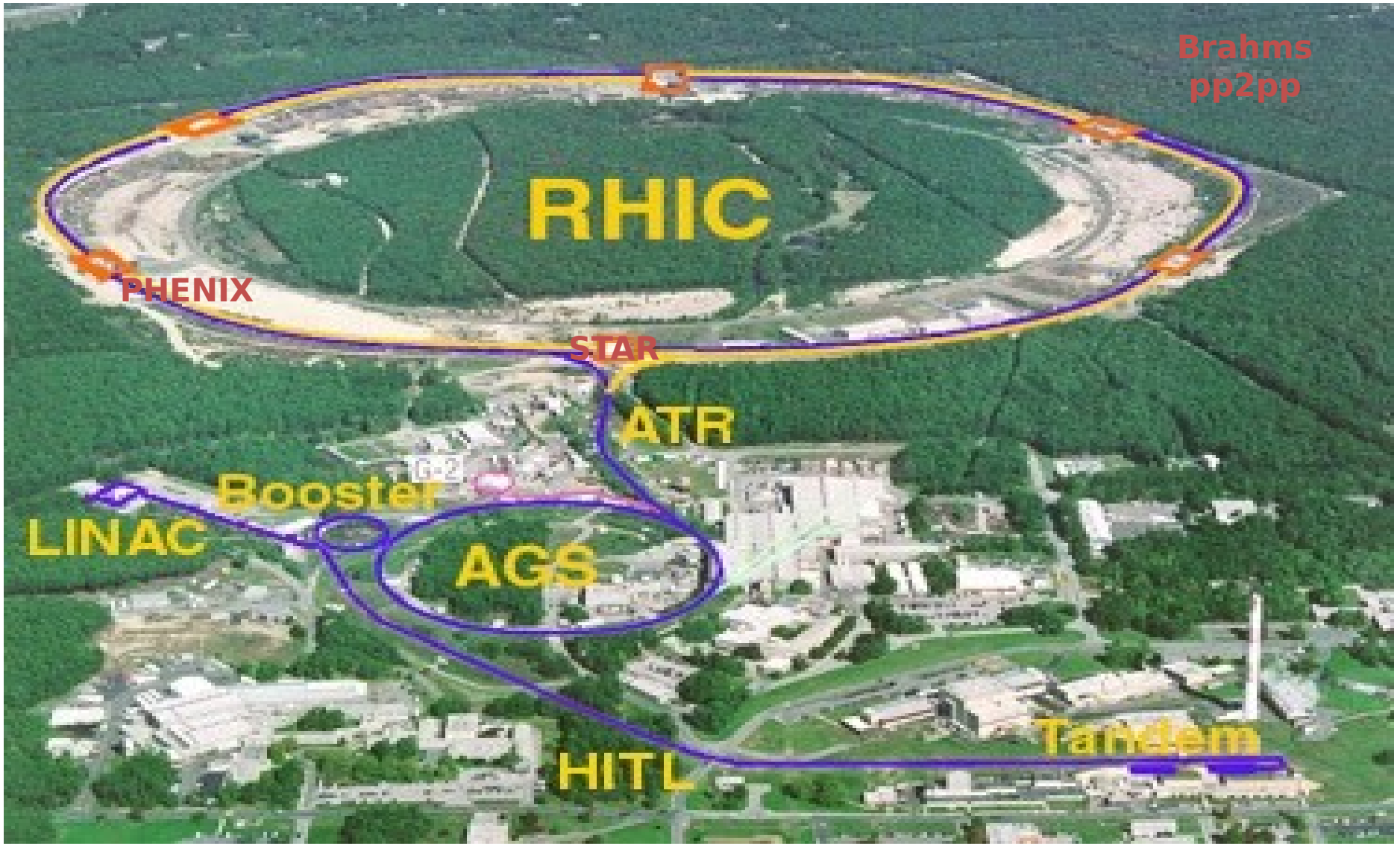
New p+p and p+A Physics Opportunities with the Forward sPHENIX Upgrade at RHIC

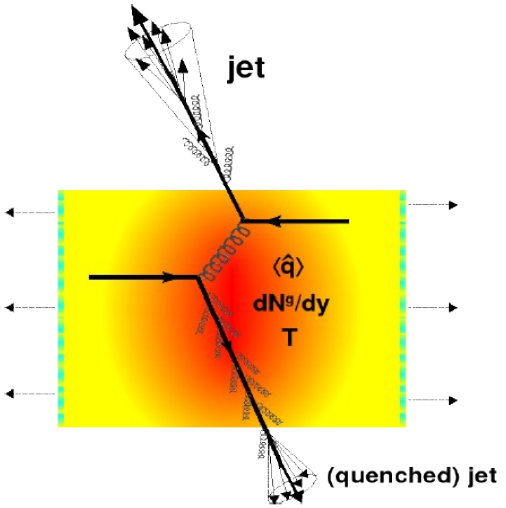
Ming Liu

Los Alamos National Laboratory
(for the PHENIX Collaboration)

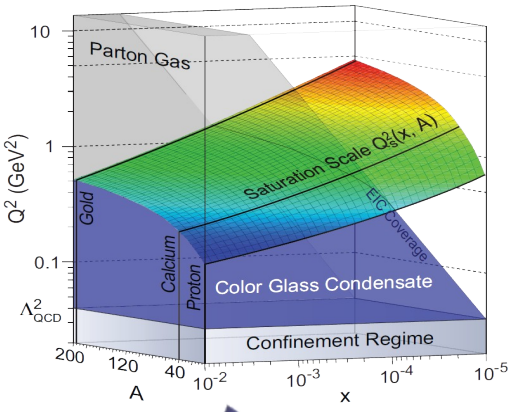
Relativistic Heavy Ion Collider at BNL
in operation since 2000



RHIC Highlights
Where to go next?

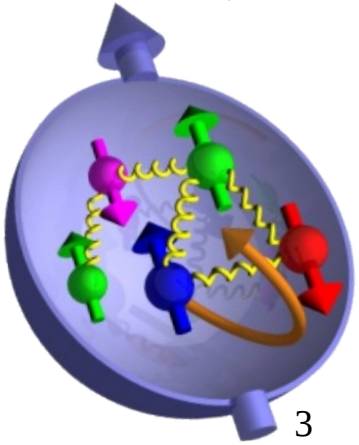


- Discovery of Quark Gluon Plasma(QGP)
  - Strongly interacting QGP
  - Gluon saturation at small-x, CGC etc



- *Surprises continue from spin program*
  - "small" gluon spin contribution
  - "large" transverse spin asymmetry

- *New questions arose:*
  - The nature of strongly interacting QGP
    --> super-PHENIX
  - Nucleon 3-D structure, nPDFs and QCD dynamics
    --> Forward sPHENIX -> eRHIC Detector



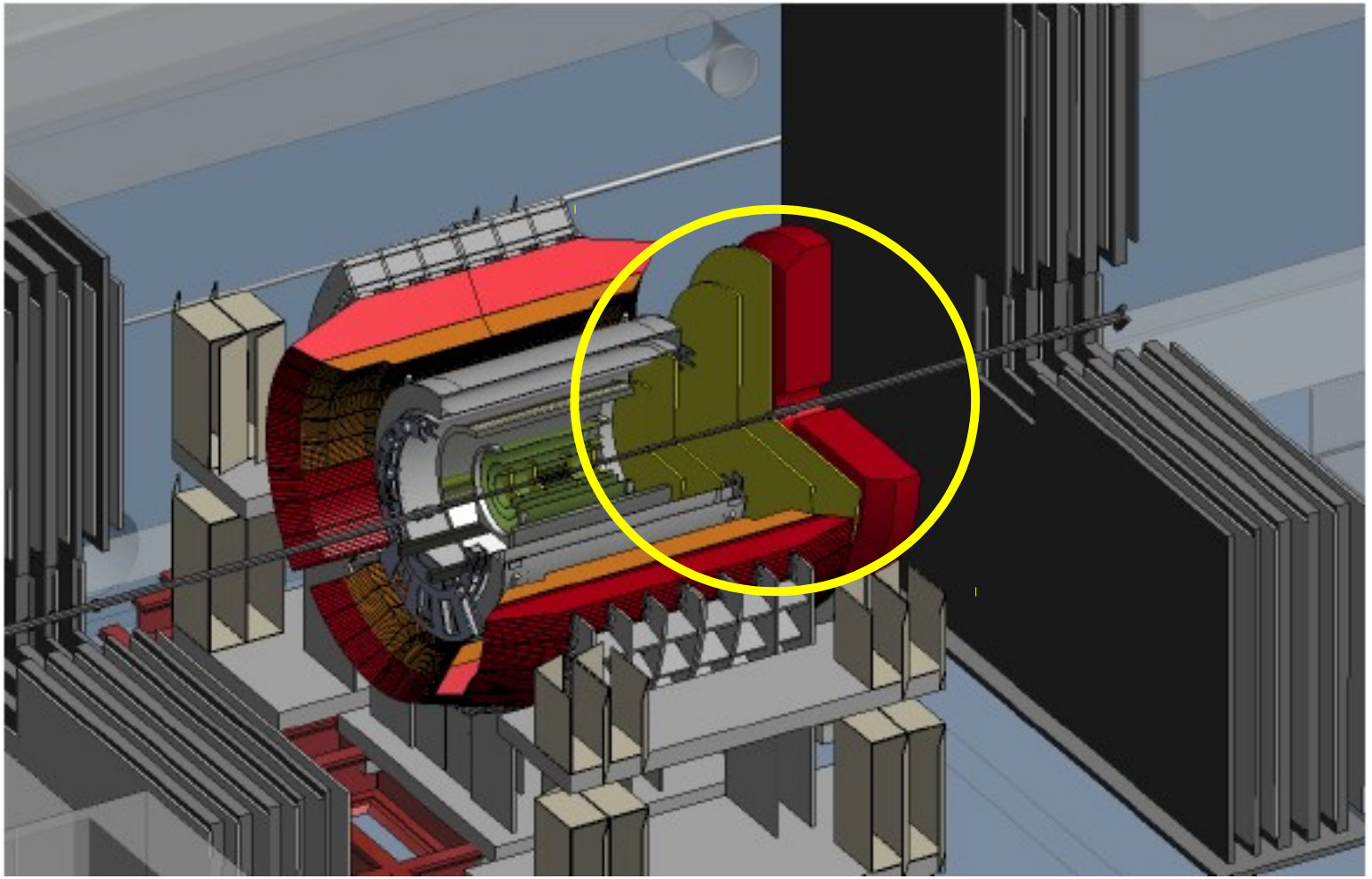
Brookhaven Lab Proposed 10 Year

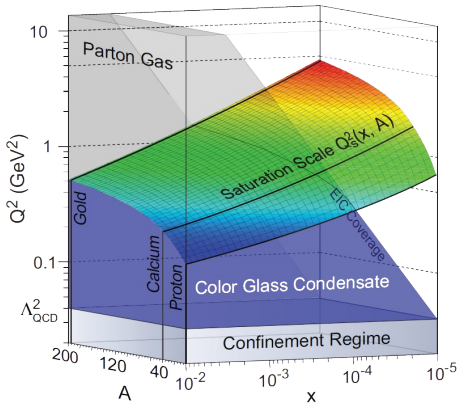
Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2014	15 GeV Au+Au 200 GeV Au+Au	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p+p at 200 GeV p+Au, d+Au, ^{3}He+Au at 200 GeV High statistics Au+Au	Extract η/s(T) + constrain initial quantum fluctuations More heavy flavor studies Sphaleron tests Transverse spin physics	PHENIX MPC-EX Coherent e-cooling test
2017	No Run		Low energy e-cooling upgrade
2018-19	5-20 GeV Au+Au (BES-2)	Search for QCD critical point and onset of deconfinement	STAR ITPC upgrade Partial commissioning of sPHENIX (in 2019)
2020	No Run		Complete sPHENIX installation STAR forward upgrades
2021-22	Long 200 GeV Au+Au with upgraded detectors p+p, p/d+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia	PHENIX
2023-24	No Runs		Transition to eRHIC

New Idea: Forward sPHENIX Proposal

Forward sPHENIX Proposal

(An upgrade path that harvests **pp, pA and AA** physics and leads to an EIC era)





- Transverse Spin and CNM Physics Centric in the Forward Rapidity
- Significant novel effects observed but not fully understood!

Physics Motivations

Novel Transverse Spin Phenomena

- Origins of large transverse spin asymmetry
- Universality and factorization, p+p v.s. SIDIS
- Nucleon Structure, QCD dynamics and evolution

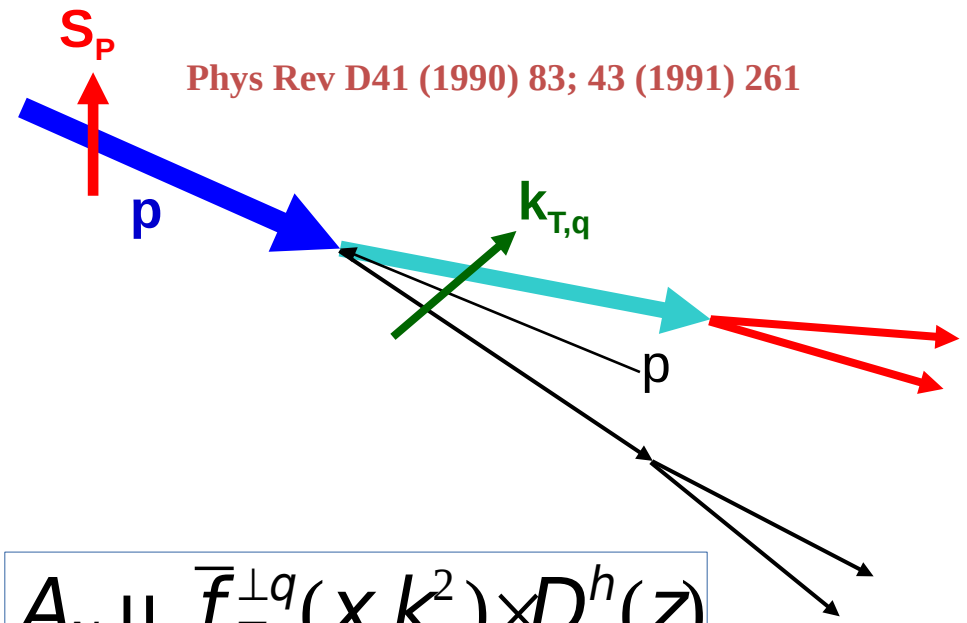
Cold Nuclear Matter Effects

- Modification of PDFs inside nucleus
- Jet fragmentation and parton energy loss

Possible Origins of Large Transverse SSAs

(i) Sivers mechanism:

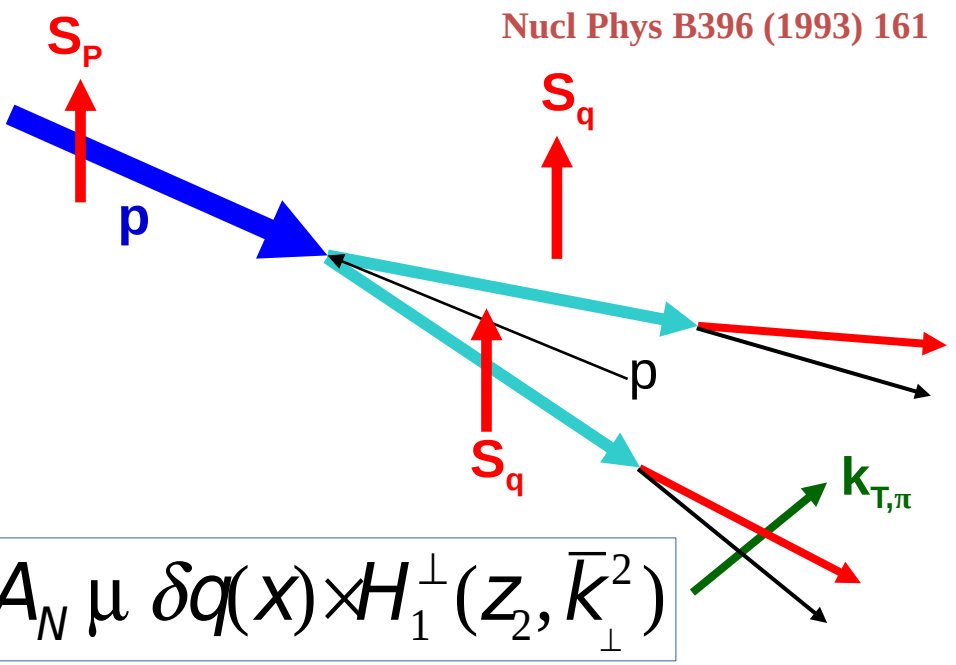
correlation between proton spin & parton k_T



$$A_N \mu \ \bar{f}_{1T}^{\perp q}(x, k_\perp^2) \otimes D_q^h(z)$$

(ii) Collins mechanism:

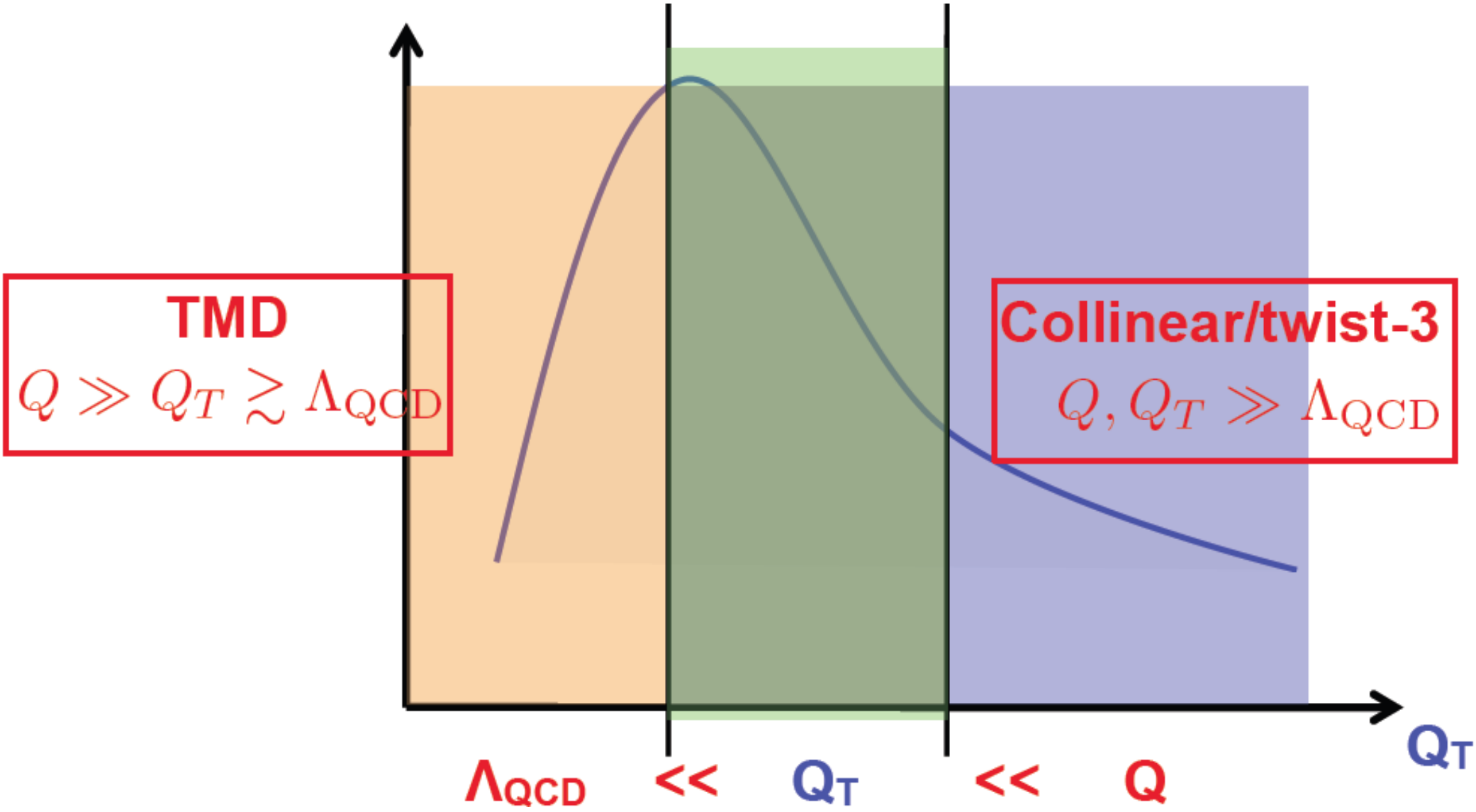
Transversity × spin-dep fragmentation



$$A_N \mu \ \delta q(x) \otimes H_1^\perp(z_2, \bar{k}_\perp^2)$$

Collinear Twist-3: quark-gluon/gluon-gluon correlation

TMD and Collinear Twist-3



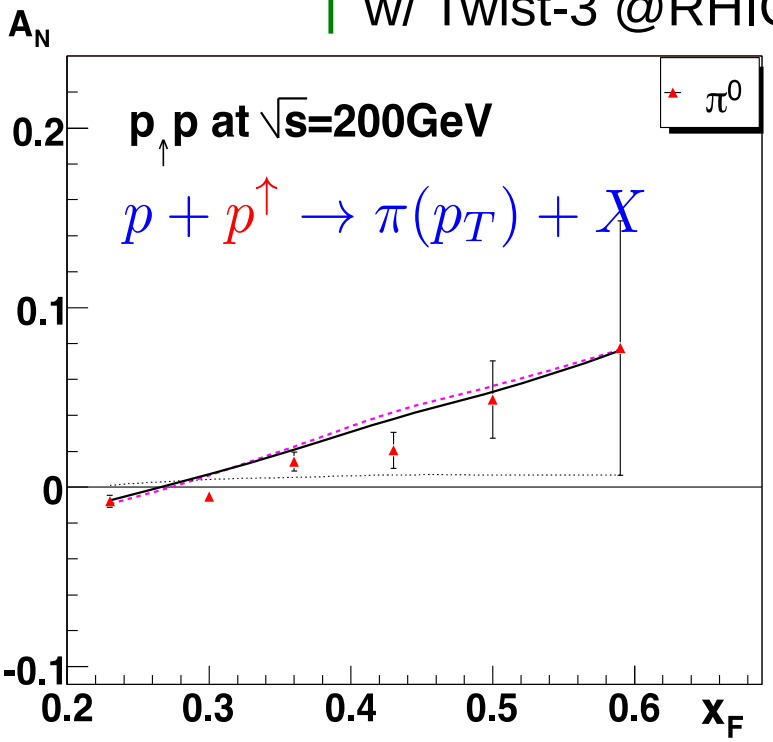
Test the Universality of QCD Descriptions

Are TMD and Twist-3 really consistent?

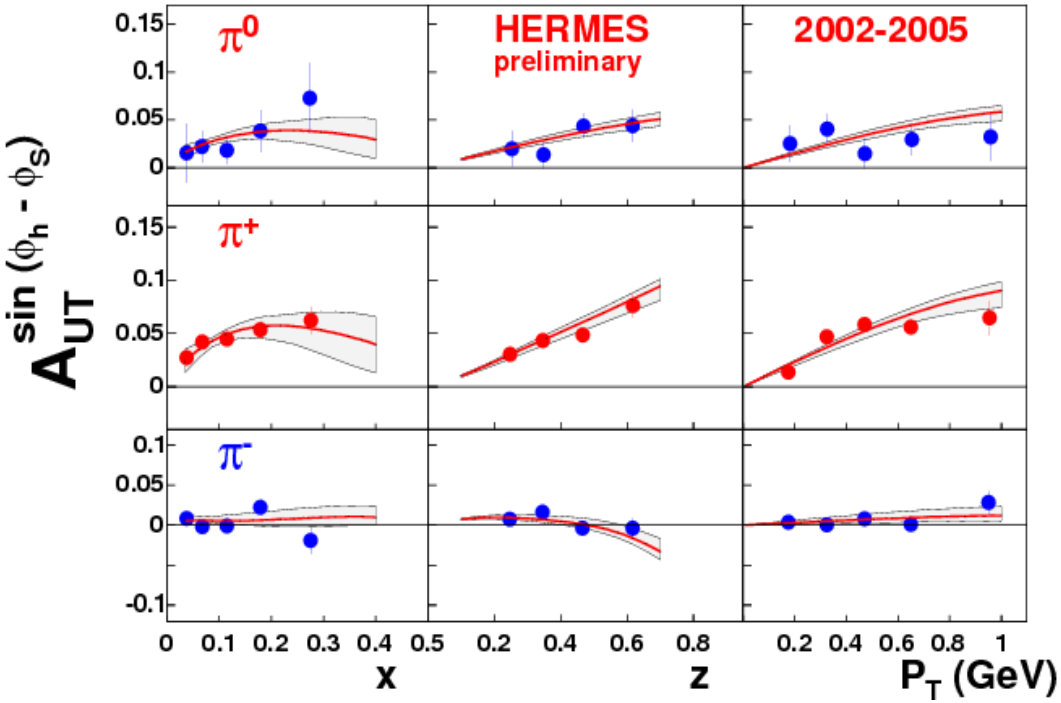
$$gT_{q,F}(x,x) \stackrel{?}{=} -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

Kang, Qiu, Vogelsang, Yuan(2011)

p+p Sivers-Like
w/ Twist-3 @RHIC



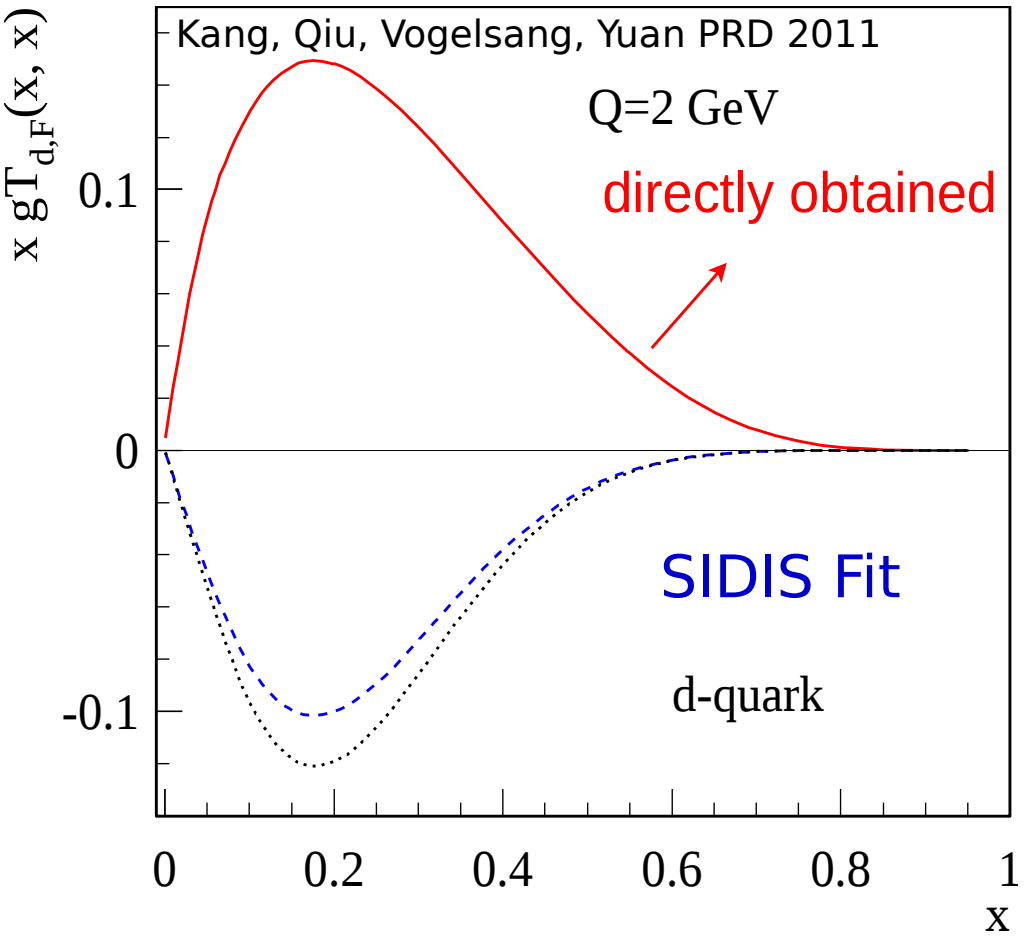
SIDIS Sivers
w/ TMD @HERMES



A Surprise: A_N Sign Mismatch?

First attempt to check the "Universality of QCD description of TSSA"

- Twist-3 (p+p) v.s. TMD Sivers (SIDIS)



Very active investigations:

- Collins
- Node in Sivers TMD functions
- Twist-3 …
- etc.

Many recent papers and presentations

Prukudin and Kang (2012)
Kanazawa, Koike, Metz and Pitonyak (2014)

Need new experimental data to test models

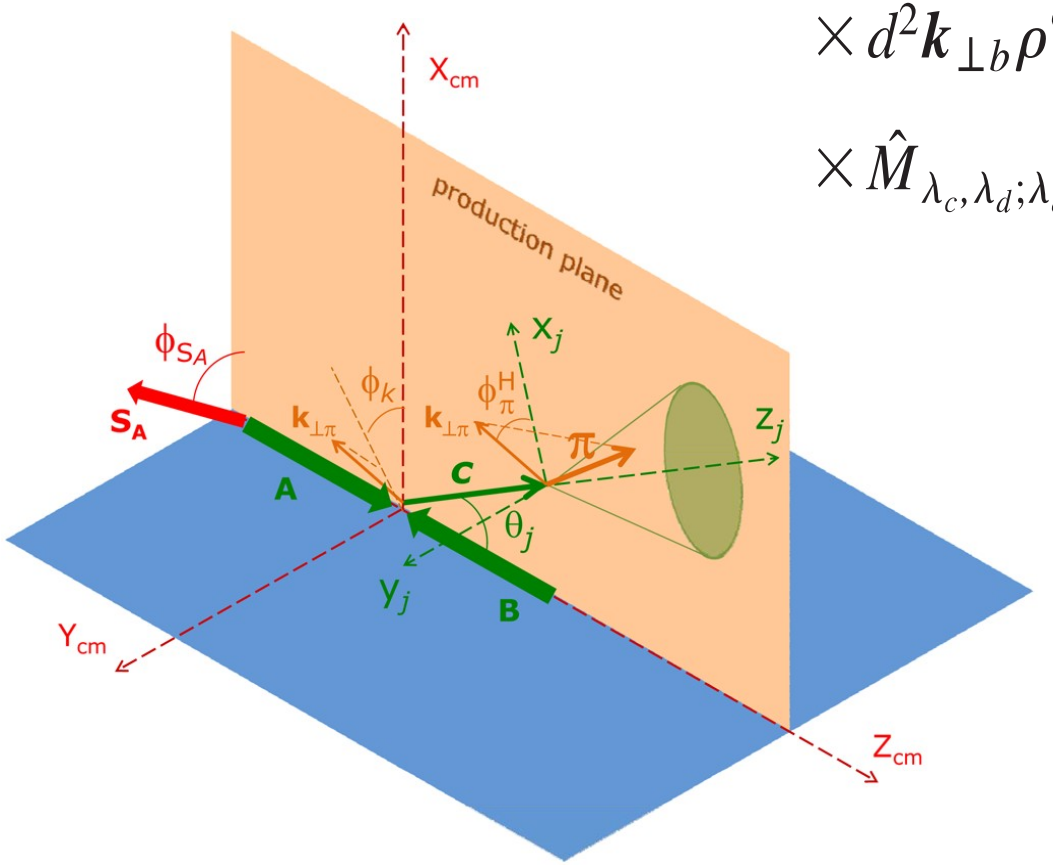
Access “Sivers” and “Collins” Asymmetries with Jets

Feng Yuan, PRL 100, 032003 (2008)
Umberto D’Alesio et al PRD 83 034021 (2011)

$$\frac{E_j d\sigma^{A(S_A)B\to \text{jet}+\pi+X}}{d^3\boldsymbol{p}_j dz d^2\boldsymbol{k}_{\perp\pi}} = \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a dx_b}{16\pi^2 x_a x_b s} d^2\boldsymbol{k}_{\perp a}$$

$$\times d^2\boldsymbol{k}_{\perp b} \rho^{a/A,S_A}_{\lambda_a\lambda'_a} \hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a}) \rho^{b/B}_{\lambda_b\lambda'_b} \hat{f}_{b/B}(x_b,\boldsymbol{k}_{\perp b})$$

$$\times \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b} \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b} \delta(\hat{s}+\hat{t}+\hat{u}) \hat{D}^{\pi}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp\pi}).$$



Experimental variables:

- Jet $P_{j,\,xF}$
- Hadrons , Charge and PID
- Beam polarization

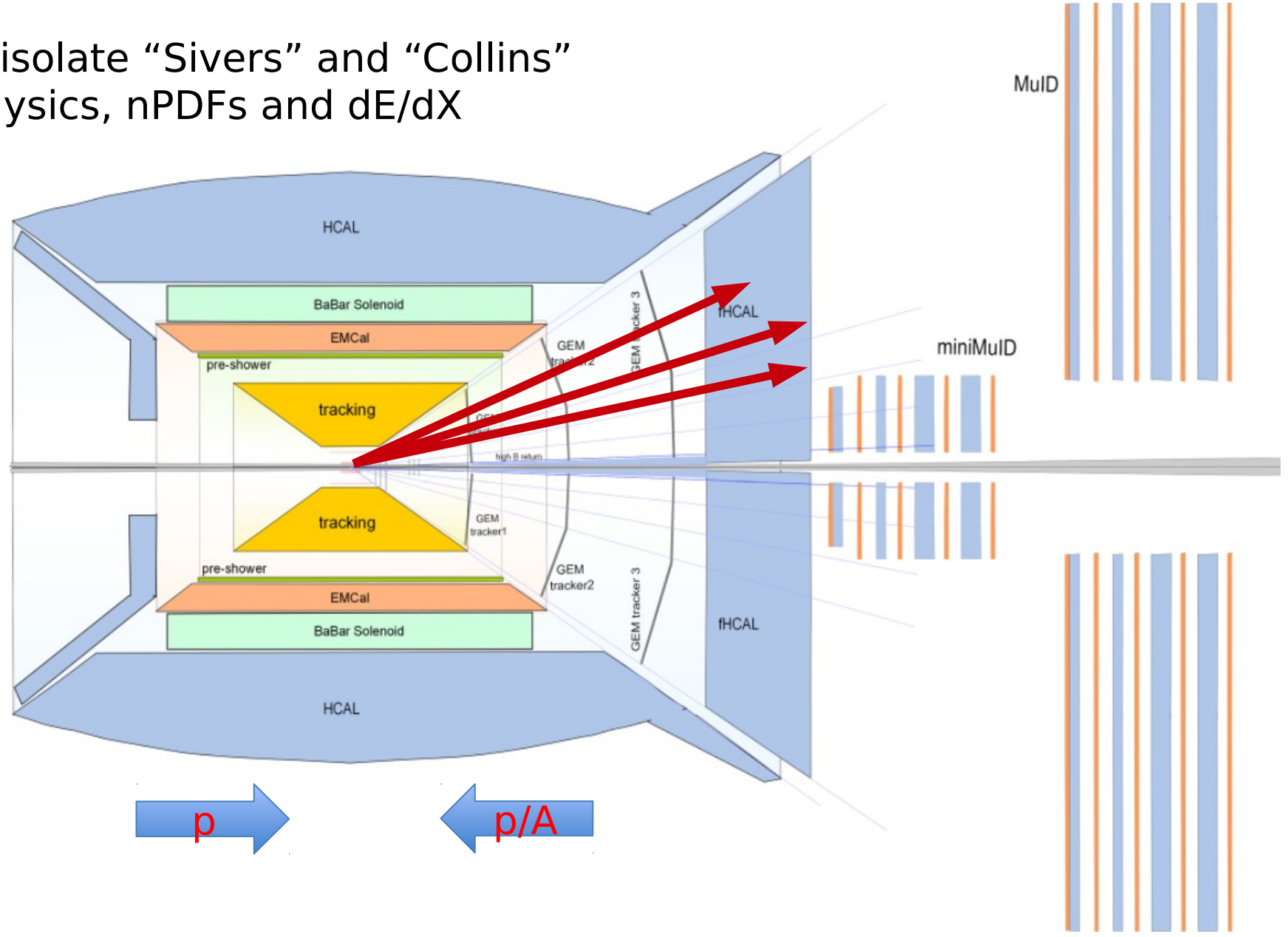
$A_N^{\sin\phi_{S_A}}$ “Sivers-Like”

$A_N^{\sin(\phi_{S_A} \mp \phi_\pi^H)}$ “Collins”

Forward sPHENIX

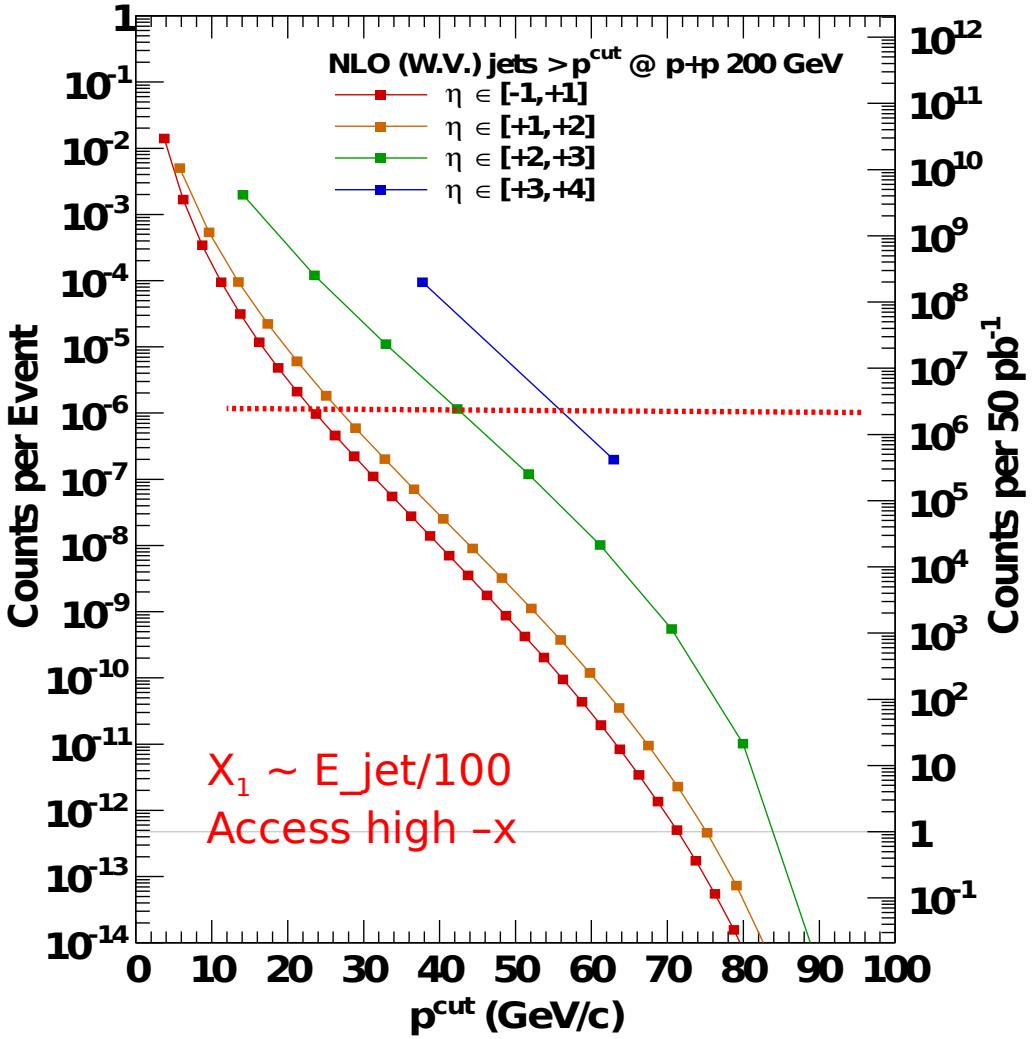
-1 < eta < 4

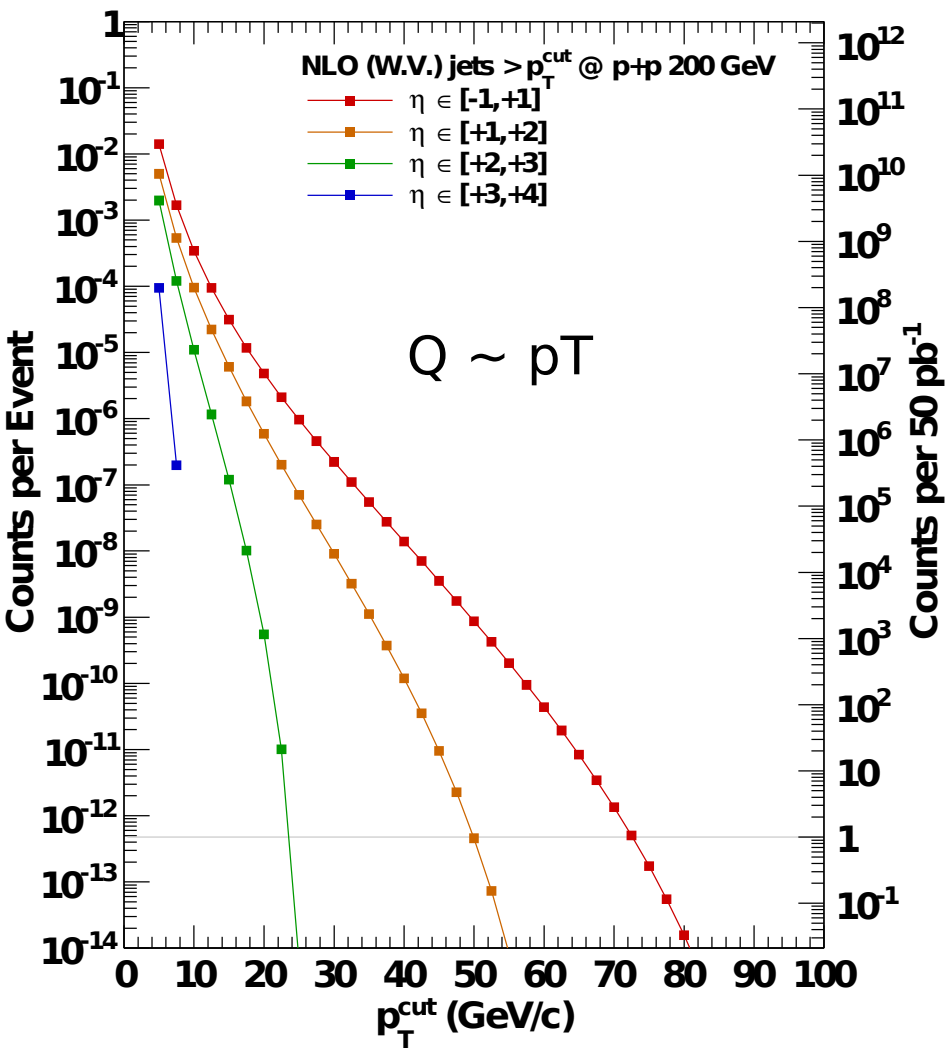
- Clearly isolate “Sivers” and “Collins”
- CNM physics, nPDFs and dE/dX



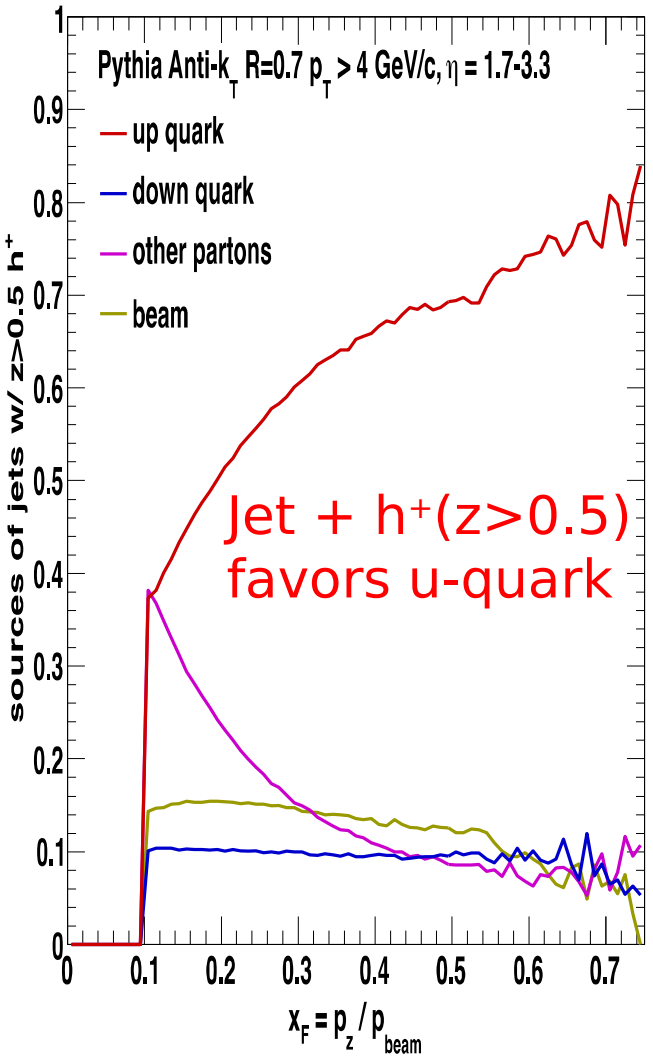
Jet Production Rates @NLO

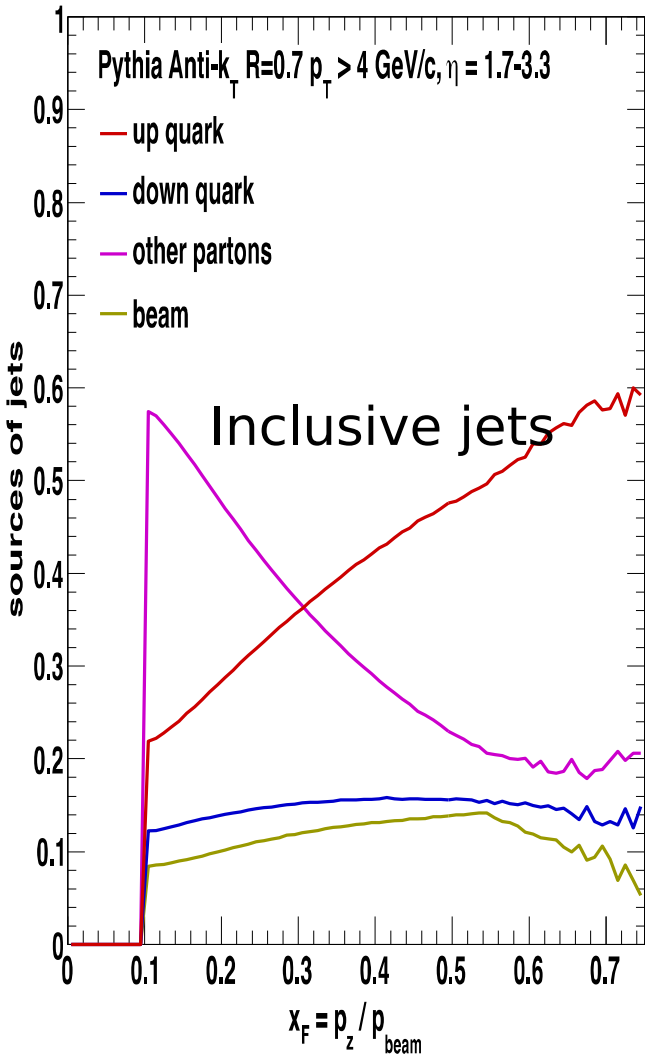
200GeV p+p: Lumi = 50pb^{-1}

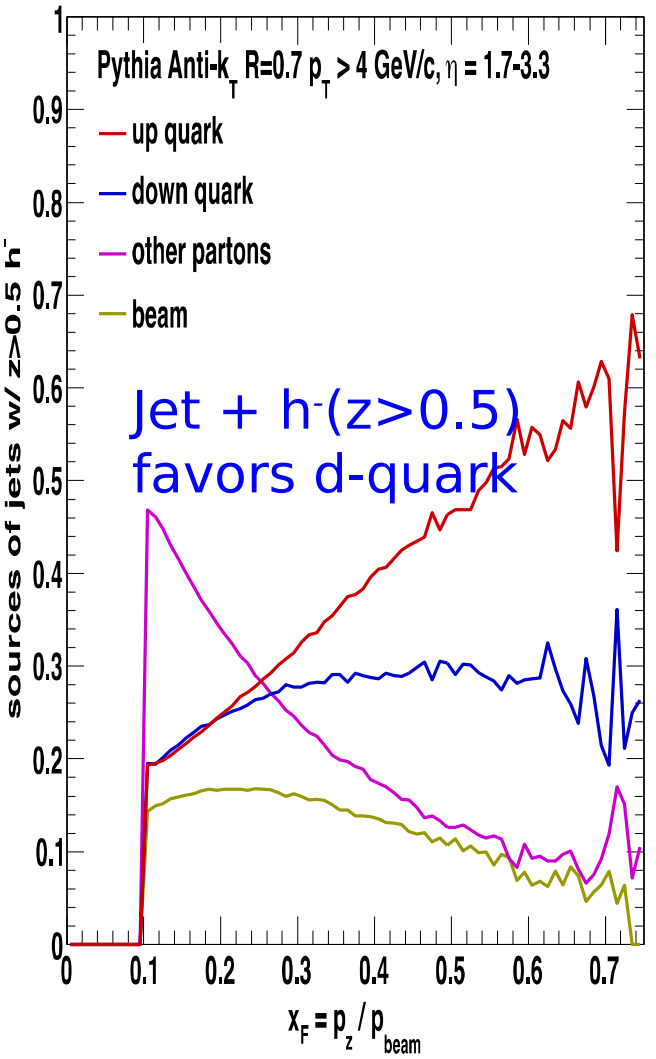




Jet Quark-Flavor Tagging with Charged Hadrons



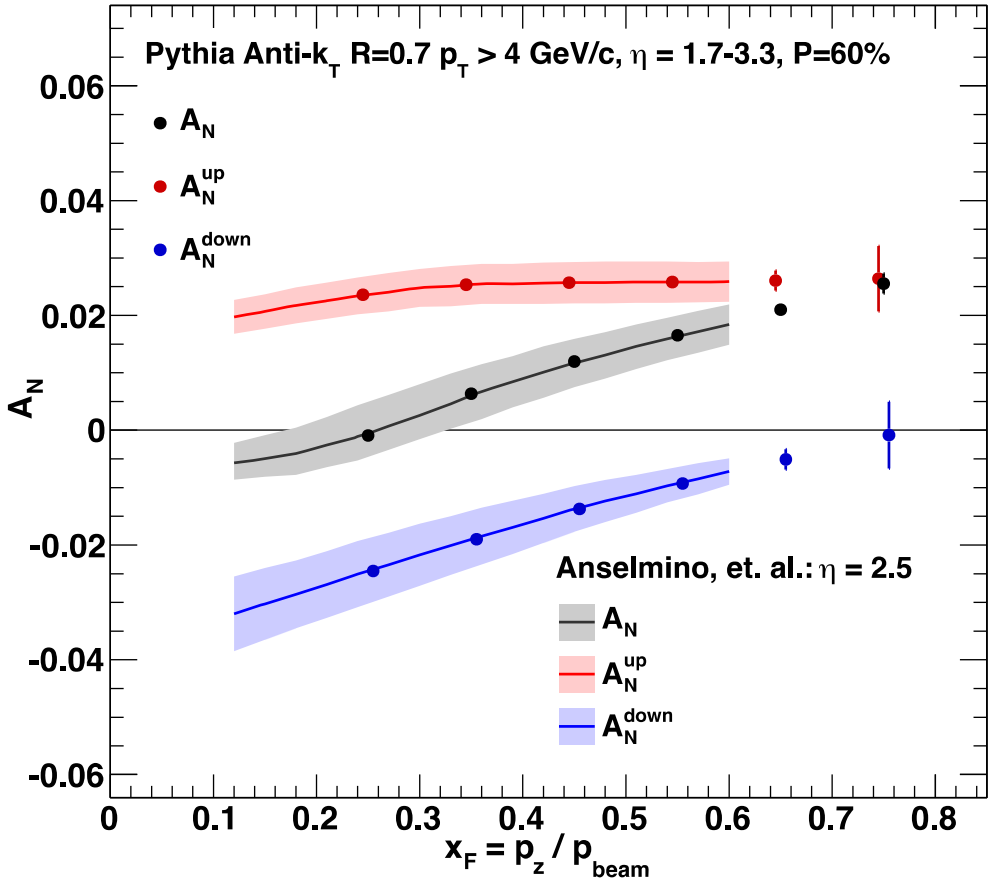




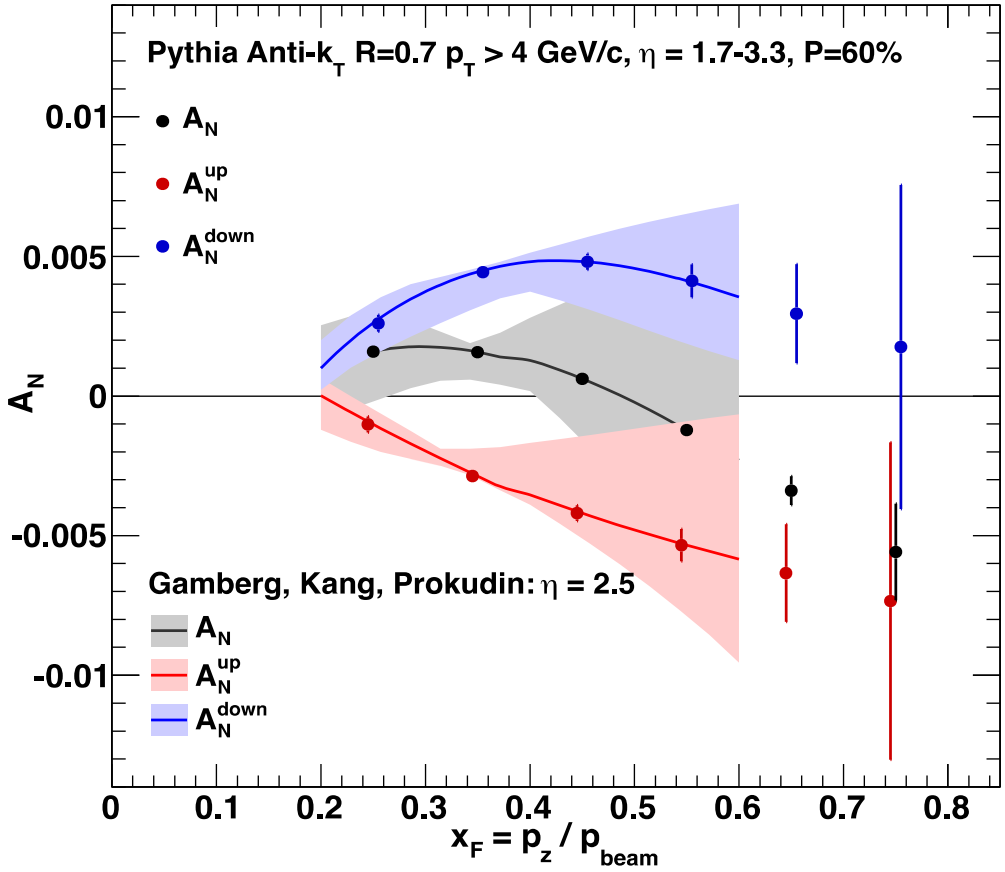
Jet TSSA: Test Process Dependence

- Change of sign in flavor-tagged Jet TSSA

Naïve DIS Fit Sivers



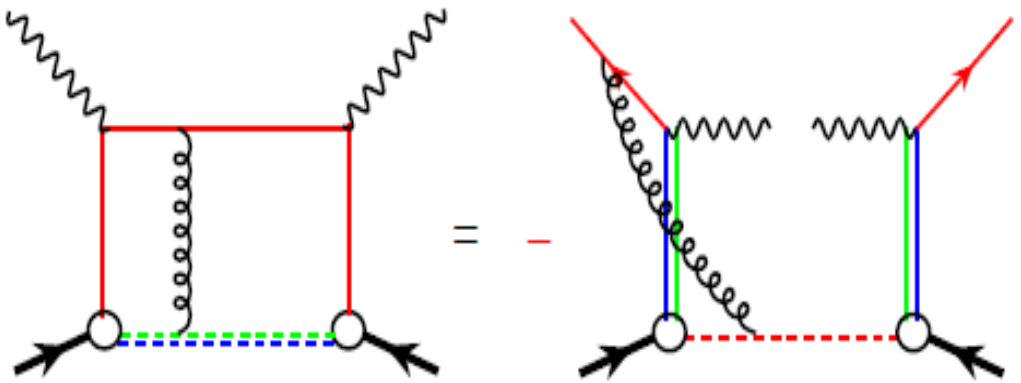
Included 1) process dependence and 2) Q^2 evolution



Drell-Yan TSSA: Test Sign Change

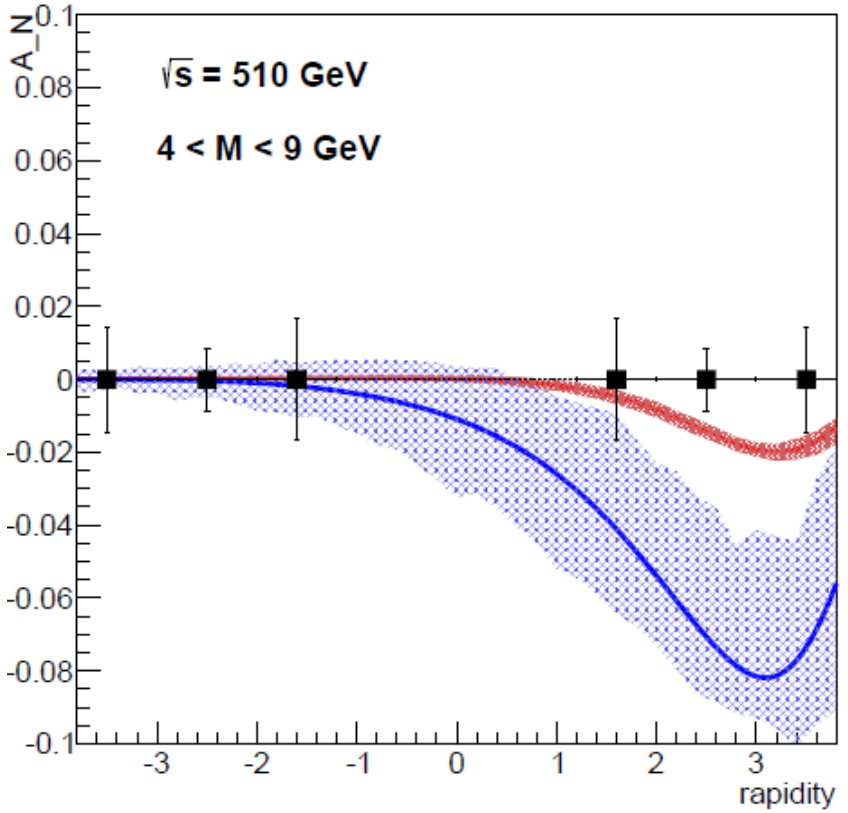
- Fundamental test of pQCD factorization and gauge-link formalism
  - Theoretically clean
  - Experimentally challenging
  - TMD (pp) vs TMD (SIDID)

$$\Delta^N f_{q/h^\uparrow}^{\mathrm{SIDIS}}(x, k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\mathrm{DY}}(x, k_\perp)$$

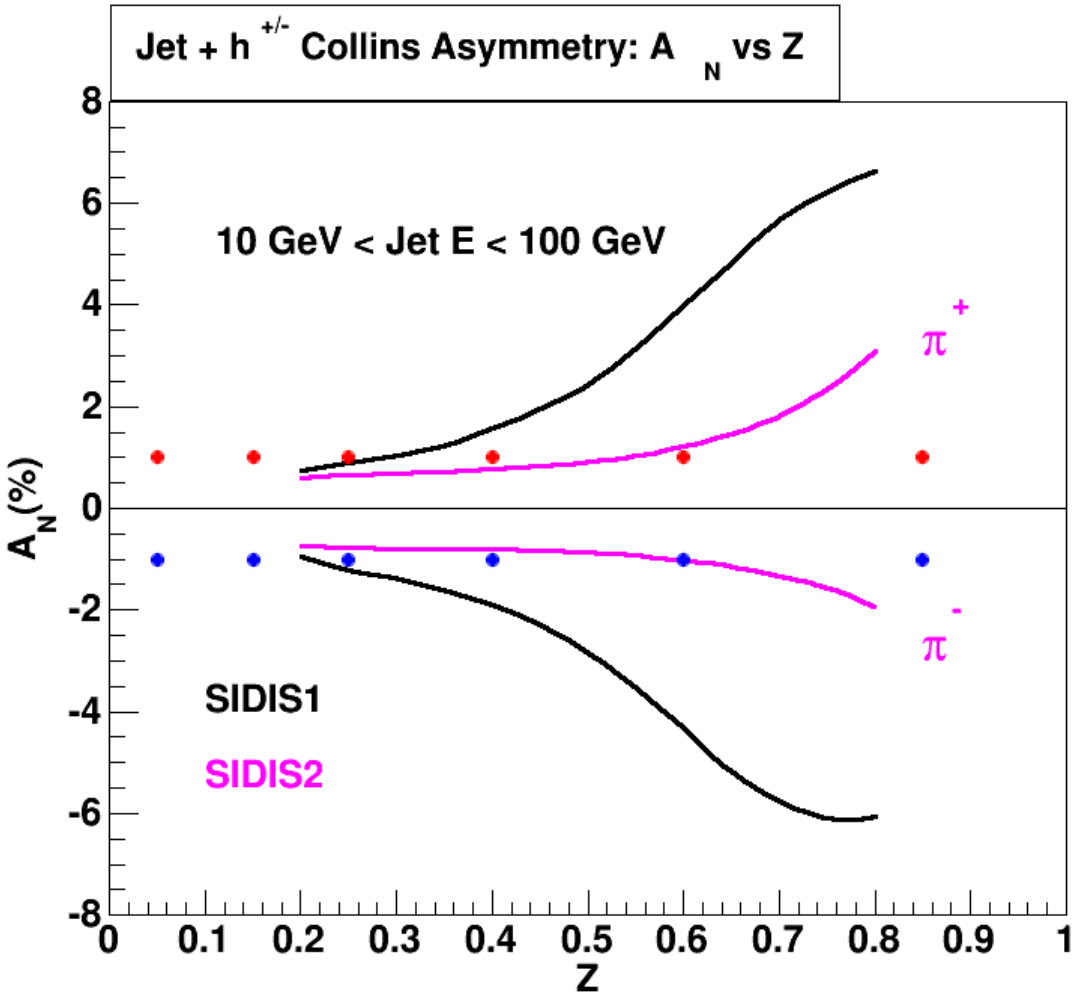


SIDIS = – DY

Kang and Qiu, PRD 84 054020
Exchevarria et. al., arXiv 1401.5078



Hadron Collins Asymmetry in Jets



- Test universality of Collins FF
- SIDIS vs pp
  - TMD
  - Twist-3

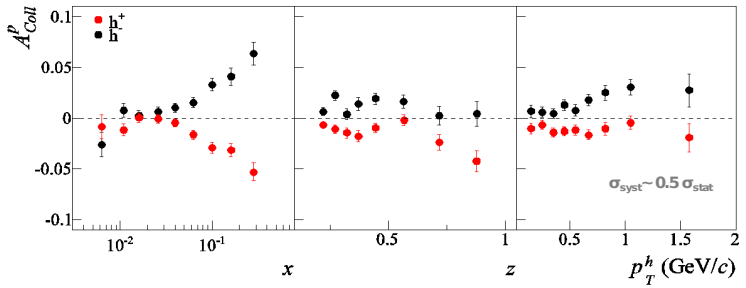
Collins asymmetry on proton

charged hadrons - published 2007 & 2010 data results

PLB 692 (2010) 240 PLB 717 (2012) 376

very good agreement between the two independent data sets

combined 2007 – 2010 results



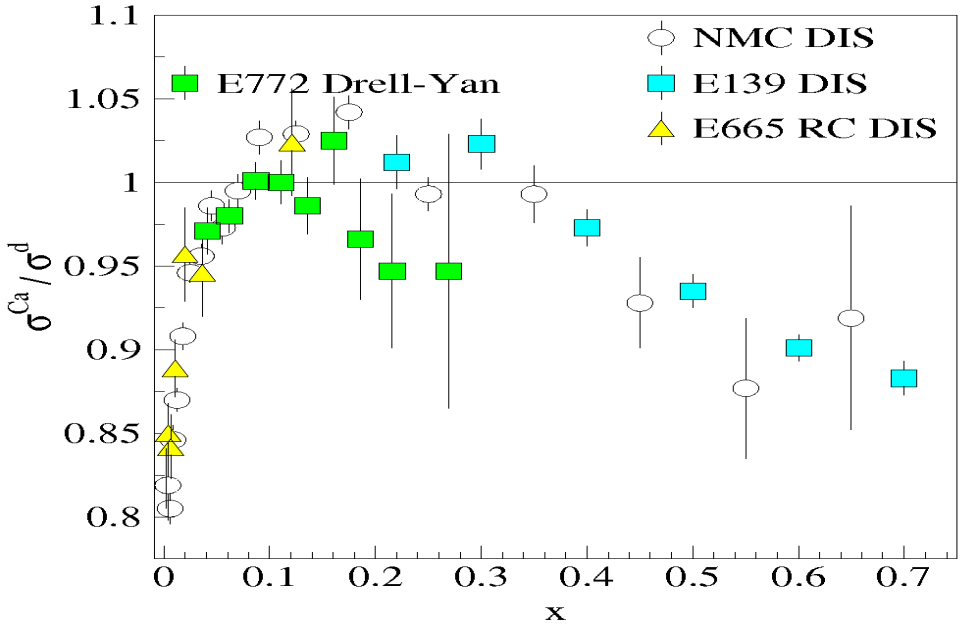
- precise measurements
- clear signal at x > 0.3, with opposite sign for h+ and h-

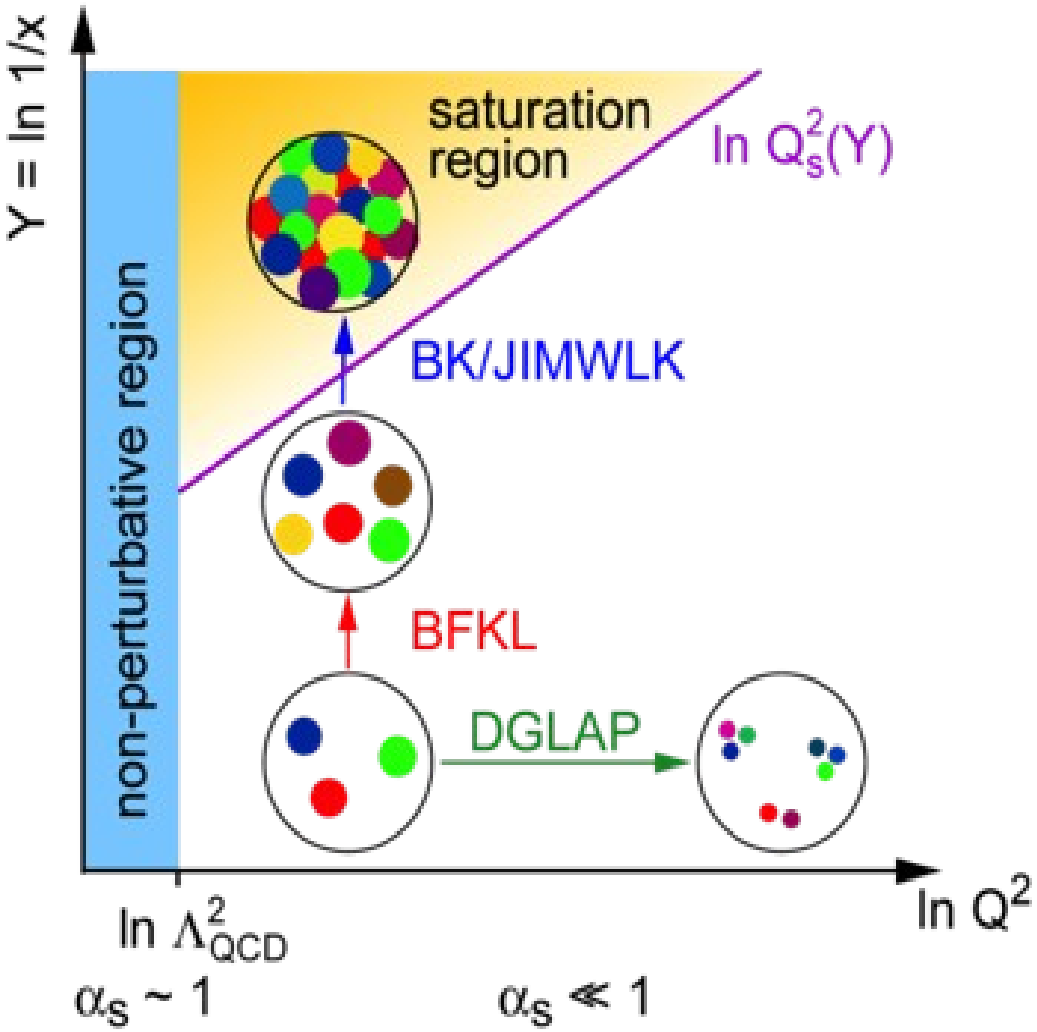
Anna Martin

p+A Physics: from Nucleon to Nucleus

Are parton distributions modified significantly inside nucleus?

- (Anti)Shadowing
  - Gluon saturation/CGC
  - EMC etc.
- Hadronization
- Energy loss dE/dx



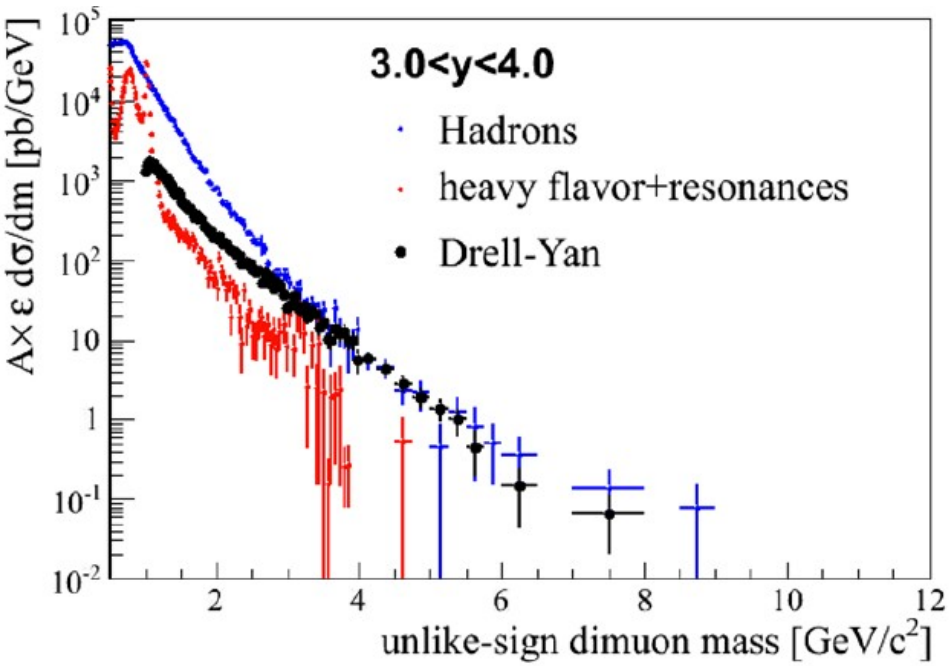


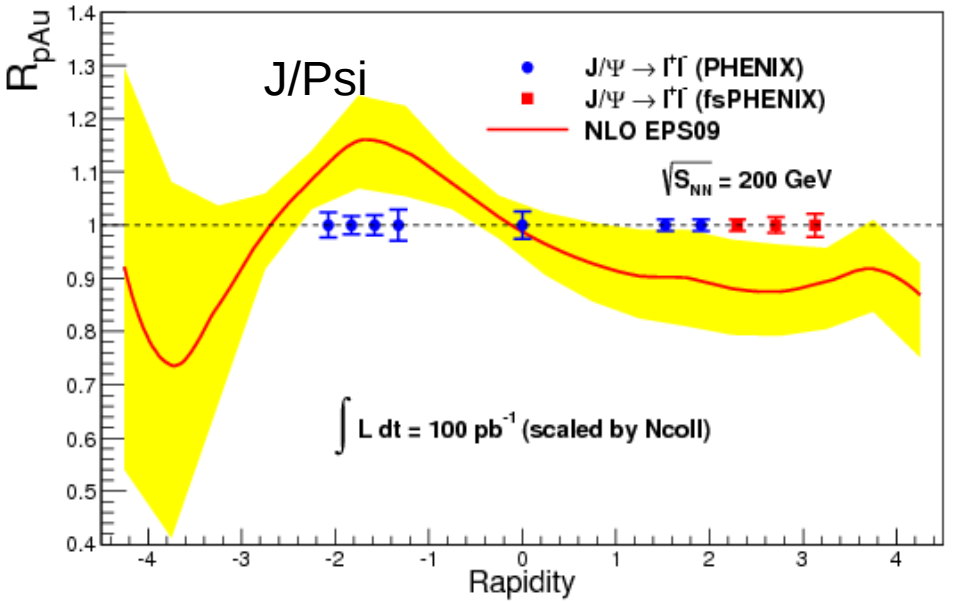
Forward J/Psi and Drell-Yan: Small-x Saturation

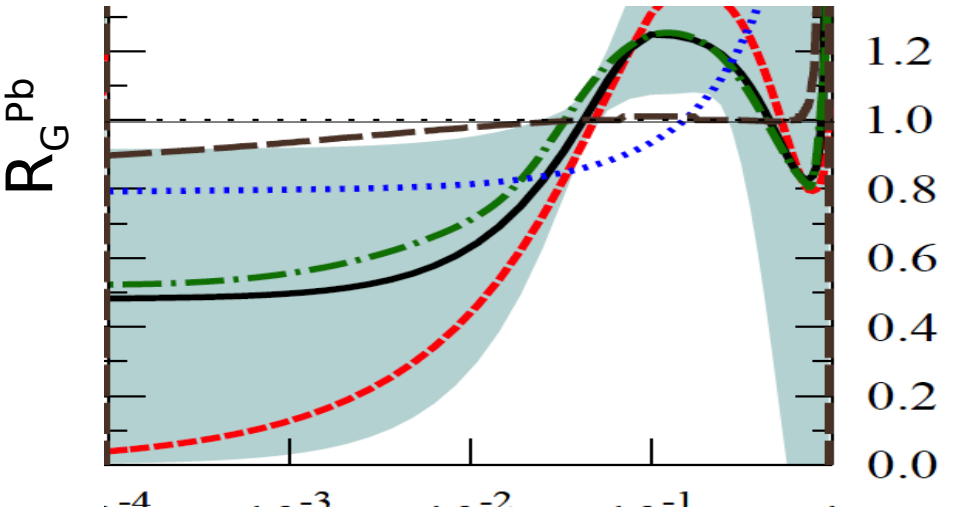
DY challenges:
- DY background rejection
- Study in progress

Other channels:
- Hadron, jet, J/Psi etc.

$$R = \frac{\sigma(p+A)}{A \times \sigma(p+p)}$$





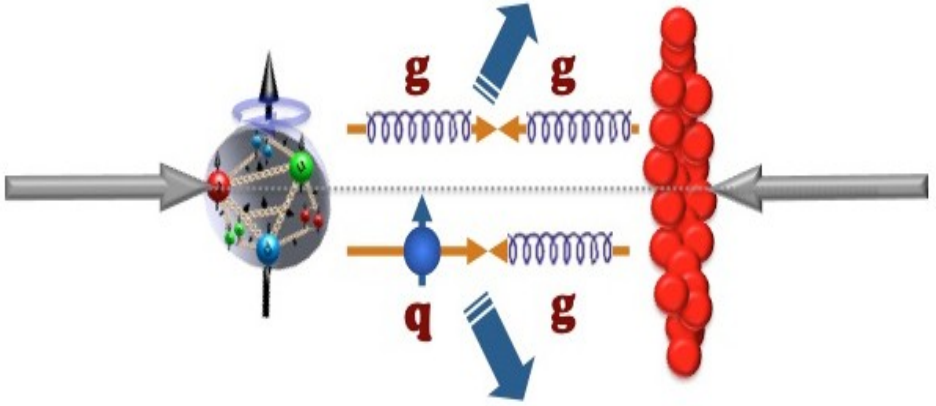


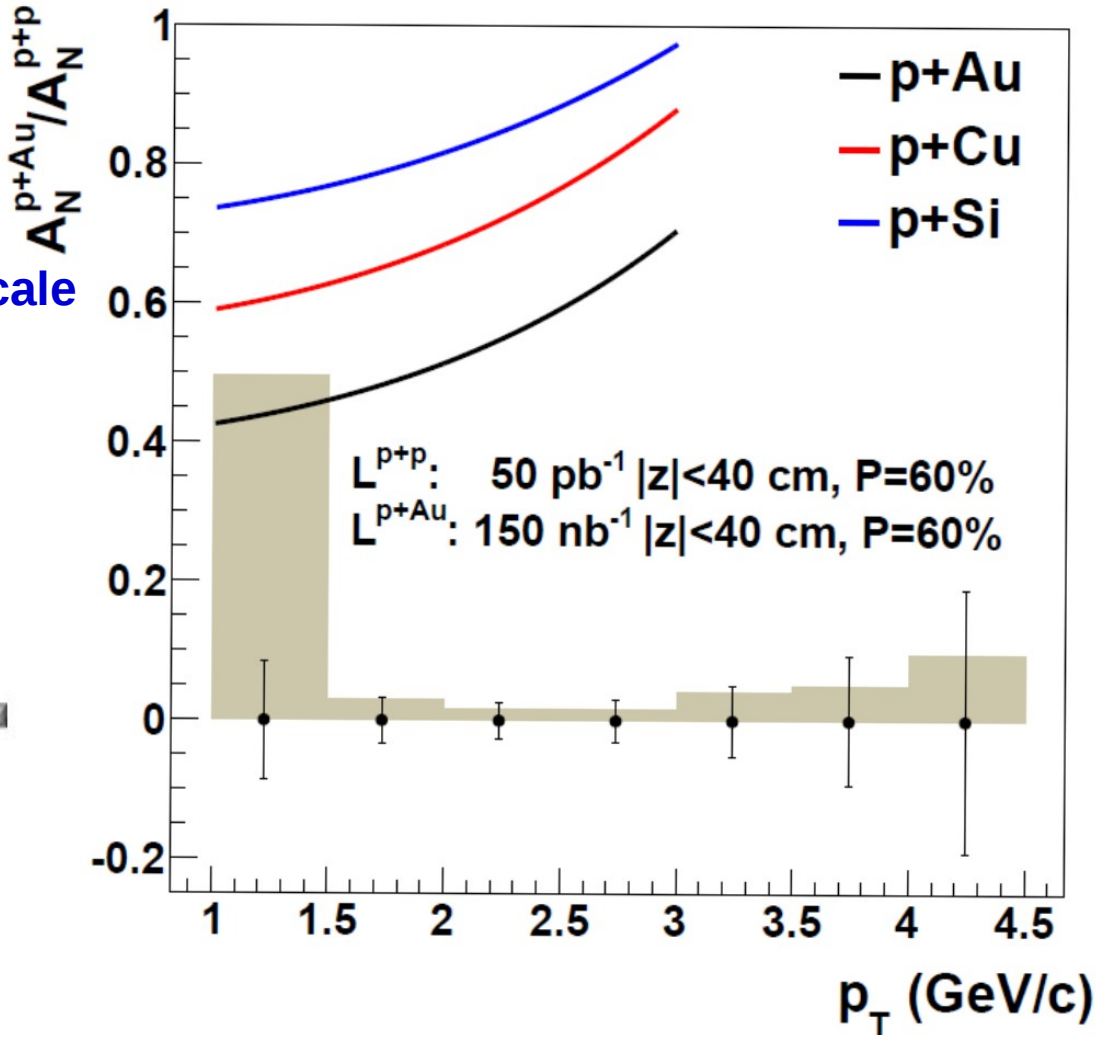
Polarized p+A

Forward pi0 TSSA to probe saturation scale

Run 2015: first transverse p+A @RHIC!

See X. Jiang's PHENIX MPC-EX talk (Tue)





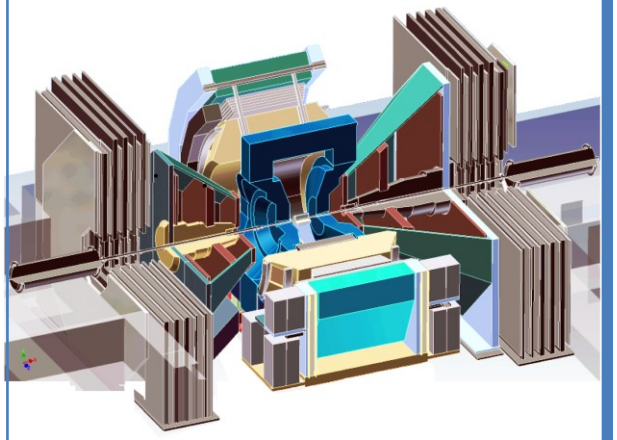
$$\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\Big|_{P_{h\perp}\ll Q_s^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{\frac{P_{h\perp}^2\,\delta^2}{Q_{sp}^4}}$$

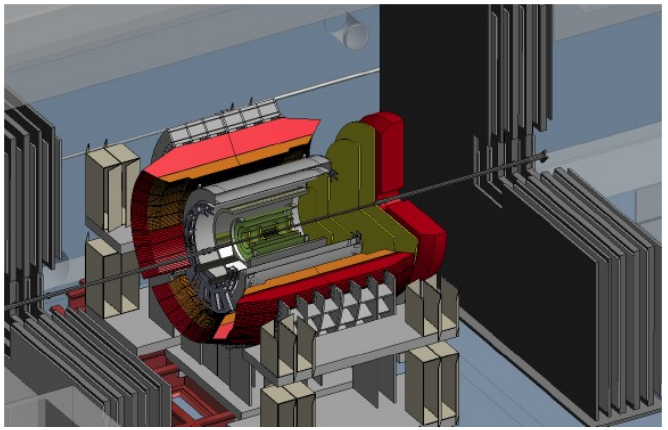
$$\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\Big|_{P_{h\perp}\gg Q_s^2} \approx 1$$

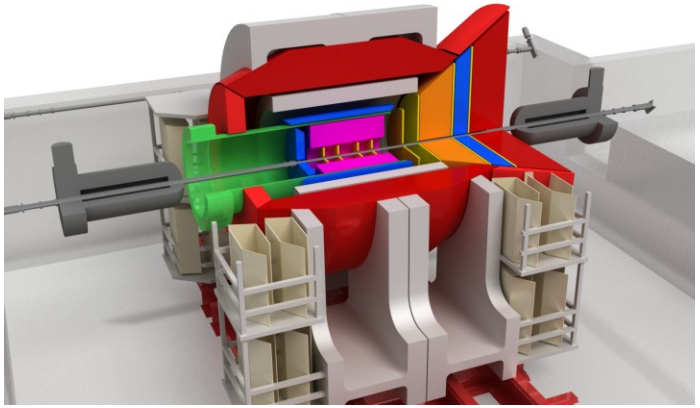
Outlook: PHENIX -> Forward/sPHENIX->eRHIC

Documented: http://www.phenix.bnl.gov/plans.html

Current PHENIX	*Forward s*PHENIX	An EIC detector
• Current PHENIX as discussed in many previous talks • 14y+ work • 100+M$ investment • 130+ published papers to date • Last run in this form 2016	‣ sPHENIX: comprehensive central upgrade based on BaBar magnet ‣ fsPHENIX: forward tracking, HCal and muon ID ‣ Key tests of theoretical frameworks for transverse spin and CNM	‣ Path of PHENIX upgrade leads to a capable EIC detector ‣ Large coverage of tracking, calorimetry and PID ‣ New collaboration/new ideas







~2000 2017→2020 ~2025 Time

RHIC: A+A, polarized p+p, polarized p+A

eRHIC: e+p, e+A

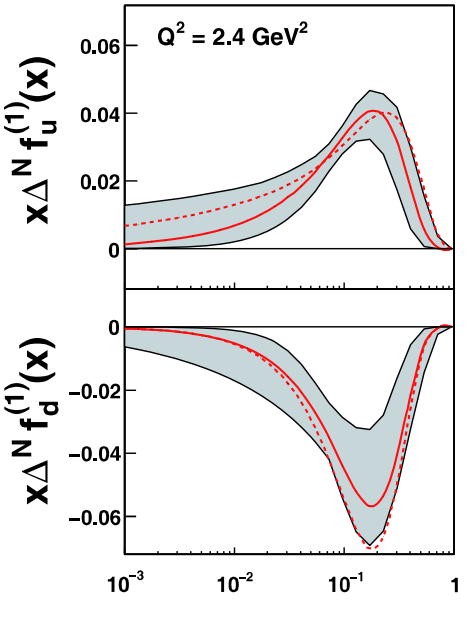
backup

Flavor Tagged Jet Asymmetry

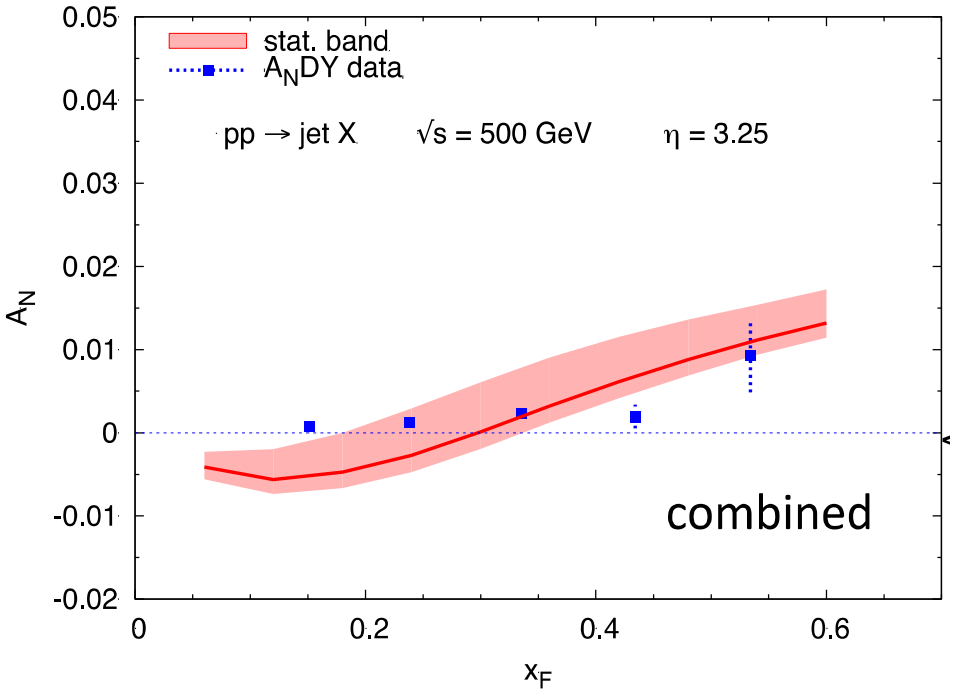
- Jet and leading h^+ and h^-
- Forward jets: eta = [1.7, 3.3]

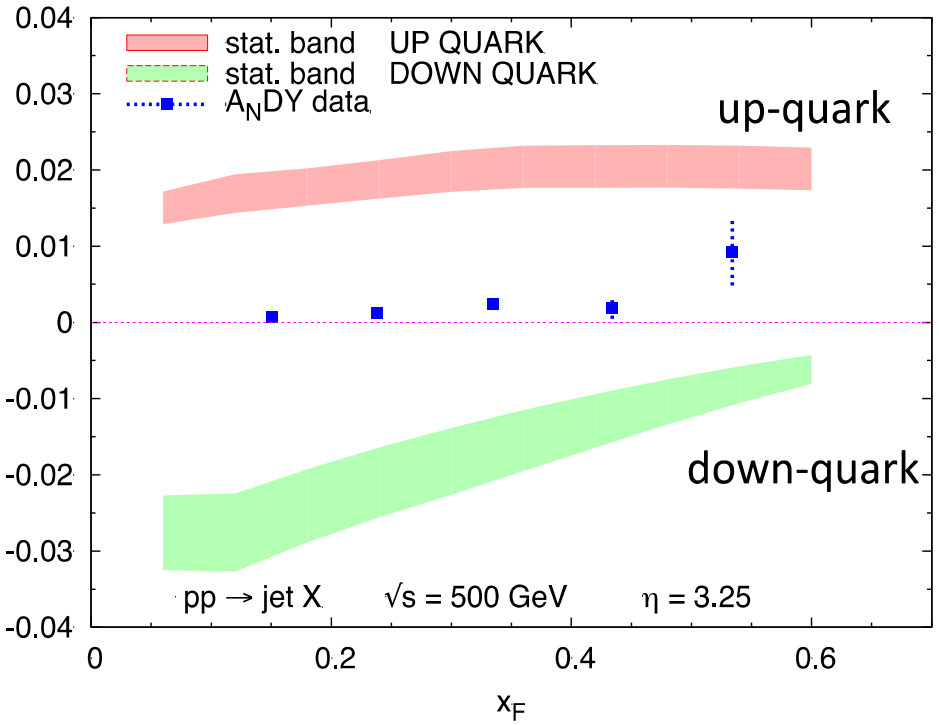
Why Jet A_N from AnDY is so small?

Cancellation of u and d quarks' Sivers asymmetry?



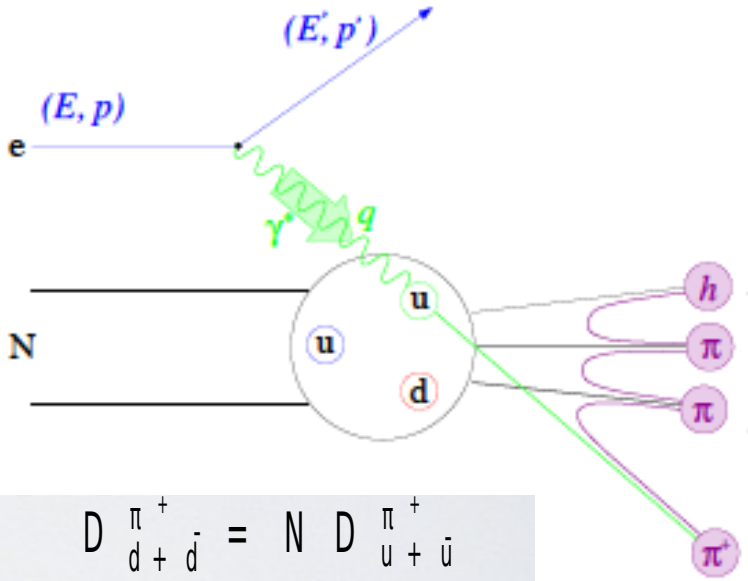
Directly use Sivers function from SIDIS fit





Tag Quark Flavor with Leading Charged Hadrons

- @Z = 0.5



$$D_{d+\bar{d}}^{\pi^+} = N D_{u+\bar{u}}^{\pi^+}$$

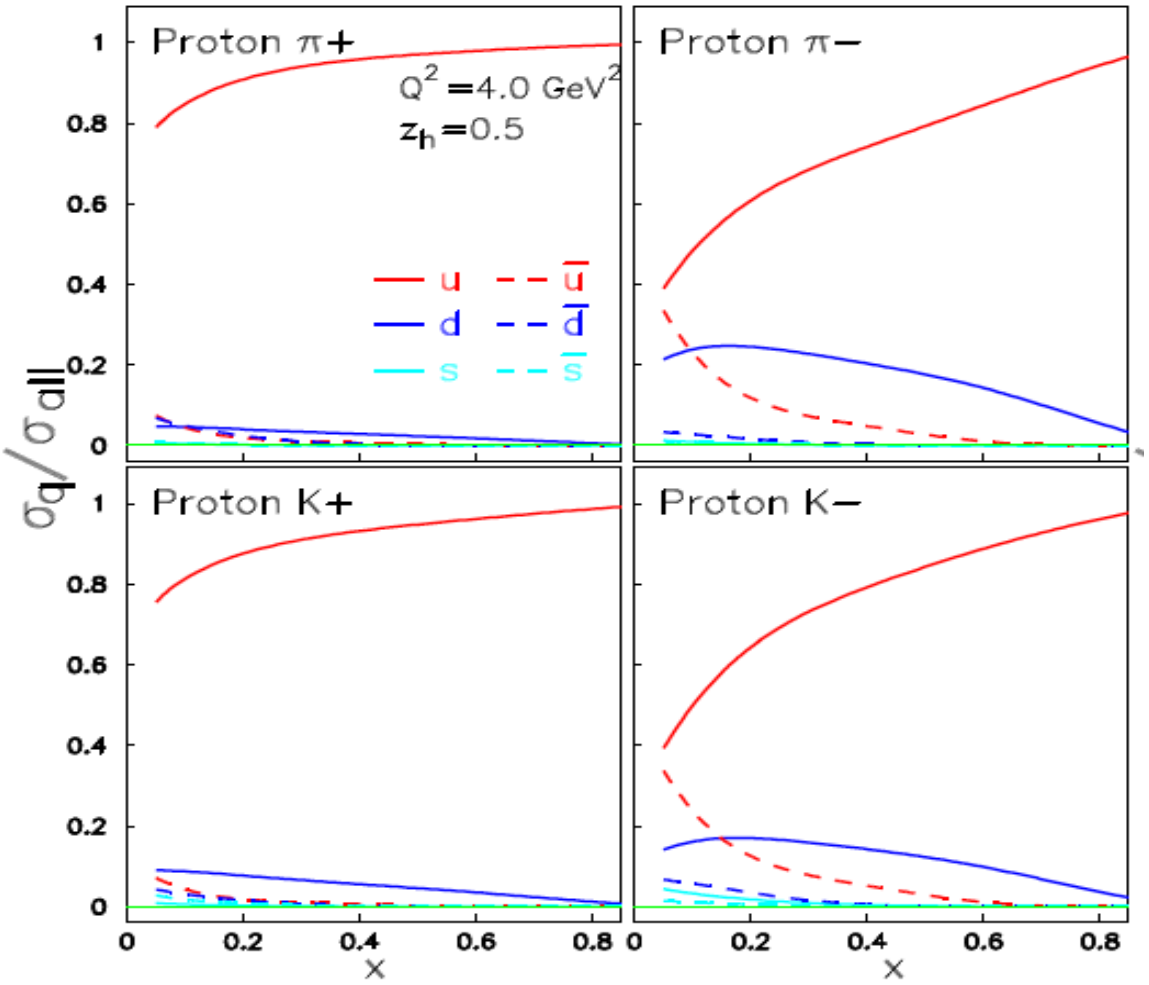
$$D_{s}^{\pi^+} = D_{\bar{s}}^{\pi^+} = N' D_{\bar{u}}^{\pi^+}$$

DSS FF

$$D_{\bar{u}}^{\pi^+} = D_{d}^{\pi^+}$$

$$D_{\bar{u}}^{K^+} = D_{s}^{K^+} = D_{d}^{K^+} = D_{\bar{d}}^{K^+}.$$

$$\sigma_q/\sigma_{all} = e_f^2 q_f \cdot D_f^h / \sum e_i^2 q_i \cdot D_i^h$$



u-quark dominates in proton

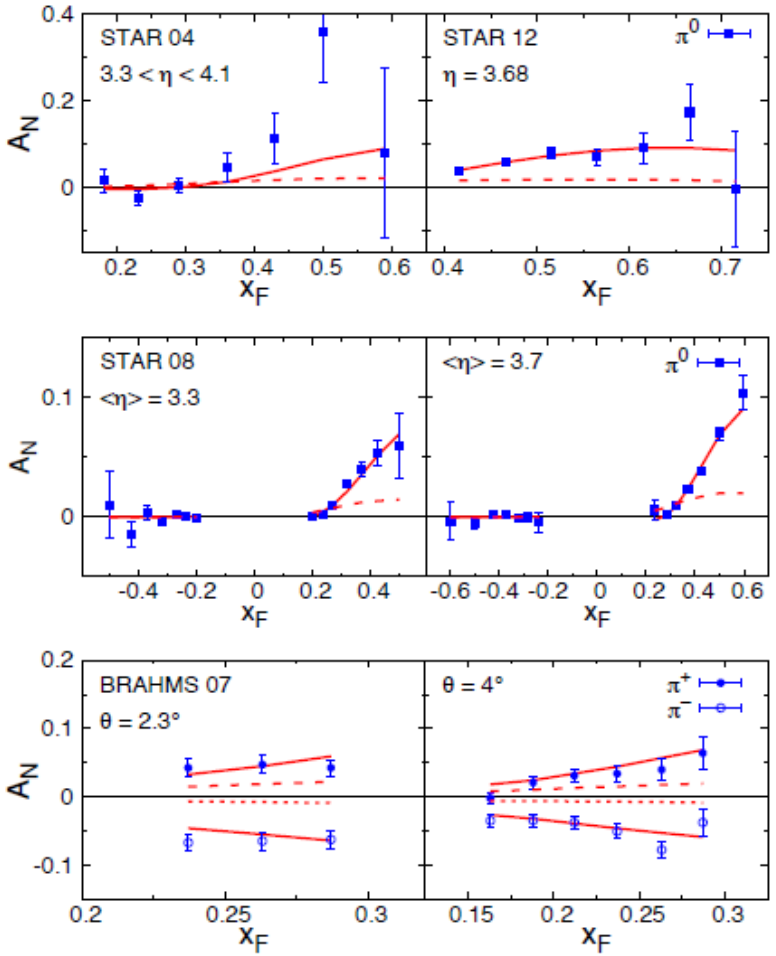
Possible Resolutions?

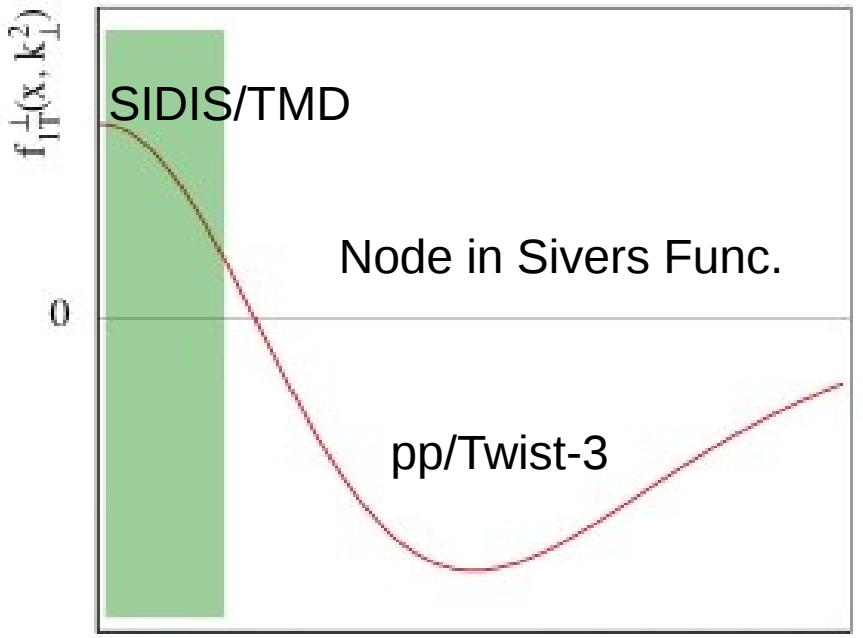
"Collins"? Node in "Sivers"? Etc.

A_N from twist-3 fragmentation functions

(Kanazawa, Koike, Metz, Pitoniak, arXiv:1404.1033)

Need new direct measurements of Sivers and Collins in p+p! fsPHENIX!



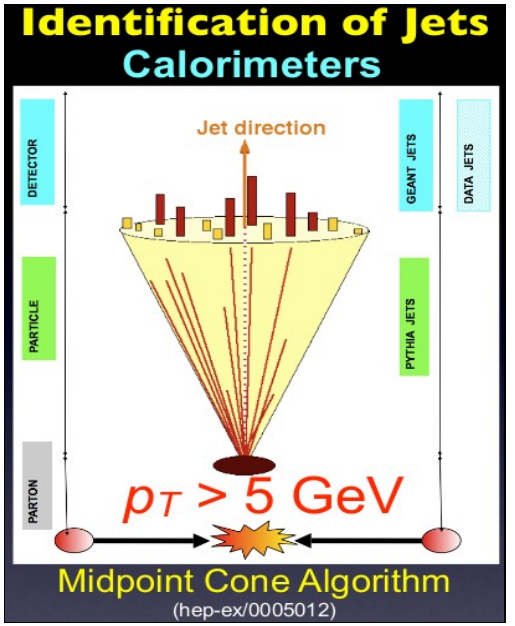


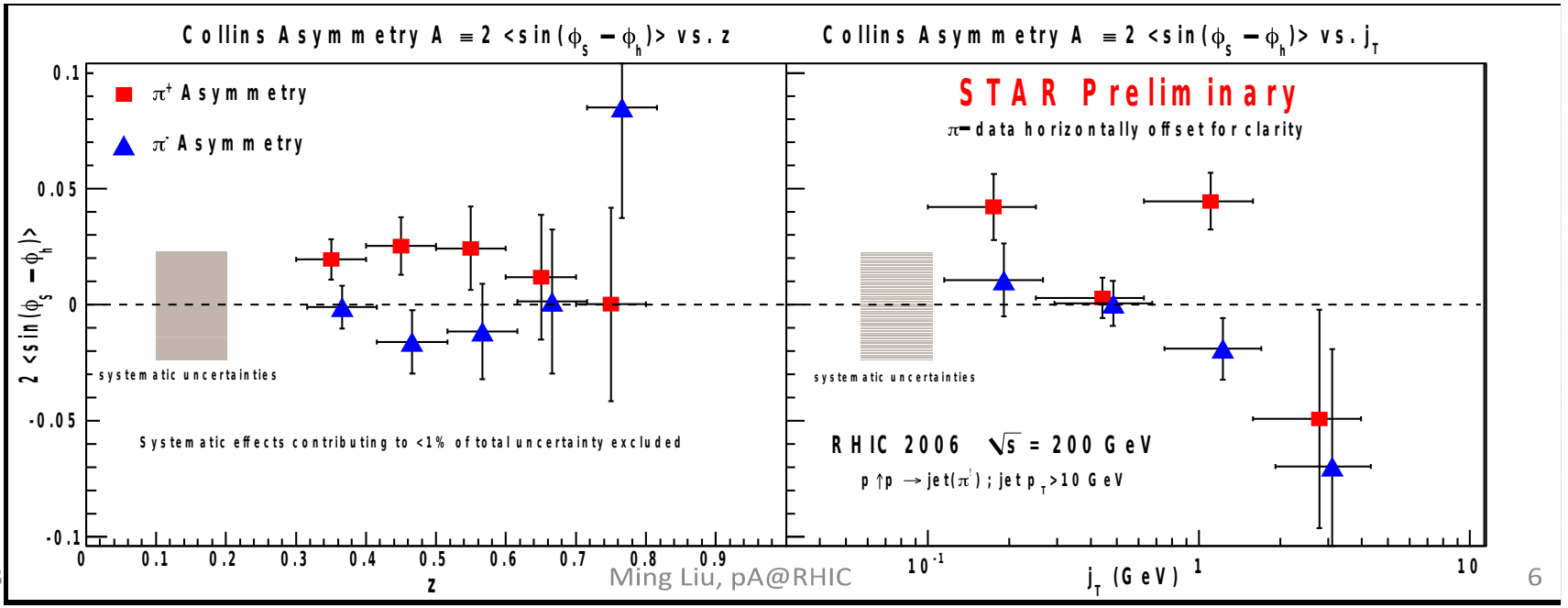
3RC/BNL

Kang, Prokudin PRD (2012)

Collins Asymmetry inside Jets

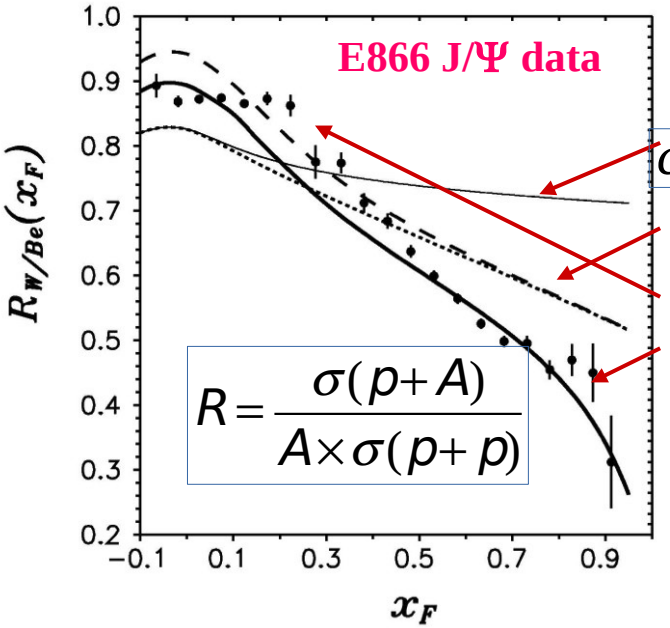
- Significant non-zero spin asymmetry observed @RHIC





Energy Loss and Hadronization in p+A

Kopeliovich etal Nucl Phys A696 (2001)



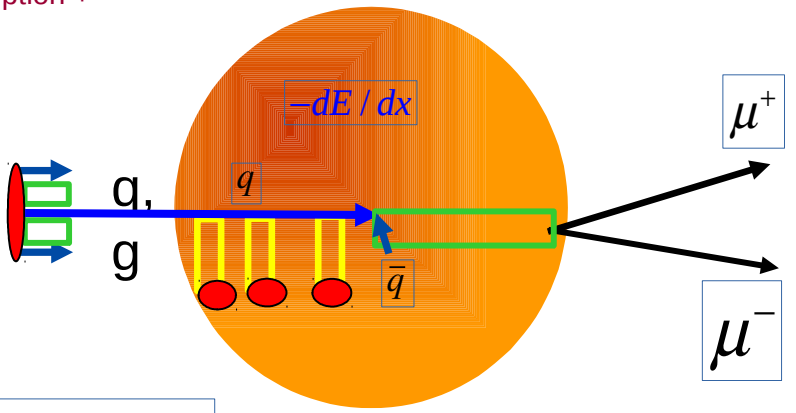
$c\bar{c}$

Quark shadowing and final state absorption +

Gluon shadowing +

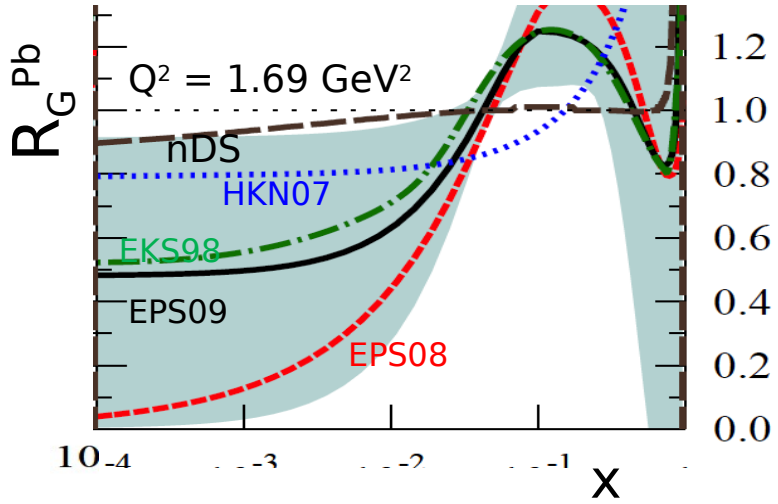
Anti-shadowing +

dE/dx



$$p + A \rightarrow J/\psi + X$$

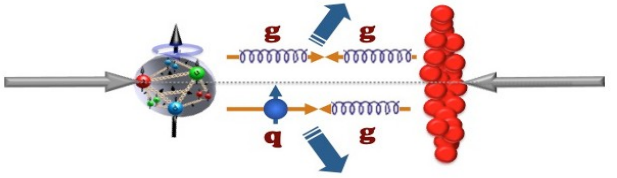
Gluon shadowing



+

dE/dx

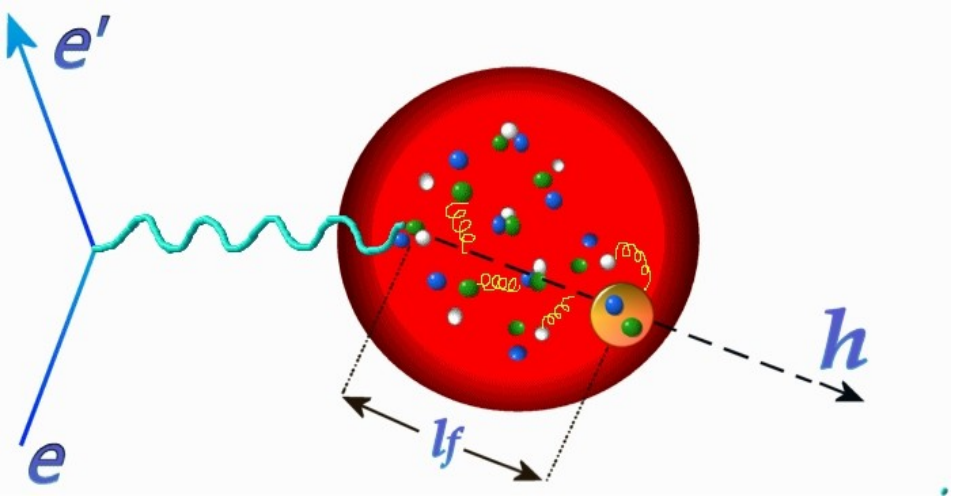
Need to isolate dE/dx from other effects => E906 @Fermilab!

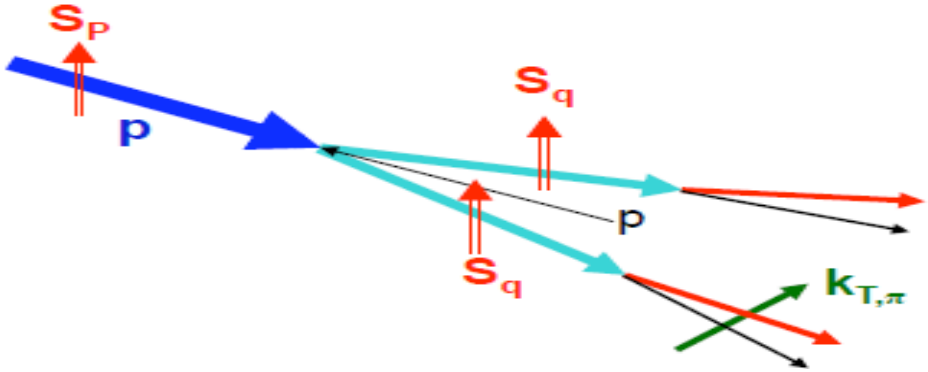


Could "A" affect Collins Fragmentation Function?

- Unpolarized quark fragmentation "is modified" in SIDIS
  - hadronization
- How about Collins polarized fragmentation functions in p+A?
  - Hadronization in CGC?

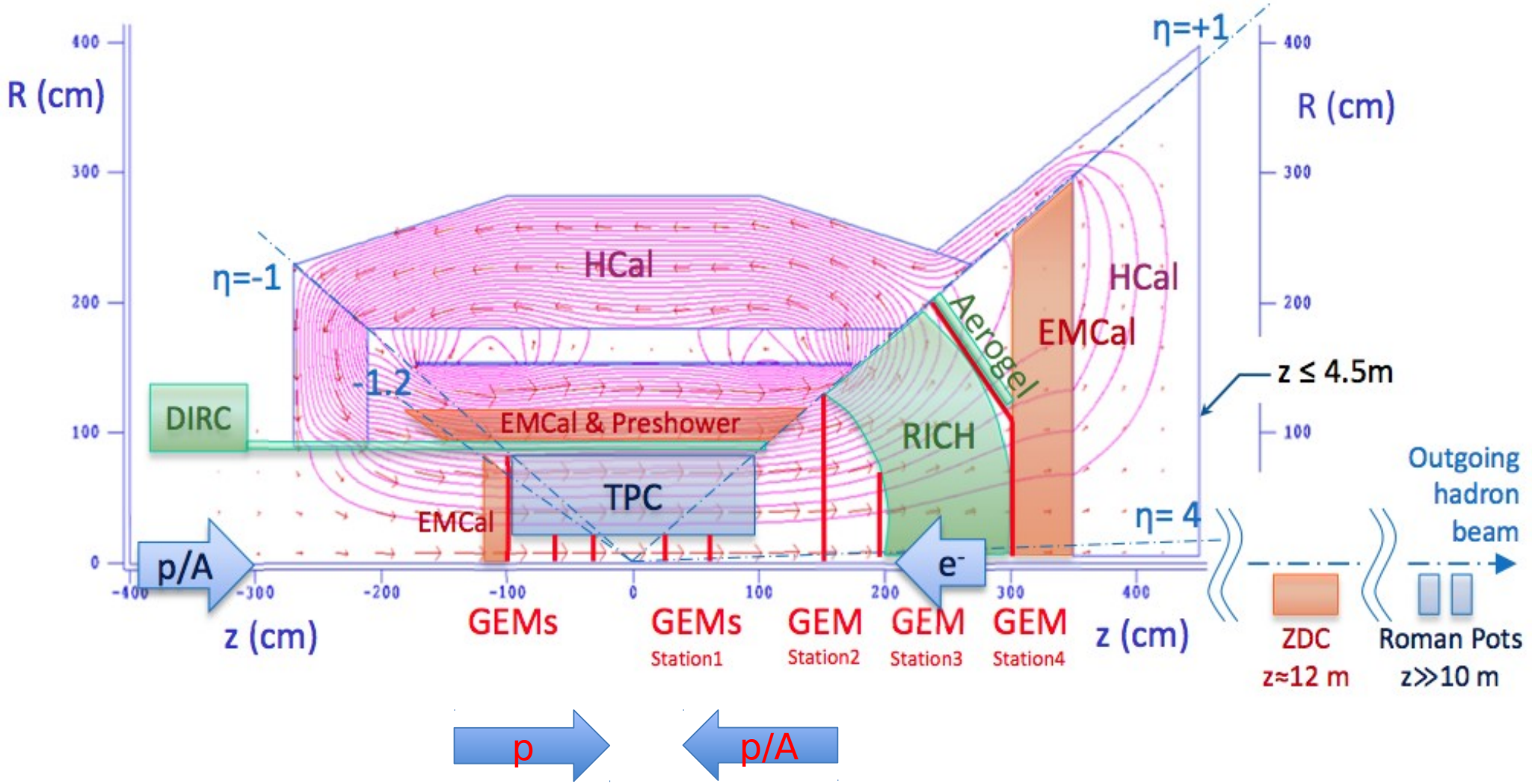
Kwatar Hafidi pA@RHIC



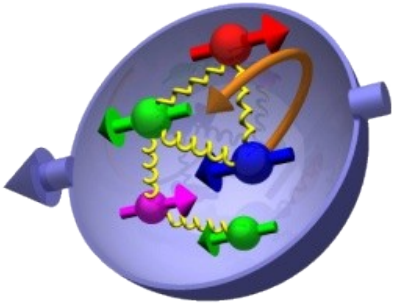


Key observables:
- Collins A_N asymmetry inside a Jet in p+A
- Centrality dependence, (pT, z, PID…)
- NO polarized e+"A", unique @RHIC

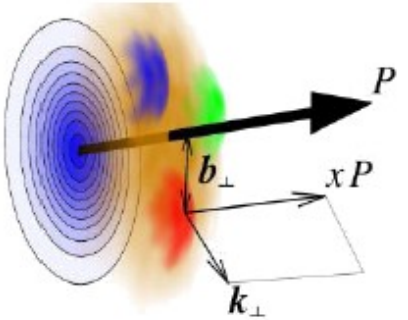
Conceptual f/s/ePHENIX Design



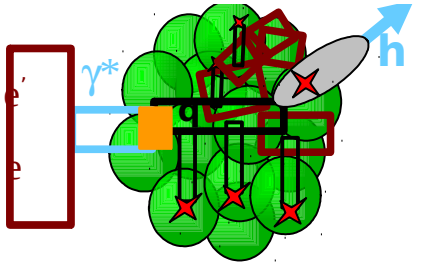
eRHIC Physics



- Gluon spin structure
  - Process: Inclusive DIS
  - Observable: scattered electron measurements
  - Detector: EMCal + tracking
- Strange spin, TMD, Propagation of hadron in nucle
  - Process: semi-inclusive DIS
  - Observable: DIS + hadron with ID
  - Detector: DIS + h-PID for -1<eta<4 ~ fsPHENIX physics



- 3D tomography of proton
  - Process: exclusive production
  - Observable: Electron, photon, proton, exclusiveness
  - Detector: tracking, EMCal, Roman pots



- Saturation physics
  - Process: diffractive production
  - Observable: rapidity gap
  - Detector: Hcal in -1<eta<5
- Not included in stage-I
  - Heavy flavor production
  - Electro-weak physics