Opportunities with polarized beams at RHIC / EIC

Ernst Sichtermann, LBL

- introduction to RHIC and its detectors,
- recent achievements, open questions,
- near-term opportunities, 2017 run
- completion of RHIC and transition to EIC

COMPASS beyond 2020
CERN - March 21, 2016

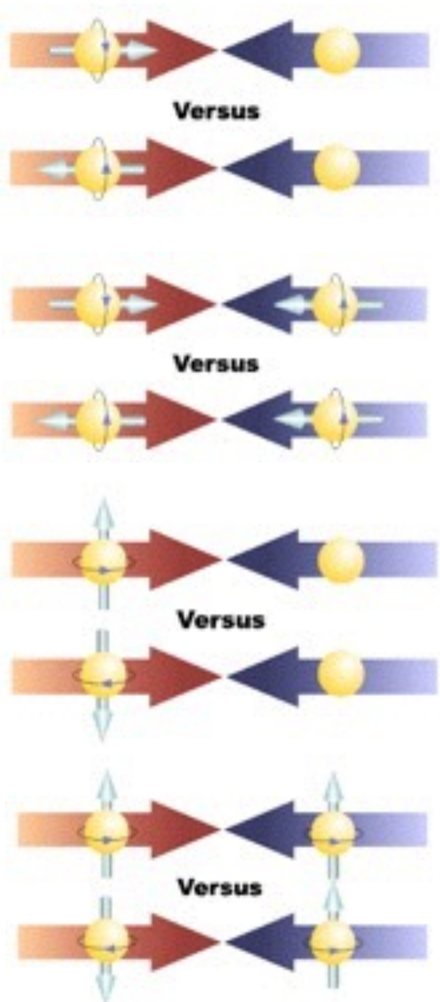
BERKELEY LAB

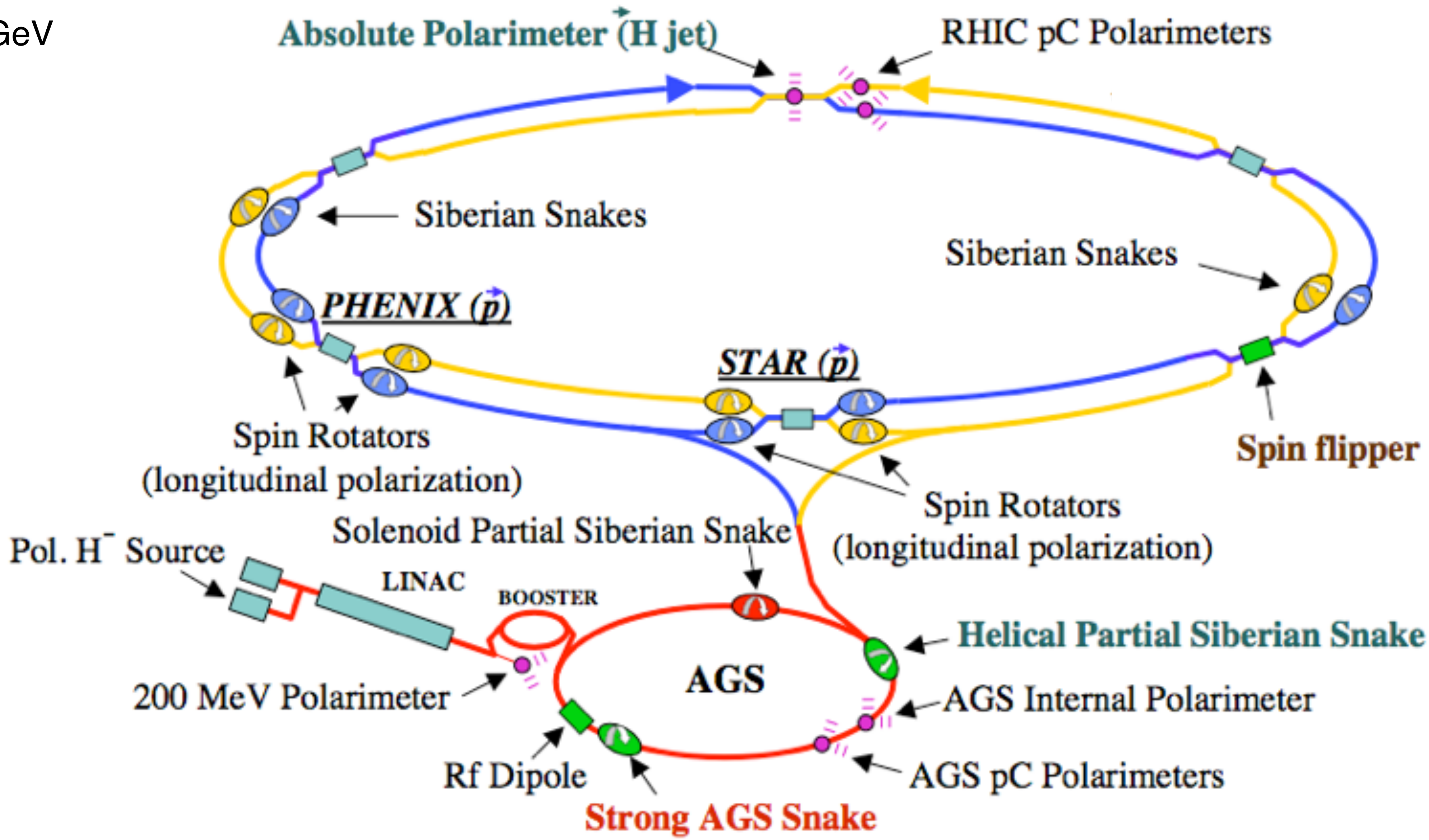
Office of Science
U.S. Department of Energy

RHIC - Polarized Proton-Proton Collider

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

$\sqrt{s}$ = 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.

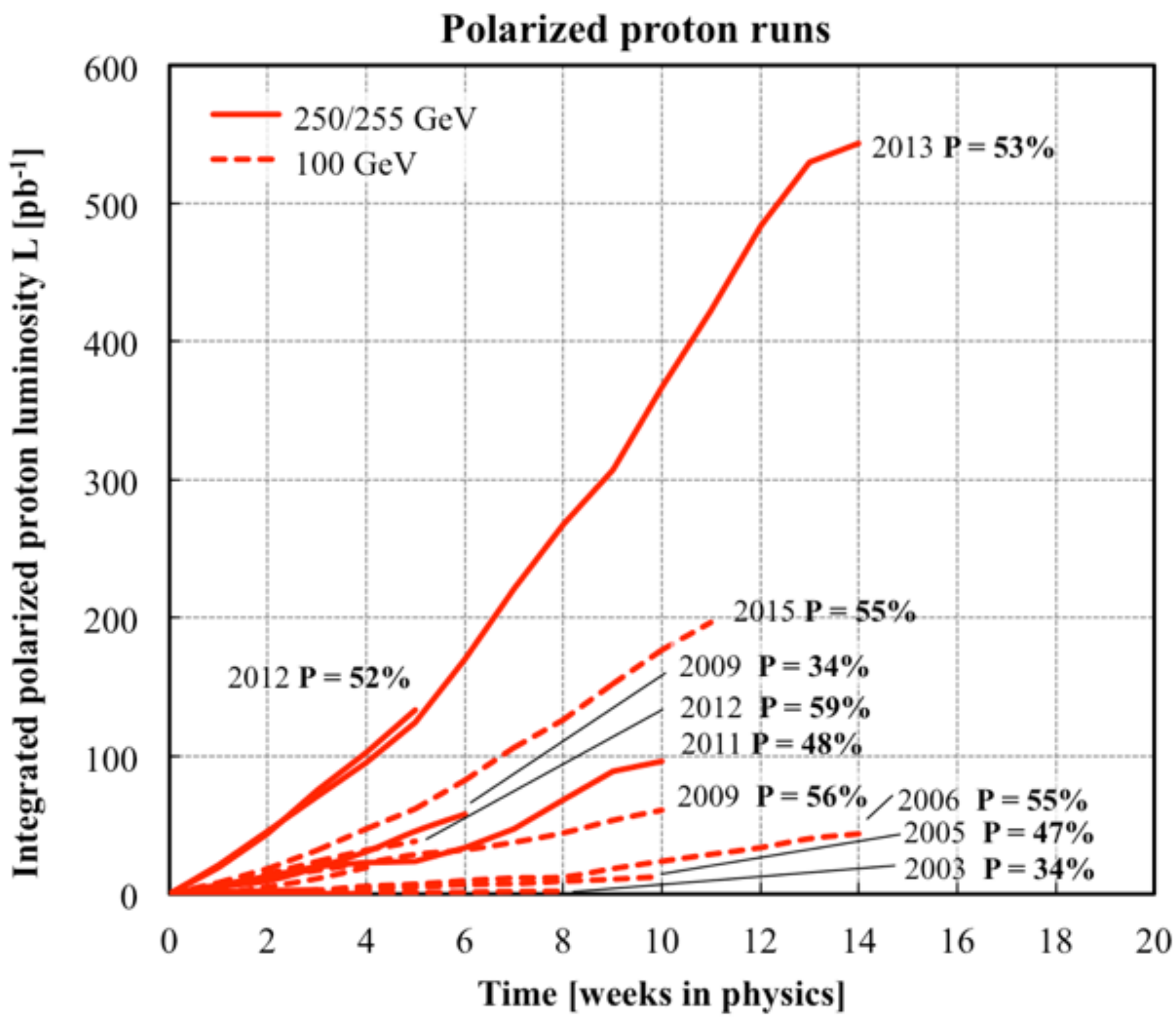
RHIC - Polarized Proton-Proton Collider

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

Longitudinal data	**STAR**
√s = **200 GeV**	
2005	
2006	35 pb^{-1}
2009	
2015	50 pb^{-1}
√s = **500 GeV**	
2009	
2011	
2012	400 pb^{-1}
2013	

Transverse data	
√s = **200 GeV**	
2006	
2008	38 pb^{-1}
2012	
2015	40 pb^{-1}
√s = **500 GeV**	
2011	25 pb^{-1}
(2017)	(400 pb^{-1})

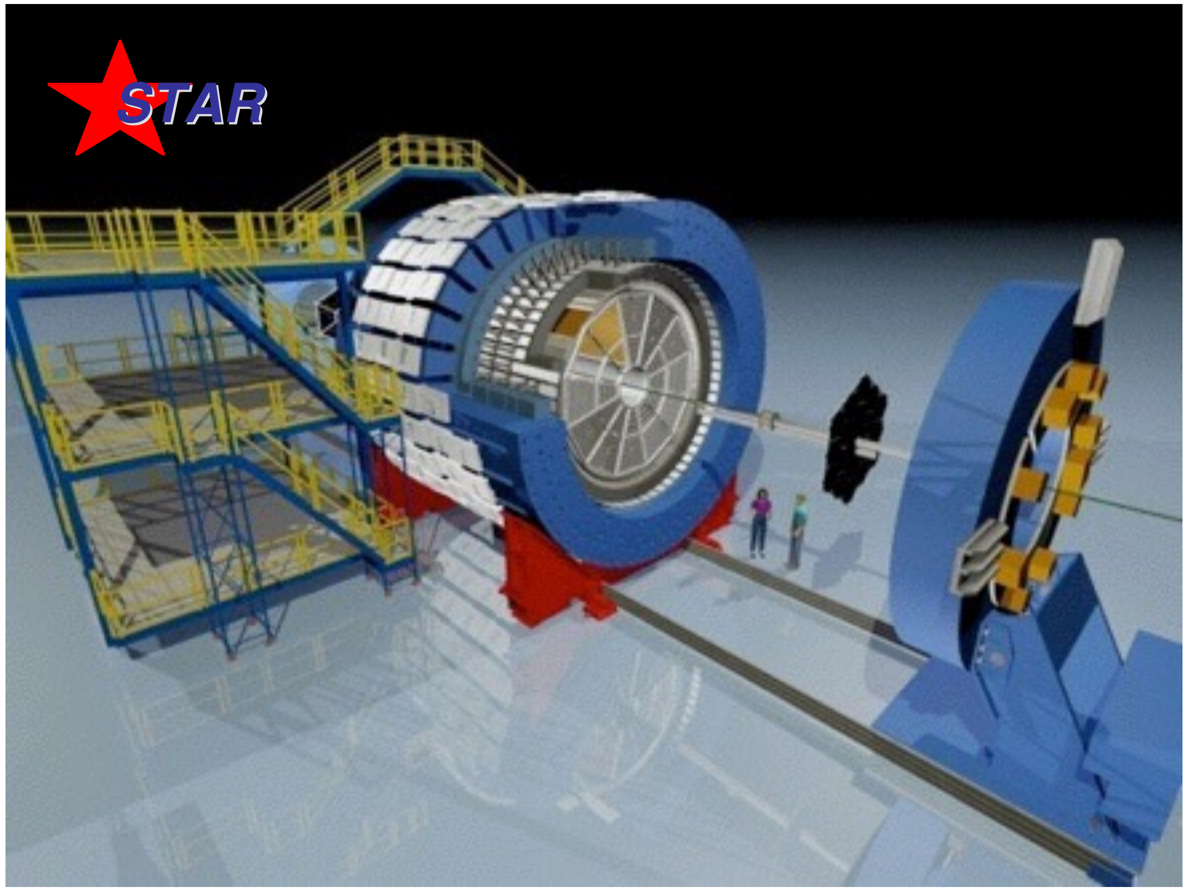
50-60% polarization

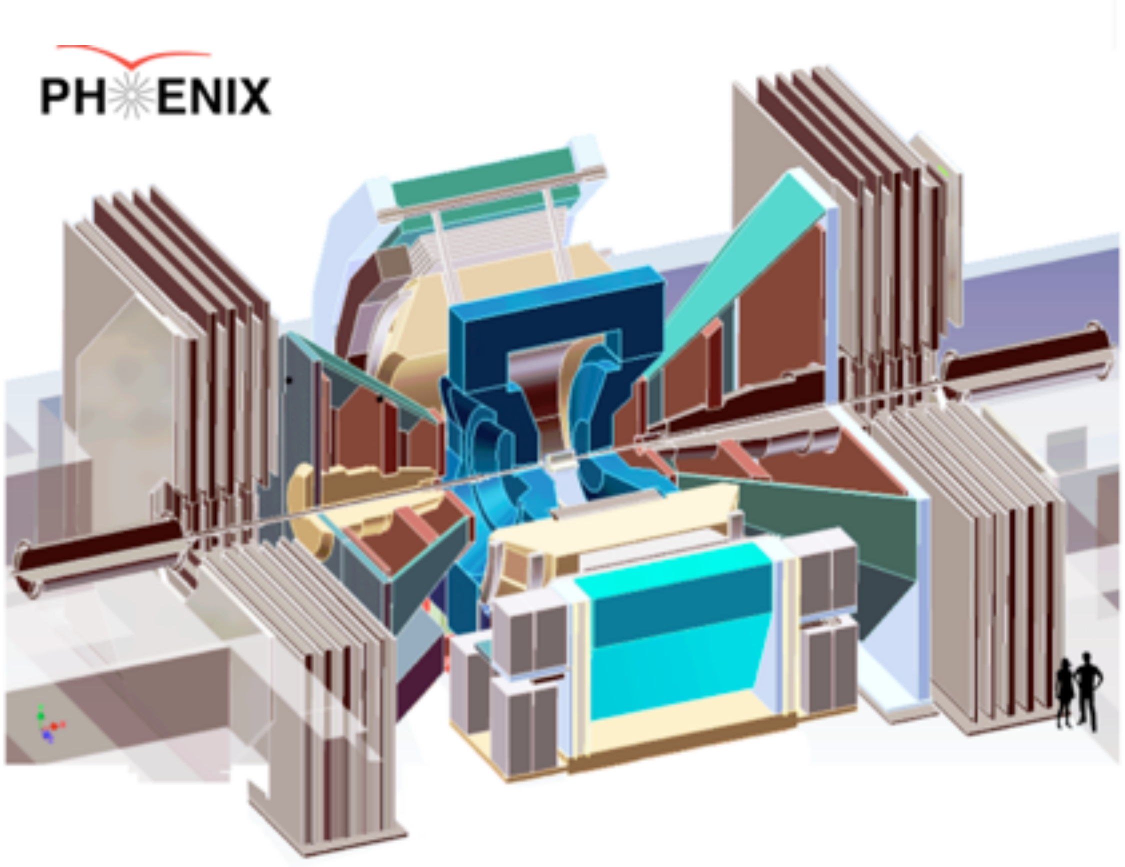


RHIC - The Current Main Experiments

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
- ongoing upgrades: near-term FMS-PSD
  iTPC, EPD, ETOF
  FCS+FTS



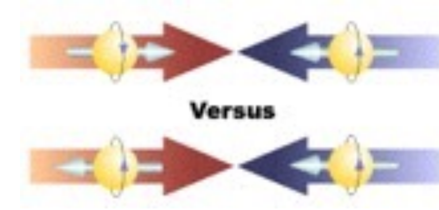


PHENIX "DNA":

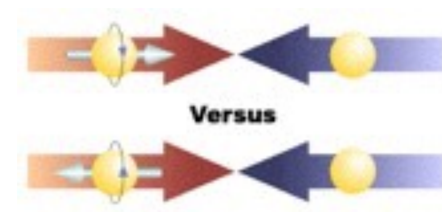
- high resolution and rate capabilities,
- central arms $|\eta|<0.35$, $\Delta\phi\sim\pi$
  with key strengths for π^0 and η
- forward muon arms $1.2<|\eta|<2.4$
- last run now, prepare transition to sPHENIX

The RHIC Spin Physics Program - Key Questions

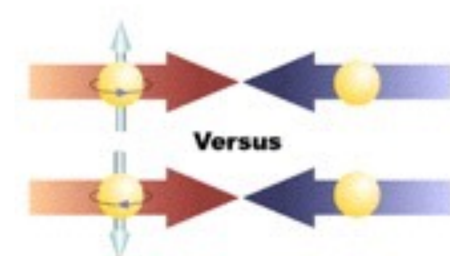
- *What is the polarization of gluons in the polarized proton?*



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

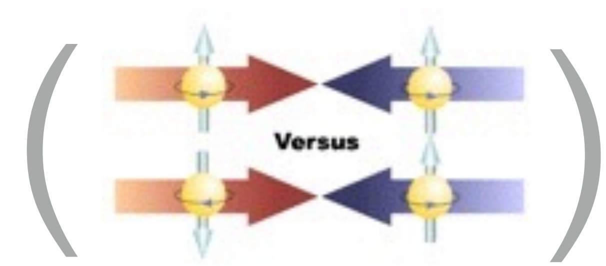


- *Does the Sivers' function change sign in proton-collisions compared to DIS?*

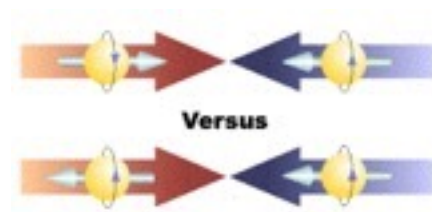


- *What are the quark transversity distributions?*

- *What is the origin of large forward A_N?*



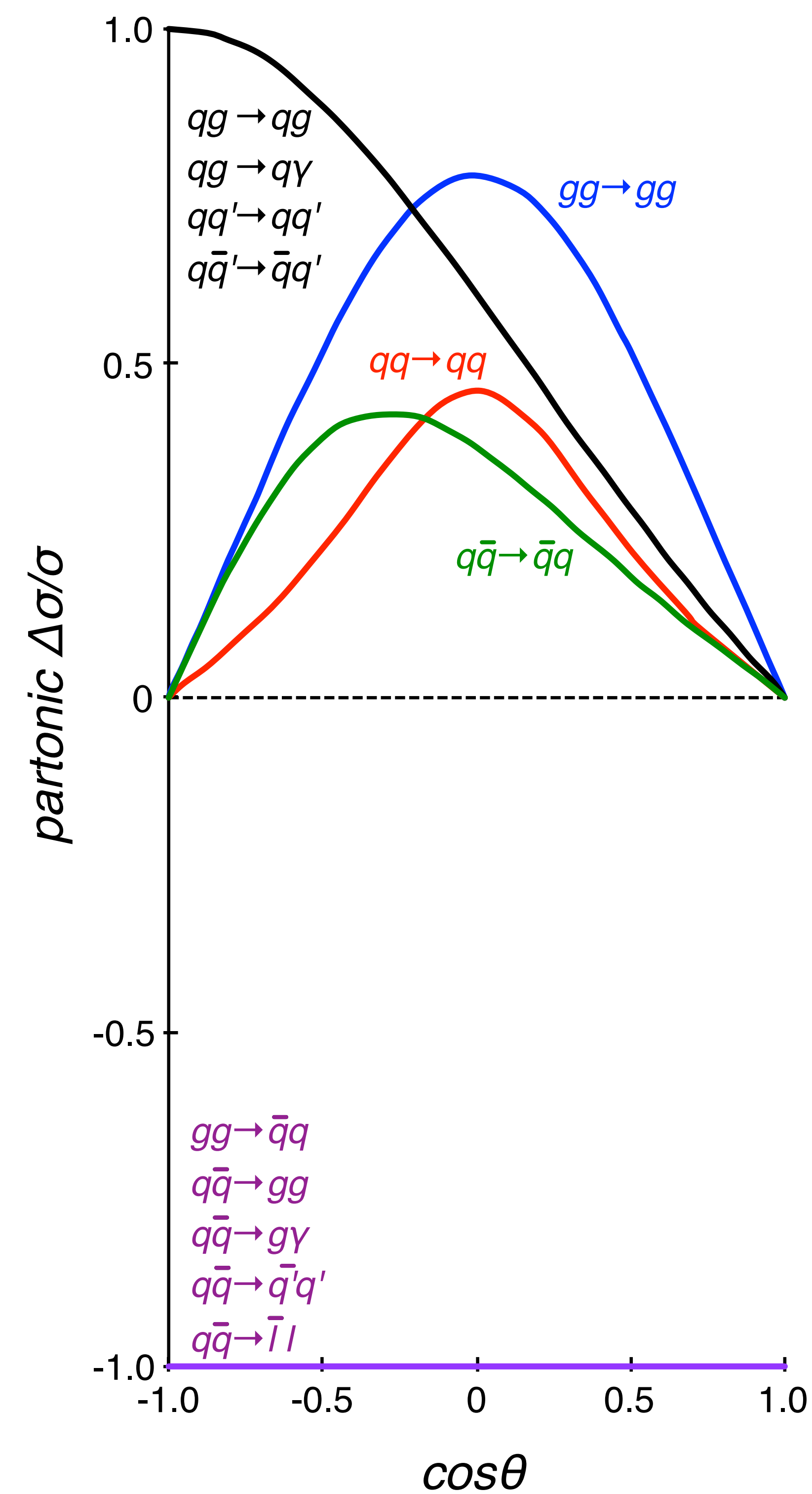
Gluon Polarization



Gluon Polarization at RHIC - Asymmetry A_{LL}

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

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



Advantages:

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

Disadvantages:

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

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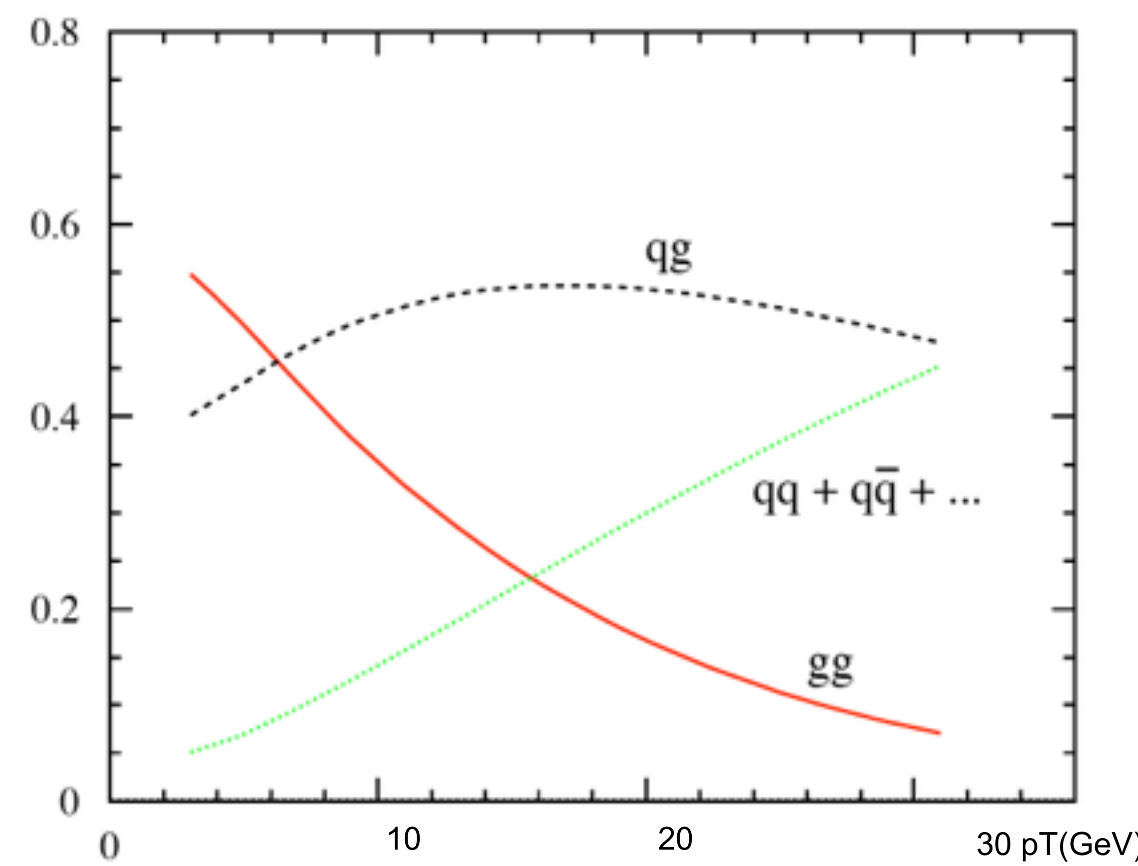

gluon-gluon and quark-*gluon* scattering contributions dominate.

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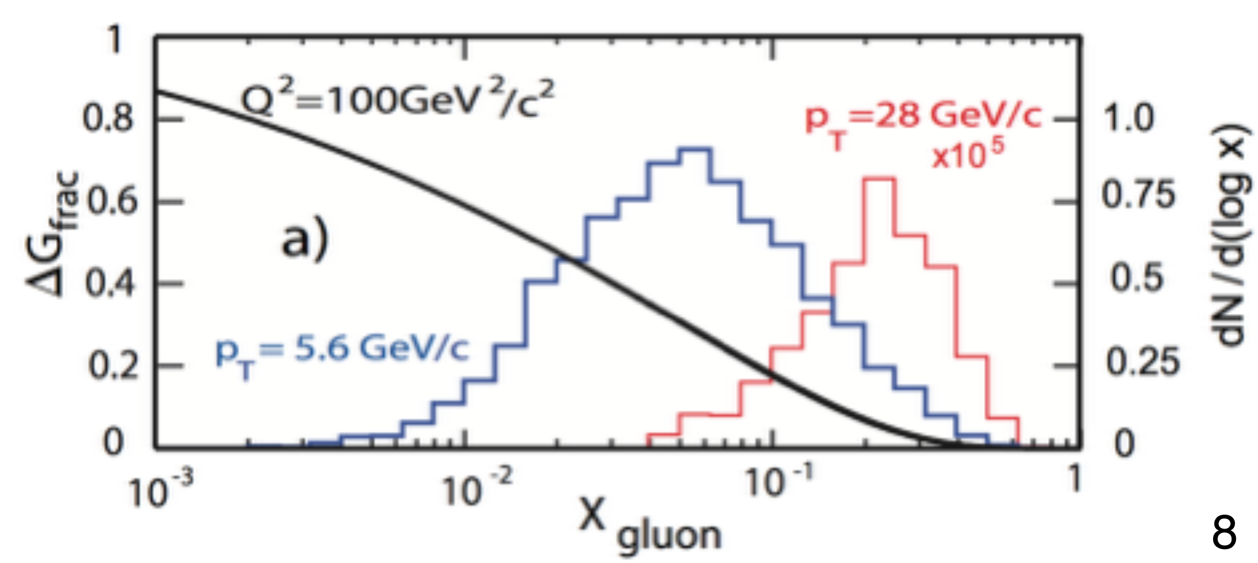
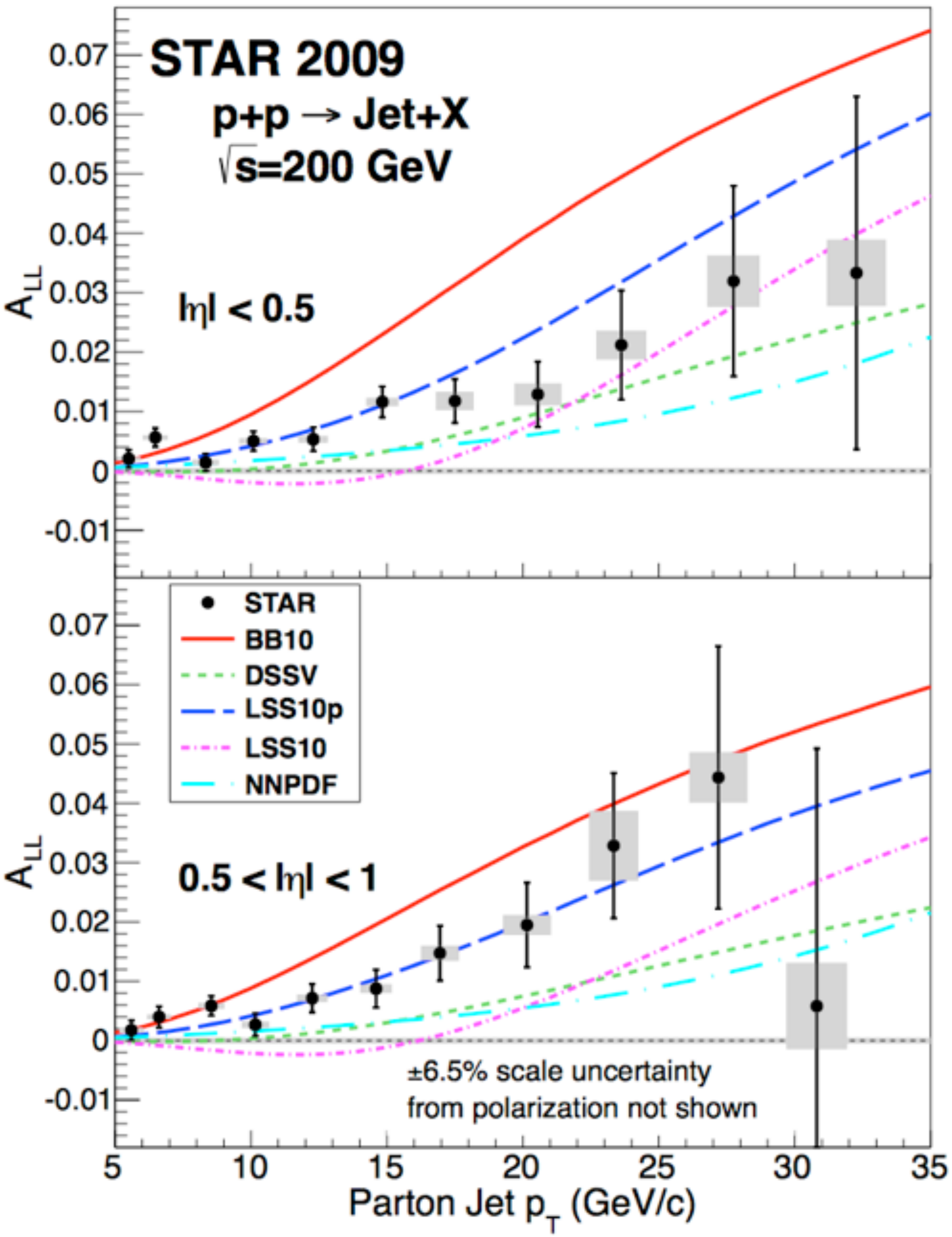


Gluon Polarization - *Precision* A_{LL} from STAR

PRL 115 (2015) 092002



Significant advance:

about an order in precision,

two to three times the kinematic range,

compared to initial RHIC data,

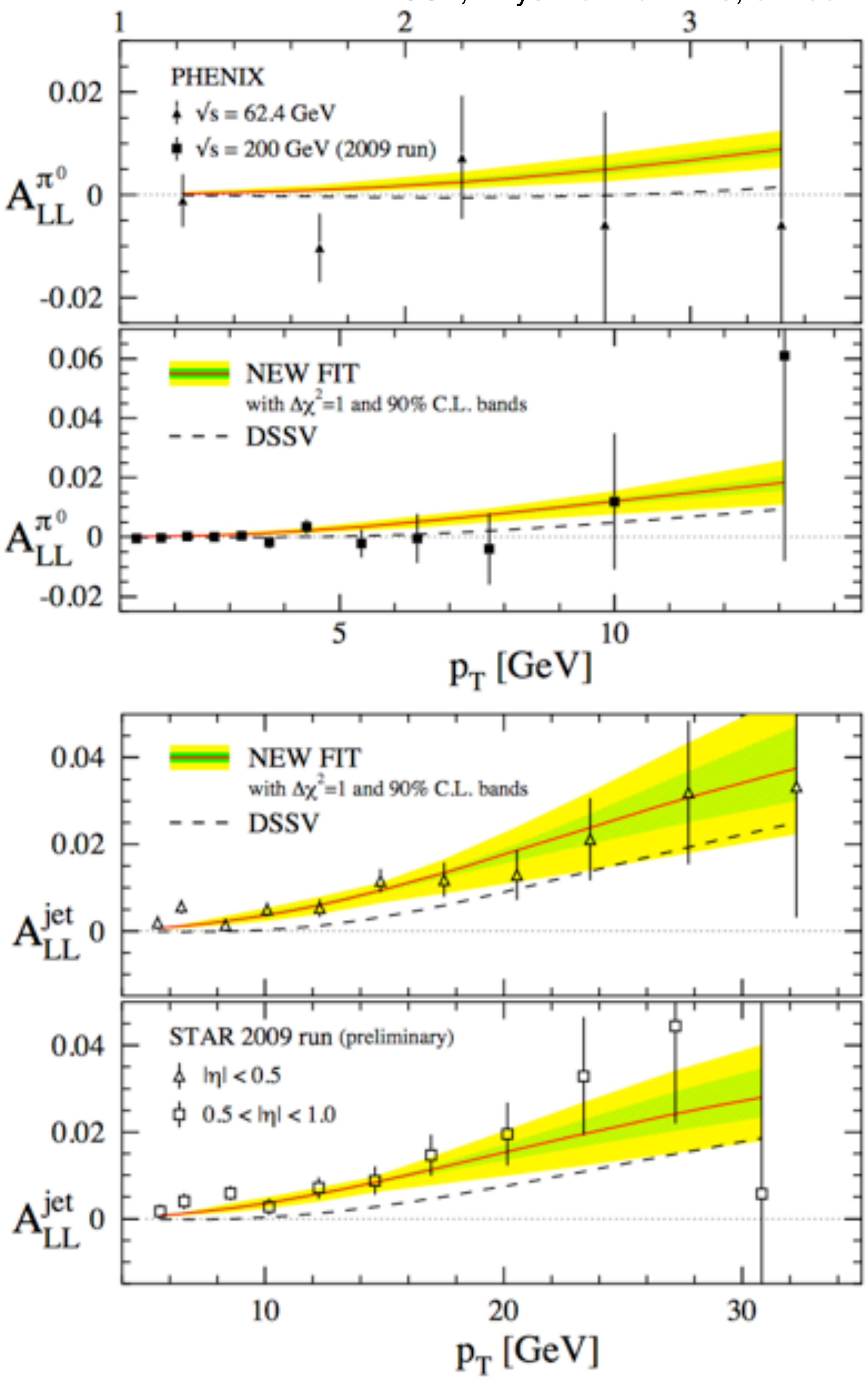
initial sensitivity to different x_g from rapidity dependence,

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

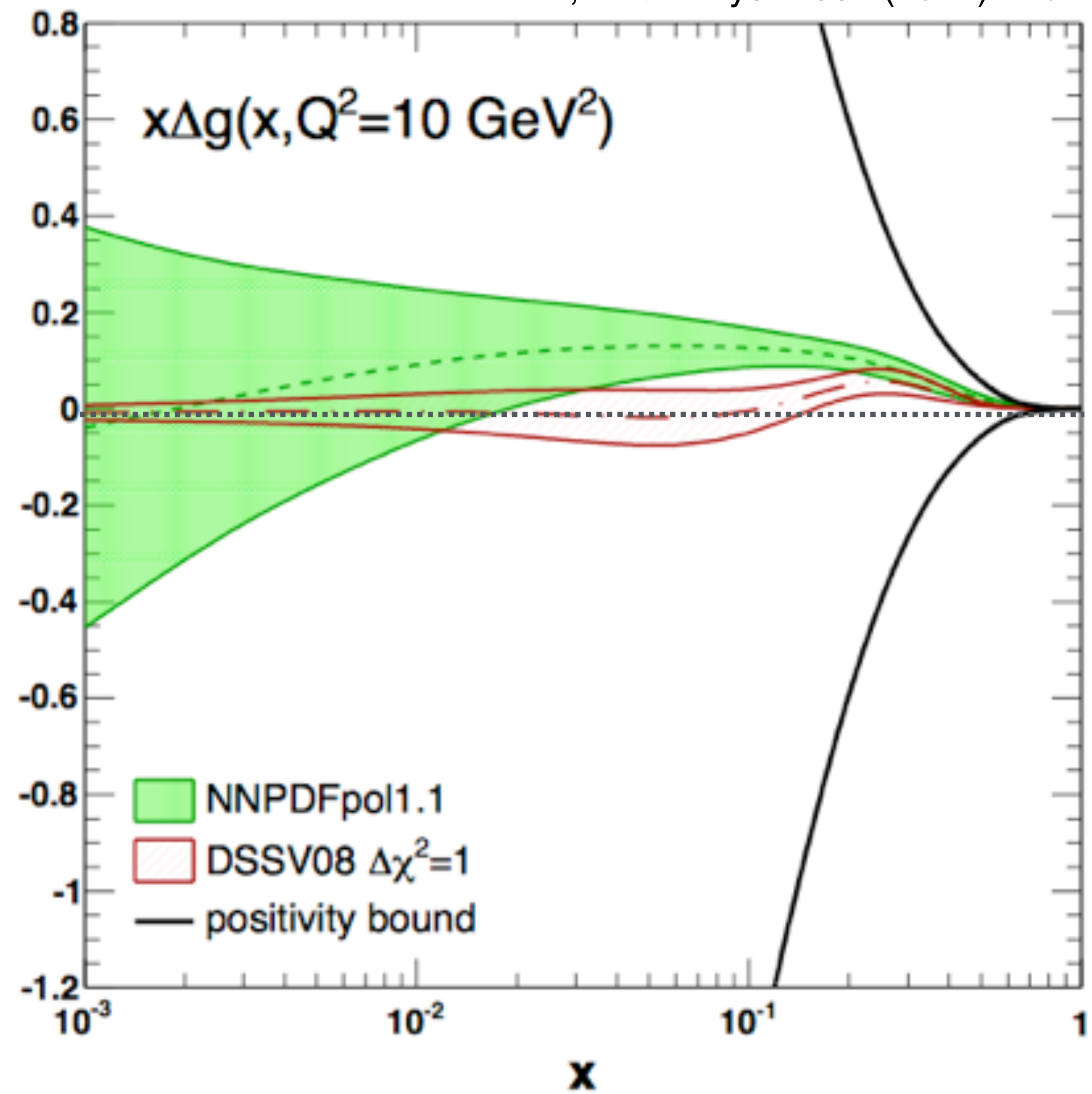
Gluon Polarization - RHIC Impact

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



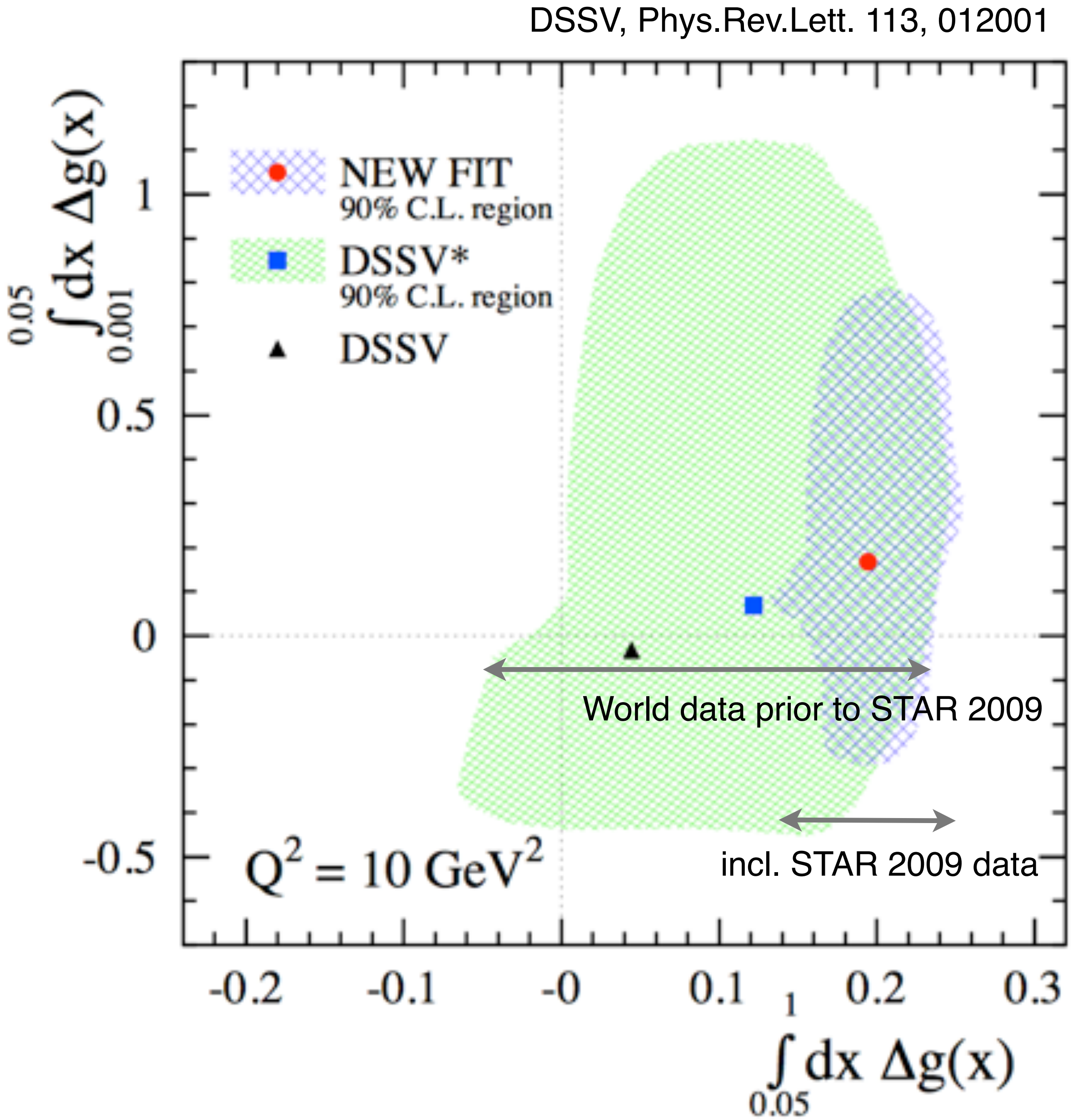
RHIC data, in particular on jets, currently drive the constraints on ΔG in both fits,

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 - Status and what is next?



Extend sensitivity to *smaller* x_g

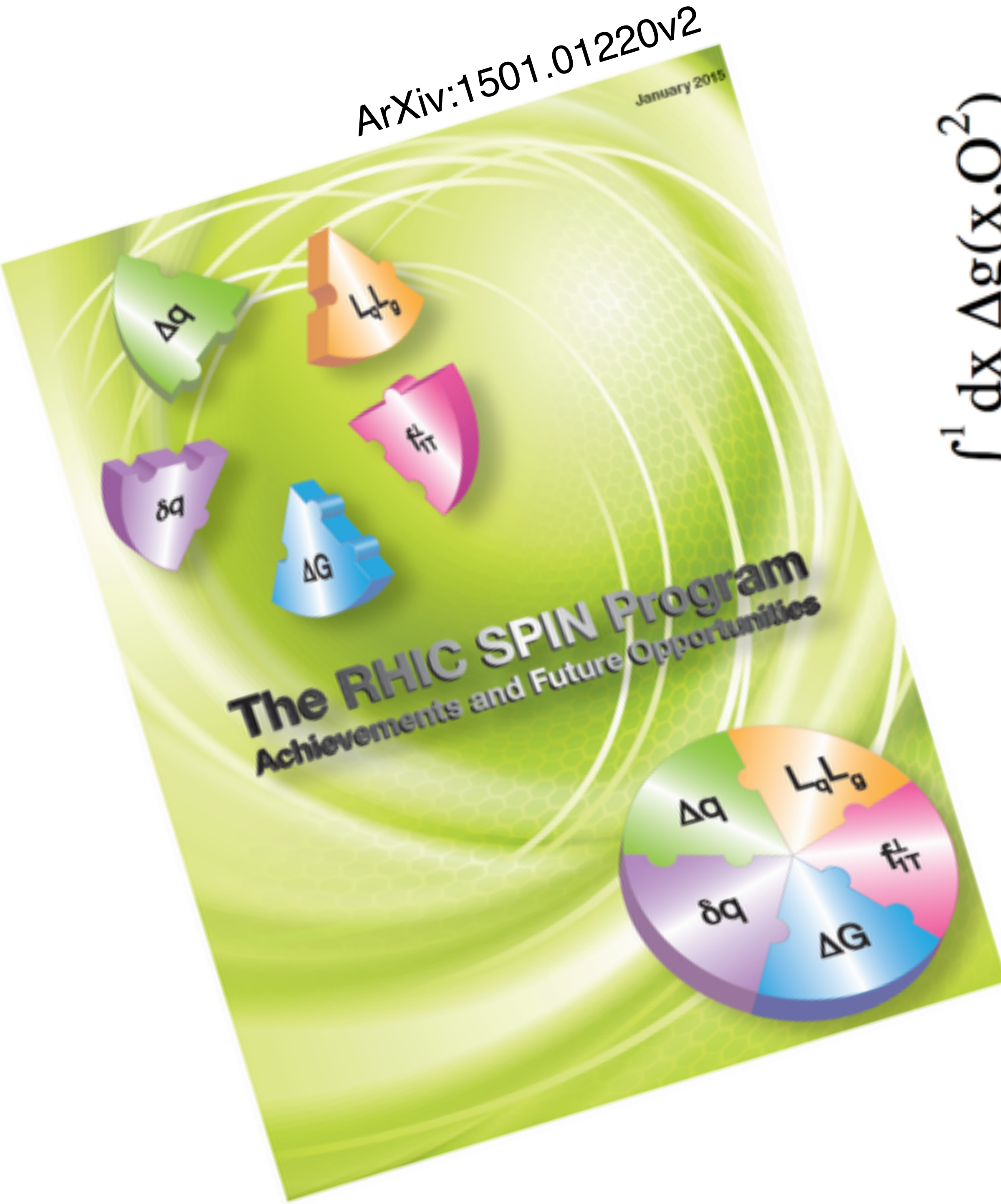
$\sqrt{s}$ = 500 GeV data, $x_g \sim 1/\sqrt{s}$,

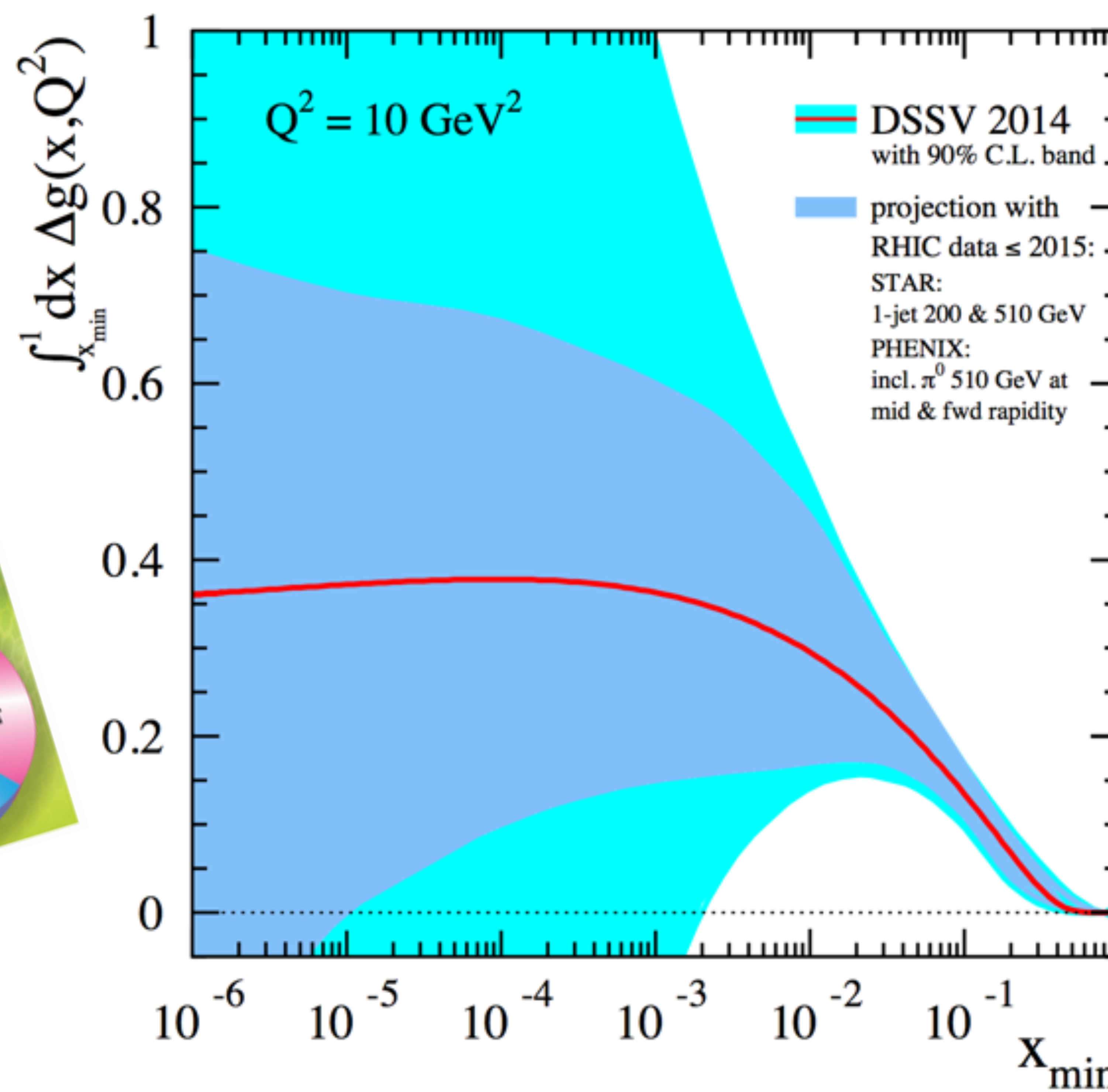
forward rapidity, $x_g \sim \exp(-\eta)$,

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

from *complementary* probes

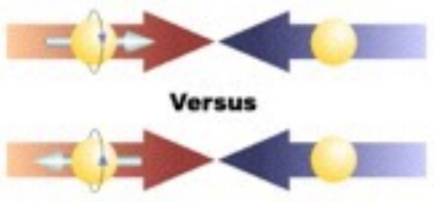
Gluon Polarization - What to expect next?



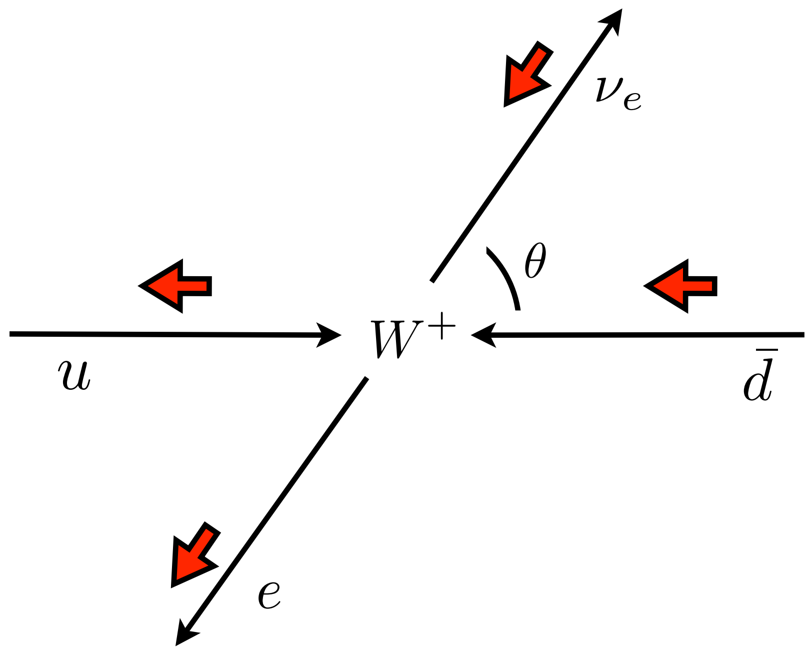


- additional constraints from correlated probes, e.g. di-jets, but *not* adtl. kin. coverage,
- longer term opportunity (2020+): EIC, *or (and?)*
  renewed √s = 500 GeV operations with forward upgrade

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 |rapidity|
electron/hadron discrimination
luminosity hungry!

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

Spin Measurements:

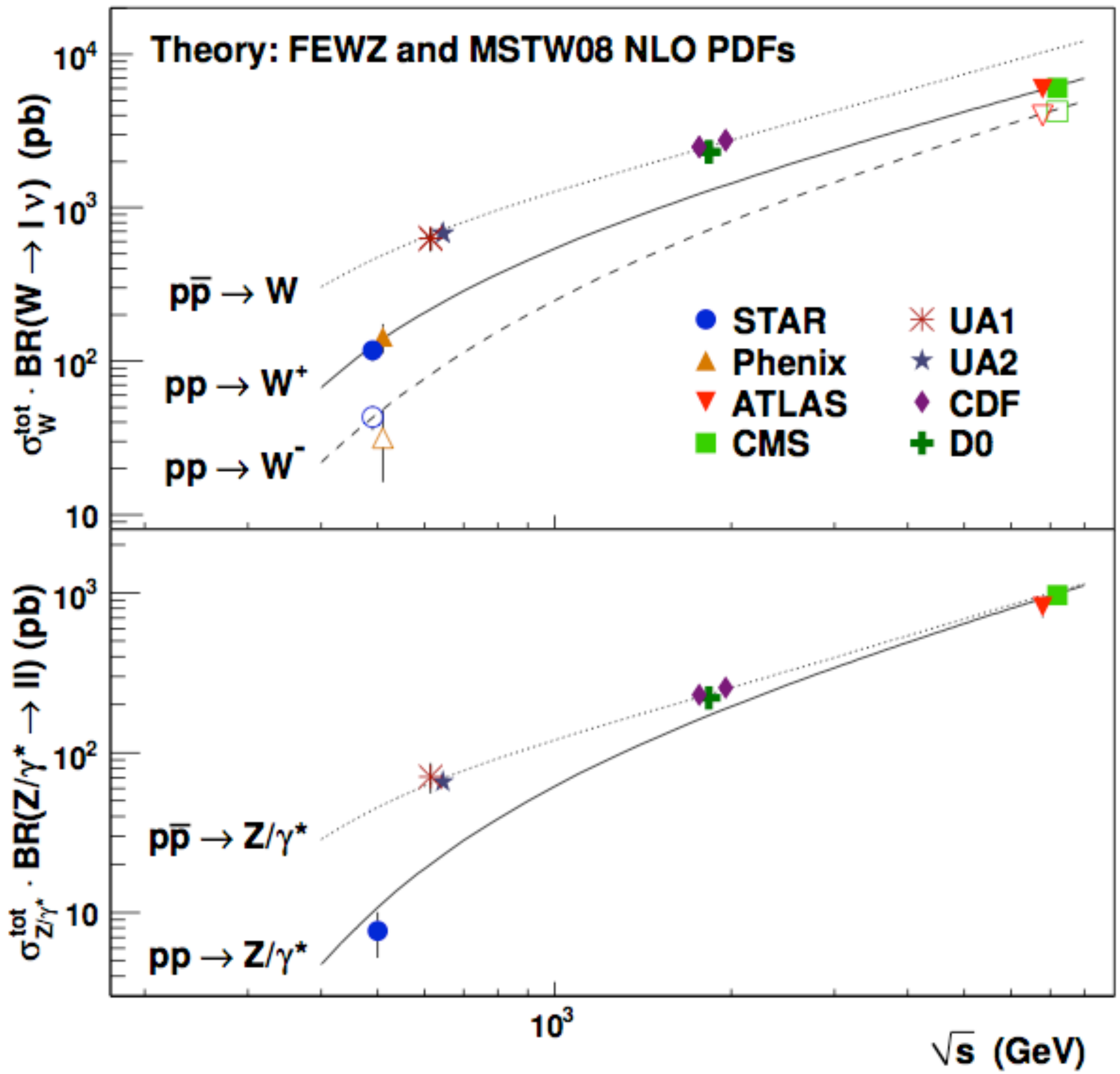
$$A_L(W^+) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} = \begin{cases} -\dfrac{\Delta u(x_a)}{u(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{d}(x_a)}{\bar{d}(x_a)}, & x_b \to 1 \end{cases}$$

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,

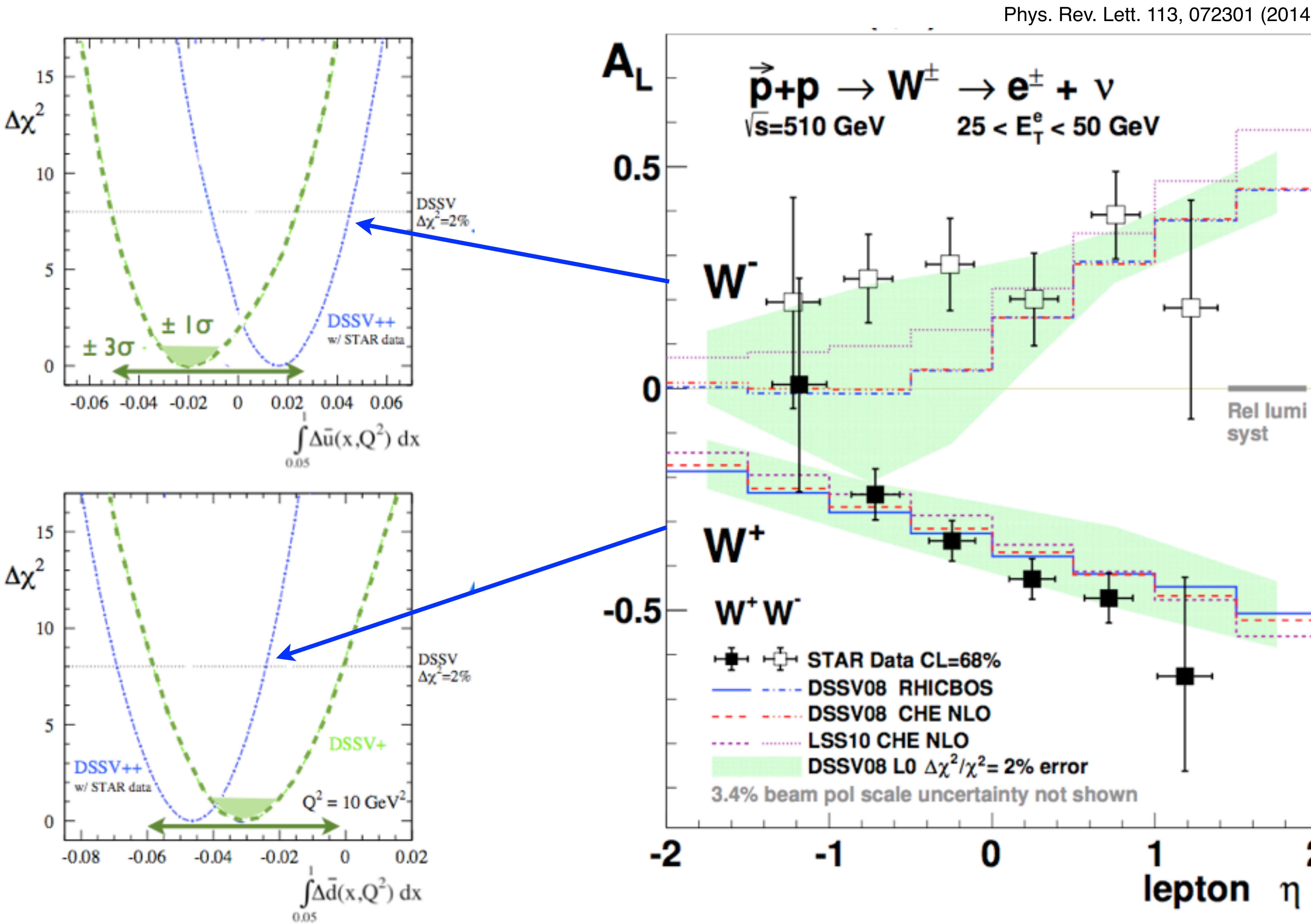
STAR: Initial NC cross section at RHIC, confirmation of PHENIX CC cross section measurements, Phys. Rev. **D85** (2012).

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

Support NLO pQCD interpretation of the asymmetry measurements,

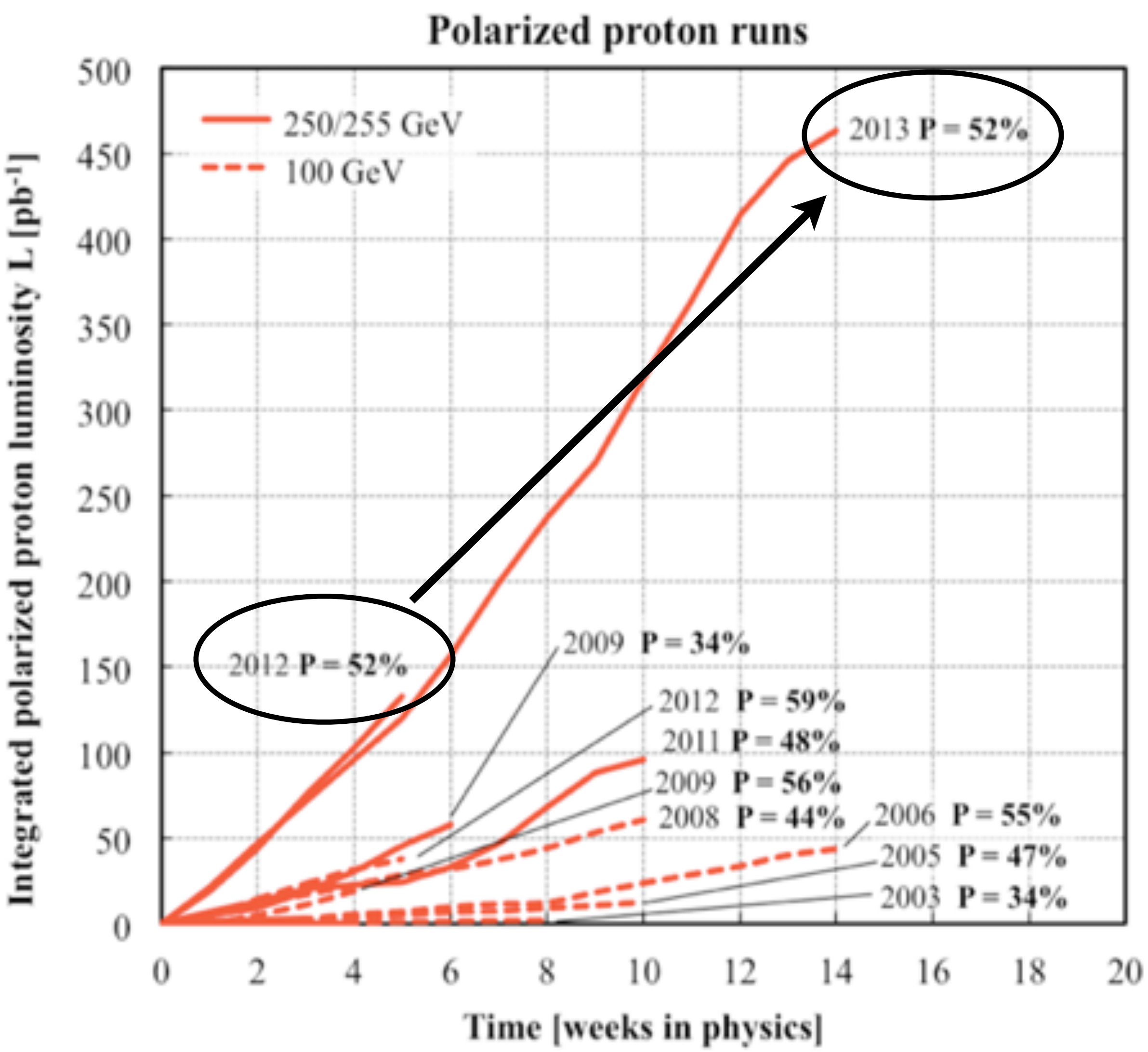
Aside, future ratio measurements may provide insights in unpolarized light quark distributions

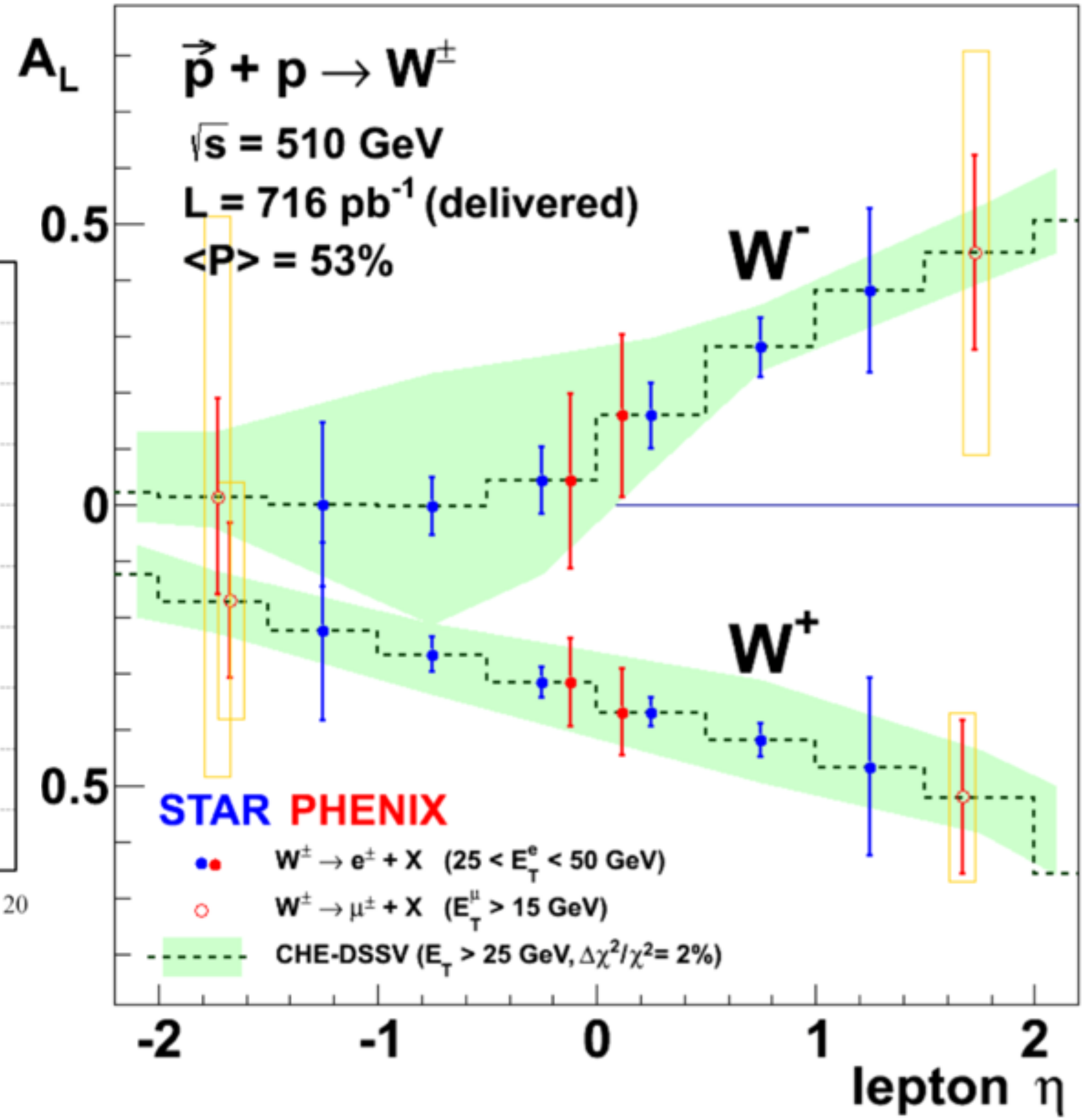
Quark Polarization - *More Precise* A_L from RHIC



Quark Polarization - Next Steps

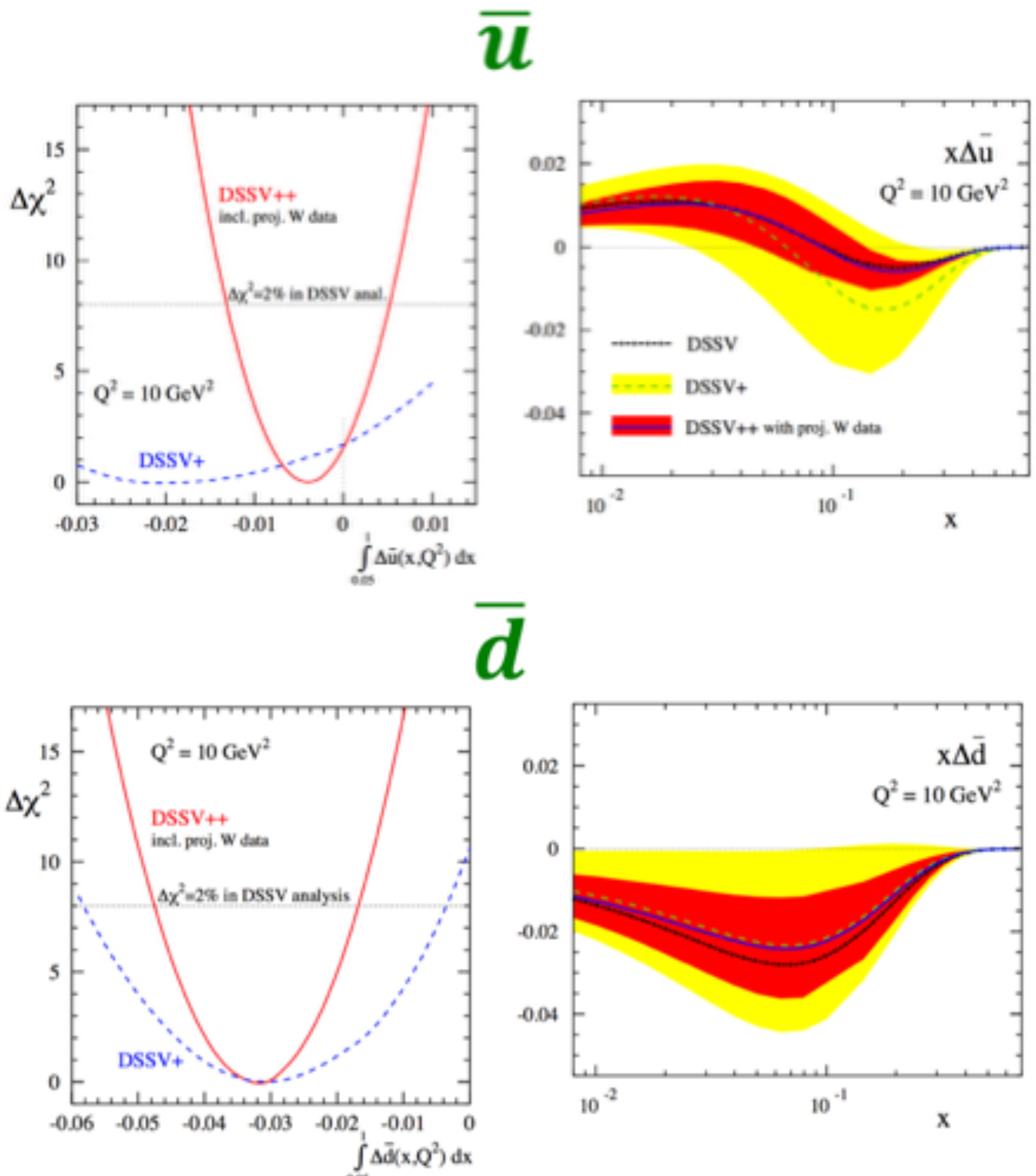
Anticipated uncertainties:

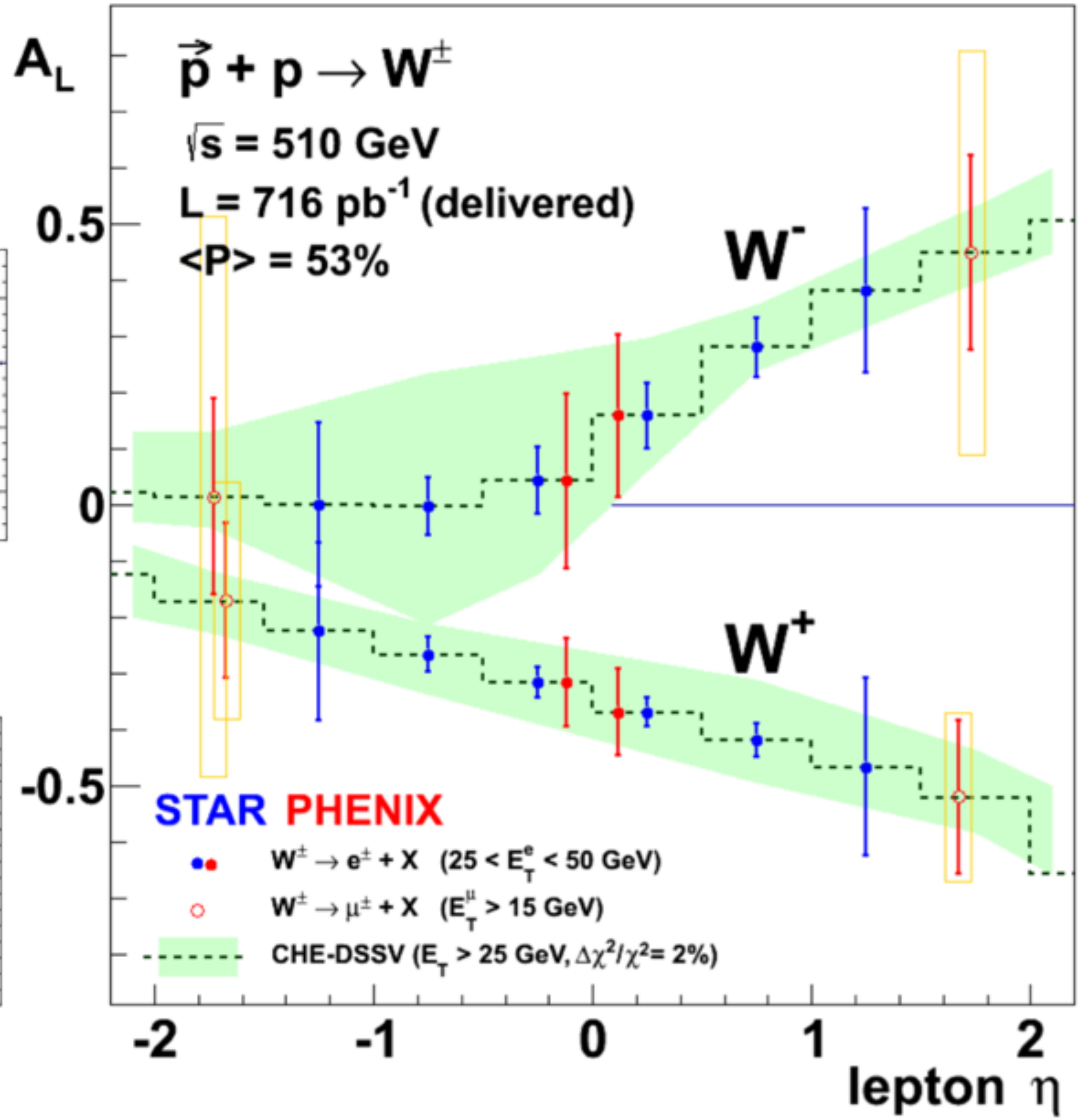




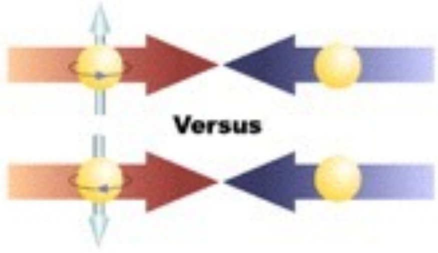
Quark Polarization - Next Steps

Anticipated uncertainties, and their projected impact:



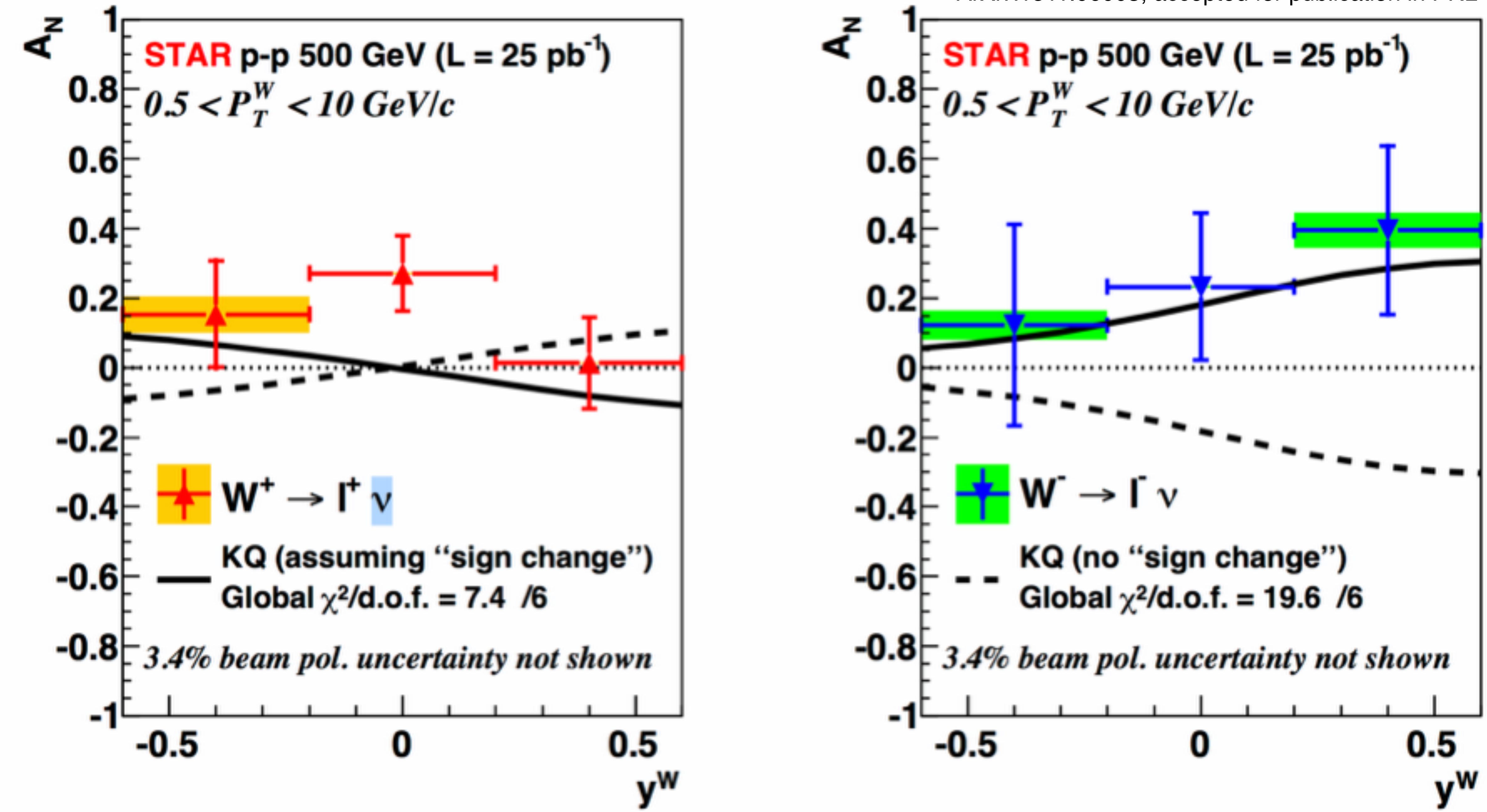


Transverse Spin Phenomena: Sivers



STAR W A_N - *"The sign change"*

ArXiv:1511.06003, accepted for publication in PRL



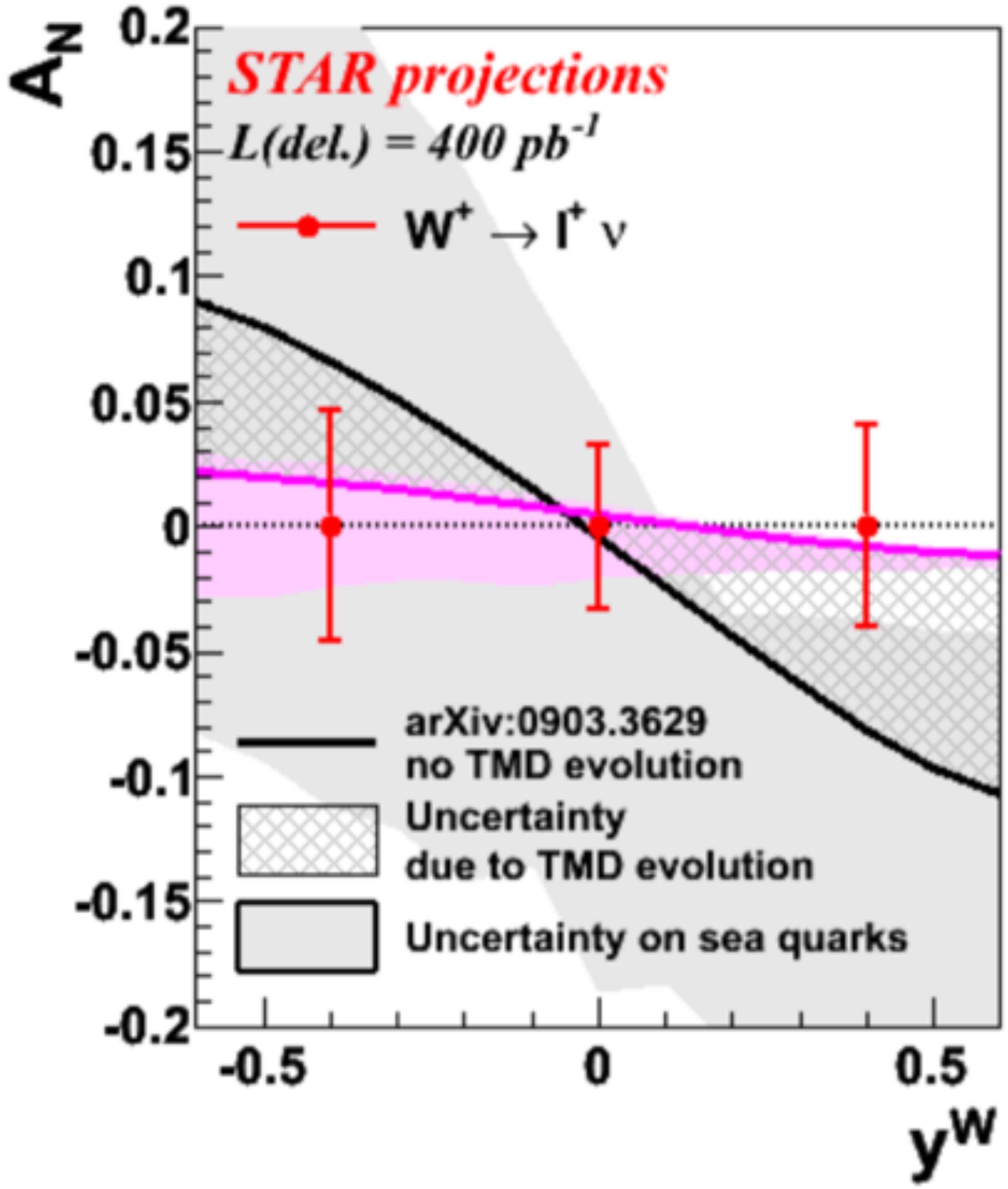
Calls for continued measurement; PAC approved, LRP supported, planned for 2017,

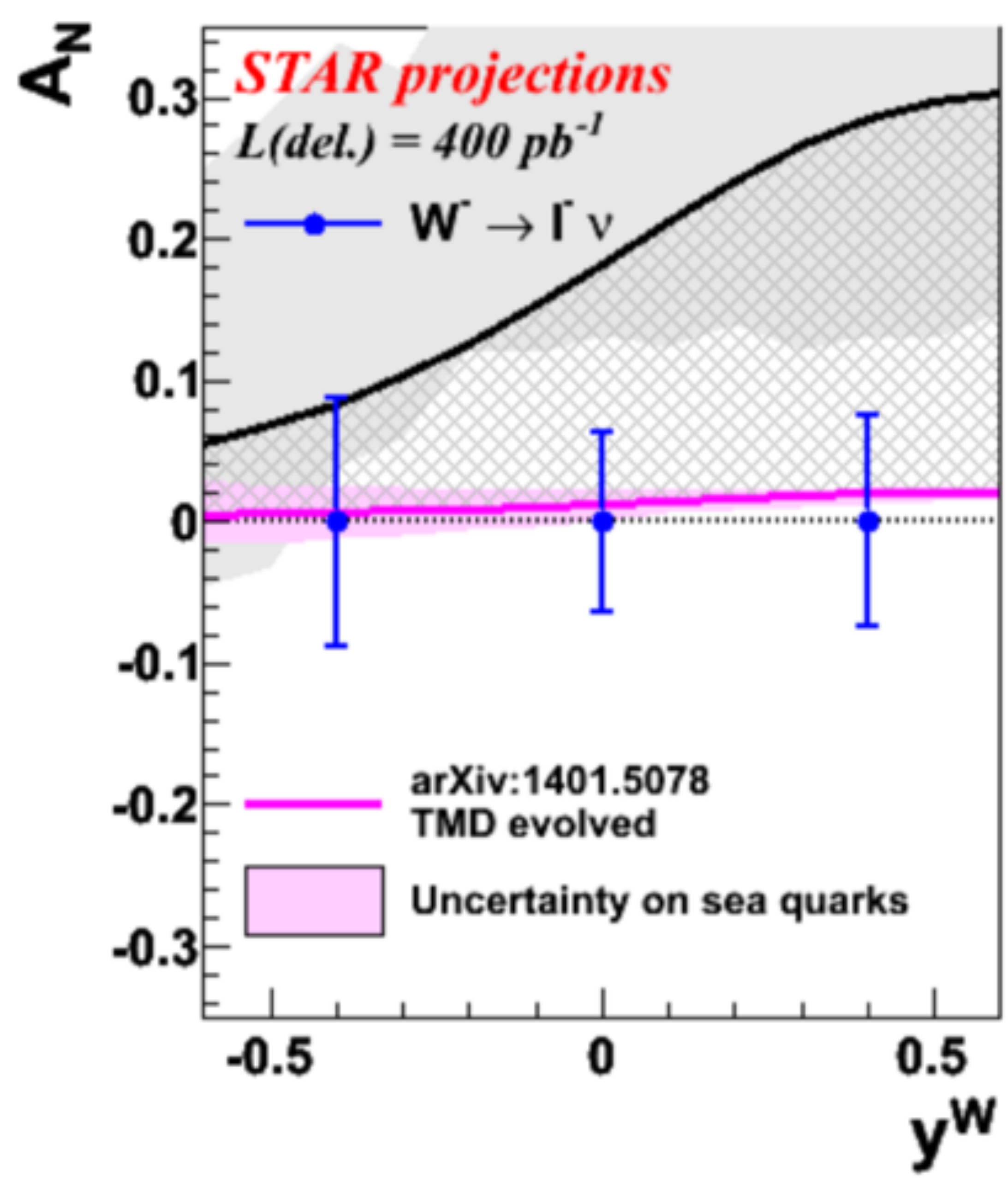
Eagerly anticipate forward photon A_N from run-15; A_NDY has published forward jet A_N,

Drell-Yan: initial measurement at RHIC in 2017 via the electron decay channel, using a post-shower (and UV) upgrade to the STAR forward EM Cal. (FMS),

future measurements, in p+A, are drivers in forward upgrade LOI's.

STAR W A_N - Prospects for 2017 Run





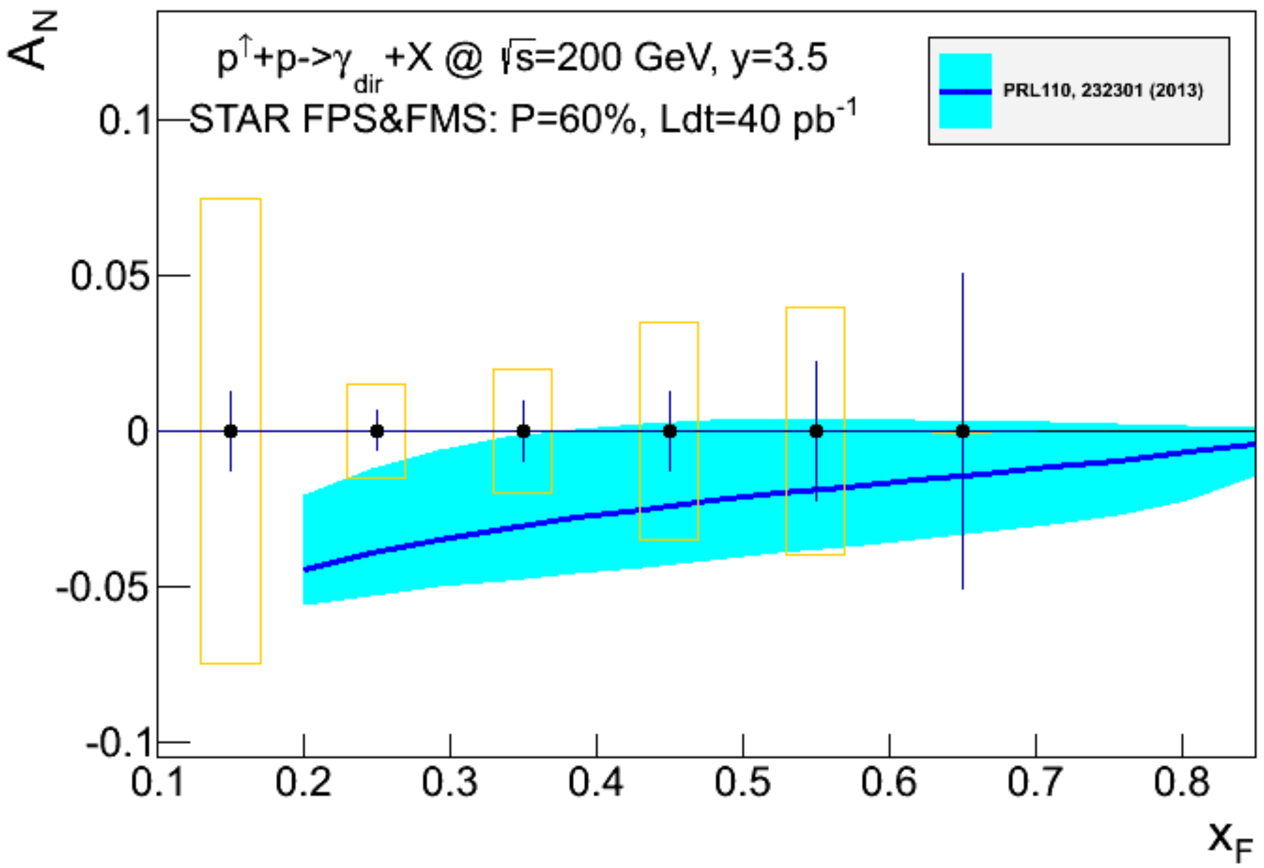
Lots of work ahead to turn these projections into actual results,

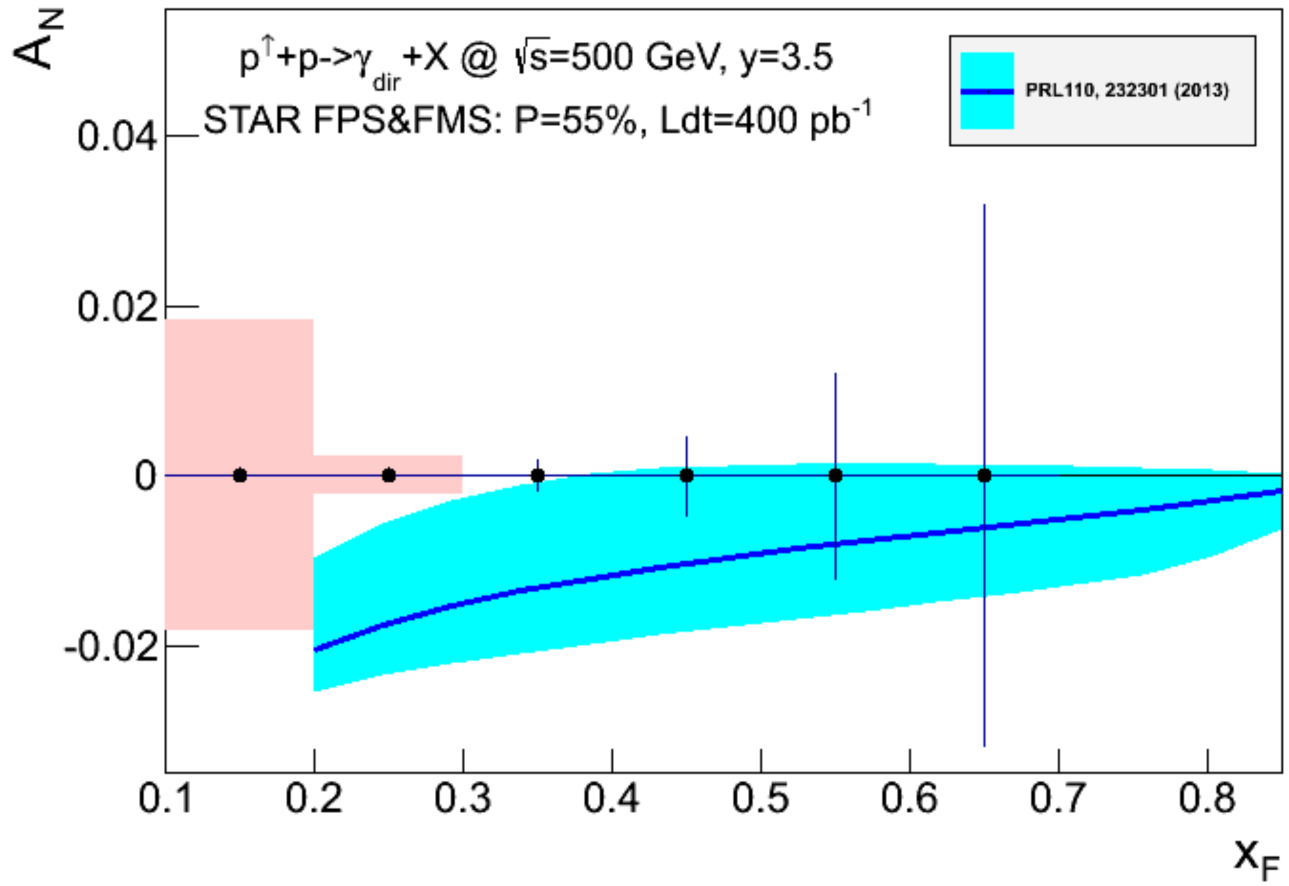
Ample other opportunities, for example

photons, Drell Yan, diffraction, mid-rapidity,

gradual upgrades to existing STAR forward instrumentation, RHICf@STAR,

STAR photon A_N - Prospects with 2017 Run



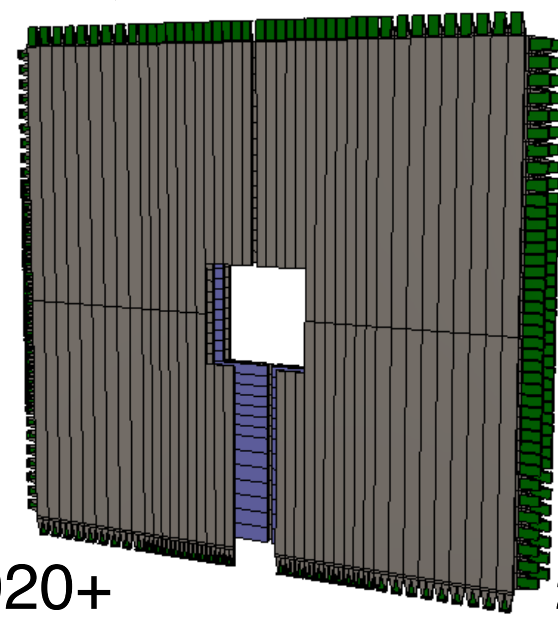


Measurement relies crucially on the now existing pre-shower to the FMS,

Sensitive to the “sign-change” in the twist-3 formalism,

light valence quarks, at relatively high-*x*,

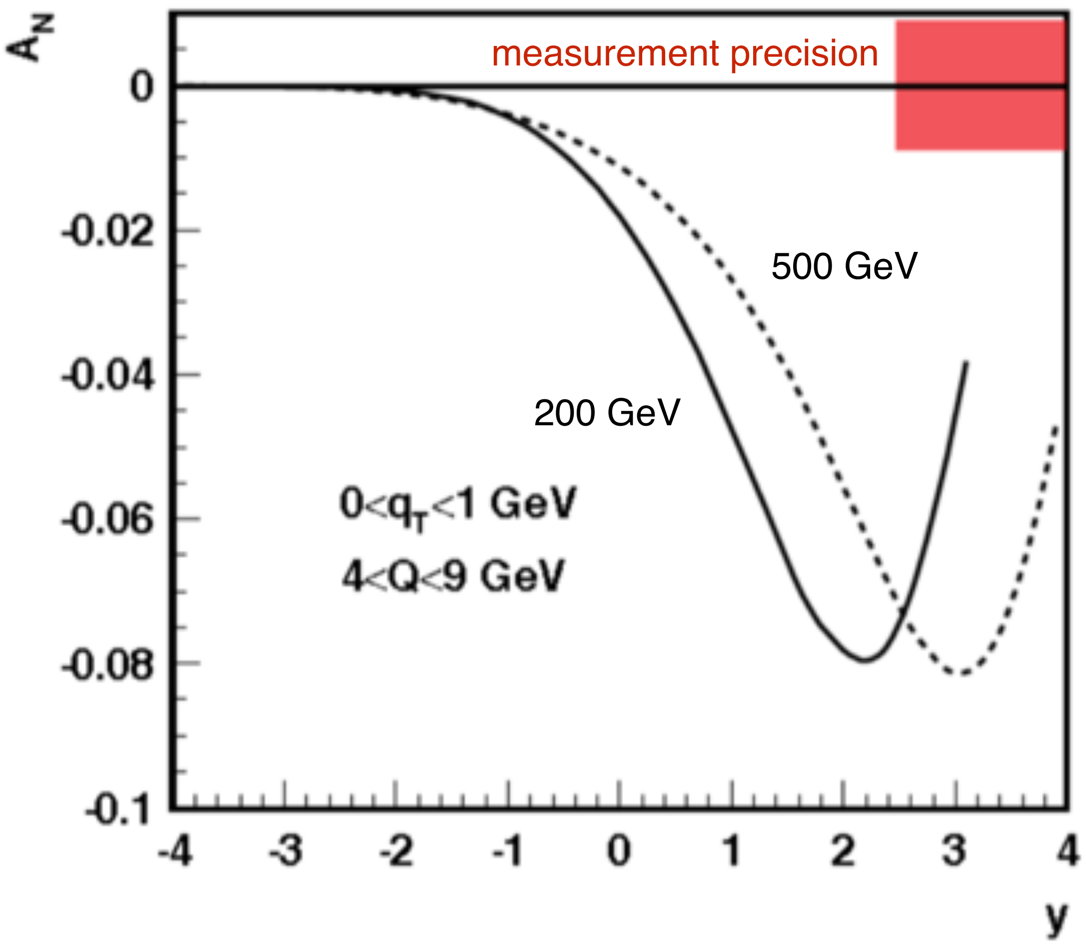
twist-3 evolution, *not* TMD evolution.



Constraining this evolution is one of the motivations for running in 2020+

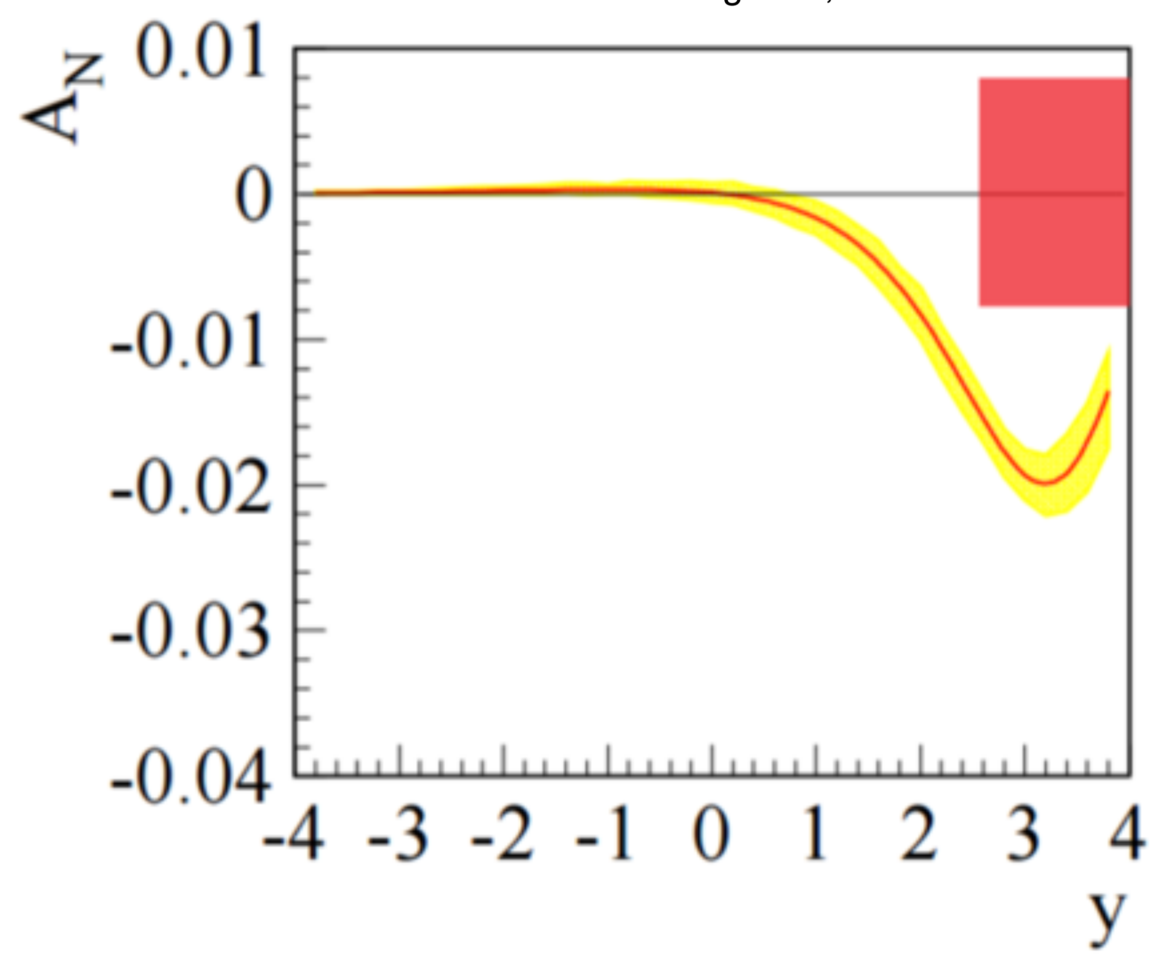
STAR Drell-Yan - Prospects for 2017 Run

No TMD evolution

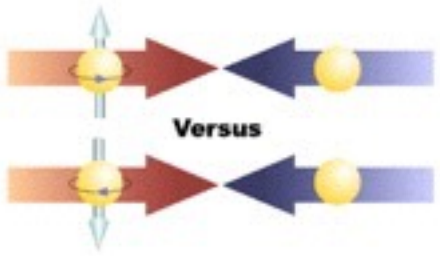


With TMD evolution

Z.B. Kang et al, ArXiv:1401.5078



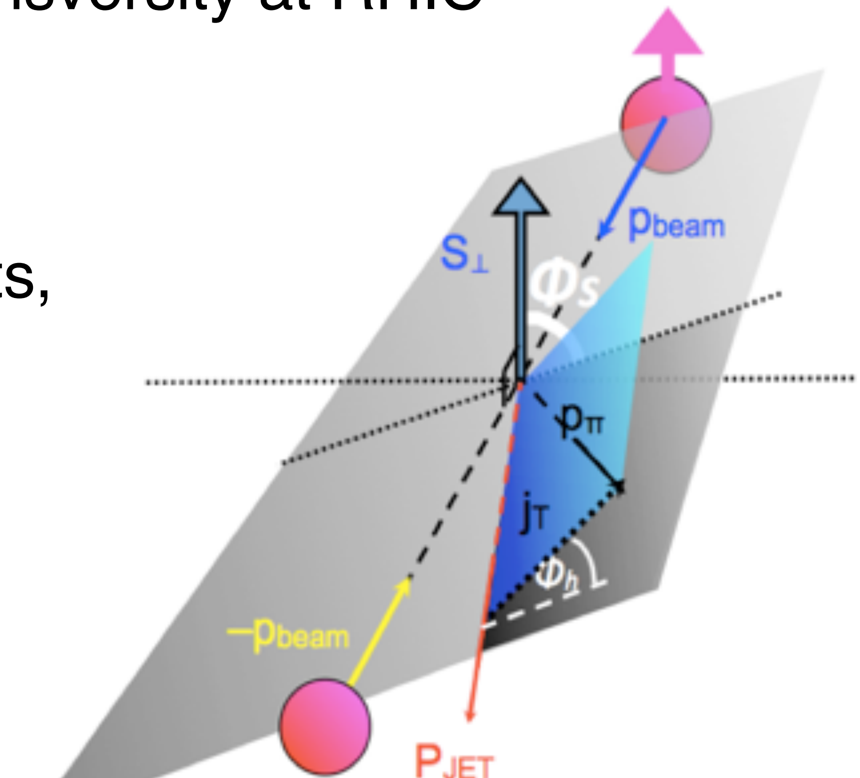
Transverse Spin Phenomena: Collins



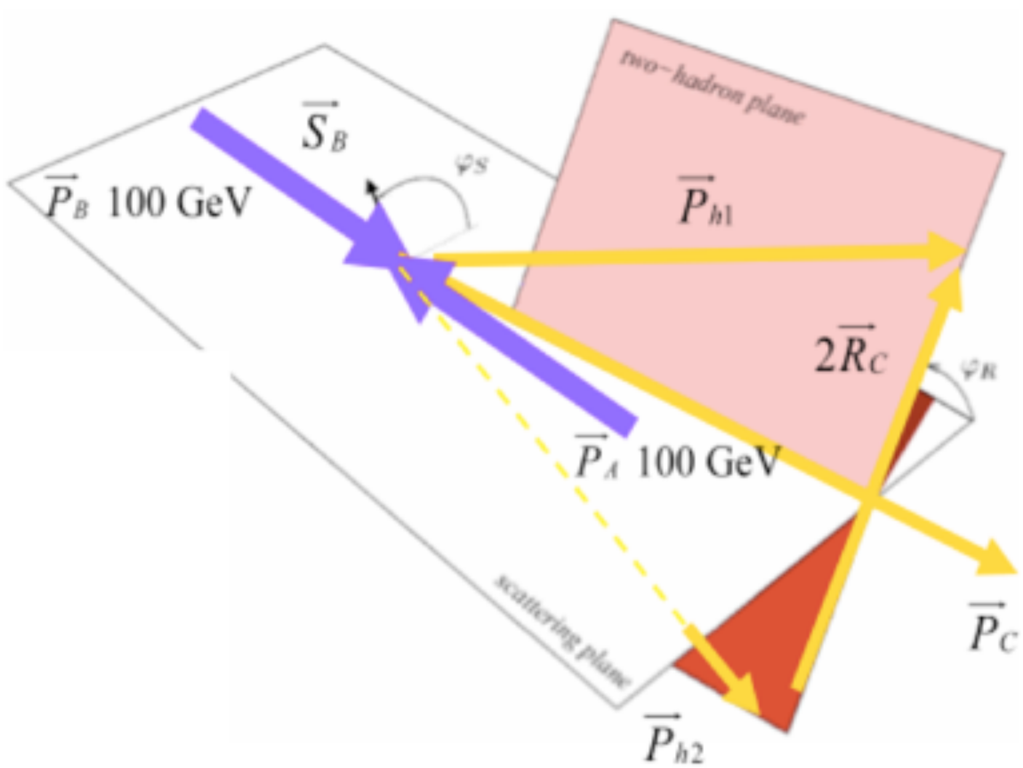
Quark Transversity at RHIC

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

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



$$h_1(x) \otimes H_1^{\perp}(z, j_T)$$

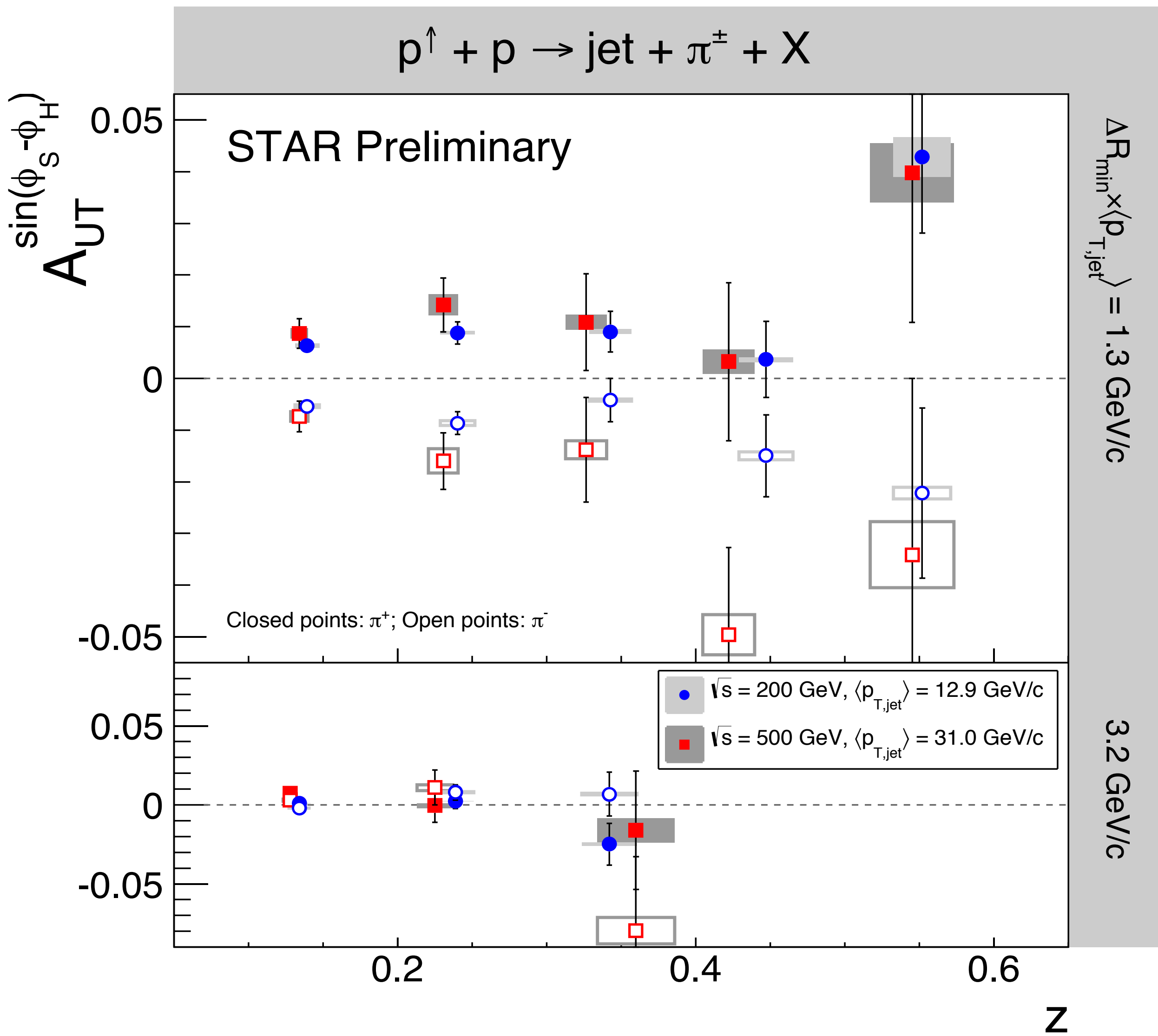


2. di-hadron correlation measurements couple transversity with interference-fragmentation.

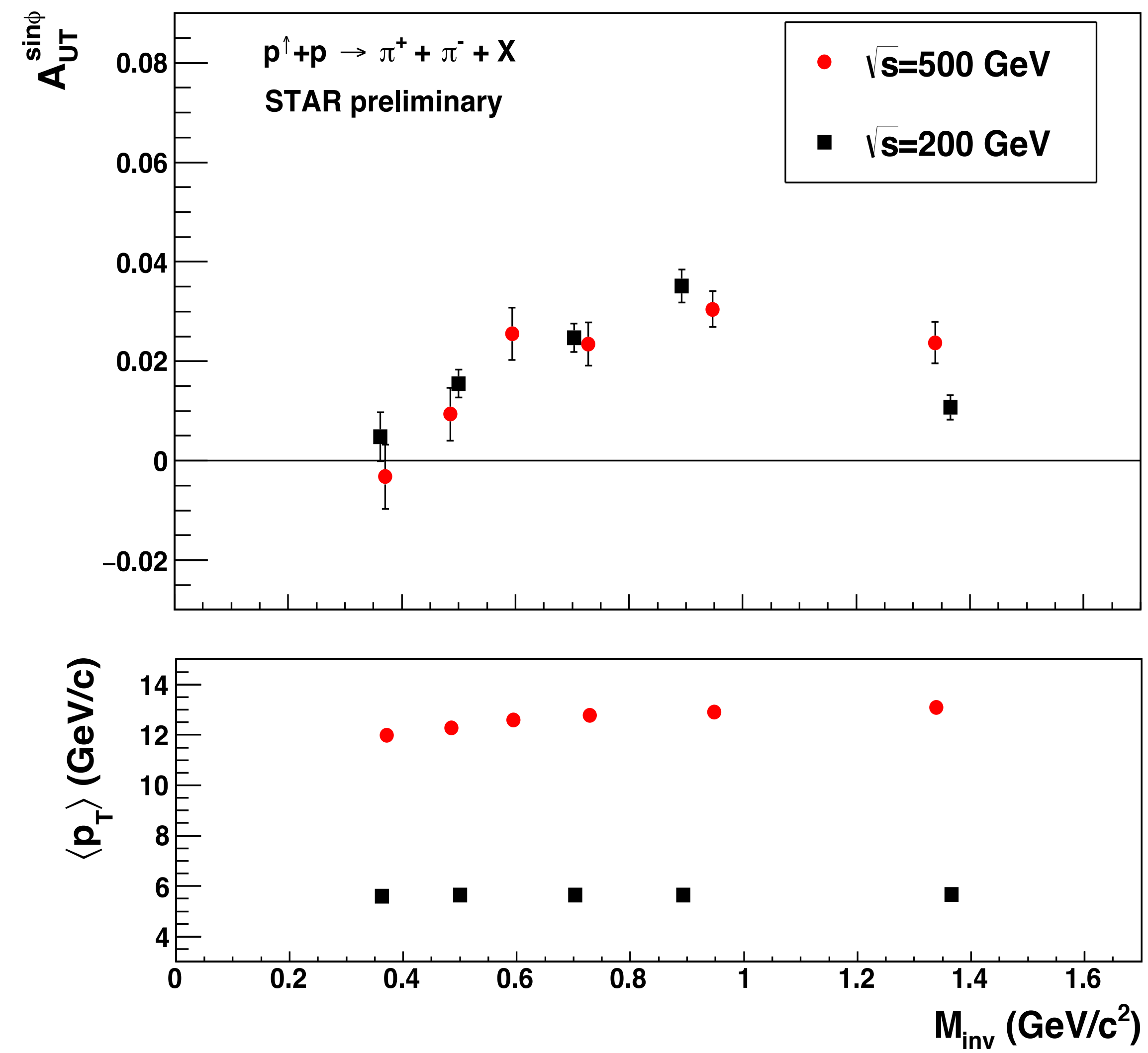
Both methods have been pursued and have delivered initial results...

STAR A_{UT} - Quark Transversity and Fragmentation

azimuthal modulation within the jet



interference fragmentation



Sensitivity to quark transversity and *polarized* fragmentation,

200 and 500 GeV results are similar; is TMD evolution in FF small?

Non-zero observations open a path to nuclear modification of polarized fragmentation, first analyses in progress,

Particle-identification key to further surprises? Theoretical/phenomenological input sought.

STAR A_{UT} - Quark Transversity and Fragmentation

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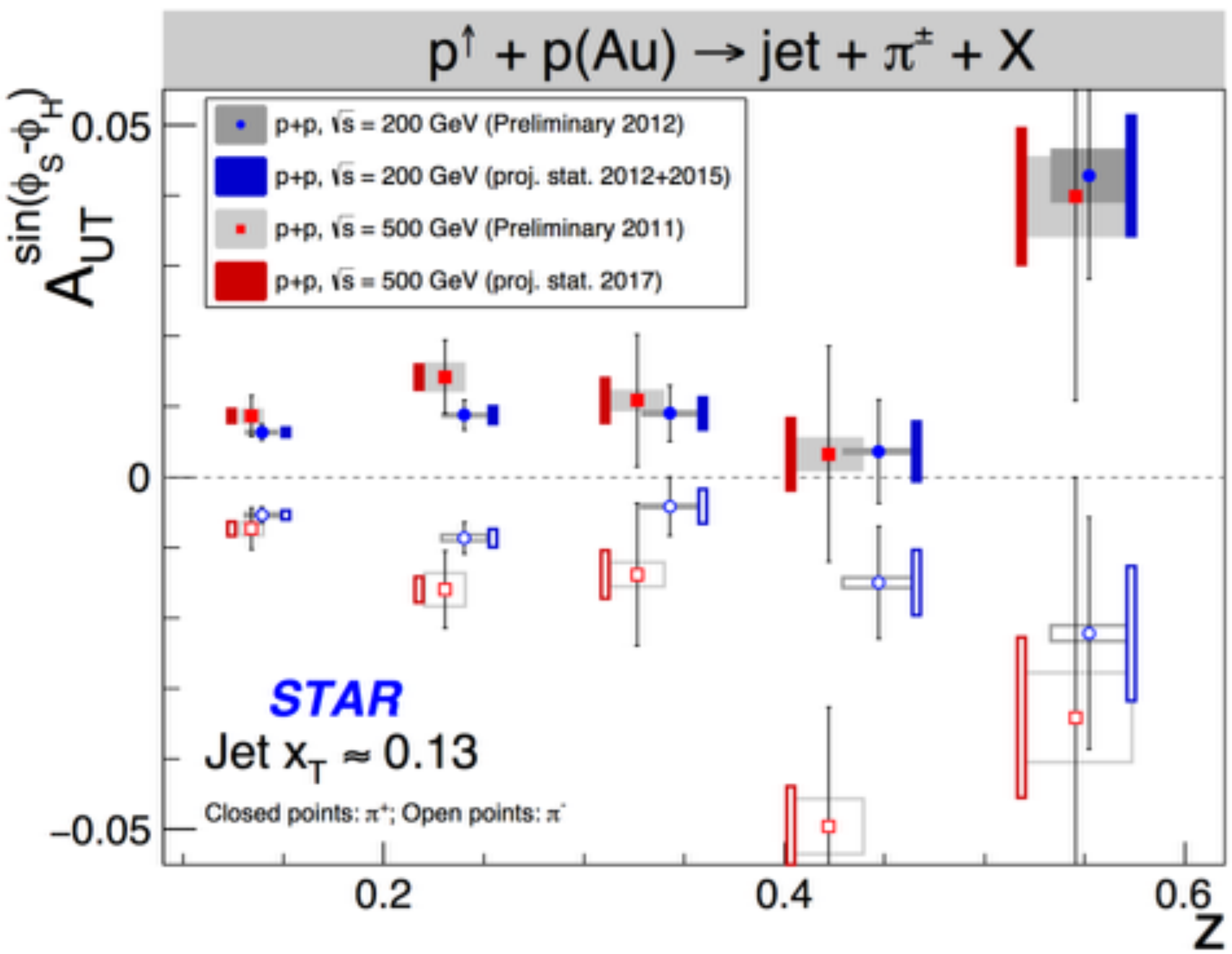
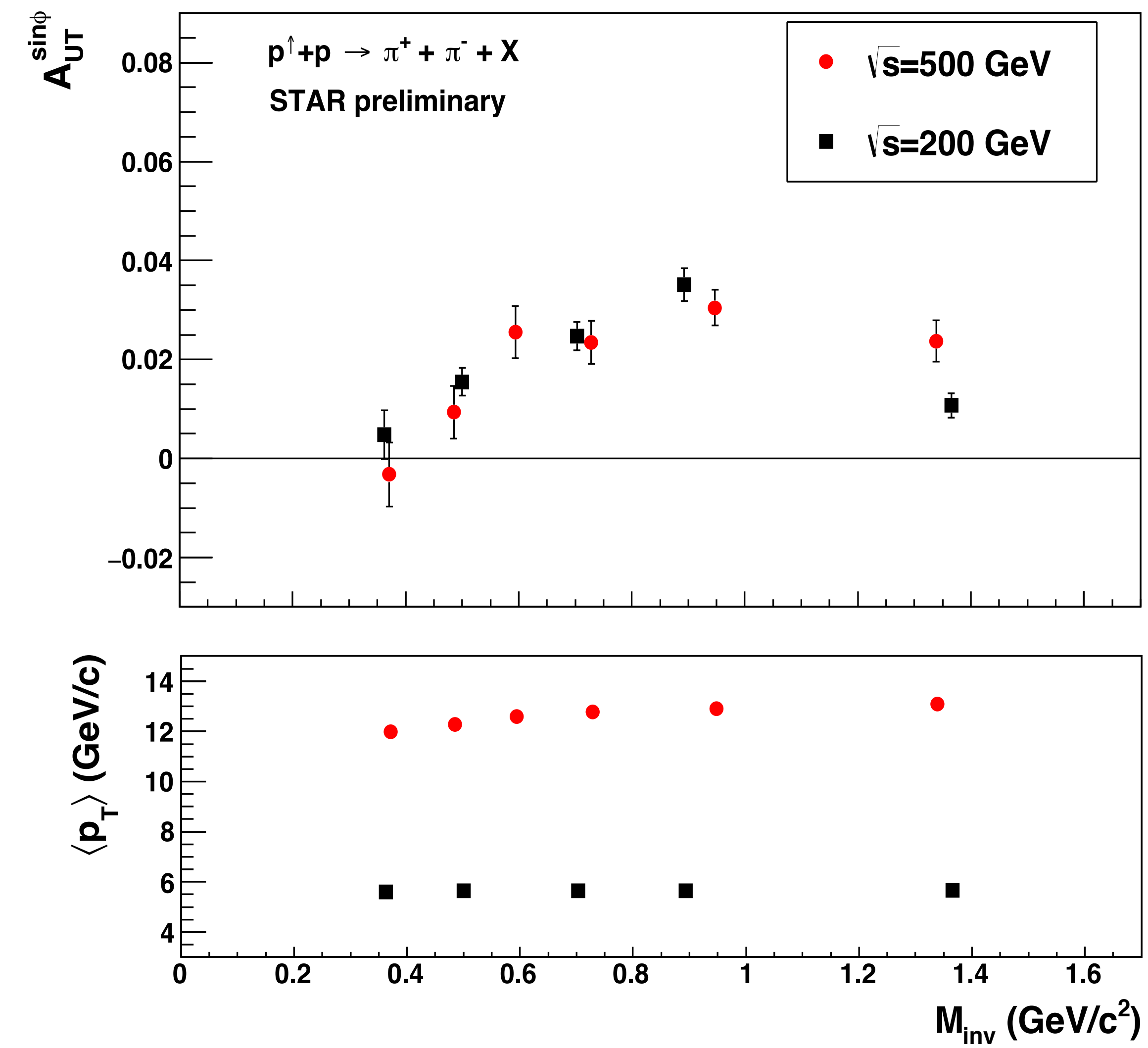


interference fragmentation



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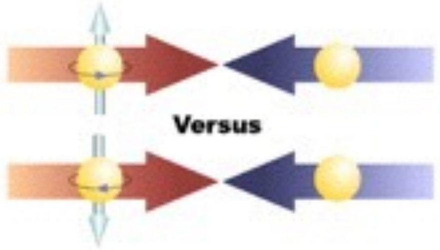
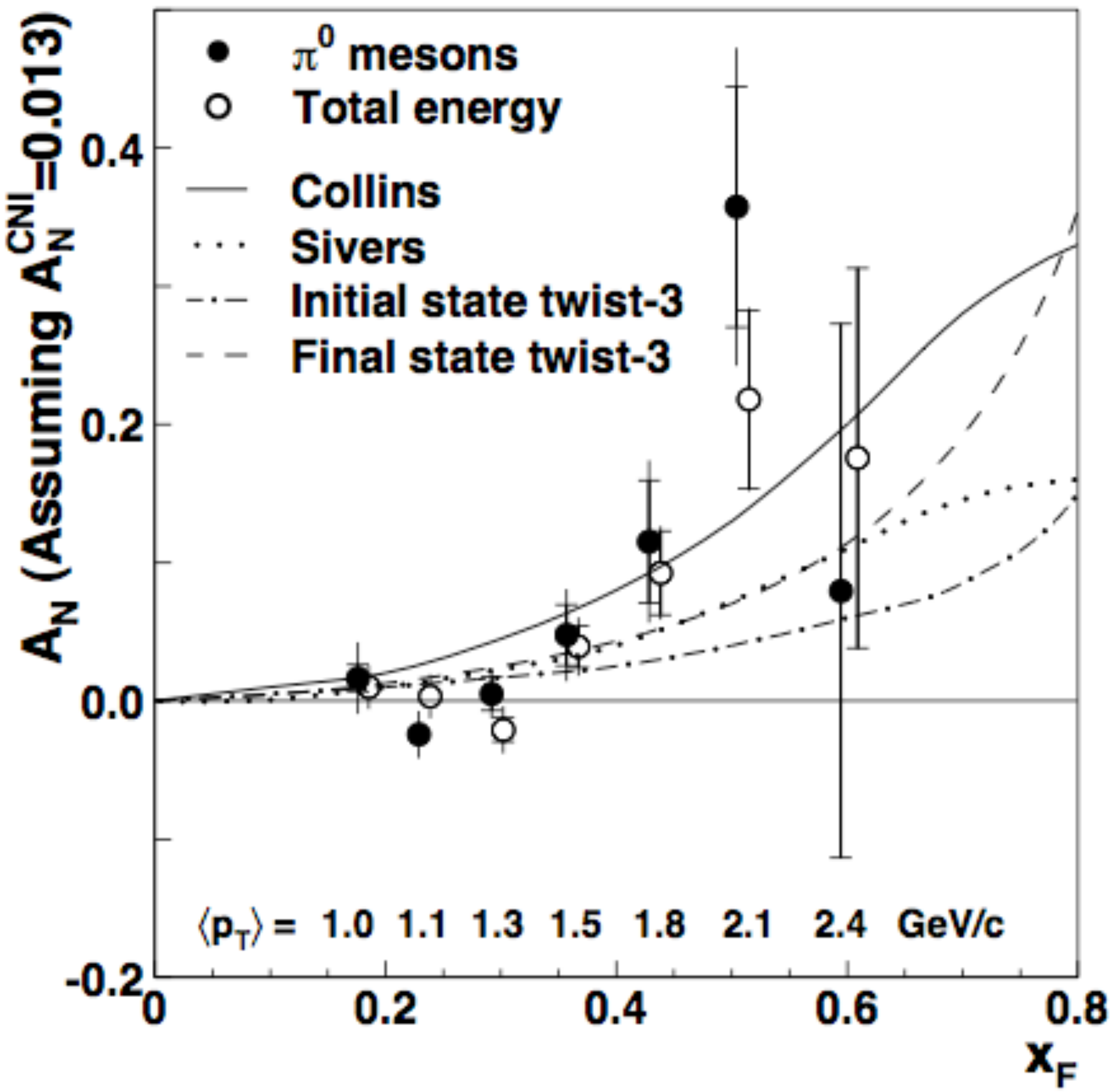
Transverse Spin Phenomena: large A_N

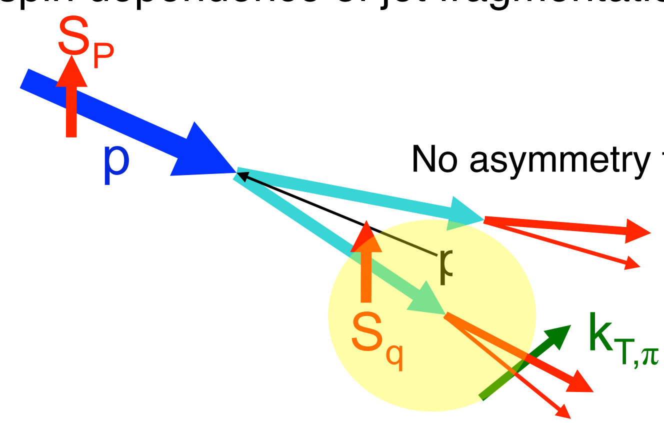


STAR neutral pion A_N - a continuing puzzle since E704

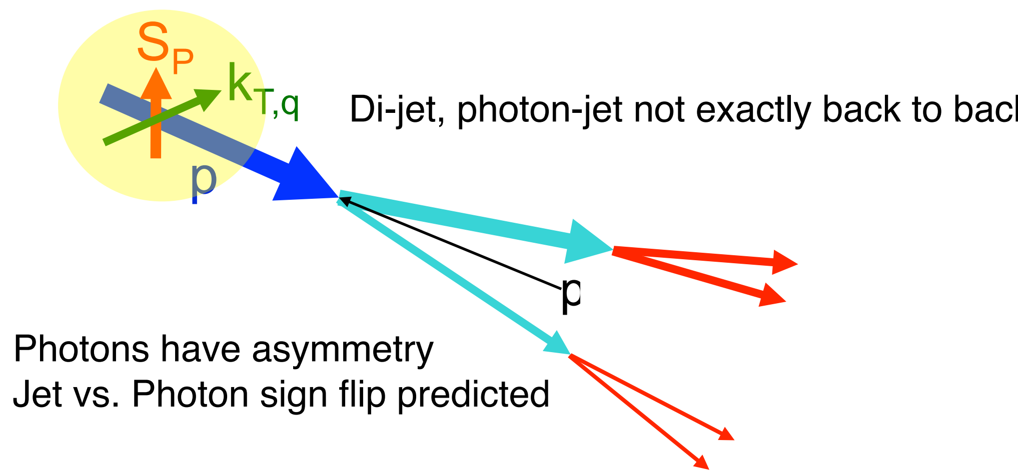
J. Adams et al, PRL 92, 171801 (2004)



- **Collins effect**: asymmetry comes from the transversity and the spin dependence of jet fragmentation.



- **Sivers effect**: asymmetry comes from spin-correlated k_T in the initial parton distribution

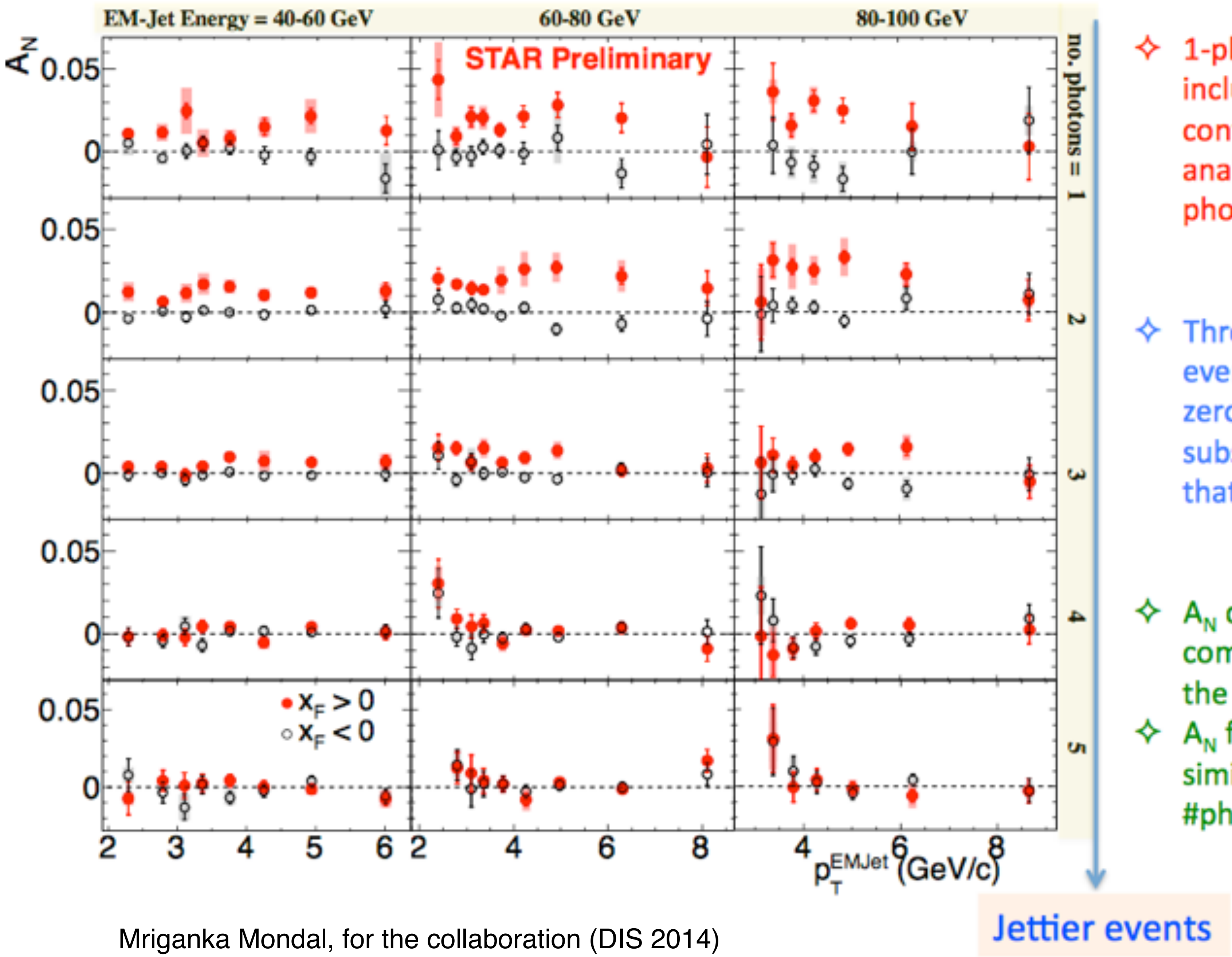


What causes this?

An experimental handle beyond collinear twist-2 perturbative QCD?

STAR neutral pion A_N - a continuing puzzle since E704

The puzzle continues...



Mriganka Mondal, for the collaboration (DIS 2014)

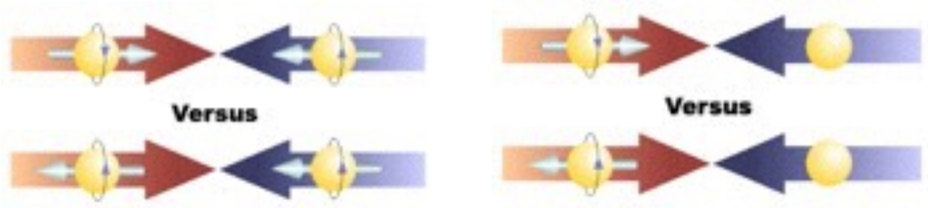
- ✧ 1-photon events, which include a large π^0 contribution in this analysis, are similar to 2-photon events
- ✧ Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated π^0's
- ✧ A_N decreases as the event complexity increases (i.e., the "jettiness"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

and points to a need for qualitatively new instrumentation and measurements,

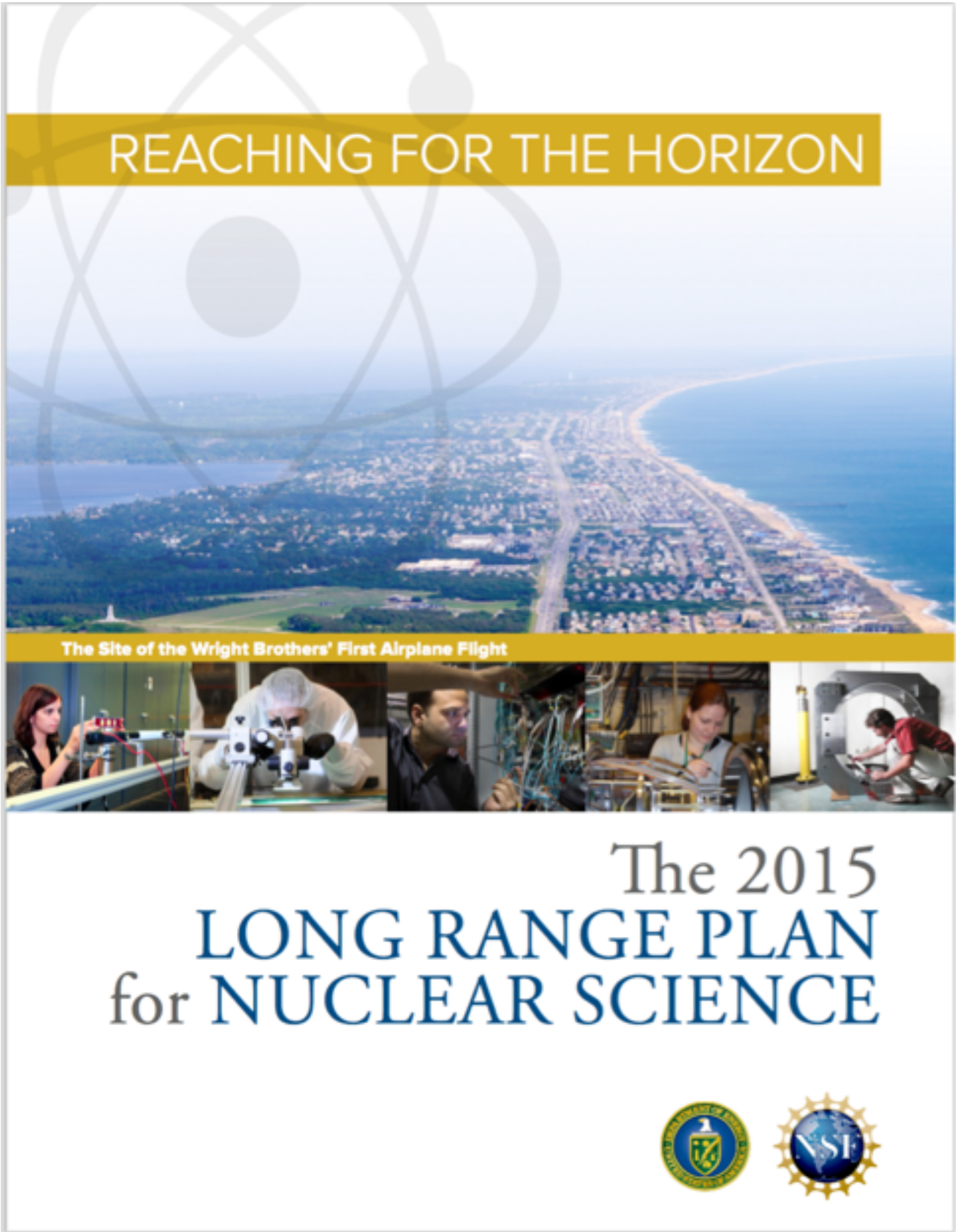
Low-multiplicity observation, consistent with a diffractive production mechanism,

STAR Roman Pots (now) directly measure diffractive A_N. Initial analyses in progress.

Completion of RHIC and transition to EIC



Completion of RHIC and transition to EIC



RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

RECOMMENDATION II

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

RECOMMENDATION III

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB. [Q3 FY22]

RECOMMENDATION IV

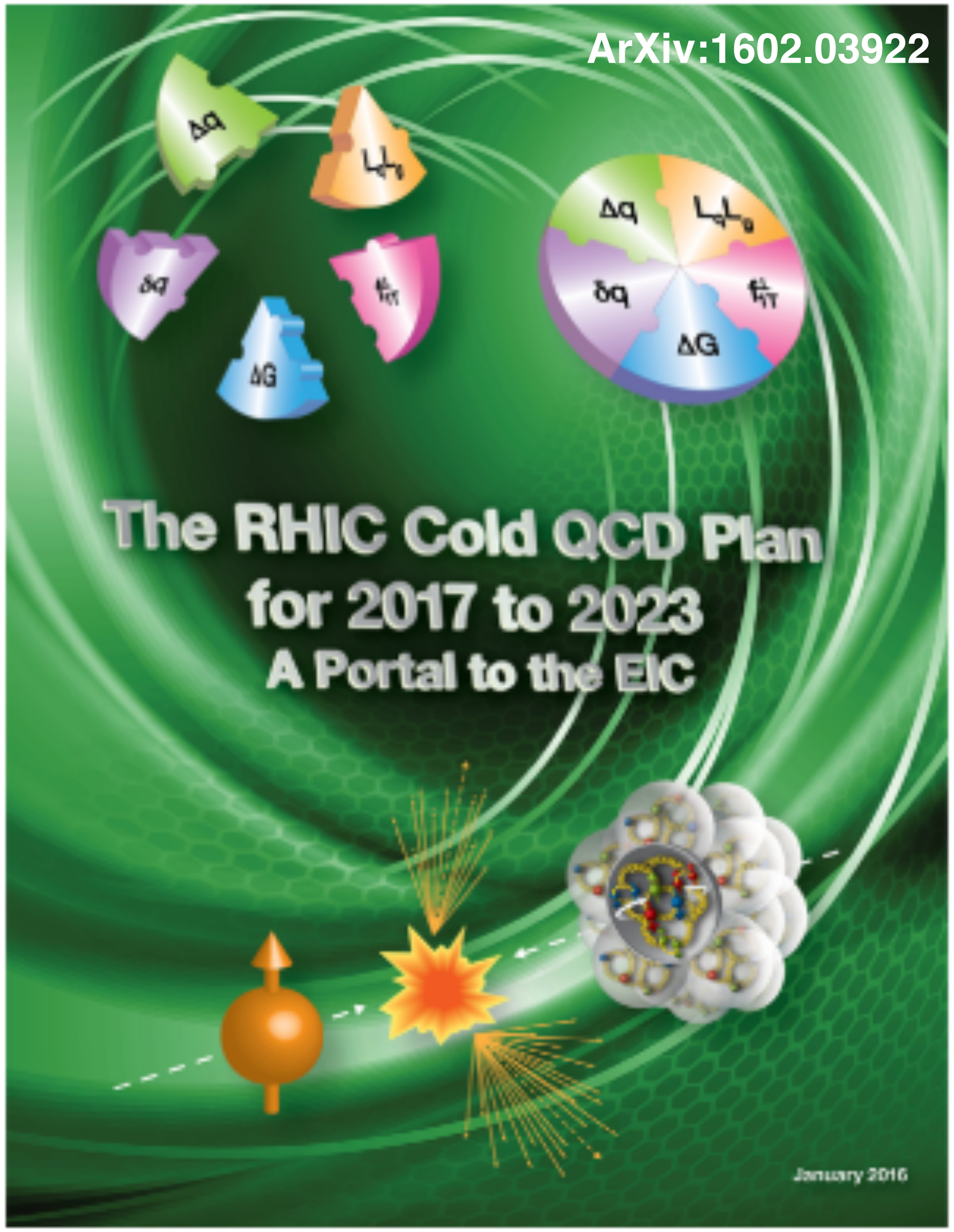
We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

BNL-ALD Berndt Mueller to STAR - January 2016

Proposed run schedule for RHIC

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2016	High statistics Au+Au d+Au energy scan	Complete heavy flavor program First measurement of Λ_c Collectivity in small systems	Coherent e-cooling test I
2017	High statistics Pol. p+p at 510 GeV	Transverse spin physics	Coherent e-cooling test II
2018	No Run		Low energy e-cooling upgrade
2019-20	7.7-20 GeV Au+Au (BES-2)	Search for QCD critical point and onset of deconfinement	STAR iTPC upgrade EPD upgrade
2021	No Run		sPHENIX installation
2022-23	200 GeV Au+Au with upgraded detectors Pol. 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	sPHENIX
2024---	No Runs		Transition to eRHIC

Completion of RHIC and transition to EIC



Requested by DOE Office of Science Nuclear Physics in Summer 2015,

Approach:

- emphasize measurements that can *only* be done at a polarized proton collider,
- relate to EIC,
- emphasize flexibility of RHIC for new explorations, e.g. polarized nuclear FF,
- propose only *modest* upgrades,

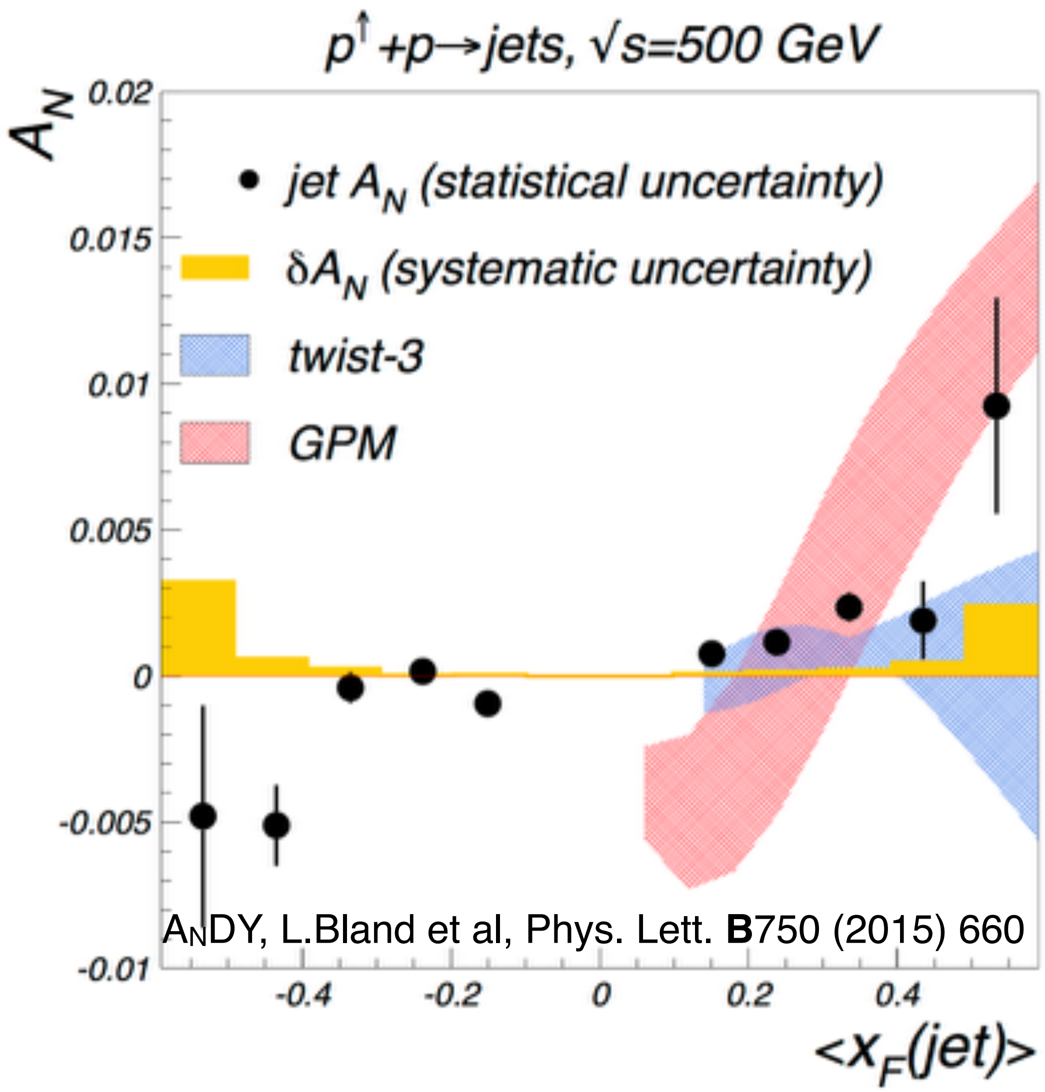
Universality, factorization focused.

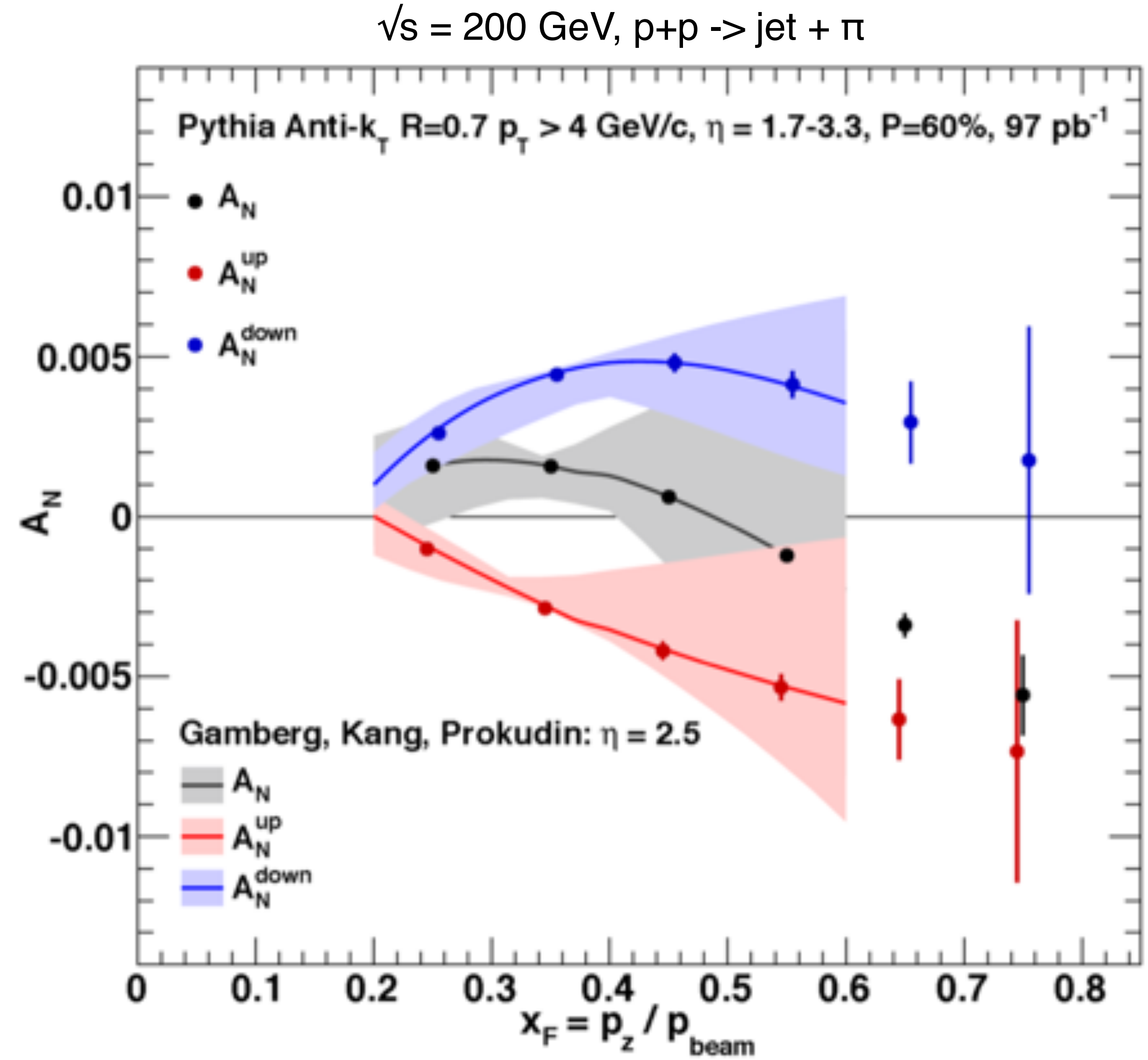
RHIC Cold QCD Plan in One Slide

	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3 First look at GPD E_g	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/Ψ in UPC	A_N^{DY}: Postshower to FMS@STAR **None** **None**
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η evolution of ETQS fct. properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for γ A_N for diffractive events	Yes Forward instrum. **None** **None**
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAu}(DY):Yes Forward instrum. **None** Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl}: direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAl}(DY): Yes Forward instrum. **None** Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity observables as in 2017 run	Yes Forward instrum. **None**
	202X	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Yes Forward instrum.

Table 1-2: Summary of the Cold QCD physics program propsed in the years 2017 and 2023 and if an additional 500 GeV run would become possible.

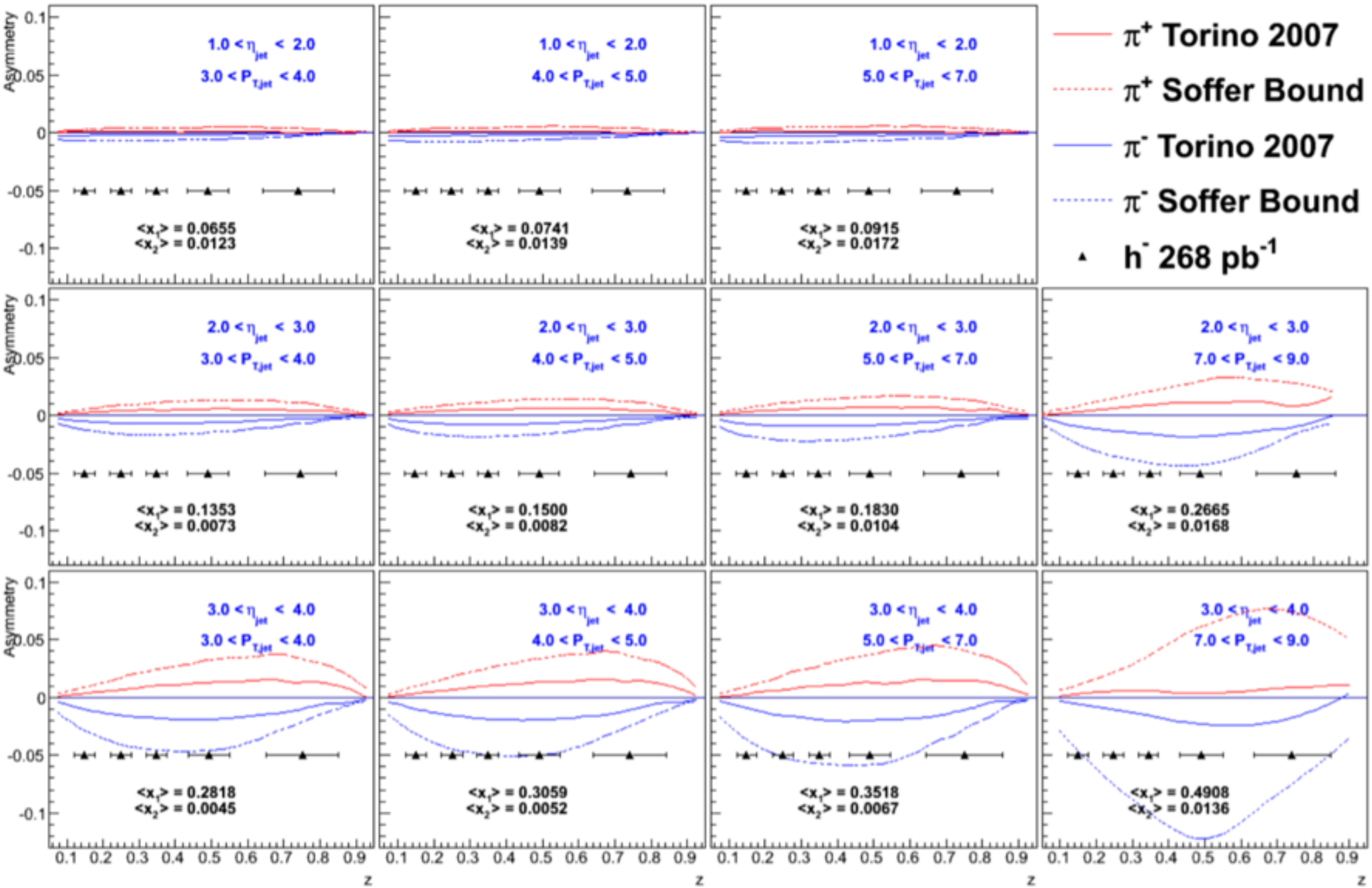
RHIC Cold QCD Plan - p+p highlights





Pursue possible Twist-3 origin of forward A_N with improved photon A_N measurements, and charged-pion enhanced jets.

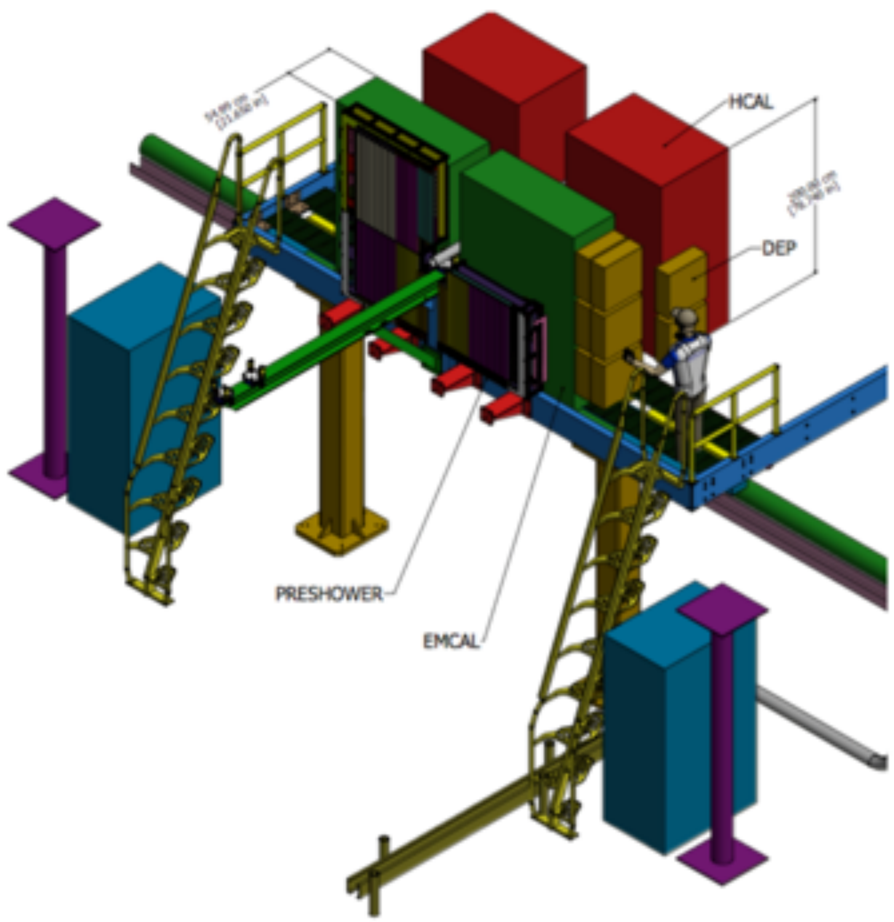
RHIC Cold QCD Plan - p+p highlights, √s = 500 GeV

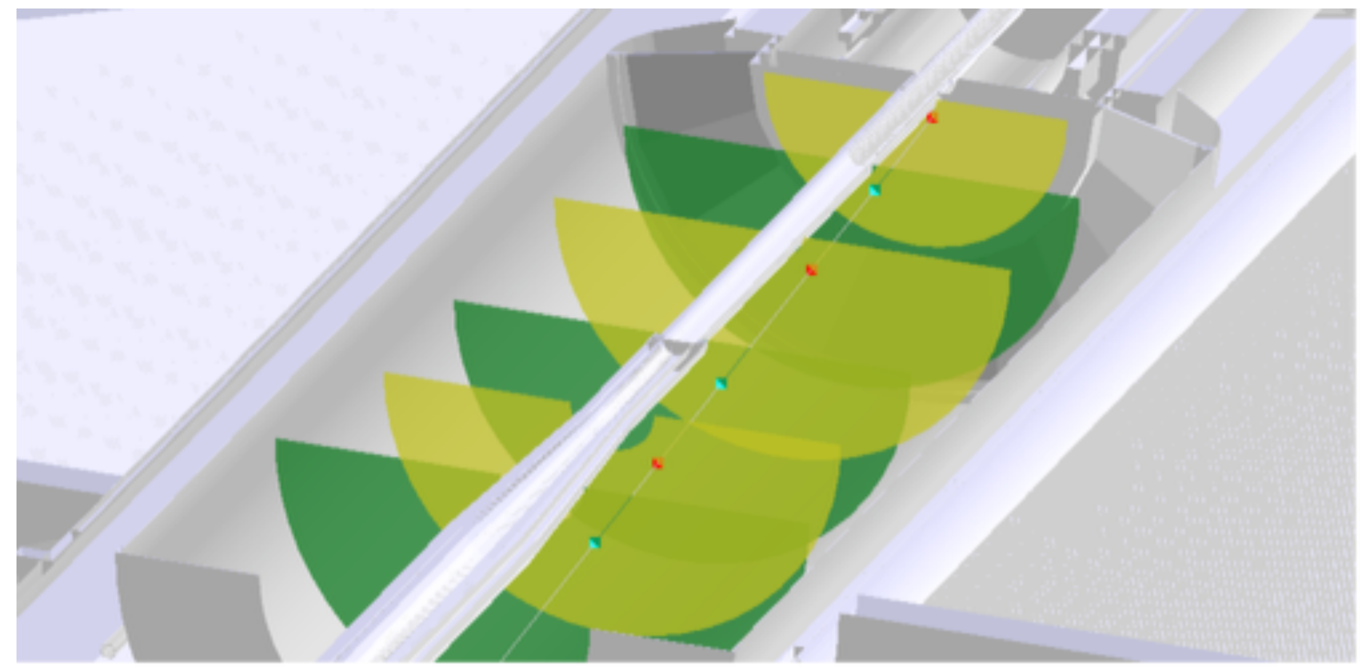


Large-*x* Collins asymmetries.

RHIC Cold QCD Plan - STAR Forward Detector Upgrade

Ensure jet capability ($\sqrt{s}$ = 500 GeV), charge-sign discrimination, Drell-Yan, “*modest*” cost





was: W-powder EM-cal

now: re-use PHENIX eCAL

new HCAL, based on
STAR-EIC R&D

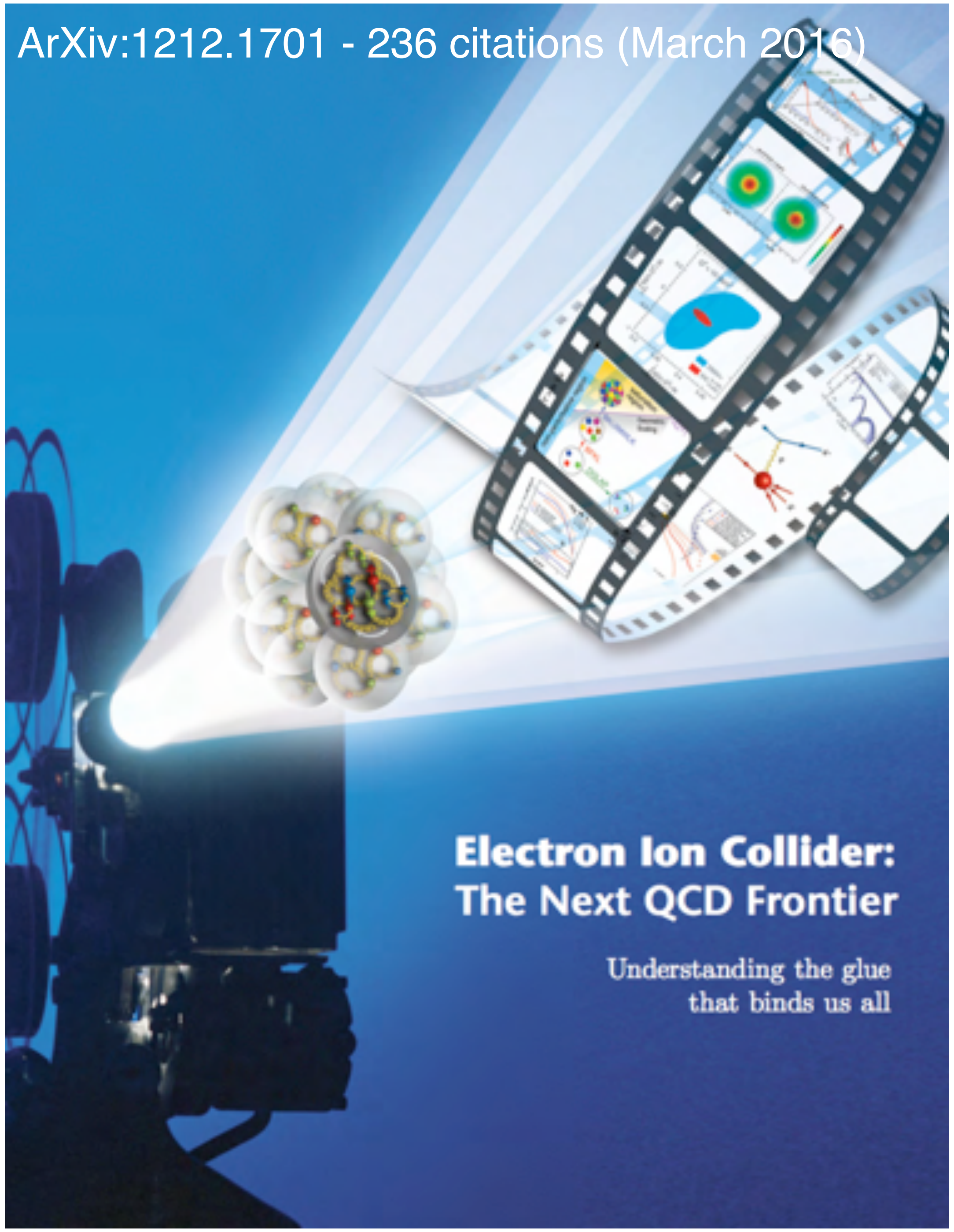
4-6 Si-strip disks, or pixels

8-10 GEM layers have been considered as well

Forward upgrade to sPHENIX is conceptually similar; only *one* will be realized (imho).

EIC

U.S.-based Electron Ion Collider



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T. Ullrich (BNL) and Y. Kovchegov (Ohio State)

Nucleon spin structure (inclusive e+N):
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GPD's and exclusive reactions:
M. Diehl (DESY) and F. Sabatie (Saclay)

TMD's and hadronization and SIDIS:
H. Gao (Duke) and F. Yuan (LBNL)

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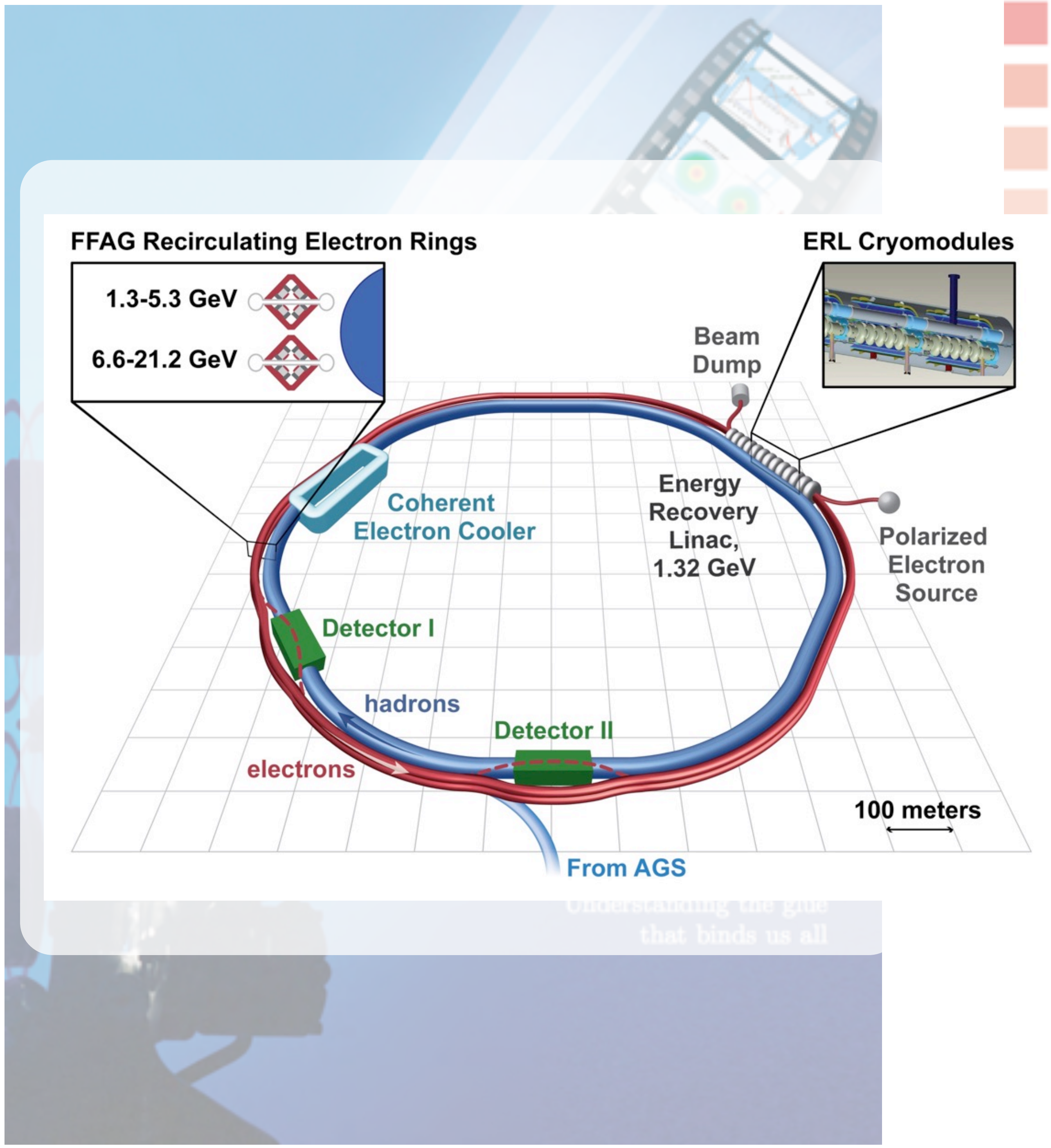
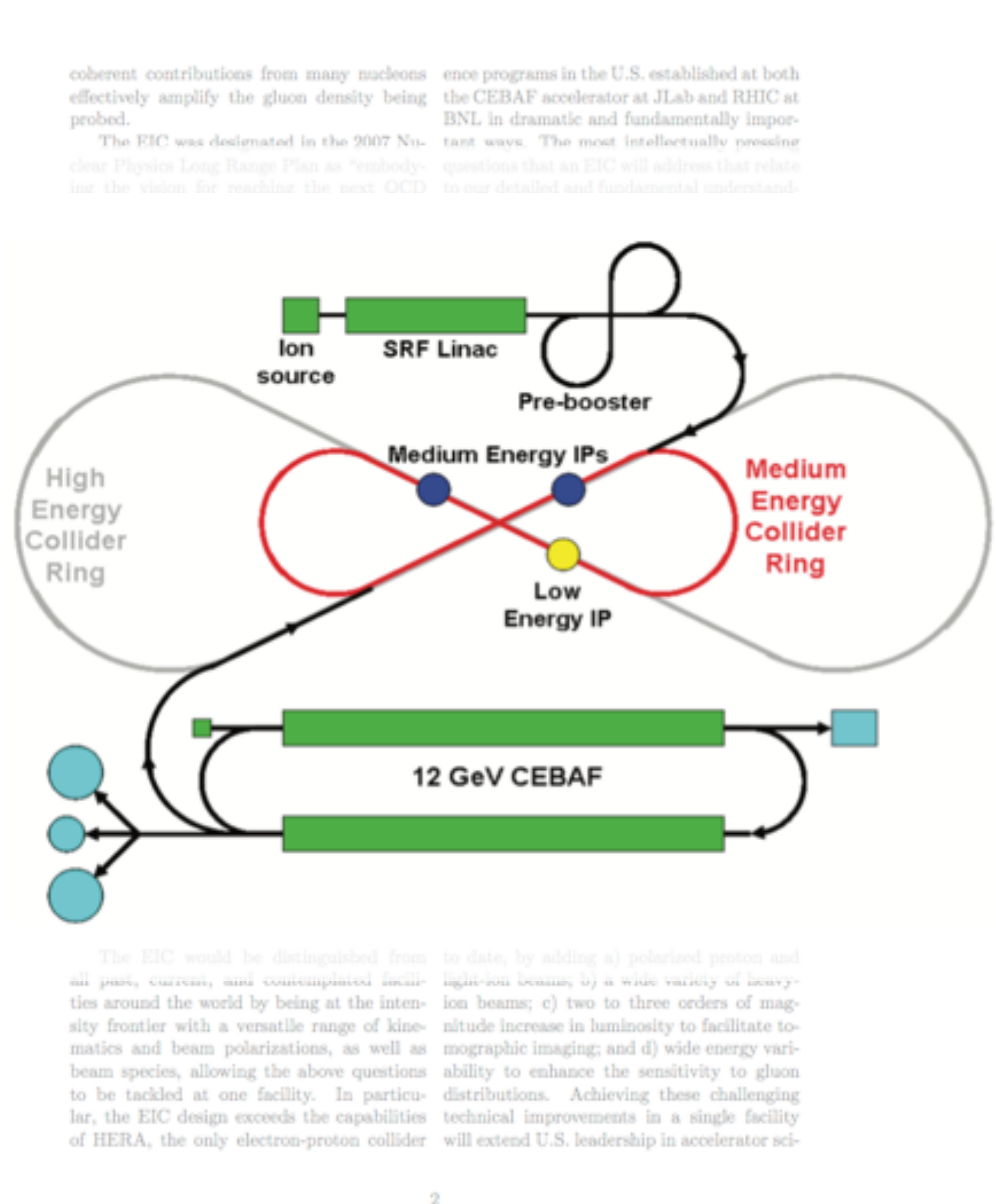
Senior Advisors:
A. Mueller (Columbia) and R. Holt (ANL)

Successful thanks to many other co-authors and contributions

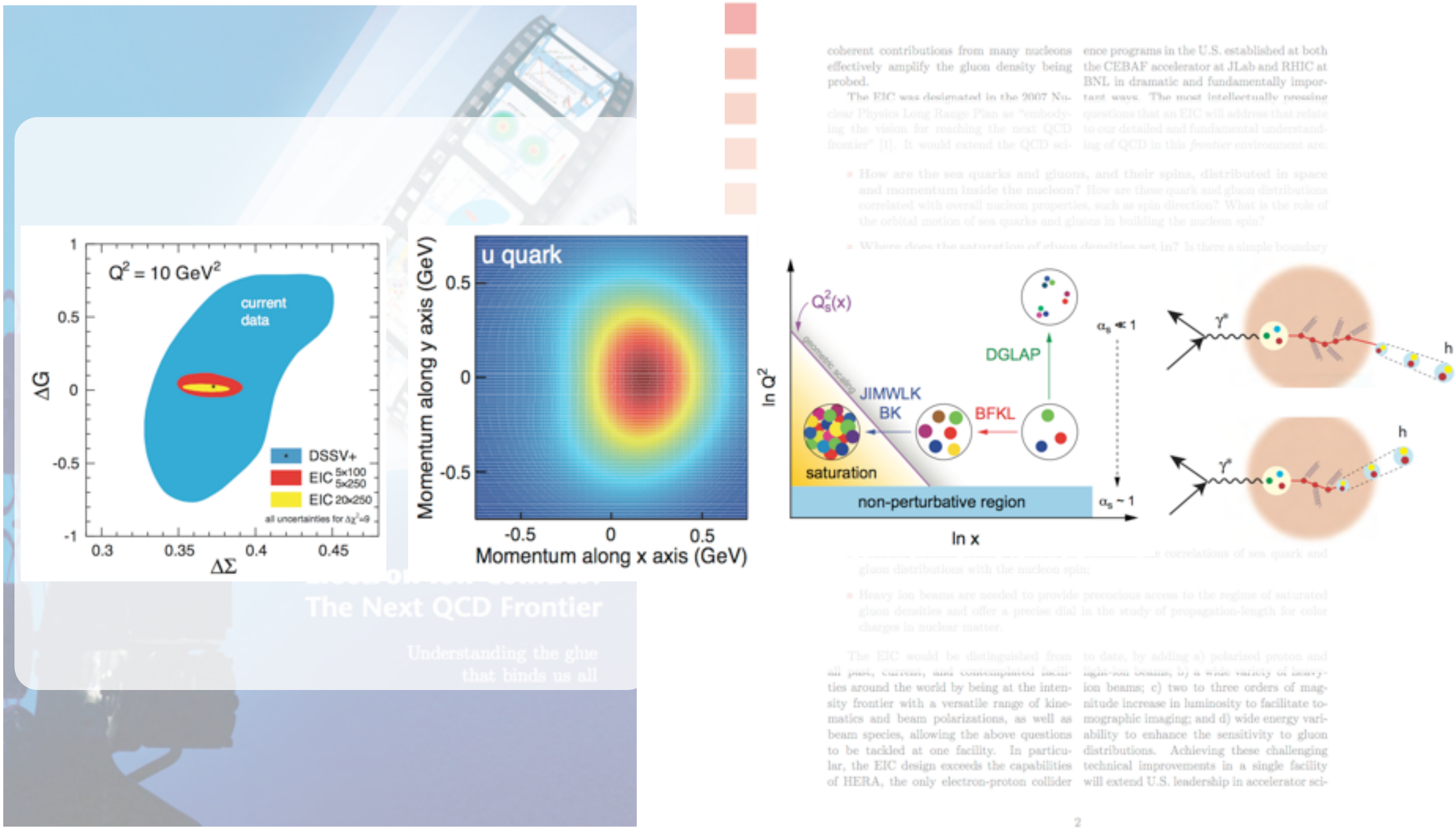
U.S.-based Electron Ion Collider





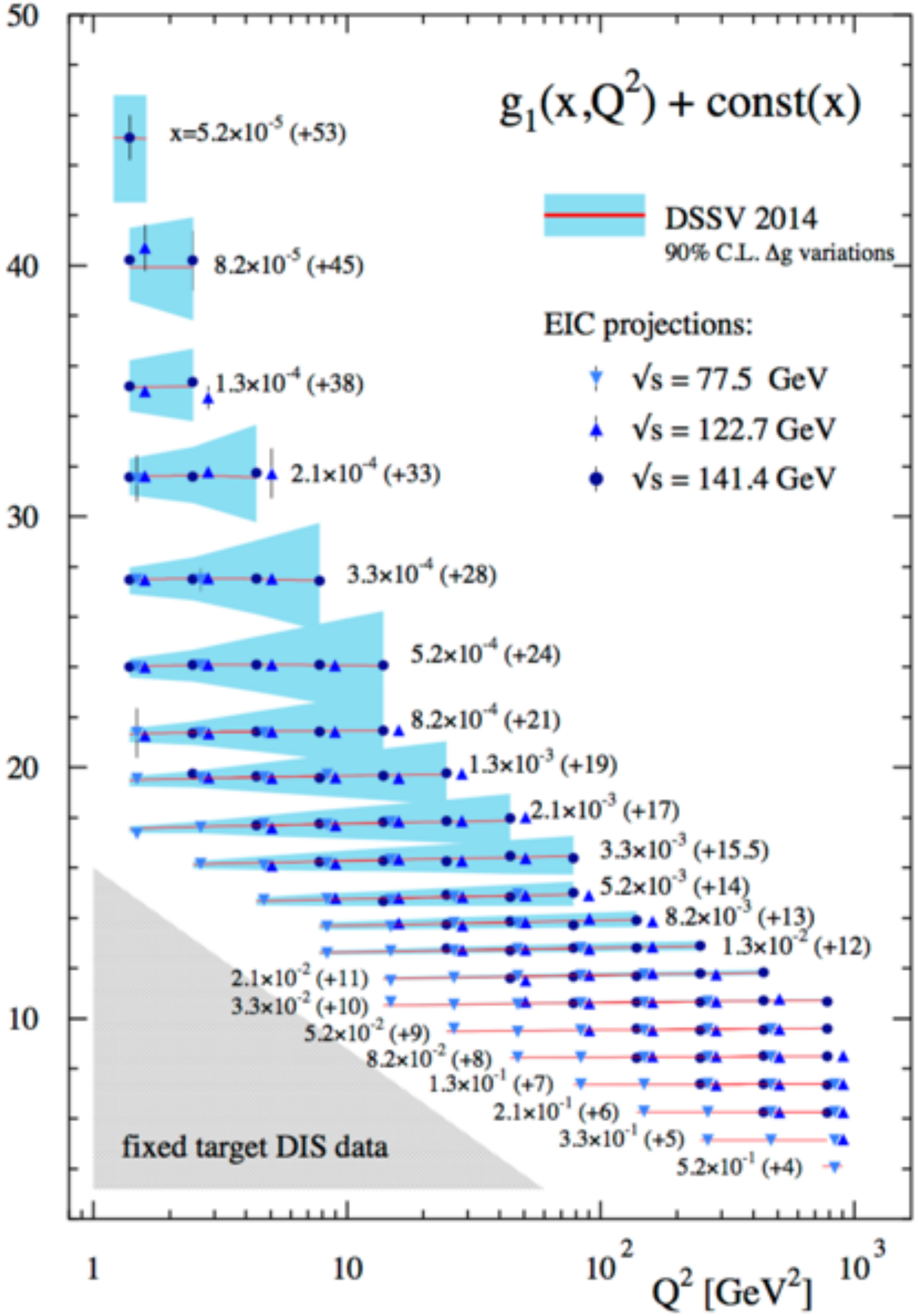
ArXiv:1212.1701

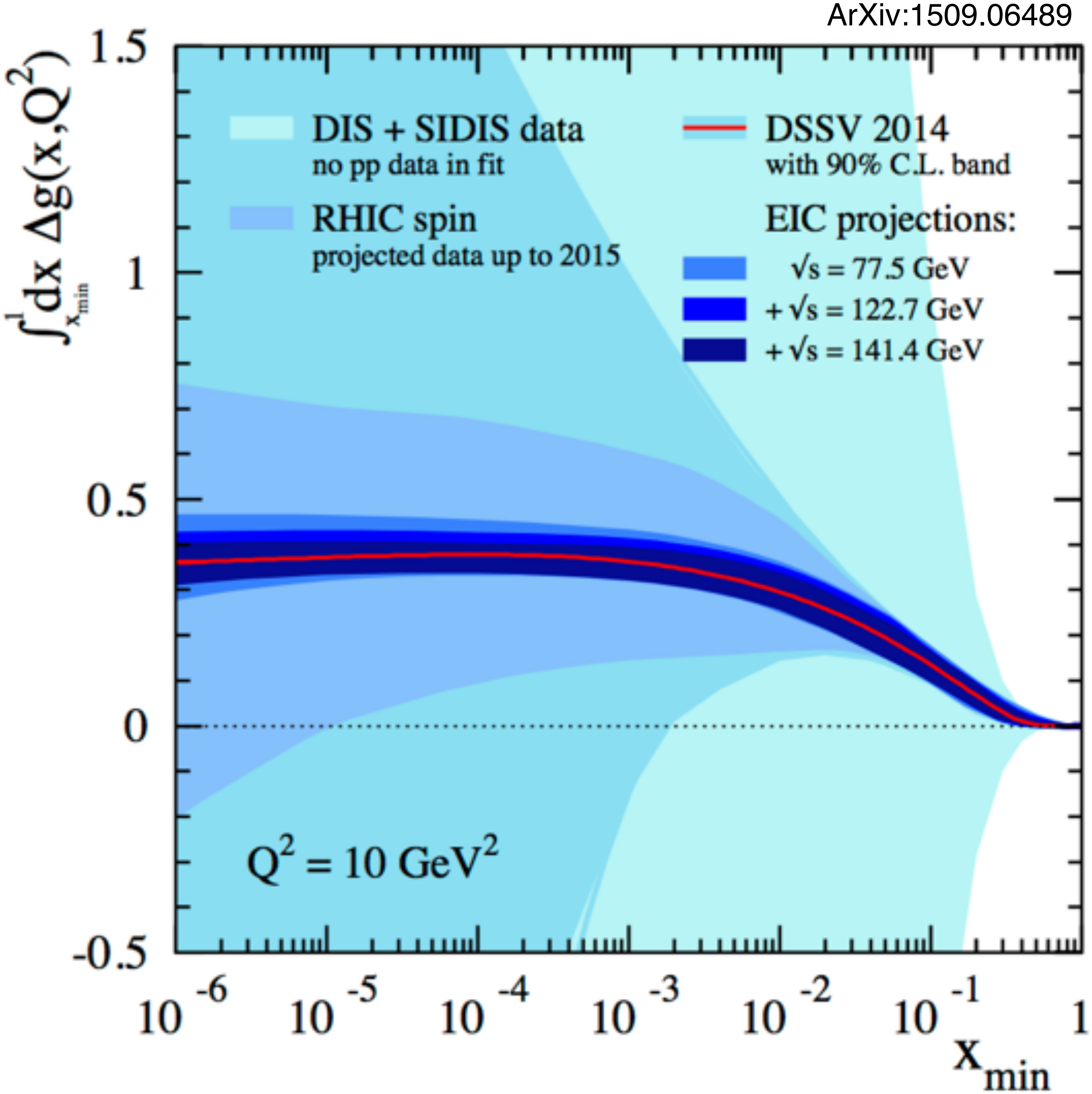
U.S.-based Electron Ion Collider



ArXiv:1212.1701

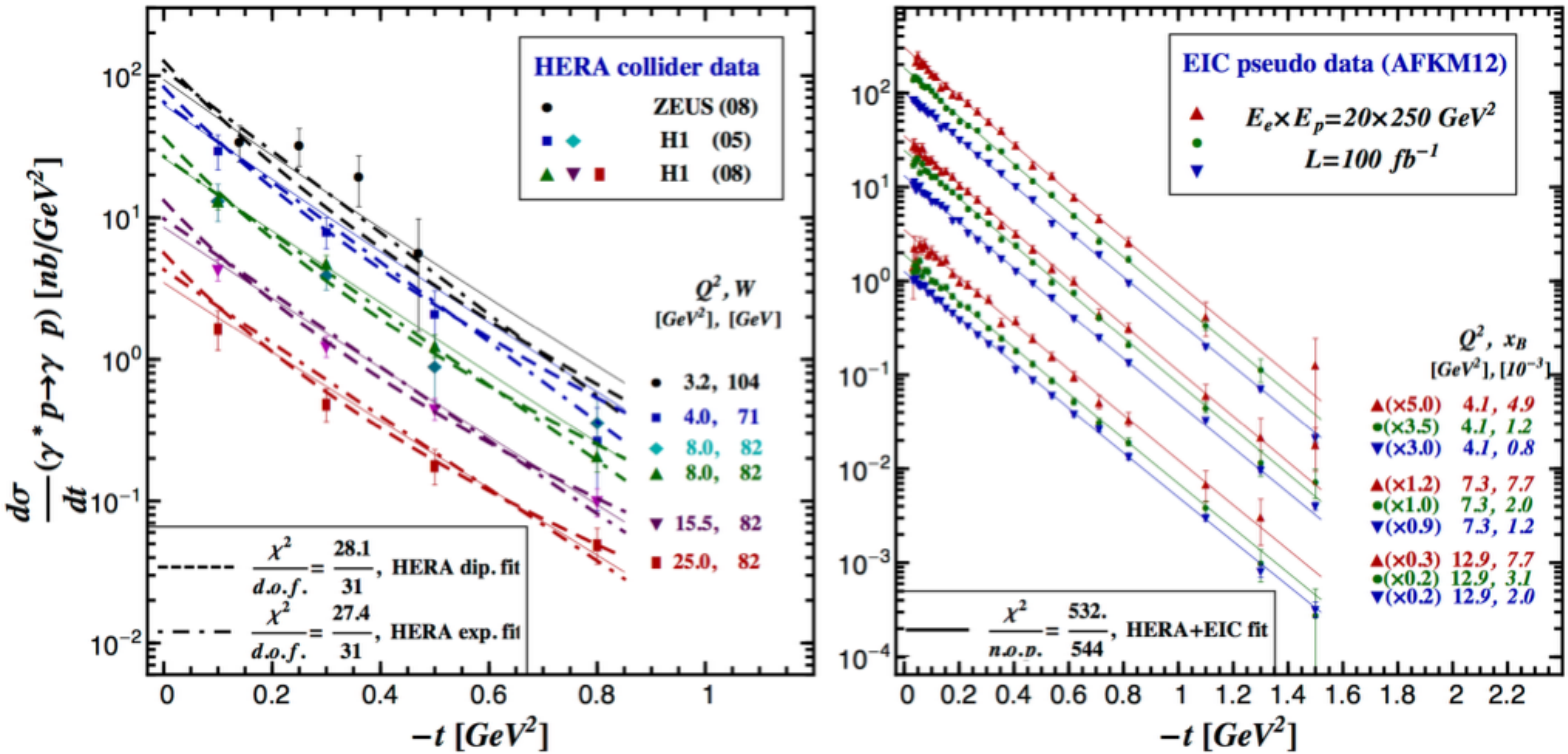
U.S.-based Electron Ion Collider





No competition, really.

U.S.-based Electron Ion Collider



No competition, really.

U.S.-based Electron Ion Collider - Reality Check

What Aspect Are We Working On Now?

We continue to work on whether the number of future electron ion colliders will be 1 or 0.

(The first possibility is of course highly anticipated based on QCD science and future mission need for the field)

Two slides from Dr. Tim Hallman, Associate Director for Nuclear Physics at the DOE Office of Science, at the recent EIC User Group meeting at Berkeley.

Outlook

Our work continues…

Independent Vetting of Science Case

R&D & Design Refinement to Reduce Risk and $$

Decision on when to go for CD0, Mission Need

Mechanism for determining “Best Value” to the United States

This was the most upbeat talk on EIC I have seen from this office in the past 10 years or so.

Closing Comments

U.S. EIC is *not* a done deal, but the prospects are better than ever;

- positive recommendation in the 2015 Long Range Plan for U.S. Nuclear Physics,
- independent science review by the National Academy of Sciences is starting,
- discussion is moving from "science case" to "next steps":
    - reduce (uncertainty in) cost estimate,
    - establish "mission need",
    - site selection,

"An EIC is envisioned to start construction after FRIB construction is completed and to be operational by the end of the 2020s." (2015 Long Range Plan, resource section).

RHIC spin:

- 2017 run is (now) firmly rooted in the BNL facility plan,
- next opportunity will be concurrent with *high-luminosity* $\sqrt{s}$ = 200 GeV p+p and p+A heavy-ion reference data taking in 2023; case articulated for both
- "modest" instrument upgrades thinkable; most likely forward calorimetry and tracking, limited or no particle-identification,
- strong case for renewed $\sqrt{s}$ = 500 GeV, but not currently part of the facility plan.