
# An Overview of Spin Physics at STAR

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Temple Univ.

for the STAR collaboration

Supported in part by:

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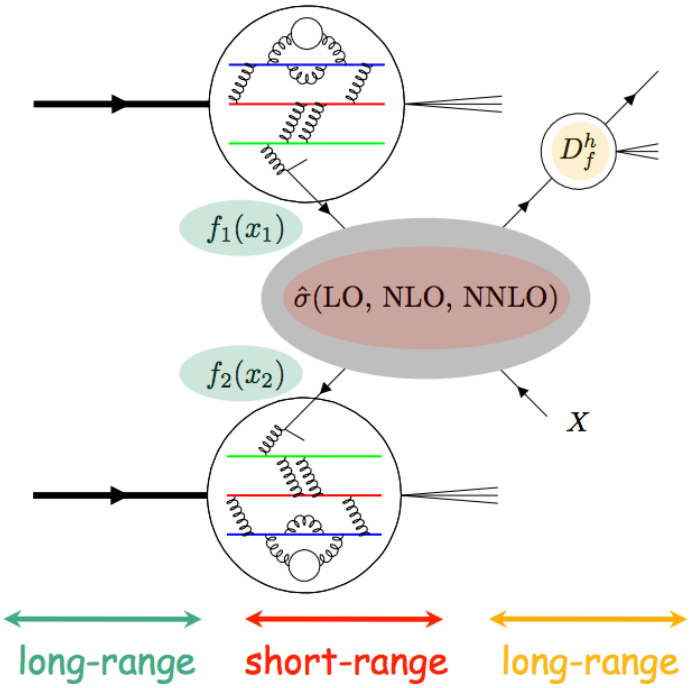
Office of Science

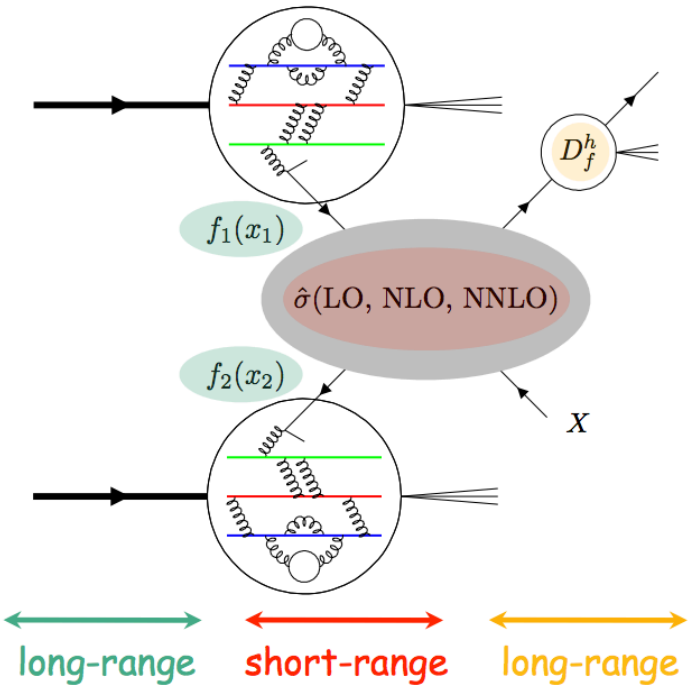
# Proton Structure in $pp$

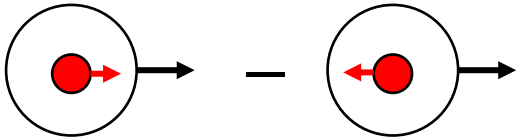



$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$

$$f(x) = \quad + \quad$$

# With Longitudinally Polarized Proton




$$\Delta f(x) =$$ 

- Proton Spin: $\frac{1}{2} = \frac{1}{2}\sum S_z^q + S_z^g + \sum L_z^q + L_z^q$
- DIS data consistent with ~30% quark helicity contribution
- RHIC data sensitive to sea quarks and gluon

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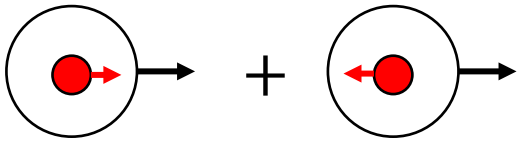
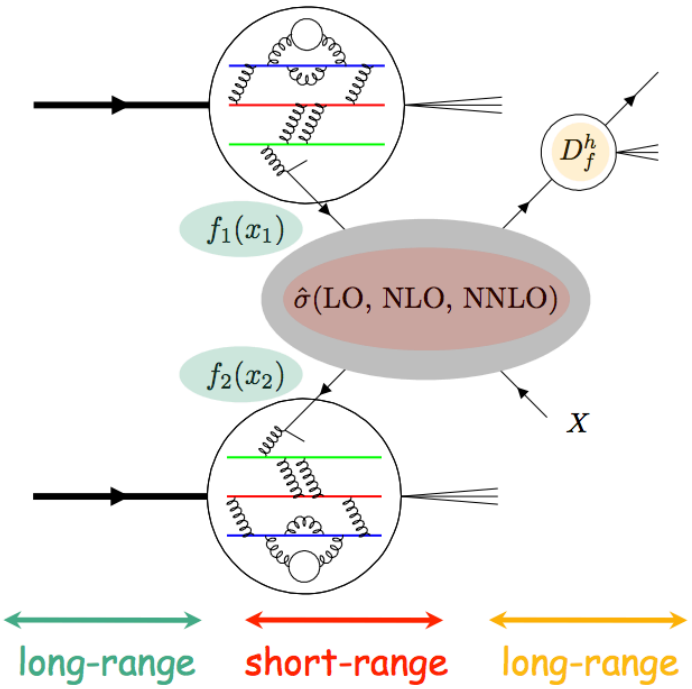
$$f(x) =$$ 

# With Transversely Polarized Proton




$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$

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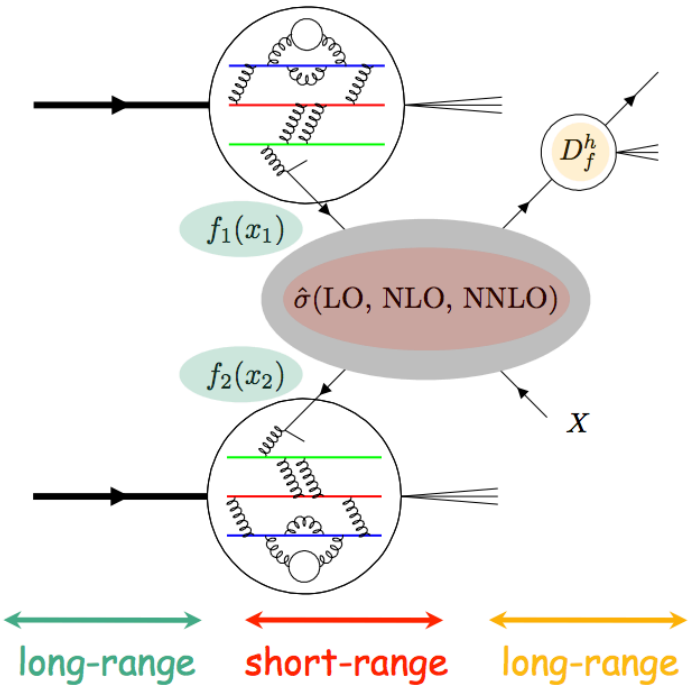
$$h_1(x) = \quad - \quad$$

- Much less known
- Chirally-Odd
  → Cannot be measured inclusively
  → Requires chiral-odd partner (Collins/interference fragmentation functions (FF), etc)

# With Transversely Polarized Proton

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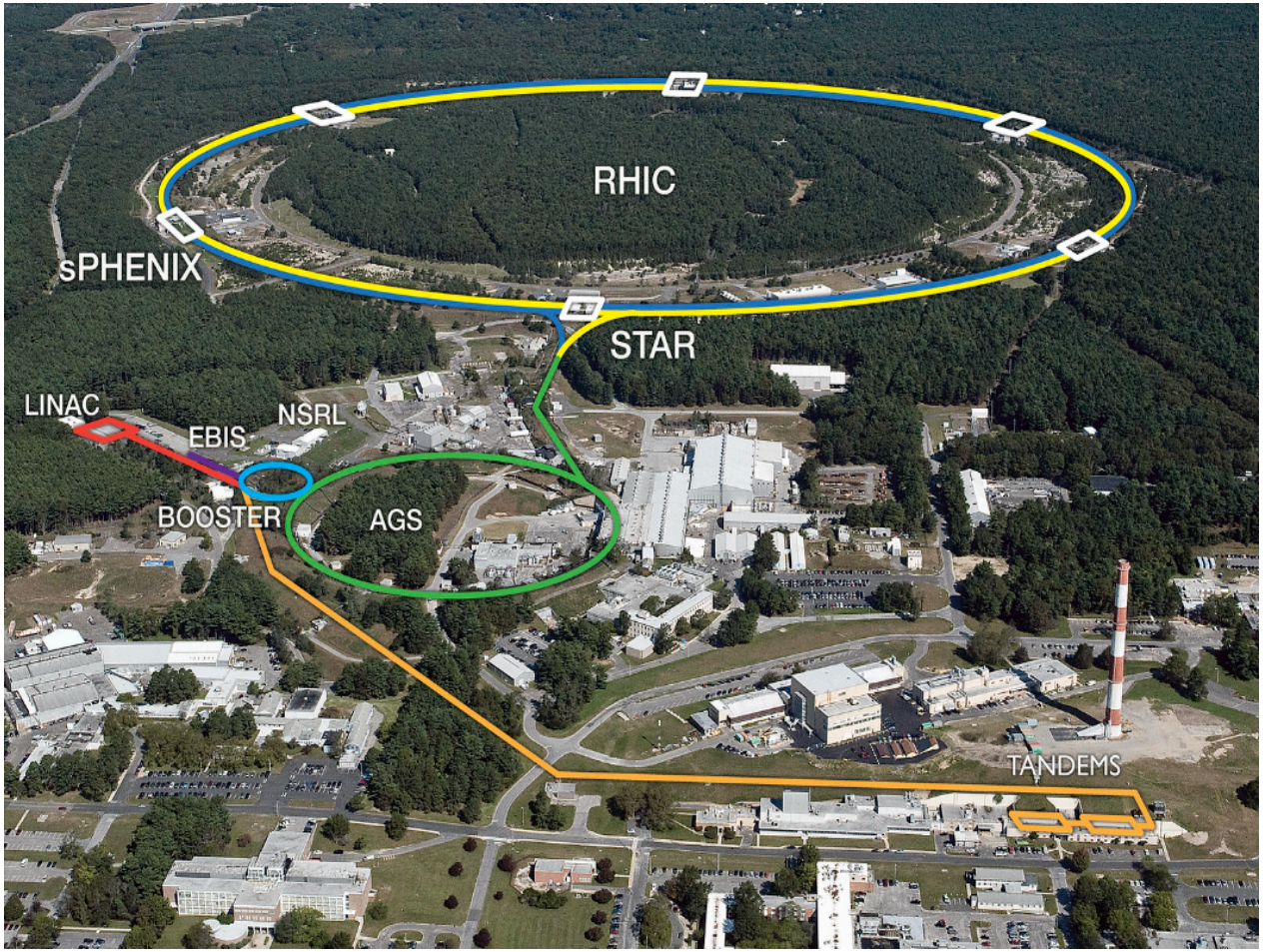
## In Addition,

- Initial-state parton $k_T$
- And its correlation with proton spin (Sivers mechanism, with $L_z$)

# Relativistic Heavy Ion Collider

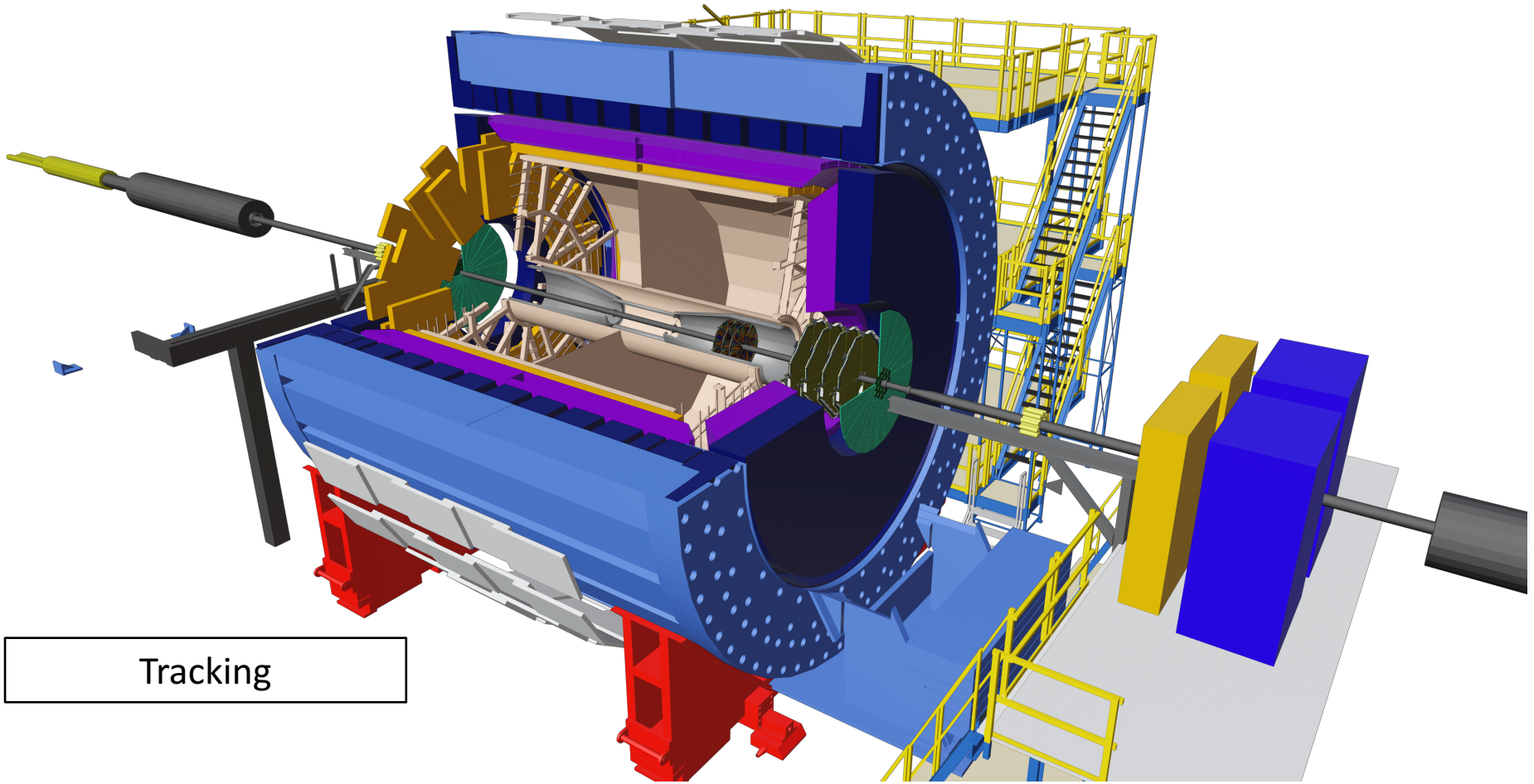



- RHIC continues to serve as the world's first and only polarized $pp$ collider
- Facilitates $pp/pA/AA$ collisions at various energies
- At RHIC, protons can be polarized either:
  - Longitudinally,
  - Transversely,
  - Or use unpolarized beams
- Main focus of STAR Spin Physics program
  - $pp\ \sqrt{s} = 200$ GeV
  - $pp\ \sqrt{s} = 500/510/508$ GeV
  - All three polarizations

# Solenoidal Tracker At RHIC

Calorimetry

PID



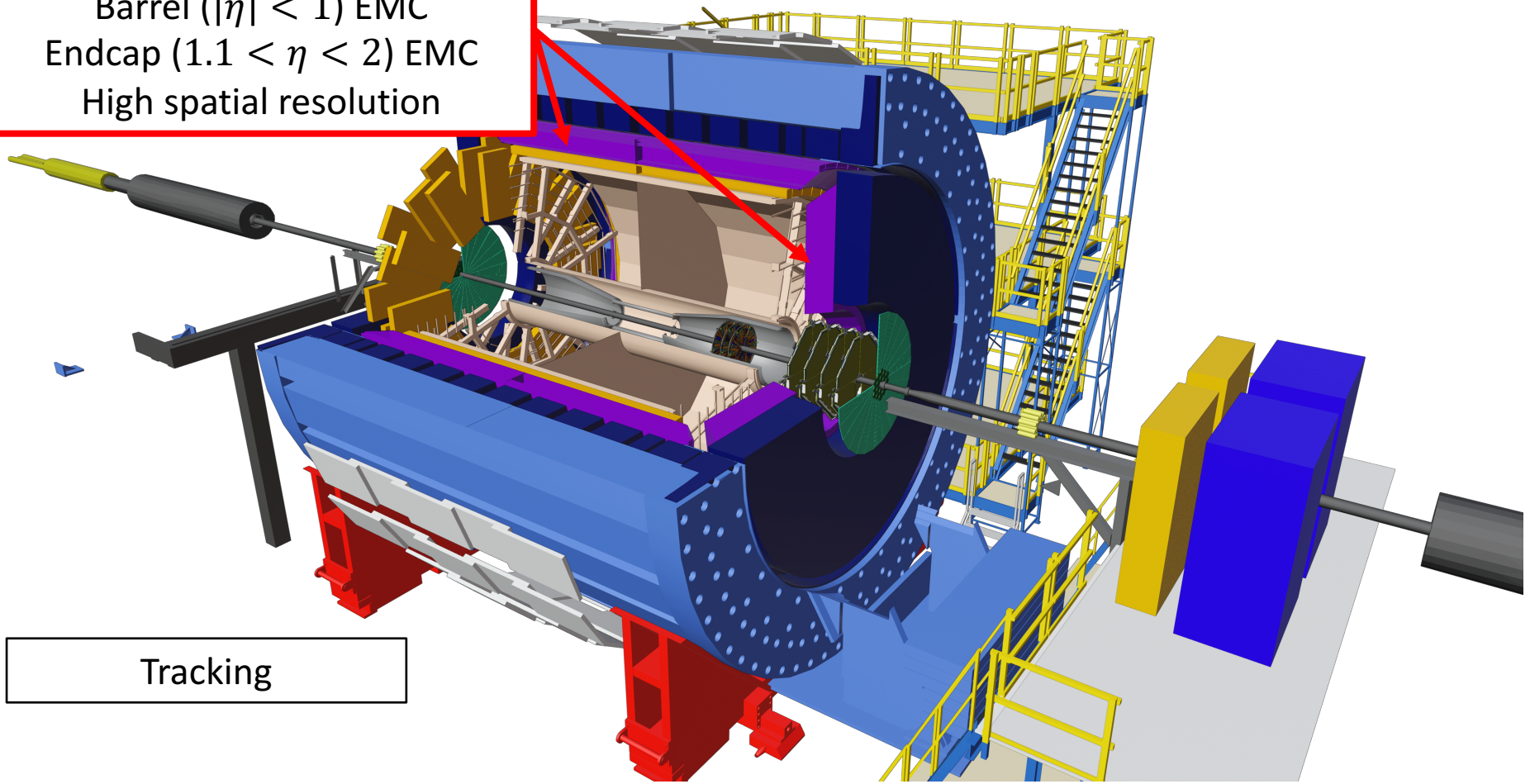
Tracking

*STAR BEMC, EEMC, TPC, TOF provide full-2$\pi$ coverage in azimuth.

# Solenoidal Tracker At RHIC

**Calorimetry**
Barrel ($|\eta| < 1$) EMC
Endcap ($1.1 < \eta < 2$) EMC
High spatial resolution

PID



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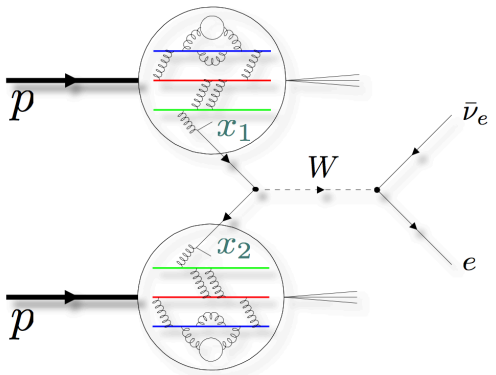
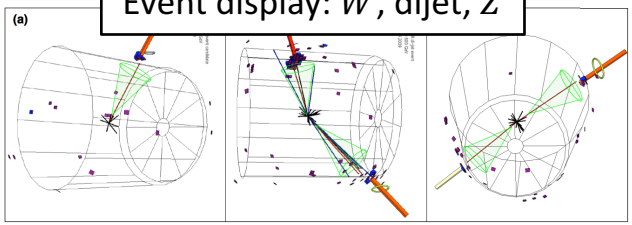
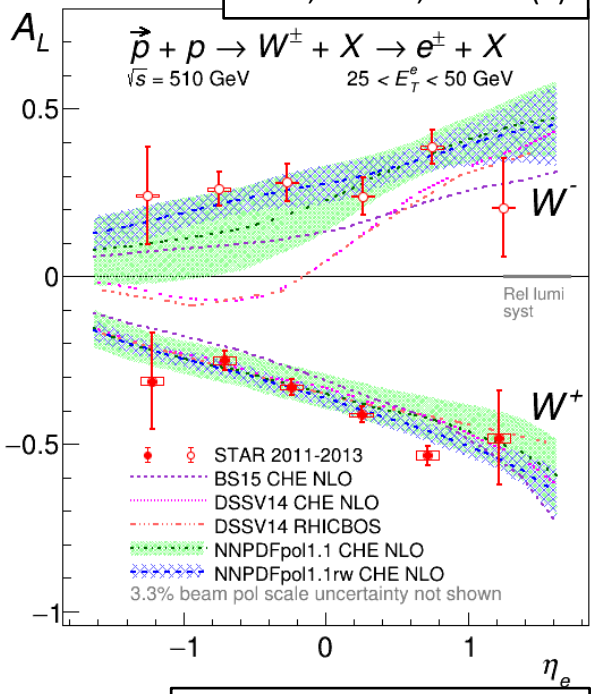
# $A_L$ with $W$ production at STAR



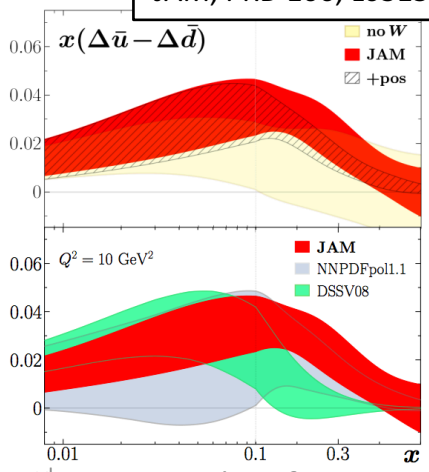

Event display: $W$, dijet, $Z$



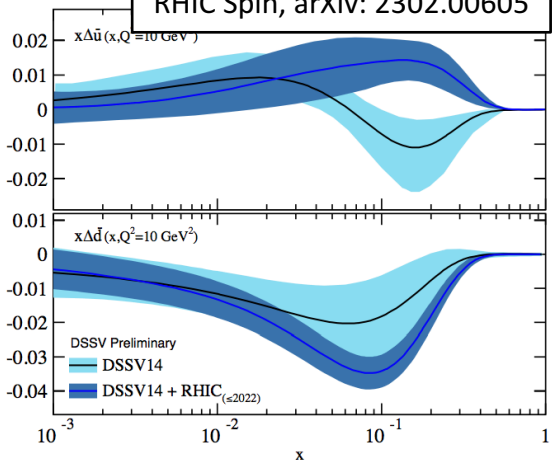

STAR, PRD 99, 051102(R)




JAM, PRD 106, L031502

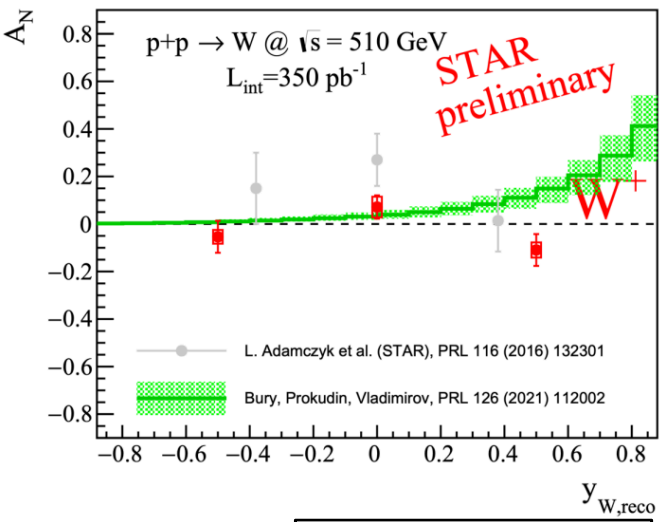


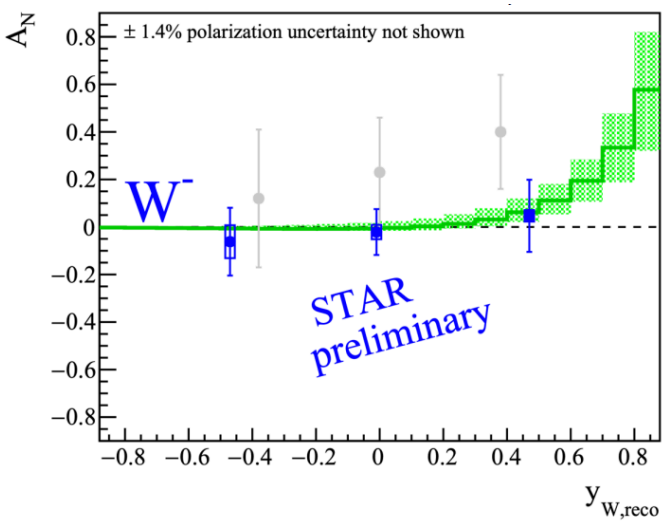

RHIC Spin, arXiv: 2302.00605



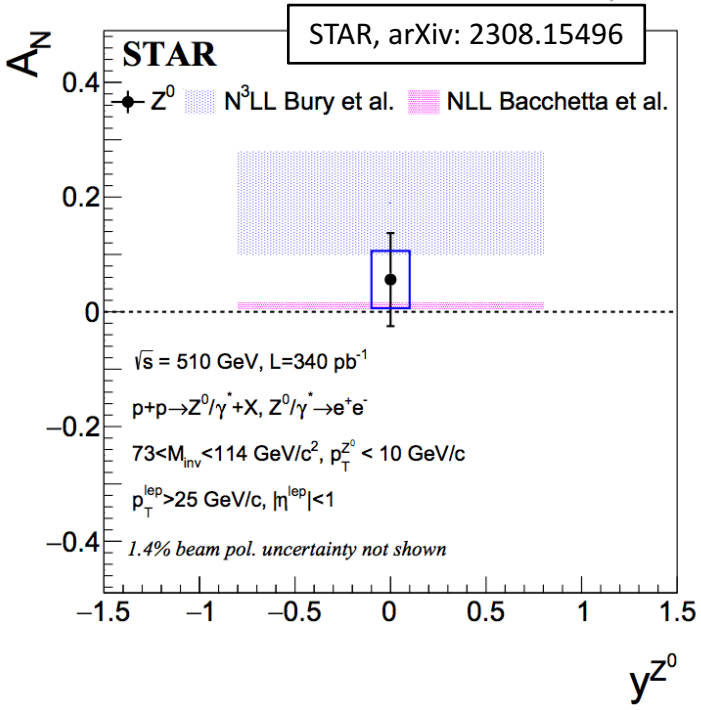

- Decay lepton $W \to e\nu$ tagged
- $A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$
  → Sensitive to $\Delta\bar{q}$.
  → Flavor given by $W$ charge
- Impact of STAR data in global fit favoring $\Delta\bar{u} > \Delta\bar{d}$
- Important constraints for non-pQCD models of $\bar{u}/\bar{d}$ asymmetry

# $A_N$ with $W/Z$ production at STAR



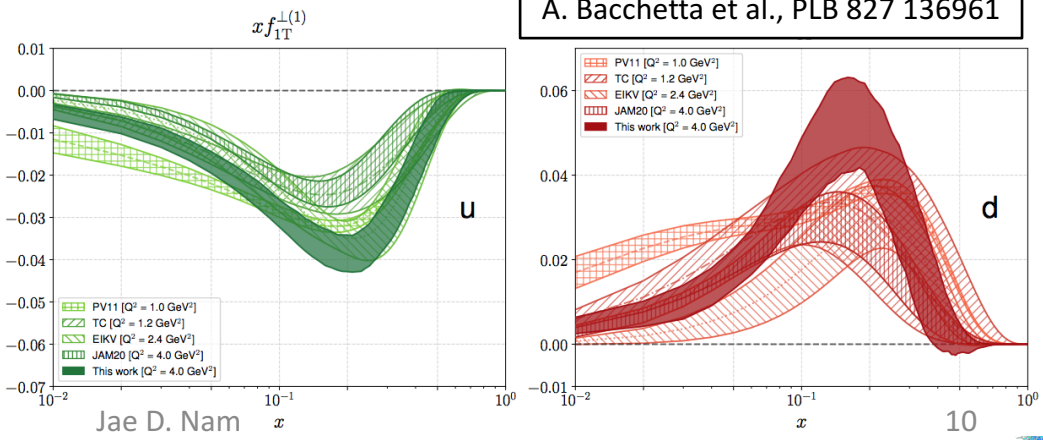




- Full $W$ kinematics reconstructed
- $Z$ bosons identified with $Z \rightarrow e^+e^-$
- $A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$ with transverse $pp$




- Tests of non-universal "sign-change" hypothesis of Sivers function between SIDIS/$W/Z$

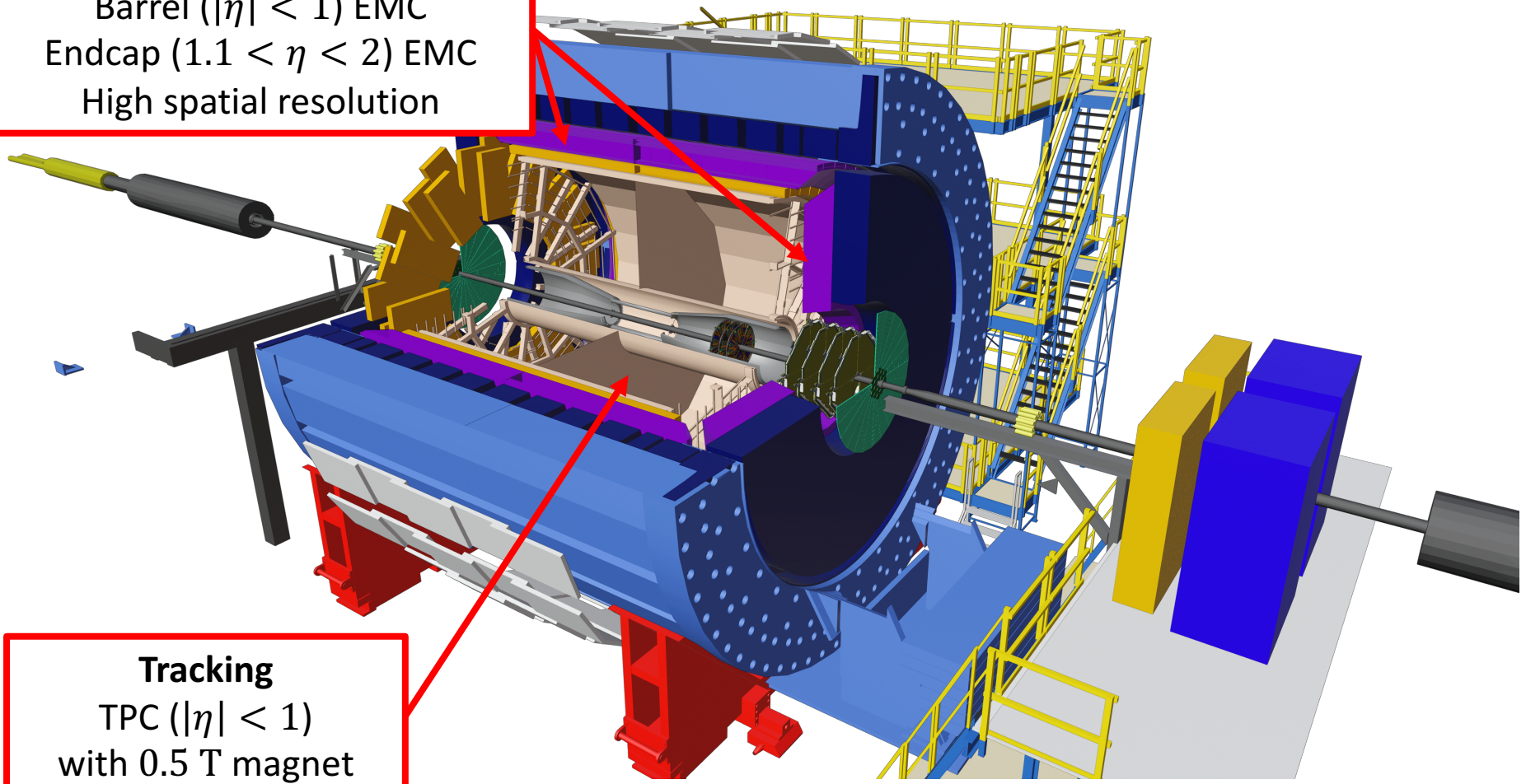
A. Bacchetta et al., PLB 827 136961



# Solenoidal Tracker At RHIC

**Calorimetry**
Barrel ($|\eta| < 1$) EMC
Endcap ($1.1 < \eta < 2$) EMC
High spatial resolution

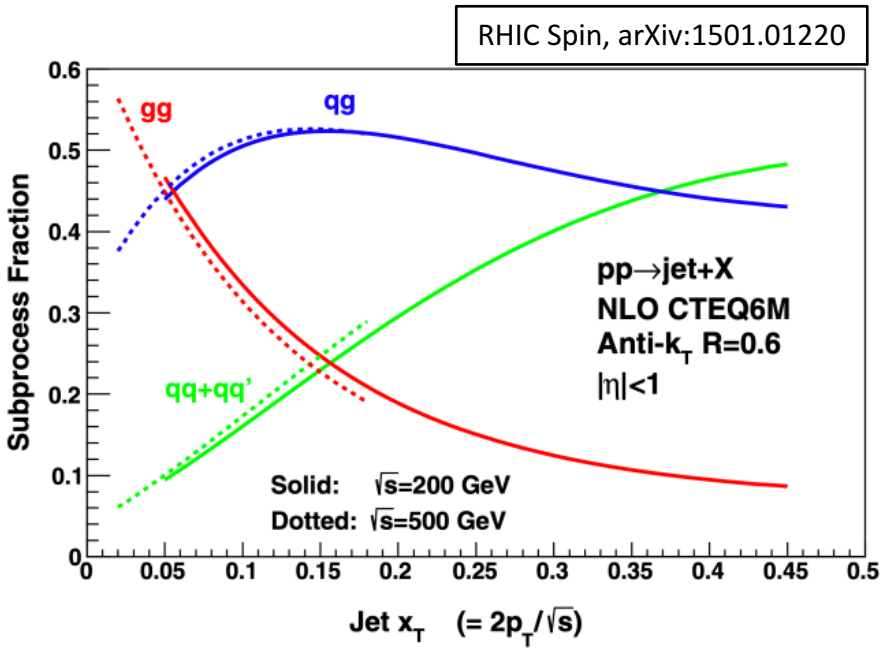
PID

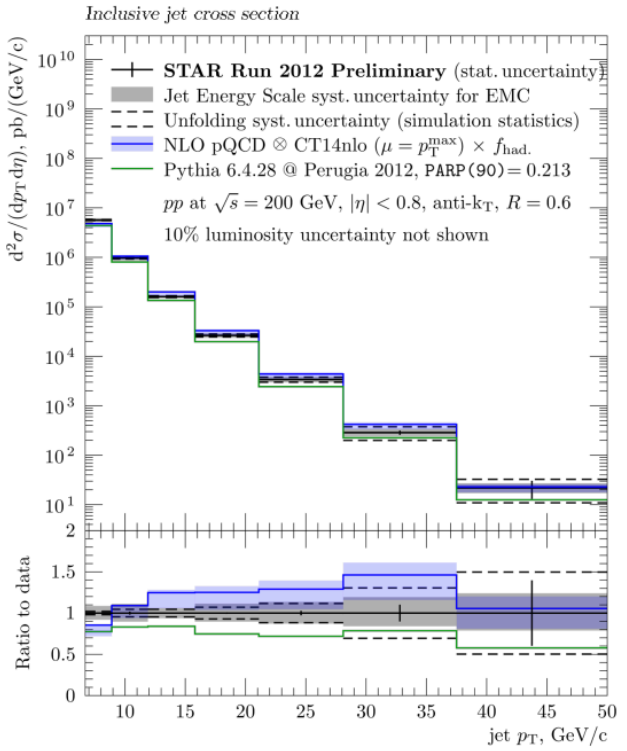


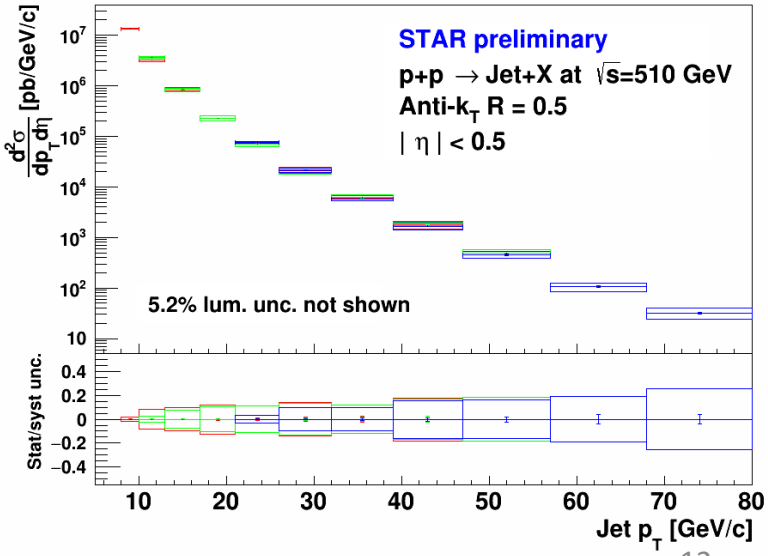
**Tracking**
TPC ($|\eta| < 1$)
with 0.5 T magnet

*STAR BEMC, EEMC, TPC, TOF provide full-$2\pi$ coverage in azimuth.

# Jets at STAR



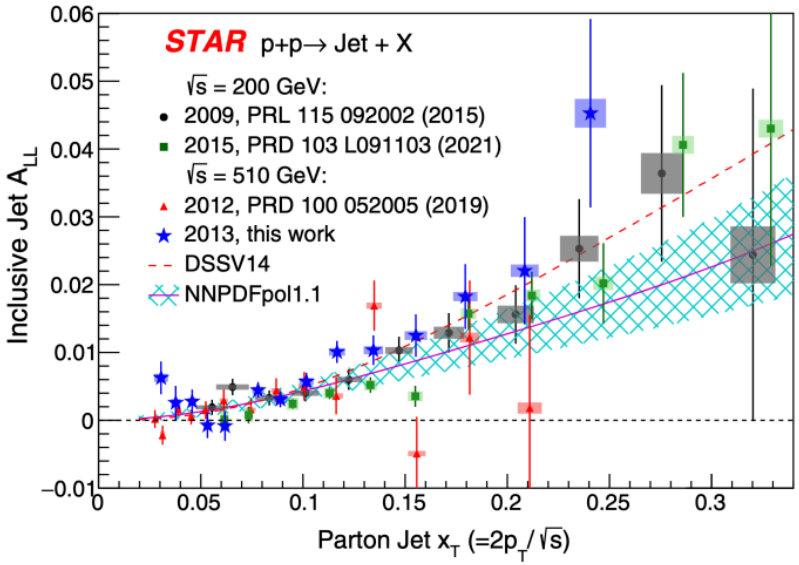



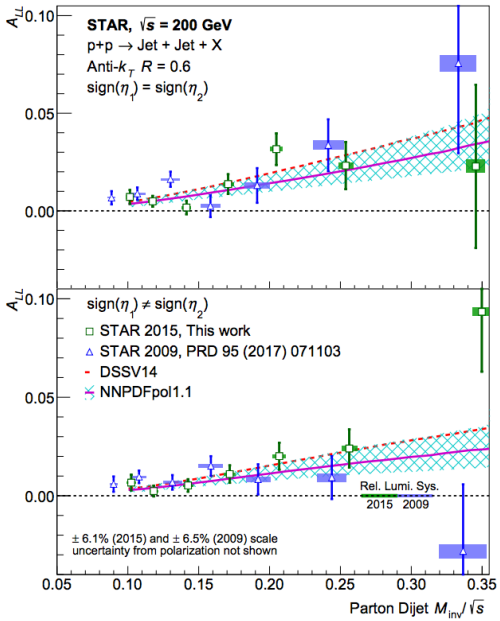



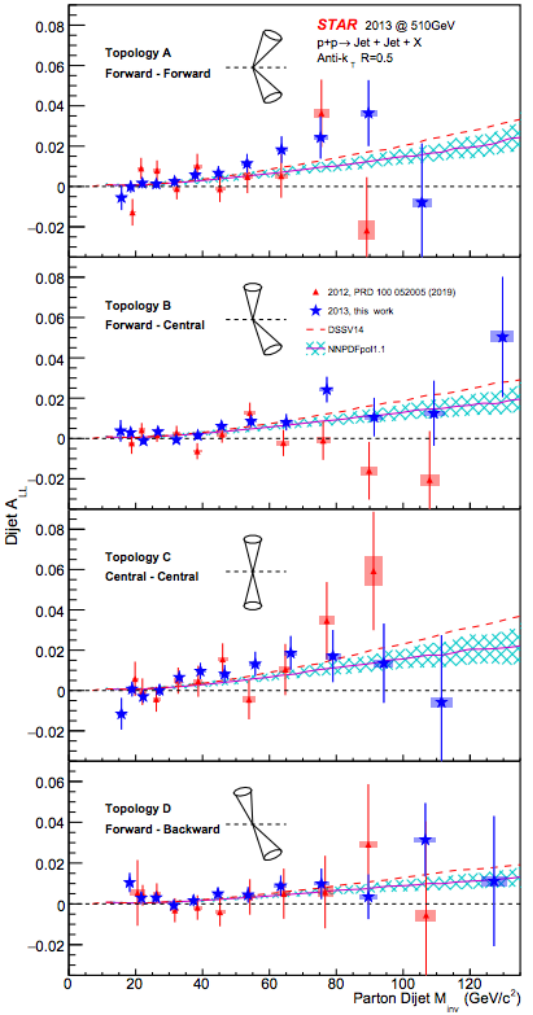

- Jets at STAR are sensitive to gluon (gg, qg)
- Anti-$k_T$ clustering algorithm with tracking + calorimetry info
- $R = 0.6\ (0.5)$ for $\sqrt{s} = 200\ (500/510) GeV$, motivated by UE
- Further tuning provided from unpolarized measurements

# Inclusive and Dijet $A_{LL}$

STAR, PRD 103, L091103 ($\sqrt{s} = 200\ GeV$)
STAR, PRD 105 092011 ($\sqrt{s} = 510\ GeV$)



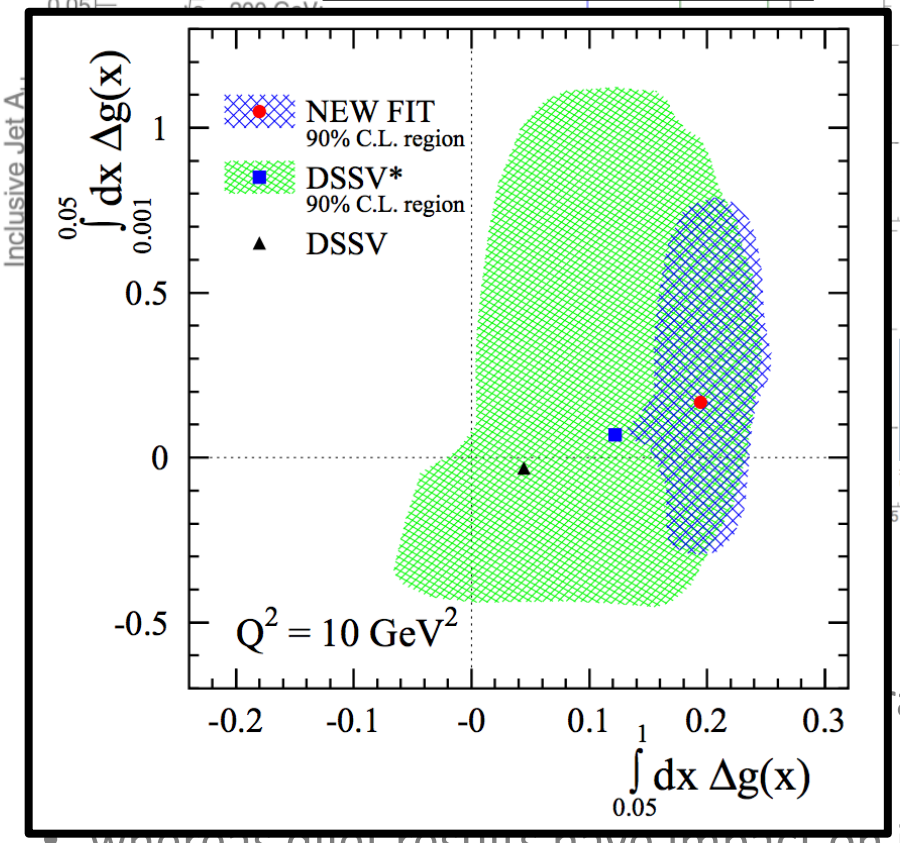




- $A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$ → sensitive to $\Delta g$
- Inclusive (left) results provide constraints on magnitude of $\Delta g$,
- whereas dijet results have impact on its functional form
- These measurements provide access to $x \gtrsim 0.015$

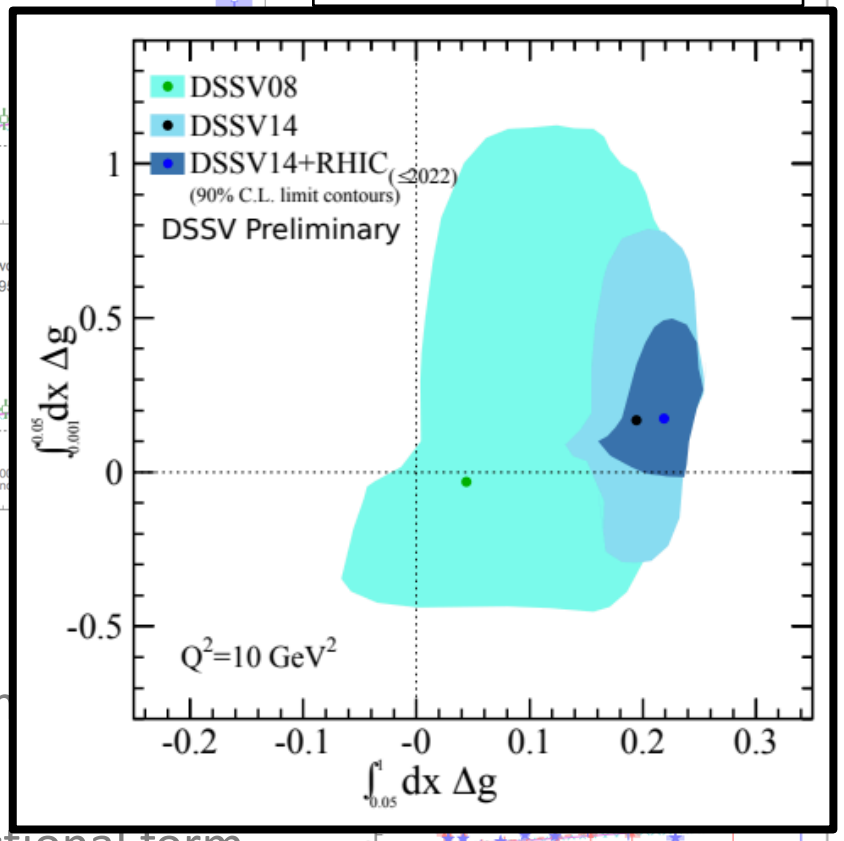
# Inclusive and Dijet $A_{LL}$

STAR, PRD 103, L091103 ($\sqrt{s} = 200\ GeV$)
STAR, PRD 105 092011 ($\sqrt{s} = 510\ GeV$)

DSSV, PRL 113 (2014) 1, 012001

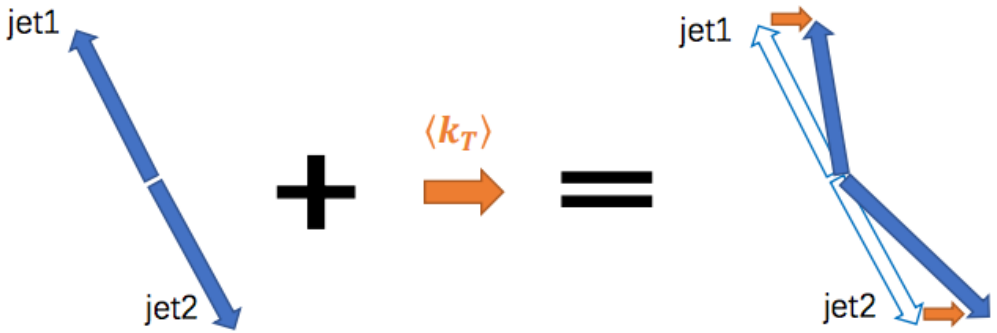


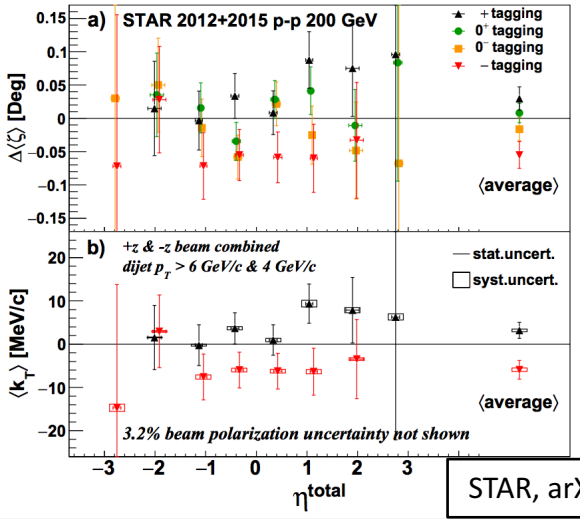

RHIC Spin, arXiv: 2302.00605




- Whereas dijet results have impact on its functional form
- These measurements provide access to $x \gtrsim 0.015$

# Dijet Azimuthal Correlation at STAR



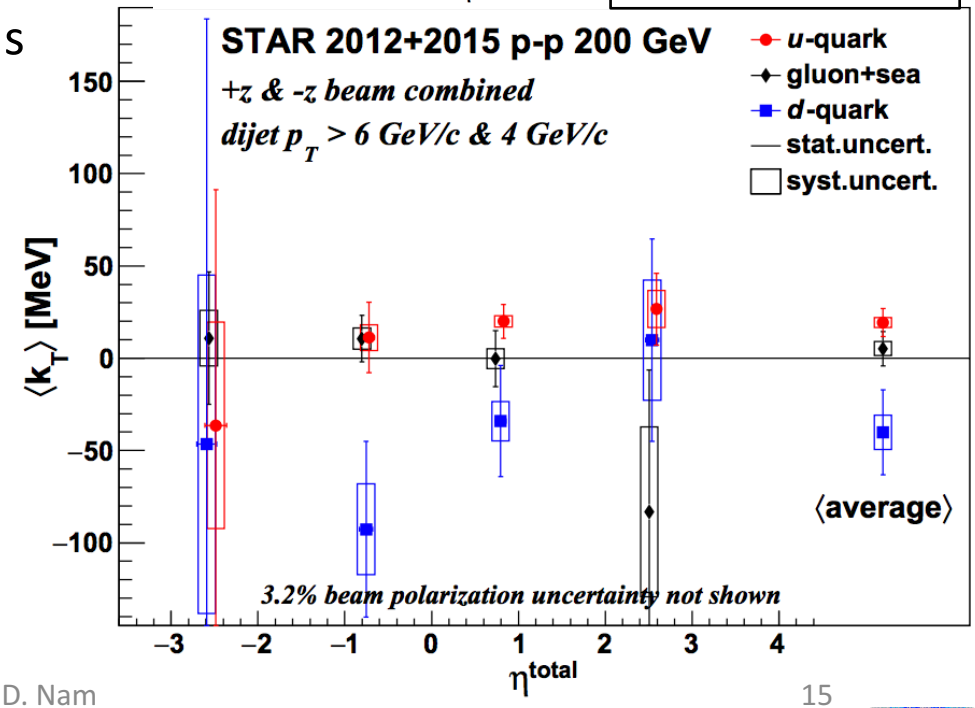

STAR, arXiv:2305.10359

- Azimuthal correlation in $pp$ dijet as proxy for intrinsic parton $k_T$
- "Jet-charge" to enhance flavor sensitivity

$$Q_{jet} = \Sigma_{trk} \frac{p_{trk}}{p_{jet}} \cdot Q_{trk}$$

$Q_{jet} > +0.25$: $u$ enhanced
$Q_{jet} < -0.25$: $d$ enhanced
$|Q_{jet}| < 0.25$: less $u$ and $d$ enhancement

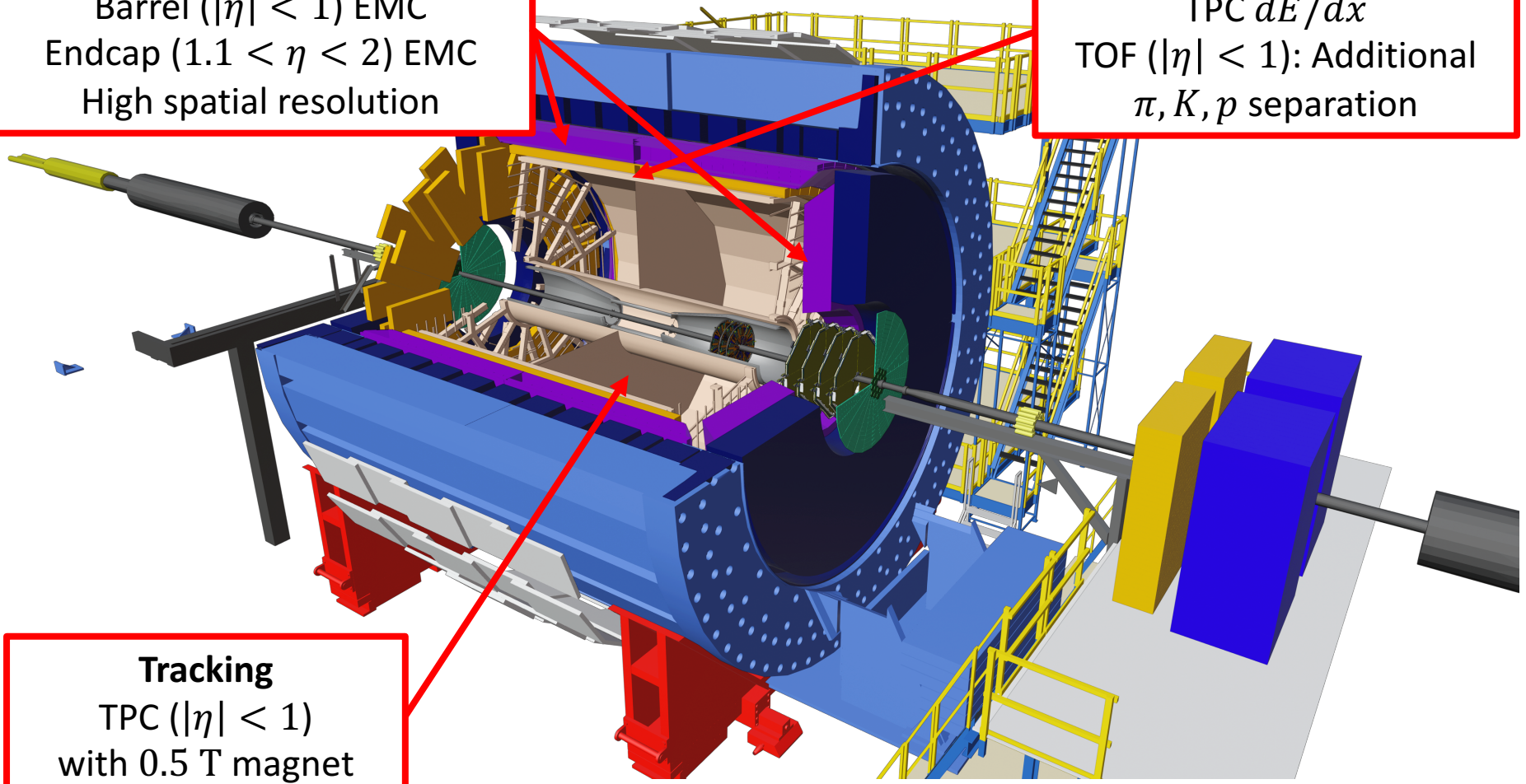
- First observation of $> 2\sigma$ Sivers asymmetries in polarized $pp$ collisions



# Solenoidal Tracker At RHIC

**Calorimetry**
Barrel ($|\eta| < 1$) EMC
Endcap ($1.1 < \eta < 2$) EMC
High spatial resolution

**PID**
TPC $dE/dx$
TOF ($|\eta| < 1$): Additional $\pi, K, p$ separation



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En… …itional

SM… …on

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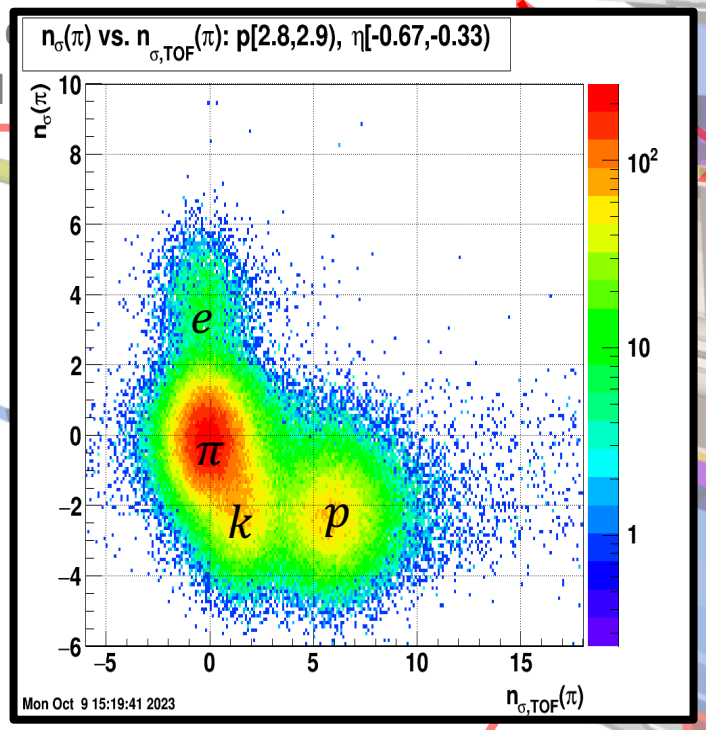


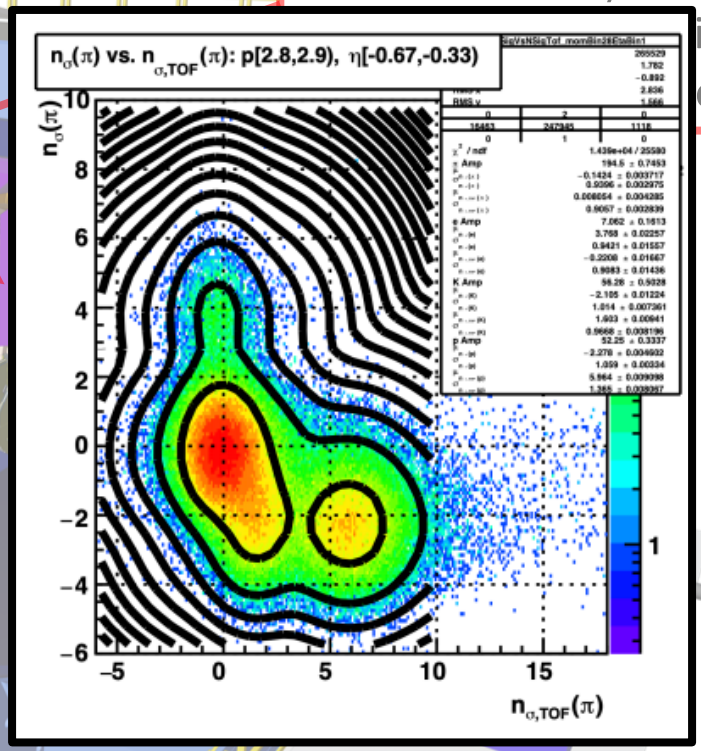


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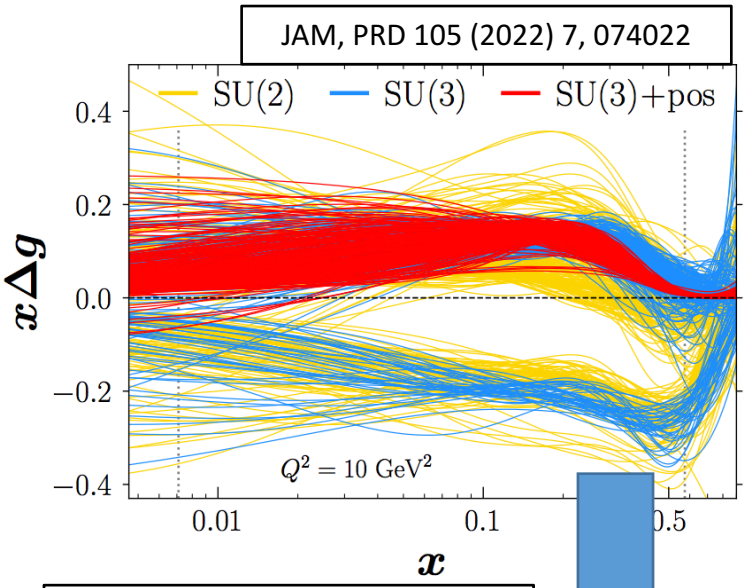
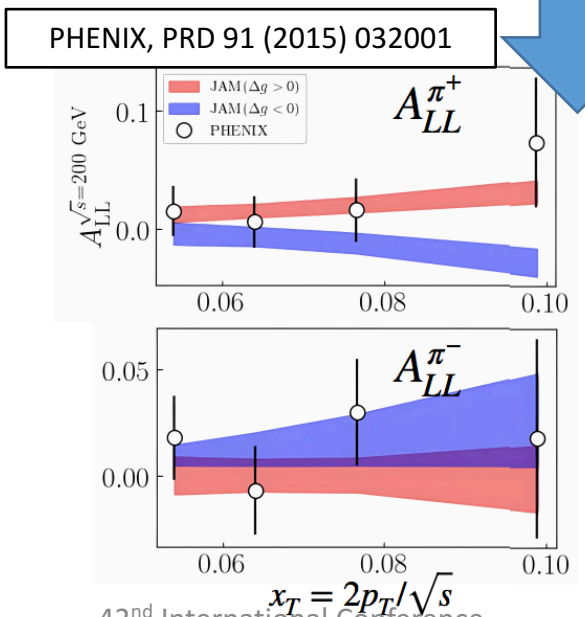
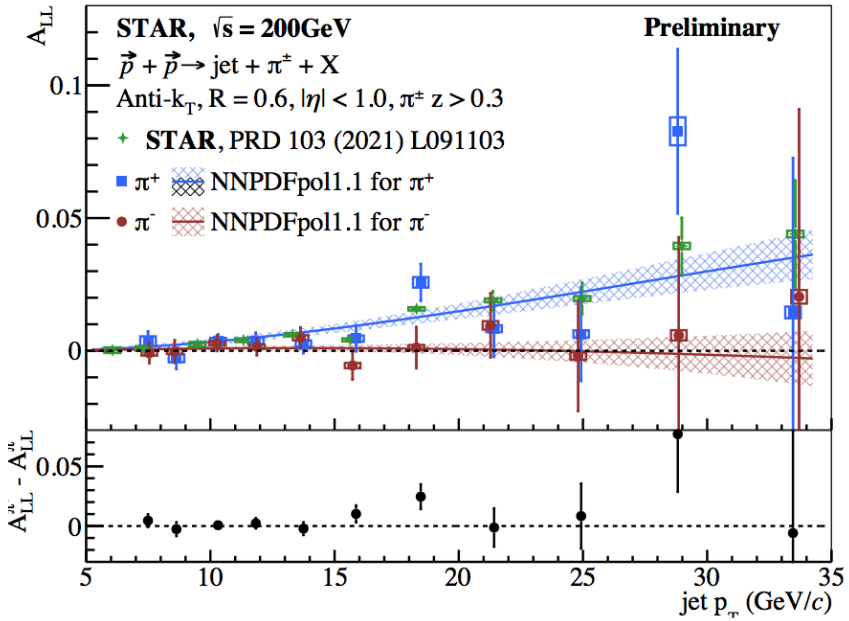
# $\pi^{\pm}$-Jet $A_{LL}$ at STAR



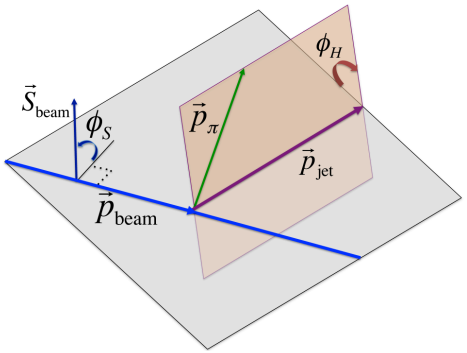




- Recent JAM QCD analysis (+STAR jet data) found two solutions for $\Delta g$ with opposite sign
- $\pi^{\pm}$-tagged $A_{LL}$ at STAR provides additional probe of sign of $\Delta g$

$$\Delta g > 0 \rightarrow A_{LL}^{\pi+} > A_{LL}^{\pi-} \qquad \Delta g < 0 \rightarrow A_{LL}^{\pi+} < A_{LL}^{\pi-}$$

- Latest STAR analysis of $A_{LL}^{\pi^{\pm}}$ prefers positive gluon helicity ($\Delta g > 0$)

# $\pi^{\pm}$- Jet $A_N$ at STAR

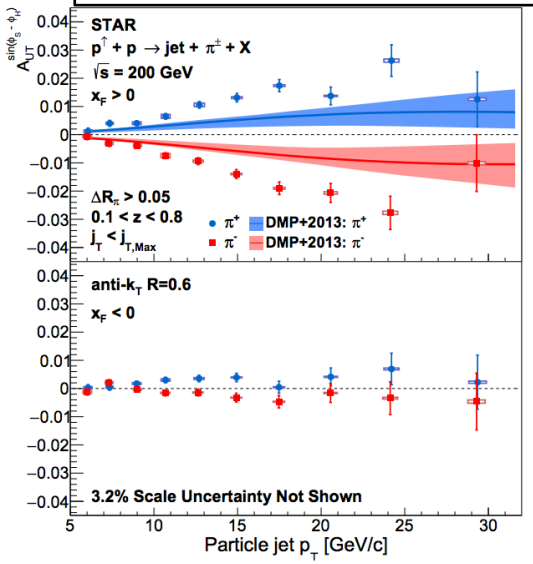


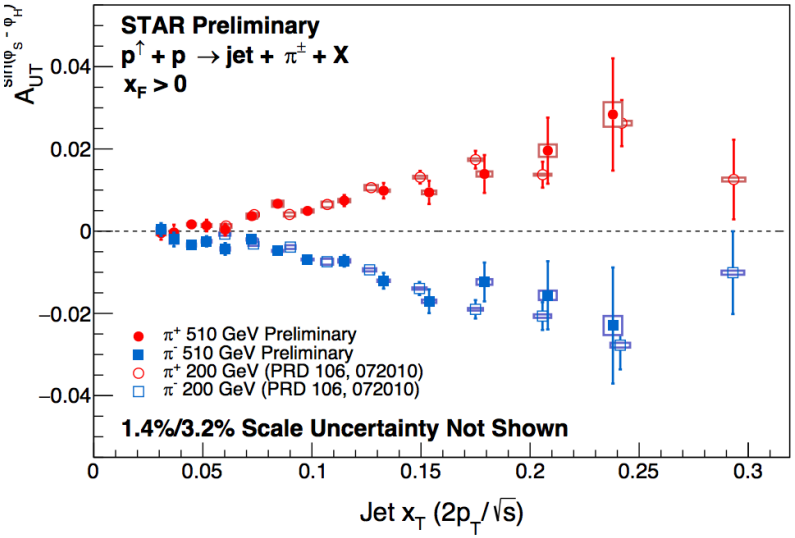

Collins Asymmetry

$$A_N^h = A_{UT}^{\sin(\phi_S)} \sin(\phi_S) + A_{UT}^{\sin(\phi_S-\phi_H)} \sin(\phi_S-\phi_H) + \cdots$$

$*A_{UT}^{\sin(\phi_S-\phi_H)} \sim h_1 \otimes H_1^{\perp}$ (Collins FF)

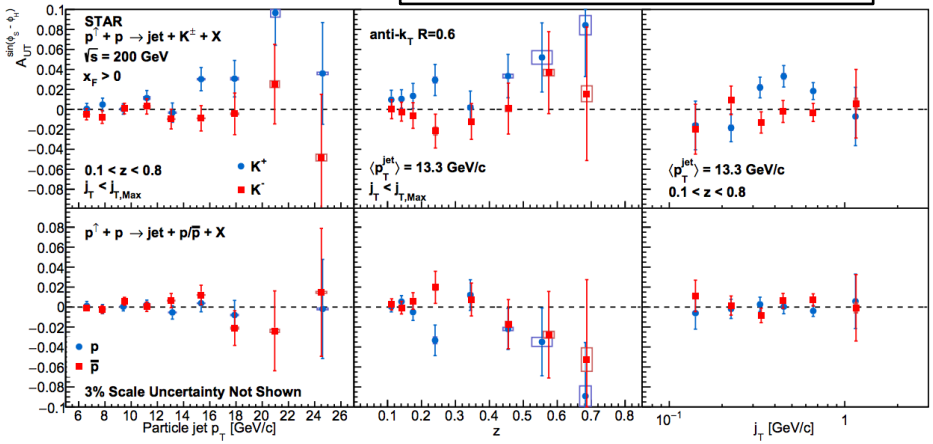
STAR, PRD 106 (2022) 7, 072010



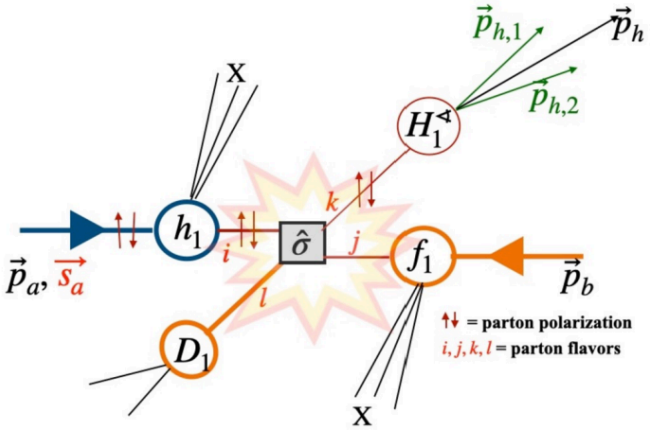



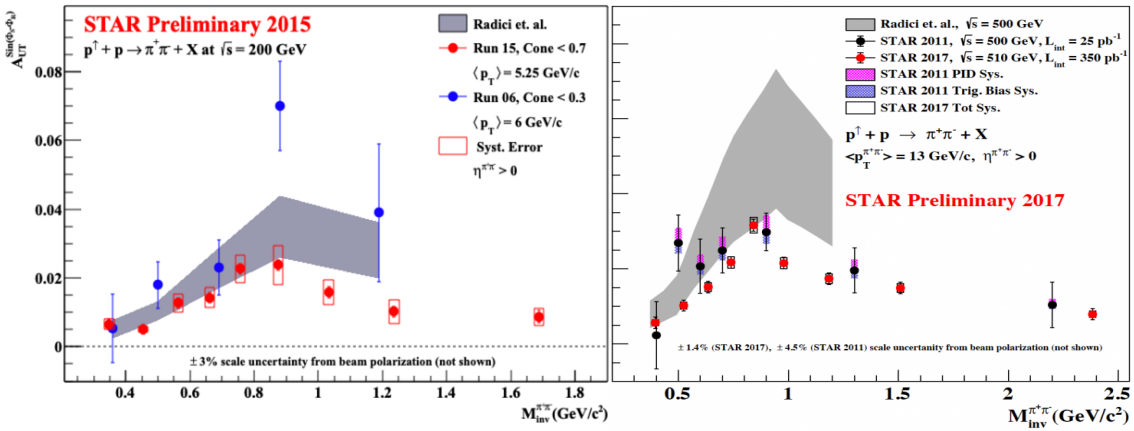

- Model calculations underestimate STAR data.
- No strong energy dependence → Important constraints on the scale evolution of Collins asymmetry
- Measurements with $K$, $p$ investigate dynamical origins of Collins FF

STAR, PRD 106 (2022) 7, 072010



# Hadrons w/o Jet Reconstruction



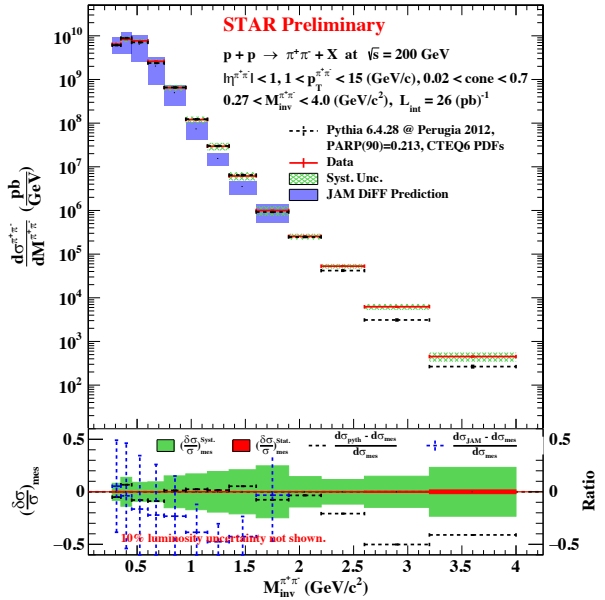




- $A_N$ with hadron pair provides complementary extraction of transversity

$$A_{UT}^{\sin(\phi_S - \phi_R)} \propto h_1 \otimes H_1^\sphericalangle \text{ (Interference FF)}$$

- Unpolarized hadron-pair cross section to extract unpolarized di-hadron FF
  → Improve systematics in interpretation $A_{UT} \to h_1$

- Choice of hadron pair ($\pi\pi$, $KK$, $\pi K$) provides flavor sensitivity



# Spin Transfers of Λ-hyperon

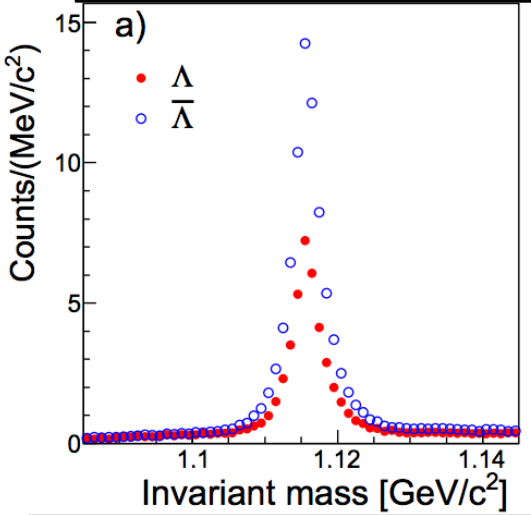
- $\Lambda$ reconstructed via $\Lambda \rightarrow p\pi$
- $P_\Lambda$ determined from angular distribution of decay daughters
  - $\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_\Lambda P_\Lambda \cos\theta^*$ $\theta^*$ = angle between $\Lambda$ & $p^*$

$$D_{LL}^{\Lambda} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \propto \Delta f \; \Delta D^{\Lambda} \rightarrow \text{Polarized FF}$$

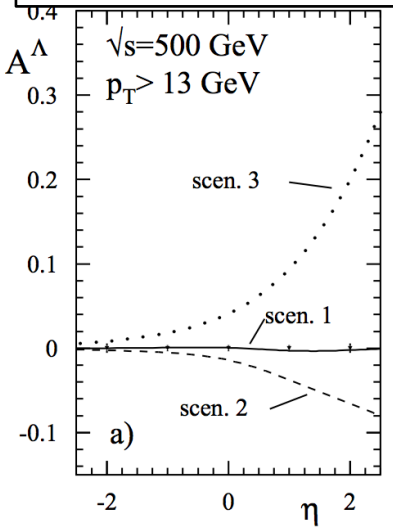
$$D_{TT}^{\Lambda} = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \propto h_1 \; \Delta_T D^{\Lambda} \rightarrow \text{Transverse PFF}$$

- $D_{LL}^{\Lambda}/D_{TT}^{\Lambda}$ probes strange helicity/transversity and origin of PFFs
  - Scen. 1: only $s$ contributes to $P_\Lambda$
  - Scen. 2: $u, d$ contribute in opposite direction
  - Scen. 3: equal contributions from $u, d, s$

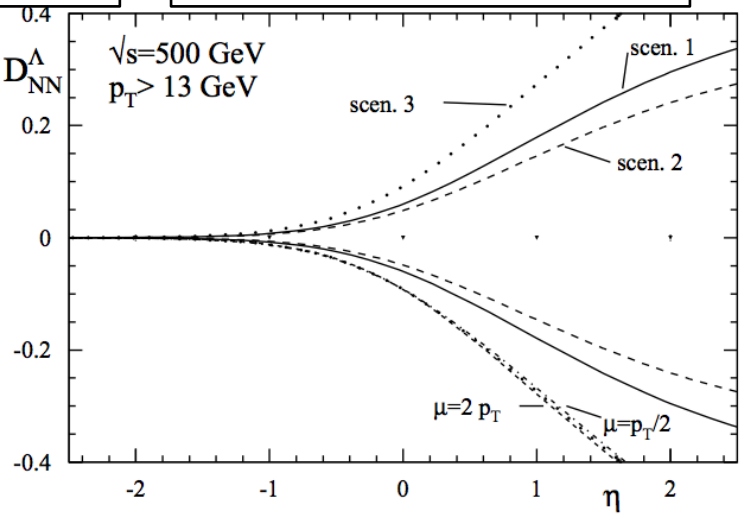
STAR, PRD 98 (2018) 11, 112009




de Florian et al., PRL 81, 530 (1998)

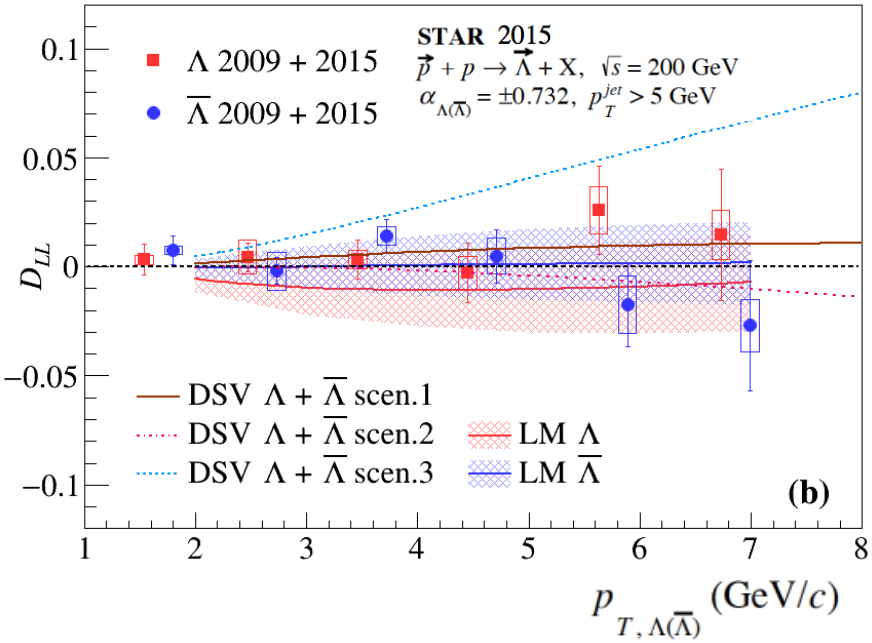


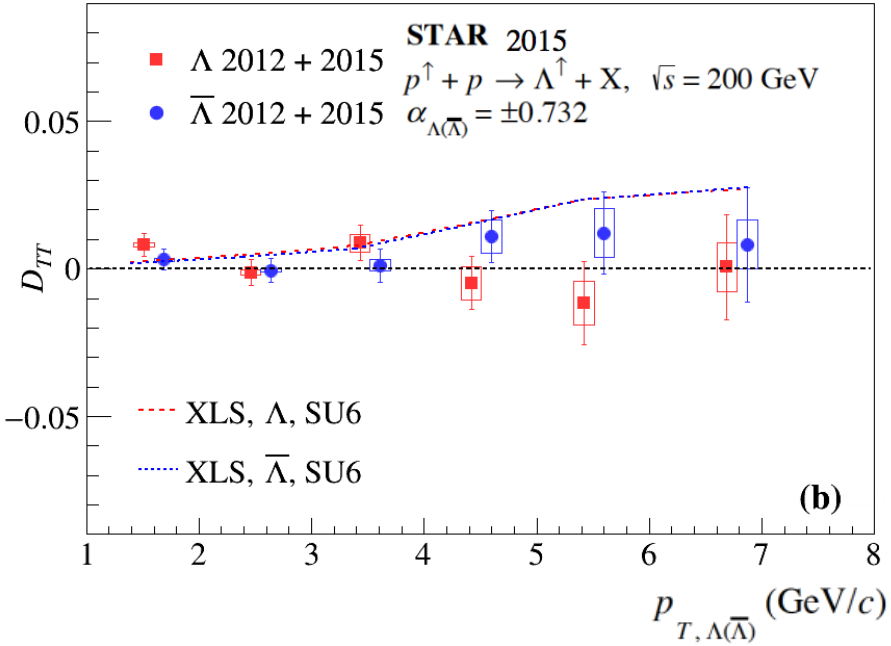

de Florian et al., PLB 439, 176 (1998)



# $D_{LL}^{\Lambda}$ and $D_{TT}^{\Lambda}$ at STAR

STAR, arXiv:2309.14220



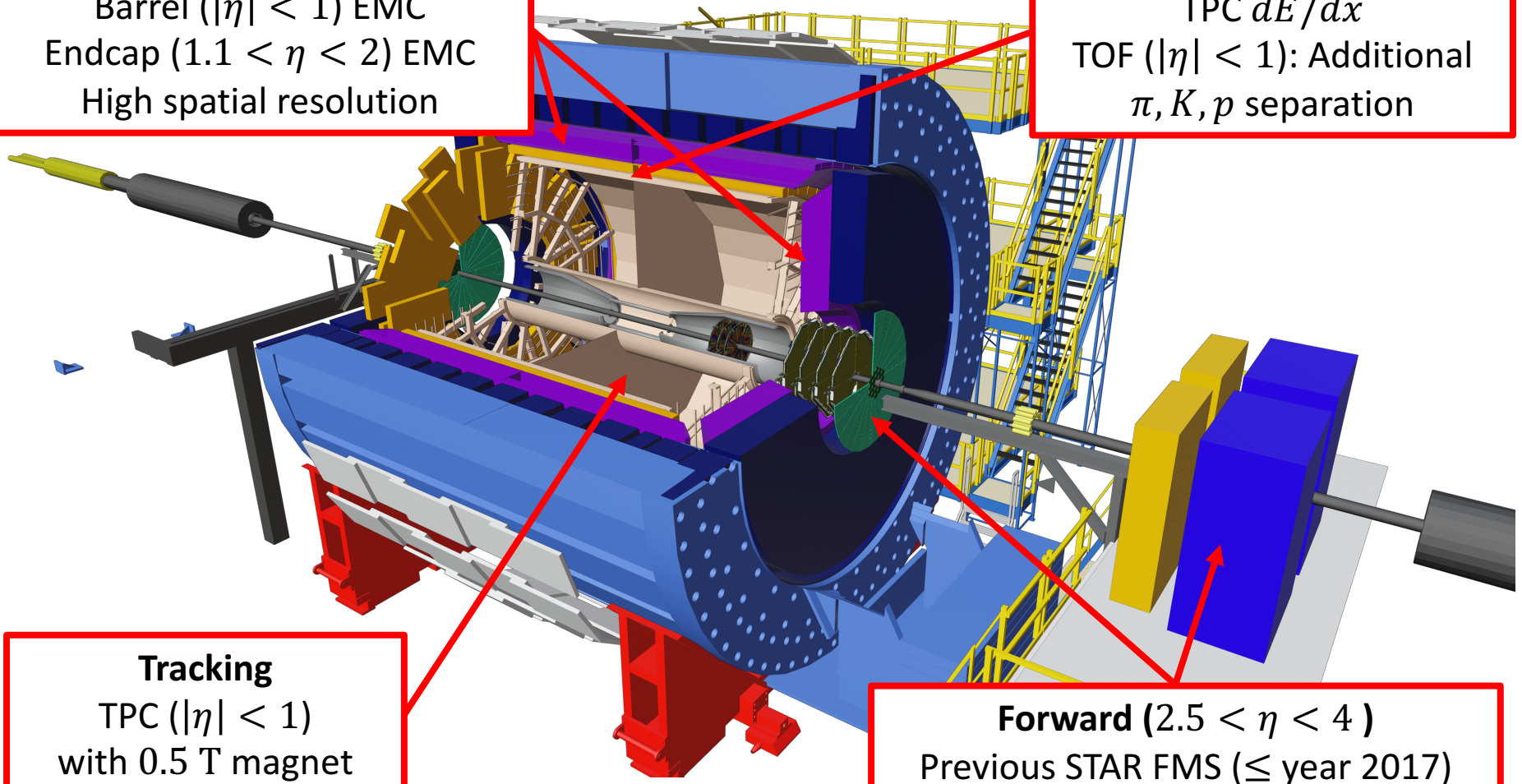




- $D_{LL}$ with STAR data prefers scen. 1 & 2 over 3
- $D_{TT}$ result consistent with zero
- $z$ ($\equiv \frac{p_{\Lambda} \cdot p_{jet}}{|p_{jet}|^2}$)-dependent extraction in relation to induced jet also performed, providing direct constraints on PFFs

# Forward Region

**Calorimetry**
Barrel ($|\eta| < 1$) EMC
Endcap ($1.1 < \eta < 2$) EMC
High spatial resolution

**PID**
TPC $dE/dx$
TOF ($|\eta| < 1$): Additional $\pi, K, p$ separation

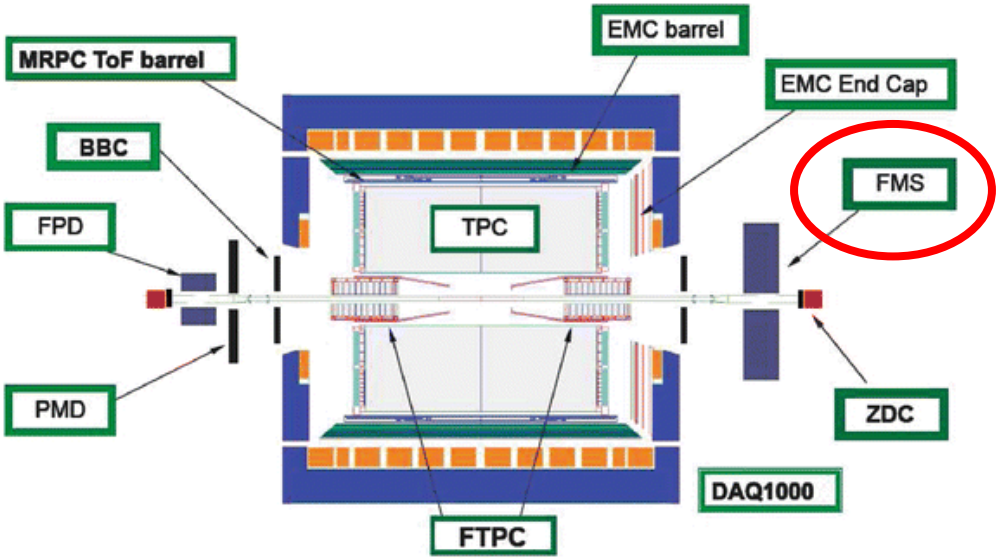


**Tracking**
TPC ($|\eta| < 1$)
with 0.5 T magnet

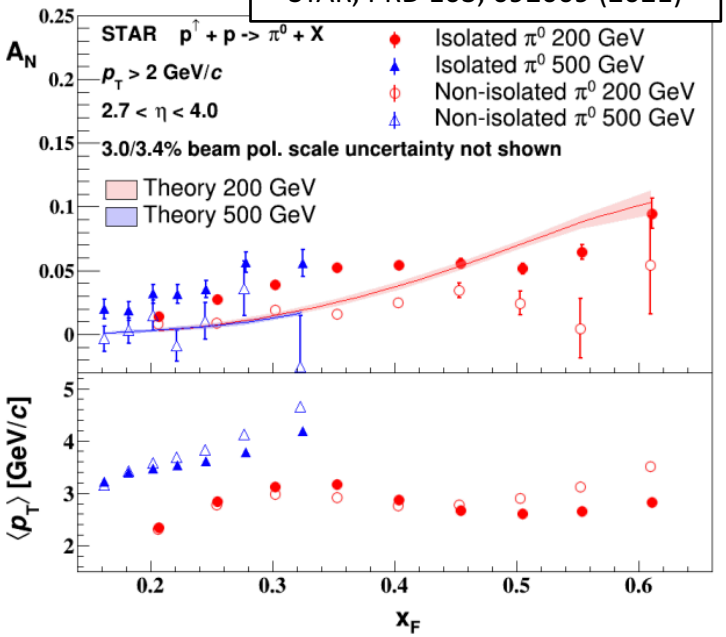
**Forward** ($2.5 < \eta < 4$)
Previous STAR FMS ($\leq$ year 2017)
STAR Forward Upgrade ($\geq$ 2022)

*STAR BEMC,

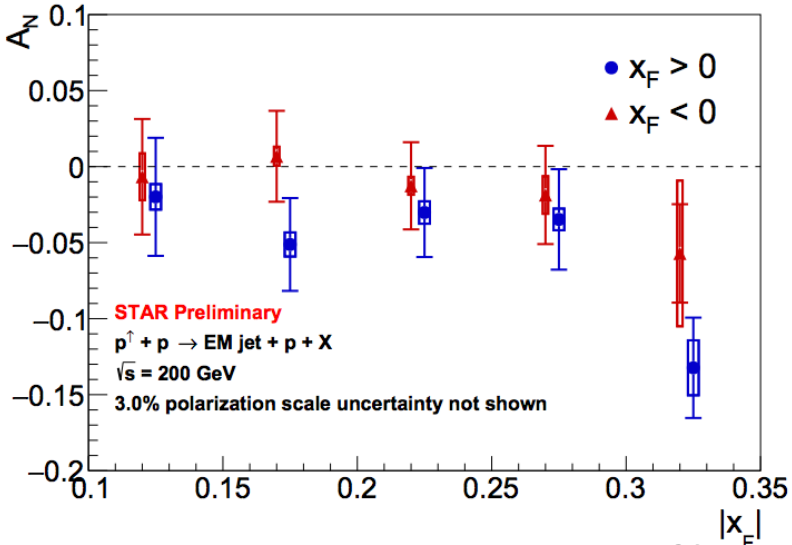
# Measurements with previous FMS




STAR, PRD 103, 092009 (2021)




- Measurements of $\pi^0$-$A_N$ with previous STAR FMS subdetector hints non-trivial contribution to large $A_N$ from diffractive process
- $A_N$ with EM-jet from diffractive process currently under investigation



# Forward Upgrade

**Forward-rapidity: 2.5 < η < 4**

## A+A

**Beam:**
Full Energy AuAu

**Physics Topics:**
- Temperature dependence of viscosity through flow harmonics up to η~4
- Longitudinal decorrelation up to η~4
- Global Lambda Polarization → strong rapidity dependence

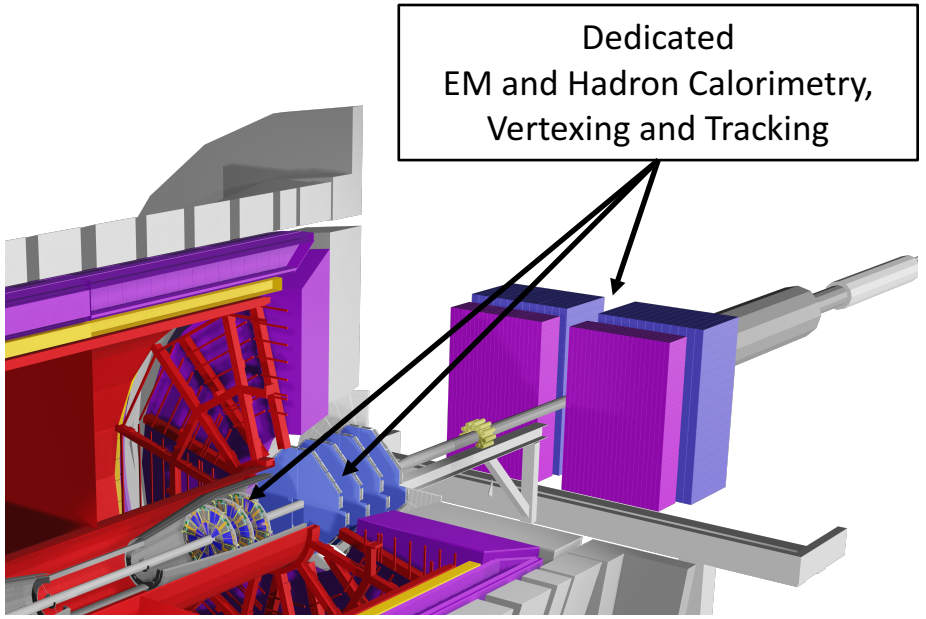
## p+p & p+A

**Beam:**
508 GeV: p+p
200 GeV: p+p and p+A

Hopefully!

**Physics Topics:**
- Sivers asymmetries for hadrons, (tagged) jets, and di-jets
- Collins asymmetries at high x transversity → tensor charge
- GPD $E_g$: gluon spin-orbit correlations
- Gluon PDFs for nuclei
  - $R_{pA}$ for direct photons & DY
- Test of Saturation predictions through di-hadrons, γ-Jets

*STAR* Forward Upgrade – SPIN 2023 – Carl Gagliardi



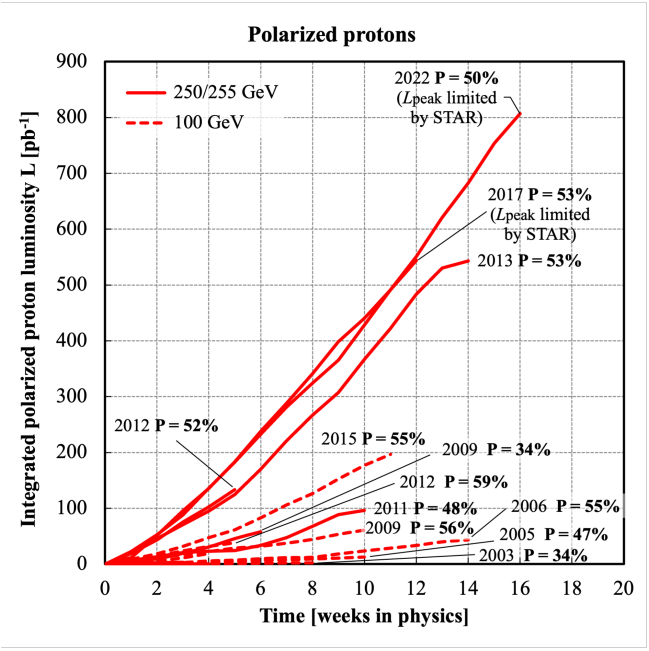

- STAR Forward Upgrade has operated successfully during 2022 and 2023
- Enables a wide range of high-impact measurements at STAR

# Summary

- Successful and continued running of RHIC
  + large acceptance & excellent PID at STAR allow:
    - Measurements of $W/Z$ to probe anti-quark polarization and "sign-change" of Sivers effect in $pp$
    - Jet production to extract gluon polarization and intrinsic parton $k_T$
    - Hadrons within jets further constraining sign of gluon polarization and quark transversity via Collins FF
    - Hadrons, without jet association, as complementary probe of transversity via Interference FF and strange contribution to proton spin
- Exciting spin physics opportunities with STAR forward upgrade
  - Stay Tuned!

# Back up

# RHIC $pp$ Run Overview

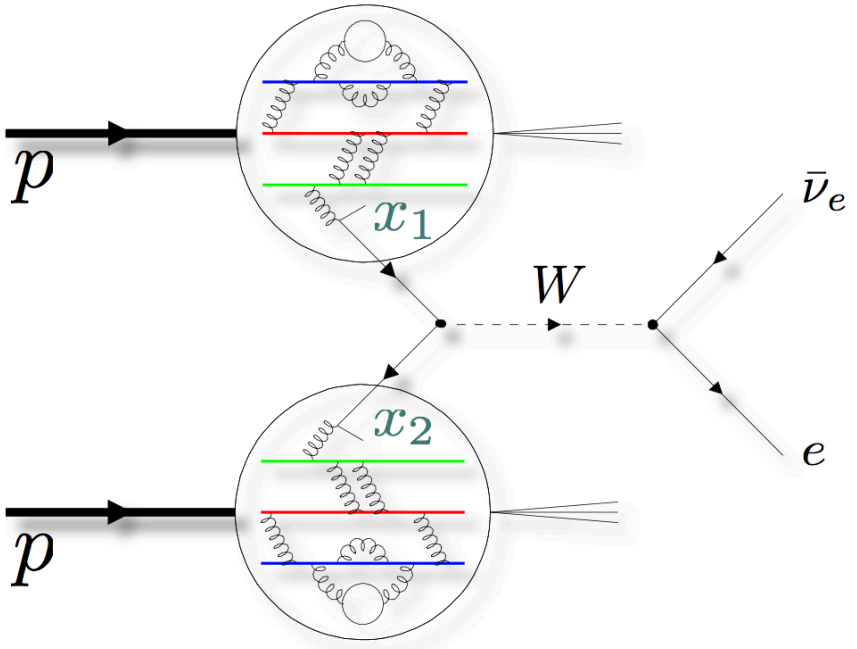



| Longitudinally-Polarized $pp$ Runs | | | | | | |
|---|---|---|---|---|---|---|
| Year | 2009 | 2009 | 2011 | 2012 | 2013 | 2015 |
| $\sqrt{s}$ (GeV) | 200 | 500 | 500 | 510 | 510 | 200 |
| $L_{\text{int}}^{\text{STAR}}$ ($\text{pb}^{-1}$) | 25 | 10 | 12 | 82 | 300 | 52 |
| Pol. | 55% | 39% | 48% | 53% | 55% | 58% |

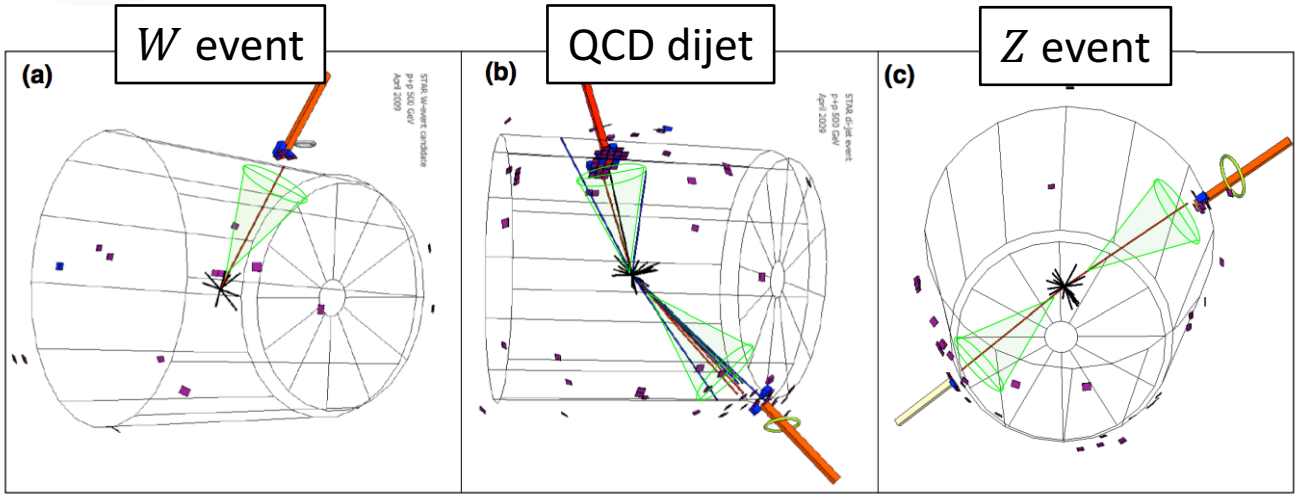
| Transversely-Polarized $pp$ Runs | | | | | | | *projection |
|---|---|---|---|---|---|---|---|
| Year | 2006 | 2011 | 2012 | 2015 | 2017 | 2022 | *2024 |
| $\sqrt{s}$ (GeV) | 200 | 500 | 200 | 200 | 510 | 508 | 200 |
| $L_{\text{int}}^{\text{STAR}}$ ($\text{pb}^{-1}$) | 1.8 | 25 | 22 | 52 | 350 | 400 | 140 |
| Pol. | 60% | 53% | 57% | 57% | 55% | 52% | |

- Key observables:
  - $W/Z$ ($\sqrt{s} \sim 500$ GeV), jet, hadron production with respect to proton spin orientation
- Two different energy modes provide large kinematic coverage and opportunities to study scale evolutions
- Polarized hadron data at RHIC provide reference for projected EIC polarized $ep$ data

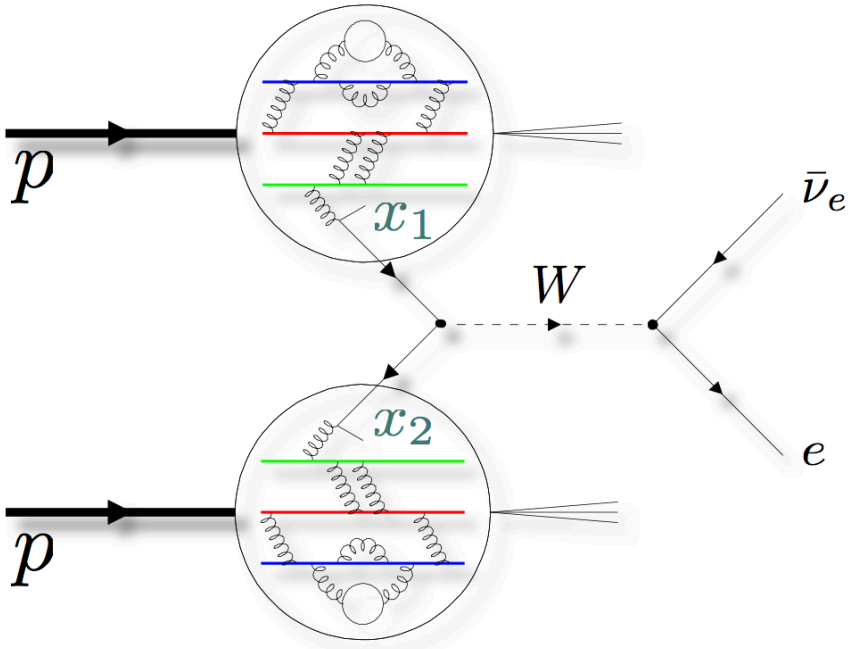
# Weak Boson Production at STAR




- Signs of $W$ production:
  - Decay electron $E_e \sim M_W/2$ w/ narrow shower
  - Missing energy from partnering neutrino
  - Clean signal, fully utilizing spatial/energy resolution of STAR EMC



# Weak Boson Production at STAR

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