

# PHYSICS IN COLLISION

42nd International Conference on Physics in Collision

October 10 – 13, 2023 | Universidad de Tarapacá, Arica, Chile

# PIC 2023

<https://indico.cern.ch/event/1190468/>

## Main Topics

Physics at the LHC  
 Electroweak Physics  
 Spectroscopy  
 Flavour Physics  
 Neutrino Physics  
 Heavy Ion Physics  
 Astroparticle Physics  
 Dark Matter Searches  
 Dark Sector  
 Gravitational waves  
 Cosmology

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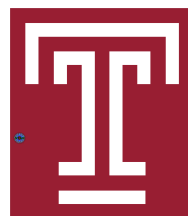


# An Overview of Spin Physics at STAR

Jae D. Nam

Temple Univ.

for the  **STAR** collaboration



Supported in part by:

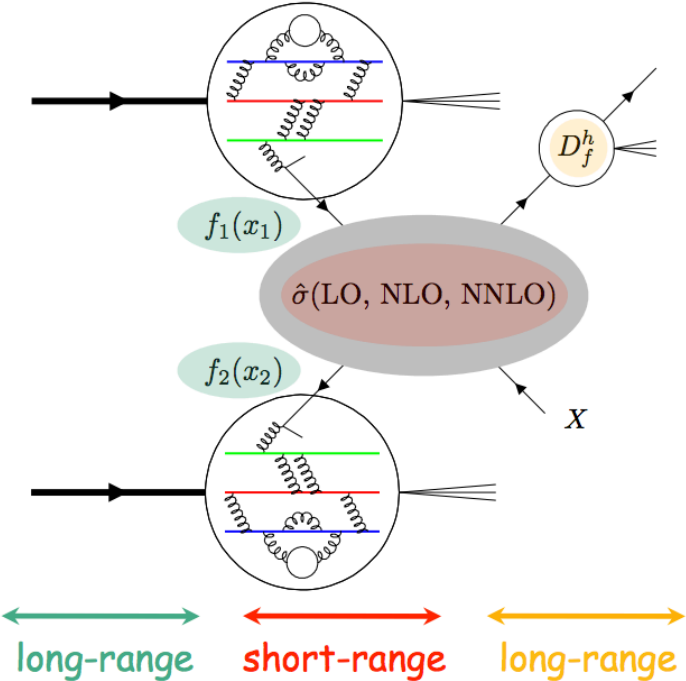


U.S. DEPARTMENT OF **ENERGY**

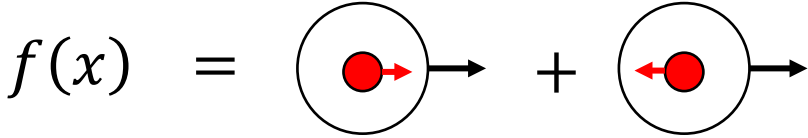
Office of Science



# Proton Structure in $pp$

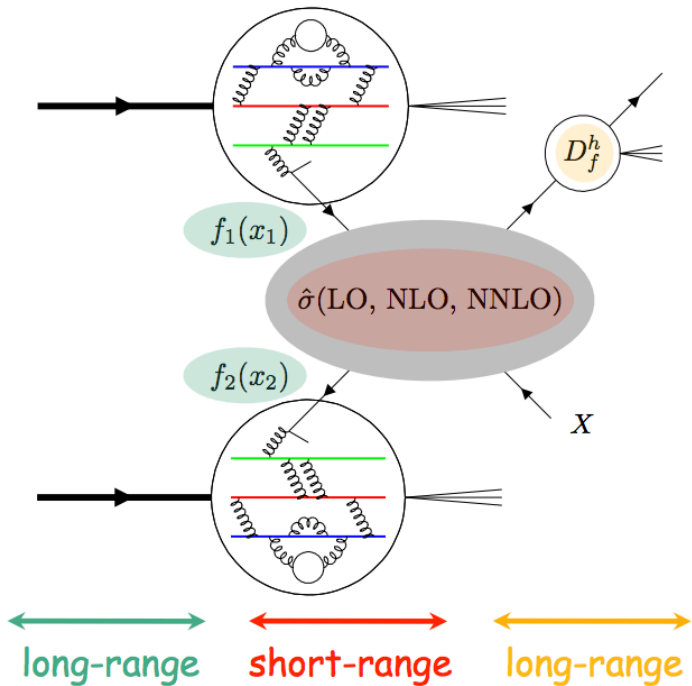


$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$





# With Longitudinally Polarized Proton



$$\Delta f(x) = \text{[circle with red dot and right arrow]} - \text{[circle with red dot and left arrow]}$$

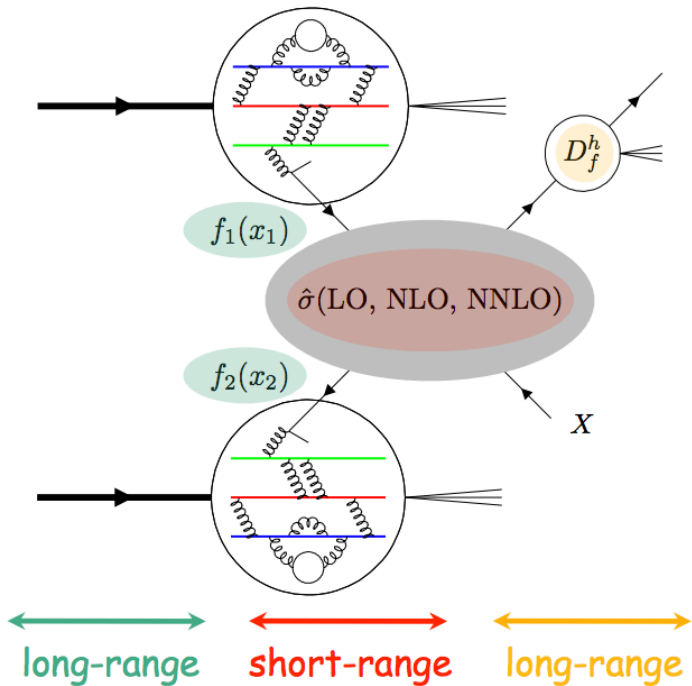
- Proton Spin:  $\frac{1}{2} = \frac{1}{2} \sum S_Z^q + S_Z^g + \sum L_Z^q + L_Z^g$
- DIS data consistent with ~30% quark helicity contribution
- RHIC data sensitive to sea quarks and gluon

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

$$f(x) = \text{[circle with red dot and right arrow]} + \text{[circle with red dot and left arrow]}$$



# With Transversely Polarized Proton



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

$$f(x) = \text{[Diagram of a proton with a red dot and a right-pointing arrow]} + \text{[Diagram of a proton with a red dot and a left-pointing arrow]}$$

$$\Delta f(x) = \text{[Diagram of a proton with a red dot and a right-pointing arrow]} - \text{[Diagram of a proton with a red dot and a left-pointing arrow]}$$

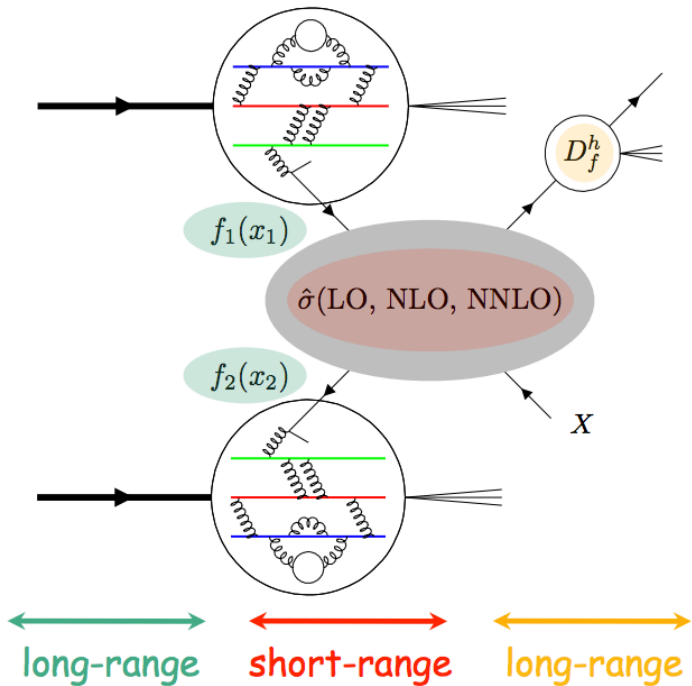
- Proton Spin:  $\frac{1}{2} = \frac{1}{2} \sum S_Z^q + S_Z^g + \sum L_Z^q + L_Z^g$
- DIS data consistent with  $\sim 30\%$  quark helicity contribution
- RHIC data sensitive to sea quarks and gluon

$$h_1(x) = \text{[Diagram of a proton with a red dot and an up-pointing arrow]} - \text{[Diagram of a proton with a red dot and a down-pointing arrow]}$$

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



# With Transversely Polarized Proton



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

$$f(x) = \text{[circle with red dot and right arrow]} + \text{[circle with red dot and left arrow]}$$

$$\Delta f(x) = \text{[circle with red dot and right arrow]} - \text{[circle with red dot and left arrow]}$$

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

$$h_1(x) = \text{[circle with red dot and up arrow]} - \text{[circle with red dot and down arrow]}$$

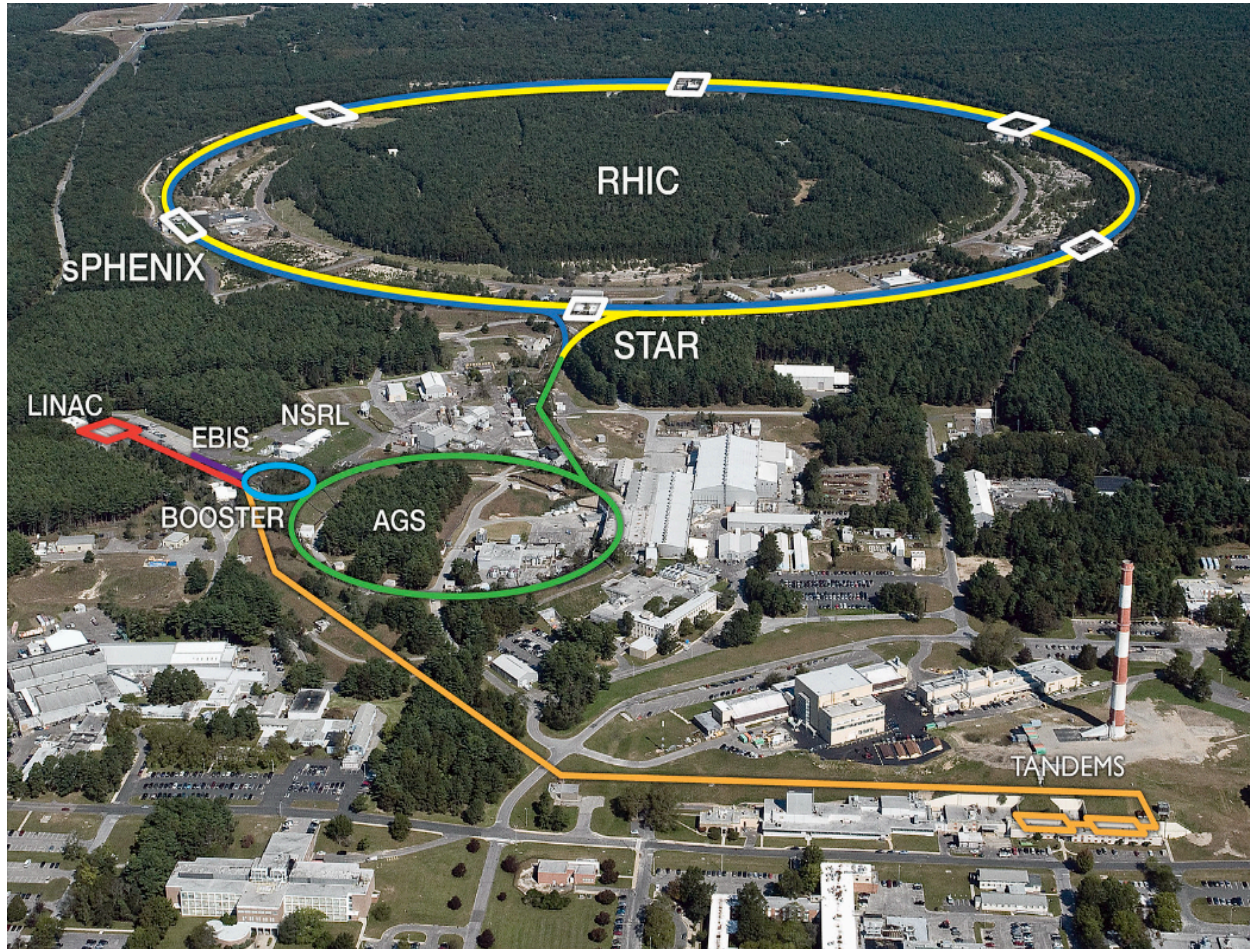
- Much less known
- Chirally-Odd
  - Cannot be measured inclusively
  - Requires chiral-odd partner (Collins/interference fragmentation functions (FF), etc)

## In Addition,

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



# Relativistic Heavy Ion Collider



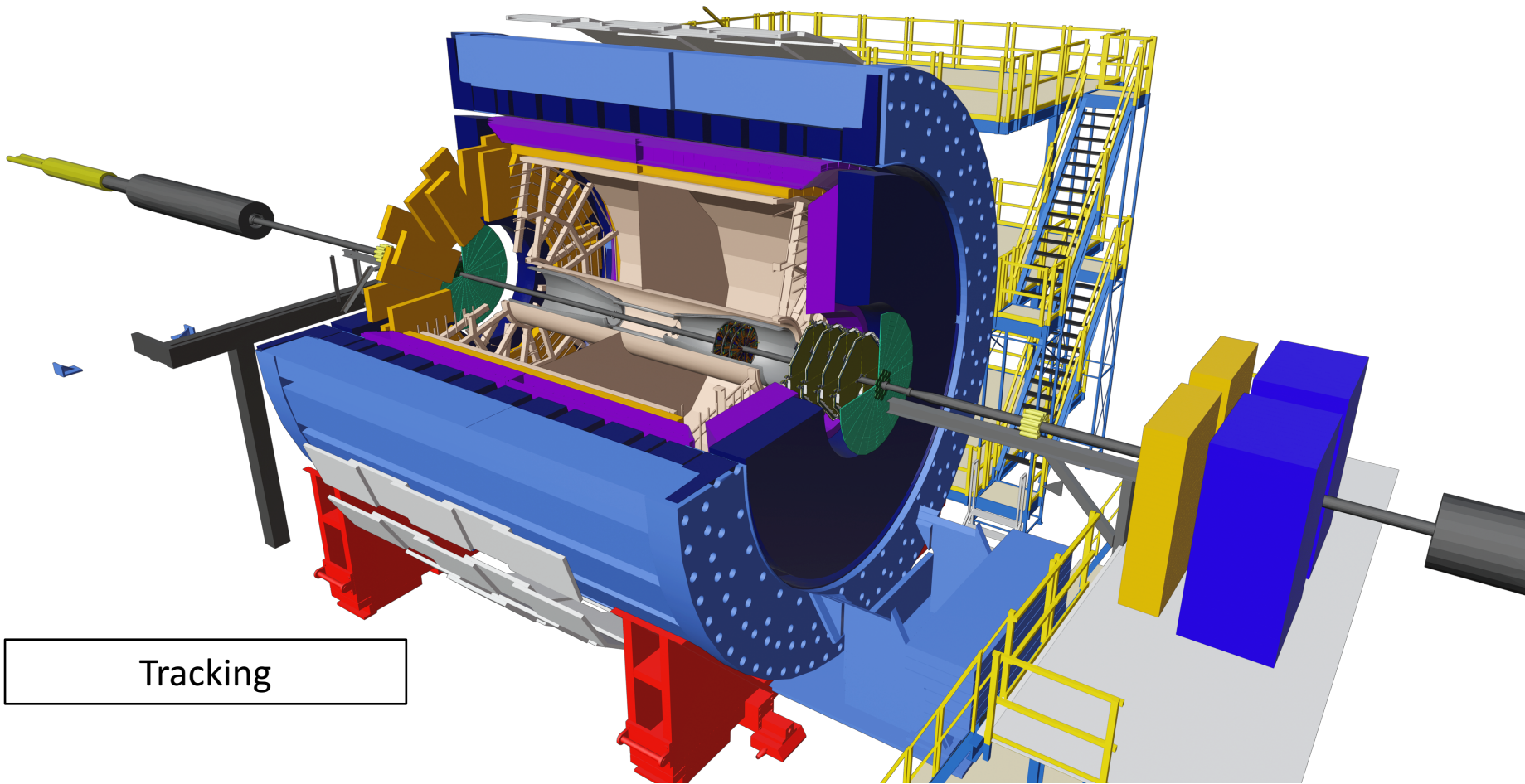
- RHIC continues to serve as the world's first and only polarized  $pp$  collider
- Facilitates  $pp/pA/AA$  collisions at various energies
- At RHIC, protons can be polarized either:
  - Longitudinally,
  - Transversely,
  - Or use unpolarized beams
- Main focus of STAR Spin Physics program
  - $pp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



# Solenoidal Tracker At RHIC

Calorimetry

PID



Tracking

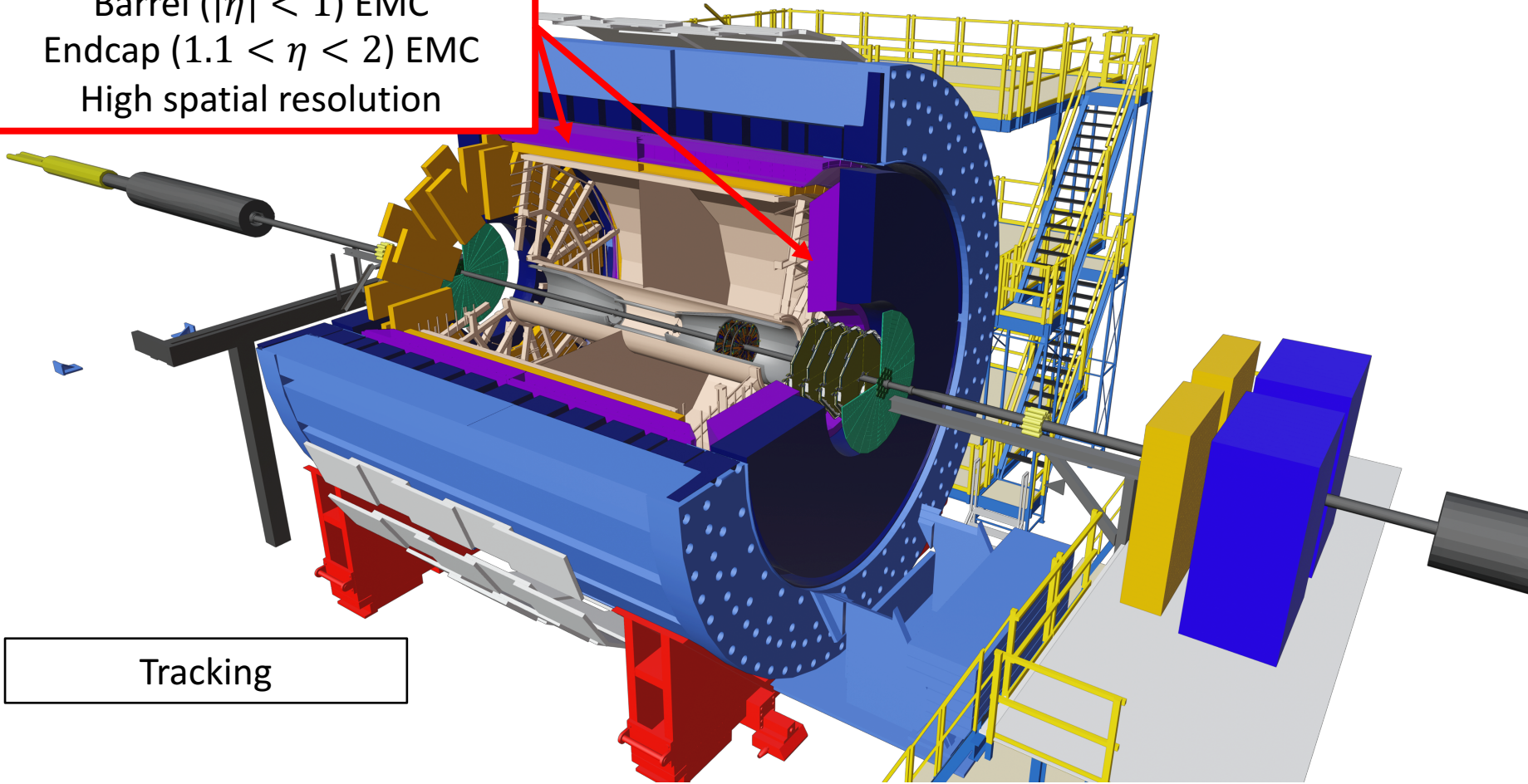
\*STAR BEMC, EEMC, TPC, TOF provide full- $2\pi$  coverage in azimuth.

# Solenoidal Tracker At RHIC

## Calorimetry

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

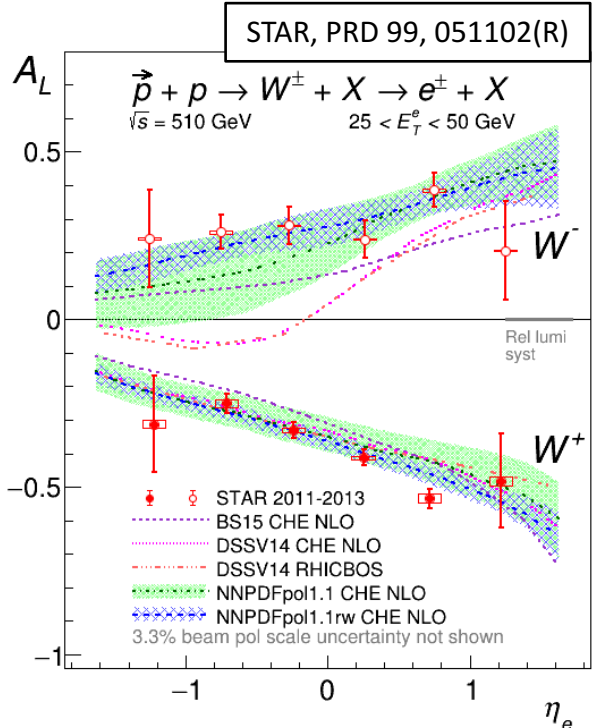
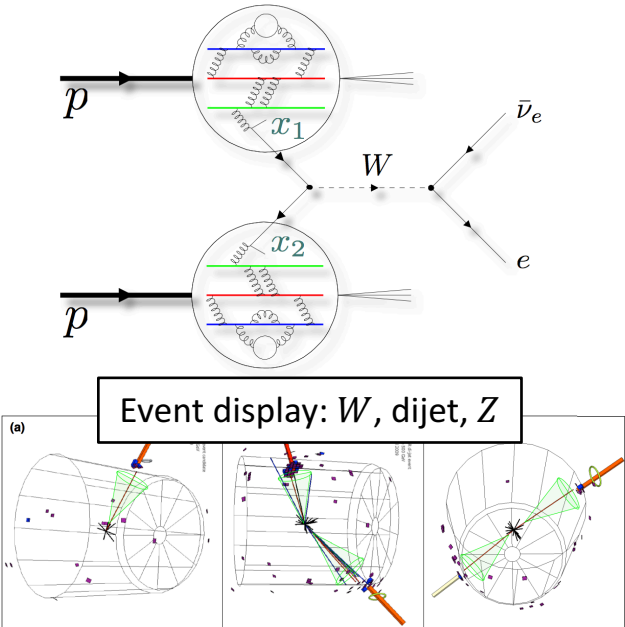
PID



Tracking

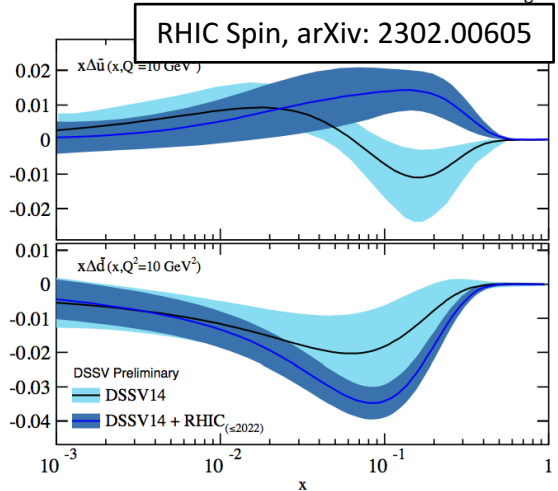
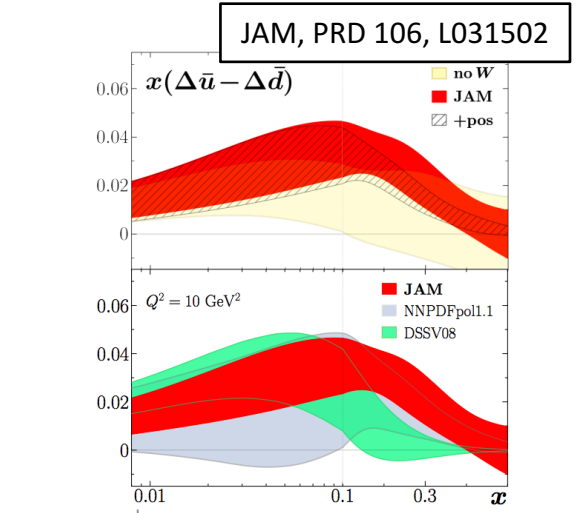
\*STAR BEMC, EEMC, TPC, TOF provide full- $2\pi$  coverage in azimuth.

# $A_L$ with $W$ production at STAR



- Decay lepton  $W \rightarrow e\nu$  tagged

- $A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$   
 → Sensitive to  $\Delta\bar{q}$ .  
 → Flavor given by  $W$  charge

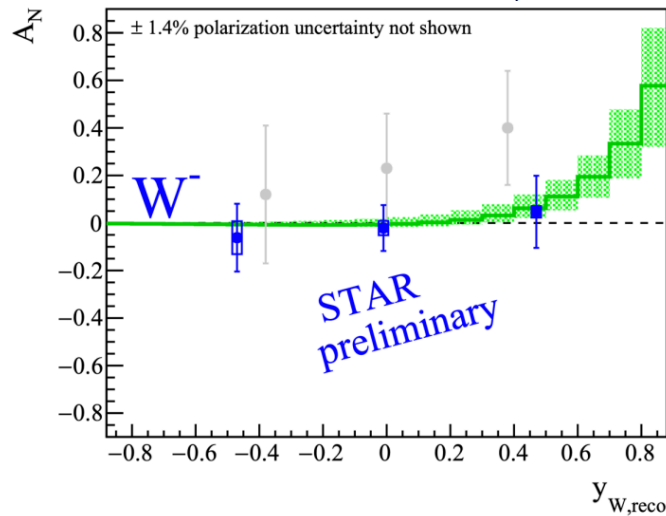
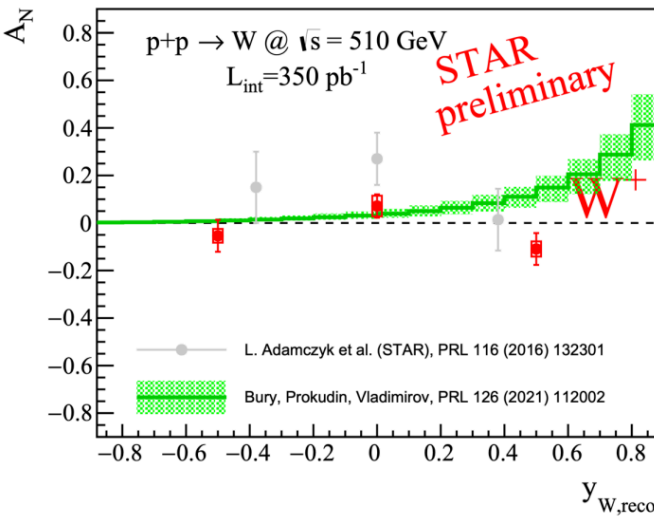


- Impact of STAR data in global fit favoring  $\Delta\bar{u} > \Delta\bar{d}$

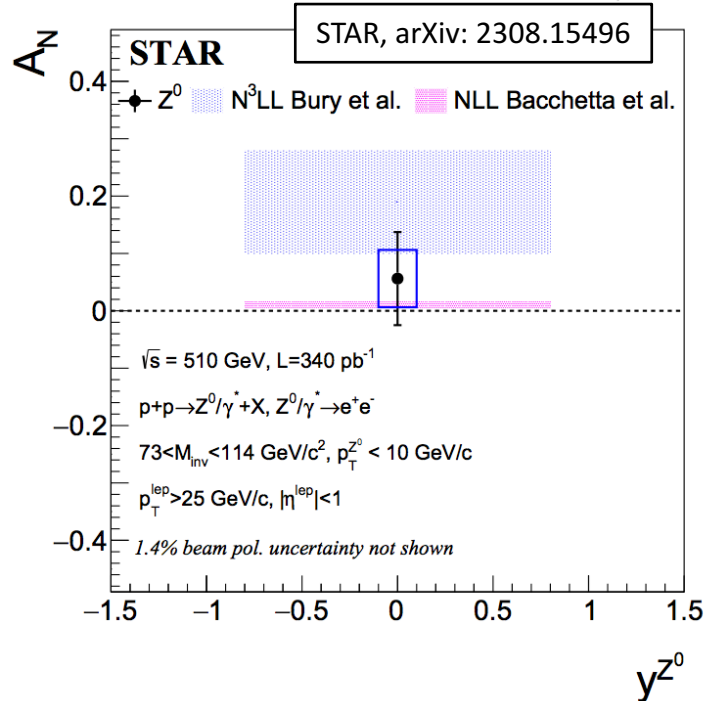
- Important constraints for non-pQCD models of  $\bar{u}/\bar{d}$  asymmetry



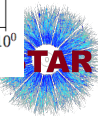
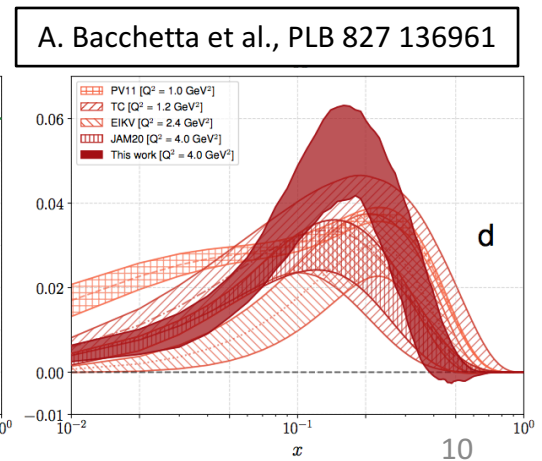
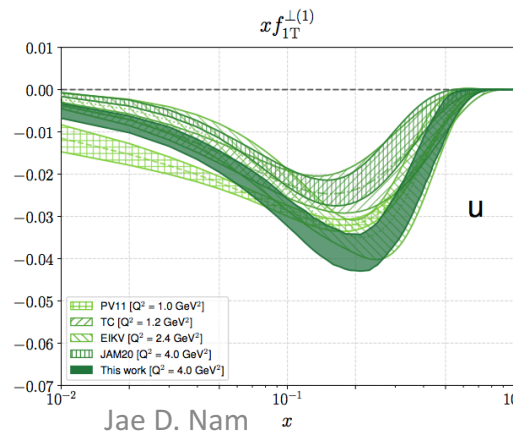
# $A_N$ with $W/Z$ production at STAR



- 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 Siverts function between SIDIS/ $W/Z$



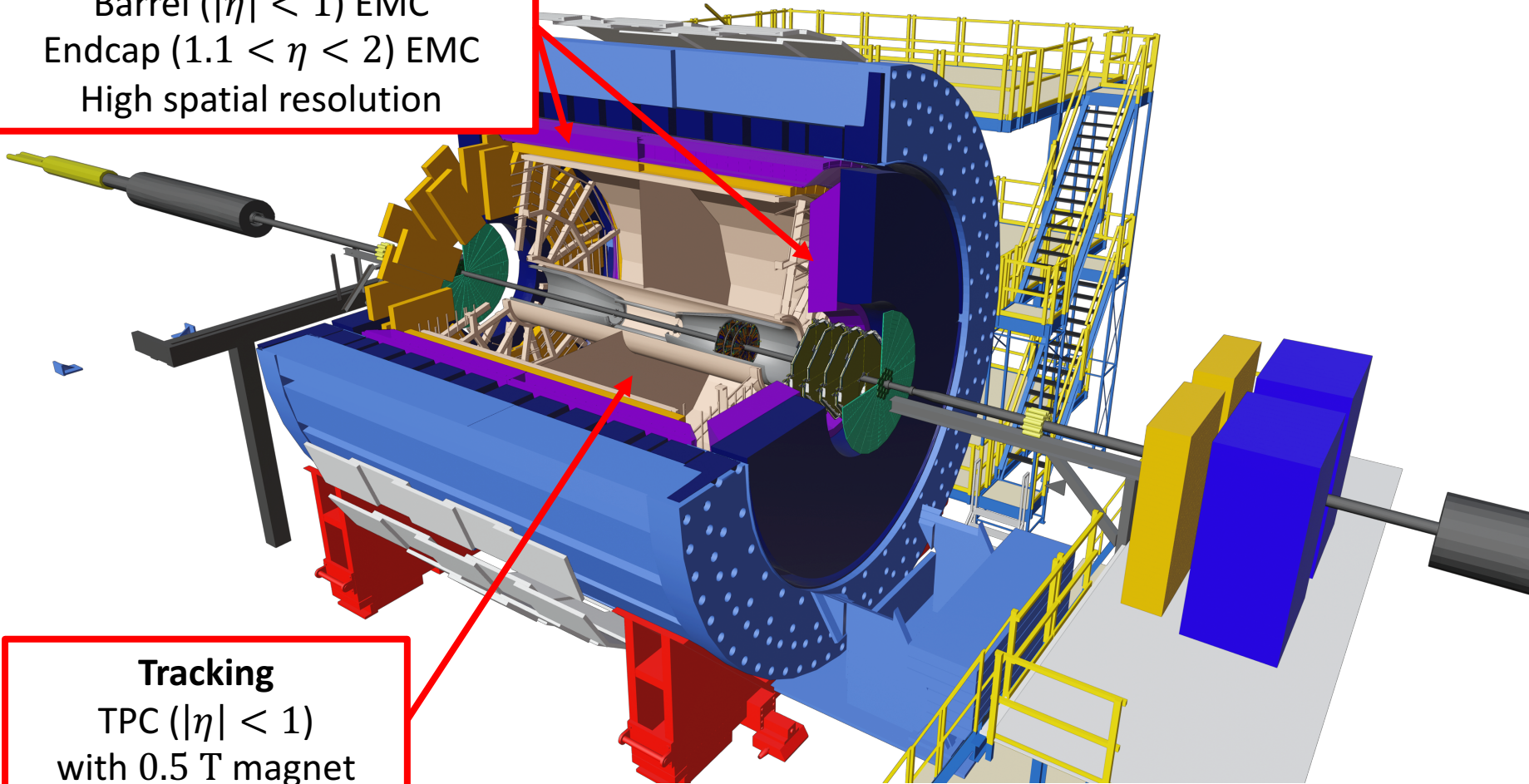


# Solenoidal Tracker At RHIC

## Calorimetry

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

PID

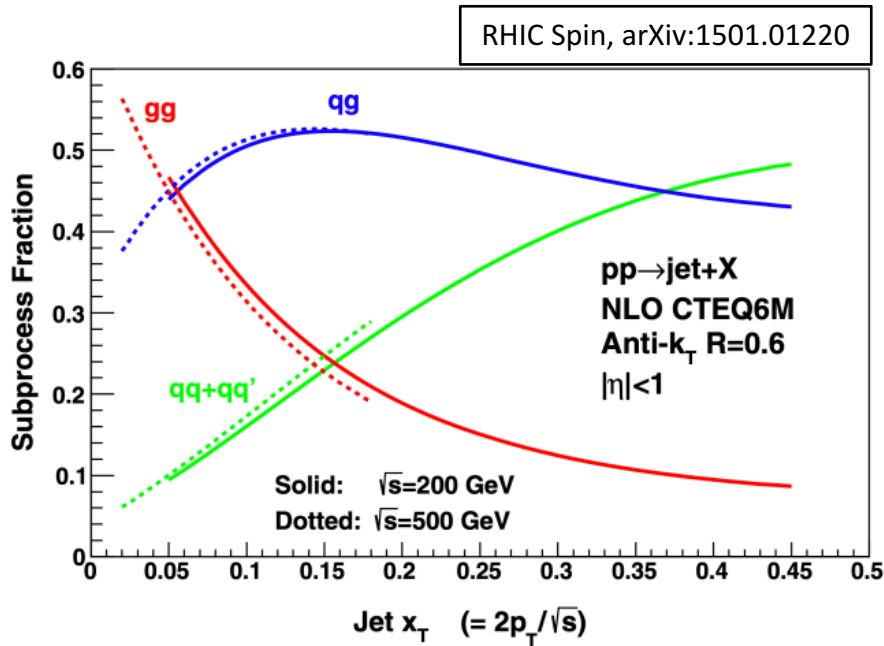


## Tracking

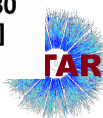
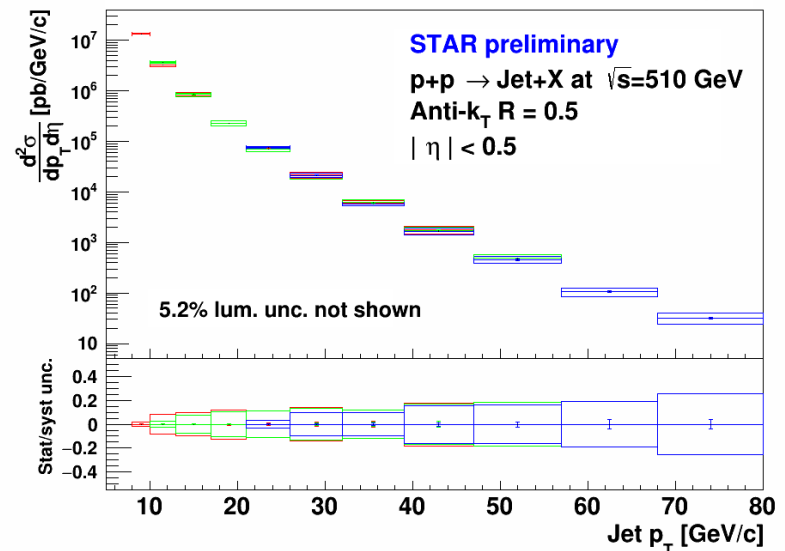
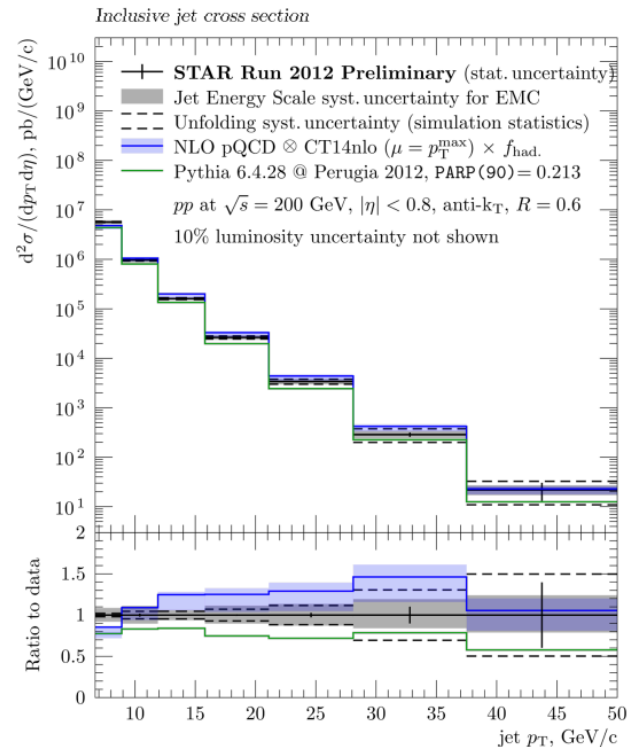
TPC ( $|\eta| < 1$ )  
with 0.5 T magnet

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

# Jets at STAR

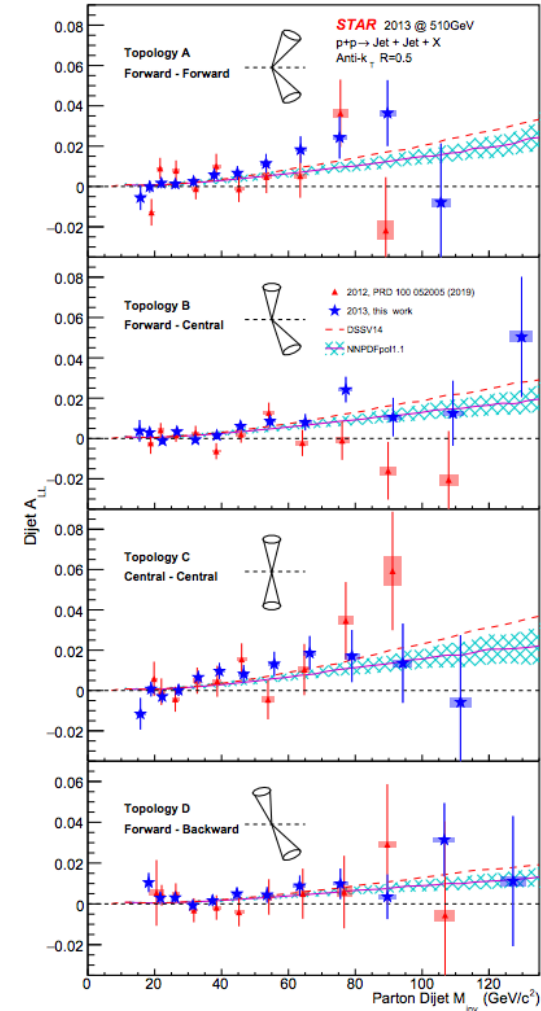
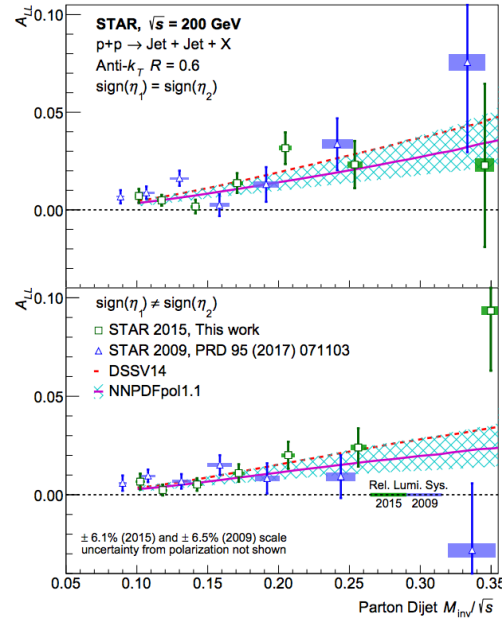
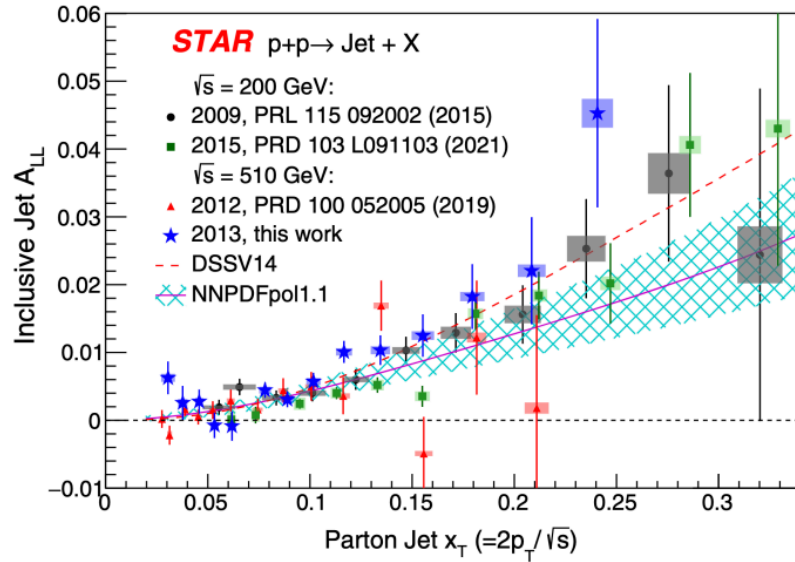


- Jets at STAR are sensitive to gluon ( $gg$ ,  $qg$ )
- Anti- $k_T$  clustering algorithm with tracking + calorimetry info
- $R = 0.6$  ( $0.5$ ) for  $\sqrt{s} = 200$  ( $500/510$ ) GeV, motivated by UE
- Further tuning provided from unpolarized measurements



# Inclusive and Dijet $A_{LL}$

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



- $A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \rightarrow$  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  $x \gtrsim 0.015$

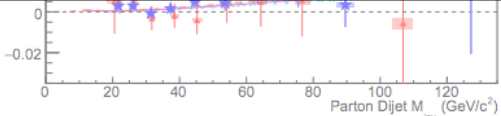
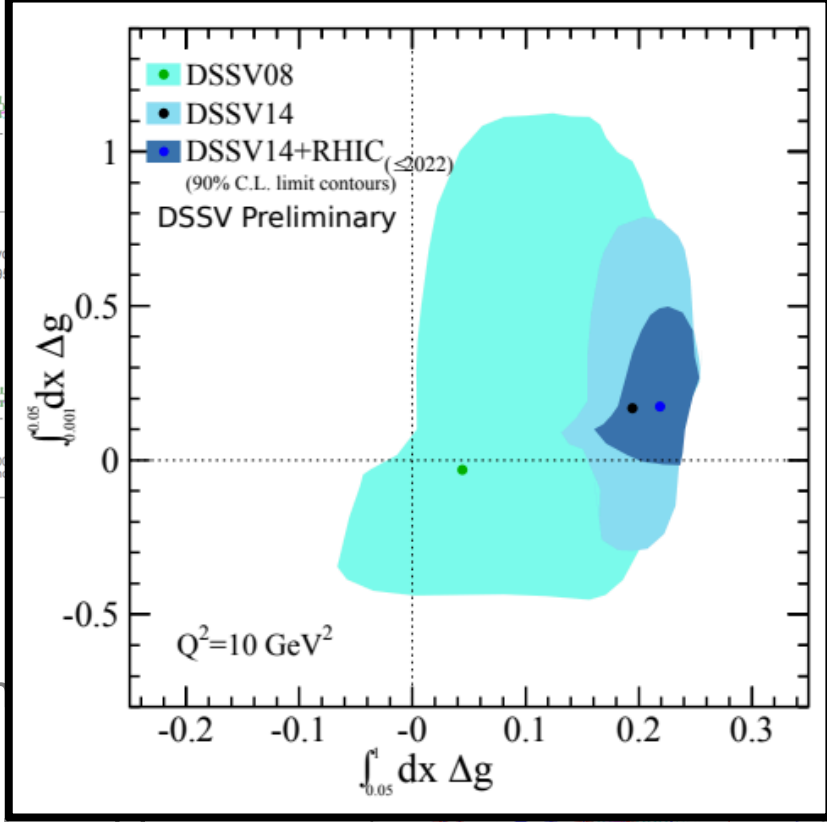
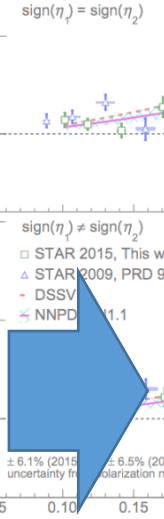
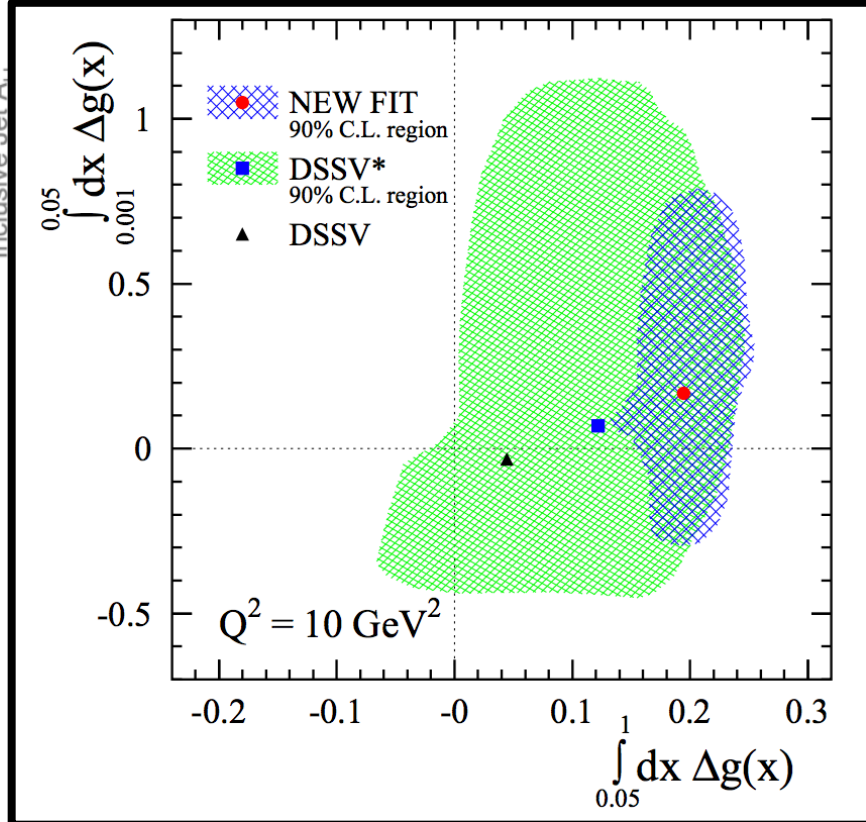


# Inclusive and Dijet $A_{LL}$

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

DSSV, PRL 113 (2014) 1, 012001

RHIC Spin, arXiv: 2302.00605

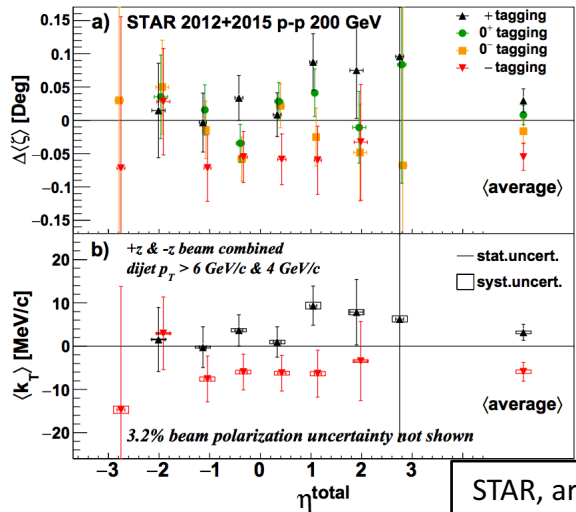
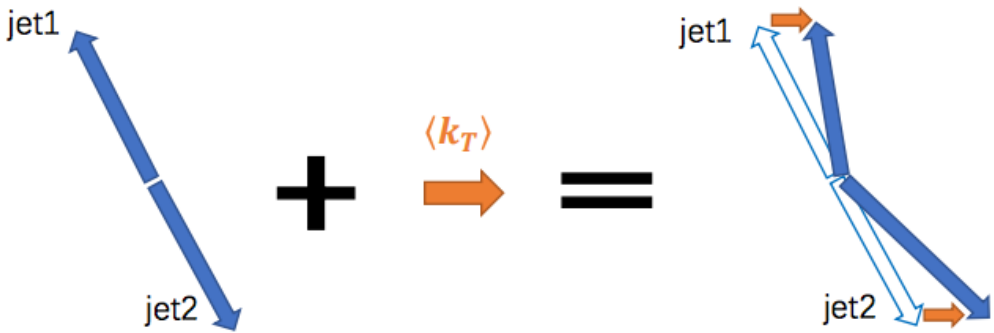


- whereas dijet results have impact on its functional form
- These measurements provide access to  $x \gtrsim 0.015$





# Dijet Azimuthal Correlation at STAR

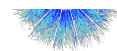
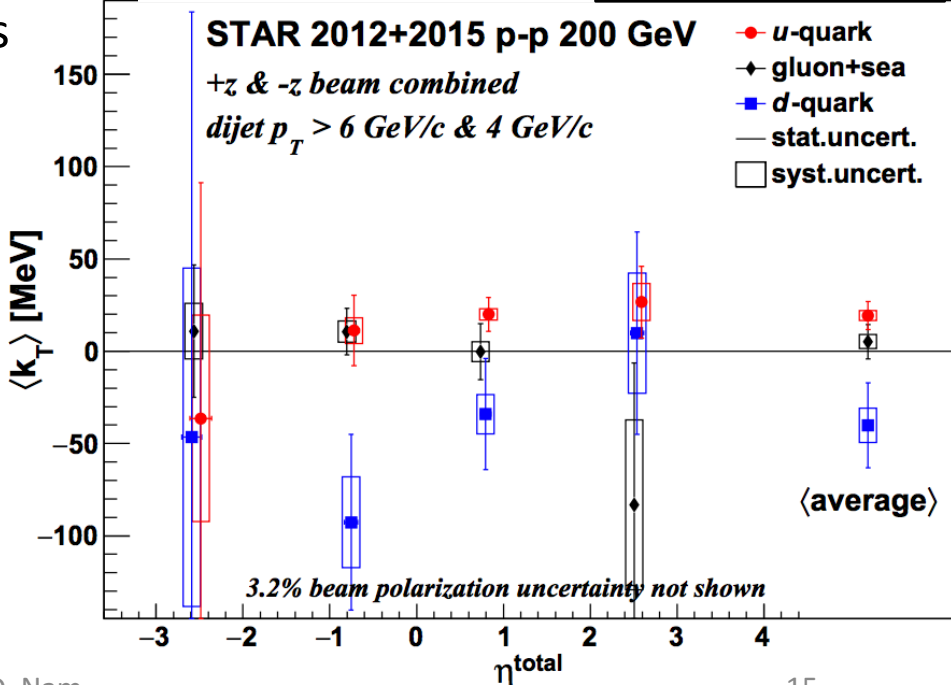


- Azimuthal correlation in  $pp$  dijet as proxy for intrinsic parton  $k_T$
- “Jet-charge” to enhance flavor sensitivity

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

$Q_{jet} > +0.25$ :  $u$  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



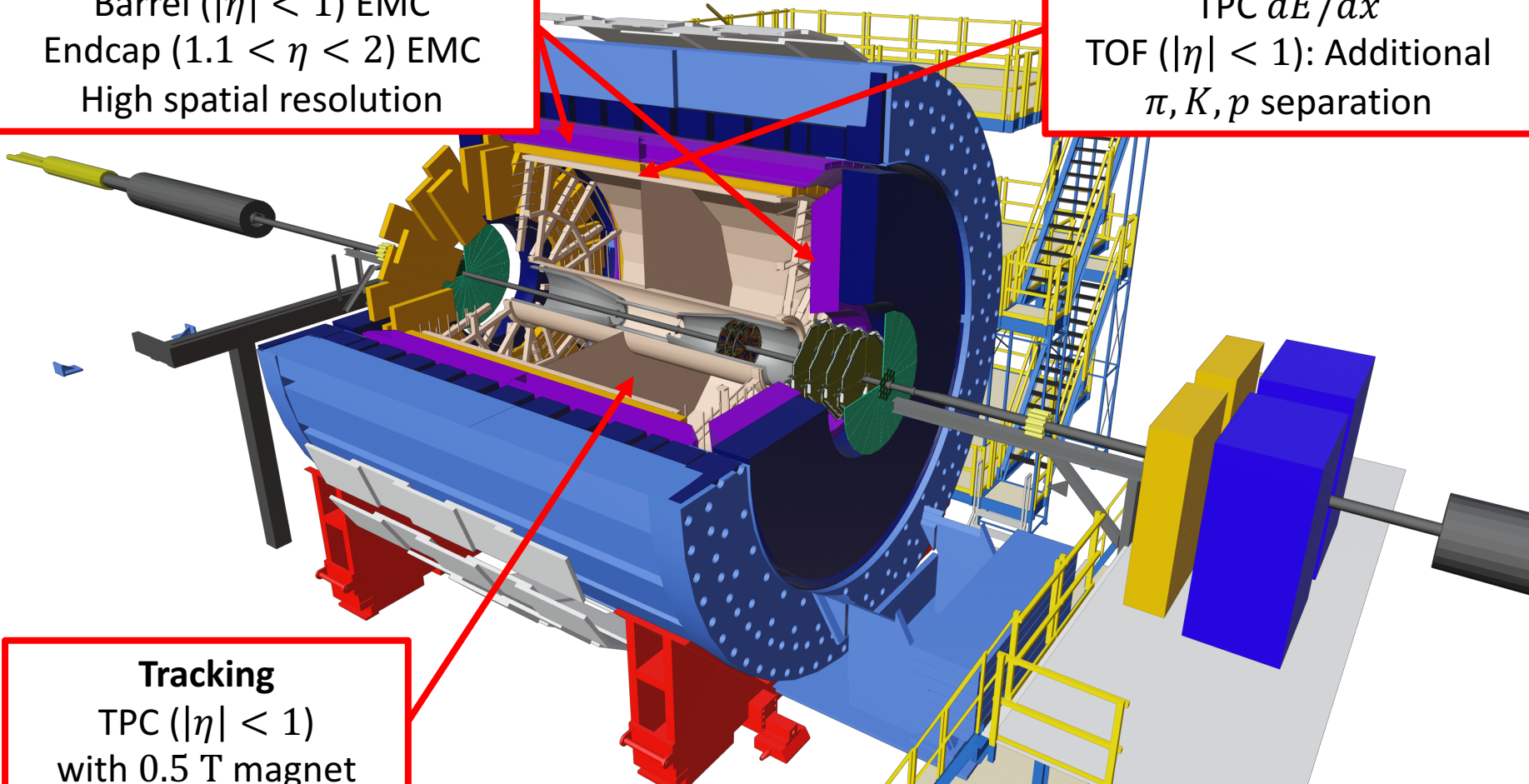
# Solenoidal Tracker At RHIC

## 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



## Tracking

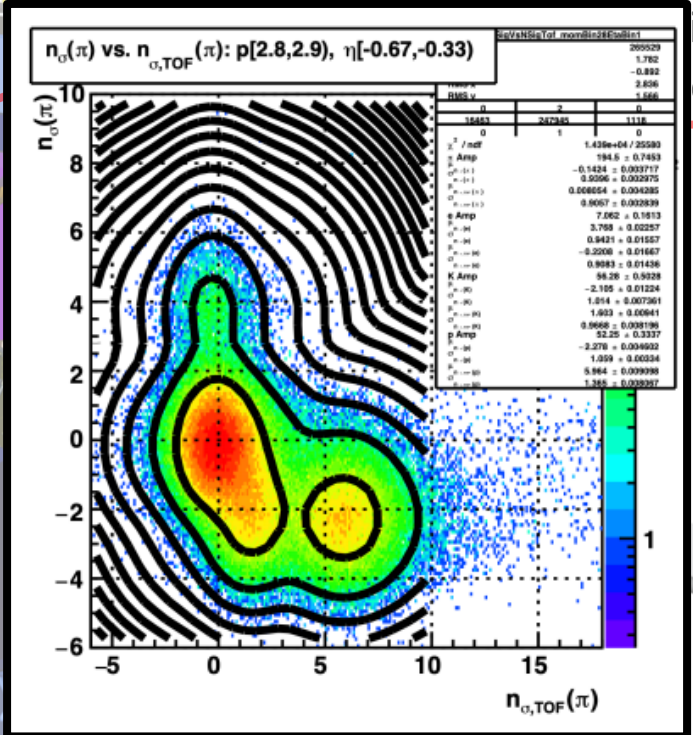
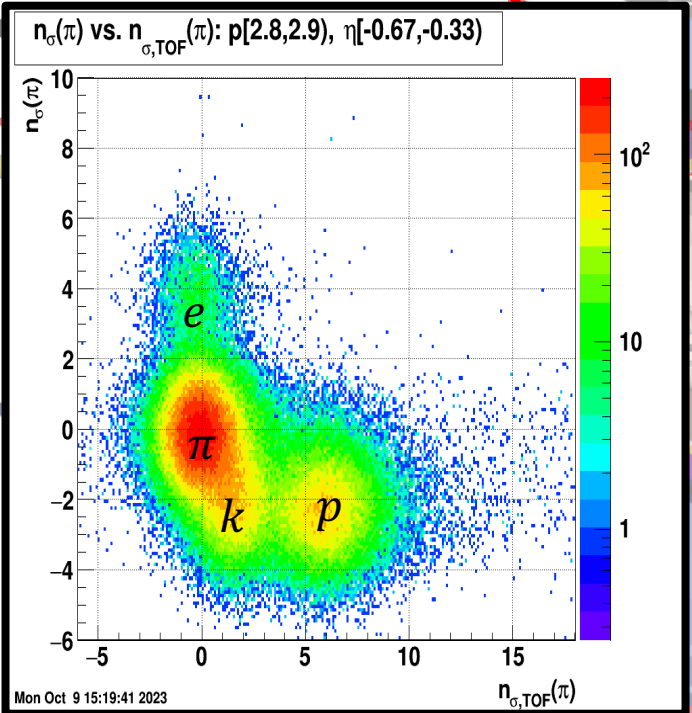
TPC ( $|\eta| < 1$ )  
with 0.5 T magnet

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

# Solenoidal Tracker At RHIC

**Calorimetry**  
Barrel ( $|\eta| < 1$ ) EMC

**PID**  
TPC  $dE/dx$



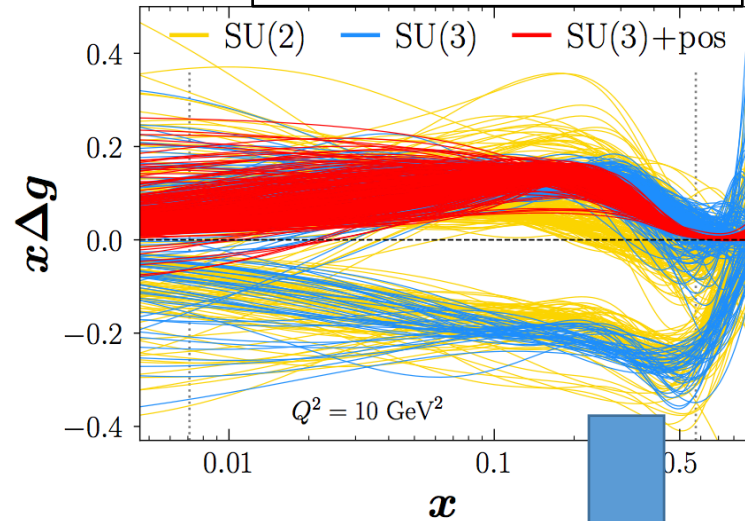
**Tracking**  
TPC ( $|\eta| < 1$ )  
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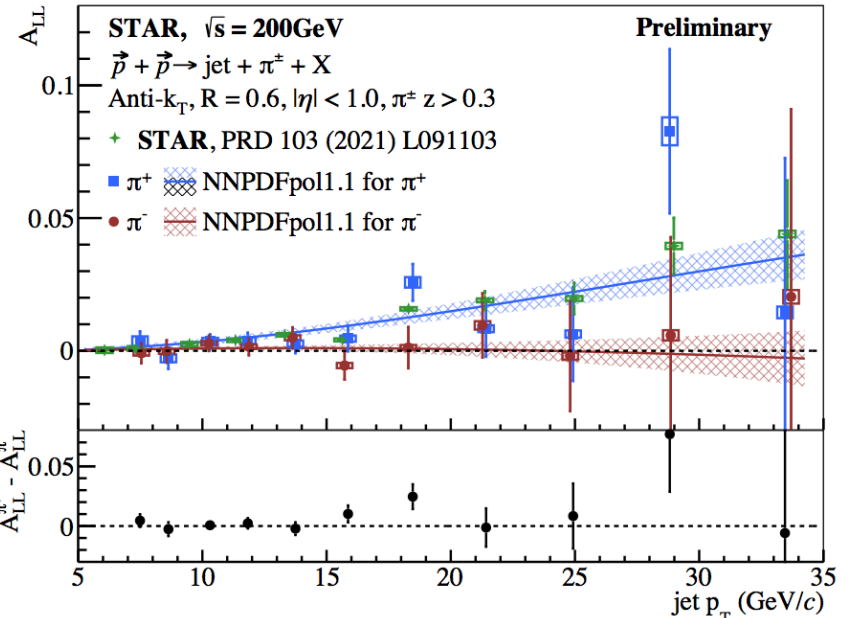
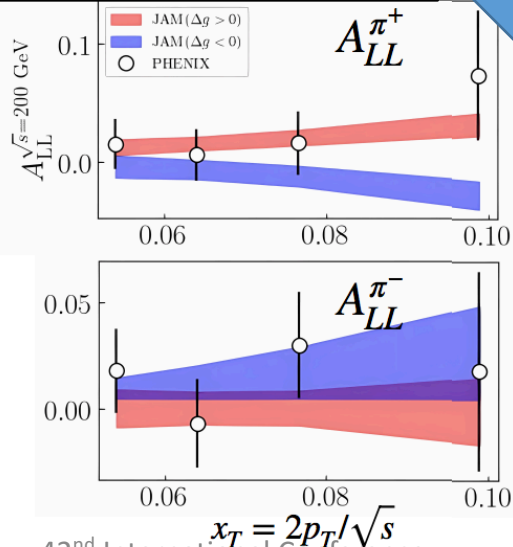


# $\pi^\pm$ -Jet $A_{LL}$ at STAR

JAM, PRD 105 (2022) 7, 074022



PHENIX, PRD 91 (2015) 032001



- 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  $\Delta g$

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

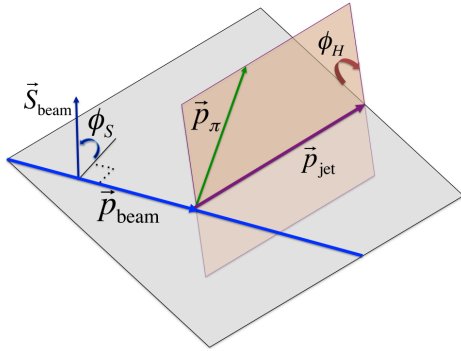
$$\Delta g < 0 \rightarrow A_{LL}^{\pi^+} < A_{LL}^{\pi^-}$$

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





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

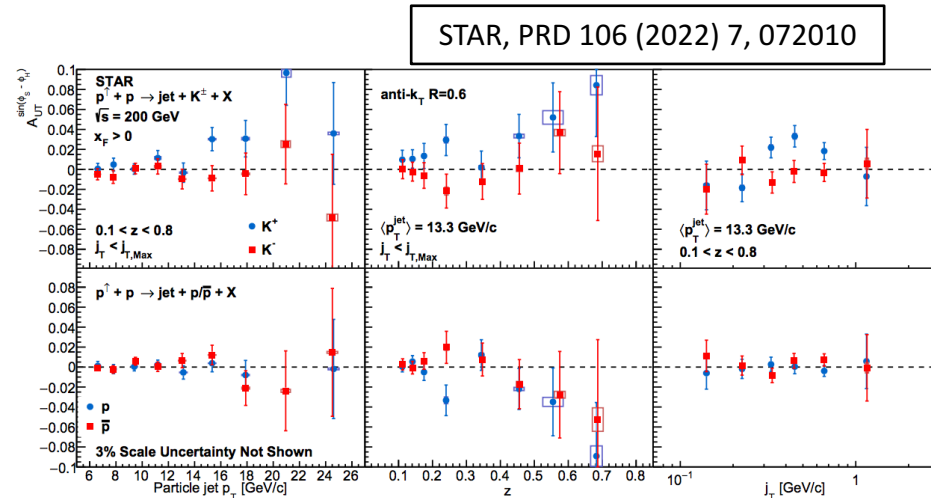
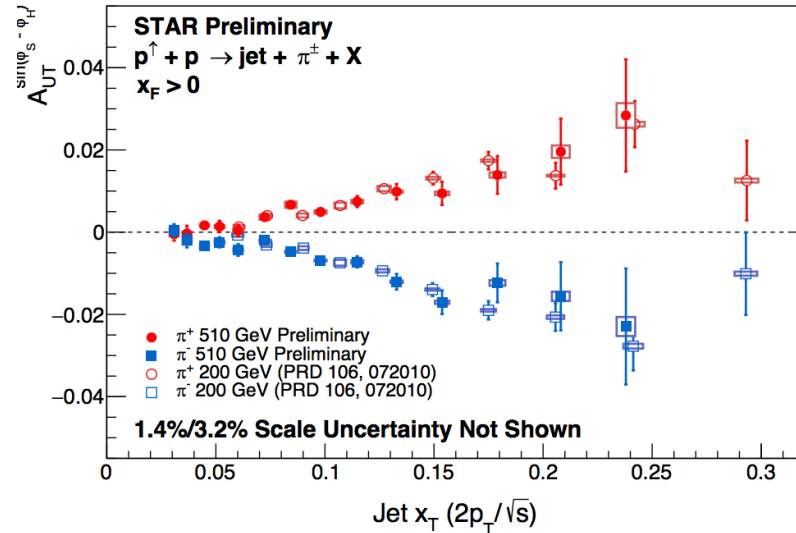
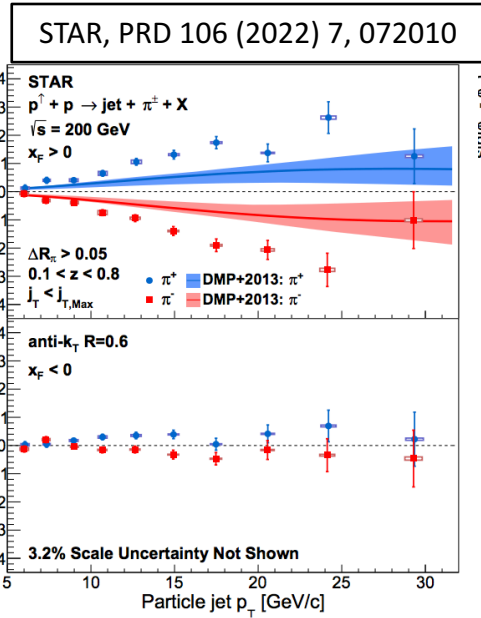


## Collins Asymmetry

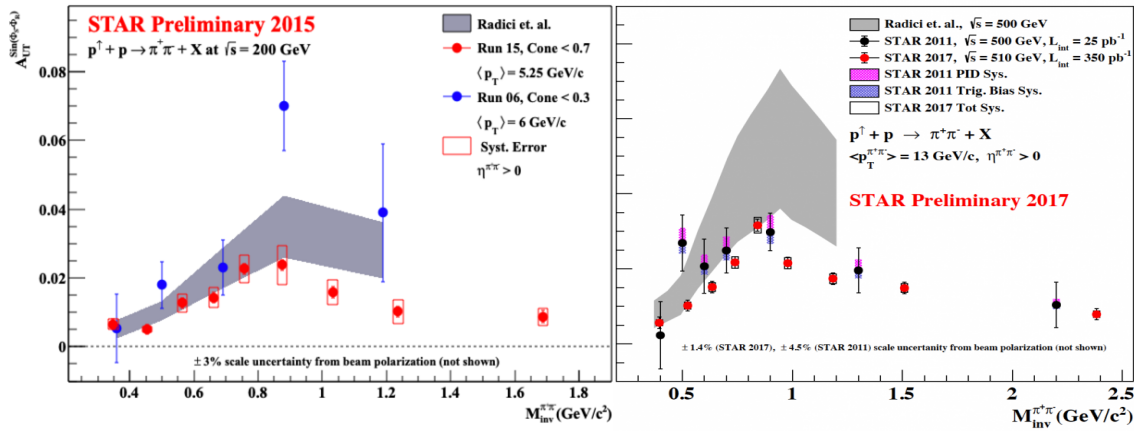
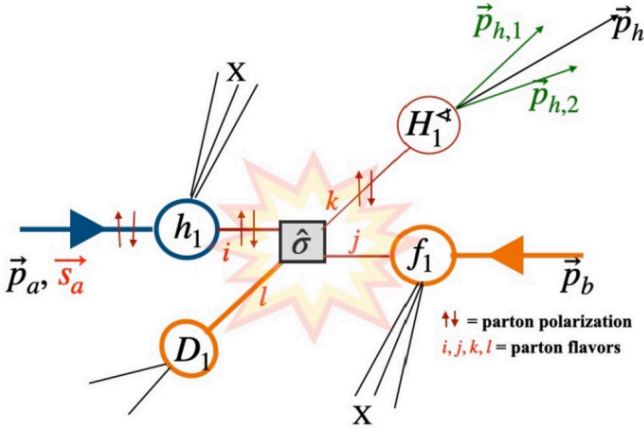
$$A_N^h = A_{UT}^{\sin(\phi_S)} \sin(\phi_S) + A_{UT}^{\sin(\phi_S - \phi_H)} \sin(\phi_S - \phi_H) + \dots$$

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

- 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



# Hadrons w/o Jet Reconstruction

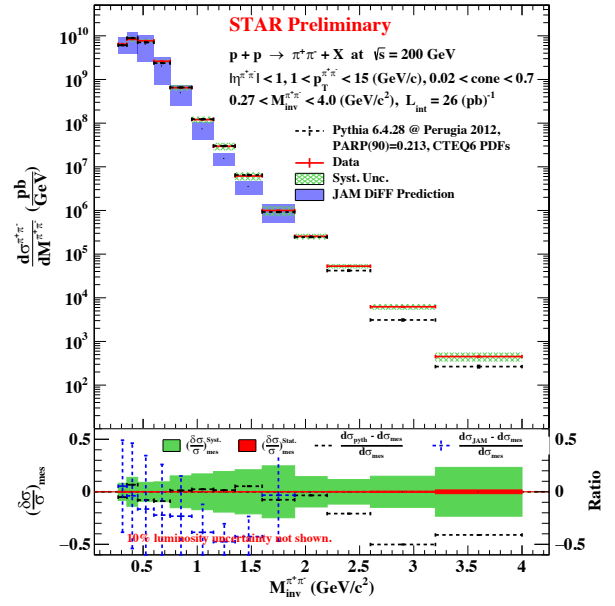


- $A_N$  with hadron pair provides complementary extraction of transversity

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

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

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

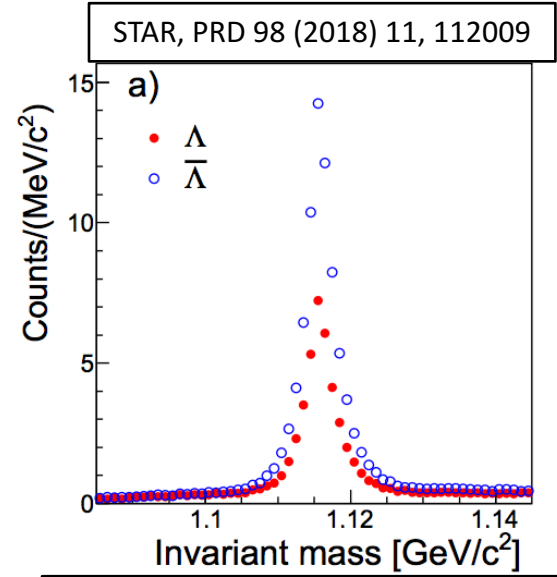


# Spin Transfers of $\Lambda$ -hyperon

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

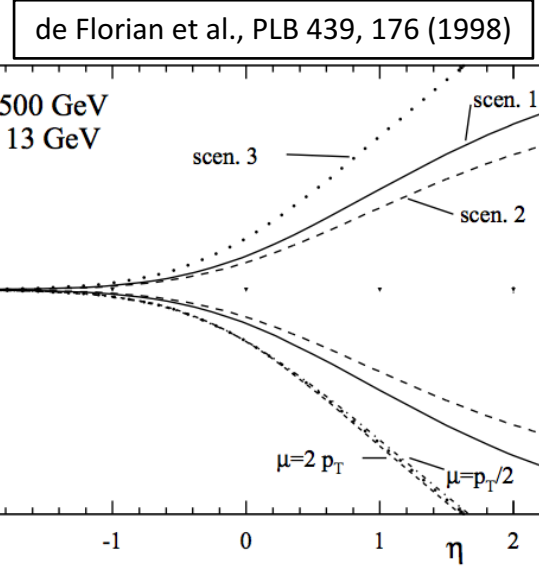
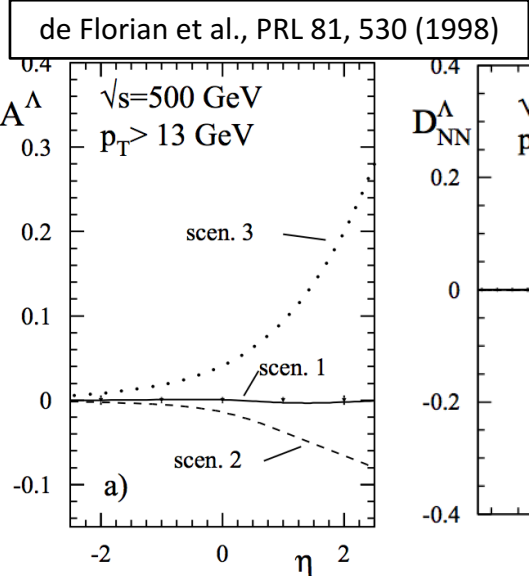
$$D_{LL}^\Lambda = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \propto \Delta f \Delta D^\Lambda \rightarrow \text{Polarized FF}$$

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

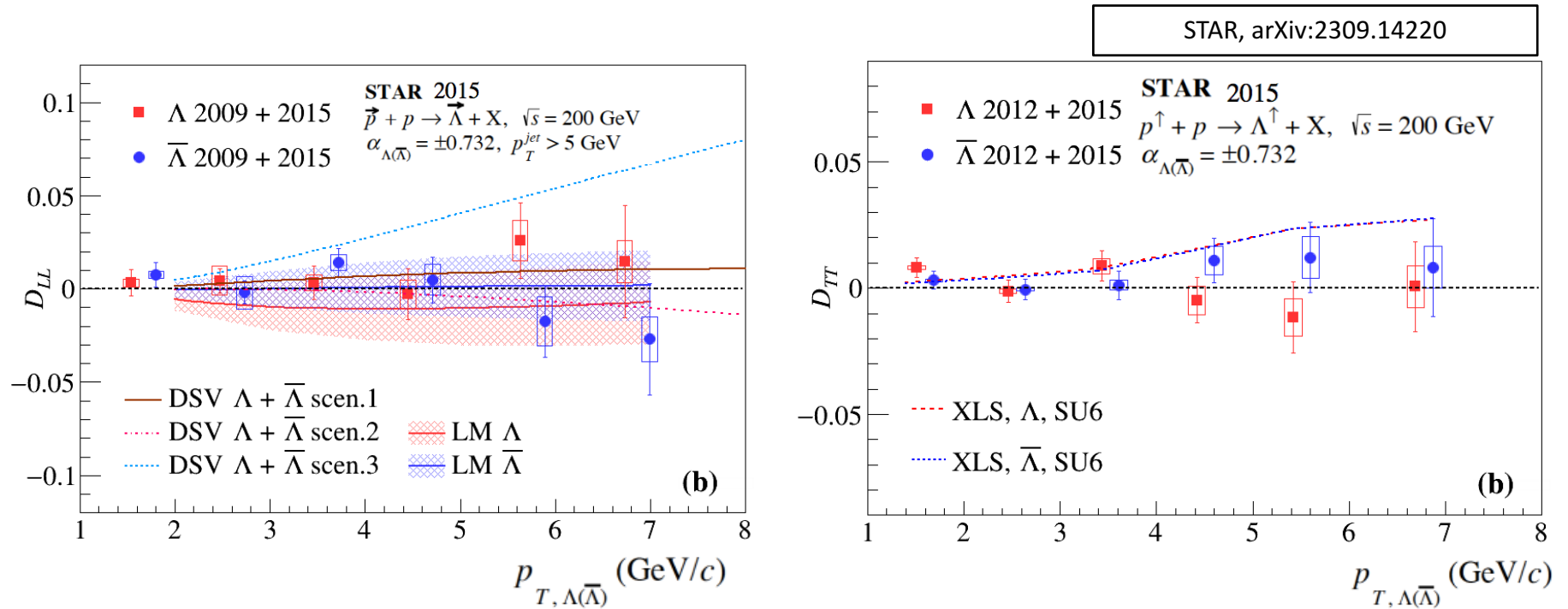


- $D_{LL}^\Lambda / D_{TT}^\Lambda$  probes strange helicity/transversity and origin of PFFs

- Scen. 1: only  $s$  contributes to  $P_\Lambda$
- Scen. 2:  $u, d$  contribute in opposite direction
- Scen. 3: equal contributions from  $u, d, s$



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



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



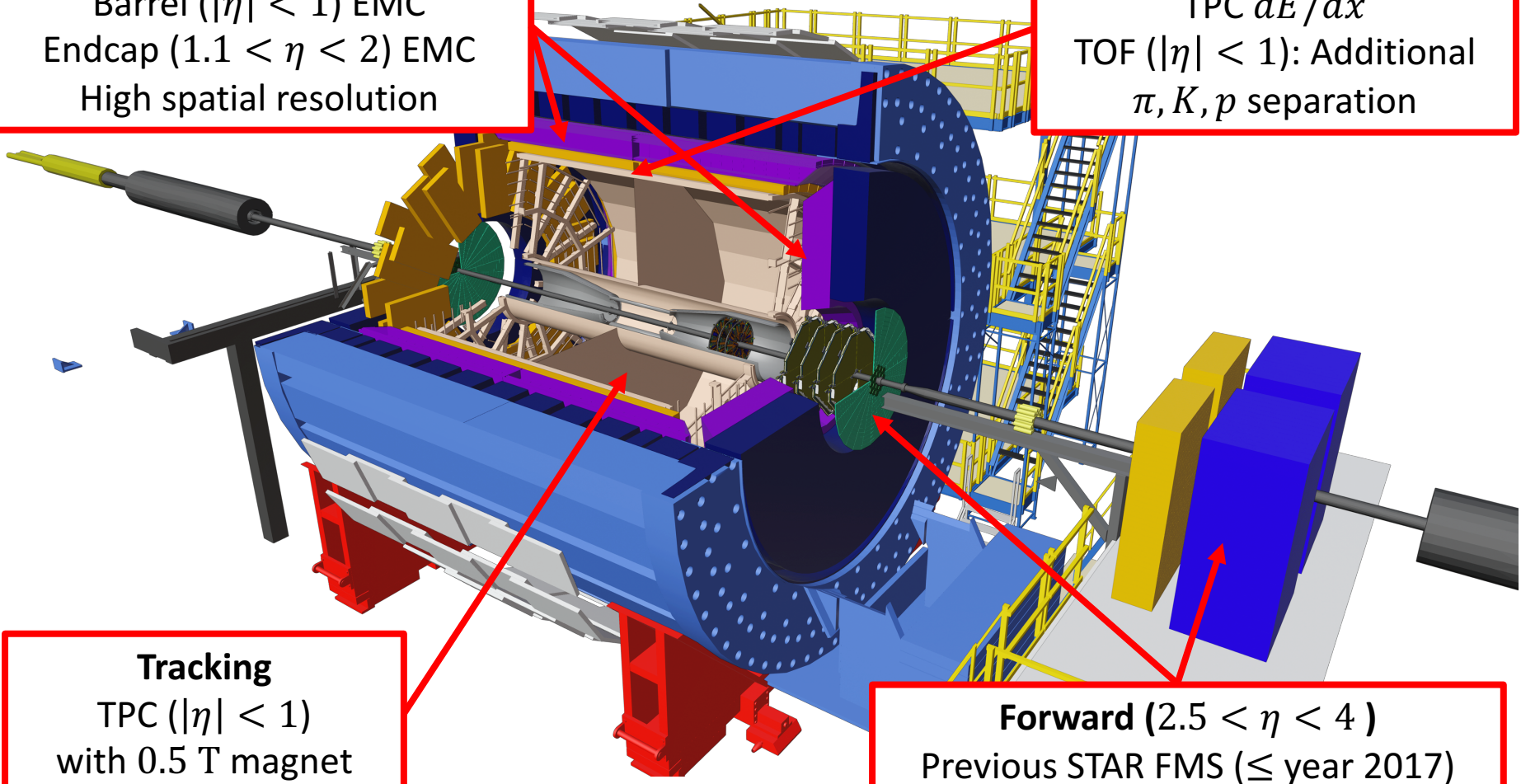
# Forward Region

## 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

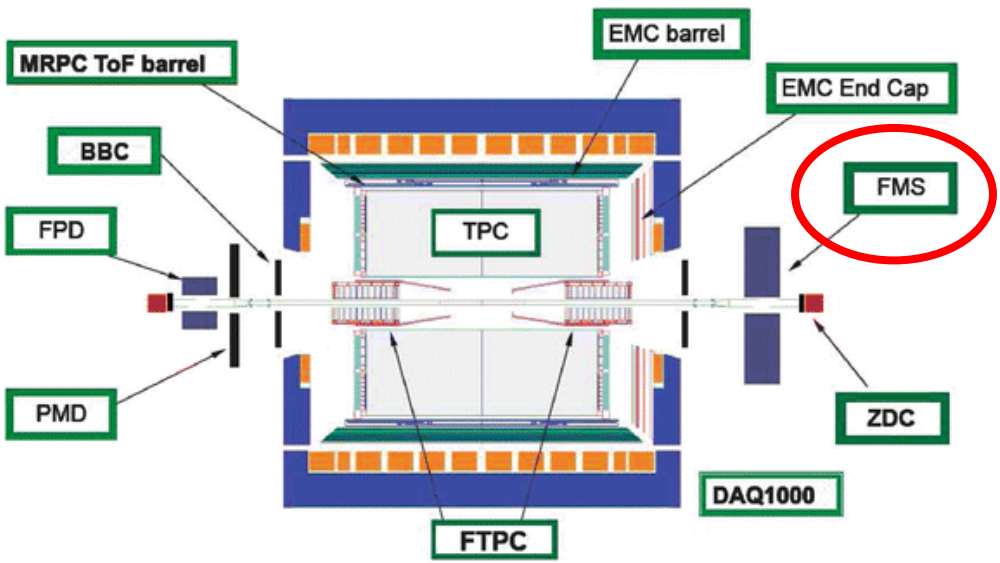
## Forward ( $2.5 < \eta < 4$ )

Previous STAR FMS ( $\leq$  year 2017)  
STAR Forward Upgrade ( $\geq$  2022)

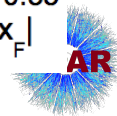
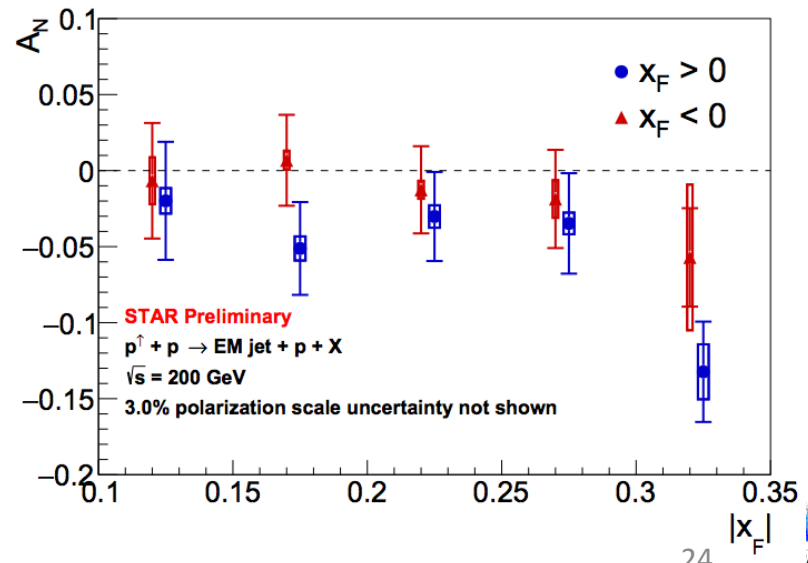
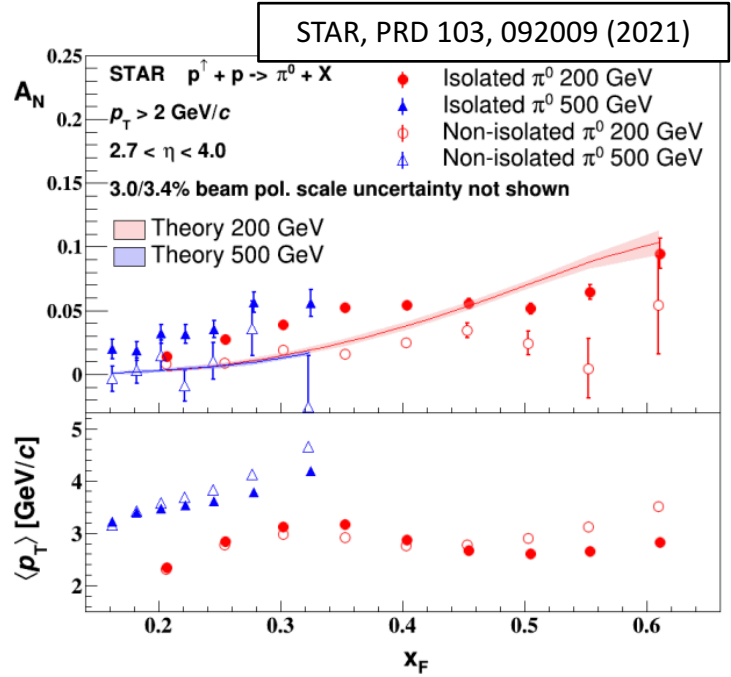
\*STAR BEMC,



# Measurements with previous FMS



- 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:  $2.5 < \eta < 4$

**A+A**

**Beam:**  
Full Energy AuAu

**Physics Topics:**

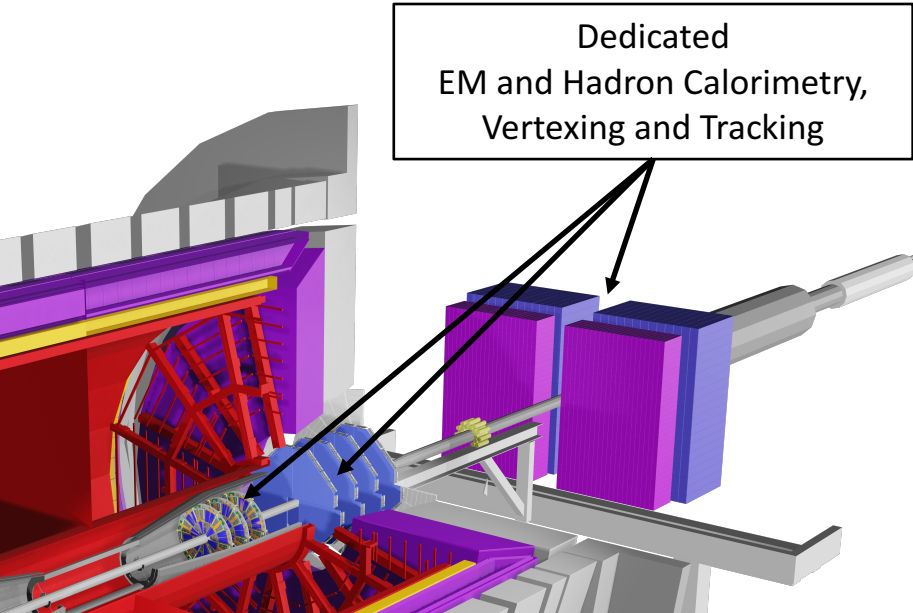
- Temperature dependence of viscosity through flow harmonics up to  $\eta \sim 4$
- Longitudinal decorrelation up to  $\eta \sim 4$
- Global Lambda Polarization  
→ strong rapidity dependence

**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,  $\gamma$ -Jets



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

STAR Forward Upgrade – SPIN 2023 – Carl Gagliardi



# 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!

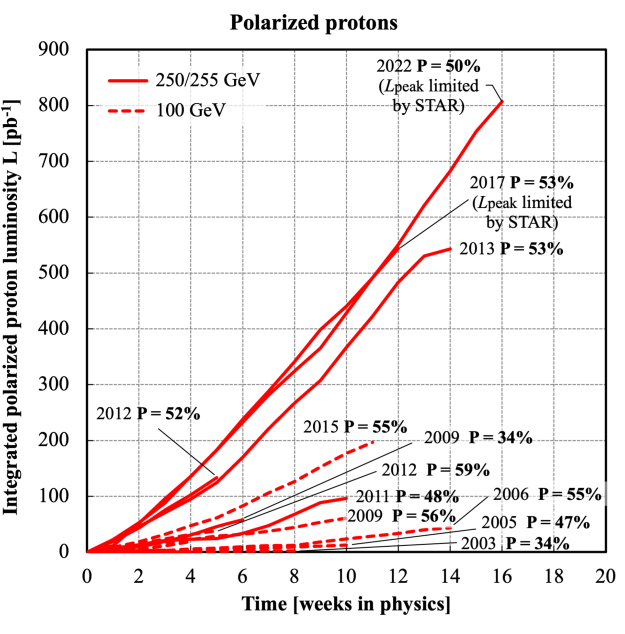




# Back up



# RHIC $pp$ Run Overview



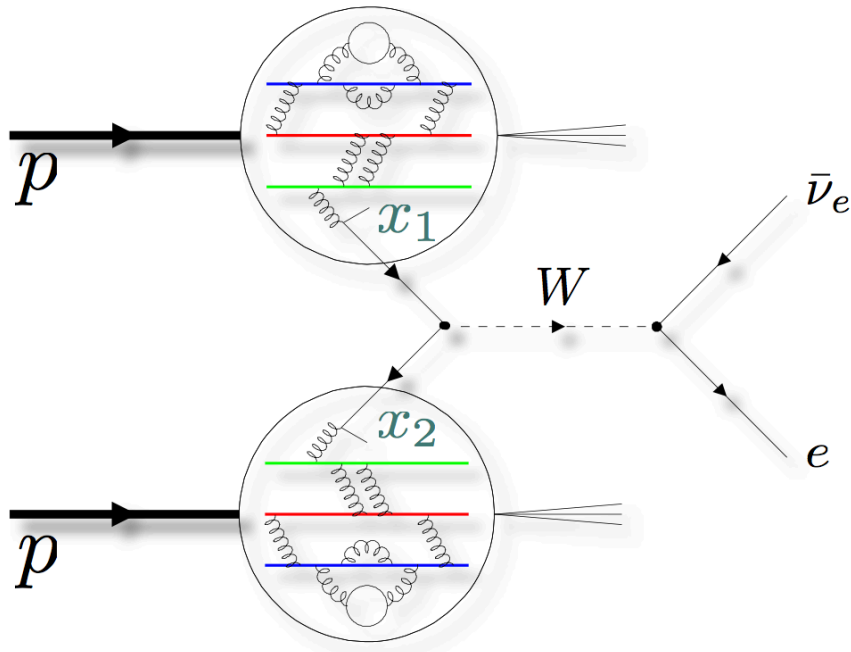
Longitudinally-Polarized $pp$ Runs						
Year	2009	2009	2011	2012	2013	2015
$\sqrt{s}$ (GeV)	200	500	500	510	510	200
$L_{int}^{STAR}$ ( $pb^{-1}$ )	25	10	12	82	300	52
Pol.	55%	39%	48%	53%	55%	58%

Transversely-Polarized $pp$ Runs							*projection
Year	2006	2011	2012	2015	2017	2022	*2024
$\sqrt{s}$ (GeV)	200	500	200	200	510	508	200
$L_{int}^{STAR}$ ( $pb^{-1}$ )	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

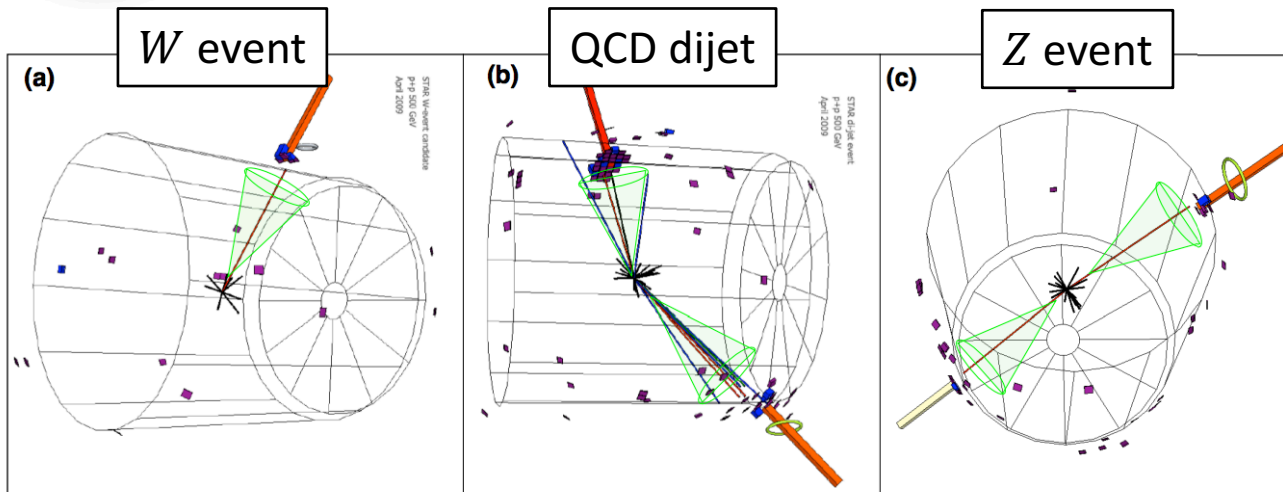


# Weak Boson Production at STAR

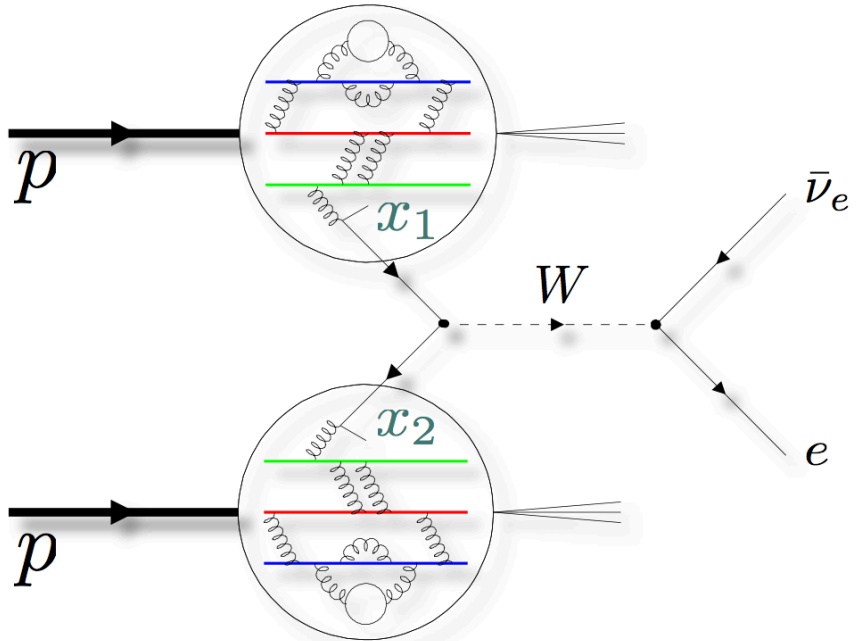


- Signs of  $W$  production:

- 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



- Signs of  $W$  production:
  - Decay electron  $E_e \sim M_W/2$  w/ narrow shower
  - Missing energy from partnering neutrino.
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