Experimental studies on the high-energy spin physics in collider experiments at RHIC

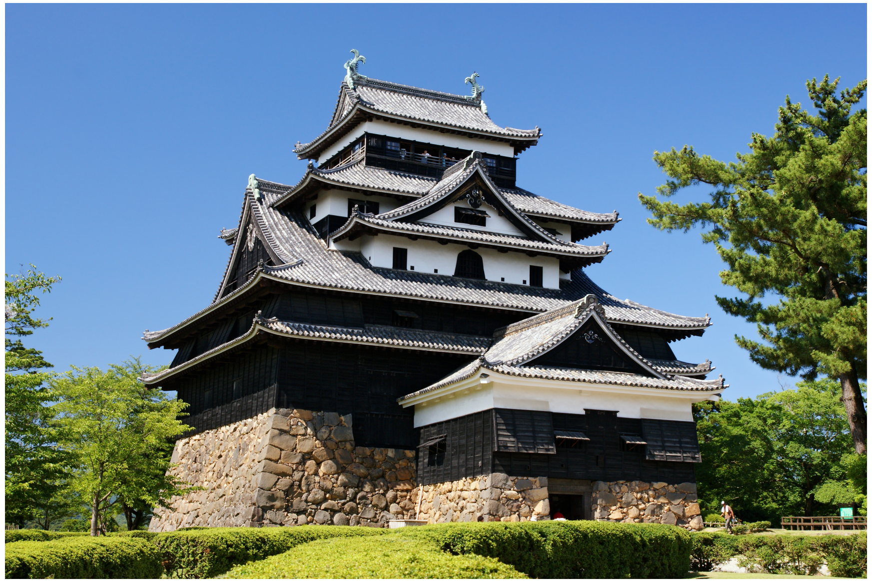
Salvatore Fazio

(Calabria University & INFN Cosenza)

Supported by: U.S. DEPARTMENT OF ENERGY

UNIVERSITÀ DELLA CALABRIA
Dipartimento di FISICA

INFN
Gruppo Collegato di Cosenza
Istituto Nazionale di Fisica Nucleare

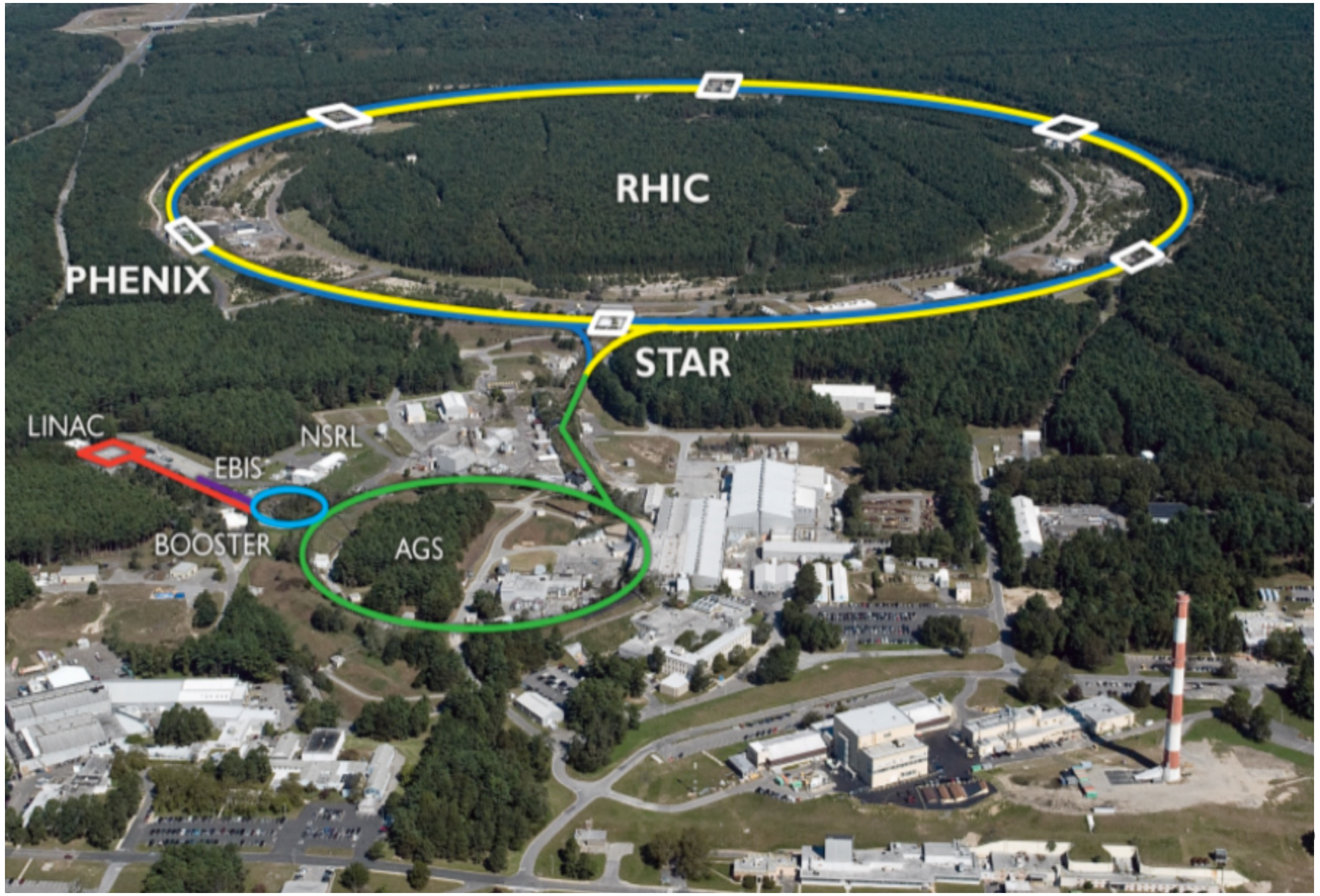


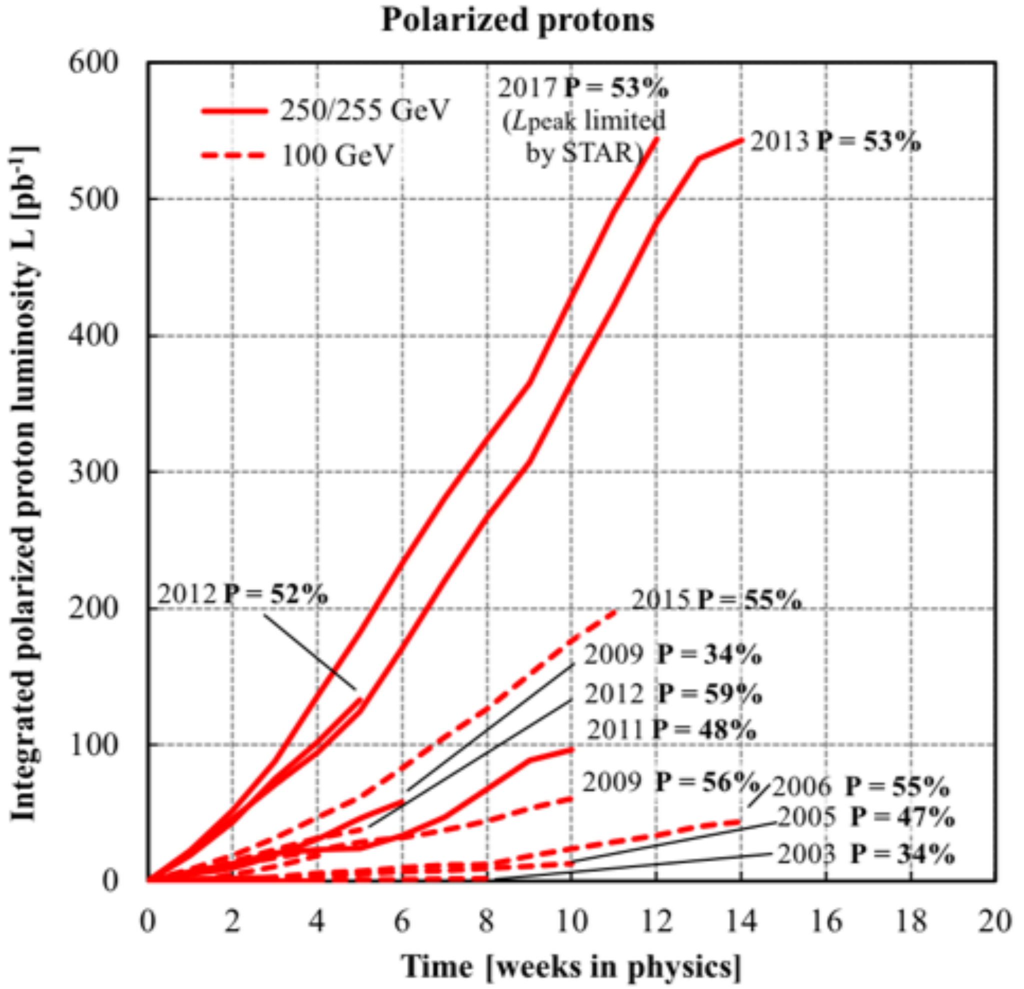
The 24th International Spin Symposium
SPIN 2021
Matsue, Shimane Prefecture, Japan, October 18 – 22, 2021

The Relativistic Heavy-Ion Collider

RHIC is the world's first and only polarized hadron collider

Beams: √s = 200 - 510 GeV *p+p*;
50-60% polarization

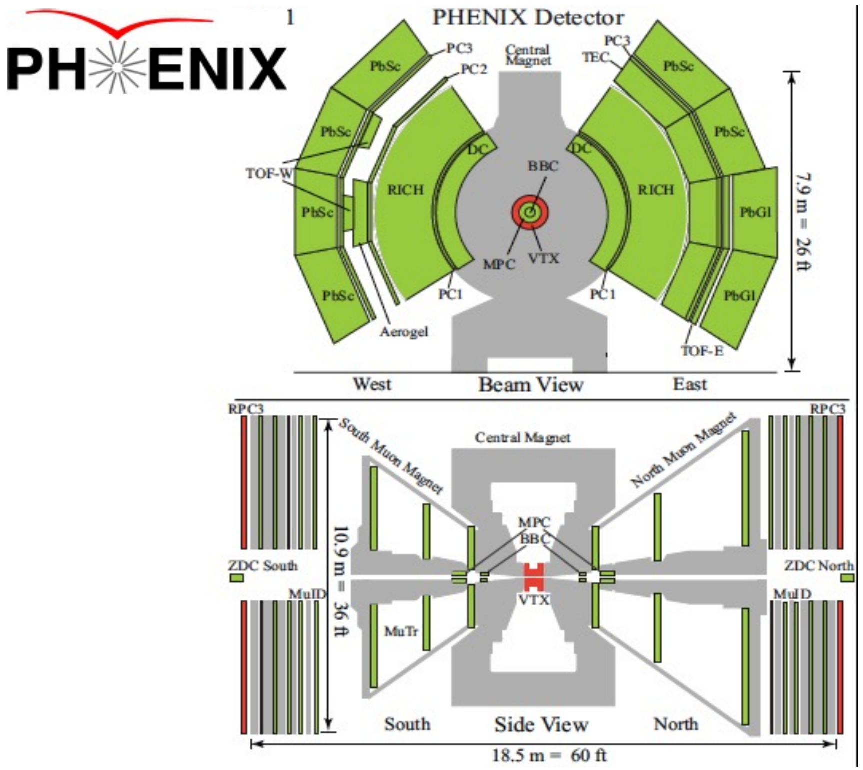




The RHIC experiments

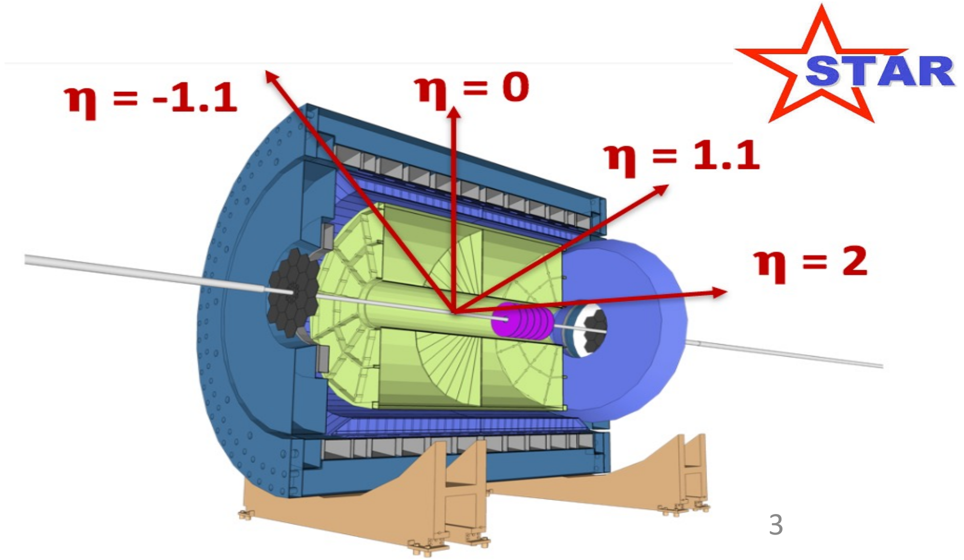
PHENIX

- Central detector (EMCal and drift/pad chambers), two central arms covering
  - $|\Delta\Phi| = \pi/2 \times 2$
  - $|\eta| < 0.35$
- Two muon arms
  - $1.2 < |\eta| < 2.4$



STAR

- 2π coverage Electromagnetic Calorimeter
  - Barrel: $-1 < \eta < 1$
  - End-cap: $1.1 < \eta < 2$
- Main tracker – Time Projection Chamber (TPC):
  - $|\eta| < 1.3$

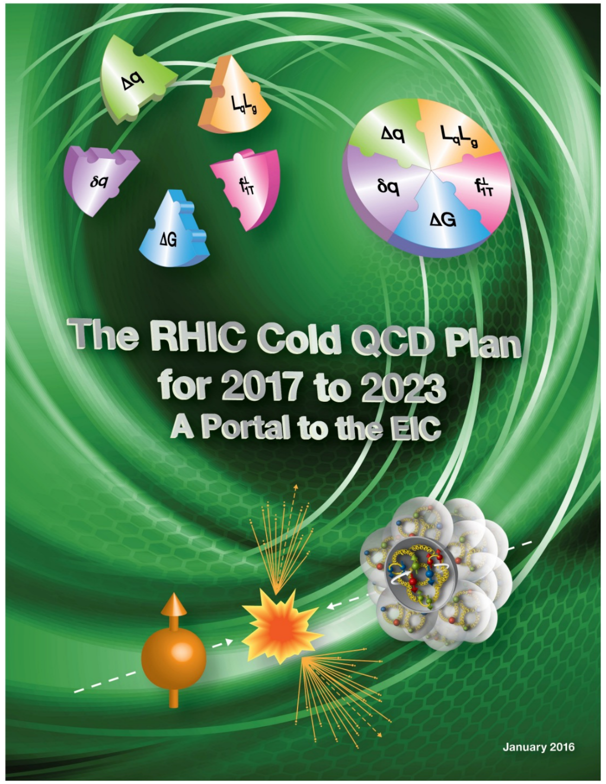


The Cold QCD program

Probing the cold nuclear matter via strong interactions in p+p and p+A collisions

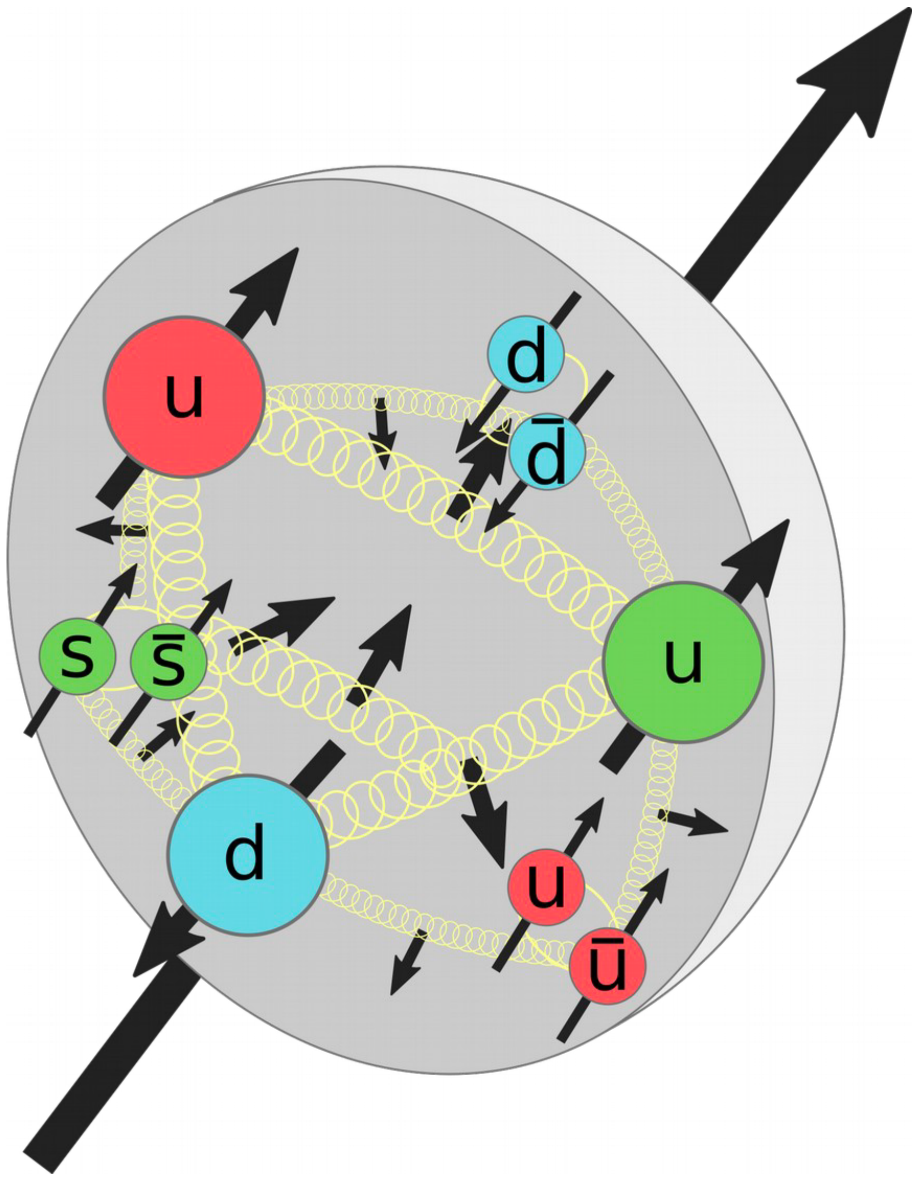
- What is the origin of the proton spin?
- What is the landscape of the (un)polarized see quarks in a nucleon?
- Understand QCD processes in cold nuclear matter
  - Investigate transverse-spin effects in QCD
- What is the initial state in nuclear collisions?

arXiv:1501.01220



arXiv:1602.03922

Proton helicity structure



Helicity of gluons

Jaffe-Manohar Spin Sum Rule:

$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}|J^z_{QCD}|P,\frac{1}{2}\right\rangle = \sum_q \frac{1}{2}S^z_q + \boxed{S^z_g} + \sum_q L^z_q + L^z_g$$

Process:

$\vec{p} + \vec{p} \rightarrow$ jets,dijets $+ X$

Observable:

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

- RHIC energies are sensitive to qg, gg interactions

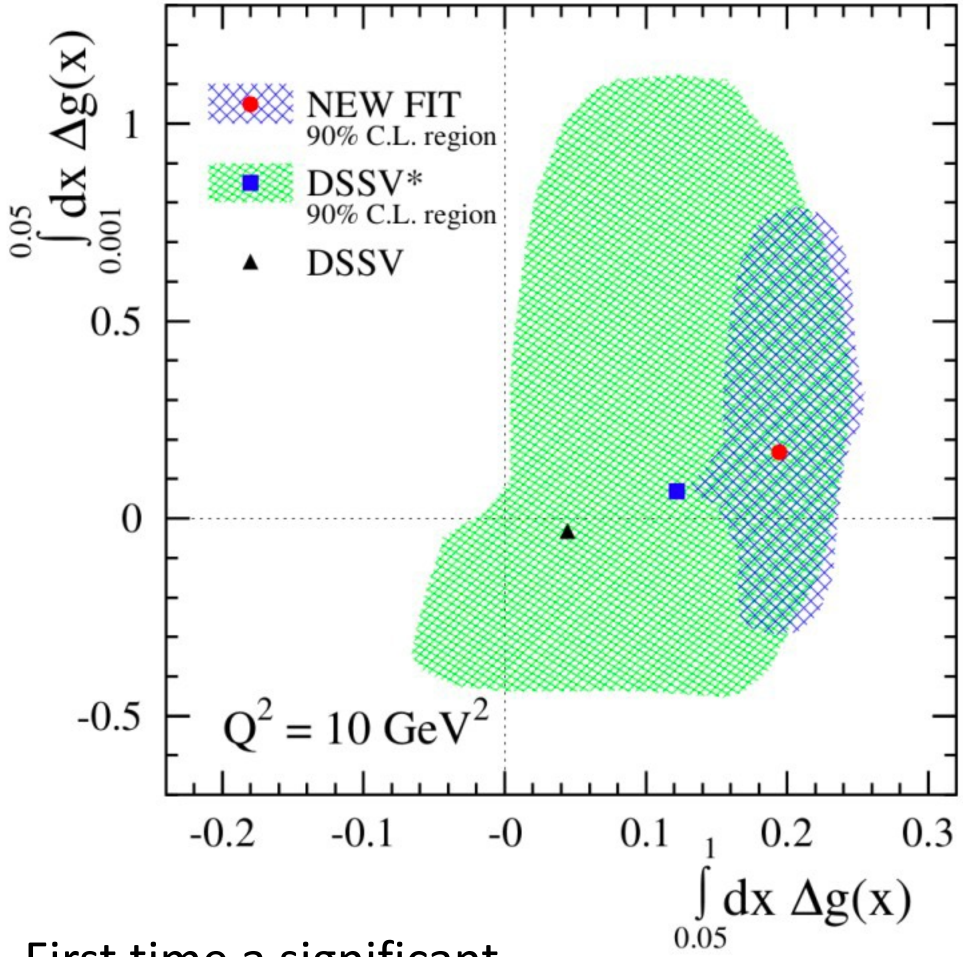
  → access to $\frac{\Delta g(x)}{g(x)}$

- First evidence for gluon polarization driven by STAR inclusive jet measurements at √s = 200 GeV (2009 run data) – [PRL 115 (2015) 9, 092002]

  → global fits: $\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07}\ @Q^2 = 10\ \text{GeV}^2$

New Fit: DIS (fixed targ.) + RHIC (till 2009)

Phys.Rev.Lett. 113 (2014) no.1, 012001

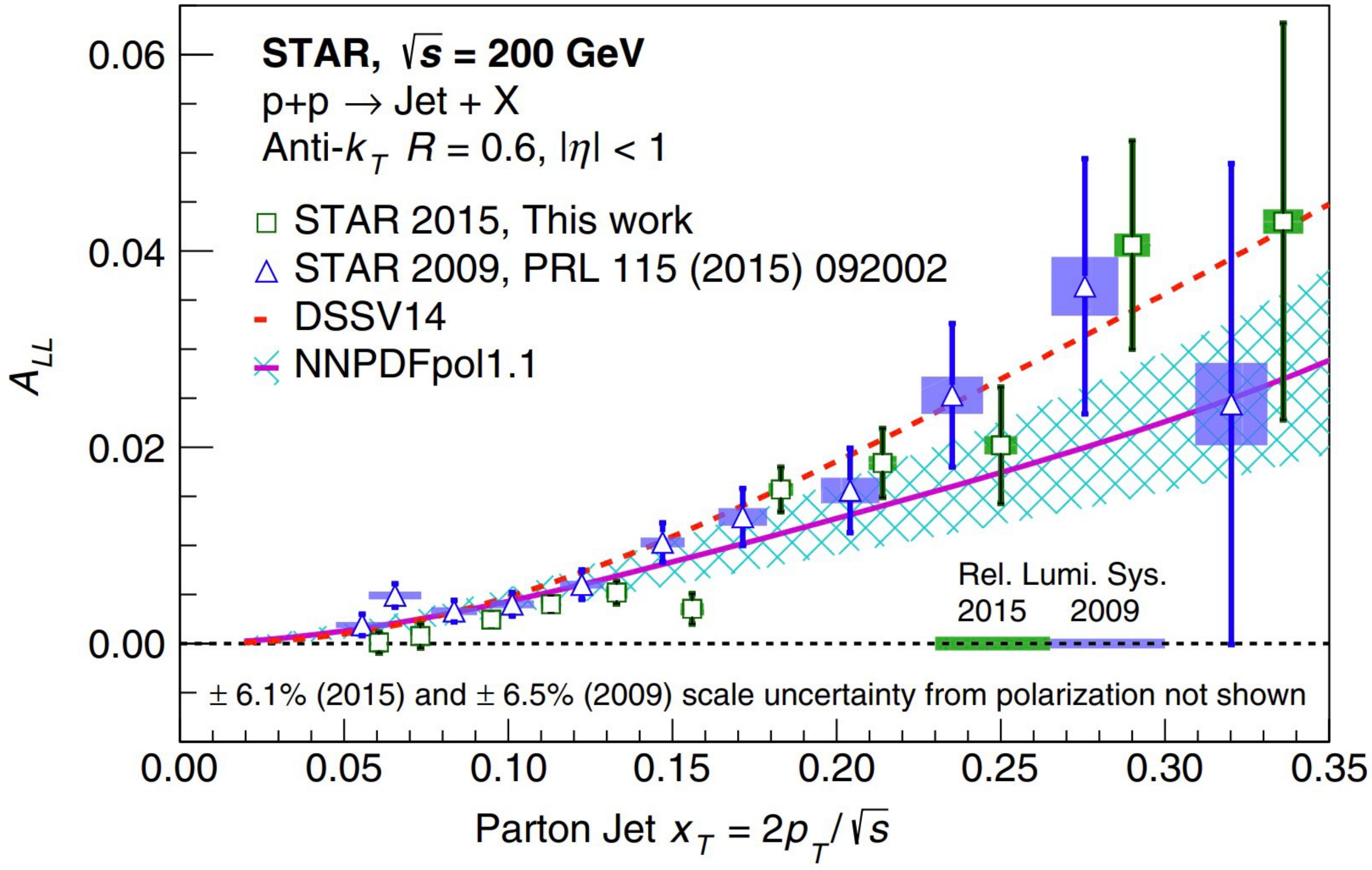


First time a significant non-zero $\Delta g(x)$

Inclusive jets from run 2015 at 200 GeV

$$\vec{p} + \vec{p} \rightarrow \text{jets} + X$$

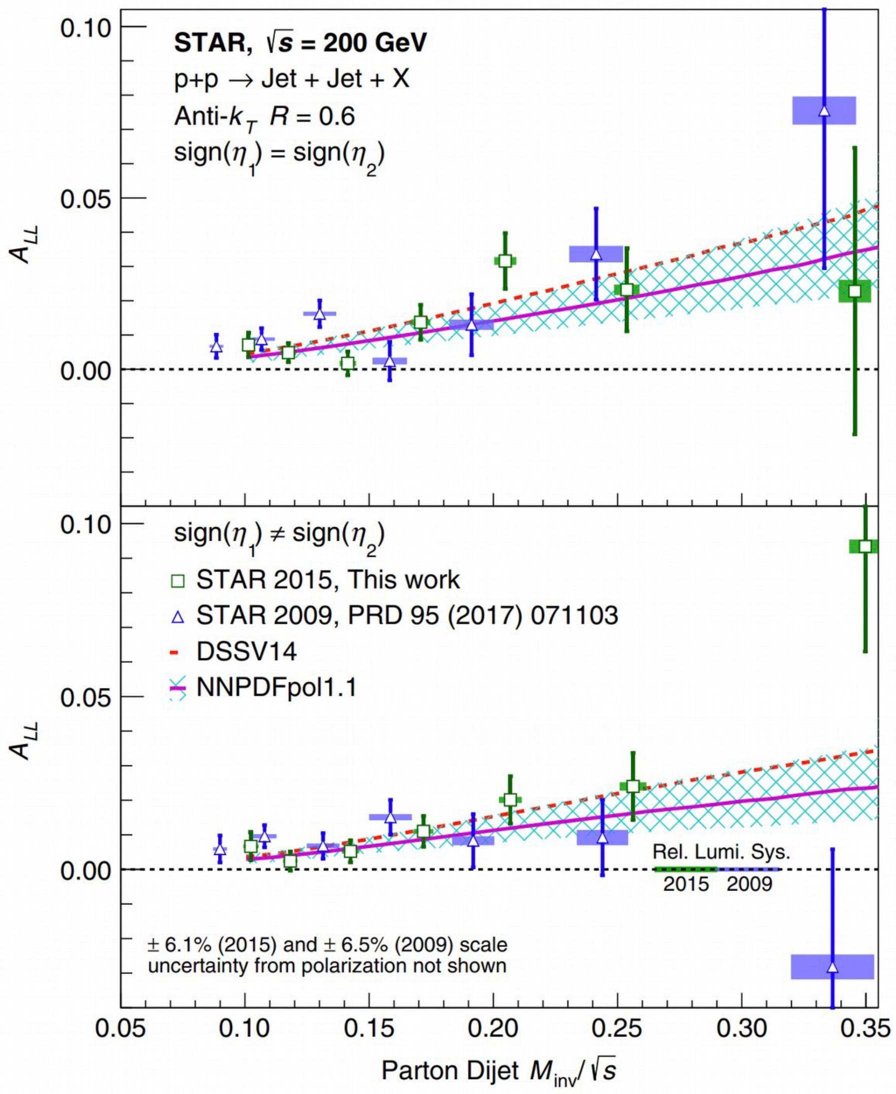
STAR - Phys. Rev. D 103, L091103 (2021)



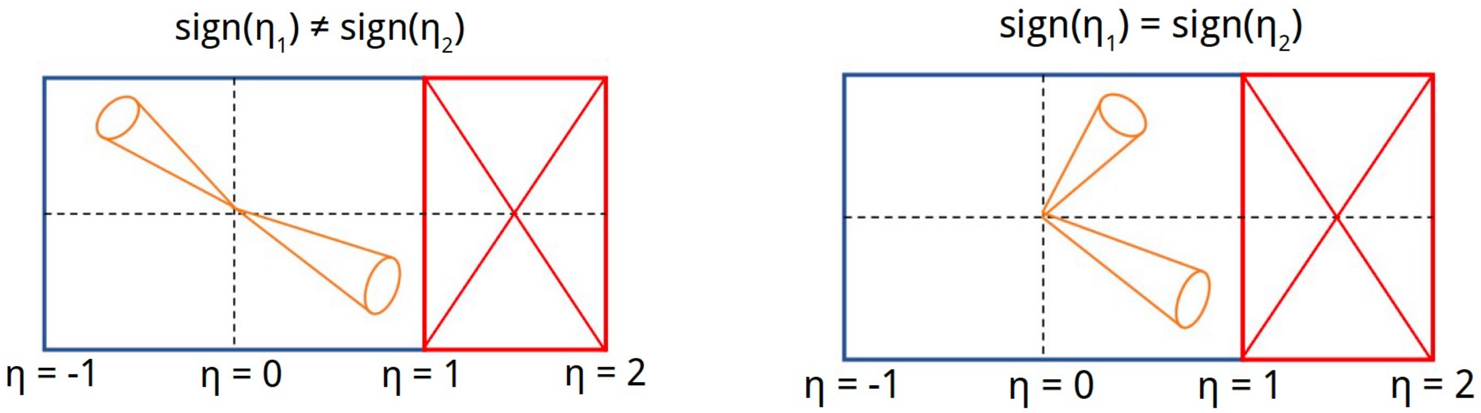
- Newly published 2015 data consistent with results from 2009
- Twice larger figure-of-merit (LP^4) and improved systematics
- When included into global fits, will further reduce uncertainty on $\frac{\Delta g(x)}{g(x)}, x > 0.05$

Dijets from run 2015 at 200 GeV

STAR - Phys. Rev. D 103, L091103 (2021)

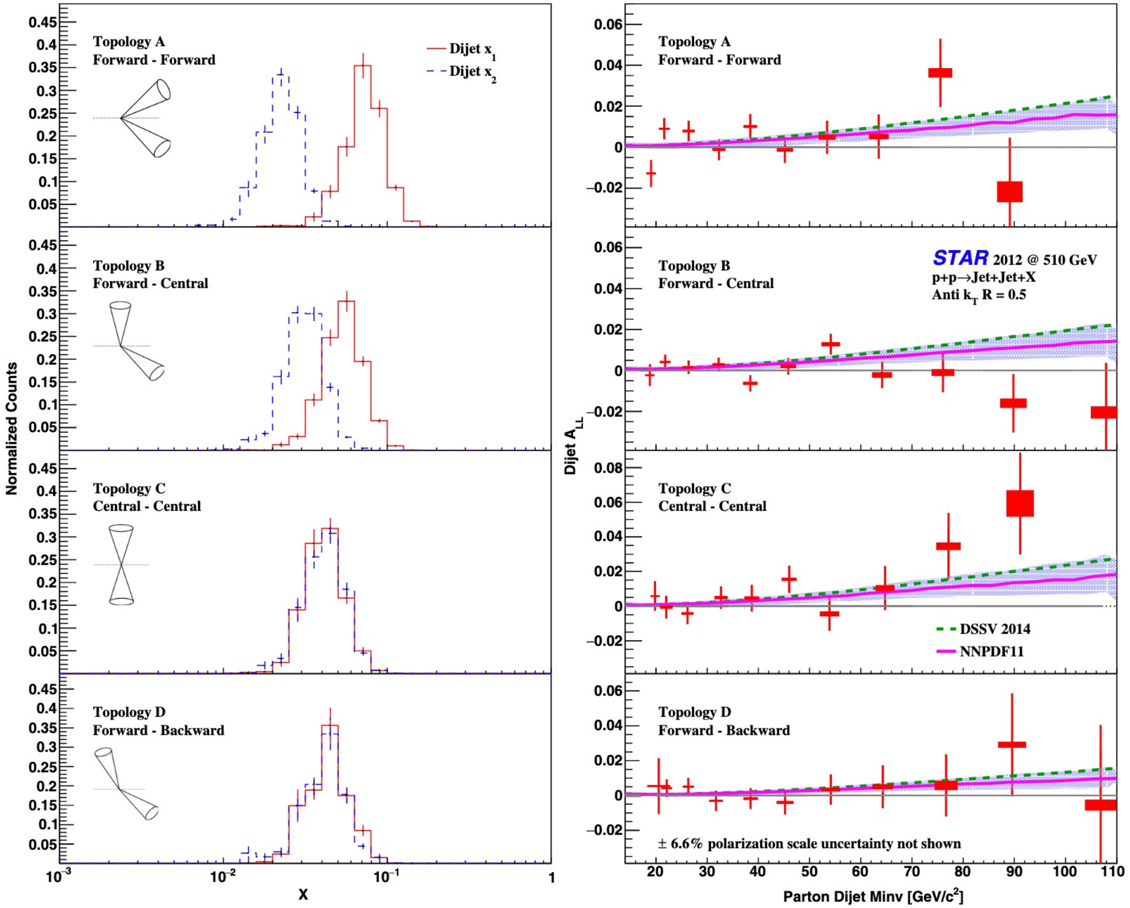


$$\vec{p} + \vec{p} \to \text{jet} + \text{jet} + X$$

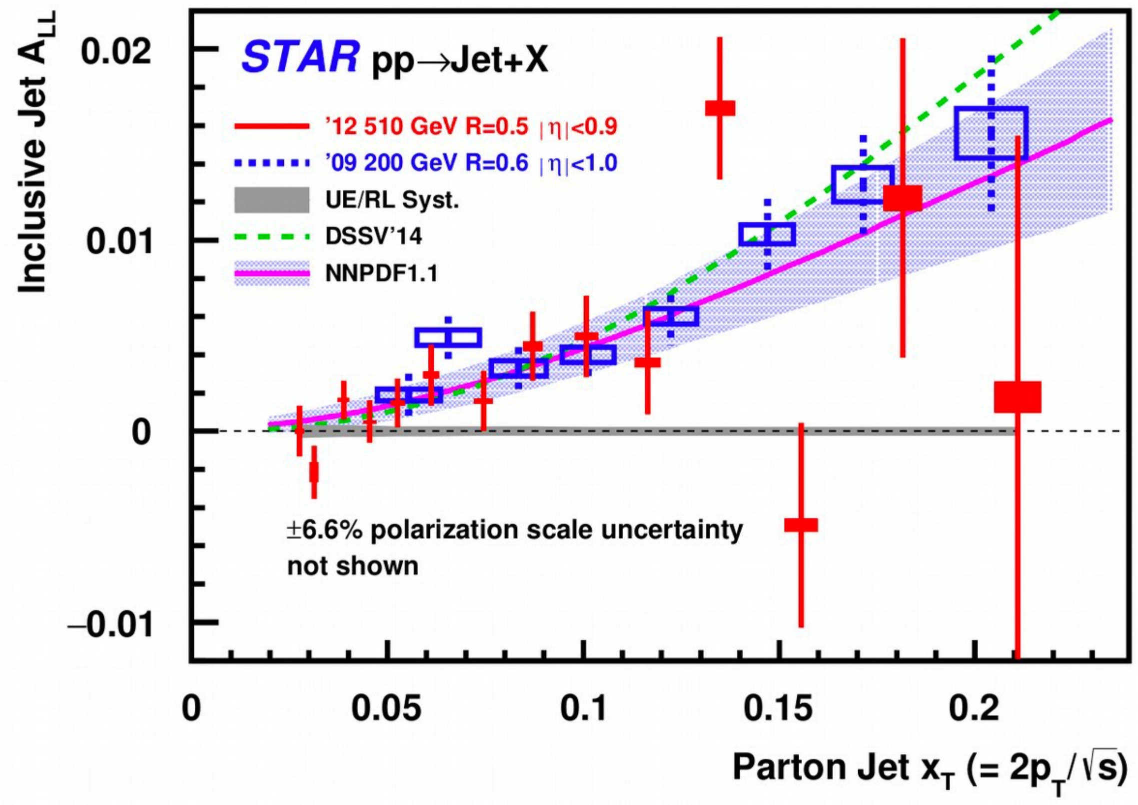


- Dijets give more stringent constraints to underlying partonic kinematics
  - Better constraints on functional form of $\Delta g(x)$ - narrow ranges of initial state partonic momentum probed
- Will further improve precision of $\Delta g(x)$ at $x > 0.05$
- STAR forward endcap: extends coverage down to $x \gtrsim 0.01$

Inclusive jets and dijets from run 2012 at 510 GeV



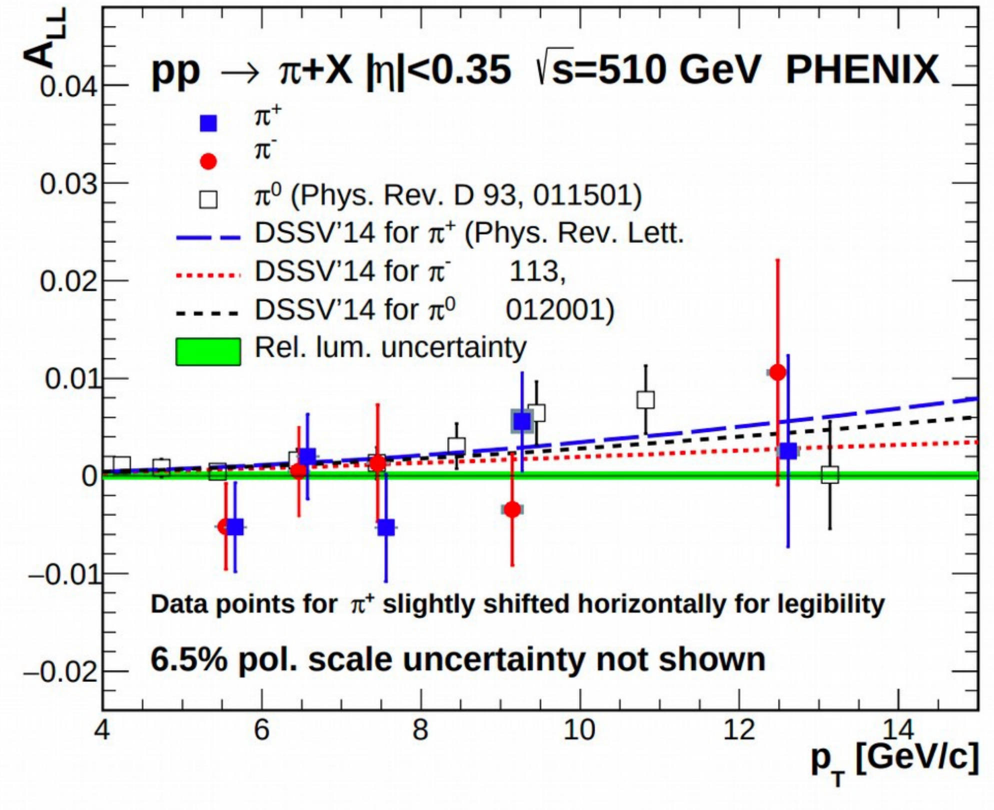
STAR - Phys Rev. D 100 (2019), 052005



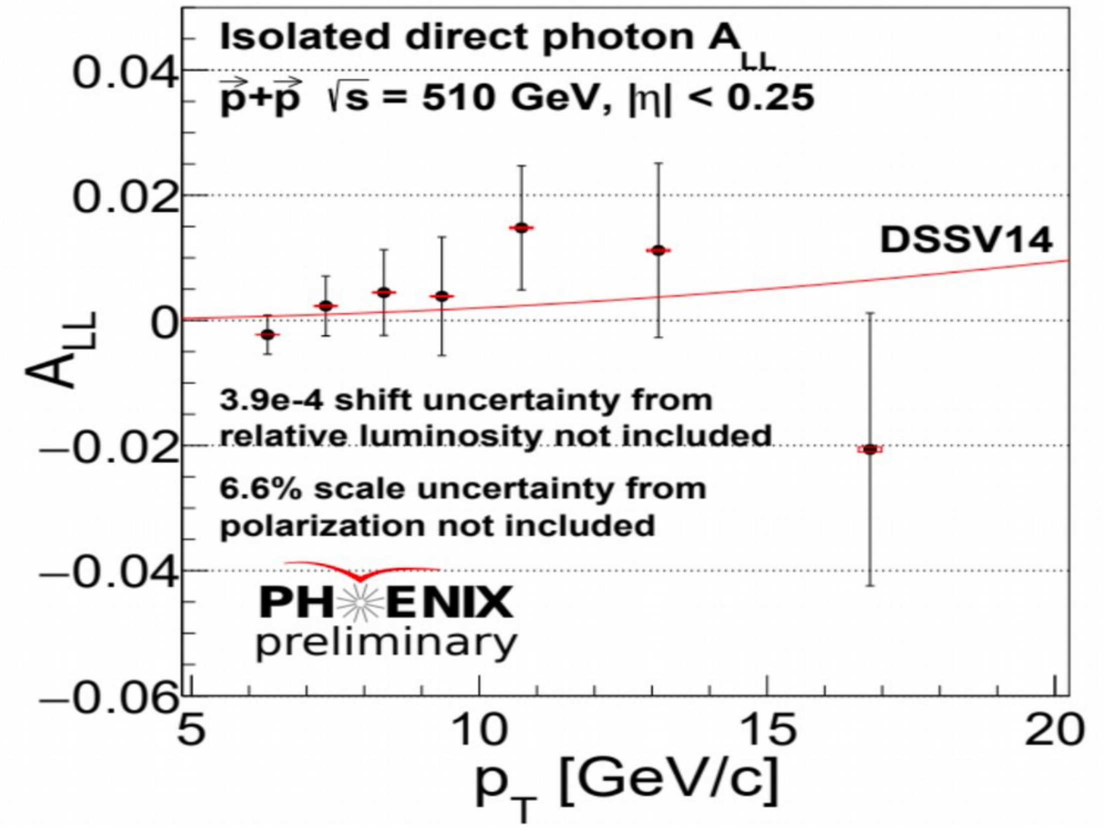
- Higher c.o.m. energy → smaller x [$x \gtrsim 0.004$ with STAR endcap dijets]
- Results from 510 GeV compatible with 200 GeV at the same x_T
- Analysis of run 2013 will add f.c.t. ~3.5 more statistics with respect to run 2012

Central pion and direct photon production at 510 GeV

PHENIX - PRD 102 (2020), 032001



PHENIX PRELIMINARY

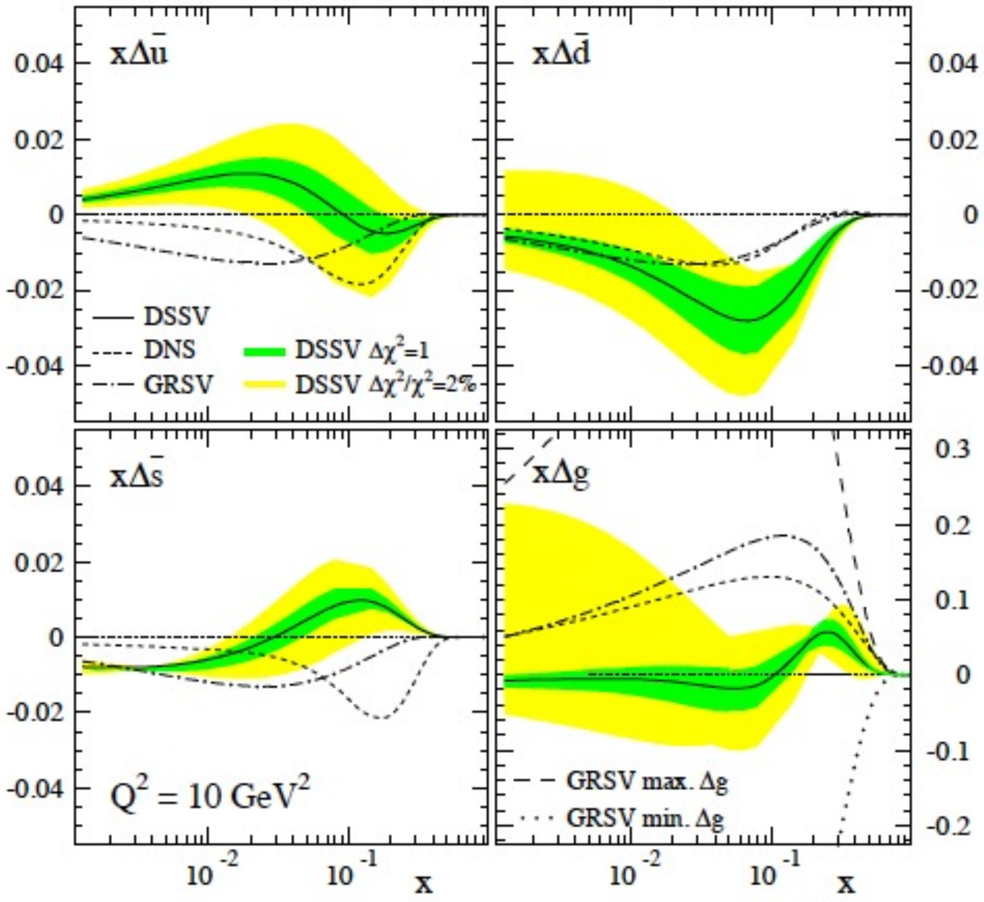


- Pion A_{LL} sensitive to the gluon polarization sign
- Direct photon sensitive to gq → γq LO process: clean access to Δg(x) (no hadronization)
- Consistent with STAR jets results in central production

Helicity of sea quarks

Jaffe-Manohar Spin Sum Rule:

$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}|J^z_{QCD}|P,\frac{1}{2}\right\rangle = \sum_q \frac{1}{2}S^z_q + S^z_g + \sum_q L^z_q + L^z_g$$



Observable: $A_L = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}}$

At LO:

$$A_L^{W^+}(y_W) \sim \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

$$A_L^{W^-}(y_W) \sim \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

- A_L of $W^{\pm}$ bosons → decompose quark flavors
  - Decay process is easily calculable: no fragmentation fcn.
  - flavor asymmetry of the light quark sea in the proton

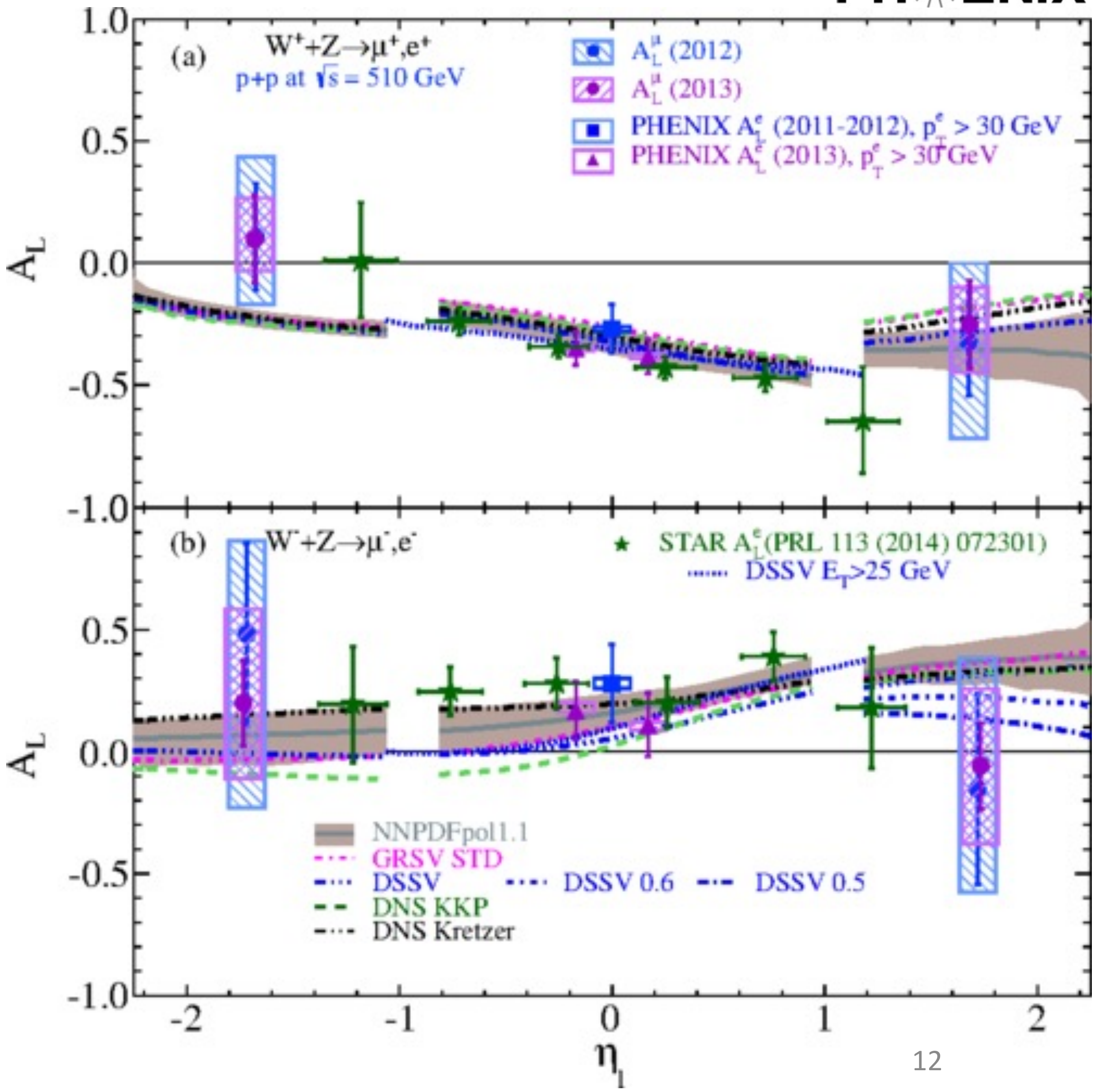
unpolarized: ubar ≠ dbar

polarized case?

A_L in $W^{\pm}$ production

PHENIX - Phys. Rev. D 98 (2018) 032007

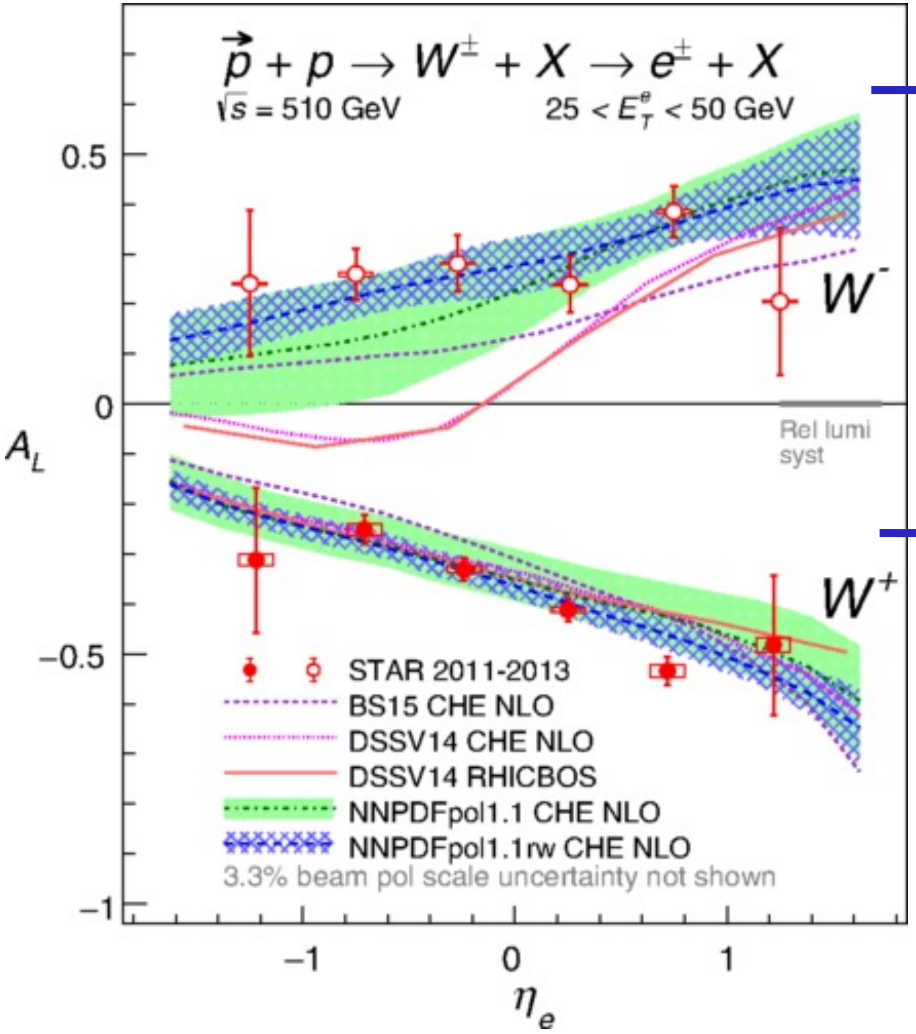
- First muon decay channel for $W^{\pm}$ A_L
- Theoretical curves use the polarized NLO generator CHE
- Backward μ^- are at upper limit of uncertainty bands. Hints that $\Delta\bar{u}$ might be larger than fits without RHIC data indicate
- Forward μ^- is below DSSV08
- Backward μ^+ show smaller than predicted asymmetries



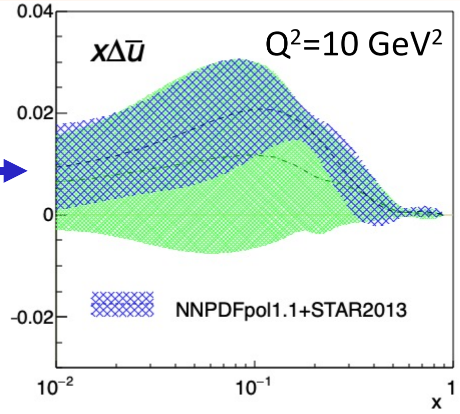
A_L in $W^{\pm}$ production

NNPDFpol1.1 reweighting

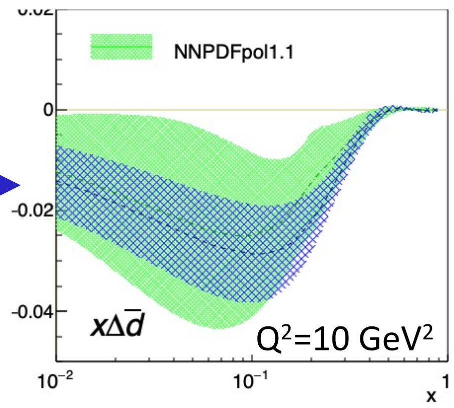
STAR - Phys, Rev. D 99, 051102(R) (2019)



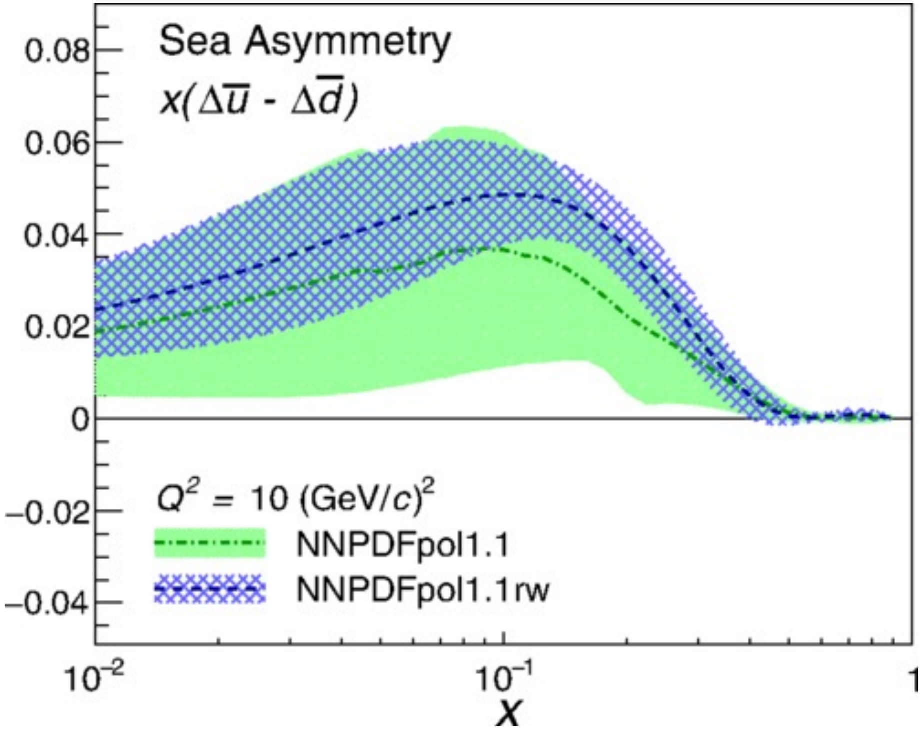
$\Delta\bar{u}$



$\Delta\bar{d}$



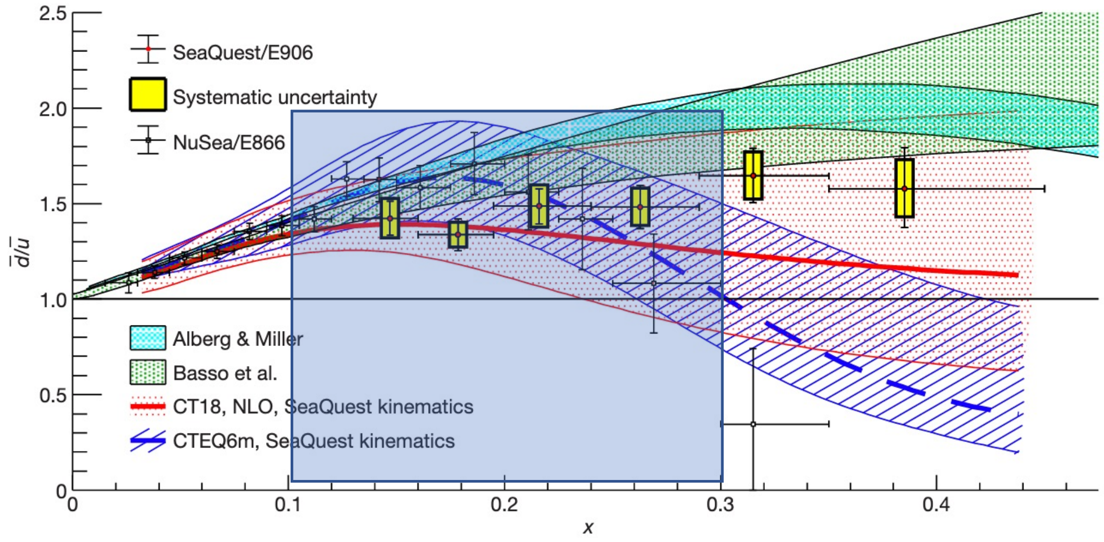
Flavor asymmetry for sea quarks



- **40% reduced uncertainties** after adding STAR run 2013
- Good agreement with DSSV and NNPDF
- **First evidence for polarized flavor asymmetry**
  - Data show a **significant preference** for $\Delta\bar{u} > \Delta\bar{d}$ for $0.05 < x < 0.25$ at $Q^2 = 10$ GeV^2

Quark flavor ratio in PDFs

Nature 590, 561–565 (2021)



- Unpolarized $\bar{d}/\bar{u}$ in PDFs can be probed via Drell-Yan
- **E-866** suggests a trend where the $\bar{d}/\bar{u}$ ratio appears to be decreasing at large-*x*, but **new SeaQuest** trend appears to level out at **higher *x***.
- **Unpolarized W cross-section charge ratios** are also **sensitive** to **quark/anti-quark** distributions.

LO:

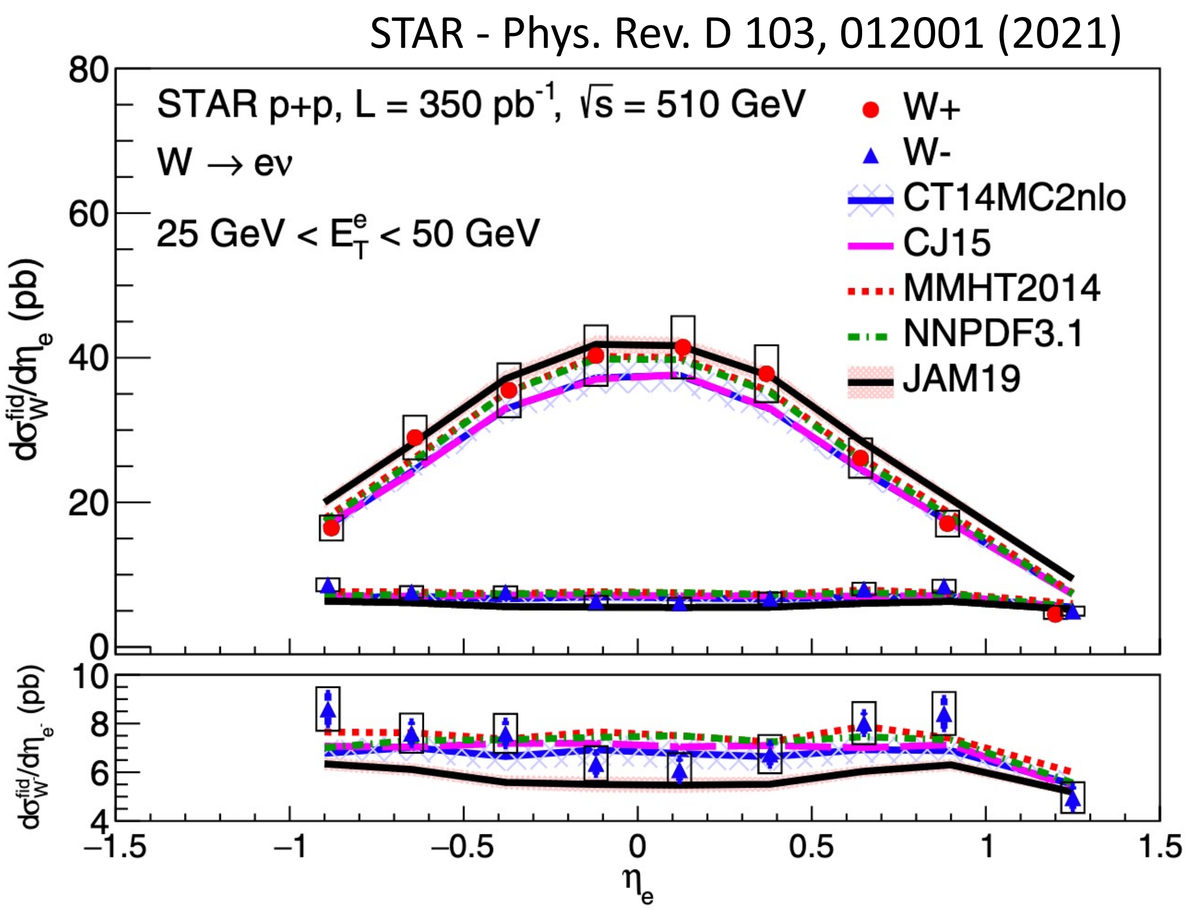
$$\frac{\sigma(W^+)}{\sigma(W^-)} = \frac{u(x_1)\bar{d}(x_2)+\bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2)+d(x_1)\bar{u}(x_2)}$$

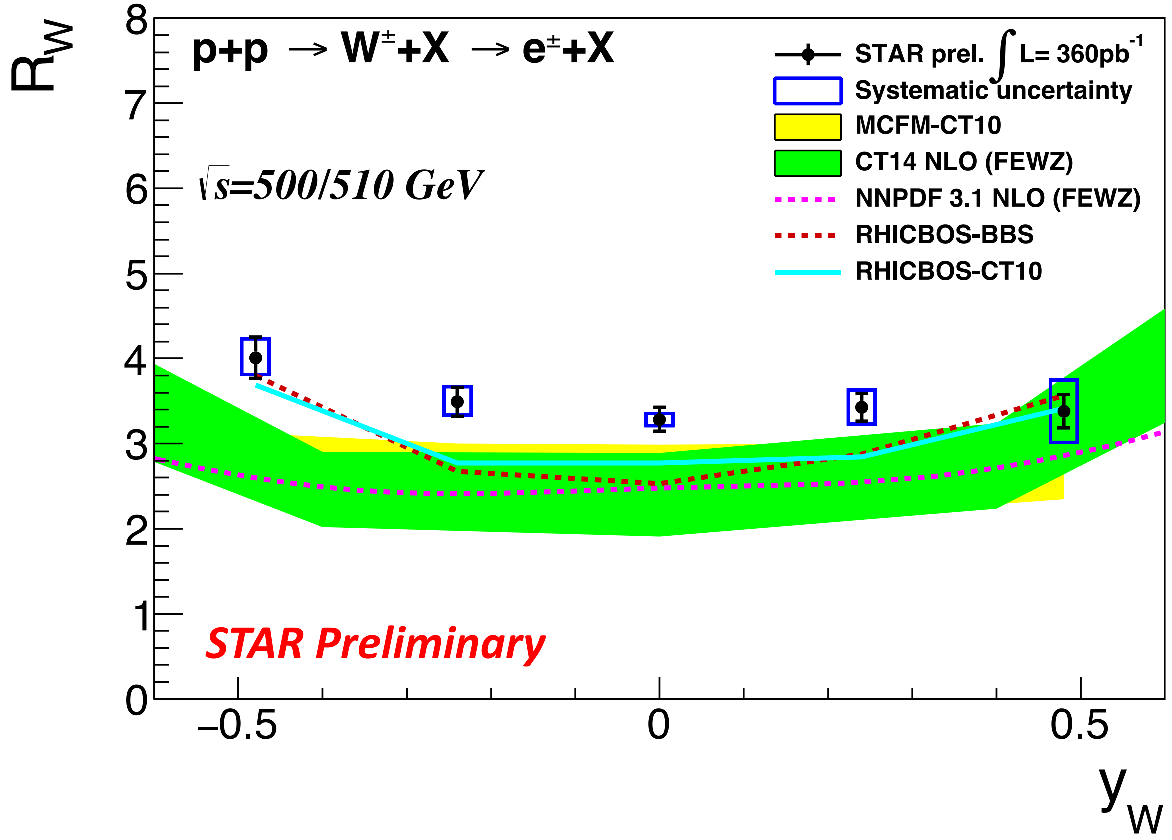
- Complementary to Drell-Yan data: $|\eta| < 1$: 0.1 < x < 0.3, at higher $Q^2 = M_W^2$
  - **LHC coverage:** ~10^{-3} < x < 10^{-1}

    $$\langle x_{1,2} \rangle = \frac{M_W}{\sqrt{s}} e^{-\eta_l/2}$$

  - **STAR coverage:**
    - **Mid-rapidity** -1 < η < 1 (**TPC +BEMC**) : 0.1 < x < 0.3
    - **Forward EEMC** 1.1 < η < 2: 0.06 < x < 0.4
- Differential cross sections of weak bosons are key inputs in global fits of **unpolarized TMDs**

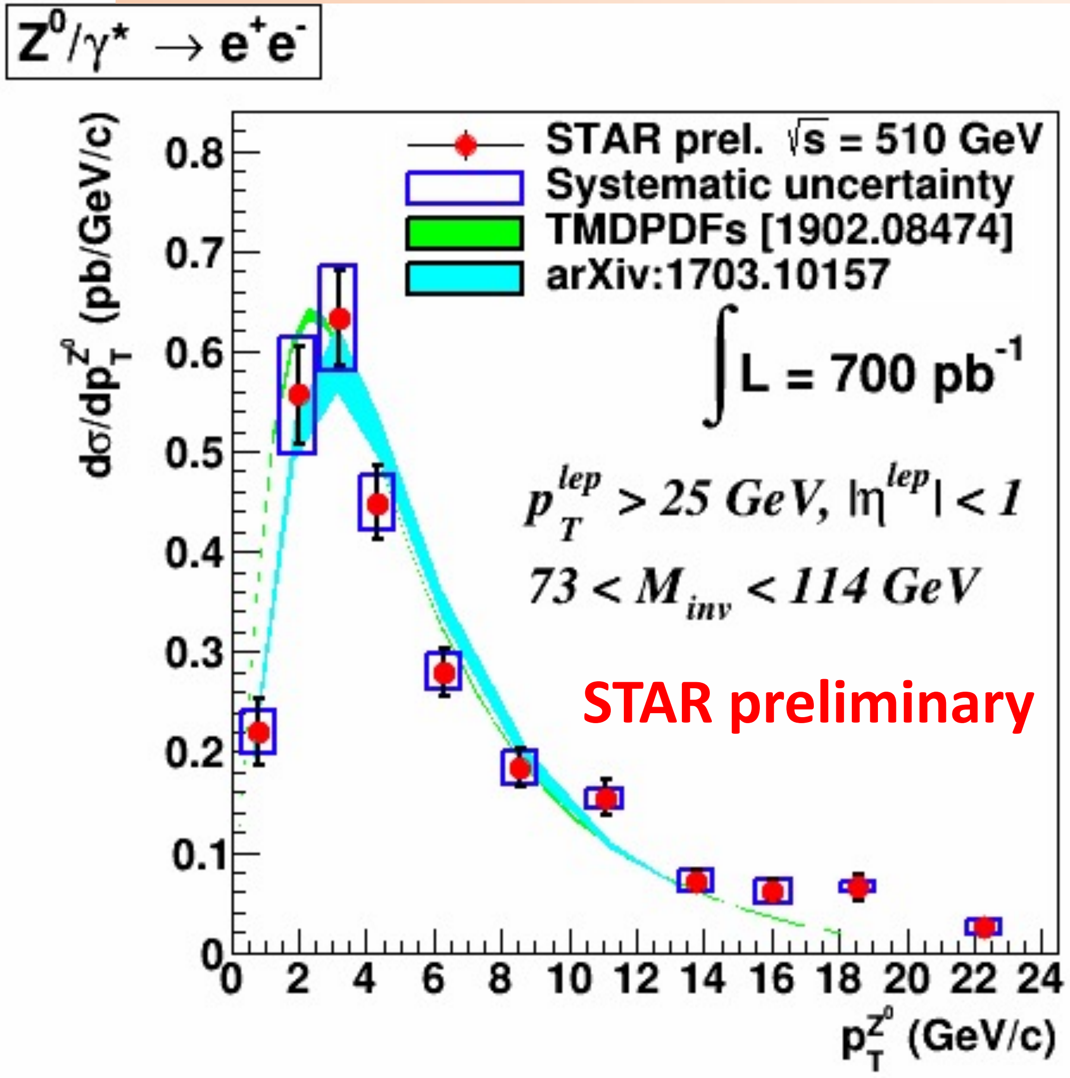
Unpolarized W^+/W^- differential cross-section ratios

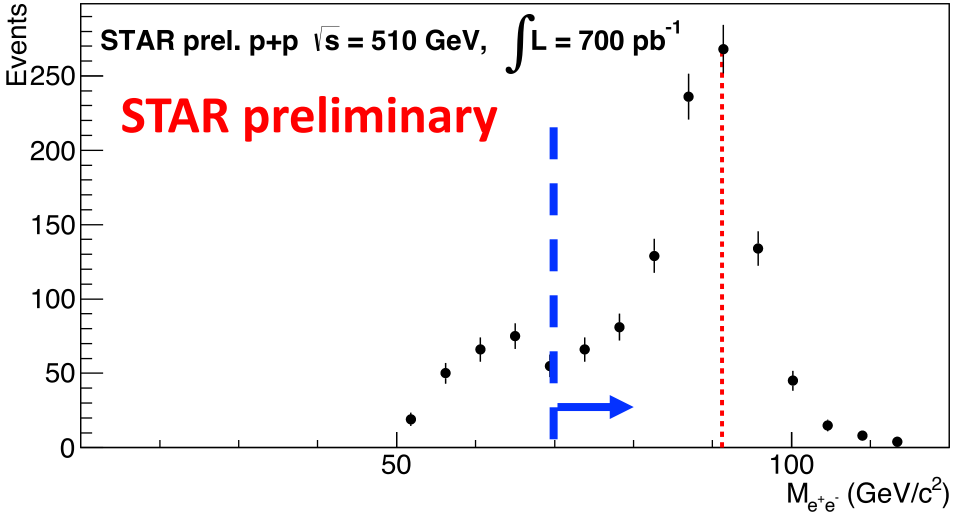




- Cross section charge ratio measured vs. both the decay lepton and the boson's kinematics
- Will provide insights into unpolarized light quark distributions *d(x), u(x),* and $\frac{\bar{d}}{\bar{u}}$ at $x > 0.05$
- Run-17 will add an additional ~350 pb^{-1}, Run-22 expected to add another ~400 pb^{-1}

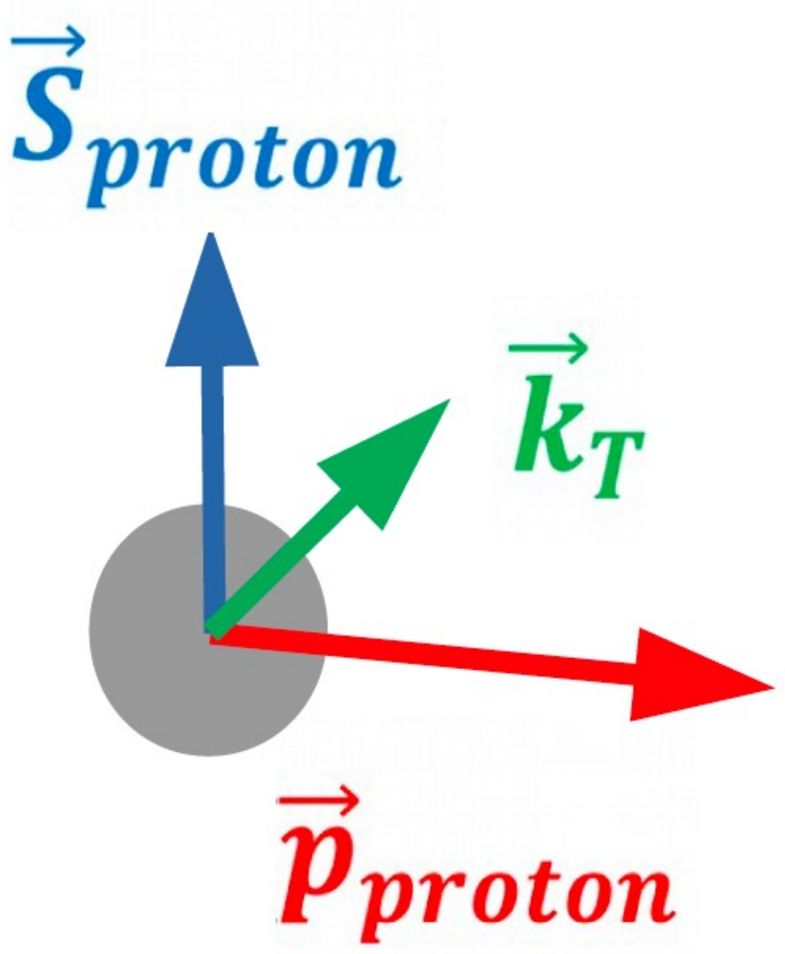
Unpolarized Z^0 p_T-differential cross section



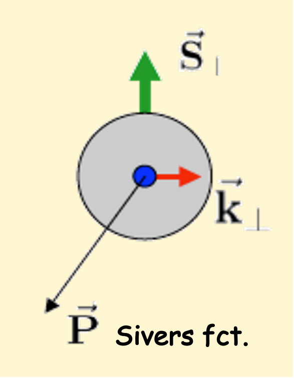


- **Now includes data from 2017:** ~2 more statistics compared to previous release
  - Unfolded p_T spectrum
  - Systematics from energy resolution and electron selection
- Key input to global fits of unpolarized TMDs
- New theory fits including all STAR measurements will be added as they become available

SIVERS



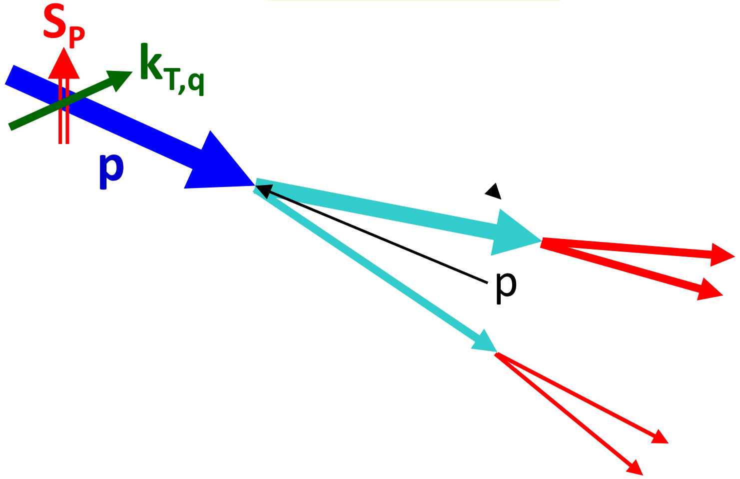
Sivers function



8 Transverse Momentum Dependent distribution functions (TMDs) are allowed by gauge invariance

The TMD known as **Sivers function** is

- ○ Sensitive to **transverse proton spin** – parton **transverse motion** correlations
- ○ Predicted not to be universal between SIDIS & p+p
  - **Sivers$_{DIS}$ = - Sivers (DY or W or Z)**
- ○ Weak bosons:
  - less background compared to DY
  - higher $Q^2 = M_W^2$: can test evolution effects
  - sensitive to sea quarks
  - but: need for reconstructing produced boson's kinematics

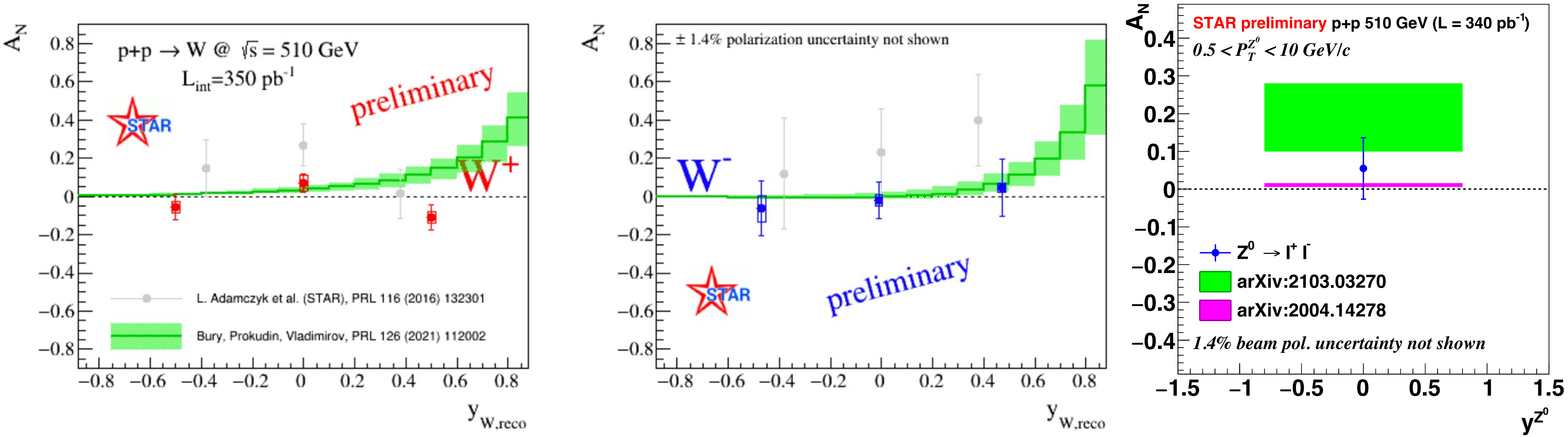


Tools to measure Sivers:

Transverse single-spin asymmetry amplitude (azimuthal modulation)

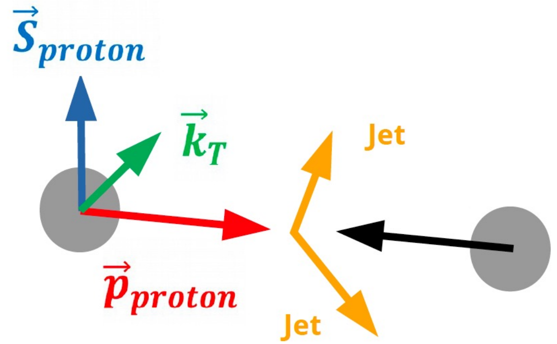
$$A_N \approx \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

A_N in weak boson production



- **Statistics much improved with run 2017 (350pb^{-1})** compared to run 2011 (25pb^{-1})
- Predictions assume sign change
  - Extraction includes SIDIS, DY and STAR run 2011 results
- Current STAR data not yet significant enough to make claims on the sign-change
  - Expect ~400 pb^{-1} more data from run 2022, with η coverage extended by STAR iTPC

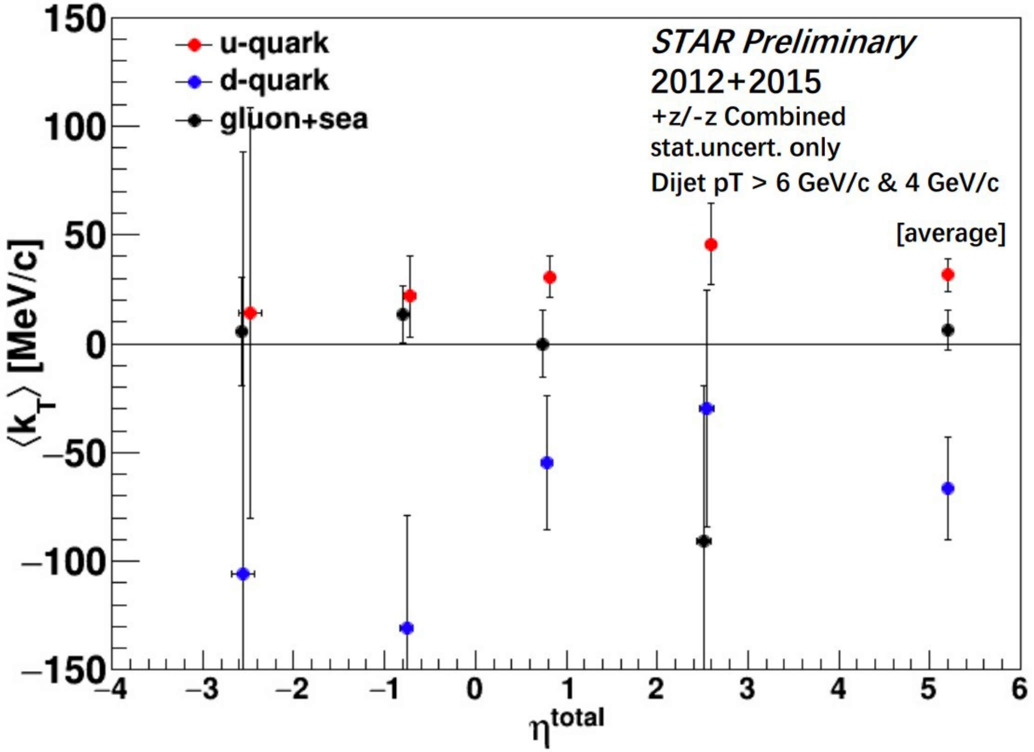
Asymmetry in dijets opening angle



Sivers fnc. is sensitive to correlation between transverse **proton spin** (initial state) and **parton transverse momentum**

$$\langle \vec{S}_{proton} \cdot (\vec{p}_{proton} \times \vec{k}_T) \rangle \neq \mathbf{0}$$

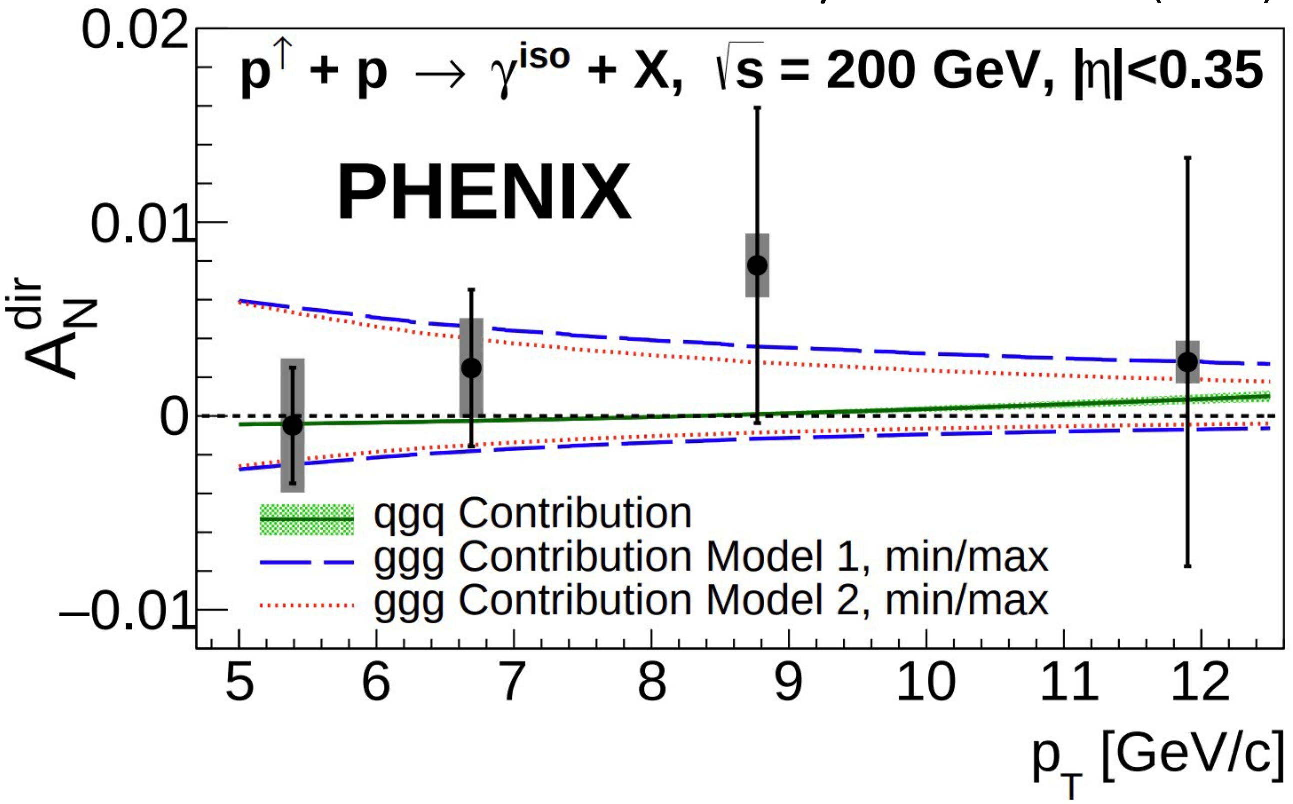
- Non-zero k_T leads to a spin-dependent tilt of dijet opening angle in transverse plane
- Enhancing contribution of *u* or *d* quarks by sorting jets by their net charge
- Tilt unfolded for the k_T of individual partons
- **Results:** k_T for *d quark* opposite in sign, and twice larger than the average k_T for u quarks
- Constraints for the Sivers fnc. at a high Q^2 scale (Q^2 > 160 GeV^2)

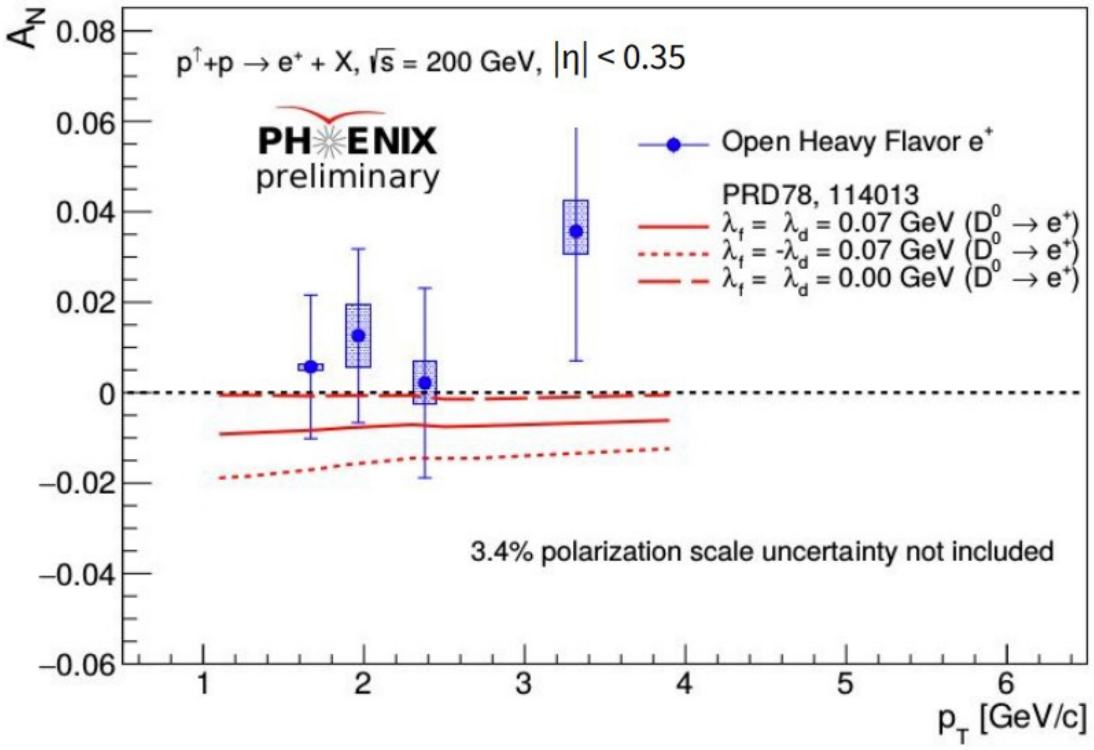


A_N in direct photons and heavy flavor production

- PHENIX detector can measure D^0 mesons and direct γ at mid rapidity ($|\eta|<0.35$)
- **Sivers indirectly constrained** via integral relationship with the **Twist-3** trigluon correlator

PHENIX - Phys. Rev. Lett. 127 (2021)

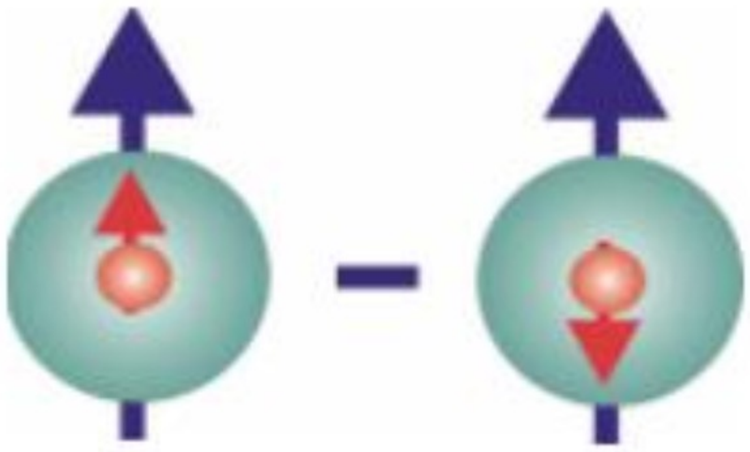




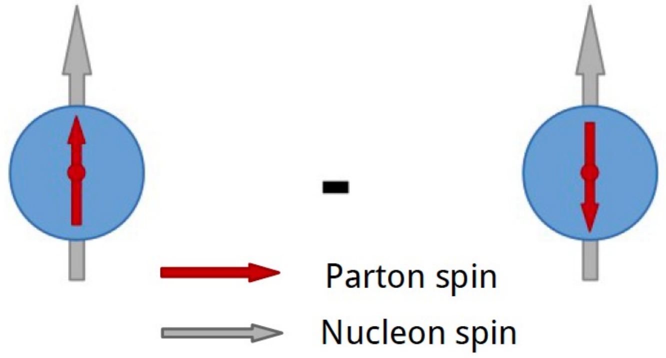
TRANSVERSITY

$\Delta_T q(x)$

$h_1^q(x)$



Transversity



Describes the net density of **quarks with spin aligned with the transversely polarized nucleon** (leading twist)

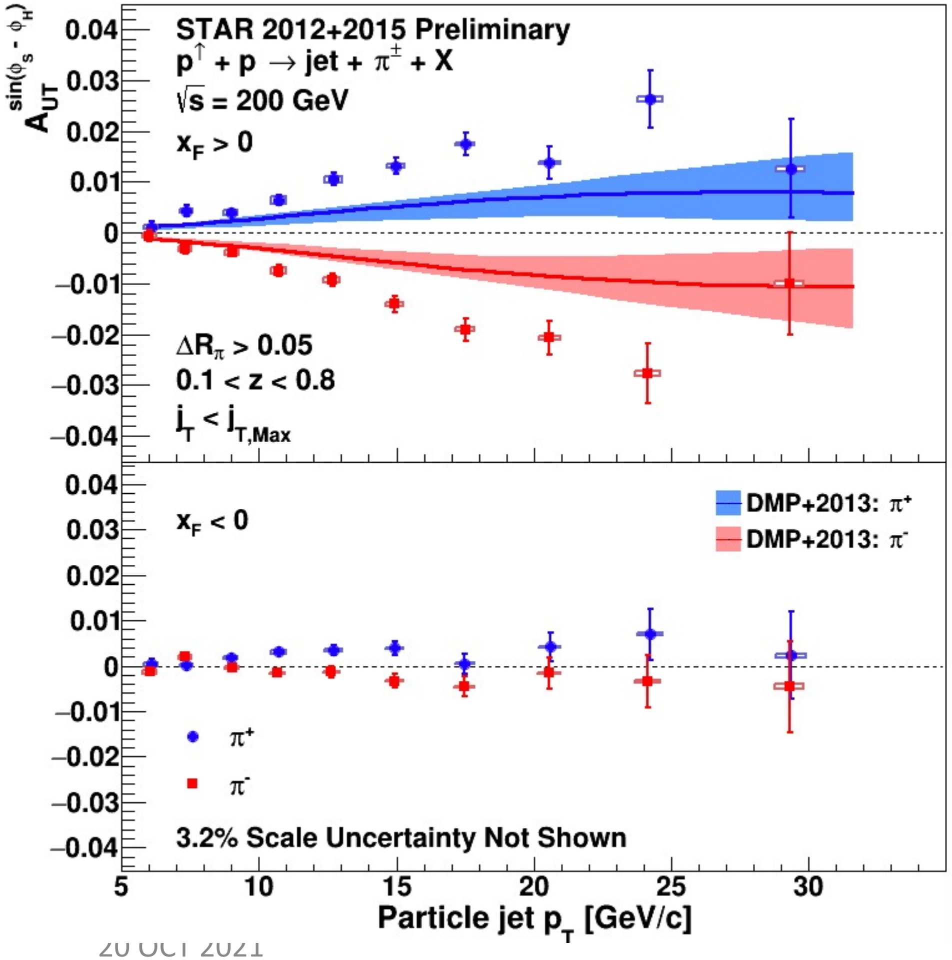
- **Tools:** azimuthal modulation of **transverse single-spin asymmetry amplitude (A_{UT})**

- **At RHIC:** sensitivity via two A_{UT} amplitudes:
  - **Spin-dependent modulation of hadrons in jets**
    - **Collins function (TMD FF) -** Correlation of transverse spin of fragmenting quark and transverse momentum kick given to fragmentation hadron
  - **Di-hadron correlation measurements**
    - **“interference FF”** (collinear framework) - Correlation of transverse spin of fragmenting quark and momentum cross-product of di-hadron pair

Transversity

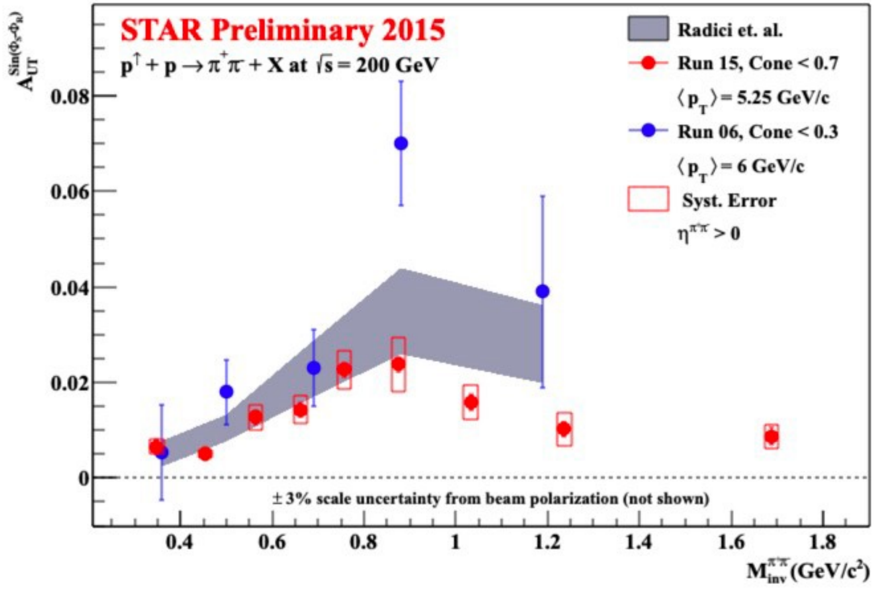
Spin-dependent modulation of hadrons in jets

Collins function (TMD FF)



Di-hadron correlation measurements

"interference FF"

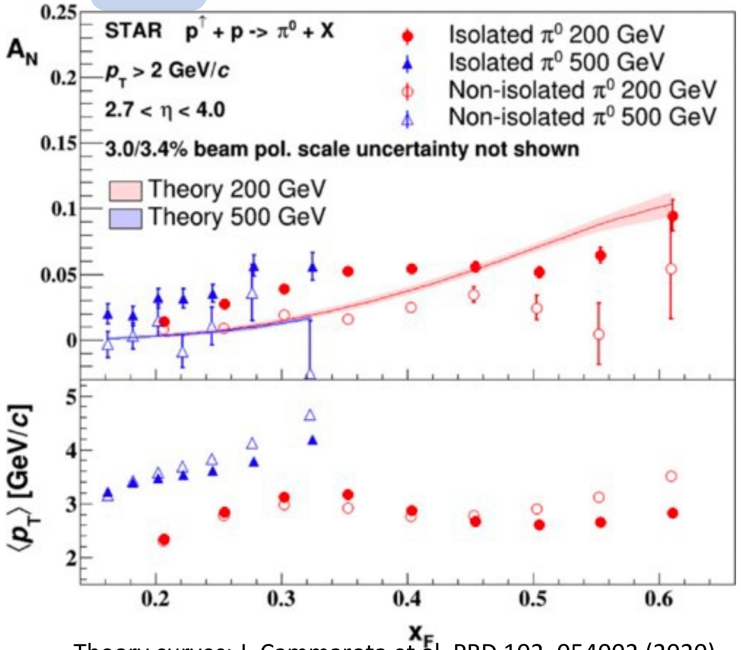


- Significant Collins asymmetries have been observed from 200 GeV data:
  - Collinear transversity is probed most directly in the jet p_T dependence;
  - Collins TMD FF is sensitive to the (j_T, z) dependence.

Forward transverse single spin asymmetries

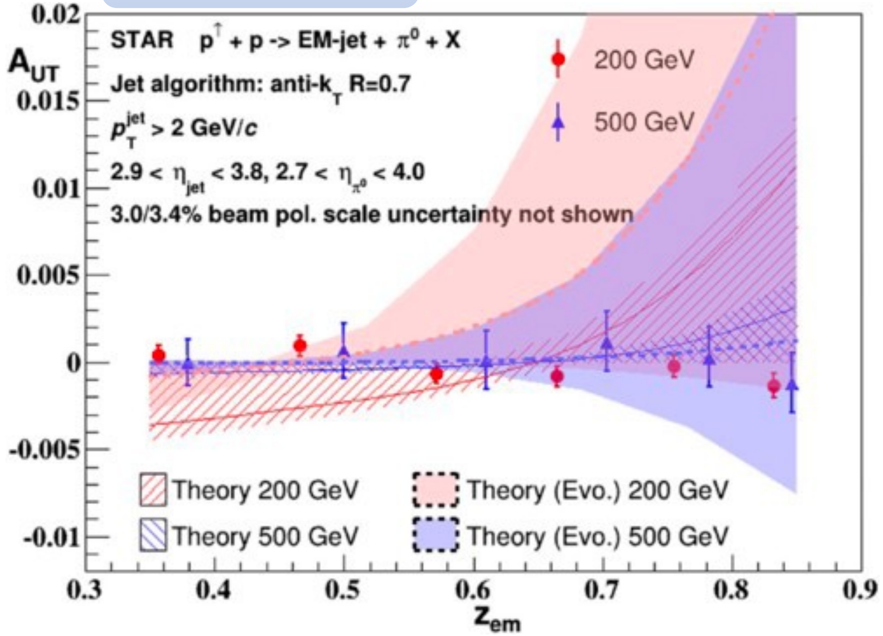
STAR - Phys. Rev. D 103 (2021) 92009

π^0



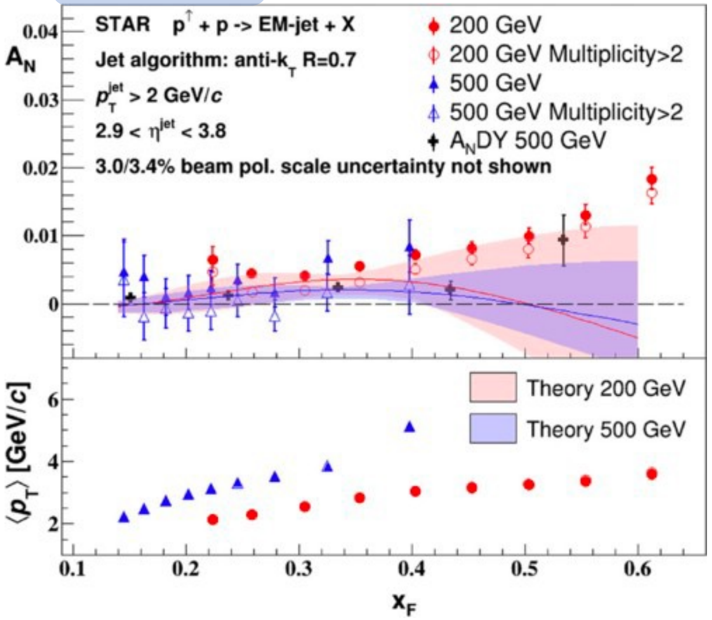
Theory curves: J. Cammarota et al. PRD 102, 054002 (2020)

π^0 in EM-jet



Theory curves : Z. Kang, et al. PLB 774, 635 (2017)

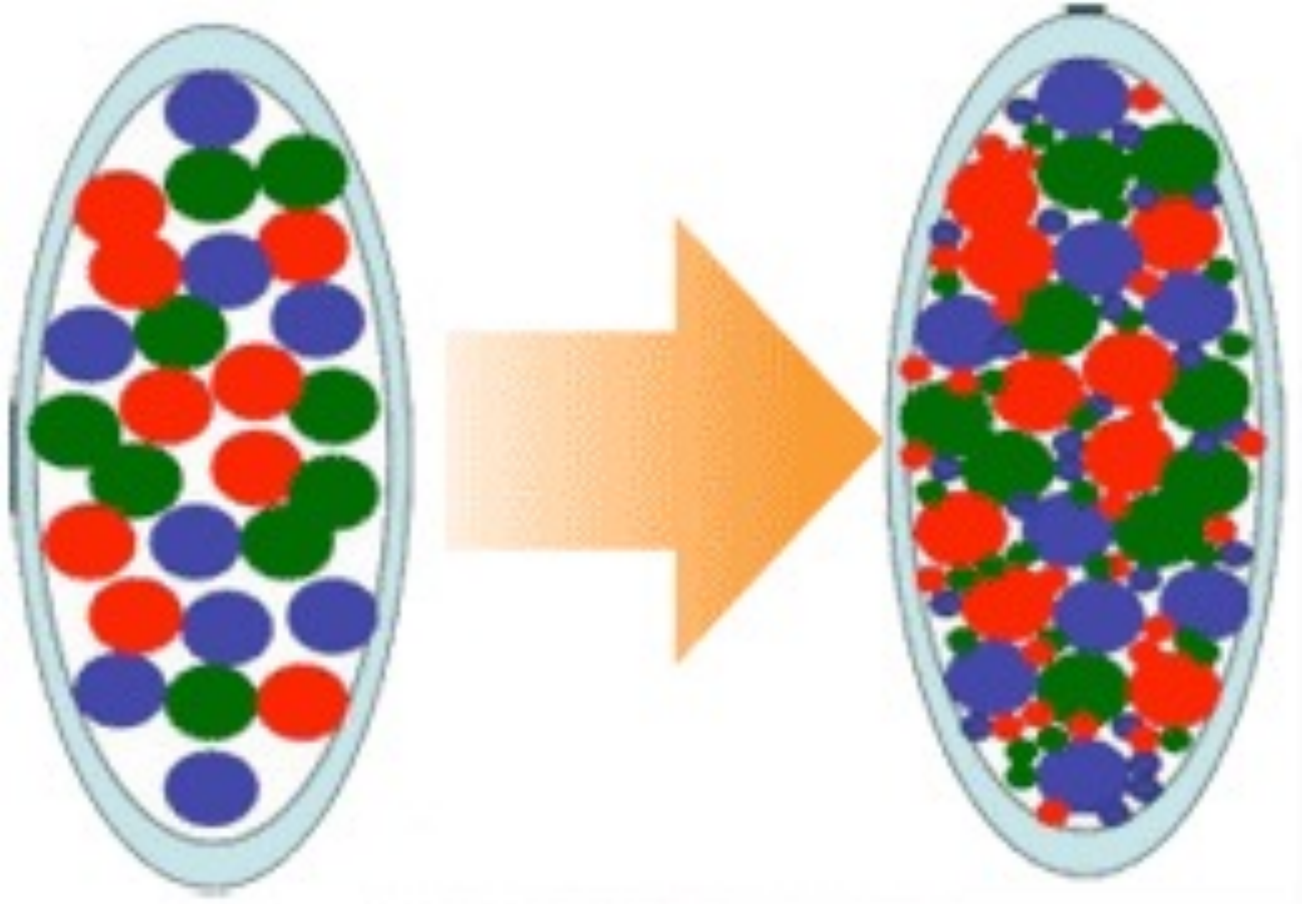
EM-jet



Theory curves :
L. Gamberg, Z. Kang, A. Prokudin,PRL 110 23, 232301 (2013)

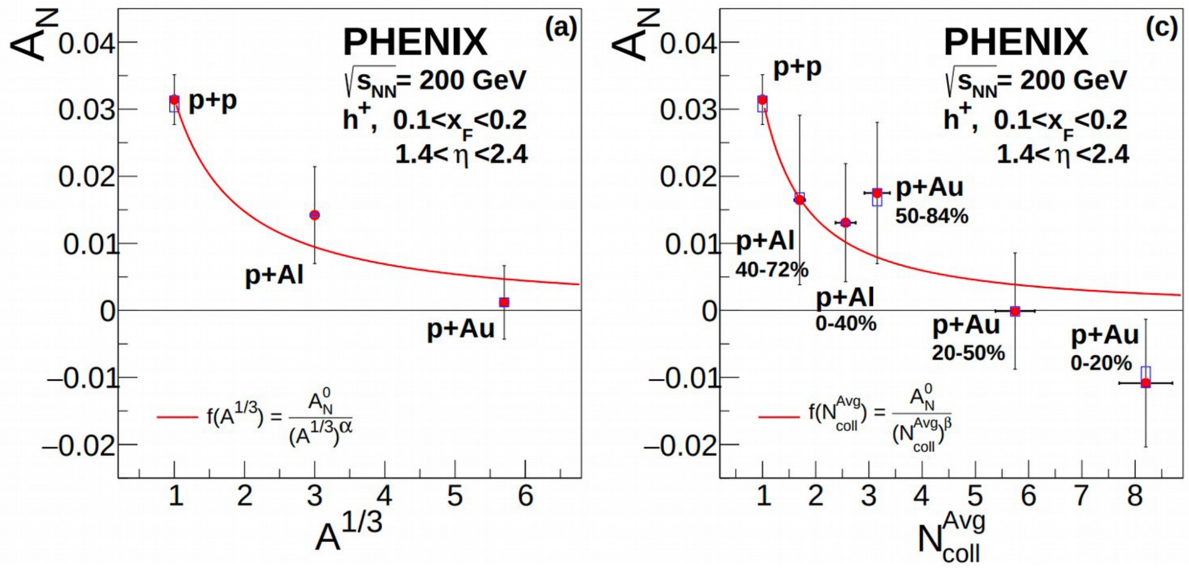
- Investigating the origin of the large asymmetries
- **Results:**
  - Observed A_N for EM-jets and Collins asymmetry for π^0 within EM jets are small
  - A_N for non-isloated π^0 and for π^0 within higher-multiplicity jets are even smaller
  - Weak dependence of the collision energy

GUON SATURATION

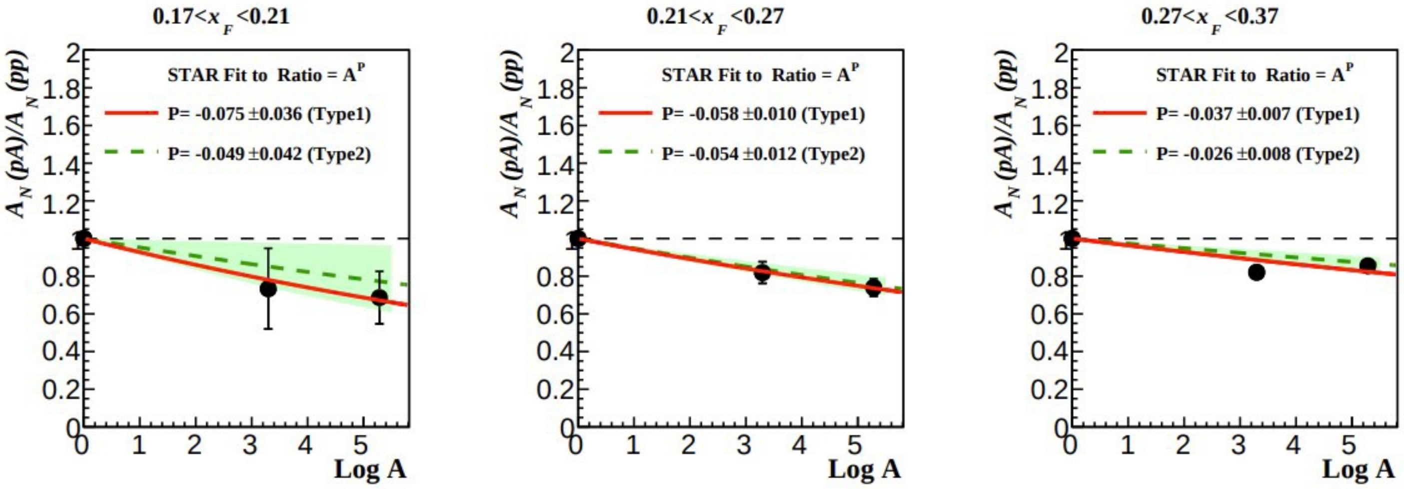


Nuclear dependence of forward transverse asymmetries

PHENIX – Phys. Rev. Lett. 123, 122001 (2019)

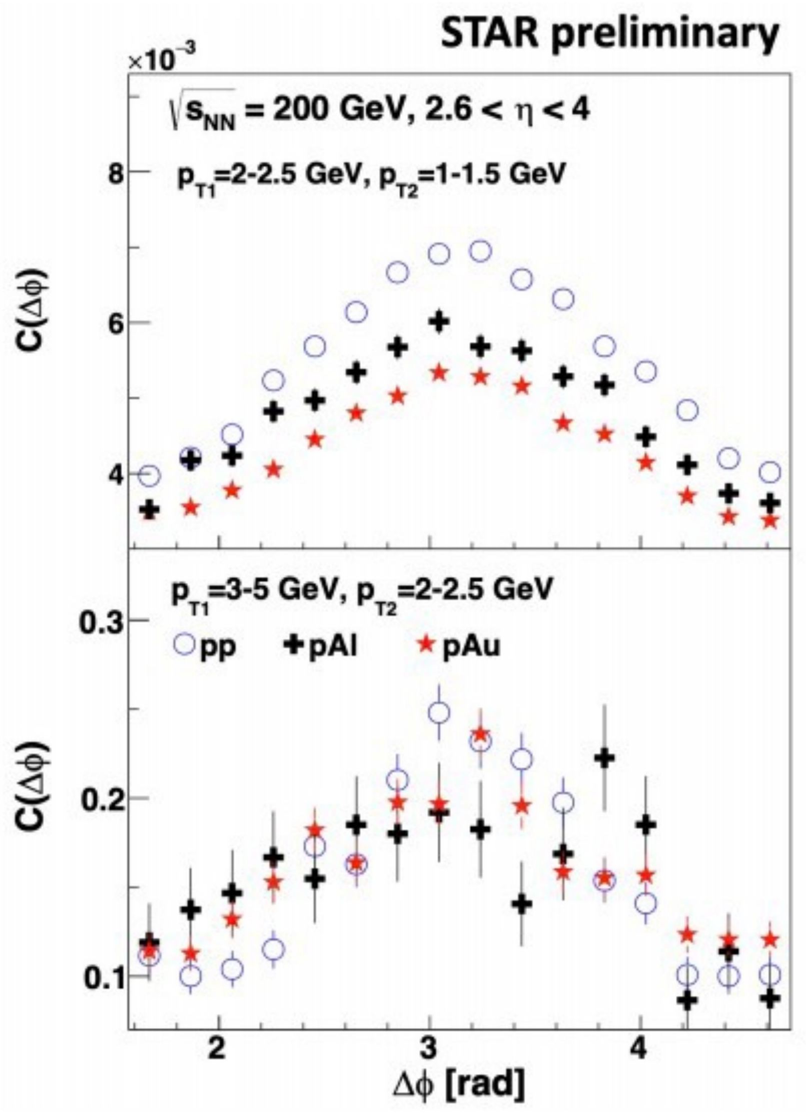


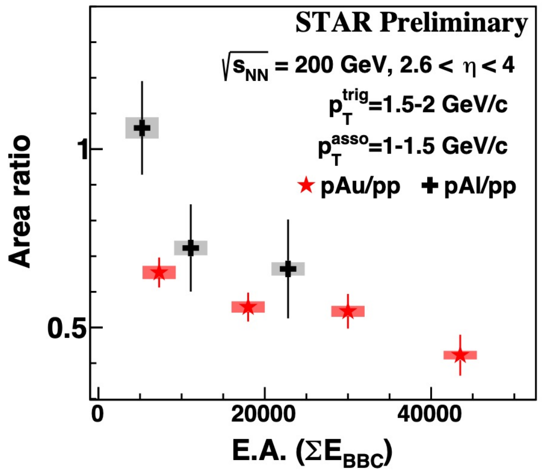
STAR - Phys. Rev. D 103 (2021) 72005

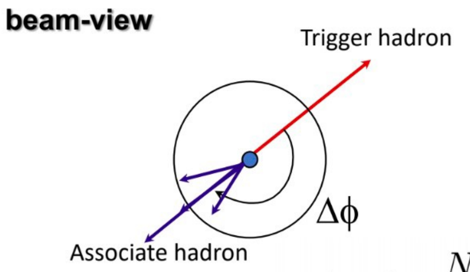


- The nuclear modification of transverse spin asymmetry is related to parton saturation in the color glass condensate
- New opportunities to use p+A collisions as a tool to investigate the rich phenomena behind TSSAs in hadronic collisions
  - **PHENIX charged hadron coverage:**
    - **$1.4 < \eta < 2.4$**
    - $0.1 < x_F < 0.2$
    - $1.8 < p_T < 7$ GeV
    - → **Strong A dependence observed**
  - **STAR π^0 coverage:**
    - **$2.6 < \eta < 4.0$**
    - $0.2 < x_F < 0.7$
    - $1.5 < p_T < 7$ GeV
    - → **Mild A dependence observed** in a regime where perturbative effects are relevant

Di-hadron correlations







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

Area: integral from $\frac{\pi}{2}$ to $\frac{3\pi}{2}$

- ❑ Measure the azimuthal correlation between two final hadrons in p+p and p+A
  - **p+p:** 2→2 process ⇒ back-to-back di-hadron
  - **p+A:** back-to-back configuration is smeared by multiple gluon interactions
- ❑ Access to non-linear gluon dynamics at small *x* (e.g. gluon saturation)
  - Remember: saturation scale grows with *A* and decreases with x

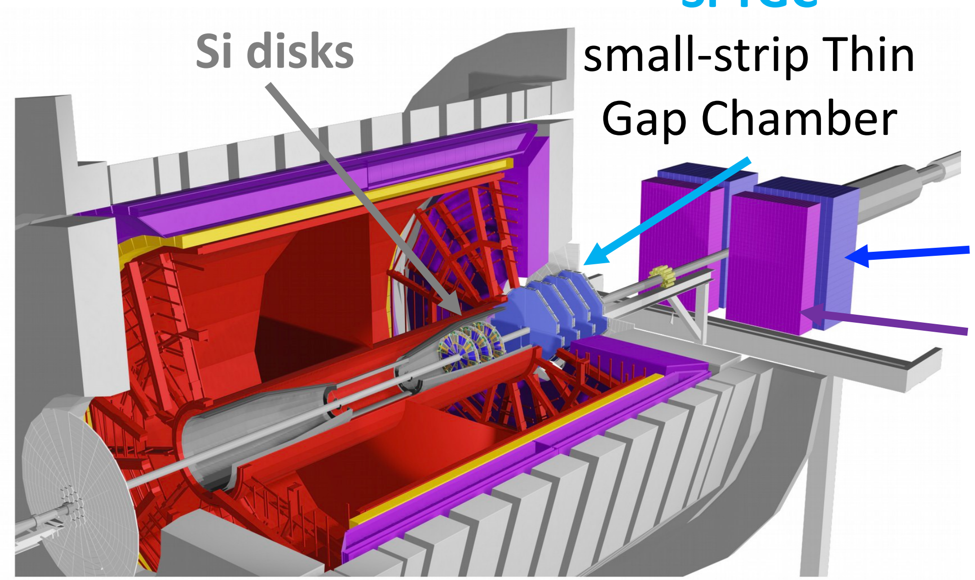
Results

- Clear signature of non-linear gluon dynamics with di-hadron correlation
- Evidence for a nuclear **dependence:** stronger suppression in p+Au than p+Al
- **Event activity dependence:** suppression enhanced in “high activity” collisions at low p_T


Coming
Up

STAR forward upgrade

Run 2022: p↑+p↑ collisions at 510 GeV with forward upgrade and enhanced PID at mid-rapidity

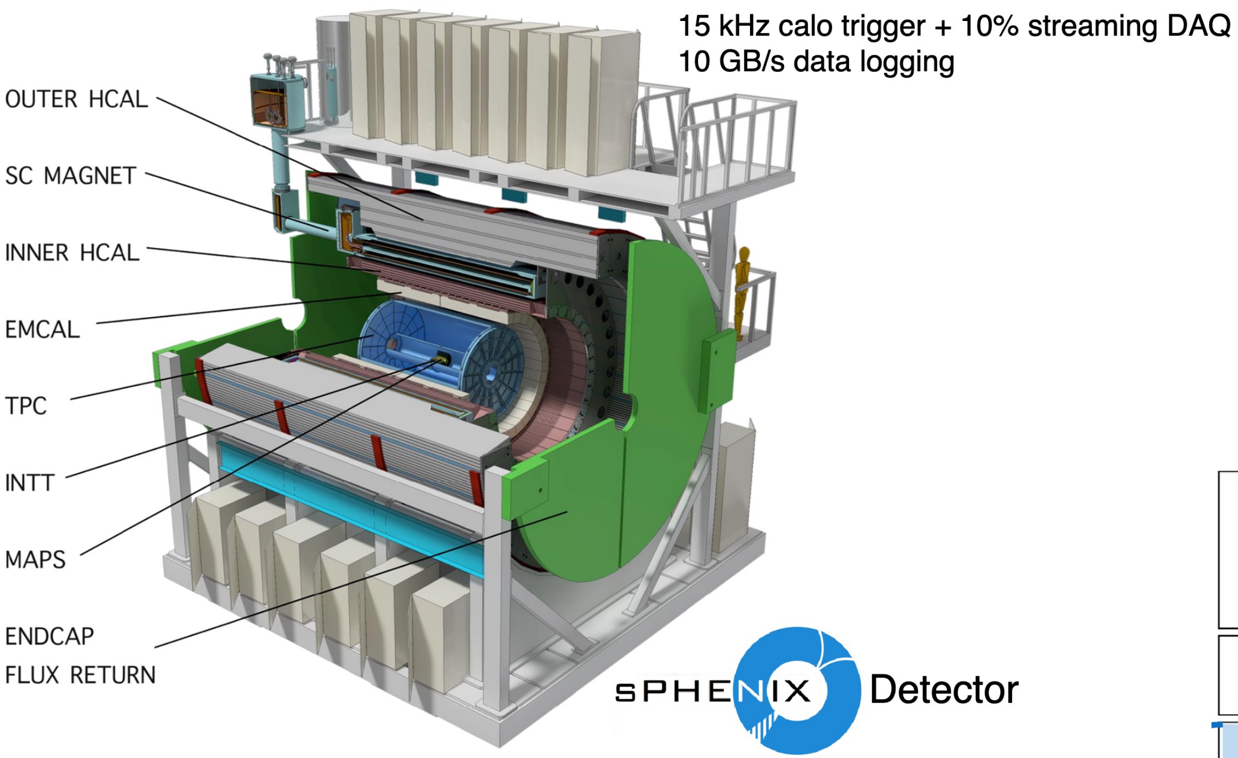


Forward rapidity 2.5 < η < 4
TMD measurements at high *x* • Sivers through tagged Drell-Yan, jets, direct photon • Transversity at high *x* + Collins/IFF
Mid rapidity -1.5 < η < 1.5
Improved statistical precision and the extended η acceptance of iTPC • Sivers measurements with *W/Z* and dijets • Transversity + Collins/IFF • Unpolarized *W/Z* cross section

Enhanced capabilities:

- Forward jet capability and charge-sign discrimination of charged particles
  - **Tracking:** Si disks + small Thin Gap Chambers
  - **Calorimetry:** hadronic and electromagnetic
- Access to highly asymmetric partonic collisions: high-*x* quark and low-*x* gluon interactions

sPHENIX



- Under constructions (running 2023+)
- **Optimized for jets:** Hermetic barrel, 1.5 T BaBar magnet, HCal
- **Cold QCD dedicated run requested for 2024**
  - Program with $p^{\uparrow}p^{\uparrow}$, $p^{\uparrow}$Au at 200 GeV
  - run together with STAR

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\|z\| <10$ cm	Samp. Lum. $\|z\| <10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-str]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-str]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

Cold QCD goals with sPHENIX

- Use the strengths of sPHENIX barrel to measure jet, heavy flavor and direct photon, in order to probe:
  - Sivers and Collins effects
  - Nuclear PDFs and FF in midrapidity

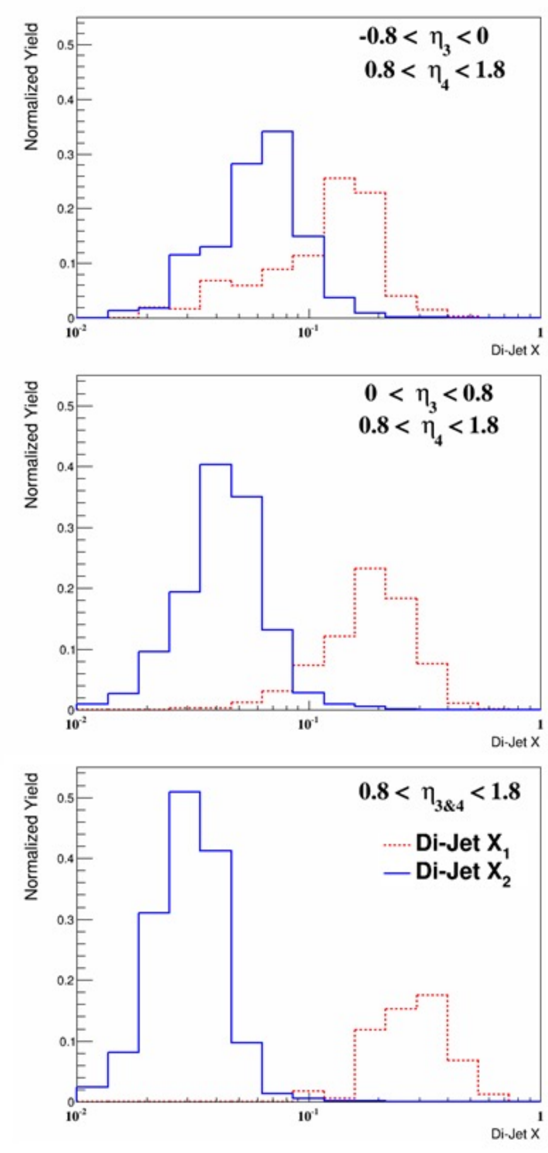
Conclusions

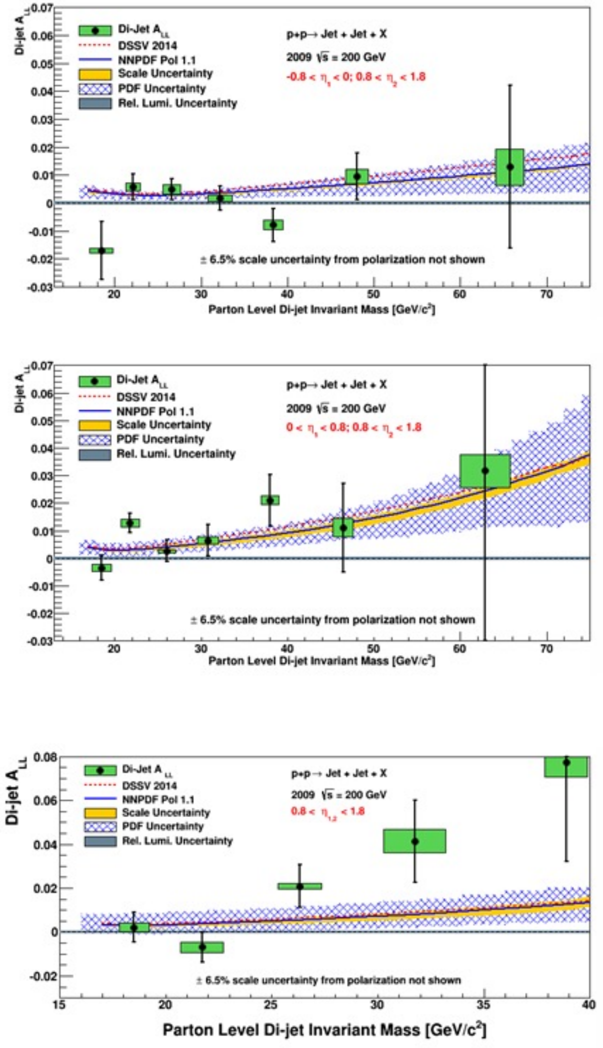
- **RHIC has provided key (often unique) insight into the spin structure of a proton**
  - Evidence for the positive gluon polarization for $x > 0.05$
  - The polarized and unpolarized sea quark distributions via W/Z production
- **Sivers function**
  - A_N from weak bosons consistent with sign change
  - Non-zero Sivers effect observed in dijets
  - Thwist-3 gluon dynamics with direct-photons and heavy flavor
- **Transversity through the Collins and IFF asymmetry**
  - Non-zero asymmetries at mid-η that are sensitive to quark transversity at hard scales
  - nuclear dependence of the asymmetries in different regimes
- **Non-linear gluon dynamics via di-hadron correlations**
  - Observed suppression in p+A over p+p at small x and grows with A
- **sPHENIX experiment and STAR Forward upgrade provide new physics opportunities**

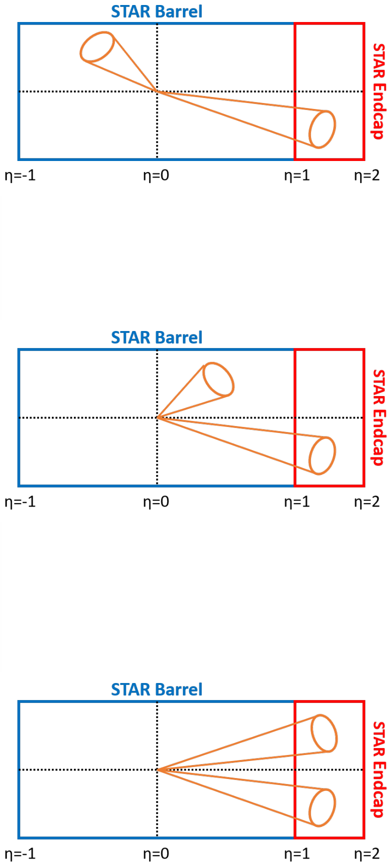

BACKUP

Dijets at moderate forward rapidity

Phys. Rev. D**98** (2018) 032011







- **Inclusive jets**

$$x \approx x_T e^{\pm\eta}$$

$$x_T = 2p_T/\sqrt{s}$$

- **Dijets**

$$x_1 = (p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4})/\sqrt{s}$$

$$x_2 = (p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4})/\sqrt{s}$$

$$M = \sqrt{x_1 x_2 s}$$

$$|\cos\theta^*| = \tanh(|\eta_3 - \eta_4|/2)$$