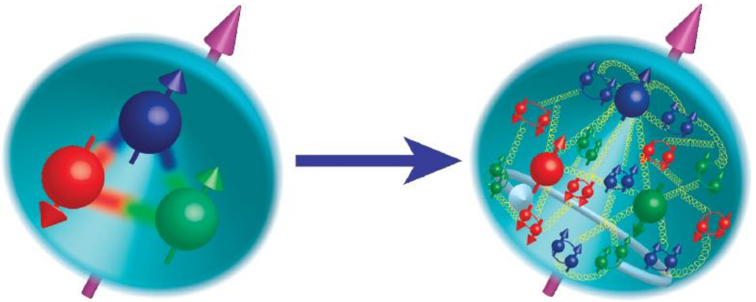
Transverse Single-Spin Asymmetries of Heavy Flavor Electrons in 200 GeV $p^{\uparrow}+p$ Collisions at Midrapidity from PHENIX

Dillon Fitzgerald for the PHENIX Collaboration
May 3, 2022

Spin Physics and Proton Structure

Our understanding of proton structure in terms of constituent quarks and gluons has evolved greatly in the past few decades



- We know that valence quarks do not carry all of the proton spin…
  - How is the spin of quarks and gluons correlated with proton spin?
  - How is the orbital motion of quarks and gluons correlated with proton spin?

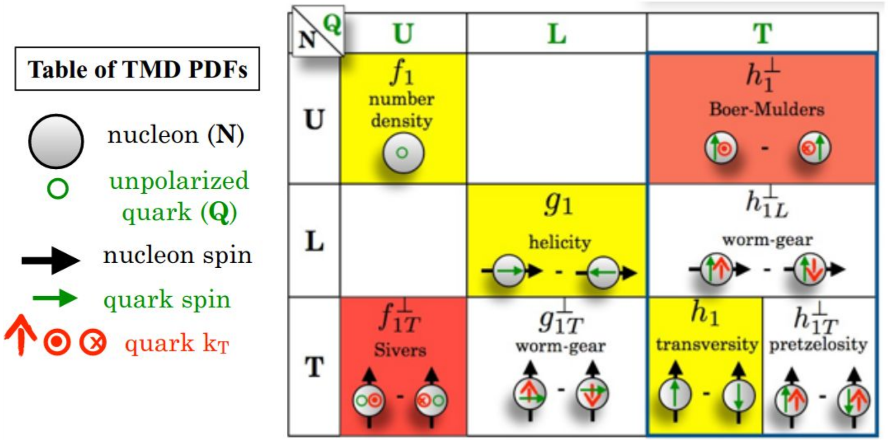


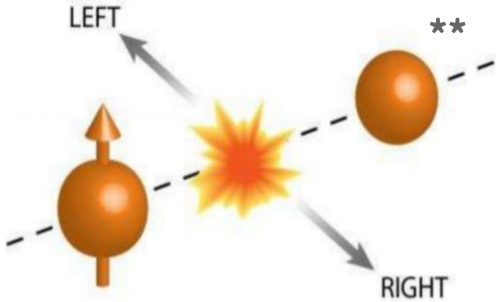
Table of TMD PDFs

- nucleon (N)
- unpolarized quark (Q)
- nucleon spin
- quark spin
- quark k_T

N \ Q	U	L	T
U	f_1 number density		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	$g_{1T}^\perp$ worm-gear	h_1 transversity $h_{1T}^\perp$ pretzelosity

Transverse Single Spin Asymmetries (TSSAs)

- $p^{\uparrow} + p$ initial state
- Measure particle production on either side of the polarized proton-going direction (measure azimuthal asymmetry)
- Perturbative QCD predicted to contribute negligibly to TSSAs in the past (<1%)*
  - Recent calculations suggest possible contributions at 2 loops ([PRD100, 094027](PRD100, 094027))
- Large TSSA measurements imply nonperturbative spin-momentum and spin-spin correlations within proton



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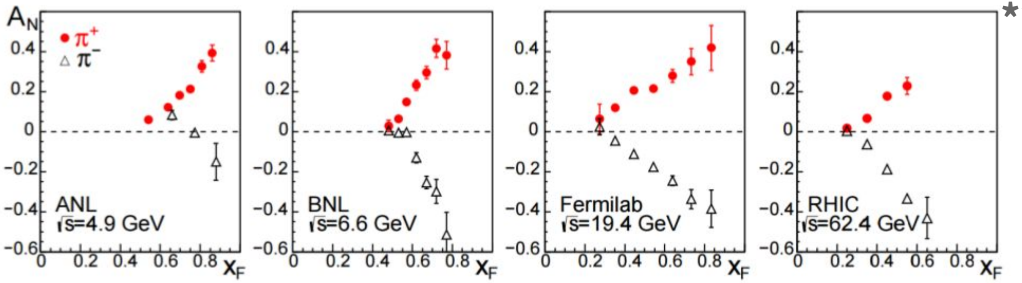
$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$



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$x_F = 2p_Z/\sqrt{s}$

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*G. L. Kane, J. Pumplin, and W. Repko PRL 41, 1689 (1978).

**https://www.bnl.gov/newsroom/news.php?a=111699

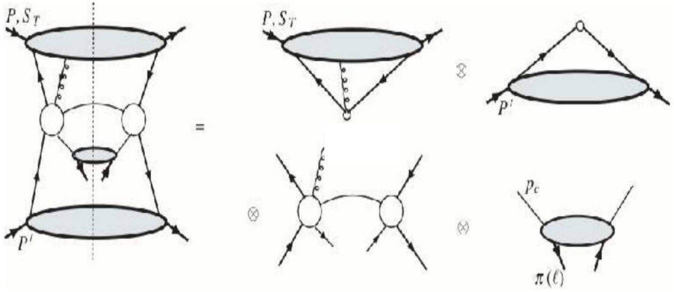
***C.A. Aidala, S.D. Bass, D. Hasch, and G.K. Mallot, Rev. Mod. Phys. **85** 655 (2013).

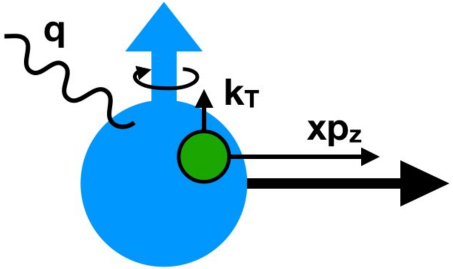
Transverse Single Spin Asymmetries (TSSAs)

Theoretical frameworks for describing measured TSSAs

- **Higher Twist Effects**
  - Collinear, so only need one hard scale (Q)
    - Access via p_T of measured particle
  - Need higher twist (i.e. twist 3) to describe observed TSSAs
    - **Higher Twist:** Power suppressed terms in factorization expansion by $(1/Q)^{n-2}$
      - Twist 3 suppressed by 1/Q
- **Transverse Momentum Dependent Functions (TMDs)**
  - Explicit dependence on transverse momentum of partons within the proton
  - Need access to both a hard and soft scale with sufficient scale separation (i.e. Q and k_T with Q >> k_T)

Quantum interference between 2 → 2 process and itself with extra gluon with similar x





Unification of two frameworks has been demonstrated

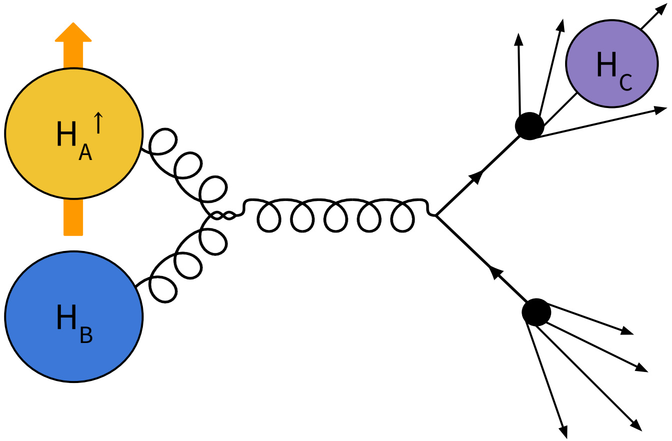
$$T_{q,F}(x,x) = \frac{1}{M_p}\int d^2\vec{k}_\perp \vec{k}_\perp^2\, q_T(x,k_\perp)$$ *

Twist 3 correlator (qgq) **Sivers TMD PDF**

*Kang, Qiu, Vogelsang, Yuan, PRD78, 114013

Twist 3 Correlators

$$\boxed{\phi^{(3)f,d}_{g/X} \rightleftharpoons T_G^{(f,d)}}$$



$$A_N \propto \sum_{abc} \phi^{(3)}_{a/A}(x_1, x_2, \vec{s}_\perp) \otimes \phi_{b/B}(x') \otimes \hat{\sigma} \otimes D_{c\to C}(z) + \\ \sum_{abc} \delta q_{a/A}(x, \vec{s}_\perp) \otimes \phi^{(3)}_{b/B}(x'_1, x'_2) \otimes \hat{\sigma}' \otimes D_{c\to C}(z) + \\ \sum_{abc} \delta q_{a/A}(x, \vec{s}_\perp) \otimes \phi_{b/B}(x') \otimes \hat{\sigma}'' \otimes D^{(3)}_{c\to C}(z_1, z_2).$$ *

- Terms with A, B in subscript → initial state effects
- Terms with C in subscript → final state effects
- Terms with (3) in superscript → twist 3 correlators

Measuring A_N for different final state particles gives access to specific terms in the sum

Heavy flavor electron production dominated by gg fusion @ 200 GeV midrapidity; gluon transversity distributions = 0 → access to trigluon correlator $\phi^{(3)}_{g/X}$

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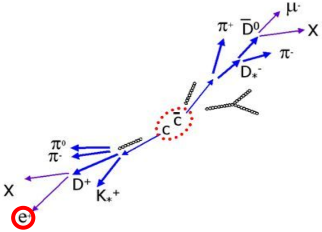
*PHENIX Collaboration - arXiv:1805.01491v2. [hep-ex]. 9, July 2018.

Open Heavy Flavor Production



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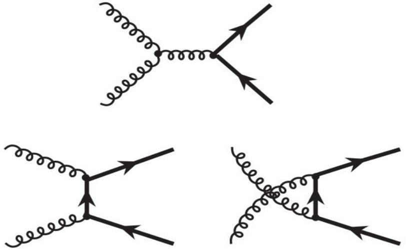
Open charm production is dominant contribution

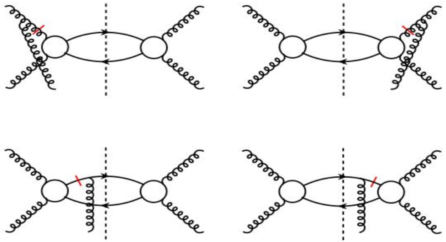
$gg\rightarrow QQ$



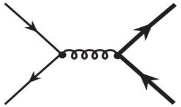
*

Dominant contribution @ 200 GeV midrapidity! ggg correlator **not** well constrained from previous measurements

ggg (trigluon) correlators *



$q\bar{q}\rightarrow QQ$



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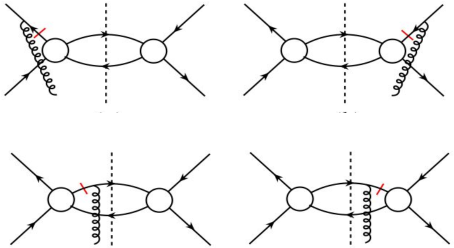
Small contribution @ 200 GeV midrapidity! qgq correlator somewhat constrained from previous measurements

qgq (Efremov-Teryaev-Qiu-Sterman) correlators *



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*Kang, Qiu, Vogelsang, Yuan, PRD78, 114013

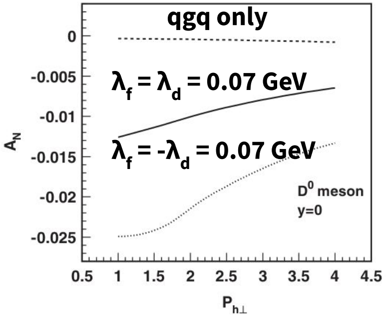
**S. Sakai, The Azimuthal Anisotropy of Electrons from Heavy Flavor Decays in sqrt(s) = 200 GeV Au-Au Collisions at PHENIX, March 26, 2000

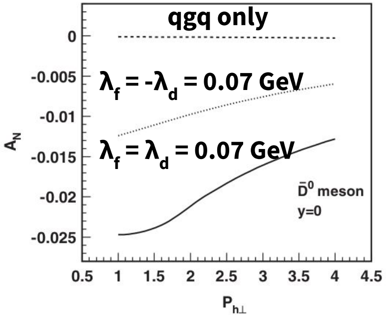
Open Charm TSSA Model Predictions

PRD78, 114013 (Z. Kang, J. Qiu, W. Vogelsang, F. Yuan)

- Contributions from twist-3 qgq correlators as well as antisymmetric and symmetric ggg correlators considered
- Authors provided TSSA calculations for $A_N^{D0}(p_T)$, and $A_N^{\bar{D}0}(p_T)$
- Trigluon (ggg) correlators written as $T_G^{(f)}(x_1,x_2)$ (antisymmetric) and $T_G^{(d)}(x_1,x_2)$ (symmetric)
    - Model calculations rely on normalizing to the unpolarized gluon PDF

$$T_G^{(f)}(x,x) = \lambda_f G(x), \qquad T_G^{(d)}(x,x) = \lambda_d G(x)$$





PRD84, 014026 (Y. Koike, S. Yoshida)

- Contributions from twist-3 antisymmetric and symmetric ggg correlators considered
- Authors provided TSSA calculations for $A_N^{D0}(p_T)$, $A_N^{D+}(p_T)$, $A_N^{\bar{D}0}(p_T)$, and $A_N^{D-}(p_T)$
- Trigluon (ggg) correlators written as $N(x_1,x_2)$ (antisymmetric) and $O(x_1,x_2)$ (symmetric)
    - 4 independent contributions from these functions: $\{N(x,x), N(x,0), O(x,x), O(x,0)\}$
    - In $\sqrt{s} = 200$ GeV $p^\uparrow+p$ collisions, m_c is negligible, and TSSAs depend on effective trigluon correlators $N(x,x) - N(x,0)$ and $O(x,x) + O(x,0)$
    - Model calculations rely on normalizing to the unpolarized gluon PDF

$$\begin{aligned} & O(x,x) = O(x,0) = N(x,x) = -N(x,0) \\ [\text{Model1}] \quad & O(x,x) = K_G x G(x) \\ [\text{Model2}] \quad & O(x,x) = K'_G \sqrt{x} G(x) \end{aligned}$$

Open Charm TSSA Model Predictions

PRD78, 114013 (Z. Kang, J. Qiu, W. Vogelsang, F. Yuan)

$$T_G^{(f)}(x,x) = \lambda_f G(x), \qquad T_G^{(d)}(x,x) = \lambda_d G(x)$$

PRD84, 014026 (Y. Koike, S. Yoshida)

$$O(x,x) = O(x,0) = N(x,x) = -N(x,0)$$

$$[\text{Model1}] \quad O(x,x) = K_G x G(x)$$

$$[\text{Model2}] \quad O(x,x) = K'_G \sqrt{x} G(x)$$

Effective trigluon correlators N(x,x) - N(x,0) and O(x,x) + O(x,0) are explicitly related to $T_G^{(f,d)}(x,x) = T_G^{(+,-)}(x,x)$ in PRD82, 054005

$$\frac{xg}{2\pi} T_G^{(+)}(x,x) = -4M_N \left(N(x,x) - N(x,0)\right)$$

$$\frac{xg}{2\pi} T_G^{(-)}(x,x) = -4M_N \left(O(x,x) + O(x,0)\right)$$

The results presented here and in arXiv:2204.12899 [PHENIX] (submitted to PRL) explicitly constrain parameters (λ_f,λ_d) from PRD78, 114013 as well as K_G and K_G' from PRD84, 014026

Spin Physics at RHIC

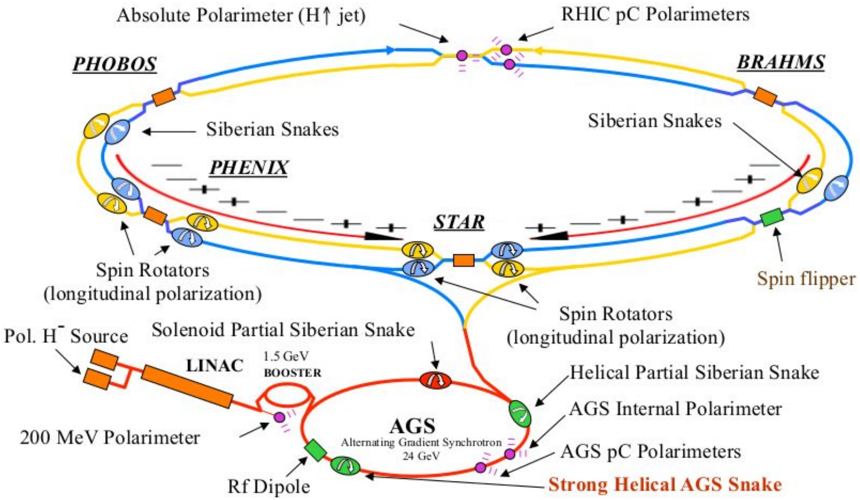
Extremely versatile collider!

- World's first polarized p+p collider
    - As well as $p^{\uparrow}$+He, $p^{\uparrow}$+Al, $p^{\uparrow}$+Au
- Capable of running with various collision energies and collision species
- Home to general purpose detectors (s)PHENIX and STAR

Collisions with polarized proton beams allow for a vast spin physics program

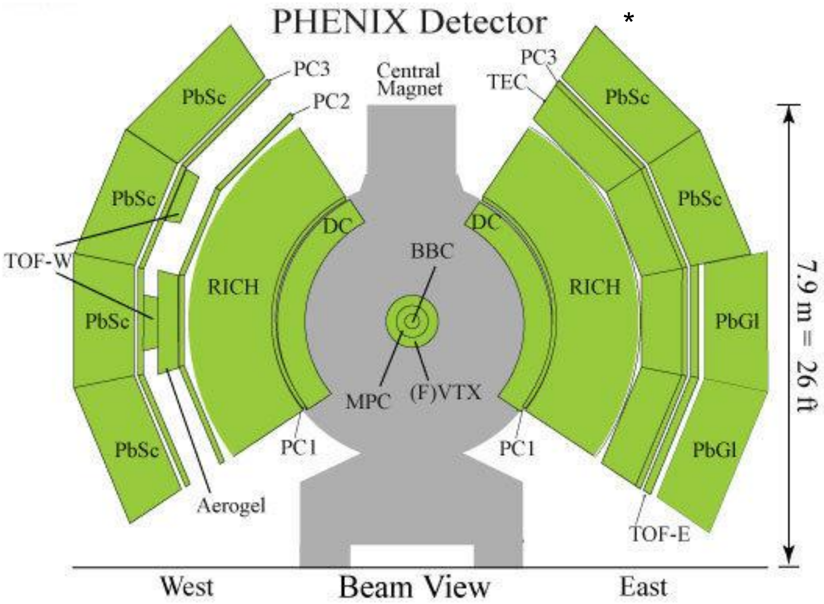
- A richer substructure of the nucleon can be studied when polarization is taken into account

RHIC is the world's first polarized proton collider



Midrapidity Charged Particle Detection at PHENIX

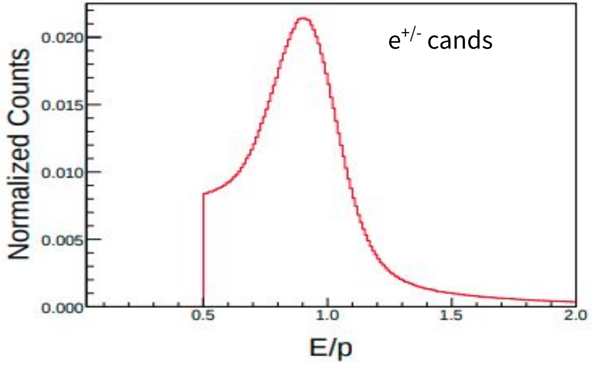
- **Acceptance:** $\Delta\phi = 0.5\pi$ per arm, $|\eta| < 0.35$
- Tracks are fitted with hit information from the drift chamber (DC), pad chambers (PCs), and VTX
- RICH used for PID
  - Cherenkov threshold of $\gamma = 35$, corresponding to p = 20 MeV/c for electrons and 4.9 GeV/c for charged pions
- EMCal measures energy deposits
  - Triggers used to select electrons and charged pions
- Hit pattern measured by the VTX
  - Require hit in inner two layers of VTX to veto photonic electron conversions



Analysis Procedure 1

$e^{+/-}$ identification at PHENIX

- $|(E/p - \langle E/p \rangle)/\sigma_{E/p}| < 2$ -- ($\langle E/p \rangle \sim 1$)
- Track matching to EMCal energy deposits and RICH shower ring center
- >1 photomultiplier firing in RICH -- $p_e > 20$ MeV/c
- EM shower shape probability > 0.01
- Hit requirement in inner 2 layers of VTX
- Conversion veto cut on opening angle of nearby $e^{+/-}$ candidates



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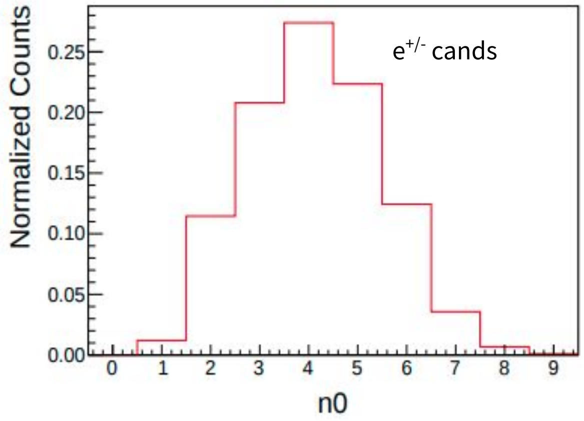


*Esha, Roli. (2020, September 15). Electron Identification in PHENIX

Analysis Procedure 2

TSSA Observable

A_N is calculated using the Relative Luminosity formula, integrating over the ϕ ranges of the east and west arms

$$A_N = \frac{1}{\langle|\cos\phi|\rangle}\frac{1}{P}\frac{N_L^{\uparrow} - R\cdot N_L^{\downarrow}}{N_L^{\uparrow} + R\cdot N_L^{\downarrow}} \quad \text{where } R = \frac{\mathcal{L}^{\uparrow}}{\mathcal{L}^{\downarrow}}$$

Background Sources (Heavy Flavor $e^{+/-}$)

- Photonic: π^0, η, γ
  - Asymmetries measured to be 0 → treated as dilution
    - π^0 and η (PRD 103, 052009)
    - γ (PRL 127, 162001)
- Nonphotonic: J/ψ, Ke3
  - Ke3 is a negligible fraction
  - J/ψ A_N taken from PRD 82, 112008
    - Large source of statistical uncertainty
- Hadron contamination: $h^{+/-}$
  - $h^{+/-}$ A_N taken from PRL 95, 202001

Cross checks and systematic studies (Heavy Flavor $e^{+/-}$)

- Square Root formula
  - $A_N^{sqrt} - A_N^{Lumi}$ taken as systematic
- cosϕ modulation fit
  - 3 ϕ bins per arm

$$A_N \cdot \cos\phi_S = \frac{1}{P}\frac{N^{\uparrow}(\phi_S) - R\cdot N^{\downarrow}(\phi_S)}{N^{\uparrow}(\phi_S) + R\cdot N^{\downarrow}(\phi_S)}$$

- Bunch shuffling
  - Randomize polarization direction, measure A_N/σ_{AN}
- Propagation of systematics on background fractions through background correction formula

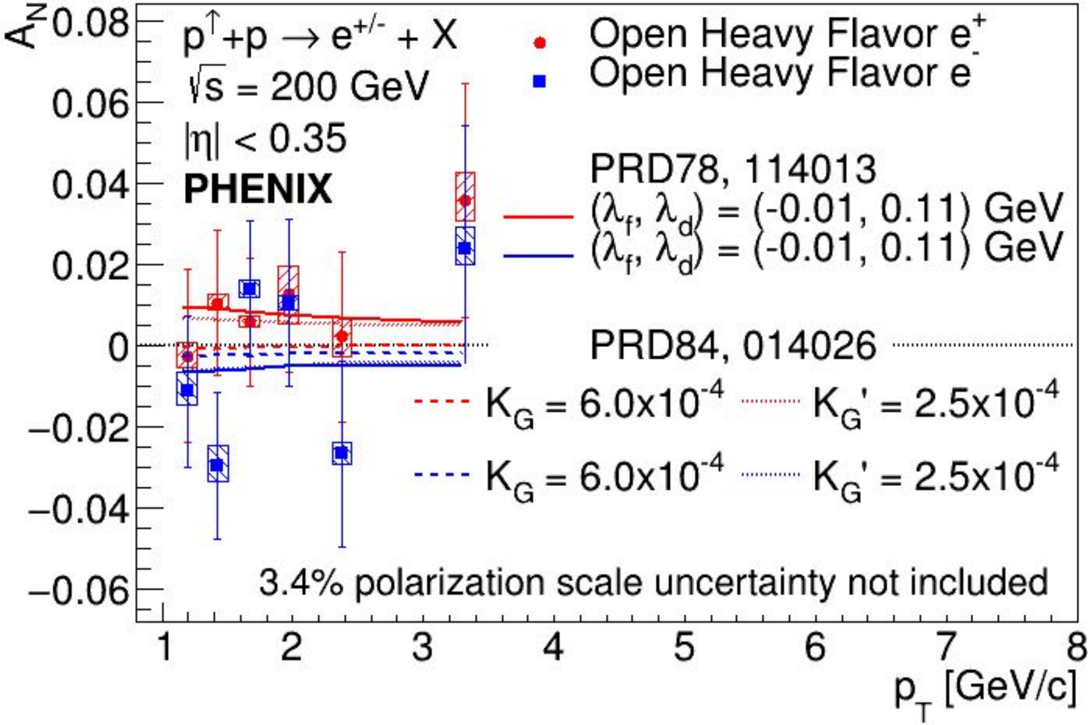
$$A_N^{OHF\to e} = \frac{A_N^e - f_{h^\pm}A_N^{h^\pm} - f_{J/\psi\to e}A_N^{J/\psi\to e}}{1 - f_{h^\pm} - f_{J/\psi\to e} - f_{\pi^0\to e} - f_{\eta\to e} - f_{\gamma\to e}}$$

$$\sigma_{A_N^{OHF\to e}} = \frac{\sqrt{(\sigma_{A_N^e})^2 + (f_{h^\pm}\sigma_{A_N^{h^\pm}})^2 + (f_{J/\psi\to e}\sigma_{A_N^{J/\psi\to e}})^2}}{1 - f_{h^\pm} - f_{J/\psi\to e} - f_{\pi^0\to e} - f_{\eta\to e} - f_{\gamma\to e}}$$

Open Heavy Flavor Electron and Positron A_N

arXiv:2204.12899 **(Submitted to PRL)**

- Most statistically precise measurement for midrapdity $A_N(p^{\uparrow}+p \rightarrow (OHF \rightarrow e^{\pm}) + X)$
- Plotted alongside theoretical predictions from PRD78, 114013 (Z. Kang, J. Qiu, W. Vogelsang, F. Yuan) and PRD84, 014026 (Y. Koike, S. Yoshida) for parameters λ_f, λ_d, K_G, and K_G' that best fit the data
  - In models with (λ_f, λ_d), and K_G' the best-fit parameters yield predictions for A_N with opposite signs for the separate charges
- Data is consistent with theoretical predictions for best-fit parameters and with zero across the measured p_T range



Results from (λ_f,λ_d) Scan

arXiv:2204.12899 (Submitted to PRL)

- -0.2 GeV < λ_f < 0.2 GeV
- -0.1 GeV < λ_d < 0.3 GeV
- 41 steps per parameter
- Calculate A_N for D^0 and $\bar{D}^0$
- Simulate $D^0 \to e^+$ and $\bar{D}^0 \to e^-$ decay with PYTHIA6
- Calculate $A_N^{D0\to e+}$ and $A_N^{\bar{D}0\to e-}$
- Calculate $\Delta\chi^2_{(+,-)}(\lambda_f,\lambda_d) = \chi^2_{(+,-)}(\lambda_f,\lambda_d) - \chi^2_{(+,-)\text{mir}}$

$$\boxed{\begin{aligned} A_N^{D^0} &= a_0 + \lambda_f a_1 + \lambda_d a_2 \\ A_N^{\bar{D}^0} &= b_0 + \lambda_f a_1 - \lambda_d a_2 \end{aligned}}$$

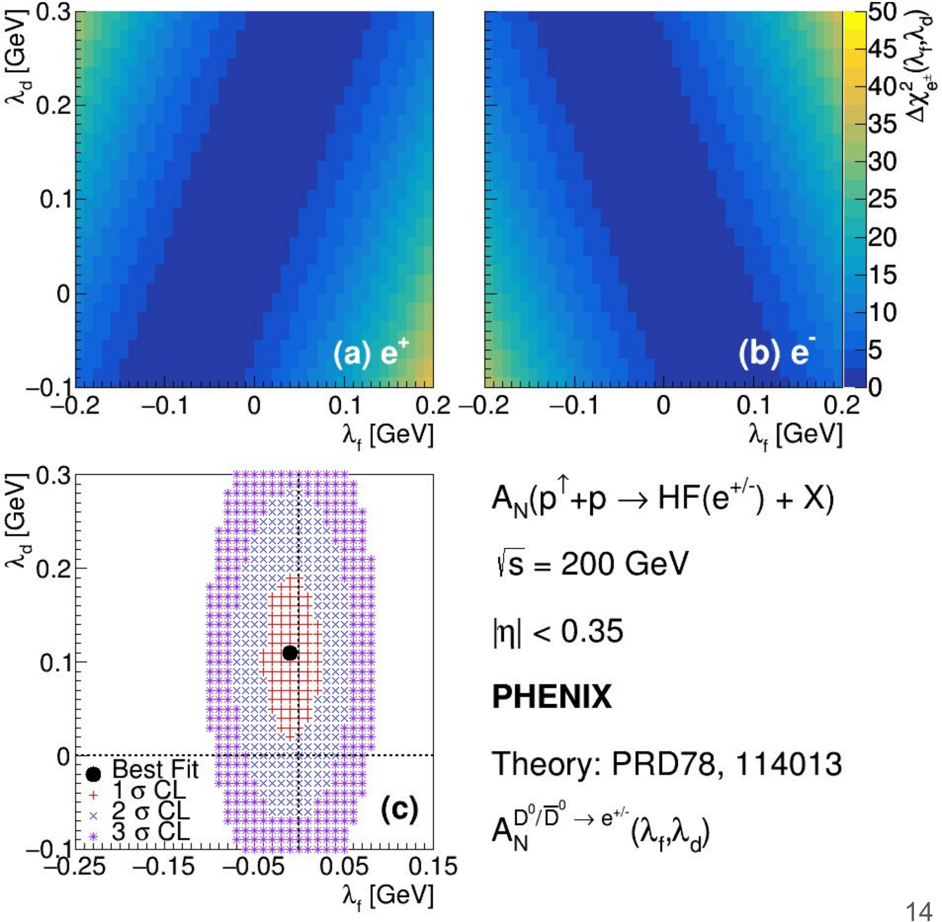
a_0, b_0, a_1, a_2 parameterizations provided by Z.B. Kang, J.W. Qiu, W. Vogelsang, F. Yuan (PRD78, 114013)

- a_0 and b_0 are contributions from qgq correlators
- a_1 and a_2 are contributions from trigluon correlators

$$\chi^2_{(+)}(\lambda_f,\lambda_d) = \sum_i^{nbins} \frac{\left(A_N^{(+)data} - A_N^{(+)theory}(\lambda_f,\lambda_d)\right)^2}{\sigma^2_{(+)data}} \qquad \chi^2_{(-)}(\lambda_f,\lambda_d) = \sum_i^{nbins} \frac{\left(A_N^{(-)data} - A_N^{(-)theory}(\lambda_f,\lambda_d)\right)^2}{\sigma^2_{(-)data}}$$

$$\chi^2(\lambda_f,\lambda_d) = \chi^2_{(+)}(\lambda_f,\lambda_d) + \chi^2_{(-)}(\lambda_f,\lambda_d)$$

$$\chi^2(\lambda_f,\lambda_d) - \chi^2_{min} < n^2$$



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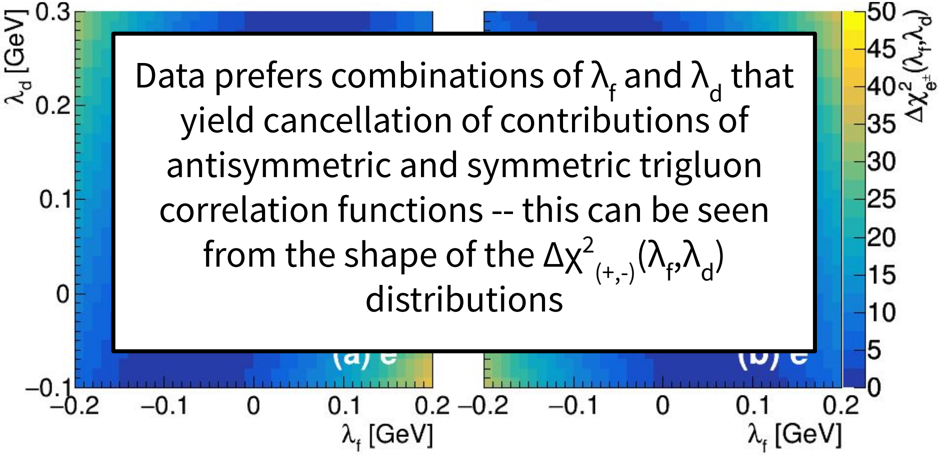
- a_1 and a_2 are contributions from trigluon correlators

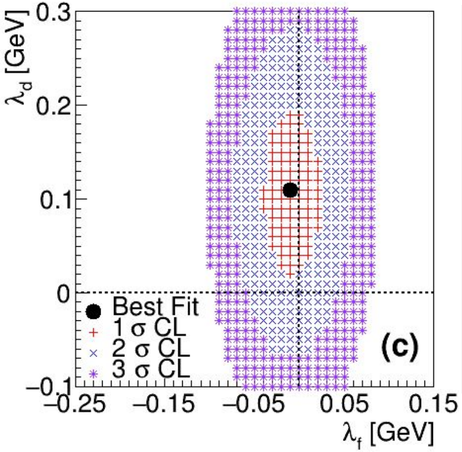
$$\chi^2(\lambda_f,\lambda_d) = \chi^2_{(+)}(\lambda_f,\lambda_d) + \chi^2_{(-)}(\lambda_f,\lambda_d)$$

$$\chi^2(\lambda_f,\lambda_d) - \chi^2_{min} < n^2$$

$$\chi^2_{(+)}(\lambda_f,\lambda_d) = \sum_i^{nbins} \frac{\left(A_N^{(+)data} - A_N^{(+)theory}(\lambda_f,\lambda_d)\right)^2}{\sigma^2_{(+)data}} \qquad \chi^2_{(-)}(\lambda_f,\lambda_d) = \sum_i^{nbins} \frac{\left(A_N^{(-)data} - A_N^{(-)theory}(\lambda_f,\lambda_d)\right)^2}{\sigma^2_{(-)data}}$$



Data prefers combinations of λ_f and λ_d that yield cancellation of contributions of antisymmetric and symmetric trigluon correlation functions -- this can be seen from the shape of the $\Delta\chi^2_{(+,-)}(\lambda_f,\lambda_d)$ distributions



1σ CL region:

λ_f = -0.01 ± 0.03 GeV

λ_d = 0.11 ± 0.09 GeV

Results from K_G and K_G' Scans

arXiv:2204.12899 (Submitted to PRL)

- $-0.005 < K_G < 0.005$
- $-0.00025 < K_G' < 0.00075$
- 101 steps per parameter
- Calculate A_N for D^0, D^+, $\bar{D}^0$, and D^-
- Simulate $D^0 \rightarrow e^+$, $D^+ \rightarrow e^+$, $\bar{D}^0 \rightarrow e^-$, and $D^- \rightarrow e^-$ decay with PYTHIA6
- Calculate $A_N^{D0 \rightarrow e+}$, $A_N^{D+ \rightarrow e+}$, $A_N^{\bar{D}0 \rightarrow e-}$, and $A_N^{D- \rightarrow e-}$
- Calculate $\Delta\chi^2_{(+,-)}(K_G) = \chi^2_{(+,-)}(K_G) - \chi^2_{(+,-)min}$ and $\Delta\chi^2_{(+,-)}(K_G') = \chi^2_{(+,-)}(K_G') - \chi^2_{(+,-)min}$

1σ Confidence Intervals:

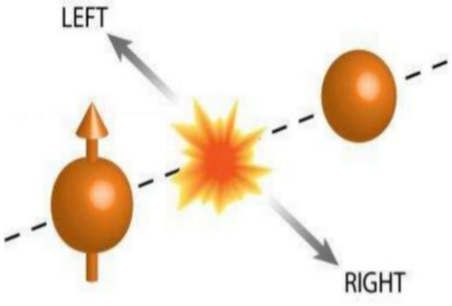
$K_G = 6.0\mathrm{x}10^{-4}$ (+0.0014 -0.0017)

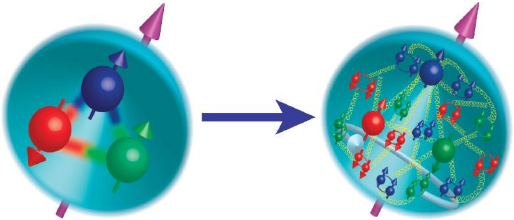
$K_G' = 2.5\mathrm{x}10^{-4}$ (± 0.00025)

Consistent with modest upper bound on K_G and K_G' derived in PRD84, 014026

Summary

- Transverse single spin asymmetries of electrons and positrons from heavy flavor decays provide access to nonperturbative spin-momentum correlations for gluons within the proton
  - Twist 3 correlators require only a single hard scale, for which the measured particle's p_T is taken as a proxy
- Most precise measurement of open heavy flavor $e^{\pm}$ A_N **(arXiv:2204.12899; Submitted to PRL)**
  - $p^{\uparrow}+p$, $\sqrt{s} = 200$ GeV, $|\eta| < 0.35$
  - Consistent with zero in measured range
  - Compared with theoretical predictions from PRD78, 114013 and PRD84, 014026
    - Data gives significant constraints to normalization parameters (λ_f, λ_d), K_G, and K_G' of trigluon correlators to the unpolarized gluon PDF
- Other results in preparation
  - Forward heavy flavor muon A_N $(p^{\uparrow} + p)$
  - Forward charged hadron A_N $(p^{\uparrow} + p,\ p^{\uparrow} + \mathrm{Al},\ p^{\uparrow} + \mathrm{Au})$

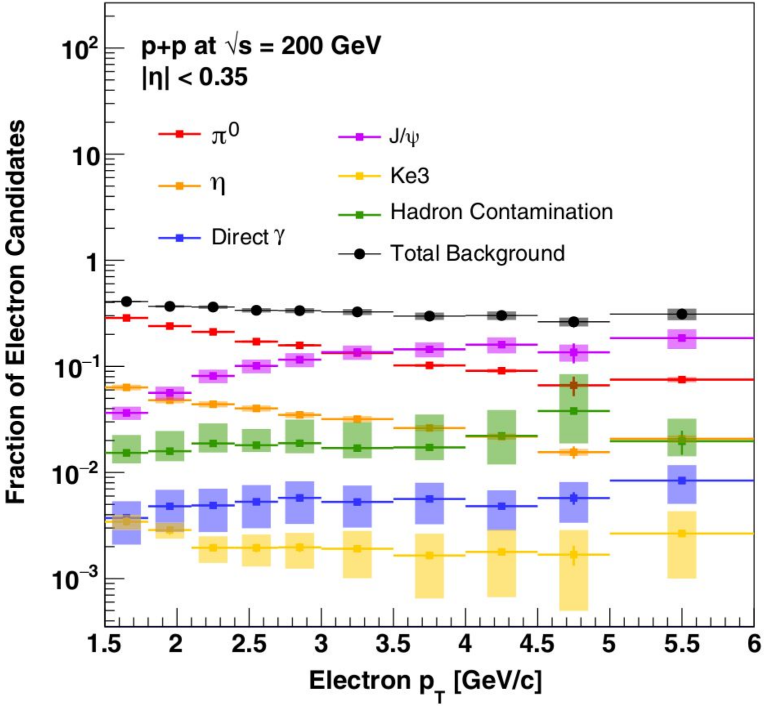




BACKUP

Heavy Flavor $e^{+/-}$ Background Fractions

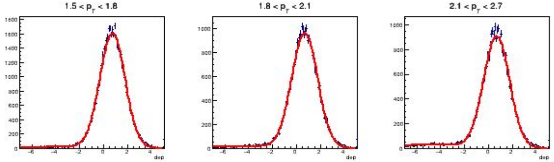
- Largest contribution from photonic electron background sources (π^0+ η + γ) at p_T < 3 GeV/c
    - Asymmetries for these sources well constrained to be zero at 200 GeV midrapidity **PRD 103, 052009, arXiv:2102.13585**
- Largest contribution from J/ψ at p_T > 3 GeV/c
    - σ_{AN} affected significantly in this region due to $A_N^{J/\psi}$ suffering from large statistical uncertainty **PRD 82, 112008**
- Ke3 is a negligible contribution -- not considered in background correction
- Hadron contamination is a consistently small contribution
    - Increase in 4.5-5.0 GeV/c bin shown here due to $\pi^{+/-}$ RICH threshold of 4.9 GeV/c
    - Input asymmetries from **PRL 95, 202001**

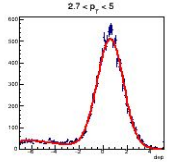


*PHENIX Collaboration (Aidala, C. *et al.*) Phys.Rev. D99 (2019) no.9, 092003 arXiv:1901.08405 [hep-ex]

Heavy Flavor $e^{+/-}$ Background Fractions

- Hadron contamination
  - Fit $e^{+/-}$ candidate E/p spectrum with Gaussian + template extracted from hadrons in data with free normalization parameter
  - Calculate algebraically using RICH n0 selection requirements
  - Average value from two methods, values taken as upper and lower systematics





$$n_{non0} = n_e + n_h$$

$$n_{n0} = \epsilon_e n_e + \epsilon_h n_h$$

$$n_{h_{n0}} = \epsilon_h \frac{n_{n0} - \epsilon_e n_{non0}}{\epsilon_h - \epsilon_e}$$

- Photonic background fractions (f_i)
  - Calculate fraction of nonphotonic electrons using conversion veto cut (~ means with conversion veto) -- use to calculate photonic background fractions

$$F_{np} = \frac{\tilde{n}_{np}}{\tilde{n}_{np} + \tilde{n}_p} = \frac{n_{np}}{n_{np} + \epsilon_p n_p} = \frac{\epsilon_{uc}\epsilon_p n_e - \tilde{n}_e - \epsilon_{uc}\epsilon_p n_{hc} + \tilde{n}_{hc}}{(\epsilon_p - 1)(\tilde{n}_e - \tilde{n}_{hc})}$$

$$f_i = (1 - \tilde{f}_{hc})(1 - F_{np}) \frac{\tilde{n}_i}{\tilde{n}_{\pi^0} + \tilde{n}_\eta + \tilde{n}_\gamma}$$

- Nonphotonic background fractions (f_j)
  - Signal open heavy flavor $e^{+/-}$ is nonphotonic, so calculate nonphotonic background fractions w.r.t. π^0 fraction

$$f_j = f_{\pi^0} \frac{\tilde{n}_j}{\tilde{n}_{\pi^0}}$$

Heavy Flavor $e^{+/-}$ Background Fractions

arXiv:2204.12899 (submitted to PRL)