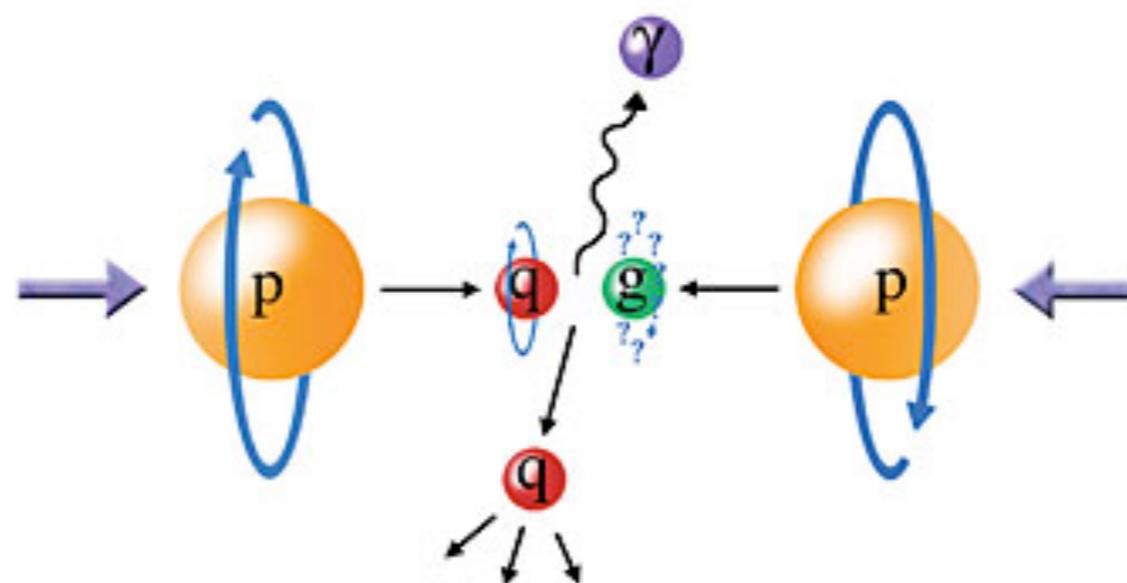


Longitudinal Spin Physics with STAR

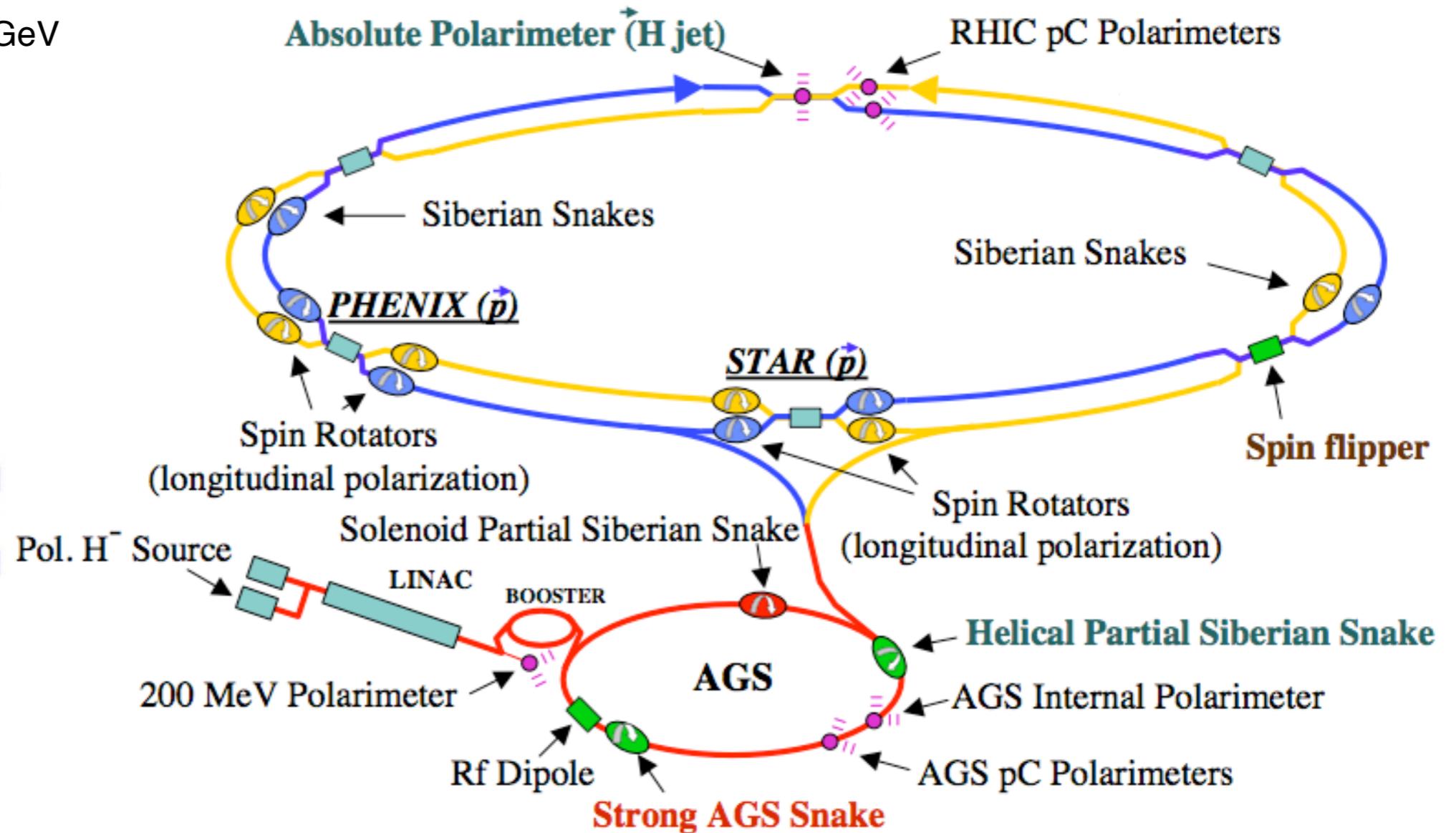
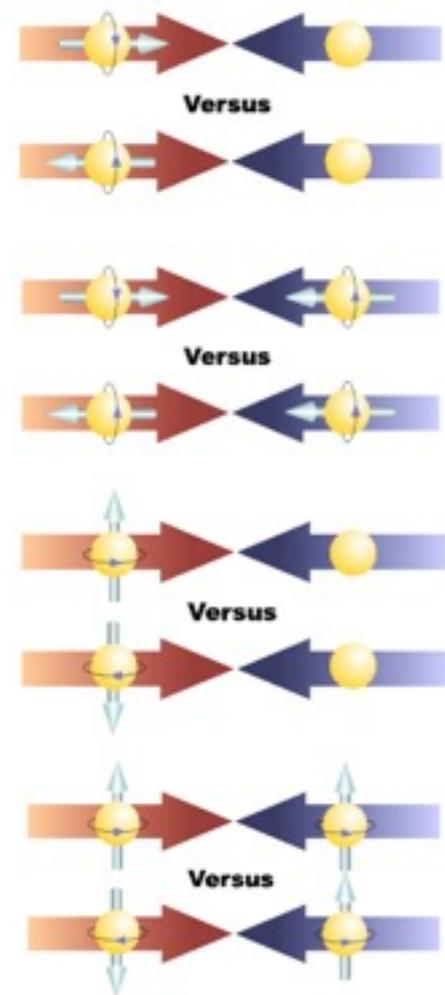


Ernst Sichtermann, LBL

RHIC - Polarized Proton-Proton Collider

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

$\sqrt{s} = 62, 200, \text{ and } 500 \text{ GeV}$



at hard (perturbative) scales with good systematic controls, e.g. from the $\sim 100\text{ns}$ 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

$\sqrt{s} = 200 \text{ GeV}$

2005

2006

2009

2015

35 pb⁻¹

50 pb⁻¹

$\sqrt{s} = 500 \text{ GeV}$

2009

2011

2012

2013

400 pb⁻¹

Transverse data

$\sqrt{s} = 200 \text{ GeV}$

2006

2008

2012

2015

38 pb⁻¹

40 pb⁻¹

$\sqrt{s} = 500 \text{ GeV}$

2011

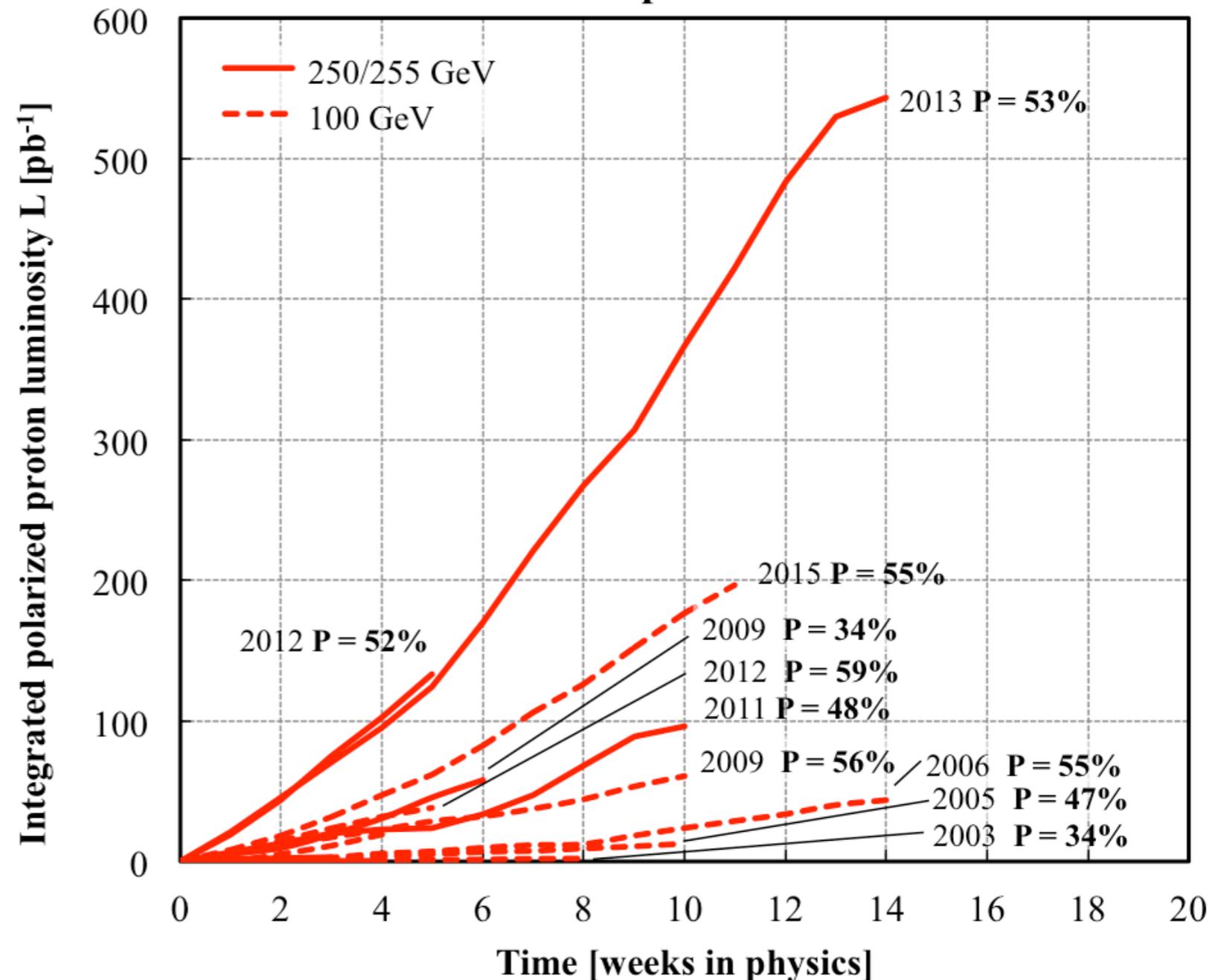
(2017)

25 pb⁻¹

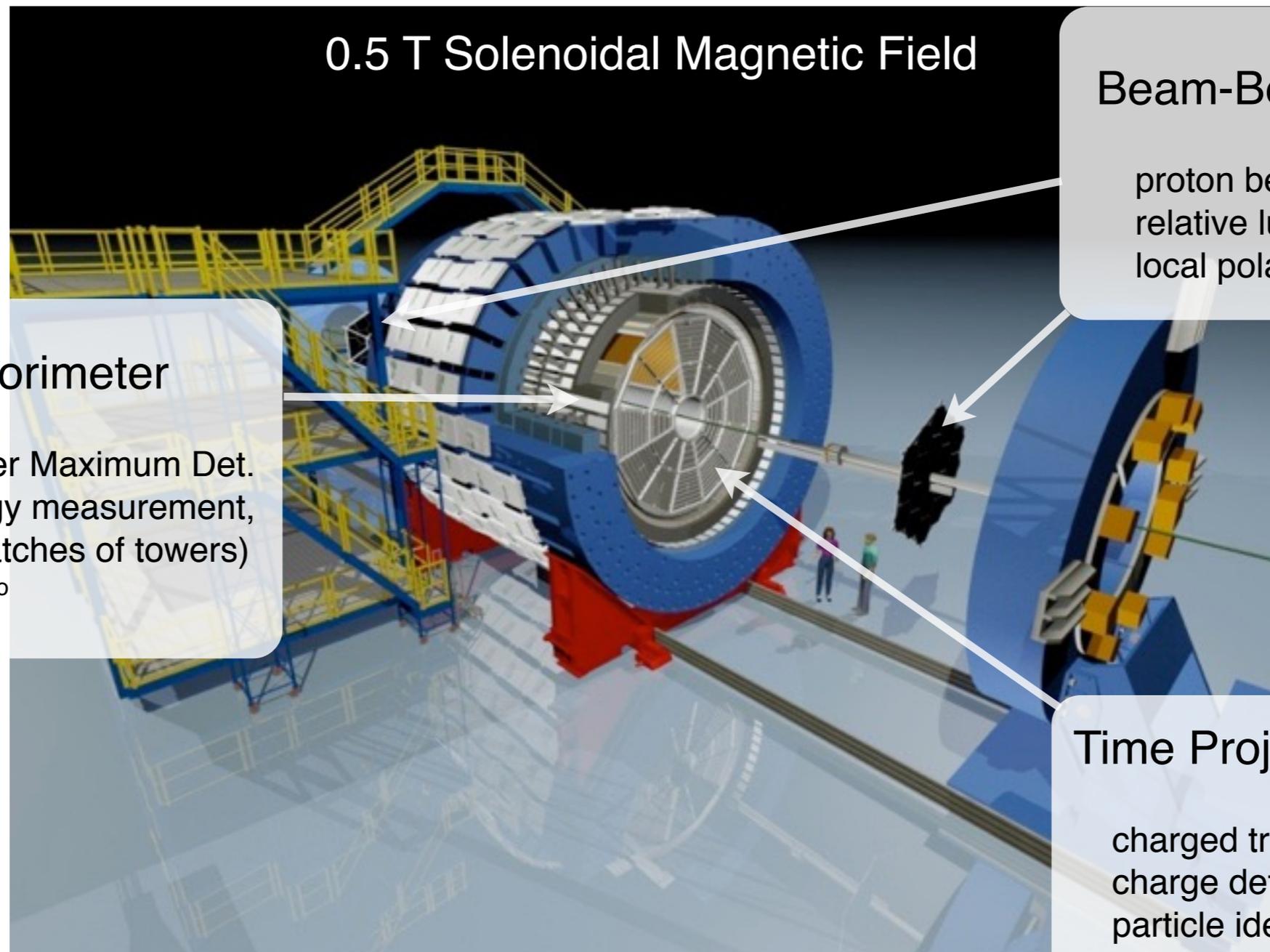
(400 pb⁻¹)

50-60% polarization

Polarized proton runs



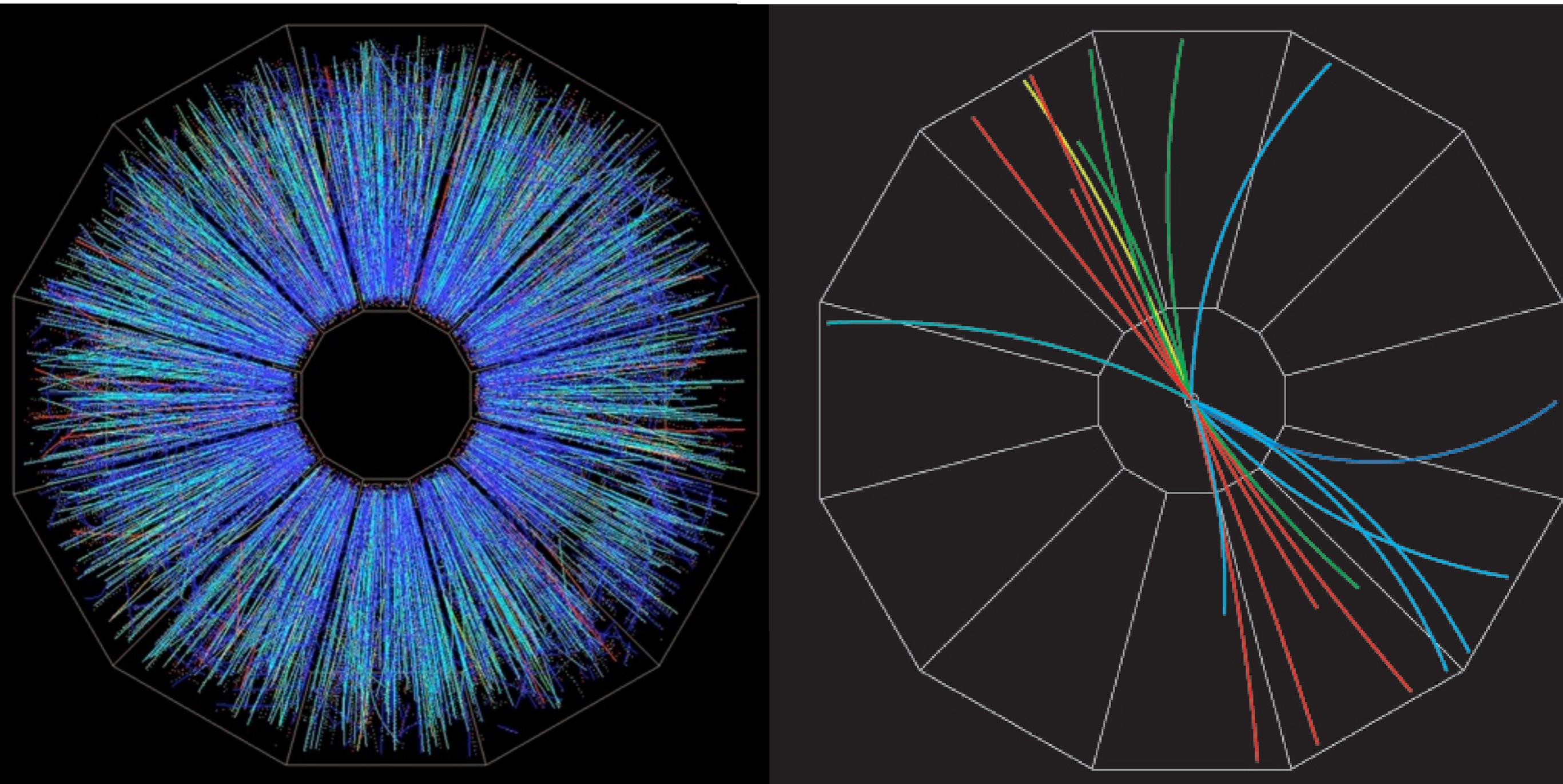
STAR - Solenoidal Tracker at RHIC



Nucl. Instrum. Meth. A499, 624, 2003

Additional subsystems, e.g. DAQ-1000, ZDC, Time-of-Flight, EEMC,
Recent Upgrades: Heavy Flavor Tracker, Muon-Telescope Detector, FMS-preshower, RP
Upgrade plans (spin): Forward Calorimeter and Tracking System

STAR - Solenoidal Tracker at RHIC

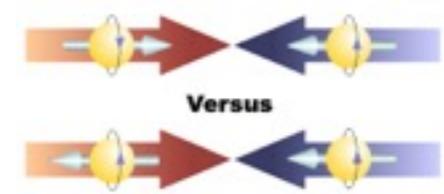


A versatile instrument to study QCD: Au+Au, d+Au, p+p, $\sqrt{s} = 7.7 - 500$ GeV, polarization.

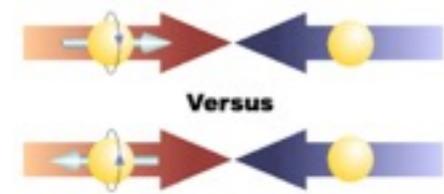
Uniquely large acceptance and jet capability at RHIC

The STAR Spin Physics Program - Key Questions

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



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

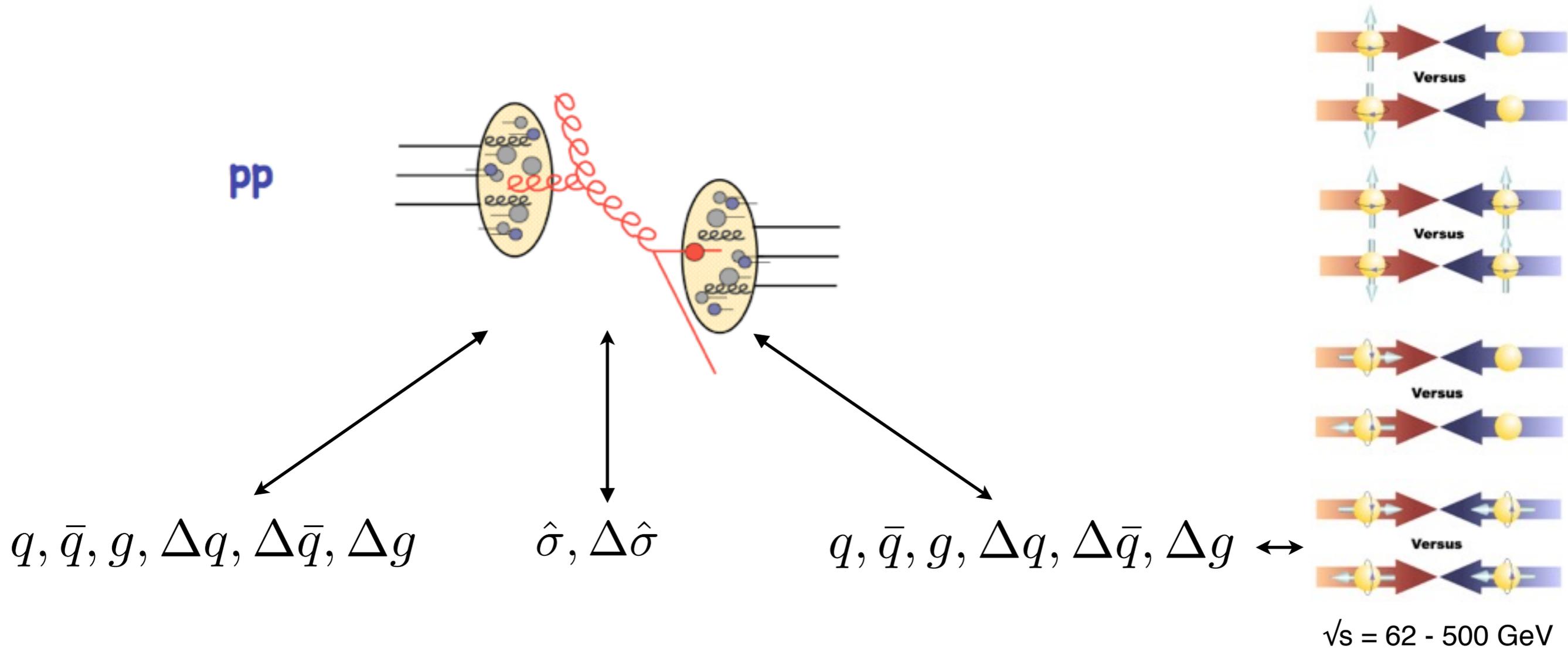


-
- *Does the Sivers' function change sign in proton-collisions compared to DIS?*
 - *What are the quark transversity distributions?*
 - *What is the origin of large forward A_N ?
does it change with nuclear targets?*



Qinghua Xu's talk tomorrow

The RHIC-Spin Program - Approach



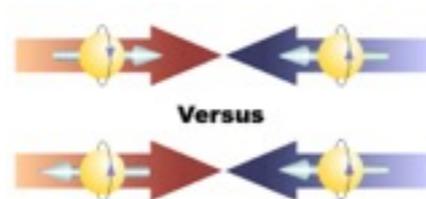
Theory: perturbative QCD evaluations, typically at next-to-leading order,

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 $q, \bar{q}, g, \Delta q, \Delta \bar{q}, \Delta g$

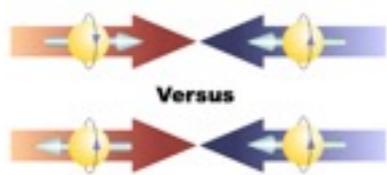
Complementary insights from measurements of A_{LL}, A_L, A_N, D_{LL} , inclusive probes, correlations ...

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,

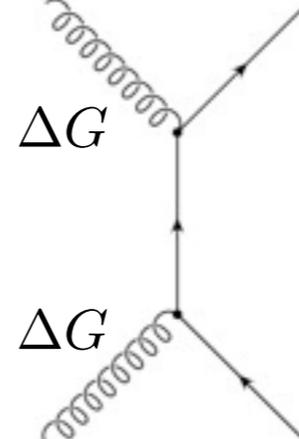
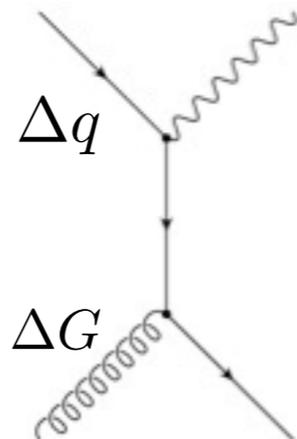
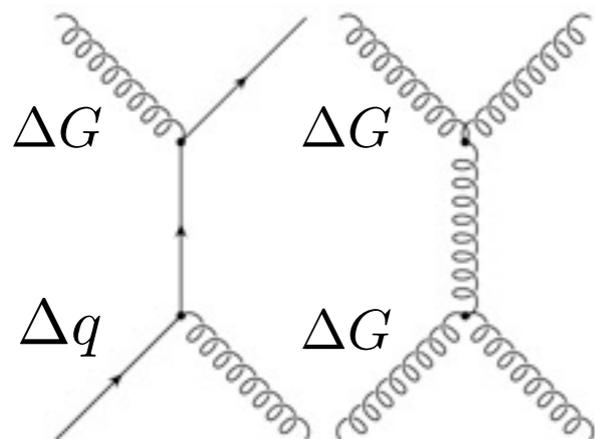
Gluon-gluon scattering contribution dominates up to jet $p_T \sim 8$ GeV, where quark-gluon scattering takes over,

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

$$\vec{p} + \vec{p} \rightarrow \text{jet}(s) + X$$

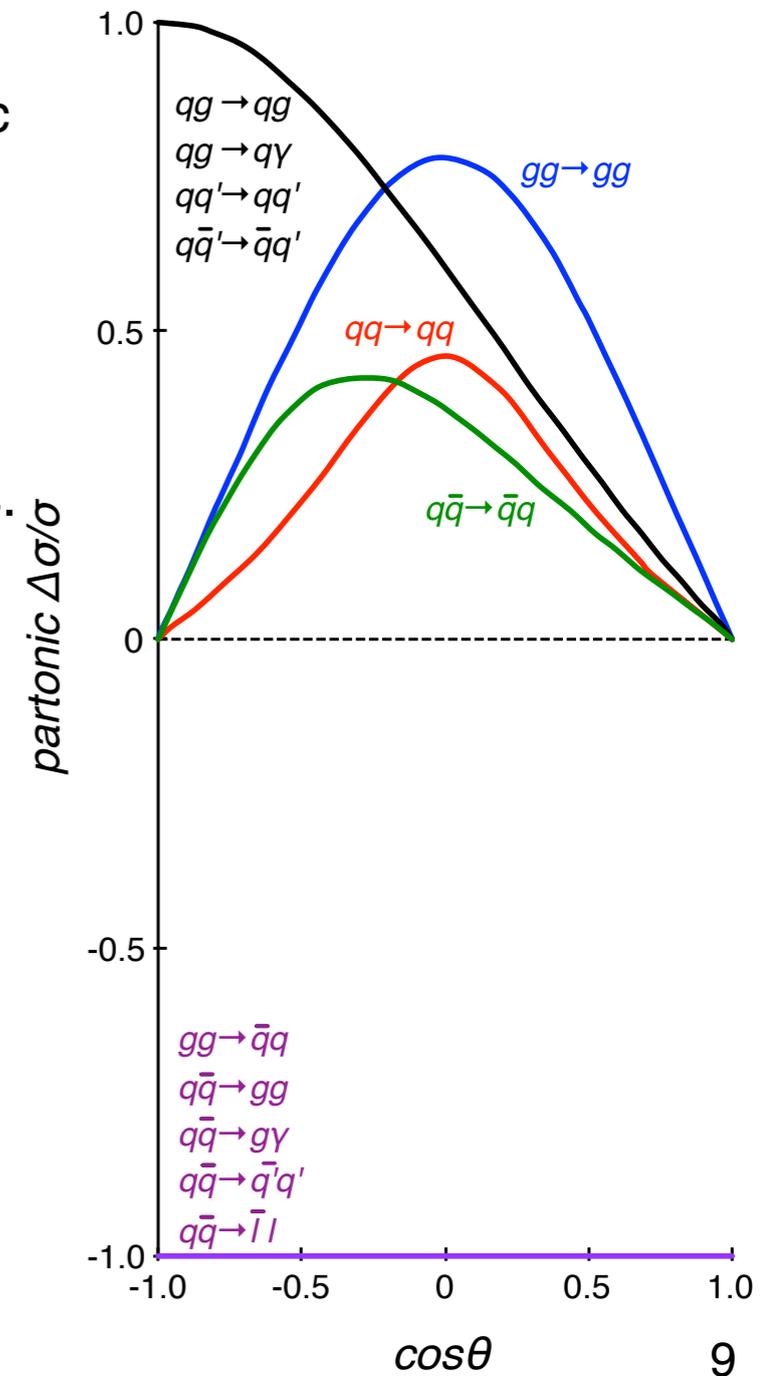
$$\vec{p} + \vec{p} \rightarrow \gamma + \text{jet}$$

$$\vec{p} + \vec{p} \rightarrow c\bar{c}, b\bar{b} + X$$



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

time

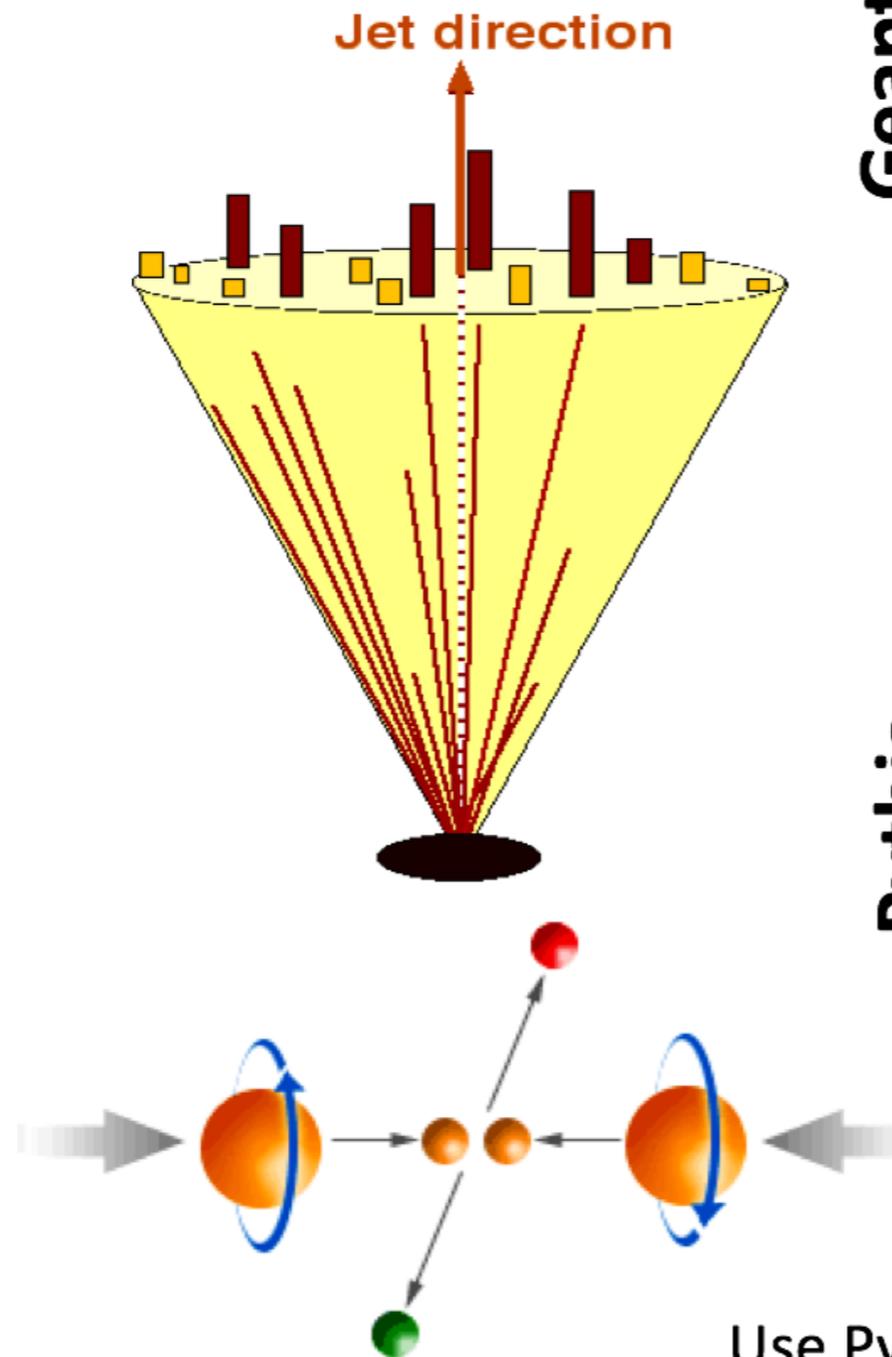


Jet Reconstruction in STAR

Detector

Particle

Parton



Geant

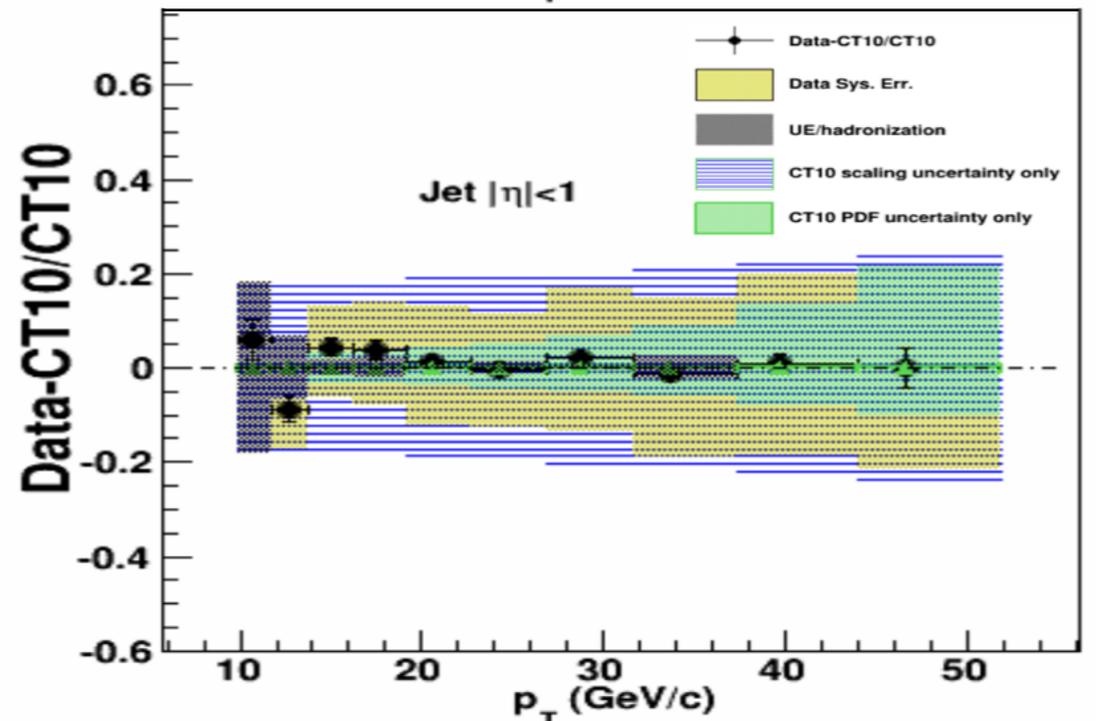
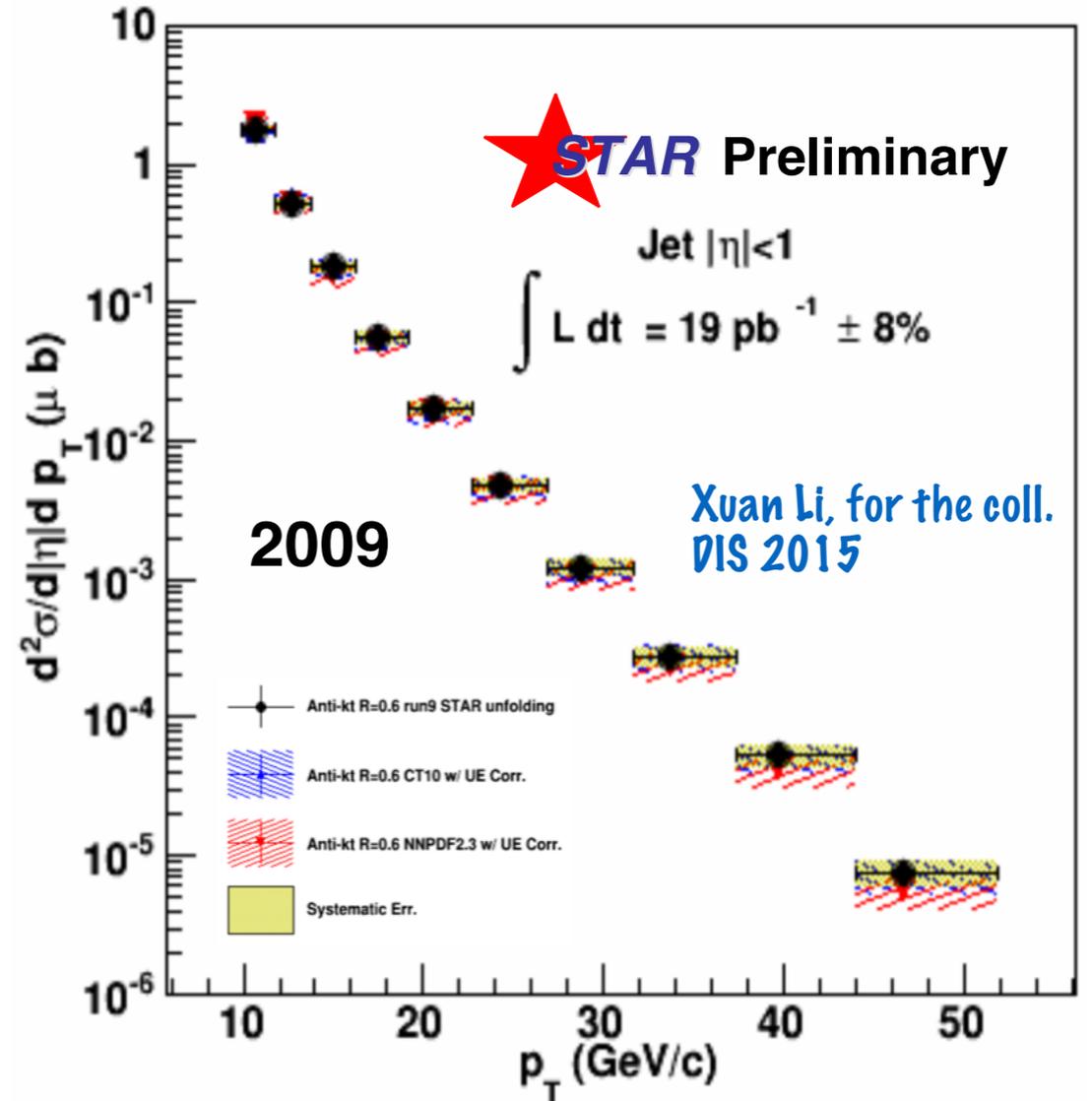
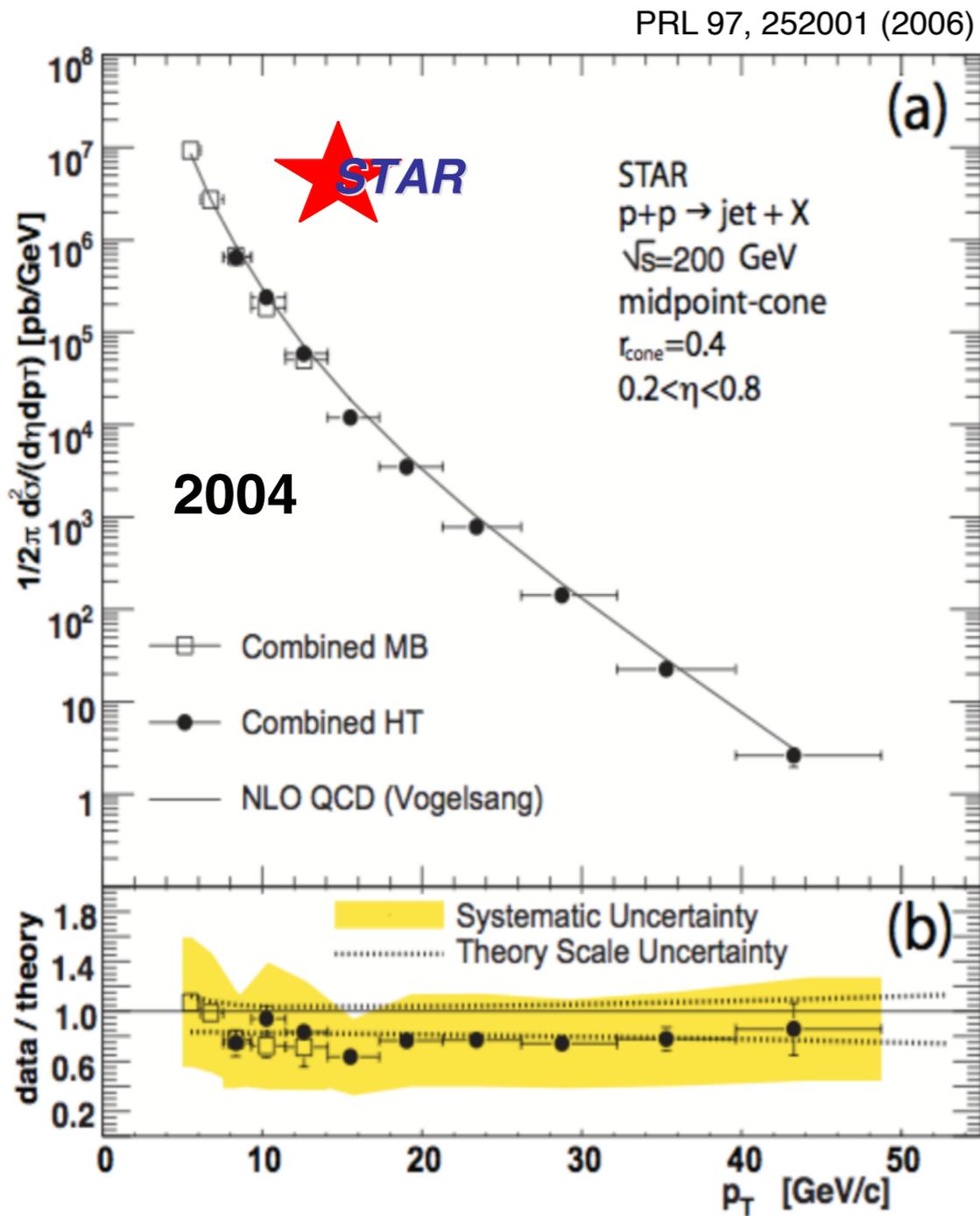
Pythia

- For 2003/4 200 GeV data
Mid-point cone algorithm
Adapted from [Tevatron II – hep-ex/0005012](#)
 - Seed energy = 0.5 GeV
 - Cone radius $R = 0.4$ in η - ϕ space
 - Split/merge fraction $f = 0.5$
- For 2009 200 GeV data
Anti- k_T algorithm
[Cacciari, Salam, and Soyez, JHEP 0804, 063](#)
 - Jet parameter **$R = 0.6$**
- For 2012 510 GeV data
Anti- k_T algorithm
 - Jet parameter **$R = 0.5$**

Use Pythia + Geant to quantify detector response

[Sjostrand, Mrenna, and Skands, JHEP 05, 026](#)

Gluon Polarization - STAR Incl. Jet Cross Sections



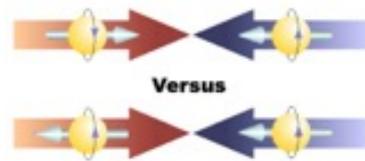
Support a NLO pQCD framework for interpretation.

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

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

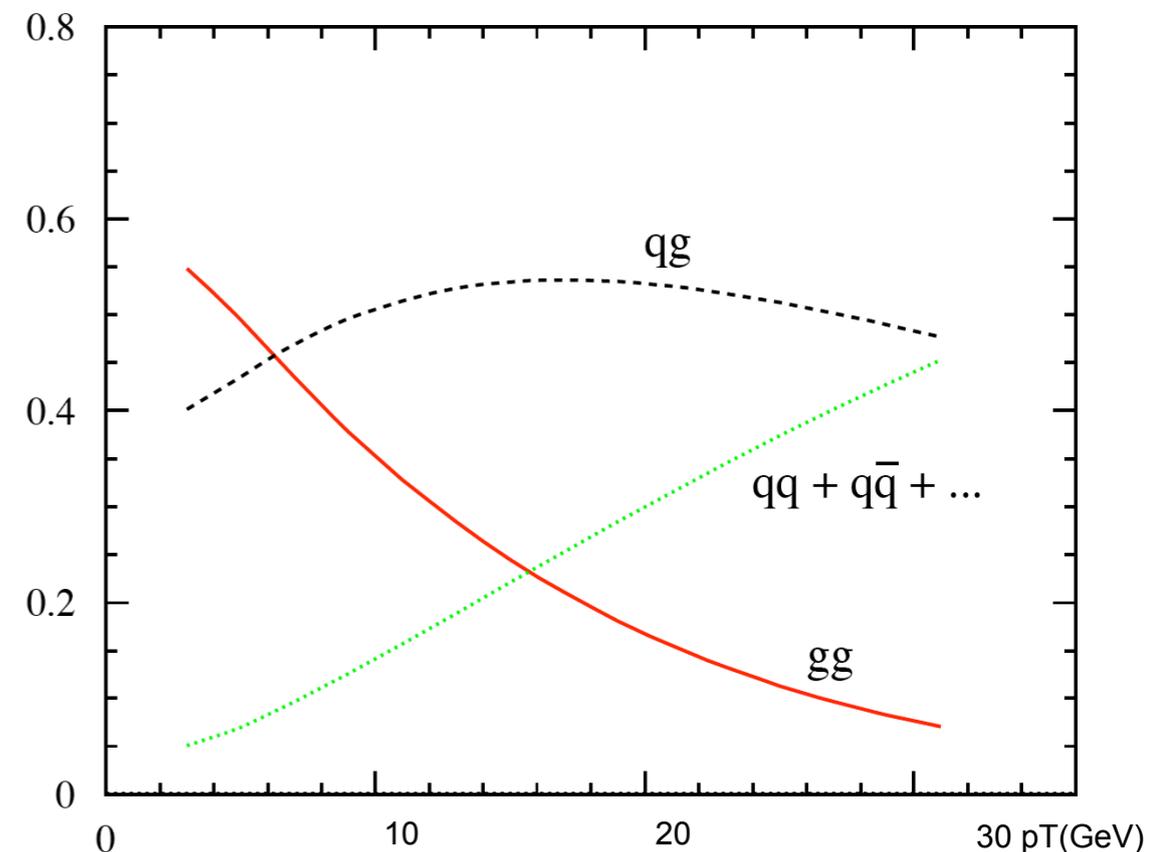


Advantages:

- 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
- $x_g, x_q \sim p_T/\sqrt{s} \cdot \exp(-\eta)$



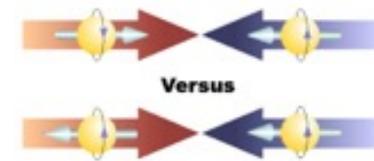
gluon-gluon and quark-gluon scattering contributions dominate. 12

Gluon Polarization at RHIC - Asymmetry A_{LL}

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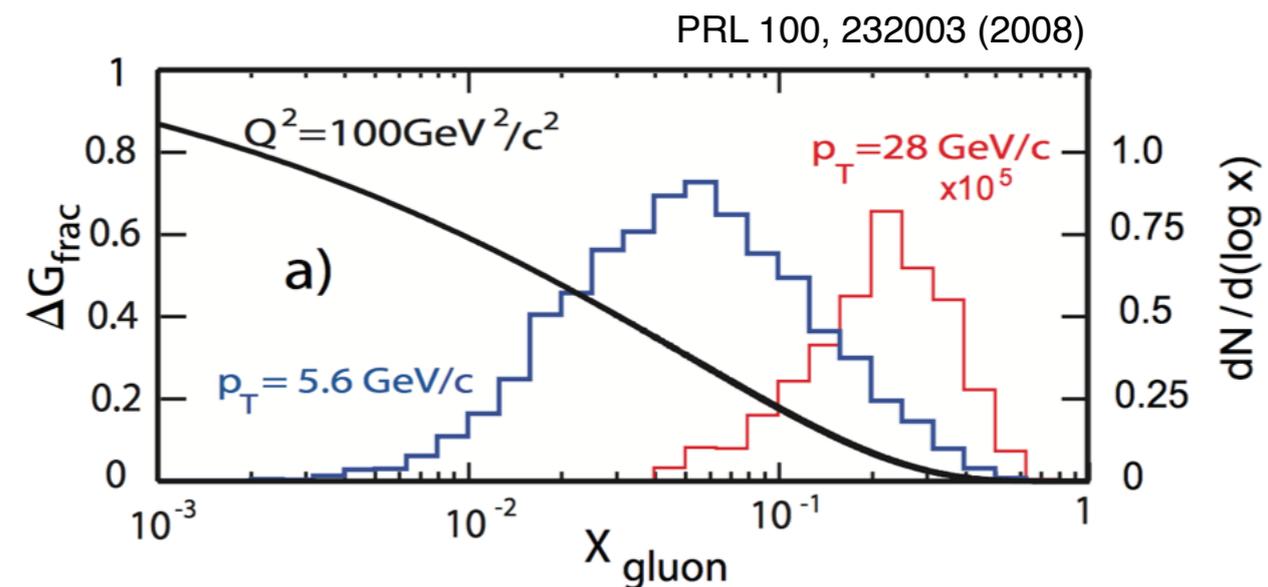


Advantages:

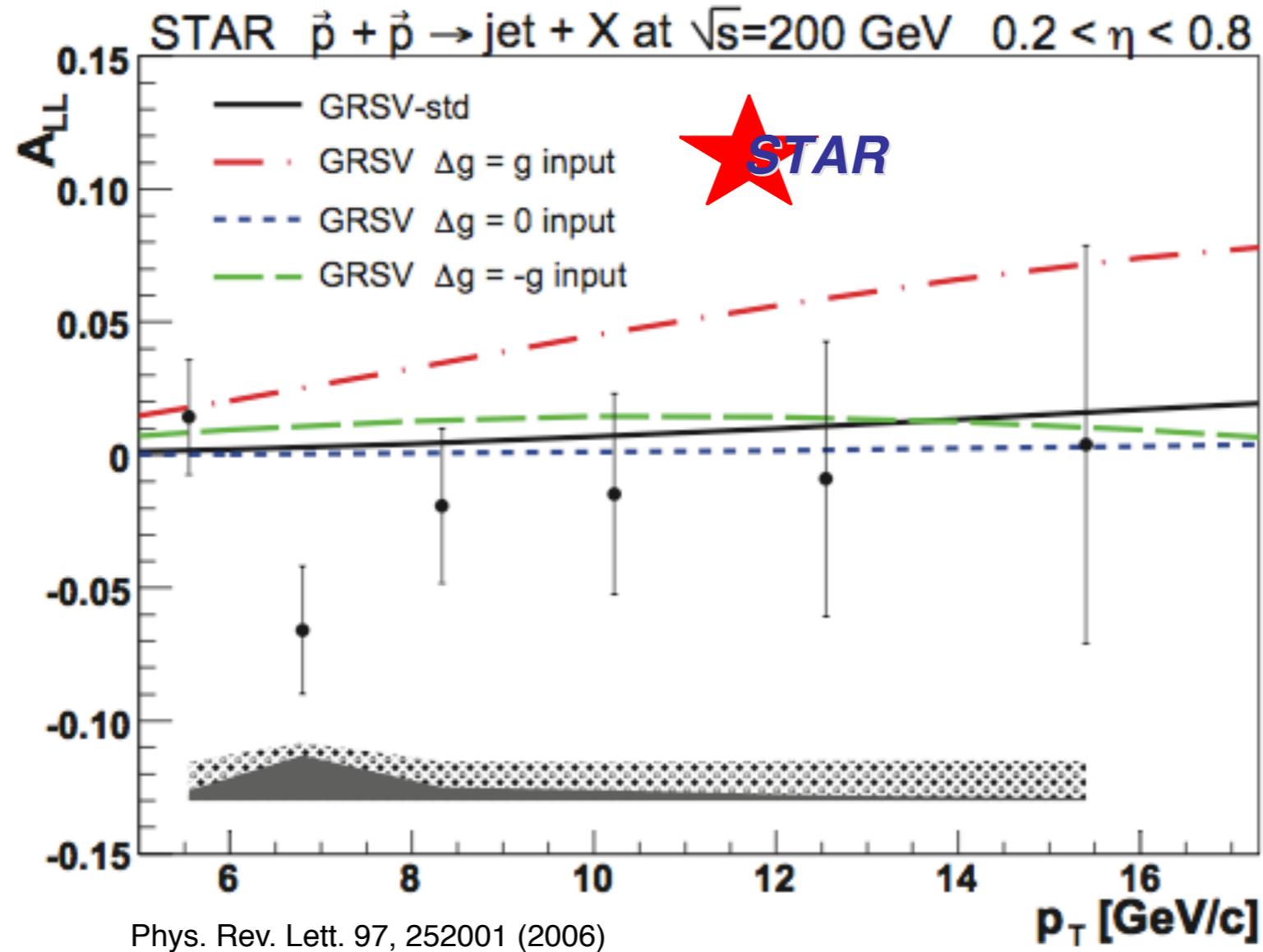
- High yields of neutral pions, jets at RHIC,
- Relatively straightforward triggering,
- Relatively simple reconstruction,

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 Polarization - *Initial* A_{LL} from RHIC

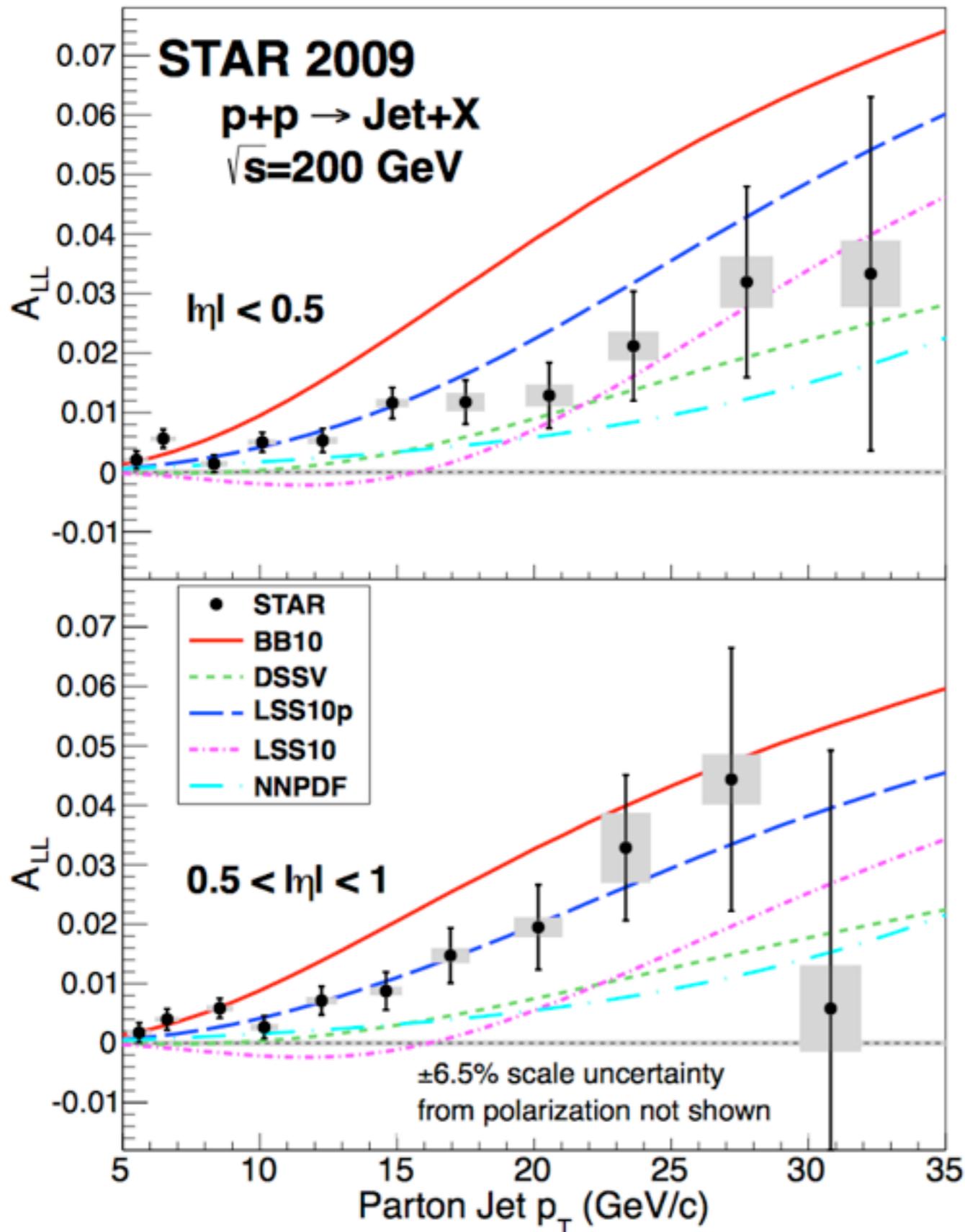


Data disfavor maximal gluon polarization, *as expected*,

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

Glauon Polarization - *Precision* A_{LL} from STAR

PRL 115 (2015) 092002



Significant advance:

about an order in precision,
 two to three times the kinematic range,

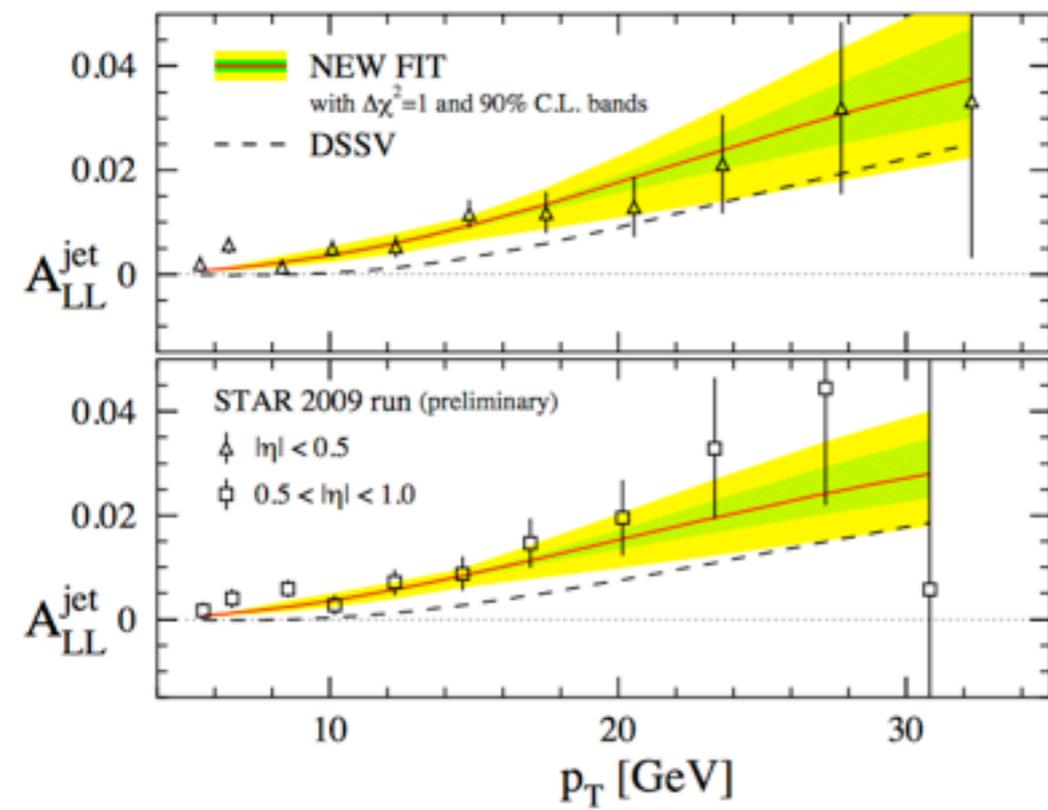
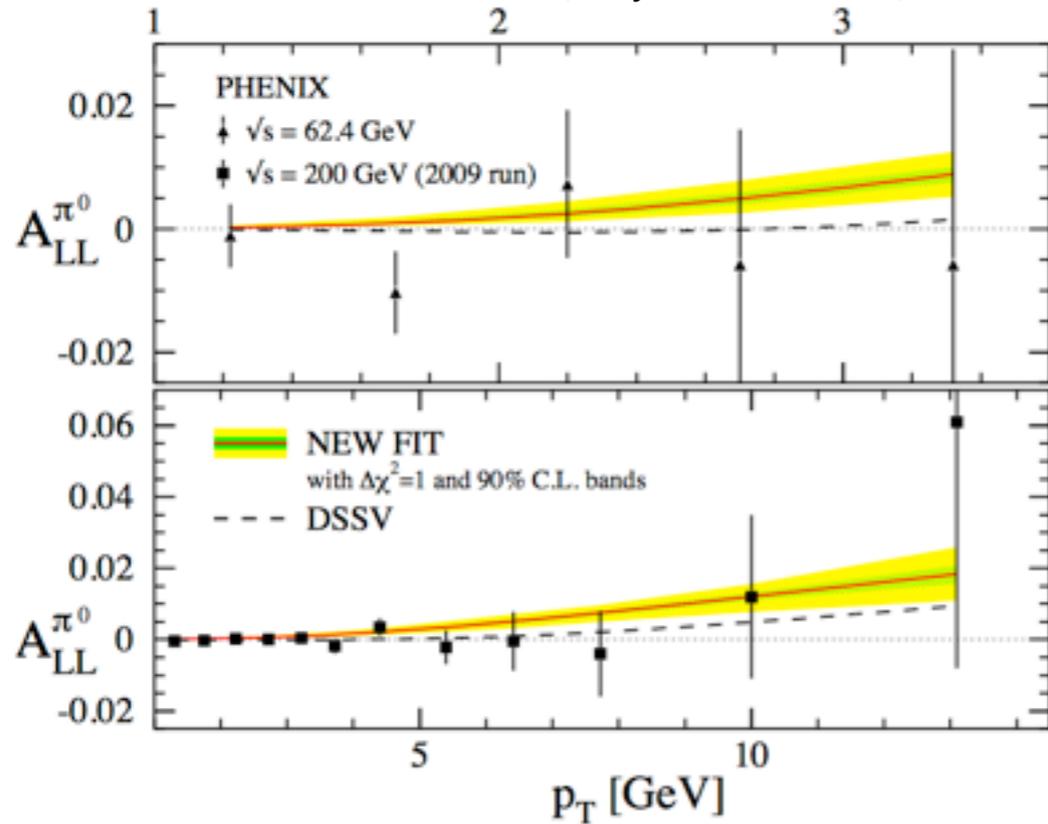
initial sensitivity to different x_g from
 rapidity dependence

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

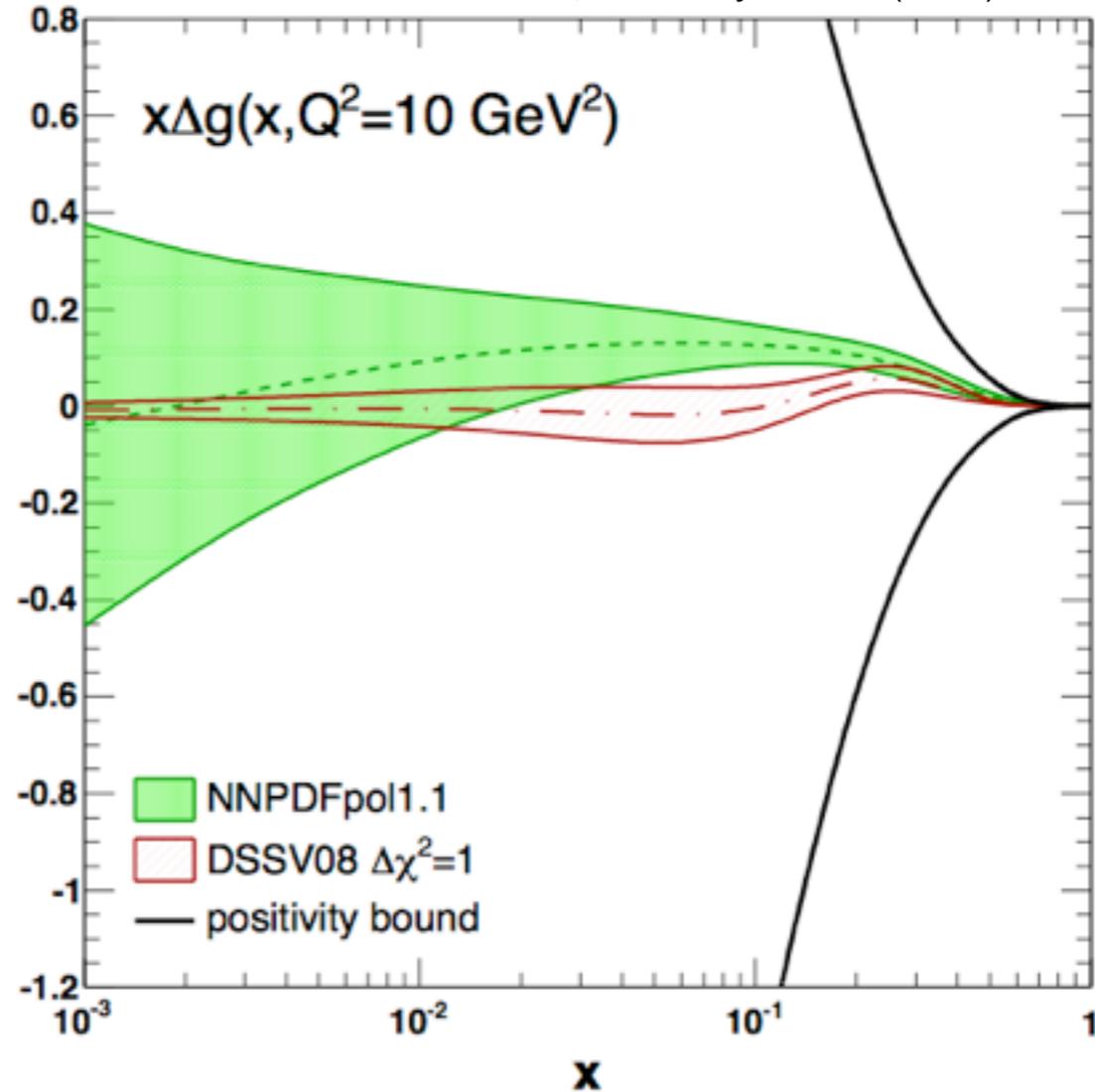
Gluon Polarization - RHIC Impact

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



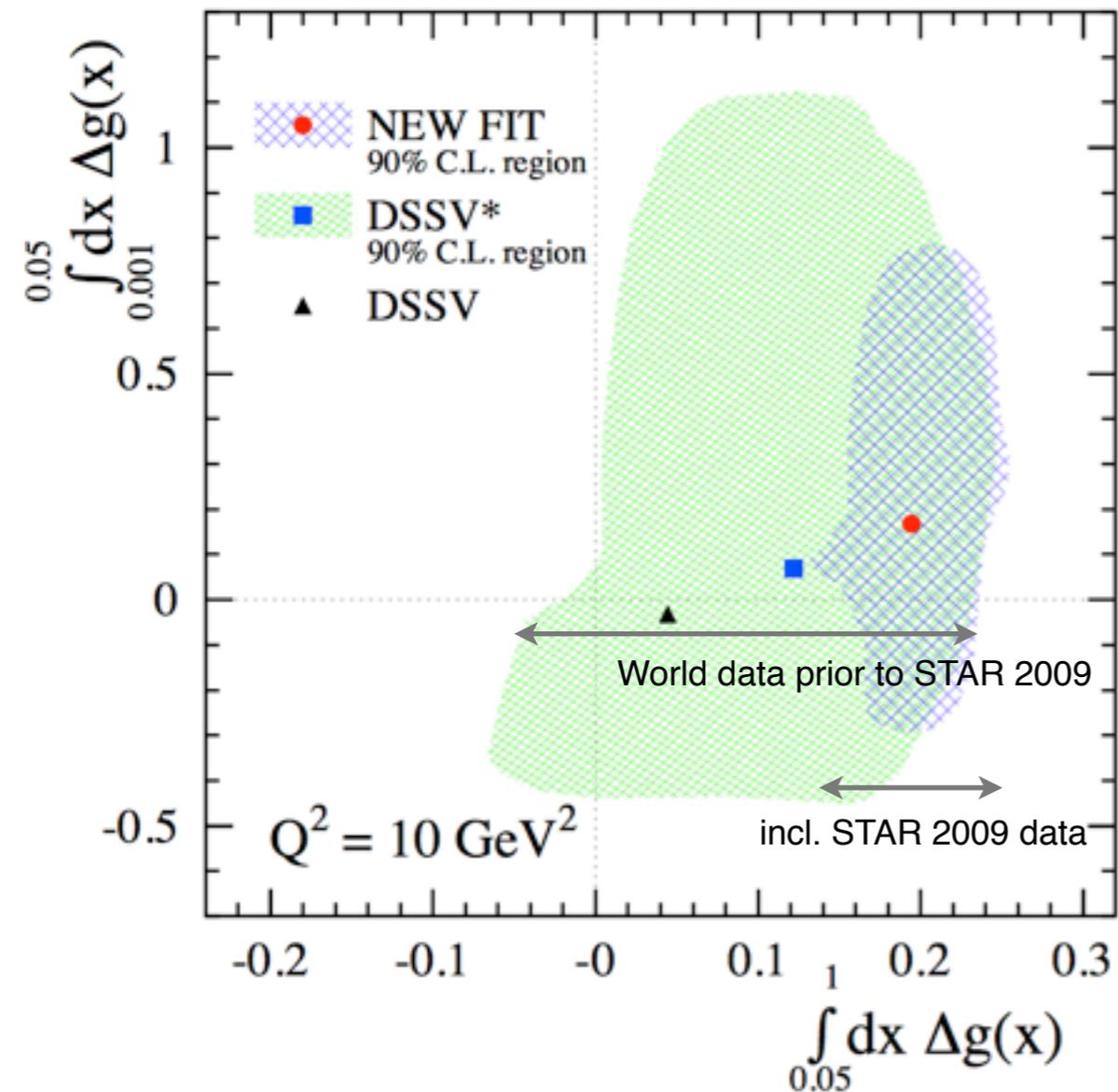
RHIC data, in particular on jets, currently drive the constraints on ΔG in both fits,

$$\begin{aligned} \text{DSSV: } & 0.19^{+0.06}_{-0.05} && \text{at 90\% C.L. for } x > 0.05 \\ \text{NNPDF: } & 0.23 \pm 0.07 && \text{for } 0.05 < x < 0.5 \end{aligned}$$

i.e. evidence for *positive gluon polarization in this kinematic range and at 10 GeV²*.

Gluon Polarization - Status and what is next?

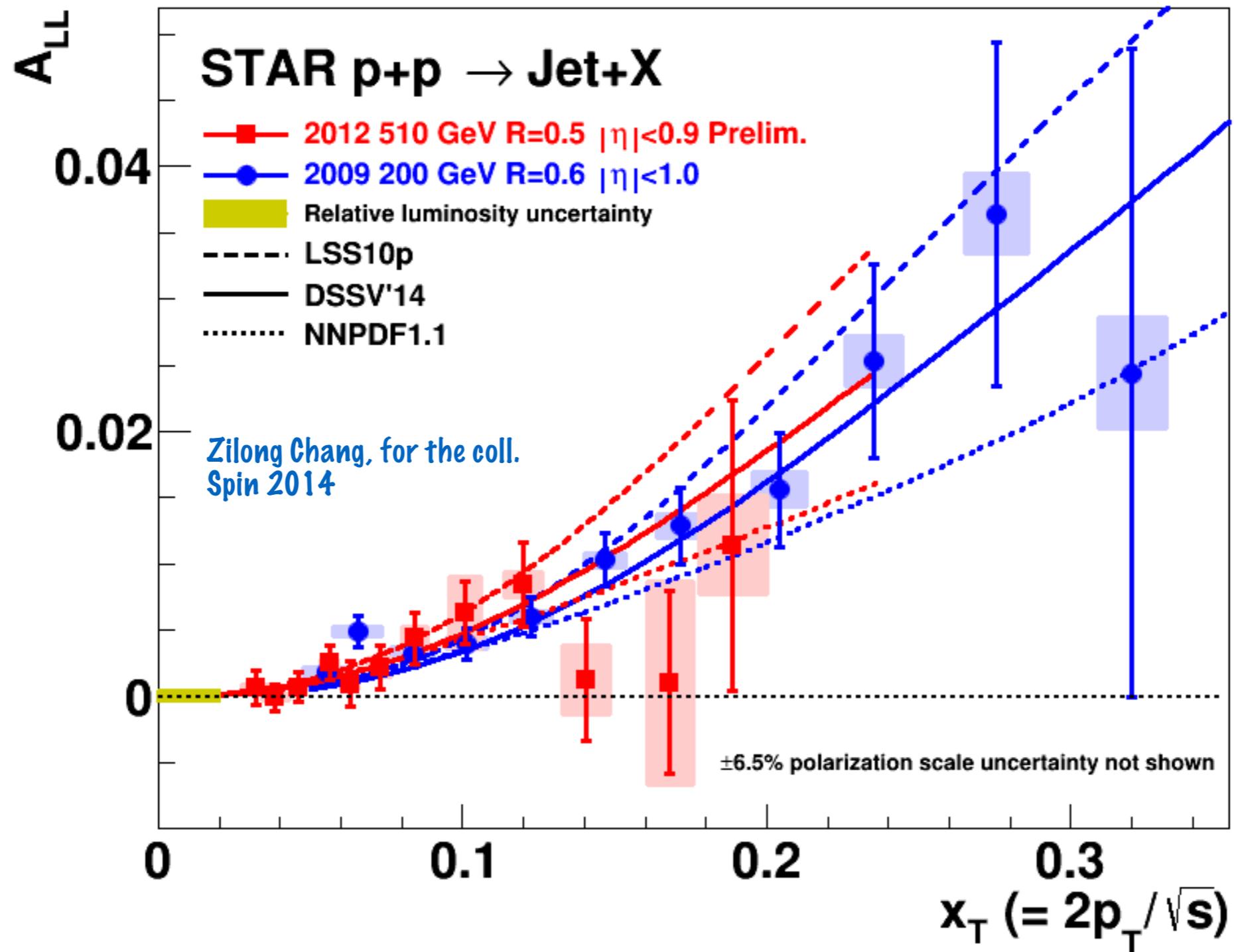
DSSV, Phys.Rev.Lett. 113, 012001



Extend sensitivity to *smaller* x_g
 forward rapidity, $x_g \sim \exp(-\eta)$,
 $\sqrt{s} = 500 \text{ GeV}$ data, $x_g \sim 1/\sqrt{s}$

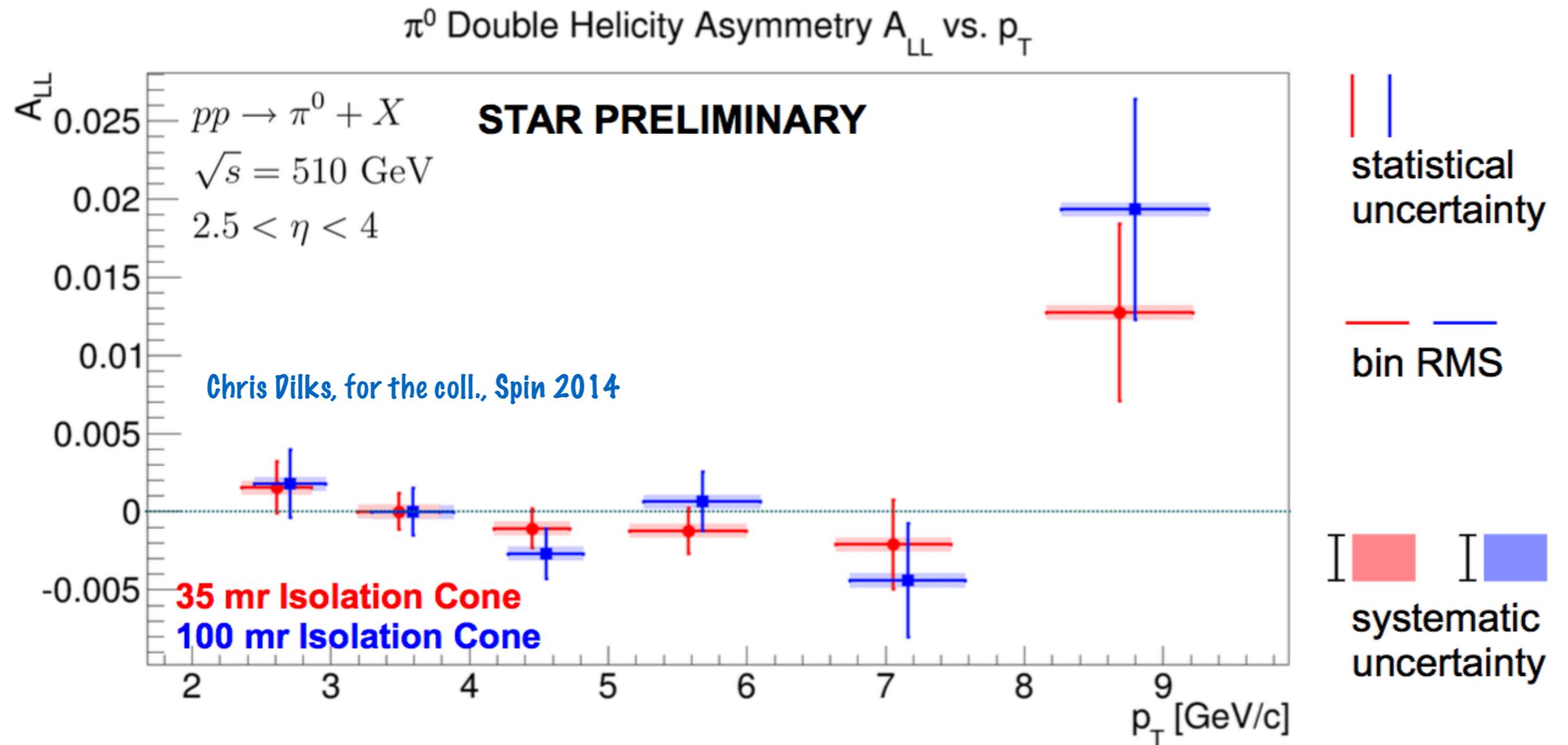
Further *precision* from jet and neutral pion probes, and
 from *complementary* probes

Gluon Polarization - Initial results at $\sqrt{s} = 510$ GeV



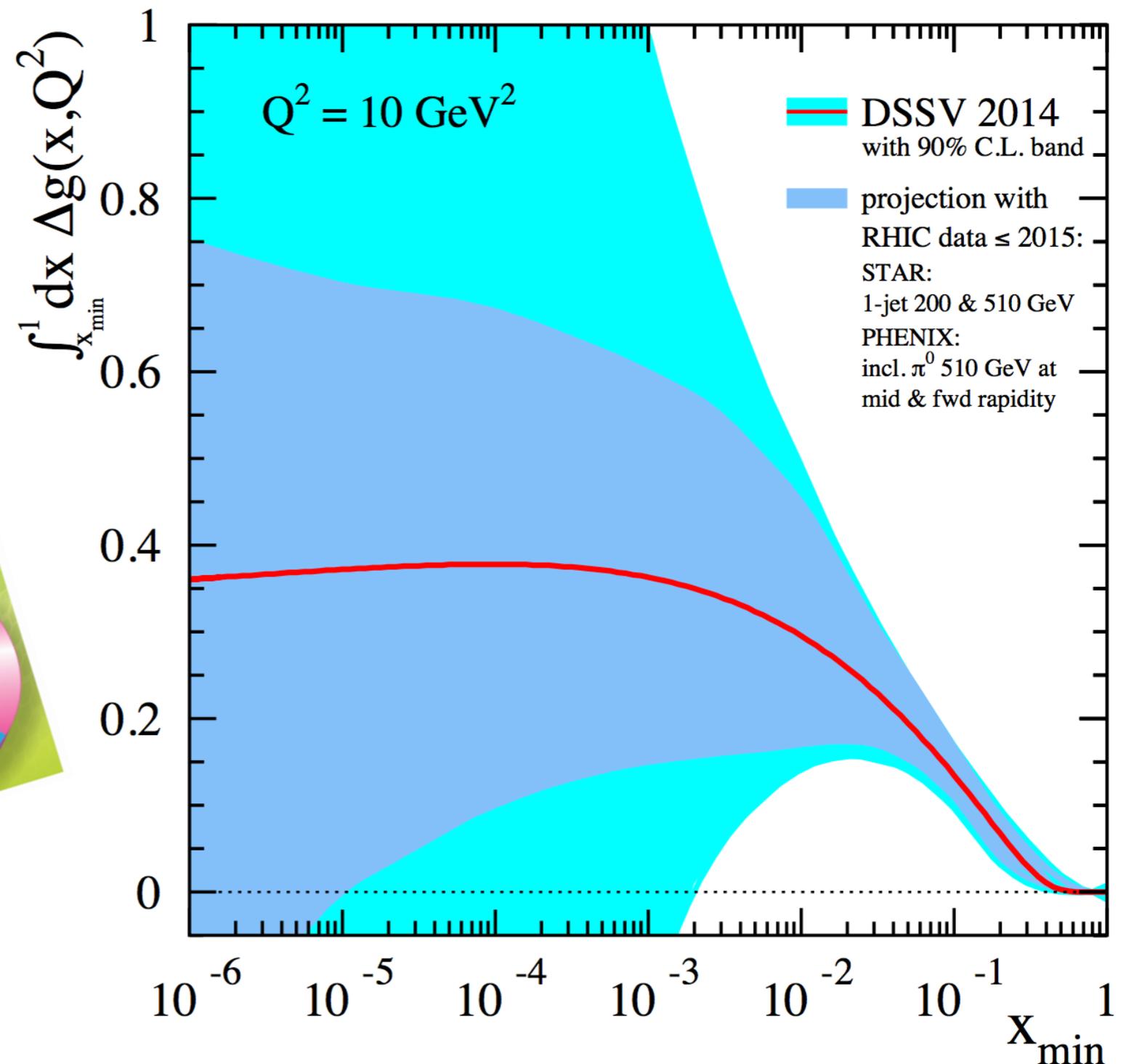
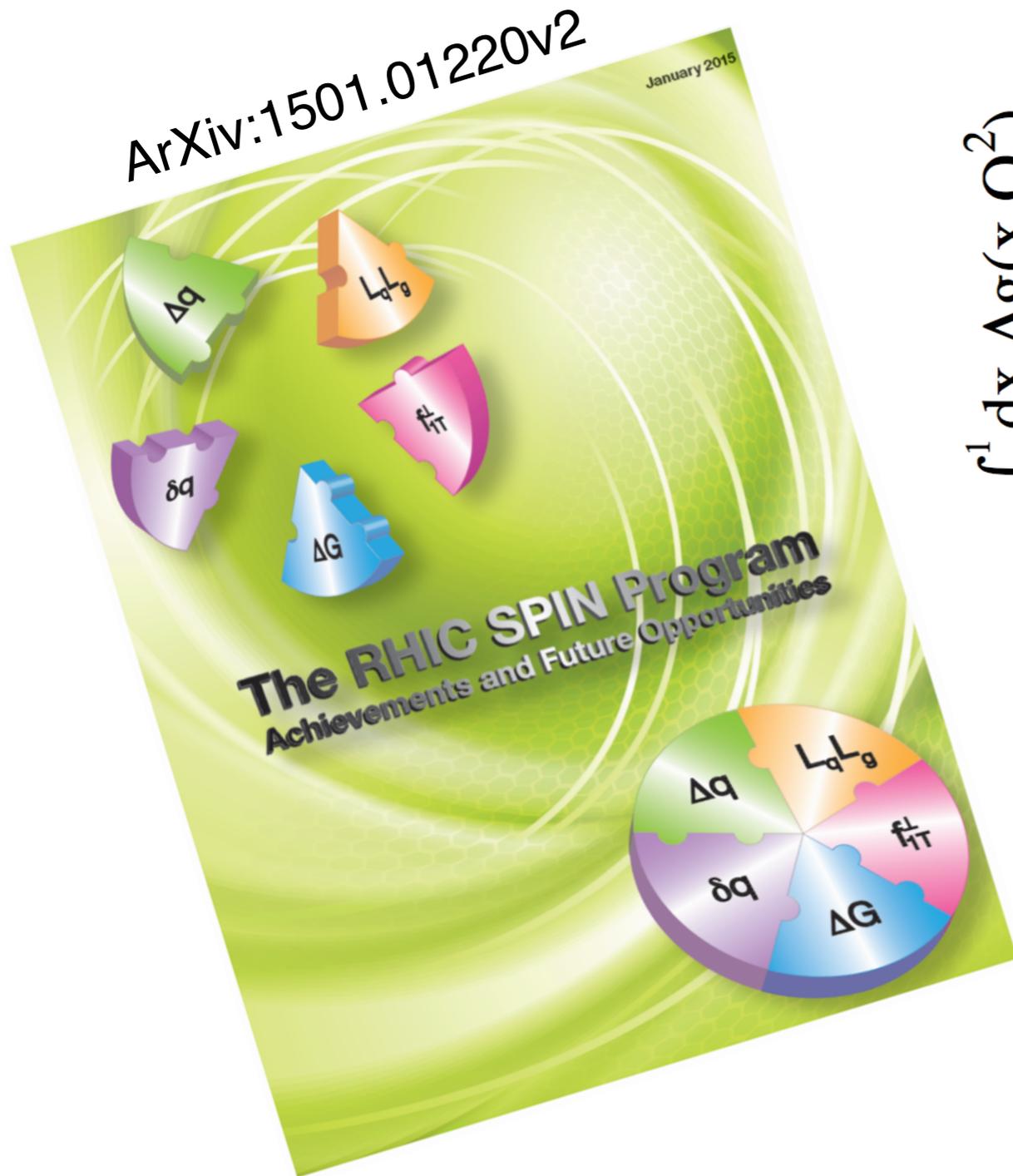
Systematics in $\sqrt{s} = 510$ GeV data are dominated by trigger and reconstruction bias
 Higher collision energy, $\sqrt{s} = 510$ GeV, extends x_T to smaller values
 Good agreement in the region of x_T overlap

Gluon Polarization - Initial forward results at $\sqrt{s} = 510$ GeV



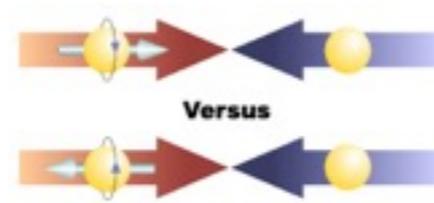
Inclusive analysis in progress

Gluon Polarization - What to expect next?

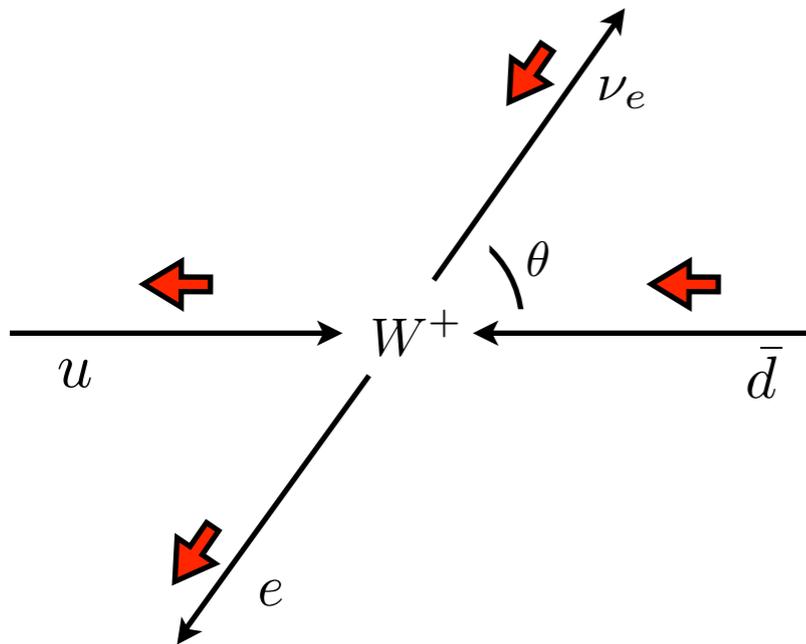


- additional constraints from correlated probes, e.g. di-jets,
- longer term opportunity (2020+): renewed $\sqrt{s} = 500 \text{ GeV}$ operations with forward upgrade

Quark Polarization



Quark Polarization at RHIC



$\sqrt{s} = 500$ GeV above W production threshold,

Experiment Signature:

large p_T lepton, missing E_T

Experiment Challenges:

charge-ID at large $|\text{rapidity}|$
electron/hadron discrimination
luminosity hungry!

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

Spin Measurements:

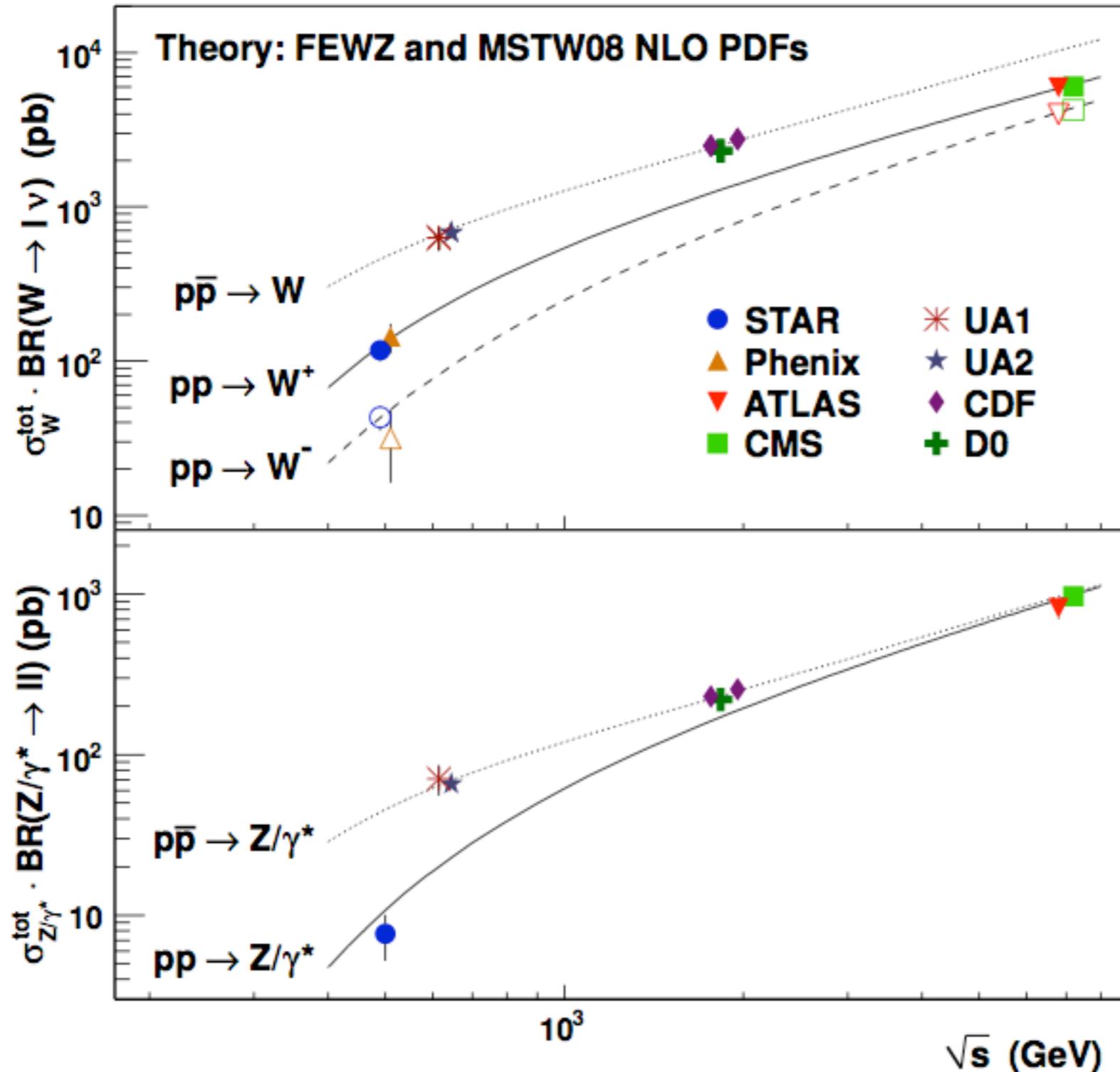
$$A_L(W^+) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} = \begin{cases} -\frac{\Delta u(x_a)}{u(x_a)}, & x_a \rightarrow 1 \\ \frac{\Delta\bar{d}(x_a)}{\bar{d}(x_a)}, & x_b \rightarrow 1 \end{cases}$$

Initial mid-rapidity data in 2009,

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

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,

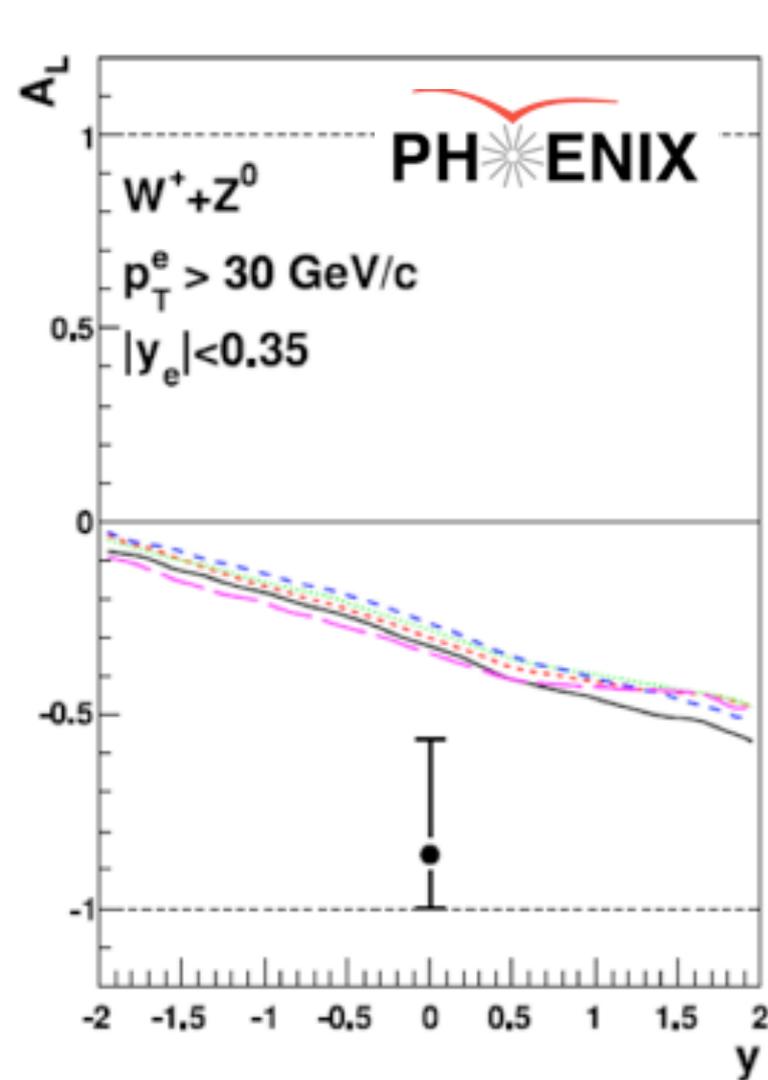
STAR: Initial NC cross section at RHIC, confirmation of PHENIX CC cross section measurements, Phys. Rev. **D85** (2012).

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

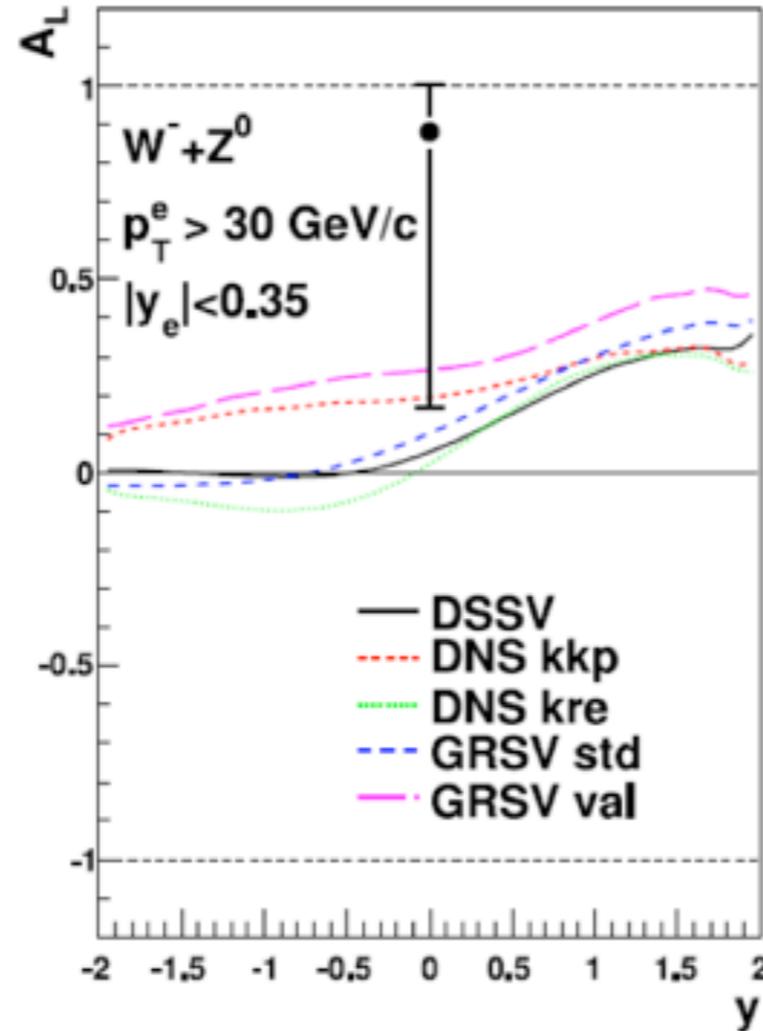
Support NLO pQCD interpretation of the asymmetry measurements,

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

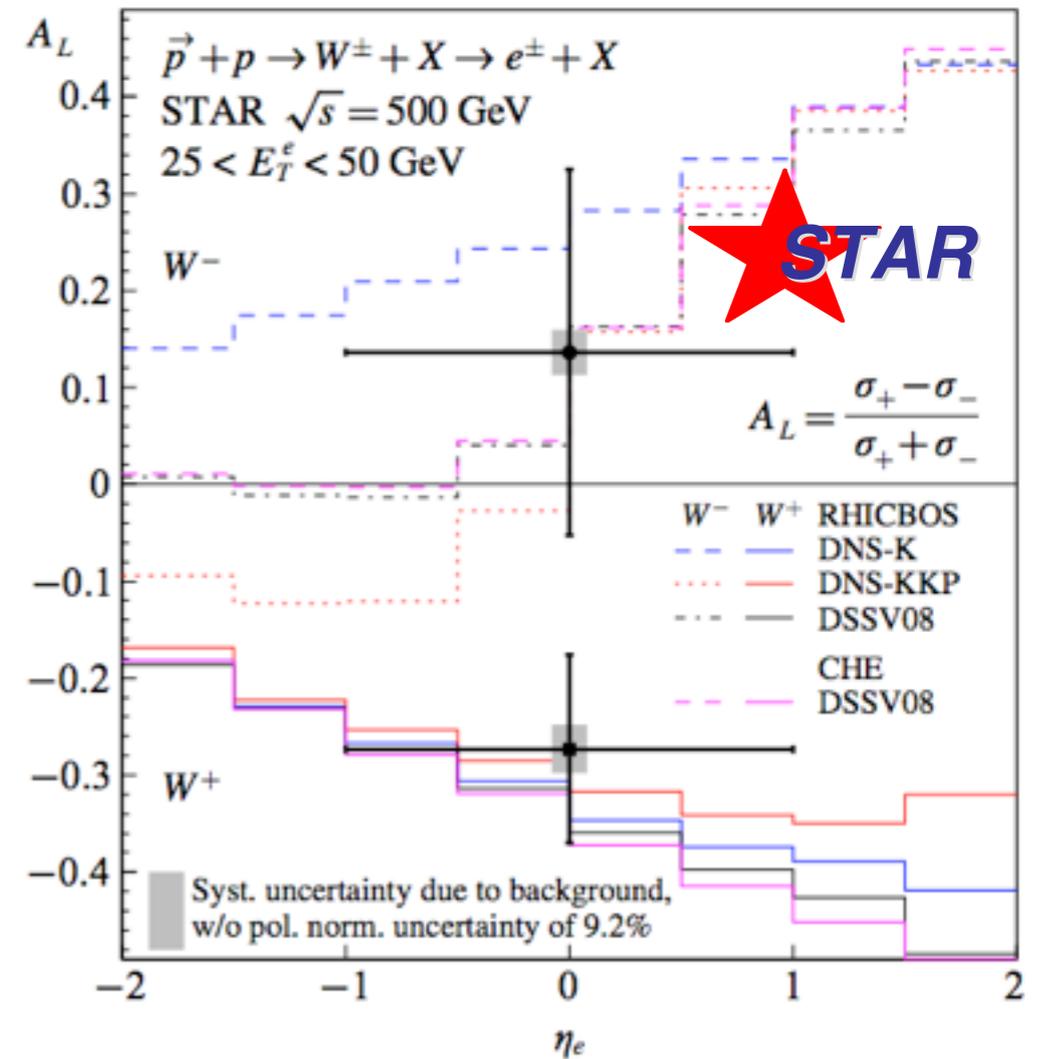
Quark Polarization - *Initial* A_L from RHIC



Phys. Rev. Lett. 106 (2011) 062001



Phys. Rev. Lett. 106 (2011) 062002



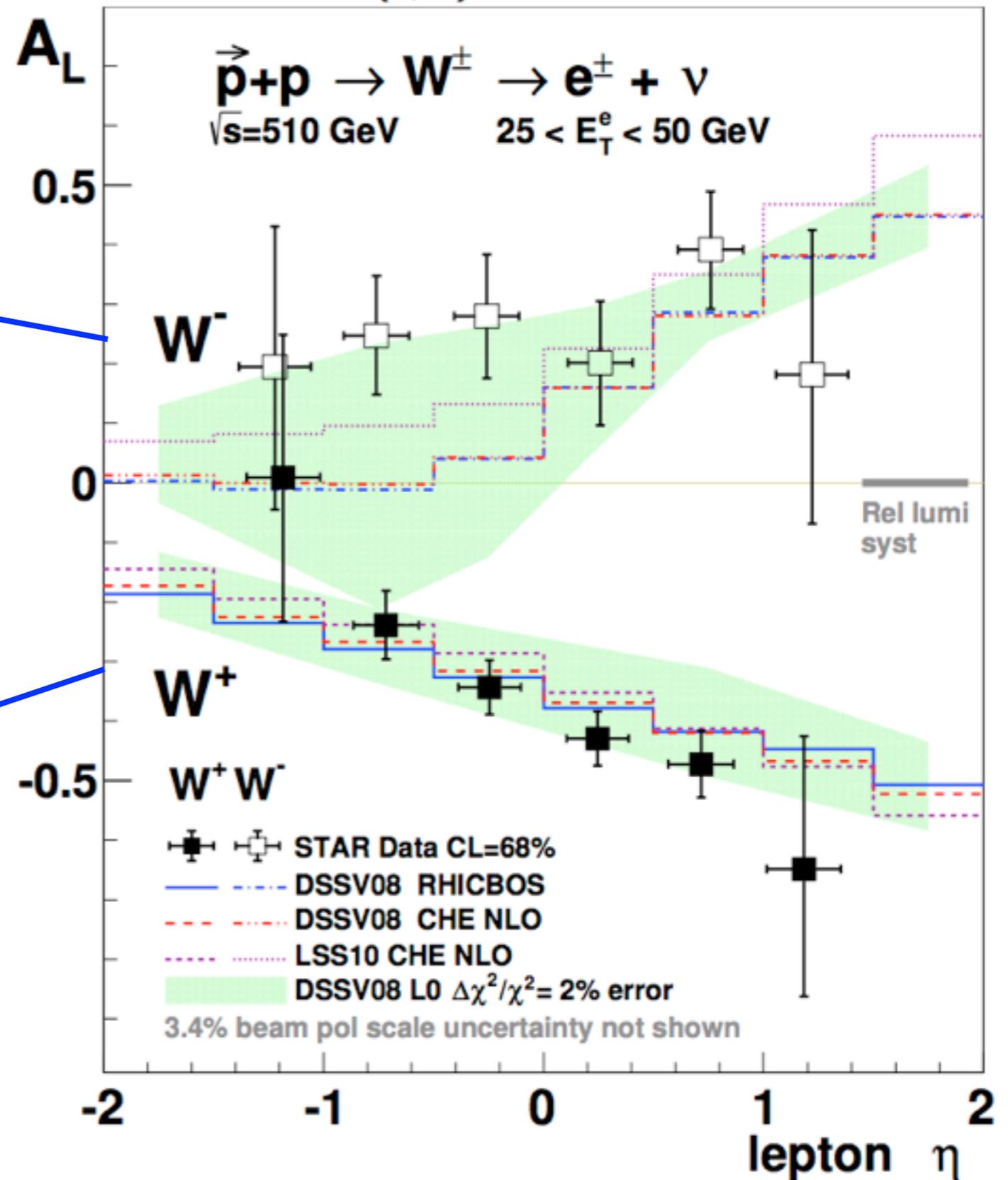
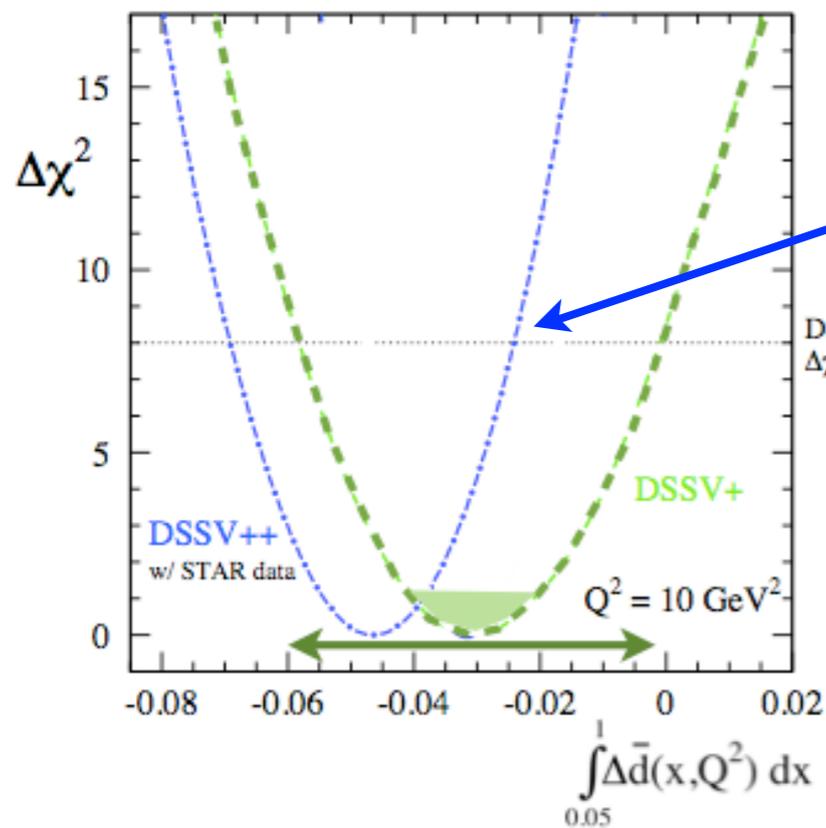
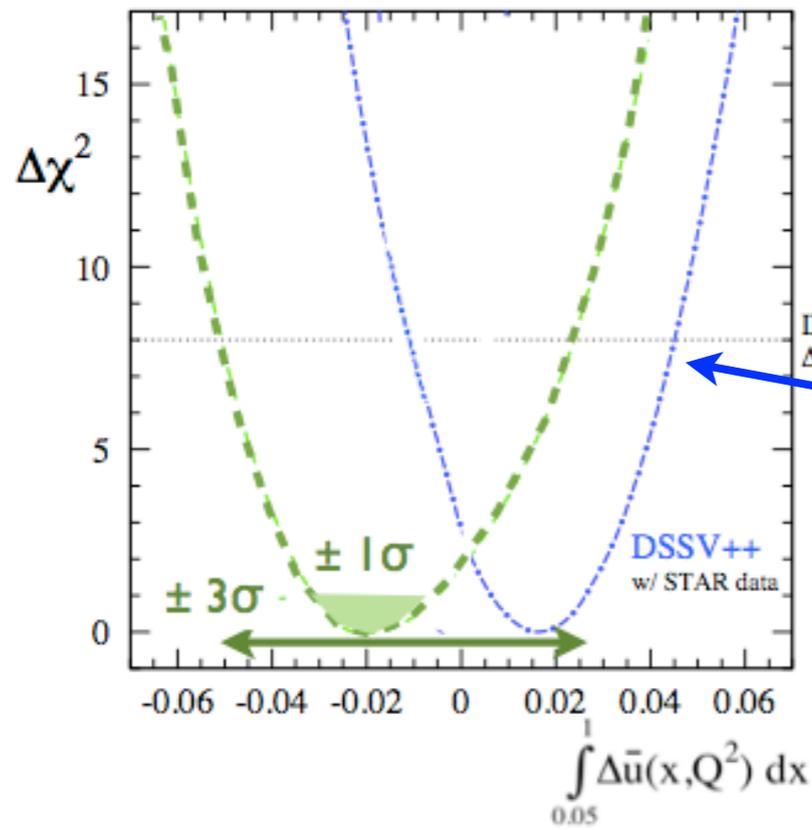
Initial mid-rapidity decay electron and positron measurements,

Confirm NLO polarized expectations, but do not discriminate,

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

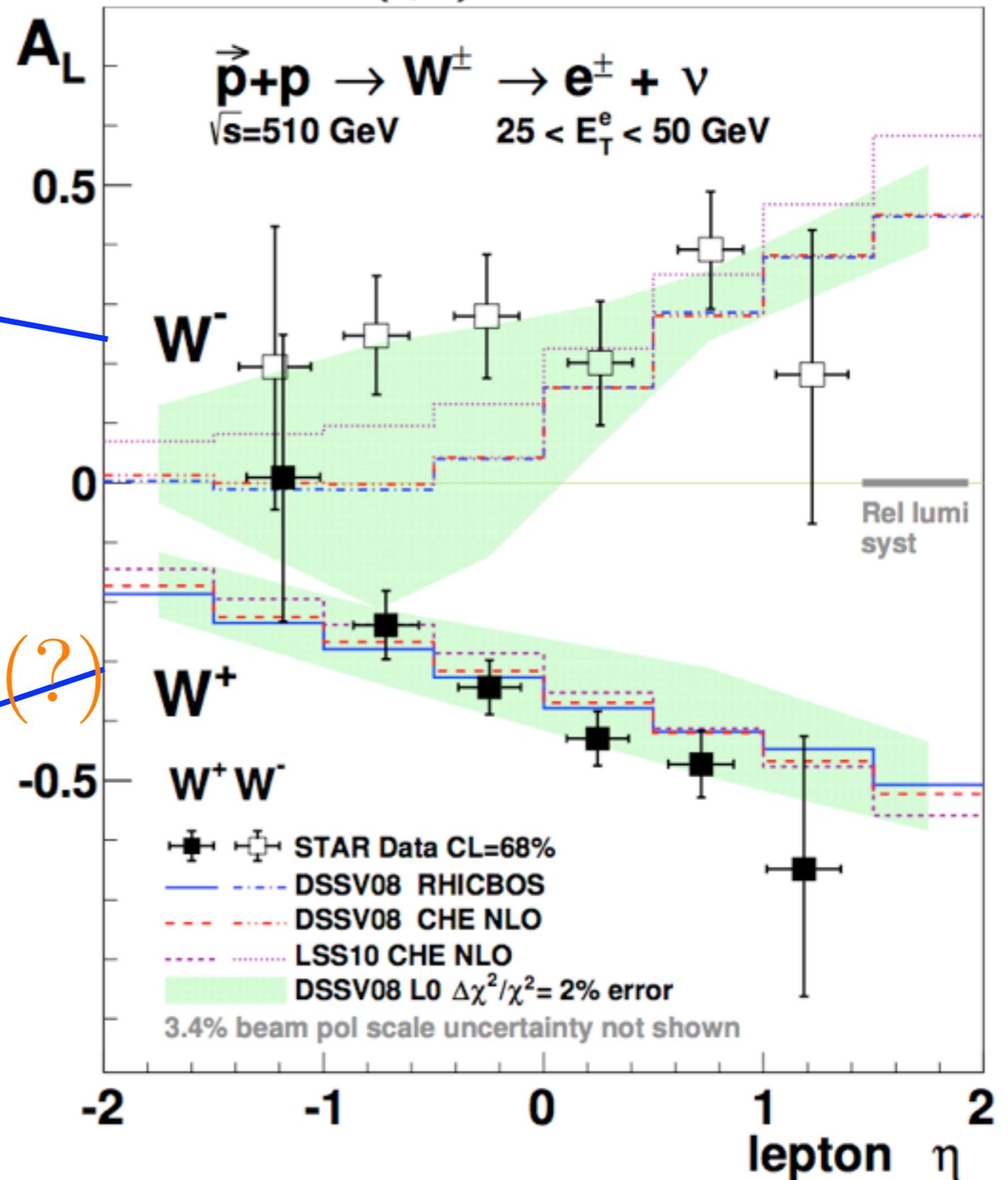
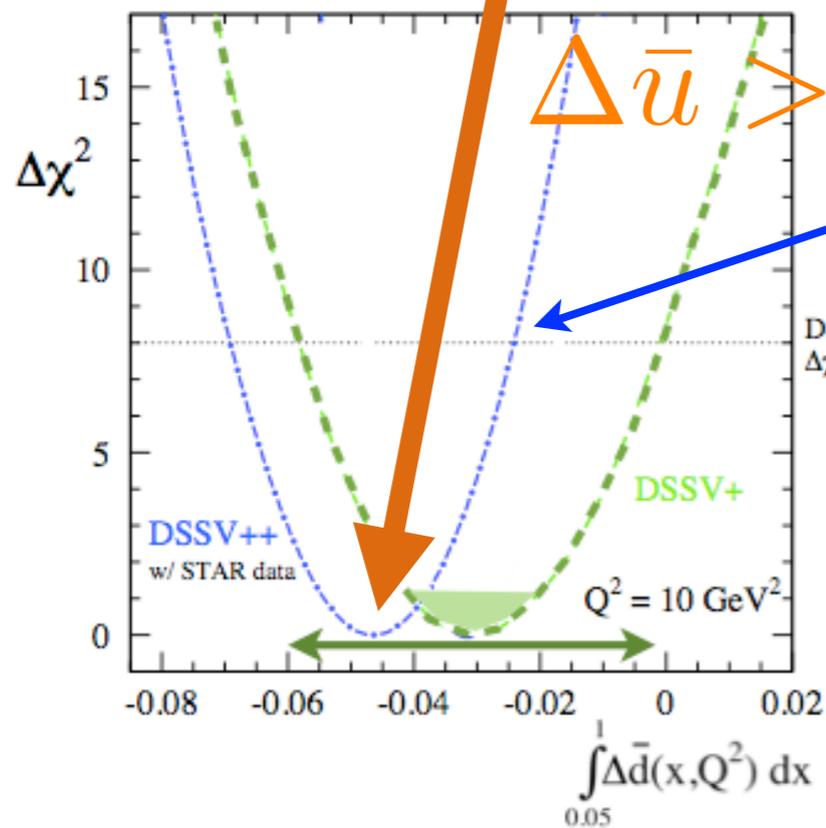
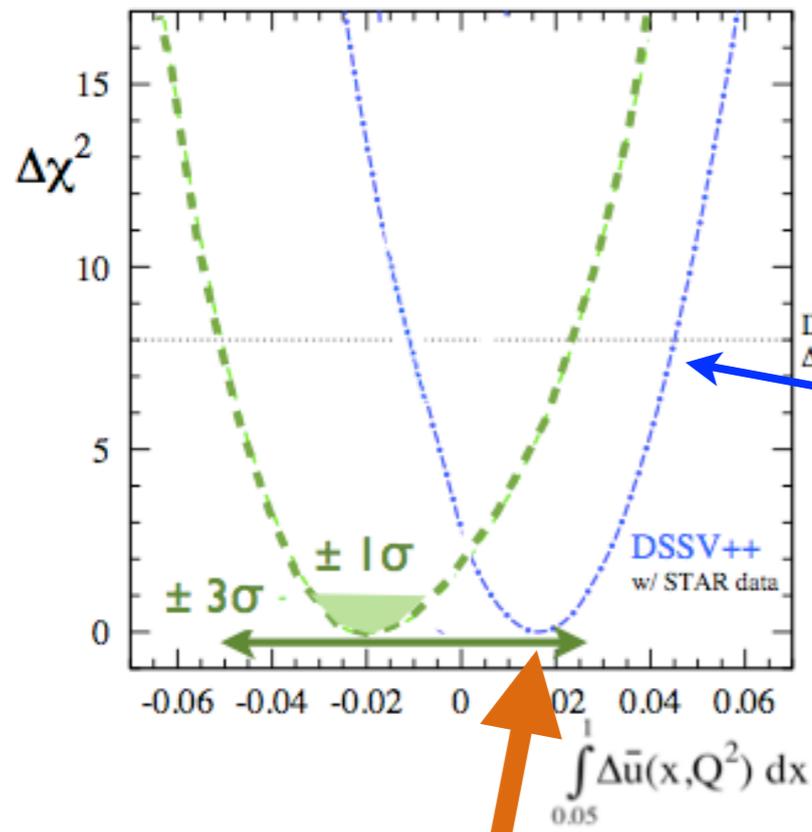
Quark Polarization - *More Precise* A_L from RHIC

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



Quark Polarization - *More Precise* A_L from RHIC

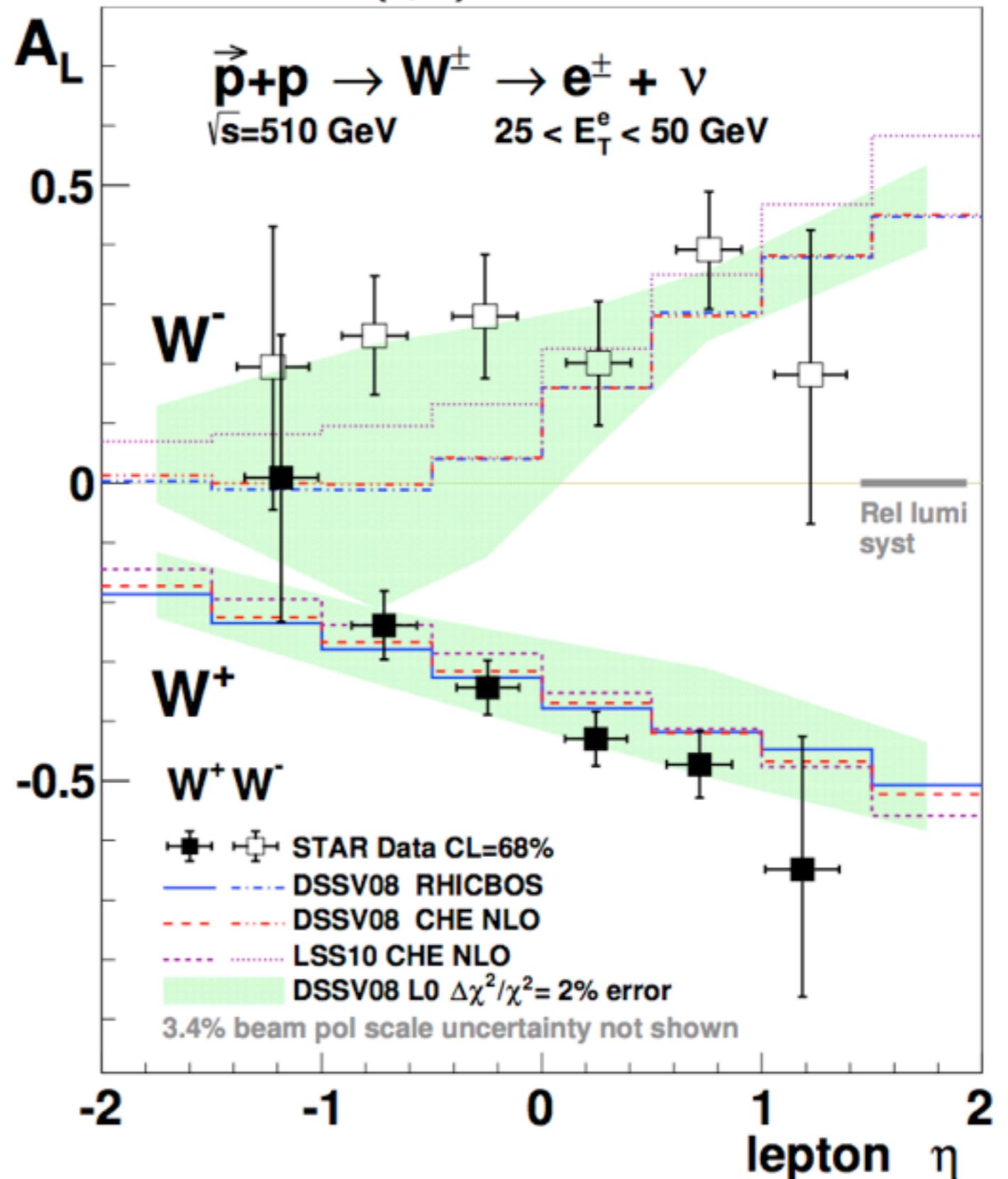
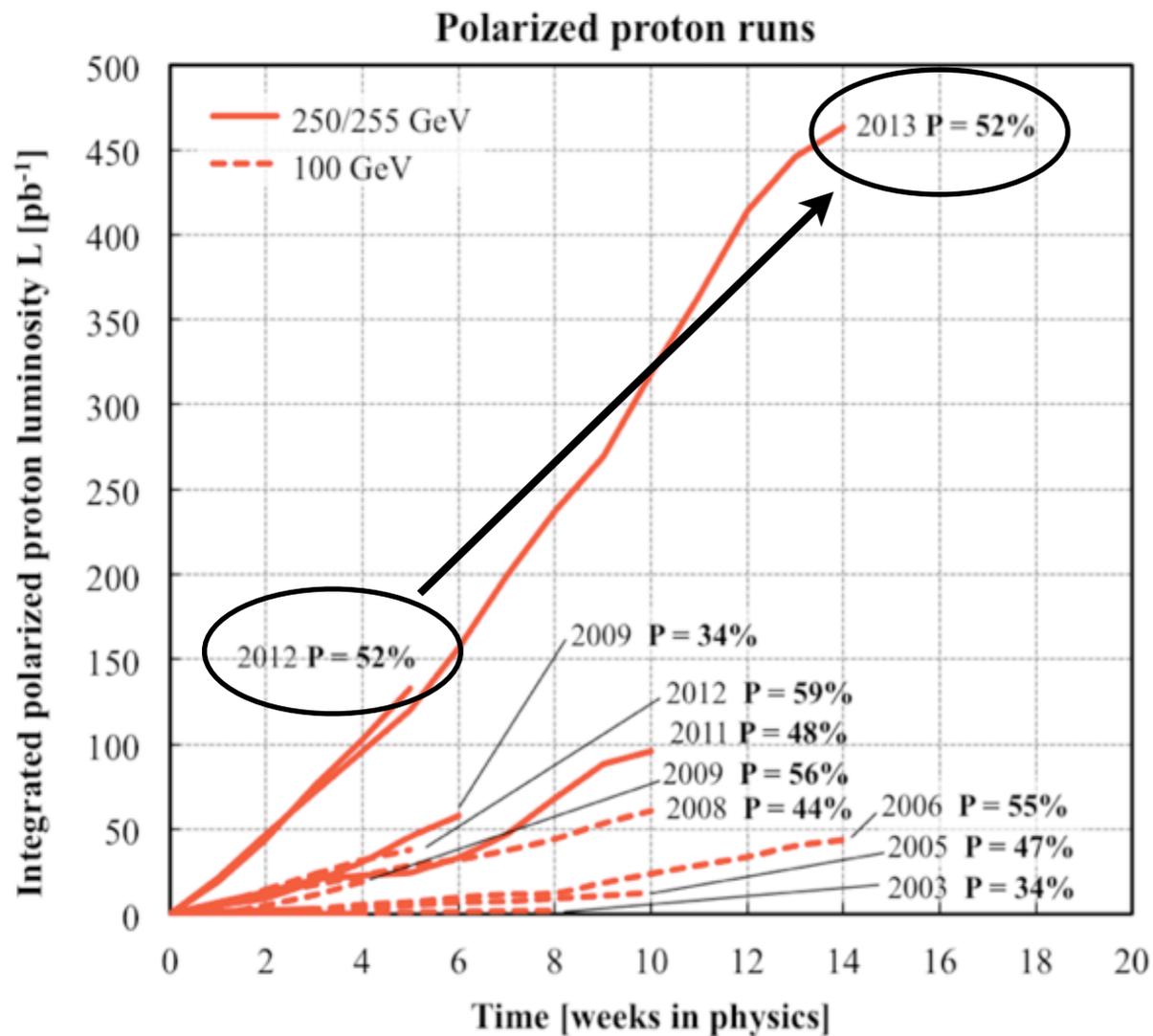
Phys. Rev. Lett. 113, 072301 (2014)



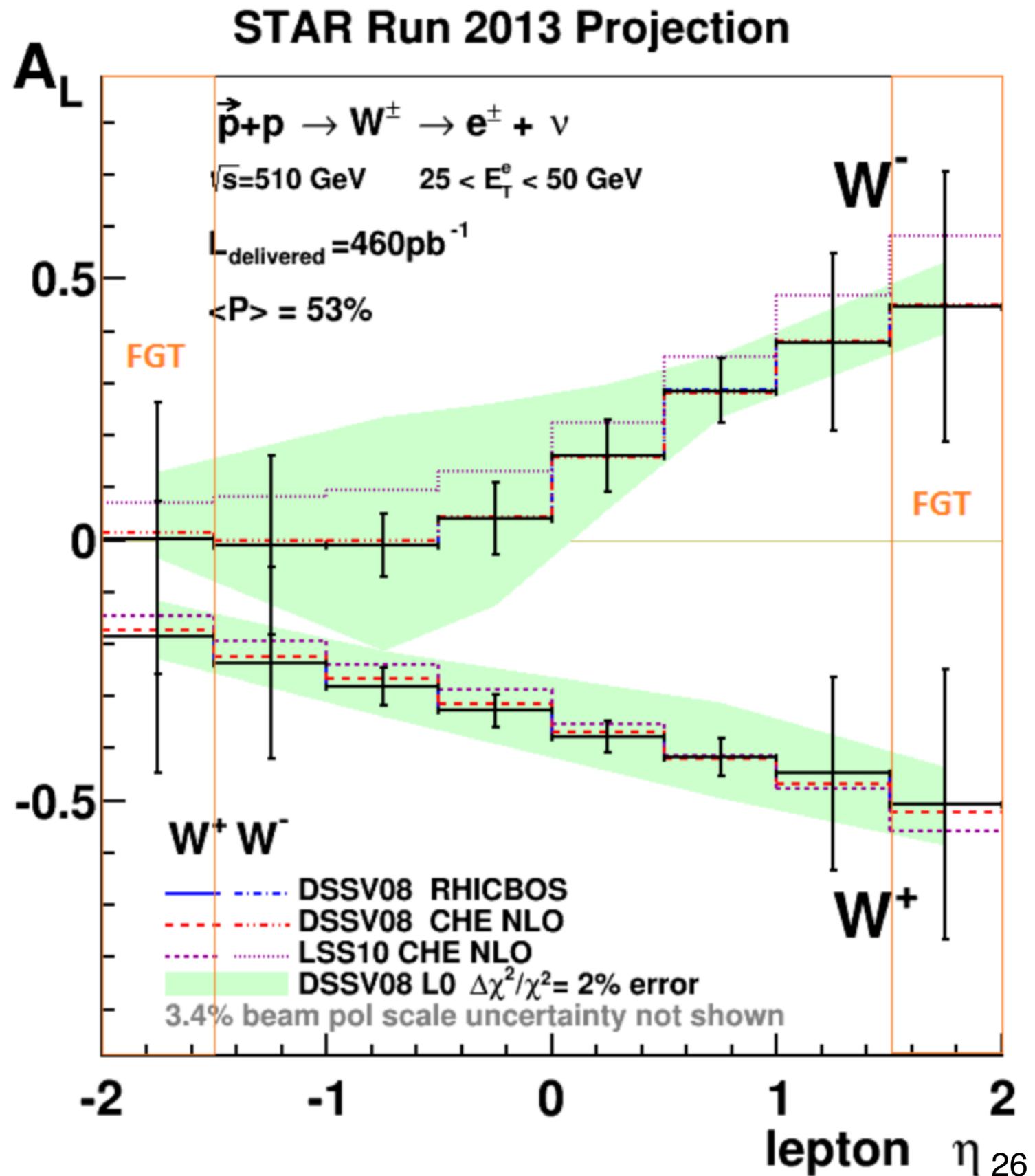
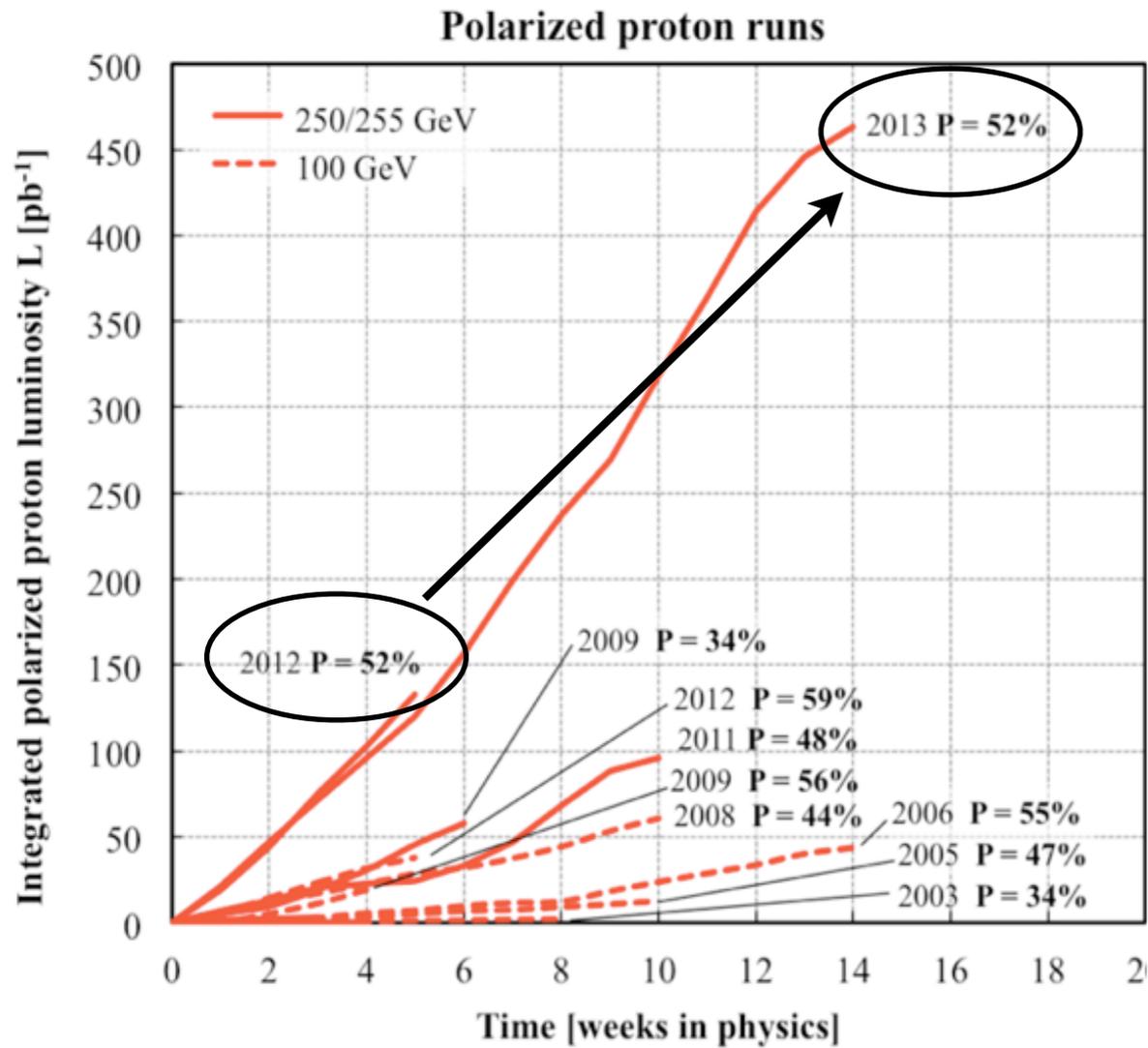
Quark Polarization - Next Steps

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

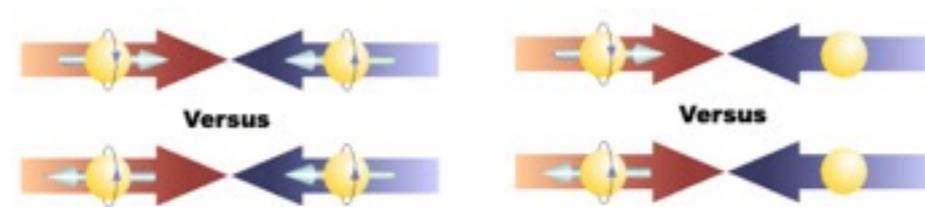
This is “only” the 2011 and 2012 data, 2013 is to come.



Quark Polarization - Next Steps



Completion of RHIC and transition to EIC

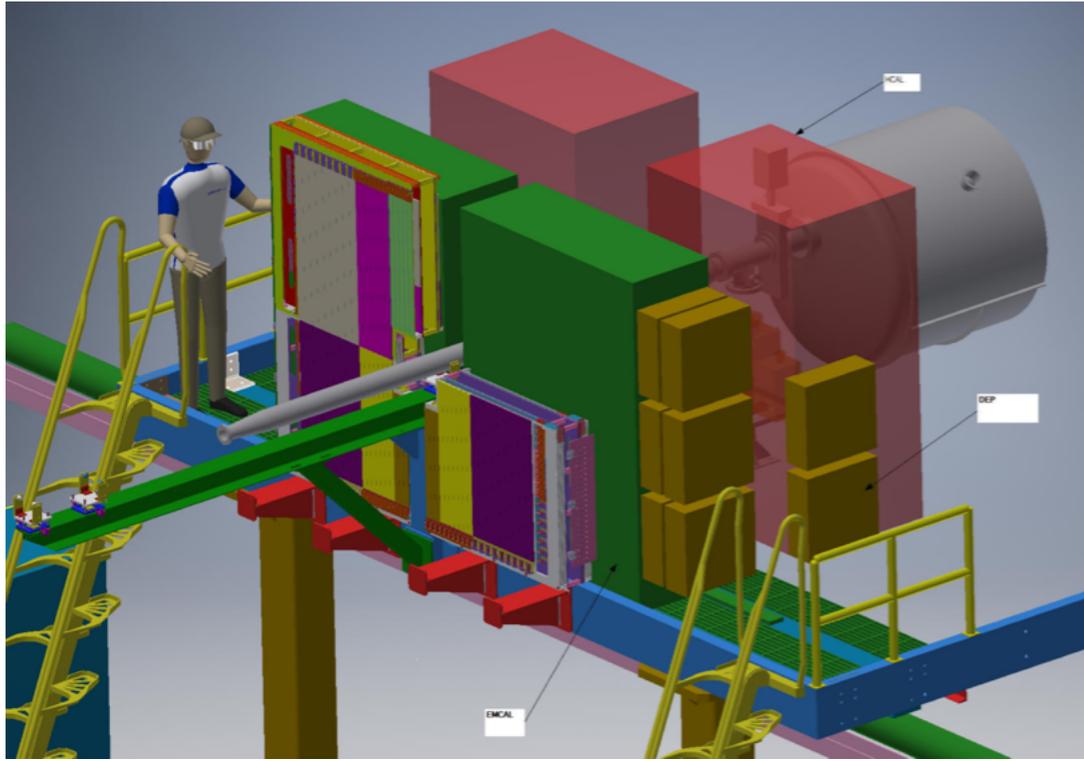


From BNL ALD Berndt Mueller presentation at the 2015 RHIC and AGS Users' Meeting:

Proposed run schedule for RHIC

Years	Beam Species and	Science Goals	New Systems
2014	Au+Au at 15 GeV Au+Au at 200 GeV ³ He+Au at 200 GeV	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p↑+p↑ at 200 GeV p↑+Au, p↑+Al at 200 GeV High statistics Au+Au Au+Au at 62 GeV ?	Extract $\eta/s(T)$ + constrain initial quantum fluctuations Complete heavy flavor studies Sphaleron tests Parton saturation tests	PHENIX MPC-EX STAR FMS preshower Roman Pots Coherent e-cooling test
2017	p↑+p↑ at 510 GeV	Transverse spin physics Sign change in Sivers function	
2018	No Run		Low energy e-cooling install. STAR iTPC upgrade
2019-20	Au+Au at 5-20 GeV (BES-2)	Search for QCD critical point and onset of deconfinement	Low energy e-cooling
2021-22	Au+Au at 200 GeV p↑+p↑, p↑+Au at 200 GeV	Jet, di-jet, γ -jet probes of parton transport and energy loss mechanism Color screening for different quarkonia Forward spin & initial state physics	sPHENIX Forward upgrades ?
≥ 2023 ?	No Runs		Transition to eRHIC

STAR Forward Upgrade



STAR plans to upgrade its forward instrument:

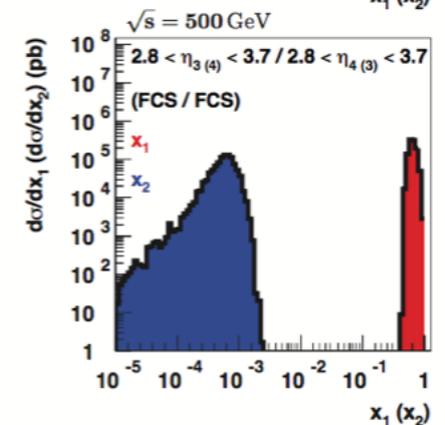
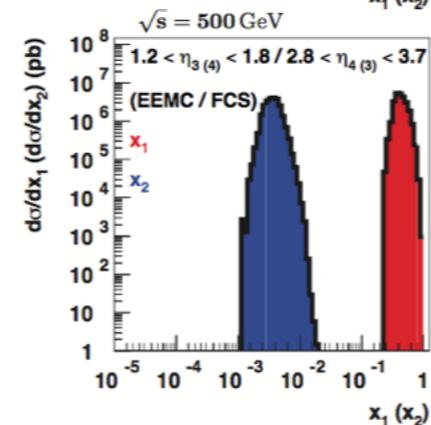
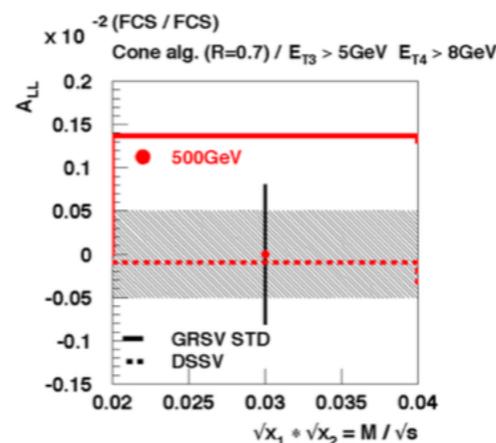
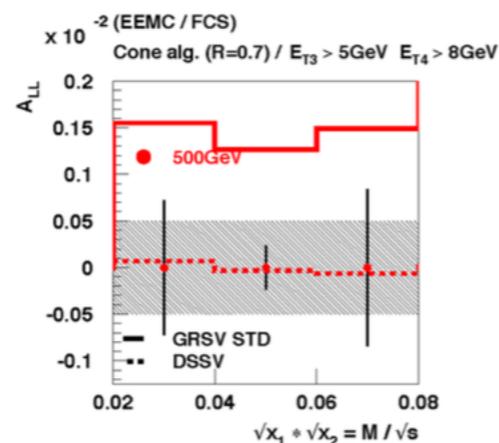
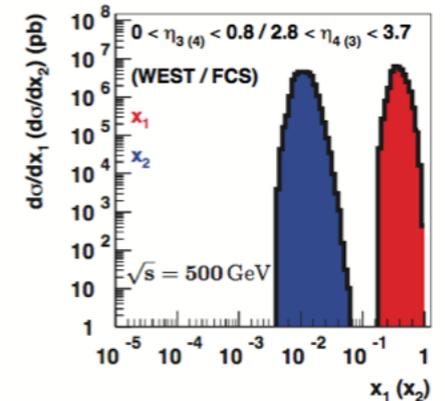
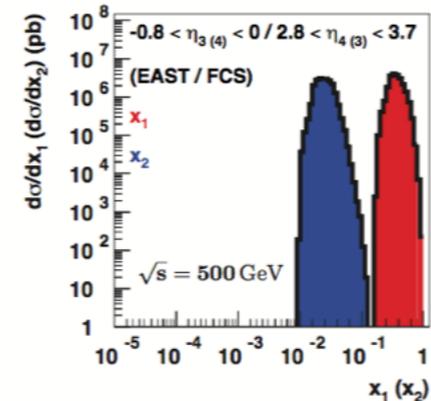
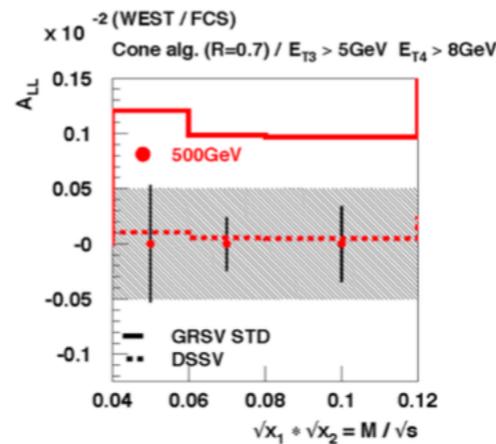
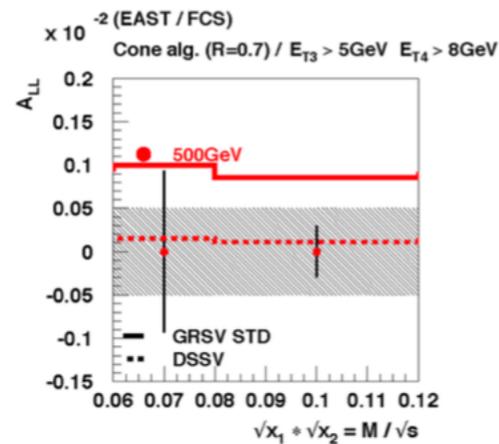
- electromagnetic and hadronic calorimetry,
- tracking,

in a *cost-effective* way as part of its overall upgrade plan,

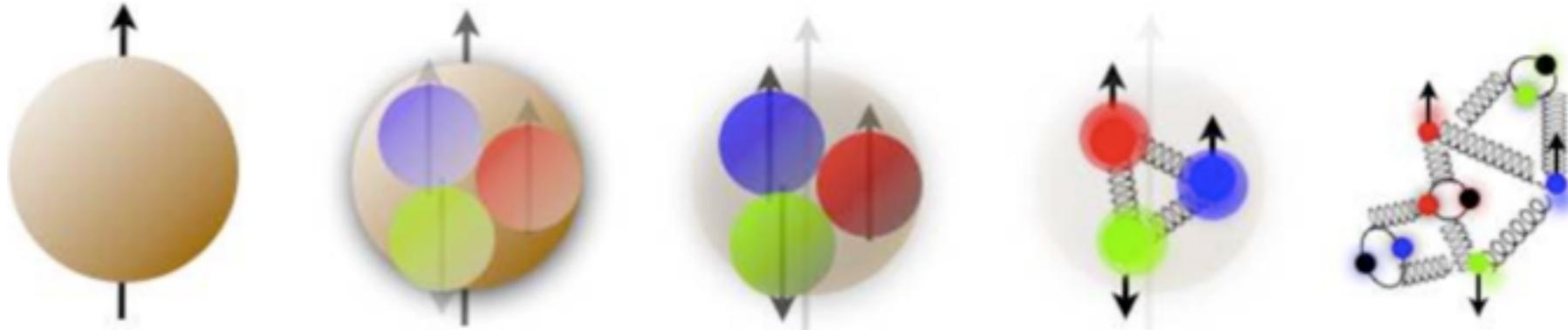
Physics objectives span p+p, p+A, and A+A,

A talk in itself, really...

Unique opportunity to extend ΔG to smaller x , prior to EIC:



Closing Remarks



Gluon Polarization - *very significant constraints from RHIC inclusive jets and pions, evidence for positive gluon polarization for $x_{\text{gluon}} \sim 0.05 - 0.2$ at the level of ~ 0.2 at 10 GeV^2*

Initial results from $\sqrt{s} = 510 \text{ GeV}$; multiple analyses in progress,
Opportunities 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,
2013 data analysis is in progress.

Transverse Spin - see Qinghua Xu's talk tomorrow.

Long-term future - transition to EIC, see Zein-Eddine Meziani's talk tomorrow.

Thank you and Stay Tuned!