# PHENIX/sPHENIX/EIC spin and cold QCD topics

**Korea Japan Workshop,**
**July 15/16**

**Ralf Seidl (RIKEN)**

# Main QCD Spin Questions

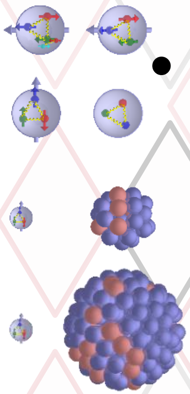
- How is the spin of the proton distributed? What is the role of gluons and sea quarks?
- What is the origin of transverse spin effects and how does it relate to the 3D momentum and position structure of the Nucleon?
- Closely intertwined: How does QCD create 99% of the visible mass of the universe? How does confinement work?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_G + \mathcal{L}_q$$

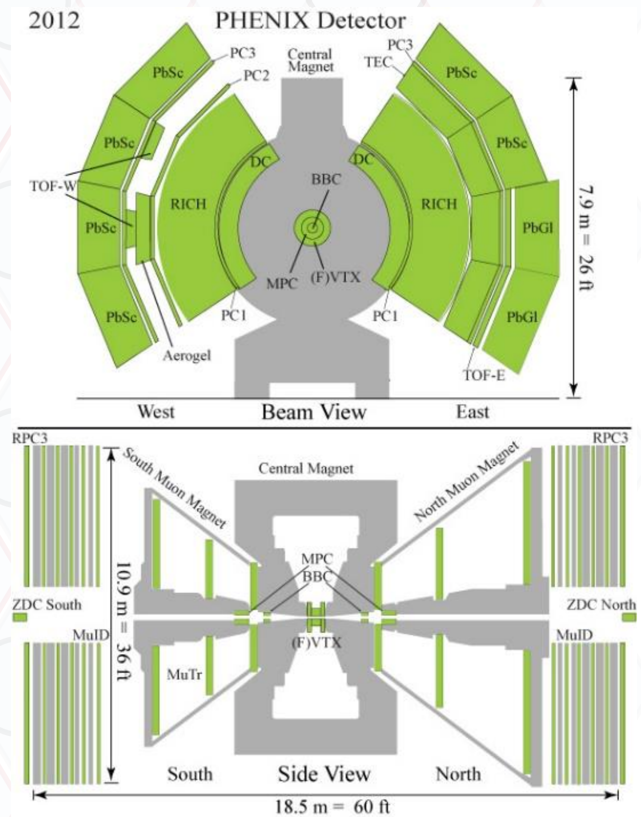
➔ Sivers, Collins effects, TMDs GPDs, orbital angular momentum, Tomography

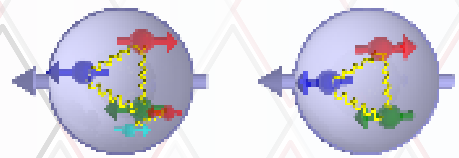
➔ Fragmentation functions and their spin, flavor, type, long. and transverse momentum dependence

# Facilities and experiments



- RHIC (@BNL):
  - longitudinally and transversely polarized p+p and p+A collisions from $\sqrt{s}$ of 62 to 510 (200) GeV beams
- PHENIX:
  - 2 Central Arms: 90 degree coverage each in η<0.35. Good EM Calorimetry, tracking, PID
  - 2 muon arms 1.2<|η|<2.4





$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_G + \mathcal{L}_q$$

# Longitudinal Spin

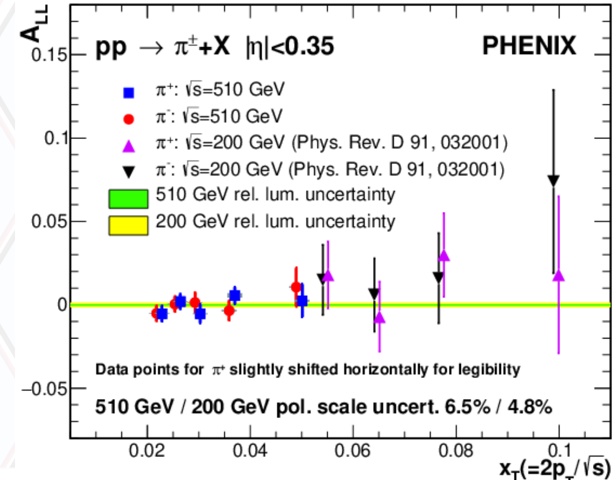
Main questions at RHIC:

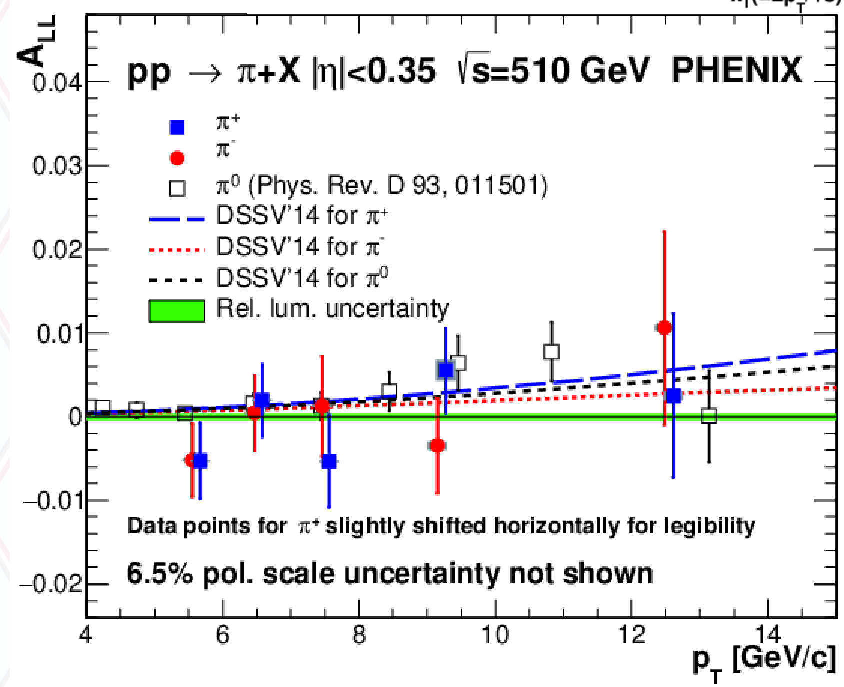
- Gluon spin contribution
- Role of sea quarks (light sea symmetry, strange sea)

Analyzer: Taebong Moon $\Delta g(x)$

# Charged pion $A_{LL}$s at 510 GeV

- Addition of charged and neutral pion results at higher $\sqrt{s}$
- 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

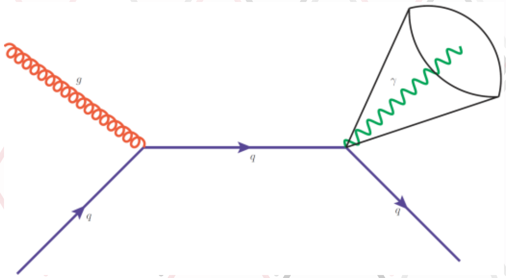


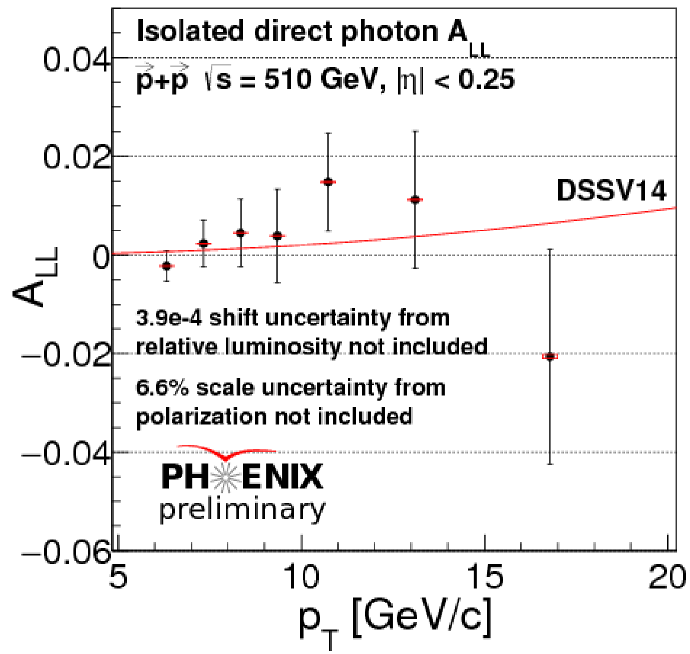



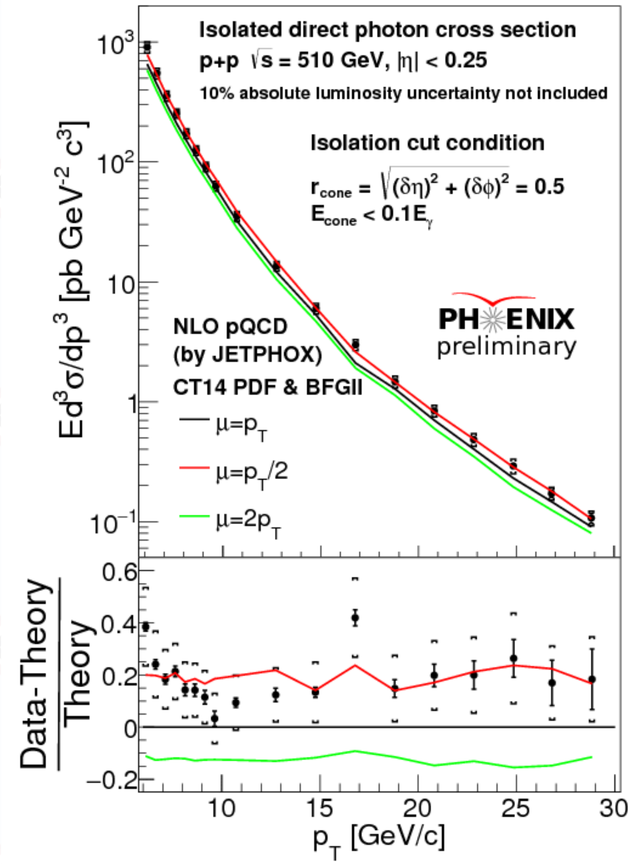

*Phys.Rev.D* 102 (2020) 3, 032001

$\Delta g(x)$

# First direct photon xsec and $A_{LL}$ at 510 GeV






- Part of initial RHIC-Spin suggestions in the \`90s
- Theoretically, the Golden channel to access gluon polarization as hard interaction mostly q-g
- Since EM process, statistically limited but consistent with global fit results

Analyzers: Chong Kim, Sanghwa Park

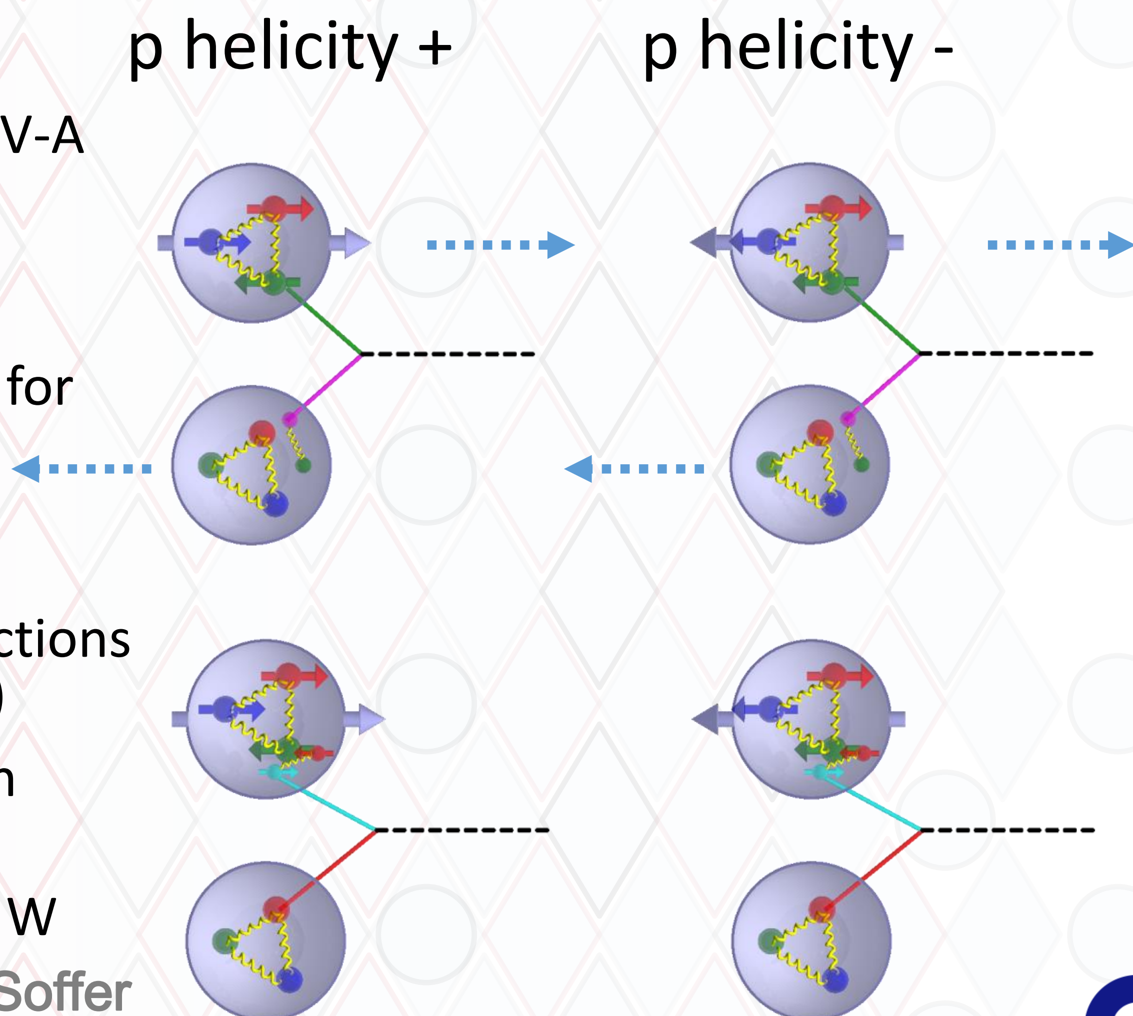
# Real W production as access to (anti)quark helicities

- Maximally parity violating V-A interaction selects only lefthanded quarks and righthanded antiquarks:

➔Having different helicities for the incoming proton then selects spin parallel or antiparallel of the quarks

➔Difference of the cross sections gives quark helicities $\Delta q(x)$

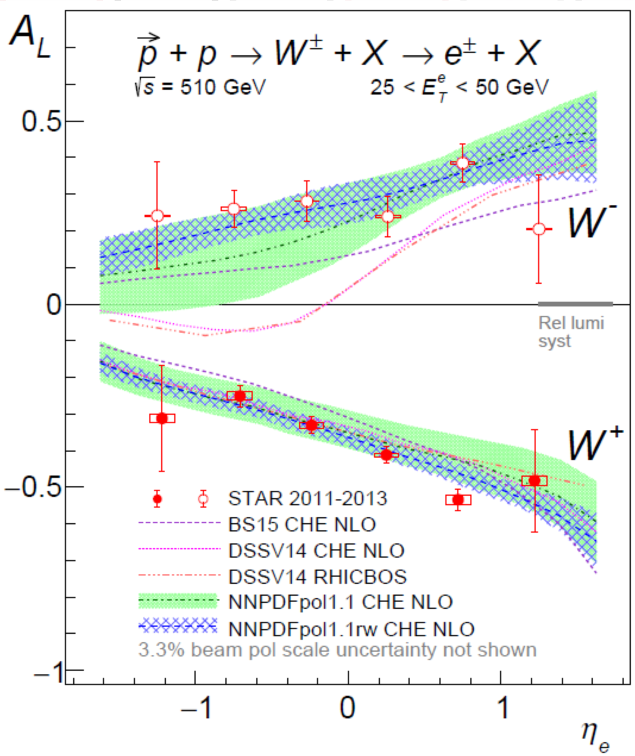
- No Fragmentation function required
- Very high scale defined by W mass



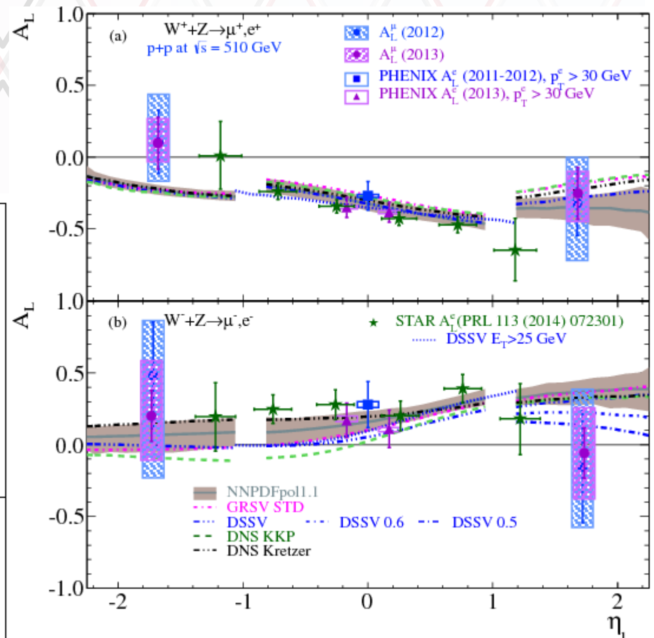

Bourrely , Soffer
Nucl.Phys. B423 (1994) 329-348

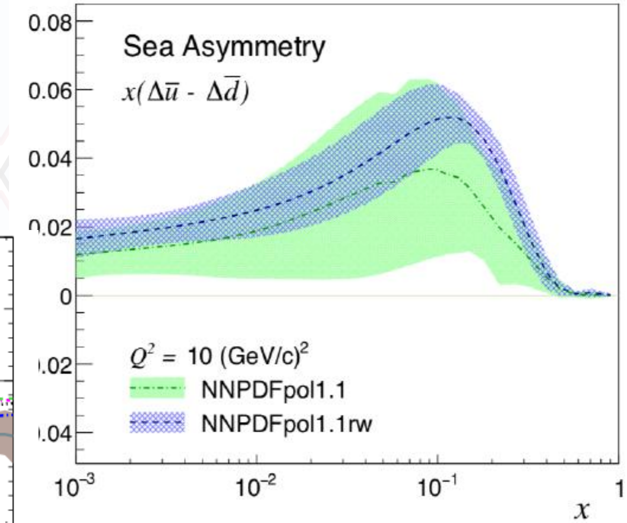
# W measurements

PRD99 (2019) 051102




PRD 98 (2018) 032007



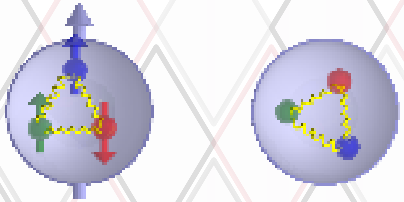

Only reweighting exercise for STAR data so far, no global fit with all W data, yet

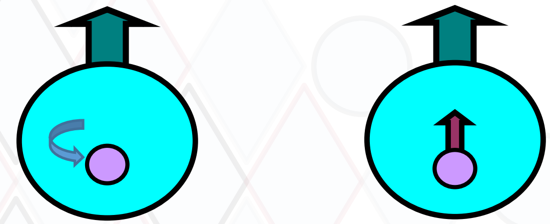
- Clearly asymmetric polarized sea seen with all of longitudinal 510 GeV running analyzed
- Sea quark helicities well constrained at x>0.1
- Asymmetric sea rules out simple pion-cloud models!

# Transverse spin

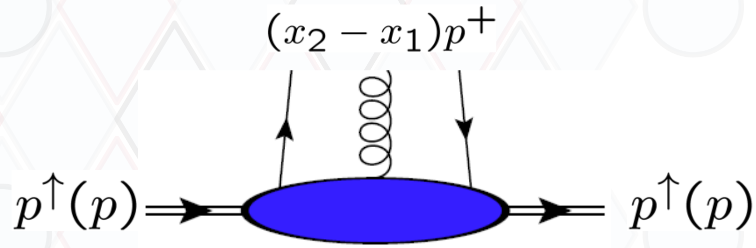
Main questions:

- Origin of large $A_N$s: initial state? Final state?
- Connections between higher twist and TMDs
- Nuclear/low-x modification of $A_N$s?

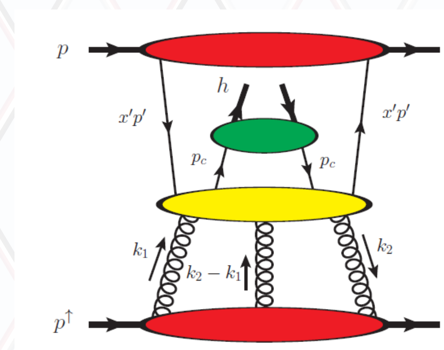




Sivers Transversity




q-g correlation

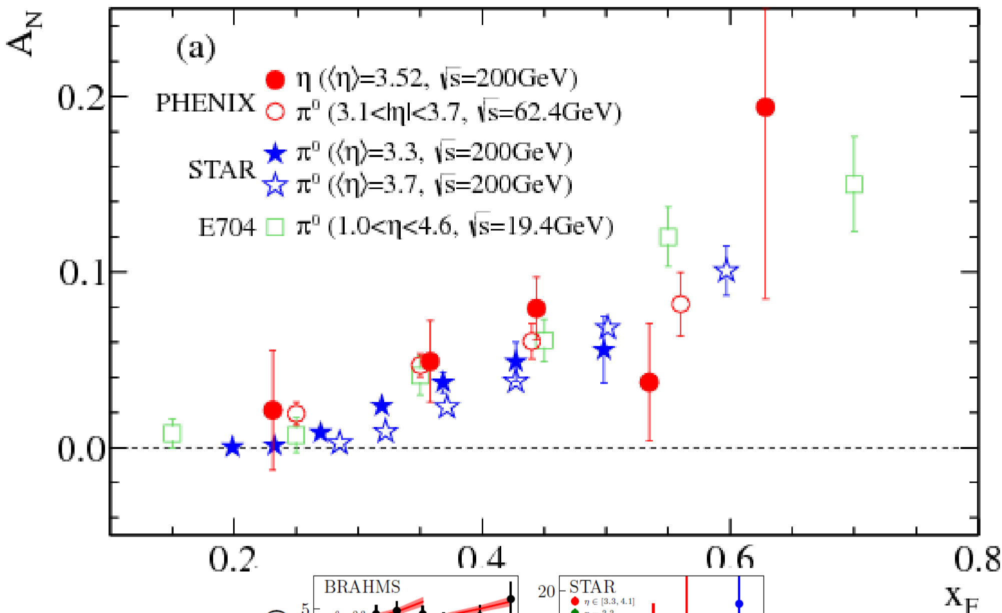


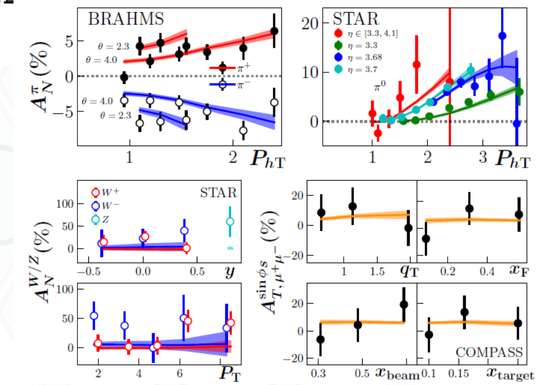

g-g correlation (trigluon)

# Transverse single spin asymmetries

- Large left-right asymmetries $A_N$ seen in polarized pp collisions from low energies up to highest RHIC energies
- Both initial state and final state effects contribute in the same asymmetries
- TMD interpretation not directly applicable as only one scale process instead of 2 scales ($P_T$ in p+p vs $Q^2$ and $P_{hT}$)
- Higher twist interpretation is applicable; related to the TMD moments

Phys.Rev. D90 (2014) 7, 072008
Phys.Rev. D90 (2014) 1, 012006

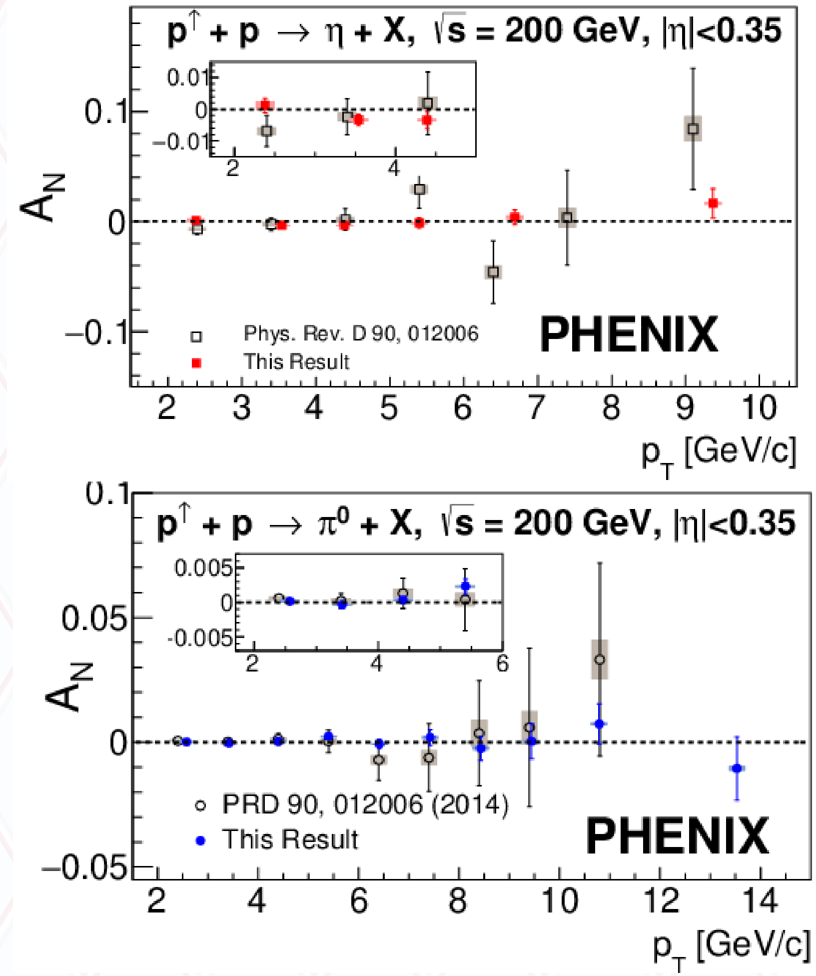


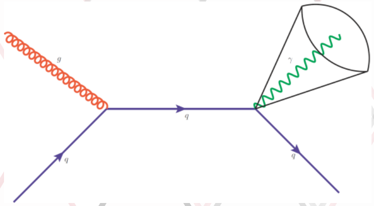
# Updated precision for central $A_N$s

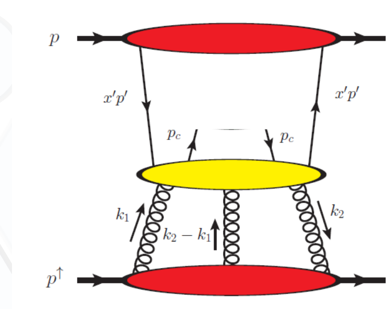
[PRD 103 (2021) 052009](#)

- Substantial updates for $\pi^0$ and $\eta$ single spin asymmetries at central rapidity
- Possible effects pushed below the 1% level
- sensitive to quark-gluon and tri-gluon correlation functions in initial and final state effects



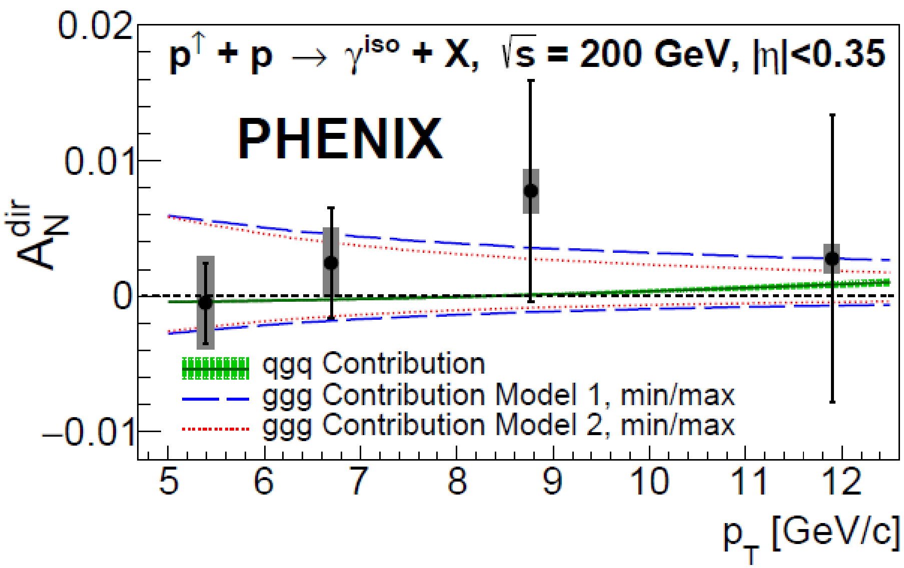
# First direct photon $A_N$s

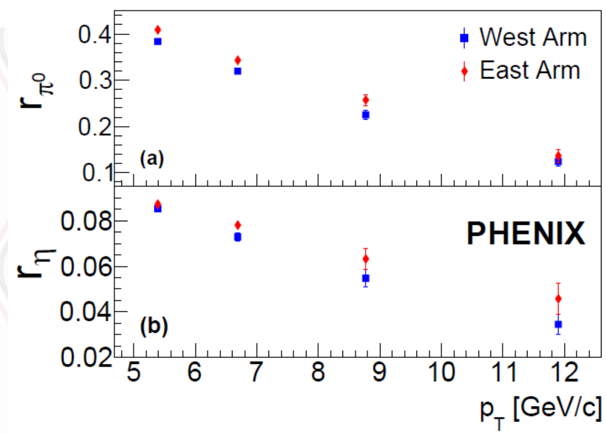





- First direct photon $A_N$ extracted at RHIC
- Mostly sensitive to initial state effects (no fragmentation) → quark-gluon and gluon-gluon correlation functions
- Power to constrain gluon-gluon correlation function as well

Submitted to PRL

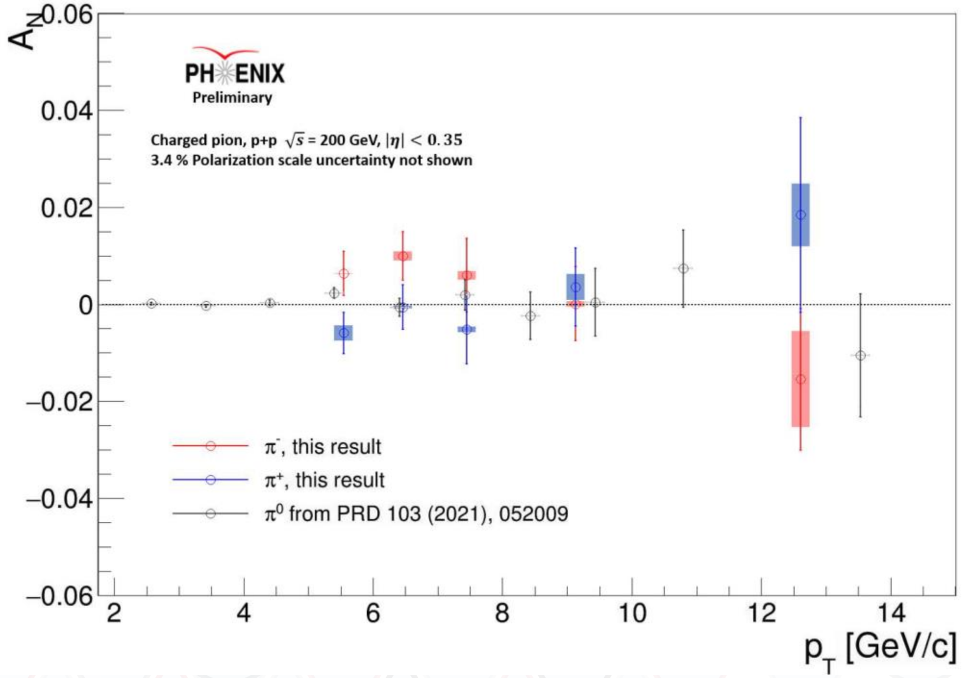


Analyzer: JaeHee Yoo

# Charged pion $A_N$s at mid-rapidity

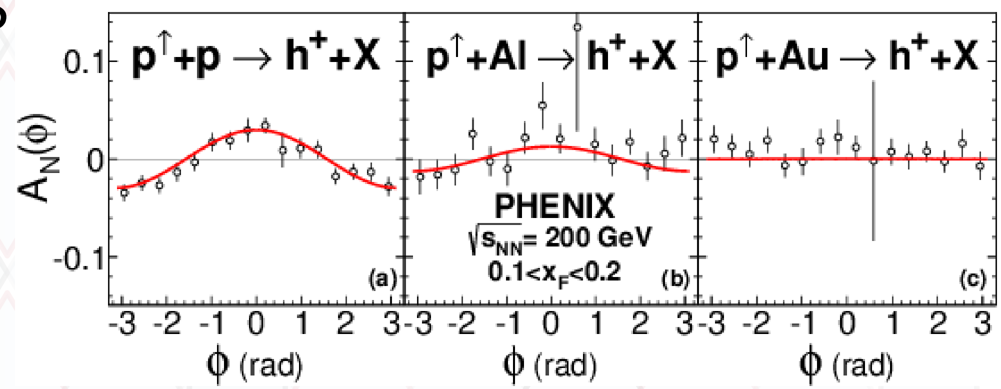
- Charged pion $A_N$ consistent with zero and $\pi^0$ results for each charge
- But indication of differences between charges seen



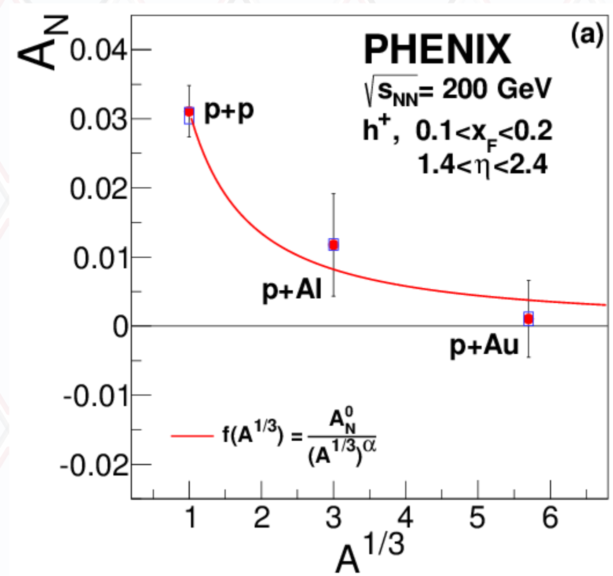
Analyzer: Jeongsu Bok

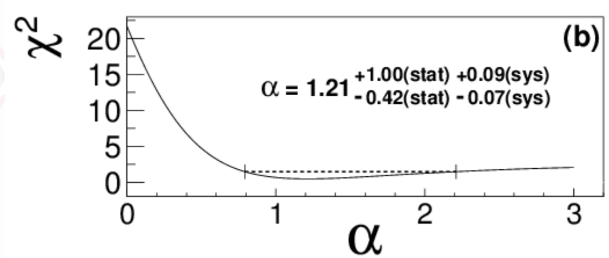
Phys.Rev.Lett. 123 (2019) 122001

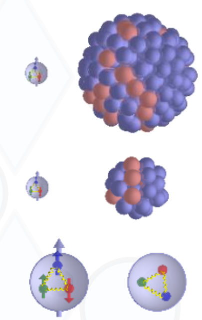
# A dependence of $A_N$s




- Asymmetries consistent with $A^{1/3}$ dependence as (initially) predicted by some CGC related nuclear effects (Hatta`17)
- No A dependence is ruled out
- Also consistent with suppression with increasing number of binary collisions
- However, probed x and scale too large for expected CGC effects! (S.Benic and Y.Hatta, PRD99, 094012 - Twist-3 fragmentation + gluon saturation)



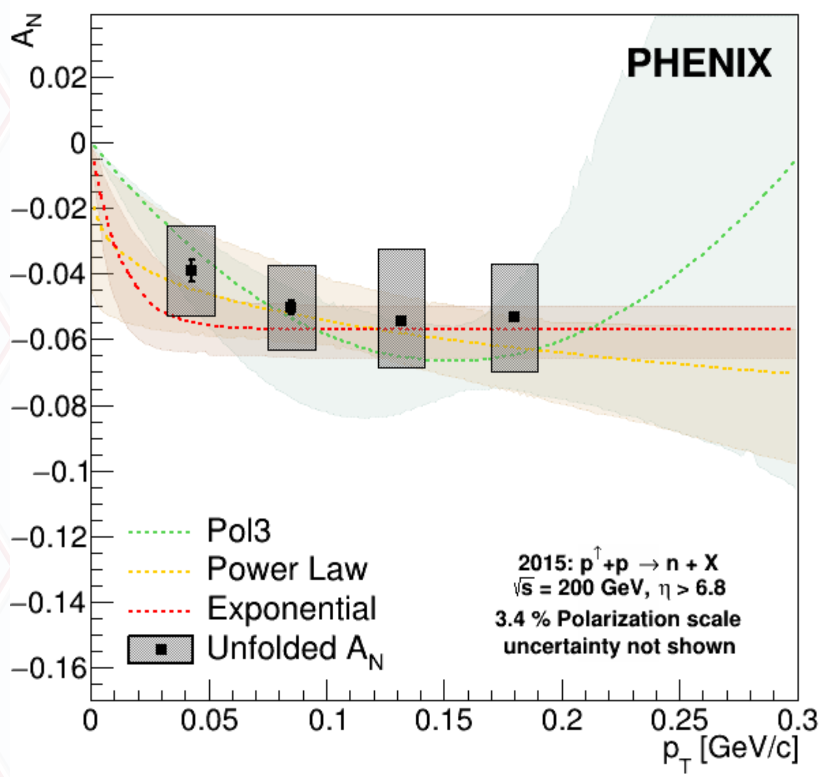



Analyzer: Benard Mulilo, Minjung Kim

# p+p unfolded forward neutron $A_N$s

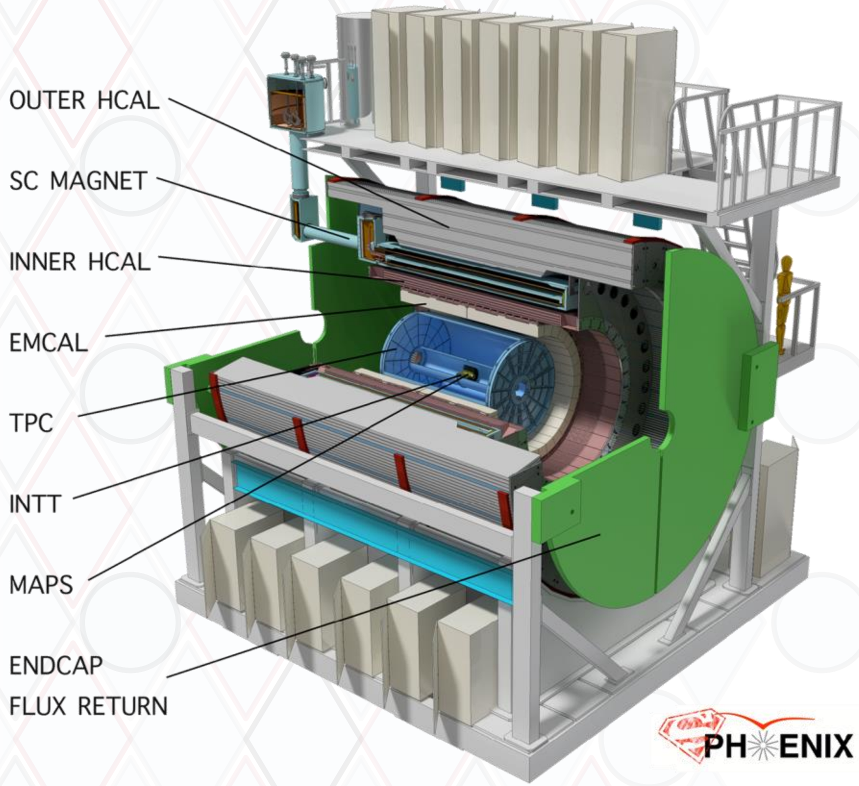
PRD 103 (2021) 032007

- First explicity transverse momentum dependent of p+p forward neutron asymmetries
- Initially rising asymmetries
- Indication of levelling off at higher transverse momenta
- Theory predictions (Kopeliovitch *PRD 84 (2011) 114012*) based on only hadronic processes suggests linear dependence



# sPHENIX

- Compact detector with good Jet and tracking capabilities over large range ($|\eta|<1.4$)
- Main purpose for remaining HI physics such as jet and Upsilon state $R_{AA}$ measurements
- Many cold-QCD possibilities



# Proposed run schedule, year 1-3

sPHENIX BUP2021 [sPH-TRG-2021-001], 24 (& 28) cryo-week scenarios

| Year | Species | $\sqrt{s_{NN}}$ [GeV] | Cryo Weeks | Physics Weeks | Rec. Lum. $\|z\| < 10$ cm | Samp. Lum. $\|z\| < 10$ cm |
|---|---|---|---|---|---|---|
| 2023 | Au+Au | 200 | 24 (28) | 9 (13) | 3.7 (5.7) $nb^{-1}$ | 4.5 (6.9) $nb^{-1}$ |
| 2024 | $p^{\uparrow}p^{\uparrow}$ | 200 | 24 (28) | 12 (16) | 0.3 (0.4) $pb^{-1}$ [5 kHz]<br>4.5 (6.2) $pb^{-1}$ [10%-$str$] | 45 (62) $pb^{-1}$ |
| 2024 | $p^{\uparrow}$+Au | 200 | – | 5 | 0.003 $pb^{-1}$ [5 kHz]<br>0.01 $pb^{-1}$ [10%-$str$] | 0.11 $pb^{-1}$ |
| 2025 | Au+Au | 200 | 24 (28) | 20.5 (24.5) | 13 (15) $nb^{-1}$ | 21 (25) $nb^{-1}$ |

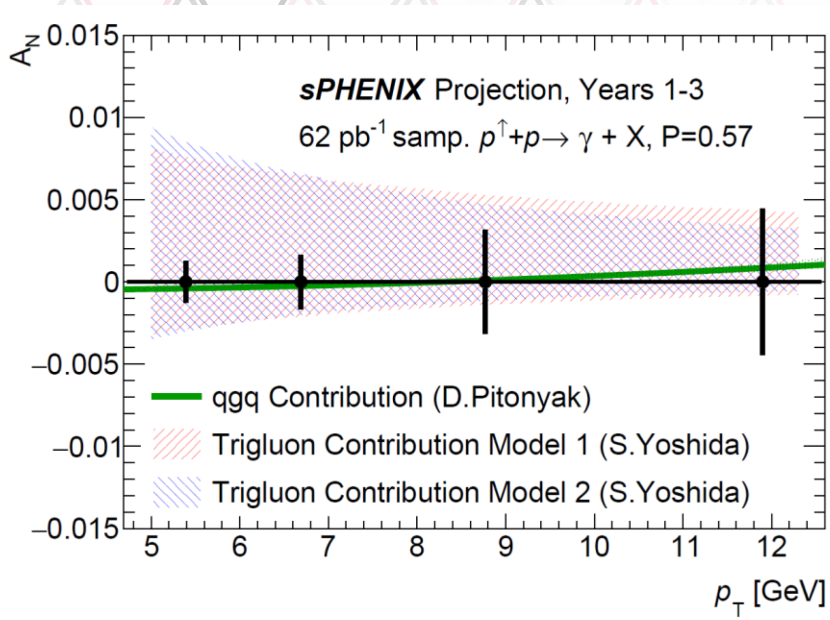
sPHENIX asked to consider
20-28 week runs in 2024

- (Trans-)polarized $p + p$, $p + A$ with streaming readout for 28 weeks in Run24
- But short Run24 would endanger the $p + A$ data!

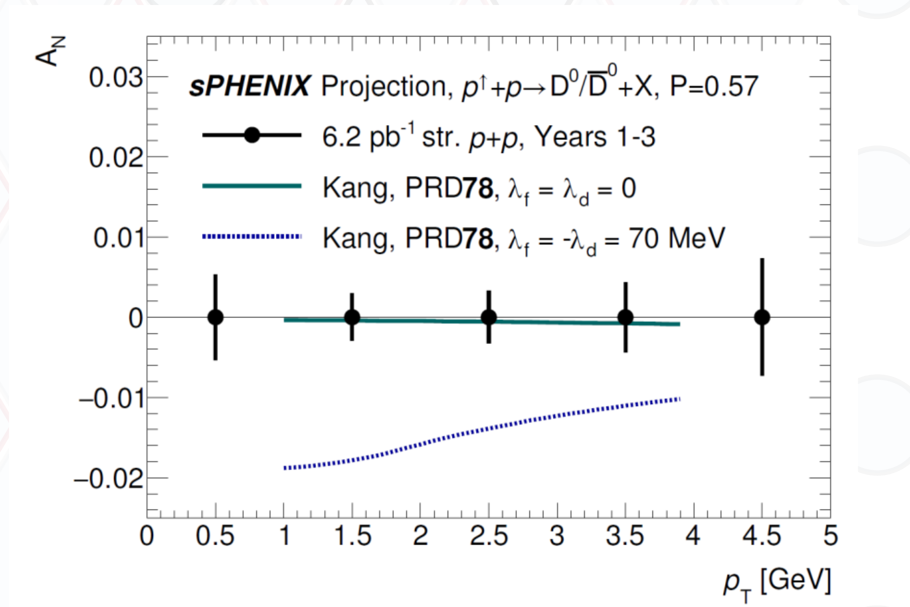
# Gluon dynamics via γ, HF TSSA

sPHENIX BUP2021 [sPH-TRG-2021-001]

**TSSA of prompt photon**
**EMCal-based trigger**



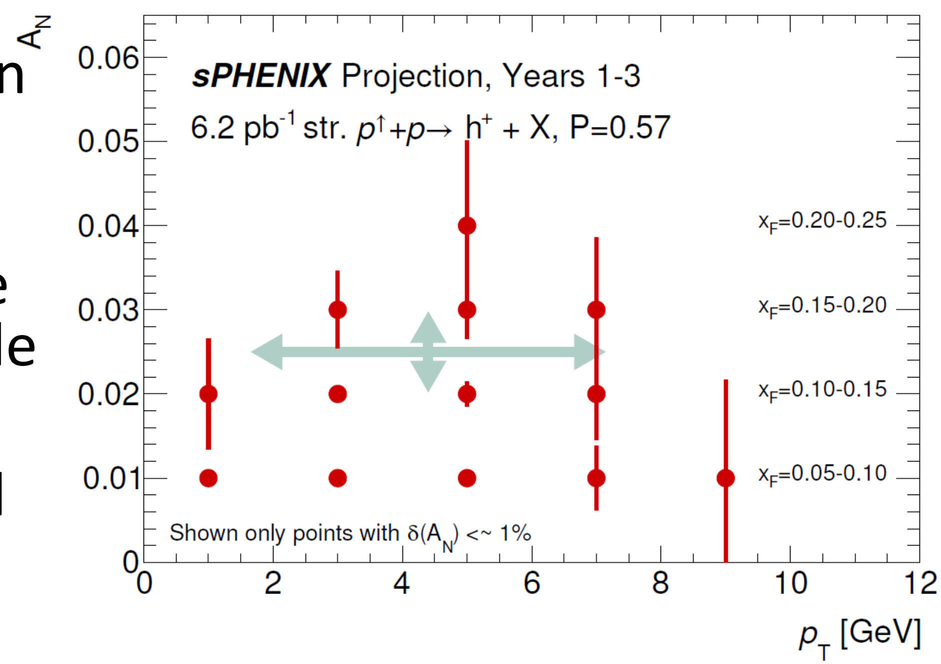

**TSSA of prompt $D^0 \rightarrow \pi K$**
**Enabled by streaming readout**



# Nature of hadron $A_N$ in pp and its nuclear modification

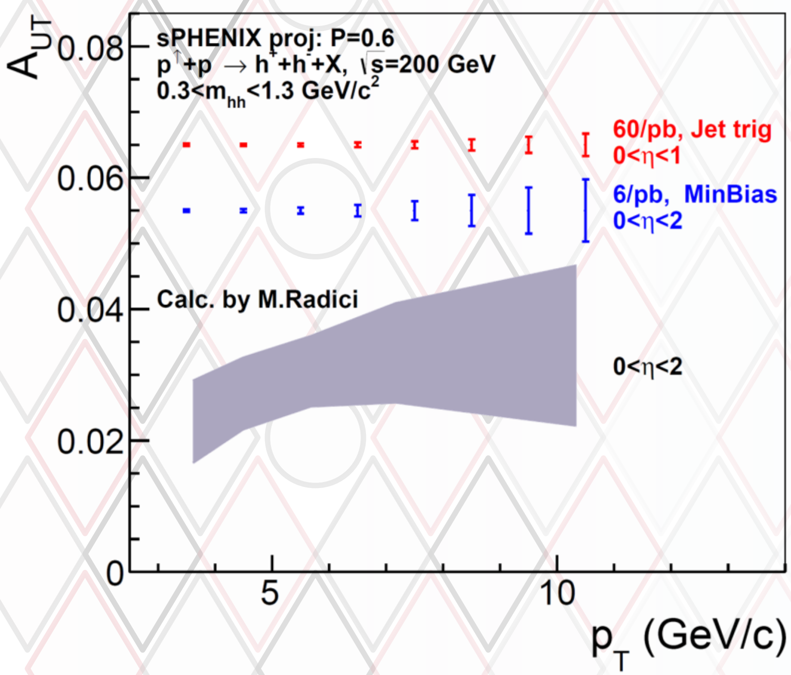
- PHENIX and STAR show significant different suppression of hadron $A_N$ from pp to pA in distinct kinematic regions
- sPHENIX hadron $A_N$ will explore wider region to help disentangle initial/final state effects
- Enabled by streaming recorded $p+p$ collision from far vertex collisions

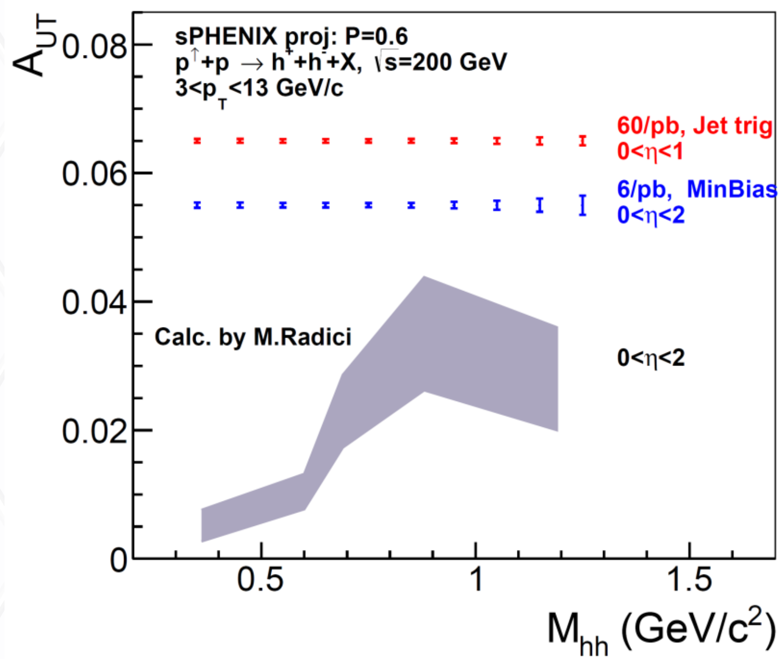
sPHENIX BUP2021 [sPH-TRG-2021-001]



# Transversity via charged particle IFF

- Tremendous stat. enabled by both calorimetric jet trigger and streaming readout
- Need theory collaboration in the treatment of no-PID charged tracks & multi-dim binning
- Similarly: Sensitivity via Collins fragmentation function (hadron in jet measurements)

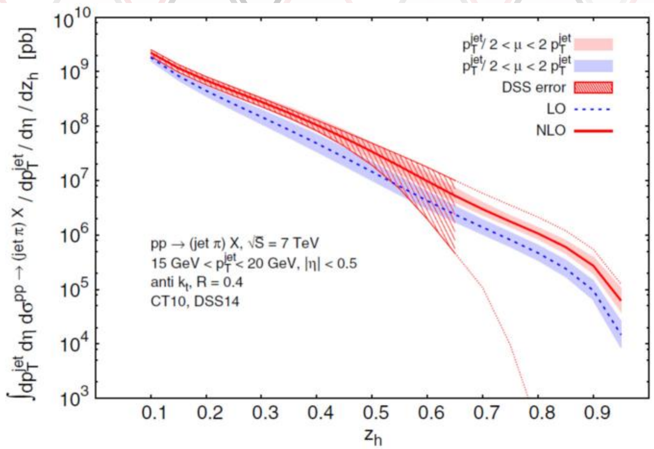


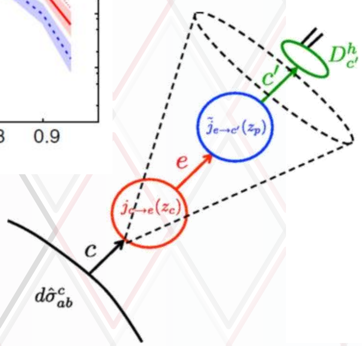



# Fragmentation in p+A

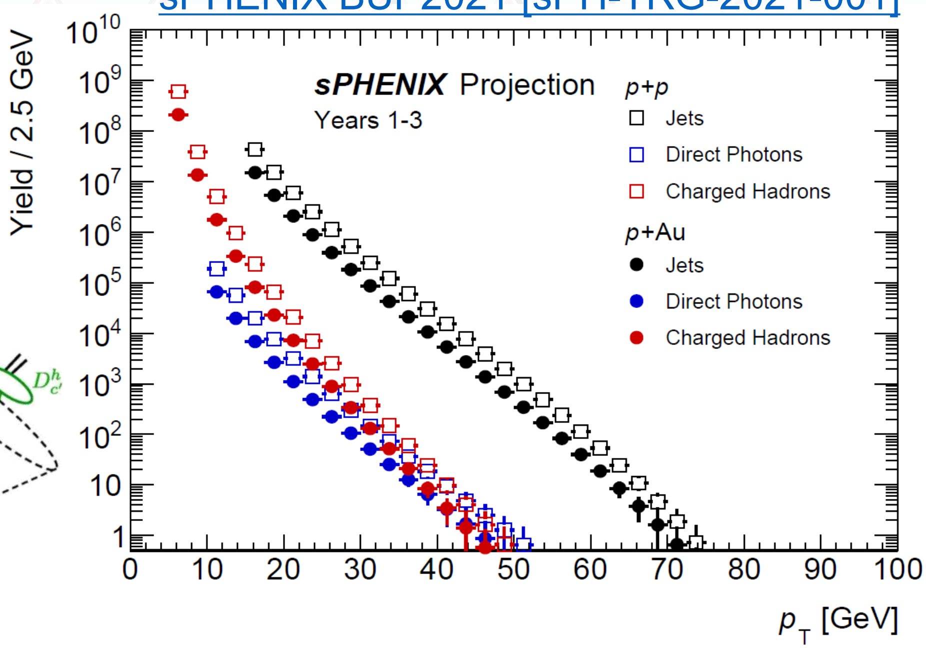
- Access gluon fragmentation function (FF) in $p + p,\ \ p + A$ via jet FF
- Calorimetric triggered jet + precision tracking

Kaufmann et al. PRD 92 5, 054015

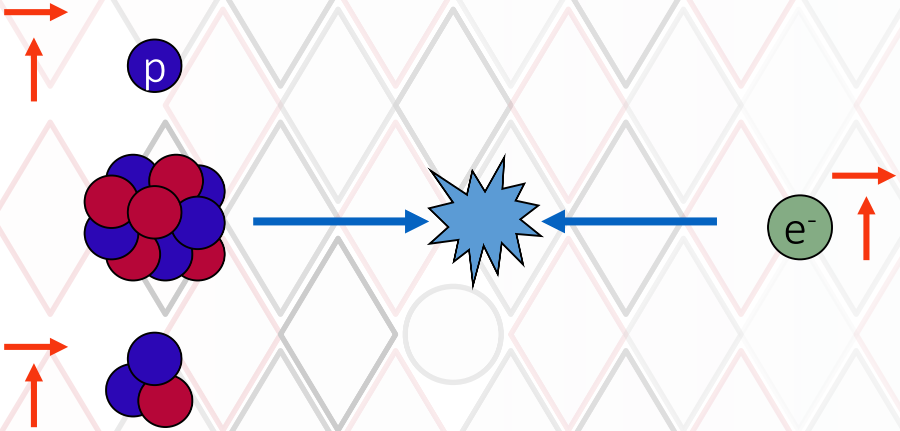


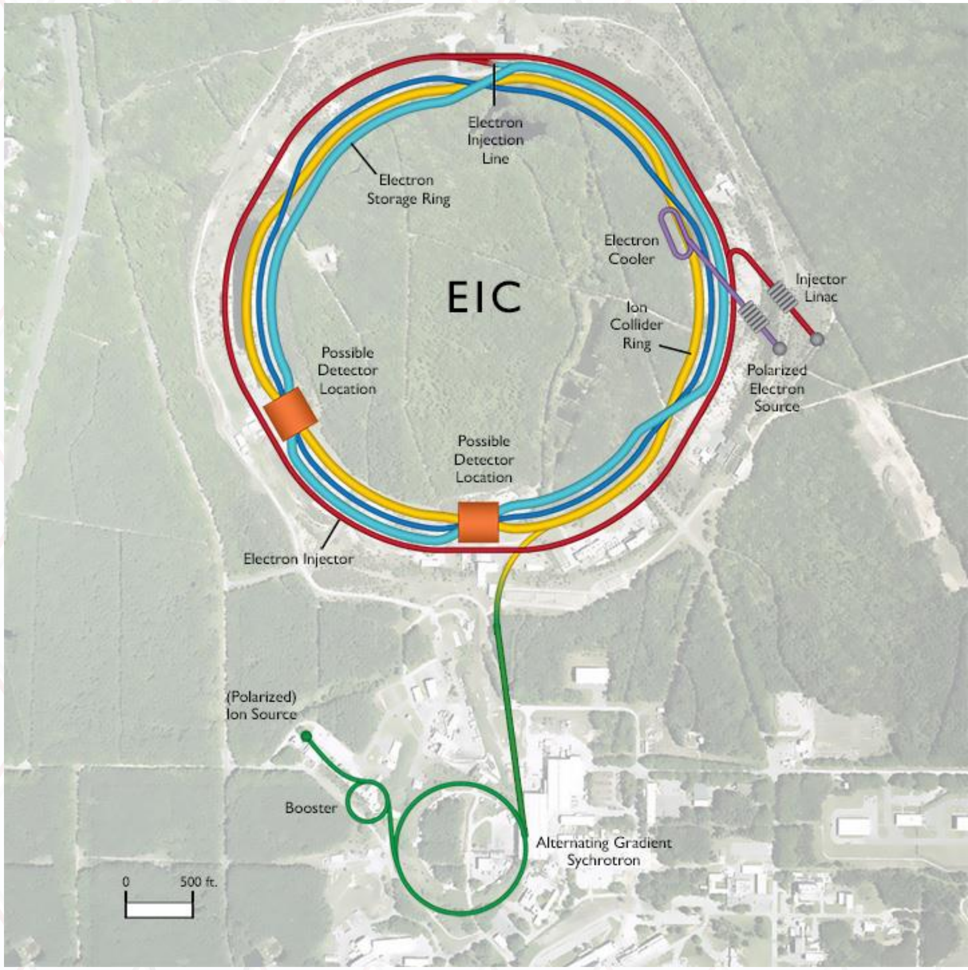



sPHENIX BUP2021 [sPH-TRG-2021-001]



# EIC accelerator to be build at BNL




- 80% polarized electrons from 5-18 GeV
- 70% polarized protons from 40-275 GeV
- Ions from 40-110 GeV/u
- Polarized light ions 40 -184 GeV ($He^3$)
- 1000x HERA luminosities: $10^{33}$-$10^{34}$ $cm^2s^{-1}$
- CMS energies √s = 29 – 140 GeV
- CD1 obtained in July 2021

## Spin of the nucleon:

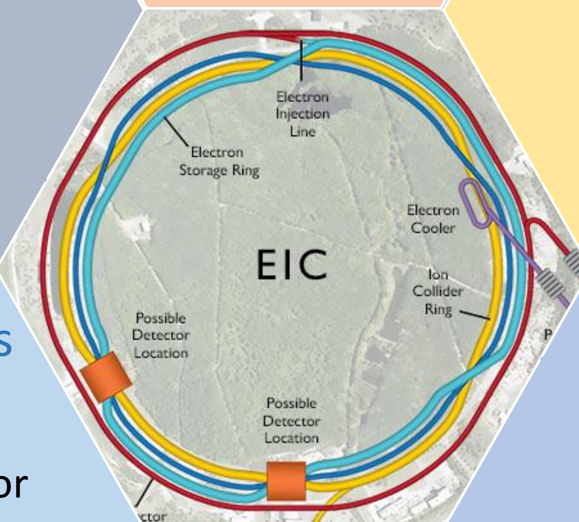
- Gluon spin
- Role Sea quarks

## QCD at high gluon densities

- Saturation effects

## Tomography :

- 3D momentum structure (q, g Sivers, Tensor charge, TMD Evolution)
- 3D spatial structure




## Nucelar effects

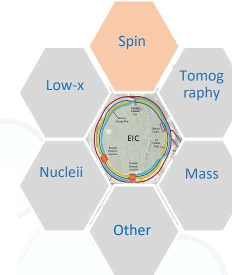
- Nuclear PDFs
- Passage of color through nuclear matter (nFFs, pT broadening)

## Origin of the Mass

- Axial anomaly contributions
- Hadron structure

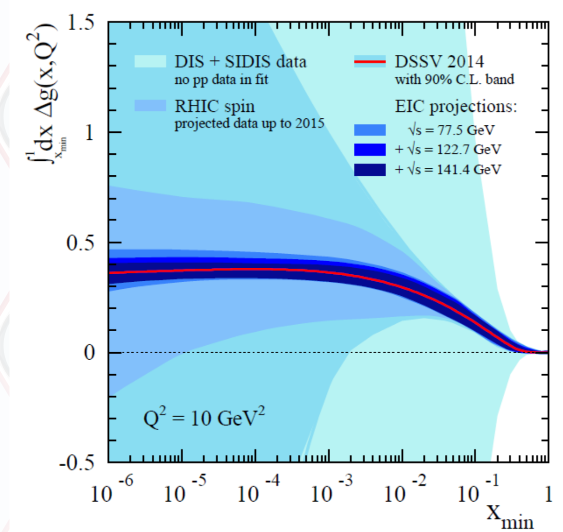
## Other

- Spectroscopy (XYZ)
- EW physics
- Other

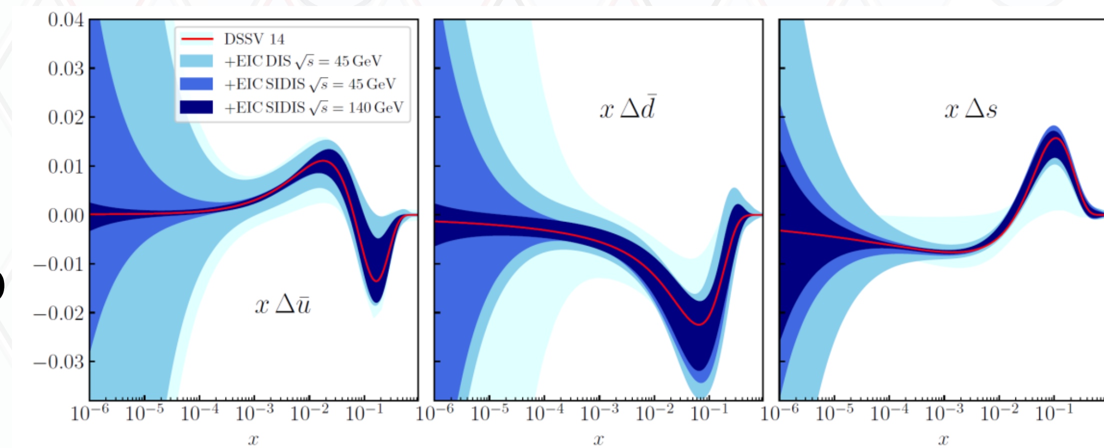



# Gluon and sea polarization

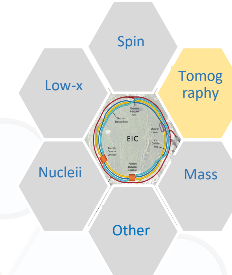
- 1 year of EIC running will pin down gluon polarization
- Using SIDIS precise determination of sea quark helicities, especially strange contribution of interest
- Indirect determination of orbital angular momentum via sum rule
- Also interesting access to flavor via charged current reactions




PRD92 (2015), 094030

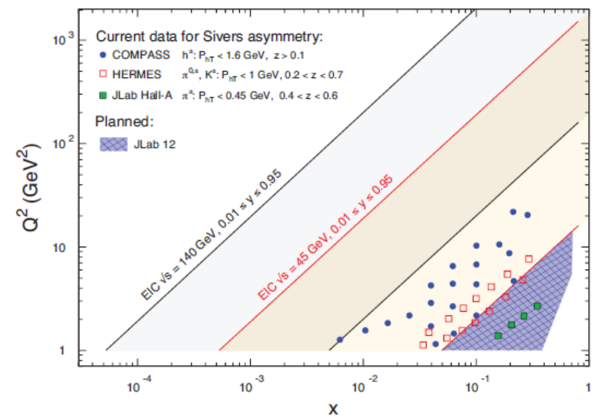



PRD 102 (2020), 094018

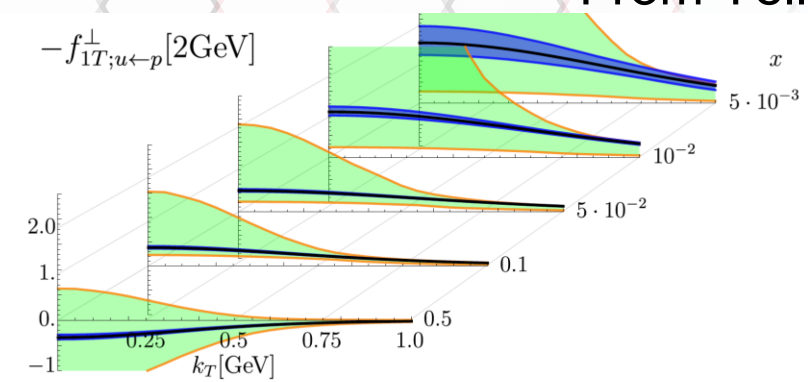


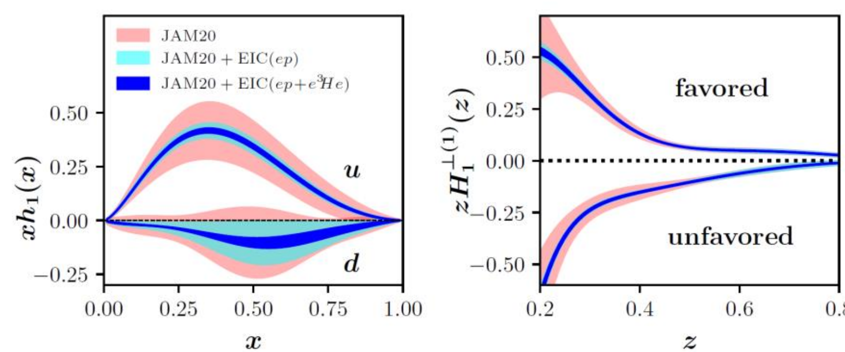

# 3D Transverse spin and momentum structure

| Deliverables | Observables | What we learn | Stage I | Stage II |
|---|---|---|---|---|
| Sivers & unpolarized TMD quarks and gluon | SIDIS with Transverse polarization; di-hadron (di-jet) | Quantum Interference & Spin-Orbital correlations | 3D Imaging of quarks valence+sea | 3D Imaging of quarks & gluon; $Q^2$ ($P_{hT}$) range QCD dynamics |
| Chiral-odd functions: Transversity; Boer-Mulders | SIDIS with Transverse polarization | 3rd basic quark PDF; novel hadronization effects | valence+sea quarks | $Q^2$ ($P_{hT}$) range for detailed QCD dynamics |

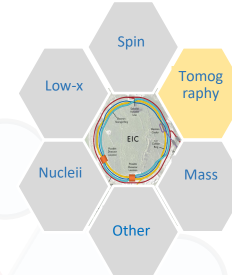



From Yellow Report:



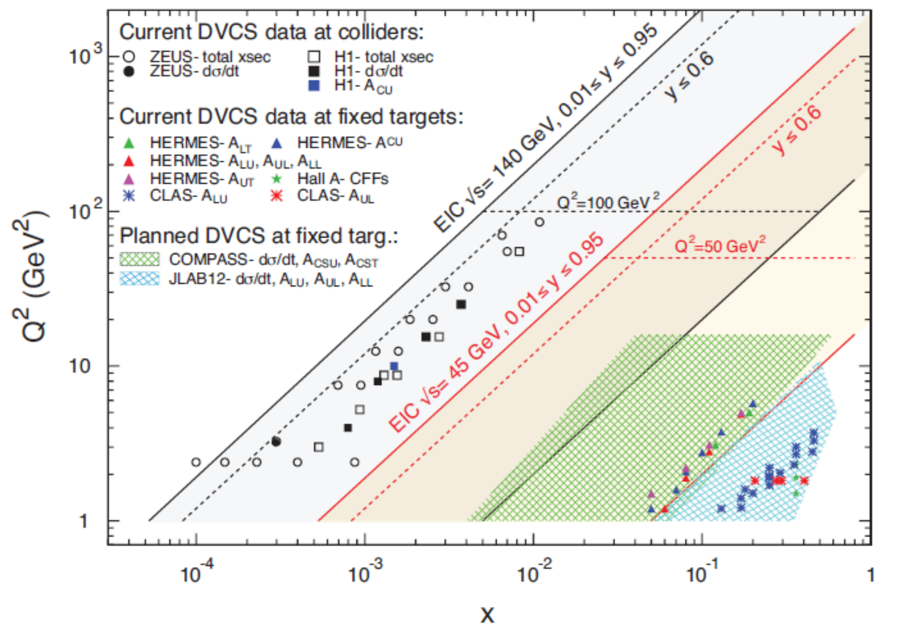




[Gamberg et al *Phys.Lett.B* 816 (2021) 136255]

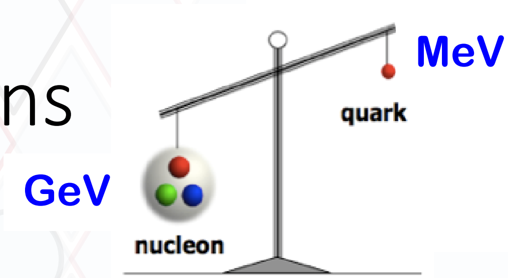


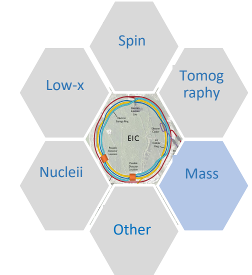

# 3 dimensional spatial structure

| Deliverables | Observables | What we learn | Requirements |
|---|---|---|---|
| GPDs of sea quarks and gluons | DVCS and $J/\Psi, \rho^0, \phi$ production cross-section and polarization asymmetries | transverse spatial distrib. of sea quarks and gluons; total angular momentum and spin-orbit correlations | $\int dt\, L \sim 10$ to $100\,\mathrm{fb}^{-1}$; leading proton detection; polarized $e^-$ and $p$ beams; wide range of $x$ and $Q^2$; range of beam energies; $e^+$ beam valuable for DVCS |
| GPDs of valence and sea quarks | electro-production of $\pi^+, K$ and $\rho^+, K^*$ | dependence on quark flavor and polarization | |



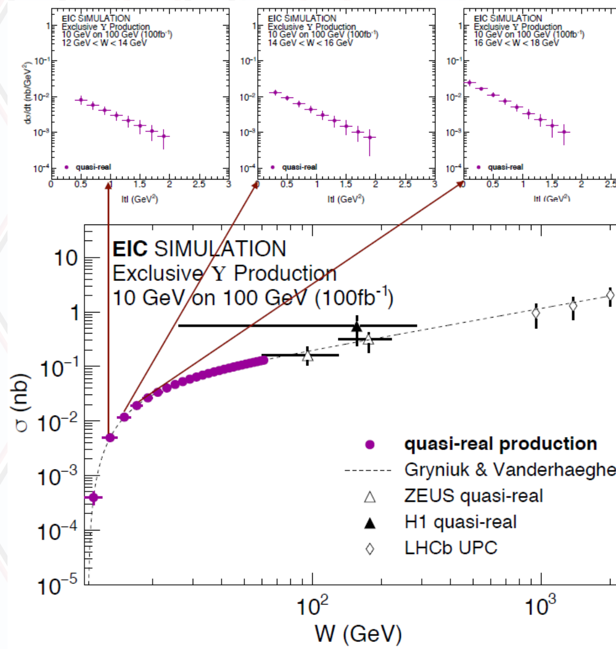
# Understanding Mass of Hadrons



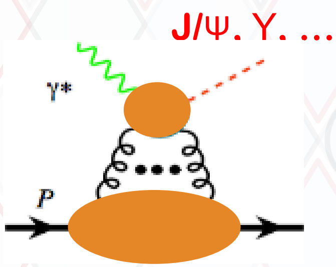



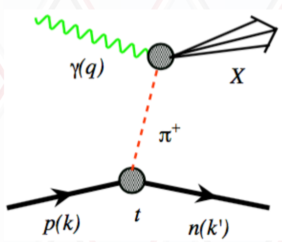

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

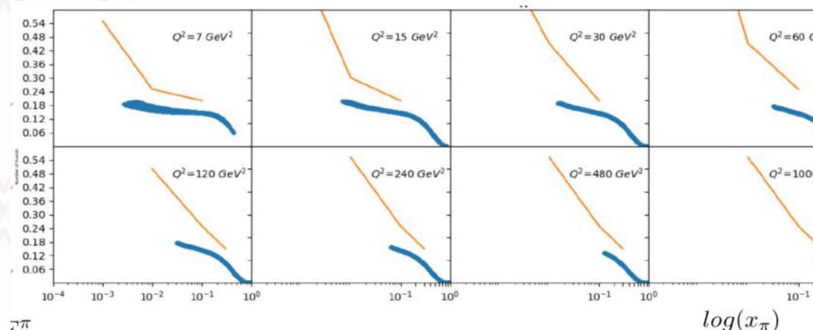
*The 2015 Long Range Plan for Nuclear Science*




- Access at the EIC:
  - Trace anomaly contribution:
    J/Psi/U production at threshold
  - Quark-gluon energy contribution:
    nucleon PDFs via (SI)DIS
    Sullivan process for pion/Kaon PDFs and Form factors

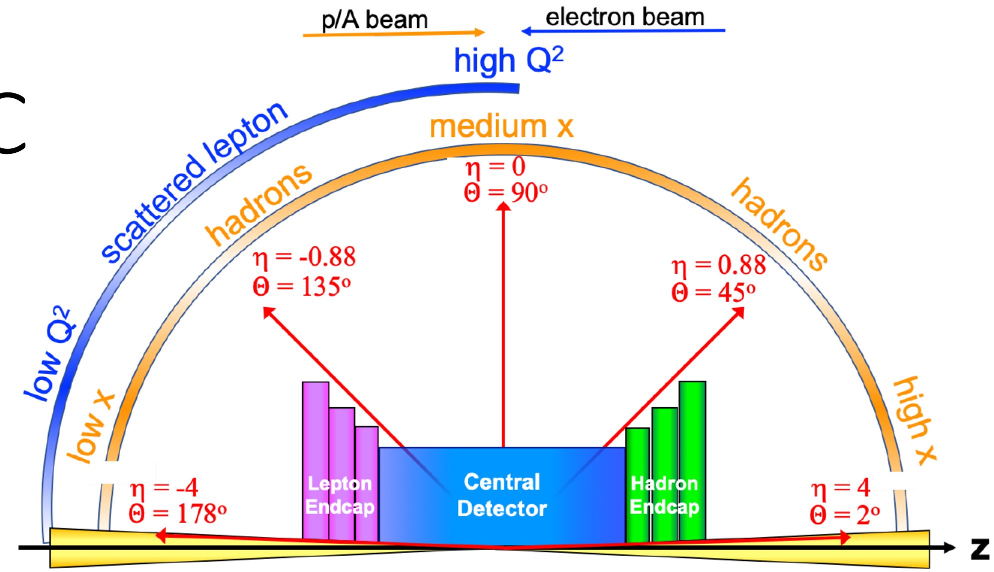


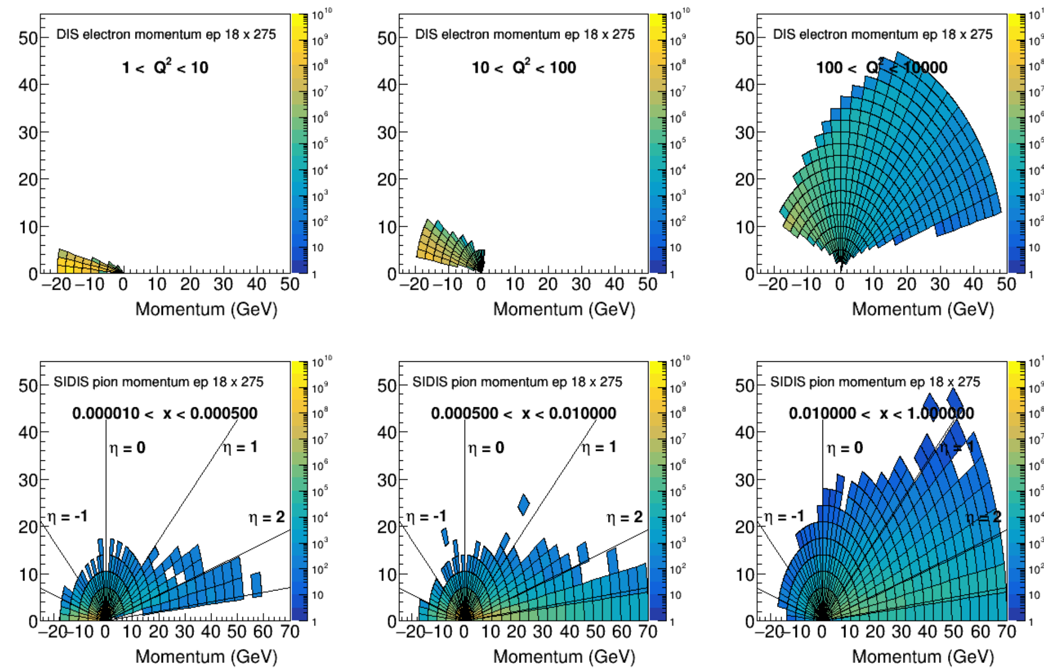



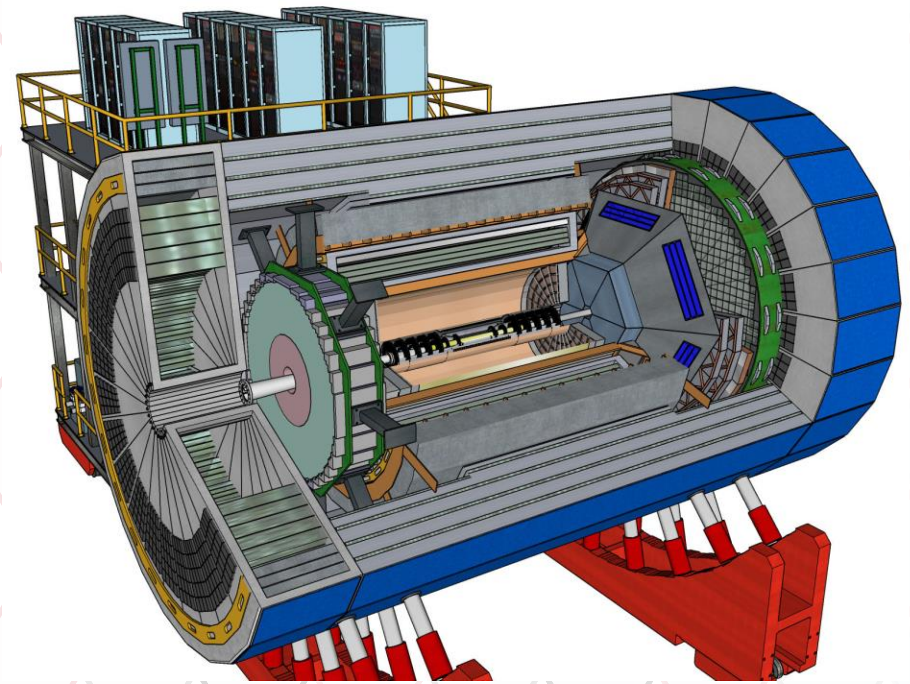
# Kinematics at an EIC

- Need full coverage over a large range of rapidities
- Scatterd leptons to backward/central rapdities
- Hadronic final state in the forward/central region
- Auxilliary detectors far forward (ZDCs, roman pots)
- Auxilliary detectors far backward (low Q2 tagger)
- Dedicated polarimetry/luminosity detectors



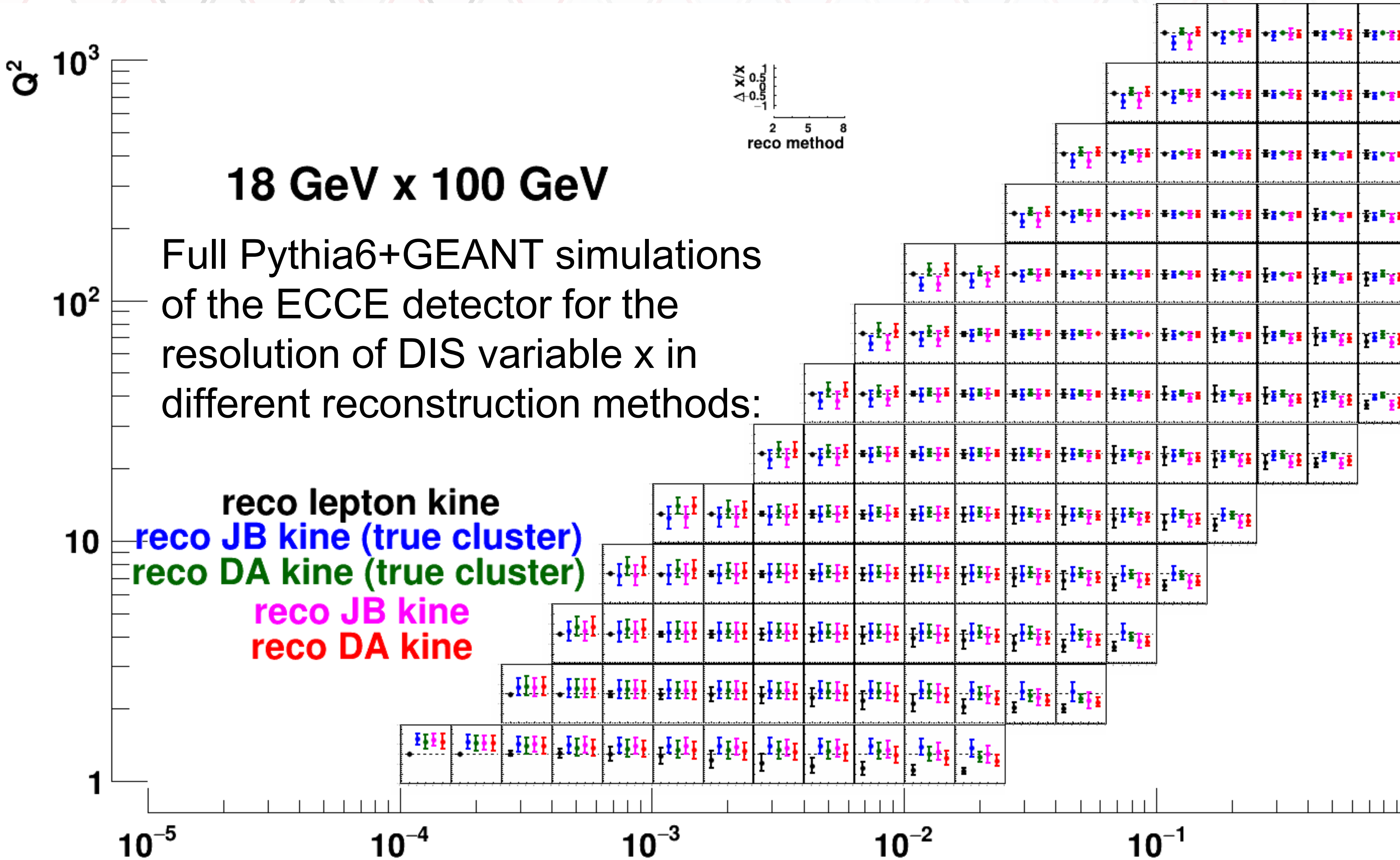



# sPHENIX → ECCE detector



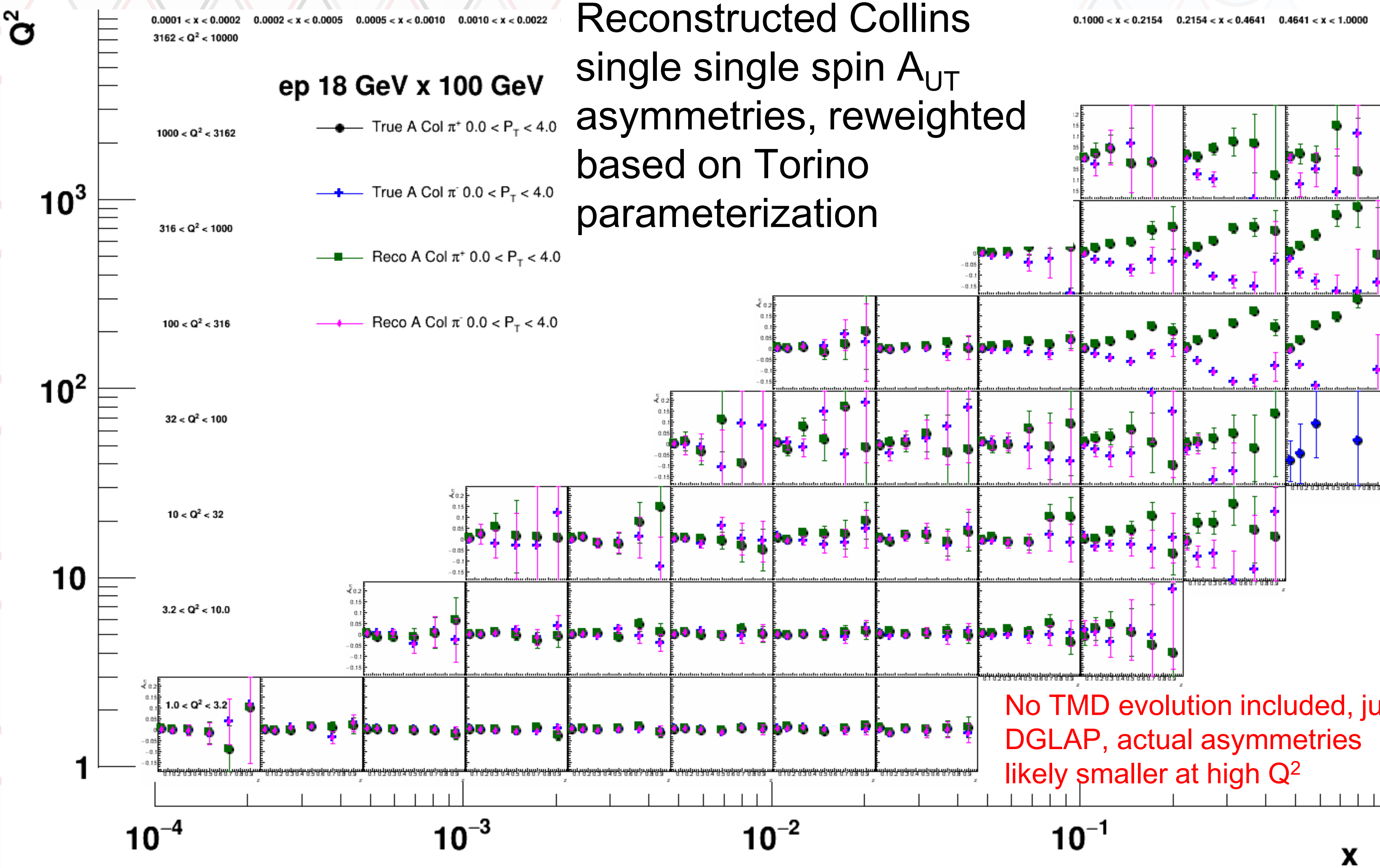
- Several detector proposals ongoing (to be submitted end of 2021): Athena (new solenoid, up to 3T), ECCE (Babar/sPHENIX magnet 1.4T), Core (very compact detector)
- Conceptually all proposals very similar

# Example of ongoing resolutions studies



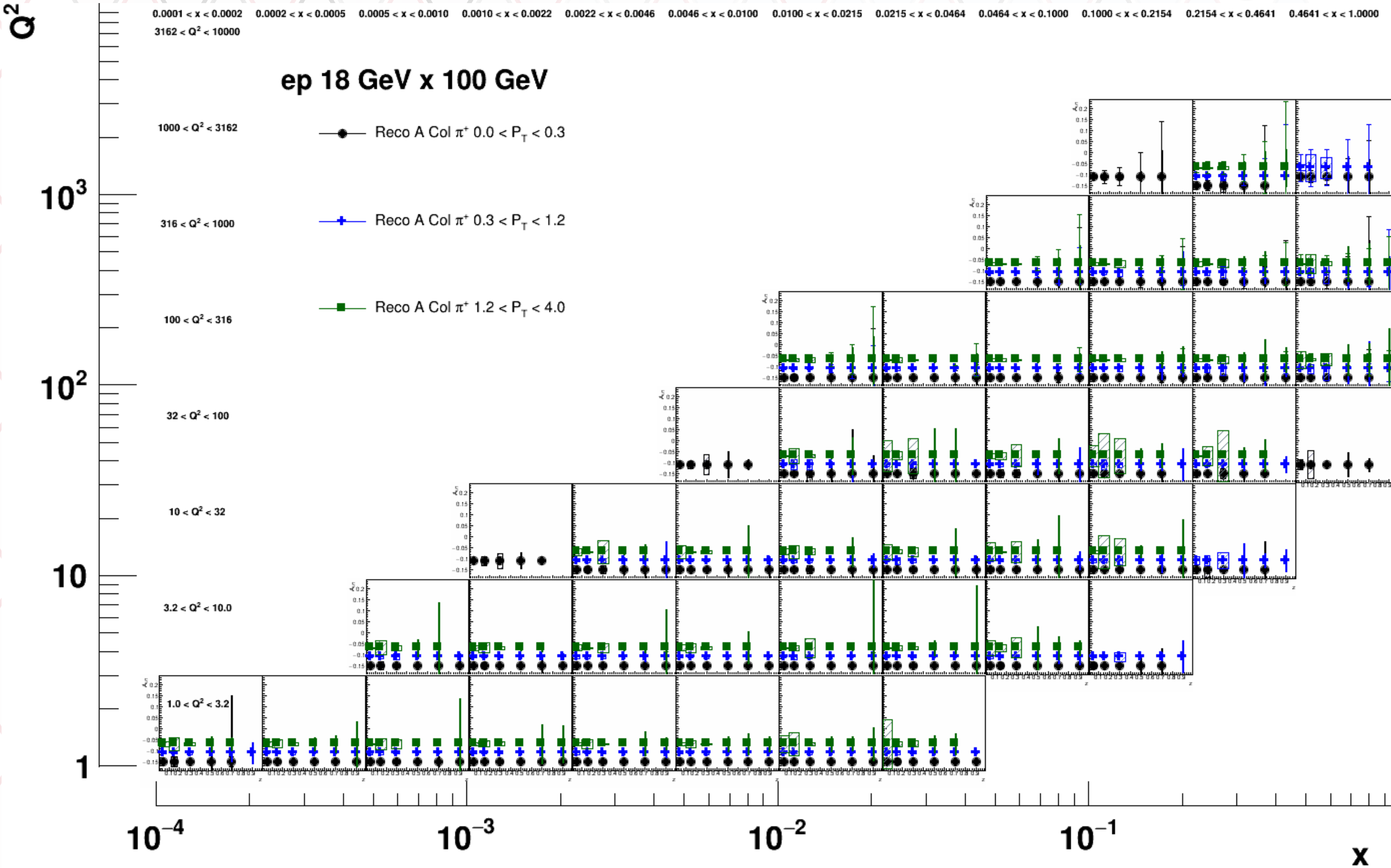
# Example of ongoing studies on actual physics variables

Reconstructed Collins single single spin $A_{UT}$ asymmetries, reweighted based on Torino parameterization




No TMD evolution included, just DGLAP, actual asymmetries likely smaller at high $Q^2$

# $A_{UT}$ projections for $10fb^{-1}$ ,Collins $\pi^+$



# Summary

- New insights into nonzero gluon polarization in the nucleon, sea quark polarizations from PHENIX
- Improved measurements for transverse spin asymmetries, nontrivial A dependence
- Several PHENIX spin results still ongoing
- sPHENIX provides unique opportunities for spin/cQCD measurements using jet and rate capabilities
- EIC is now moving fast (CD1), with collaborations in the formation process trying to make these exciting measurements a reality