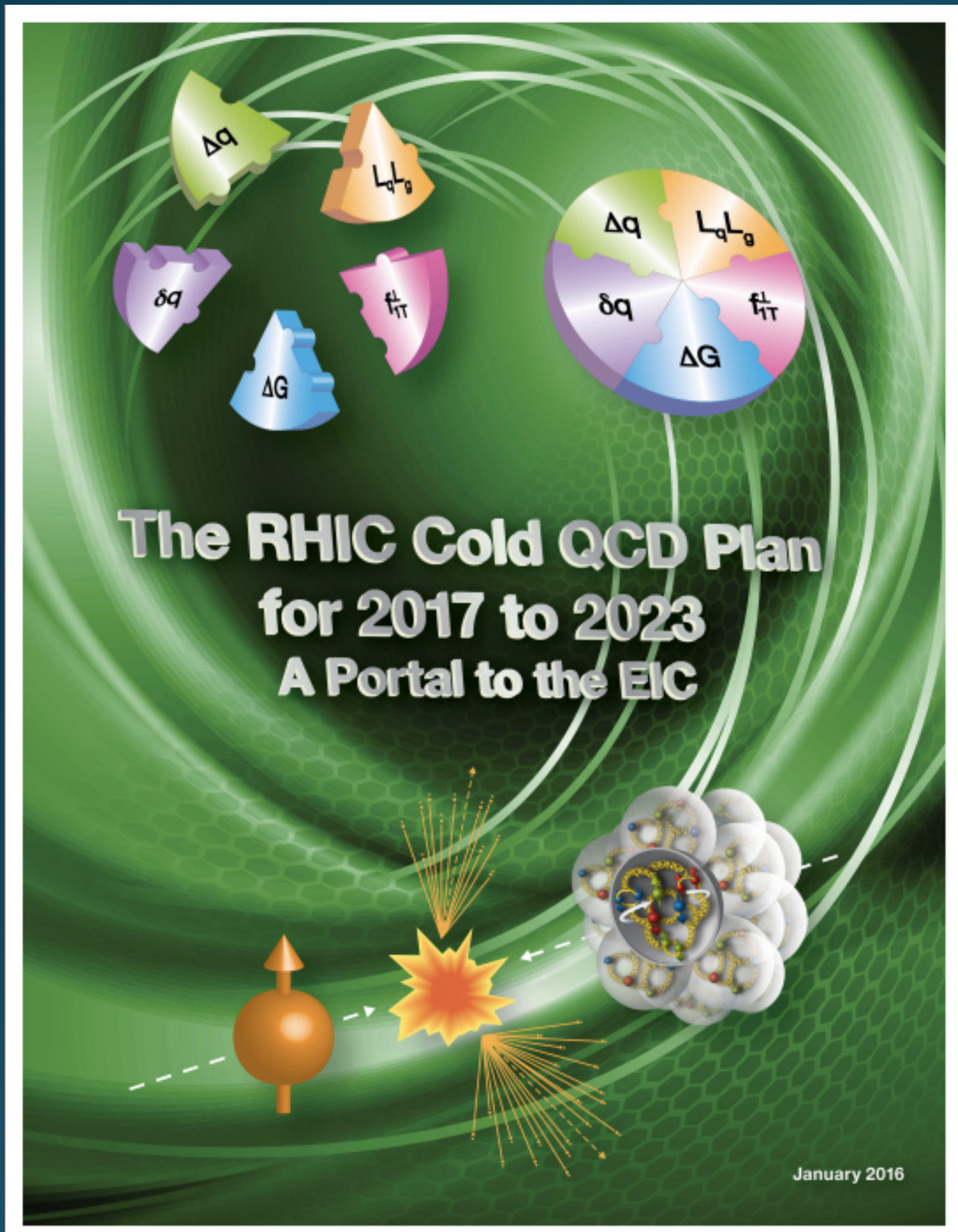
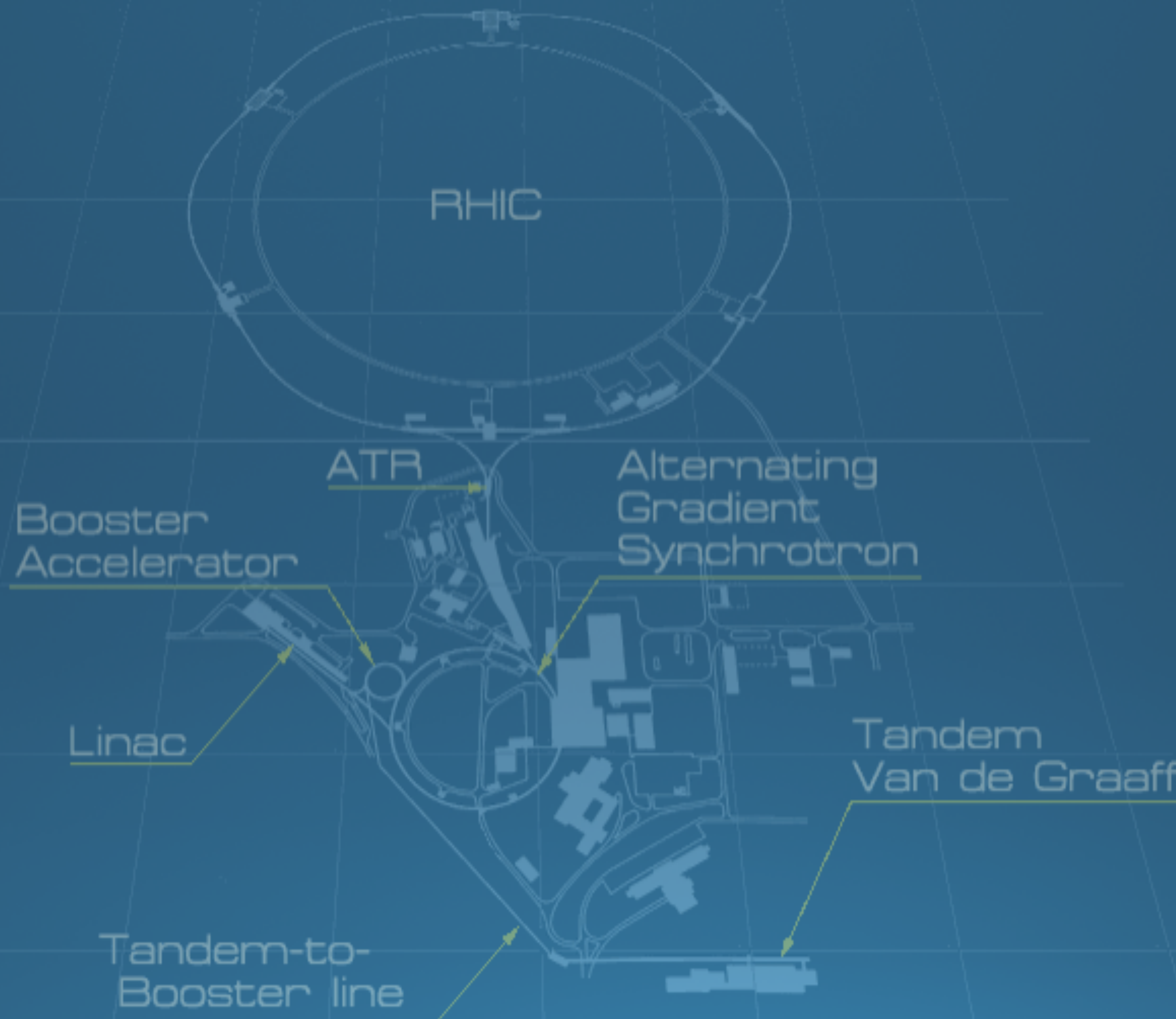
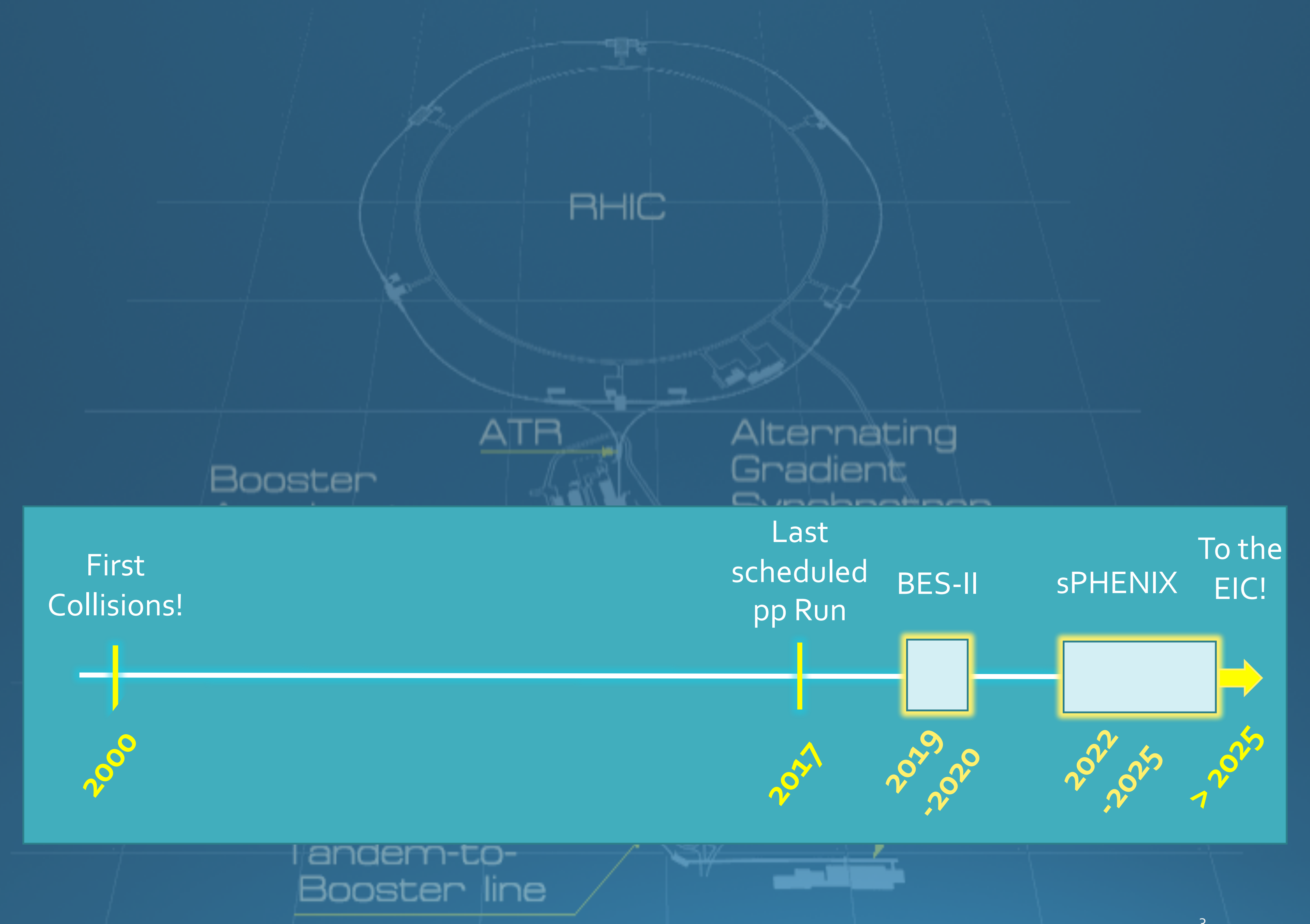


Renee Fatemi

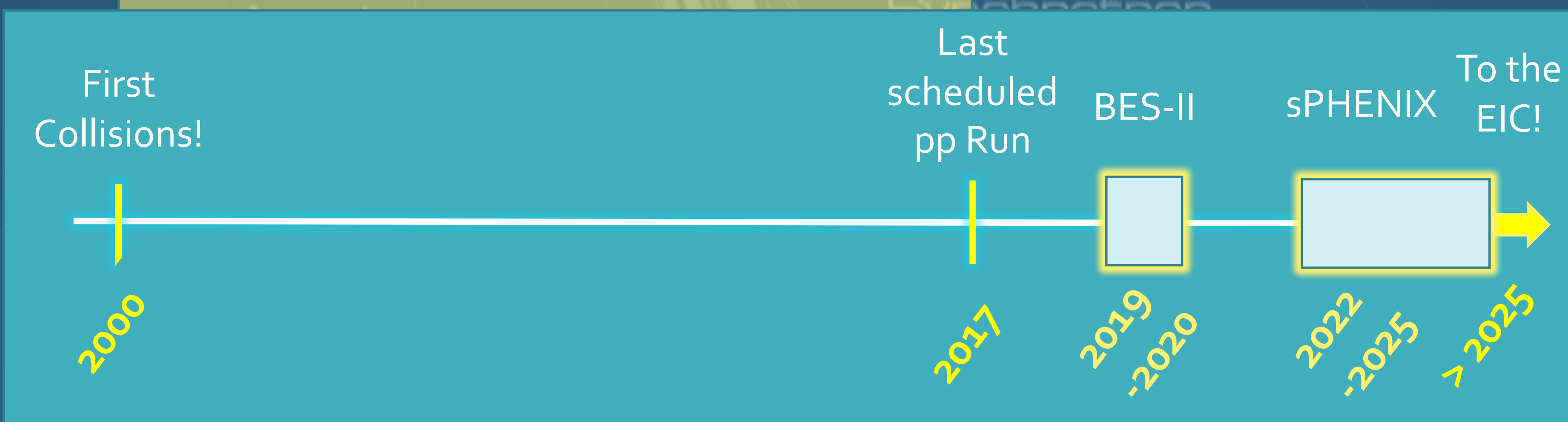
UK
UNIVERSITY OF
KENTUCKY

September 27th, 2016


RHIC
ATR
Alternating Gradient Synchrotron
Booster Accelerator
Linac
Tandem Van de Graaff
Tandem-to-Booster line


RHIC
ATR
Booster
Alternating
Gradient
Booster line
First Collisions!
Last scheduled pp Run
BES-II
sPHENIX
To the EIC!
2000
2017
2019 -2020
2022 -2025
> 2025

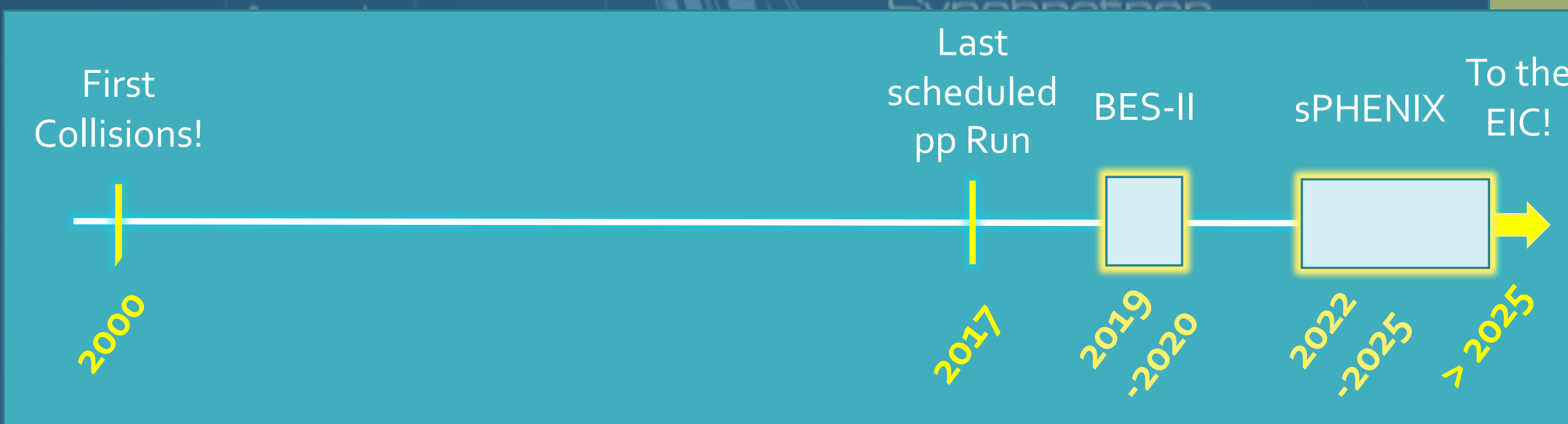
Extremely productive time for RHIC!



This is where we are coming from…

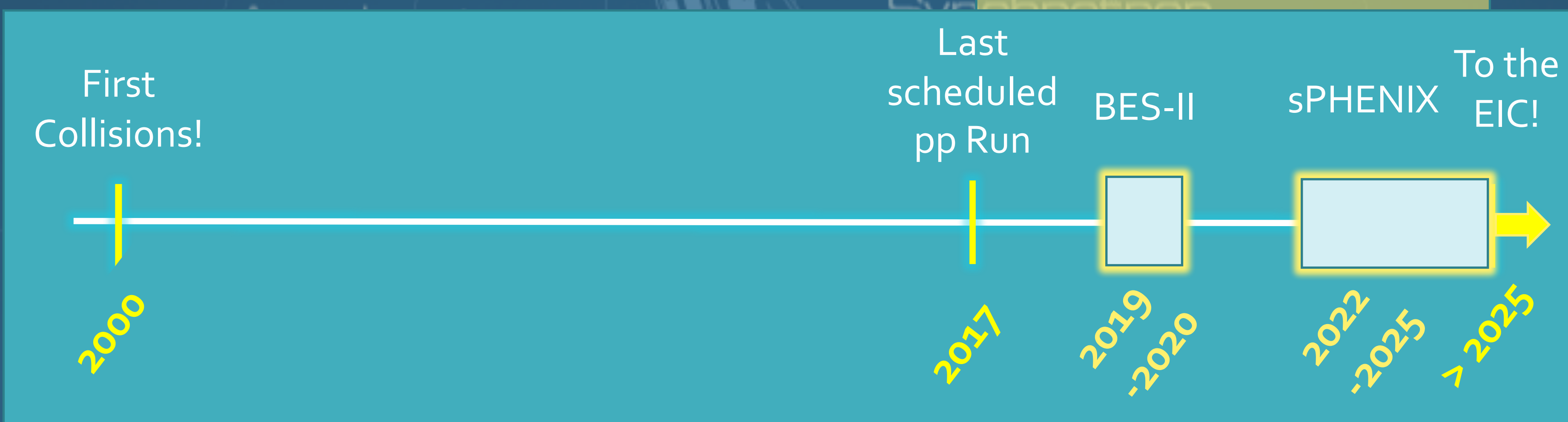
"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB."

- LRP recommendation III



This is where we want to go!

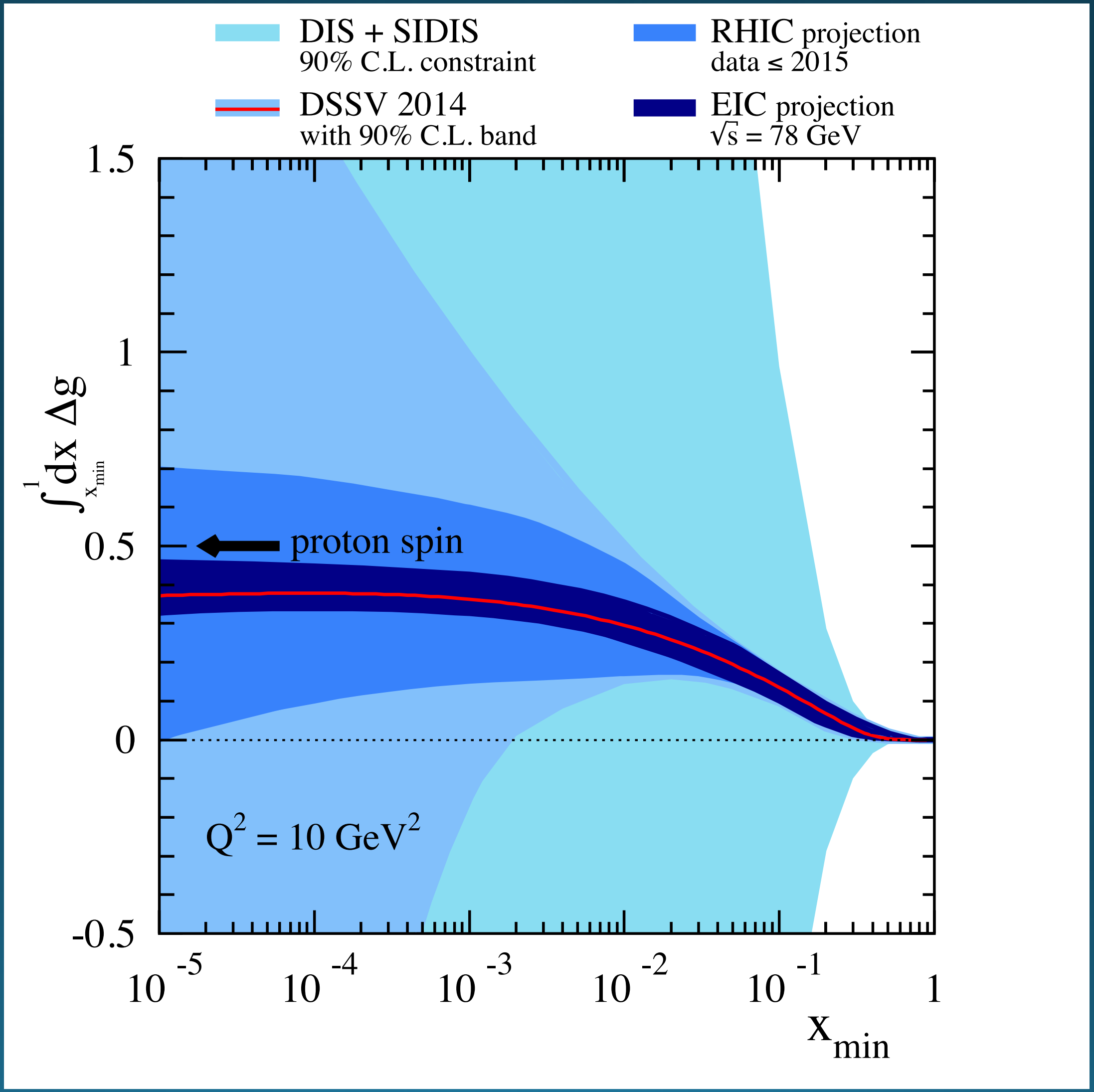
How can we best utilize RHIC in the period leading up to the EIC?



How do we get there?

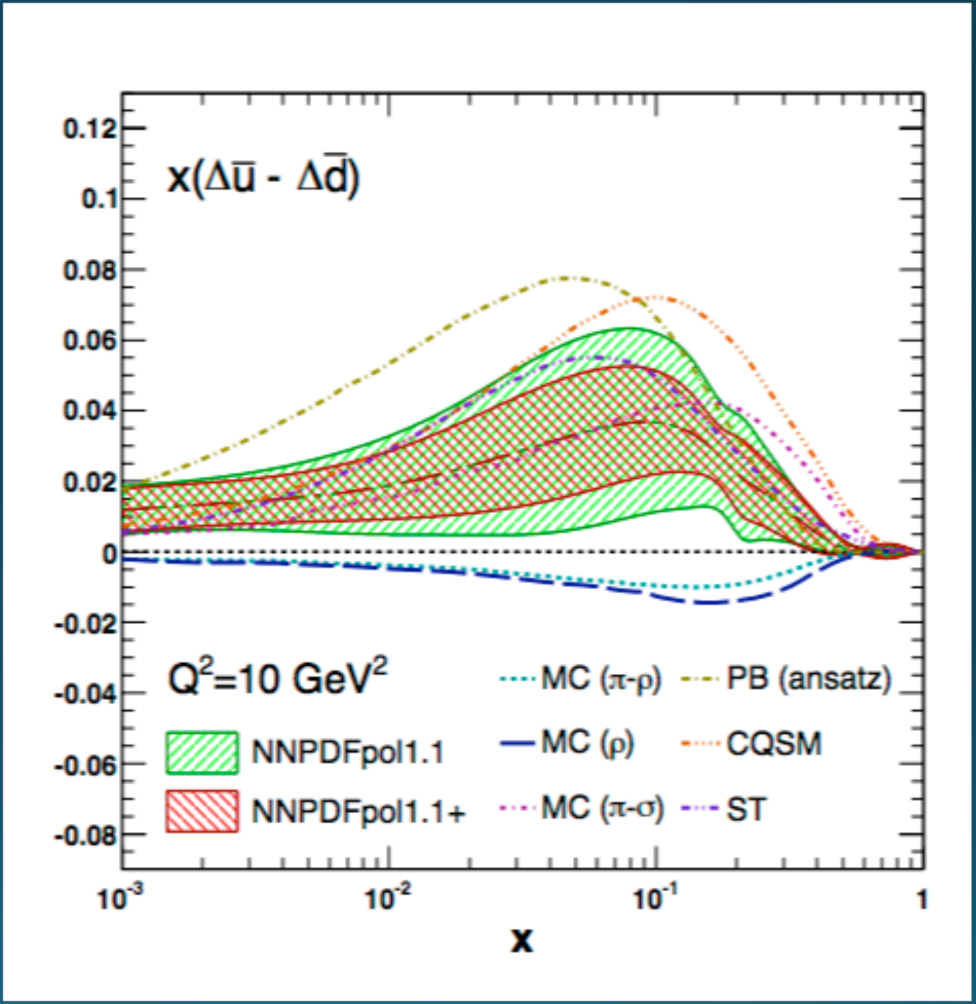
RHIC SPIN HIGHLIGHTS

First indication of a non-zero gluon spin in the Proton!



DSSV Collaboration arXiv:1602.03922

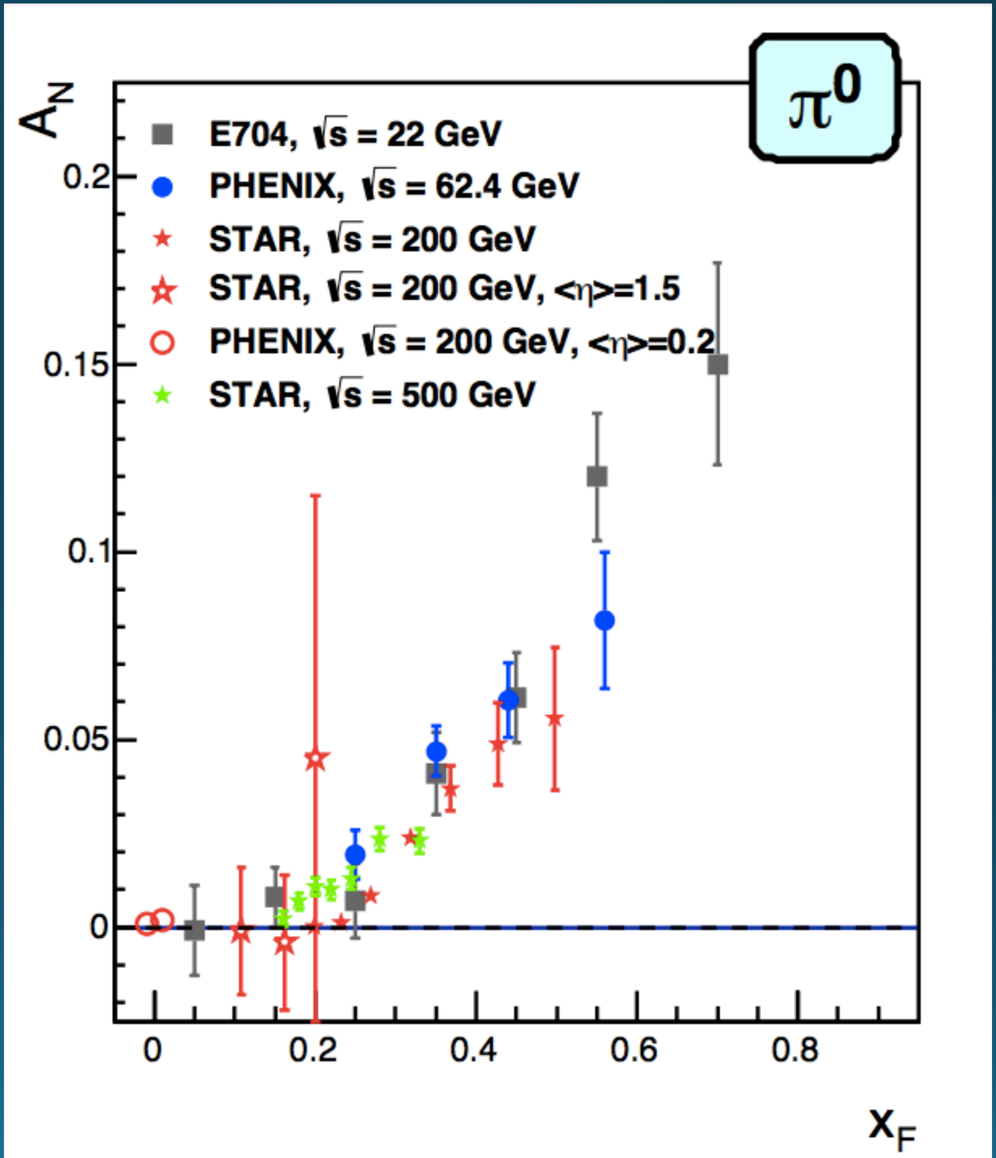
First significant indication of flavor symmetry breaking in the light polarized sea.



NNPDF Collaboration, Nucl. Phys. B887 276 (2014)

RHIC SPIN HIGHLIGHTS

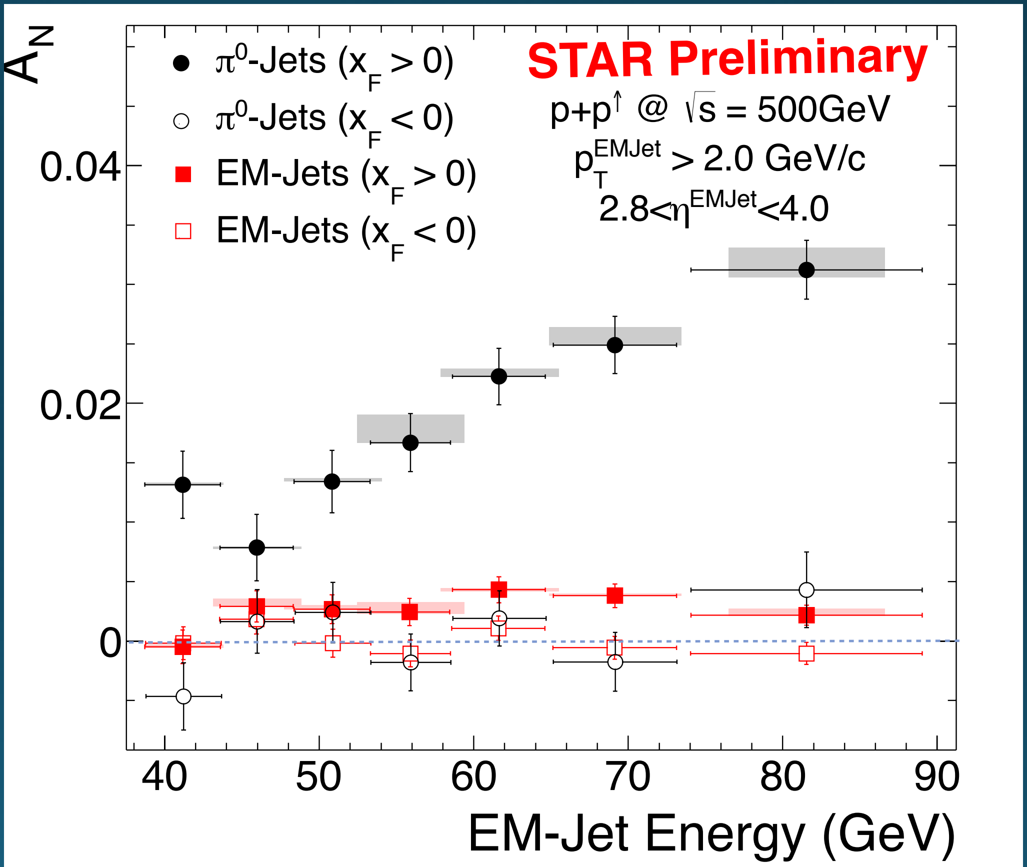
Large transverse single spin asymmetries persist at high center of mass energies



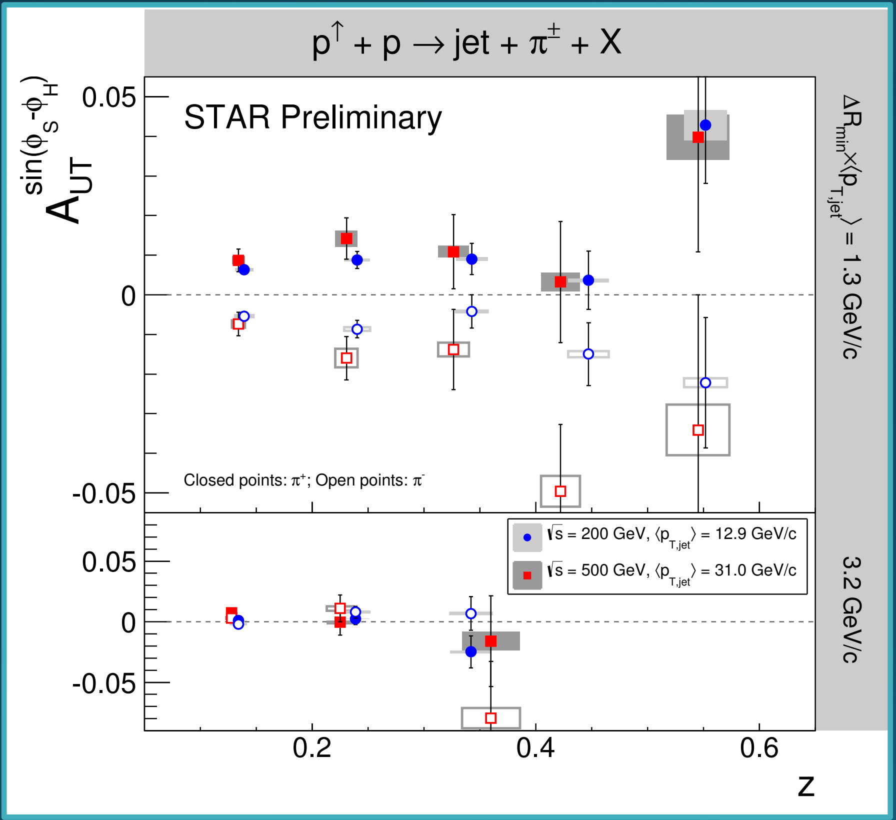
RHIC SPIN HIGHLIGHTS

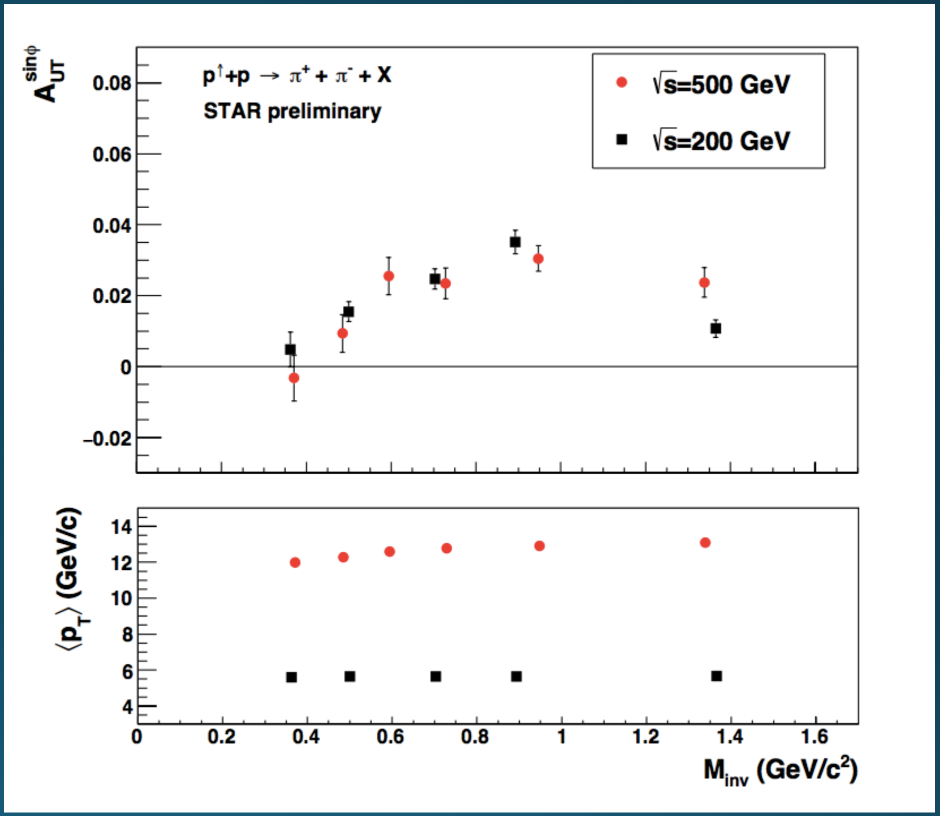
Large transverse single spin asymmetries persist at high center of mass energies

...and **do not** appear to originate from 2-2 scattering.



RHIC SPIN HIGHLIGHTS

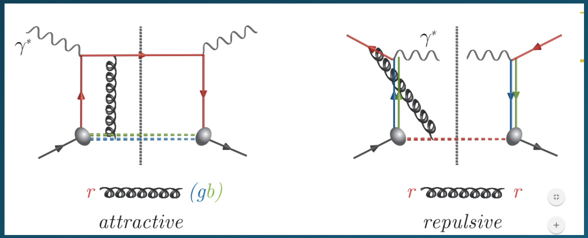


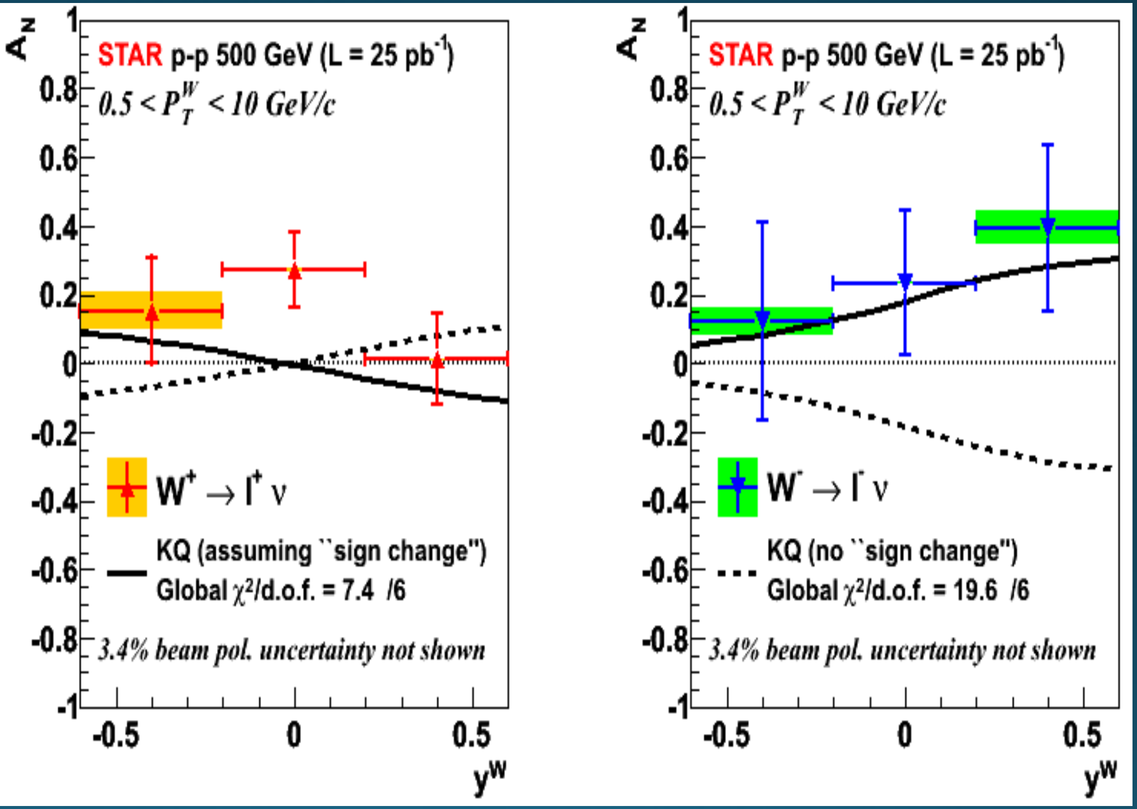


First significant asymmetries sensitive to transversity measured in hadronic collisions!

RHIC SPIN HIGHLIGHTS

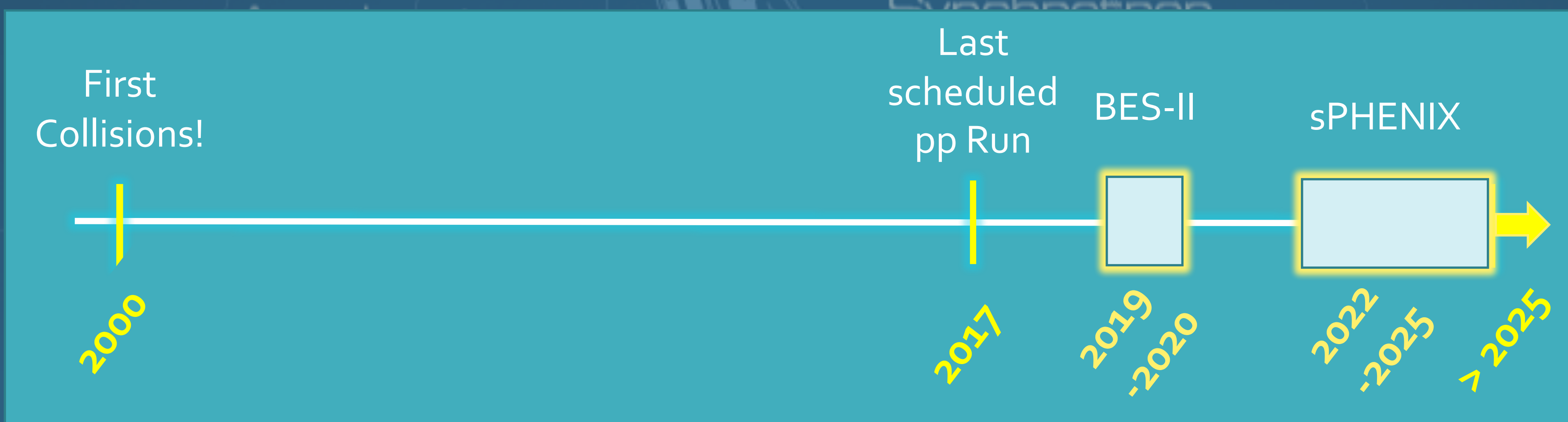
First measurements of the predicted **Sivers' sign change**.





What are the opportunities for additional running before an EIC?

- 2017 - 12 weeks at 500 GeV approved by PAC
- 2021? - PAC encouraged collaborations and BNL to consider additional pp/pA running during the time between BES-II and the turn on of sPHENIX
- 2023 - 8 weeks of transversely polarized pp at 200 GeV
- 2023 - 8 weeks each of transversely polarized p+Al and p+ Au at 200 GeV



What are the most pressing questions to answer during this time?

	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	A_N for γ, $W^{\pm}$, Z^0, DY	A_N^{DY}: Postshower to FMS@STAR
				Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3	$A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets	**None**
				First look at GPD *Eg*	A_{UT} for J/Ψ in UPC	**None**
	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.
				evolution of ETQS fct.	A_N for γ	**None**
				properties and nature of the diffractive exchange in p+p collisions.	A_N for diffractive events	**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	R_{pAu} direct photons and DY	R_{pAu}(DY):Yes Forward instrum.
				Nuclear dependence of TMDs and nFF	$A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF	**None**
				Clear signatures for Saturation	Dihadrons, γ-jet, h-jet, diffraction	Yes Forward instrum.
	2023	$p^{\uparrow}$Al @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF,	R_{pAl}: direct photons and DY	R_{pAl}(DY): Yes Forward instrum.
				A-dependence of TMDs and nFF	$A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF	**None**
				A-dependence for Saturation	Dihadrons, γ-jet, h-jet, diffraction	Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high *x*	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Yes Forward instrum.
				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**
	202X	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	*Δg(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.

Selected Topics Presented

See Lajoie's fsPHENIX talk for additional discussion

	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 [illegible]	A_N for γ, $W^{\pm}$, [illegible] [illegible] $A_{UT}^{\sin(\phi_s-\phi_h)}$ modul[illegible] [illegible]ons of $h^{\pm}$ in jets, $A^{\sin}$ [illegible] jets A_{UT} fo[illegible] J/ψ [illegible] UPC	A_N^{DY}: Postshow[illegible] to FMS@[illegible] **None** **None**
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving [illegible] la[illegible] A_N [illegible]gh x_F and η [illegible]olu[illegible]on of ETQS fct. [illegible]pert[illegible]s a[illegible] n[illegible]e of the diffrac[illegible]ve [illegible]x[illegible]nge in p[illegible]p collisi[illegible]s.	A_N [illegible]r [illegible]ged 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	[illegible]hat is [illegible] nature of the initial [illegible] [illegible]nd hadronization in nuc[illegible]ar [illegible]is[illegible]ns N[illegible]c[illegible]ar [illegible]endence 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.
	20[illegible]	[illegible]p Al @ 200	[illegible]2[illegible]p[illegible] [illegible] 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	[illegible]2X	$p^{\uparrow}p$ @ 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.

RUN 17

Lumi : 400 pb^{-1}
Species : proton+proton
Spin : Transverse + Transverse
$\sqrt{s}$: 500 GeV

PHYSICS OPPORTUNITIES:

i. Tests of non-universality of Sivers function and transverse momentum dependent (TMD) factorization

ii. Collect critical experimental input on TMD evolution

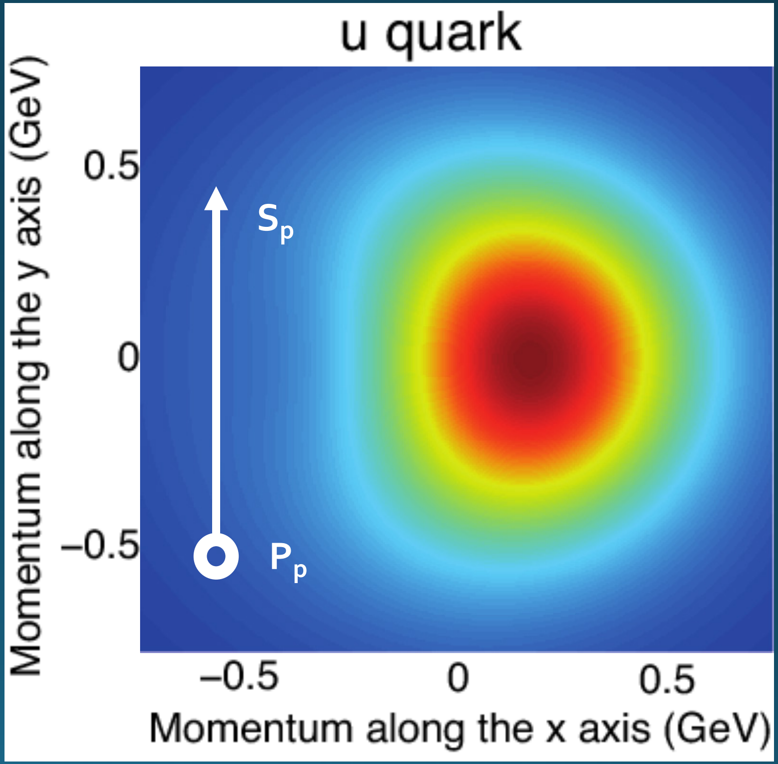
iii. Measure virtually unconstrained sea quark Sivers functions

iv. Verify relationship between TMD and twist-3 observables

v. Provide access to transversity, Collins fragmentation functions and linear gluon polarization

Transverse Momentum Distributions

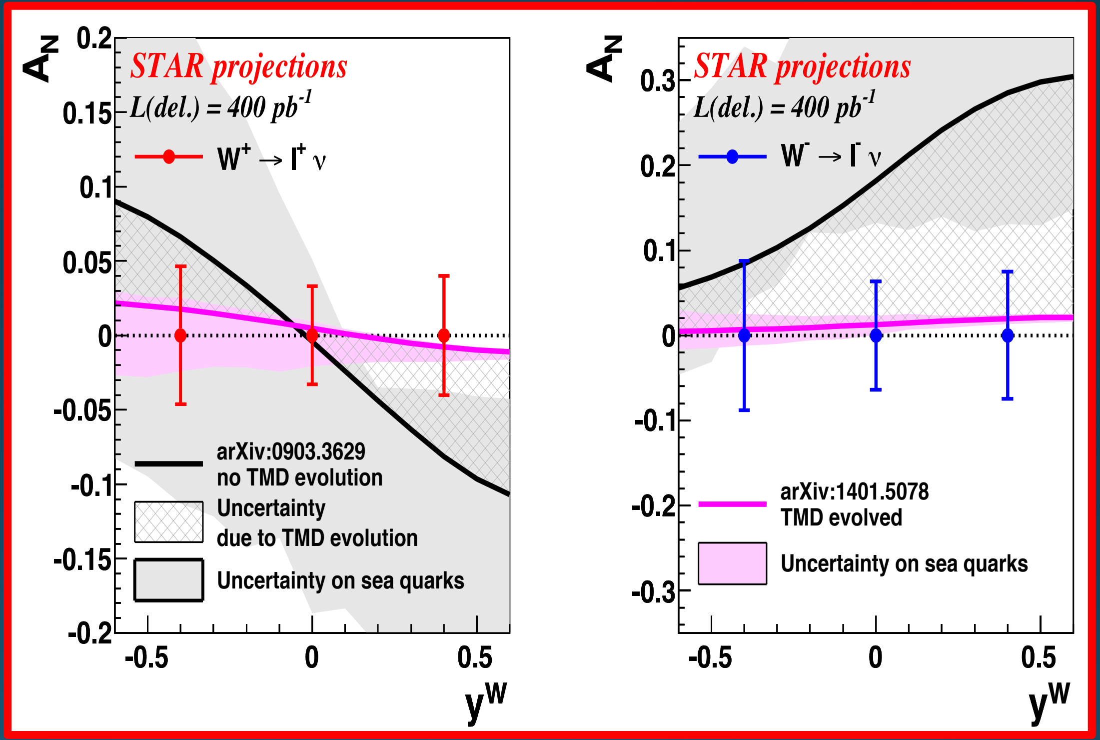
- Expand traditional 1D momentum PDF's ⇨ 3D !
- Correlations between proton spin and parton transverse momentum are sensitive to orbital angular momentum. Effects are encapsulated in a PDF called the **Sivers** function.
- Theoretical efforts initially driven by QCD spin community but are essential in particle physics as well, for example in describing Higgs production.
- As in collinear case, interpretation of data rests on robustness of the theoretical framework and experimental tests of **factorization** and **evolution**.



arXiv:1212.1701

TMD Factorization and Evolution

- RHIC will test TMD factorization and evolution via measurements of the single spin asymmetry A_{UT} of reconstructed W^+, W^- and Z^o.
- Asymmetries also provide new constraints on sea-quark Sivers functions.

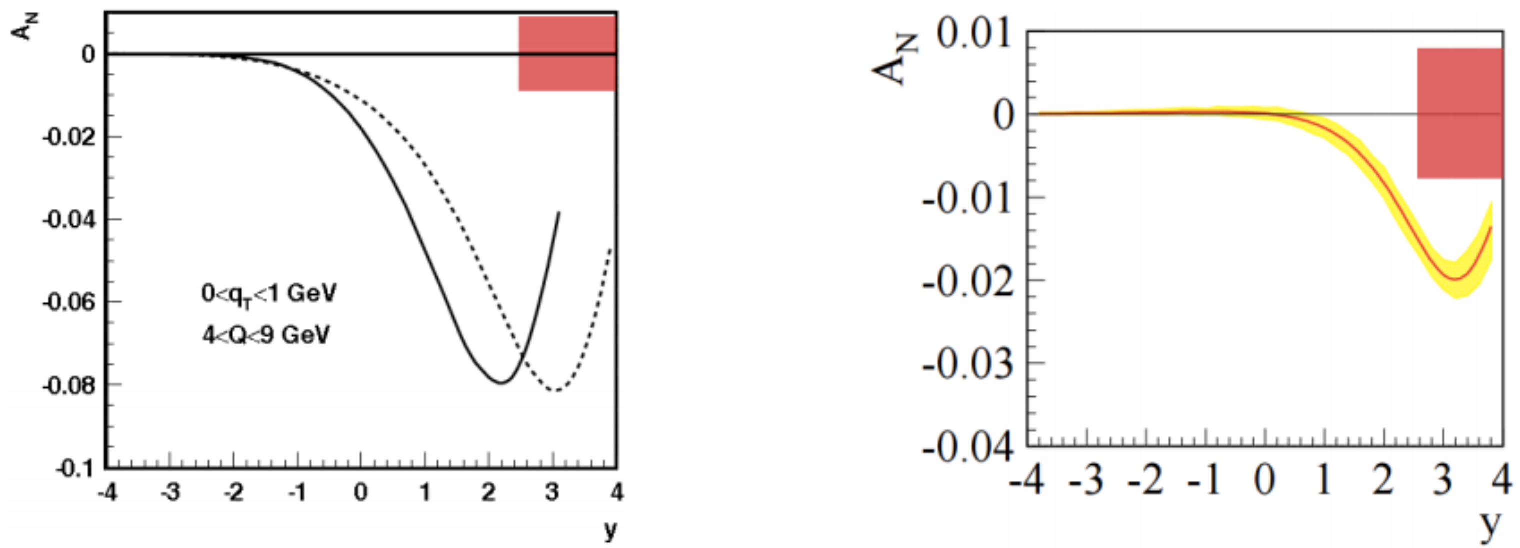


DETECTOR: EMCal + mid-rapidity charge sign discrimination. Requires wide acceptance of soft hadrons for full W reconstruction.

TMD Factorization and Evolution

- RHIC will also measure forward Drell-Yan e+e- pairs for $2.5 < \eta < 4.0$
- The orange square is the statistical uncertainty achievable with 400 pb^{-1}. The theoretical curves are before and after including possible evolution.

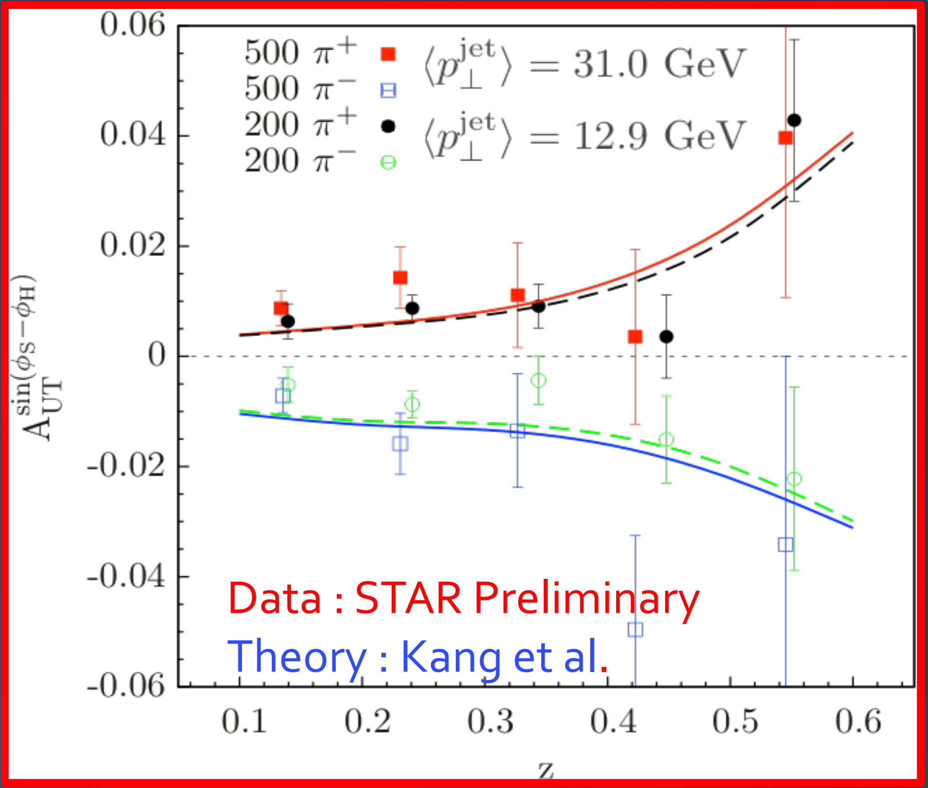
STAR FMS



DETECTOR: Forward EMCal + pre/post shower for QCD background suppression.

TMD Universality and Evolution

- TMD's may also be studied in fragmentation. The **Collins FF** encapsulates the correlation between the transverse spin of the quark and the transverse momentum of the fragmentation hadrons.
- **The Collins function is accessible the single spin asymmetry A_{UT} of the azimuthal distribution of charged pions, kaons and protons inside of a jet.**
- **Measurements of A_{UT} will test the universality and evolution of the Collins FF.**



With 400 pb^{-1} errors at 500 GeV ≈ 200 GeV

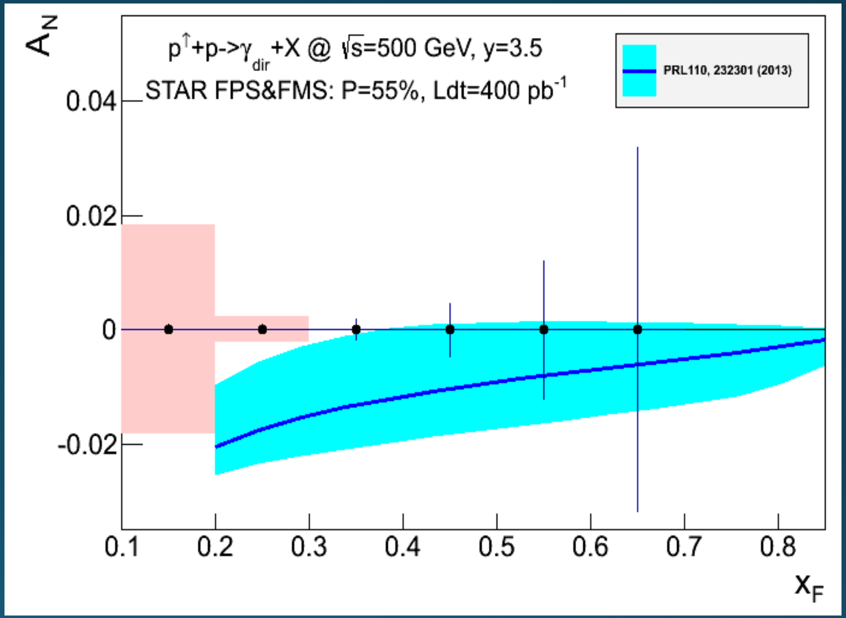
DETECTOR: mid-rapidity pion, kaon and proton PID, charged and neutral particle detection for jet reconstruction and tracker for vertexing.

Sign Change and Evolution in Twist-3 Framework

- The Sivers TMD has a twist-3 analogue - an initial state q-g-q correlator .
- Twist-3 and TMD frameworks encapsulate the same physics and are related via :

  $T_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS}$

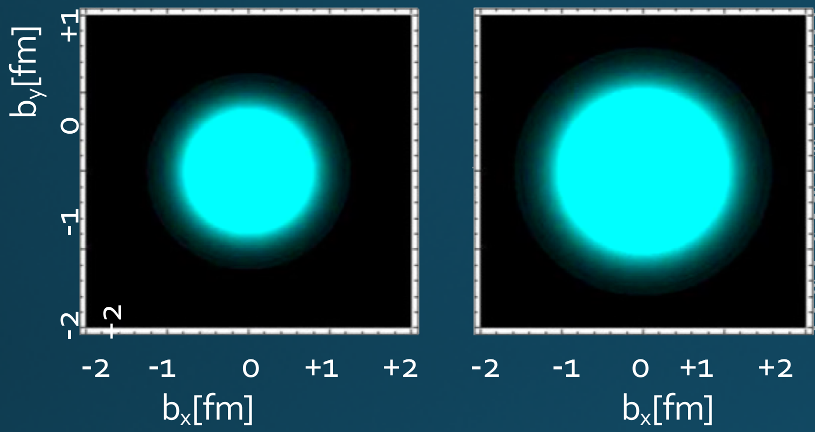
- Measurements of **A_{UT} of direct photons** for 2.5 < n < 4 will provide a direct test of this relationship!



- 200 GeV measurement made in run 15 will provide information on twist-3 evolution.

DETECTOR: Forward EMCal + pre-shower

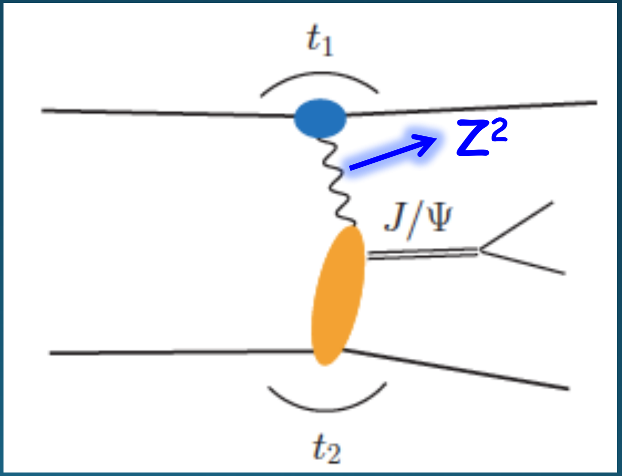
Generalized Parton Distributions



arXiv:1212.1701

GPD's provide a snapshot of the spatial distributions, as a function of momentum fraction, of the quarks and gluons inside the proton.

- RHIC can access the GPD E function for gluons via measurements of **A_{UT}** of **J/ψ** in ultra-peripheral collisions.
- A significant asymmetry would be the **FIRST** sign of a non-zero GPD E_g.
- GPD E_g is sensitive to spin-orbit correlations and provides input on **angular momentum** component of the spin puzzle.



DETECTOR: EMCals to reconstruct mid-rapidity J/ψ and Roman pots to reconstruct elastically scattered proton

RUN 21?	
	Lumi : 1 fb^{-1}
	Species : proton+proton
	Spin : T+T or L+L
	$\sqrt{s}$: 500 GeV

PHYSICS OPPORTUNITIES:

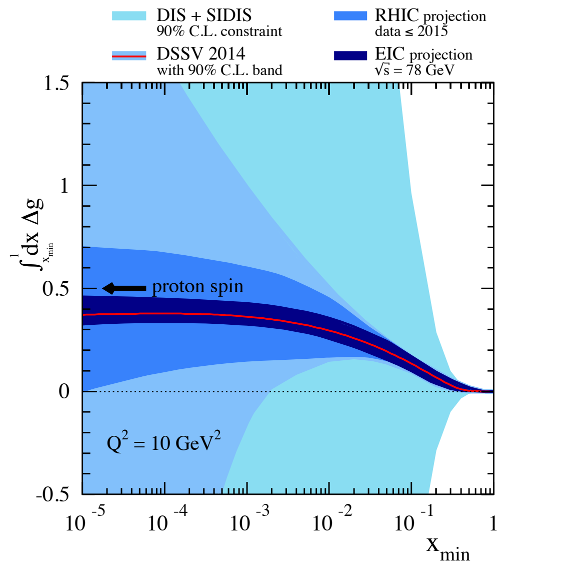
i. Reduce uncertainties on ΔG in low x (~10^{-3}) regime

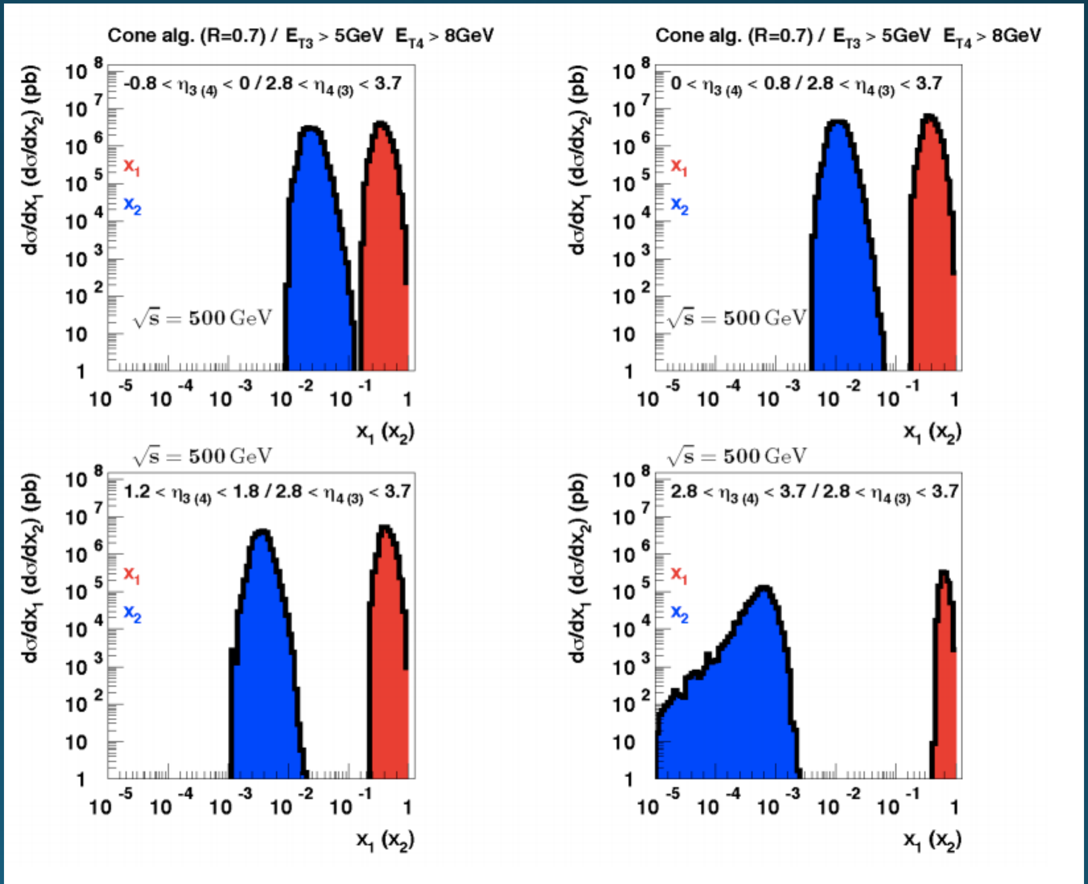
ii. Push Sivers, transversity and Collins measurements into high (>0.3) and low (~ 10^{-3}) regimes

iii. Reduce uncertainties on ALL observables in run 17 by factor of2, allowing for a quantitative test on the limits of universality and factorization in e+p and p+p collisions.

Accessing ΔG at lower X

Di jet reconstruction at mid-rapidity and forward regions will provide access to low x regime.

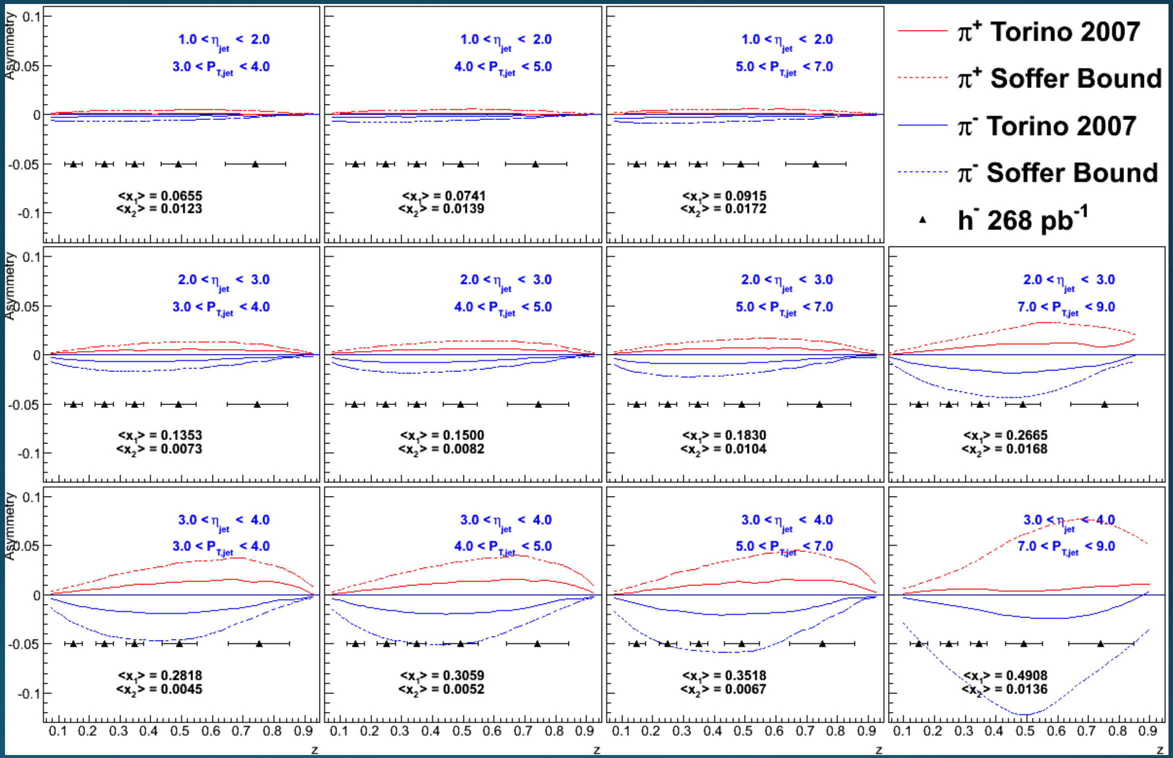




DETECTOR: charged and neutral particle detection for jet reconstruction and tracking for vertexing.

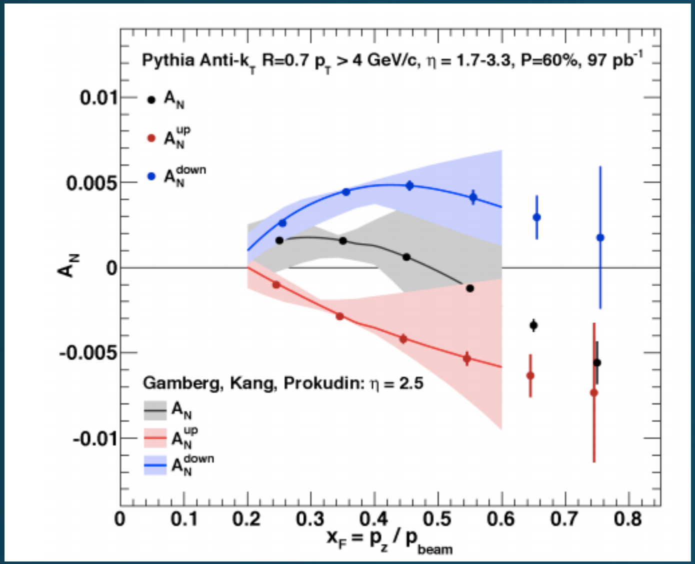
A_{UT} of Charged Hadrons in Forward Jets

- Mid-rapidity jet A_{UT} samples an x range of 0.02-0.3.
- RHIC could push sensitivity to high x (> 0.3) as well as lower x (~10^{-3}) by reconstructing jets and charged hadrons (h^+/h^-) in the forward direction.
- Measurements of A_{UT} will test the universality and evolution of the Collins FF.



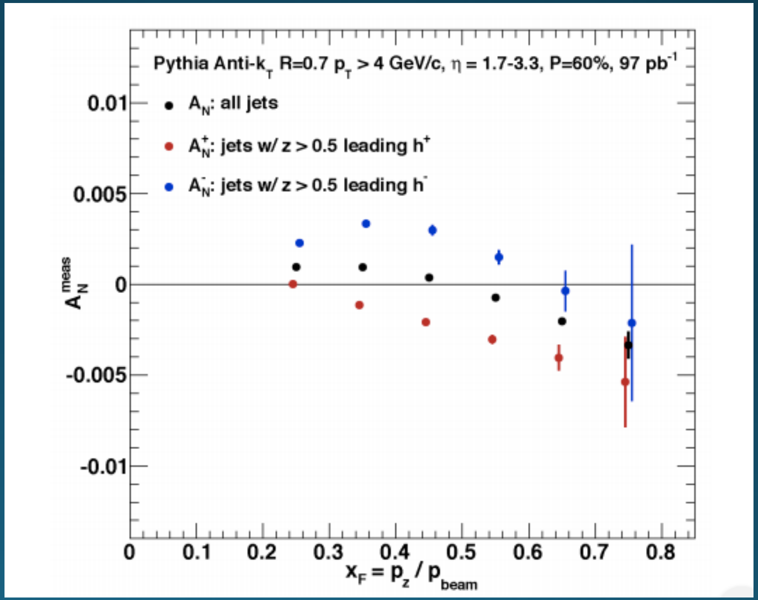
DETECTOR: Charged sign separation for h+/h- (no PID), charged and neutral particle detection for jet reconstruction and tracking for vertexing.

A_{UT} of Forward Jets with high z hadrons



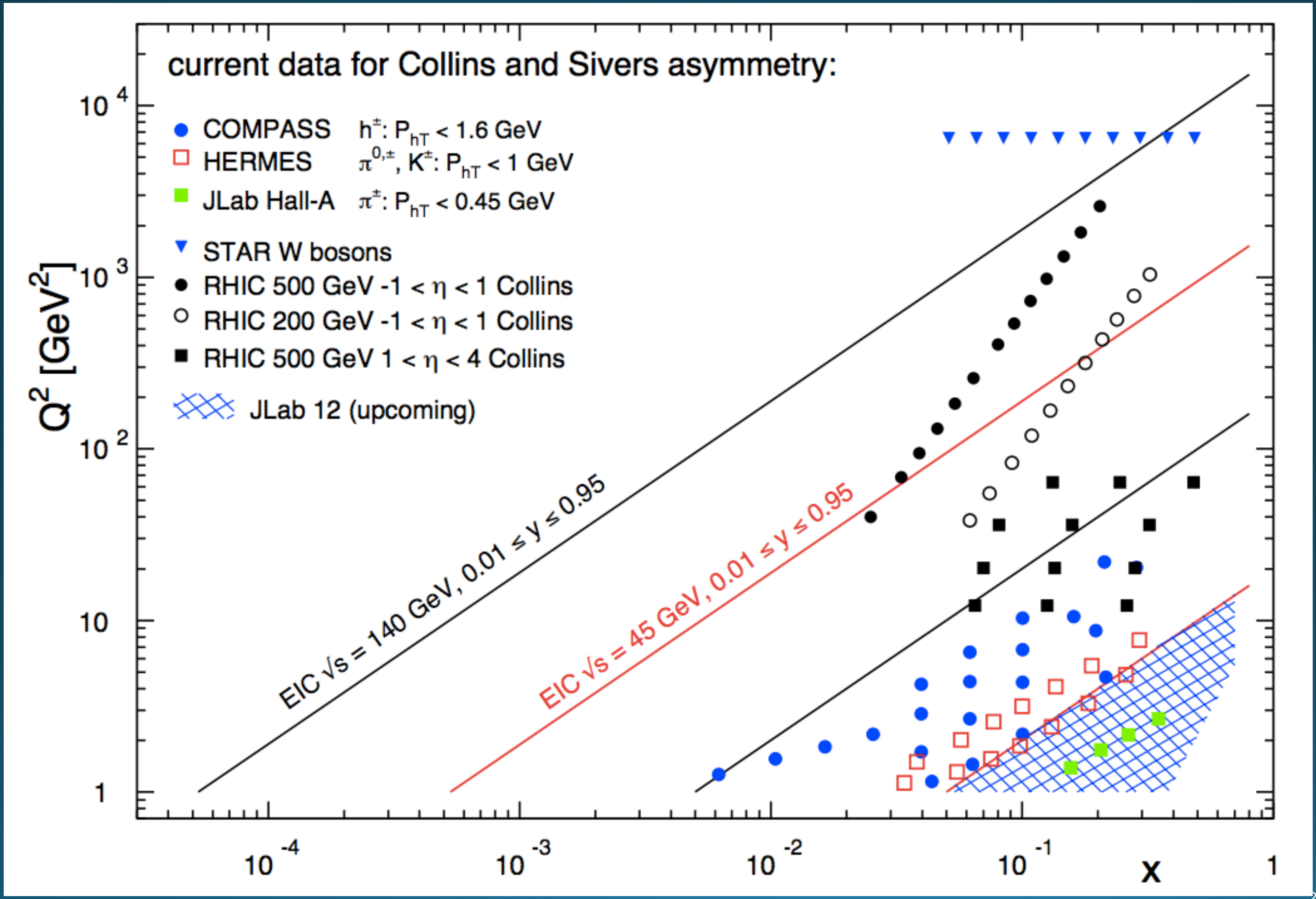
Jet A_{UT} is sensitive to twist-3 "Sivers-like" correlators, which are expected to be opposite sign for u and d quarks.

- Test of the relationship between twist-3 and TMD formalism
- Facilitates interpretation of the small inclusive jet A_{UT} measured by AnDY



DETECTOR: Charged sign separation for h+/h- (no PID), charged and neutral particle detection for jet reconstruction and tracking for vertexing.

Current and Projected TMD Data



RUN 23

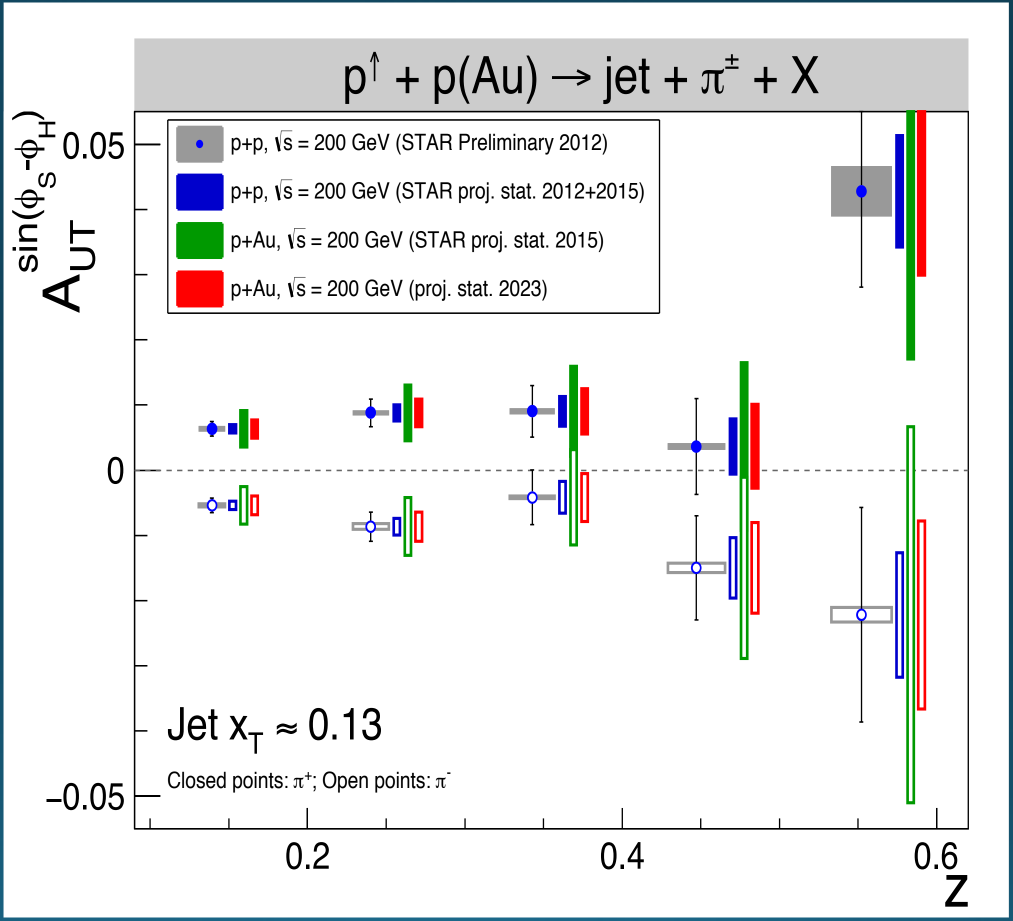
Lumi : 1.8 pb^{-1}
Species : proton+ A
Spin : Transverse + unpolarized
$\sqrt{s}$: 200 GeV

PHYSICS OPPORTUNITES:

i. Study A dependence of spin dependent fragmentation in nuclear matter

Fragmentation Properties in Nuclei

- Extend current hadron in jet AUT analysis from p+p to p+A.
- First dataset collected on p+Au in 2015.
- Run in 2023 will permit the study of A-dependence.



DETECTOR: PID, charged and neutral particle detection for jet reconstruction and tracking for vertexing.

RUN 23	Lumi : 300 pb^{-1} Species : proton+proton Spin : T+T $\sqrt{s}$: 200 GeV

PHYSICS OPPORTUNITES:

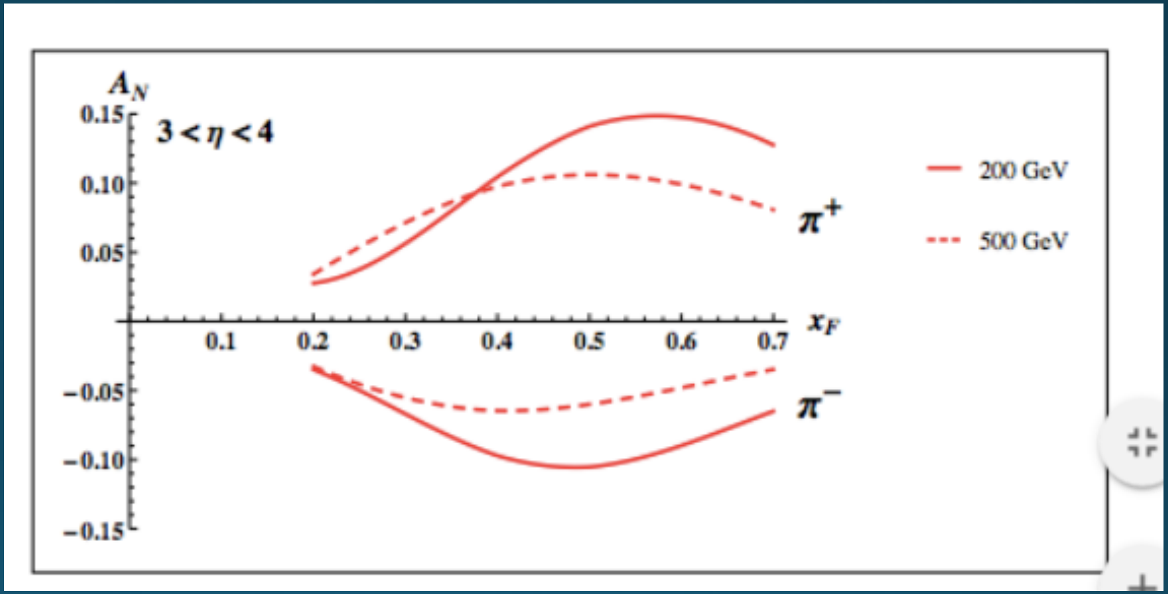
i. Isolate origin of the large forward single spin asymmetries.

ii. Study spin effects in Diffraction

Origin of Large Single Spin Asymmetries

- New work suggests that twist-3 FF could explain large forward pion A_N
- Predictions for charged hadrons at both 200 and 500 GeV in the forward region would help confirm the validity of this approach.

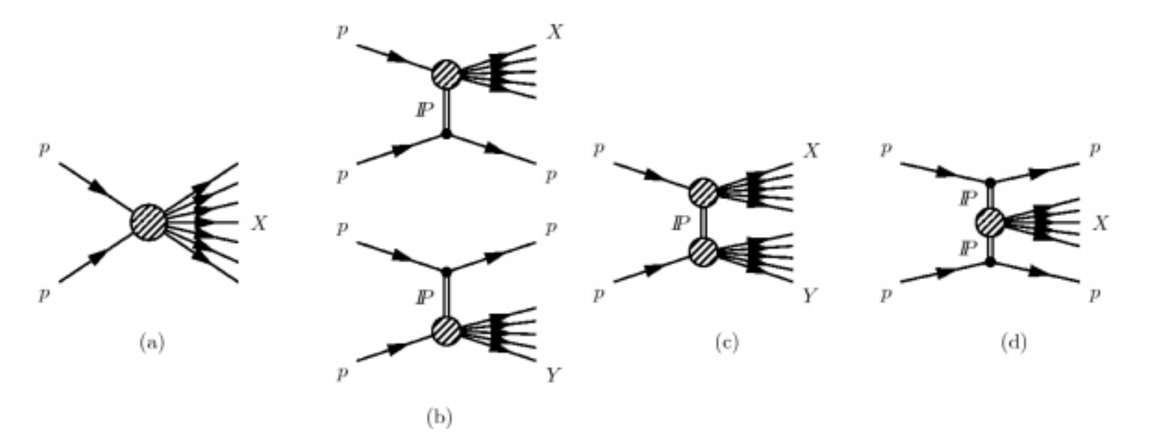
Phys. Rev. D 89 (2014) 111501



DETECTOR: Forward tracking with PID would be ideal. Charged sign separation for h+/h- would be sufficient for negative pions.

Origin of Large Single Spin Asymmetries

- If data taken in 2015 and 2017 reveals a large diffractive contribution to the SSA this opens a new area of study
- Motivates study of spin dependent diffraction via detection of rapidity-gap jet events.



DETECTOR: charged and neutral particle detection for jet reconstruction and tracking for vertexing. Roman Pots to detect protons.

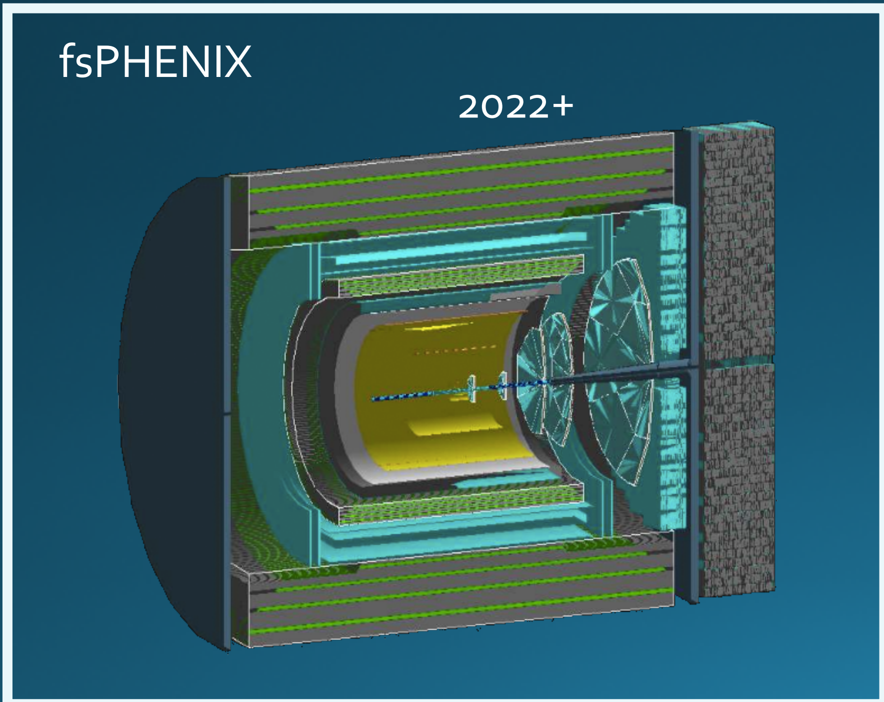
What upgrades are necessary?

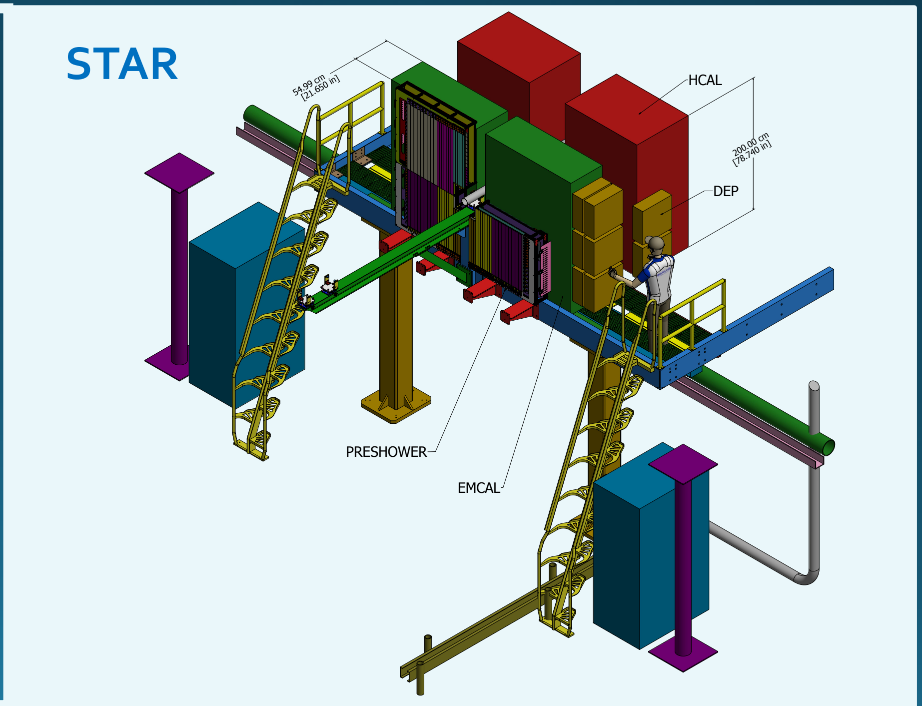
RUN 17 - Use standard STAR suite for mid-rapidity. Postshower upgrade for Forward Meson Spectrometer will be complete before spring running.

RUN 2021+

MID-RAPIDITY - Both STAR and sPHENIX can do jet reconstruction. STAR also has PID capabilities.

FORWARD -RAPIDITY - Both STAR and sPHENIX need additional Electromagnetic and Hadronic Calorimeters and tracking.



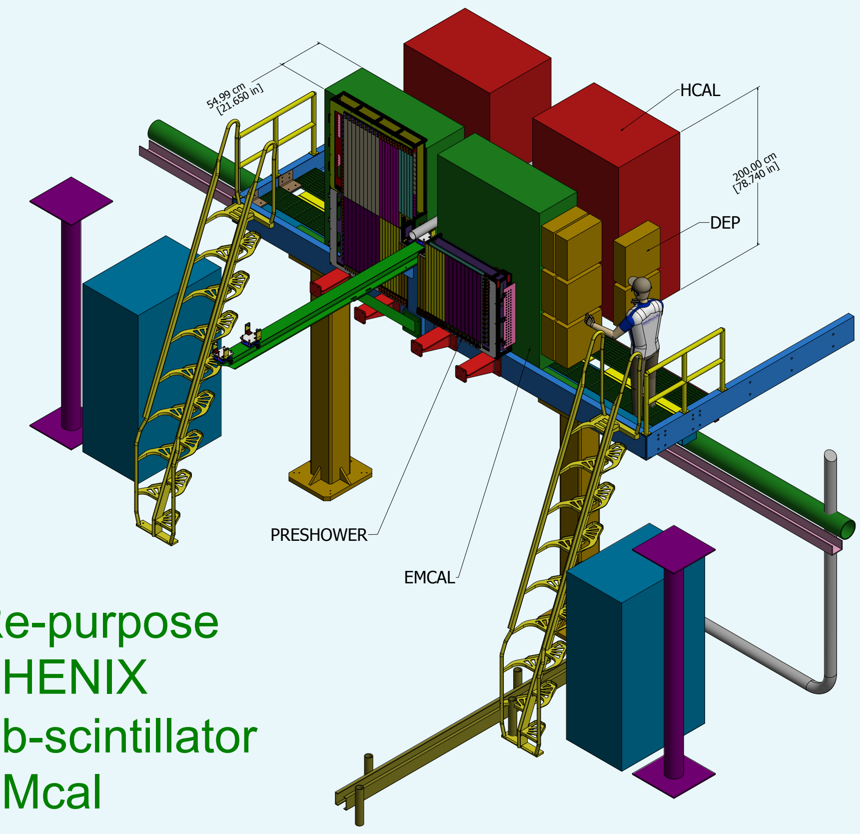


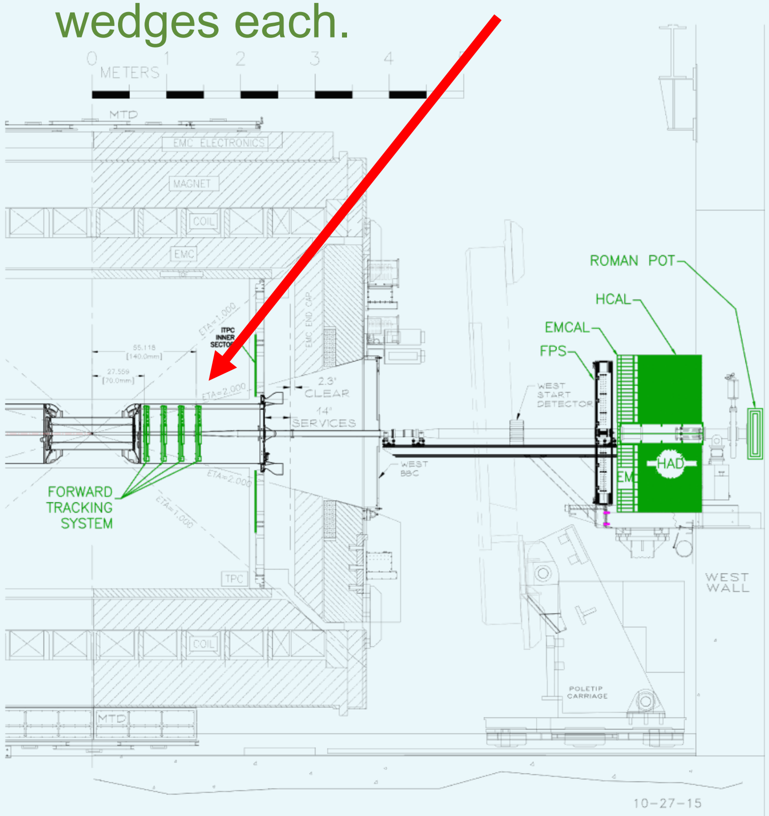
STAR Forward Calorimeter + Tracking Upgrade

Install in
forward region
2.3 > η > 4.0

4-interaction length
thick Pb-scintillator
plate HCAL

Four planes of silicon strip
detectors comprised of 12
wedges each.





Re-purpose
PHENIX
Pb-scintillator
EMcal

Designed to provide charge-sign
discrimination and vertex
determination.

Wrap-up

- The RHIC Spin Program has made significant contributions since first collisions in 2001. And there are more still in the pipeline!

- As recommended by the LRP, we should utilize the existing RHIC infrastructure to continue to explore the spin structure of the proton.
  i. Complete the measurements that can only be done at a p+p, p+A collider
  ii. Pursue measurements that will allow us to optimize the EIC program.
  iii. Keep the cold QCD community strong and engaged as we move towards an EIC.

- The RHIC Spin and cold QCD community has developed a plan to complete the RHIC mission arXiv: 1602.03922.

- Additional investments in detector upgrades are necessary.