The RHIC Spin Program: Status and Opportunities

Ernst Sichtermann

- introduction to RHIC and its detectors,
- recent achievements, open questions,
- near-term opportunities, 2017 run
- looking ahead towards EIC

8th Workshop on Hadron Physics
in China and Opportunities Worldwide
CCNU - August 8, 2016

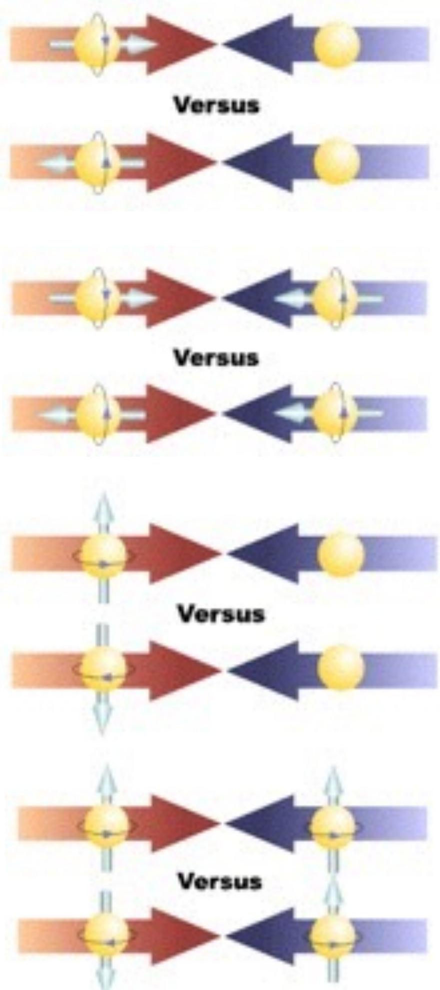
Berkeley Lab

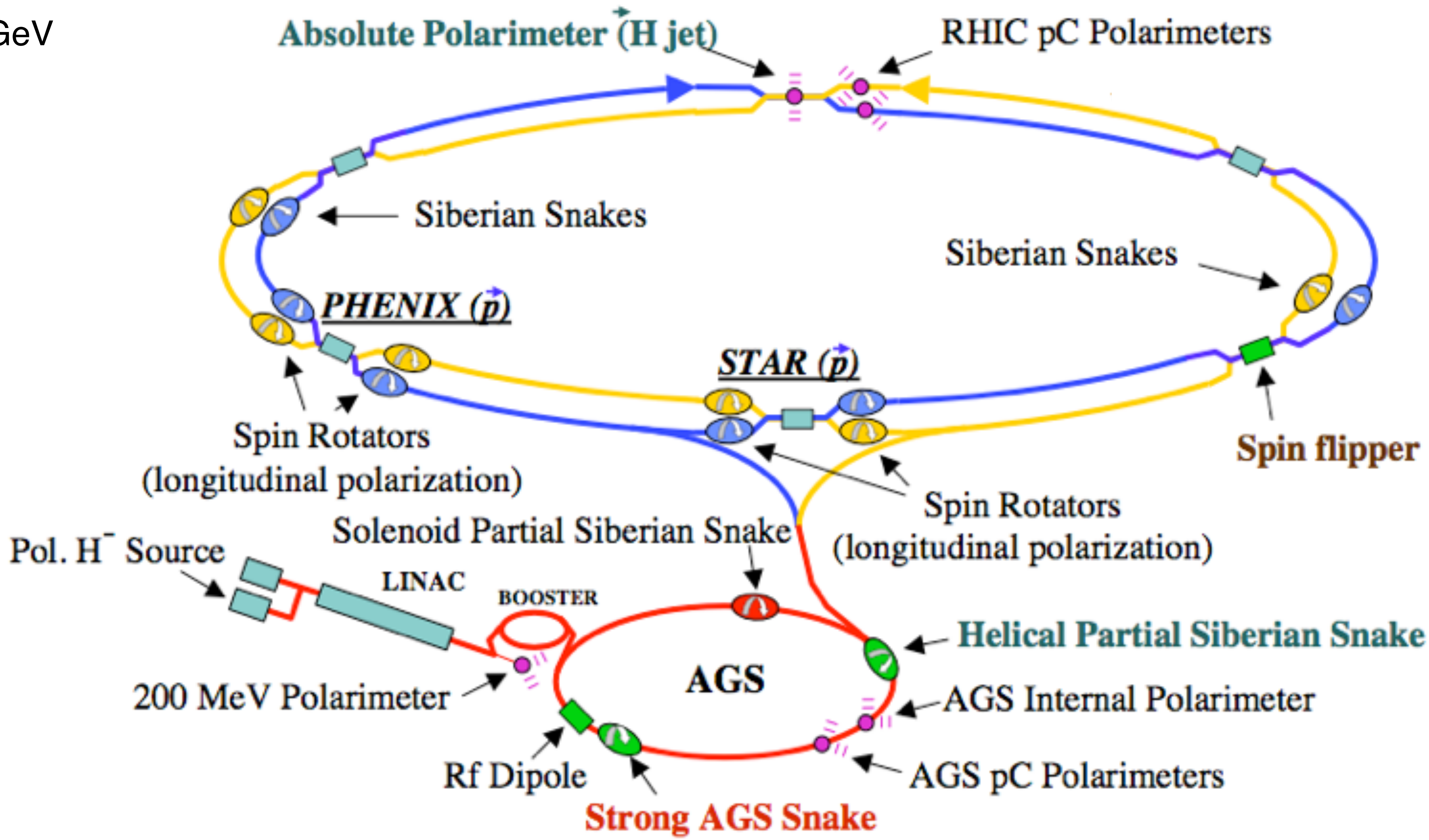
Office of Science
U.S. Department of Energy

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.

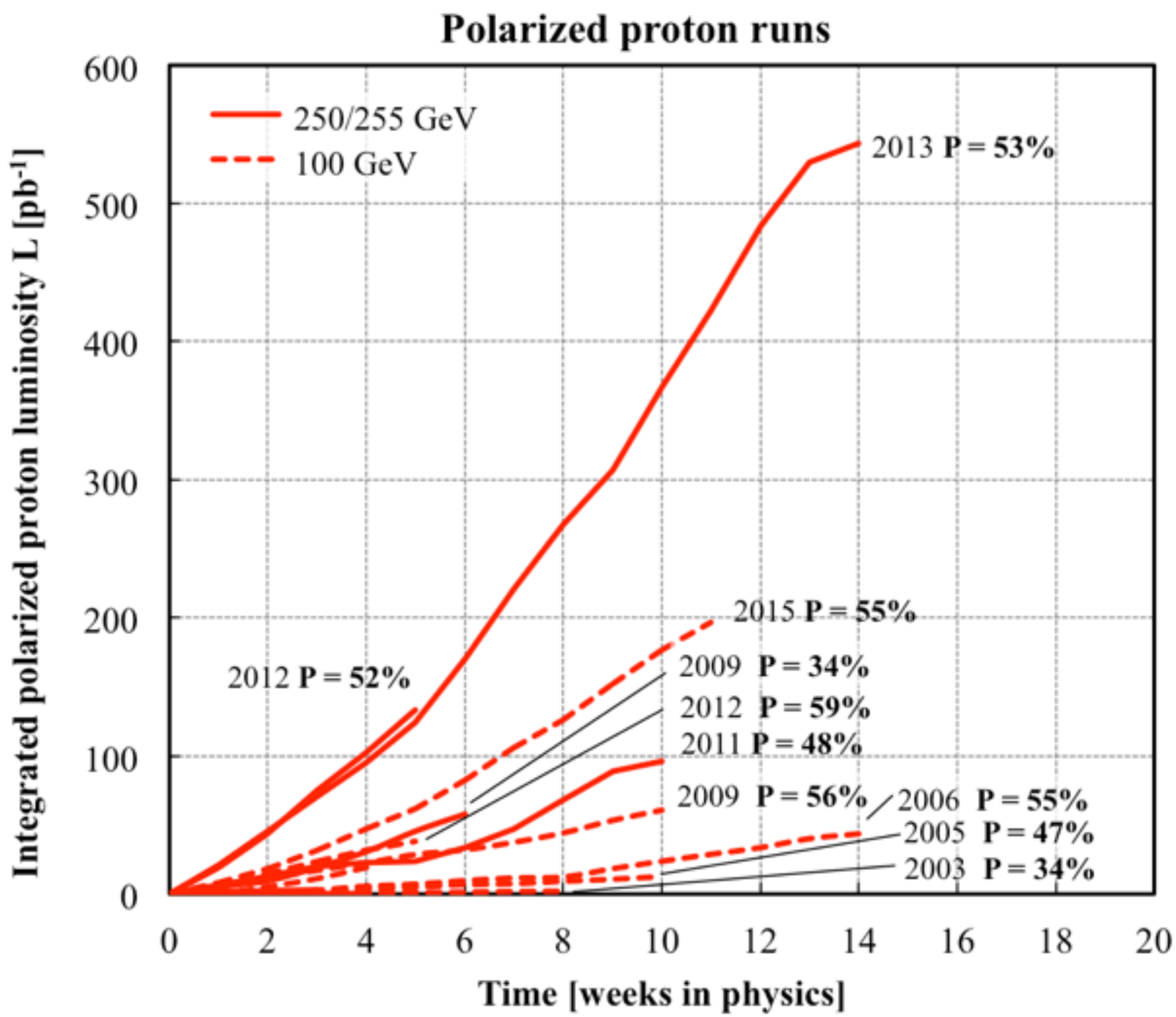
RHIC - Polarized Proton-Proton Collider

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})

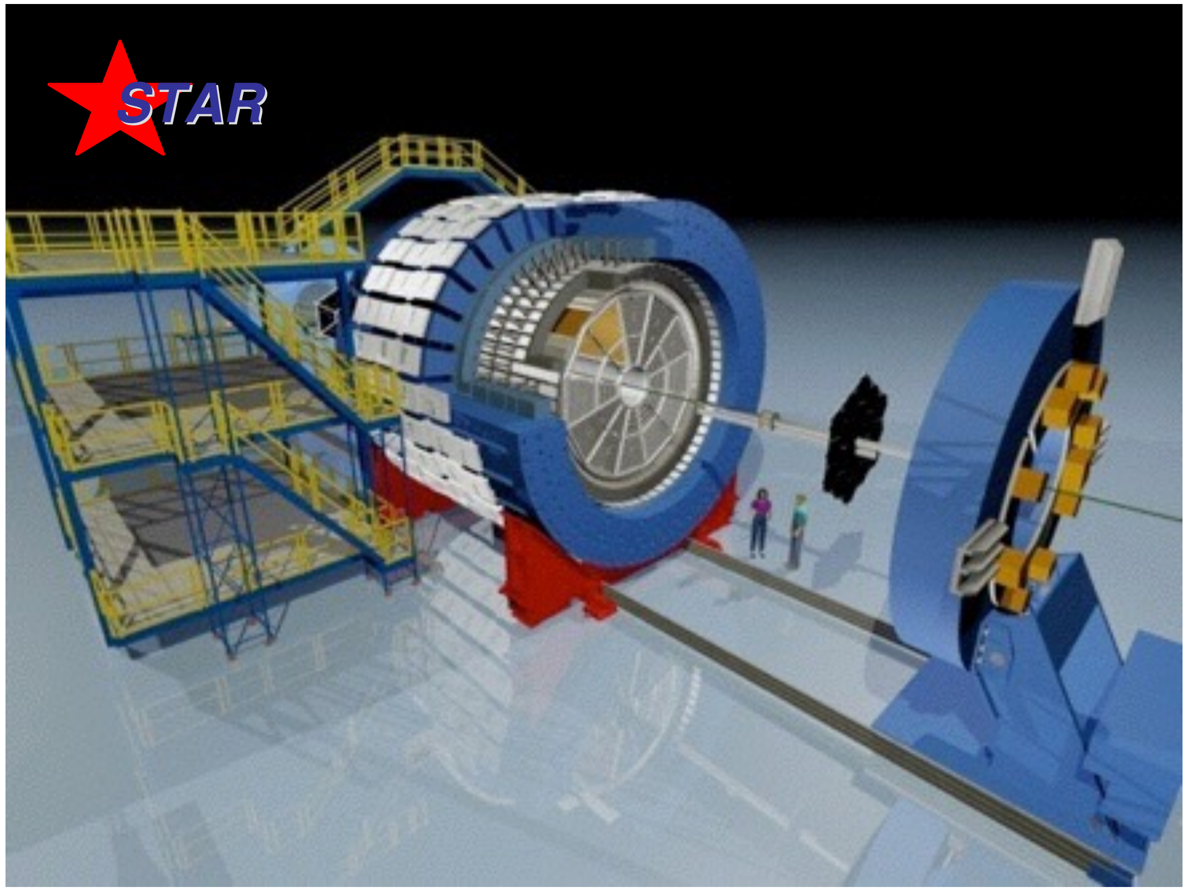
50-60% polarization

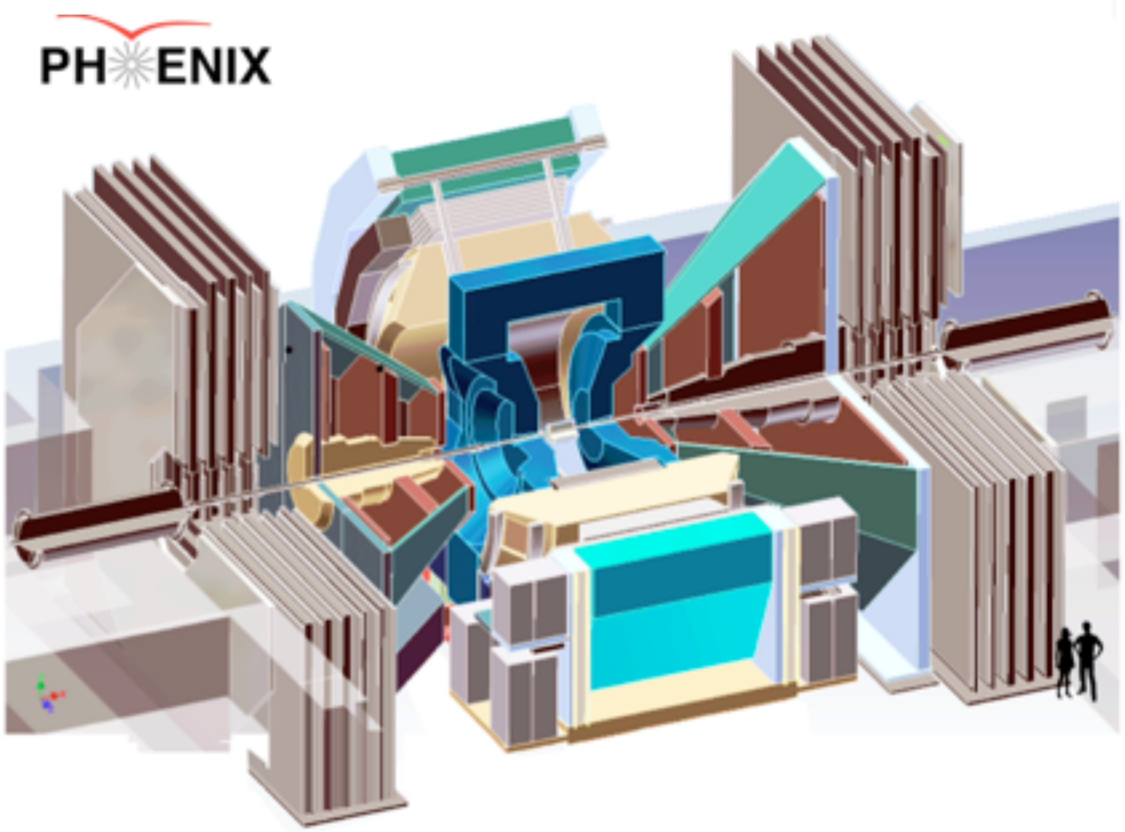


RHIC - The Main Experiments

STAR "DNA":

- large acceptance and low mass,
- full acceptance and PID for $|\eta|< 1$, $\Delta\phi \sim 2\pi$,
- complemented with forward E.M. calorimetry
- key strengths for jets and correlations
- ongoing upgrades: near-term FMS-PSD
  iTPC, EPD, ETOF
  FCS+FTS



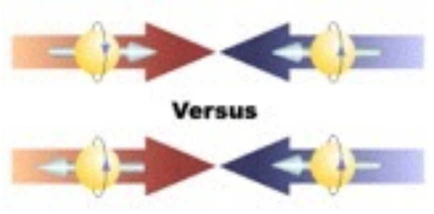


PHENIX "DNA":

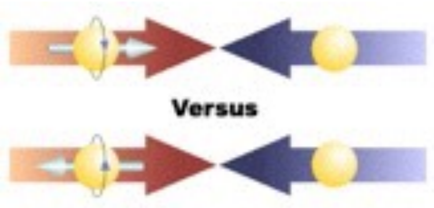
- high resolution and rate capabilities,
- central arms $|\eta|<0.35$, $\Delta\phi \sim \pi$
  with key strengths for π^0 and η
- forward muon arms $1.2<|\eta|<2.4$
- final run, preparing upgrade to sPHENIX

The RHIC Spin Physics Program - Key Questions

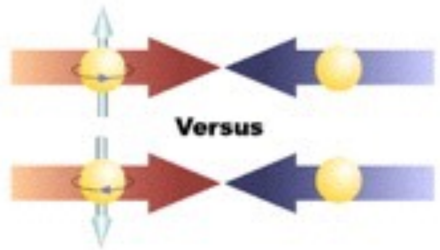
- *What is the polarization of gluons in the polarized proton?*



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

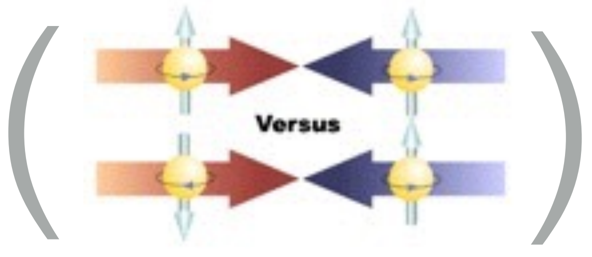


- *Does the Sivers' function change sign in proton-collisions compared to DIS?*

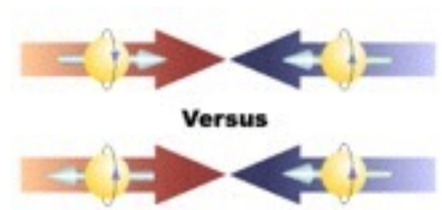


- *What are the quark transversity distributions?*

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



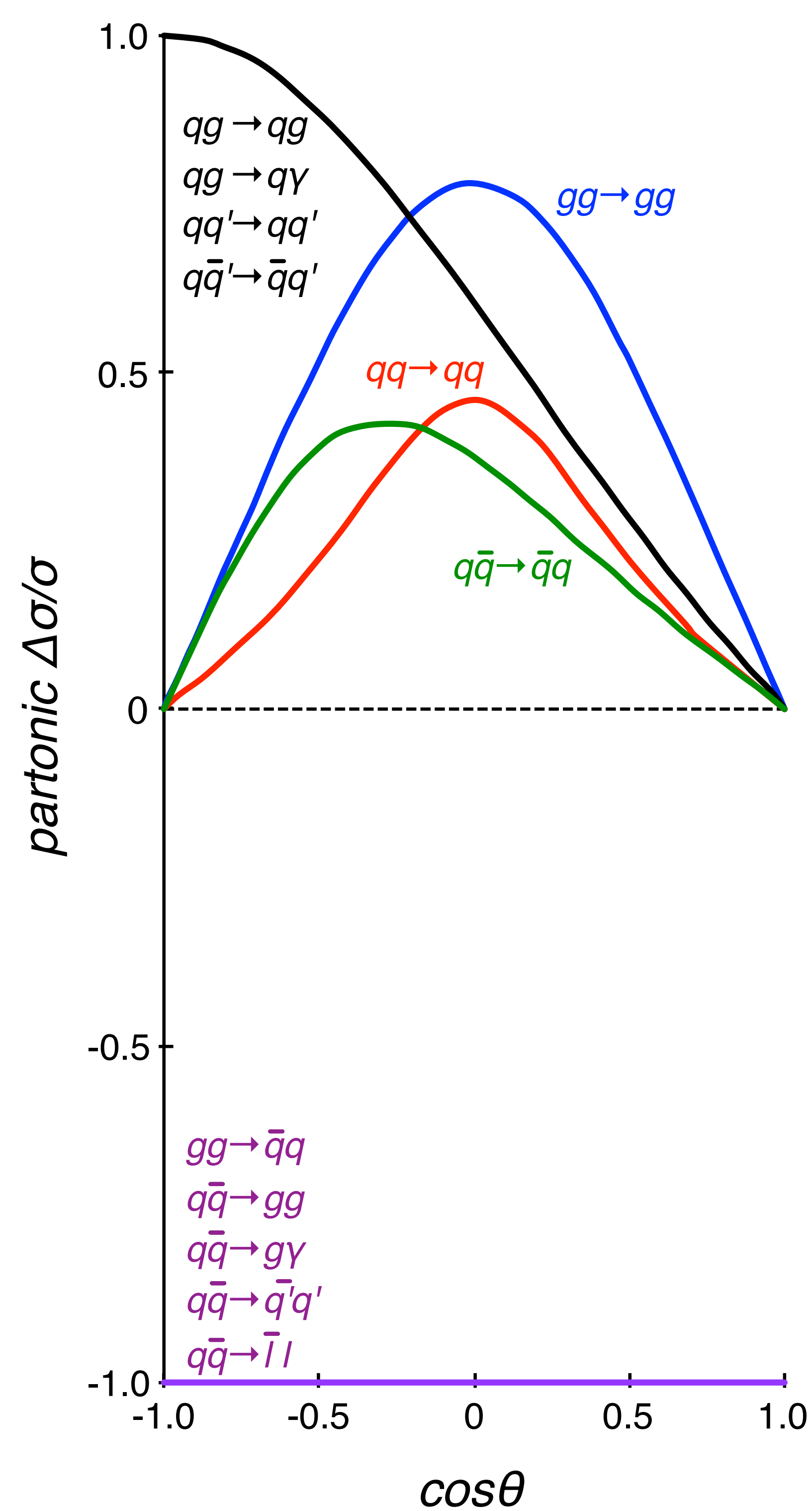
Gluon Polarization



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,
- Understood reconstruction techniques,
- Sizable partonic asymmetries

Disadvantages:

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

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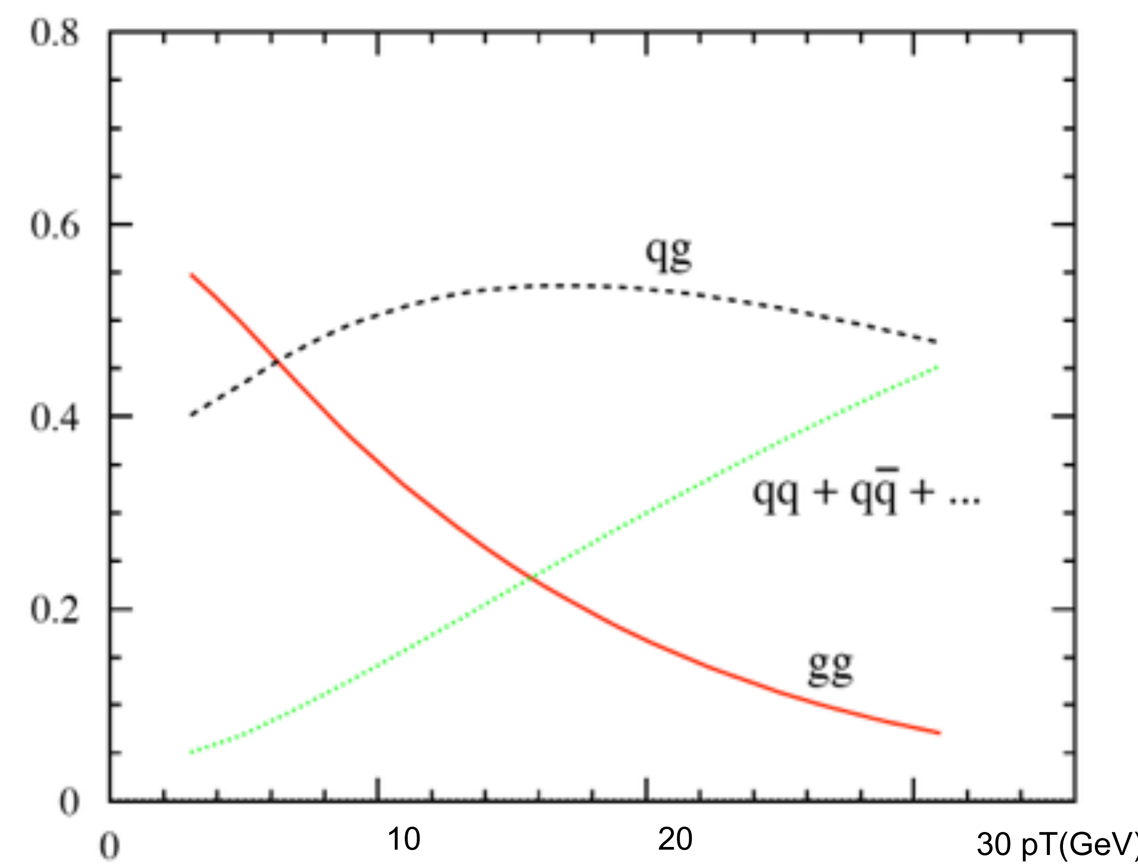

gluon-gluon and quark-*gluon* scattering contributions dominate.

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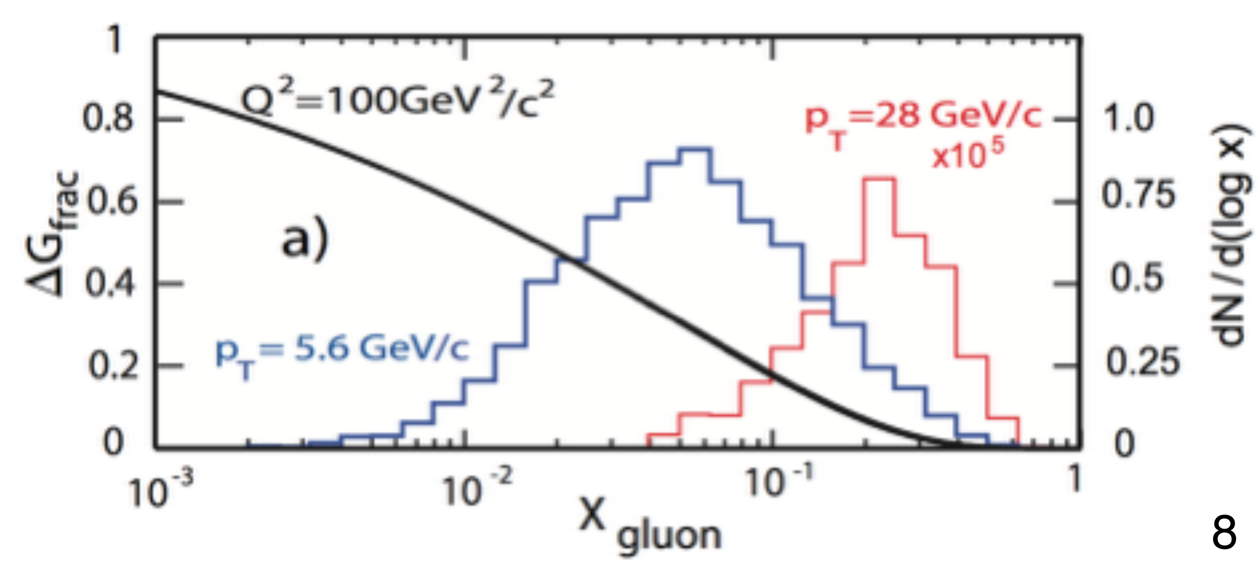
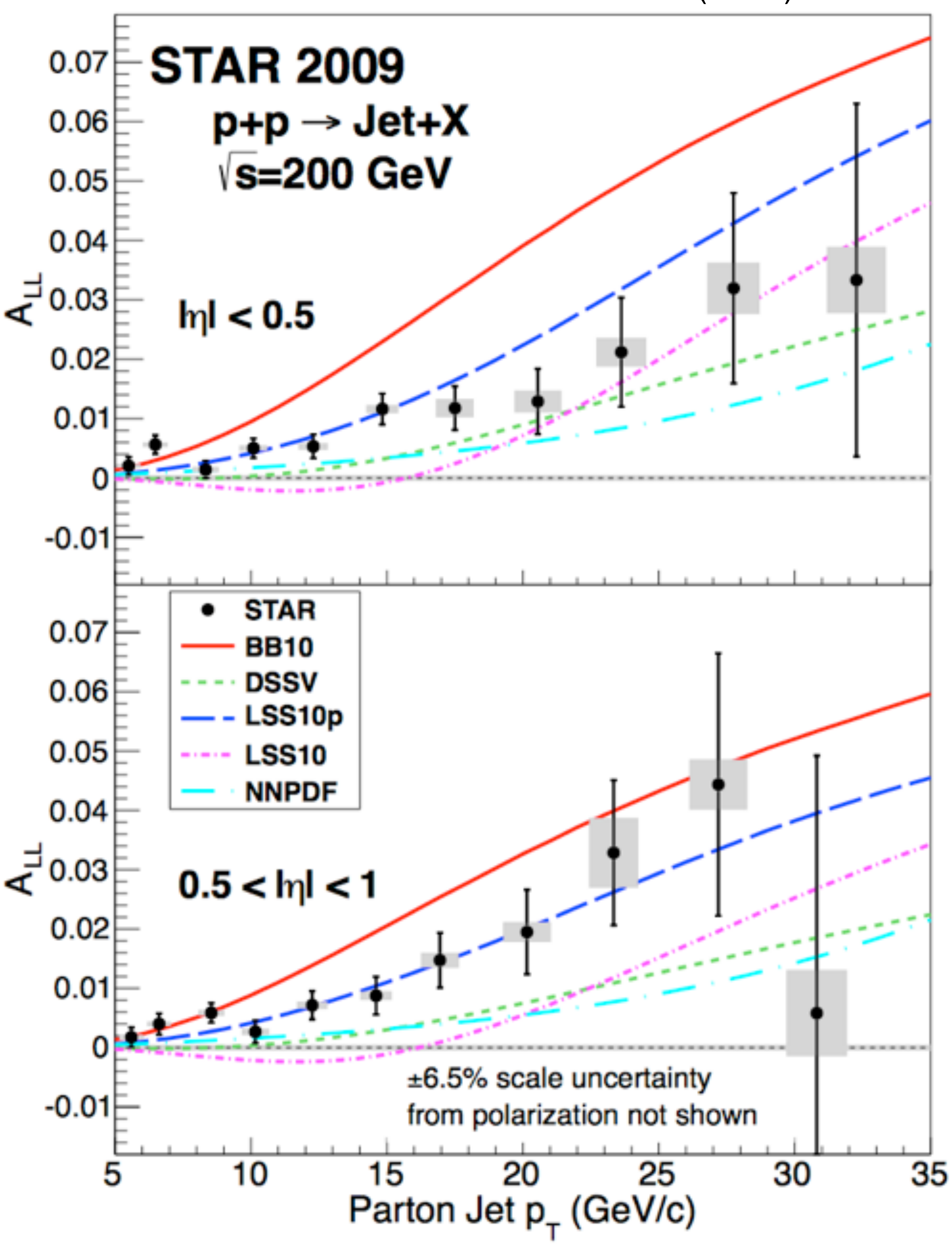
- Contributions from several sub-processes,
- Wide x_g range sampled for each fixed p_T
- x_g, x_q ~ $p_T/\sqrt{s} \cdot \exp(-\eta)$



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

PRL 115 (2015) 092002



Significant advance compared to first RHIC-spin data (2003, 2004):

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

Initial sensitivity to different x_g from

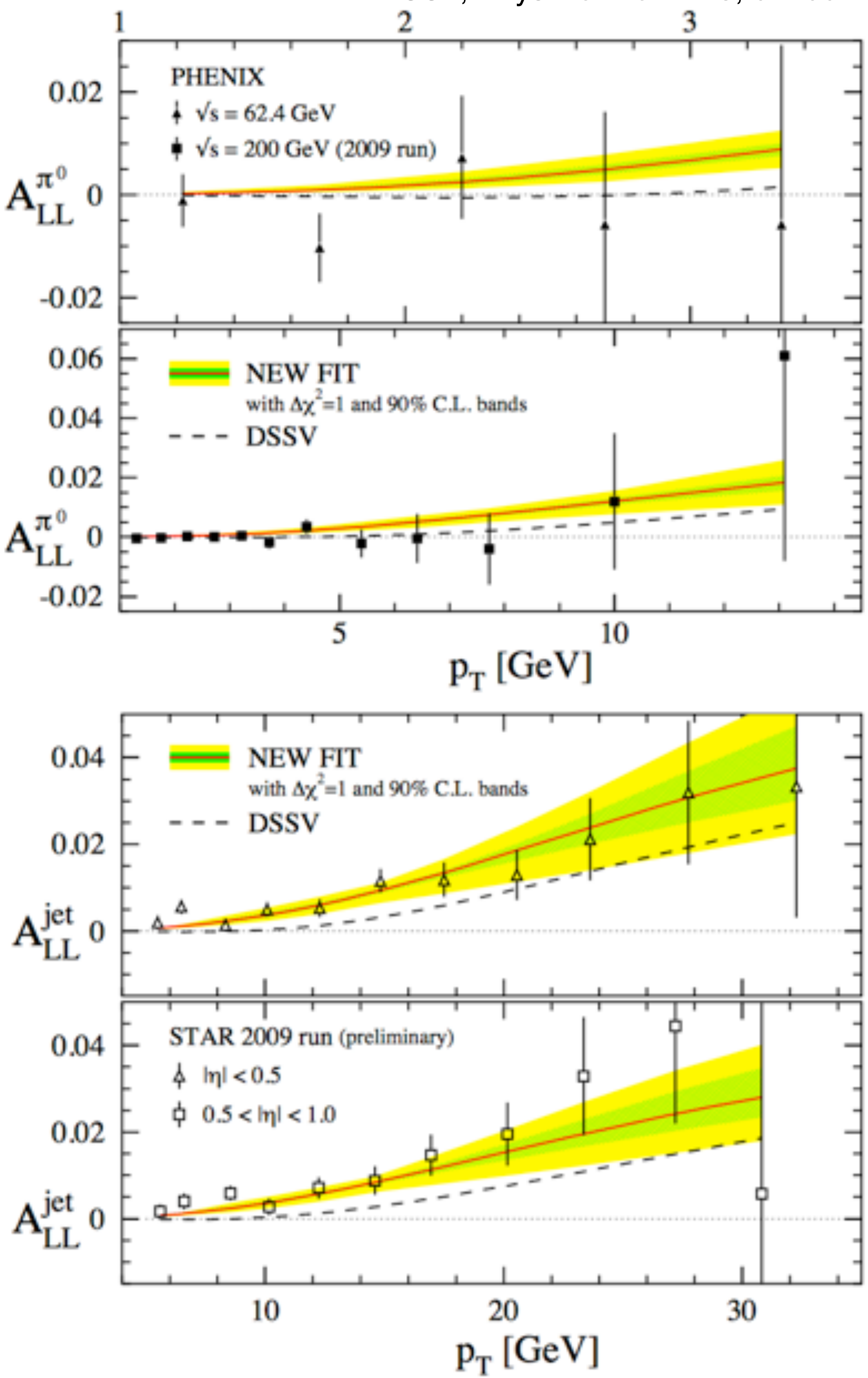
rapidity dependence,

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

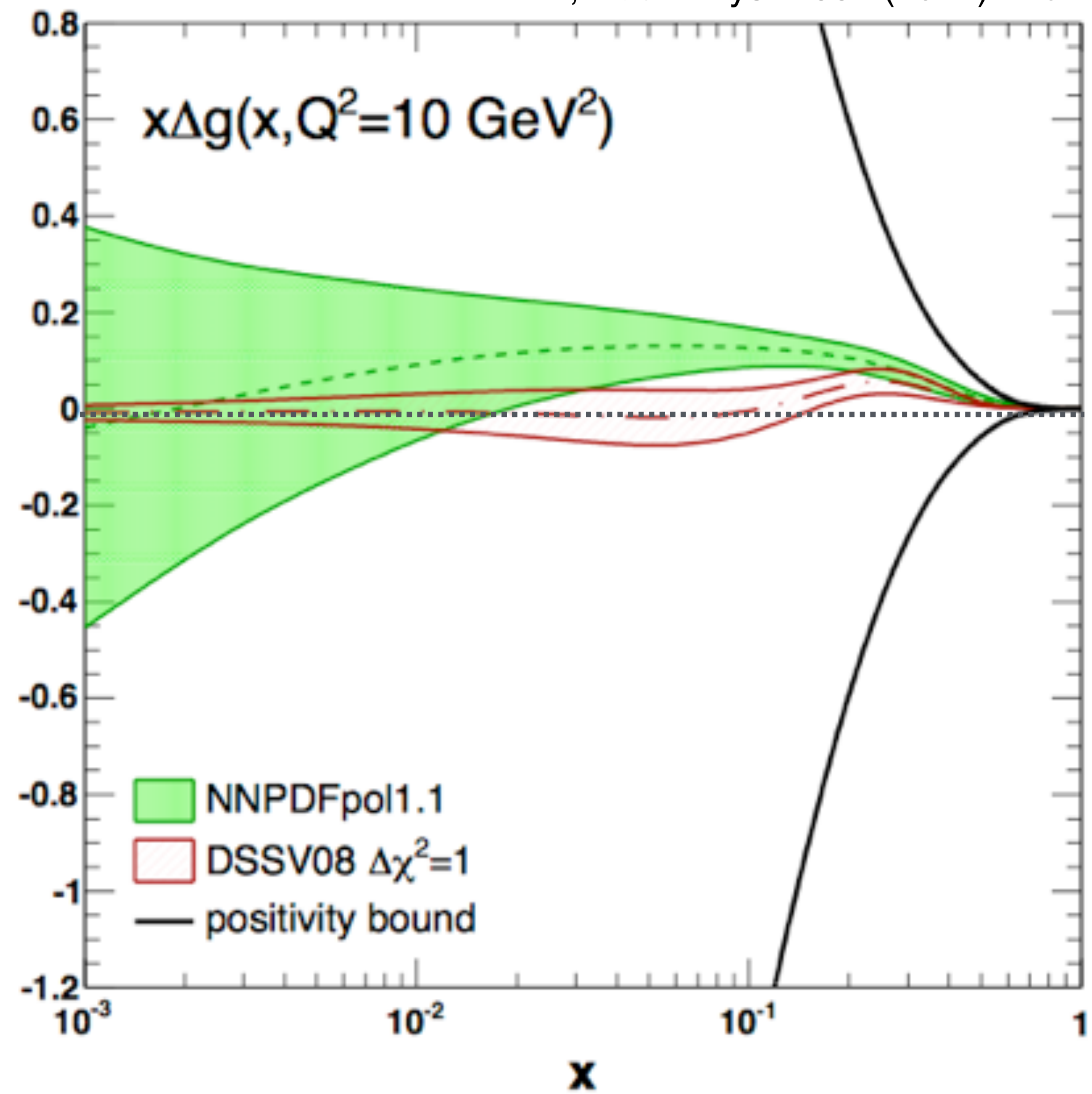
Gluon Polarization - RHIC Impact

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



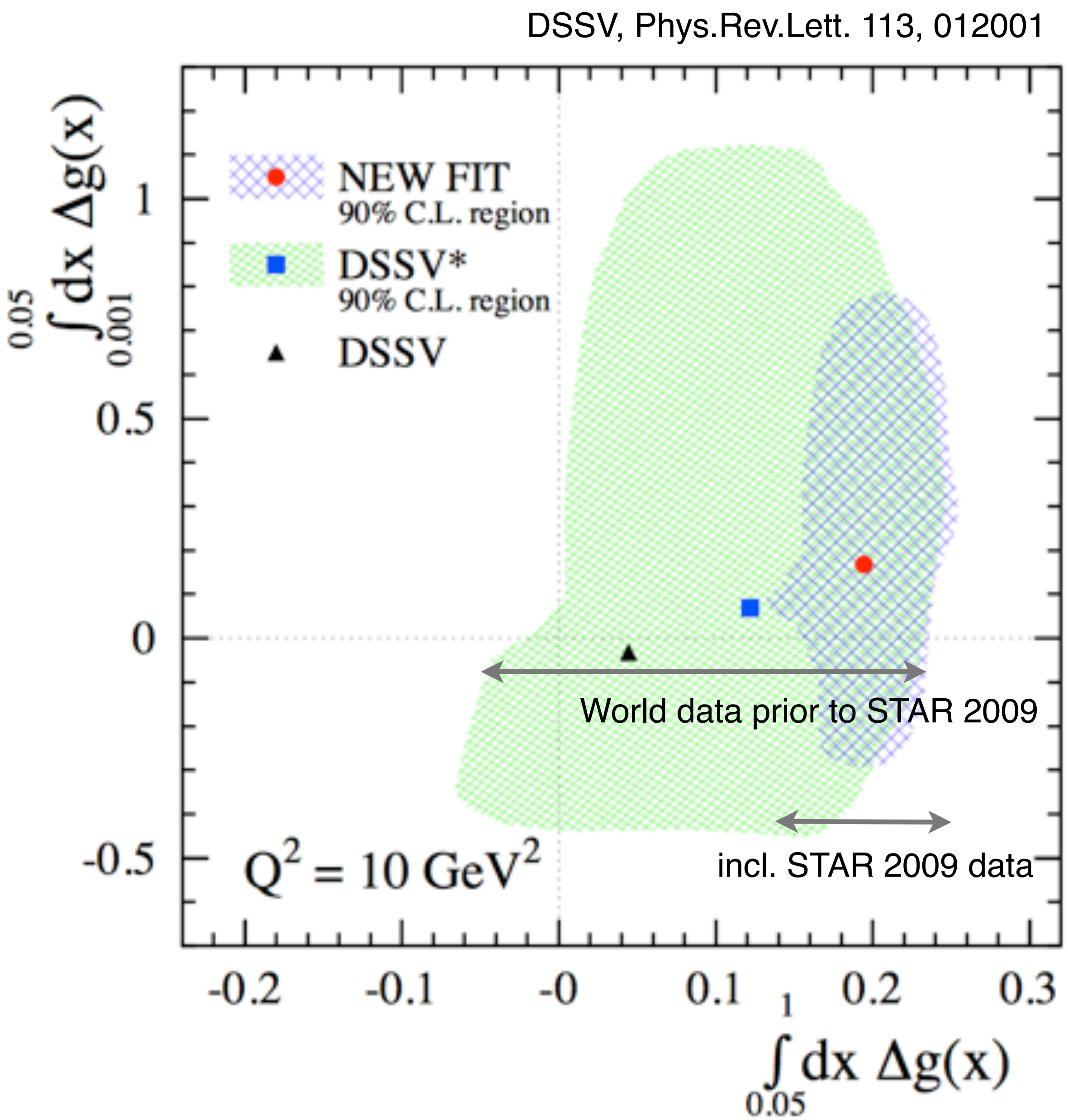
RHIC data, in particular on jets, currently drive the constraints on ΔG in both fits,

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 GeV².

Gluon Polarization - Status and what is next?



Extend sensitivity to *smaller* x_g

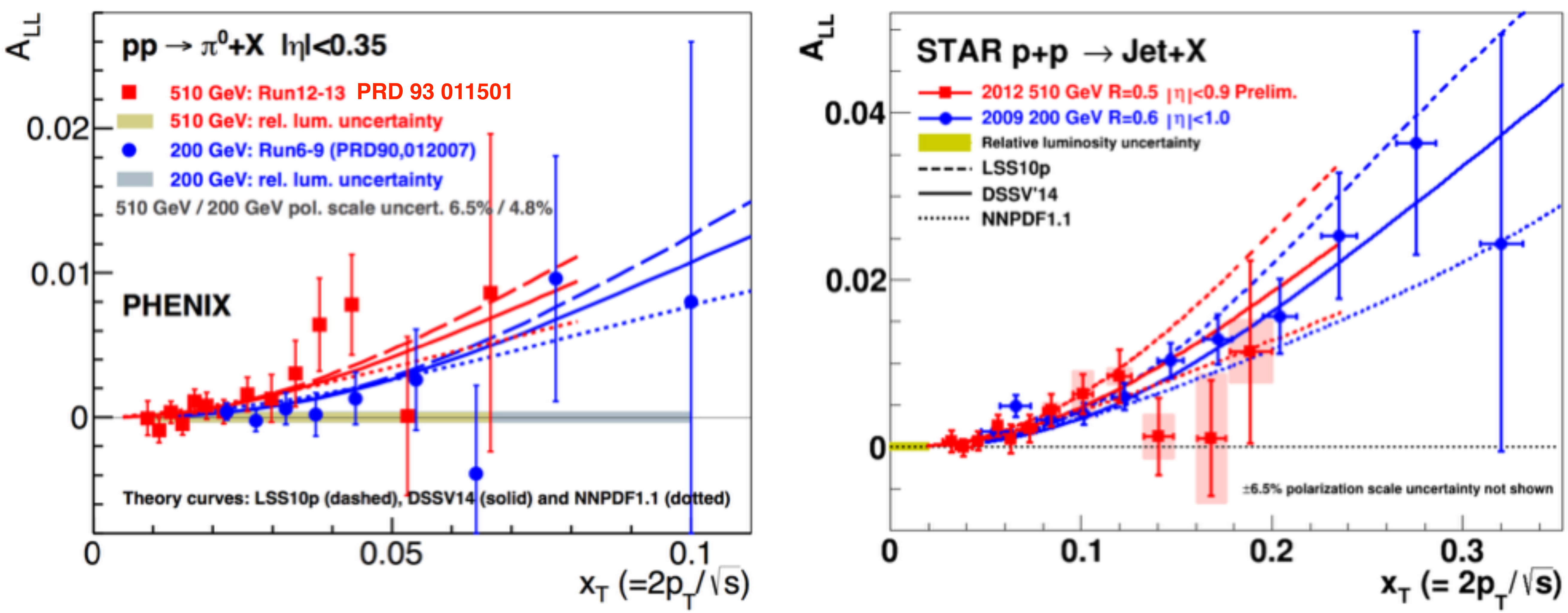
$\sqrt{s}$ = 500 GeV data, $x_g \sim 1/\sqrt{s}$,

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

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

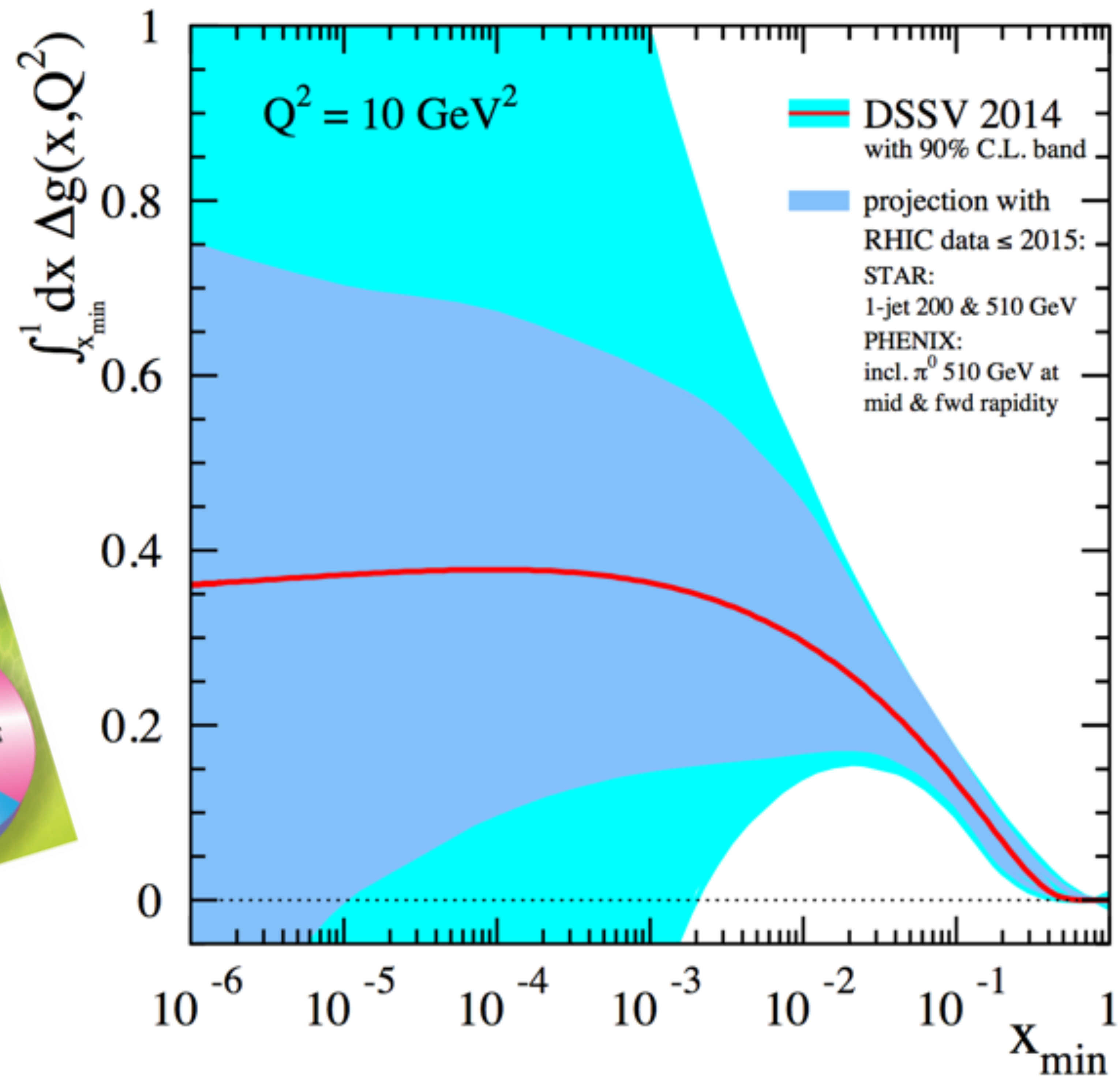
from *complementary* probes

Gluon Polarization - Precision and √s = 500 GeV



- A consistent picture from both energies and both experiments,
- Top-energy data provides access to new kinematic region at ~twice smaller *x*, precision in the region of overlap,
- More to come, e.g. from run-15 (√s = 200 GeV).

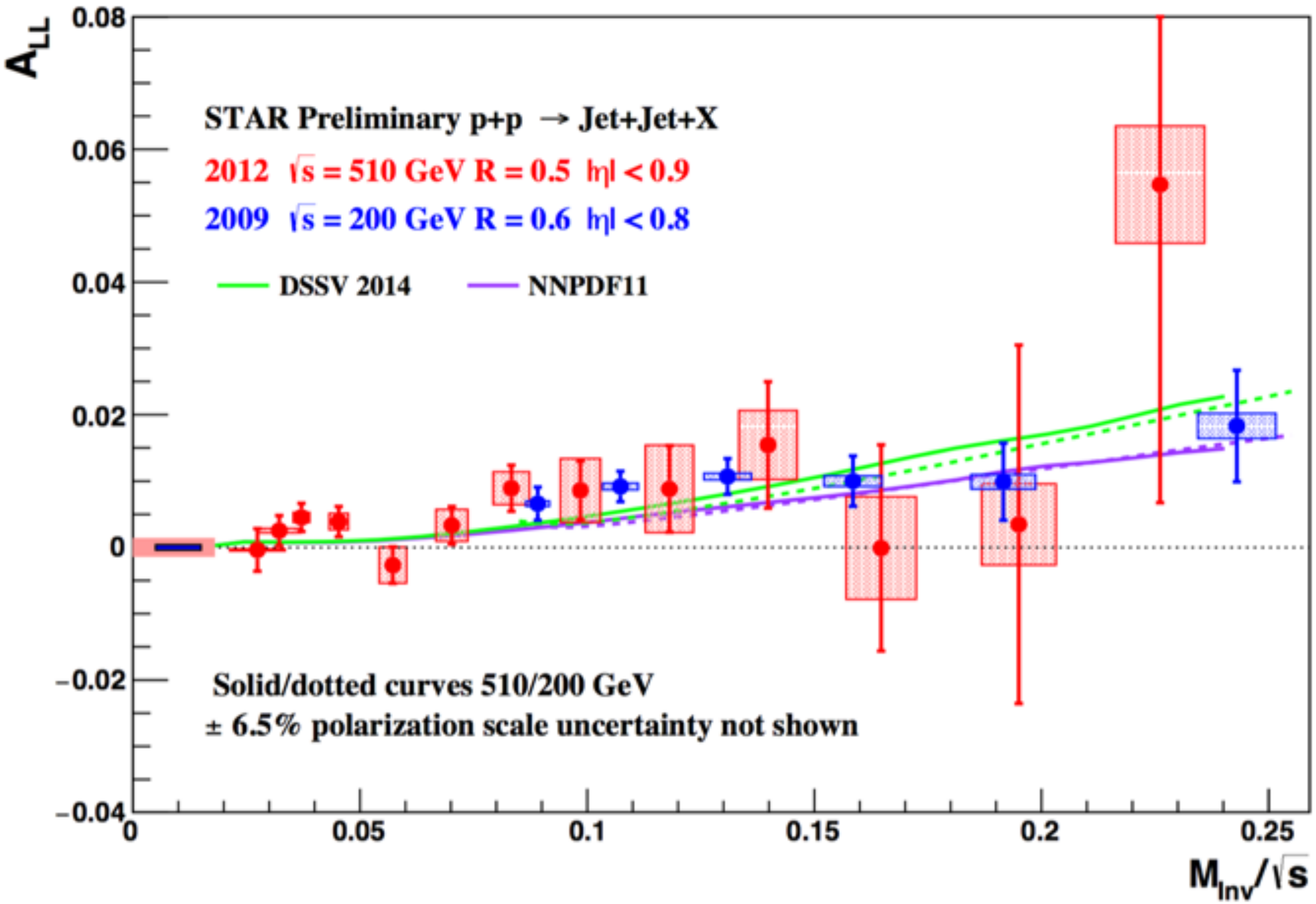
Gluon Polarization - What to expect next?



- 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.

Gluon Polarization - Initial dijet results

B. Paige et al. (STAR Collaboration), Moriond 2016. (Run 9 / 200GeV)
S. Rakmachandran et al. (STAR Collaboration), DIS 2016. (Run 12 / 500GeV)



Sensitivity to parton kinematics,

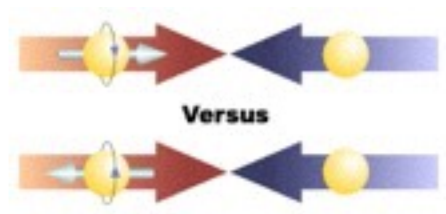
c.f. 2-to-2 scattering at LO:

$$\frac{M_{\mathrm{inv}}}{\sqrt{s}} = \sqrt{x_1 x_2}$$

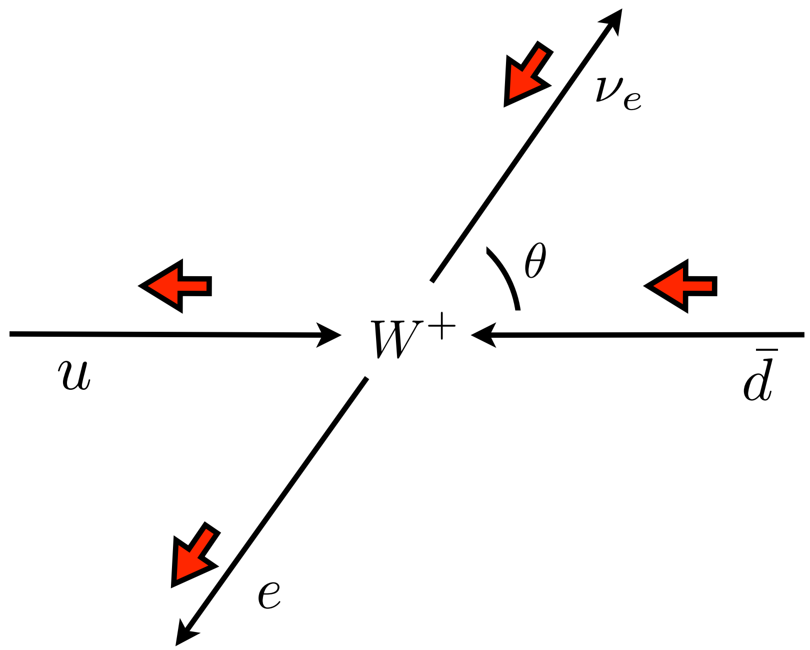
$$\eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$

Initial dijet A_{LL} data are consistent with DSSV and NNPDF expectations.

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 Irapidityl
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:

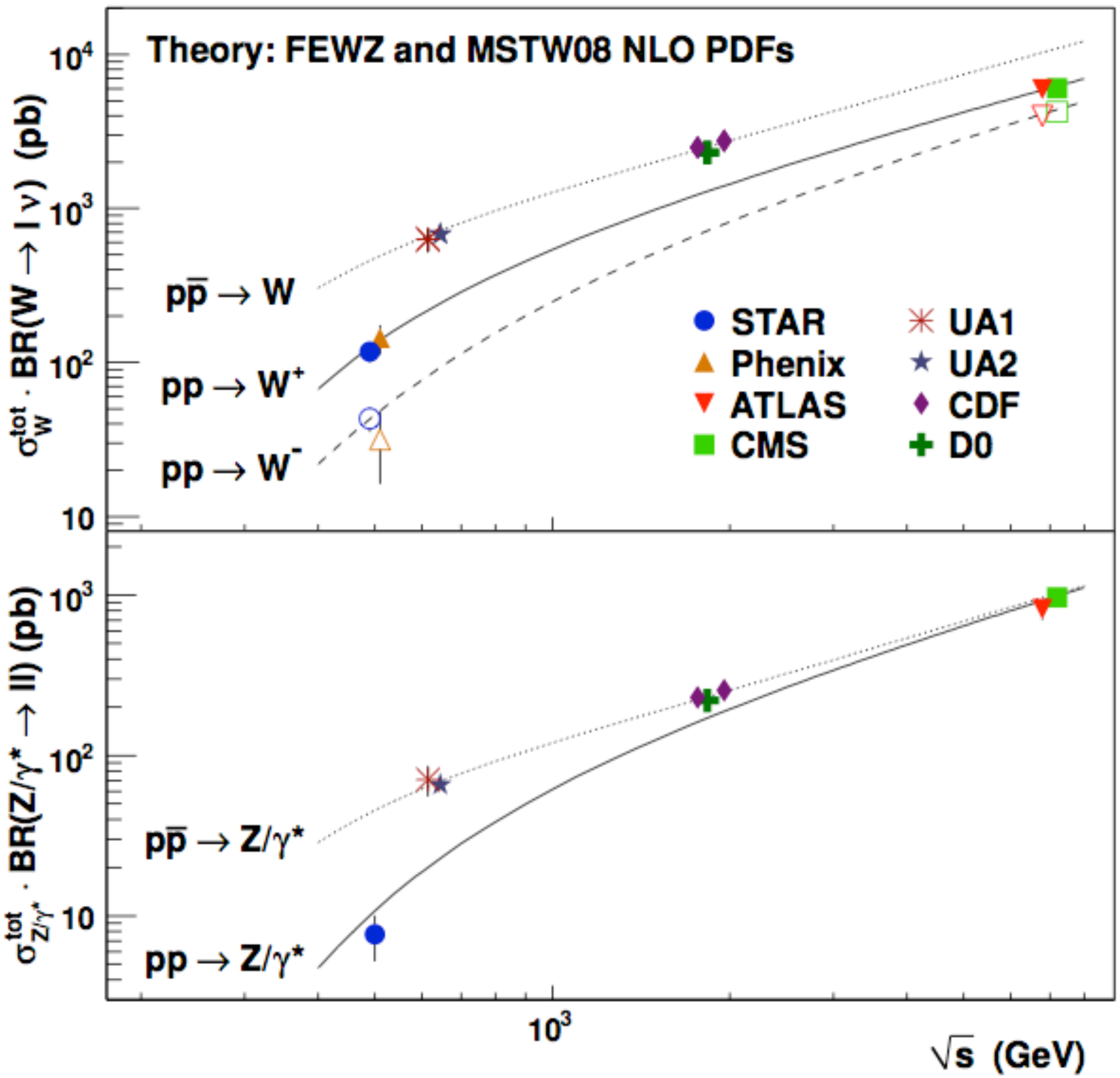
$$A_L(W^+) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} = \begin{cases} -\dfrac{\Delta u(x_a)}{u(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{d}(x_a)}{\bar{d}(x_a)}, & x_b \to 1 \end{cases}$$

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!

Towards Quark Polarization - 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).

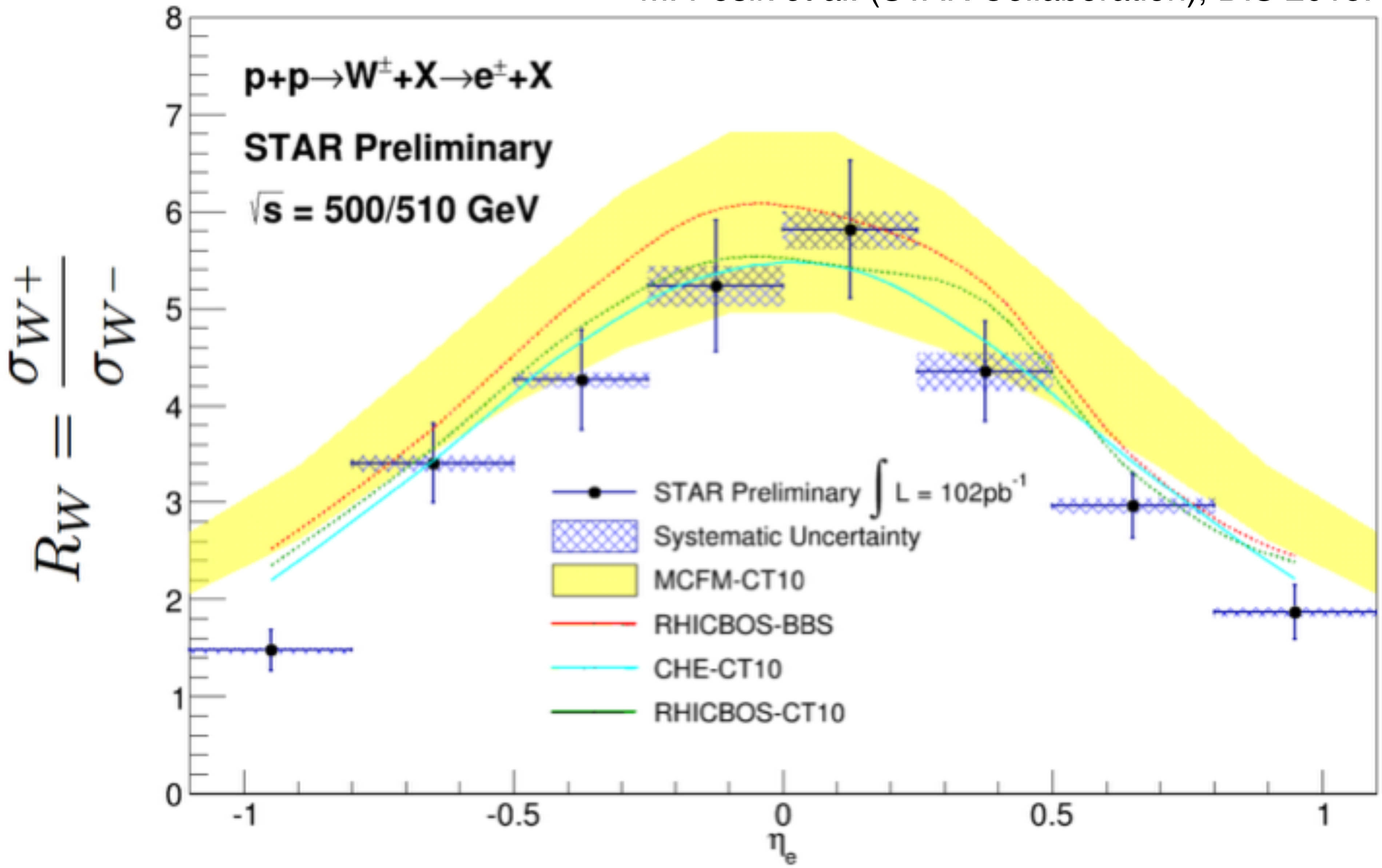
Data are well-described by NLO pQCD theory (FEWZ + MSTW08),

Support NLO pQCD interpretation of the asymmetry measurements,

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

Intermezzo I - Cross Section Ratios

M. Posik et al. (STAR Collaboration), DIS 2015.



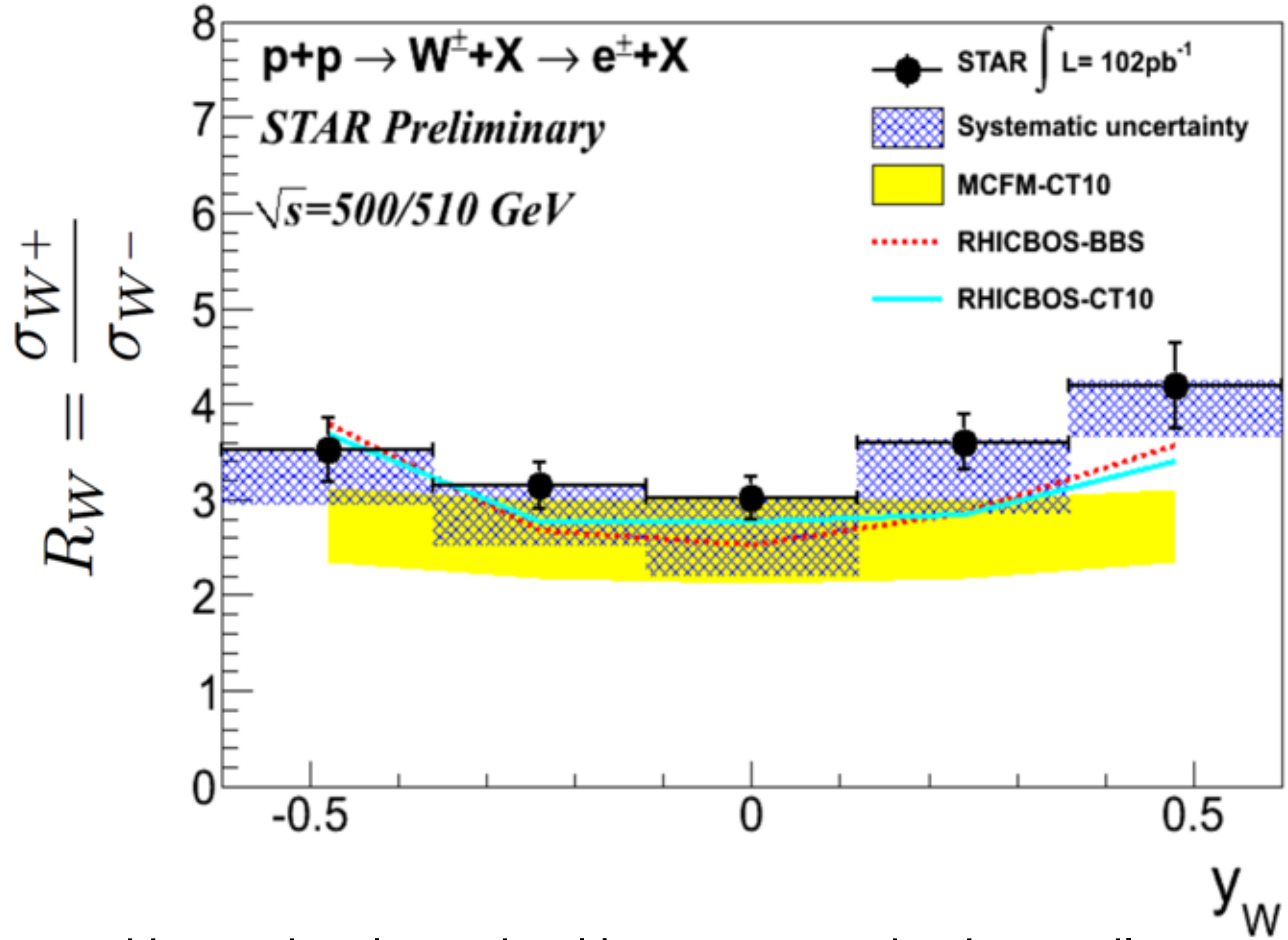
Preliminary data from 102 pb^{-1} obtained during run-11 and run-12,

~300 pb^{-1} recorded during run-13,
~400 pb^{-1} anticipated from run-17,

Complementary to NA51, E866, and SeaQuest; STAR data cover ~0.1 < x < ~0.3

Intermezzo II - Cross Section Ratios

S. Fazio et al. (STAR Collaboration), DIS 2015.



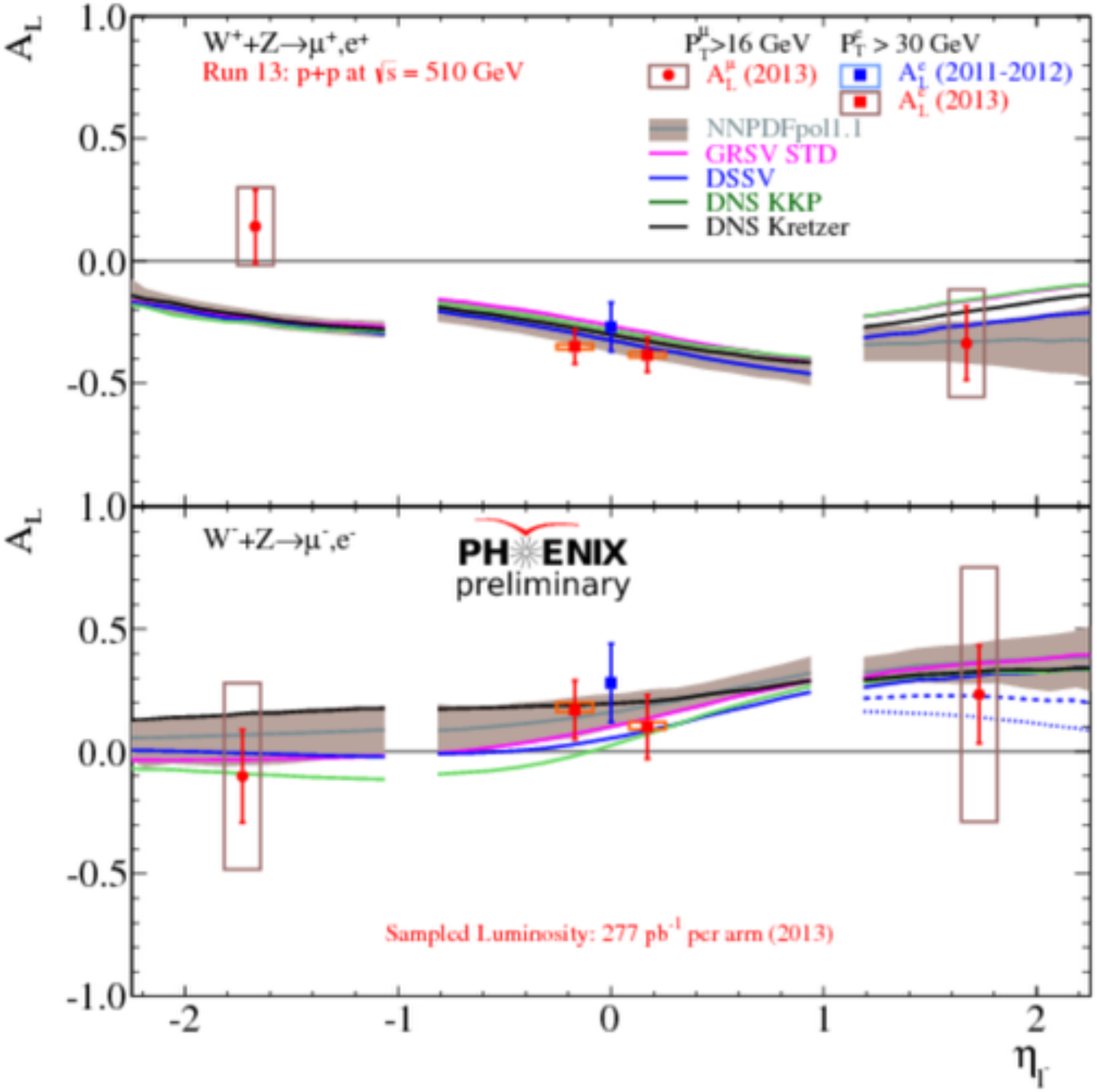
W-boson kinematics determined by reconstructing its recoil,

Rapidity determined from data combined with simulations,

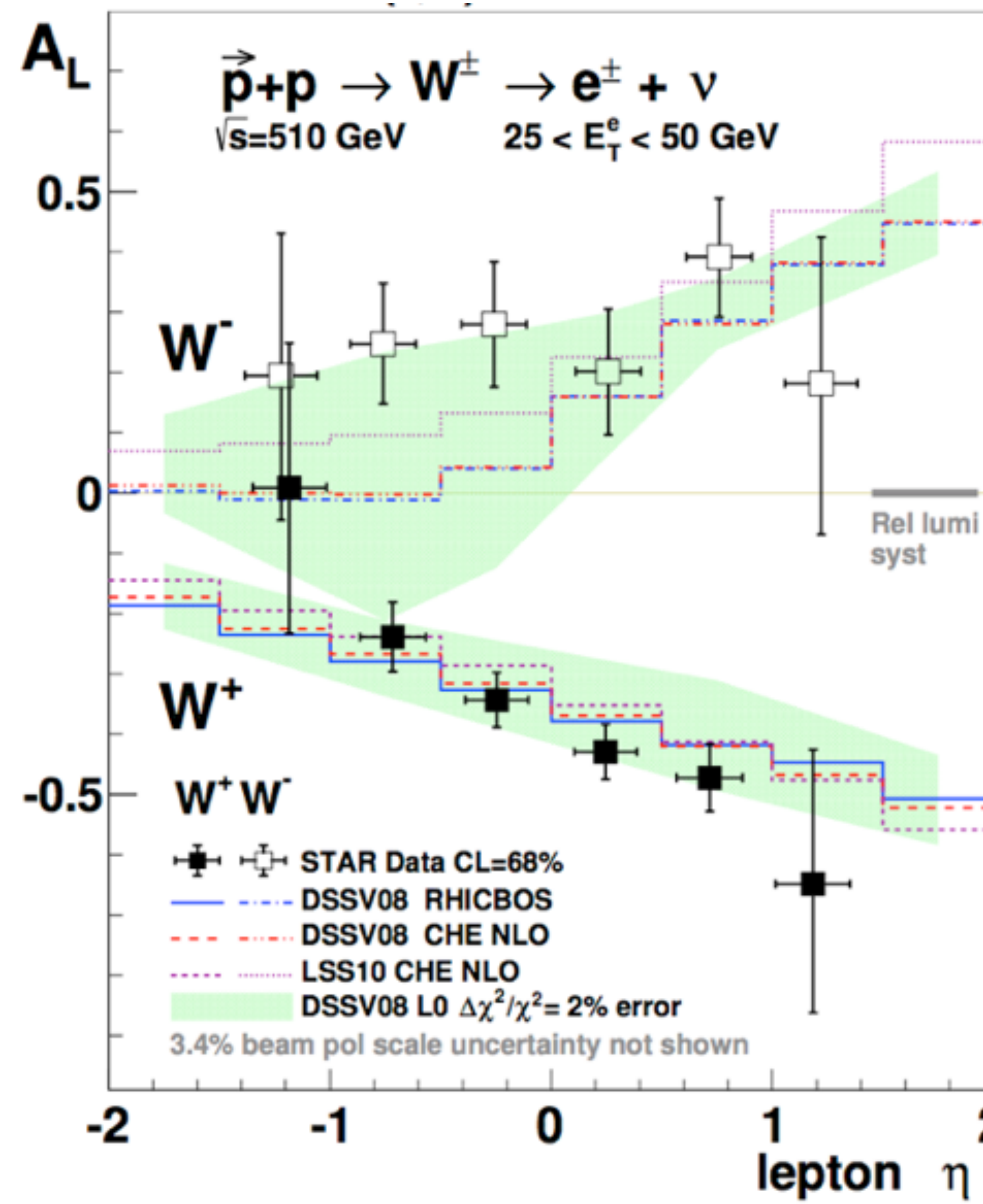
Key step in measurements of W A_N (Sivers' function and sign-change).

Quark Polarization - A_L from RHIC

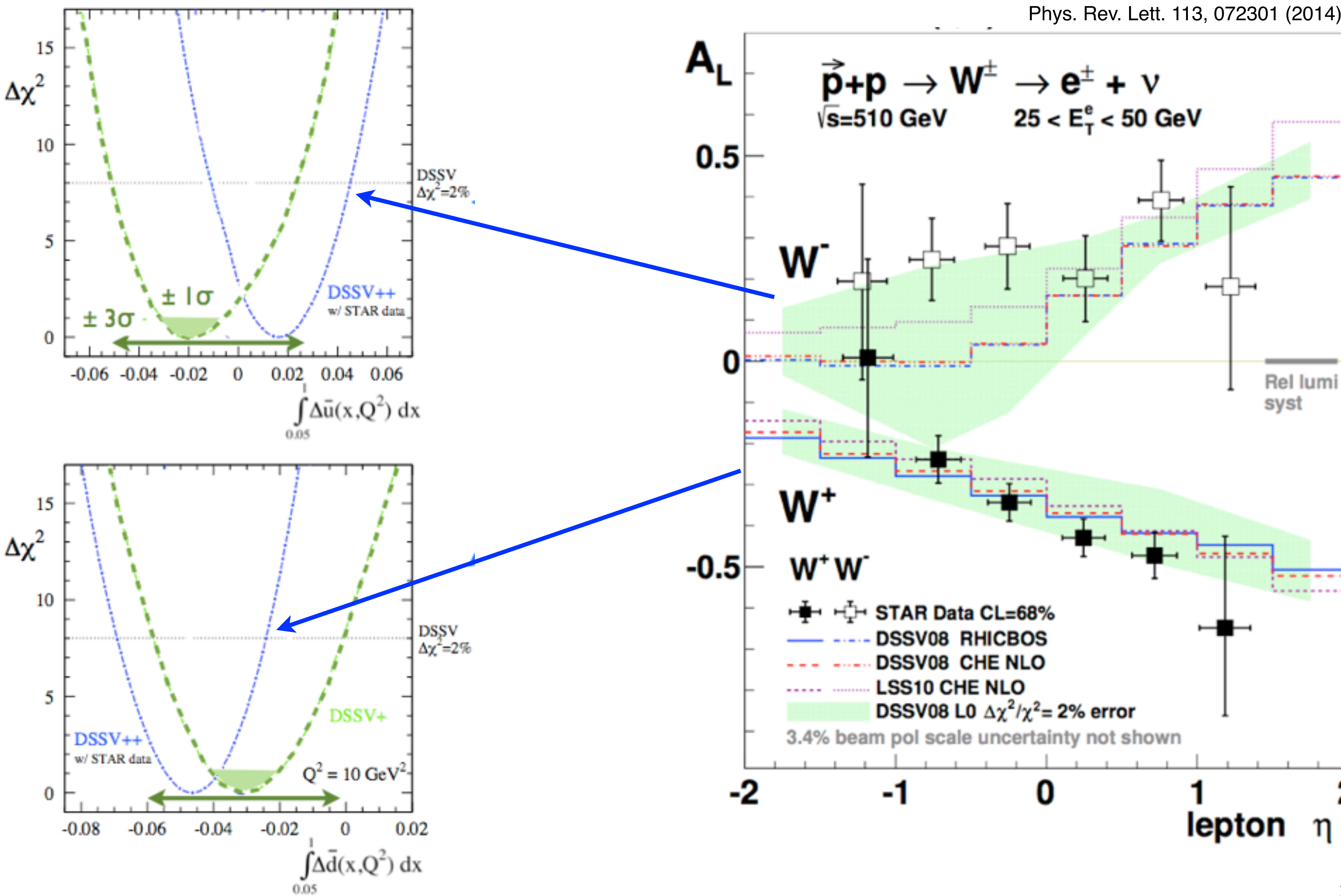
Submitted to PRD, arXiv:1504.07451



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



Quark Polarization - A_L from RHIC



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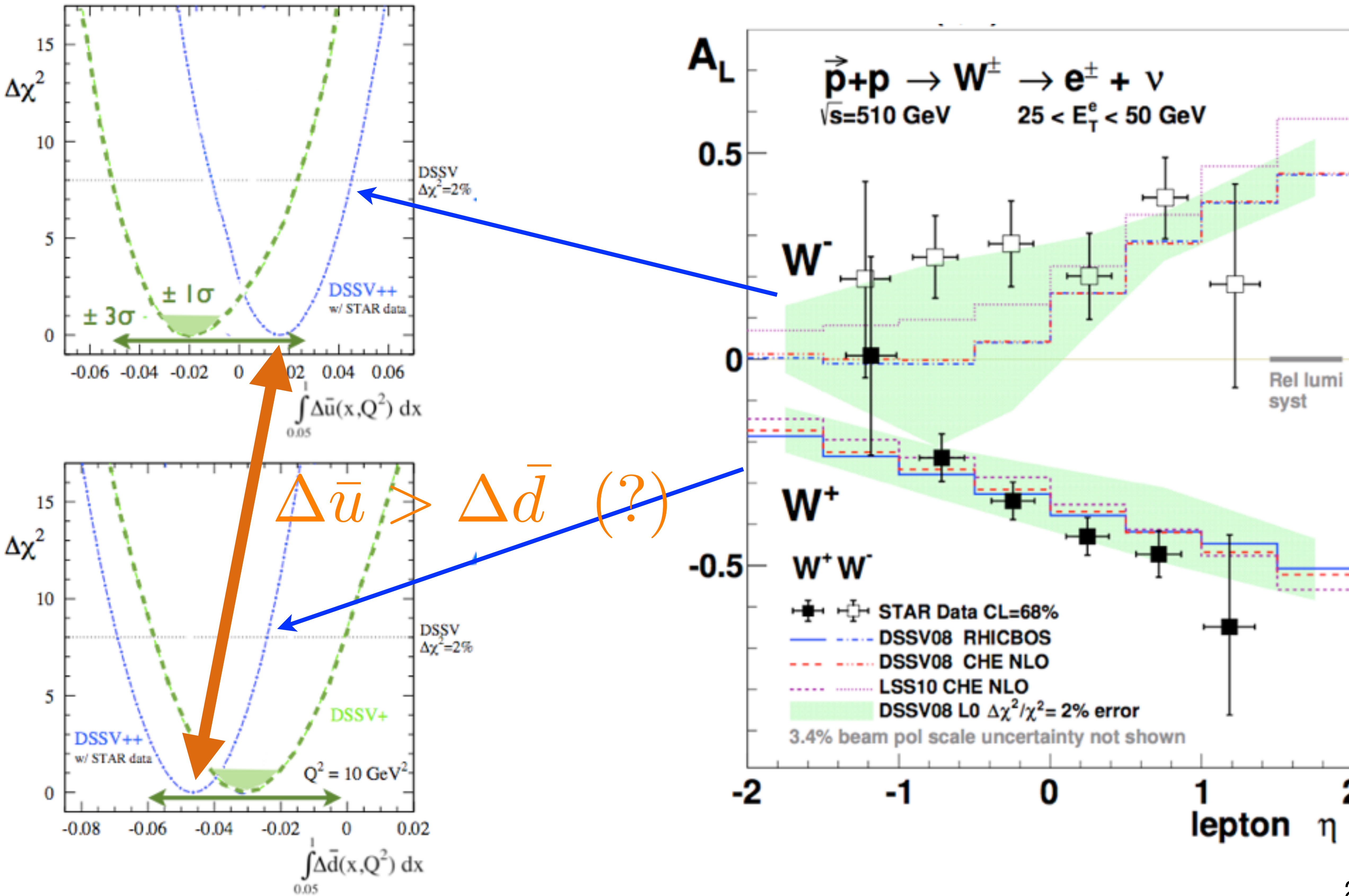

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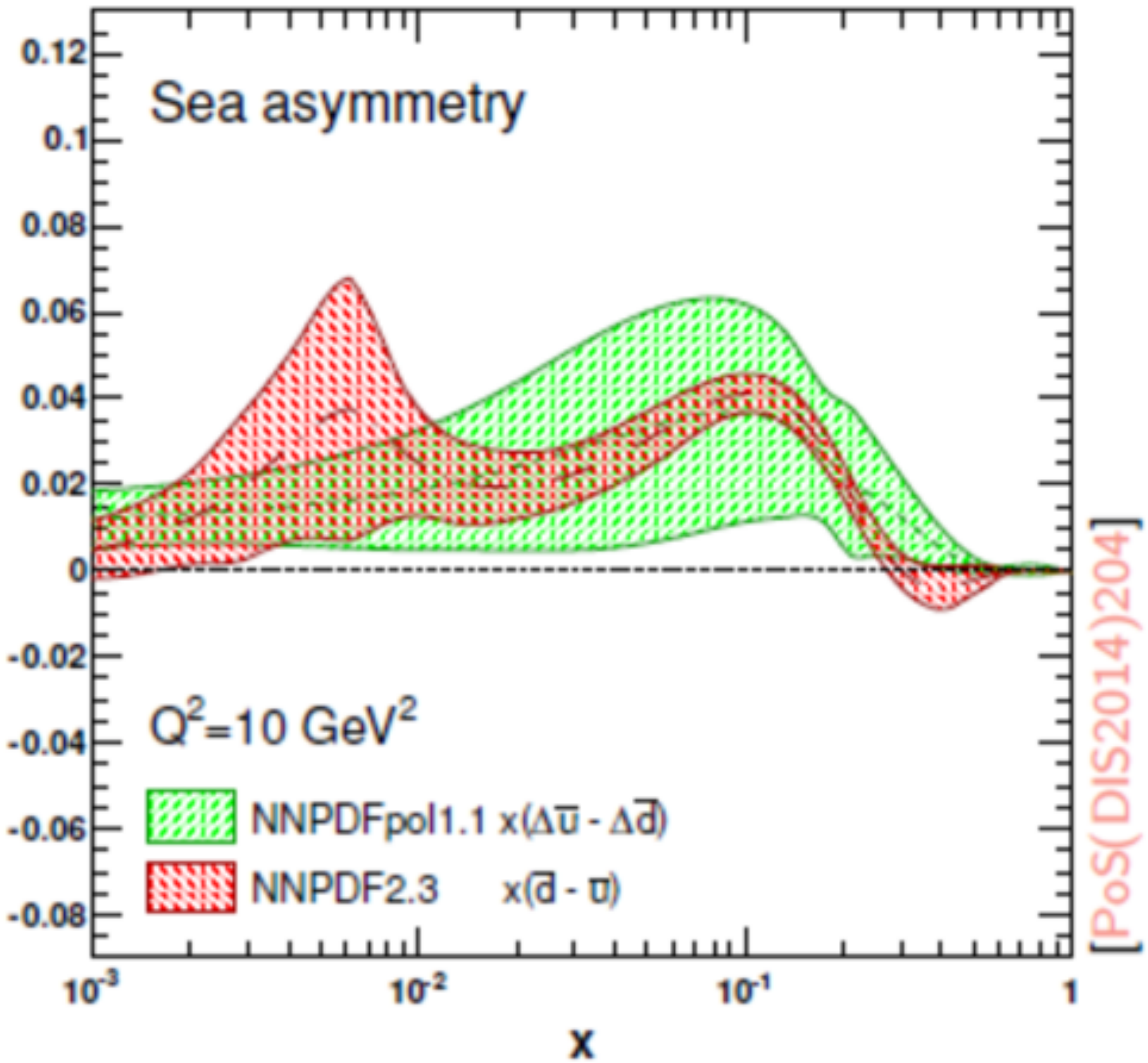
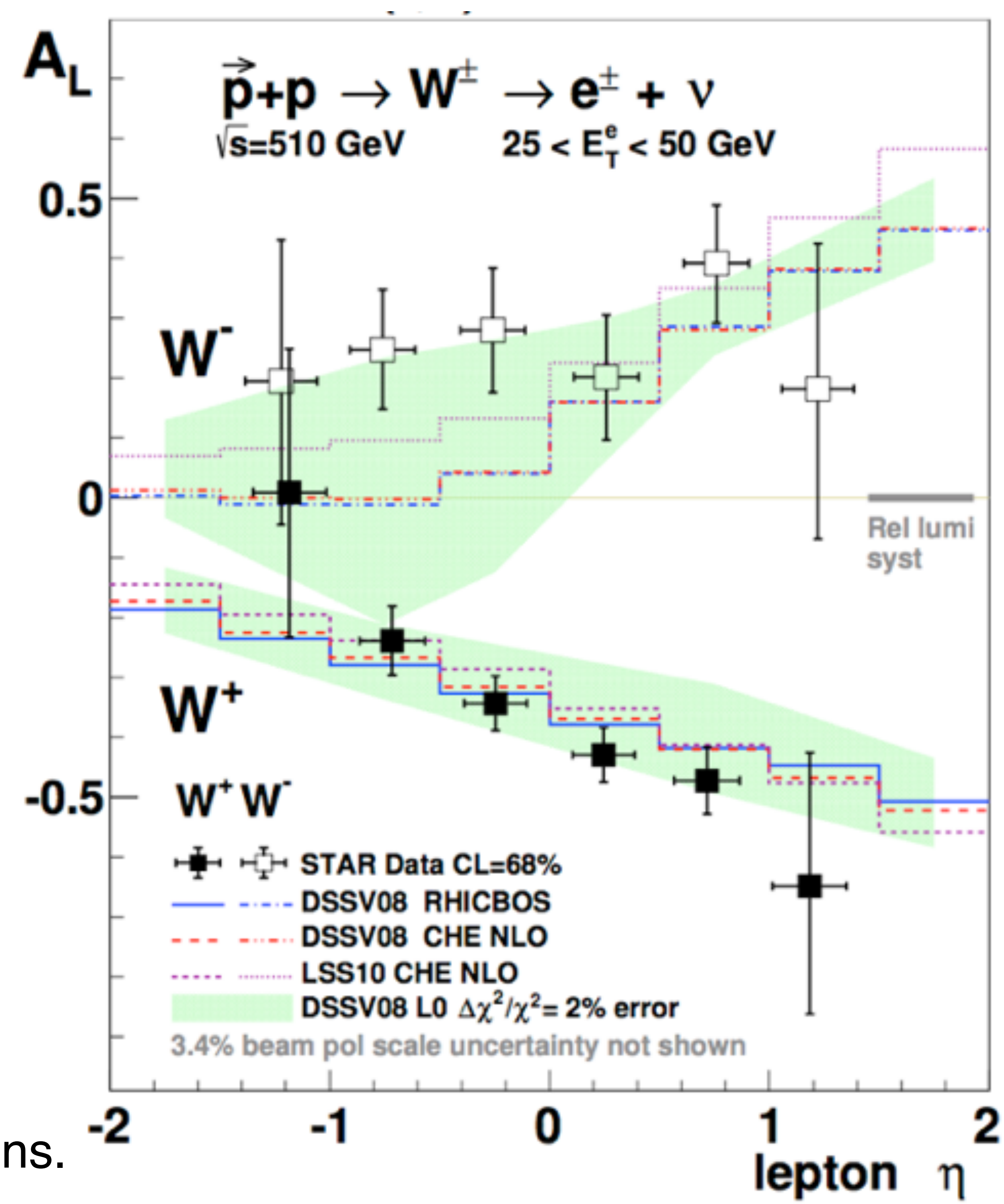
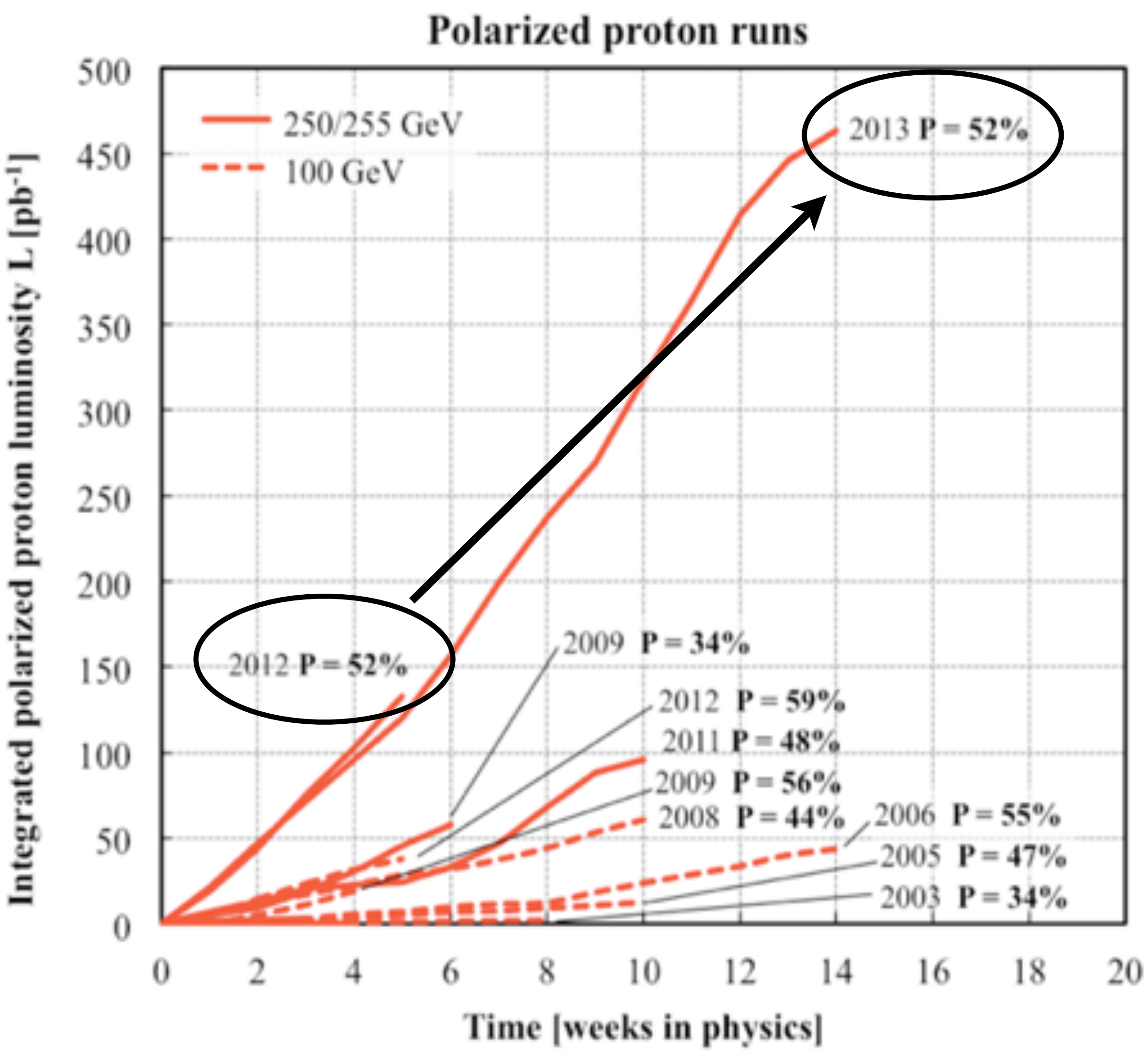


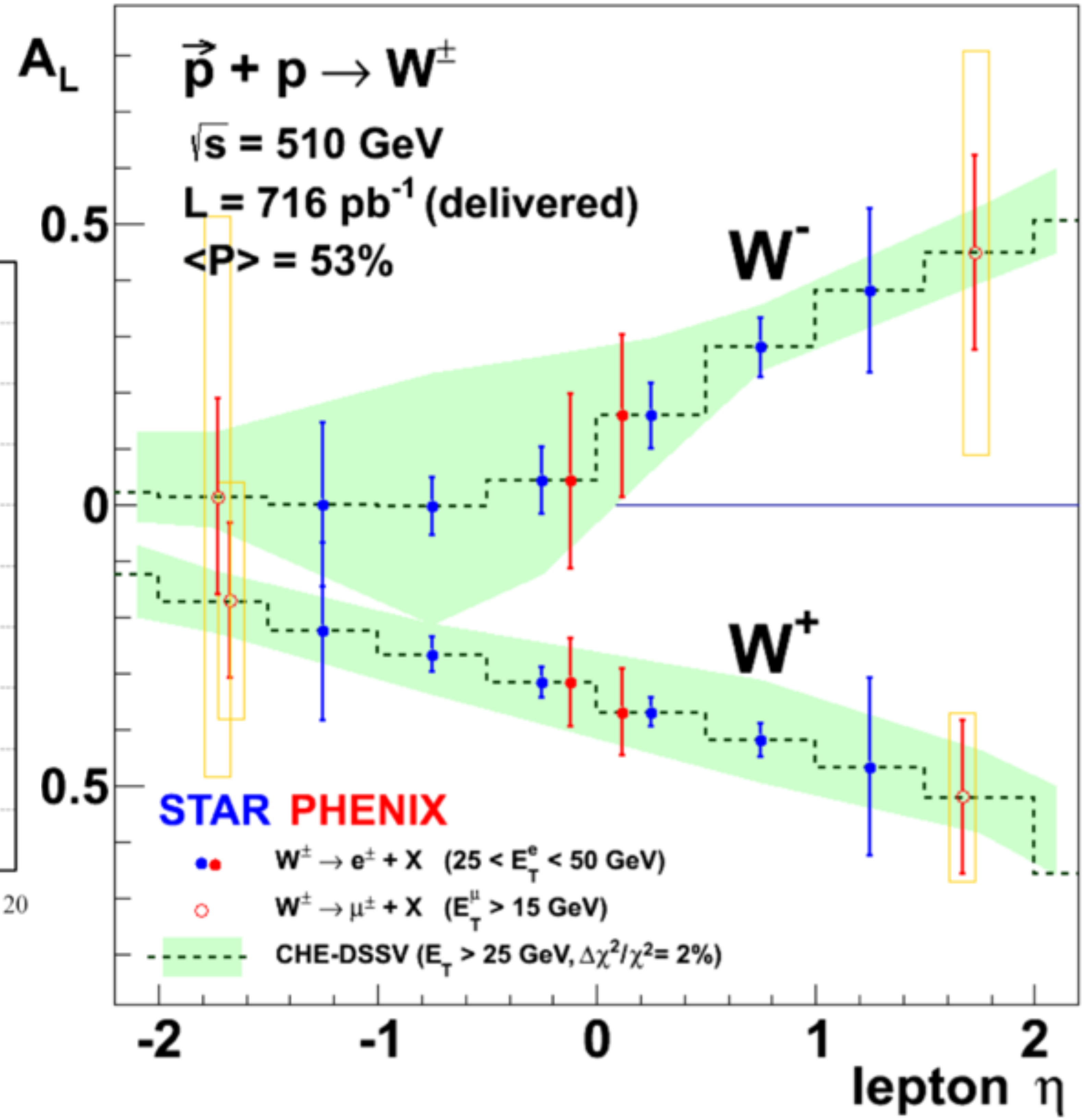


- $\Delta\bar{u} > \Delta\bar{d}$ (?) from DSSV *and* NNPDF,
- opposite from the spin-averaged distributions.

Quark Polarization - Next Steps

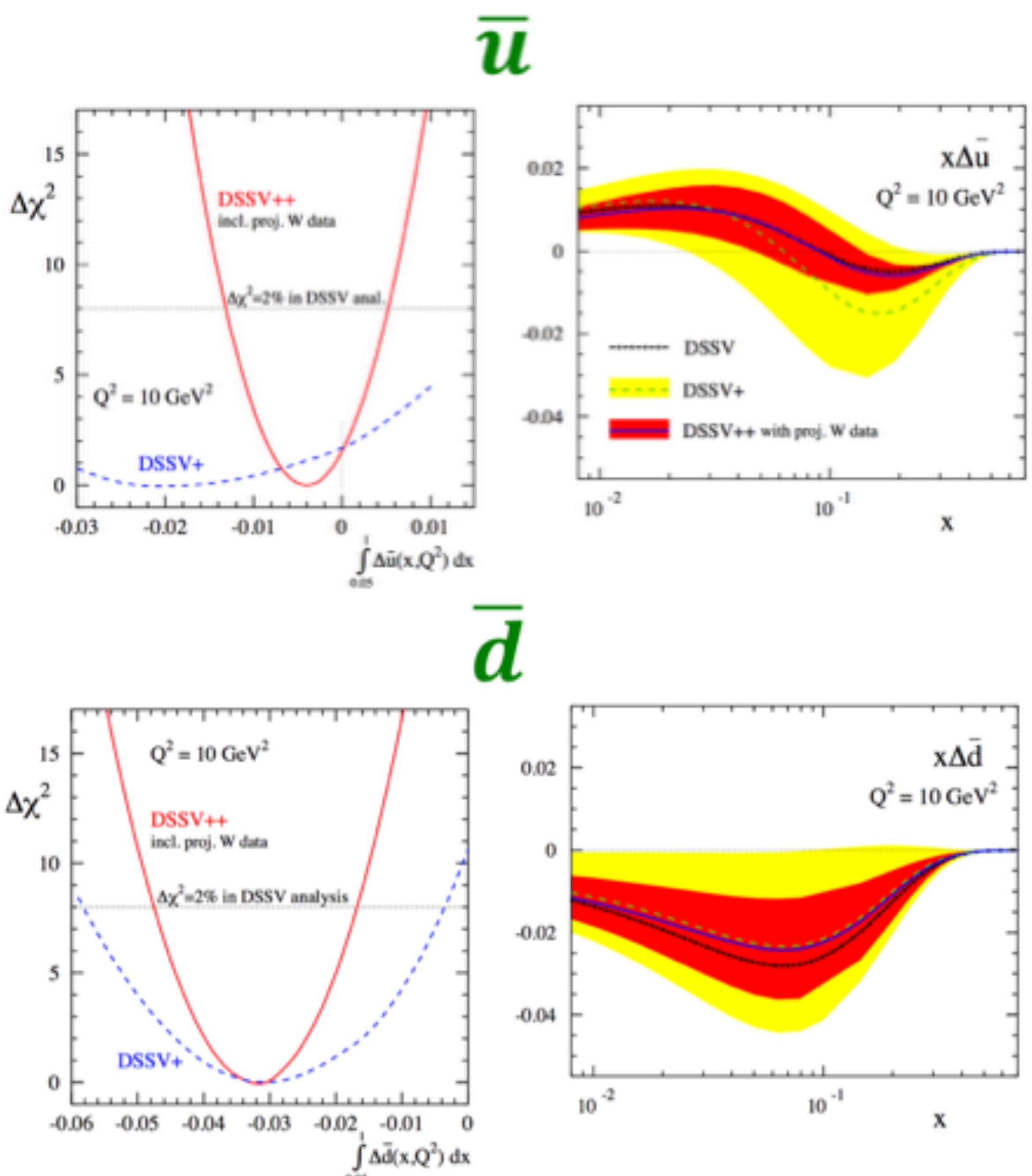
Anticipated uncertainties:

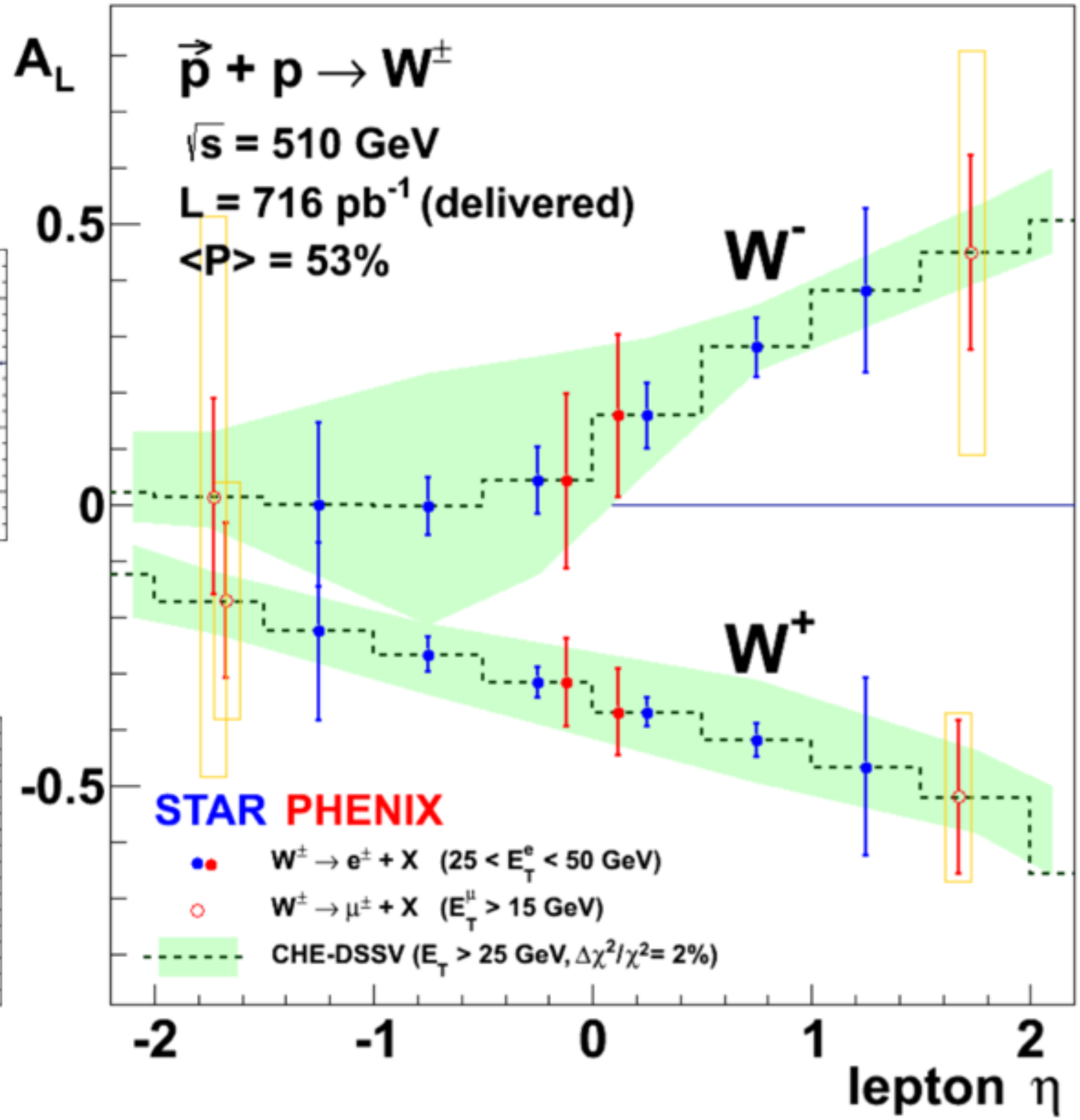




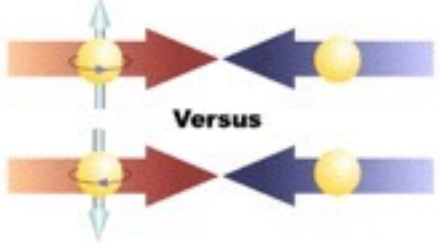
Quark Polarization - Next Steps

Anticipated uncertainties, and their projected impact:



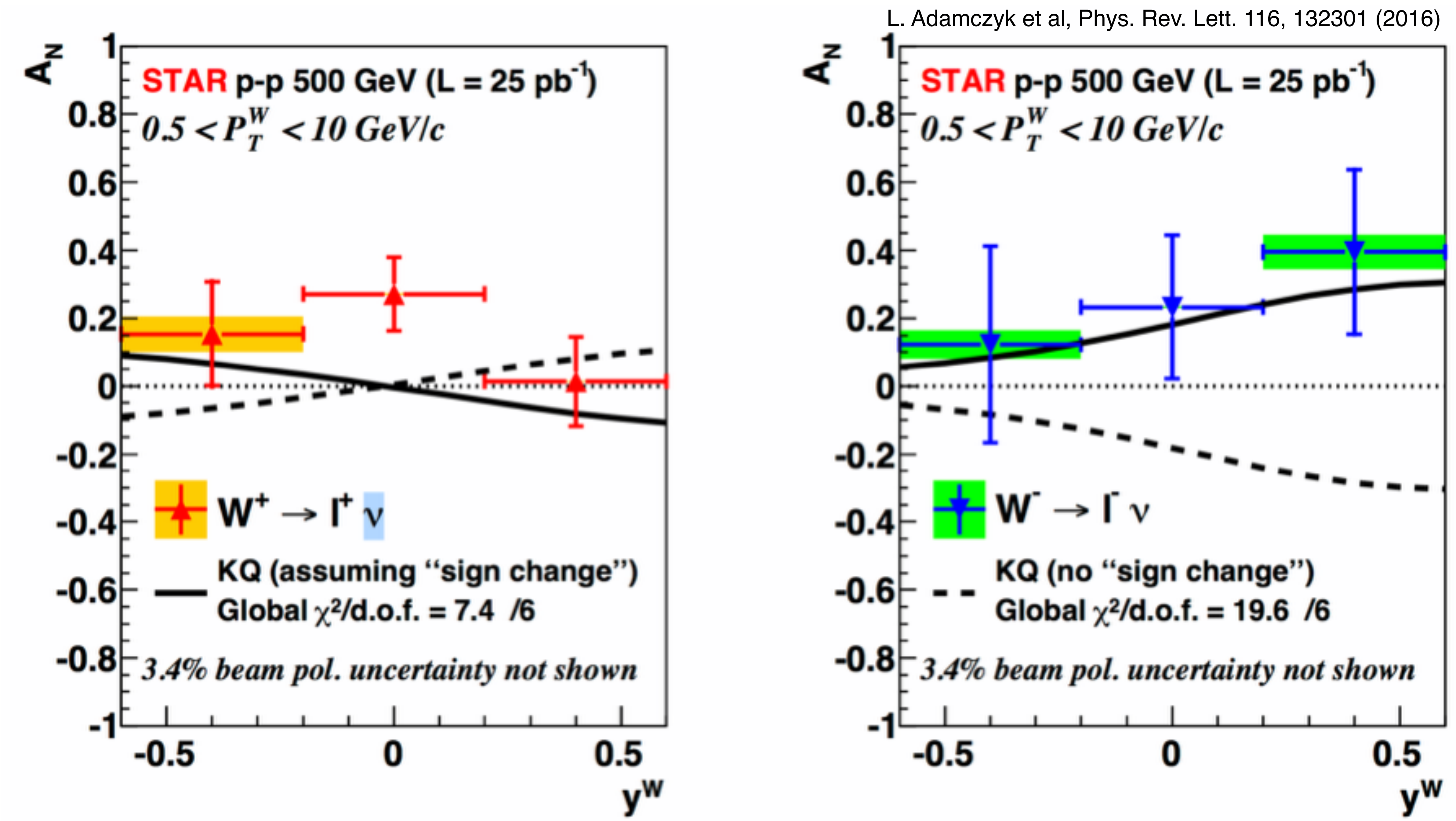


Transverse Spin Phenomena: Sivers Function



STAR W A_N - *"The sign change"*

L. Adamczyk et al, Phys. Rev. Lett. 116, 132301 (2016)

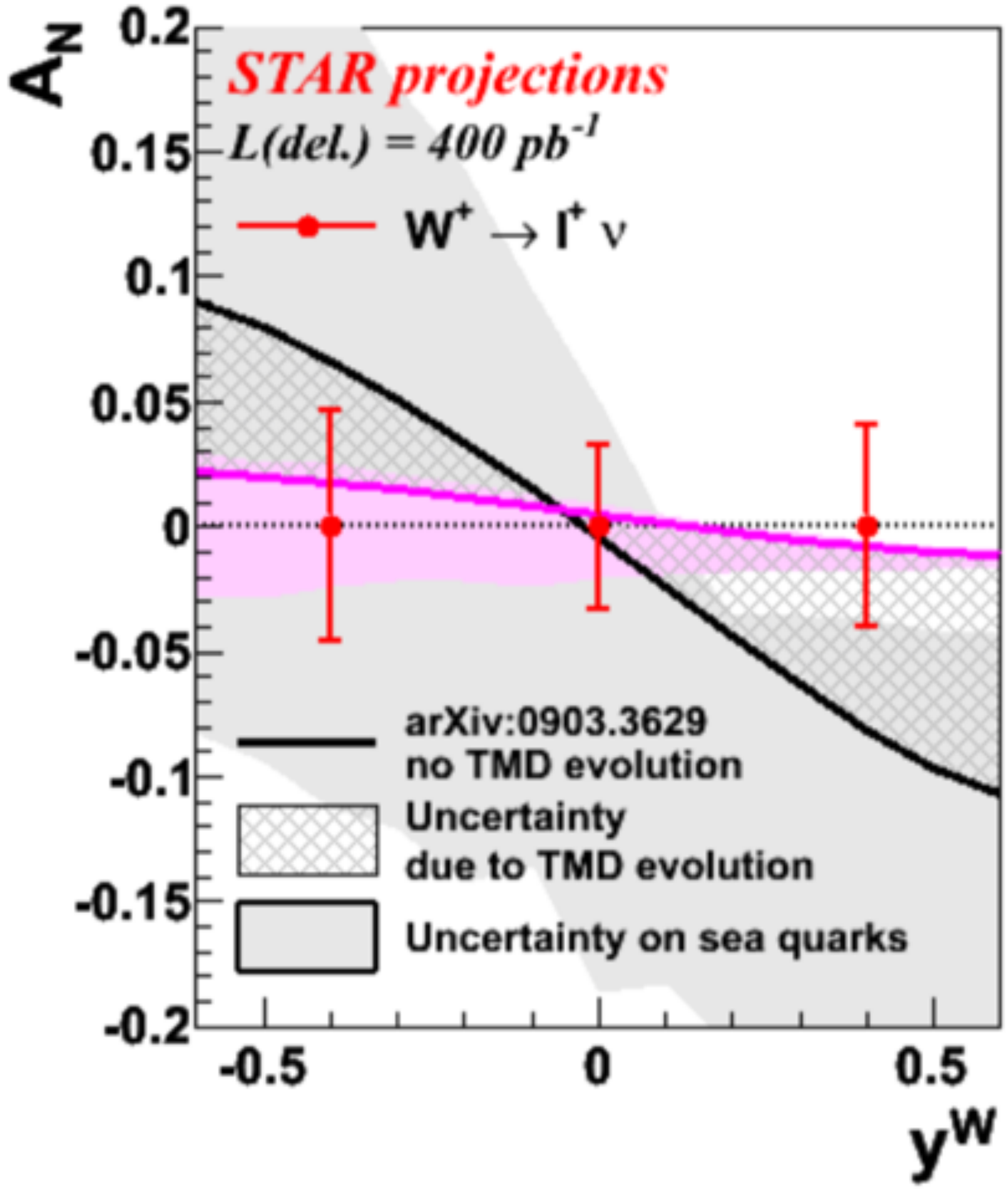


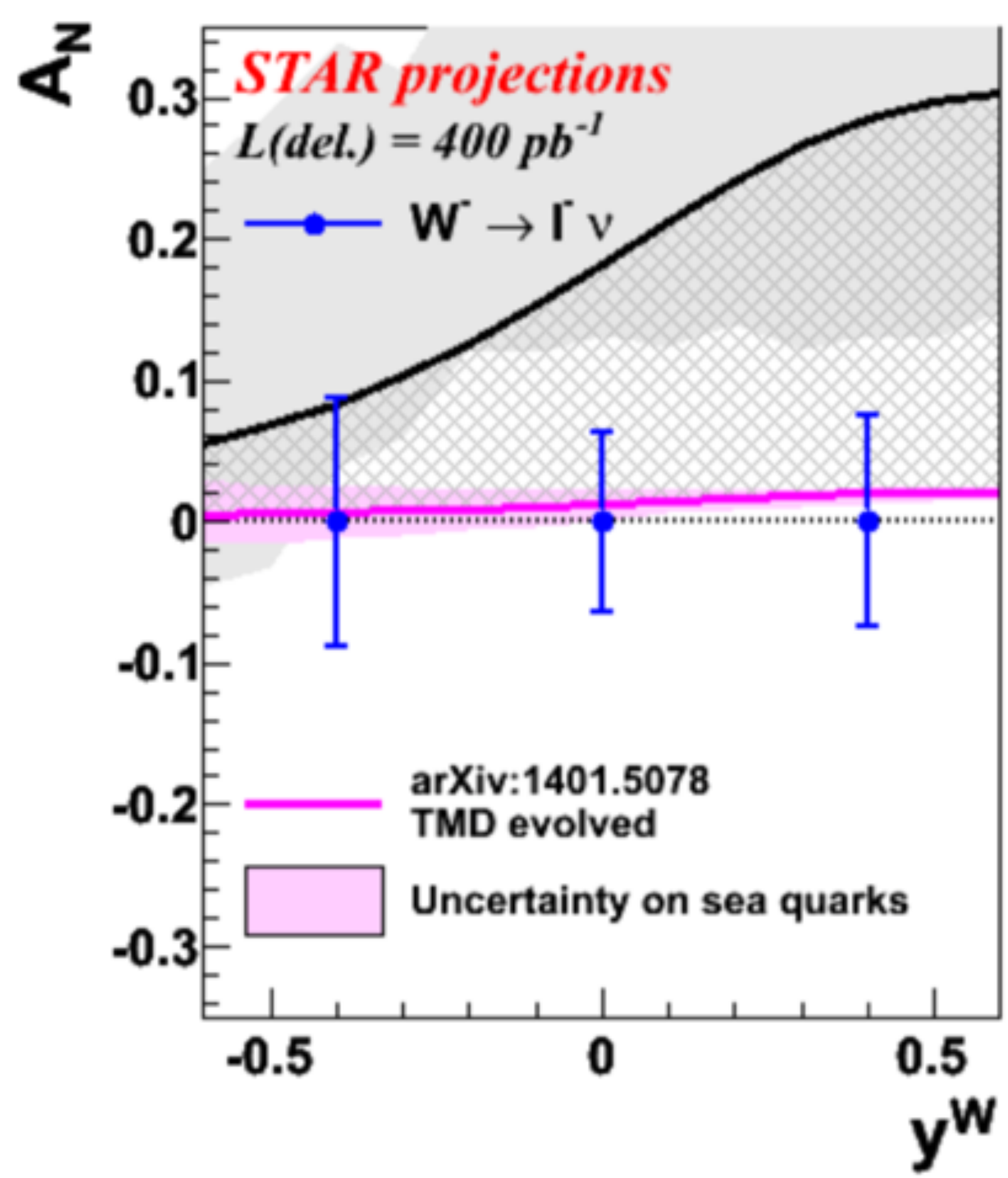
Calls for continued measurement; PAC approved, LRP supported, planned for 2017,

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).

STAR W A_N - Prospects for 2017 Run

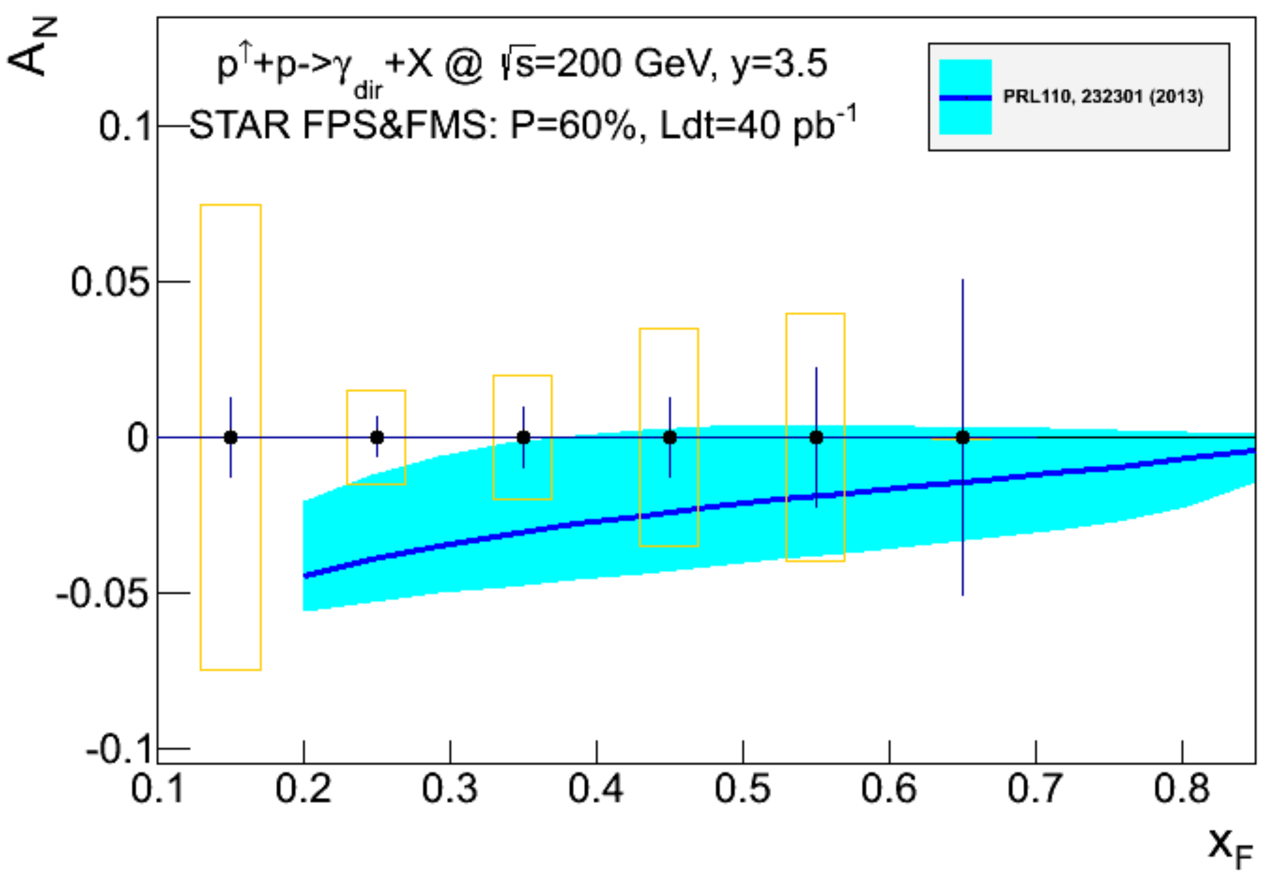


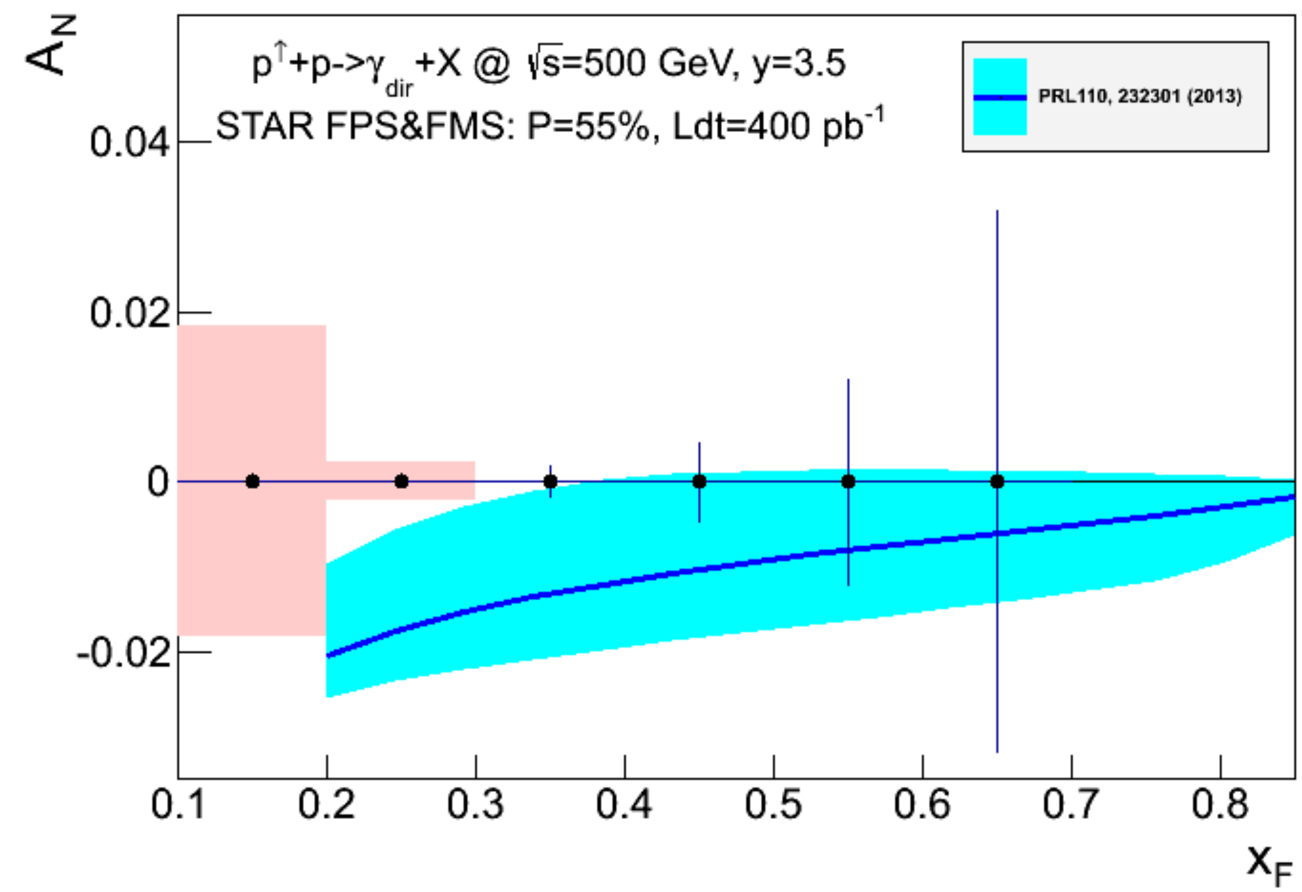


Lots of work ahead to turn these projections into actual results,

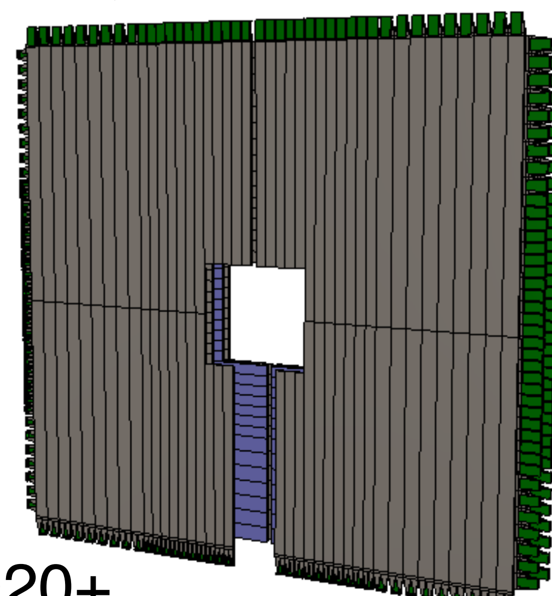
Ample other opportunities, for example
photons, Drell Yan, diffraction, mid-rapidity,
gradual upgrades to existing STAR forward instrumentation, RHICf@STAR,

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,

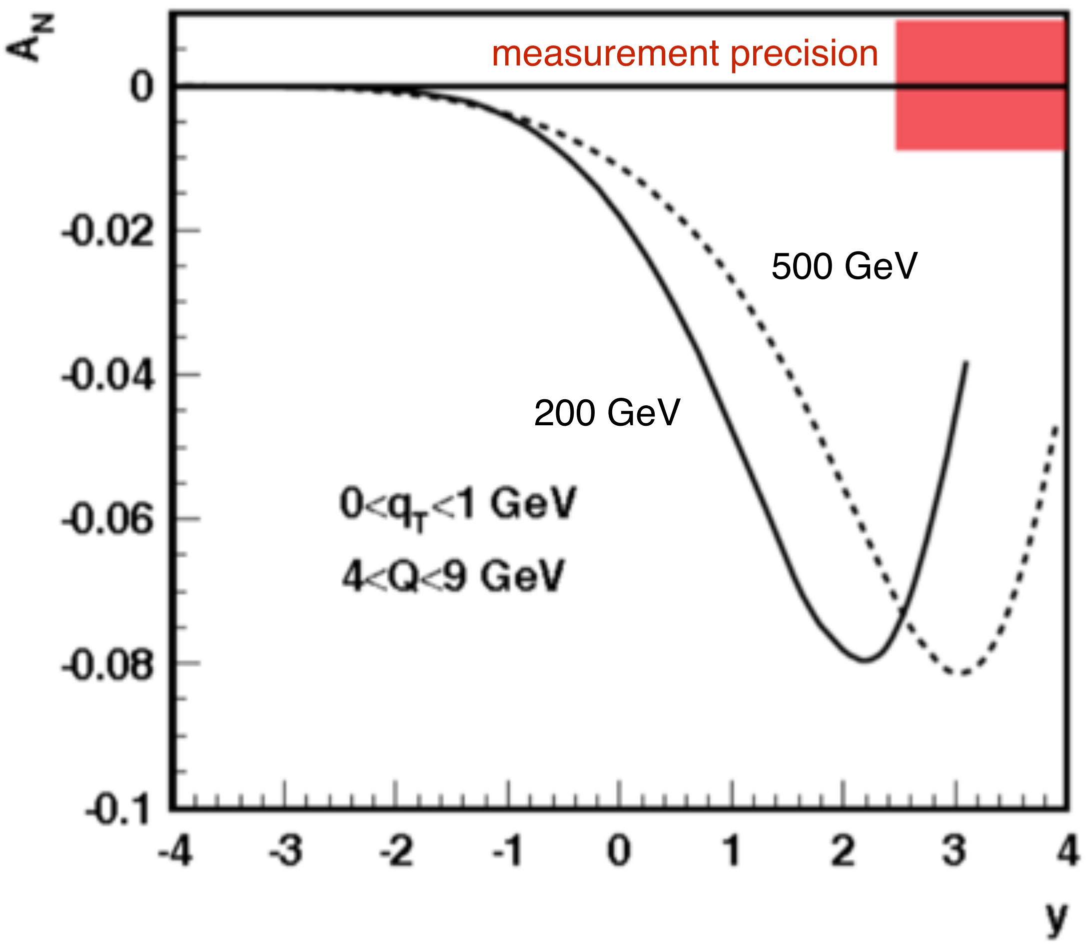
light valence quarks, at relatively high-*x*,

twist-3 evolution, *not* TMD evolution.

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

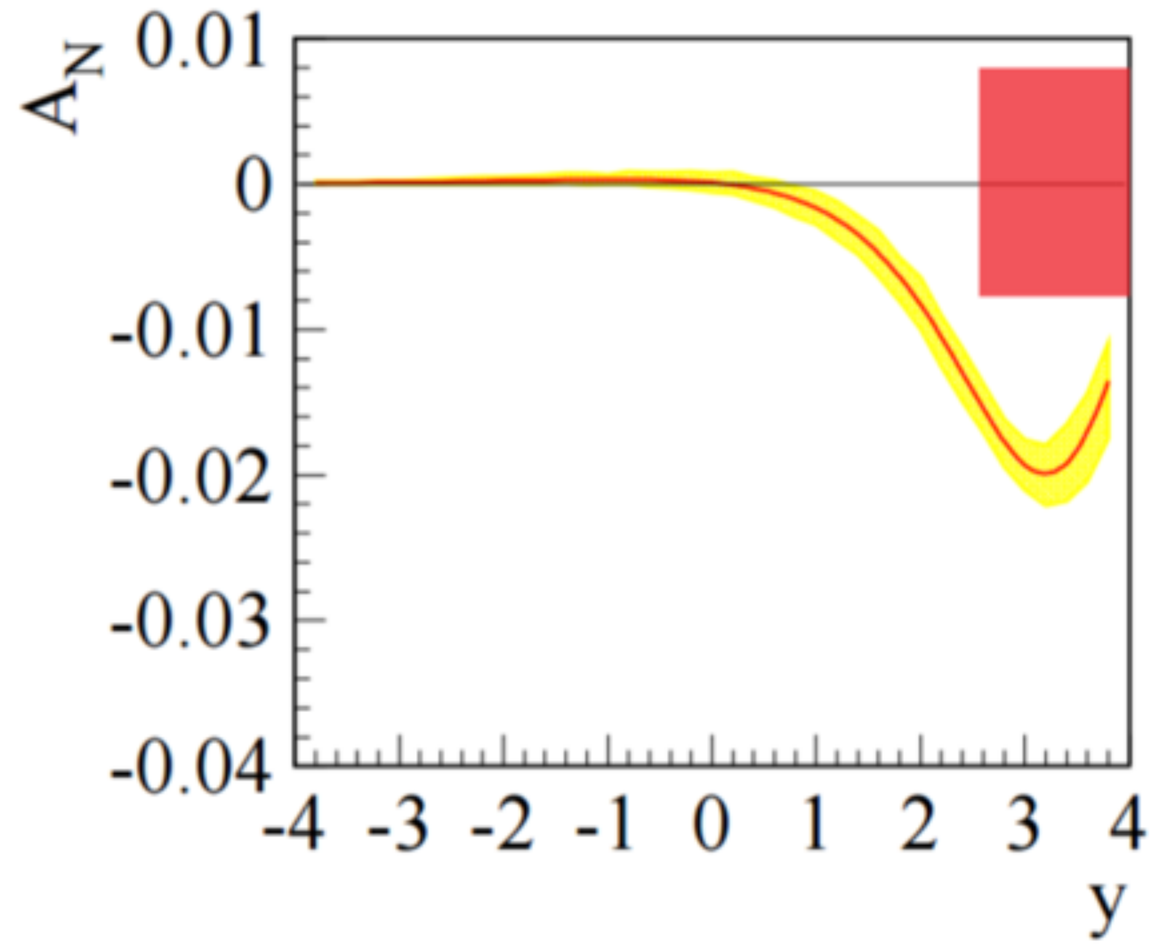
STAR Drell-Yan - Prospects for 2017 Run

No TMD evolution



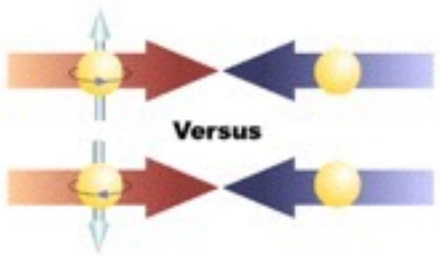
With TMD evolution

Z.B. Kang et al, ArXiv:1401.5078



Measurement relies crucially on the FMS, the now existing pre-shower to the FMS, a new tail-catcher (post-shower) to the FMS, and in-situ annealing of the FMS with UV LEDs.

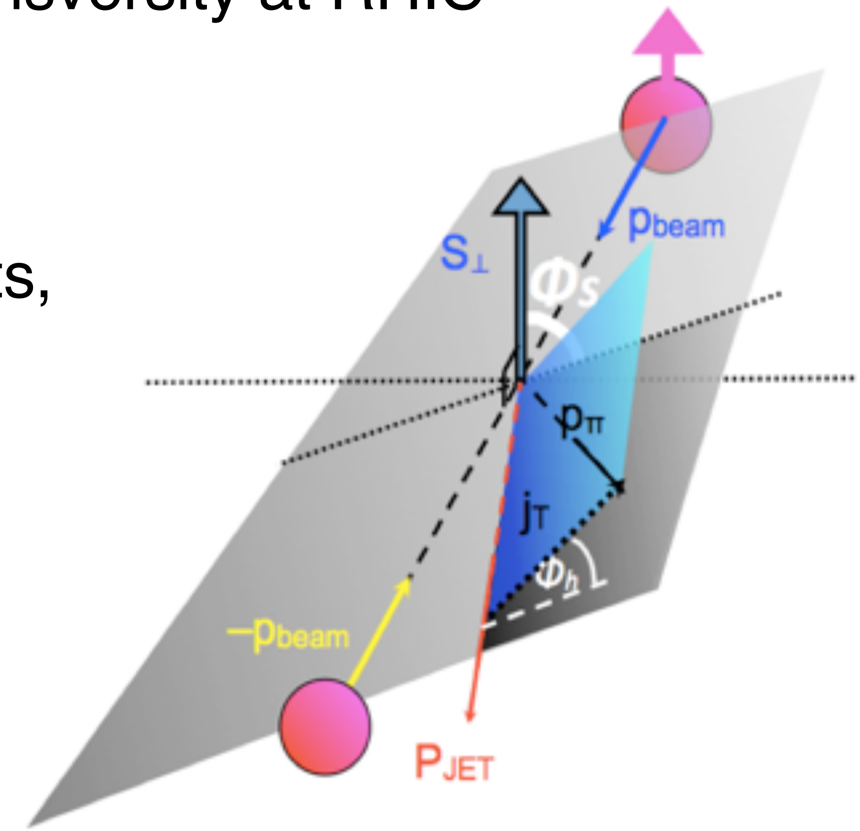
Transverse Spin Phenomena: Quark Transversity



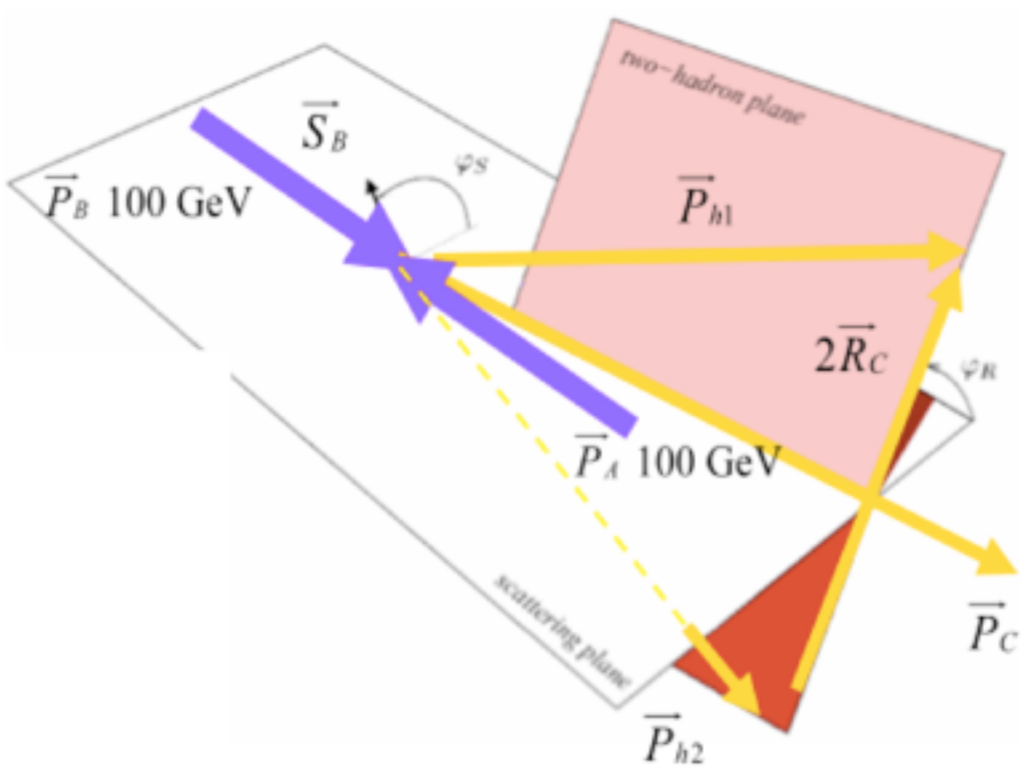
Quark Transversity at RHIC

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

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



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

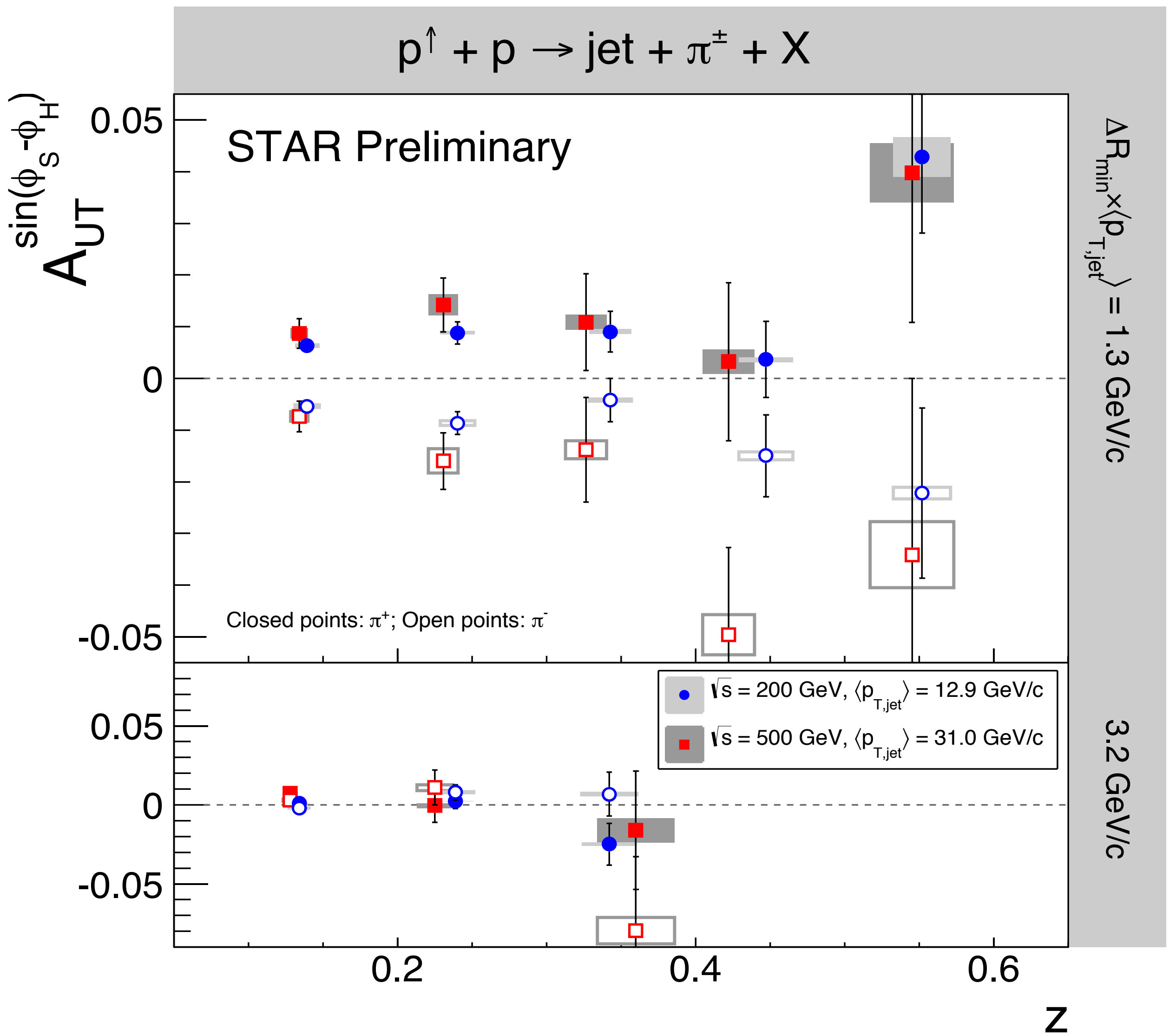


2. di-hadron correlation measurements couple transversity with interference-fragmentation.

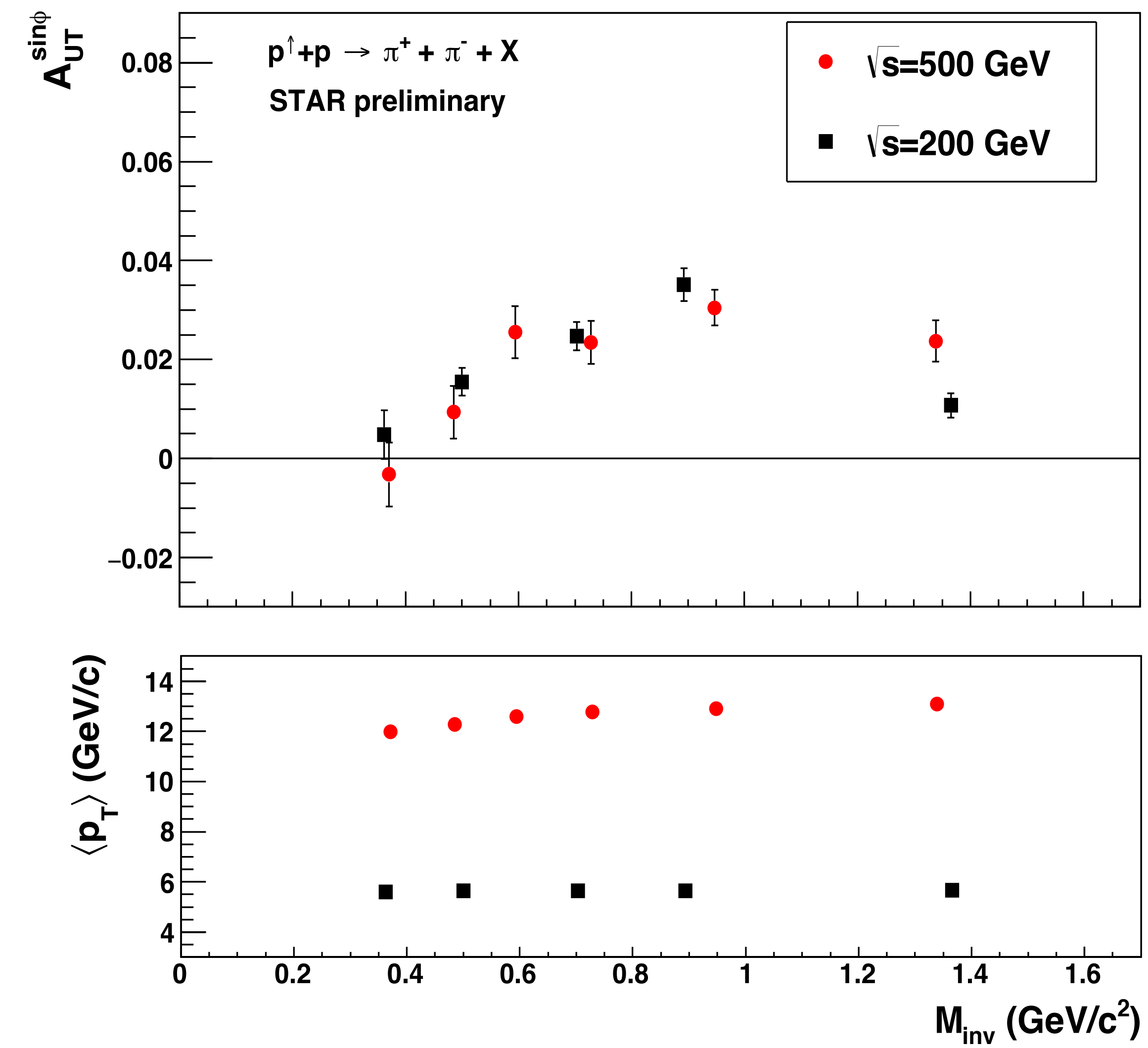
Both methods have been pursued and have delivered initial results...

STAR A_{UT} - Quark Transversity and Fragmentation

azimuthal modulation within the jet



interference fragmentation



Sensitivity to quark transversity at hard scales and *polarized* fragmentation,

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

STAR A_{UT} - Quark Transversity and Fragmentation

azimuthal modulation within the jet

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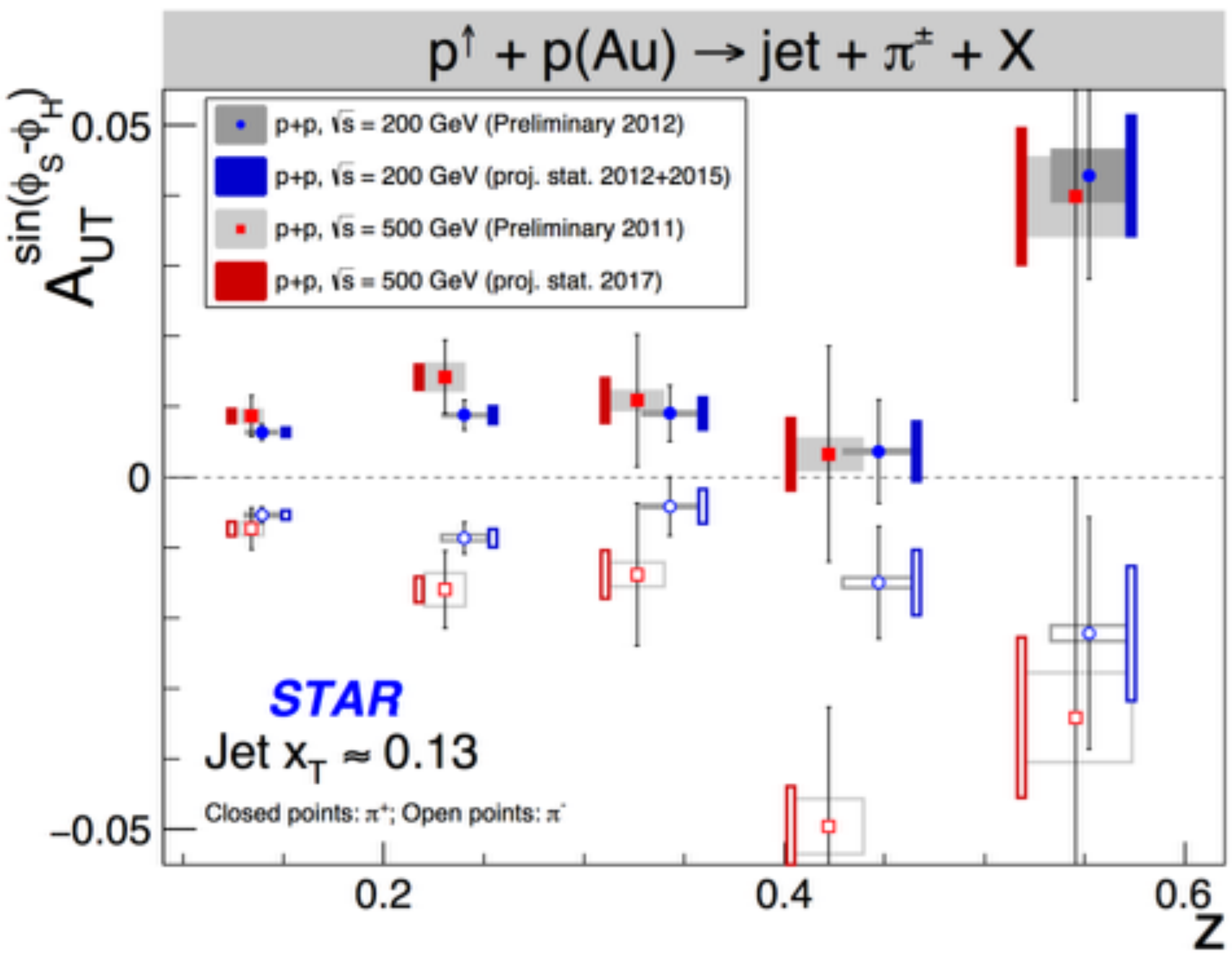

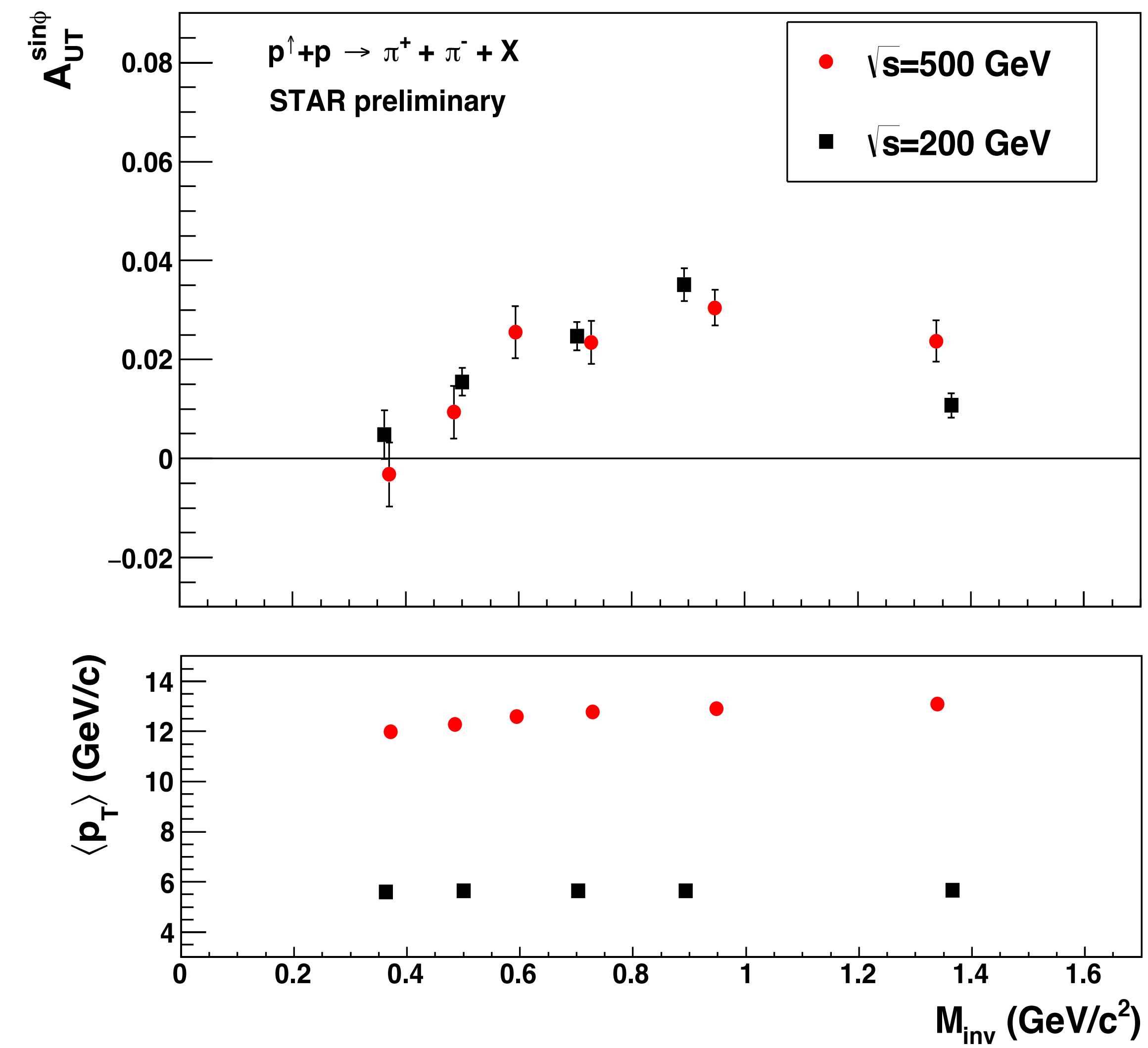

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200 and 500 GeV results are similar; is TMD evolution in FF small? Better *precision* to come

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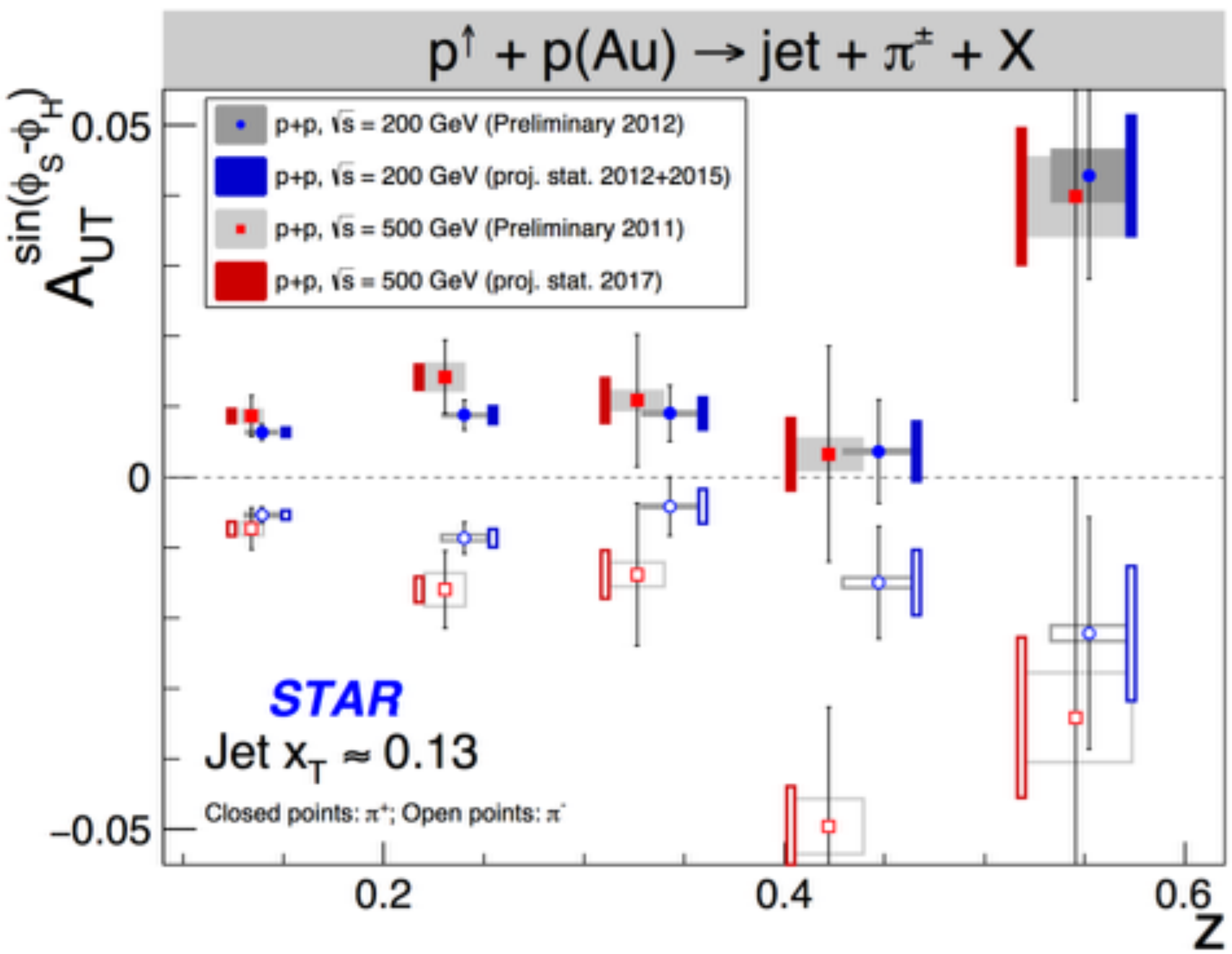
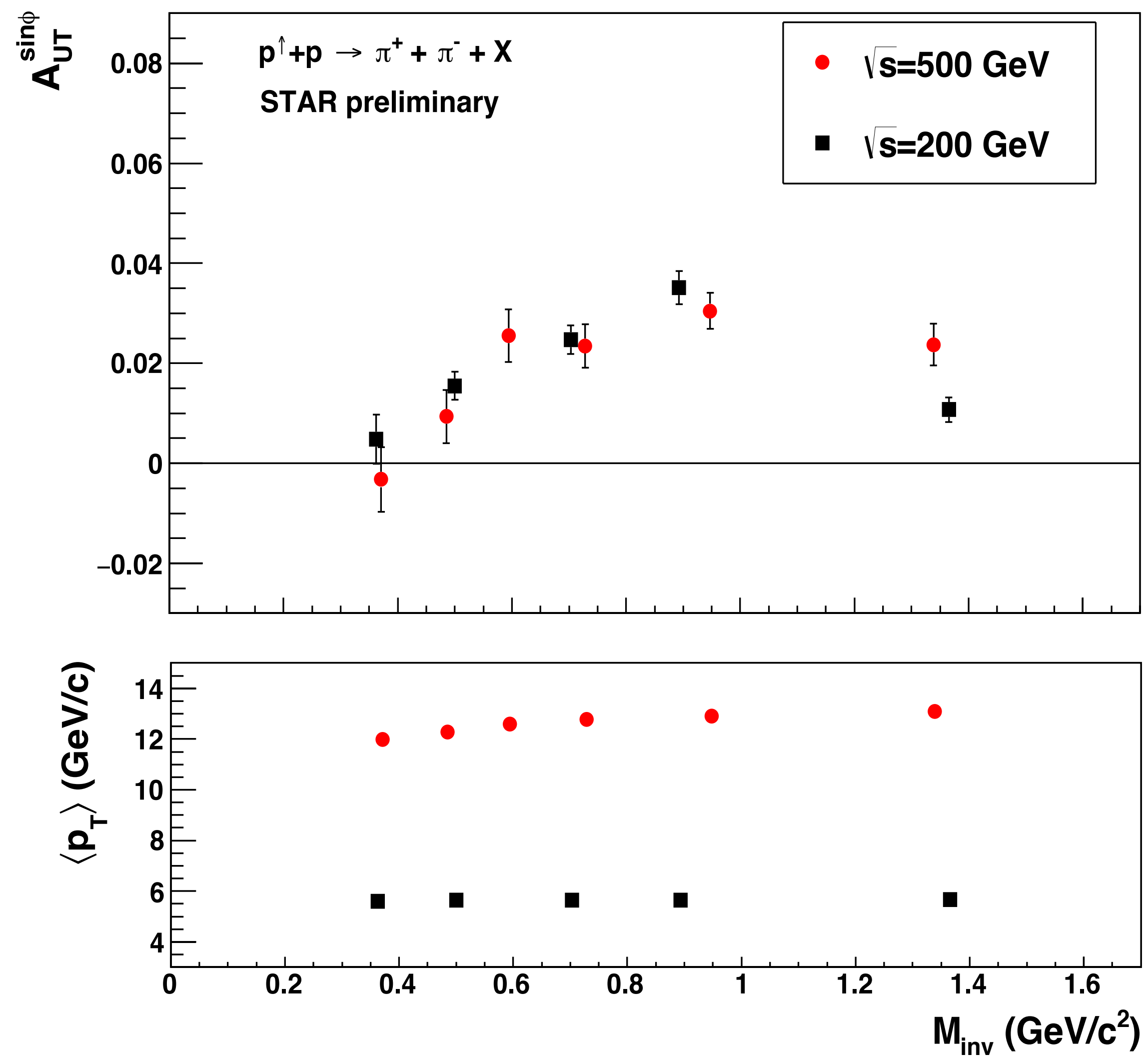


interference fragmentation



Sensitivity to quark transversity at hard scales and *polarized* fragmentation,

200 and 500 GeV results are similar; is TMD evolution in FF small? Better *precision* to come

Non-zero observations open a path to *nuclear modification* of polarized fragmentation, first exploratory analyses in progress (2015 data),

STAR A_{UT} - Quark Transversity and Fragmentation

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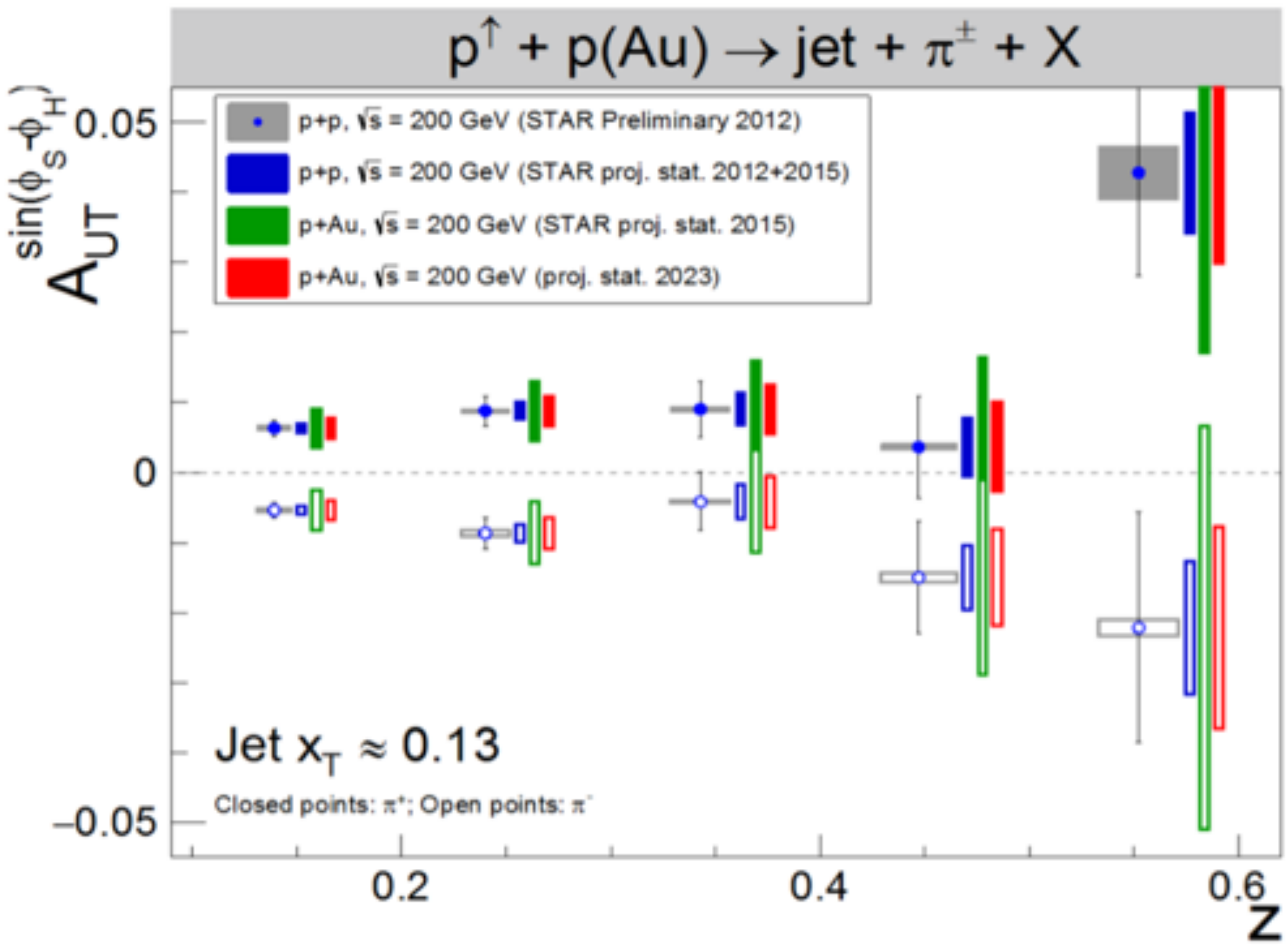
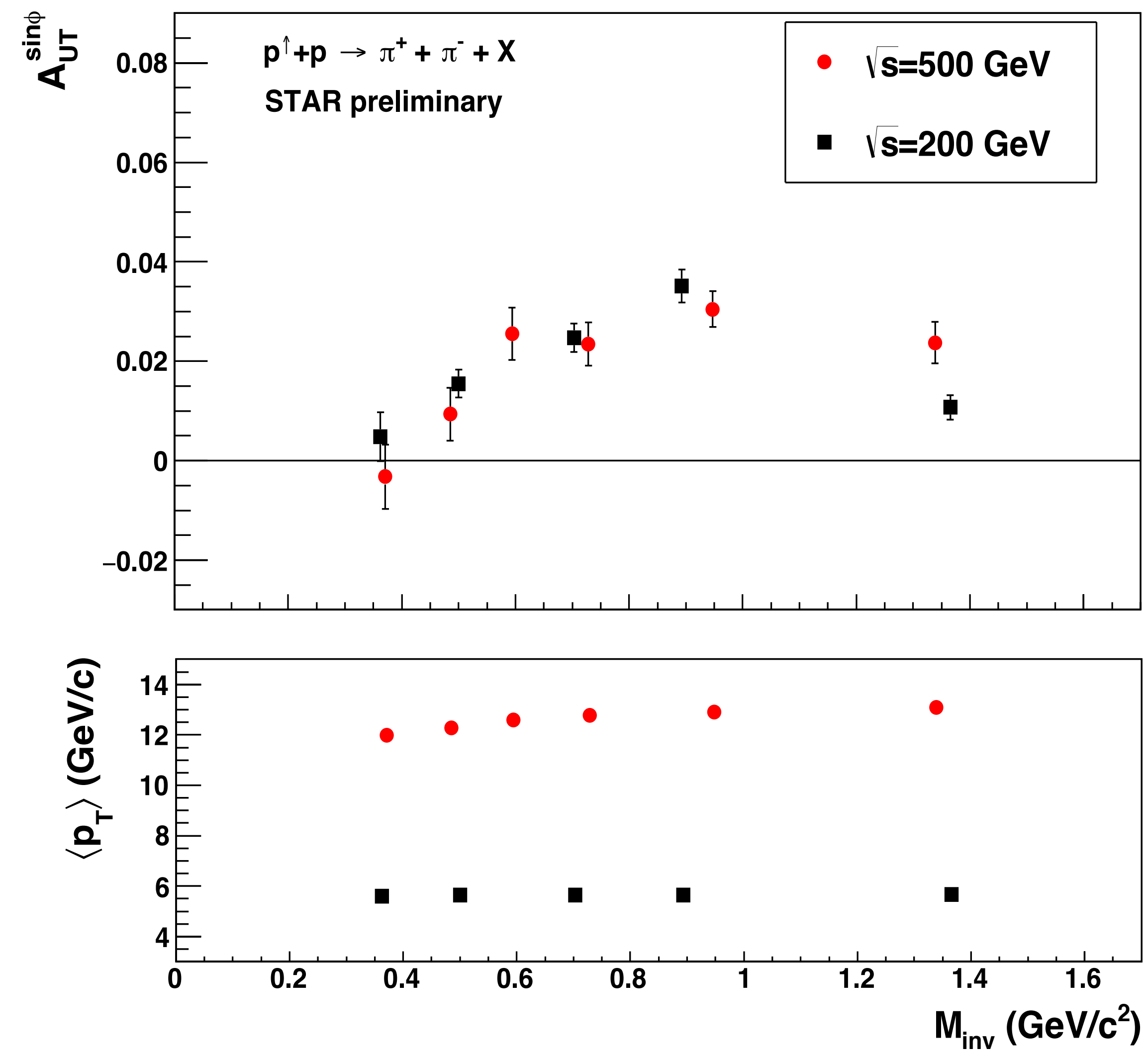


interference fragmentation



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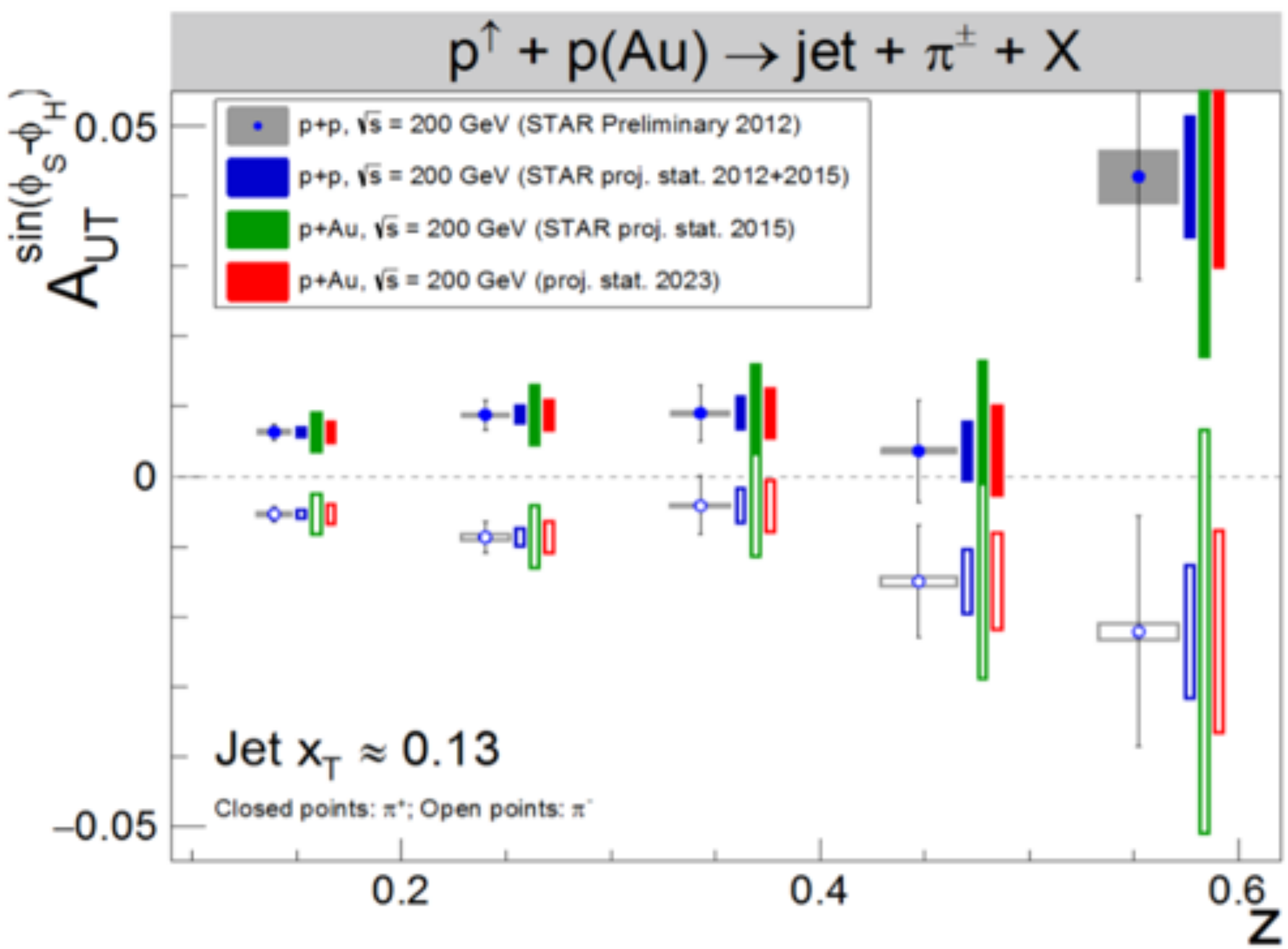
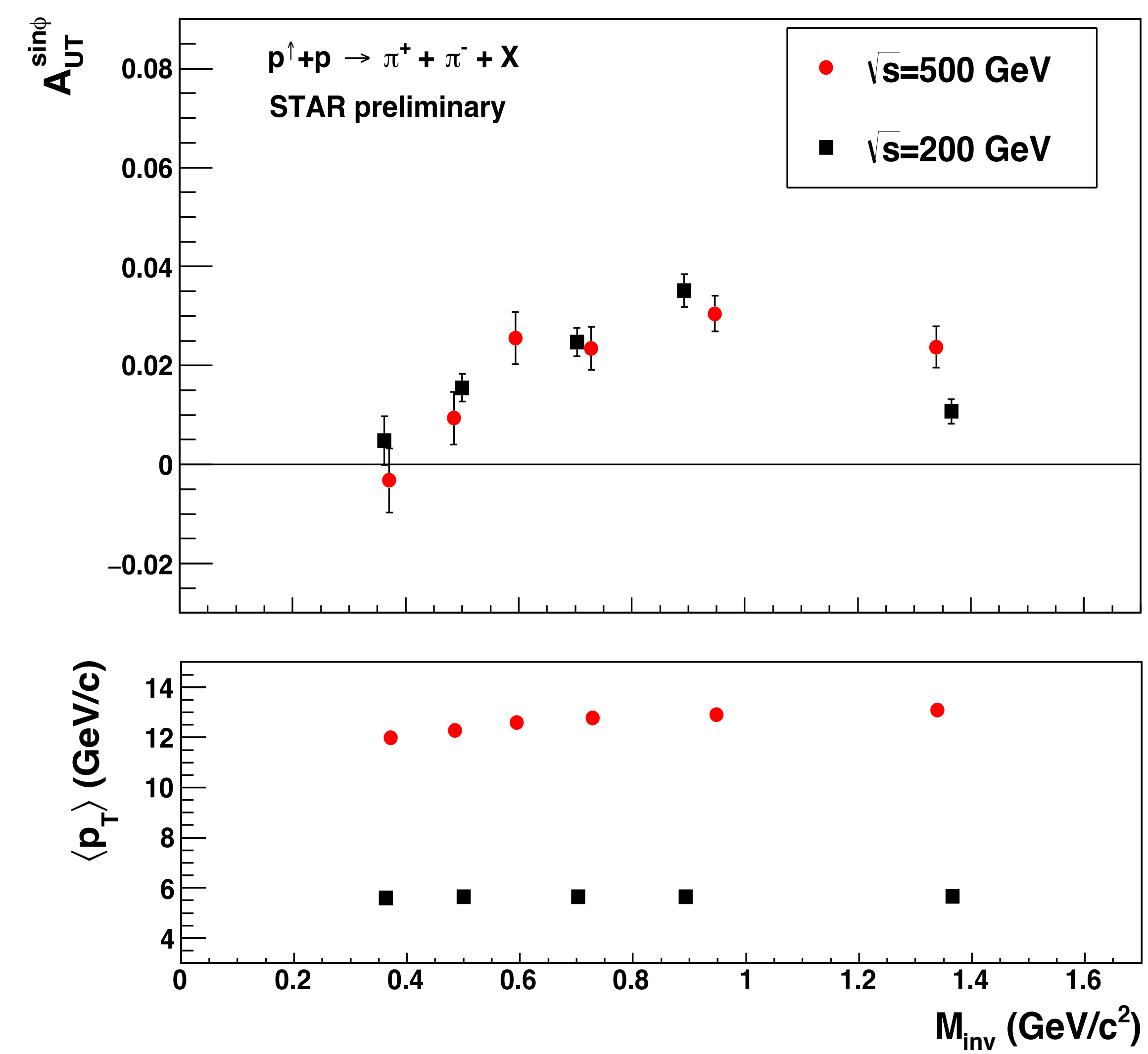


interference fragmentation



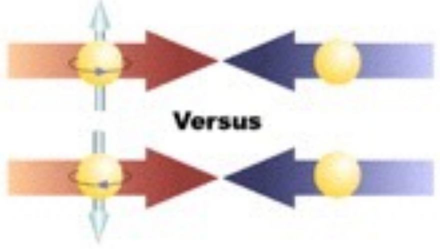
Sensitivity to quark transversity at hard scales and *polarized* fragmentation,

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 exploratory analyses in progress (2015 data),

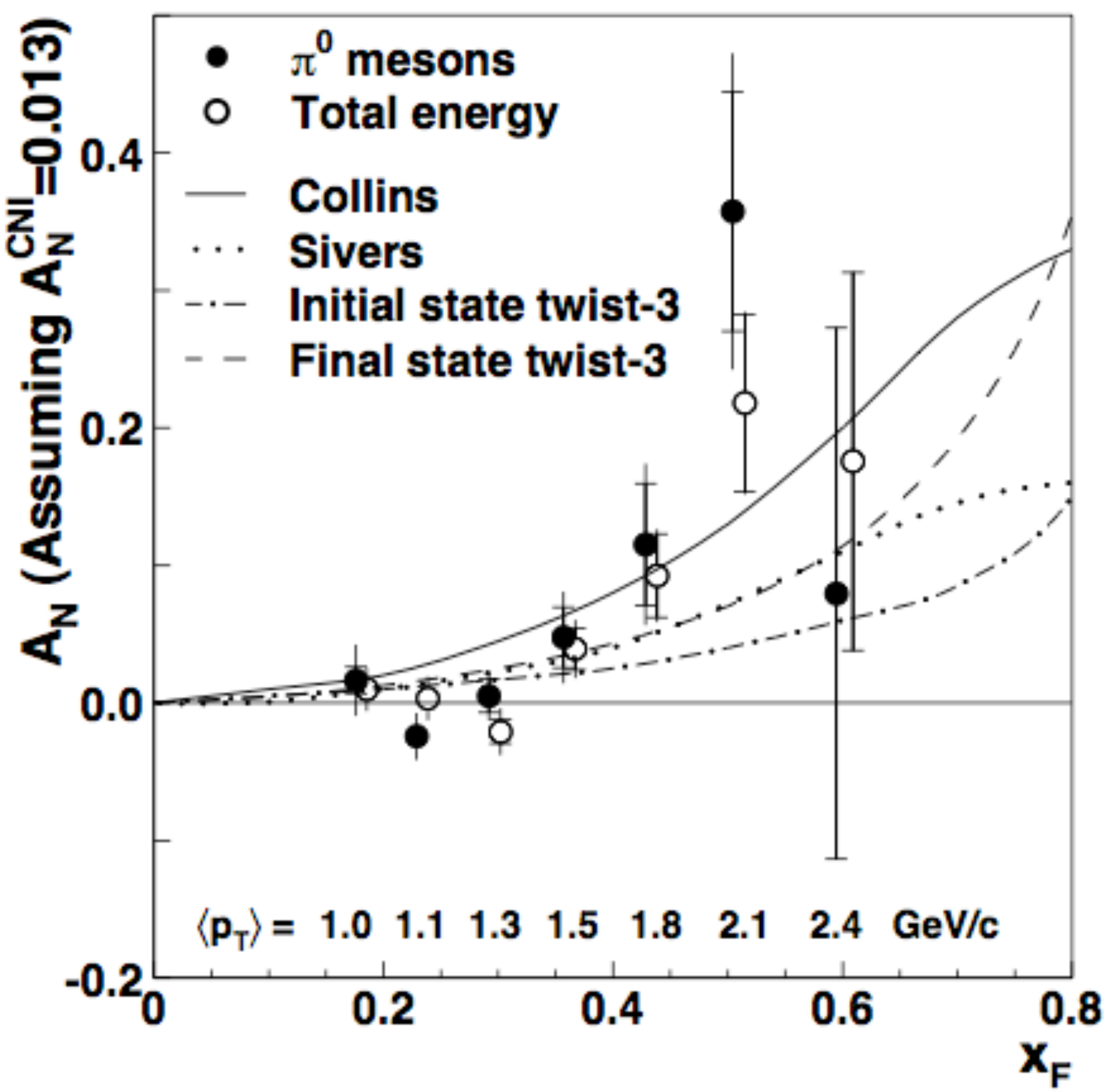
Particle-identification key to further surprises? Theoretical/phenomenological input sought.

Transverse Spin Phenomena: large A_N

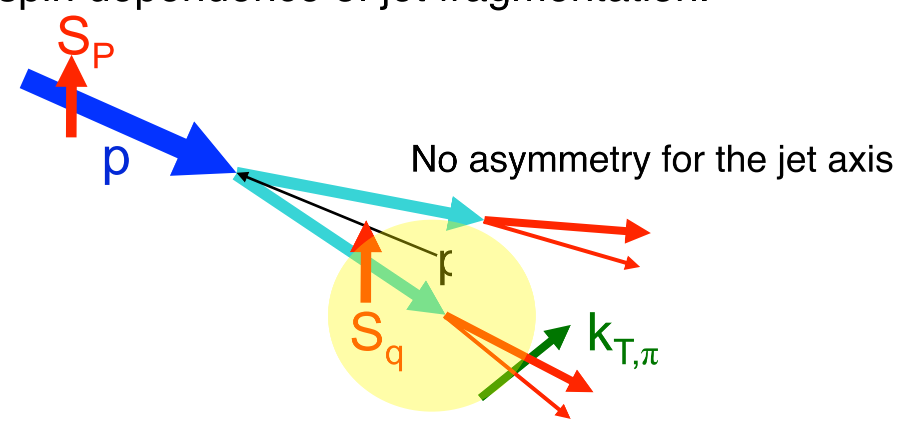


STAR neutral pion A_N - a continuing puzzle since E704

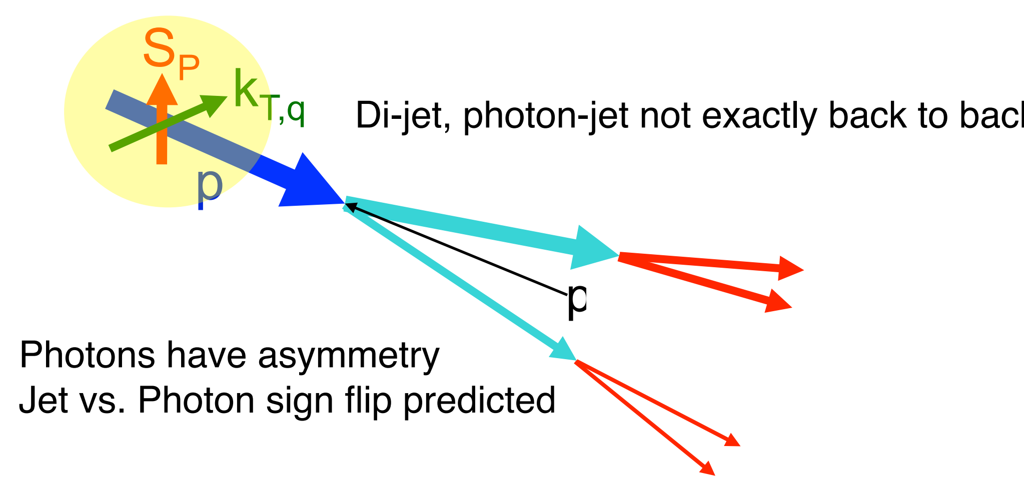
J. Adams et al, PRL 92, 171801 (2004)



• **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

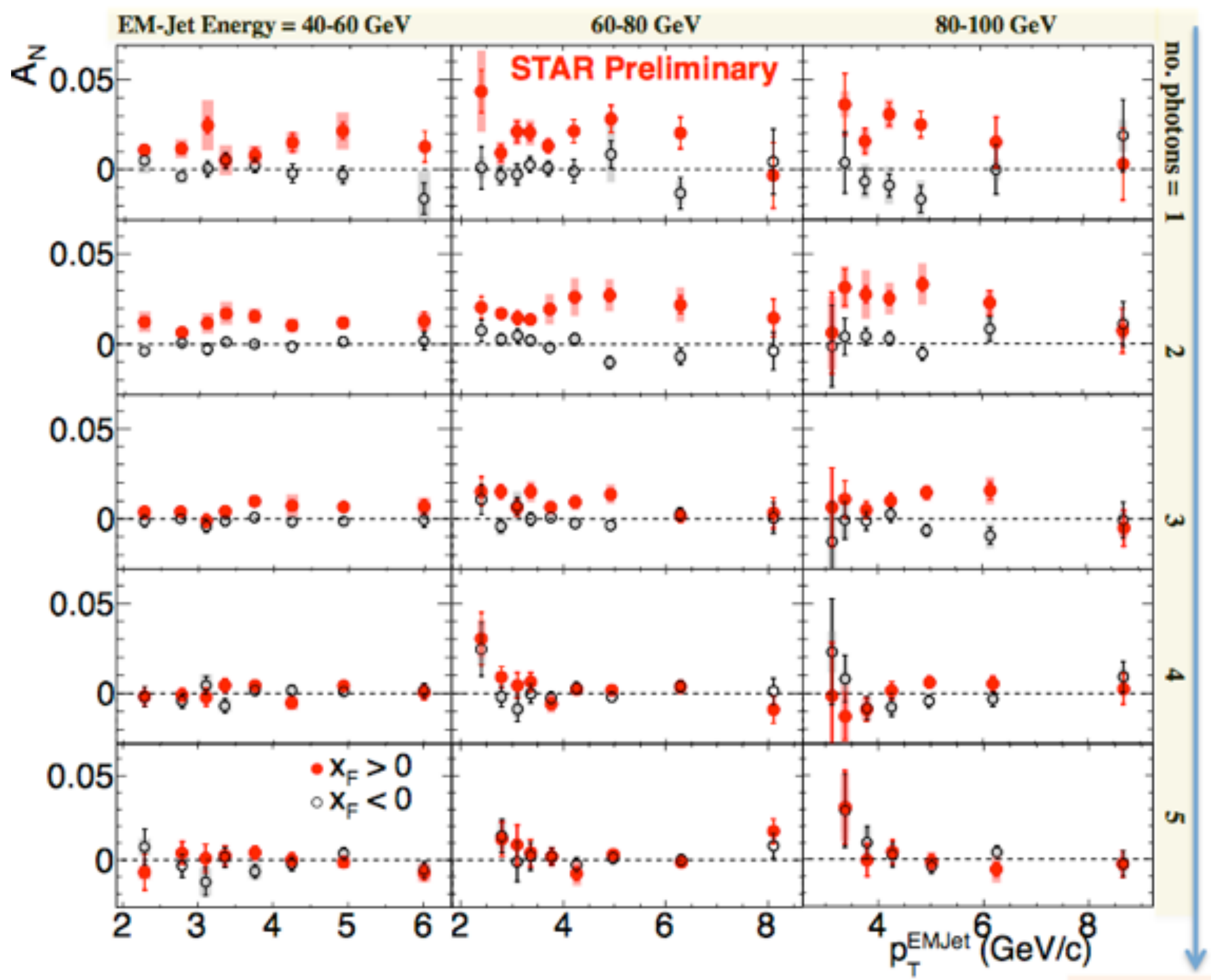


What causes this?

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

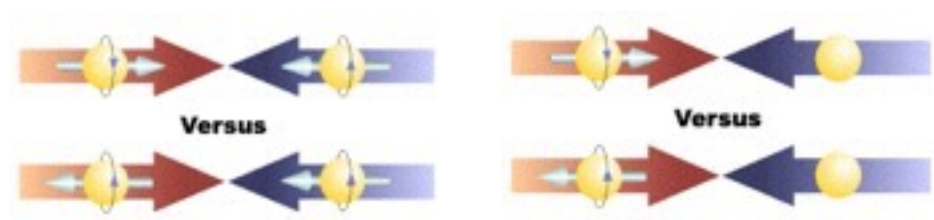
Jettier events

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

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

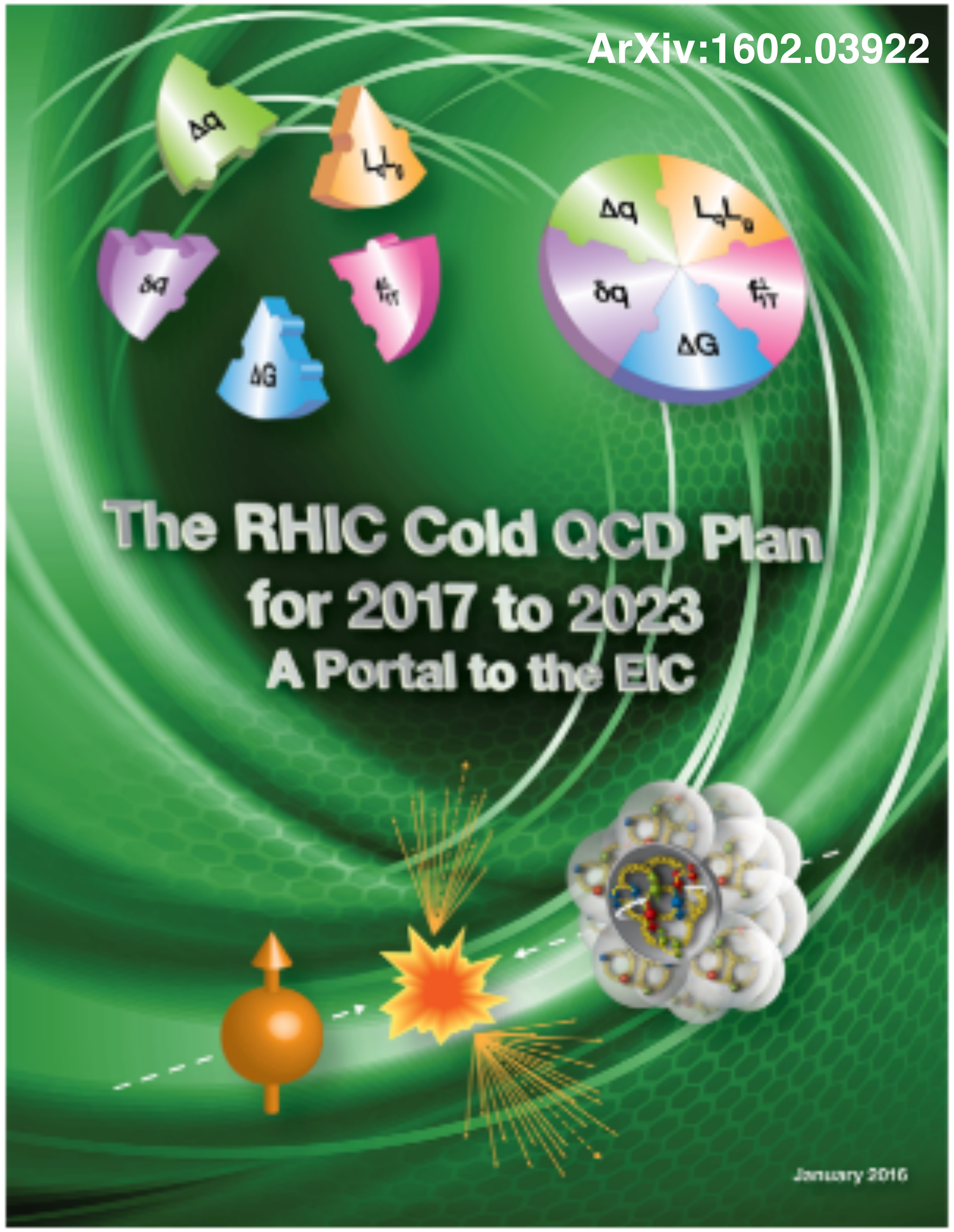
STAR Roman Pots (now) directly measure diffractive A_N. Initial analyses in progress.

Looking ahead towards EIC



See the talks by T. Hallman, B. Mueller, and B. McKeown earlier today,
A. Deshpande and X. Chen on Wednesday

Cool QCD at RHIC - Opportunities



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

Focused 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,
- work *mostly* within beam-use scenarios set by sPHENIX science deliverables,
- consider *cost-effective* upgrades,

Universality, factorization focused/themed.

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 Eg	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 in One Slide

Firmly part of the plan,
on track for 2017

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				First look at GPD E_g	A_{UT} for J/Ψ in UPC	None
Scheduled RHIC running	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Yes Forward instrum.
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				Nuclear dependence of TMDs and nFF	$A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF	None
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				quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	and mid-rapidity observables as in 2017 run	None
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RHIC Cold QCD Plan in One Slide

Firmly part of the plan, on track for 2017

Concurrent with sPHENIX run plan opportunities with and without forward upgrade

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RHIC Cold QCD Plan in One Slide

Firmly part of the plan, on track for 2017

Concurrent with sPHENIX run plan opportunities with and without forward upgrade

More high-impact science if the opportunity arises

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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 - Detector(s)

Mid-rapidity:

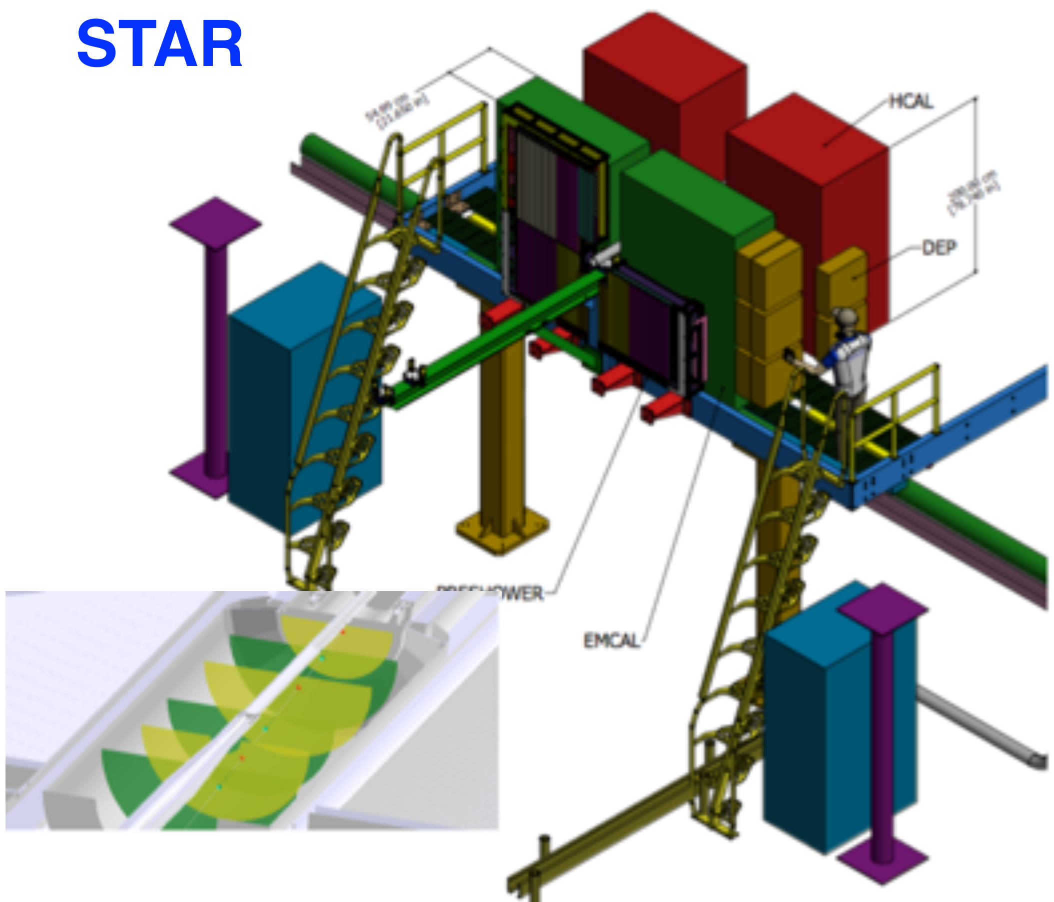
sPHENIX (baseline) can make measurements that do not rely on π/K/p separation (or Roman Pots),

STAR can make all proposed measurements,

Forward-rapidity:

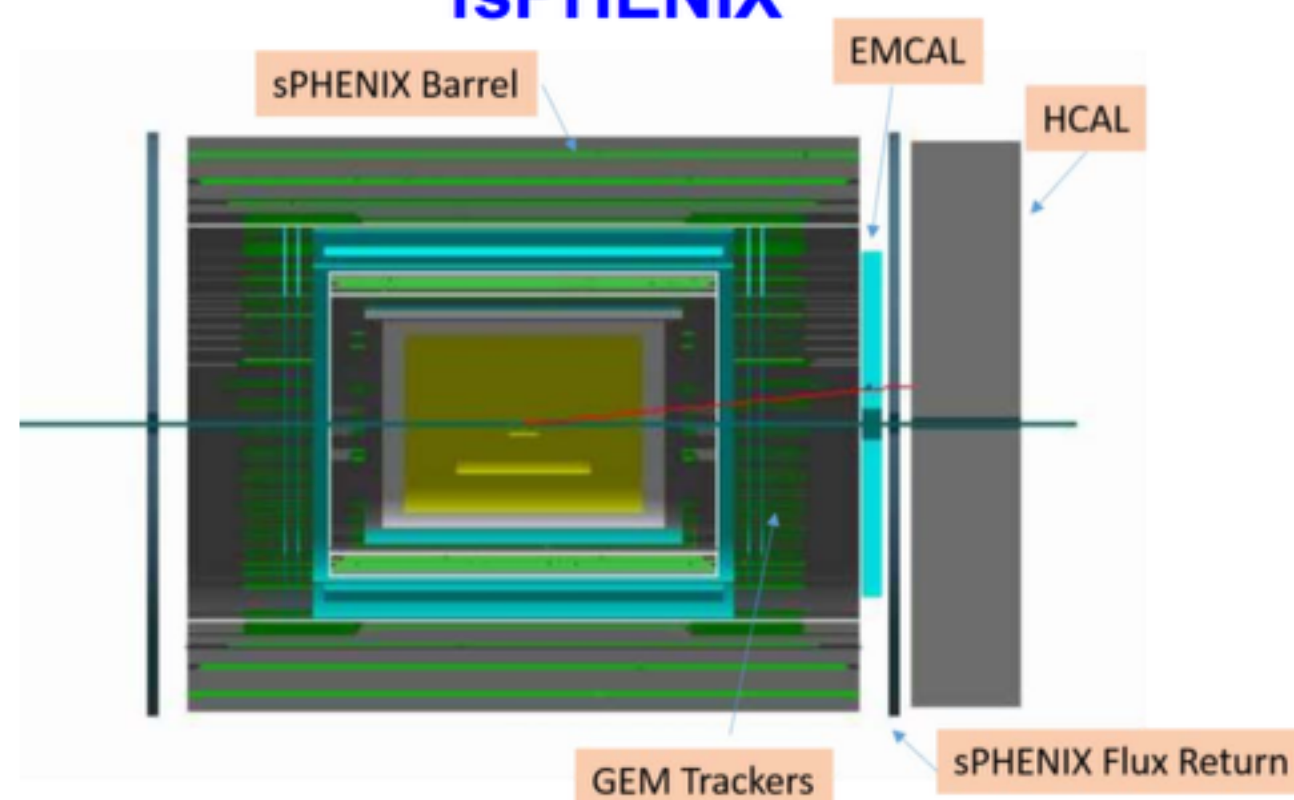
Ensure jet ($\sqrt{s}$ = 500 GeV) and Drell-Yan capability, charge-sign discrimination

STAR



Cost estimate: 6M$

fsPHENIX



Cost estimate: 12M$ + labor

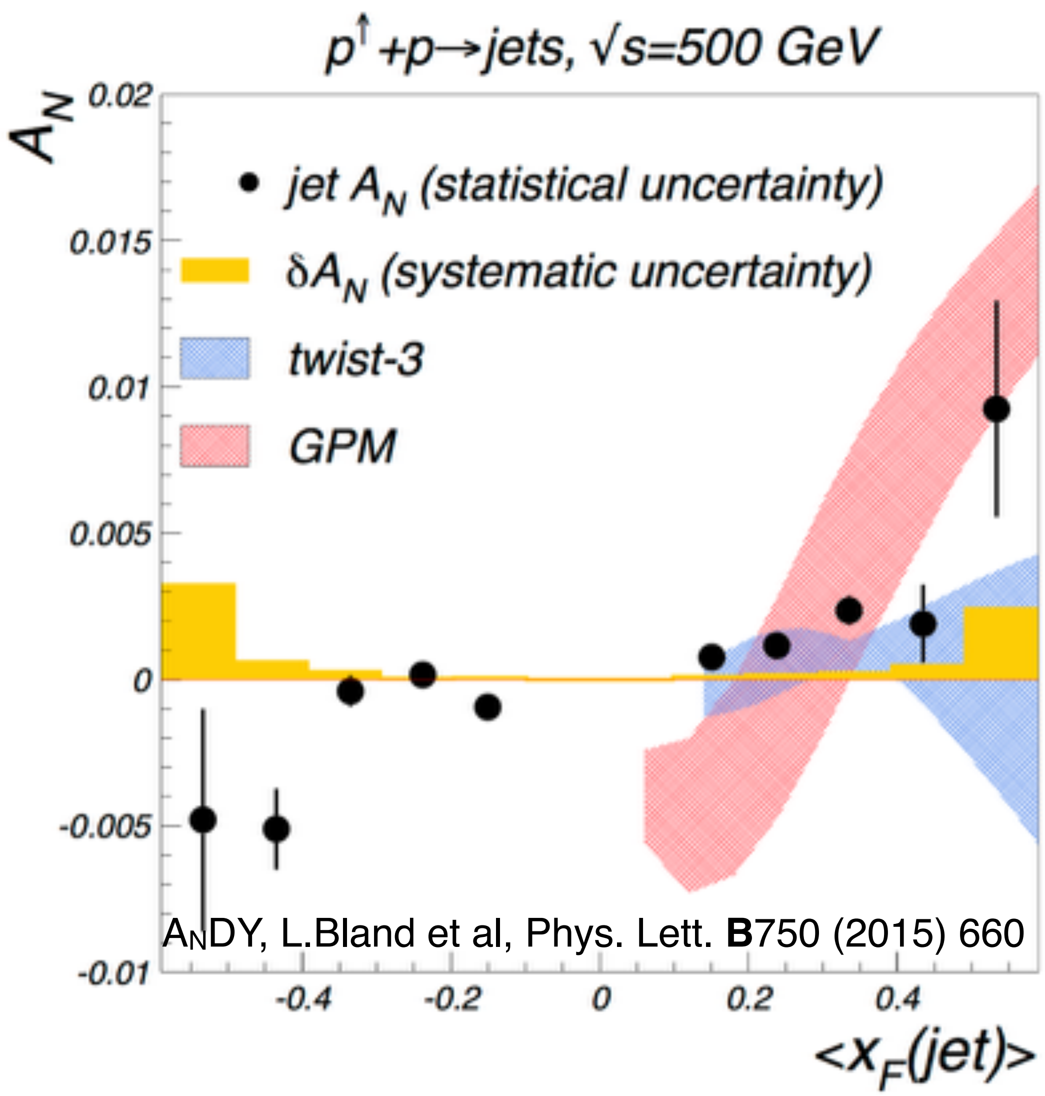
Requires a combination of electromagnetic and (new) hadronic calorimetry, and tracking.

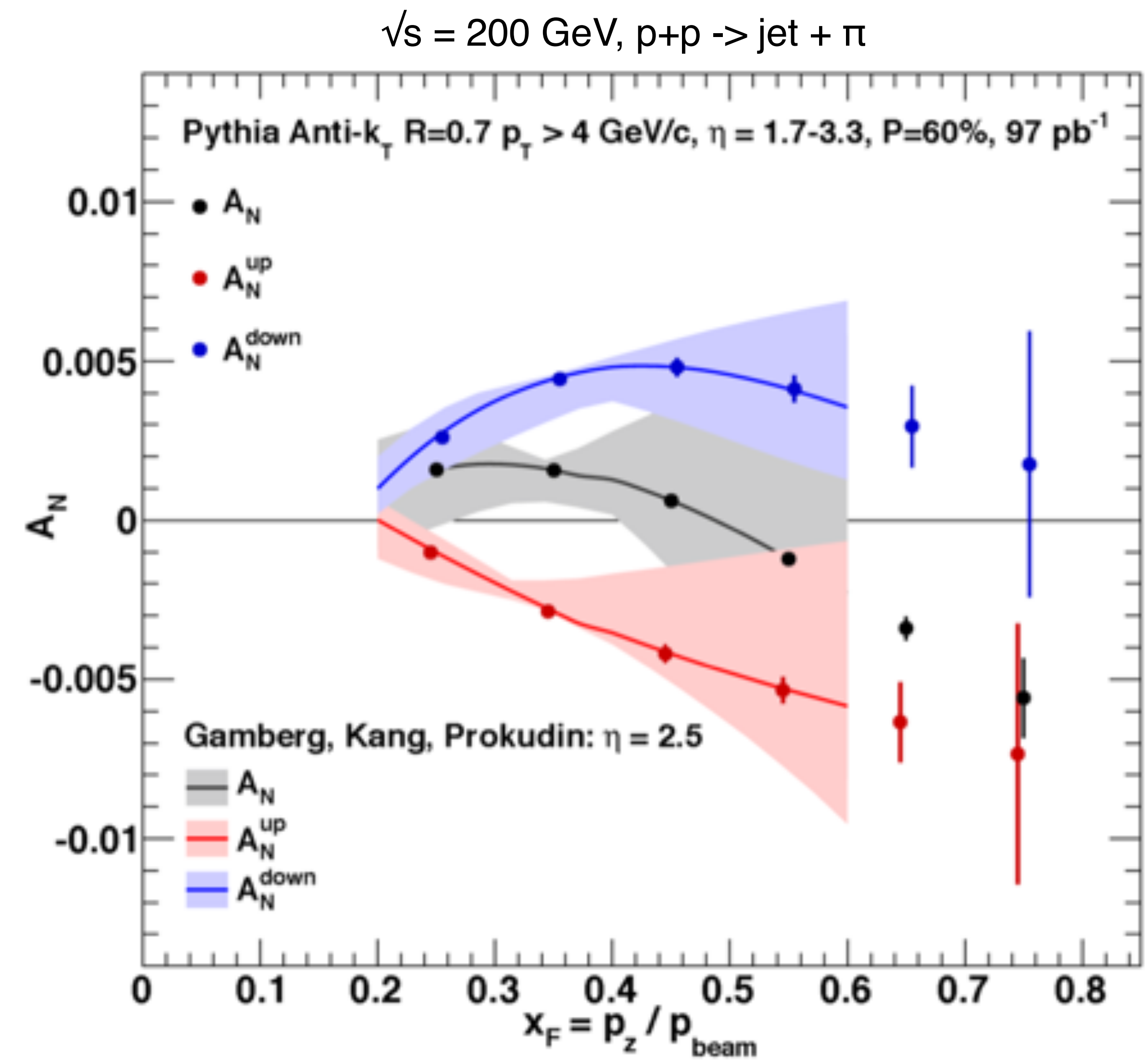
RHIC Cold QCD Plan - the puzzle of forward A_N

Large forward A_N seen over a vast range in $\sqrt{s}$, wide p_T, … What causes them?

STAR forward asymmetries decrease with increasing cluster multiplicity; ANDY has (now) published small A_N for jet-*like* events,

Roman-Pot data exist (on tape) to elucidate diffractive origins, full forward jet-capability and tracking are needed to pursue cancellation scenarios.

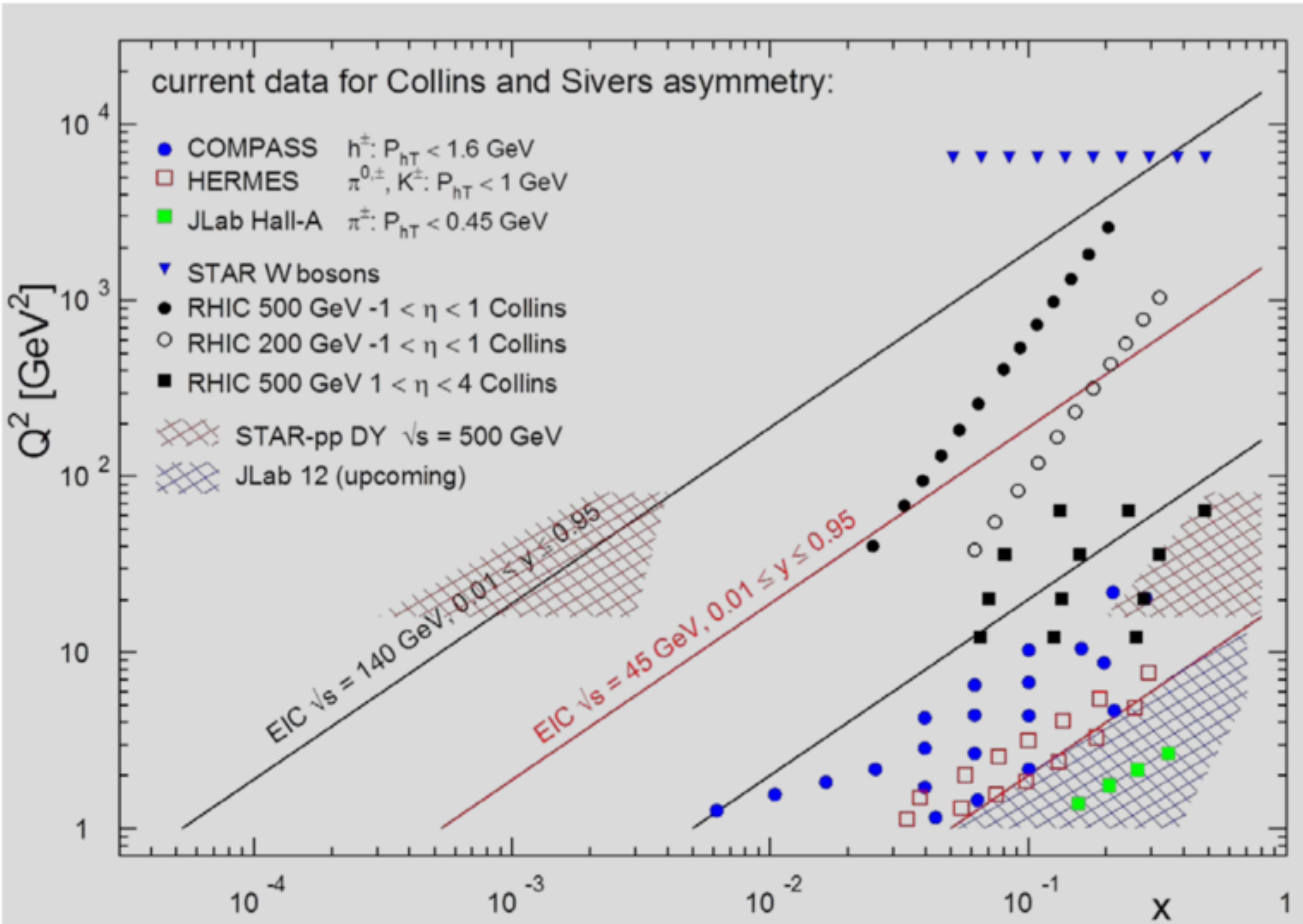




Pursue charged-pion enhanced jets, and

possible Twist-3 origin of forward A_N with improved photon A_N measurements.

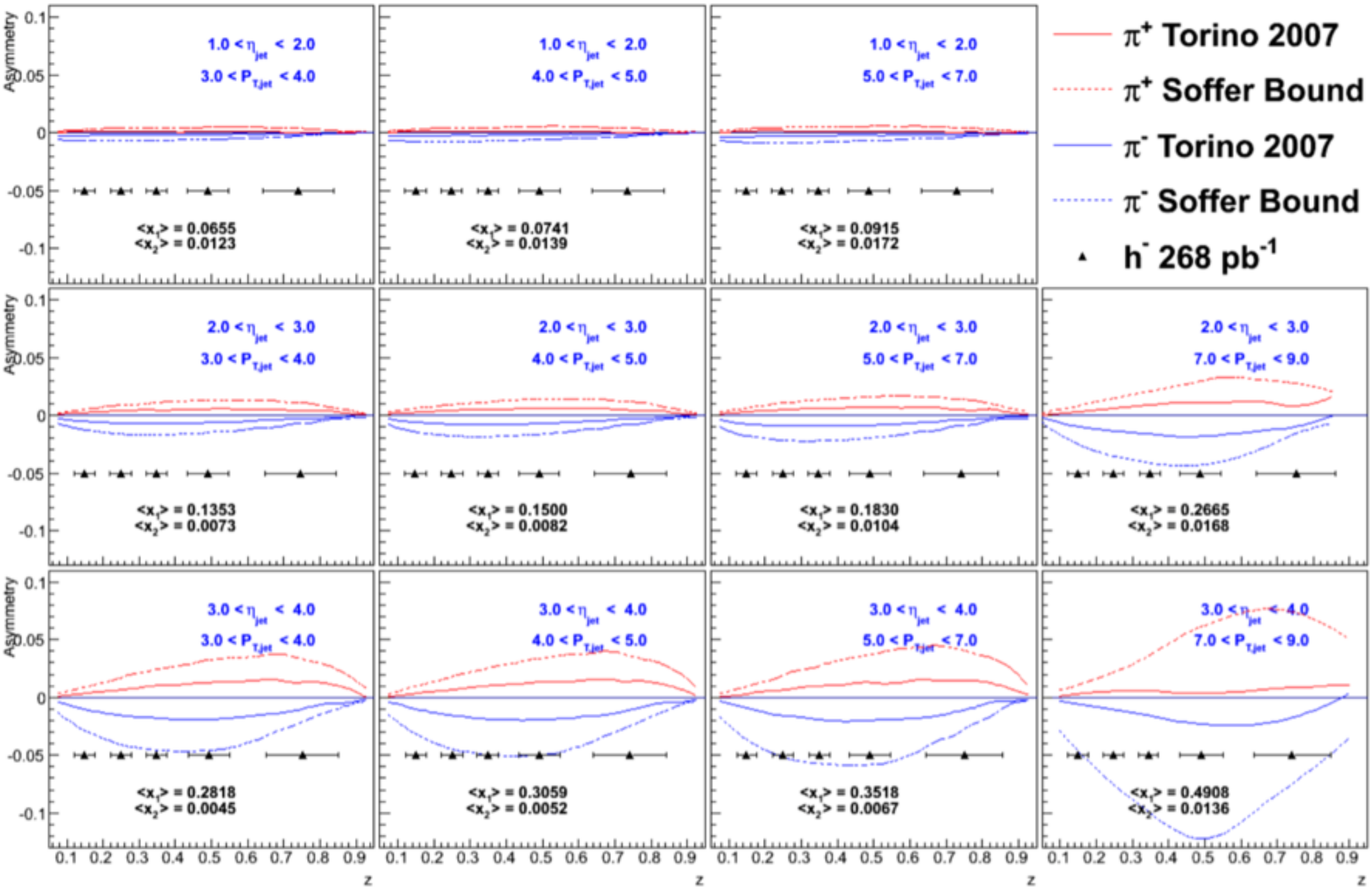
RHIC Cold QCD Plan - Collins and Sivers



Fixed-target DIS, RHIC-spin, and EIC are truly complementary,

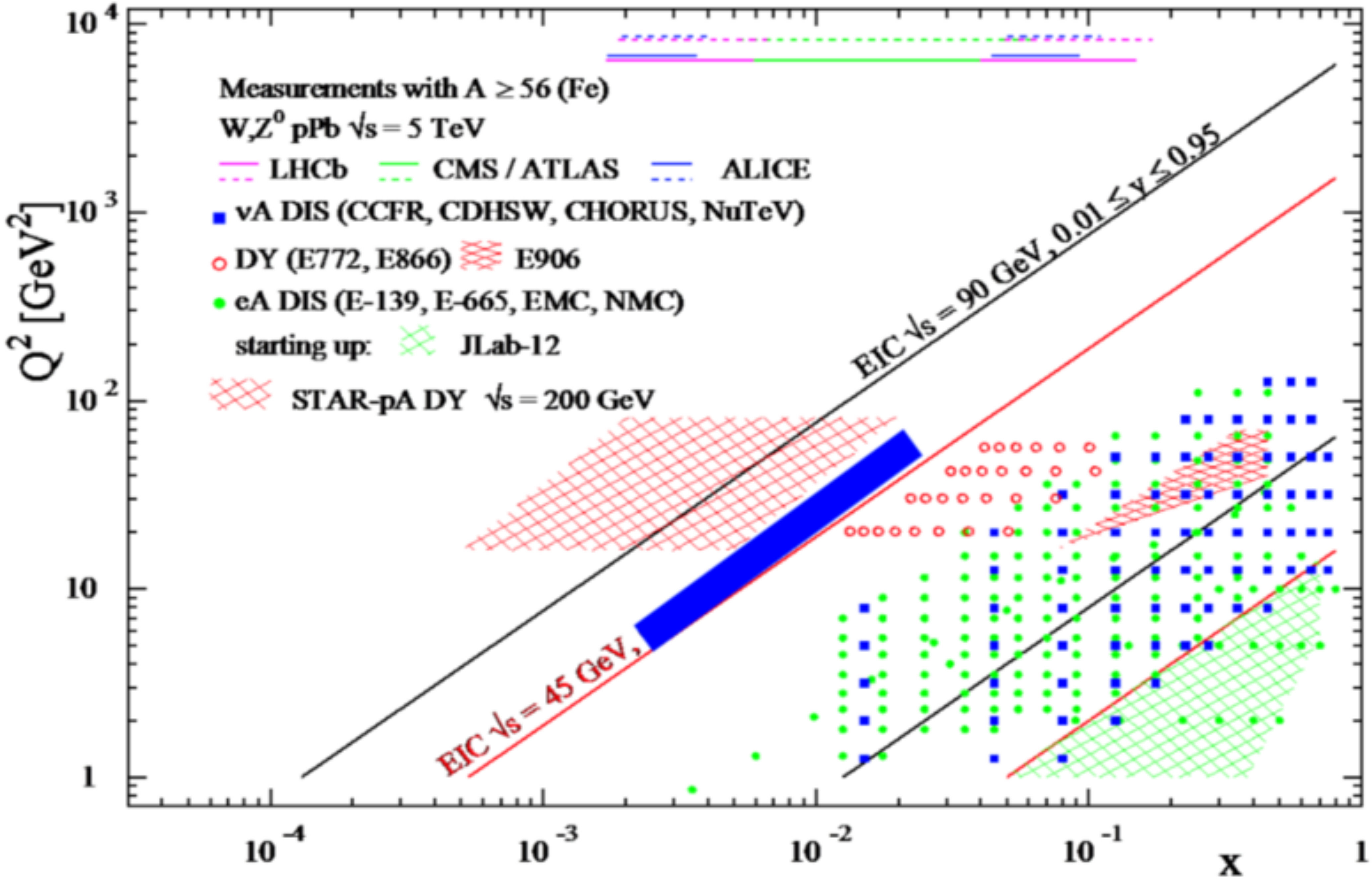
RHIC-spin has a unique role in hadro-production.

RHIC Cold QCD Plan - Collins and Sivers



Impactful uncertainty projections. Shown here are $\sqrt{s}$ = 500 GeV forward Collins A_{UT}

RHIC Cold QCD Plan - nuclear distributions



Forward photon and Drell-Yan processes:

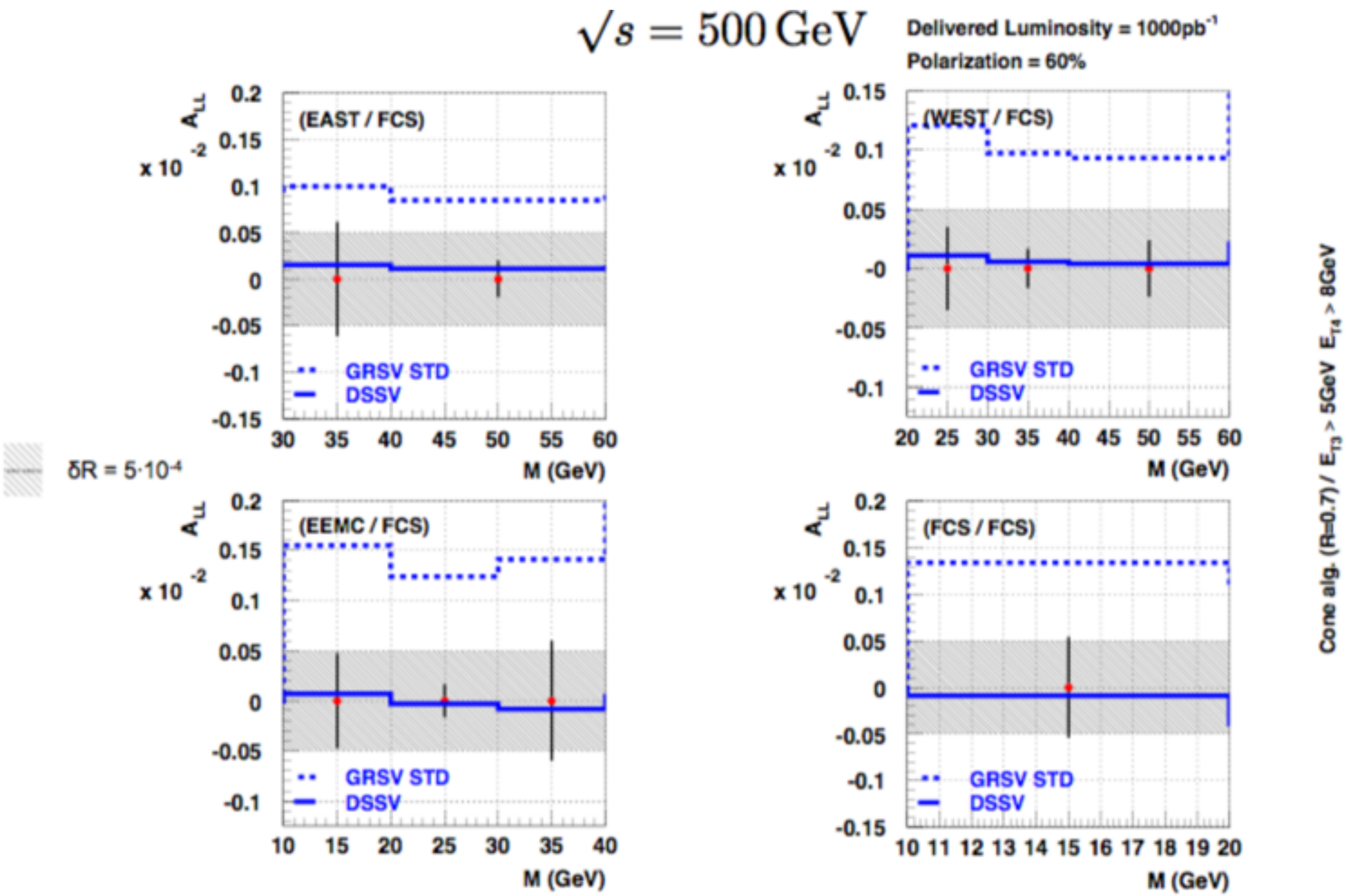
~free of final state effects,

cover compelling kinematic ranges vis-a-vis JLab, LHC, and EIC,

Ultra-peripheral p+A collisions are sensitive to g(x,Q^2,b),

Polarized p+A is an enticing capability; phenomenology/theory input essential.

RHIC Cold QCD Plan - Gluon Polarization



Improvement over existing data can be had with continued

Polarized p+A is an enticing capability; phenomenology/theory input essential.

Closing Comments

RHIC spin program:

- has achieved the most sensitive insights in **gluon polarization** in the nucleon,
  gluons are positively polarized for momentum fractions x > 0.05,
  at the level of 0.2 h for Q^2 = 10 GeV^2

- has provided evidence, with measurements at the W-mass scale that are free of fragmentation uncertainties, of non-perturbative **sea-quark polarization**,

$$\Delta\bar{u} > \Delta\bar{d},\ \text{while}\ \bar{d} > \bar{u}$$

- has recently observed non-zero asymmetries at mid-rapidity that are sensitive to **quark-transversity** at hard scales,

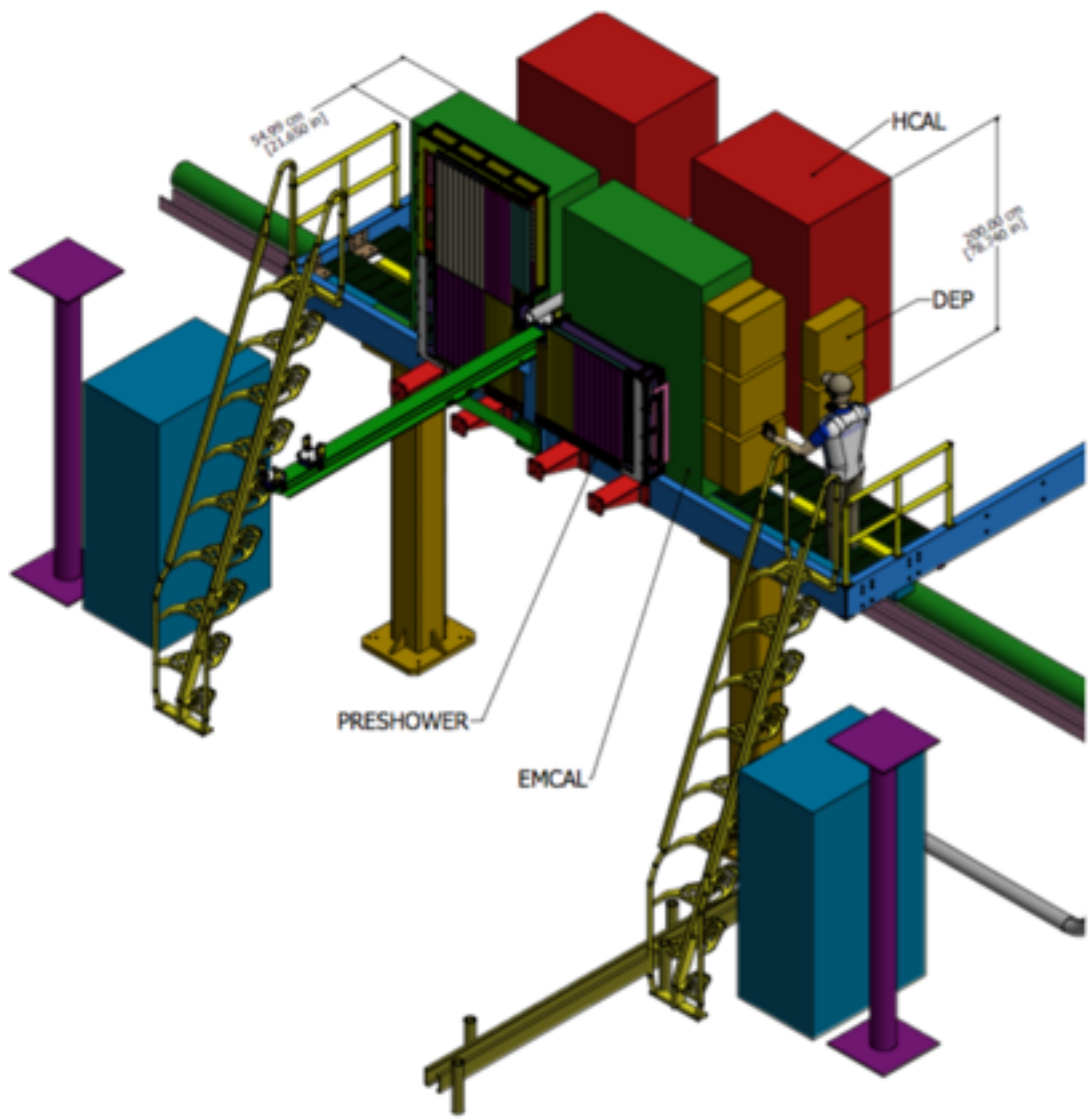
- has initial transverse W-boson data that are consistent with the **Sivers' sign-change** from an integrated luminosity of ~25 pb^{-1}

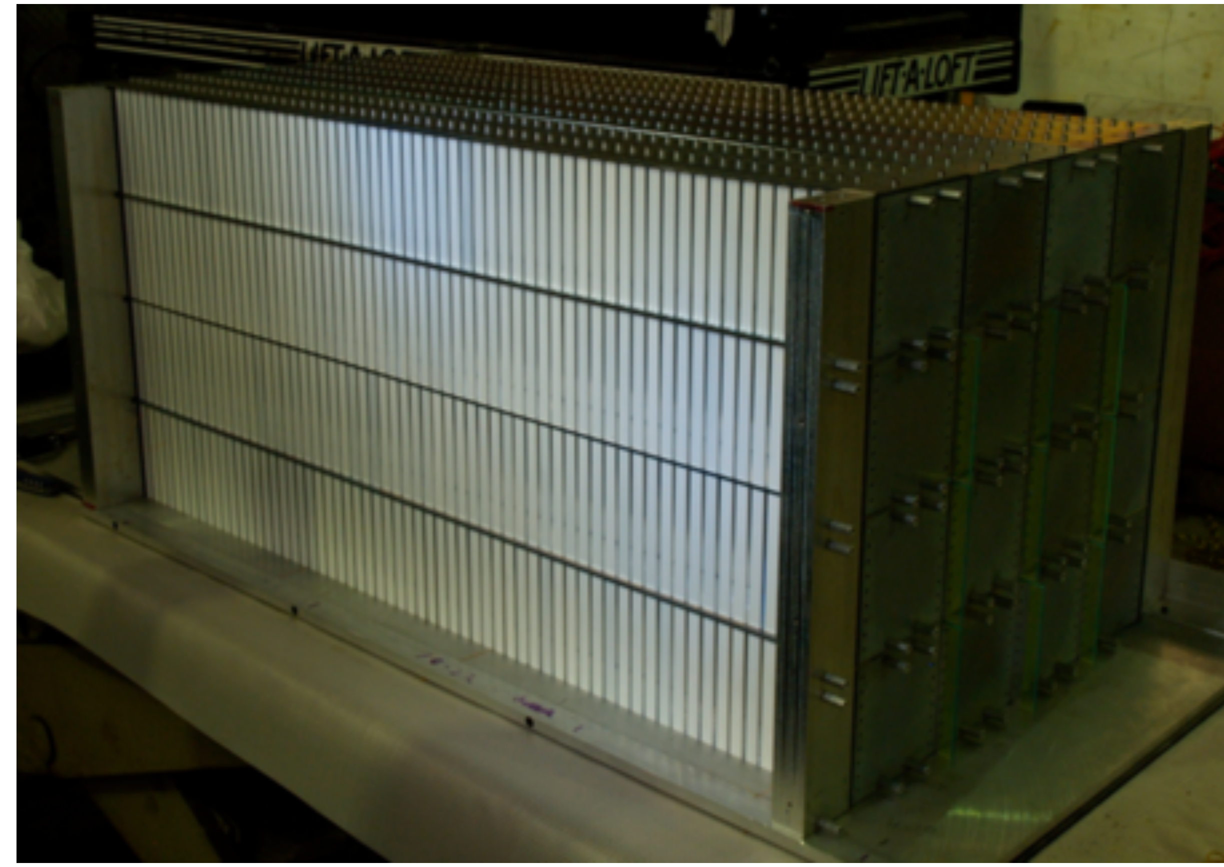
- will pursue Sivers' measurements with W-bosons, Drell-Yan, and photons in 2017, with 16-fold larger (anticipated) integrated luminosity

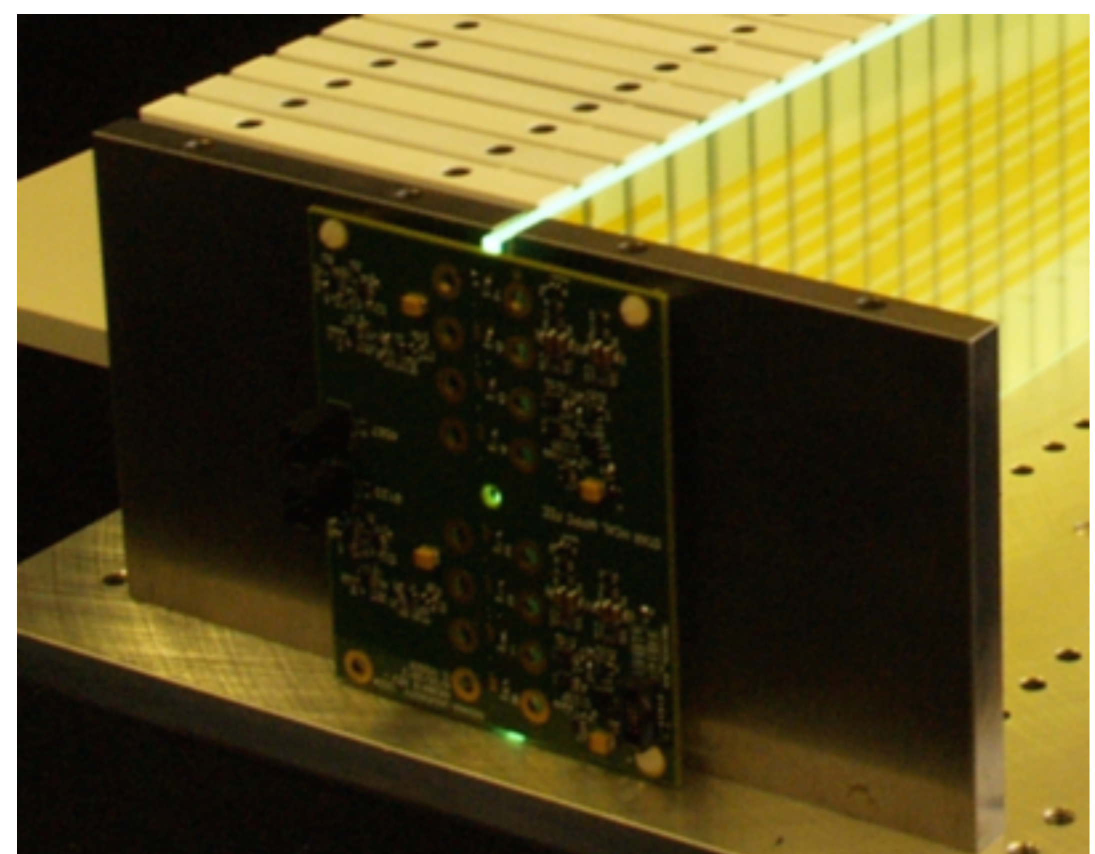
RHIC cold-QCD plan for 2017-2023 (arXiv:1602.03922):

- outlines, and in many cases quantifies, new opportunities within constraints on beam-use scenarios and upgrades: **nuclear Drell-Yan** is a prime example,
- advocates timely realization of a modest **forward calorimetry and tracking upgrade**, renewed **√s = 500 GeV beam-operations** for precision measurements of Sivers, Collins, and gluon polarization measurements.
- **neither the first nor the last word; ample opportunities for impactful collaboration.**

STAR FCS+FTS upgrade





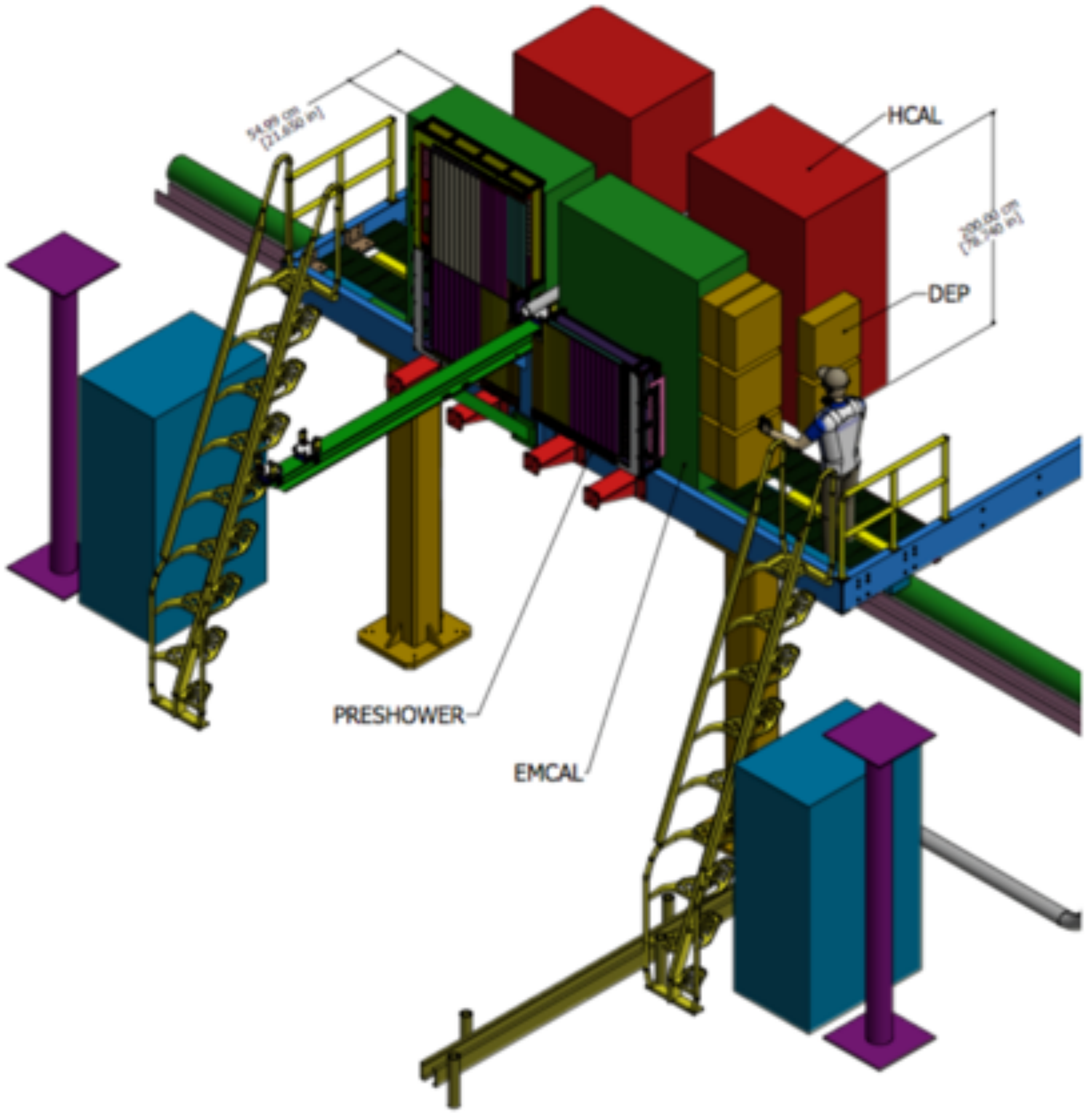


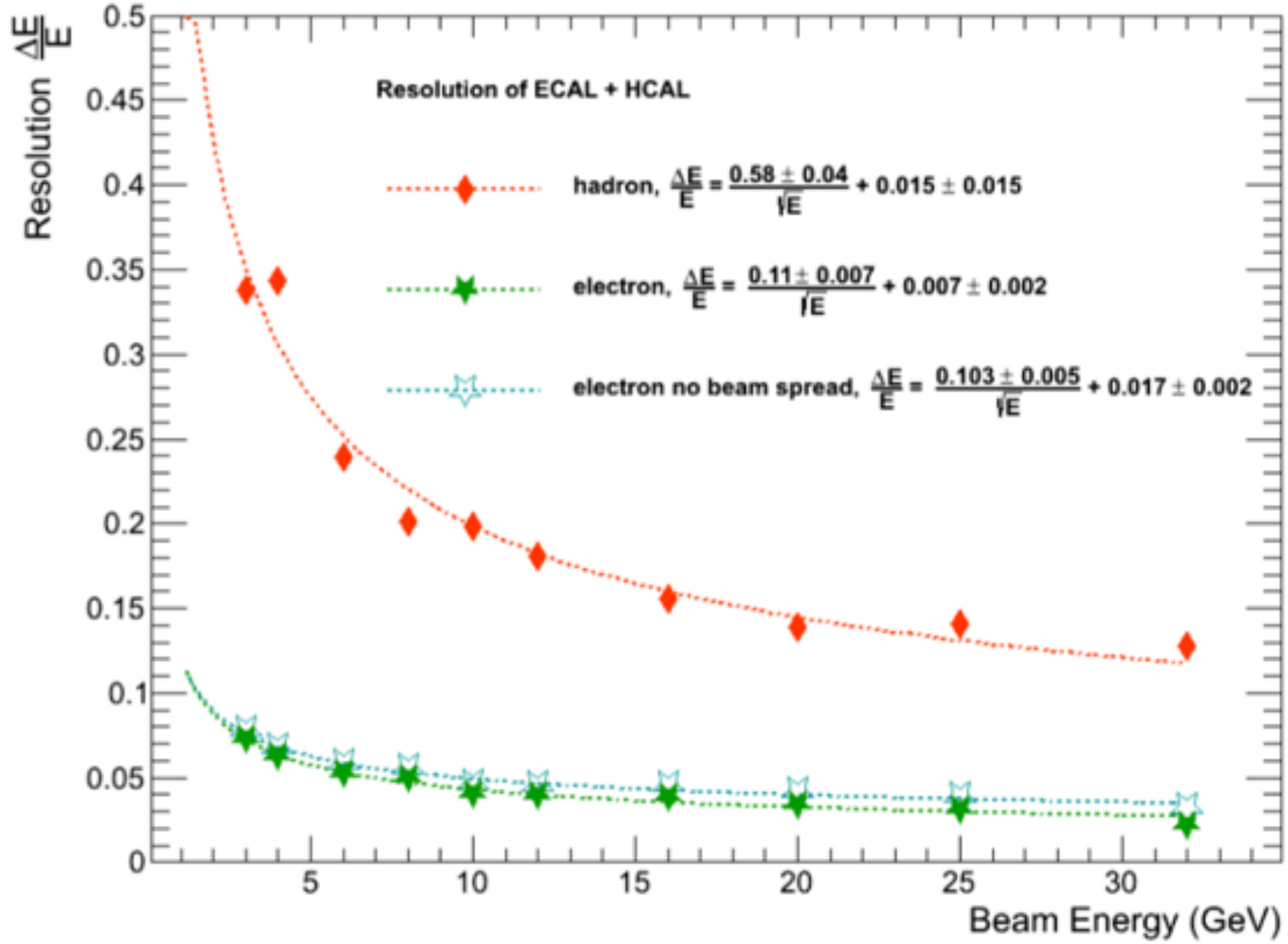
was: W-powder EM-cal (sim.)

now: re-use PHENIX eCAL (cost)

new HCAL, based on
STAR/UCLA-EIC R&D

STAR FCS+FTS upgrade





was: W-powder EM-cal

now: re-use PHENIX eCAL — 0.6M$, incl. overhead and contingency

new HCAL, based on STAR-EIC R&D — 1.4M$, incl. overhead and contingency