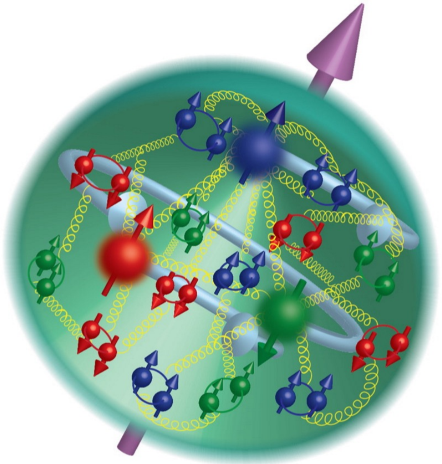
Title suggested by Yi Yin

质子扒马褂



Title suggested by Yi Yin

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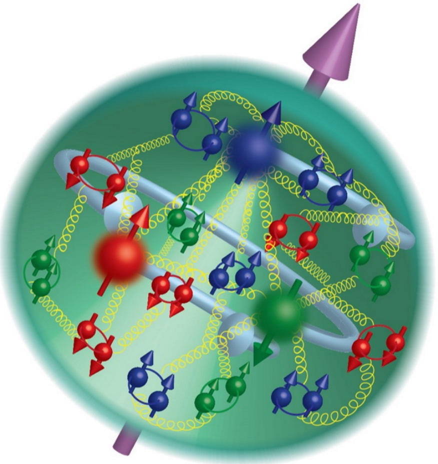
自旋结构



SpicyGluons
胶麻2024

Spinning Gluons
胶旋

Spin in high energy experiments

Zhang, Jinlong (张金龙), Shandong University

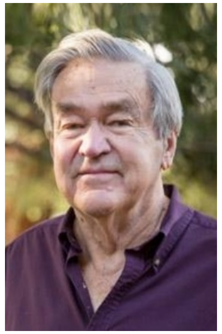
A lot materials in this talk are stolen from A. Deshpande, C. Gagliardi, T. Liu, E. Sichtermann etc.

20th Century could be called “Century of Spin Surprises!”

“Experiments with spin have killed more theories in physics, than any other single physical variable”

Elliot Leader

“If theorists had their way, they would ban all experiments involving spin”



James D. Bjorken

Spin Milestones

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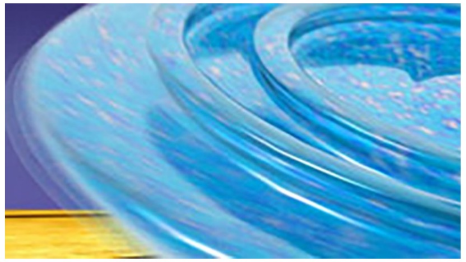
nature › nature physics › milestone

Milestone | 28 February 2008

Nature Milestones in Spin

The Milestones are a series of specially written articles, highlighting the most influential discoveries in the field of 'spin' since 1896. *Nature Milestones in Spin* also includes a Collection of relevant articles and an online-only Library of papers and reviews from Nature Publishing Group.



Milestones

Milestones
28 Feb 2008
Nature Physics

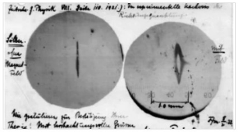
Physics is set spinning

Andreas Trabesinger

Milestones
28 Feb 2008
Nature Physics

Answers on a postcard

Ed Gerstner



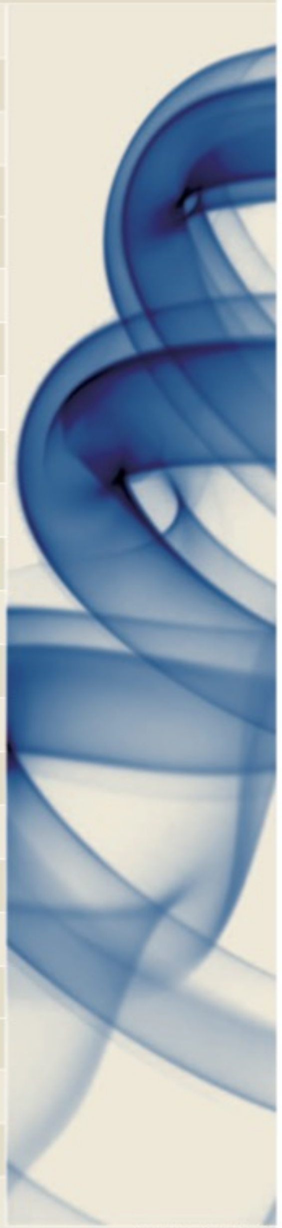
Milestones
28 Feb 2008
Nature Physics

The spinning electron

Alison Wright

MILESTONES TIMELINE

1896	Zeeman effect (1)
1922	Stern–Gerlach experiment (2)
1925	The spinning electron (3)
1928	Dirac equation (4)
	Quantum magnetism (5)
1932	Isospin (6)
1940	Spin–statistics connection (7)
1946	Nuclear magnetic resonance (8)
1950s	Development of magnetic devices (9)
1950–1951	NMR for chemical analysis (10)
1951	Einstein–Podolsky–Rosen argument in spin variables (11)
1964	Kondo effect (12)
1971	Supersymmetry (13)
1972	Superfluid helium-3 (14)
1973	Magnetic resonance imaging (15)
1975–1976	NMR for protein structure determination (16)
1978	Dilute magnetic semiconductors (17)
1988	Giant magnetoresistance (18)
1990	Functional MRI (19)
	Proposal for spin field-effect transistor (20)
1991	Magnetic resonance force microscopy (21)
1996	Mesoscopic tunnelling of magnetization (22)
1997	Semiconductor spintronics (23)



A brief history of spin

As an English word, it existed before the 12th century

A brief history of spin (electron)

As a fundamental observable of (sub)-atomic physics it was ”discovered” by **Goudsmit** & **Uhlenbeck** (1925)

- Authur Compton (1921), E. H. Kennard (1922)
- R. Kronig (1925), Nature 117, 550 (1926)

  Pauli: "This is surely a clever idea, but the nature is not like that."
- S. Goodsmit and G. Uhlenback, Naturwissenscaten, 12, 953 (1925), Nature 117, 264 (1926).

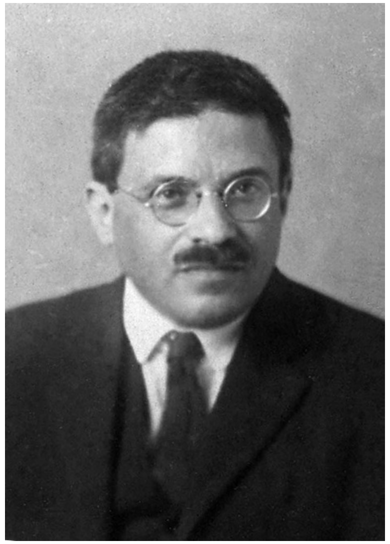
  g_e = 2 (Heisenberg) Einstein, "surely there must be relativistic effect."
- L. H. Thomas, Nature 117, 515 (1926).

The discovery of the electron spin --*by Goudsmit*
https://www.lorentz.leidenuniv.nl/history/spin/goudsmit.html

A brief history of spin (electron)

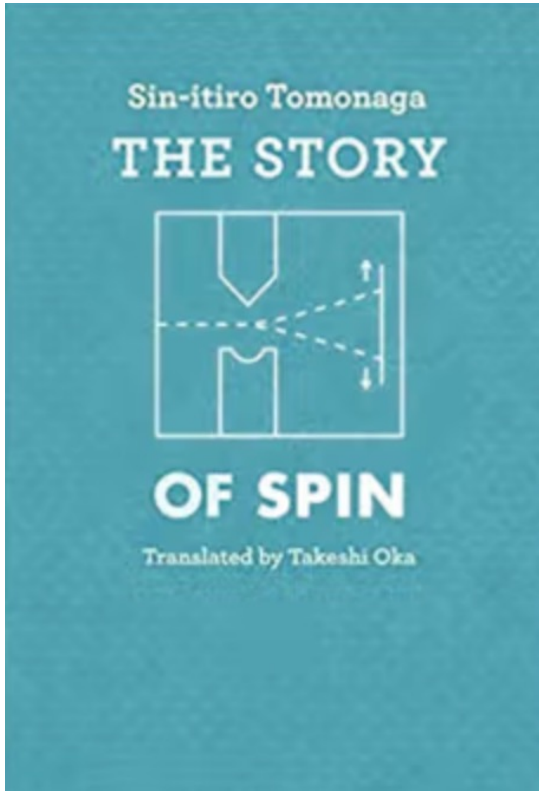
“Well, this is a good idea. Your idea may be wrong, but since both of you are so young without any reputation, you would not loose anything by making a stupid mistake.”

-- Ehrenfest upon receiving Goudsmit & Uhlenbeck



A brief history of spin (proton)

details, see



The story of the proton spin begins in 1927

Hund: rotational part of specific heat of H_2 molecule (theoretical)

Hori: band spectrum of H_2 (experimental)

spectroscopy and statistics do not agree

Dennison: resolves discrepancy between their results and concludes (June 16th, 1927)

"precisely that the proton is a fermion of spin 1/2"

朝永振一郎

Proton has structure

1933 O. Stern: Magnetic moment of the proton

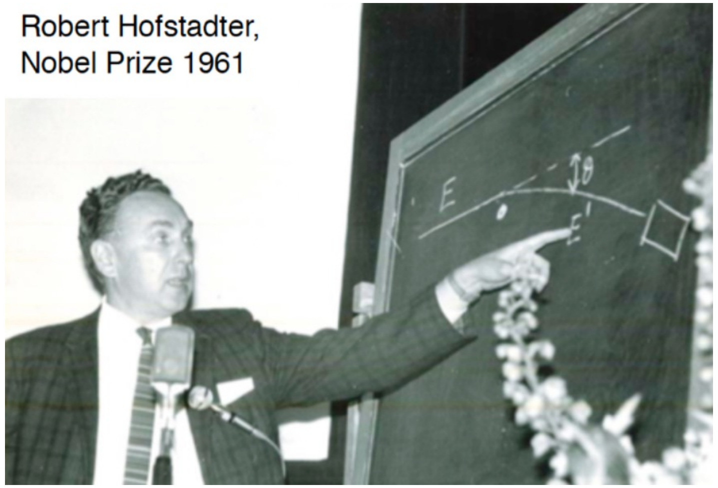
- expected: $\mu_p = e\hbar/2m_pc$ (since S_p =1/2)
- measured: $\mu_p = e\hbar/2m_pc(1+\kappa_p)!$ *first spin crisis*

anomalous magnetic moment (a.m.m) $\kappa_p = 1.5 \pm 10\%$

Nobel Prize 1943

1958 R. Hofstadter: Elastic Electron Scattering

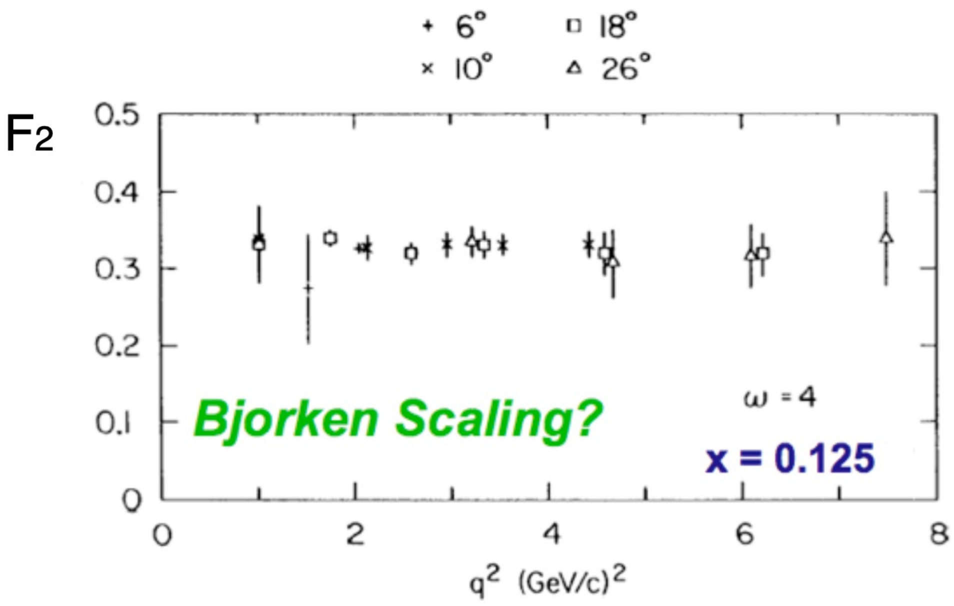
- Significant divergency from Mott cross section
- Charged radius: $(0.74{\pm}0.24){\times}10^{13}$ cm



Robert Hofstadter, Nobel Prize 1961

proton has internal structure

Confirmed by Deep Inelastic Scattering




J.T. Friedman

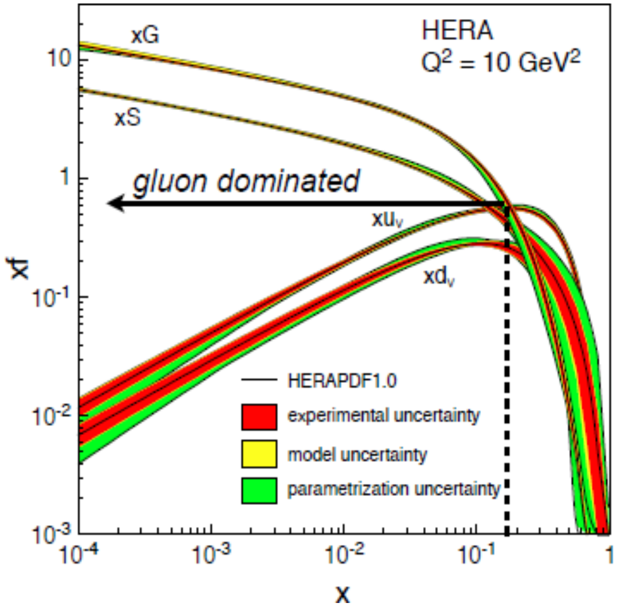

R. Taylor
Nobel Prize 1990

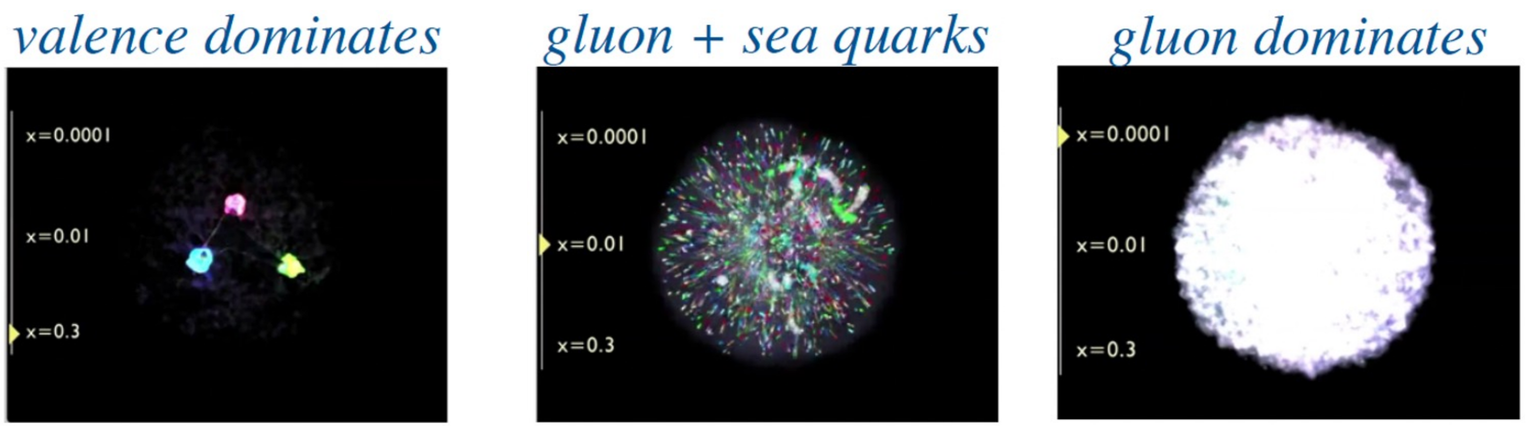

H.W. Kendall

- Point particles cannot be further resolved;
- their measurement does not depend on wavelength, hence Q^2

Precise unpolarized picture

From unpolarized fixed target and collider DIS experiments





R.G. Milner and R. Ent, *Visualizing the proton* 2022

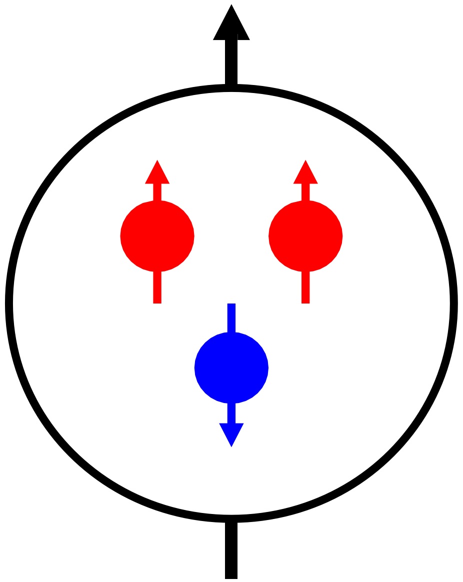
Probability of finding a quark or gluon inside the proton carrying a fraction *x* of the total momentum of the proton

- Find **more gluons** than anything else
- Gluons carry **half the momentum** of the proton

But, how do they constitute the nucleon Spin?

The proton in quark model

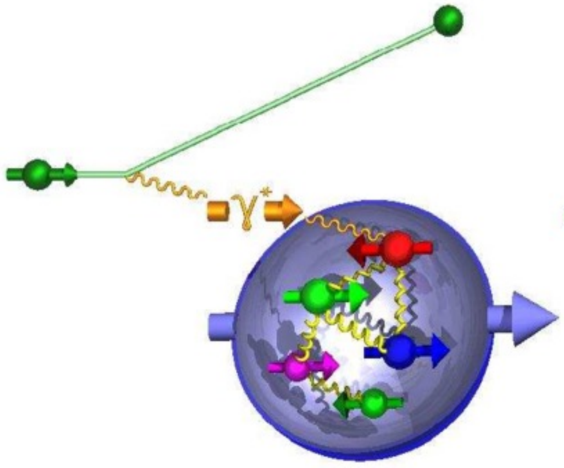
- The 2 up quarks and 1 down quark together explain the proton quantum numbers: charge, parity, *spin*, …
- Relativistic quark model
  - Quarks are no longer restricted to *s*-wave states
  - Quark spin accounts for ~60% of the proton spin
  - Rest of proton spin comes from quark orbital angular momentum

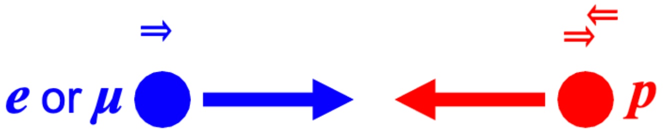


$$< S_p > = \frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

Probe proton spin with polarized DIS

- Measure deep-inelastic scattering with polarized electrons or muons off polarized protons
- Difference in cross section for like vs. unlike helicity beams provides information about spin orientations of the quarks inside the polarized proton





$$A_{\gamma * p} \propto \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

Experimental needs in pDIS

Polarized target, polarized beam

Polarized targets: hydrogen (p), deuteron (pn), helium (3He: 2p+n)

Polarized beams: electron, muon used in DIS experiments

Determine the kinematics: measure with high accuracy:

Energy of incoming lepton

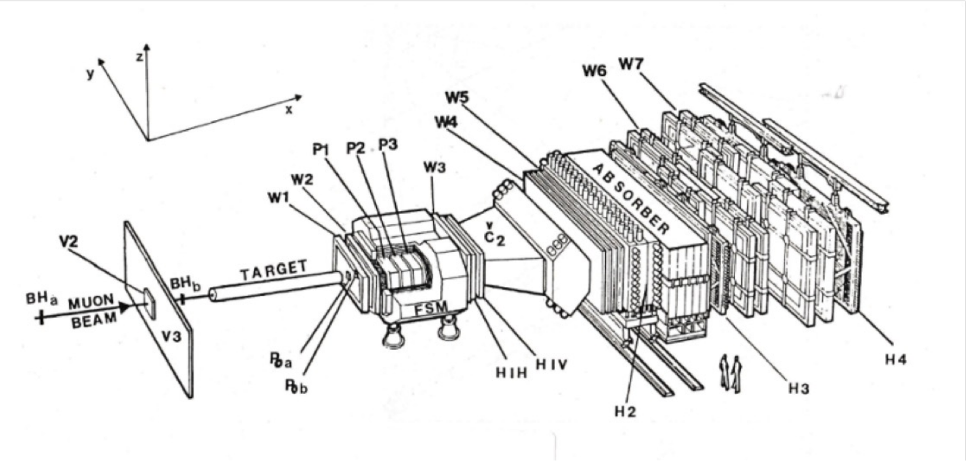
Energy, direction of scattered lepton: energy, direction

Good identification of scattered lepton

Control of false asymmetries:

Need excellent understanding and control of false asymmetries (time variation of the detector efficiency etc.)

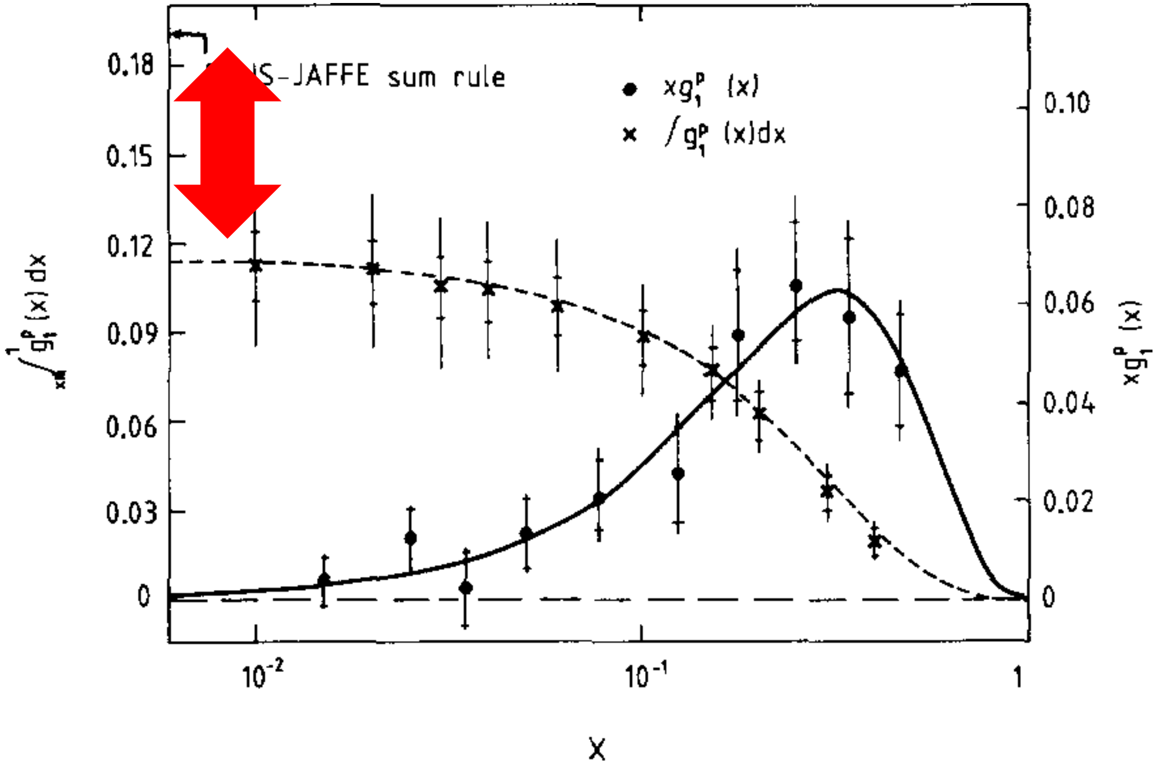
Proton crisis!



European Muon Collaboration at CERN

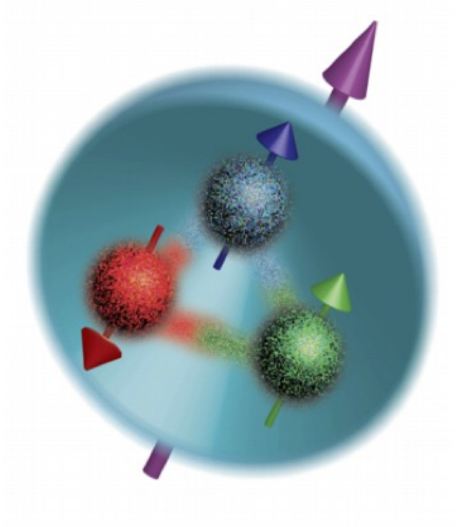
160 GeV muon beam

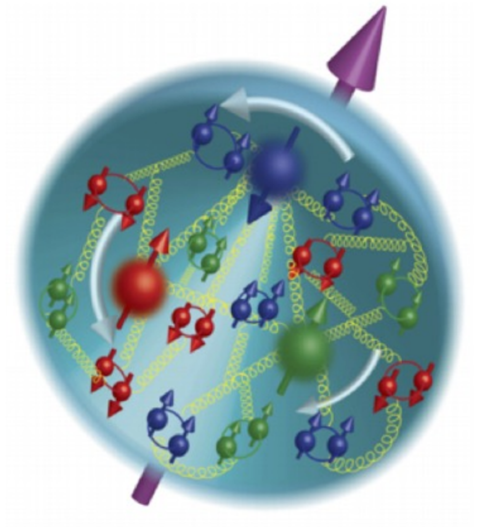
EMC, PLB 206, 364 1988



- First measurement over a broad kinematic region was performed by the European Muon Collaboration in the mid-’80s
- Found that quarks contribute only **(14 ± 9 ± 21)%** of the proton spin

Proton spin structure





Jaffe-Manohar 1990

$$< S_p > = \frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

quark spin

$$< S_p > = \frac{1}{2} = \frac{1}{2}\,\Delta\boldsymbol{\Sigma} + \Delta G + L_q + L_g$$

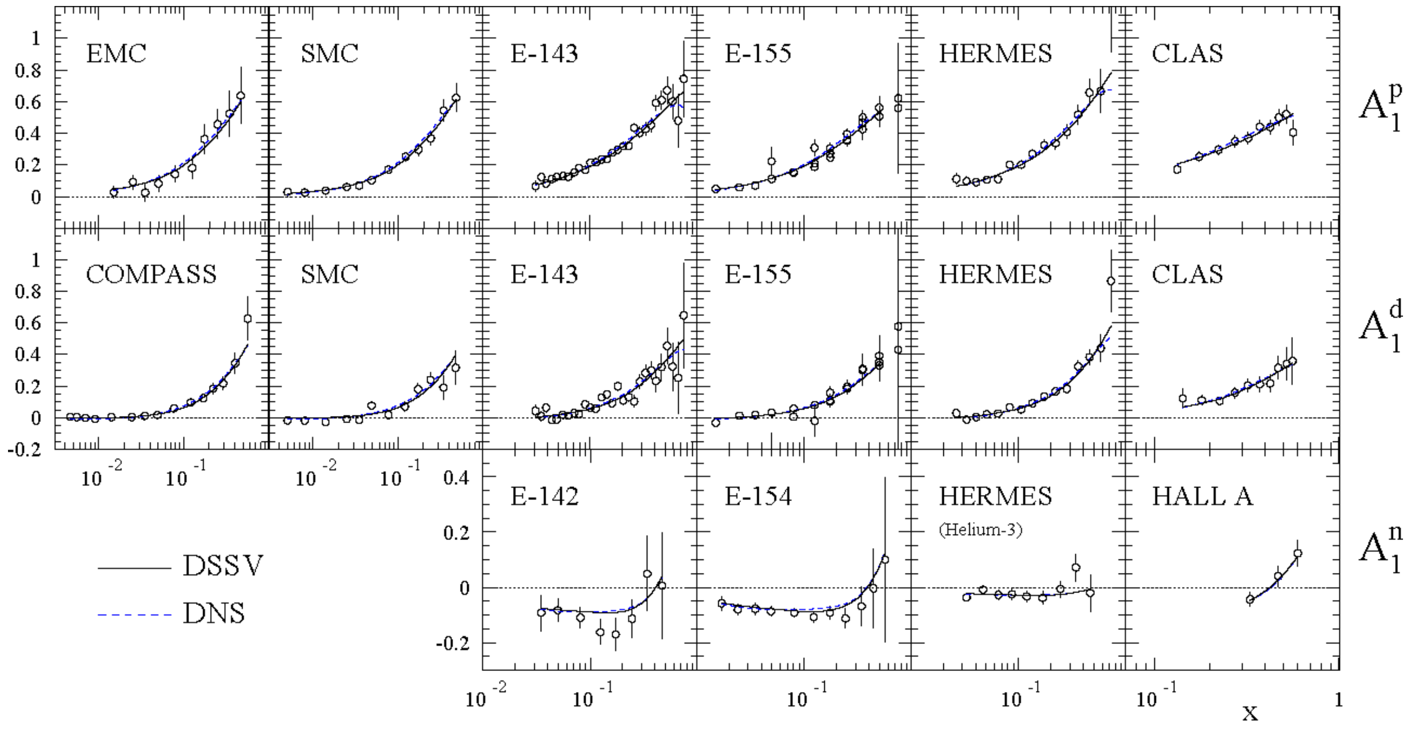
quark spin

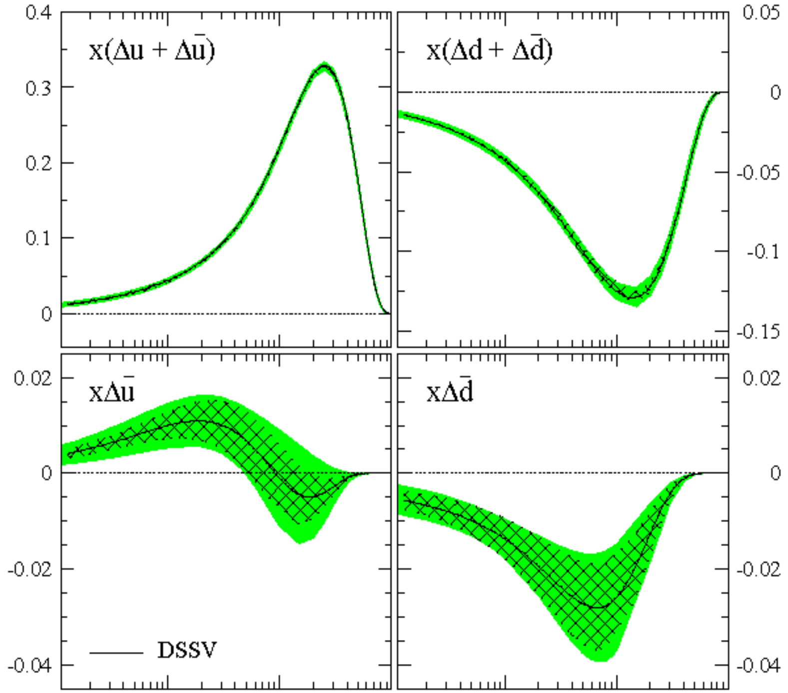
gluon spin

orbital angular momentum

Since EMC

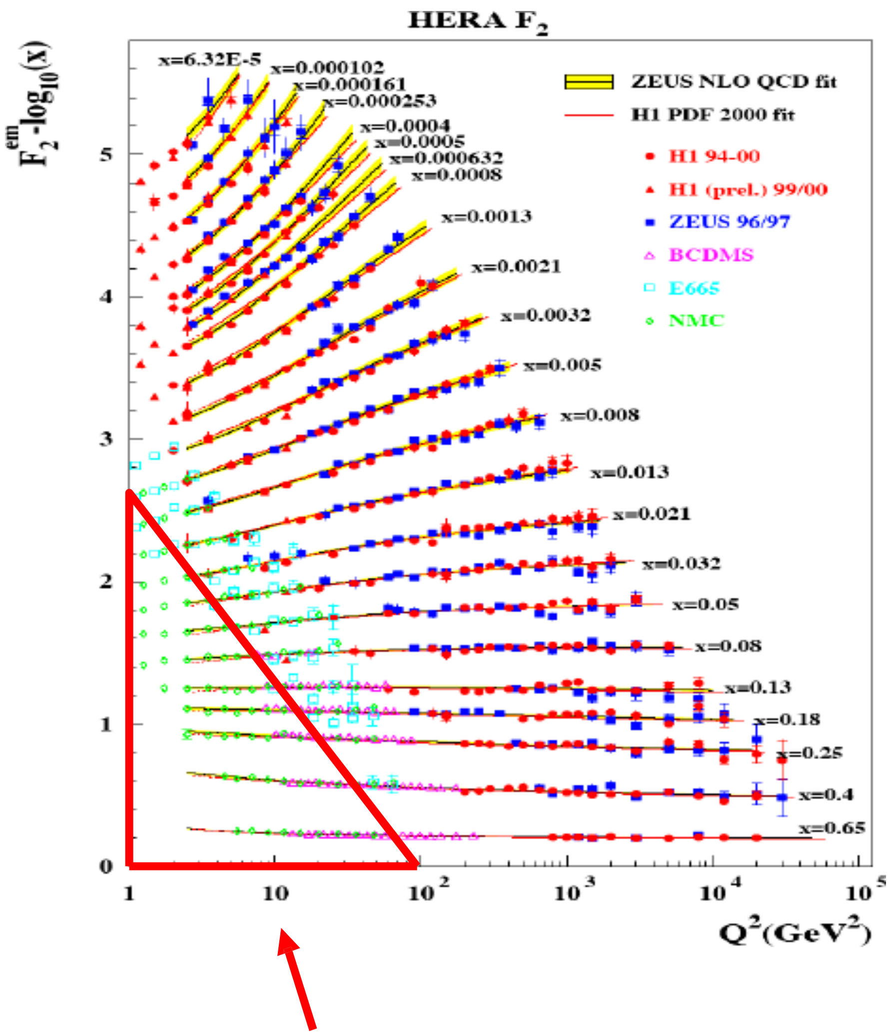
DSSV, PRD 80, 034030 (2009)



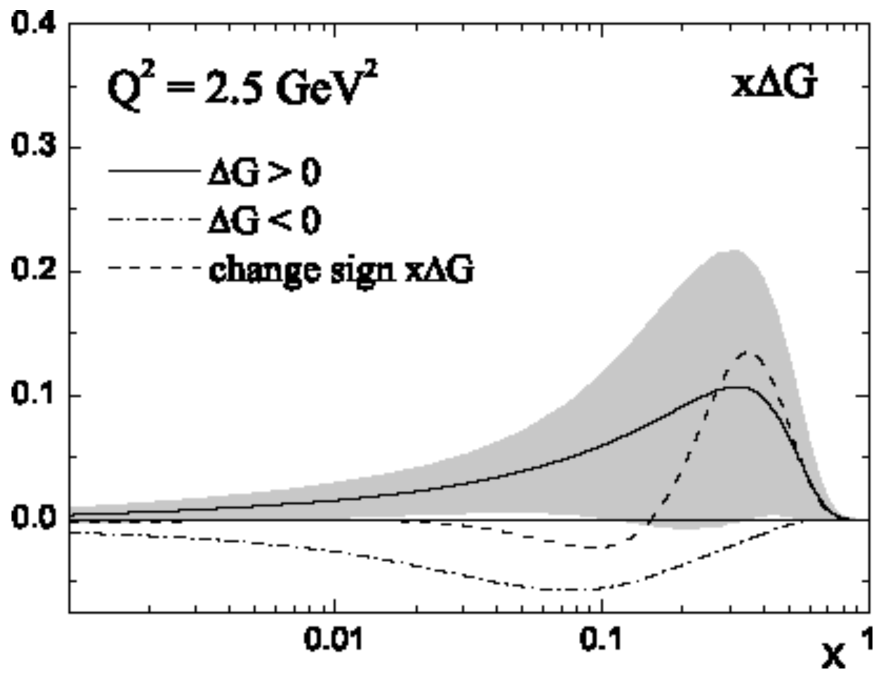


- Many subsequent measurements
- Results are well described by "global analyses" that find best-fit *polarized* PDF
- Polarization of $u + \bar{u}$ and $d + \bar{d}$ quarks well determined
  - Individual u, $\bar{u}$, d, $\bar{d}$ polarizations have much larger uncertainty
- Only **~30% of the proton spin** arises from quarks and antiquarks

What about gluons?



Kinematic region of ***Polarized DIS*** measurements



Three fits of equal quality:

- $\Delta G = 0.13 \pm 0.16$
- $\Delta G \sim 0.006$
- $\Delta G = -0.20 \pm 0.41$

all at $Q^2 = 1$ GeV^2

Leader et al, PRD 75, 074027

Limitations of fixed target DIS experiments

- Does not allow exploration of low-x region
- Extraction of gluon polarization needed large Q2 arm, and fixed target experiments did not allow that either….

  Ideally we needed a polarized e-p collider!

- In 1990's ideas to achieve high energy polarized proton beams evolved… Siberian Snake Magnets
- High energy polarized proton beam polarimetry was developed as a future need …
- Polarized HERA was proposed, but failed!   EIC/EicC in the future.

Motivation of RHIC spin

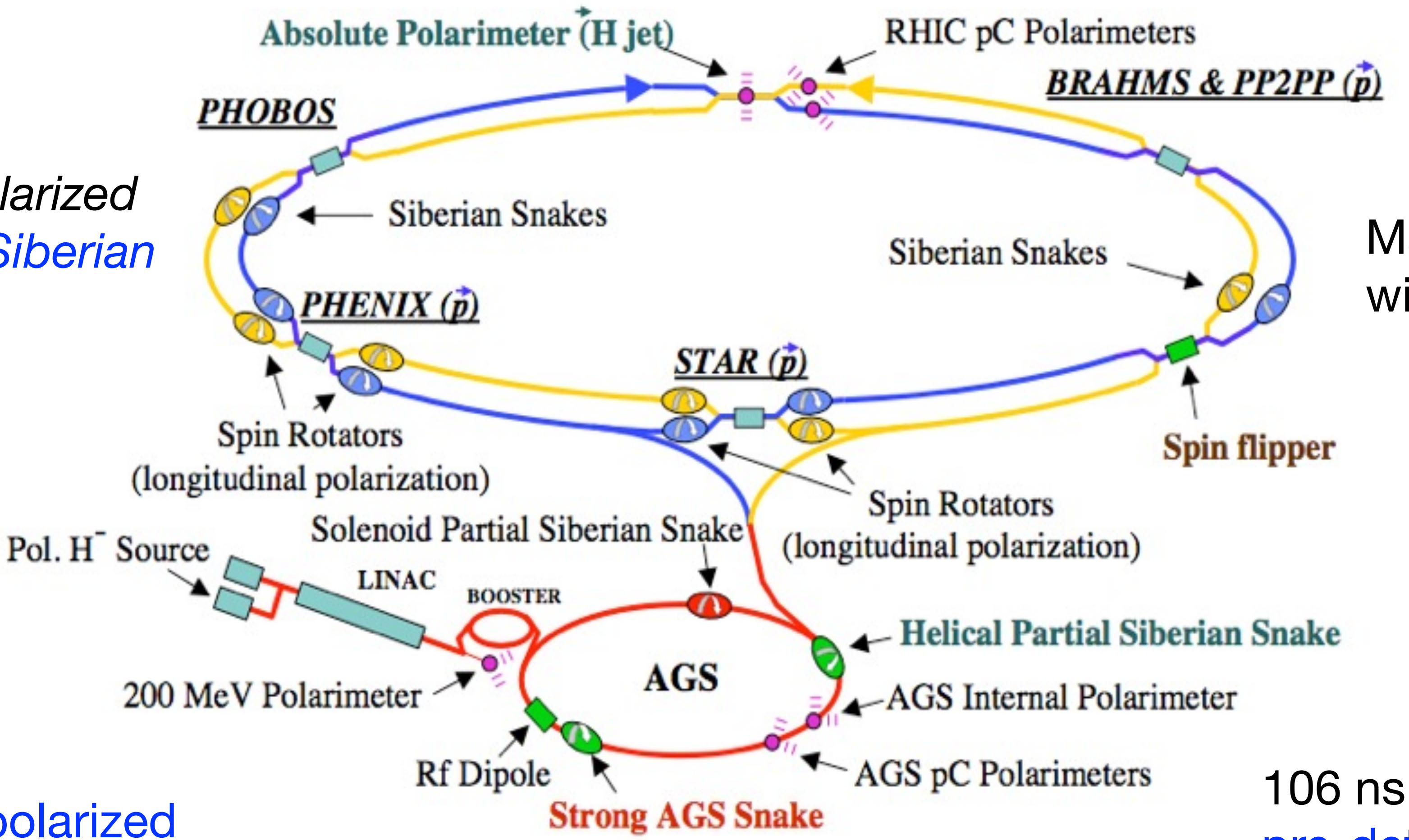
If gluons really carry the bulk of nucleon's spin, why not use polarized proton? (*known by then to be predominantly made of gluons!*)

Why $\Delta\Sigma$ (quark + anti-quark's spin) small? Are quark and antiquark spins anti-aligned? Polarized p+p at high energy, through W+/- production could address this

A severe need for investigations of the surprising transverse spin effects was naturally possible and needed with the proposed polarized p+p collider…

Polarized RHIC

Accelerate polarized protons with Siberian Snakes

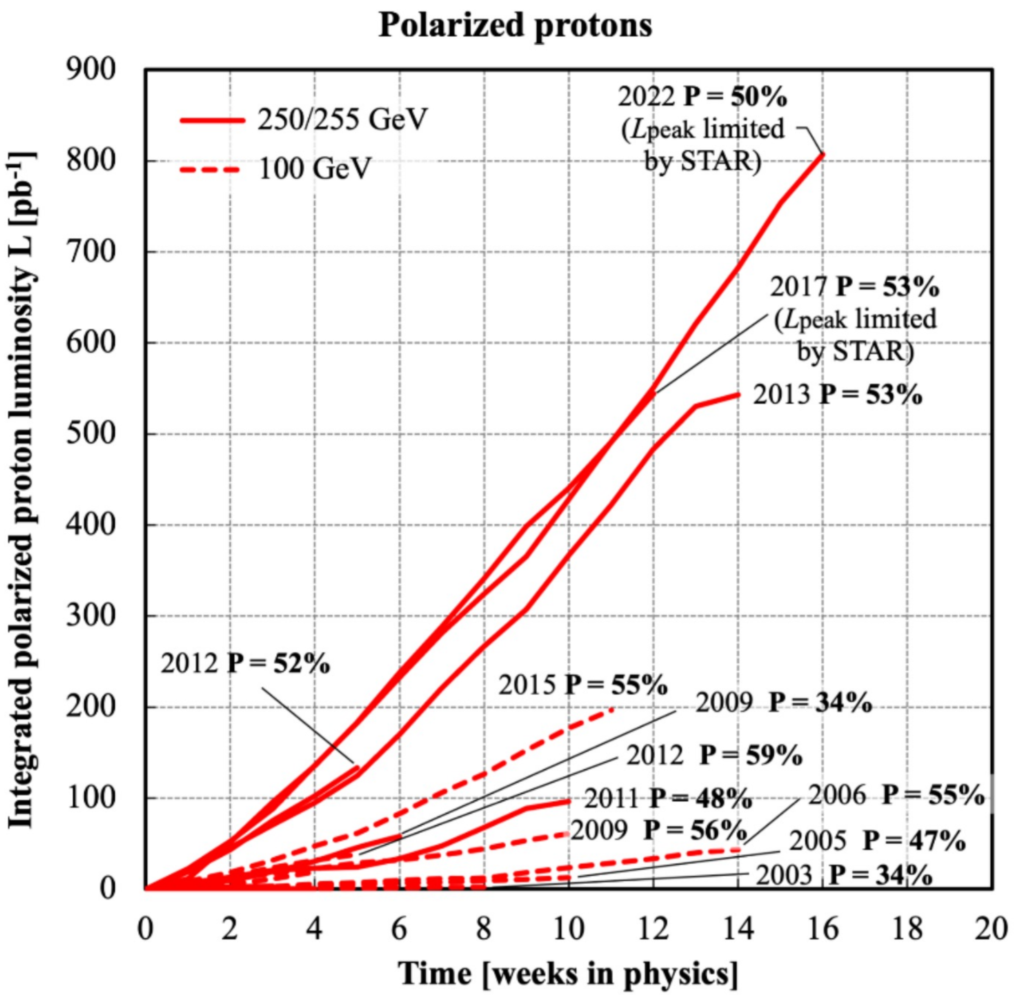


Manipulate spin direction with spin rotator

High current polarized proton source

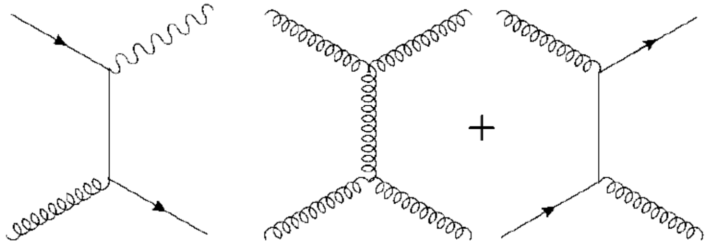
106 ns bunch crossing with pre-determined spin directions

RHIC spin data accumulation



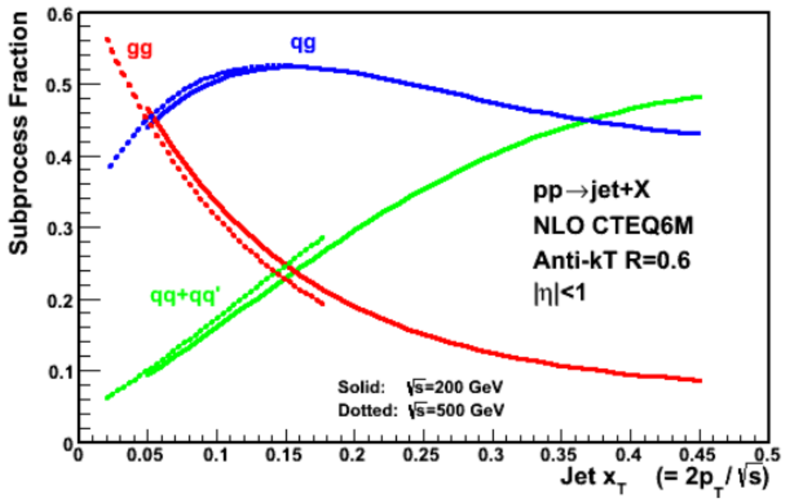
	Year	√s (GeV)	L (pb^{-1})	<P> (%)
Long	2006	62.4	--	48
		200	6.8	57
	2009	200	25	38
		500	10	55
	2011	500	12	48
	2012	510	82	56
	2013	510	256	56
	2015	200	50	60
Trans	2006	62.4	0.2	48
		200	8.5	57
	2008	200	7.8	45
	2011	500	25	55
	2012	200	22	60
	2015	200	50	60
	2017	510	356	55
	2022	510	800	50

Probe gluon polarization at RHIC



QCD Compton scattering

Quark-gluon, gluon-gluon elastic scattering



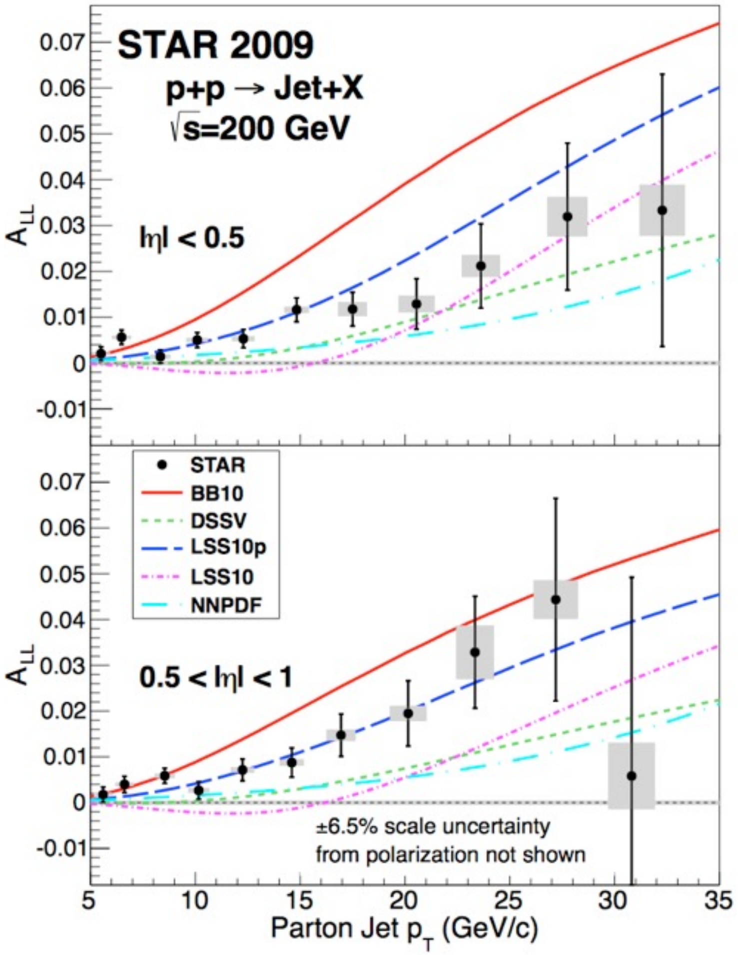
- Abundant yields of π and jets at RHIC
- Sub-processes directly sensitive to gluon
- $x_{g,q} \sim p_T^{\pi^0,\text{jets}} / \sqrt{s} \cdot e^{-\eta}$
- Constrain gluon helicity-dependent PDFs

Double-spin asymmetry:

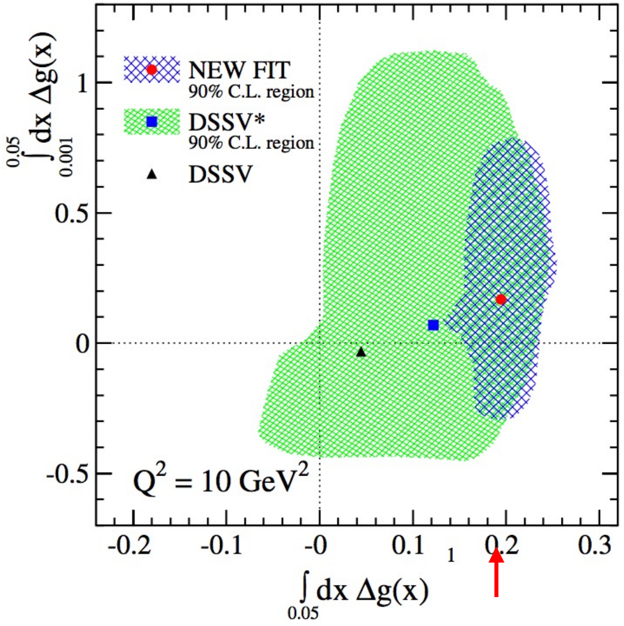
$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \propto \underbrace{\frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2}}_{\text{probed}} \otimes \underbrace{\hat{a}_{LL} \otimes D_f^h}_{\text{inputs}}$$

Yes, gluon spin does contribute!

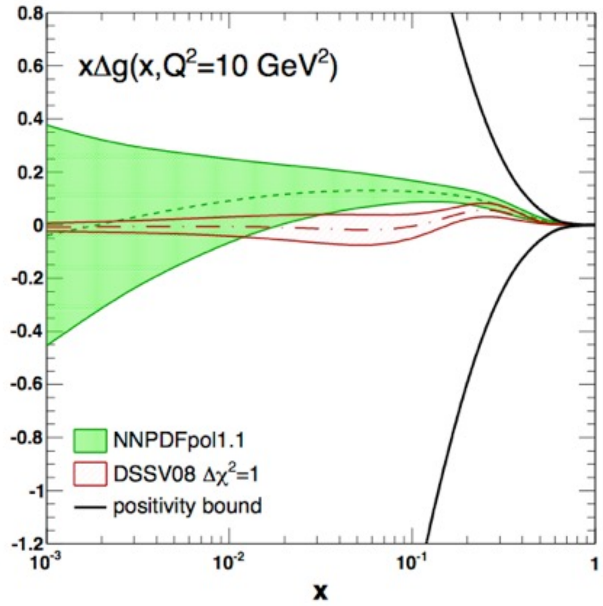
STAR, PRL115 (2015) 092002



DSSV, PRL113 (2014) 012001

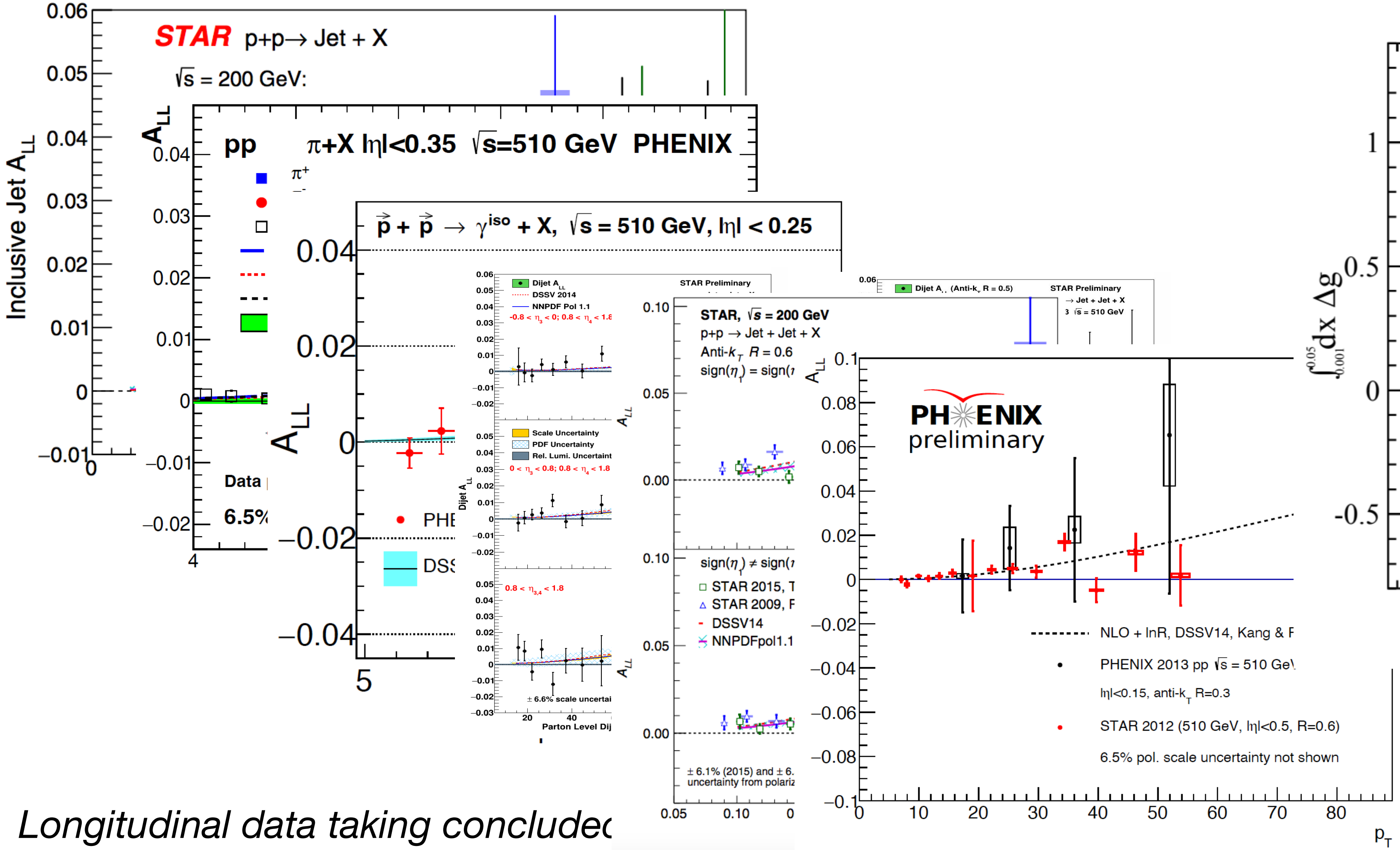


NNPDF, NPB887 (2014) 276

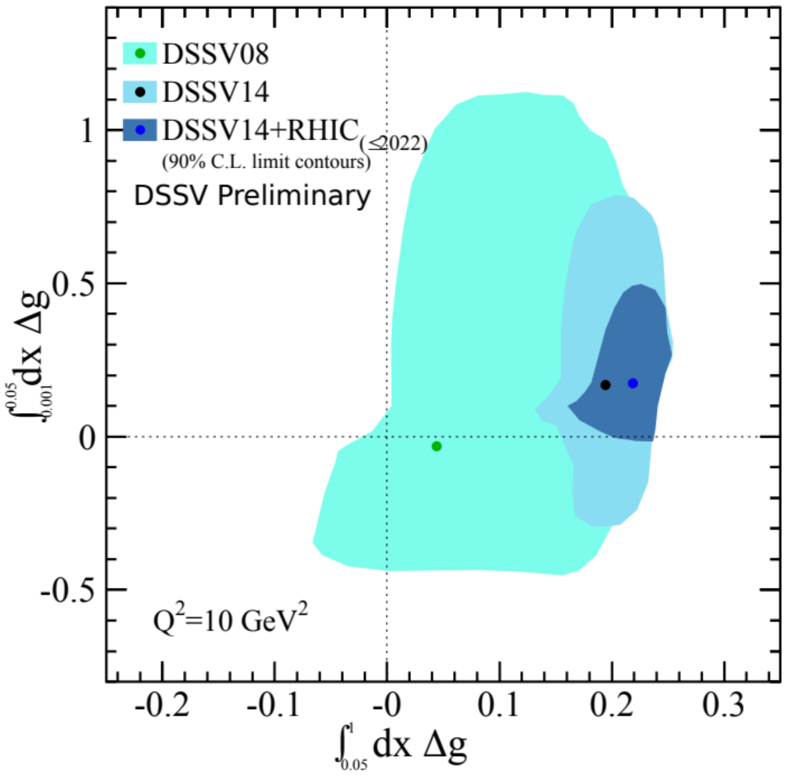


- **First evidence** of non-zero contributions from gluon spin at $Q^2 \sim 10\ \text{GeV}^2$

A big wave of data



The RHIC Cold QCD Program, White Paper, arXiv:2302.00605

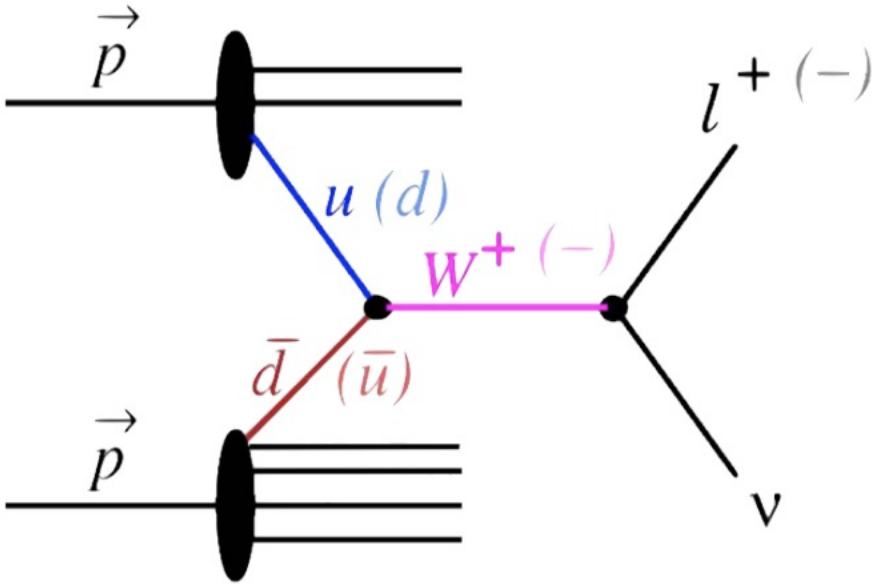


Longitudinal data taking concluded and STAR released the full statistics results.

Flavor separation with W boson

Unique way to study proton spin-flavor structure:

- W boson selects quarks/antiquarks with specific helicity.
- W bosons are measured via leptonic decay.

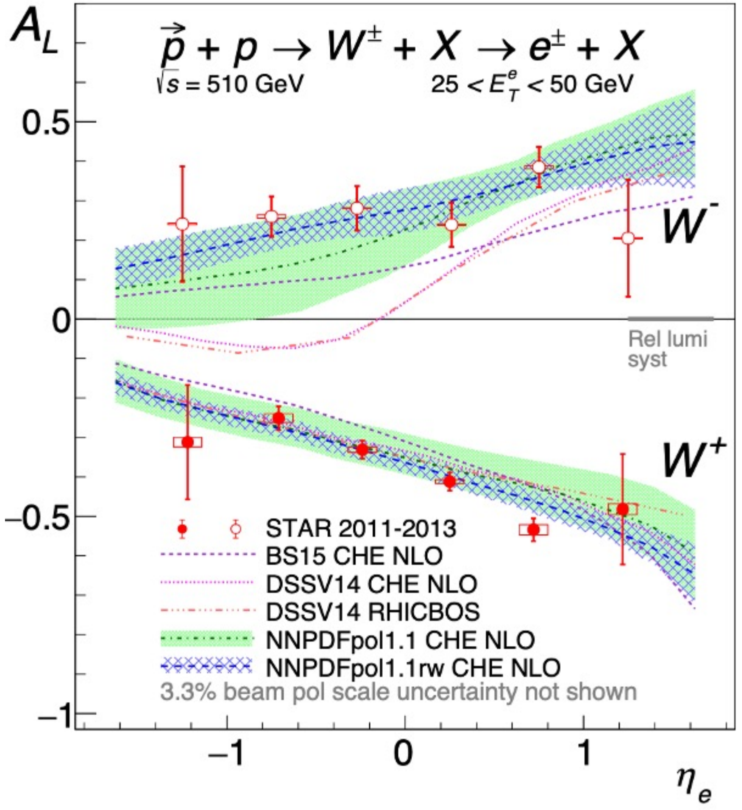


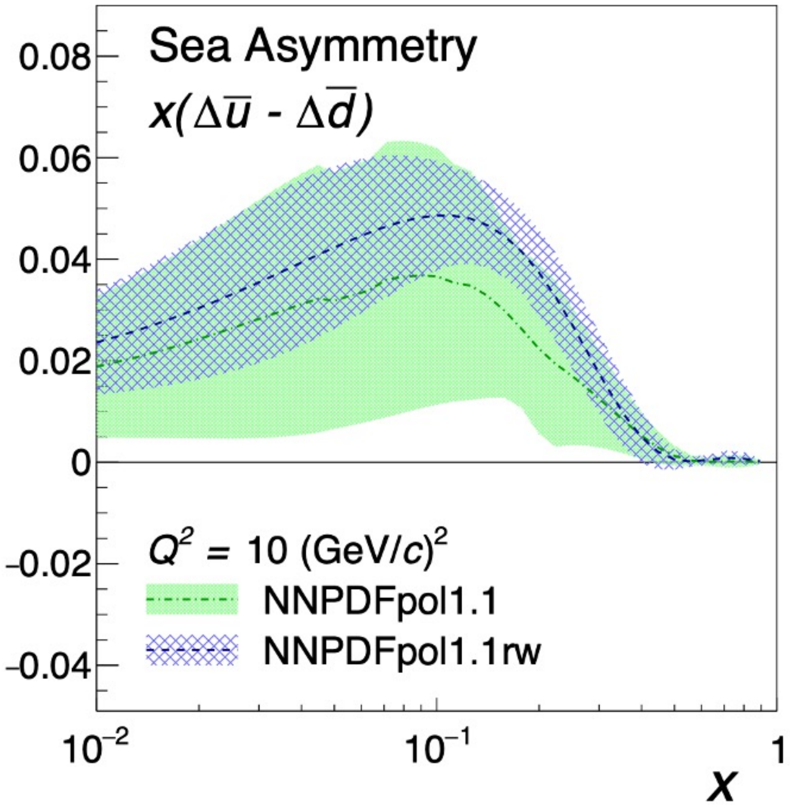
Parity violating single-spin asymmetry:

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

Impact of W results

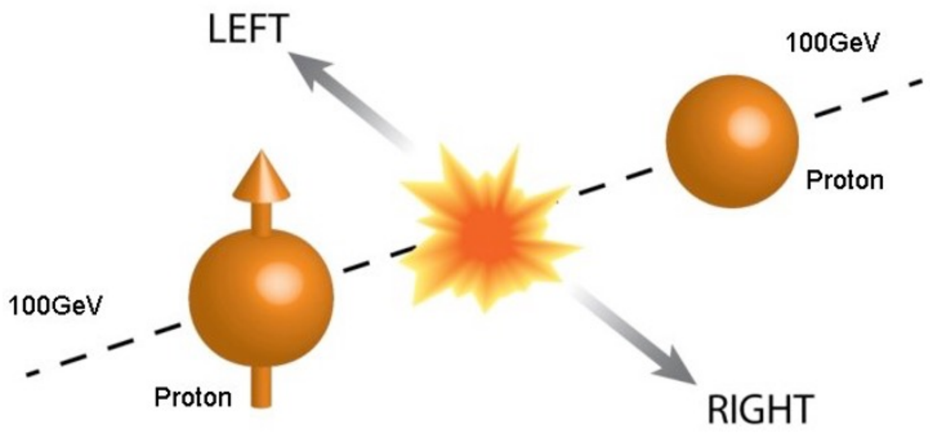
STAR, PRD99, 051102 (2019)





- Now we know: $\Delta\bar{u} > 0$ and $\Delta\bar{d} < 0$
- The flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ similar size but opposite sign to the unpolarized case.

Another longstanding spin puzzle



Transverse single spin asymmetry:

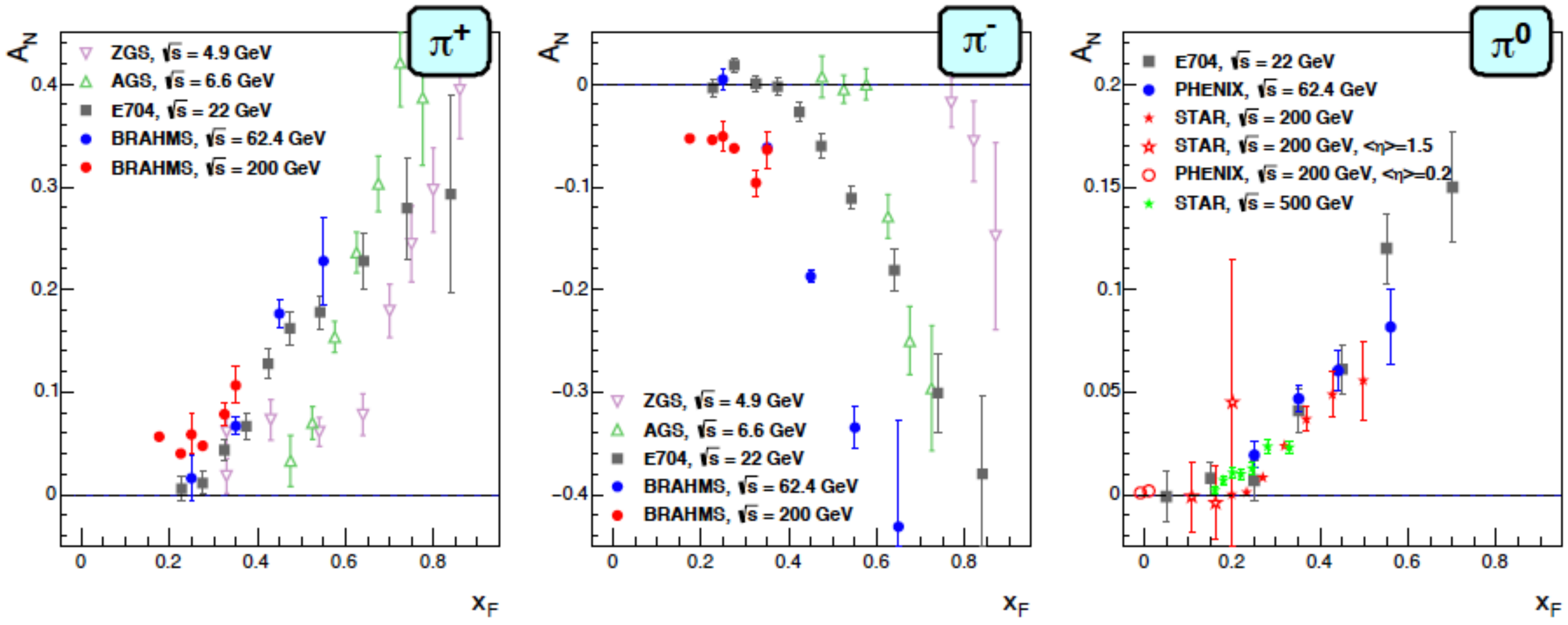
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Transverse spin effect expected to be small at high energies…

--- but FNAL came with a big surprise: it is very large!

Remains mystery after 40+ years

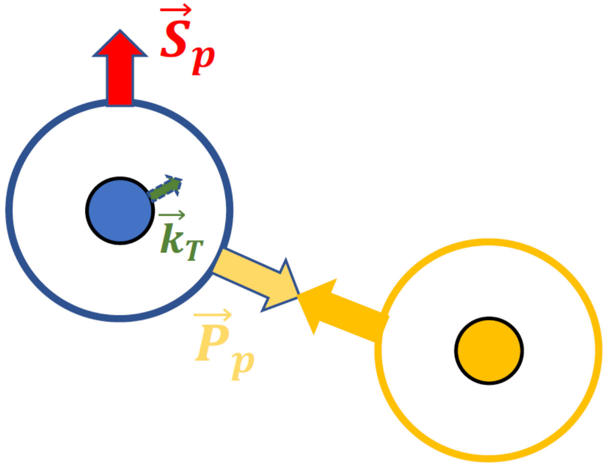
RHIC Cold QCD plan, arXiv: 1602.03922



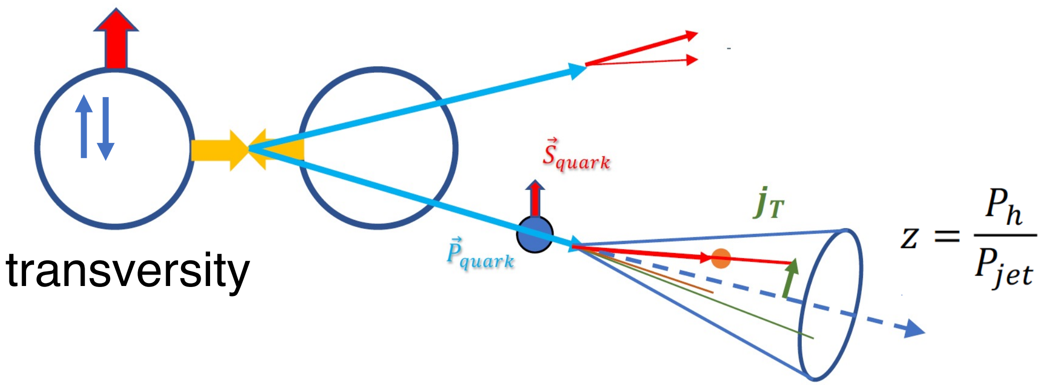
Large asymmetry over a very wide range ($\sqrt{s}$: 4.9 GeV to 500 GeV)

Possible origins

Sivers effect



Collins effect



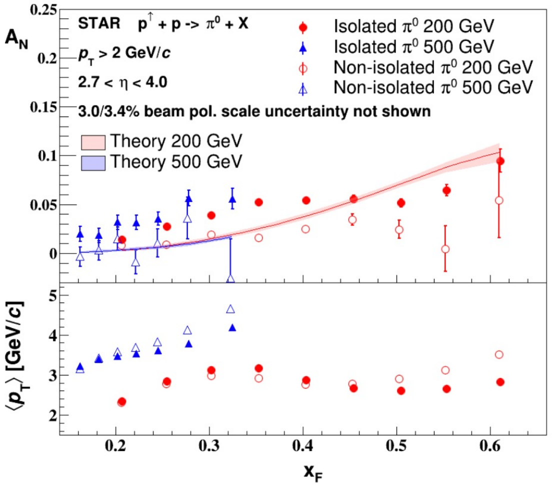
Due to transverse motion of quarks in the nucleon: initial state effect

Asymmetry in the fragmentation hadrons: final state effect

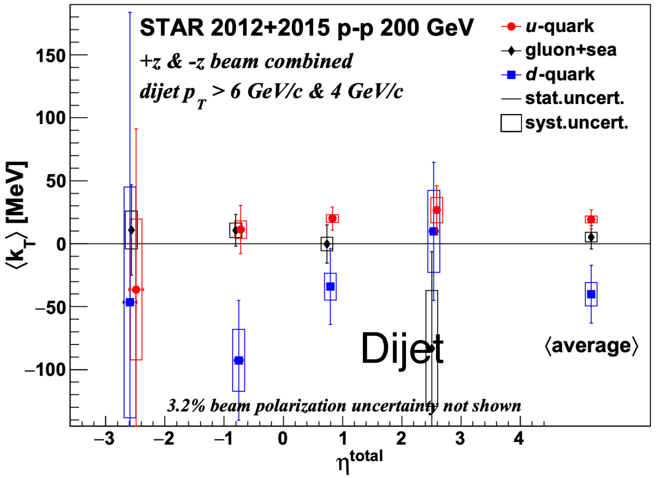
(for more professional description, see Tianbo's talk)

Example results RHIC transverse program

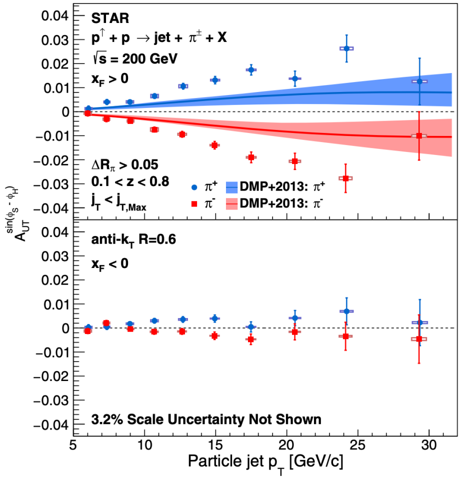
STAR, PRD 103 (2021) 9, 092009



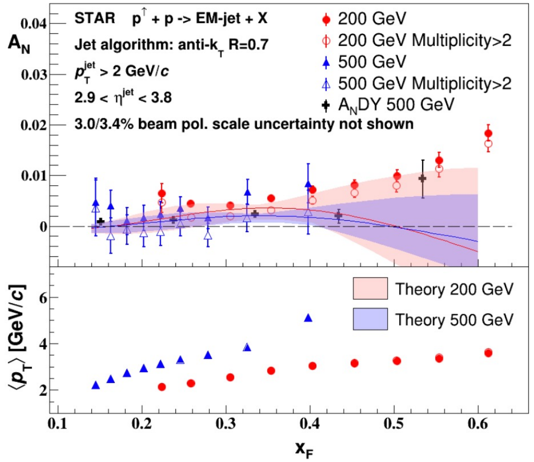
arXiv: 2305.10359

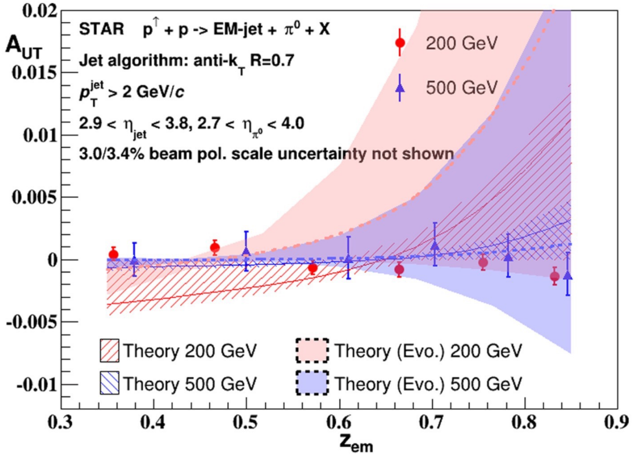


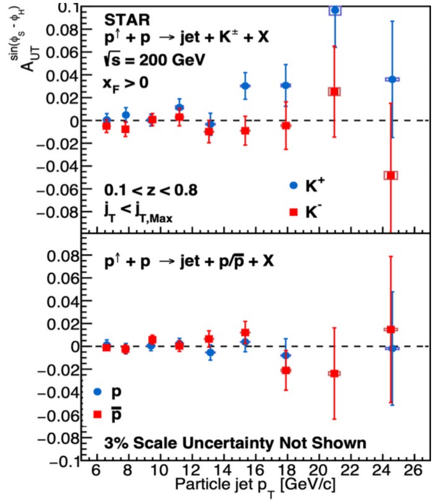
STAR, PRD 106 (2022), 072010



STAR, PRD 103 (2021) , 092009







RHIC spin is concluding

For RHIC spin operation: this year is the last year!

RHIC is making significant contributions to three poorly constrained pieces of the spin puzzle

- **Gluon polarization** $\Delta G > 0$
- **Flavor-separated quark and anti-quark polarizations** $\Delta\bar{u} > \Delta\bar{d}$
- **Transverse** program in progress: existing data being published/analyzed and more data from last spin run in 2024

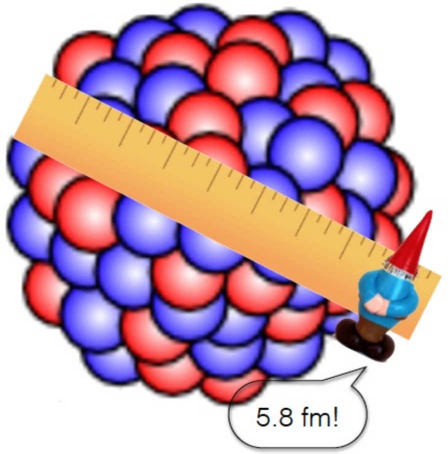
Next generation: polarized Electron-ion Collider

(also see Tianbo's Talk)

What's the size of nucleus?

- Proton distribution:
  - Owing to the electric charge, this has been accurately measured for many atomic nuclei
- Neutron distribution: poorly known
  - Primarily from hadron experiments (pN, HIC, Rare Isotope, electric dipole polarizability, etc), model dependent
  - Parity-violating electron scattering: via the weak charge

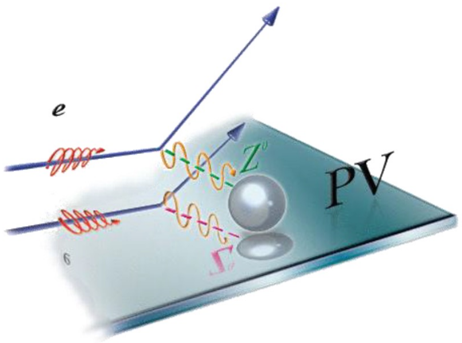
Charge type	Proton	Neutron
Electric	1	0
Weak	~0.07	-1

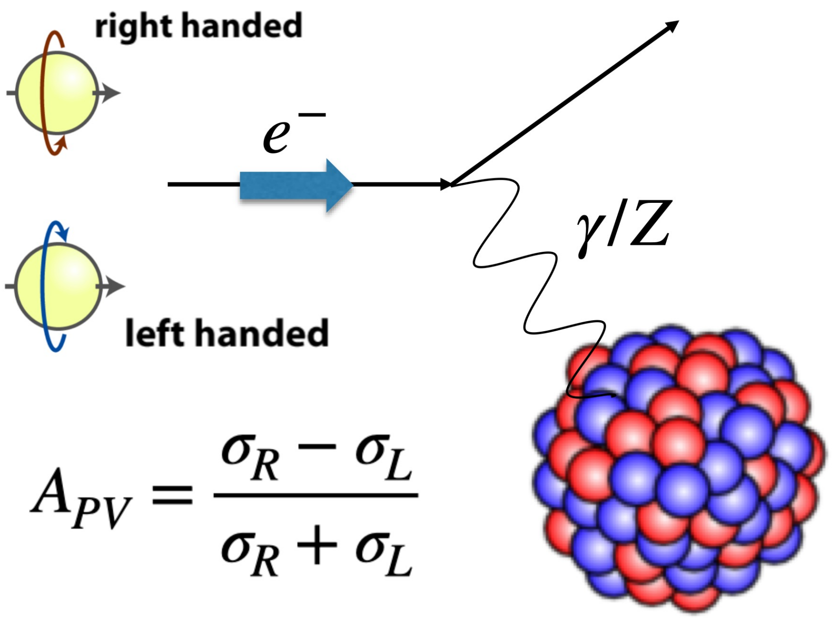


Weak interaction sees neutrons

Parity Violating Electron Scattering

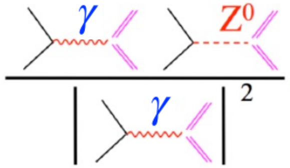
Flip spin of electrons and look for difference in scattering rate





$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$



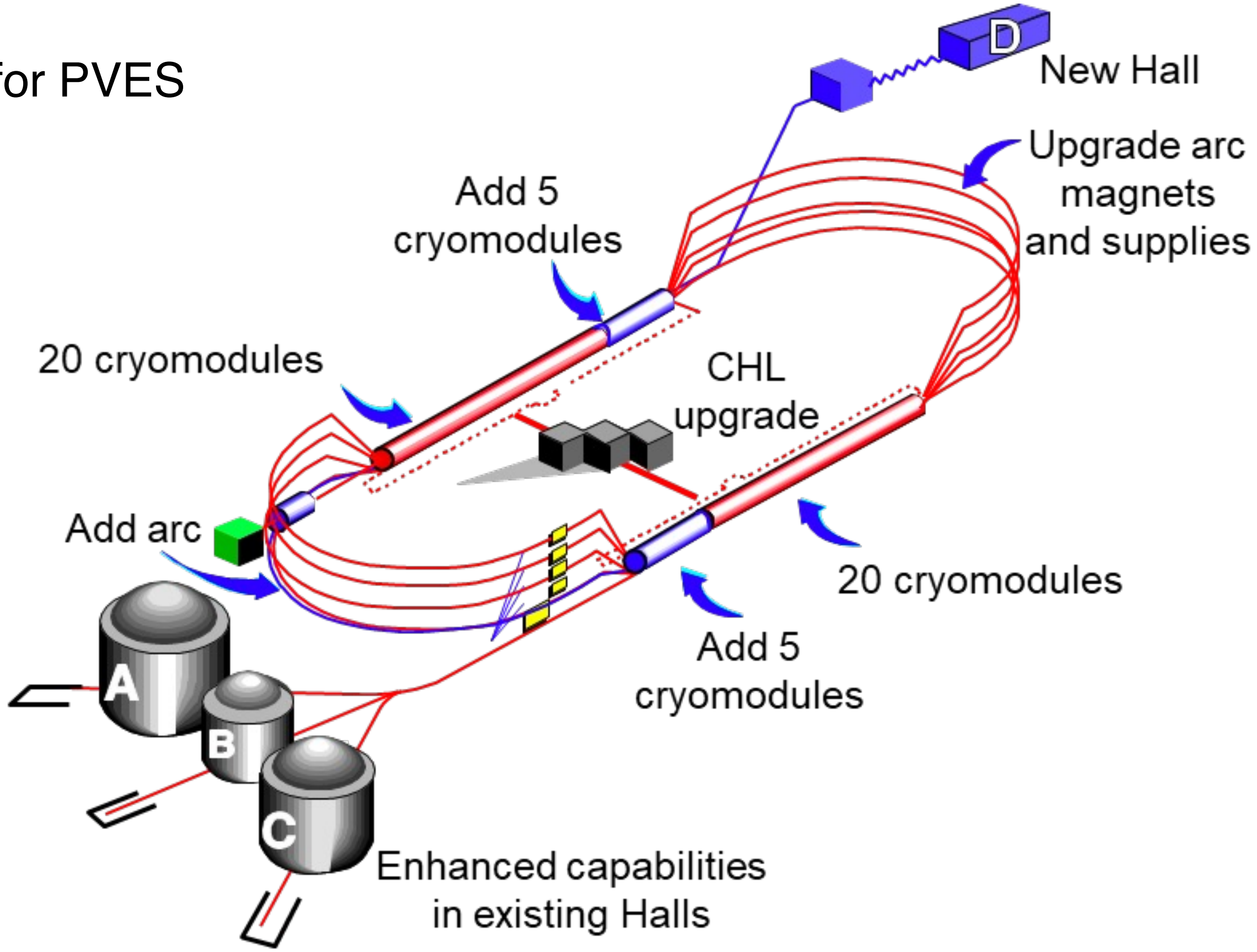
$$\propto \frac{|M_Z|}{|M_\gamma|} \approx \frac{G_F Q^2 Q_W}{4\pi\alpha\sqrt{2}Z} \frac{F_W(Q^2)}{F_{ch}(Q^2)} \sim 10^{-4} \times Q^2$$

Clean and theoretically easy interpretation, but very challenging!

Continuous Electron Beam Accelerator Facility at JLab

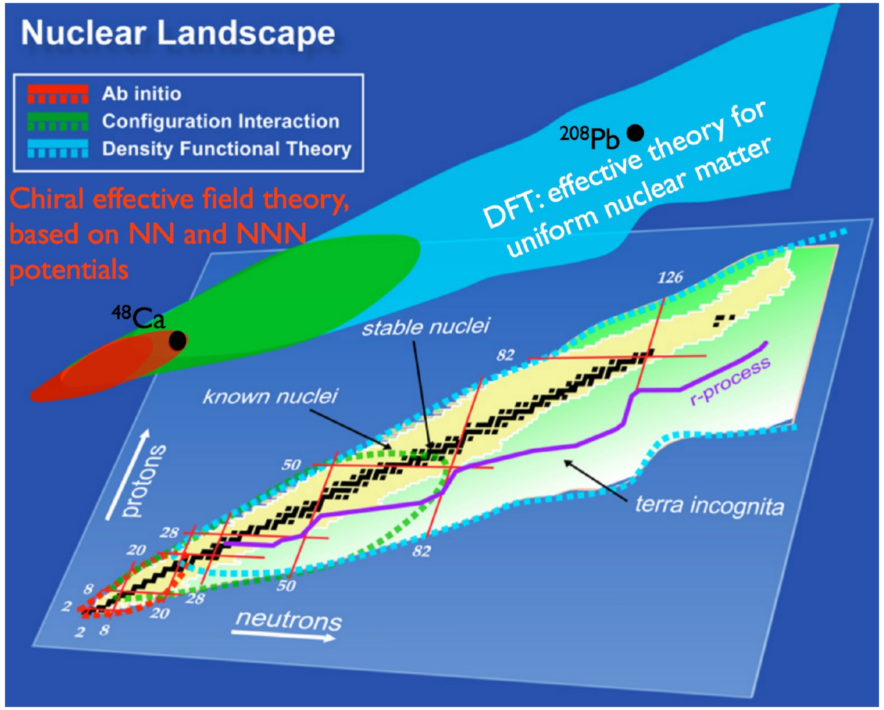
Excellent electron beam for PVES

- Up to 180 uA
- Polarization ~90%
- Up to 1kHz helicity flip



Choice of Nuclei Target

Stable and Least theoretical uncertainties
- Doubly-magic;
- Neutron excess;
- First excited state far from elastic



^{208}Pb: PREX

- in realm of uniform nuclear matter & Density Functional Theory
- serves as terrestrial laboratory to test neutron star structure

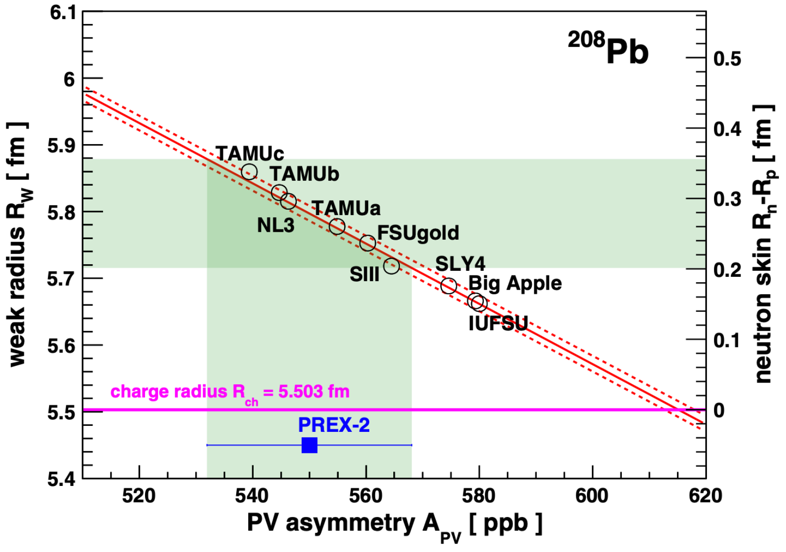
^{48}Ca: CREX

- ab initio calculations of neutron skin for 48Ca available.

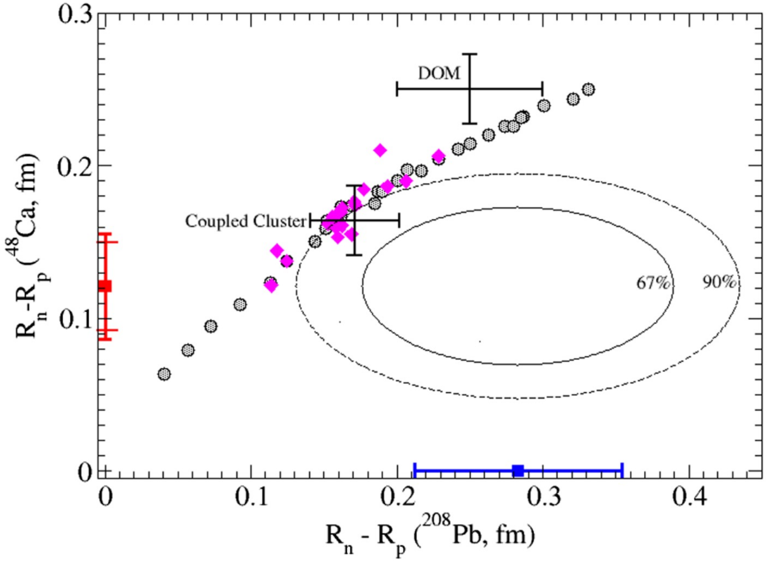
  G. Hagen et al., Nature Phy. 12, 186(2016).
- bridge between “ab initio” models and effective theory (DFT)

PREX and CREX results

PREX, PRL126, 172502 (2021)



CREX, PRL129, 042501(2022)

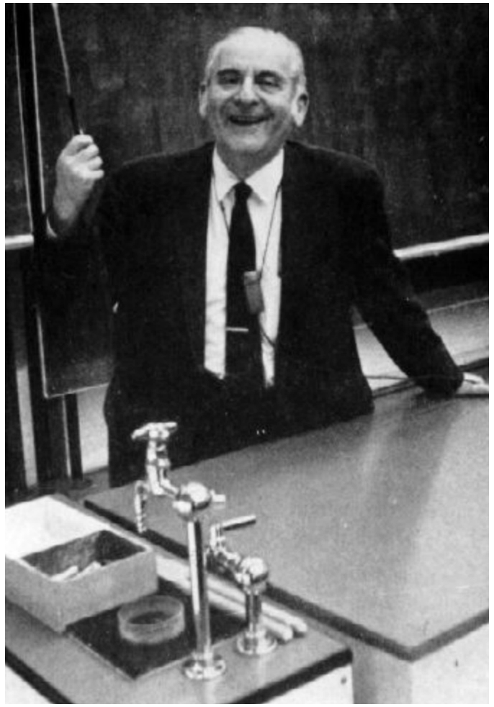


- PREX-2 : Pb-208 **thick** neutron skin 0.283 (0.071) fm
  - Prefer to a larger L and larger neutron star
- CREX: Ca-48 **thin** neutron skin 0.121 (0.035)fm
  - Model independent extraction for weak form factors
  - Provided tests of DFTs and microscopic calculations and thus provide valuable new insight into nuclear structure

Closing remarks by Goudsmit in his 1971 lecture

“you need not be a genius to make an important contribution to physics because, I do admit, the electron spin is an important contribution.”

“…Therefore I do believe that one should not always aspire to tackle what is most important, but try to have fun working in physics and obtain results.”



与君共勉

Thank you for your attention!

Backup slides

- With $\Delta q = \int \Delta q(x) dx$

$$g_1(x) = \frac{1}{2}\Sigma_f e_f^2 \{q_f^+(x) - q_f^-(x)\} = \frac{1}{2}\Sigma_f e_f^2 \Delta q_f(x)$$

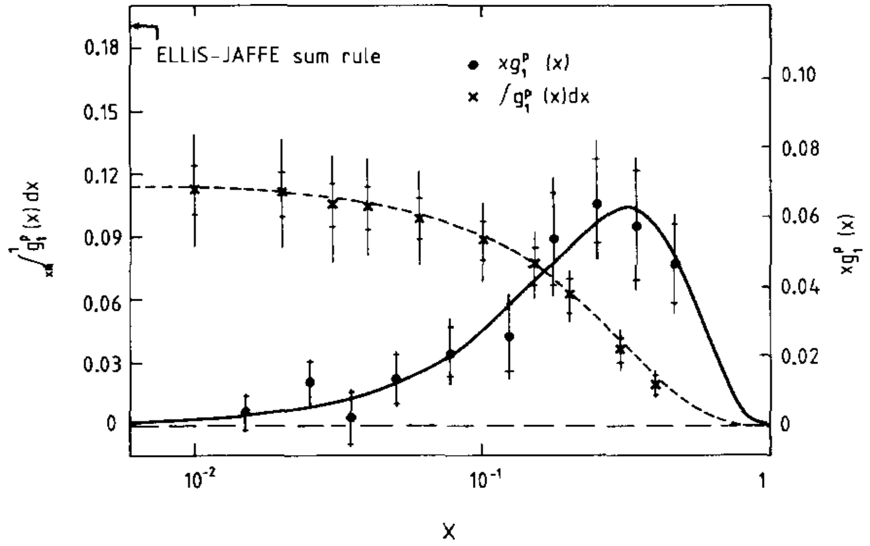
$$\Gamma_1^p = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right]$$

$$= \frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3 = g_a} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{a_0}$$

Neutron decay

(3F-D)/3
Hyperon Decay

$\Delta\Sigma$



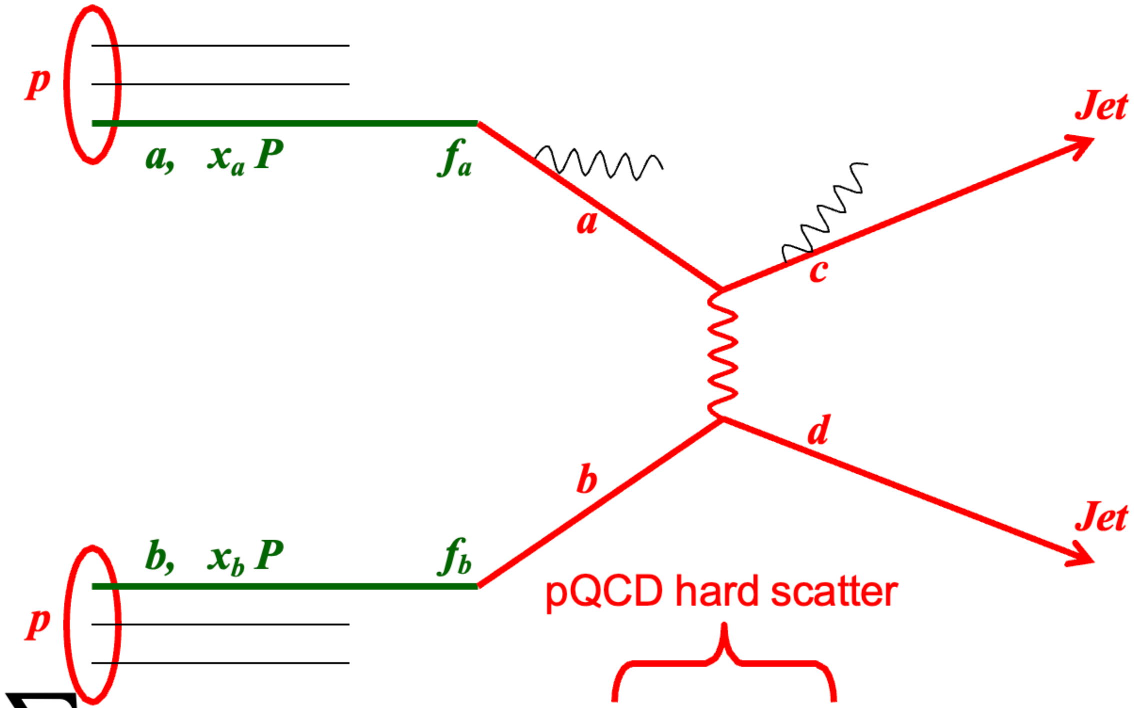
$$\Gamma_1^{p,n} = \frac{1}{12}\left[\pm a_3 + \frac{1}{\sqrt{3}} a_8\right] + \frac{1}{9} a_0$$

$$a_3 = \frac{g_A}{g_V} = F + D = 1.2601 \pm 0.0025$$

$$a_8 = 3F - D \Longrightarrow F/D = 0.575 \pm 0.016$$

Assuming $SU(3)_f$ & $\Delta s = 0$, Ellis & Jaffe: $\Gamma_1^p = 0.170 \pm 0.004$

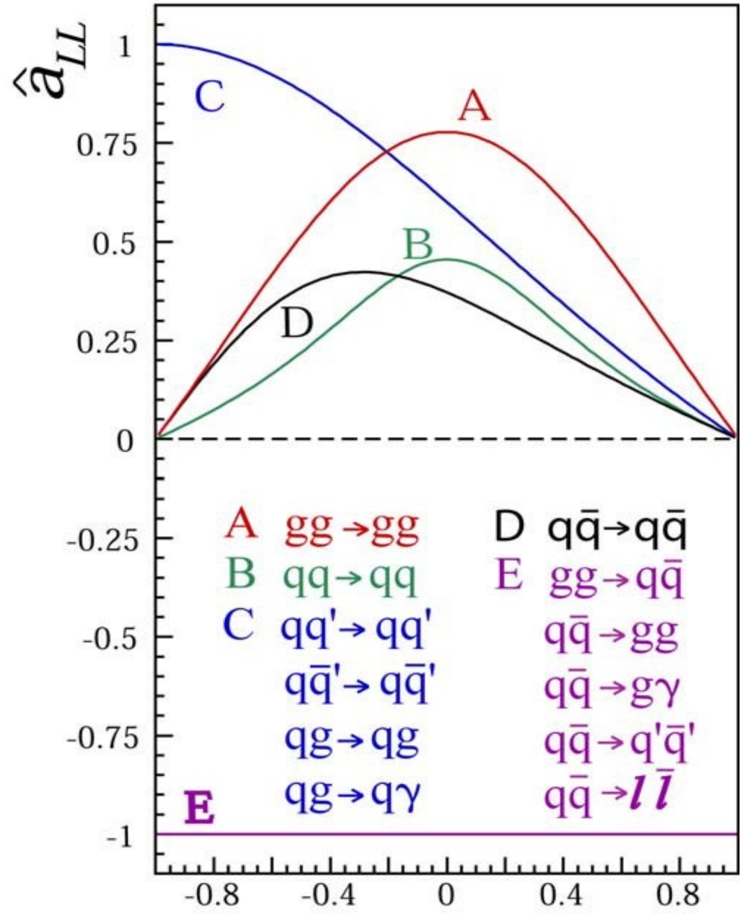
proton-proton collision in perturbative QCD



$$\sigma = \sum f_a(x_a, Q^2) f_b(x_b, Q^2) \hat{\sigma}_{a+b \rightarrow c+d}$$

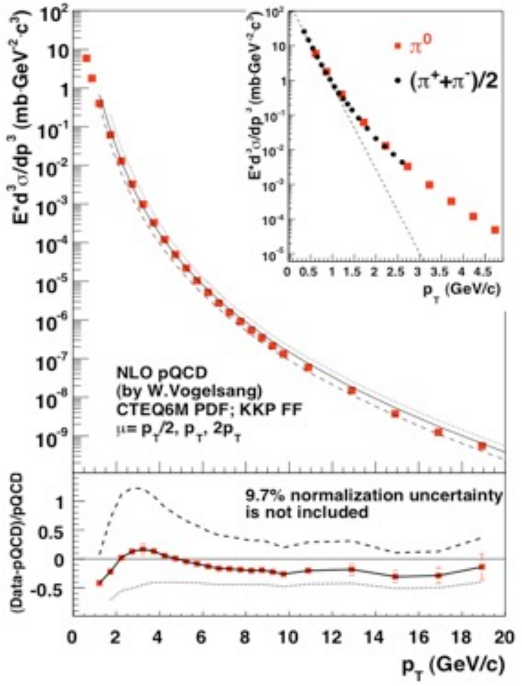
Parton distribution functions

***a* and *b* can be quarks, gluons, or a combination**

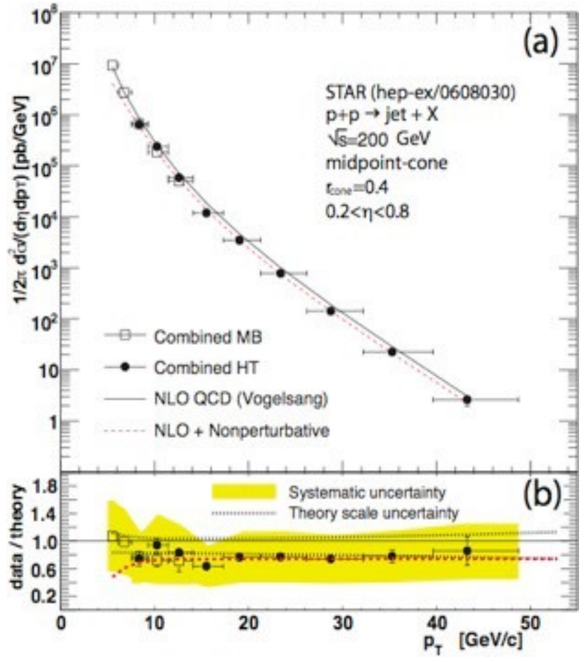


Unpol. Cross Section in *pp*

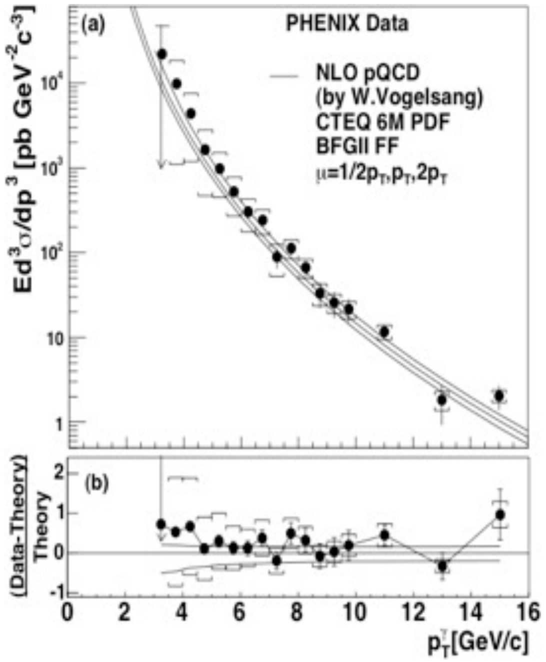
PHENIX, PRD76, 051106



STAR, PRL 97, 252001



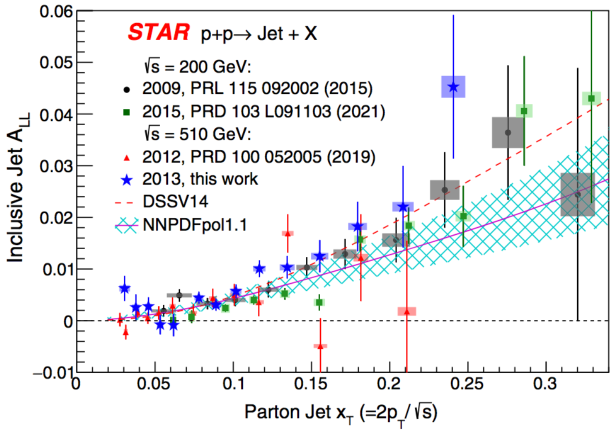
PHENIX, PRL 98, 012002



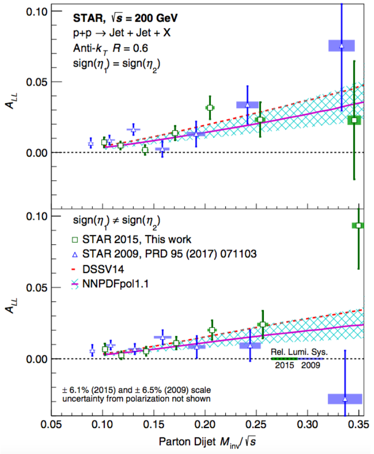
Excellent agreement between NLO pQCD calculations and data

Inclusive-jet/di-jet/hadrons/direct-photon A_{LL} Results

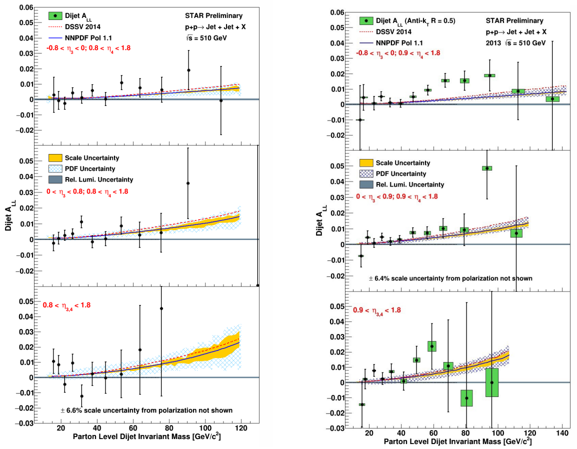
STAR, PRD 105, 092011 (2022)



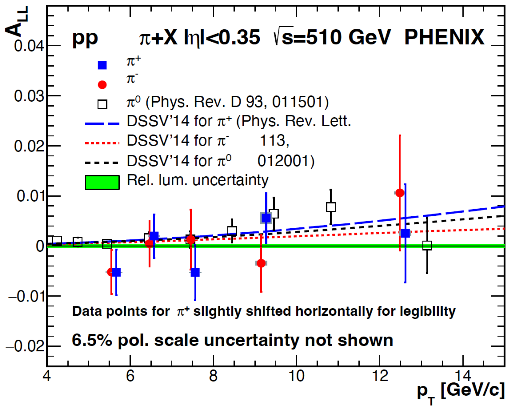
STAR, PRD 103 (2021) L091103



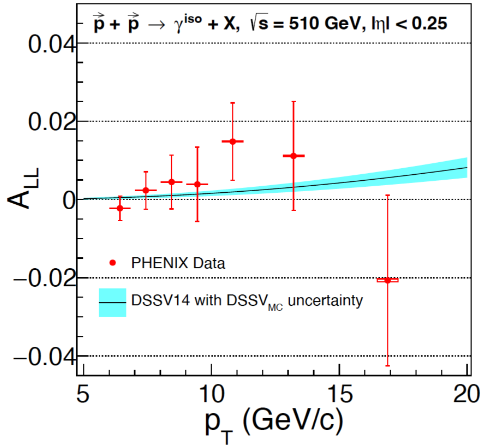
STAR di-jet preliminary results



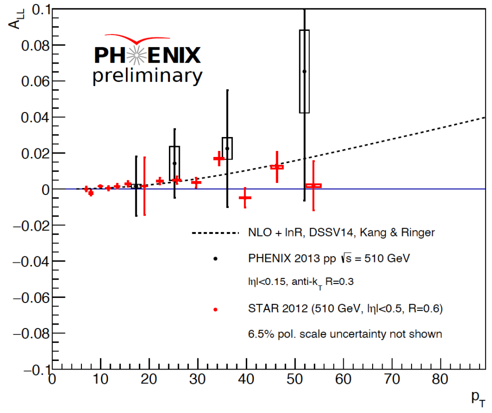
PHENIX, PRD 102, 032001 (2020)



PHENIX, PRL130, 251901 (2023)



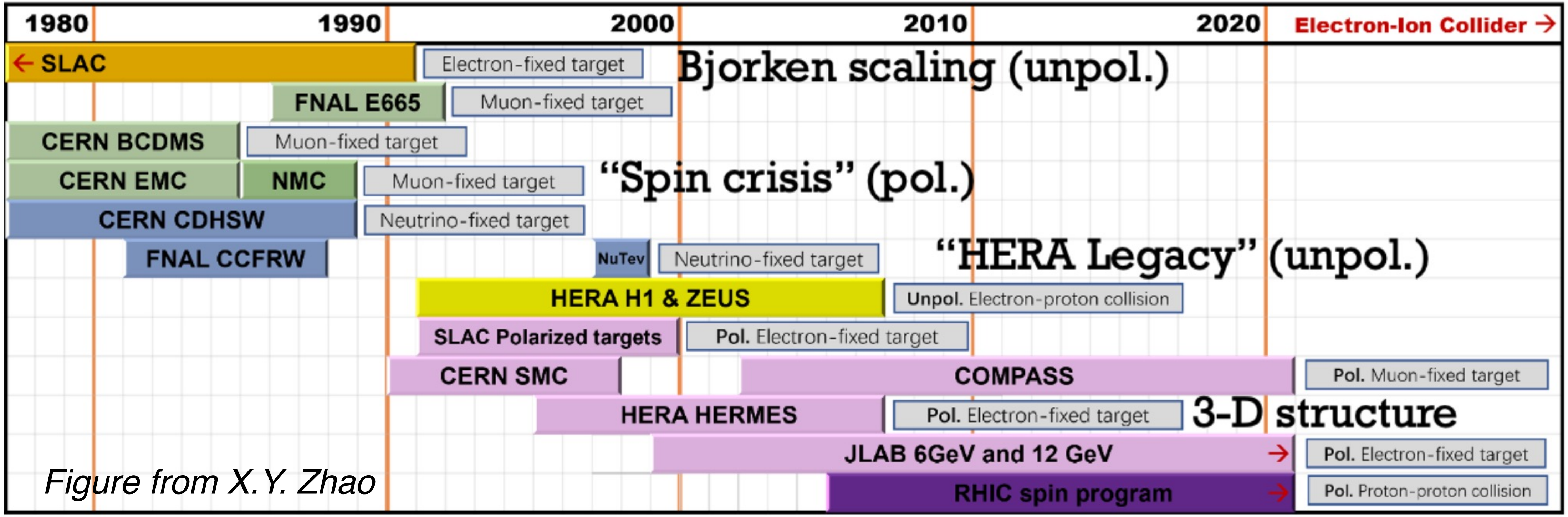
PHENIX preliminary



Longitudinal data taking concluded at RHIC, PHENIX and STAR released the full statistics results.

Lepton scattering: an ideal tool

T. B. Liu, SPIN2023



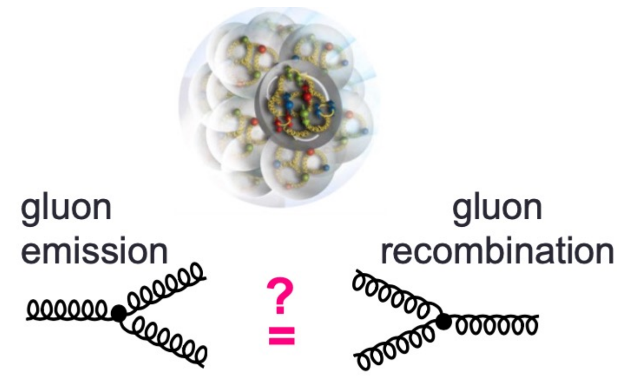
Modern "Rutherford Scattering" Experiment

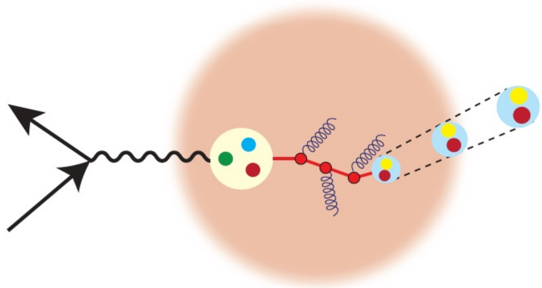
- Start from unpolarized fixed targets
- Extended unpolarized collider experiments
- and polarized fixed-target experiments

Need polarized electron-ion collider

- High luminosity: 100~1000 × HERA lumi.
- High polarization: both electron and ion beams
- Large acceptance: nearly full detector coverage

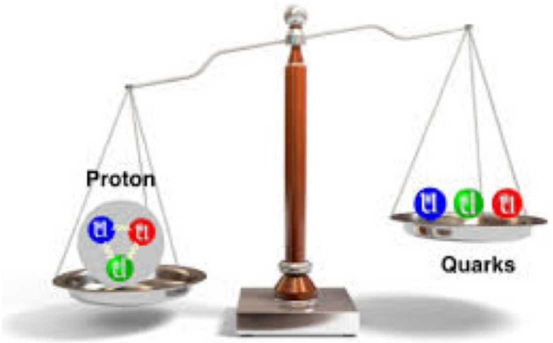
Questions expecting EIC to answer

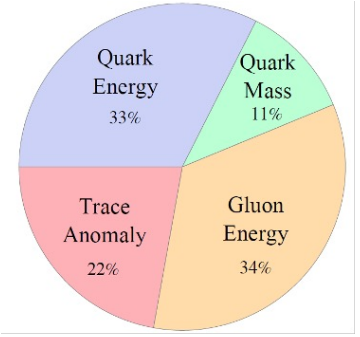


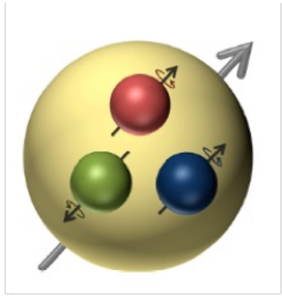


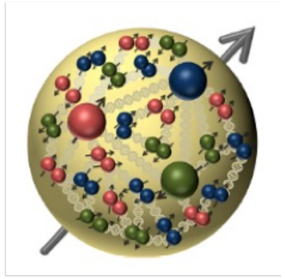
Does gluon saturate at high energy?
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

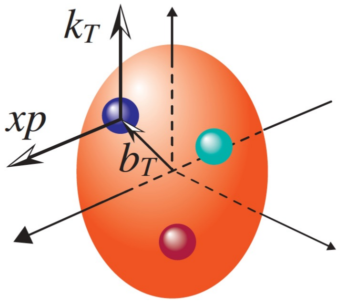
How do the nucleon properties (mass & spin) emerge from their interactions?











How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

Proposed Electron-ion colliders (incomplete list)

FAIR ➔ ENC

LHC ➔ LHeC

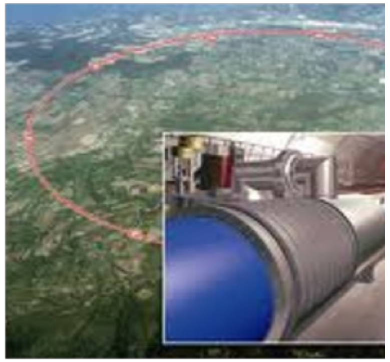
RHIC ➔ eRHIC/EIC

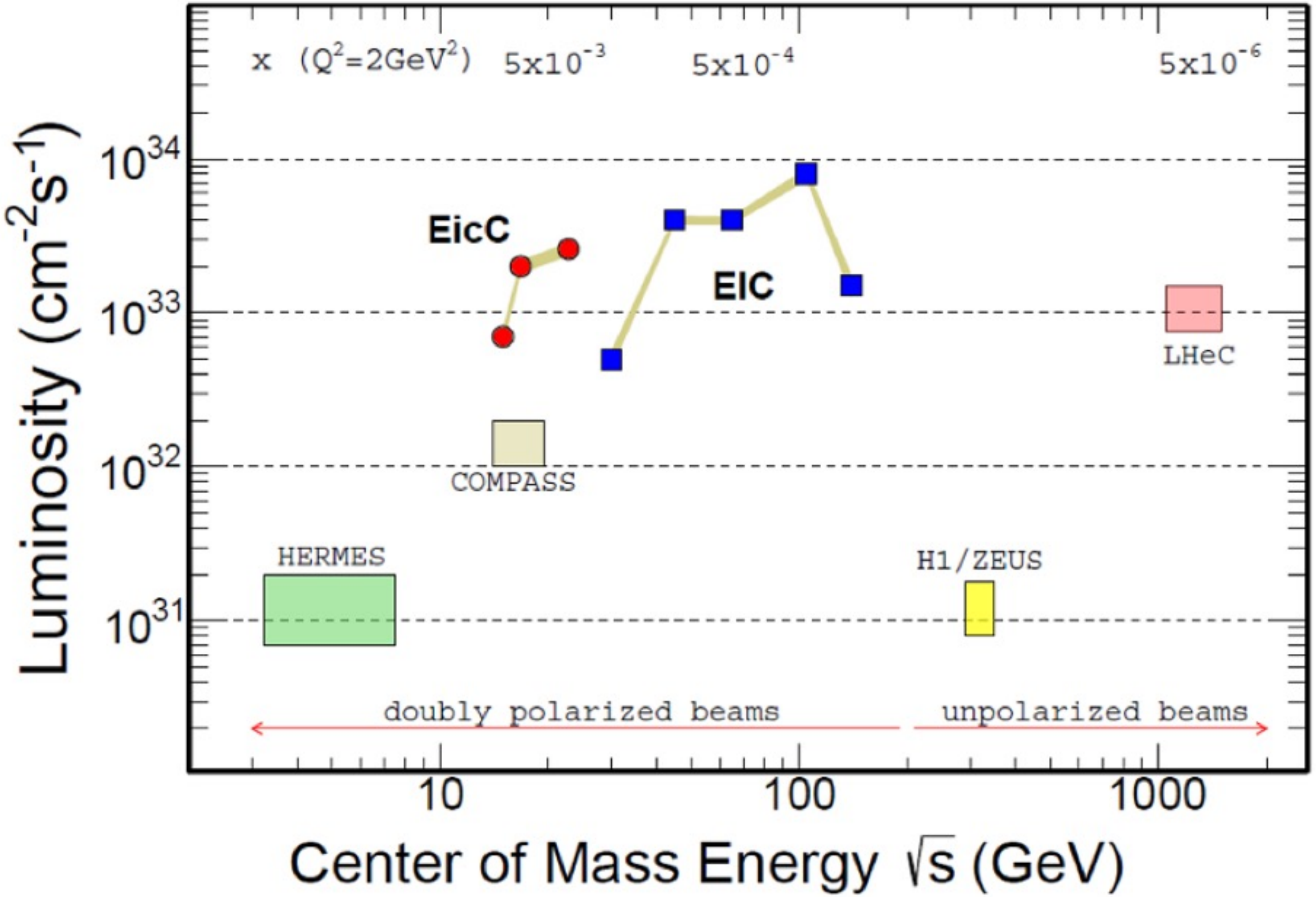
HIAF ➔ EicC

Proposed Electron-ion colliders (incomplete list)

FAIR ➔ EN

LHC ➔ LHe





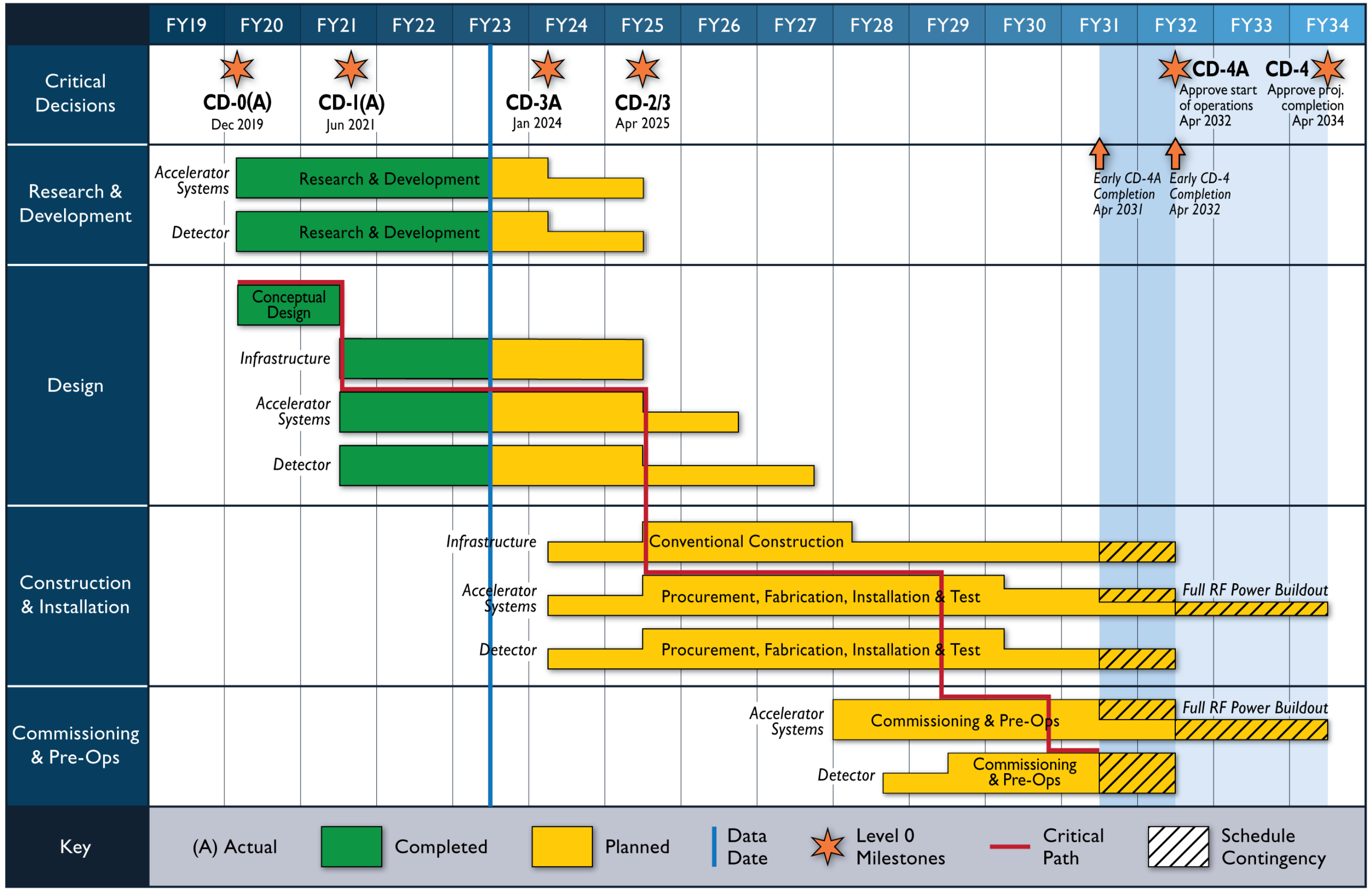
IC ➔ eRHIC/EIC

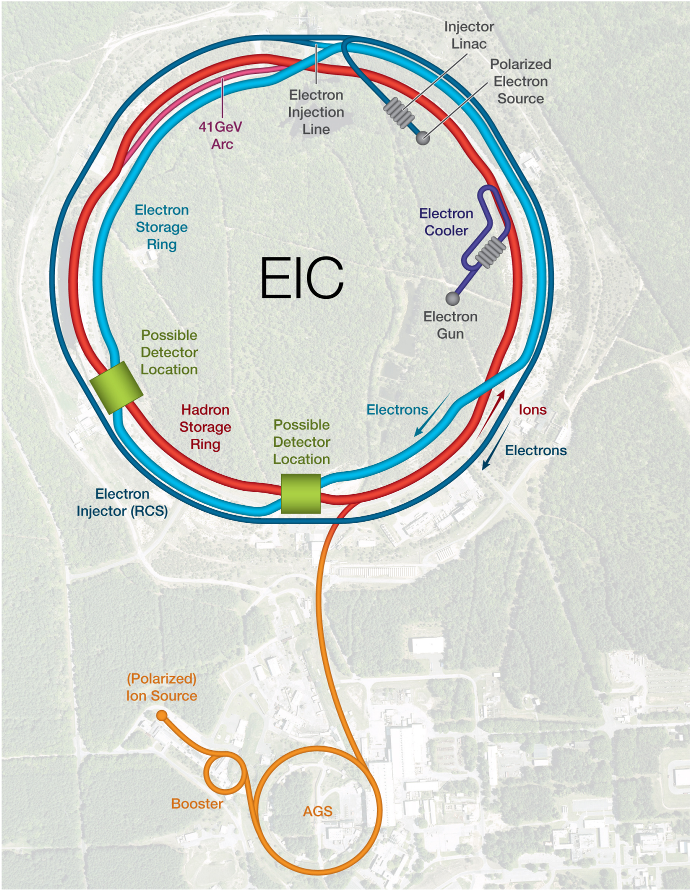
HIAF ➔ EicC

US-EIC Status

Approved in Dec 2019 (CD0)

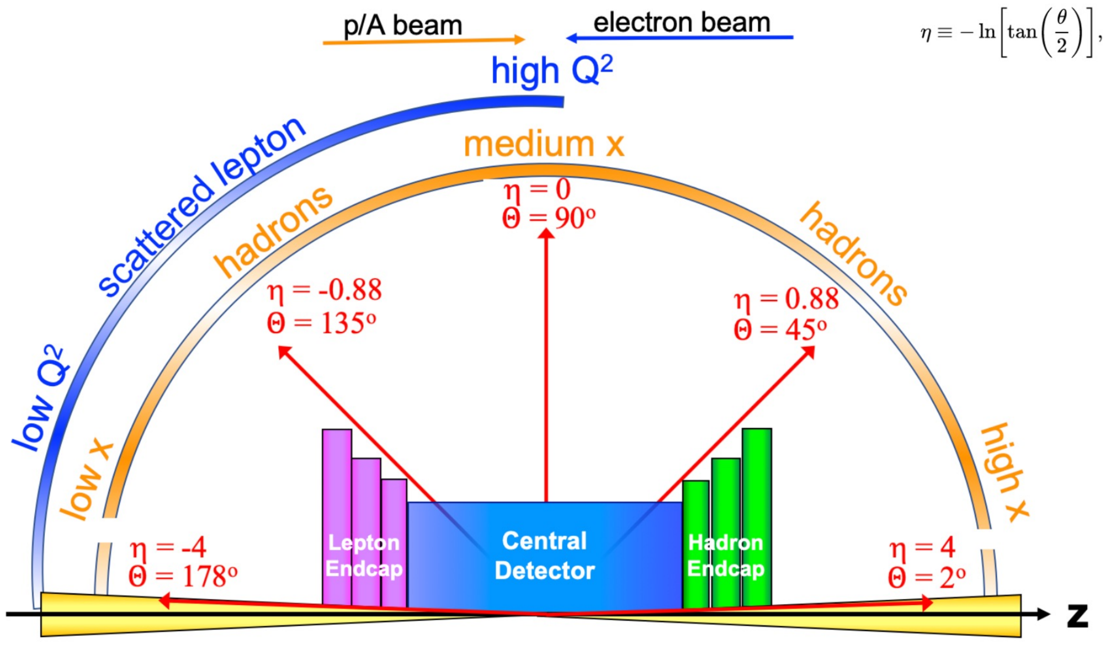
- US EIC is based on the RHIC complex: proton/ion ring, injectors, ion sources, infrastructure
- Add a 5 to18 GeV electron storage ring and its injector complex to the RHIC facility



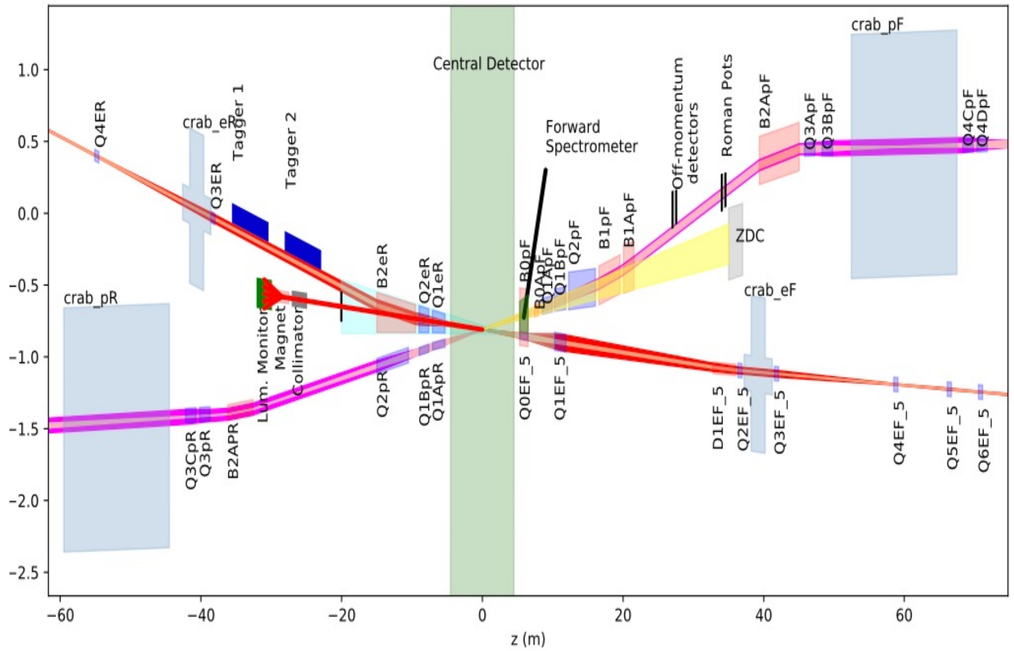


C. Montag, SPIN2023

General concept of an EIC detector



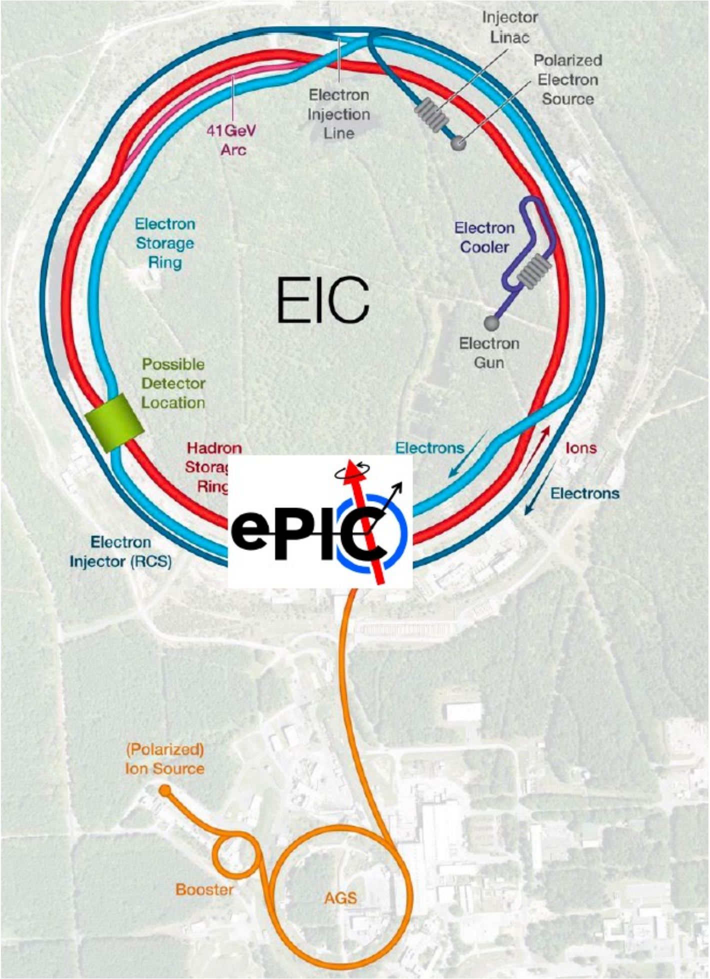
Central detector

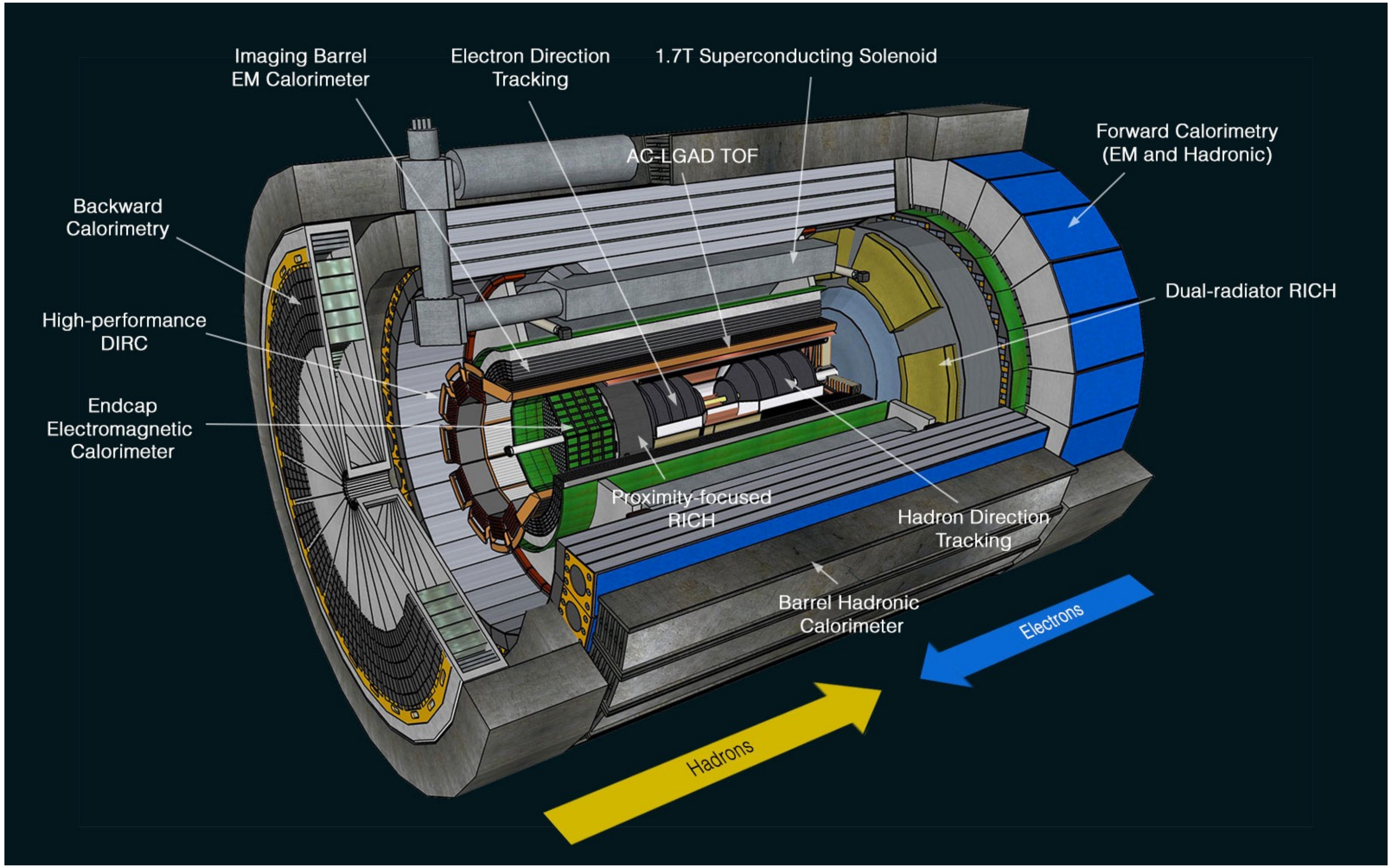


Forward and backward detector

- Hermetic detector, low mass inner tracking, good PID (e and π/K/p) in wide range, calorimetry
- Moderate radiation hardness requirements, low pile-up, low multiplicity.

US-EIC first detector: ePIC





ePIC: mature design and innovative technologies; Technical Design Report (TDR) is coming.

The 2nd detector at IP8 is also being discussed and pushed forward.

EIC participation status from China-mainland

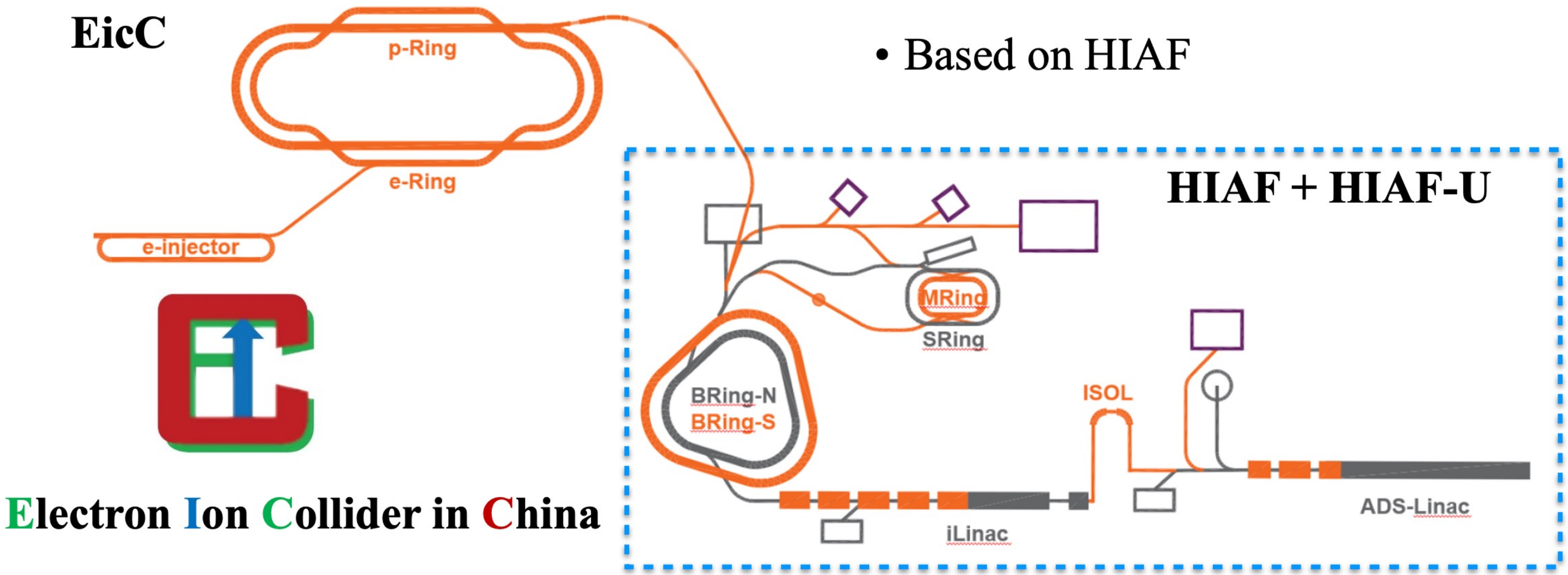
Materials from Q. H. Xu

- **Express of Interest (Oct 2020)**
  - ✓ 8 institutions submitted EOI to EIC, with main detector interests on calorimetry and tracking
- **Yellow Report (2020~2021)**
  - ✓ Authors from 14 Chinese institutions involved in YR writing including both theorists and experimentalist, Bowen Xiao served as co-convener of semi-inclusive WG
- **EIC detector proposals (2021)**
  - ✓ 8 institutions joined ATHENA proposal, Qinghua Xu served as co-convener of inclusive WG, with detector interest on EMCal etc.
  - ✓ 6 institutions joined ECCE proposal, Wangmei Zha served as co-convener of jets and heavy flavor WG, with detector interest on silicon tracker, MPGD etc.
- **ePIC collaboration (March 2022)** (24 countries, 171 institutions)
  - ✓ 6 universities from China-mainland are members of ePIC
  - ✓ Subsystems of interest: Forward Emcal (fECal) : W powder/ScFi

EicC Status

中国极化电子-离子对撞机
Polarized electron ion collider in China

• Based on HIAF



[Figure by EicC Accelerator WG]

High Intensity heavy-ion Accelerator Facility in Huizhou, Guangdong province

- a national facility on nuclear physics, atomic physics, heavy-ion applications …
- beam commissioning is planned in 2025

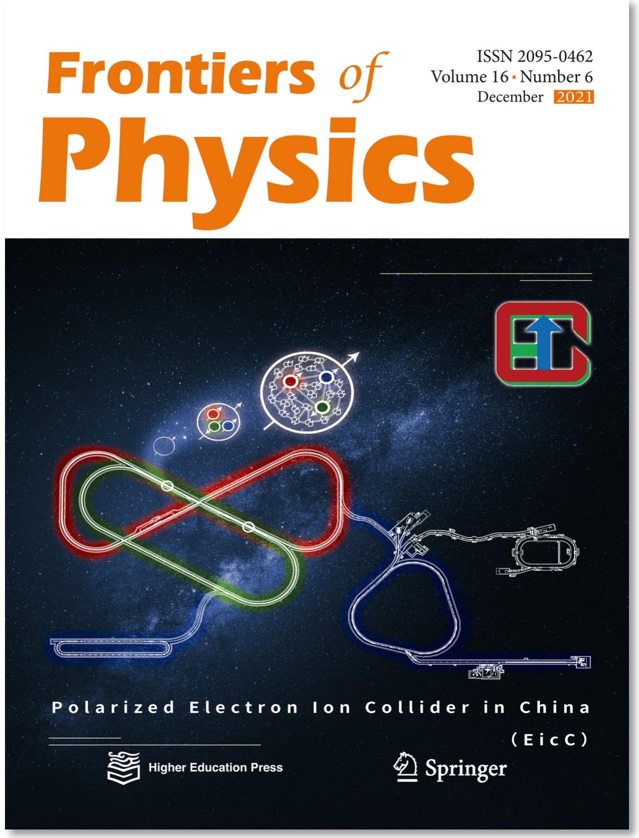
EicC is based on HIAF

- electron: 3.5 GeV, polarization ~ 80%
- ion: p, d, $^{3}He^{++}$, $^{7}\mathrm{Li}^{3+}$, $^{12}\mathrm{C}^{6+}$, $^{40}\mathrm{Ca}^{20+}$, $^{197}\mathrm{Au}^{79+}$, $^{208}\mathrm{Pb}^{82+}$, $^{238}\mathrm{U}^{92+}$

EicC Status

中国极化电子-离子对撞机
Polarized electron ion collider in China

EicC white paper



Published in 2021
(Chinese version in 2020)

EicC Conceptual Design Report (CDR)

Volume I: Accelerator

Contents

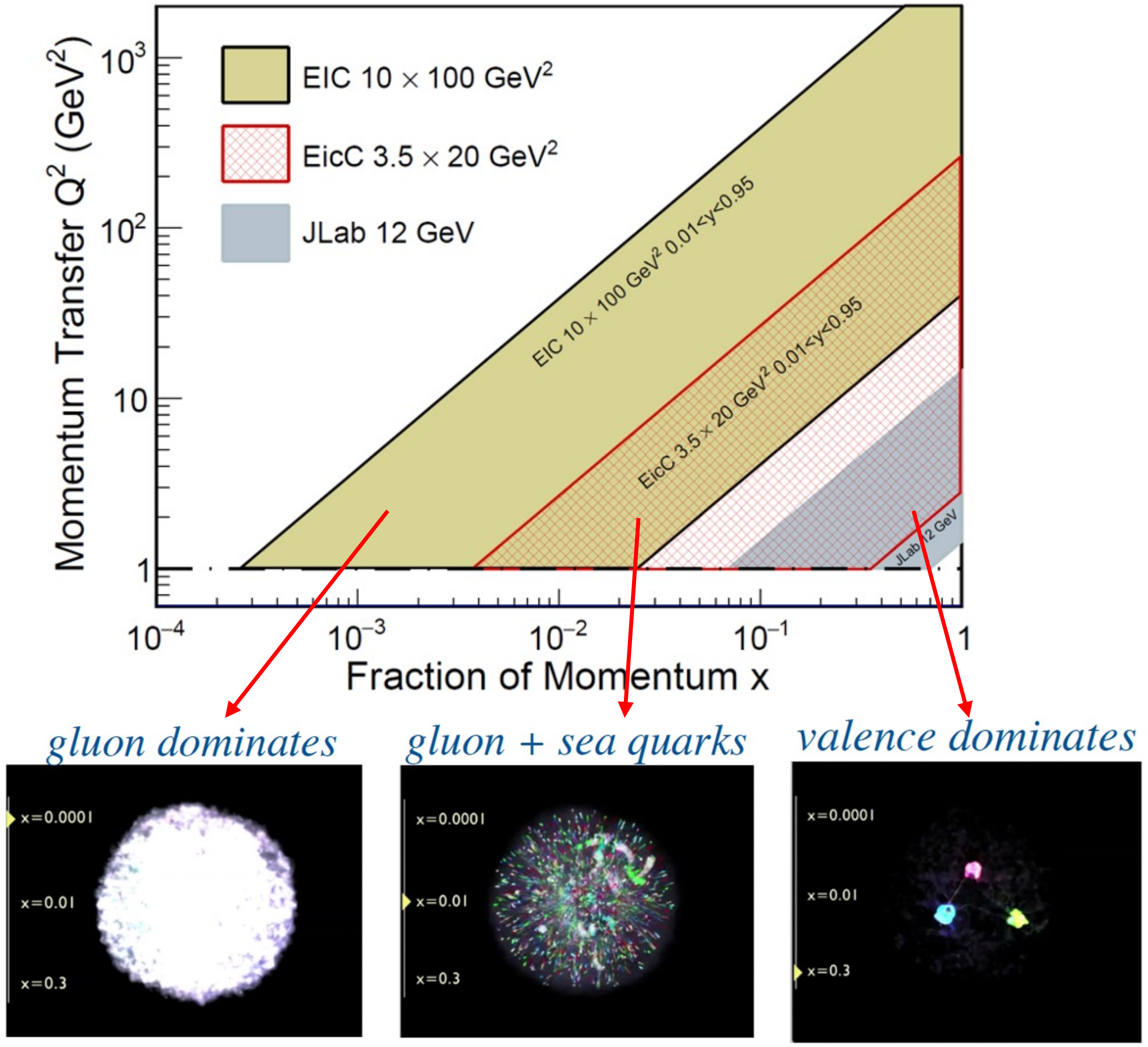
Volume II: Physics and Detectors

Contents

First draft by the end of 2023
Final version expected by the end of 2024

The 6th CDR workshop in Huizhou after QPT

Complementarity of US-EIC and EicC



R.G. Milner and R. Ent, *Visualizing the proton* 2022

Common physics goal:

- nucleon 1D, 3D spin structure
- Nucleon mass origin
- Nuclear environment effect

Complementary QCD phase space:

- US-EIC: small-x gluon dominated region; saturation behavior; etc.
- EicC: moderate x sea quark region; exotic hadron states, especially those with heavy flavor quark contents; etc