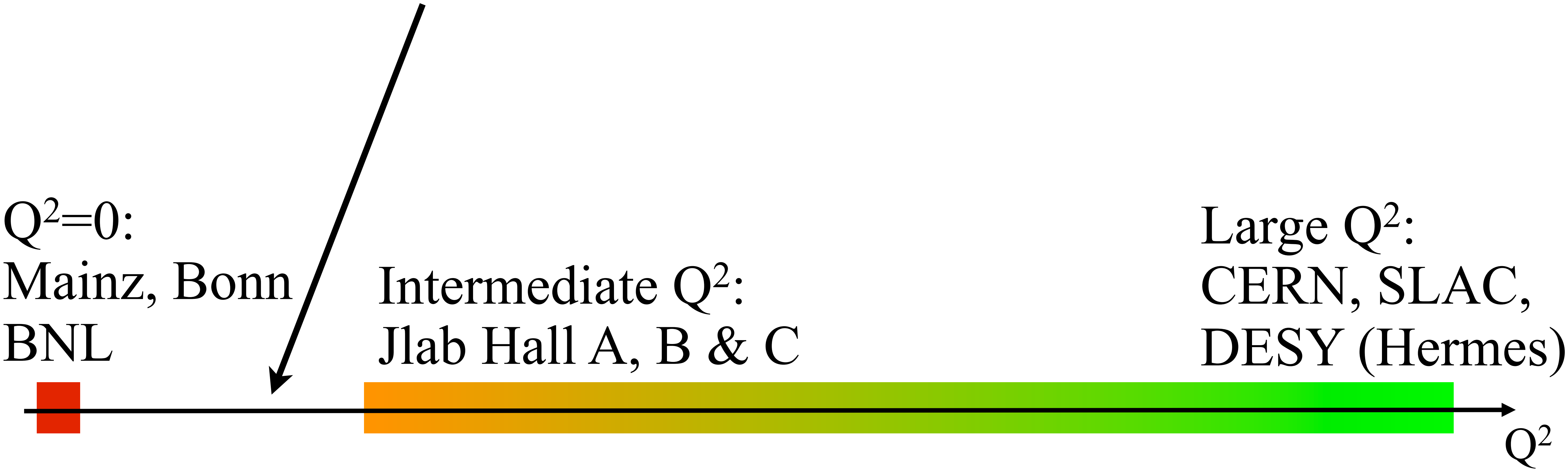
GDH at low Q^2 in:

- JLab Hall A: E97-110, neutron(^{3}He), E08-027 (proton)
- JLab Hall B: EG4, proton & neutron(D)

Bridge the remaining gap:

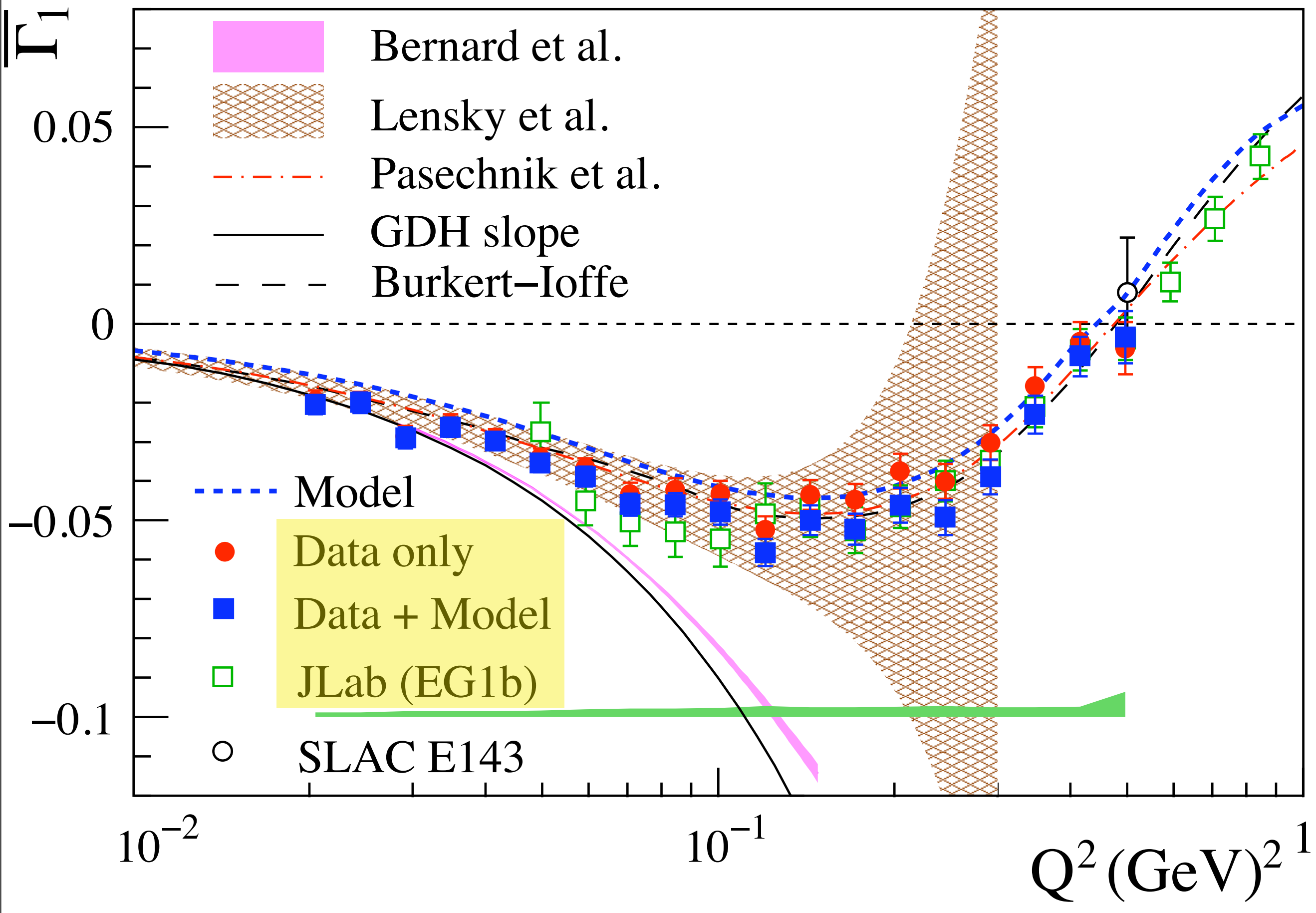


Q^2=0:
Mainz, Bonn
BNL

Intermediate Q^2:
Jlab Hall A, B & C

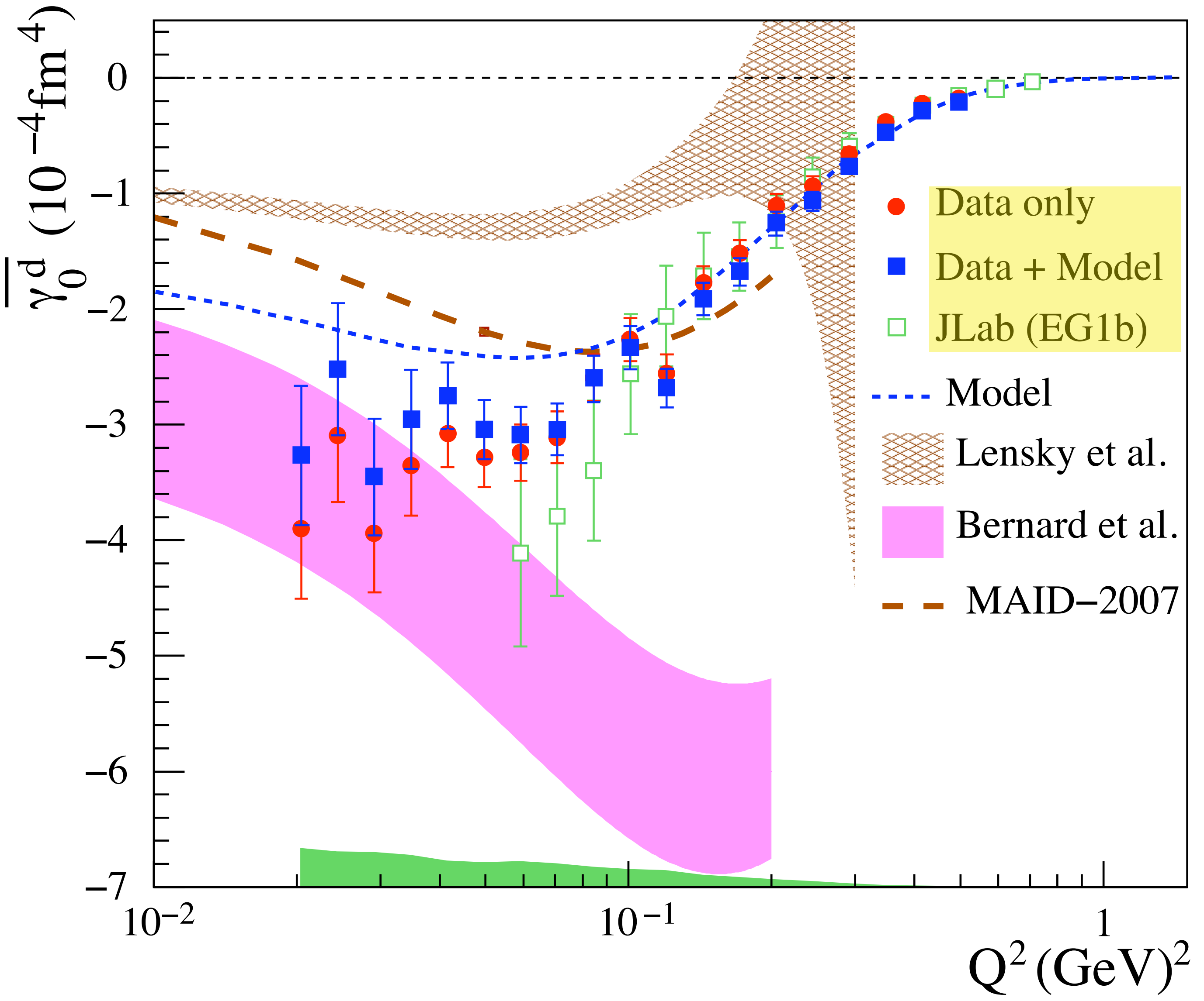
Large Q^2:
CERN, SLAC,
DESY (Hermes)

EG4 Deuteron results on ∫g₁ dx and polarizabilities

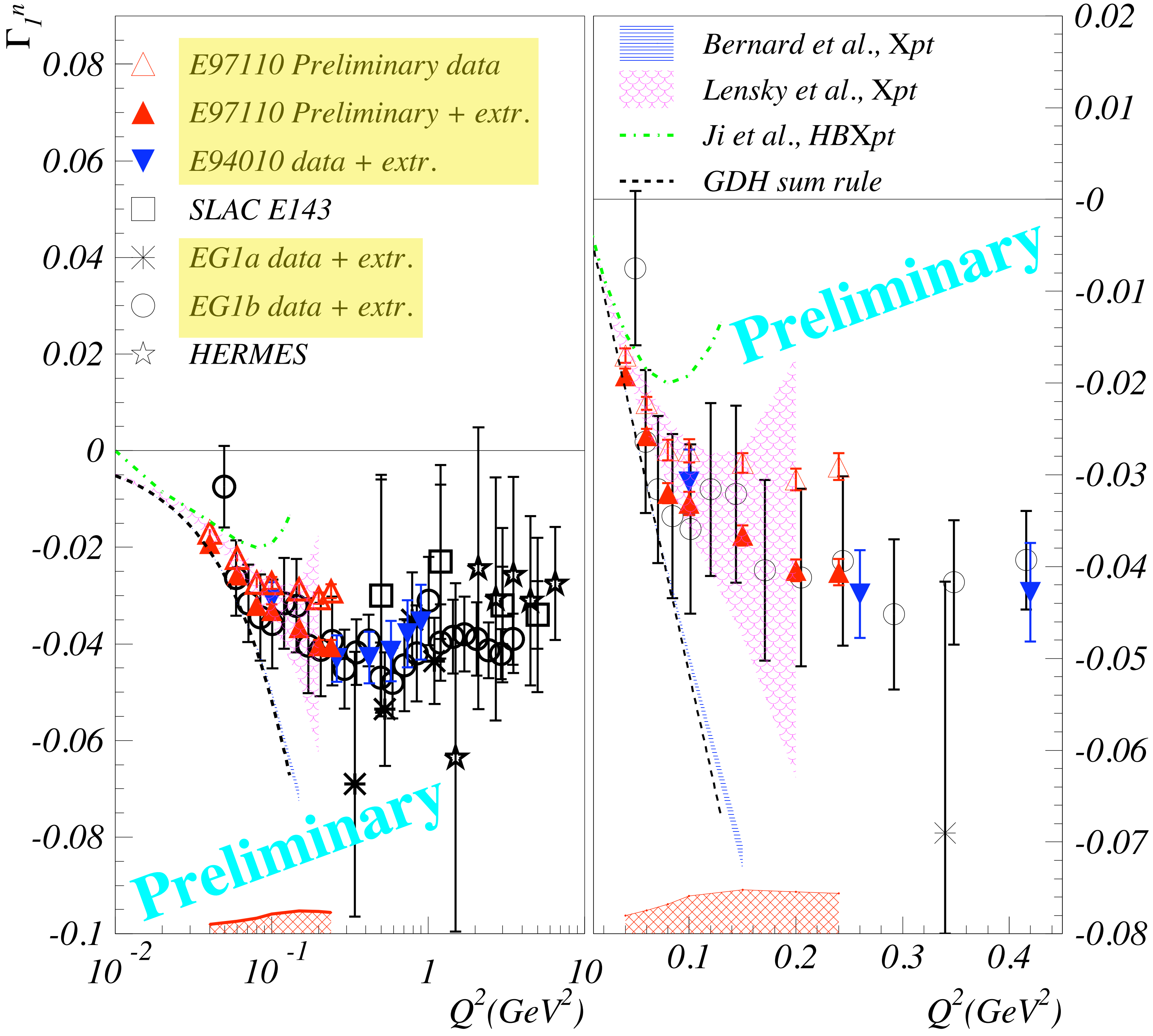


Just Published.

Adhikari *et al.* PRL 120, 062501 (2018)

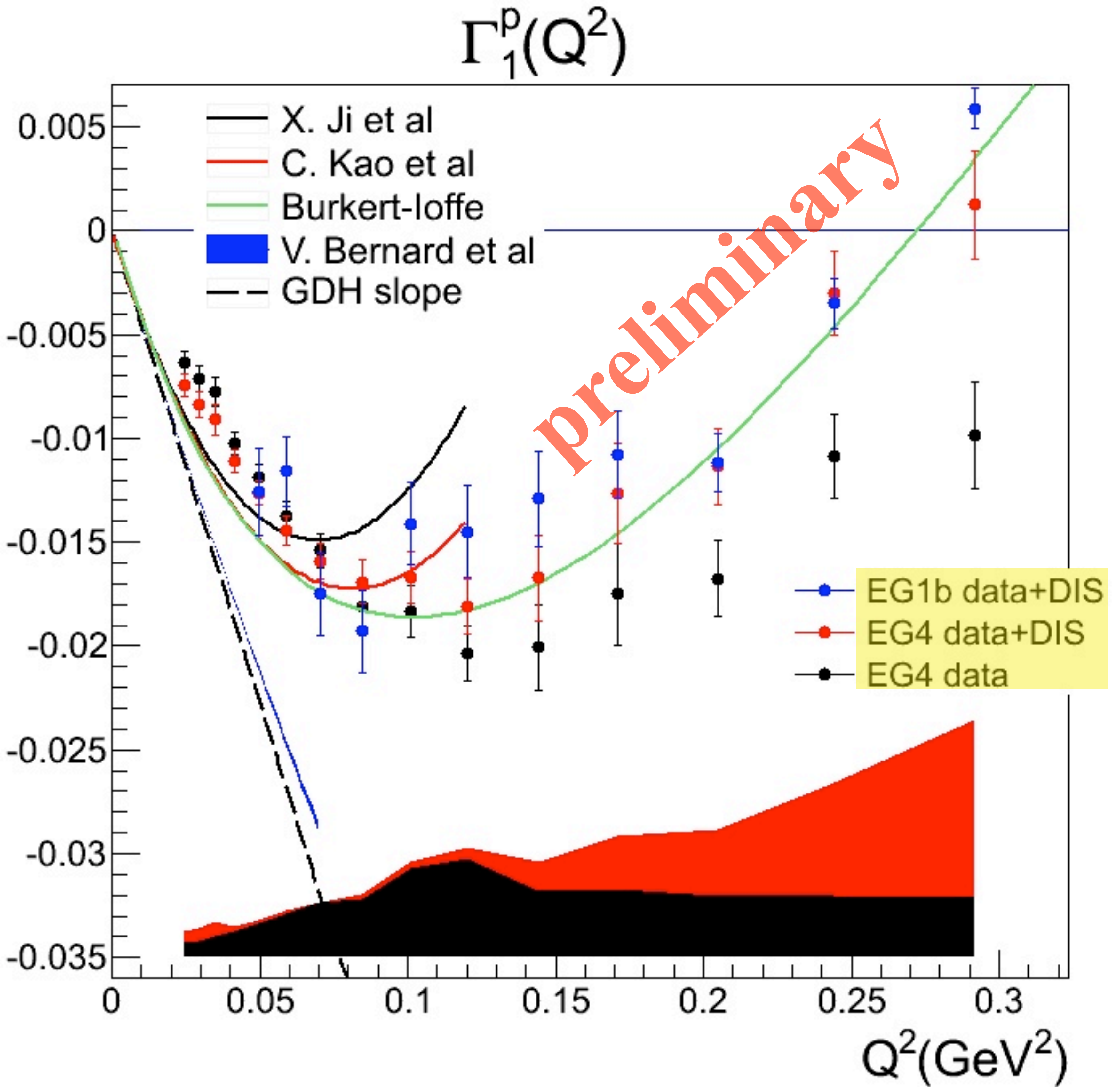


E97-110 preliminary neutron(^{3}He) results on $\int g_1\,dx$



Near final
(draft paper in June)

EG4 preliminary proton results on ∫g_1 dx



What do we learn from these measurements?

Test of χpt

Ref.	Γ_1^p	Γ_1^n	$\boldsymbol{\Gamma_1^{p-n}}$	Γ_1^{p+n}	γ_0^p	γ_0^n	$\boldsymbol{\gamma_0^{p-n}}$	γ_0^{p+n}	$\boldsymbol{\delta_{LT}^n}$	d_2^n
Ji 1999	**X**	**X**	**A**	**X**	-	-	-	-	-	-
Bernard 2002	**X**	**X**	**A**	**X**	**X**	**A**	**X**	**X**	**X**	**X**
Kao 2002	-	-	-	-	**X**	**A**	**X**	**X**	**X**	**X**
Bernard 2012	**X**	**X**	**A**	**X**	**X**	**A**	**X**	**X**	**X**	-
Lensky 2014	**X**	**A**	**A**	**A**	**A**	**X**	**X**	**X**	$\sim$ **A**	**A**

Test of χpt

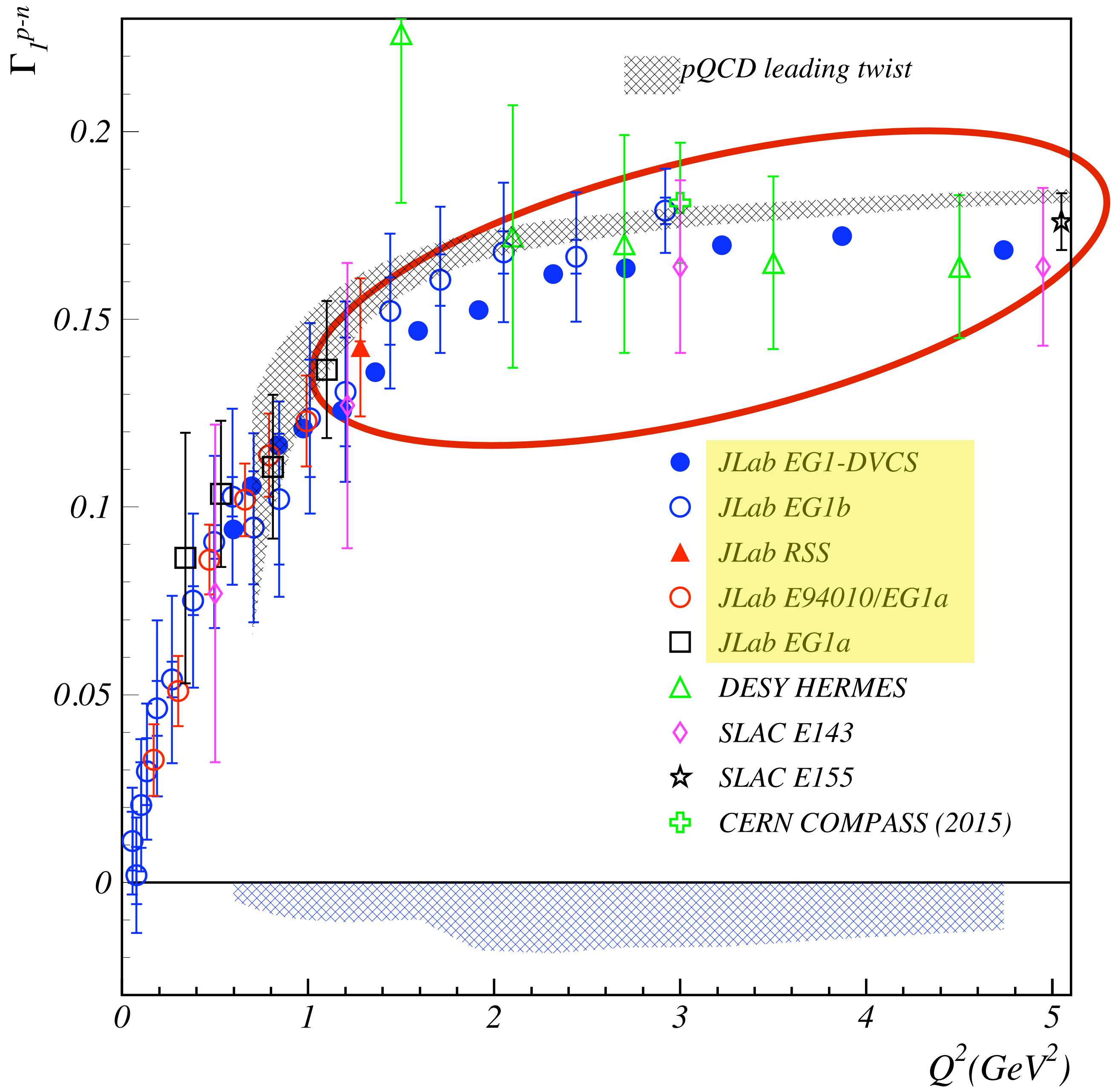
No significant low-x contribution
(More robust observables)

Ref.	Γ_1^p	Γ_1^n	$\boldsymbol{\Gamma_1^{p-n}}$	Γ_1^{p+n}	γ_0^p	γ_0^n	$\boldsymbol{\gamma_0^{p-n}}$	γ_0^{p+n}	$\boldsymbol{\delta_{LT}^n}$	d_2^n
Ji 1999	X	X	A	X	-	-	-	-	-	-
Bernard 2002	X	X	A	X	X	A	X	X	X	X
Kao 2002	-	-	-	-	X	A	X	X	X	X
Bernard 2012	X	X	A	X	X	A	X	X	X	-
Lensky 2014	X	A	A	A	A	X	X	X	$\sim$ A	A

No Δ_{1232} contributions
(More robust χpt calculations)

"Study transition from hadronic to partonic description of strong force"

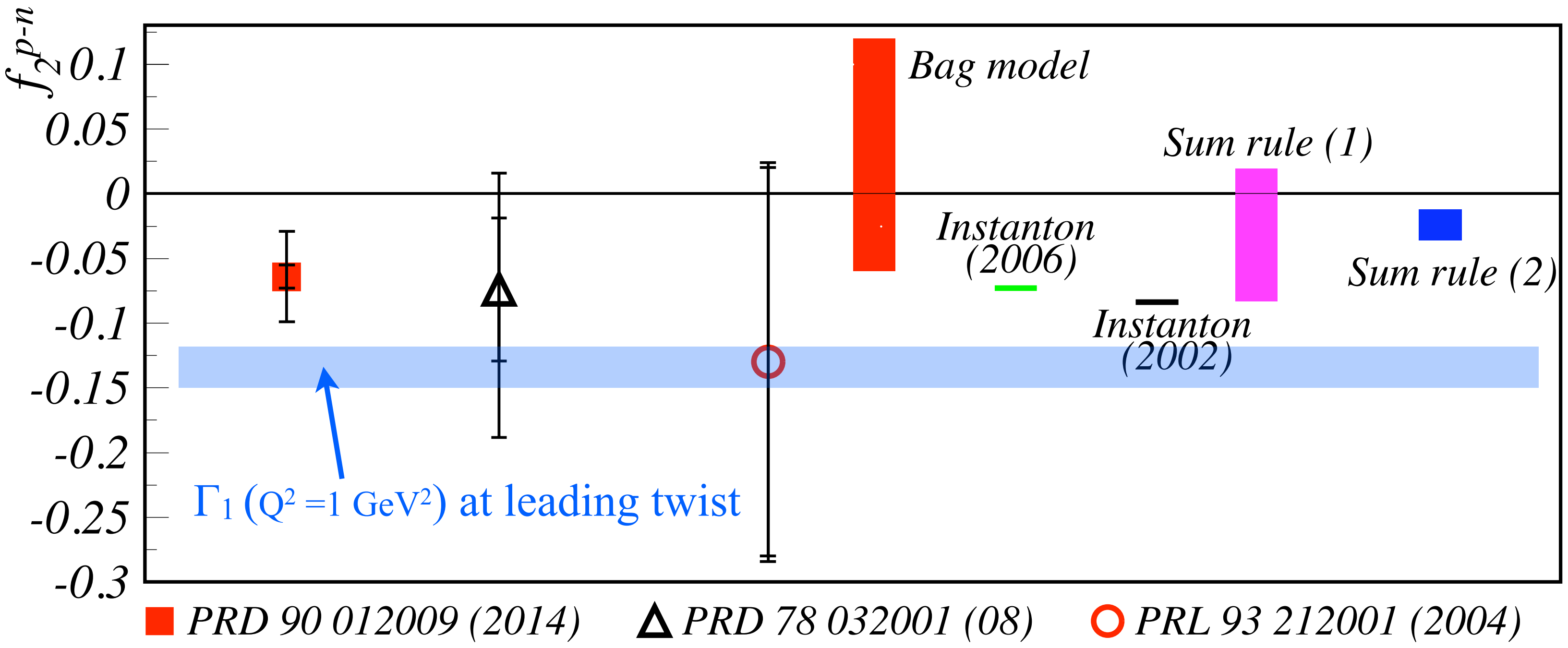
Ex. Bjorken sum data:



"Study transition from hadronic to partonic description of strong force"

Twist-4 f_2: Next to leading twist.

Extraction at Q^2 =1 GeV^2.



f_2 is large (about half of leading twist at Q^2 =1 GeV^2) in accordance to intuition.

Twist-6 is small. Twist-8 is of similar size as f_2 but opposite sign.

Overall, higher twist contribution small at Q^2 =1 GeV^2.

⇒ Elusive higher twists

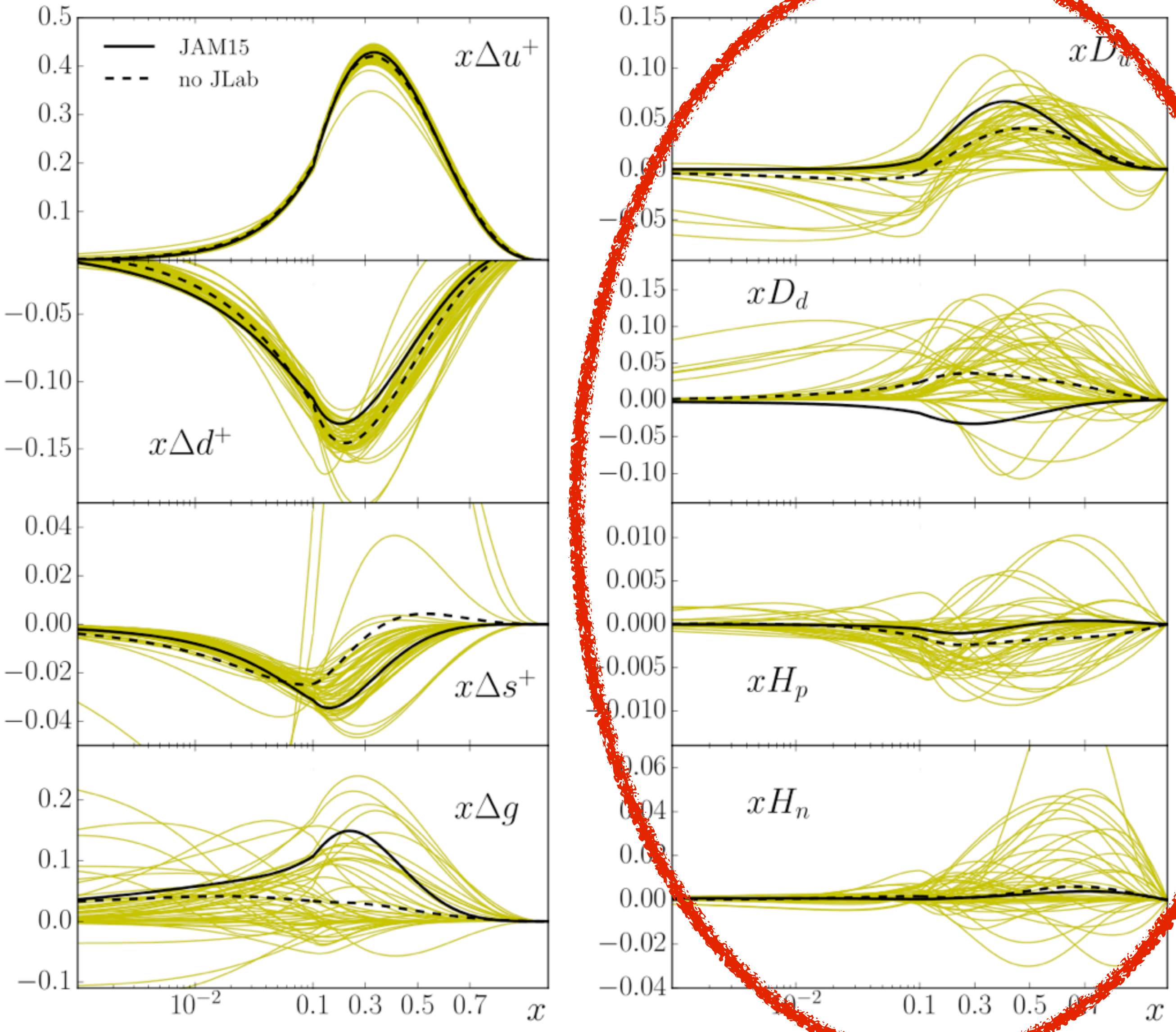
PDFs measurements at JLab

Slide from J. Ethier

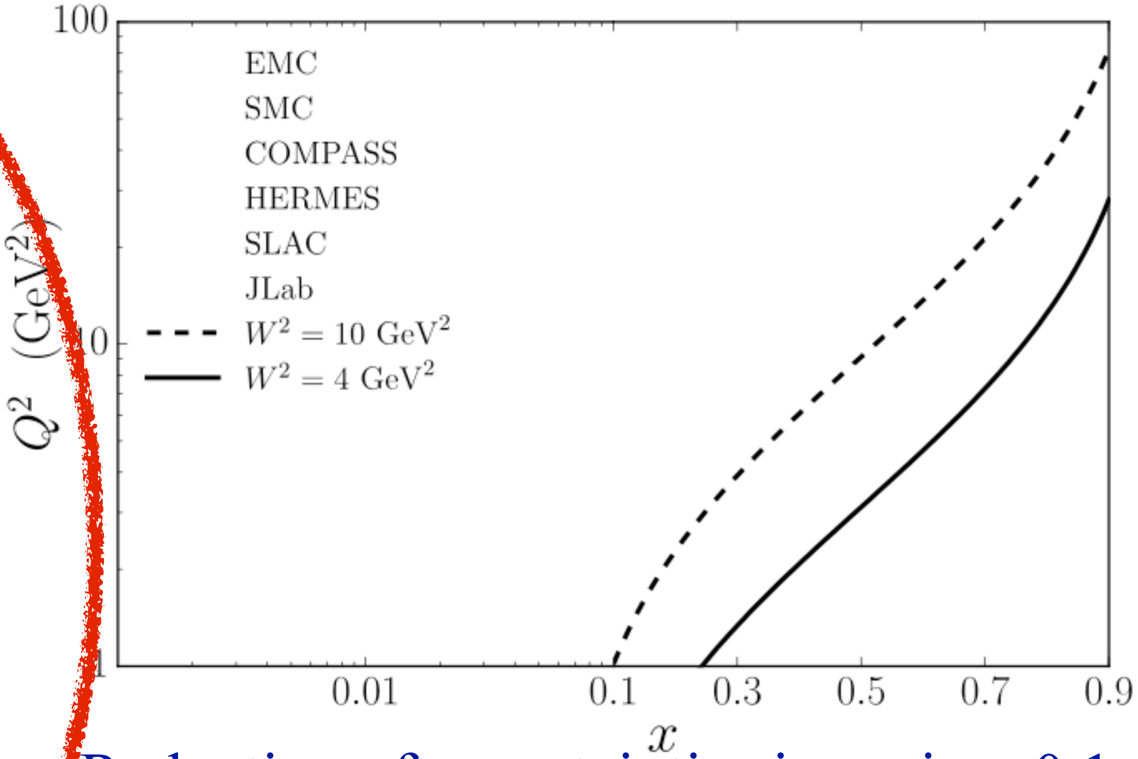
JAM15 Analysis – Impact of JLab Data

$$g_1(x,Q^2) = g_1^{\mathrm{LT+TMC}}(\Delta u^+, \Delta d^+, \Delta g, ...) + g_1^{\mathrm{T3+TMC}}(D_u, D_d) + g_1^{\mathrm{T4}}(H_{p,n})$$

$$g_2(x,Q^2) = g_2^{\mathrm{LT+TMC}}(\Delta u^+, \Delta d^+, \Delta g, ...) + g_2^{\mathrm{T3+TMC}}(D_u, D_d)$$



N. Sato et. al. Phys. Rev. D93 074005 (2016)

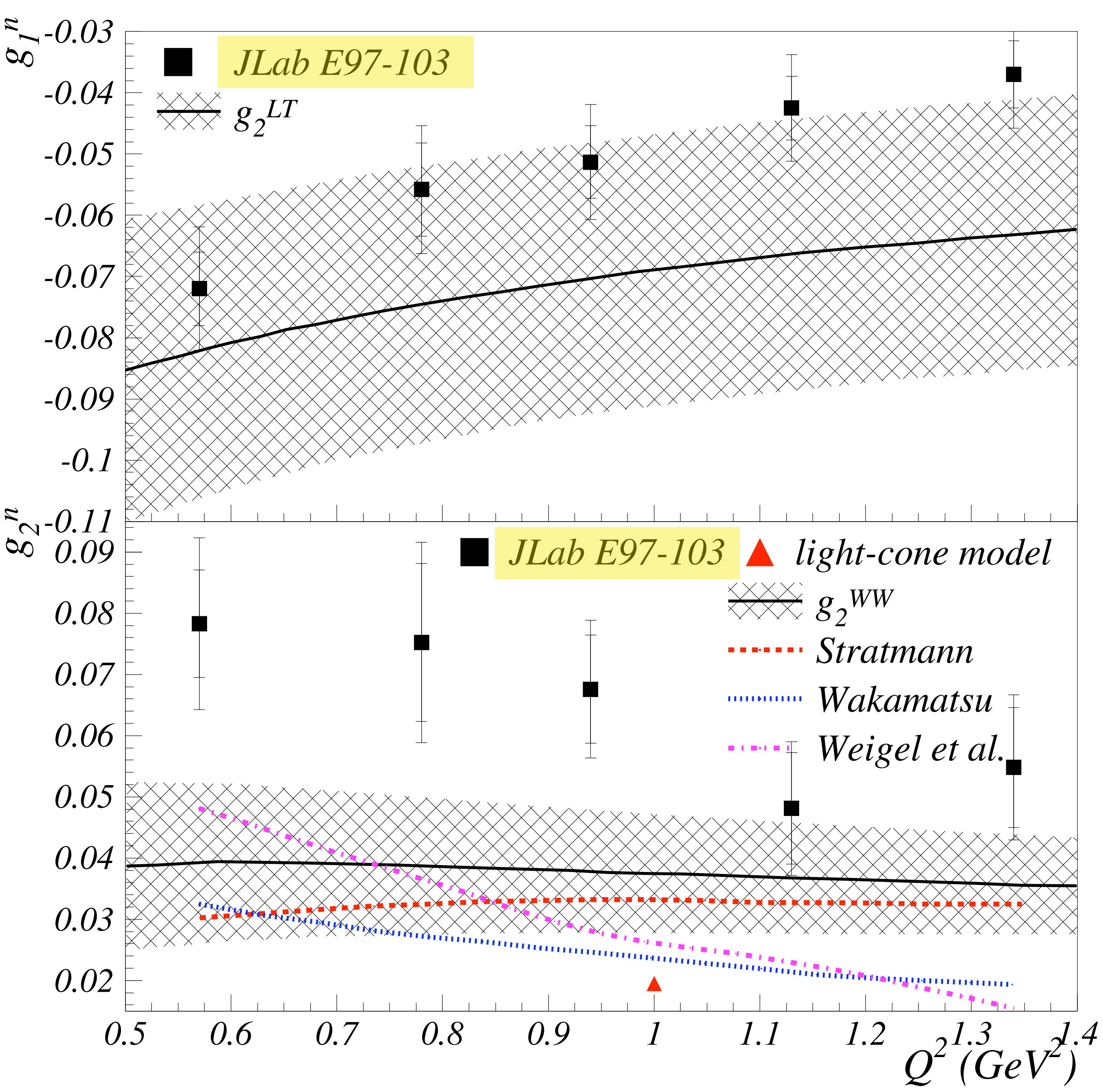


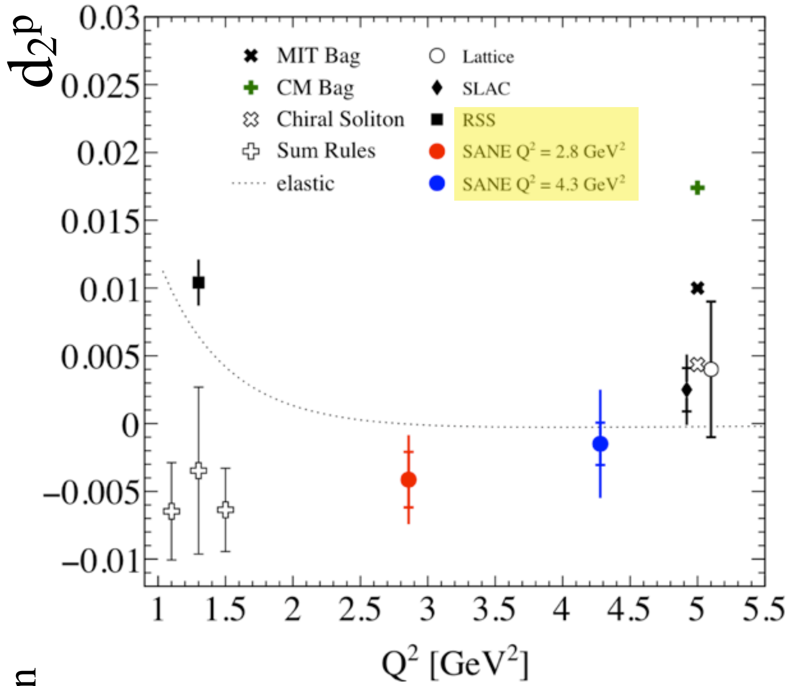
- Reduction of uncertainties in region $0.1 < x < 0.7$
- Impact on low-x uncertainties from imposing SU(3)$_f$ constraints
- JLab data prefers positive glue for $x > 0.1$
  → constrained via evolution
- Non-zero twist-3 quark distributions ; twist-4 consistent with zero

Jefferson Lab

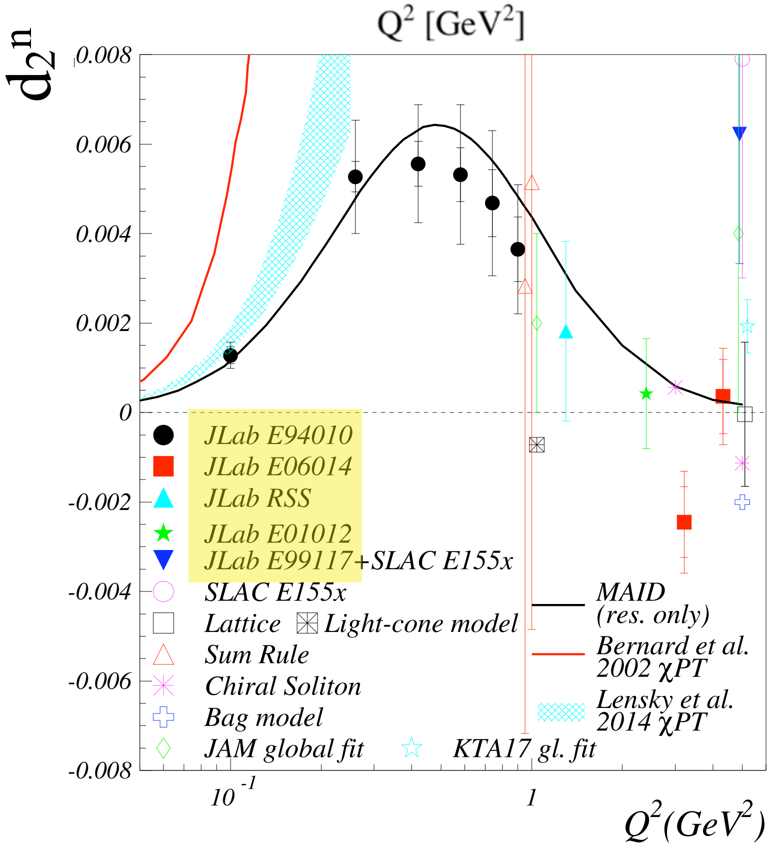
"Study transition from hadronic to partonic description of strong force"

Dedicated higher-twist measurements: Hall A E97-103, E01012, E06014, Hall C SANE





SANE results on arXiv last Thursday (arXiv:1805:08835)



Is the bridge between the hadronic and partonic banks built yet?

Hadrons
(low Q^2)

Partons
(High Q^2)

Is the bridge built?

- Precise mapping of the low and intermediate Q^2 regions.

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- Improved χpt (low Q^2) calculations;

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- Triggered improved perturbative techniques (high Q^2).
    - Analytic and Massive perturbation theories, Schwinger-Dyson equations:

Pasechnik, Soffer, Teryaev, Phys.Rev. D 82 076007 (2010)
Natale, Nucl.Phys.Proc.Suppl. 199 (2010) 178
Shirkov, Phys. Part. Nucl. Lett. 10 (2013) 186

Work motivated by
JLab's Bjorken
sum measurements

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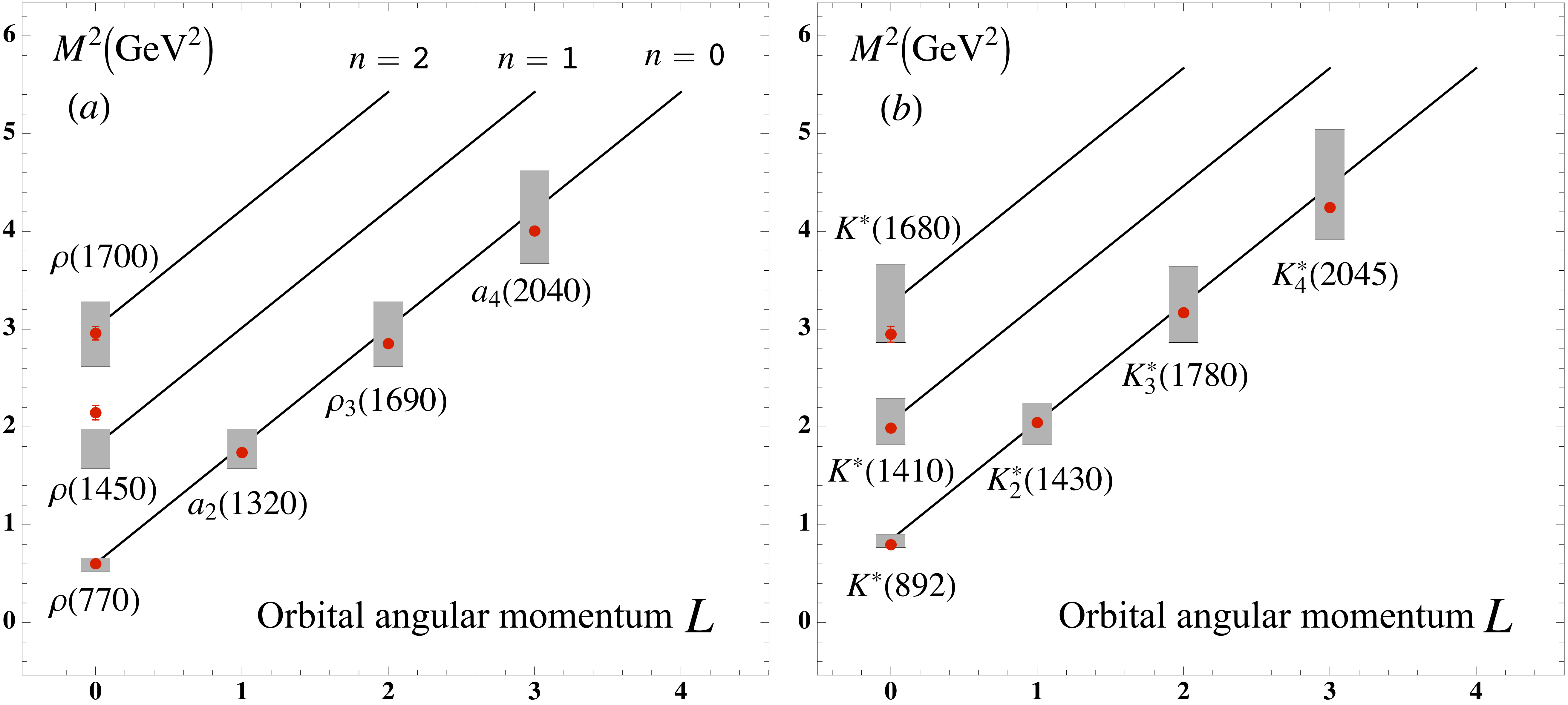
Work motivated by JLab's Bjorken sum measurements

- Jlab Bjorken sum data: AdS/QCD calculation of $\alpha_s(Q^2)$. Matching it to pQCD prediction allow to analytically determinate hadron spectrum from Λ_s


AD, Brodsky, de Teramond, Phys. Lett. B 750, 528 (2015)

▨ : AdS/QCD predictions with Λ_s from PDG as (only) input.

╱ : Slopes predicted by AdS/QCD.

● : Measurements.

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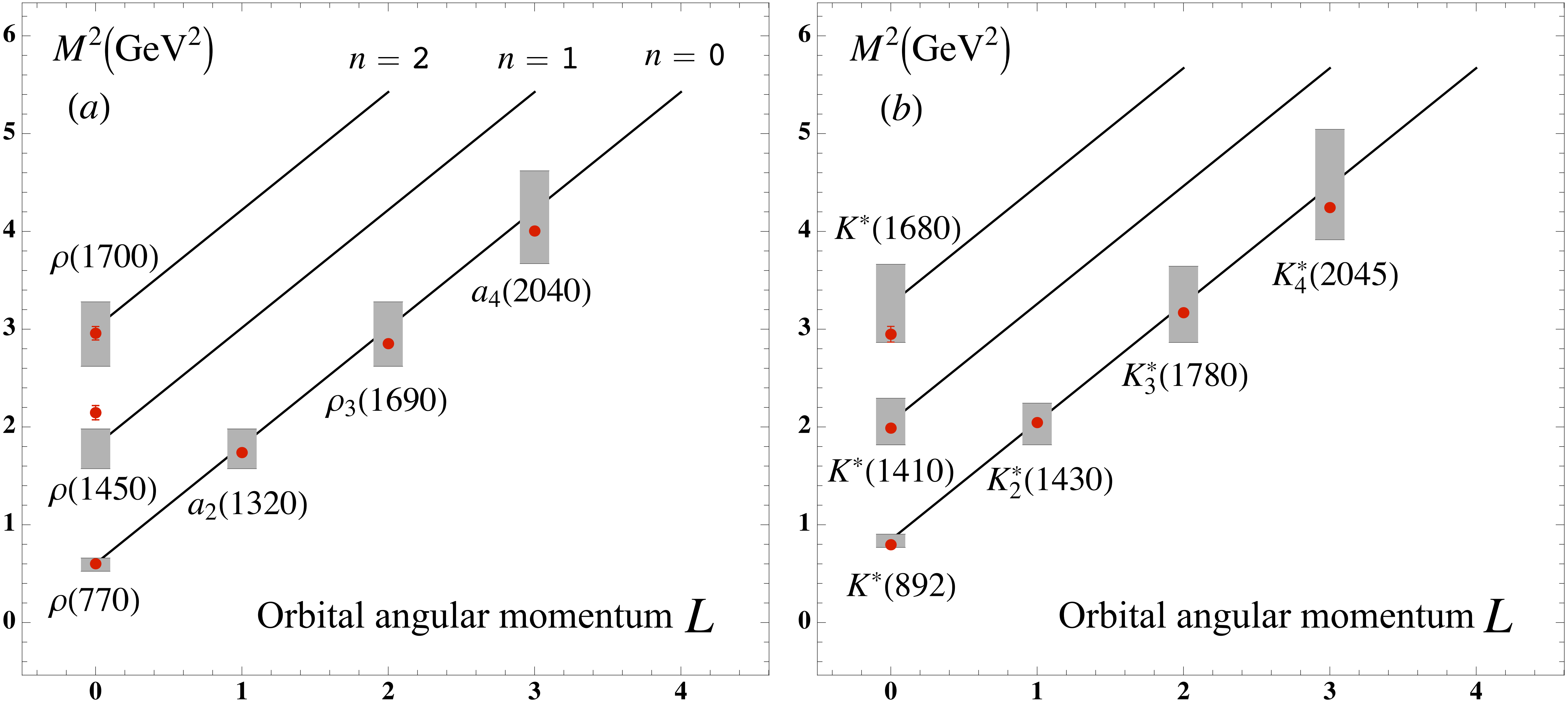

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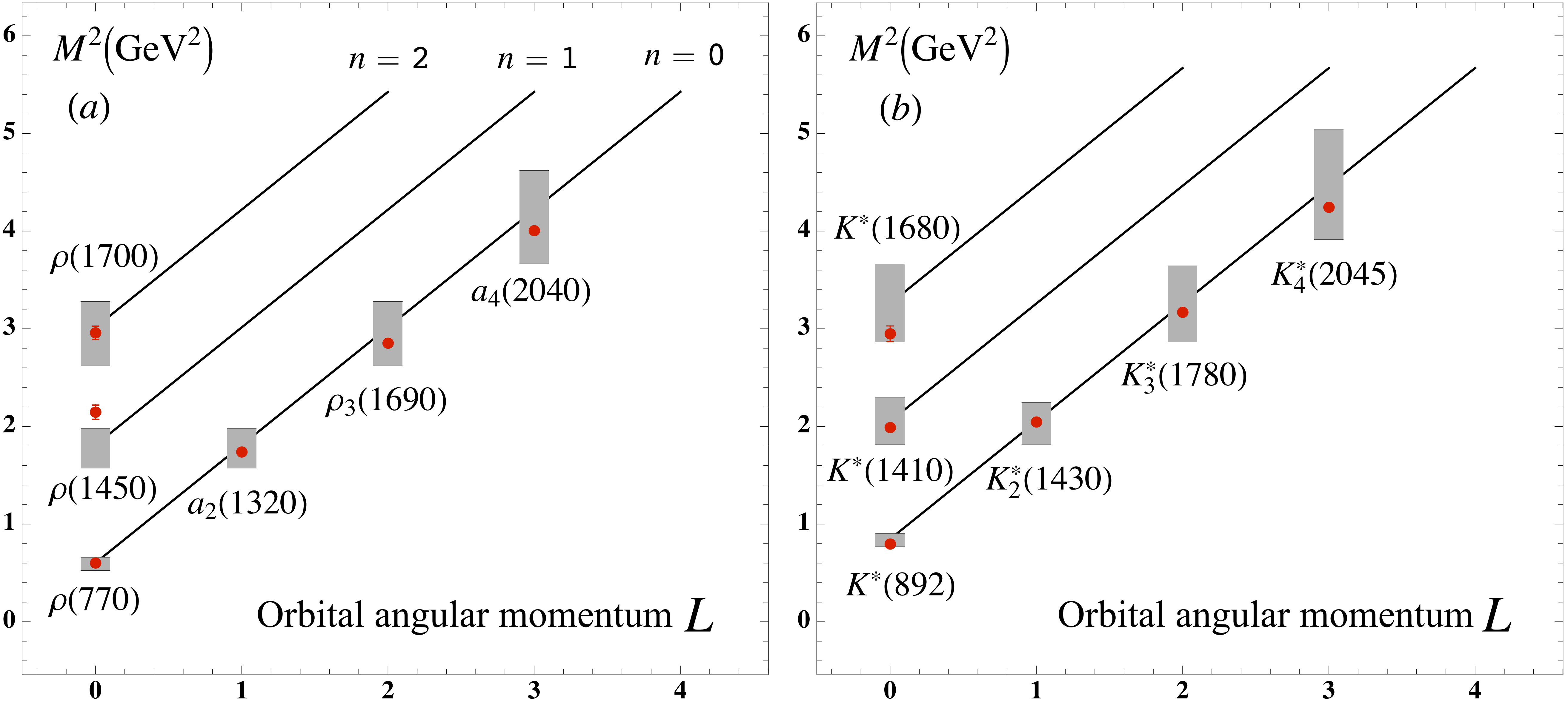
The analytic determination of hadron spectrum from Λ_s has been a long-thought goal of strong interaction studies.



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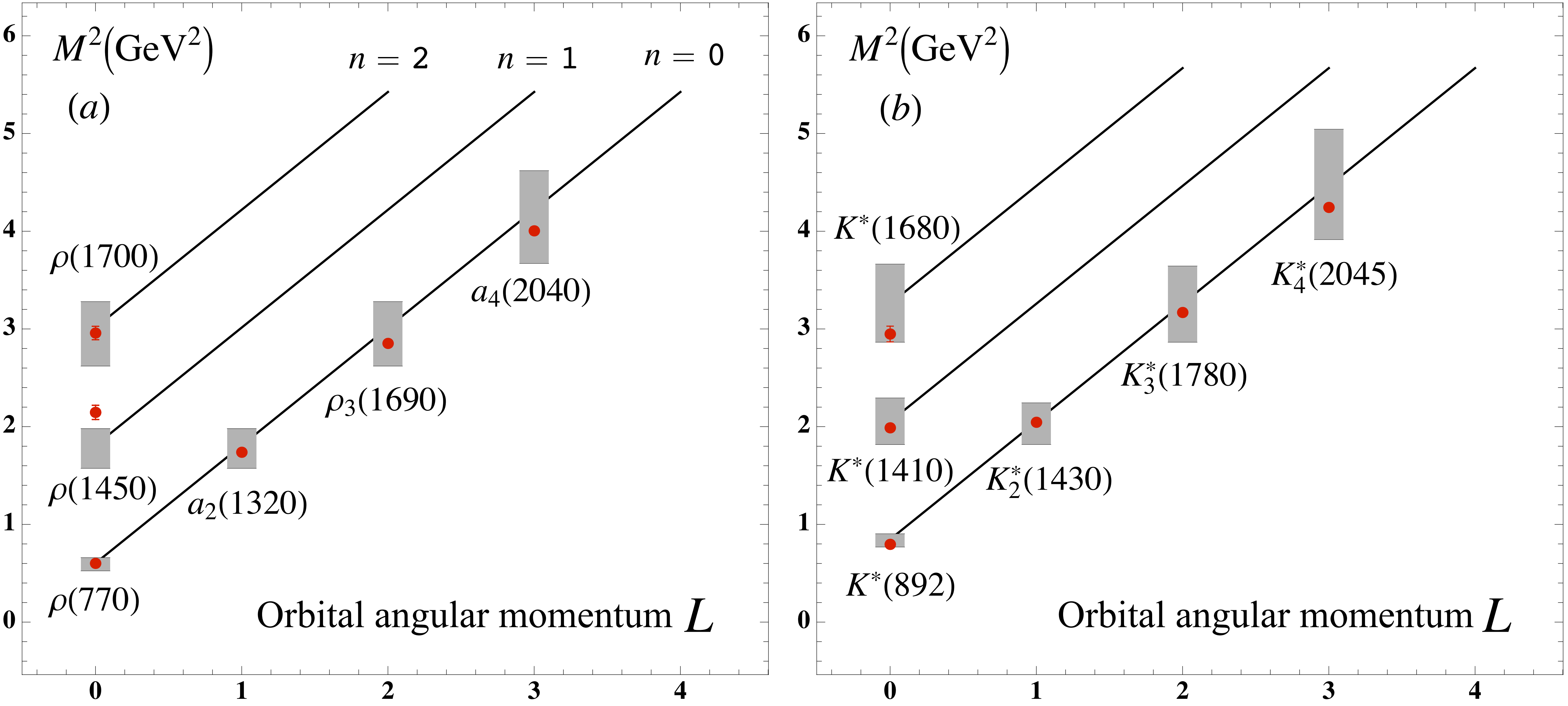

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AdS/QCD: Semi-classical approximation of QCD.)

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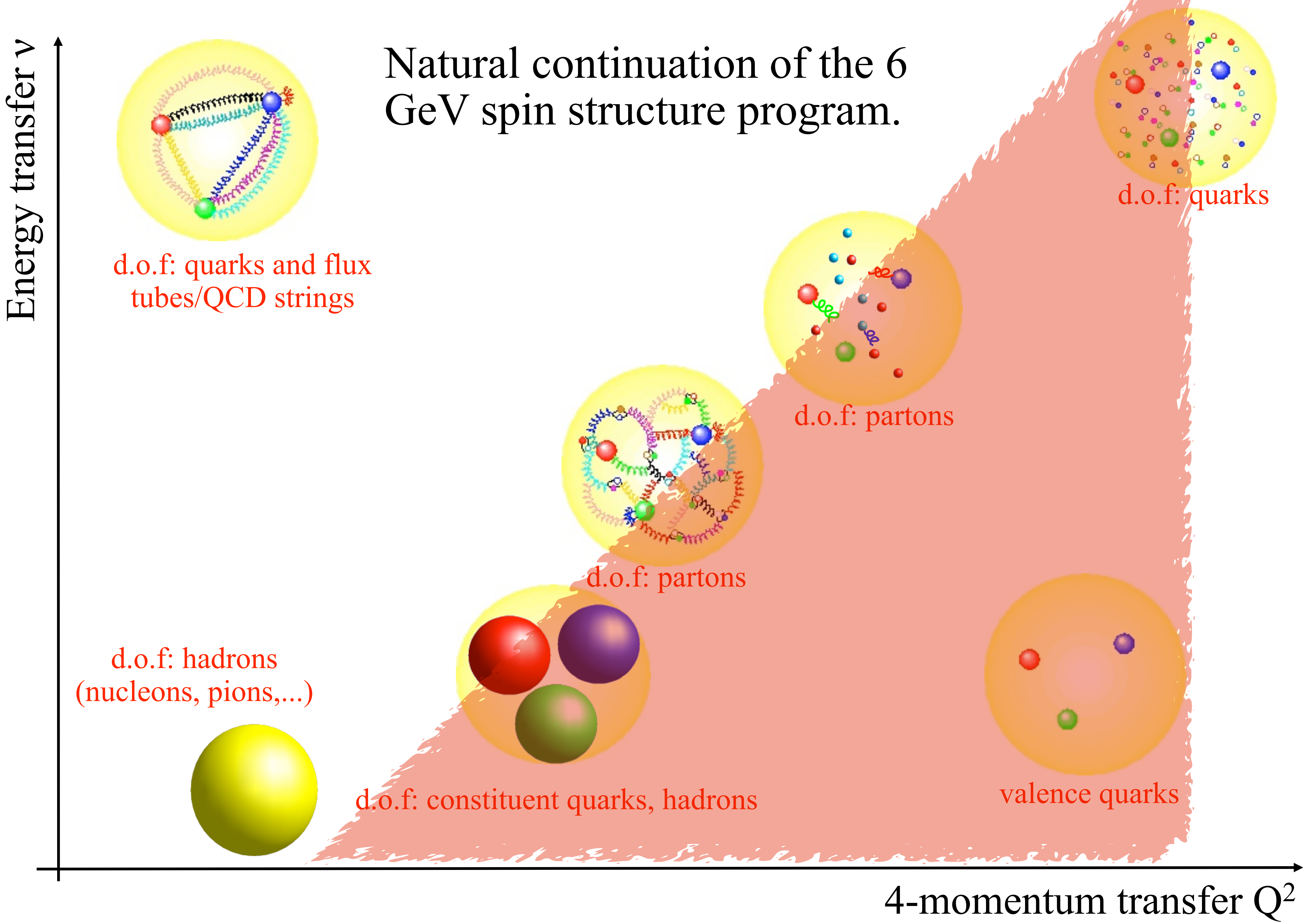
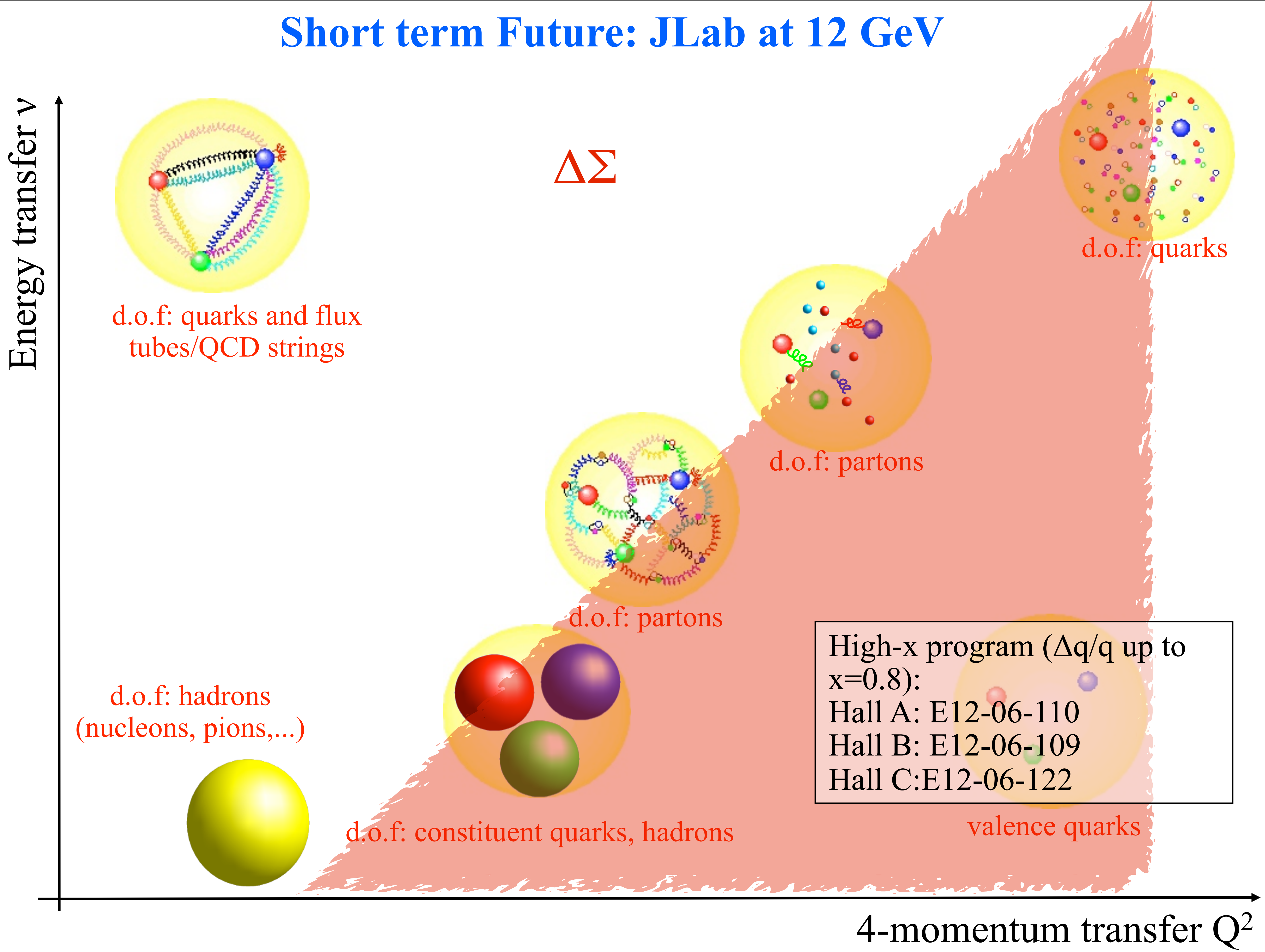
Short term Future: JLab at 12 GeV

Natural continuation of the 6 GeV spin structure program.



Short term Future: JLab at 12 GeV



Energy transfer ν

ΔΣ

d.o.f: quarks and flux tubes/QCD strings

d.o.f: quarks

d.o.f: partons

d.o.f: partons

d.o.f: hadrons (nucleons, pions,...)

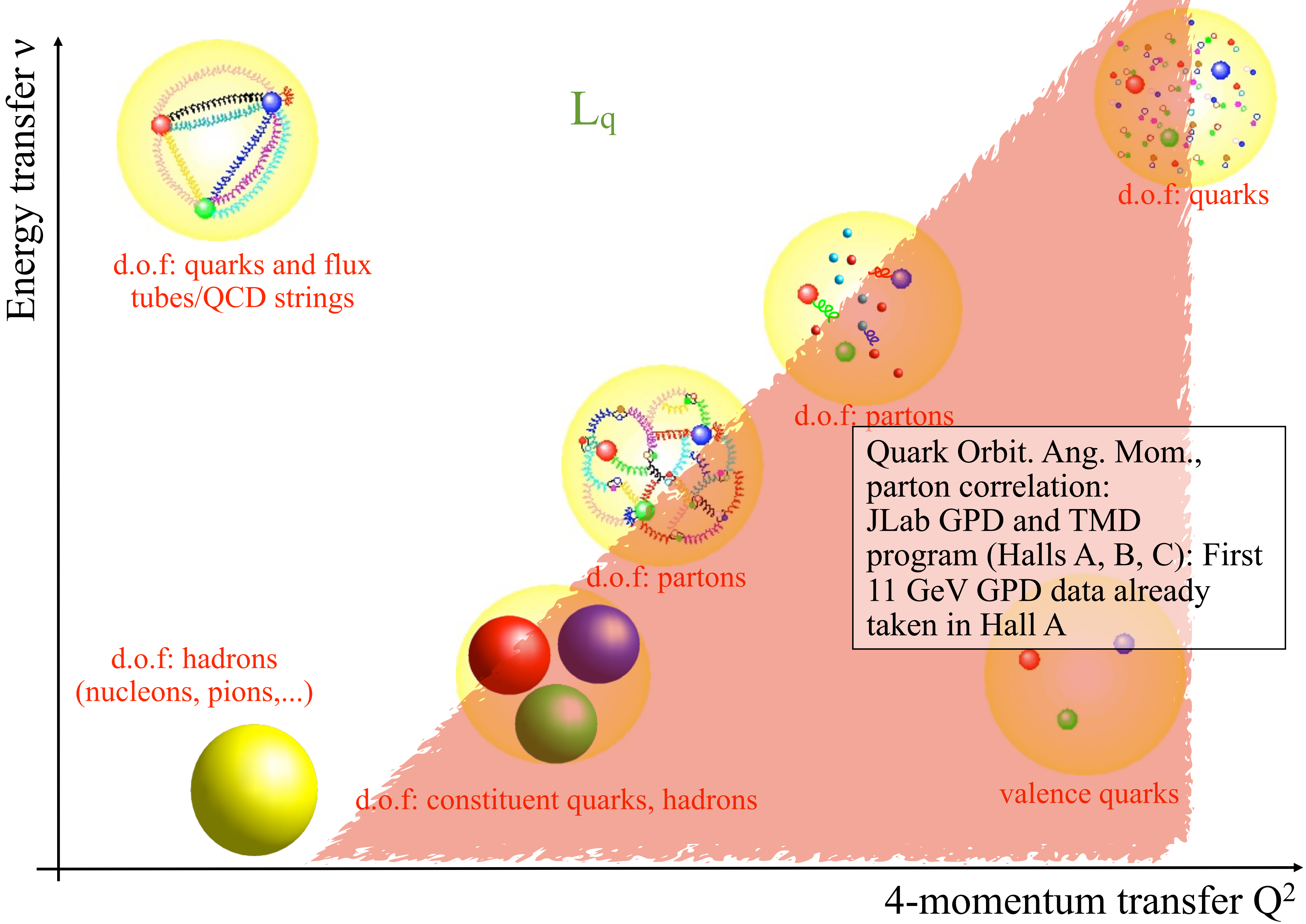
d.o.f: constituent quarks, hadrons

valence quarks

High-x program (Δq/q up to x=0.8):
Hall A: E12-06-110
Hall B: E12-06-109
Hall C:E12-06-122

4-momentum transfer Q^2

Short term Future: JLab at 12 GeV



Energy transfer ν

L_q

d.o.f: quarks and flux tubes/QCD strings

d.o.f: quarks

d.o.f: partons

d.o.f: partons

Quark Orbit. Ang. Mom., parton correlation: JLab GPD and TMD program (Halls A, B, C): First 11 GeV GPD data already taken in Hall A

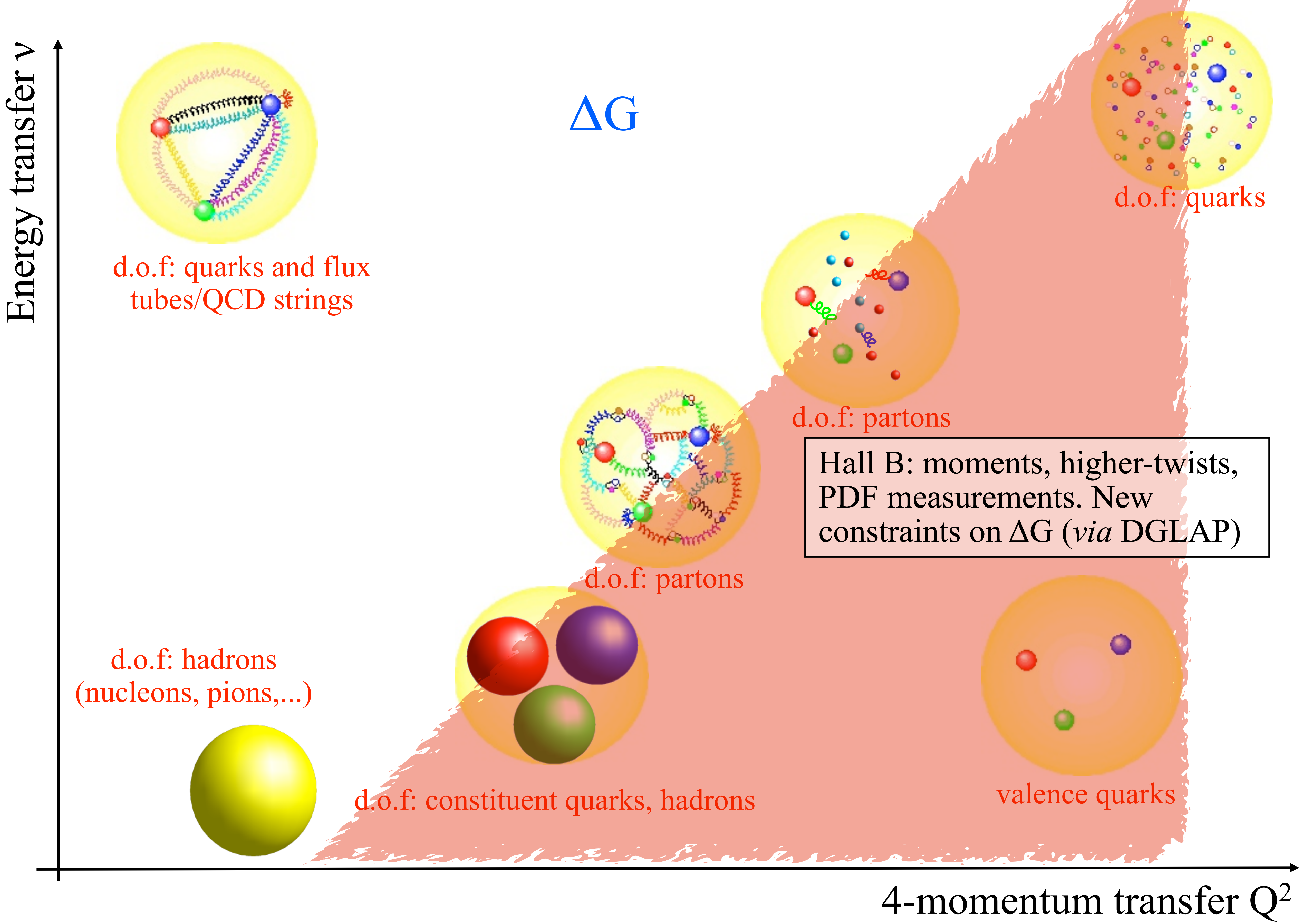
d.o.f: hadrons (nucleons, pions,...)

d.o.f: constituent quarks, hadrons

valence quarks

4-momentum transfer Q^2

Short term Future: JLab at 12 GeV



Energy transfer ν

4-momentum transfer Q^2

ΔG

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d.o.f: hadrons (nucleons, pions,...)

d.o.f: constituent quarks, hadrons

d.o.f: partons

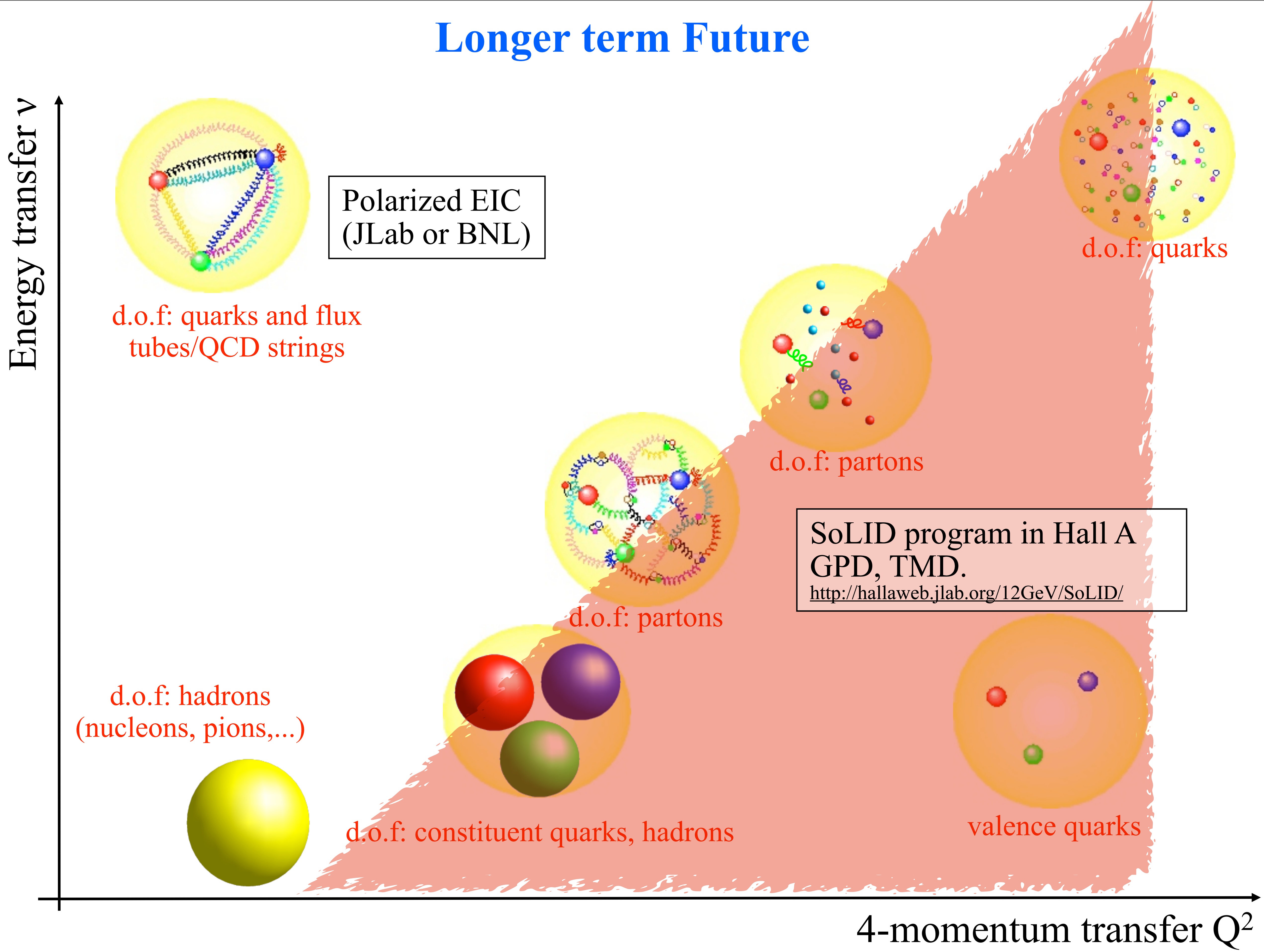
d.o.f: partons

d.o.f: quarks

valence quarks

Hall B: moments, higher-twists, PDF measurements. New constraints on ΔG (*via* DGLAP)

Longer term Future



Energy transfer ν

4-momentum transfer Q^2

Polarized EIC
(JLab or BNL)

d.o.f: quarks and flux
tubes/QCD strings

d.o.f: quarks

d.o.f: partons

d.o.f: partons

SoLID program in Hall A
GPD, TMD.
http://hallaweb.jlab.org/12GeV/SoLID/

d.o.f: hadrons
(nucleons, pions,...)

d.o.f: constituent quarks, hadrons

valence quarks

Thank You!