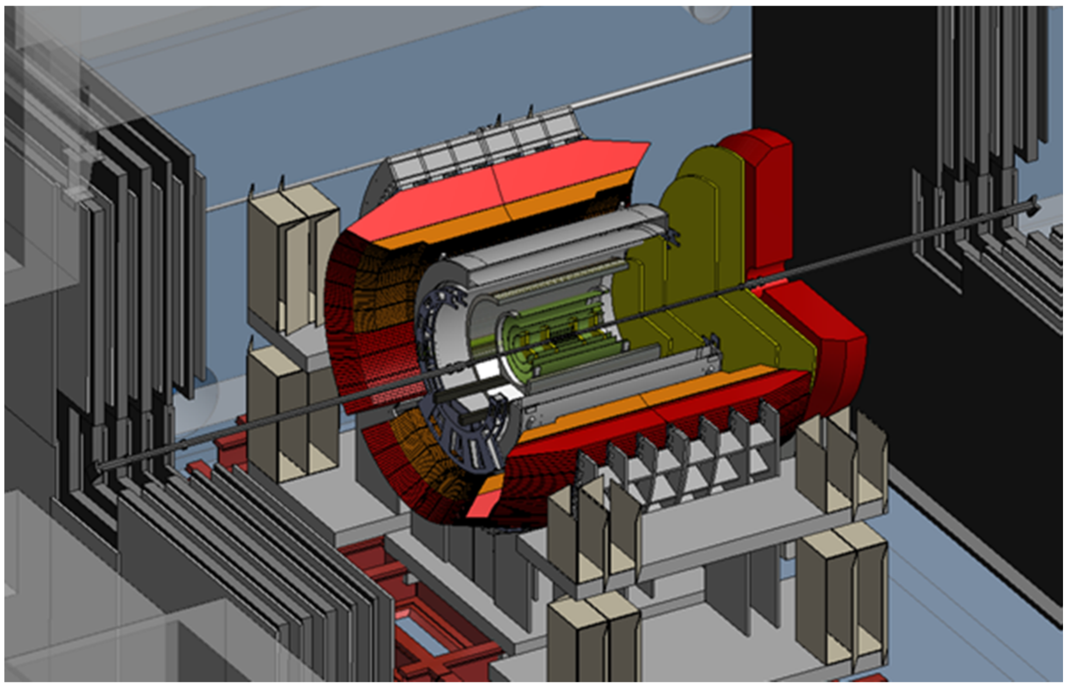
A Detector for the Study of Nucleon Spin Structure and Cold Nuclear Matter at RHIC



John Lajoie
Iowa State University

The RHIC Evolution to the EIC

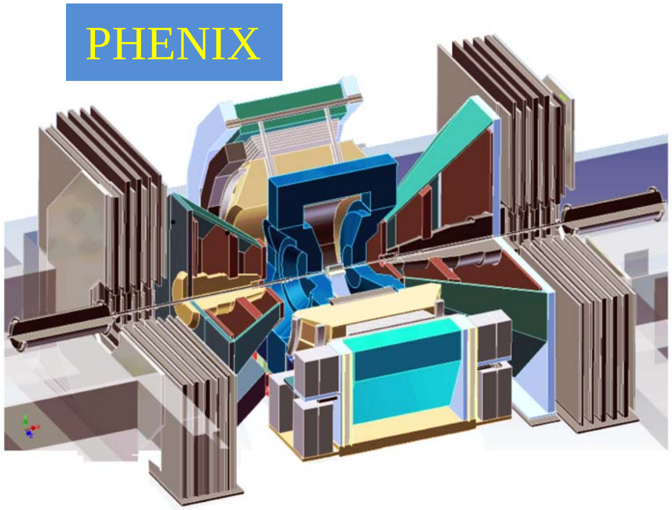
- STAR/PHENIX charged by the BNL ALD to define a polarized p+p/p+A physics program in 2021-22 :

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2013	• 510 GeV pol p+p	• Sea quark and gluon polarization	• upgraded pol'd source • STAR HFT test
2014	• 200 GeV Au+Au • 15 GeV Au+Au	• Heavy flavor flow, energy loss, thermalization, etc. • Quarkonium studies • QCD critical point search	• Electron lenses • 56 MHz SRF • full STAR HFT • STAR MTD
2015-2016	• p+p at 200 GeV • p+Au, d+Au, ^{3}He+Au at 200 GeV • High statistics Au+Au	• Extract $\eta/s(T)$ + constrain initial quantum fluctuations • More heavy flavor studies • Sphaleron tests	• PHENIX MPC-EX • Coherent electron cooling test
2017	• No Run		• Electron cooling upgrade
2018-2019	• 5-20 GeV Au+Au (BES-2)	Search for QCD critical point and deconfinement onset	• STAR ITPC upgrade
2020	• No Run		• sPHENIX installation
2021-2022	• Long 200 GeV Au+Au w/ upgraded detectors • p+p/d+Au at 200 GeV	• Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism • Color screening for different QQ states	• sPHENIX
2023-24	• No Runs		Transition to eRHIC

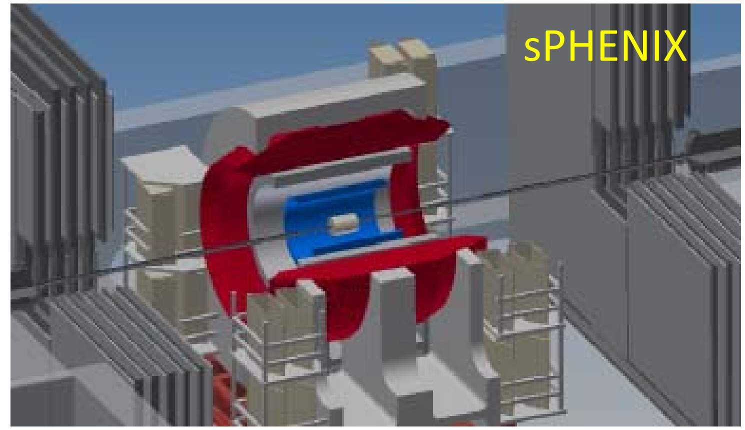
Overlap with planned sPHENIX running.

10 weeks p+p @ 200 GeV
10 weeks p+Au @ 200 GeV

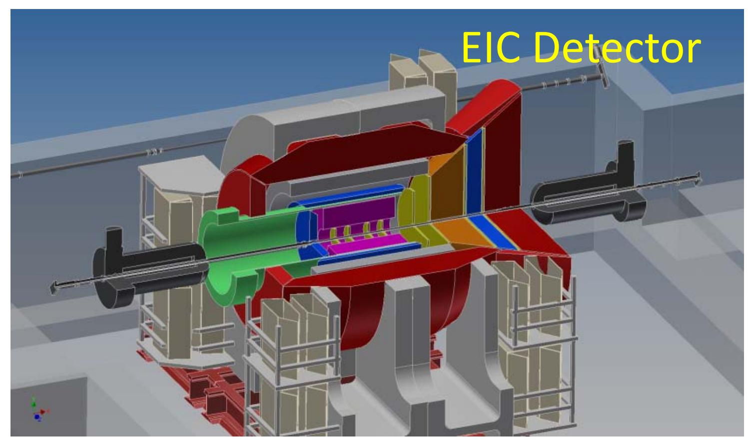
The PHENIX -> EIC Detector Path



~2021-22



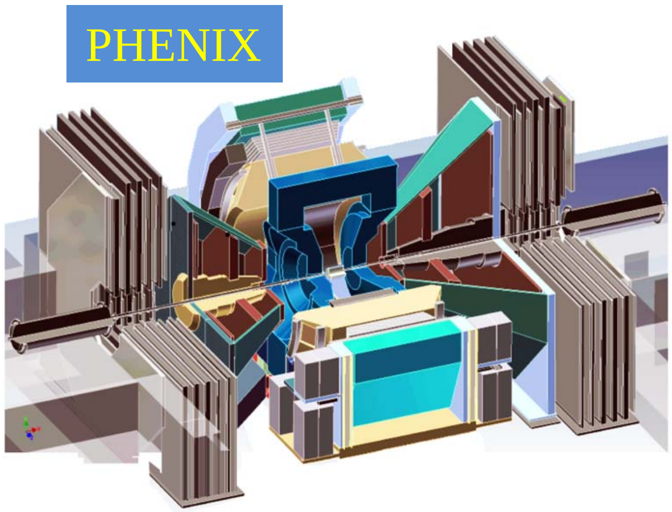
~2025



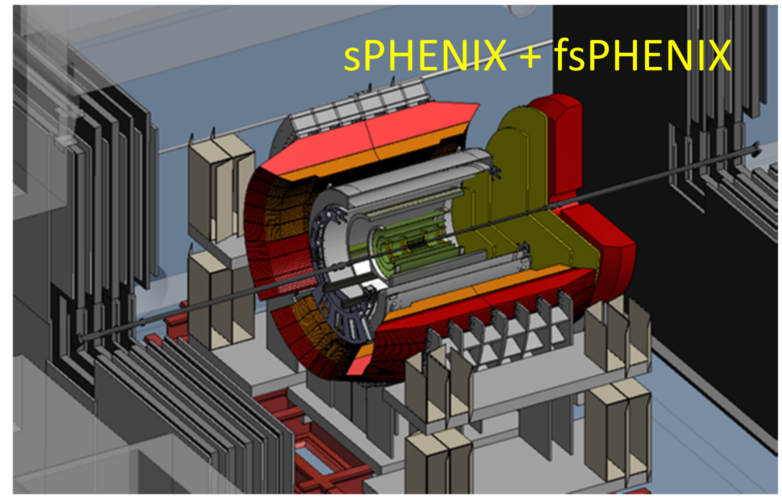
Evolve sPHENIX (pp and HI detector) to an EIC Detector (ep and eA detector):

- To utilize e and p (A) beams at eRHIC with *e*-energy up to 15 GeV and *p*(*A*)-energy up to 250 GeV (100 GeV/n)
- *e*, *p*, He^3 polarized
- Stage-1 luminosity ~10^{33} cm^{-2} s^{-1} (~$1fb^{-1}$ /month)

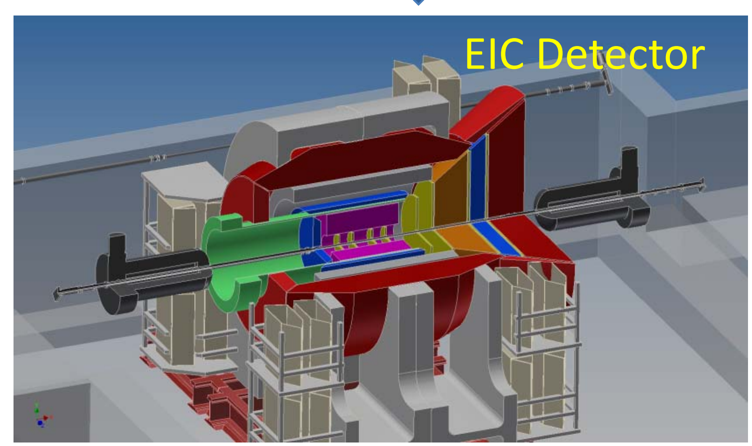
The PHENIX -> EIC Detector Path



~2021-22



~2025



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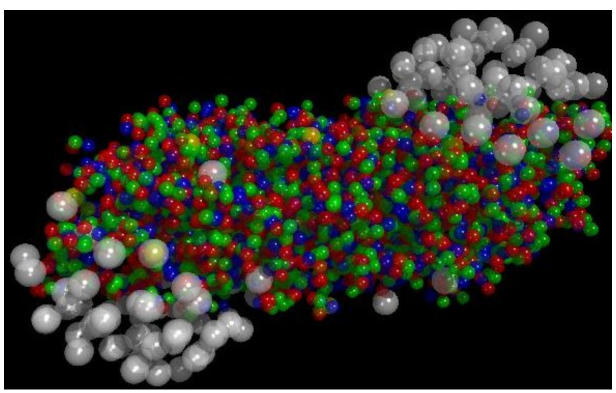
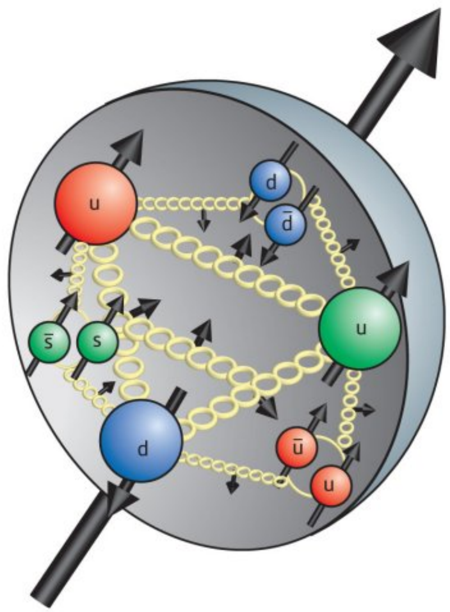
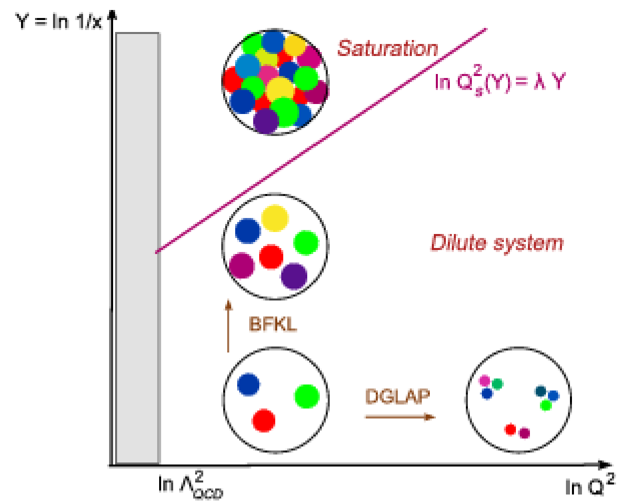
The Big Picture At RHIC

How do collective, many-body phenomena arise from first-principles QCD?



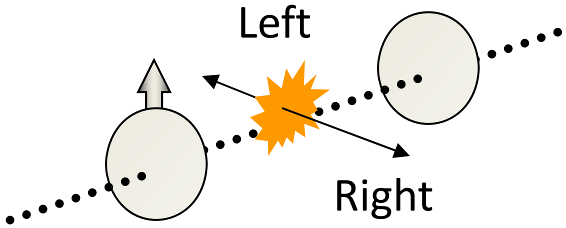




fsPHENIX Physics

- **The fsPHENIX physics program seeks to address key issues in nucleon/nuclear structure:**
  - How is transverse spin carried by the partonic constituents of the nucleon?
    - Key tests of theoretical framework – can we relate what we know from SIDIS and polarized p+p?
    - Jet A_N, DY modified universality, Q^2 evolution,…
  - How are PDF's modified in the nuclear environment at small-x?
    - Saturation (CGC), parton energy loss…

Single Transverse Spin Asymmetries



$$A_N = \frac{1}{P}\frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi}$$

A_N difference in cross-section between particles produced to the left and right

Theory Expectation:

Small asymmetries at high energies

(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

A_N O(10^{-4}) Theory

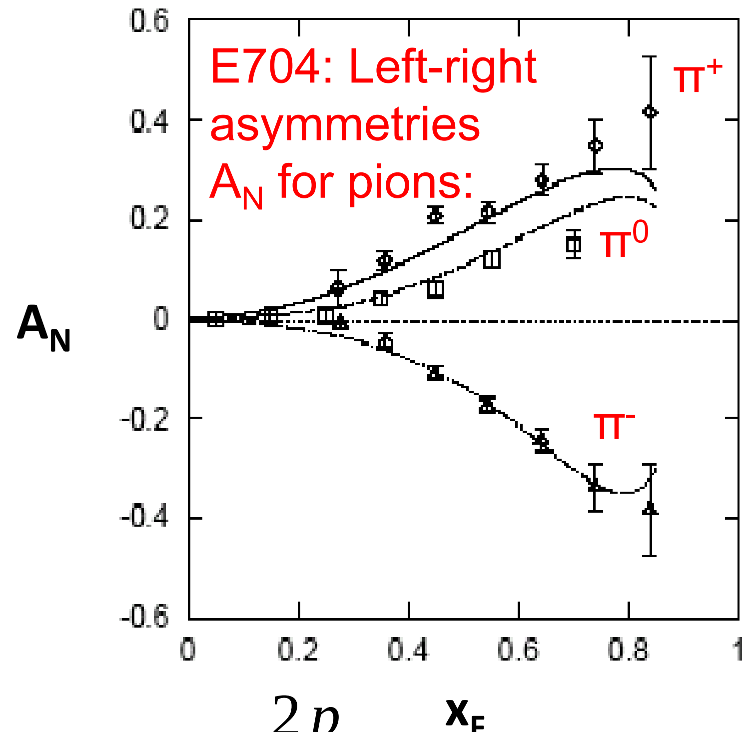
Experiment:

(E704, Fermi National Laboratory, 1991)

$$pp^\uparrow \rightarrow \pi + X$$

$$\sqrt{s} = 20\,\mathrm{GeV}$$

A_N O(10^{-1}) Measured



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

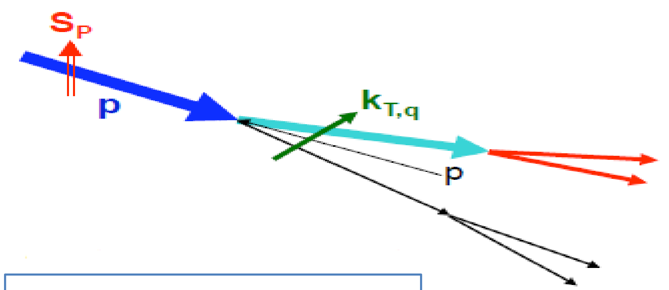
Sources of Transverse SSA's

"Sivers effect"

TMD: Correlation between nucleon spin and parton k_T.

Phys. Rev. D **41**, 83 (1990)
Phys. Rev. D **43**, 261, (1991)

$$d\sigma^{\uparrow} \propto \underbrace{\bar{f}_{1T}^{\perp q}(x,k_{\perp}^{2})}_{\text{Sivers distribution}} \cdot D_{q}^{h}(z)$$



Twist-3: Quark-gluon correlations in polarized hadron
Phys. Rev. D **59**, 014004 (1998)

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

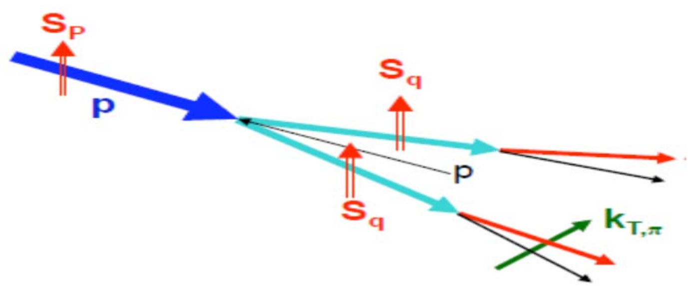
Also evolution…

"Collins effect"

TMD: Transversity distributions + Spin dependent fragmentation functions

Nucl. Phys. B 396, 161 (1993)

$$d\sigma^{\uparrow} \propto \underbrace{\delta q(x)}_{\text{Transversity}} \cdot \underbrace{H_{1}^{\perp}(z_{2},\bar{k}_{\perp}^{2})}_{\text{Collins FF}}$$

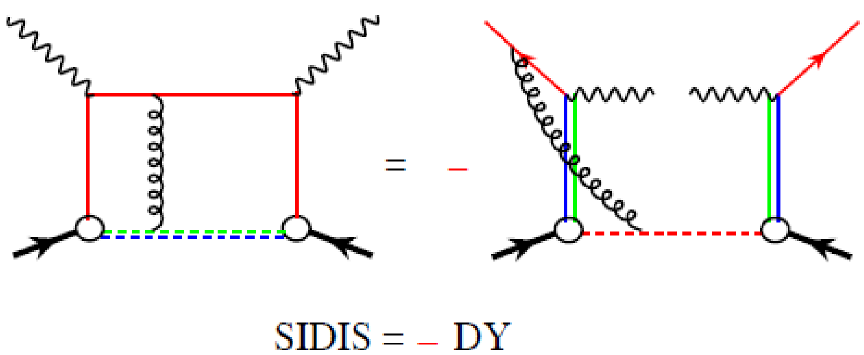


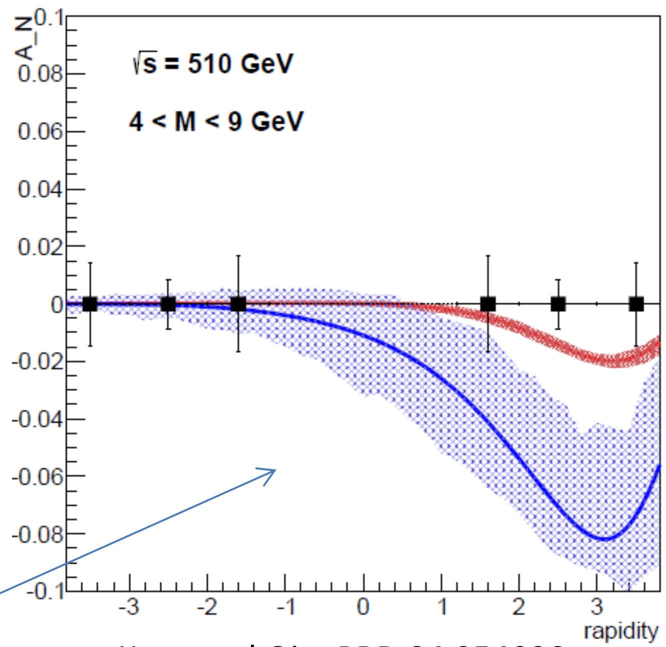
Twist-3: Transversity combined with twist-3 quark-gluon fragmentation function

Drell-Yan in Polarized p+p

- A <u>theoretically clean</u>, fundamental study of the *Sivers effect*, *modified universality*, and *evolution of TMD's*:

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

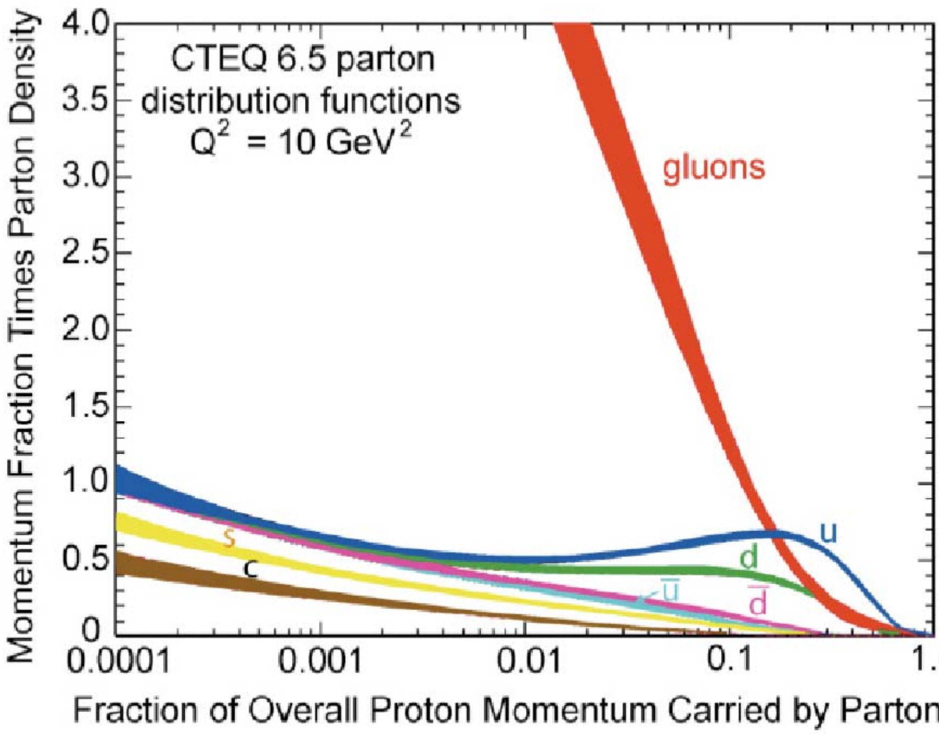




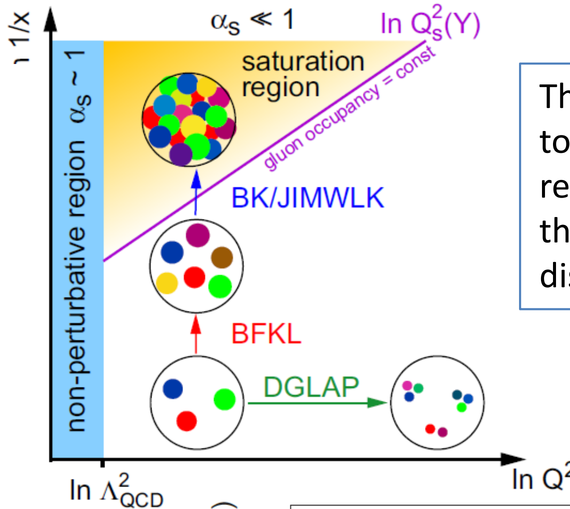
Kang and Qiu, PRD 84 054020
Echevarria et. al., arXiv 1401.5078

How does evolution change the anticipated asymmetries? Theory predictions vary.
Useful to look at <u>low mass</u> and <u>high mass</u> DY pairs.

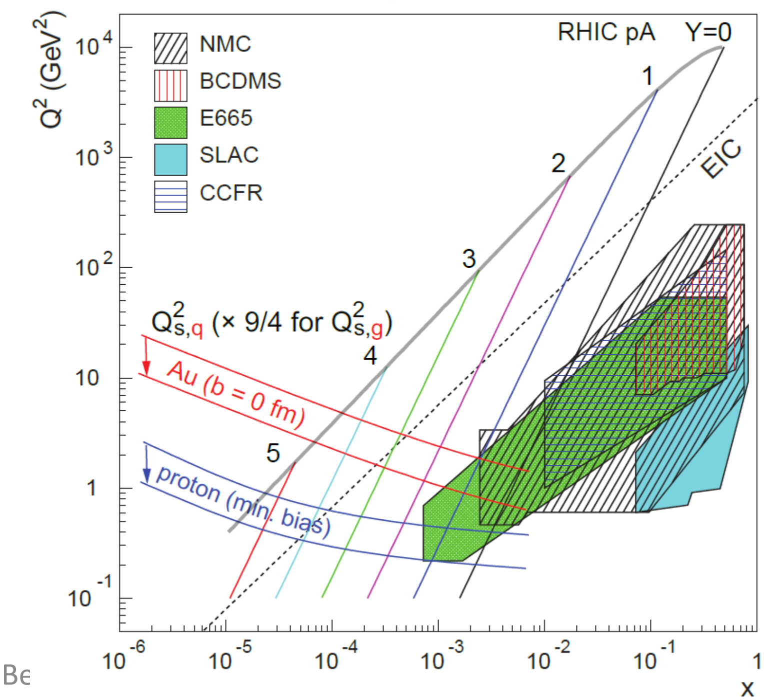
Gluon Saturation



(x)



The gluon density grows to the point where recombination tames the growth of the gluon distribution at small x.



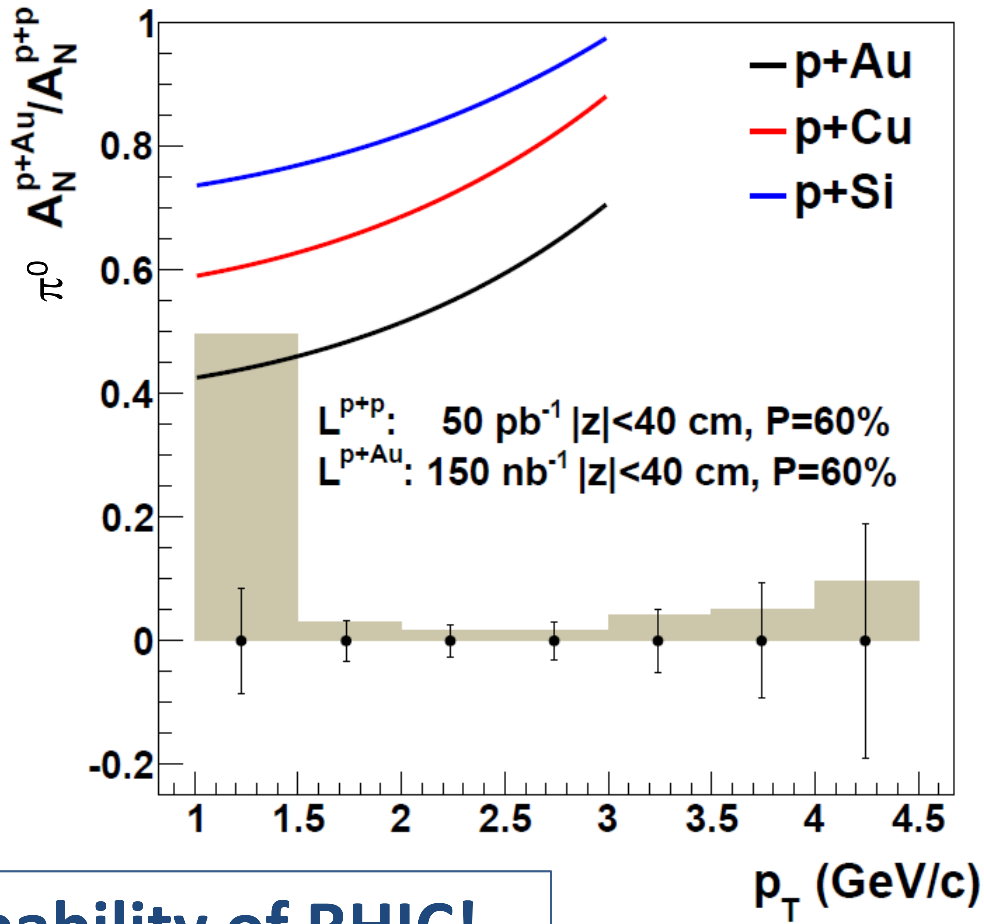
The nucleus is an *amplifier* of high gluon densities.

$$\left(Q_S^A\right)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

Polarized p+A Collisions

- **The *fsPHENIX* physics program really depends on what we learn from Run-15:**
  - Are the single spin asymmetries suppressed in polarized p+A?
  - Does DY offer any advantages as a small-x probe?
  - Jet-Jet vs. Hadron-Hadron correlations
    - Take full advantage of *fsPHENIX+sPHENIX* jet coverage

Kang, Yuan: PRD 84, 034019 (2011)

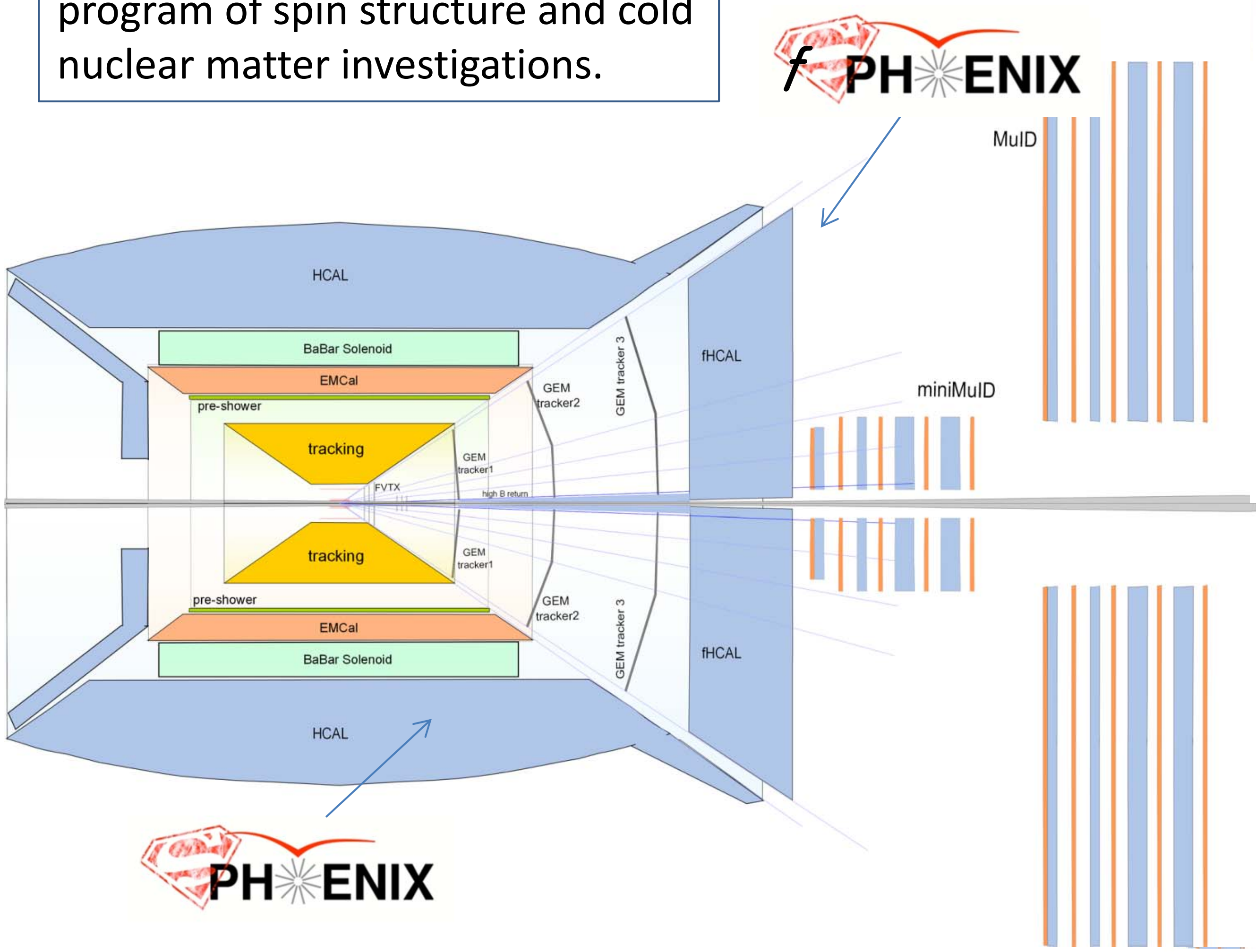


Polarized p+A a unique capability of RHIC!

fsPHENIX –"forward" sPHENIX!

A detector for a *comprehensive* program of spin structure and cold nuclear matter investigations.

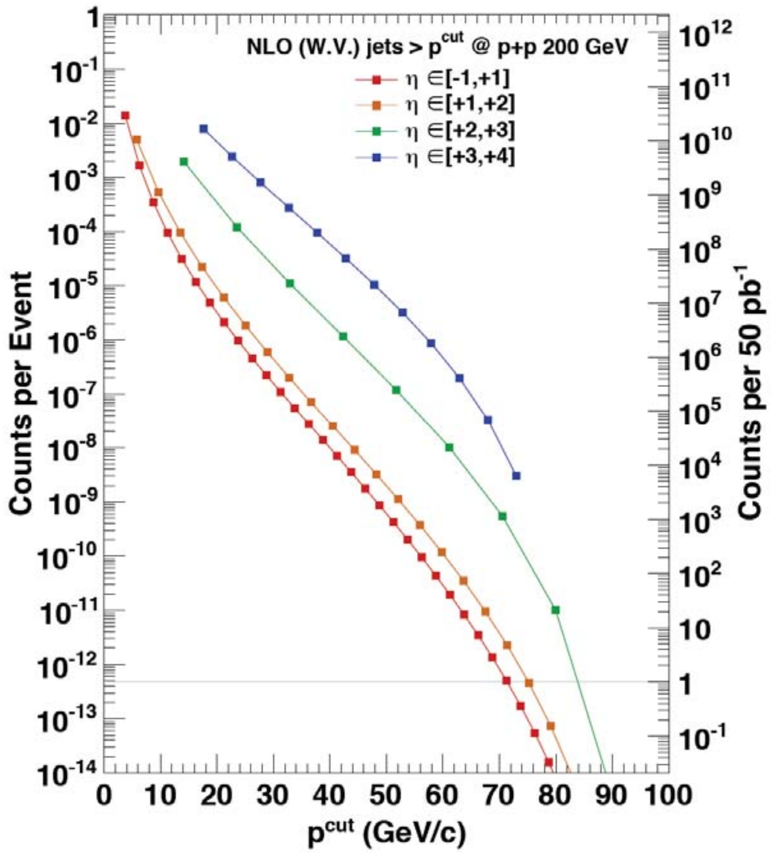
fsPHENIX HCAL, GEM trackers derived from EIC detector

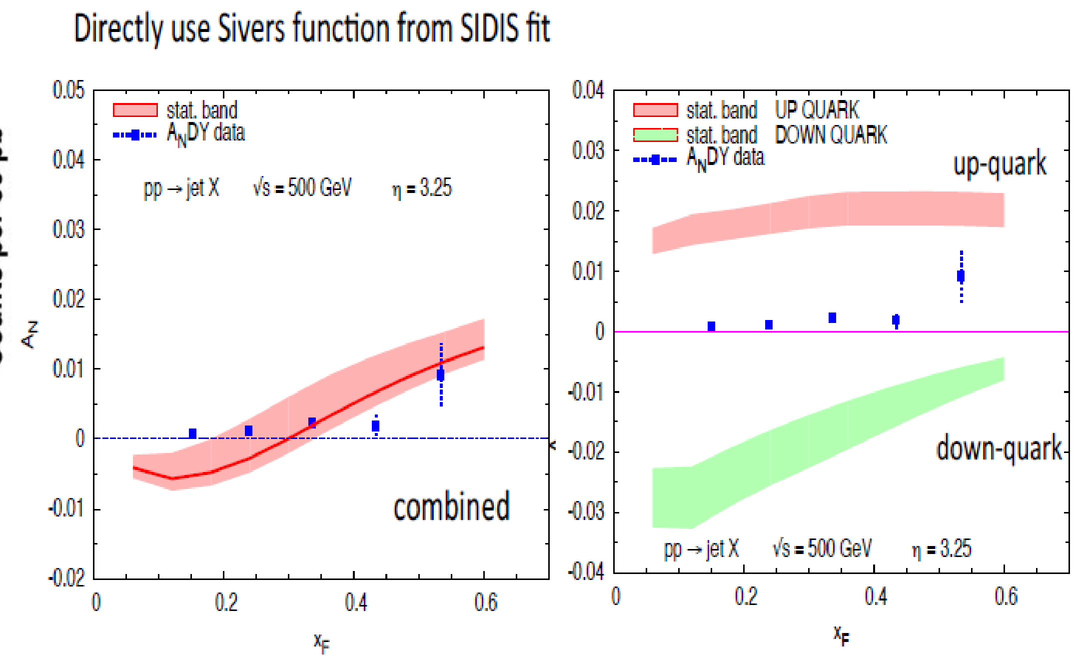


- FVTX covering two regions
  - 3 planes covering $1.1< \eta <3$
  - 3 planes covering $3< \eta <4$
- field shaper piston made of 50% Co + 50%Fe
- 3 GEM tracker stations
- forward HCAL
- current MuID

fsPHENIX Jets @ 200GeV

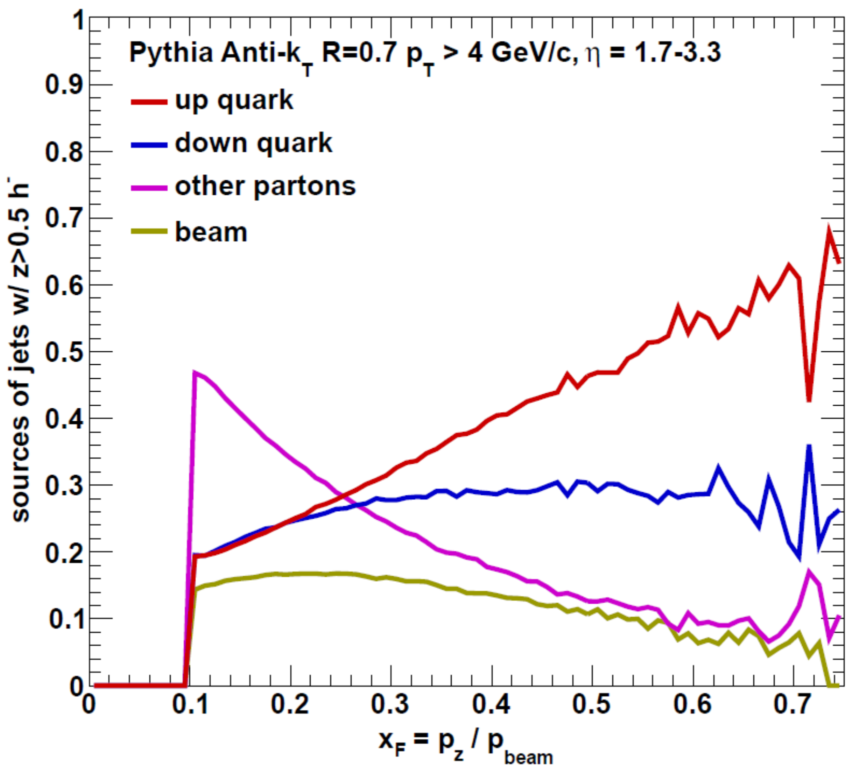
fsPHENIX Jet acceptance 1.7 < η < 3.3 with anti-k_T R=0.7

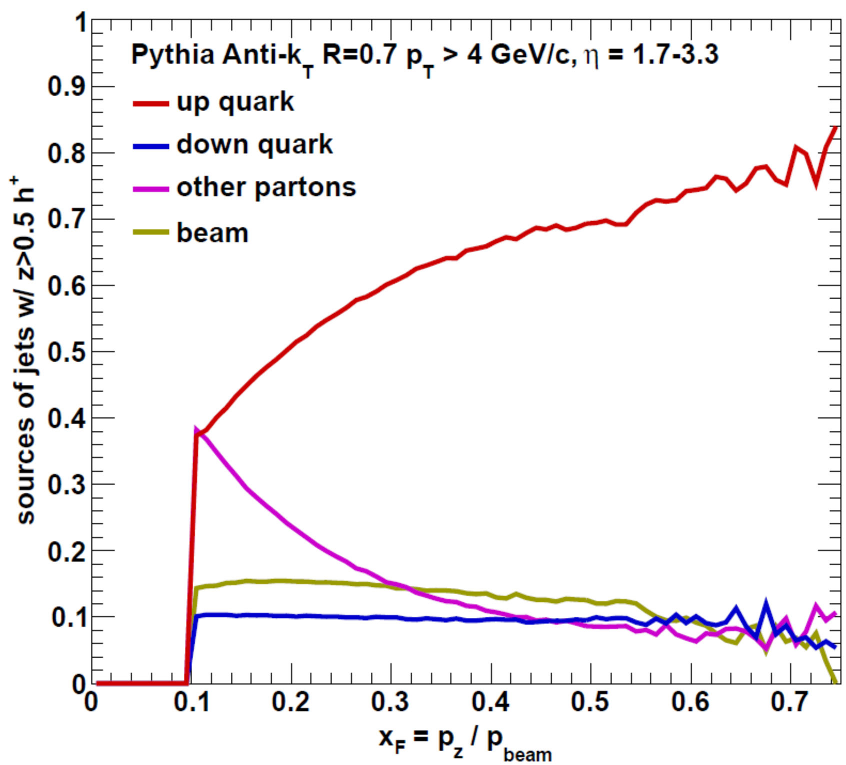




Is the small A_NDY asymmetry a cancellation between u and d quarks?

Jet Sources

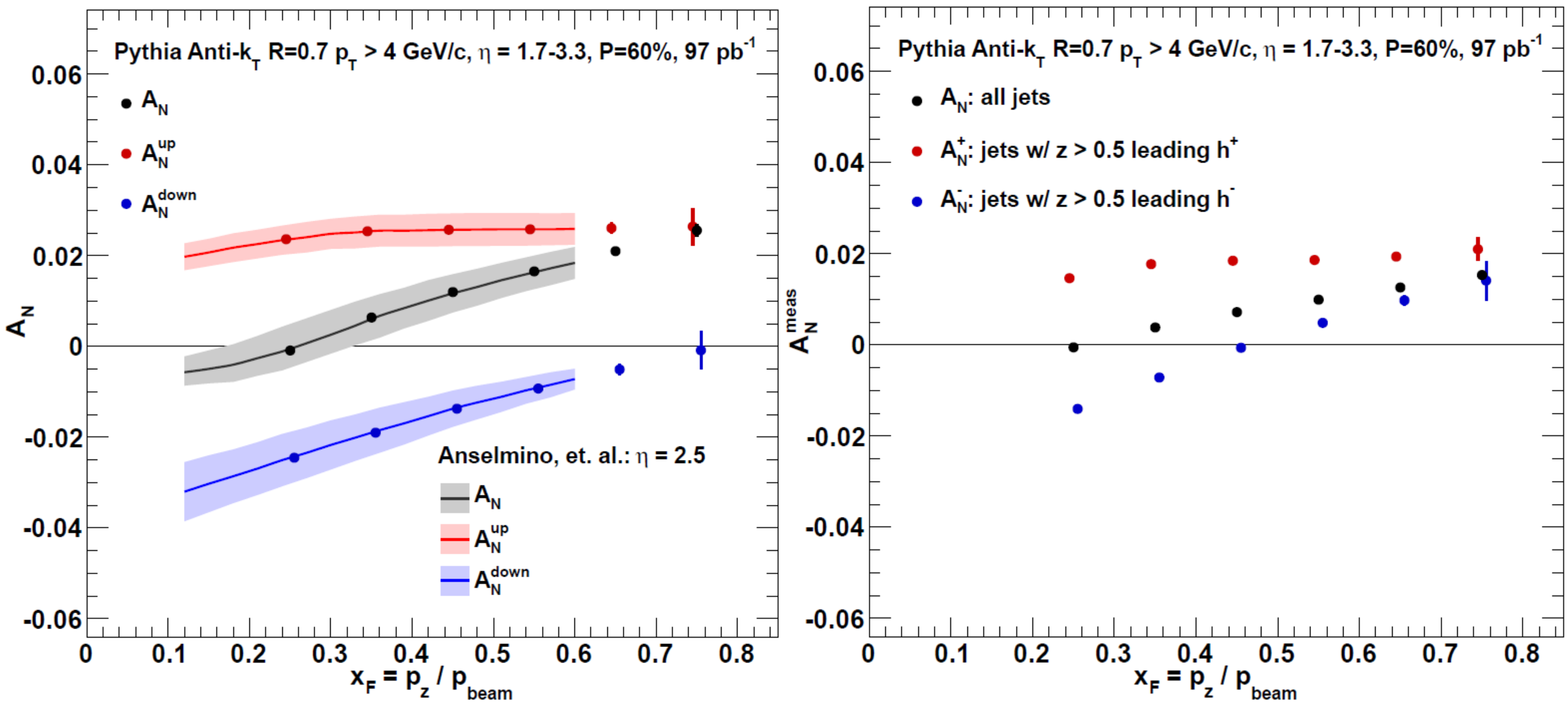




Jets from standard PYTHIA Tune A, beam remnants from Tune A with k_T=0.36.

A cut on the charge of the leading hadron changes the composition of the jet sample.

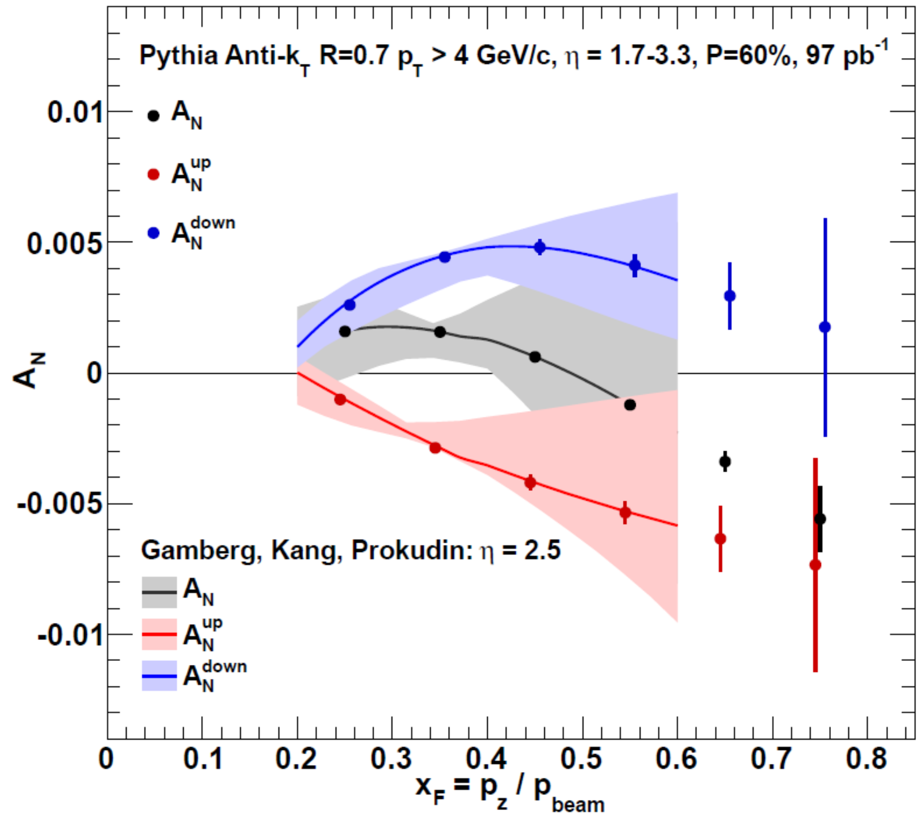
Jet Measurements in fsPHENIX

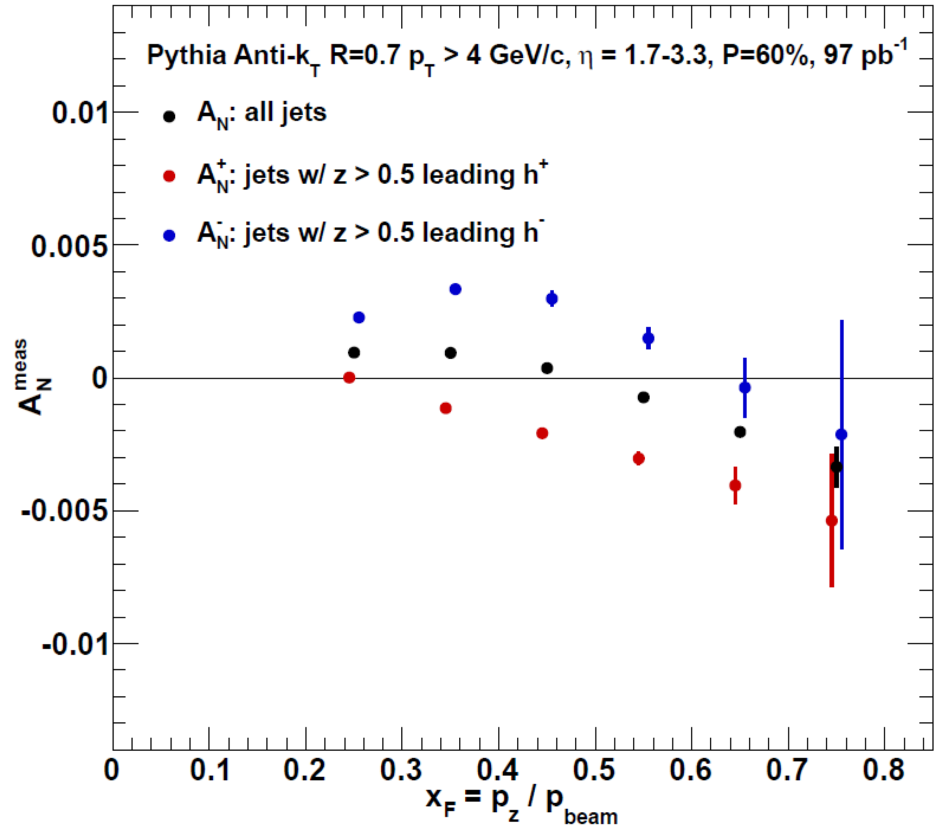


Anselmino et. al. : *Phys Rev. D* 88 054023 (2013)

Projected fsPHENIX data points (97pb^{-1}) compared to theoretical model.

Jet Measurements in fsPHENIX

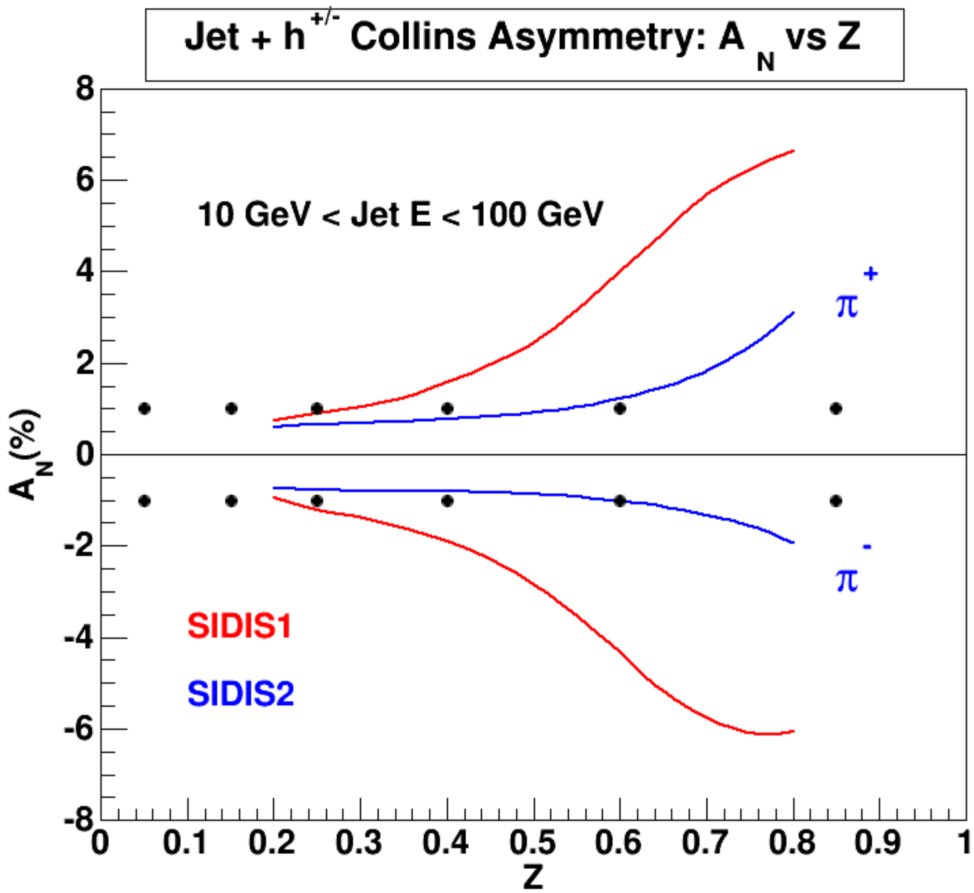




Gamberg, Kang and Prokudin: *Phys Rev. Lett*. 110:232301 (2013)

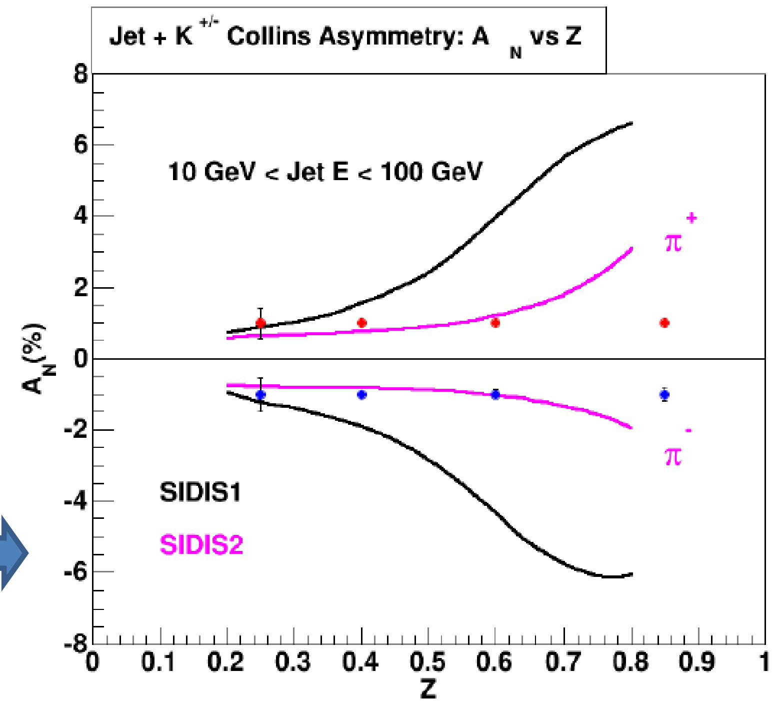
Projected fsPHENIX data points (97pb^{-1}) compared to theoretical model.

Collins in Jets



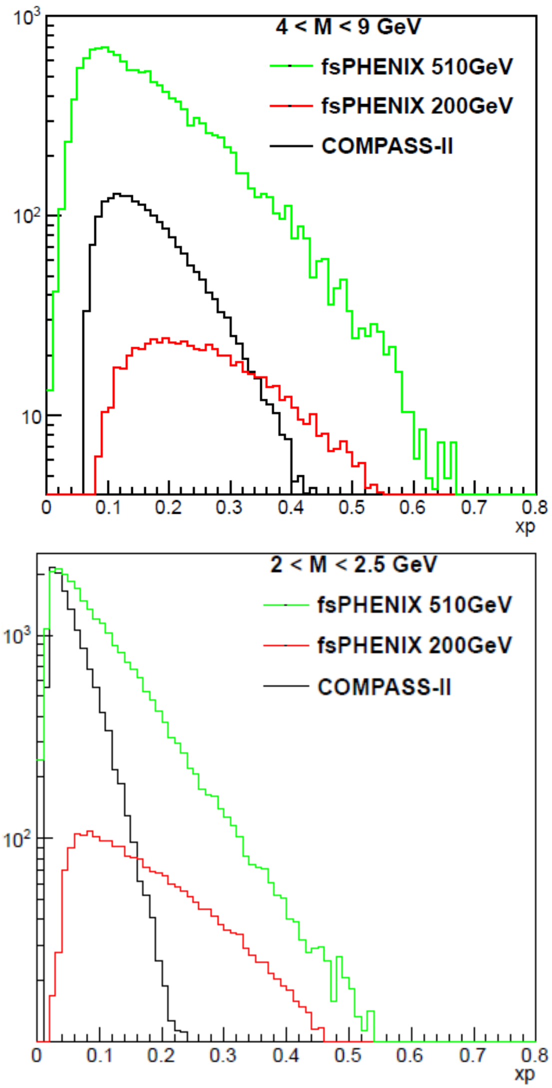
Lots of statistics for Collins in jets using charged hadrons. Issue is z-resolution as a function of jet energy.

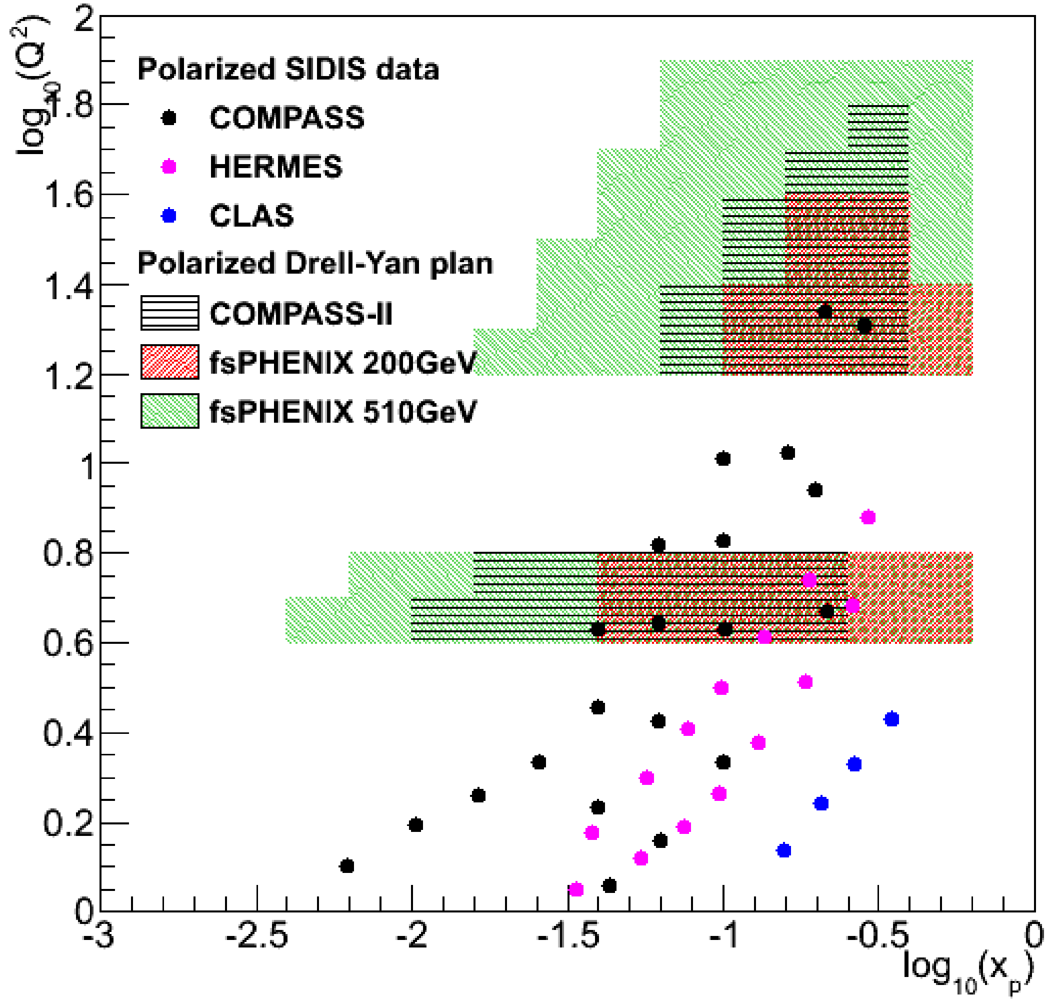
With addition of PID kaon measurements also have excellent statistics (not part of baseline).



Drell-Yan : fsPHENIX and COMPASS-II

$$FoM = (1/\delta A_T^{\sin\phi_S})^2 = \frac{N}{2}P^2$$

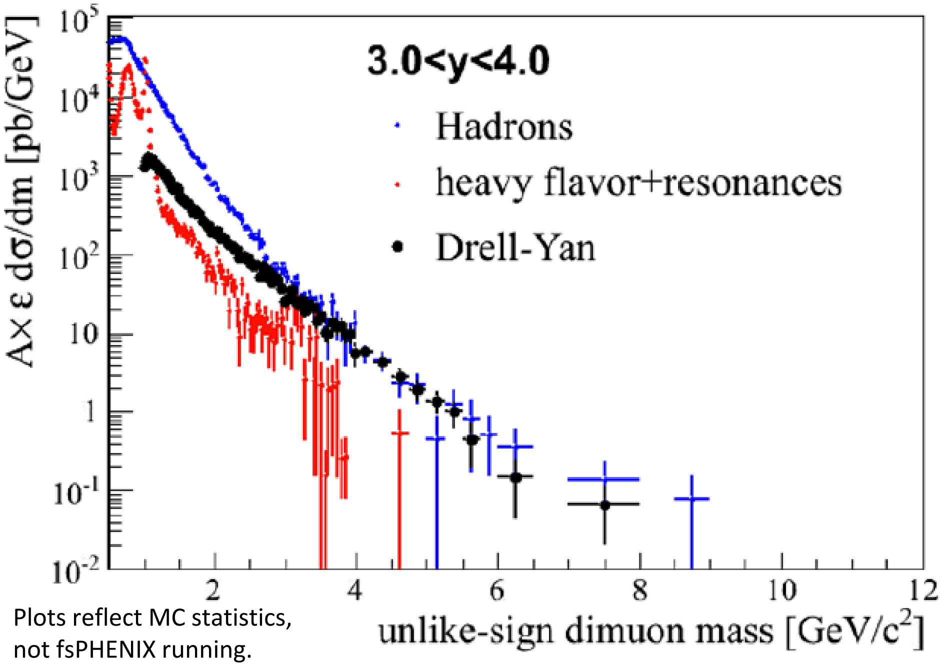




Shaded regions deliniate $\delta A_T^{\sin\phi_S} < 0.1$

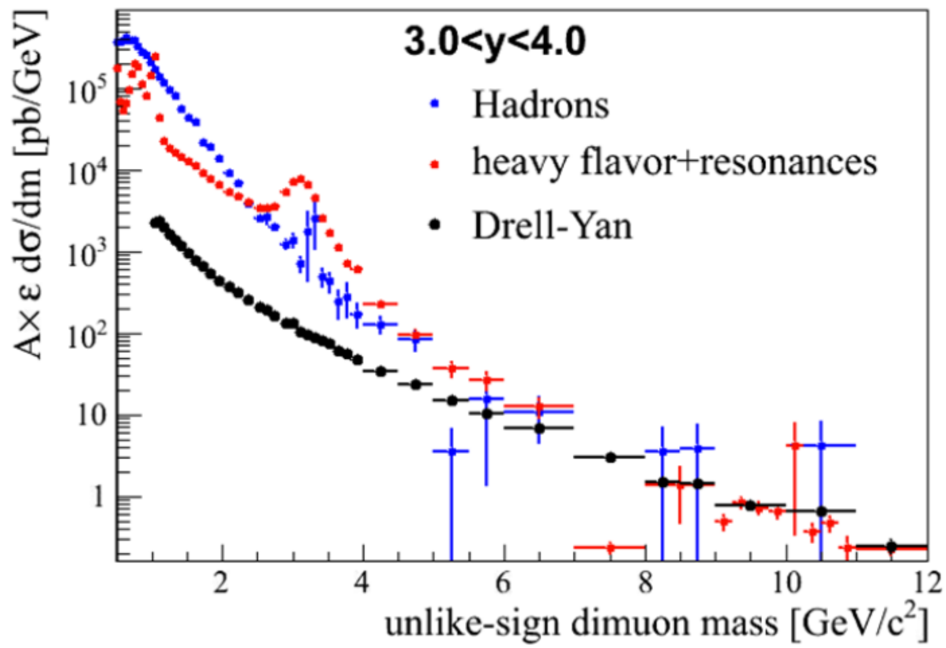
The Challenge of Drell-Yan

200 GeV



Plots reflect MC statistics, not fsPHENIX running.

510 GeV



Very basic cuts <u>without</u> concerted effort to reduce backgrounds.

200 GeV offers better S/B (lower HF cross section), but reduced luminosity makes it difficult to get high statistics. 510 Gev offers much higher luminosity (higher statistics) but higher backgrounds as well.

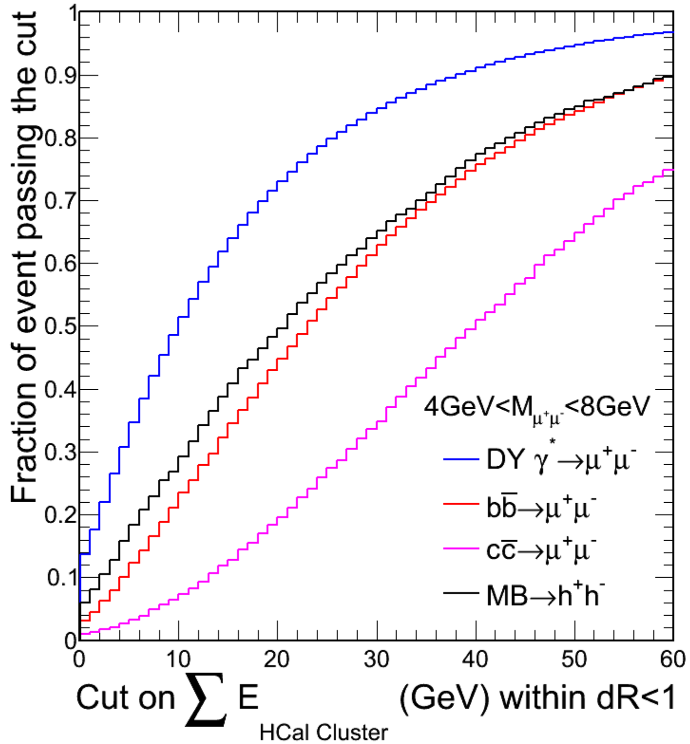
Dramatically improve S/B at higher p_T, Drell-Yan at p_T>Q similar to direct photon.

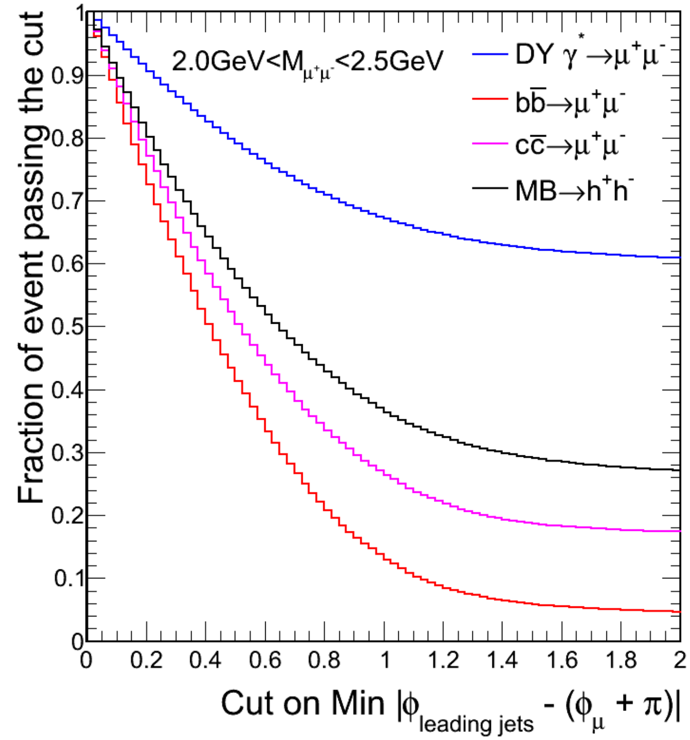
Berger et. al., PRD 65 034006

Improving Drell-Yan Background

Make use of the fact that most of the background is jet-associated, and DY is not (*fsPHENIX* is a jet detector!)

New results (post-whitepaper)





- HCal jet-cone isolation cut
- Back-to-back jet-veto cut

Improving Drell-Yan Background

New results (post-whitepaper)

Drell-Yan S/B with event shape cuts added.

Kinematics (200 GeV)		Low mass ($2.0 < M < 2.5$ GeV)			High mass ($4.0 < M < 8.0$ GeV)		
Rapidity	p_T cut	S/B in WP	DY Eff.	S/B after	S/B in WP	DY Eff.	S/B after
1.2<y<4	No Cut	0.07	68%	0.18	0.40	50%	0.65
3<y<4	No Cut	0.28	76%	0.52	0.94	50%	1.3
1.2<y<4	p_T>2 GeV	0.20	56%	0.83	0.50	51%	0.83
3<y<4	p_T>2 GeV	1.8	68%	4.3	2.3	100%	2.3

Kinematics (510 GeV)		Low mass ($2.0 < M < 2.5$ GeV)			High mass ($4.0 < M < 8.0$ GeV)		
Rapidity	p_T cut	S/B in WP	DY Eff.	S/B after	S/B in WP	DY Eff.	S/B after
1.2<y<4	No Cut	0.01	60%	0.03	0.05	50%	0.10
3<y<4	No Cut	0.03	62%	0.07	0.15	50%	0.31
1.2<y<4	p_T>2 GeV	0.02	49%	0.06	0.06	49%	0.13
3<y<4	p_T>2 GeV	0.07	50%	0.24	0.19	50%	0.36

Improving Drell-Yan Background

New results (post-whitepaper)

Drell-Yan S/B with event shape cuts added.

Kinematics (200 GeV)		Low mass (2.0 < M < 2.5 GeV)			High mass (4.0 < M < 8.0 GeV)		
Rapidity	p_T cut	S/B in WP	DY Eff.	S/B after	S/B in WP	DY Eff.	S/B after
1.2<y<4	No Cut	0.07	68%	0.18	0.40	50%	0.65
3<y<4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.3
1.2<y<4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.83
3<y<4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.3

Kinematics [illegible]		[illegible]			[illegible] .0 GeV)		
Rapidity	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	/B after
1.2<y<4	No Cut	0.01	60%	0.03	0.05	50%	0.10
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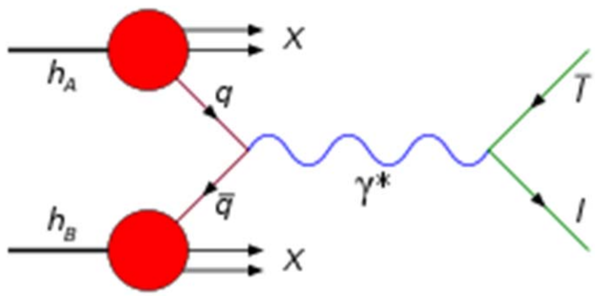
3<y<4	p_T>2 GeV	0.07	50%	0.24	0.19	50%	0.36

Very encouraging at this level of simulation. Full, detailed simulations required to evolve *fsPHENIX* design and verify physics capabilities.

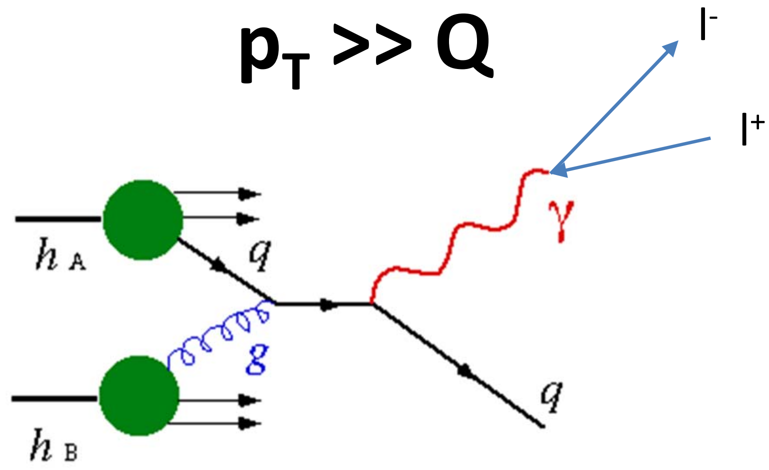
Drell-Yan vs. p_T

$p_T \ll Q$



- Dominant process is quark-antiquark annihilation
- TMD factorization valid
- Direct comparison of modified universality with SIDIS

$p_T \gg Q$



- Dominant process is gluon-Compton scattering to virtual photon
- Same information as direct photon
- TMD factorization NOT valid
- Can be interpreted in Twist-3 approach

Berger, Qiu and Zhang, Phys. Rev. D 65, 034006
Kang, Qiu and Vogelsang, Phys. Rev. D 79, 054007

Conclusions

- **The *fsPHENIX* physics program covers a broad range of key scientific questions:**
  - The spin structure of the nucleon
  - The structure of nuclear matter at small-x
- **The ability to pursue these questions in p+p and p+A collisions will be lost in the transition to the EIC without the *fsPHENIX* program.**
- ***fsPHENIX* builds on the *sPHENIX* detector and integrates with a future EIC detector.**
  - Extends jet acceptance of sPHENIX
  - 90% of the estimated cost of *fsPHENIX* is in common with the EIC detector

BACKUP

fsPHENIX Cost

	Cost	Overhead	Contingency	Total
HCal	3.90	0.68	2.29	6.87
GEM Tracker	0.67	0.17	0.41	1.25
FVTX reconfiguration	0.53	0.11	0.31	0.95
Mini-MUID	0.13	0.03	0.08	0.24
Piston Field Shaper	0.06	0.02	0.04	0.12
HCal electronics/sensors	0.38	0.05	0.22	0.65
GEM electronics/sensors	0.63	0.16	0.39	1.18
Mini-MUID electronics/sensors	0.05	0.01	0.03	0.09
MUID trigger electronics	0.35	0.07	0.21	0.63
Total	6.7	1.3	3.98	11.98

$12M overall cost, about 90% common with the EIC Detector.

fsPHENIX Luminosity Assumptions

- **Guidance from ALD (CAD Delivered):**
  - ALD guidance also cautions <u>to assume lower estimates</u>…
  - p+p@510GeV: 200pb^{-1}/week
    - Increase in bunch intensity by factor of 1.62 over achieved (electron cooling)
    - CAD 2014-2018 Projections (4 June 2013): 216pb^{-1} /week (max), 40pb^{-1} /week (min)
    - Max/Min Average = 128pb^{-1}/week <u>average</u>
  - p+Au@200GeV: 300nb^{-1}/week
    - Run-14 BUP guidance was 175nb^{-1}/week
    - Conservative: 225nb^{-1}/week (75% of maximum)
    - p+p equivalent: 44pb^{-1}/week
  - p+p@200GeV: no ALD guidance
    - CAD projection 28pb^{-1} (max), 9.3pb^{-1}/week (min)
    - Max/Min Average = 18.7pb^{-1}/week

Use these #'s for fsPHENIX

fsPHENIX Run Length

- **PHENIX Guidance:**
  - Assume 10 weeks running for p+p@200GeV
  - Assume 10 weeks running for p+Au@200GeV
- **What do we assume for Drell Yan p+p@510GeV?**
  - Make table assuming one 15-week run
- **Additional running time for different p+A species?**
- **Dell-Yan:**
  - **Assuming PHENIX Efficiency**
    = 0.6 (uptime) x 0.62 ($-30<z_V<10$cm vertex)
  - p+p@200GeV PHENIX Sampled = **$69pb^{-1}$**
  - p+A@200GeV PHENIX Sampled = $831nb^{-1}$ p+Au, **$163pb^{-1}$ (pp equiv)**
  - p+p@510GeV PHENIX Sampled = **$714pb^{-1}$**
- **Jets:**
  - **Assuming PHENIX Efficiency**
    = 0.6 (uptime) x 0.84 (+/-30cm vertex)
  - p+p@200GeV PHENIX Sampled = **$97pb^{-1}$**
  - p+A@200GeV PHENIX Sampled = $1165nb^{-1}$ p+Au, **$230pb^{-1}$ (pp equiv)**
  - p+p@510GeV PHENIX Sampled = **$1002pb^{-1}$**