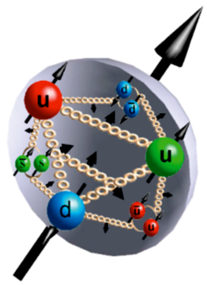
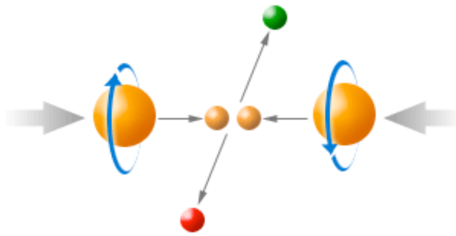


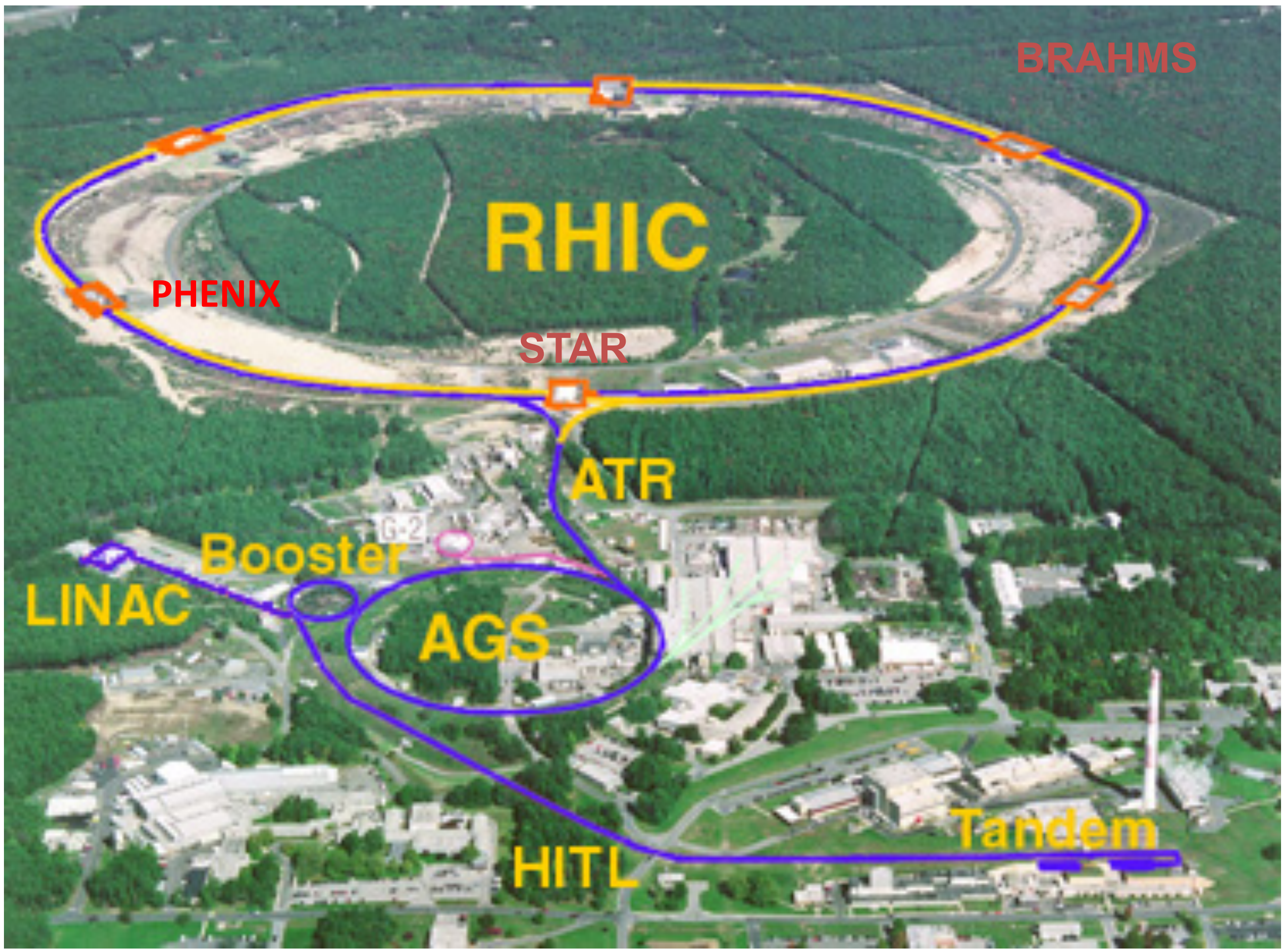


Highlights from RHIC Spin Program

Ming Xiong Liu
Los Alamos National Lab

- Longitudinal spin program
- Transverse spin program

The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

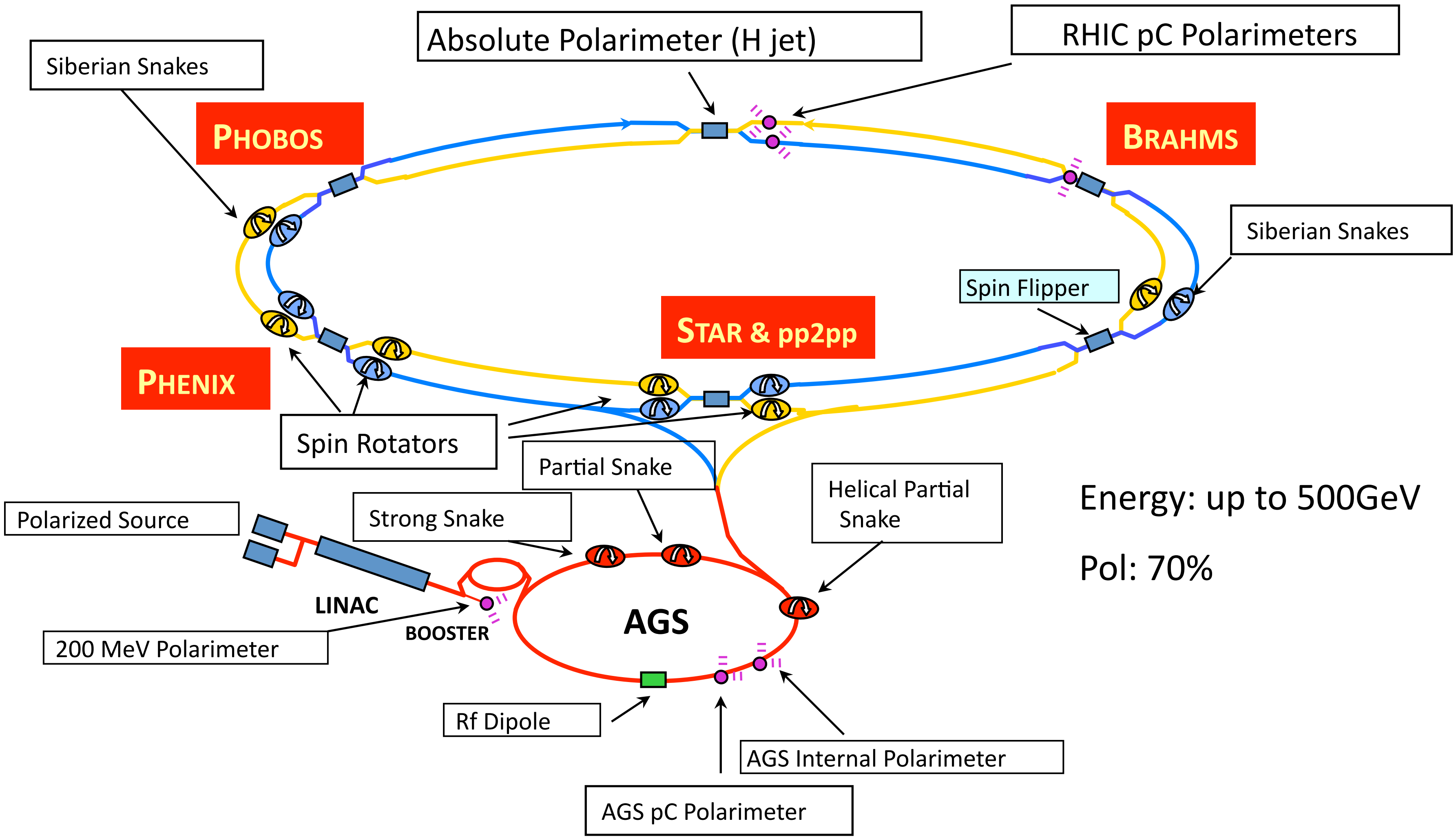


R-HI
New state of matter
QGP
De-confinement
…

polarized proton
Nucleon Spin Structure
Spin Fragmentation
pQCD
…

RHIC is a QCD lab

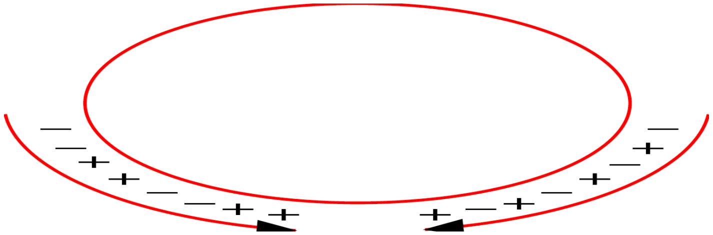
Highest Energy Polarized Proton Collider @RHIC



Energy: up to 500GeV

Pol: 70%

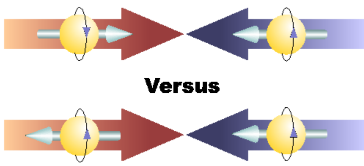
Experimental Observables



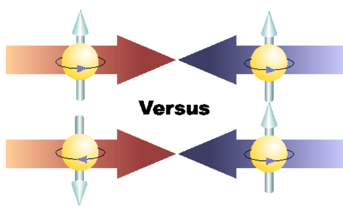
Asymmetries

- PHENIX and STAR: all
- BRAHMS: transverse beams only

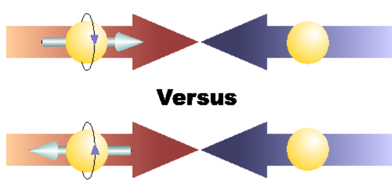
$$A_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}$$



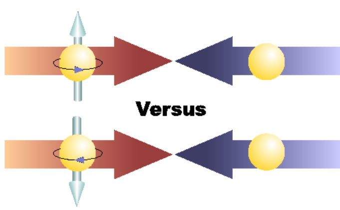
$$A_{TT} = \frac{\sigma(\uparrow\uparrow)-\sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow)+\sigma(\uparrow\downarrow)}$$



$$A_{L} = \frac{\sigma(+)-\sigma(-)}{\sigma(+)+\sigma(-)}$$



$$A_{T} = \frac{\sigma(\uparrow)-\sigma(\downarrow)}{\sigma(\uparrow)+\sigma(\downarrow)}$$



The PHENIX Detectors

Philosophy:

High rate capability to measure rare probes, limited acceptance.

- 2 central spectrometers
  - Track charged particles and detect electromagnetic processes

$|\eta| < 0.35$

$90^\circ + 90^\circ$ azimuth

- 2 forward muon spectrometers
  - Identify and track muons

$1.2 < |\eta| < 2.4$

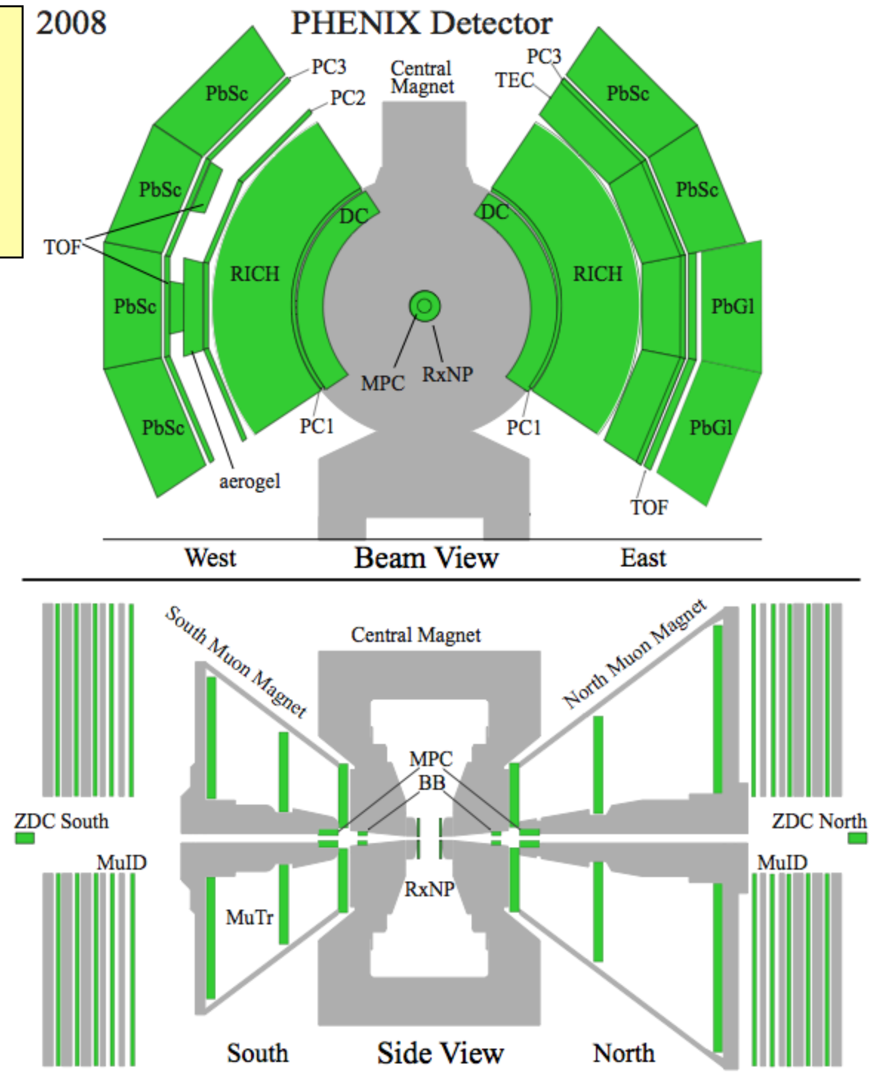
2π azimuth

- 2 forward calorimeters (as of 2007!)
  - Measure forward pions

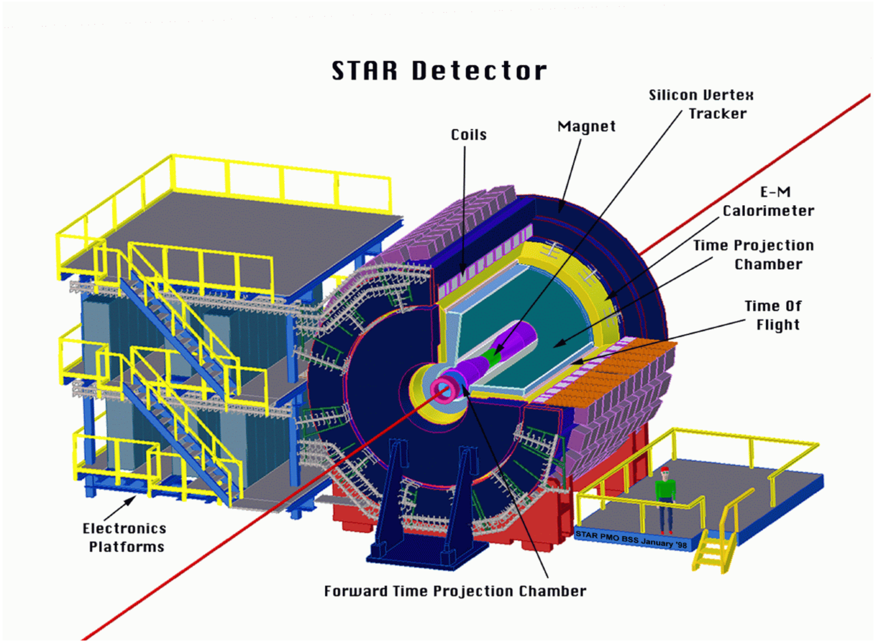
$3.1 < |\eta| < 3.7$

2π azimuth

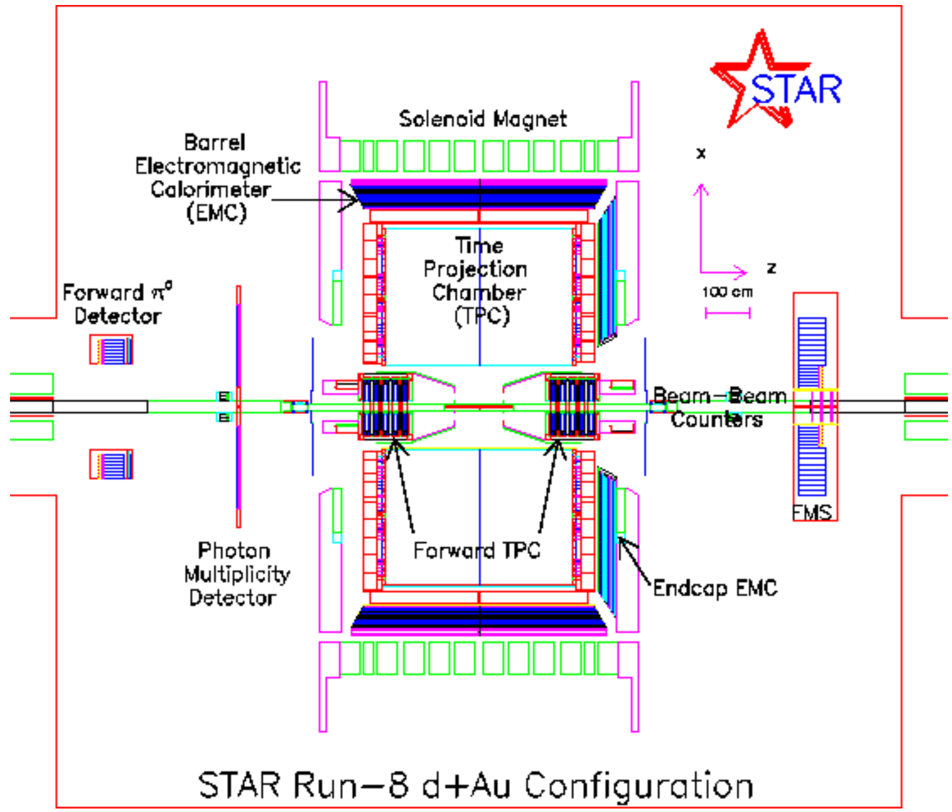
- Relative Luminosity
  - Beam-Beam Counter (BBC)
  - Zero-Degree Calorimeter (ZDC)

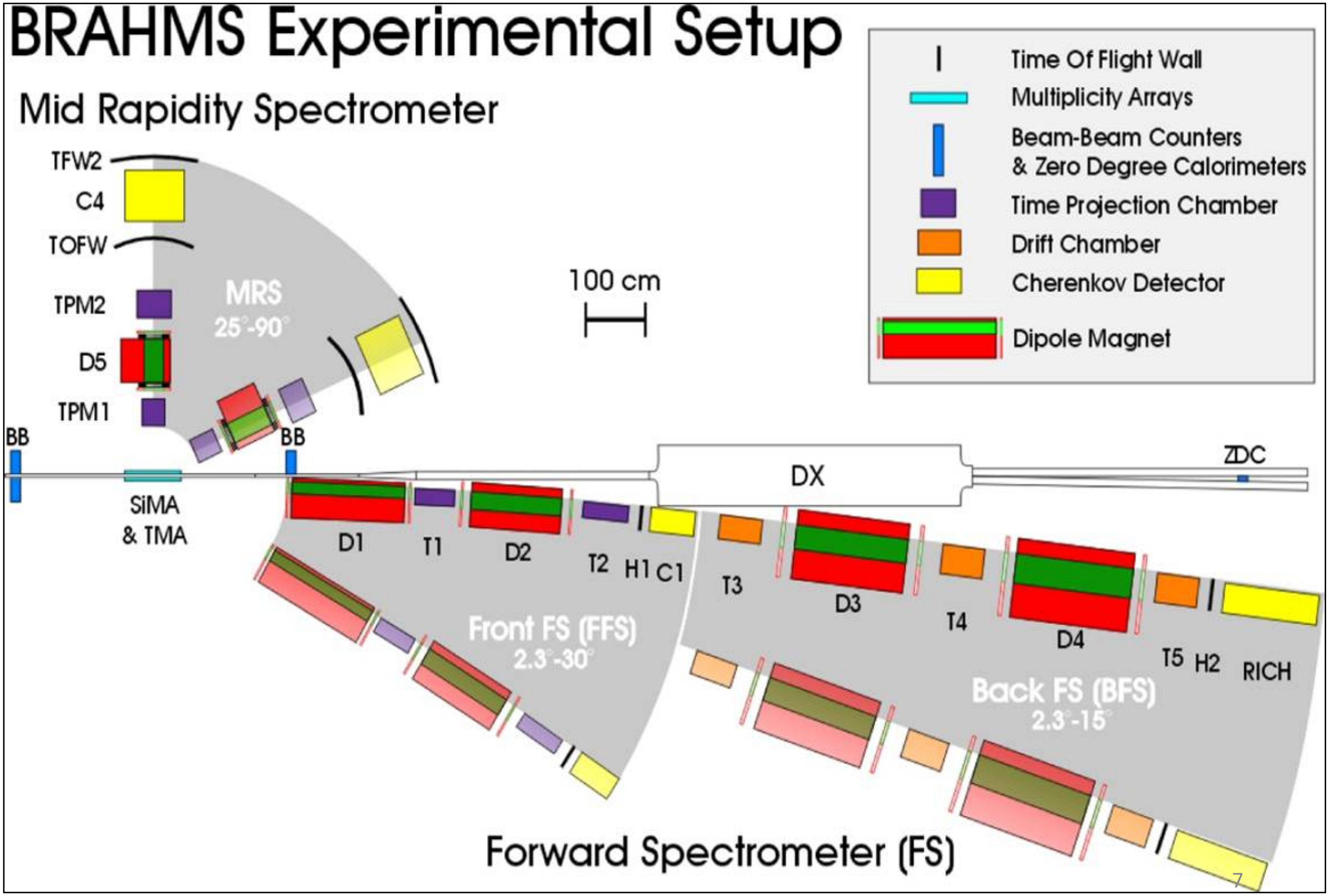


The STAR Detectors



- Time Projection Chamber $|\eta|<1.6$
- Forward TPC $2.5<|\eta|<4.0$
- Silicon Vertex Tracker $|\eta|<1$
- Barrel EMC $|\eta|<1$
- Endcap EMC $1.0< \eta <2.0$
- Forward Pion Detector $3.3<|\eta|<4.1$
- Forward Meson Spectr. $2.5 < \eta < 4$



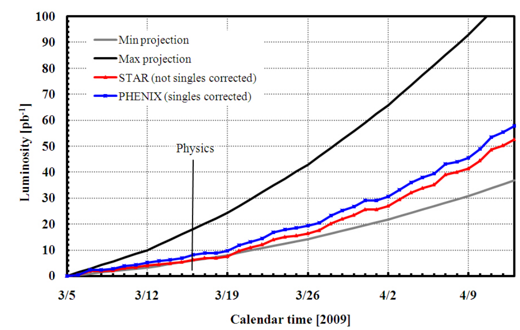


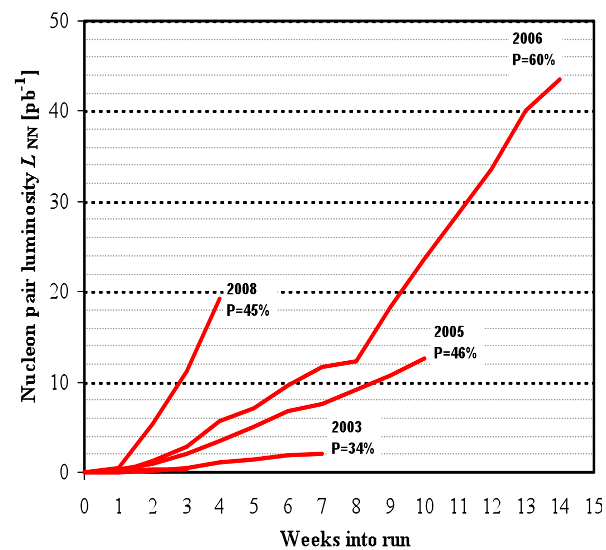
BRAHMS Experimental Setup
Mid Rapidity Spectrometer
TFW2
C4
TOFW
TPM2
D5
TPM1
BB
MRS
25°-90°
BB
SiMA
& TMA
100 cm
Time Of Flight Wall
Multiplicity Arrays
Beam-Beam Counters
& Zero Degree Calorimeters
Time Projection Chamber
Drift Chamber
Cherenkov Detector
Dipole Magnet
DX
ZDC
D1
T1
D2
T2
H1
C1
T3
D3
T4
D4
T5
H2
RICH
Front FS (FFS)
2.3°-30°
Back FS (BFS)
2.3°-15°
Forward Spectrometer (FS)

RHIC Spin Run History

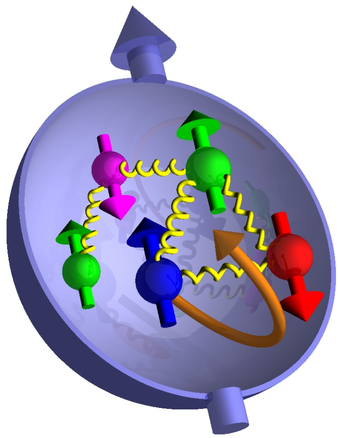
	Pol	L(pb^-1)	Results
2002	15%	0.15	first pol. pp collisions!
2003	30%	1.6	pi^0, photon cross section, A_LL(pi^0)
2004	40%	3.0	absolute beam polarization with polarized H jet
2005	50%	13	large gluon pol. ruled out (P^4 x L = 0.8)
2006	60%	46	first long spin run (P^4 x L = 6)
2007	---	---	no spin running
2008	50%	20	(short) run
2009	500GeV/200GeV		first W measurements

Run9 500 GeV





Part I: Longitudinal Spin Physics Program



The proton is viewed as being a "bag" of bound quarks and gluons interacting via QCD

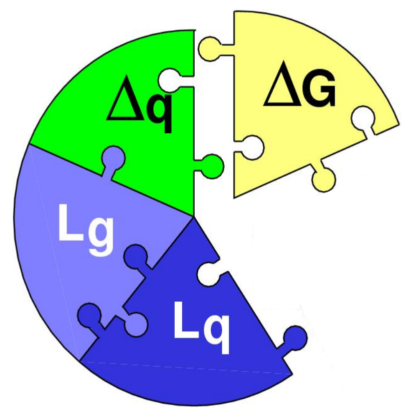
Spins + orbital angular momentum need to give the observed spin 1/2 of proton

$$\frac{1}{2} = \frac{1}{2}\Delta q + L_q^z + \Delta g + L_g^z$$

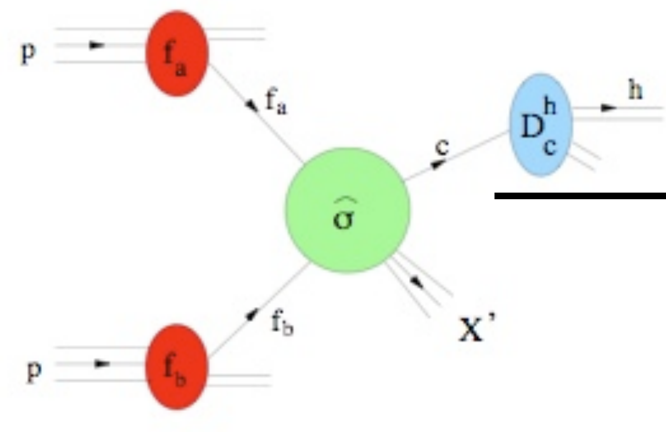
Fairly well measured only ~30% of spin

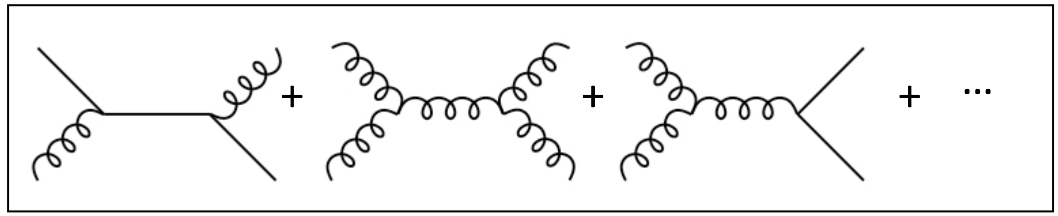
Beginning to be measured at RHIC

A future challenge



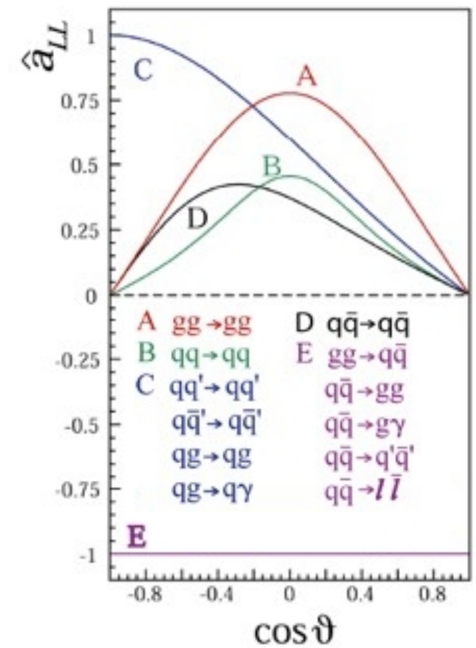
Δg and Polarized p+p Collisions





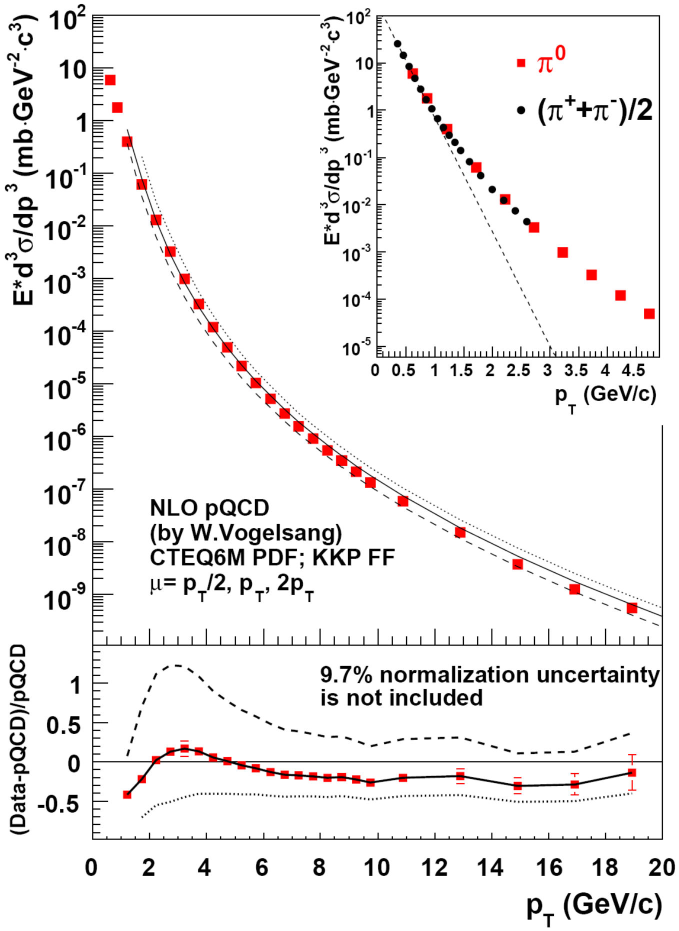
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \cdot \hat{a}_{LL}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}{\sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}$$

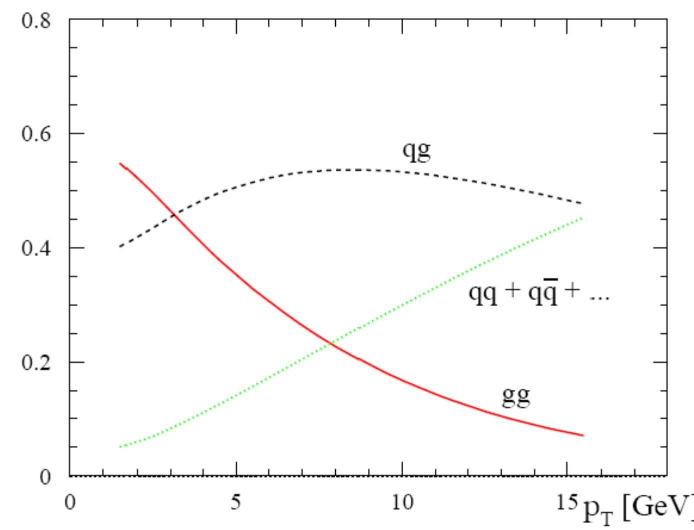
$$A_{LL} \approx a_{gg} \Delta g^2 + a_{qg} \Delta q \Delta g + a_{qq} \Delta q \Delta q'$$



The LO result for a_{LL} is nonzero for all subprocesses

Pion production and NLO pQCD





* NLO QCD Calculation Cross-sections consistent with Data

--- CTEQ6M pdf

--- KKP and Kretzer Fragmentation Fcns

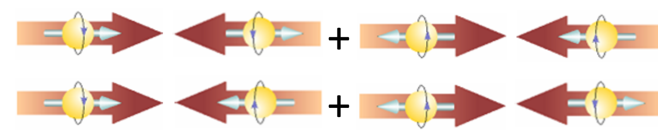
* Necessary Confirmation that pQCD can be used successfully at RHIC to extract spin dependent pdf's

Measuring A_{LL}

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_b P_y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

+ - = Opposite helicity =

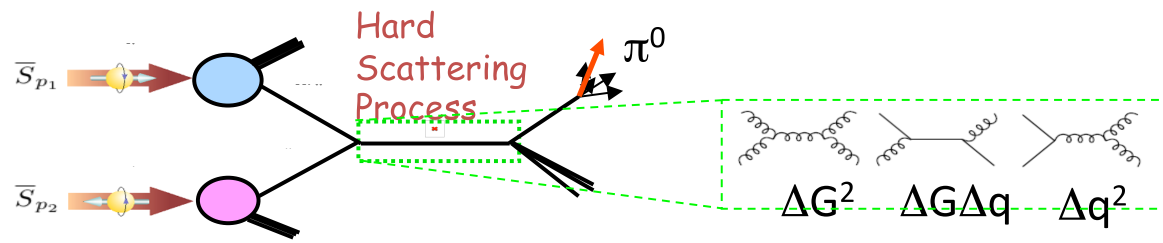
++ = Same helicity =



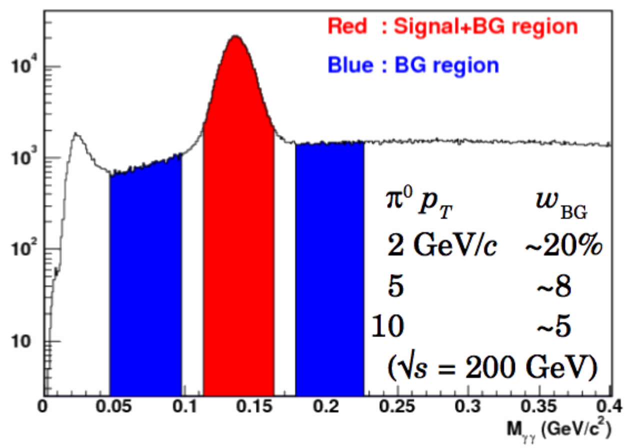
- Helicity Dependent Particle Yields (N)
  - π^0, π^+, π^-, γ, η, etc
- Polarization (P)
- Relative Luminosity ($R=L_{++}/L_{+-}$)

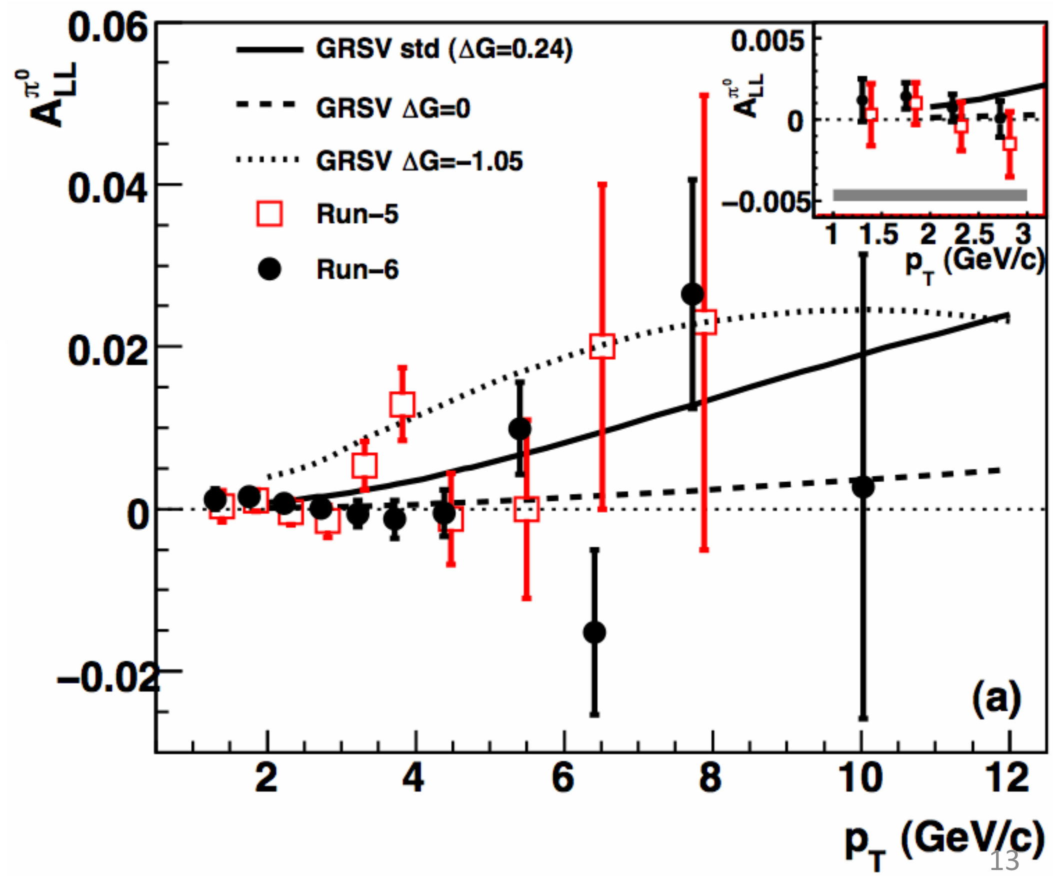
Neutral Pion A_{LL}

- Large cross section + finely segmented EMCal + high p_T photon trigger → large statistics
- $|\eta|<0.35$
- 2005: PRD 76, 051106
- 2006: PRL 103, 012003

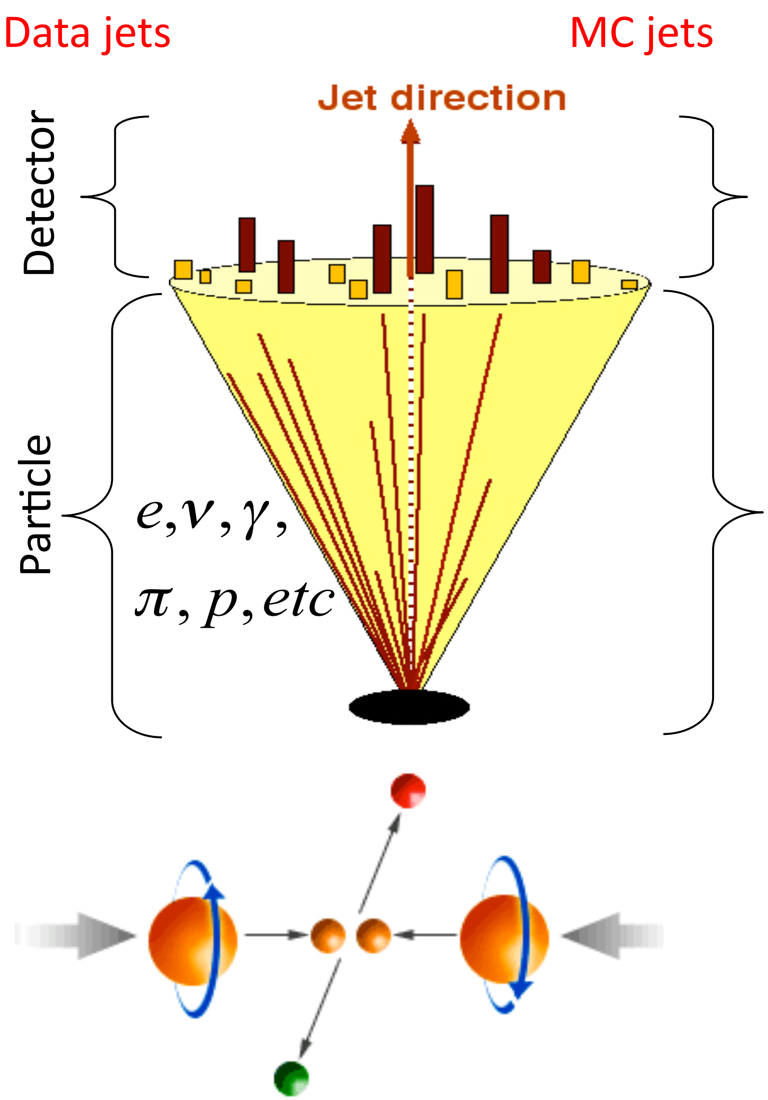


$$A_{LL}^{\pi 0} = \frac{A_{LL}^{\pi 0+BG} - w_{BG} A_{LL}^{BG}}{1 - w_{BG}}$$





Jet reconstruction in *STAR*



Midpoint cone algorithm

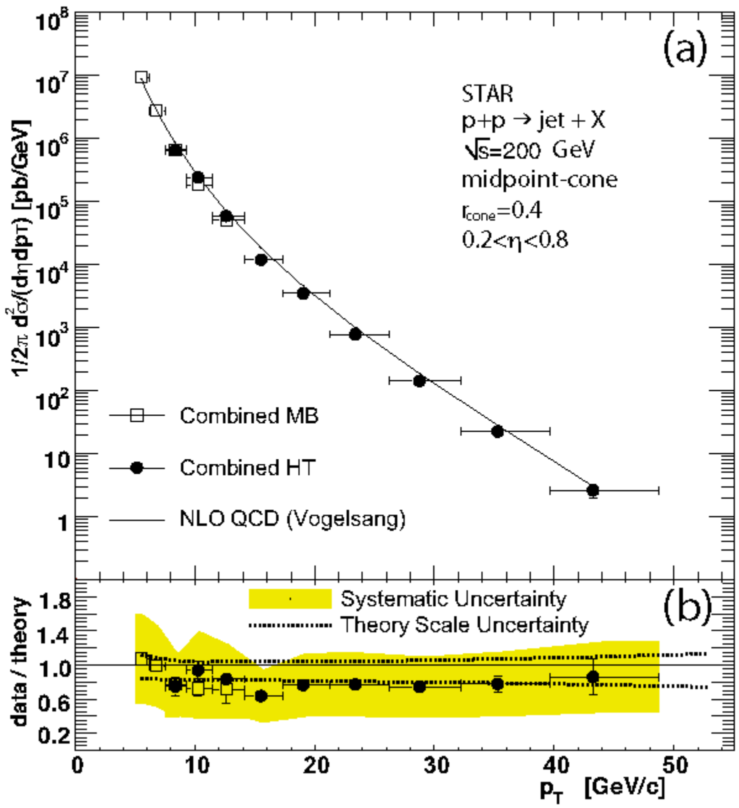
(Adapted from Tevatron II - hep-ex/0005012)

- Seed energy = 0.5 GeV
- Cone radius in η-ϕ
  - R=0.4 with 0.2 < η < 0.8 (till 2005)
  - R=0.7 with -0.7 < η < 0.9 (since '06)
- Splitting/merging fraction f=0.5

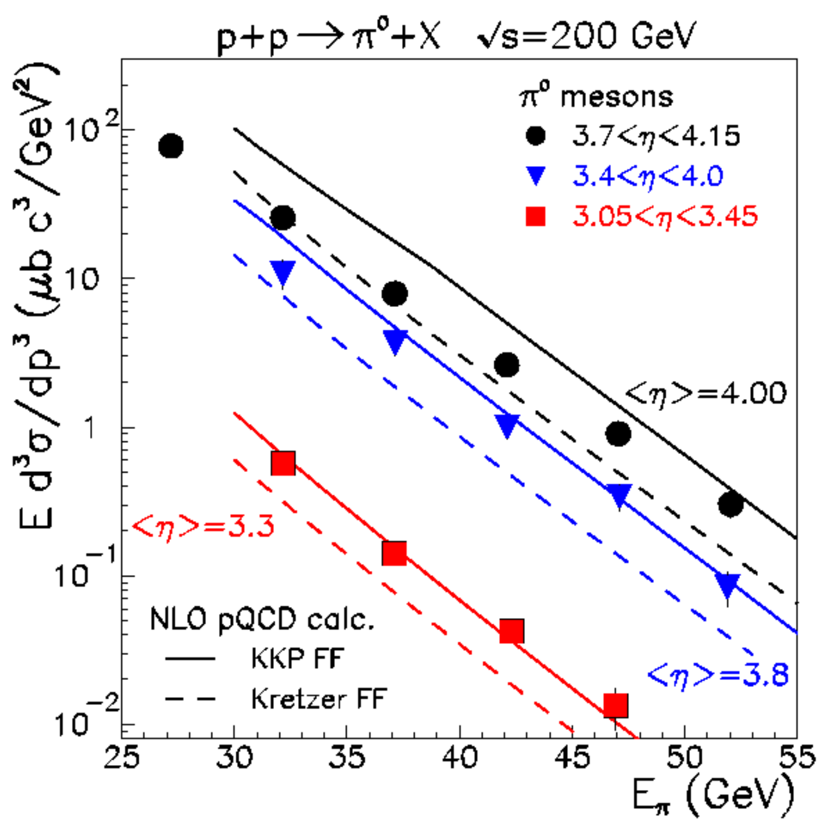
Use PYTHIA + GEANT to quantify detector response

Essential benchmark – unpolarized cross sections

STAR PRL 97, 252001



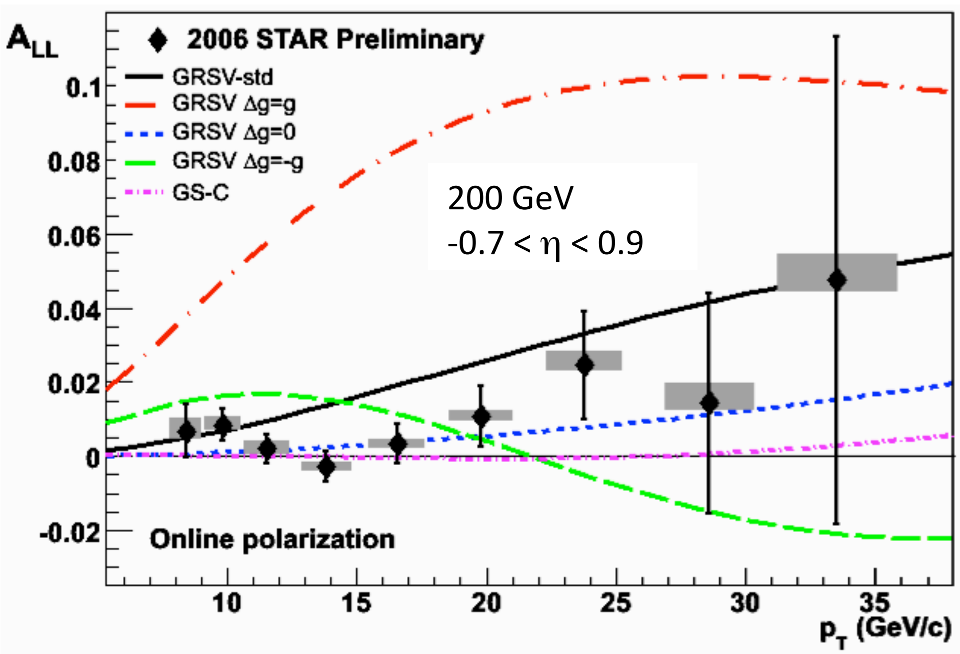
STAR PRL 97, 152302

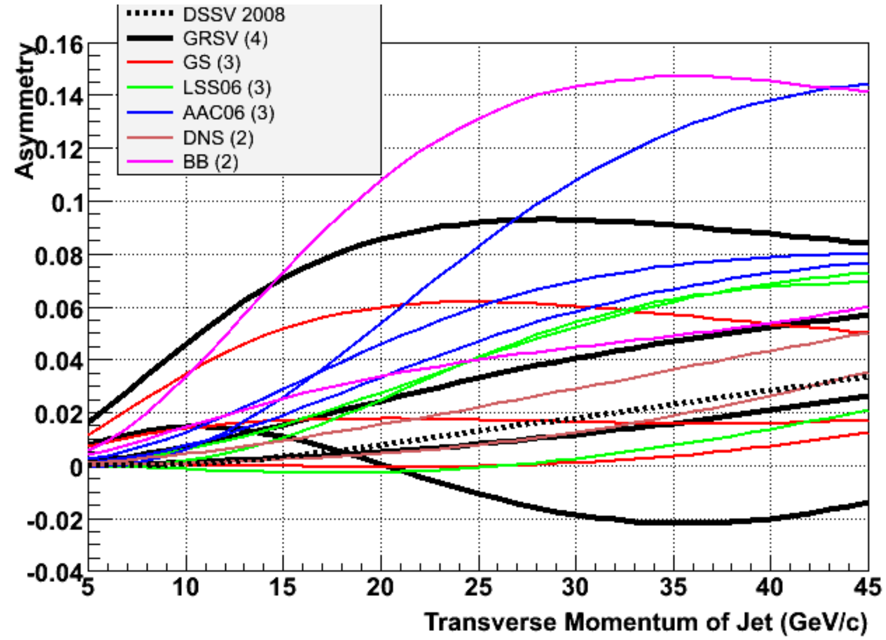


- Mid-rapidity jet cross section is consistent with NLO pQCD over 7 orders of magnitude
- Forward rapidity π^0 cross section also consistent with NLO pQCD
- Many other examples
- **pQCD works over a very broad kinematic range at RHIC energies**

STAR inclusive jet A_{LL} from Run 6

STAR



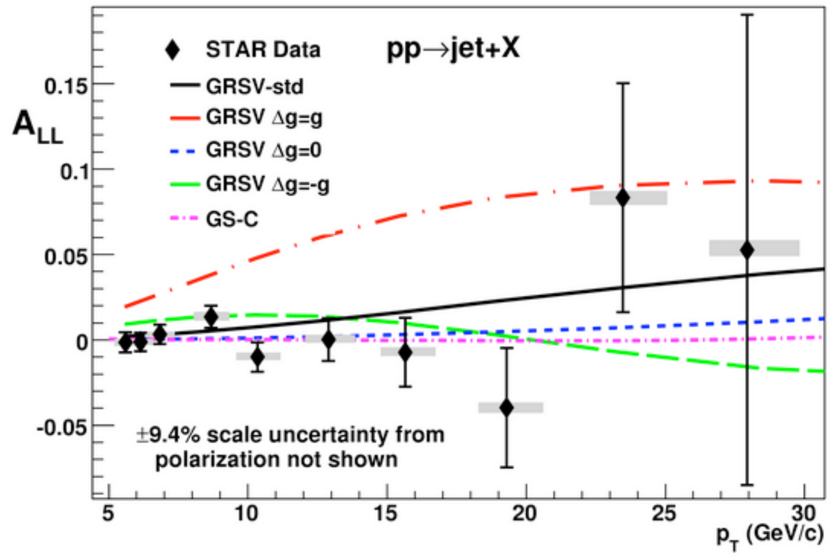


- Run 6 inclusive jet A_{LL} results exclude many polarized parton fits that include large gluon polarizations

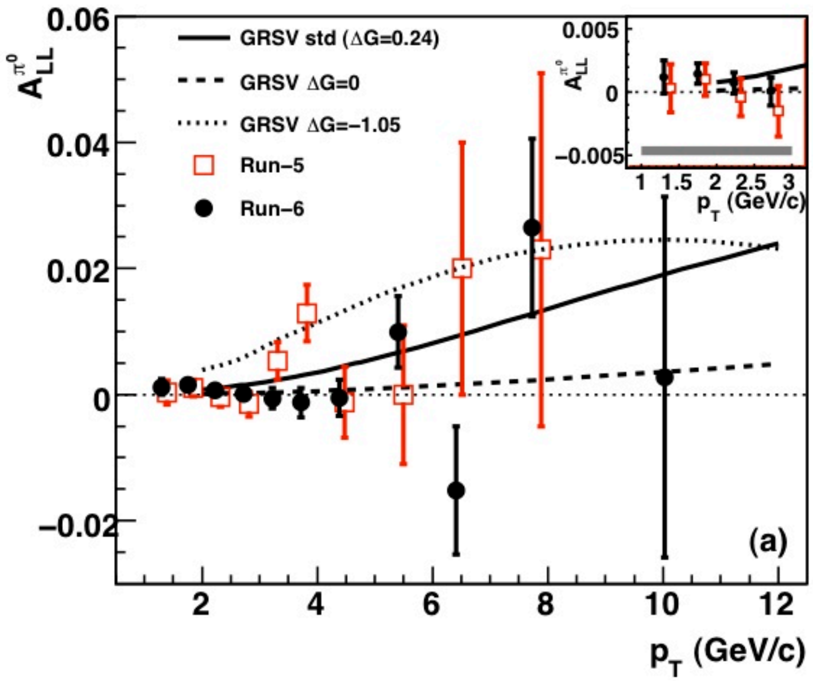
RHIC data and Δg

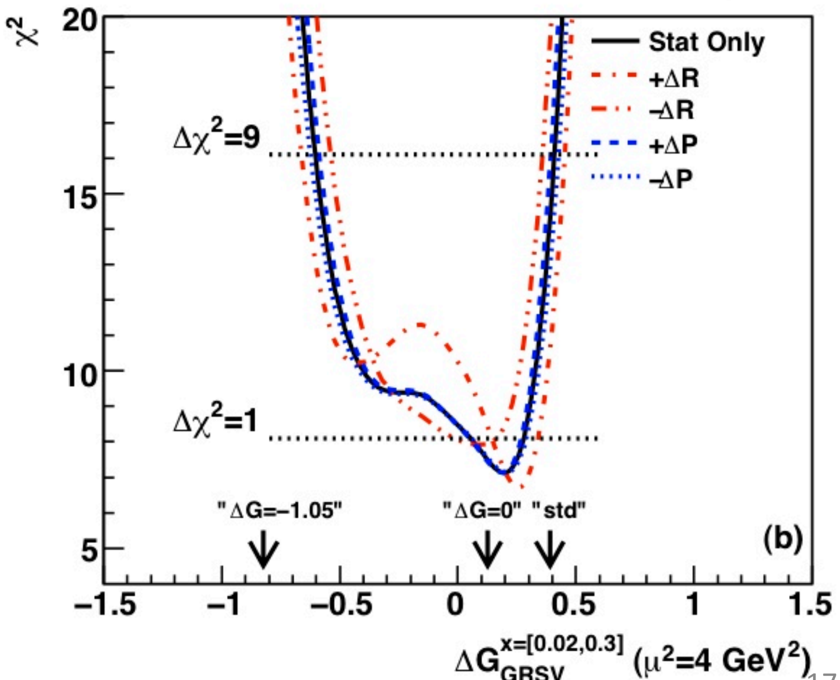
- PHENIX pi0
- STAR inclusive jets

STAR, PRL 100 232003 (2008)



PHENIX, PRL 103 012003 (2009)

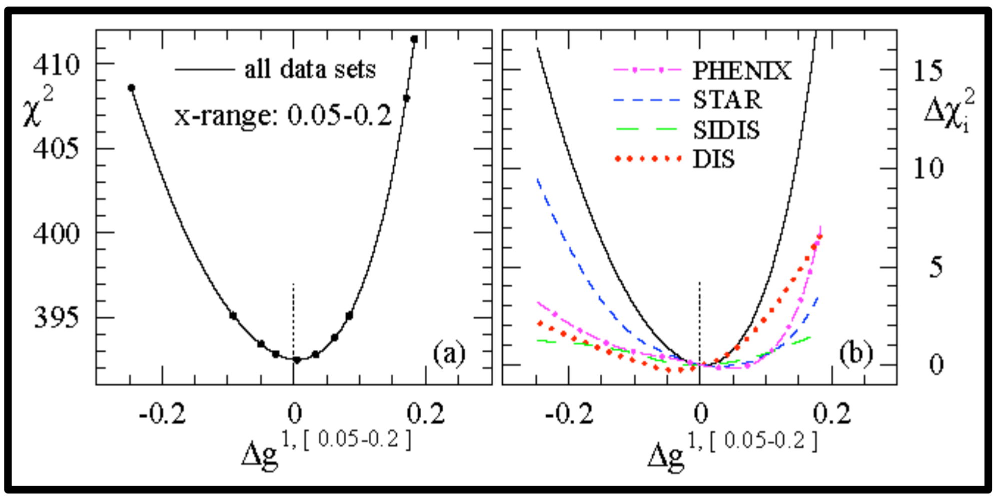




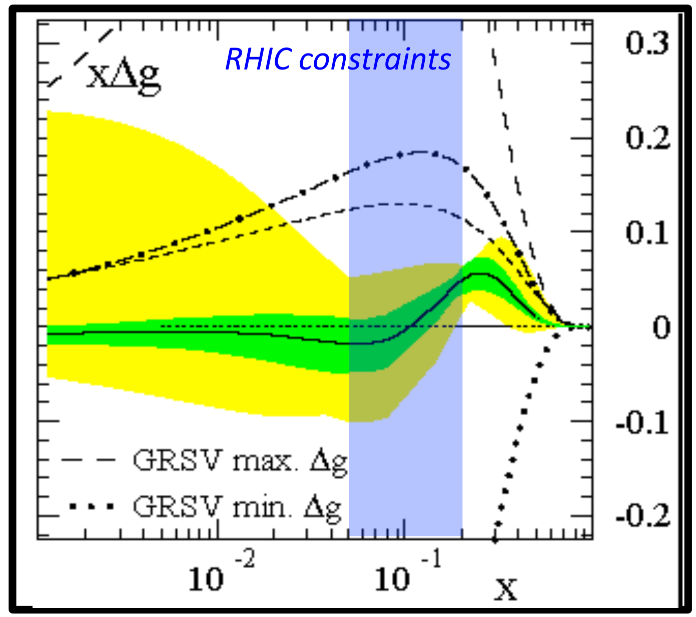
Impact of RHIC-Spin Program on Δg

- Prior to RHIC-Spin Program, Δg = 1~2 expected at scale of 1GeV
  - Restored consistency between data and quark model predictions
- Major impact of program
  - such large values of Δg seem to be excluded

χ^2 distribution as Δg is varied w/in x-range constrained by the RHIC data.



DSSV 08



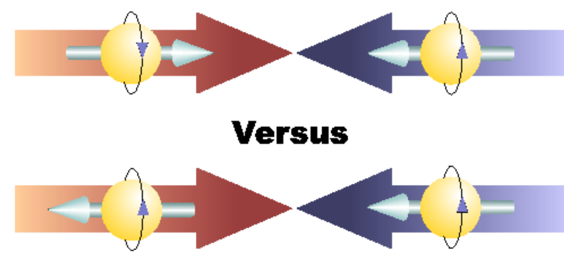
It is interesting to note that the best fit has a zero-crossing at x ≈ 0.1.

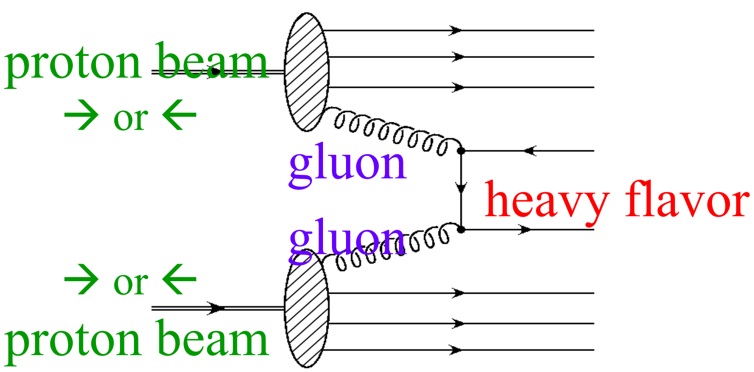
Future New Probes @RHIC: Δg

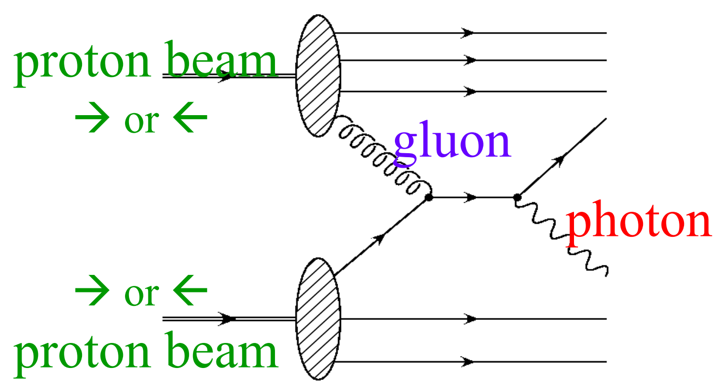
- Polarized hadron collisions
  - double longitudinal spin asymmetry

$$\boxed{A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} - \sigma^{+-}} \propto \Delta f_A^a(x_a, Q^2) \otimes \Delta f_B^b(x_b, Q^2) \otimes \frac{d\Delta\sigma_{ab}^{cd}}{dt}}$$

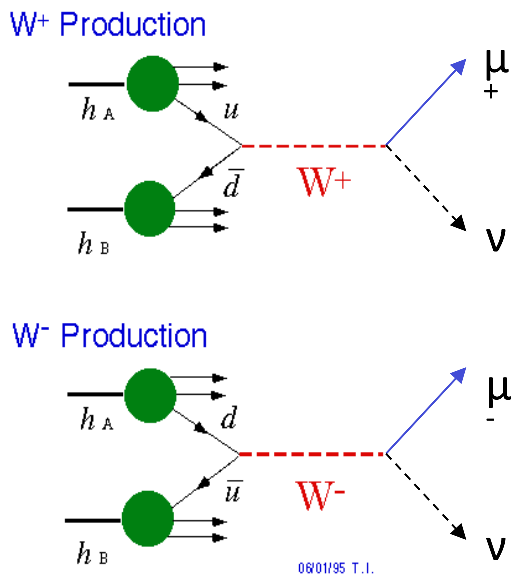
  - leading-order gluon interactions
    - direct-photon production
    - heavy-flavor production
    - Other channels (light hadrons etc.)

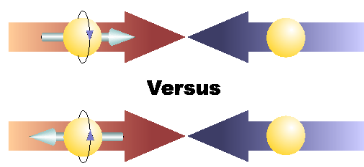




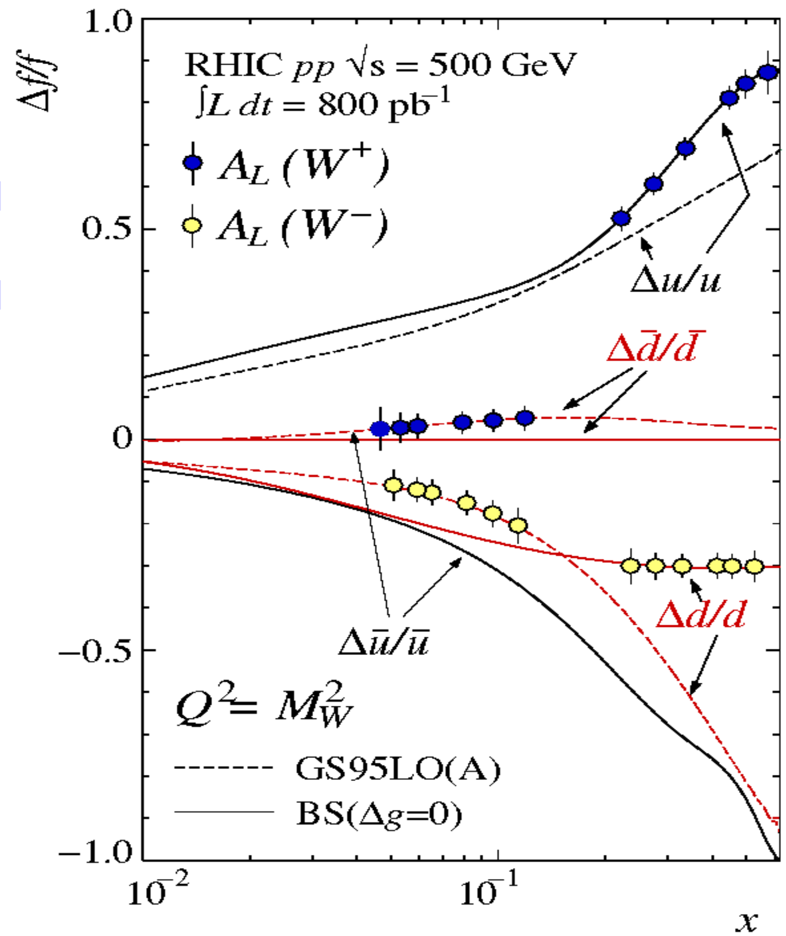


Latest News: $W^{\pm}$ Production and A_L @500GeV





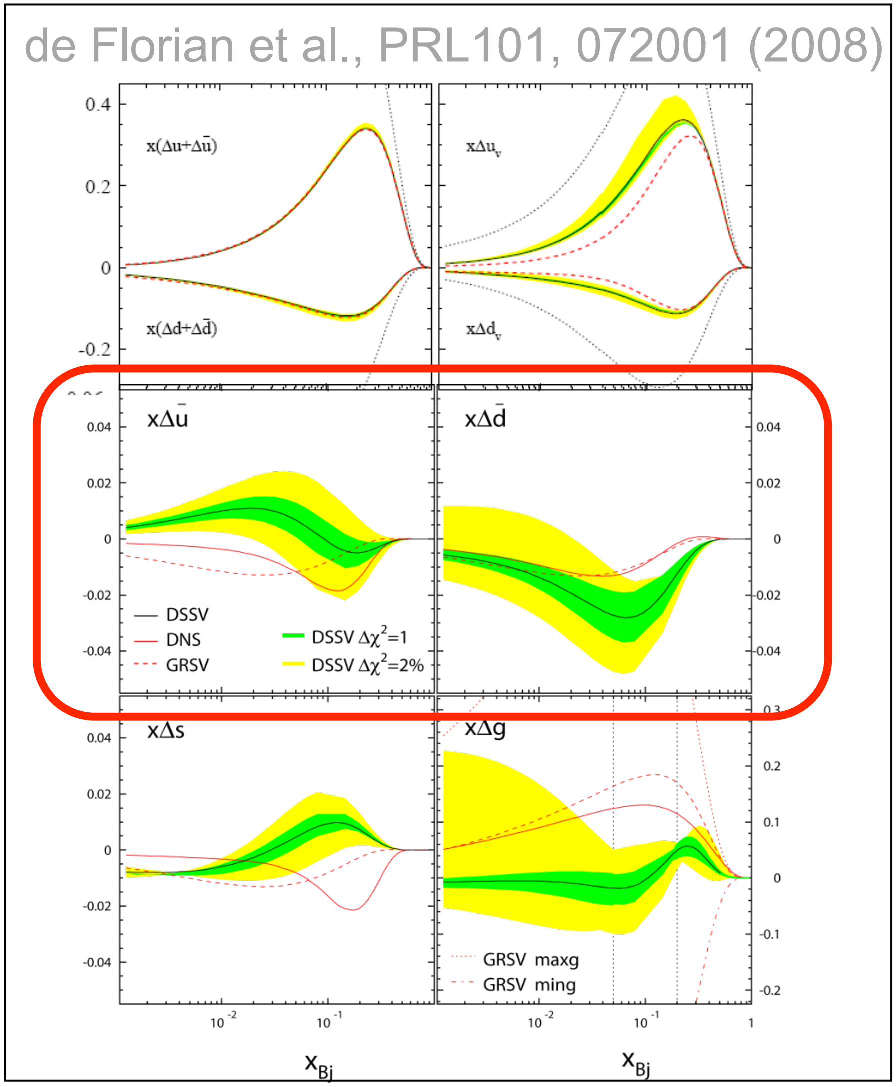
Bunce G. et al, hep-ph/0007218



$$A_L^{W+} = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}} \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$A_L^{W+} : \frac{\Delta u}{u} \text{ and } \frac{\Delta\bar{d}}{\bar{d}}. \qquad A_L^{W-} : \frac{\Delta d}{d} \text{ and } \frac{\Delta\bar{u}}{\bar{u}}.$$

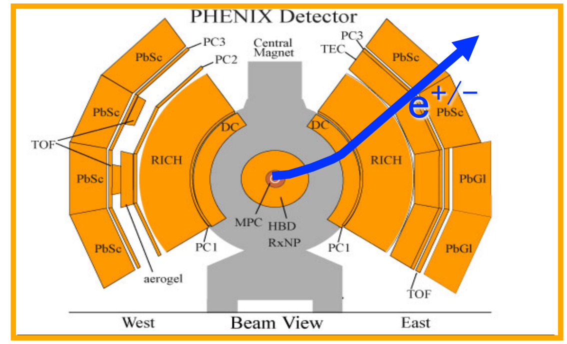
Polarized Parton Distributions

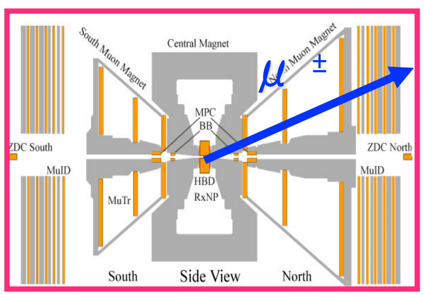


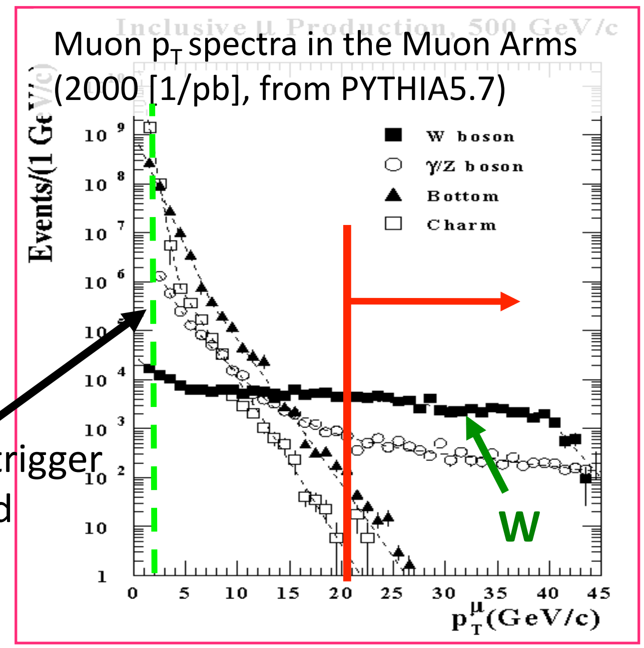
- DIS:
  - Valence quark distributions well determined
  - Flavor separated sea quark distributions are not accessible
- SIDIS:
  - Can access in semi-inclusive DIS
  - Rely on fragmentation functions
- p+p:
  - Accessible through parity violating W production

Two ways to get $W^{+/-} \rightarrow l^{+/-} + \nu$ in PHENIX

- Central Rapidity: $|\eta|<0.35$
  - Measure electron in the central arms EMCal
  - Determine charge sign from tracking
- Forward/Backward: $1.2<\eta<2.4$
  - Measure muon in muon arms
  - W dominates muon signal above 20 GeV
  - For measurement, we require:
    - Ability to trigger on high momentum μ
    - Hadron background reduction
  - Upgrading PHENIX for this purpose



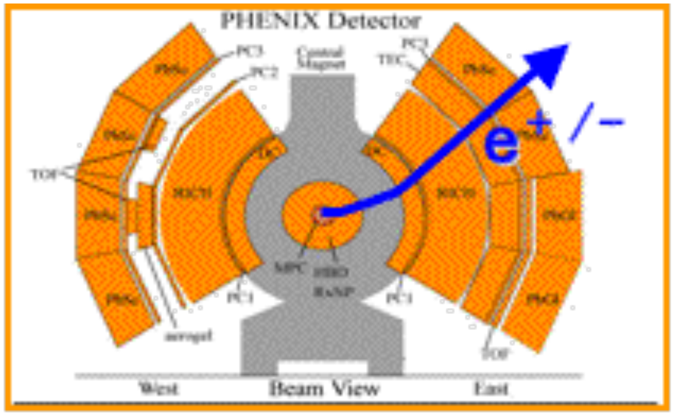


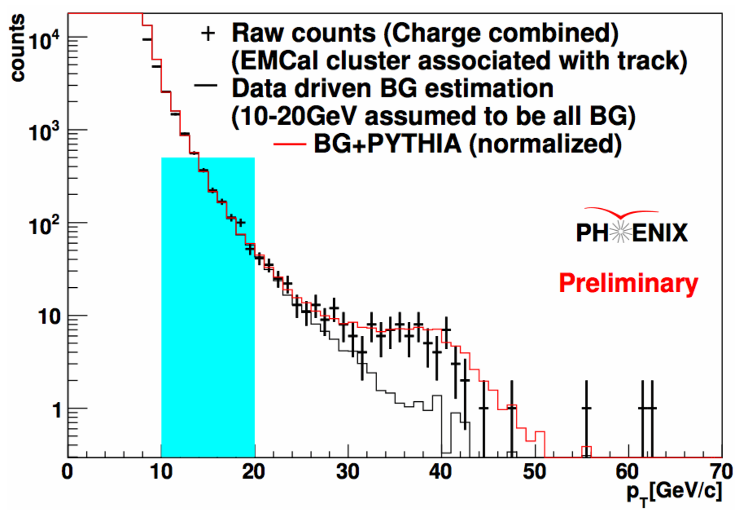


Present trigger threshold

First Results ($W^{+/-} \rightarrow e^{+/-}$)

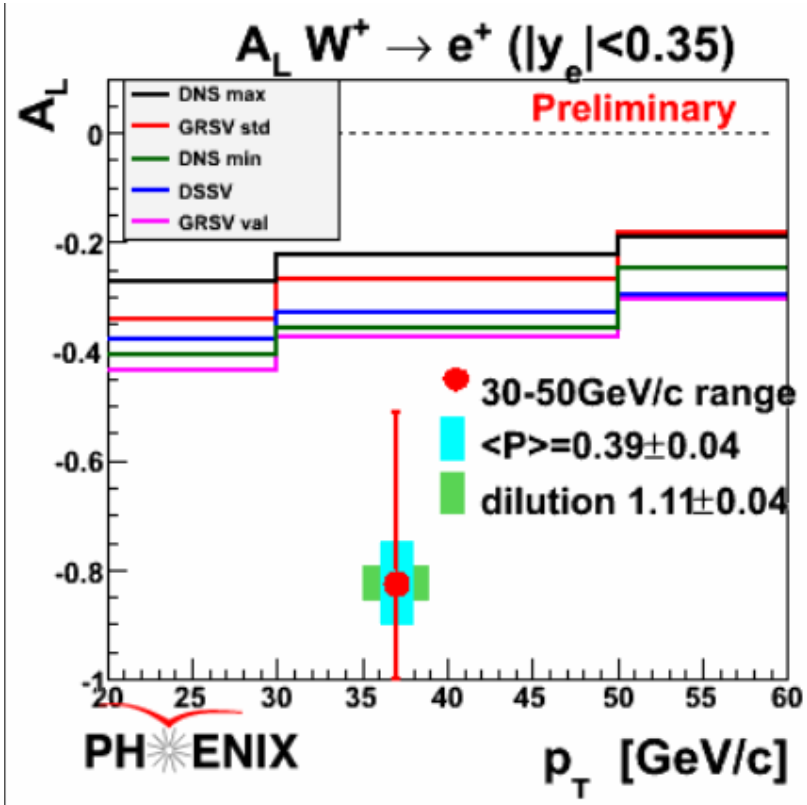
- Run9 was first 500 GeV run
  - P=40%, L=~10 pb^{-1}
  - First measurement of $W \rightarrow e$ for $|\eta|<0.35$
- EMCal:
  - High energy trigger
    - Reduces hadron contamination
- DC/PC
  - Charge sign determination
- Background
  - γ conversions and hadrons.
  - Normalized to yield in p_T=10-20 GeV

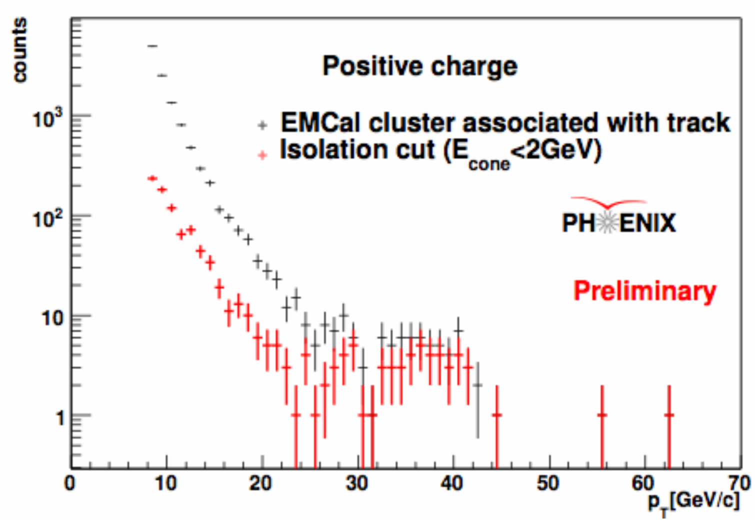


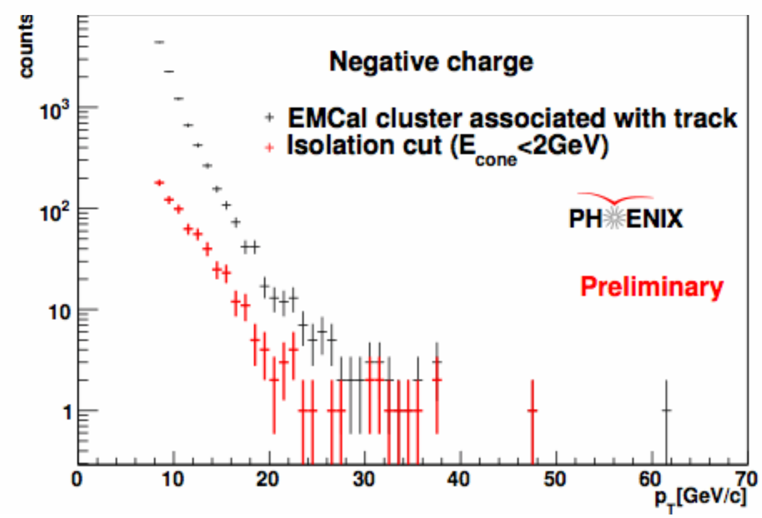


Measuring A_L

- For asymmetry, use additional isolation cut
  - Background reduced
- Non-zero asymmetry found
- Agrees within large statistical uncertainty
- Not corrected for Z, DY
- In future, VTX will allow better background determination





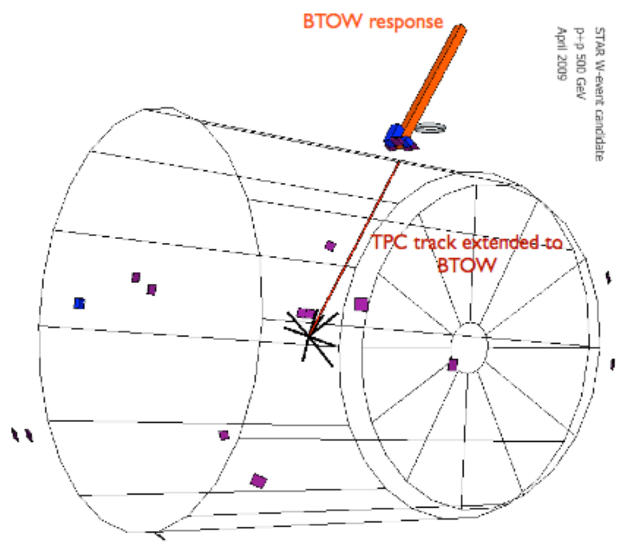


STAR $W^{+/-} \to e^{+/-} + \nu$ Measurements

- W->e+v signal event
- QCD background event

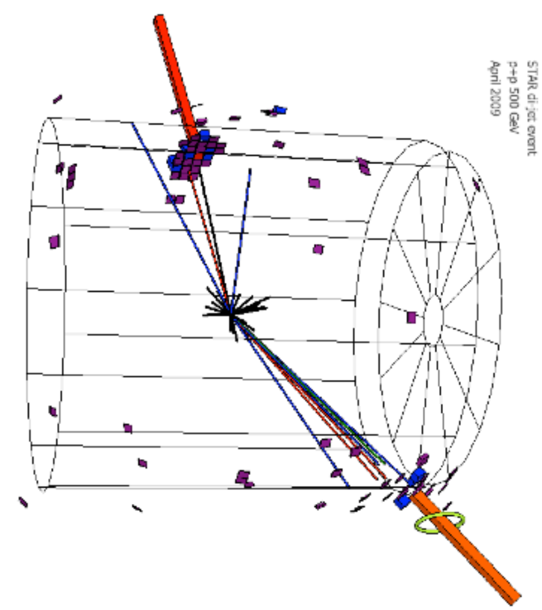
□ Event display (W event candidate) and detector signature

We found ~600 of those kinds of events!



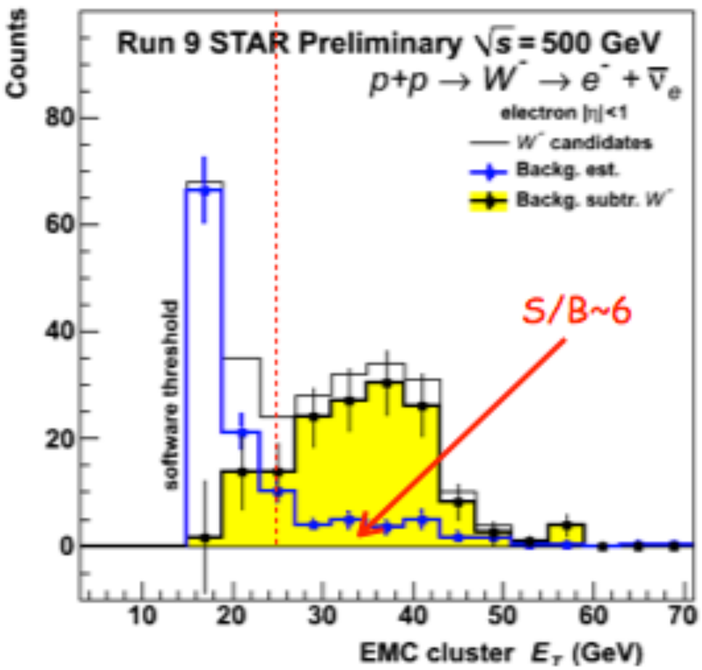
□ Event display (Di-Jet event candidate) and detector signature

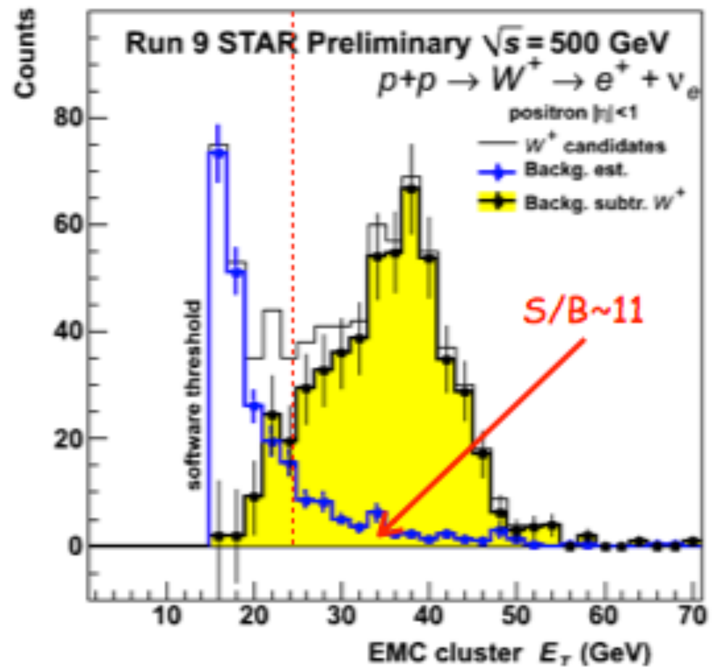
We recorded and rejected ~1.5M of those kinds of events!



STAR $W^{+/-}$ Results

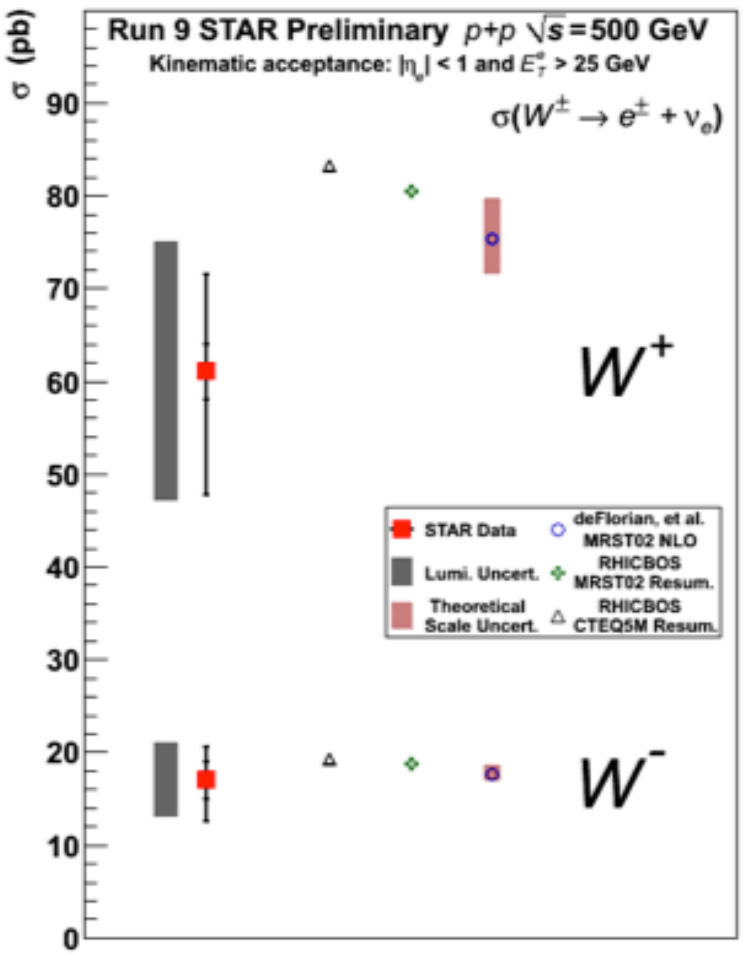
- High pT electrons





$W^{+/-}$ Cross Sections

- Total W^+/W^- Cross-section results



	$W^- \to e^- + \bar{\nu}_e$	$W^+ \to e^+ + \nu_e$
N_W^{obs}	156	513
N_{back}	$25\ ^{+21}_{-7}$	$46\ ^{+36}_{-11}$
ϵ_{total}	$0.56\ ^{+0.11}_{-0.09}$	$0.56\ ^{+0.12}_{-0.09}$
$\int Ldt\ (\mathrm{pb}^{-1})$	13.7 ± 3.2	13.7 ± 3.2

STAR Preliminary Run 9 (p+p √s=500 GeV)

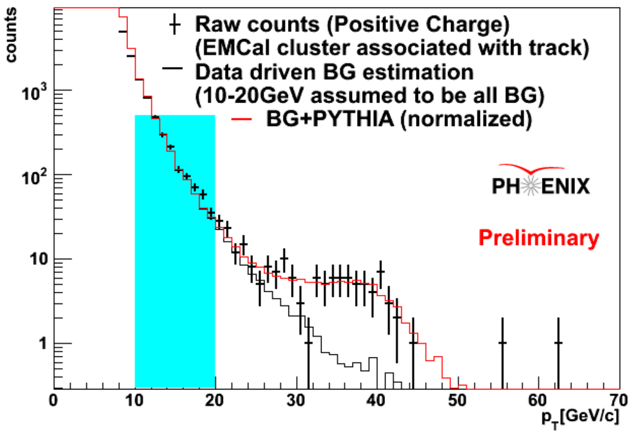
$$\sigma_{W^+ \to e^+ + \nu} = 61 \pm 3\ (\mathrm{stat.})\ ^{+10}_{-13}\ (\mathrm{syst.}) \pm 14\ (\mathrm{lumi.})\ \mathrm{pb}$$

$$\sigma_{W^- \to e^- + \bar{\nu}} = 17 \pm 2\ (\mathrm{stat.})\ ^{+3}_{-4}\ (\mathrm{syst.}) \pm 4\ (\mathrm{lumi.})\ \mathrm{pb}$$

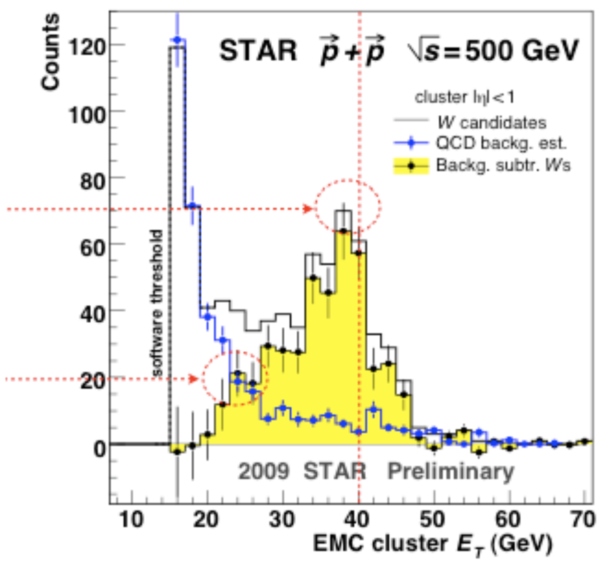
- Reasonable agreement between measured and theory evaluated cross-sections within uncertainties!

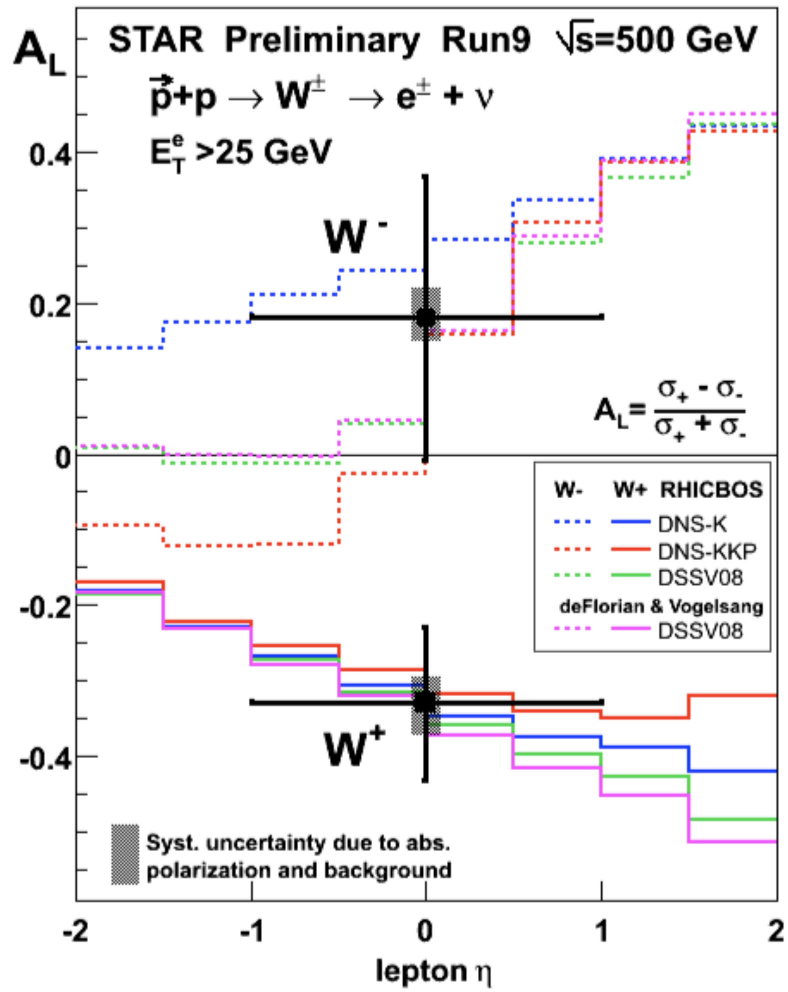
Mini Summary

First W± Measurements from Run9 500 pp!

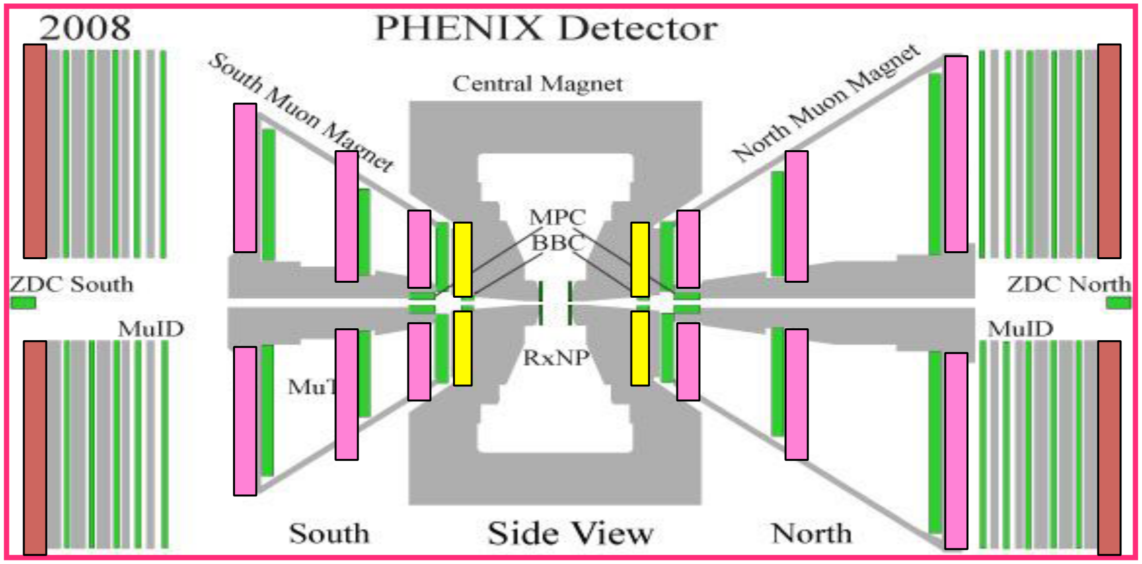


J. Seele (MIT): DNP 2009





$W^{+/-} \rightarrow \mu^{+/-}$



- Trigger upgrade:
  - MuTrig
    - Uses fraction of signal in Muon Tracker
    - Tested in Run10
  - RPC 3
    - Fast timing
    - North commisioned in Run10
    - South will be installed this summer

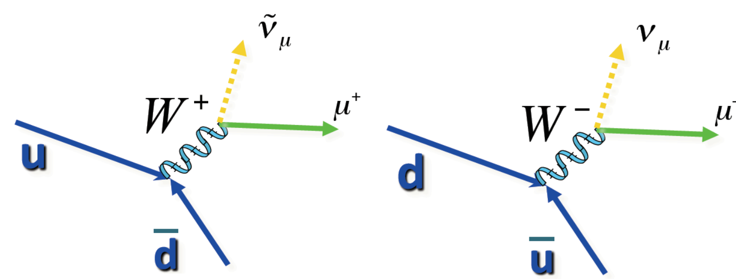
- Background Reduction
  - Absorber
    - Reduce background hadrons by order of magnitude
    - Will be installed in both arms this summer

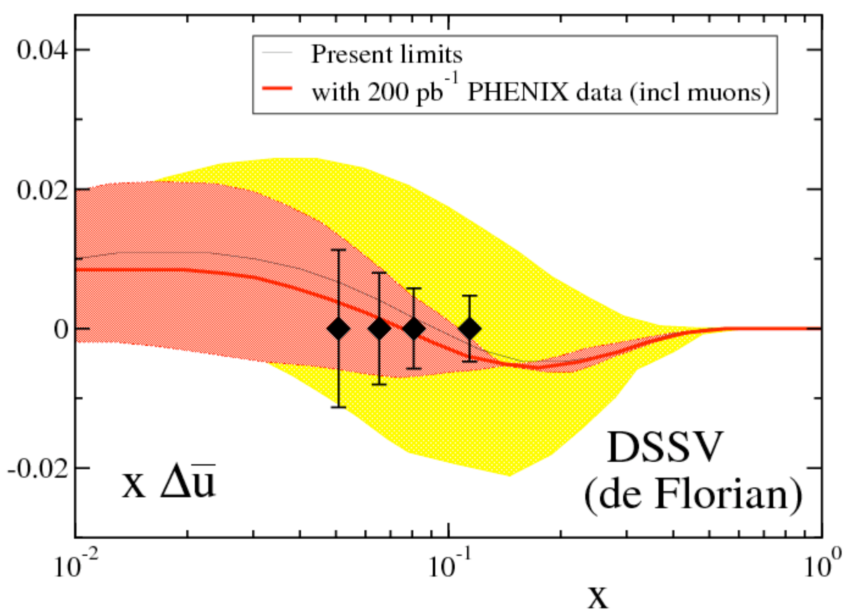
Δq and $\Delta \bar{q}$ through $W^{\pm}$ decay

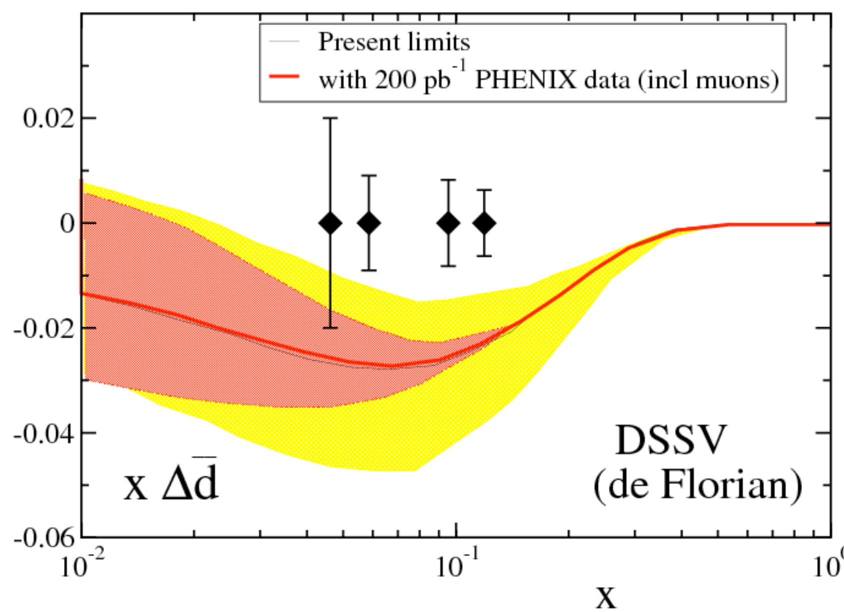
(DOE Milestone HP8, 2013)

$$A_L^{W+} = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}} \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$A_L^{W+}: \ \frac{\Delta u}{u} \text{ and } \frac{\Delta\bar{d}}{\bar{d}}. \qquad A_L^{W-}: \ \frac{\Delta d}{d} \text{ and } \frac{\Delta\bar{u}}{\bar{u}}.$$



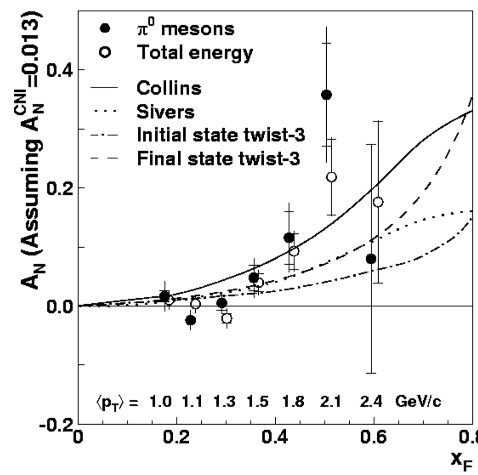




Part II: Transverse Spin Physics Program

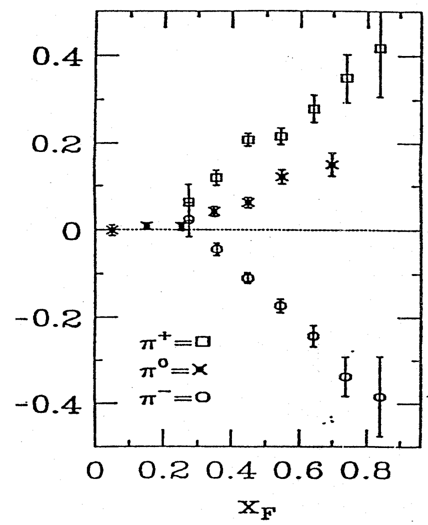
Large Transverse Single Spin Asymmetry (SSA) in forward meson production persists up to RHIC energy.

RHIC 20,000 GeV beam



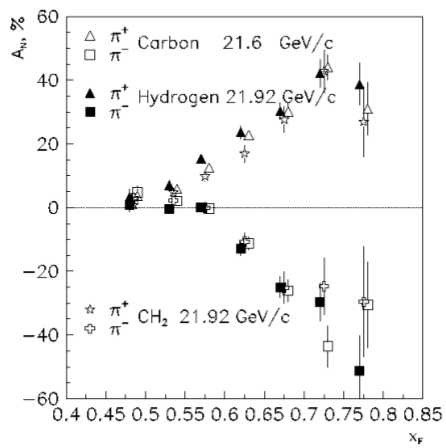
PRL (2004)

FNAL 200 GeV beam



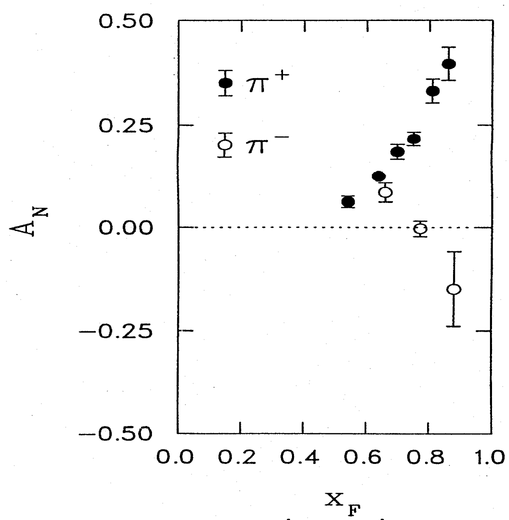
PLB261, 201 (1991)
PLB264, 462 (1991)

AGS 22 GeV beam

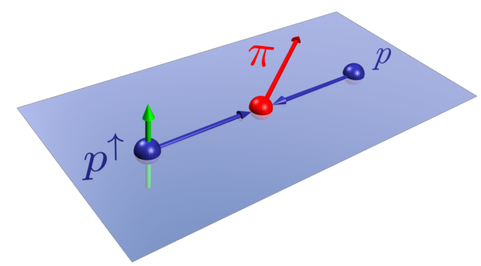


PRD65, 092008 (2002)

ZGS 12 GeV beam



PRL36, 929 (1976)

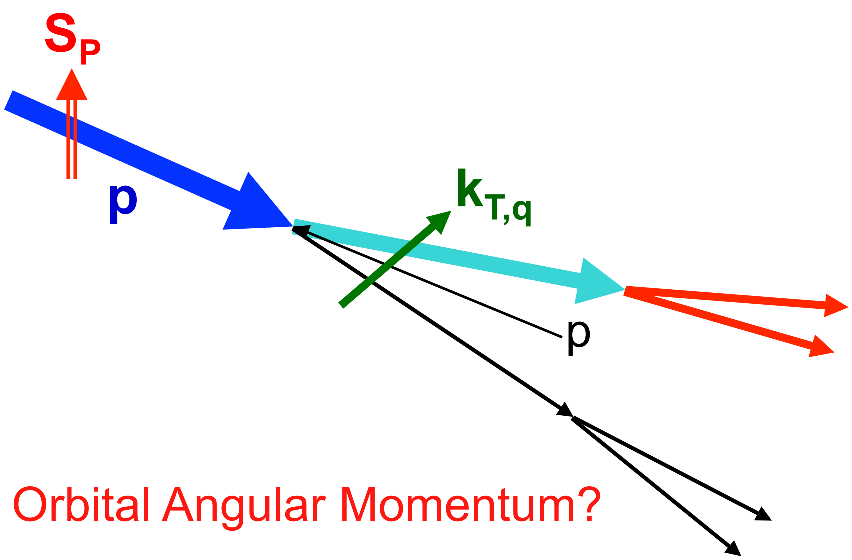


Non-Perturbative cross section → Perturbative cross section

Possible Mechanisms …

Sivers mechanism: Correlation between nucleon spin and parton k_T

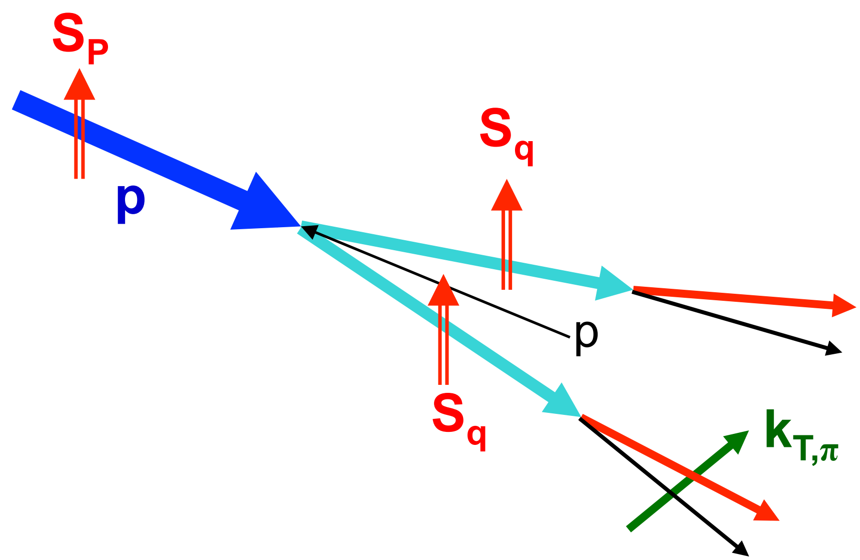
Phys Rev D41 (1990) 83; 43 (1991) 261



Orbital Angular Momentum?

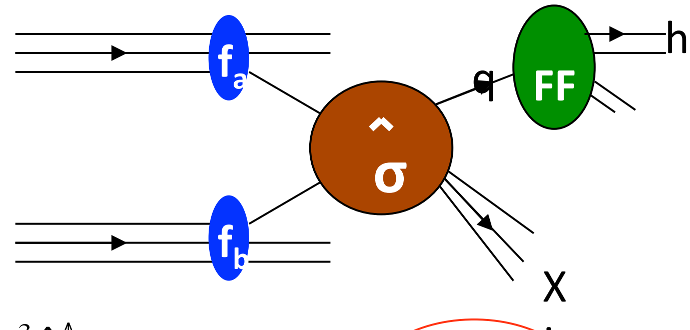
Collins mechanism: Transversity (quark polarization) * asymmetry in the jet fragmentation

Nucl Phys B396 (1993) 161



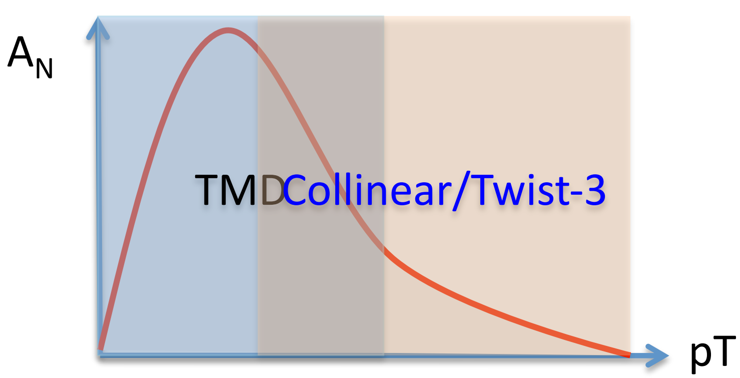
Theory: K_T vs Collinear Factorization

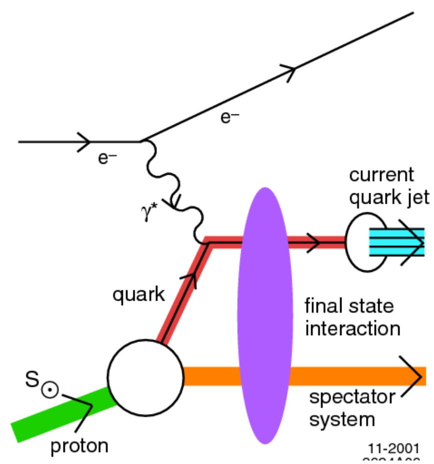
- Tran. Mom. Dep. Funs
  - Sivers Fun
  - Collins Fun

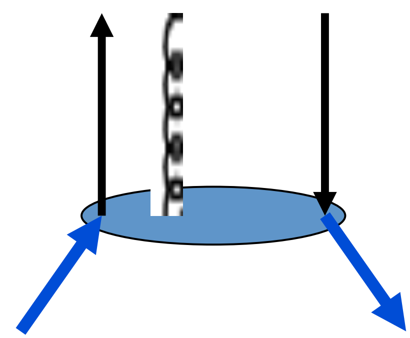


$$\frac{d^3\sigma^{\uparrow}\left(pp^{\uparrow} \to h + X\right)}{dx_1 dx_2 dz} \propto q_i^{\uparrow}(x_1, k_{q,T}) \cdot q_j(x_2) \times \frac{d^3\hat{\sigma}^{\uparrow}(q_i q_j \to q_k q_l)}{dx_1 dx_2} \times FF_{q_{k,l}}(z, p_{h,T})$$

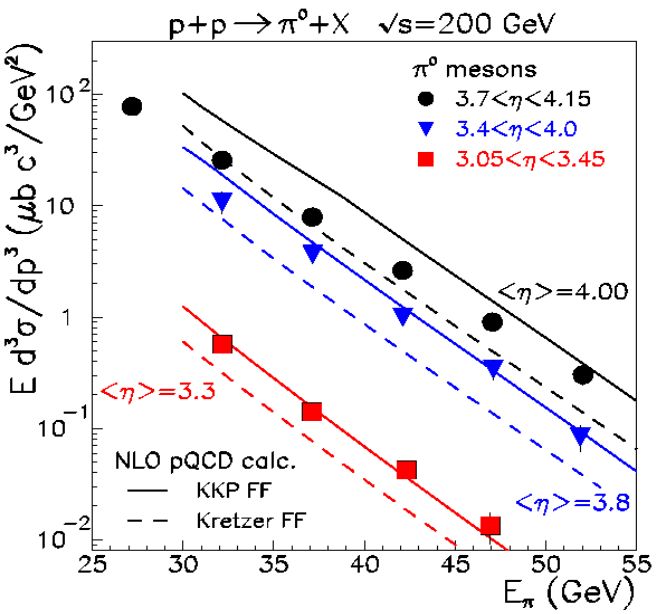
- Twist-3 collinear
  - Quark-gluon correl.
  - Gluon-gluon correl.







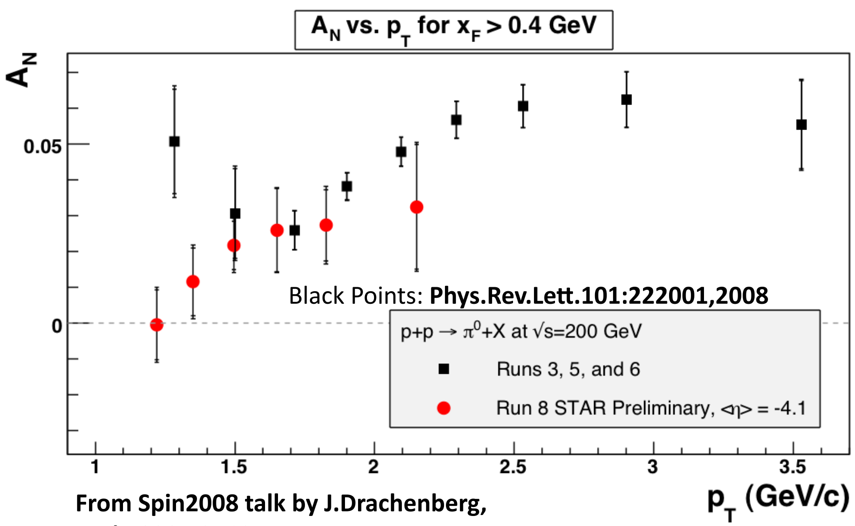
Forward π^0 Single Spin Asymmetry(SSA)



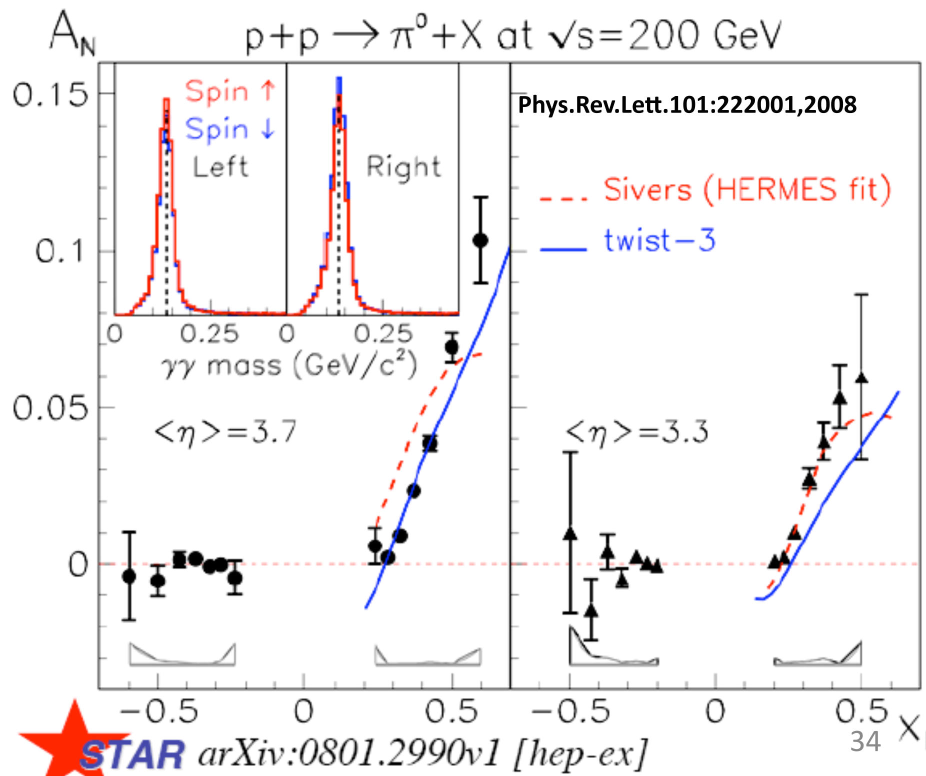
Phys. Rev. Lett. 97 (2006) 152302

At √s=200GeV, π^0 cross-section measured by STAR FPD is consistent with the NLO pQCD calculation. Results at <η>=3.3 and <η>=3.8 have been included in the DSS global pion fragmentation function analysis. *(Phys.Rev.D75(2007) 114010)*

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \cong \frac{1}{P}\frac{\sqrt{N^\uparrow S^\downarrow} - \sqrt{S^\uparrow N^\downarrow}}{\sqrt{N^\uparrow S^\downarrow} + \sqrt{S^\uparrow N^\downarrow}}$$

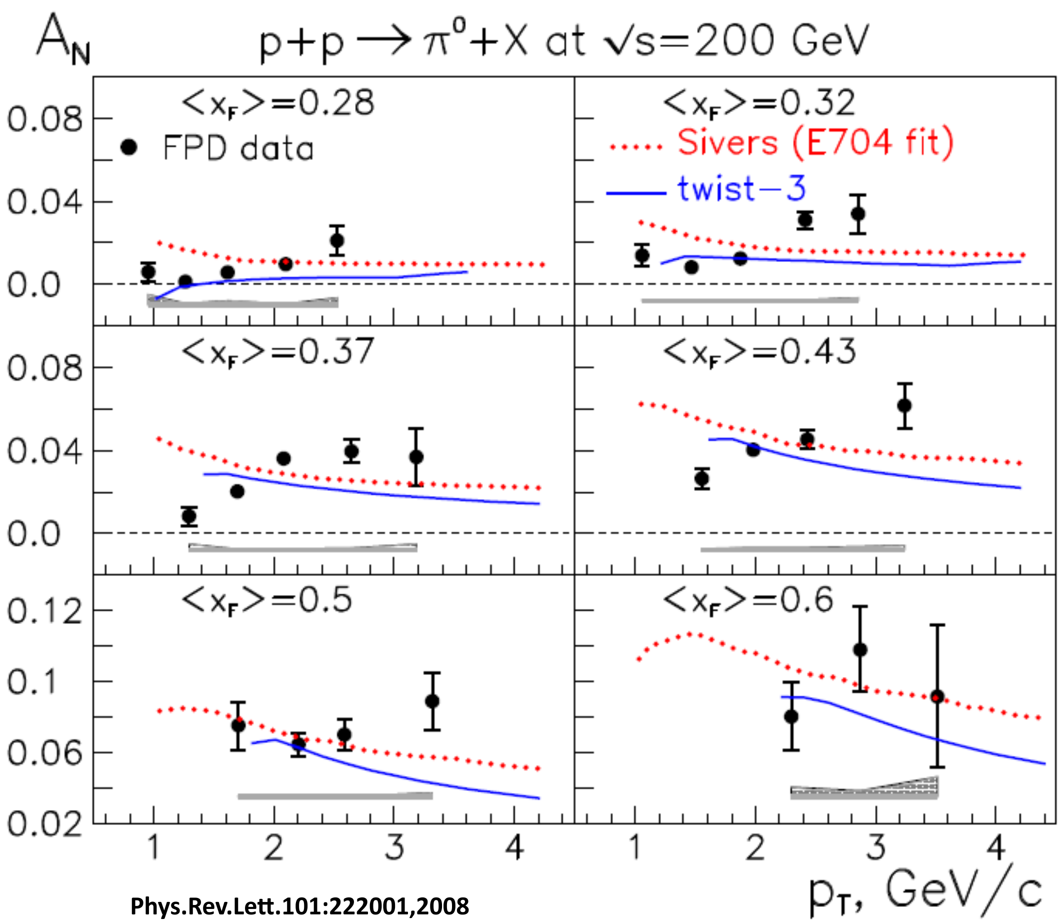


From Spin2008 talk by J.Drachenberg, arXiv:0901.2763



p_T Dependence of A_N

For Fixed X_F, the asymmetry A_N does not fall with p_T as predicted by models and perhaps expected on very general grounds.



Phys.Rev.Lett.101:222001,2008

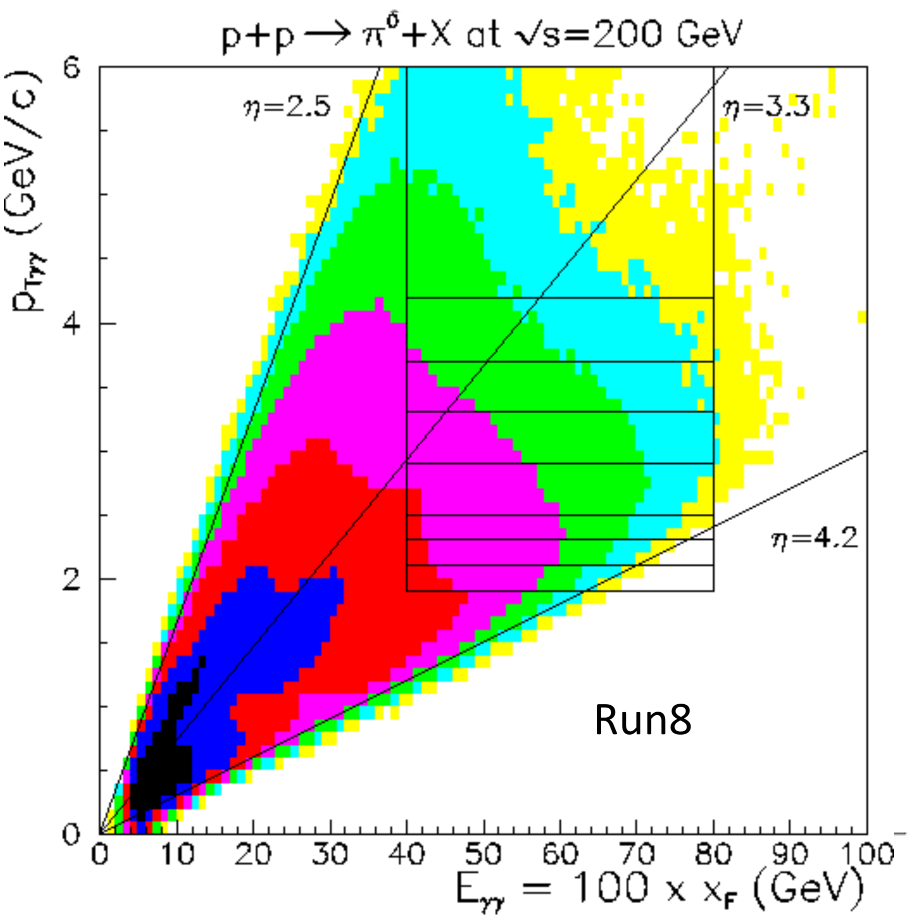
U. D'Alesio, F. Murgia, Phys. Rev. D **70**, 074009 (2004).
J. Qiu, G. Sterman, Phys. Rev. D **59**, 014004 (1998).

✓ NLO PQCD **<u>does describe</u>** the size and shape of this forward π^0 cross section.

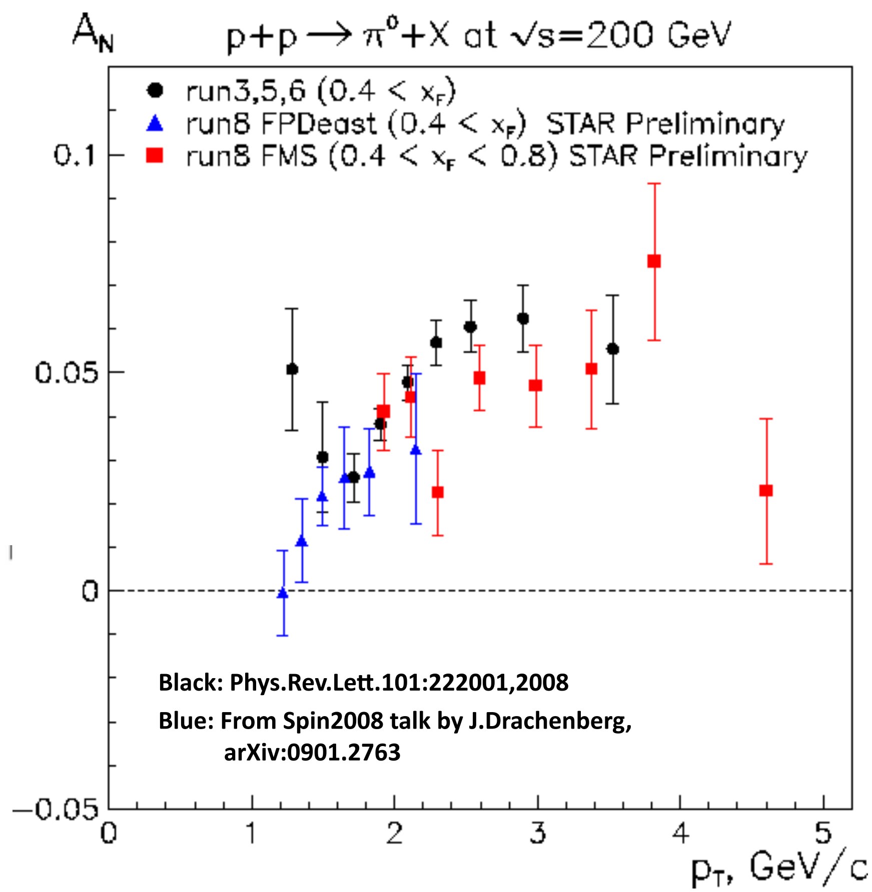
✓ Model calculations (Sivers, Collins or twist-3) **<u>can explain</u>** the X_F dependence of A_N.

X Flat or increasing dependence of A_N on p_T **<u>is very difficult to understand</u>** within any of these frameworks!

Latest Run 8 REsults: p_T-dependence of π^0 A_N



• Large solid angle of FMS allows simultaneous mapping of x_F vs p_T with greater statistics

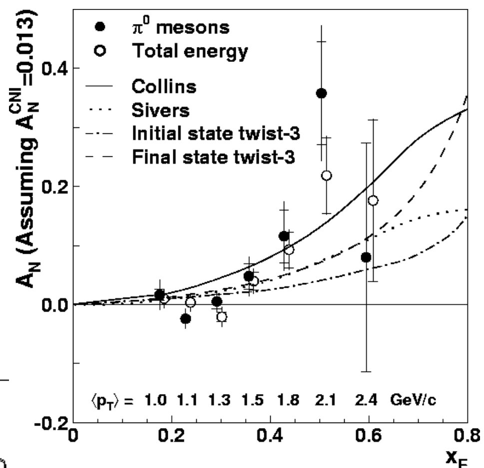


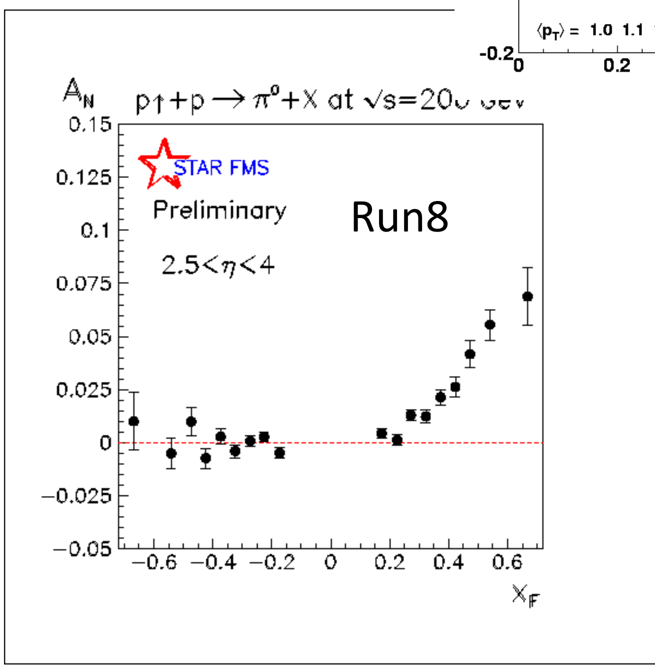
F.o.M. was smaller in run8 than in run6

→ More statistics needed

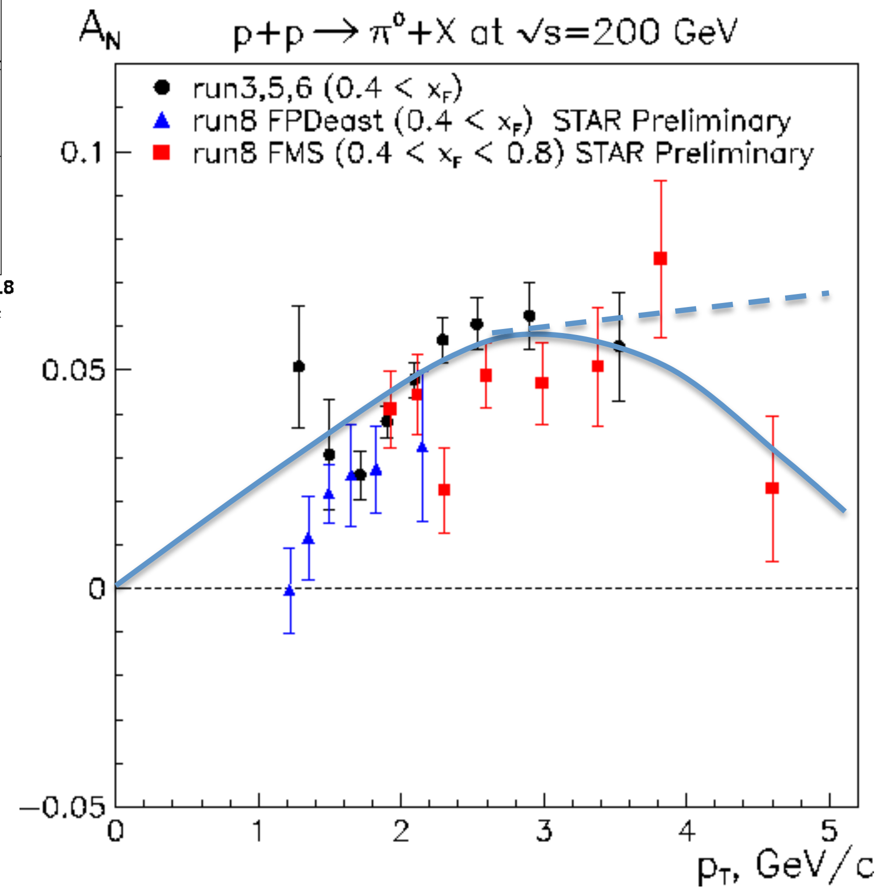
A_N P_T Dependence Remains as a Challenge

A_N vs x_F





A_N vs p_T



Pattern from Previous Transverse SSA Measurements of Forward Pion / Eta Production with High Energy Polarized Proton / Antiproton Beams

1. Majority valence quark in polarized proton.
   - u for proton
   - $\bar{u}$ for antiproton.

2. Minority valence quark
   - d for proton
   - $\bar{d}$ for antiproton.

3. Pion containing only majority quarks: **large positive AN.**

4. Pion containing only minority quarks: **large negative A_N.**

5. Pion containing both majority and minority quarks: **intermediate positive A_N.**

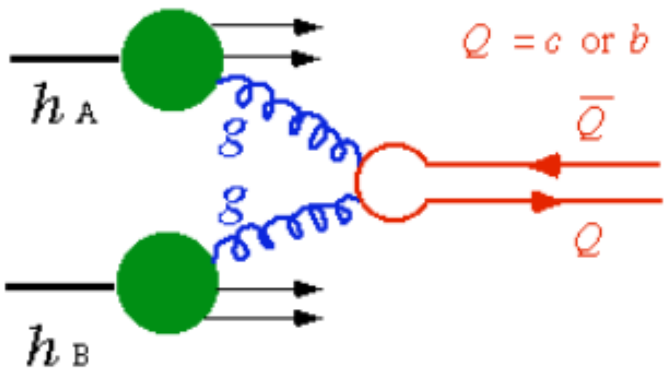
Polarized Beam	Observed Meson	Exp.	$\langle s \rangle$	$\langle p_T \rangle$	$\sim X_F$	$\sim A_N$	Comment on A_N
Proton uud	$\pi^+ : \quad u\bar{d}$	E 704 BRAHMS	19.4 GeV 62.4 GeV	~ 1 GeV/c ~ 1 GeV/c	0.5 - 0.7 0.4 – 0.6	+0.15 to +0.25 +0.2 to +0.25	Large Positive
Proton uud	$\pi^0 :$ $\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	E 704 **STAR**	19.4 GeV **200 GeV**	~ 1 GeV/c **~ 2.5 GeV/c**	0.5 - 0.7 **0.5 - .065**	+0.10 to +0.15 +0.06 to + 0.1	Medium Positive
Proton uud	$\pi^- : \quad d\bar{u}$	E 704 BRAHMS	19.4 GeV 62.4 GeV	~ 1 GeV/c ~ 1 GeV/c	0.5 - 0.7 0.4 – 0.6	-0.10 to -0.25 -0.25 to -0.3	Large Negative
Anti Proton $\bar{u}\,\bar{u}\,\bar{d}$	$\pi^- : \quad d\bar{u}$	E 704	19.4 GeV	~ 1 GeV/c	0.5 - 0.7	0.10 to +0.20	Large Positive
Anti Proton $\bar{u}\,\bar{u}\,\bar{d}$	$\pi^0 :$ $\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	E 704	19.4 GeV	~ 1 GeV/c	0.5 - 0.7	0.05 to +0.10	Medium Positive
Anti Proton $\bar{u}\,\bar{u}\,\bar{d}$	$\pi^+ : \quad u\bar{d}$	E 704	19.4 GeV	~ 1 GeV/c	0.5 - 0.7	-0.10 to -0.25	Large Negative
Proton uud	$\eta :$ $\frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} - s\bar{s})$	E 704	19.4 GeV	~ 1 GeV/c	0.50 - 0.60	0.25 ± .09	Possibly Larger than for π^0

PENNSTATE
1855

New Channels: Heavy Quark

D meson A_N

- Production dominated by gluon-gluon fusion at RHIC energy



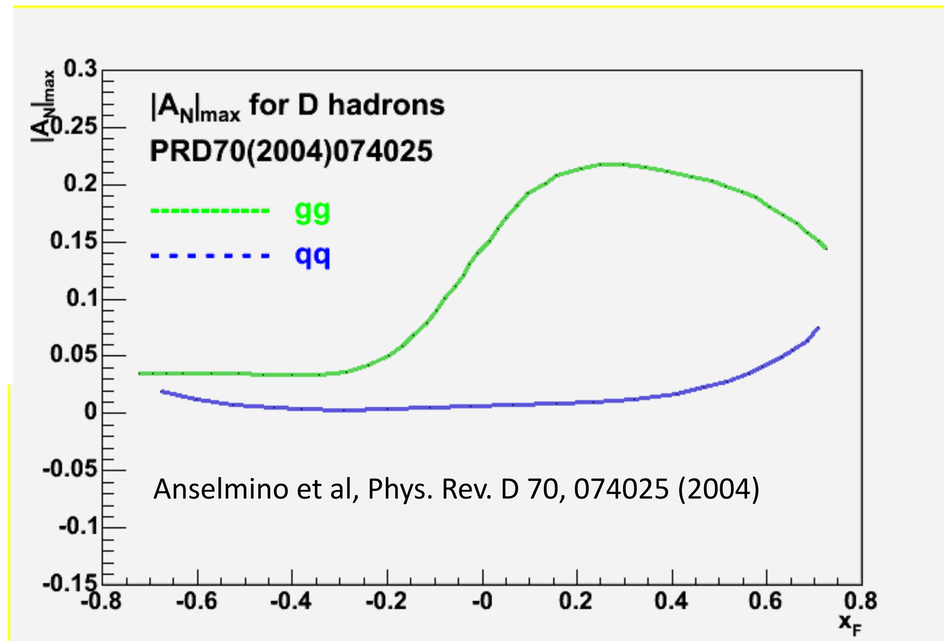
- Gluon transversity zero

→Asymmetry cannot originate from Transversity x Collins

- Sensitive to gluon Sivers effect (poorly constrained by pol DIS)

Theoretical prediction:

$p^{\uparrow}p \rightarrow DX$



Theoretical Models: J/Psi SSA

can be measured @RHIC/PHENIX!

- Singlet vs Octet channels

F. Yuan (2008)

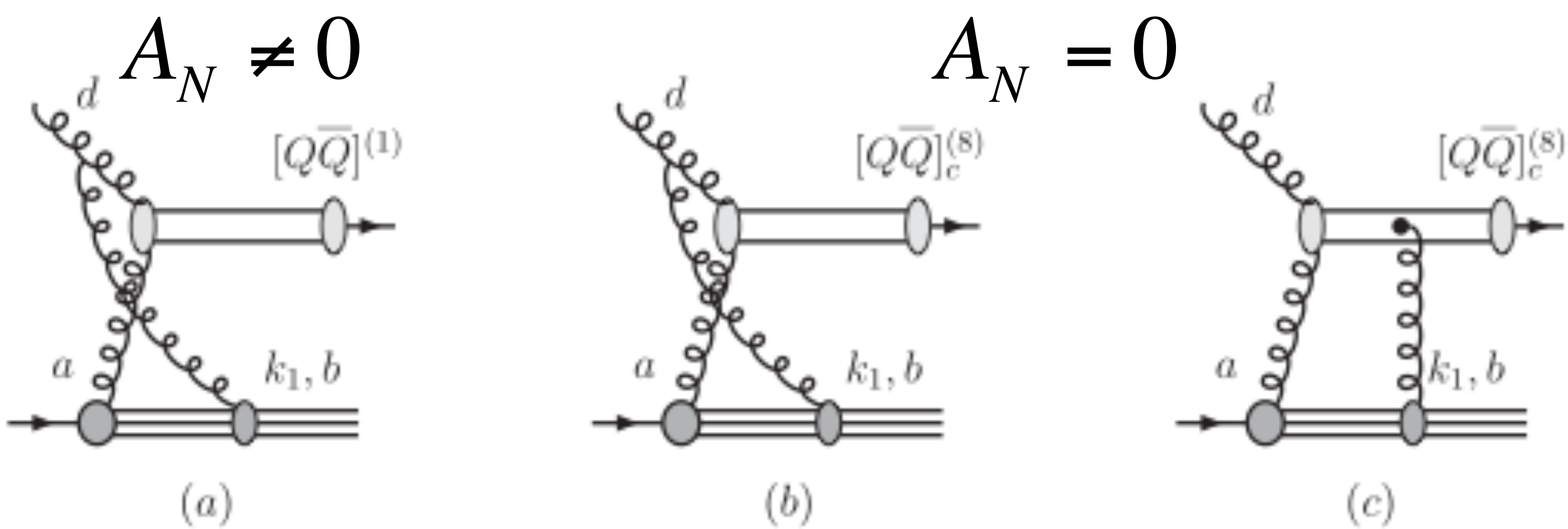
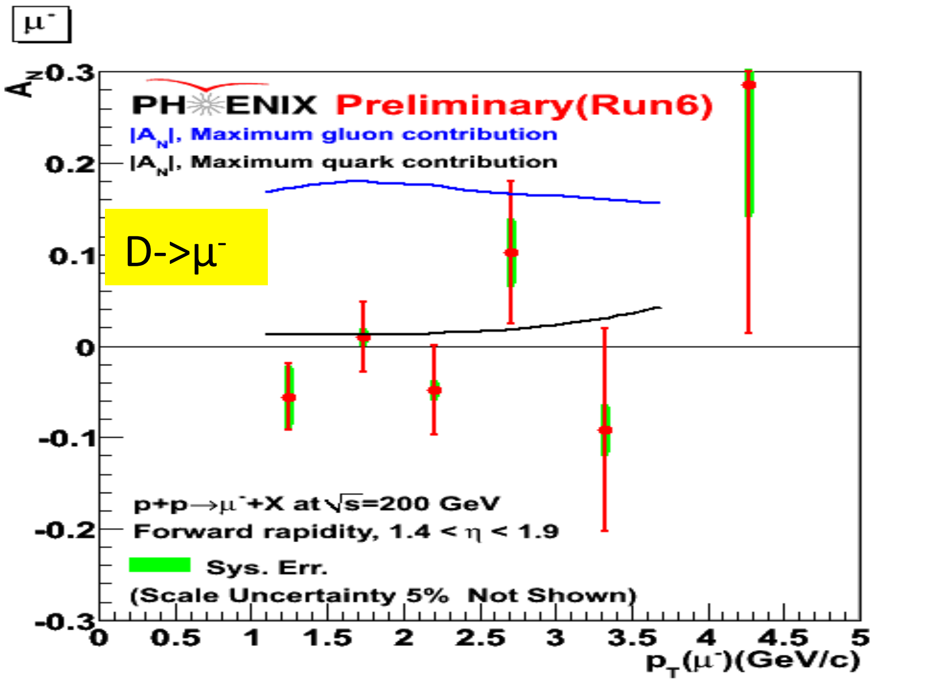
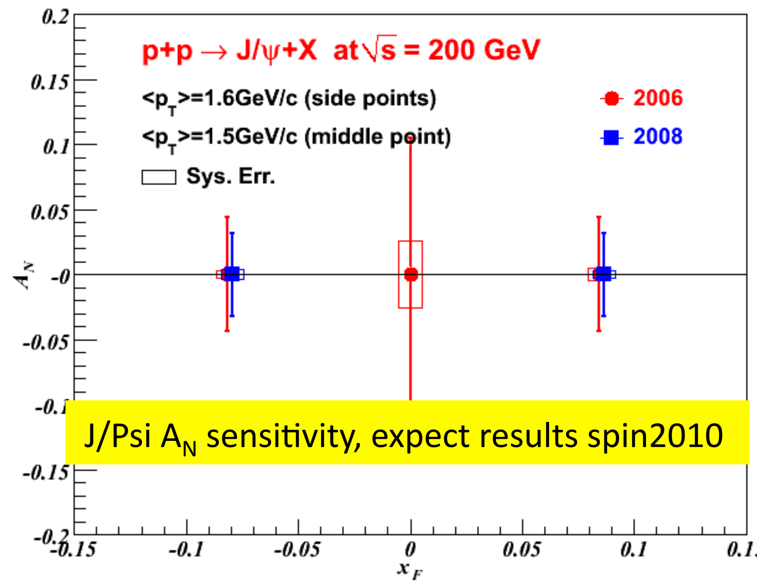


FIG. 4. Only initial state interactions contribute to the SSA in hadron-production process in the color-singlet model (a). On the other hand, the SSA vanishes in the color-octet model because of the cancellation between initial (b) and final (c) state interactions.

Latest Results of Heavy Quark SSA

Probing Gluon's Sivers Asymmetry



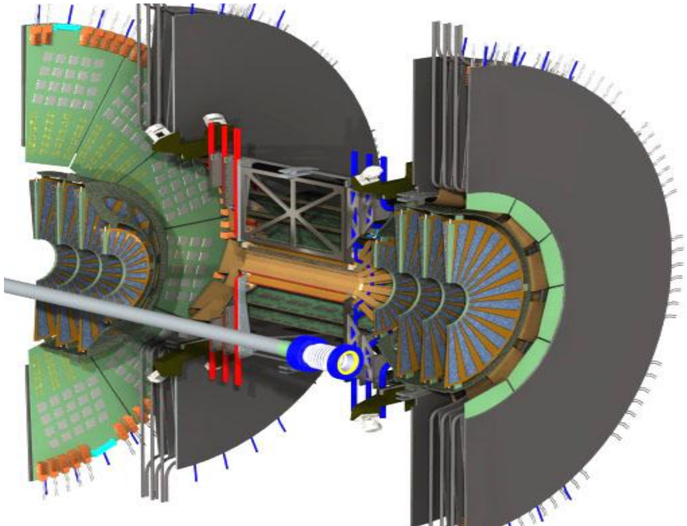


- Gluon's Sivers fun was not constrained well by DIS data
- PHENIX Charm data exclude the maximum gluon Sivers Fun (Anselmino et al, 06)
- Much improved results expected soon (Run6+Run8)

Future Opportunity

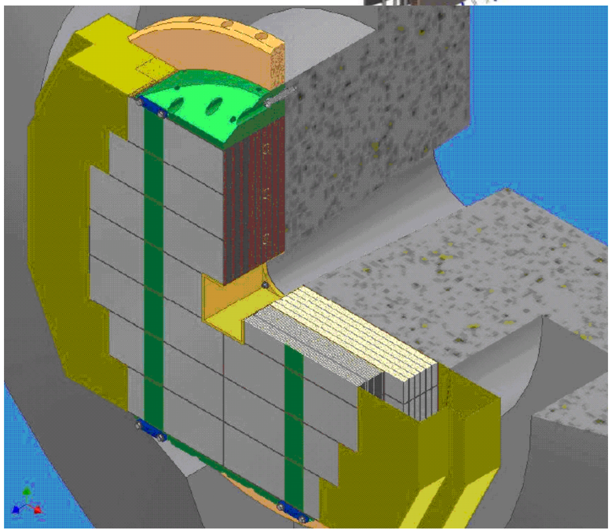
- Vertex Detectors (2011-2012)

  Large acceptance precision tracking
  - Drell-Yan
  - Heavy quarks
  - Jets



- Forward Calorimeter(2012-2013?)

  Proposed PHENIX Upgrade (1 < eta < 3)
  - A_N π^0, Direct γ, γ-Jet
  - Collins-type measurements

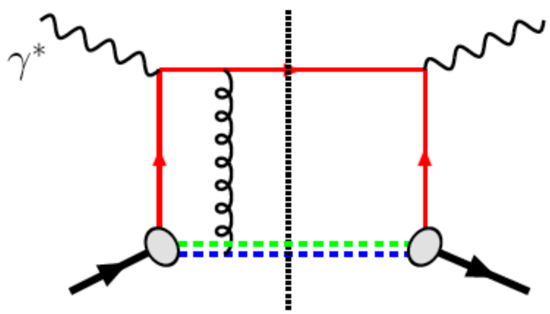


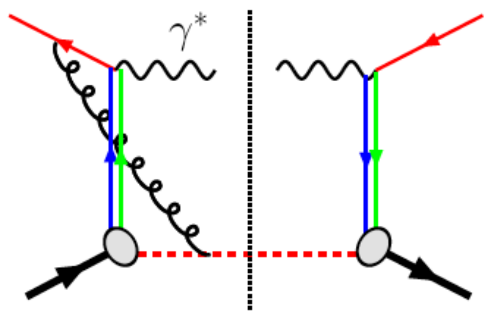
Attractive vs Repulsive "Sivers" Effects

Unique Prediction of Gauge Theory !

DIS: attractive

Drell-Yan: repulsive

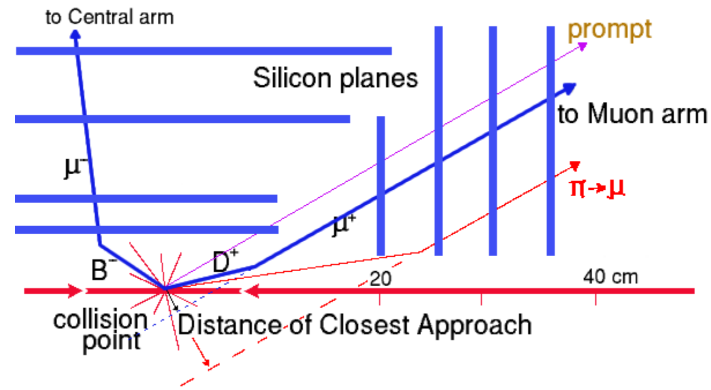


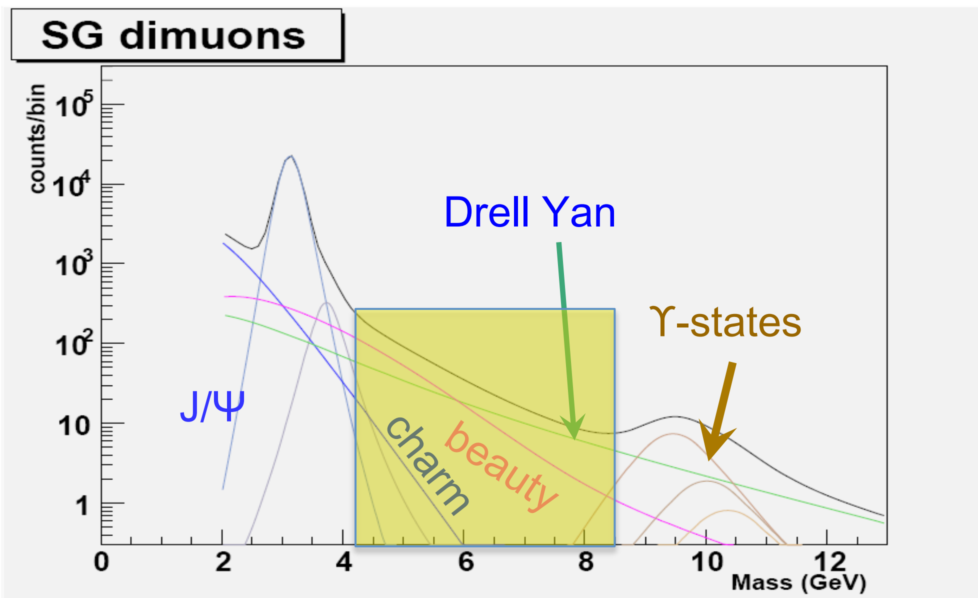


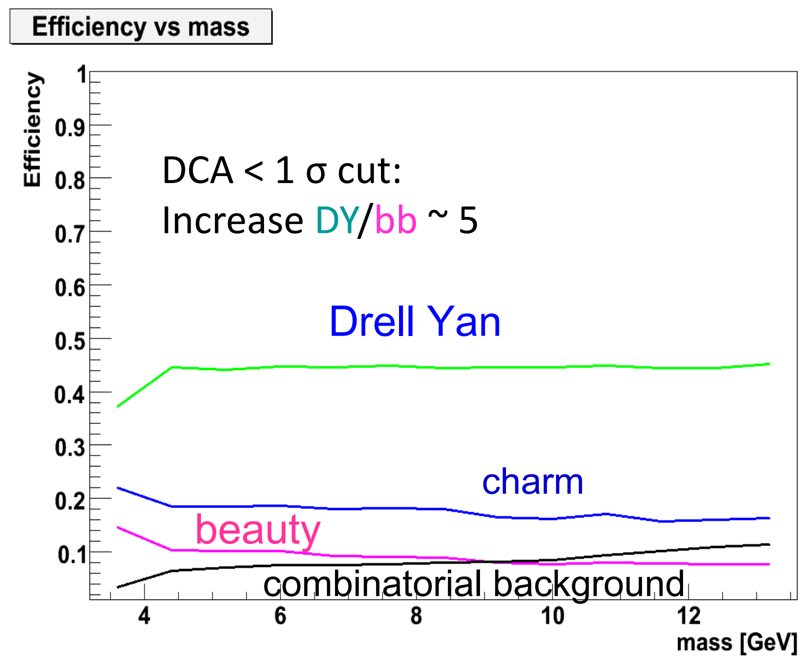
$$\boxed{\mathrm{Sivers}|_{\mathrm{DIS}} = -\mathrm{Sivers}|_{\mathrm{DY}}}$$

Critical Role of VTX/FVTX for Drell-Yan

- Tracking muons with MuTr+FVTX
  - Prompt muons from DY
  - Displaced tracks from π/K and heavy quark decays





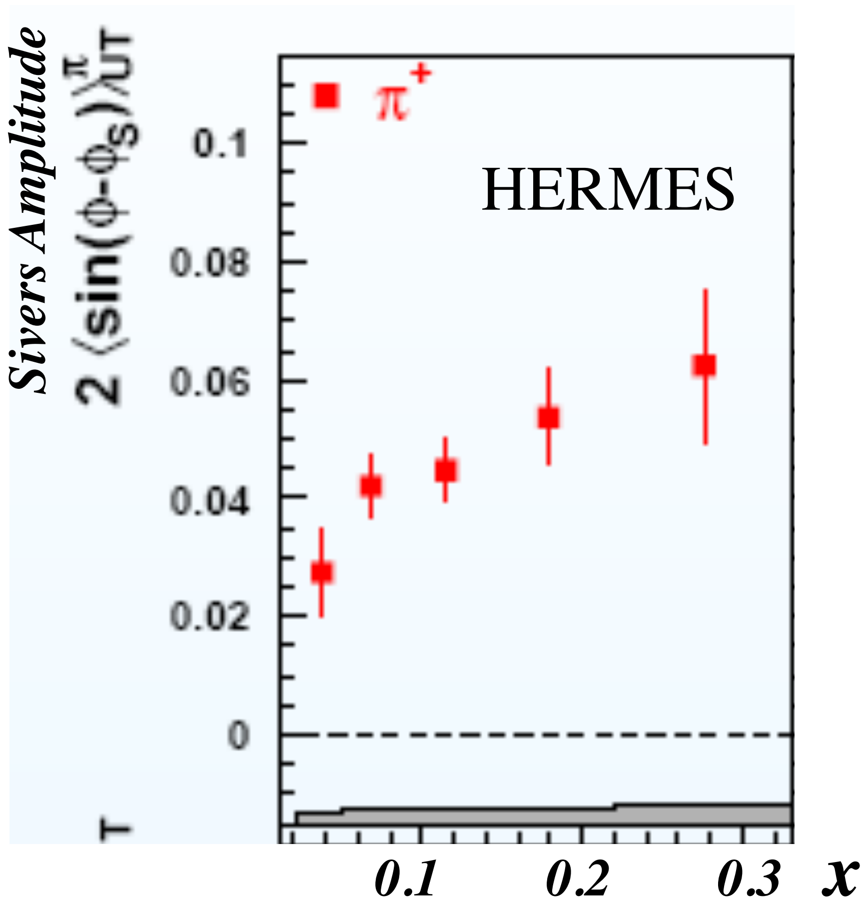


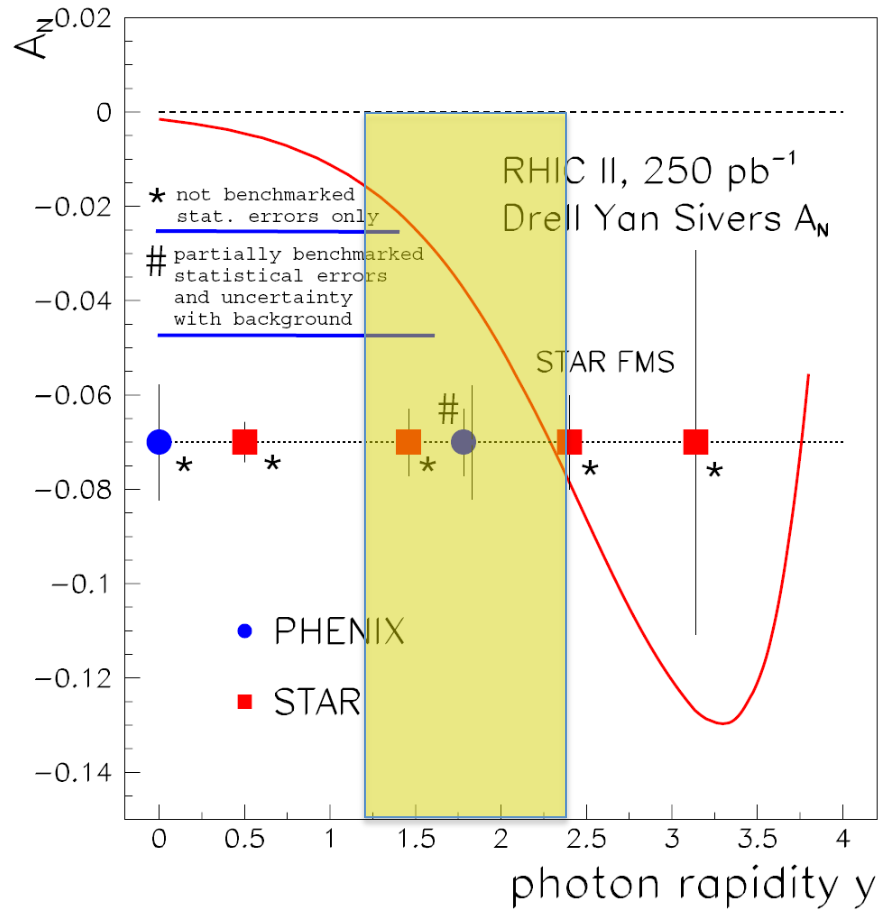
➔DY: 4 GeV < M < 9 GeV; B-background: use FVTX

Future Transverse Spin Physics: A_N (Drell-Yan ->$\mu^+\mu^-$)

"Transverse-Spin Drell-Yan Physics at RHIC" (http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf)

- Important test at RHIC of recent fundamental QCD predictions for the Sivers effect, demonstrating… attractive vs repulsive color charge forces

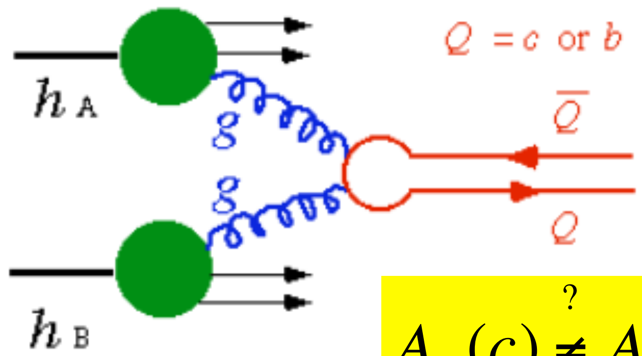




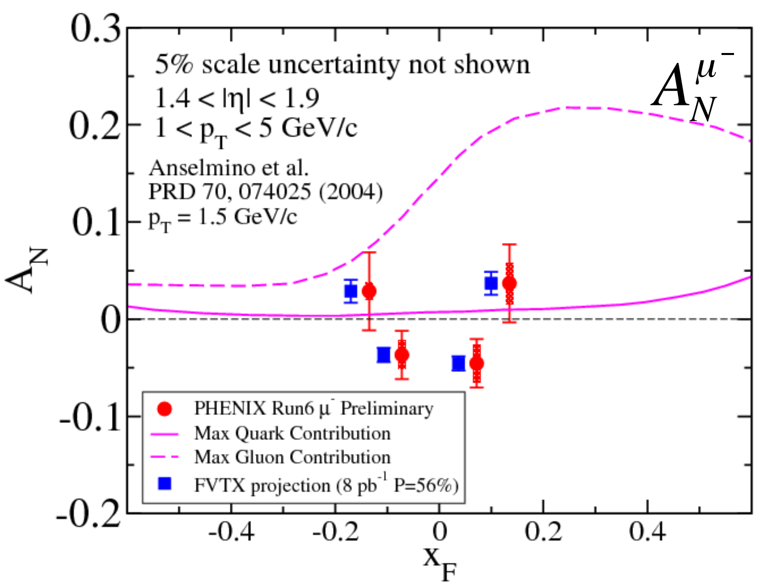
Charm SSA to Probe Gluon Sivers Distribution

D meson Single-Spin Asymmetry:

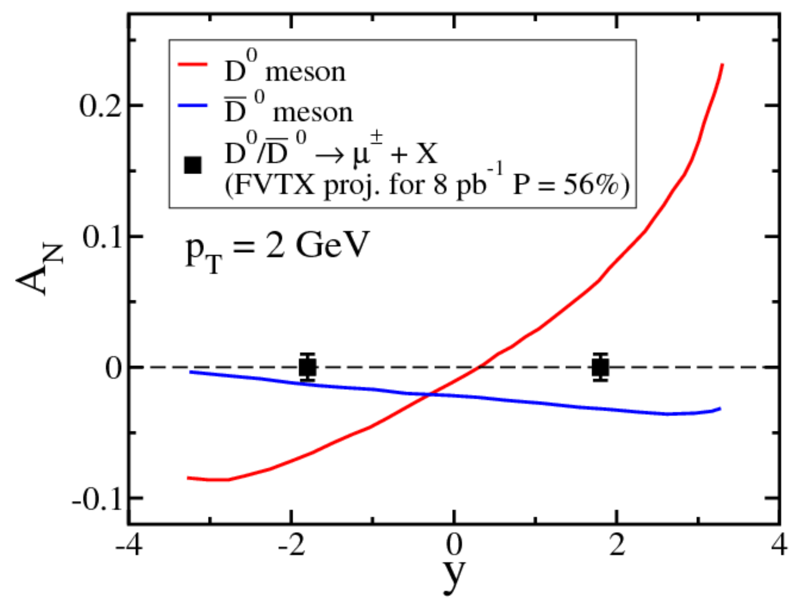
- Production dominated by gluon-gluon fusion
- Sensitive to gluon Sivers distribution
  - PHENIX-2006 data ruled out the max. gluon Sivers
  - Much improved results expected (Run2006+2008)



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



Kang, Qiu, Yuan, Vogelsang, Phys. Rev. D 78,114013(2008)



Transverse Physics

$W^{+/-}$ & Z^0 SSA @500GeV ?

Kang & Qiu PRL 103, 172001 (2009)

- Latest theoretical progress
  - Test time-reversal universality of Sivers functions with W/Z
  - Expect large asymmetry (from DIS fit)

- Flavor-identified Sivers Funs

- Expected Statistics @1fb^{-1} 500GeV
  - $W^{+/-} \rightarrow \mu^{+/-}$ ~20K
  - $Z^0 \rightarrow \mu^+\mu^-$ ~ 1K

$W^{+/-}$

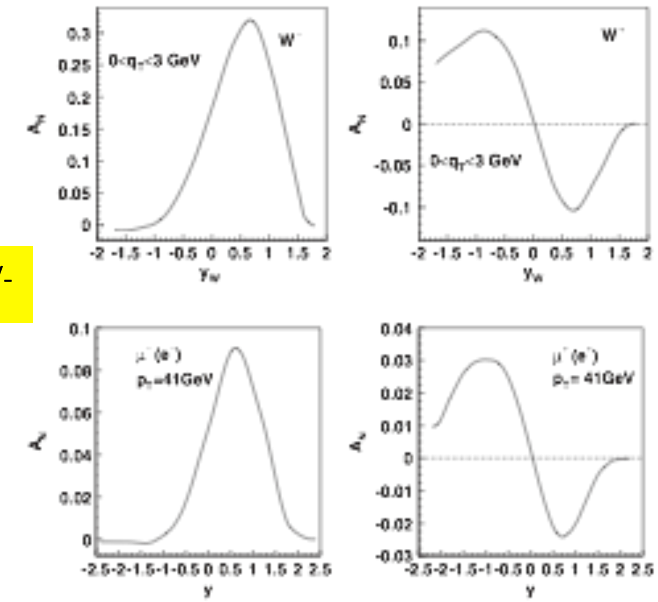


FIG. 3. A_N as a function of lepton rapidity.

$$W^{\pm}: \quad \delta A_N \approx \frac{1}{\sqrt{P^2 \cdot 2 \cdot N}}; \quad P = 0.6, \quad N = 6300(6900)$$
$$\approx 1.5\%(1.4\%)$$
$$Z^0: \quad \delta A_N \approx \frac{1}{\sqrt{P^2 \cdot 2 \cdot N}}; \quad P = 0.6, \quad N = 380$$
$$\approx 6.0\%$$

Z^0

Kang & Qiu arX 0912.1319

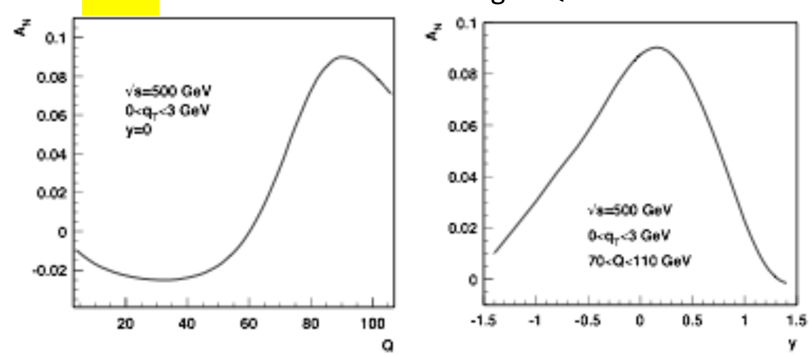
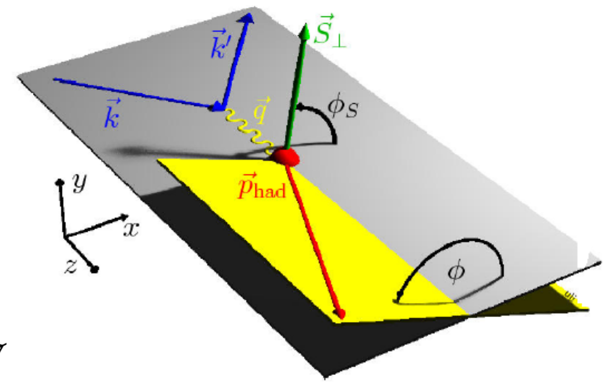
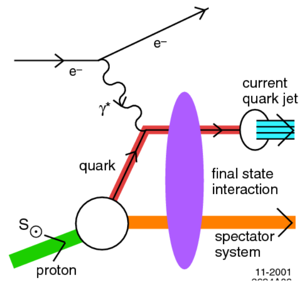


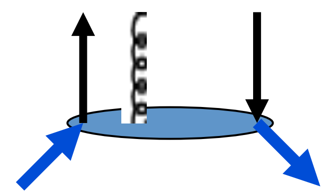
FIG. 3: Left: SSA of lepton pair production as a function of the pair's invariant mass Q. Right: SSA of lepton pair accumulated around Z^0 pole as a function of rapidity y.

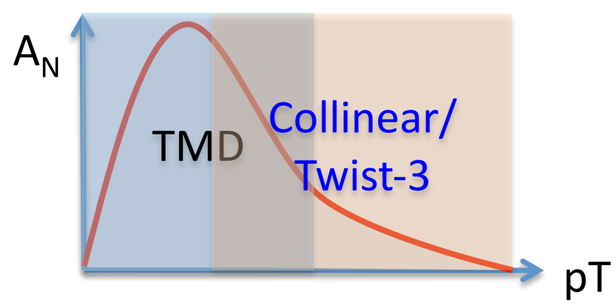
Renaissance of Transverse Spin Physics

- Recent experimental observation of non-Zero Sivers and Collins effects
  - HERMES, 05,09;   COMPASS, 05,09 ;   BELLE 06
- Very active/rapid theoretical progress
  - Spin-dependent TMD
    - Sivers 90; Colllins 93; Brodsky-Hwang-Schmidt, 02
  - Twist-3 quark-gluon correlations (coll.) in DIS
    - Efremov-Teryaev, 82, 84; Qiu-Sterman, 91,98
  - Twist-3 tri-gluon correlations in p+p
    - Kang-Qiu-Vogelsang-Yuan 08
  - Unified picture of TMD and Twist-3
    - Ji-Qiu-Vogelsang-Yuan 06; Yuan-Zhou, 09
- Opportunity for new study of QCD dynamics
  - Sivers Funs in DIS & DY
  - Flavor Dep. Sivers Fun & OAM
  - quark-gluon and tri-gluon correlation
- Future direction @RHIC-SPIN?
  - Large SSA observed at forward rapidity @RHIC
  - Open charm and beauty
  - Drell-Yan and Vector mesons
  - Light hadrons at forward rapidity





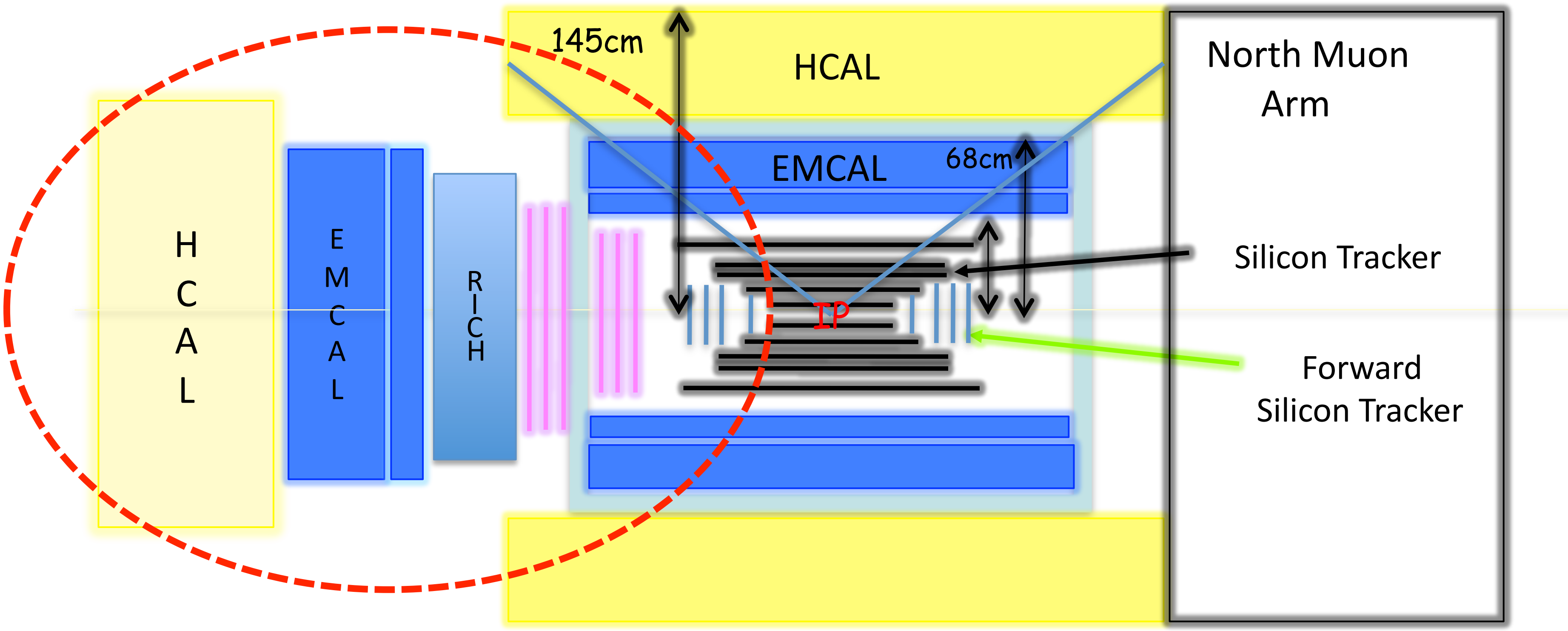




The Forward S-PHENIX Spectrometer (2016+x)

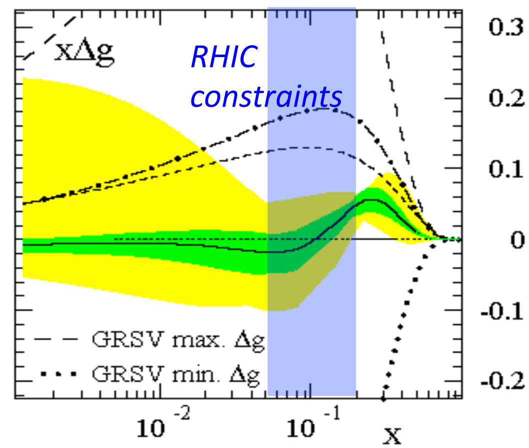
(Courtesy E. Aschenauer)

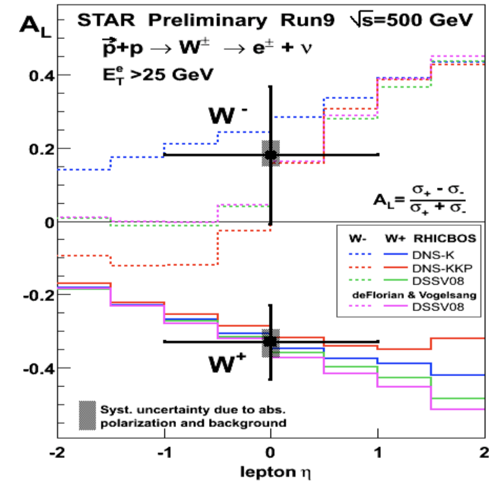
- o Acceptance: $-1 < \eta < 4$ and $-2.4 < \eta < -1.2$
- o Full jet capability: electromagnetic + hadronic calorimetery
- o Heavy flavor tagging, PID for : $1 < \eta < 4$
- o W-physics: a) reconstruct missing mass, b) access to hadronic final states
- o Opportunity to improve relative luminosity measurement ➔ access to asymmetries $< 10^{-3}$

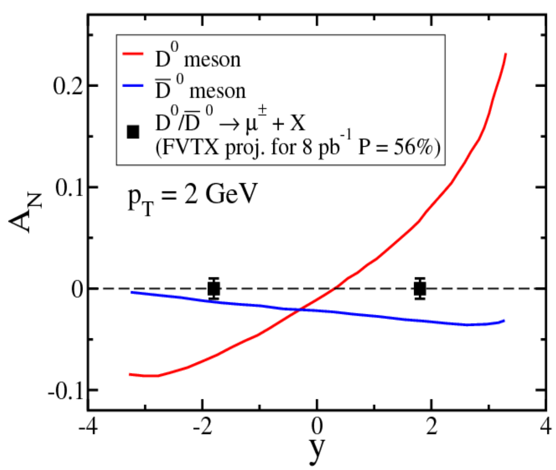


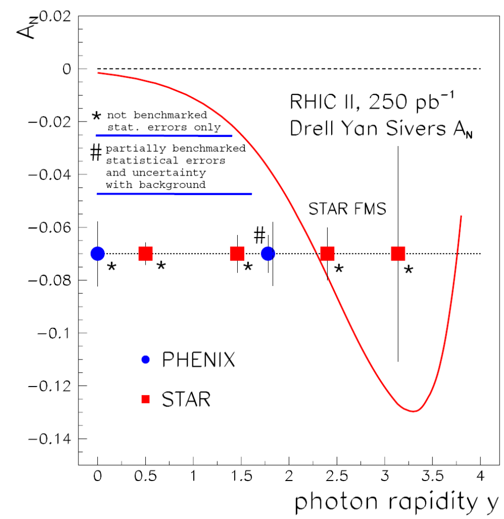
Summary and Outlook

- Spin puzzle
  - Gluon polarization
    - Large Δg ruled out
    - New probes, direct-photon, open charm …
    - Larger x-range in the future
- Sea quark polarization
  - First W asymmetry observed
  - Much improved results in the future
- Transverse spin physics
  - Large SSAs observed at RHIC
  - New study of QCD dynamics
    - Charm SSA
    - Drell-Yan SSA









backup

RHIC/PHENIX Spin Run History and Prospect

RHIC-RUN	Pol(%)	$L(pb^{-1})$	Results
2002	15%	0.15	first pol p+p run@RHIC! Transverse
2003	30%	0.35	π^0 cross section, $A_{LL}(\pi^0)$
2004	40%	0.12	Pol H-Jet, absolute beam polarization
2005	50%	3.5	$A_{LL}(\pi^0)$ ruled out large Δg, GRSV-Max-Like
2006	60%	7.5	first dedicated long spin run
		2.7	Transverse run
2007	--	--	NO spin run
2008	45%	5.2	short run for HI baseline pp physics
2009	35%	14	first 500GeV run!
	55%	16	200GeV

Goals

$800pb^{-1}$@500GeV
$300pb^{-1}$@200GeV

$300pb^{-1}$@500GeV
$70pb^{-1}$@200GeV

CAD(10.2009): From Run9 experience, reduced the "enhanced" design goals: P=70%, $\mathcal{L} = 3 \times 10^{31}\ cm^{-2}s^{-1}$ (or $\approx 7.5\ pb^{-1}$/week) at $\sqrt{s} = 200$ GeV

12-week Run Delivered: $90pb^{-1}$

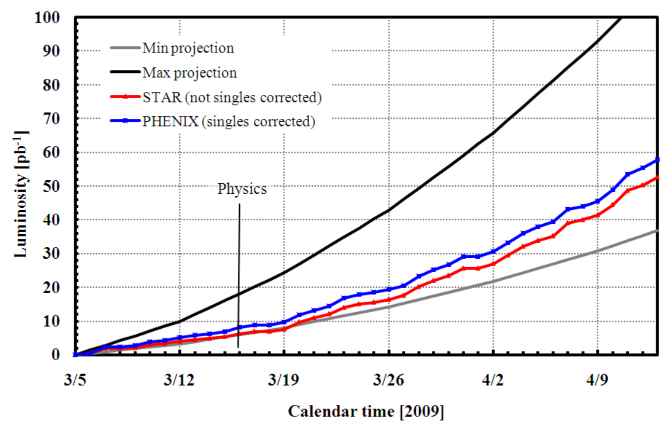
PHENIX(ε=1/3) = $30pb^{-1}$

With hardware upgrade, expect to achieve: 18~83 pb^{-1}/week@500GeV

12-week Run Delivered: 220~1000pb^{-1}

PHENIX(ε=1/2) = 100~500pb^{-1}

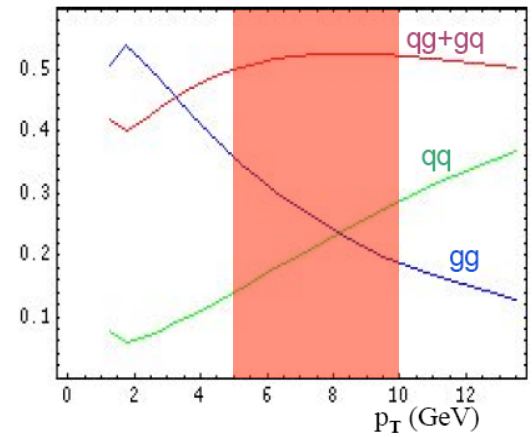
CAD Delivered Run9@500GeV

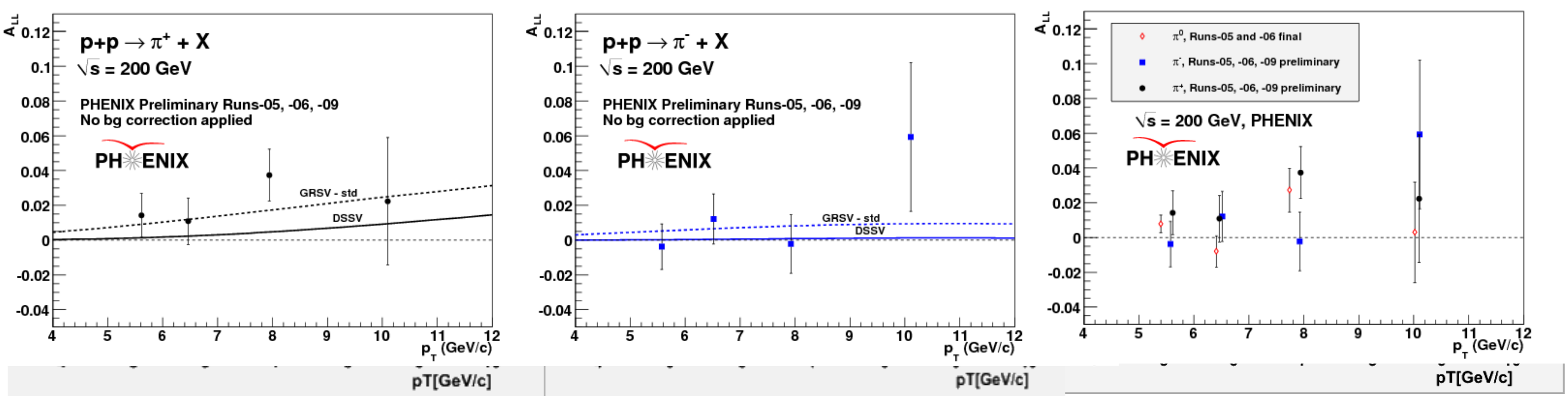


Charged Pion A_{LL}

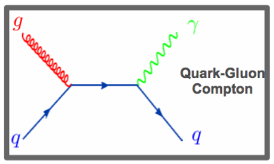
- Use RICH ($|\eta|<0.35$) to identify pions with $p_T>4.7$ GeV
  - Cross section in this region is dominated by qg scattering
- Favored/Disfavored FF → different *qg* contributions for π^+, π^0, π^- due to sign of Δu and Δd

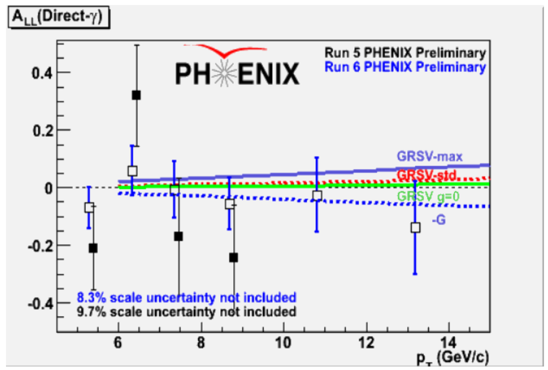
→ access sign of ΔG





Direct photon and η A_{LL}

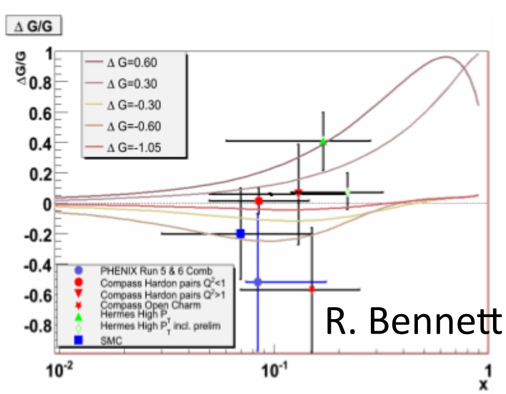




Direct Photon

- |η|<0.35
- Quark-gluon compton scattering process dominates (~80%)
- Limited statistics, but unique access to ΔG

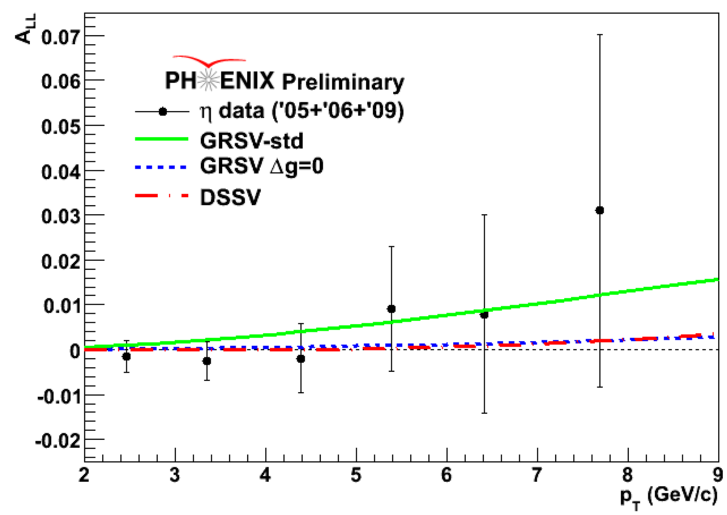
$$\frac{\Delta G(x_t)}{G(x_T)} = \frac{A_{LL}(p+p \to \gamma + X)|_{\theta=90^0}}{A_1^p(x_T) \times \hat{a}_{LL}(g+q \to \gamma + q)|_{\theta^*=90^0}}$$



R. Bennett

η

- (|η|<0.35)
- Analysis similar to π^0
- Fractional subprocess differ somewhat
- Independent confirmation of ΔG

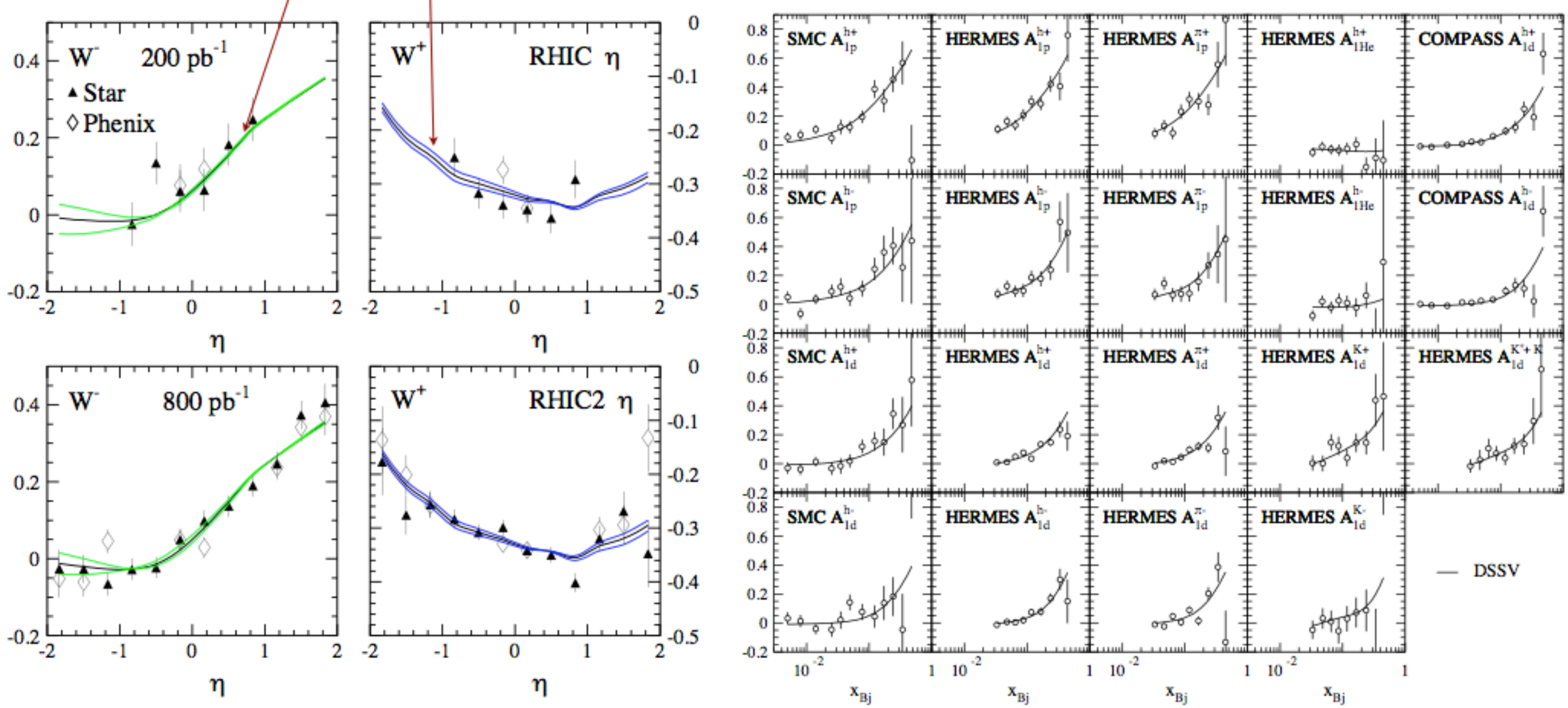


Effect of uncertainties on antiquark distributions over asymmetries

already pretty tight bands! (partly from SIDIS)

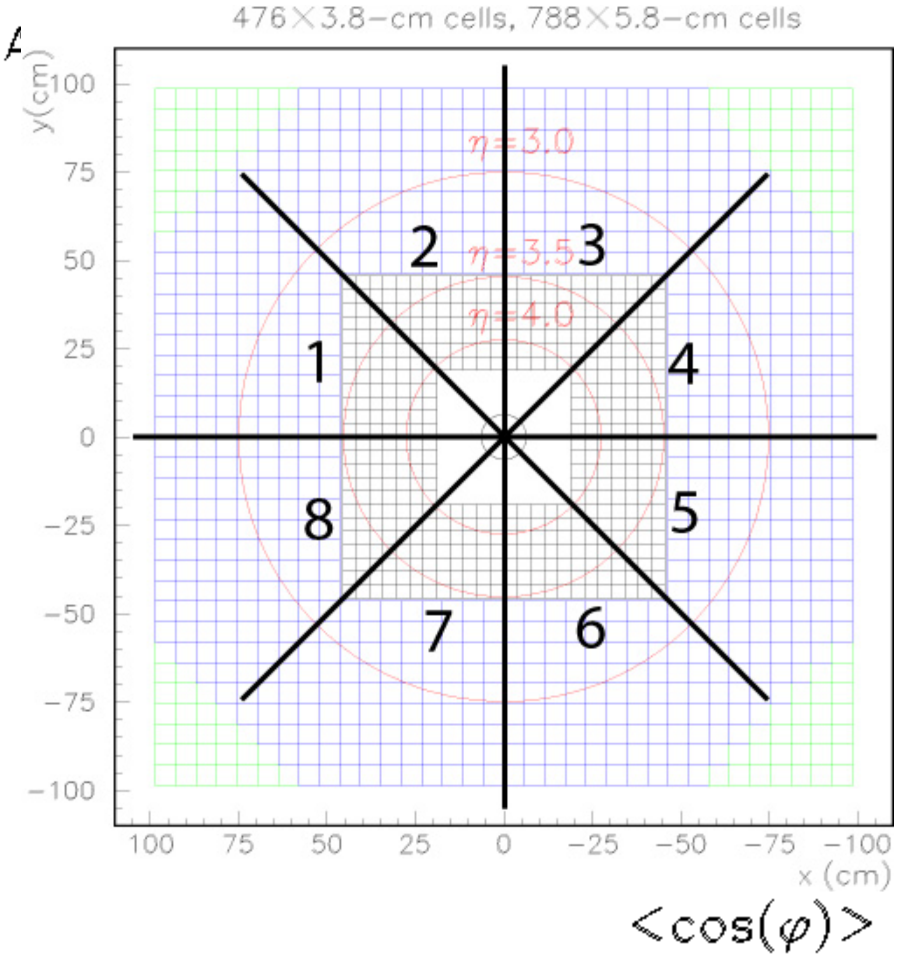
Daniel de Florian, RSC'09

$\Delta\bar{u}$ $\Delta\bar{d}$



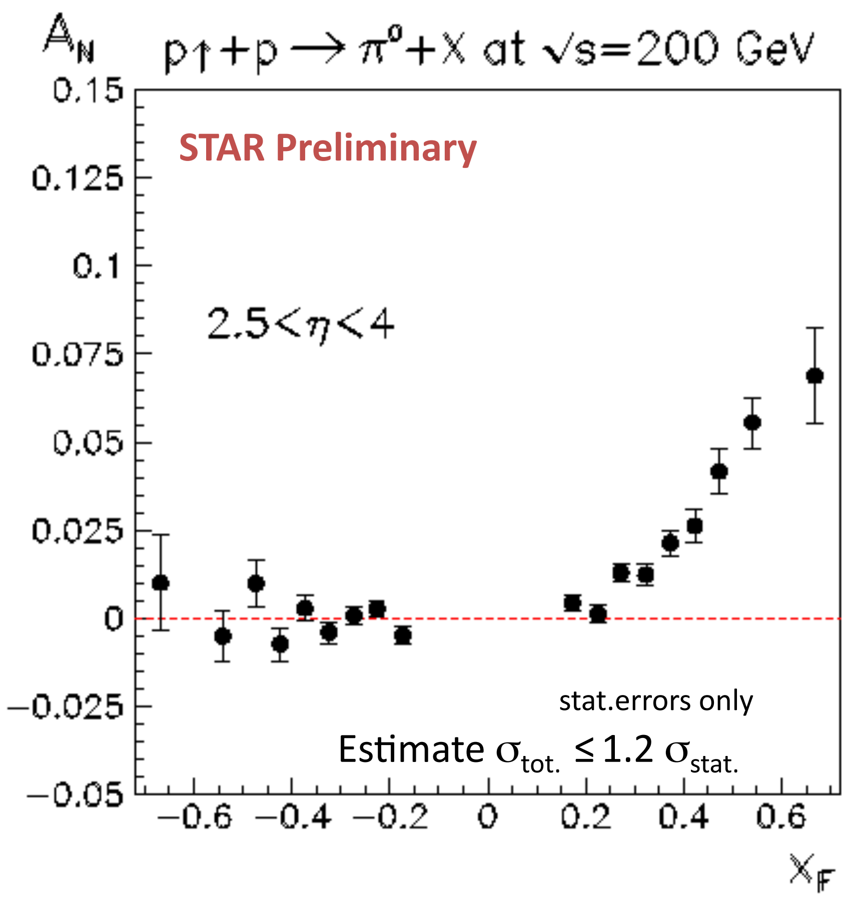
Preliminary Run8 FMS π^0 A_N

Azimuthal Angle Dependence of A_N



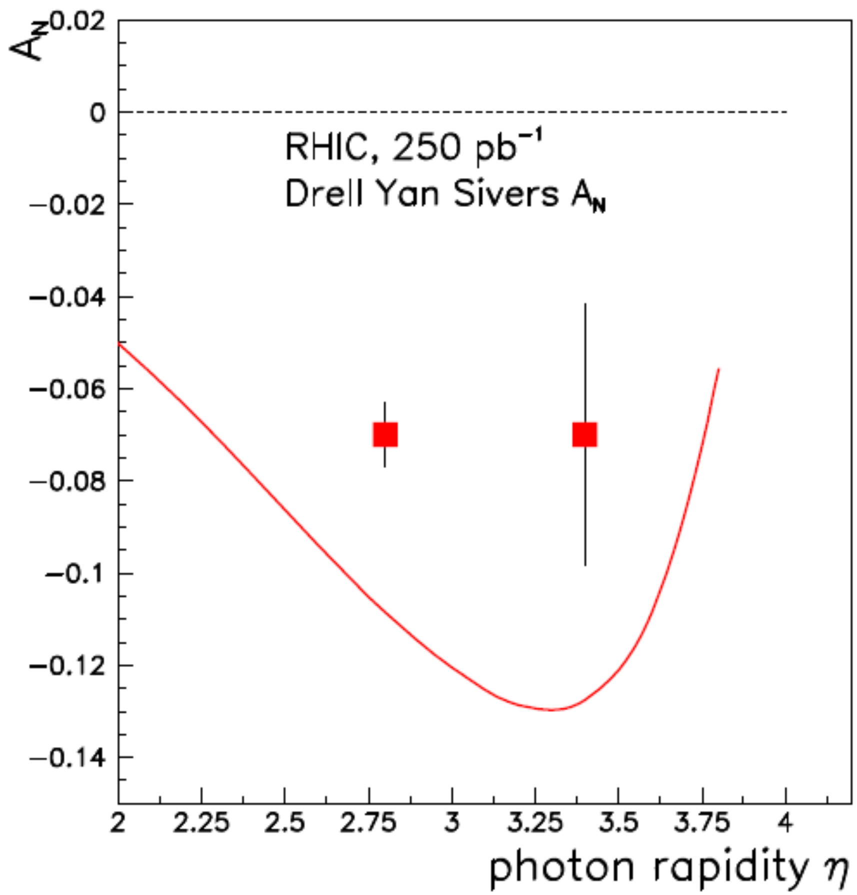
A_N vs. xF

→ Consistent with previous measurements



From SPIN08 talk by N. Poljack, arXiv:0901.2828

Sivers Asymmetries in Drell Yan (IV) Sensitivities with S-PHENIX



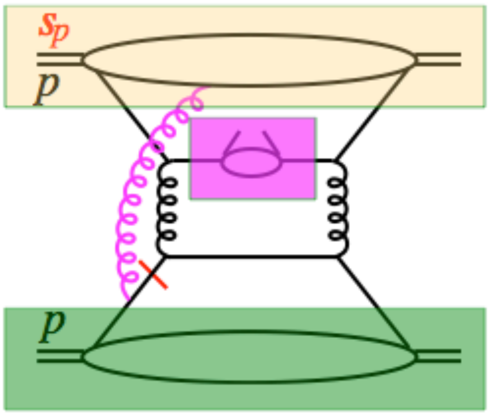
A_{UT} prediciton from Feng Yuan and Werner Vogelsang based on Hermes data.

Acceptance assumed to be $2.5 < \eta < 4$. Backgrounds assumed to be identical to background in PHENIX muon arms for Drell-Yan.

Presently the S-PHENIX forward acceptance is assumed to be $1 < \eta < 4$

Color Flow in Twist-3

Kang @this workshop

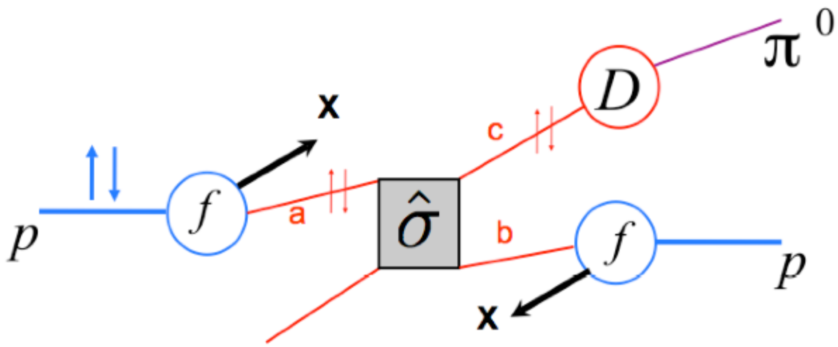


- **From polarized hadron**
- **From unpolarized hadron**
- **From fragmentation function**

$$
\begin{aligned}
\Delta\sigma_{A+B\to hX}(\ell_\perp,\vec{s}_T) &= \sum_{abc}\phi^{(3)}_{a/A}(x_1,x_2,\vec{s}_T)\otimes\phi_{b/B}(x')\otimes H_{ab\to c}(\ell_\perp,\vec{s}_T)\otimes D_{c\to h}(z) \\
&+ \sum_{abc}\delta q_{a/A}(x,\vec{s}_T)\otimes\phi^{(3)}_{b/B}(x'_1,x'_2)\otimes H'_{ab\to c}(\ell_\perp,\vec{s}_T)\otimes D_{c\to h}(z) \\
&+ \sum_{abc}\delta q_{a/A}(x,\vec{s}_T)\otimes\phi_{b/B}(x')\otimes H''_{ab\to c}(\ell_\perp,\vec{s}_T)\otimes D^{(3)}_{c\to h}(z_1,z_2)
\end{aligned}
$$

Generalized Parton Model

- Assume TMD factorization



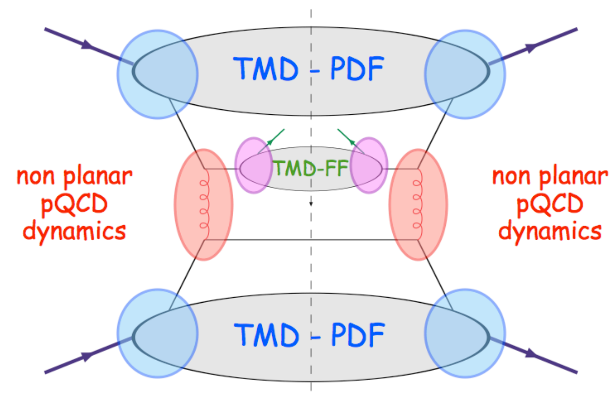
Anselmino et al.

- Spin-dependent cross section:

$$d\Delta\sigma \propto f_{1T}^{\perp}(x_a, k_{aT}) \otimes f_{b/B}(x_b, k_{bT}) \otimes H^{U}_{ab\to c} \otimes D_{h/c}(z_c, p_T)$$

- Spin-averaged cross section:

$$d\sigma \propto f_{a/A}(x_a, k_{aT}) \otimes f_{b/B}(x_b, k_{bT}) \otimes H^{U}_{ab\to c} \otimes D_{h/c}(z_c, p_T)$$

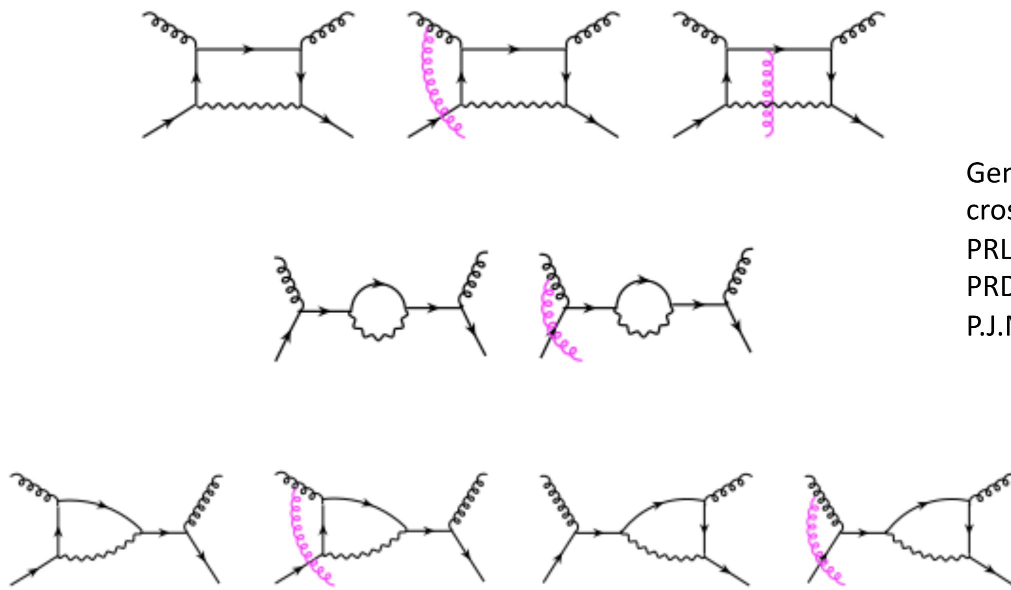


TMD factorization breakdown… a failure or an opportunity?

Mulders, Xiao..
@this workshop

Color modification of hard cross sections due to Gauge Link

Gamberg, Kang
@this workshop



Generalizing GPM… with modified hard cross sections (gluonic-pole cross sections)
PRL 99 (2007) A. Bacchetta et al,
PRD 72 (2005) A. Bacchetta, C.J. Bomhof, P.J.Mulders, F.Pijlman

Formula: Two partonic channel contribute to direct photon production:

- $qg \to \gamma q$:

$$H^{U}_{qg\to\gamma q} = \frac{1}{N_c} e_q^2 \left[-\frac{\hat{t}}{\hat{s}} - \frac{\hat{s}}{\hat{t}} \right]$$
$$H^{\rm Inc}_{qg\to\gamma q} = -\frac{N_c}{N_c^2-1} e_q^2 \left[-\frac{\hat{t}}{\hat{s}} - \frac{\hat{s}}{\hat{t}} \right]$$

- $q\bar{q} \to \gamma g$:

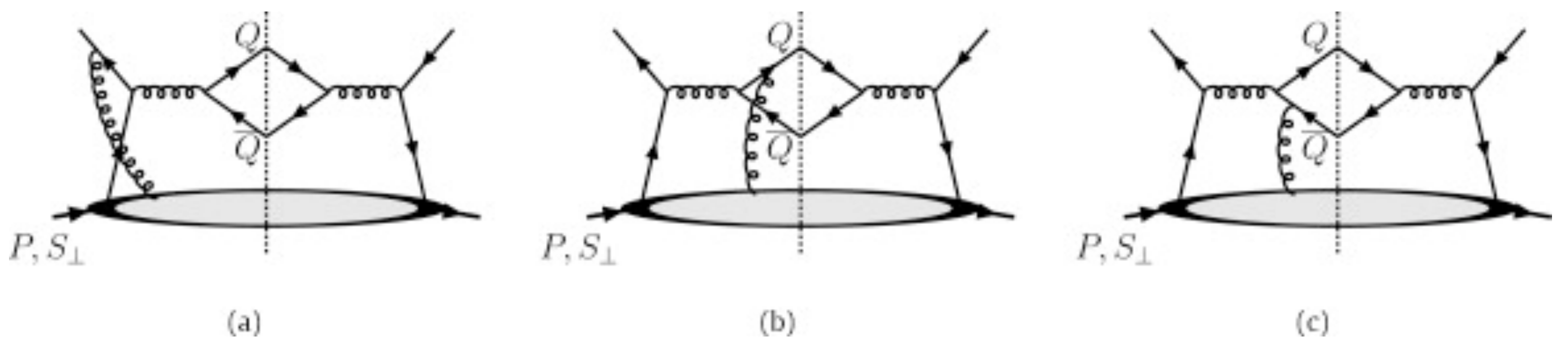
$$H^{U}_{q\bar{q}\to\gamma g} = \frac{N_c^2-1}{N_c^2} e_q^2 \left[\frac{\hat{t}}{\hat{u}} + \frac{\hat{u}}{\hat{t}} \right]$$
$$H^{\rm Inc}_{q\bar{q}\to\gamma g} = \frac{1}{N_c^2} e_q^2 \left[\frac{\hat{t}}{\hat{u}} + \frac{\hat{u}}{\hat{t}} \right]$$

Heavy Quark TSSA (I)
Twist-3 quark-gluon correlation

- Different color factors for charm and anti-charm

$$q + \overline{q} \to c\overline{c}$$

F. Yuan and J. Zhou PLB 668 (2008) 216-220



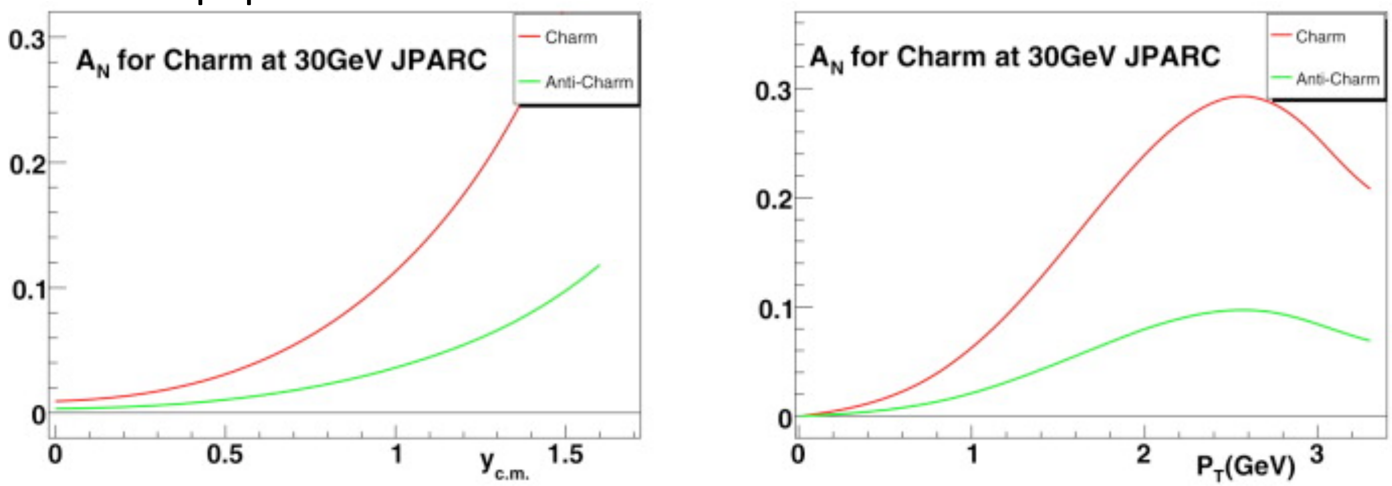
$\sim \frac{1}{2N_C}$ Initial state

$\sim \frac{N_C^2 - 2}{2N_C}$ Charm

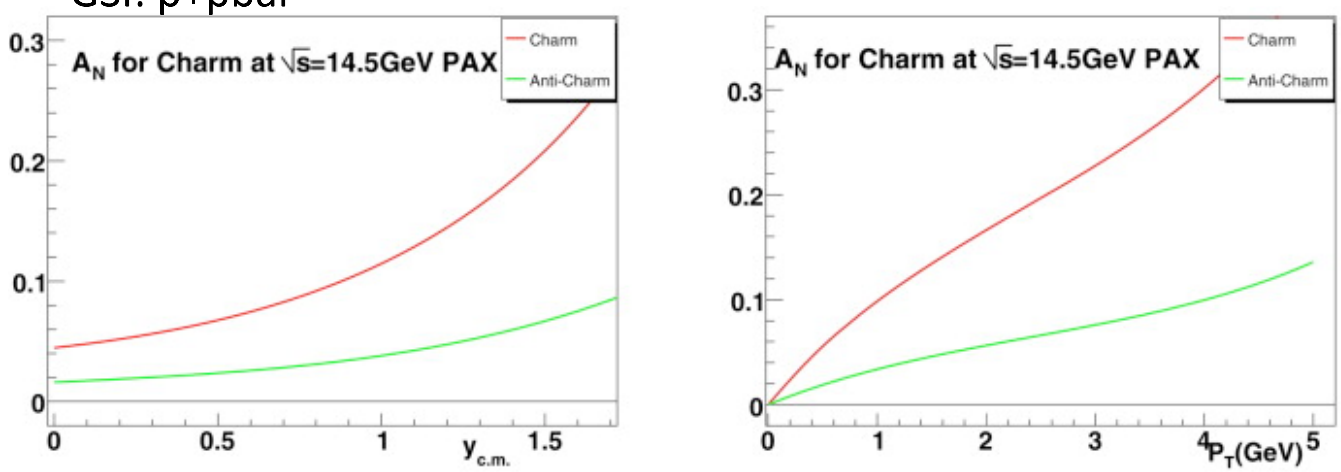
$\sim \frac{2}{2N_C}$ Anti-charm

$$A_N : q + \overline{q} \rightarrow c\overline{c}$$

JPARC p+p



GSI: p+pbar



Heavy Quark SSA (II)

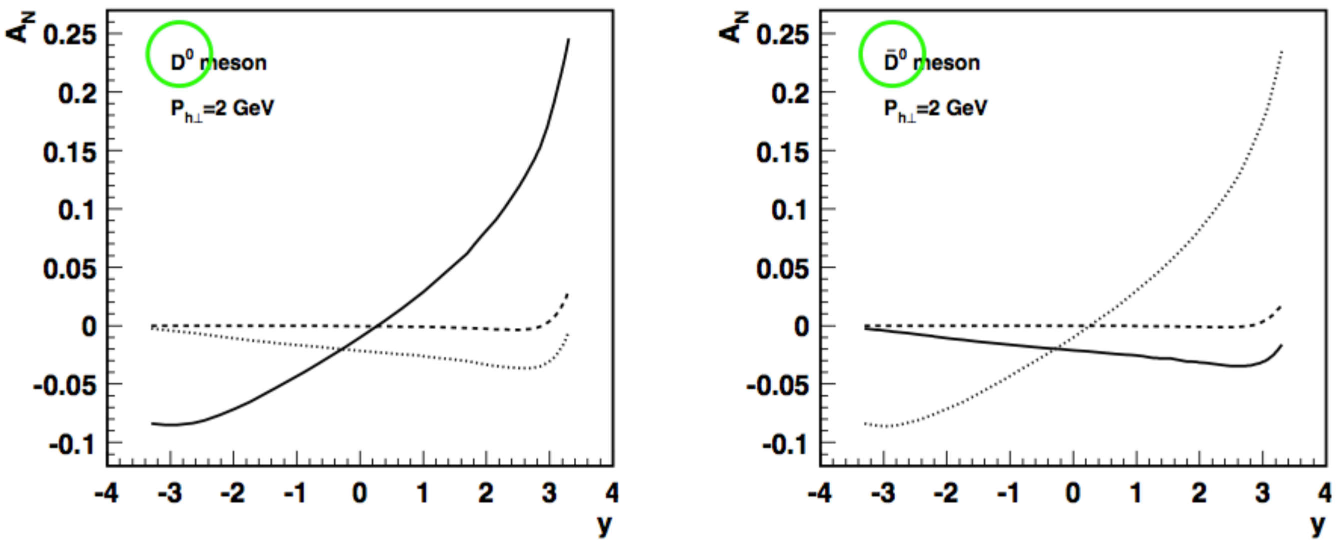
Twist-3 tri-gluon correlation

$$g + g \rightarrow c + \bar{c}$$

- Consequence of different color factors for charm and anti-charm

Rapidity dependence of D-meson production

SSA at RHIC: $\sqrt{s} = 200$ GeV $\quad \mu = \sqrt{m_c^2 + P_{h\perp}^2} \quad m_c = 1.3$ GeV



Kang, Spin2008

Solid: $(1)\lambda_f = \lambda_d = 0.07$ GeV $\quad T_G^{(d)} = T_G^{(f)}$

Dashed: $(2)\lambda_f = \lambda_d = 0 \quad T_G^{(d)} = T_G^{(f)} = 0$

Dotted: $(3)\lambda_f = -\lambda_d = 0.07$ GeV $\quad T_G^{(d)} = -T_G^{(f)}$

$$\boxed{A_N(D) = A_N(\overline{D}) \text{ if } T_G^{(d)} = 0}$$