

Single-Spin Asymmetries and Transverse-Momentum-Dependent Distributions at RHIC

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Quarks, Hadrons, and the LHC, IIT Bombay August 30, 2011



Pushing the boundaries of pQCD

"Modern-day 'testing' of (perturbative) QCD is as much about pushing the boundaries of its
applicability as about the verification that QCD is the correct theory of hadronic physics."
– G. Salam, hep-ph/0207147 (DIS2002 proceedings)

- Since 1990s starting to consider detailed internal QCD dynamics that parts with traditional parton model ways of looking at hadrons—and perform phenomenological calculations using these new ideas/tools!
 - Non-linear evolution at small momentum fractions
 - Various *resummation* techniques
 - Non-collinearity of partons with parent hadron



Dropping the simplifying assumption of collinearity: Transverse-momentum-dependent distributions

Mulders & Tangerman, NPB 461 (1996) 197 Distribution Functions Fragmentation Functions f₁ = OCollinear Worm gear $D_1 = OCollinear$ $G_{1T} = \bigcirc - \bigcirc + \bigcirc$ - $h_1 = 4$ - 4 Transversity $f_{1T}^{L} = \bigcirc - \bigcirc$ $\mathbf{D}_{\mathbf{i}\mathbf{T}}^{\perp} = \mathbf{O}^{\top} - \mathbf{O}^{\top}$ Polarizing FF Sivers $\mathbf{h}_{1}^{\perp} = \mathbf{O}$ – **(b)** Boer-Mulders **?** Collins Pretzelosity Worm gear $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$ \downarrow \downarrow \downarrow $\rightarrow - \bigcirc \rightarrow H_{1T}^{\perp} = \bigcirc -$



Dropping the simplifying assumption of collinearity: Transverse-momentum-dependent distributions

Mulders & Tangerman, NPB 461 (1996) 197





Dropping the simplifying assumption of collinearity: Transverse-momentum-dependent distributions







COMPASS 2007 proton data



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NATIONAL LABORATORY

EST. 1943



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EST. 1943



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Transversely polarized hadronic collisions: A historical discovery ground







Striking asymmetries!! After more than a decade, will inspire the birth of a new subfield . . .

W.H. Dragoset et al., PRL36, 929 (1976)



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Transverse-momentum-dependent distributions and single-spin asymmetries



1989: "Sivers mechanism" proposed

Take into account the *transverse momentum* (k_T) of quarks within the proton, and postulate a *correlation* between quark k_T and proton spin!

Single-spin asymmetries ~ $S \cdot (p_1 \quad p_2)$ Probe spin-momentum correlations!

D.W. Sivers, PRD41, 83 (1990)



Transverse single-spin asymmetries: From low to high energies!

BRAHMS



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Transverse single-spin asymmetries: From low to high energies!

BRAHMS



These soft effects—due to QCD *dynamics* within the nucleon—remain relevant up to scales where we can attempt to describe them using pQCD!



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High- x_F asymmetries, but not valence quarks??

Pattern of pion species asymmetries in the forward direction → valence quark effect. But this conclusion confounded by kaon and antiproton

asymmetries from RHIC!



Another surprise: Transverse single-spin asymmetry in eta meson production

Further evidence against a valence quark effect??

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$$p^{\uparrow} + p \rightarrow \eta + X \quad \sqrt{s} = 200 \,\text{GeV}$$

 $n \rightarrow \gamma + \gamma$

Larger than the neutral pion!

$$\pi^{0} \equiv \frac{u\overline{u} - d\overline{d}}{\sqrt{2}}$$
$$\eta \equiv \frac{u\overline{u} + d\overline{d} - 2s\overline{s}}{\sqrt{6}}$$





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Note earlier FNAL E704 data consistent . . .





Recent PHENIX etas show no sharp increase for $x_F > 0.5!$





PHENIX eta vs. neutral pion



Still suggests larger asymmetry for etas than for (mergedcluster) neutral pions!



PHENIX eta vs. neutral pion



Still suggests larger asymmetry for etas than for (mergedcluster) neutral pions!

Will need to wait for final results from both collaborations . . .



Neutral pions at midrapidity $(x_F = 0)$



Midrapidity neutral pion production asymmetry consistent with zero, even out to large $p_T (x \sim 0.2)$





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What about p_T dependence of forward asymmetries?



Kinematically constrained to be 0 at $p_T = 0$. Predicted for many years to fall off at larger p_T as $1/p_T$, but no clear indication of this in data . . .



p_T dependence of PHENIX data similar



Eta p_T shape consistent with neutral pions





Trying to understand p_T dependence



More recent phenomenology by Zhongbo Kang: $1/p_T \rightarrow p_T/(p_T^2 + \Delta^2)$ (add a constant term) Additional data in 2012 expected to clarify high-p_T behavior of observed

asymmetries!

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p_T dependence of HERMES inclusive(!) hadron data



Clear rise from low p_T and turnover at ~ 0.8 GeV/c, for both pions and kaons



p_T dependence of HERMES inclusive(!) hadron data



Clear rise from low p_T and turnover at ~0.8 GeV/c, for both pions and kaons



What can we learn by comparing DIS vs. p+p measurements?

<u>Modified universality</u> of T-odd transverse-momentum-dependent distributions: Color in action!

Semi-inclusive DIS: attractive final-state interaction



Drell-Yan: repulsive initial-state interaction



As a result: $Sivers|_{DIS} = -Sivers|_{DY}$



<u>Modified universality</u> of T-odd transverse-momentum-dependent distributions: <u>Color in action!</u>



Some semi-inclusive DIS measurements already exist. Polarized Drell-Yan measurements will be a crucial test of our understanding of quantum **chromo**dynamics!



New (small) experiment at RHIC: A_NDY



- Drell-Yan feasibility test at former BRAHMS IP
- Take transversely polarized data at $\sqrt{s} = 500 \text{ GeV}$ during STAR + PHENIX longitudinal W program
- Reuse existing detectors
- $\eta > 3, M > 4 \text{ GeV/c}^2, 0.1 < x_F < 0.3$
- Measure jet, π^0 , Drell-Yan σ and transverse single-spin asym.
- Expect single D-Y asym. point with uncertainty ~0.015 (predicted asym ~0.05-0.10)
- In collaboration w/institutions not previously involved in RHIC: JLab, William & Mary



New (small) experiment at RHIC: A_NDY



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Factorization, color, and hadronic collisions

- Last year, theoretical work by T.C. Rogers, P.J. Mulders (PRD 81:094006, 2010) claimed pQCD factorization broken in processes involving hadro-production of hadrons if parton k_T taken into account (TMD pdfs and/or FFs)
 - "Color entanglement"



$$p + p \rightarrow h_1 + h_2 + X$$

Color flow can't be described as flow in the two gluons separately. Requires simultaneous presence of both!



Testing TMD-factorization breaking with (unpolarized) p+p collisions at RHIC

- Implications for observables describable using Collins-Soper-Sterman ("Q_T") resummation formalism
- Try to test using photon-hadron and dihadron correlation measurements in unpolarized p+p collisions at RHIC
- Lots of expertise on such measurements within PHENIX, driven by heavy ion program!





PHENIX, PRD82, 072001 (2010)



(Curves shown here just empirical parameterizations from PHENIX paper)



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Testing TMD-factorization breaking with (unpolarized) p+p collisions at RHIC

- Calculate p_{out} distributions *assuming factorization works*
 - Will show different shape than data?
 - Difference b/w factorized calculations and data will vary for 3-hadron vs. 4-hadron processes?
- Take CSS soft factor (unpolarized TMDs) from parameterizations of Drell-Yan and Z measurements
 - New Z p_T spectra coming out of LHC and Tevatron will greatly improve parametrizations!
 - Evolution worked out earlier this year: Aybat and Rogers, PRD83, 114042 (2011)





Conclusions

- Now starting to explore QCD *dynamics*!
- Transverse-momentum-dependent distributions probe *spinmomentum correlations* in QCD, both in nucleon and process of hadronization
- Flurry of activity since 2002, with experimental data from semi-inclusive DIS, e+e-, and p+p
- Field has brought to the forefront fundamental issues of *universality*, *factorization* and *color interactions*
 - Fruitful interplay among different collision systems!
- Remaining puzzles and open questions—look forward to more data from RHIC and other facilities in upcoming years!



Additional Material





Spin physics at RHIC

- Polarized protons at RHIC 2002-present
- Mainly $\sqrt{s} = 200$ GeV, also 62.4 GeV in 2006, started 500 GeV program in 2009
- Two large multipurpose detectors: STAR and PHENIX
 - Longitudinal or transverse polarization
- One small spectrometer until 2006: BRAHMS
 - Transverse polarization only





Forward $\pi^{+-}A_N$ at $\sqrt{s} = 200$ GeV: $x_F - p_T$ dependence





Forward $\pi^0 A_N$ at 200 GeV: $x_F - p_T$ dependence

AN

<x_>=0.28

0.08 Sivers (E704 fit) FPD data twist-3 0.04 0.0 <x_F>=0.37 <x_F>=0.43 0.08 0.04 Phys. Rev. Lett. 101, 222001 (2008) 0.0 <x₅>=0.5 $< x_{r} > = 0.6$ 0.12 0.1 0.06 0.02 3 2 4 2 3 p_T, GeV∕c



 $p+p \rightarrow \pi^{\circ}+X$ at $\sqrt{s}=200$ GeV

 $< x_{F} > = 0.32$

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Cluster A_N at 200 GeV: x_F - p_T dependence





Direct photon



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Forward $\pi^{+-}A_N$ at $\sqrt{s} = 62.4$ GeV: $x_F - p_T$ dependence



At low- $p_T A_N(\pi)$ increases with p_T . (Theoretically constrained to be 0 at $p_T=0$)





Forward $\pi^0 A_N$ at 62.4 GeV: Rapidity dependence



0.6

-0.4

-0.2



44

PLB 603,173 (2004)

0.6

XF

0.4

0.2

n

TMDs and Universality: <u>Modified Universality</u> of T-Odd TMDs

DIS: attractive FSI

Drell-Yan: repulsive ISI



As a result: $Sivers|_{DIS} = -Sivers|_{DY}$



Interference fragmentation function to probe transversity



Need more statistics!



Tensor charges

$\Delta_T u = 0.59^{+0.14}_{-0.13}, \ \Delta_T d = -0.20^{+0.05}_{-0.07}$ at $Q^2 = 0.8 \ { m GeV^2}$



Prokudin et al. at Ferrara

 Quark-diquark model: Cloet, Bentz and Thomas PLB 659, 214 (2008), Q² = 0.4 GeV²

 CQSM: M. Wakamatsu, PLB B 653 (2007) 398 Q² = 0.3 GeV²

 Lattice QCD: M. Gockeler et al., Phys.Lett.B627:113-123,2005 , Q² = GeV²

 QCD sum rules: Han-xin He, Xiang-Dong Ji, PRD 52:2960-2963,1995, Q² ~ 1 GeV²



Forward neutrons at $\sqrt{s}=200$ GeV at PHENIX

Large negative SSA observed for $x_F>0$, enhanced by requiring concidence with forward charged particles ("MinBias" trigger). No x_F dependence seen.



Neutron SSA for local polarimetry

Spin Rotators OFF Vertical polarization

Spin Rotators ON Radial polarization







05

15

Spin Rotators ON Longitudinal polarization





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Bunch-by-bunch polarization information

From ~10 minutes of 500 GeV commissioning data in March 2009!



With transverse polarization, use scalers to count raw left-right SSA in forward neutron production for each bunch crossing. Measurement of *bunch-by-bunch variation* in polarization. (Sign flip for bunches polarized vertically up vs. down.) C. Aidala, Quarks, Hadrons, and LHC, ITT Bombay, August 2011

Forward neutrons at other energies

Significant forward neutron asymmetries observed down to 62.4 and up to 410 GeV!

$$A = \frac{N_+ - RN_-}{N_+ + RN_-}$$



p_T scaling of forward neutron SSA?



Inclusive neutrons 62.4, 200, 500 GeV

Neutrons with charged particle trigger 200, 500 GeV

Large SSA remains unexplained— Challenge to theorists!



Polarization-averaged cross sections at $\sqrt{s}=200 \text{ GeV}$



Good description at 200 GeV over all rapidities down to p_T of 1-2 GeV/c.



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Lower energies: $\sqrt{s}=62.4 \ GeV$ PRD79, 021002 (2009)Midrapidity pions





Comparisons to NLO and NLL pQCD calculations using $\mu=p_T$ shown. Unlike at 200 GeV, scale choice of $\mu=p_T$ underpredicts the data. → Threshold logarithm effects still relevant at this intermediate energy?

But—overall, pretty good agreement!

$\sqrt{s}=62.4 \ GeV$ Forward pions



Comparison of NLO pQCD calculations with BRAHMS π data at high rapidity. The calculations are for a scale factor of $\mu=p_T$, KKP (solid) and DSS (dashed) with CTEQ5 and CTEQ6.5.

Surprisingly good description of data, in apparent disagreement with earlier analysis of ISR π^0 data at 53 GeV.

No comparison to NLL yet.



Still not so bad!

$\sqrt{s}=62.4 \ GeV$ Forward kaons



K⁻ *data* suppressed ~order of magnitude (valence quark effect).

NLO pQCD using recent DSS FF's gives ~same yield for both charges(??).

Related to FF's? PDF's??

No comparison to NLL yet.

K⁺: Not bad! K⁻: Hmm...







Planning for the longer-term future

- Last fall PHENIX and STAR handed in (independent) "Decadal Plans" to BNL management
- Joint discussions among BNL management and the two collaborations ongoing
- Long-term future at RHIC (past ~2018) clearly affected by what happens with the proposed Electron-Ion Collider!



Improved forward detection capabilities

- PHENIX discussing major overhaul of detector beyond ~2016
- STAR discussing much more modest upgrades
- Details aside, anticipate good forward jet reconstruction would be possible at RHIC, and strong forward Drell-Yan capabilities as well





Long-term accelerator prospects

- Could go up to energies as high as sqrt(s)=650
 GeV with new DX magnets
 - W cross sections ~double w.r.t. 500 GeV: quark and antiquark flavor separation for various transversemomentum-dependent distributions, alternate probe to D-Y for Sivers sign change, ...
- Polarized He³ beams foreseen for EIC—could run He³ in hadron-hadron mode at RHIC as well
 He³ workshop at BNL in late September



He³ for flavor separation of transverse spin observables



- With polarized He³ as well as proton beams at RHIC, new handles on flavor separation of various transverse spin observables possible
 - What will the status of the (non-)valence quark puzzle be
 by then??



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