第三届高能物理理论与实验融合发展研讨会
辽宁师范大学，2024年11月1-4日

核子自旋结构的实验研究

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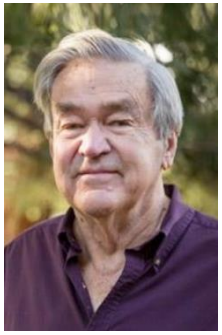
2024-11-03

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

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

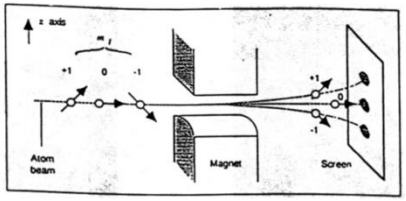
Elliot Leader



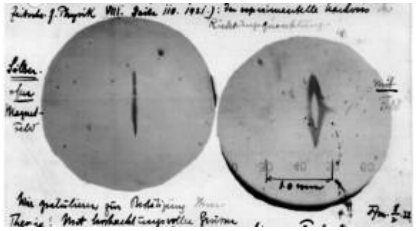
“If theorists had their way, they would ban all experiments involving spin”

James D. Bjorken

(a few) Milestones in Spin

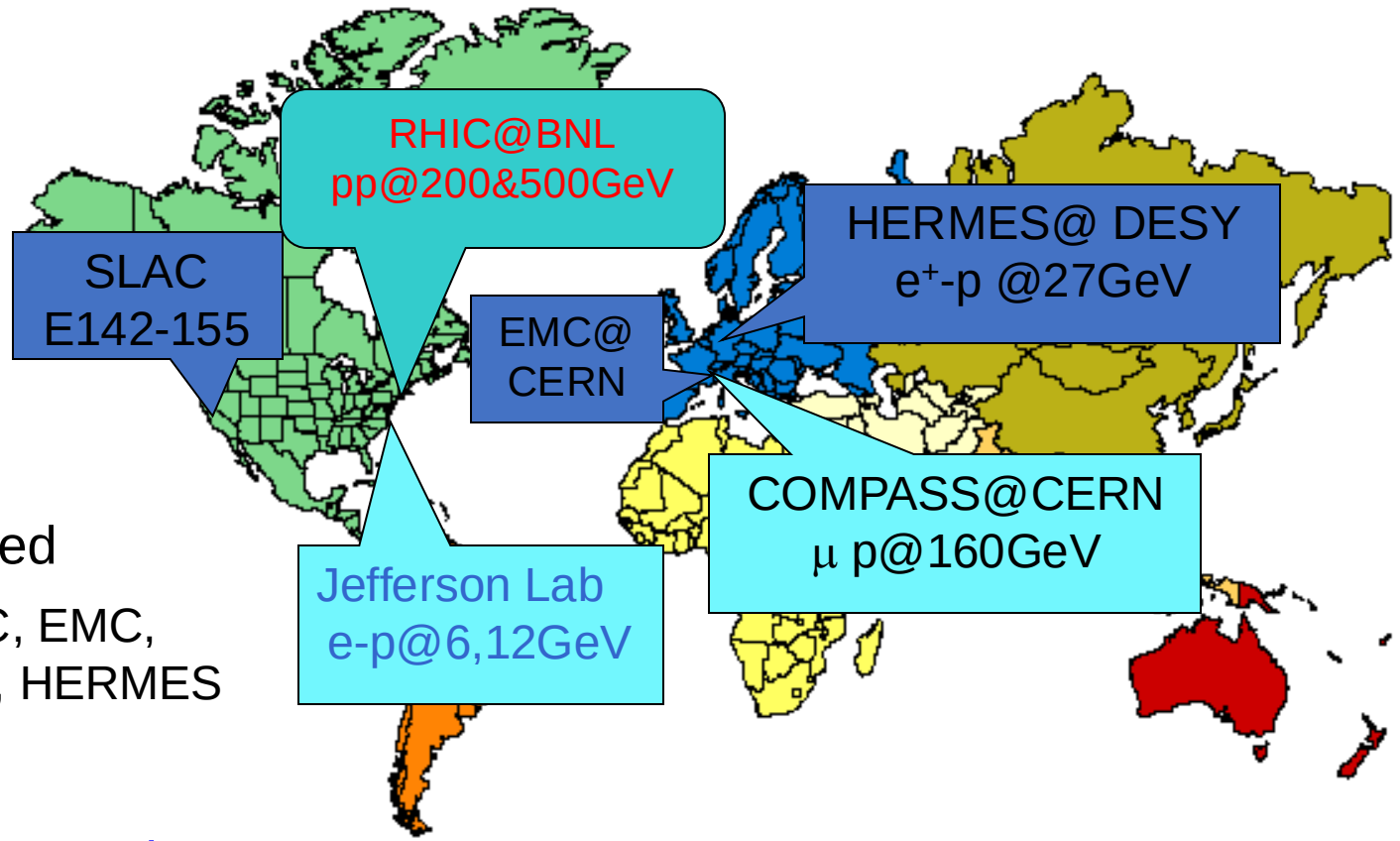


- Stern & Gerlach (1922) Space quantization
- Goudschmidt & Uhlenbeck (1925) **Discovery** of electron spin
- Stern (1933) Proton anomalous magnetic moment $\mu_p = 2.79$
- Yale-SLAC Collaboration (1978) Electro-Weak interference in polarized e-D: **parity violation**
- European Muon Collaboration (1988) **proton spin crisis**



Postcard from Gerlach to Bohr.

World efforts for high energy spin physics



Finished

SLAC, EMC, SMC, HERMES

Current running

- DIS: *COMPASS*, JLab
- Polarized proton-proton scattering, RHIC

Future

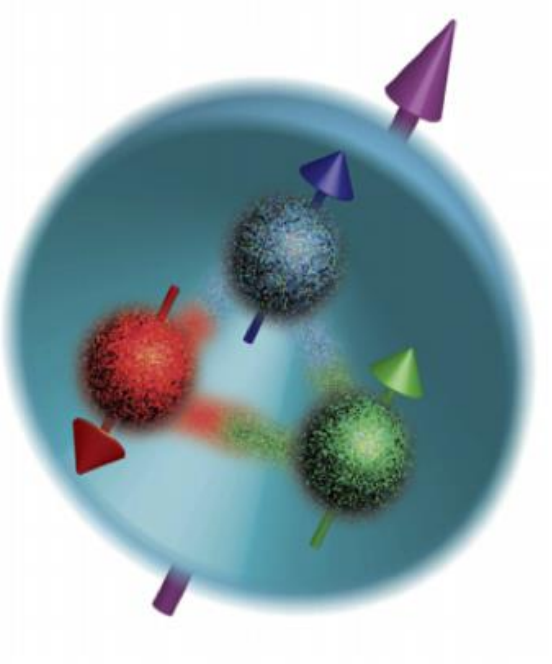
- DIS: EIC (US) EicC (China)
- Polarized proton-proton: JPARC (Japan) GSI-FAIR (Germany) NICA (Russia)

Proton Spin Structure

Well known:

Proton has structure

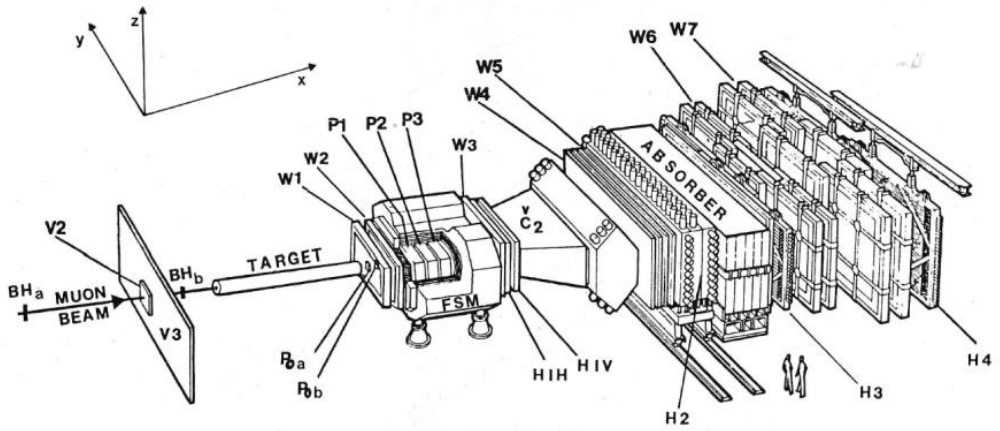
Its spin is 1/2

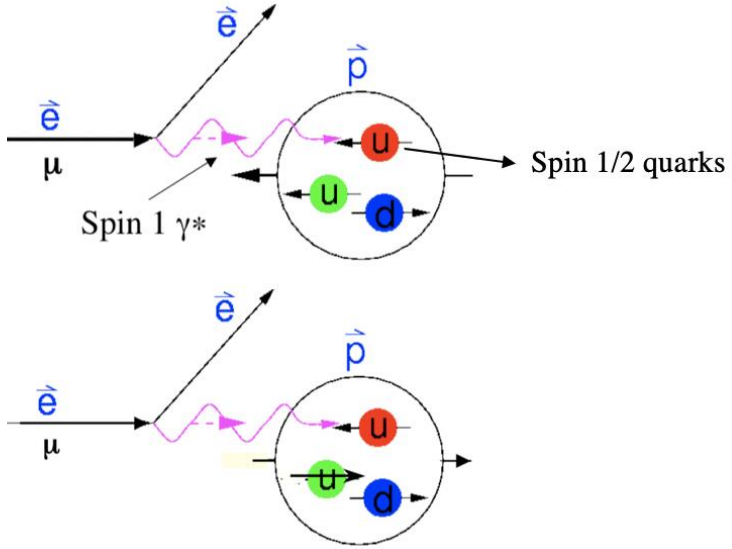


Naïve guess-based quark model:

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

Spin crisis





EMC Picture: CERN-EP-80-134

European Muon Collaboration (EMC)

Beam: 100-280 GeV muon, pol 80%

Target: Ammonia, pol 80%

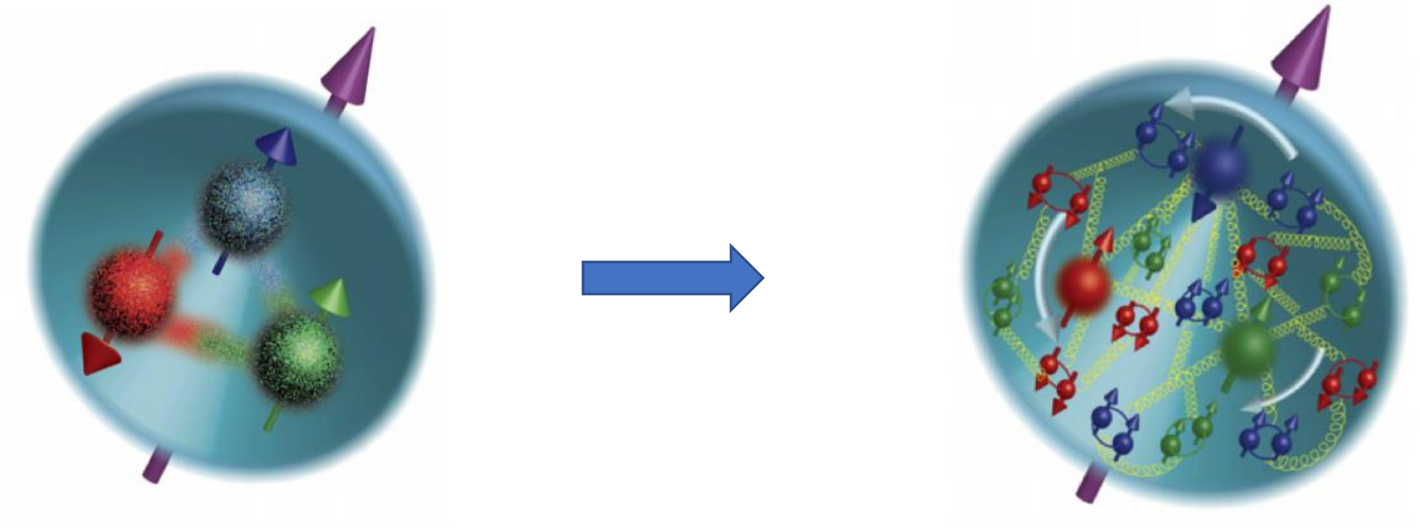
EMC, PLB 206 (1988) 364-370

Quark spin contributes only ~20% of proton spin

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

What make up the proton spin?

High-energy spin structure is much more complicated than quark-model



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

quark spin

Jaffe-Manohar 1990

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

quark spin

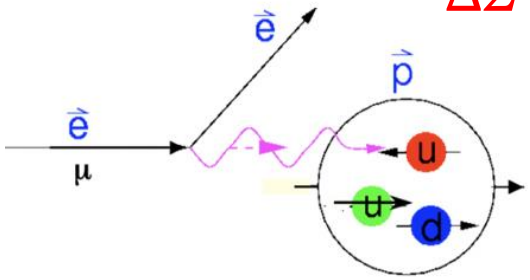
gluon spin

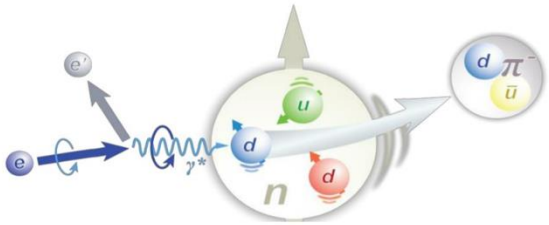
orbital angular momentum

Limitation of Inclusive DIS

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

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

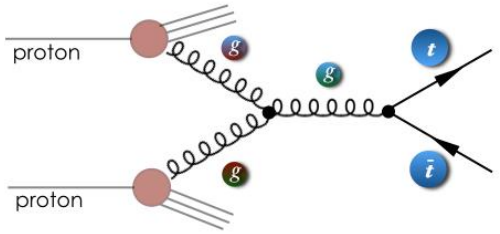


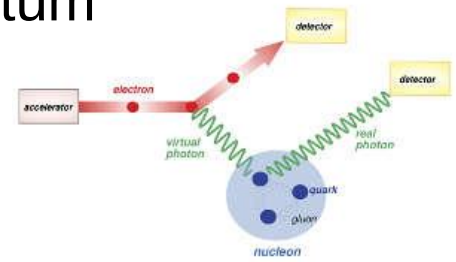


can not distinguish quark flavors

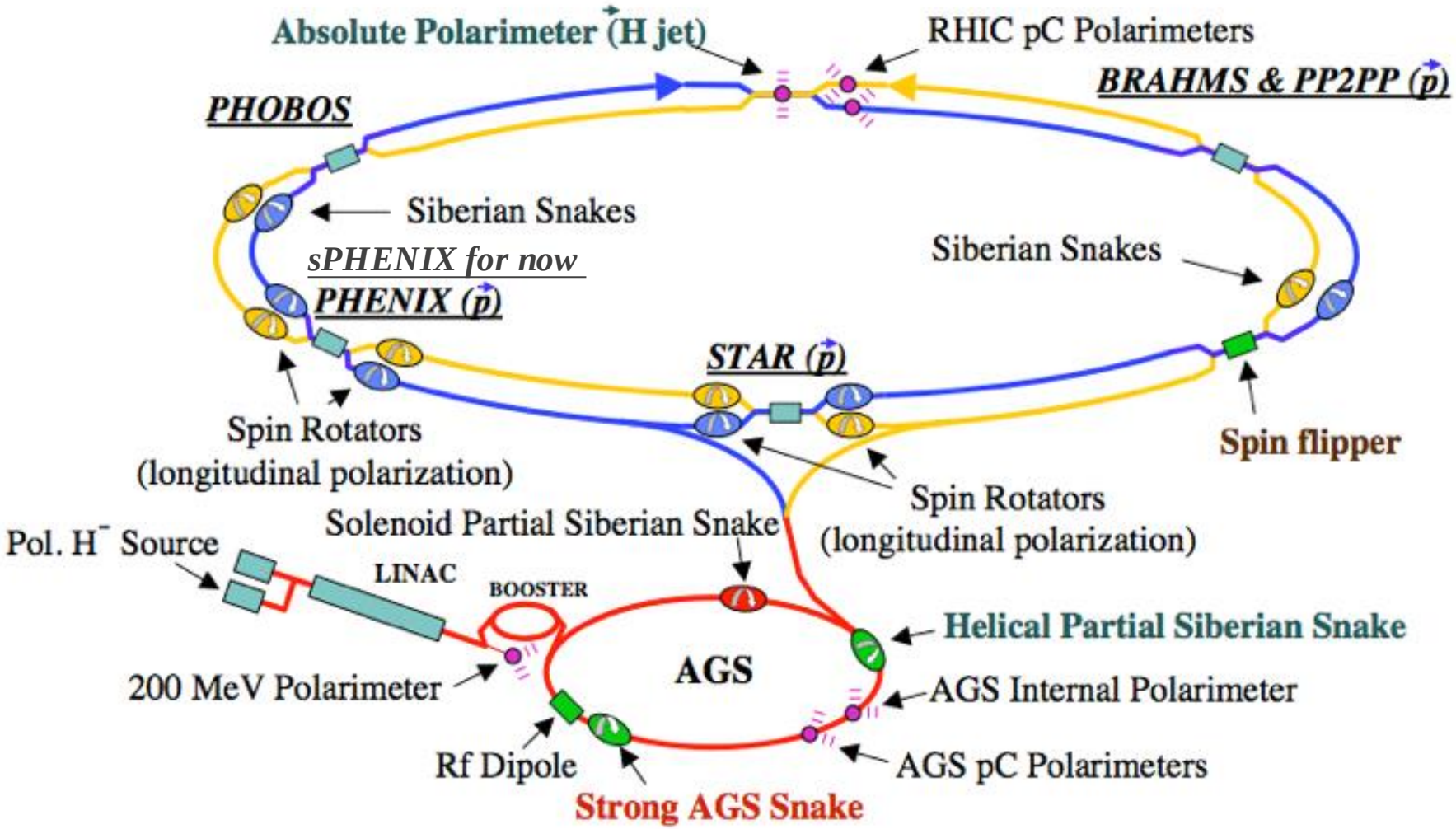
see gluons (directly)

access orbital angular momentum



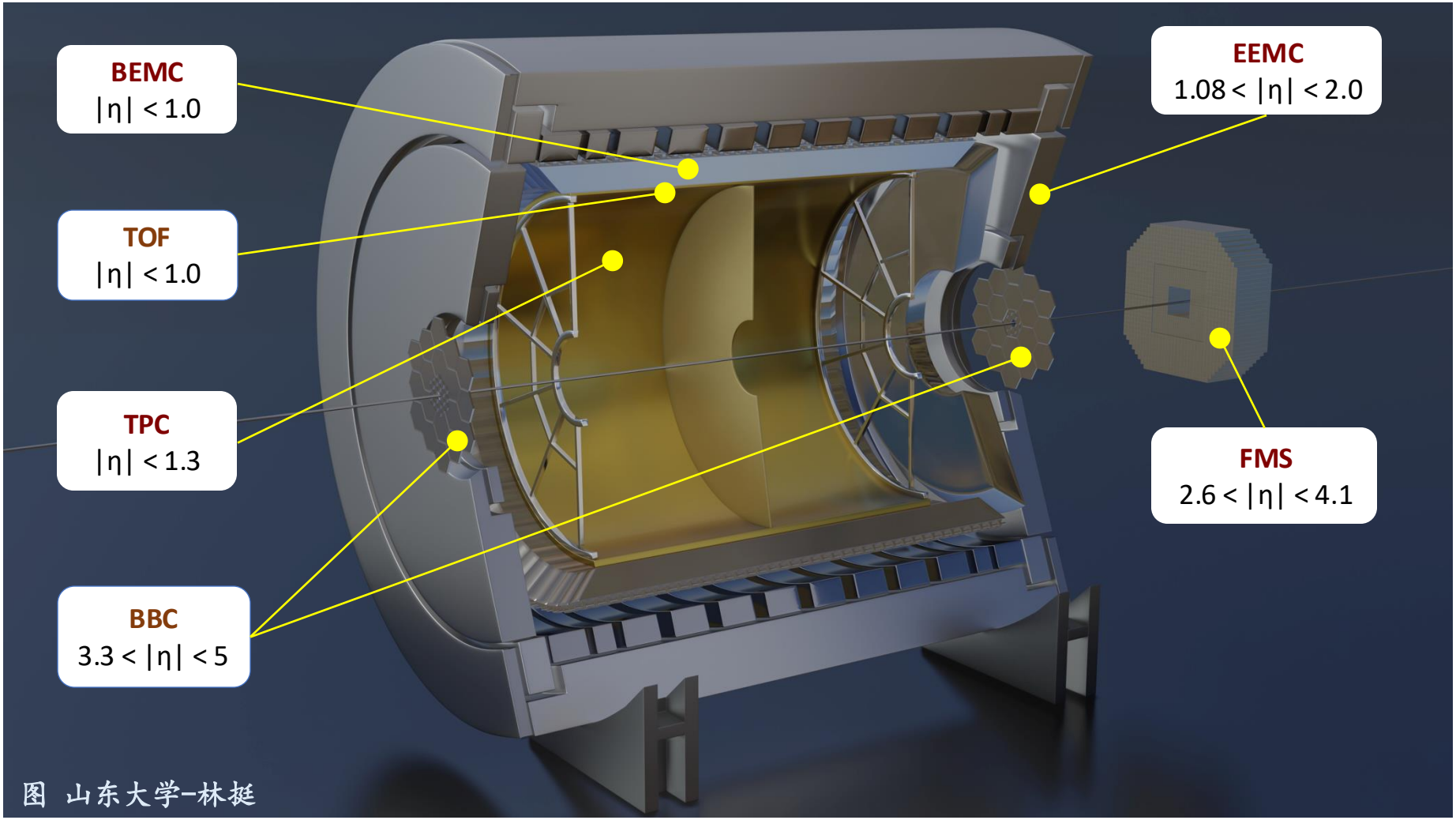


RHIC – Polarized Proton-Proton Collider

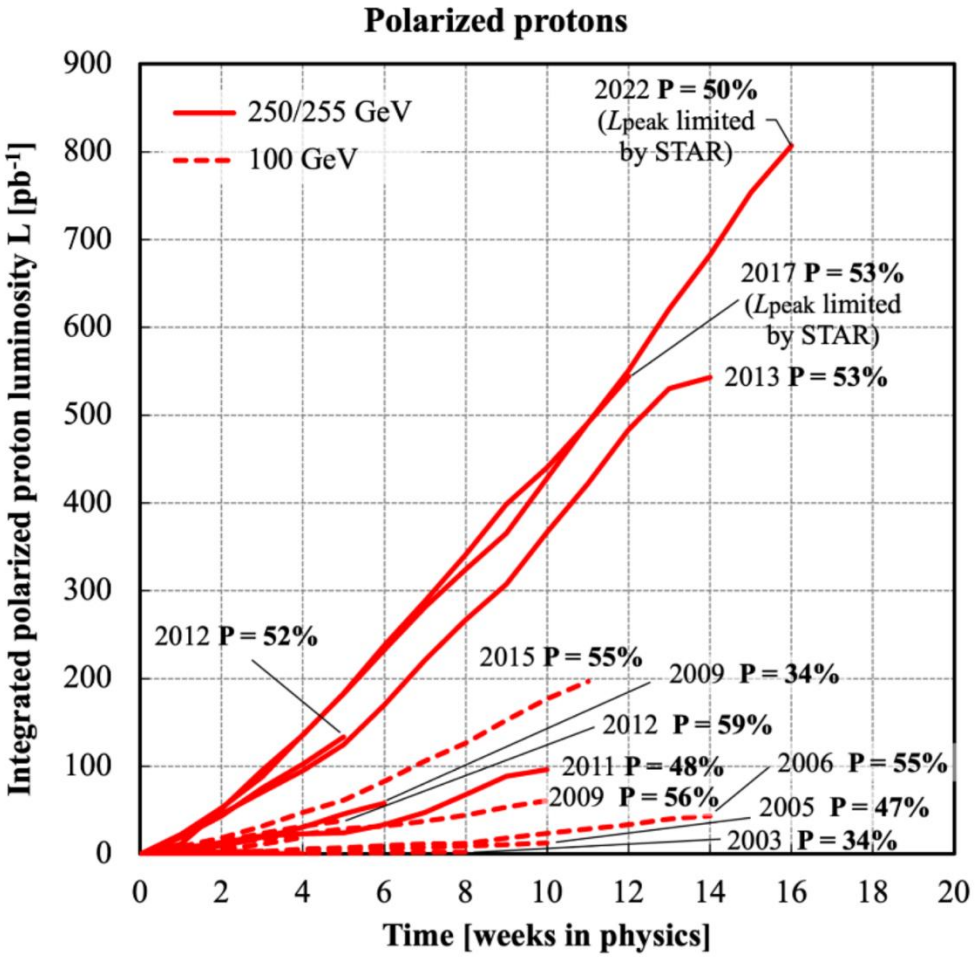


Shutdown in 2025, next stage: Electron-ion Collider

STAR Detector Overview



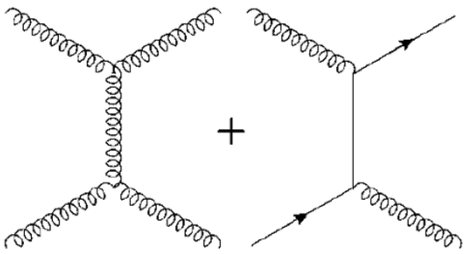
RHIC spin data



	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
	2024	200	164	55

Sampled by STAR

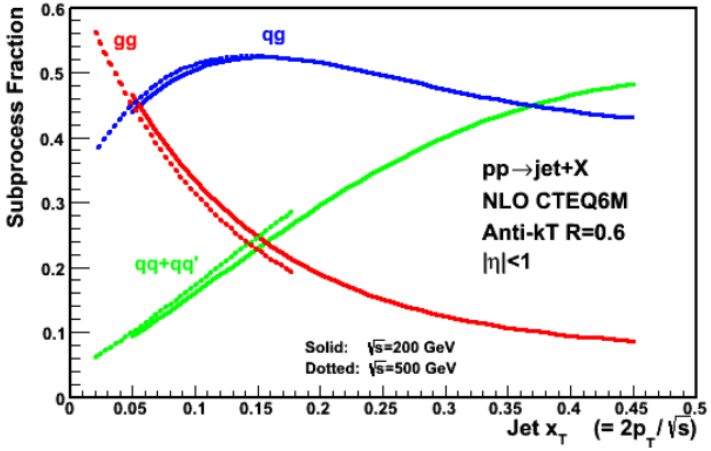
Probe gluon spin in proton-proton collision



Quark-gluon, gluon-gluon elastic scattering

Double-spin asymmetry:

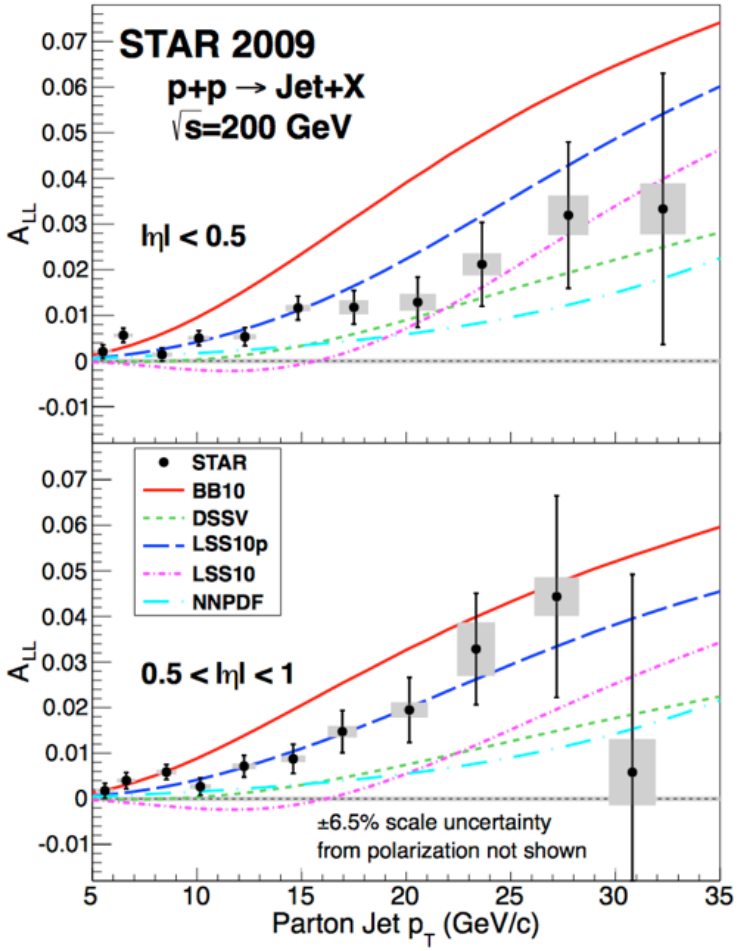
$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \propto \overbrace{\frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2}}^{\text{probed}} \otimes \overbrace{\hat{a}_{LL} \otimes D_f^h}^{\text{inputs}}$$



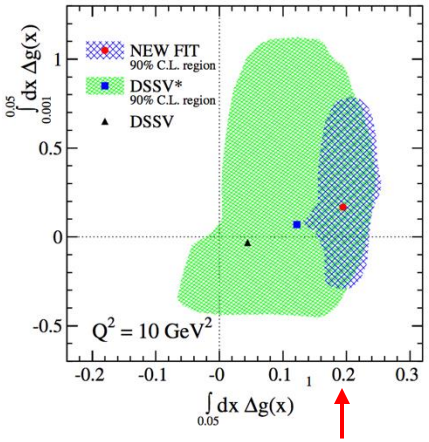
- Abundant yields of jets at RHIC
- Sub-processes directly sensitive to gluon
- $x_{g,q} \sim p_T^{\text{jets}} / \sqrt{s} \bullet e^{-\eta}$
- Constrain gluon helicity-dependent PDFs

Yes, gluon spin does contribute!

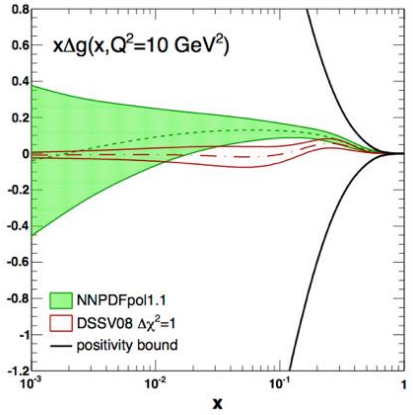
PRL115 (2015) 092002



PRL113 (2014) 012001



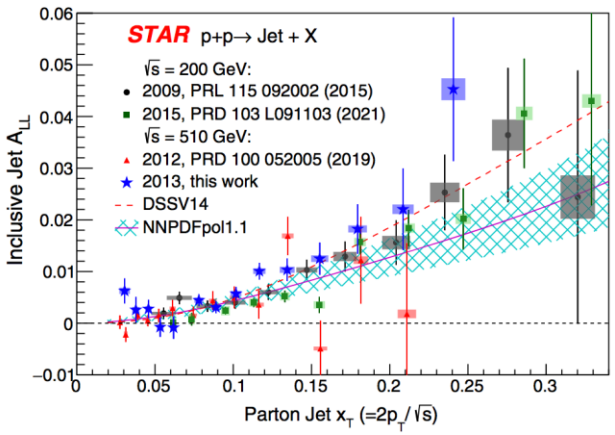
Nucl. Phys. B887 (2014) 276



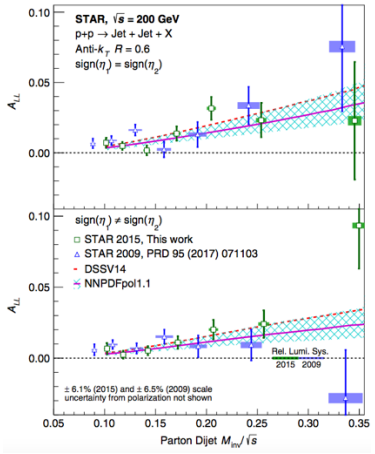
- **First evidence** of non-zero contributions from gluon spin at $Q^2 \sim 10\ GeV^2$
- Drive the constraints on ΔG

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

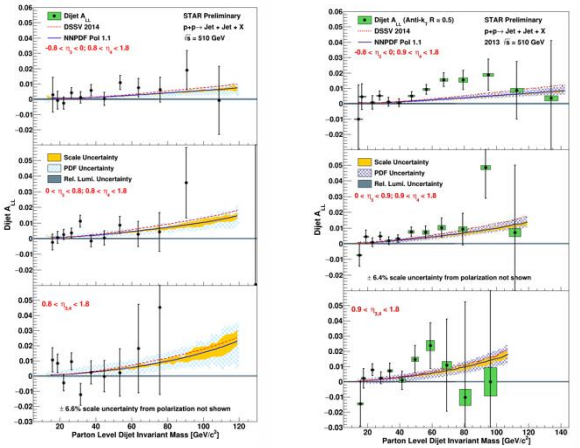
STAR, PRD 105, 092011 (2022)



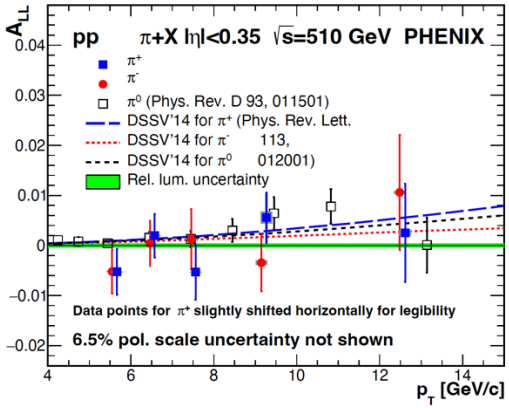
STAR, PRD 103 (2021) L091103



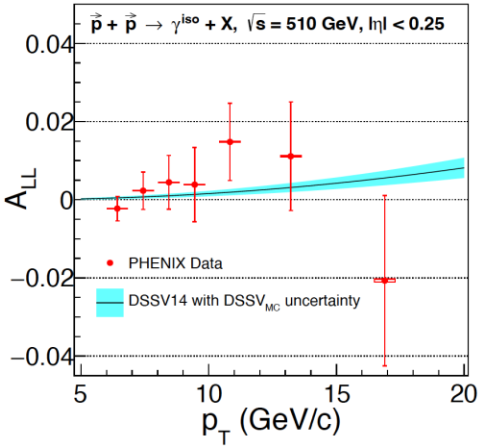
STAR di-jet preliminary results



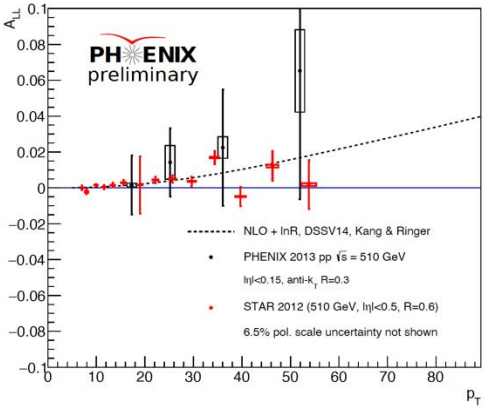
PHENIX, PRD 102, 032001 (2020)



PHENIX, PRL130, 251901 (2023)



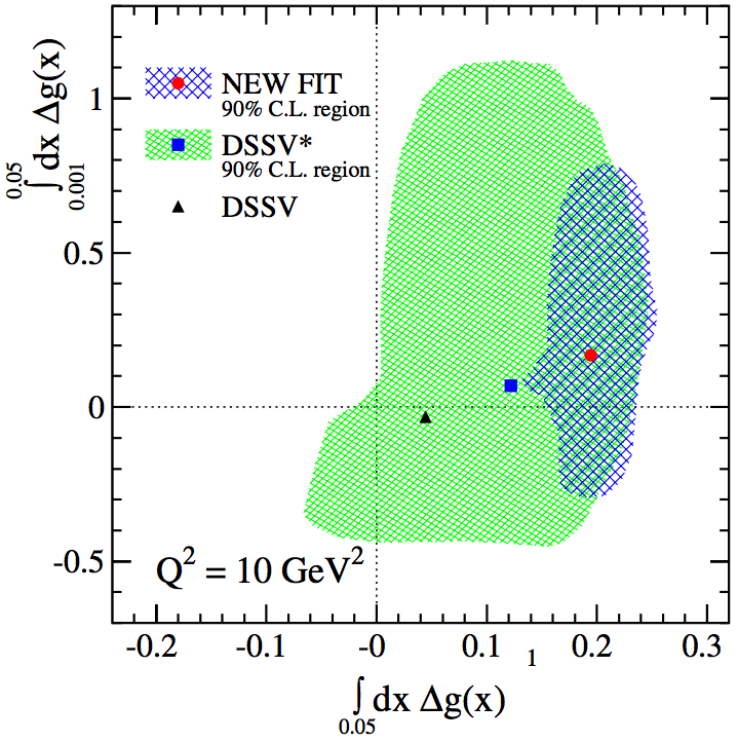
PHENIX preliminary



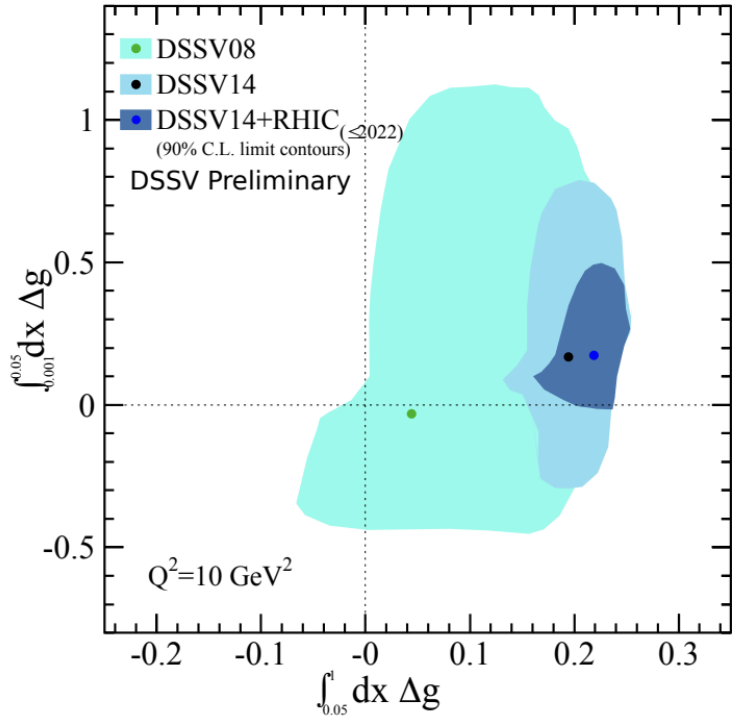
Longitudinal data taking concluded at RHIC, PHENIX and STAR released the full statistics results.

Impact on gluon polarization ΔG

PRL113 (2014) 012001



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



DSSV14:

- $\Delta G = \int_{0.05}^{1} \Delta g(x) dx = 0.20^{+0.06}_{-0.07}$
- $\Delta G = \int_{0.001}^{0.05} \Delta g(x) dx = 0.15^{+0.65}_{-0.45}$

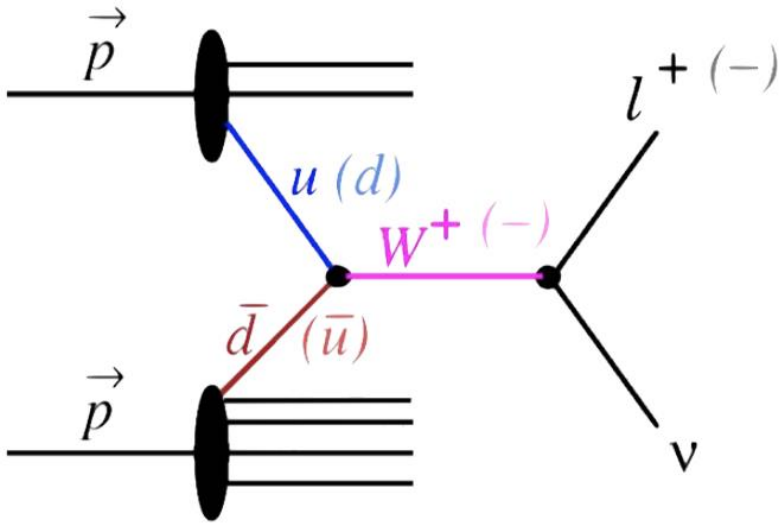
DSSV14 + RHIC ($\leq$2022):

- $\Delta G = \int_{0.05}^{1} \Delta g(x) dx = 0.22^{+0.03}_{-0.06}$
- $\Delta G = \int_{0.001}^{0.05} \Delta g(x) dx = 0.17^{+0.33}_{-0.17}$

Probing sea quarks via W boson production

Unique way to study proton spin-flavor structure:

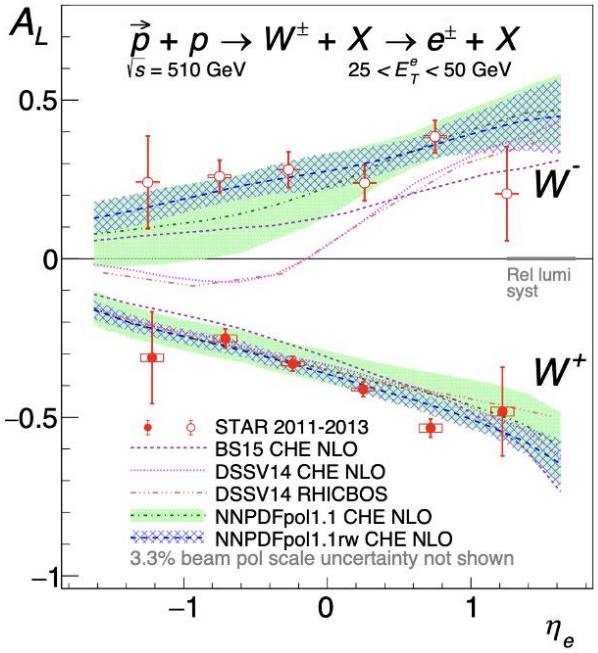
- W boson selects quarks/antiquarks with specific helicity.
- W bosons are measured via leptonic decay.

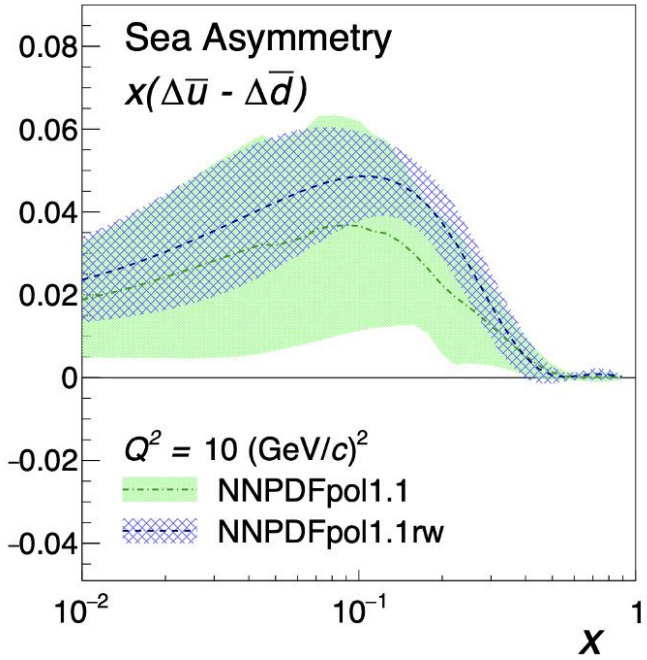


Parity violating single-spin asymmetry:

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

Impact of W results





STAR,PRL113, 072301 (2014)

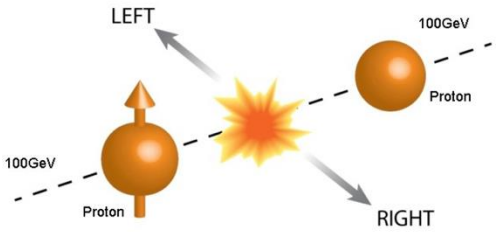
STAR, PRD99, 051102 (2019)

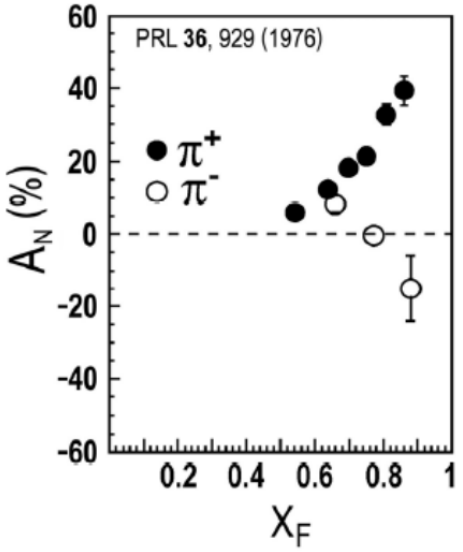
- Now we know: $\Delta\bar{u} > 0$ and $\Delta\bar{d} < 0$
- The flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ similar size but opposite sign to the unpolarized flavor asymmetry $\bar{u} - \bar{d}$

Another spin puzzle

Transverse single spin asymmetry:

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



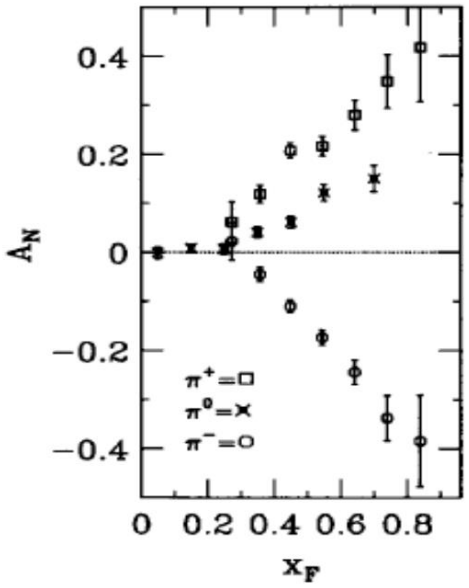


Significant asymmetries seen at low energies results from ZGS and AGS

Transverse spin effect expected to be **small** at high energies…

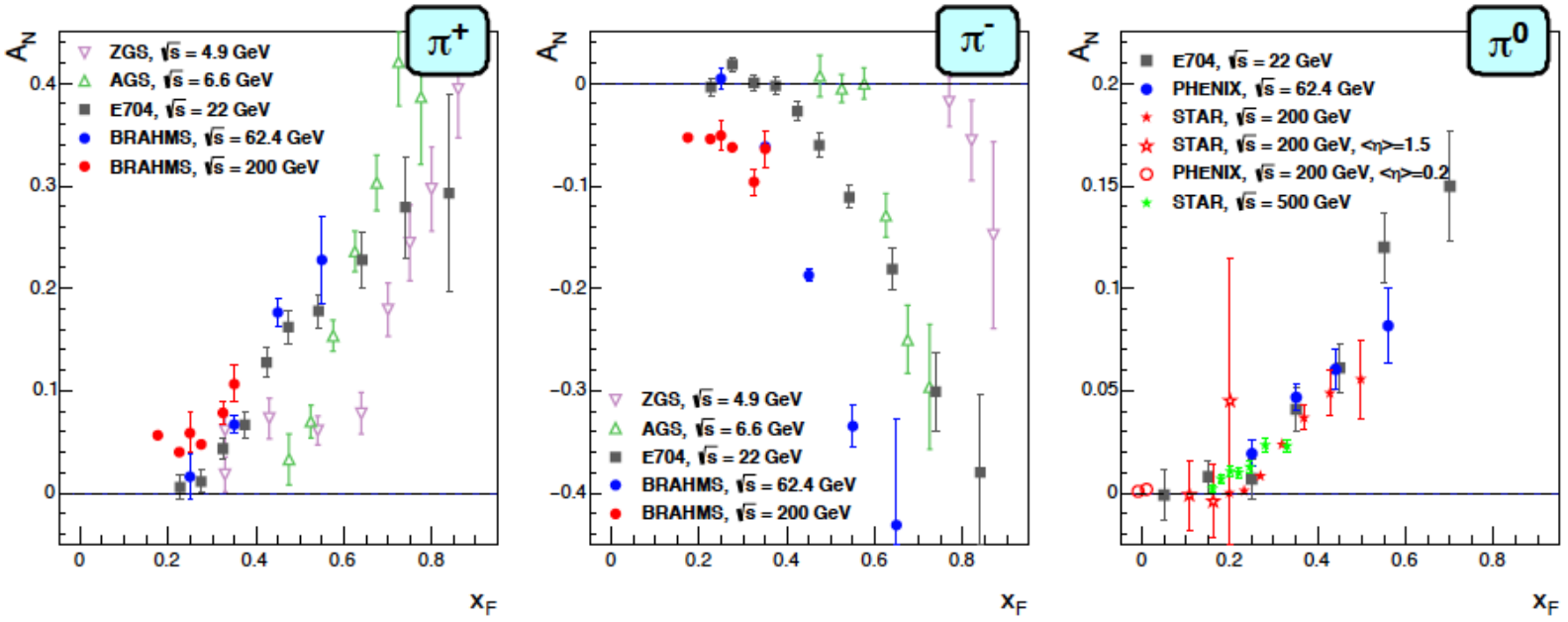
--- but FNAL came with a big surprise:

Large transverse asymmetries E704



Remains mystery after 40+ years

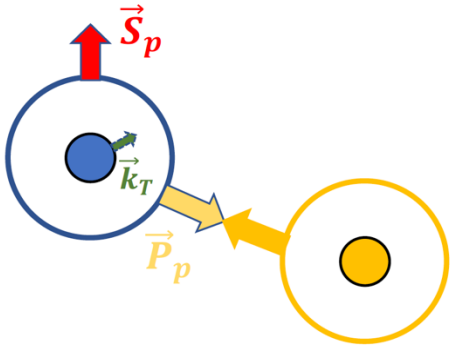
RHIC Cold QCD plan, arXiv: 1602.03922



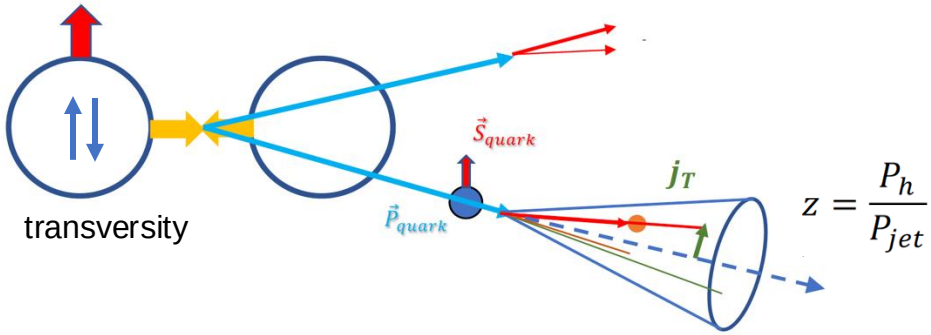
- Nearly independent of √s over a very wide range (√s: 4.9 GeV to 500 GeV).
- TMDs and colinear Twist-3 frameworks developed to explain A_N origin
  - Qiu-Sterman functions, Sivers effect, Collins effect, etc.

Transverse single-spin asymmetries at RHIC

Sivers effect



Collins effect



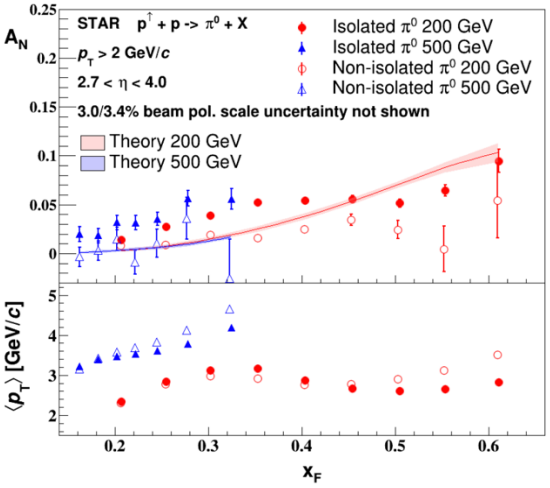
Sivers: Correlations between initial-state parton transverse momentum with proton's spin and momentum; process dependent.

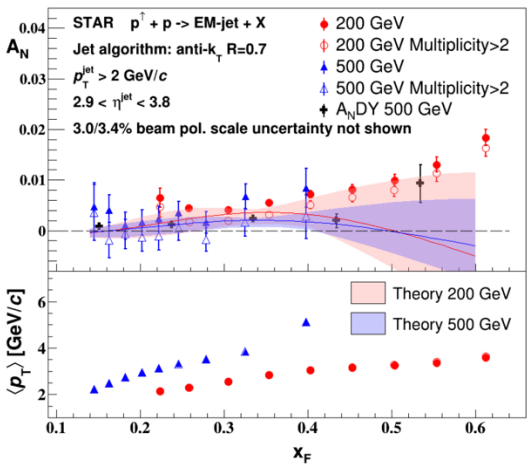
Collins: Correlations between the polarization of a scattered quark and the momentum of a hadron fragment transverse to the scattered quark direction.

Transversity: transverse polarization of partons inside transversely polarized proton.

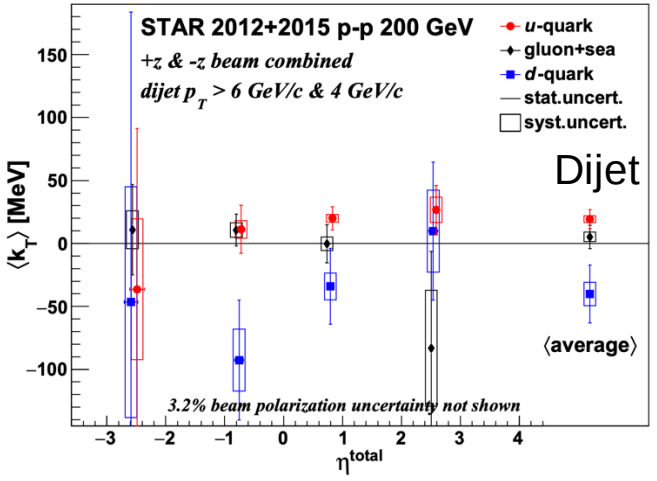
π^0, EM-jet, Di-jet A_N – Sivers

STAR, PRD 103 (2021) 9, 092009





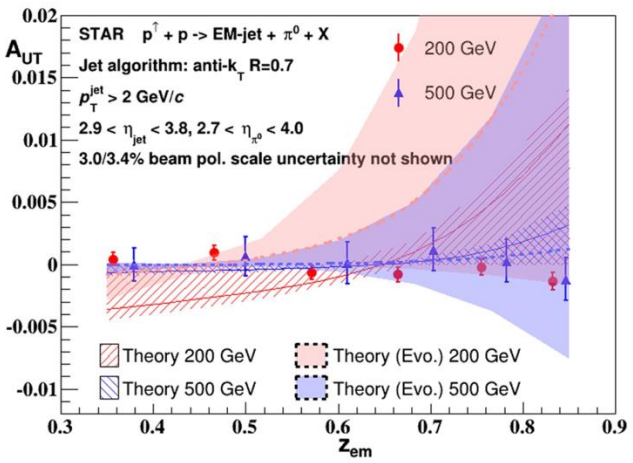
arXiv: 2305.10359



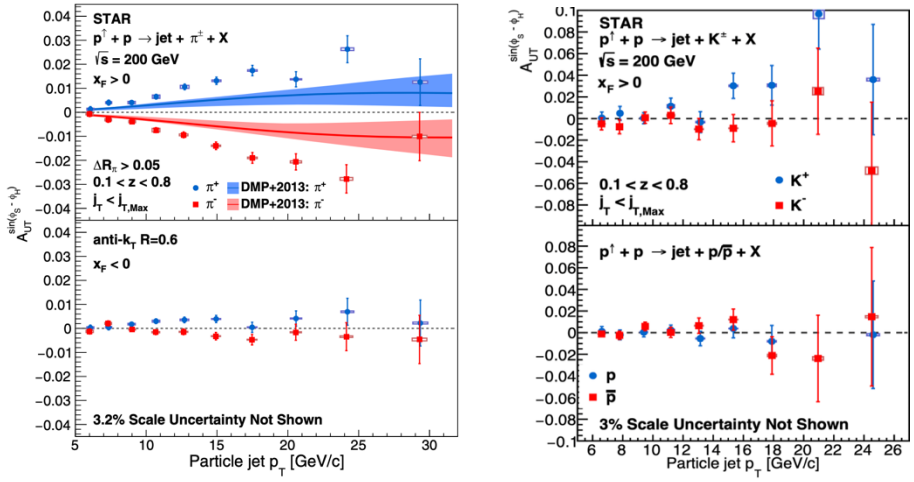
- A_N measured with forward EM-jets, dijet and π^0 in 200/500 GeV pp collisions
- High multiplicity EM-jets (n_γ > 2) and non-isolated π^0 (w/ nearby γ) tend to generate smaller A_N
- First observation of non-zero Sivers asymmetries in dijet production in polarized *p*+*p* collisions
- No significant collision energy dependence observed

Hadron in Jet A_N – Transversity + Collins

STAR, PRD 103 (2021) , 092009



STAR, PRD 106 (2022), 072010



- Transversity is probed most directly in the jet p_T dependence
- Collins TMD FF is sensitive to the (j_T,z) dependence
- Significant Collins asymmetries have been observed in 200 GeV measurement
- **Discrepancy with theoretical predictions**

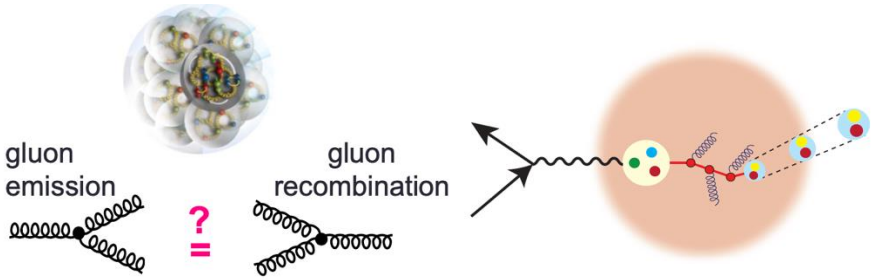
RHIC spin is just concluded

Complementary to DIS, RHIC is unique machine for studying proton spin structure, 1D and 3D

- Featured measurements of gluon and sea quark helicity dependent PDFs (mostly) concluded successfully: $\Delta G > 0$ and $\Delta\bar{u} > \Delta\bar{d}$
- Transverse program in progress: existing data being published/analyzed and more data from last spin run in 2024

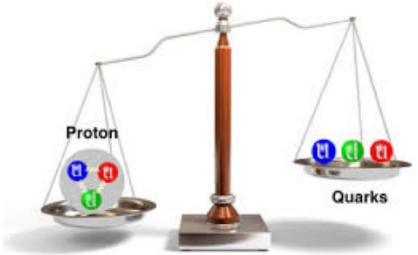
Next generation: polarized Electron-ion Collider

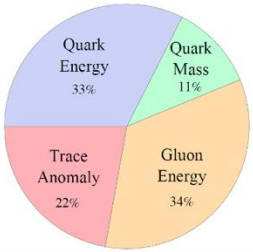
Questions expecting EIC to answer

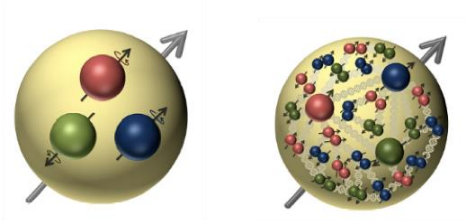


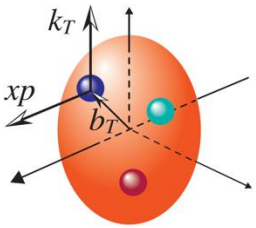
Does gluon saturate at high energy? How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

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?

Nex generation: Electron-ion Collider

FAIR ➔ ENC

RHIC ➔ eRHIC/EIC

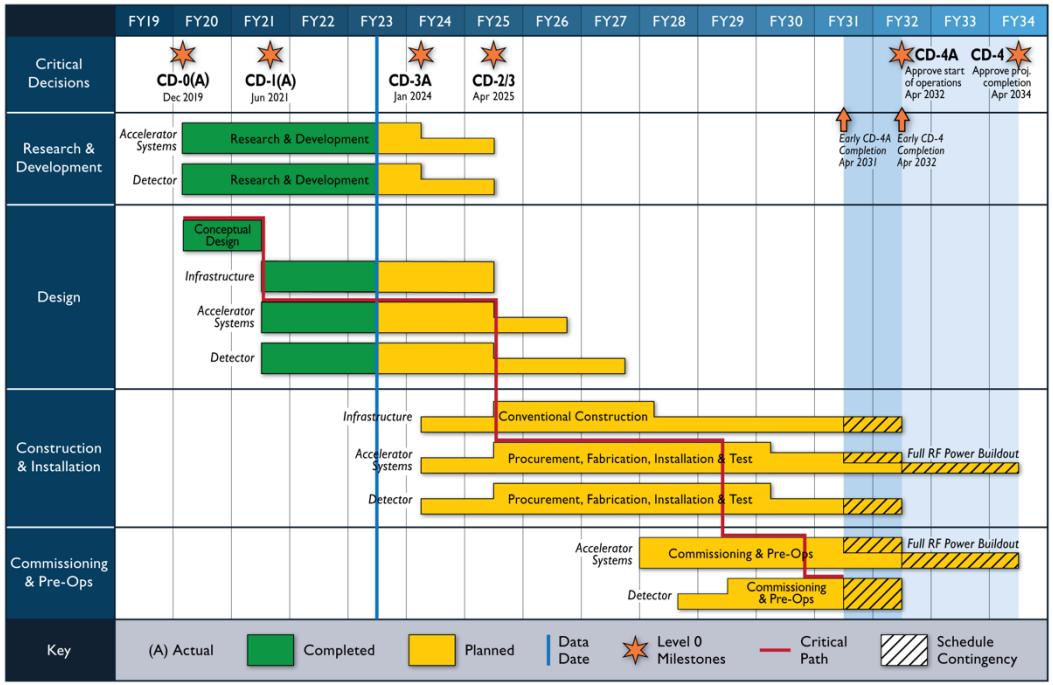
LHC ➔ LHeC

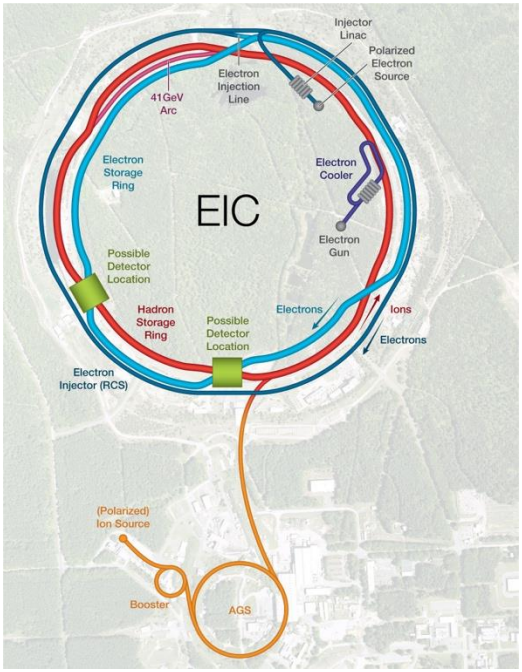
HIAF ➔ EicC

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

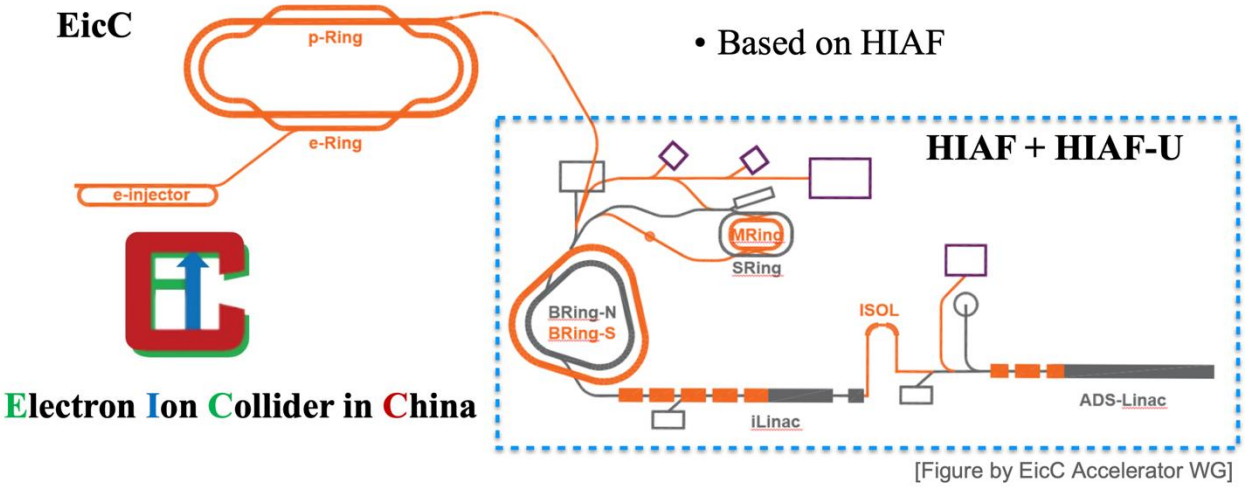




C. Montag, SPIN2023

EicC Status

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



[Figure by EicC Accelerator WG]

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

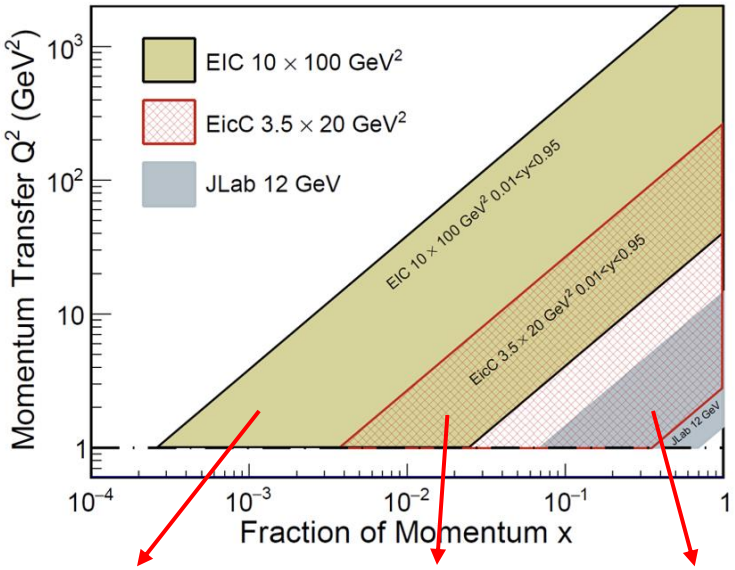
- a national facility on nuclear physics, atomic physics, heavy-ion applications …
- beam commissioning is planned in 2025

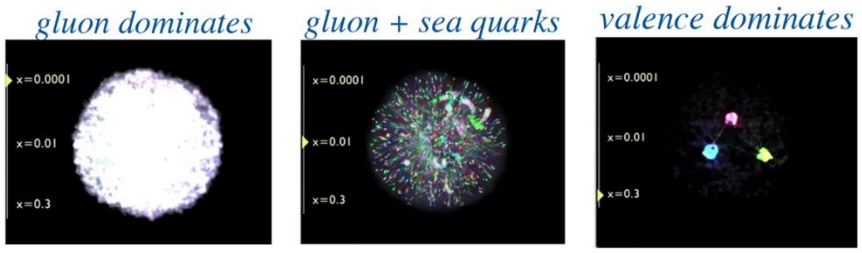
EicC is based on HIAF

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

polarized

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

Summary

- A lot of discoveries from spin experiments in the past 100 years
- Spin in high energy physics: from spin crisis to spin puzzle, a lot achievements but still many open questions.
- Next generation experiments for proton spin structure – polarized electron-proton collider: EIC, EicC, …
- More interesting experiments not covered: polarization effects at final state, Lambda spontaneous polarization, global polarization in HIC, …

谢谢！