Impact of Future SPD Asymmetry Measurements

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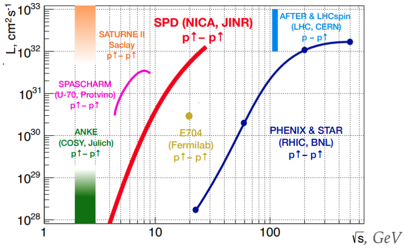
Introduction

Spin Physics Detector (SPD) will be a great laboratory to probe nucleon structure, especially polarized Parton Distribution Functions (PDF) of gluons

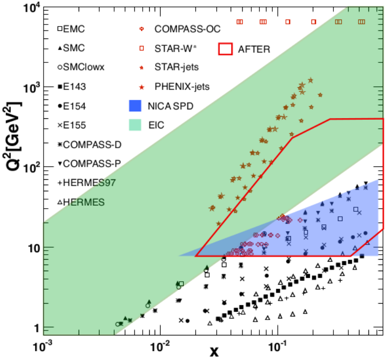
Physics overview : Alexey Guskov's talk

- At NICA accelerator facility, SPD will be able to measure cross-sections and spin asymmetries from polarized $p + p$ at $\sqrt{s} = 27$ GeV, $d + d$ at $\sqrt{s} = 13.5$ GeV and $d + p$ at $\sqrt{s} = 19$ GeV with 70% polarization
- SPD plans to focus on three measurement channels :
  1. Open charm mesons (D^+D^-, $D^0\bar{D}^0$)
  2. Charmonia (J/Ψ, Ψ')
  3. Prompt photon (γ)

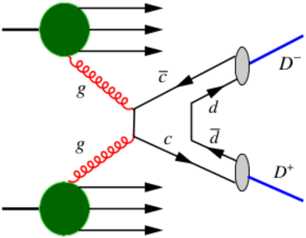
Design luminosity $10^{32} cm^{-2} s^{-1}$
Energy range $10 - 27$ GeV for $p^{\uparrow} + p^{\uparrow}$



SPD will make significant contributions in the large Bjorken x range

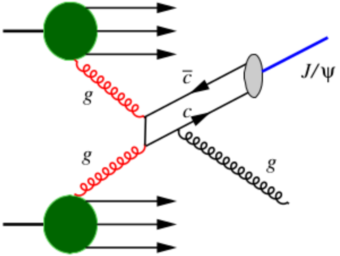


Open Charm Asymmetry



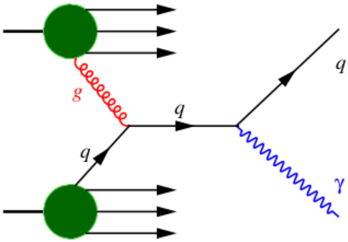
- Also D^0 $\bar{D}^0$ pair
- High statistics channel (largest cross-section among the three)
- Measured via hadronic (charged, neutral) decay channel (VTX, ST, TOF, ECAL)
- Requires good PID, multiple detectors, challenging measurements
- Requires fragmentation functions (FF) in the interpretation

Charmonia Asymmetry



- J/Ψ, Ψ′ and heavier charmonia
- Measured via $\mu^+\mu^-$ decay channel (RS)
- Clear signal with invariant mass reconstruction
- No fragmentation needed but model dependent interpretation (different $c\bar{c}$ $\rightarrow$meson production mechanisms)
- Details in Igor Denisenko's talk

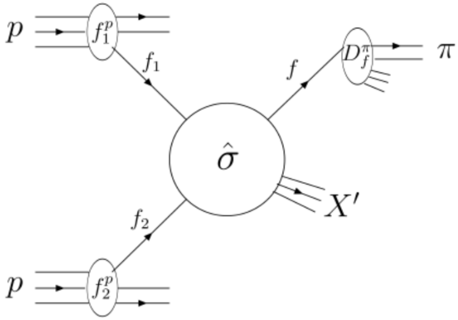
Prompt Photon Asymmetry



- Smallest cross-section, large background from neutral meson (π^0, η) decays
- Measured at ECAL
- Background reduction and background asymmetry correction are crucial
- Cleanest interpretation (though fragmentation/radiative contributions from scattered partons possible)

Factorization and Spin Asymmetries

Spin asymmetry measurements are typically interpreted under certain assumptions like factorizations : production of observed particle can be factorized as a convolution of soft (non-perturbative) and hard (perturbative) components.
Example :



$$\sigma(pp \to hX) \propto f_1(x_1) \otimes f_2(x_2) \otimes \widehat{\sigma}(q_1 q_2 \to q_3 X) \otimes D_3^h(z)$$

Helicity Asymmetry at SPD and Gluon Helicity

- Polarized Helicity PDF ($\Delta g_{1L}(x)$) : difference between longitudinal distributions of partons inside longitudinally polarized proton
- Double longitudinal spin asymmetries (A_{LL}) are of interest at SPD to probe gluon helicity distributions

Example :

$$A_{LL}^{\gamma} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \approx \frac{\Delta q(x)}{q(x)} \otimes \frac{\Delta g(x)}{g(x)} \otimes \hat{a}_{LL}^{gq \to \gamma q}$$

Transverse Asymmetries

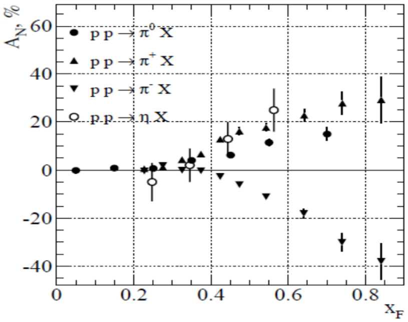


Figure 1: E704 A_N measurements

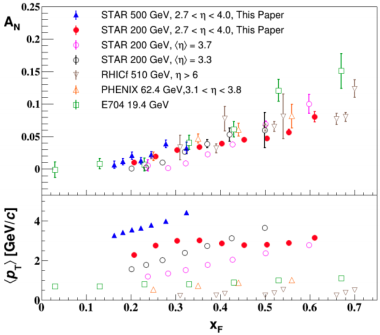


Figure 2: Recent STAR results : https://arxiv.org/abs/2012.11428

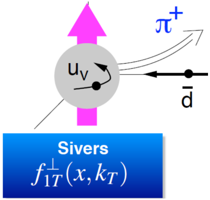
Large A_N measurements were a surprising at the beginning and gave rise to more detailed descriptions of partons inside hadrons

Large A_N is observed at positive x_F different energies. At negative x_F, typically it vanishes

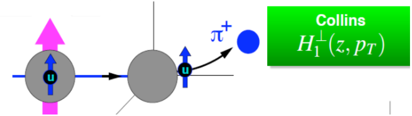
Possible Mechanisms and Interest at SPD

Single transverse spin asymmetries (A_N) are of interest at SPD to probe gluon Sivers distributions

- Sivers PDF ($f_{1T}^{\perp}(x, k_T)$) : difference between transverse momentum dependent PDFs in a polarized hadron
- Imagine preferential direction of final state product due to intrinsic transverse motion



- Collins effect : k_T asymmetric fragmentation of a scattered transversely polarized parton
- Can be important for fragmentation dependent processes i.e. open charm meson productions



Global Analysis : Gluon Helicity PDF

- DIS, SIDIS and RHIC data (STAR jet and PHENIX π^0 A_{LL} results) were combined to perform 'global analysis'
- PDF sets are parameterized, pQCD calculations are performed at NLO level, combined with Fragmentation Functions, A_{LL} are estimated
- χ^2 between calculated and measured A_{LL} are minimized in the parameter space using Lagrange Multiplier methods
- Notice the evolving understanding of the Δg in DSSV global analysis

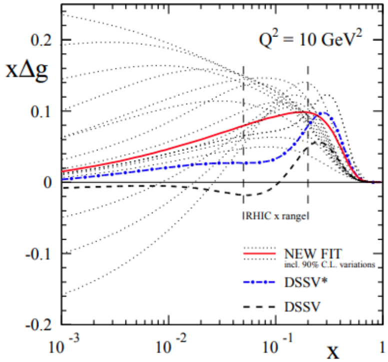


Figure 3: Phys. Rev. Lett. 113, 012001 (2014)

Global Analysis : Gluon Helicity Contd.

- There can be other approaches
- NNPDF collaboration use Neural Netwark techniques to generate somewhat randomized PDF sets to compare with data
- However, they use DIS data predominantly and no p+p asymmetries
- Notice SPD can make useful contribution in restricting the shaded region in the horizontal direction (large Bjorken x region)

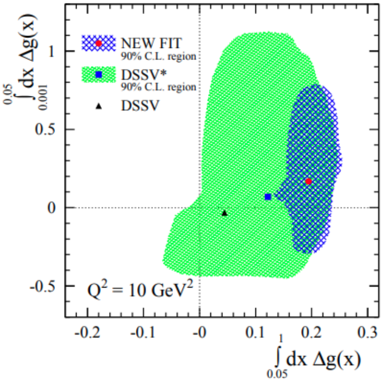


Figure 4: Phys. Rev. Lett. 113, 012001 (2014)

Prompt γ A_{LL} Calculations for SPD Kinematics

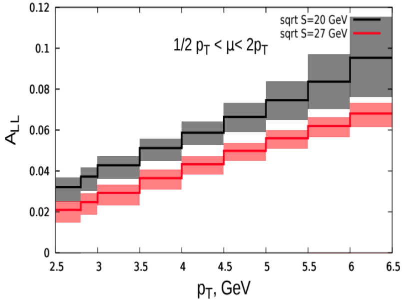


Figure 5: courtesy : Alexandra Shipilova

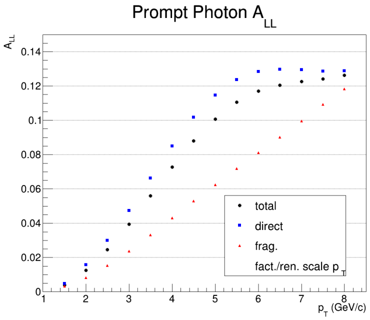


Figure 6: courtesy : Werner Vogelsang

DSSV New Approach

- DSSV et al. recently used techniques similar to that of NNPDF
- Each data point is used with its error (assumed Gaussian) to create MC replicas in the multi-Gaussian data space
- PDF sets (u,d,s, anti-quarks, g etc.) are extracted from EACH data replica
- Left with a set of PDF replicas, the average giving the central value and the standard deviation is the natural uncertainty of the PDF
- Notice the pole in the NNPDF line

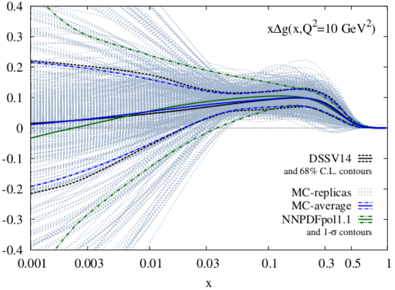


Figure 7: Phys. Rev. D 100, 114027 (2019)

DSSV Weighted MC to Quantify Impact of A_{LL}

- Once extracted, the set of replica PDF sets can be used to measure the impact of a new asymmetry measurement WITHOUT doing full global analysis again
- "The Bayesian reweighting is fully equivalent to a refit uncluding the addition set of data ..."
- Example shows the impact of STAR mid rapidity dijet result on the central value and the uncertainty band of the gluon helicity

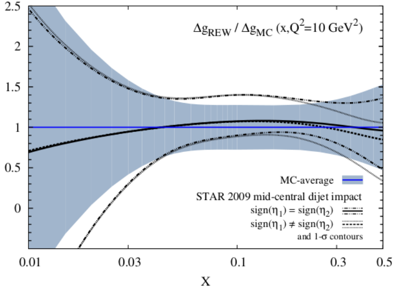


Figure 8: Phys. Rev. D 100, 114027 (2019)

Estimated Impact of A_{LL}^{γ} at SPD

- Used Werner Vogelsang's A_{LL} calculations and projected uncertainties at SPD one year of data collection at $\sqrt{s} = 27$ GeV
- Rodolfo Sassot and Ignacio Borsa produced the plot showing the possible quantitative impact of double helicity asymmetry measurements at SPD
- Uncertainties are reduced by $\sim$ factor of 2 in $0.3 \leq x \leq 0.5$
- Although the interpretation is more complicated, in principal, we can repeat the excercise for other (J/Ψ) A_{LL} when we have theoretical calculations

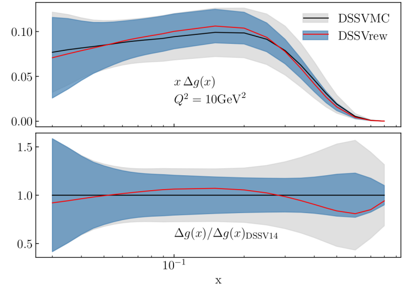


Figure 9: courtesy : Vogelsang, Sassot, Borsa

Global Analysis : Sivers TMD

- There are different schools of thoughts about interpretation of A_N using TMD formalism and collinear twist-three approach
- There is lack of data sensitive to gluon Sivers in general, especially among DIS, SIDIS (gluons do not interact in the leading order)
- It is extremely difficult to perform a 'global analysis' to extract gluon Sivers function
- There has been very recent attempts at quark Sivers extraction from global analysis (see plot on right)

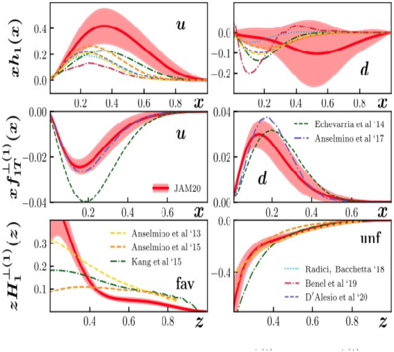


Figure 10: Phys. Rev. D 102, 054002 (2020)

Sivers TMD Global Analysis

- D'Alesio et al. in their recent works have calculated A_N for various models of production mechanism at RHIC energy ($\sqrt{s} = 200$ GeV)
- Similar calculations at SPD can be useful to compare with projected uncertainties to see if SPD measurements will be helpful in constraining model dependence
- Vladimir Saleev's talk already showed the model dependence and measurements can help support one and rule out others
- We are in a happy position to be leaders in the field with new data for a variety of channels probing gluon Sivers function

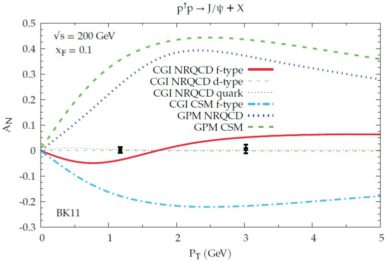


Figure 11: arXiv:2011.10350

Impact on Unpolarized Gluon PDF

- PROSA coll. performed global analysis to extract unpolarized gluon PDF
- Data used : HERA inclusive + c,b hadrons, LHCb c,b hadrons
- Unceratinty is high $x \geq 0.3$, where SPD open charm hadron cross-section measurements make a significant impact
- Work ongoing on cross-section measurements and error estimations that can be used to project improved uncertainties in the large x region

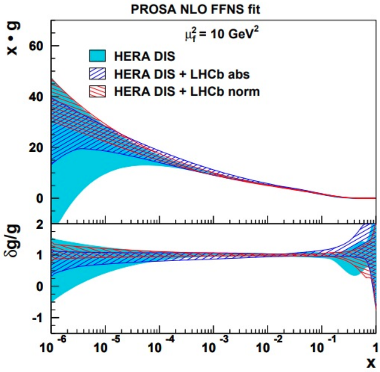


Figure 12: Eur. Phys. J. C 75, 396 (2015)

Outlook

- Work is ongoing for calculations of asymmetries and cross-sections of all our channels of interest and error estimates using MC simulations
- Asymmetries at SPD, both single spin and double spin, can be very useful in constraining gluon spin PDFs in the high Bjorken x region
- We need to collaborate with interested theory groups to try to quantify the impact in the transverse spin dependent PDFs in a reliable and meaningful way
- We need to investigate less frequently discussed TMD functions like transversity ($h_{1T}^{\perp}$: distribution of transverly polarized partons in a transversely polarized proton) and Boer-Mulders ($h_1^{\perp}$: TMD distributions of partons in an unpolarized proton)

Backup

Data Used in Quark Sivers Global Analysis

Observable	Reactions	Non-Perturbative Function(s)	$\chi^2/N_{\text{pts.}}$	Refs.
$A_{\text{SIDIS}}^{\text{Siv}}$	$e+(p,d)^{\uparrow} \to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^{\perp}(x,k_T^2)$	$150.0/126 = 1.19$	[65, 66, 68]
$A_{\text{SIDIS}}^{\text{Col}}$	$e+(p,d)^{\uparrow} \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,k_T^2), H_1^{\perp}(z,z^2p_\perp^2)$	$111.3/126 = 0.88$	[66, 68, 71]
$A_{\text{SIA}}^{\text{Col}}$	$e^+ + e^- \to \pi^+\pi^-(UC,UL)+X$	$H_1^{\perp}(z,z^2p_\perp^2)$	$154.5/176 = 0.88$	[74–77]
$A_{\text{DY}}^{\text{Siv}}$	$\pi^- + p^{\uparrow} \to \mu^+\mu^- + X$	$f_{1T}^{\perp}(x,k_T^2)$	$5.96/12 = 0.50$	[73]
$A_{\text{DY}}^{\text{Siv}}$	$p^{\uparrow} + p \to (W^+,W^-,Z)+X$	$f_{1T}^{\perp}(x,k_T^2)$	$31.8/17 = 1.87$	[72]
A_N^h	$p^{\uparrow} + p \to (\pi^+,\pi^-,\pi^0)+X$	$h_1(x), F_{FT}(x,x) = \frac{1}{\pi} f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z)$	$66.5/60 = 1.11$	[7, 9, 10, 13]

Figure 13: Phys. Rev. D 102, 054002 (2020)