Recent longitudinal spin asymmetry and cross section results at PHENIX

Devon Loomis for the PHENIX Collaboration

DIS2023 - Devon Loomis

1

Accessing collinear PDFs
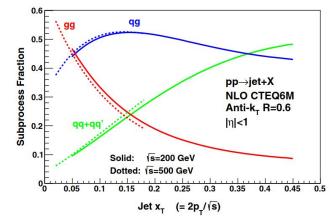

STAR collaboration. Phys. Rev. D 100, 052005 (2019)

❏ Deep inelastic scattering and Drell-Yan

$$d\sigma_{DIS} \propto f_a(x_a)d\sigma^{ab \to cd} \qquad d\sigma_{DY} \propto f_a(x_a)f_b(x_b)d\sigma^{ab \to cd}$$
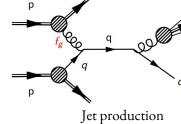
   ❏ Good constraint on quark distribution functions but
      contribute to gluon distribution at next to leading order

❏ p+p collisions

$$d\sigma_{pp} \propto f_a(x_a)f_b(x_b)d\sigma^{ab \to cX}D_c^h(z_c)$$

   ❏ Access gluon pdf at leading order
   ❏ Inclusive jet and direct photon cross sections
      ❏ small final state fragmentation effects

Jet production

Direct photon production

$f_a(x_a)$ Parton distribution function of parton a with momentum fraction x_a

$D_c^h(z_c)$ Fragmentation function of parton c into hadron h with momentum fraction z_c
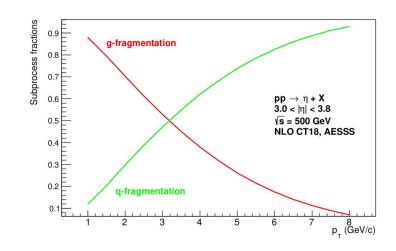
Accessing collinear FFs
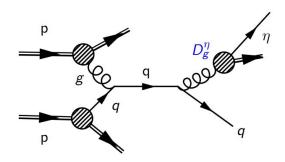
- e+e- collisions

$$d\sigma_{ee} \propto d\sigma^{ab \to cX} D_c^h(z_c)$$

  - Clean measurements for the quark fragmentation functions
  - No leading order access to gluon fragmentation
- p+p collisions

$$d\sigma_{pp} \propto f_a(x_a) f_b(x_b) d\sigma^{ab \to cX} D_c^h(z_c)$$

  - Access gluon and flavor-separated quark fragmentation with inclusive hadronic cross sections from RHIC
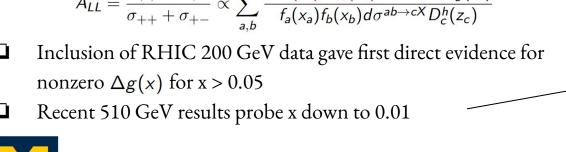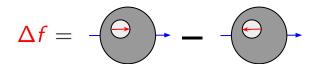

$pp \to \eta + X$
$3.0 < |\eta| < 3.8$
$\sqrt{s} = 500$ GeV
NLO CT18, AESSS

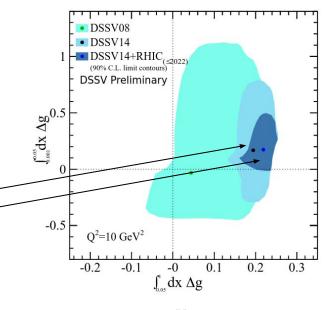

η meson production

Gluon helicity distributions

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \Delta g + L_q + L_g$$

proton spin   quark helicity   gluon helicity   quark and gluon orbital motion

$\Delta f =$

❏ Gluon helicity, $\Delta g(x)$, needed for proton spin puzzle

❏ Longitudinally polarized protons access $\Delta g(x)$ through measurement of the longitudinal double spin asymmetry

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \propto \sum_{a,b} \frac{\Delta f_a(x_a)\Delta f_b(x_b)d\sigma^{ab\to cX}D_c^h(z_c)}{f_a(x_a)f_b(x_b)d\sigma^{ab\to cX}D_c^h(z_c)}$$

❏ Inclusion of RHIC 200 GeV data gave first direct evidence for nonzero $\Delta g(x)$ for x > 0.05

❏ Recent 510 GeV results probe x down to 0.01

DSSV08
DSSV14
DSSV14+RHIC (≤2022)
(90% C.L. limit contours)
DSSV Preliminary

$Q^2 = 10$ GeV^2

$\int_{0.001}^{0.05} dx\, \Delta g$

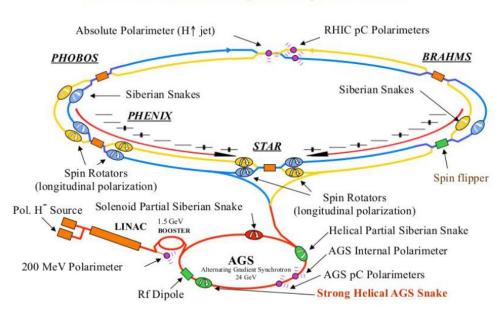$\int_{0.05}^{1} dx\, \Delta g$

arXiv:2302.00605

4

Polarized Physics Runs at PHENIX

RHIC is the world's first polarized proton collider

Year	System	$\sqrt{s}$ (GeV)	Polarization Direction	Recorded Luminosity (pb^{-1})
2006	p+p	62.4	transverse	0.02
			longitudinal	0.08
		200	transverse	2.7
			longitudinal	7.5
2008	p+p	200	transverse	5.2
2009	p+p	200	longitudinal	16
		500		14
2011	p+p	500	longitudinal	18
2012	p+p	200	transverse	9.7
		510	longitudinal	32
2013	p+p	510	longitudinal	155
2015	p+p	200	transverse	60
	p+Au			1.27
	p+Al			3.97

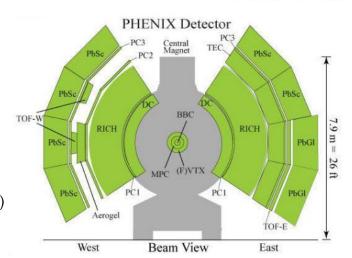# PHENIX Detector

Midrapidity

- ❏ $|\eta| < 0.35$
- ❏ Tracking: drift chamber (DC), pad chambers (PC)
- ❏ RICH
  - ❏ PID for electrons and charged pions
- ❏ TOF
  - ❏ PID for low momentum charged particles (pions, kaons, protons)
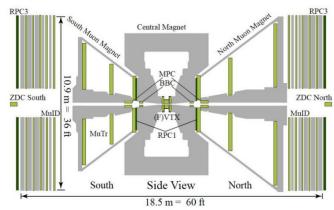- ❏ EMCal
  - ❏ Energy deposits of photons and electrons

Forward rapidity

- ❏ Muon Piston Calorimeter (MPC)
  - ❏ π^0 and η identification through $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$
  - ❏ ~ $3.0 < |\eta| < 3.8$
- ❏ Beam-Beam Counter (BBC)
  - ❏ Collision vertex
  - ❏ Minimum bias trigger

Cross Section Results
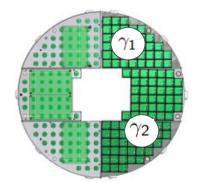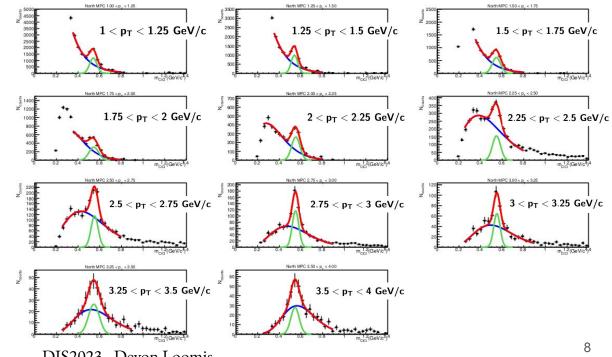
Forward η meson cross section

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\mathcal{L}}\frac{1}{\mathcal{BR}_{\eta\to\gamma\gamma}}\frac{1}{2\pi p_T}\frac{\Delta N^{meas}}{\epsilon_{trig}\epsilon_{reco}\Delta p_T \Delta\eta}$$

❏ $\eta \to \gamma\gamma$ reconstructed as pairs of photon clusters in the MPC

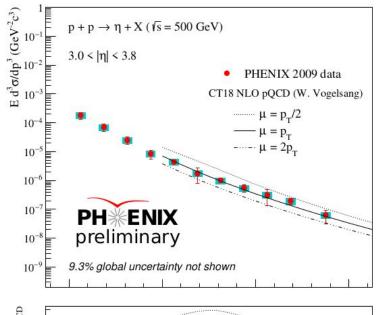❏ Clear signal peaks in minimum bias data from $1 < p_T < 4$ GeV/c
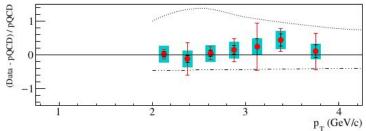
Forward η meson cross section

- ❏ First measurement of η meson cross section at forward rapidity at 500 GeV
- ❏ Consistent with NLO pQCD using CT18 PDFs and AESSS η meson fragmentation functions
- ❏ New input for relatively poorly constrained η meson fragmentation functions
  - ❏ $\delta D_{u,d}^{\eta} = {}^{+30\%}_{-20\%}$
  - ❏ $\delta D_{g}^{\eta} = \pm 15\%$

  PRD. 83 034002 (2011)

$p + p \rightarrow \eta + X$ ($\sqrt{s}$ = 500 GeV)

$3.0 < |\eta| < 3.8$

- PHENIX 2009 data
- CT18 NLO pQCD (W. Vogelsang)
  - ⋯⋯ $\mu = p_T/2$
  - —— $\mu = p_T$
  - —·— $\mu = 2p_T$
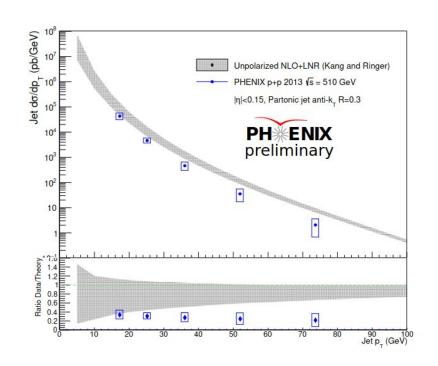
PH✸ENIX preliminary

9.3% global uncertainty not shown

Midrapidity jet cross section

❑ Small jet radius R=0.3 with anti-kT jet clustering algorithm

❑ NLO + ln(R) resummation theory calculation overestimates data for small R jets

   ❑ Partonic level calculation does not account for MPI and hadronization effects

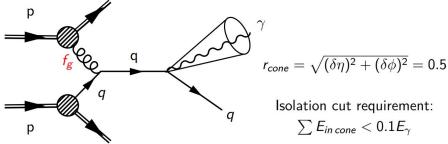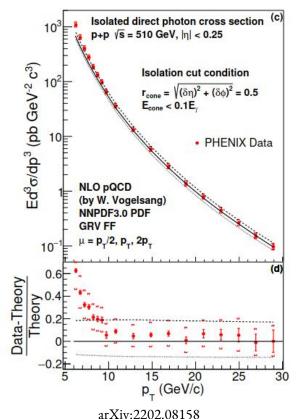   ❑ Similar effect found in CMS, ALICE small R jets

Midrapidity direct photon cross section

- ❏ Dominated by quark-gluon compton scattering $qg \rightarrow \gamma q$
- ❏ Isolation cut removes parton fragmentation to photon and quark bremsstrahlung

$r_{cone} = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} = 0.5$

Isolation cut requirement:
$\sum E_{in\ cone} < 0.1 E_\gamma$

(c) Isolated direct photon cross section
p+p $\sqrt{s}$ = 510 GeV, $|\eta|$ < 0.25

Isolation cut condition
$r_{cone} = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} = 0.5$
$E_{cone} < 0.1 E_\gamma$

• PHENIX Data

NLO pQCD
(by W. Vogelsang)
NNPDF3.0 PDF
GRV FF
$\mu = p_T/2, p_T, 2p_T$

arXiv:2202.08158

DIS2023 - Devon Loomis

11

Midrapidity direct photon cross section

❏ Dominated by quark-gluon compton scattering $qg \to \gamma q$

❏ Isolation cut removes parton fragmentation to photon and quark bremsstrahlung

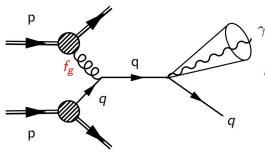❏ NLO pQCD underestimates inclusive cross section but is roughly consistent with isolated cross section
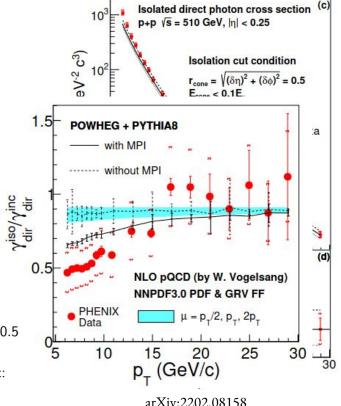
    ❏ MPI lessens data/theory disagreement at low p_T

$r_{cone} = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} = 0.5$

Isolation cut requirement:
$\sum E_{in\,cone} < 0.1 E_\gamma$

PH⬦ENIX

(c) Isolated direct photon cross section
p+p √s = 510 GeV, |η| < 0.25

Isolation cut condition
$r_{cone} = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} = 0.5$
$E_{cone} < 0.1 E.$

POWHEG + PYTHIA8
— with MPI
- - - without MPI

NLO pQCD (by W. Vogelsang)
NNPDF3.0 PDF & GRV FF

● PHENIX Data

$\mu = p_T/2, p_T, 2p_T$

$\gamma_{dir}^{iso} / \gamma_{dir}^{inc}$
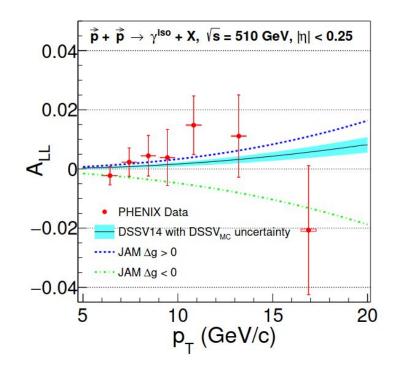
p_T (GeV/c)

arXiv:2202.08158

UNIVERSITY OF MICHIGAN

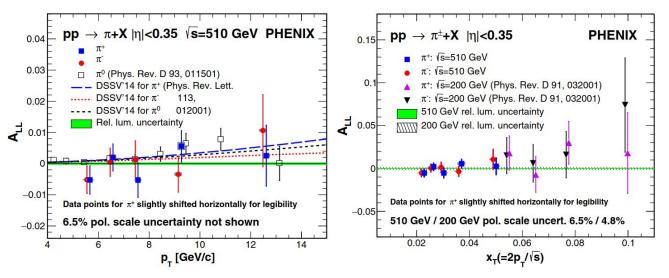# Longitudinal Spin Results

Midrapidity direct photon A_{LL}

- ❏ First published direct photon A_{LL}
- ❏ Theoretically clean measurement: little fragmentation contributions
- ❏ Sensitive to sign and magnitude of $\Delta g(x)$
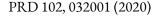- ❏ Consistent with DSSV14 global analysis
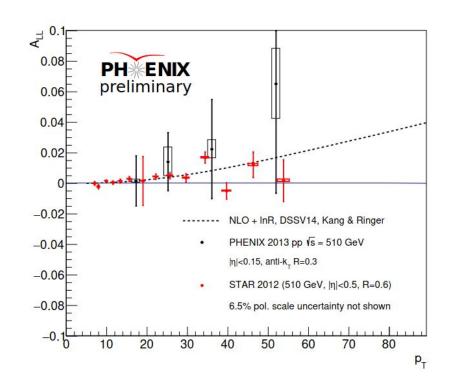
Midrapidity charged pion A_{LL}

PRD 102, 032001 (2020)

- ❏ Higher energy charged pion A_{LL} probes x down to 0.02
- ❏ Consistent with DSSV14 for π^+, π^-, and π^0
- ❏ Sensitive to $\Delta g(x)$

Midrapidity jet A_{LL}

- ❏ Consistent with STAR 510 GeV data and NLO + ln(R) resummation calculation within large uncertainties
- ❏ Unfolding applied to correct energy resolution from underlying event fluctuations

A_{LL} vs p_T plot:

PH✴ENIX preliminary

Legend:
- ---- NLO + lnR, DSSV14, Kang & Ringer
- • PHENIX 2013 pp $\sqrt{s}$ = 510 GeV, $|\eta|<0.15$, anti-k_T R=0.3
- • STAR 2012 (510 GeV, $|\eta|<0.5$, R=0.6)
- 6.5% pol. scale uncertainty not shown

UNIVERSITY OF MICHIGAN

Summary

- ❏ Recent PHENIX measurements access:
  - ❏ Gluon and flavor-separated quark fragmentation functions (forward eta meson cross section)
  - ❏ Unpolarized parton distribution functions (inclusive jet cross section, direct photon cross section)
  - ❏ Gluon helicity distribution (midrapidity jet A_{LL}, midrapidity direct photon A_{LL}, midrapidity charged pion A_{LL})
- ❏ Future measurements: forward π^0 cluster and η meson A_{LL} at 510 GeV will access low x region (x $\sim 10^{-3}$) of gluon helicity distribution

Backup

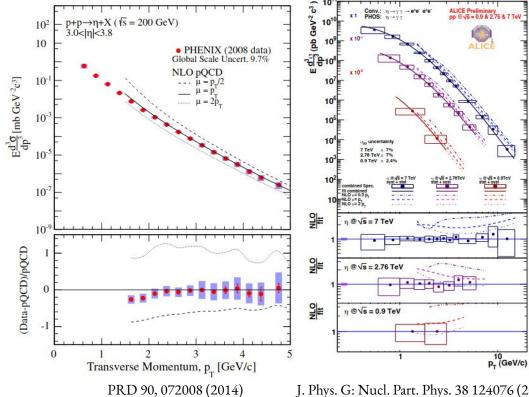# Dominant partonic processes at PHENIX

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	

η meson cross sections

- 200 GeV forward η cross section from PHENIX consistent with NLO pQCD
- NLO pQCD agrees with 900 GeV ALICE midrapidity η cross section but overestimates cross section at 7 TeV and 8 TeV
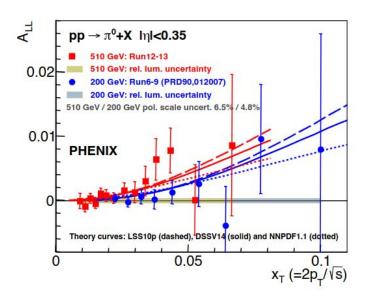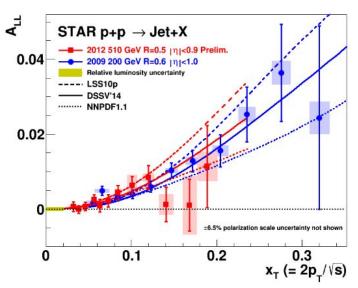

PRD 90, 072008 (2014)

J. Phys. G: Nucl. Part. Phys. 38 124076 (2011)

RHIC π^0 A_{LL} at 510 GeV

❏ π^0 A_{LL} from RHIC at 510 GeV confirmed nonzero $\Delta g(x)$ and extended x down to 0.01