Center for Frontiers in Nuclear Science

20 Years of Cold QCD at RHIC

RHIC – AGS Annual Users (Virtual) Meeting

June 12, 2020

To the attendees of the 1st RHIC Spin Workshop 1990 @ Penn State

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BROOKHAVEN NATIONAL LABORATORY

Thanks

Yasuyuki Akiba, Elke Aschenauer, Sasha Bazilevsky, Helen Caines, Carl Gagliardi, Ciprian Gal, Sanghwa Park, Lijuan Ruan, Desmond Shangase (Christine Aidala), Michael Tannenbaum, Werner Vogelsang, Qinghua Xu, Jinlong Zhang

For contributions
(direct, indirect & in some cases unknowingly)
to this talk.

All mistakes and limitations are of course mine.

Cold QCD Program at RHIC: Pioneering & Vast

Physics with **polarized** beams: A pioneering program on many fronts:

- High energy polarized protons: Siberian Snakes
- Invented & then perfected tools for polarization measurements
- Invented and then perfected the tools for control of spin orientation & to monitor
- Measurement of small asymmetries: Relative luminosity
- Physics with **asymmetric energy combinations** wide variety

PHENIX and STAR together have ~120 Ph.D. theses, and about as many peer reviewed publications, and more than ~6000+ citations.

It will be impossible to cover all results and do justice to all efforts.

Forced to be highly selective; mostly show recent published results…

Outline this talk is somewhat like this:

Brief history & origins of the program

RHIC Spin program

- Motivation: nucleon spin puzzle before RHIC
- RHIC Spin: Delta-G, Anti-Quarks and transverse spin effects & surprises

Future of Cold QCD

- Cold QCD at STAR, Cold QCD at sPHENIX ➔ QCD with the EIC

Appreciation & congratulations

1983 NSAC Long Range Plan

RHIC Recommendation

1) **The research program in nuclear physics, with the facilities in existence or under construction, faces many challenges and opportunities *now*. To address those opportunities, central to the vitality of our field, it is essential that the $20 million incremental adjustment in operating and equipment funds for the ongoing research program that we recommended earlier this year be forthcoming.**

2) **We identify a relativistic heavy ion collider as the highest priority for the next major facility to be constructed, with the potential of addressing a new scientific frontier of fundamental importance.**

3) **To effectively utilize the national electron accelerator, the relativistic heavy ion collider and the other vital facilities of the nuclear research program, we recommend a level of funding rising to $270 million per year (FY 1983 dollars) by the time the above two major construction projects have been completed.**

Spin is not mentioned in the RHIC recommendation

Our increasing understanding of the underlying structure of nuclei and of the strong interaction between hadrons has developed into a new scientific opportunity of fundamental importance—the chance to find and to explore an entirely new phase of nuclear matter. In the interaction of very energetic colliding beams of heavy atomic nuclei, extreme conditions of energy density will occur, conditions which hitherto have prevailed only in the very early instants of the creation of the universe. We expect many qualitatively new phenomena under these conditions; for example a spectacular transition to a new phase of matter, a quark-gluon plasma, may occur. Observation and study of this new form of strongly interacting matter would clearly have a major impact, not only on nuclear physics, but also on astrophysics, high-energy physics, and on the broader community of science. The facility necessary to achieve this scientific breakthrough is now technically feasible and within our grasp; it is an accelerator that can provide colliding beams of very heavy nuclei with energies of about 30 GeV per nucleon. Its cost can be estimated at this time only very roughly as about 250 million dollars. ***It is the opinion of this Committee that the United States should proceed with the planning for the construction of this relativistic heavy ion collider facility expeditiously, and we see it as the highest priority new scientific opportunity within the purview of our science.*** The tasks of specifying the detailed characteristics of the accelerator, identifying technical issues, and planning for the necessary instrumentation will have to be taken up by workshops and NSAC subcommittees as soon as is appropriate and practical.

Brookhaven National Laboratory has proposed major expansion of its present facility by combining it with the AGS (the 30-GeV Alternating Gradient Synchrotron) to accelerate heavy ions to relativistic energies up to ~15 GeV per nucleon. Using direct injection of the AGS, ions up to A = 32 and currents $>10^9$ pps would be available. Construction of a modest intermediate booster accelerator would permit injection of heavier ions, up to about A = 130, into the AGS. This system would provide significantly higher-energy relativistic heavy-ion beams than are now available at the Bevalac. Present studies indicate that beams accelerated in the AGS are suitable for injection into a relativistic collider system which BNL is designing for possible future construction.

A fun fact:
RHIC was being talked about even before AGS HI program was realized

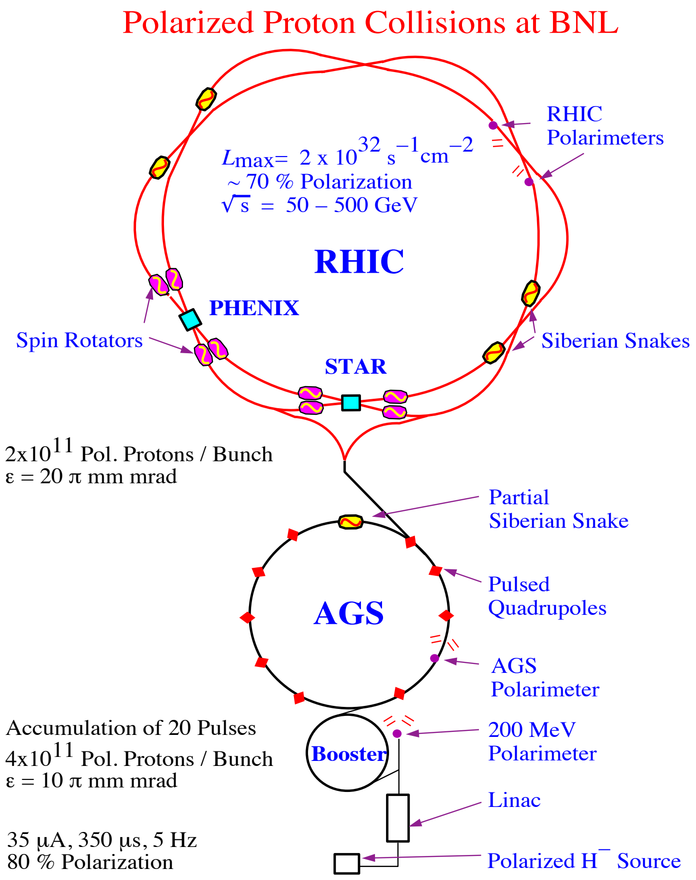
A very short History of the birth of the RHIC Spin Program

Erice Proceedings: M. Tannenbaum 1995

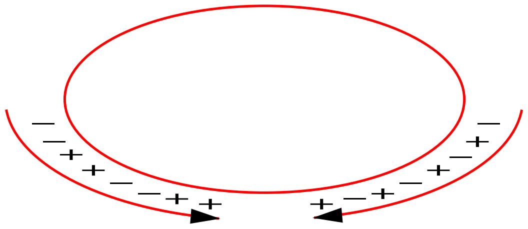
- Snowmass ’82: “*Measuring and using polarized protons at CBA*” ,G. Bunce, L. Trueman, F. Page, R. Longacre and M. Tannenbaum.
- **1983 NSAC recommends RHIC**, but no mention of polarization/spin
- 1989 Larry Trueman (ALD) and Sam Aronson (Dep. Chair) setup a task force on Future High Energy Physics at BNL, **G. Bunce and M. Tannenbaum** co-leaders.
- The group includes accelerator scientists and theorists to lay out potential physics program with polarized proton beams at RHIC.
- **1990 RHIC is approved by DOE**
- Polarized Collider Workshop at Penn State November 1990, RHIC Spin Collaboration is formed
- 1993 PHENIX/Spin and STAR/Spin collaborations formed and in1995 PP2PP/Spin took root
- 1995 Review of RHIC Spin by an external committee Chaired by Charlie Prescott : “*If sensitivities are reached, the result will be profound and form a cornerstone of the theory of hadronic structure*”
- **RIKEN-BNL Agreement September 1995:** Promise of two sets of spin rotators, Siberian Snakes, polarimeters and other hardware & PHENIX muon Spectrometer

Polarized RHIC
circa 1997

- Early schematic layouts of the two rings with Siberian Snakes, spin rotators, polarimetry (at 2 o'clock)
- Recognition that bunch-by-bunch polarization control was equivalent to fast spin rotations essential for spin experiments:
  - confidence in reaching 10^{-3-4} for false asymmetries
  - perform A_N, A_{LL}, A_{TT}.. measurements



One bunch filled at a time:



$$A_{LL} = \frac{1}{P_1P_2}\,\frac{N(++)/L(++)-N(+-)/L(+-)-N(-+)/L(-+)+N(--)/L(--)}{N(++)/L(++)+N(+-)/L(+-)+N(-+)/L(-+)+N(--)/L(--)}$$

Statistical error:

$$\Delta A_{LL}^2 = 2\left(\frac{\Delta P}{P}A_{LL}\right)^2 + \left(\frac{1}{P_1P_2}\right)^2\left(\frac{1}{N}+\frac{1}{L}\right)$$

≅ 0.05 L >> N

Systematic error:

Absolute beam polarization: 5 – 10 %, scale factor

False asymmetry from variations correlated with spin direction:

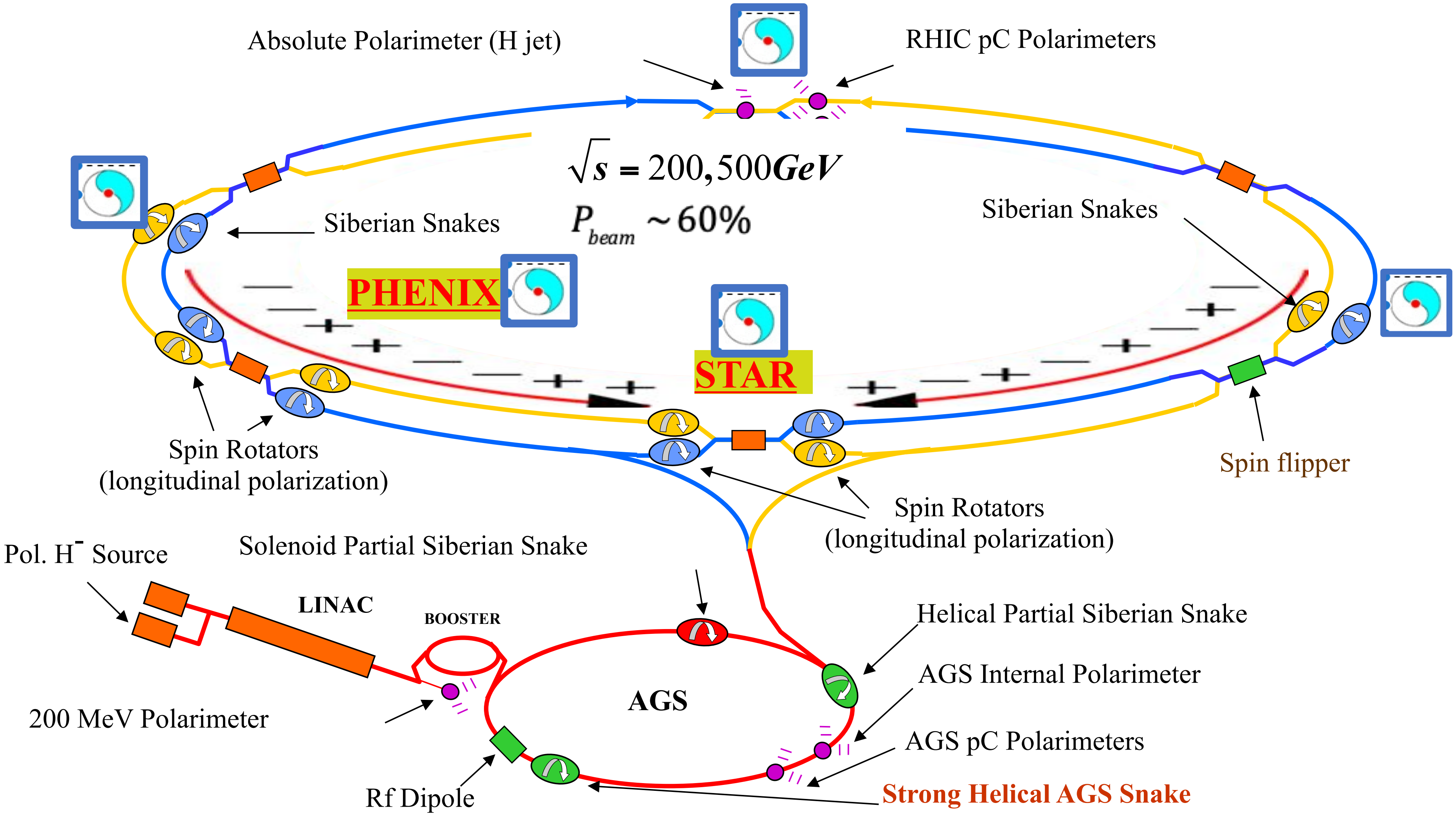
Intensity modulations: $<10^{-4}$, Spin flipper
Asymmetry in Luminusity monitor, depends on process

Variations of collision parameters →
Change spin direction often at all time scales

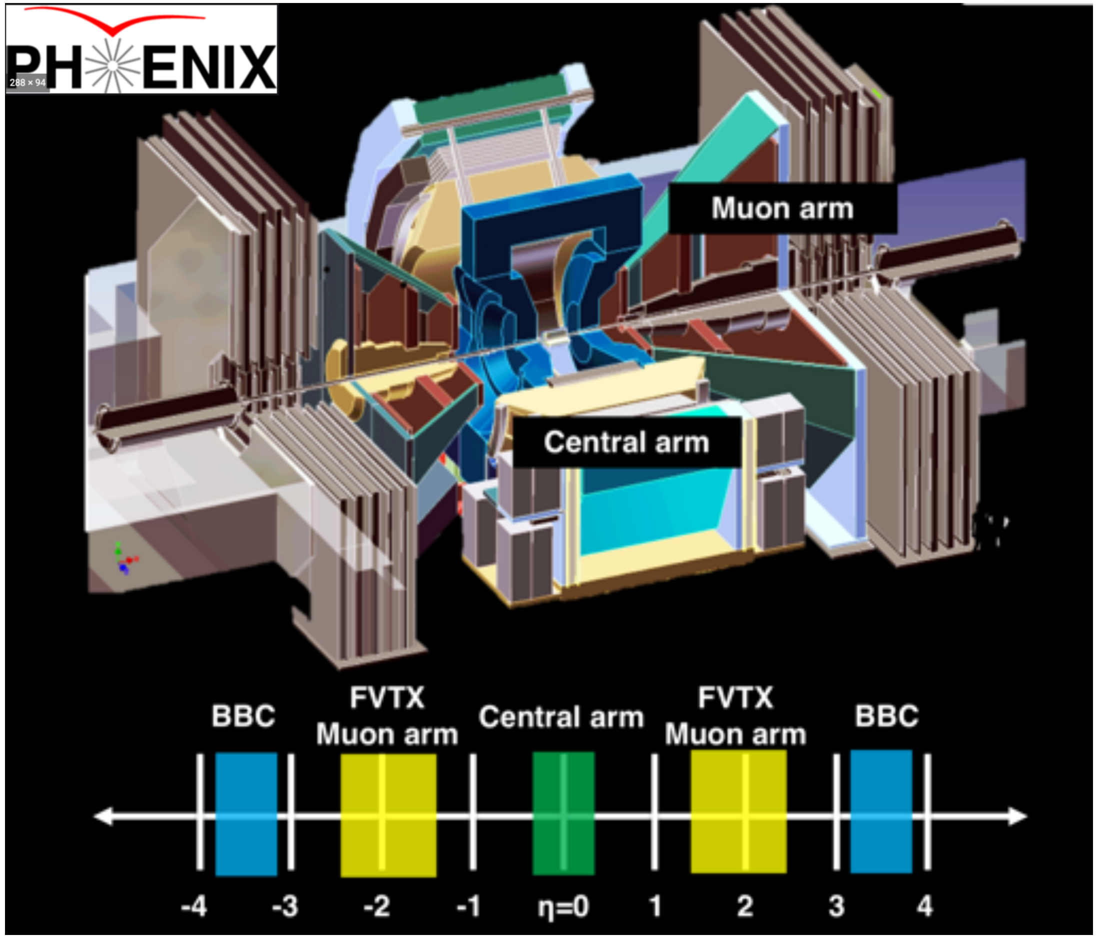
Every bunch has different spin
Spin flip every hour
Fill RHIC with different pattern every fill

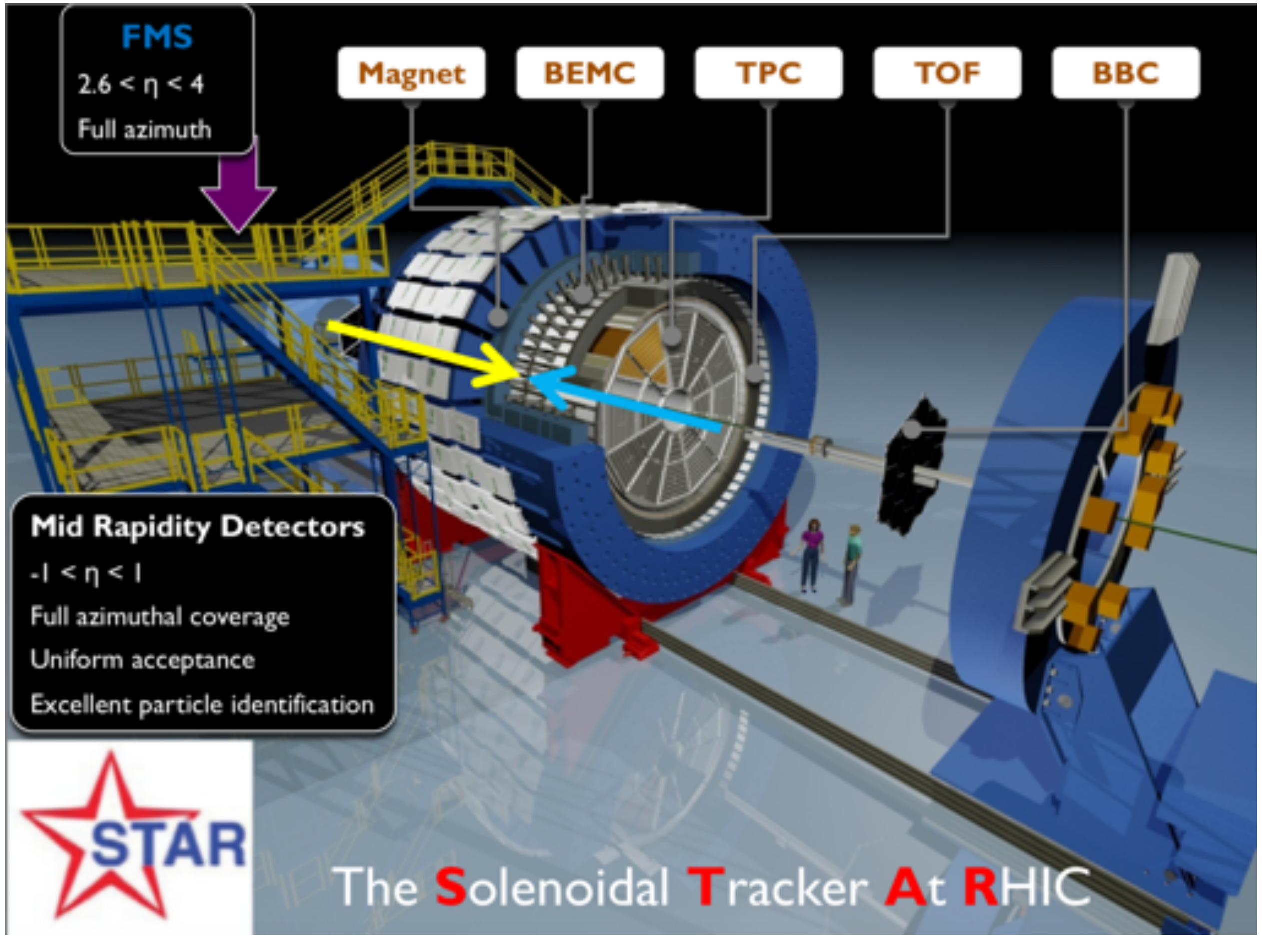
Slide from Thomas Roser
1996 Polarimetry Workshop organized by Yousef Makdisi
My first visit to BNL for RHIC-Spin

Polarized RHIC now

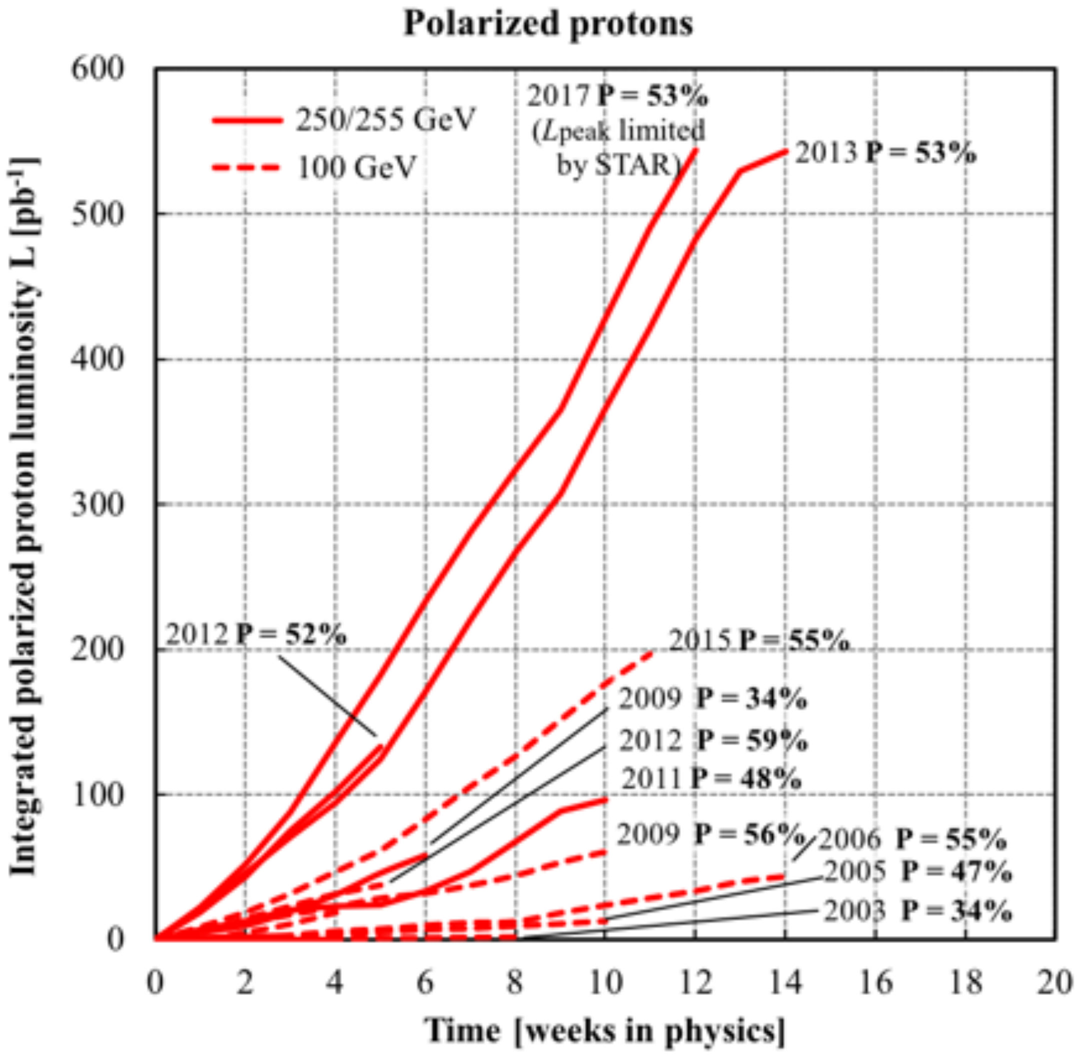


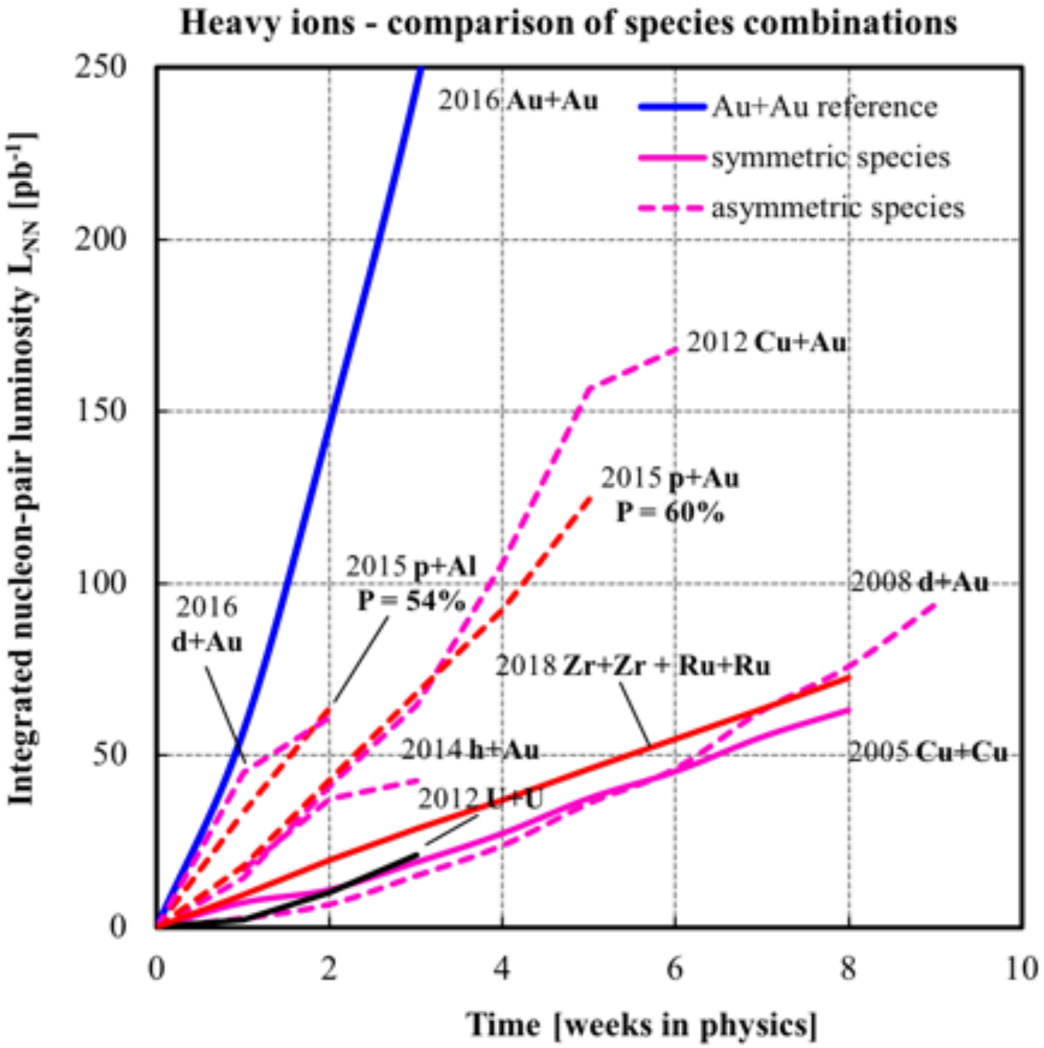
Two main detectors for spin studies





RHIC delivered



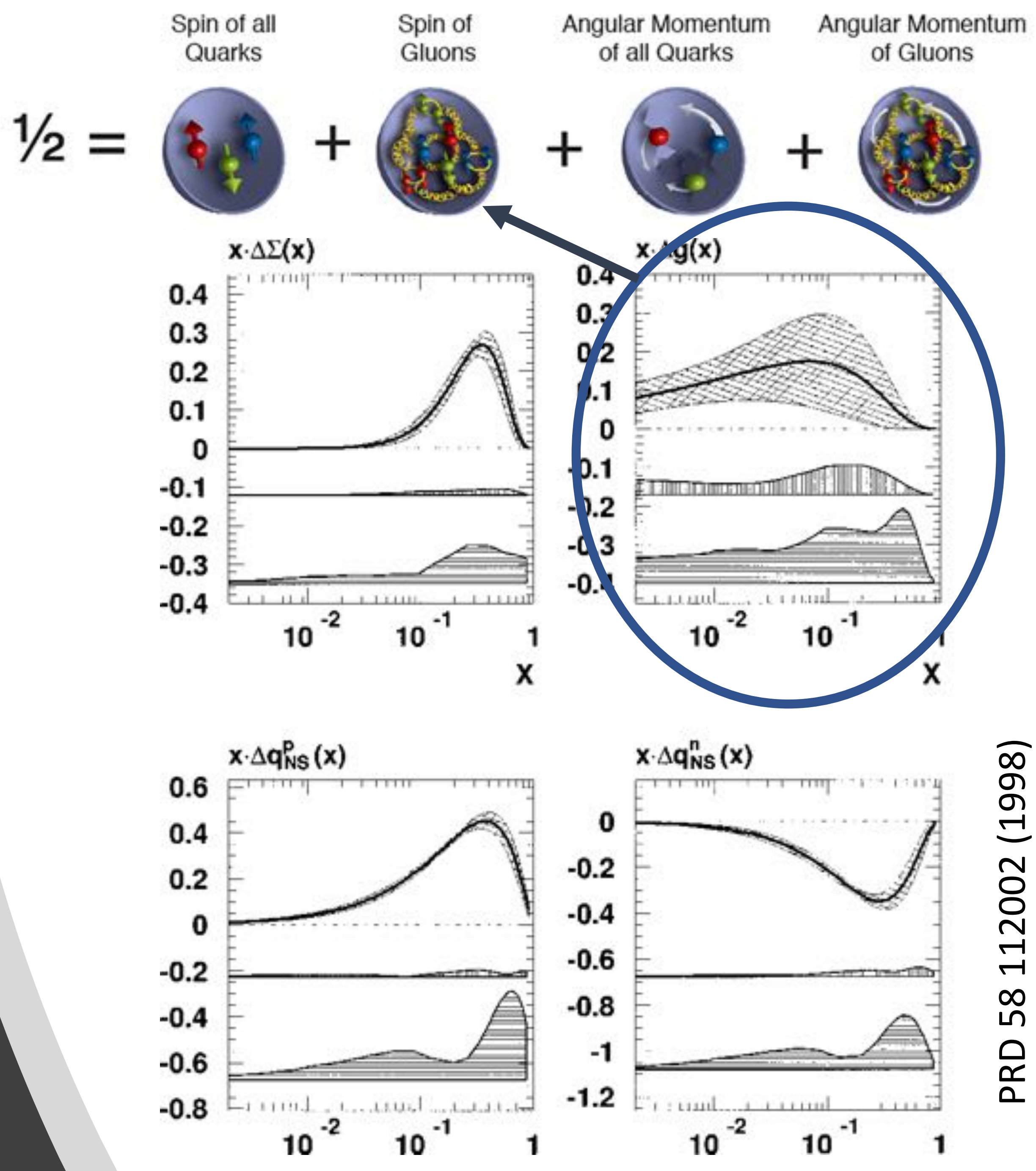


Proton spin structure before RHIC

- 1989-1995 : Based on SLAC (E142/E143) and EMC/SMC (CERN) data we had learnt that gluons may contribute significantly to the nucleon spin

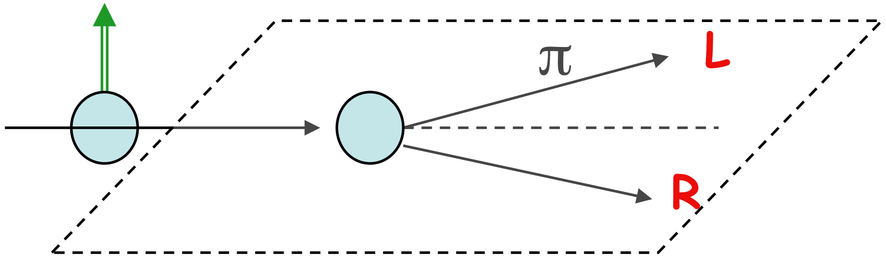
$$\eta_g = \int_0^1 \Delta g(Q^2 = 1\ \ \mathrm{GeV}^2)dx$$
$$= 0.99^{+1.17}_{-0.31}(\mathrm{stat})^{+0.42}_{-0.22}(\mathrm{syst})^{+1.43}_{-0.45}(\mathrm{th}).$$

- **Large gluon component** anticipated (unnaturally large?)
- **Sea quarks** distribution not known, and
- **Quark+Anti-quark** contribution about 25% of nucleon spin

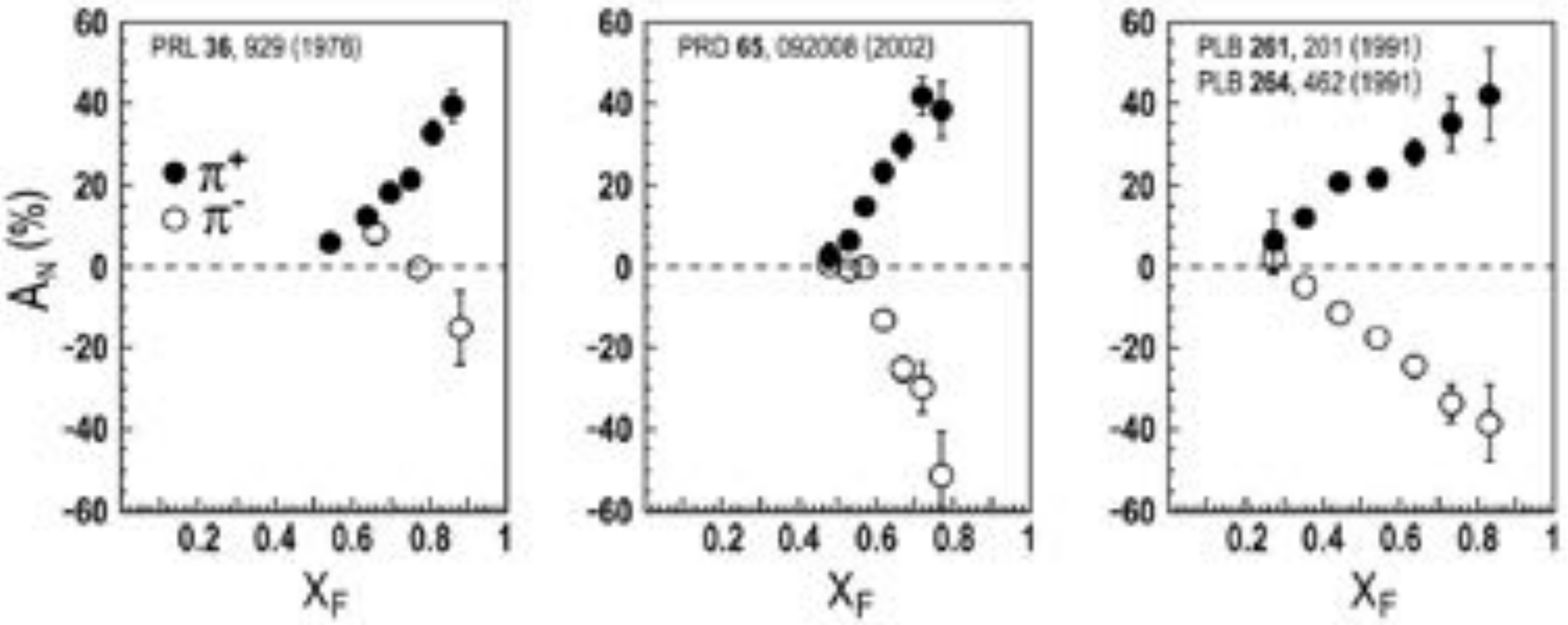


PRD 58 112002 (1998)

The transverse spin puzzle



$$A_N = \frac{N_L - N_R}{N_L + N_R}$$



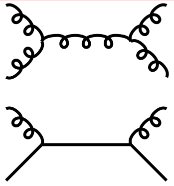
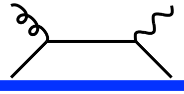
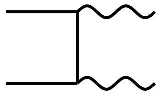
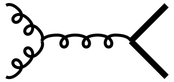
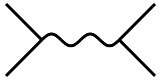
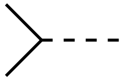
$$A_N \sim \frac{m_q}{p_T} \cdot \alpha_S \sim 0.001$$

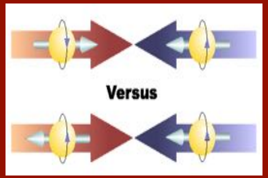
Kane, Pumplin and Repko
PRL 41 1689 (1978)

~100’s times larger asymmetries observed
Got little theoretical attention
Often blamed on soft color effects(?), impossible to deal with.
A systematic study was definitely needed

The RHIC Spin Program

- How do gluons contribute to the nucleon spin?
  - Measurement of polarized gluon distribution using two longitudinally polarized proton
- What are the patters of up, down, strange and **anti-quark** polarization in a proton?
  - Use the precise electroweak probe provided by W+/W- in longitudinally polarized proton collisions to distinguish between quarks and anti-quarks
- What role does transverse spin play in QCD?
  - By precisely and systematically measuring transverse spin phenomena, provide input to QCD/theorists to help understand the transverse dynamics of partons

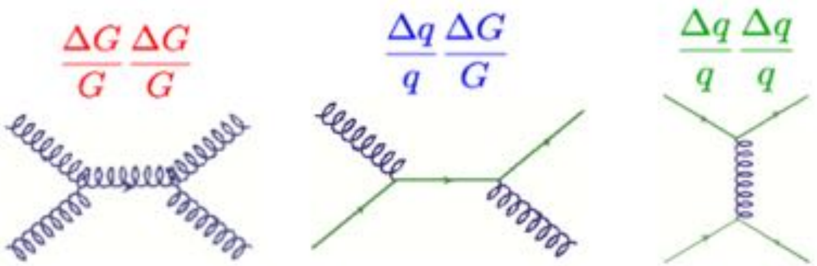
Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$ [61, 62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$	Δg Δg	
$\vec{p}\vec{p} \to \gamma\gamma + X$ [67, 73, 74, 75, 76]	$\vec{q}\vec{\bar{q}} \to \gamma\gamma$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$ [77]	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan) [78, 79, 80]	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$ [78]	$\vec{q}\vec{\bar{q}} \to Z^0$, $\vec{q}'\vec{\bar{q}} \to W^\pm$ $\vec{q}'\bar{q} \to W^\pm$, $q'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$	



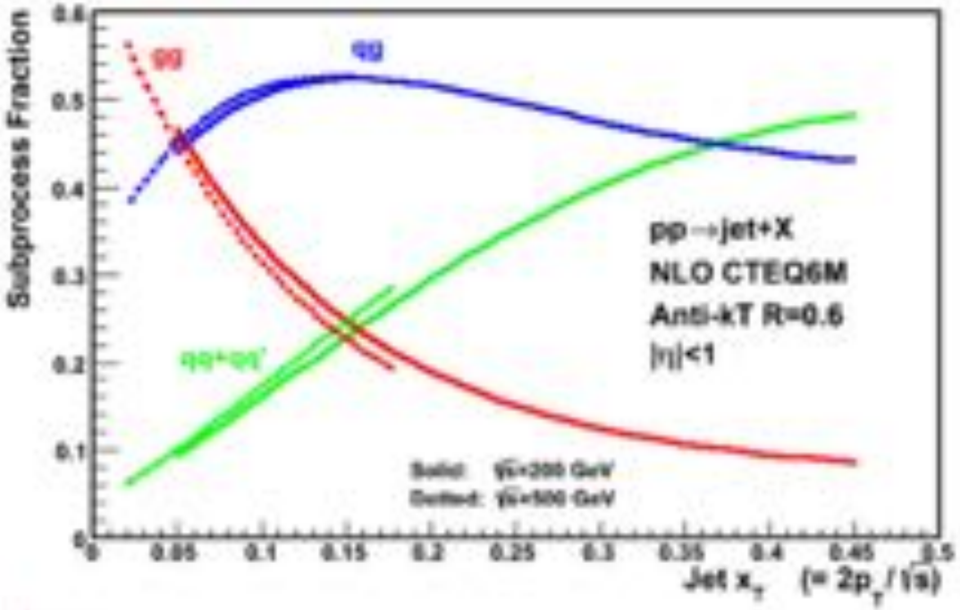
Accessing $\Delta G(x)$ at RHIC

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to f X} \cdot \hat{a}_{LL}^{f_1 f_2 \to f X} \otimes D_f^{\pi}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to f X} \otimes D_f^{\pi}}$$

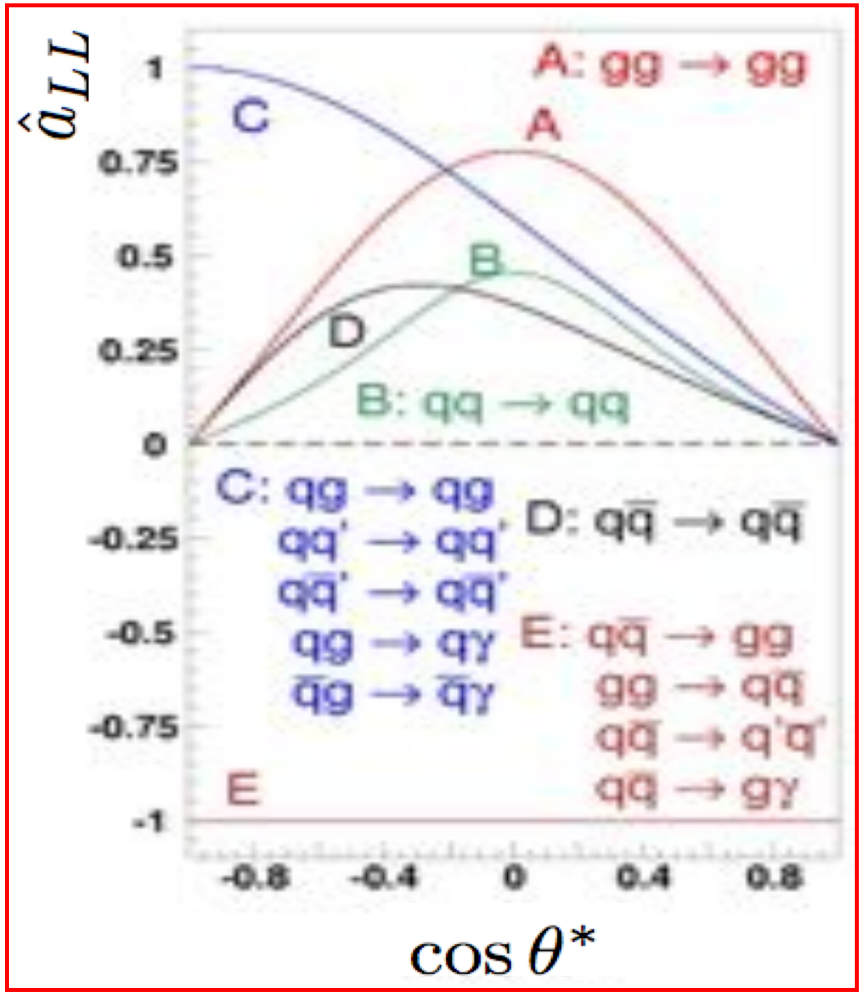
G. Bunce et al, Annu. Rev. Nucl. Part. Sci. 50, 525(2000)



$\Delta G(x)$ measured through double longitudinal spin asymmetry



Partonic fraction for π^0/Jet production



2009 RHIC data established non-zero ΔG

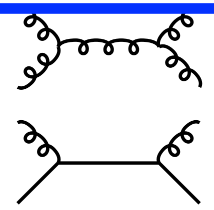
-- PHENIX 2005-9, PRD 90, 12007 (2014)

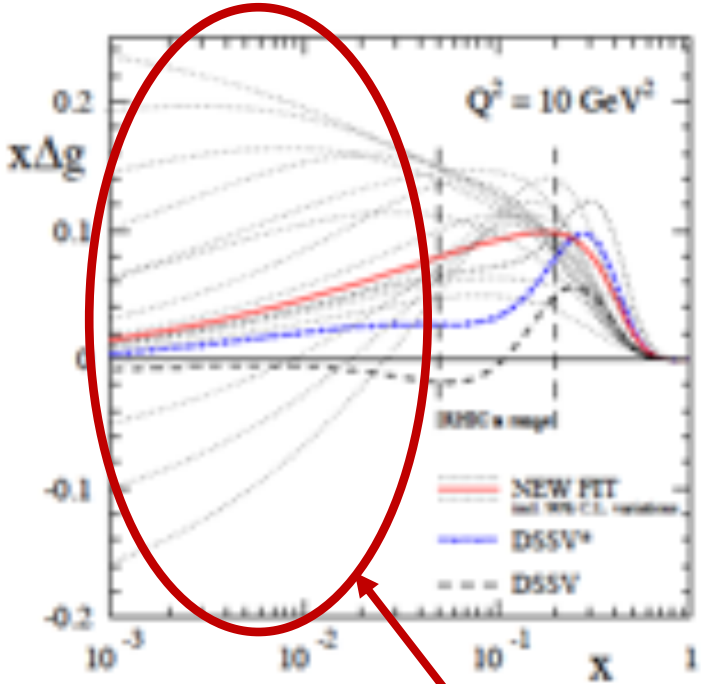
-- STAR 2009, PRL 115 (2015) 92002

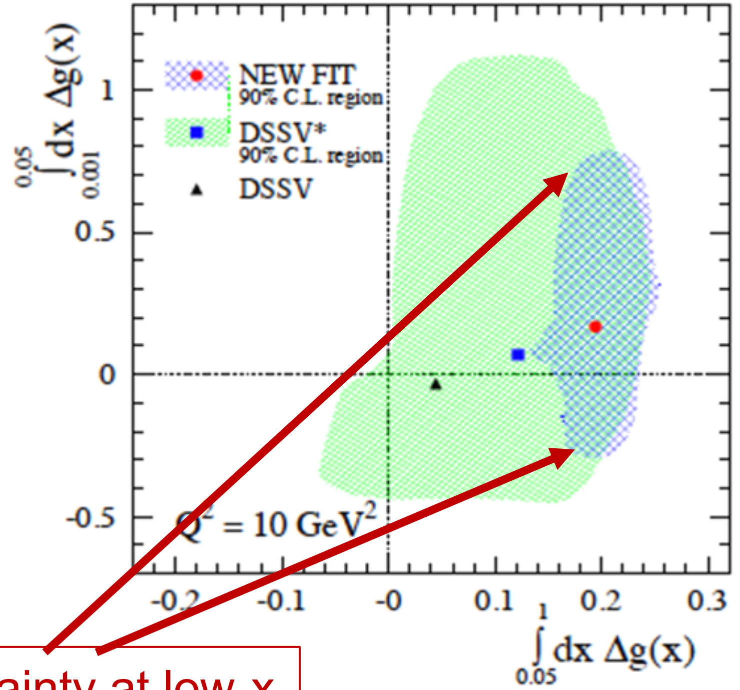
-- DSSV PRL (113) 12001 (2014)

$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} \ @\ 10\ \mathrm{GeV}^2$$

6/12/20

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$ [61, 62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \mathrm{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)

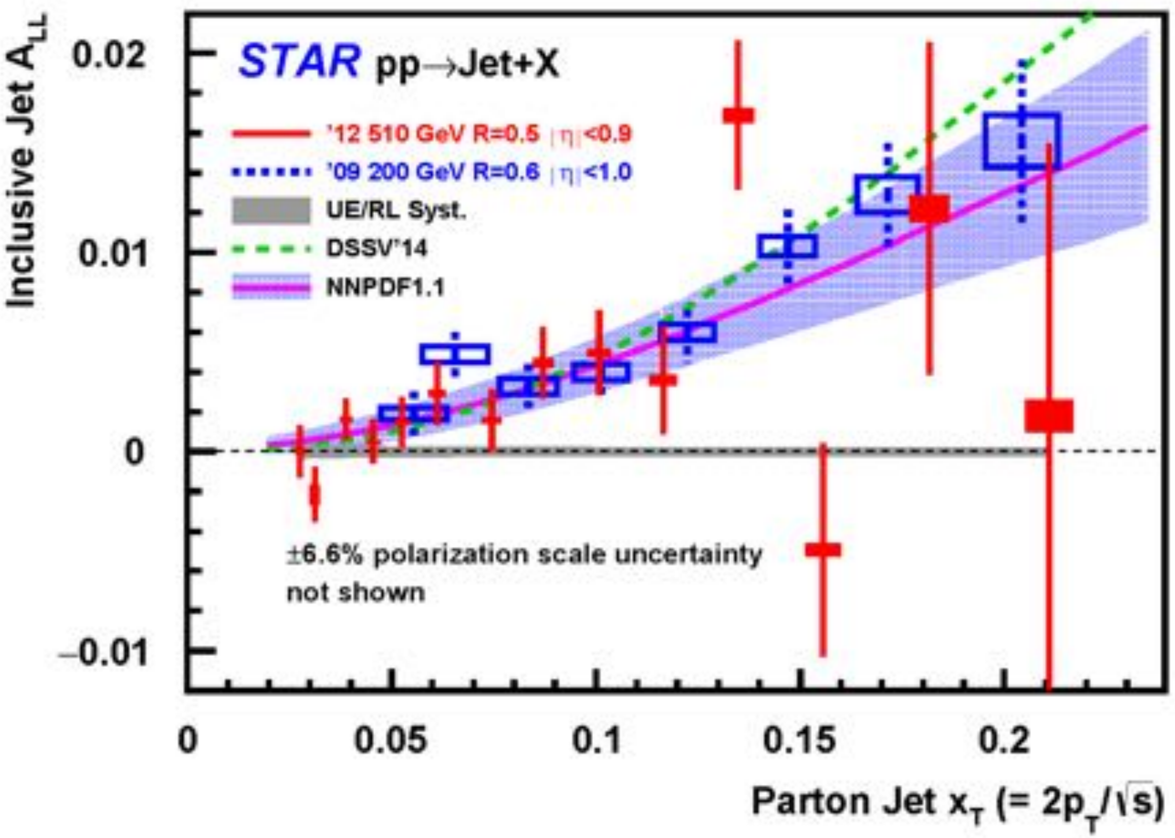




Large uncertainty at low-x

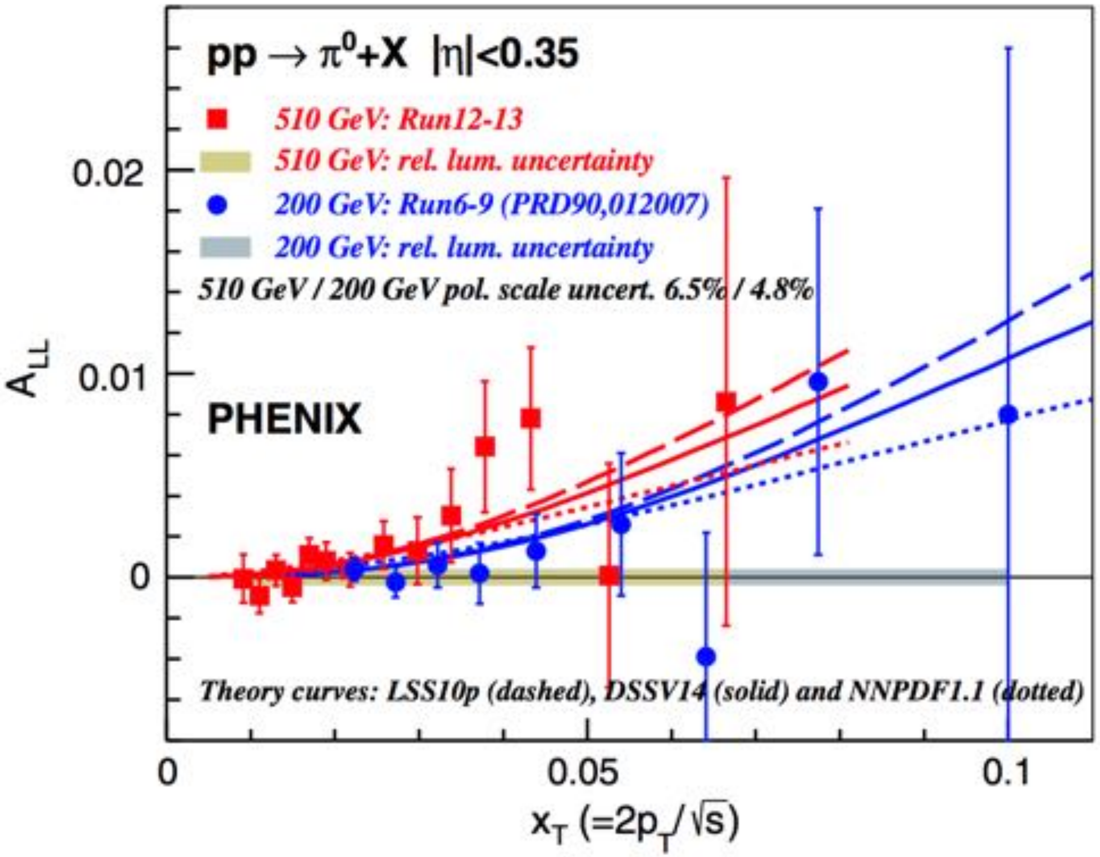
Low-x with sqrt(s) = 510 GeV RHIC

STAR PRD 100 52005 (2019)



STAR Jet A_{LL} access x ~ 0.015 (down from 0.05 at 200 GeV)

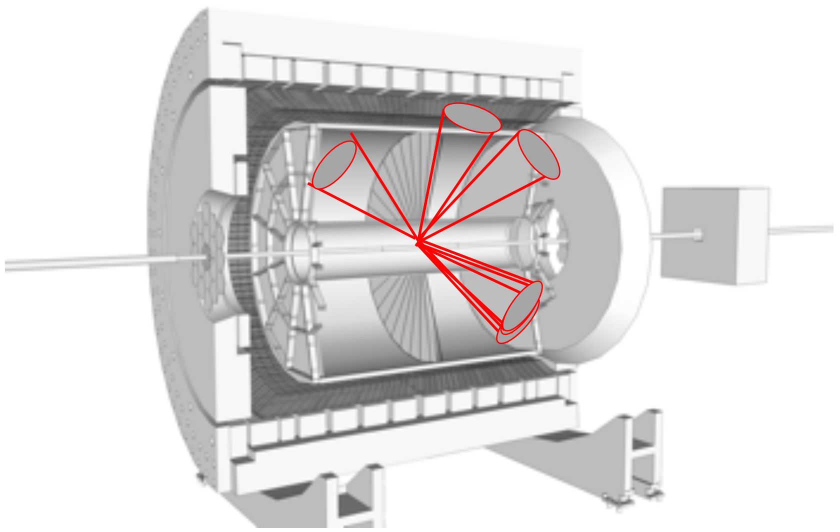
PHENIX PRD 93, 011501 (2016)

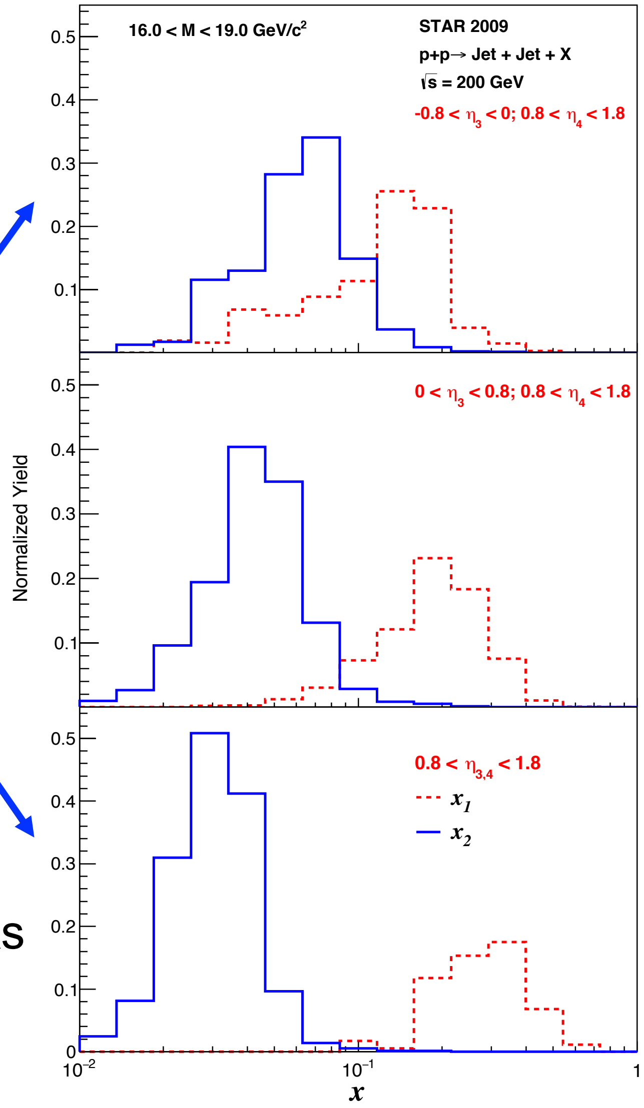


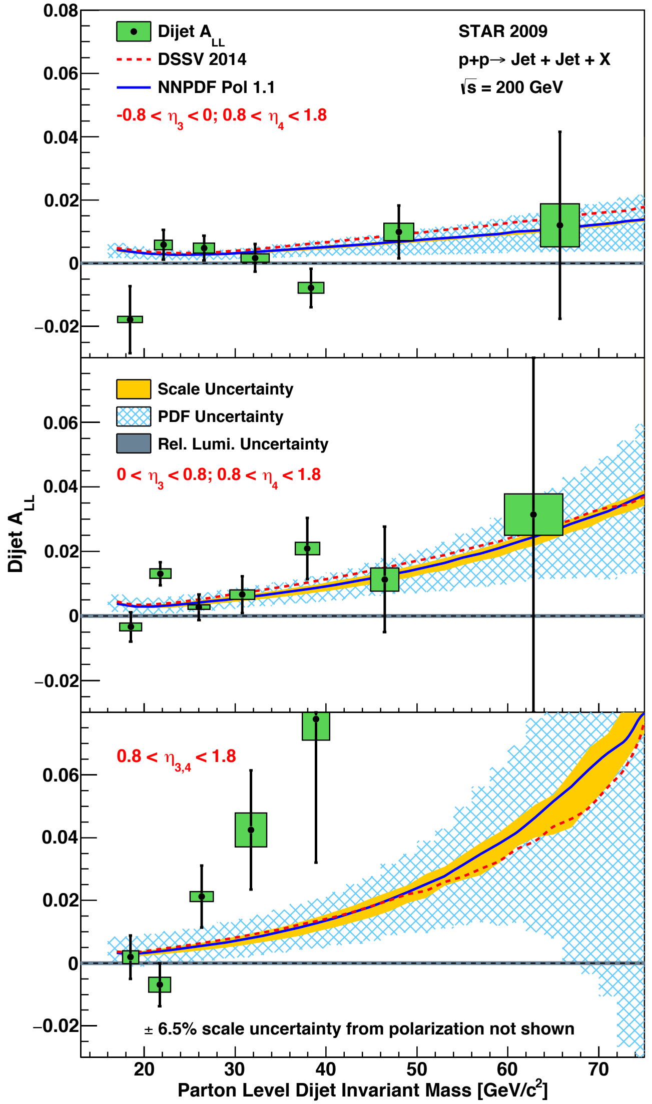
PHNENIX π^0 A_{LL} access x ~ 0.008 (down from 0.02 at 200 GeV)

Advantage of large acceptance: STAR

Select event topology to access different regions of x





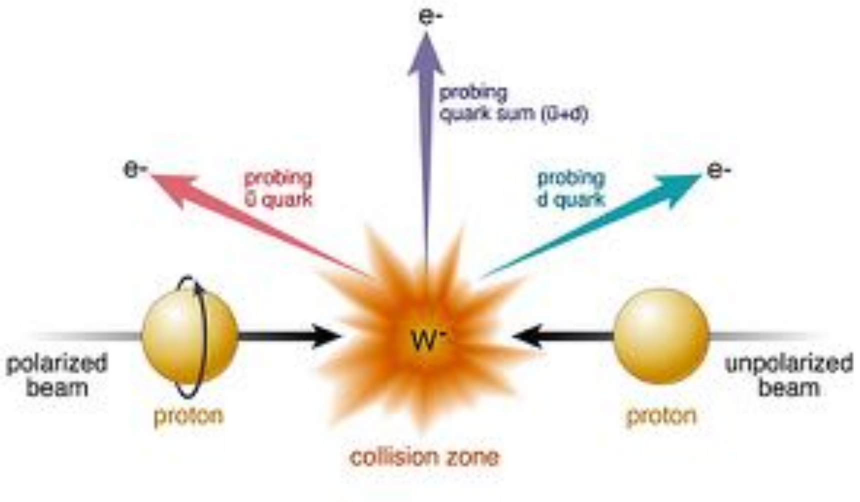


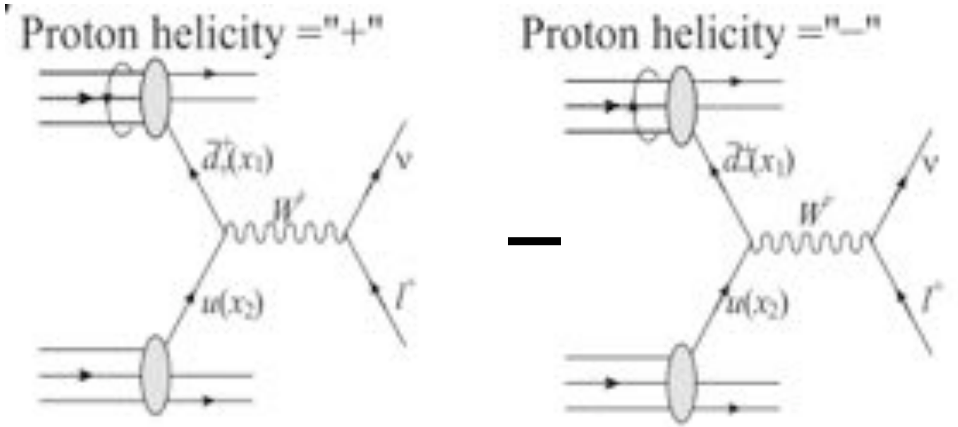
Measured asymmetries sample low & high x quarks
PRD 98 (2018) 32011
See arXiv: 1906.02740 for 510 GeV results

Event topology animation: E.C. Aschenauer

Anti-Quark Polarization via W production

(Method: devoid of Fragmentation Functions)





$\propto \Delta\bar{d}(x)\Delta u(x)$

- Maximally parity violating W probes helicity of the quark or anti-quark, detected via decay into e/μ .

$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \sim \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_{W^+} << 0 \end{cases}$$

$$A_L^{W^-} \sim \begin{cases} -\dfrac{\Delta d(x_1)}{d(x_1)}, & y_{W^-} >> 0 \\ \dfrac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}, & y_{W^-} << 0 \end{cases}$$

- PHENIX Central Arm : e+/e-, forward/backward μ+/μ-   STAR: e+/e- Central and forward arms

PHENIX

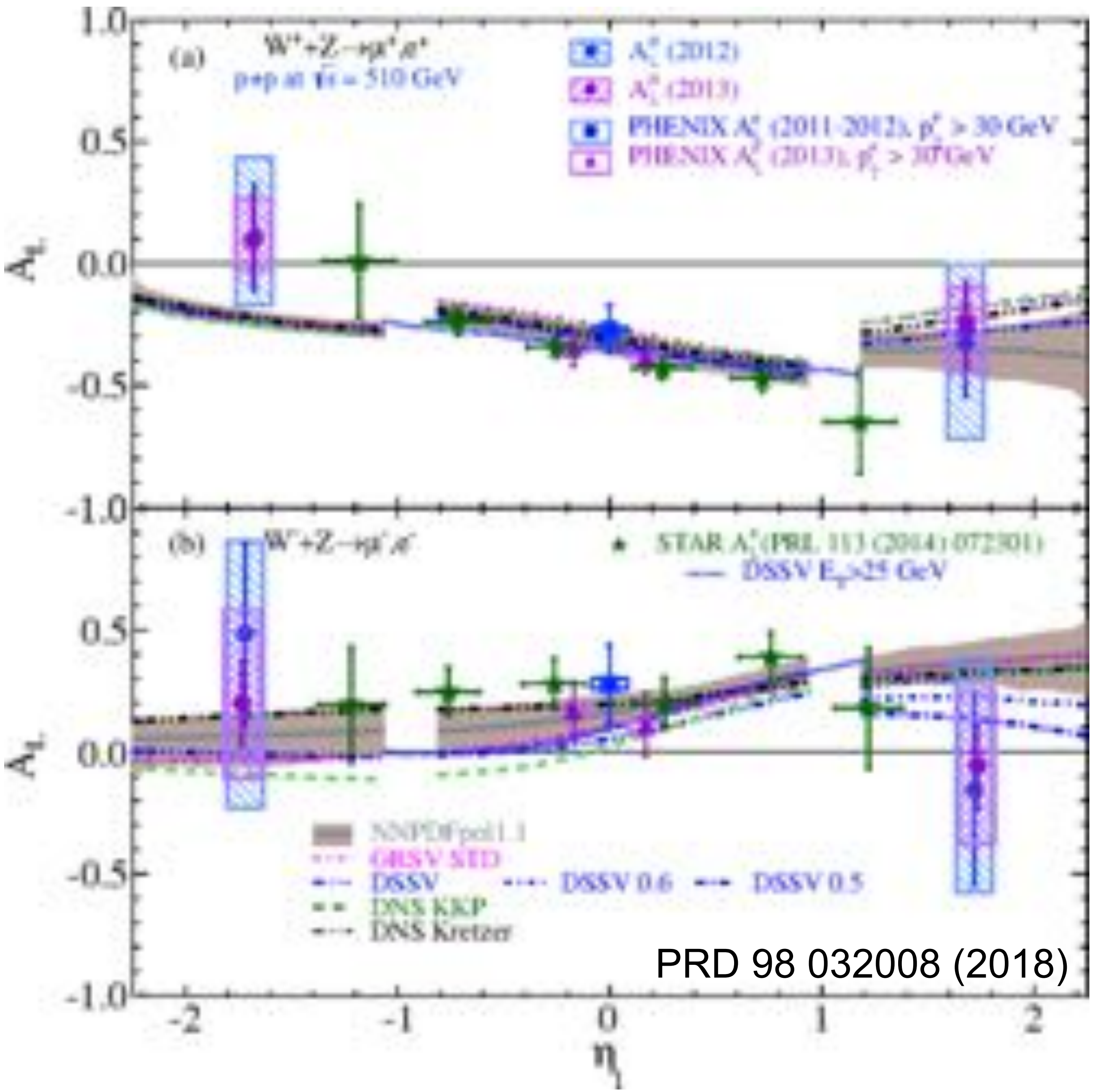
PHENIX e,μ channel measurements over a broad η range.

Observation:

Within the large uncertainties:

Backward μ- and central e- @ upper limit of uncertainty band (DSSV08), **suggests** Δubar larger than the global fit indicates

Forward μ- below DSSV08 **hints** possibly a sign change in Δd at high x

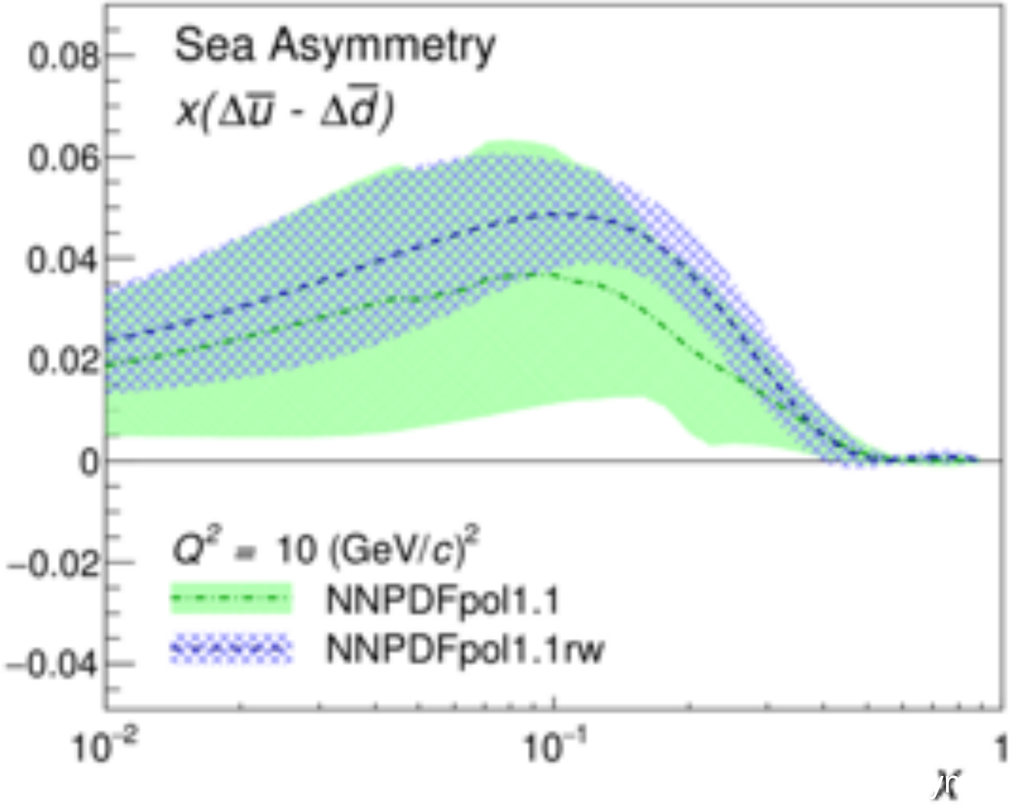


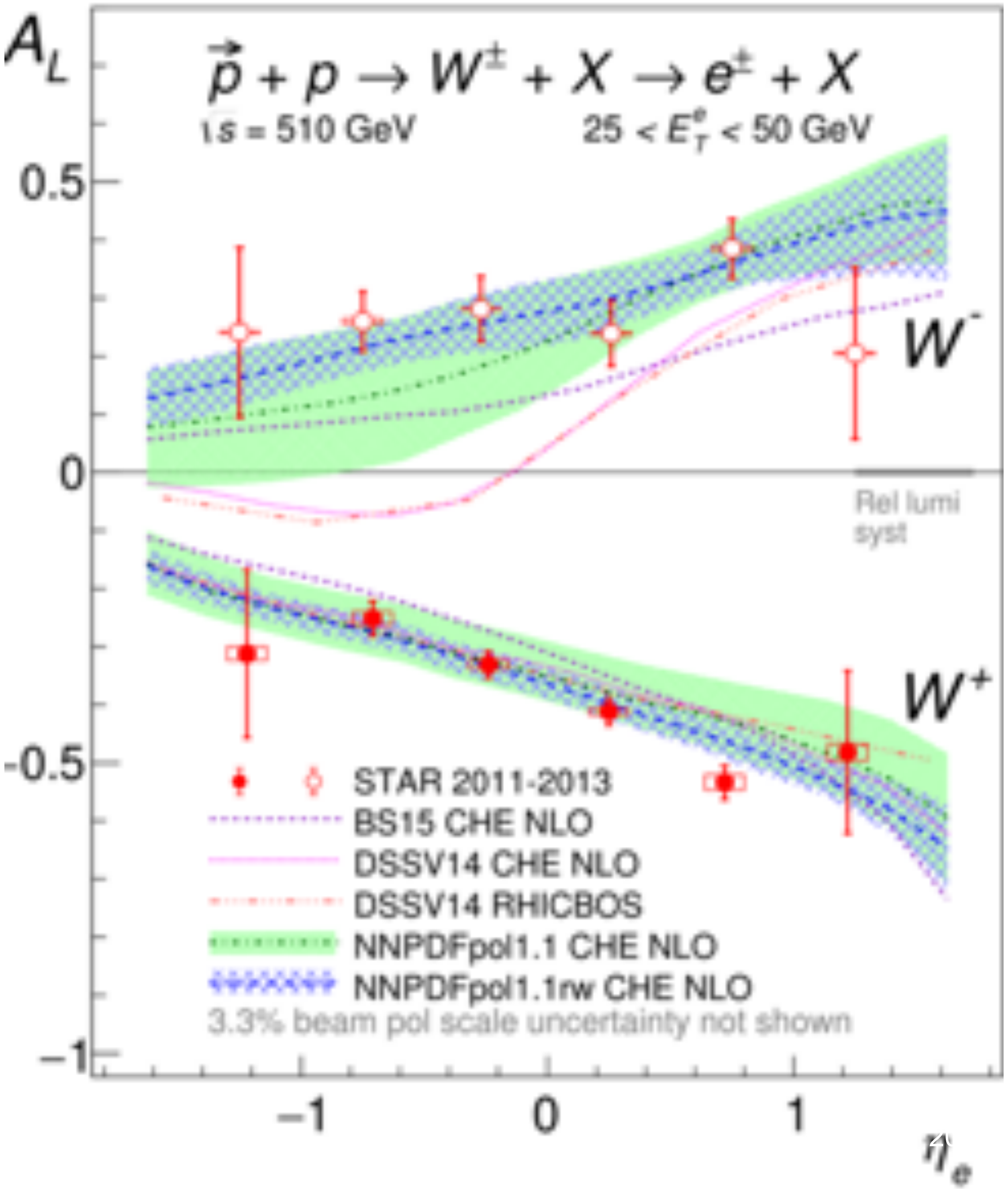
PRD 98 032008 (2018)

Precise data from STAR:
$-2 < \eta < 2$
Run 13 data

PRD 99 (2019) 51102

- Direct observation of asymmetric polarized sea
- Opposite in direction to the asymmetry found in unpolarized sea





Transverse Spin Phenomena

- Essential part of the world-wide campaign for the *(2+1)D structure* of the nucleon
  - Needs **h-h**, e-h and e-e scatterings to build the complete picture
- A systematic study with precision measurements of transverse spin effects @RHIC
- Most TMD measurements from fixed target (DIS) experiments (high-x and low-Q^2). RHIC data provides the first high-Q^2 measurements ➔ study of TMD evolution

Initial State (IS) effects

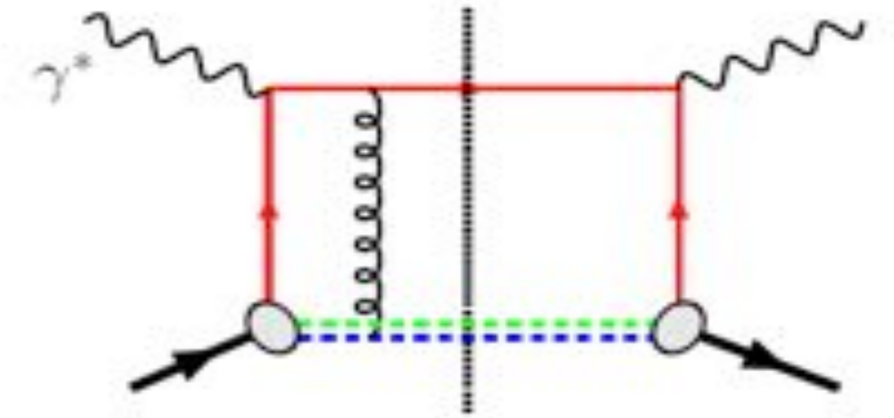
- A_N for W+/-, Z^0, Drell Yan ➔ **Sivers**
- A_N for jets **gluon Sivers** in Twist 3
- A_N for photons **quark Sivers** in twist 3

Final State (FS) effects

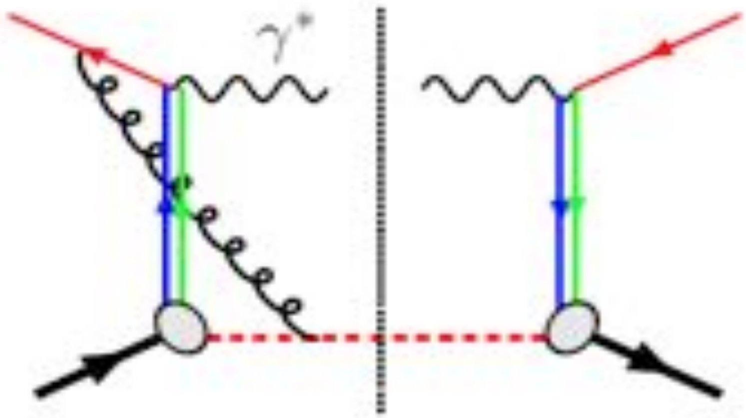
- A_{UT} for π+/π- azimuthal distributions in Jets ➔ **transversity** X Collins
- A_{UT} in di-hadron production ➔ **transversity** x Interference Fragmentation Function (IFF)
- A_N for $\pi^{+/-}$ and π^0 ➔ novel twist 3 FF mechanism

Transverse single spin asymmetry (A_N) for W boson

- Sign change in the Sivers function in DIS vs. DY (W or Z) process:
  - A test of collinear factorization….QCD



DIS: attractive FSI

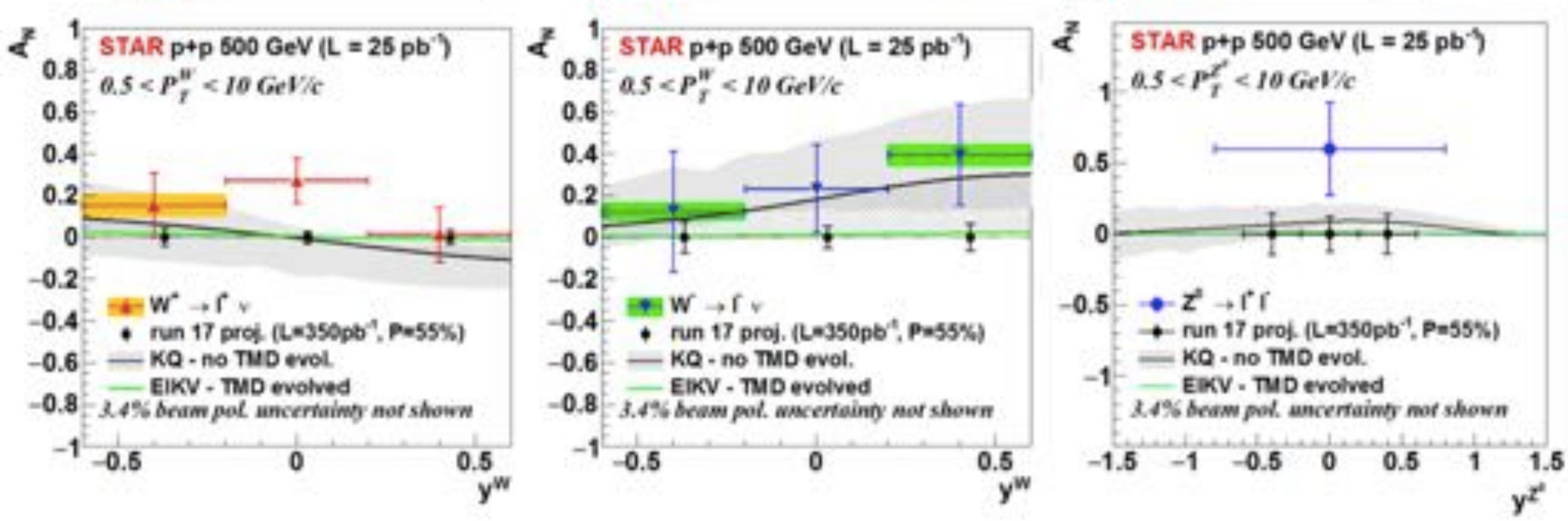


DY: repulsive FSI

- RHIC (W production), COMPASS (DY, SIDIS), FNAL SpinQuest (E1039, DY)
- RHIC's distinct advantages: high-Q^2 (W/Z mass) & low background

First W, Z A_N results at 510 GeV STAR
(Sivers Effect Sign Change)

- 2011 (2017) data set transverse collisions, Luminosity 25 (350) pb-1



- Sign change scenario preferred

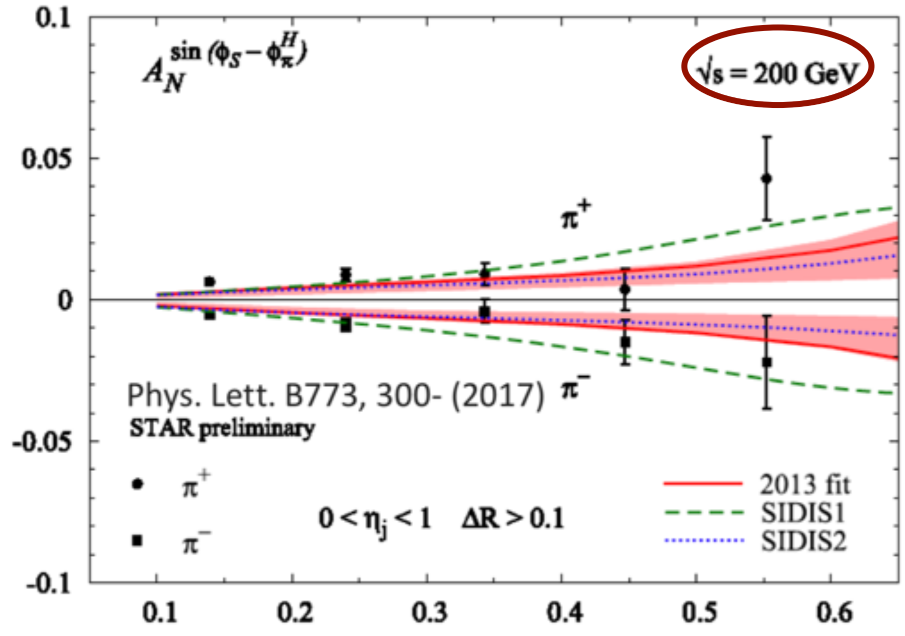
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

Run 11 STAR, PRL 116 132301 (2016)

Jets probe transversity x **Collins** function

- $\pi^{+/-}$ azimuthal distribution in jets
- TMD evolution small but survives at lower-x, high-Q^2. (Compare 200 and 500 GeV data)

PRL B773, 300 (2017)

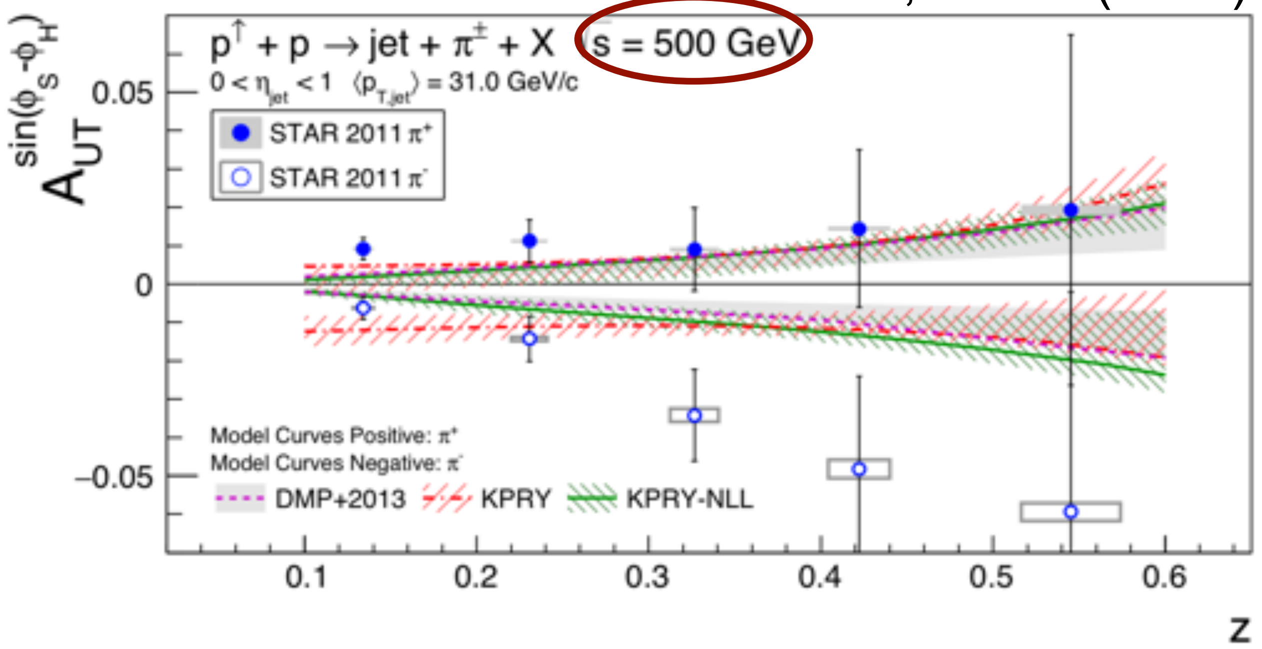


Collins asymmetries at 500 GeV and comparison with 2 theory calculations

- DMP : PLB 773, 300 (2017) – SIDIS based
- KPRY: PLB 774, 635 (2017) – Collins FF from e+e-

Study of universality of Collins function (Kang et al, JHEP 11, 068 (2017)

STAR PRD 97, 32004 (2018)

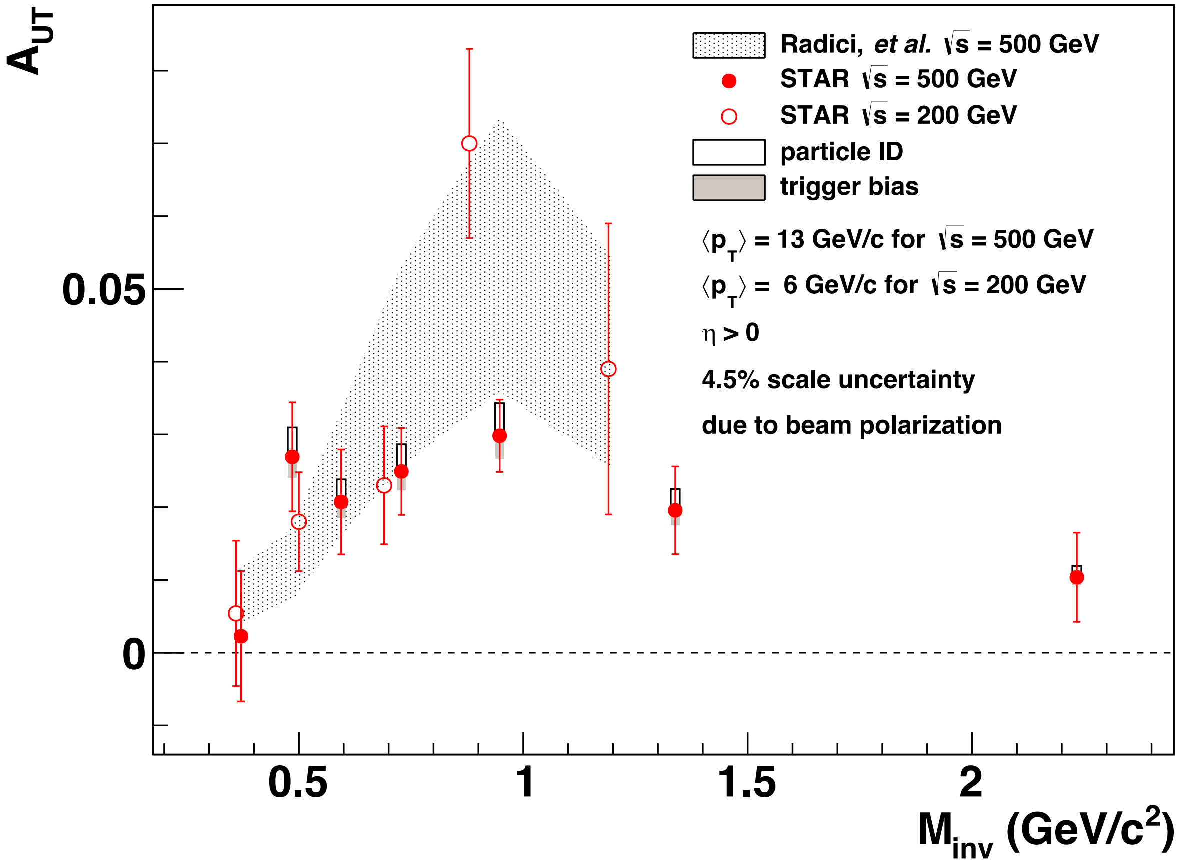


Transversity x Interference Fragmentation Function

STAR p + p → π+ π- + X Study di-hedron correlation → **transversity** x Fragmentation Function

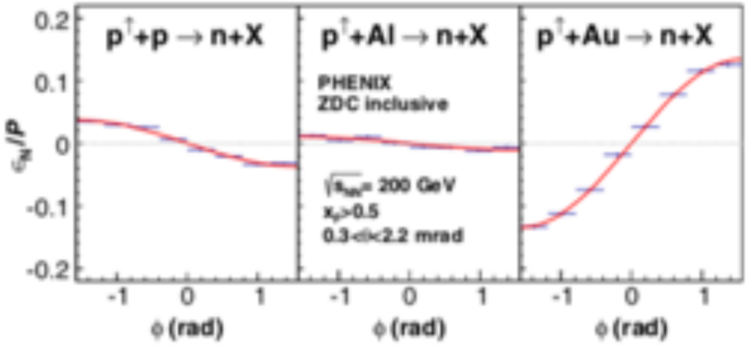
- First significant transversity measured in proton+proton collisions
- Despite different scales, asymmetries are similar at 200 and 500 GeV when <x_T> is similar
- STAR data well described by IFF theoretical calculations (which include e-e and e-h data)
- Global analysis by Radici and Bachetta (PRL 120, 192001) : significant reduction in uncertainty for u quark transversity using STAR data

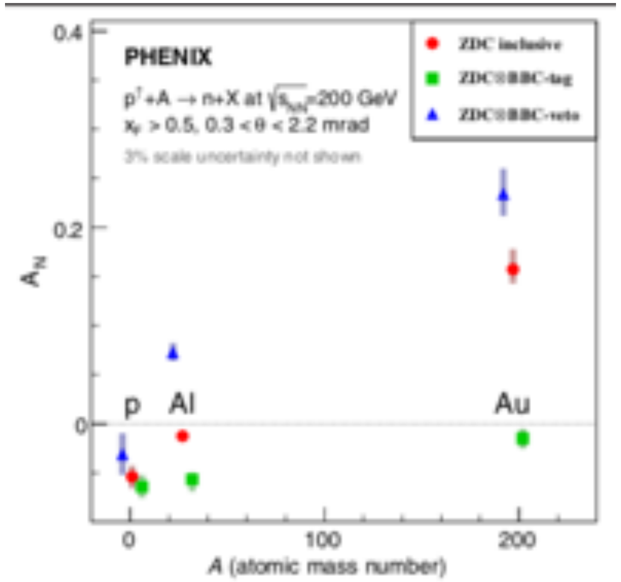
Phys.Lett. B780 (2018) 332



And some unexpected… PHENIX A_N: p-p, p-A (Al, Au)

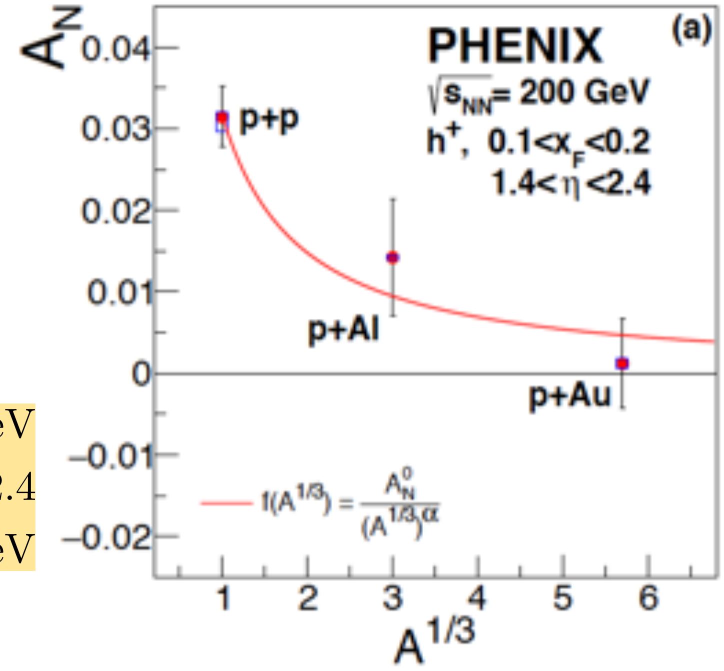
PRL 120, 022001 (2018)





PRL 123, 122001 (2019)

$\sqrt{s} = 200$ GeV
$1.4 \leq \eta \leq 2.4$
$1.8 \leq p_T \leq 7$ GeV



- **A dependence of A_N: forward n production (in ZDCs)**
- Small t, possible interference from EM interactions. They should gain significance with Z.
- Alternate: Pion and a1 Reggeon interference…
- Needs systematic dedicated studies

- **A dependent A_N : forward hadron** production
- Saturation based scenarios: J. Zhou PRD92 14034 (2015), Y. Hatta et al. PRD94 54013 (2016) and PRD95, 14008 (2017)
- Other scenarios: S Benic and Y. Hatta PRD99 09401 (2019)

Near term future: STAR Forward Upgrade 2021+

Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
2021/22	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Ecal + Hcal +Tracking
2021/22	$\vec{p}\vec{p}$ @ 510	1.1fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Ecal + HCal
2024	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	Subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Ecal + Hcal +Tracking
2024	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	Nature of the initial state and hadronization in nuclear collisions Clear signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Ecal + Hcal +Tracking
	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Ecal + Hcal +Tracking

- Measurements can be performed uniquely with hadron-hadron and hadron-nucleus collisions at high energy
- RHIC the only **polarized** collider. Opportunity not be available in the EIC era.
- NSF approved MRI grant for the upgrade
- Time consistent with RHIC operations plan

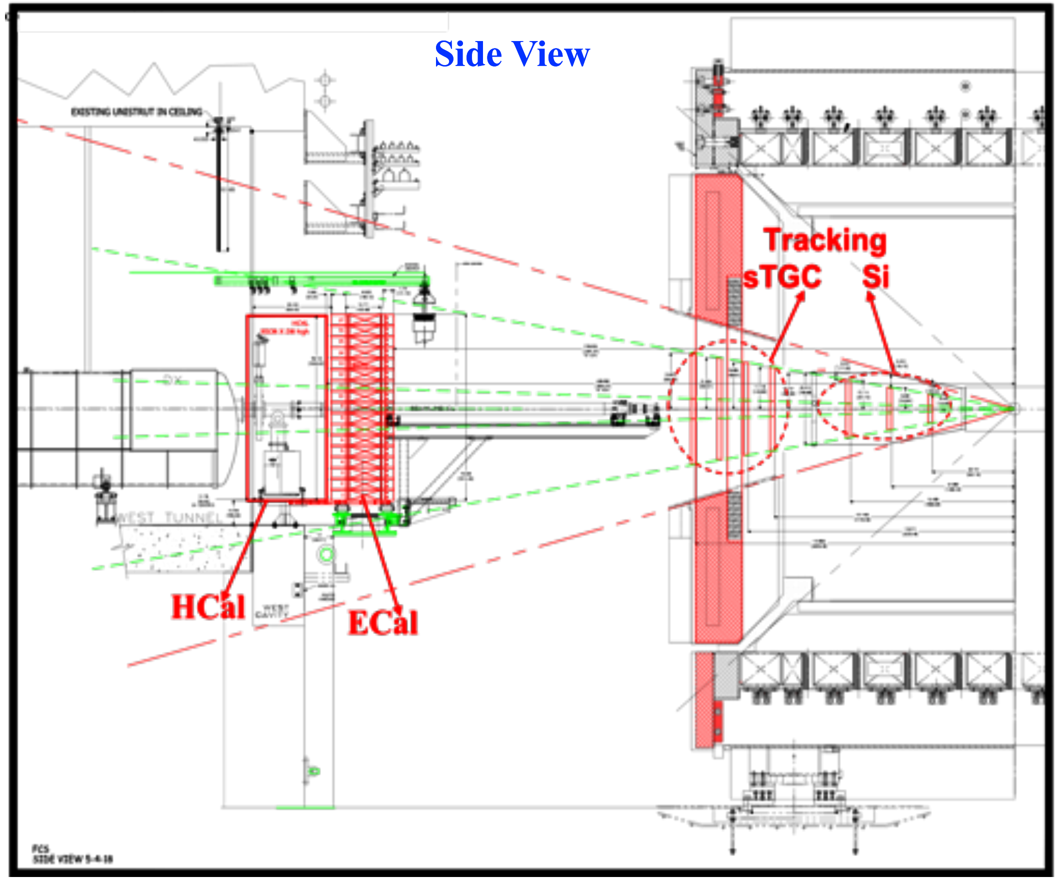
STAR forward upgrade for cold QCD

2021-2025

- Complete the mission of RHIC physics program in cold QCD
- Lay groundwork for the EIC scientifically, and also equipment in the very forward kinematic region
- Test EIC forward detector technologies in real life conditions

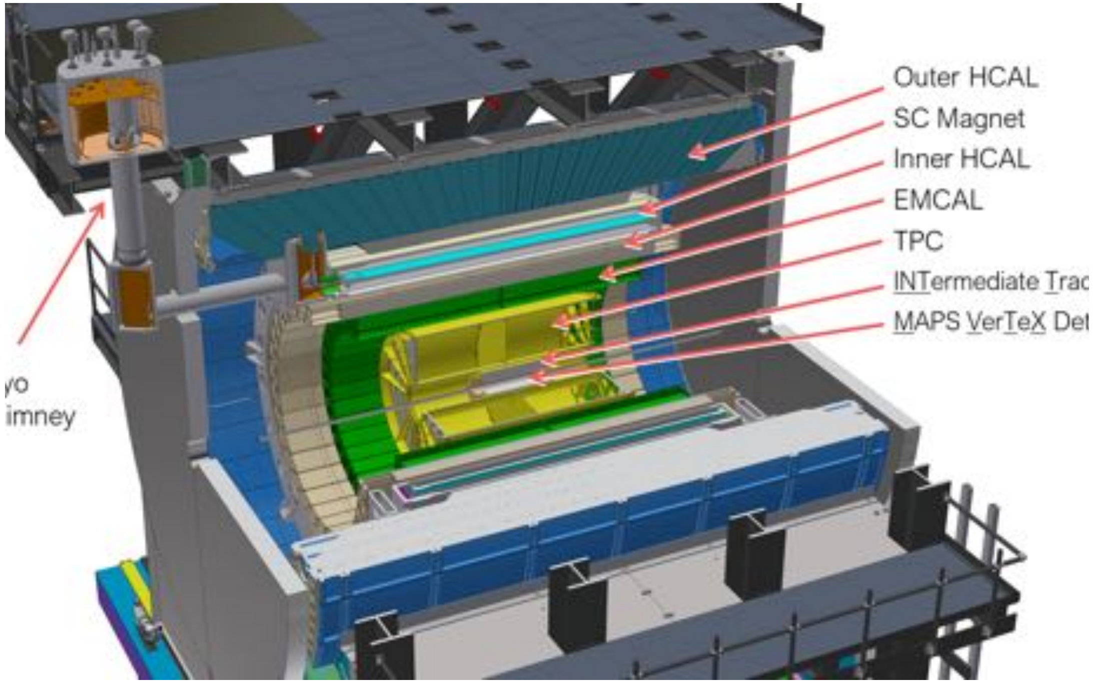
Detector Upgrades:

- West side of STAR 2.5 < η < 4.0
- EM and H Calorimetry with SiPM readout and new ADC+Trigger modules
- Tracking detectors and small strip thin gap chambers (sTGC)
- Will operate starting FY2021 and will run concurrent with sPHENIX



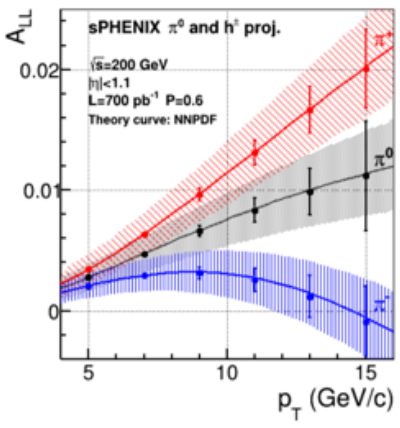
2023-2025

Cold QCD program with sPHENIX

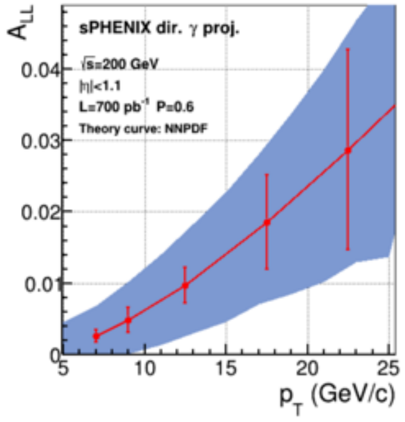


- Study the properties of QGP using jets and quarkonia but could also pursue an compelling cold-QCD program p-p, p-A

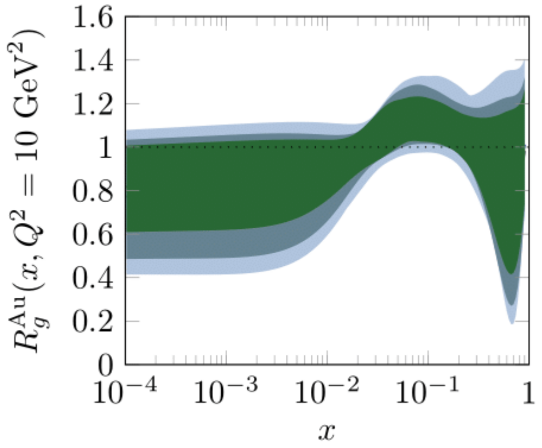
π0 and h±



Dir. Photons



Nuclear gluon PDF



RHIC → EIC

RHIC's life just got extended by 20+ years

- CD0 : December 19, 2019
- Site BNL : January 9, 2020
- BNL and JLab realize EIC as partners

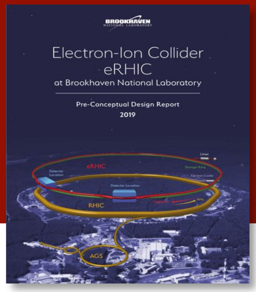
- A formal EIC project is now setup at BNL
- BNL+Jlab management & scientists are working together to realize it on a fast timeline.

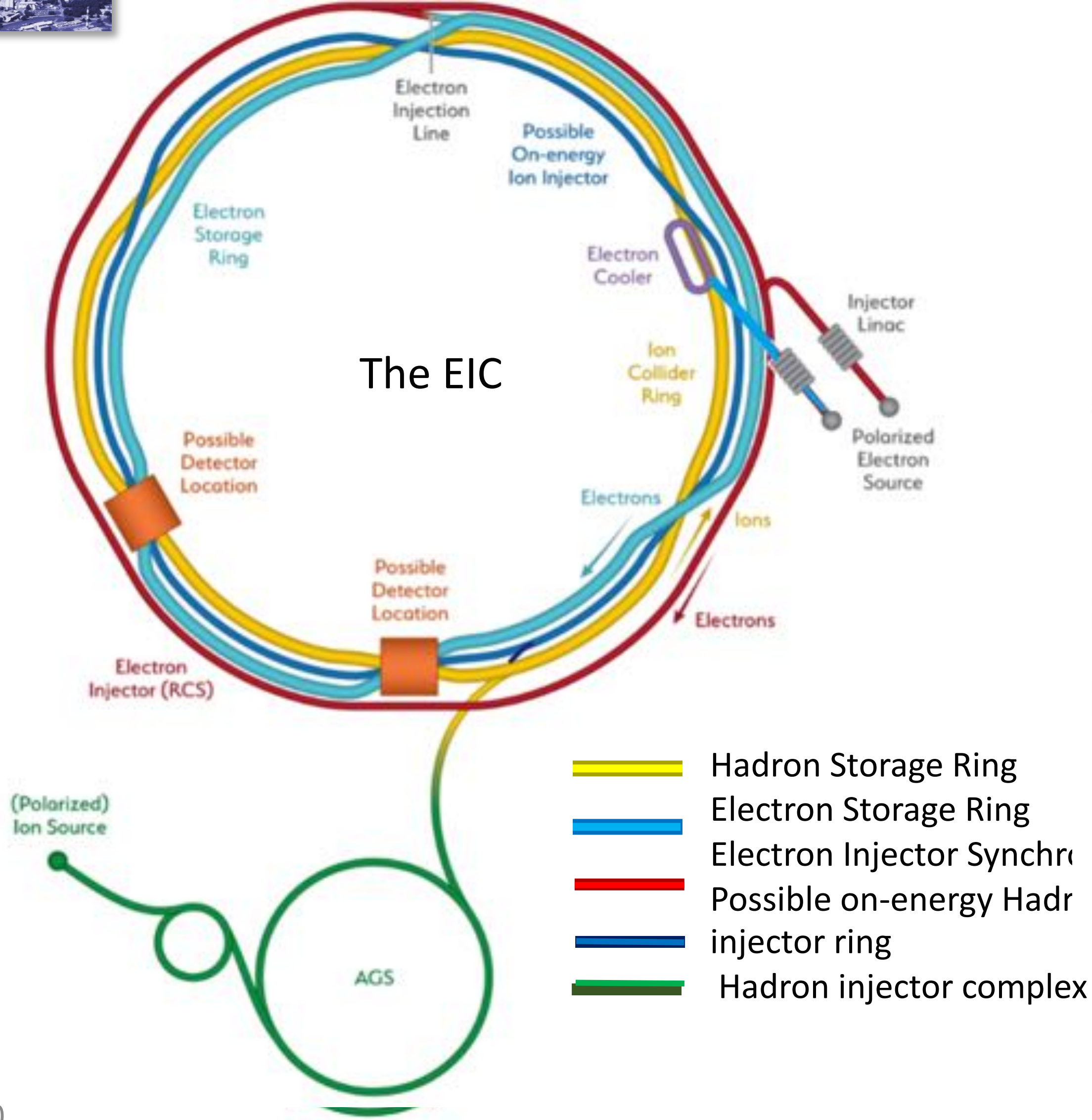
- CD1 anticipated March 2021
- CD2 September 2022 (final design)
- CD3 4th Quarter FY2023 (start construction)

- EIC Early Finish 4th Q FY2029
- EIC CD4 4th Q FY 2030

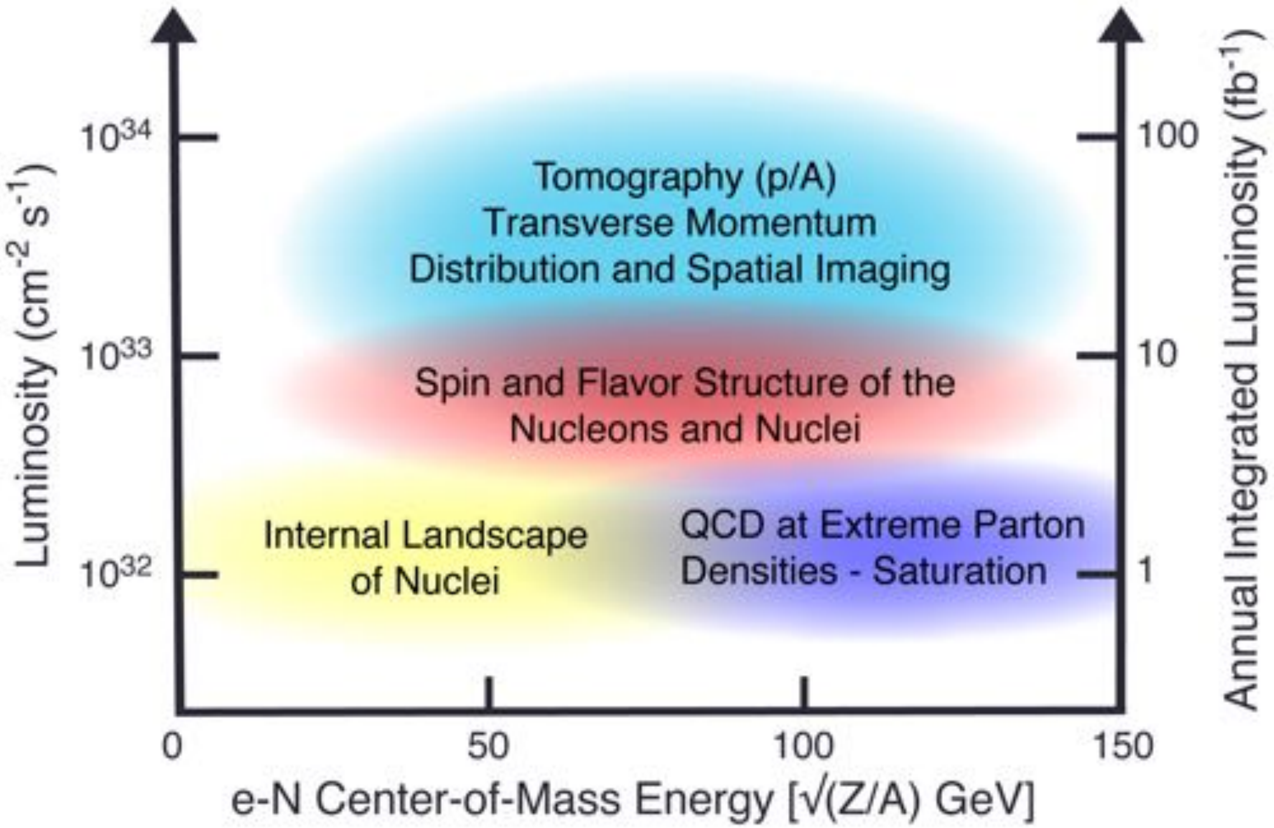
You can join the party by registering at EICUG.ORG

Electron Ion Collider





EIC Physics



Appreciation

20 year of cold QCD @ RHIC

The RHIC spin program has decisively established:

- **Gluon's** contribution to proton spin is non-zero & positive
- **Anti-quarks** are polarized & (polarized) sea is asymmetric
- Measured transversity, Sivers, Collins effects and provided essential insights into the "imaging of a nucleon", and clues to other richness of QCD (low-x) through various **transverse spin measurements**
- **Future QCD programs are being built upon RHIC**

The Standard Model of Physics was developed over the the last century using measurements made over a broad range of energy using **complementary probes: e-e, p-p and e-p collisions** – at different facilities around the world.

Similarly, a complete understanding of QCD & test of universality need: **complementary probes** and control of **Spin** & variation of **energy** & **nuclei**: **RHIC has provided one of the most unique & essential tool (variable energy, polarization & species)**

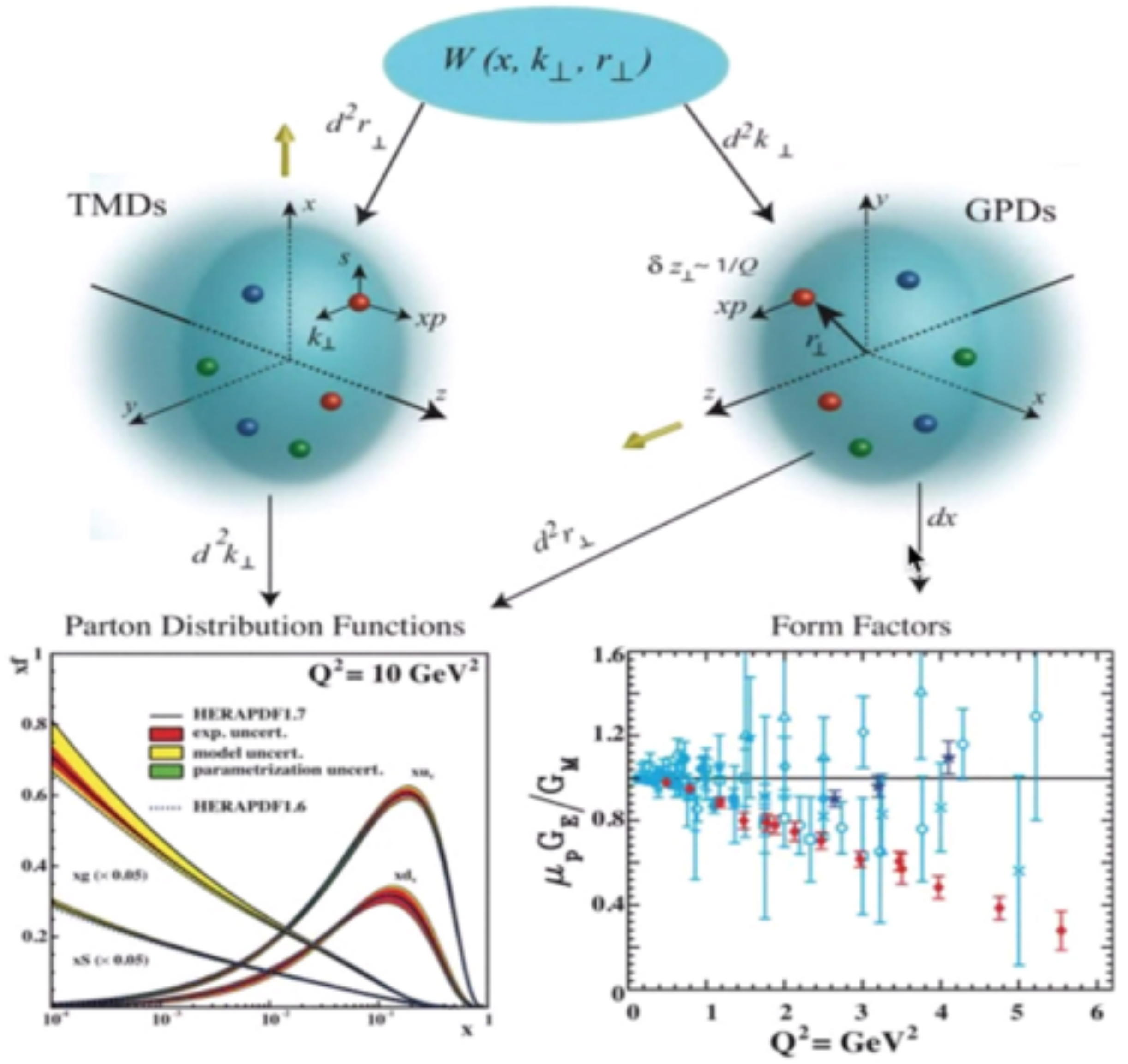
Congratulations

- RHIC's accomplishments would not have been possible without the accelerator scientists, theorists and experimentalists working closely together. Congratulations are due to all of them!

- We have produced over 120 Ph.D.'s
- About the same number of peer reviewed publications with a total citation of ~6000+
- 70+ post doctoral fellows graduated from this programs
- Many UNDERGRADUATE Researchers from Universities
- 20+ faculty positions and tenures
- Many RHIC AGS Thesis prizes, and prizes at Universities for research done on this program
- APS/GHP Fellows, Humboldt Research Awards, Special RIKEN Prizes & recognitions, BNL Science and technology award….

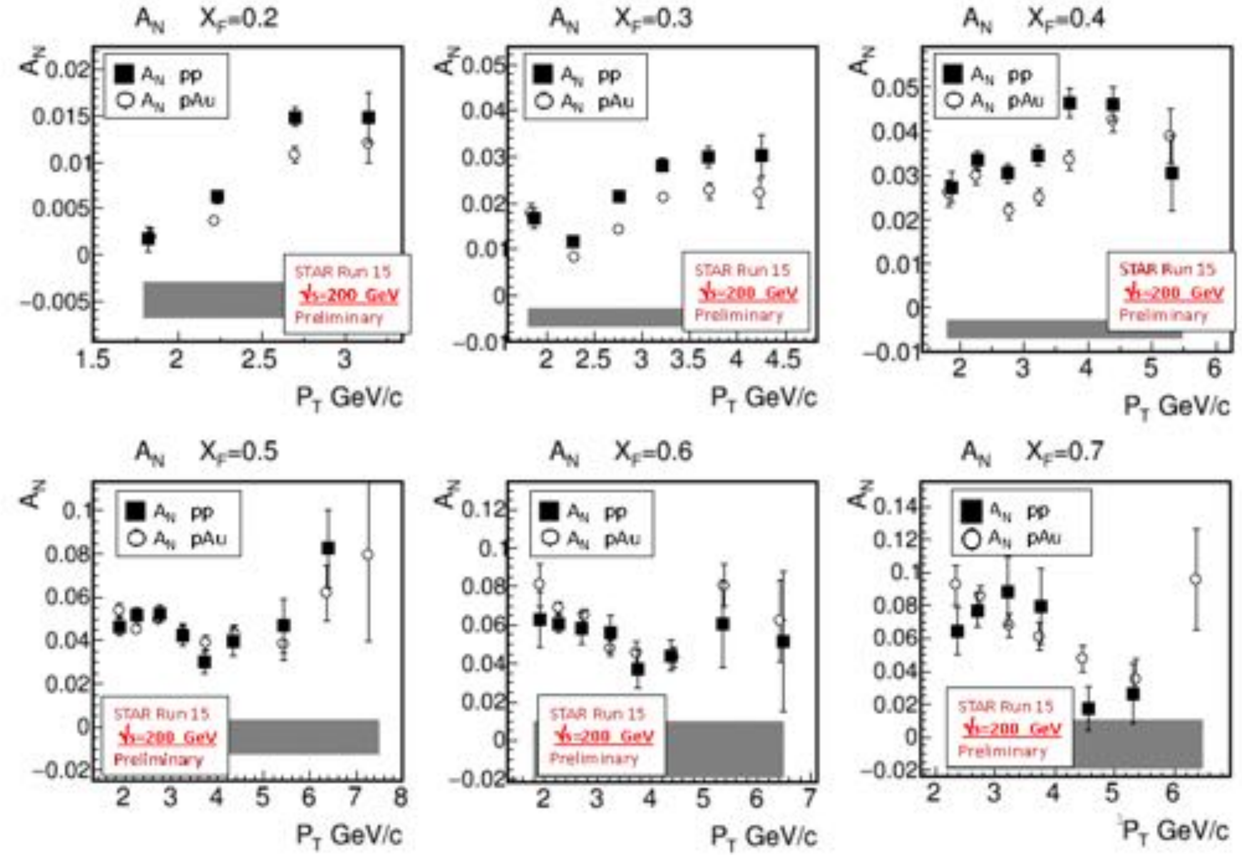
- You all deserve to be congratulated and recognized.

Thank you.

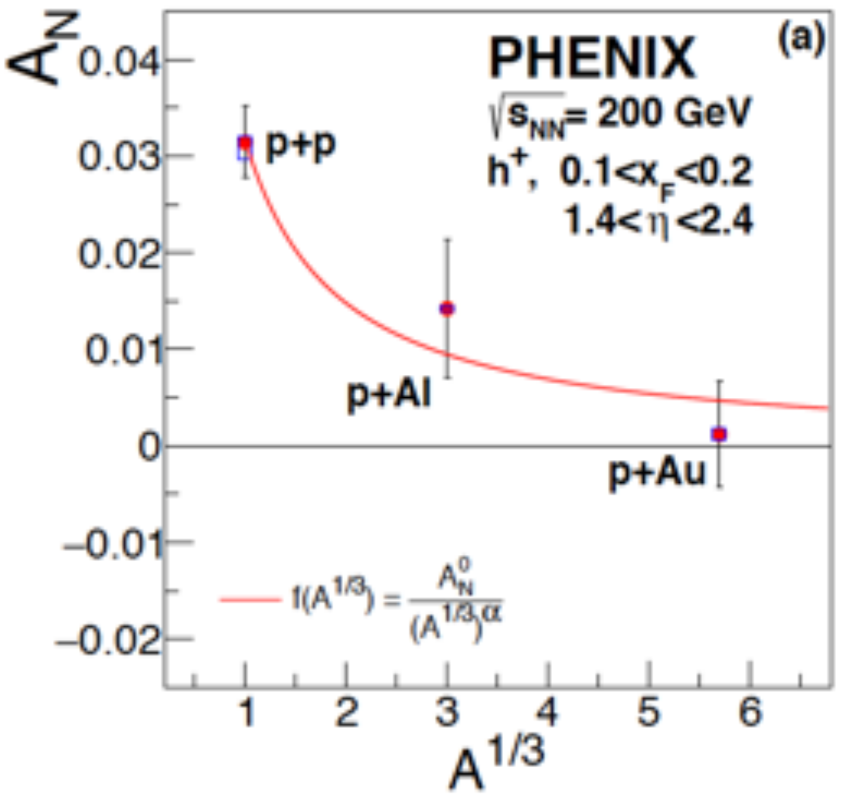


$W(x, k_\perp, r_\perp)$
$d^2 r_\perp$
$d^2 k_\perp$
TMDs
GPDs
$\delta z_\perp \sim 1/Q$
$d^2 k_\perp$
$d^2 r_\perp$
dx
Parton Distribution Functions
Form Factors
$Q^2 = 10$ GeV^2
HERAPDF1.7
exp. uncert.
model uncert.
parametrization uncert.
HERAPDF1.6
$\mu_p G_E / G_M$
$Q^2 =$ GeV^2

And some unexpected… PHENIX A_N: p-p, p-A (Al, Au)



PHENIX, ArXiv:1903.07422



- A dependent A_N is observed for hadron production: quite a surprise (STAR results inconclusive)
- Is it a gluonic saturation effect? J. Zhou PRD92 14034 (2015), Y. Hatta et al. PRD94 54013 (2016) and PRD95, 14008 (2017)
- Alternative scenarios (different A dependence) S Benic and Y. Hatta PRD99 09401 (2019)