The 37th Winter Workshop on Nuclear Dynamics

February 27, 2022 to March 5, 2022
Marriott Puerto Vallarta Resort & Spa

PHENIX

Spin Physics Overview

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March 1, 2022

Proton Spin 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, and can learn different things by studying collisions with longitudinally and transversely polarized protons

- **Longitudinal:** How does the spin of quarks and gluons contribute to the proton spin?
- **Transverse:** How is the spin and orbital motion of quarks and gluons correlated with proton spin?

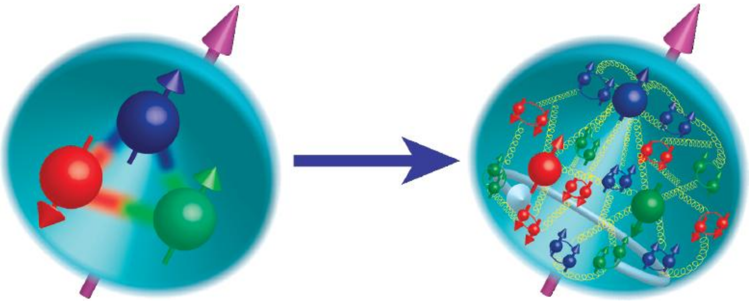


Table of TMD PDFs

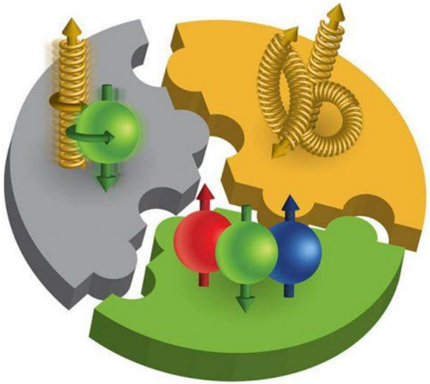
- nucleon (N)
- unpolarized quark (Q)
- nucleon spin
- quark spin
- quark k_T

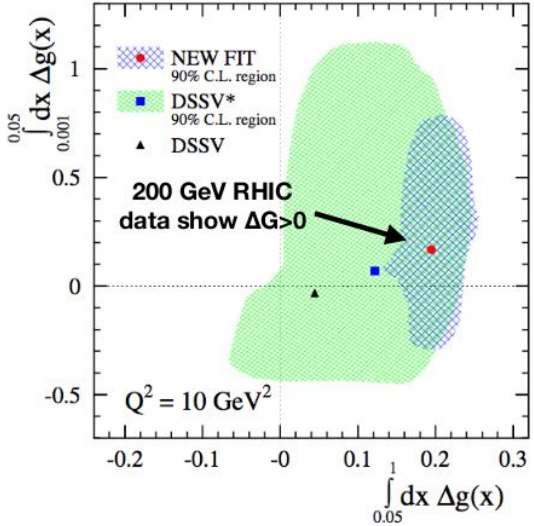
N \ Q	U	L	T	
U	f_1 number density		$h_1^\perp$ Boer-Mulders	
L		g_1 helicity	$h_{1L}^\perp$ worm-gear	
T	$f_{1T}^\perp$ Sivers	$g_{1T}^\perp$ worm-gear	h_1 transversity	$h_{1T}^\perp$ pretzelosity

Longitudinal Spin and the Proton Spin Puzzle

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \Delta g + L_q + L_g$$

proton spin = quark helicity + gluon helicity + quark and gluon orbital motion

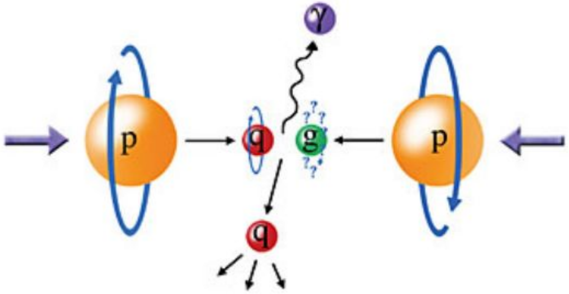




- Δq is well constrained from lepton-hadron scattering experiments
- RHIC is the world's first and only polarized proton collider, allowing for leading order access to gluons, and significantly improved constraints on Δg

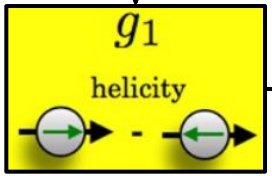
Longitudinal Double Spin Asymmetries

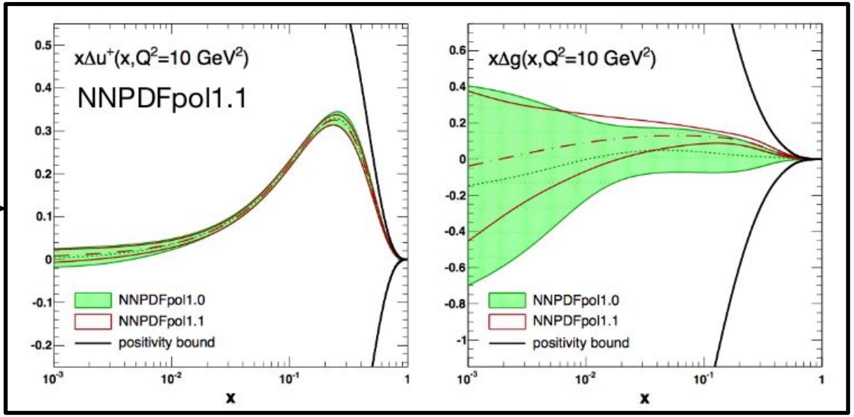
- $\vec{p}+\vec{p}$ initial state
- Measure particle production as a function of proton helicity
- Combine different production channels to extract polarized PDFs (helicity distributions) via global fits

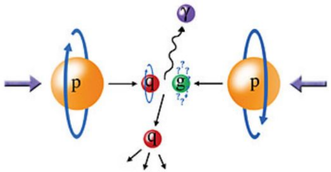


$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\Delta\sigma}{\sigma}$$

$$\Delta\sigma \propto \sum_{a,b} \boxed{\Delta f_{a/A}(x_a) \otimes \Delta f_{b/B}(x_b)} \otimes \Delta\sigma_{ab}$$

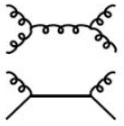
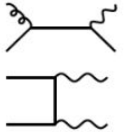
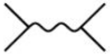


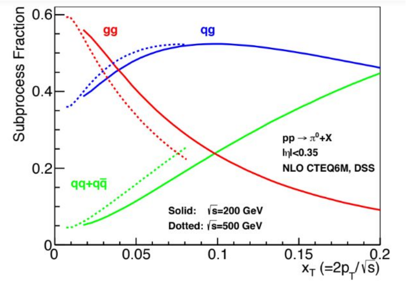


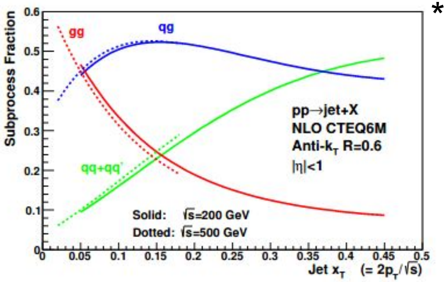


Access to Δg

- Measurements of pions, jets, and direct photons provide sensitivity to Δg at leading order
    - Direct photons additionally serve as a clean probe, as there are no final state effects

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan)	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$	$\vec{q}\vec{\bar{q}} \to Z^0,\ \vec{q}'\vec{\bar{q}} \to W^\pm$ $\vec{q}'\bar{q} \to W^\pm,\ q'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$	





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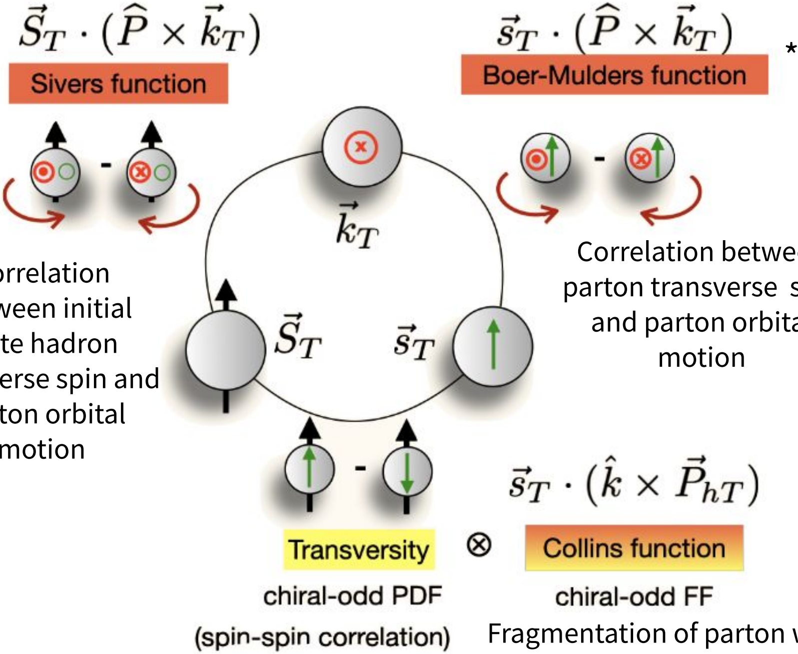
*STAR Collaboration - [Phys. Rev. D 100, 052005 (2019)]

Transverse Spin and Proton Structure

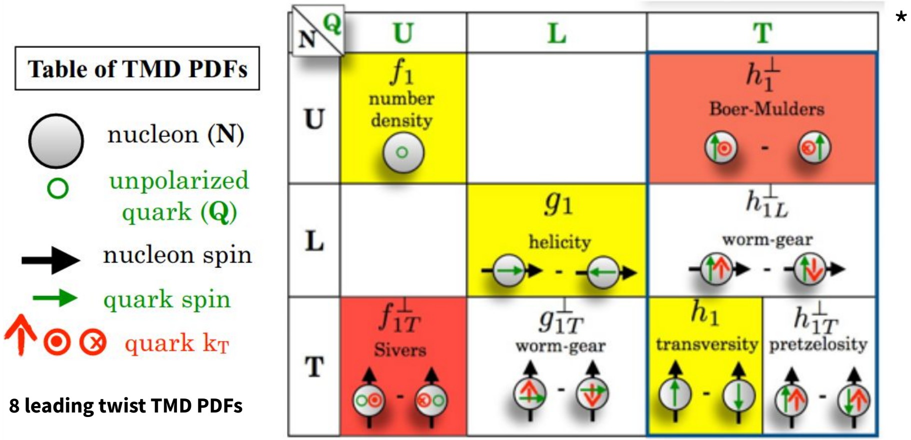


Correlation between initial state hadron transverse spin and parton orbital motion

Correlation between parton transverse spin and parton orbital motion

Correlation between initial state hadron transverse spin and parton transverse spin

Fragmentation of parton with transverse spin to hadron with momentum transverse to parton going direction

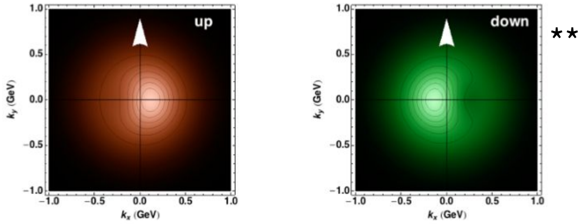


8 leading twist TMD PDFs

Yellow: integrated over k_T

Red: explicit dependence on k_T -- describes strength of spin orbit coupling

Distributions obtained by parameterizing the Sivers effect

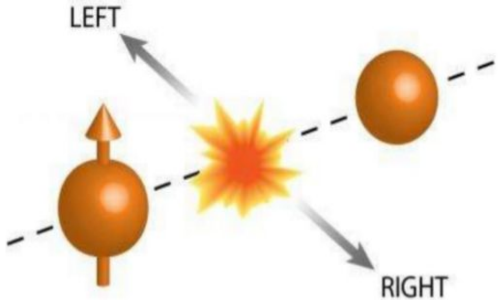


*Thanks to Caroline Riedl for the figures: https://wwwcompass.cern.ch/compass/publications/talks/t2016/riedl_aps2016.pdf

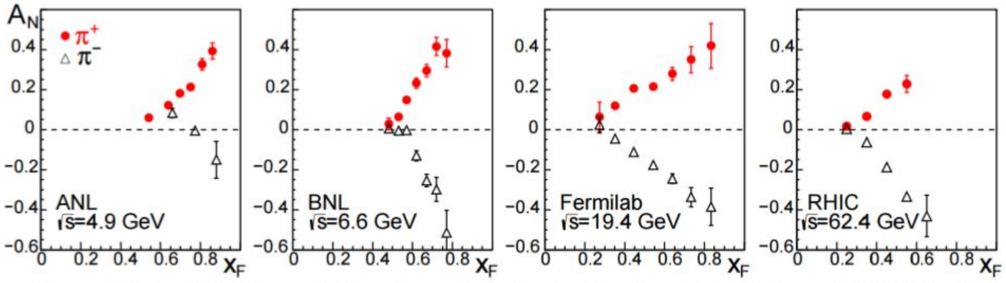
**AIP Conference Proceedings 1735, 020003 (2016); https://doi.org/10.1063/1.4949371

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 (<1%)*
- Large TSSA measurements imply nonperturbative spin-momentum and spin-spin correlations within proton



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



**

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

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

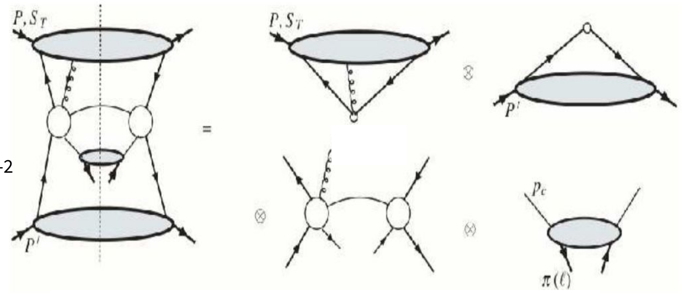
C.A. Aidala, S.D. Bass, D. Hasch, and G.K. Mallot, Rev. Mod. Phys. **85 655 (2013).

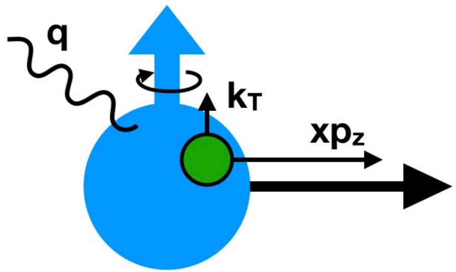
Transverse Single Spin Asymmetries (TSSAs)

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 an extra gluon with similar x





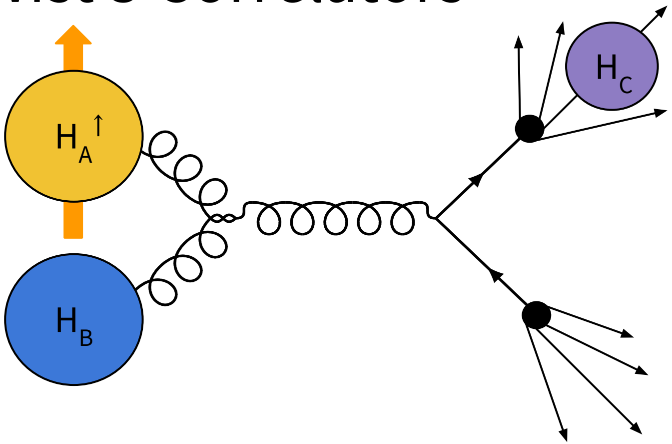
Unification of two frameworks has been demonstrated

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

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

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

Twist 3 Correlators



$$\phi^{(3)f,d}_{g/X} = T^{(f,d)}_{G,F}$$

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

- 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 correlators $\phi^{(3)}_{g/X}$

Direct photon production dominated by qg compton scattering @ 200 GeV midrapidity, no final state fragmentation effects → access to trigluon correlators $\phi^{(3)}_{g/X}$

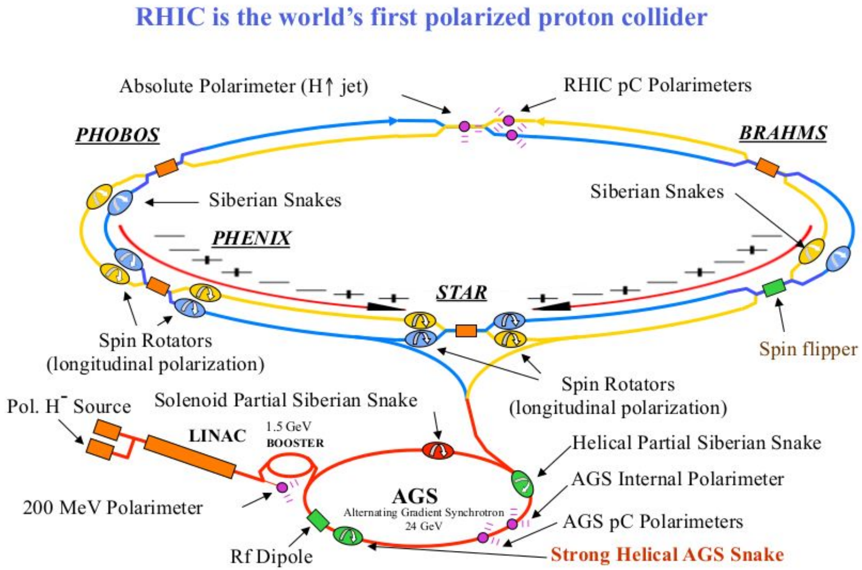
Pion and eta production dominated by qg scattering @ 200 GeV midrapidity → sensitivity to quark flavor (u,d,s)

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

Spin Physics at RHIC

Year	$\sqrt{s}$ (GeV)	Recorded Luminosity for longitudinally / transverse polarized p+p STAR	Recorded Luminosity for longitudinally / transverse polarized p+p PHENIX	<P> in %
2006	62.4	-- pb^{-1} / 0.2 pb^{-1}	0.08 pb^{-1} / 0.02 pb^{-1}	48
	200	6.8 pb^{-1} / 8.5 pb^{-1}	7.5 pb^{-1} / 2.7 pb^{-1}	57
2008	200	-- pb^{-1} / 7.8 pb^{-1}	-- pb^{-1} / 5.2 pb^{-1}	45
2009	200	25 pb^{-1} / -- pb^{-1}	16 pb^{-1} / -- pb^{-1}	55
	500	10 pb^{-1} / -- pb^{-1}	14 pb^{-1} / -- pb^{-1}	39
2011	500	12 pb^{-1} / 25 pb^{-1}	18 pb^{-1} / -- pb^{-1}	48
2012	200	-- pb^{-1} / 22 pb^{-1}	-- pb^{-1} / 9.7 pb^{-1}	61/56
	510	82 pb^{-1} / -- pb^{-1}	32 pb^{-1} / -- pb^{-1}	50/53
2013	510	300 pb^{-1} / -- pb^{-1}	155 pb^{-1}/ -- pb^{-1}	51/52
2015	200	52 pb^{-1} / 52 pb^{-1}	-- pb^{-1}/ 60 pb^{-1}	53/57
2015	200 *p* Au	total delivered Luminosity = 1.27 pb^{-1}		60
2015	200 *p* Al	total delivered Luminosity = 3.97 pb^{-1}		54

(circle) = Transversely polarized



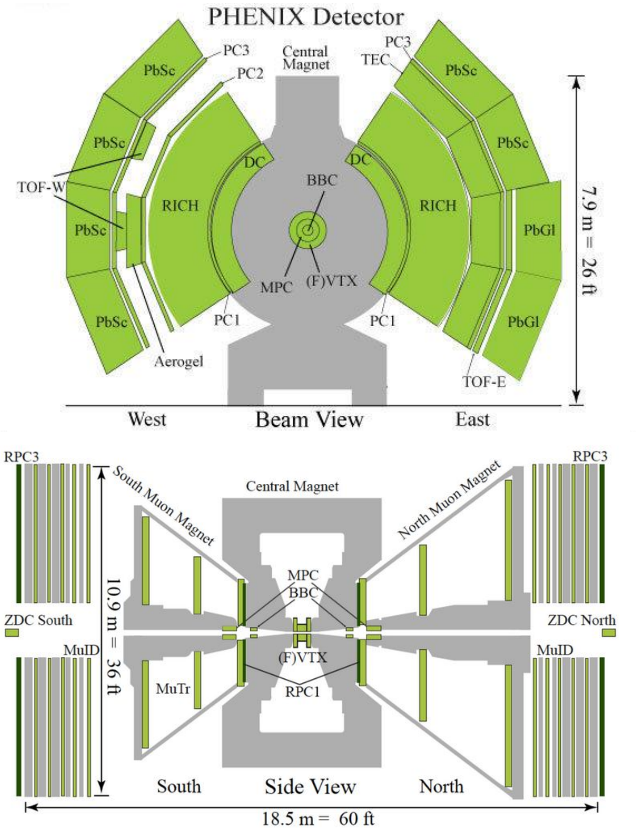
The PHENIX Detector

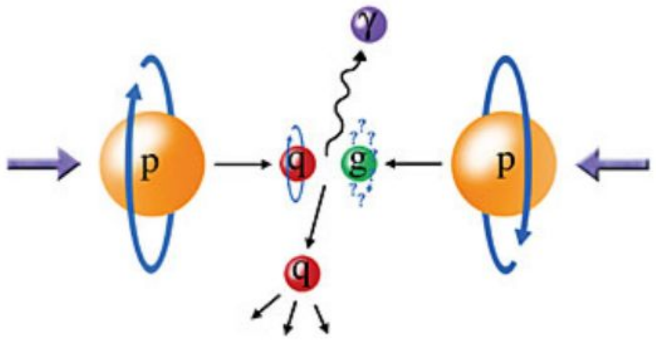
Detection capabilities:

- Central: π^0, $\pi^\pm$, η, *jets*, $e^\pm$, γ, …
- Forward: π^0, η, $\mu^\pm$, n, …

Midrapidity:

- 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
  - Useful for removing conversion electrons

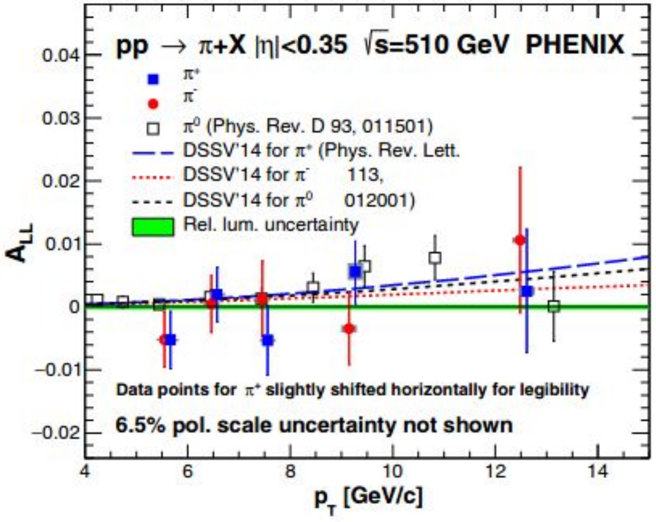


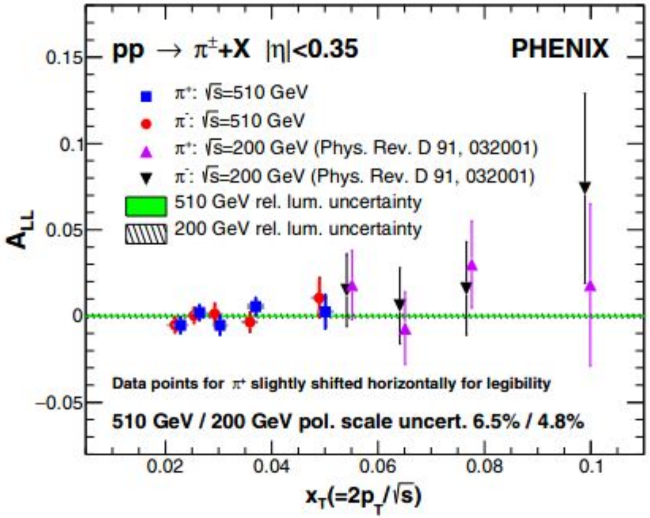


Longitudinal Spin Results

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\Delta\sigma}{\sigma}$$

Midrapidity Pion A_{LL} at $\sqrt{s} = 510\ GeV$



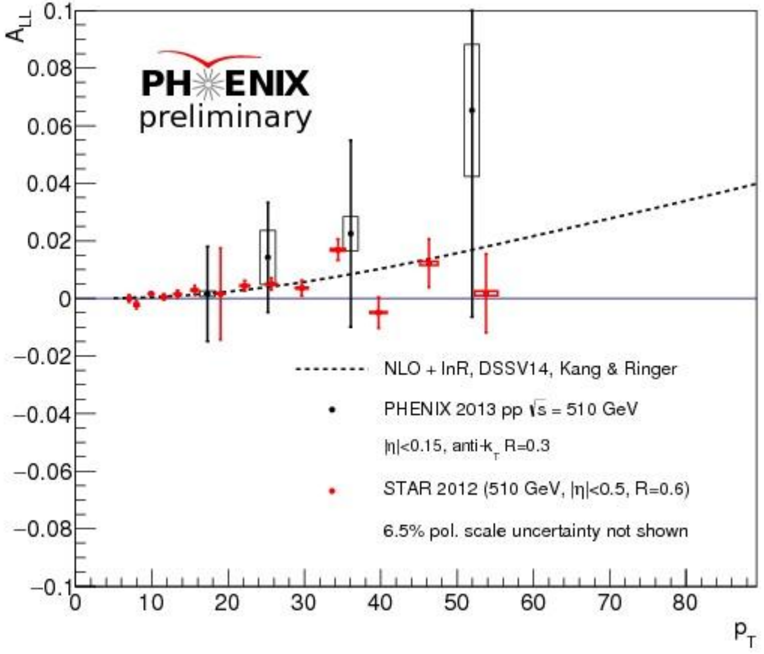


- Asymmetries are consistent with predictions from DSSV14 fits for $\pi^{\pm}$ and π^0 across measured range (left panel)
- Significantly improved statistical precision from previous results (right panel)
- Measured x_T range corresponds to $0.04 \lesssim x_B \lesssim 0.09$
- Largest longitudinally polarized dataset from PHENIX (*155 pb*$^{-1}$) -- will help in constraining global fits of Δg

PHENIX Collaboration - Phys.Rev.D102, 032001 (2020)

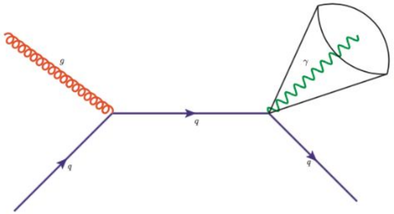
Midrapidity Jet A_{LL} at $\sqrt{s} = 510\ GeV$

- Asymmetries are consistent with theoretical predictions and STAR measurement
- Jet radius of R=0.3 used based on midrapidity PHENIX acceptance
- Bins are correlated from the unfolding procedure
- Largest longitudinally polarized dataset from PHENIX (*155 pb*$^{-1}$) -- will help in constraining global fits of Δg



Midrapidity Direct Photon A_{LL} at $\sqrt{s} = 510$ GeV

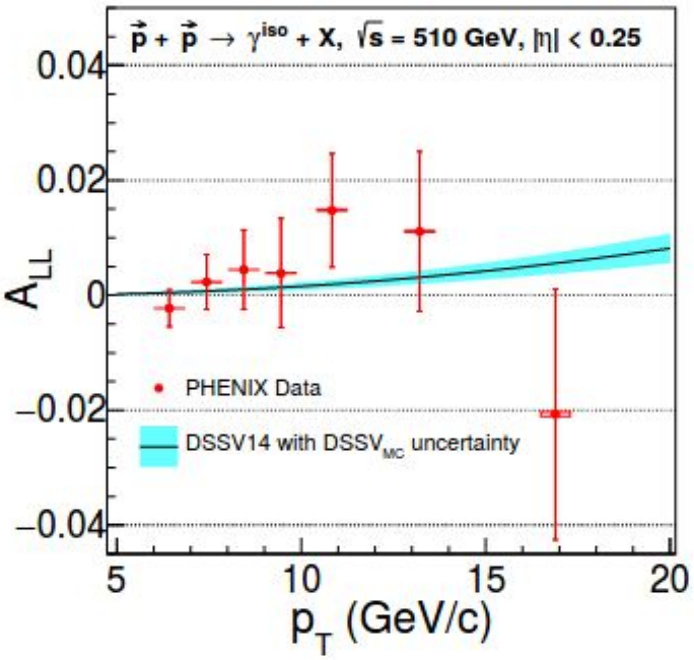
- First measurement of direct photon A_{LL}
- Asymmetries are consistent with predictions from DSSV14 fits within the measured range
- Largest longitudinally polarized dataset from PHENIX (*155 pb*$^{-1}$) -- will help in constraining global fits of Δg
- Direct photon production is a clean channel as there are no final state effects from fragmentation
- Isolation criteria imposed to remove background from hadronic decays



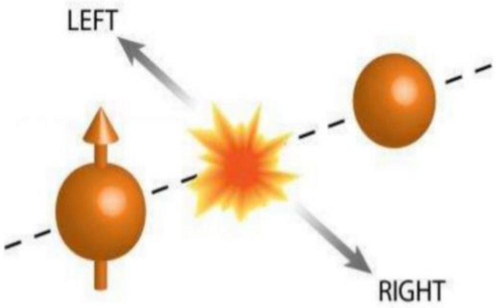
$$r = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} = 0.5$$

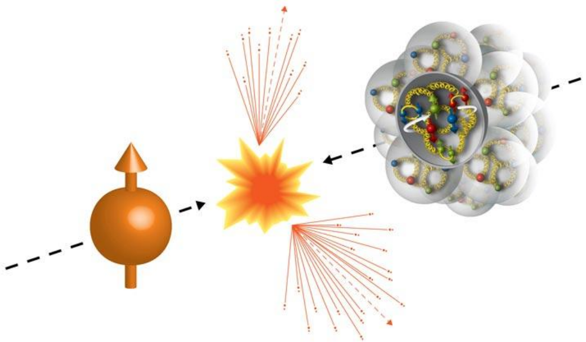
Isolation cut requirement:

$$\sum E_{neutral} + \sum E_{charged} < 0.1 E_\gamma$$



PHENIX Collaboration - arXiv:2202.08158 (submitted to PRL)



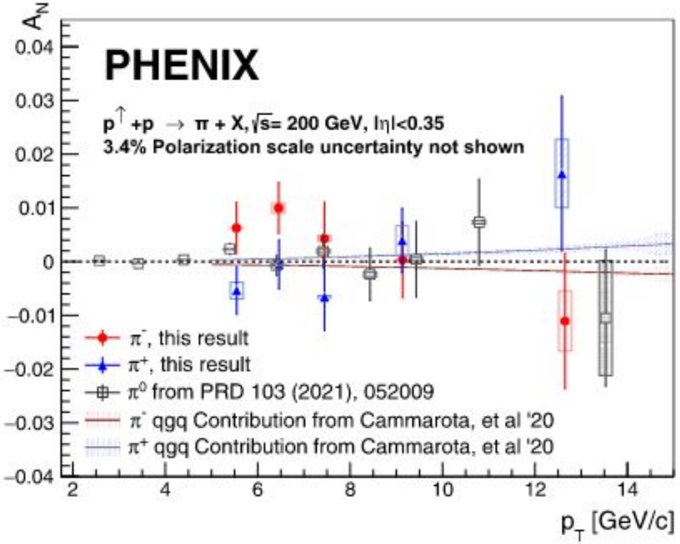


Transverse Spin Results

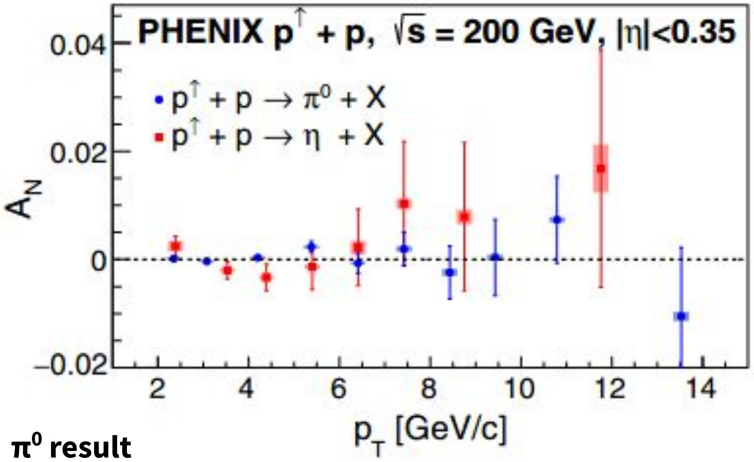
$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

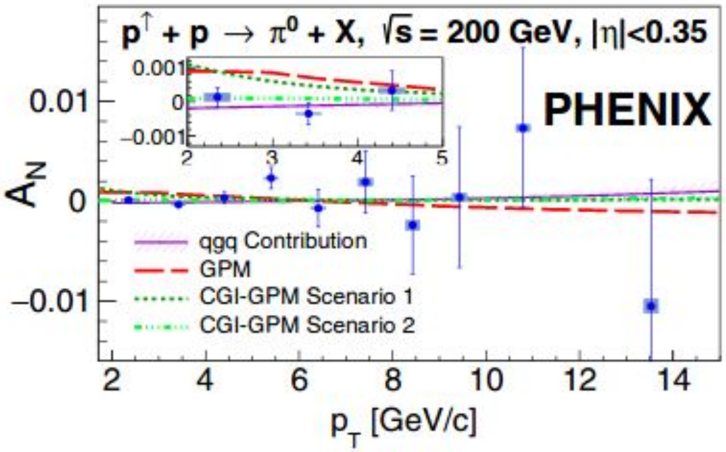
Midrapidity Charged Pion A_N at $\sqrt{s}$ = *200 GeV*

- First results of midrapidity charged pion A_N from PHENIX
- Compared with π^0 A_N from **PRD 103, 052009**
- $\pi^{+/-}$ A_N consistent with zero and theoretical predictions in measured range, but there is an indication that $\pi^{+/-}$ behave differently (potential flavor dependence)
    - Flavor dependence can be seen in the *qqq* theory calculations at higher p_T



Midrapidity Neutral Pion and Eta Meson A_N at $\sqrt{s}$ = *200 GeV*





π^0 result

- Higher reach in p_T and factor of 3 increase in statistical precision compared to previous PHENIX result
- Consistent with 0 in the measured p_T range
- Useful in constraining twist-3 trigluon correlation functions **Phys. Rev. D 89, 034029 (2014)**
- Useful in constraining the gluon Sivers TMD function in the Generalized Parton Model (GPM) **Phys. Rev. D 99, 036013 (2019)**

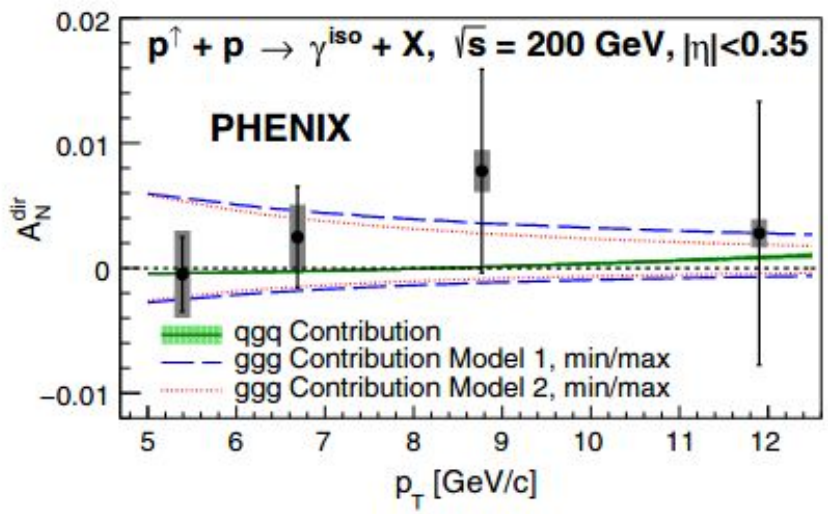
η result

- Again a higher reach in pT and factor of 3 increase in statistical precision compared to previous PHENIX result
- Consistent with 0 in the measured p_T range
- Sensitive to strangeness effects in twist 3 correlation functions

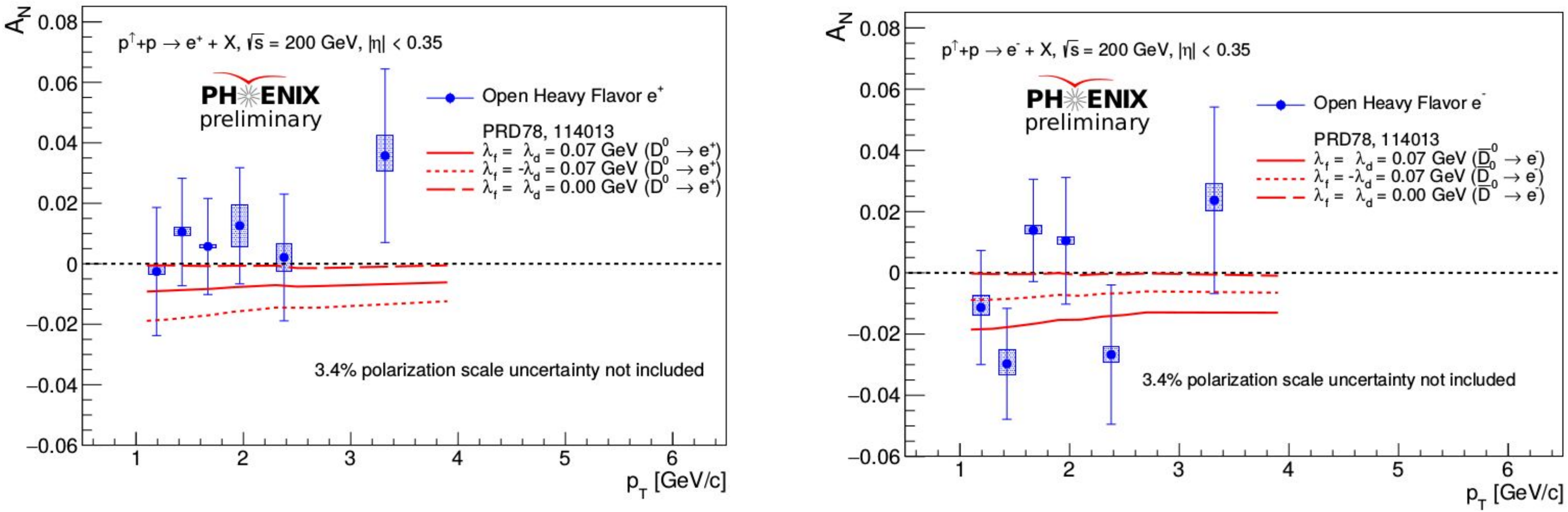
PHENIX Collaboration - Phys. Rev. D 103, 052009 (2021)

Midrapidity Direct Photon A_N at $\sqrt{s} = 200$ GeV

- First midrapidity direct photon TSSA measurement at RHIC
- Consistent with 0 within the measured p_T range within ~2%
- Useful in constraining trigluon correlation functions **Phys. Rev. D 85, 034030 (2012)**



Midrapidity Open Heavy Flavor Electron A_N at $\sqrt{s}$ = *200 GeV*



- Open heavy flavor results plotted alongside $D^0 \rightarrow e^{+/-}$ contributions as calculated in **PRD78, 114013** **(Z.B. Kang, J.W. Qiu, W. Vogelsang, F. Yuan)**
  - Ordering of curves is different for different charges → sensitivity to constrain λ parameters

- λ parameters correspond to normalizations of trigluon correlators with respect to unpolarized gluon PDF
  - $\phi^{(3),f}_g(x,x) = \lambda_f\, g(x)$, $\phi^{(3),d}_g(x,x) = \lambda_d\, g(x)$ $\quad d^{abc},\ if^{abc} \Longrightarrow T^{(d)}_{G,F}(x_1,x_2),\ T^{(f)}_{G,F}(x_1,x_2)$

Midrapidity Open Heavy Flavor Electron A_N at $\sqrt{s}$ = *200 GeV* Results from (λ_f,λ_d) Parameter Scan

Data prefers combinations of λ_f and λ_d that yield cancellation of contributions of antisymmetric and symmetric trigluon correlation functions

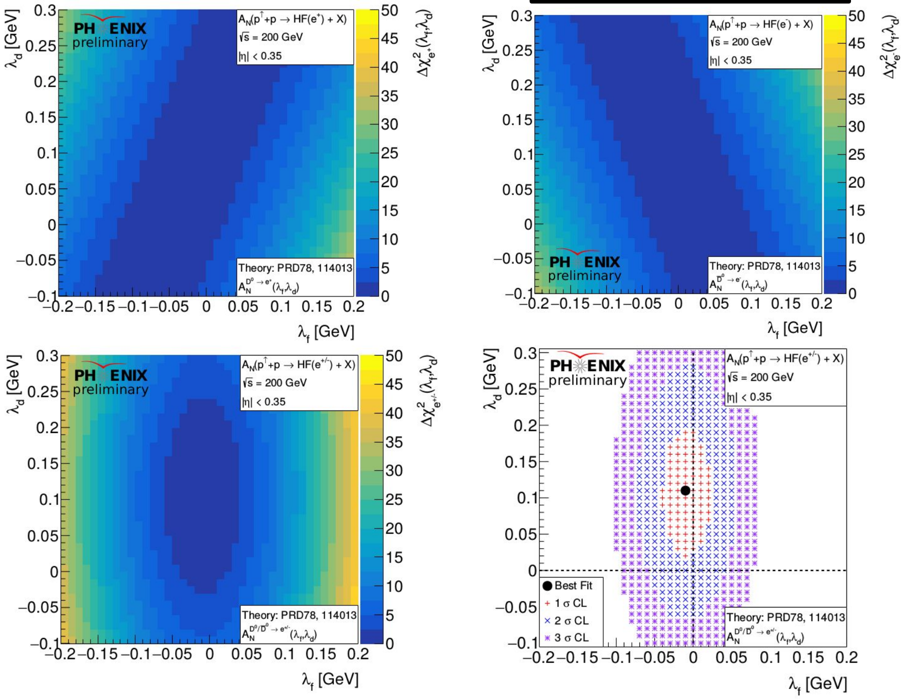
1σ CL region:

- $\lambda_f = -0.01 \pm 0.03$ *GeV*
- $\lambda_d = 0.11 \pm 0.09$ *GeV*

Data provides significant constraints to normalization parameters (λ_f,λ_d) of trigluon correlators to the unpolarized gluon PDF

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

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



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

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

Scan over (λ_f,λ_d) parameter space:

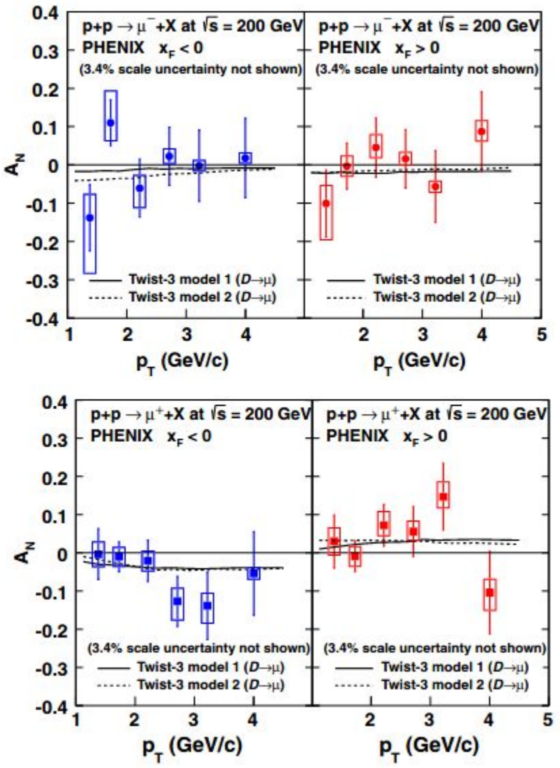
- -0.2 GeV < λ_f < 0.2 GeV
- -0.1 GeV < λ_d < 0.3 GeV
- Calculate A_N for D^0 and $\bar{D}^0$
- Simulate $D^0 \to e^+$ and $\bar{D}^0 \to e^-$ decay with PYTHIA6
- Calculate $A_N^{D0\to e+}$ and $A_N^{\bar{D}0\to e-}$
- Compare to data

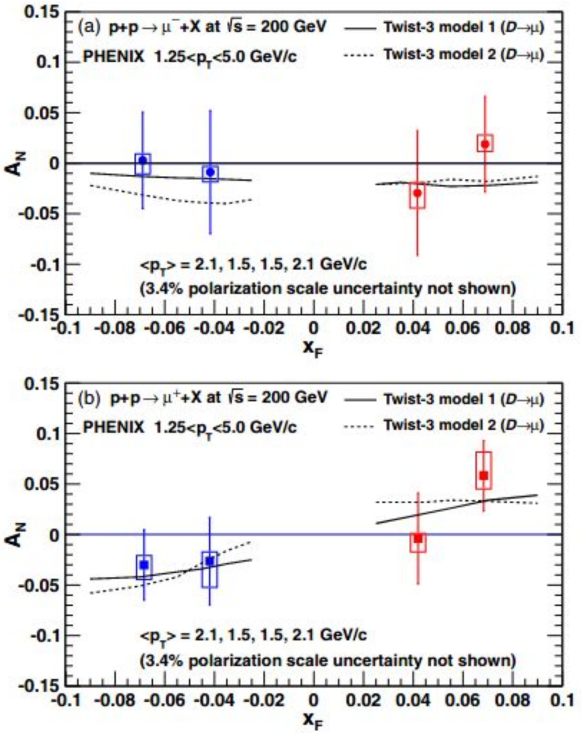
$$A_N^{D^0} = a_0 + \lambda_f a_1 + \lambda_d a_2$$
$$A_N^{\bar{D}^0} = b_0 + \lambda_f a_1 - \lambda_d a_2$$

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

Forward Open Heavy Flavor Muon A_N at $\sqrt{s} = 200$ GeV

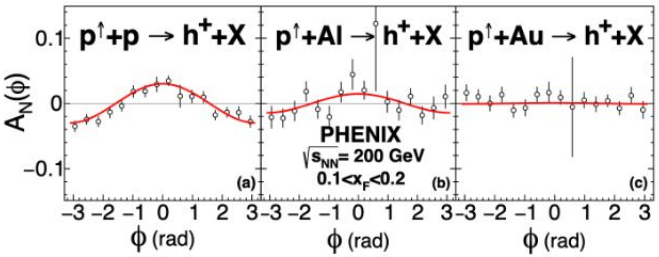


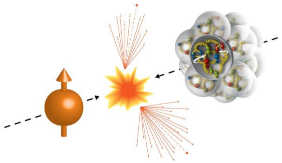


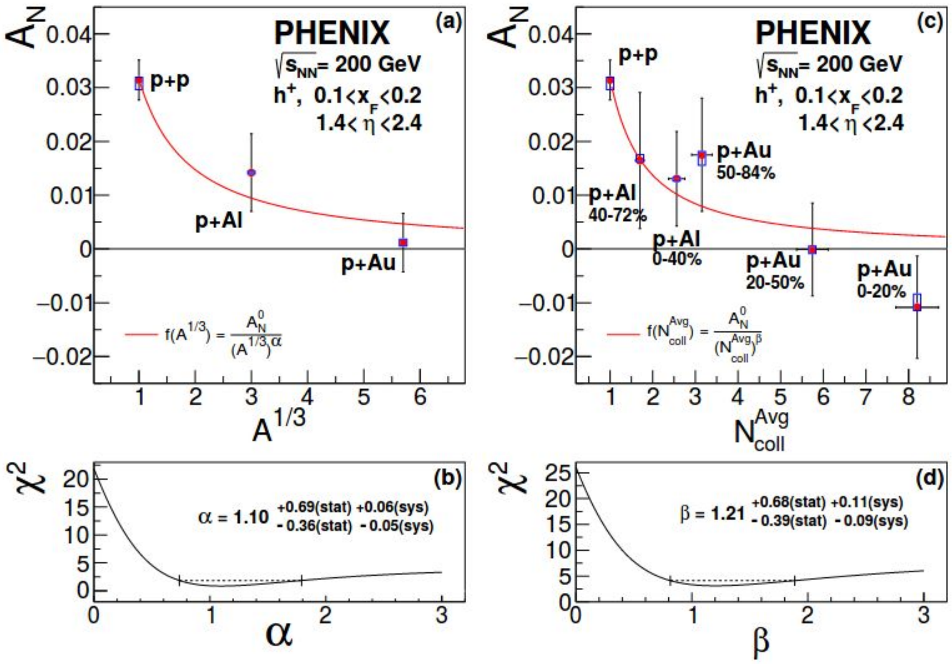
- Asymmetries are consistent with 0 and theoretical predictions taking into account contributions from trigluon correlation functions from Phys. Rev. D 84, 014026 (2011)
- **This measurement uses 2012 data. A follow up measurement is planned using 2015 data with ~6.5 times the 2012 integrated luminosity**
  - This will help significantly in differentiating between different trigluon correlator models

PHENIX Collaboration - Phys. Rev. D 95, 112001 (2017)

Forward hadron A_N at $\sqrt{s_{NN}} = 200$ GeV ($p^{\uparrow}+p$, $p^{\uparrow}+Al$, $p^{\uparrow}+Au$)



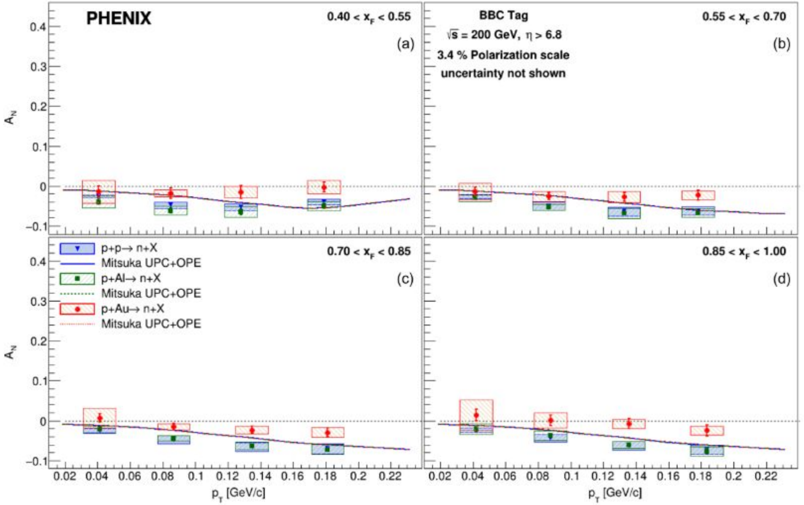


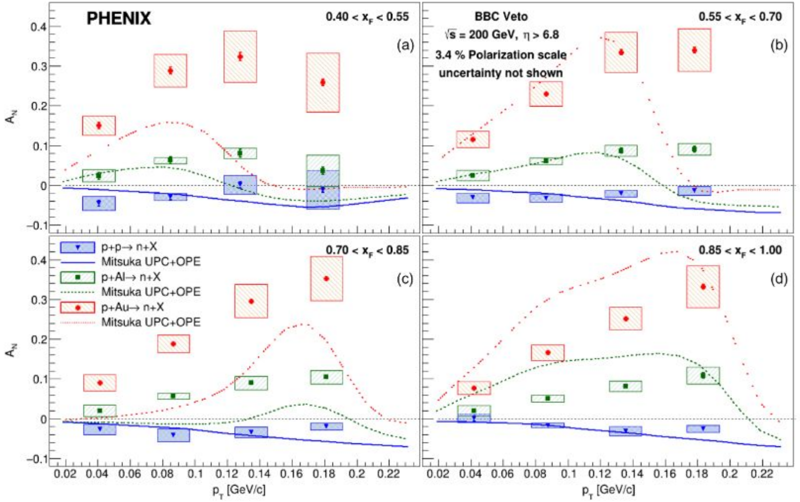


- Inclusive positively charged forward hadron TSSAs
  - *π^+/K^+/p: 0.45/0.47/0.05*
- Clear suppression of A_N in p+A observed
  - $A^{1/3}$ suppression predicted in models with gluon saturation effects: PRD84 034019 (2011), PRD95 014008 (2017)
    - **Note:** $\langle p_T \rangle$ for this measurement is above the saturation scale for Au

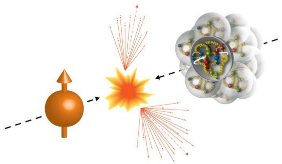
PHENIX Collaboration - Phys. Rev. Lett. 123, 122001 (2019)

Forward neutron A_N at $\sqrt{s_{NN}} = 200$ GeV ($p^{\uparrow}+p$, $p^{\uparrow}+Al$, $p^{\uparrow}+Au$)





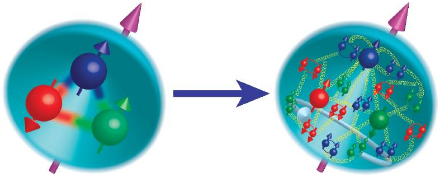
- Very forward neutron asymmetries are shown for $p^{\uparrow}+p$, $p^{\uparrow}+Al$, $p^{\uparrow}+Au$ collision systems for both beam-beam-counter (BBC) tagged events, dominated by hadronic interactions, and BBC vetoed events (with little activity in the BBC) that show an enhancement of ultra peripheral collisions (UPC)
- The asymmetries qualitatively agree with the UPC + one-pion-exchange (OPE) theory predictions



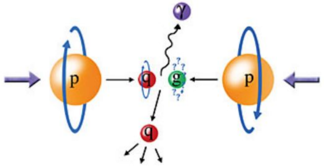
PHENIX Collaboration - [Phys. Rev. D 105, 032004 (2022)]

Summary

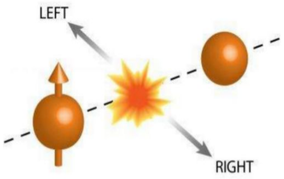
The PHENIX spin physics program continues to provide insight into many remaining mysteries in QCD



- Gluonic contributions to the proton spin

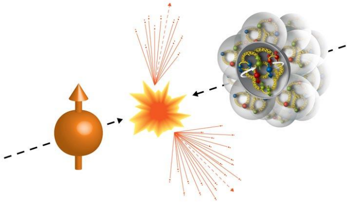


- A clearer picture of the theoretical origins of TSSAs



- Gluon dynamics in transversely polarized protons

- Nuclear matter effects on TSSA measurements, helping to pin down underlying mechanisms

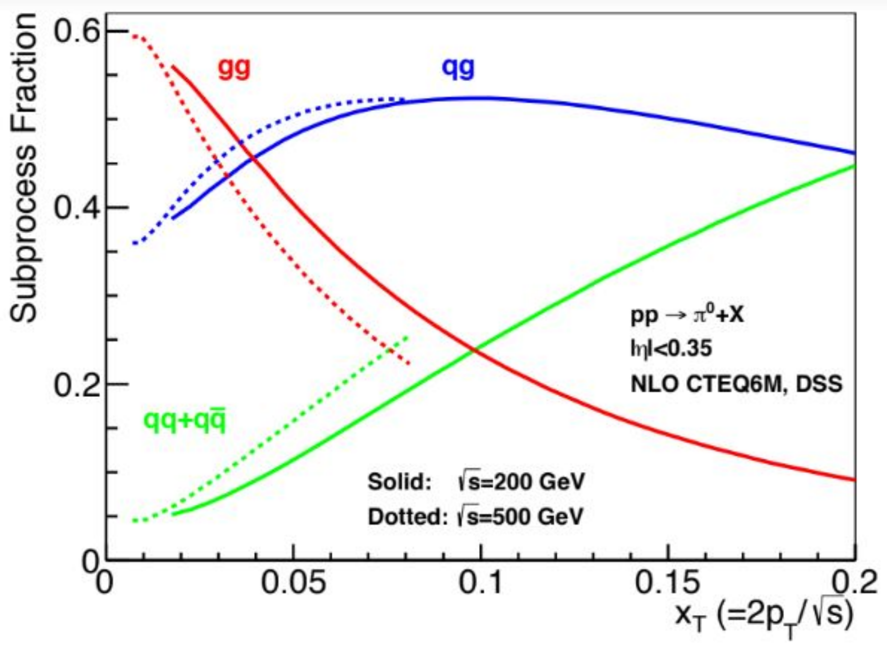


BACKUP

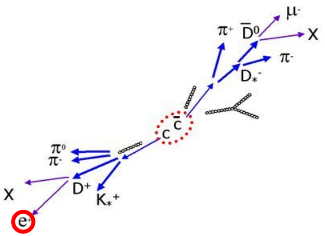
Charged Pion Production

- Produced via qg, gg , qq 2 → 2 processes - **dominated by qg @ 200 GeV midrapidity (until high p_T)**
  - $\pi^0 \sim (\pi^+ + \pi^-)/2$
  - qg contributions are sensitive to quark flavors when looking at $\pi^{+/-}$ separately

- π^+, π^-, π^0 is an isospin triplet -- comparing A_N in these different systems is a good test for theoretical models



Open Heavy Flavor Production



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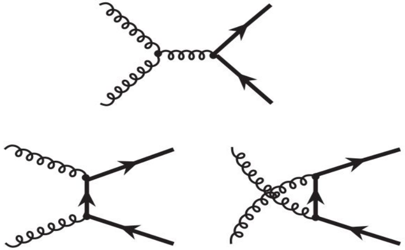
Open charm production is dominant contribution

gg→QQ

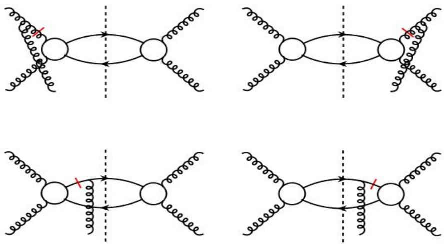
*



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

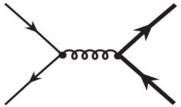
ggg (trigluon) correlators

*



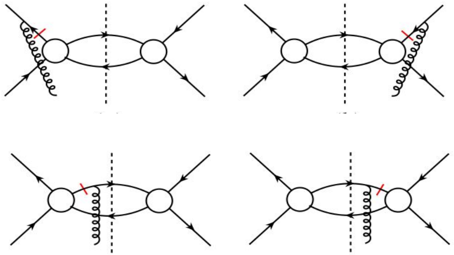
$q\bar{q}$→QQ

*



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

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



*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

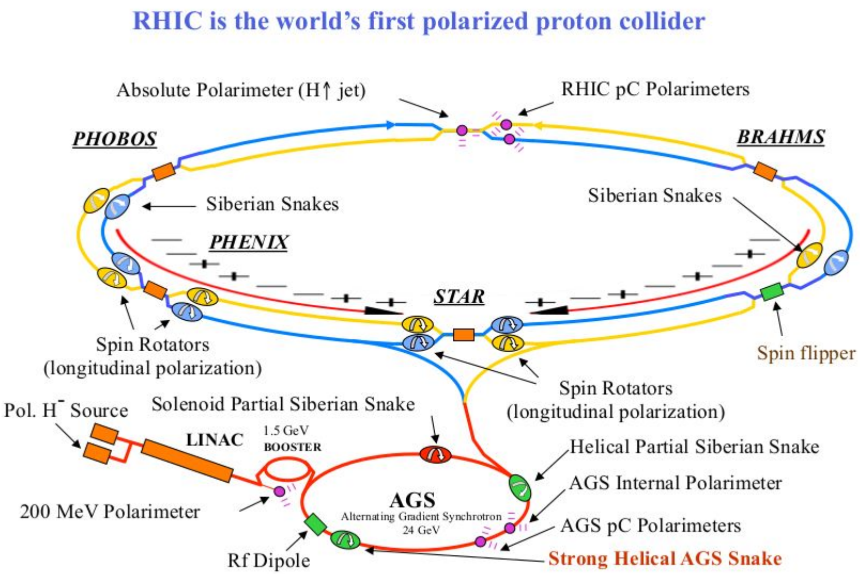
Spin Physics at RHIC

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

- Nonperturbative initial and final state functions become more complicated when polarization is taken into account

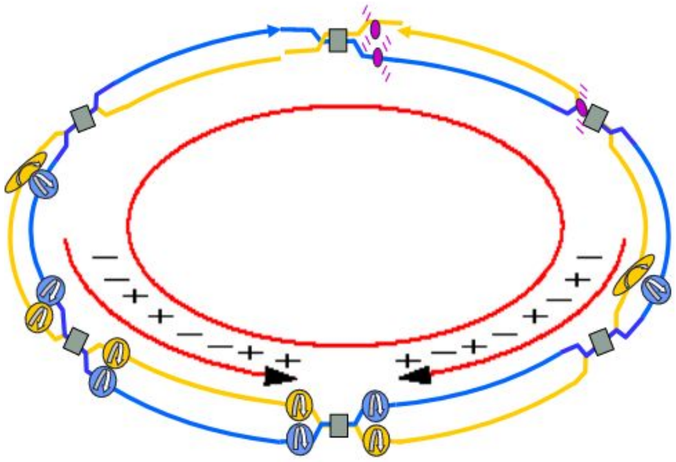


Measuring A_{LL} at PHENIX

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{1}{P_B P_Y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

P: polarization
N: particle yields
R: relative luminosity
$R = L_{++}/L_{+-}$

- Bunch polarization alternates every 106 ns
- Data separated into 4 spin patterns (++, --, +-, -+)
  - In the above equation for A_{LL}, ++ corresponds to the same helicity spin patterns and +- corresponds to opposite helicity spin patterns)
- Data separated by even and odd bunch crossing number
- This allows for cross checks and control over systematics



Measuring A_N at PHENIX

TSSA Observable

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

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

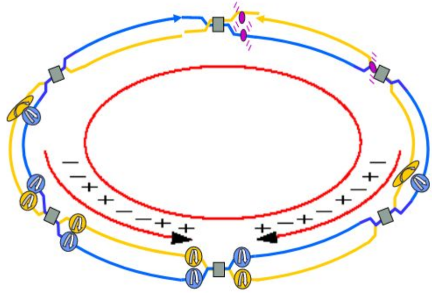
- Both beams are transversely polarized, with polarization varying from bunch to bunch, allowing for
  a. The polarization of one beam to be considered at a time by averaging over the polarization of the other
  b. Minimizing systematics related to detector coverage and performance
- There is an equivalent relative luminosity formula for the right side of the detector (modulo a factor of -1)
  a. **Hence, there are 4 independent datasets used for cross validation and averaging**

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

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

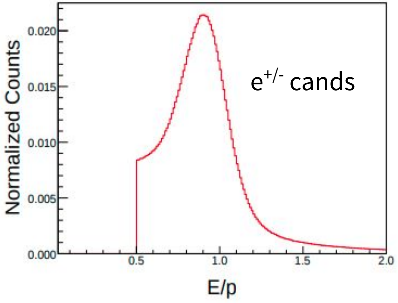
- Bunch shuffling
  - Randomize polarization direction, measure A_N/σ_{AN}
- Propagation of systematics on background fractions through background correction formula

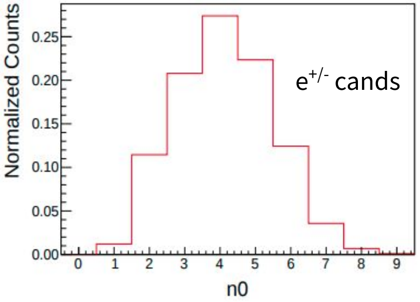


$e^{+/-}$ and $\pi^{+/-}$ Identification at PHENIX

$e^{+/-}$ identification

- $|(E/p - \langle E/p \rangle)/\sigma_{E/p}| < 2$ -- ($\langle E/p \rangle \sim 1$)
- 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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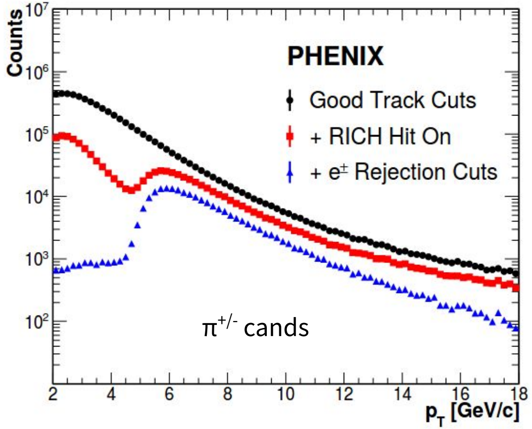
$\pi^{+/-}$ identification**

- $0.2 < E/p < 0.8$ preselection rule
- Logical OR of EMCal triggers
- Track matching to EMCal energy deposits
- >1 photomultiplier firing in RICH -- $p_\pi > 4.9$ GeV/c
- EM shower shape probability < 0.1



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*Esha, Roli. (2020, September 15). Electron Identification in PHENIX
**(PHENIX Collaboration) PRD 102, 032001

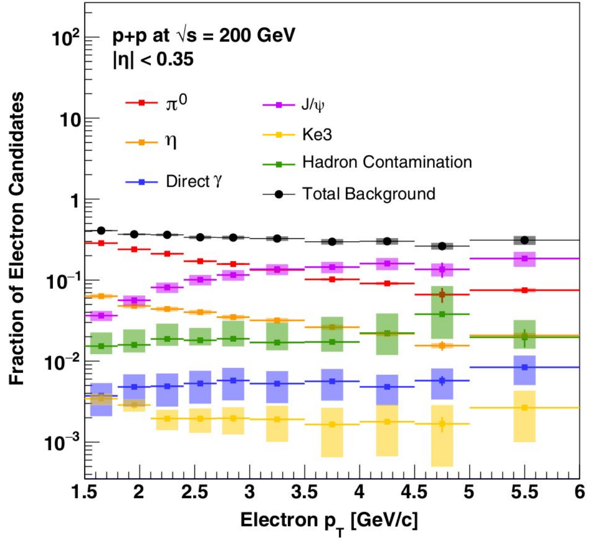
Heavy Flavor $e^{+/-}$ Background Fractions

PHENIX

- 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**

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

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



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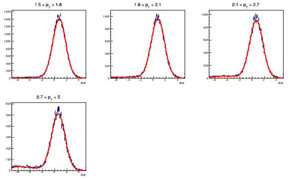
*PHENIX Collaboration (Aidala, C. *et al.*) Phys.Rev. D99 (2019) no.9, 092003 arXiv:1901.08405 [hep-ex]

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



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

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

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

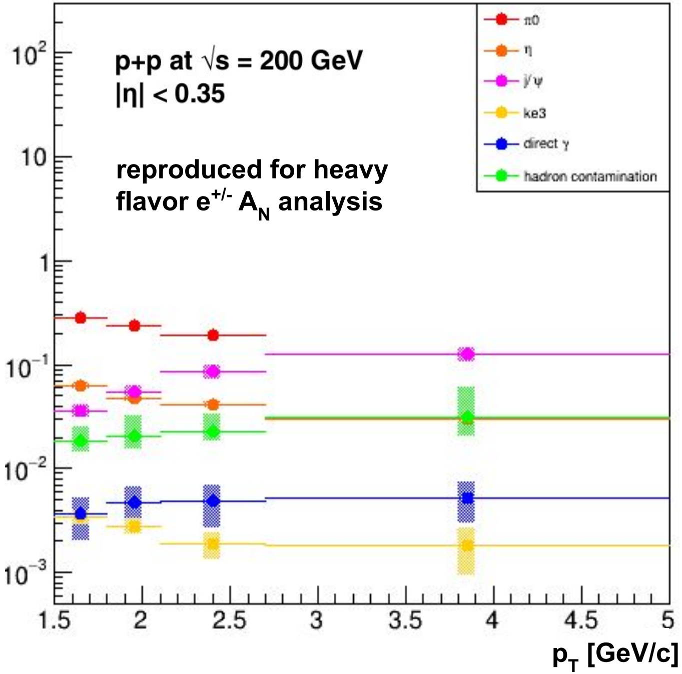
- Photonic background fractions
  - Calculate fraction of nonphotonic electrons using conversion veto cut (~ means with conversion veto) -- use to calculate photonic background fractions

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

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

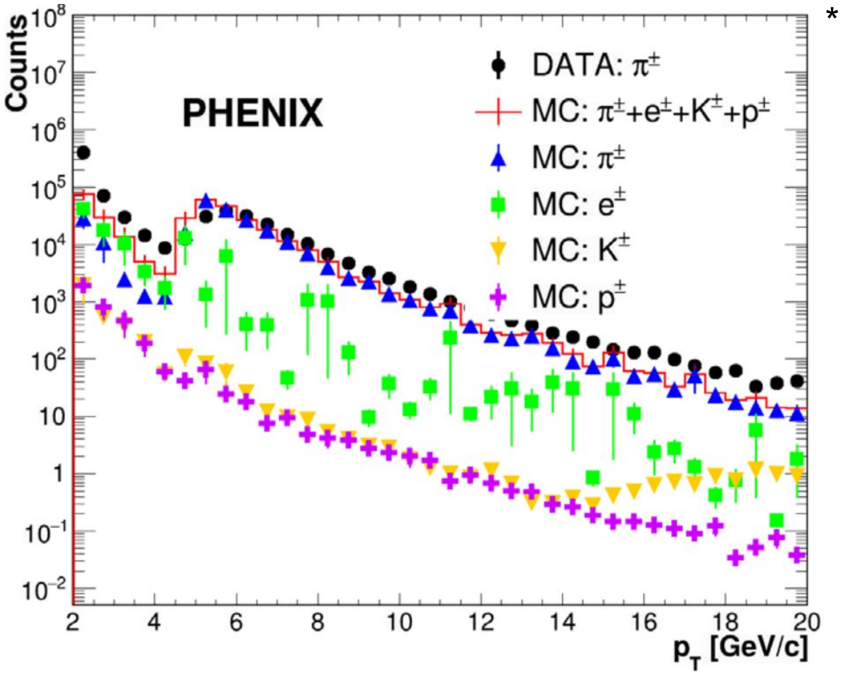
- Nonphotonic background fractions
  - Signal open heavy flavor $e^{+/-}$ is nonphotonic, so calculate nonphotonic background fractions w.r.t. π^0 fraction

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



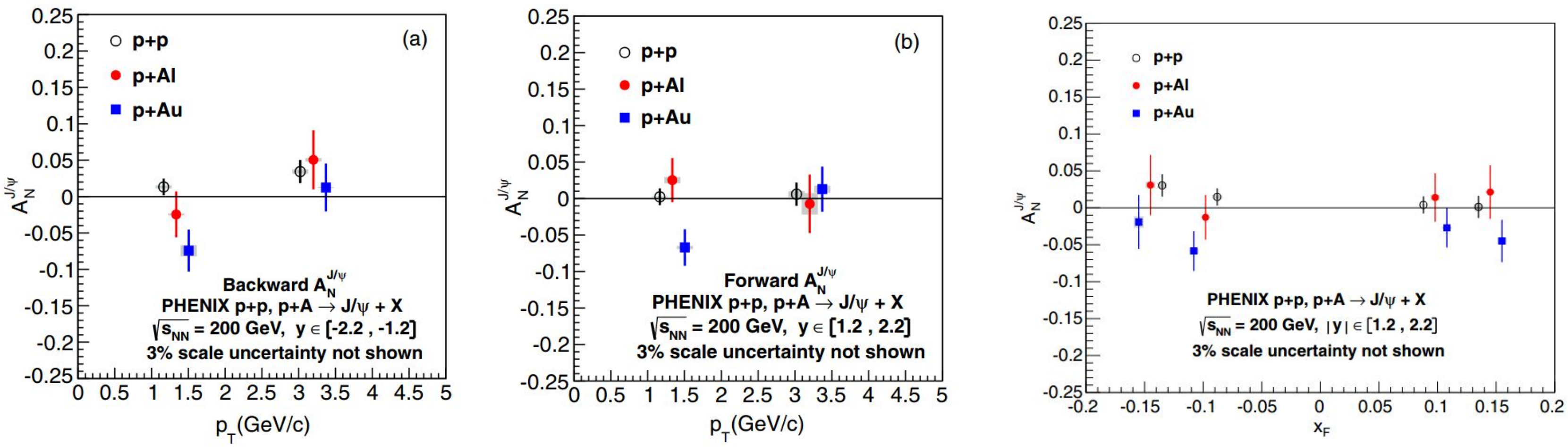
$\pi^{+/-}$ Background Fractions

- Spectrum dominated by $e^{+/-}$ below 4.9 GeV/c (RICH threshold for $\pi^{+/-}$)
- $e^{+/-}$ are main source of background in range of A_N measurement 5 GeV/c < p_T < 15 GeV/c
  - Only source considered in background subtraction
  - Charged kaons and protons are an insignificant contribution

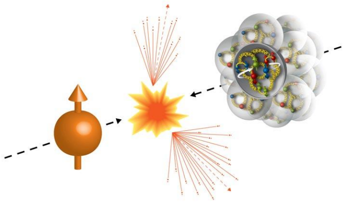


*(PHENIX Collaboration) PRD 102, 032001

Forward J/ψ A_N at $\sqrt{s_{NN}} = 200$ GeV ($p^{\uparrow}+p$, $p^{\uparrow}+Al$, $p^{\uparrow}+Au$)

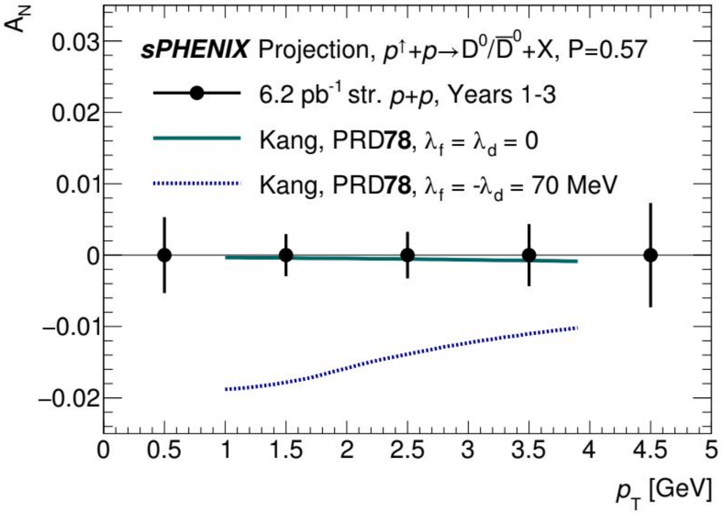


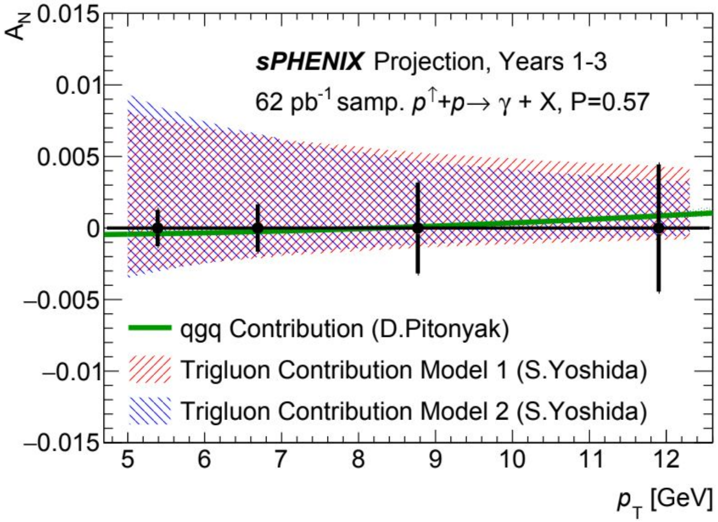
- p+p results consistent with previously published PHENIX measurement
- p+Al results consistent with 0 in all p_T and x_F bins
- p+Au results favor negative asymmetries in all x_F bins
  - This could be due to an enhancement in ultra peripheral collisions



PHENIX Collaboration - Phys. Rev. D 98, 012006 (2018)

Transverse Spin at sPHENIX





- With sufficient transverse running time, projected statistics from sPHENIX have significant constraining power on the trigluon (ggg) correlation function