Nucleon spin structure studies at Jefferson Lab

A. Deur
Thomas Jefferson National Accelerator Facility

Many reasons to study the nucleon spin structure:

* Interesting: $S_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + (\Delta G + L_G) + L_q$.

* More complete study of fundamental theory (QCD);

  * mechanism of confinement;

  * how effective degrees of freedom (hadrons) emerge from fundamental ones (quark and gluons);

  * Test non-perturbative methods (χpt, Lattice, SDE, AdS/CFT,...). Nuclear structure.

* Useful PDFs for high energy or atomic physics.

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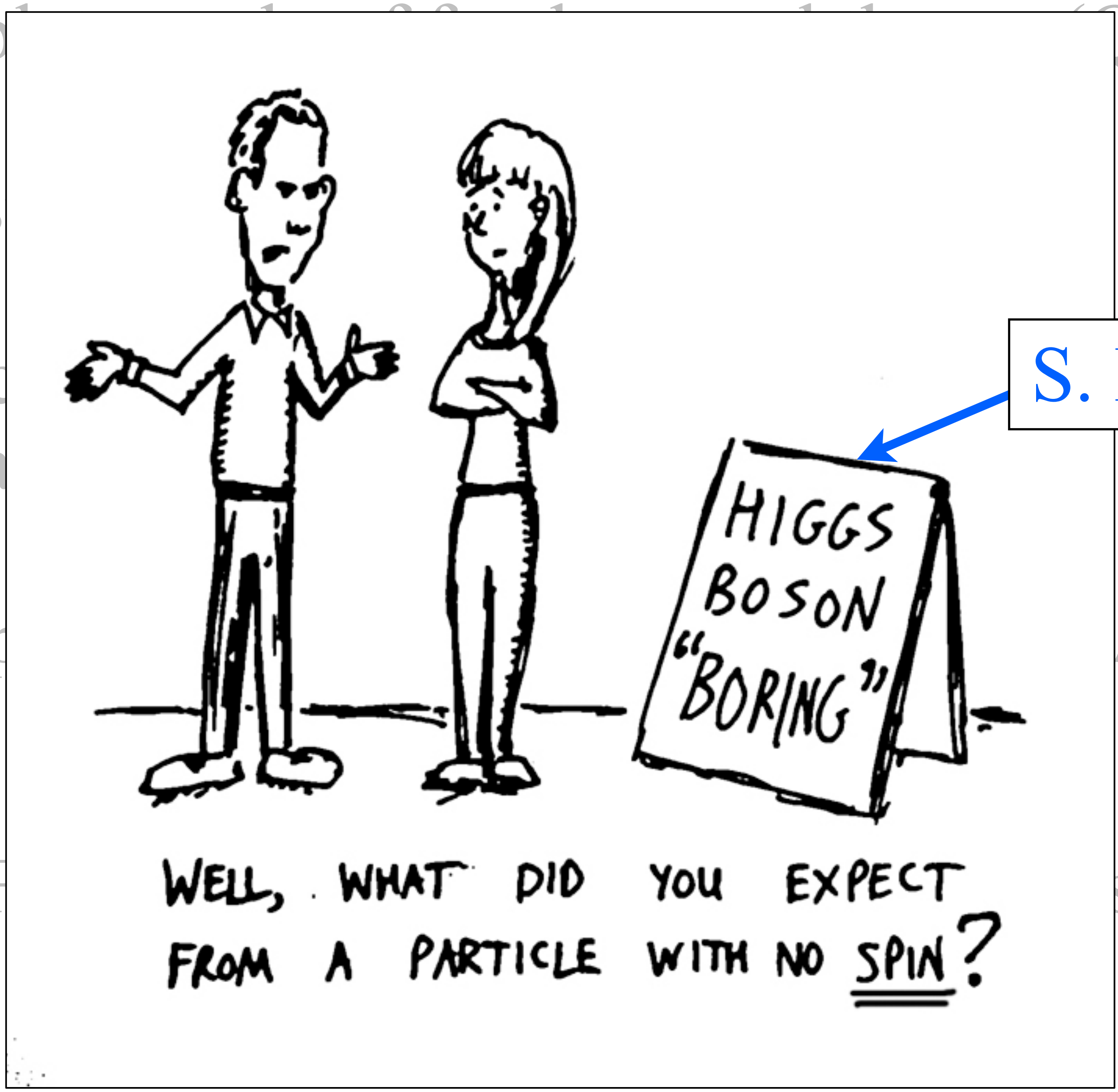

S. Hawking

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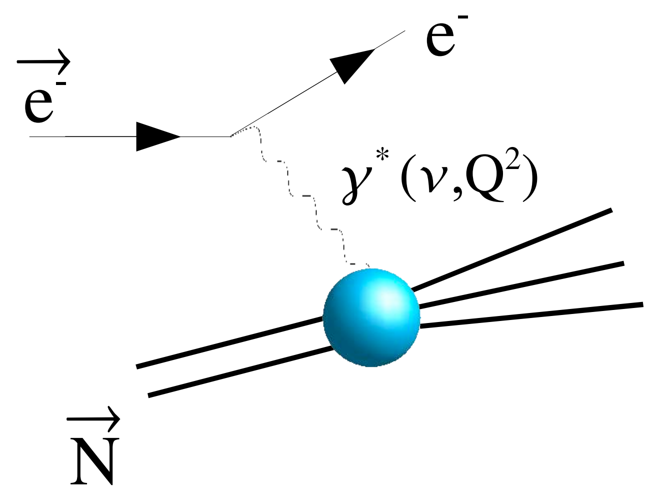
* Useful PDF

Plenary talk Wednesday by V. Burkert:
Nucleon spin studies at JLab

Next talk by W. Armstrong:
Jlab SANE experiment

Plenary talk Friday by K. Slifer:
nucleon spin at low Q^2 at JLab
Talk by C. Peng in next session:
GDH sum rule neutron and ^{3}He at low Q^2 at JLab

Inclusive polarized lepton scattering



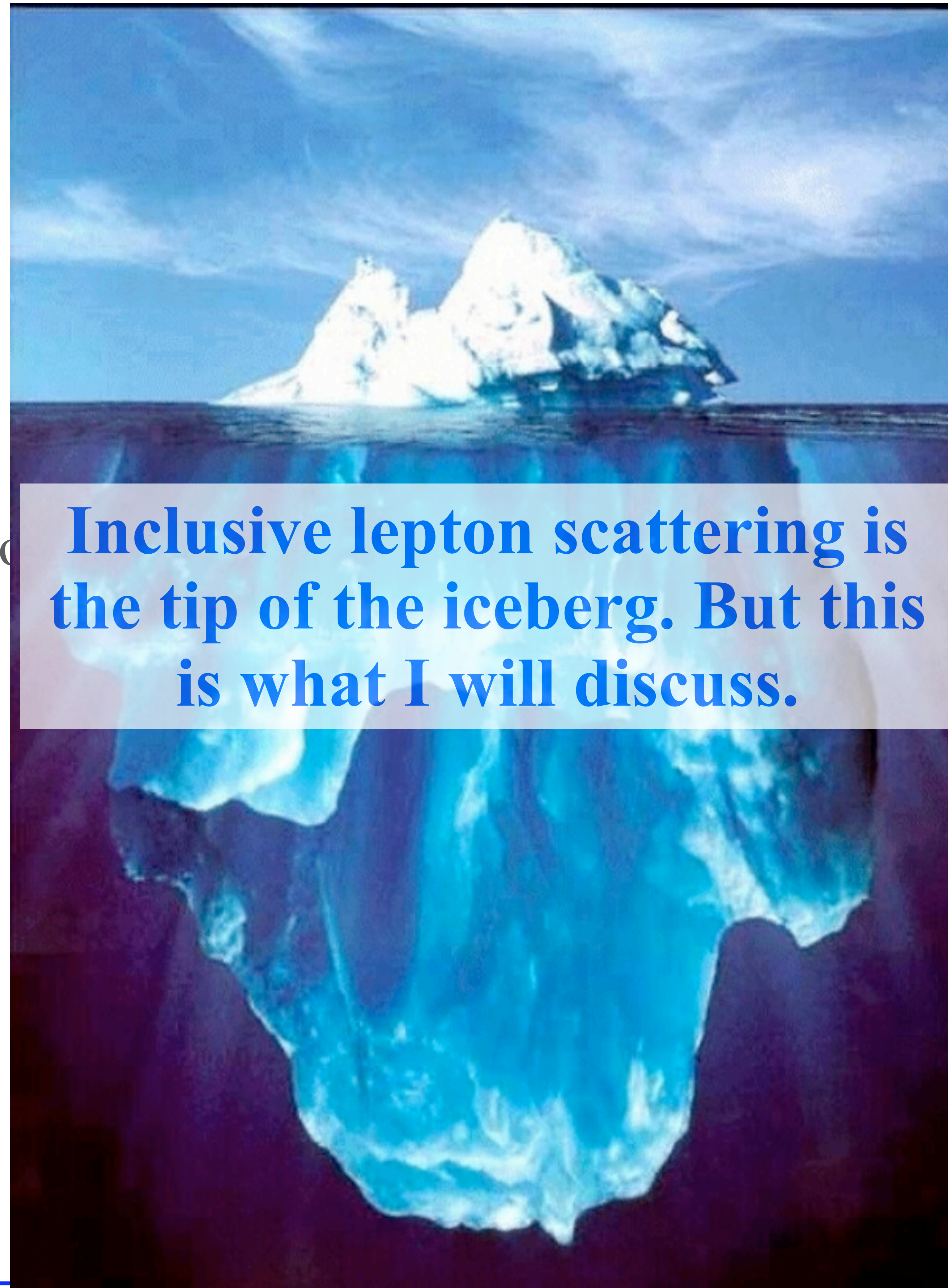
$$\text{cross section} = [\text{cross section}_{\text{pointlike object}}] \times [\alpha F_1(x,Q^2) + \beta F_2(x,Q^2) + (\gamma g_1(x,Q^2) + \delta g_2(x,Q^2))]$$

⇧ ⇧ ⇧ ⇧

unpolarized polarized

Inclusive polarized lepton scattering

cross section=[cr … $\gamma g_1(x,Q^2)+\delta g_2(x,Q^2))]$



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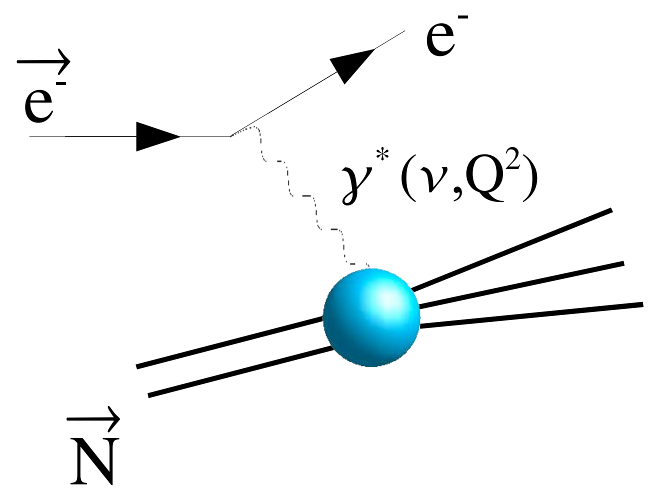
polarized

Inclusive polarized lepton scattering



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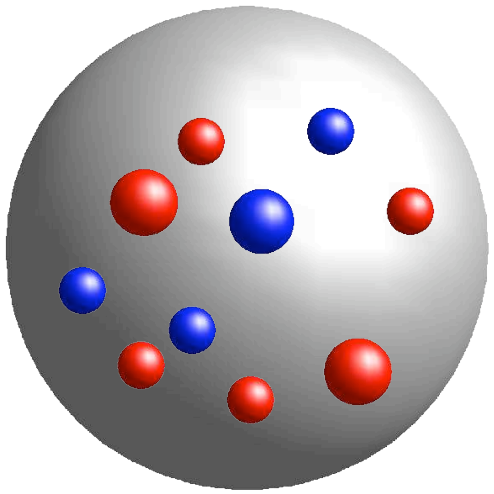
⇧ ⇧ ⇧ ⇧

unpolarized polarized

In the Bjorken limit ($Q^2 \to \infty$, Q^2/ν finite), $F_{1,2}$ are constructed from **quark densities**:



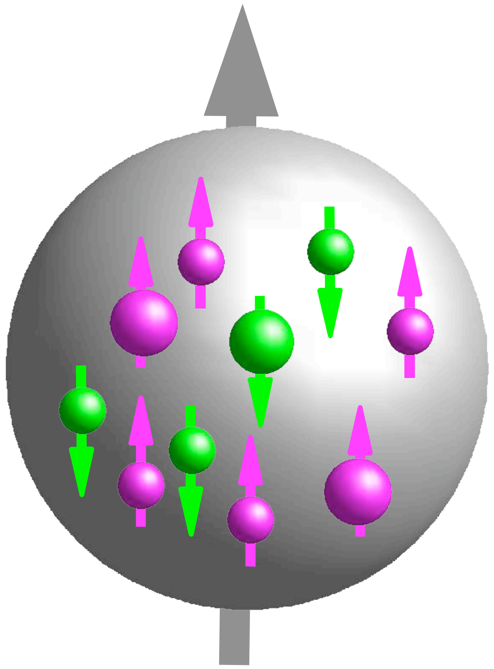
- $u(x) \propto$ amount of up quarks with momentum x in the nucleon.
- $d(x) \propto$ amount of down quarks with momentum x in the nucleon.
- $s(x) \propto$ amount of strange quarks...
- $\bar{u}(x)$ and $\bar{d}(x) \propto$ amount of anti-quarks

$$F_1(x) = \frac{4}{9}[u(x)+\bar{u}(x)] + \frac{1}{9}[d(x)+\bar{d}(x)] + \ldots$$

$$F_2(x) = 2xF_1(x)$$

In the Bjorken limit, g_1 is constructed from **quark polarizations**

$Q^2 \to \infty$
Q^2/ν finite

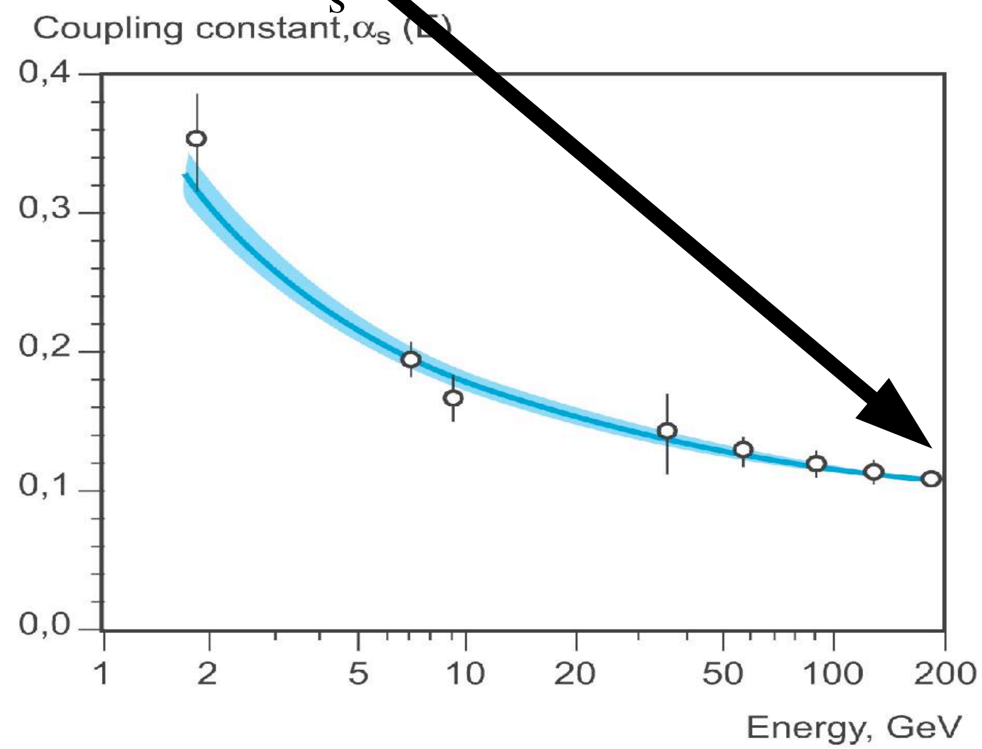


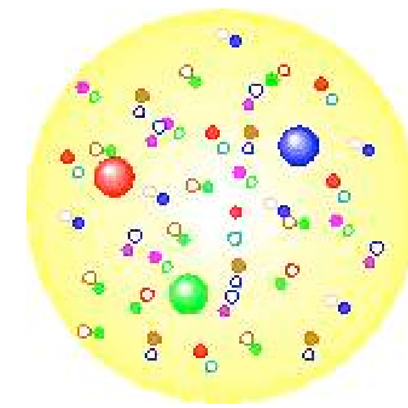
$\Delta q(x) \propto$ (quarks with spin parallel to nucleon spin - quarks with spin antiparallel to nucleon spin)

$$g_1(x)=\frac{4}{9}[\Delta u(x)+\Delta\bar{u}(x)]+\frac{1}{9}[\Delta d(x)+\Delta\bar{d}(x)]+\ldots$$

$$g_2(x)=0$$

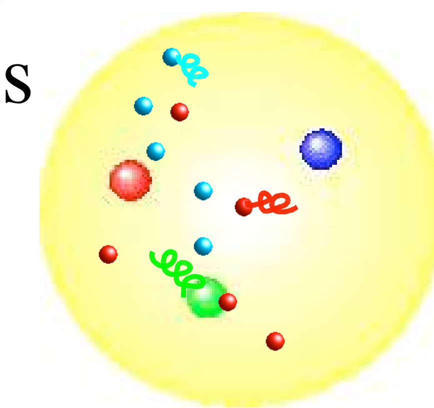
All this is valid at $Q^2 \to \infty$ only where $\alpha_s = 0$ (quarks are free).





At finite (but still large) Q^2:

- quarks start to interact: gluon corrections
- $M^2/Q^2 \neq 0$: Mass corrections



$$F_1(x,Q^2)=\frac{4}{9}[u(x,Q^2)+\bar{u}(x,Q^2)]+\frac{1}{9}[d(x,Q^2)+\bar{d}(x,Q^2)]+... \quad ; \quad F_2 \neq 2xF_1$$

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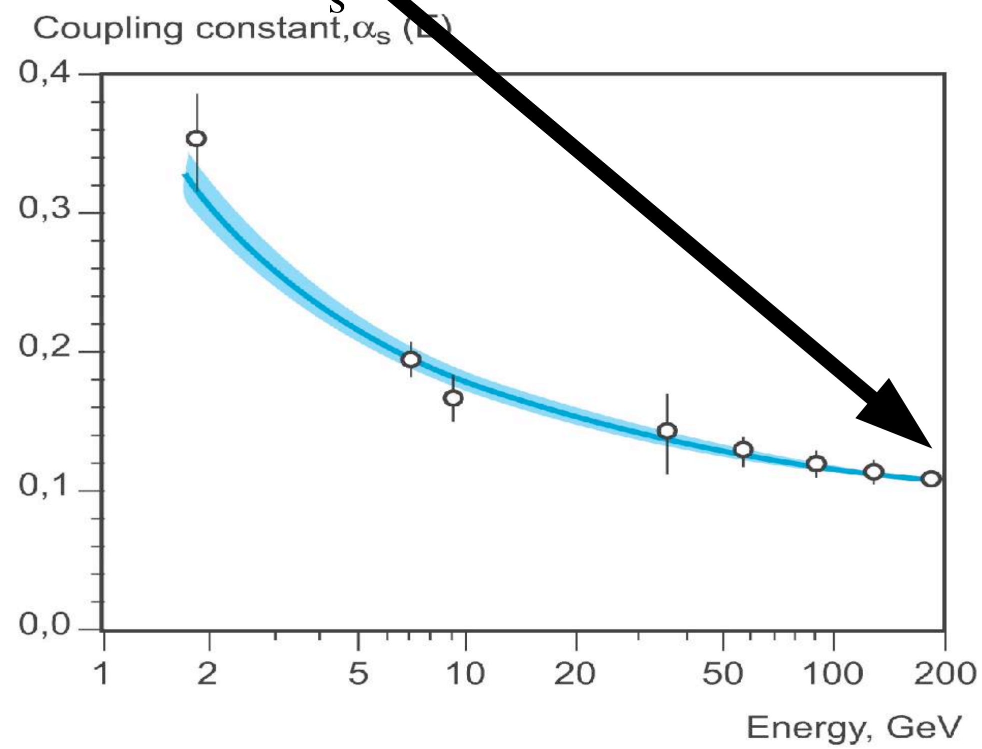
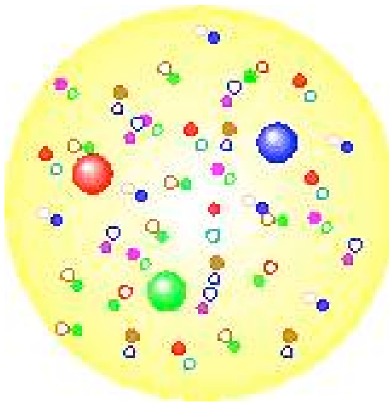
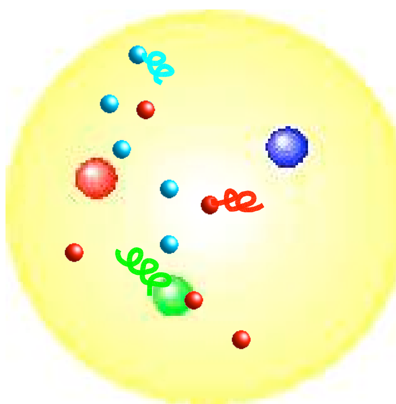




At finite (but still large) Q^2:

Bjorken scaling violations:
- quarks start to interact: gluon corrections
- $M^2/Q^2 \neq 0$: Mass corrections



$$F_1(x,Q^2) = \frac{4}{9}[u(x,Q^2) + \bar{u}(x,Q^2)] + \frac{1}{9}[d(x,Q^2) + \bar{d}(x,Q^2)] + \ldots \quad ; \quad F_2 \neq 2xF_1$$

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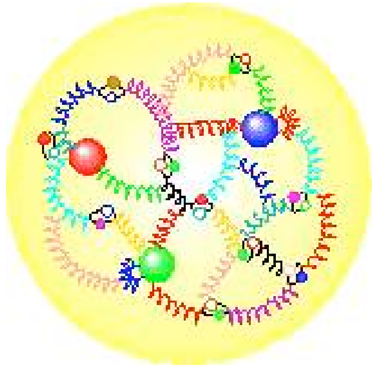
At smaller Q^2 (~GeV^2): correlations between quarks: *higher twists*



$$F_1 \neq \frac{4}{9}\left[u(x,Q^2)+\bar{u}(x,Q^2)\right]+\frac{1}{9}\left[d(x,Q^2)+\bar{d}(x,Q^2)\right]+\ldots \quad ; \quad F_2 \neq 2xF_1$$

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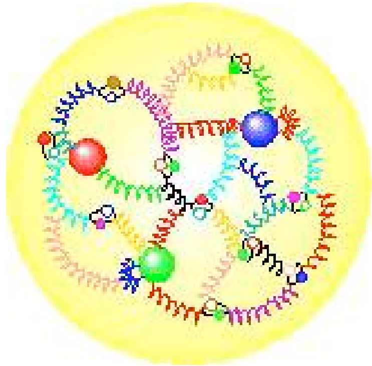

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Higher-twist: transverse confining force. M. Burkardt, PRD 88, 114502 (2013)

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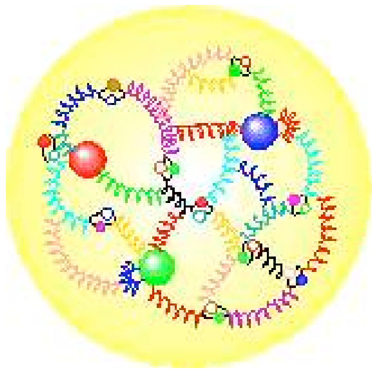

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Higher-twist: transverse confining force. M. Burkardt, PRD 88, 114502 (2013)

Jlab

- Hall A E97-103, E99-117, E06-014. Hall C RSS HT from $g_2^{n,p}$ and moments. X. Zheng *et al.*, PRC 70, 065207 (2004); K. Kramer *et al.*, PRL 95, 142002 (2005); M. Posik *et al.*, PRL 13, 022002 (2014); K. Slifer *et al.*, PRL 105, 101601 (2010)
- Hall A E94-010: HT for $\int g_1^n dx$. Z.-E. Meziani *et al.*, PLB 613, 148 (2005)
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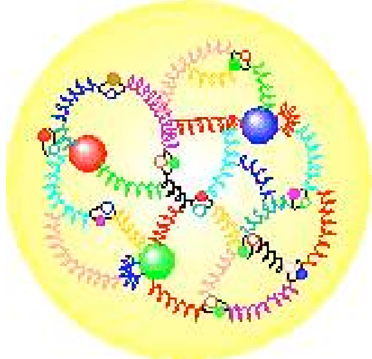
At smaller Q^2 ($\sim$GeV^2): correlations between quarks: *higher twists*



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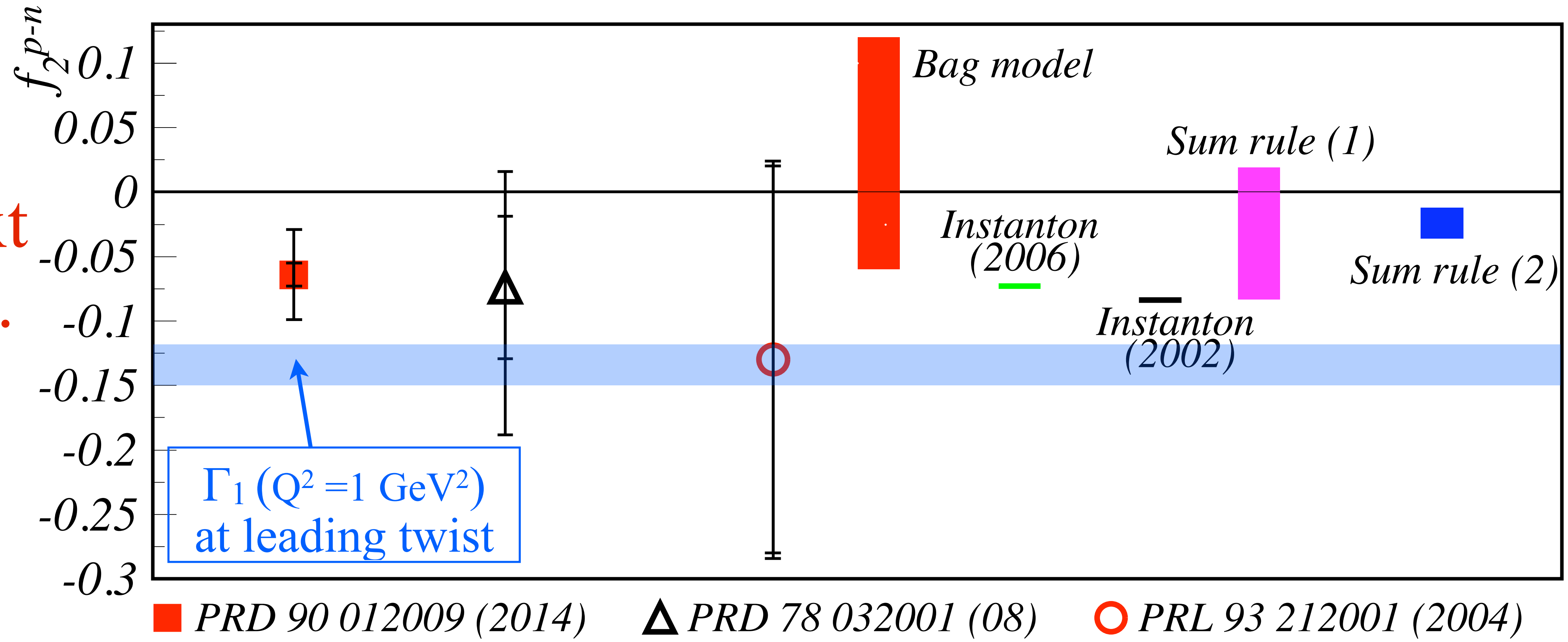
Next talk by W. Armstrong:
SANE experiment

HT for Bjorken sum $\Gamma_1^{p\text{-}n} \equiv \int g_1^{p\text{-}n} dx$

Twist-4 f_2: Next to leading twist.
Extraction at $Q^2 = 1$ GeV^2.



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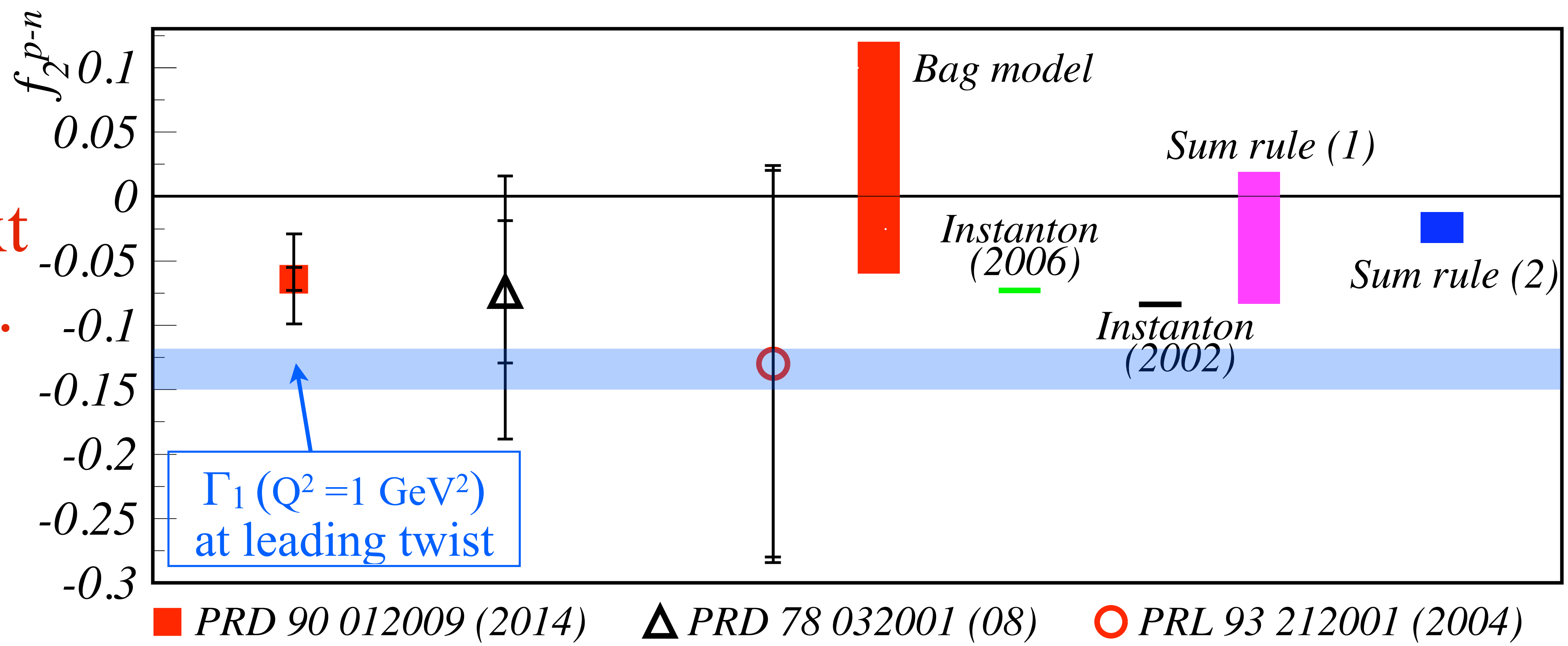

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What are the effects of higher twists?
Practical connection to confinement?
To discuss that, need to talk first about sum rules.

Sum Rules

A **sum rule** is a *rule* (e.g. "=") that relates a *sum* (e.g. moment of structure functions) to a quantity characterizing the target particle.

Gerasimov-Drell-Hearn (GDH) sum rule:

Originally derived for $Q^2=0$, later generalized to $Q^2>0$.

Gerasimov, Drell, Hearn and others. Ji and Osborne

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

spin-dep. DDVCS (S_1)

Bjorken scaling variable (x)

First spin structure function (g_1)

See talk by C. Peng in next session.

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g_1: First spin structure function

x: Bjorken scaling variable

S_1: spin-dep. DDVCS

Bjorken sum rule

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

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GDH(proton)-GDH(neutron) $\propto Q^2 \times$ Bjorken Sum

Other sum rules

A **sum rule** is a *rule* (e.g. "=") that relates a *sum* (e.g. moment of structure functions) to a quantity characterizing the target particle.

Burkhardt-Cottingham:

$$\Gamma_2 \equiv \int g_2(x,Q^2)dx=0$$

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

Generalized forward spin polarizability:

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

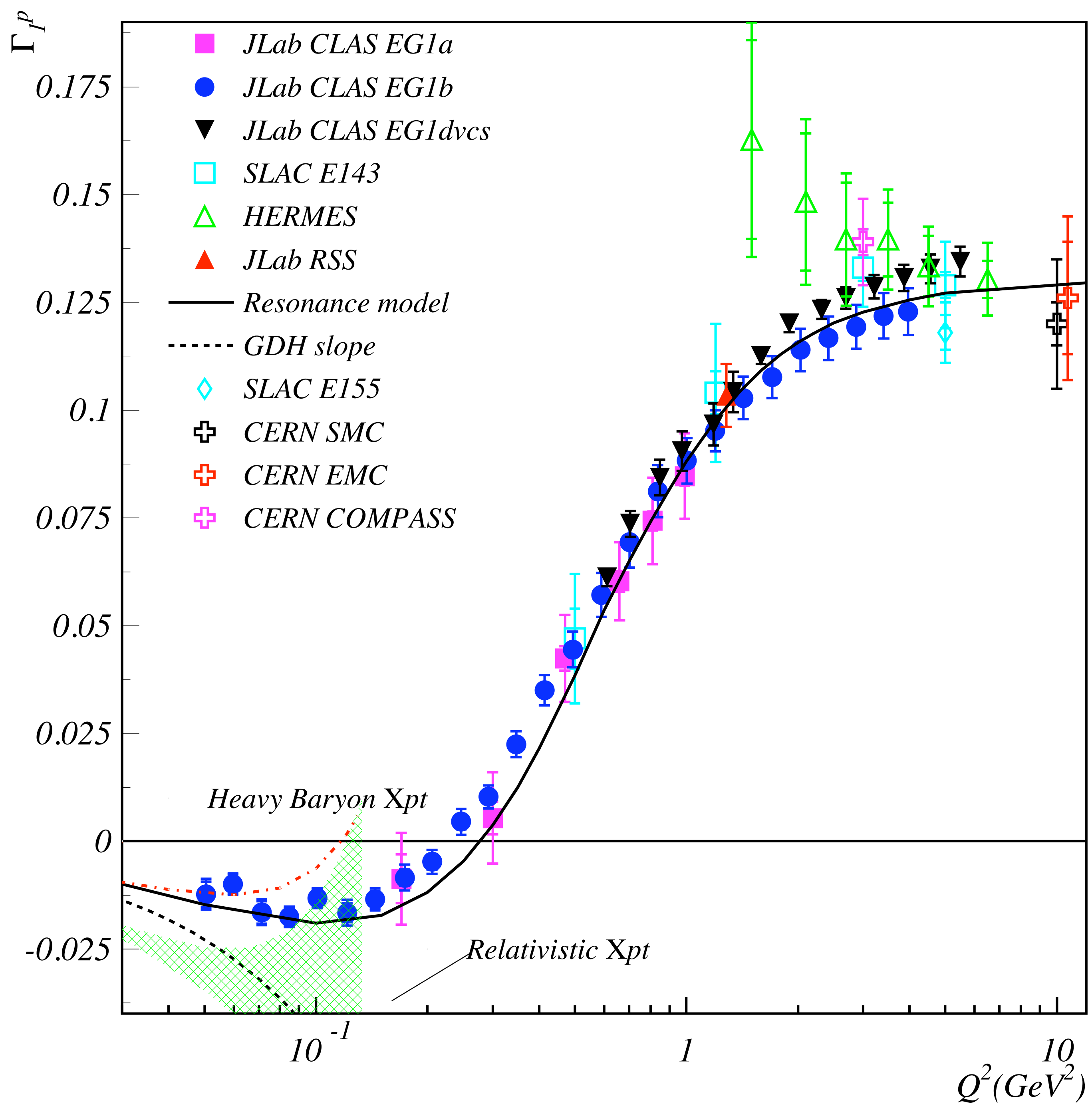
Longitudinal-Transverse polarizability:

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

See talks by C. Peng in next session, and by K. Slifer Friday.

Existing data

$\Gamma_1 \equiv \int g_1 dx$
on **proton**

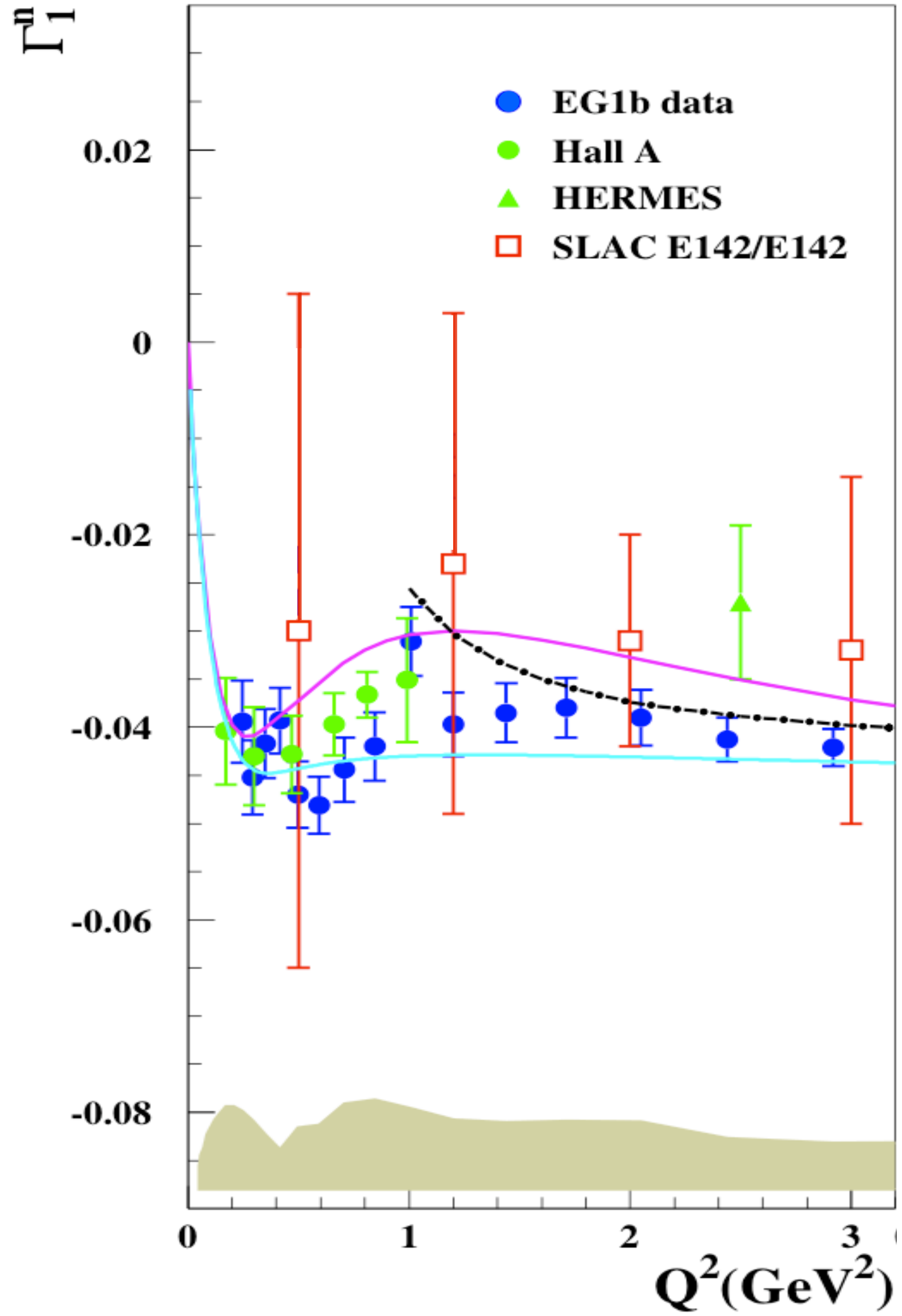


EG1dvcs: Y. Prok *et al.* PRC 90, 025212 (2014)

EG1b: full data set: Fersch et al. (preliminary)

Existing data

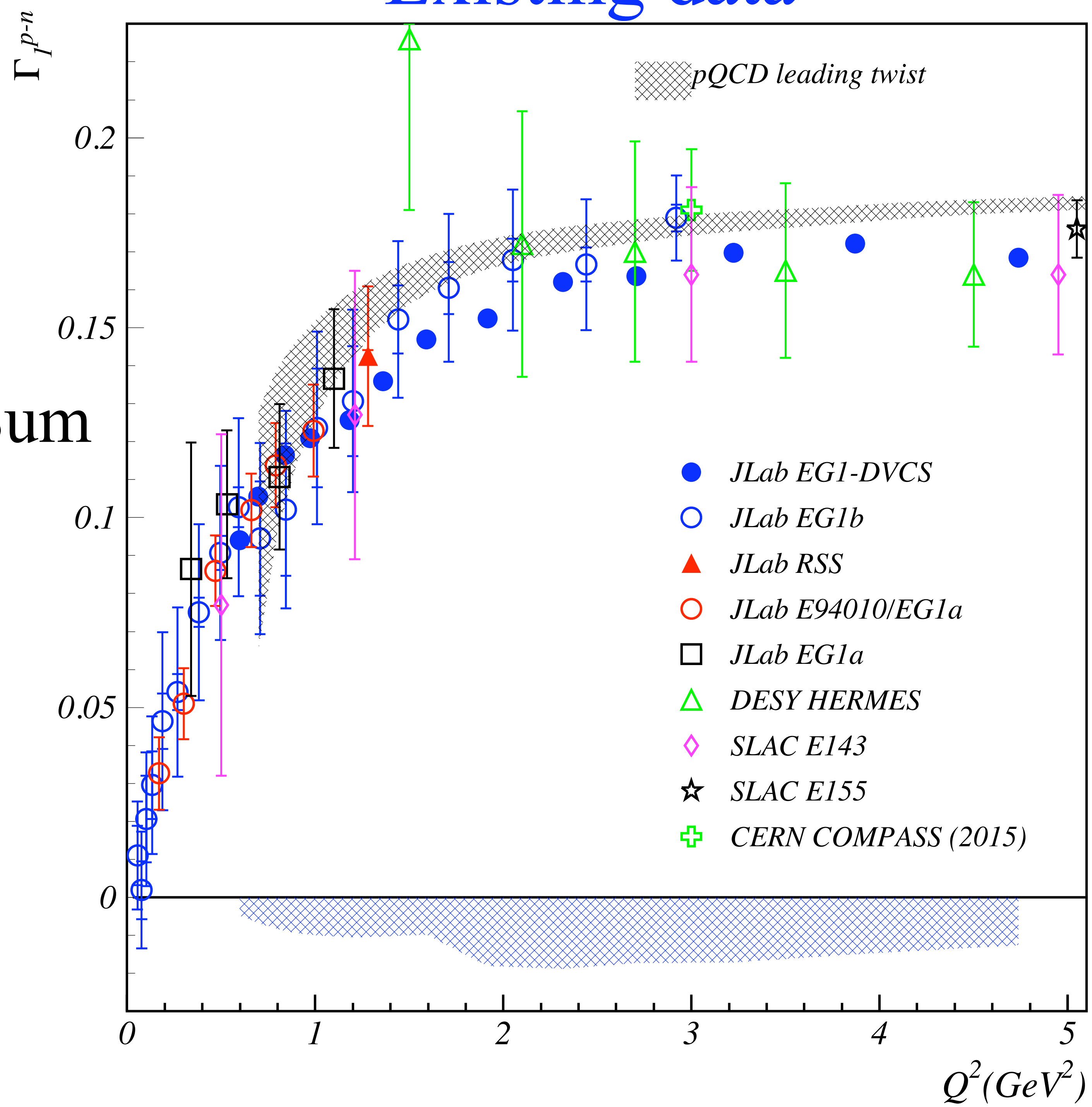
$\Gamma_1 \equiv \int g_1 dx$
on **neutron**



N. Guler *et al.*
PRC 92, 055201 (2015)

Existing data

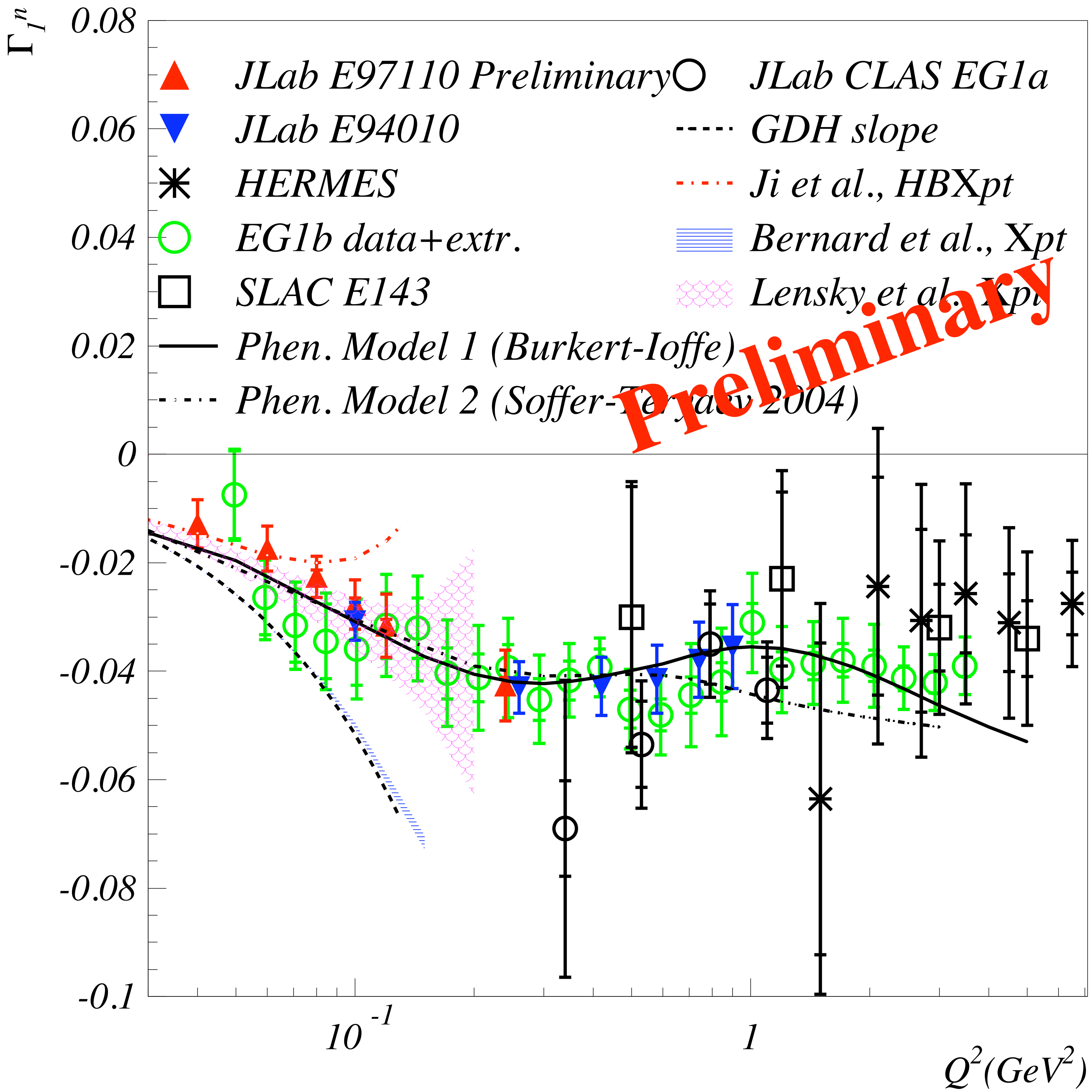
Γ_1^{p-n}:Bjorken Sum



EG1dvcs: A. Deur *et al.*
PRD 90, 012009 (2014)

Preliminary results on ∫g₁ dx

$\Gamma_1 \equiv \int g_1\, dx$ on **neutron** from Hall A E97110



Remaining tasks before publication:
Finalize radiative corrections (almost done). Finalize neutron information extraction.

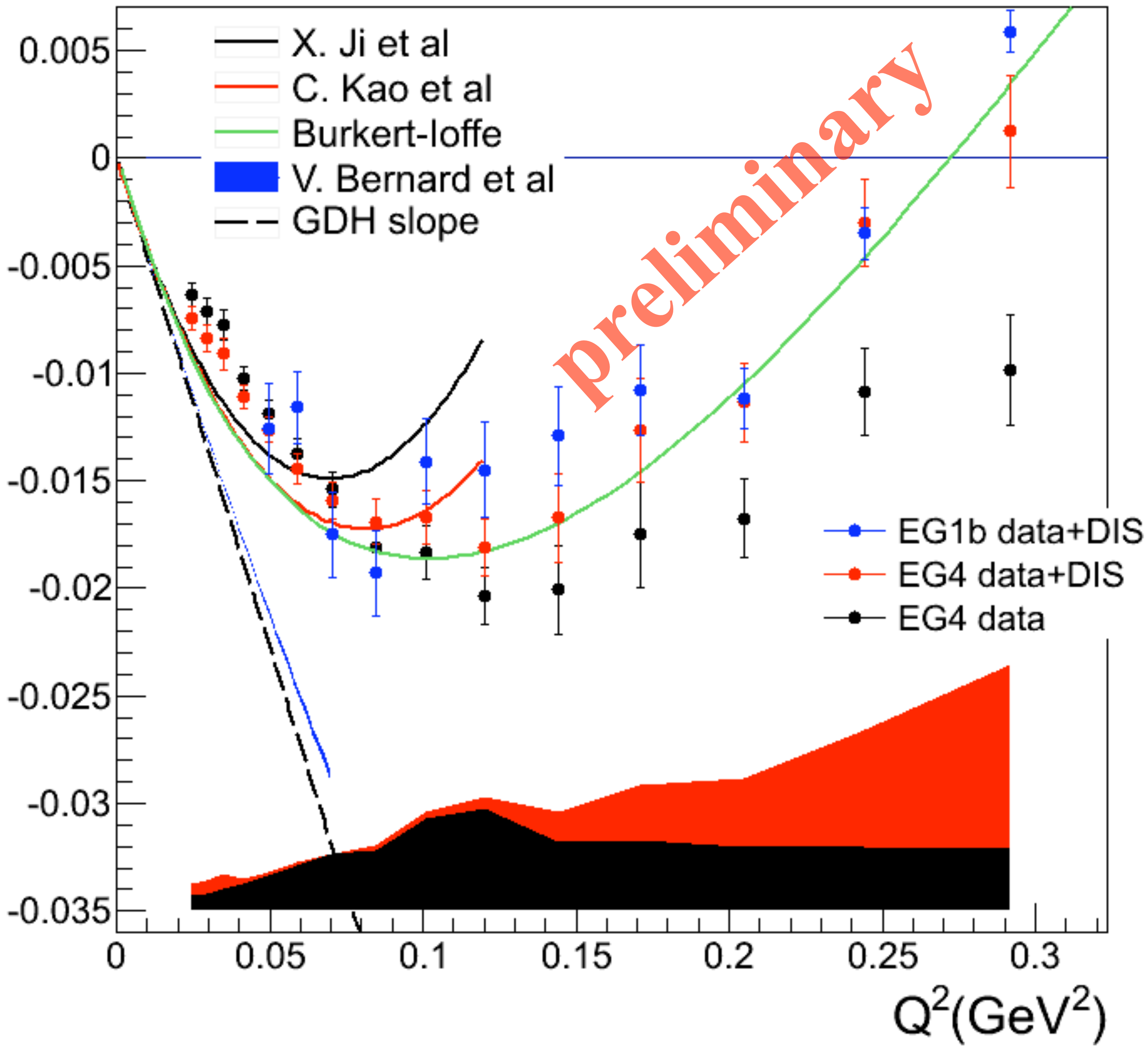
V. Sulkosky, UVa & C. Peng, Duke U..

For next publication:
Analyze the lowest Q^2 points (on-going. N. Ton, UVa).

From V. Sulkosky (UVa)

Preliminary results on $\int g_1\, dx$

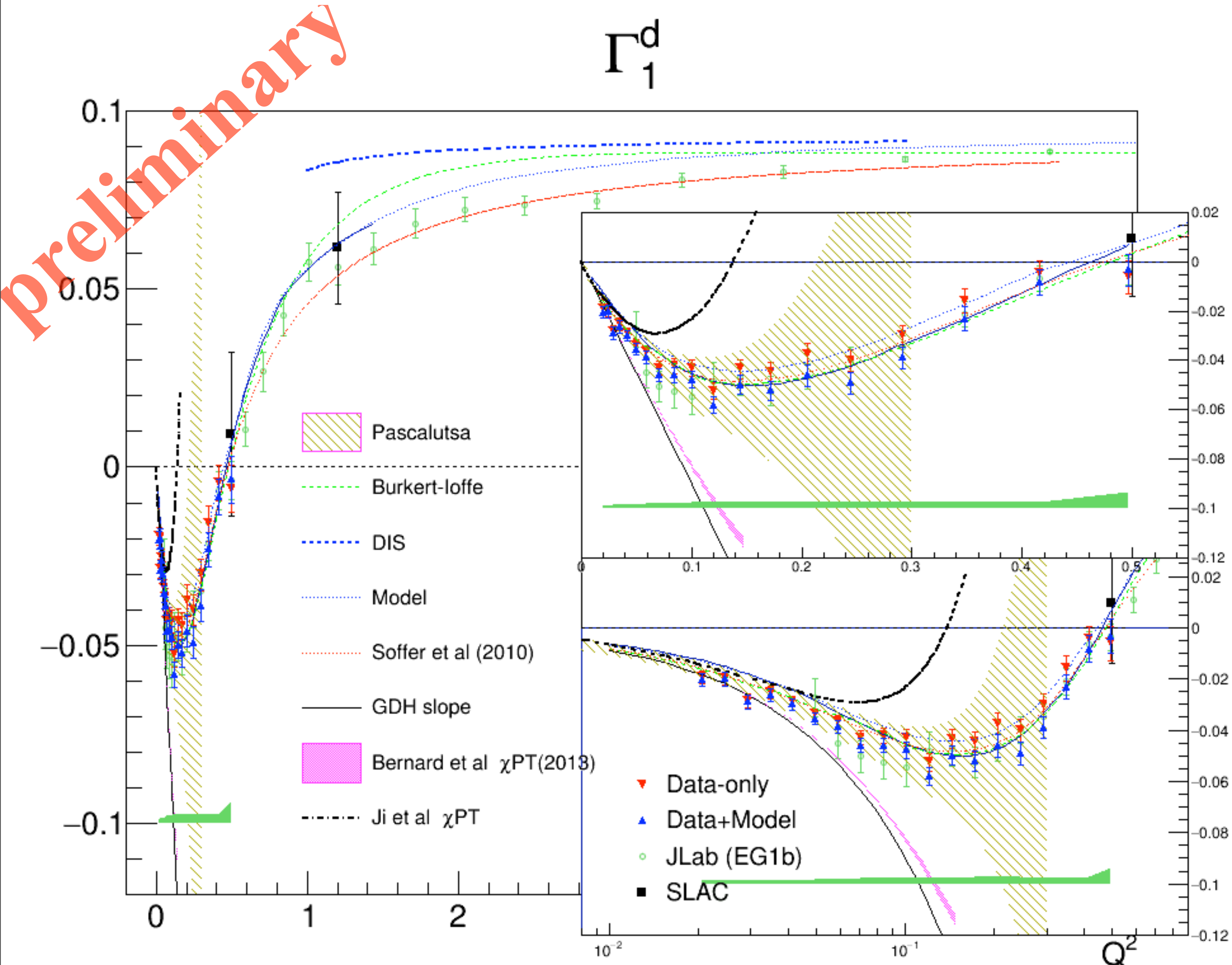
$\Gamma_1 \equiv \int g_1\, dx$ on **proton** from Hall B EG4



From H. Kang
(Seoul U.)

Preliminary results on $\int g_1\, dx$

$\Gamma_1 \equiv \int g_1\, dx$ on **deuteron** from Hall B EG4



From K. Adhikari (ODU, MSU)

What do we learn from these measurements?

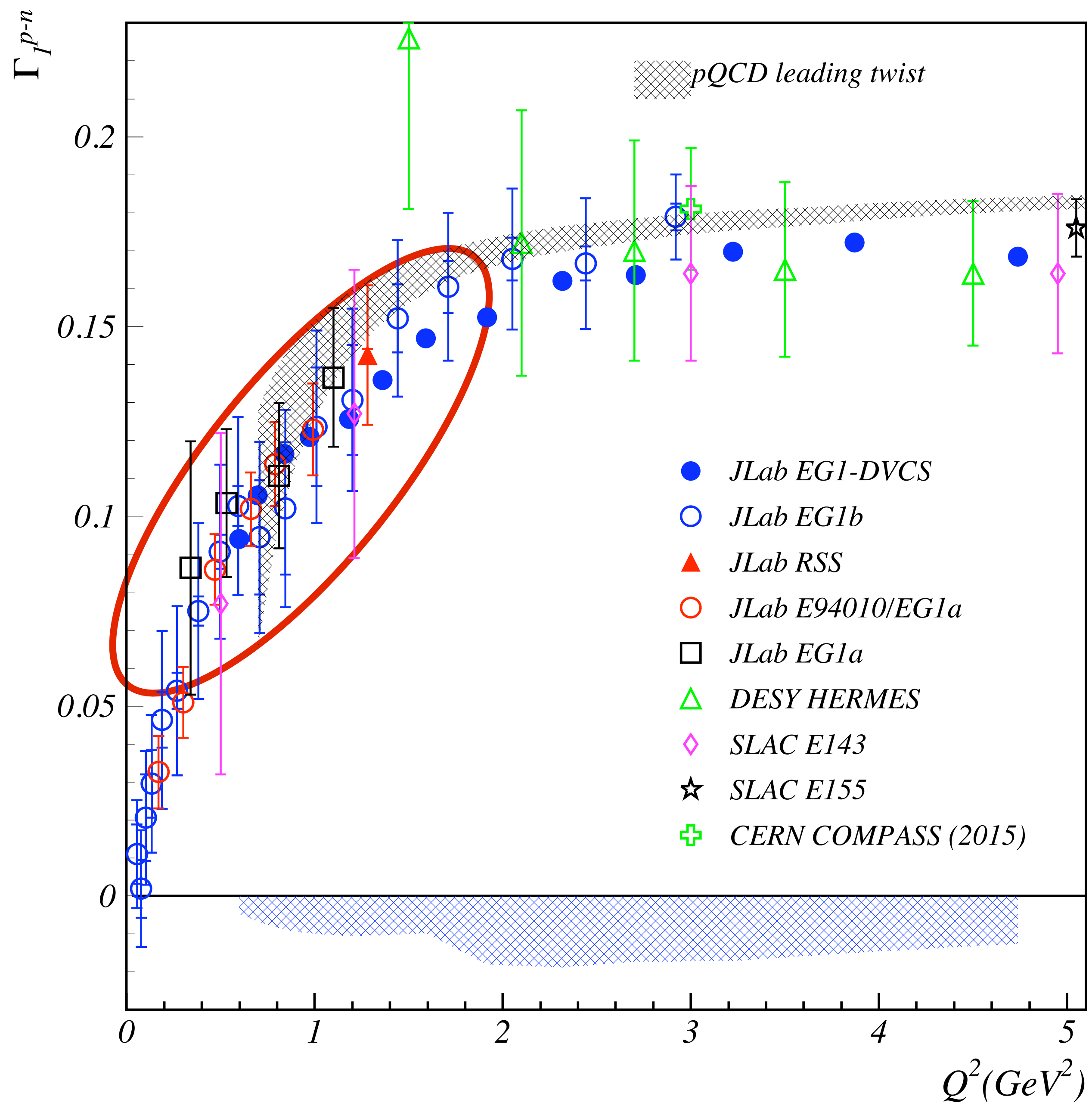
Important constraints for Chiral Perturbation theory, see talks by C. Peng and K. Slifer.

Higher Twist determinations.

Connection between hadronic and partonic descriptions of QCD.

JLab intermediate Q^2 data bridge the hadronic and partonic domains

Ex. Bjorken sum from EG1 and E94010:



Is the bridge built?

low Q^2

High Q^2

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JLab's GDH/Bjorken sum program reached its goal.

The precise mapping of low and intermediate Q^2 regions motivated:

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The precise mapping of low and intermediate Q^2 regions motivated:

- Improved χpt (low Q^2) calculations, in particular to address δ_{LT} puzzle;

low Q^2

See talks by C. Peng and K. Slifer

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- Pushed 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

Essentially: partially fold higher twists into definition of α_s.

⇒Extend domain of applicability of pQCD series to lower Q^2 .

high Q^2

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⇒Extend domain of applicability of pQCD series to lower Q^2 .

high Q^2

Jlab Bjorken sum data: motivated α_s calculation from AdS/QCD method.

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Is the bridge built?

JLab's GDH/Bjorken sum program reached its goal.

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See talks by C. Peng and K. Slifer

- Pushed improved perturbative techniques (high Q^2).
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Review: Brodsky, de Teramond, Dosch, Erlich, Phys. Rep. 05 (2015) 001. arXiv:1407.8131

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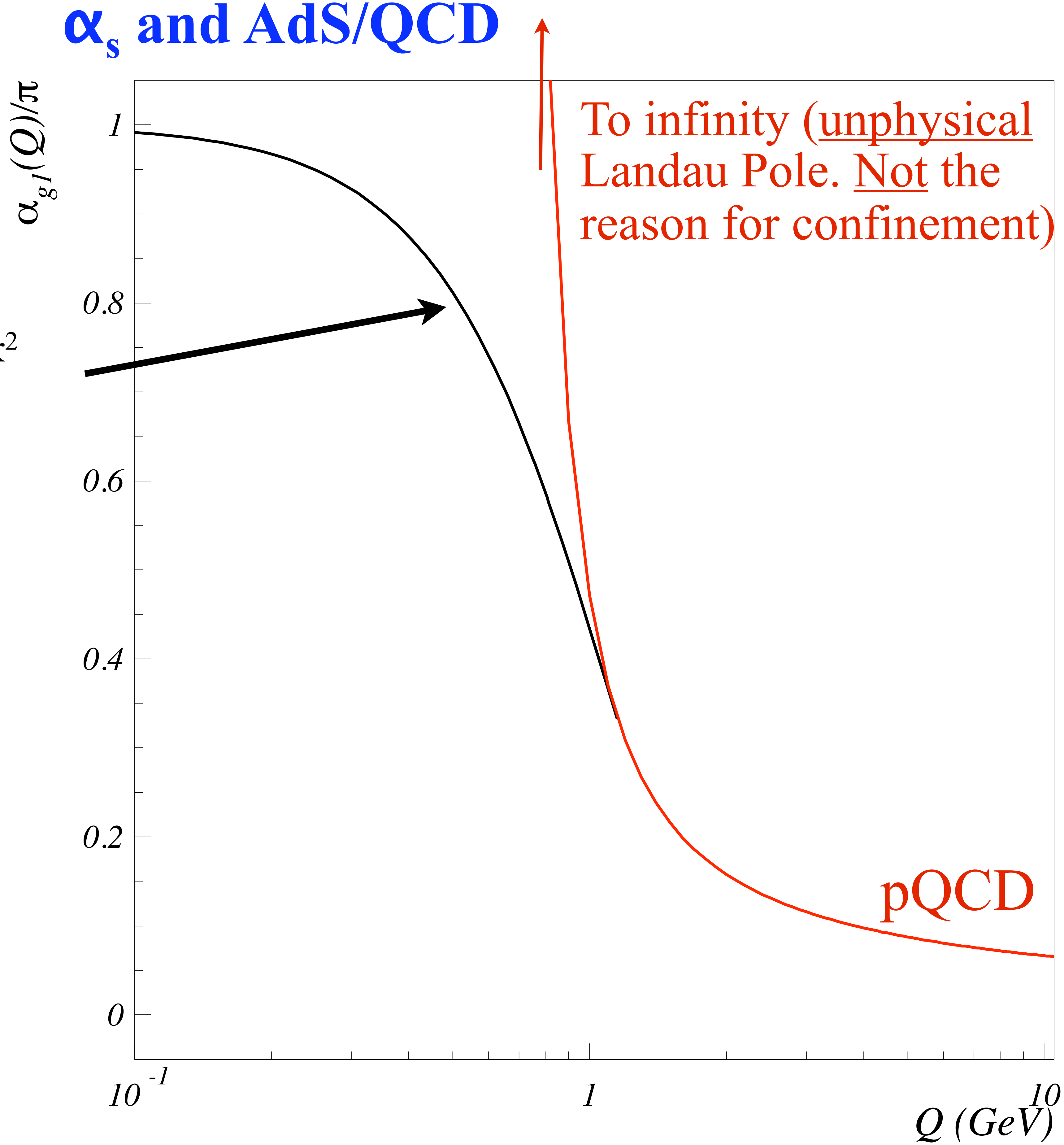
$$\alpha_s^{AdS}(Q^2) = \pi\, e^{-Q^2/4\kappa^2}$$

Brodsky, de Téramond, Deur. PRD 81, 096010 (2010)

κ: universal AdS/QCD parameter obtained from meson or baryon masses, or fundamental QCD parameter Λ_s, or hadron form factors. $\kappa \sim 0.52(3)$ GeV.

α_s and AdS/QCD

$$\alpha_s^{AdS}(Q^2)/\pi = e^{-Q^2/4\kappa^2}$$



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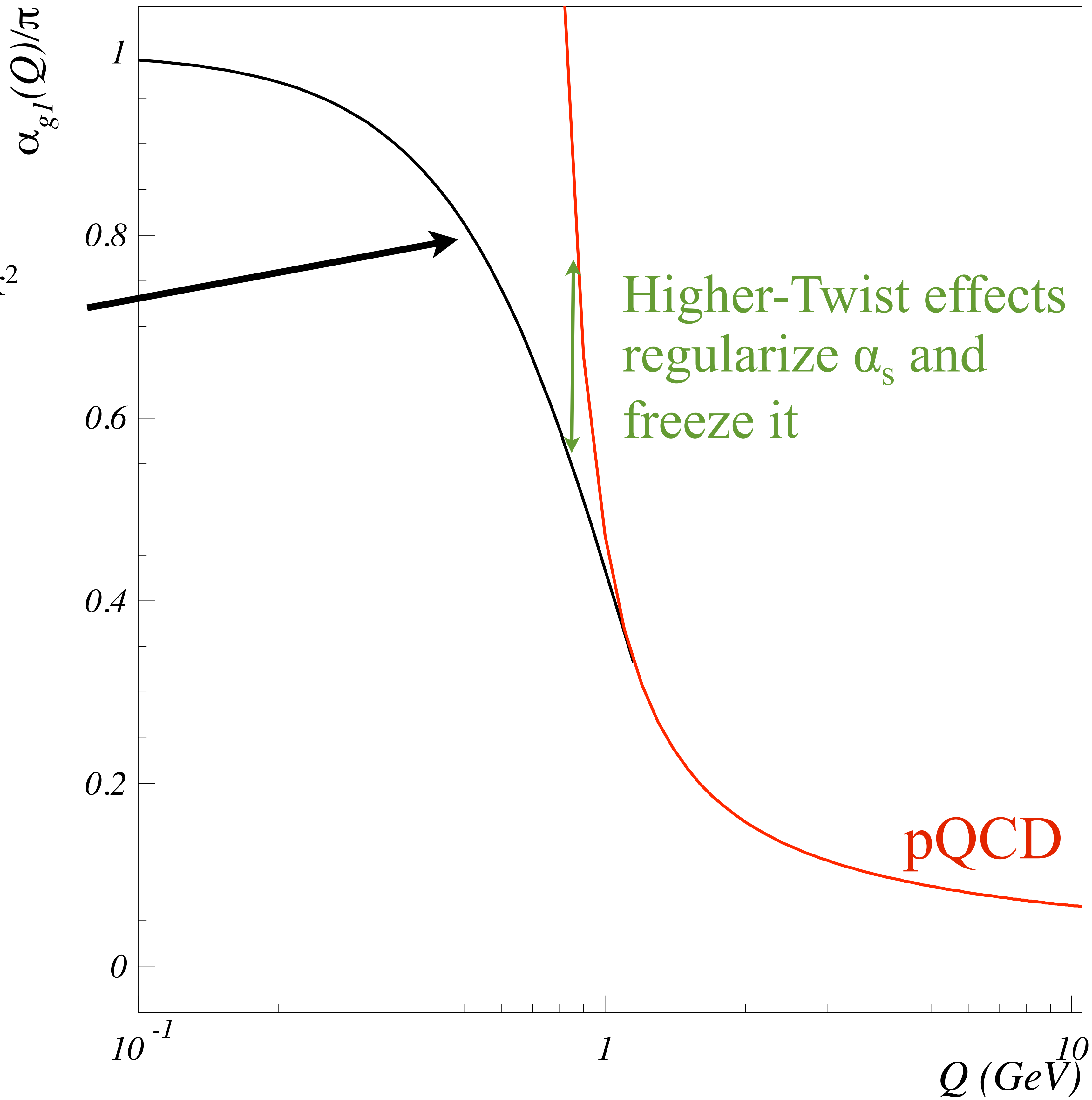
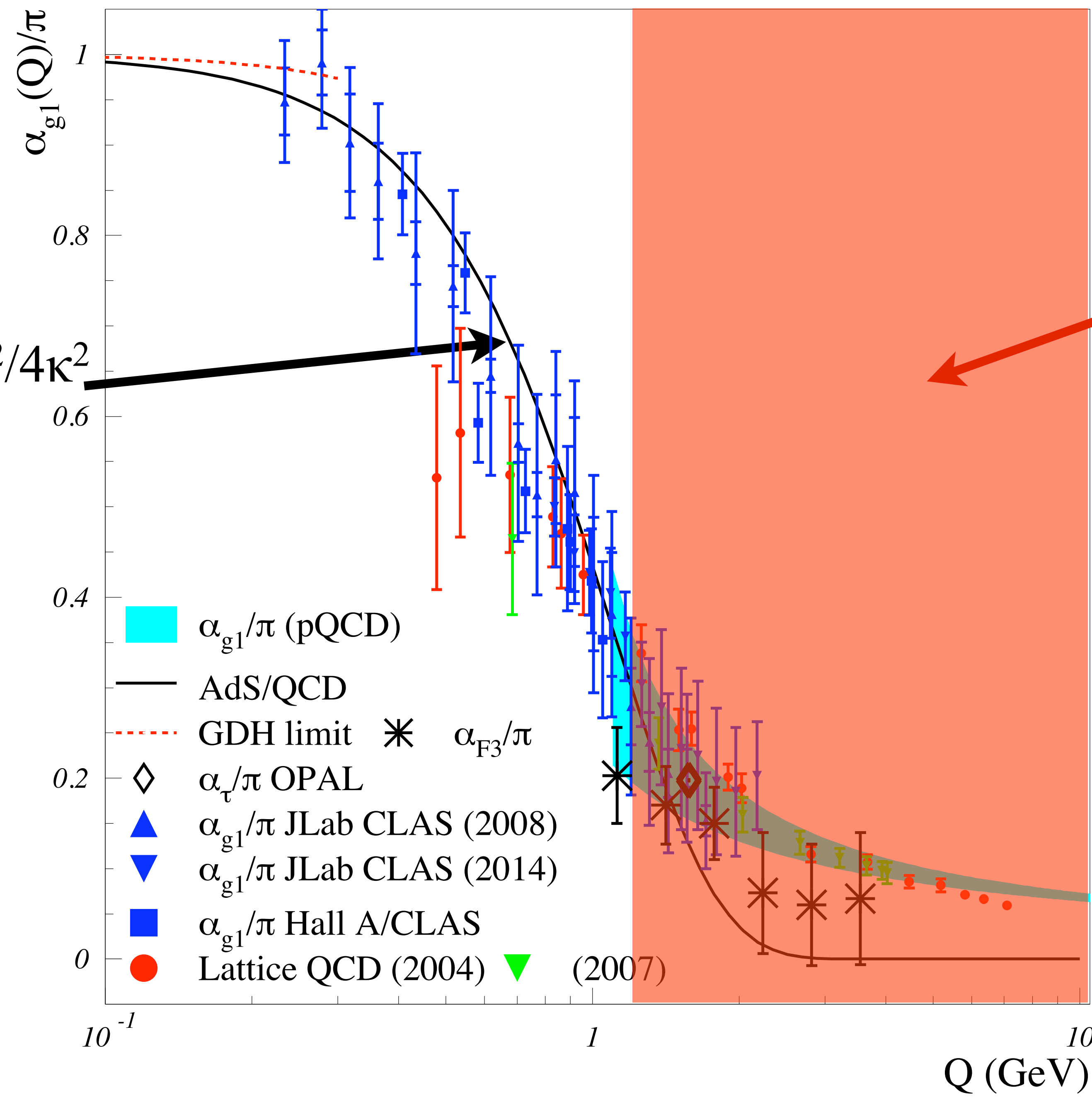


α_s and AdS/QCD: Comparison with data

$\alpha_s^{AdS}(Q^2)/\pi = e^{-Q^2/4\kappa^2}$

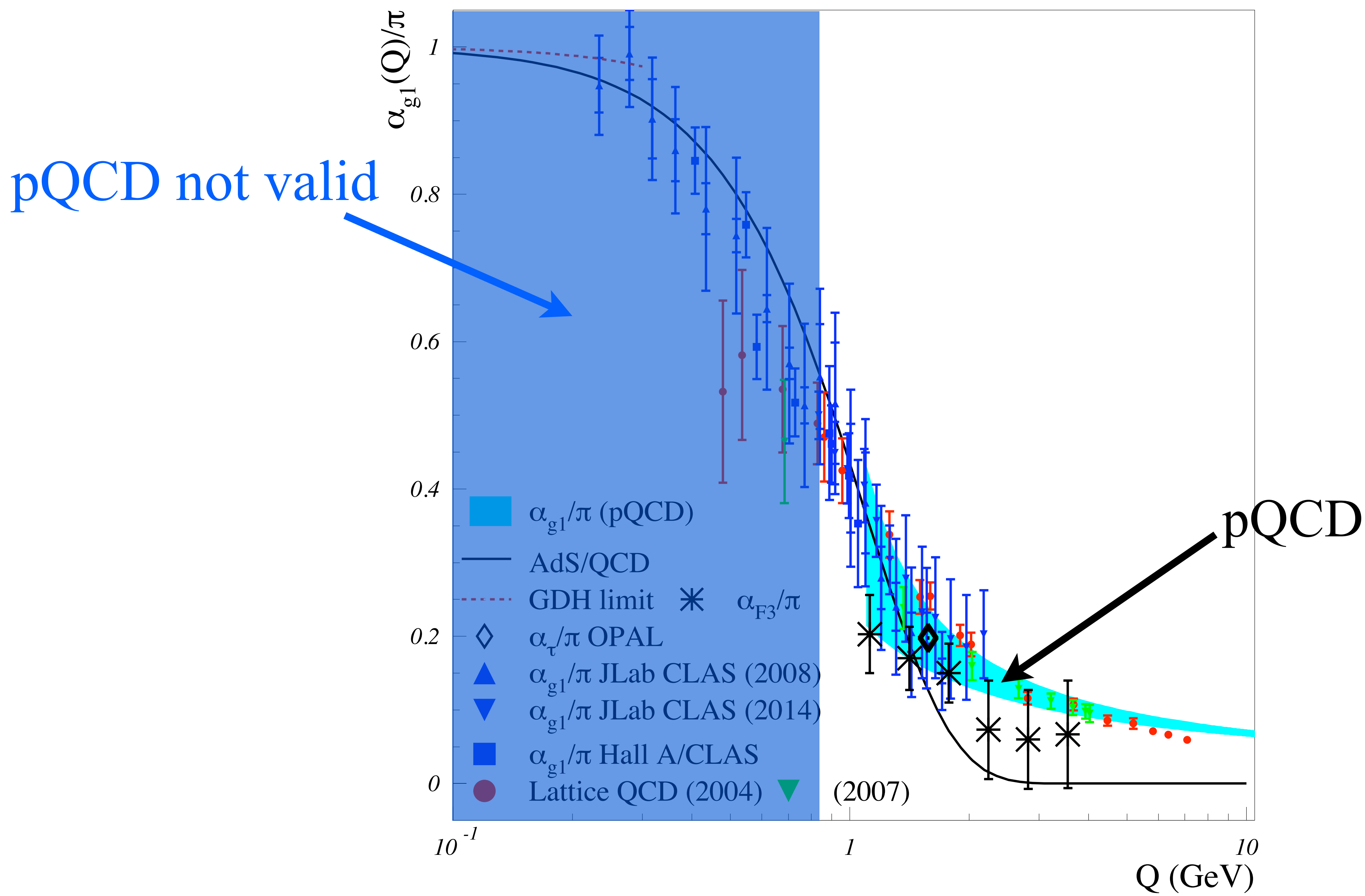
$\kappa = M_\rho/\sqrt{2}$



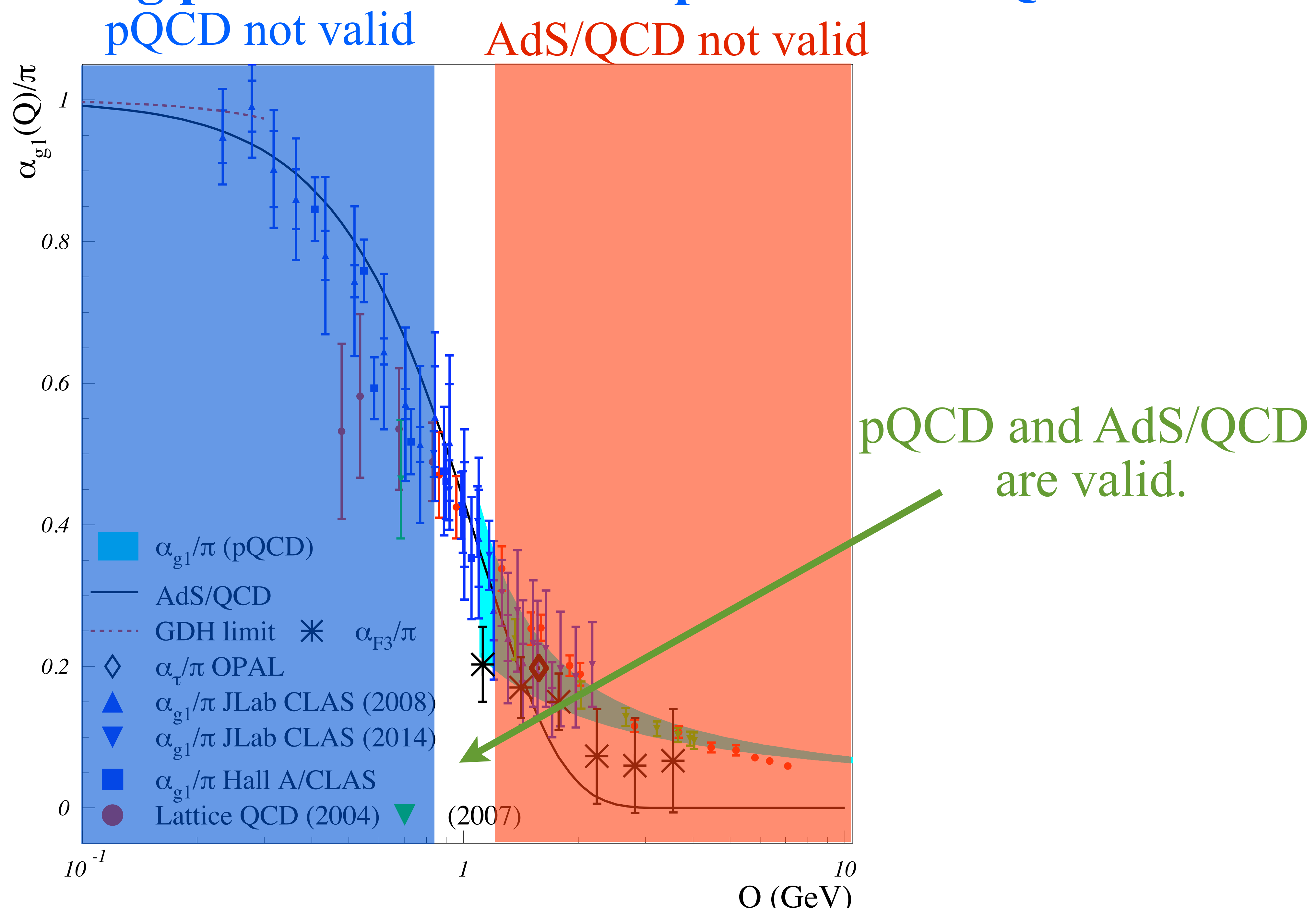
AdS/QCD not valid

⇒ **Prediction for α_s at long distances. No free parameters ($\kappa = M_\rho/\sqrt{2}$).**
Agrees very well with the α_s extracted from Lab's Bjorken sum data.

α_s and AdS/QCD: Comparison with data



Connecting perturbative to non-perturbative QCD



Can match α_s from pQCD to α_s from AdS/QCD.

⇒ can relate **hadronic masses** to fundamental QCD parameter Λ_s.

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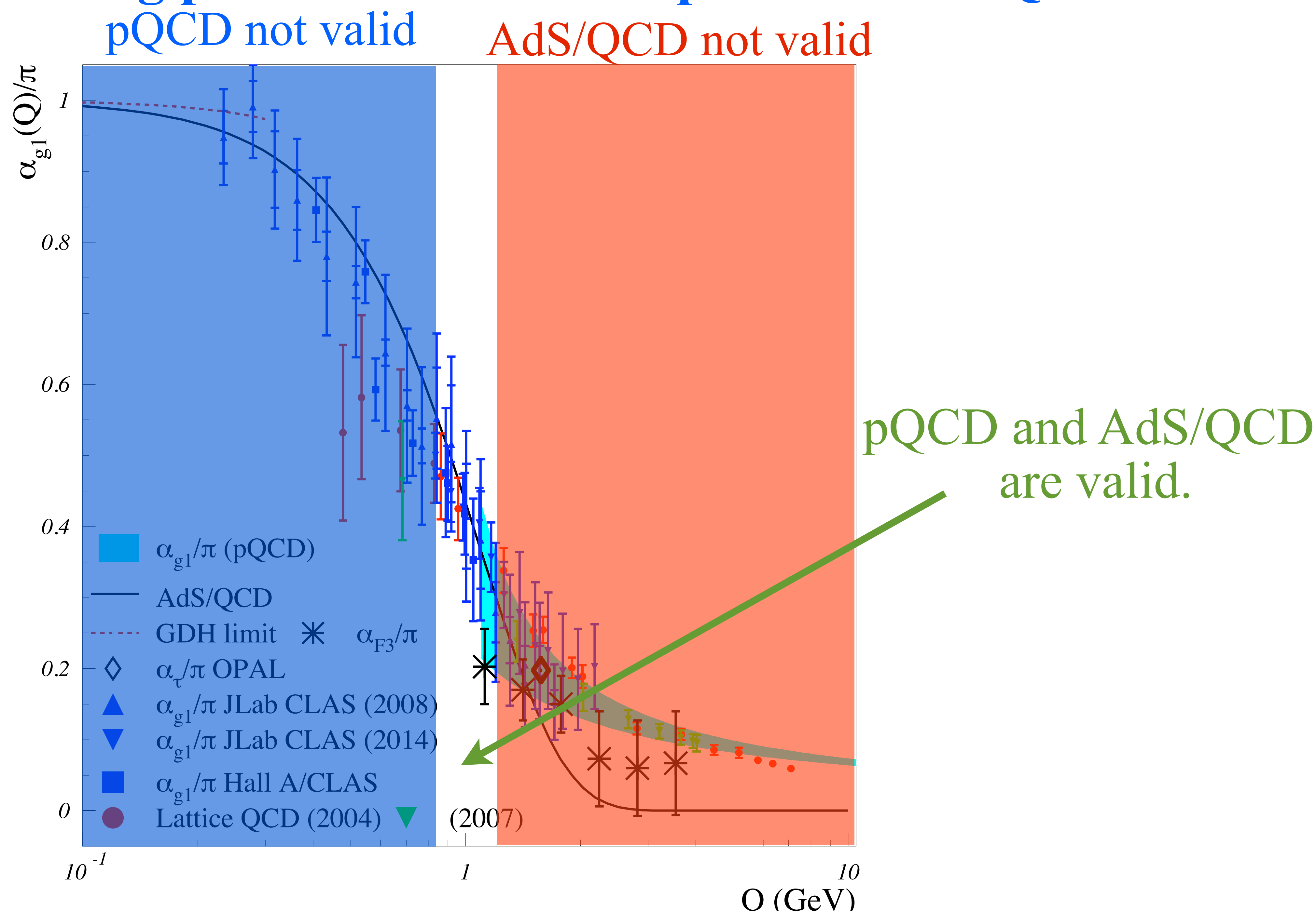


Can match α_s from pQCD to α_s from AdS/QCD.

$\Rightarrow$ can relate **hadronic masses** to fundamental QCD parameter Λ_s.

$$\Lambda_{\overline{MS}} = 0.440 M_\rho \sim M_\rho e^{-(a+1)} a^{-1/2}$$

$a = 4(\sqrt{\ln(2)^2 - 1 + \beta_0/4} - \ln(2))/\beta_0$

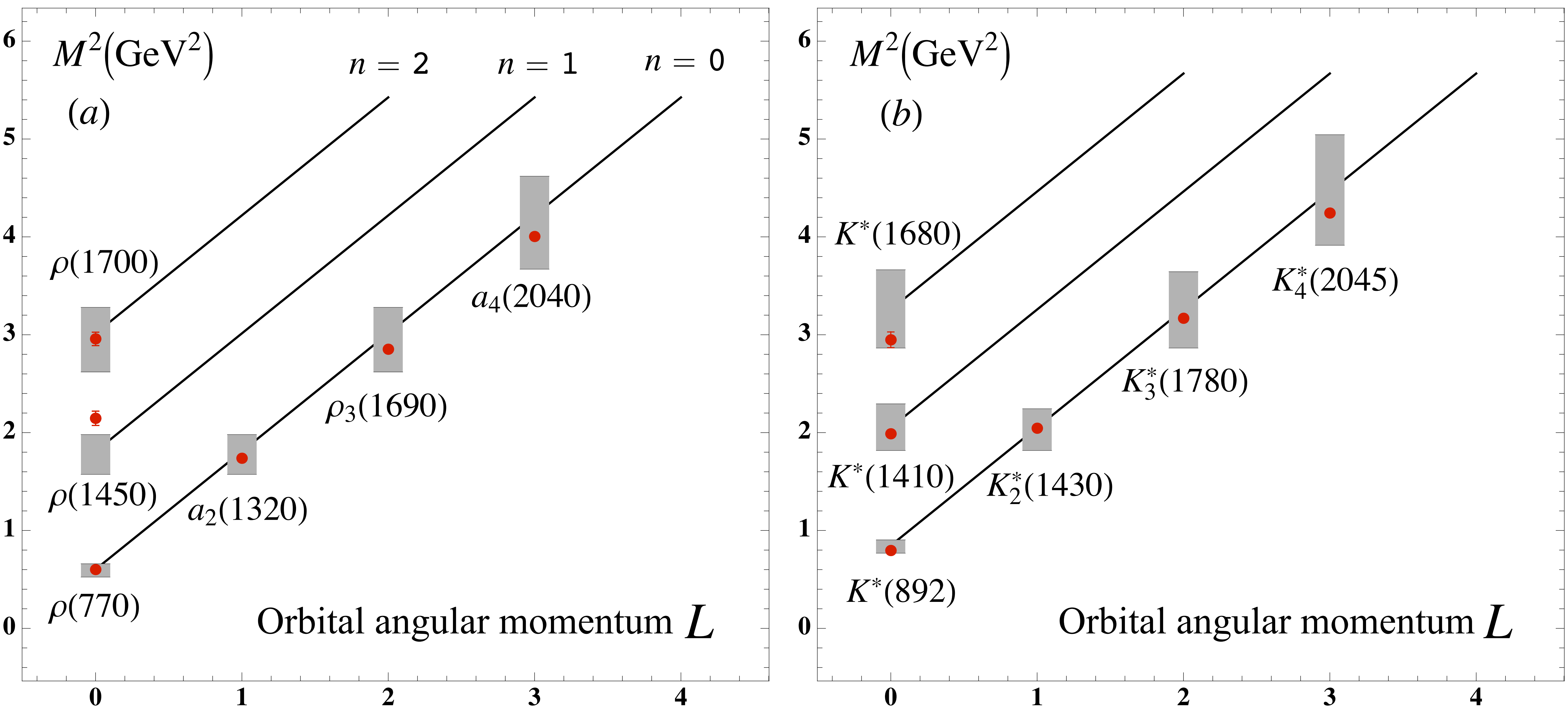
Deur, Brodsky, de Teramond, Phys. Lett. B 750, 528 (2015)

At N^3LO

At LO (here, equations are solvable analytically).

Higher order predictions for meson spectrum

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



: Holographic QCD predictions with Λ_s from PDG as (only) input.

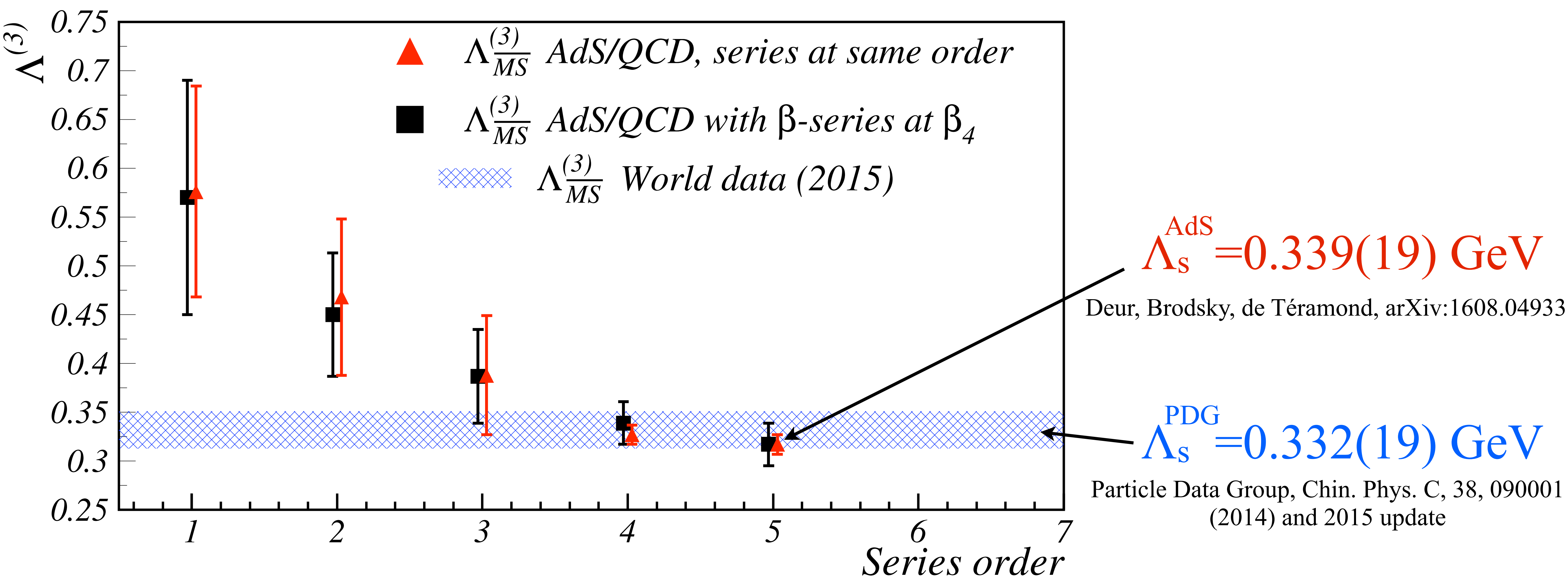
: Slopes predicted by Light Front Holographic QCD.

: Measurements.

Analytic determination of hadron spectrum from Λ_s

Prediction of Λ_s from hadronic observable

Conversely, one can use κ, from hadron masses or form factors and use the same matching procedure to predict Λ_s.



κ from hadron masses, n_f=3, use recent 5-loop α_s calculation.

Determination of Λ_s in excellent agreement with PDG world average and with similar uncertainty.

Conclusion

•Low and intermediate Q^2 -measurements at JLab complement high energy data from CERN/SLAC/DESY.

- •Most of intermediate Q^2 data now available. Remaining data (EG1b, SANE) will be available soon.
- •Low Q^2 data are being finalized for neutron (available in a few months?). More work remains for proton and deuteron (a year?)

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- •Good progress in description of strong force over full Q^2 - range: improved χpt (low Q^2) and pQCD series (high Q^2)
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