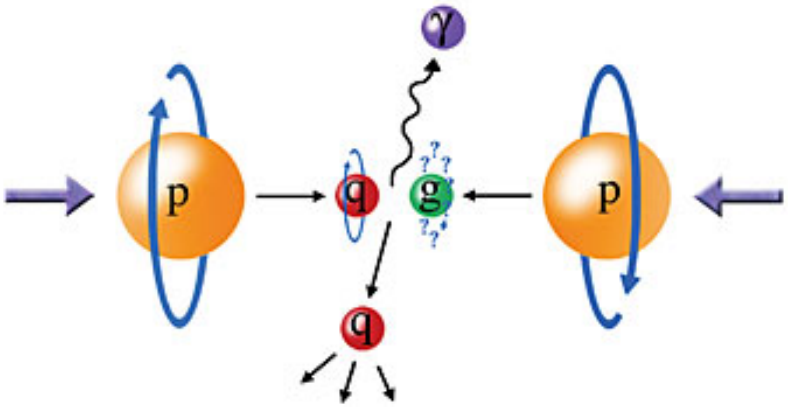
Results from the RHIC Spin Program



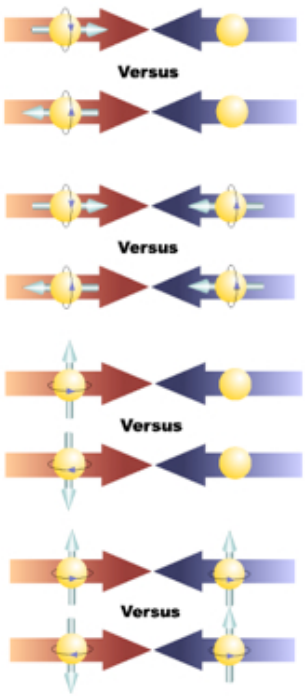
Renee Fatemi, University of Kentucky

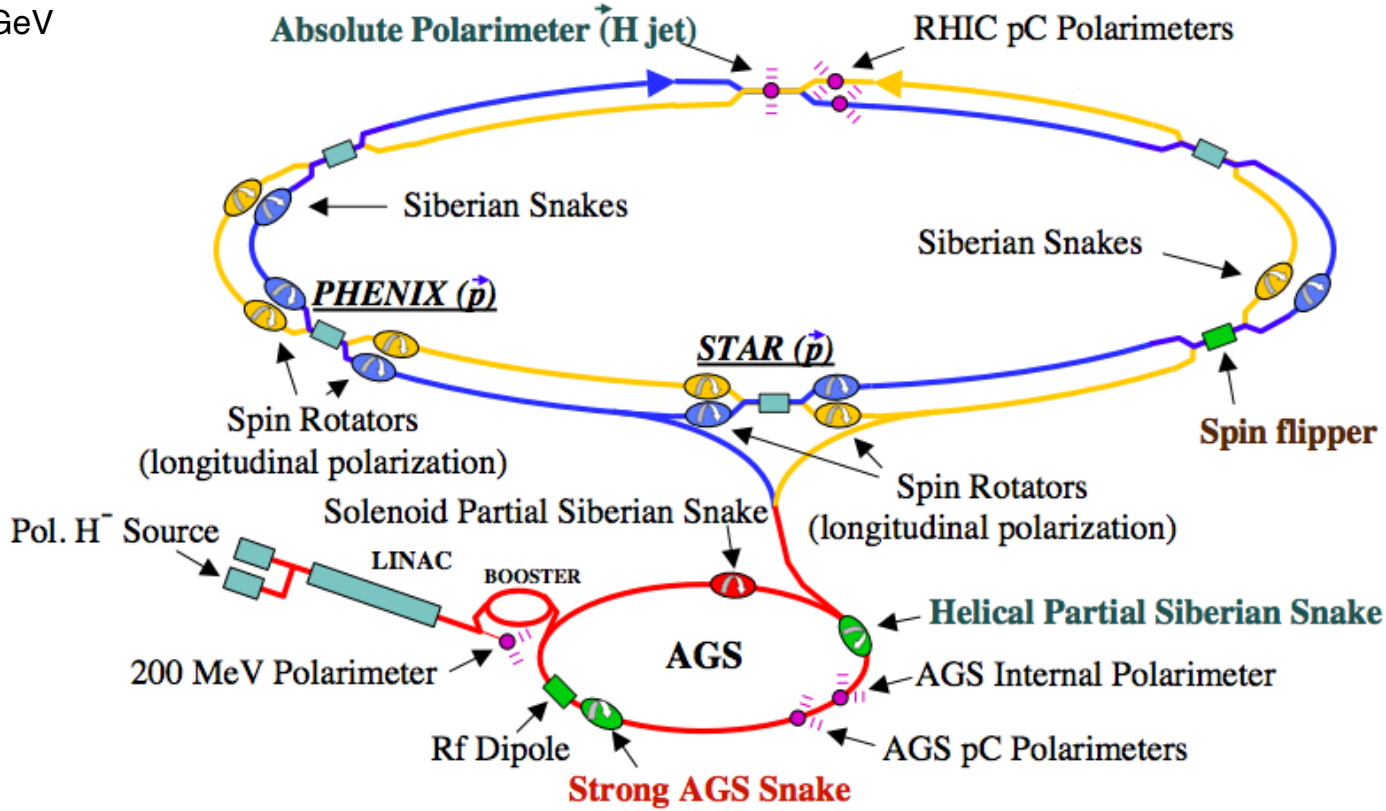
SPIN-2014
Peking University
October 21, 2014

RHIC - Polarized Proton-Proton Collider

Unique opportunities to study nucleon spin properties and spin in QCD,

√s = 62, 200, and 500 GeV





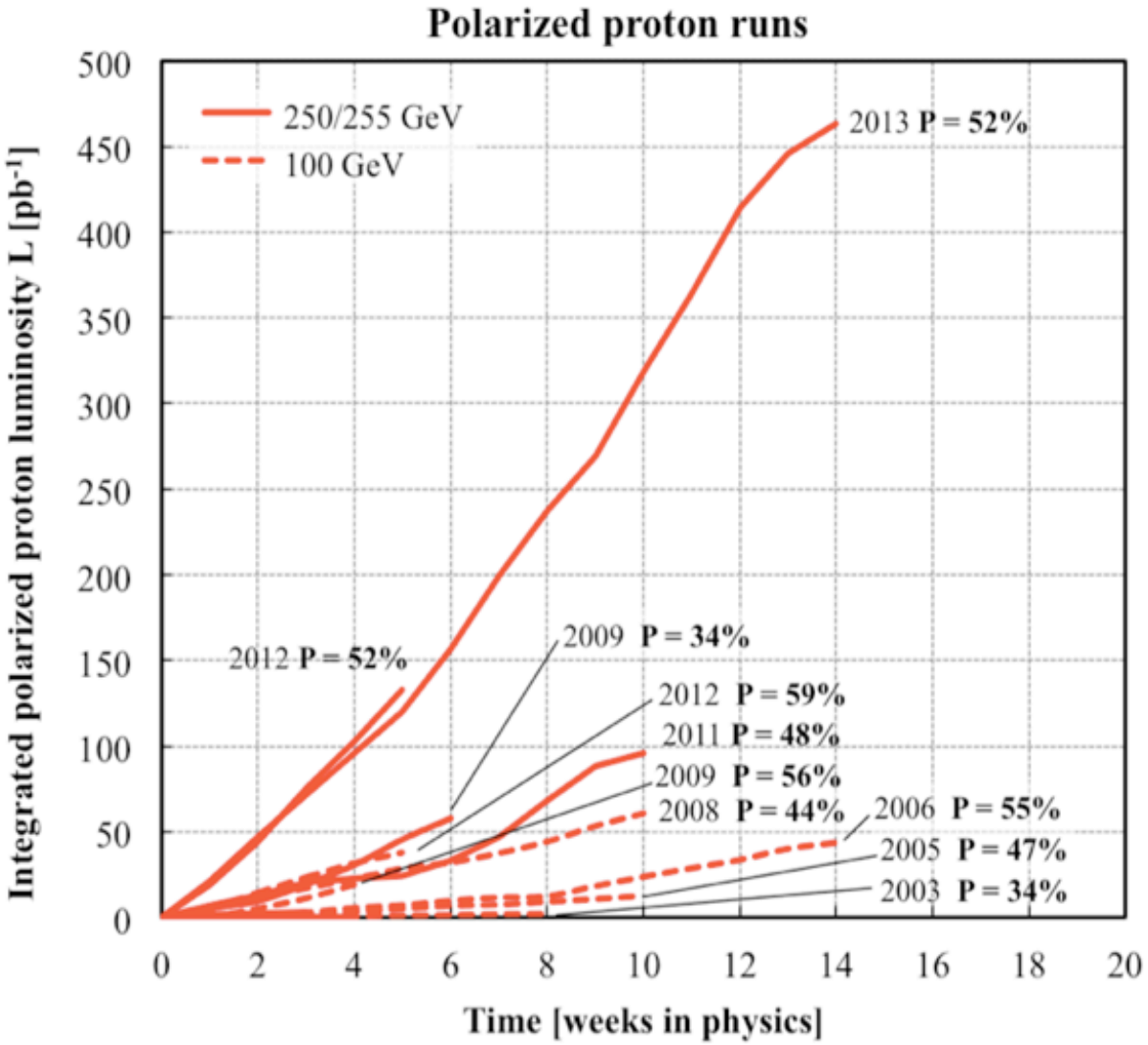
at hard (perturbative) scales with good systematic controls, e.g. from the ~100ns succession of beam bunches with alternating beam spin configurations.

RHIC - Polarized Proton-Proton Collider

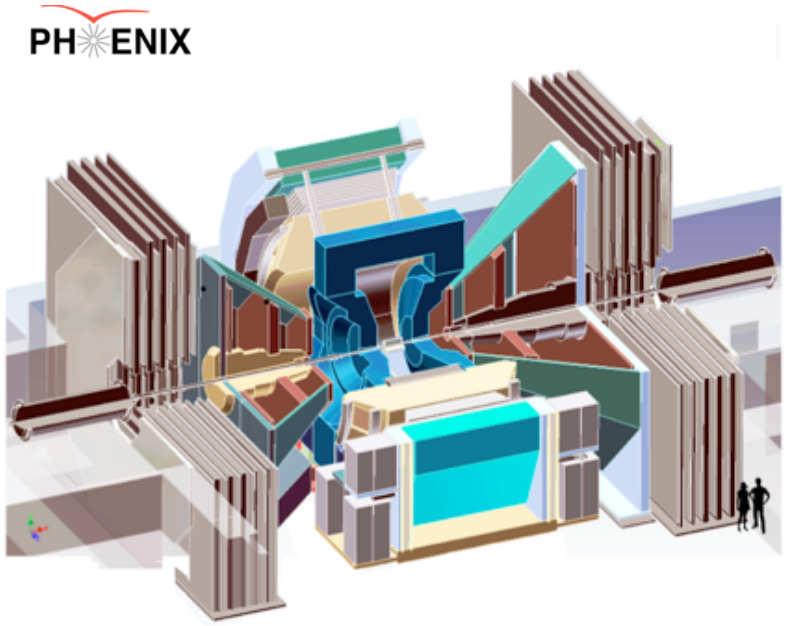
Unique opportunities to study nucleon spin properties and spin in QCD

Longitudinal data	**STAR**
√s = **200 GeV**	
2005	3 pb^{-1}
2006	7 pb^{-1}
2009 (2015)	35 pb^{-1} (50 pb^{-1})
√s = **500 GeV**	
2009	10 pb^{-1}
2011	12 pb^{-1}
2012	82 pb^{-1}
2013	300 pb^{-1}

Transverse data	
√s = **200 GeV**	
2006	9 pb^{-1}
2008	8 pb^{-1}
2012 (2015)	22 pb^{-1} (50 pb^{-1})
√s = **500 GeV**	
2011 (2016)	25 pb^{-1} (400 pb^{-1})

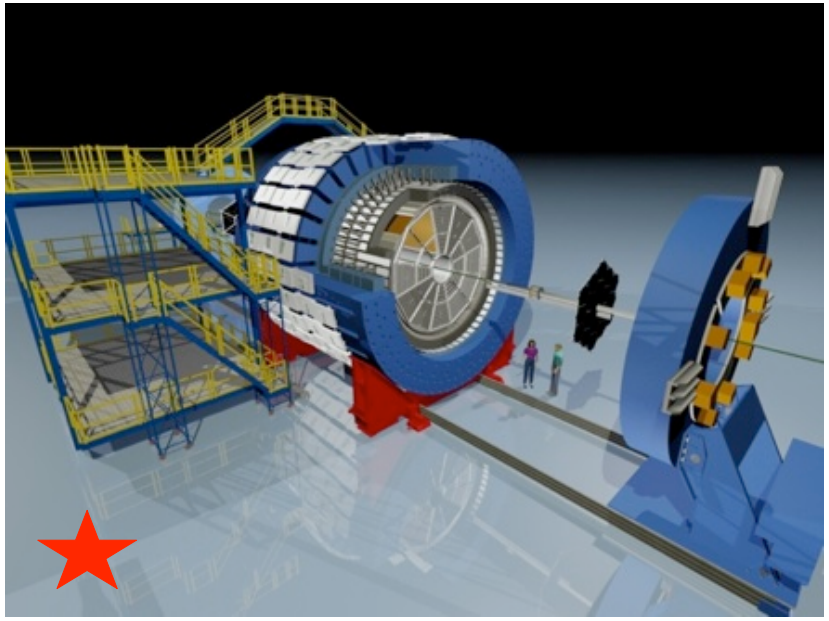


RHIC - The Current Main Experiments



PHENIX "DNA":

- high resolution and rate capabilities,
- central arms $|\eta|<0.35, \Delta\phi\sim\pi$ with key strengths for π^0 and η
- forward muon arms $1.2<|\eta|<2.4$



STAR "DNA":

large acceptance and low mass,

full acceptance and PID for $|\eta|< 1$, $\Delta\phi\sim2\pi$,

complemented with forward E.M. calorimetry

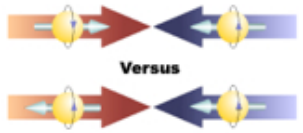
key strengths for jets and correlations

Vigorous ongoing upgrade programs, e.g. PHENIX FVTX, MPC-EX

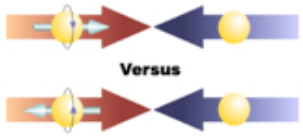
STAR FMS-PS, Roman Pots

The RHIC-Spin Program - Key Questions

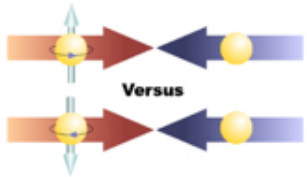
- *What is the polarization of gluons in the polarized proton?*



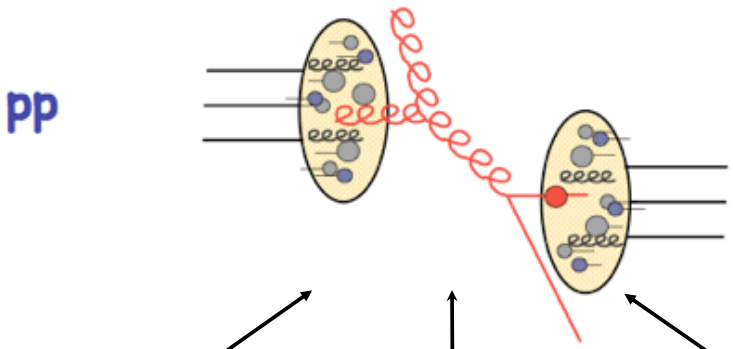
- *What is the polarization of the light quarks and anti-quarks?*

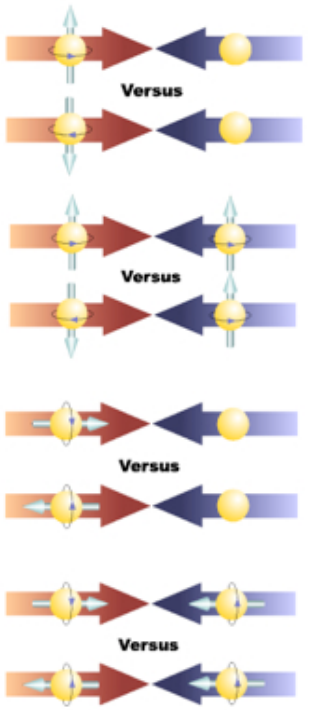


- *Does the Sivers' function change sign in proton-collisions compared to DIS?*
- *What are the quark transversity distributions?*
- *What is the origin of large forward A_N?*



The RHIC-Spin Program - Approach





$q, \bar{q}, g, \Delta q, \Delta \bar{q}, \Delta g$ $\quad \hat{\sigma}, \Delta\hat{\sigma}$ $\quad q, \bar{q}, g, \Delta q, \Delta \bar{q}, \Delta g$ $\longleftrightarrow$

$\sqrt{s}$ = 62 - 500 GeV

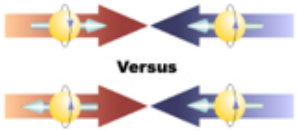
Theory: perturbative QCD evaluations, typically at next-to-leading order,

Experiment: observe cross sections (asymmetries) of (hadronized) final states,
test applicability of theoretical framework,
extend measurements to correlated and selective final states.

Combination: insight in $q, \bar{q}, g, \Delta q, \Delta \bar{q}, \Delta g$

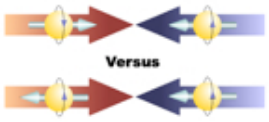
Complementary insights from measurements of A_{LL}, A_L, A_N, D_{LL}, inclusive probes, correlations ...

Gluon Polarization



Gluon Polarization at RHIC

Measure double longitudinal spin asymmetries and establish the factorized framework,



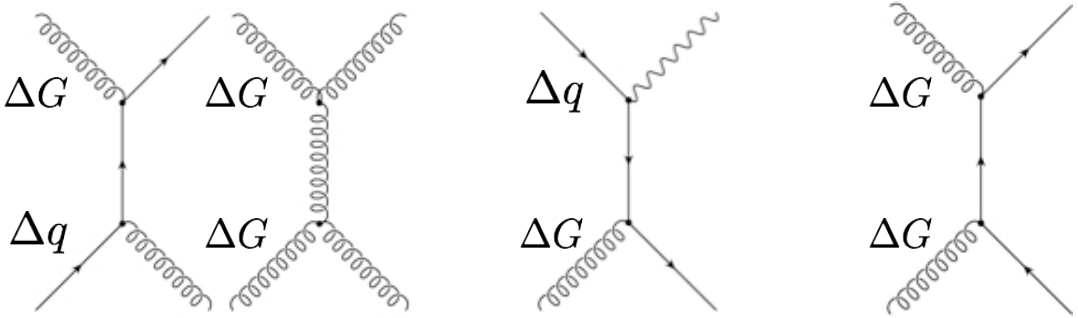
$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \stackrel{?}{=} \sum_{f=q,g} \frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2} \otimes \hat{a}_{LL} \otimes (\text{fragmentation functions})$$

Start with abundantly produced pions or jets at mid-rapidity, where the partonic asymmetries are sizable,

Gluon-gluon scattering contribution dominates up to jet $p_T \sim 8$ GeV, where quark-gluon scattering takes over,

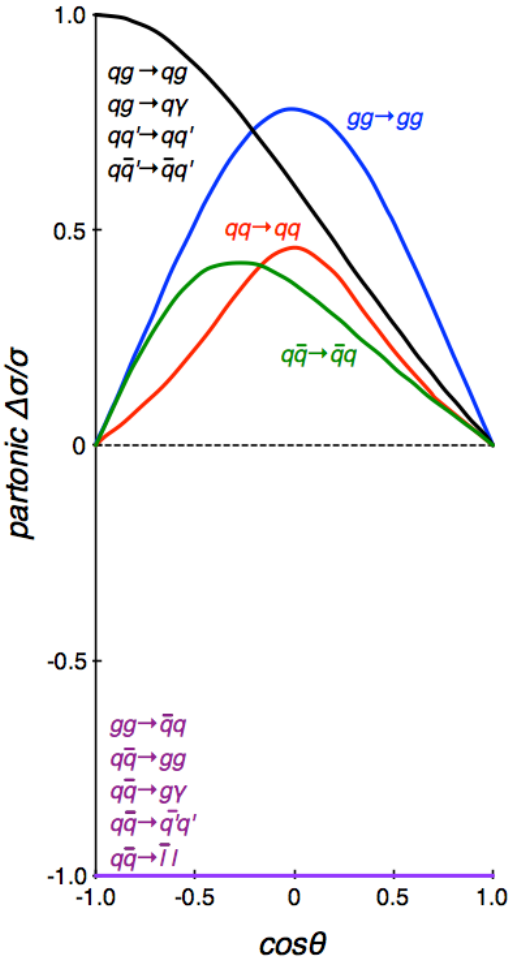
Path: precision, coverage, sensitivity to initial kinematics, and selective probes.

$\vec{p}+\vec{p} \to \text{jet(s)} + X$ $\quad$ $\vec{p}+\vec{p} \to \gamma + \text{jet}$ $\quad$ $\vec{p}+\vec{p} \to c\bar{c}, b\bar{b} + X$



$$\mathcal{L} \simeq 3 - 8 \cdot 10^2\,\text{pb}^{-1}, \quad P = 0.4 - 0.7, \quad \sqrt{s} = 200 - 500\,\text{GeV}$$

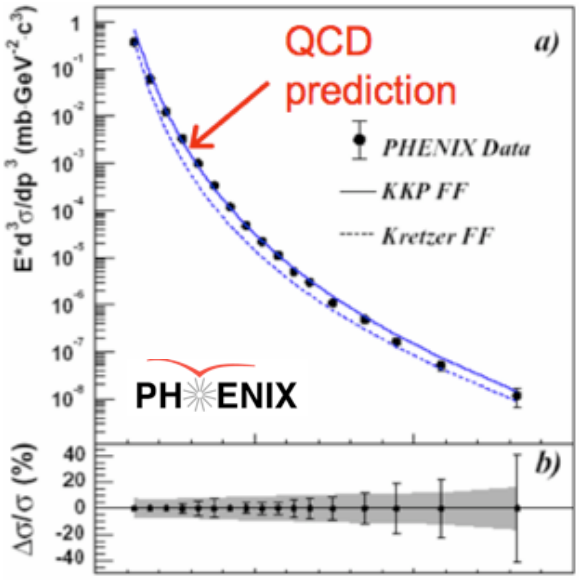
time

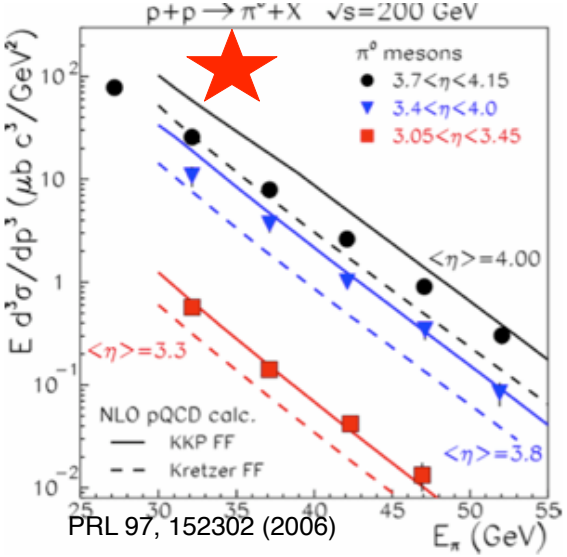


Gluon Polarization at RHIC - Cross Sections

pions

PRL 91, 241803 (2003)

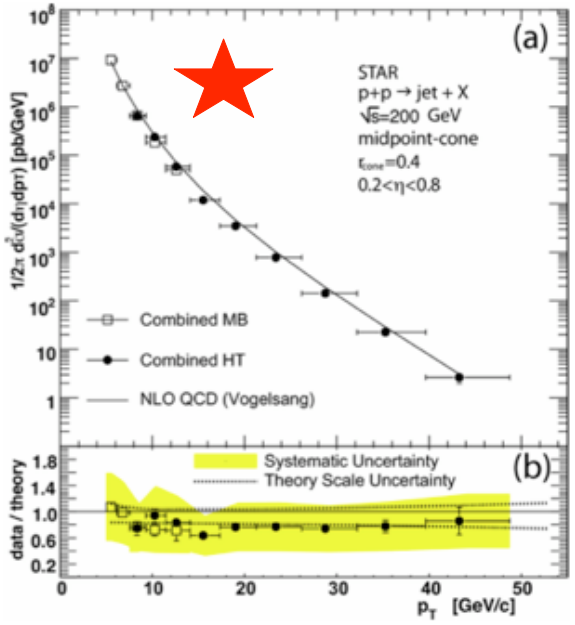




PRL 97, 152302 (2006)

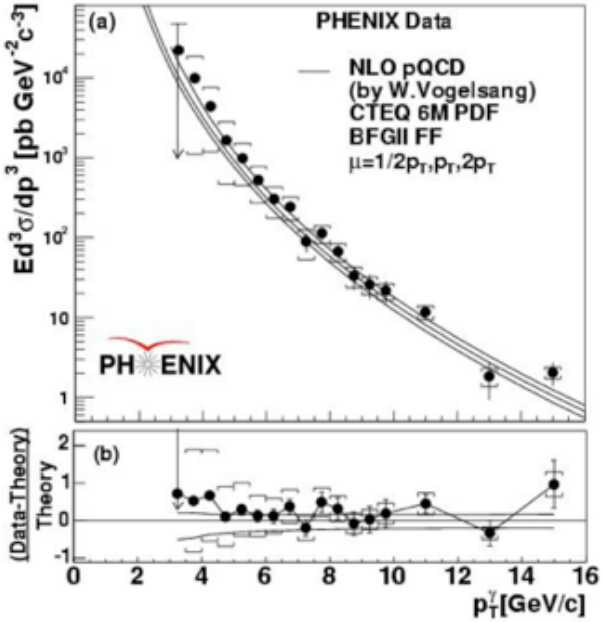
jets

PRL 97, 252001 (2006)



photons

PRL 98, 012002 (2007)



Good agreement between data and NLO pQCD theory for mid-rapidity pions, jets, and photons;

Start to see a break-down at *very* forward rapidities, as expected;

W and *Z* cross sections later in this talk;

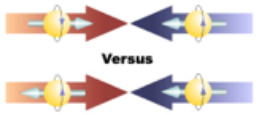
Support a NLO pQCD framework for interpretation.

Gluon Polarization at RHIC - Asymmetry A_{LL}

Measurement:

- Detect and reconstruct particle, jet,
- Extract beam-spin dependent yields,
- Measure relative luminosity, beam polarization
- Evaluate double beam-helicity asymmetry

$$A_{\mathrm{LL}} = \frac{1}{P^2} \cdot \frac{N^{++} - R \cdot N^{+-}}{N^{++} + R \cdot N^{+-}}$$

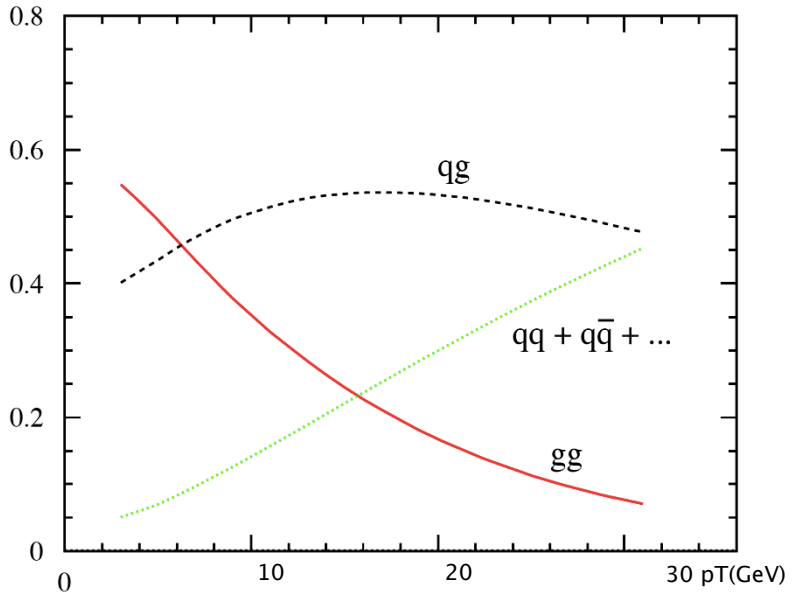


Advantages:

- High yields of neutral pions, jets at RHIC,
- Relatively straightforward triggering,
- Relatively simple reconstruction,

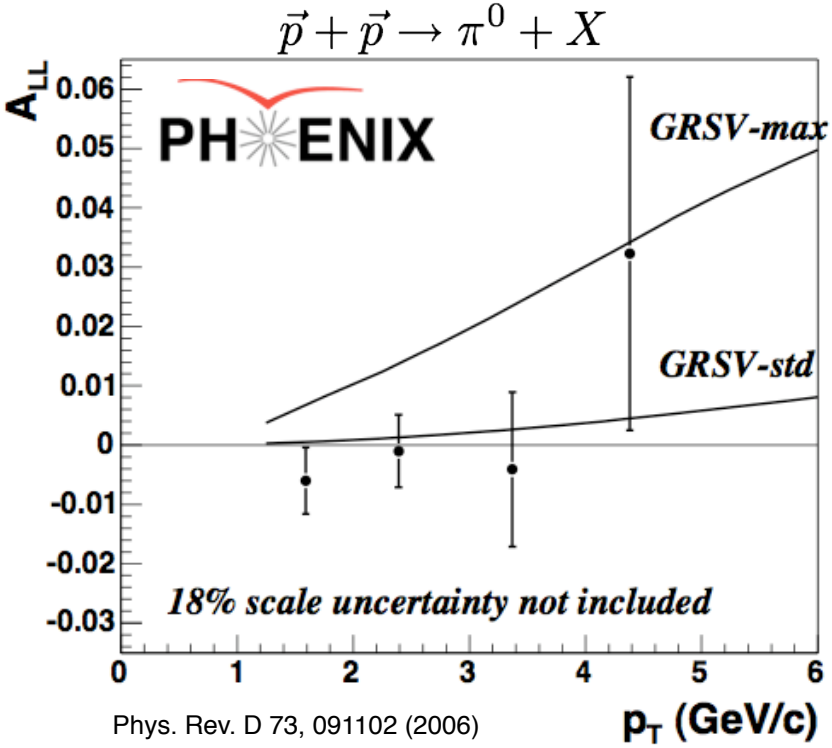
Disadvantages:

- Contributions from several sub-processes,
- Wide x_g range sampled for each fixed p_T
- x_g, $x_q \sim p_T/\sqrt{s} \cdot \exp(-\eta)$

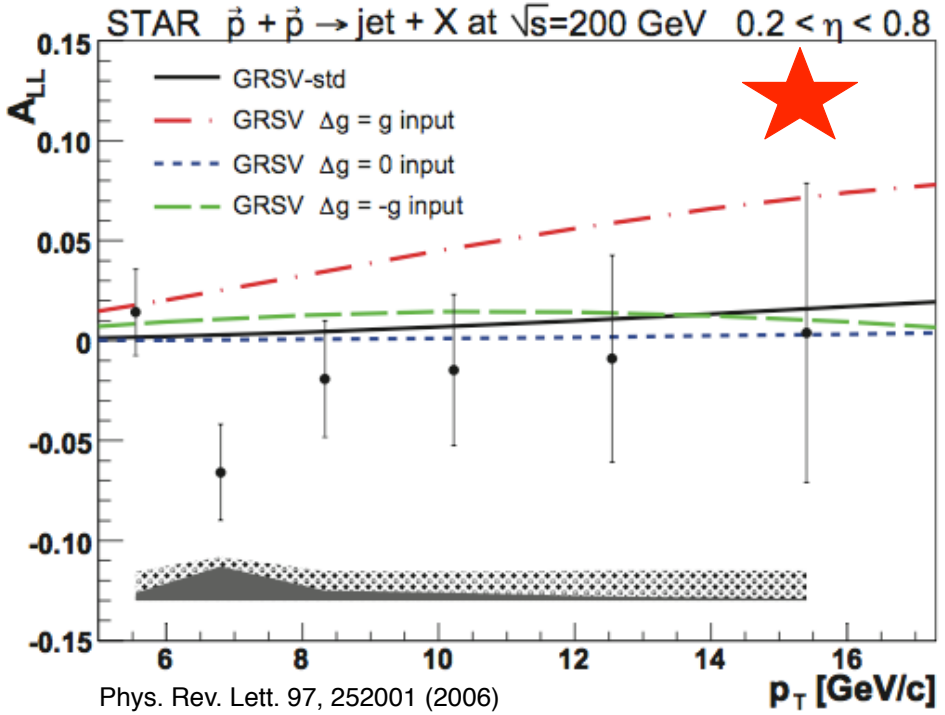


gluon-gluon and quark-*gluon* scattering contributions dominate.

Gluon Polarization - *Initial* A_{LL} from RHIC



Phys. Rev. D 73, 091102 (2006)



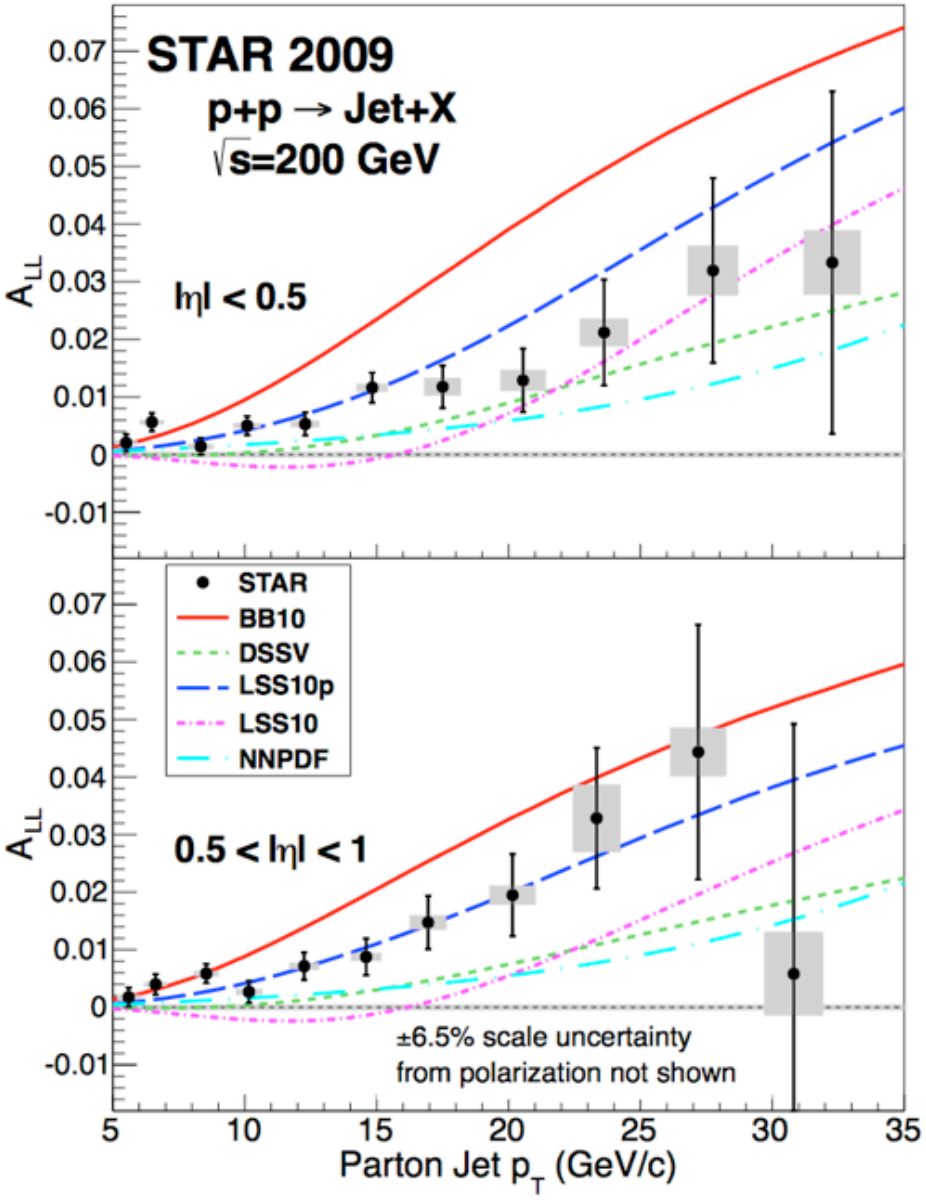
Phys. Rev. Lett. 97, 252001 (2006)

Data disfavor maximal gluon polarization, *as expected,*

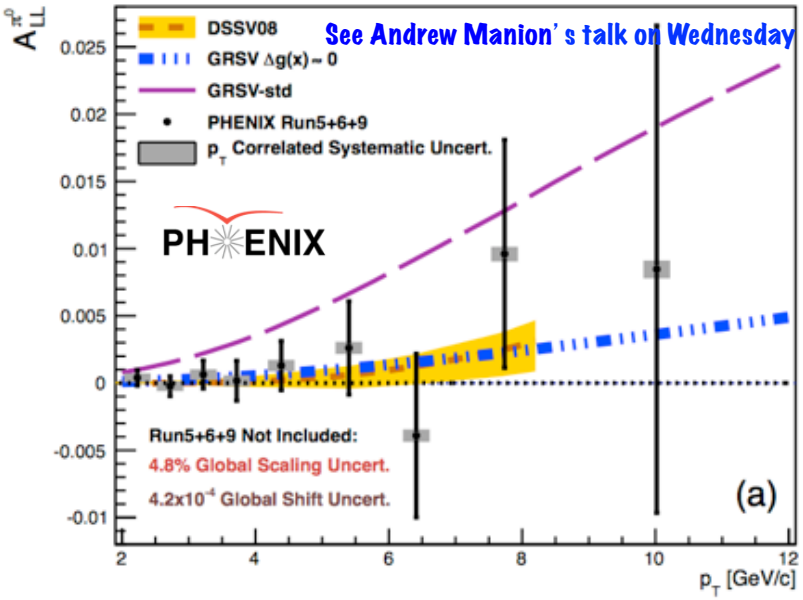
Clear need for *precision.* Main focus of experiment follow-up in 2005, 2006, **2009**, ...

Gluon Polarization - *Precision* A_{LL} from RHIC

ArXiv:1405.5134



Phys. Rev. **D 90**, 012007 (2014)



See Andrew Manion's talk on Wednesday

Significant advance:

about an order in precision,

two to three times the kinematic range,

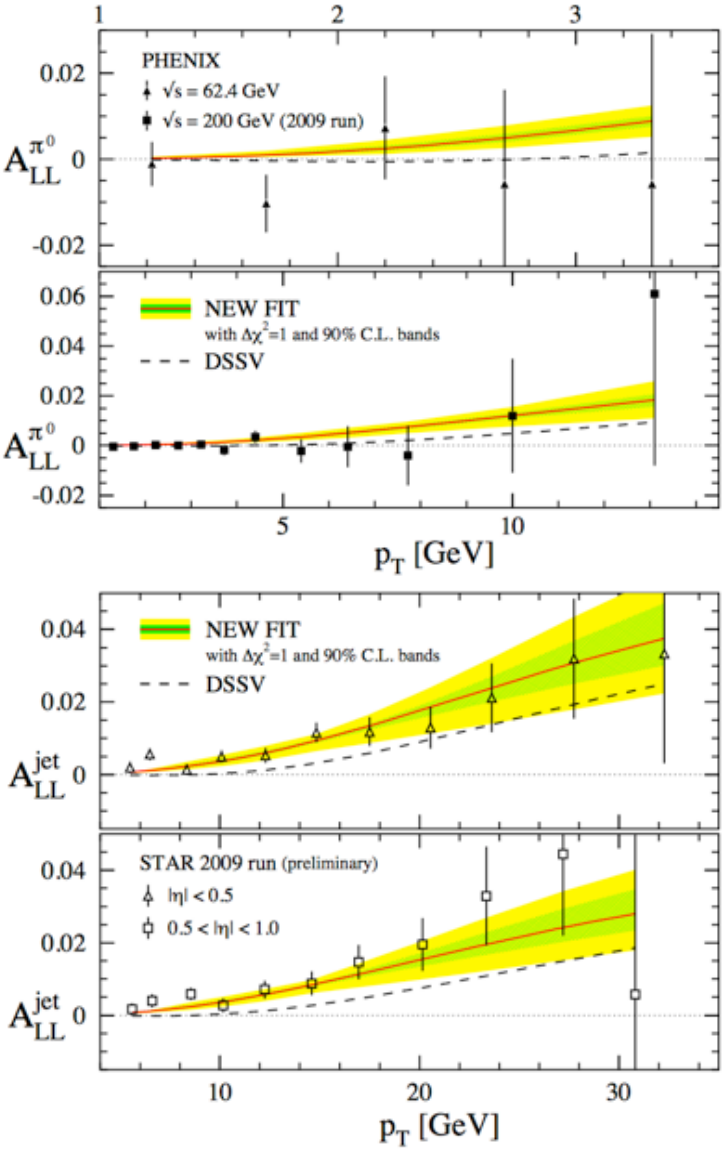
initial sensitivity to different x_g from rapidity dependence

A_{LL} is positive for large p_T, indicative of *positive gluon polarization*.

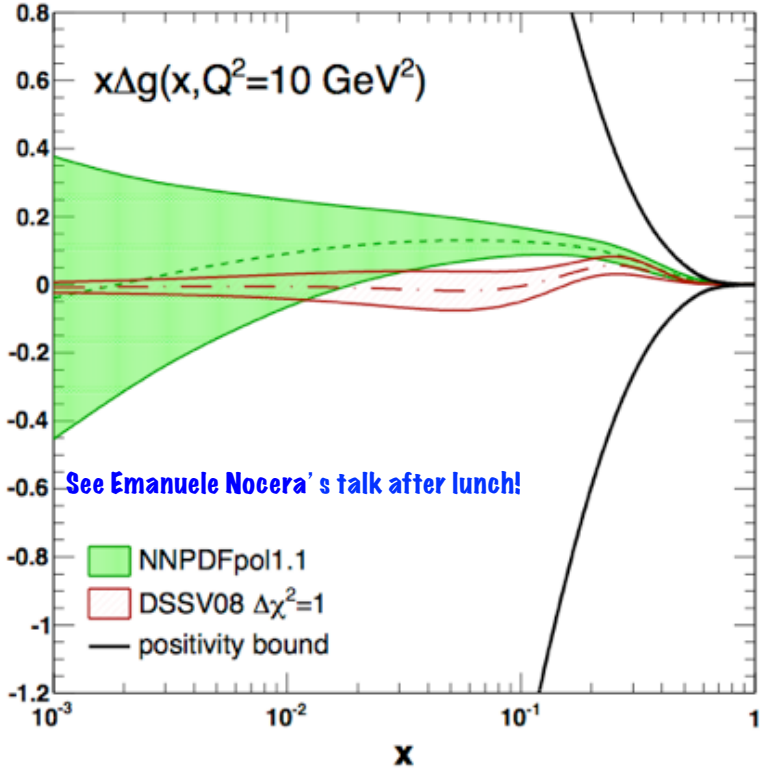
Gluon Polarization - RHIC Impact

Both the DSSV and the NNPDF groups use RHIC data in their latest PDF fits,

DSSV, Phys.Rev.Lett. 113, 012001



NNPDF, Nucl. Phys. B887 (2014) 276



RHIC data, in particular on jets, currently drive the constraints on ΔG in both fits,

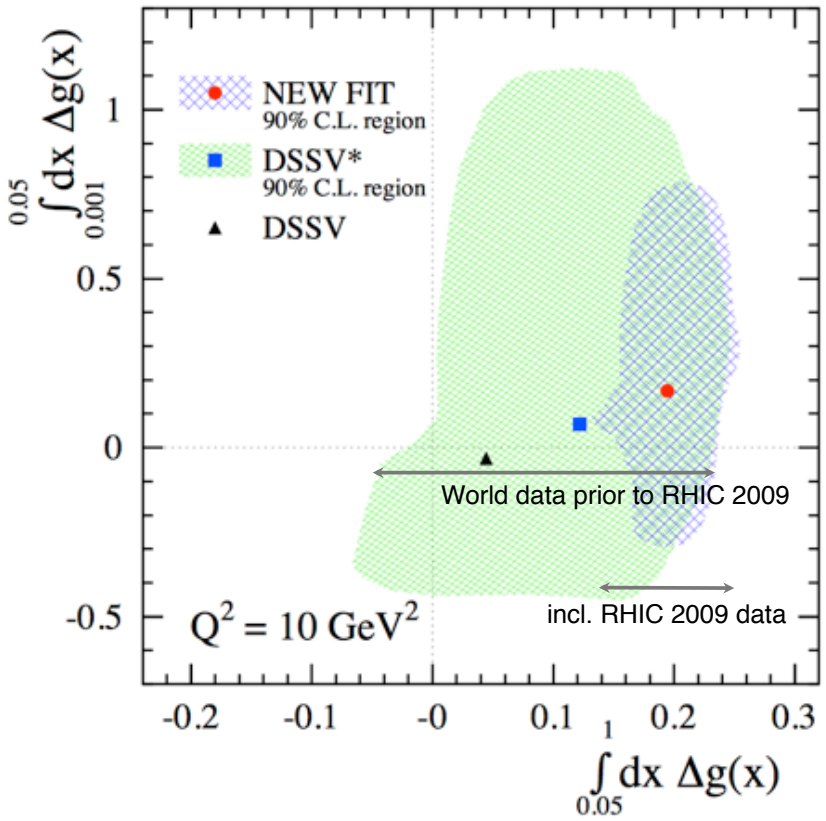
DSSV: $0.19^{+0.06}_{-0.05}$ at 90% C.L. for x > 0.05

NNPDF: 0.23 ± 0.07 for 0.05 < x < 0.5

i.e. evidence for *positive gluon polarization in this kinematic range and at* 10 GeV^2.

Gluon Polarization at RHIC - What is next?

DSSV, Phys.Rev.Lett. 113, 012001



Extend sensitivity to *smaller* x_g

forward rapidity, $x_g \sim \exp(-\eta)$,

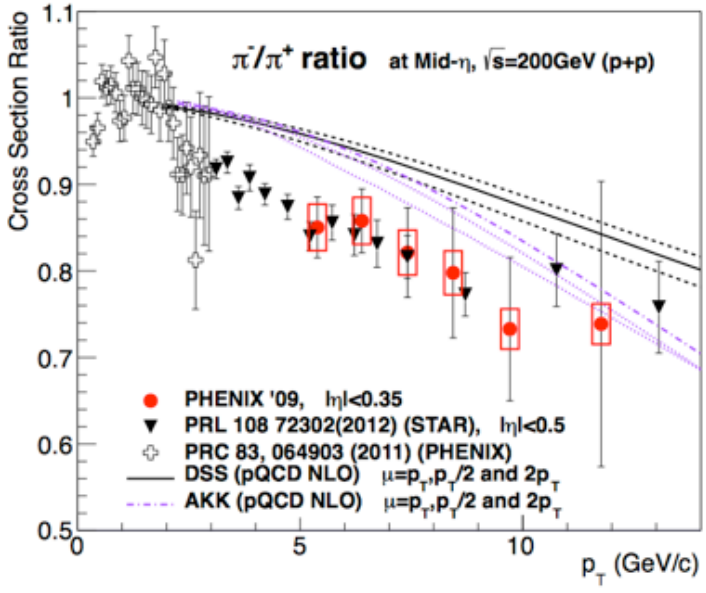
$\sqrt{s} = 500$ GeV data, $x_g \sim 1/\sqrt{s}$

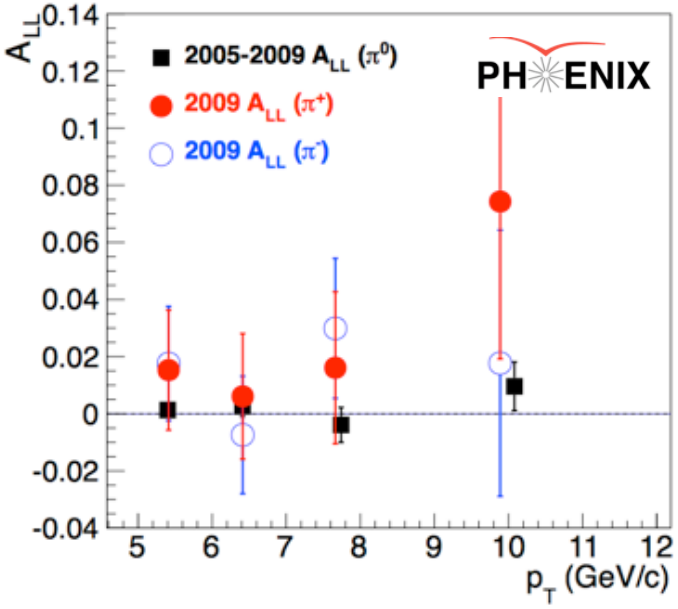
Further *precision* from jet and neutral pion probes, and

from *complementary* probes

Gluon Polarization - other channels, smaller x_g

A look at *charged* pion data:



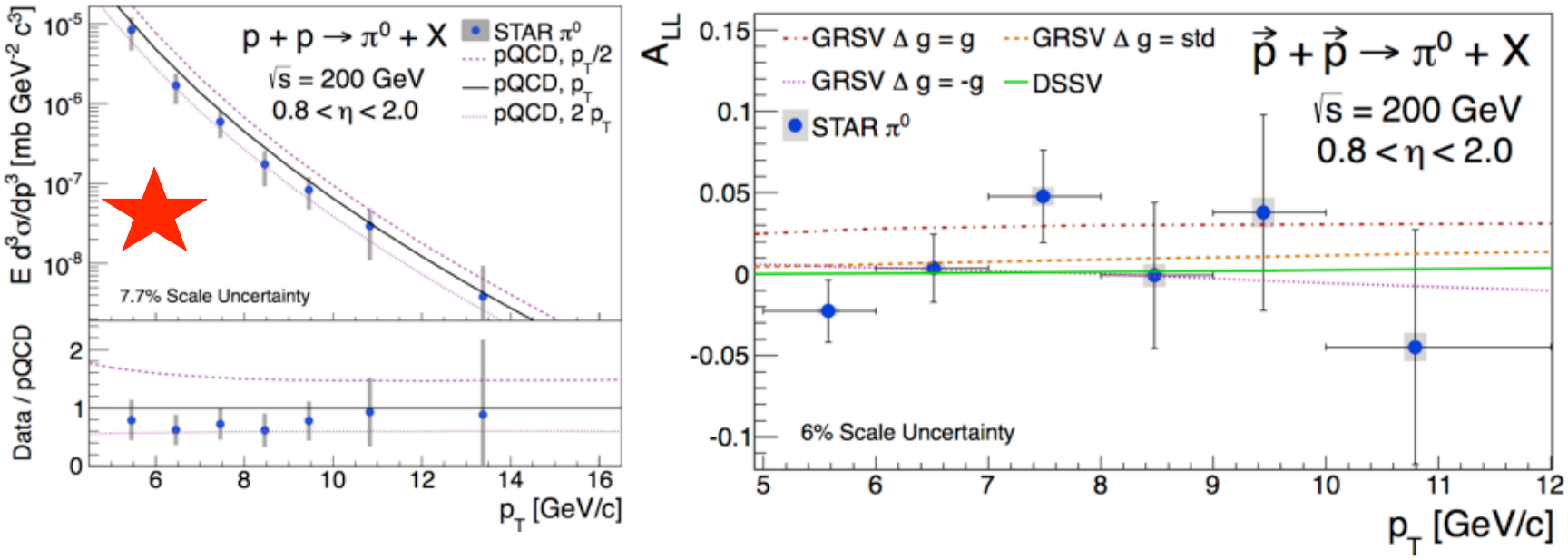


Proof-of-concept: sensitivity to and through fragmentation, albeit limited in A_{LL}

Gluon Polarization - other channels, smaller x_g

Initial neutral pion data, 4.8 pb^{-1} at $\sqrt{s}$ = 200 GeV, at more forward rapidity:

Phys.Rev. D89 (2014) 1, 012001



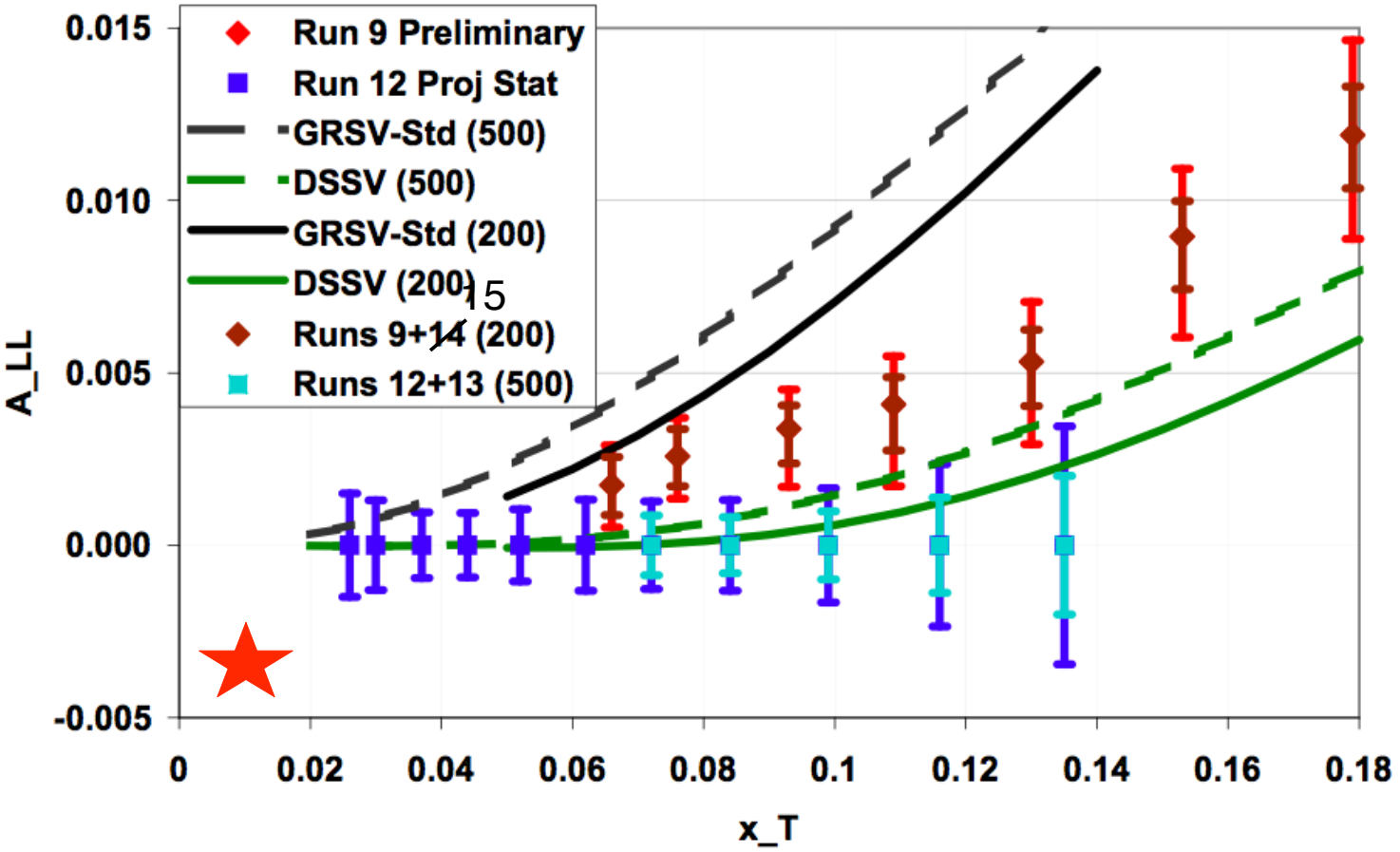
Proof-of-concept; needs further precision and $\sqrt{s}$ = 500 GeV and, eventually, upgrades.

Tomorrow's parallel session V, S2 will feature all of this and more from both experiments:

RHIC top-energy inclusive jet and pion data - Zilong Chang, Inseok Yoon

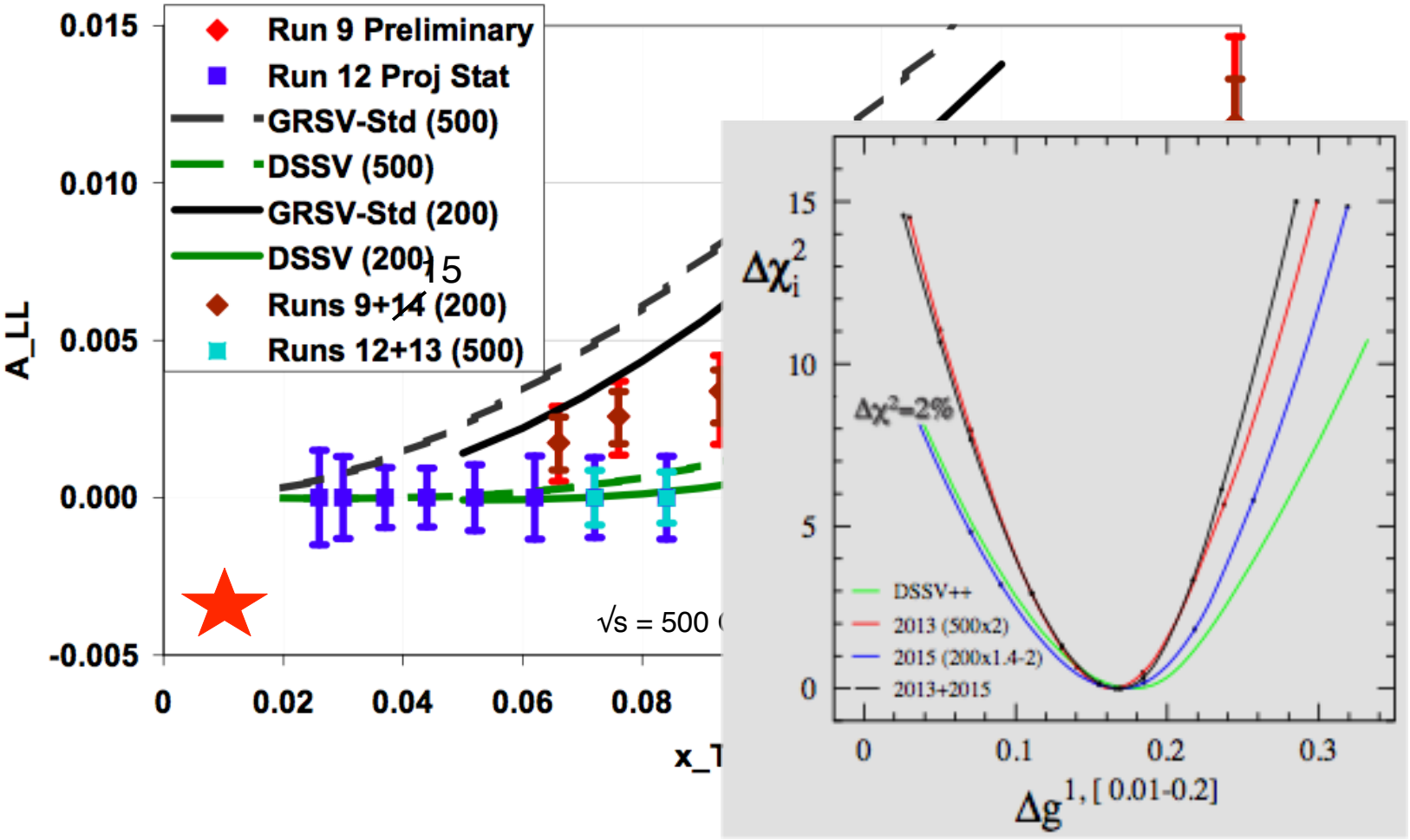
RHIC forward data on pions and J/psi - Christopher Dilks, Haiwang Yu

Gluon Polarization - What impact to expect near-term?



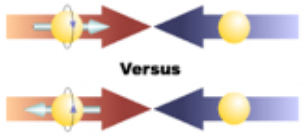
Inclusive jets are not the only probe, but will certainly remain important,

Gluon Polarization - What impact to expect near-term?

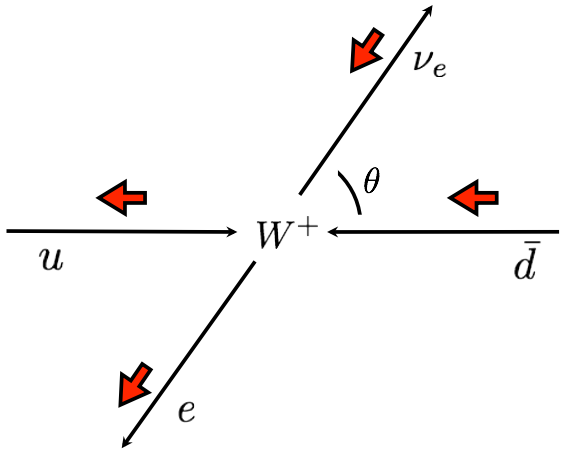


Inclusive jets are not the only probe, but will certainly remain important,
Their impact can be, and has been, quantified - expect at least 40%,
Other probes can only improve this further!

Quark Polarization



Quark Polarization at RHIC



√s = 500 GeV above W production threshold,

Experiment Signature:
large p_T lepton, missing E_T

Experiment Challenges:
charge-ID at large |rapidity|
electron/hadron discrimination
luminosity hungry!

$$\Delta\sigma^{\mathrm{Born}}(\vec{p}p \to W^+ \to e^+\nu_e) \propto -\Delta u(x_a)\bar{d}(x_b)(1+\cos\theta)^2 + \Delta\bar{d}(x_a)u(x_b)(1-\cos\theta)^2$$

Spin Measurements:

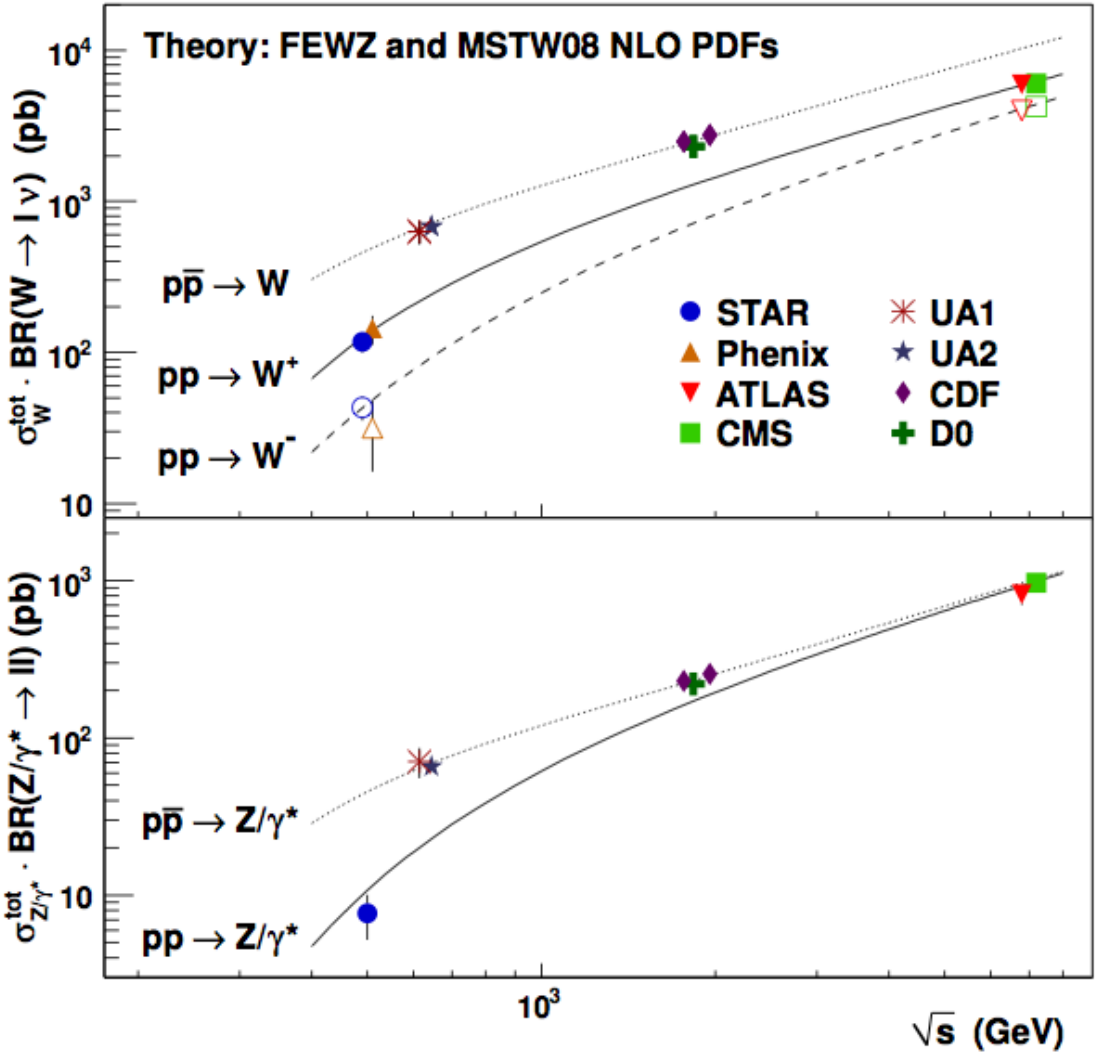
$$A_L(W^+) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} = \begin{cases} -\dfrac{\Delta u(x_a)}{u(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{d}(x_a)}{\bar{d}(x_a)}, & x_b \to 1 \end{cases}$$

Initial mid-rapidity data in 2009,

$$A_L(W^-) = \begin{cases} -\dfrac{\Delta d(x_a)}{d(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{u}(x_a)}{\bar{u}(x_a)}, & x_b \to 1 \end{cases}$$

Analysis tour-de-force for both experiments!

Quark Polarization at RHIC - Cross Sections



PHENIX: first W^+ and W^- production cross sections in proton-proton collisions, Phys.Rev.Lett. **106** (2011) 062001,

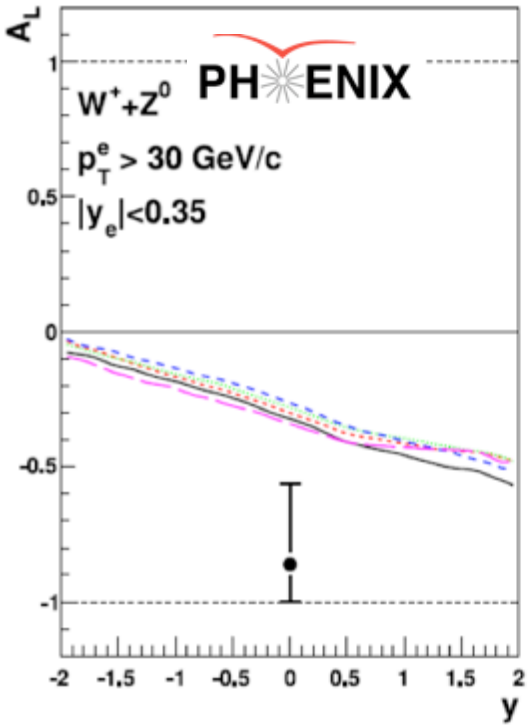
STAR: Initial NC cross section at RHIC, confirmation of PHENIX CC cross section measurements, Phys. Rev. **D85** (2012).

Data are well-described by NLO pQCD theory (FEWZ + MSTW08),

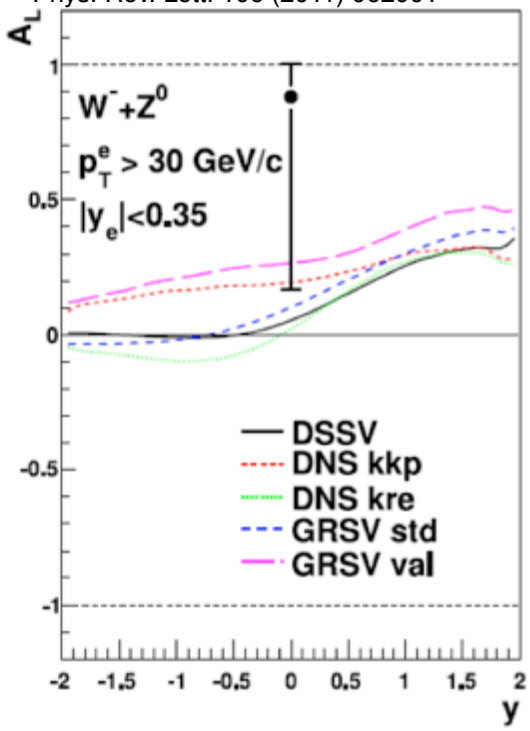
Support NLO pQCD interpretation of the asymmetry measurements,

Aside, future ratio measurements may provide insights in unpolarized light quark distributions

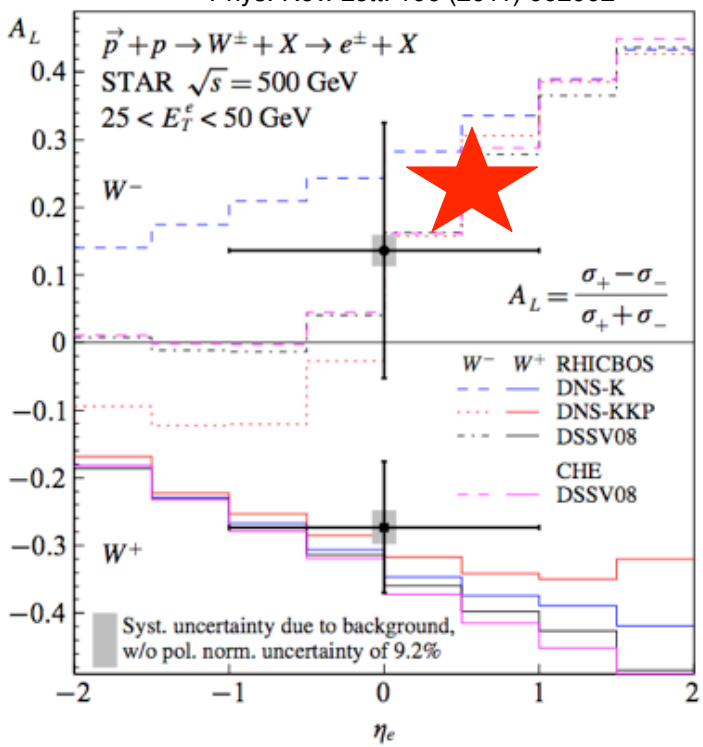
Quark Polarization - *Initial* A_L from RHIC



Phys. Rev. Lett. 106 (2011) 062001



Phys. Rev. Lett. 106 (2011) 062002

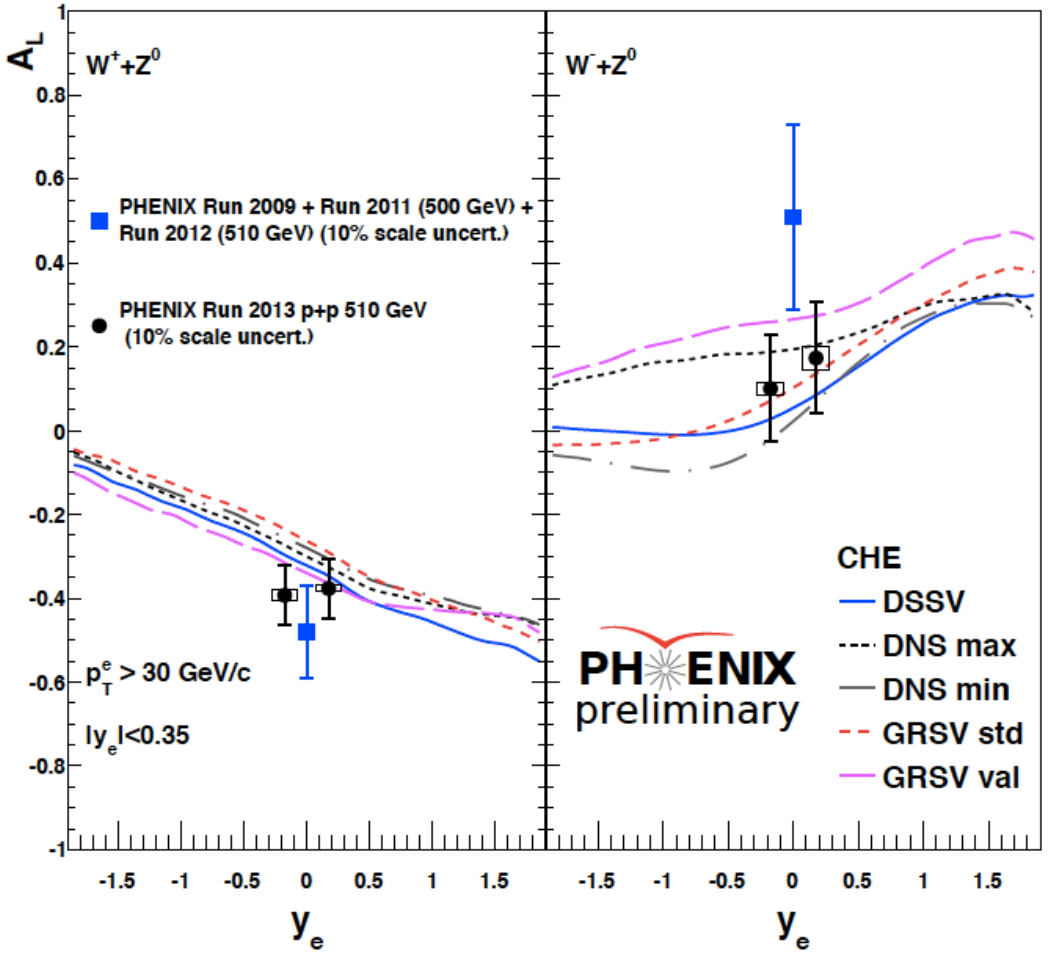


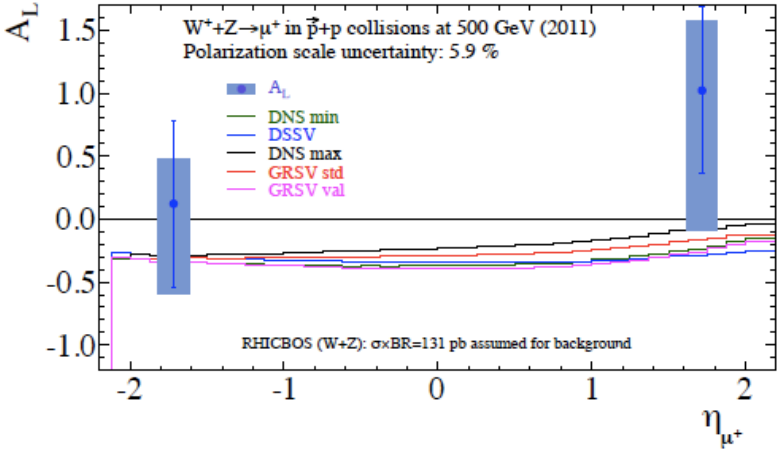
Initial mid-rapidity decay electron and positron measurements,

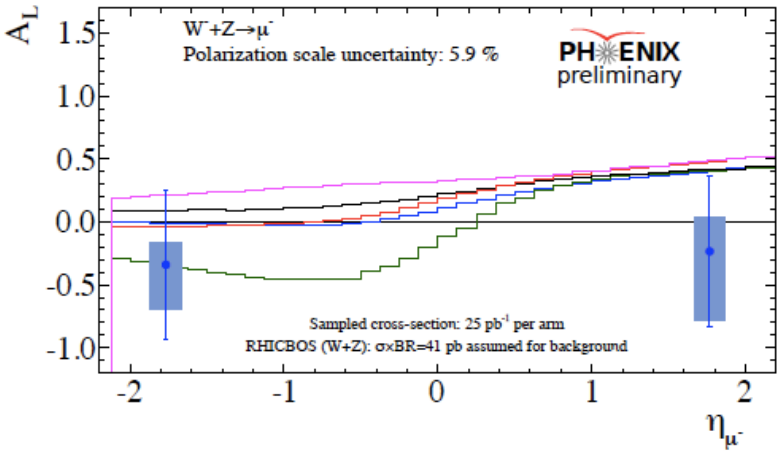
Confirm NLO polarized expectations, but do not discriminate,

Clear need for *precision.* Main focus of experiment follow-up in 2011, 2012 and **2013**

Quark Polarization - *More Precise* A_L from RHIC

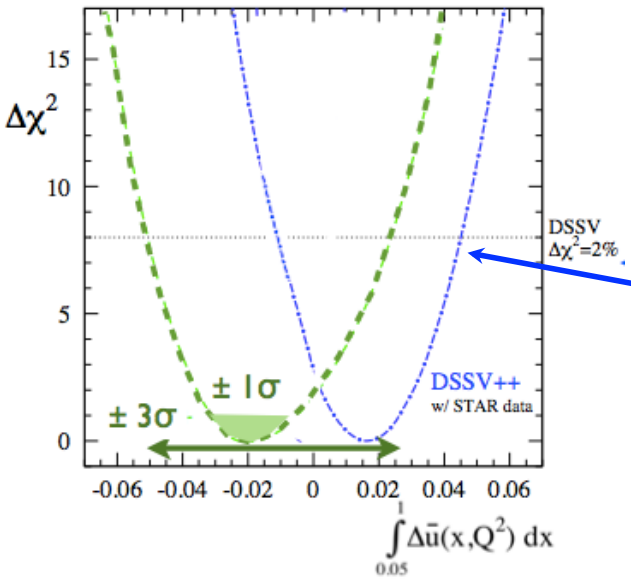


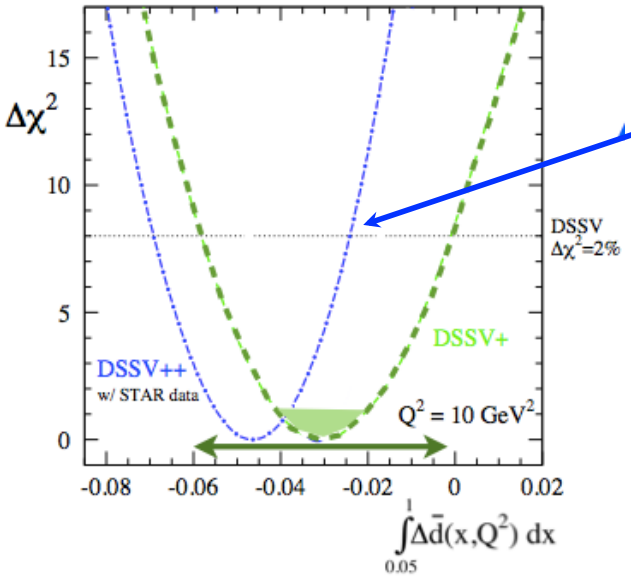


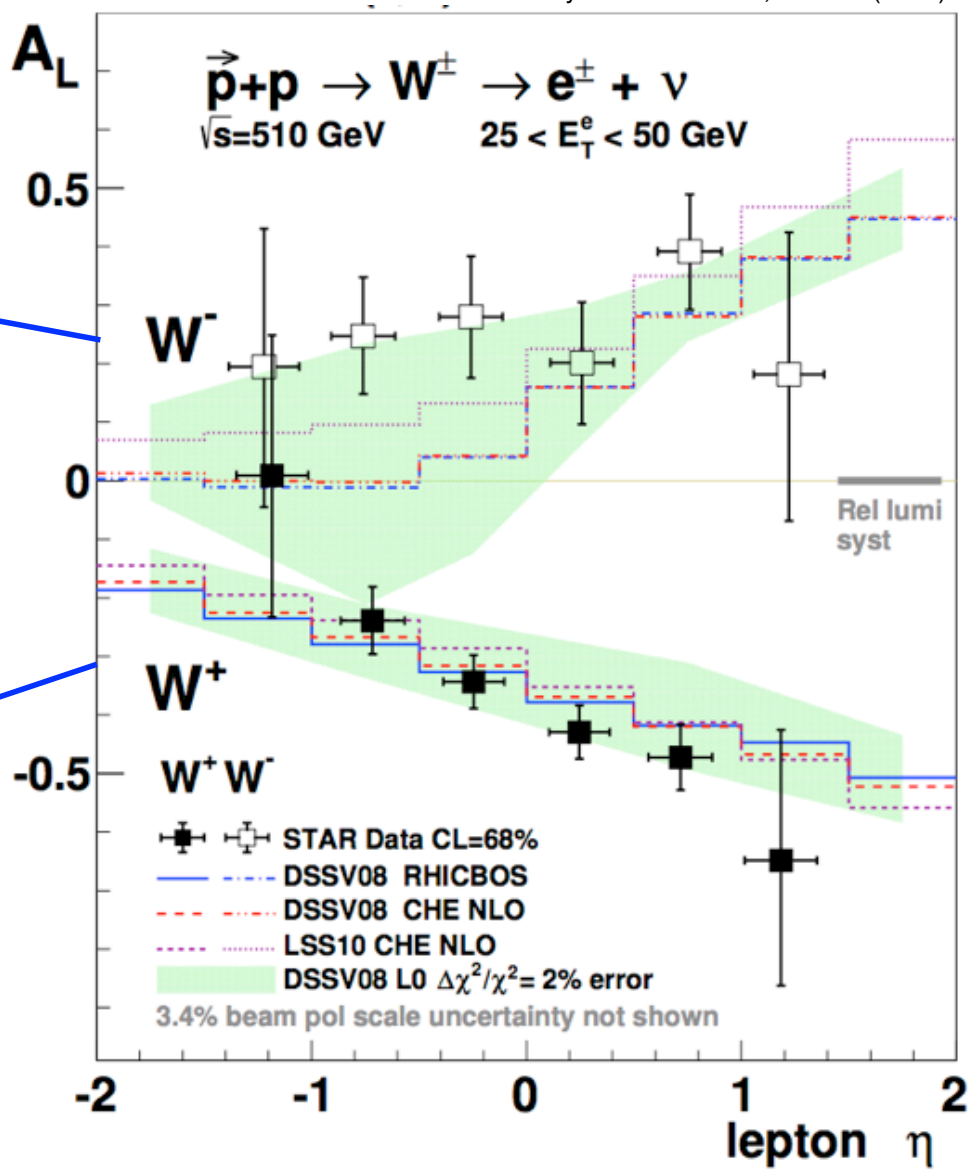


Quark Polarization - *More Precise* A_L from RHIC

Phys. Rev. Lett. 113, 072301 (2014)

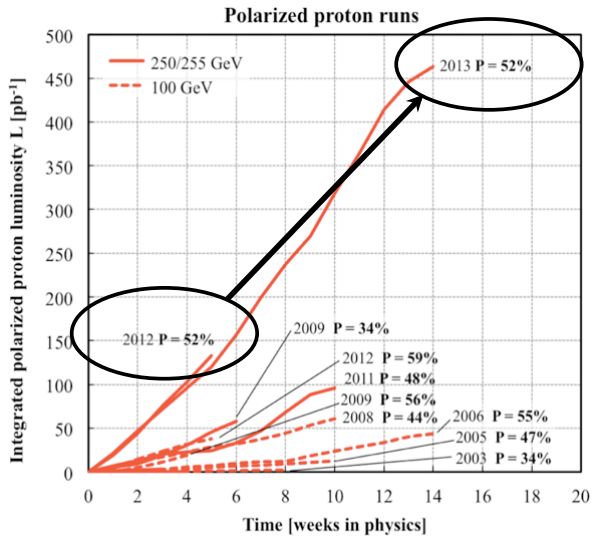






Quark Polarization - Next Steps

This is “only” the 2011 and 2012 data, 2013 is to come.



Eagerly anticipate also the new data from the PHENIX forward muon-arm

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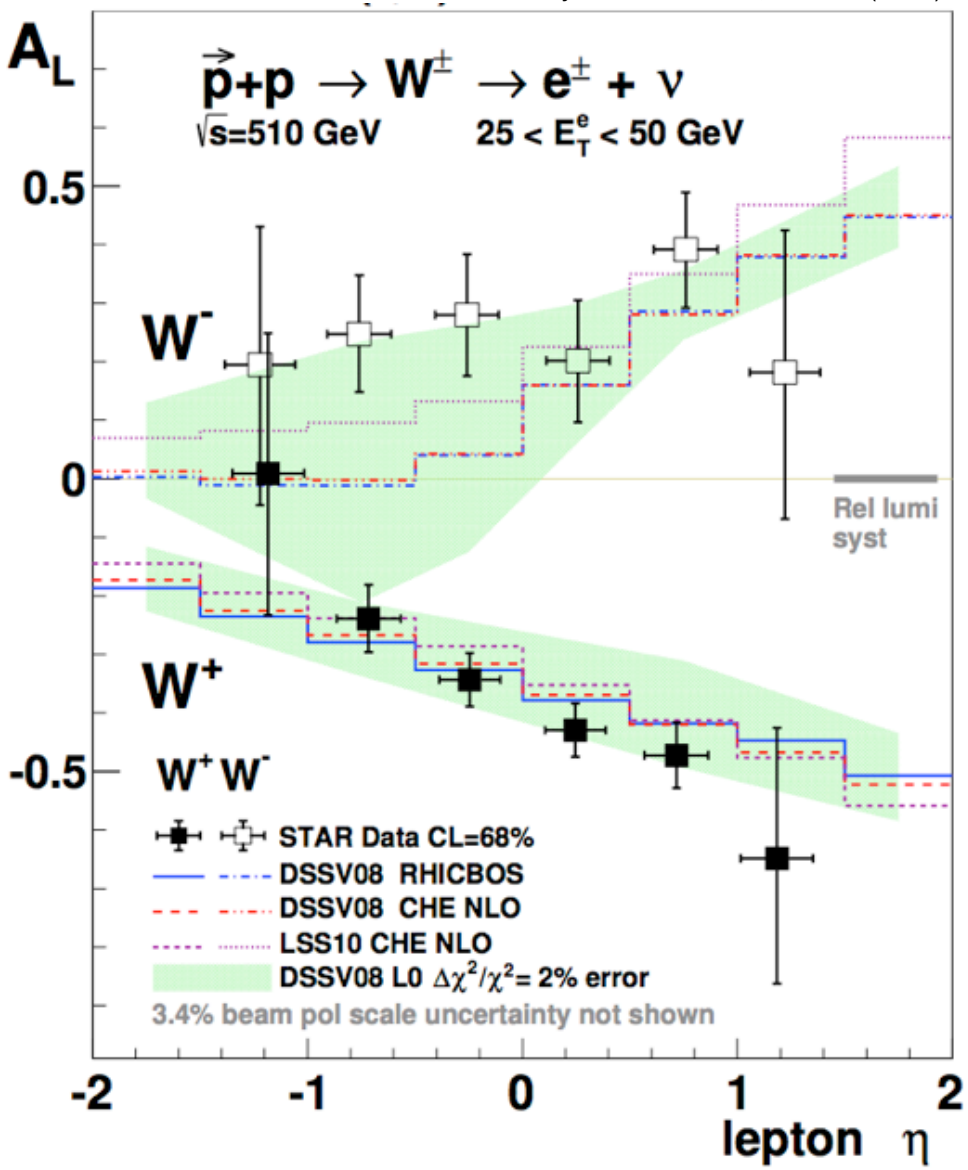
See the talks by

Francesca Giordano, and

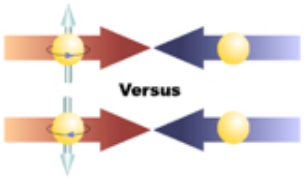
Jinlong Zhang

in today’s parallel session IV, S2

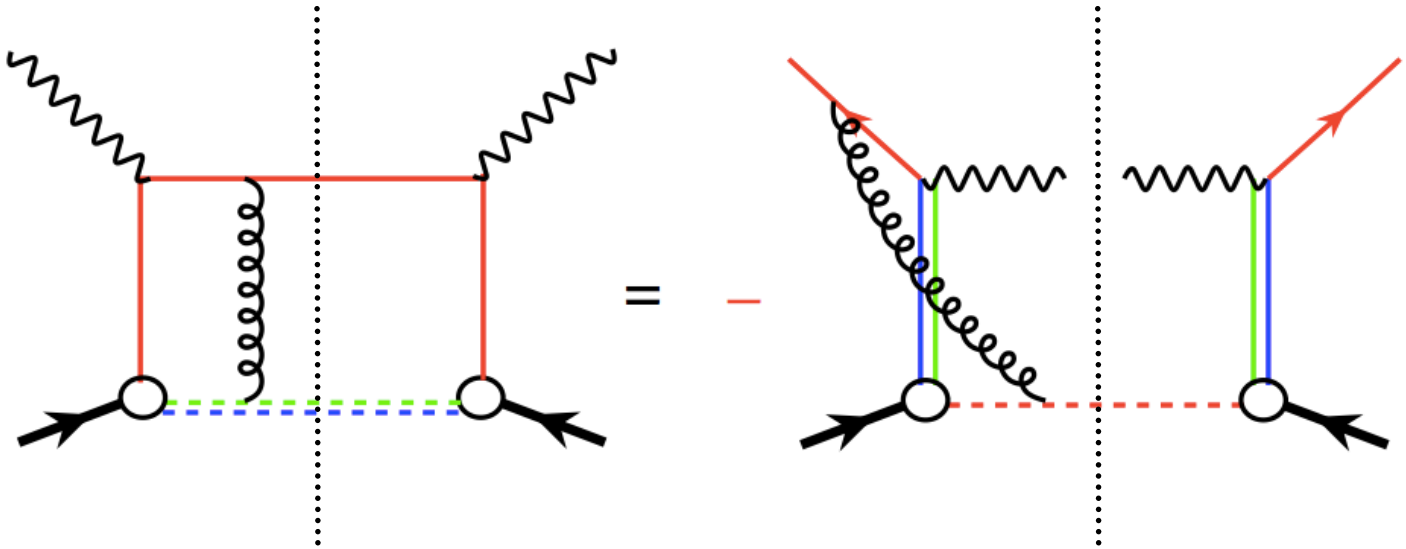
Phys. Rev. Lett. 113, 072301 (2014)



Transverse Spin Phenomena



Transverse Spin Phenomena - The Sivers' Sign Change



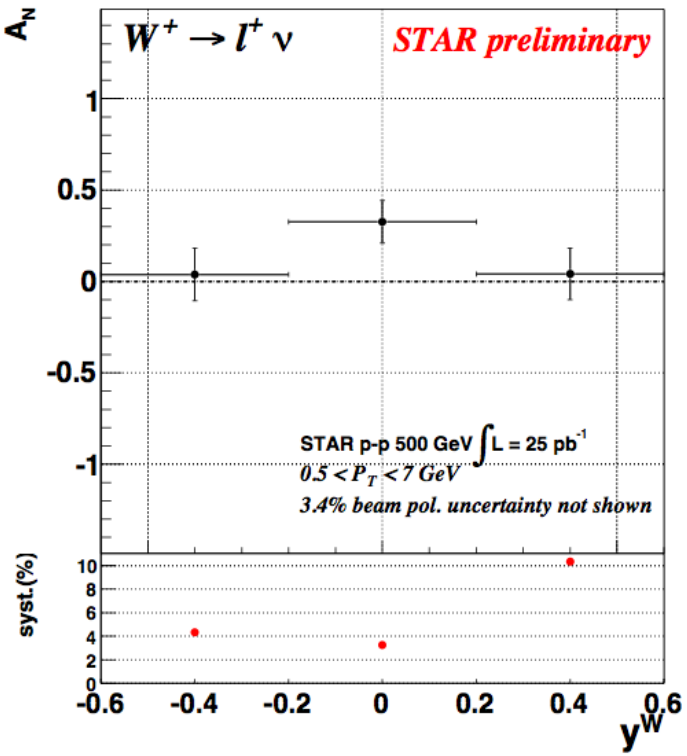
SIDIS = – DY

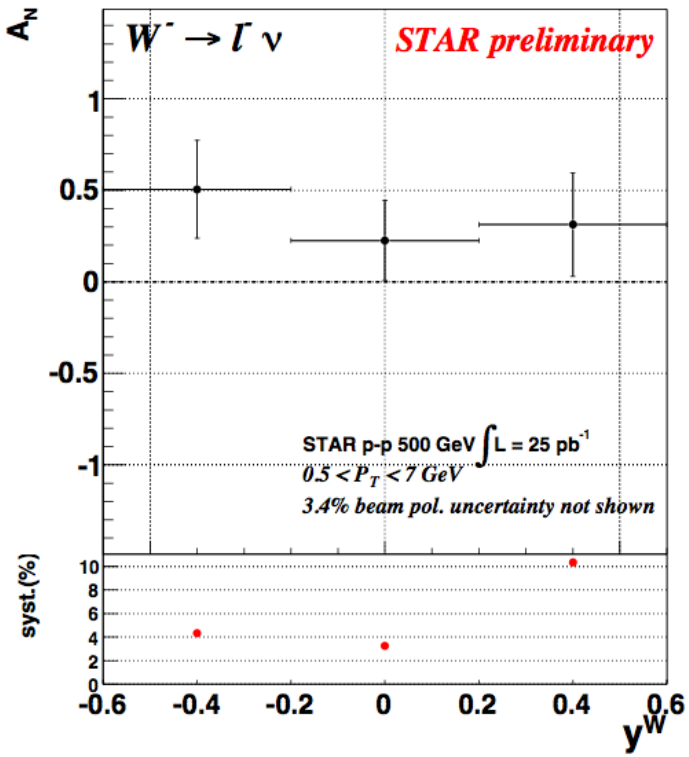
HP13 (2015): Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering

In colloquial english: Quarks with unlike color charge attract one another in QCD.

Transverse Spin Phenomena - The Sivers' Sign Change

First measurement of W A_N, using a recoil technique to determine the boson kinematics





Analysis tour-de-force!

Salvatore Fazio, for the collaboration - DIS 2014

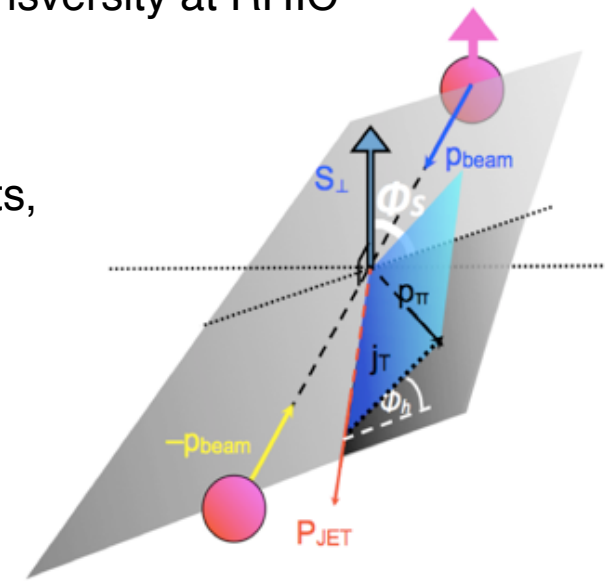
Expect ~2% asymmetry, depending on evolution and PDF uncertainties, areas of active theory development

Precision is achievable with RHIC beam operations at top-energy in 2016.

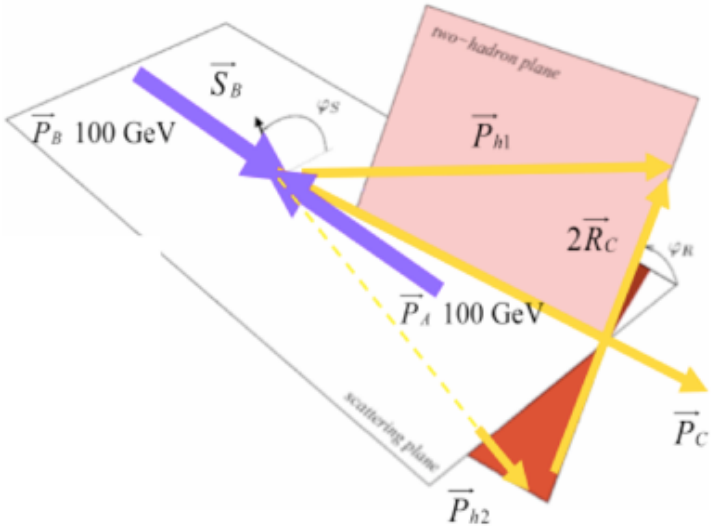
Transverse Spin Phenomena - Quark Transversity

At least two methods can provide sensitivity to quark transversity at RHIC

1. spin-dependent modulation of hadron yields within jets,



$$h_1(x) \otimes H_1^{\perp}(z, j_{\mathrm{T}})$$

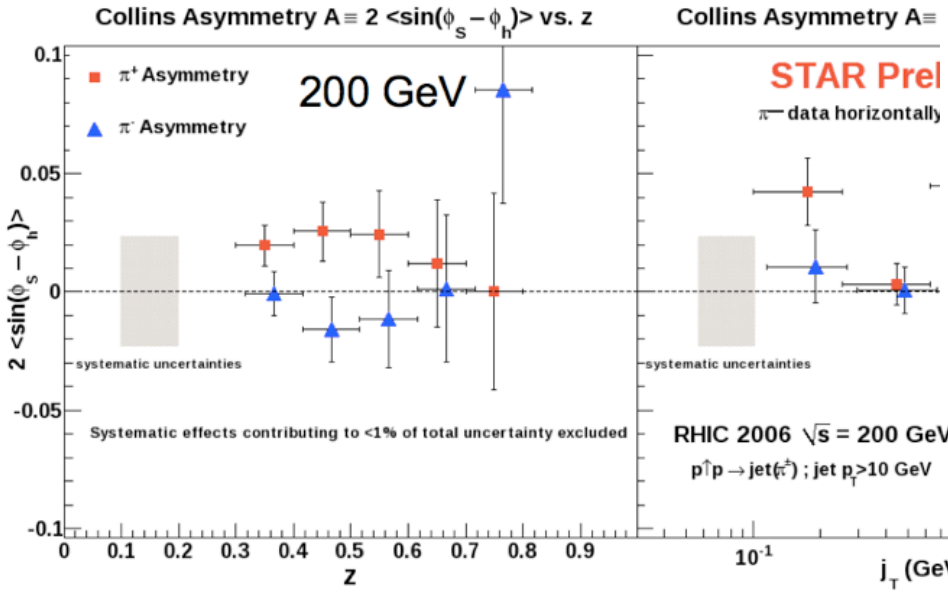


2. di-hadron correlation measurements couple transversity with interference-fragmentation.

Both methods have been pursued and have delivered initial results...

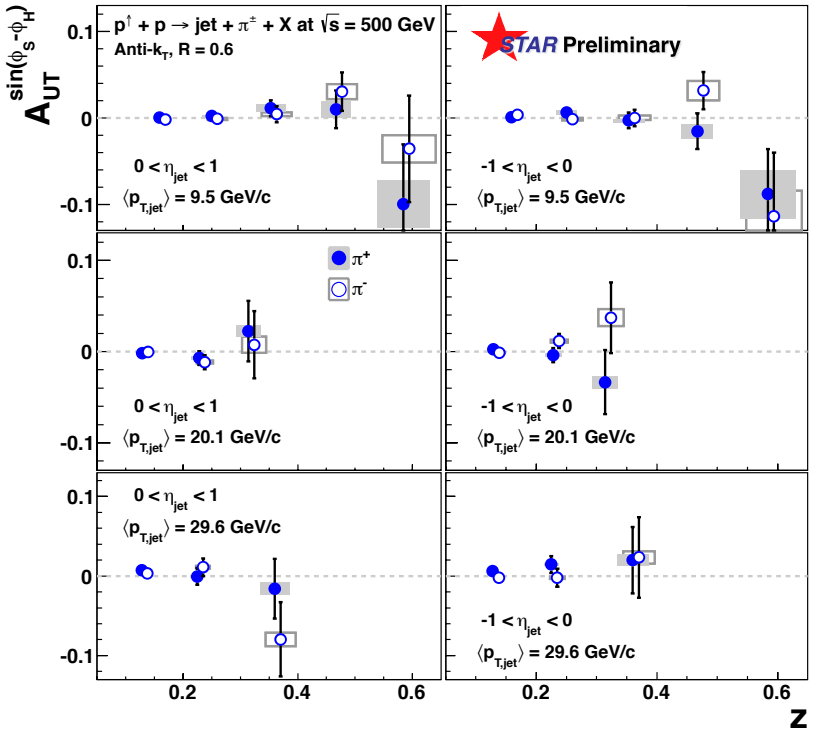
Transverse Spin Phenomena - Quark Transversity

1. Spin-dependent modulation of hadron yields within jets, are suggestive of a non-zero effect at √s = 200 GeV and thus call for follow-up.



RHF for the collaboration (PANIC 2011)

J. Drachenberg for the collaboration (PANIC 2014)



2. Limited kinematic reach at √s = 500 GeV is consistent with zero.

Friday's parallel session VII S3:

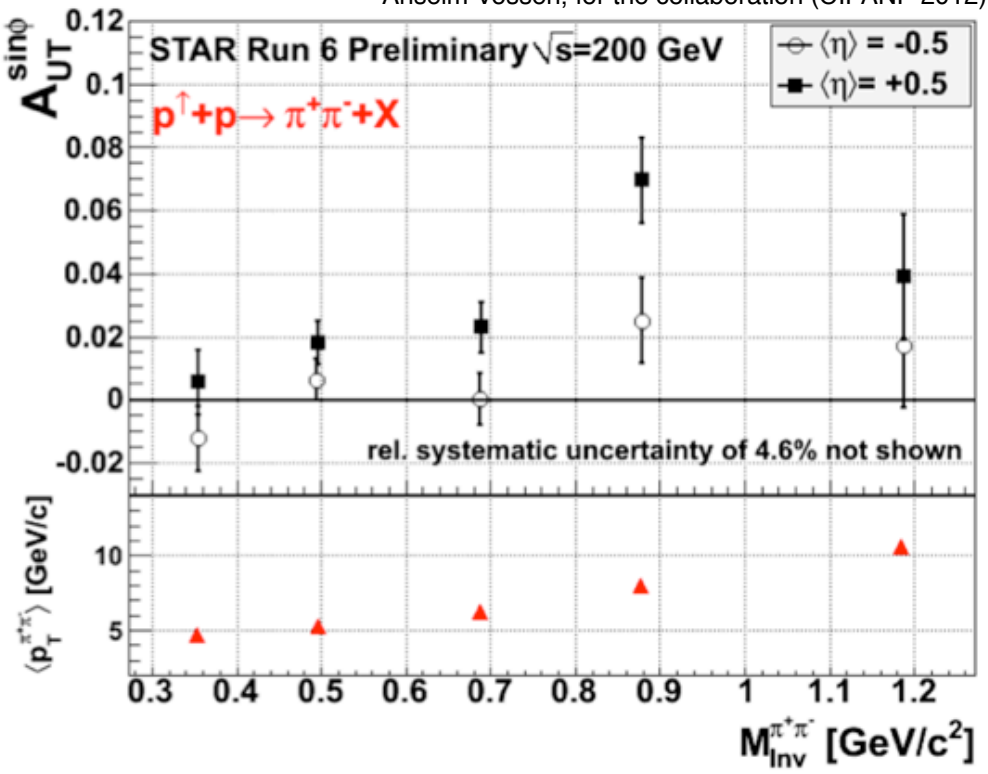
Significantly more precise data on this topic - Kevin Adkins

New data in forward region on the neutral pion - Yuxi Pan

Transverse Spin Phenomena - Quark Transversity

2. Spin-dependent di-hadron correlation measurements,

Anselm Vossen, for the collaboration (CIPANP 2012)



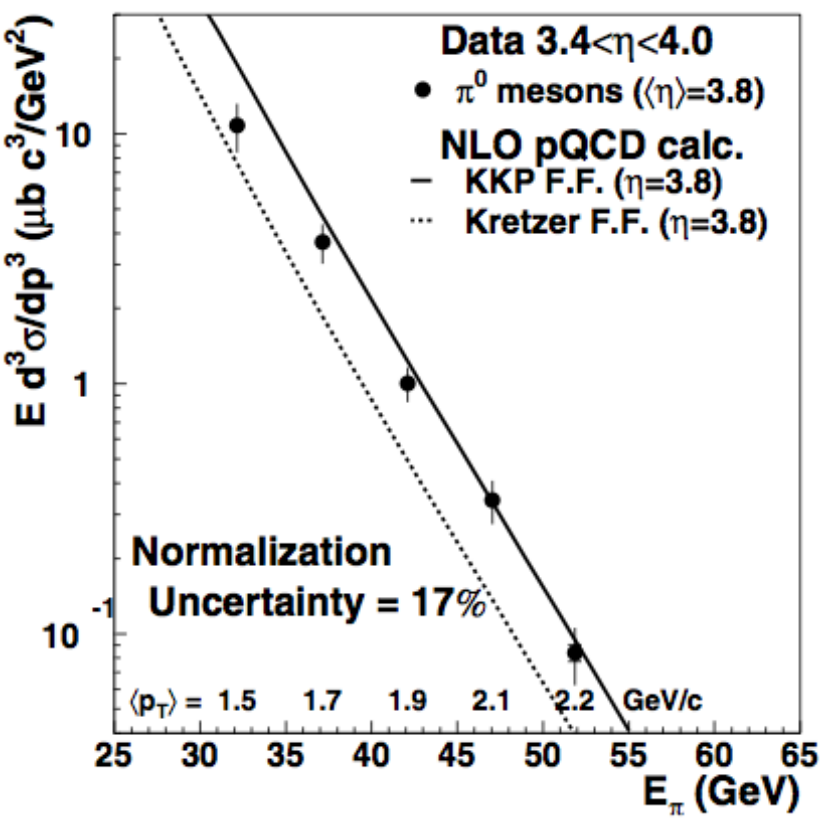
show a clear effect and call for follow-up

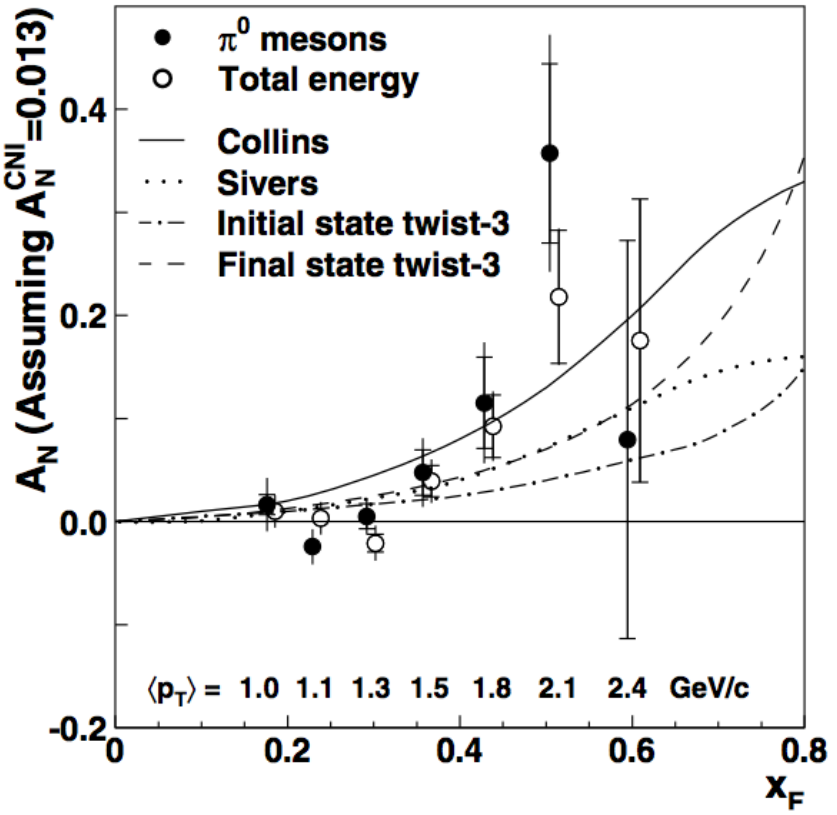
Friday's parallel session VII S3:

New data at √s = 500 GeV - Michael Skoby

Transverse Spin Phenomena - Large Forward A_N

Large A_N persists at RHIC, where the cross-section is consistent with NLO pQCD, as is very well known:





J. Adams et al, PRL 92, 171801 (2004)

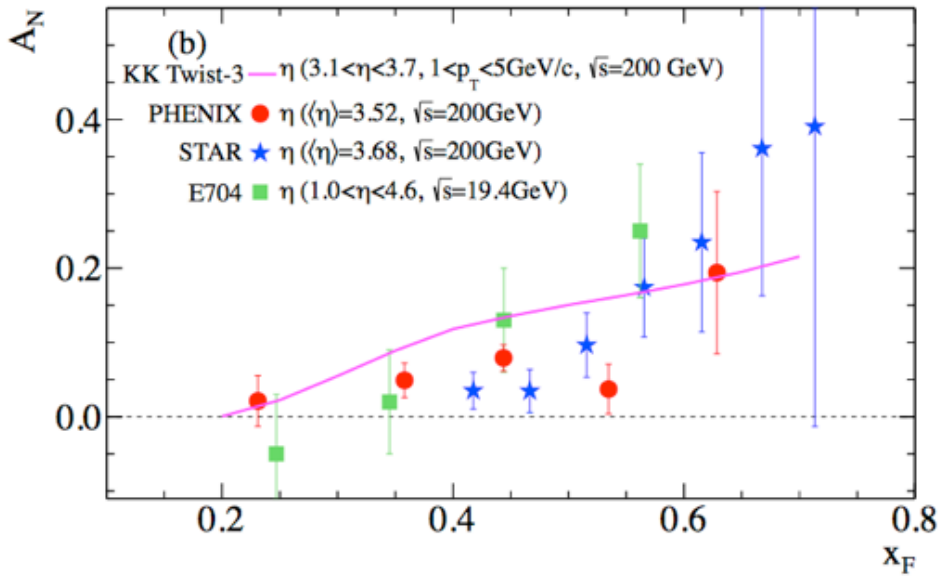
But why? Contributions from Sivers and/or Collins effects? Higher twists?
Or, perhaps, an entirely different origin - diffraction?

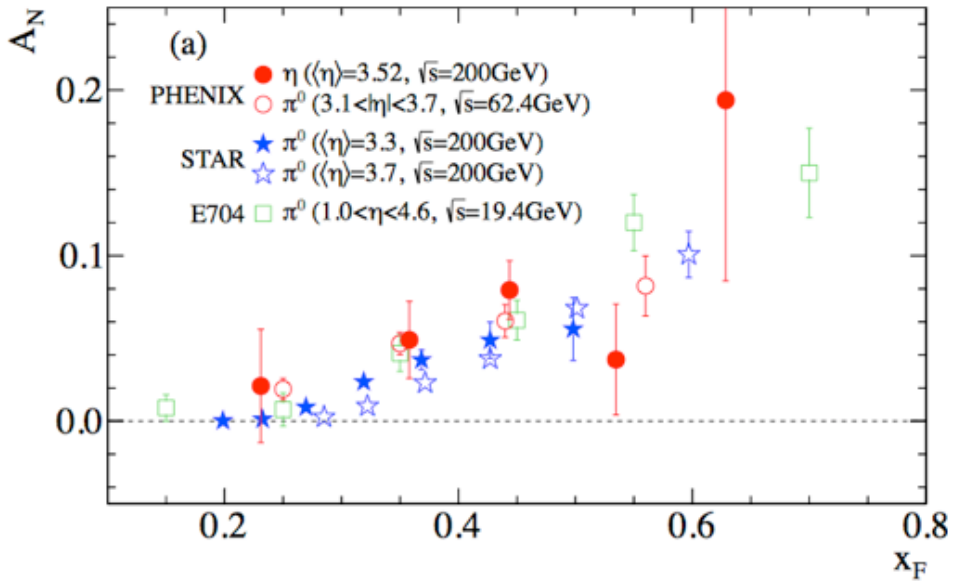
Significant experiment follow-up to *characterize* and *classify*.

Transverse Spin Phenomena - Large Forward A_N

A recently published example of such classification is the A_N for the eta-meson,

A.Adare et al, ArXiv:1406.3541





leaving open the possibility of an intricate role for the strange (anti-)quark also here...

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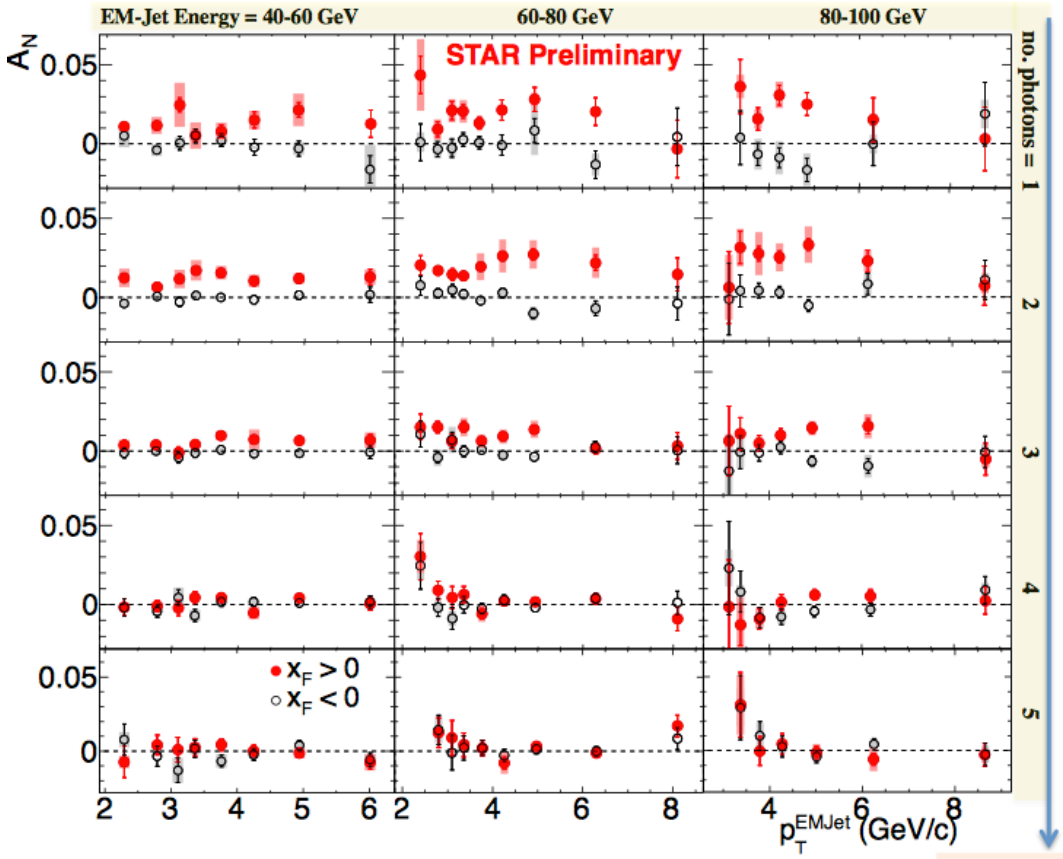
c.f. Xiaorong Wang's talk in parallel session VIII S3 on Friday

Transverse Spin Phenomena - Large Forward A_N

The puzzle continues...



Mriganka Mondal, for the collaboration (DIS 2014)

- 1-photon events, which include a large π^0 contribution in this analysis, are similar to 2-photon events
- Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated π^0's
- A_N decreases as the event complexity increases (i.e., the "jettiness"
- A_N for #photons >5 is similar to that for #photons = 5

Jettier events

and points to a need for qualitatively new instrumentation and measurements

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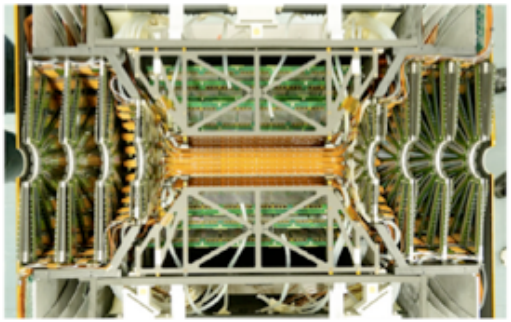
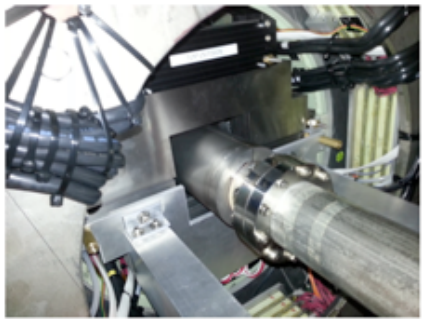
See also Yuxi Pan's discussion of event-topology in parallel session VII S3 on Friday

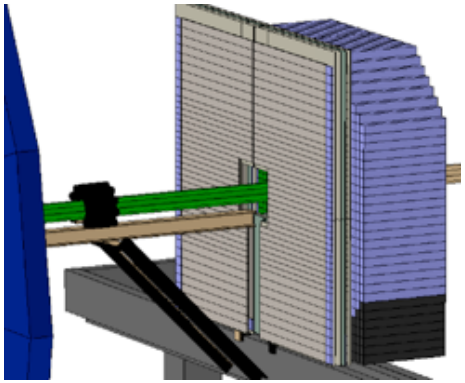
RHIC-Spin - Near-term Experiment Capabilities

PHENIX Forward *heavy-flavor* and *photon* capabilities with FVTX and MPC-EX, respectively





Forward *photon* and *diffractive* measurement capabilities with FMS-PS and Roman Pots



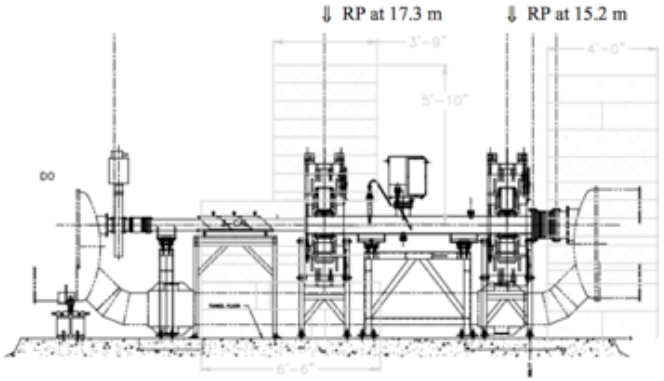
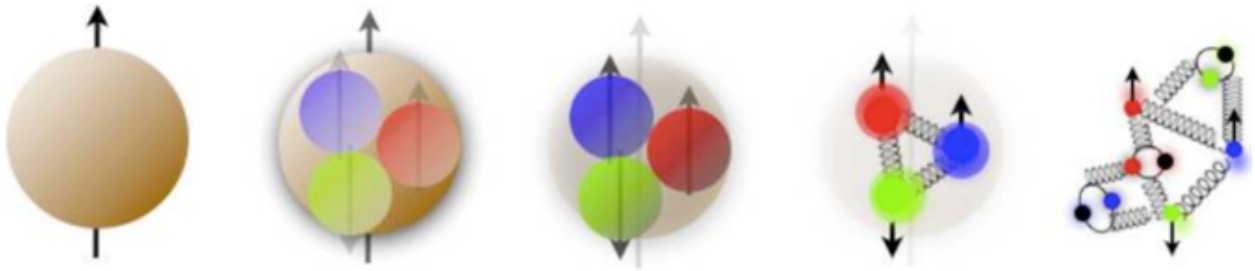


Figure 4.3-1: Proposed location and layout of Phase-II* Roman Pots.

See Kieran Boyle's plenary talk, "Future Spin Physics at RHIC" on Thursday.

For discussion about polarized He3 source at RHIC see James Maxell's talk in session S10 on Wednesday

Closing Remarks



Gluon Polarization - *very* significant constraints from RHIC inclusive jets and pions,

evidence for *positive gluon polarization* for $x_{gluon} \sim 0.05$ - 0.2
at the level of ~ 0.2 at 10 GeV^2
bright future with forward measurements and further running,

Quark Polarization - Initial measurements of production cross sections and
spin asymmetries have been published,

Discriminating precision from STAR mid-rapidity 2011+12 data,

look forward to PHENIX muon arm data and 2013 data

Transverse Spin - Proof-of-concept measurement to test the Sivers' sign-change,

Initial sensitivity to Quark transversity,

Large A_N continues to puzzle; qualitatively new measurement
capability in 2015 with PHENIX FVTX, MPC-EX and
STAR FMS-PS and Roman Pots.

Thank you and Stay Tuned!