The 7th Workshop on Hadron Physics in China and Opportunities Worldwide

Duke Kunshan University, Kunshan, China, August 3-7, 2017

Overview of Hadron Physics in the United States

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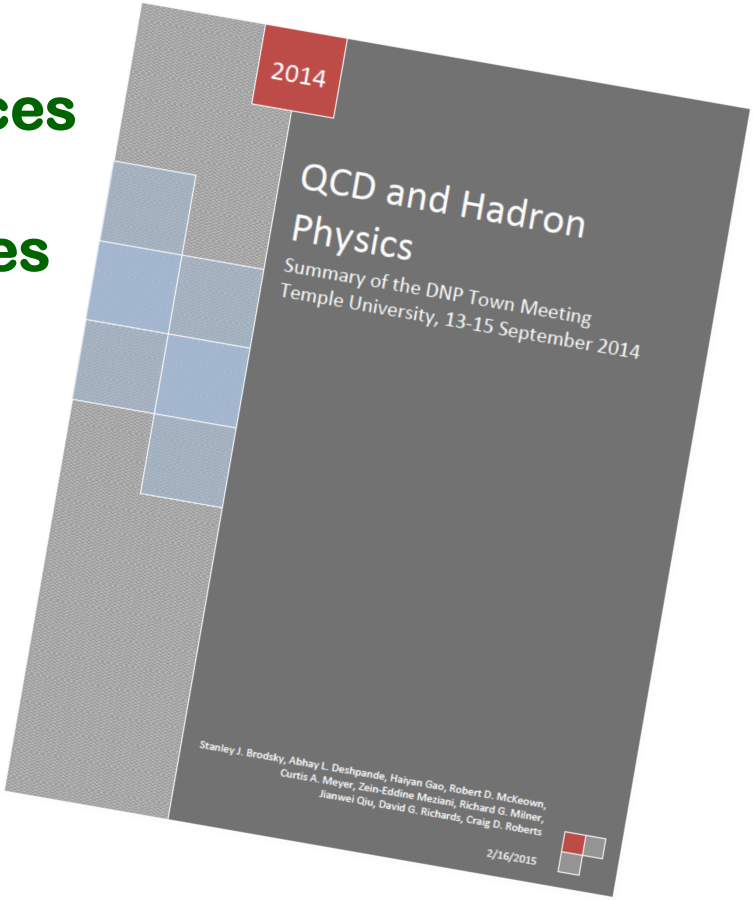
Acknowledgement:

Much of the materials presented here are from "QCD & Hadron Physics", Town Meetings of on-going Nuclear Physics Long Range Planning process in US [arXiv:1502.05728, …]

Outline

- ❑ Questions defining the field
- ❑ Facilities and theoretical approaches
- ❑ **Hadron structure at short distances**
- ❑ **Hadron structure at long distances**
- ❑ **Hadron spectroscopy**
- ❑ QCD and nuclei
- ❑ Future opportunities - EIC



Questions for QCD and hadron physics

- ❑ What does QCD predict for the properties of hadrons?
- ❑ What is the internal structure of hadrons?
- ❑ How hadrons are emerged from quarks and gluons?
- ❑ How do the nuclear forces arise from QCD?
- ❑ What is the role of glue in all of these?

Without the glue, there would be no hadrons,

no atomic nuclei, no human, …, and no visible world!

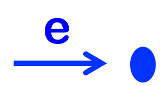
The Challenge:

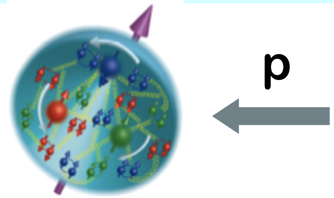
Probe hadron structure without "seeing"
quarks and gluons directly?

Theoretical approaches – approximations

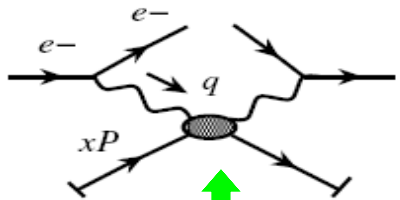
❑ QCD Factorization:

– Approximation at Feynman diagram level

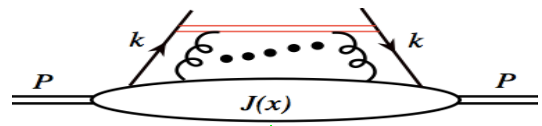




$\sigma_{\text{tot}}^{\text{DIS}}$:



$\otimes$



$+\, O\left(\frac{1}{QR}\right)$

Probe Hard-part	Structure Parton-distribution	Approximation Power corrections

❑ Effective field theory (EFT):

– Approximation at the Lagrangian level

Soft-collinear effective theory (SCET), Non-relativistic QCD (NRQCD), Heavy quark EFT, chiral EFT(s), …

❑ Other approximate approaches:

Light-cone perturbation theory, Dyson-Schwinger Equations (DSE), Constituent quark models, AdS/CFT correspondence, …

See Brodsky's talk

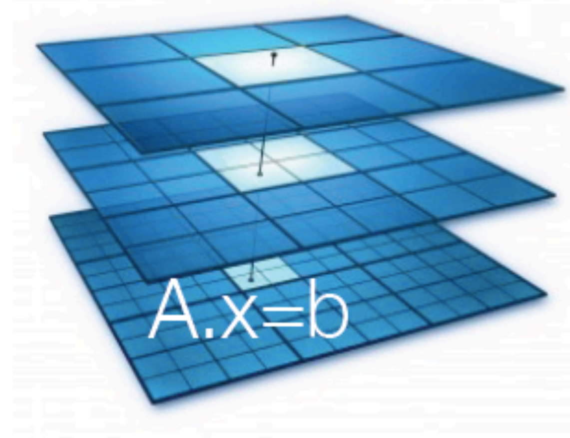
❑ Lattice QCD:

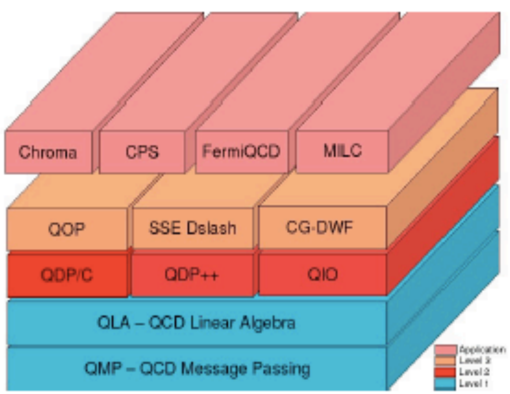
– Approximation due to computer power

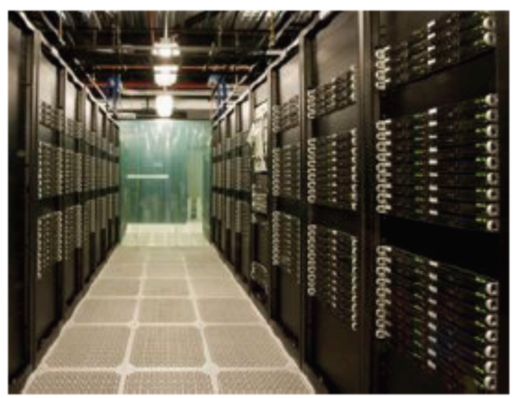
USQCD: hadron structure, hadron spectroscopy, nuclear structure, …

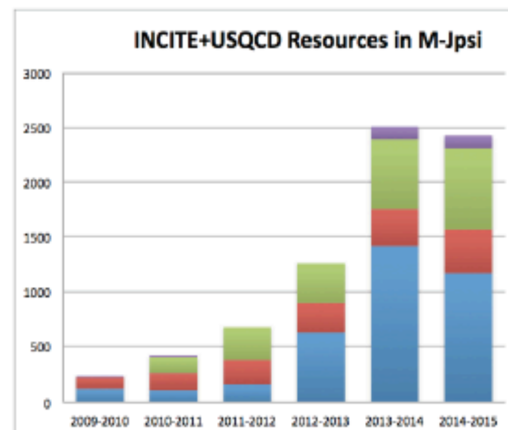
USQCD – a collaboration of collaborations

SciDAC
Scientific Discovery through Advanced Computing





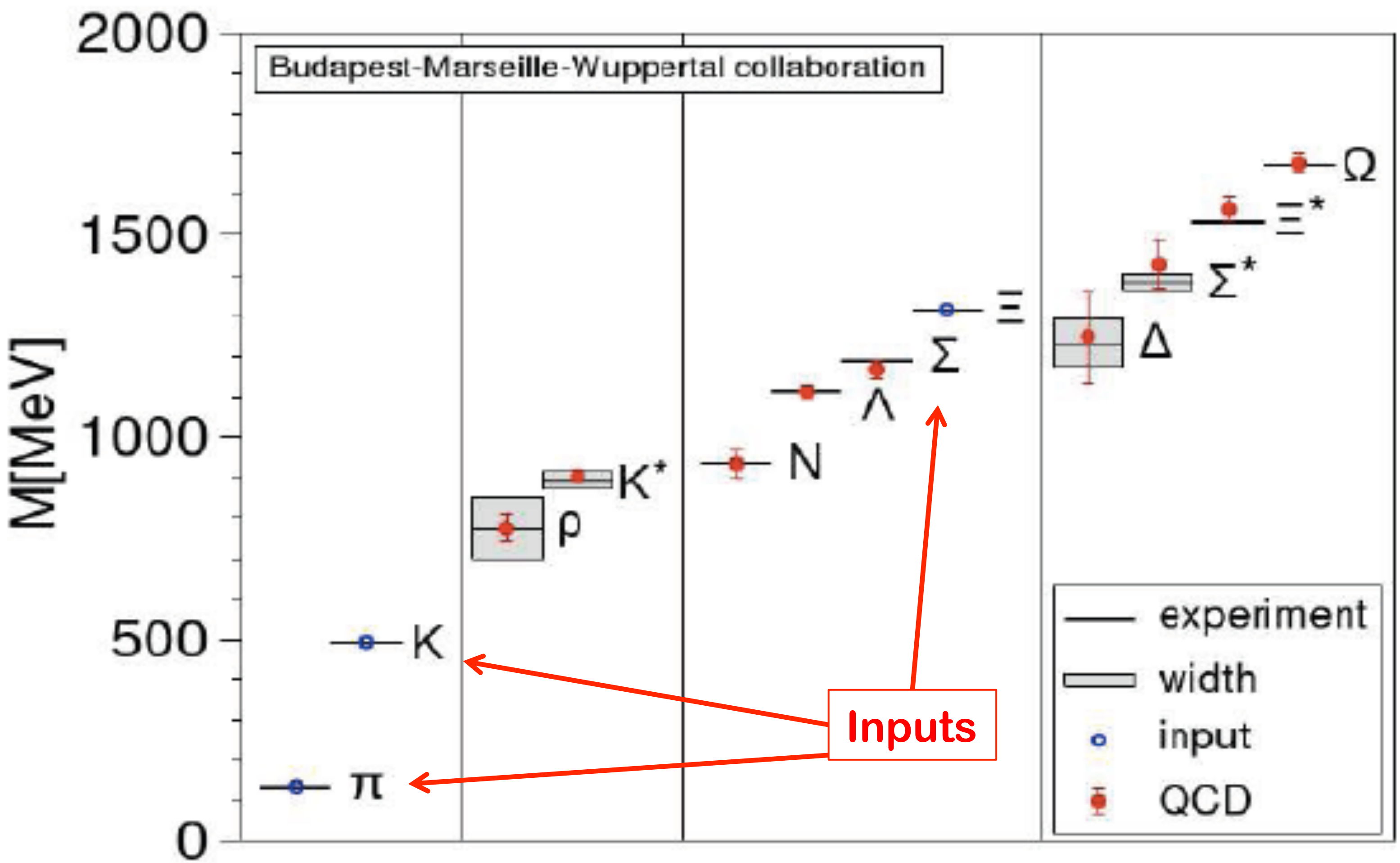




Credit to M. Savage

Hadron properties from Lattice QCD

❑ **Low-lying hadron mass spectrum:** S. Durr et al. Science 322, 1124 2008

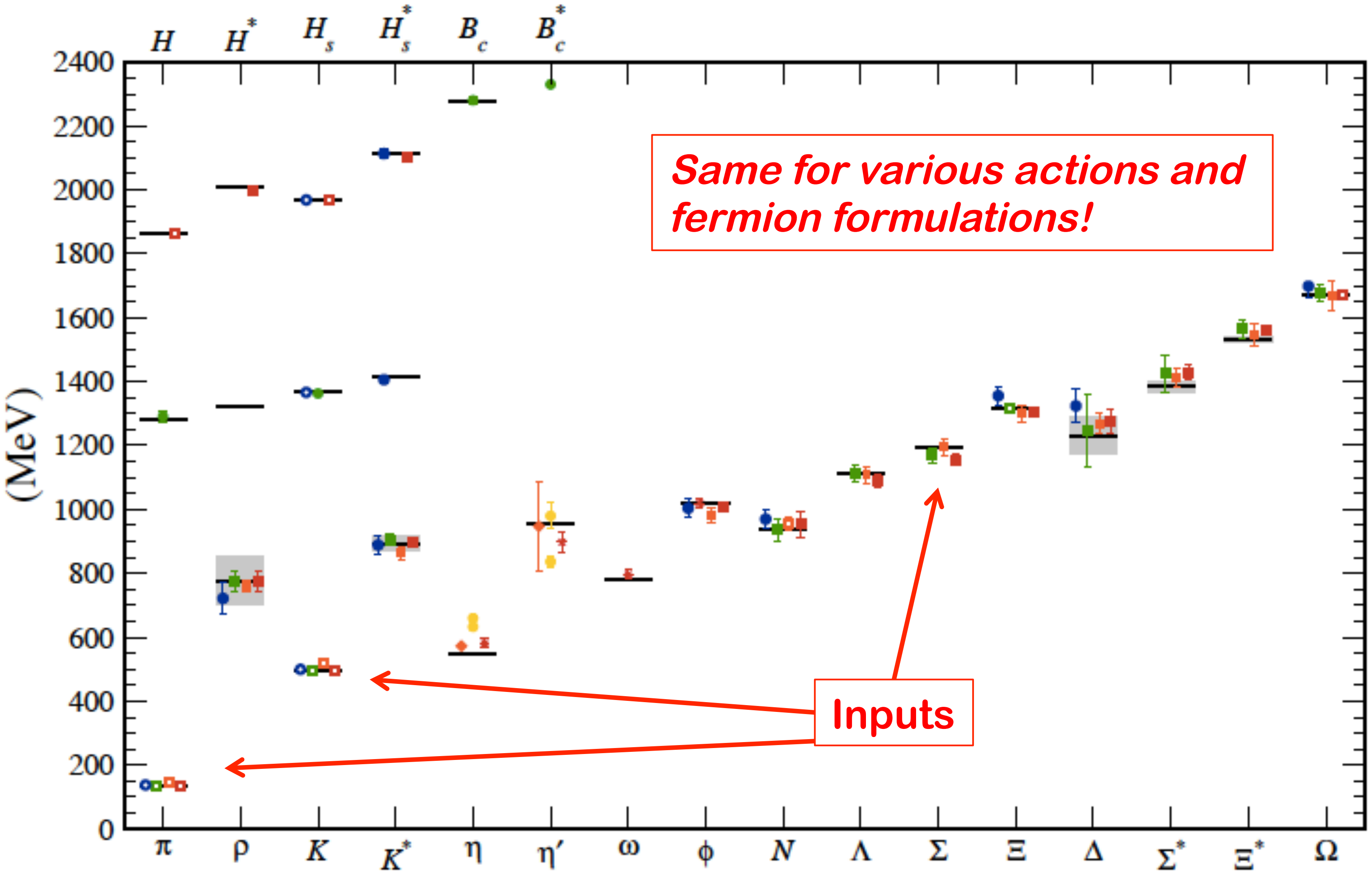


Predictions with limited inputs

Hadron properties from Lattice QCD

❑ **Low-lying hadron mass spectrum:**

A. Kronfeld, 1209.3468

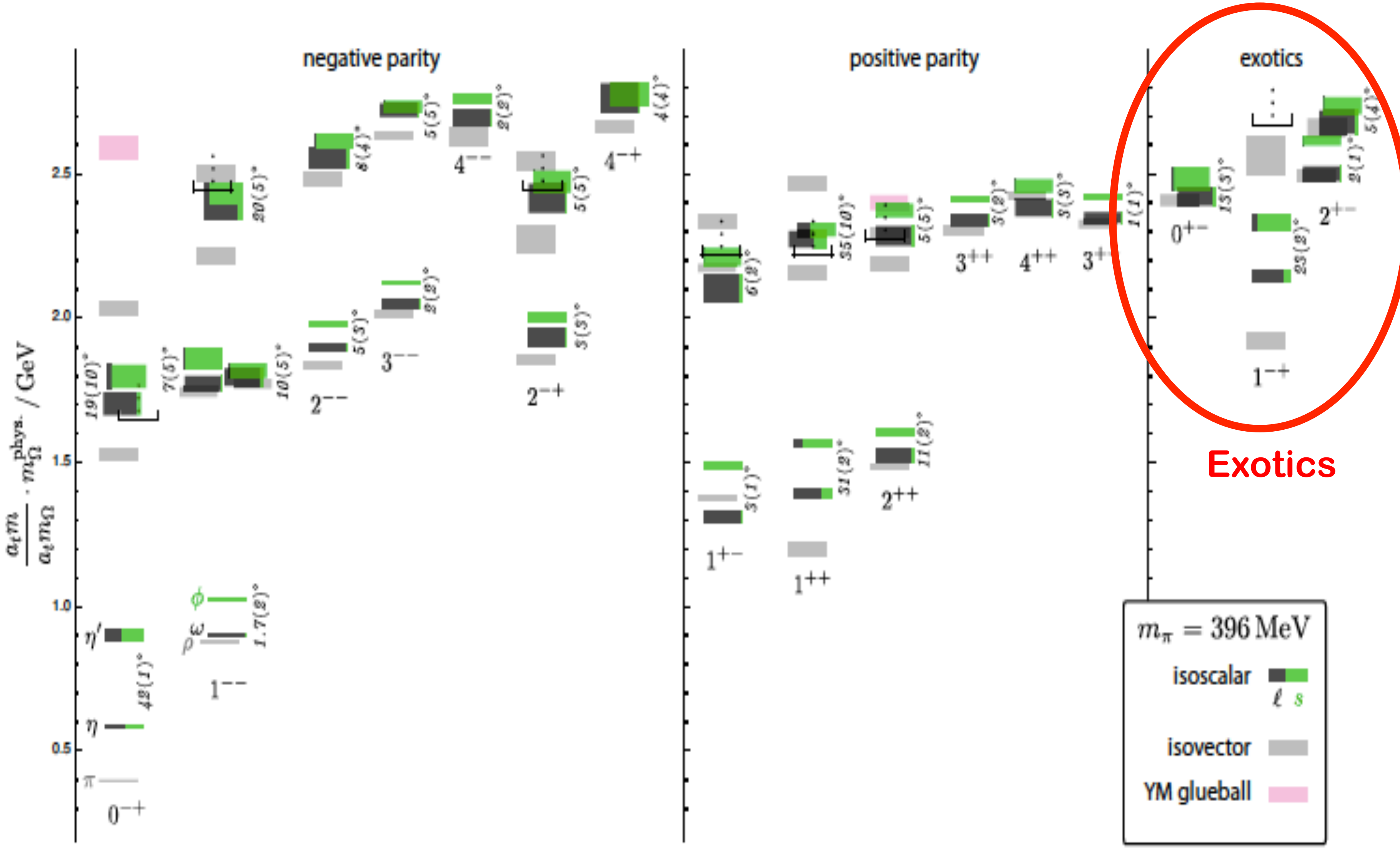


Predictions with limited inputs

Hadron properties from Lattice QCD

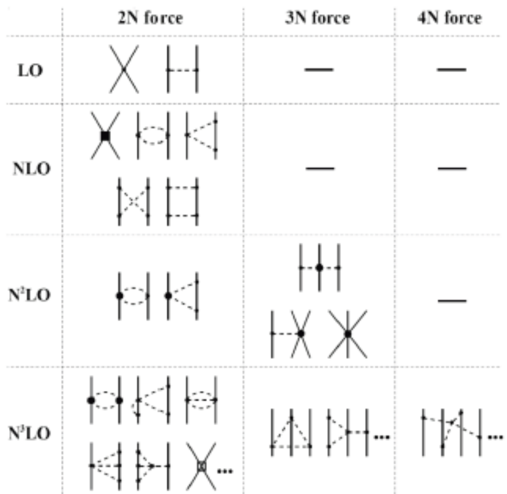
❑ Meson resonances:

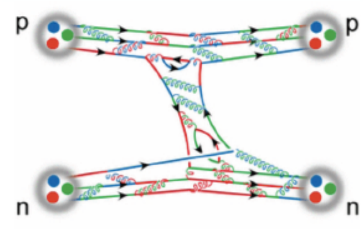
Dudek et al, Phys.Rev. D88 (2013) 094505



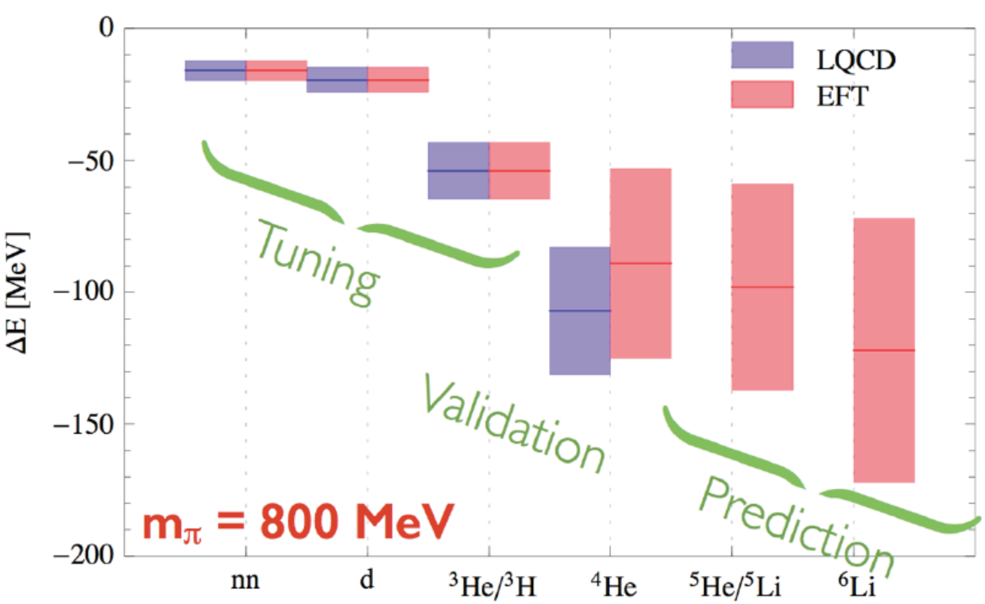
Physics of nuclei from Lattice QCD

❑ The Periodic Table:



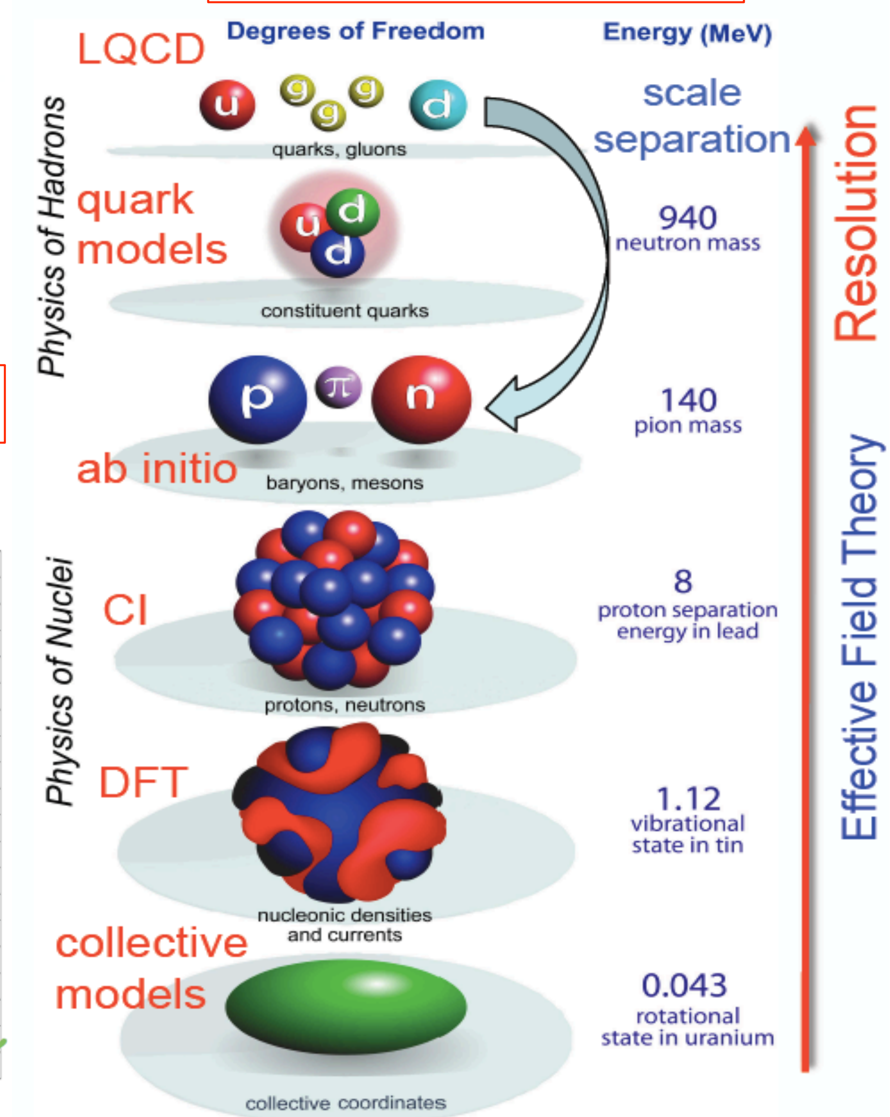


Nuclear forces



Barnea et al., Phys.Rev.Lett. 114 (2015) 5

Separation of scales

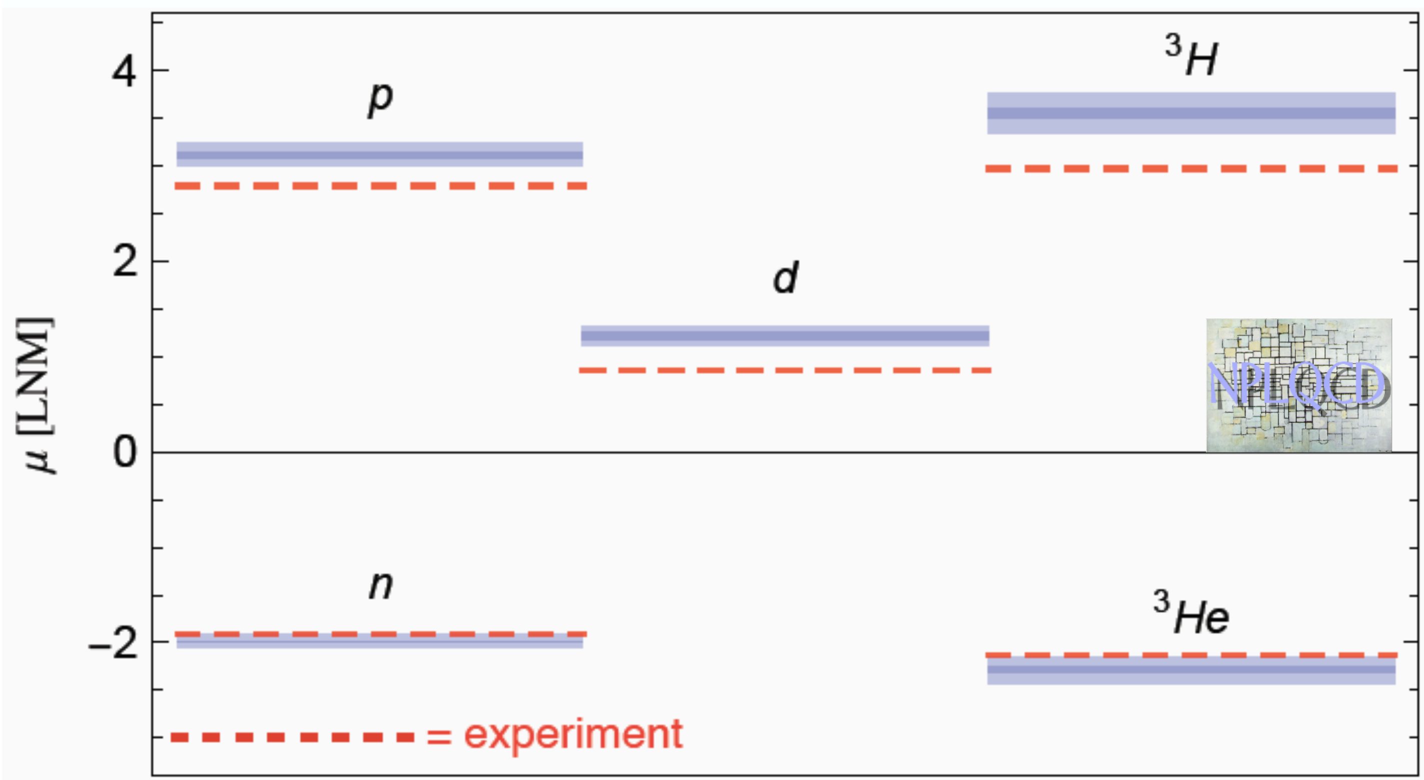


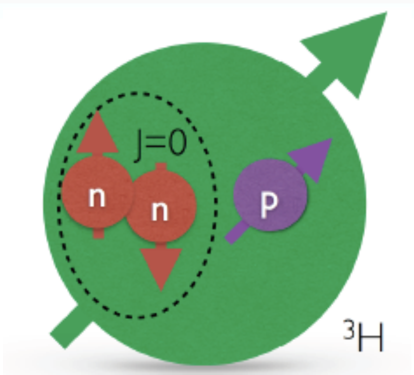
Credit to W. Nazarewicz

Hadron properties from Lattice QCD

- **Magnetic moments:**

S.R. Beane et al., Phys.Rev.Lett. 113 (2014) 252001





Theory at m_π = 806 MeV vs. the nature!

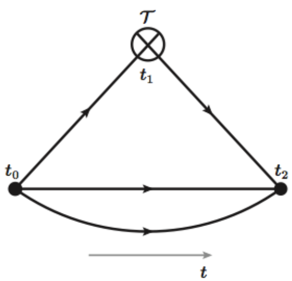
Nuclei are (nearly) collections of nucleons – shell model phenomenology!

Hadron properties from Lattice QCD

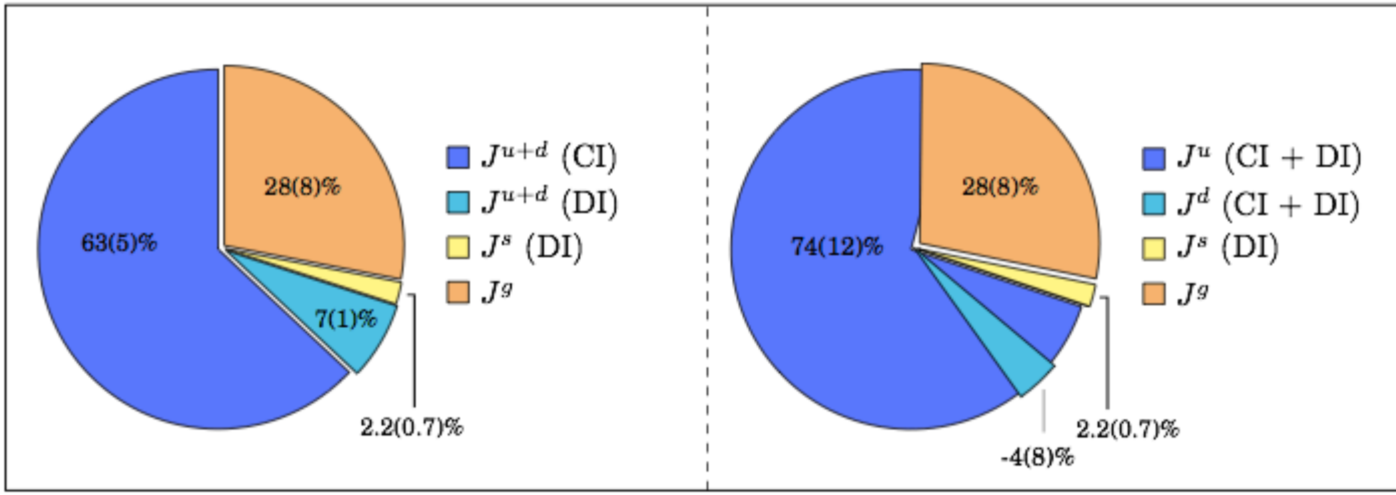
❑ Proton spin:

χQCD Collaboration

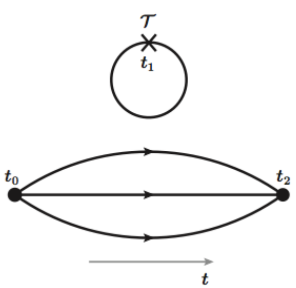
Deka *et al.* arXiv:1312.4816



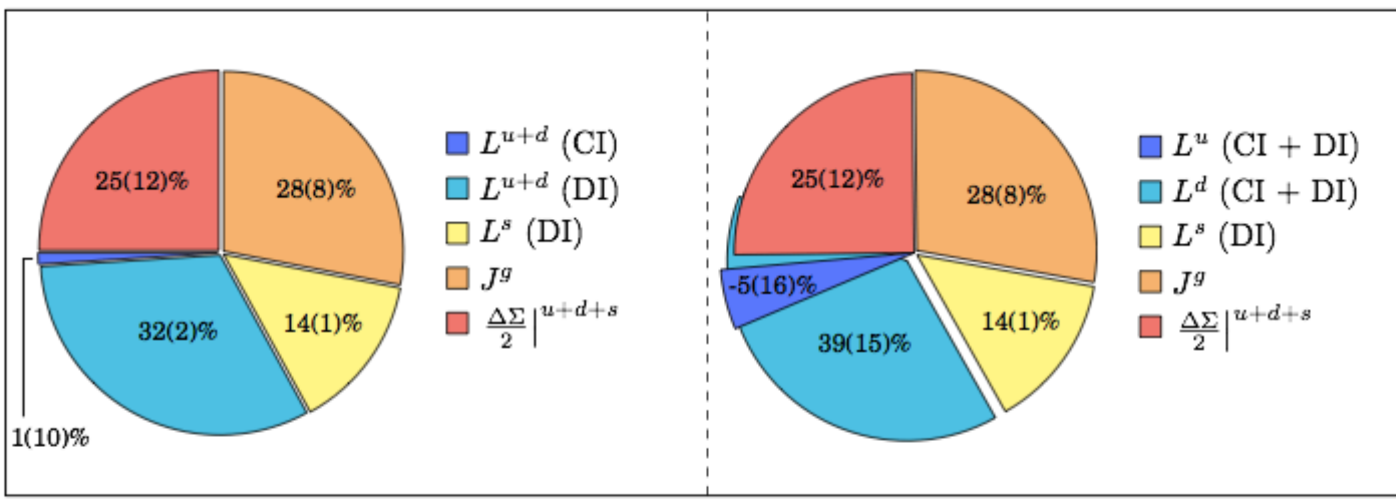
Connected Interaction (CI)



(b)



Disconnected Interaction (DI)



(c)

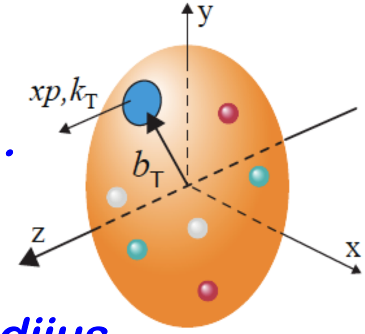
See talks by Chen, Ji, Ma, Yuan, …

Hadron physics landscape

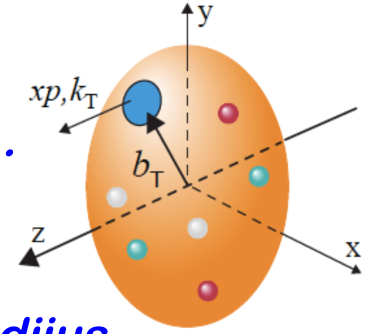
- **Short distance structure:**
  - ✧ **PDFs:** $q(x), \Delta q(x), \overline{q}(x), \Delta\overline{q}(x), g(x), \Delta g(x)$ ***Proton spin, …***
  - ✧ **TMDs:** $f(x, k_T)$ ***Confined motion, Sivers sign change, …***
  - ✧ **GPDs:** $\widetilde{f}(x, b_T)$ ***Spatial distribution, quark radius, gluon radiius, …***

    $x \to 1:$ ***Hadron's small configuration – confinement sensitive, …***

    $x \to 0:$ ***High density of gluons – condensed matter of QCD, CGC, …***



Hadron physics landscape



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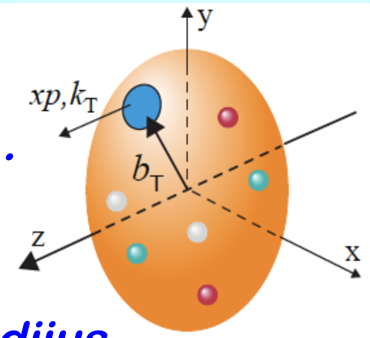
❑ Long distance structure:

- ✧ **Form factors:** $G_E(Q^2), G_M(Q^2), F_\pi(Q^2), \ldots$ ***Proton radius, structure, …***
- ✧ **Transition form factors:** $F_{\gamma^*\gamma\pi^0}(Q^2), F_{\gamma NN^*}(Q^2), \ldots$ ***Distribution amplitude, …***
- ✧ **Spectroscopy:** $N^*, X, Y, Z, \ldots$ ***Fundamentals of QCD bound states?***

Hadron physics landscape

❑ Short distance structure:



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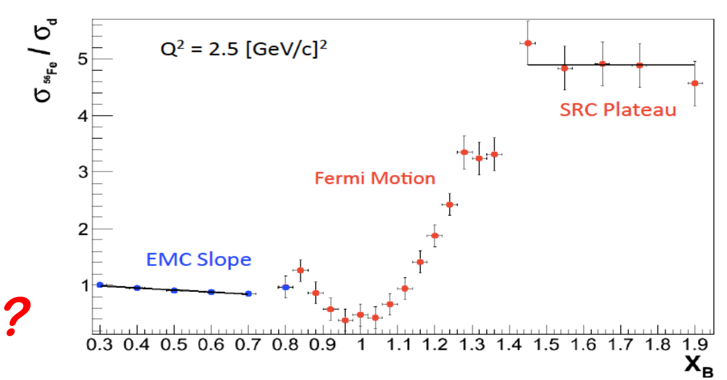
❑ Nuclear medium modifications:

✧ **EMC effect, short-range correlation, …**

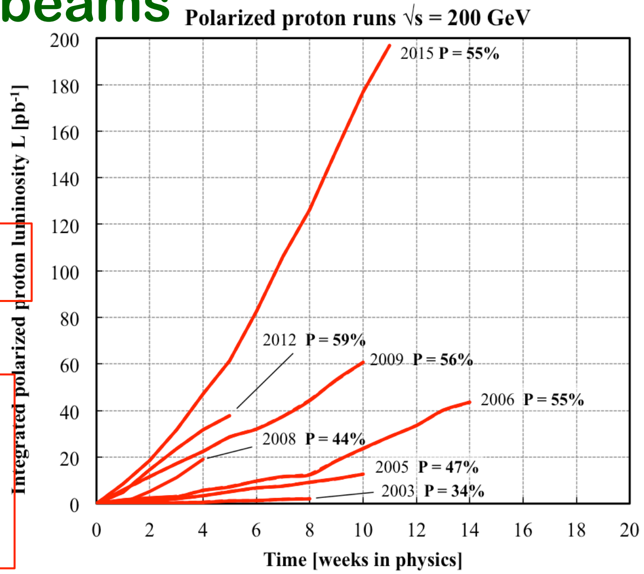
✧ **Small x shadowing, saturation, …**

Nuclear structure if we only see partons?



US facilities

BROOKHAVEN NATIONAL LABORATORY – high energy polarized proton beams



✧ Longitudinal polarization:

$$A_{LL}^{\mathrm{Jet}}(\mathtt{STAR}) + A_{LL}^{\mathrm{Hadron}}(\mathtt{PHENIX}) \to \Delta G(x) > 0$$

$$A_L^{W^\pm}(\sqrt{s} \geq 500\ \mathrm{GeV}) \to \Delta\bar{q}(x)$$

Proton spin, …

✧ Trasverse polarization:

$$A_N^{\mathrm{Hadron,Jet,\ldots}} \to$$

$$A_N^{W^\pm,\gamma^*} \to$$

QCD quantum correlation, confined parton motion, …, Sivers' sign change, …

US facilities

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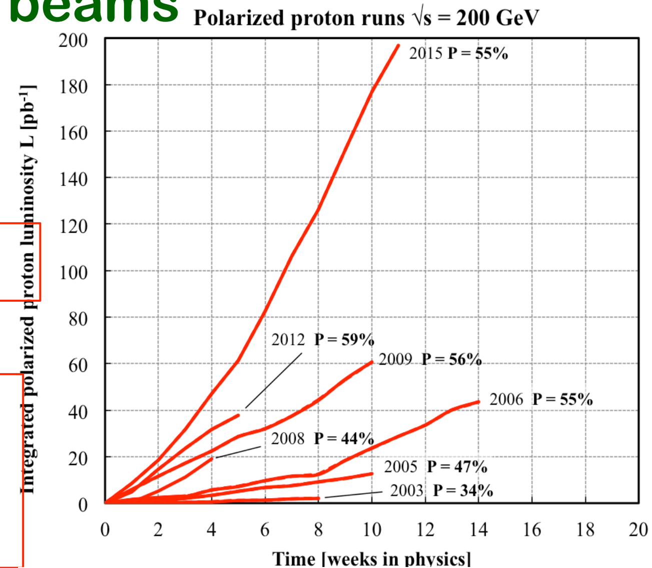

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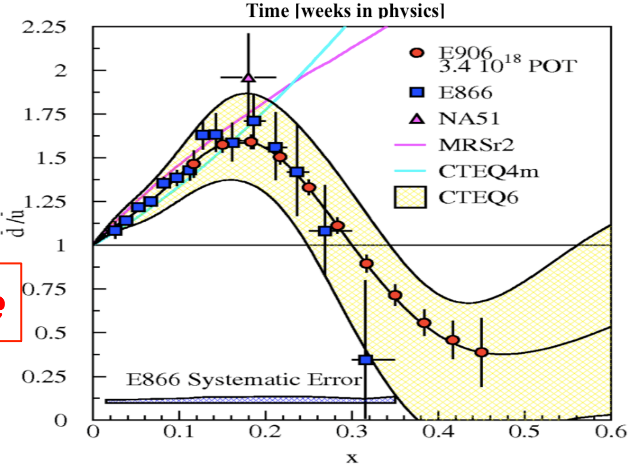
Fermilab – high intensity proton beam

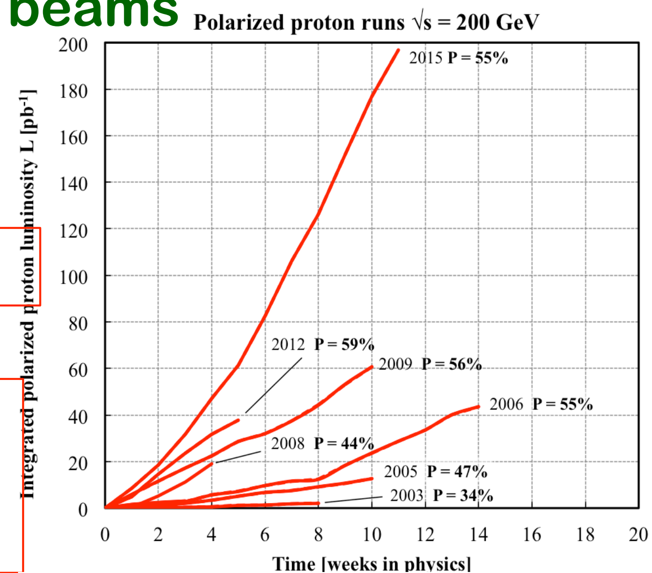


✧ **E906:** $p, d, A\,\text{targets} \to V(\gamma^*, {\rm J}/\psi, \Upsilon) \to \mu^+\mu^-$

Hadron's sea structure, more

US facilities

BROOKHAVEN NATIONAL LABORATORY – high energy polarized proton beams



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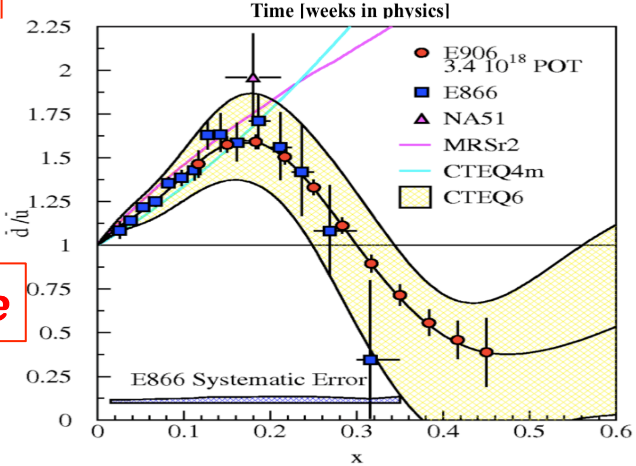


- ✧ **E906:** $p, d, A\,\text{targets} \rightarrow V(\gamma^*, \text{J}/\psi, \Upsilon) \rightarrow \mu^+\mu^-$

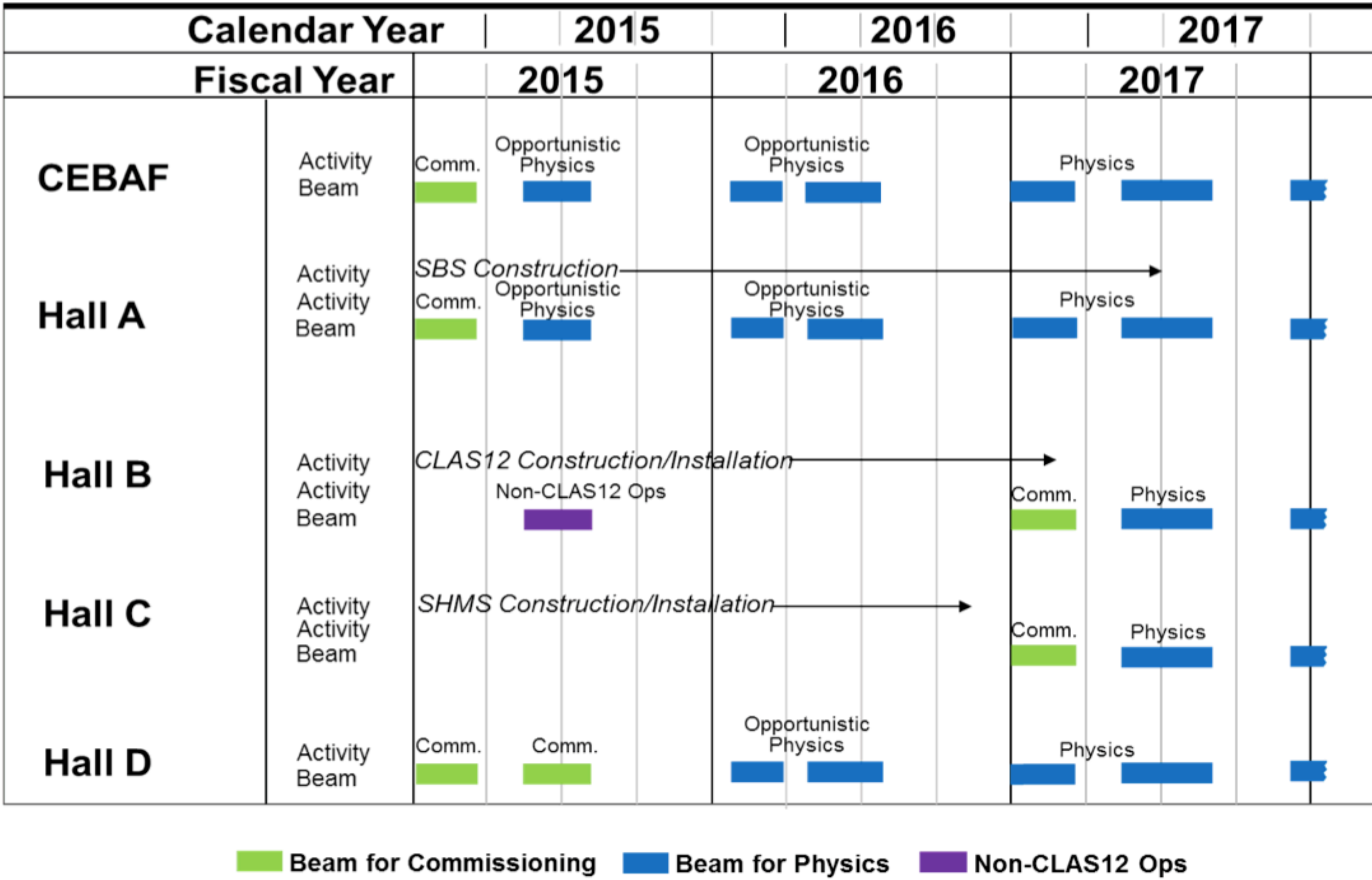
  Hadron's sea structure, more

Jefferson Lab – high intensity electron beam

- ✧ **12 GeV program:** ***A broad physics program from complementary capabilities of 4 experimental halls***

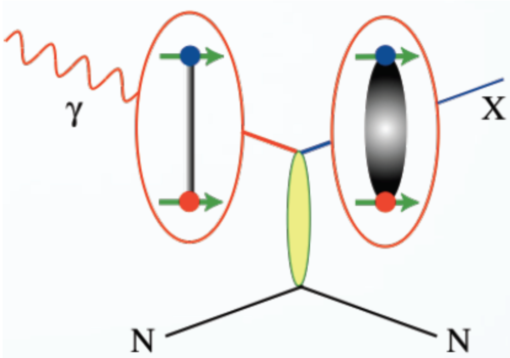
See McKoewn's talk

US facilities – JLab12



Meson spectroscopy – JLab12

- **Photoproduction – look for exotic states:**

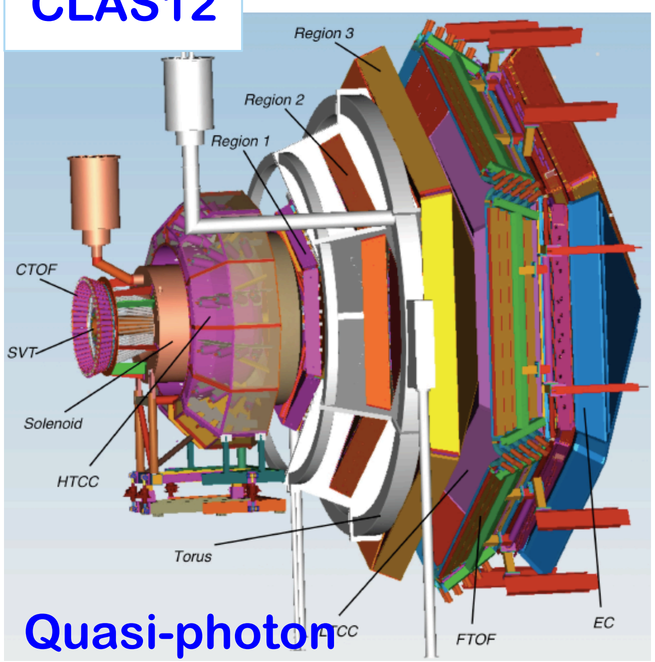


Simple (0^{++}) exchange with L=1: 0^{+-}, 1^{+-}, 2^{+-}

Simple (0^{-+}) exchange with L=1: 0^{-}, 1^{-}, 2^{-}

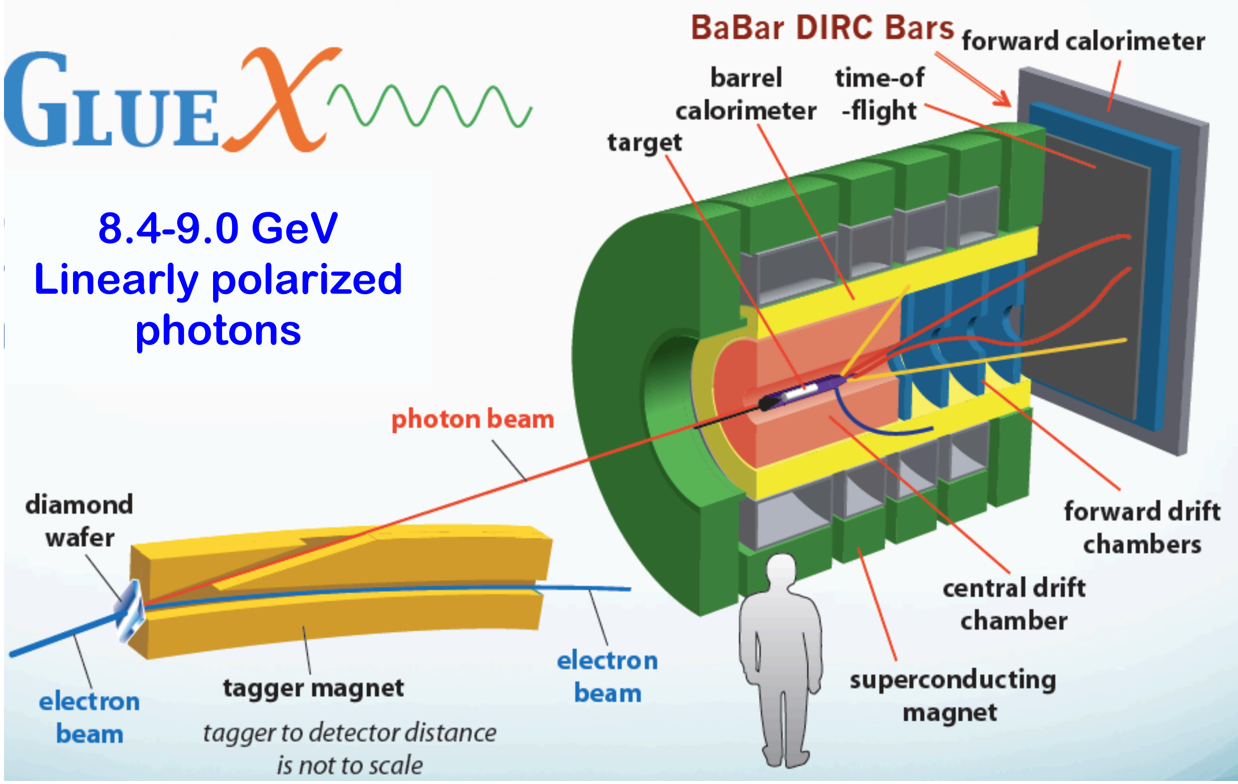
Simple (1^{--}) exchange with L=1: 0^{-+}, 1^{-+}, 2^{-+}

CLAS12



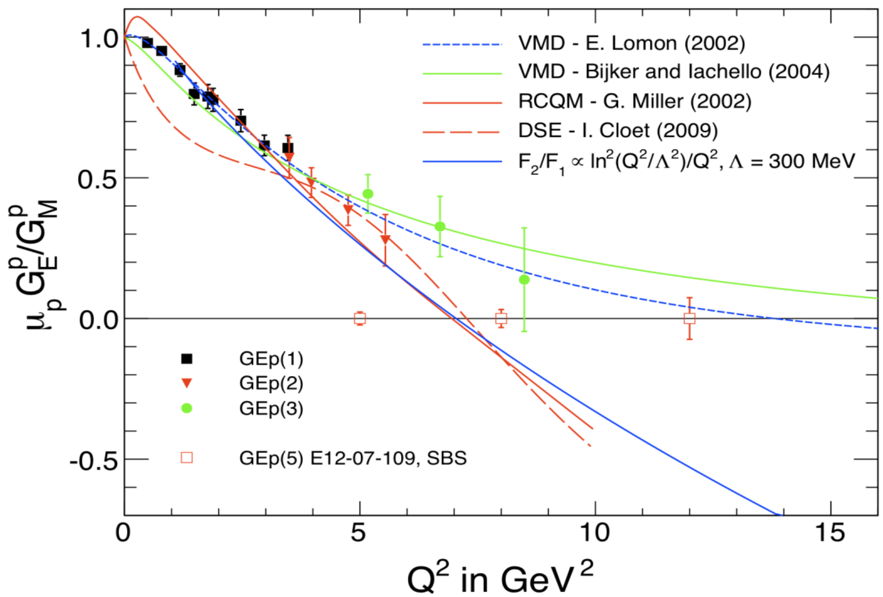
Quasi-photon

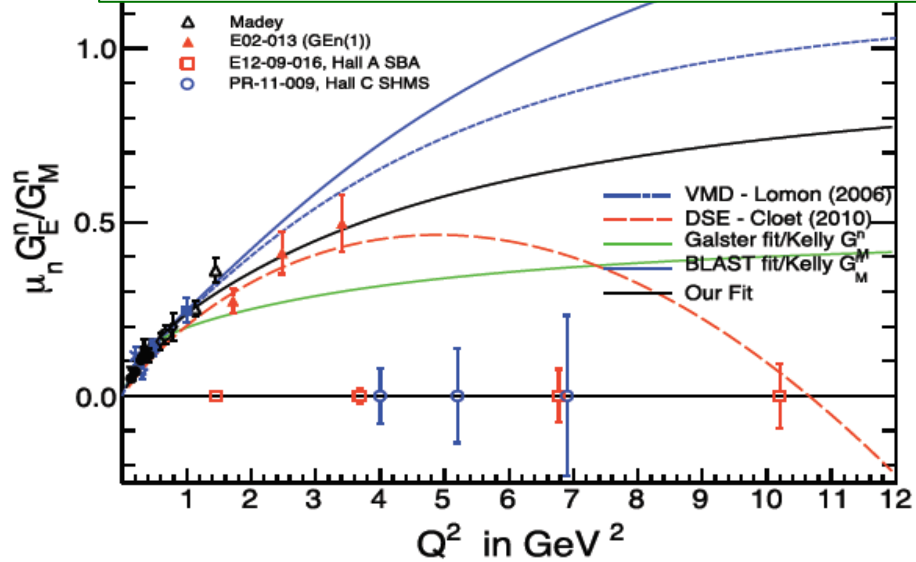
8.4-9.0 GeV
Linearly polarized photons

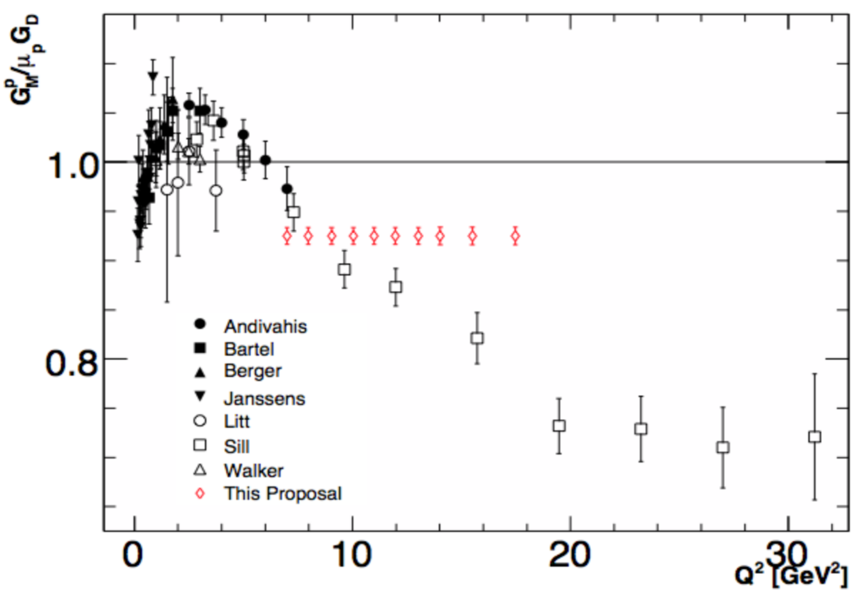


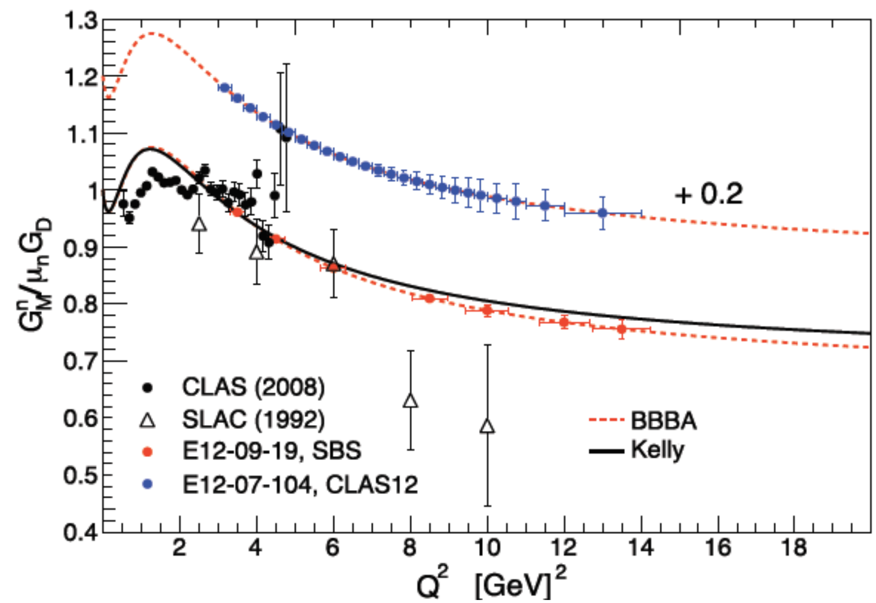
Nucleon form factors – JLab12

Many approved experiments at JLab 12



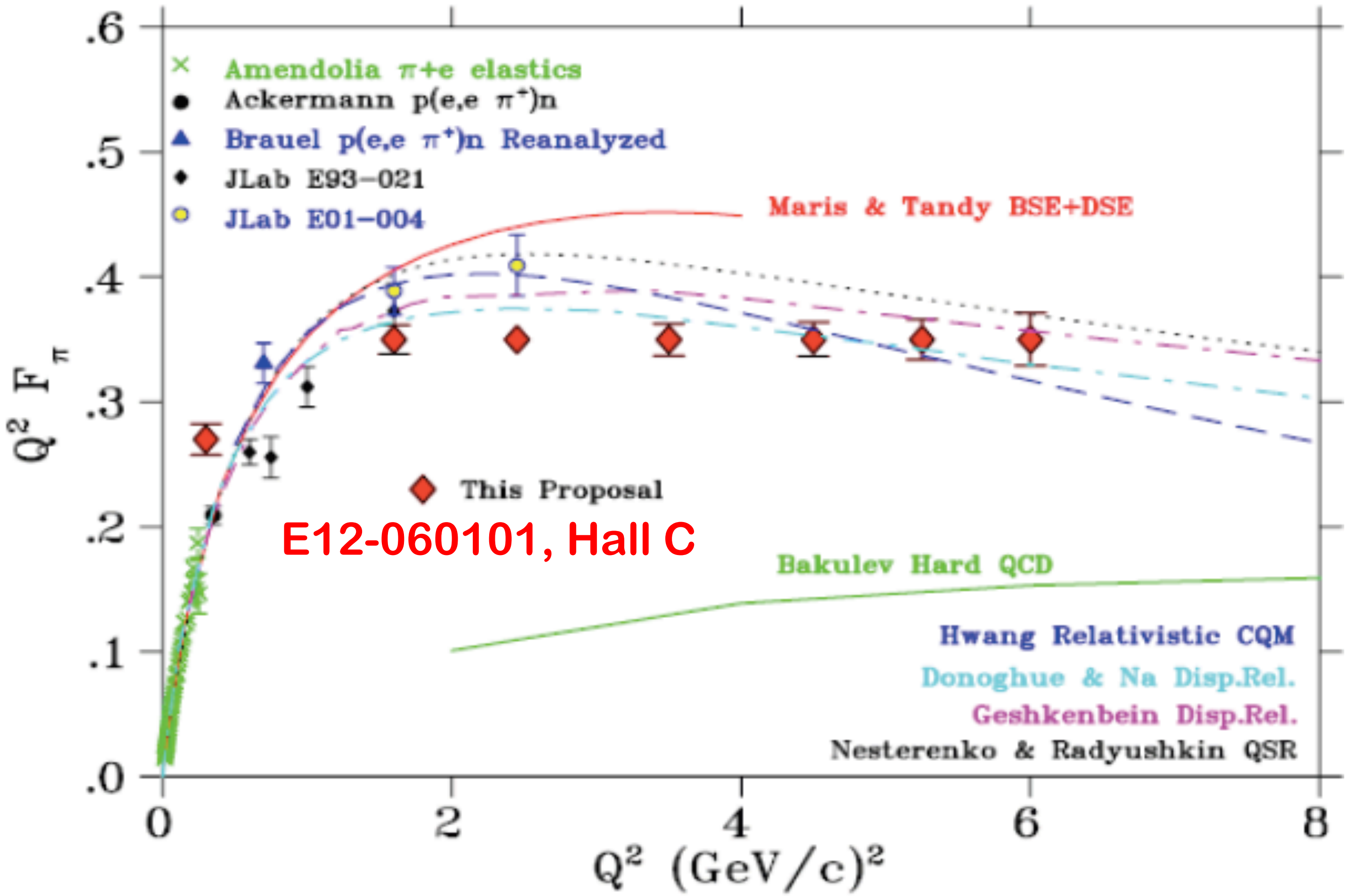






Charged pion form factor – JLab12

❑ **Transition from non-perturbative to perturbative regime:**

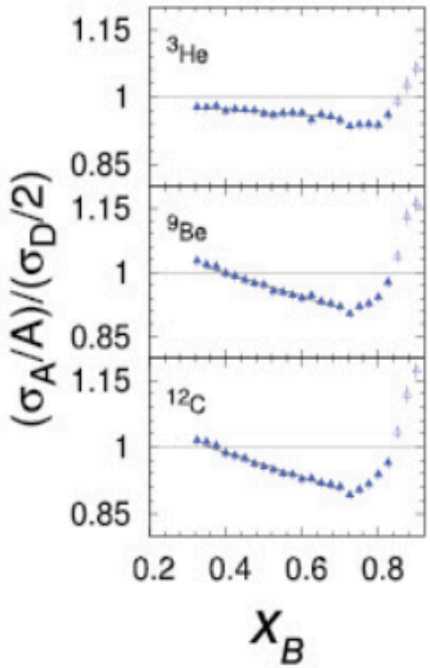


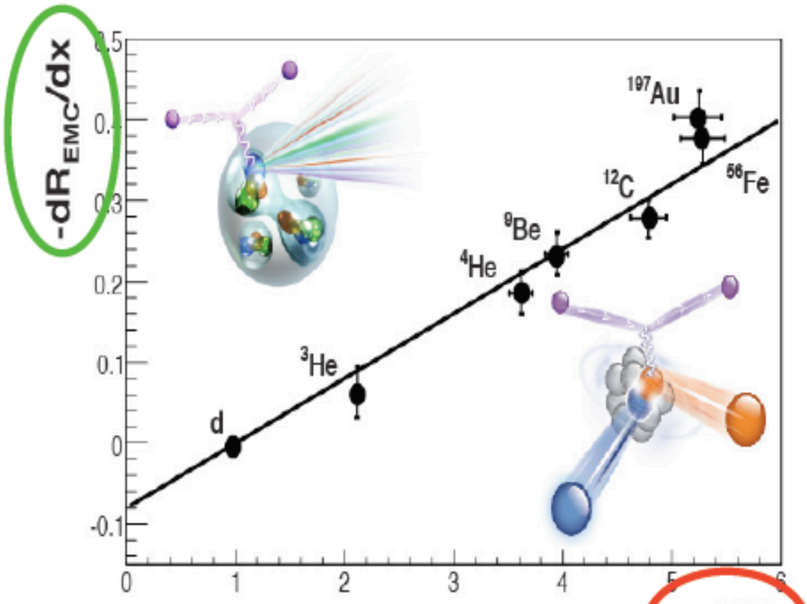
✧ *Models from relativistic CQM to pQCD calculations*

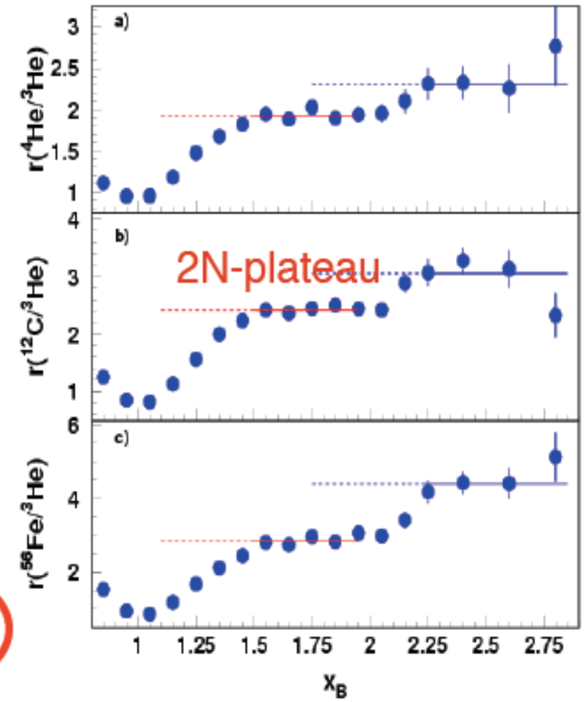
✧ *pQCD makes an exact prediction for $Q^2 \rightarrow \infty$*

EMC effects and SRCs – JLab12

- **Inclusive nuclear DIS cross section at x > 1:**



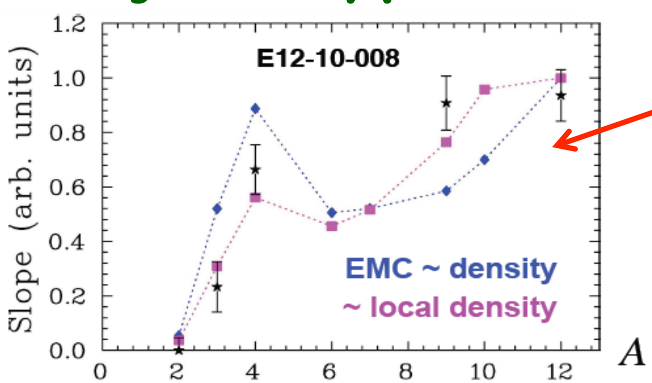




$$a_2(A/d) = \left(\frac{2}{A}\right)\frac{\sigma_A(\text{2N-plateau})}{\sigma_d(\text{2N-plateau})}$$

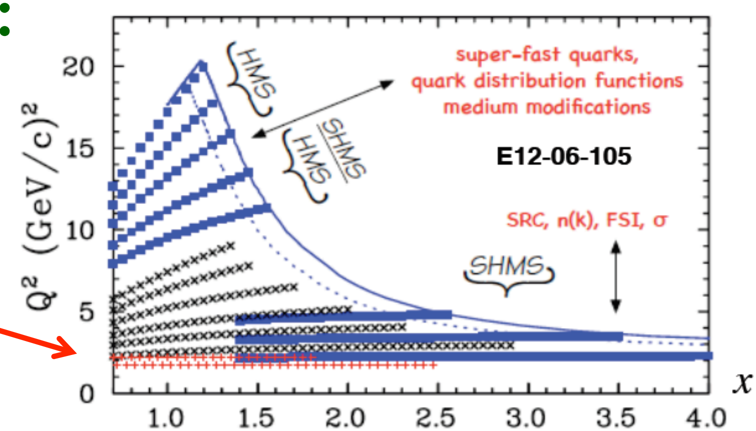
K. Egiyan et al, PRL96, 082501 (2006)

- **Many new approved expts at JLab12:**



A with different EMC slops

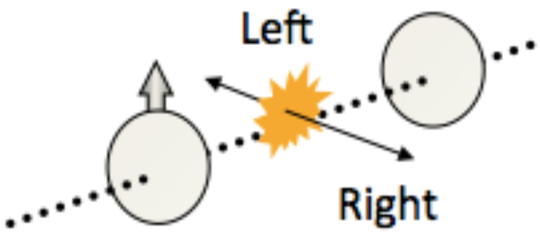
kinematic reach



Polarized p+A at RHIC – saturation physics

- **Asymmetry – A_N:**

$$A_N = \frac{1}{P}\frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi}$$



- **Predictions:**

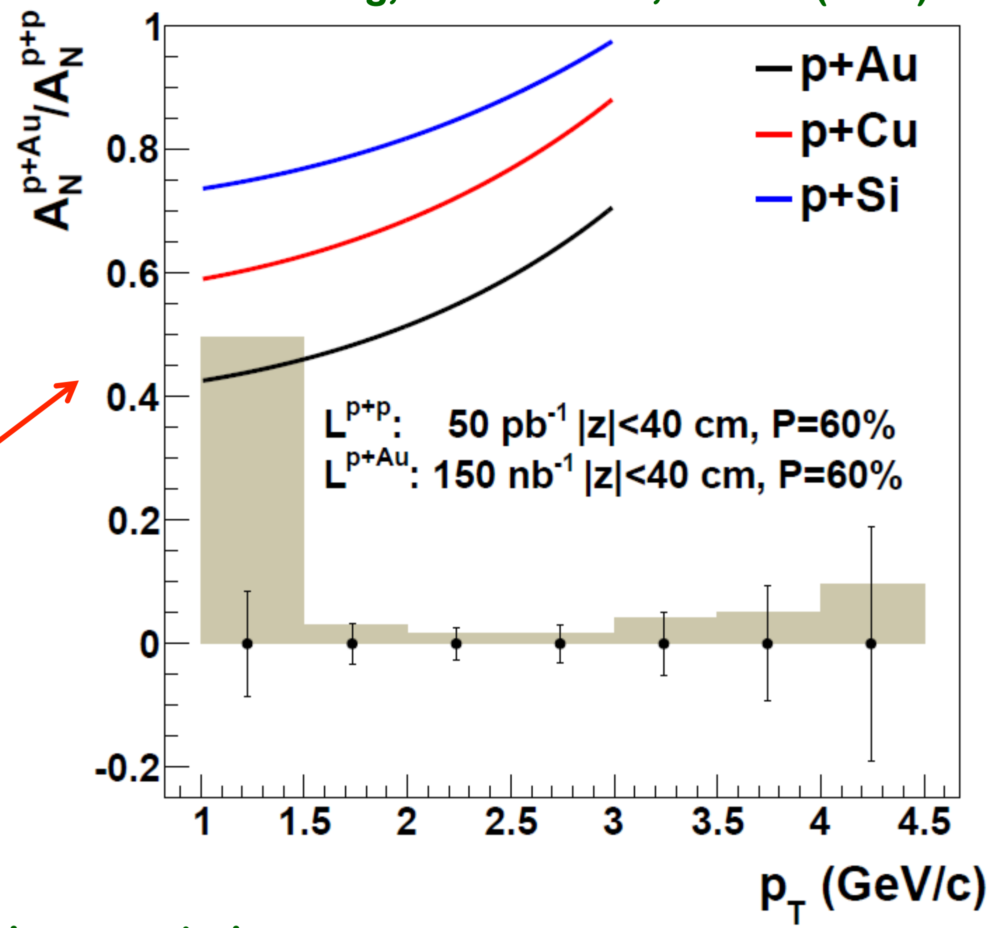
$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 << Q_{sA}^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2}\, e^{P_{h\perp}^2 \delta^2 / Q_{sp}^2}$$

But,

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp} \gg Q_s^2} \longrightarrow \begin{cases} 0 & \text{Kovchegov, et al.} \\ 1 & \text{Kang, et al.} \end{cases}$$

Kovchegov, Sievert: PRD 86, 034028 (2012)

Kang, Yuan: PRD 84, 034019 (2011)

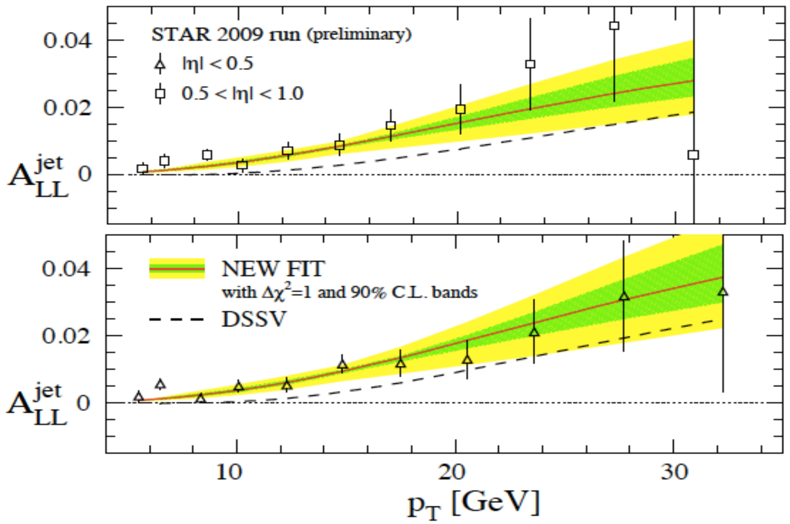


Unique capability of RHIC!

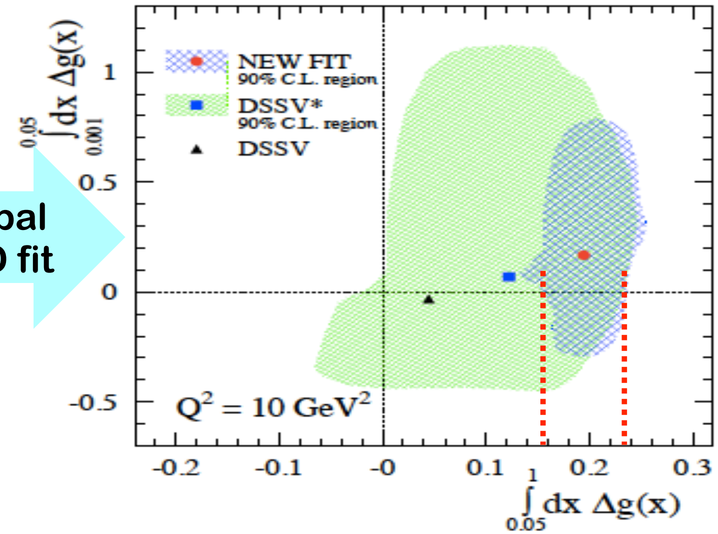
Helicity contribution to proton's spin (RHIC)

❑ Gluon polarization – $\Delta g(x)$:

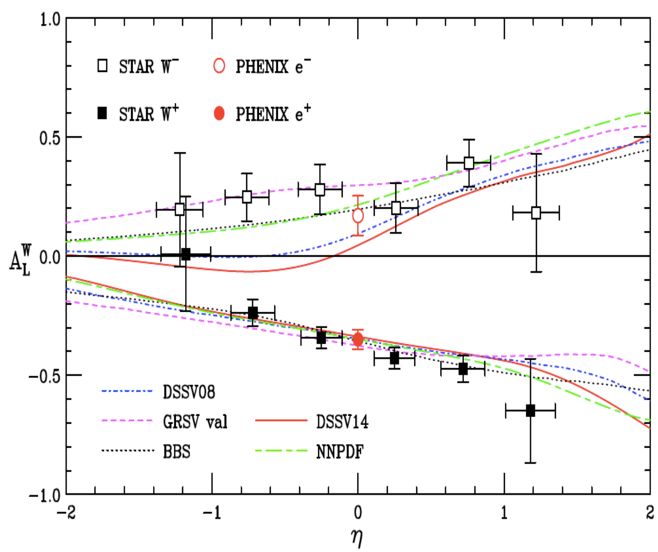
See Surrow's talk

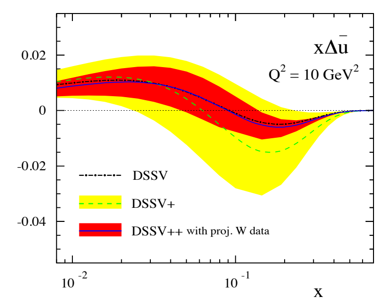


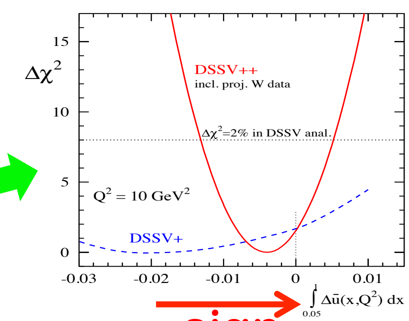
Global QCD fit



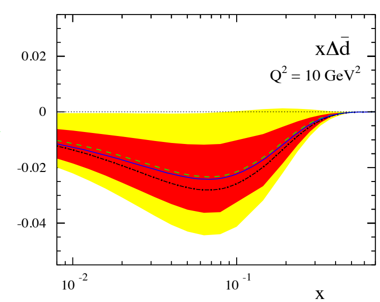
❑ Sea polarization – Δ qbar(x):

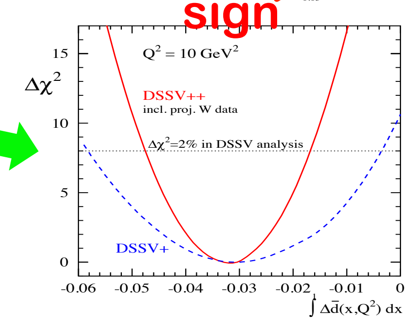






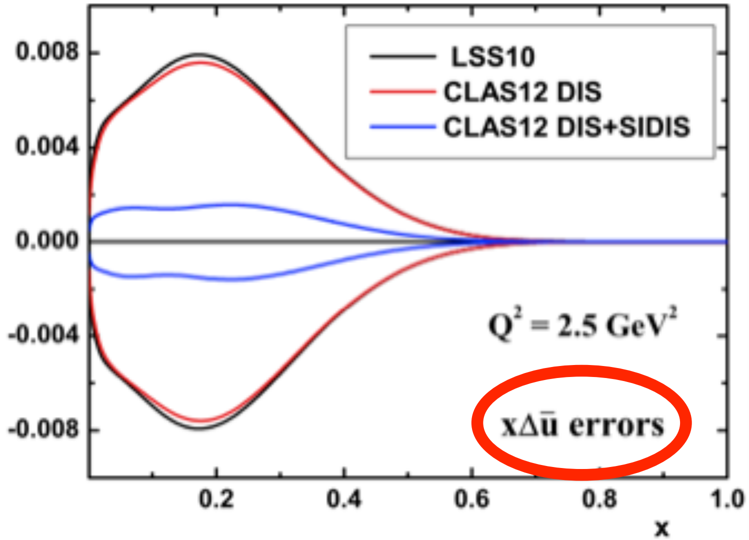
sign

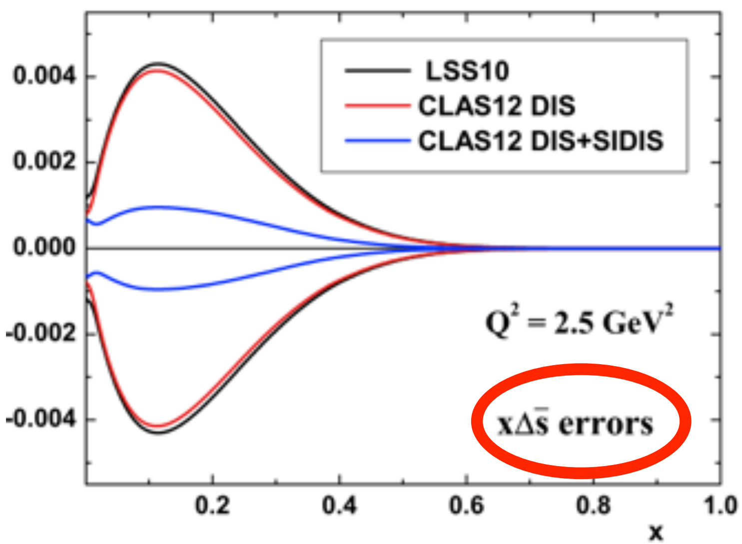


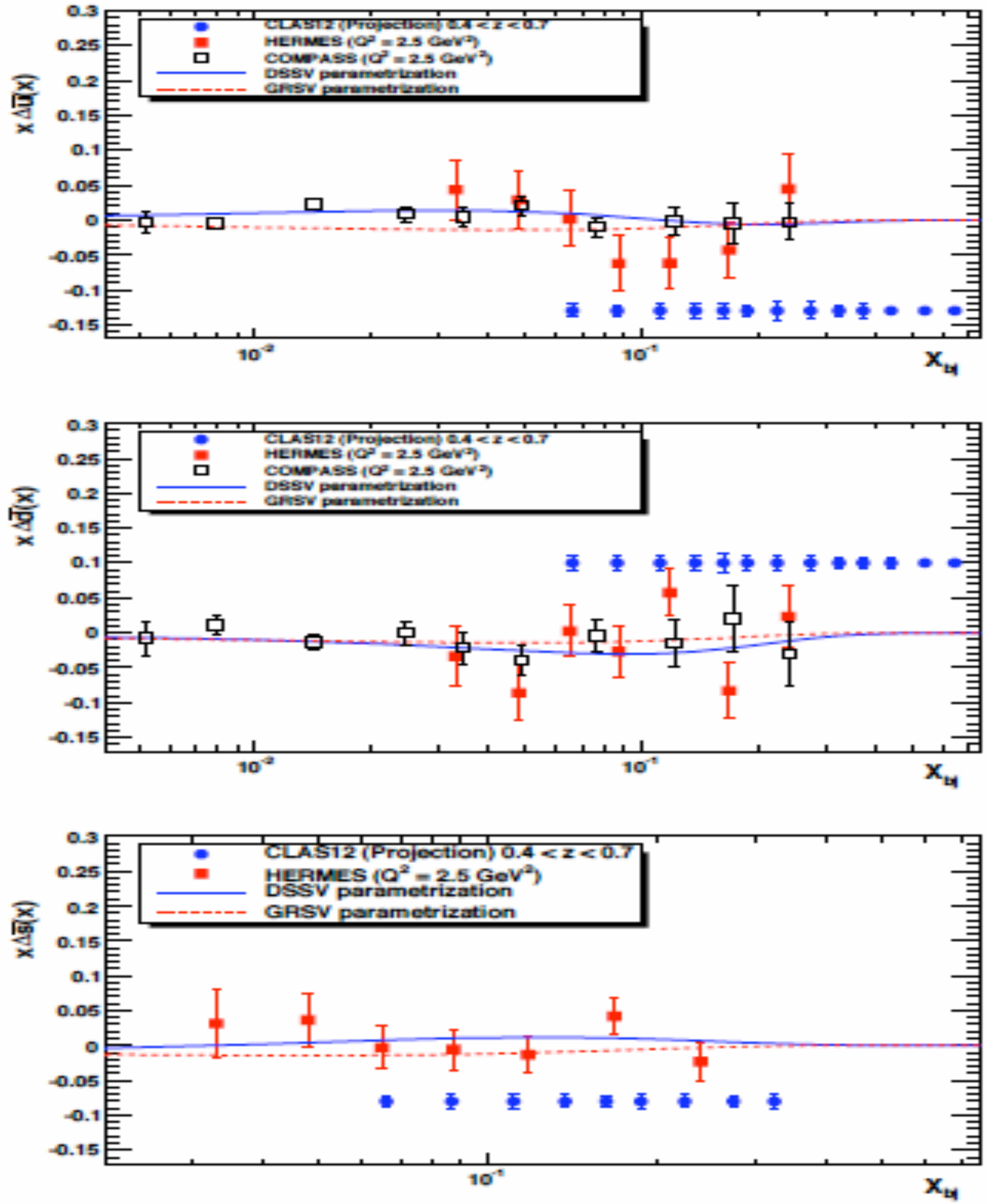


Helicity contribution to proton's spin (JLab)

❑ CLAS12 projections:



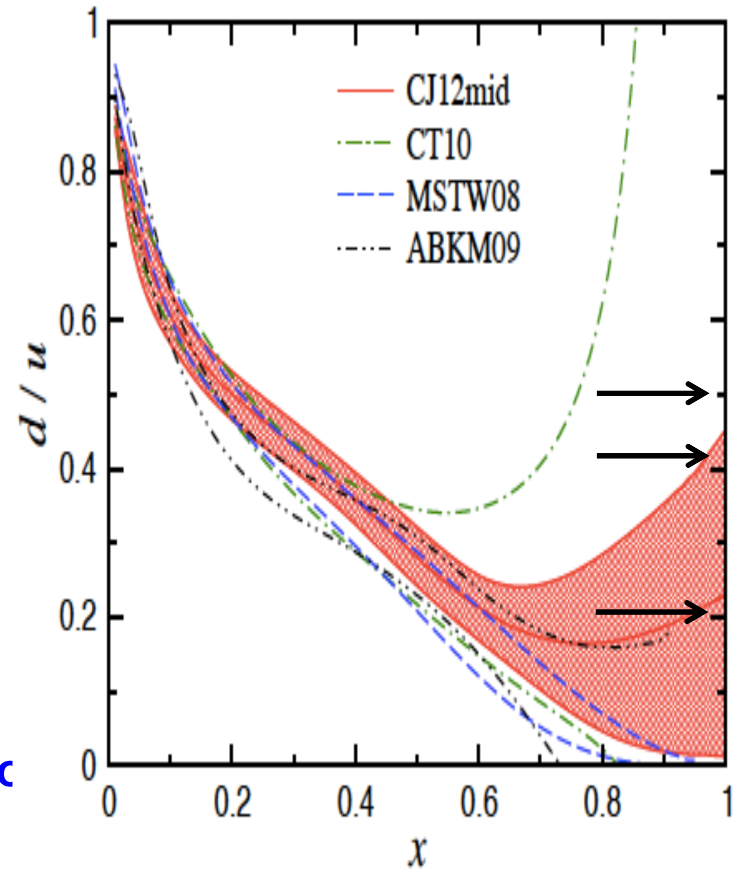




PDFs at large x

❑ **Testing ground for hadron structure at x → 1:**

- ✧ $d/u \to 1/2$ — **SU(6) Spin-flavor symmetry**
- ✧ $d/u \to 0$ — **Scalar diquark dominance**
- ✧ $d/u \to 1/5$ — **pQCD power counting**
- ✧ $d/u \to \dfrac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \approx 0.42$ — **Local quark-hadrc duality**



PDFs at large x

❑ **Testing ground for hadron structure at x → 1:**

✧ $d/u \to 1/2$ — **SU(6) Spin-flavor symmetry** — ✧ $\Delta u/u \to 2/3$, $\Delta d/d \to -1/3$

✧ $d/u \to 0$ — **Scalar diquark dominance** — ✧ $\Delta u/u \to 1$, $\Delta d/d \to -1/3$

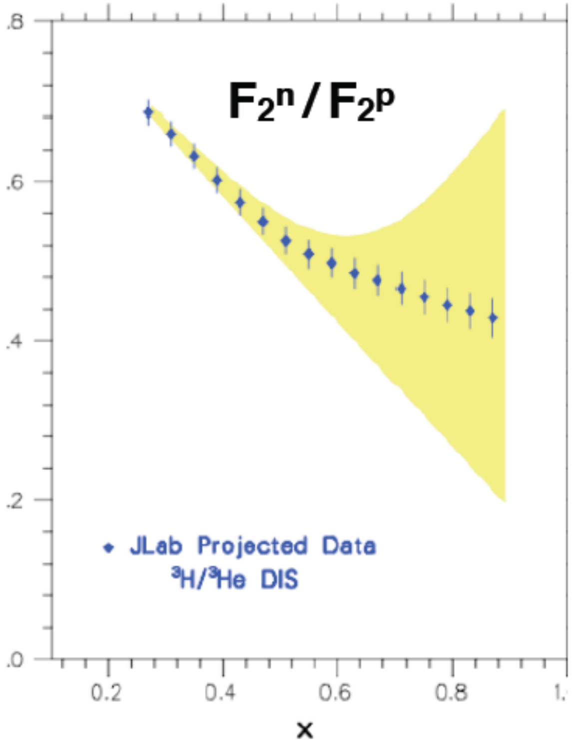
✧ $d/u \to 1/5$ — **pQCD power counting** — ✧ $\Delta u/u \to 1$, $\Delta d/d \to 1$

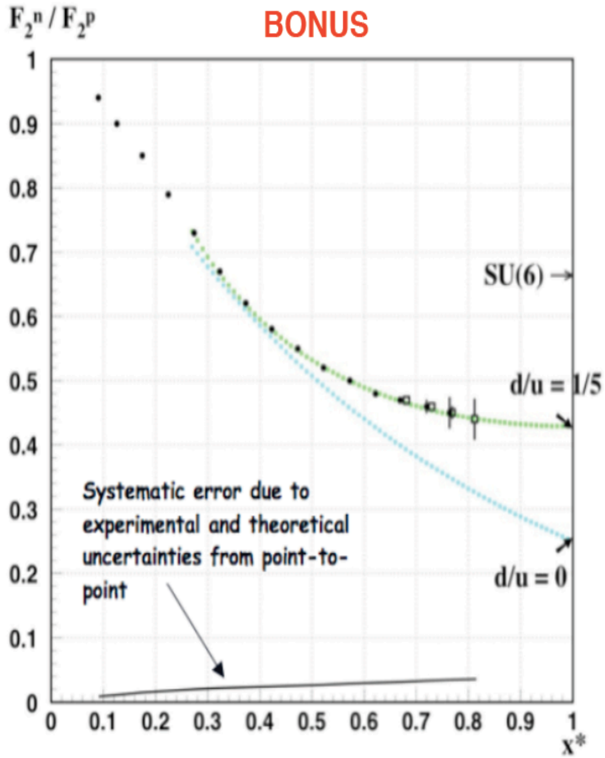
✧ $d/u \to \dfrac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \approx 0.42$ — **Local quark-hadron duality** — ✧ $\Delta u/u \to 1$, $\Delta d/d \to 1$

Upcoming experiments – JLab12

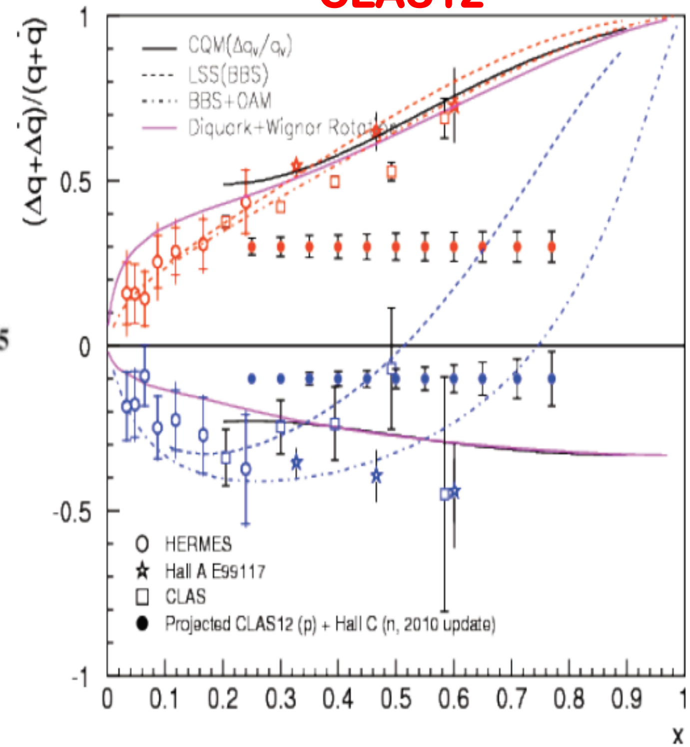
- ❑ **NSAC milestone HP14 (2018):**

MARATHON





CLAS12



Plus many more JLab experiments:

E12-06-110 (Hall C on ^{3}He), E12-06-122 (Hall A on ^{3}He),

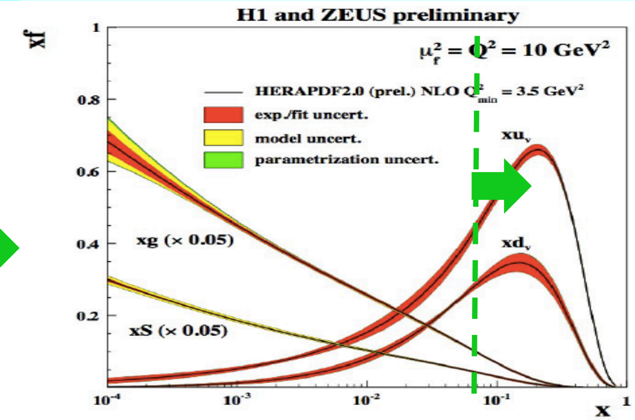
E12-06-109 (CLAS on NH_3, ND_3), …

and Fermilab E906, …

Plus complementary Lattice QCD effort

Lattice calculations of hadron structure

Lattice QCD



X-dep distributions

❑ New ideas – from quasi-PDFs (lattice calculable) to PDFs:

✧ High P_z effective field theory approach:

$$\tilde{q}(x,\mu^2,P_z) = \int_x^1 \frac{dy}{y}\, Z\left(\frac{x}{y},\frac{\mu}{P_z}\right) q(y,\mu^2) + \mathcal{O}\left(\frac{\Lambda^2}{P_z^2},\frac{M^2}{P_z^2}\right)$$

Ji, et al., arXiv:1305.1539, 1404.6680

✧ QCD collinear factorization approach:

$$\tilde{q}(x,\mu^2,P_z) = \sum_f \int_0^1 \frac{dy}{y}\, \mathcal{C}_f\left(\frac{x}{y},\frac{\mu^2}{\bar{\mu}^2},P_z\right) f(y,\bar{\mu}^2) + \mathcal{O}\left(\frac{1}{\mu^2}\right)$$

Ma and Qiu, arXiv:1404.6860, 1412.2688

Ishikawa, Qiu, Yoshida,

Parameter like $\sqrt{s}$

Factorization scale

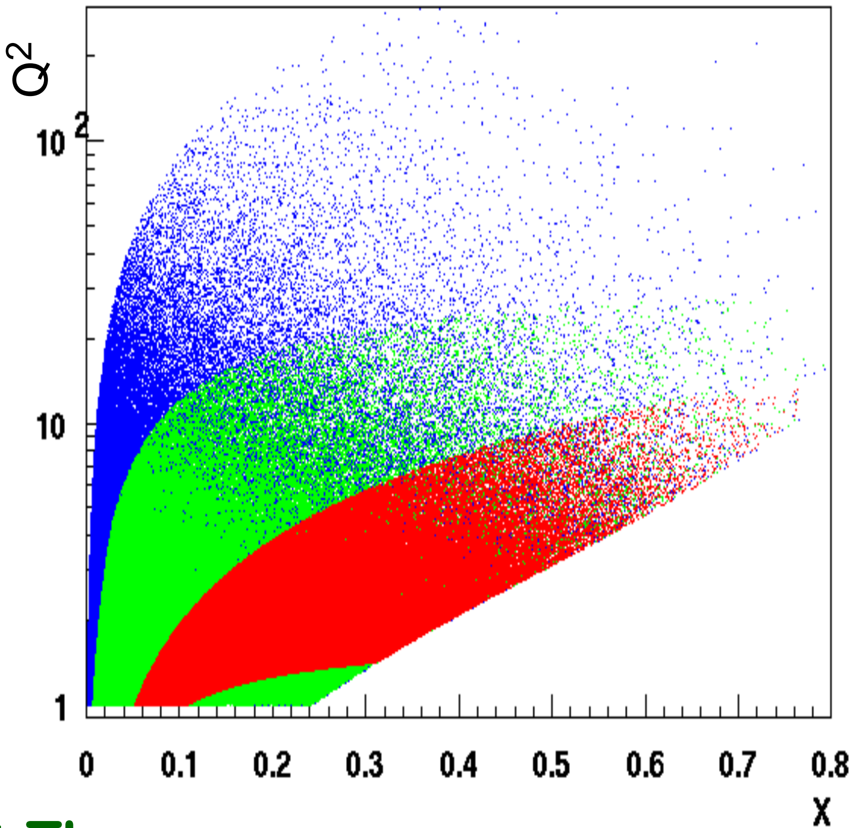
High twist Power corrections

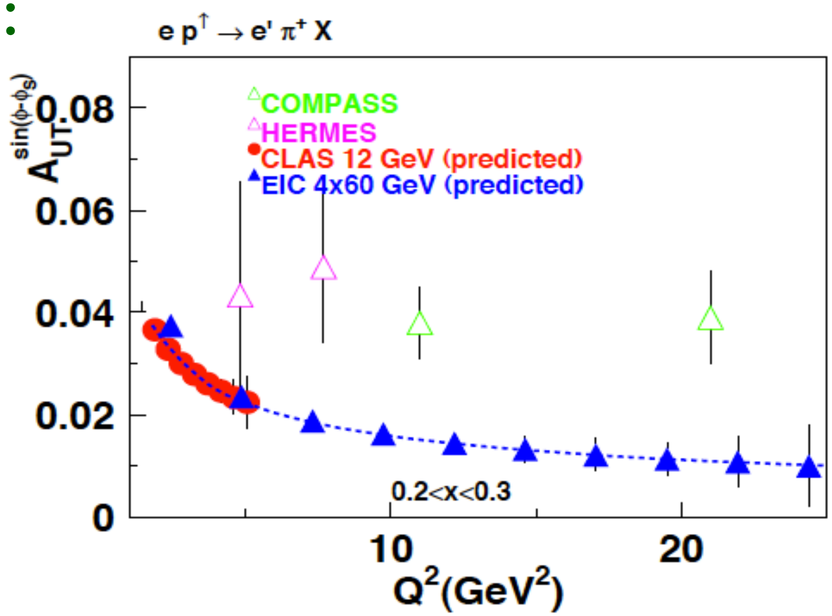
Unmatched potential: ***PDFs of proton, neutron, pion, …, and TMDs and GPDs, …***

The Future: TMDs, GPDs, and OAM

See talks by Allada, Deshpande, Ji, Sabatie, Yuan

- Sivers TMD – from JLab12 to EIC:





JLab@12GeV (25/50/75)
→ $0.1<x_B<0.7$: valence quarks
EIC √s = 140, 50, 15 GeV
→ $10^{-4}<x_B<0.3$: gluons and quarks, higher P_T and Q^2.

- Theory:
  - ✧ Theoretical control of Q^2-evolution of TMDs, and its sensitivity on Non-perturbative input TMDs – confined parton motion in hadrons
  - ✧ Any connection to orbital angular momentum?

Summary

- After 40 years, we have learned a lot of QCD dynamics, especially, at very short-distance - less than 0.1 fm
- There still a long-way to go to completely understand the hadron physics from QCD
- GPDs and TMDs are fundamental, and measurable with controlled approximation. They are necessary for getting a comprehensive 3D ``view'' of hadron’s internal structure
- Nuclear physics community in the US has a rigorous program to pursue the physics of hadrons, with complementary facilities: RHIC, Fermilab, JLab12, EIC

Thank you!

Backup Slides

Quark and gluon helicity contribution

- **QCD Factorization at the leading power:**

  Link the helicity distributions to the longitudinal spin asymmetries

- **Quark helicity at x ~ 1:**

Roberts et al, 2013
See also Peng's talk

	$\frac{F_2^n}{F_2^p}$	$\frac{d}{u}$	$\frac{\Delta d}{\Delta u}$	$\frac{\Delta u}{u}$	$\frac{\Delta d}{d}$	A_1^n	A_1^p
DSE-1	0.49	0.28	−0.11	0.65	−0.26	0.17	0.59
DSE-2	0.41	0.18	−0.07	0.88	−0.33	0.34	0.88
$0^+_{[ud]}$	$\frac{1}{4}$	0	0	1	0	1	1
NJL	0.43	0.20	−0.06	0.80	−0.25	0.35	0.77
SU(6)	$\frac{2}{3}$	$\frac{1}{2}$	$-\frac{1}{4}$	$\frac{2}{3}$	$-\frac{1}{3}$	0	$\frac{5}{9}$
CQM	$\frac{1}{4}$	0	0	1	$-\frac{1}{3}$	1	1
pQCD	$\frac{3}{7}$	$\frac{1}{5}$	$\frac{1}{5}$	1	1	1	1

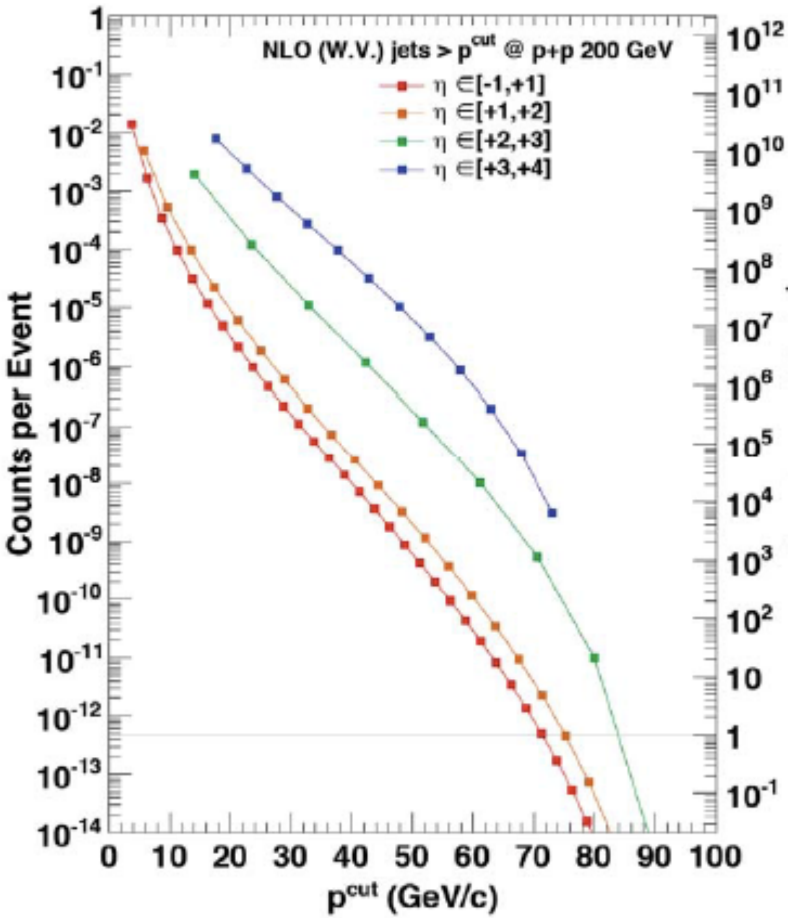
Extremely sensitive to the nucleon's partonic structure and internal spin correlation!

Big difference between two approximations of the DSE treatments

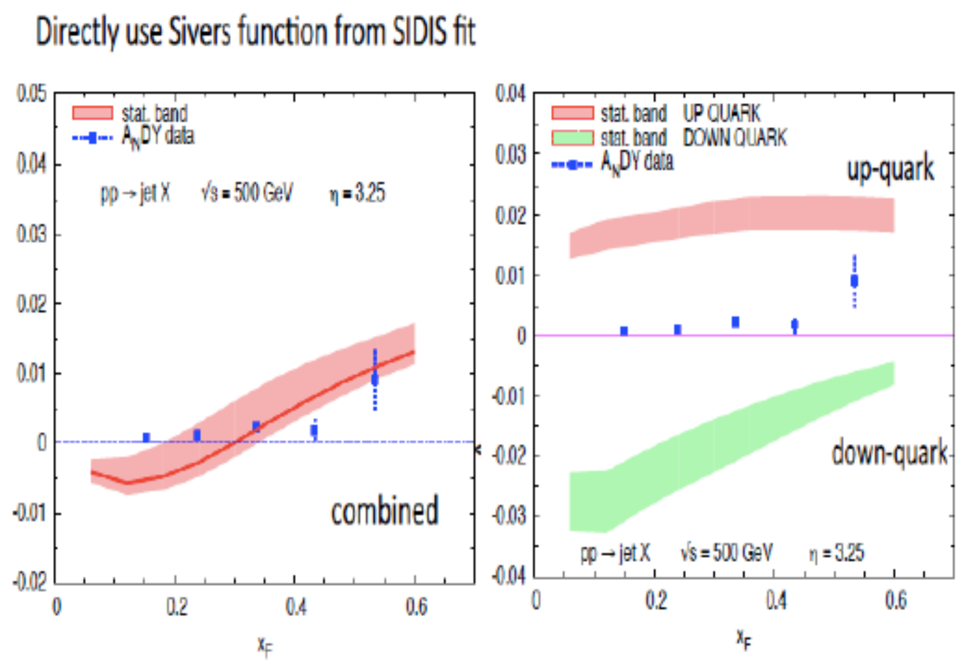
The Future: TMDs, GPDs, and OAM

- Sivers Effect – from fsPHENIX:

Lajoie, 2014



fsPHENIX Jet acceptance $1.7 < \eta < 3.3$
with anti-k_T R=0.7



- Theory:

✧ TMD approach vs high twist collinear approach, and parton correlation!

The Future: TMDs, GPDs, and OAM

See talk by Chen

❑ SoLId at JLab:

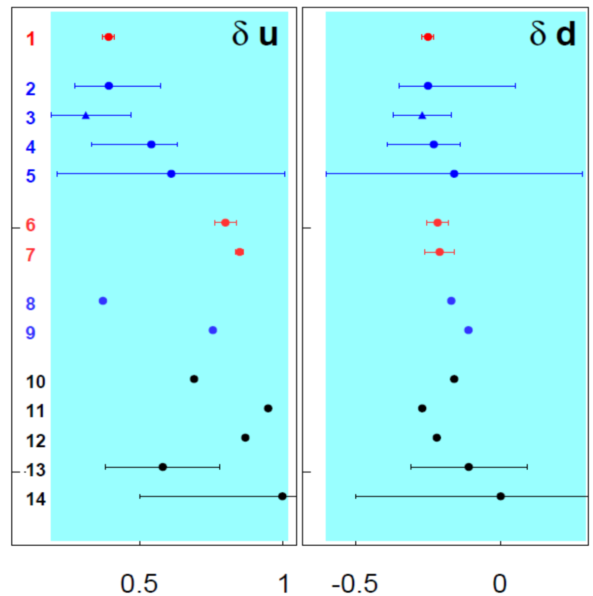
- ✧ **Transversity:**

  Chiral-odd,
  no coupling to gluon,
  Transverse spin flip,
  Least known PDFs…

- ✧ **Tensor charges:**

  Fundamental, many predictions

Tensor Charges



SoLID projections

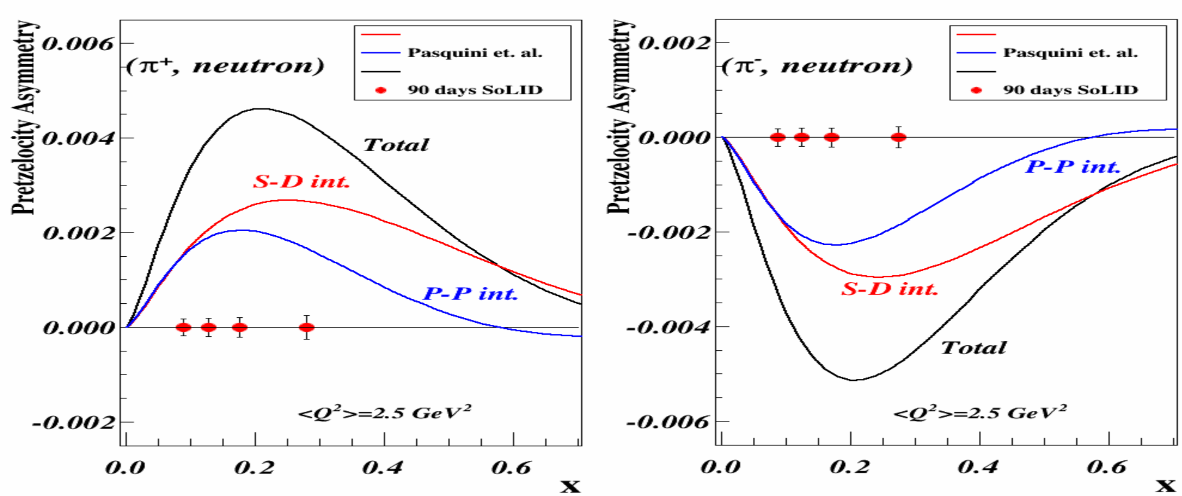
Extractions from existing data

LQCD

DSE

Models

- ✧ **Pretzelosity: TMD with ΔL=2 (L=0 an L=2 interference)**



Model relates it to OAM