Probing the Gluon Helicity Distribution at SPD

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Introduction to SPD

Figure 1: NICA facility : Conceptual Design Report of SPD : arxiv:2102.00442

The proposed Spin Physics Detector (SPD) will be an excellent laboratory to probe nucleon structure, especially polarized Parton Distribution Functions (PDF) of gluons

- At NICA accelerator facility in JINR (Dubna), 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 photons (γ)

SPD Detectors

- SPD will have 4π coverage with a barrel part and two endcaps
- Prominent components will be : Vertex detector, Straw Tracker for charged tracks, PID detector (TOF and Aerogel), Electromagnetic Calrometer, Range System (for muon identification)
- Solenoidal magnetic field (1 T) in the tracker will provide $\delta p_T/p_T \sim 2\%$ for tracks with momentum 1 GeV/c
- Expected ECAL energy resolution $\sim 5\%/\sqrt{E}$

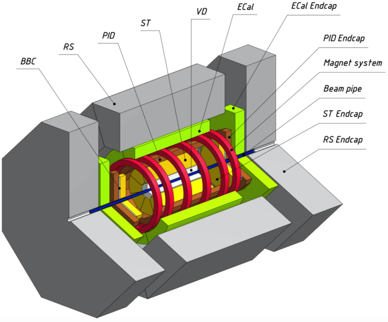

Figure 2: Schematic of SPD detector system : SPD CDR

SPD Design and Kinematic Coverage

Design luminosity $10^{32} cm^{-2} s^{-1}$

Energy range up to 27 GeV for $p^{\uparrow} + p^{\uparrow}$

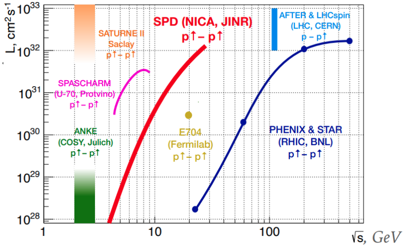

Figure 3: Luminosity (L) and center of mass energy (S) range : SPD CDR

SPD will contribute data in the large Bjorken x range

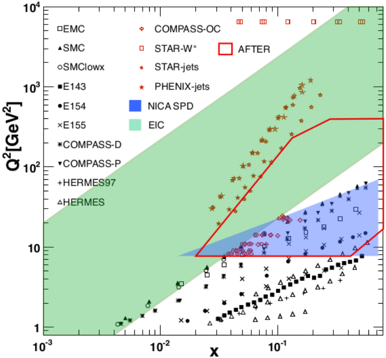

Figure 4: Energy transfer (Q^2) and momentum fraction (x) range : SPD CDR

Open Charm Channel

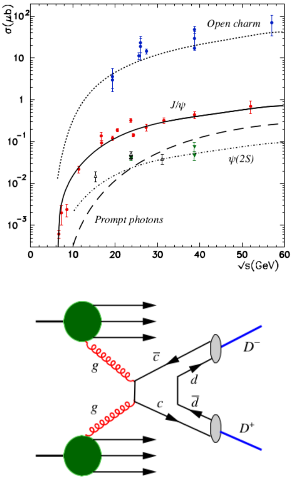

Figure 5: Process cross-sections (upper : SPD CDR) and schematic of open charm production (lower)

- D^+D^- and $D^0\bar{D}^0$ pairs
- High statistics channel (largest cross-section among the three channels of interest)
- 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

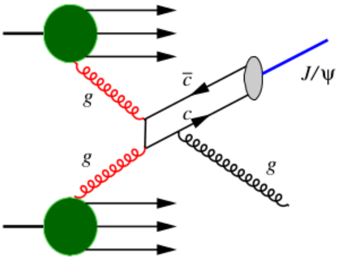

Figure 6: Schematic of charmonia meson production

- 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)

Prompt Photon Channel

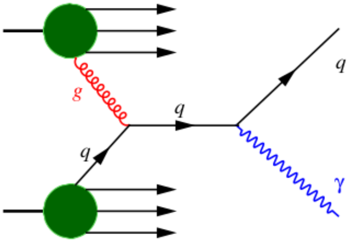

Figure 7: Schematic of prompt photon production

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

- DIS experiments (i..e EMC, SMC, COMPASS, HERMES) built our understanding of quark PDFs (polarized and unpolarized)
- DIS interactions probing gluon are of necessity higher order processes making measuremnets more difficult and the data scarce

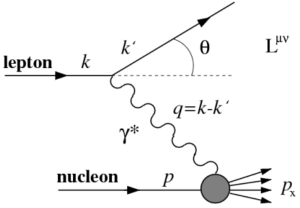

Figure 8: Schematic of inclusive DIS

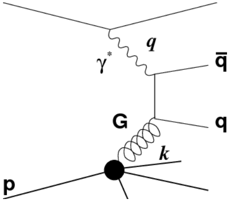

Figure 9: Schematic of semi-inclusive DIS probing gluon

EMC has shown decades ago that all quarks contribute only about a quarter of total proton spin. Gluon spin distributions have been of interest since then

Limitations of DIS Probing Gluon PDF

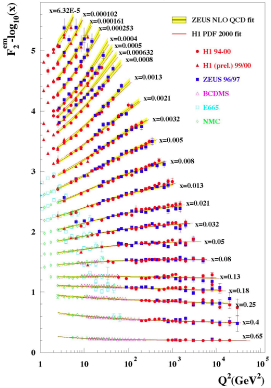

Figure 10: Unpolazied structure function of proton $F_2^p(x)$: EPJ C71, 1573 (2011)

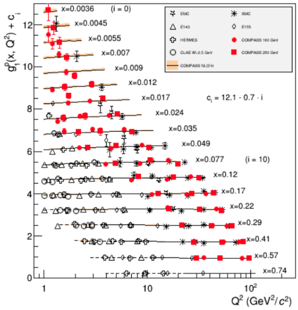

Figure 11: Polarized structure function of proton $g_1^p(x)$: EPJ Web of Conferences 164, 01007 (2017)

Notice the limited range of energy Q^2 and momentum fraction x in the polarized plot on the right when compared to the unpolarized plot on the left

- Solution : experiments with polarized gluon interactions as first order process i.e. polarized proton collisions like PHENIX, STAR at RHIC
- Spin asymmetry measurements are typically interpreted under certain assumptions like collinear factorization : production of observed particle can be factorized as a convolution of soft (non-perturbative) and hard (perturbative) components

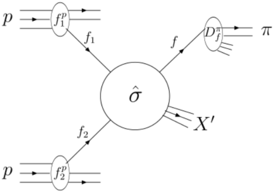

Figure 12: Schematic of a $p + p$ hard process

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

Helicity Asymmetry at SPD and Gluon Helicity

- Polarized Helicity PDF ($\Delta g(x)$) : 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

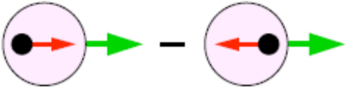

Figure 13: Illustrative diagram for parton helicity

Example (for aymmetries dominated by quark-gluon processes) :

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

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

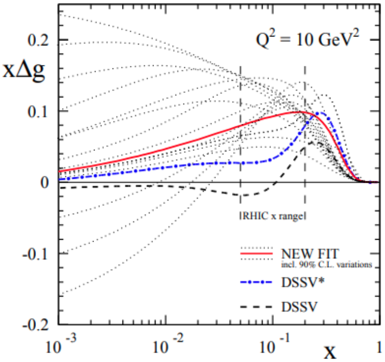

Figure 14: Phys. Rev. Lett. 113, 012001 (2014)

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 that SPD can make useful contribution in restricting the shaded region in the horizontal direction (large Bjorken x region)

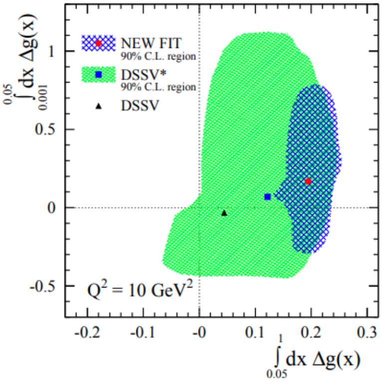

Figure 15: Phys. Rev. Lett. 113, 012001 (2014)

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
- The average gives the central value and the standard deviation is the natural uncertainty of the PDF
- Notice the pole (zero crossing) in the NNPDF line

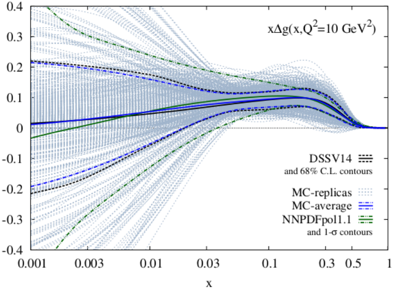

Figure 16: Phys. Rev. D 100, 114027 (2019)

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

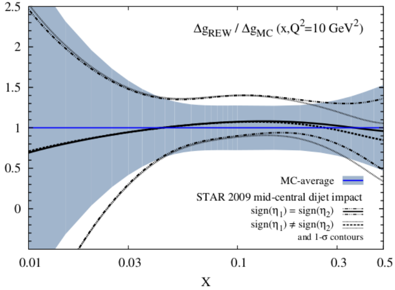

Figure 17: Phys. Rev. D 100, 114027 (2019)

Prompt γ A_{LL} Calculations for SPD Kinematics

- We studied the impact of A_{LL} measurements via prompt photon channel at SPD
- NLO calculations of A_{LL} produced with NNPDF3.0 unpolarized and DSSV2014 polarized PDF sets
- MC simulations performed for background estimation and statistics
- Lower plot with combined estimated statistical and systematic uncertainties for one year of data at SPD

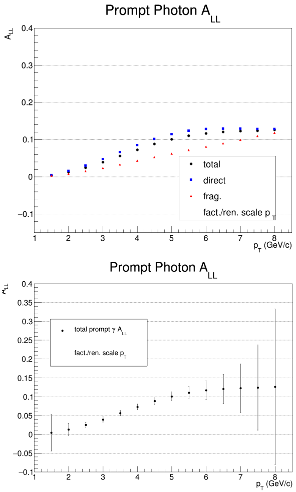

Figure 18: NLO A_{LL} calculation (Werner Vogelsang)

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 (estimated integrated luminosity 1 fb^{-1})
- Plot (courtesy of Rodolfo Sassot, Ignacio Borsa) showing the possible quantitative impact of double helicity asymmetry measurements at SPD
- Uncertainties are reduced by $\sim$ factor of 2 in $0.3 \leq x \leq 0.5$

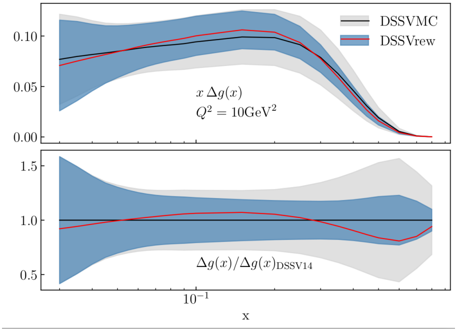

Figure 19: $\Delta g(x)$ distribution (upper) and ratio of 'new' to standard DSSV $\Delta g(x)$ (lower) (Sassot, Borsa)

Summary

- One of the major focus at SPD is to probe the transverse momentum dependent (TMD) spin distributions of gluon (a field in dire need of data)
- However, we demonstrate here that asymmetry measurements at SPD can also make significant contributions to the present knowldge of the gluon helicity distributions
- Operating at energy lower than at PHENIX and STAR, SPD will help constrain the gluon PDF at the higher end of the Bjoerken x
- We demonstrated the usefulness of one of the channels of ineterst (prompt photons). In principal, we can improve the global analyses with other A_{LL} measurements like J/Ψ (although the interpretations are more difficult)
- J/Ψ productions are highly model dependent, but with various measurements at SPD (cross-sections, A_N, A_{LL}), SPD can even help constrain aplicability of models for the relevant kinematic ranges

Thank You