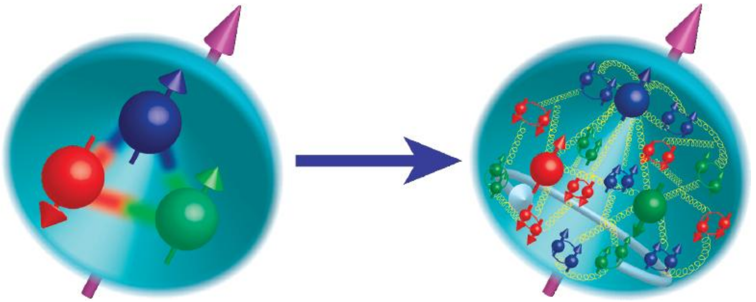
Transverse Single Spin Asymmetries of Heavy Flavor Electrons and Charged Pions in 200 GeV $p^{\uparrow}$+p Collisions at Midrapidity from PHENIX

Dillon Fitzgerald for the PHENIX Collaboration

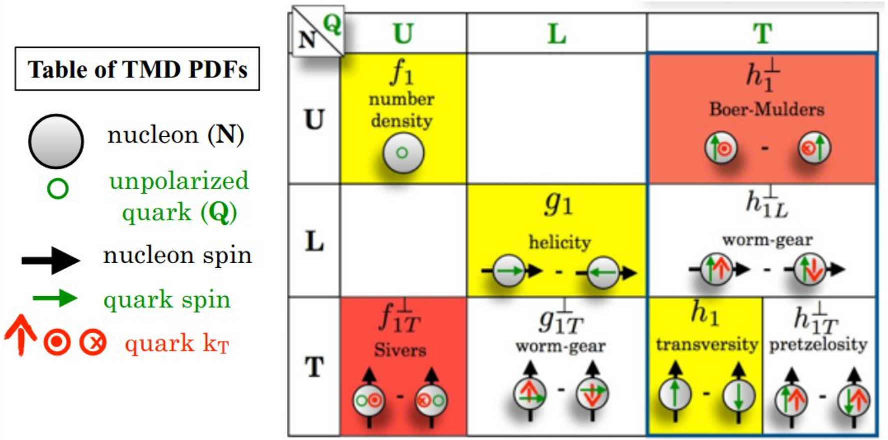
04/13/2021

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

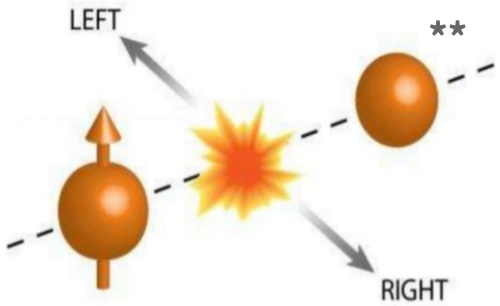


- We know that valence quarks do not carry all of the proton spin…
  - How is the spin of quarks and gluons correlated with proton spin?
  - How is the orbital motion of quarks and gluons correlated with proton spin?



Transverse Single Spin Asymmetries (TSSAs)

- $p^{\uparrow} + p$ initial state
- Quantify counts 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



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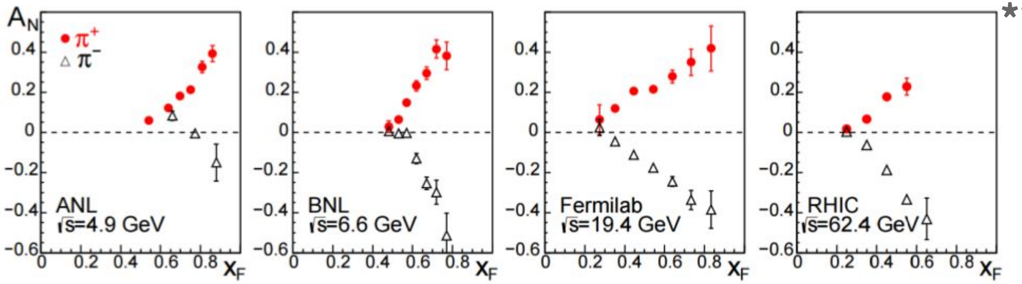
$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$



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

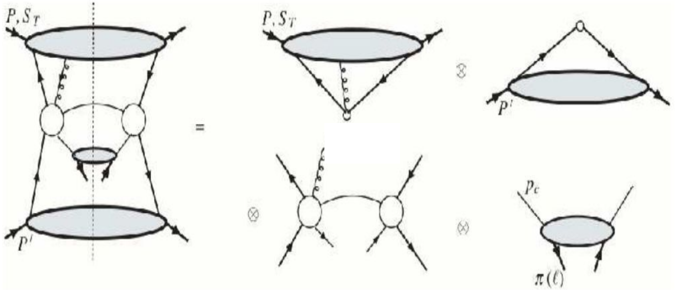
*G. L. Kane, J. Pumplin, and W. Repko PRL 41, 1689 (1978).
**https://www.bnl.gov/newsroom/news.php?a=111699
***C.A. Aidala, S.D. Bass, D. Hasch, and G.K. Mallot, Rev. Mod. Phys. **85** 655 (2013).

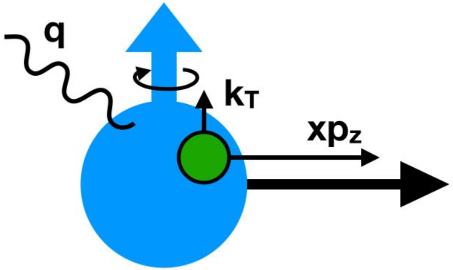
Transverse Single Spin Asymmetries (TSSAs)

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

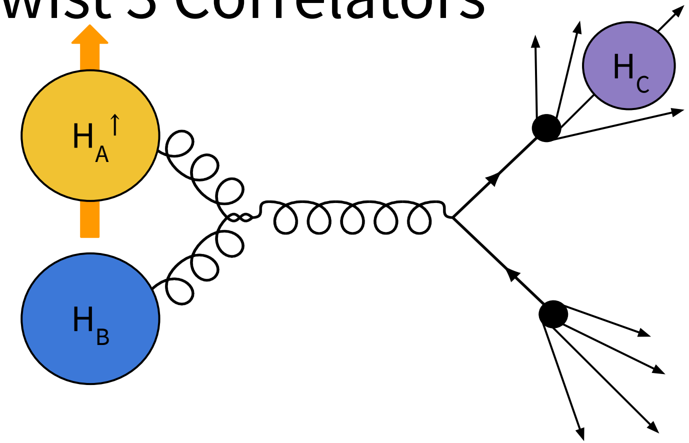
$$T_{q,F}(x,x) = \frac{1}{M_p}\int d^2\vec{k}_\perp \vec{k}_\perp^2 q_T(x,k_\perp)$$ *

Twist 3 correlator (qgq) — Sivers TMD PDF

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

Twist 3 Correlators

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



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

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

Charged pion production dominated by qg scattering @ 200 GeV midrapidity → sensitivity to quark flavor (u,d)

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

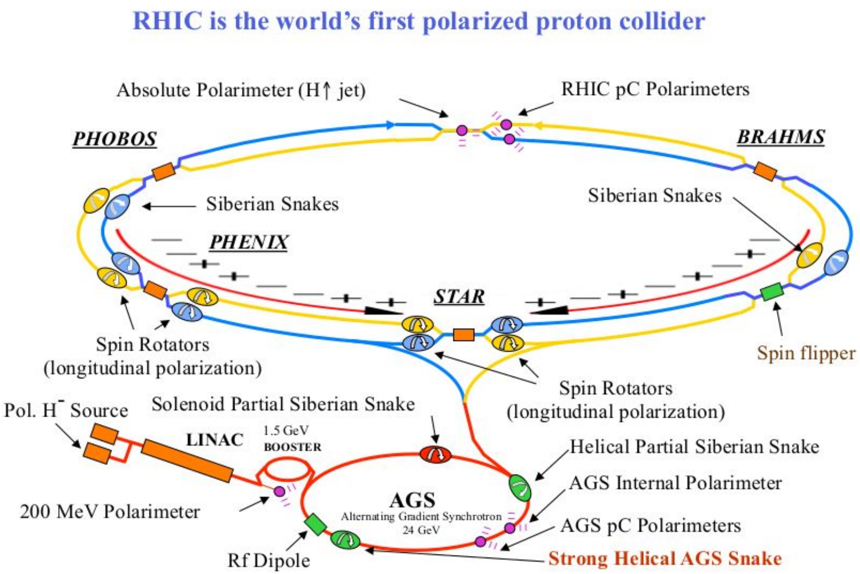
Spin Physics at RHIC

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

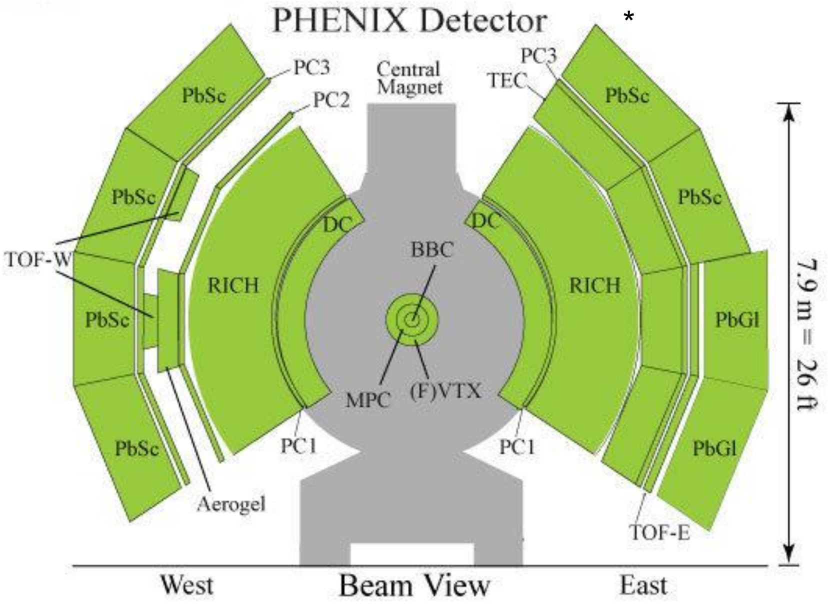
Collisions with polarized proton beams allow for a vast spin physics program

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



Midrapidity Charged Particle Detection at PHENIX

- **Acceptance:** $\Delta\phi$ = 0.5π per arm, |η| < 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 γ = 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

PHENIX

TSSA Observable

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

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

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

- Photonic: π^0, η, γ
  - Asymmetries measured to be 0 → treated as dilution
- 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

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

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

$$A_N^{NPe} = \frac{A_N^e - f_{h^\pm}A_N^{h^\pm}}{1 - f_{h^\pm} - f_{\pi^0\to e} - f_{\eta\to e} - f_{\gamma\to e}}$$

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

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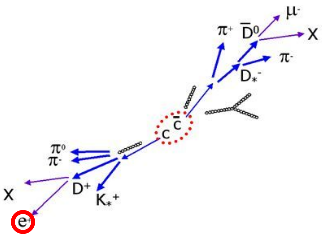
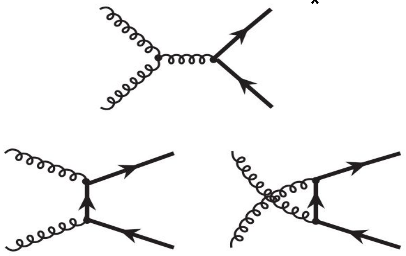
Open Heavy Flavor Production



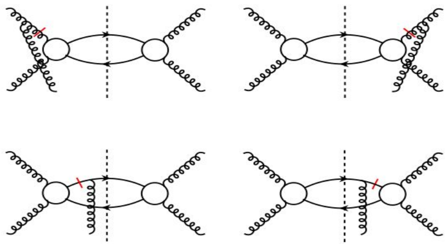
Open charm production is dominant contribution

gg→QQ *

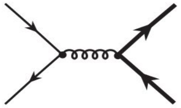


Dominant contribution @ 200 GeV midrapidity! ggg correlator **not** well constrained from previous measurements

ggg (trigluon) correlators *

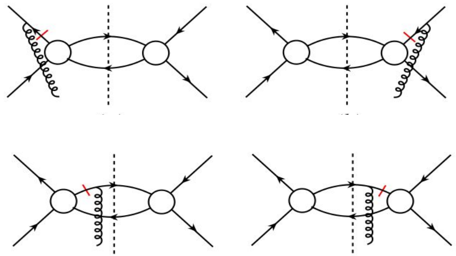


qq→QQ *



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

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



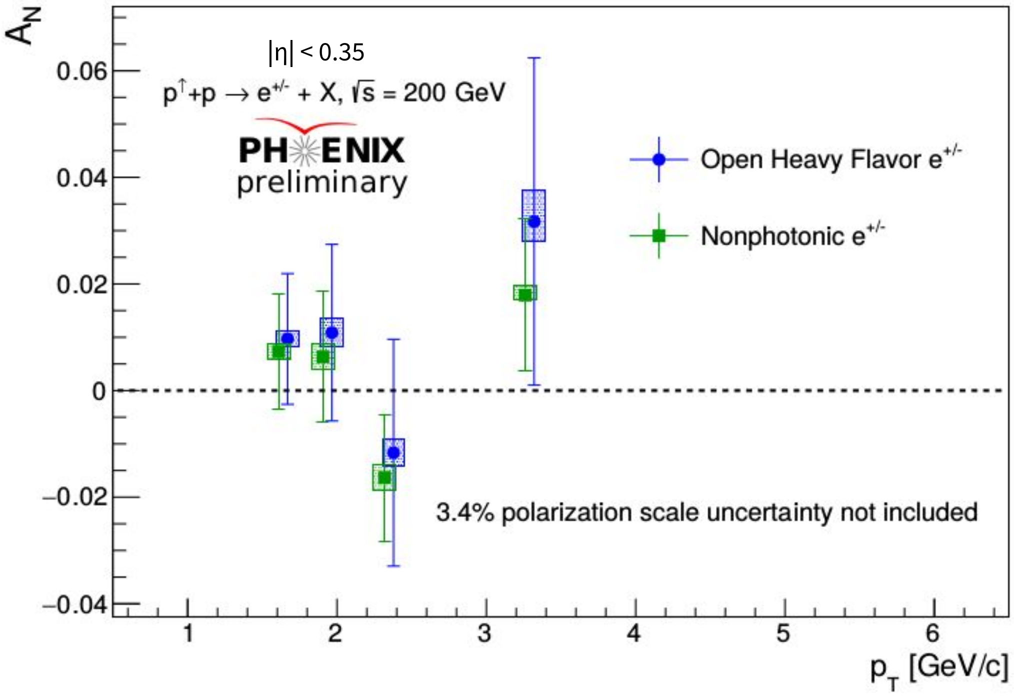
*Kang, Qiu, Vogelsang, Yuan, PRD78, 114013

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

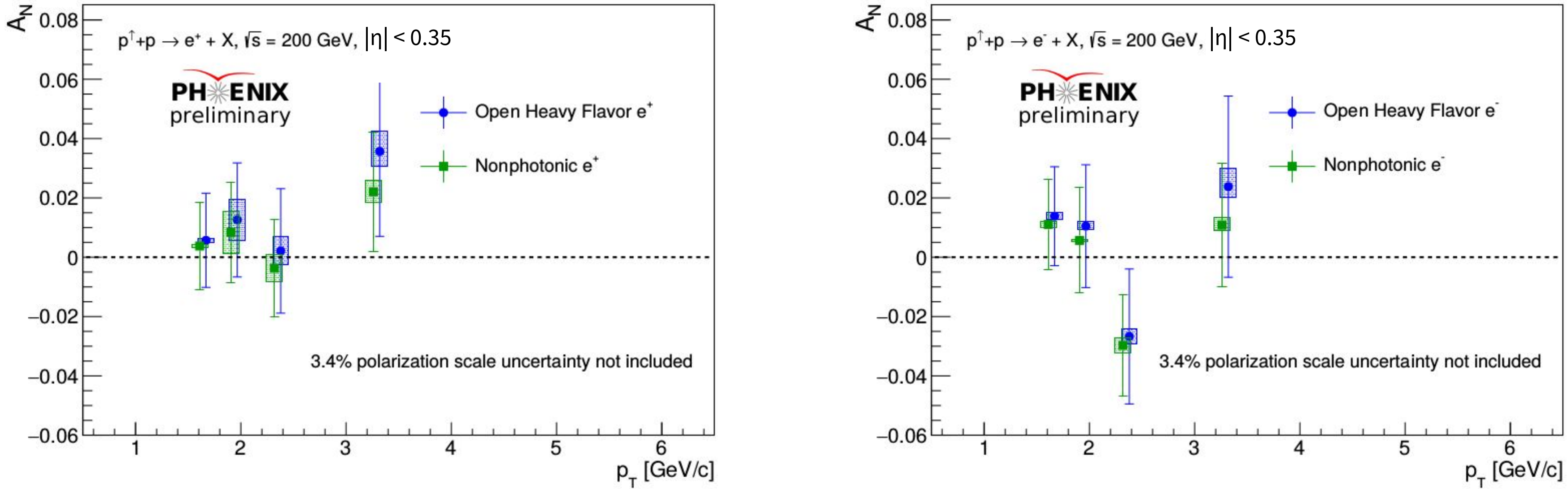
Charge Combined Open Heavy Flavor Electron A_N

- Most precise measurement of open heavy flavor and nonphotonic electron TSSA at midrapidity

- Consistent with zero in measured range

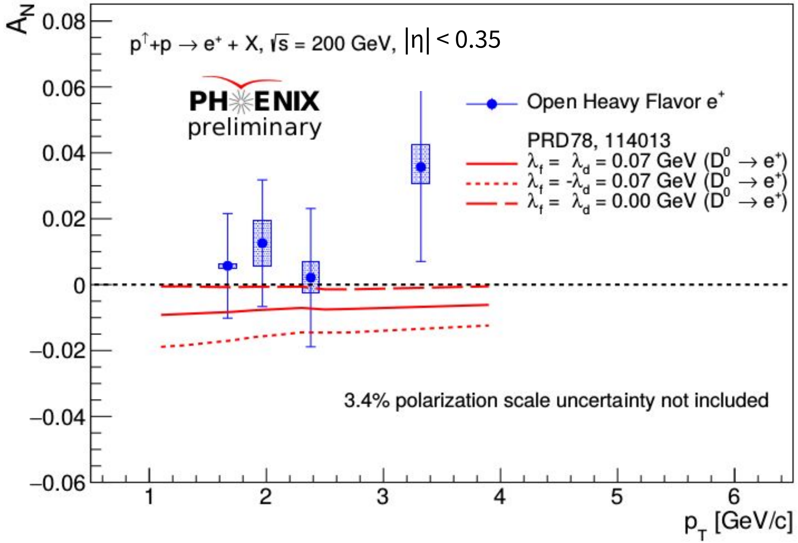


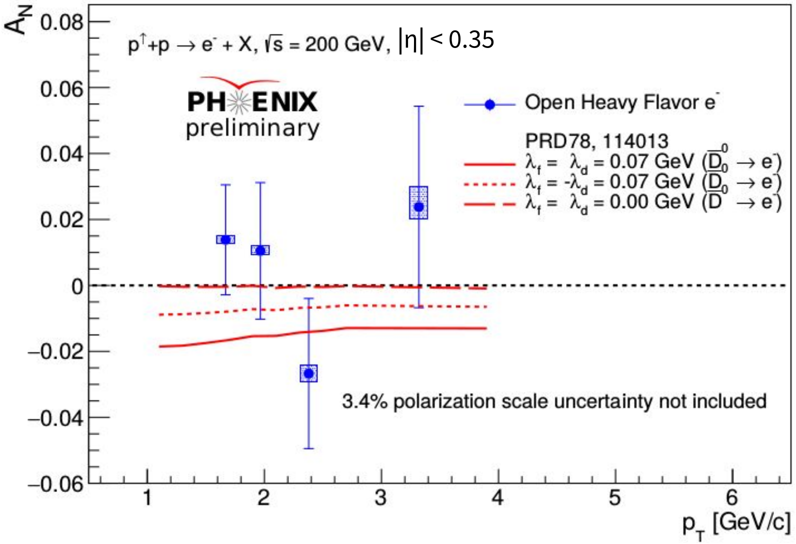
Charge Separated Open Heavy Flavor Electron A_N



- Charge separated results also consistent with zero in measured range

Charge Separated Open Heavy Flavor Electron A_N



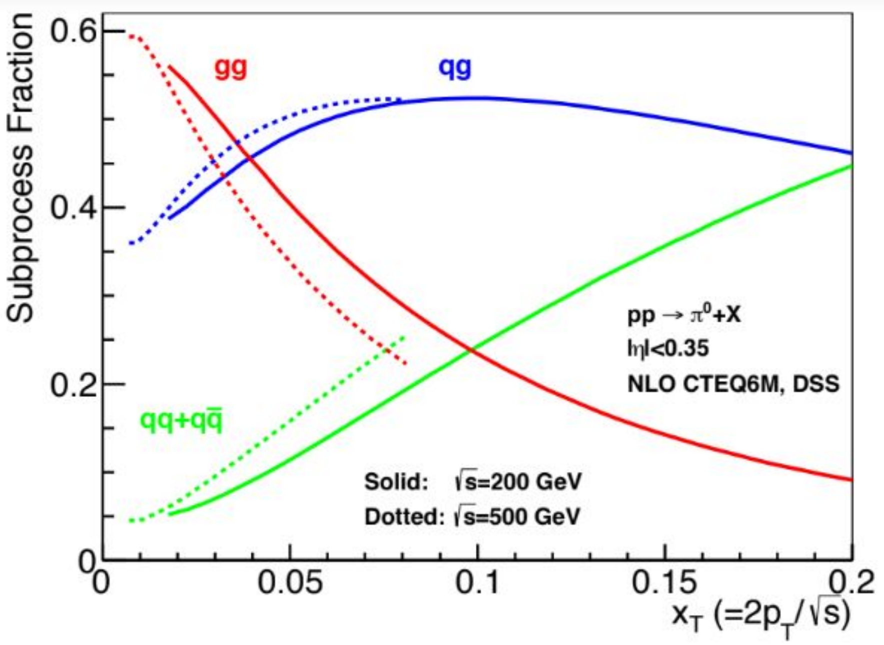


- Open heavy flavor results plotted alongside $D^0 \rightarrow e^{+/-}$ contributions as calculated in **PRD78, 114013**
  - Ordering of curves is different for different charges → sensitivity to constrain λ parameters
- λ parameters correspond to normalizations of trigluon correlators with respect to unpolarized gluon PDF
  - $\phi^{(3),f}_g(x, x) = \lambda_f\, g(x), \quad \phi^{(3),d}_g(x, x) = \lambda_d\, g(x)$ $\quad d^{abc}, \; if^{abc} \implies T^{(d)}_{G,F}(x_1, x_2), \quad T^{(f)}_{G,F}(x_1, x_2)$

Charged Pion Production

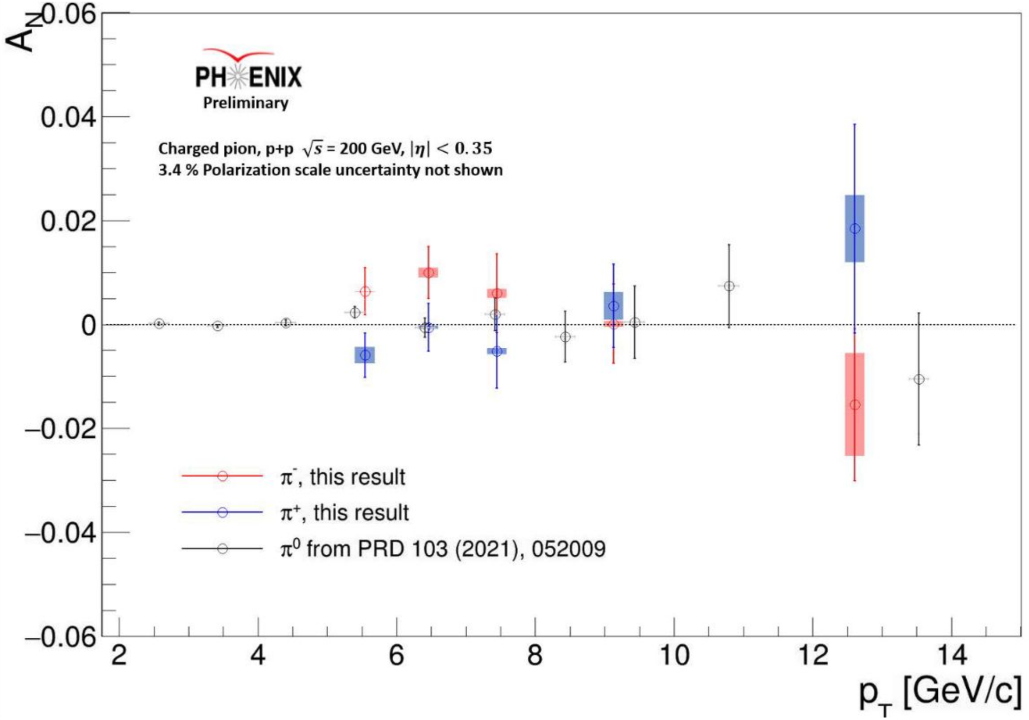
- Produced via qg, gg , qq 2 → 2 processes - **dominated by qg @ 200 GeV midrapidity (until high p_T)**
  - $\pi^0 \sim (\pi^+ + \pi^-)/2$
  - qg contributions are sensitive to quark flavors when looking at $\pi^{+/-}$ separately

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



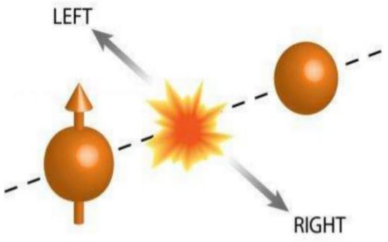
Charged Pion A_N

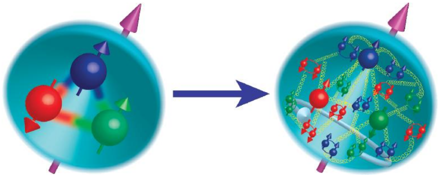
- First results of midrapidity charged pion A_N from PHENIX
- Compared with π^0 A_N from **PRD 103, 052009**
- $\pi^{+/-}$ A_N consistent with zero in measured range, but there is an indication that $\pi^{+/-}$ behave differently (potential flavor dependence)



Summary

- Transverse single spin asymmetries provide access to nonperturbative spin-momentum and spin-spin correlations 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 $e^{+/-}$ A_N
  - $p^{\uparrow} + p$, $\sqrt{s} = 200$ GeV, $|\eta| < 0.35$
  - Consistent with zero in measured range
  - Compared with theoretical predictions from **PRD78, 114013**
- First measurement of $\pi^{+/-}$ A_N at midrapidity at RHIC
  - $p^{\uparrow} + p$, $\sqrt{s} = 200$ GeV, $|\eta| < 0.35$
  - Consistent with zero in measured range
  - Compared with π^0 A_N from **PRD 103, 052009**
- Both results presented are in preparation for publication
- Other results in preparation
  - Forward heavy flavor muon A_N ($p^{\uparrow} + p$)
  - Forward charged hadron A_N ($p^{\uparrow} + p$, $p^{\uparrow} +$ Al, $p^{\uparrow} +$ Au)



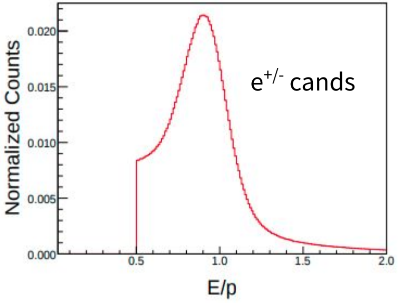


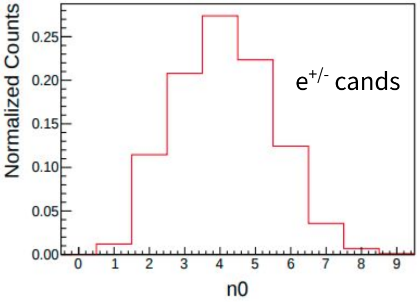
BACKUP

$e^{+/-}$ 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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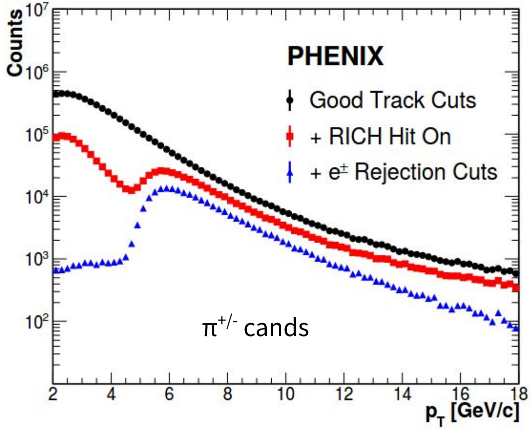
$\pi^{+/-}$ identification**

- $0.2 < E/p < 0.8$ 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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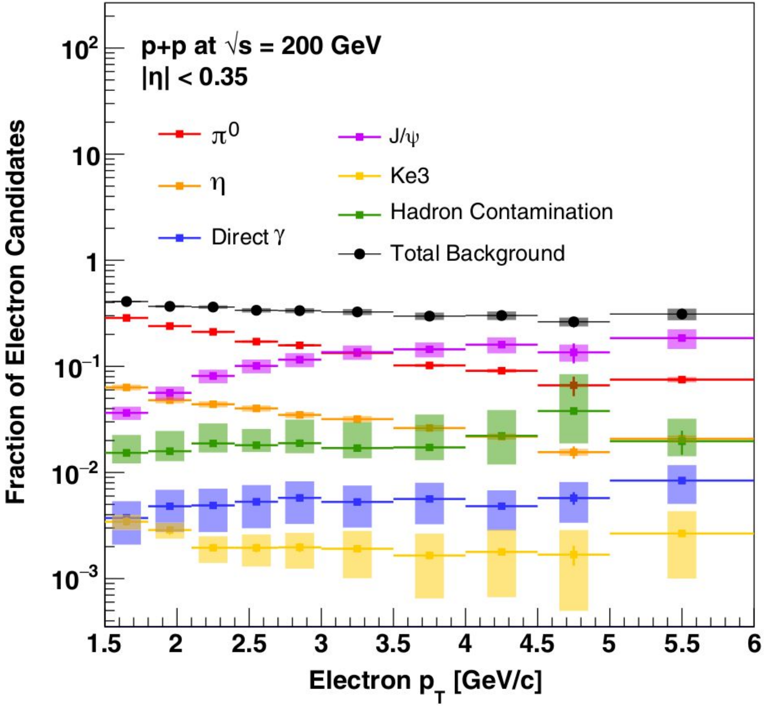
*Esha, Roli. (2020, September 15). Electron Identification in PHENIX

**(PHENIX Collaboration) PRD 102, 032001

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

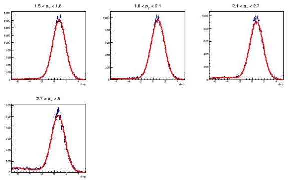
- Largest contribution from photonic electron background sources (π^0+ η + γ) at p_T < 3 GeV/c
  - Asymmetries for these sources well constrained to be zero at 200 GeV midrapidity **PRD 103, 052009, arXiv:2102.13585**
- Largest contribution from J/ψ at p_T > 3 GeV/c
  - σ_{AN} affected significantly 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



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

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

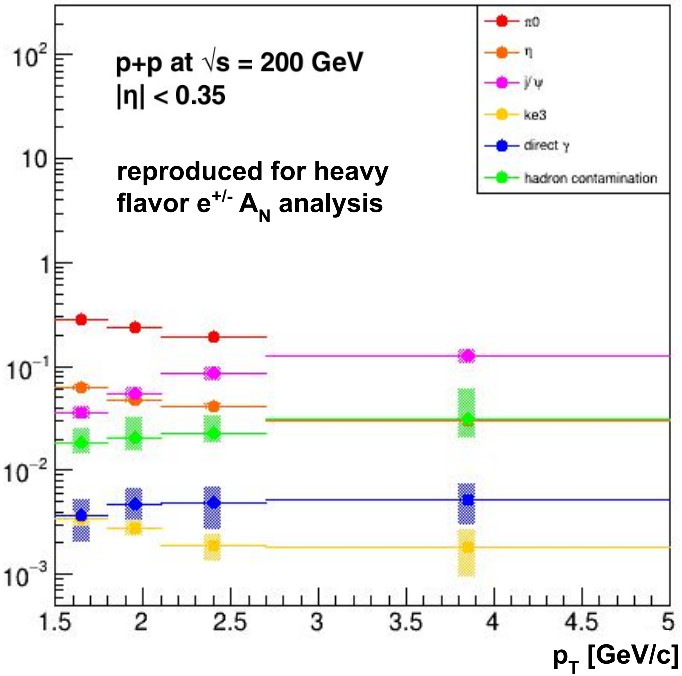
$$n_{h_{n0}} = \epsilon_h \frac{n_{n0} - \epsilon_e n_{nor}}{\epsilon_h - \epsilon_e}$$

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

$$F_{np} = \frac{\tilde{n}_{np}}{\tilde{n}_{np} + \tilde{n}_p} = \frac{n_{np}}{n_{np} + \epsilon_p n_p} = \frac{\epsilon_{uc}\epsilon_p n_e - \tilde{n}_e - \epsilon_{uc}\epsilon_p n_{hc} + \tilde{n}_{hc}}{(\epsilon_p - 1)(\tilde{n}_e - \tilde{n}_{hc})} \qquad f_i = (1 - \tilde{f}_{hc})(1 - F_{np})\frac{\tilde{n}_i}{\tilde{n}_{\pi^0} + \tilde{n}_\eta + \tilde{n}_\gamma}$$

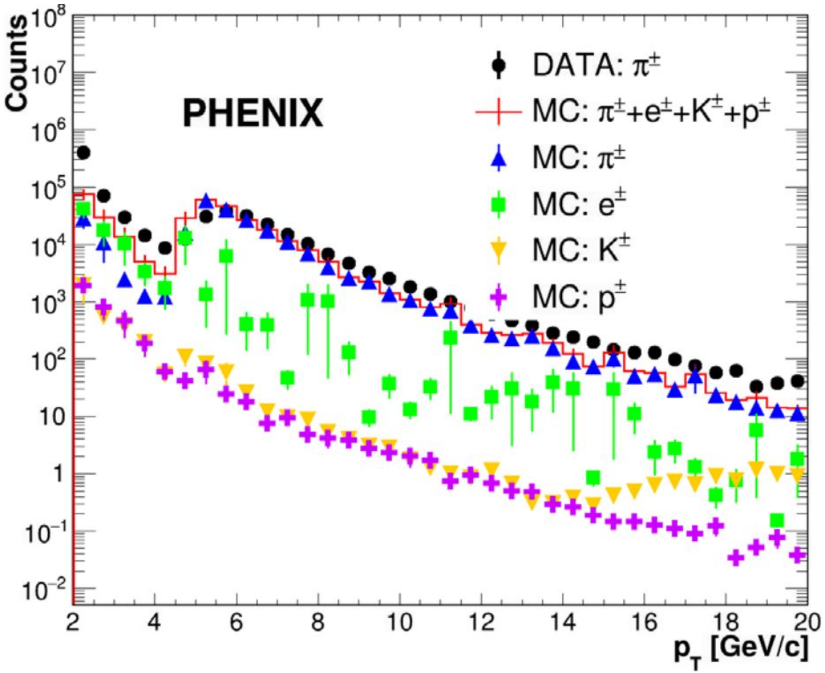
- Nonphotonic background fractions
  - Signal open heavy flavor $e^{+/-}$ is nonphotonic, so calculate nonphotonic background fractions w.r.t. π^0 fraction

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



$\pi^{+/-}$ 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



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*(PHENIX Collaboration) PRD 102, 032001