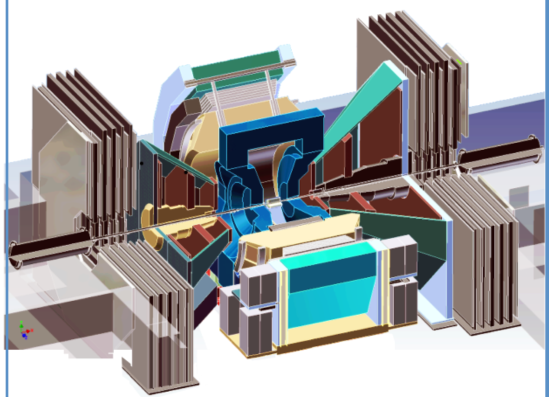
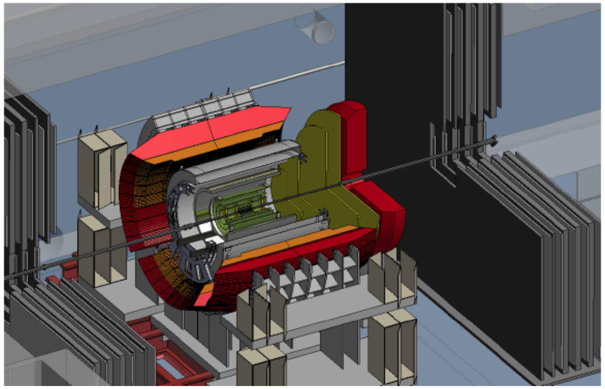
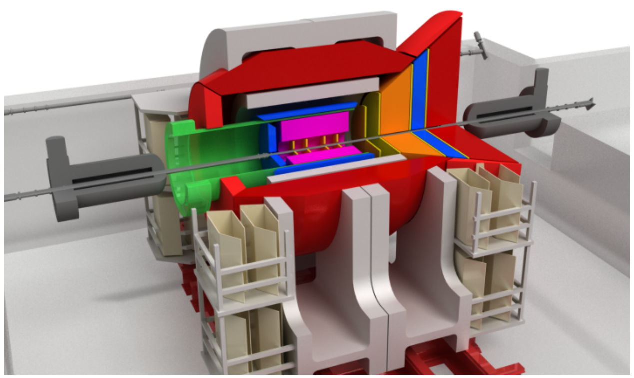
EIC and LANL's Interest

Ming Liu
LANL

Our Vision: PHENIX -> Forward/sPHENIX->ePHENIX

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

Current PHENIX	*f/s*PHENIX	An EIC detector
• PHENIX completed 2016 • 16y+ work 100+M$ investment • 130+ published papers to date	• Comprehensive central upgrade based on BaBar magnet • fsPHENIX: forward tracking, HCal and muon ID • Key study of transverse spin • New collaboration/new ideas	• Path of PHENIX upgrade leads to a capable EIC detector • Large coverage of tracking, calorimetry and PID • New collaboration/new ideas

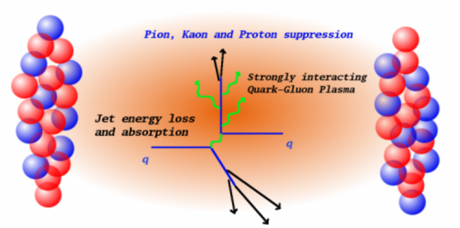
~2000 2017→2022 ~2025 Time

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

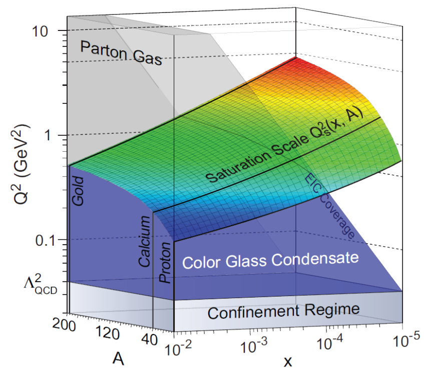
eRHIC: e+p, e+A

Recent Activities & Efforts

- PHENIX@BNL and SeaQuest@Fermilab
  - QGP, CNM and Spin; Dark photon/Higgs
  - Muon Trackers, FVTX @RHIC
  - MuID, Polarized NH3 target, DAQ, trigger @Fermilab
  - Mechanical and electronics engineering

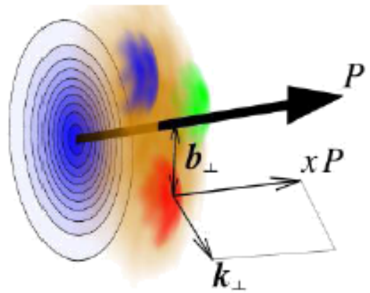


- sPHENIX
  - QGP B-jet physics
  - MAPS tracking
  - Si mini-strip tracking (~FVTX)



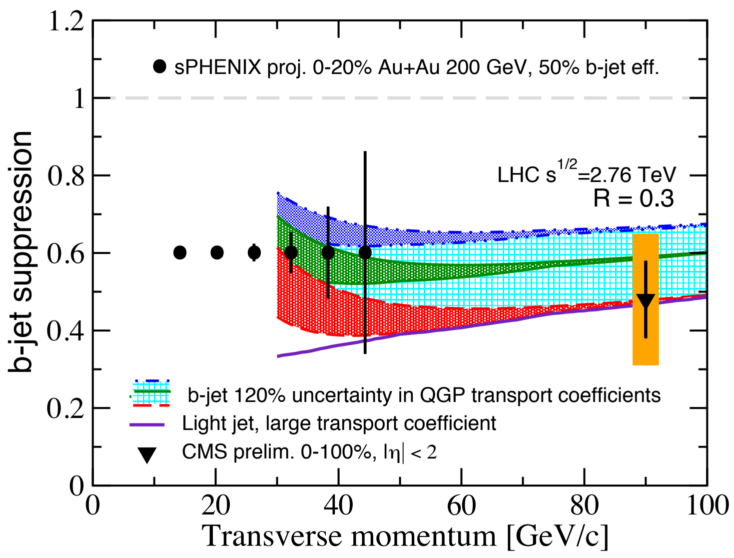
- f/sPHENIX
  - TMD spin physics: Jet A_N, Drell-Yan
  - CNM physics: dE/dx, shadowing in pA
  - Tracking: MAPS & GEM tracker

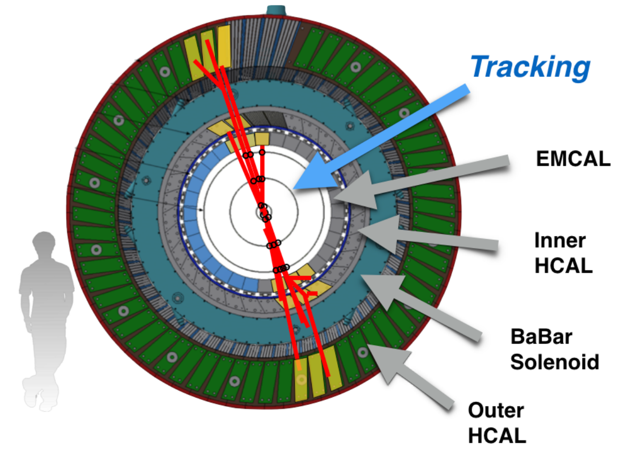
- EIC
  - TMD, GPD, CNM physics
  - Tracking, MAPS & GEM
  - Hadron PID, Modular Cerenkov detector

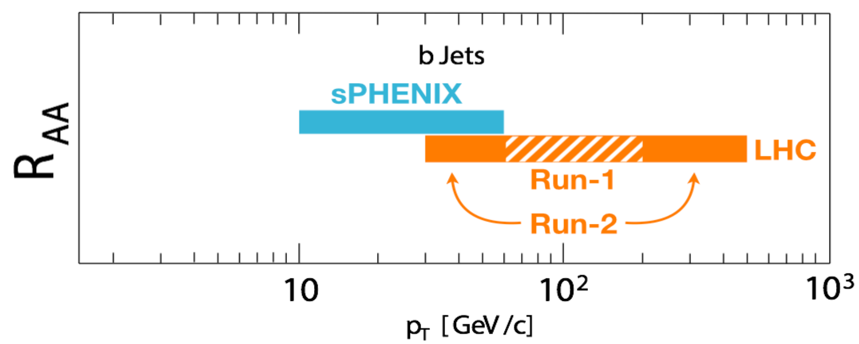


sPHENIX

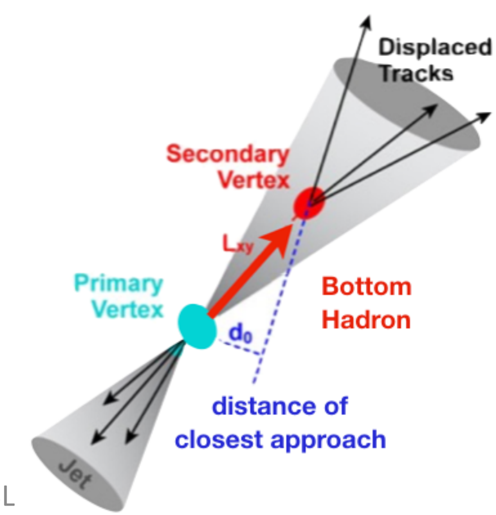
- B-jet Physics







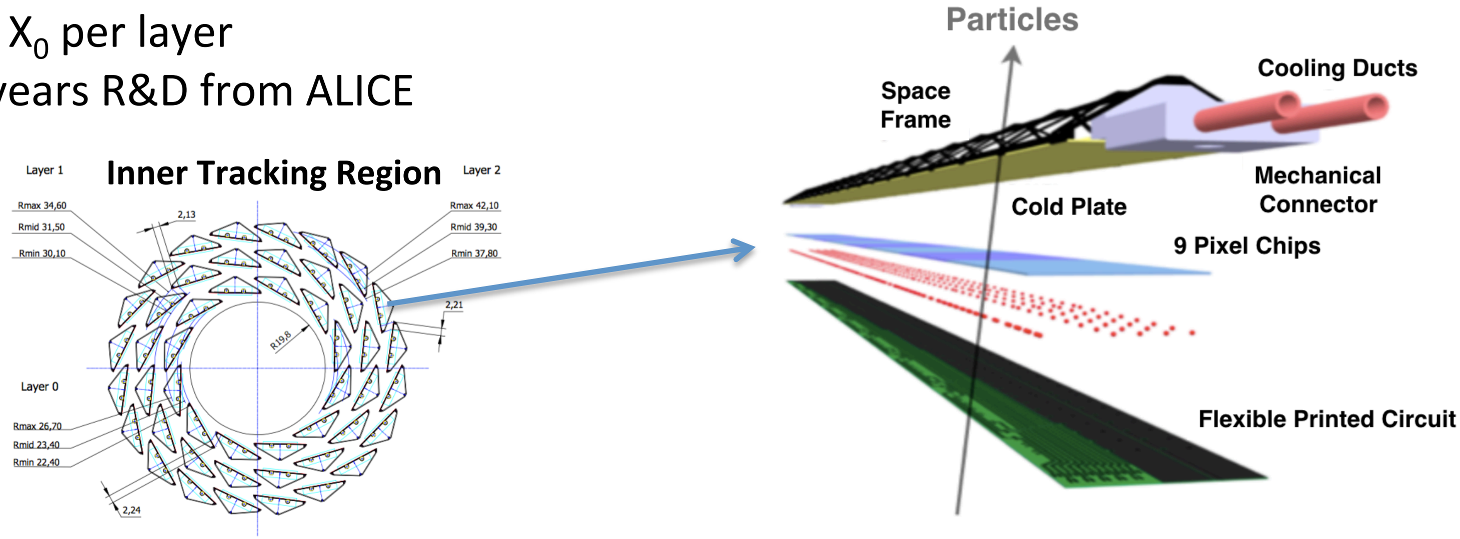
- Precision tracking w/ MAPS
  - Low mass pixel detector
  - Excellent technology for EIC



Monolithic Active Pixel Sensor (MAPS) Technology

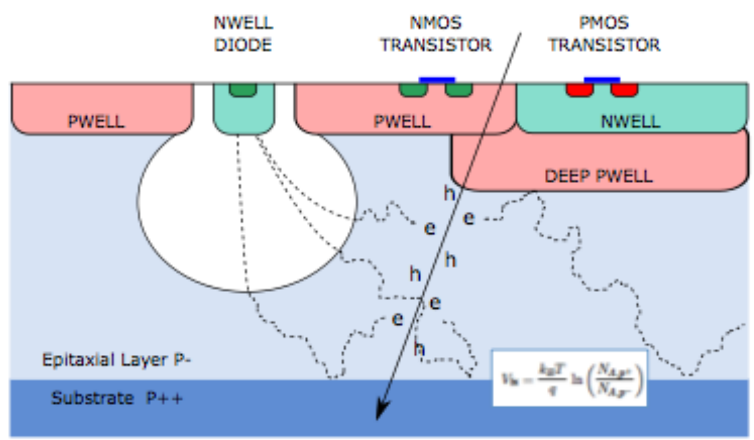
Inner Silicon Tracker with MAPS:

- 0.3% X_0 per layer
- 15+ years R&D from ALICE



MAPS sensor:

- Low mass, ultrathin 50um
- Fine pixel 28x28 um
- On-chip digitization



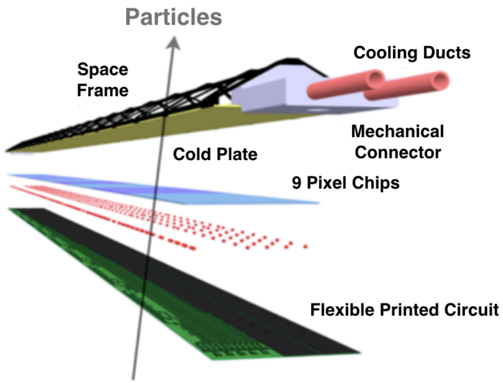
Excellent choice for

(1) EIC tracking

(2) Forward sPHENIX tracking

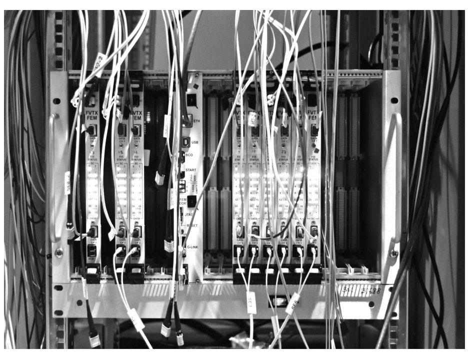
LANL LDRD: FY17-19, $5M

LDRD Experimental Goal: LANL-built 4-stave prototype tracker at test beam with custom sPHENIX readout



MAPS stave construction

1st MAPS prototype sensor being studied at **LANL**

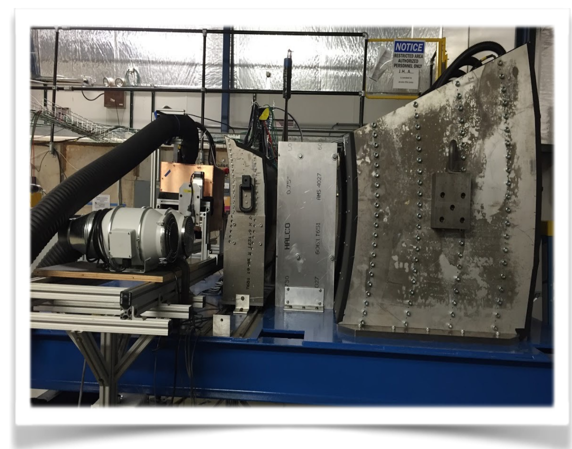


Custom front end, integrate into sPHENIX readout (FVTX expertise)

Annual Fermilab Test beam

Test prototype tracker

Validate tracking and reconstruction



sPHENIX EMCAL & HCAL prototypes – April 2016

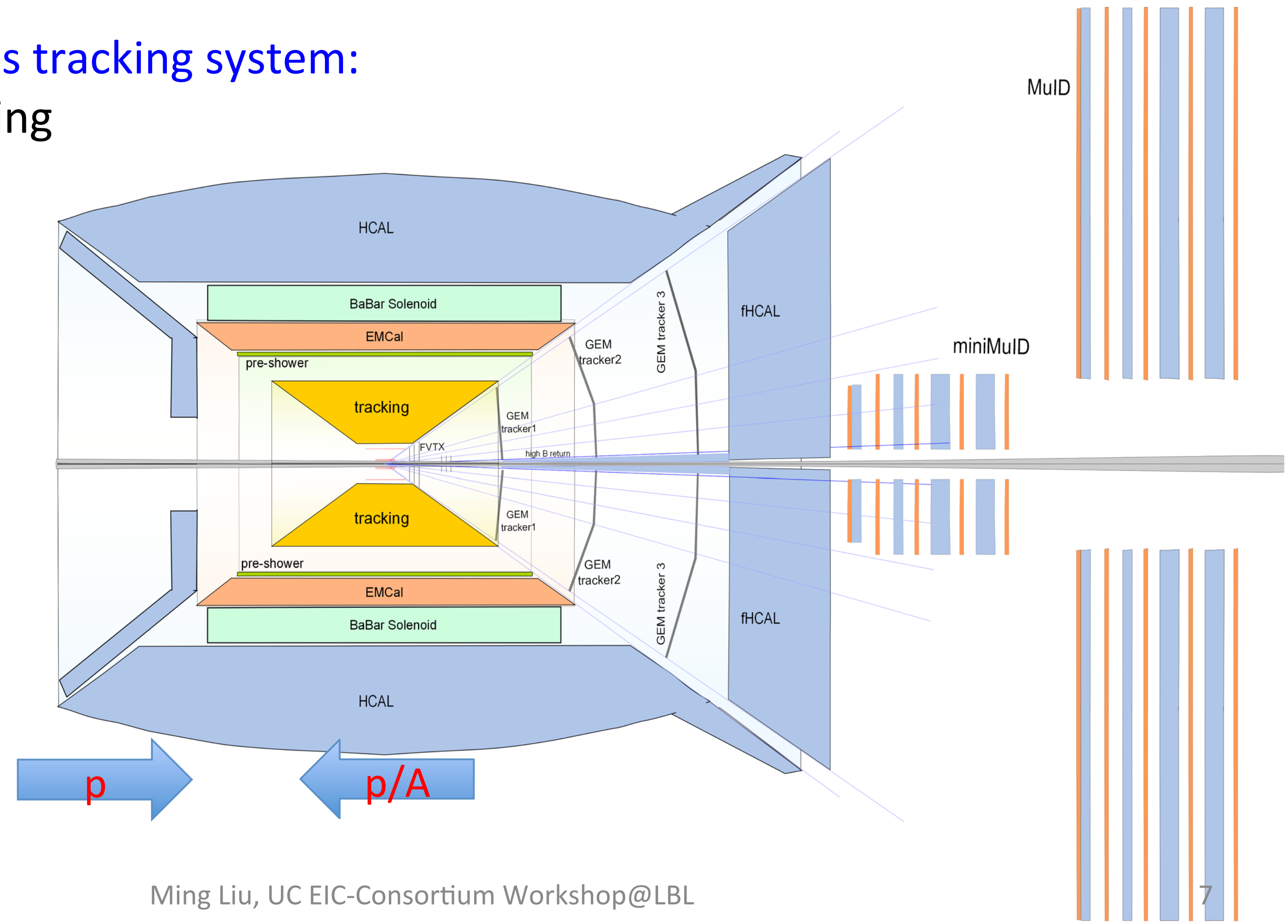
Forward sPHENIX

-1 < eta < 4

Clearly isolate and measure
Sivers-like and Collins-like effects in p+p, and more

Interests in low mass tracking system:

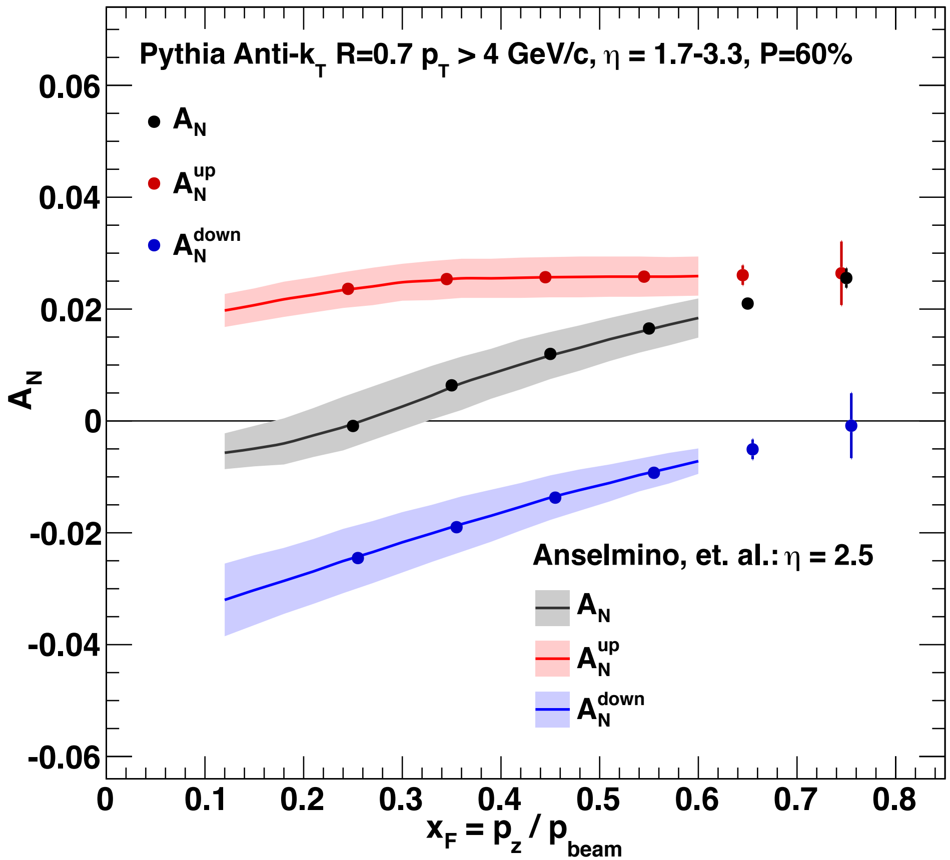
- MAPS for vertexing
- GEM for tracking
- Cerenkov PID



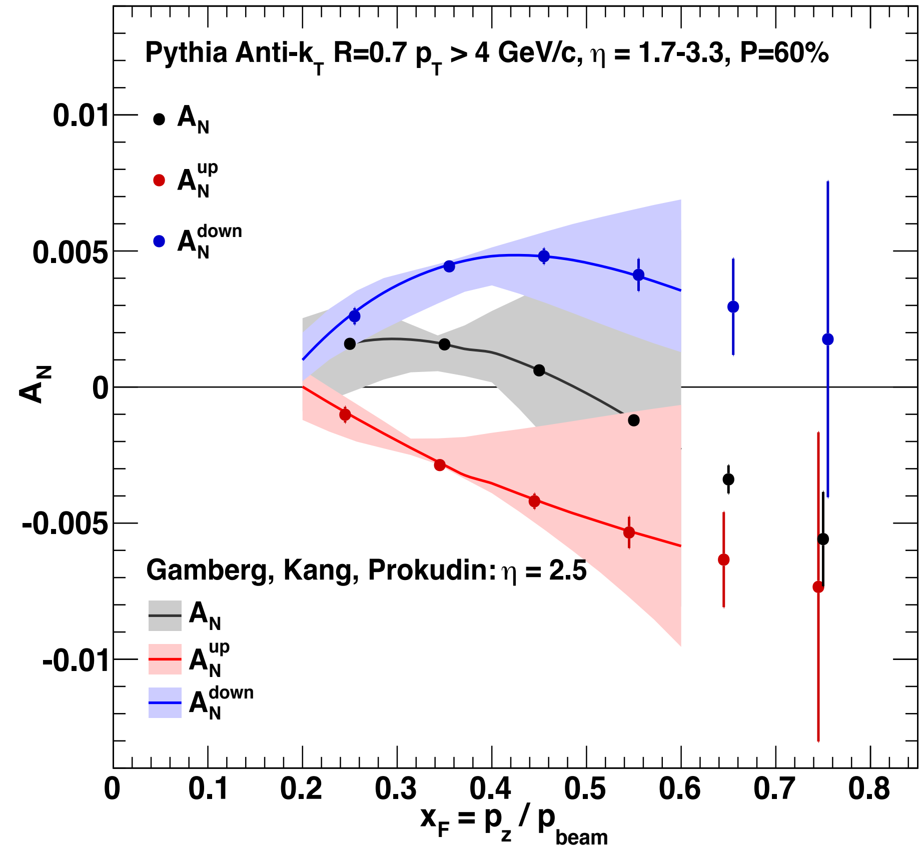
Process Dependence of Sivers TSSA: QCD dynamics

- Change of sign in flavor-tagged Jet TSSA

Naïve DIS Fit Sivers

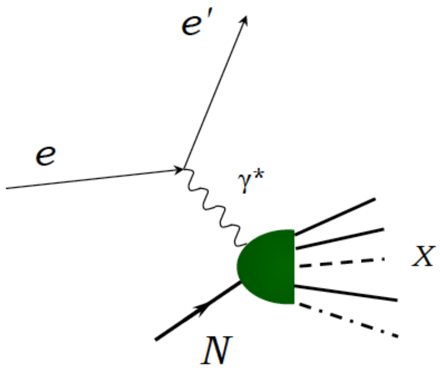


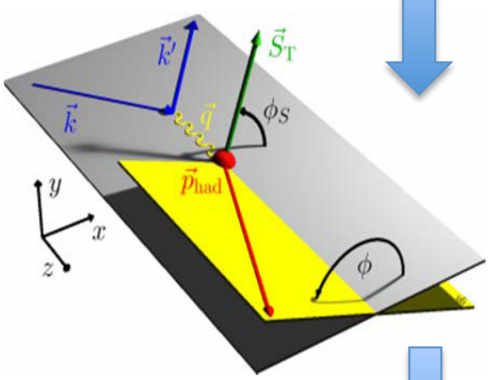
Included process dependence
And Q^2 evolution

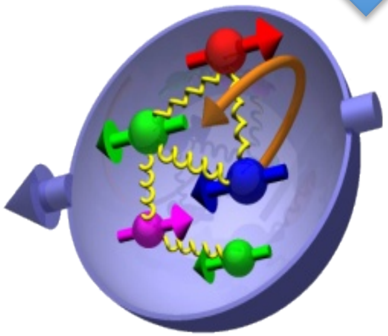


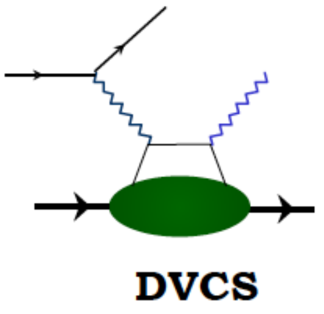
EIC Physics Interests

- Physics of Gluon distributions, interactions and correlations – QCD dynamics
  - Gluon polarization
  - Gluon TMDs, heavy quark and di-jet
  - Gluon saturation
- Propagation of parton/hadron in nuclei
  - Jet fragmentation and dE/dx
- 3D tomography of the proton
  - GPDs
  - DVCS and alike









EIC "Technical" Interests

- Low mass tracking detectors
  - MAPS for heavy quark physics
  - GEM for general tracking

- Hadron PID
  - Modular Cerenkov detectors (partially supported by EIC R&D through BNL)

- Other groups @LANL
  - ISR: detectors
  - AOT: electronics, accelerator etc
  - Computing & simulations: big data?

  - Theory synergy: QGP, CNM, Spin, physics BSM

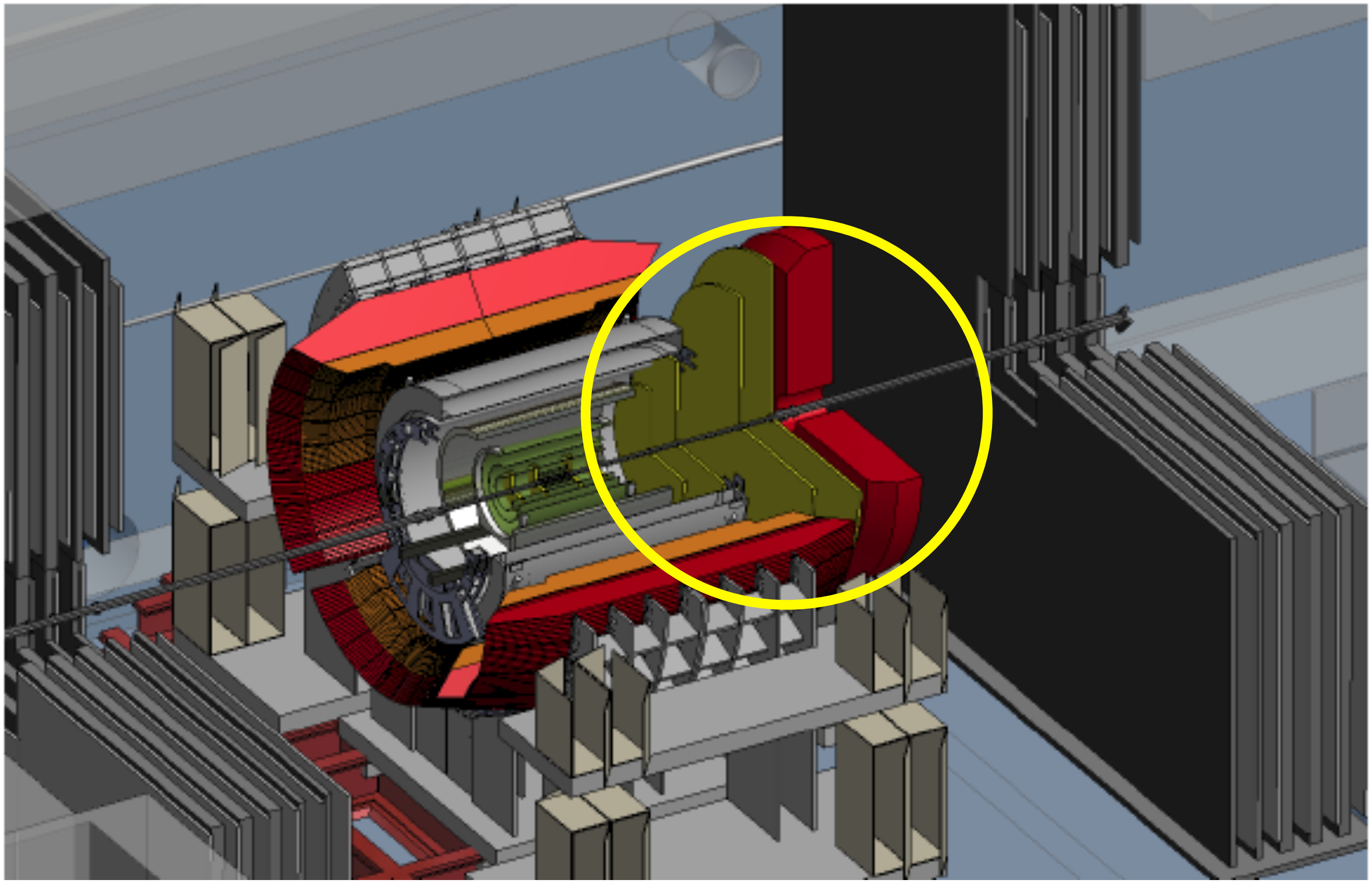
Forward Physics Ideas for sPHENIX & Applicability for EIC

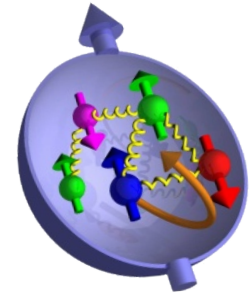
Ming Liu

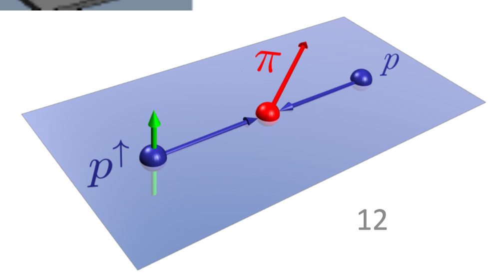
LANL

Forward sPHENIX Proposal

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



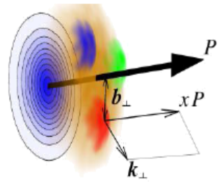




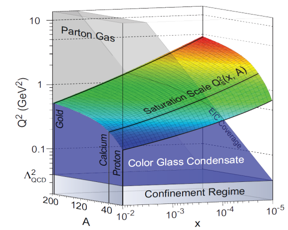
Transverse Spin Physics Centric in the Forward Rapidity:
Where significant novel effects observed!

Forward sPHENIX and EIC

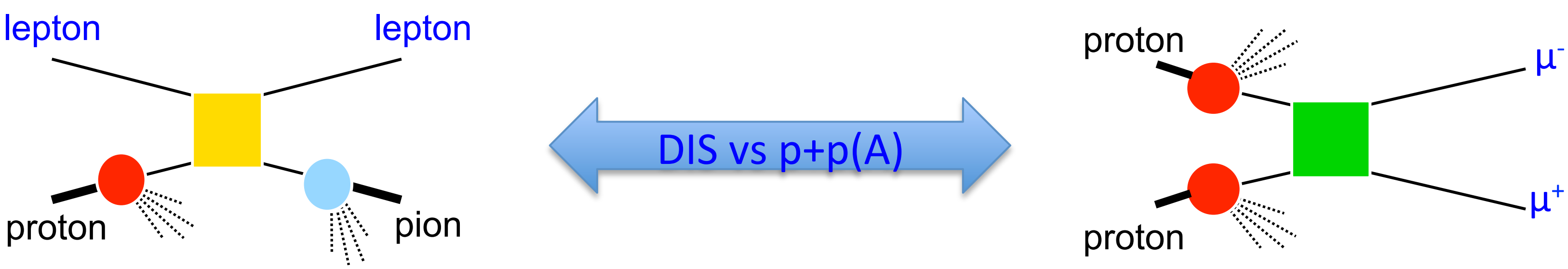
- Address many of the same key physics of EIC
  - Spin Physics and 3D structure
  - CNM Physics



- Complementary to EIC measurements
  - TMD vs Collinear factorization
  - Saturation physics



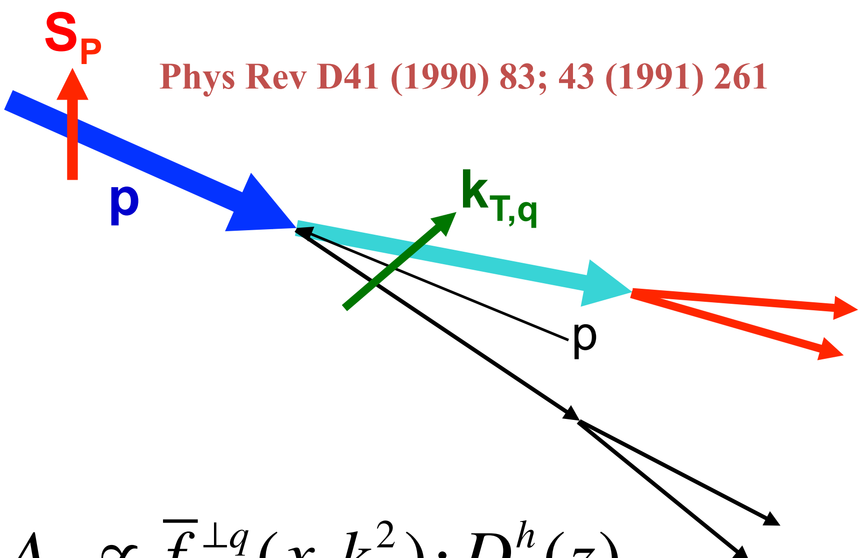
- Critical to cross check of consistency among various theoretical framework



TSSA Physics: EIC & fsPHENIX, an example

(i) Sivers mechanism:

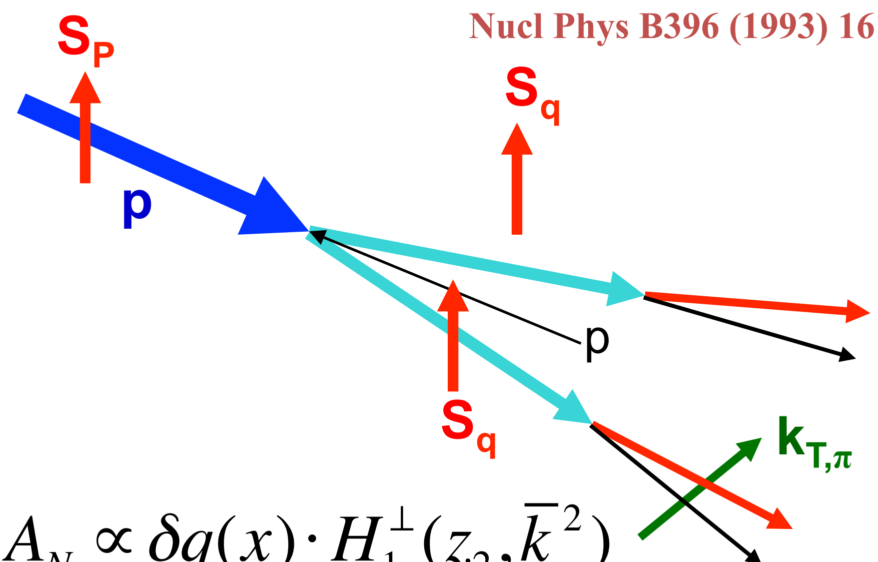
correlation between proton spin & parton k_T



$$A_N \propto \overline{f}_{1T}^{\perp q}(x, k_\perp^2) \cdot D_q^h(z)$$

(ii) Collins mechanism:

Transversity × spin-dep fragmentation



$$A_N \propto \delta q(x) \cdot H_1^\perp(z_2, \overline{k}_\perp^2)$$

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

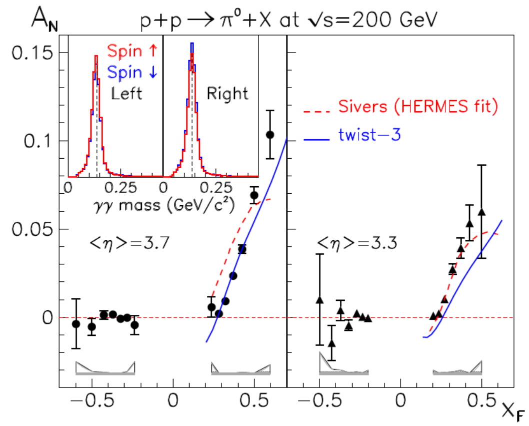
Sivers-like, Collins-like and more

A Surprise: A_N Sign Mismatch?

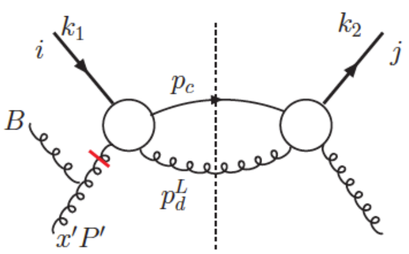
First attempt to check the "Universality of QCD description of TSSA"

- Kang, Qiu, Vogelsang, Yuan PRD 2011

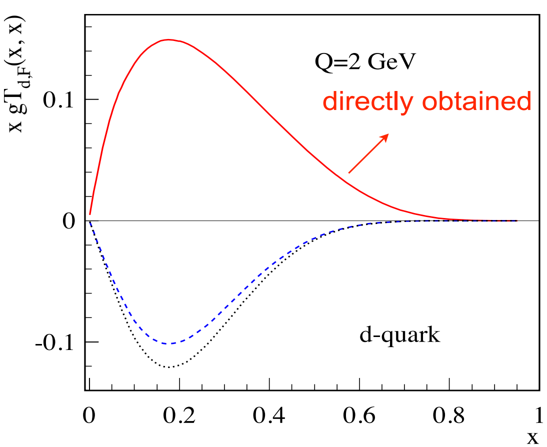
- Twist-3 (RHIC) v.s. Sivers (SIDIS)



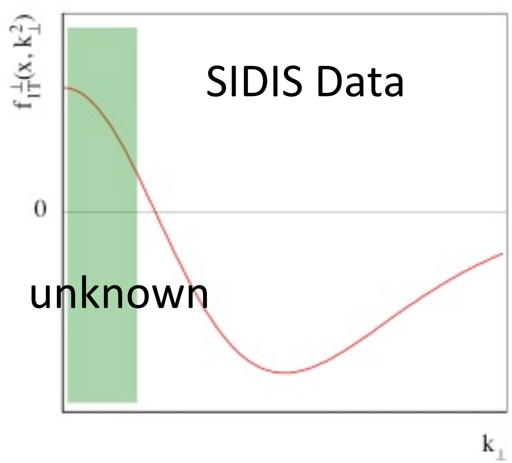
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$



Qiu,Sterman
Kouvaris et al.
Kanazawa,Koike
Kang,Prokudin



A possible solution? Kang, Prokudin PRD (2012)



Hadron TSSA in Twist-3 Framework

Qiu & Sterman PRD 59 (1998)

$$\Delta\sigma_{A+B\to\pi}(\vec{s}_T)=\sum_{abc}\phi^{(3)}_{a/A}(x_1,x_2,\vec{s}_T)\otimes\phi_{b/B}(x')\otimes H_{a+b\to c}(\vec{s}_T)\otimes D_{c\to\pi}(z)$$

$$+\sum_{abc}\delta q^{(2)}_{a/A}(x,\vec{s}_T)\otimes\phi^{(3)}_{b/B}(x_1',x_2')\otimes H''_{a+b\to c}(\vec{s}_T)\otimes D_{c\to\pi}(z)$$

$$+\sum_{abc}\delta q^{(2)}_{a/A}(x,\vec{s}_T)\otimes\phi_{b/B}(x')\otimes H'_{a+b\to c}(\vec{s}_T)\otimes D^{(3)}_{c\to\pi}(z_1,z_2)$$

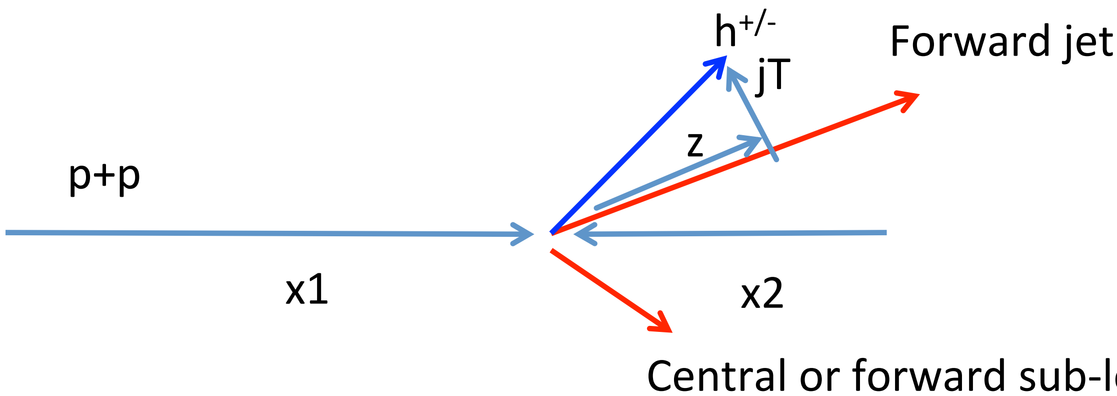
$$+\text{higher power corrections,}$$

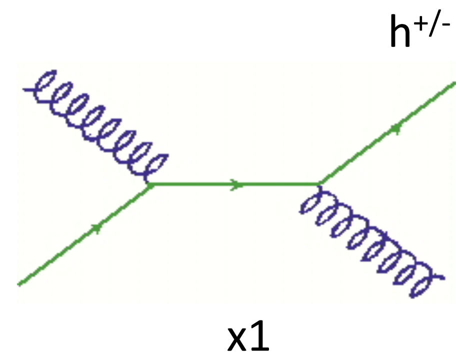
1st term: twsit-3 correlation functions, "Sivers"
2nd term: twist-2 transversity * twist-3 from unpol beam (expected small)
3rd term: twist-2 transversity * twist-3 FF, "Collins"

Need new direct measurements of Sivers and Collins TSSA in p+p!
Forward sPHENIX Upgrade Proposal

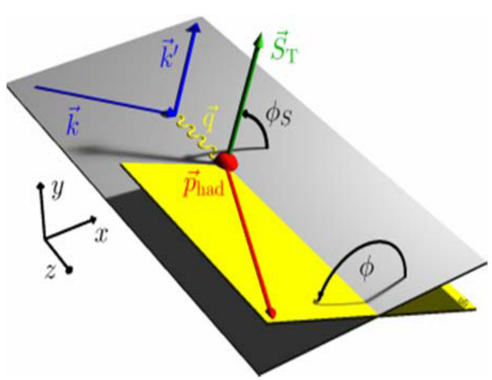
Access Sivers and Collins in p+p in the right Kinematic region X = 0.1 ~ 0.5

- Forward jet and hadron fragmentation TSSA measurement!





SIDIS

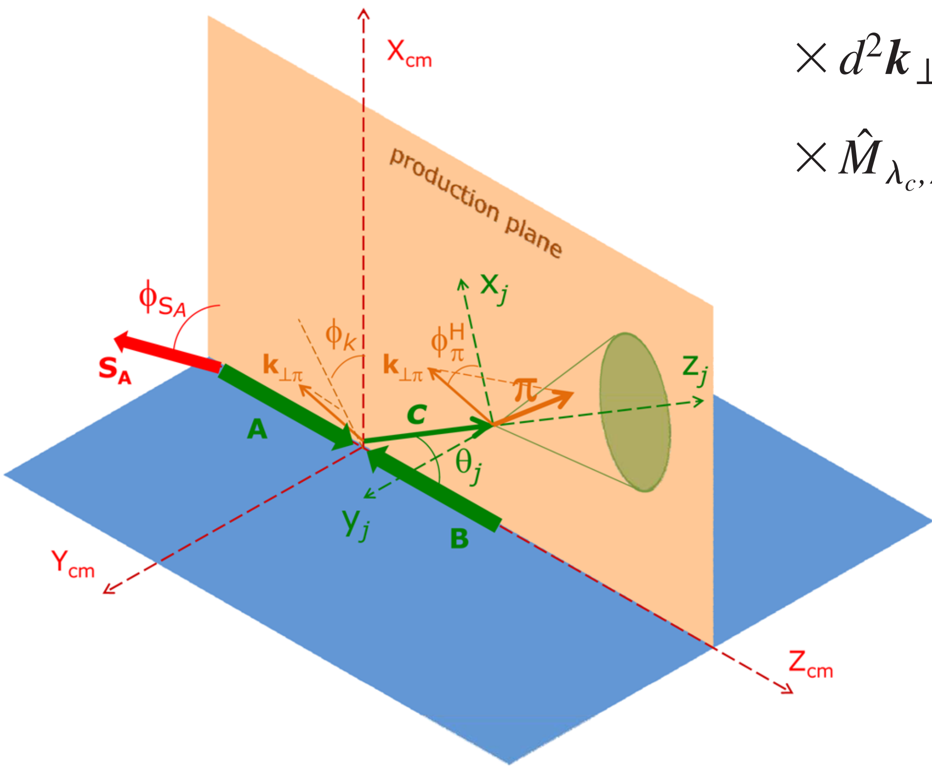


xF = (X1 – X2) ~ X1 = (pZ1 + pZ2)/100, when x1 >> x2

- q(x1) + g(x2) process dominates
- quark q(x1) Sivers and Collins asymmetry

Access Sivers and Collins with Jet and Hadron Azimuthal Distributions in Transversely Polarized p+p Collisions

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



$$\frac{E_j d\sigma^{A(S_A)B\to \mathrm{jet}+\pi+X}}{d^3 \boldsymbol{p}_j dz d^2\boldsymbol{k}_{\perp\pi}} = \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a dx_b}{16\pi^2 x_a x_b s} d^2\boldsymbol{k}_{\perp a}$$
$$\times d^2\boldsymbol{k}_{\perp b} \rho^{a/A,S_A}_{\lambda_a \lambda'_a} \hat{f}_{a/A,S_A}(x_a, \boldsymbol{k}_{\perp a}) \rho^{b/B}_{\lambda_b\lambda'_b} \hat{f}_{b/B}(x_b, \boldsymbol{k}_{\perp b})$$
$$\times \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b} \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b} \delta(\hat{s}+\hat{t}+\hat{u}) \hat{D}^{\pi}_{\lambda_c,\lambda'_c}(z, \boldsymbol{k}_{\perp\pi}).$$

Experimental variables:

- Jet $P_{j,}$ xF
- Hadron P_h , PID
- Beam polarization

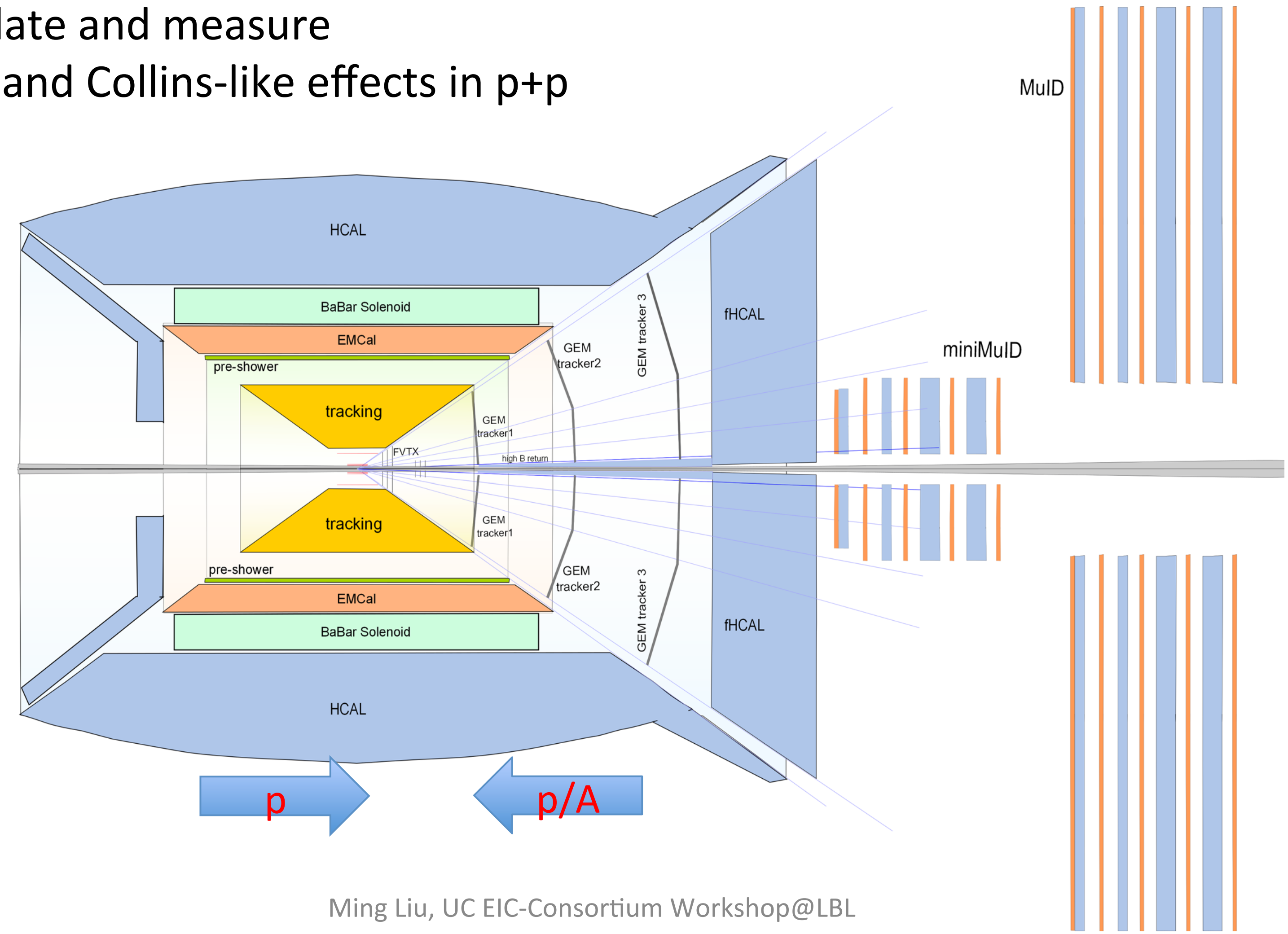
$A_N^{\sin\phi_{S_A}}$ → "Sivers-like"

$A_N^{\sin(\phi_{S_A} \mp \phi_\pi^H)}$ → "Collins-like"

Forward sPHENIX

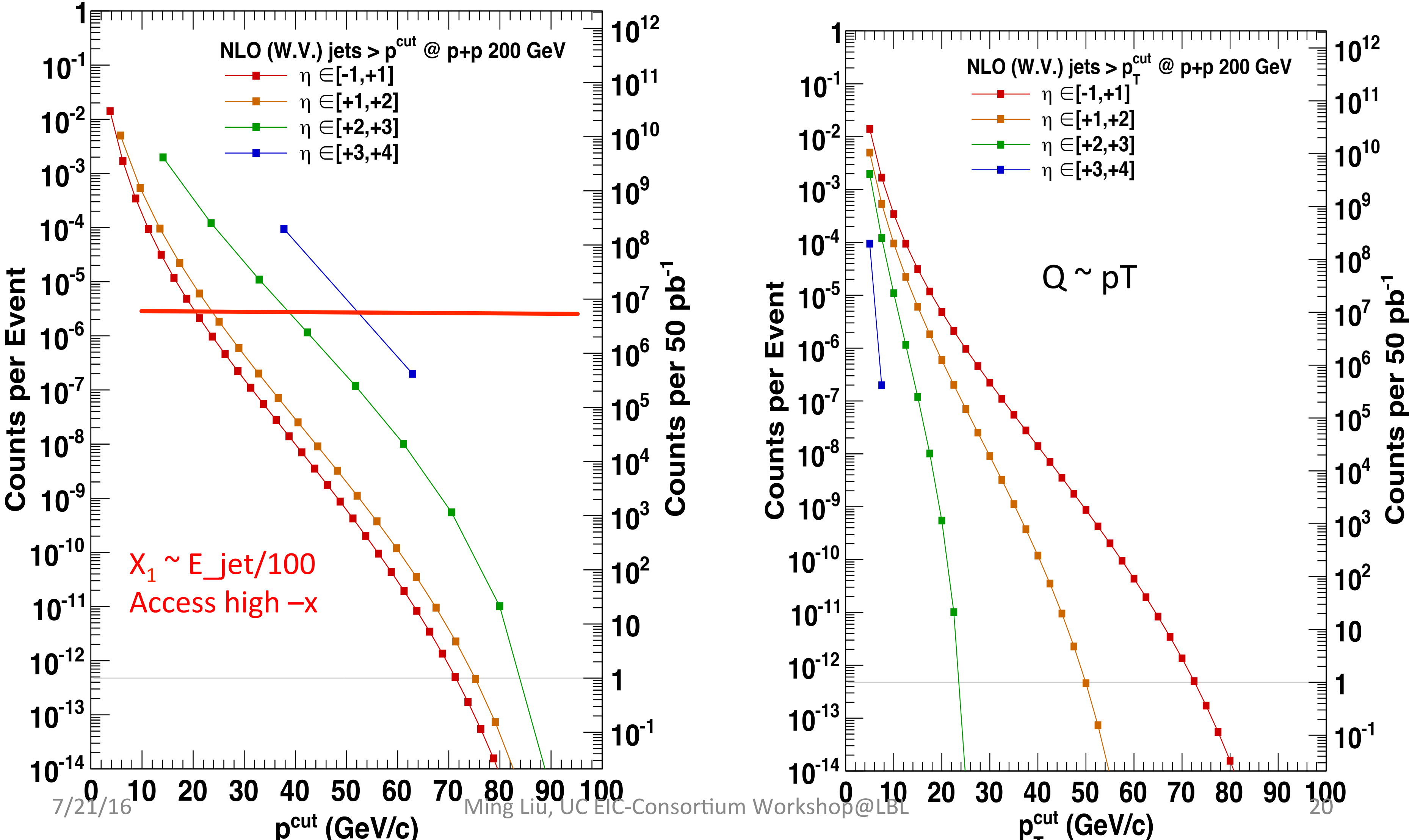
-1 < eta < 4

Clearly isolate and measure
Sivers-like and Collins-like effects in p+p



Jet Production Rates @NLO

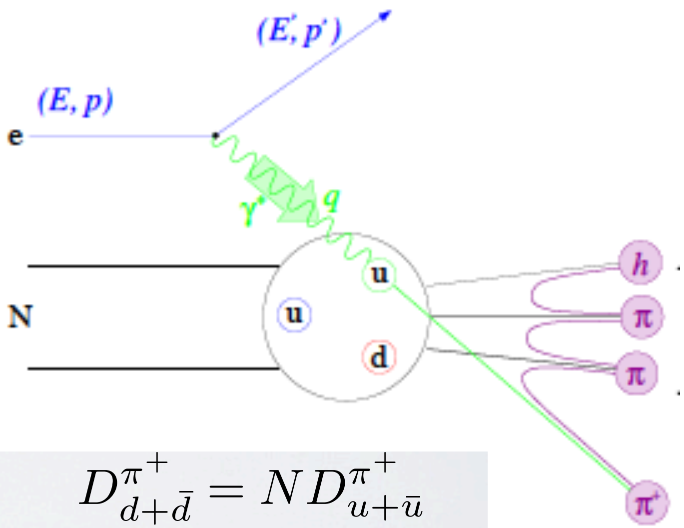
200GeV pp: Lumi = 50pb^{-1}



Tagging Quark Flavor in SIDIS

with Leading Charged Hadron

- @Z = 0.5



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

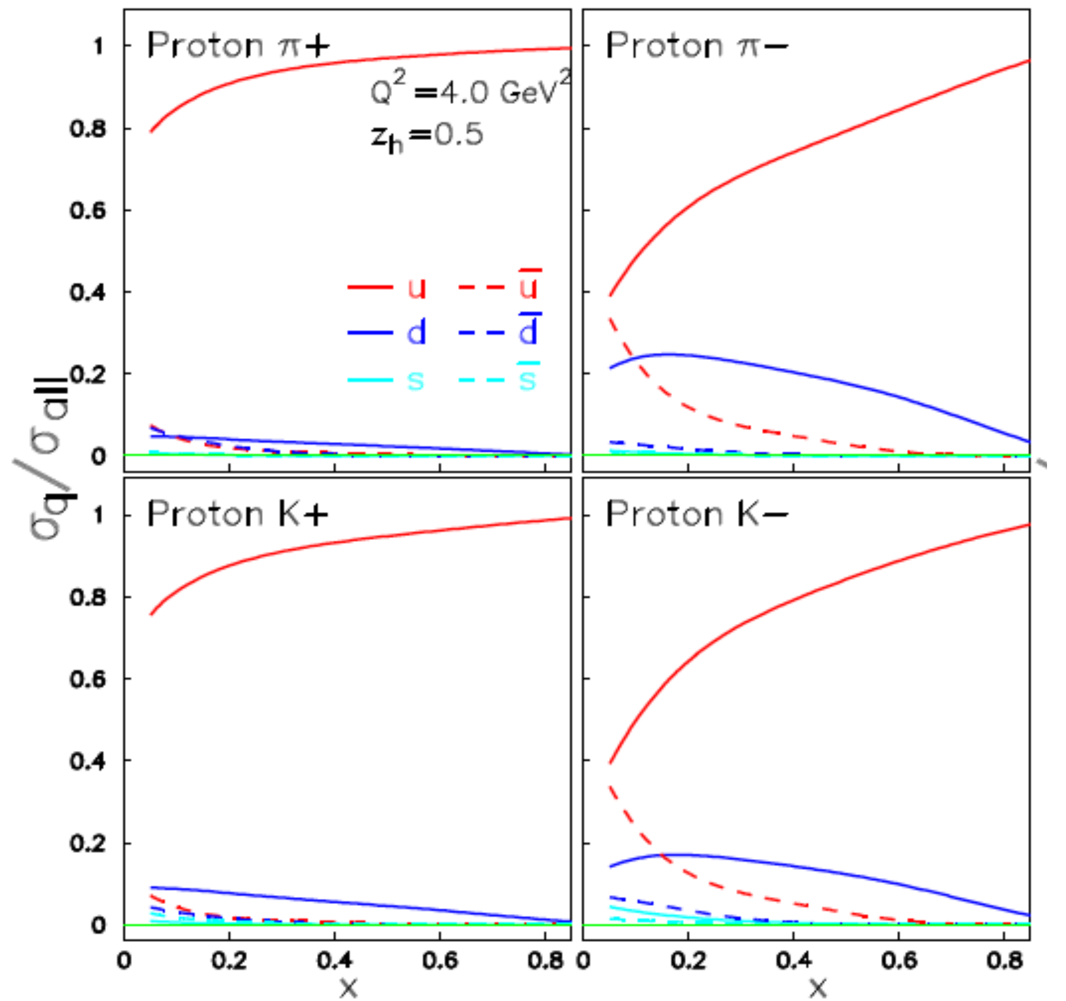
$$D^{\pi^+}_{s} = D^{\pi^+}_{\bar{s}} = N' D^{\pi^+}_{\bar{u}}$$

$$D^{\pi^+}_{\bar{u}} = D^{\pi^+}_{d}$$

$$D^{K^+}_{\bar{u}} = D^{K^+}_{s} = D^{K^+}_{d} = D^{K^+}_{\bar{d}}$$

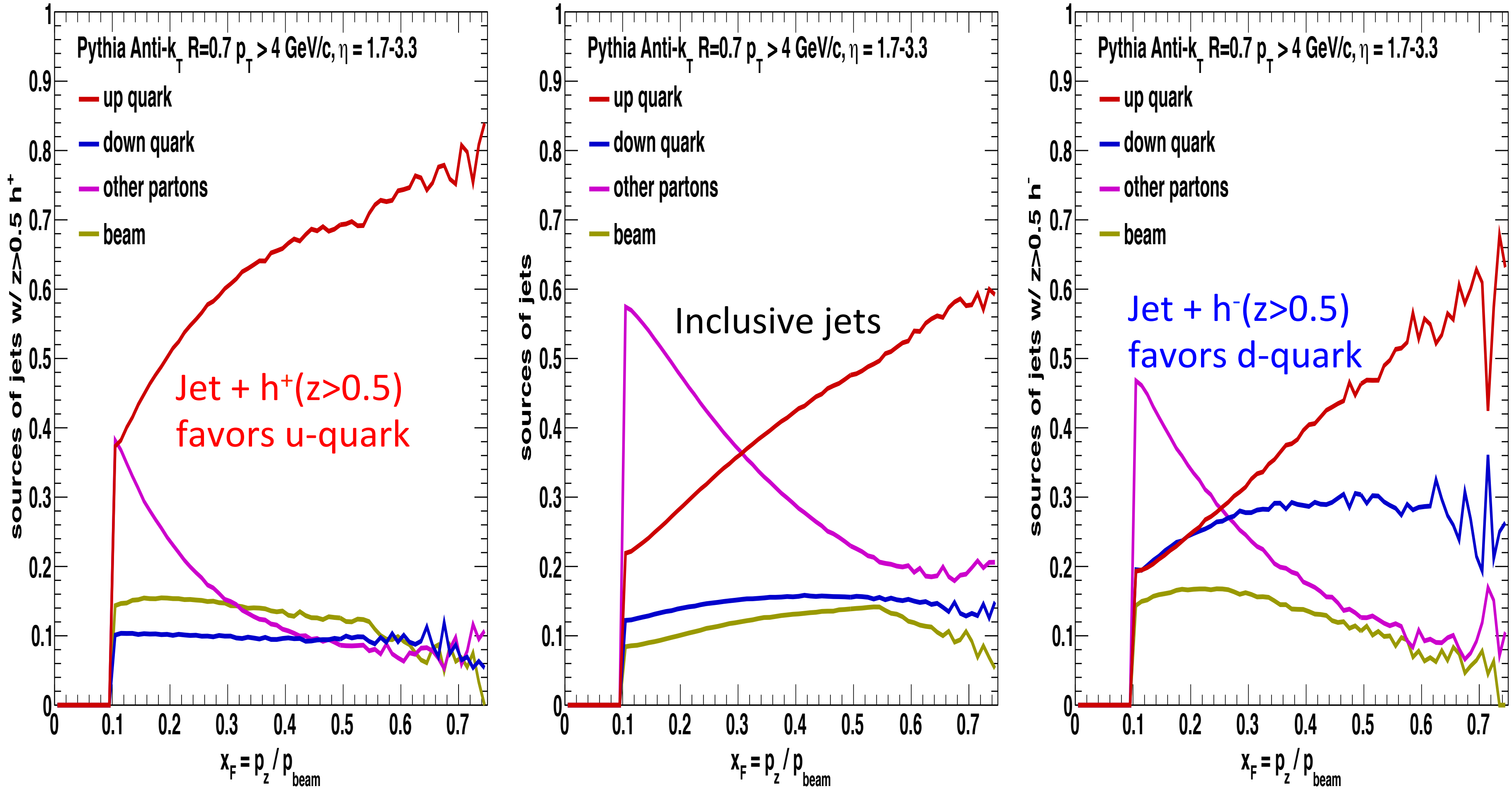
DSS FF

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



u-quark dominates in proton

Jet Quark-Flavor Tagging With Leading Charged Hadrons in p+p

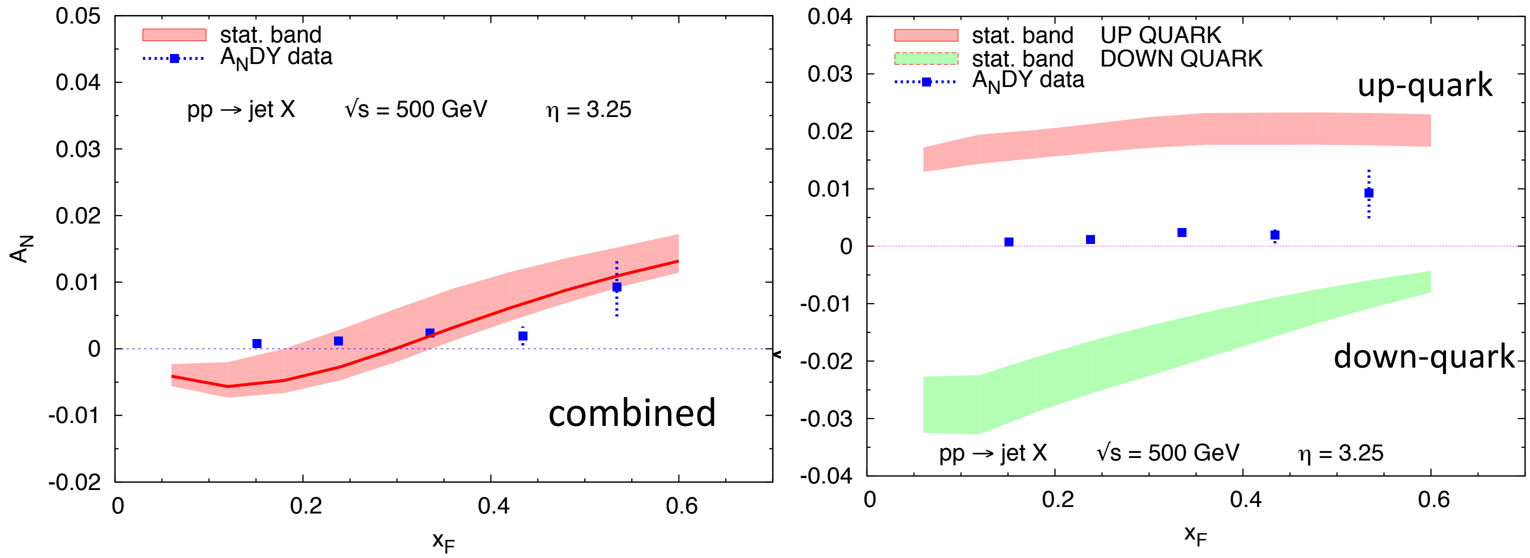


Flavor Tagged Jet Sivers Asymmetry

- Jet and leading h^+ and h^-
- jet_eta= [1,4]

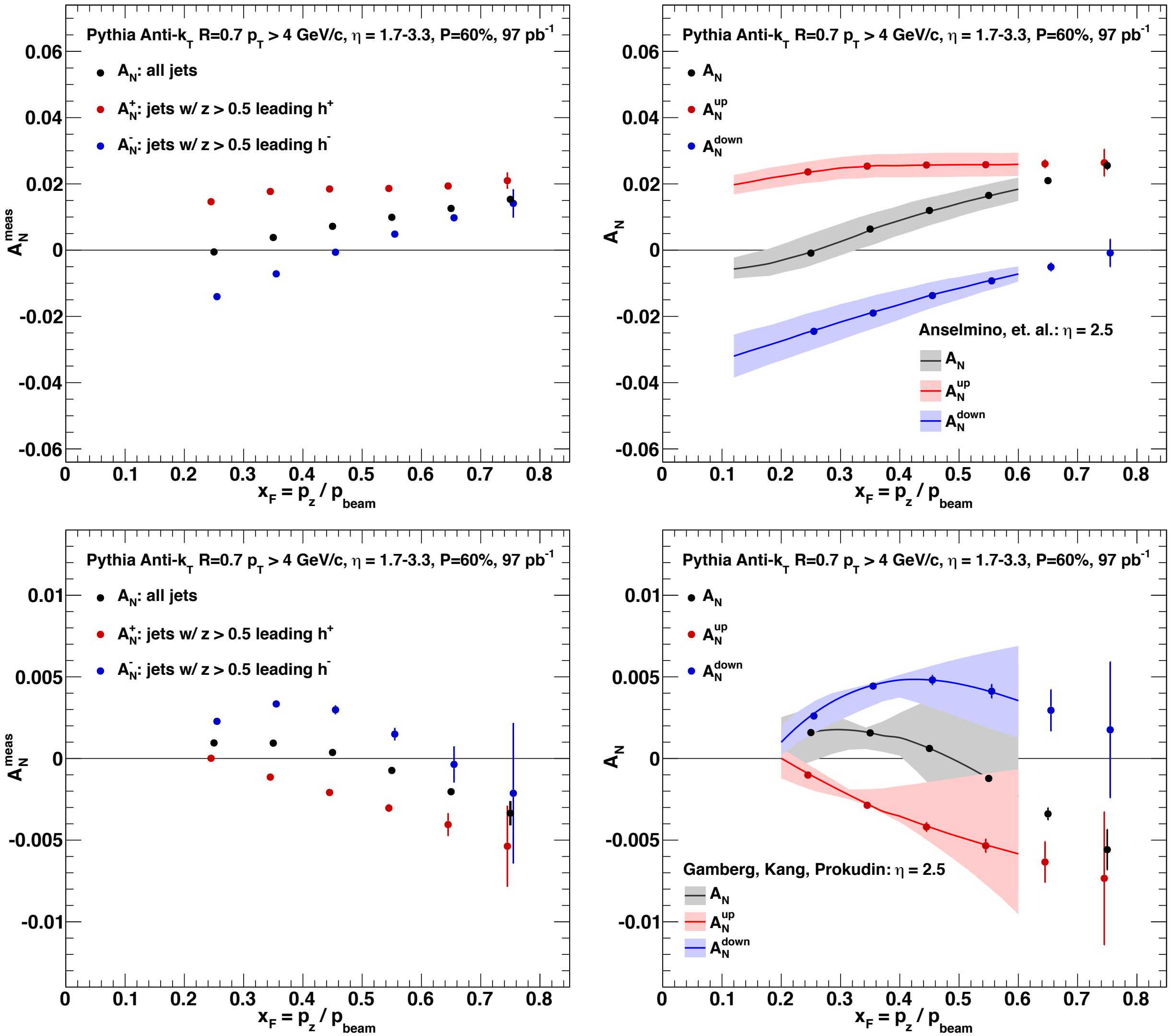
We can do this!

Directly use Sivers function from SIDIS fit



fsPHENIX Projected Jet Sivers Asymmetries

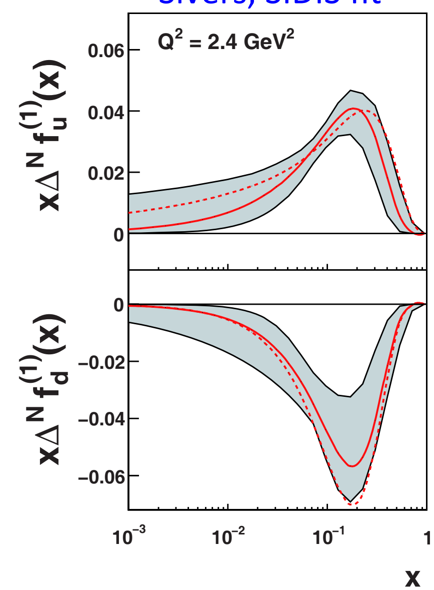
Test the universality of QCD description of TSSA: pp vs SIDIS



Naïve direct mapping from SIDIS Sivers

- “u-quark jet” A_N >0

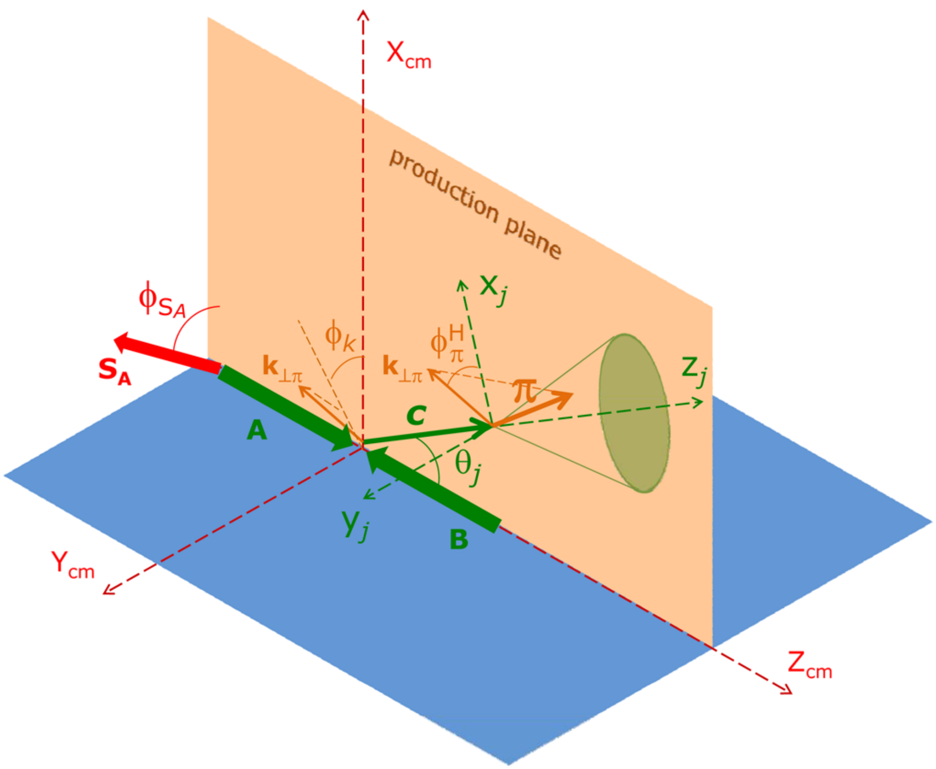
Sivers, SIDIS fit

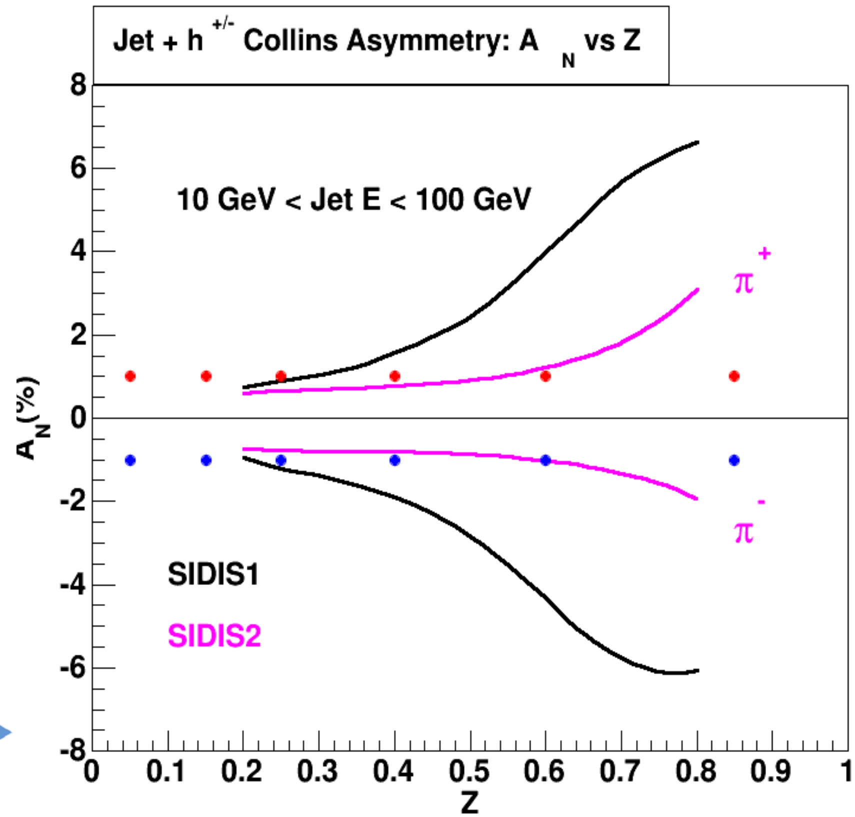


With process-dep from SIDIS Sivers

- “u-quark jet” A_N < 0

Forward sPHENIX Collins Asymmetry Projeciton





Access Gluons: Open Charm TSSA

Factorized formula for D-meson production

Qiu, 2010

- Same factorized formula for both subprocesses:

$$E_{P_h}\frac{d\Delta\sigma}{d^3P_h}\bigg|_{q\bar{q}\to c\bar{c}} = \frac{\alpha_s^2}{S}\sum_q\int\frac{dz}{z^2}D_{c\to h}(z)\int\frac{dx'}{x'}\phi_{\bar{q}/B}(x')\int\frac{dx}{x}\sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{P_h s_T n\bar{n}}}{z\tilde{u}}\right)\delta\left(\tilde{s}+\tilde{t}+\tilde{u}\right)$$
$$\times\left[\left(T_{q,F}(x,x)-x\frac{d}{dx}T_{q,F}(x,x)\right)H_{q\bar{q}\to c}(\tilde{s},\tilde{t},\tilde{u})+T_{q,F}(x,x)\mathcal{H}_{q\bar{q}\to c}(\tilde{s},\tilde{t},\tilde{u})\right],$$

$$E_{P_h}\frac{d\Delta\sigma}{d^3P_h}\bigg|_{gg\to c\bar{c}} = \frac{\alpha_s^2}{S}\sum_{i=f,d}\int\frac{dz}{z^2}D_{c\to h}(z)\int\frac{dx'}{x'}\phi_{g/B}(x')\int\frac{dx}{x}\sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{P_h s_T n\bar{n}}}{z\tilde{u}}\right)\delta\left(\tilde{s}+\tilde{t}+\tilde{u}\right)$$
$$\times\left[\left(T_G^{(i)}(x,x)-x\frac{d}{dx}T_G^{(i)}(x,x)\right)H^{(i)}_{gg\to c}(\tilde{s},\tilde{t},\tilde{u})+T_G^{(i)}(x,x)\mathcal{H}^{(i)}_{gg\to c}(\tilde{s},\tilde{t},\tilde{u})\right],$$

- Hard parts:

$$H_{q\bar{q}\to c} = H^I_{q\bar{q}\to c}+H^F_{q\bar{q}\to c}\left(1+\frac{\tilde{u}}{\tilde{t}}\right) \qquad H^{(i)}_{gg\to c} = H^{I(i)}_{gg\to c}+H^{F(i)}_{gg\to c}\left(1+\frac{\tilde{u}}{\tilde{t}}\right)$$

All $\mathcal{H}_{q\bar{q}\to c}$ and $\mathcal{H}^{I(i)}_{gg\to c}$ and $\mathcal{H}^{F(i)}_{gg\to c}$ vanish as $m_c^2\to 0$

- Hard parts change sign for $T_G^{(d)}(x,x)$ when $c\to\bar{c}$

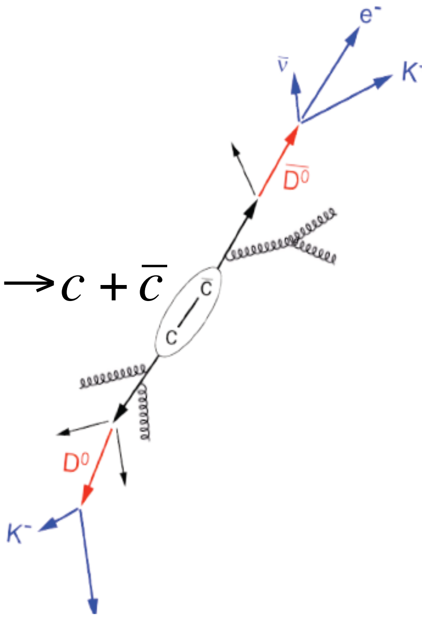
$$H^{(f)}_{gg\to\bar{c}} = H^{(f)}_{gg\to c}, \qquad H^{(d)}_{gg\to\bar{c}} = -H^{(d)}_{gg\to c},$$
$$\mathcal{H}^{(f)}_{gg\to\bar{c}} = \mathcal{H}^{(f)}_{gg\to c}, \qquad \mathcal{H}^{(d)}_{gg\to\bar{c}} = -\mathcal{H}^{(d)}_{gg\to c}.$$

Study Novel Heavy Quark TSSA at RHIC

Twist-3 tri-gluon correlation Funs

$$P_h^0 \frac{d\sigma^{3\text{gluon}}}{d^3P_h} \simeq \frac{\alpha_s^2 M_N \pi}{S}\epsilon^{P_h p n S_\perp}\sum_{f=c\bar c}\int\frac{dx'}{x'}G(x')\int\frac{dz}{z^3}D_a(z)\int\frac{dx}{x}\delta\left(\tilde s+\tilde t+\tilde u\right)\frac{1}{\tilde u} \times\left[\delta_f\left(\frac{d}{dx}O(x)-\frac{2O(x)}{x}\right)\hat\sigma^{O1}+\left(\frac{d}{dx}N(x)-\frac{2N(x)}{x}\right)\hat\sigma^{N1}\right].$$

$$g + g \rightarrow c + \bar c$$



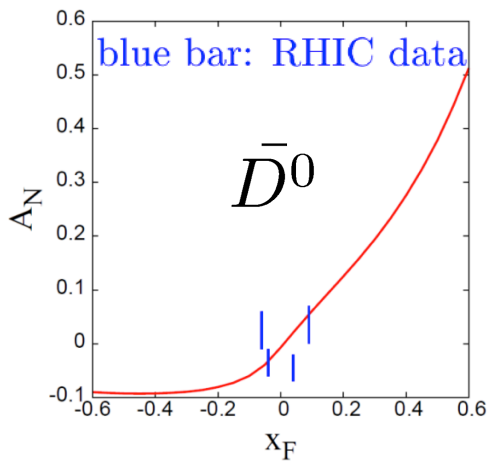
where $O(x) \equiv O(x,x) + O(x,0)$, $N(x) \equiv N(x,x) - N(x,0)$.

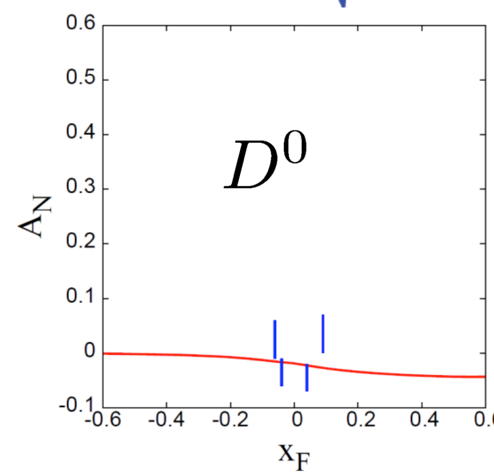
$\delta_f = +1(c);\ \ -1(\bar c)$

$$A_N(D) \overset{?}{\neq} A_N(\bar D)$$

Model 1:
$O(x) = 0.004xG(x)$

Koike *et. al.* (2011)
Kang, Qiu, Vogelsang, Yuan (2008)

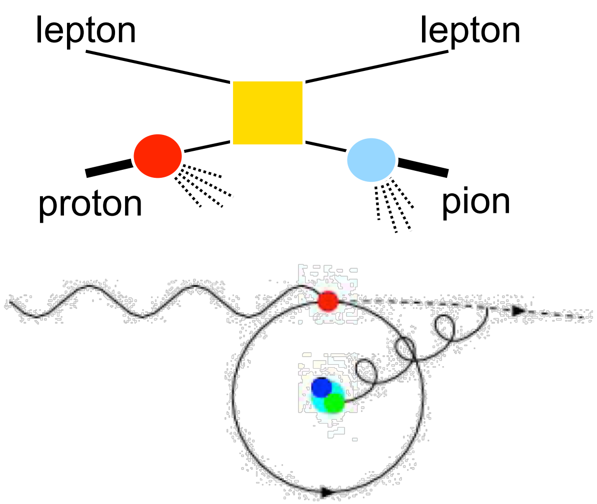




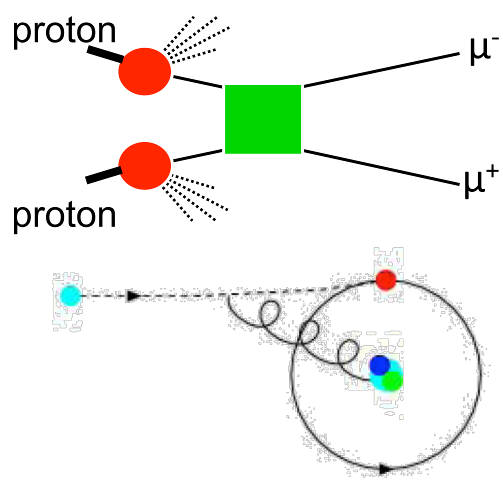
Forward Dimuon Drell-Yan A_N

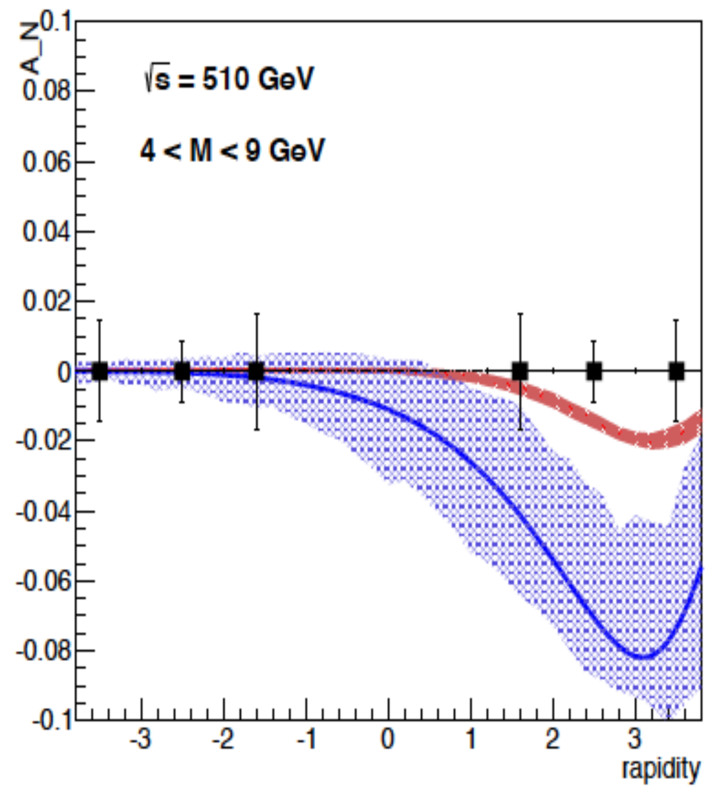
- DY A_N accesses quark Sivers effect ($f_{1T}^{\perp}$) in proton
- $f_{1T}^{\perp}$ expected to reverse in sign from SIDIS to DY meas.

Semi-inclusive DIS (SIDIS)



Drell-Yan





Drell-Yan

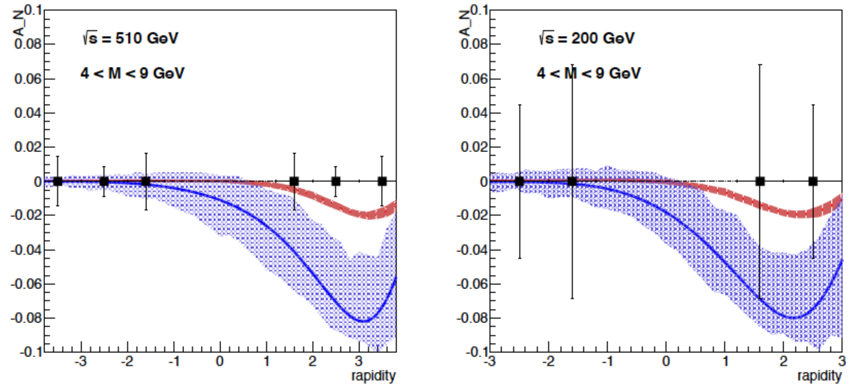
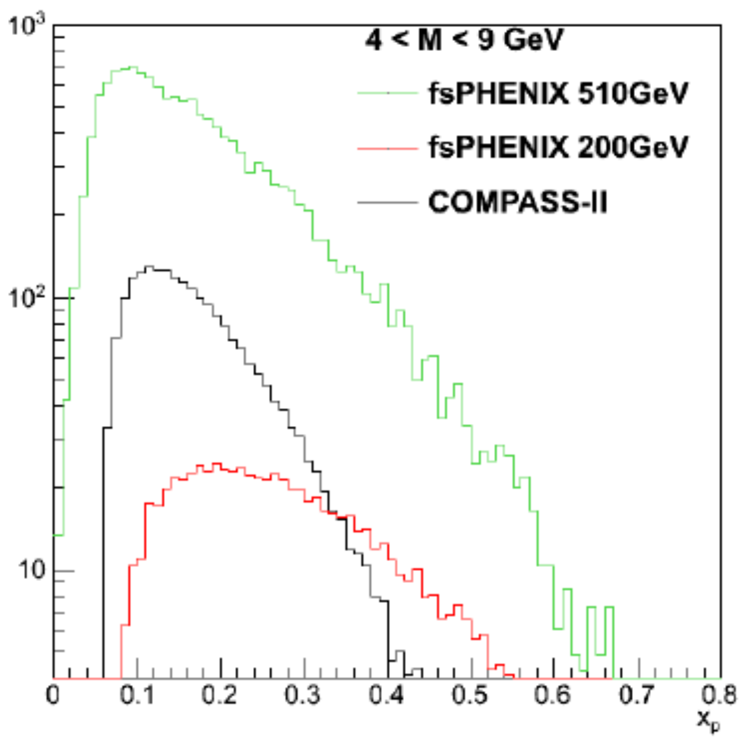
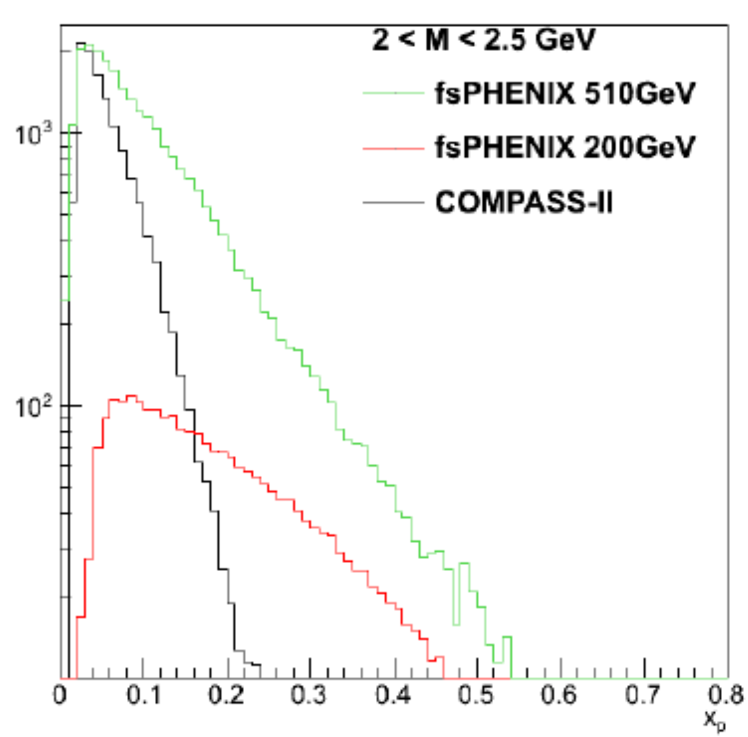


Figure 3.12: Statistical sensitivities of Drell-Yan A_N measurement at fsPHENIX (left panel at $\sqrt{s} = 510$ GeV and right panel at $\sqrt{s} = 200$ GeV) compared with theoretical calculation of the Drell-Yan A_N without Sivers function evolution [50] (blue line and band) and with Sivers function evolution [42] (red line and band).





Forward sPHENIX – a Portal to EIC

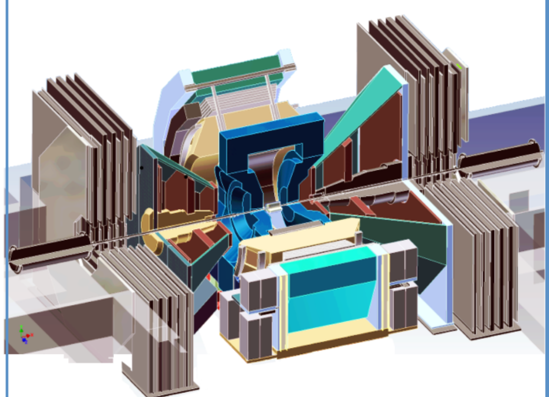
- For the first time to clearly identify and separate key spin observables in forward jet and hadron productions in p+p collisions, in the quark sector
  - Forward jet TSSA (Sivers-like)
  - Hadron TSSA inside a jet (Collins-like)
  - Larger effect with quark-flavor tagged jets
  - Test process dependence of TSSA
  - High statistics and precision
- Access gluon TMDs/Twist-3 via heavy quarks
  - Open charm, J/Psi TSSAs etc.
- Complementary to EIC physics program
  - Spin physics
  - CNM physics

Our Vision PHENIX -> Forward/sPHENIX->ePHENIX

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

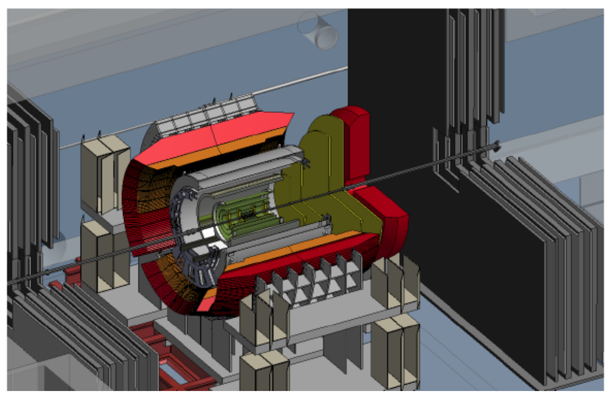
Current PHENIX

- PHENIX completed 2016
- 16y+ work
  100+M$ investment
- 130+ published papers to date



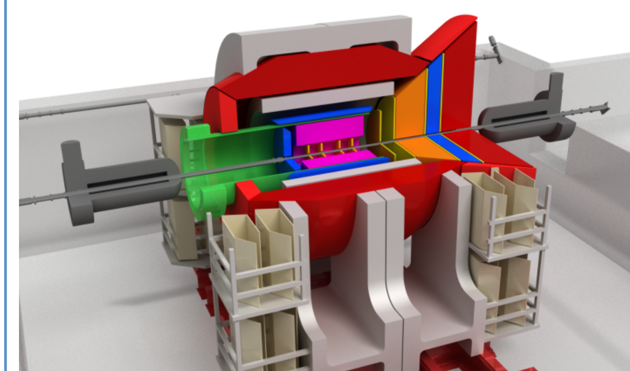
*f/s*PHENIX

- Comprehensive central upgrade based on BaBar magnet
- fsPHENIX: forward tracking, HCal and muon ID
- Key study of transverse spin
- New collaboration/new ideas



An EIC detector

- Path of PHENIX upgrade leads to a capable EIC detector
- Large coverage of tracking, calorimetry and PID
- New collaboration/new ideas



~2000 | 2017→2022 | ~2025 | Time

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

eRHIC: e+p, e+A

Projected Luminosities

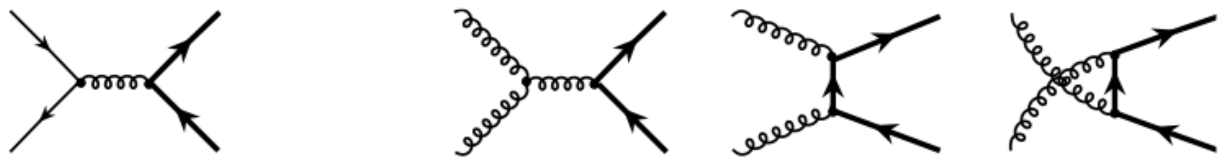
	COMPASS-II	fsPHENIX 200 GeV	fsPHENIX 510 GeV
$L_{avg}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	1.18×10^{32}	0.76×10^{32}	6.48×10^{32}
Average L /week	14.3 pb^{-1}/week	18.7 pb^{-1}/week	128 pb^{-1}/week
Accelerator eff.	0.8	(included above)	(included above)
Detector up-time	0.85	0.6	0.6
Vertex cut	n/a	0.62	0.62
Sampled L /week	9.7 pb^{-1}/week	6.9 pb^{-1}/week	47.6 pb^{-1}/week
week/year	20	10	15
Sampled L /year	194 pb^{-1}/year	69 pb^{-1}/year	714 pb^{-1}/year
Dimuon trigger eff.	0.81	0.81	0.81
High mass: $4\ \mathrm{GeV}/c^2 < M < 9\ \mathrm{GeV}/c^2$			
Reconstruction eff.	0.8	0.312	0.305
Offline L /year	126 pb^{-1}/year	17.5 pb^{-1}/year	177 pb^{-1}/year
Cross section σ	1291 pb	1199 pb	2542 pb
Acceptance Ω	0.35	0.14	0.19
$\sigma\cdot\Omega$	452 pb	171 pb	478 pb
K factor (assumption)	2	1.38	1.38
Dimuon/year $L\cdot\sigma\cdot\Omega\cdot K$	115000/year	4150/year	117000/year
FoM/year	2230/year	747/year	14600/year
$\delta A_T^{\sin\phi_S} = 1/\sqrt{FoM}$	0.021	0.037	0.0083

TSSA in Heavy Quark Production in p+p

Kang, Qiu, Vogelsang, Yuan, PRD 2008

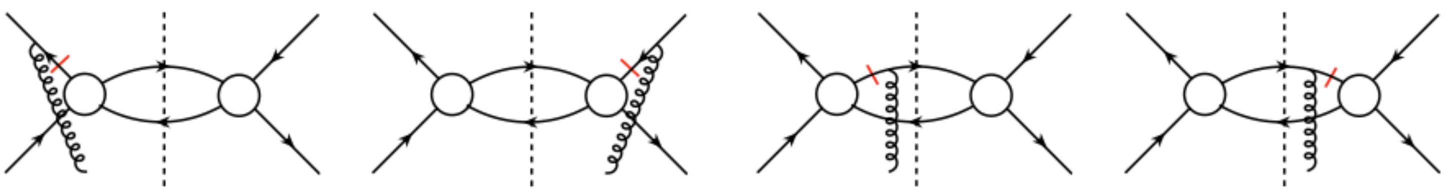
D-meson production in hadronic collisions

- Two partonic subprocesses:



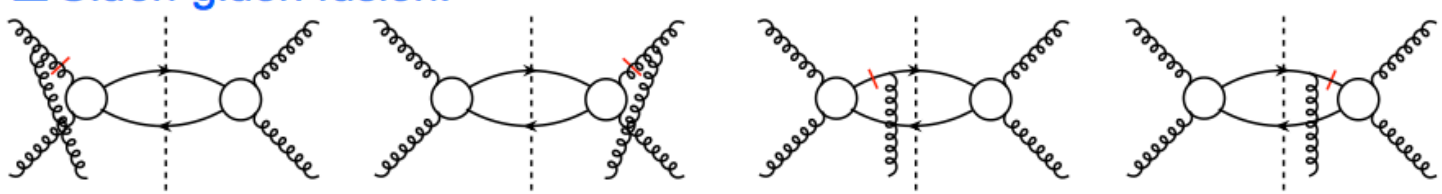
(a) (b)

- Quark-antiquark annihilation:



(a) (b) (c) (d)

- Gluon-gluon fusion:



(a) (b) (c) (d)