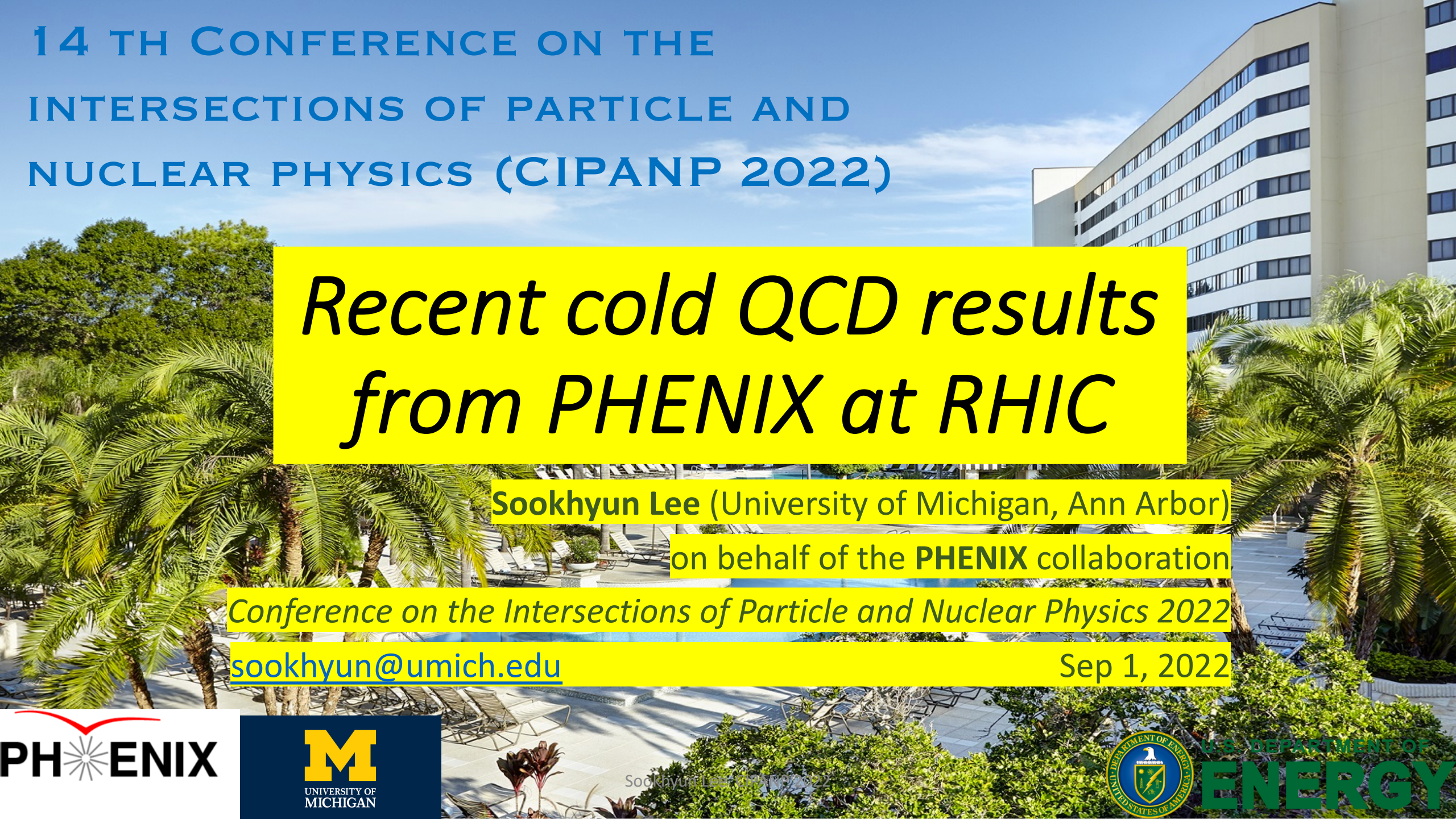

Recent cold QCD results from PHENIX at RHIC

Sookhyun Lee (University of Michigan, Ann Arbor)

on behalf of the **PHENIX** collaboration

Conference on the Intersections of Particle and Nuclear Physics 2022

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Sep 1, 2022

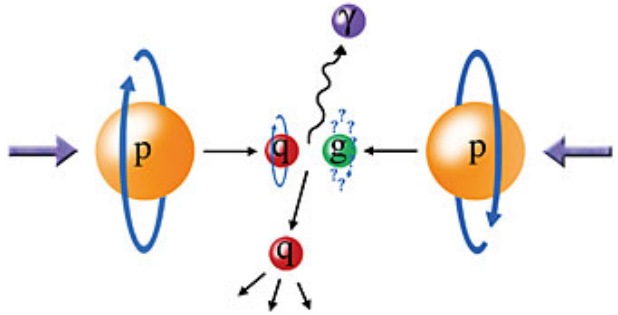
PHENIX

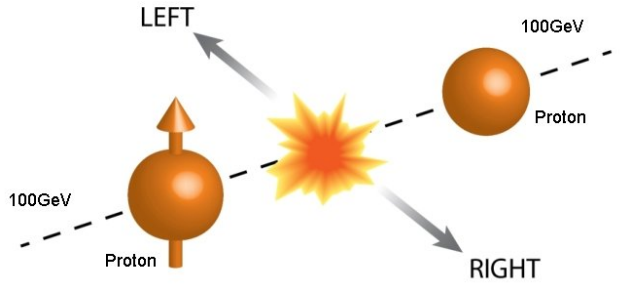
UNIVERSITY OF MICHIGAN

U.S. DEPARTMENT OF ENERGY

Overview of PHENIX cold QCD results

- Gluon polarization - Longitudinal double spin asymmetry A_{LL}
  - Direct photon γ
  - Jets
- Nucleon-parton spin-momentum correlation - Transverse single spin asymmetry A_{N}
  - Direct photon
  - π^0 , η and $\pi^{\pm}$
  - Open heavy flavor
- Forward neutron A_{N} in $p+p$ and $p+\mathrm{A}$.

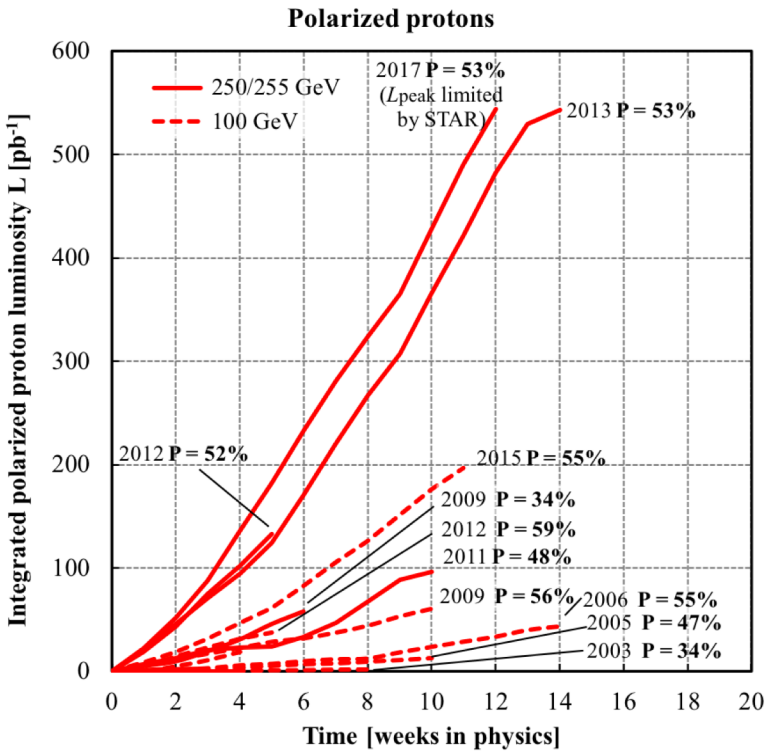


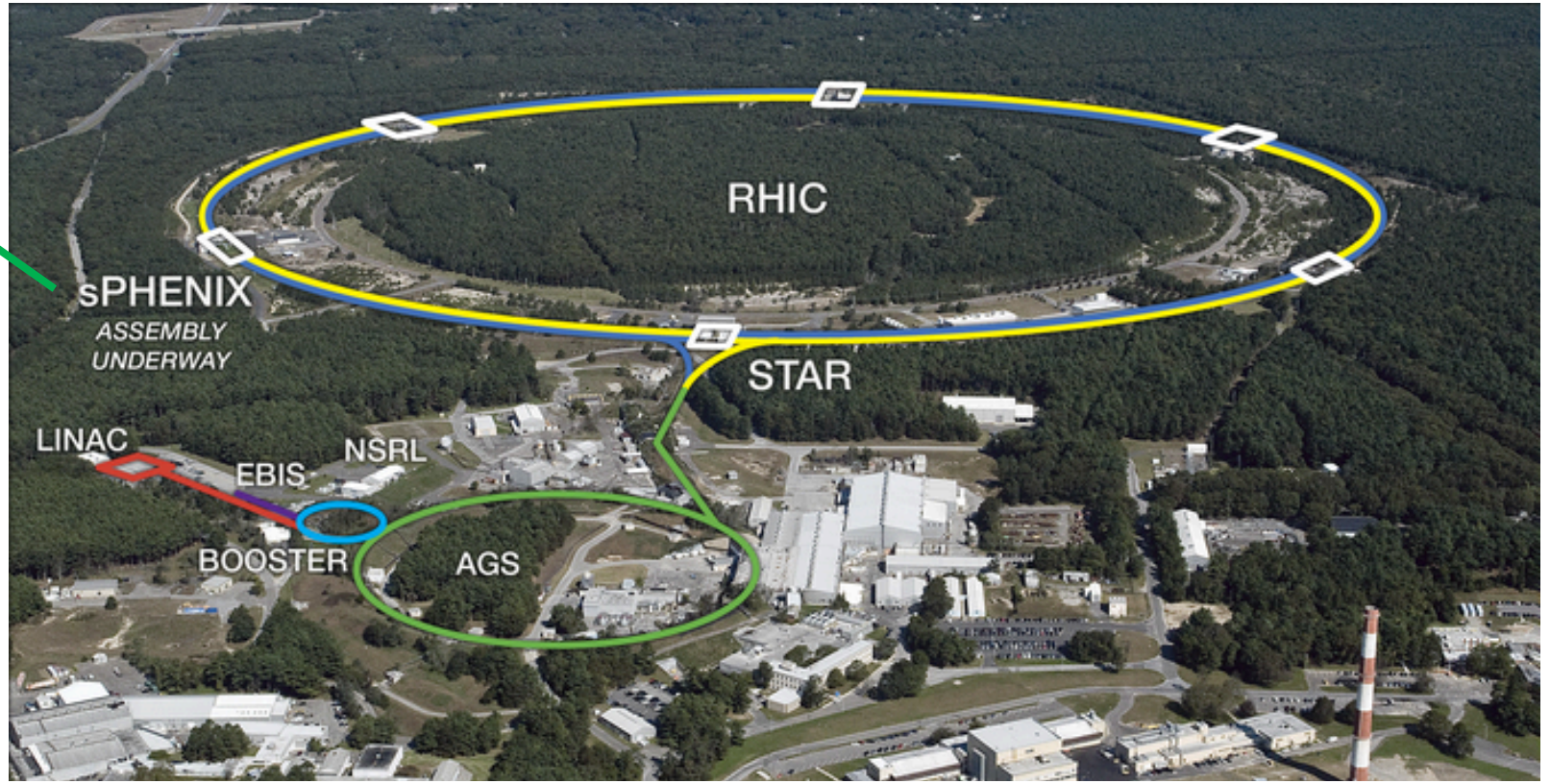


Relativistic Heavy Ion Collider

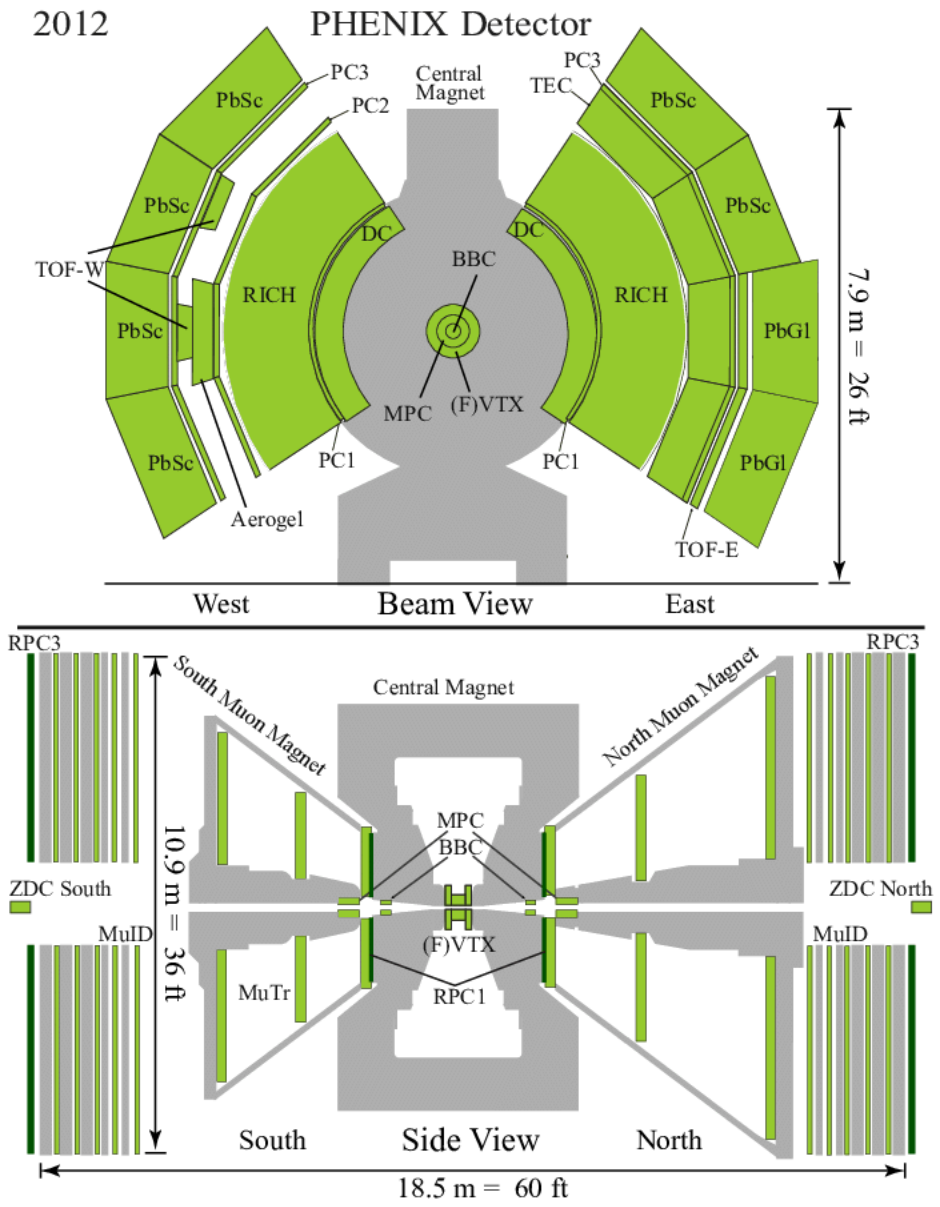
PHENIX
was here
taking data
until 2016

STAR
polarized p+p
running in 2022





- Located at Brookhaven National Laboratory in Long Island, NY.
- World's only polarized synchrotron collider.
- Spin patterns are predetermined for each bunch.



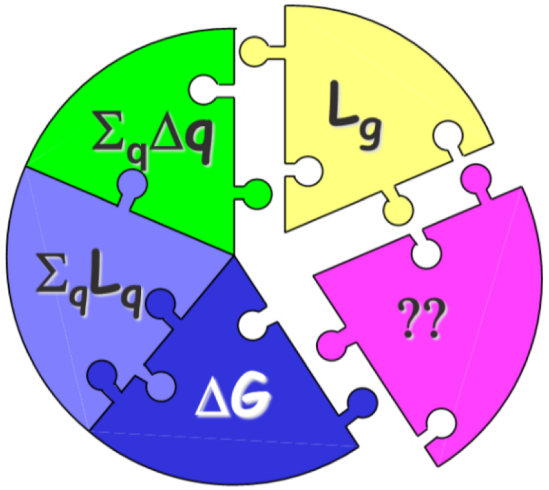
The PHENIX detector

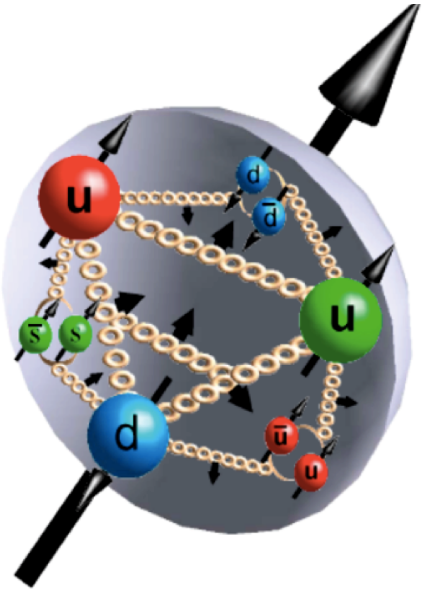
- Central Arm detectors
  - $|\eta|$<0.35, $2\times\frac{\pi}{2}$ coverage for ϕ
  - EMCal, RICH, DC and PC
- Forward Arm detectors
  - $1.2 < \eta < 2.2$
  - MPC, FVTX, MuID, MuTr
- Luminosity counters

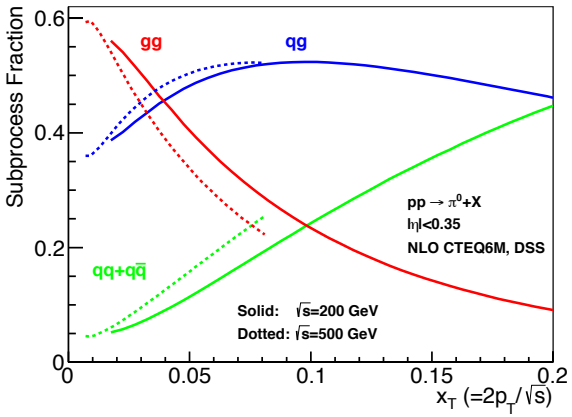
  BBC ($3<|\eta|<3.9$), ZDC ($\eta>6.8$)

ΔG - Gluon polarization

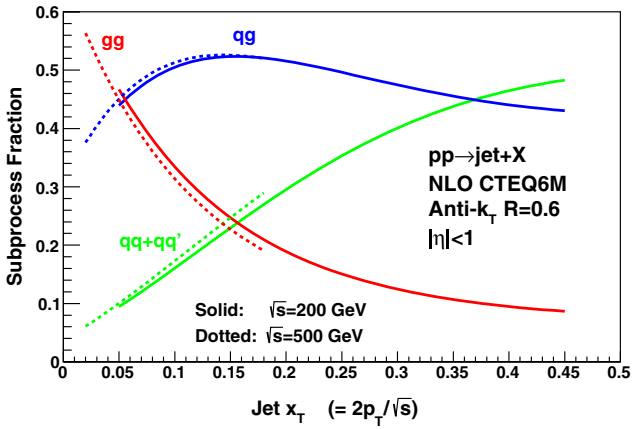
- In 80's, polarized DIS data showed $\Delta\Sigma$ contribution to proton spin was only 30%.
- Polarized gluon PDF can be directly accessed via A_{LL} measurements in $\vec{p}+\vec{p}$ collisions.
- RHIC kinematics for jets and hadrons - dominated by gg and qg at low x ; their A_{LL}'s sensitive to gluon polarization.







Phys. Rev. D **100** (2019) 052005



$$\mathrm{J_z} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathrm{L}$$

Longitudinal Double Spin Asymmetry

$$A_{\mathrm{LL}} \equiv \frac{\sigma^{++}-\sigma^{+-}}{\sigma^{++}+\sigma^{+-}},$$

$++\,(+-)$: same-sign (opposite-sign) incoming proton helicity

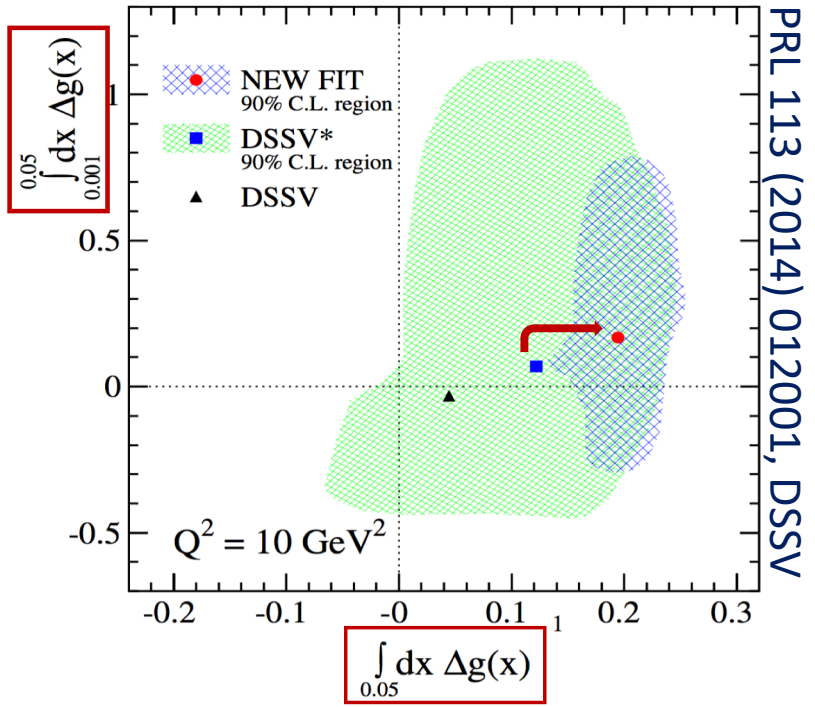
Gluon helicity distributions

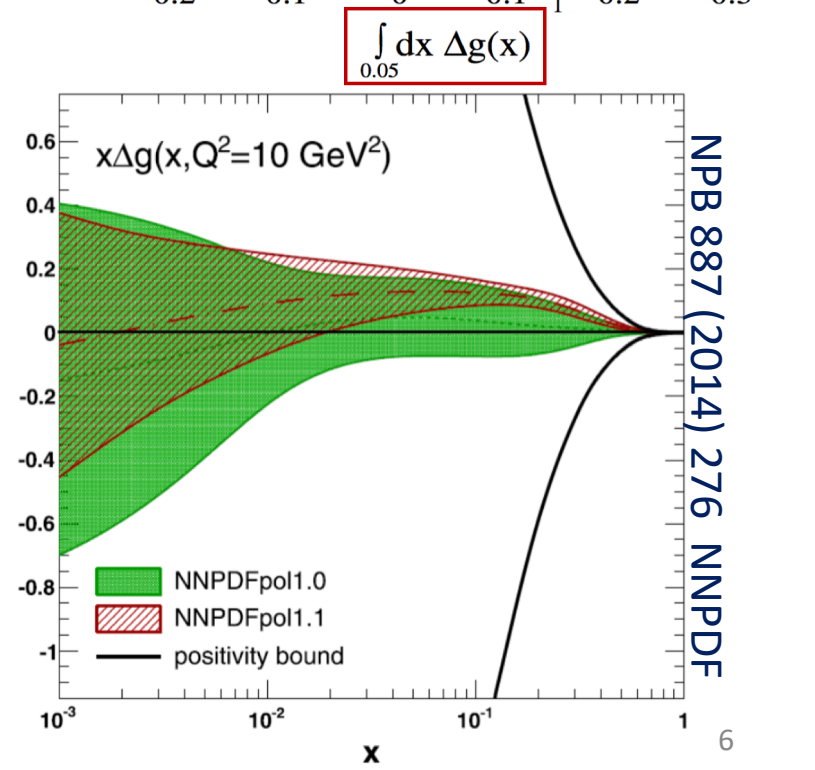
- PHENIX and STAR midrapidity data from 2009 $\vec{p}+\vec{p}$ at $\sqrt{s}$ = 200 GeV have had a significant on understanding gluon polarization.
  - PHENIX π^0 PRD 90 (2014) 012007
  - STAR inclusive jets PRL 115, (2015) 092002

- DSSV $\int_{0.05}^{1}\Delta g(x)dx = 0.20^{+0.06}_{-0.07}$

- NNPDF $\int_{0.05}^{1}\Delta g(x)dx = 0.17^{+0.06}_{-0.06}$

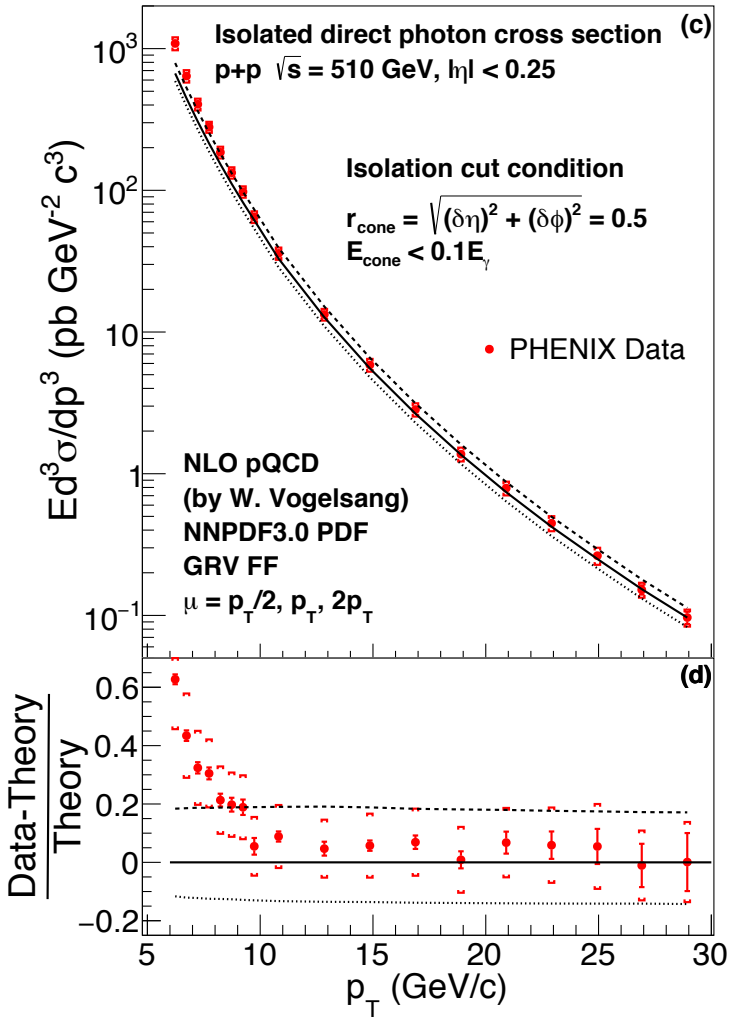
- With more data to be included (higher $\sqrt{s}$, forward measurements, more differential, diverse probes)
  - Dijets, $\pi^{\pm}$ at 200 GeV in 2009 (STAR dijet impact study done in Phys. Rev. D **100** (2019) 114027)
  - Jets, dijets and π^0 at 200 GeV in 2015
  - Jets, dijets, π^0, $\pi^{\pm}$, γ at 510 GeV in 2012 and 2013



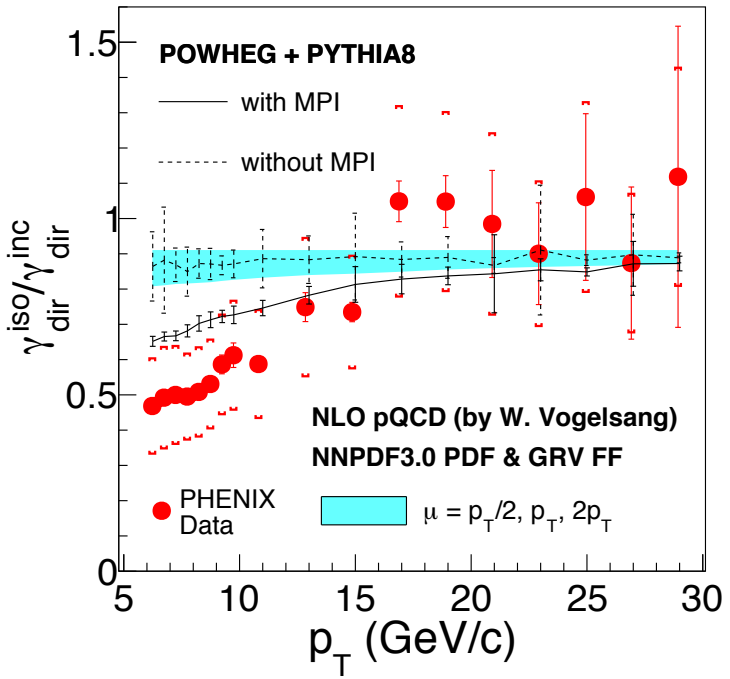


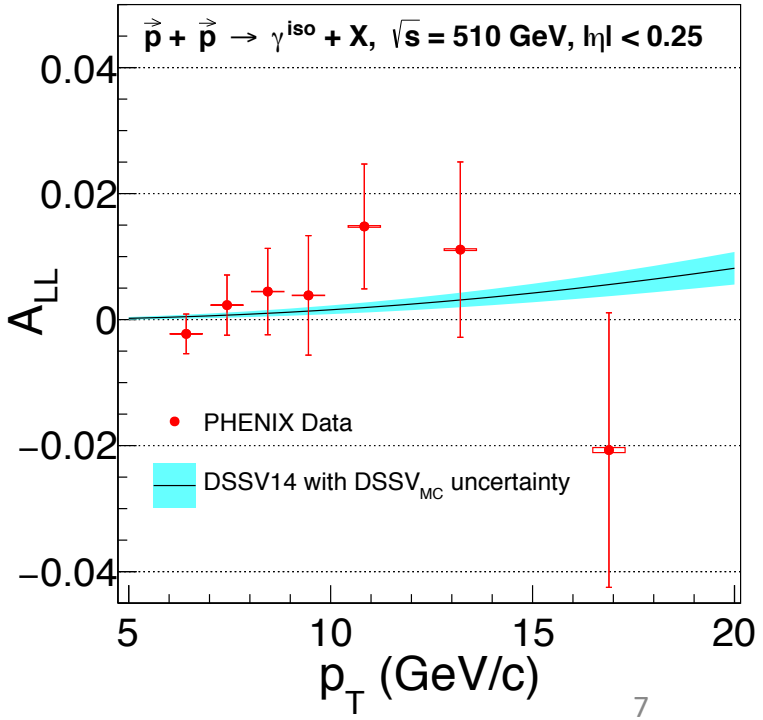
Direct photon cross sections and A_{LL}

arXiv:2202.08158

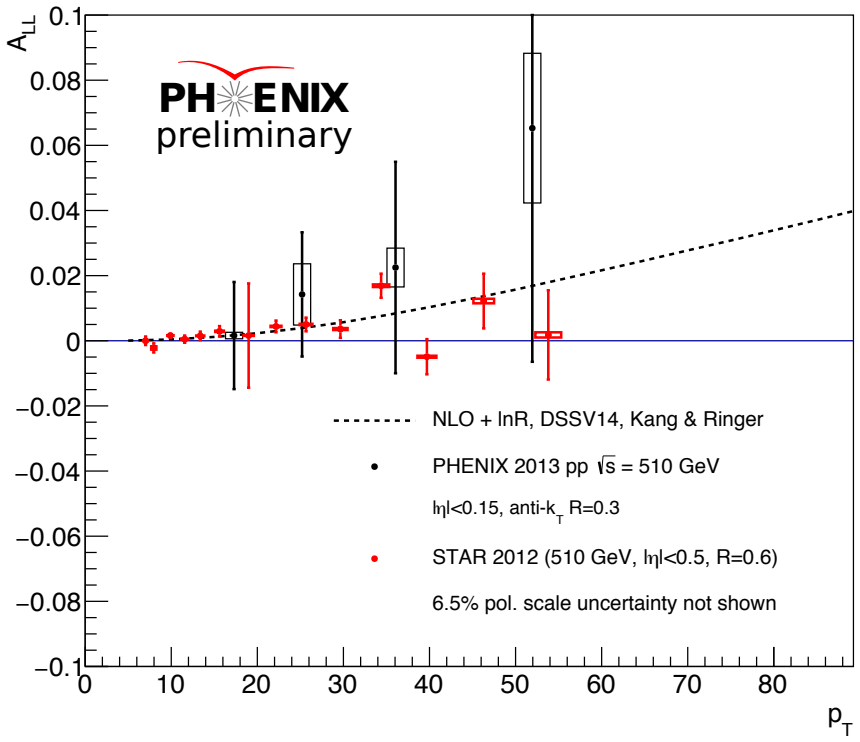


- Theoretically golden channel to access gluon polarization; hard process predominantly qg, no fragmentation function.
- Statistically limited due to being EM process.
- Isolated production consistent with predictions from NLO pQCD + NNPDF3.0 + GRV FF.
- Inclusive production affected by multi-parton interactions (MPI).
- Measured asymmetries isolated photons consistent with global fit.



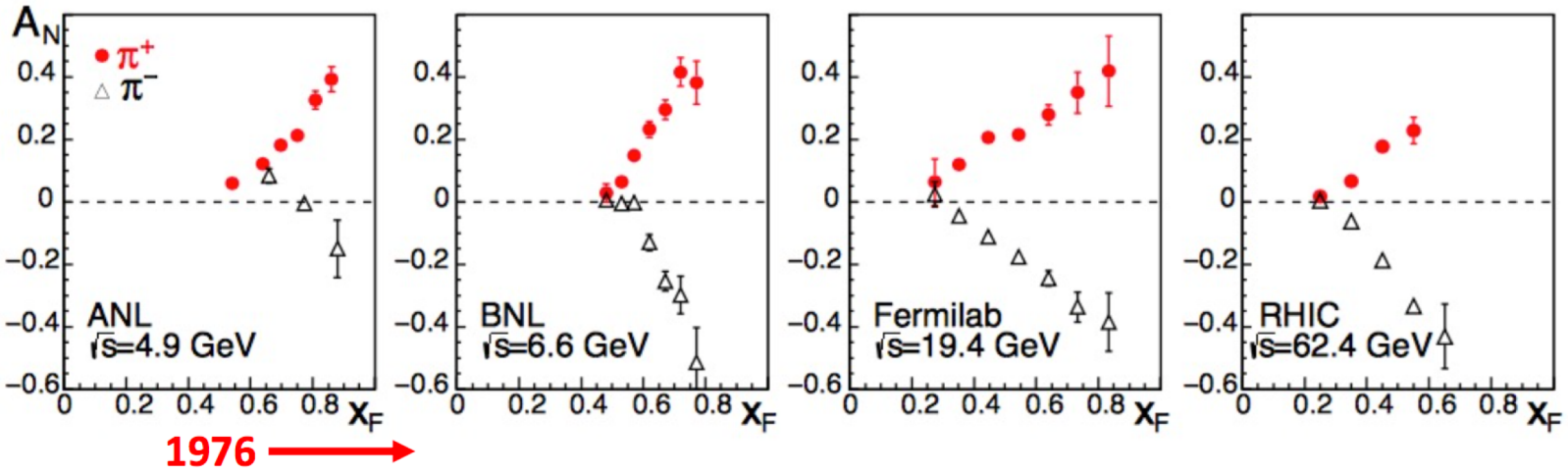


Jet A_{LL} at 510 GeV

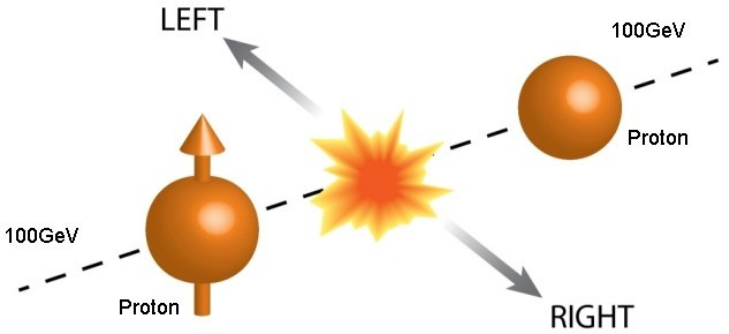


- PHENIX jet measurements limited by acceptance, smaller jet radius of R = 0.3.
- Measured asymmetries consistent with nonzero gluon polarization findings based on STAR Jet and PHENIX π^0 A_{LL} results.

Transverse structure of proton



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



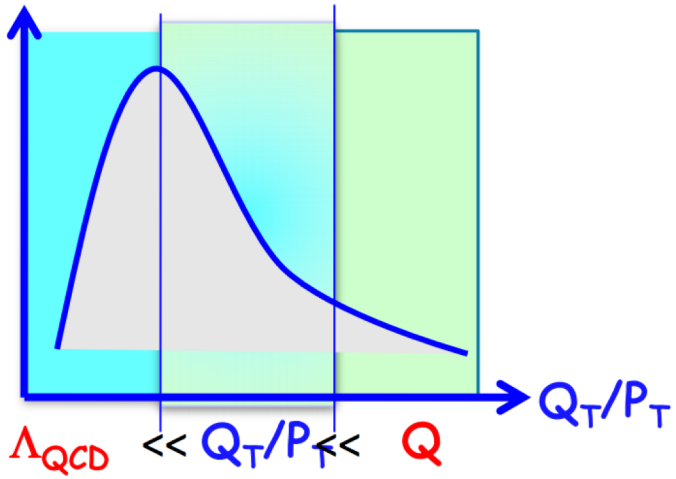
Transverse Single Spin Asymmetry (TSSA)

$$A_N \equiv \frac{\sigma^{\uparrow 0} - \sigma^{\downarrow 0}}{\sigma^{\uparrow 0} + \sigma^{\downarrow 0}}$$

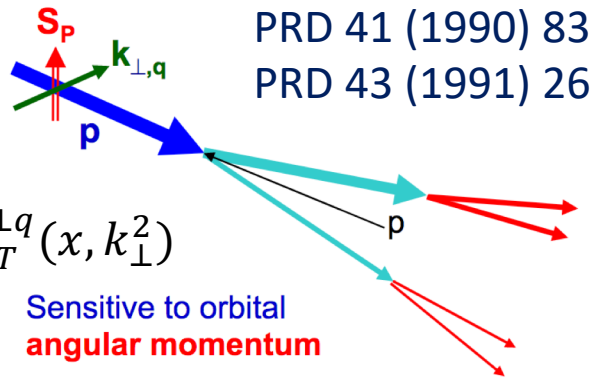
↑ or ↓ : proton transverse spin states.

TMD

- Requires 2 scales:
  - Hard scale Q
  - Soft scale $p_T \ll Q$
- Suitable for
  - SIDIS, DY, W/Z and hadrons in jets



e.g. Sivers Fn:



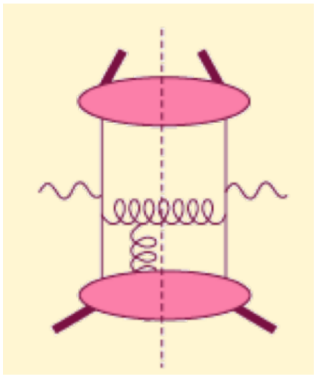
PRD 41 (1990) 83
PRD 43 (1991) 261

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

Nucl. Phys. B **667** (2003) 201
Phys. Rev. Lett. **97** (2006) 082002

Collinear Twist-3

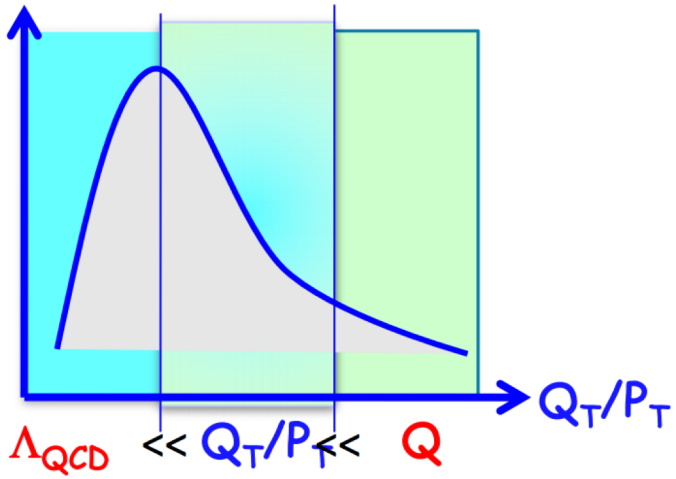
- Only require single scale
  - Hard scale: $p_T \sim Q$
- Suitable for
  - Inclusive π^0, jet, γ and Λ



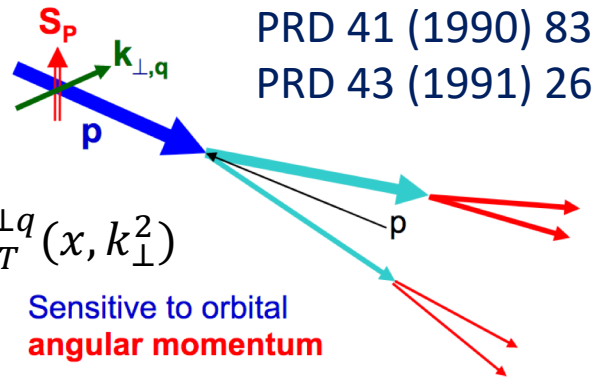
Efremov, Teryaev;
Sterman, Qiu qgq correlator

TMD

- Requires 2 scales:
  - Hard scale Q
  - Soft scale $p_T \ll Q$
- Suitable for
  - SIDIS, DY, W/Z and hadrons in jets



e.g. Sivers Fn:



PRD 41 (1990) 83
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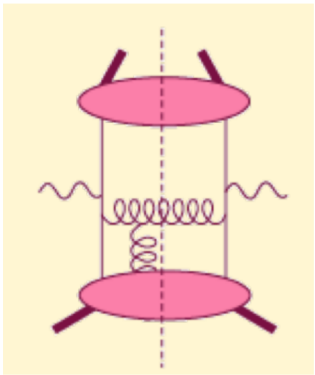


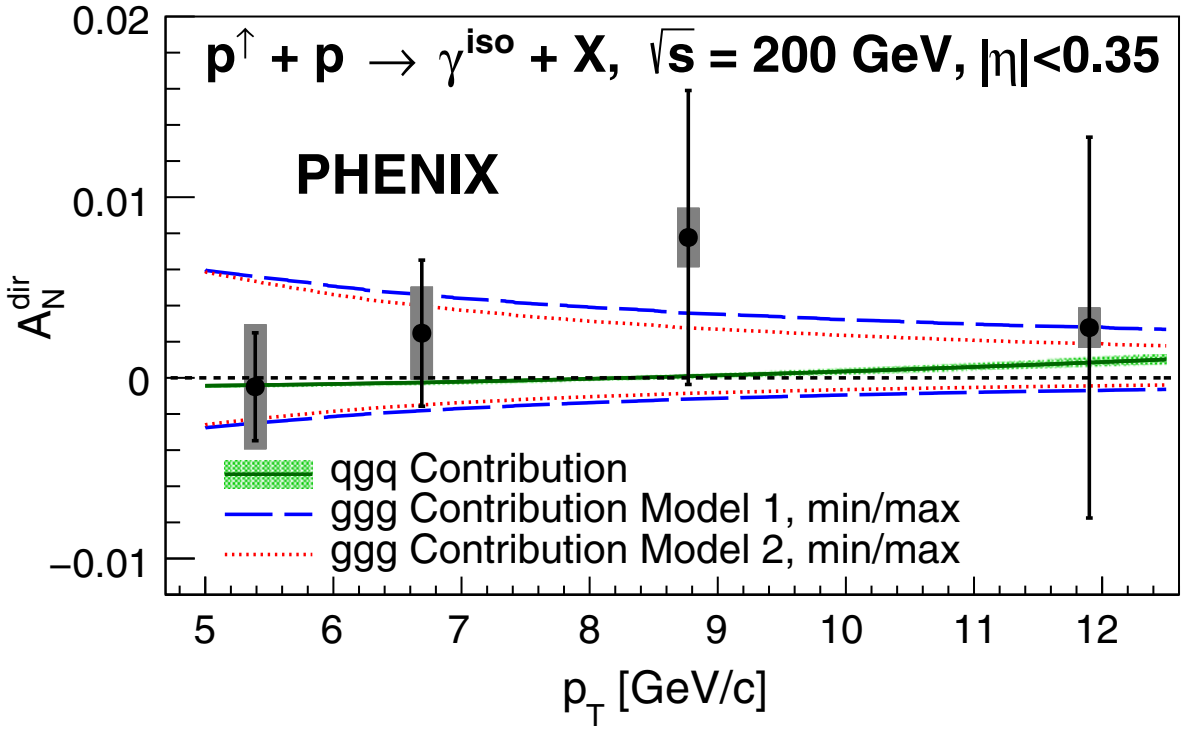
Efremov, Teryaev;
Sterman, Qiu qgq correlator

*Similar relation holds for **gluon** Sivers Fn and **ggg** correlator.*

Direct photon A_N

- First direct photon A_N
- Measured asymmetry consistent with zero.
- Sensitive to transverse gluon structure inside proton
  - Direct photon production predominantly from QCD Compton scattering.
  - Small contribution from qgq correlation function predicted at midrapidity.
- Clean probe for extraction of trigluon correlator and sensitive to gluon Sivers fn.

Phys. Rev. Lett. **127** (2021) 162001

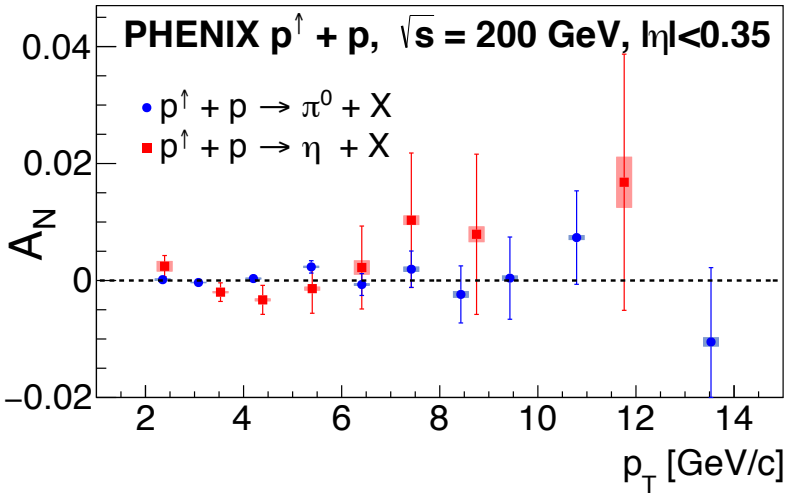


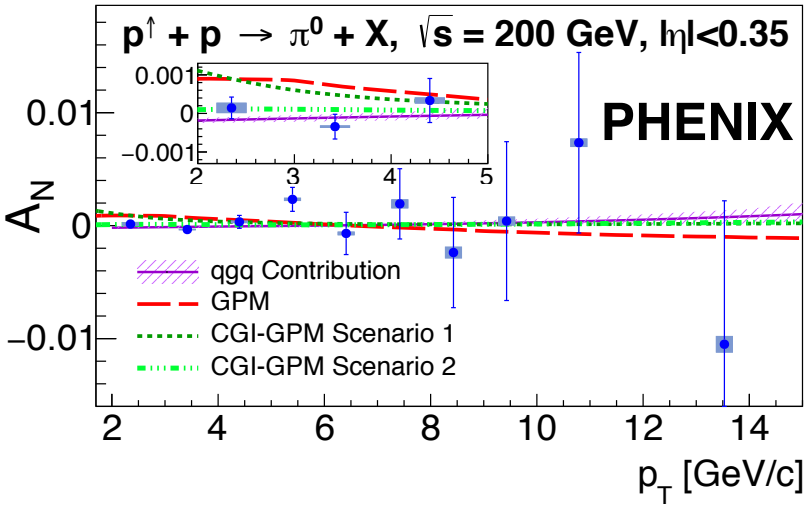
π^0 and η A_N

- Improved statistical precision to sub-percent level.
- Measured asymmetries consistent with zero and with previous measurements.
- A_N (π^0) ***vs.*** A_N (η)**:** no evidence of differences due to strangeness, isospin or mass.

- Small contribution from qgq correlator predicted at midrapidity by JAM Collaboration.
- Moderately sensitive to trigluon correlator and gluon Sivers fn.
- CPI-GPM scenario 1 and 2 maximize (minimize) previously measured open heavy flavor A_N generated by *gluon Sivers* Fn within statistical uncertainties.

Phys. Rev. D **103** (2021) 052009





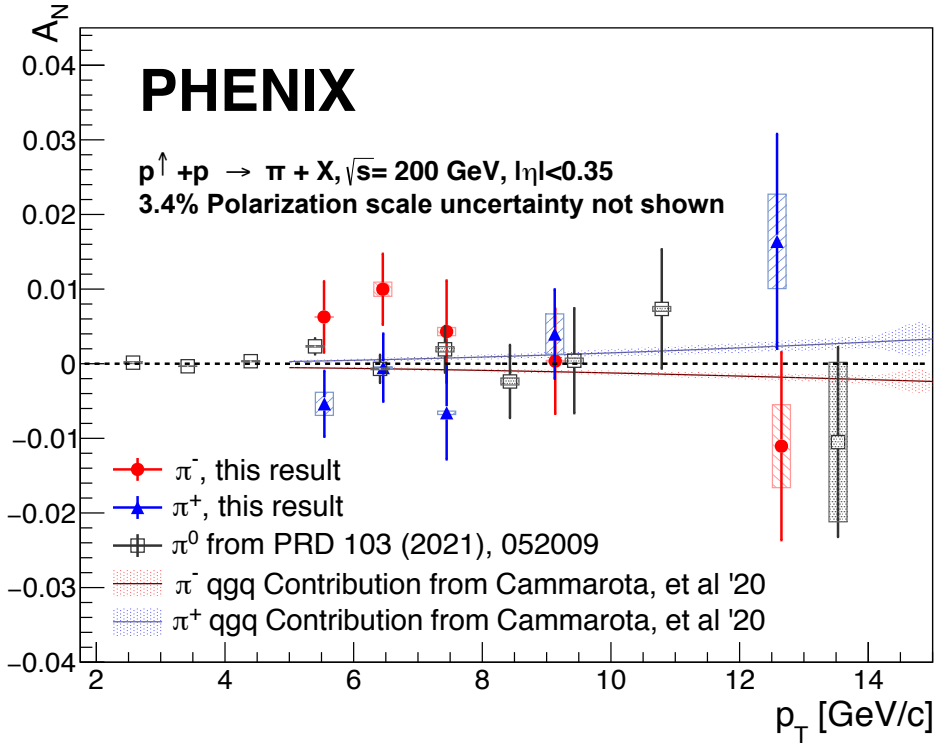
GPM: Generalized parton model.

$\pi^{\pm}$ A_N

- First charged pion A_N.
- Difference between π^+ and π^- at 2σ deviation level.
- A_N $(\pi^{\pm})$ ***vs.*** A_N (π^0)**:** Charge average of charged pion asymmetries consistent with neutral pion asymmetries.

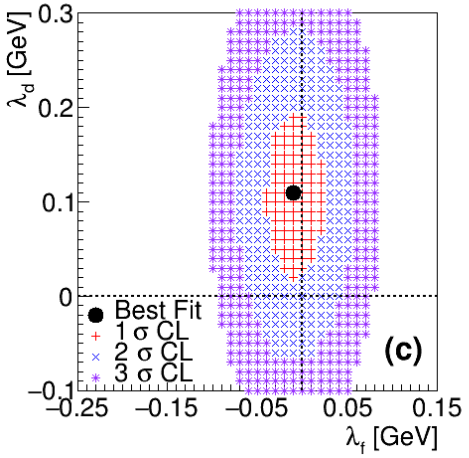
- Provide different flavor sensitivities than neutral particles via fragmentation functions; hard process dominated by qg scattering at high p_T.
- Increasing qgq contribution predicted with hard scale and opposite sign for oppositely charged $\pi's$ (which was seen cancelled in π^0 A_N).
- Can provide additional information on qgq correlators and constrain trigluon correlators.

Phys. Rev. D **105** (2022) 032003



Open heavy flavor A_N

- Charge separated e^+ and e^- A_N.
- Measured asymmetries consistent with zero.
- Most sensitive probe of trigluon correlator; $gg \to Q\bar{Q}$ dominance relative to $q\bar{q} \to Q\bar{Q}$.
- Model calculations provided by two groups rely on normalizing symmetric and antisymmetric trigluon correlators $T_G^{(f,d)}$ to unpolarized gluon PDF.
- First quantitative extraction of trigluon correlators.



$A_N(p^{\uparrow}+p \to HF(e^{+/-}) + X)$

$\sqrt{s}$ = 200 GeV

$|\eta| < 0.35$

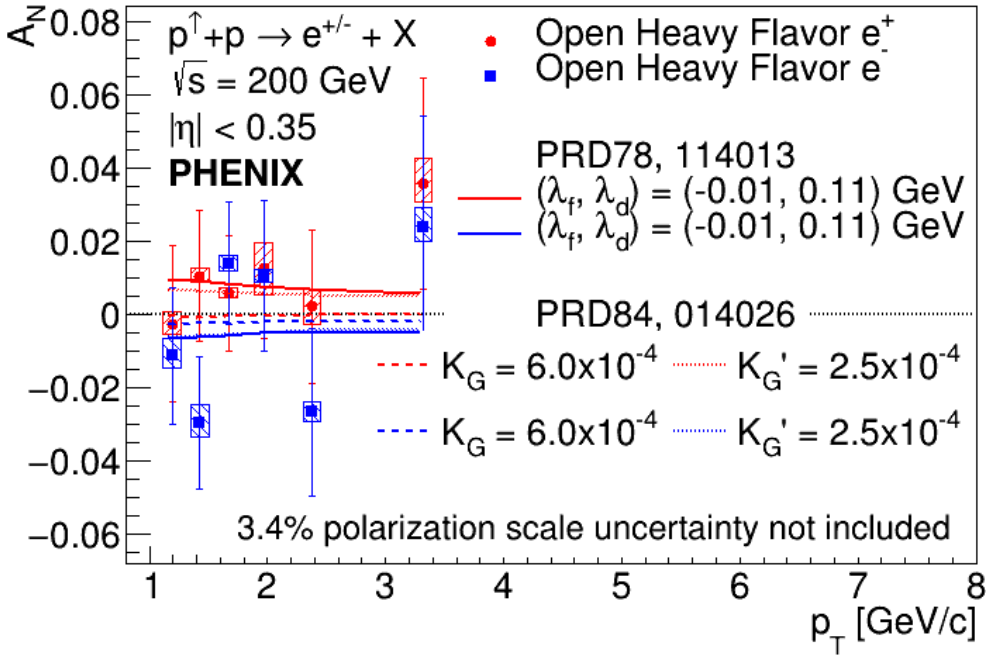
PHENIX

Theory: PRD78, 114013

$A_N^{D^0/\bar{D}^0 \to e^{+/-}}(\lambda_f,\lambda_d)$

$$T_G^{(f,d)}(x,x) = \lambda_{f,d}\, G(x)$$

arXiv:2204.12899



Best fit results:

PRD78, 114013 Kang-Qiu-Vogelsang-Yuan

λ_f = -0.01 ± 0.03 GeV

λ_d = 0.11 ± 0.09 GeV

PRD84, 014026 Koike-Yosida model

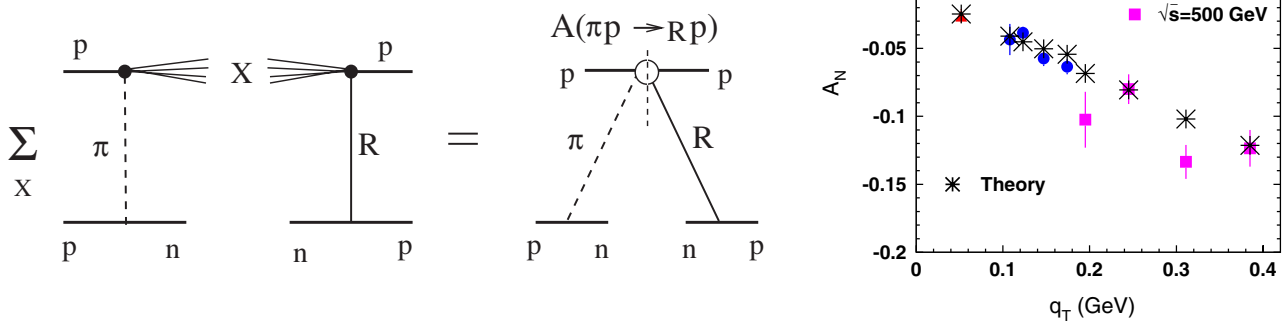
K_G = 6.0x10-4 (+0.0014 -0.0017)

K_G, = 2.5x10-4 (± 0.00025)

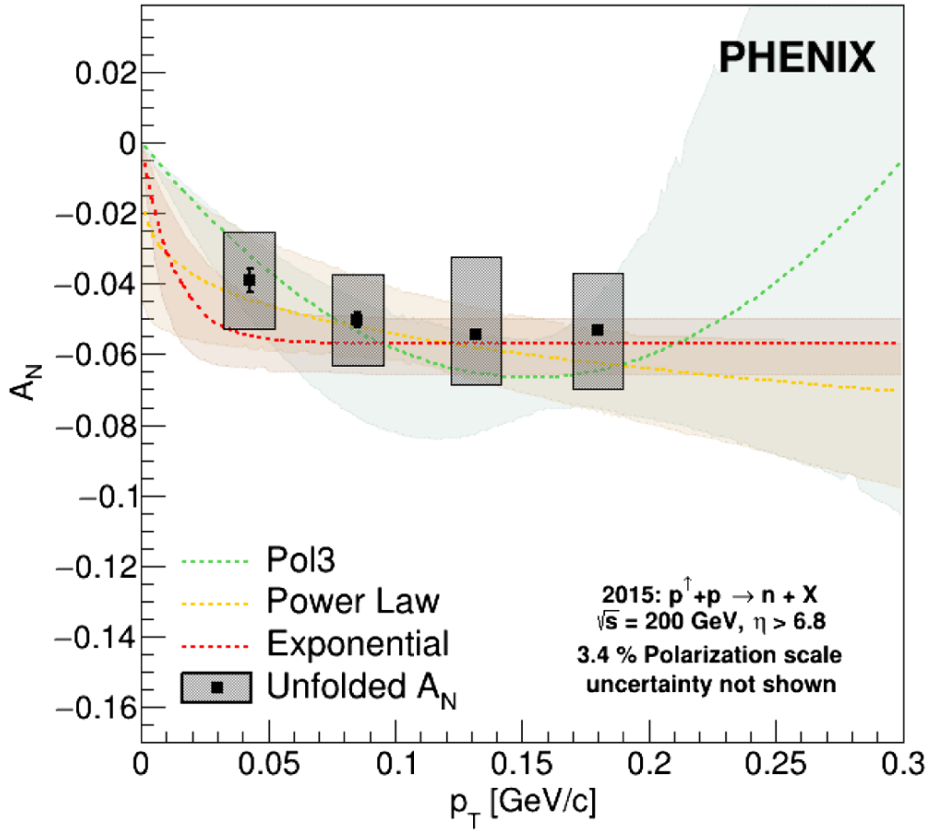
Forward neutron A_N in p+p

- Hadronic interactions based model:
  - Interference between amplitudes with π and Reggeon exchange proposed to be dominant source of asymmetries in $p_T < 0.2$ GeV.
  - Negative A_N and linear dependence with p_T predicted by π–R interference; not sufficient to describe data

Phys. Rev. D **84** (2011) 114012



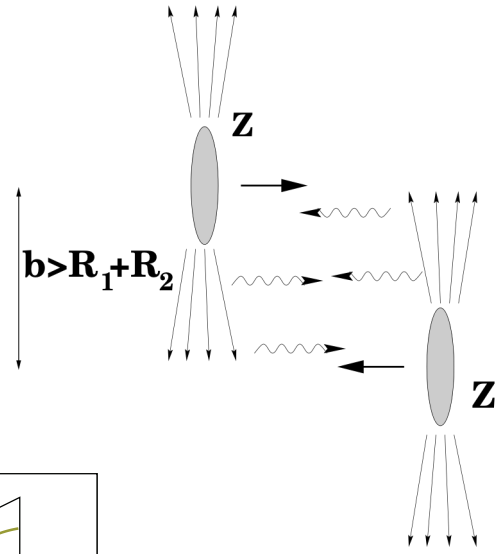
Phys. Rev. D **103** (2021) 032007



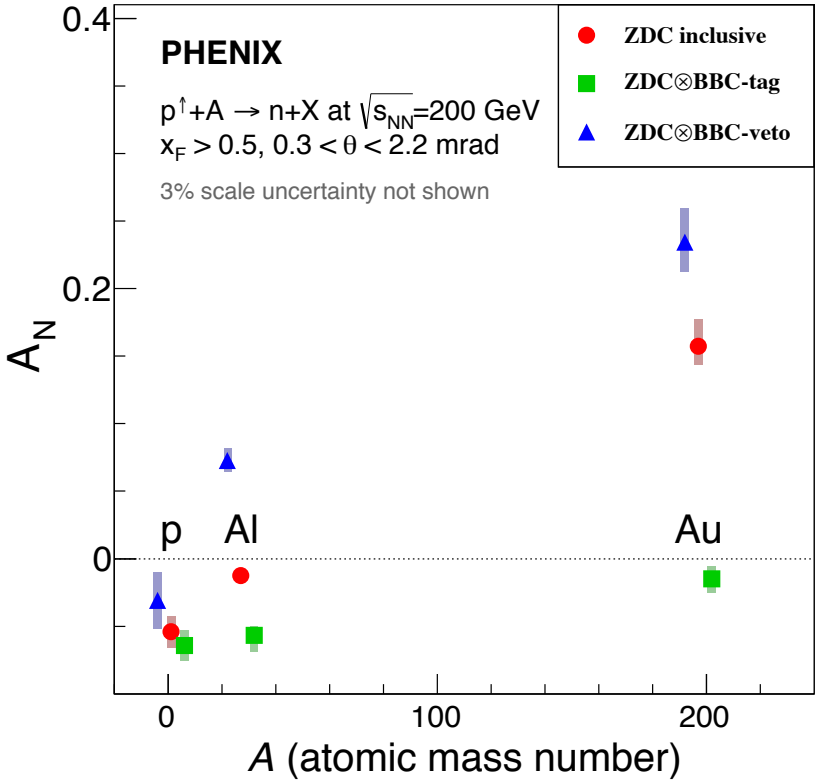
Forward neutron A_N in p+A

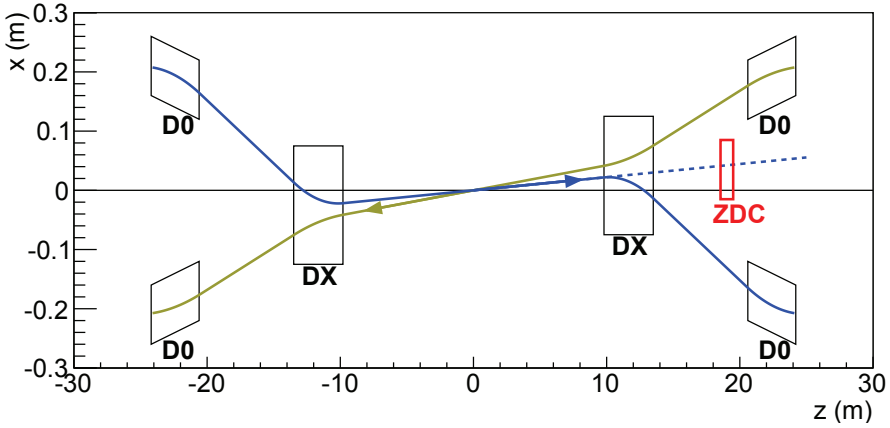
- Ultra Peripheral Collision (UPC)
  - Positive A_N with Z^2 dependence due to EM interaction.

Phys. Rept. **163** (1988) 299



Phys. Rev. Lett. **120** (2018) 022001

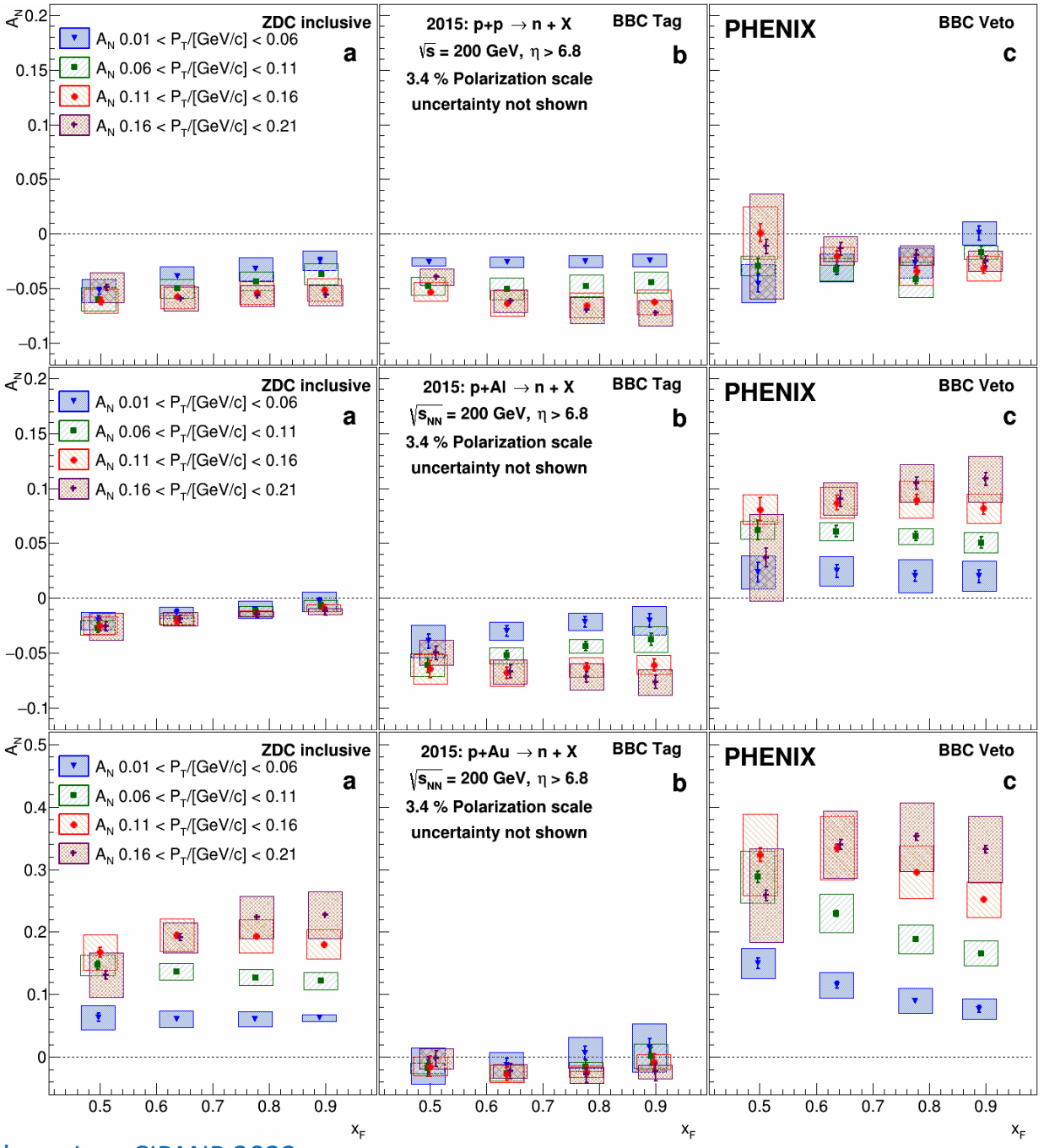




- Selection of two mutually exclusive event types:
  - ZDC⊗BBC- tag ($N \cap S$): hadronic interactions.
  - ZDC⊗BBC- veto ($\bar{N} \cap \bar{S}$): UPC interactions.

Forward neutron A_N in p+A

- p_T and x_F dependence.
- A_N stays negative and approaches zero in hadronic interaction enhanced data.
- Nuclear dependence of A_N amplified in UPC enhanced data.



Phys. Rev. D **105** (2022) 032004

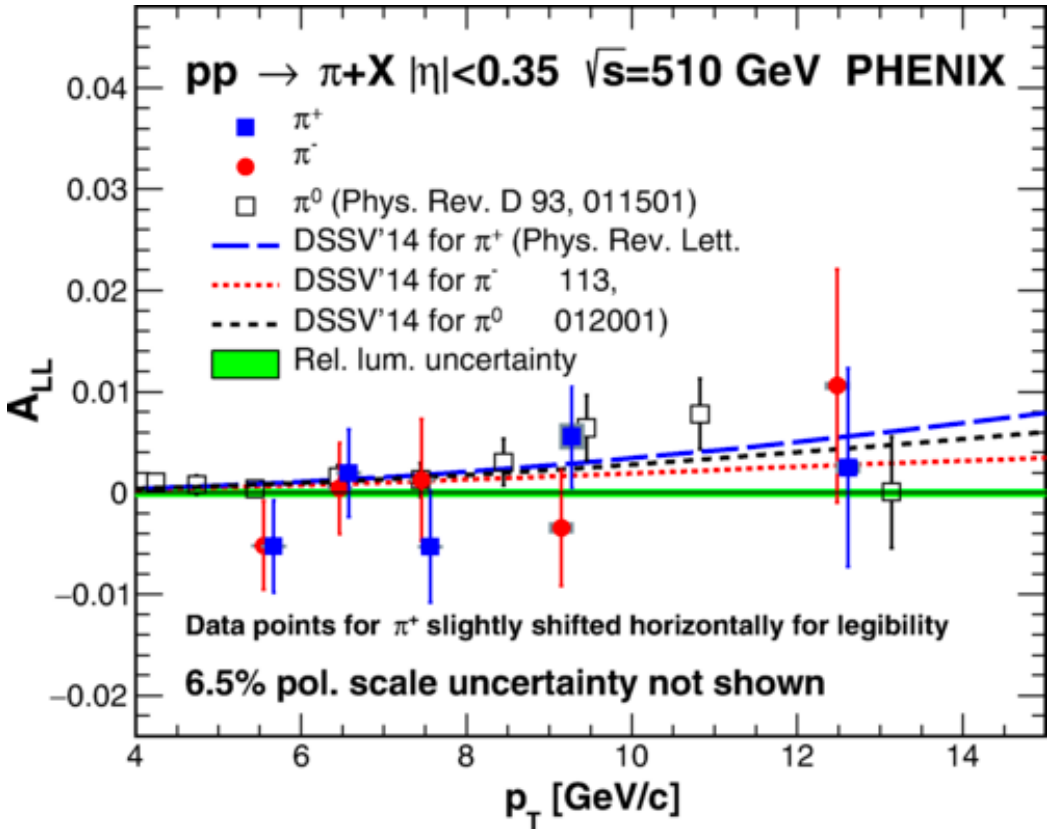
Summary

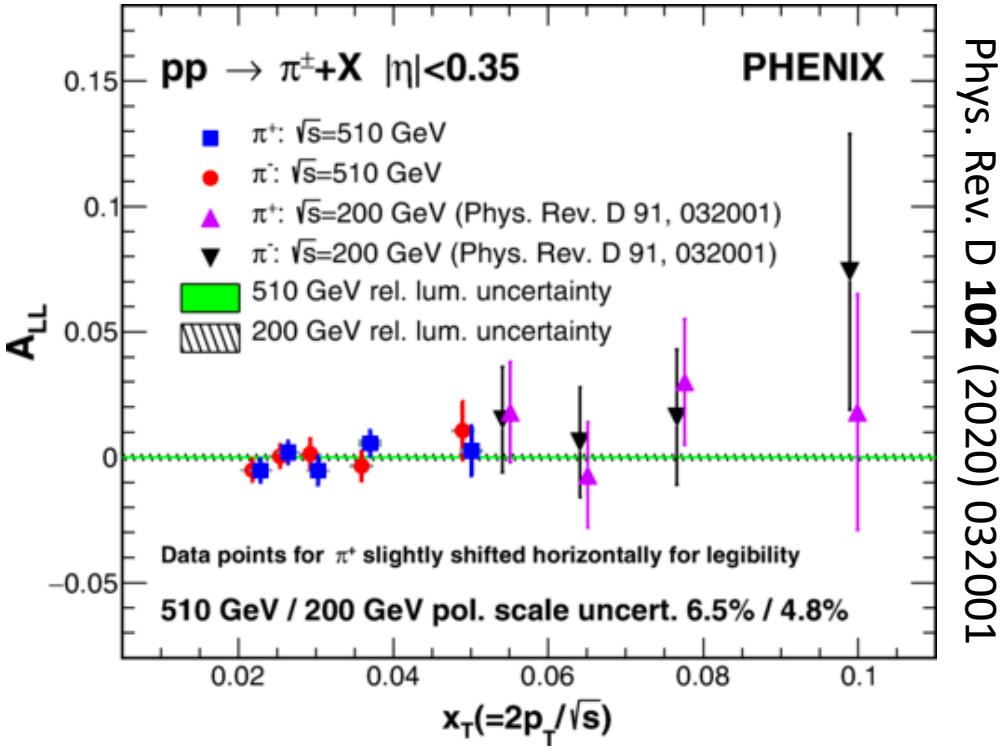
- PHENIX measured first direct photon cross sections and A_{LL}. Theoretically favorable, but statistically limited. Isolated production and asymmetries consistent with NLO predictions.
- A set of new TSSA measurements sensitive to qgq and trigluon correlators;
  - Direct photon, open heavy flavor measurements most clean and sensitive to qgq correlators. First quantitative estimations obtained using OHF measurements.
  - Neutral hadrons moderately sensitive to trigluon correlators with suppressed qgq contribution expected.
  - Charged $\boldsymbol{\pi}^{\pm}$ asymmetries provide more information on qgq correlators that is cancelled between opposite charges in neutral hadrons.
- Forward neutron TSSA measurements revealed different mechanisms in generating asymmetries in the forward region; Hadronic interactions results in mostly negative asymmetries and show little to no nuclear dependence while UPC interactions show positive asymmetries and strong nuclear dependence.

Thank you!

Charged pion A_{LL}

Phys. Rev. D **102** (2020) 032001

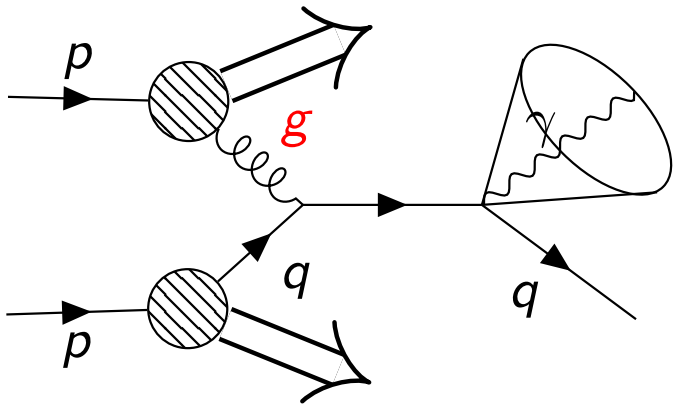




Phys. Rev. D **102** (2020) 032001

- Lower x reach compared to previously published 200 GeV A_{LL} data.
- Ideally sign of $\Delta g(x)$ visible in charge ordering of pion A_{LL}s.
- Statistics limited due to EM shower based trigger, but important input for global fits.

Identifying direct photon through isolation

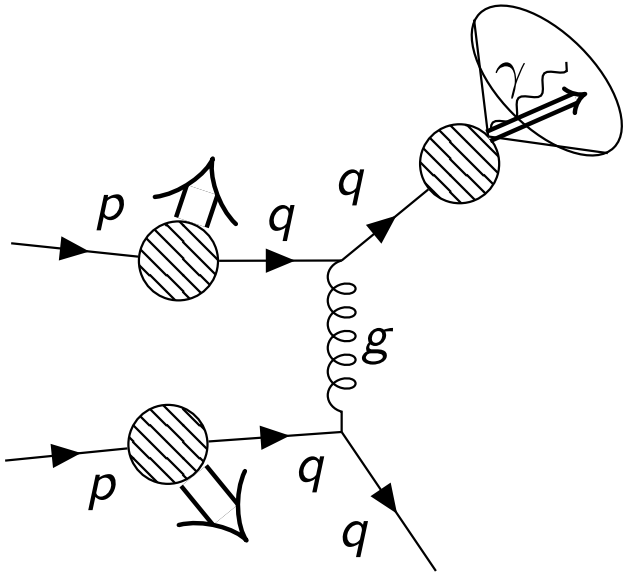


$$r_{cone} = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} = 0.5$$

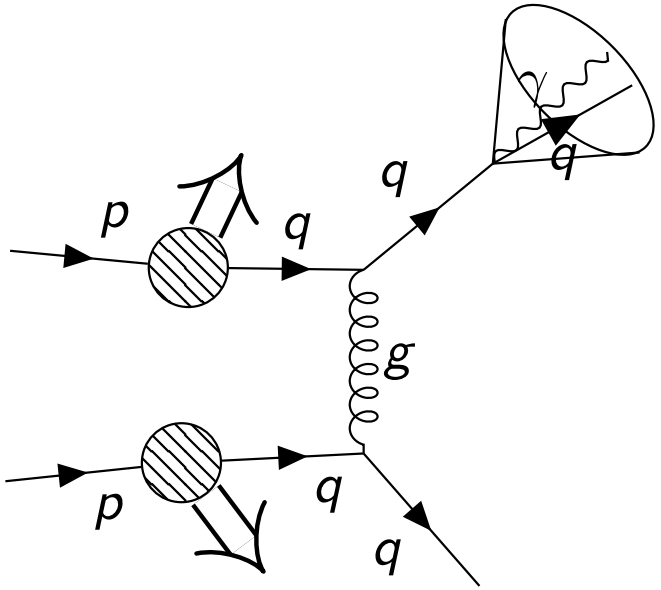
Isolation cut requirement:

$$\sum E_{in\ cone} < 0.1 E_\gamma$$

Quark-gluon Compton scattering: Easy to pass isolation cut



Fragmentation: Hard to pass isolation cut



Bremsstrahlung: Hard to pass isolation cut