Studying Nucleon Spin Structure at the Spin Physics Detector (SPD)

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(On behalf of the SPD collaboration)

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Plans for the Presentation

- Physics goals and detector system
- Focus on nucleon spin structure
- Measurements, challenges, expectations
  1. Charmonia
  2. Direct Photon
  3. Open-charm meson

SPD Stage II : Physics

- Primary focus : accessing gluon PDFs
  1. Unpolarized gluon PDF
  2. Gluon helicity PDF
  3. Gluon transverse momentum dependent (TMD) PDF (Sivers, Boer-Mulders)
  4. Transversity and tensor polarized gluon in deuteron

- Test of QCD factorization

- Charmonia production mechanism
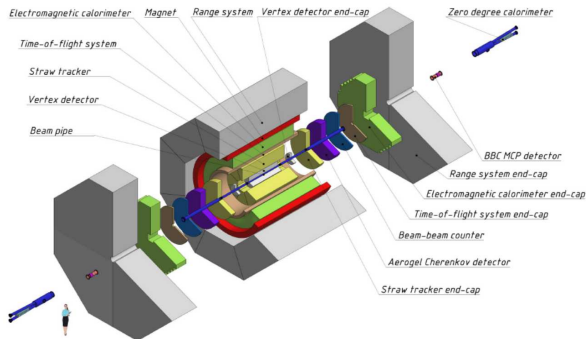
SPD Stage II : Detector

Figure 1: SPD detector in stage II : SPD TDR

- MAPS/DSSD based vertex detector : secondary vertex reconstruction : resolution $\sim 50~\mu m$
- Range System : hadronic calorimeter, μ/h separation

- Event rate at peak L and $\sqrt{s}$: ~ 3 MHz
- Straw Tracker $\delta \sim 240~\mu m$
- Electromagnetic calorimeter (ECAL) ($\frac{\delta_E}{E} = \frac{5\%}{\sqrt{E}} + 1\%$)
- Time of flight (TOF) for PID ($\delta_t \sim 50$ ps), π/K separation upto 1.5 GeV/c
- Focusing RICH in end-caps, extend π/K separation up to 5.5 GeV/c

Detector Performances
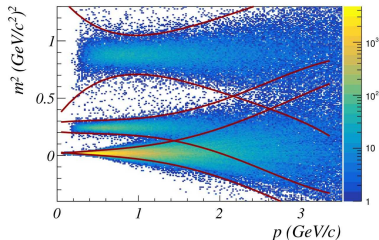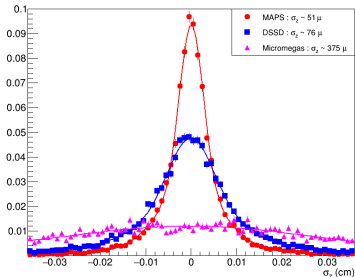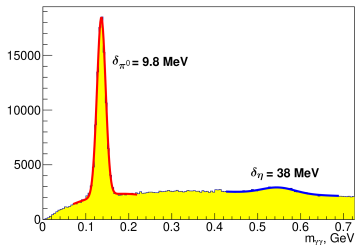
- Clockwise from lower left (SPD TDR) :
- Resolution of reconstructed D^0 vertex : $\delta_z \sim 50$ μm for MAPS
- Invariant mass of 2-photons : $\delta_m^{\pi^0} \sim 10$ MeV
- TOF performance:provides a 3σ separation of π/K up to 1.5 GeV/c
- Additionally:in the straw tracker, $\frac{\delta_{p_T}}{p_T} \sim 2\%$ for 1 GeV/c tracks (magnetic field ~ 1 T)

Probing Gluon Spin Distributions at the SPD

	Unpolarized	Circular	Linear
Unpolarized	$g(x)$ density		$h_1^{\perp g}(x, k_T)$ Boer-Mulders function
Longitudinal		$\Delta g(x)$ helicity	Kotzinian-Mulders function
Transverse	$\Delta_N^g(x, k_T)$ Sivers function	Worm-gear function	$\Delta_T g(x)$ transversity (deuteron only), pretzelosity

Figure 2: Various spin distributions of gluons that will be accessible via cross-section and asymmetry measurements at the SPD
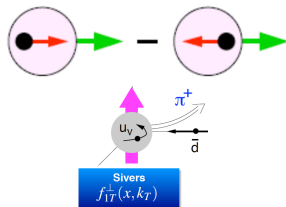
- Unpolarized gluon distributions ($g(x)$)

- Gluon helicity PDF ($\Delta g(x)$)

- TMD gluon spin distributions i.e. Sivers ($\Delta_N^g(x, k_T)$), Boer-Mulders ($h_1^{\perp g}(x, k_T)$)

- Transversity ($\Delta_T g(x)$) : deuteron

Gluon Helicity $\Delta g(x)$

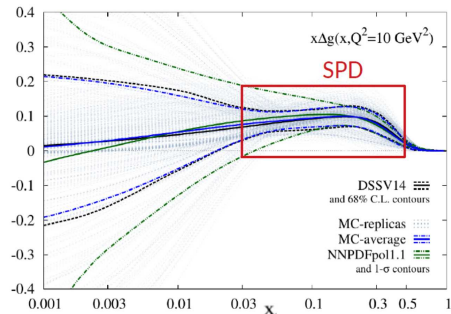Important to understand proton spin as a whole (spin puzzle)

Figure 3: Gluon helicity distribution from DSSV group: Phys. Rev. D 100 114027(2019). Highlighted region shows where SPD will make a major impact
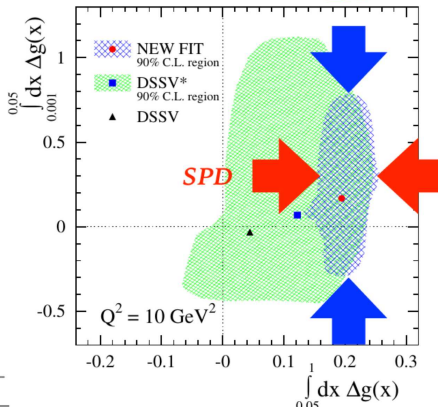

Figure 4: Truncated moments of $\Delta g(x)$ illustrate SPD impact on high-x and future EIC impact in low-x region
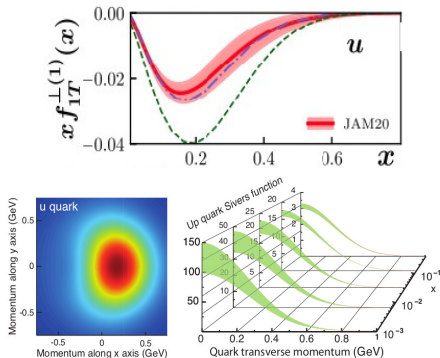
Gluon TMD : Sivers

Figure 5: Extracted quark Sivers as functions of x and k_T [above : Phys. rev. D 102, 054002, below : EIC white paper]

- Sivers function can be described as a corrleation between parton k_T and hadron transverse spin
- Transverse single spin asymmetries (A_N) are sensitive to the gluon Sivers function
- Extracted in generalized parton model(GPM), color gauge invariant GPM(CGI-GPM) descriptions of partonic structure
- Unlike gluon helicity PDF, there has not been extraction of gluon Sivers from global analysis, SPD can provide much needed data points
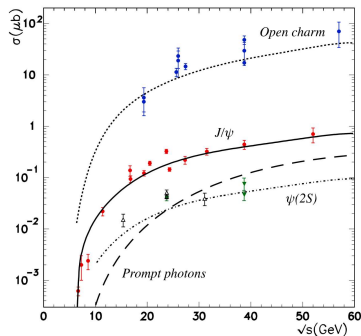
SPD : Prominent Measurements

Figure 6: Partonic sub-process cross-sections from $p + p$ vs. collision energy : SPD CDR
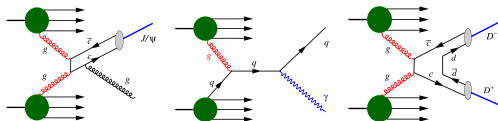

Figure 7: Sub-process diagrams

- Flagship probes at SPD accessing gluon content :
  1. gluon fusion to charmonia ($J/\Psi, \Psi(2S), \chi_{c_1/c_2}$), primarily via dimuon decay channel
  2. quark-gluon to prompt-photons, cleanest channel for interpretation
  3. gluon fusion to open-charm mesons, highest statistics but also very high background

Various SPD Probes

Probe	$\sigma_{27\,\text{GeV}}$, nb ($\times$BF)	$\sigma_{13.5\,\text{GeV}}$, nb ($\times$BF)	$N_{27\,\text{GeV}}$, 10^6	$N_{13.5\,\text{GeV}}$, 10^6
Prompt-γ ($p_T > 3$ GeV/c)	35	2	35	0.2
J/ψ	200	60		
$\quad \to \mu^+\mu^-$	12	3.6	12	0.36
$\psi(2S)$	25	5		
$\quad \to J/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$	0.5	0.1	0.5	0.01
$\quad \to \mu^+\mu^-$	0.2	0.04	0.2	0.004
$\chi_{c1} + \chi_{c2}$	200			
$\quad \to \gamma J/\psi \to \gamma\mu^+\mu^-$	2.4		2.4	
η_c	400			
$\quad \to p\bar{p}$	0.6		0.6	
Open charm: $D\overline{D}$ pairs	14000	1300		
Single D-mesons				
$\quad D^+ \to K^-2\pi^+ (D^- \to K^+2\pi^-)$	520	48	520	4.8
$\quad D^0 \to K^-\pi^+ (\overline{D}^0 \to K^+\pi^-)$	360	33	360	3.3

Figure 8: Expected statistics for probes for one year of data at SPD
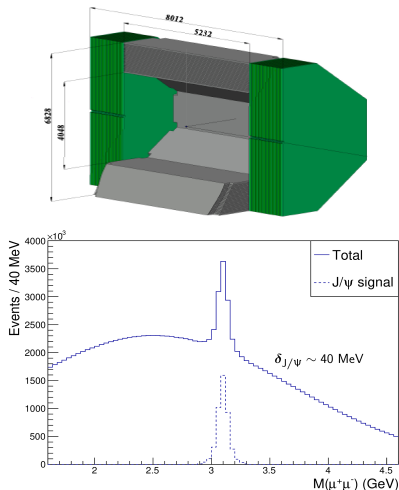
Charmonia Measurements

- Productions are dominated by *gg* fusion at SPD kinematics
- Reconstructed from di-muon decay channels using Range System as muon identifier
- Hadronization poorly understood (various models : CSM, CEM, NRQCD)
- TMD factorization not always applicable
- J/Ψ most abundant ~ 12 M events expected in one year of data in this channel

Figure 9: Above: Range System at SPD Below: di-muon invariant mass spectra for J/Ψ : SPD TDR

J/Ψ Double Helicity Asymmetry ($A_{LL}^{J/\Psi}$)
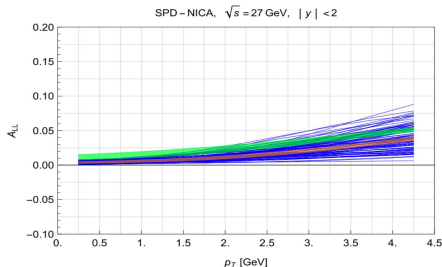

Figure 10: Estimated $A_{LL}^{J/\Psi}$ for different PDF replicas (brown and green bands are uncertainties for scale and LDME variations) : Physics 2023, 5(3), 672-687
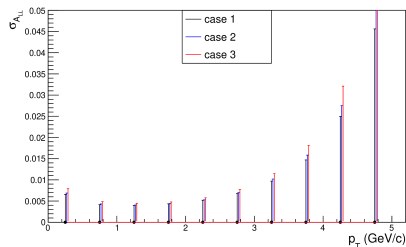

Figure 11: Projected statistical uncertainties for $A_{LL}^{J/\Psi}$ measurements from one year of recorded data at the SPD in p_T for three different selection criteria of muon polar angle θ_μ : SPD CDR

- $A_{LL}^{J/\Psi} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta g(x_2)}{g(x_2)} \otimes \hat{a}_{LL}^{gg \to J/\Psi + x}$
- Sensitive to gluon helicity PDF
- SPD kinematic will probe $x_{Bjorken} \sim 0.03 - 0.5$
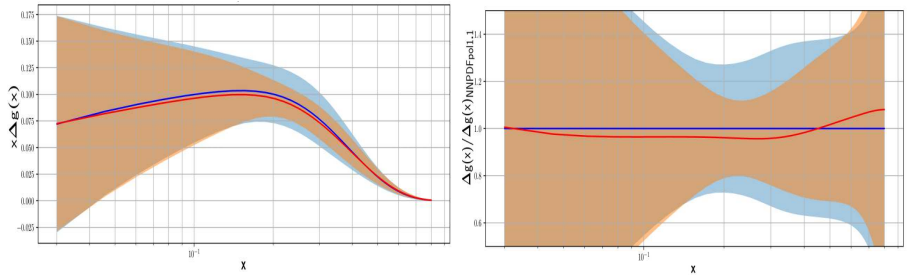
Impact of SPD $A_{LL}^{J/\Psi}$ Measurements

Figure 12: Estimated impact of $A_{LL}^{J/\Psi}$ measurements at the SPD on the gluon helicity distribution $\Delta g(x)$. Blue and red lines show the mean of the NNPDFpol1.1 replica sets before and after the re-weighting, respectively. Light blue and light orange bands show the corresponding standard deviation uncertainties (Physics 2023, 5(3), 672-687).

SPD impact in $0.1 \le x \le 0.6$ range

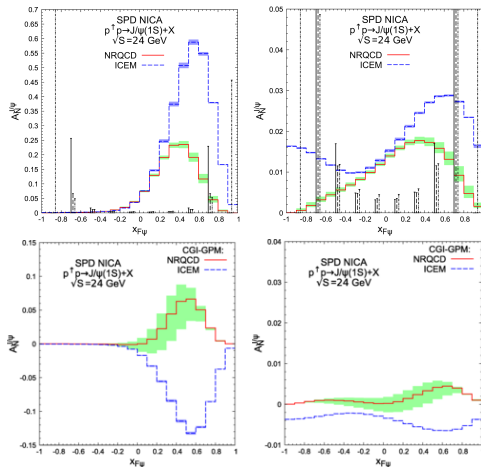# J/Ψ Single Transverse Spin Asymmetry ($A_N^{J/\Psi}$)

Figure 13: $A_N^{J/\Psi}$ predictions for SPD kinematics (and projected uncertainties for one year of recorded data) [Phys. Rev. D *104*, 016008]

- Top to bottom : GPM and CGI-GPM. Left to right : SIDIS1 and D'Alesio parameterization of Sivers Function

- Various combinations of PDFs and hadronization models illustrate strong model dependence

- For example, asymmetry predictions using SIDIS1 and d'Alesio params. are different by an order of magnitude

- SPD measurements and precision can be crucial in restricting such model dependence in future
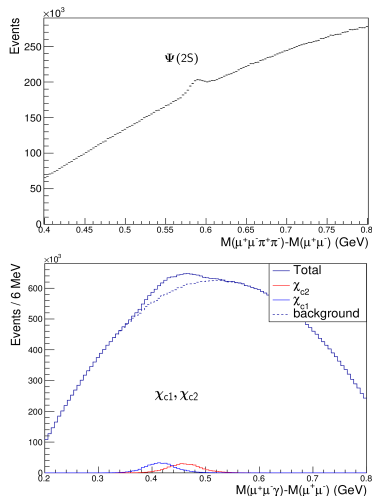
Other Charmonia Probes

Figure 14: Di-muon invariant mass spectra for various charmonia probes : SPD CDR

- $\Psi(2S)$ via di-muon decay channels ($\mu^+\mu^-\pi^+\pi^-$, $\mu^+\mu^-$) : $\sim$ 700 K events/year

- χ_{c1}, χ_{c2} via di-muon decay channel ($\gamma\mu^+\mu^-$) : $\sim$ 2.4 M events/year

- Double J/Ψ productions : both J/Ψ into di-leptonic decay channels $\sim$ 100 events/year

- Limited η_c measurements could also be possible (of special ineterest as TMD factorization is proven for this probe)

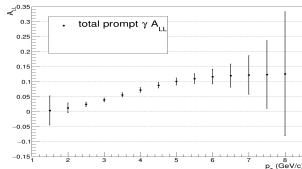# Prompt Photon Double Helicity Asymmetry (A_{LL}^{γ})

Figure 15: Predictions of A_{LL}^{γ} as function of transverse momentum p_T (Physics 2023, 5(3), 672-687)

Estimates (right plot) show that measurements at the SPD can reduce uncertainties of gluon heicity at large x by $\sim 1/2$
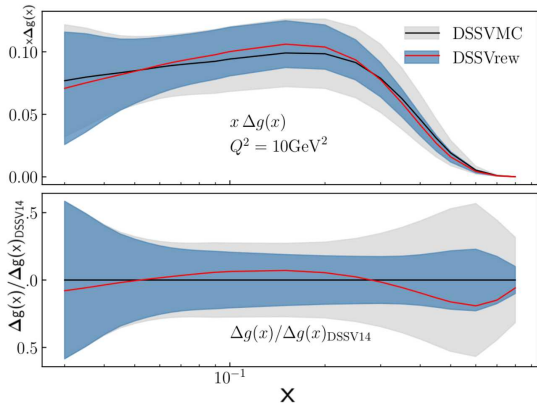

Figure 16: Impact of SPD A_{LL}^{γ} (Physics 2023, 5(3), 672-687) : Vogelsang, Sassot, Borsa

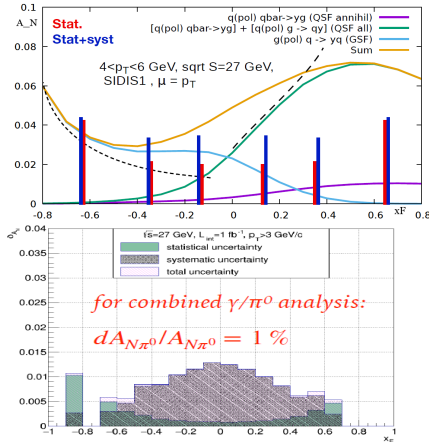# Prompt Photon Transverse Single Spin Asymmetry (A_N^γ)

Figure 17: Above: Predicted A_N^γ vs. x_F from V. Saleev, A. Shipilova with projected uncertainties for one year of data at SPD Below: Estimation of uncertainty due to background : SPD CDR

- Prompt photon is an 'clean' channel as it does not include hadronization

- Particularly sensitive to gluons in the backward (-ve rapidity) region production

- Challenge to remove stray photons from neutral light meson (π^0, η) decays

- Uncertainties arising from photons from π^0 decays are estimated as systematic on lower left plot
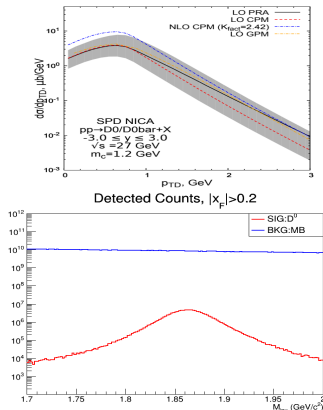
Open Charm Measurements

Figure 18: Above: inclusive D^0, $\bar{D}^0$ cross-section prediction (A. Karpishkov), Below: Projected π-K invariant mass spectra for one year of data at the SPD
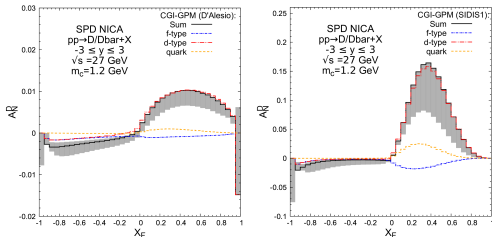

Figure 19: Predicted A_N at SPD kinematics (Prog. Part. Nucl. Phys. 2021, 119, 103858)

- Productions dominated ($\sim 70\%$) by gg fusion
- Expected high A_N at $x_F \geq 0.2$
- Detected via hadronic decay channel at SPD
- Challenging due to very high combinatorial background ($S/B \sim 10^{-5}$)

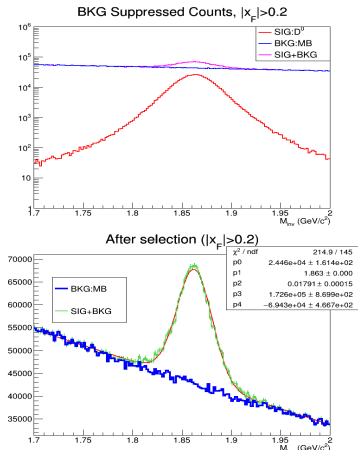# Neutral D Transverse Single Spin Asymmetry at the SPD

Figure 20: Above: Projected π-K invariant mass spectra after selection criteria are applied Below: $D^0 \rightarrow \pi^+ K^-$ fit to signal and background

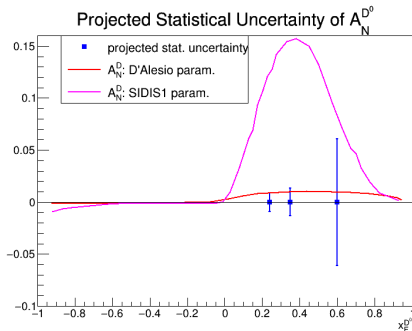Figure 21: Predicted inclusive A_N^D at SPD kinematics with projected statistical uncertainties δ_N^{stat} for D^0 (Physics 2023, 5(3), 672-687)

Expected statistical precision could be crucial to (dis)favour certain GSF models decisively

Figure 22: NICA complex with ongoing constructions

Summary and Outlook

- Spin Physics Detector (SPD) at the NICA facility will be a unique facility focusing on the unpolarized and polarized gluon distributions inside protons and deuterons from $p + p$ and $d + d$ collisions up to $\sqrt{s} = 27$ and 13.5 GeV respectively

- In the first stage, SPD will probe several interesting unpolarized and spin-dependent effects from $p + p$ and $d + d$ at low ($\sqrt{s_{NN}} = 5 - 10$ GeV) energies

- In the final stage, SPD measurements (of charmonia ($J/\Psi, \Psi(2S), \chi_c$), prompt-photon and open-charm (D mesons)) will be sensitive to

  1. unpolarized gluon PDF
  2. gluon helicity
  3. gluon TMD (Sivers, Boer-Mulders)
  4. gluon transversity in deuteron

- SPD contributions to the polarized gluon distributions will be complementary to similar existing and future collider (RHIC, EIC) and fixed target (AFTER, LHC-Spin) experiments

Thank You

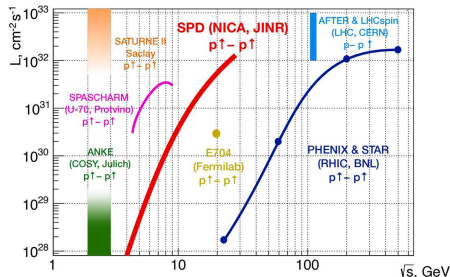# Backup

SPD Kinematics

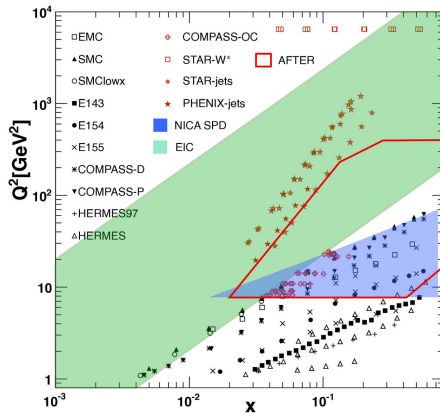Figure 23: Luminosity vs. energy : SPD CDR

Figure 24: Kinematic coverage for major probes at the SPD : charmed mesons, high-p_T photons and charmonia : CDR

Bayesian Re-weighting

- Each data point is used with its error (assumed Gaussian) to create MC replicas in the multi-Gaussian data space (virtual ensemble of data sets)

- PDF sets (u,d,s, anti-quarks, g etc.) are extracted from EACH data replica

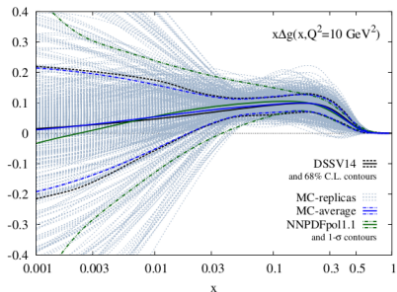- The average gives the central value and the standard deviation is the natural uncertainty of the PDF

Figure 25: Phys. Rev. D 100, 114027 (2019)

Re-weighting Technique to Quantify Impact of New A_{LL}

- Once extracted, the set of replica PDFs 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 including the additional 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
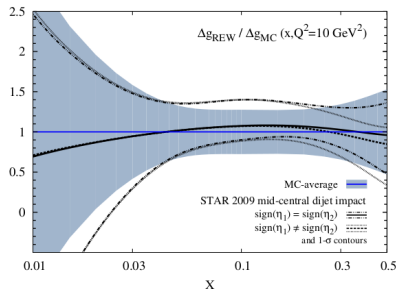

Figure 26: Phys. Rev. D 100, 114027 (2019)

Deuteron at SPD

$\sigma(x_F, p_T)$, *vector and tensor angular asymmetries*

Nonbaryonic content of deuteron:

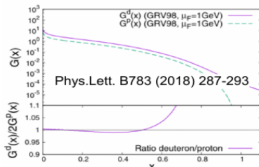$$|6q\rangle = c_1|NN\rangle + c_2|\Delta\Delta\rangle + c_3|CC\rangle$$

Phys.Lett. B783 (2018) 287-293

Fig. 6. Gluon PDF in the deuteron and in the nucleon.

Unpolarized gluons at high x:

Gluon transversity

$\Delta s = 2$

$A_{++,--}$

A_{Exy}

Sh. Kumano for DY:

$$\Delta_T g(x) = \Delta g(x)$$

$\phi = 0$
$y = 0.5$

- · · · · $q_T = 0.2$ GeV
- ─── $q_T = 0.5$ GeV
- ─ ─ ─ $q_T = 1.0$ GeV

$M_{\pm}^2$(GeV^2)

Tensor PDFs

$x\delta_T f(x)$

- · · · · $Q^2 = 2.5$ GeV^2
- ─── $Q^2 = 30$ GeV^2

$x\delta_T u = x\delta_T d = x\delta_T s$

$x\delta_T c = x\delta_T \bar{c}$

$x\delta_T \bar{g}$

$x\delta_T \bar{u}_v = x\delta_T \bar{d}_v$

x