RHIC and COMPASS results

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STAR

RHICf





Main QCD Spin Questions

- How is the spin of the proton distributed? What is the role of gluons and sea quarks?
- What is the origin of transverse spin effects and how does it relate to the 3D momentum and position structure of the Nucleon?
- Closely intertwined: How does QCD create 99% of the visible mass of the universe? How does confinement work?

$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_G + \mathcal{L}_q$

Sivers, Collins effects, TMDs GPDs, orbital angular momentum, Tomography

Fragmentation functions and their spin, flavor, type, long. and transverse momentum dependence



Facilities and experiments

RHIC (@BNL): longitudinally and transversely polarized p+p and p+A collisions from \sqrt{s} of 62 to 510 (200) GeV beams

Large acceptance experiments PHENIX/STAR and dedicated addition RHICf

RHICf

- COMPASS (@CERN SPS):
 - Fixed Target (LiD,NH₃, longitudinally and transversely polarized)
 - Polarized muon beams for (SI)DIS from 160 to 200 GeV
 - Pion beams for DY
 - Large forward spectrometer

COMP ASS







$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_G + \mathcal{L}_q$

Longitudinal Spin

Main questions at RHIC and COMPASS:

- Gluon spin contribution
- Role of sea quarks (light sea symmetry, strange sea)



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 $\Delta g(x)$

Jet and di-Jet A_{LL} to pin down gluon spin





PRD 100 (2019) 052005

- Jets brought first indication for nonzero gluon polarization, since confirmed also by p0 in PHENIX
- Higher collision energy → lower x
- Di-jets at different rapidities to improve sensitivity to x dependence





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Charged pion A_{LL}s at 510 GeV

- Addition of charged and neutral pion results at higher \sqrt{s}
- Lower x reach compared to previously published 200 GeV A_{LL} data
- Ideally sign of ∆g(x) visible in charge ordering of pion A_{LL}s
- Statistics limited due to EM shower based trigger, but important input for global fits



First direct photon xsec and A_{LL} at 510 GeV





- Part of initial RHIC-Spin suggestions in the `90s
- Theoretically, the Golden channel to access gluon polarization as hard interaction mostly q-g

(Juny

 Since EM process, statistically limited but consistent with global fit results

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$\Delta q(x) \ \Delta \bar{q}(x)$

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Real W production as access to (anti)quark helicities

p helicity + p helicity -

- Maximally parity violating V-A interaction selects only lefthanded quarks and righthanded antiquarks:
- Having different helicities for the incoming proton then selects spin parallel or antiparallel of the quarks
- → Difference of the cross sections gives quark helicities ∆q(x)
- No Fragmentation function required
- Very high scale defined by W
 mass
 Bourrely, Soffer

J-Spin 2/23/2021 Nucl.Phys. B423 (1994) 329-348 R.Seidl: RHIC+COMPASS





exercise for STAR data so far, no global fit with all W data, yet

Clearly asymmetric polarized sea seen with all of longitudinal 510 GeV running analyzed

STAR A, (PRL 113 (2014) 072301)

DSSV E_T>25 GeV

- Sea quark helicities well constrained at
- Asymmetric sea rules out simple pioncloud models!



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Transverse spin/ Tomography

Main questions:

- 3D imaging of nucleon in momentum and position space
- Origin of large A_Ns: initial state? Final state?
- Connections between higher twist and TMDs
- Nuclear/low-x modification of A_Ns?

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DVCS to access to partonic extend



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- Deeply Virtual Compton Scattering (ep→e'p'γ) provides access to generalized parton distributions (GPDs)
- In DIS concurrent Bethe-Heitler (ISR/FSR) process, but only dominant at low energies and well understood
- Possible to access DVCS cross sections and asymmetries



Partonic size of the proton

- Momentum transfer t is FT of impact parameter
- t dependence can be related to the partonic transverse size of the proton
- Indication of a smaller size of the proton for higher x than in HERA measurements → spatial extent of sea and valence quarks?

Phys.Lett.B 793 (2019) 188



Transverse single spin asymmetries Large left-right asymmetries $A_N = \frac{1}{P} \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$

- Large left-right asymmetries A_N seen in polarized pp collisions from low energies up to RHIC energies
- Both initial state and final state effects contribute
- Some indications for potentially other origins
- Concentrate on disentangling initial state (direct γ, jets) from final state (Collins in jet)
- Drell Yan as test for our understanding in sign change compared to SIDIS Sivers asymmetries J-Spin 2/23/2021



 Polarized p+A collisions taken in 2015 of interest for low x behavior of cold nuclear matter → A dependence of single spin asymmetries?



Updated precision for central A_N s and γ !

- Substantial updates for π^0 and η single spin asymmetries at central rapidity
 - Possible effects pushed below the 1% level
 - First direct photon A_N extracted at RHIC:
 - Mostly sensitive to initial state effects (quark-gluon correlation function)
 - Power to constrain trigluon correlation part



Phys.Rev.Lett. 123 (2019) 122001

A dependence of A_Ns

- Asymmetries consistent with A^{1/3} dependence as (initially) predicted by some CGC related nuclear effects (Hatta`17)
- No A dependence is ruled out
- Also consistent with suppression with increasing number of binary collisions
- However, probed x and scale too large for expected CGC effects! (S.Benic and Y.Hatta, PRD99, 094012 - Twist-3 fragmentation + gluon saturation)



A dependence at higher x_F

- At STAR coverage of higher x_F only (>0.17)
- Substantially smaller effect seen than at PHENIX, however effect visible and increasing with decreasing x_F
- Little difference if only concentrating on lower P_T range (where low-x effects may be more likely)





More forward A_Ns and EM jets

- Using STAR FMS EM jet A_Ns extracted (less sensitive to Final state effects → ETQS/Sivers)
- Much smaller than π^0 A_Ns, consistent with AnDY result
- Hadron in jet Collins asymmetries small
- π⁰ result shows some multiplicity dependence (FF related, diffractive or other mechanism?)

hep-ex:2012.11428 STAR $p^{\uparrow} + p -> EM - jet + X$ 200 GeV 0.04 • 200 GeV Multiplicity>2 A_N Jet algorithm: anti-k_ R=0.7 500 GeV $p_{\tau}^{\text{jet}} > 2 \text{ GeV}/c$ 0.03 4 500 GeV Multiplicity>2 **2.9** < η^{jet} < **3.8** + A_NDY 500 GeV 3.0/3.4% beam pol. scale uncertainty not shown 0.01 Theory 200 GeV *p*_>[GeV/*c*] Theory 500 GeV 0.1 0.20.3 0.40.5 0.6 XF STAR $p^T + p \rightarrow \pi^0 + X$ Isolated nº 200 GeV Isolated nº 500 GeV _*p_* > 2 GeV/*c* Non-isolated π⁰ 200 GeV $2.7 < \eta < 4.0$ Non-isolated nº 500 GeV 3.0/3.4% beam pol. scale uncertainty not shown Theory 200 GeV 0.1 Theory 500 GeV 0.05

p_>[GeV/c]

0.2

0.3

0.4

XF

0.5

0.6

Weighted Sivers asymmetries

Nucl.Phys.B 940 (2019) 34

- Using Pt-weighted hadron yields in SIDIS to evaluate single spin Sivers asymmetries
- Weighting de-convolutes transverse momenta in distribution and fragmentation → Sivers moments
- Extraction and fit of up and down Sivers moments, consistent with global Sivers fits



Exclusive VM removal from unpol azimuthal asymmetries



- hadrons selected for SIDIS measurements can contain a substantial contribution fom exclusive VM decays
- Highest contribution at low-x, low Pt, high-z
- As exclusive VMs carry nonzero asymmetries themselves, not just a dilution to SIDIS asymmetries → Correct the asymmetries



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Excl. VM corrected $cos\phi_h$ moments

- Cos\u03c6_h moment dominated by Cahn effect
- Cahn effect sould be negative and charge independent
- Corrected data mostly consistent with predictions → deviations as indication for Boer-Mulders contribution



Very forward neutron asymmetries in p+p/p+A

PRL 120 (2018), 022001



Mitsuka: Phys.Rev. C95 (2017) 044908 J-Spin 2/23/2021

- Unexpectedly large A dependence in neutron asymmetries
- Sign change seen
- Possibility of ultraperipheral collisions (UPC) effect, enhanced by Z² for nucleii
- (anti-)Correlations with main Collision detector system enhance/reduce UPC contribution



p+p unfolded forward neutron A_Ns

Accepted to PRD

- Initially rising asymmetries
- Indication of levelling off at higher transverse momenta
- Theory predictions (Kopeliovitch <u>PRD 84</u> (2011) 114012) based on only hadronic processes suggests linear dependence
- P_T dependent A_Ns for p+A and correlations ongoing



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Very forward π^0 asymmetries



- Large nonzero pion asymmetries in perturbative regime well established (TMDs/Twist3)
- Also at low scales nonzero asymmetries now found (diffractive/Regge?)
- Is there a connection between low and high scale mechanisms?

PRL 124 (2020) 252501



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Summary

- New insights into nonzero gluon polarization in the nucleon
- Light quark Sea polarized and asymmetric
- First partonic size of the proton measurement close to the valence region
- Improved measurements for transverse spin asymmetries, nontrivial A dependence
- More results that were not covered or are ongoing
- Many future measurements at the EIC (\rightarrow Goto)

