Future Cold QCD at STAR
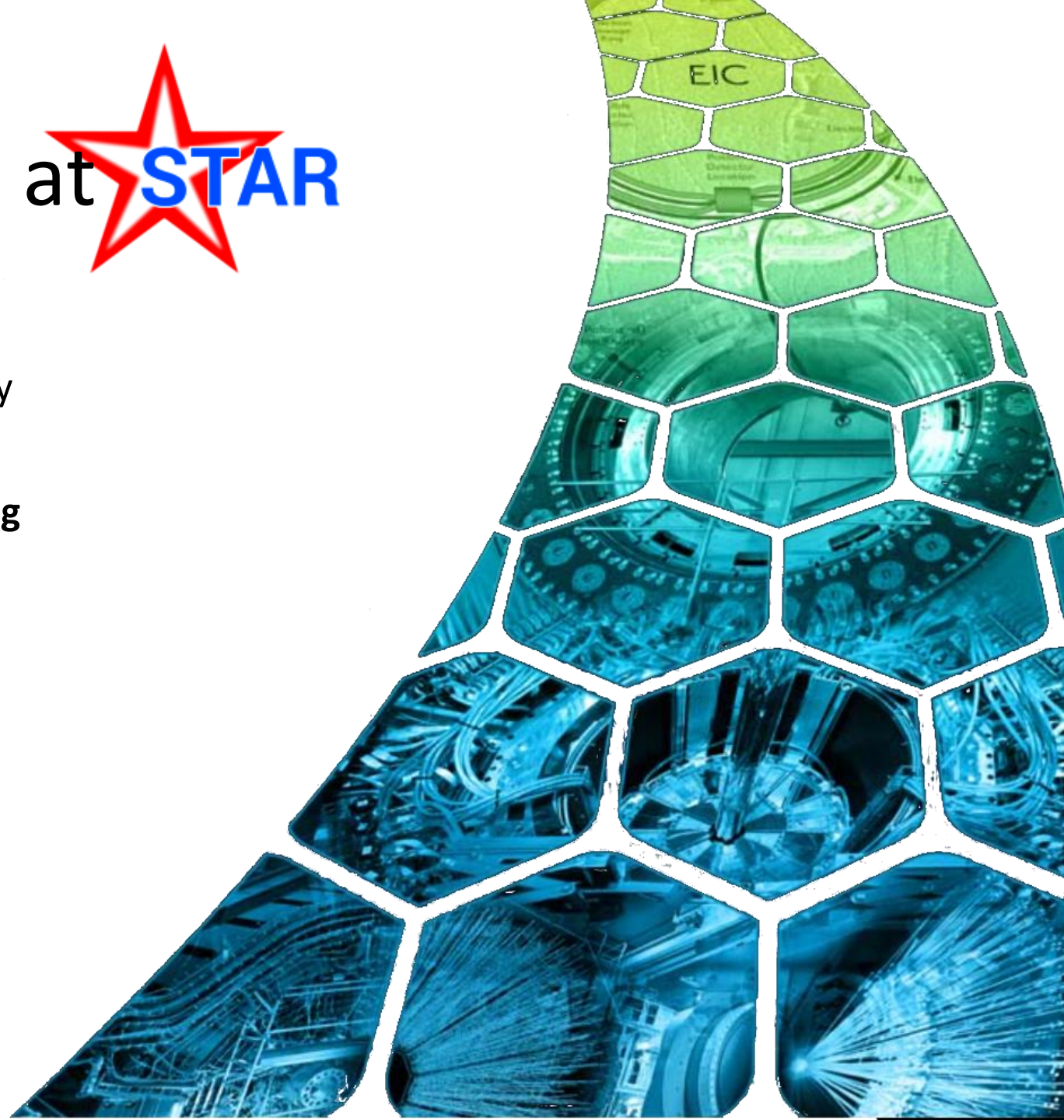
Oleg Eyser

Brookhaven National Laboratory
for the STAR Collaboration

RHIC/AGS Annual Users Meeting
June 7-10, 2022

Brookhaven
National Laboratory

Completing the RHIC Program

- Unique polarized $p + p$ / $p + A$ collisions

- RHIC Run 22: $p^{\uparrow} + p$ at $\sqrt{s} = 508$ GeV

  - STAR Forward Detector upgrade

- Plan for the remaining years: $\sqrt{s_{NN}} = 200$ GeV

  - $\text{Au} + \text{Au}$

  - $p^{\uparrow} + \text{Au}$

  - $p^{\uparrow} + p$

  Beam Use Request 2024
  Equal integrated luminosity per nucleon

- EIC starts after 2030

  - The full potential of the EIC relies on complementary probes
    → unique data from hadronic collisions

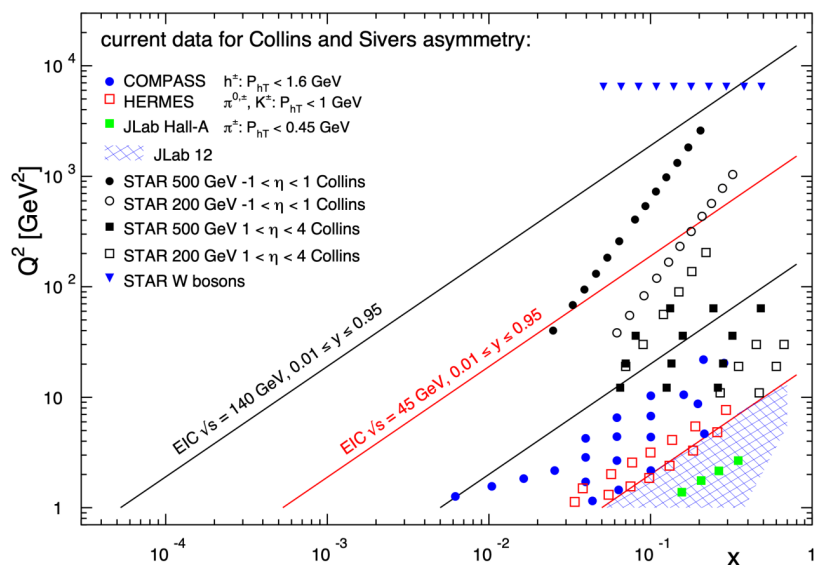The RHIC Cold QCD Plan for 2017 to 2023 A Portal to the EIC

January 2016

Physics Opportunities with STAR

- $\sqrt{s} = 200 - 510$ GeV

- Forward detector $2.5 < \eta < 4.0$

- Wide coverage $0.005 < x < 0.5$

- $x - Q^2$ range

- TMD parton distribution functions
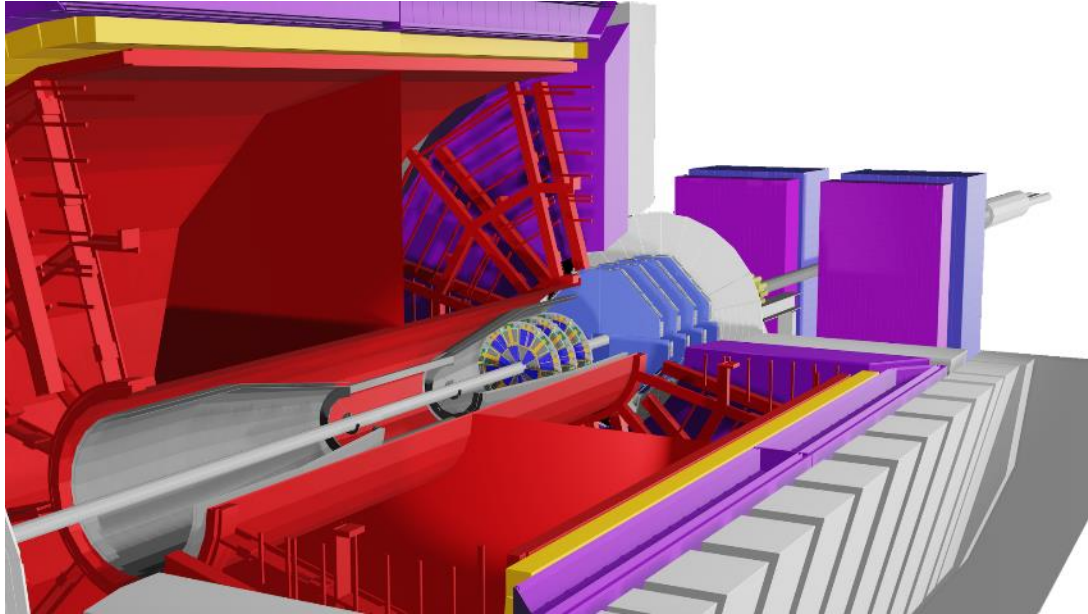
- Evolution effects

$p^\uparrow + \text{Au}$

$p^\uparrow + p$

$e + p^\uparrow$

- Non-linear parton dynamics

- Hadronization in heavy nuclei

- Factorization and universality

current data for Collins and Sivers asymmetry:

- COMPASS $h^\pm$: $P_{hT} < 1.6$ GeV
- HERMES $\pi^{0,\pm}$, $K^\pm$: $P_{hT} < 1$ GeV
- JLab Hall-A $\pi^\pm$: $P_{hT} < 0.45$ GeV
- JLab 12
- STAR 500 GeV $-1 < \eta < 1$ Collins
- STAR 200 GeV $-1 < \eta < 1$ Collins
- STAR 500 GeV $1 < \eta < 4$ Collins
- STAR 200 GeV $1 < \eta < 4$ Collins
- STAR W bosons

EIC $\sqrt{s}$ = 140 GeV, 0.01 ≤ y ≤ 0.95

EIC $\sqrt{s}$ = 45 GeV, 0.01 ≤ y ≤ 0.95

Q^2 [GeV^2]
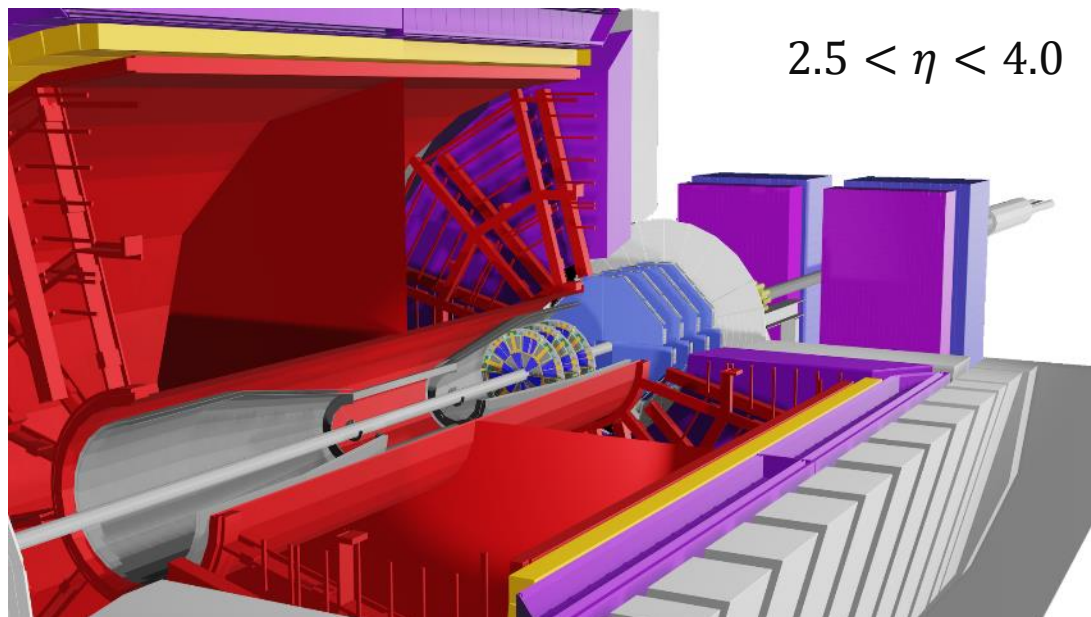
x

STAR in Run 22

- Barrel: $-1 < \eta < 2.0$ / Forward $2.5 < \eta < 4.0$
- Full azimuthal coverage
- Exceeded projection: $\mathcal{L}_{int} > 400$ pb^{-1}
- Figure of merit $LP^2 \approx 120$ pb^{-1} with Forward Detectors and iTPC
- Midrapidity and forward triggers
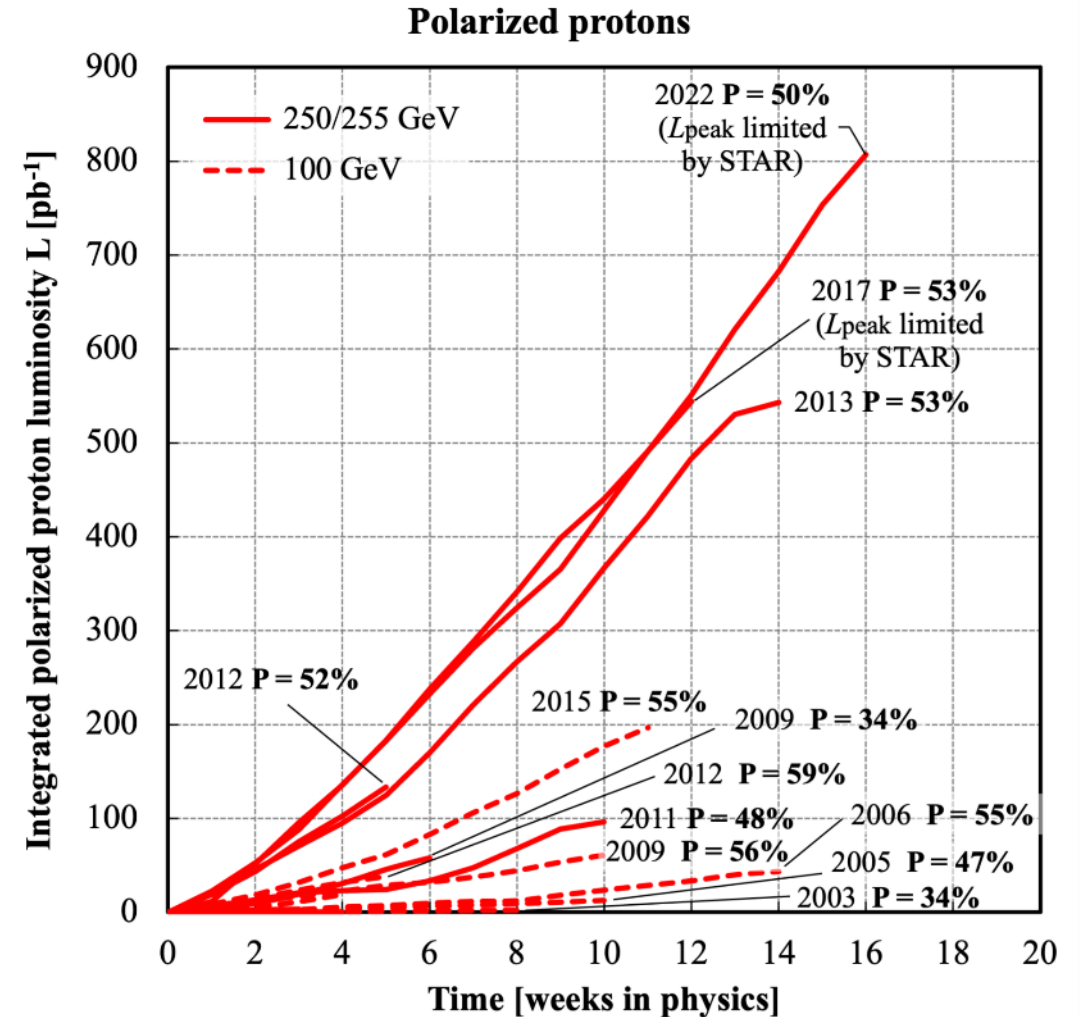
Polarized protons

250/255 GeV
100 GeV

2022 P = 50% (L_{peak} limited by STAR)
2017 P = 53% (L_{peak} limited by STAR)
2013 P = 53%
2012 P = 52%
2015 P = 55%
2009 P = 34%
2012 P = 59%
2011 P = 48%
2006 P = 55%
2009 P = 56%
2005 P = 47%
2003 P = 34%

Integrated polarized proton luminosity L [pb^{-1}]

Time [weeks in physics]

Forward Detector Upgrade

$2.5 < \eta < 4.0$

- Calorimeters
  - Hadronic calorimeter (FeSci)
  - Electromagnetic calorimeter (PbSci)
- Preshower detector (EPD)
- Tracking
  - Small-strip Thin Gas Chambers (4 planes)
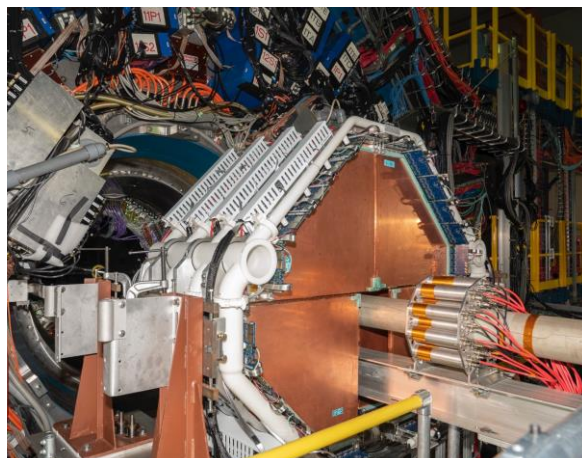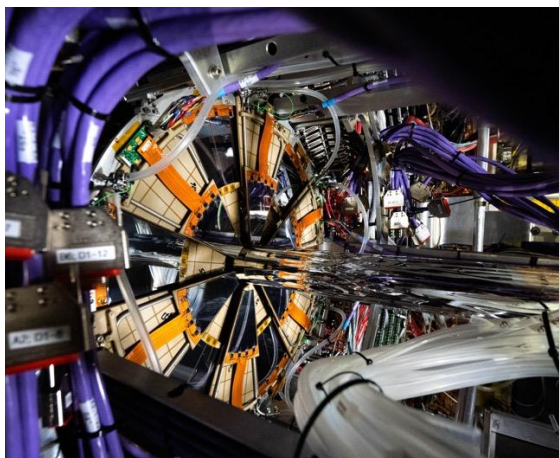 - Silicon tracker (3 disks)

	p+p / p+A	A+A
Tracking	charge separation photon suppression	$\frac{\delta p}{p} \approx 20 - 30\%$ at $0.2 < p_T < 2.0$ GeV/c

	p+p / p+A	A+A
ECAL	$\approx 10\%/\sqrt{E}$	$\approx 20\%/\sqrt{E}$
HCAL	$\approx 60\%/\sqrt{E}$	n/a

Forward Detector Upgrade
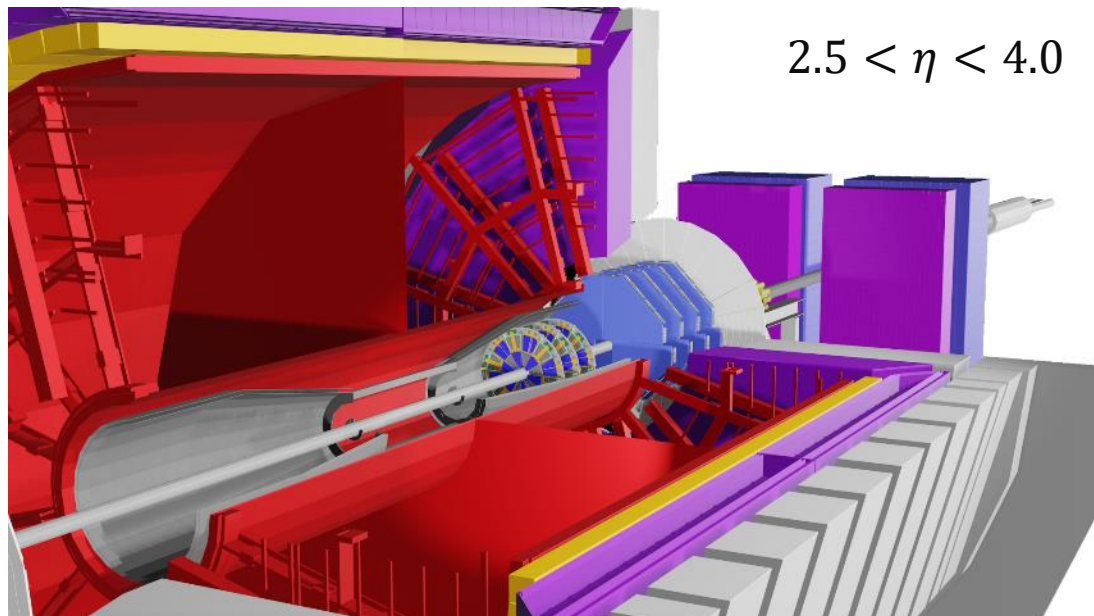
$$2.5 < \eta < 4.0$$

- Calorimeters
  - Hadronic calorimeter (FeSci)
  - Electromagnetic calorimeter (PbSci)

- Preshower detector (EPD)

- Tracking
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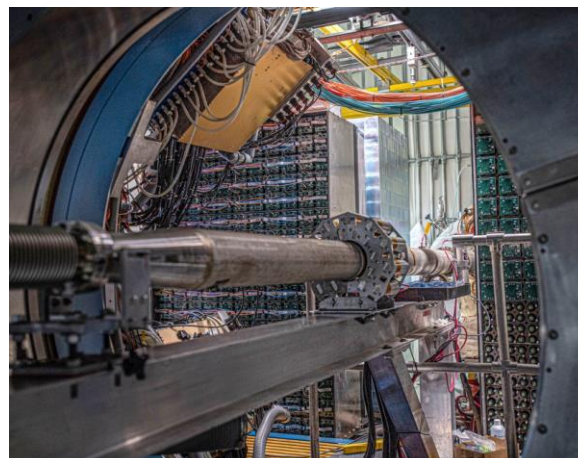
Despite Covid, installation and commissioning finished on schedule and were ready for data taking in Run 22!

Transverse Spin Asymmetries
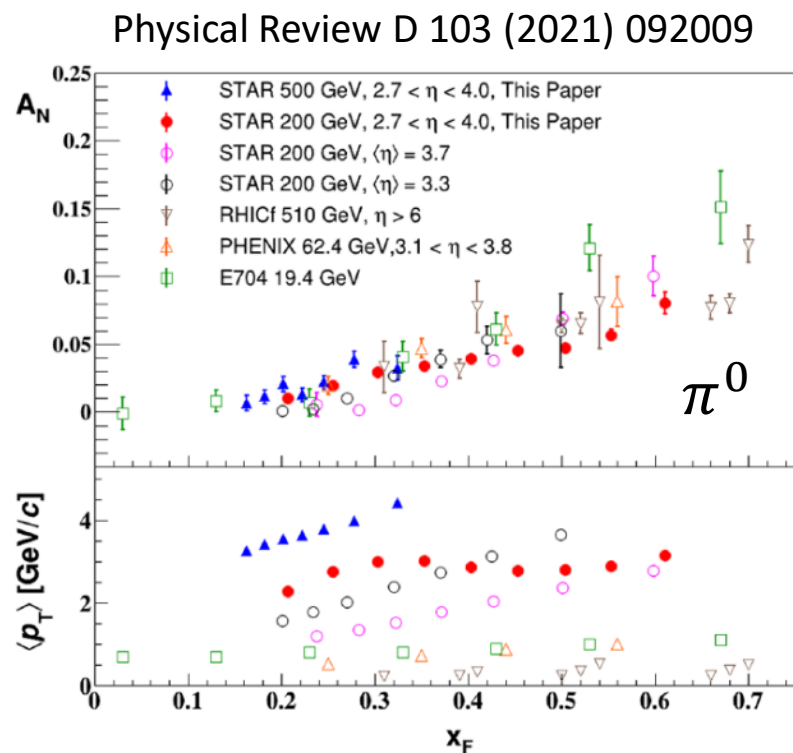
Physical Review D 103 (2021) 092009

- Observation of large transverse single-spin asymmetries at forward rapidity
- Persistent at energies up to $\sqrt{s} = 500$ GeV
- Not consistent with LO pQCD

$$\delta f_a \qquad d\hat{\sigma} \qquad D_f^h$$
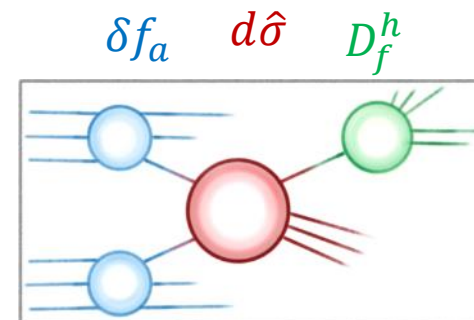
- TMDs can introduce a k_T-dependence (initial and/or final state, not collinear)
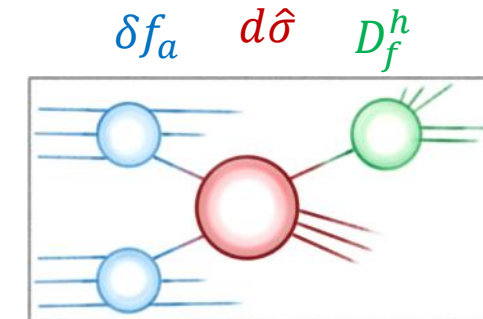
$$\Lambda_{QCD} < Q_T \ll Q$$

- Collinear higher-twist effects

Transverse Spin Asymmetries

- Sivers effect:
  - Correlation of proton spin and parton transverse momentum (initial state)
  - Process dependent asymmetry
    Sivers$_{DIS}$ = - (Sivers$_{DY}$ or Sivers$_{W/Z}$)
- Collins effect:
  - Correlation of parton spin and transverse momentum of hadron (final state)
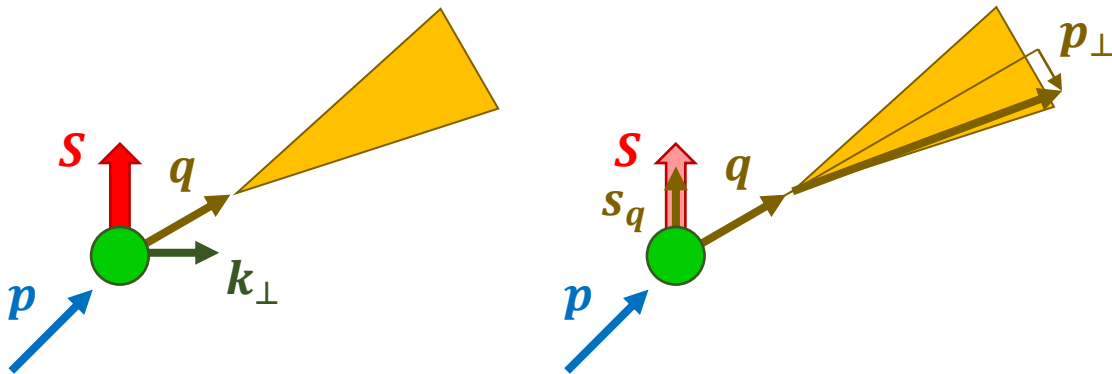
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$$\delta f_a \qquad d\hat{\sigma} \qquad D_f^h$$

- TMDs can introduce a k_T-dependence (initial and/or final state, not collinear)

$$\Lambda_{QCD} < Q_T \ll Q$$

- Collinear higher-twist effects

Inclusive Hadrons

arxiv:1602.03922
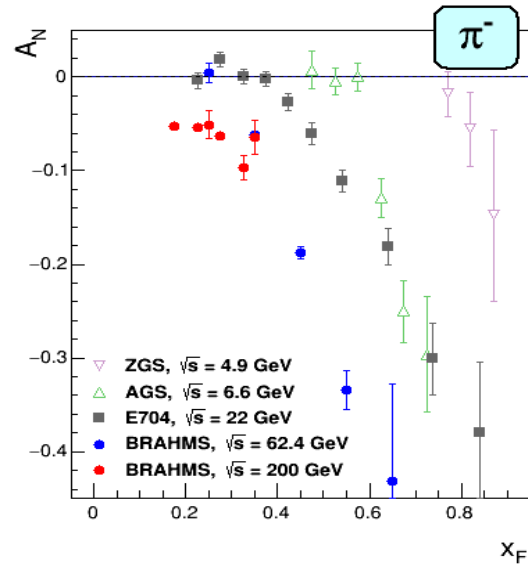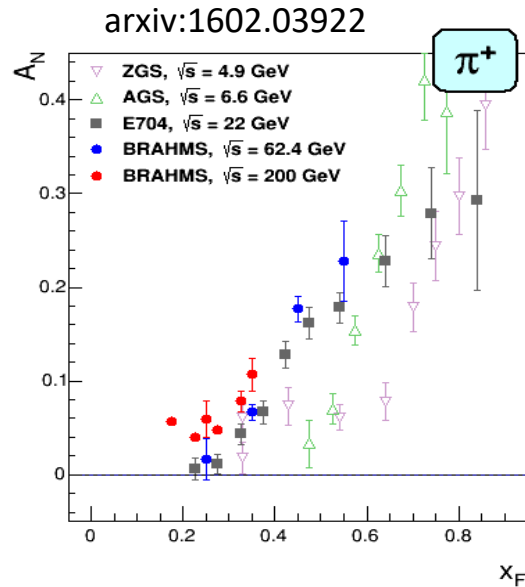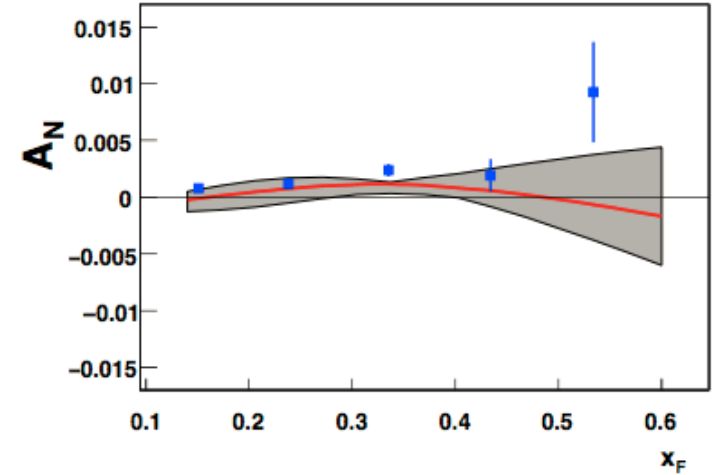
Kanazawa et al. PRD 89 (2014) 111501
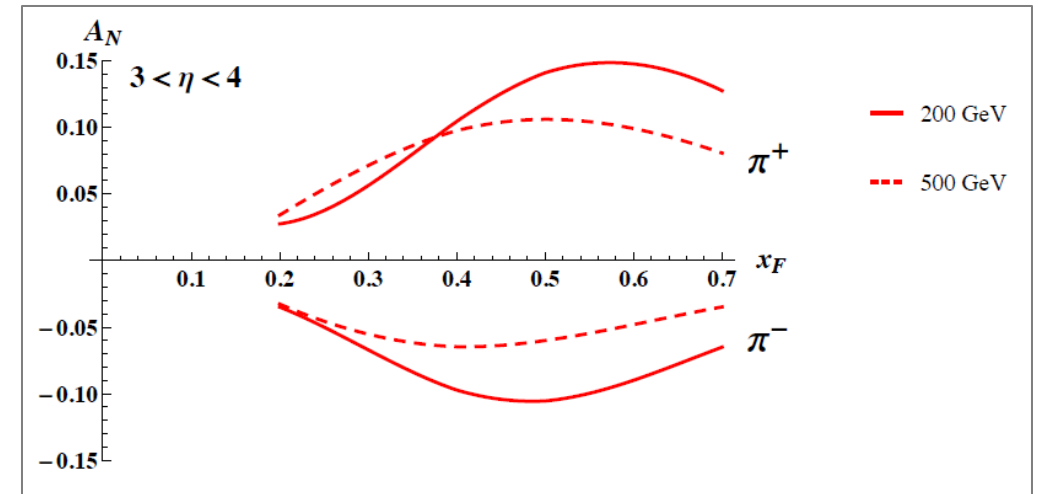
- STAR Forward $2.5 < \eta < 4.0$
- Hadronic calorimeter
- Dedicated hadron triggers with different thresholds (p_T)
- $\sqrt{s} = 508$ GeV (2022) and $\sqrt{s} = 200$ GeV (2024)

Inclusive Jets

- Use charge tagging to avoid cancellation of Sivers asymmetry
- Hadronic calorimeter → enhance high-z hadrons
- Not statistically limited
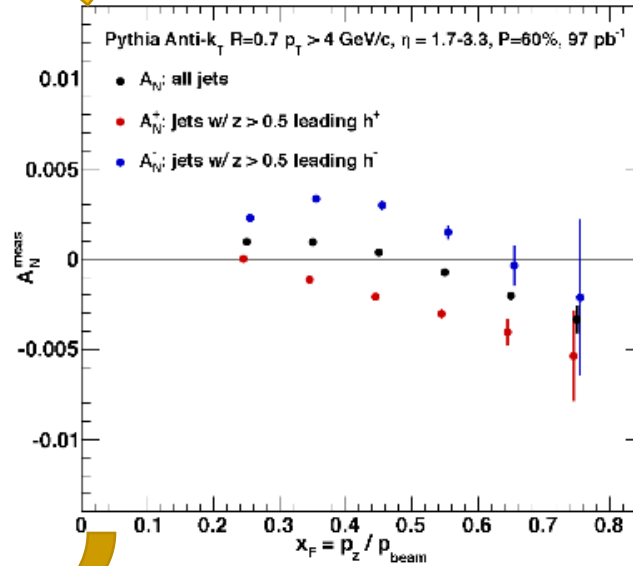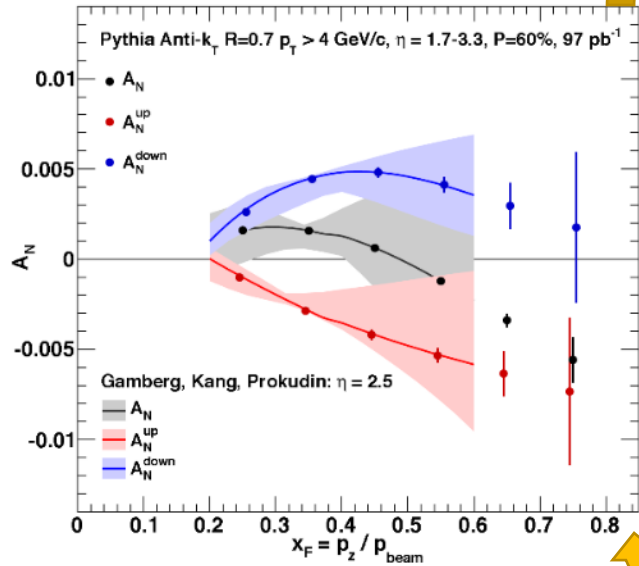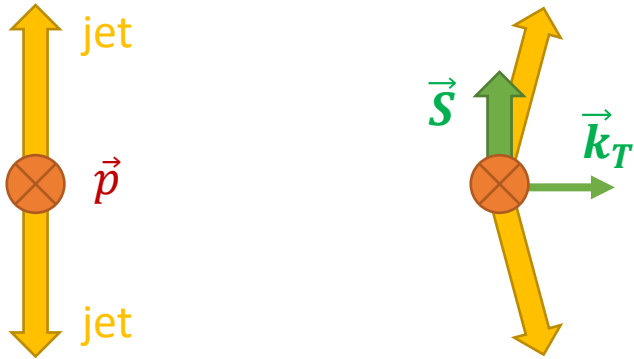
AnDY: PLB 750 (2015) 660

Projection for $\sqrt{s} = 200$ GeV
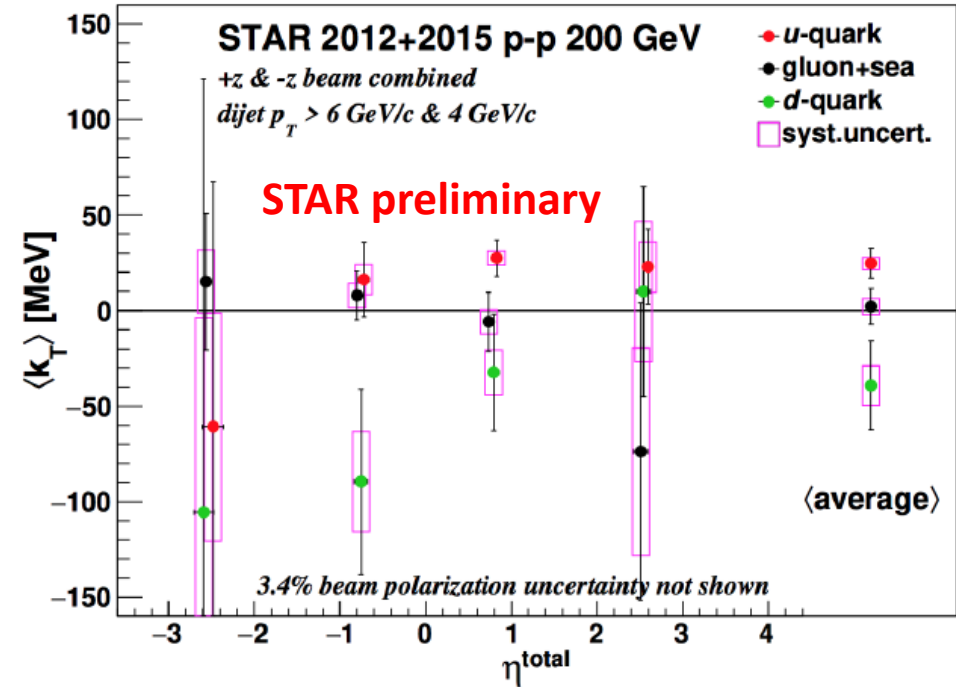
Similar to 2024 request

First Observation of Sivers-Effect in Dijets

- Direct observation of spin-orbit correlation:

$$\left\langle \vec{S} \cdot \left(\vec{p} \times \vec{k}_T \right) \right\rangle \neq 0$$

- Sort by net-charge to enhance u/d quarks
- Corrected to partonic level with embedded simulation
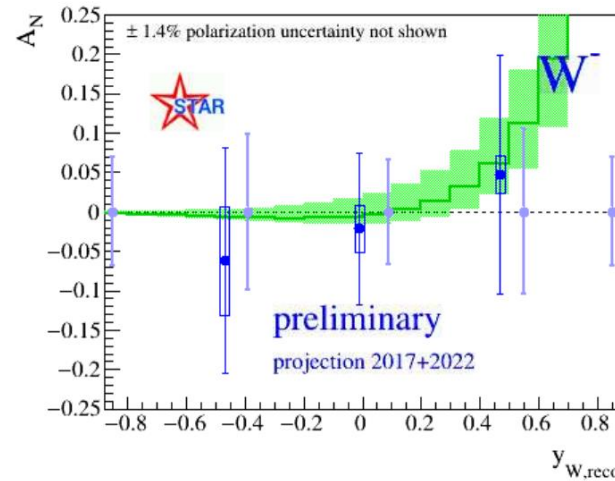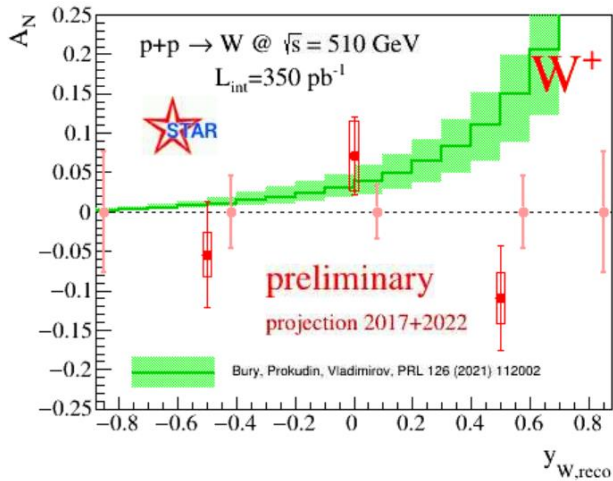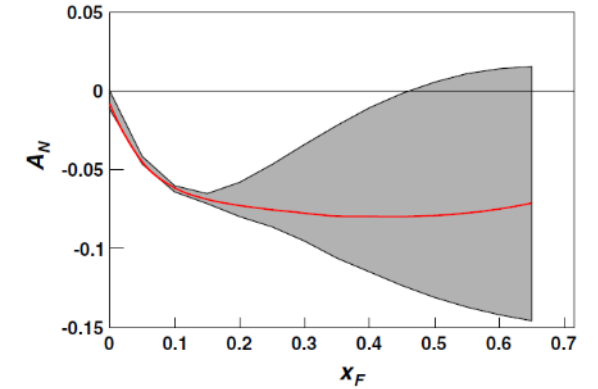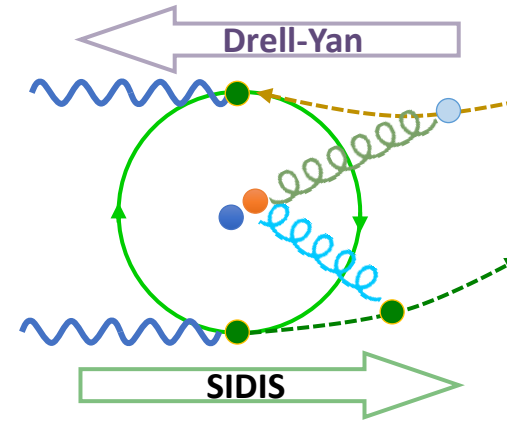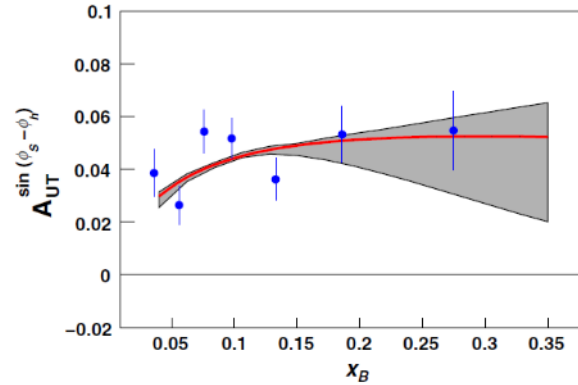- 2012+2015: $\sqrt{s} = 200$ GeV

- Dedicated dijet triggers in Run 22
- $\sqrt{s} = 508$ GeV
- Forward rapidity → high x

Drell-Yan / Weak Bosons

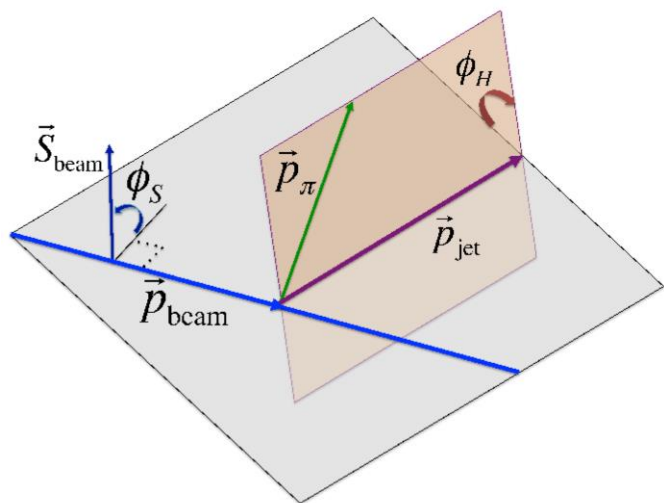- Process dependence of spin-orbit correlations: SIDIS vs. $p + p$

Gamberg, Kang, Prokudin
PRL 110 (2013) 232301
with HERMES data

- Note: recent theory predictions show small asymmetries for $W^{\pm}/Z^0$ (few percent)
  - Bacchetta et al., Phys. Lett. B 827 (2022) 136961
- Increased acceptance in Run 22
- Improved recoil determination (low p_T)
- Dedicated Drell-Yan trigger at forward η

Hadron Asymmetries in Jets

- Two scales for TMD measurement
  - p_T of jet
  - j_T of hadron in jet
- Identified hadrons ($\pi^\pm, K^\pm, p$)
- Multi-dimensional binning: p_T, j_T, x_F, z

Collins asymmetries:

arxiv:2205.11800
$\sqrt{s} = 200$ GeV
2012/2015

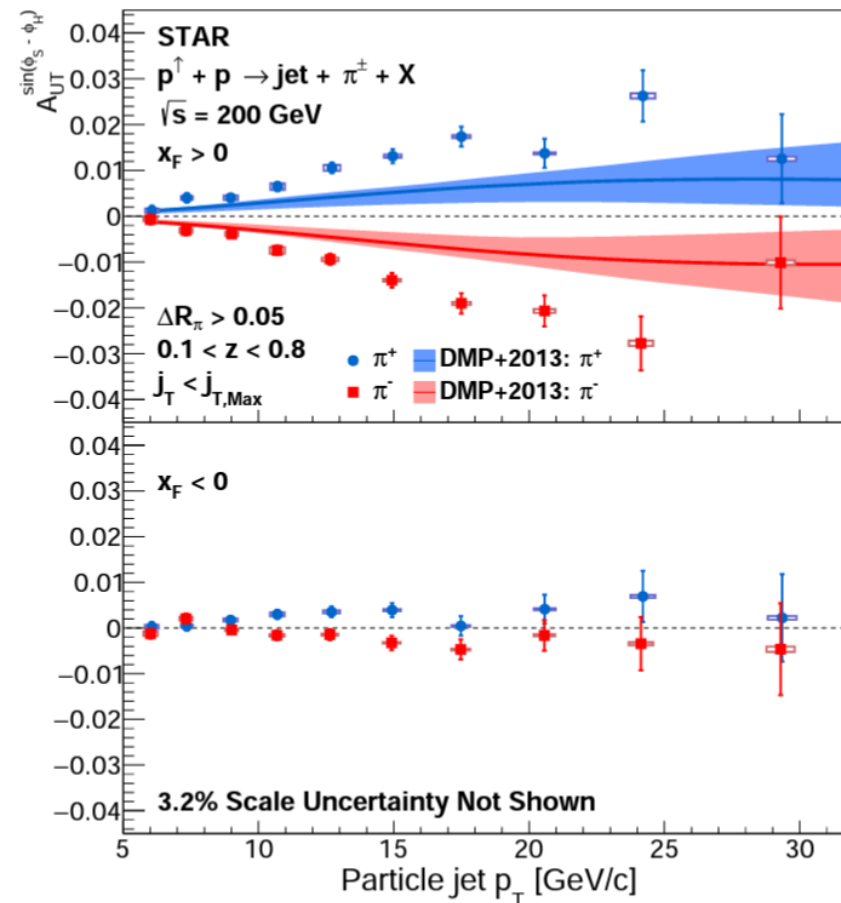Previously: $\sqrt{s} = 500$ GeV
Phys. Rev. D97 (2018) 032004

$$d\sigma^\uparrow - d\sigma^\downarrow \propto d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^+ \sin(\phi_S + \phi_H) + d\Delta\sigma_2^+ \sin(\phi_S + 2\phi_H)$$
$$+ d\Delta\sigma_1^- \sin(\phi_S - \phi_H) + d\Delta\sigma_2^- \sin(\phi_S - 2\phi_H)$$
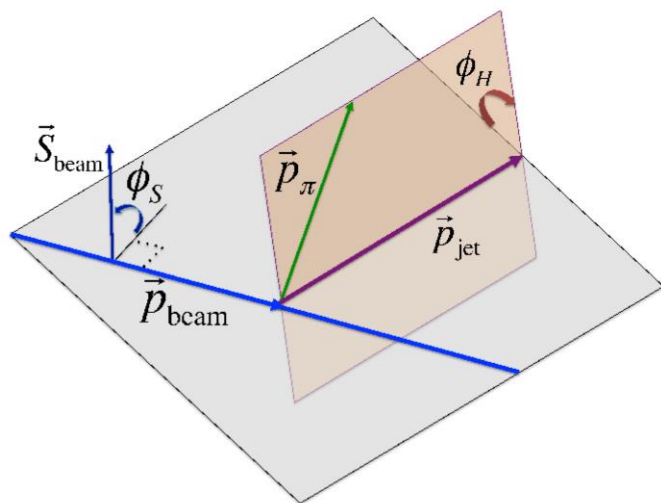
Hadron Asymmetries in Jets

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Collins asymmetries:

arxiv:2205.11800
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2012/2015

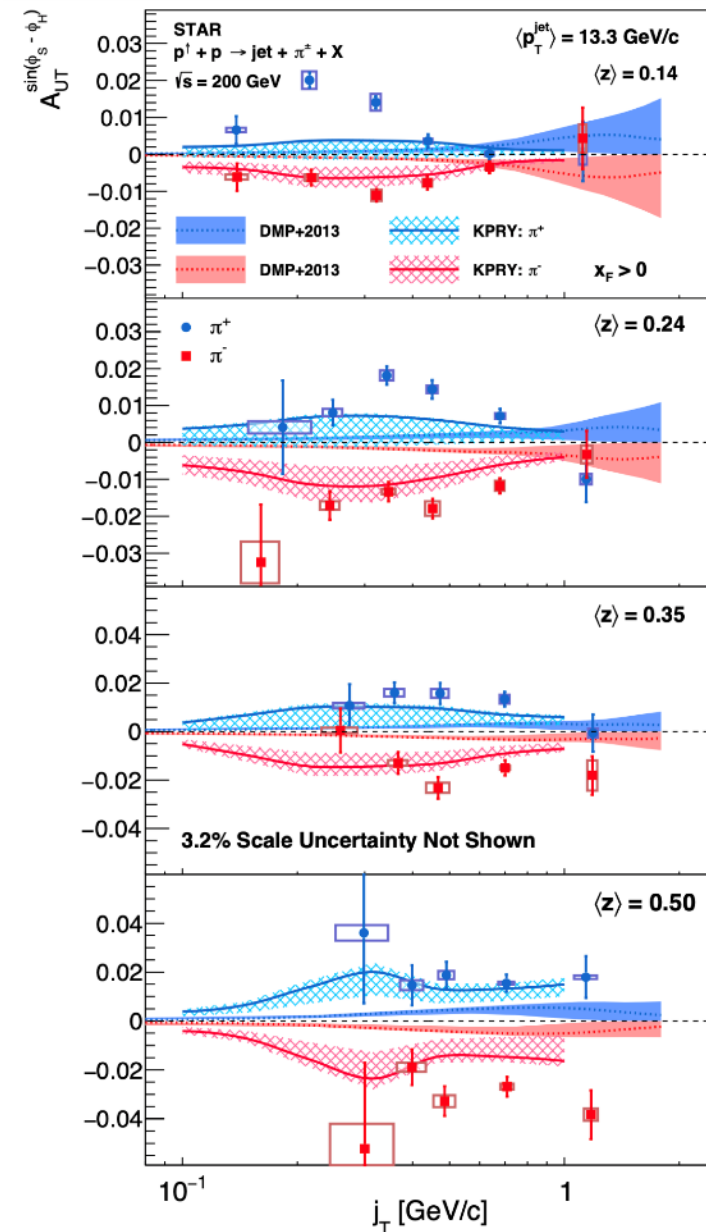Previously: $\sqrt{s} = 500$ GeV
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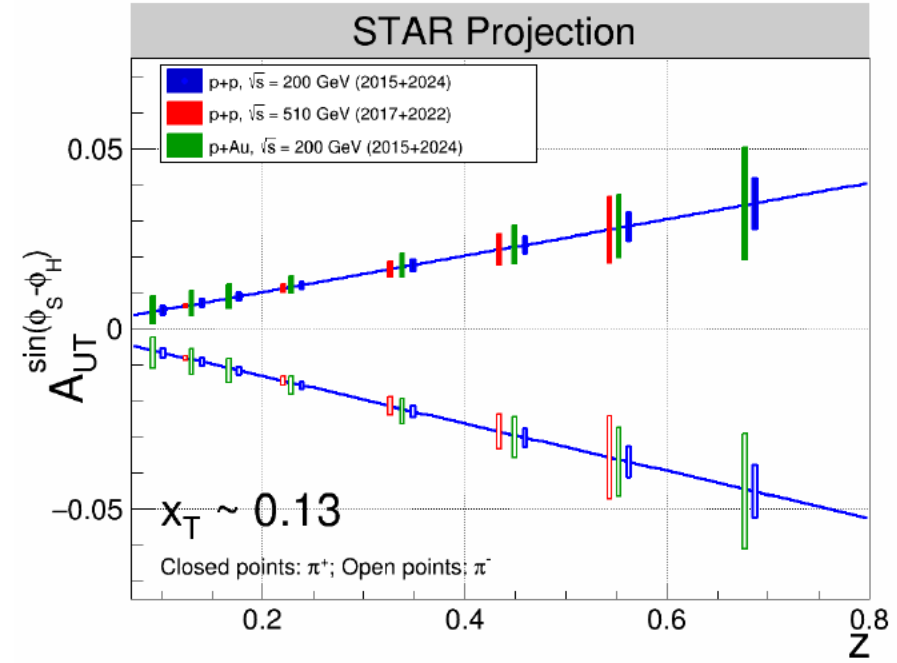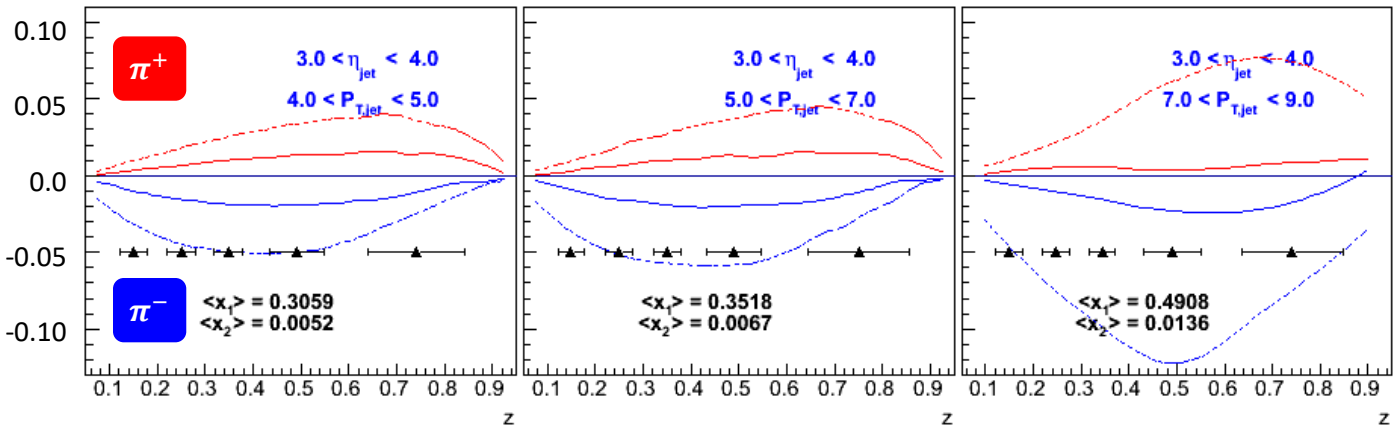$d\sigma^\uparrow - d\sigma^\downarrow \propto d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^+ \sin(\phi_S + \phi_H) + d\Delta\sigma_2^+ \sin(\phi_S + 2\phi_H)$
$\qquad + d\Delta\sigma_1^- \sin(\phi_S - \phi_H) + d\Delta\sigma_2^- \sin(\phi_S - 2\phi_H)$

Hadron Asymmetries in Jets

- Two scales for TMD measurement

  - p_T of jet
  - j_T of hadron in jet

- Identified hadrons ($\pi^{\pm}, K^{\pm}, p$)

- Multi-dimensional binning: p_T, j_T, x_F, z

<u>Collins asymmetries:</u>

- Q^2 evolution
- Nuclear effects
- Improved PID with iTPC
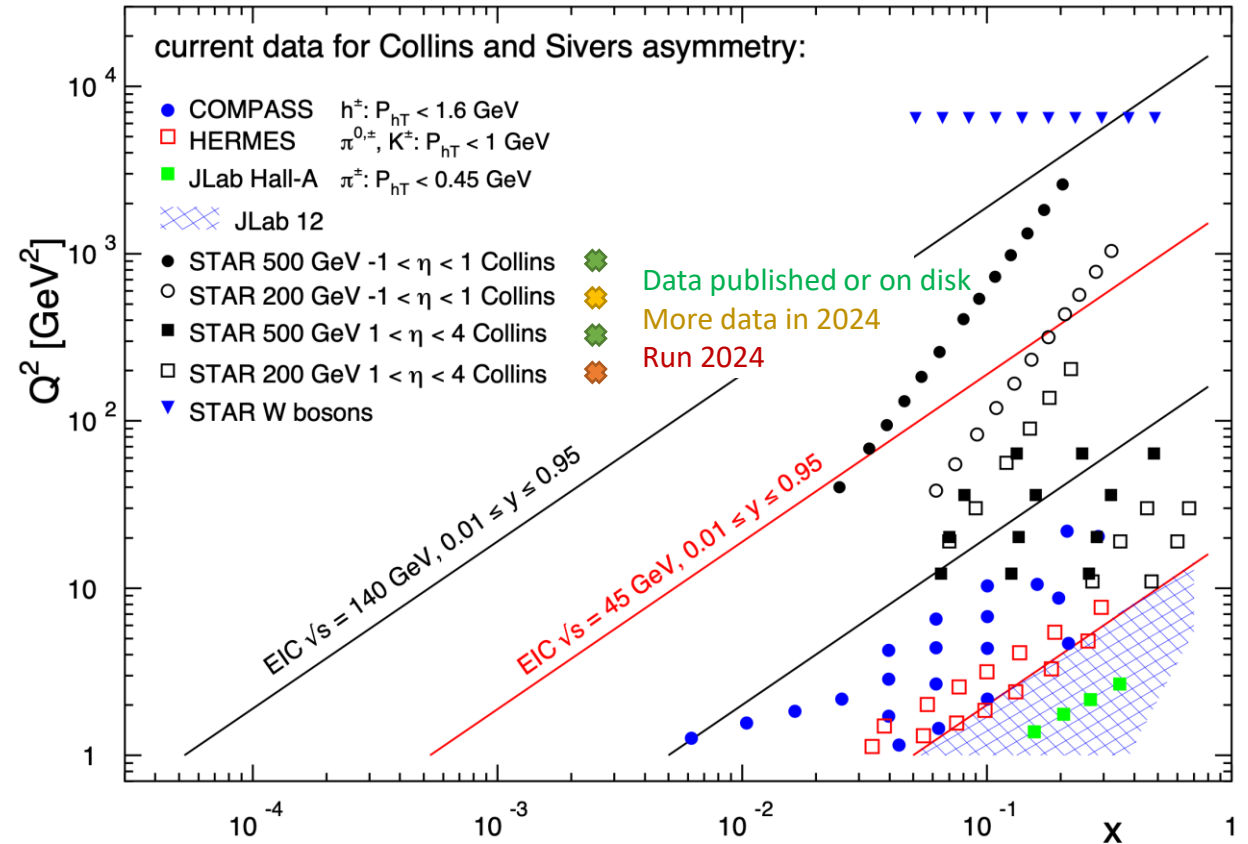- Additional data with Forward Detectors

Torino: Phys. Rev. D87 (2013) 094019   Soffer bound&transversity: Phys. Rev. Lett. 74 (1995) 1292

Hadron Asymmetries in Jets

- Two scales for TMD measurement

  - p_T of jet

  - j_T of hadron in jet

- Identified hadrons ($\pi^\pm, K^\pm, p$)

- Multi-dimensional binning: p_T, j_T, x_F, z

- Large overlap with EIC kinematics
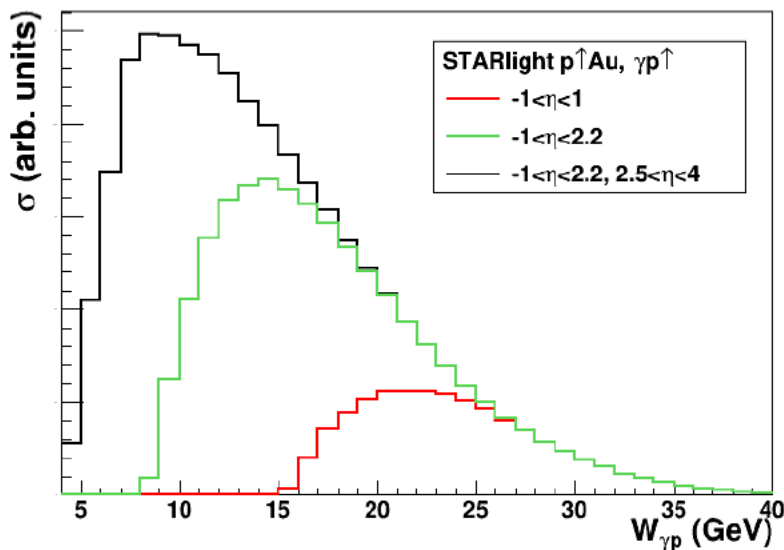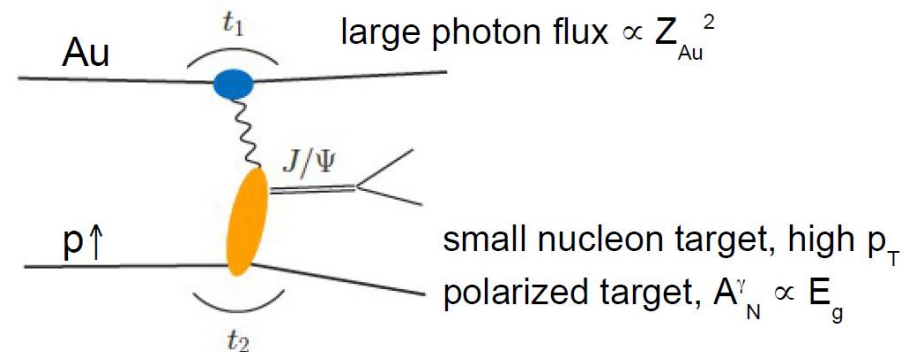
- Complement existing SIDIS data at high-x

Recap from page 3

current data for Collins and Sivers asymmetry:

- COMPASS $h^\pm$: P_{hT} < 1.6 GeV
- HERMES $\pi^{0,\pm}$, $K^\pm$: P_{hT} < 1 GeV
- JLab Hall-A $\pi^\pm$: P_{hT} < 0.45 GeV
- JLab 12
- STAR 500 GeV -1 < η < 1 Collins
- STAR 200 GeV -1 < η < 1 Collins
- STAR 500 GeV 1 < η < 4 Collins
- STAR 200 GeV 1 < η < 4 Collins
- STAR W bosons

Data published or on disk
More data in 2024
Run 2024

EIC √s = 140 GeV, 0.01 ≤ y ≤ 0.95

EIC √s = 45 GeV, 0.01 ≤ y ≤ 0.95

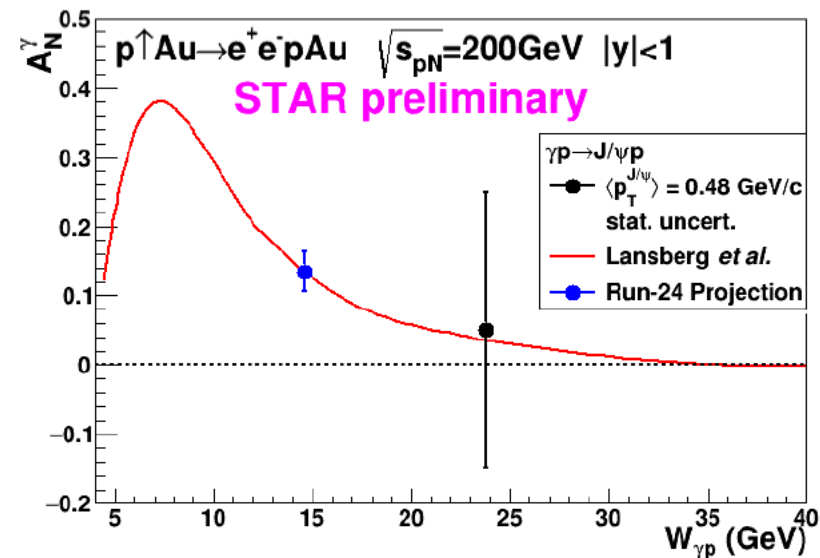Q^2 [GeV^2]

x

Ultraperipheral Collisions

- Generalized Parton Distributions: 2+1D picture of the proton

- Current knowledge from exclusive measurements in DIS

- Unique at RHIC: transversely polarized UPC

- First look at E_g

$$A_N^\gamma \propto p_T \frac{\text{Im}H^g E^{g*}}{|H^g|^2}$$

large photon flux $\propto Z_{Au}^2$

small nucleon target, high p_T

polarized target, $A_N^\gamma \propto E_g$
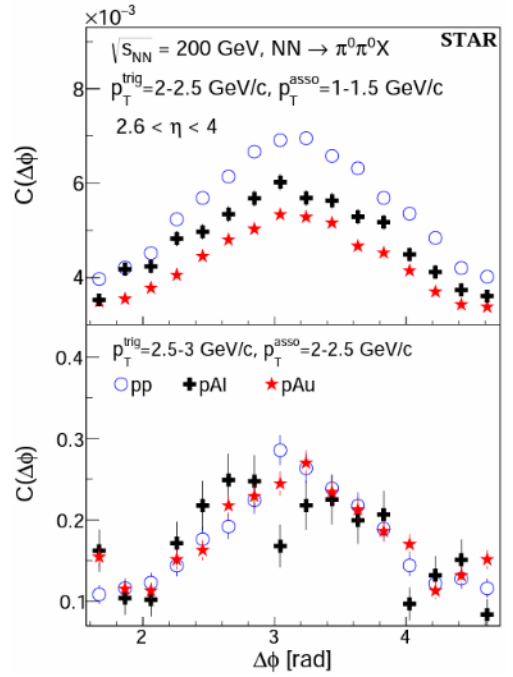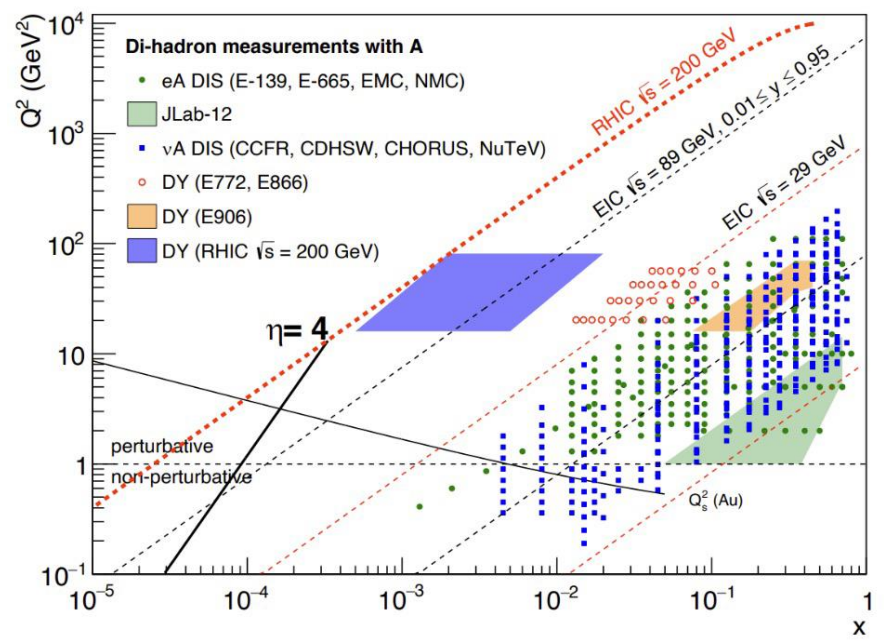

Forward Detectors
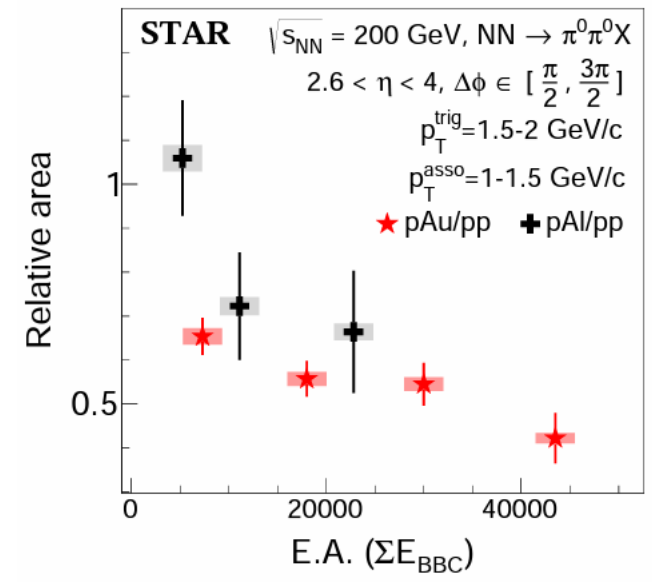
Dedicated triggers in Run 22

Non-linear Parton Dynamics

- Recent analysis of dihadron correlations
- Compare $p + p, p + A$
  - Run 15: Only Ecal at $2.6 < \eta < 4.0 \to \pi^0 \pi^0$

$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig}\Delta\phi}$$

$p_{T,trig} > p_{T,assoc}$

arxiv:2111.10396

Various probes to test non-linear QCD effects with new Forward Detectors:

- charged dihadrons
- γ-jet
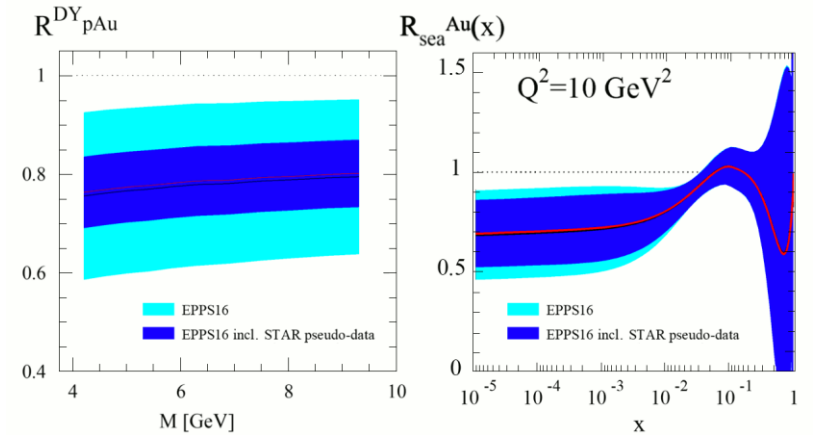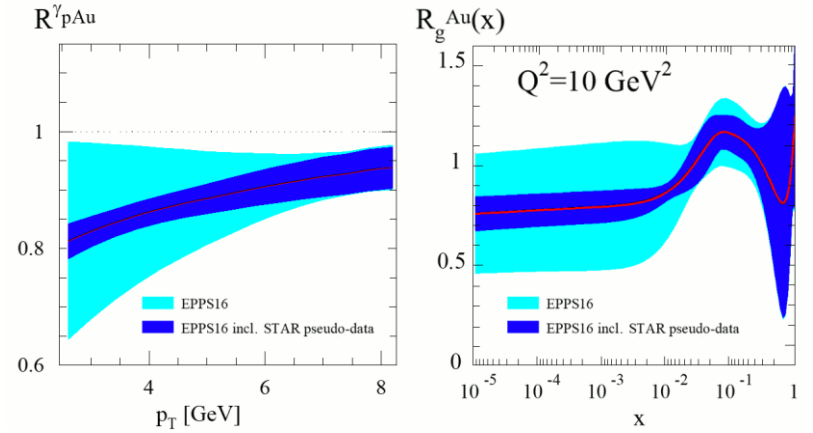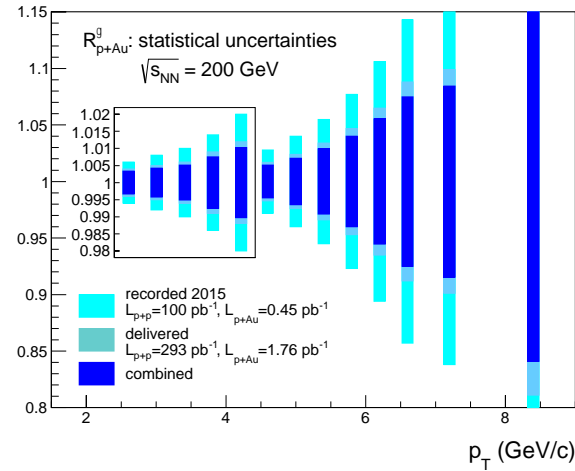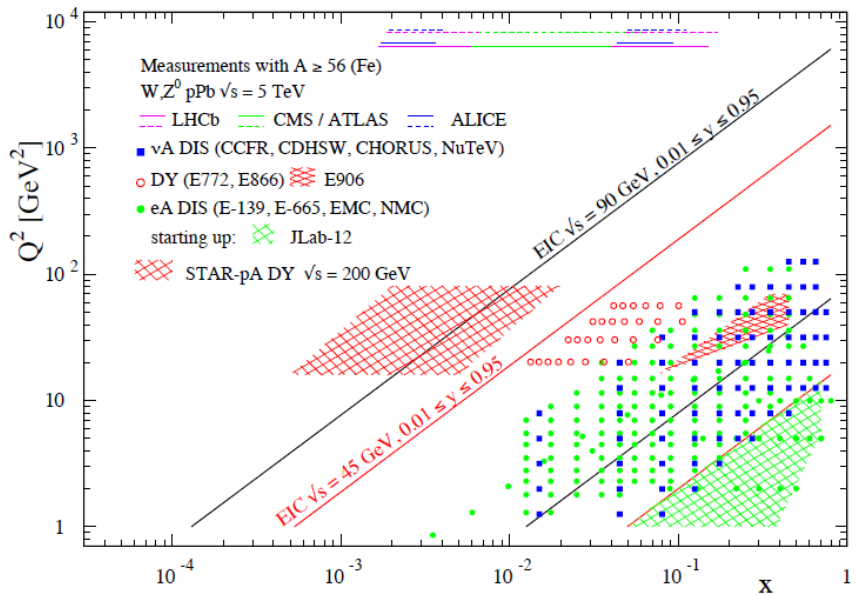- dijets

Nuclear Modification & Nuclear PDFs/FFs

Direct photon and Drell-Yan at forward rapidity

- Direct access to initial state
- Medium to low x at moderate Q^2
- Nuclear modification R_{pA}

Hadrons in jets

- In-medium effect of hadronization

$$R_{pA} = \frac{1}{\langle N_{coll}\rangle}\frac{dN^{pA}}{dN^{pp}}$$

Summary

- STAR has finished a very successful Run 22 at $\sqrt{s} = 508$ GeV
  - Forward detector upgrade $2.5 < \eta < 4.0$
  - $LP^2 \approx 120$ pb^{-1}
  - Dedicated triggers for jets/dijets, hadrons, Drell-Yan
- Polarized $p^{\uparrow} + p$ and $p^{\uparrow} +$ Au collisions at $\sqrt{s_{NN}} = 200$ GeV in 2024
  - Expand kinematic range of transverse spin measurements
  - Unambiguous probes at forward rapidity: charged hadrons, jets, γ, Drell-Yan
- Wide coverage in $x - Q^2$ with large overlap at EIC
  - Transversity, Sivers & Collins effects, nuclear PDFs and more
  - Onset of non-linear effects in QCD
  - QCD evolution of TMDs
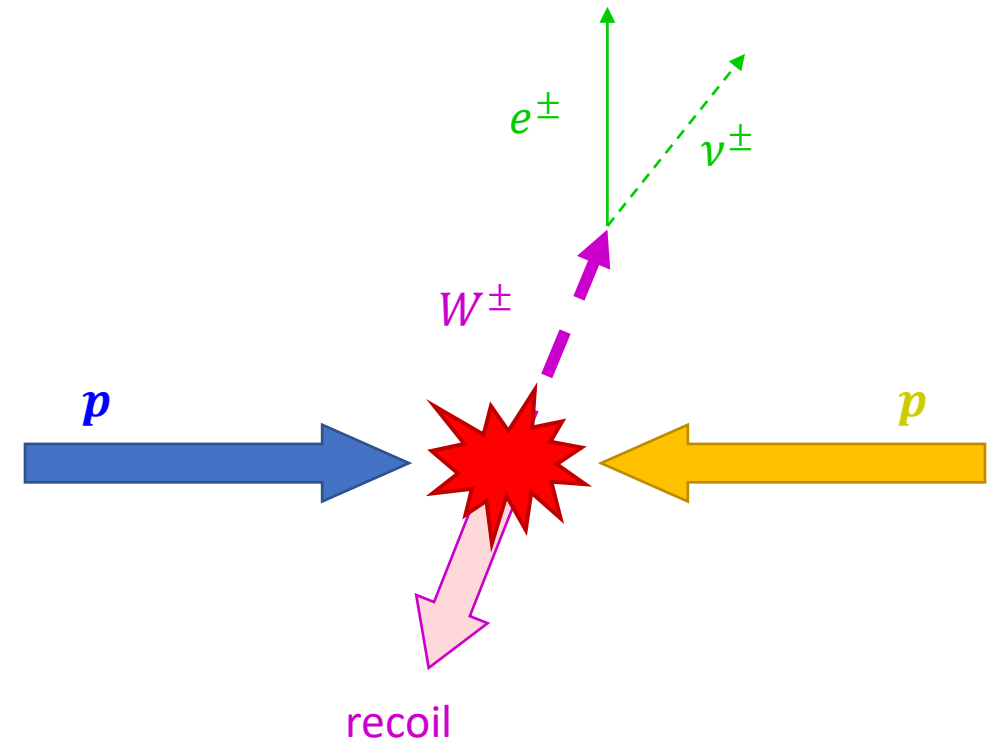 - Test properties of universality and factorization

Backup

W-Boson Reconstruction

$$p + p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$$

- W-boson decay

  - $p_{T,W}$ is lost

  - Almost no azimuthal angle correlation

- Measure recoil from the collision (tracks and EMC)

$$p_{T,W} = p_{T,e} + p_{T,\nu} = p_{T,recoil}$$

$$p_{T,recoil} = \sum(p_{T,TPC} + E_{T,EMC})$$

$e^{\pm}$

$\nu^{\pm}$

$W^{\pm}$

p

p

recoil

Azimuthal Angle Smearing

- Transverse spin asymmetries are measured through azimuthal modulations:

$$d\sigma(\phi) = \sigma_0[1 + PA_N \cos(\phi)]$$

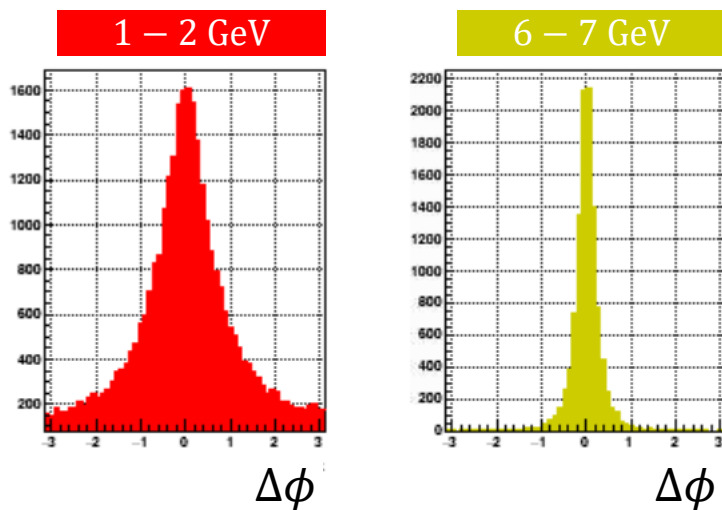$$A_N = \frac{d\sigma(\phi) - d\sigma(\phi + \pi)}{d\sigma(\phi) + d\sigma(\phi + \pi)} \qquad\qquad A_N = \frac{1}{P}\frac{N_\phi - N_{\phi+\pi}}{N_\phi + N_{\phi+\pi}}$$

- Toy Monte Carlo study → determine asymmetry dilution
  - 100k MC samples based on input distribution from embedding (per η-bin)
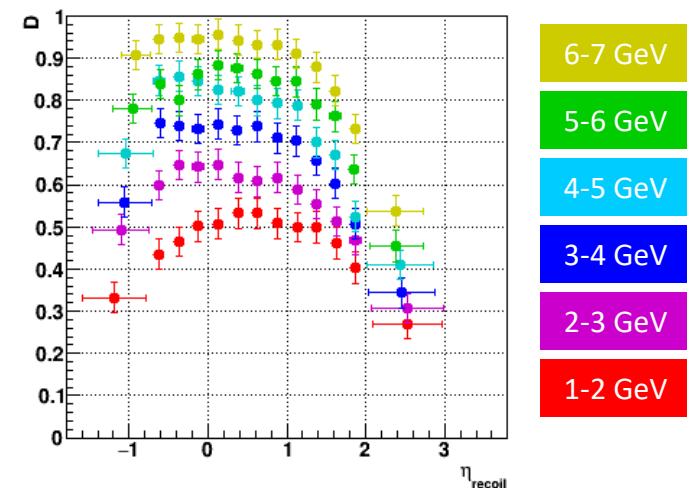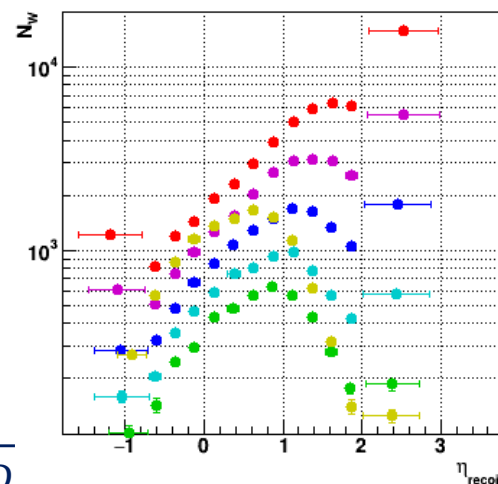
$$D = A_{N,meas}/A_{N,input}$$

$p_{T,recoil}$ 1 − 2 GeV   6 − 7 GeV

$\Delta\phi$ $\Delta\phi$

$\sigma_{A_N} \propto \dfrac{1}{\sqrt{ND}}$

$\Delta\phi = \phi_W - \phi_{recoil}$

6-7 GeV
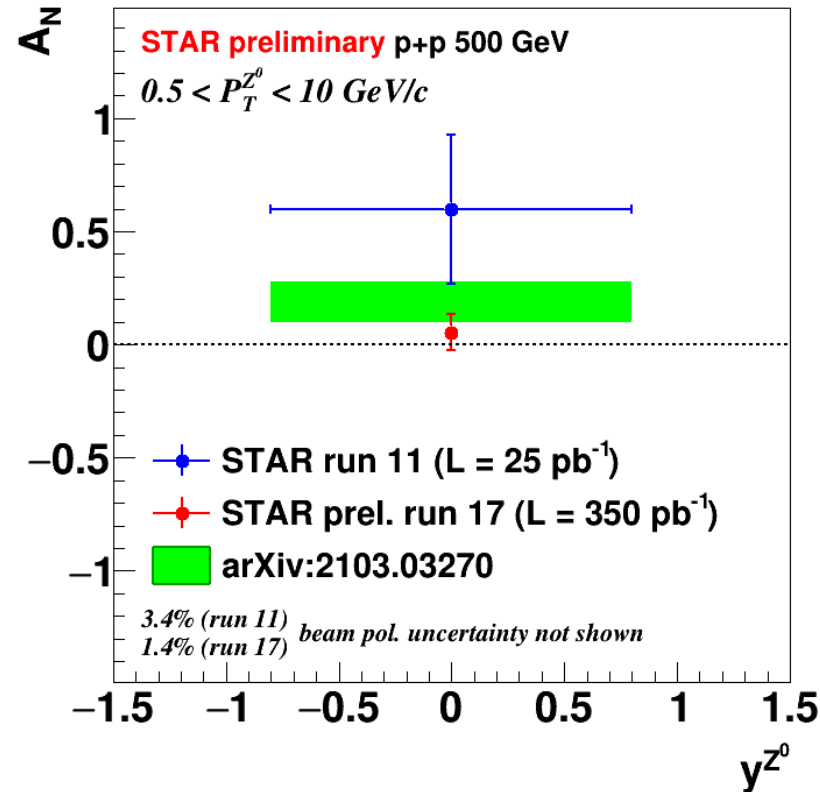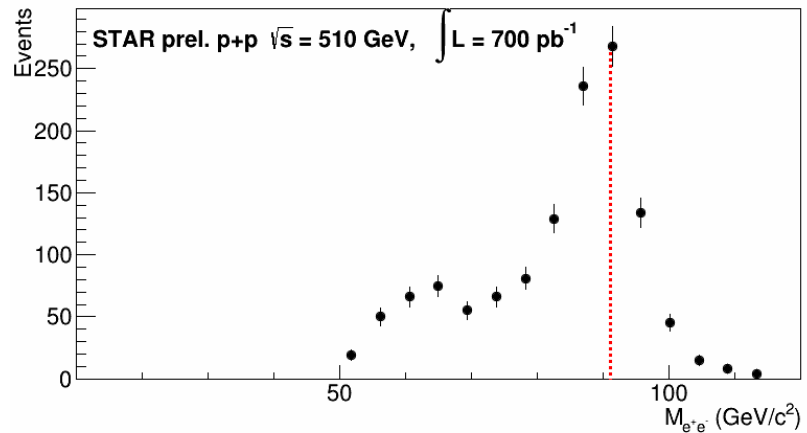5-6 GeV
4-5 GeV
3-4 GeV
2-3 GeV
1-2 GeV

O. Eyser / RAUM 2022

Asymmetry correction: $A_N = A_{N,meas}/D$

New Results for Z^0
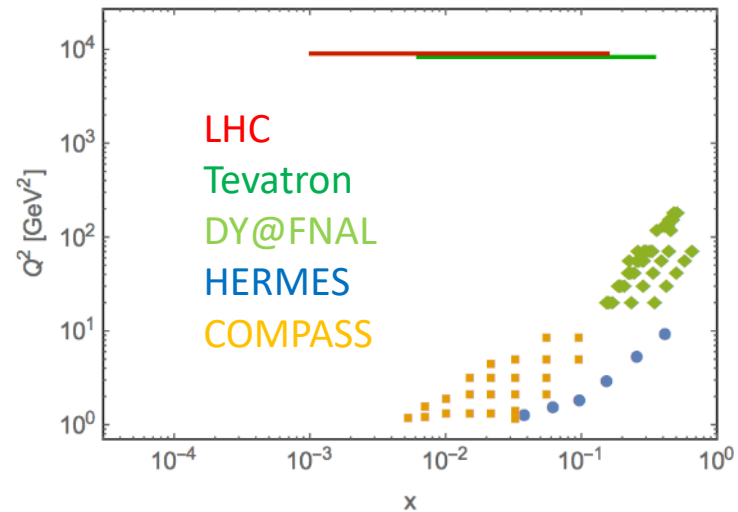
$$p + p \rightarrow Z^0 \rightarrow e^+ + e^-$$

- Experimentally very clean
  - Two high-p_T electrons (e^+, e^-) from same vertex
- Leading systematic uncertainty from energy resolution
- Comparison with PRL 126 (2021) 112002
  (more details in arxiv:2103.03270)
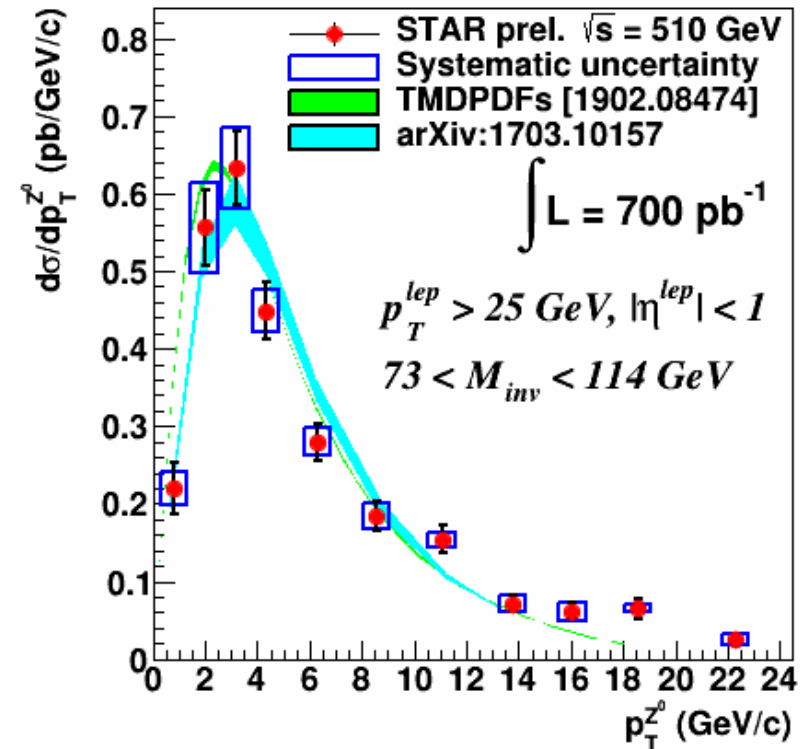
Unpolarized TMDs

$$p + p \rightarrow Z^0 \rightarrow e^+ + e^-$$

- Differential cross section of high interest for TMD-PDF fits

  - Pavia group, *JHEP* 07 (2020) 117

- 2017 data doubles the previous statistics

- Unfolded p_T spectrum

- Systematics from energy resolution and electron selection

Global luminosity uncertainty 8.5% not included in the plot