Precision measurement of the gluon polarization inside the proton

RIBF Nuclear Physics Seminar

Oct. 28th (Fri), 2016

Yuji Goto (Radiation Lab. / RBRC)

Spin structure of the proton

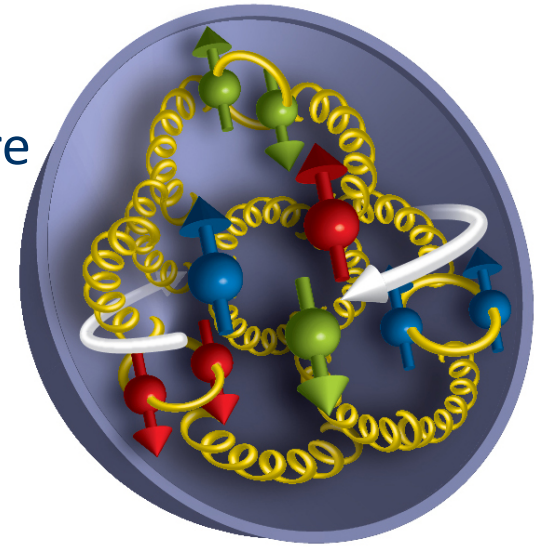
- "Spin puzzle"
  - Origin of the nucleon spin in quark-gluon picture

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

Quark spin contribution

Gluon spin contribution

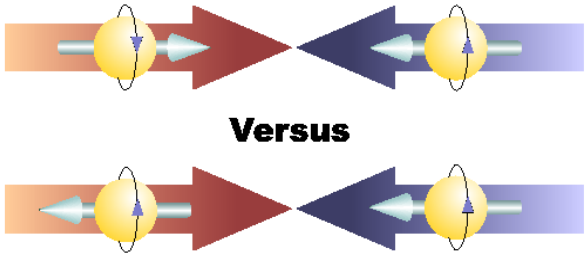
Orbital angular momentum



  - Quark-spin contribution is only 20%-30% of the nucleon spin
- Longitudinal-spin asymmetry measurement
  - Gluon polarization
  - Anti-quark polarization with W boson
- Transverse-spin asymmetry measurement
  - Understanding of orbital motion inside the nucleon and orbital angular momenta of quarks and gluons from large transverse single-spin asymmetry in the forward kinematic region

Helicity structure of the nucleon

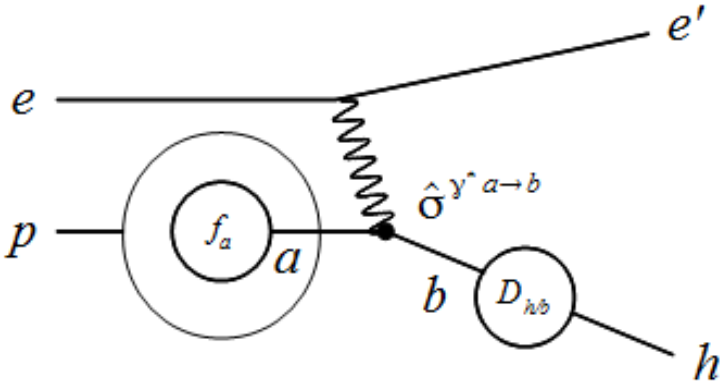
- Longitudinally polarized experiment
  - Polarized in beam or collision direction



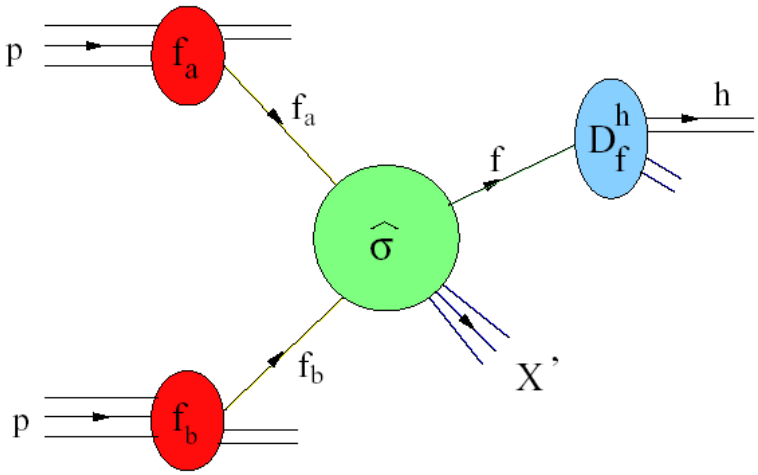
$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$

  - $f_a(x)$ or $q(x)$: parton distribution function (PDF)
    - "universal" property of the nucleon – same in all reactions

Deep Inelastic Scattering (DIS)



p+p Collision



unpolarized structure function

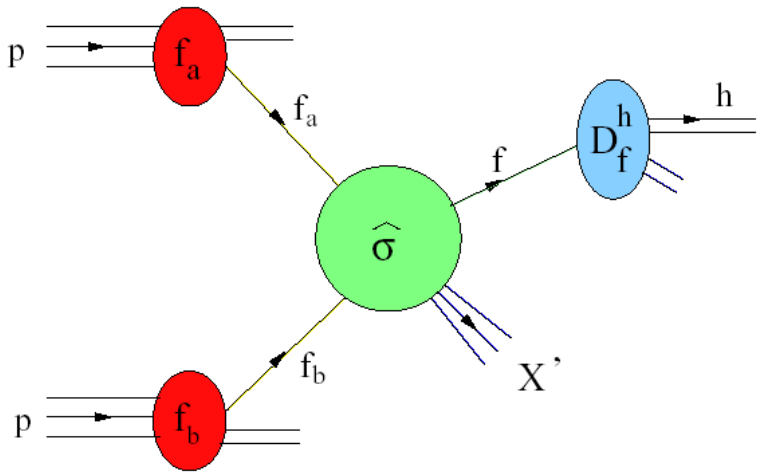
$$F_2(x) = x\sum_a e_a^2 f_a(x)$$

polarized structure function

$$g_1(x) = \sum_a e_a^2 \Delta f_a(x)$$

$\Delta f_a(x)$ or $\Delta q(x)$: polarized PDF

QCD factorization



$$d\sigma = \sum_{a,b,c} \int dx_a \int dx_b \int dz_c \; f_a(x_a,\mu)\, f_b(x_b,\mu)\, D_c^h(z_c,\mu)\, d\hat{\sigma}_{ab}^c(x_a P_A, x_b P_B, P_h / z_c, \mu)$$

$f_a(x_a,\mu)$, $f_b(x_b,\mu)$ parton distribution function (PDF)

$D_c^h(z_c,\mu)$ fragmentation function (FF)

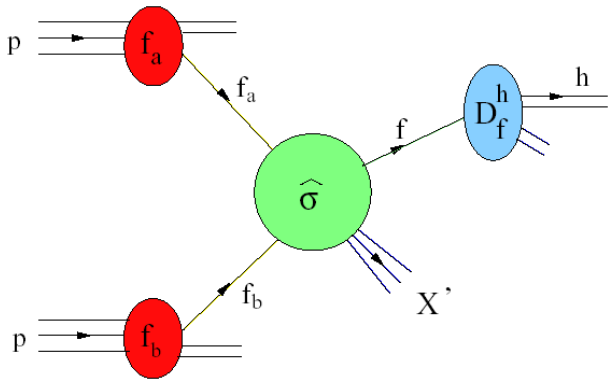
} long distance term

$d\hat{\sigma}_{ab}^c(x_a P_A, x_b P_B, P_h / z_c, \mu)$ partonic cross section — short distance term

μ factorization scale – boundary between short and long distance

A_{LL} of inclusive hadron production

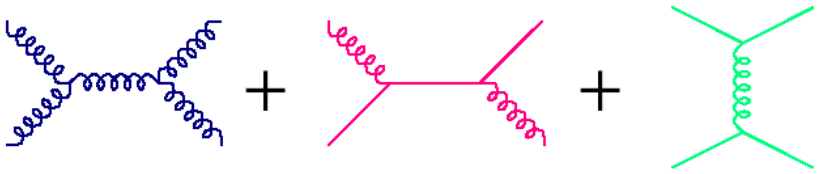
- QCD factorization
  - A_{LL}: double longitudinal-spin asymmetry or double helicity asymmetry
  - Inclusive hadron production
    - p+p→h+X

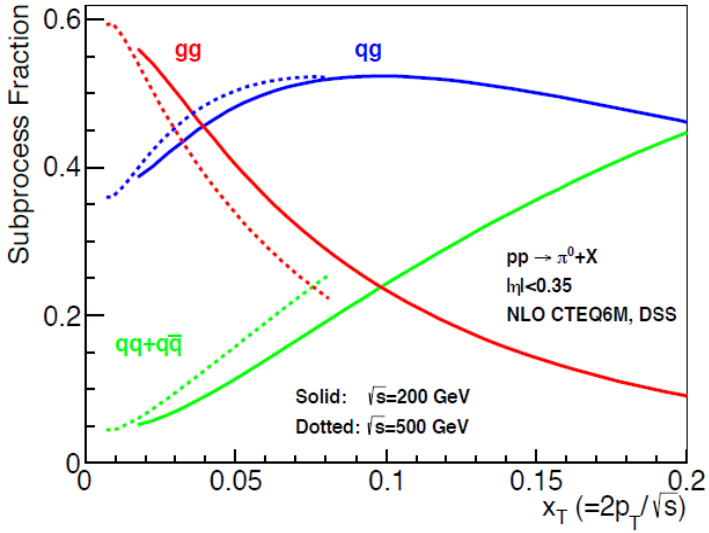


$$A_{LL} = \frac{\sum_{abc} \Delta f_a(x_1,\mu_F^2) \otimes \Delta f_b(x_2,\mu_F^2) \otimes \Delta\sigma^{a+b\to c+X}(x_1,x_2,p_c,\mu_F^2,\mu_R^2,\mu_{FF}^2) \otimes D_c^h(z,\mu_{FF}^2)}{\sum_{abc} f_a(x_1,\mu_F^2) \otimes f_b(x_2,\mu_F^2) \otimes \sigma^{a+b\to c+X}(x_1,x_2,p_c,\mu_F^2,\mu_R^2,\mu_{FF}^2) \otimes D_c^h(z,\mu_{FF}^2)}$$

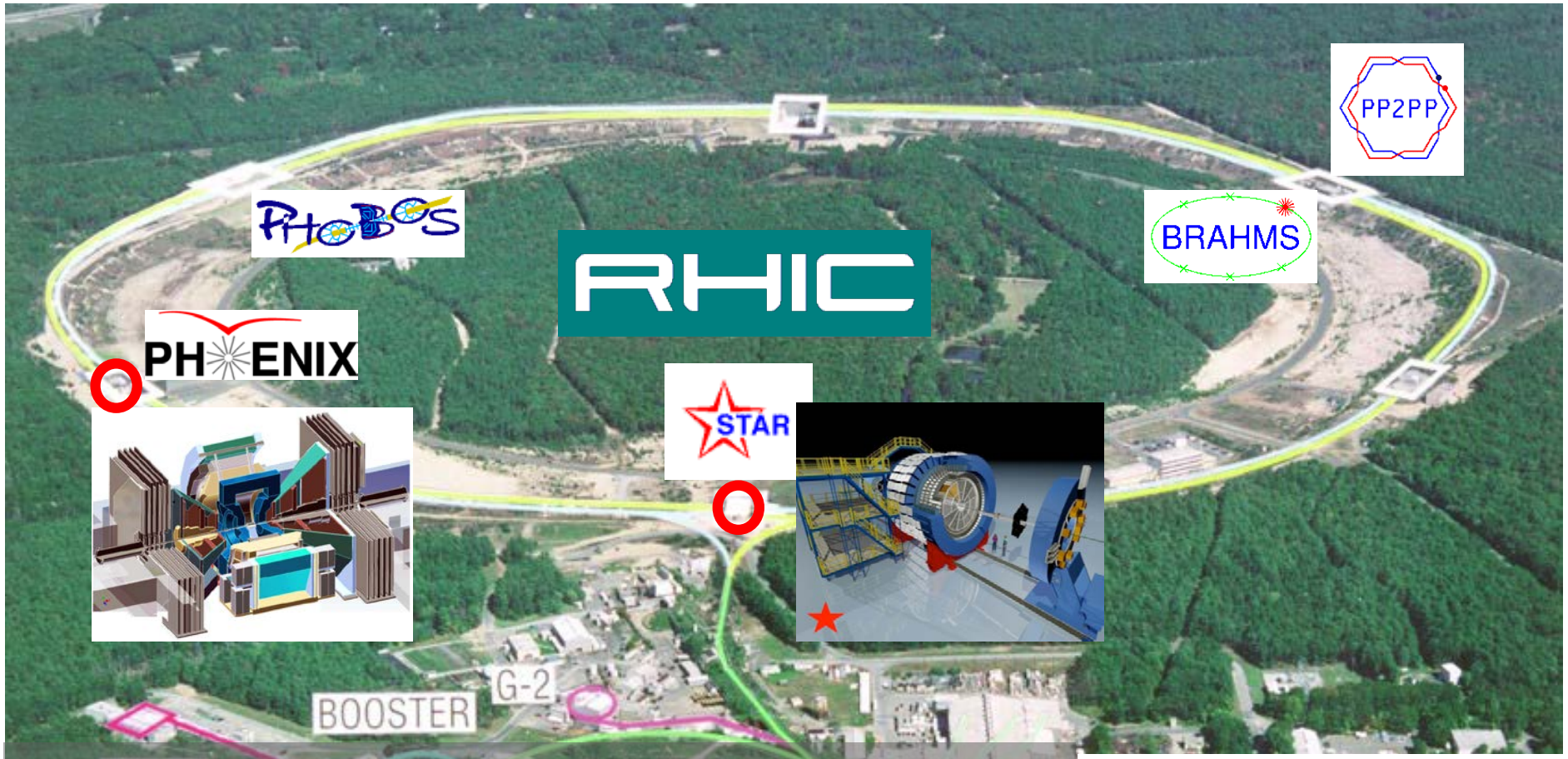
- QCD processes & mixture

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$
$$= [\omega_{gg}]\Delta g\Delta g + [\omega_{gq}\Delta q]\Delta g + [\omega_{qq}\Delta q\Delta q]$$





RHIC (Relativistic Heavy-Ion Collider)



High-energy collision experiments with heavy-ion collisions, polarized proton collisions, and many other combinations of particle species and collision energies

Au+Au collisions of 7.7 – 200 GeV/A

polarized proton collisions of 62.4 – 510 GeV

d+Au, Cu+Cu, U+U, Cu+Au, ^{3}He+Au, polaeized-p+Au/Al

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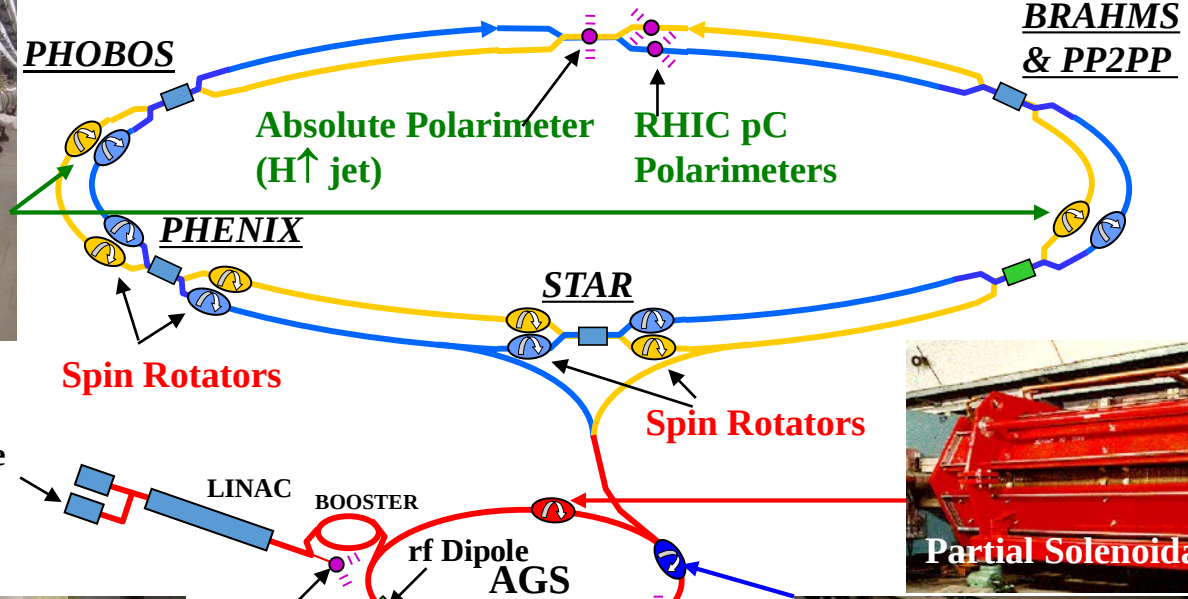
RHIC polarized proton collider

Full Helical
Siberian Snakes



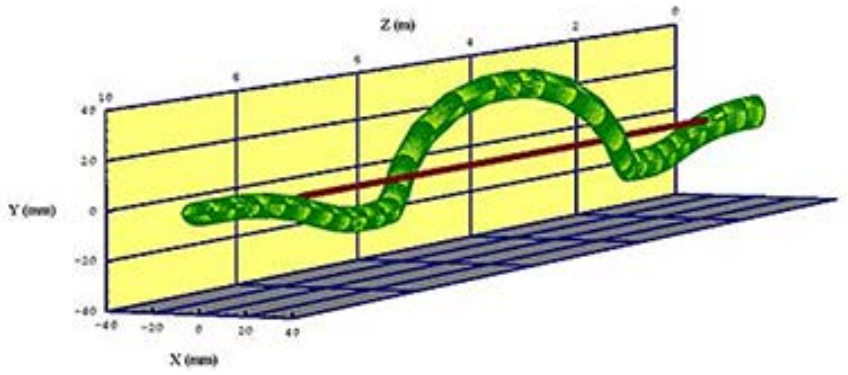
Partial Solenoidal Snake


Cold Partial
Helical Siberian Snake


Warm Partial
Helical Siberian Snake

RIKEN-BNL collaboration

- RHIC spin program from 1997
  - More than $100M
- Polarized proton acceleration at RHIC
  - Snake magnets / polarimeters / …
- PHENIX
  - Muon-south / MuTrig / ERT / Localpol / VTX / …
  - Silicon tracker for sPHENIX …
- RIKEN BNL Research Center

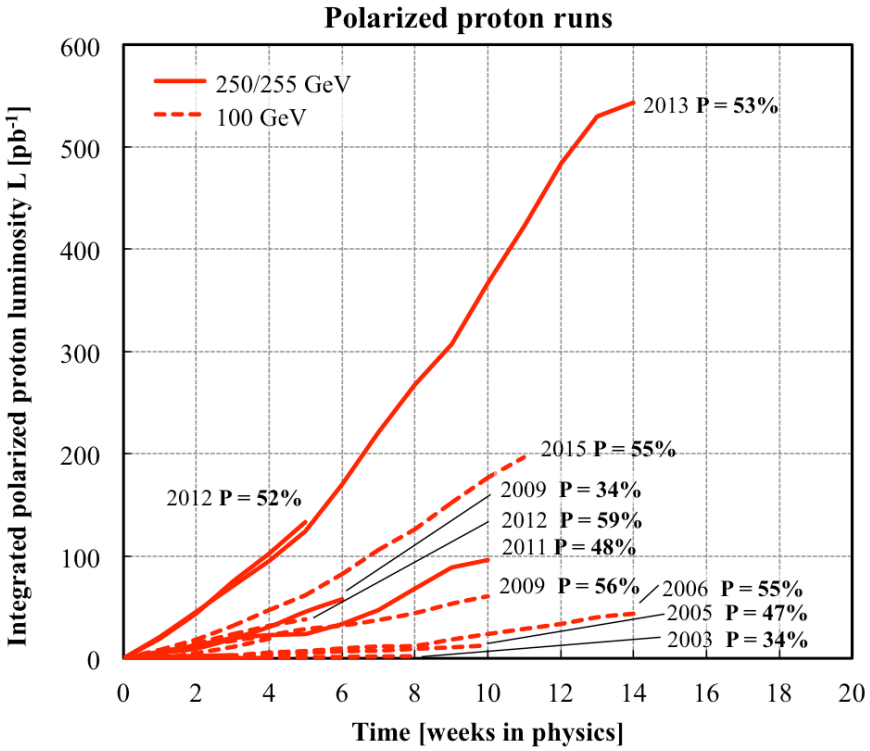


RHIC performance

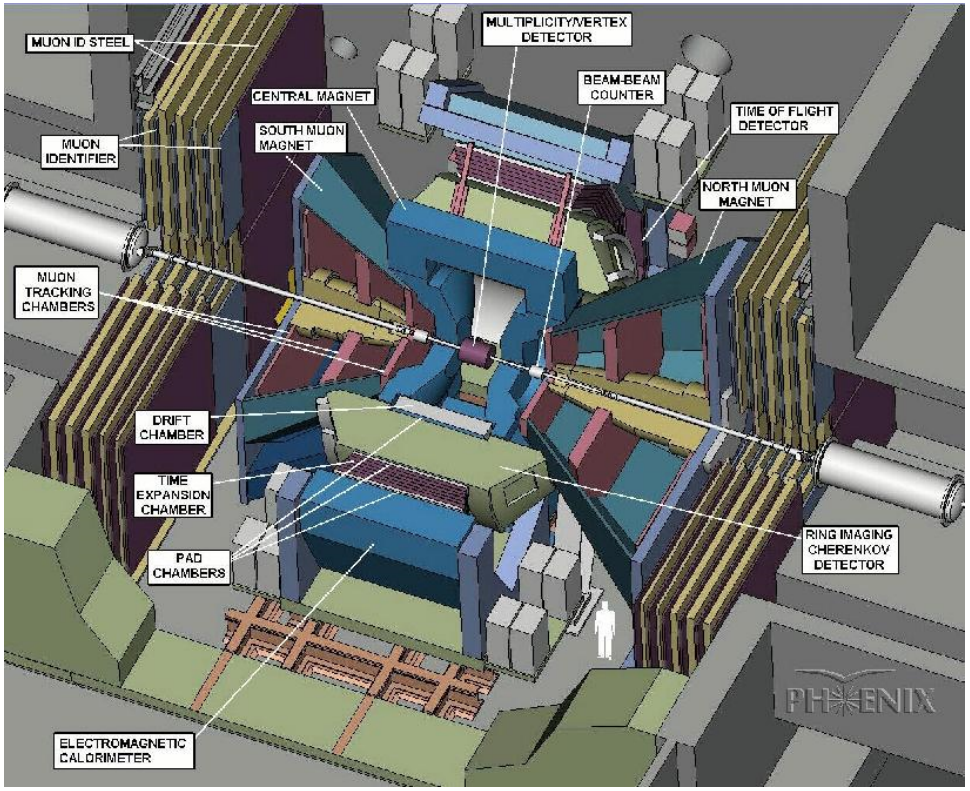
- $\sqrt{s}$ = 200 GeV longitudinal run in 2009
  - $L_{avg} = 2.8\times10^{31}\ cm^{-2}s^{-1}$
  - P = 56%
- $\sqrt{s}$ = 510 GeV longitudinal run in 2013
  - $L_{avg} = 1.6\times10^{32}\ cm^{-2}s^{-1}$
  - P = 53%

PHENIX Recent Longitudinal Runs

Year	$\sqrt{s}$(GeV)	L(Pb^{-1})	P(%)	FoM(P^4L)
2003	200	0.35	27	0.0019
2004	200	0.12	40	0.0031
2005	200	3.4	49	0.2
2006	200	7.5	57	0.79
2006	62.4	0.08	48	0.0042
2009	500	10	40	0.26
2009	200	14	57	1.4
2011	500	16.7	48	0.88
2012	510	30.03	52	2.2
2013	510	150	55	14



PHENIX detector

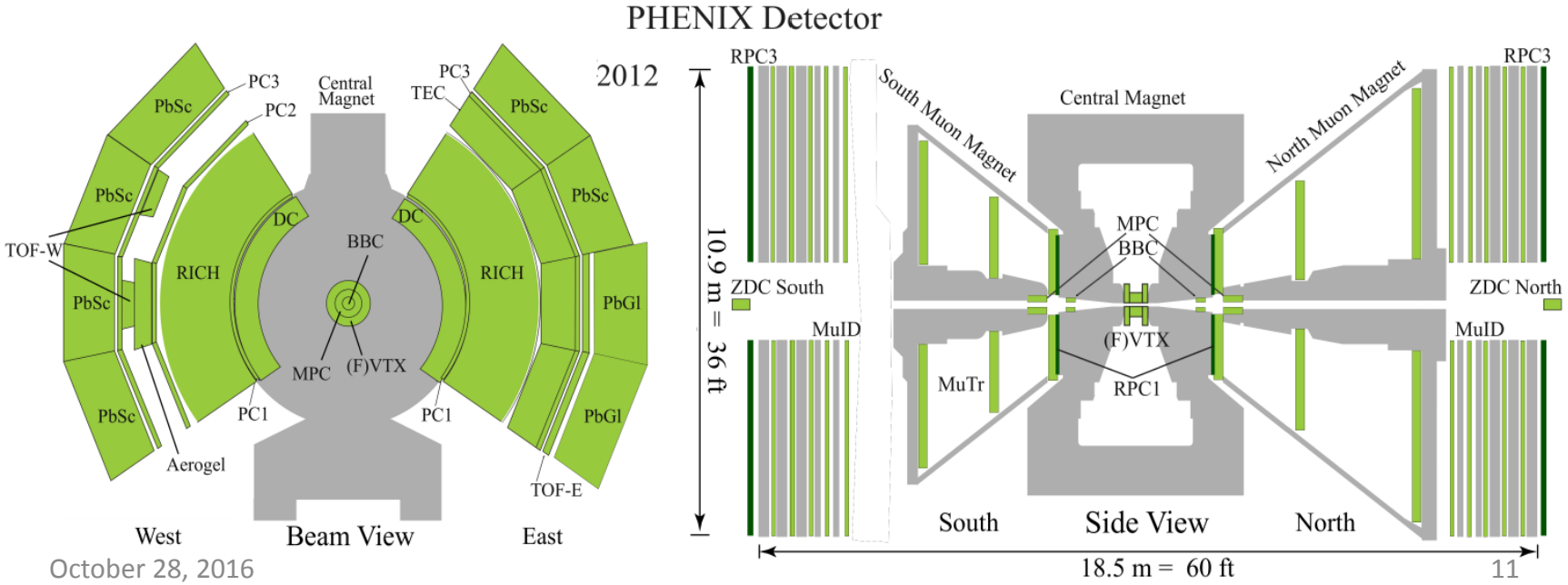


- Philosophy
  - high resolution at the cost of acceptance
  - high rate capable DAQ
  - excellent trigger capability for rare events
- Central Arms
  - $|\eta| < 0.35$, $\Delta\phi = \pi/2 \times 2$
  - Momentum and energy measurement, particle-ID
  - Detecting electron, photon, hadron
  - Small amount of material to reduce conversion background
- Muon Arms
  - $1.2 < |\eta| < 2.4$
  - Momentum measurement and muon-ID
  - Hadron absorber (muon piston)

- Global detectors
  - beam-beam counter (BBC), zero-degree calorimeter (ZDC)
    - Minimum-bias trigger
    - Luminosity measurement
    - Local polarimeter

PHENIX detector

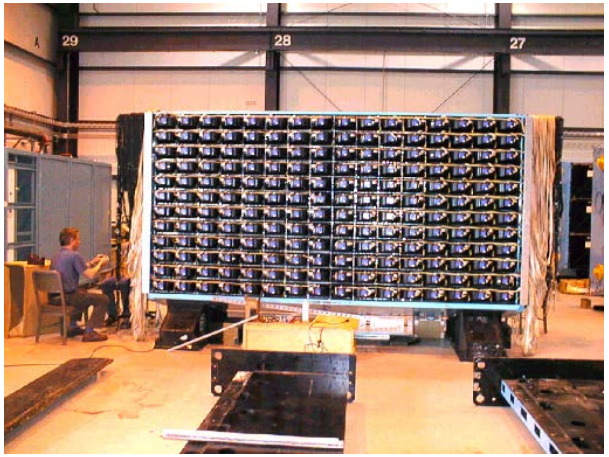
- PHENIX EMCal
  - PbSc
    - Lead-scintillator sampling calorimeter
    - $\Delta\eta\times\Delta\phi \sim 0.011\times0.011$
  - PbGl
    - Lead-glass Cherenkov calorimeter
    - $\Delta\eta\times\Delta\phi \sim 0.008\times0.008$
  - High-p_T photon trigger
    - 4×4 towers
    - 3 threshold levels



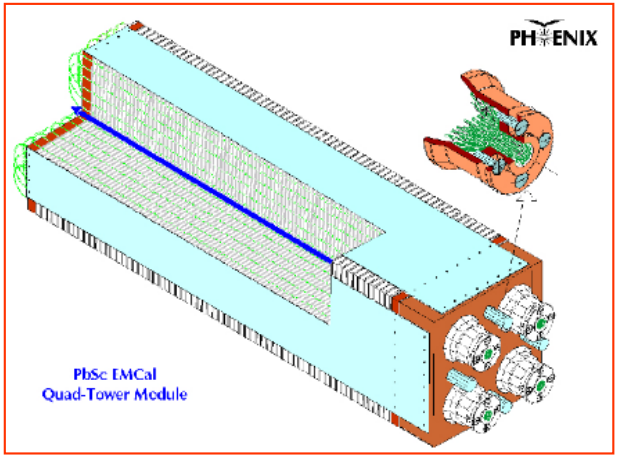
PHENIX EMCal

PbSc Sector

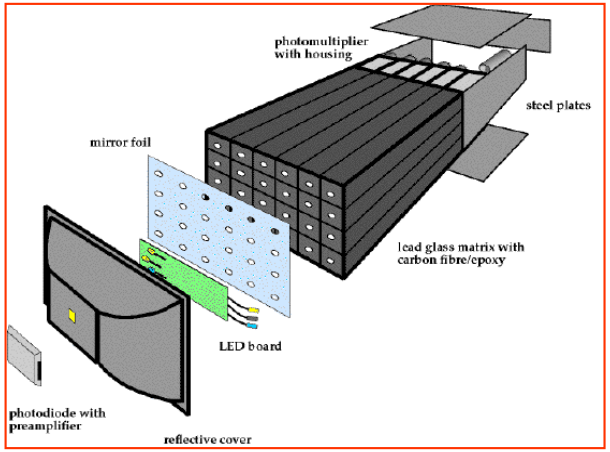
PbGl Sector



PbSc Module



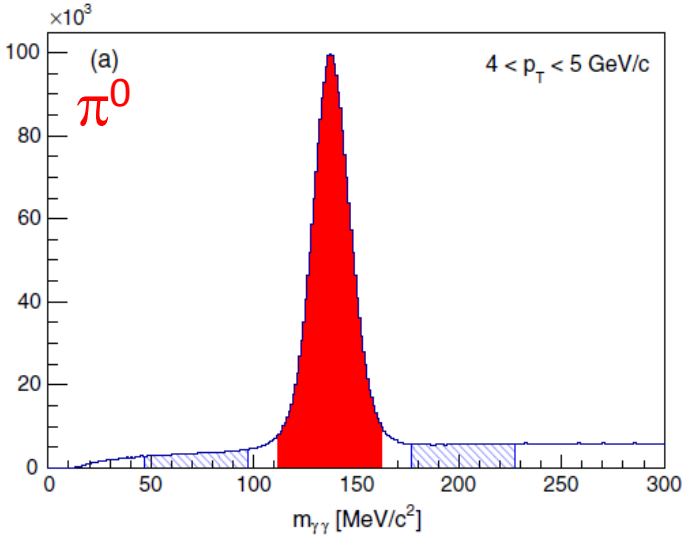
PbGl Super-module

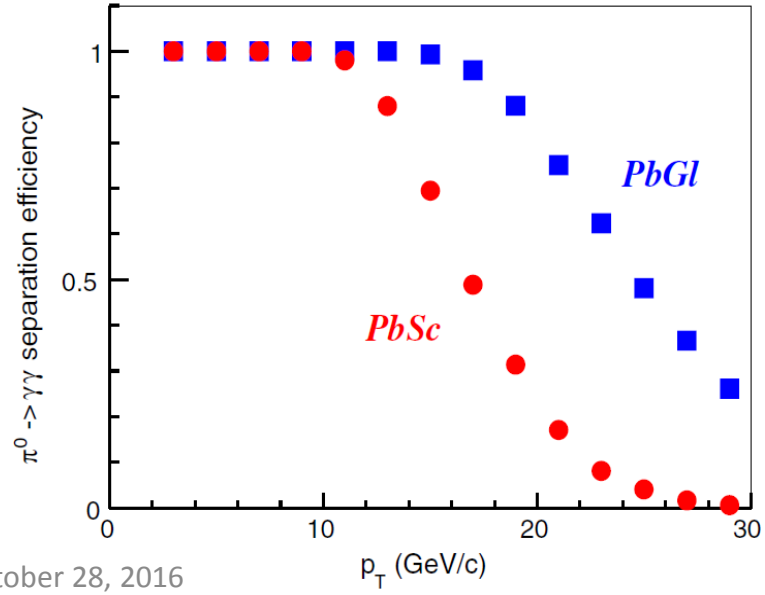


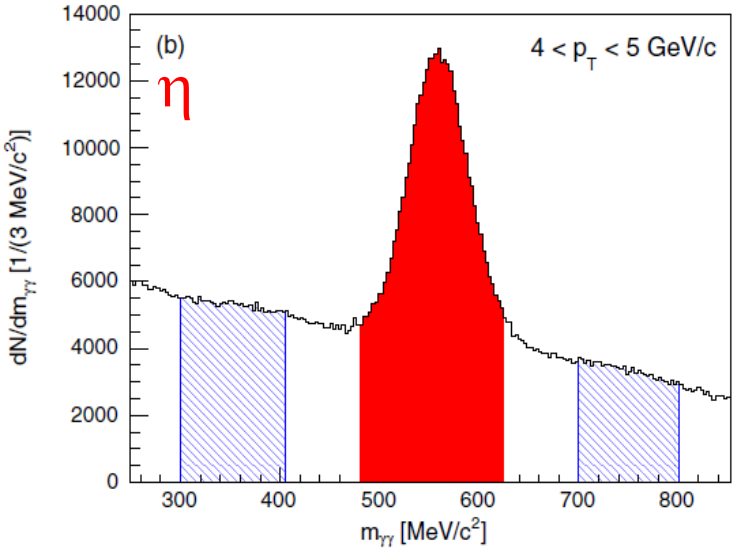
π^0 (and η) at PHENIX

- 2-γ decay
  - B.R. 99% for π^0
  - B.R. 39% for η
- Invariant mass
  - Peak area: signal + b.g.
  - Side area: b.g. evaluation
  - Choose cuts to minimize total uncerntainty

$\sqrt{s}$ = 200 GeV



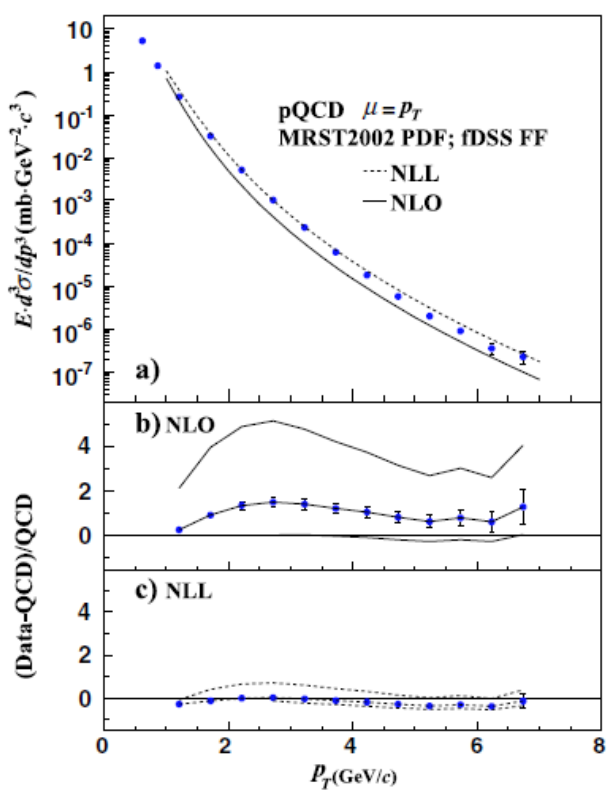




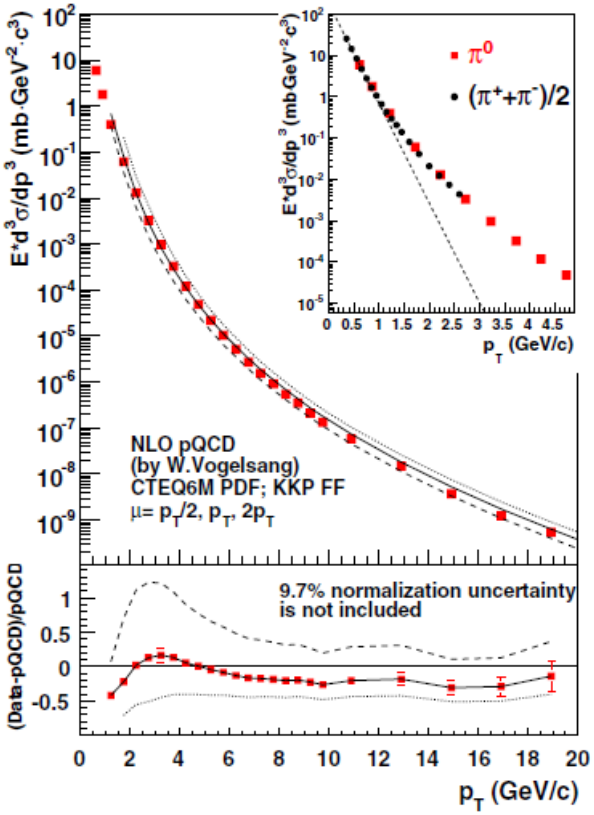
Cross section measurements

- Applicability of perturbative QCD
  - Midrapidity π^0 measurements at PHENIX

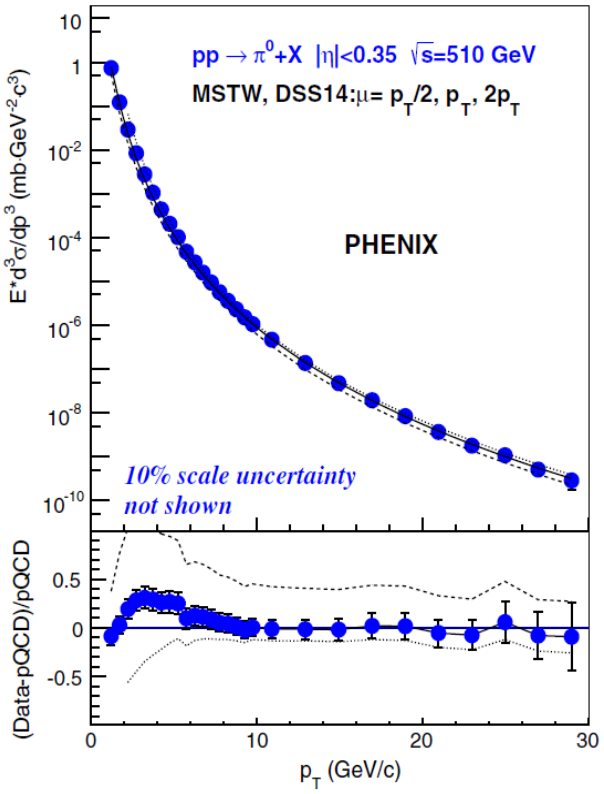
√s = 62.4 GeV



√s = 200 GeV



√s = 510 GeV

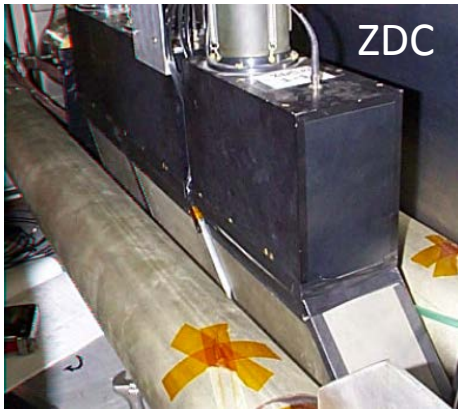


π^0 asymmetry

- A_{LL} measurement

$$A_{LL} = \frac{1}{P_B P_Y} \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}} \qquad R = \frac{L_{++}}{L_{+-}}$$

- R: Relative luminosity
  - Crossing-by-crossing luminosity ratio
  - Measured with minimum-bias BBC scaler
    - BBC: Beam-Beam Counter ($3<|\eta|<3.9$)
  - Evaluated by comparing BBC and ZDC scalers
    - ZDC: Zero-Degree Calorimeter ($\eta>6$)



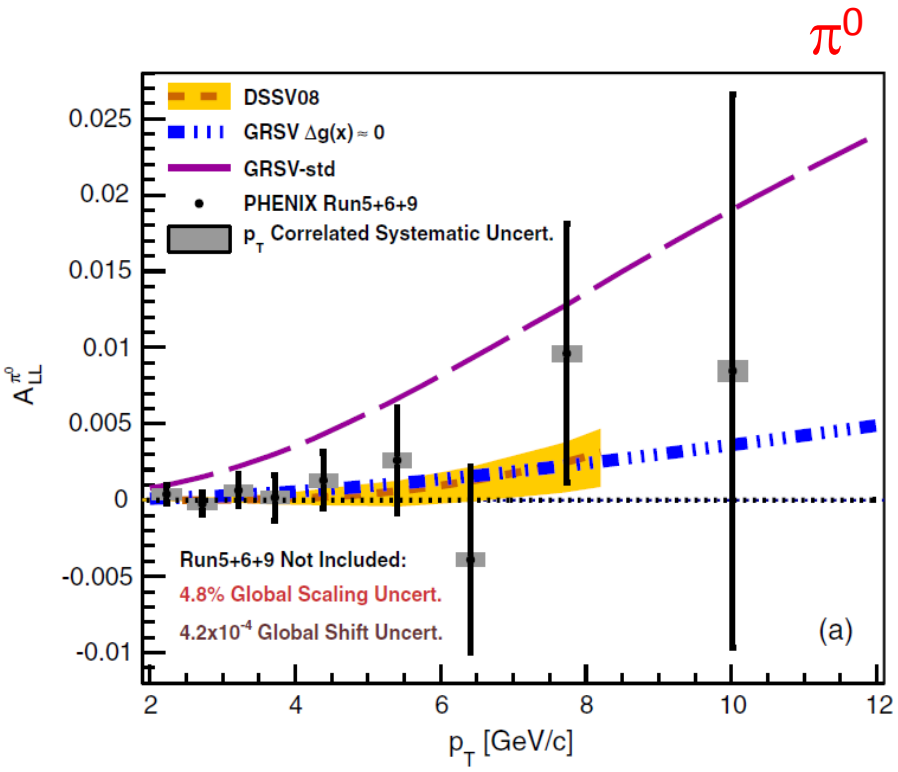
$$A = \frac{1}{P_B P_Y} \frac{\left(\frac{N_{ZDC}}{N_{BBC}}\right)_{++} - \left(\frac{N_{ZDC}}{N_{BBC}}\right)_{+-}}{\left(\frac{N_{ZDC}}{N_{BBC}}\right)_{++} + \left(\frac{N_{ZDC}}{N_{BBC}}\right)_{+-}}$$

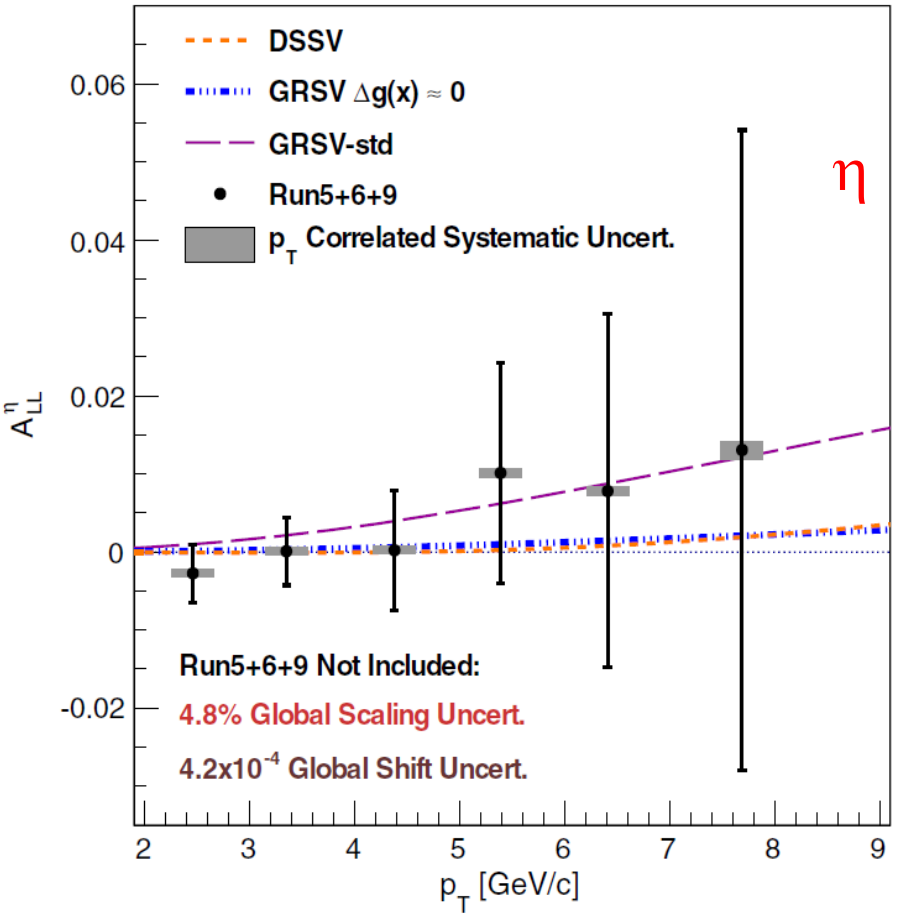
- Background subtraction
  - r: background fraction

$$A_{LL}^{\pi^0} = \frac{A_{LL}^{\pi^0 + b.g.} - r \cdot A_{LL}^{b.g.}}{1 - r} \qquad \Delta A_{LL}^{\pi^0} = \frac{\sqrt{\left(\Delta A_{LL}^{\pi^0 + b.g.}\right)^2 + \left(r \cdot \Delta A_{LL}^{b.g.}\right)^2}}{1 - r}$$

π^0 (and η) asymmetry at $\sqrt{s}$ = 200 GeV

- Phys. Rev. D90 (2014) 012007
  - Run5 (2005) + Run6 (2006) + Run9 (2009) data





π^0 asymmetry at $\sqrt{s}$ = 200 GeV

- Systematic uncertainties
  - Relative luminosity
    - Largest systematic uncertainty
    - $\Delta A_{LL} = 1.4\times10^{-3}$
  - Polarization measurement
    - Scale uncerntainty
  - Event overlap in the EMCal
    - Events from previous crossings contribute background to current crossing
  - Background fraction
- Cross check
  - False parity-violating asymmetry
  - Bunch shuffling

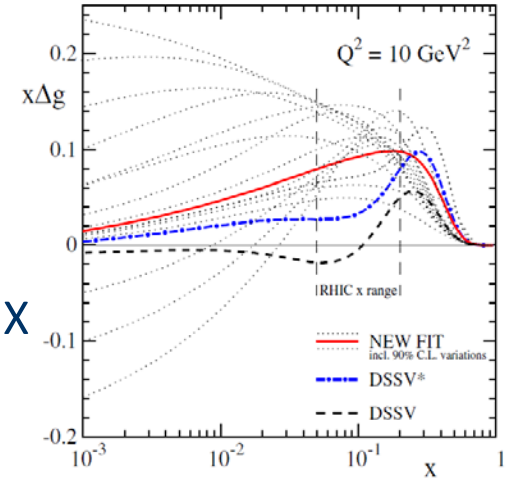
TABLE II. Summary of systematic uncertainties on π^0 and η A_{LL} for the 2009 data. The systematics listed as "π^0 only" were not evaluated for the η asymmetries.

Description	ΔA_{LL}(syst)	p_T correlated?	Note
Relative luminosity	1.4×10^{-3}	Yes	...
Polarization magnitude	$0.065 \times A_{LL}$	Yes	...
Polarization direction	$^{+0.026}_{-0.042} \times A_{LL}$	Yes	...
w_{BG} Determination	$< 0.01 \times \Delta A_{LL}^{stat}$	No	π^0 only
EMCal readout	1.6×10^{-4}	No	π^0 only, lowest p_T bin

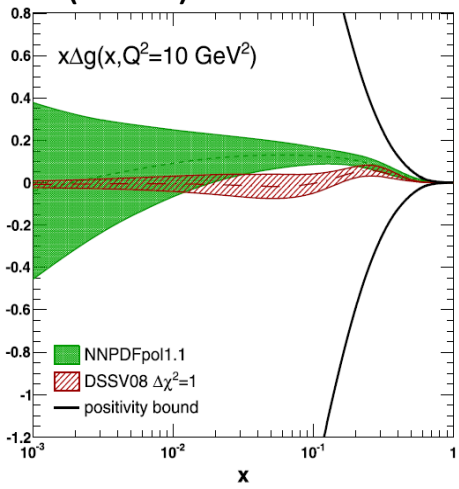
Gluon polarization

- Positive gluon polarization has been finally obtained with QCD global analyses by DSSV and NNPDF groups including experimental data from RHIC polarized proton collisions
  - Gluon polarization
    - $\sqrt{s}$ = 200 GeV
    - Jet A_{LL} measurement from STAR
    - π^0 A_{LL} measurement from PHENIX
  - Anti-quark polarization
    - $\sqrt{s}$ = 510 GeV
    - W-boson measurement

DSSV
Phys. Rev. Lett. 113 (2014) 012001



NNPDF
Nucl. Phys. B 887 (2014) 276



	$\langle \Delta g(Q^2) \rangle^{[0,1]}$	$\langle \Delta g(Q^2) \rangle^{[10^{-3},1]}$	$\langle \Delta g(Q^2) \rangle^{[0.05,0.2]}$
NNPDFpol1.0	-0.95 ± 3.87	-0.06 ± 1.12	$+0.05 \pm 0.15$
NNPDFpol1.1	$+0.03 \pm 3.24$	$+0.49 \pm 0.75$	$+0.17 \pm 0.06$
DSSV08	–	$0.013^{+0.702}_{-0.314}(+0.097)$	$0.005^{+0.129}_{-0.164}$
DSSV++	–	–	$0.10^{+0.06}_{-0.07}$

Gluon polarization

- Positive gluon polarization has been finally obtained at RHIC

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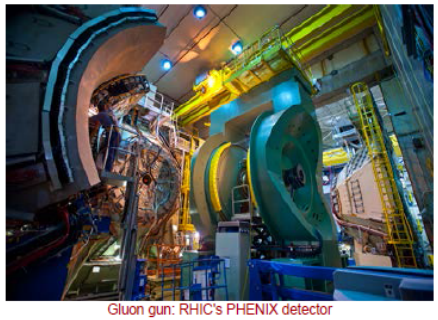
Gluons get in on proton spin

Jul 11, 2014 14 comments



Gluon gun: RHIC's PHENIX detector

For a quarter of a century, physicists have faced a paradox regarding the net spin of protons and neutrons – the spin of their constituent quarks accounts for only a small fraction of their overall spin. Now, new research carried out by physicists in Argentina and Germany who have analysed data produced by the Relativistic Heavy Ion Collider (RHIC), suggests that the missing spin might come from gluons that hold quarks together.

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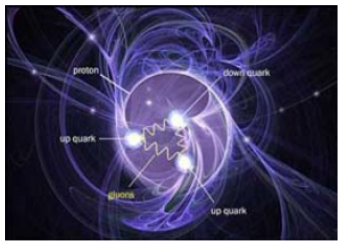
Proton Spin Mystery Gains a New Clue

Physicists long assumed a proton's spin came from its three constituent quarks. New measurements suggest particles called gluons make a significant contribution

July 21, 2014 | By Clara Moskowitz



Brookhaven National Laboratory

Protons have a constant spin that is an intrinsic particle property like mass or charge. Yet where this spin comes from is such a mystery it's dubbed the "proton spin crisis." Initially physicists thought a proton's spin was the sum of the spins of its three constituent quarks. But a 1987 experiment showed that quarks can account for only a small portion of a proton's spin, raising the question of where the rest arises. The quarks inside a proton are held together by gluons, so scientists suggested perhaps they contribute spin. That idea now has support from a pair of studies analyzing the results of proton collisions inside the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory in Upton, N.Y.

2014. 7. 2

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Synopsis: Gluons Chip in for Proton Spin

Brookhaven National Laboratory

Evidence for Polarization of Gluons in the Proton

Daniel de Florian, Rodolfo Sassot, Marco Stratmann, and Werner Vogelsang
Phys. Rev. Lett. **113**, 012001 (2014)

Published July 2, 2014

The proton has a spin that comes from its constituent quarks and gluons. Experiments in the 1980s found—unexpectedly—that the contribution from the intrinsic spins of the quarks was small. This so-called "proton spin crisis" remains unresolved, but a new comprehensive analysis of proton scattering data, reported in *Physical Review Letters*, finds the first clear evidence that the gluon spin polarization is not zero, suggesting that gluons may have a significant role in the spin of the proton.

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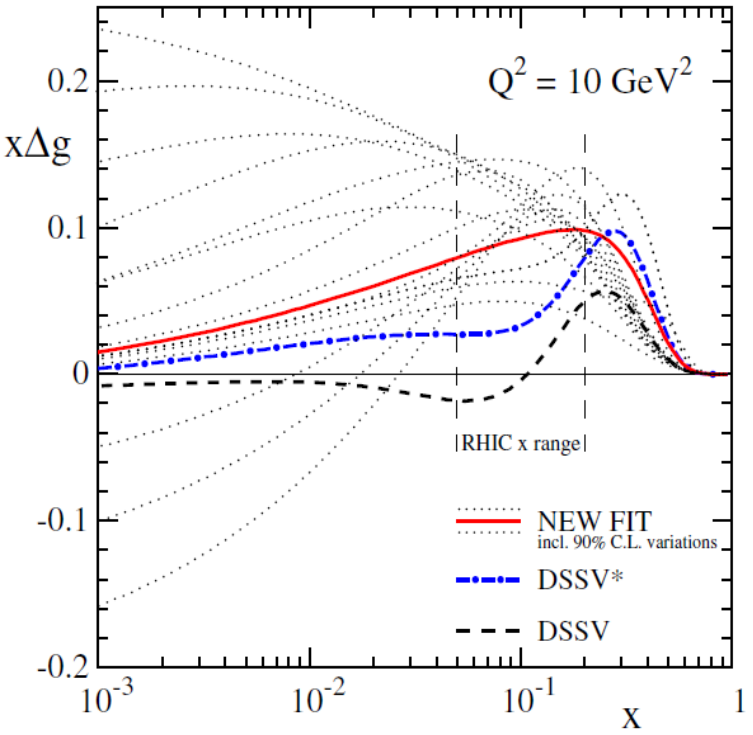
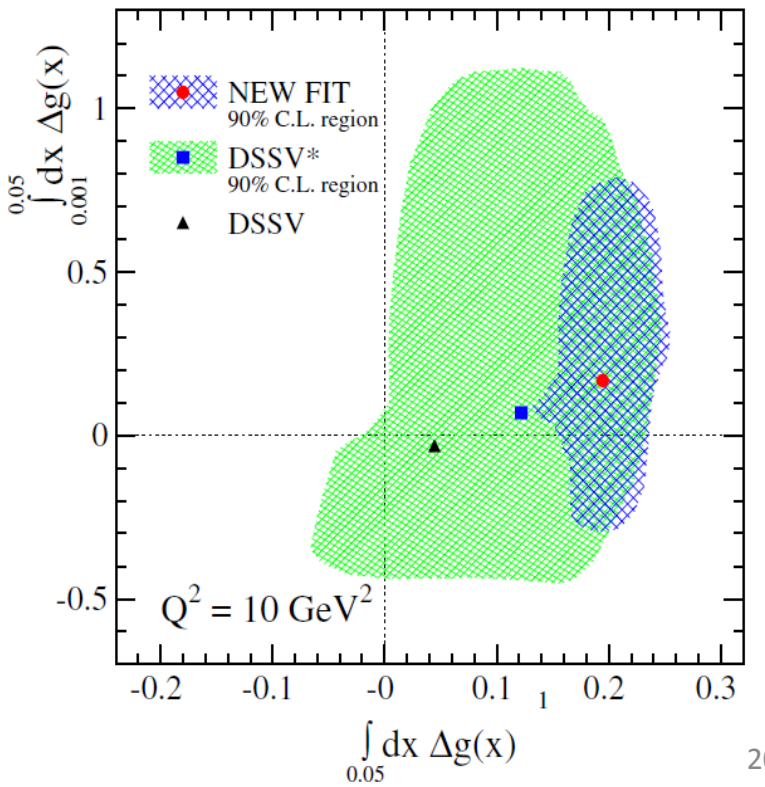
Gluon polarization

- DSSV (de Florian, Sassot, Stratmann and Vogelsang), Phys. Rev. Lett. 113 (2014) 012001
  - Non-zero $\Delta g(x)$ in the kinematic region probed by RHIC

$$\int_{0.05}^{1} dx \Delta g(x) = 0.2^{+0.06}_{-0.07}$$

  - Still large uncertainty in unmeasured region (x<0.05)
  - Next goal: extension of Bjorken-x coverage



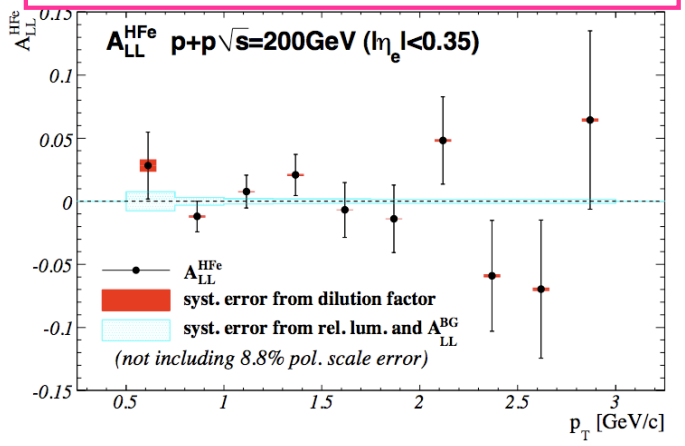


Other asymmetries at √s = 200 GeV

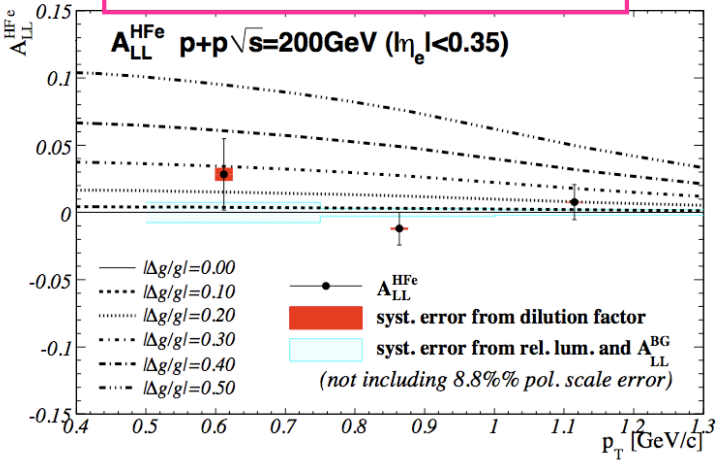
- Single electron

Phys. Rev. D87 (2013) 012011

heavy-quarks produced dominantly by gg interaction

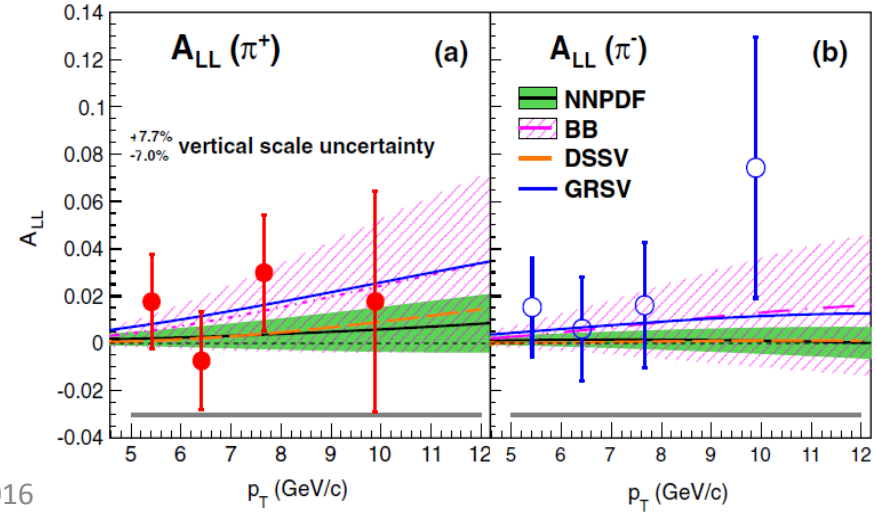


constraint to small-x gluon-spin contribution



- Charged pions

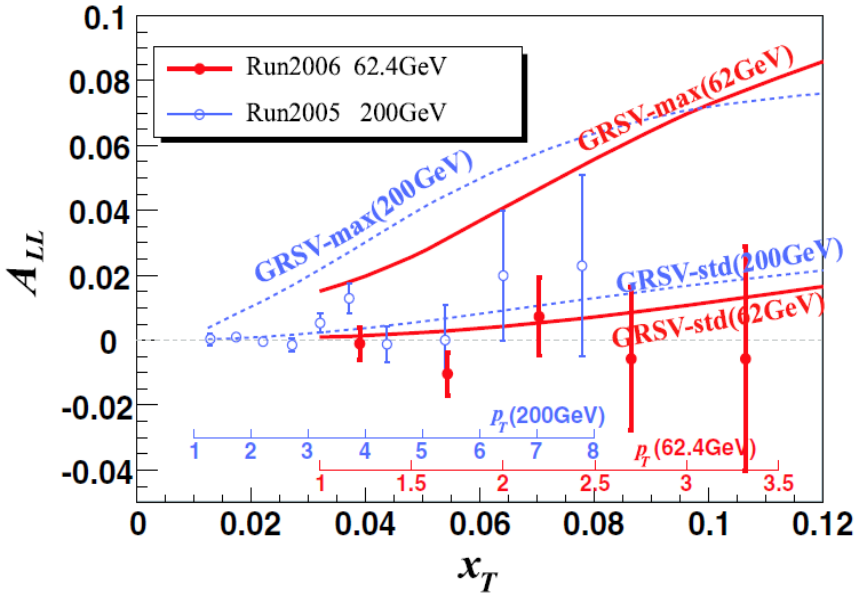
Phys. Rev. D91 (2015) 032001



Sign of ΔG via A_{LL} ordering

Extension of Bjorken-x coverage

- Large-*x*
  - Low collision energy
  - π^0 A_{LL} at $\sqrt{s}$ = 62.4 GeV
  - Phys. Rev. D79 (2009) 012003

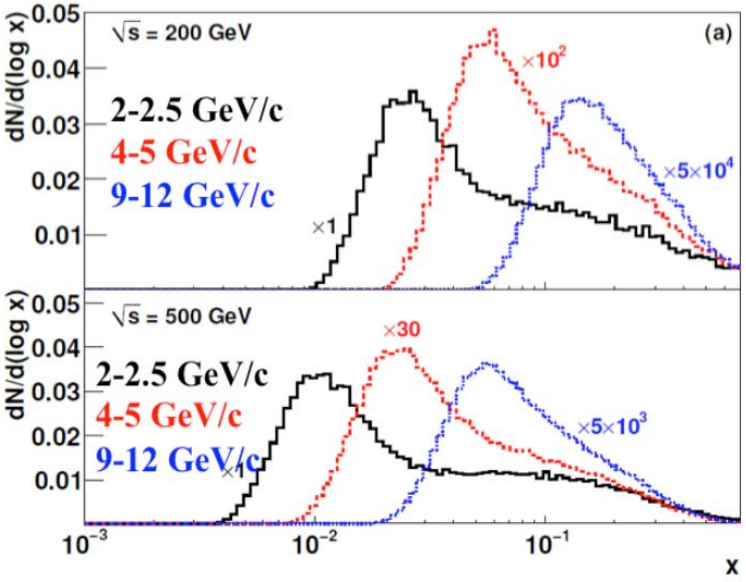


- Small-*x*
  - High collision energy $\sqrt{s}$ = 510 GeV
  - Forward measurement

π^0 asymmetry at $\sqrt{s}$ = 510 GeV

Inseok Yoon
(SNU / RIKEN IPA)

- Phys. Rev. D93 (2016) 011501(R)
  - 2012 – 2013 data
  - Gluon polarization measurement at smaller *x* region
    - down to x ~ 0.01 region
  - Larger asymmetry (supported by pQCD)
  - Higher luminosity, higher statistics
    - than measurement at $\sqrt{s}$ = 200 GeV

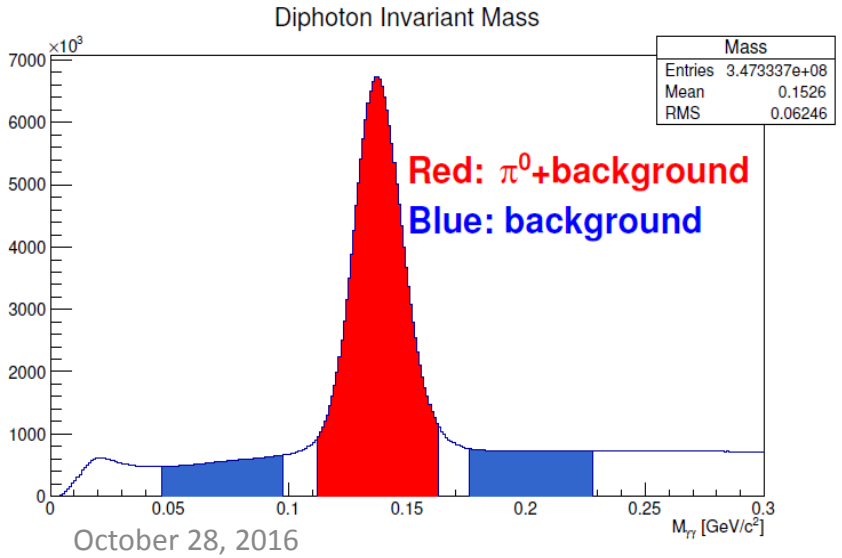


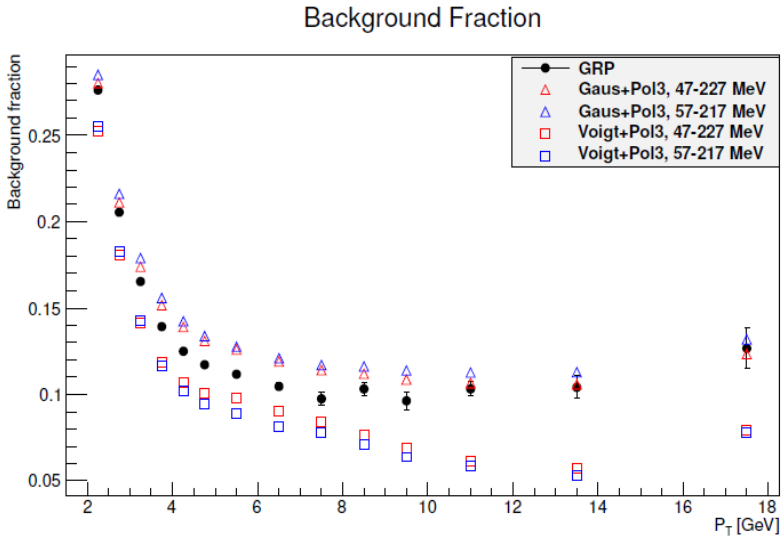
π^0 asymmetry at $\sqrt{s}$ = 510 GeV

- 2-γ invariant mass
  - Peak area: signal + b.g.
  - Side area: b.g. evaluation
- Background subtraction
  - *r*: background fraction

$$A_{LL}^{\pi^0} = \frac{A_{LL}^{\pi^0+b.g.} - r \cdot A_{LL}^{b.g.}}{1-r}$$

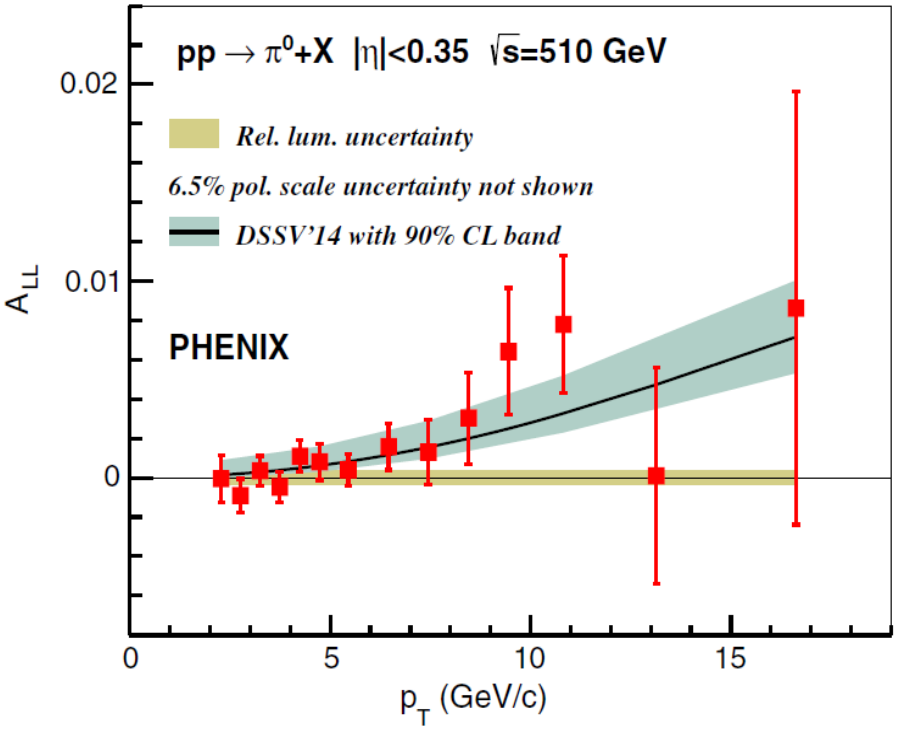
$$\Delta A_{LL}^{\pi^0} = \frac{\sqrt{\left(\Delta A_{LL}^{\pi^0+b.g.}\right)^2 + \left(r \cdot \Delta A_{LL}^{b.g.}\right)^2}}{1-r}$$

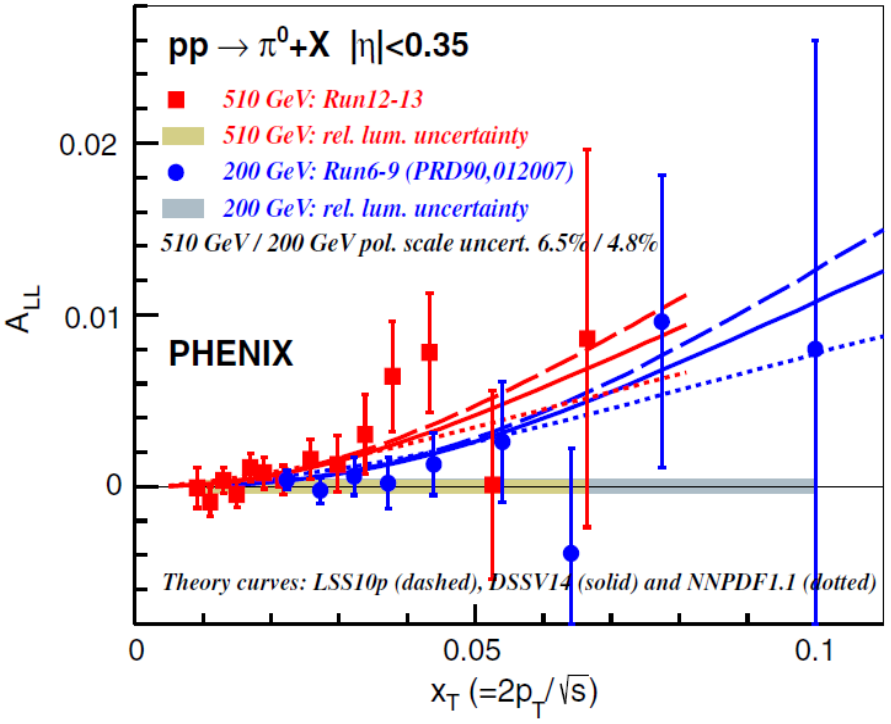




π^0 asymmetry at $\sqrt{s}$ = 510 GeV

- Positive A_{LL} measured
  - pQCD is reliable for small-*x* gluon distribution





- Relative luminosity measurement
  - Multiple collisions & vertex smearing fully corrected
  - $\Delta A_{LL} = 2.0\times10^{-4}$ (2012) & 3.8×10^{-4} (2013)

Press Releases

RIKEN Press Release
January 8th, 2016

http://www.riken.jp/pr/press/2016/20160108_4/

2016/10/25 陽子内部のグルーオンの向きを精密測定 | 理化学研究所

理化学研究所

広報活動

2016年1月8日
理化学研究所

陽子内部のグルーオンの向きを精密測定
－陽子の向きの謎を解明するための大きな一歩－

要旨

背景

http://www.riken.jp/pr/press/2016/20160108_4/ 1/5

BNL Features
February 16th, 2016

https://www.bnl.gov/newsroom/news.php?a=26123

2016/10/25 BNL Newsroom | Physicists Zoom In on Gluons' Contribution to Proton Spin

By Karen McNulty Walsh | February 16, 2016

Physicists Zoom in on Gluons' Contribution to Proton Spin

Latest data from high-energy proton collisions at RHIC indicate that "wimpy" gluons have a big impact on proton spin, and gluons overall may contribute more than quarks

The PHENIX detector at the Relativistic Heavy Ion Collider (RHIC), a particle accelerator at Brookhaven National Laboratory uniquely capable of measuring how a proton's internal building blocks — quarks and gluons — contribute to its overall intrinsic angular momentum, or "spin."

By analyzing the highest-energy proton collisions at the Relativistic Heavy Ion Collider (RHIC), a particle collider at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory, nuclear physicists have gotten a glimpse of how a multitude of gluons that individually carry very little of the protons' overall momentum contribute to the protons' spin. The data described in a recently published paper indicate that these glue-like particles—named for their role in binding the quarks that make up each proton—play a substantial role in determining the intrinsic angular momentum, or spin, of these building blocks of matter.

"These results confirm our suspicion that a lot of the gluons' contribution to proton spin comes from the gluons with relatively low momentum," said Ralf Seidl, a physicist from the RIKEN-BNL Research Center (RBRC) and a member of RHIC's PHENIX collaboration, which published these results. The results also suggest that gluons' overall contribution to spin might be even greater than the contribution from quarks.

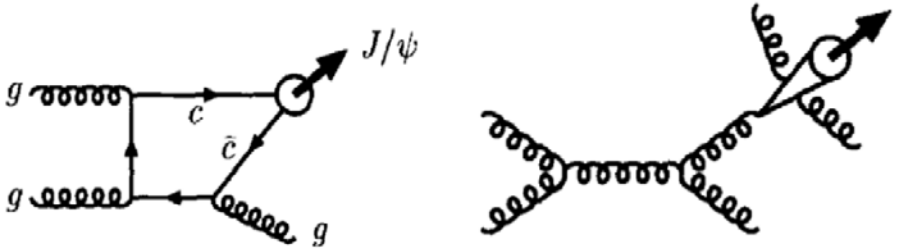
> "These results confirm our suspicion that a lot of the gluons' contribution to proton spin comes from the gluons with relatively low momentum."
>
> — PHENIX collaborator Ralf Seidl of the RIKEN-BNL Research Center (RBRC)

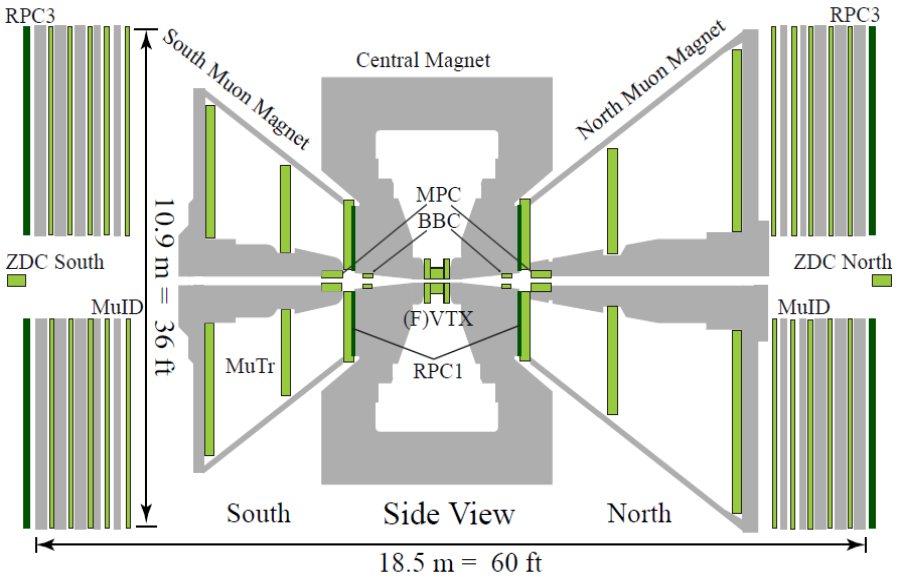
Exploring the sources of proton spin is one of the major scientific missions at RHIC, a DOE Office of Science User Facility and the only machine in the world capable of colliding protons with their spins aligned in a chosen direction. Nuclear physicists from around the globe

https://www.bnl.gov/newsroom/news.php?a=26123 1/4

Forward asymmetry

- J/ψ A_{LL} measurement at √s = 510 GeV
  - PHENIX Muon Arms
  - arXiv:1606.01815
- Gluon fusion process



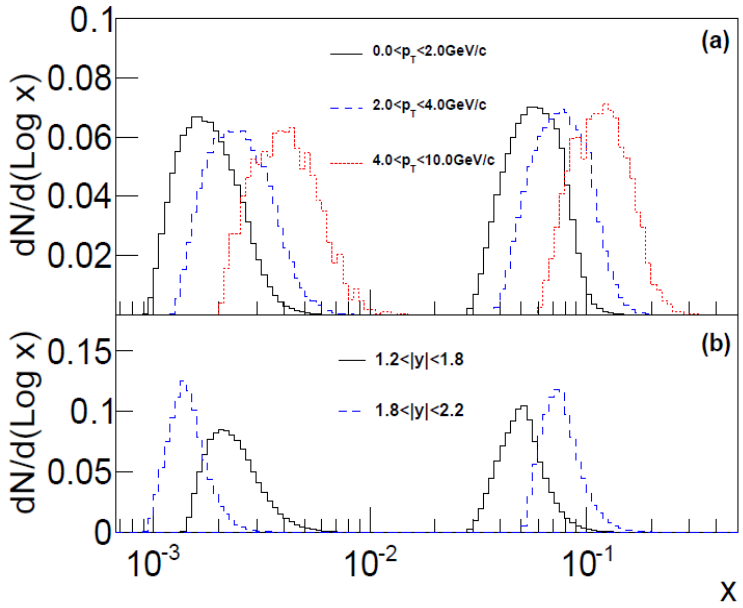


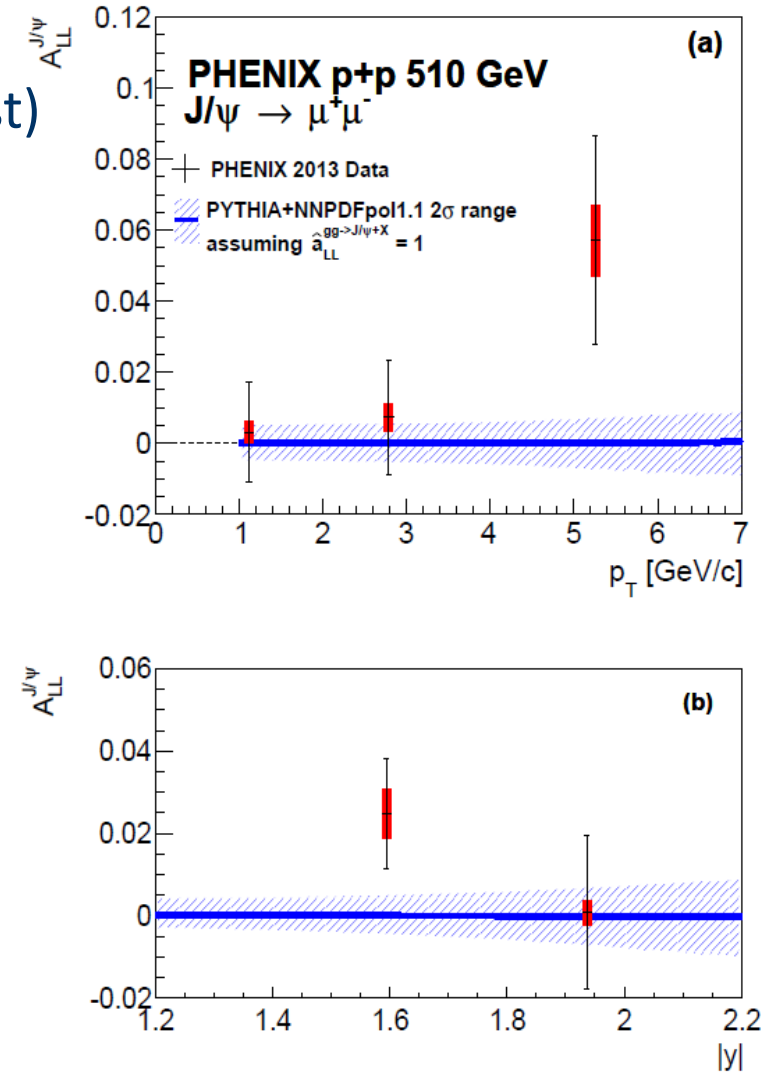
$$A_{LL}^{J/\psi} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

$$\approx \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta g(x_2)}{g(x_2)} \otimes \hat{a}_{LL}^{gg \to J/\psi + X}$$

Forward asymmetry

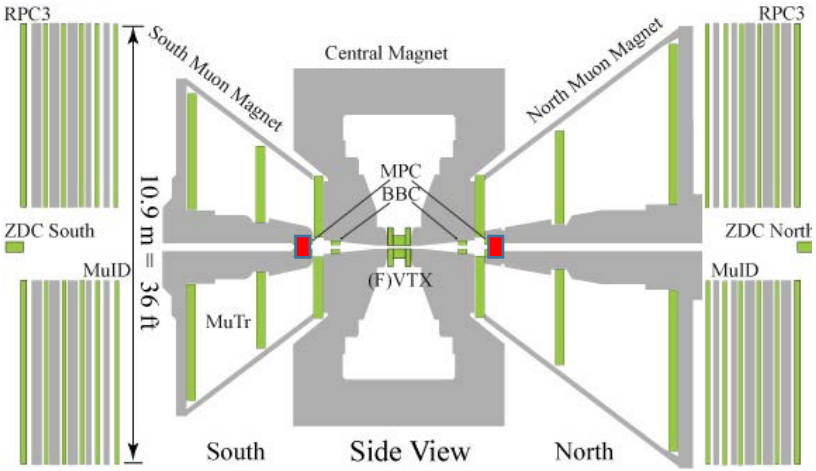
- J/ψ A_{LL} measurement at √s = 510 GeV
  - arXiv:1606.01815
  - $A_{LL}^{J/\psi} = 0.012 \pm 0.010\,(\text{stat}) \pm 0.003\,(\text{syst})$
  - 1.2 < |y| < 2.2
- Gluons from two distinct ranges of *x*
  - *x* ~ 0.05 & *x* ~ 0.002

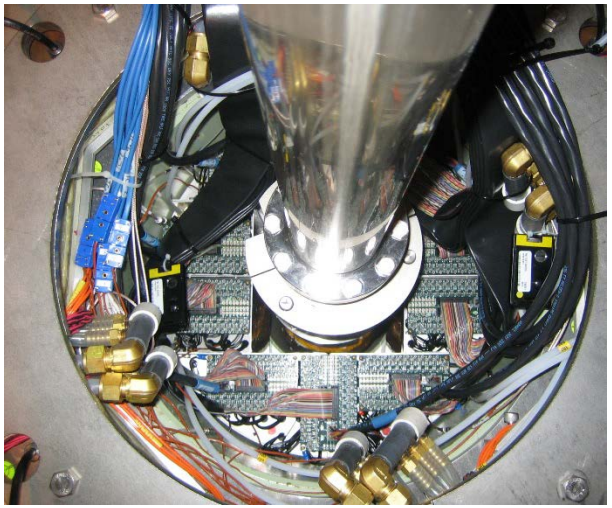


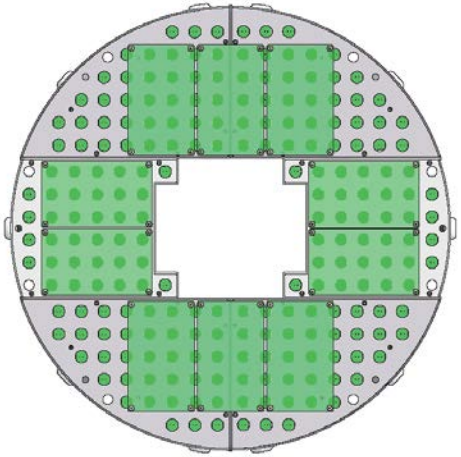


Forward asymmetry

- MPC (Muon Piston Calorimeter)
  - EM calorimeter installed in the small cylindrical hole in muon magnet piston
    - $PbWO_4$ crystals
      - $2.2 \times 2.2 \times 18\ cm^3$
    - 22.5 cm radius
    - 43.1 cm depth
    - $3.1 < |\eta| < 3.9$



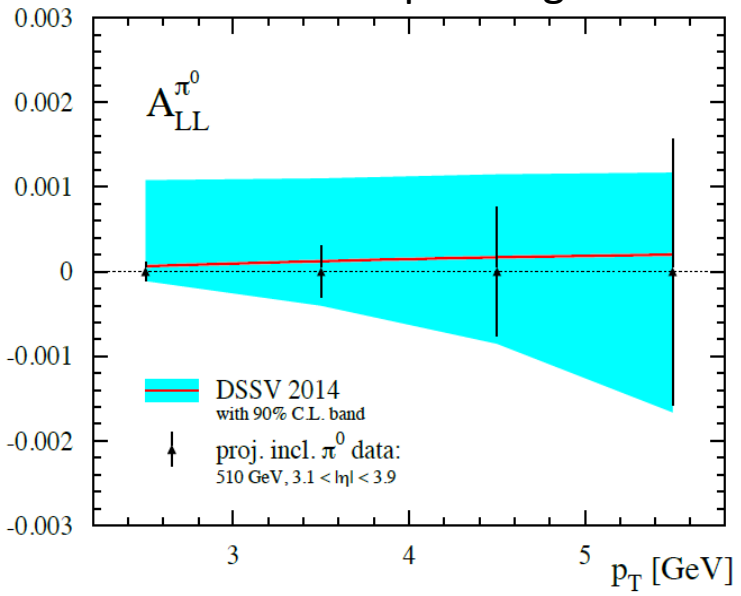


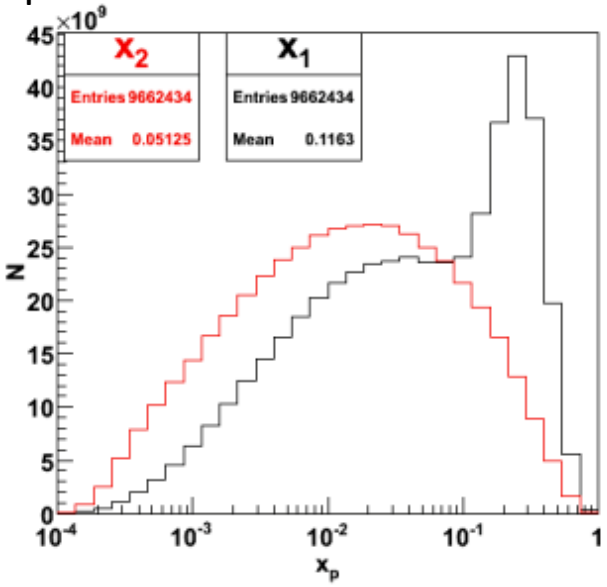


Other ongoing analyses at $\sqrt{s}$ = 510 GeV

- A_{LL} of π^0 or clusters with MPC

RHIC Spin Program White Paper arXiv:1501.01220



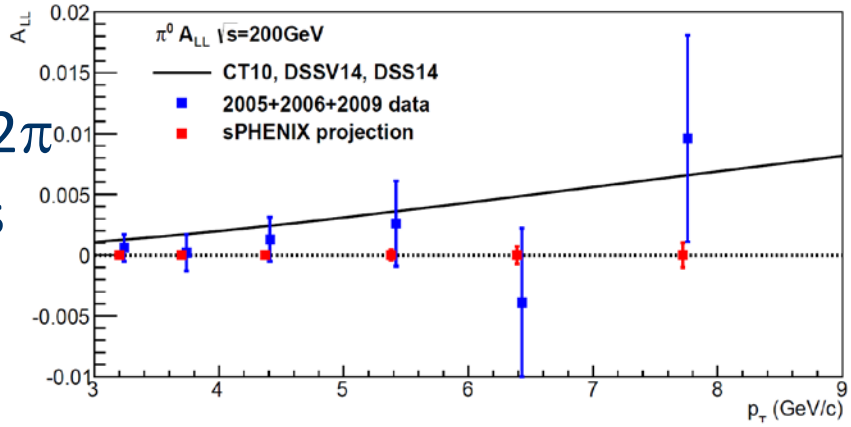


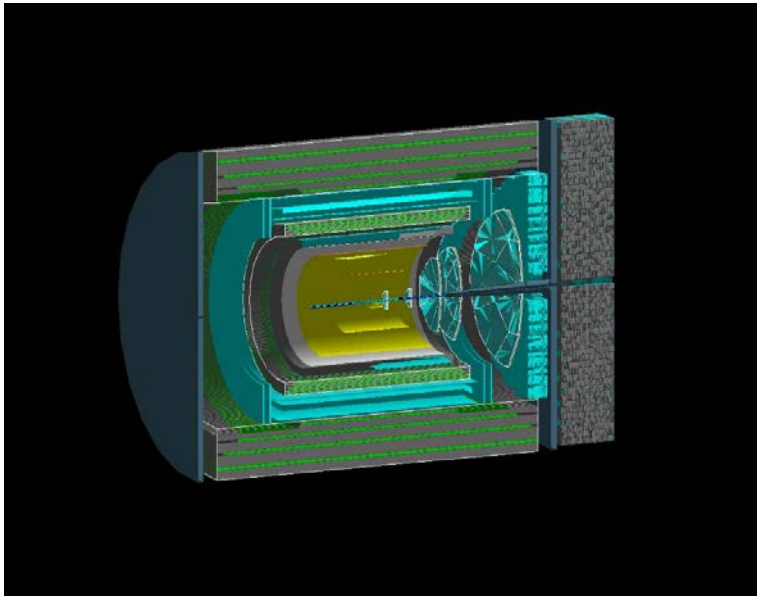
- A_{LL} of charged pions, jet, direct photon
  - analysis ongoing

Future measurements

- sPHENIX (2022-)
  - Tracking, EMCal and Hcal covering $-1 < \eta < 1$ and $\Delta\phi = 2\pi$
  - 70 times of the final statistics of PHENIX
  - Better jet scale uncertainty
  - Improved statistical precision of A_{LL} of pions, jet, and direct photon
- fsPHENIX
  - Forward spectrometer
  - Small *x* pions, jet, and direct photon

π^0 A_{LL} at $\sqrt{s}$ = 510 GeV

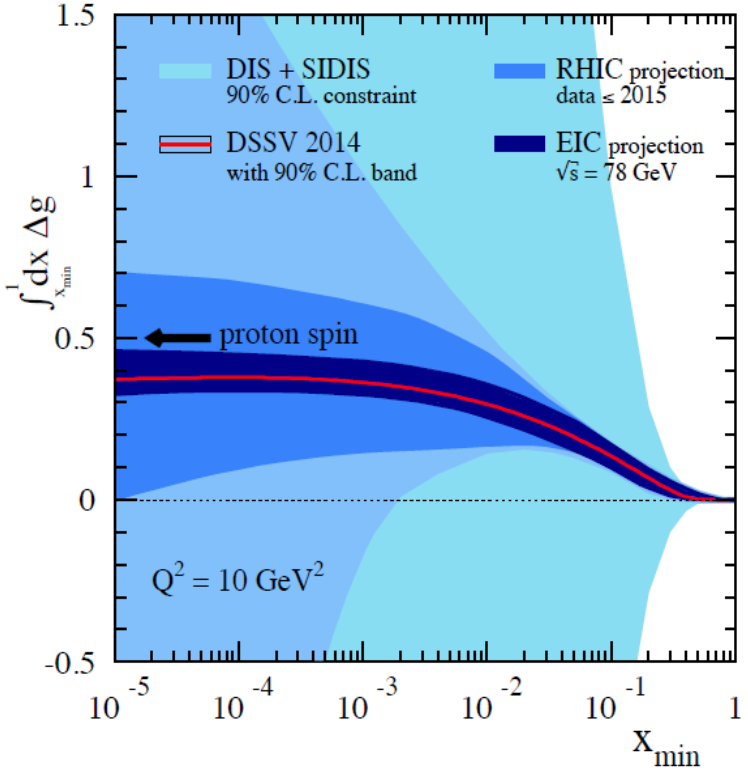




Future measurements

- Towards EIC (Electron-Ion Collider)
  - RHIC projection data $\leq$ 2015
    - Midrapidity jet & π^0
    - Forward π^0
  - EIC projection (2025-)
    - Pol-DIS scaling violation

RHIC Cold QCD Plan for 2017 to 2023
arXiv:1602.03922



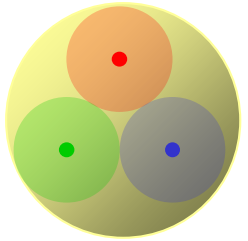
Summary

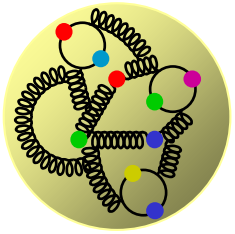
- Gluon polarization, or helicity distribution, has been measured from A_{LL} measurement
  - Positive gluon polarization has been obtained from A_{LL} measurement of jet & π^0 at $\sqrt{s}$ = 200 GeV
- Extension of Bjorken *x* coverage
  - High collision energy $\sqrt{s}$ = 510 GeV
    - π^0 asymmetry at midrapidity
    - Positive A_{LL} measured
    - Charged pions / jet / direct photon results coming soon
  - Forward measurement
    - J/ψ, MPC cluster/π^0, …
  - sPHENIX / fsPHENIX (2022-)
    - Last chance at RHIC
  - Pol-DIS at EIC (2025-)

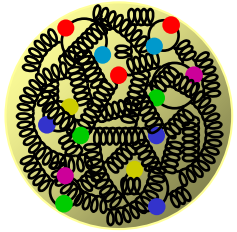
Backup Slides …

Nucleon structure

- Constituent-quark model
  - Quarks with the effective mass (caused by the gluon)
  - Explains the magnetic moment of the nucleons
  - But, the quark spin cannot explain the nucleon spin (“spin puzzle”)
- Quark-gluon model
  - Current quarks and gluon interaction
  - Initial state of high-energy hadron colliders
- Understanding the differences (or gap) of these models
  - Chiral symmetry (breaking)
  - Confinement







Origin of the nucleon spin 1/2

- Expected to be explained by the quark spin (from the constituent quark model)
- Experiments
  - CERN-EMC experiment (polarized DIS experiment)
    - Quark-spin contribution

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$$

    - Combining with neutron and hyperon decay data
    - Total quark spin constitutes a small fraction of the nucleon spin
    - Integration in x = 0 ~ 1 makes uncertainty
  - SLAC/CERN/DESY/JLAB experiments
    - More data to cover wider x region with more precision

x: Bjorken's x
"longitudinal" momentum fraction

- Based on the quark-gluon model

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

Orbital angular momentum
Gluon spin contribution
Quark spin contribution